Star formation in galaxies (main processes and tracers)

Darko Donevski, SISSA, Trieste, Italy

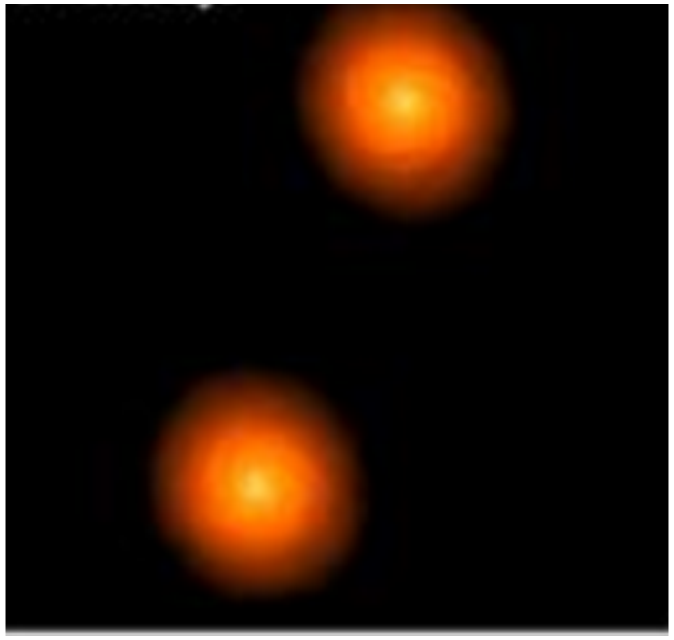
Evolution of a chess game = evolution of galaxies

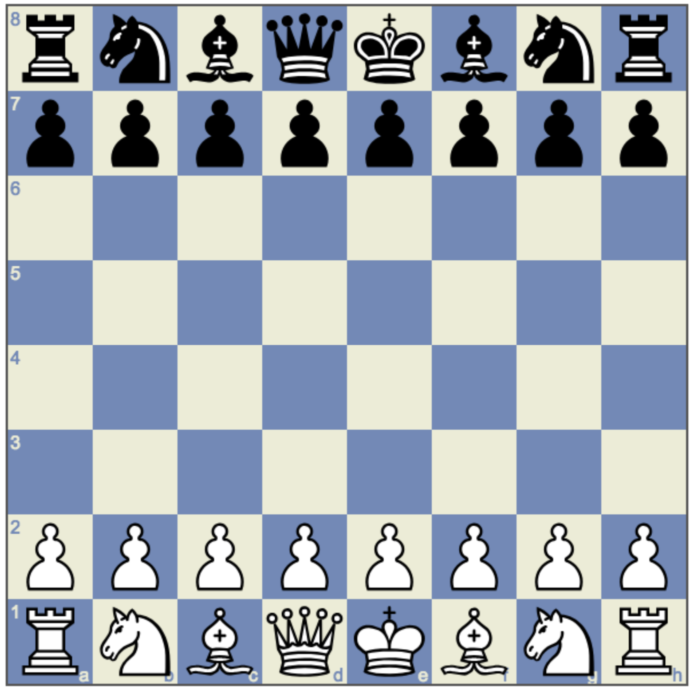
Astronomy is like poetry…

When I heard the learn'd astronomer;
When the proofs, the figures, were ranged in columns before me;
When I was shown the charts and diagrams, to add, divide, and measure them;
When I, sitting, heard the astronomer where they lectured with much applause in the lecture-room,
How soon, unaccountable, I became tired and sick;
Till rising and gliding out, I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

Walt Whitman

Evolution of a chess game = evolution of galaxies

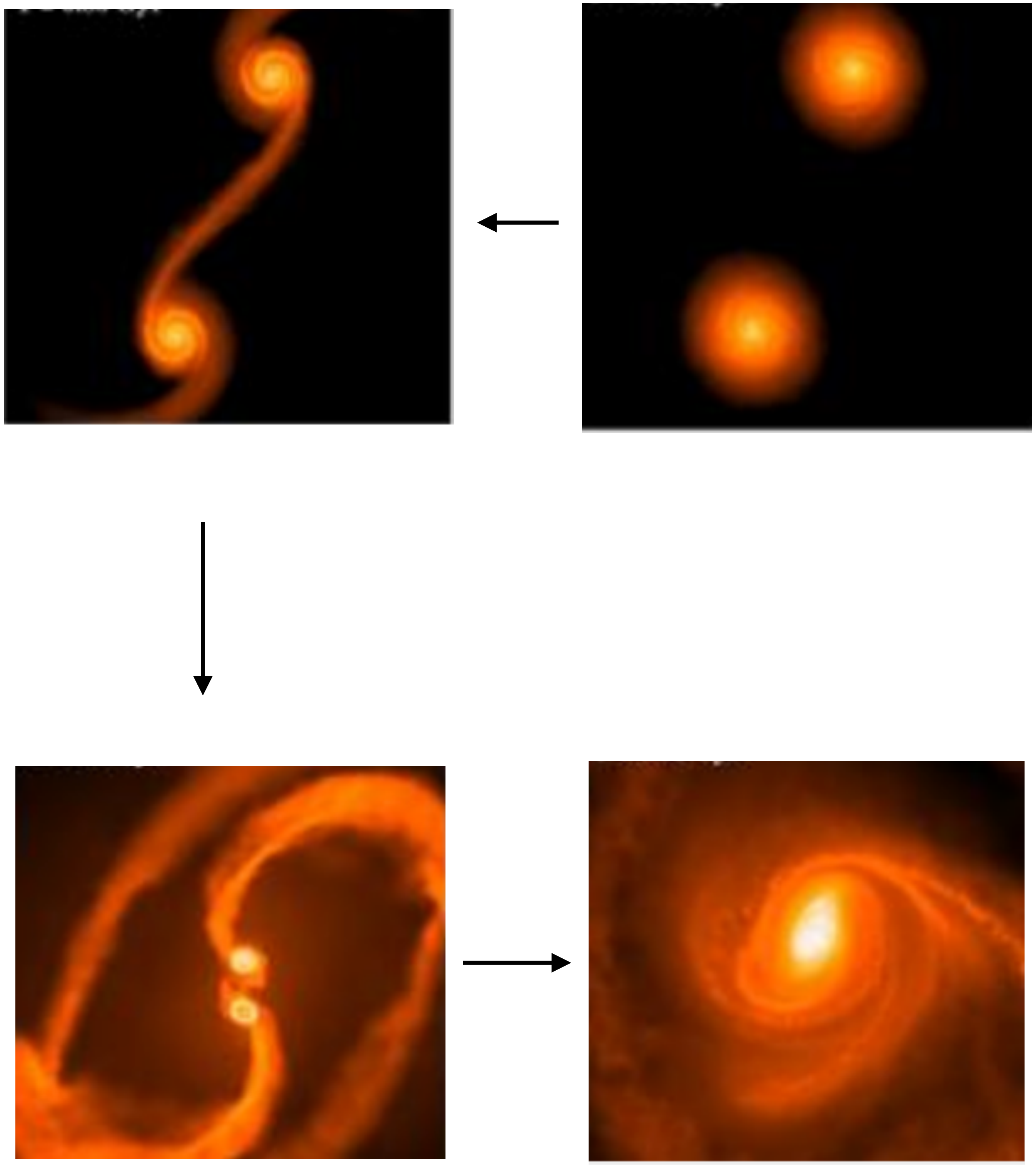




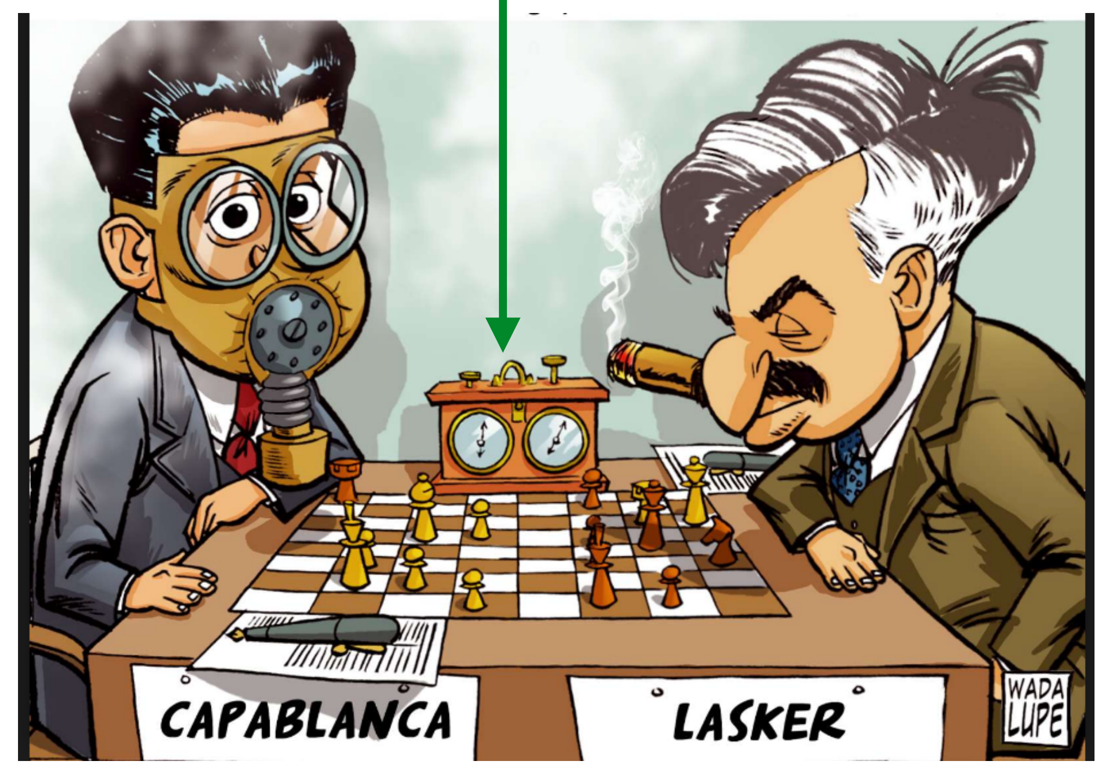
but, Universe is more like a chess game
(and poetry as well) :

Everything starts from the homogeneous beginning

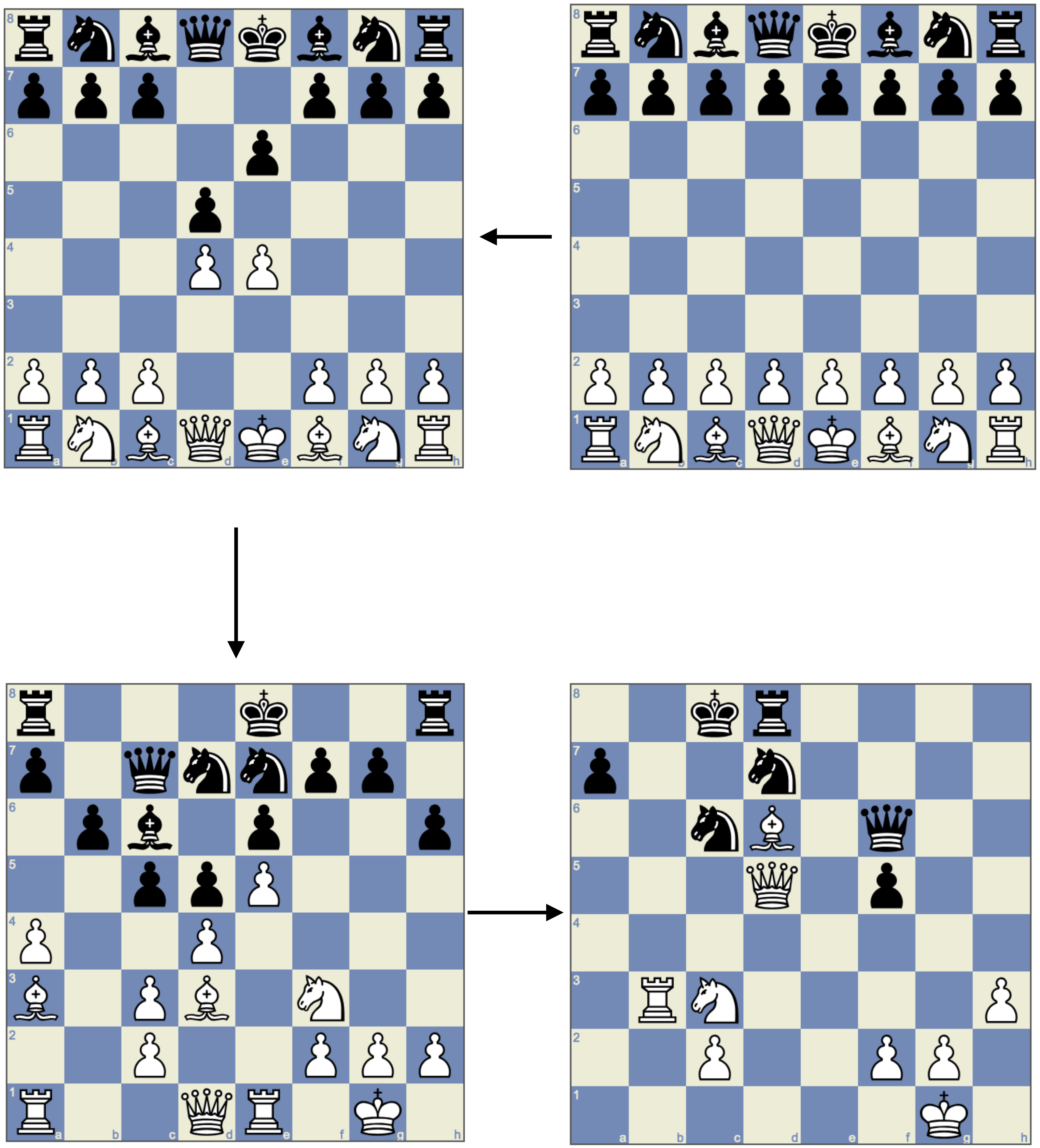
Evolution of a chess game = evolution of galaxies



And evolves with the time



Evolution of a chess game = evolution of galaxies



This is the **evolution** of some of the most beautiful games that former world champion Bobby Fischer played !

Why worrying about star-formation in the Universe?

1. **How the galaxies form their stars?**
2. **How are the galaxy fed by fresh gas? How is the gas accretion regulated/stopped ?**
3. **Why infrared observations are crucial to unveil the history of sta formation?**
4. **How and why do galaxy properties evolve? How is the stellar mass of galaxies assembled across cosmic times (star formation mergers)?**
5. **How do the star-forming galaxies trace larger scale structures ?**

Lecture 1

Lecture 2

Lecture 3-4

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Lecture 1

Lecture 2

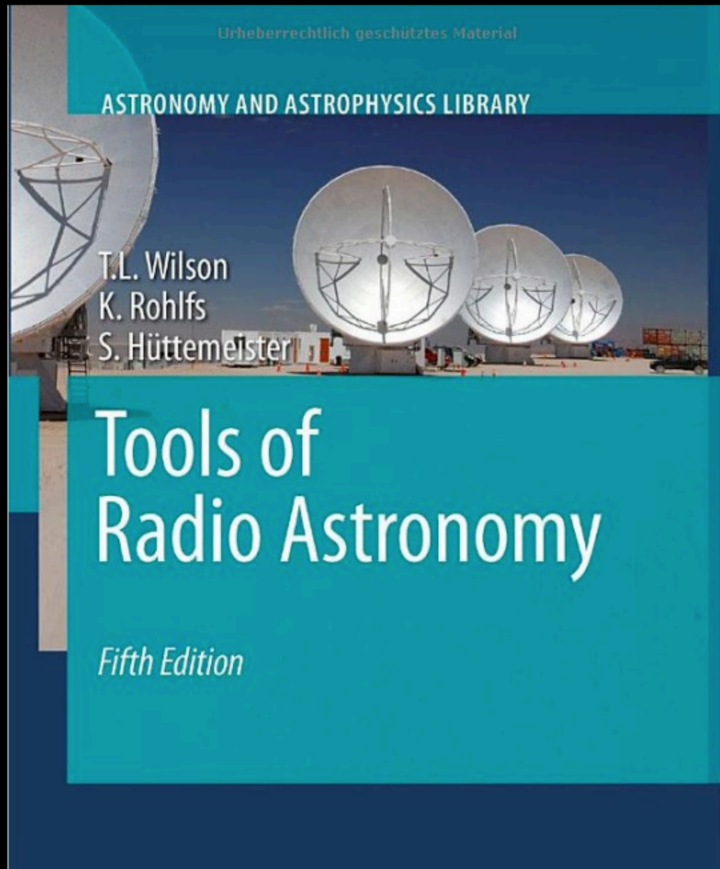
Lecture 3-4

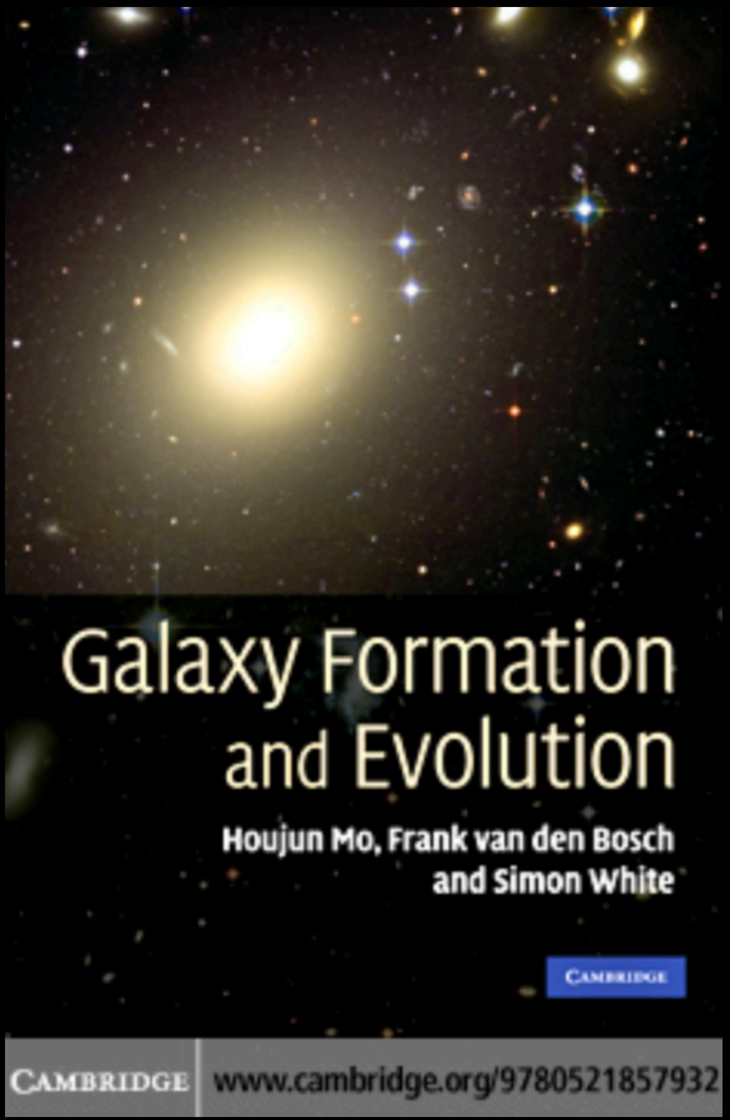
I Rumble in the jungle
or
Connecting dark matter halos & baryons

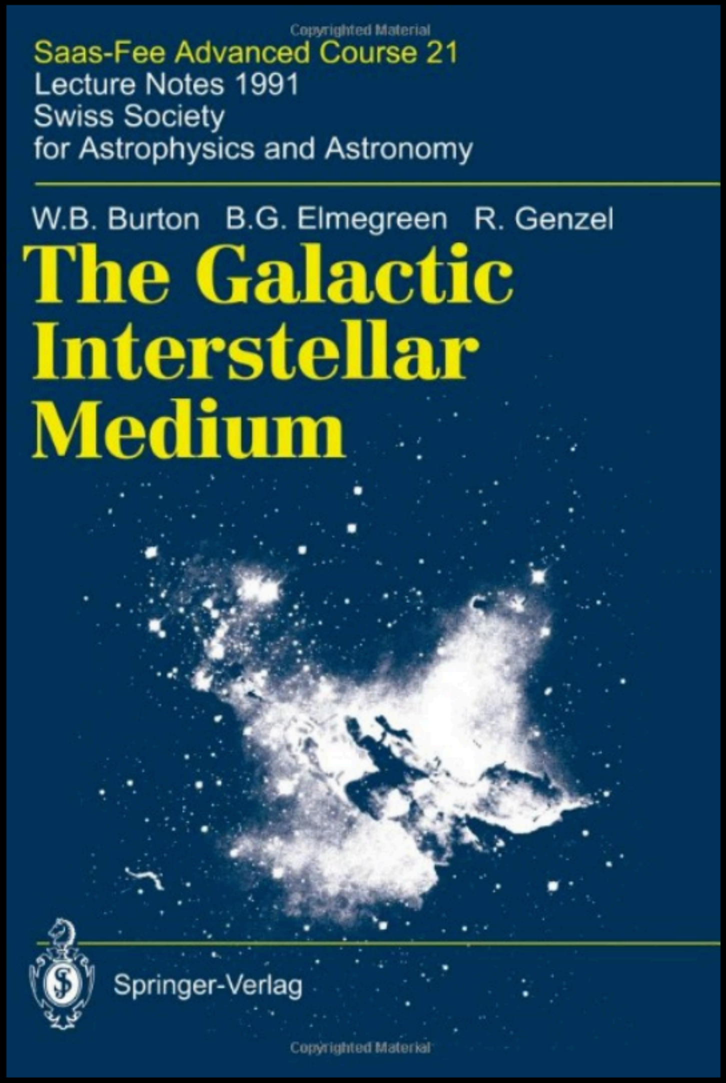
"Why we have problems understanding stellar content in the Universe?"

For those who don’t know… :)

Rumble in the jungle







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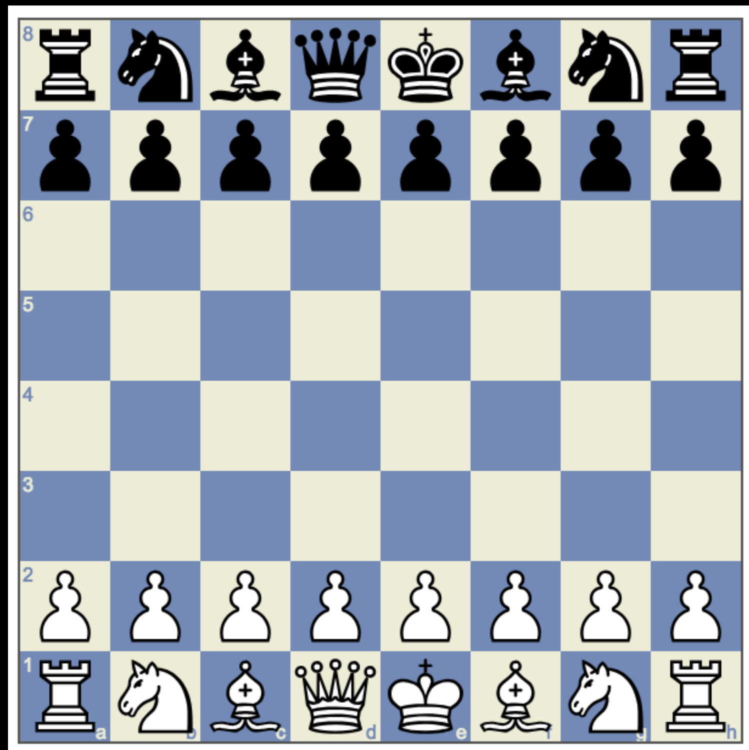
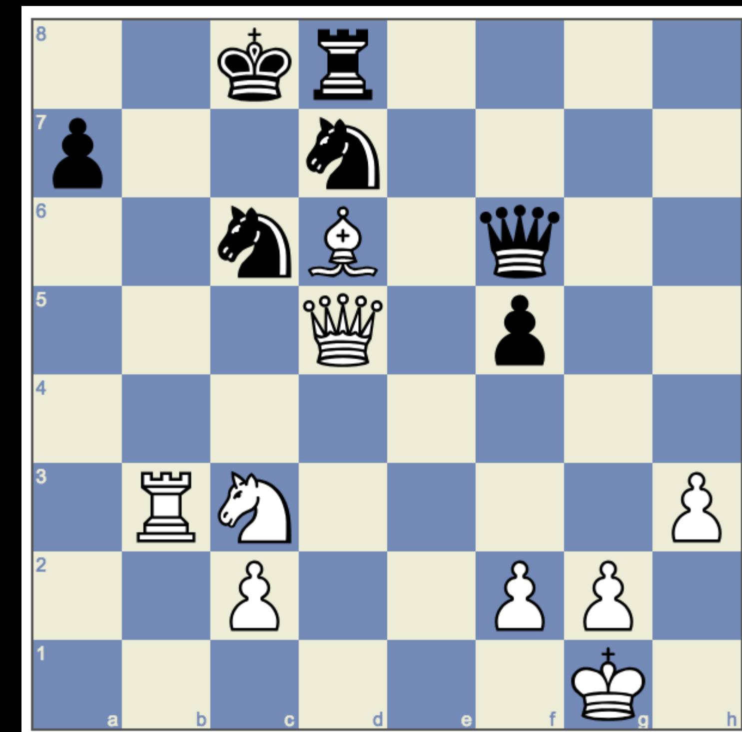
Dusty star-forming galaxies at high redshift

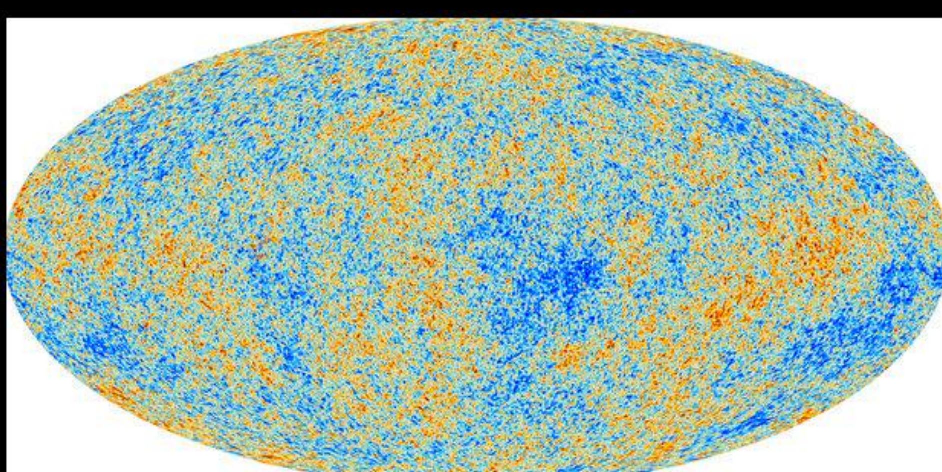
Caitlin M. Casey[a,b,*], Desika Narayanan[c], Asantha Cooray[a]

Evolution = change of heritable characteristics of populations over successive generations

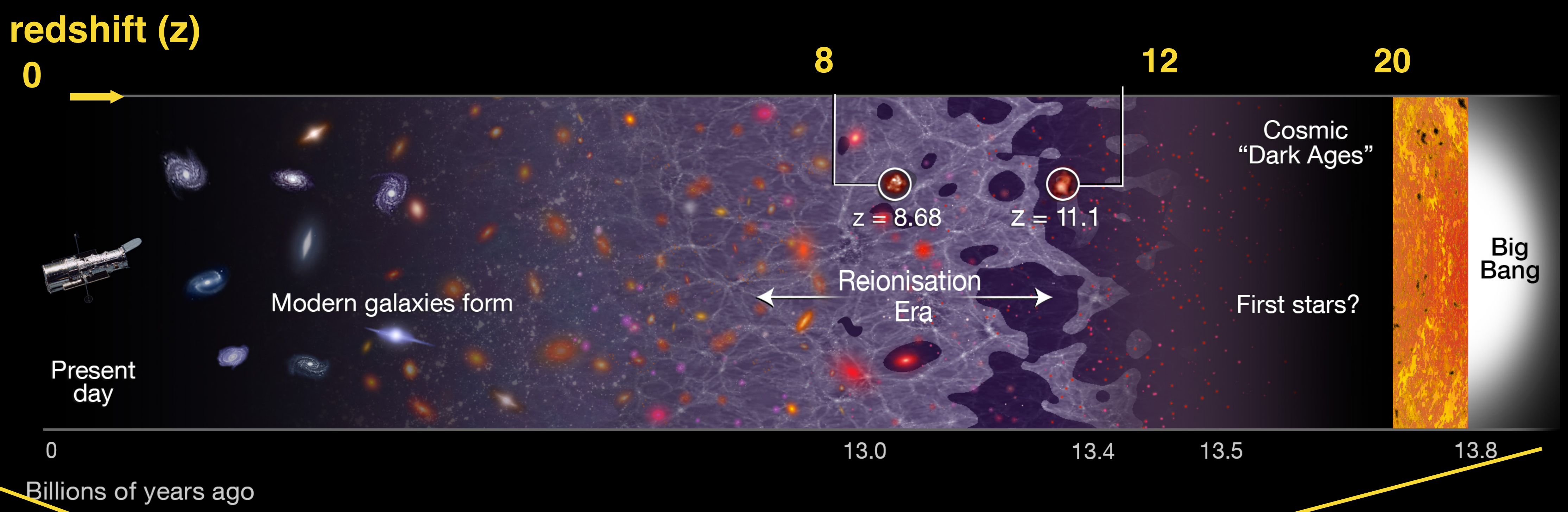




Evolution of galaxies can be understood as a chess game:
we need to understand heterogenious end from the homogenious beggining.



Galaxy formation and evolution in a nutshell



- Galaxy formation and evolution = study which explores how did the Universe evolve from homogeneous beginning to heterogeneous end.

- Three widely complex aspects:

(1) Cosmology

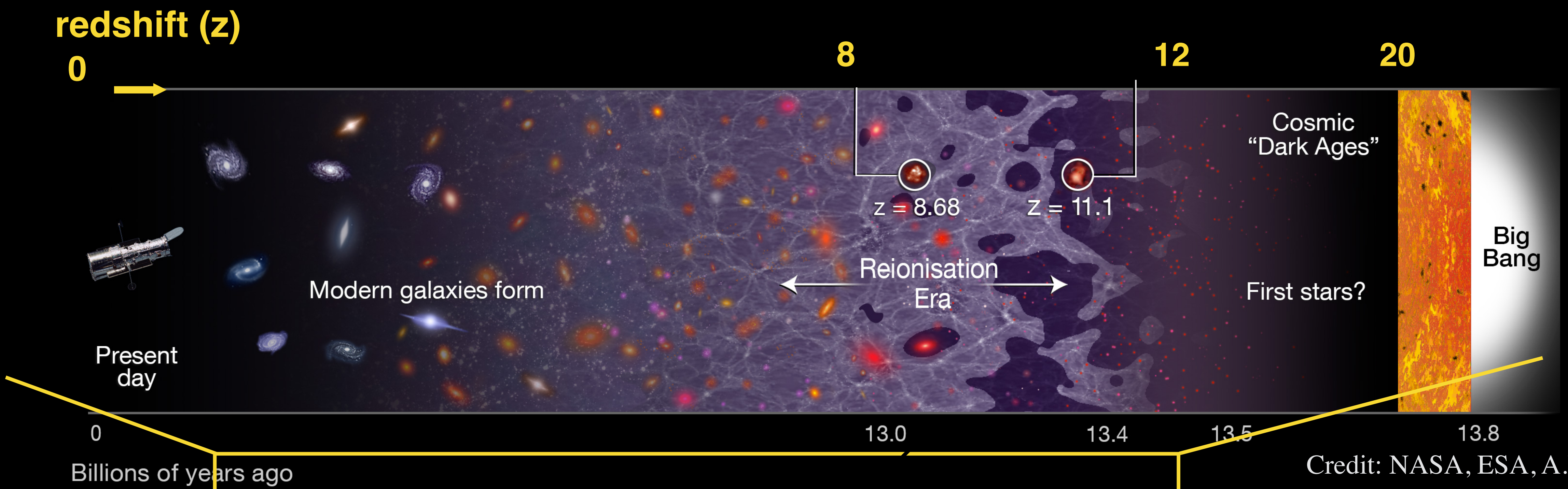
(2) Initial conditions

(3) Physics

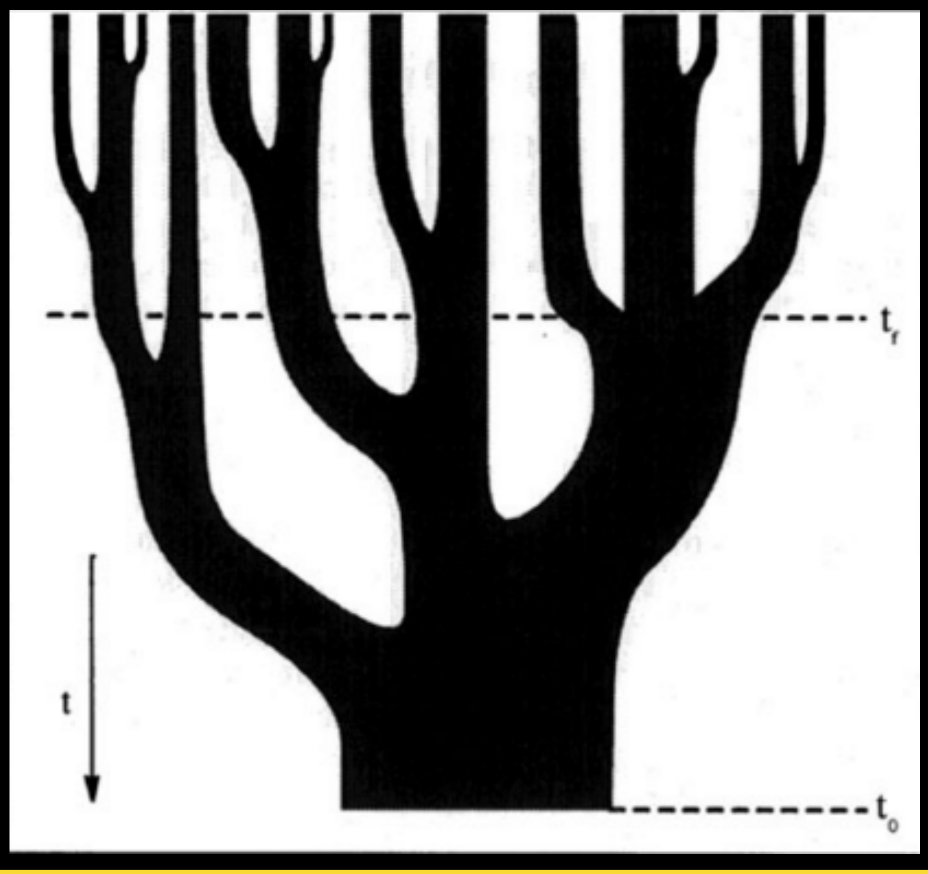
- The spatial scale diversity of about 20 orders of magnitude, from Universe itself to individual stars.

Galaxy formation and evolution in a nutshell

Galaxy formation and evolution in a nutshell



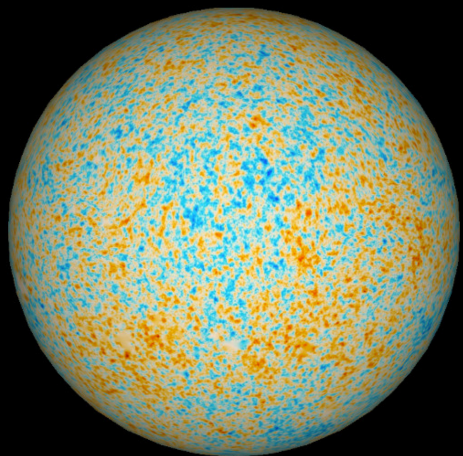
Credit: NASA, ESA, A.Field



In the early Universe, Dark Matter (DM) halos started to grow...

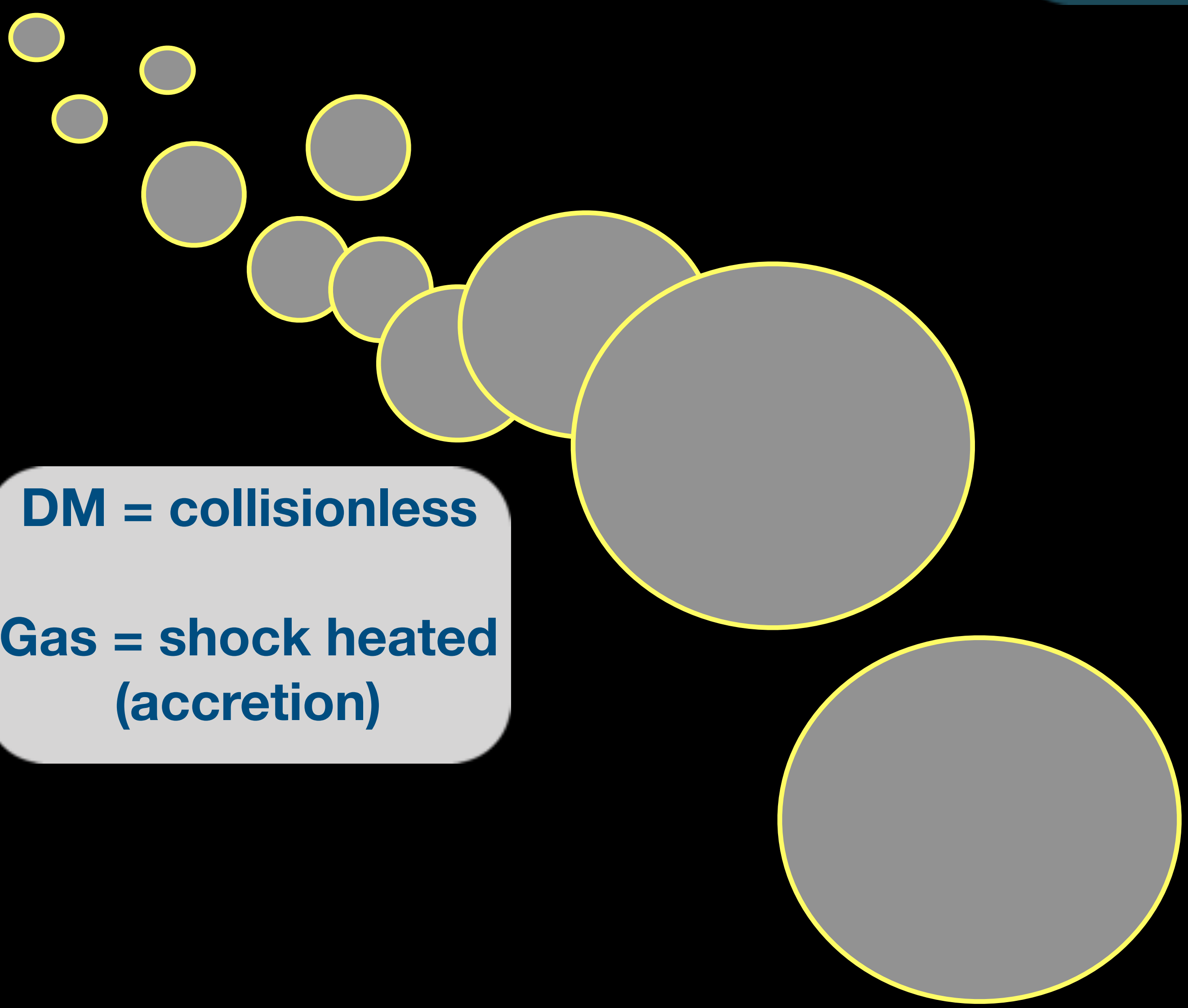
Bottom-up process, like a tree :)

Galaxy formation and evolution in a nutshell



➡ Small mass fluctuations in the early Universe = seeds of the structure formation !

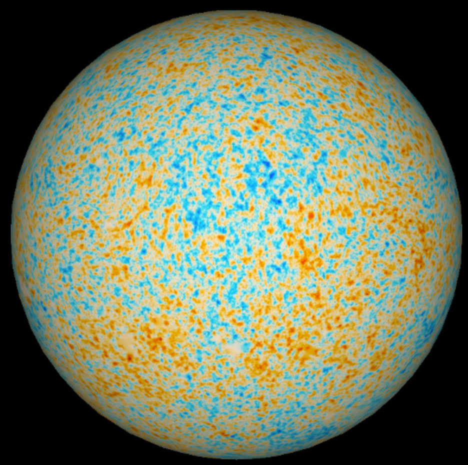
➡ Dark matter halos (DM halos) collapse from ambient background —> tracing the initial mass distribution !



DM = collisionless

Gas = shock heated (accretion)

Galaxy formation and evolution in a nutshell



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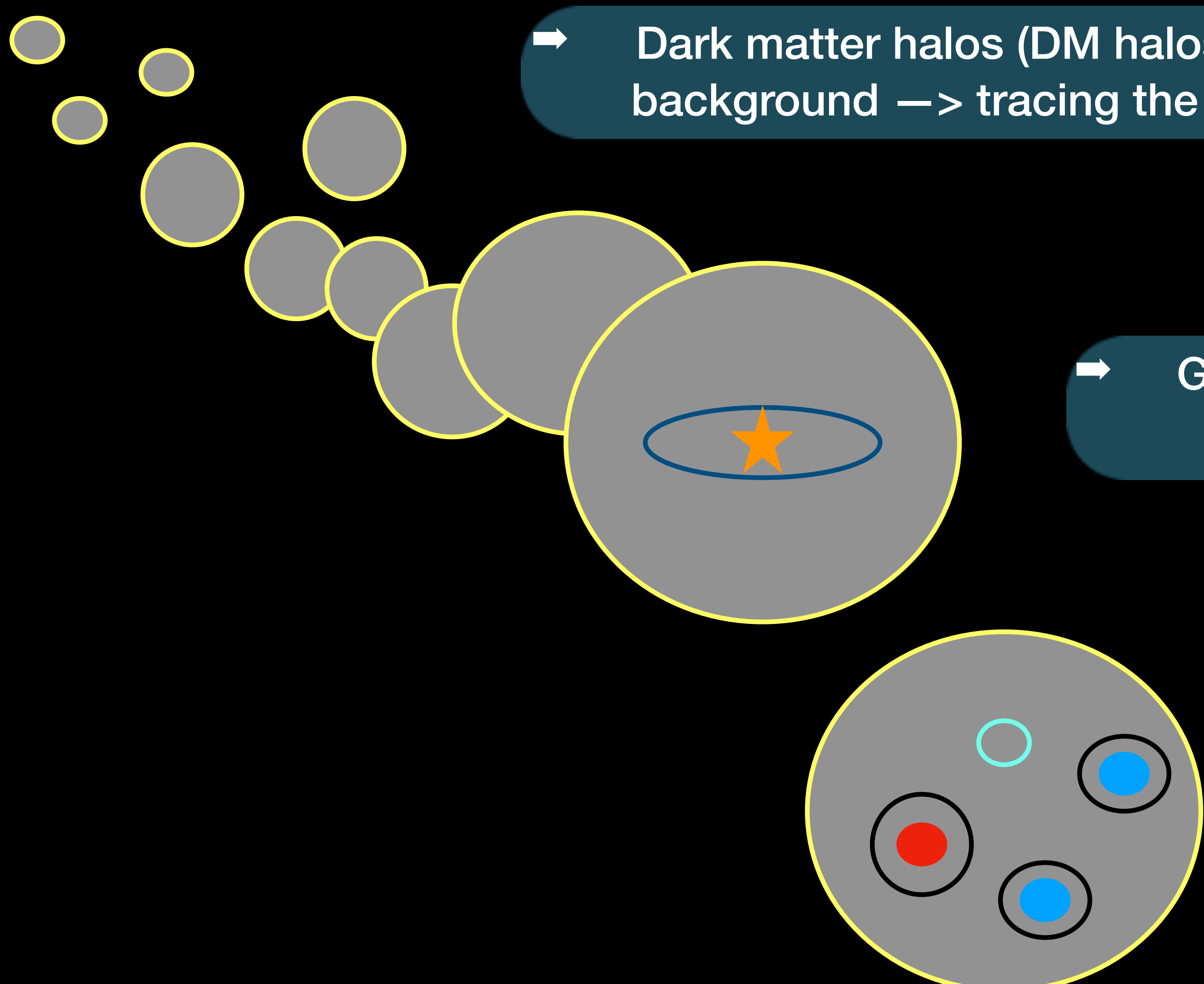
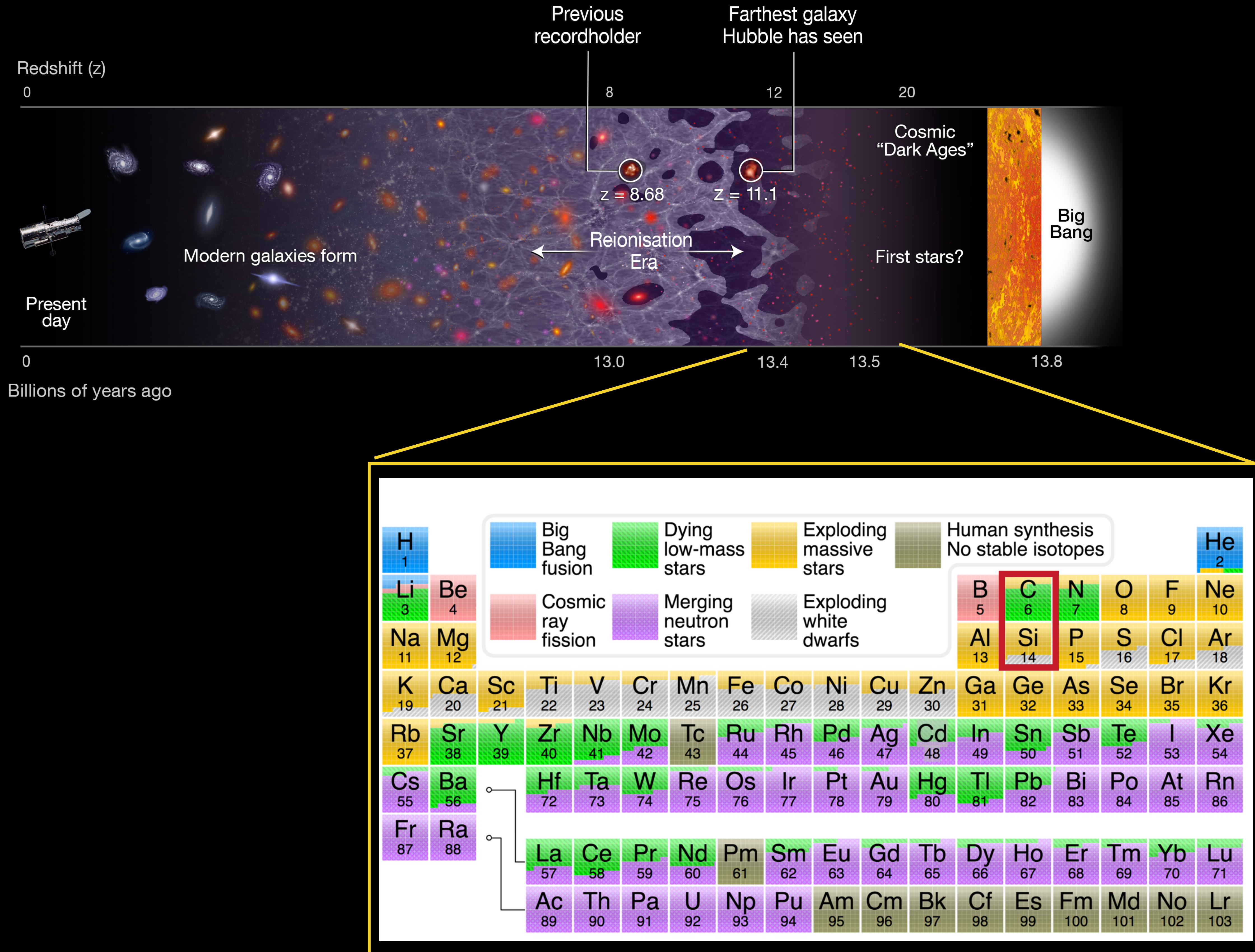


➡ Gas cools and condense… this is crucial step which allows star-formation…

➡ Dark matter halo collection of sub halos - some of the filled with galaxies, some not.

Galaxy formation and evolution in a nutshell



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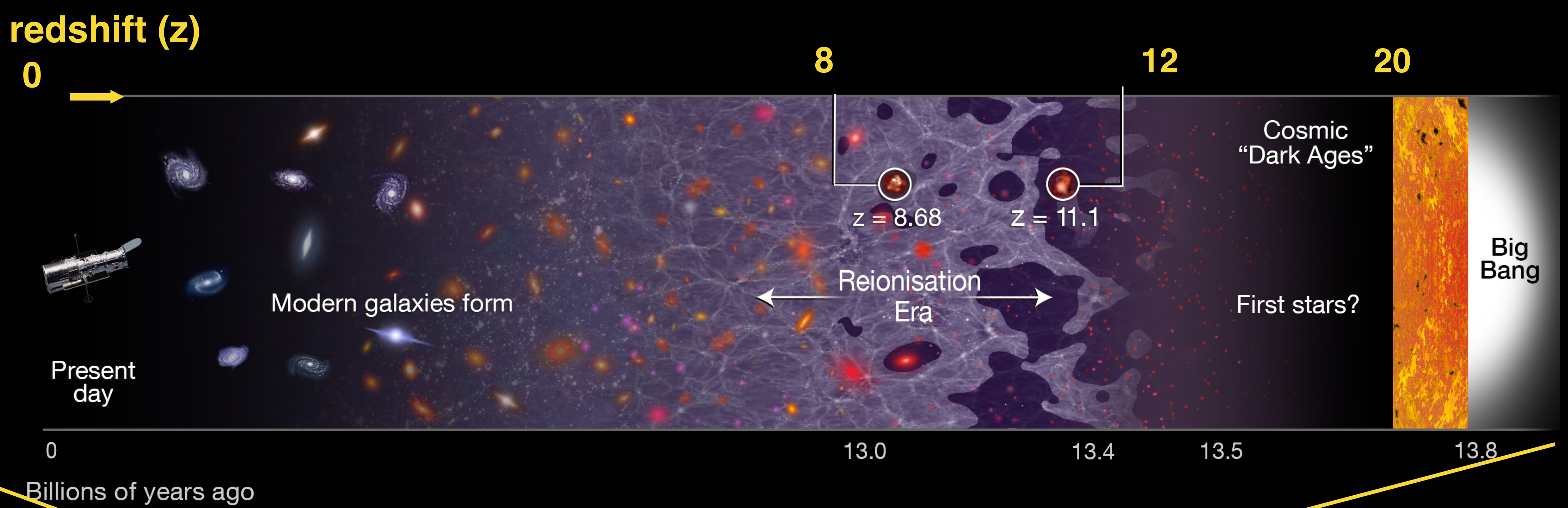
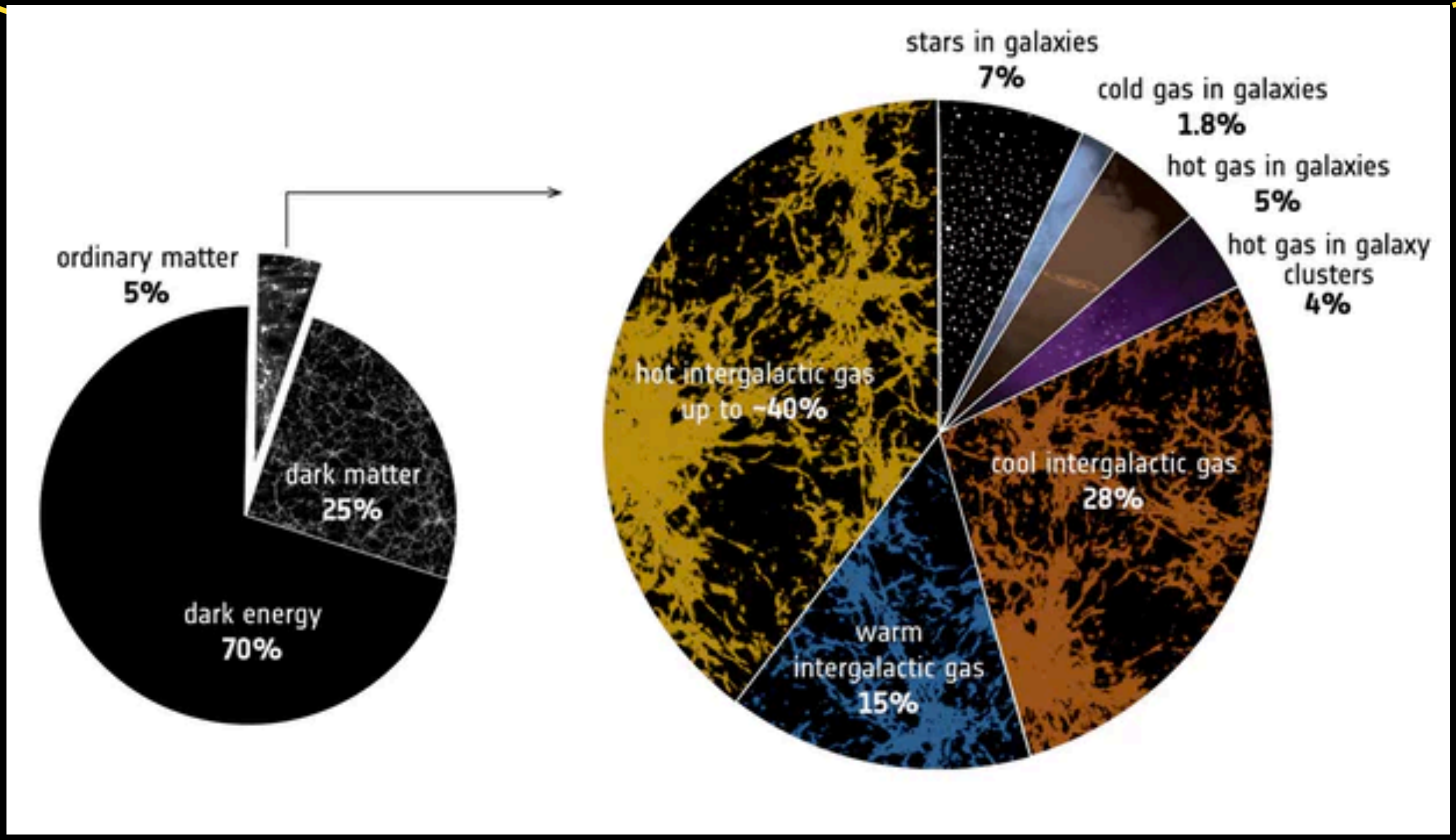




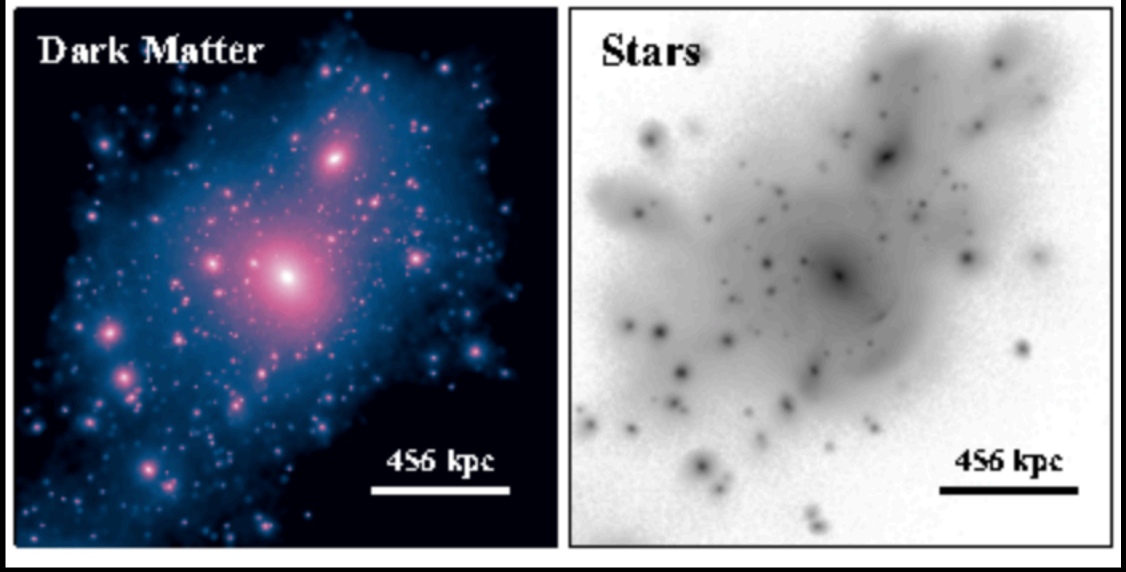
Credit: NASA, ESA, A.Field

What we know from simulations?

Simulations great and small

Some models operate at cosmic scales, whereas others generate individual, realistic-looking galaxies (left). They divide space into volume elements or model matter as swarms of particles, then trace their interactions.

NAME	SIMULATION SIZE (LIGHT-YEARS)	NUMBER OF VOLUME ELEMENTS/PARTICLES	MINIMUM ELEMENT MASS (SOLAR MASSES)	FOCUS	FIRST PAPERS
Millennium	2.2 billion	10 billion	1 billion	Dark matter only	2005
VELA	45 million	500 million	1000	Individual galaxies	2009
◄ **FIRE**	3 million–10 million	Few hundred million–1 billion	200–2000	Individual galaxies	2014
EAGLE	80 million–325 million	100 million–7 billion	1.8 million	Cosmic evolution	2014
BlueTides	1.9 billion	700 billion	2 million	First galaxies	2015
IllustrisTNG	110 million–1 billion	270 million–30 billion	1 million–10 million	Cosmic evolution	2018

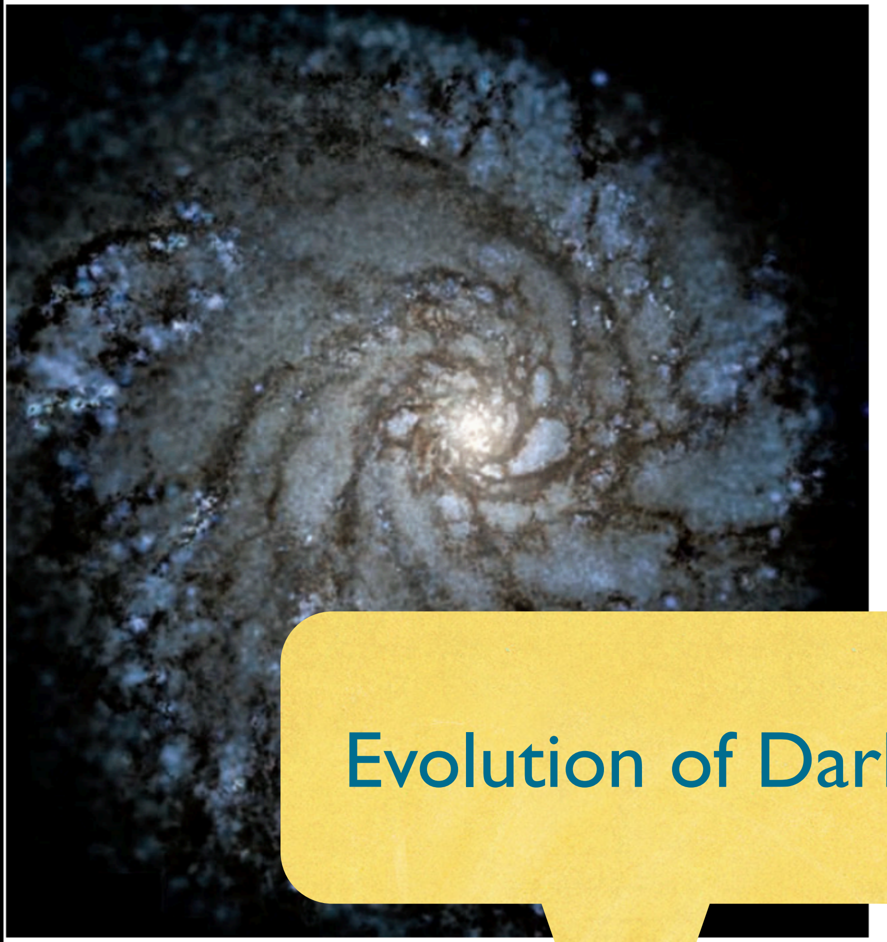


MESSAGE No.1

Very nice progress, BUT…

Existing simulations have problem in making star-forming galaxies !!!

1.1 What we learnt from MHD simulations?



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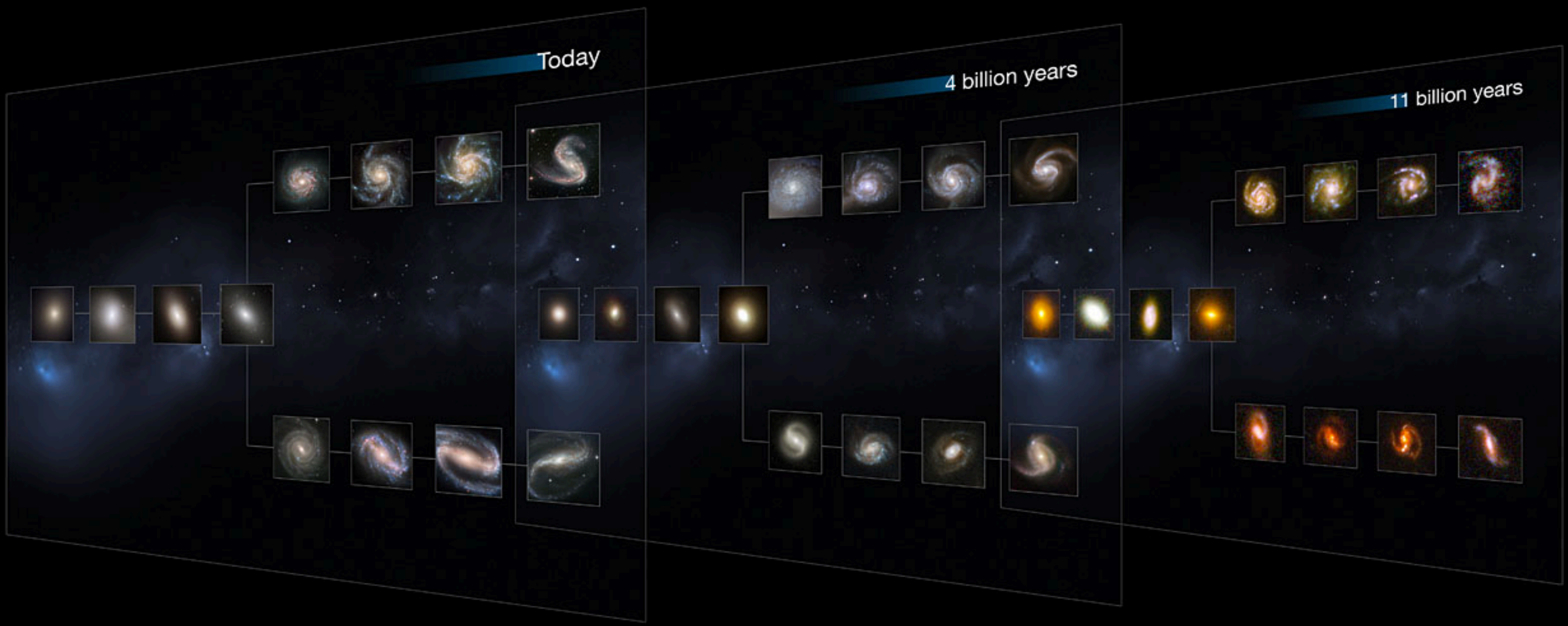
Evolution of Dark Matter

Evolution of baryons

II From fluctuation to star-formation: global view from galaxy models

“ How do stars can shine within halos? “

2. General view of star formation



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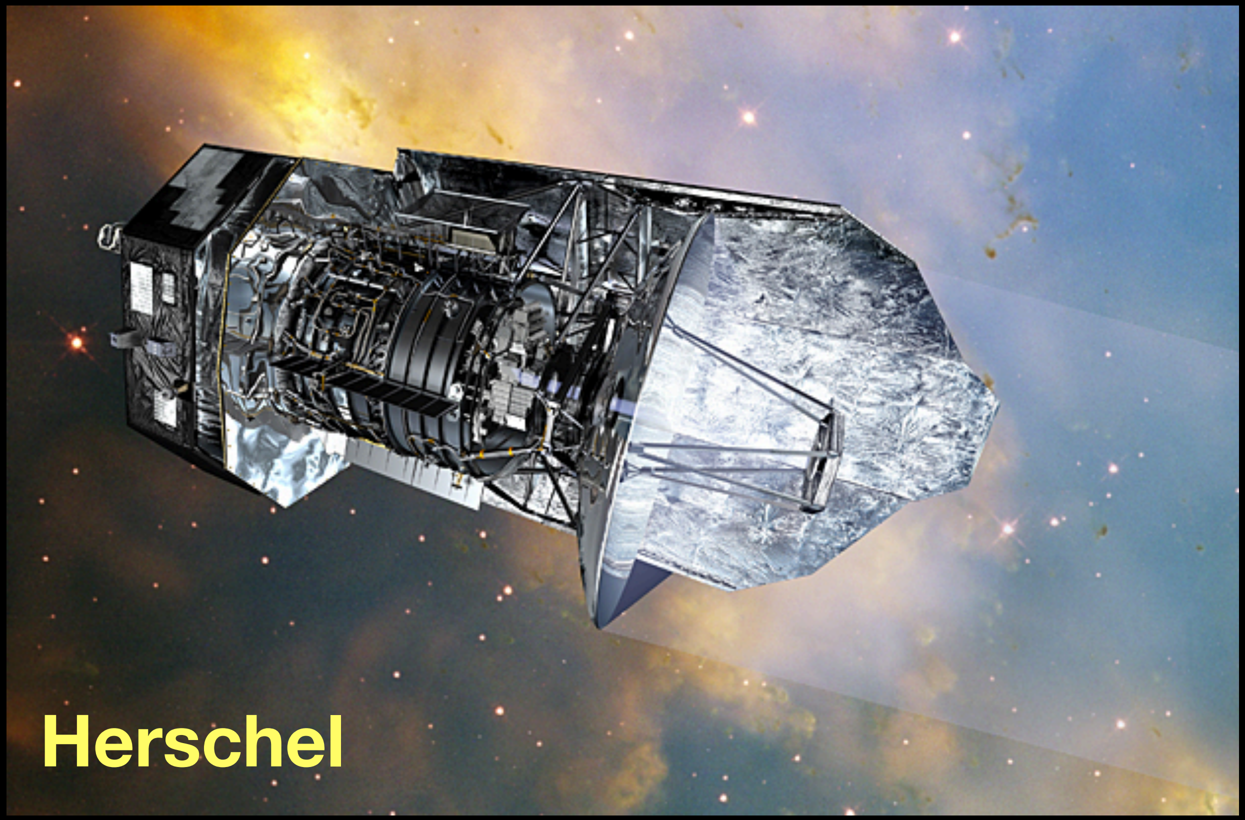
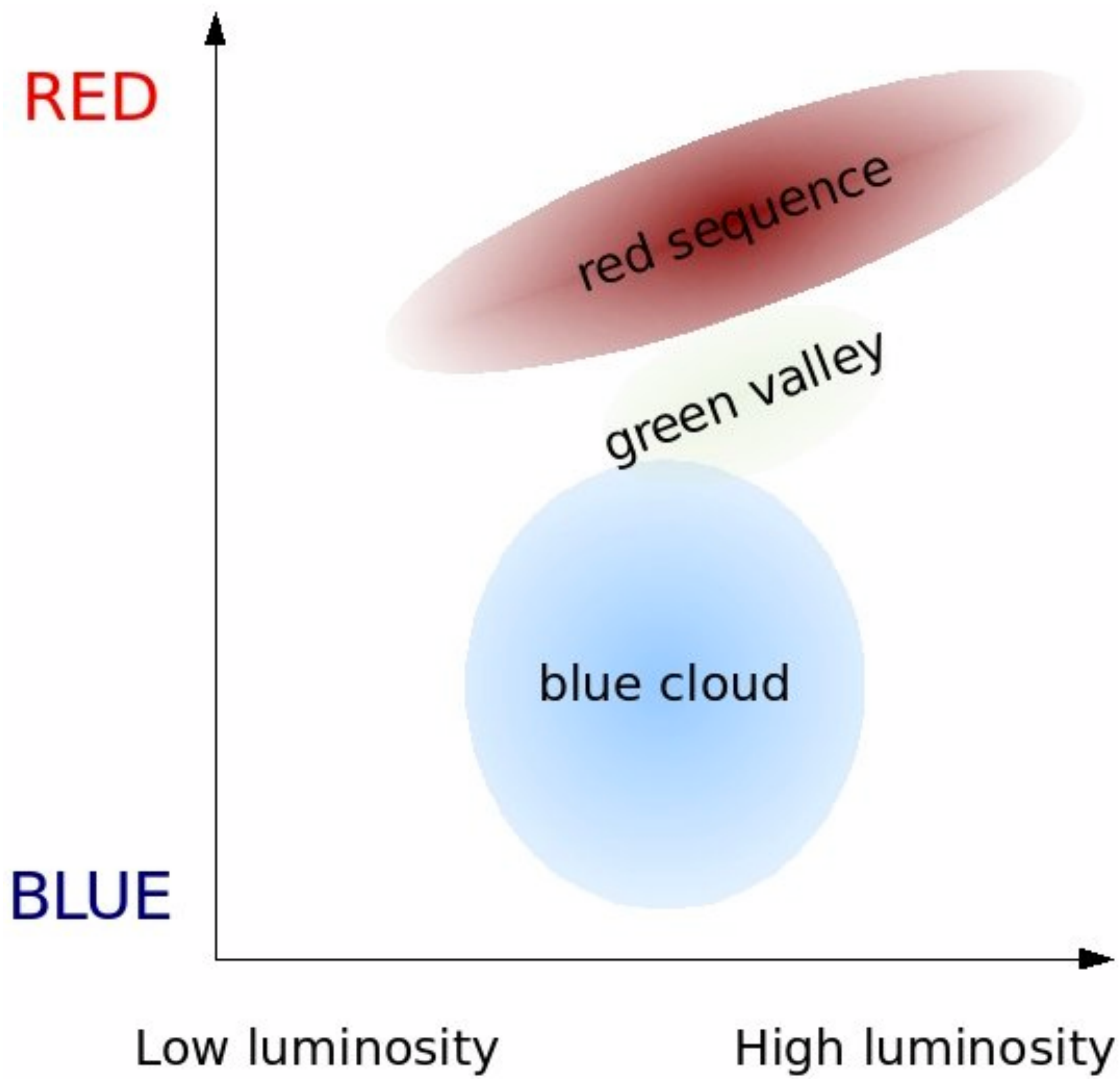


2. General view of star-formation



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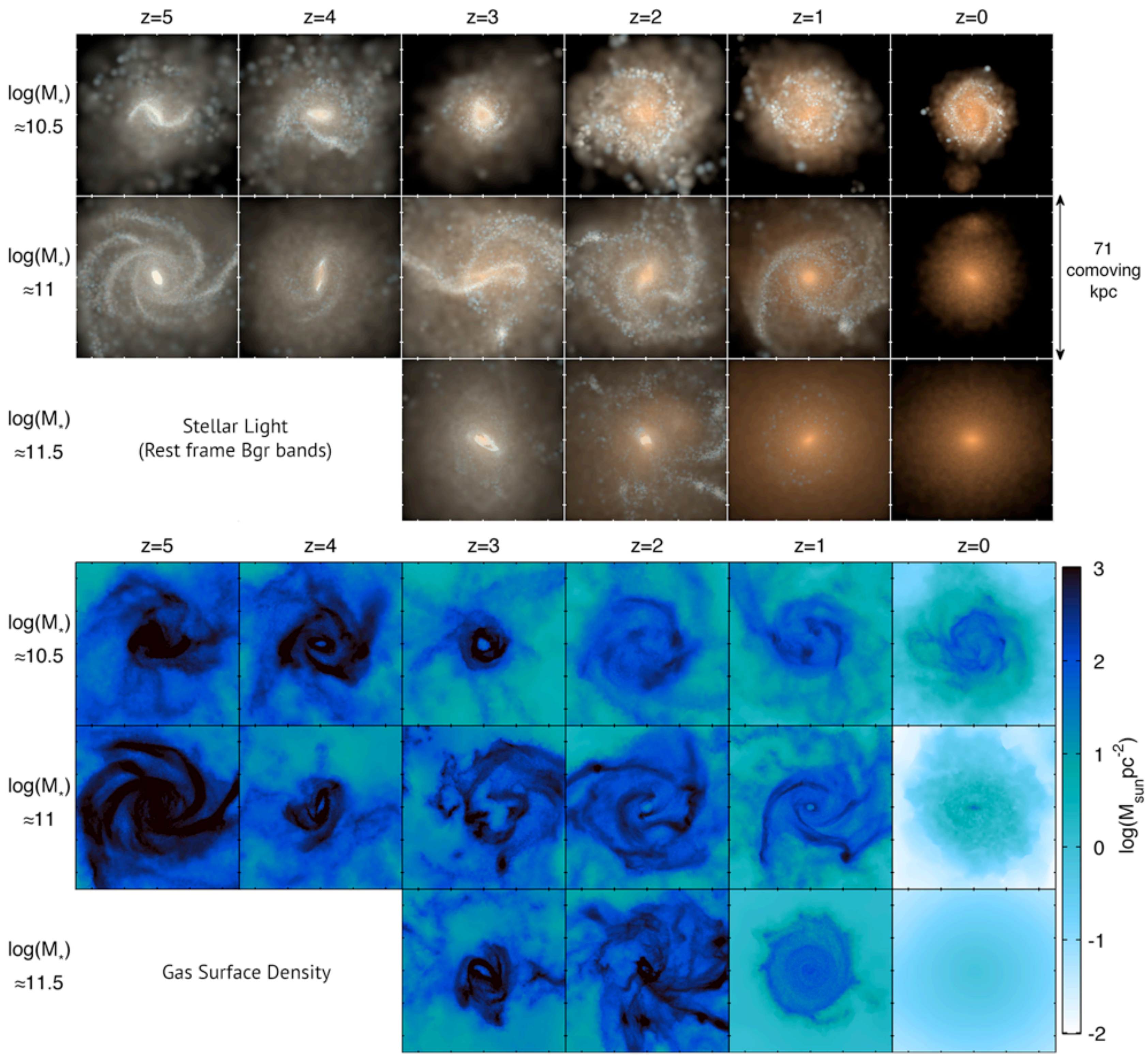

Credit: Illustris collaboration

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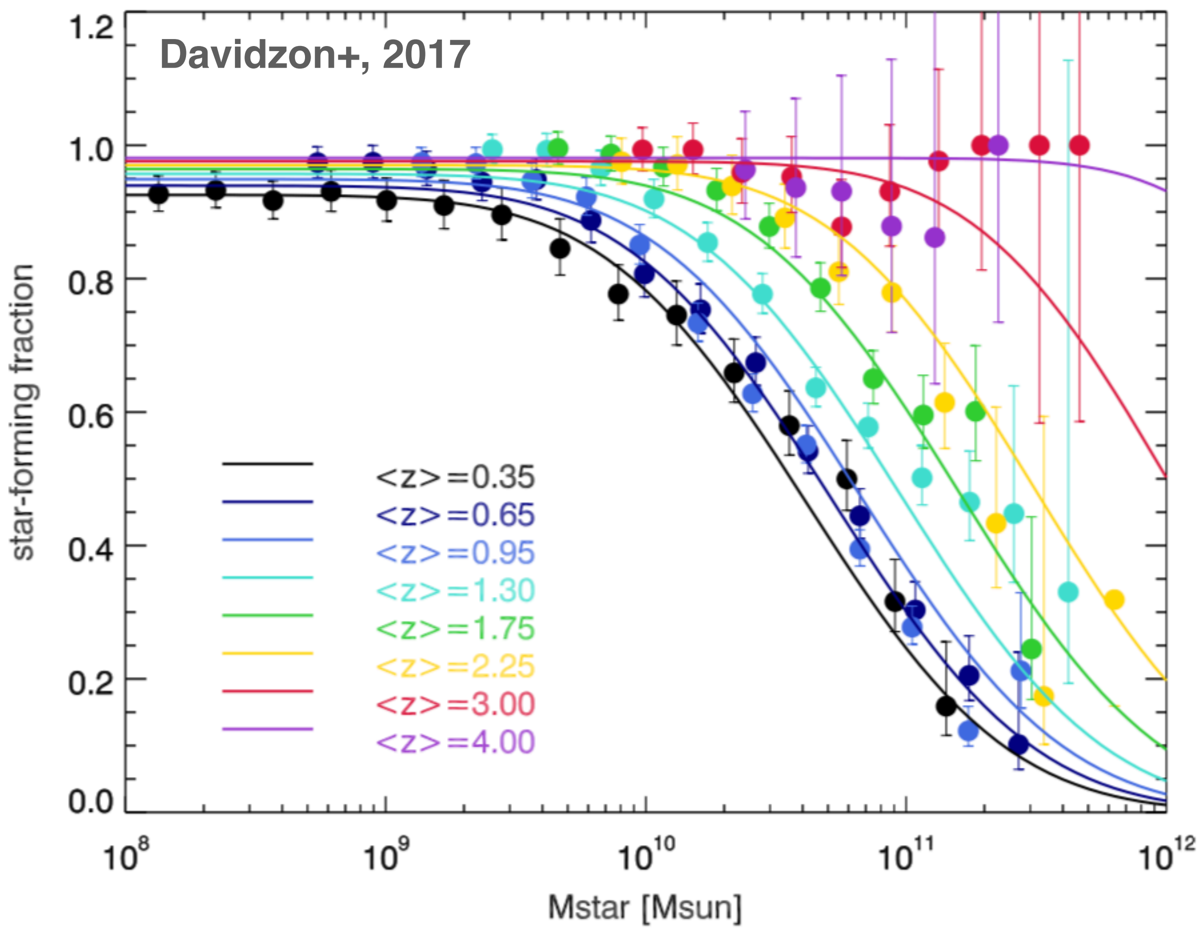

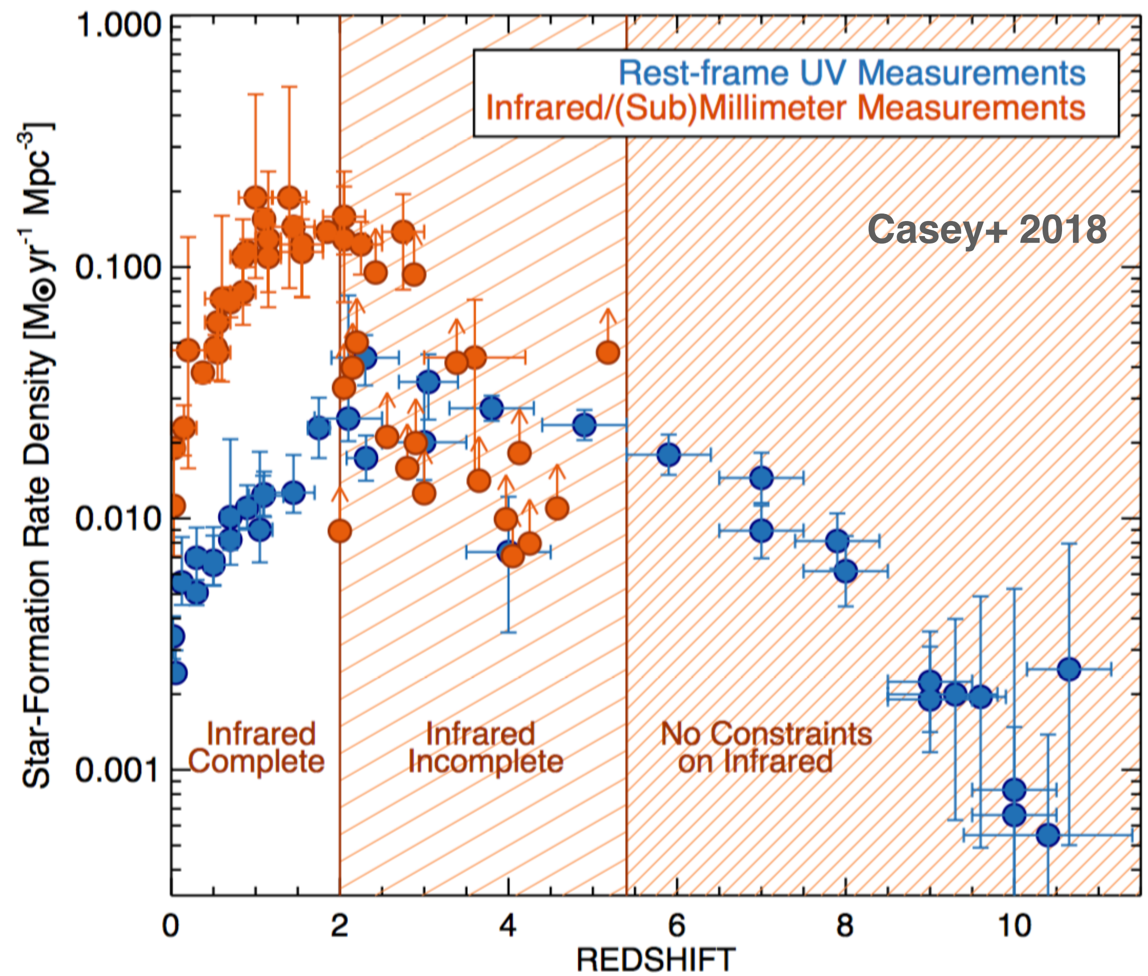

Tail of star-forming galaxies towards high-redshifts…

… but we need moderately luminous DSFGs to better constrain SFRD @ z > 4

Theory vs. Observations

- **There is a tension between the models of galaxy formation and evolutions with observations !**

2. General view of star-formation

Distant SF

?

0 3 6

Redshift (z)

(Toft et al. 2014)

1. How could such massive galaxies have been formed so early ?

In-situ star formation?
(Lapi 2018, Dave 2010)
Mergers?
(Hayward 2013)
Protoclusters?
(Chiang+ 2017)

Detailed explanation in Lecture 3-4

2. General view of star-formation

[redacted]

Distant SF

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0 3 6

Redshift *(z)*

(Toft et al. 2014)

1. How could such massive galaxies have been formed so early ?

2. How the nature of distant SFGs differ from local dusty galaxies (e.g. Arp220) ?

In-situ star formation?
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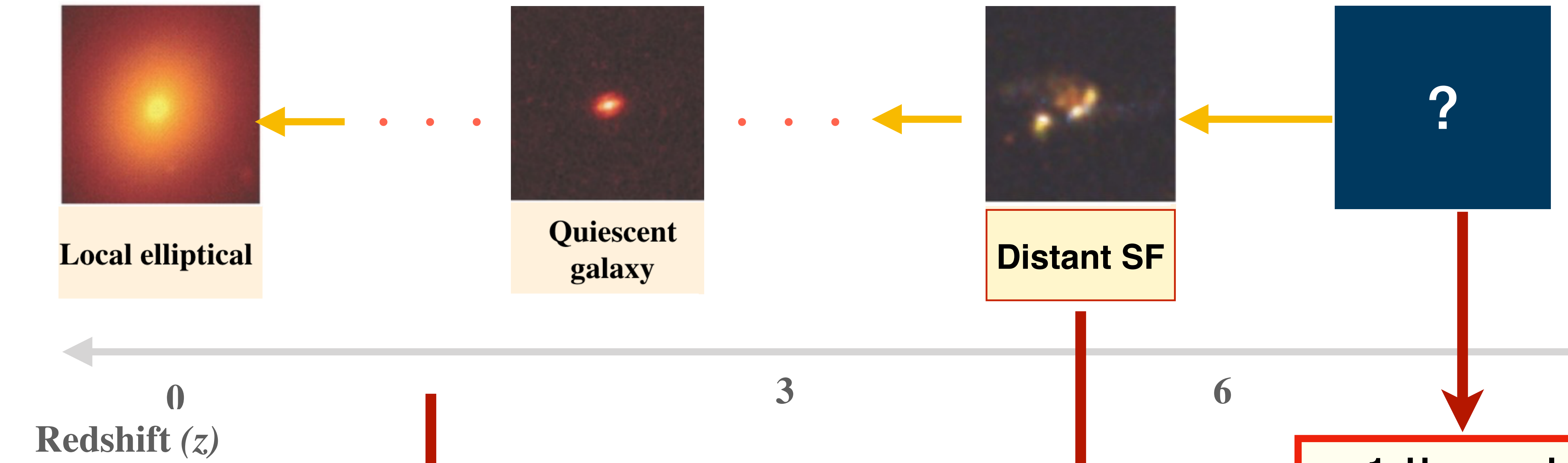
2. General view of star-formation



(Toft et al. 2014)

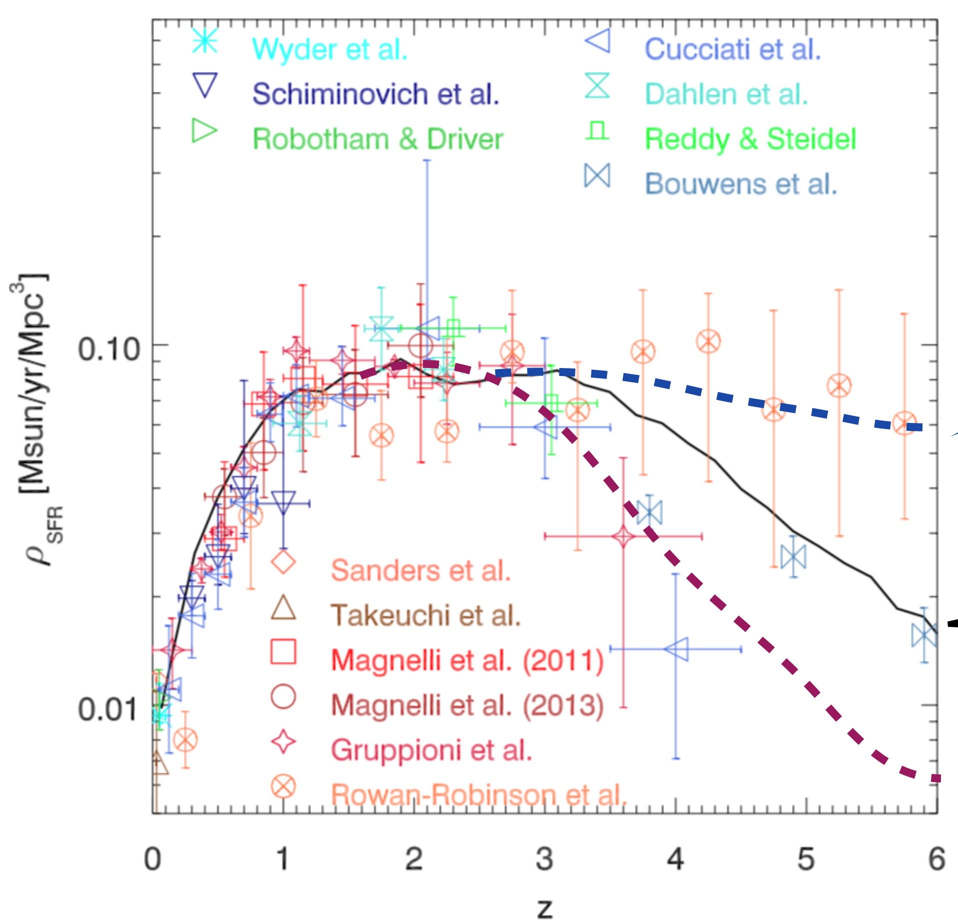
1. How could such massive galaxies have been formed so early ?

In-situ star formation?
(Lapi+ 2018, Dave+ 2010)
Mergers?
(Hayward+ 2013, Lacey+ 2016)
Protoclusters?
(Chiang+ 2017)

2. How the nature of distant SFGs differ from local dusty galaxies (e.g. Arp220) ?

3. Do we understand evolutionary links between galaxy populations?

2. General view of star-formation



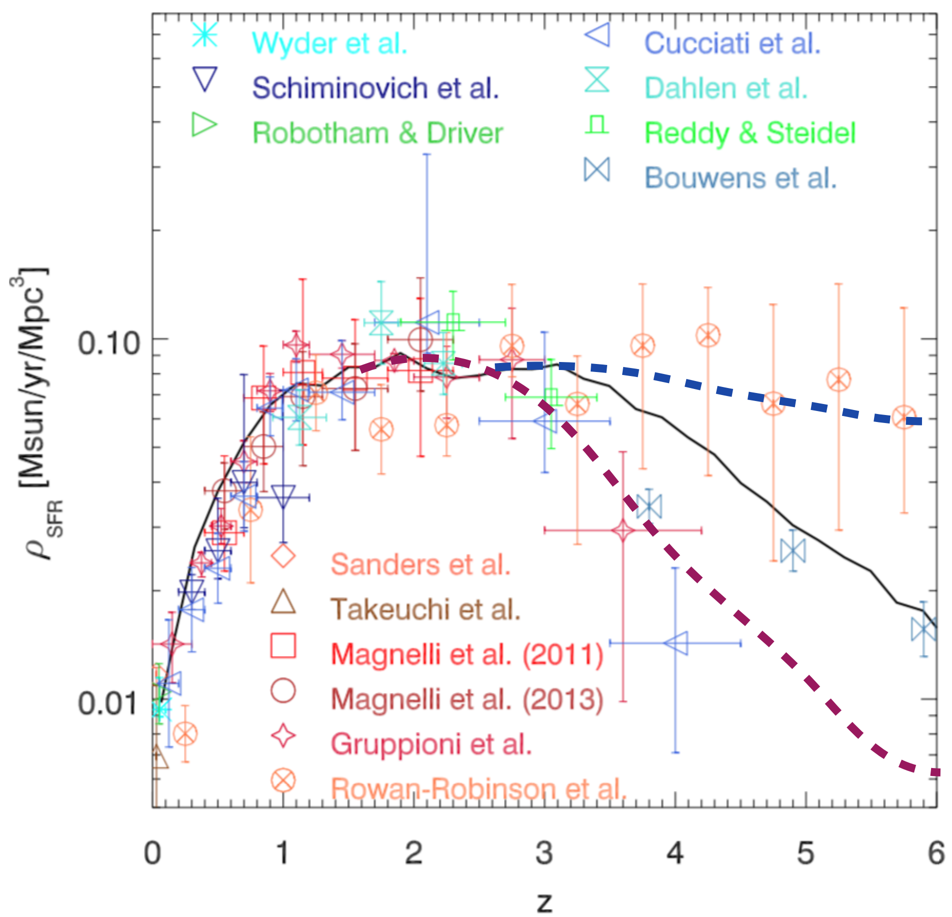
"DSFGs are main contributors @ z>4, and their maximum SFR>10000 Ms/yr " (Rowan-Robinson+ 2016)

Model predictions @ z>4 (Bethermin+ 2017, Donevski+ 2018, Casey+, 2018)

"DSFGs are negligible contributors @ z>4" (Koprowski+ 2017)

SFRD = Total star formation occurring per unit time and volume at a given epoch

2. General view of star-formation

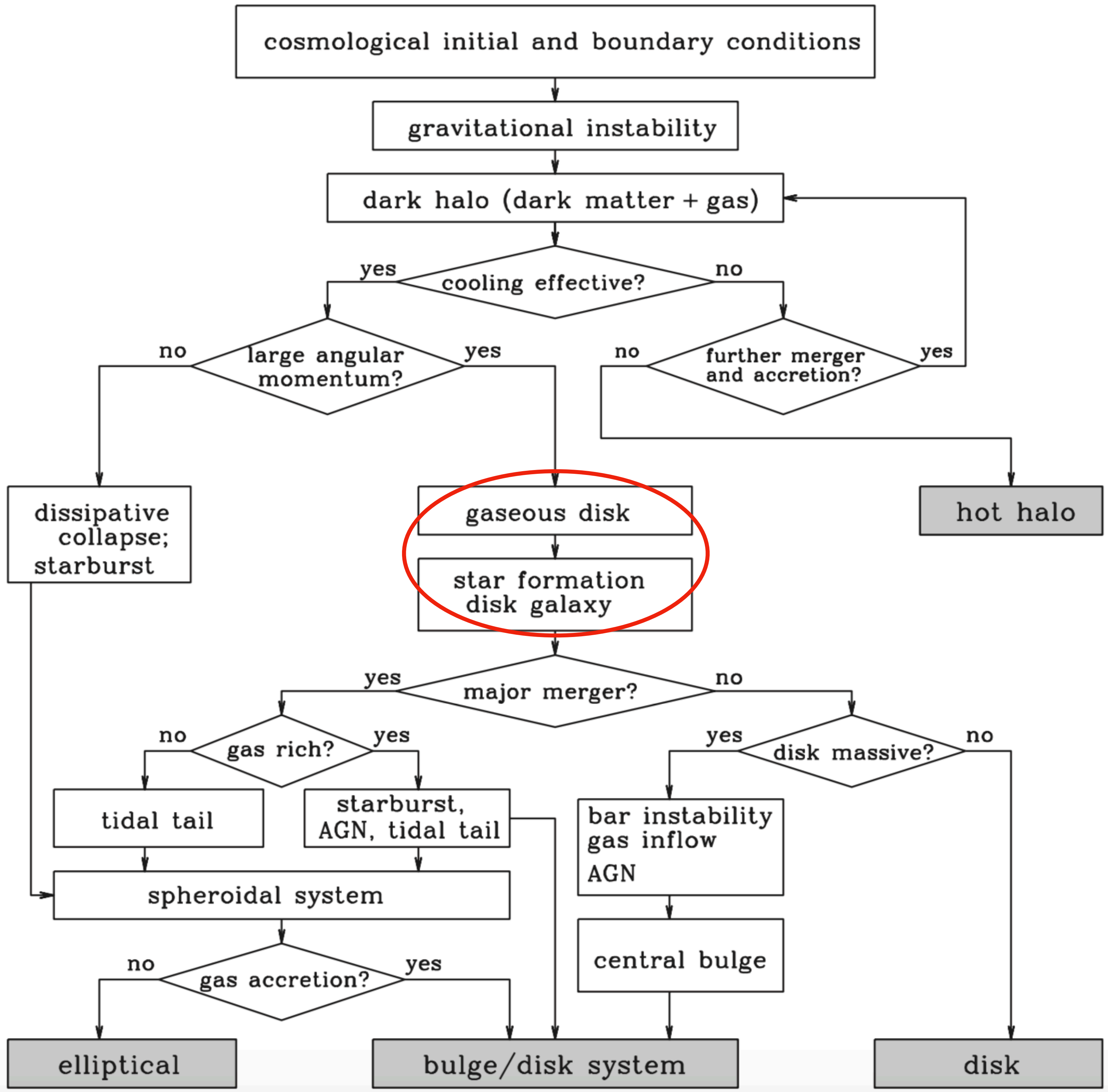


MESSAGE No.2

- **At high-redshifts, we still don't understand physics of star-formation**

SFRD = Total star formation occurring per unit time and volume at a given epoch

2.1 From small fluctuations to stars



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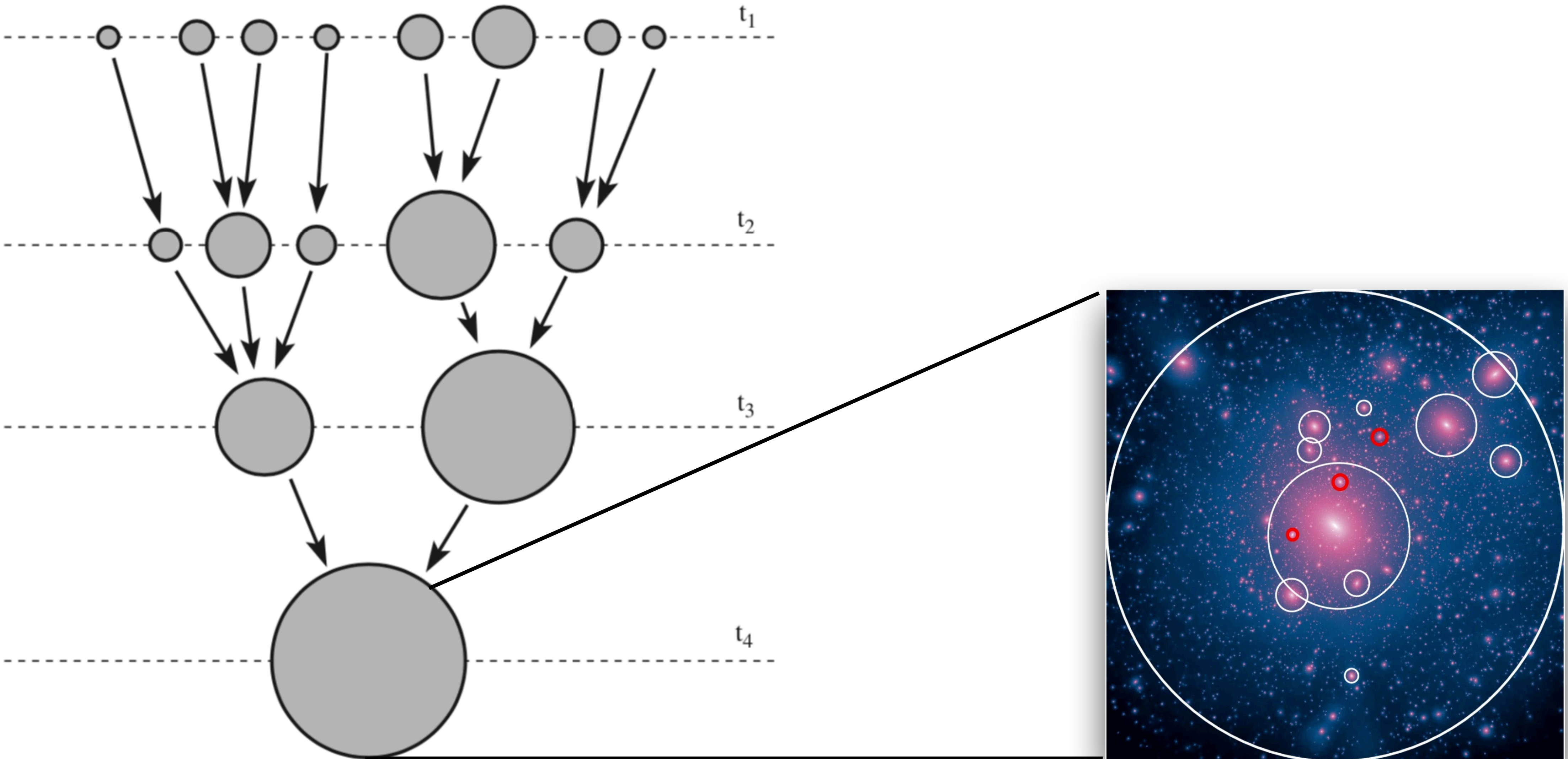
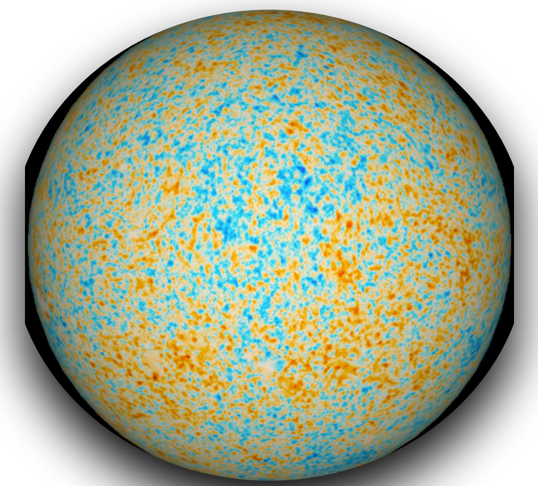


Mo, Bosch, White, 2019

Caterpillar Project A Milky-Way-size dark-matter halo and its subhalos circled.
*The mass resolution is 3*10^4 solar masses per particle.*
Griffen et al. 2016

2.1 From small fluctuations to stars



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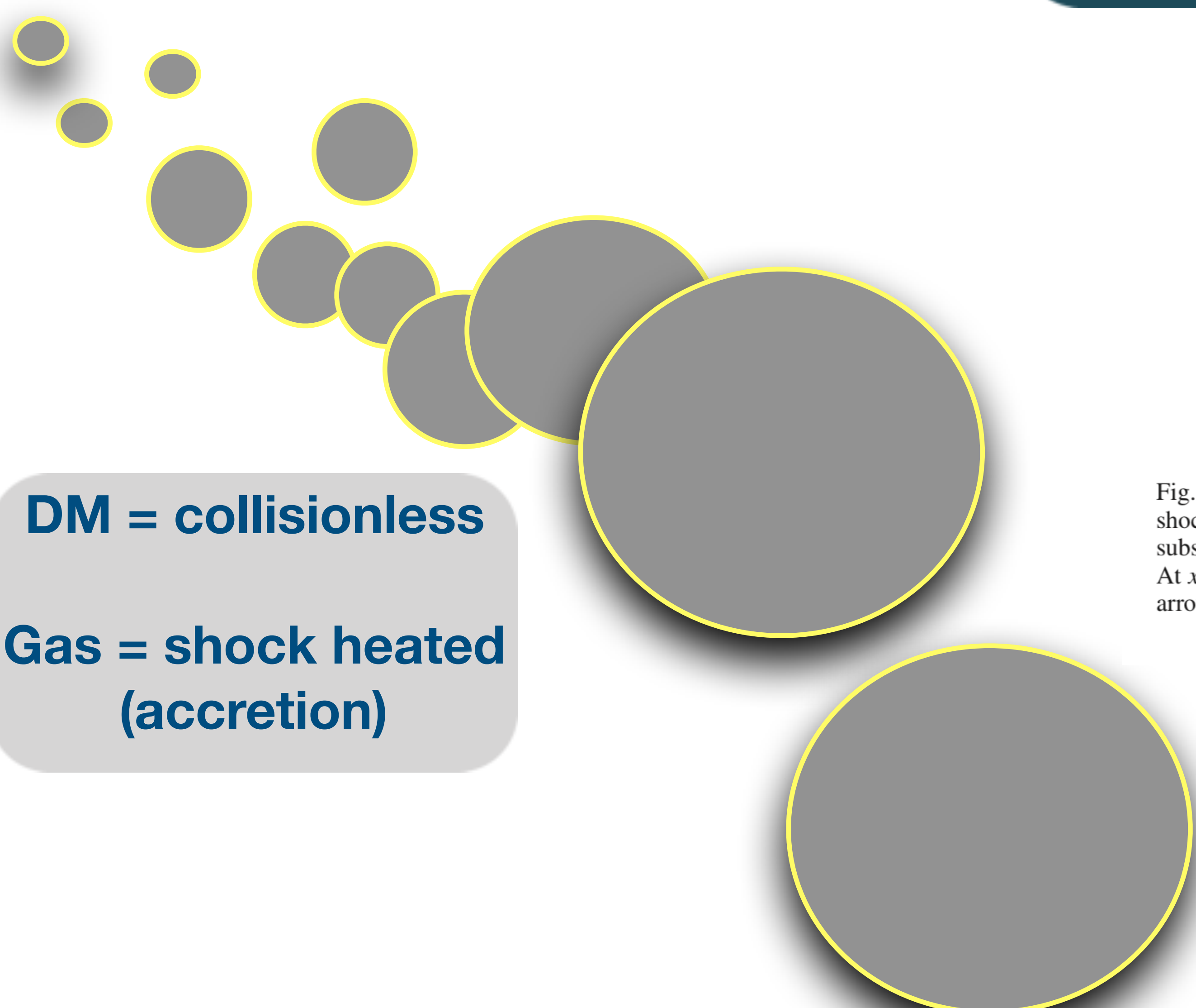


DM = collisionless

Gas = shock heated (accretion)

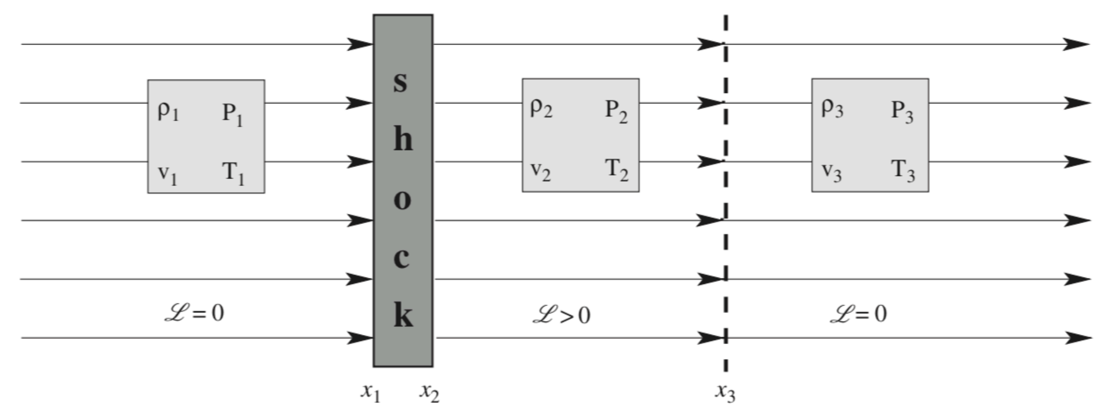
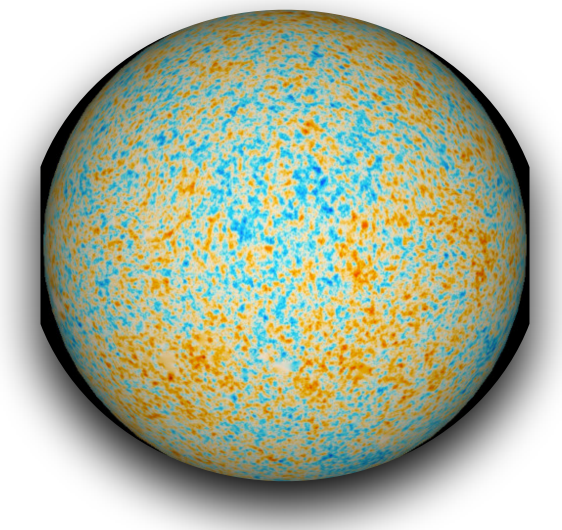


Fig. 8.3. An illustration of different regions of a planar shock. The supersonic flow in the region $x < x_1$ is shocked between x_1 and x_2 (i.e. the shock has a finite, though small, width), after which it becomes a hot subsonic flow. In between x_2 and x_3 the gas is out of thermal equilibrium resulting in net cooling ($\mathscr{L} > 0$). At $x > x_3$ the gas has cooled, reached a new thermal equilibrium, and continues to flow subsonically. The arrows indicate the direction (but not the speed) of the flow.

2.1 From small fluctuations to stars



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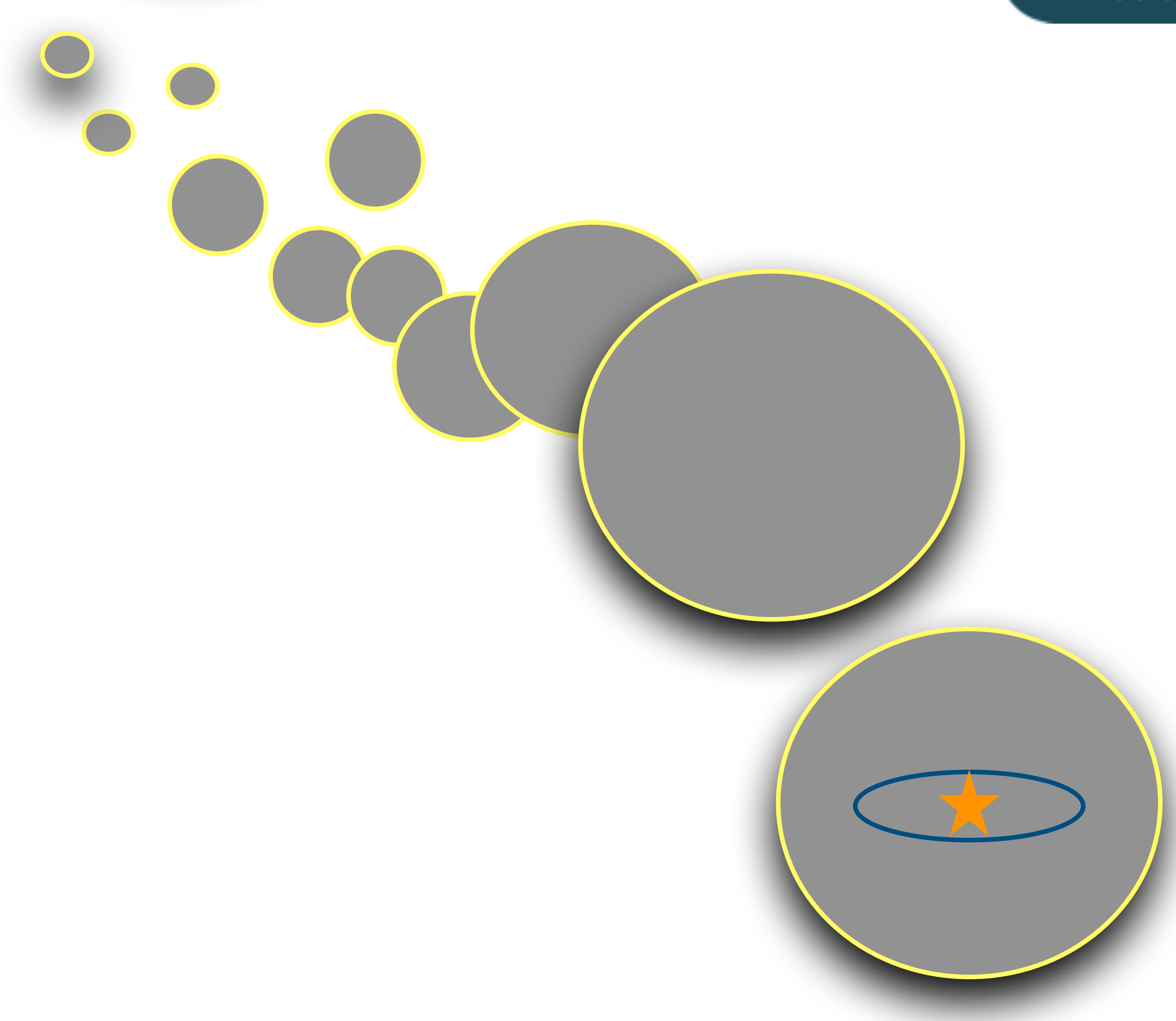
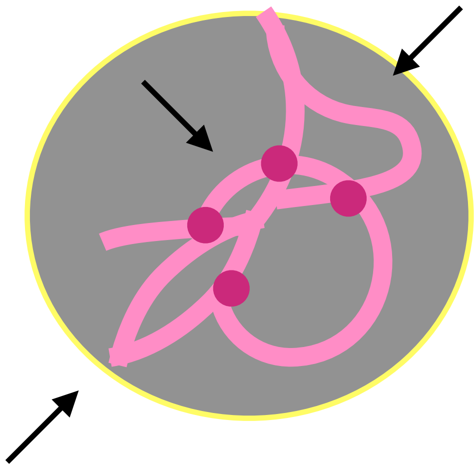


➡ Gas cools and condense… this is crucial step which allows star-formation…

2.2 Gas cooling and condensation

- **When gas falling into halos —> shock heating**



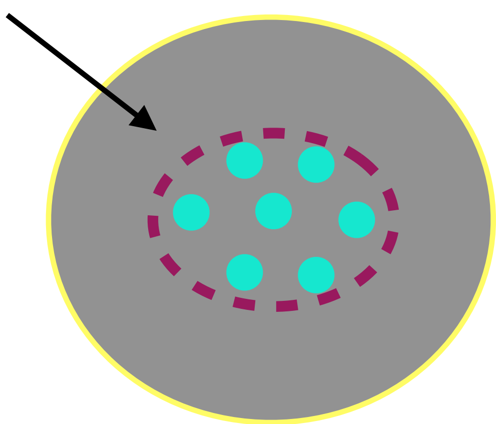
$$T_{\rm vir} = (\mu\, m_{\rm H}/2\, k_{\rm B}) V_{\rm vir}^2$$ **[2.1]**

Virial temperature

Here μ is mean molecular weight, and m(H) is Hydrogen atom mass, $V_{\rm vir} = (G\, M_{\rm vir}/r_{\rm vir})^{1/2}$

$$U_{\rm hot}(r) = \frac{3}{2}\frac{k_{\rm B} T_{\rm vir}}{\mu\, m_{\rm H}} \rho_{\rm hot}(r)$$ **[2.2]**

Thermal energy per unit volume of the gas



- **Gas is than settled into central sphere radius —> radiative cooling**

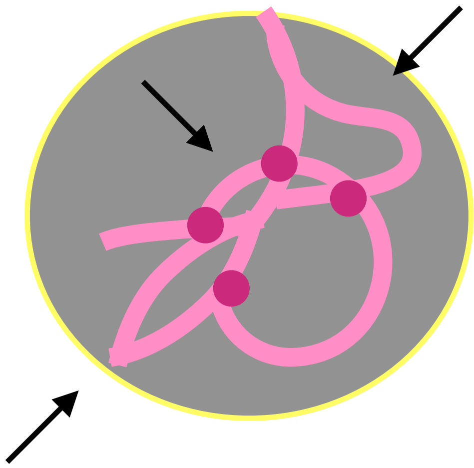
$$\tau_{\rm cool}(r) = \frac{3}{2}\frac{k_{\rm B}}{\mu\, m_{\rm H}} \frac{T_{\rm vir}}{\rho_{\rm hot}(r)\Lambda(T_{\rm vir}, Z_{\rm hot})}$$ **[2.3]**

Cooling rate

Hot gas loses energy through atomic processes

$$\mathcal{L}_{\rm cool}(r) = \rho_{\rm hot}^2(r)\Lambda(T_{\rm vir}, Z_{\rm hot})$$

2.2 Gas cooling and condensation



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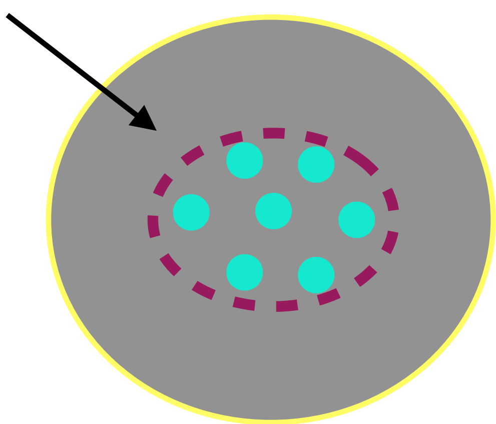
Thermal energy per unit volume of the gas



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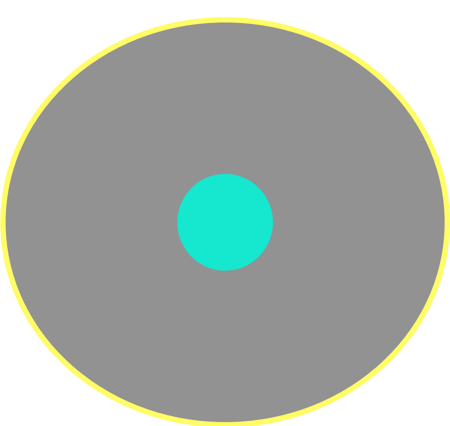
Cooling rate



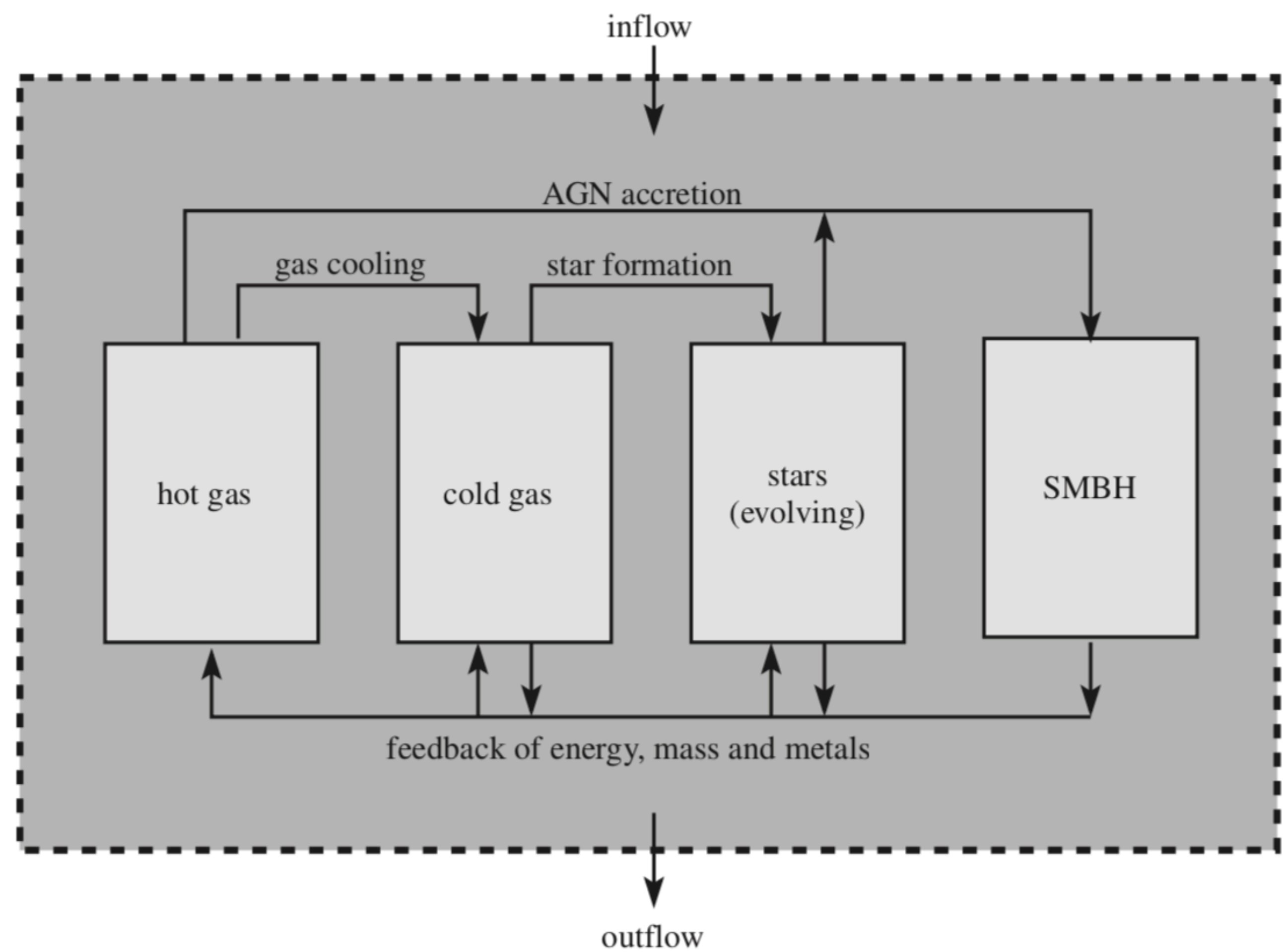
- **Hot gas accreted onto cold disc —> angular momentum change**

$$\dot{M}_{\rm acc} = 4\pi\, \rho_{\rm hot}(r_{\rm acc})\, r_{\rm acc}^2\, \dot{r}_{\rm acc} \quad [2.4]$$

Mass accretion rate

2.3 Galaxy (together with stars) evolves ! But, how?

Bathtub model



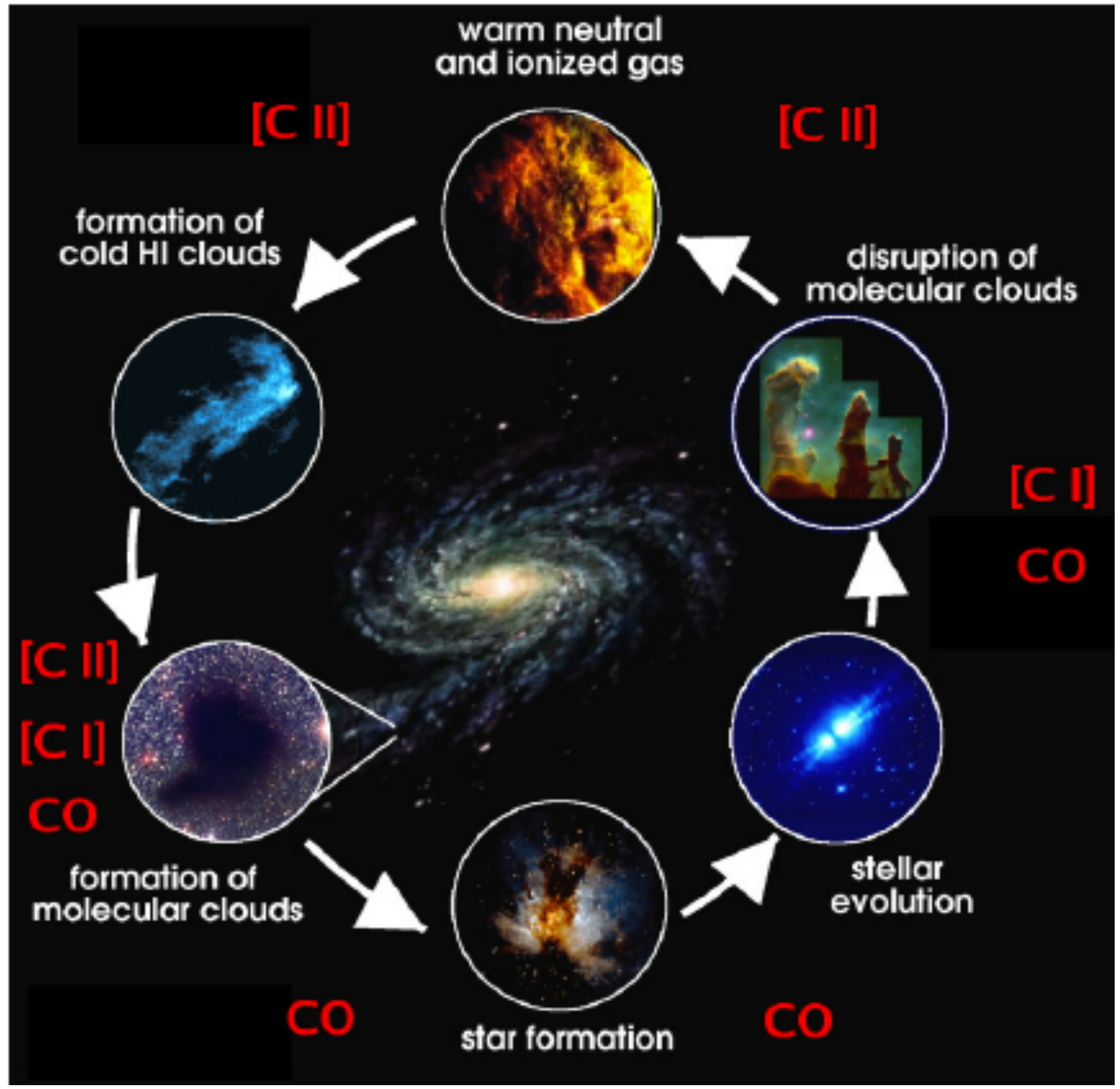
$$\dot{M}_{\rm gas} = \dot{M}_{\rm gas,in} - (1-R)\dot{M}_{\star} - \dot{M}_{\rm gas,out}$$

- $\dot{M}_{\rm gas}$: Variation of the gas content
- $\dot{M}_{\rm gas,in}$: Cosmological accretion
- $(1-R)\dot{M}_{\star}$: Gas consumed by long-live stars
- $\dot{M}_{\rm gas,out}$: Outflows

III Astrophysics of star-formation: gas consumption and star-formation rates

“Is star-formation efficient process or not? ”

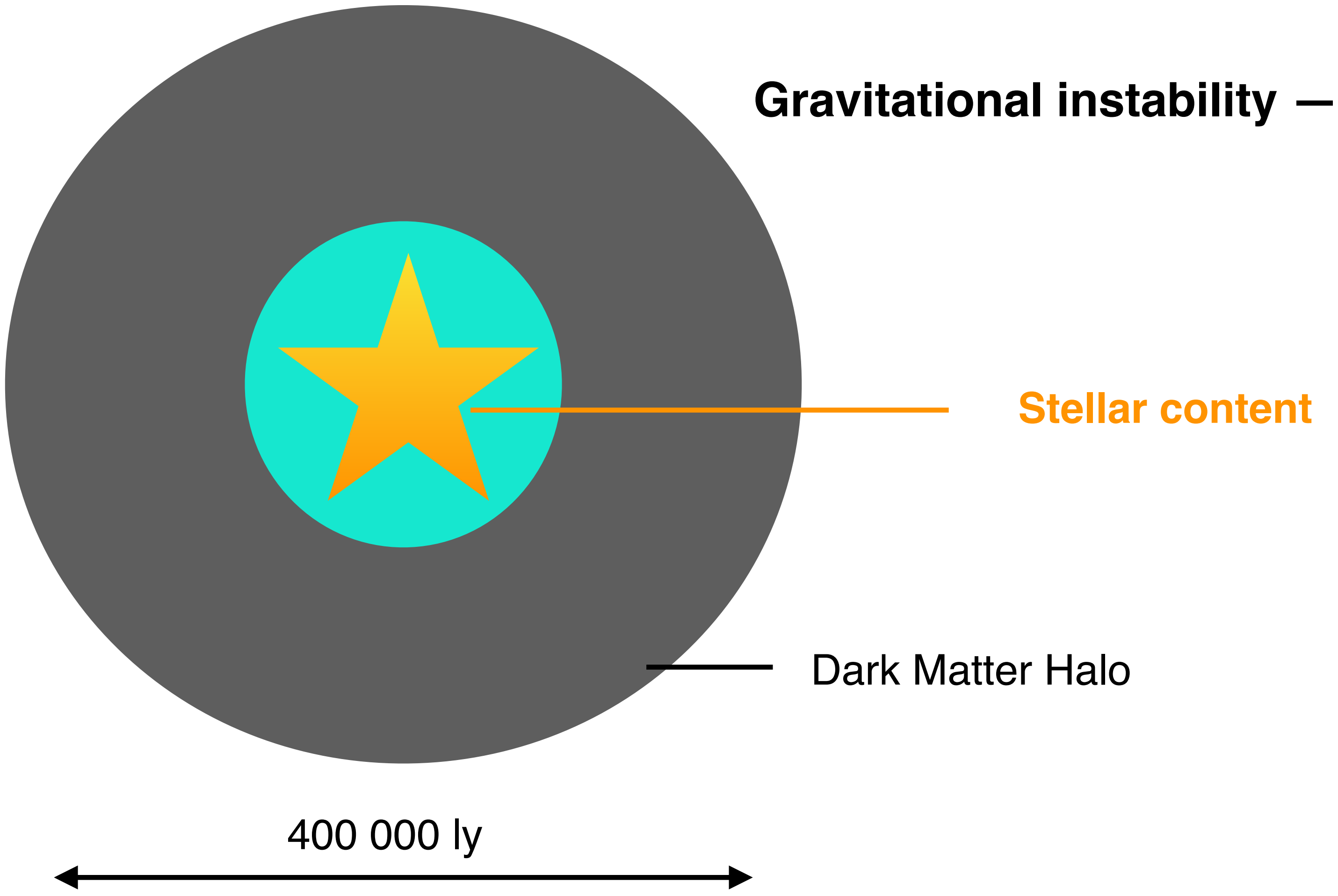
3.1 Astrophysics of star-formation



The answers to these questions play an important role in our treatment of galaxy formation and evolution. In fact, **if we know the star-formation history of a galaxy**, which describes the total mass in stars formed per unit time, and if we know the IMF, then we can use stellar evolution models, which describe how stars of different masses evolve with time, to **predict the luminosity and colour of the galaxy as a function of time.**

3.1 Astrophysics of star-formation

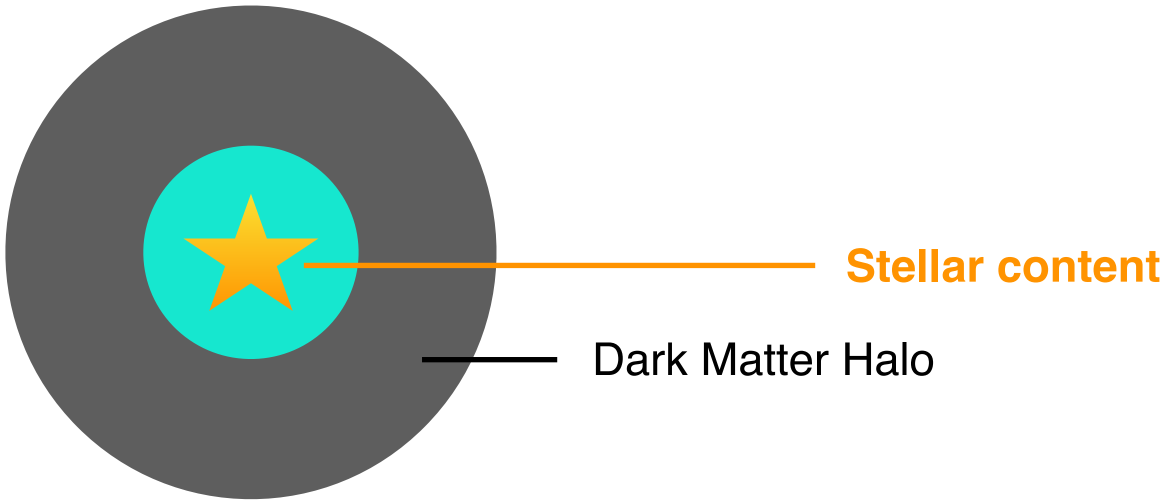
Gravitational instability —> Gas cooling —> Star formation

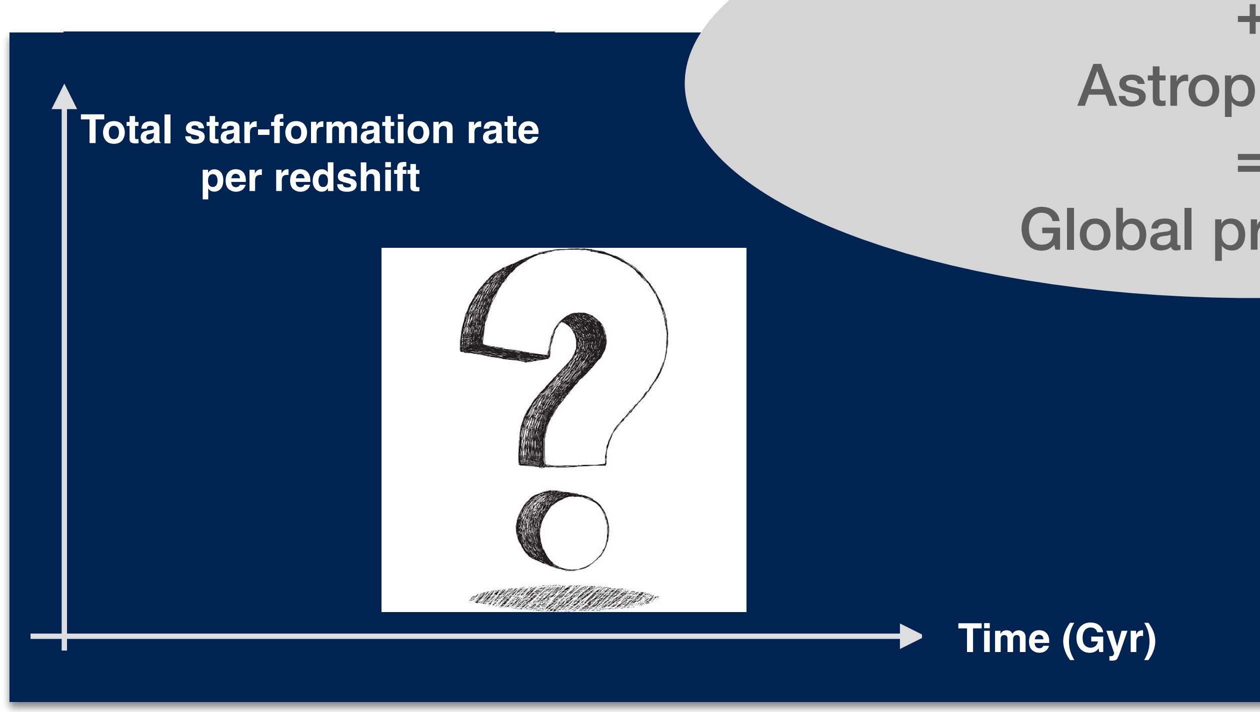


Main questions to be addressed at this stage:

- When & how does large-scale star-formation happen in galaxy ?
- What is the rate at which stars are formed ?
- Is consumption of gas to stars efficient process (or not) ?

3.1 Astrophysics of star-formation



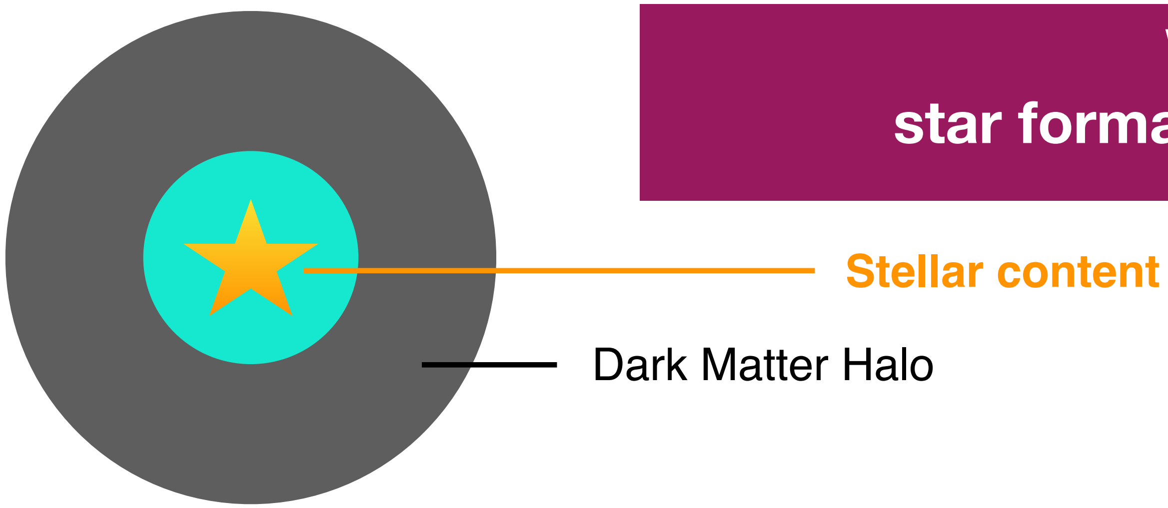


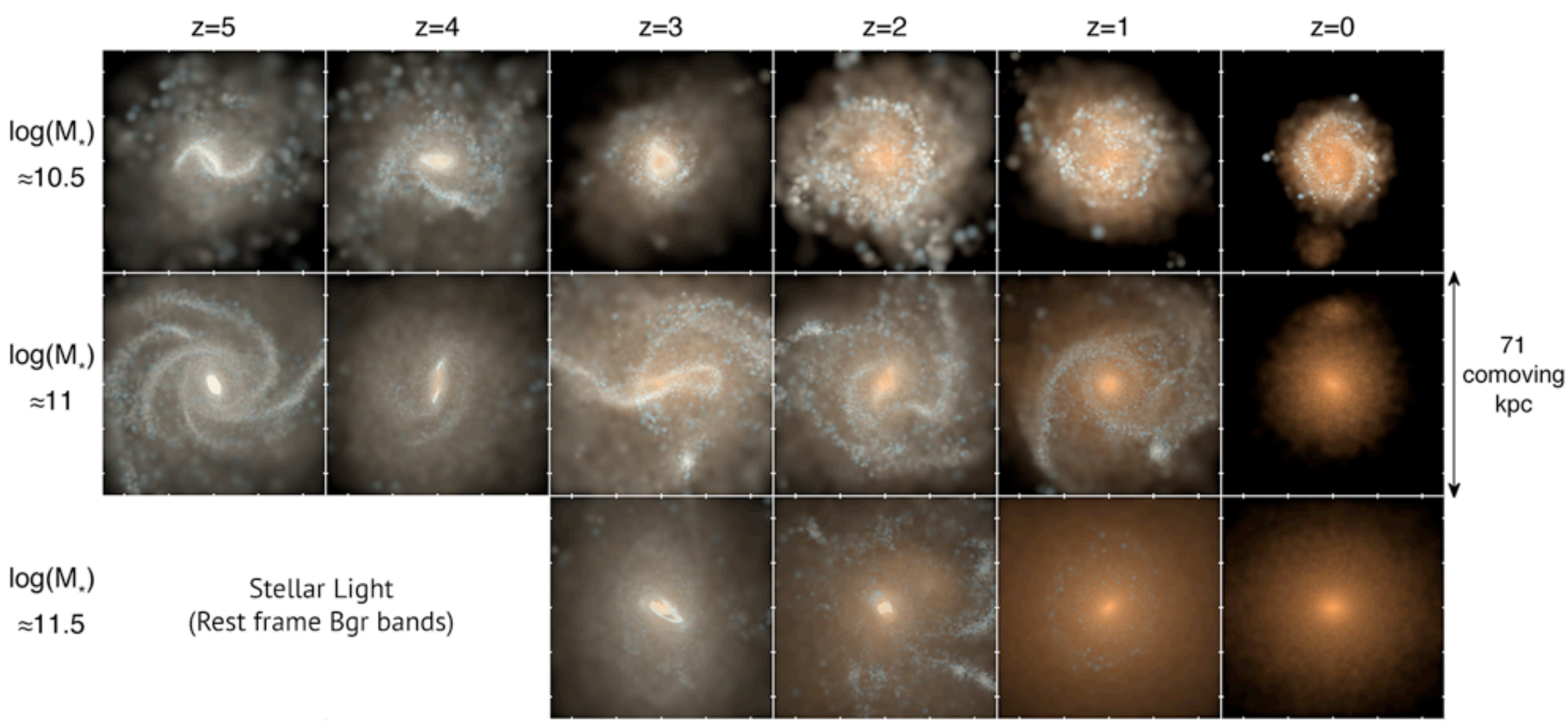
Physics
+
Astrophysics
=
Global properties

REMEMBER:
MAIN GOAL IS TO UNDERSTAND HOW BARYONS FORM AND EVOLVE !

3.1 Astrophysics of star-formation

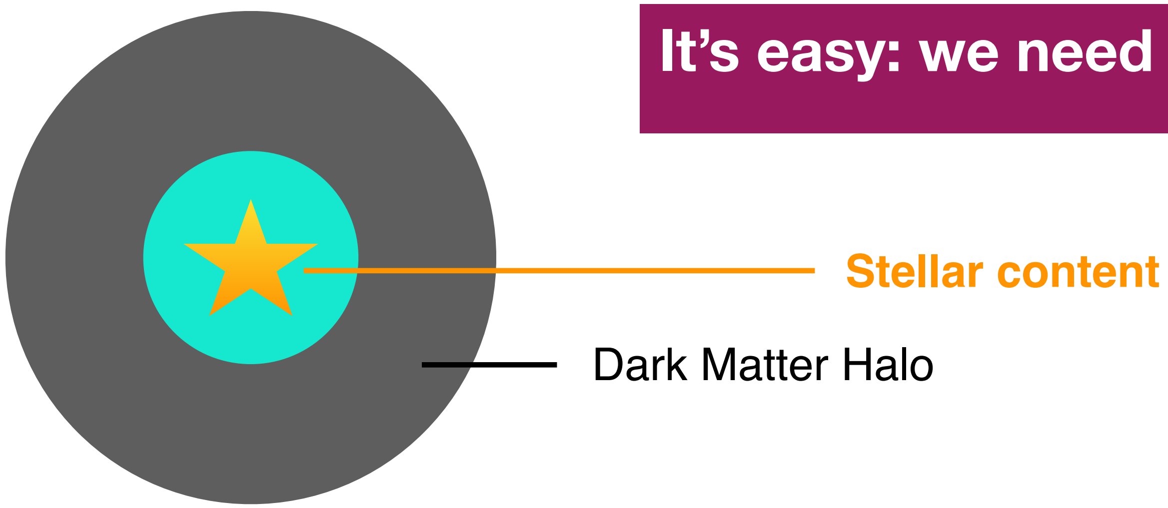
We need to predict star formation rate and galaxy colour !

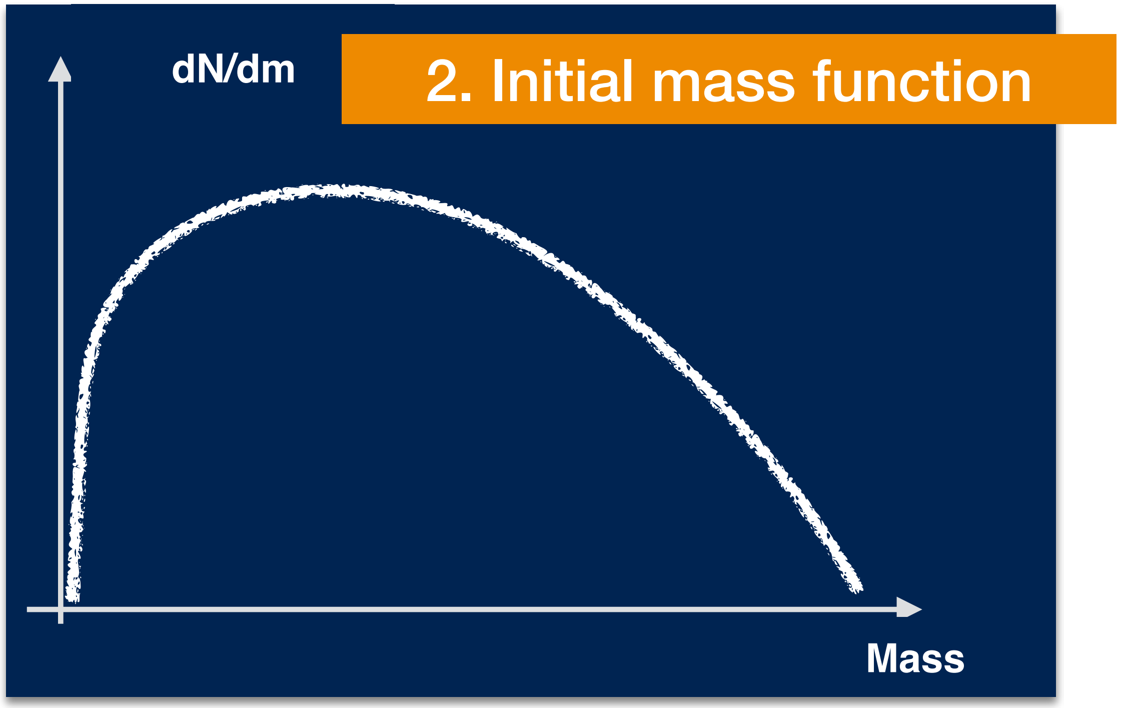


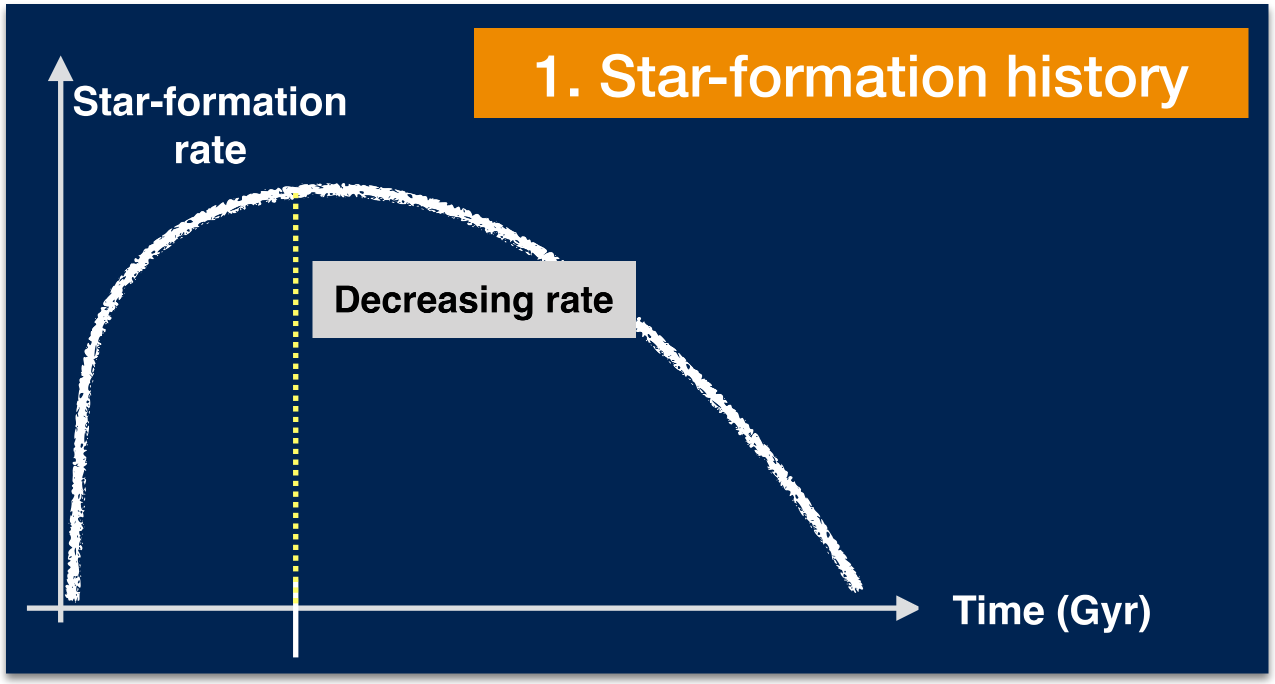


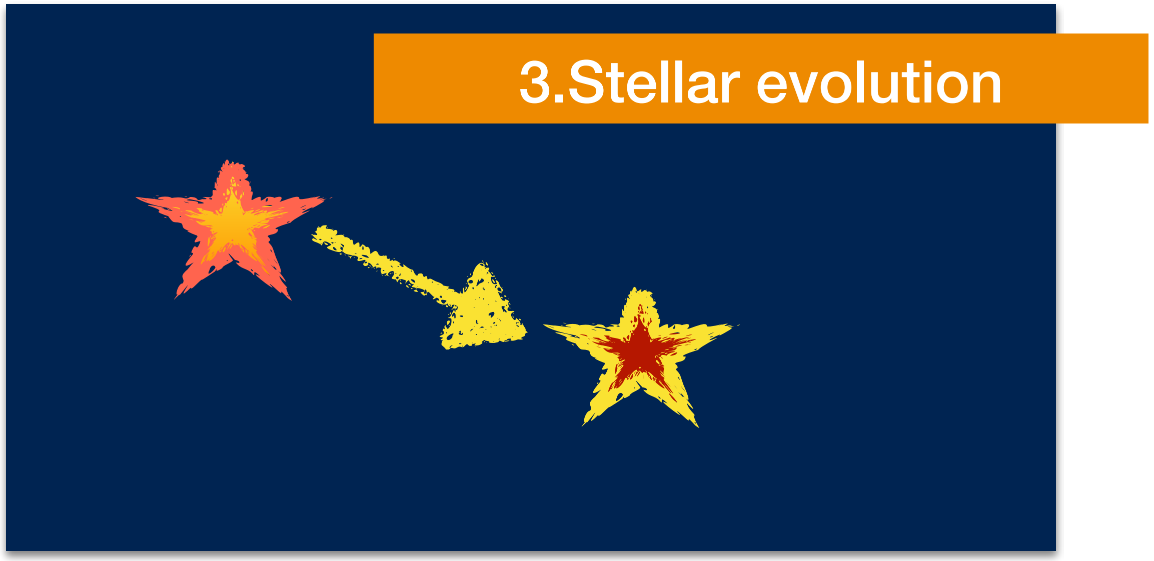
3.1 Astrophysics of star-formation

It's easy: we need to know "ONLY" three components!!!



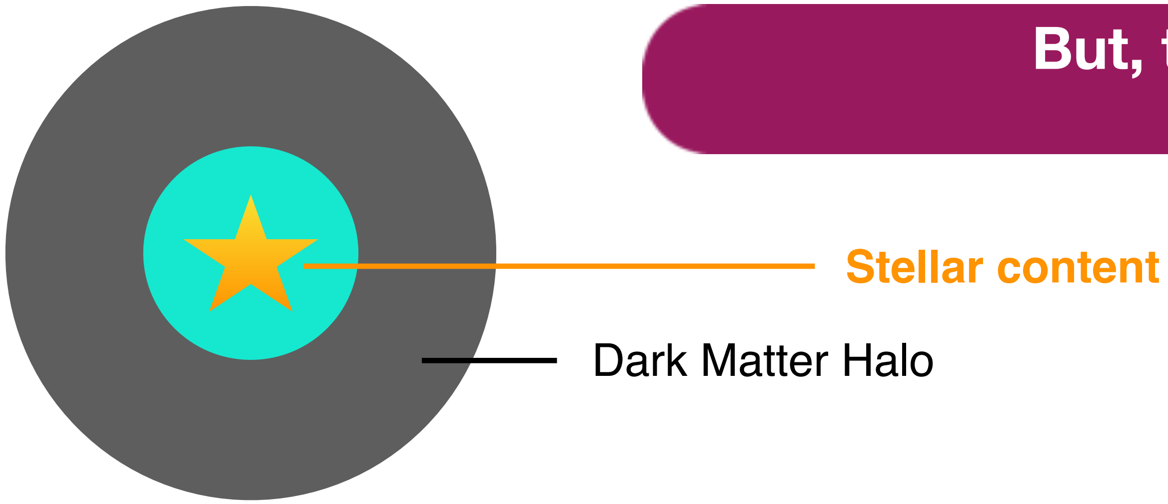




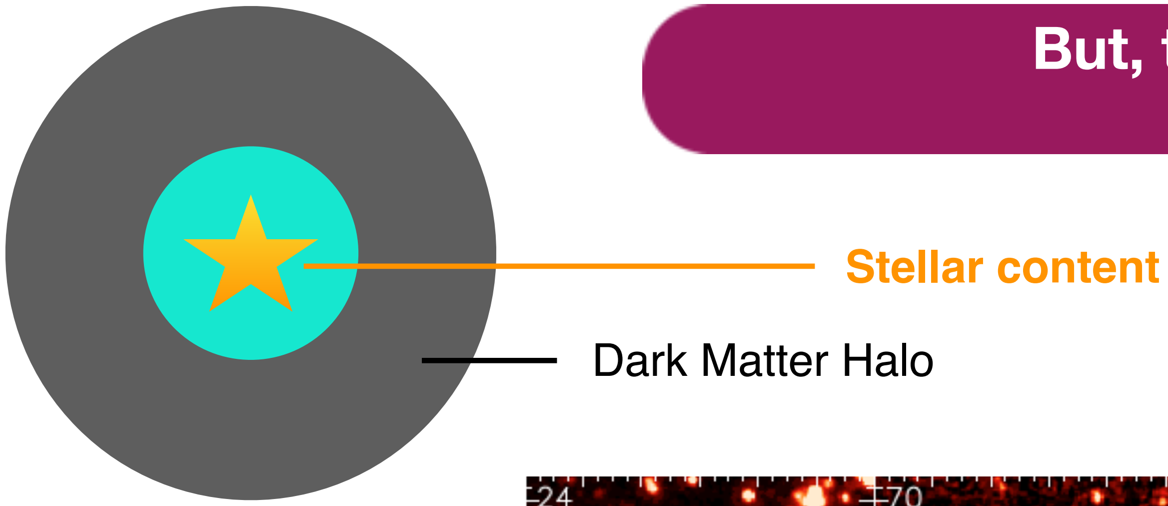


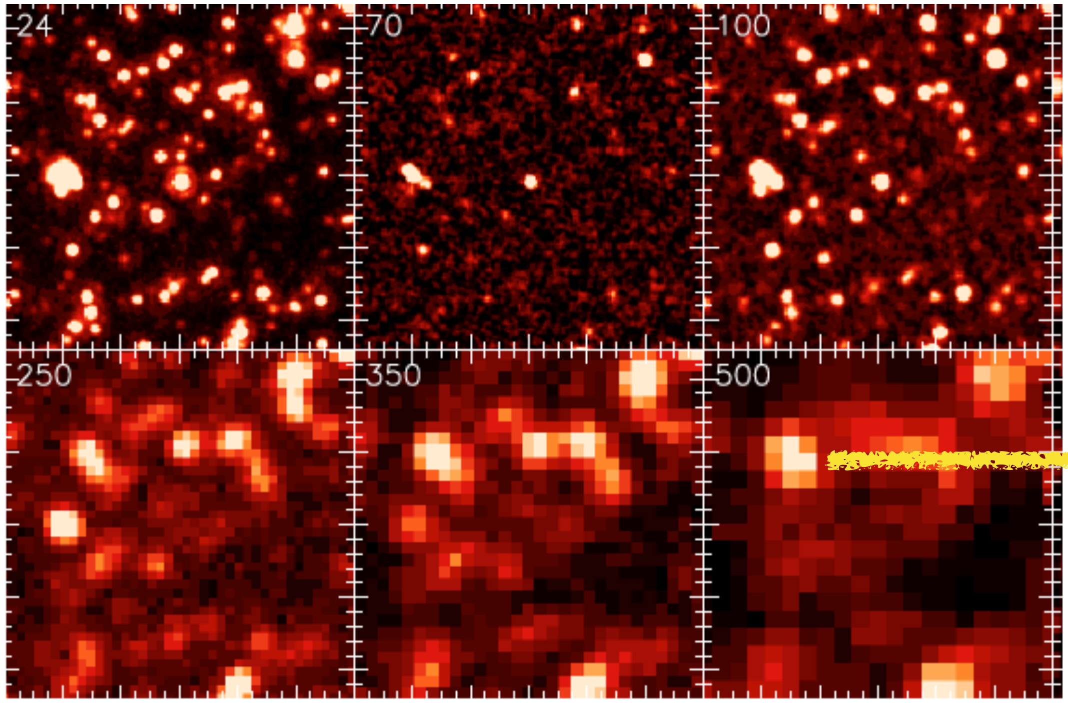
3.1 Astrophysics of star-formation

But, the real life is though ! :-)



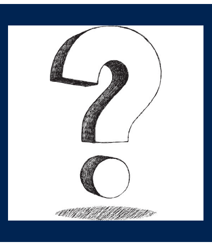
But, the real life is though ! :-)

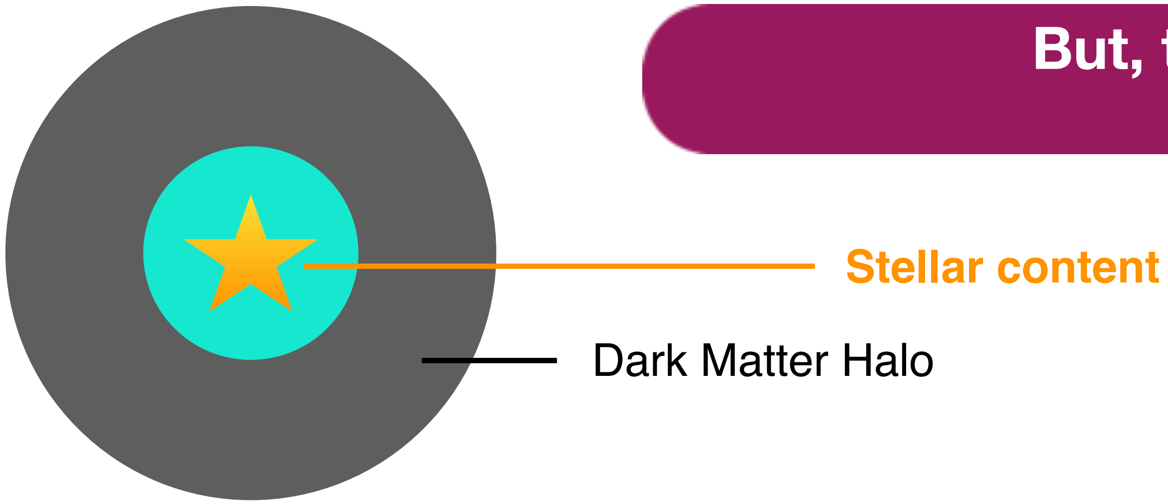




Only information we have is how bright are these blobs we see with our telescopes…

Star-formation history
IMF
Stellar content



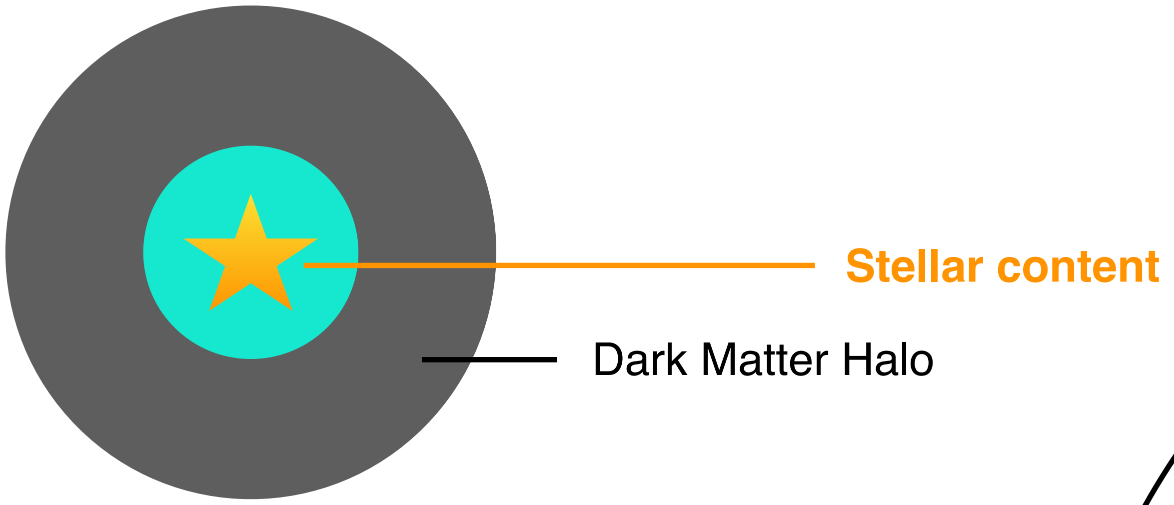


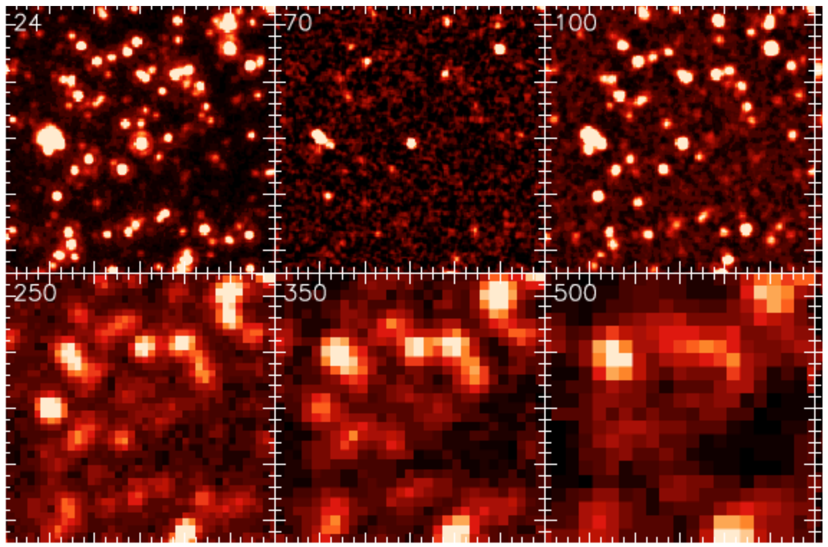
But, the real life is though ! :-)

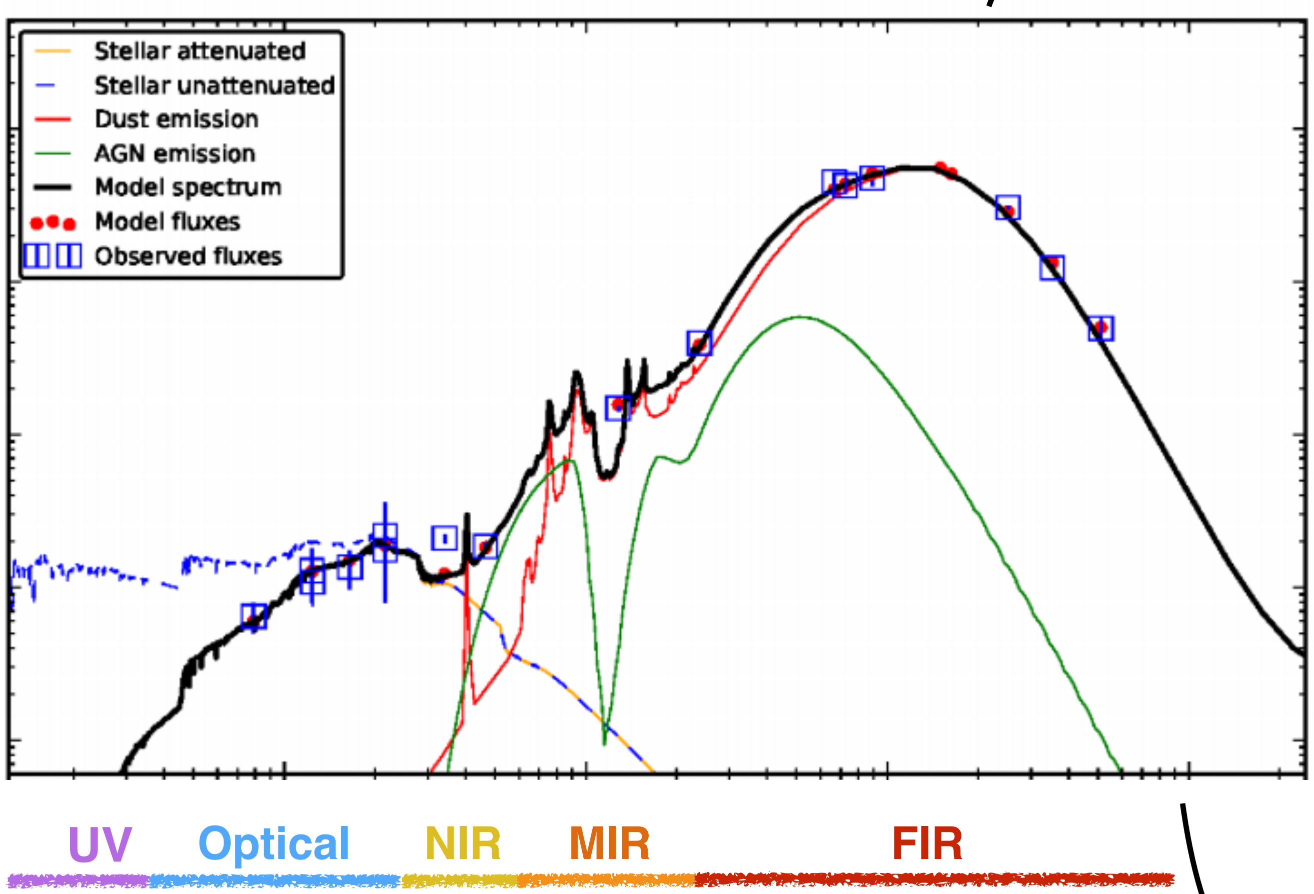
MESSAGE No.3

- **In reality, we are doing opposite:**
  from global SED properties (distribution of galaxy colours/ fluxes),
  we infer (somehow) local properties
  (star-formation rate, dust mass, stellar mass, temperature of dust etc.) !

3.1 Astrophysics of star-formation

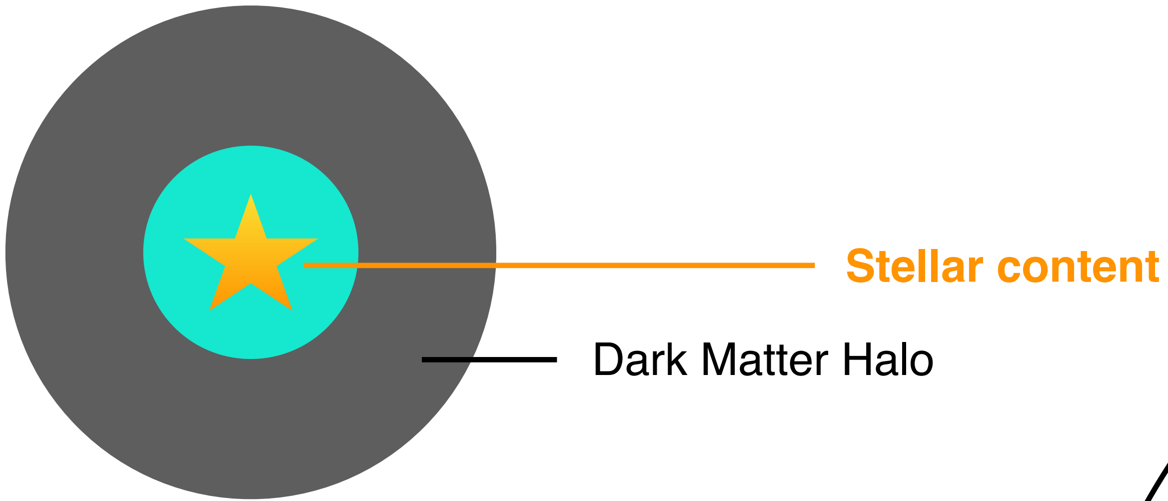


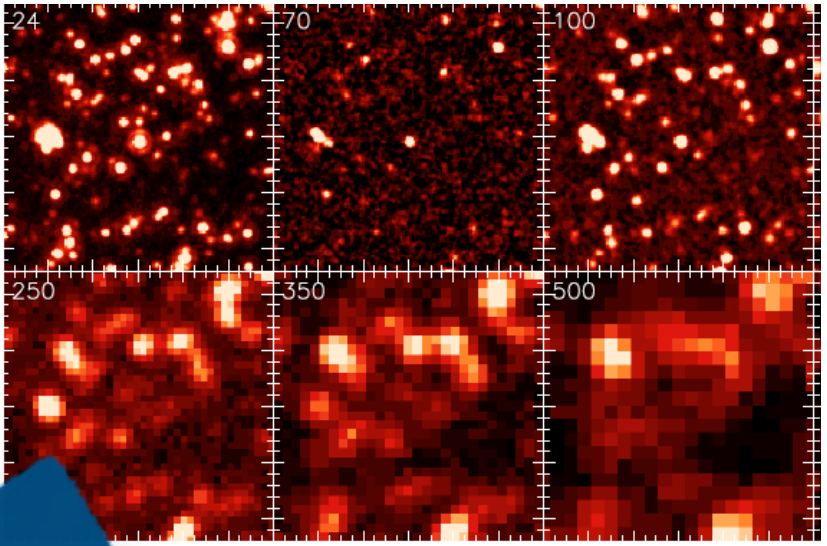


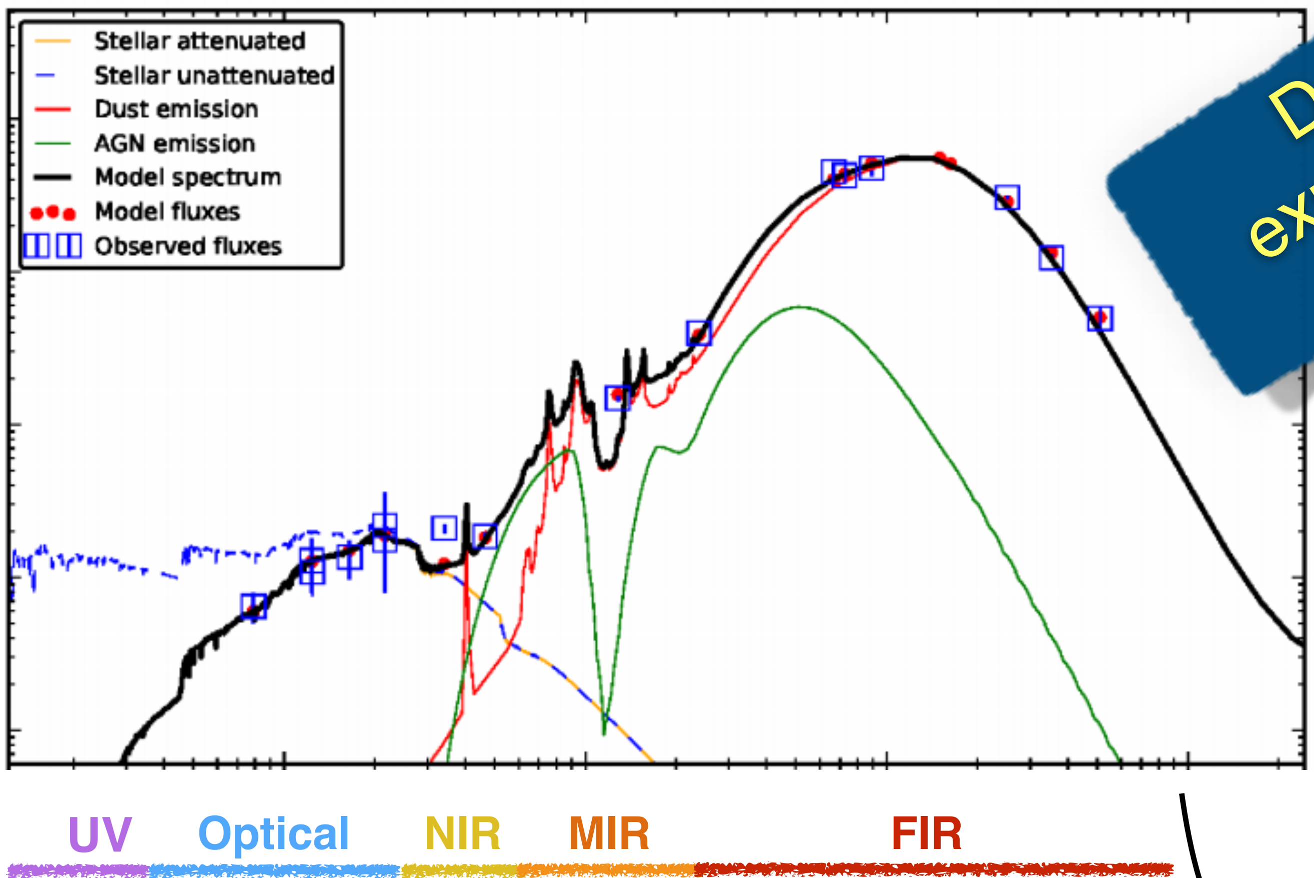


Luminosities;
Star-Formation rate (SFR):
Stellar mass;
Dust mass;
Attenuation;
Star-formation history …

3.1 Astrophysics of star-formation



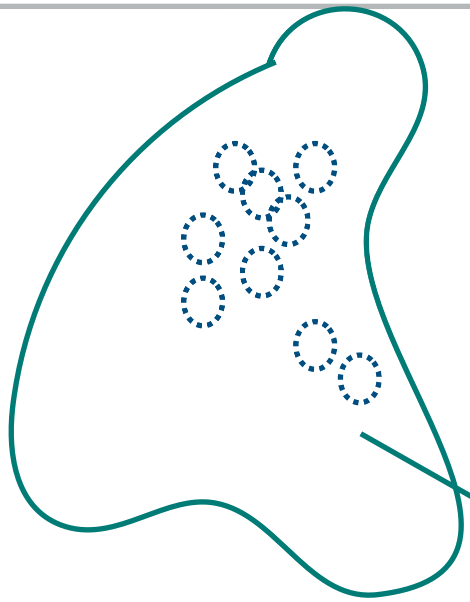




Detailed explanation in Lecture 3

Luminosities;
Star-Formation rate (SFR):
Stellar mass;
Dust mass;
Attenuation;
Star-formation history …

3.2 Giant molecular clouds (GMC)



GMC are large structures = sites of star-formation !

- GMC Mass: 10^3 to 10^6 solar masses;
- GMC lifetime: 10^7 yr

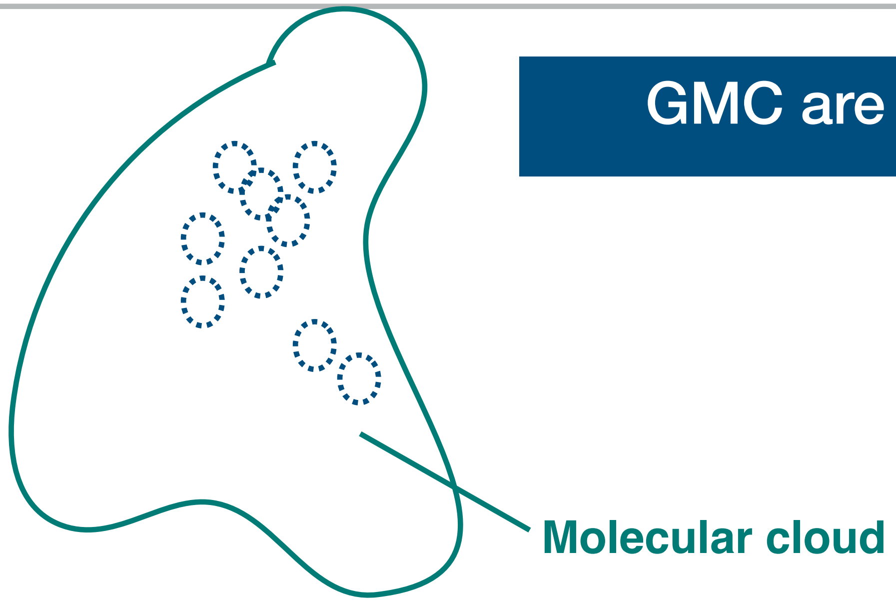
Notes about molecular hydrogen:

- **Formation process:** ***H2 molecules recombine on the dust grain surfaces in ISM.***
- **Gas-to-dust ratio is around 100 in clouds !**

$$t_{\rm form} = 1.5 \times 10^7\,{\rm yr} \left(\frac{n}{100\,{\rm cm}^{-3}} \right)^{-1}$$

- **Destruction process:** ***Photodissociation*** **!**
- **But, remember: Interstellar radiation fields (ISRF) in galaxies are not of constant intensity, meaning that n(H2) / n(HI) is strongly dependent on ISRF !!!**

3.2 Giant molecular clouds (GMC)



GMC are large structures = sites of star-formation !

- GMC Mass: 10^3 to 10^6 solar masses;
- GMC lifetime: 10^7 yr

How do GMC form ???

(1) Gravitational instability (could be due to different thermal layers in the ISM).

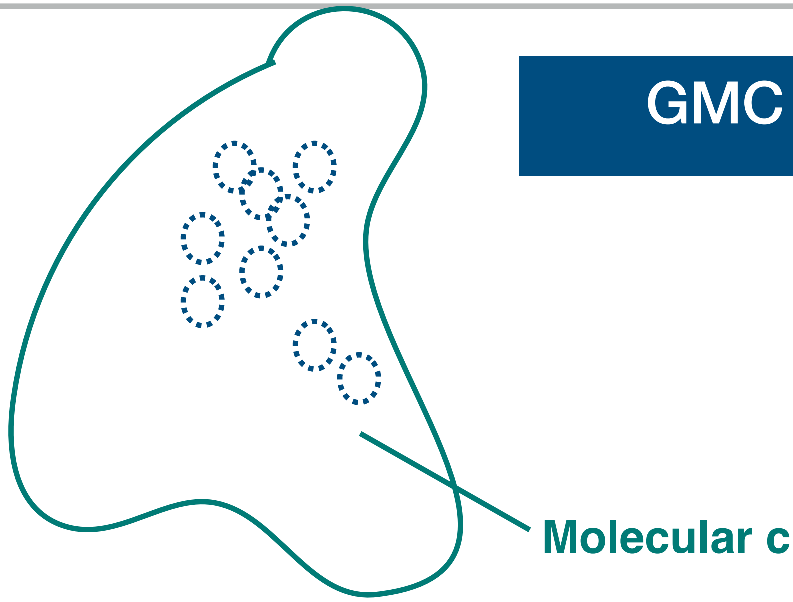
(2) Turbulence

(3) Spiral arms

(4) Galaxy interactions & mergers

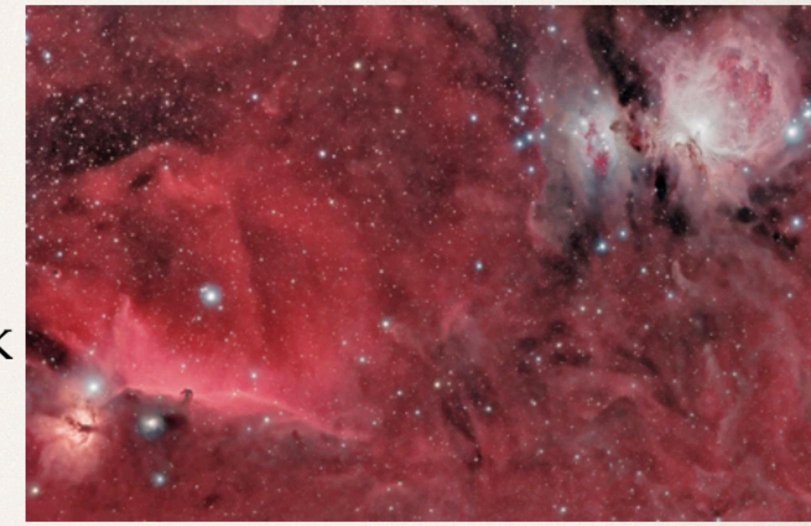
e.g. turbulent flow —> thermal instability …
… —> gas compression
… —> rapid formation of molecular hydrogen.

3.2 Giant molecular clouds (GMC)



GMC are large structures = sites of star-formation !

- Typical characteristics of GMCs:
  - Mass = 10^4-10^6 $M_\odot$
  - Distance to nearest GMC = 140 pc (Taurus)
  - Typical size = 5-100 pc
  - Size on the sky of nearby GMCs = 5-20 x full moon
  - Average temperature (in cold parts) = 20-30 K
  - Typical density = 10^3-10^6 cm^{-3}
  - Typical (estimated) life time ~10^7 year
  - Star formation efficiency ~1-10%



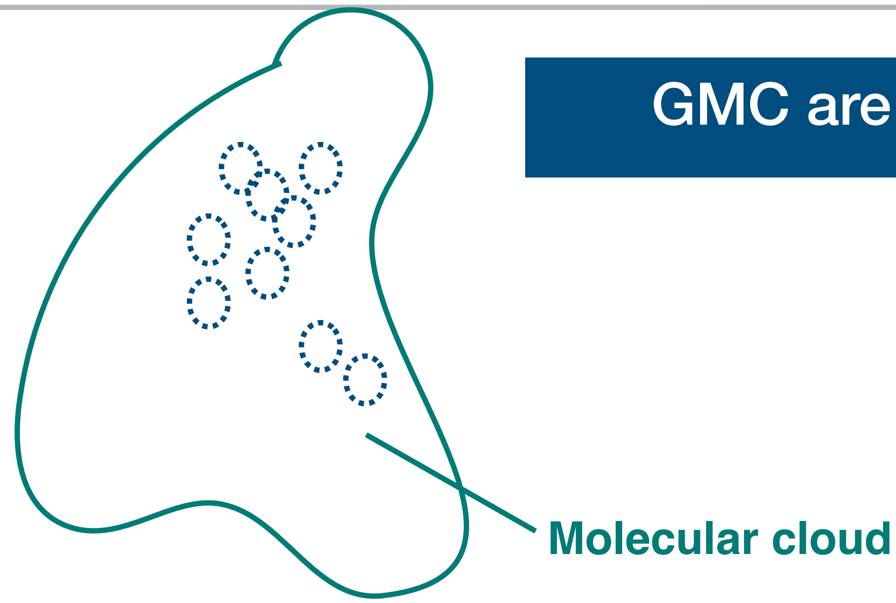
- Composition of material (by mass):
  - 99% gas: 0.9 H_2/H, 0.1 He, 10^{-4} CO, 10^{-5} other molecules (by number)
  - 1% solid sub-micron particles (dust) : Mostly silicates + carbonaceous (< μm in size)
- Properties of the gas:
  - Gas mostly in molecular form: H in H_2, C in CO, O in O_2 (?), N in N_2 (?).
  - At the edges of molecular clouds: transition to atomic species. "Photo-Dissociation Regions" (PDRs).
  - H_2 not directly observable → need a tracer (e.g., dust, CO).

2

MESSAGE No.4

- **GMC are**
  (1) Huge
  (2) Cold
  (3) Full of hydrogen molecule, which is no observed directly !

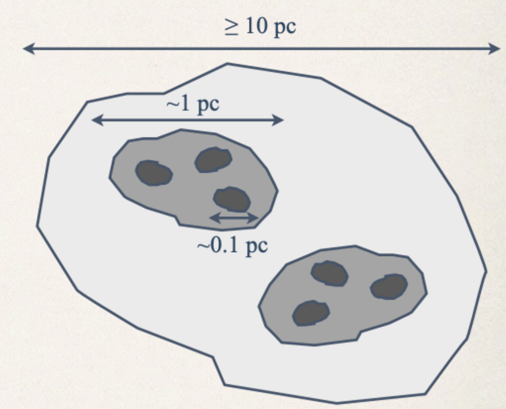
3.2 Giant molecular clouds (GMC)



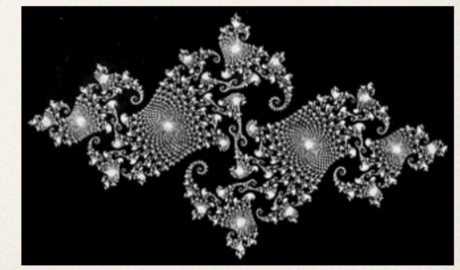
GMC are large structures = sites of star-formation !

Two descriptions :

- Clump picture : hierarchical structure
  - Clouds (≥ 10 pc)
  - Clumps (~1 pc) : Precursors of stellar clusters
  - Cores (~0.1 pc) : High density regions which form individual stars or binaries



- Fractal picture : clouds are scale-free ; suggested by power-law fits to relationships between cloud parameters.
  Limits: self-gravitating systems are not self-similar (e.g. self-similarity breaks down at ~0.2-0.3pc in Taurus — Williams 1998)



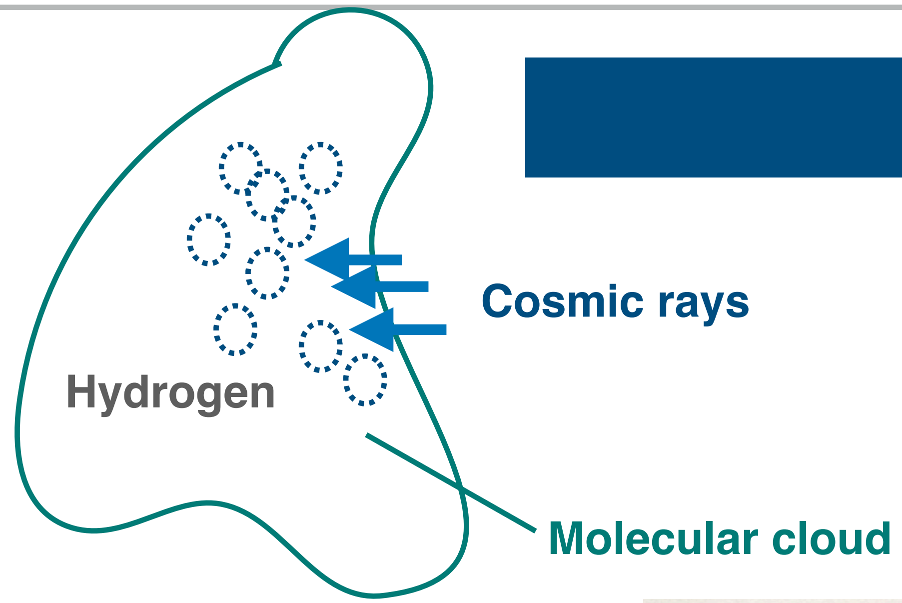
Example of a fractal object: $f(z) = z^2+c$, $(z,c) \in \mathbb{Z}$, $c=-0.745+0.113i$ 5

MESSAGE No.5

- **GMC are complicated to explore… :)**

- GMC Lifetimes: controversial
  - Long estimates: $>10^8$ yr based on z-distribution and presence GMCs in interarm regions
  - Short estimates: $\sim 2\times10^7$ yr because OB stars destroy GMC rapidly and GMCs mostly confined to spiral arms
- GMC Formation: random collisions of smaller clouds or spiral density wave?

Ionization

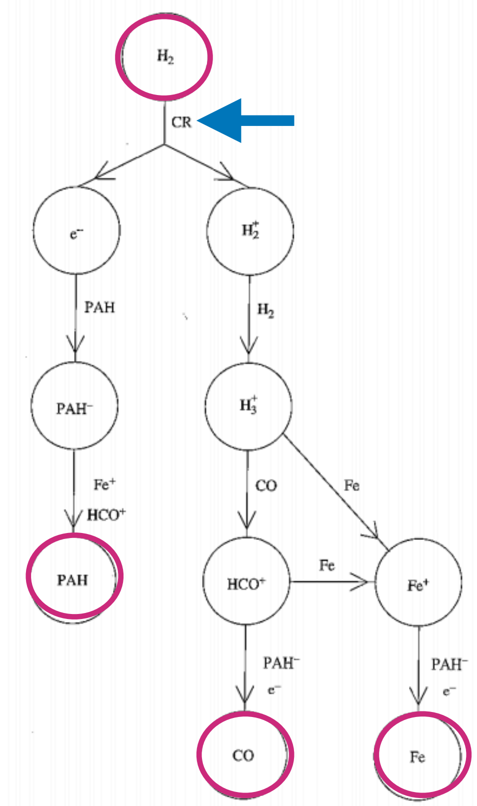


- Ions play a central role in gas-phase chemistry of molecular clouds
- UV do not penetrate (dense) molecular clouds ⇒ ionization via CR
- Degree of ionization:

$$x \simeq \left(\frac{\zeta_{CR}}{k_{rec} n}\right)^{1/2} \simeq \frac{10^{-5}}{\sqrt{n}}$$

with ζ_{CR} = primary CR ionization rate ~ 3×10^{-17} s^{-1}

k_{rec} = recombination rate ~ 3×10^{-7} s^{-1}

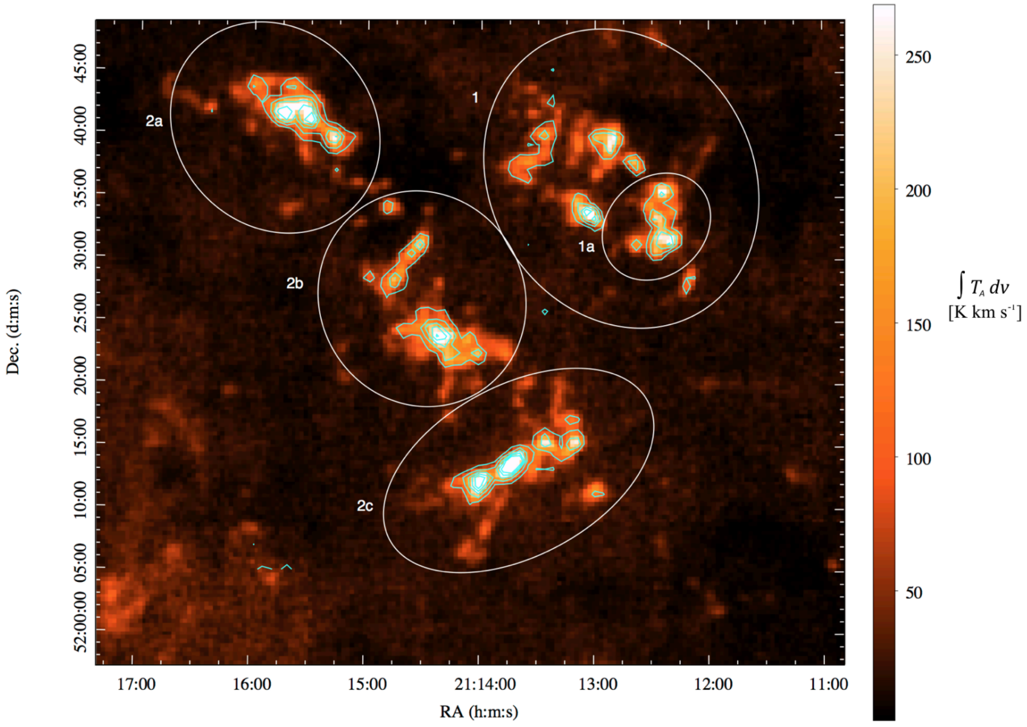


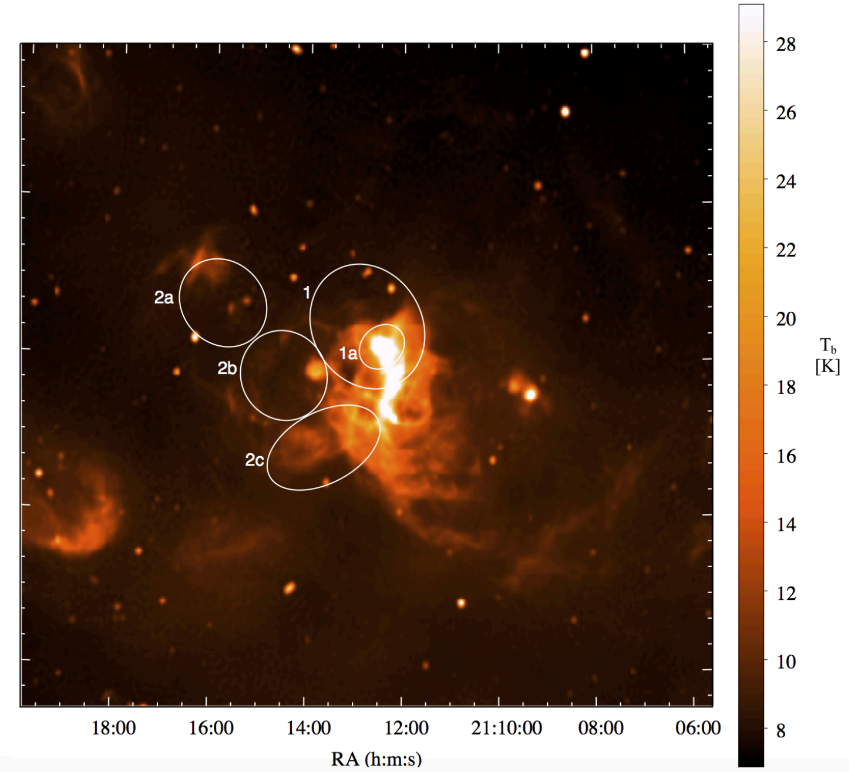
The flow of ionization in molecular clouds. Cosmic rays ionize molecular hydrogen. Reaction with H_2 rapidly forms H_3^+. The latter transfers its proton to other molecular species (HCO^+ is shown as the prime example of this reaction). H_3^+ and other molecular ions can charge transfer with trace metal atoms such as iron. The electron will be quickly soaked up by large molecules with high electron affinities such as PAHs. Eventually, the charge is lost through recombination between molecular or metallic cations with PAH anions.

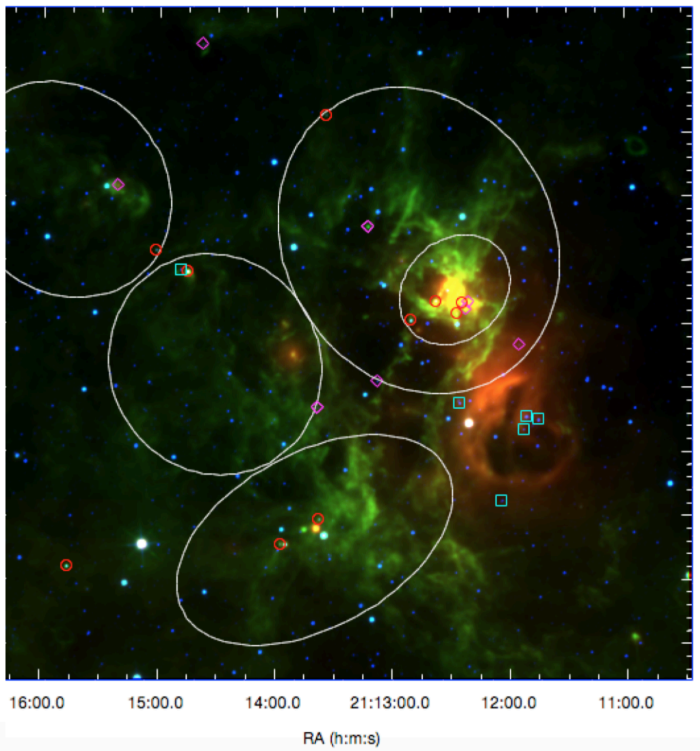
7

(Fig. 10.1 of Tielens)

3.2 Giant molecular clouds (GMC)







First high-resolution radio image of molecular clouds

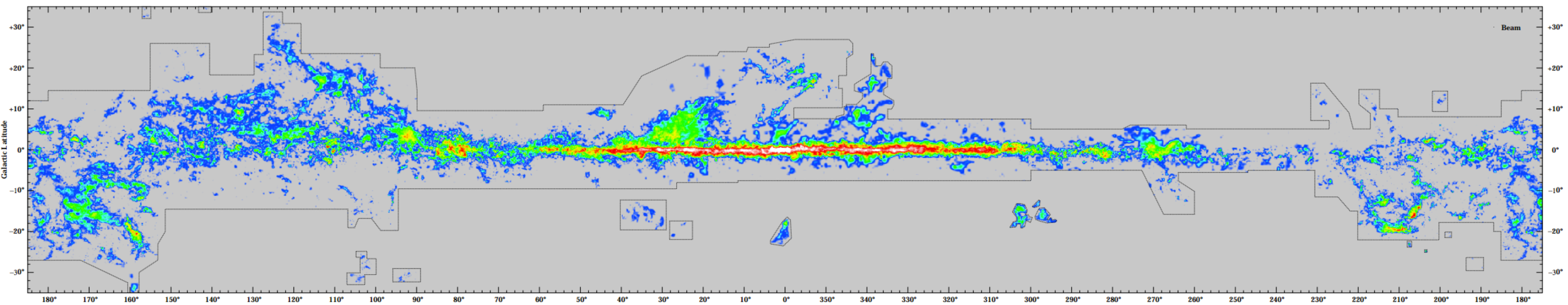
Integrated 12CO map of CTB 102.Cyan contours show the integrated 13CO emission. Five contour levels were generated starting 3σ above the median background.

1420 MHz image of CTB.

IR (WISE) RGB image

3.2 Giant molecular clouds (GMC)

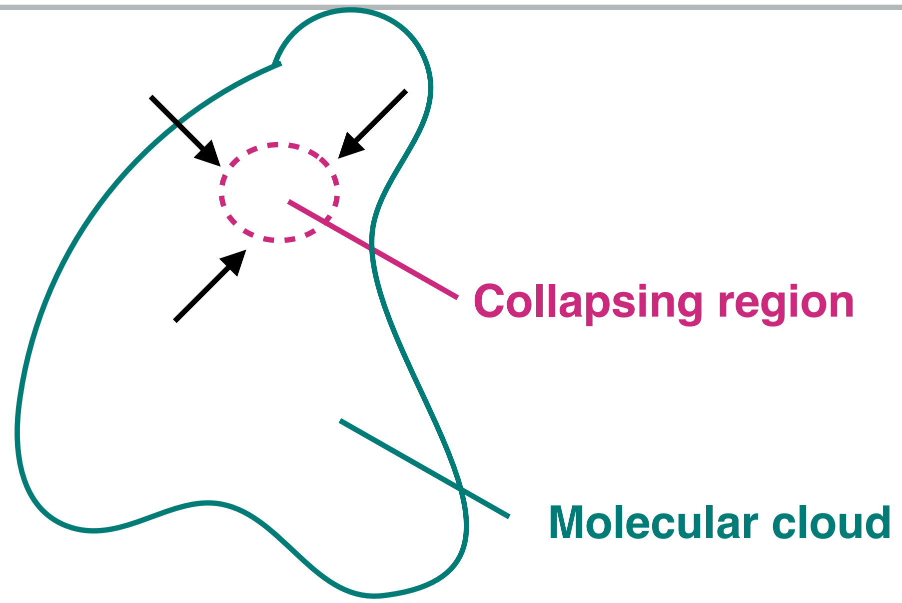
- More generally, determination of cloud mass from CO as tracer of H_2 requires a relation between the observed integrated CO intensity, $I_{CO} = \int T_A(V)dV = 1.06\, T_A\, \Delta V$, and H_2 column density
- Various methods used to calibrate this relation



Velocity integrated mapping of molecular hydrogen in MW (colour is related to density)

However, such a detailed map available only for MW !!!

3.3 From gas to stars: Initial Mass Function (IMF)

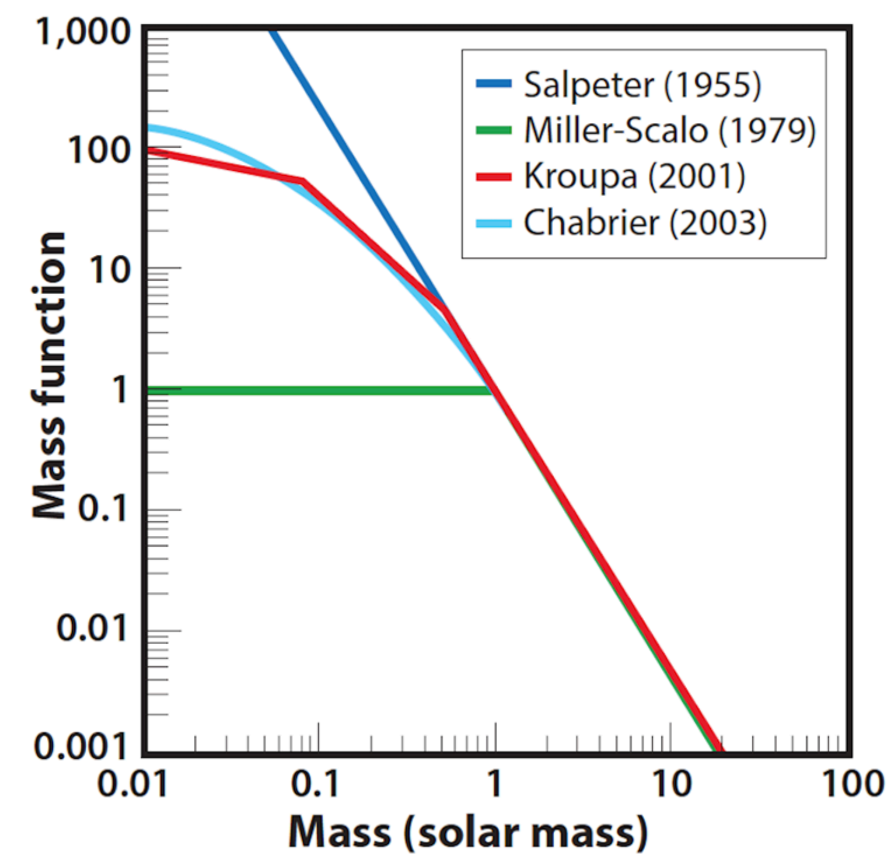


IMF… or:
What is the mass distribution of newly formed stars?

- **Little is known what is the distribution of stars according to their masses in galaxies** ***(Salpeter, Chabrier, Scalo, Kroupa…)***
- **IMF is very uncertain parameter !**
- **Best results obtained for Chabrier IMF**

Initial Mass Function (IMF)

$$\int_{m_\ell}^{m_u} m\phi(m)\,dm = 1\,M_\odot,$$

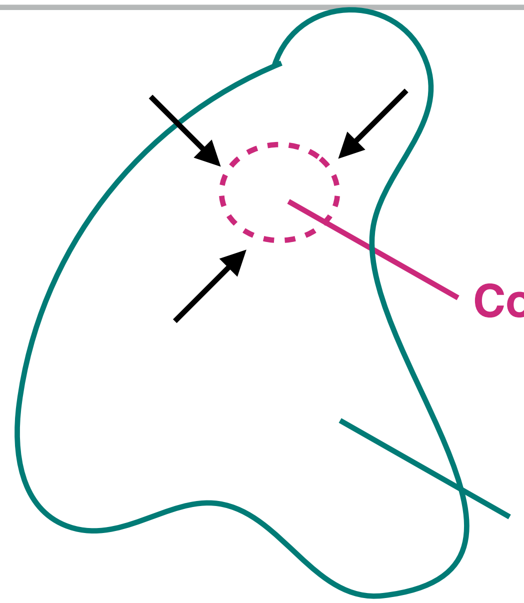


Of 400 billion stars in the Milky Way, some 300 billion are red dwarfs.

(smallest red dwarfs have 0.08 solar mass)

Below that limit are brown dwarfs — failed stars without enough mass to fuse hydrogen into helium.

3.3 From gas to stars: star-formation efficiency



How do star form ?
What controls star-star-formation efficiency (SFE) ?

- Star formed in giant clouds of dust and gas.
- Contains H, He, H2O, OH, CO, HCN etc.
- Dust is made of silicates, carbons, iron, ices, etc.

➡ Molecular cloud fragments into many clumps —> dense gas in the centre —> star-formation !

➡ Number of stars form from the cloud could be up to 2000 !

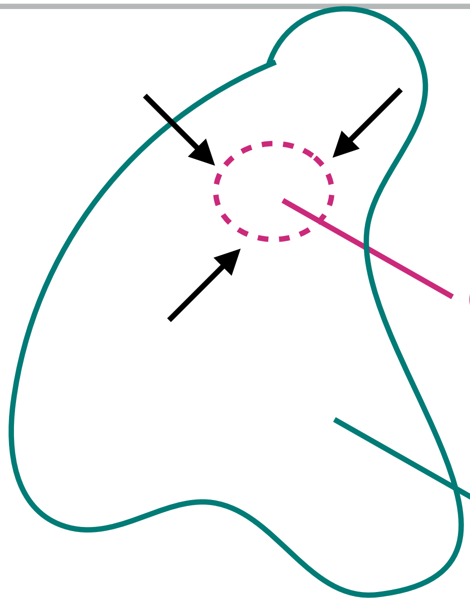
Problem: Star formation is highly inefficient process !!!

Depletion time
(or star-formation time-scale)

$$\tau_{\rm SF} \equiv M_{\rm gas}/\dot{M}_{\rm gas}$$

Question: What causes different galaxies having different SFE ?

3.3 From gas to stars: star-formation efficiency



How do star form ?
What controls star-star-formation efficiency (SFE) ?

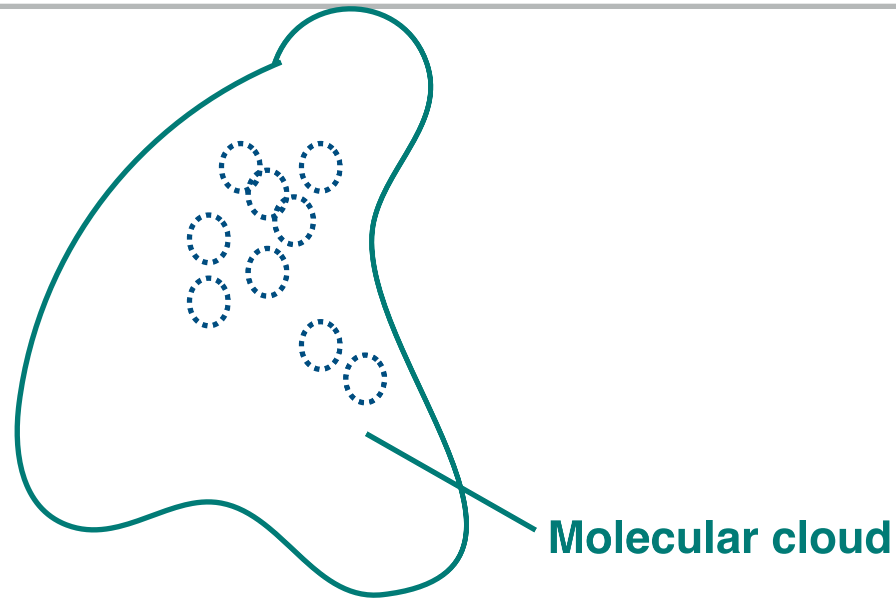
➡ Molecular cloud fragments into many clumps —> dense gas in the centre —> star-formation!

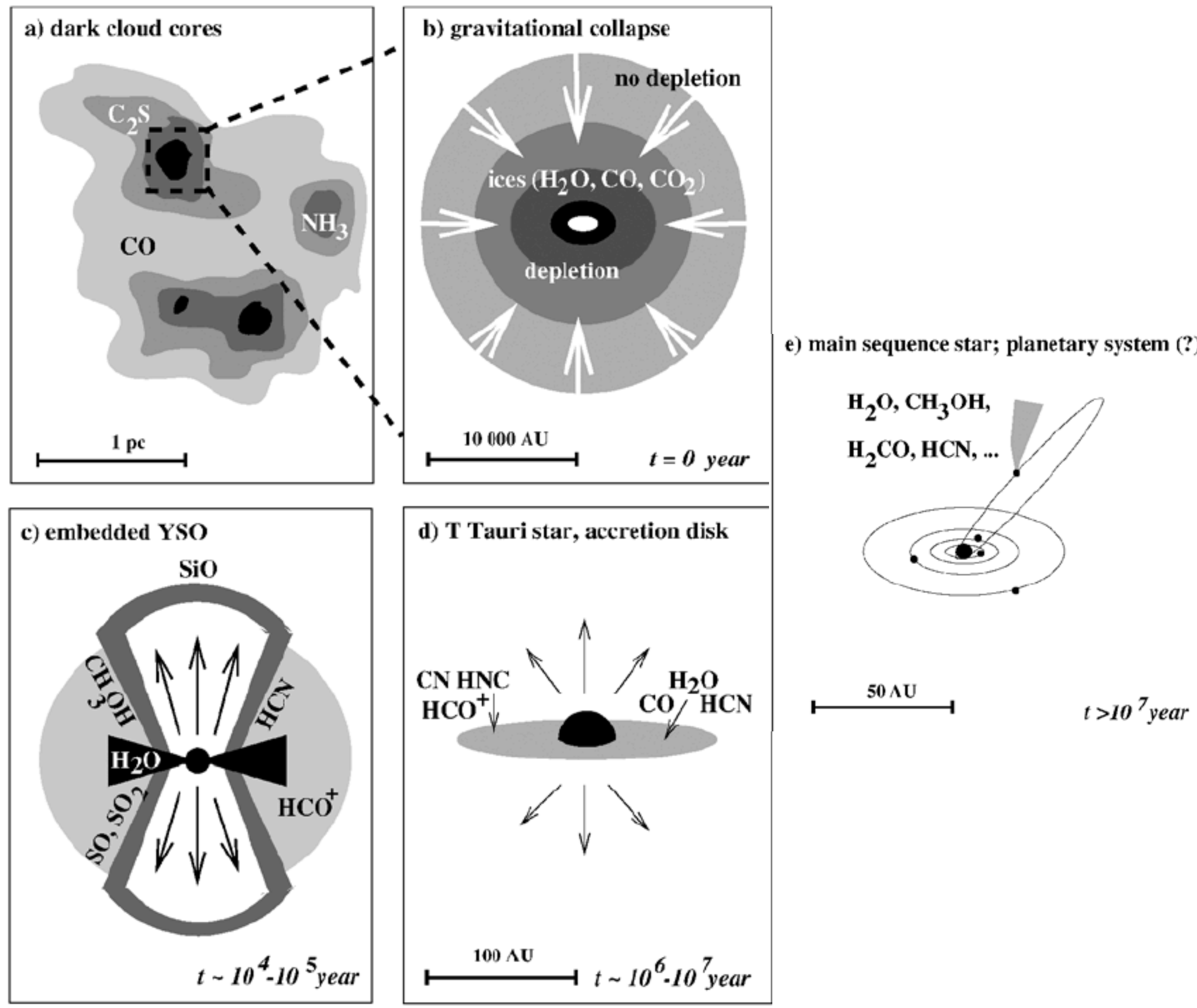
- Interstellar gas converts from atomic to molecular only in regions that are well shielded from interstellar ultraviolet (UV) photons.
- Only in these shielded regions does the gas become cold enough to be subject to *Jeans instability* (Krumholz 2012)!

Problem: Star formation is highly inefficient process !!!

Question: What causes different galaxies having different SFE ?

3.3 From gas to stars: star-formation efficiency

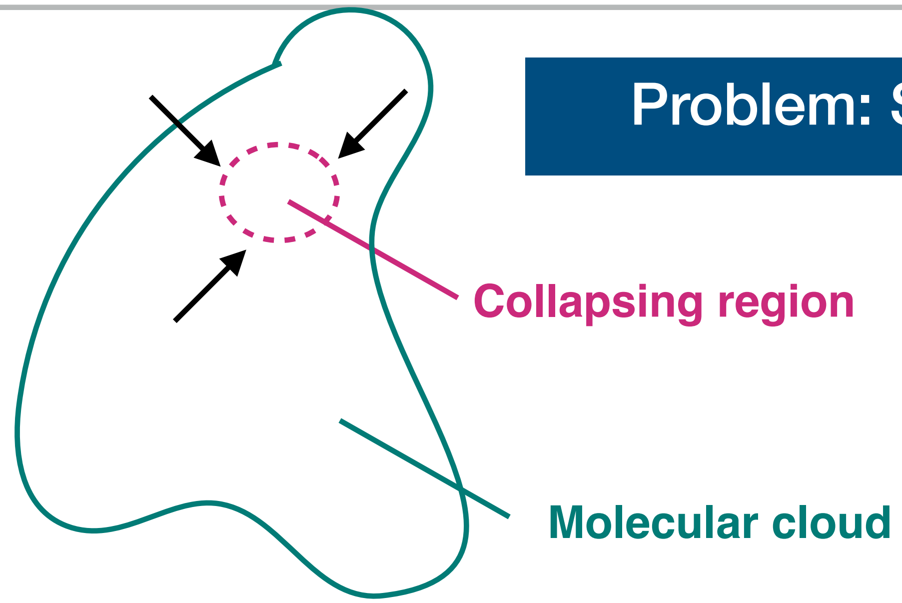




Summary of main phases of star-formation

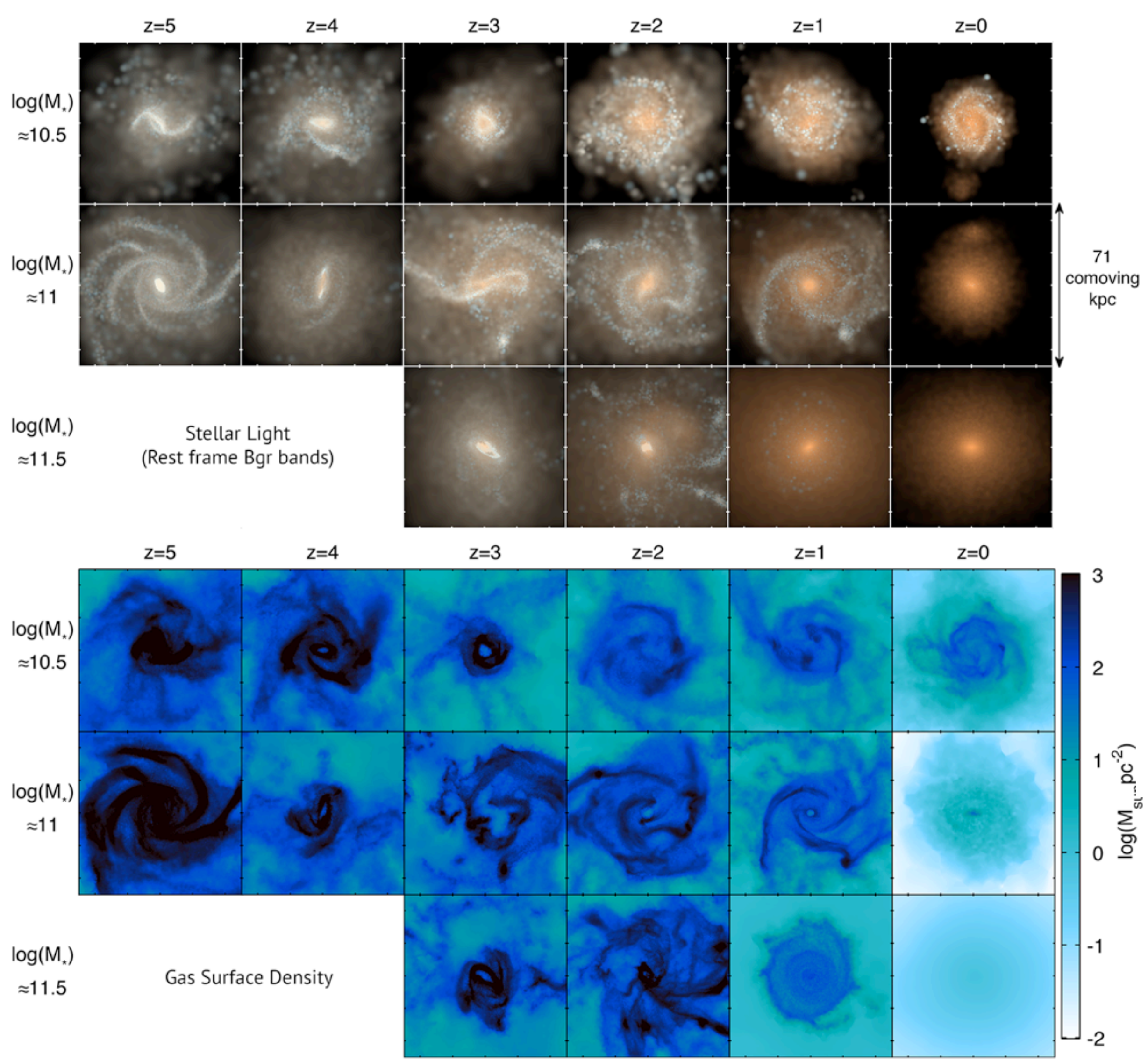
A collapsing molecular cloud will give birth to stars with a range of masses, defined by the Initial Mass Function (IMF).

3.3 From gas to stars: star-formation efficiency



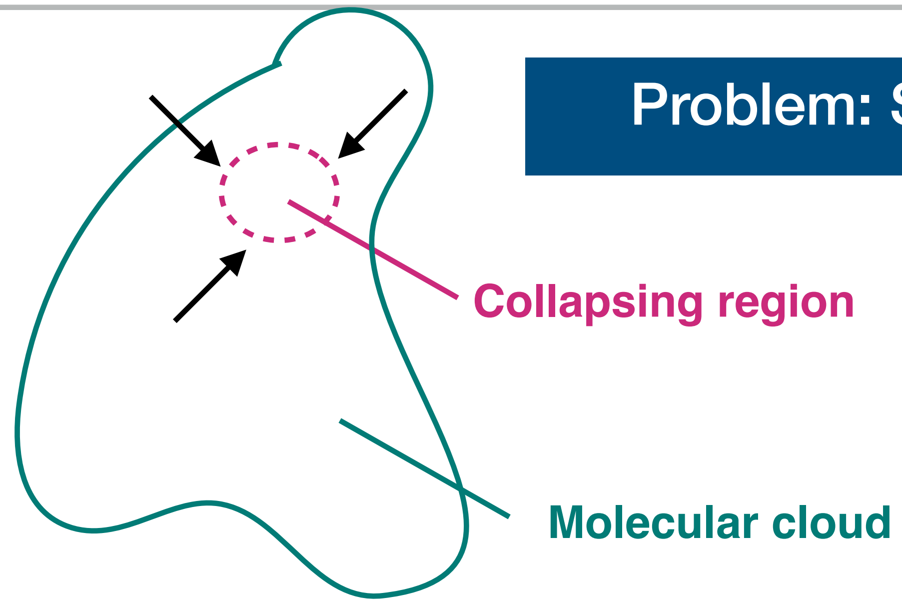
Problem: Star formation is highly inefficient process !!!

How do star form ?
What controls star-star-formation efficiency (SFE) ?



Some of galaxies have high SFE, but most of them have low SFE !!!

3.3 From gas to stars: star-formation efficiency



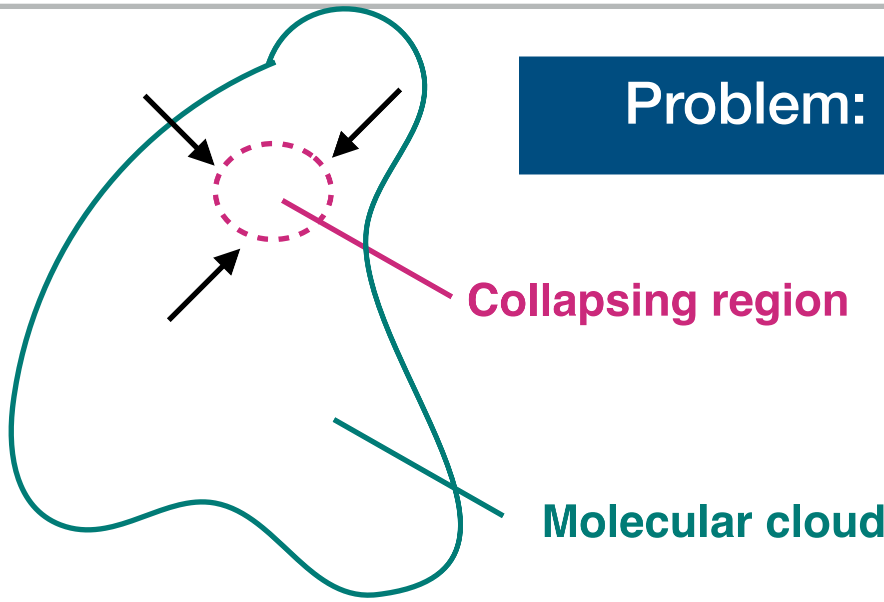
Problem: Star formation is highly inefficient process !!!

How do star form ?
What controls star-star-formation efficiency (SFE) ?

Smaller depletion time (SFE is high)

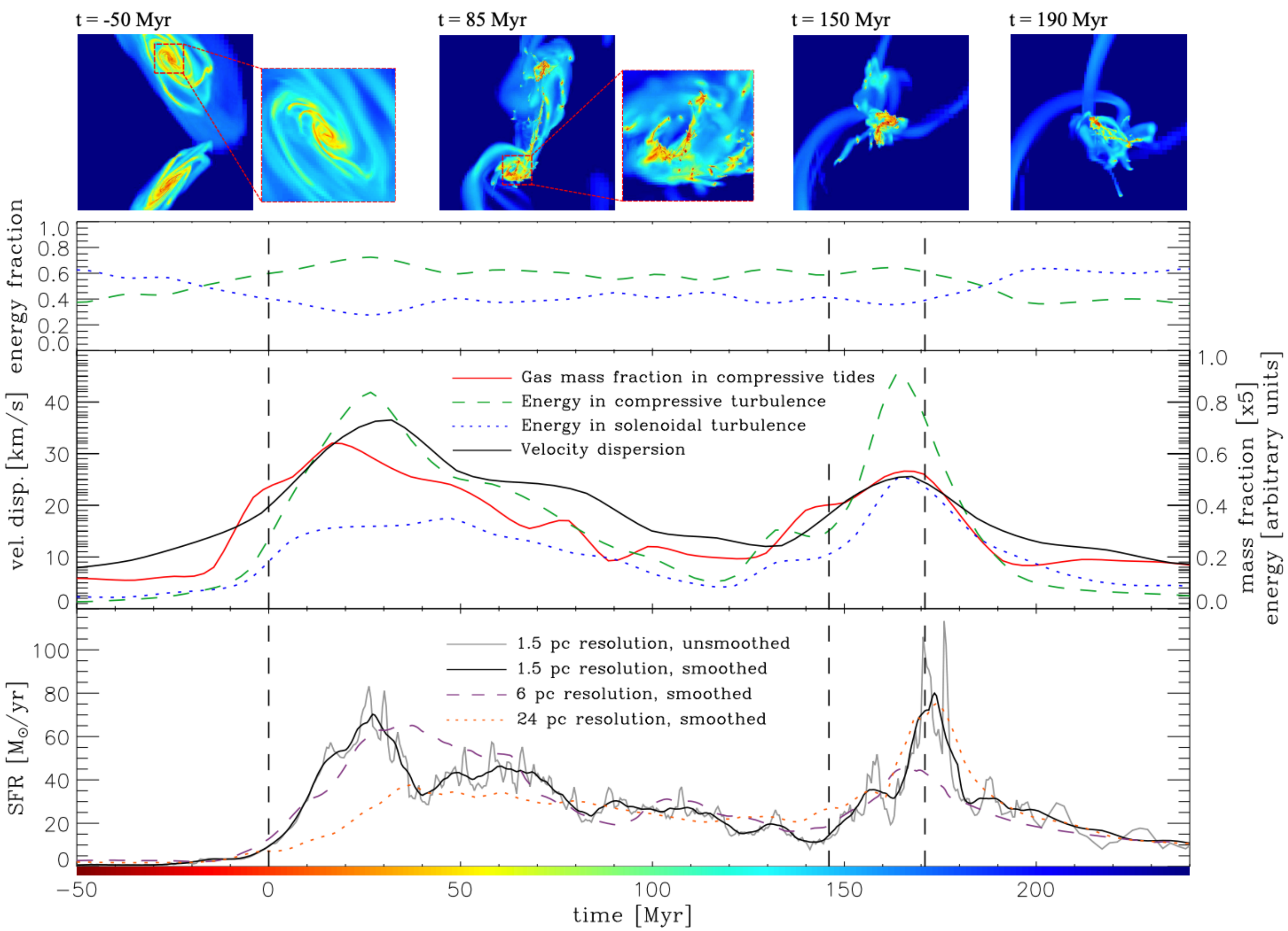
Long depletion time (SFE is low)

3.3 From gas to stars: star-formation efficiency



Problem: Star formation is highly inefficient process !!!

How do star form ?
What controls star-star-formation efficiency (SFE) ?



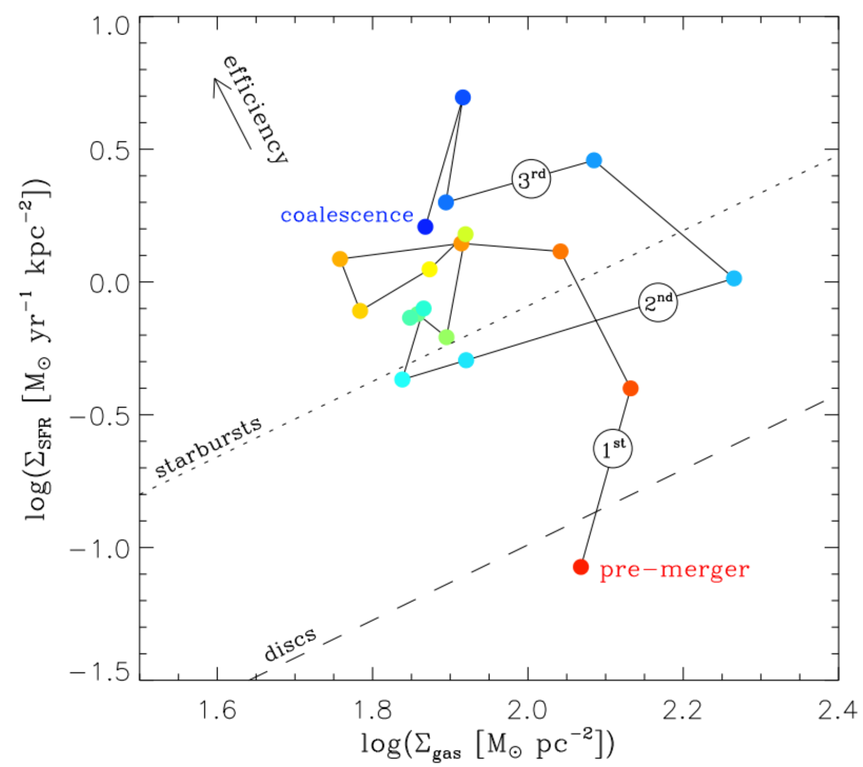


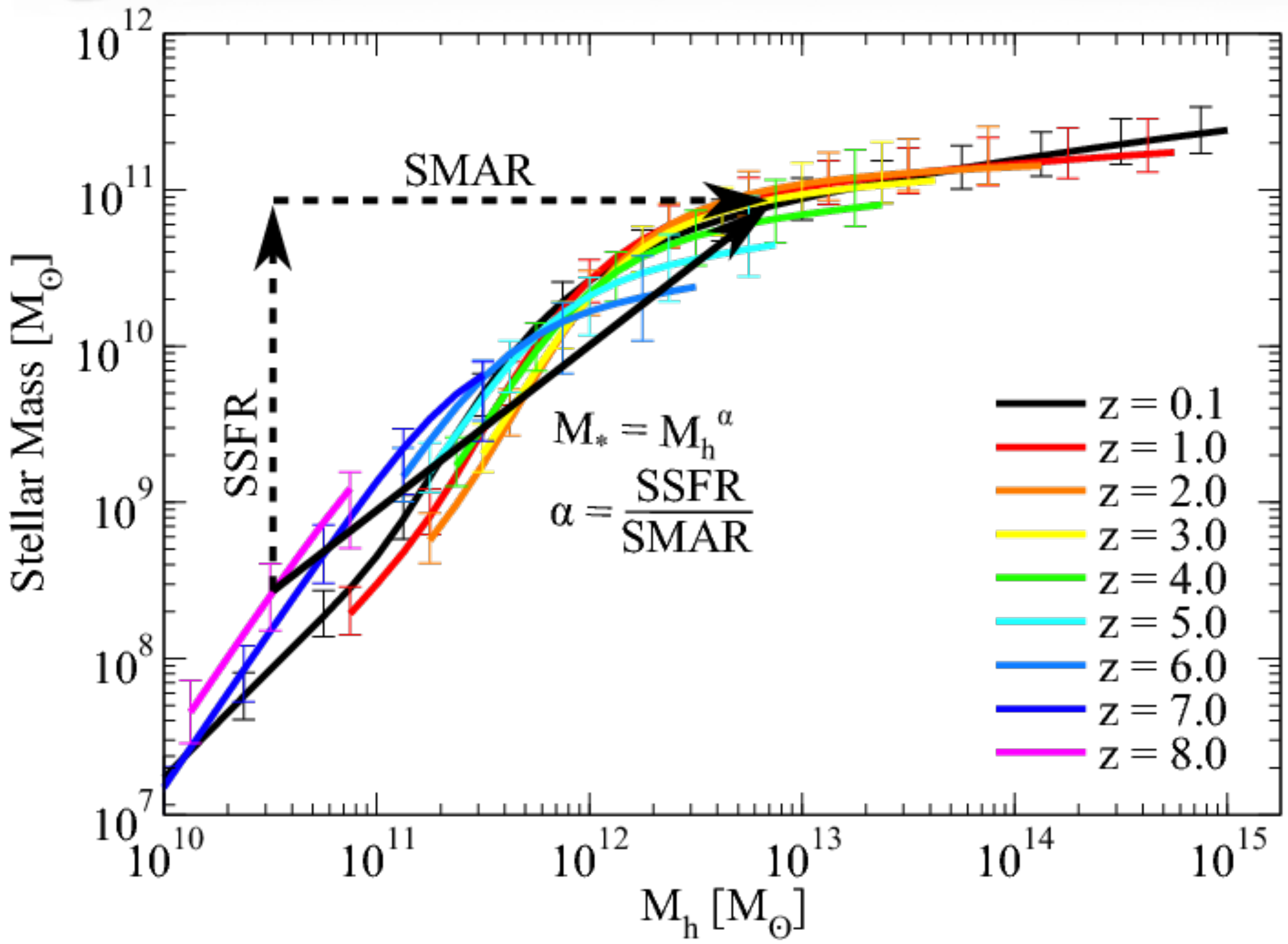
Figure 3. Evolution of surface density of gas and of star formation rate inside the half-mass radii of the galaxy(ies) (2±0.3 kpc), every ≈ 10 Myr along the merger. Colour running from red to blue codes time, as in the colour bar of Fig. 1. The numbers in circles indicate the three encounters ($t = 0$, 146 Myr and 171 Myr). The dashed and dotted lines indicate the sequences of discs and of starbursts, as in Daddi et al. (2010).

Renaud et al. 2014

3.3 From gas to stars: star-formation efficiency

Problem: Star formation is highly inefficient process !!!

How does it relate to DM halo ???

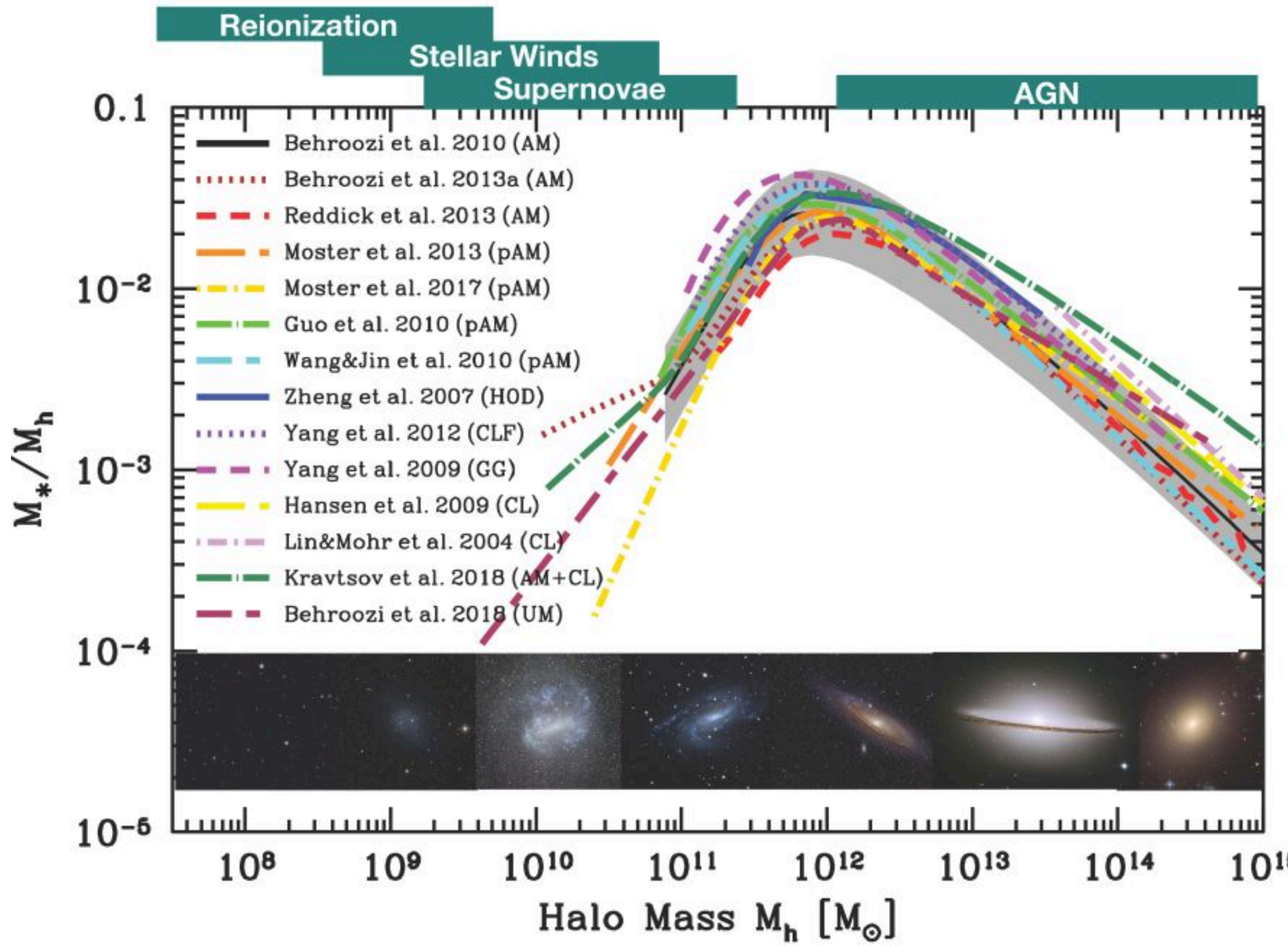


Star-formation efficient up to some certain halo mass !

3.3 From gas to stars: star-formation efficiency

Problem: Star formation is highly inefficient process !!!

How does it relate to DM halo ???



MESSAGE No.5

There is a maximum limit of producing stars in galaxies ! And it depends on DM halo mass !

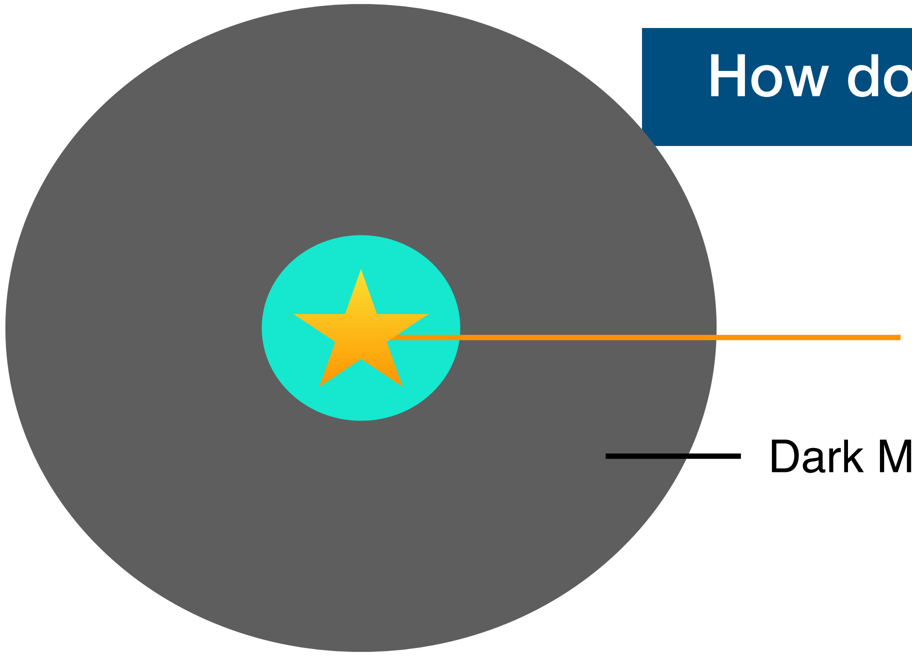
Star-formation efficient up to some certain halo mass !

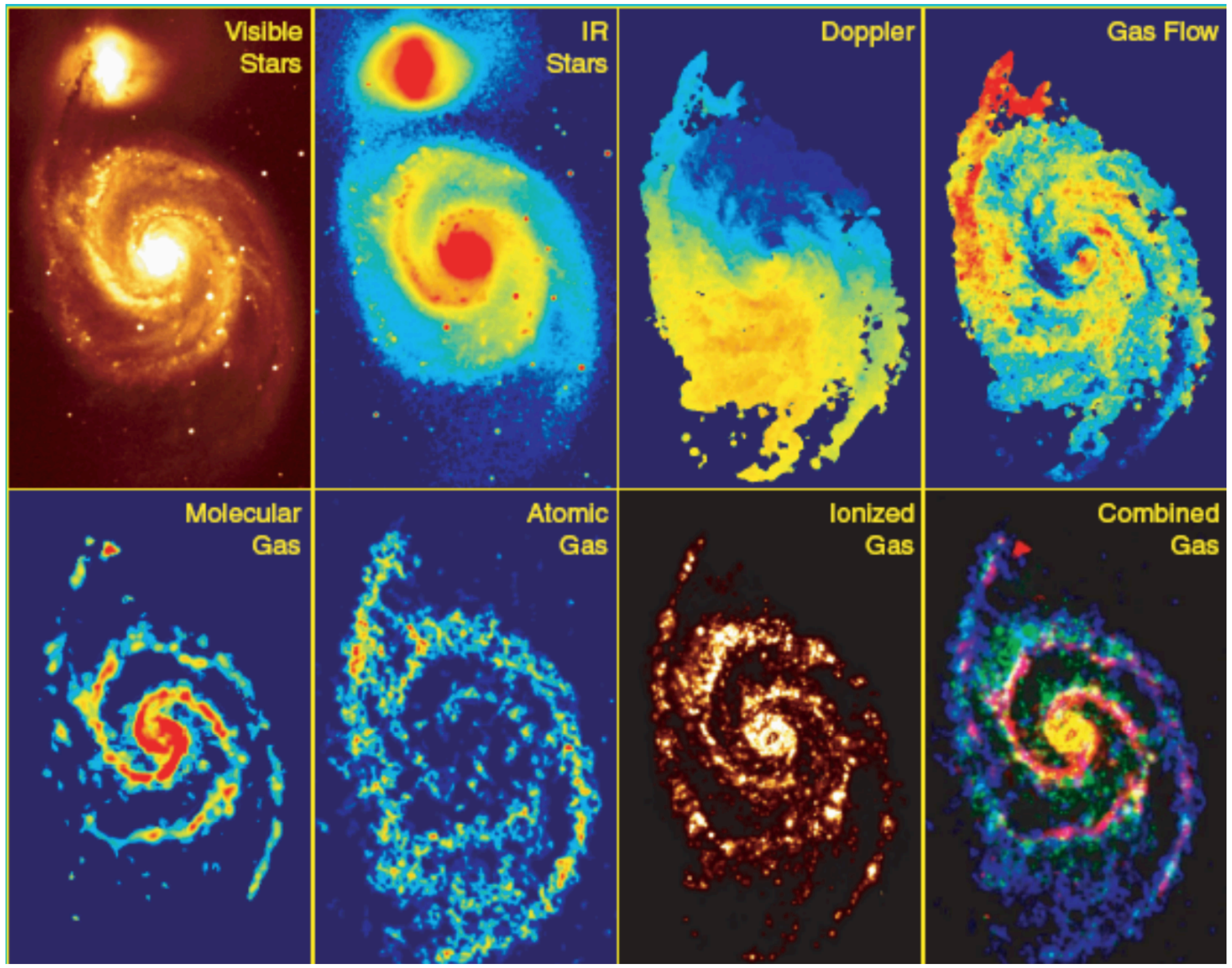
IV Observational tracers of star-formation

"What we infer, and what we miss from observational data ? "

4.1 Observational tracers of star-formation

How do we know there is ongoing star-formation in galaxies?



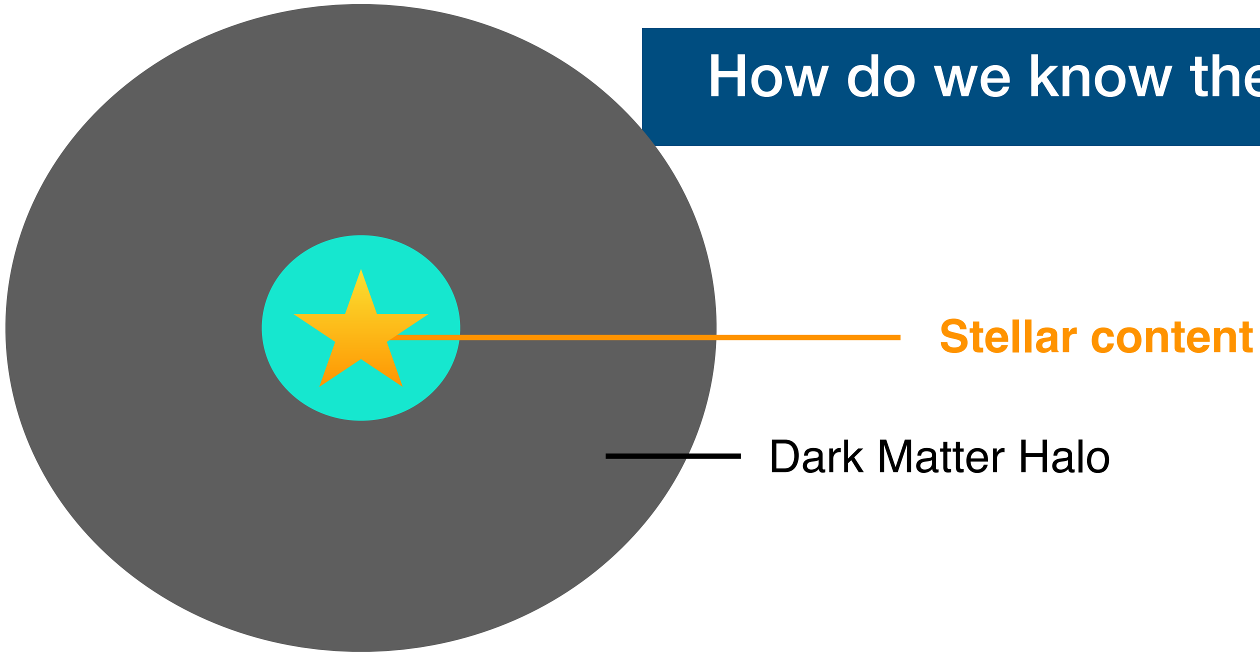


★ Stars:

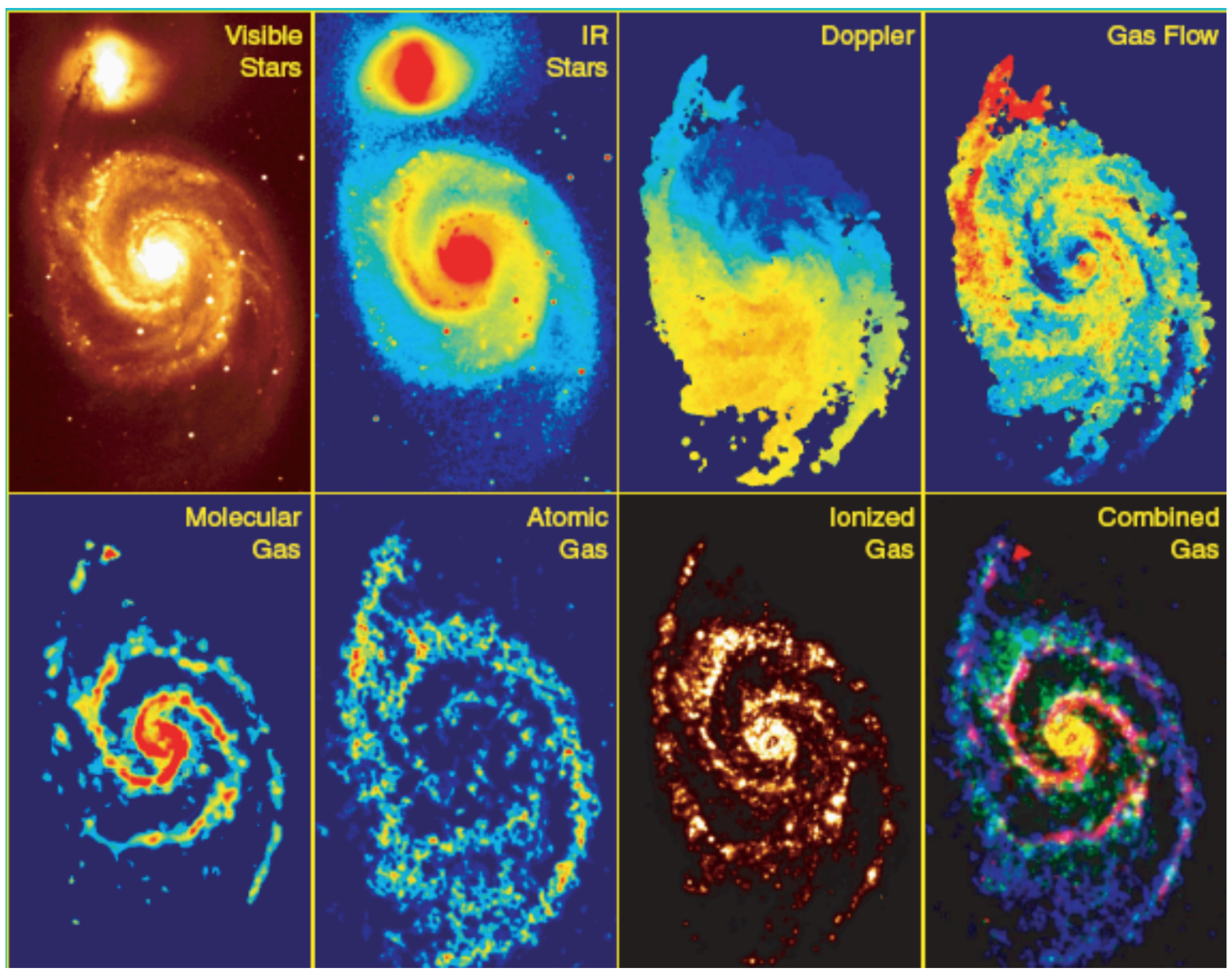
(1) Bulge (old stars, gas poor, low metal)
(2) Disk (young stars, gas rich, more metal)

★ ISM:
- Ionised gas (HII)
- Atomic gas (HI)
- Molecular gas (H2)

4.1 Observational tracers of star-formation



How do we know there is ongoing star-formation in galaxies?

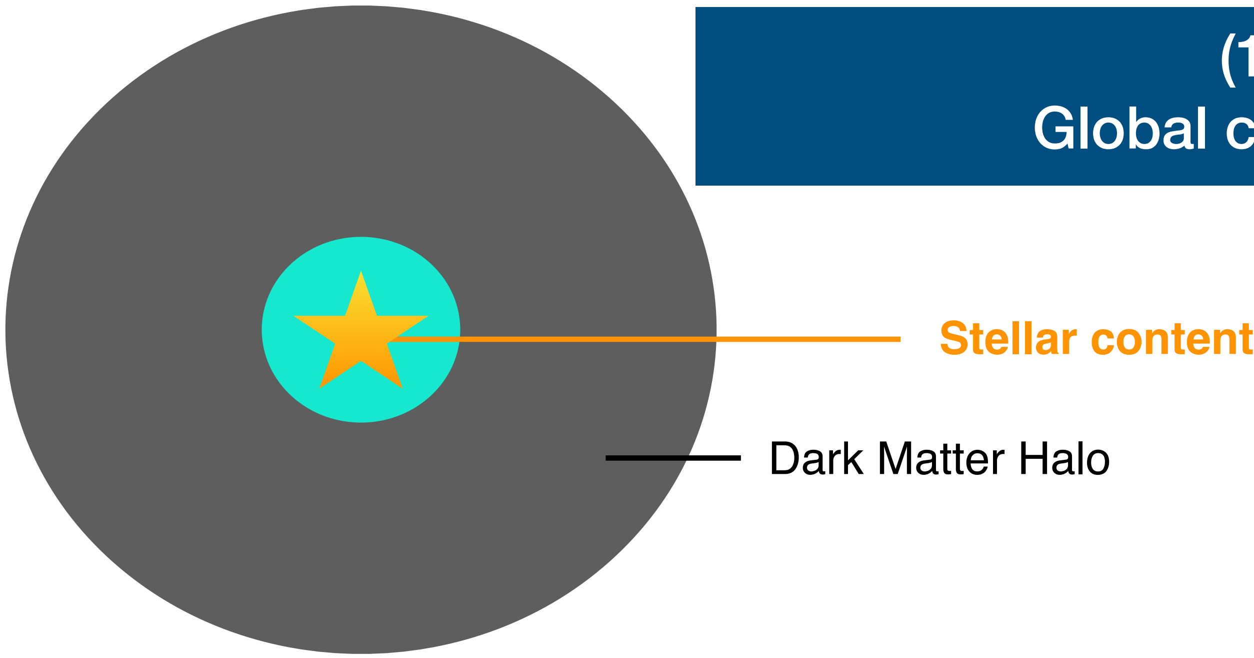


★ Most of the star formation is in spirals !
(T<10K in spiral arms, T>10k in disk)

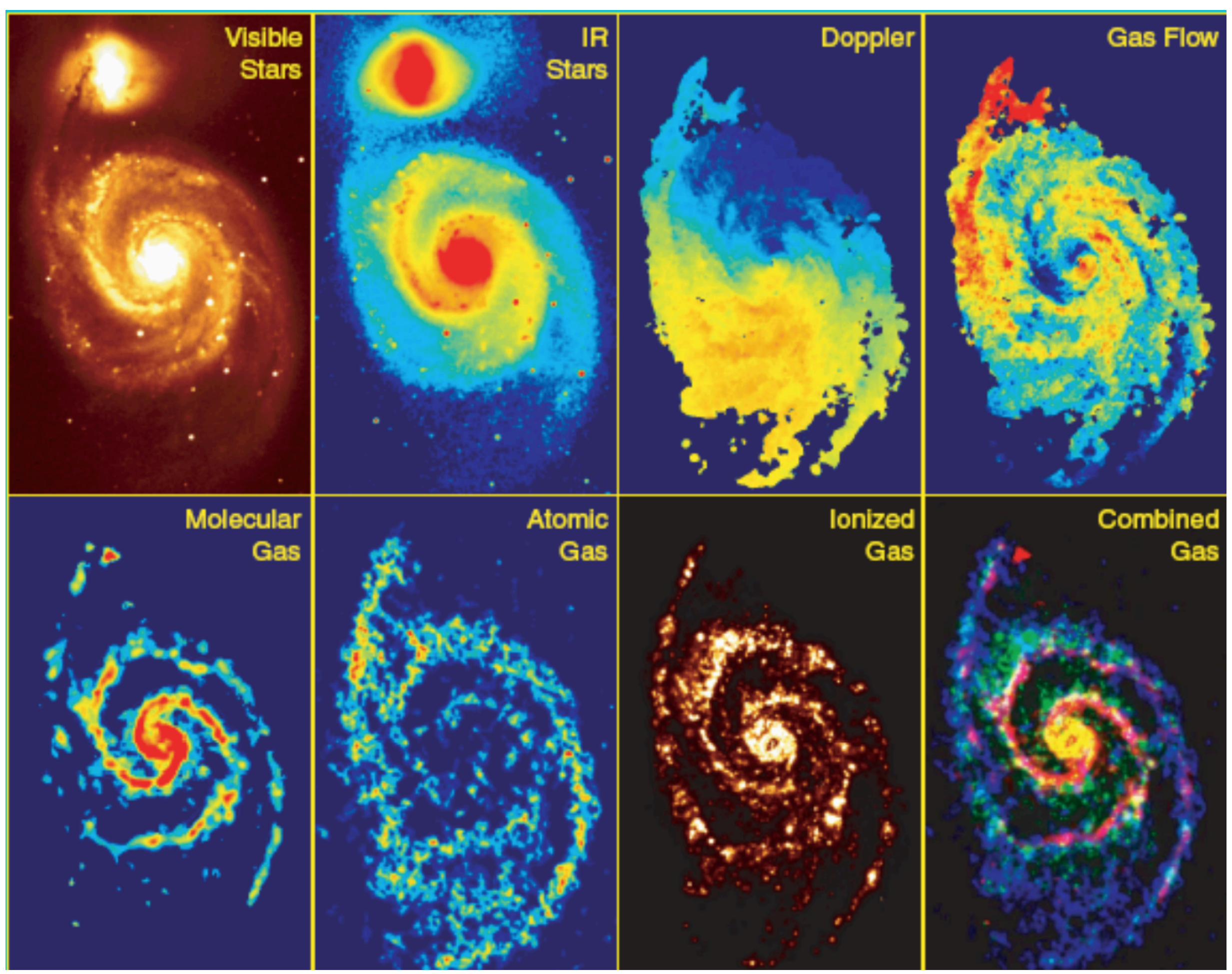
★ But… ellipticals have enormous stellar masses, but no star-formation.

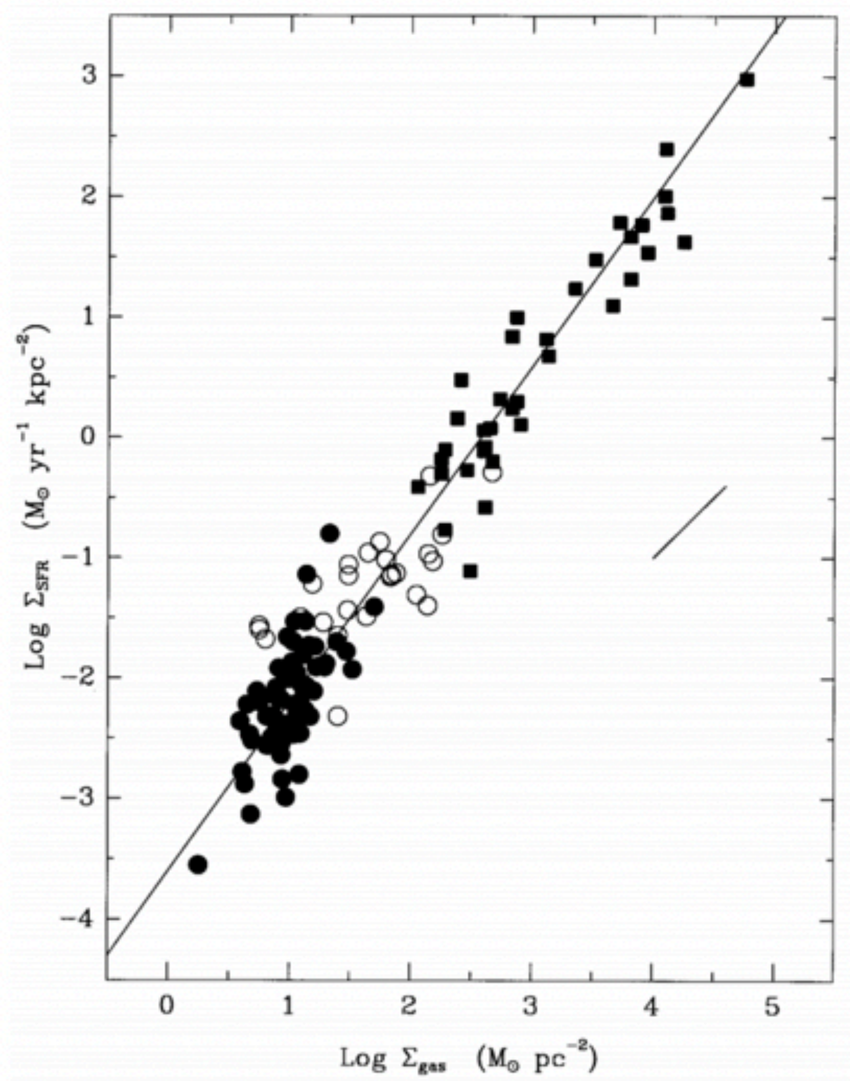
★Thus:
- evolution of galaxies stellar content
- evolution of galaxies sizes/ morphology / gas content !

4.1 Observational tracers of star-formation



(1) Kennicutt-Schmidt Law:
Global connection between gas and SFR

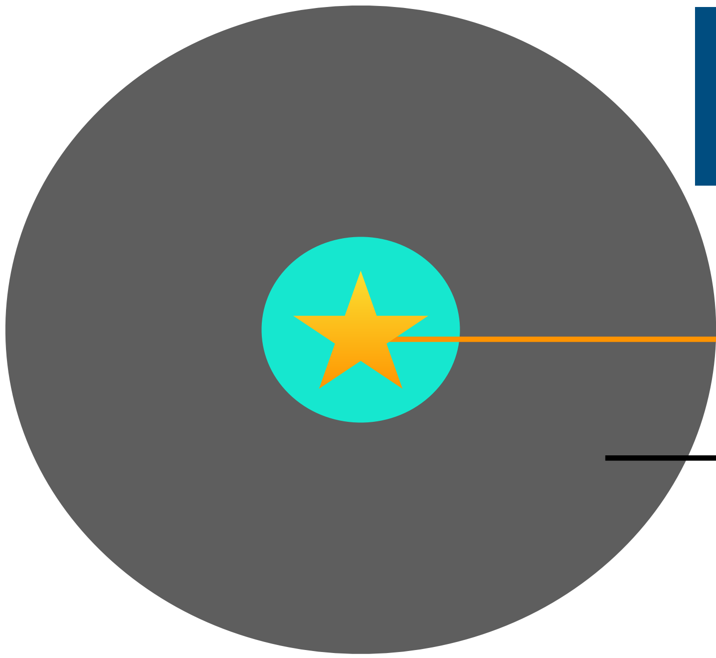


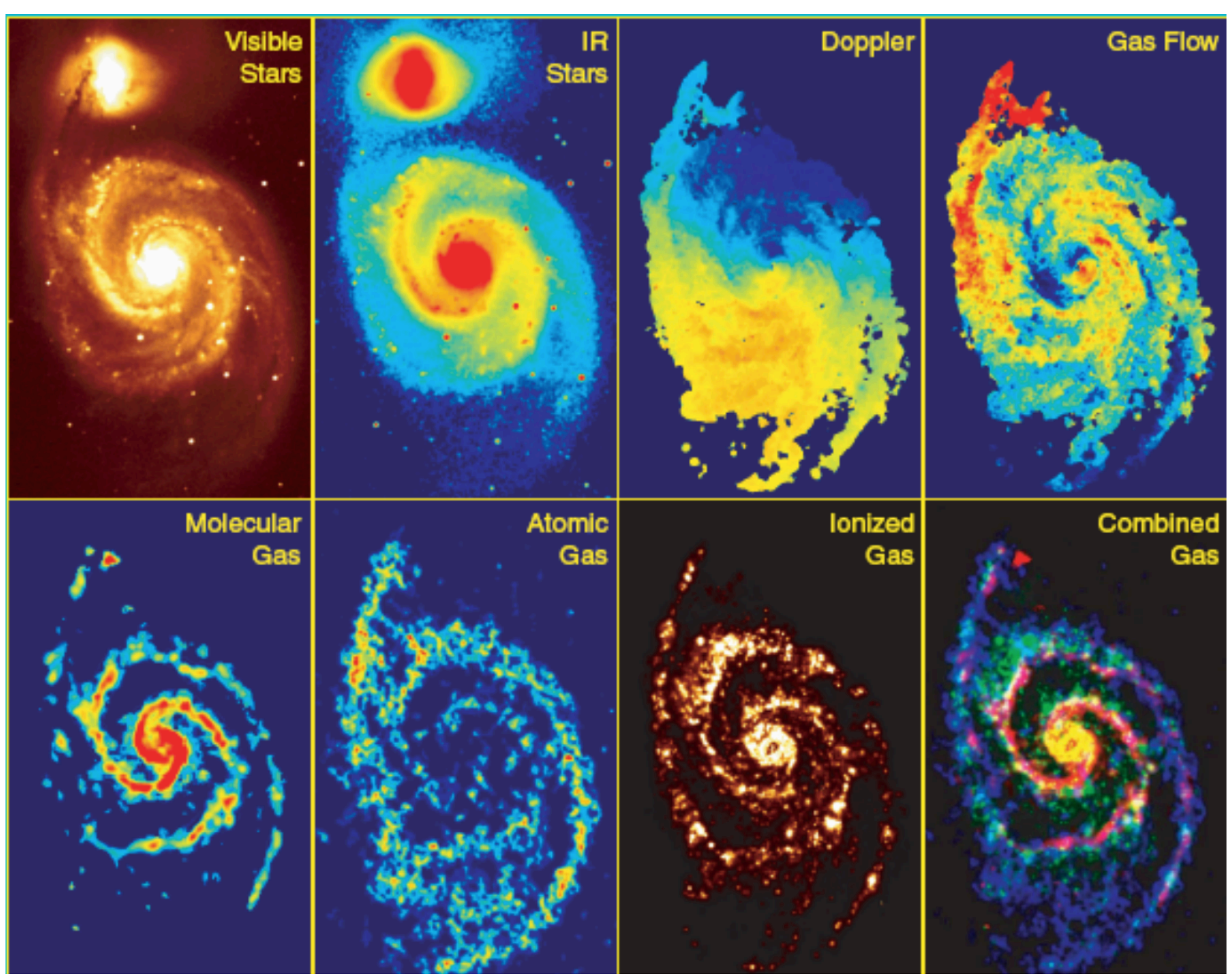


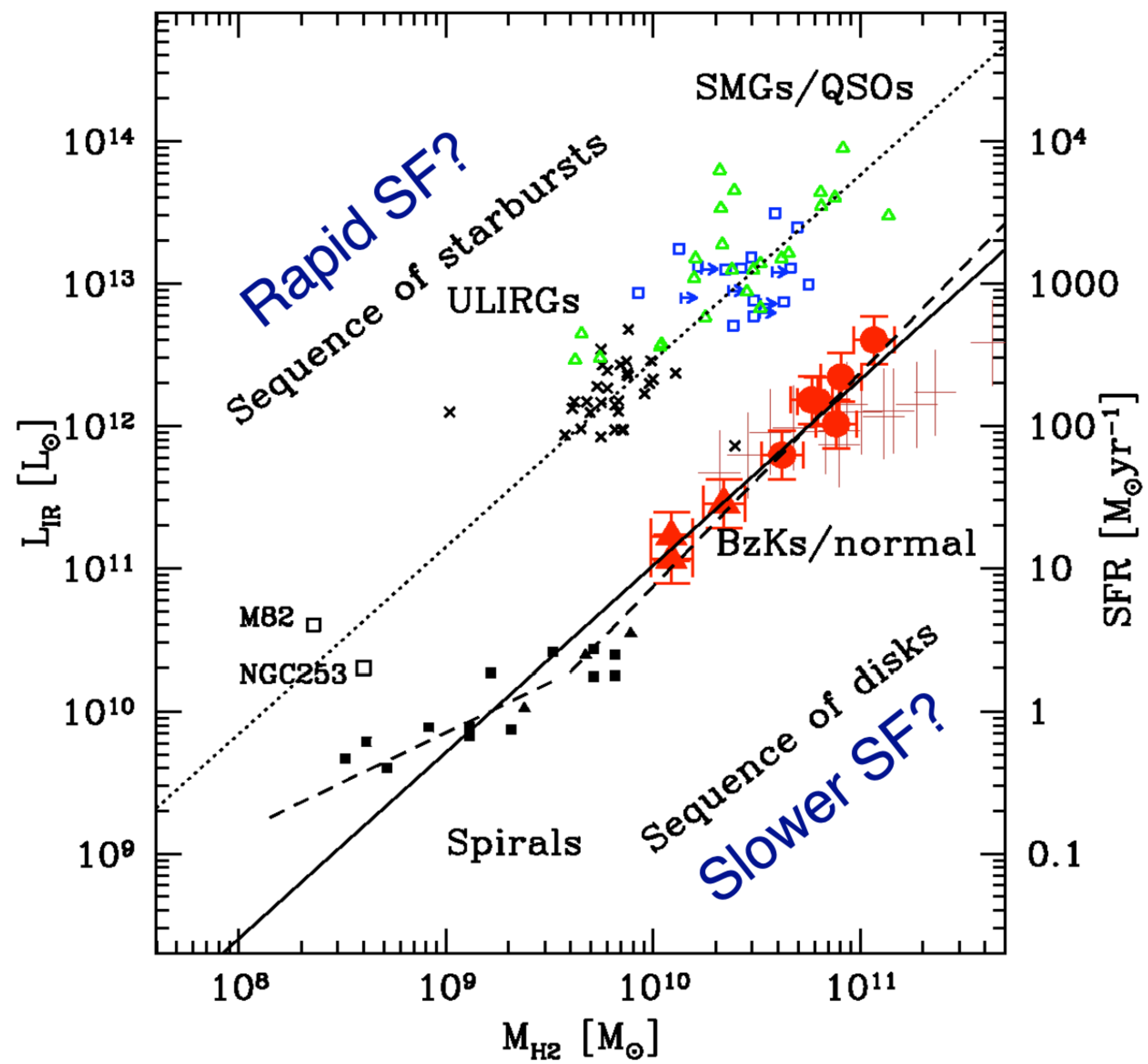
KS seems elegant, logical and simple ! :)

4.1 Observational tracers of star-formation

(1) Kennicutt-Schmidt Law:
Global connection between gas and SFR

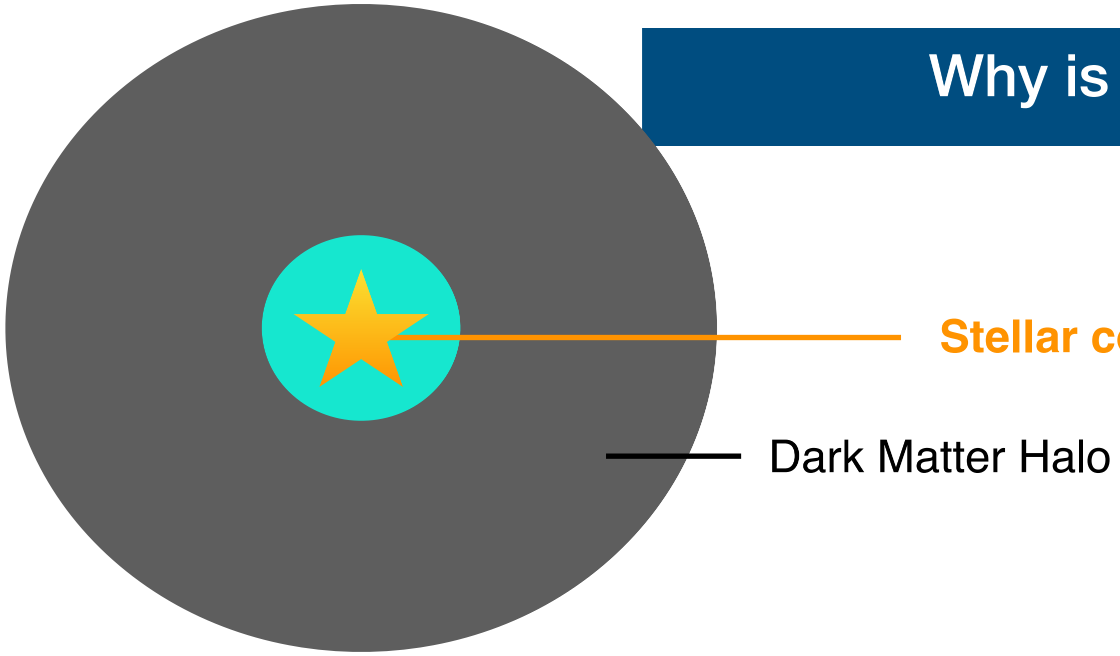




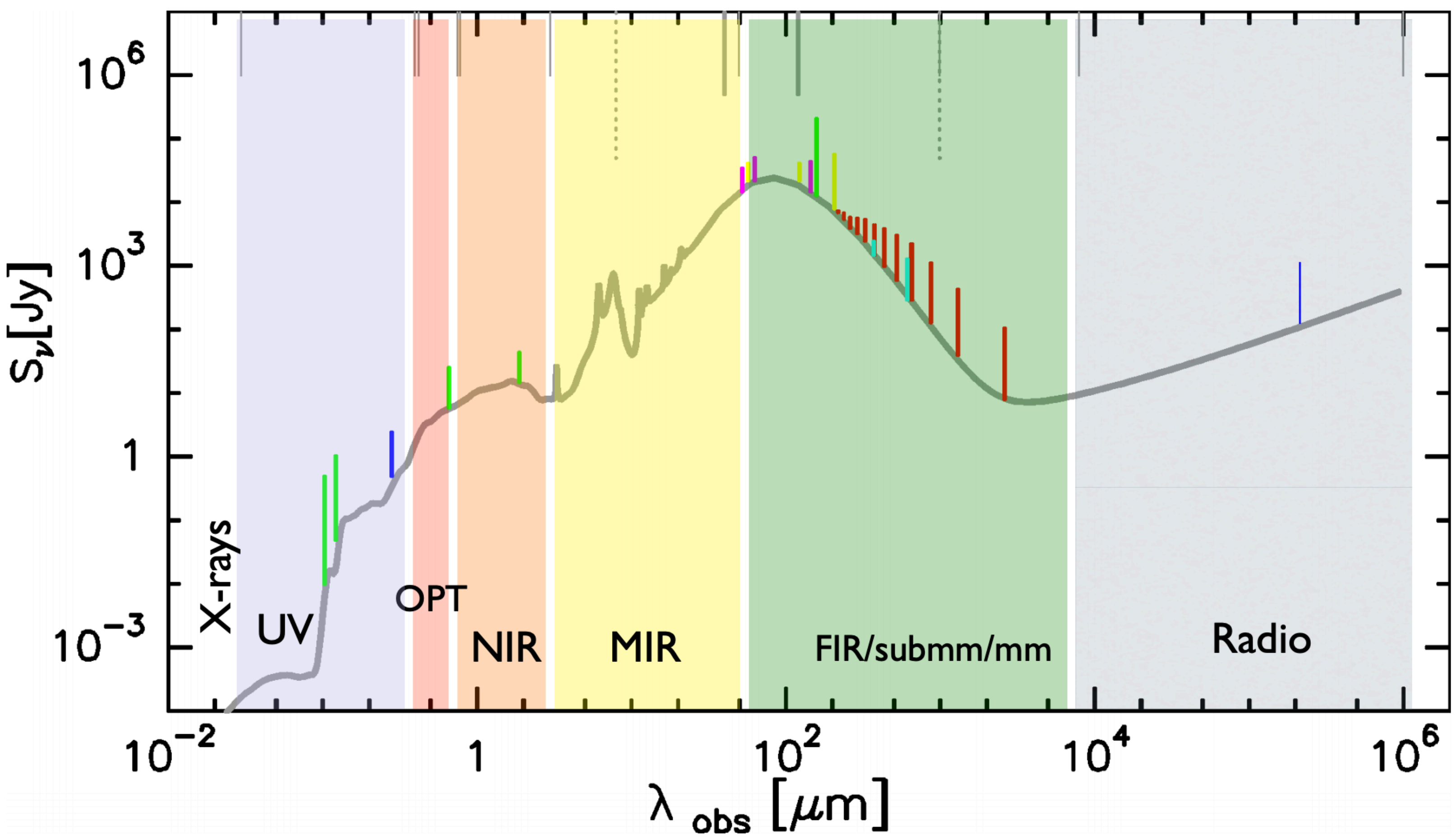


...but, we discover a lot of galaxies offsetting from KS line !

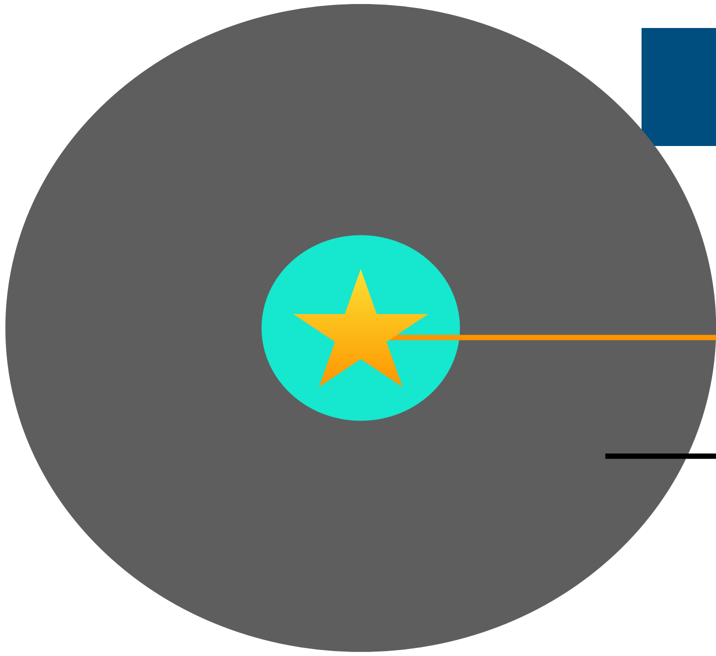
Why is important to look at different tracers?



Full Spectral Energy Distribution (SED) of galaxies

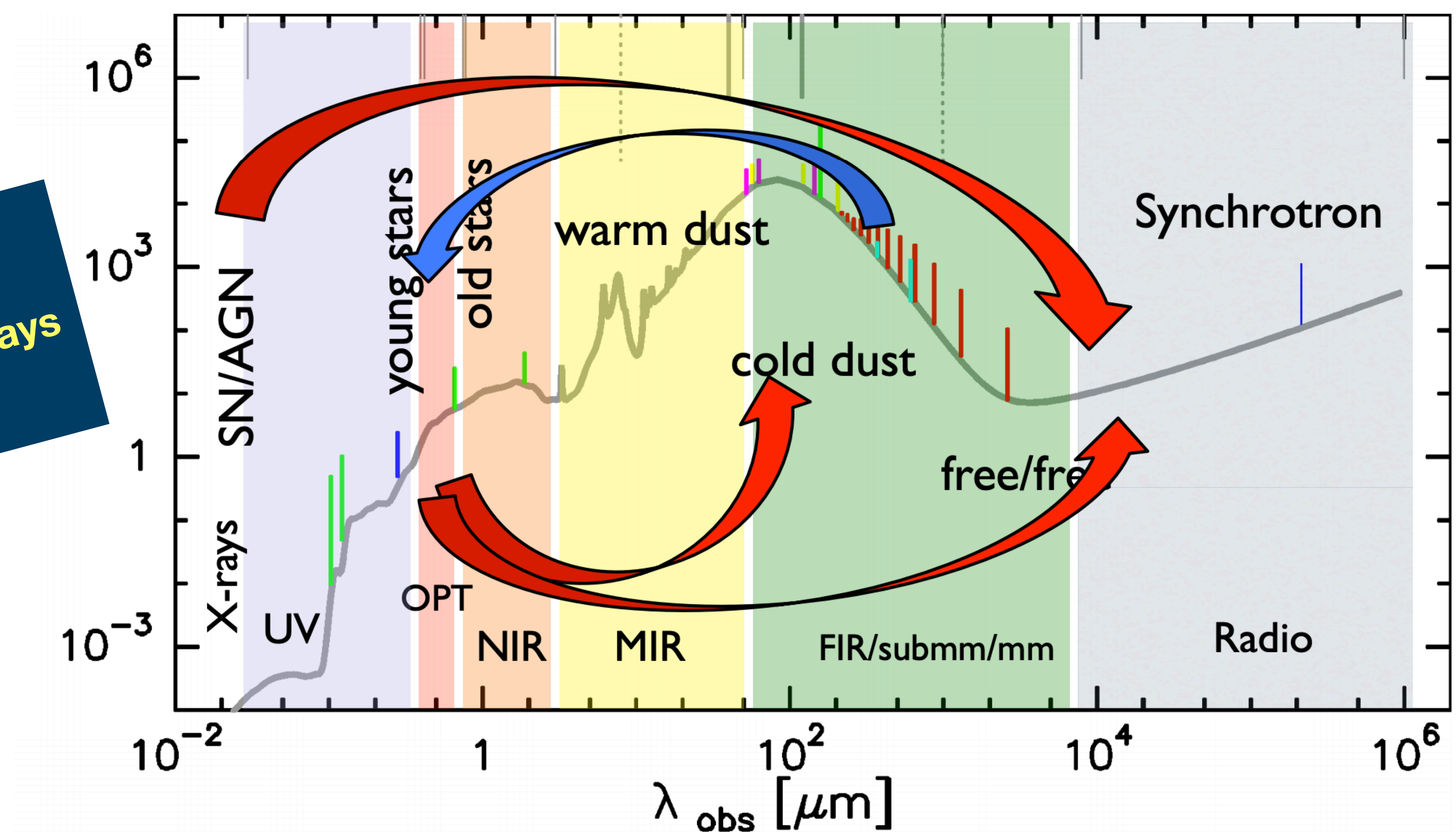


4.1 Observational tracers of star-formation



Why is important to look at different tracers?

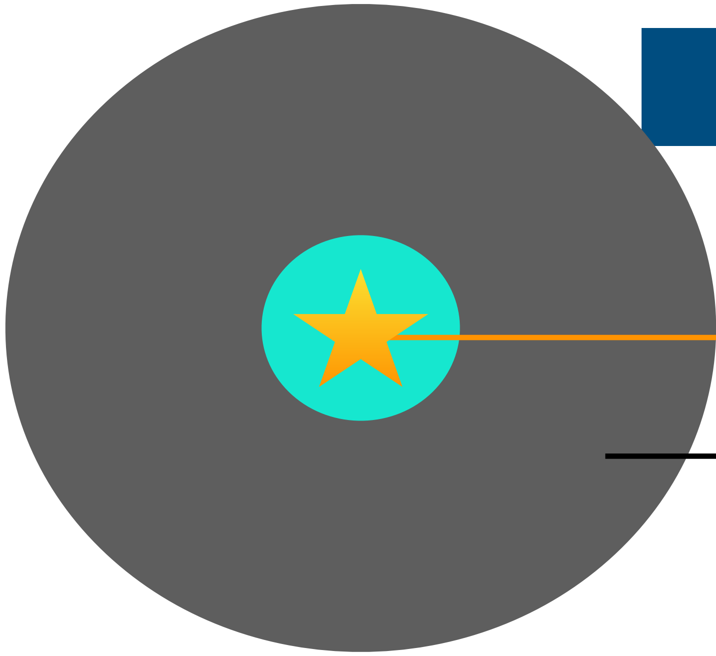
Different emission mechanisms



MESSAGE No.6

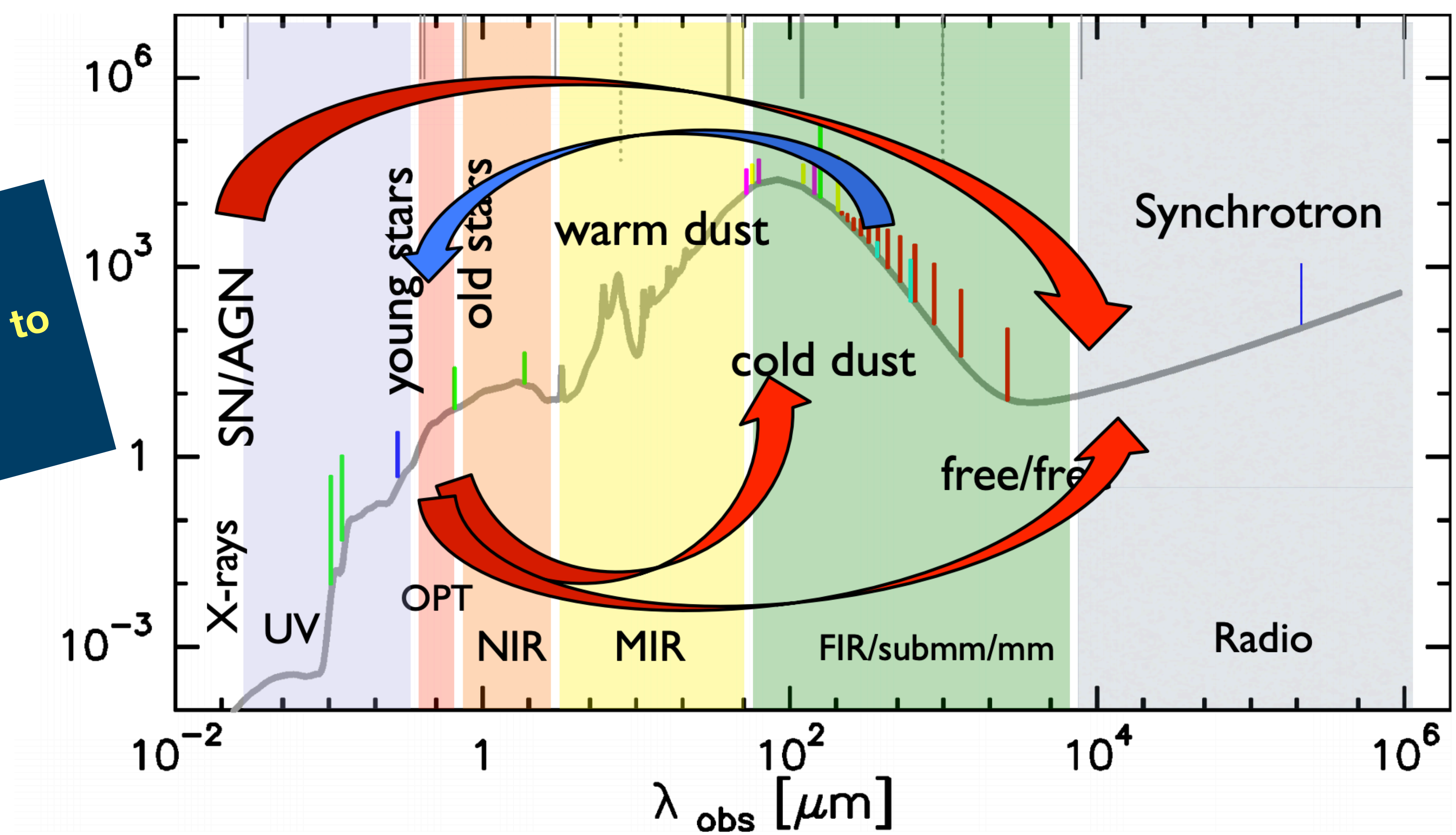
To avoid calibration problems, always search for parallel tracers !

4.1 Observational tracers of star-formation



Why is important to look at different tracers?

Different emission mechanisms

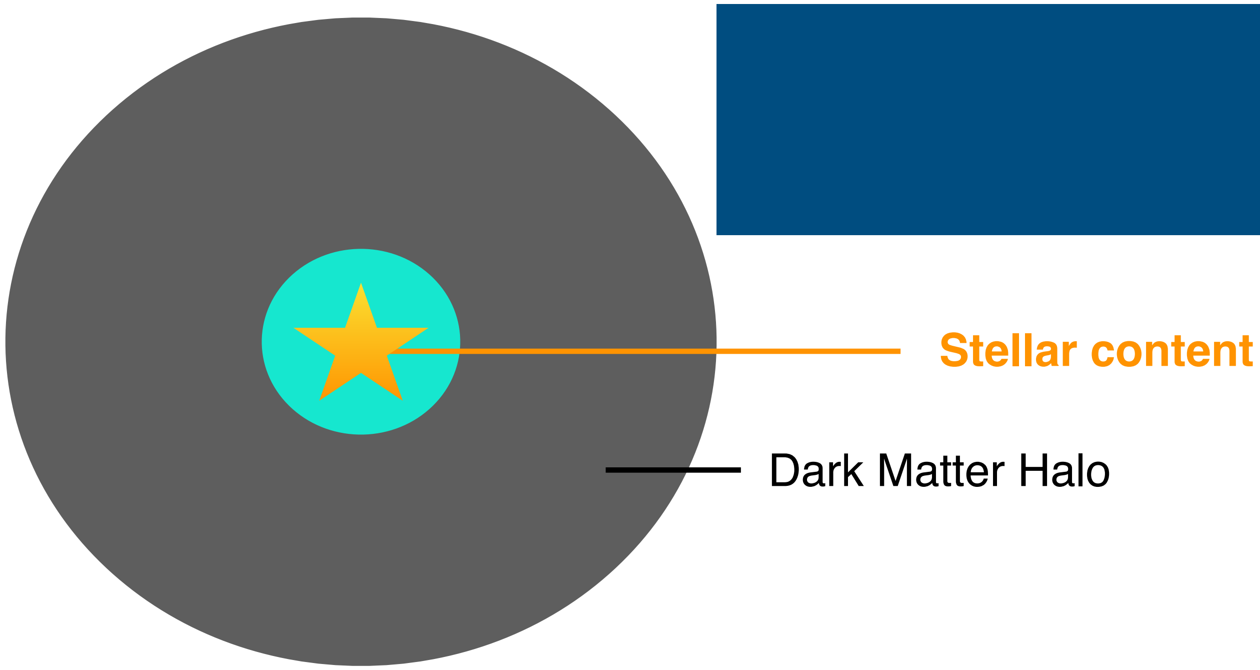


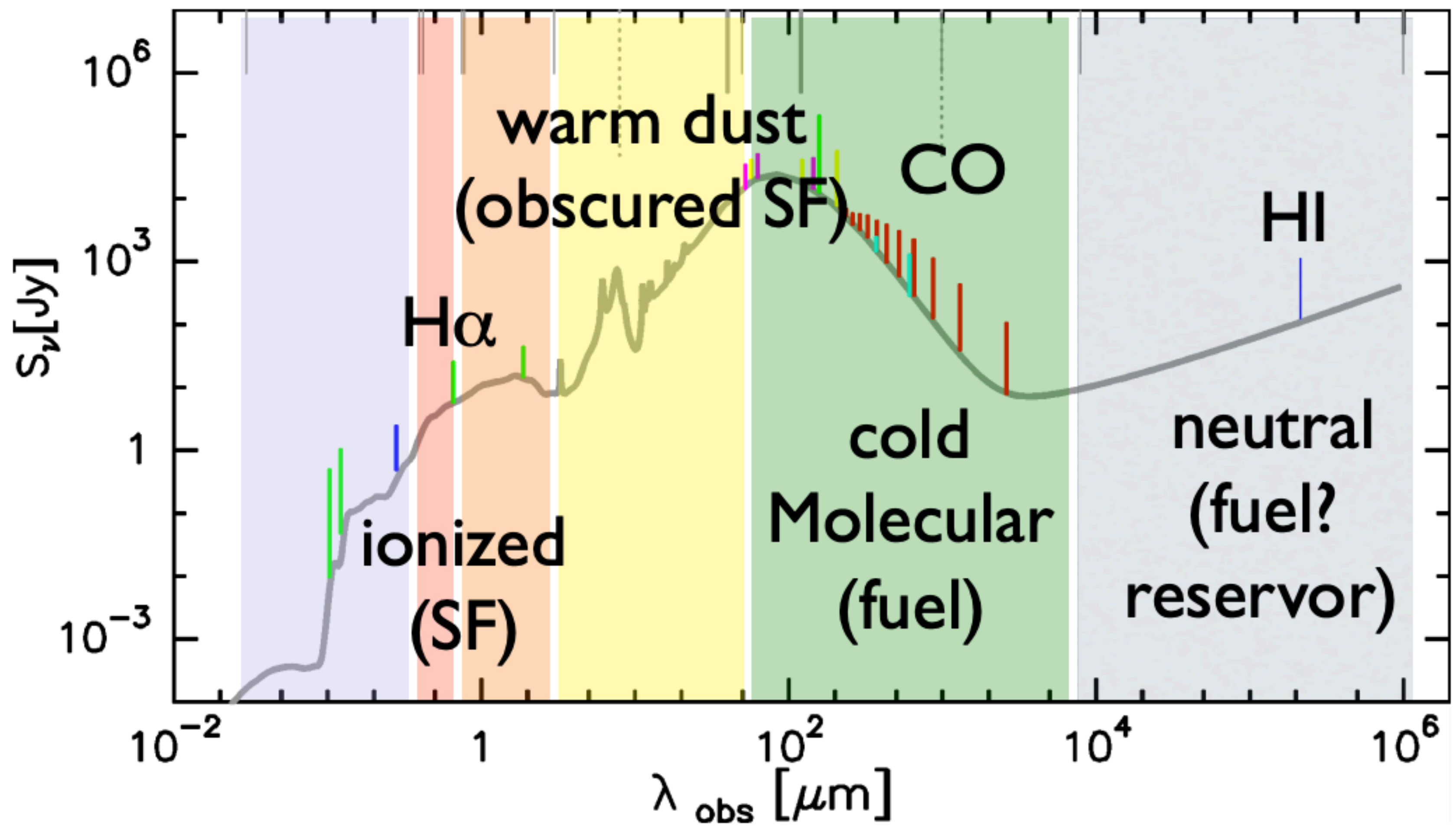
MESSAGE No.7

That means you have to learn how to use telescopes (+ theory!) …

sorry !

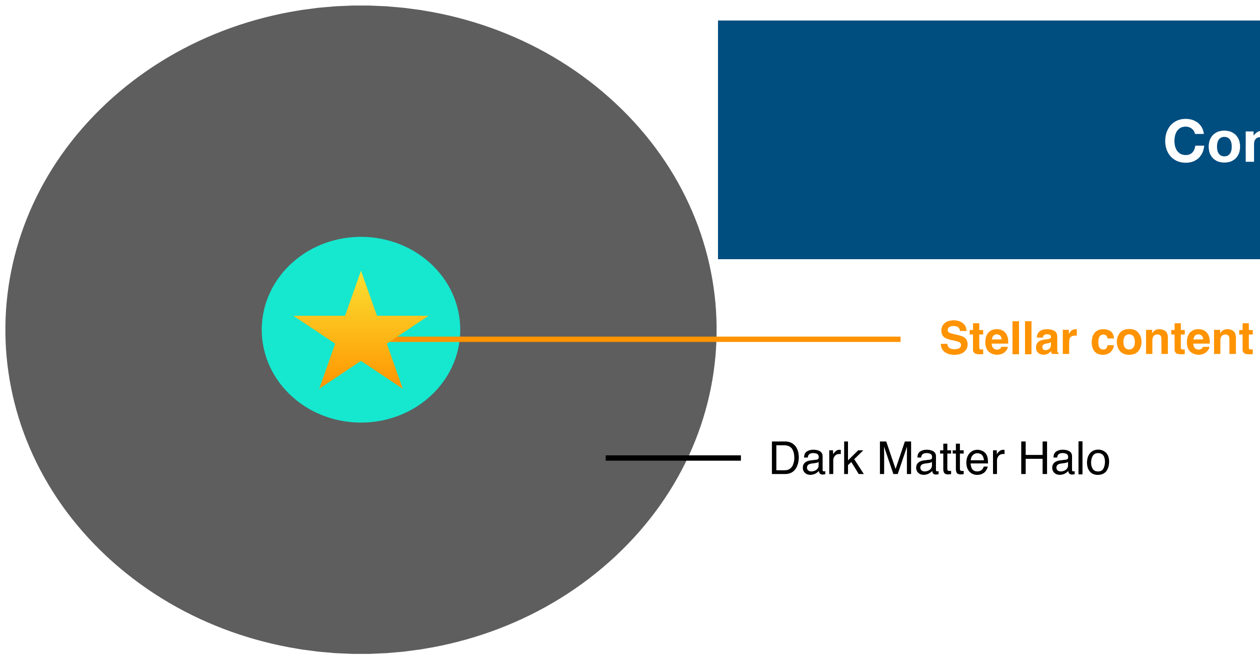
Gas tracers over full SED

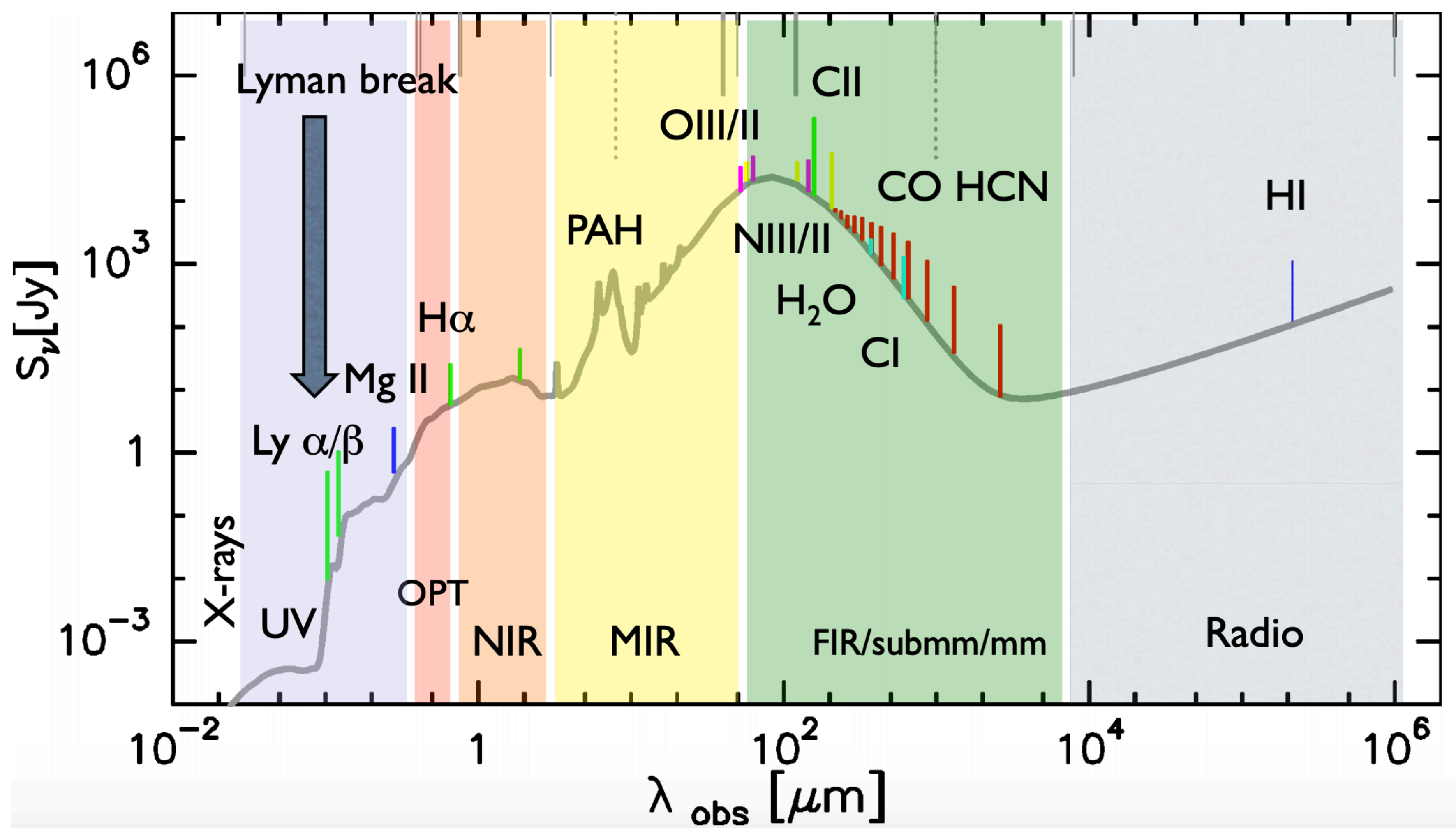




4.1 Observational tracers of star-formation

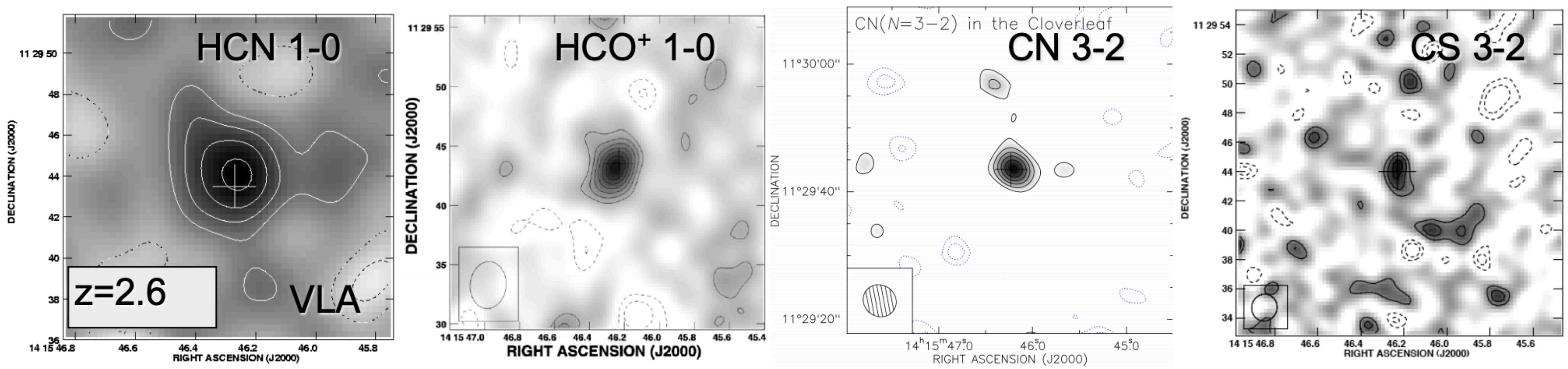
Combining continuum and lines !





How do we know there is ongoing star-formation in galaxies?

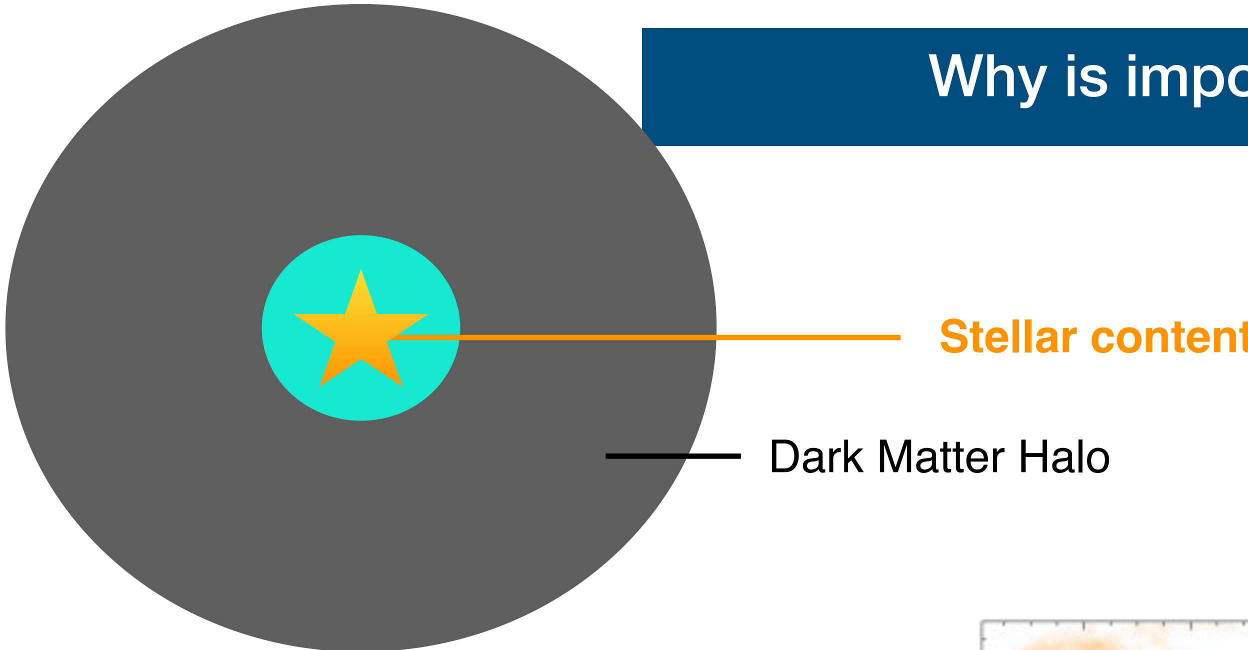
MAIN IDEA:
Tracing the short lived, young and massive OB stars !

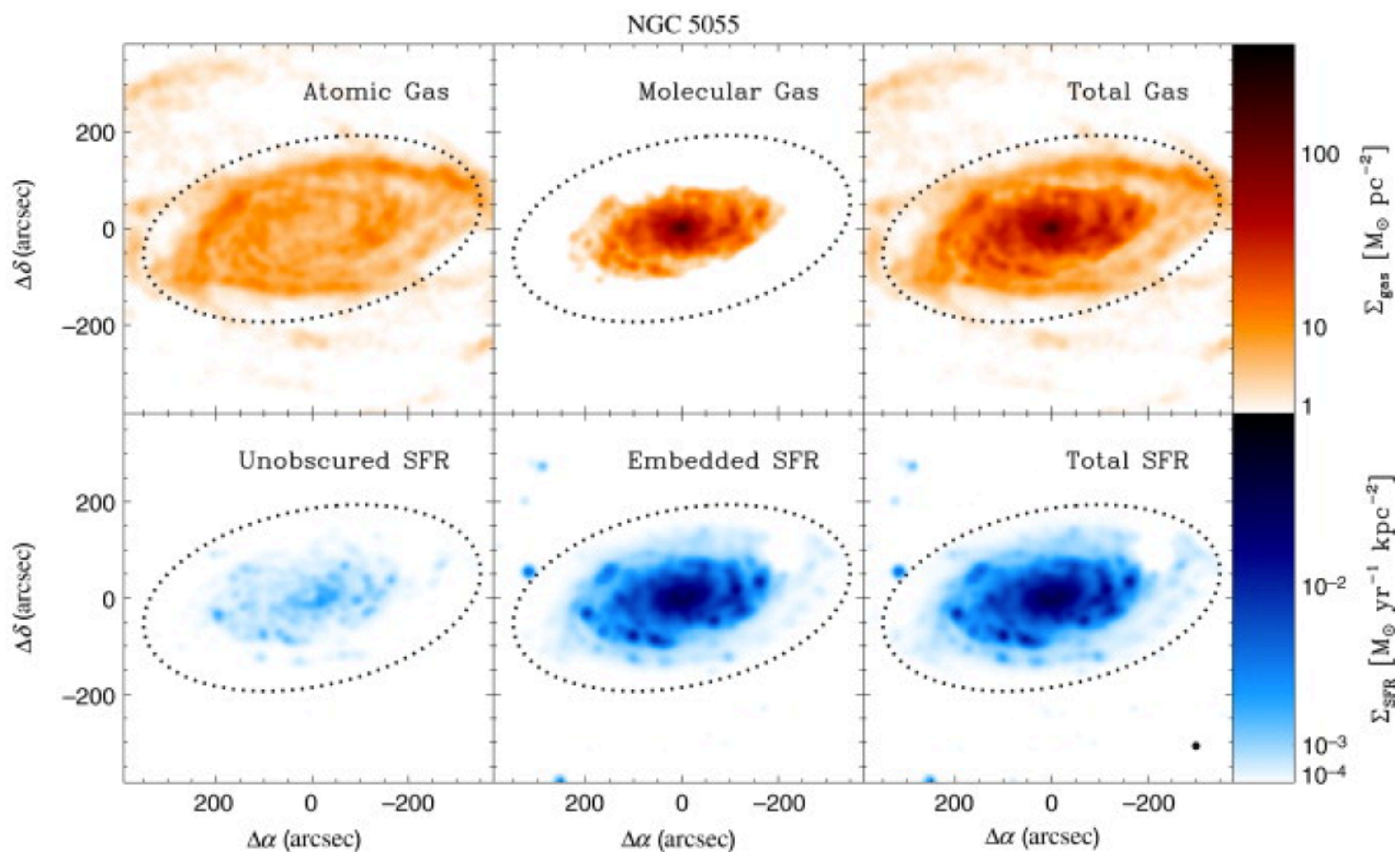


Dense Gas Tracers

Molecule	Transition	Frequency (GHz)	*E/k* (K)	n_{crit} (cm^{-3}) @ 10 K	n_{eff} (cm^{-3}) @ 10 K
CS	1-0	49.0	2.4	4.6×10^4	7.0×10^3
	2-1	98.0	7.1	3.0×10^5	1.8×10^4
	3-2	147.0	14	1.3×10^6	7.0×10^4
HCO^+	1-0	89.2	4.3	1.7×10^5	2.4×10^3
	3-2	267.6	26	4.2×10^6	6.3×10^4
HCN	1-0	88.6	4.3	2.6×10^6	2.9×10^4
	3-2	265.9	26	7.8×10^7	7.0×10^5
H_2CO	2_{12}-1_{11}	140.8	6.8	1.1×10^6	6.0×10^4
	3_{13}-2_{12}	211.2	17	5.6×10^6	3.2×10^5
	4_{14}-3_{13}	281.5	30	9.7×10^6	2.2×10^6
NH_3	(1,1)	23.7	1.1	1.8×10^3	1.2×10^3
	(2,2)	23.7	42	2.1×10^3	3.6×10^4

Why is important to look at different tracers?





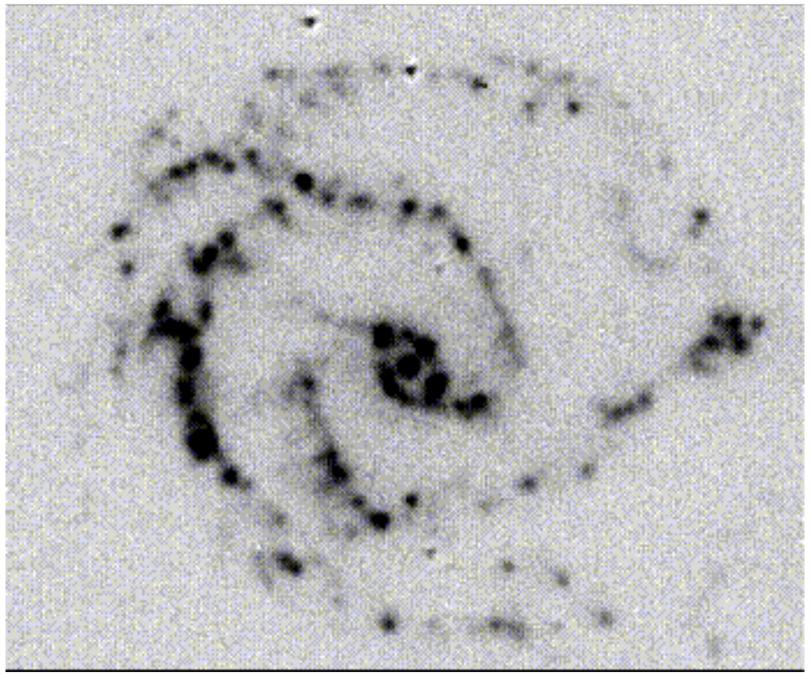
Nebular + optical lines: Hα, Hβ, O[II], O[III]

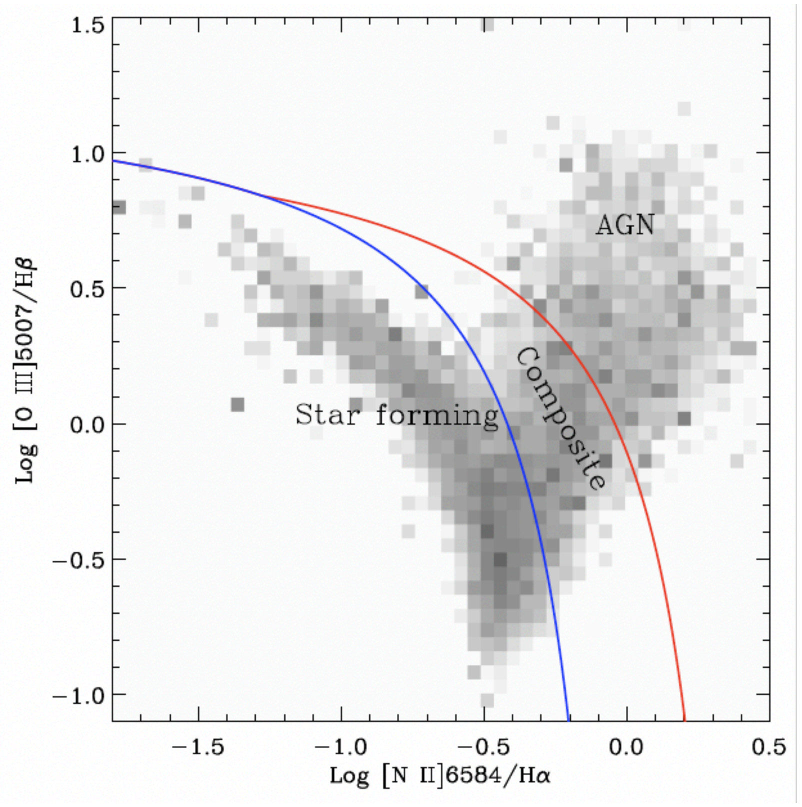
Motivation: hydrogen recombination lines (Hα, Hβ) and forbidden line emission ([OII], [OIII]) trace the ionizing photons.

- E.g. Hydrogen recombination cascades produce line emission, including the Balmer series lines of Hα(6563Å) and Hβ (4861Å), which are strong!
- Mass range and time scale: only massive stars ($>10M_{\odot}$) can ionize gas; short life span of 10Myr —> tracers of the current SFR.
- **Instantaneous SFR !**

Problems:

- Sensitive to the upper end of IMF
- Only be observe from the ground in optical @ z<0.4 and at z<2.5 from NIR
- Dust extinction
- Metallicity and ionisation conditions





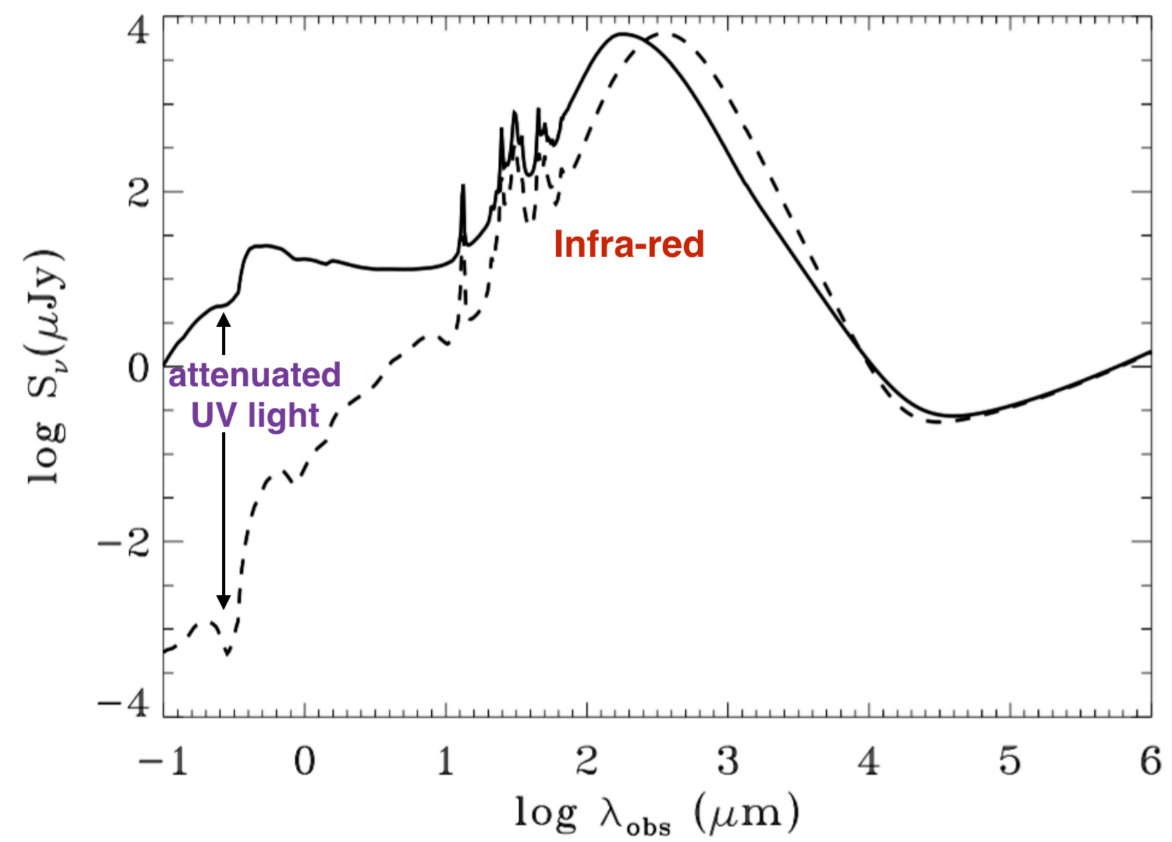
UV continuum

Motivation:The youngest stellar populations emit the bulk of their energy in the rest frame UV (<0.3μm); in the absence of dust attenuation, this is the wavelength range par excellence to investigate star formation in galaxies over timescales of ≈10–300Myr

- **B stars live longer —> dominate UV flux at longer timescales! (>100 Myr)**

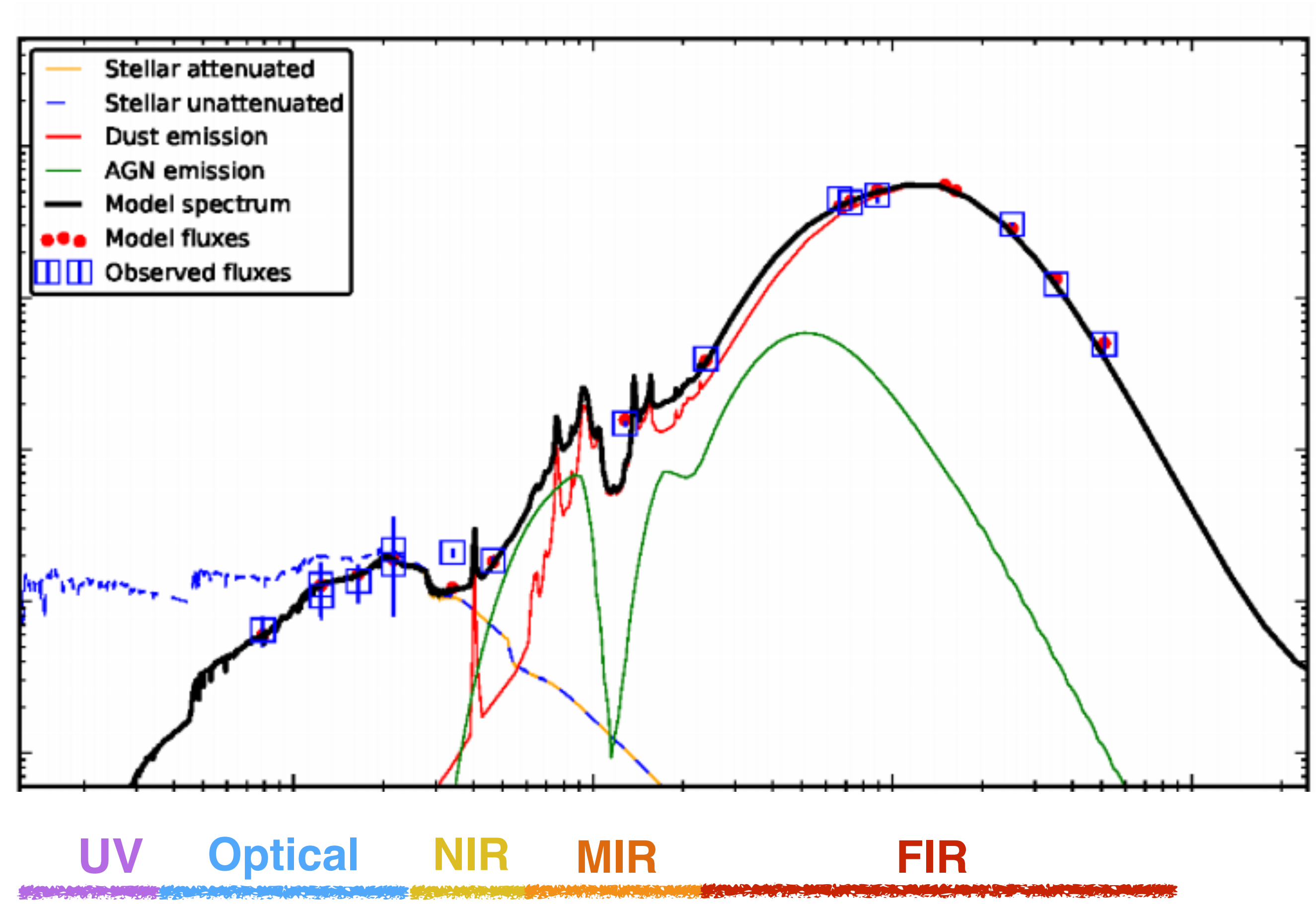
Problems:

- Dust attenuation !!!
- IMF



4.1 Observational tracers of star-formation

Total SFR (from UV-IR)



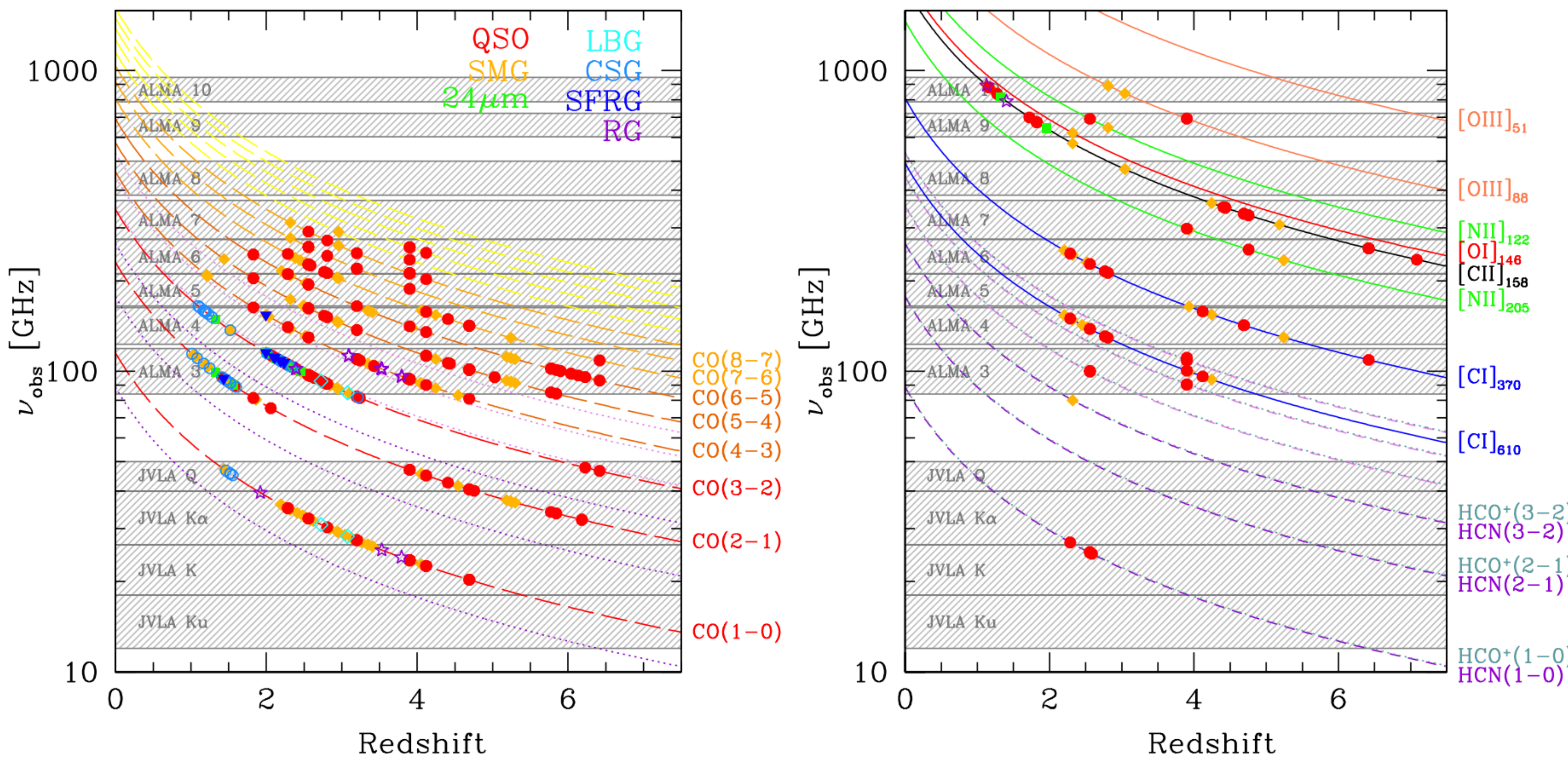
$$\mathrm{SFR_{tot}} = K_{\mathrm{UV}} \times L_{\nu}(\mathrm{UV}) + K_{\mathrm{IR}} \times L_{\nu}(\mathrm{IR})$$

Radiation from young stars (UV)

Re-radiation from dust grains (IR)

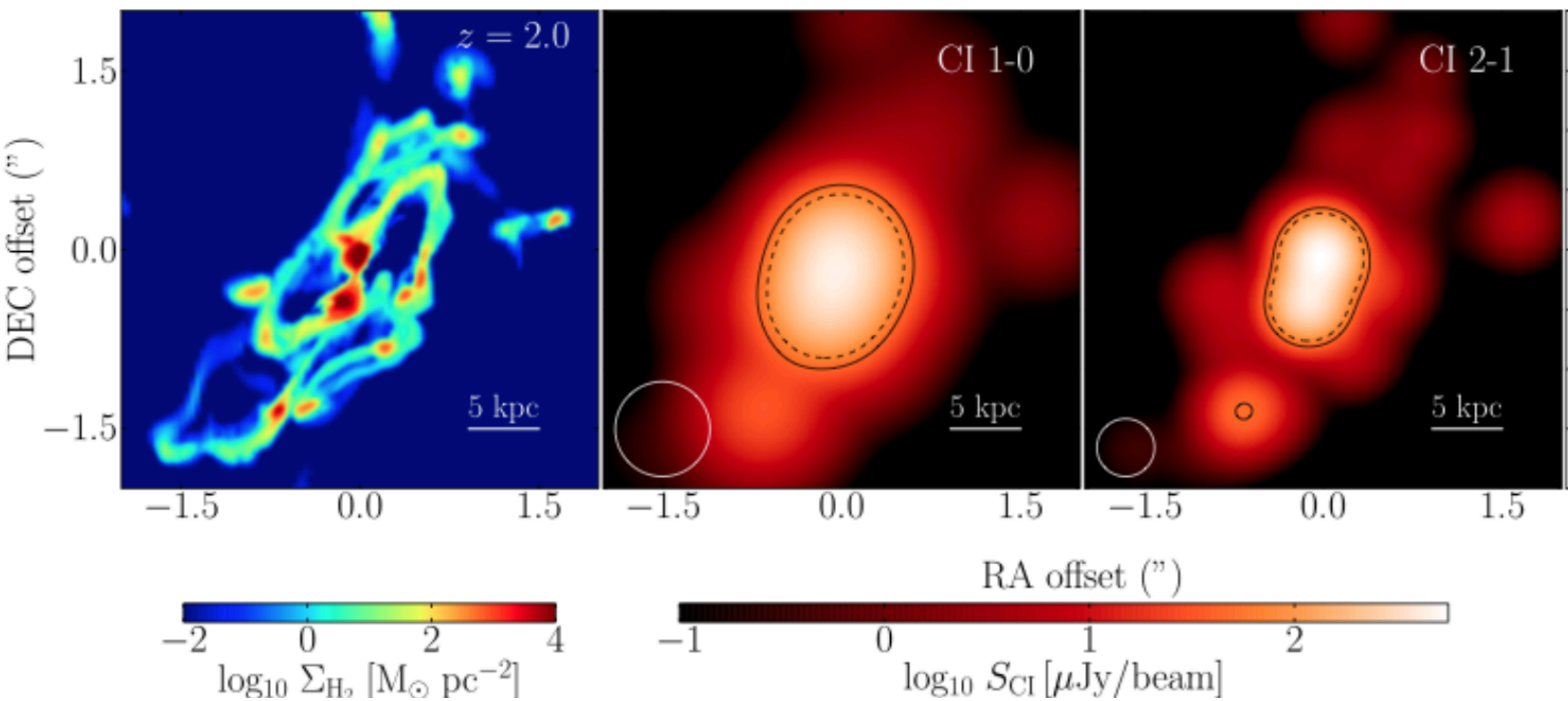
- **Infrared luminosity:** $L_{\mathrm{IR}} = \int_{8\mu\mathrm{m}}^{1000\mu\mathrm{m}} 4\pi D_L(z)^2 S_{\nu}(\lambda) d\lambda$
- **Star-formation rate:** $\mathrm{SFR}(M_{\odot}\ \mathrm{yr}^{-1}) = 4.5 \times 10^{-44} L_{\mathrm{IR}}(\mathrm{erg\ s}^{-1}) = 1.71 \times 10^{-10} L_{\mathrm{IR}}(L_{\odot})$

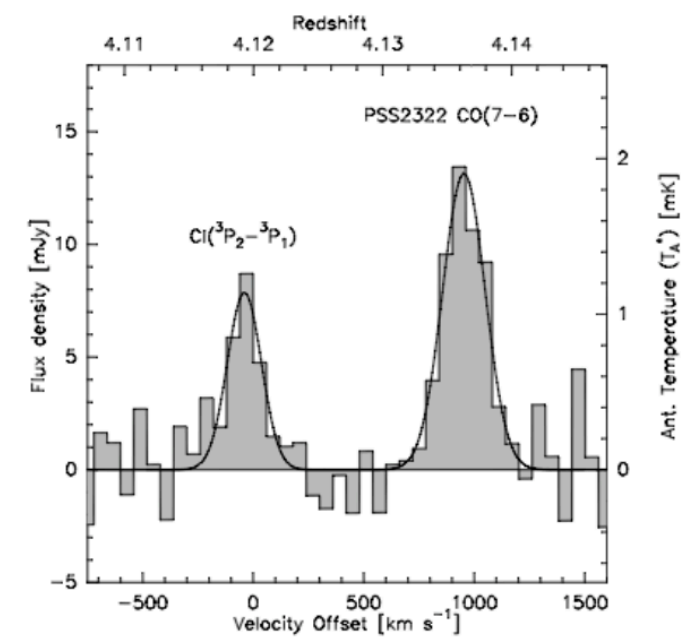
Gas tracers:
importance of mm/radio observations
(e.g. ALMA, NOEMA & VLA)



Redshifted lines for CO (left) and other SFR tracers (right) at mm and radio wavelengths (Weiss 2013)

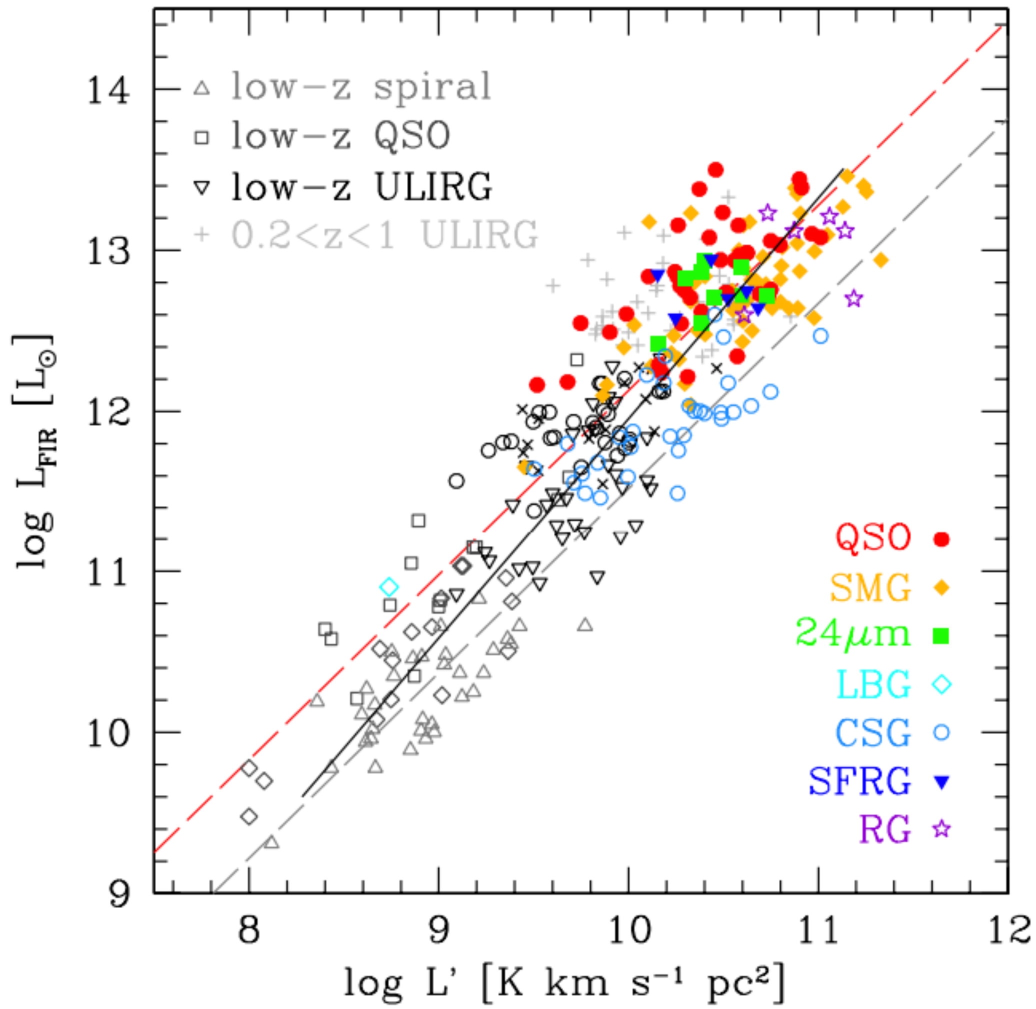
Alternative gas tracers to CO:
Atomic carbon @158um





Redshifted lines for CO (left) and other SFR tracers (right) at mm and radio wavelengths (Weiss 2013)

We can combine continuum + lines…
i.e. FIR continnuum vs Lco (very scattered !)

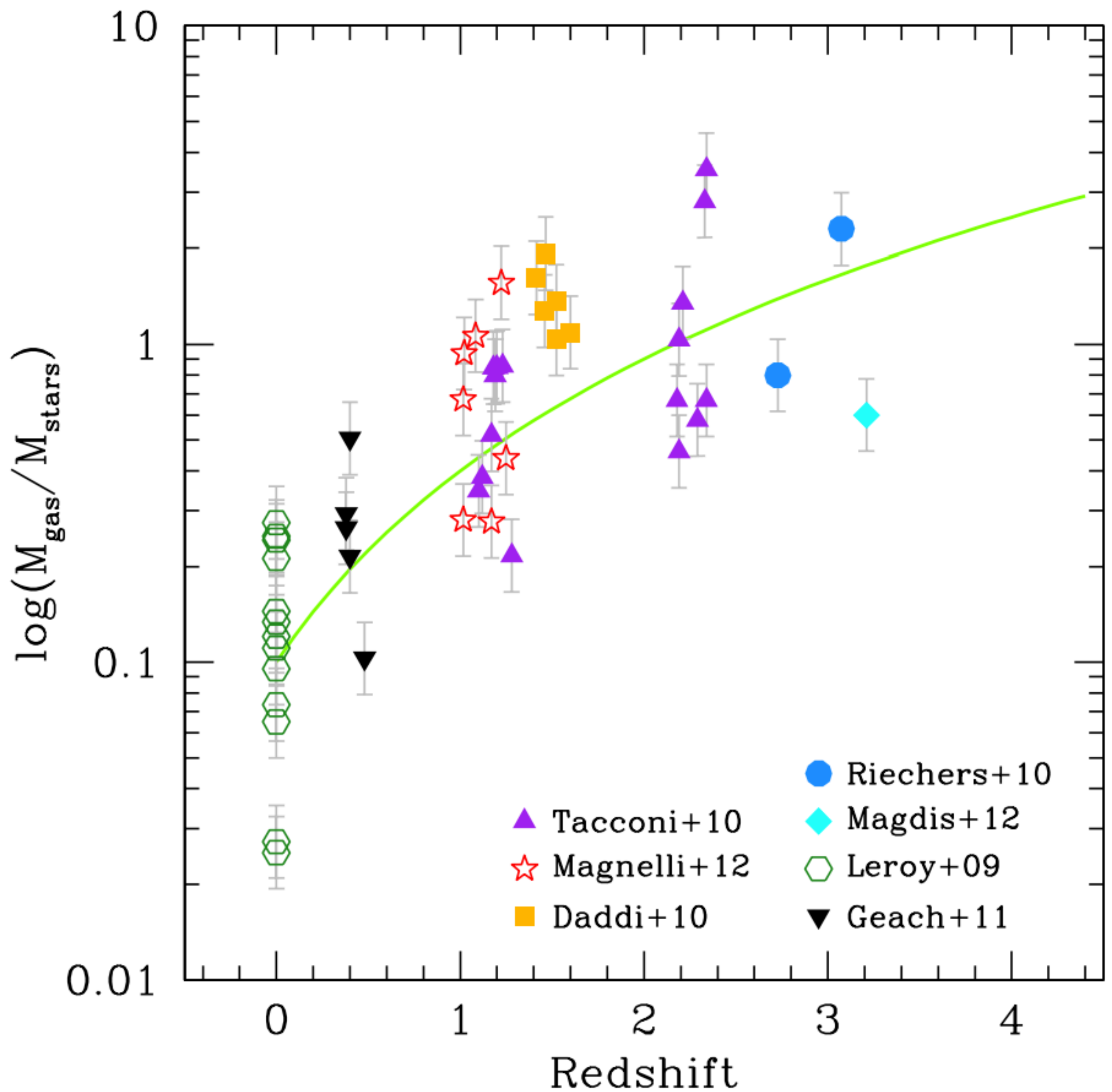


Callibration made for low-z galaxies, doesn't stand for high-z !!!

4.2 Why we need deep observations in high-redshift Universe ?

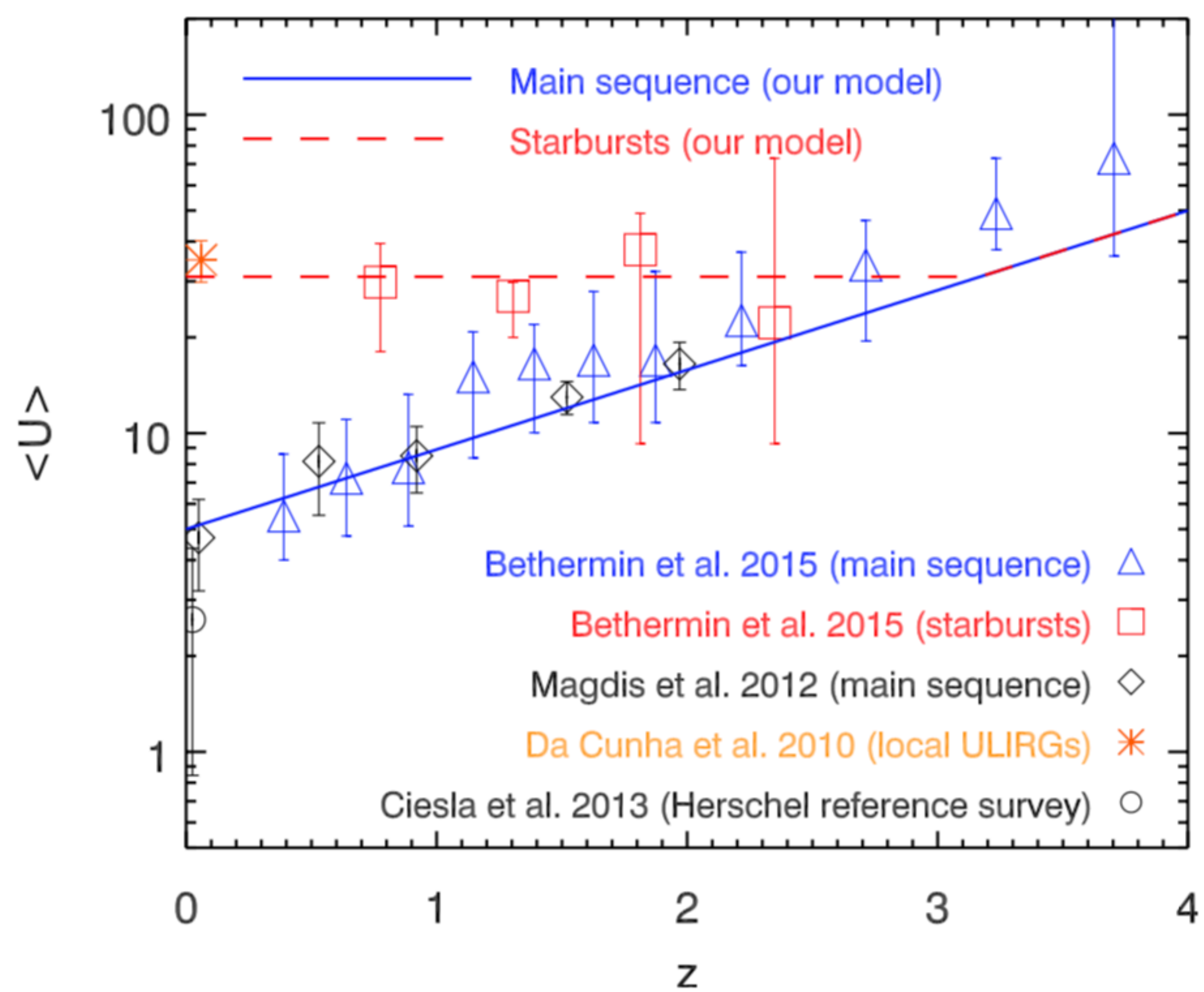
How gas and star masses relate in the Universe?

Gas-to-star ratio



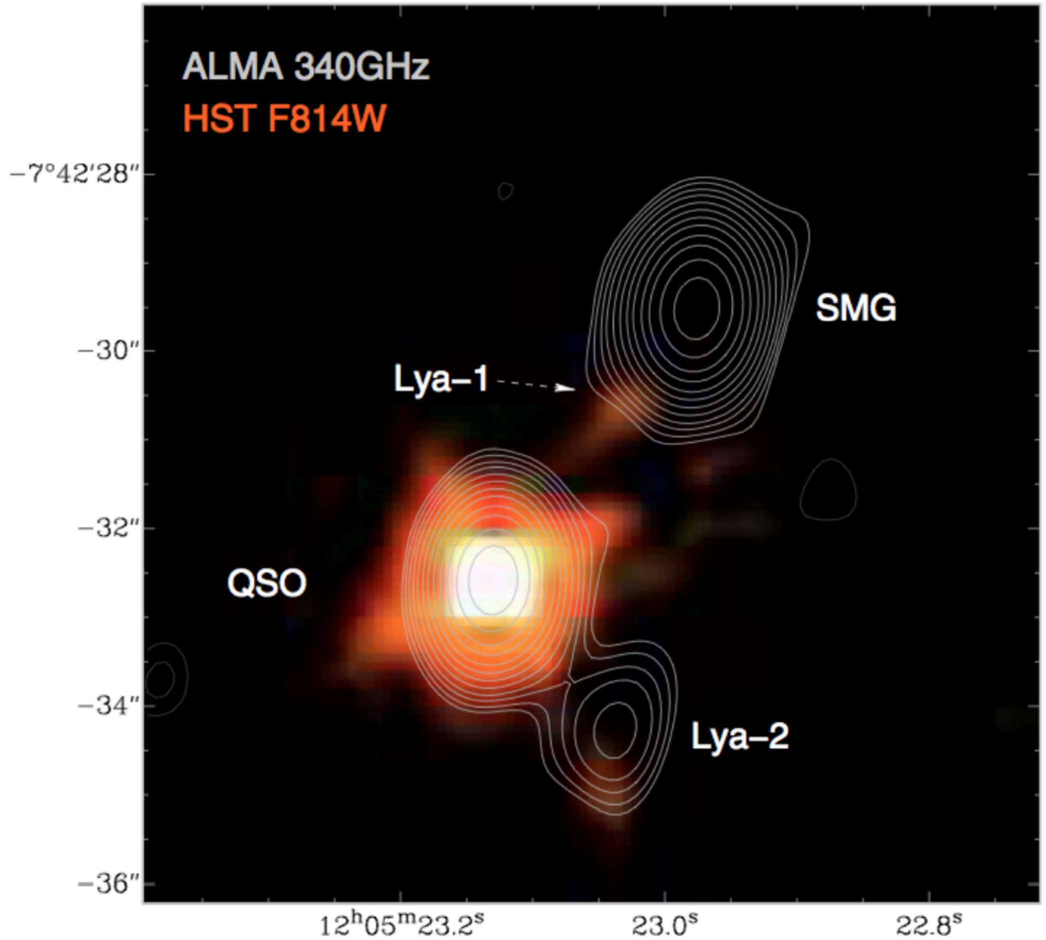
Gas fraction larger at high-z —> massive galaxies are also gas rich?

Interstellar radiation field evolves with redshift

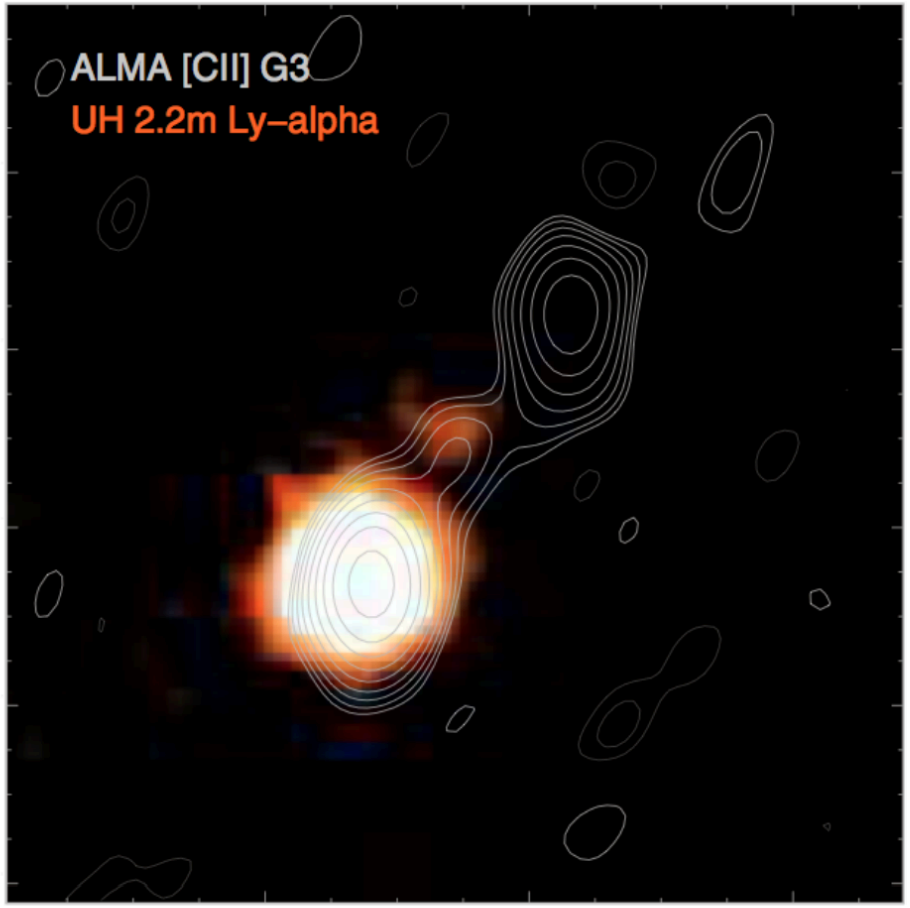


If mean intensity of ISRF increases with z, it means that Tdust changes !!!

Difference between star-forming regions "seen" in UV & FIR



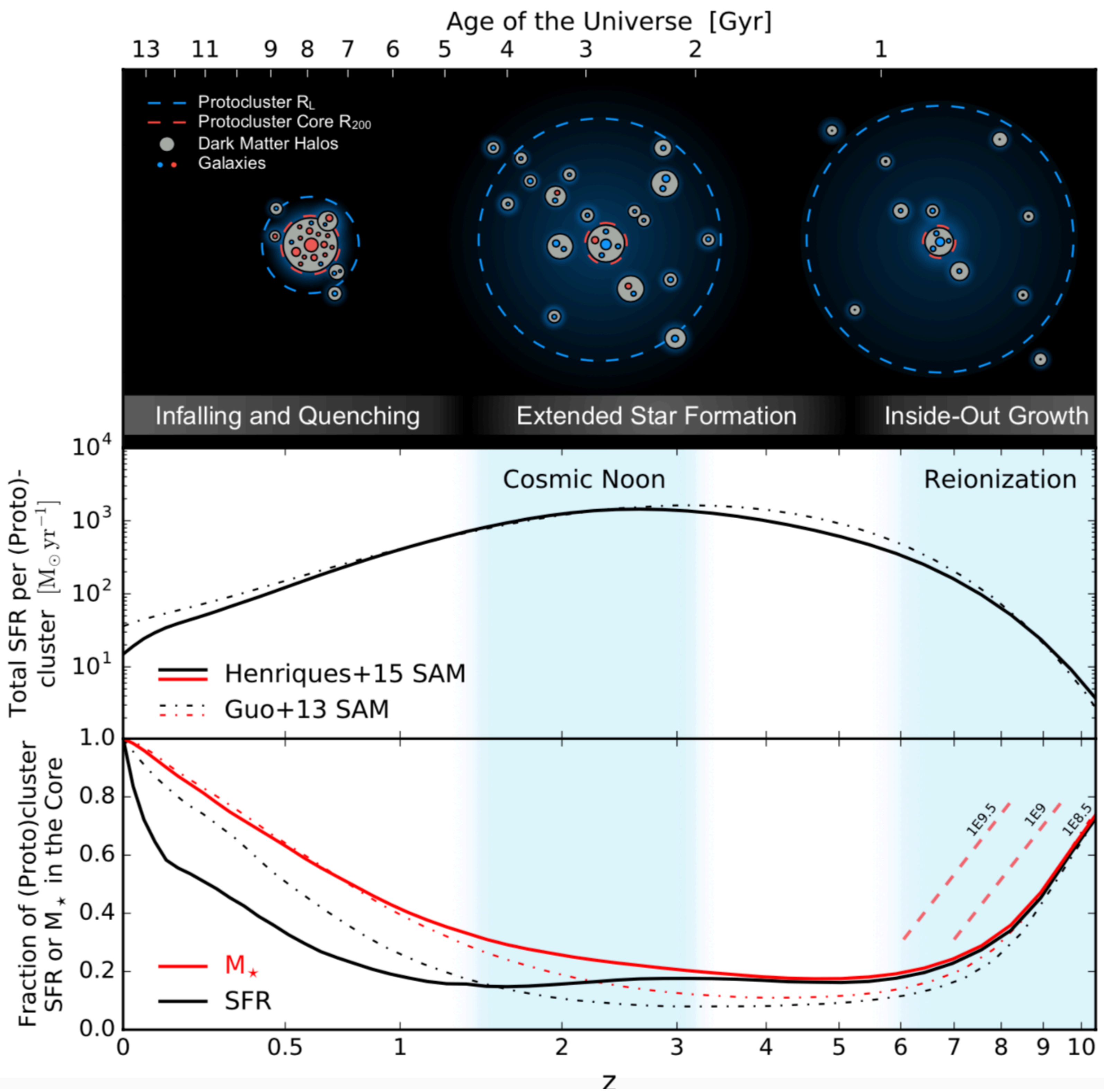
ALMA 0.85mm (158μm rest) continuum



[CII]

ALMA: massive, dusty galaxy at high-z
Hubble Space Telescope: Ly-alpha emitter

4.2 Why we need deep observations in high-redshift Universe ?



(Chiang +, 2017)

- **Ancestors of clusters are very highly star-forming regions !**
- In simulation is easy to spot DM over density.
- Not so easy with baryon locators…
- PROBLEM OF FINDING THEM
- And ANALYSING THEM…
- Ergo: we don't know the total SFR ! :)

Messages summary

MESSAGE No.1

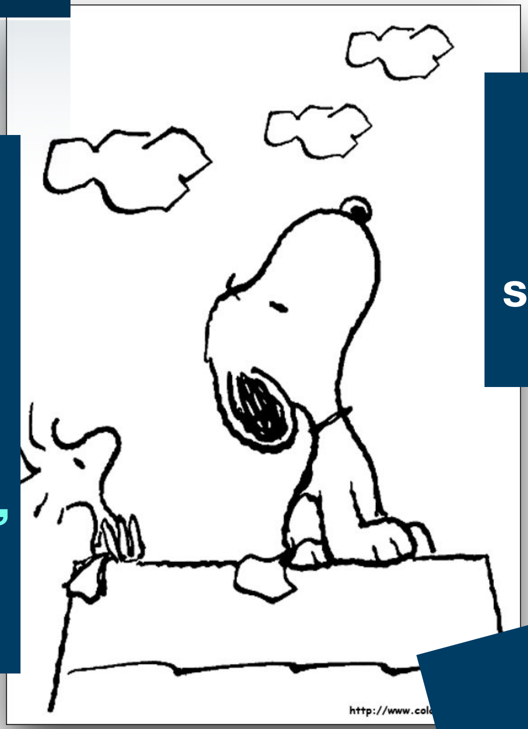
Theory have problem in making massive star-forming galaxies !
(problem of baryon evolution)

MESSAGE No.2

- At high-redshifts, we still don’t understand physics of star-formation
(problem of baryon evolution)

MESSAGE No.3

- In reality, from global SED properties (distribution of galaxy colours/fluxes), we infer (somehow) local properties (star-formation rate, dust mass, stellar mass, temperature of dust etc.) !



MESSAGE No.4

- GMC are
(1) Huge
(2) Cold
(3) Full of hydrogen molecule, which is no observed directly !

MESSAGE No.5

There is a maximum limit of producing stars in galaxies ! And it depends on DM halo mass !

MESSAGE No.6

Best SFR tracers are dense gas and FIR…. but: To avoid calibration problems, always search for parallel tracers !

MESSAGE No.7

Think about the evolution !!!

email: darko.donevski@sissa.it

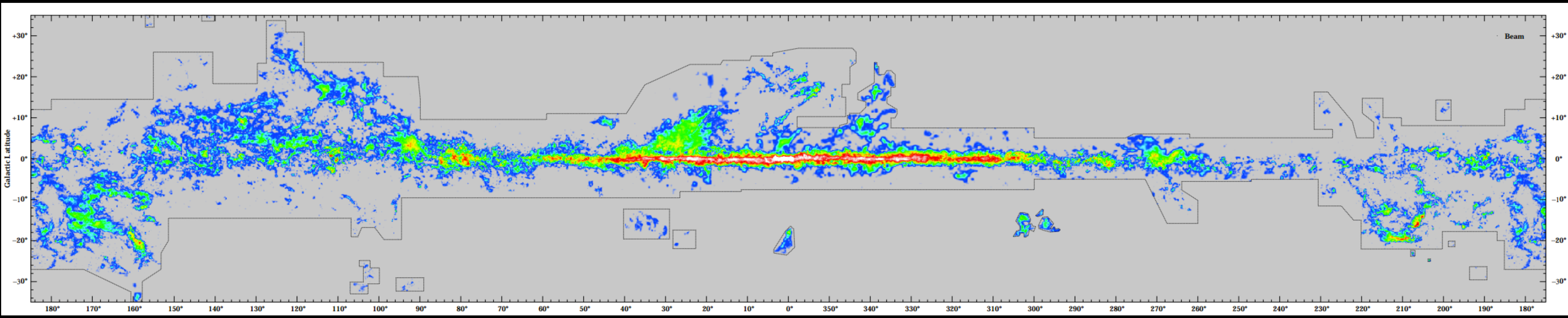
V Infrared Universe

“I can see in infrared” (Queensryche)


A
b
ACO – ONERA/CNRS/MPIA/MPE/ESO ©

but, let's see what we learnt so far?

What did we learn?



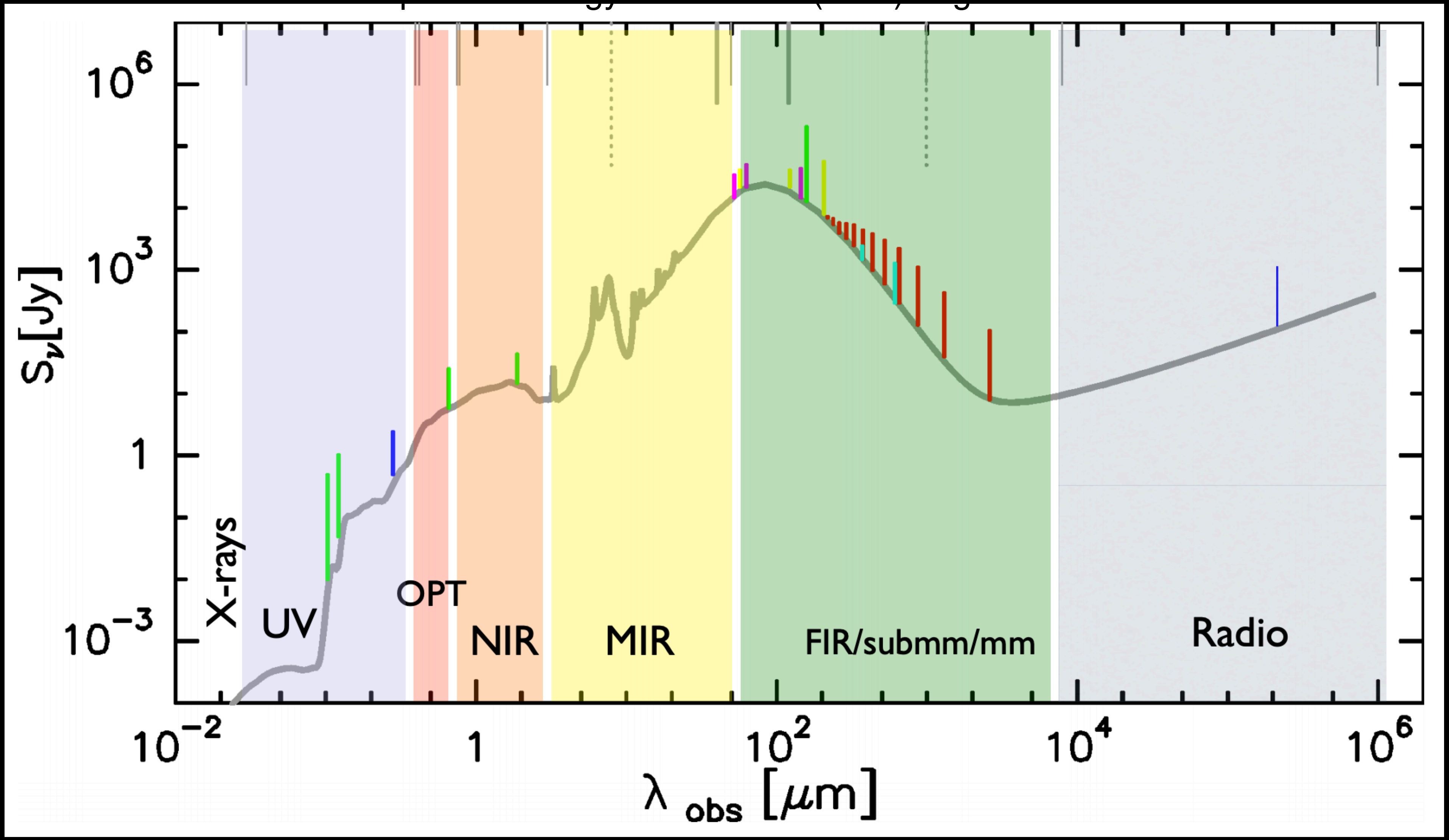
What is the typical size, mass and lifetime of GMC?

What is the temperature of GMC?

How can we observe them?

What is % of gas converted to stars?

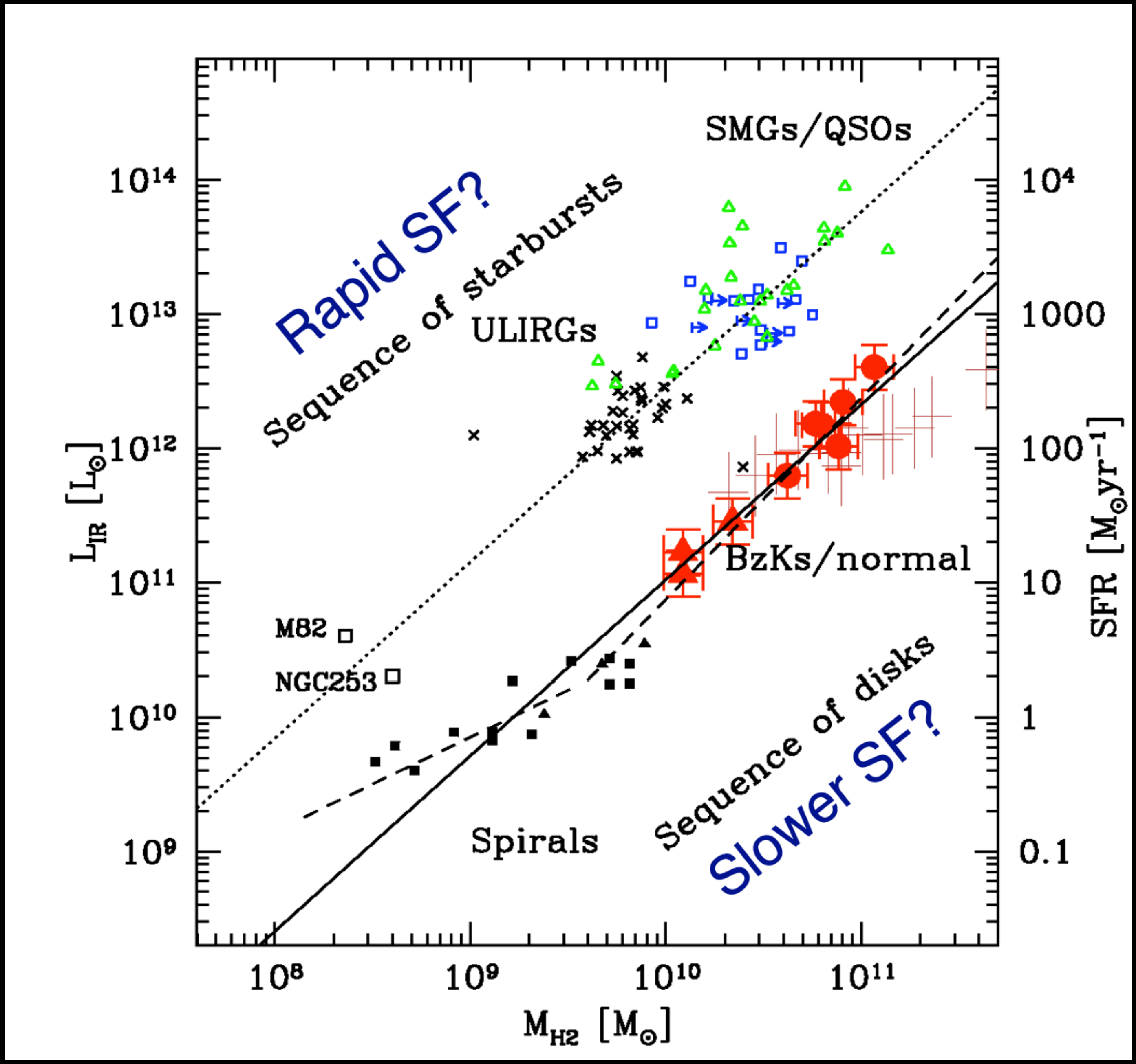
General view of star-formation



Where in this SED we expect H-alpha, CO and HI line to be detected?

Where is a warm dust component, and where is cold?

General view of star-formation



Which galaxies on this diagram are expected to have short depletion time?

What does it mean?

Where are the galaxies with highest SFR at this diagram?

First thoughts about distant, infrared galaxies …

ARE YOUNG GALAXIES VISIBLE?

Year is 1966 !!!

R. B. PARTRIDGE AND P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University

Received August 5, 1966; revised September 8, 1966

ABSTRACT

The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about 1.5×10^8 years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

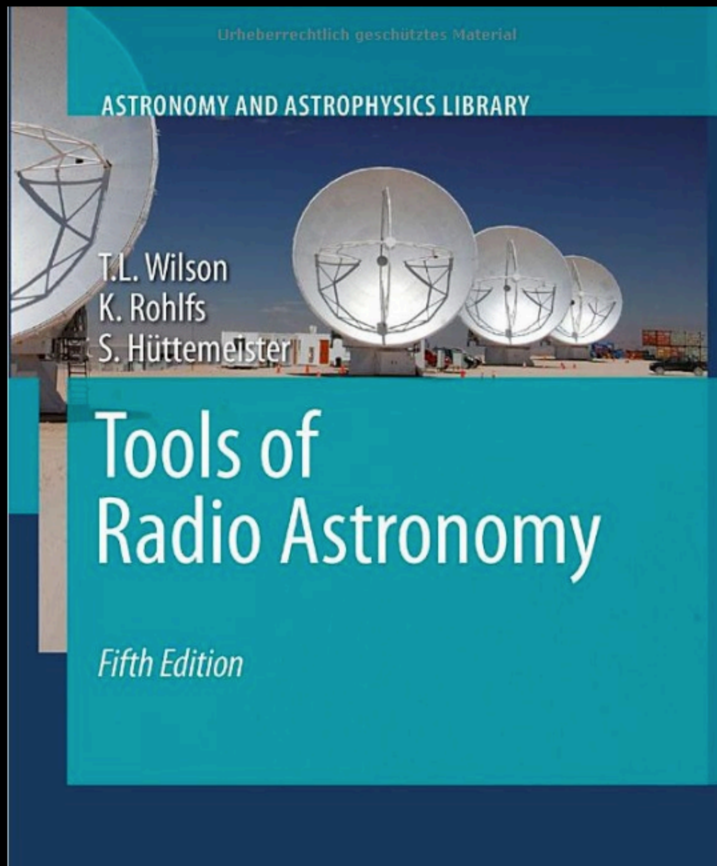
The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies.

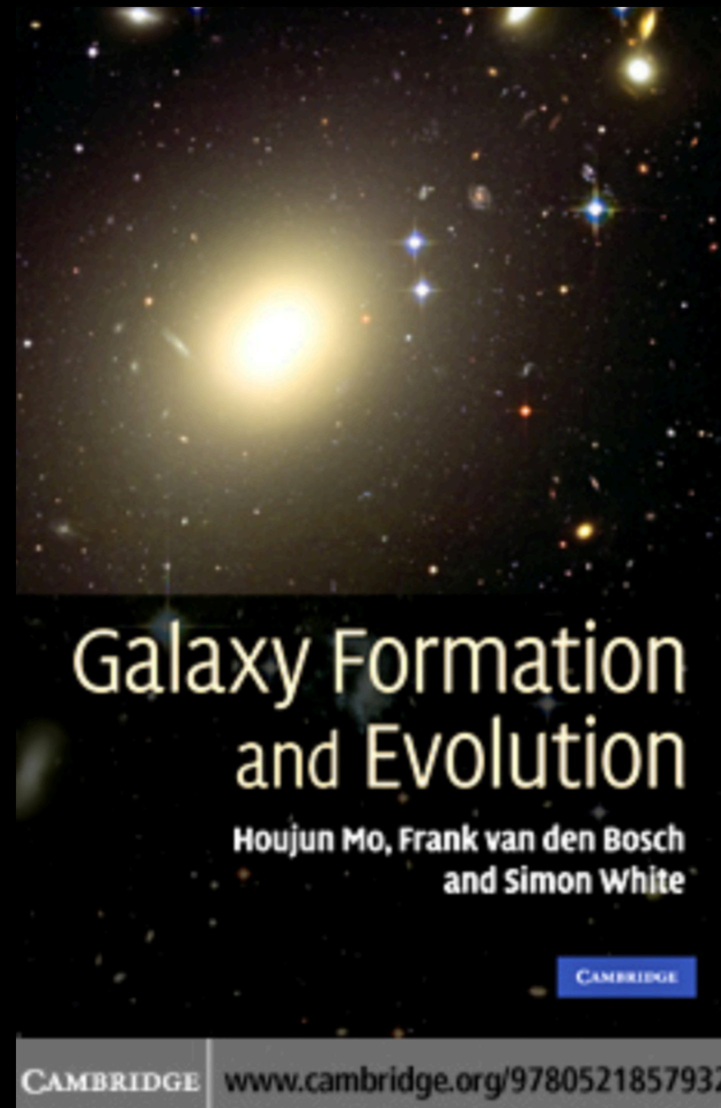
It is also shown how such an experiment might help us to distinguish between various cosmological models.

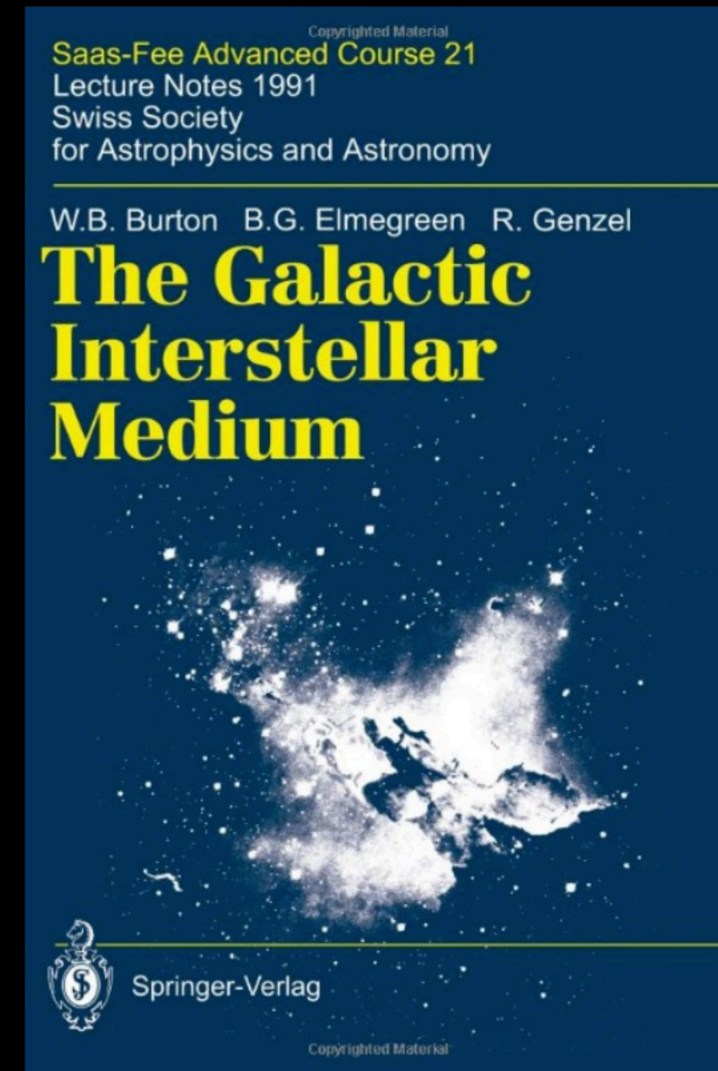
I. INTRODUCTION

The galaxies are thought to have formed from gaseous hydrogen originally distributed more or less uniformly throughout the expanding universe, but there is very little observational evidence on how or when the galaxies formed, or how they evolved. Some idea

Exploring the dusty Universe !







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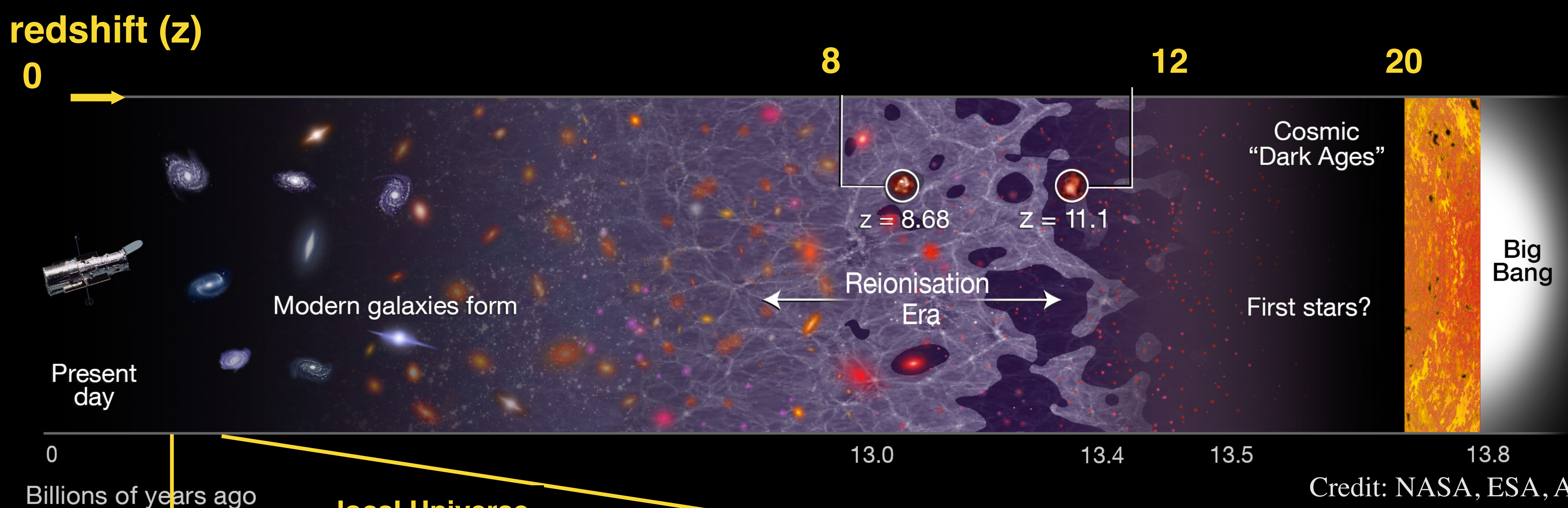
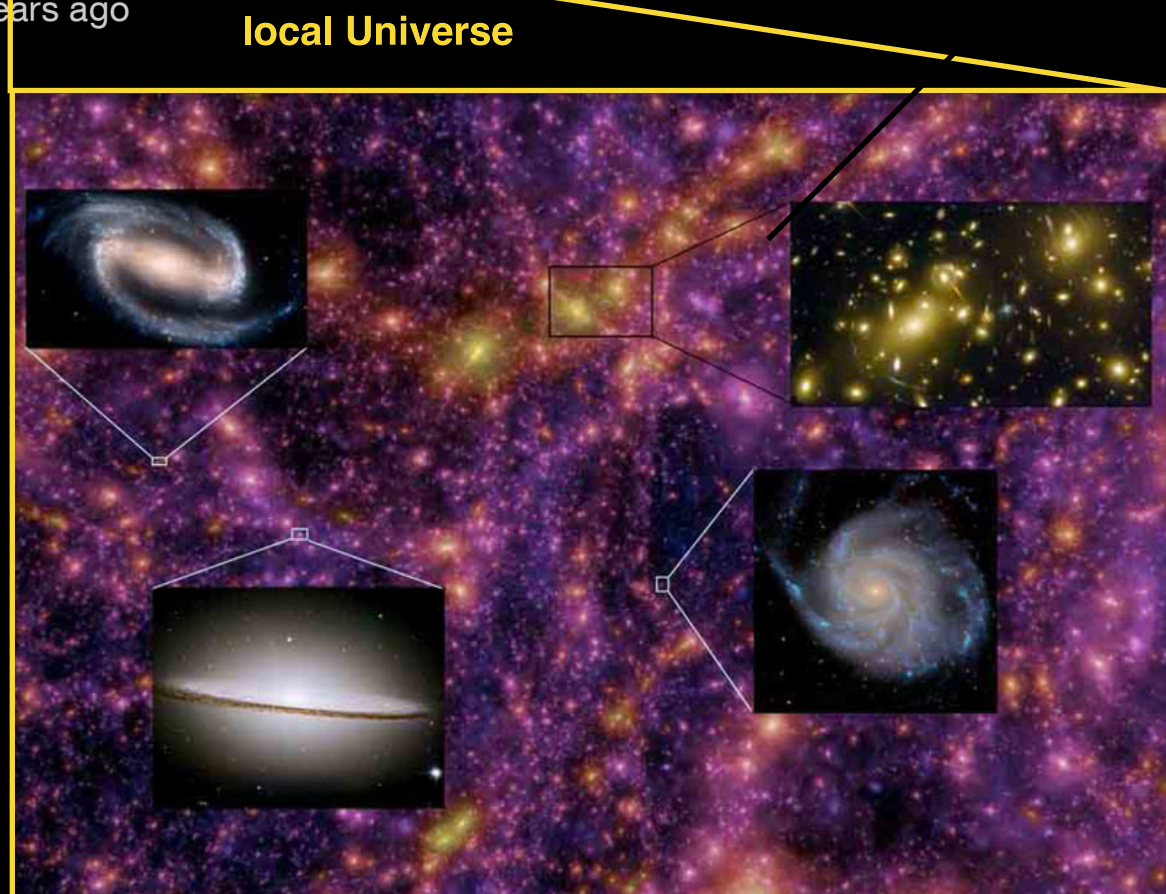
ELSEVIER

Dusty star-forming galaxies at high redshift

Caitlin M. Casey[a,b,*], Desika Narayanan[c], Asantha Cooray[a]



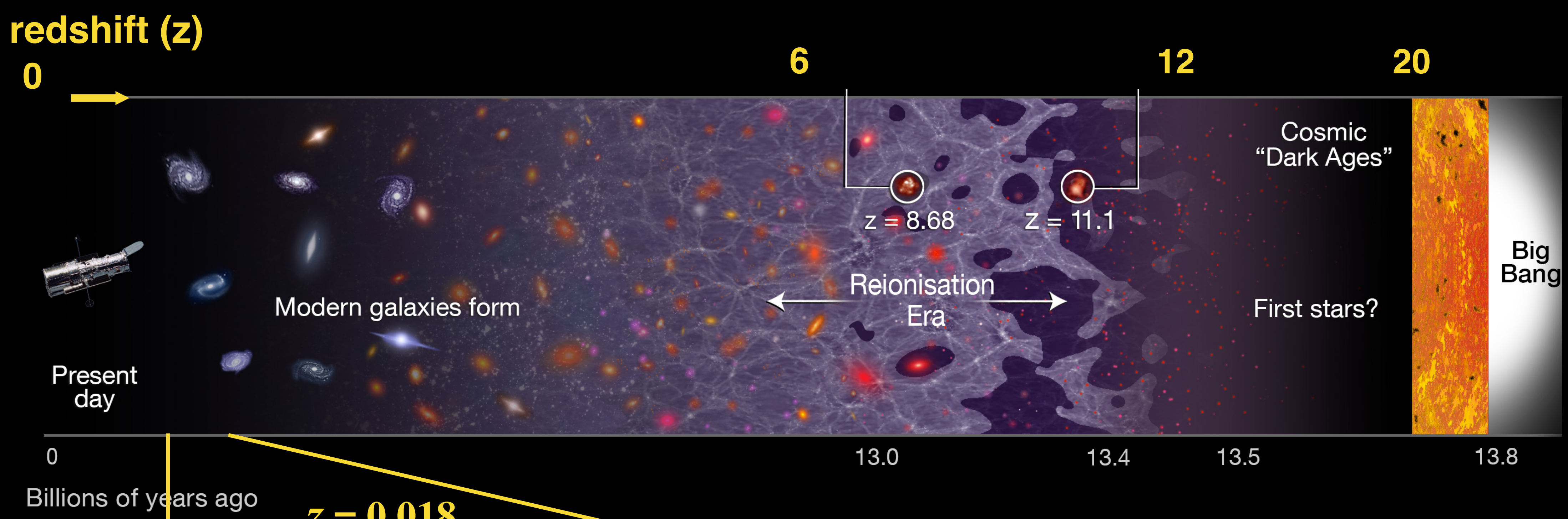
Credit: NASA, ESA, A.Field



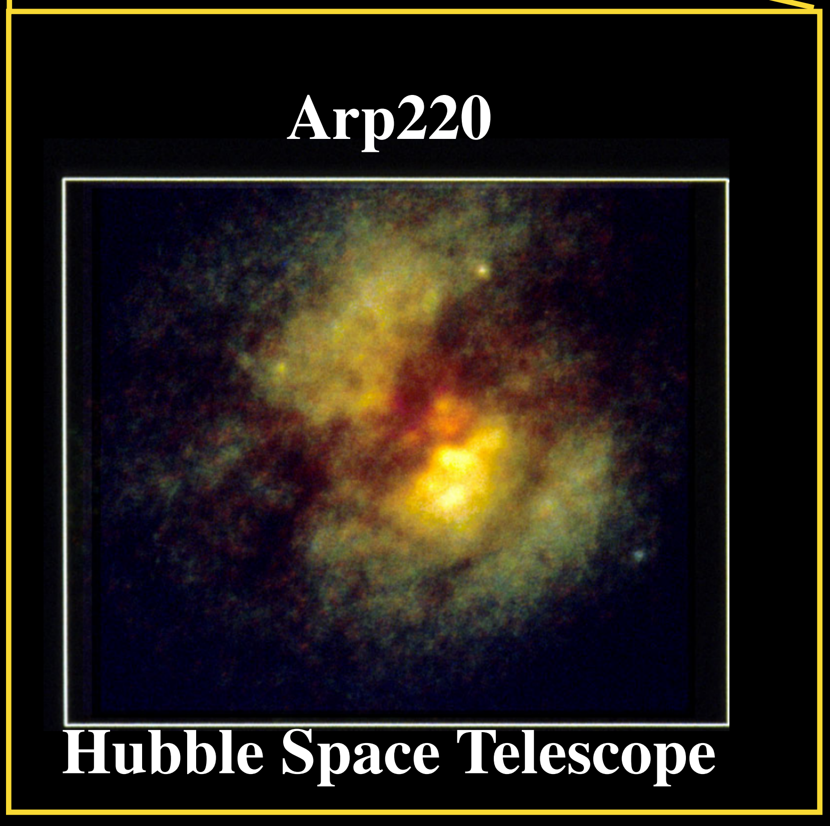
Credit: Millenium Simulation

Local Universe:
there exist very massive galaxies which are not forming new stars (ellipticals).

A lot of galaxies are star-forming, but do not have a lot of dust.



$z = 0.018$



Credit: N.Scoville

Arp220 = galaxy with a large amount of dust.

Forming new stars 200 times more than a Milky Way (300 solar masses/yr).

↓

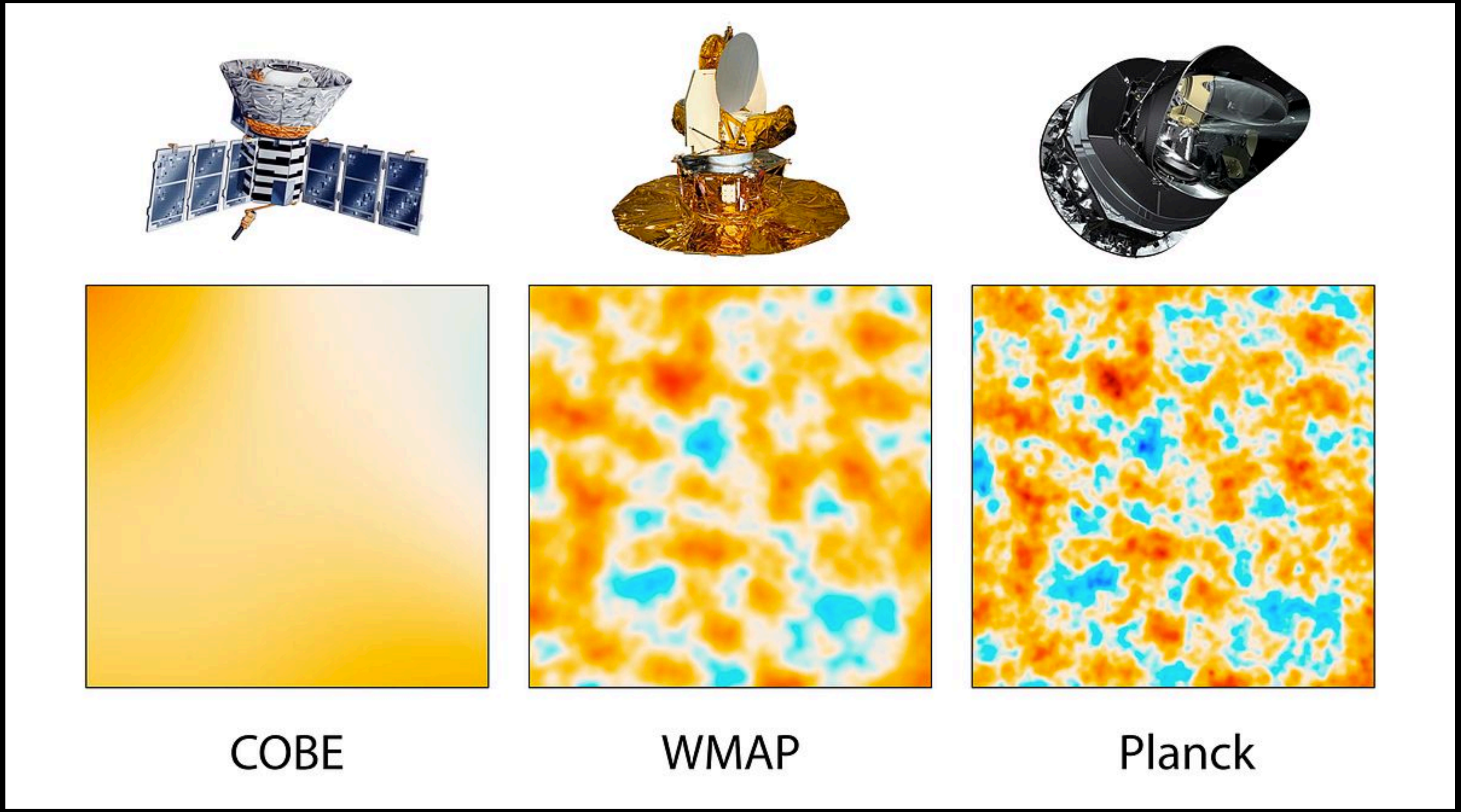
Dusty Star-forming Galaxy (DSFG)

(definition: generic term for star-forming galaxy with substantial amount of dust; Casey et al. 2014)

1.1 Our knowledge about dusty Universe…

Until 1980's 1989-1992 2003 2009

1.2 Dusty Star-Forming Galaxies (DSFGs)



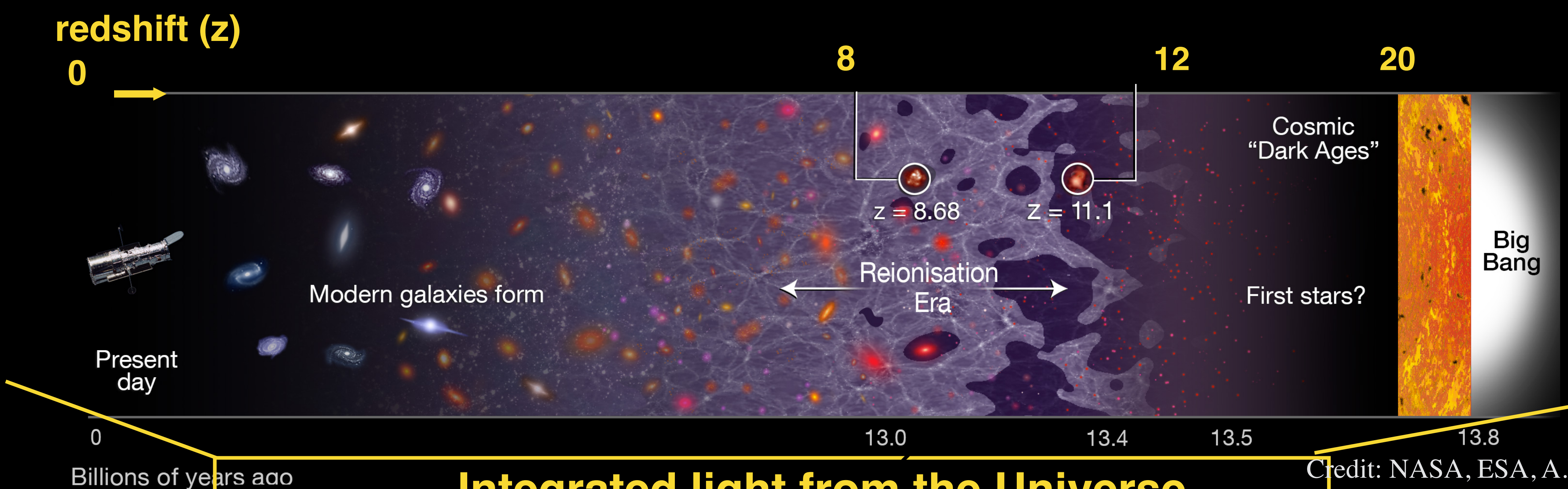
Until 1980's

1989-1992

2003

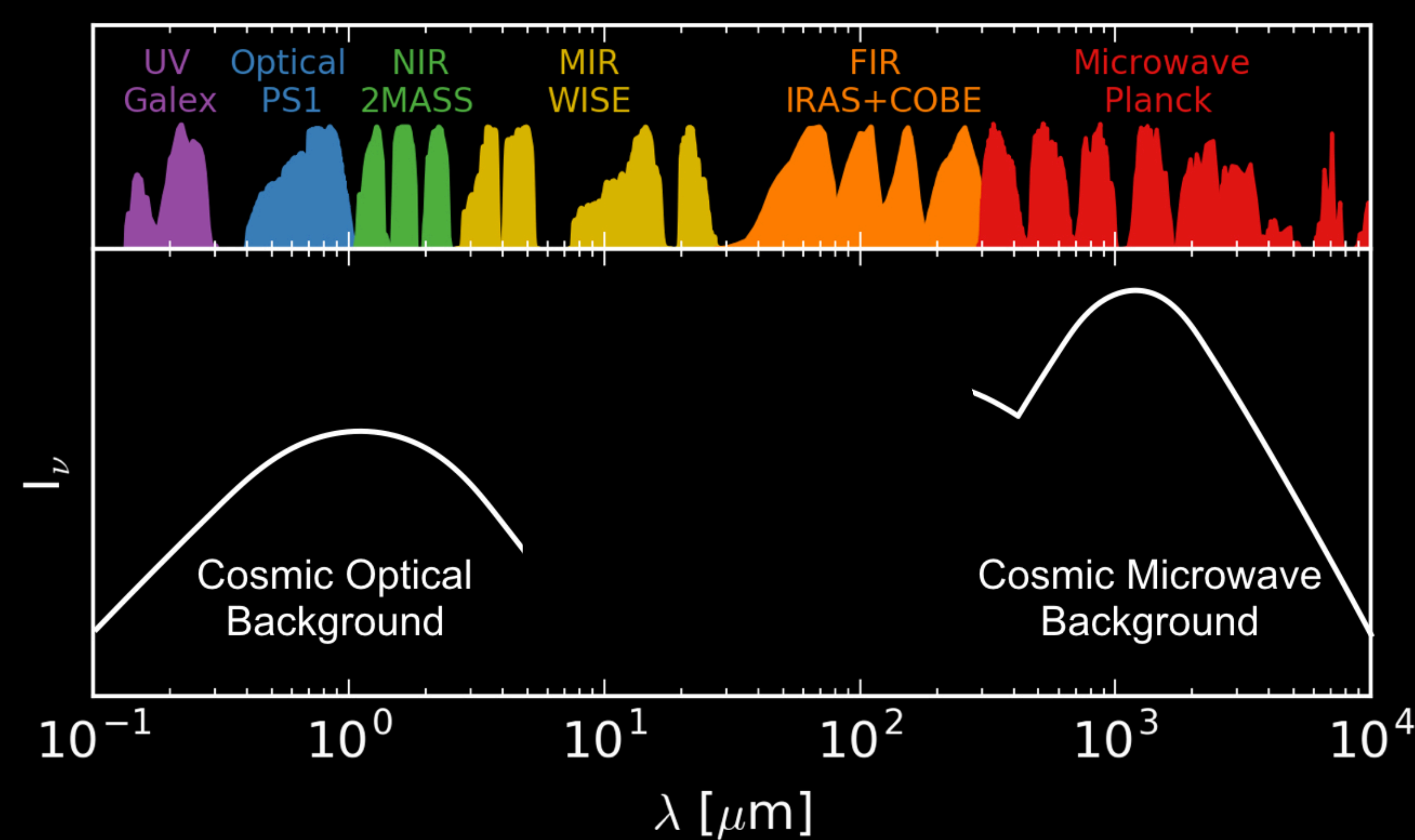
2009

1.2 Dusty Star-Forming Galaxies (DSFGs)

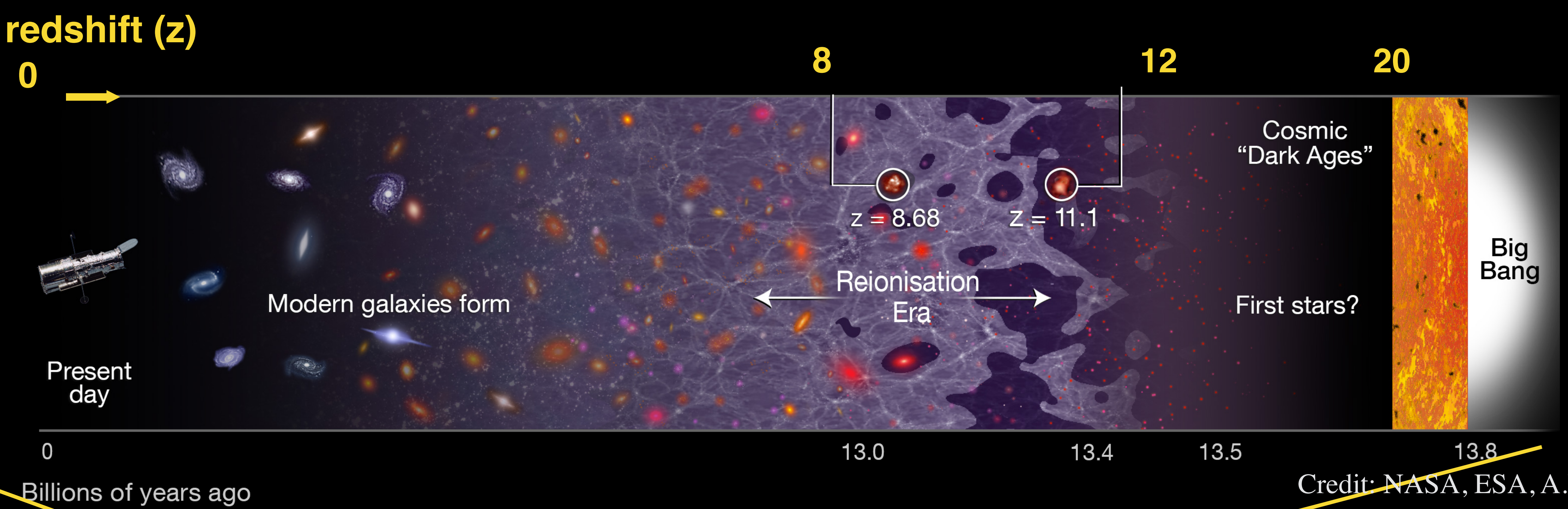


Credit: NASA, ESA, A.Field

Integrated light from the Universe



2.1 The world of evolving galaxies: data issue

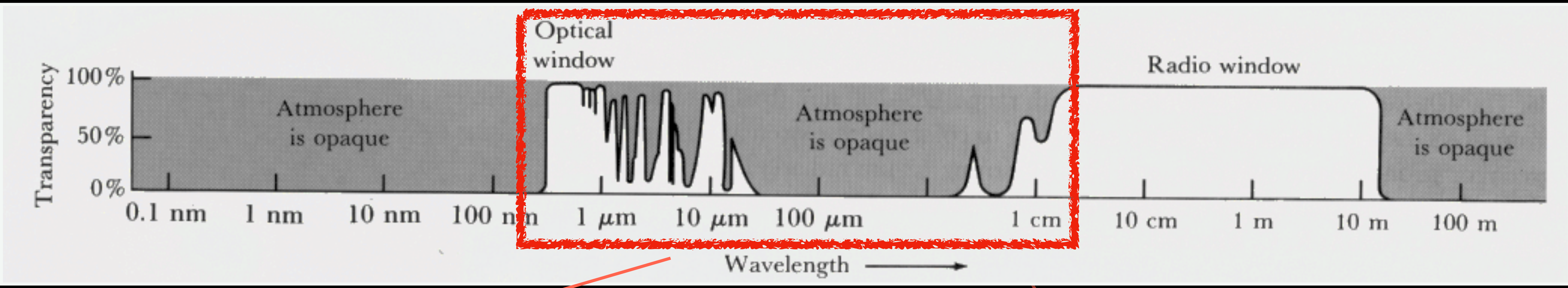


Credit: NASA, ESA, A.Field

MESSAGE No. 1

To fully understand evolution of diverse galaxies, we need large STATISTICS and samples of galaxies observed at DIFFERENT COSMIC TIMES

2.1 The world of evolving galaxies: data issue



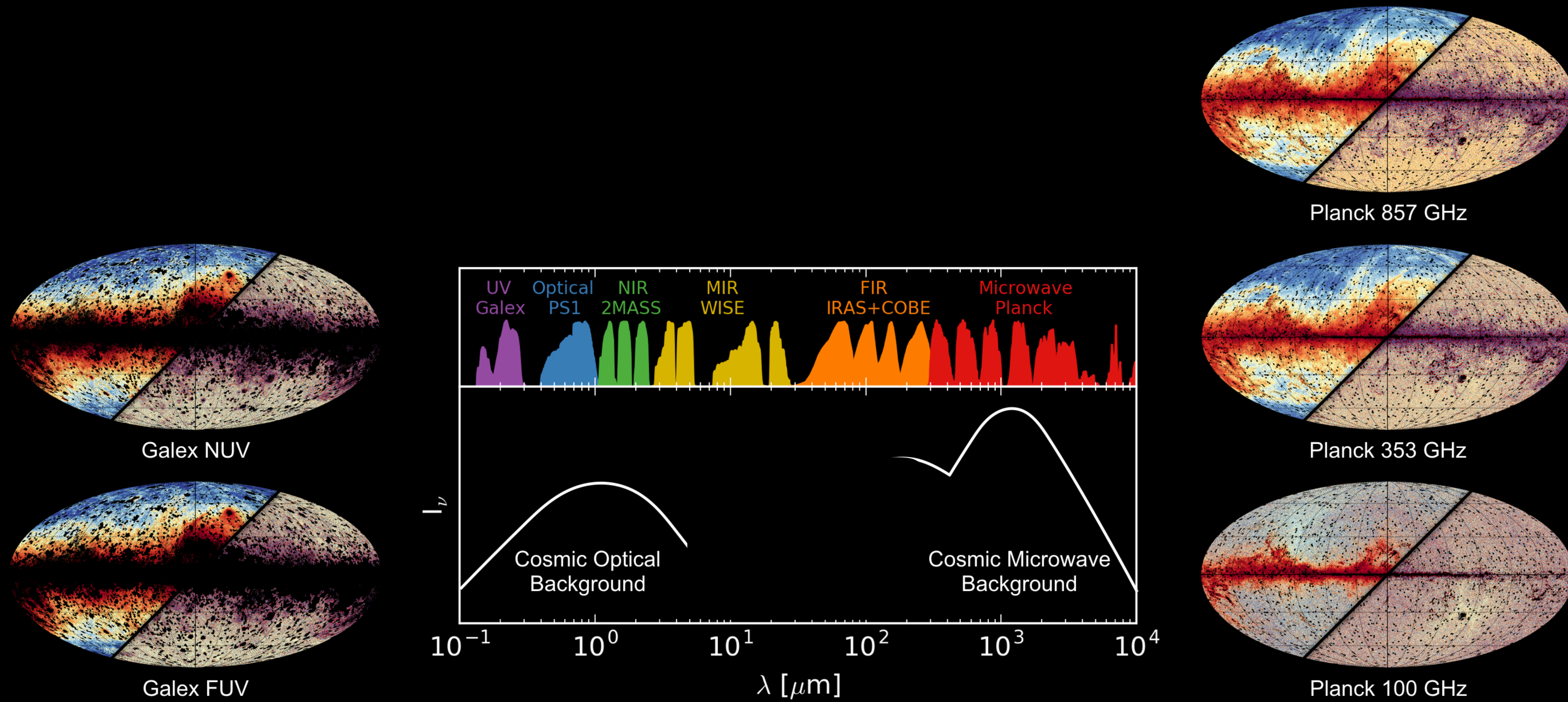
MESSAGE No. 2

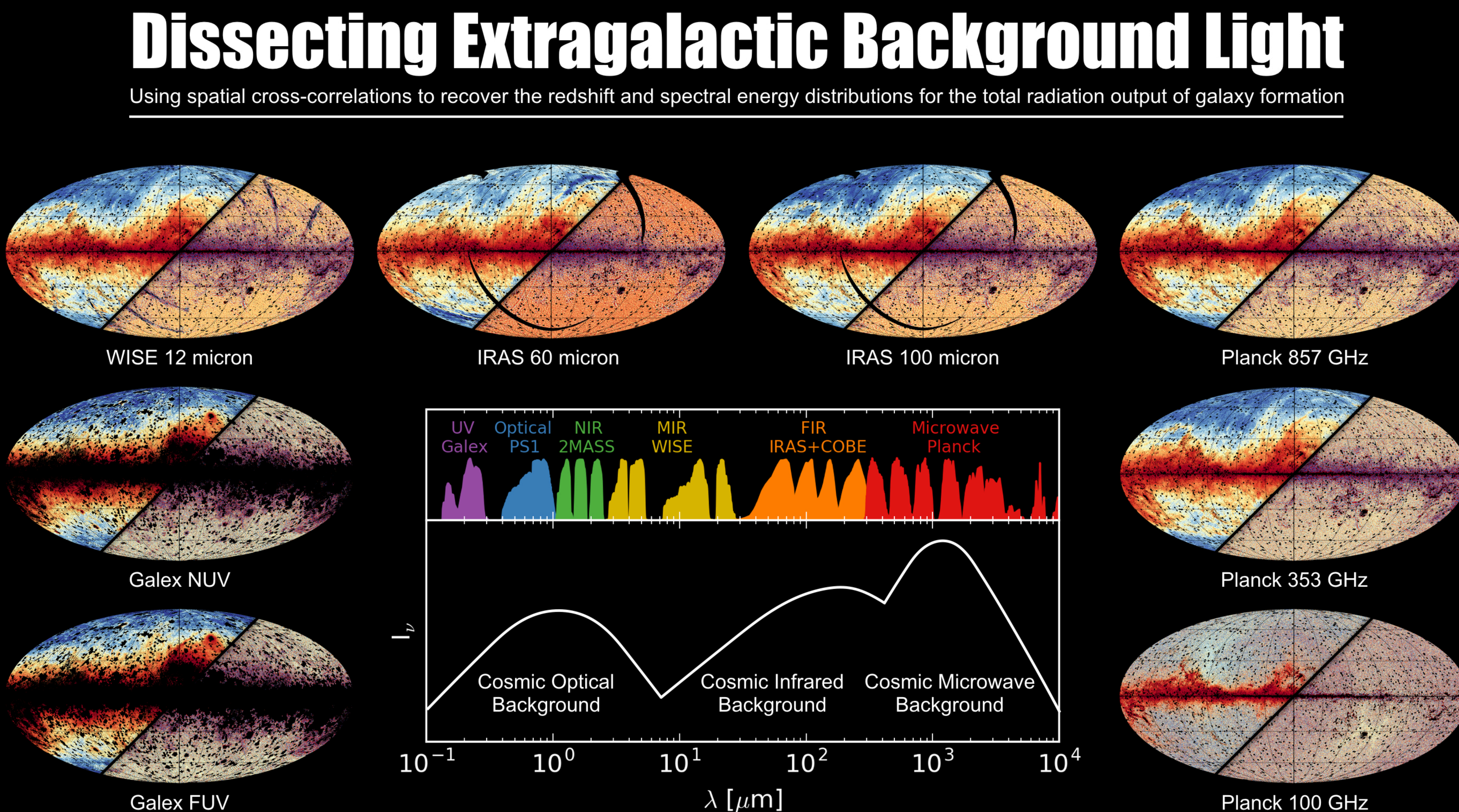
But, for most of the far-infrared (FIR) surveys, we have to use space-based surveys !

2.1 Discovering the Cosmic Infrared Background (CIR)

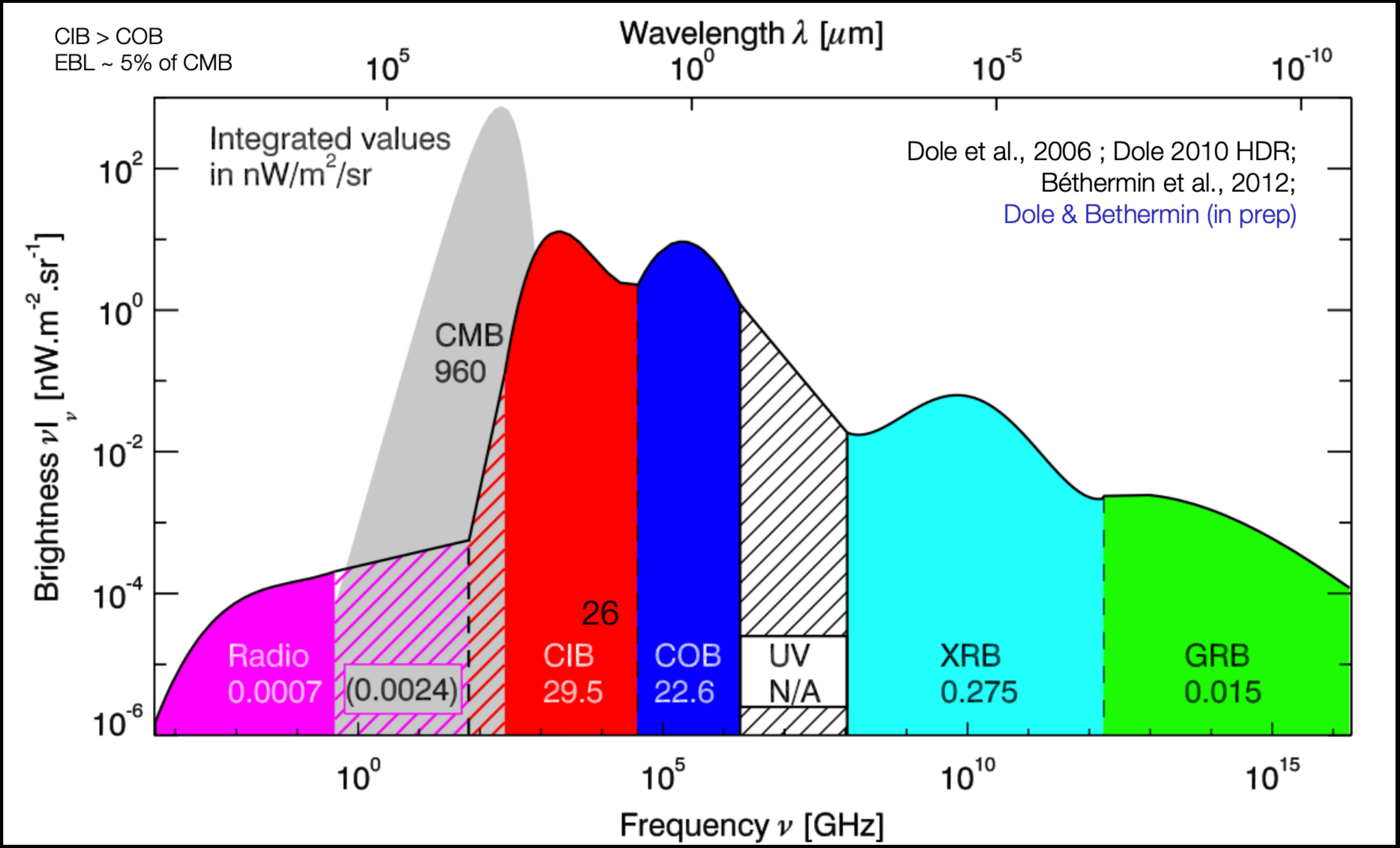
Dissecting Extragalactic Background Light

Using spatial cross-correlations to recover the redshift and spectral energy distributions for the total radiation output of galaxy formation



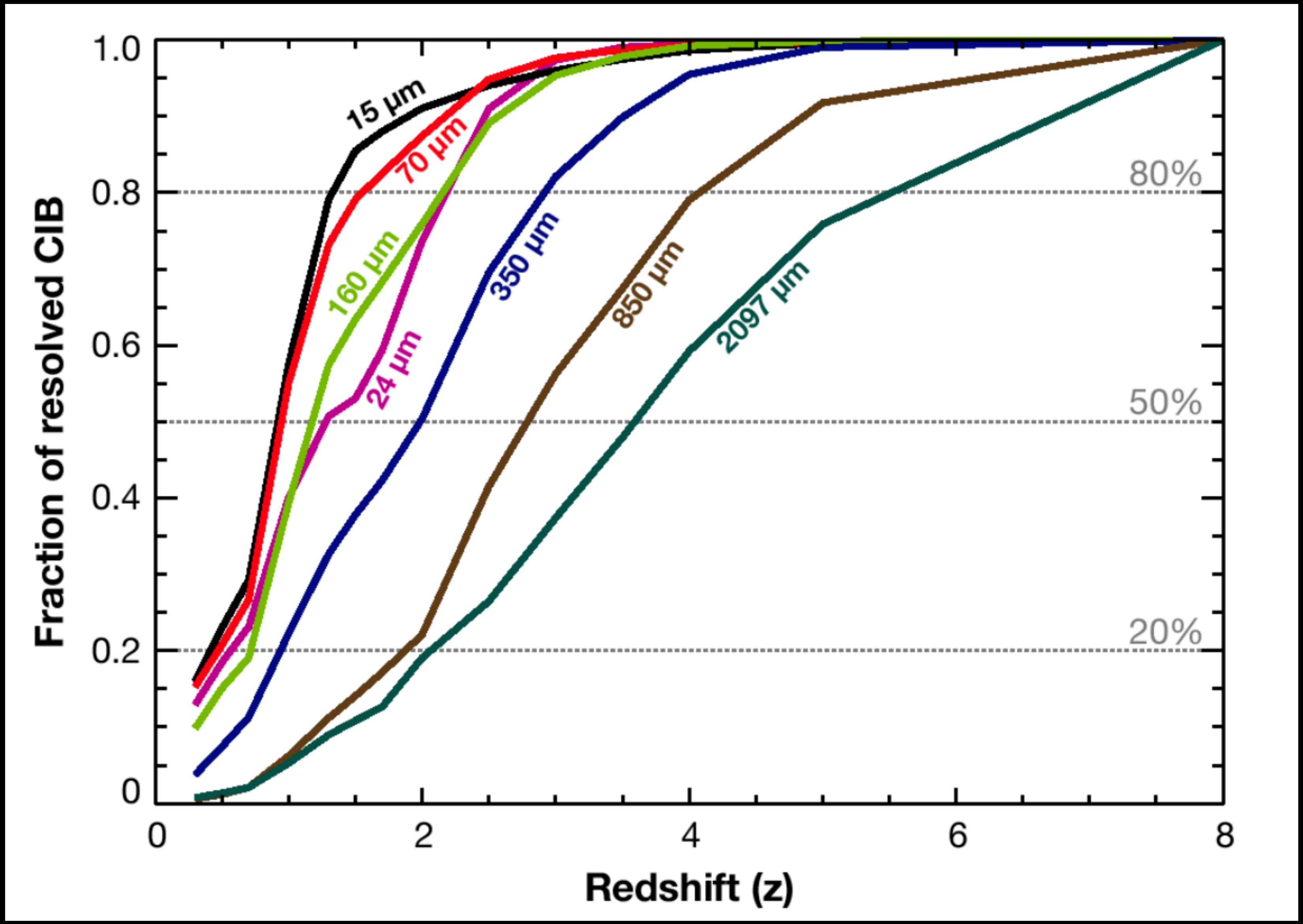

Dissecting Extragalactic Background Light
Using spatial cross-correlations to recover the redshift and spectral energy distributions for the total radiation output of galaxy formation
WISE 12 micron
IRAS 60 micron
IRAS 100 micron
Planck 857 GHz
Galex NUV
Galex FUV
Planck 353 GHz
Planck 100 GHz
UV Galex
Optical PS1
NIR 2MASS
MIR WISE
FIR IRAS+COBE
Microwave Planck
I_ν
Cosmic Optical Background
Cosmic Infrared Background
Cosmic Microwave Background
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
λ [μm]

2.1 Discovering the Cosmic Infrared Background (CIR)



CIR background = second most dominant background

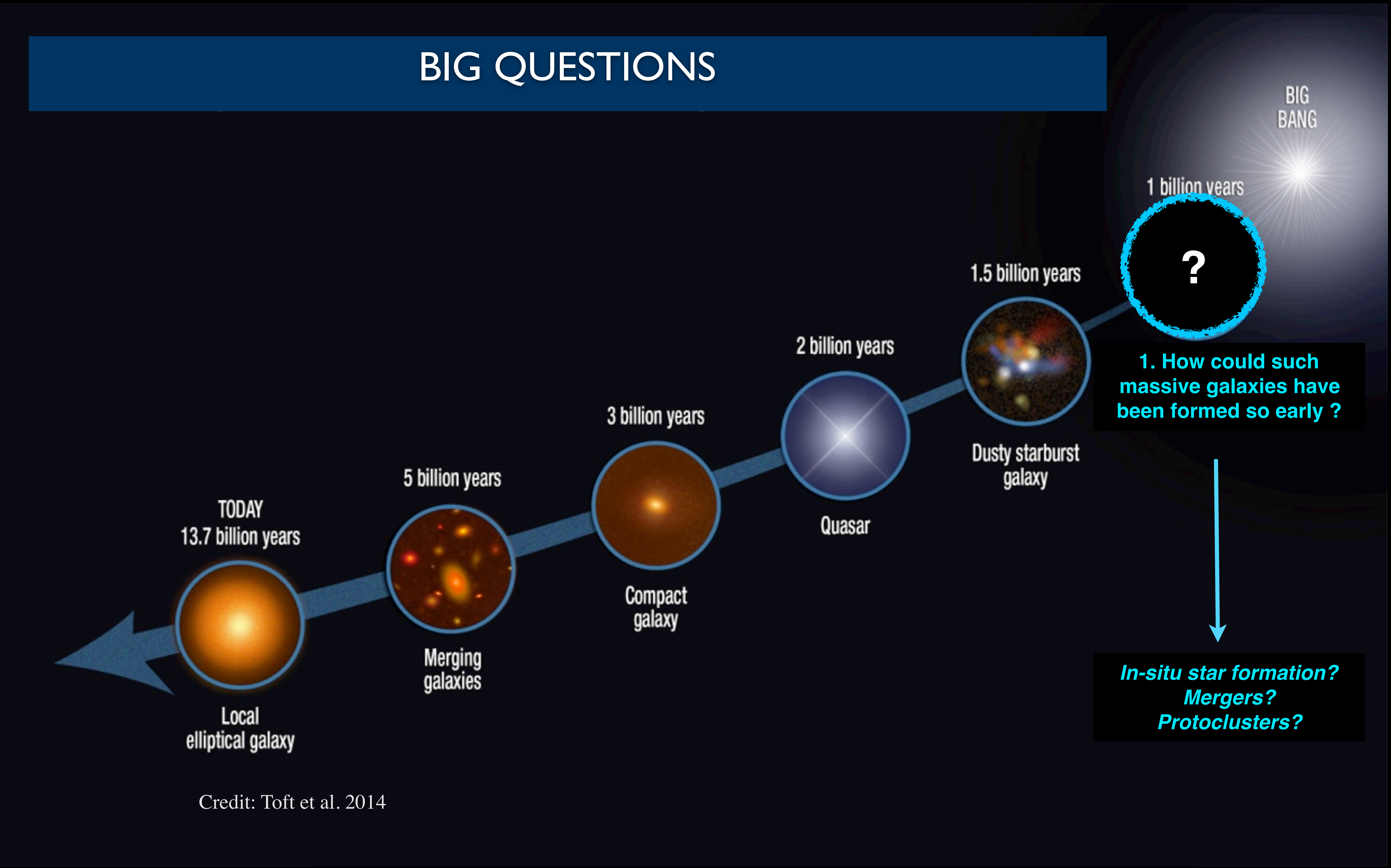
2.1 Era of Infrared Surveys (1984-present)



CIR background = second most dominant background

Problem: how to resolve it ?

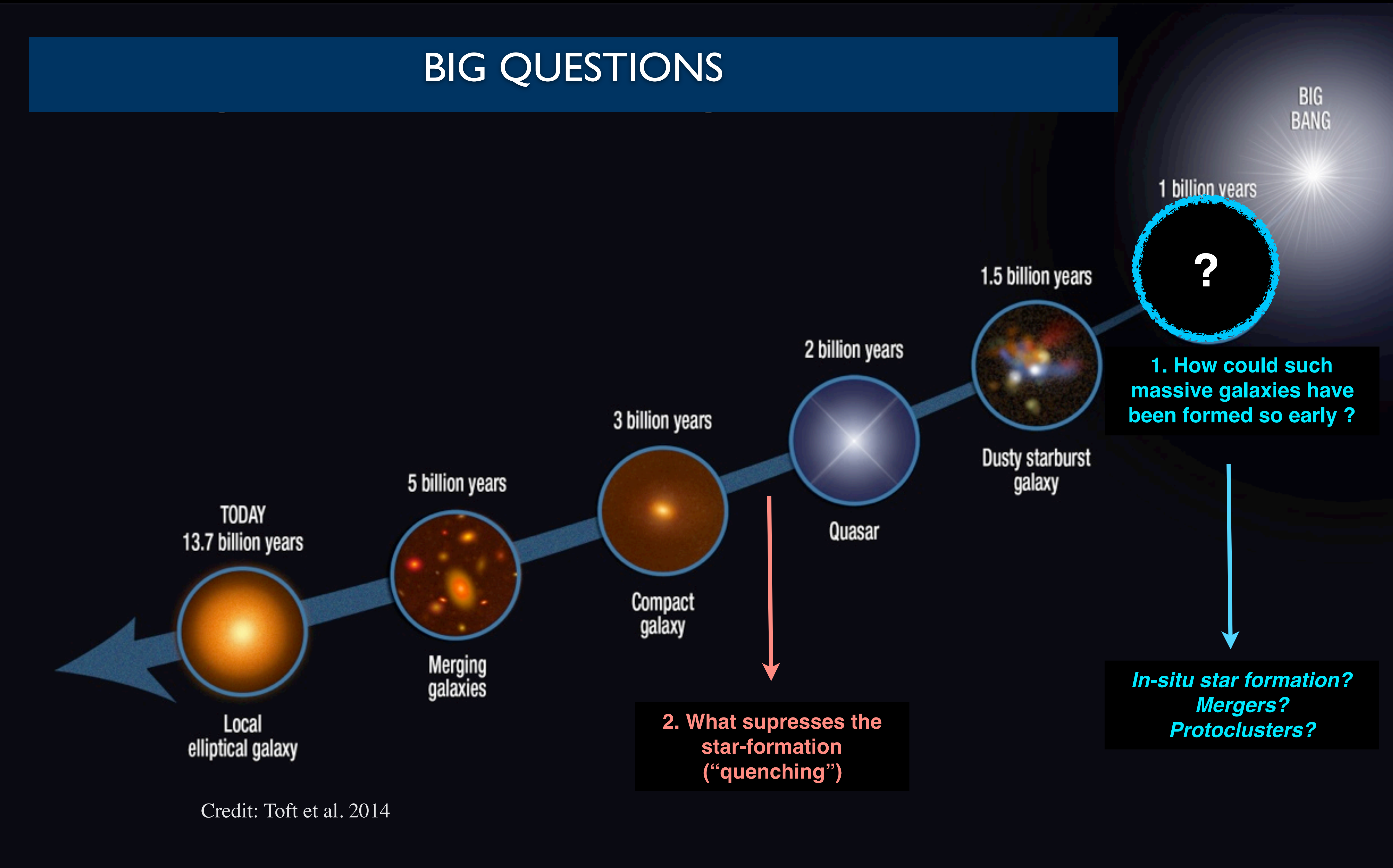
2.1 Which information we can infer from the dusty Universe?



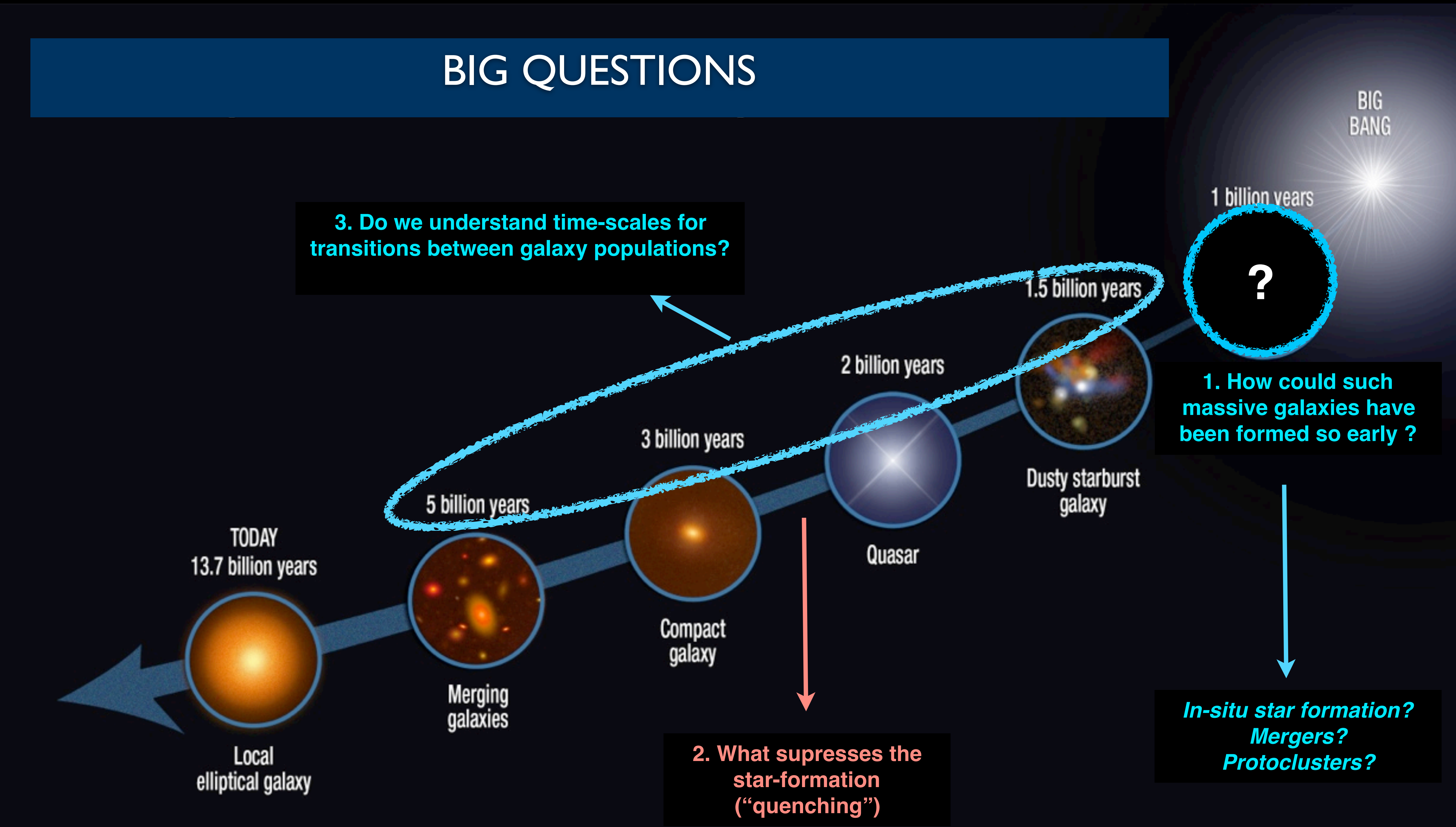
1. How could such massive galaxies have been formed so early ?

In-situ star formation? Mergers? Protoclusters?

2.1 Which information we can infer from the dusty Universe?



2.1 Which information we can infer from the dusty Universe?



Credit: Toft et al. 2014

2.1 Which information we can infer from the dusty Universe?

MESSAGE No. 2

Dusty star-forming galaxies at high-z are crucial for understanding of galaxy evolution.
Why?
Because they are progenitors of local elliptical galaxies !!!

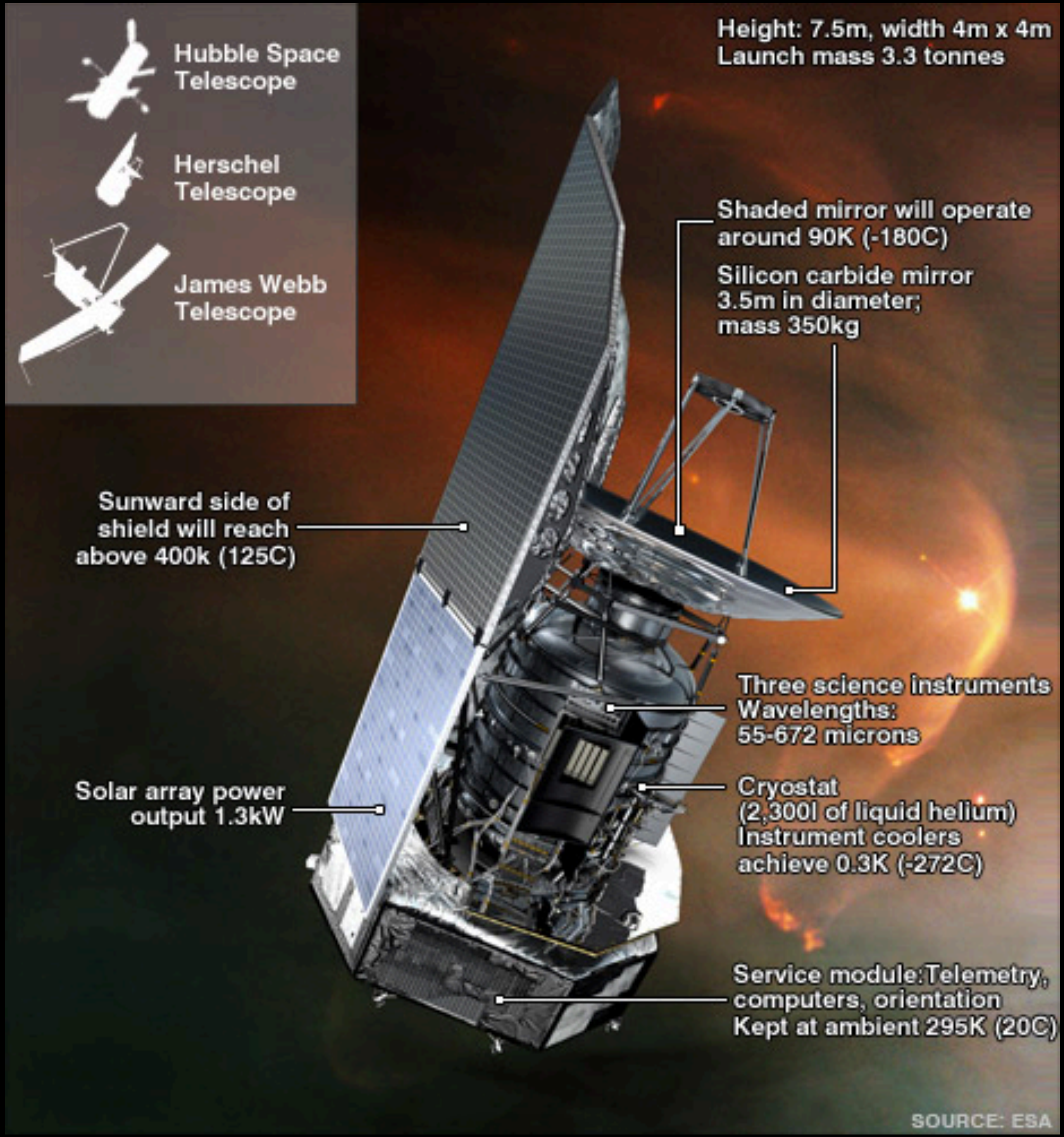
How could such massive galaxies have been formed so early ?

Credit: Toft et al. 2014

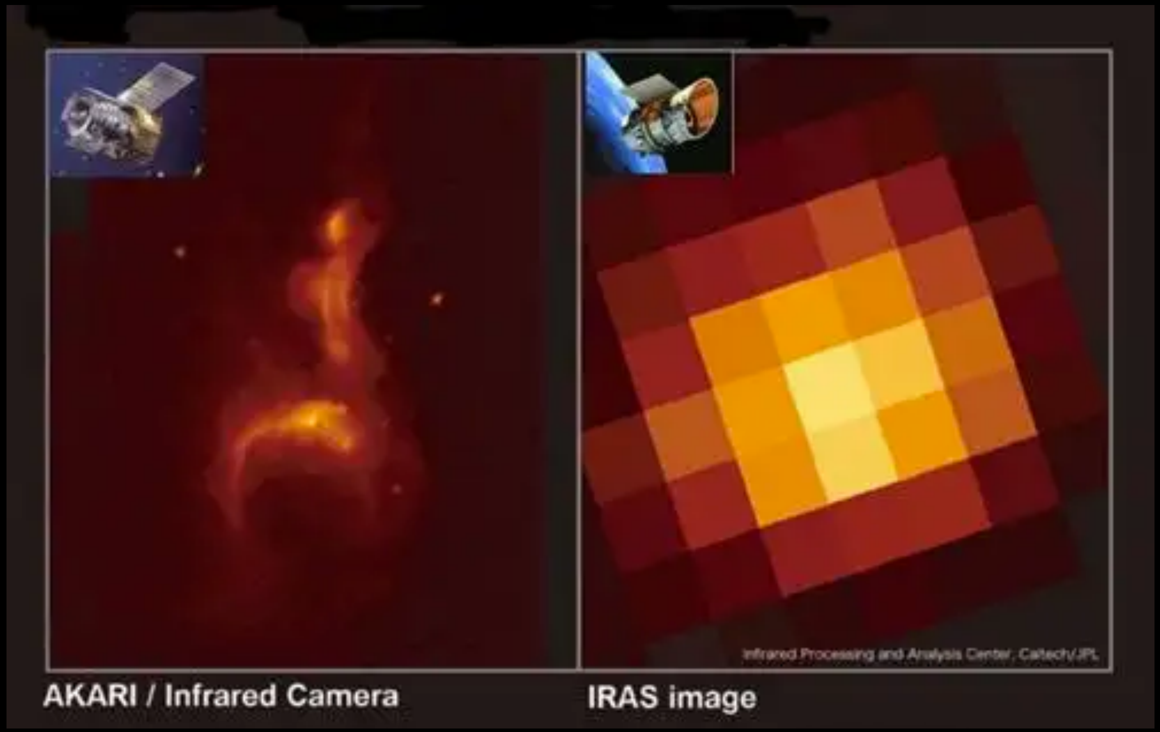
2.2 Era of Infrared Surveys (1984-present)

Philatelic information on the first
InfraRed Astronomy Satellite (IRAS)

2.2 Era of Infrared Surveys (1984-present)



2009



2006

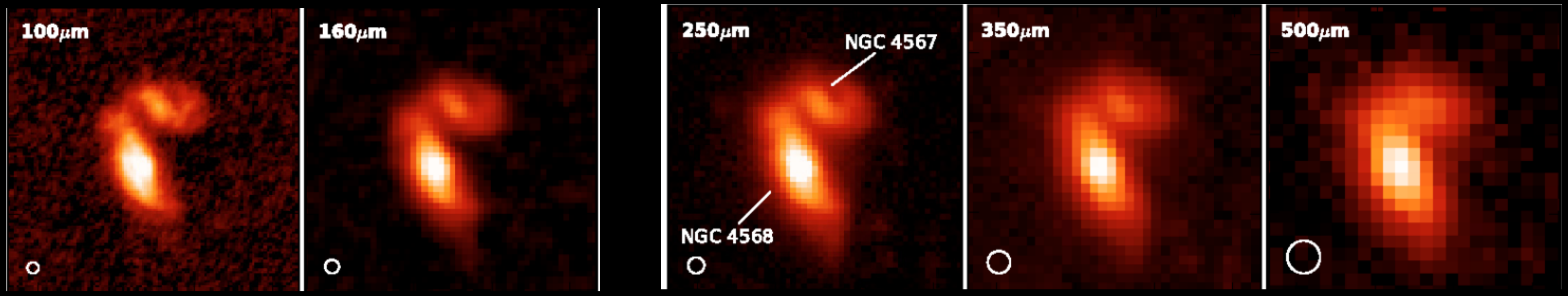
1984

2.2 Era of Infrared Surveys (1984-present)

Herschel Space Observatory

- **Launched by ESA; in operation from 2009 to 2013.**
- **Mirror 3.5m; Two broad-band photometers:**

1. **PACS** (100 μm, 160 μm)
2. **SPIRE** (**250 μm, 350 μm 500 μm**)

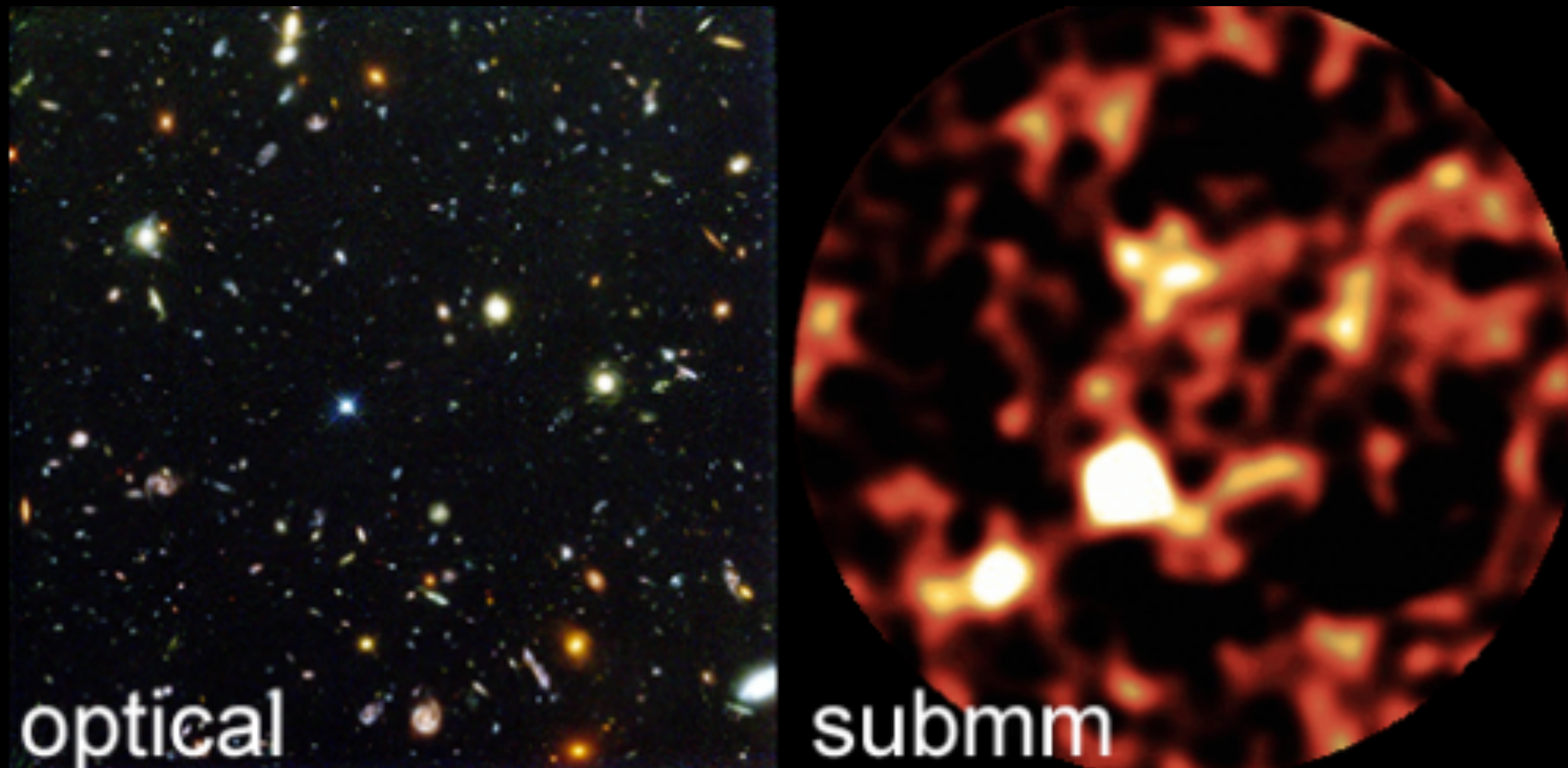


8” **11”** **18”** **25”** **36”**

(NGC4567/8; Smith et al. 2010)

Beam size (Full Width Half Maximum)

First image of HUDF in FIR (1998, Holland et al.)



SFR (from UV)

$$\mathrm{SFR_{tot}} = K_{\mathrm{UV}} \times L_{\nu}(\mathrm{UV})$$

But needs dust correction

Ideally (UV+IR)

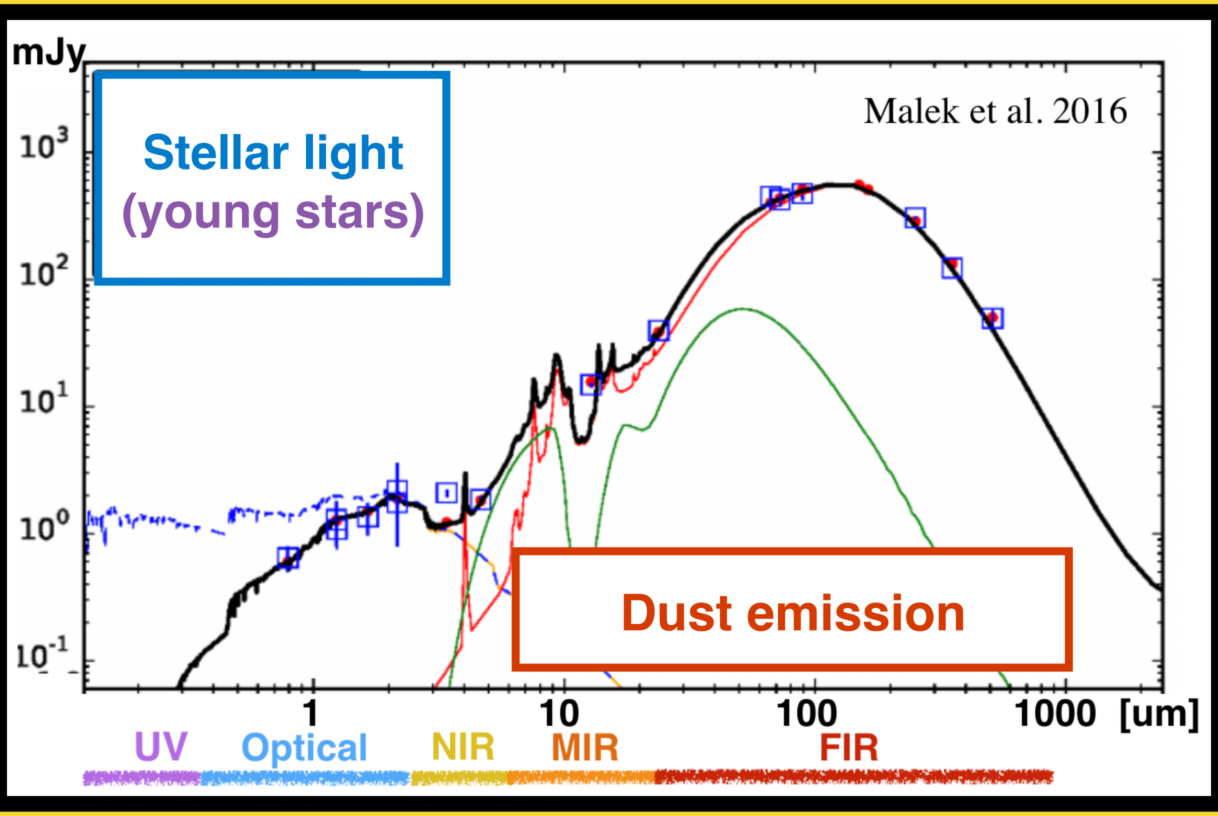
$$\mathrm{SFR_{tot}} = K_{\mathrm{UV}} \times L_{\nu}(\mathrm{UV}) + K_{\mathrm{IR}} \times L_{\nu}(\mathrm{IR})$$

2.3 Selecting the dusty star-forming galaxies

Which information we can encode from dust SED?

- **Infrared luminosity:** $L_{\mathrm{IR}} = \int_{8\mu m}^{1000\mu m} 4\pi D_L(z)^2 S_\nu(\lambda) d\lambda$
- **Star-formation rate:** $\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 4.5 \times 10^{-44} L_{\mathrm{IR}}(\mathrm{erg\,s}^{-1}) = 1.71 \times 10^{-10} L_{\mathrm{IR}}(L_\odot)$

(good approximation for massive DSFGs)



- Spectral Energy Distribution (SED) of galaxies
- Dust emission <=> star formation

2.3 Selecting the dusty star-forming galaxies

Which information we can encode from dust SED?

- **Infrared luminosity:** $$L_{\rm IR} = \int_{8\mu m}^{1000\mu m} 4\pi D_L(z)^2 S_\nu(\lambda) d\lambda$$
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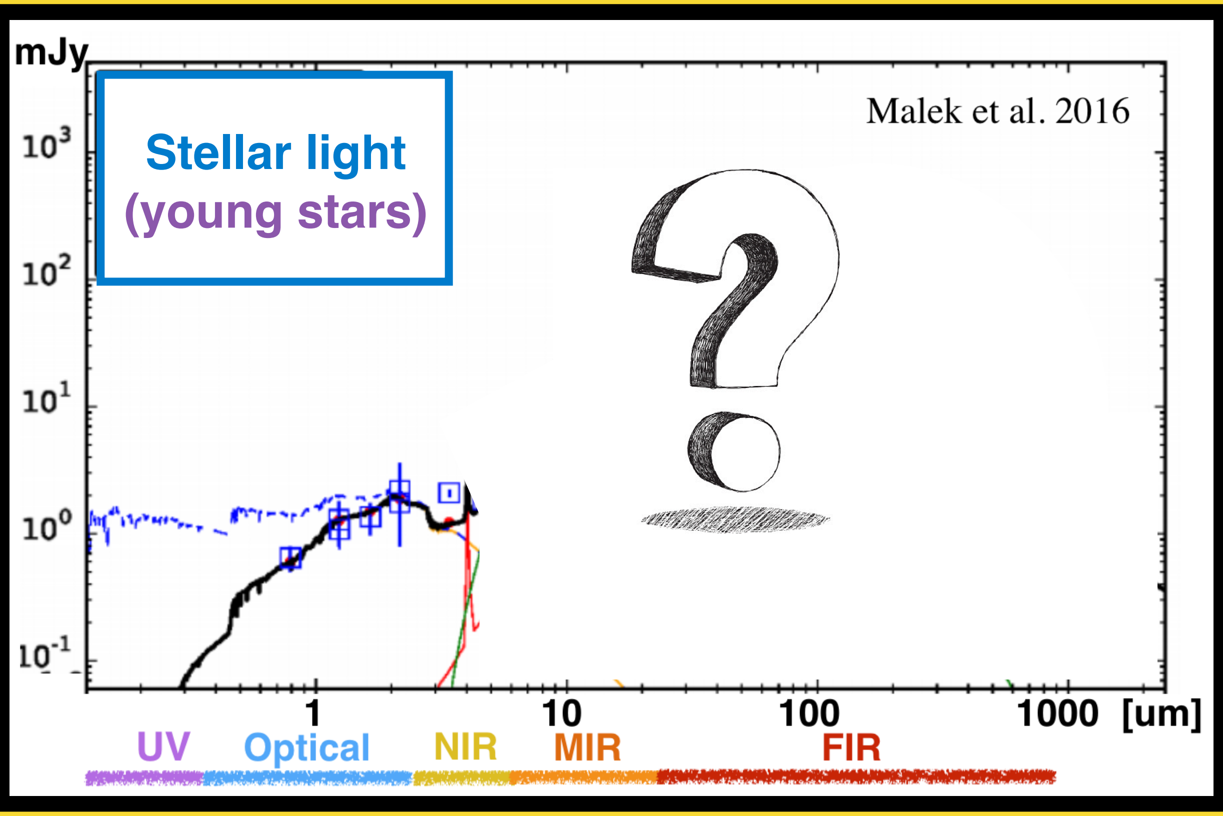
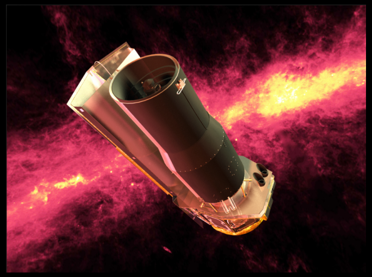


2.3 Selecting the dusty star-forming galaxies

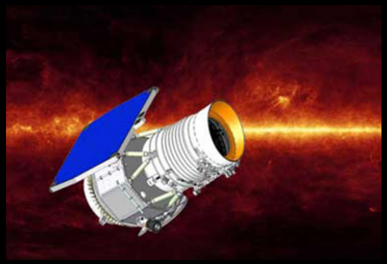
- **Space-based**

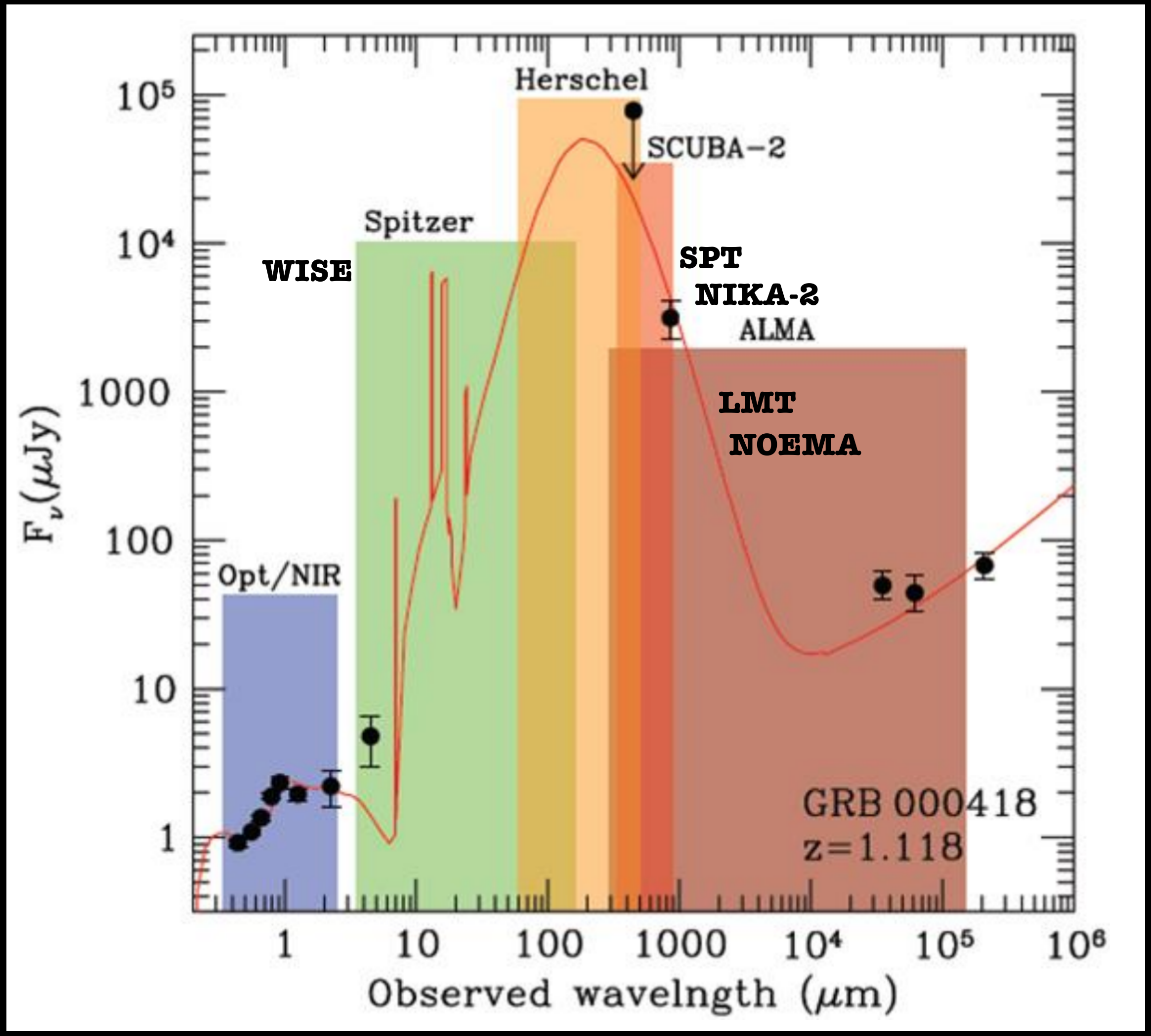
Spitzer



Herschel

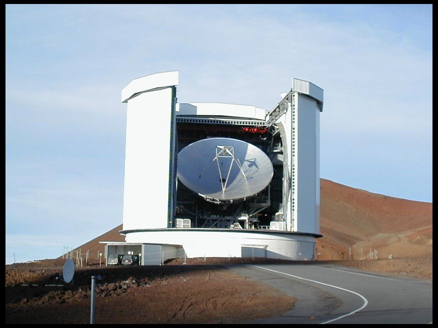
WISE





(Savaglio et al. 2012)

- **Ground-based**



SCUBA-2

SPT

ALMA

ALMA

Atacama Large Millimeter/Submillimeter Array

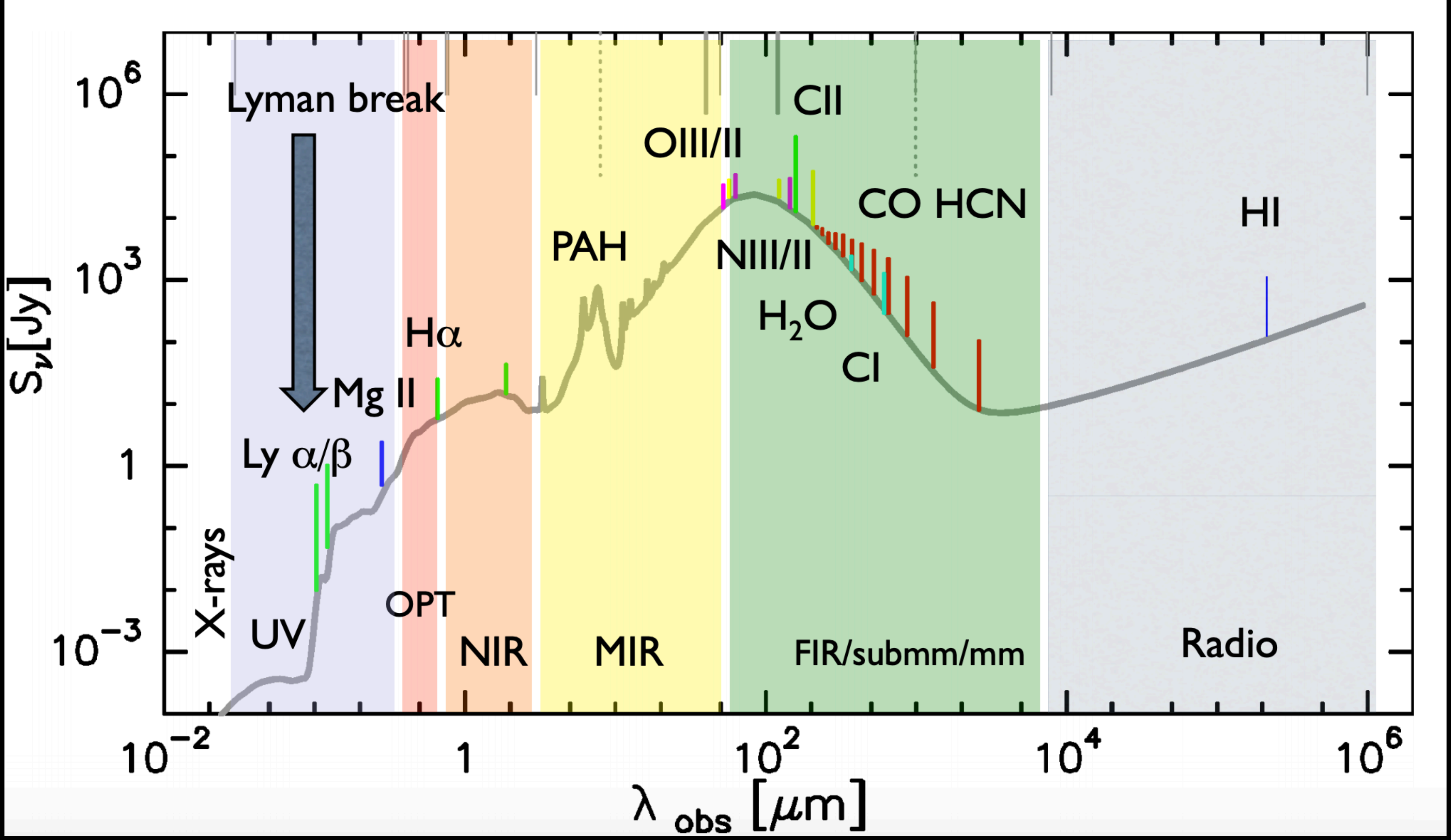
World-wide collaboration

- Europe (**ESO**)
- North America (USA, Canada, Taiwan)
- Eastern Asia (Japan, Taiwan, South Korea)
- Chile

- Main array: 50 x 12 m antennas
- ALMA Compact Array (ACA): 4 x 12m + 12 x 7m
- Frequency range: 30—900 GHz (0.3—10 mm)
- 16 km max. baseline

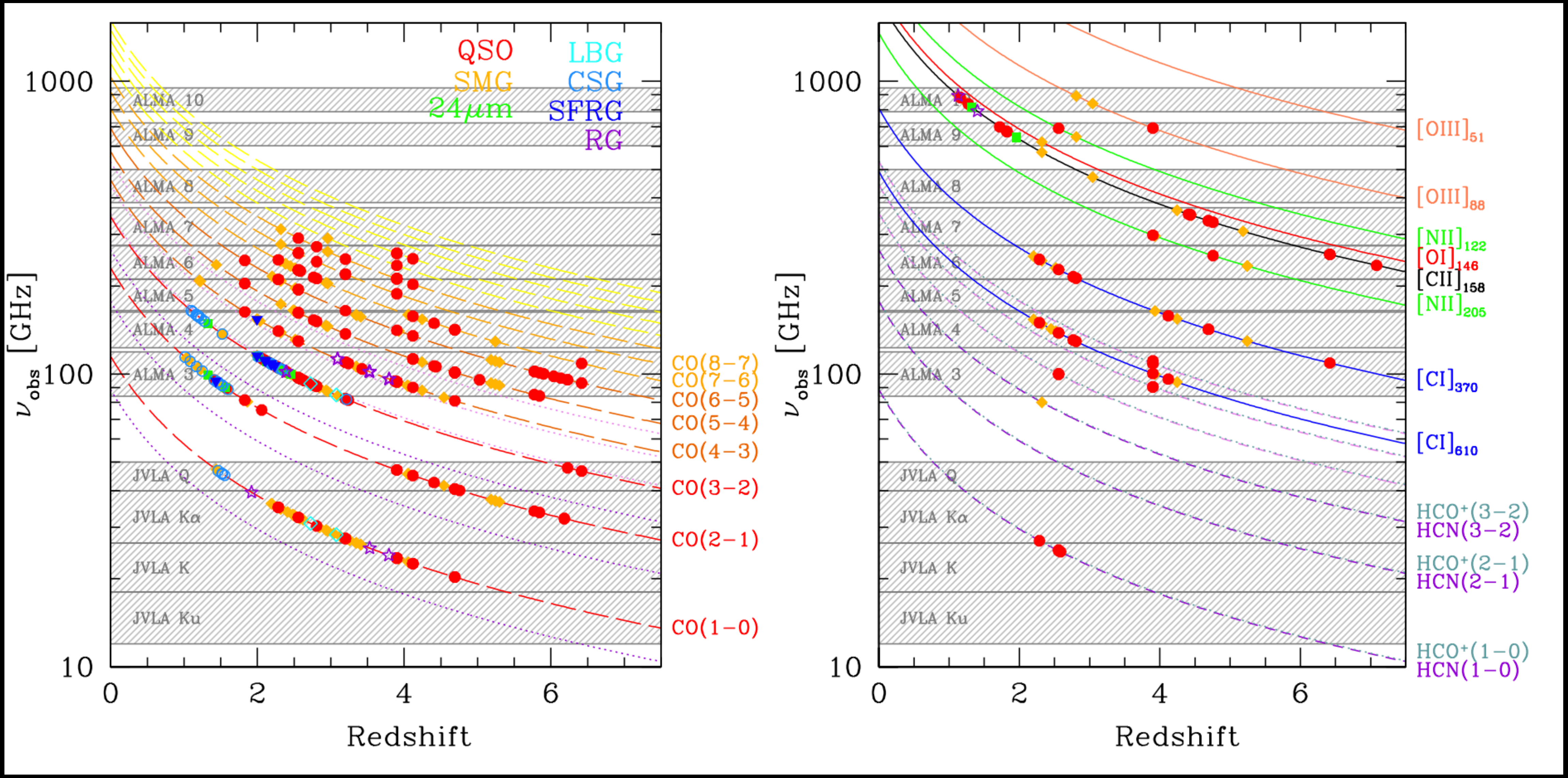
2.3 Selecting the dusty star-forming galaxies

Combining continuum and lines !
(ALMA+NOEMA+IRAM+SMA)



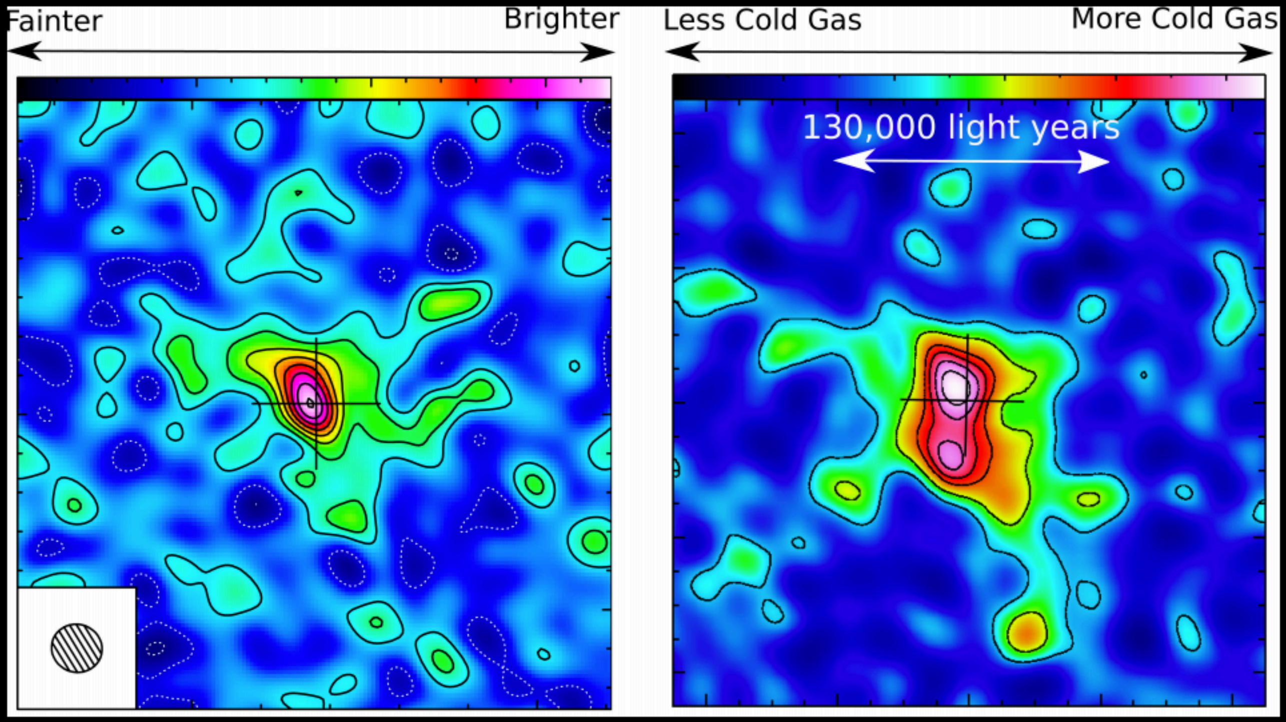
2.3 Selecting the dusty star-forming galaxies

Gas tracers:
importance of mm/radio observations
(e.g. ALMA, NOEMA & VLA)



Redshifted lines for CO (left) and other SFR tracers (right) at mm and radio wavelengths
(Weiss 2013)

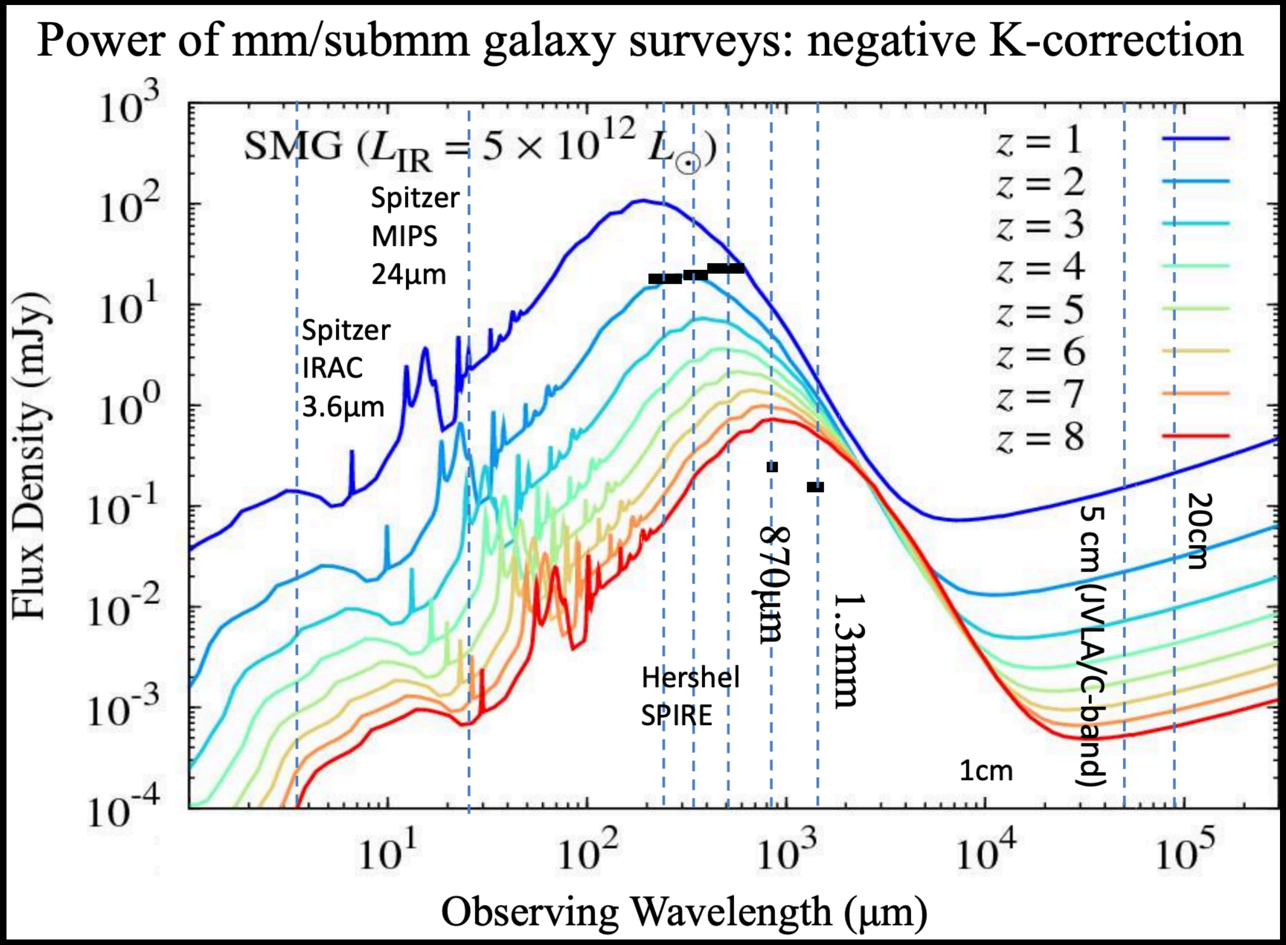
Gas tracers:
importance of mm/radio observations
(e.g. ALMA, NOEMA & VLA)

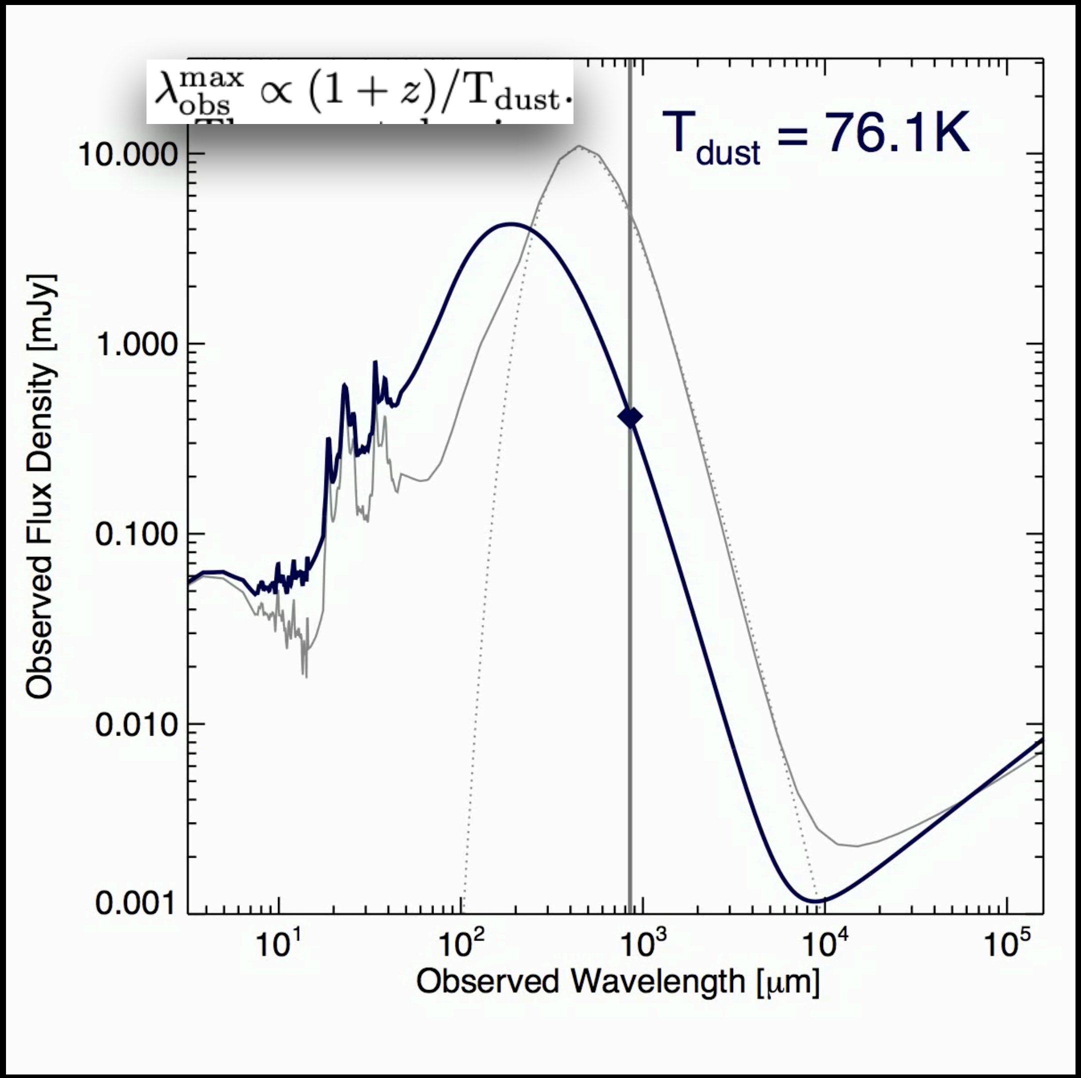


observations simulations

[CII] @ 256 GHz / NOEMA

SED peak correlated with dust temperature/redshift !





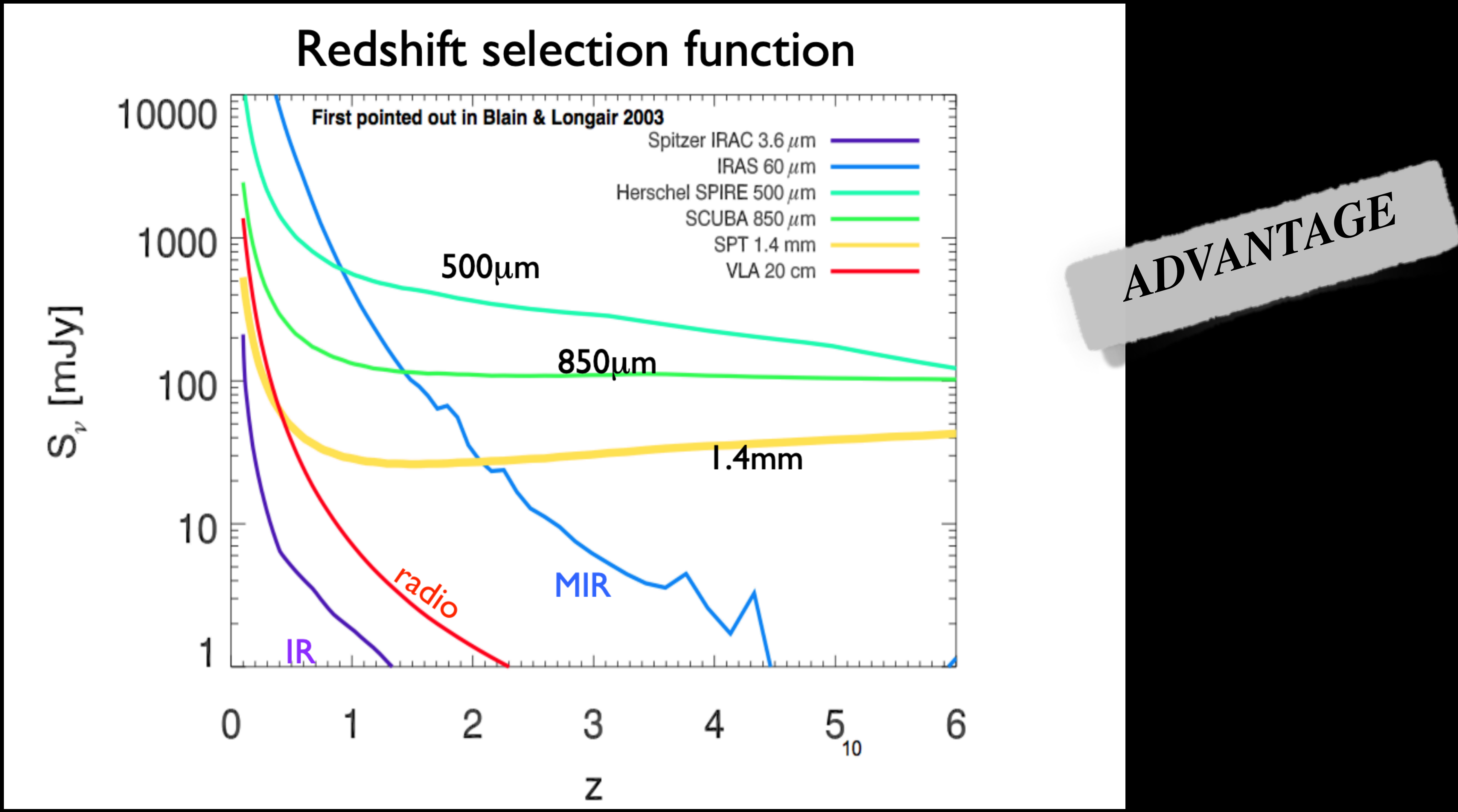
Negative K-correction —> we can observe distant galaxies

But, Tdust and redshift (z) are completely degenerate !!!

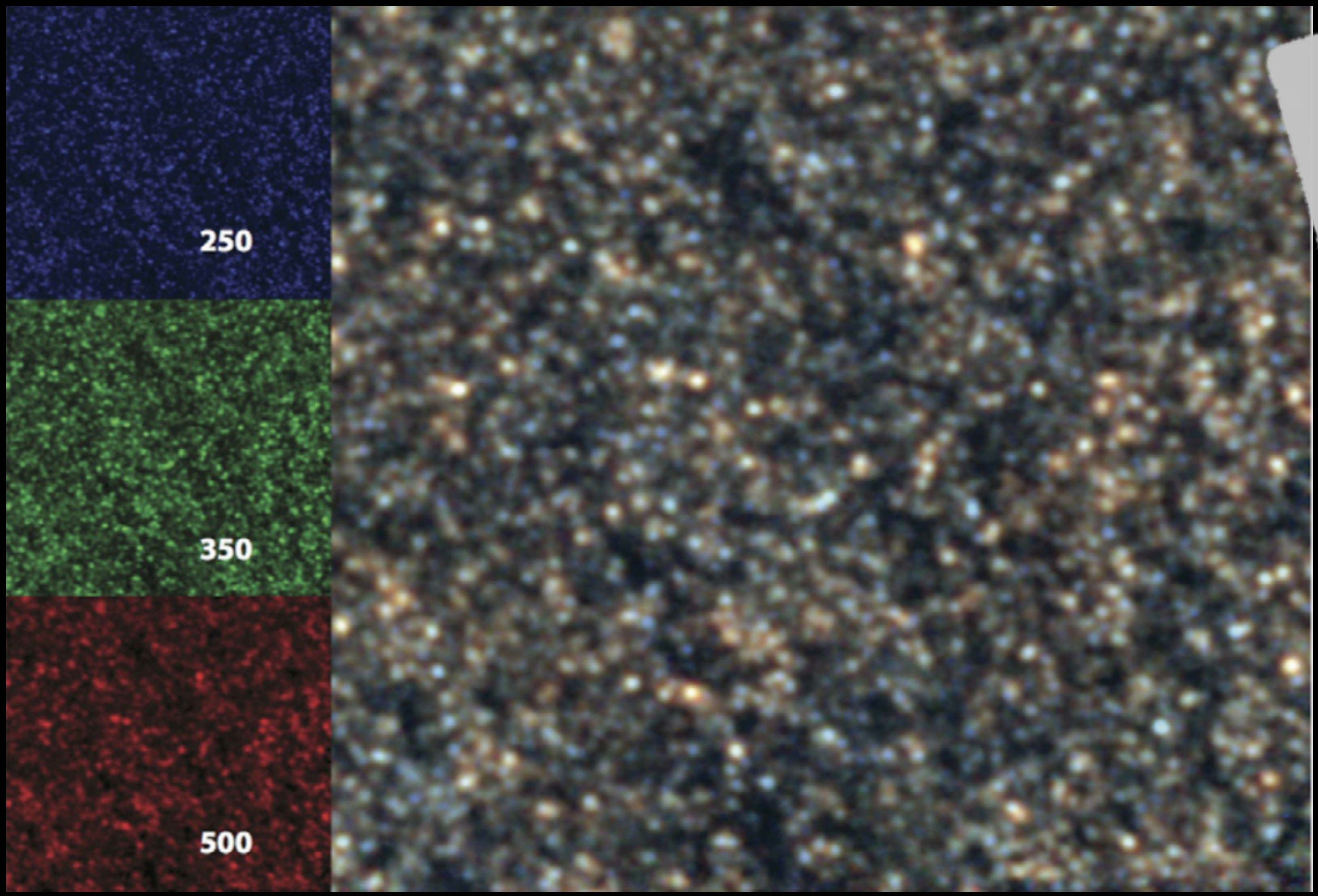
2.3 Selecting the dusty star-forming galaxies: advantages

Negative "K-correction" = flux stays constant even at high-z

$$S_\nu(z) \propto \nu^{2+\beta}/4\pi D_L^2 \propto \nu_{\rm rest}^{2+\beta}(1+z)^{2+\beta}/(1+z)^4 \propto (1+z)^{\beta-2}.$$



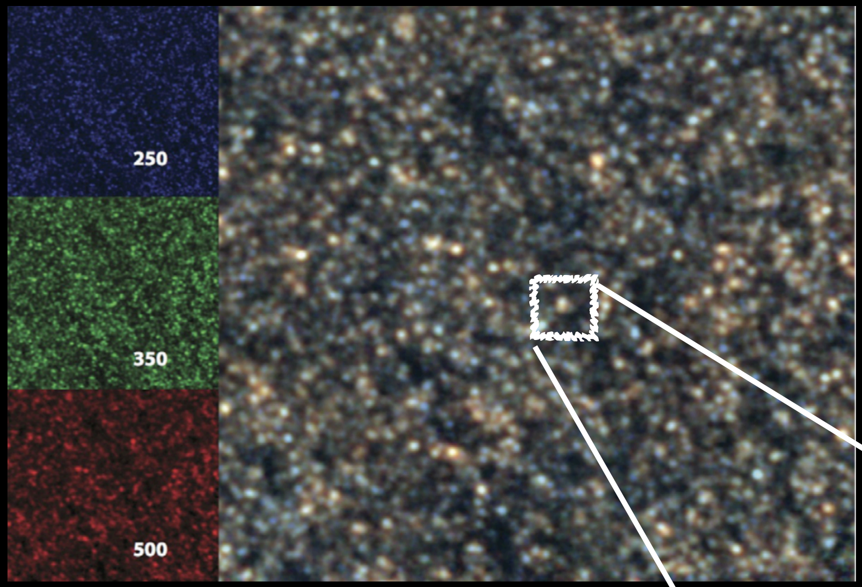
2.3 Selecting the dusty star-forming galaxies: problems

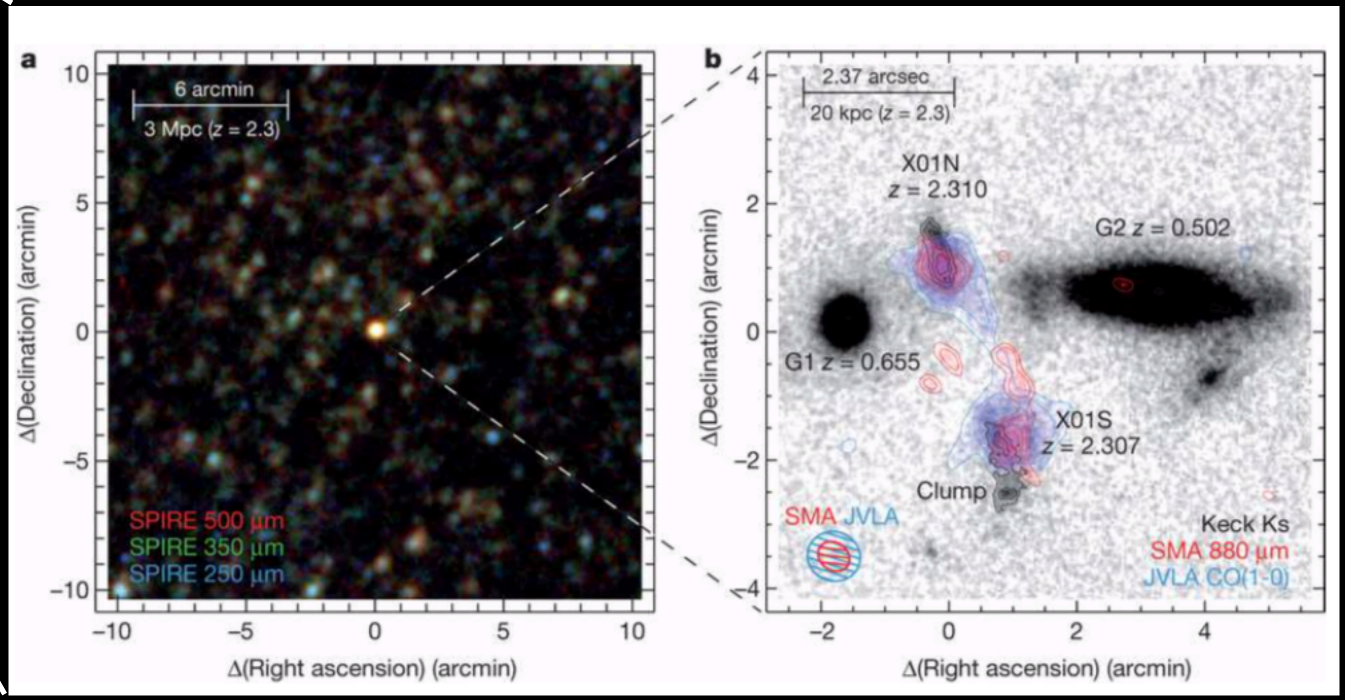


ADVANTAGE
&
PROBLEM

Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

2.3 Selecting the dusty star-forming galaxies: challenges

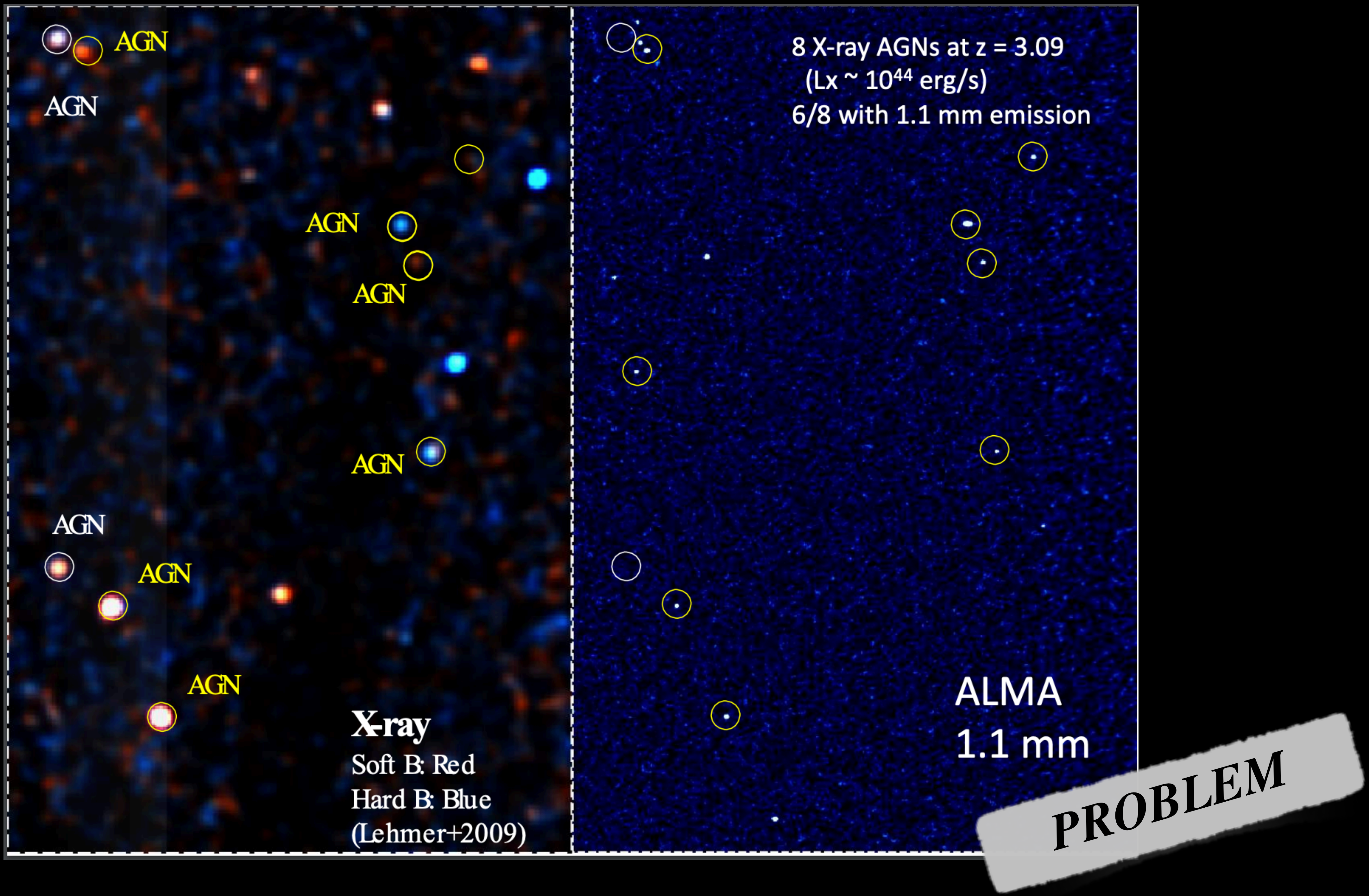


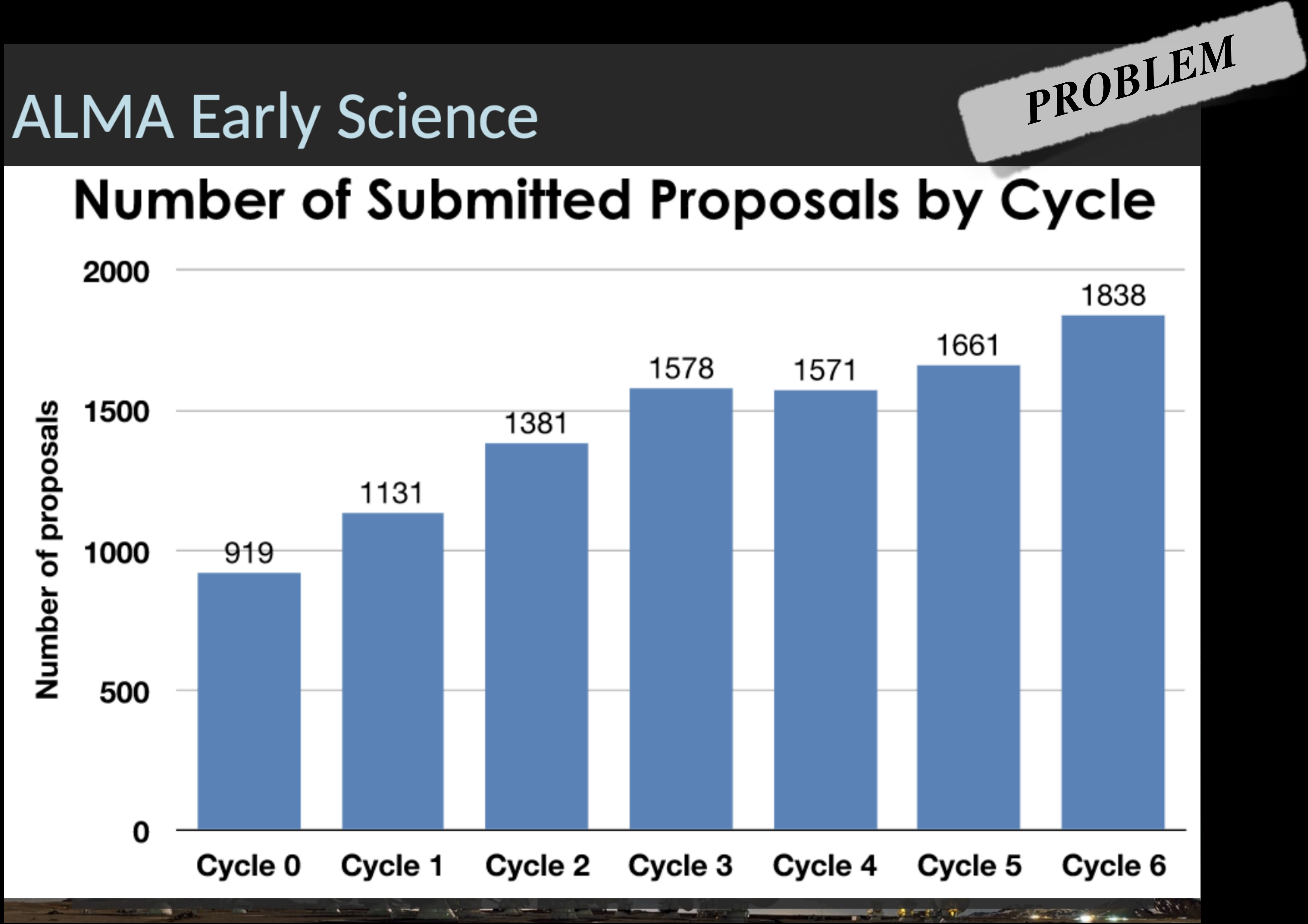


Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

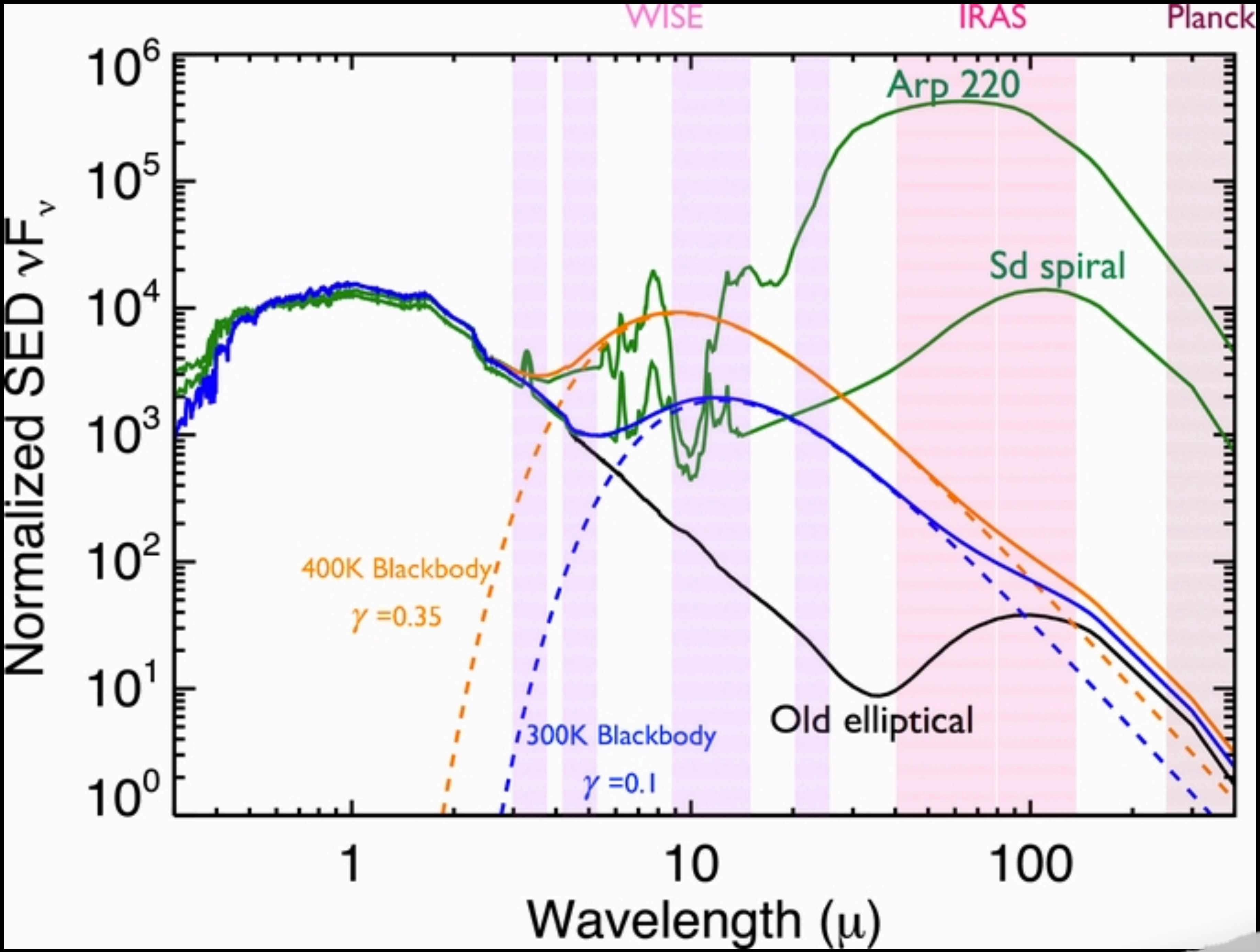
2.3 Selecting the dusty star-forming galaxies: challenges

We don't have a knowledge about physics in galaxies



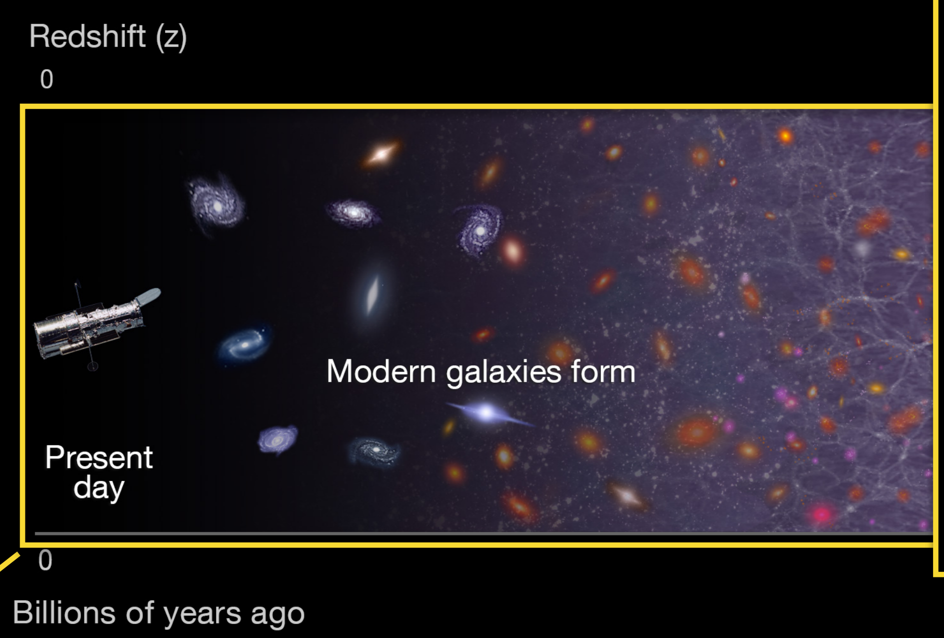

ALMA Early Science
PROBLEM
Number of Submitted Proposals by Cycle
Number of proposals
2000
1500
1000
500
0
919
1131
1381
1578
1571
1661
1838
Cycle 0
Cycle 1
Cycle 2
Cycle 3
Cycle 4
Cycle 5
Cycle 6

2.3 Selecting the dusty star-forming galaxies: challenges



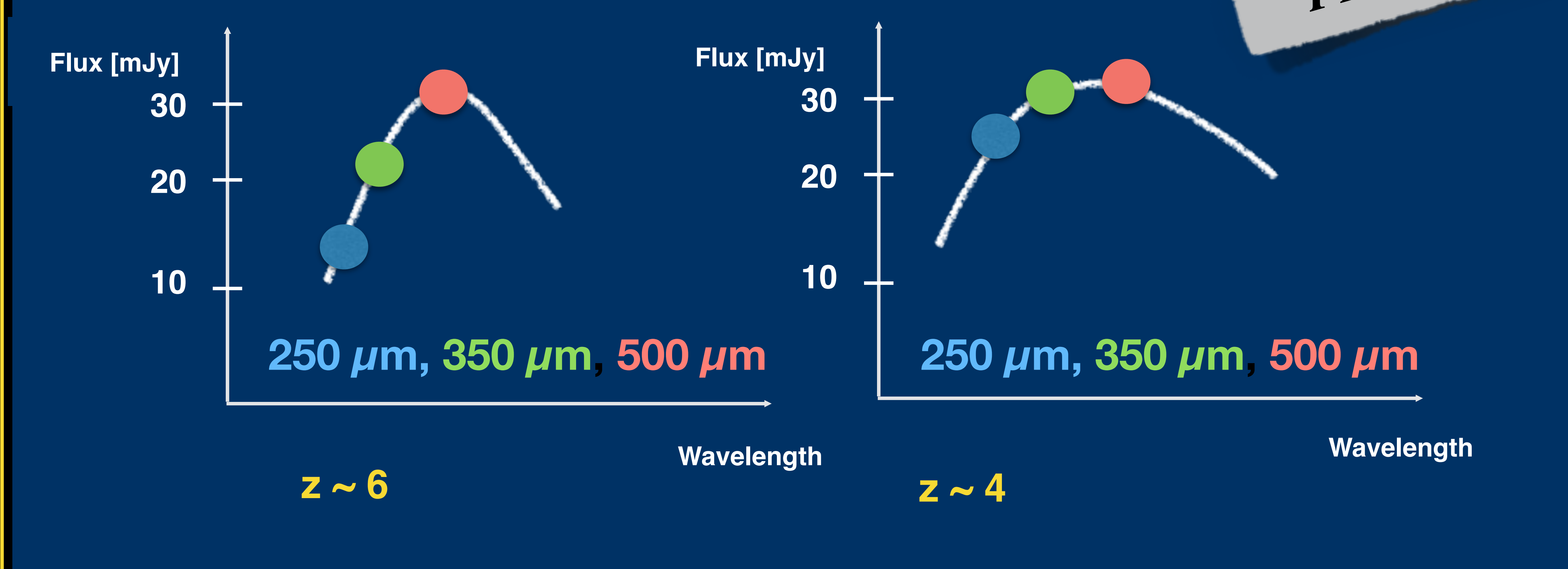
PROBLEM

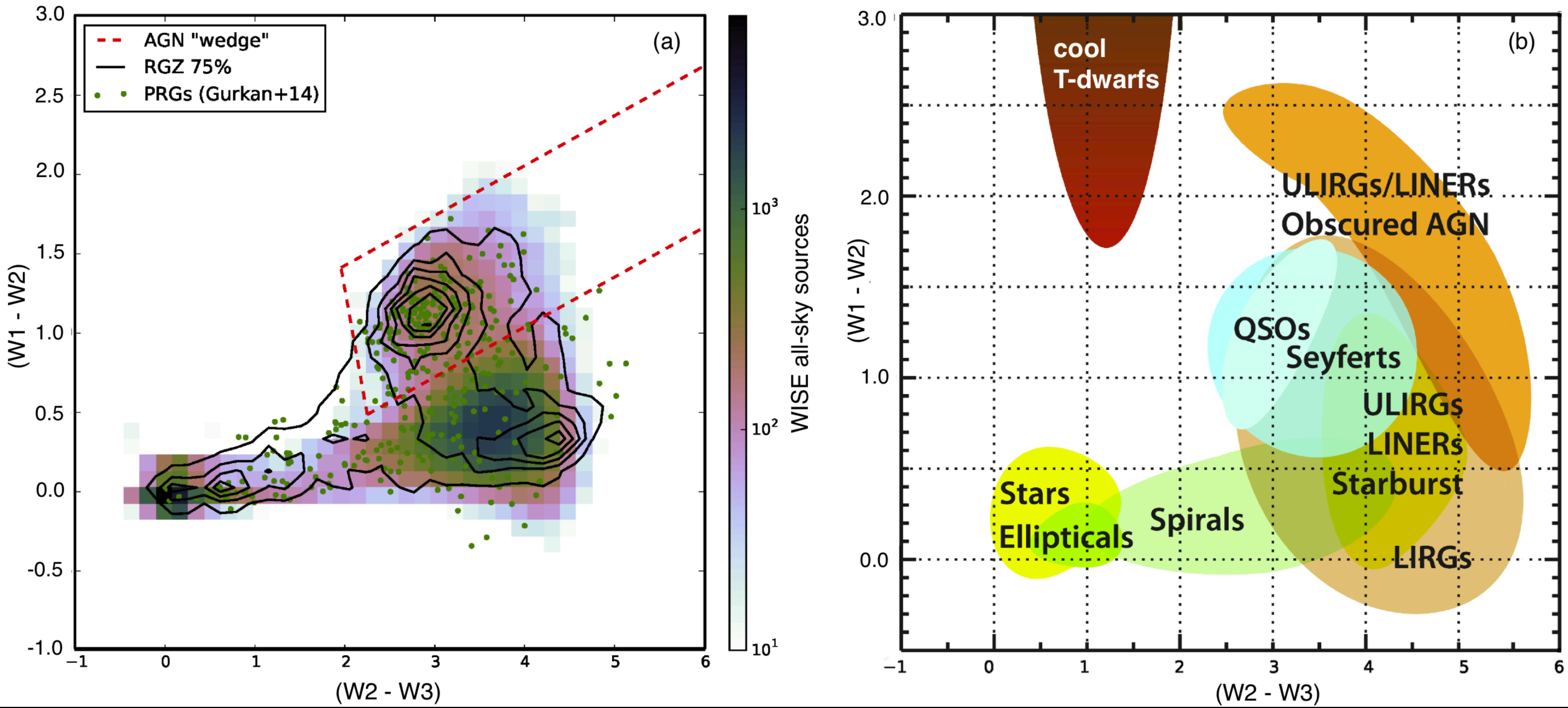
Remember: challenges



Using IR colour technique to select statistical sample of DSFGs at z~4: difficult task due to SED shape.

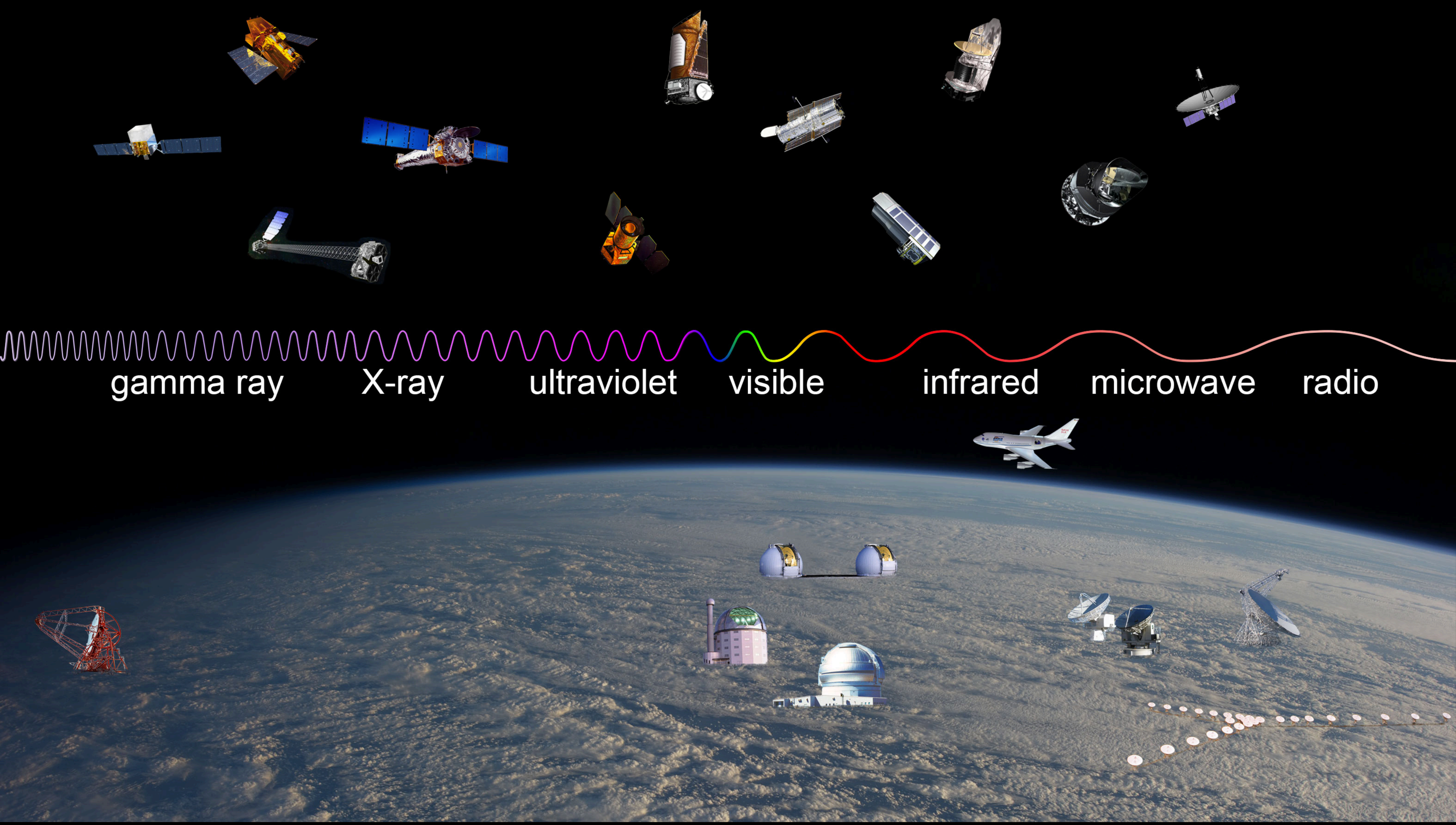
PROBLEM





Selection of galaxies with **W**ide **F**ield **I**nfrared **S**urveryor **(WISE)**

2.3 Selecting the dusty star-forming galaxies



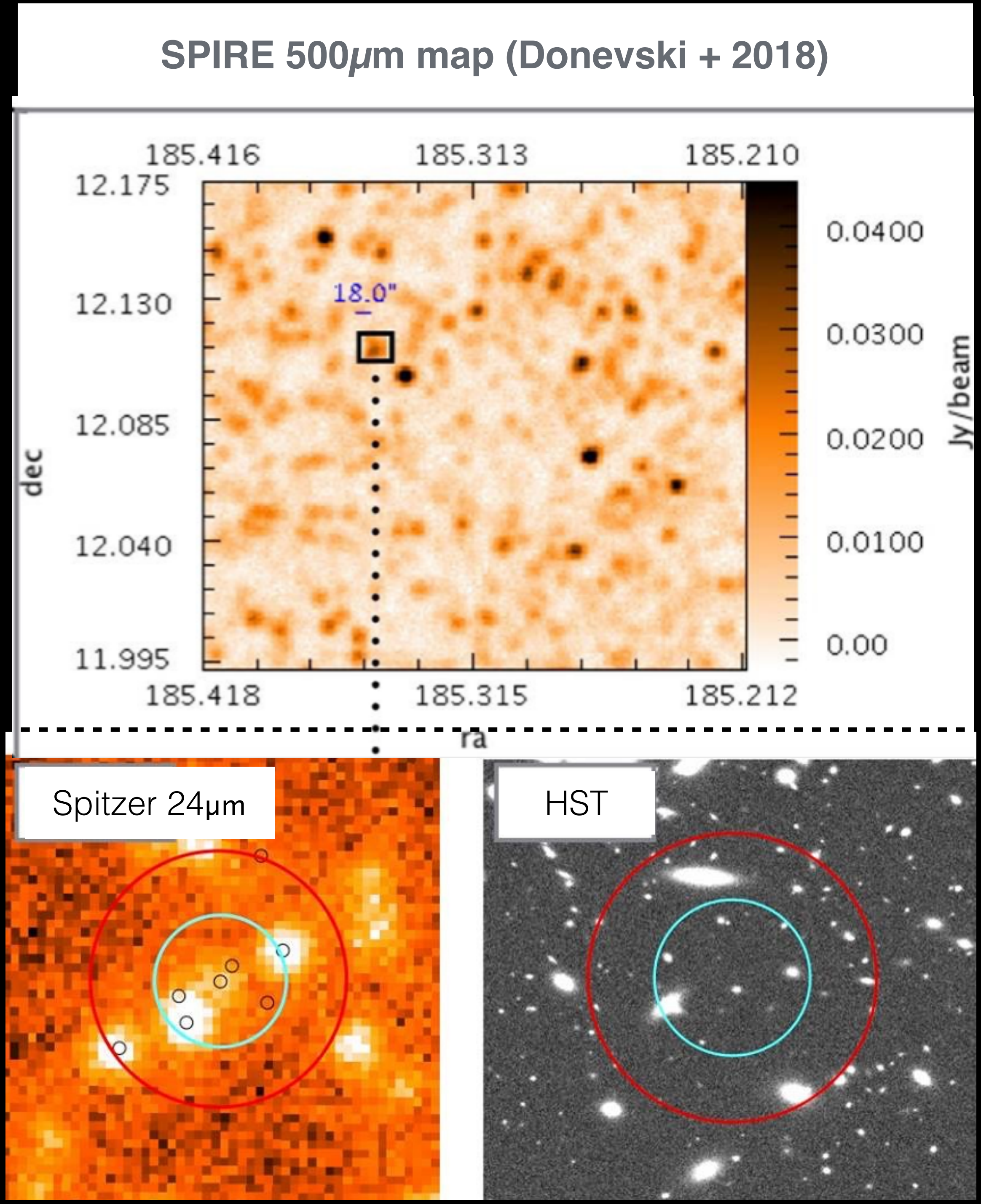
2.3 Selecting the dusty star-forming galaxies

Challenges:

(a) Optical selection ? => No ! Dust obscuration

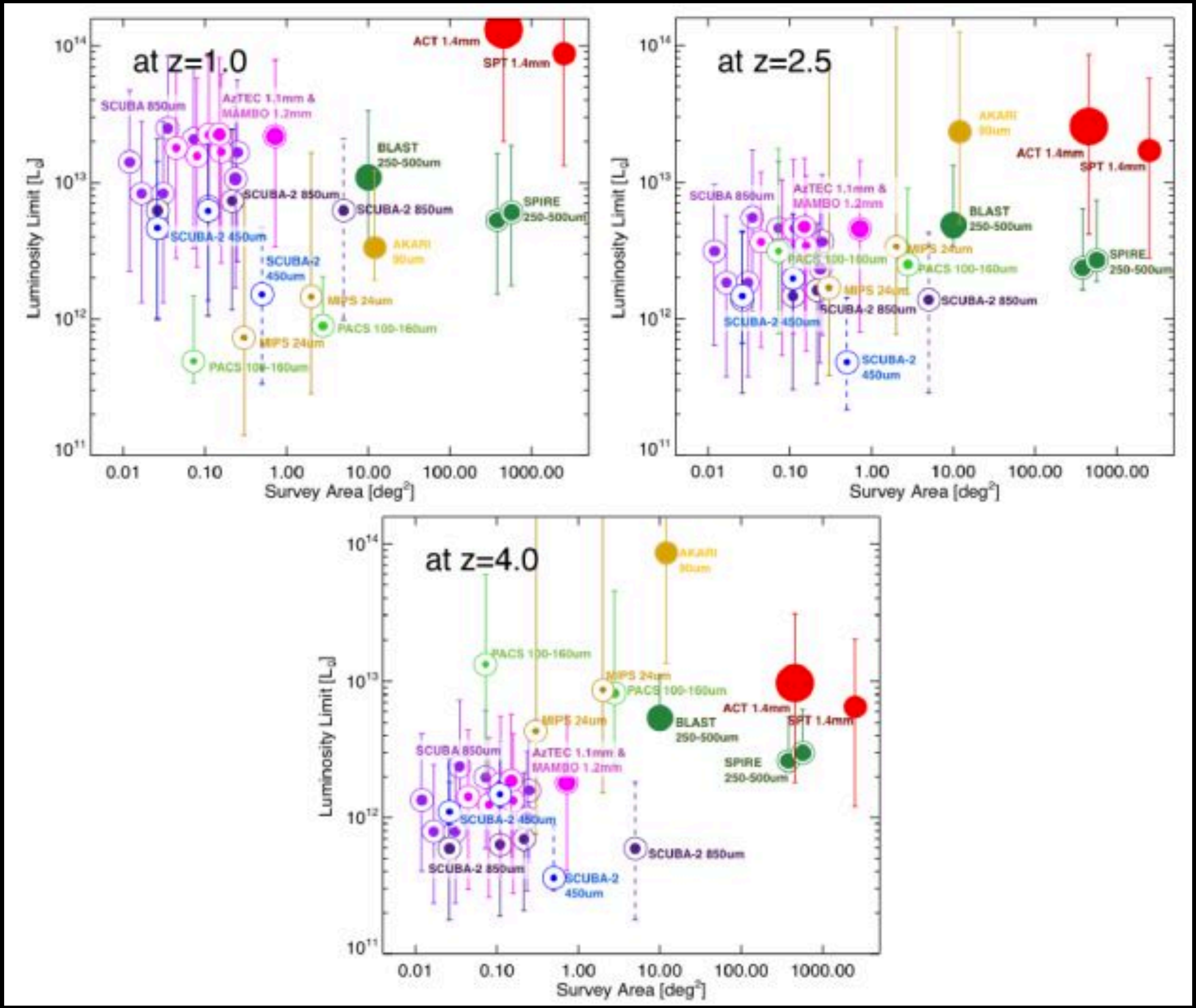
(b) Far-IR selection ? => Yes ! But we need to worry about:

1. Coarse angular resolution of *Herschel* (source confusion / blending).
2. Redshift determination is difficult.
3. Contamination from other bright SPIRE sources (e.g. quasars).
4. Intrinsic variations of SEDs.



SPIRE 250μm beam (18”)
SPIRE 500μm (36”)

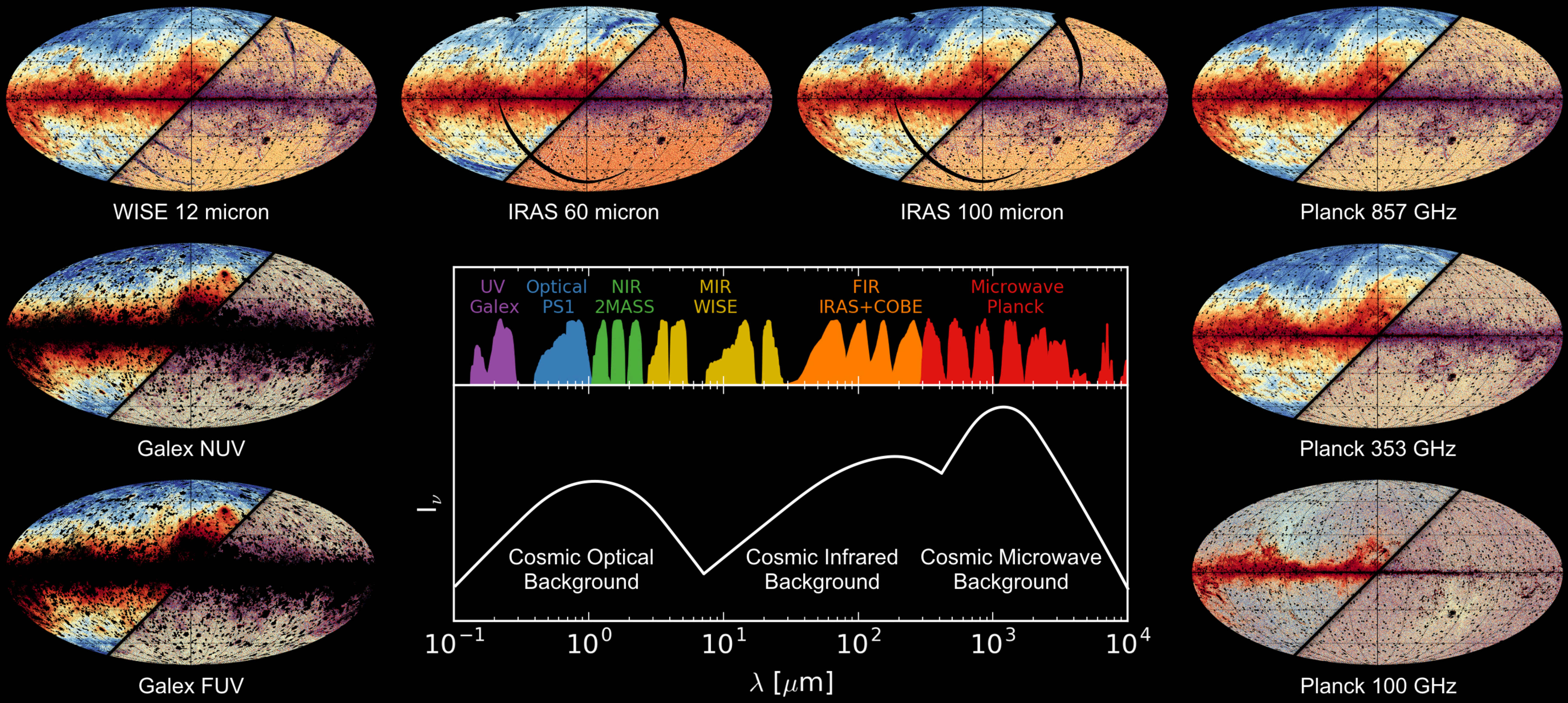
2.3 Infrared Surveys



How to combine observations & simulations ?

Dissecting Extragalactic Background Light

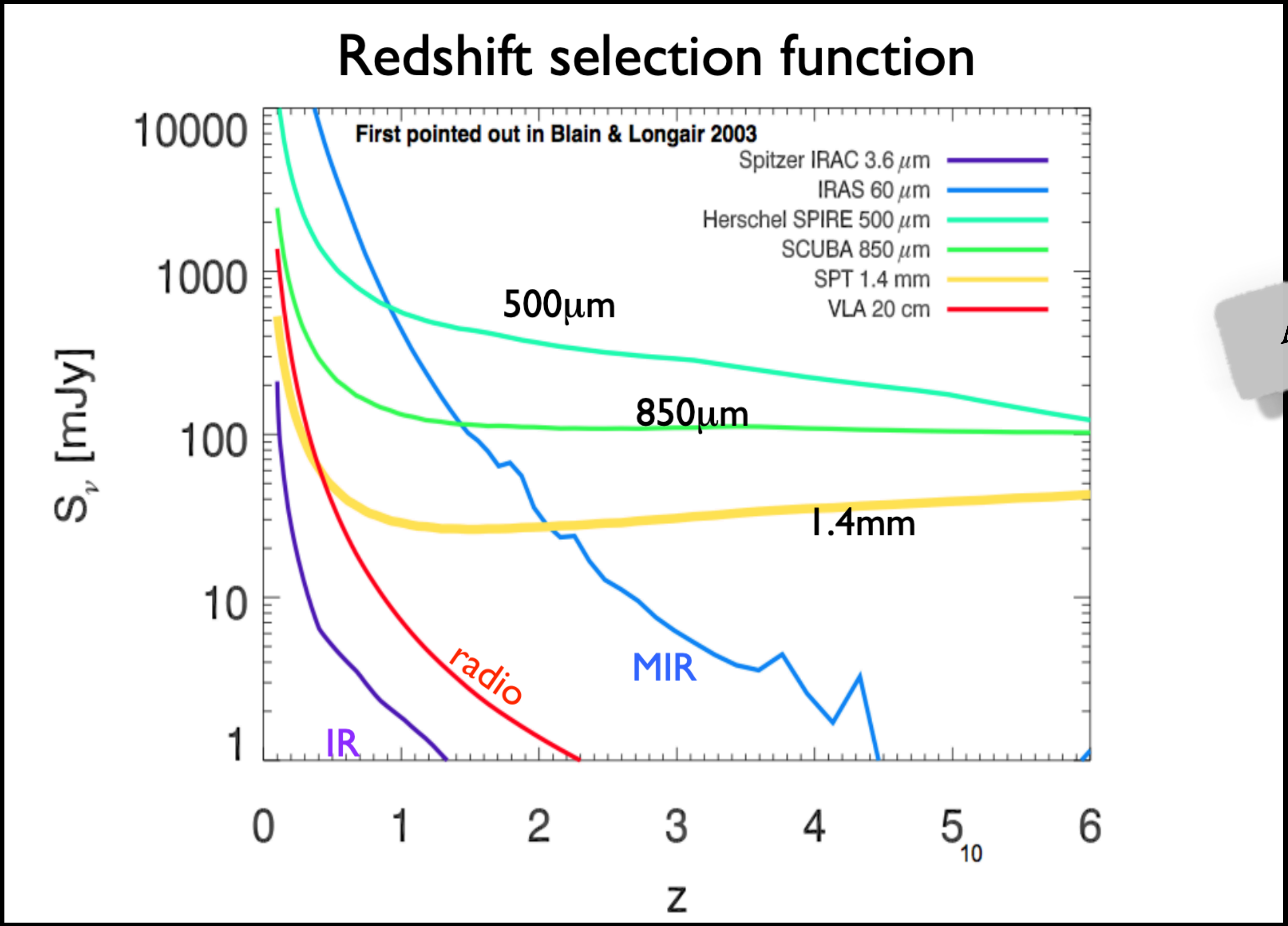
Using spatial cross-correlations to recover the redshift and spectral energy distributions for the total radiation output of galaxy formation



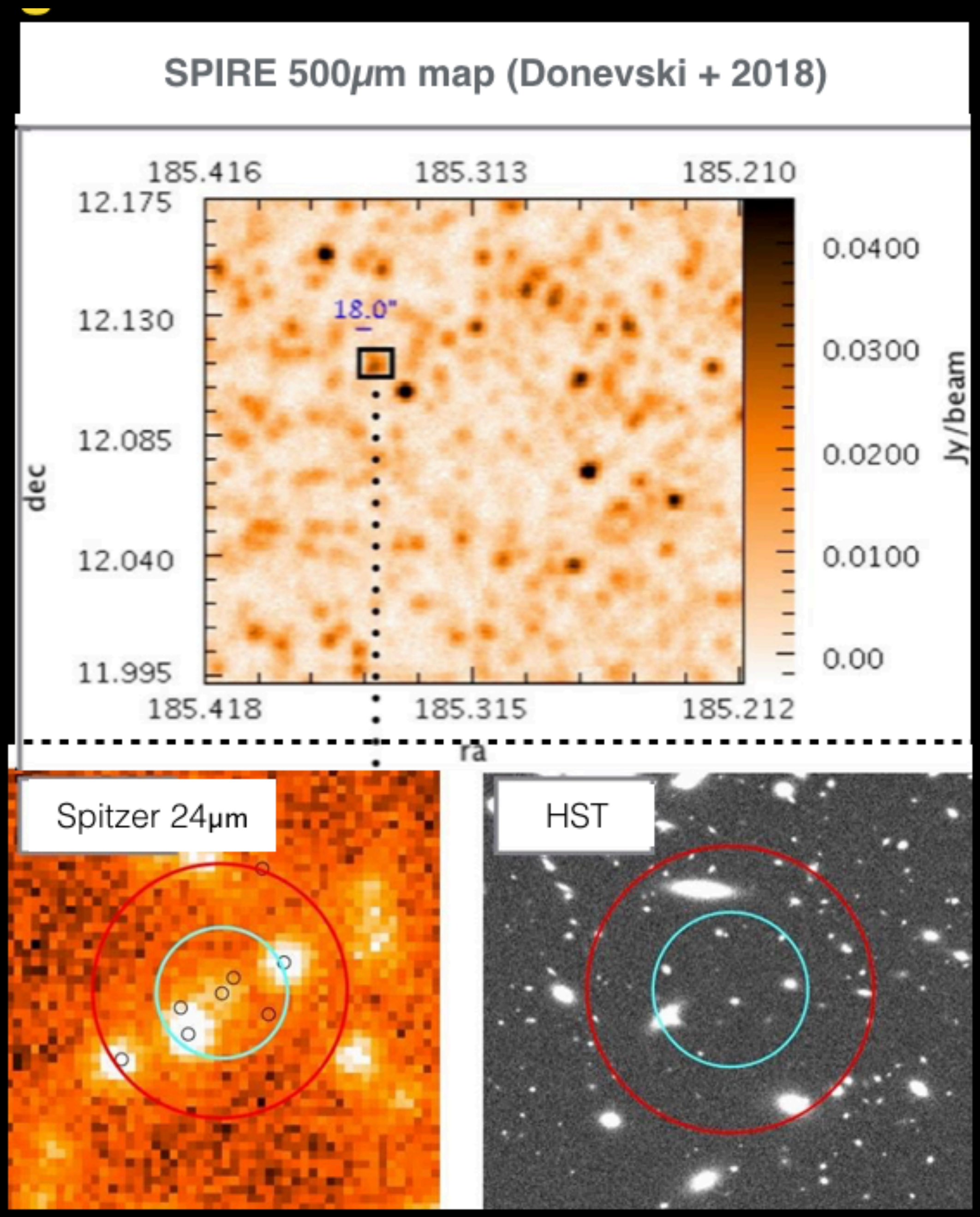
Previous lecture

Negative "K-correction" = flux stays constant even at high-z

$$S_\nu(z) \propto \nu^{2+\beta}/4\pi D_L^2 \propto \nu_{rest}^{2+\beta}(1+z)^{2+\beta}/(1+z)^4 \propto (1+z)^{\beta-2}.$$



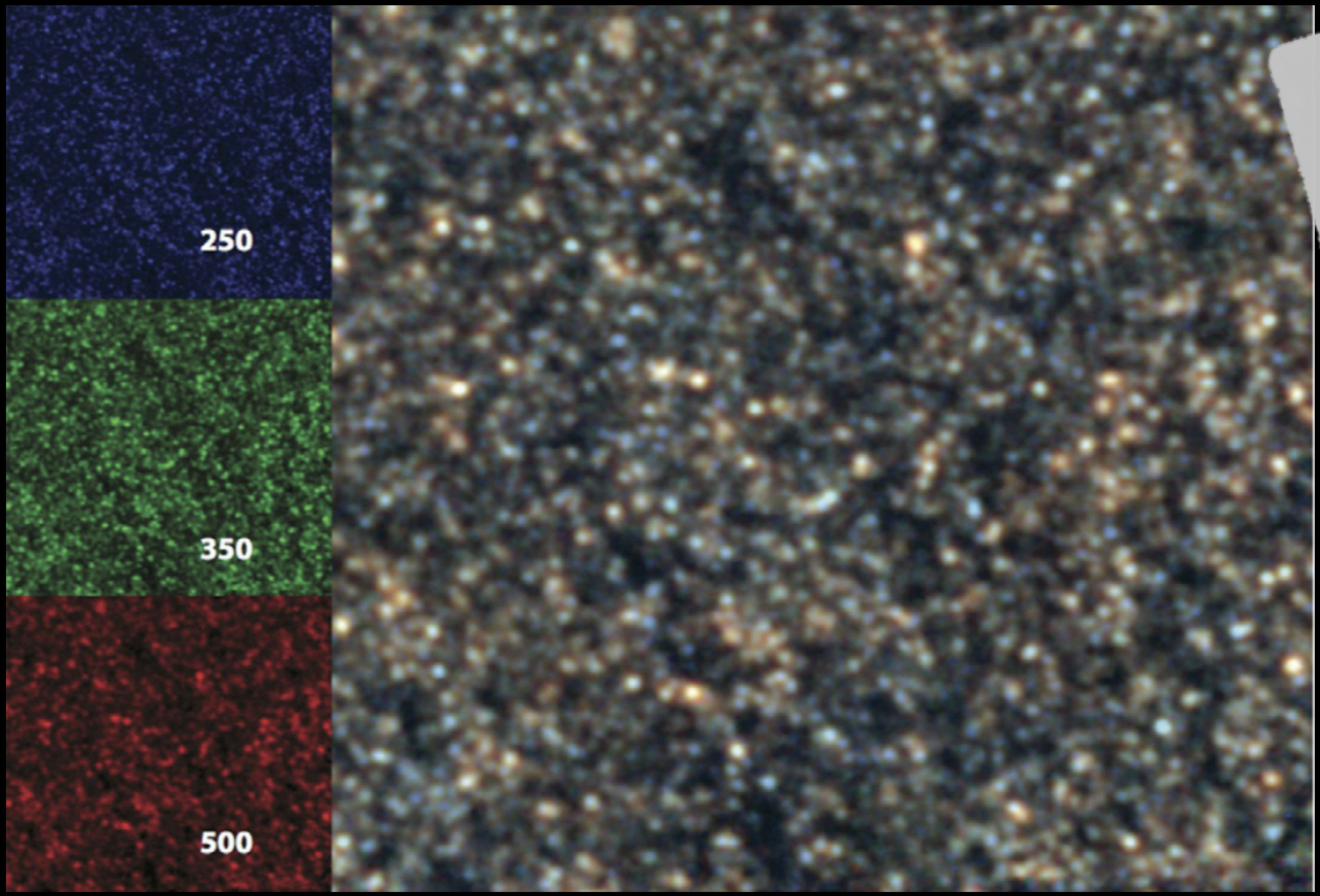
Previous lecture



SPIRE 250μm beam (18”)
SPIRE 500μm (36”)

(A) Source extraction and photometry

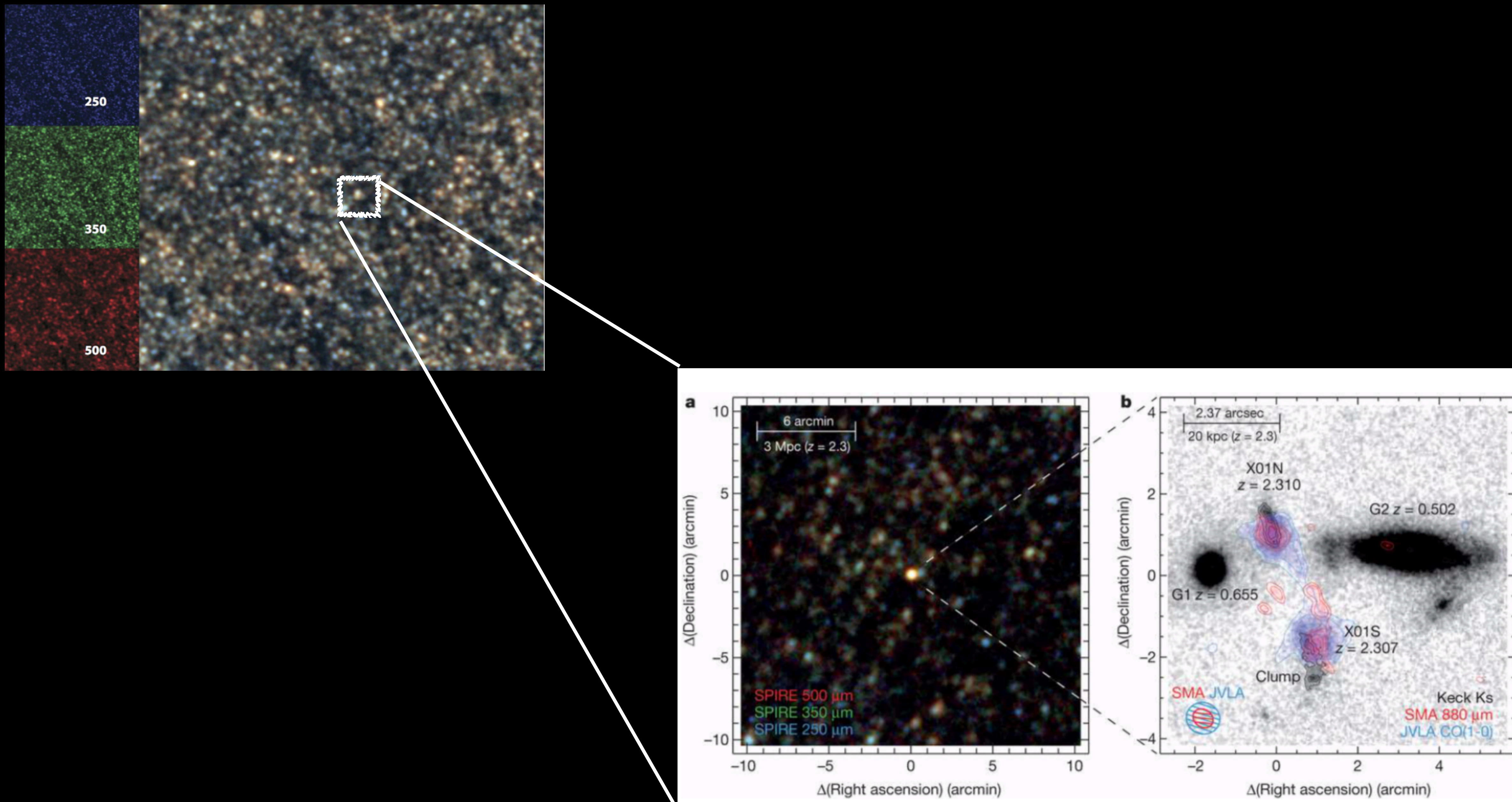
3. From observations to galaxy evolution



ADVANTAGE
&
PROBLEM

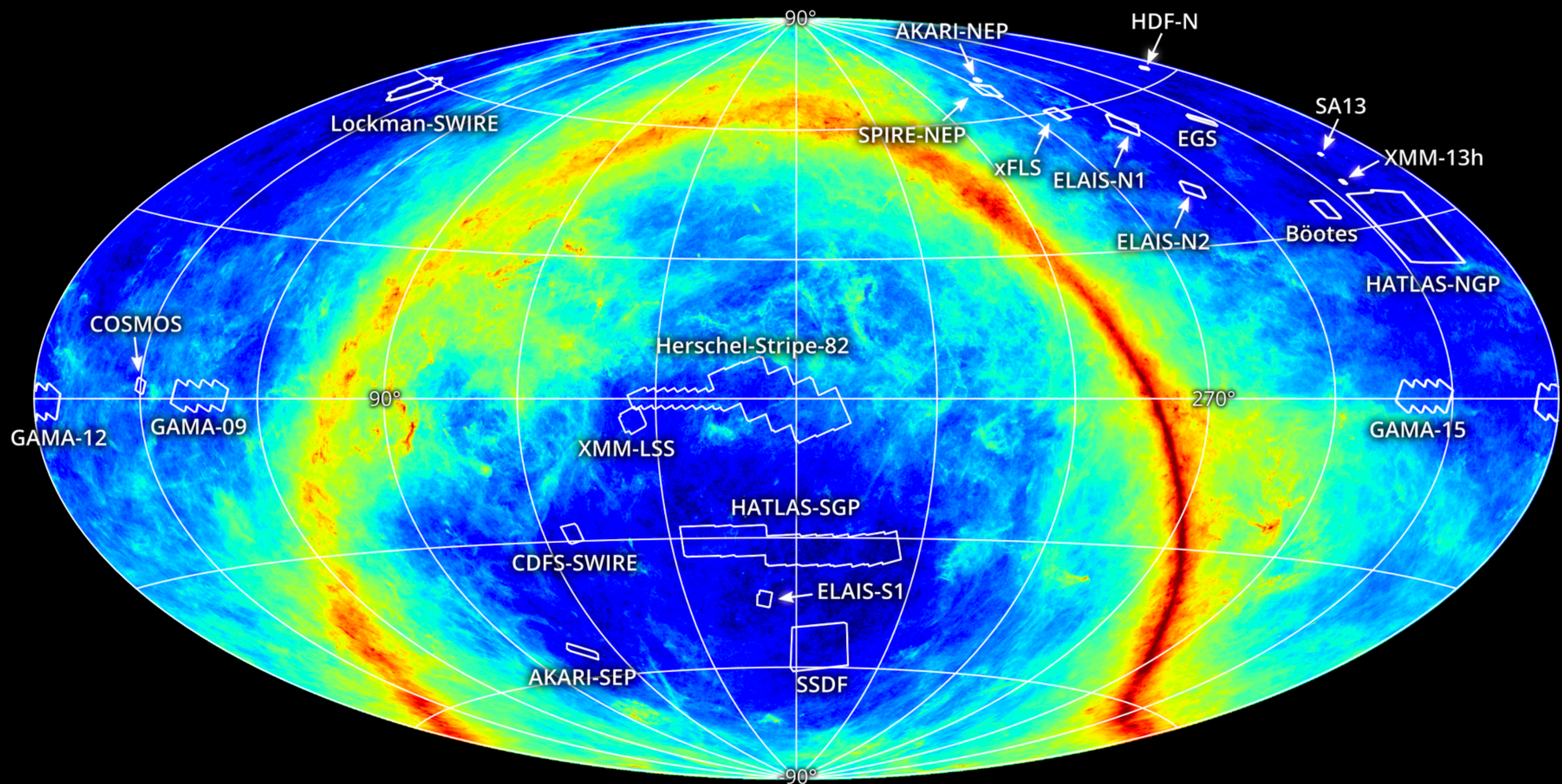
Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

2.3 Selecting the dusty star-forming galaxies: challenges



Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

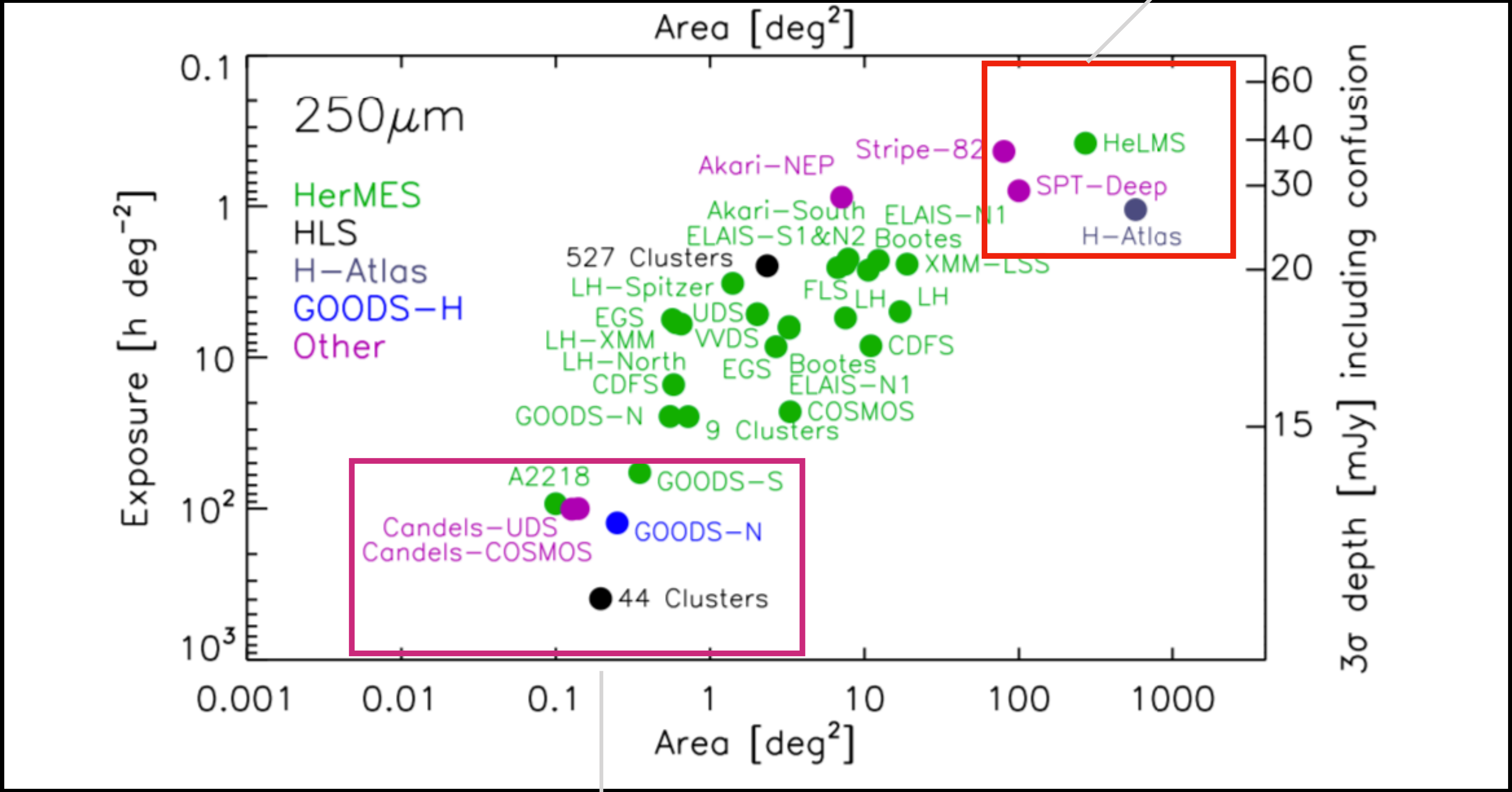
Large extragalactic surveys



SPT (mm) and Herschel (FIR) observed more than 1000 sq.degrees of the sky

2.3 Infrared Surveys

Large, but shallow

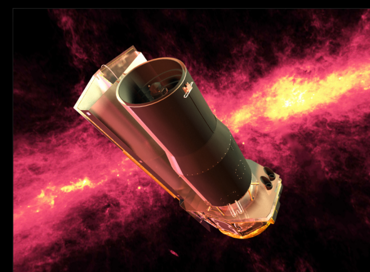


Small, but deep

2.3 Selecting the dusty star-forming galaxies

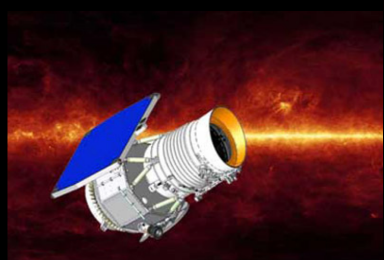
- **Space-based**

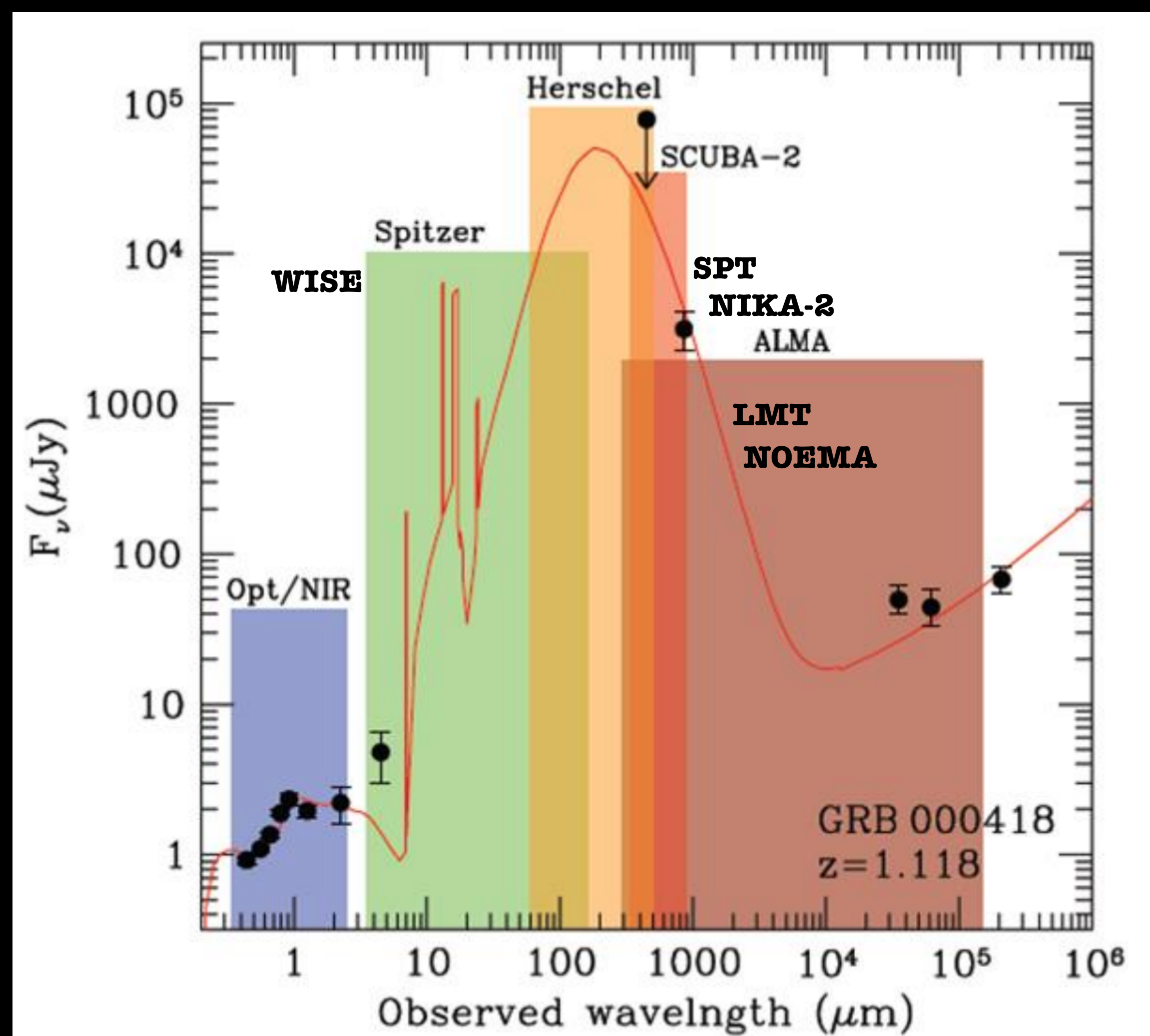
Spitzer



Herschel

WISE





(Savaglio et al. 2012)

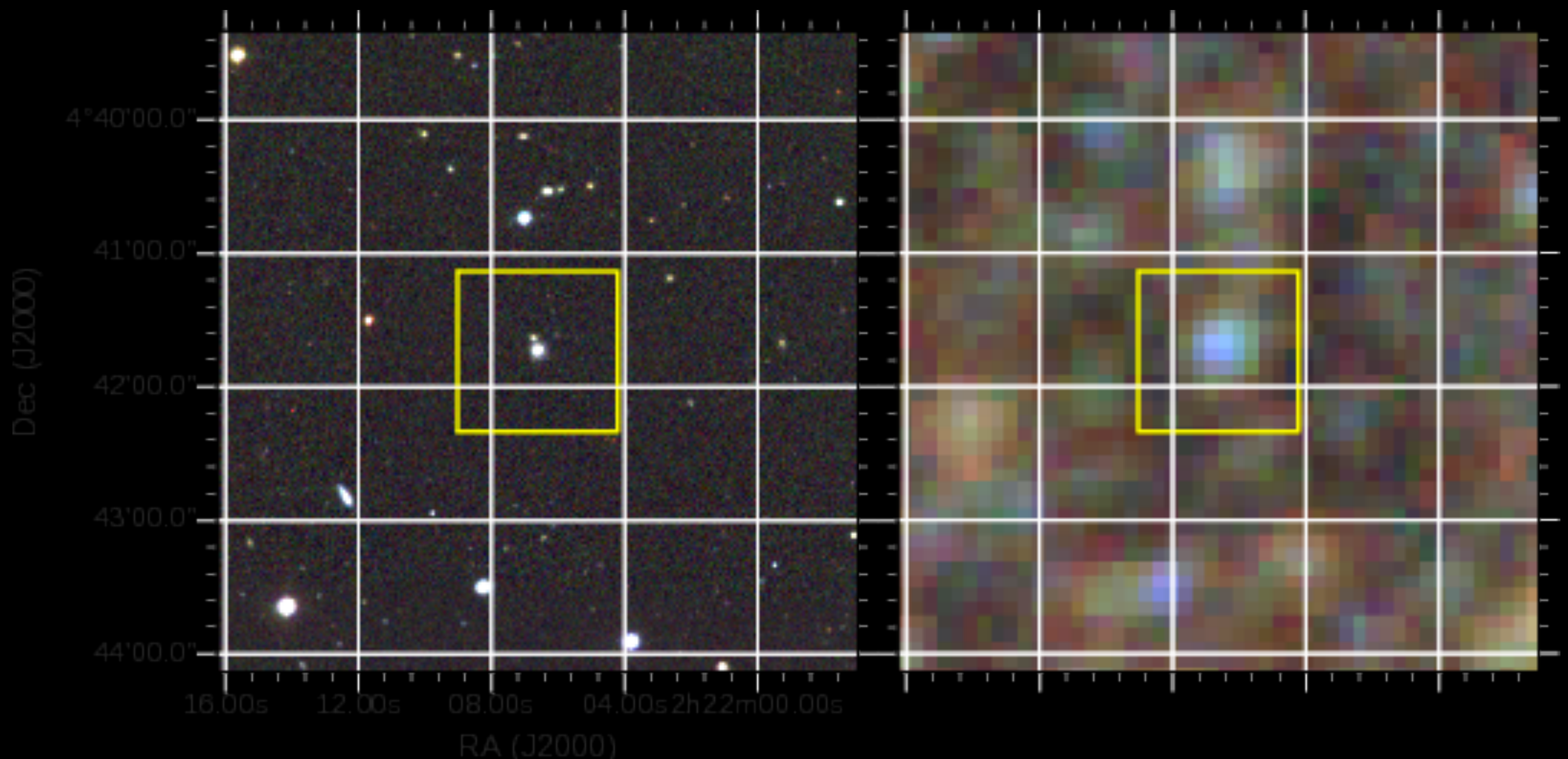
- **Ground-based**

SCUBA-2

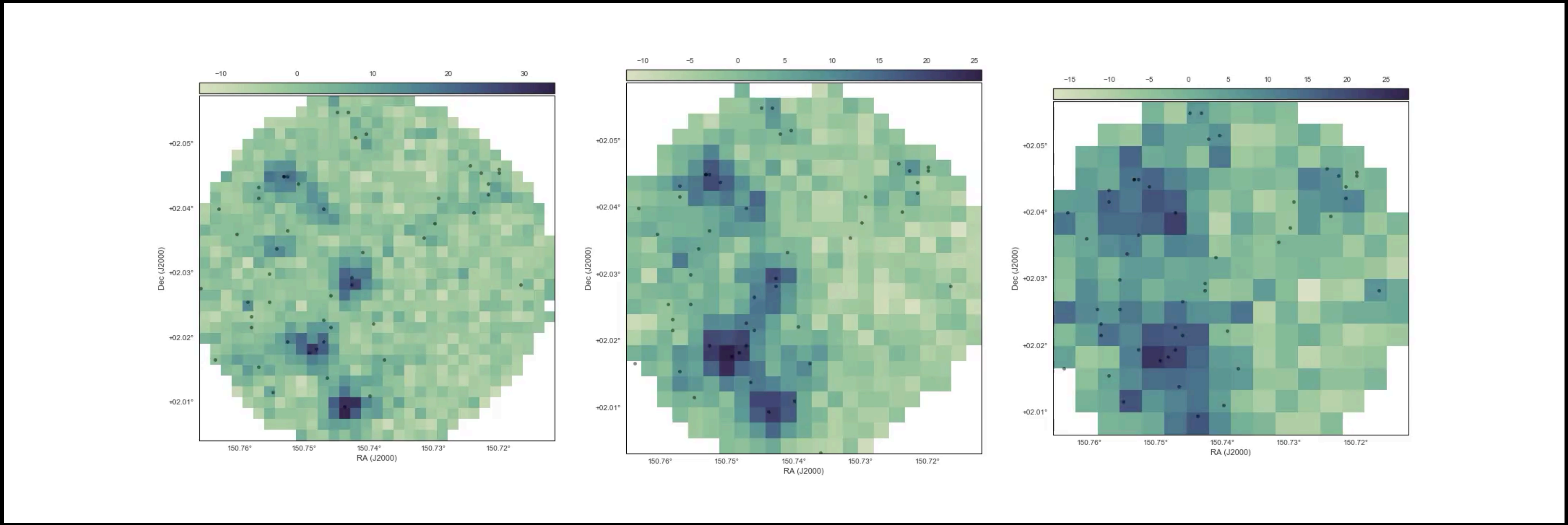
SPT

ALMA

3. From observations to galaxy evolution

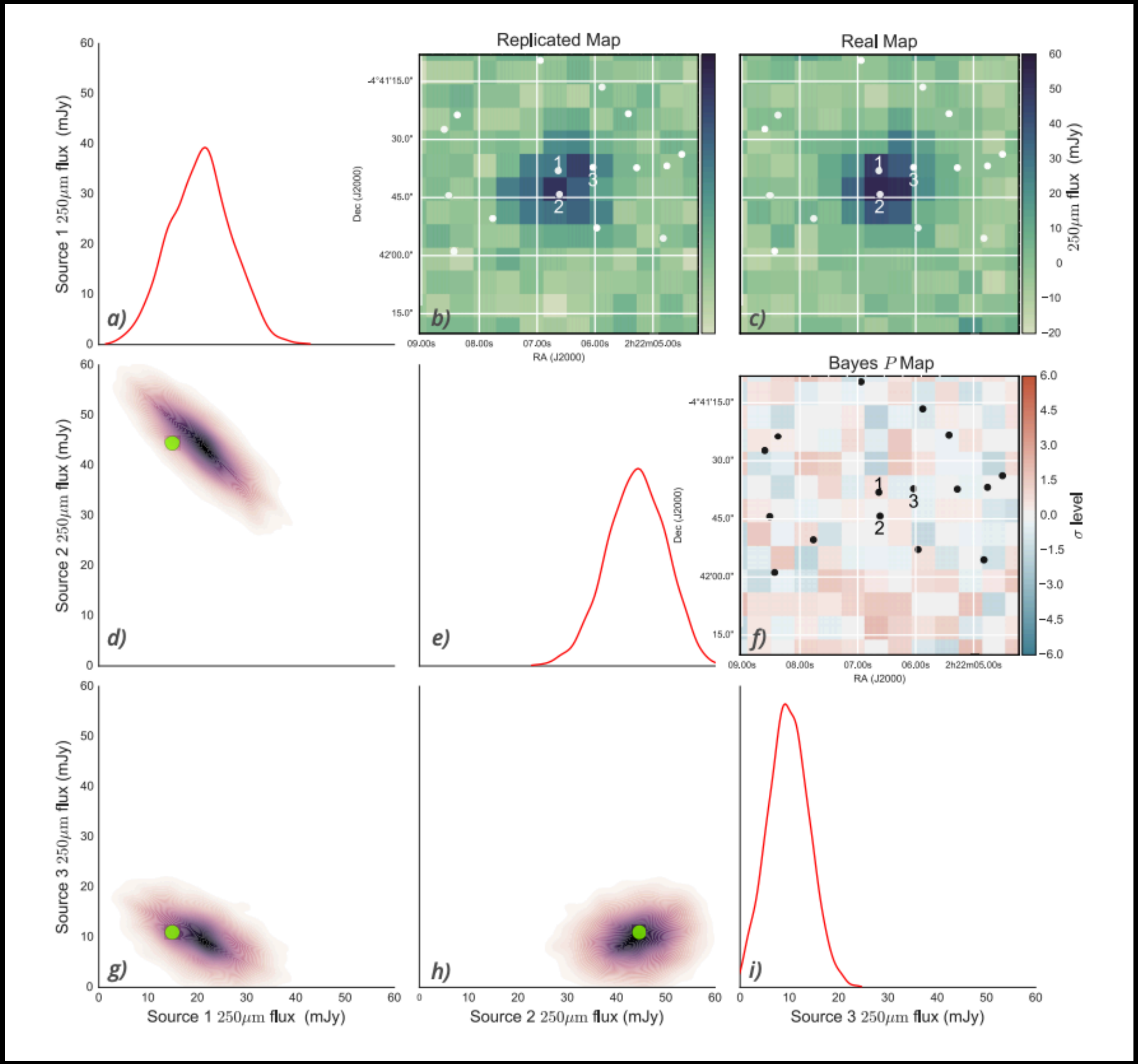


3. From observations to galaxy evolution



Source de-blending techniques

(i.e. Hurley et al. 2018; Liu et al. 2018; Donevski et al. 2018)

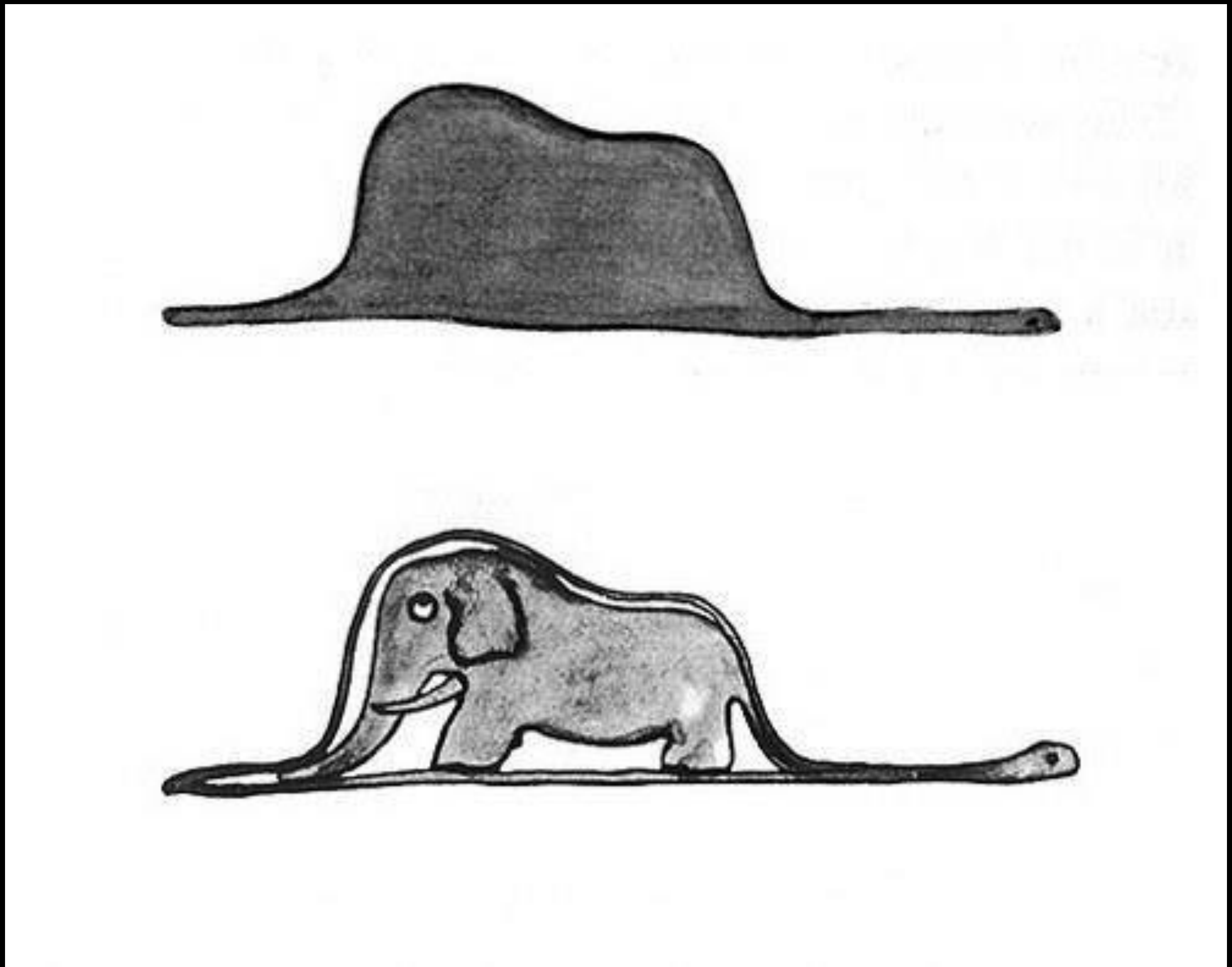


Source de-blending techniques

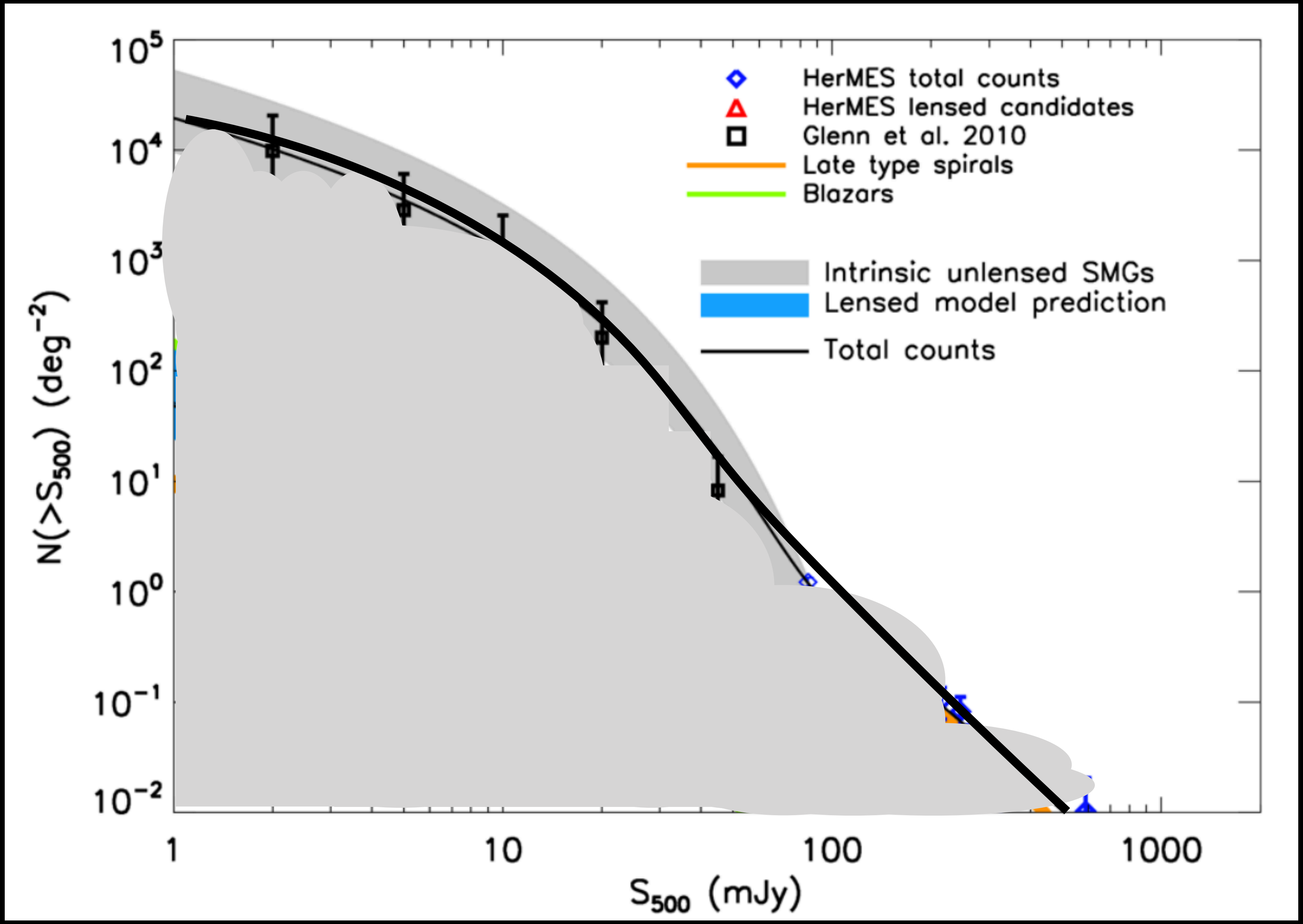
(i.e. Hurley et al. 2018; Liu et al. 2018; Donevski et al. 2018)

(B) Understanding the selected statistics

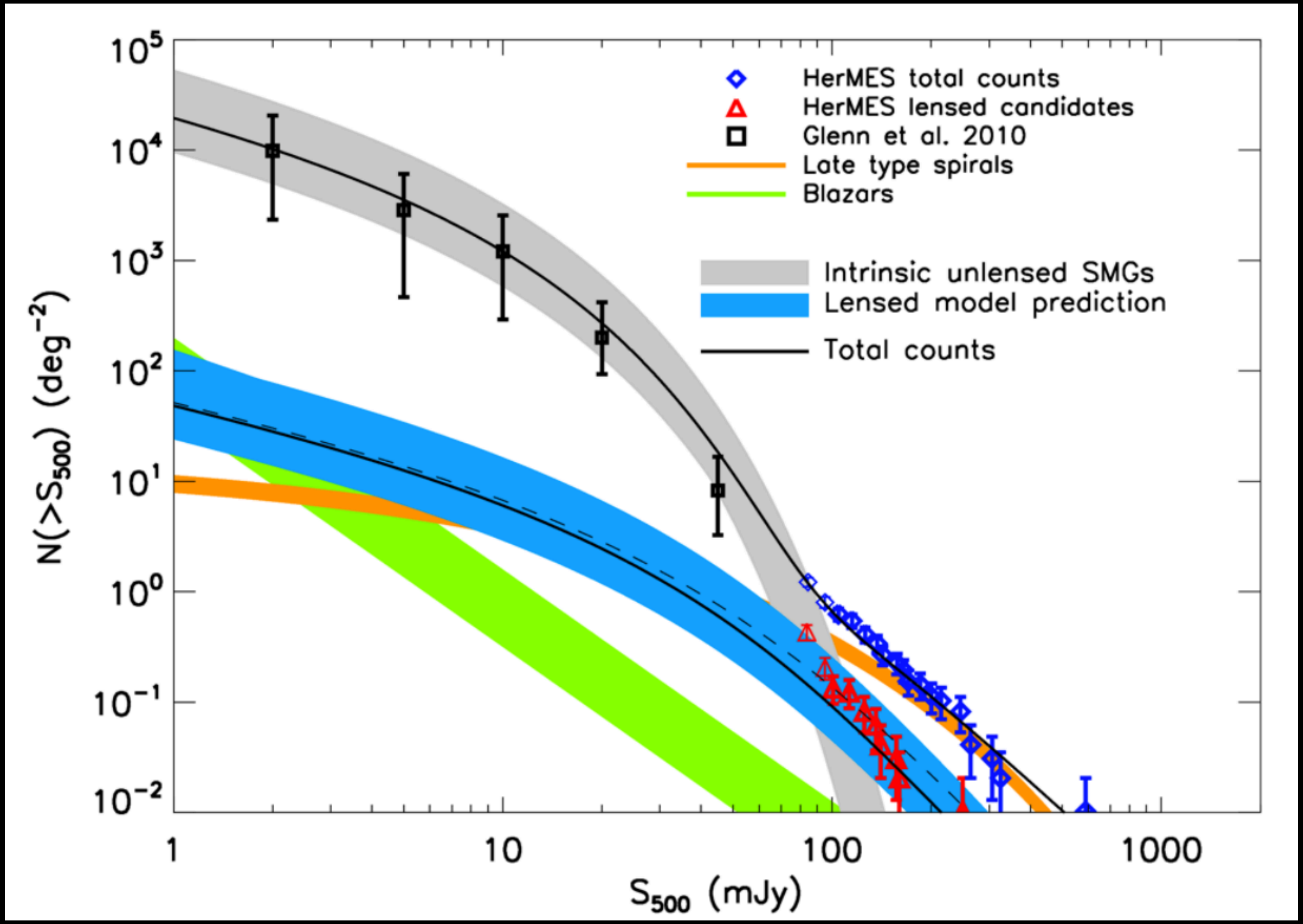
3. From observations to galaxy evolution



3. From observations to galaxy evolution: how to understand observed number of galaxies ?



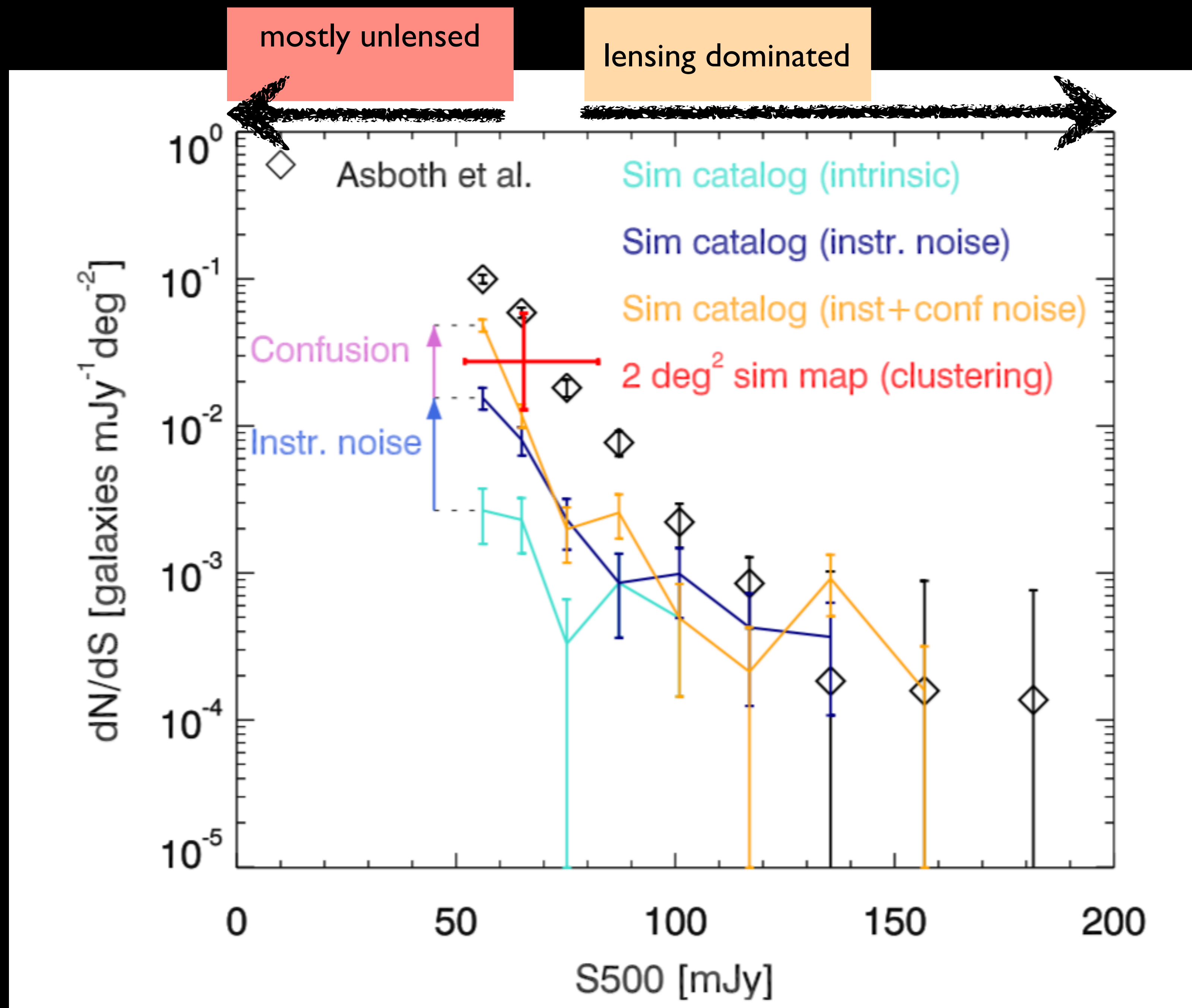
3. From observations to galaxy evolution: how to understand observed number of galaxies ?



Number counts

(i.e. Wardlow et al. 2013)

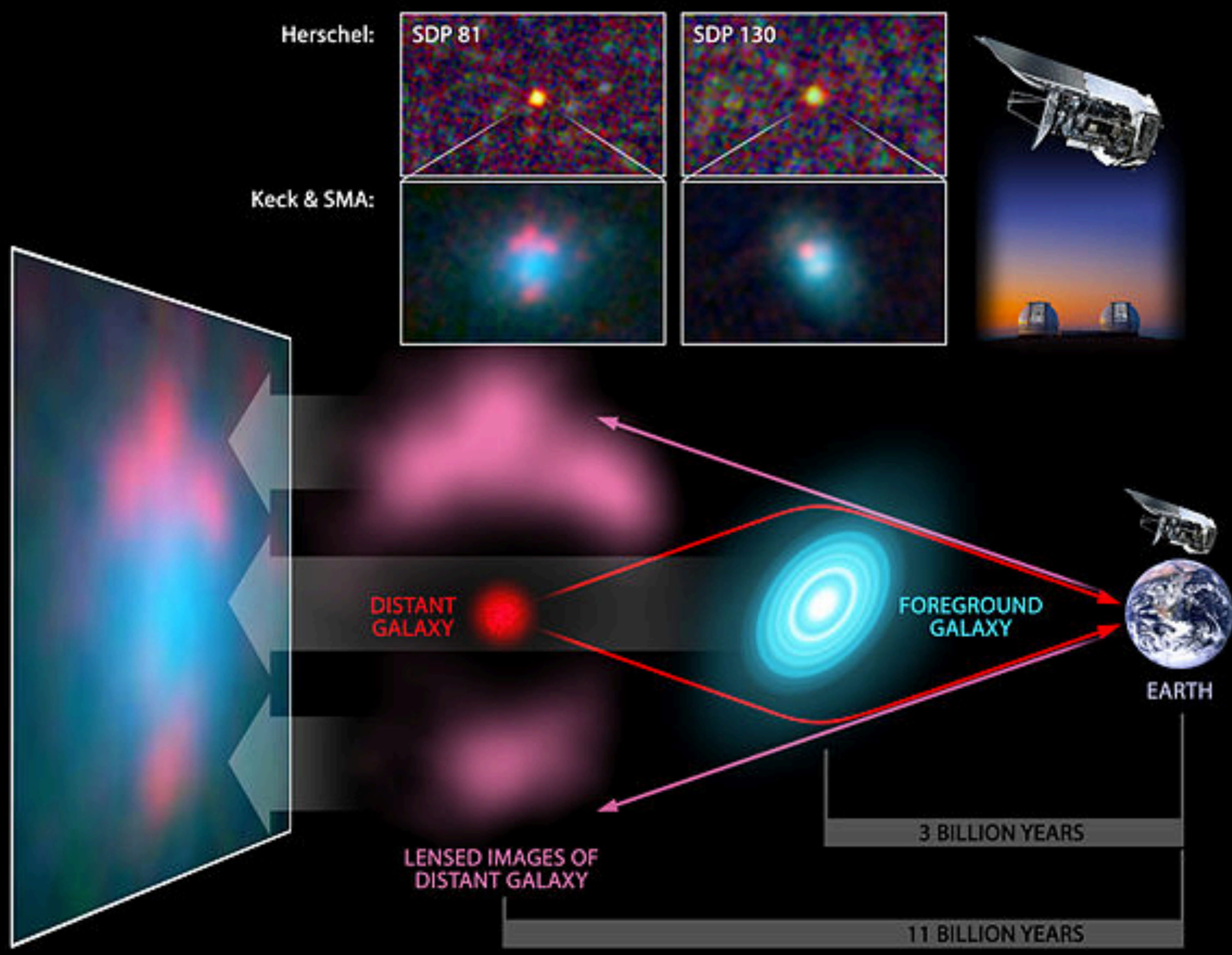
3. From observations to galaxy evolution: how to understand observed number of galaxies ?



Number counts vs. Simulations !

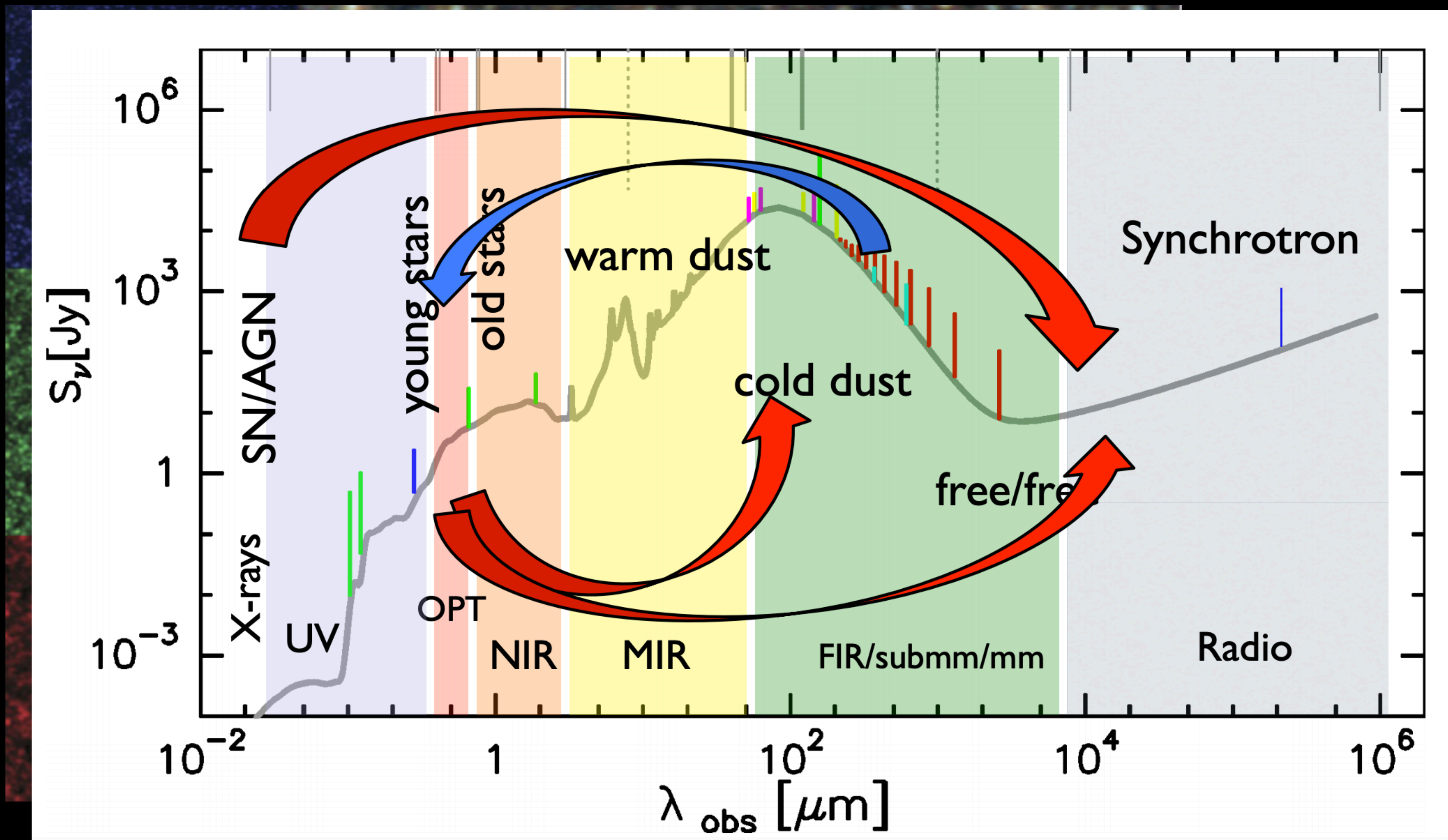
(i.e. Bethermin et al. 2017; Donevski et al. 2018;)

3. From observations to galaxy evolution



(C) What is the nature of star-forming galaxies ?

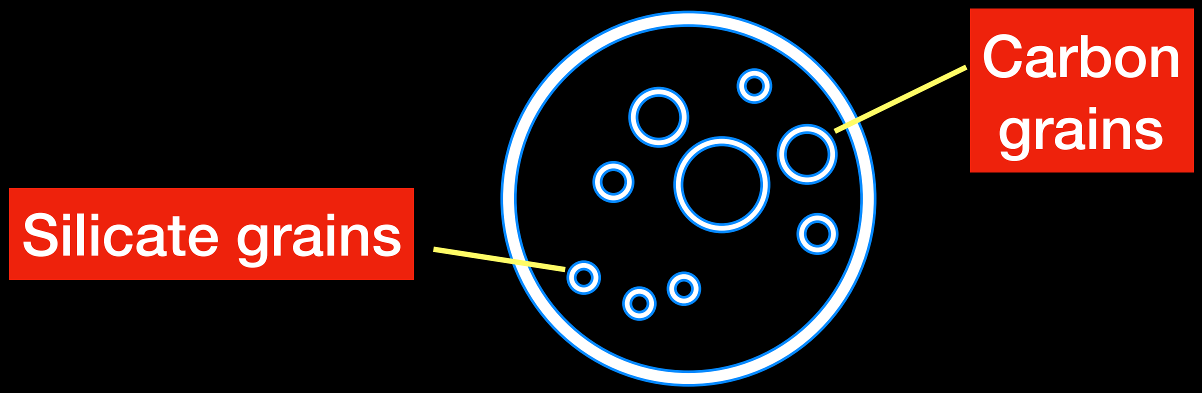
3. From observations to galaxy evolution



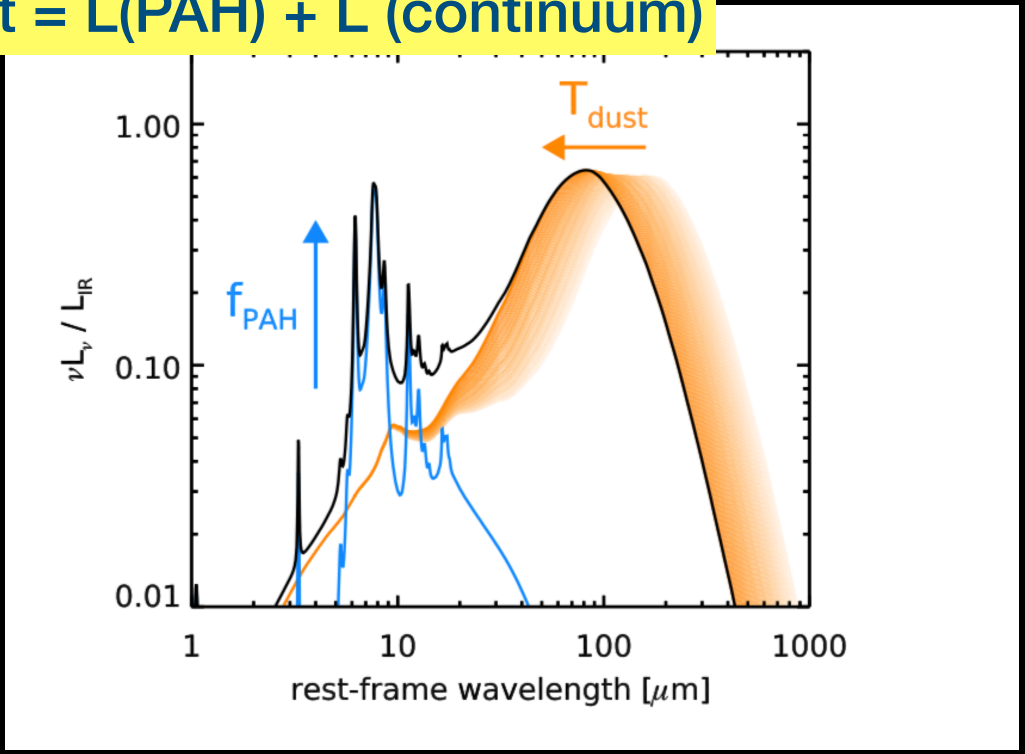
Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

3. Important results and challenges: cosmic star formation density

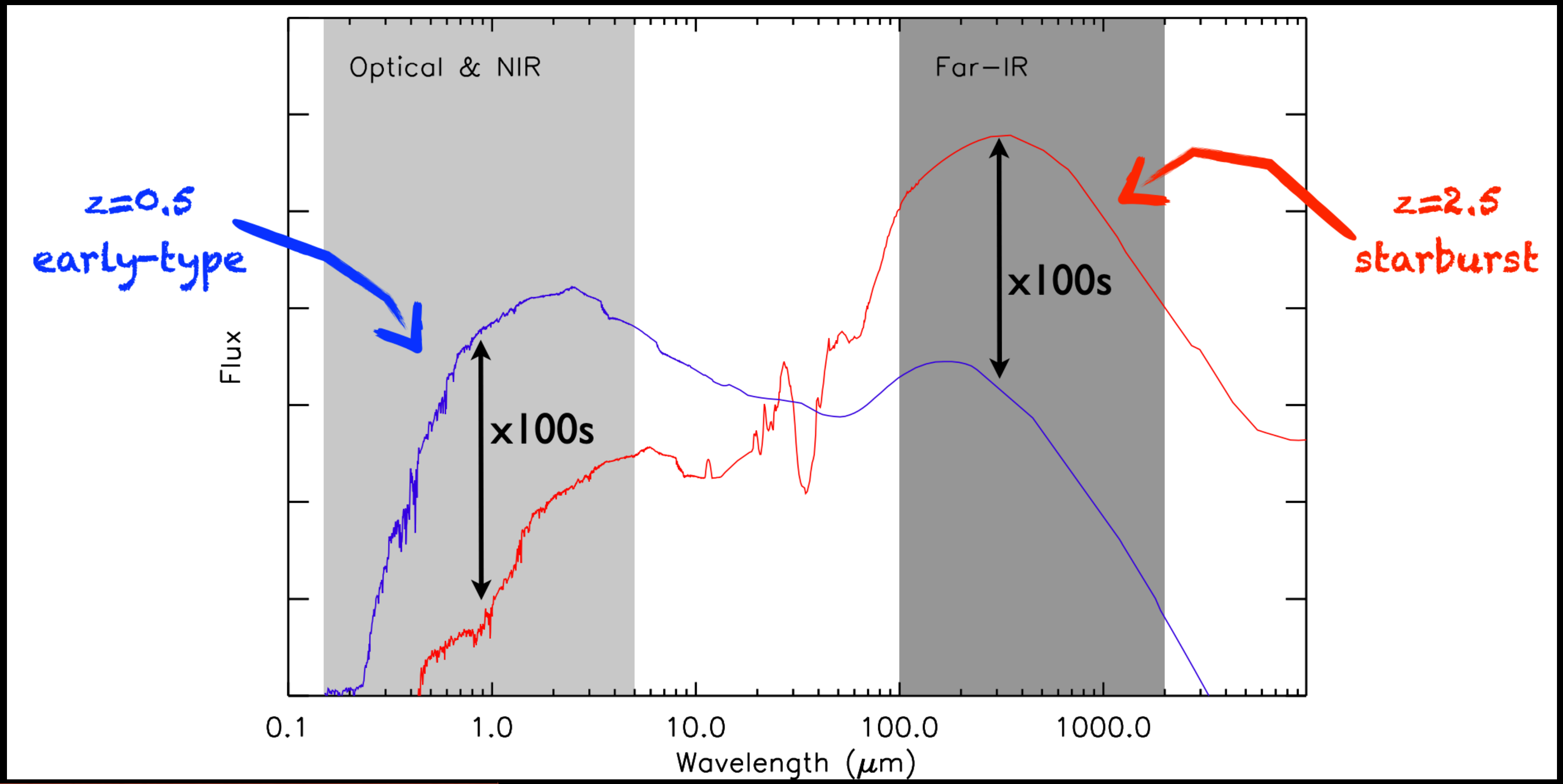
Interstellar Radiation = Diffuse ISM + PDR



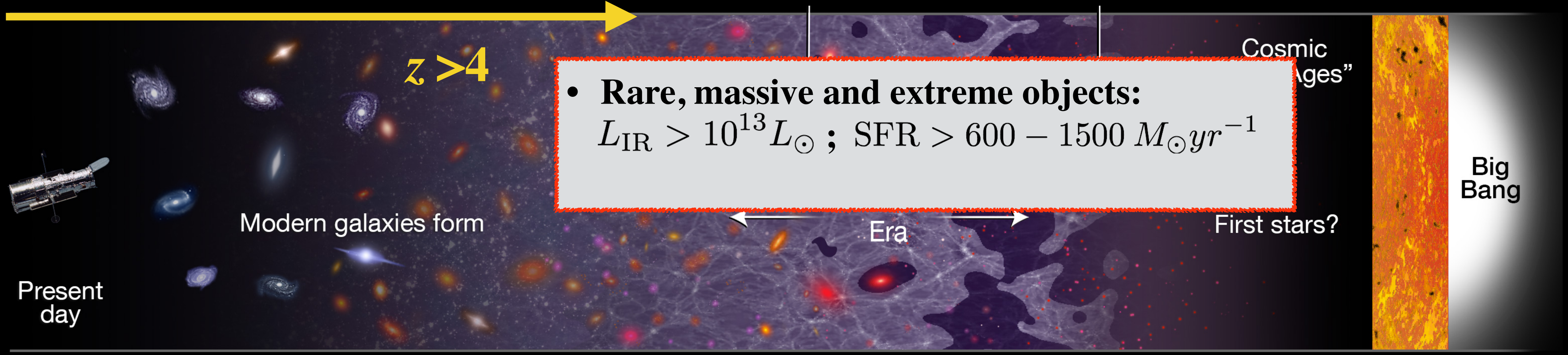
Ldust = L(PAH) + L (continuum)



Modelling dusty SED



1.5 Selecting the candidate DSFGs at z > 4

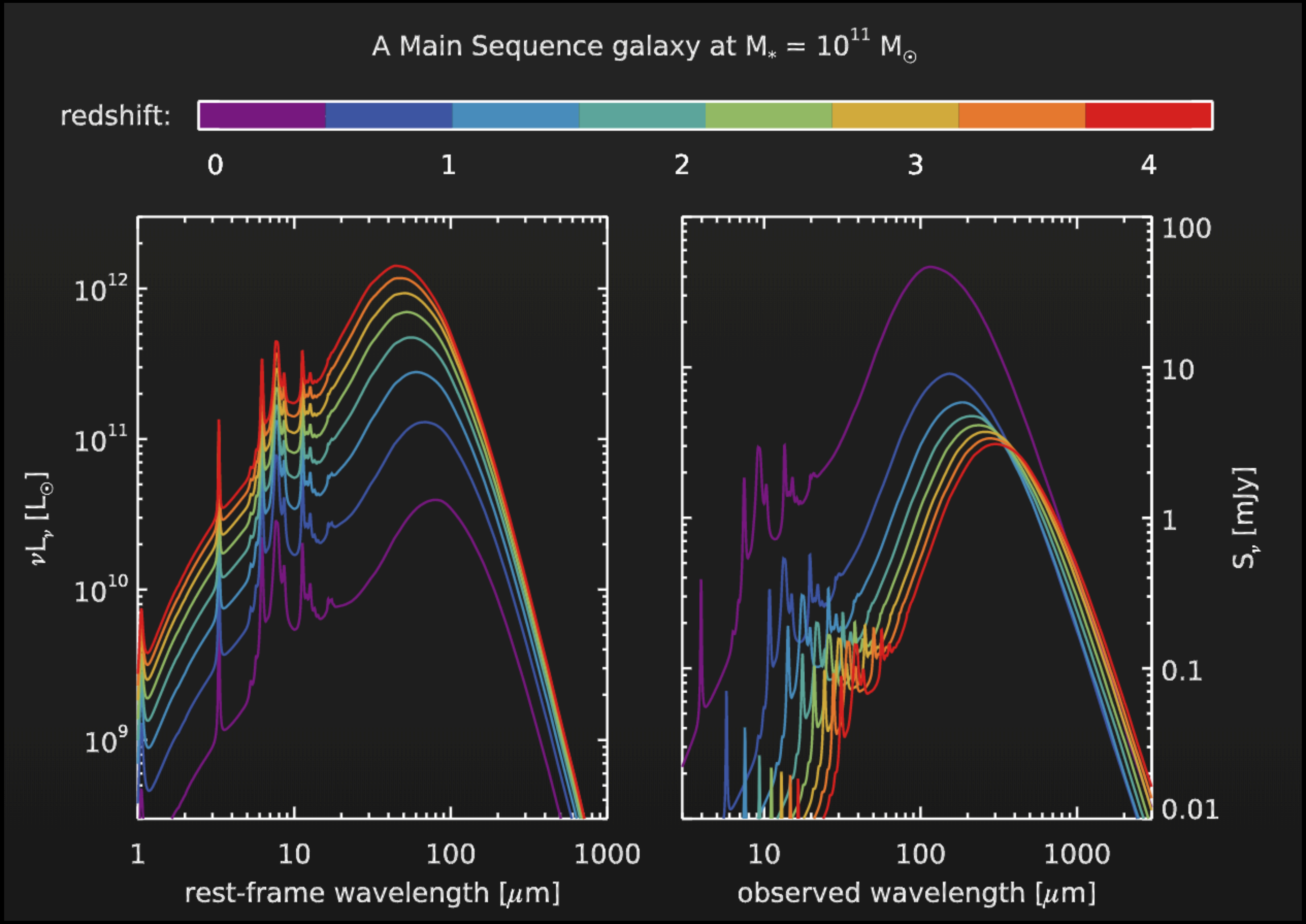


- **Rare, massive and extreme objects:**
  $L_{\rm IR} > 10^{13} L_\odot$; $\rm SFR > 600 - 1500\ M_\odot yr^{-1}$

Riechers et al. 2017

- 250 μm
- 350 μm
- 500 μm

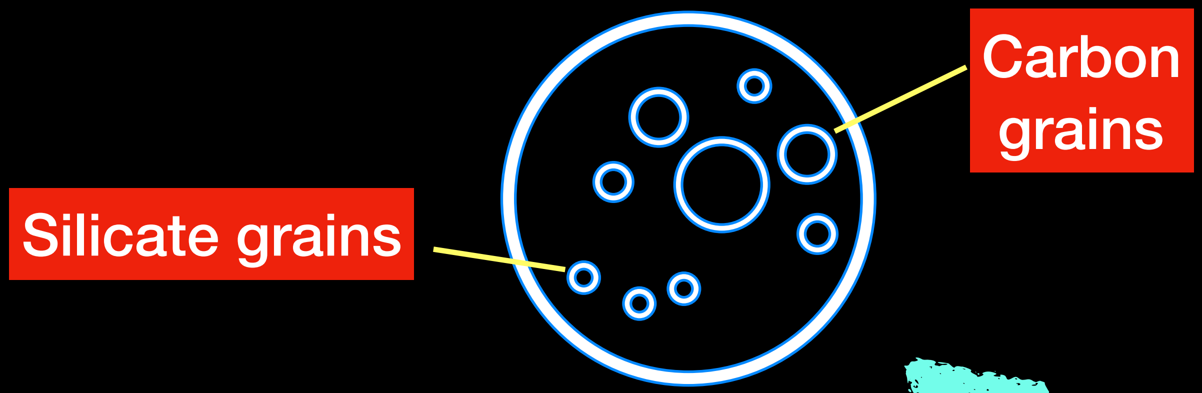
3. From observations to galaxy evolution



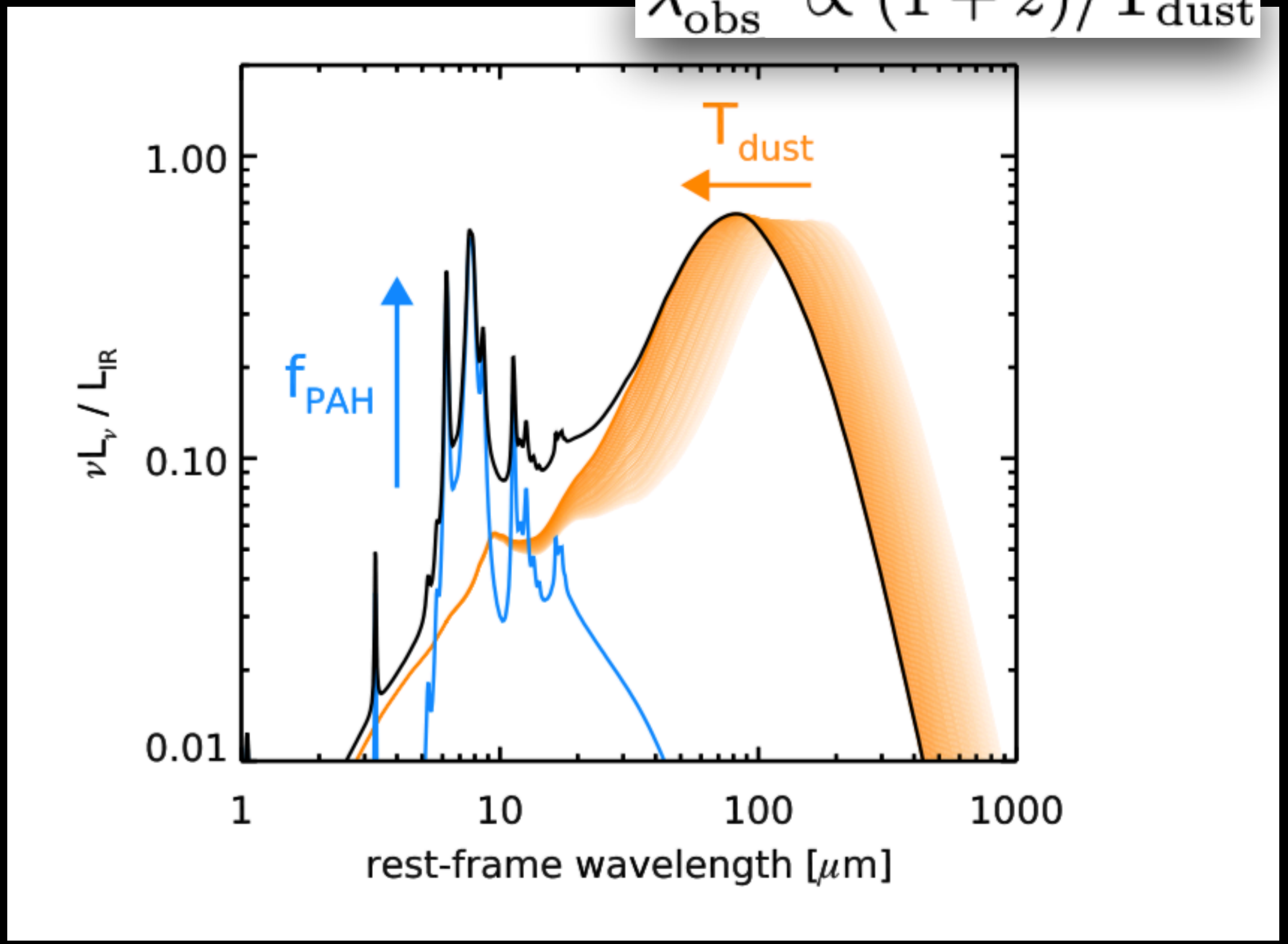
Confusion and sensitivity problem = need to constrain models of galaxy formation and evolution

3. Important results and challenges: cosmic star formation density

Interstellar Radiation = Diffuse ISM + PDR



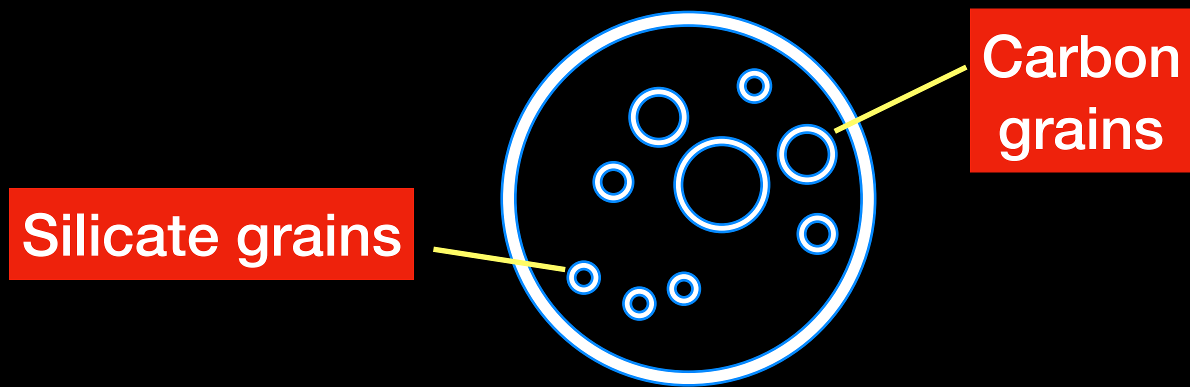
$$\lambda_{obs}^{max} \propto (1+z)/T_{dust}$$



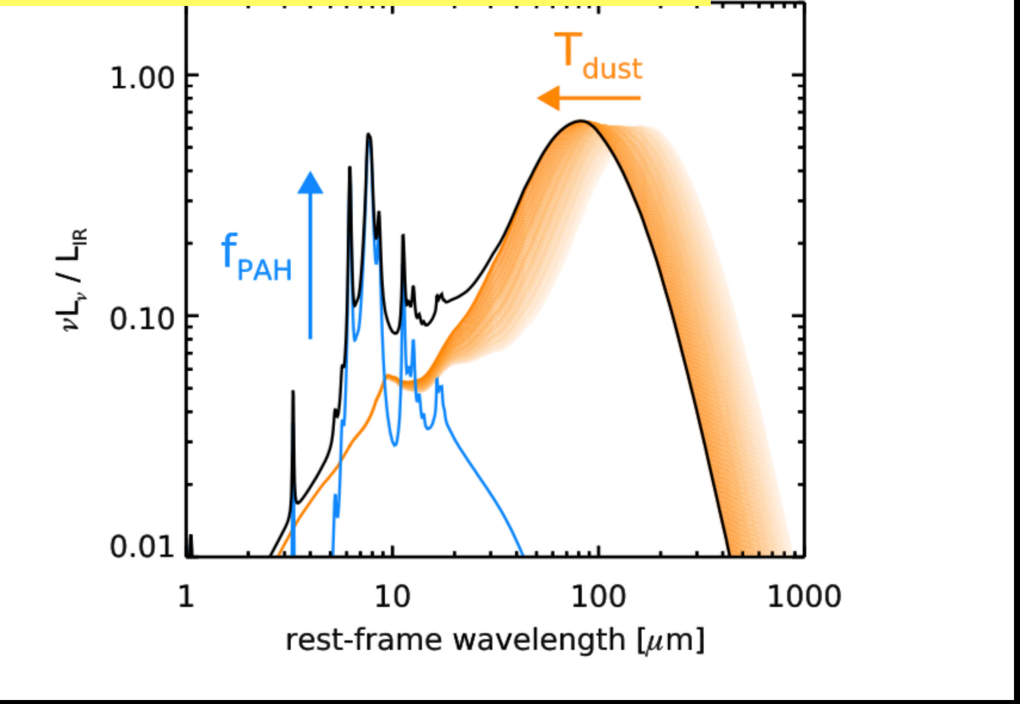
Ldust = L(PAH) + L (continuum)

3. Important results and challenges: cosmic star formation density

Interstellar Radiation = Diffuse ISM + PDR



Ldust = L(PAH) + L (continuum)



Modelling dusty SED

Draine model 2014

$$\frac{dM_{dust}}{dU} = (1-\gamma)M_{dust}\delta(U - U_{min}) + \gamma M_{dust}\frac{\alpha - 1}{U_{min}^{1-\alpha} - U_{max}^{1-\alpha}}U^{-\alpha}$$

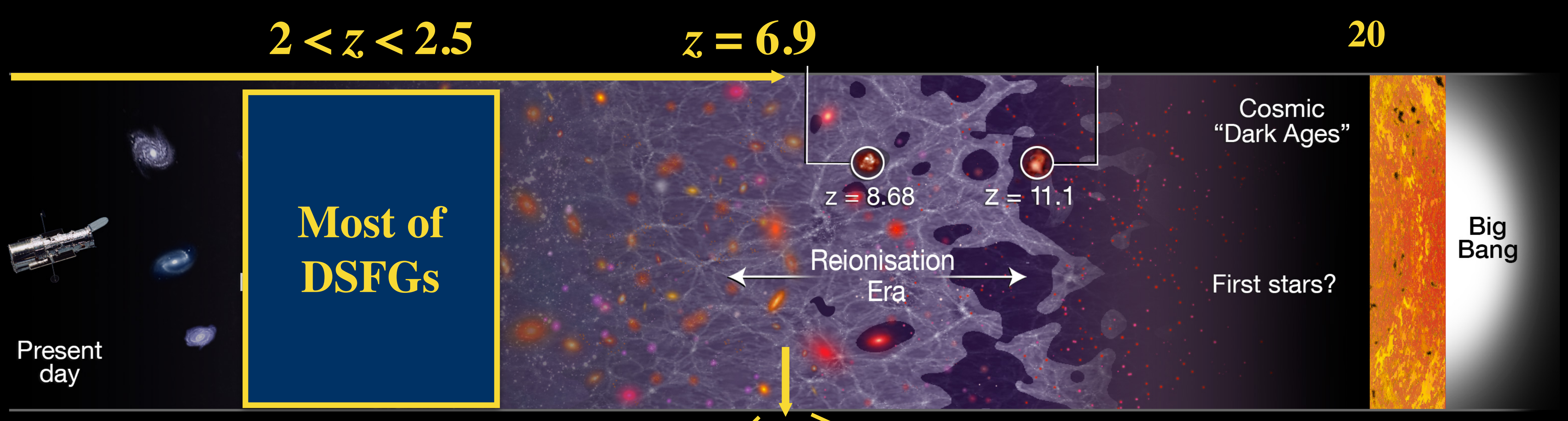
$$f_\nu^{model} = \Omega_* B_\nu(T_*) + \frac{M_{dust}}{4\pi D^2}\left[(1-\gamma)p_\nu^{(0)} + \gamma p_\nu\right]$$

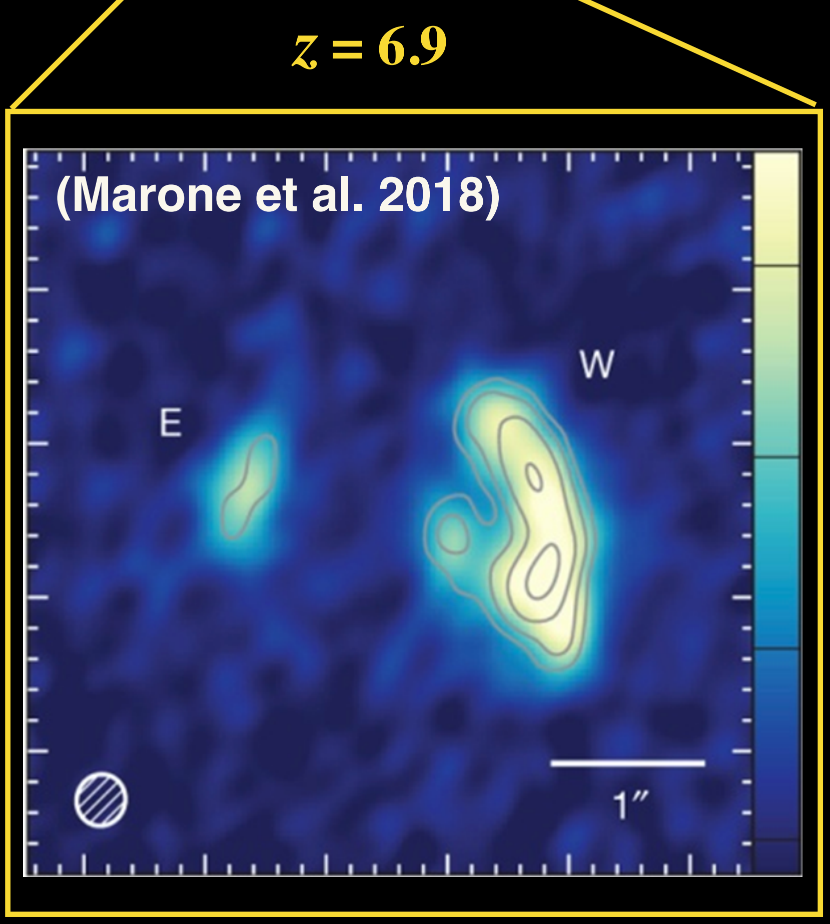
$$\frac{L_{IR}}{L_\odot} = 185\,\frac{M_{dust}}{M_\odot}\left(\frac{T_{dust}}{17.5K}\right)^{5.54} = 185\,\frac{M_{dust}}{M_\odot}\langle U\rangle\ .$$

$$\lambda_{obs}^{max} \propto (1+z)/T_{dust}$$

(D) What did we learn from large surveys ?

1.3 What did we learn from existing studies of DSFGs ?



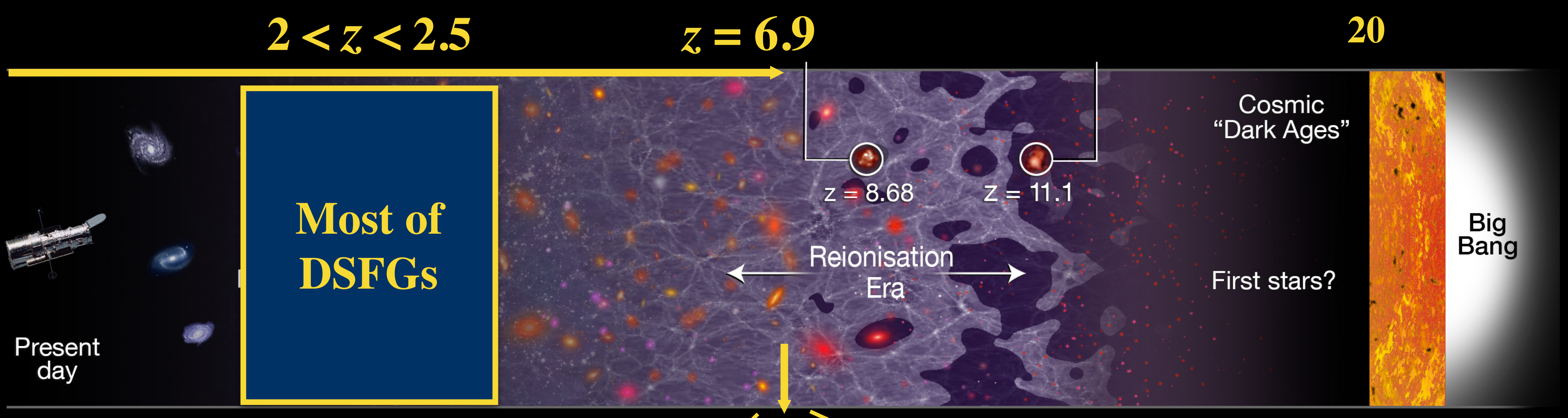


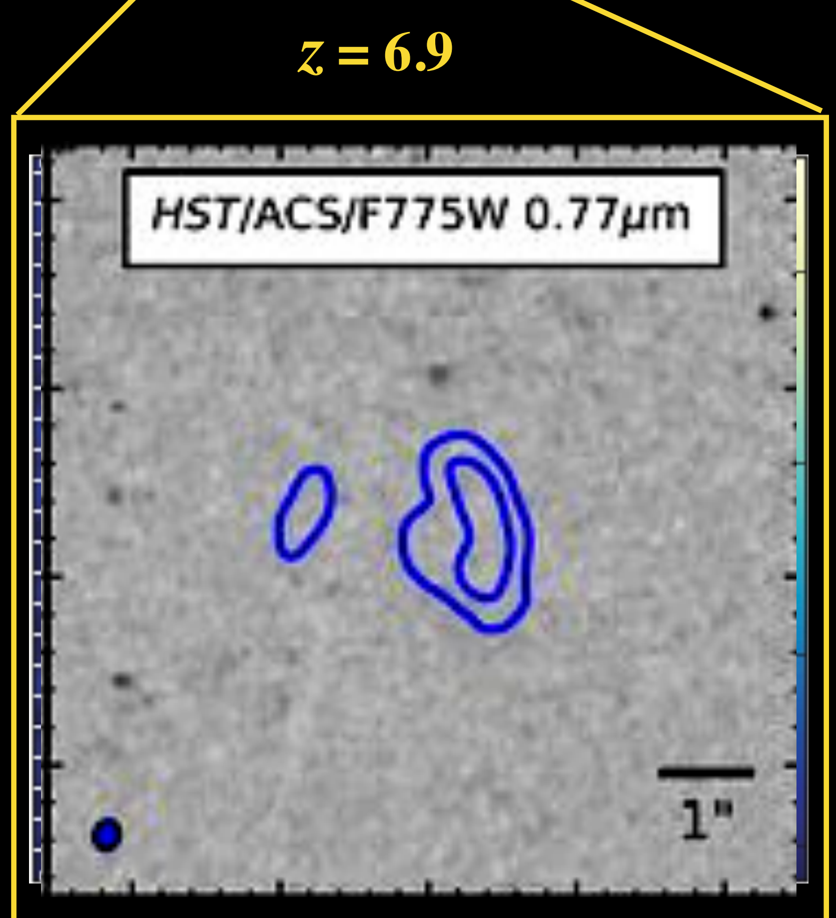
"Dusty view" of the most distant dusty galaxy (780 million of years old) found from IR/submm data

↓

Invisible in Hubble Space Telescope (HST) data

1.3 What did we learn from existing studies of DSFGs ?





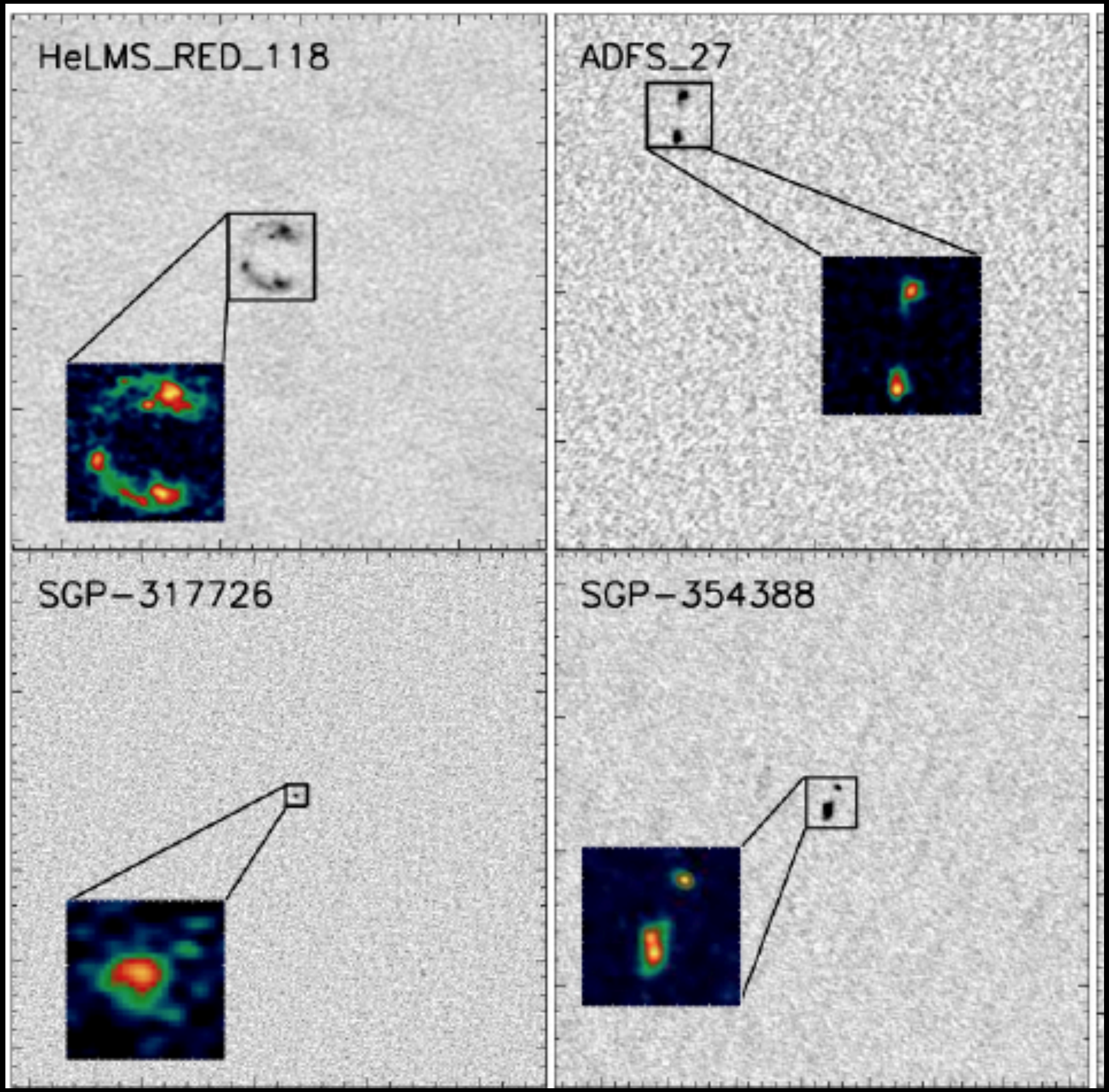
"Dusty view" of the most distant dusty galaxy (780 million of years old) found from IR/submm data

↓

Invisible in Hubble Space Telescope (HST) data

3. Important results and challenges

ALMA (870um) follow-up studies



ID of dusty galaxies !!!

1. Extreme stellar masses (>100 billion solar masses)

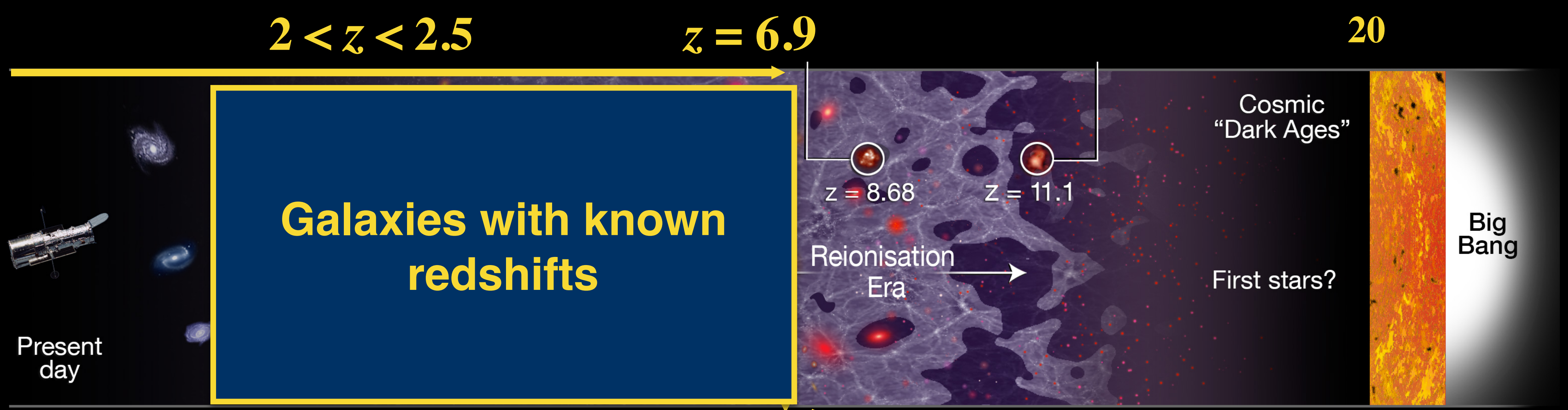
2. Extreme dust luminosity (10^13 solar luminosities)

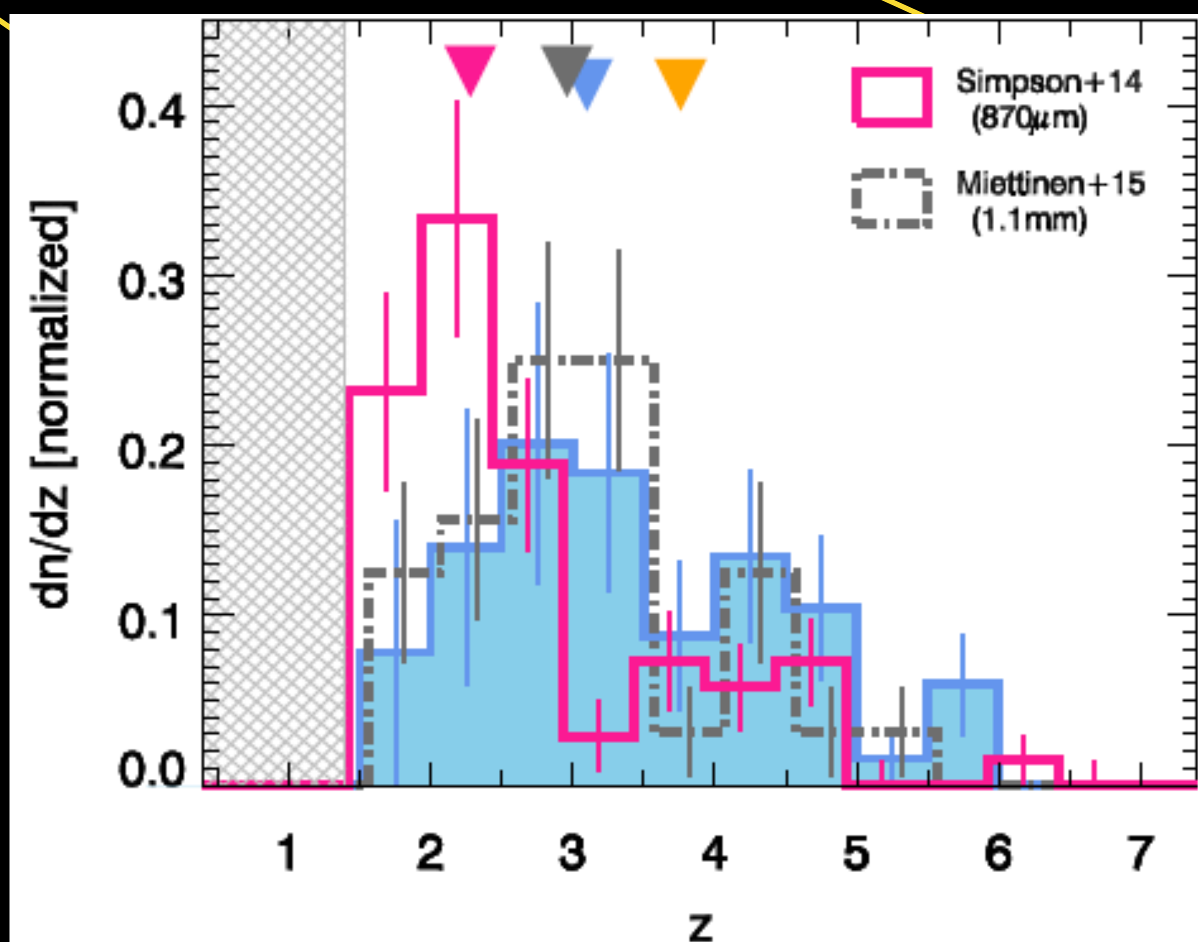
3. Extreme star-formation rates (>100-1000 solar masses per yr)

4. Large amount of CO, atomic carbon and dense HCN

ALMA: resolution 0.2" (around 800pc)

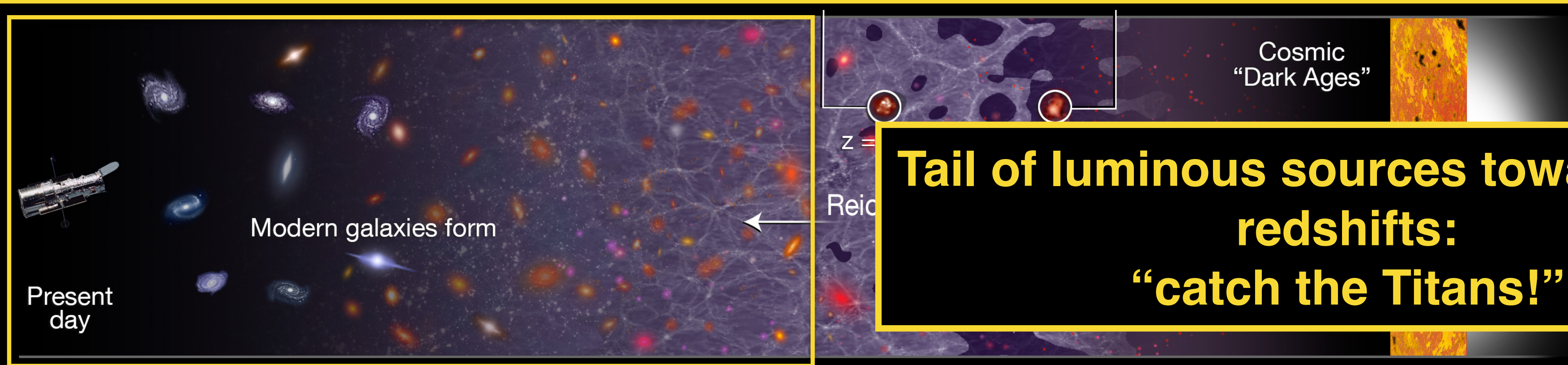
3. Important results and challenges: redshift distribution



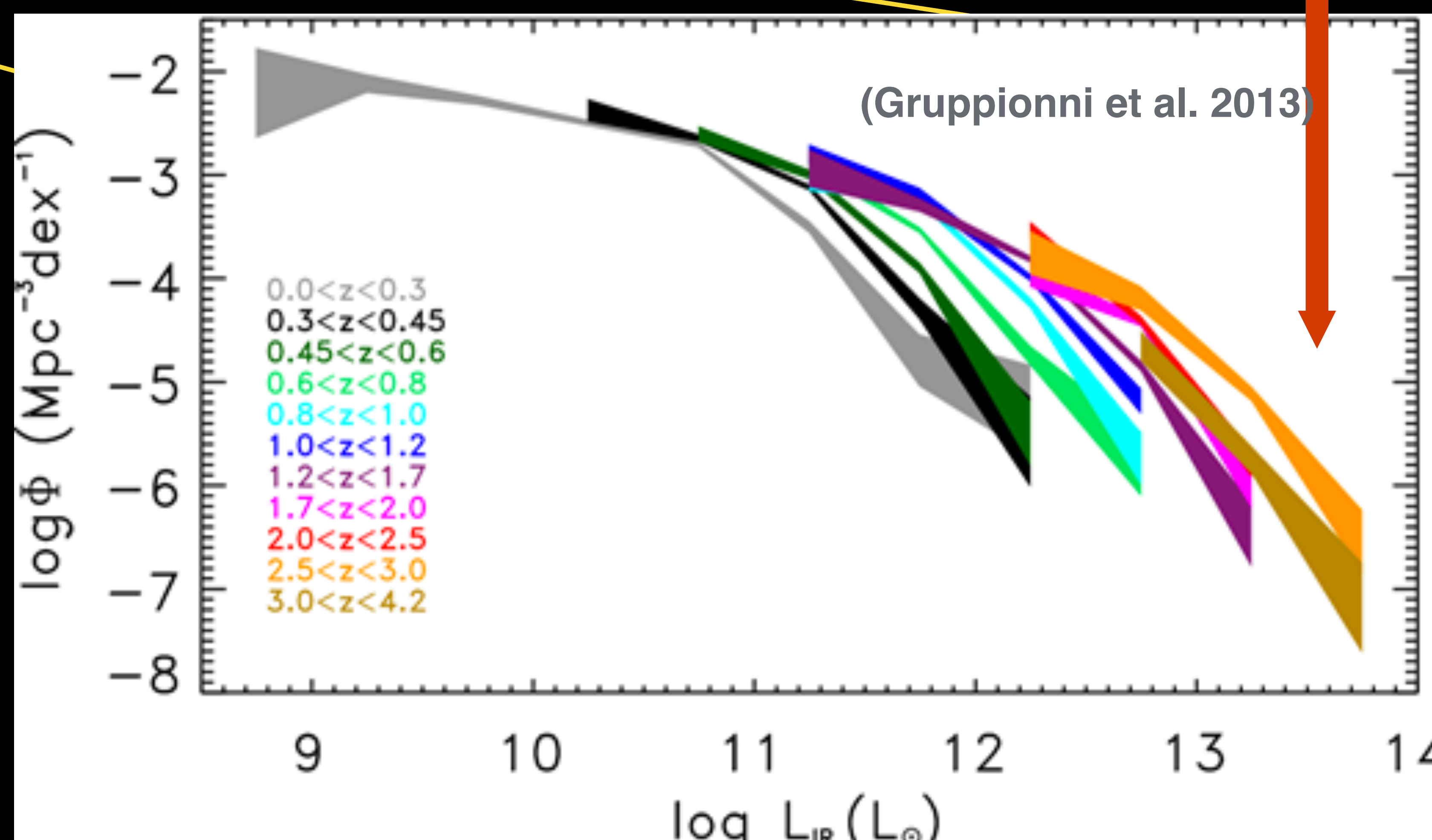


3. Important results and challenges: luminosity functions

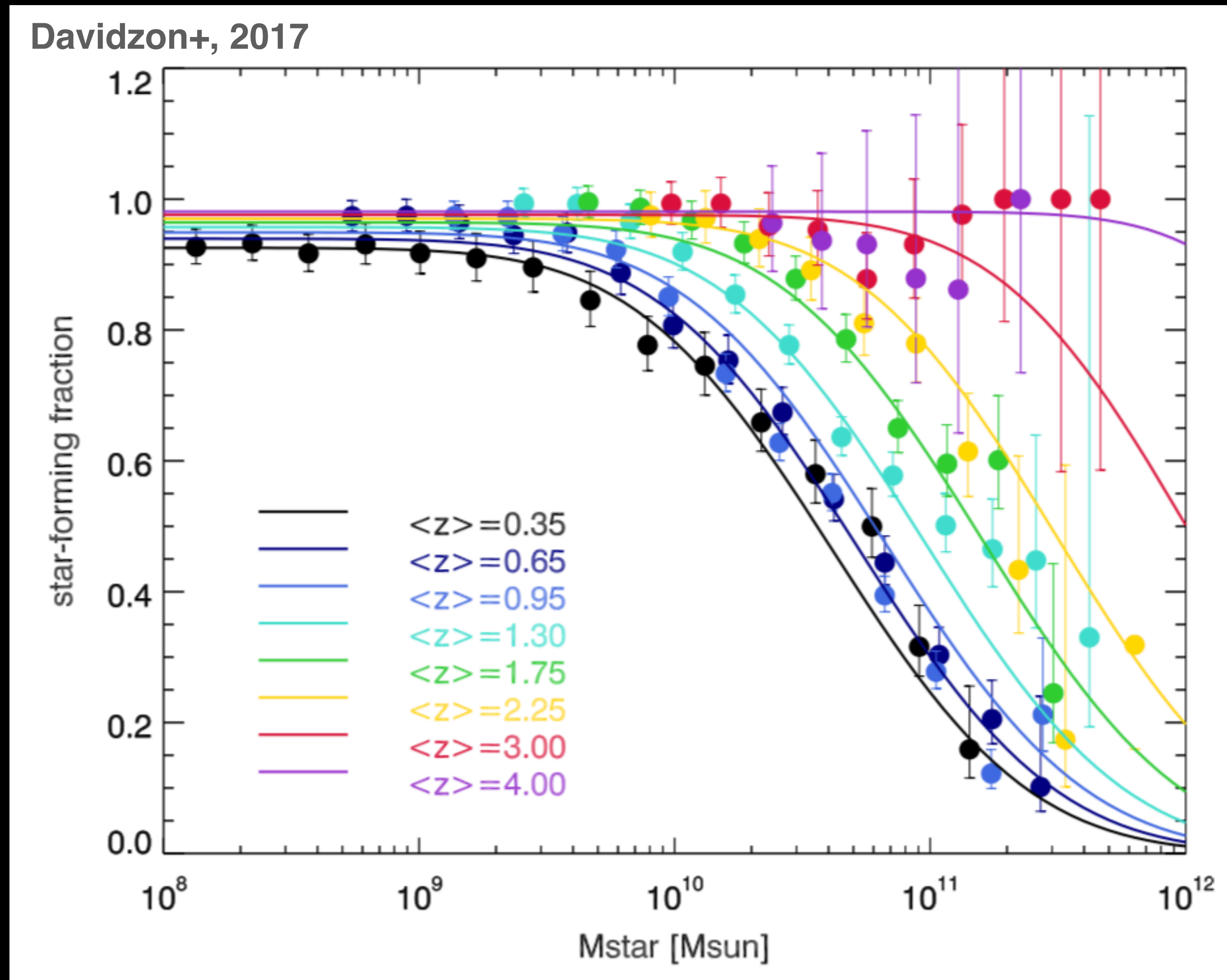
redshift (z) 2 6



Tail of luminous sources towards high-redshifts: "catch the Titans!"



3. Important results and challenges: stellar mass function



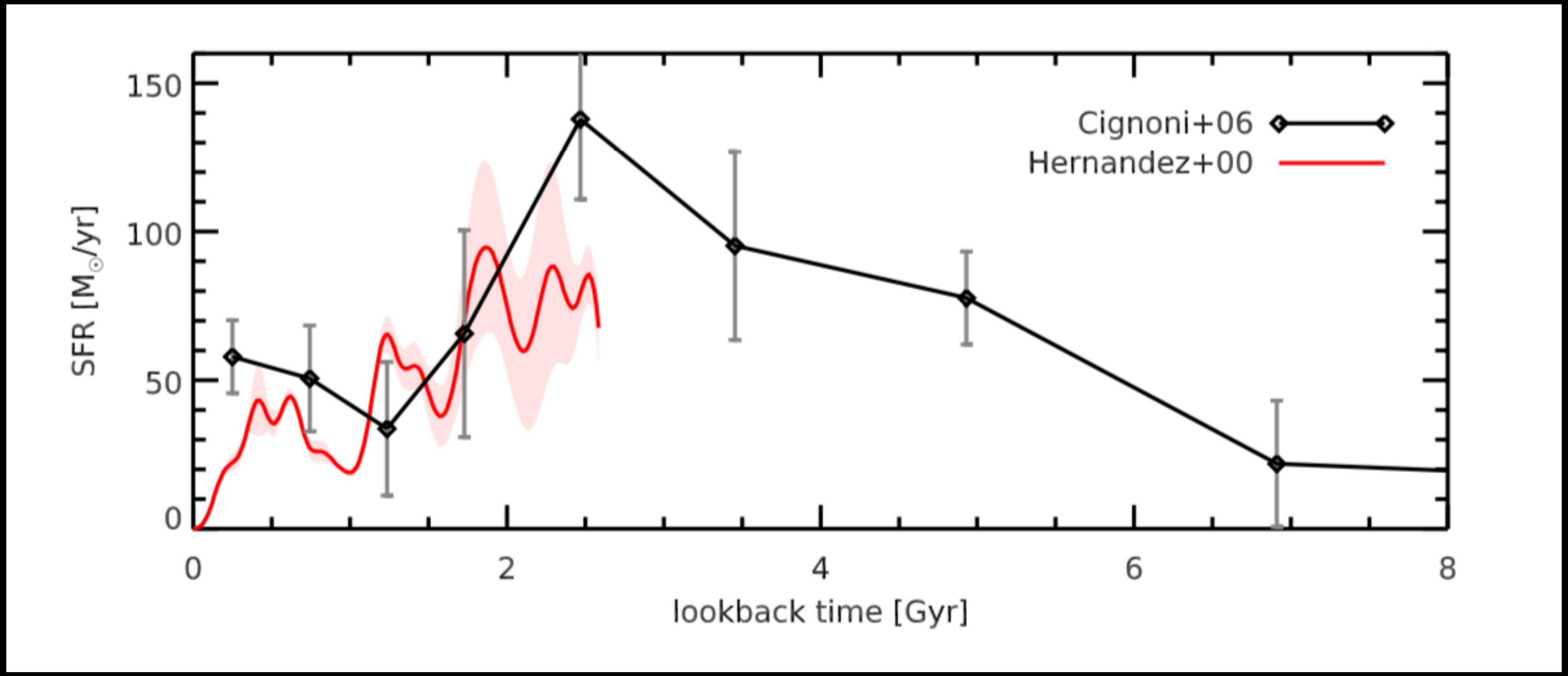
$$\phi(M_\star)\,\mathrm{d}(M_\star) = \mathrm{e}^{-\frac{M_\star}{\mathcal{M}^\star}} \left[\Phi_1^\star \left(\frac{M_\star}{\mathcal{M}^\star}\right)^{\alpha_1} + \Phi_2^* \left(\frac{M_\star}{\mathcal{M}^*}\right)^{\alpha_2}\right] \frac{\mathrm{d}(M_\star)}{\mathcal{M}^\star}$$

MESSAGE No. 2

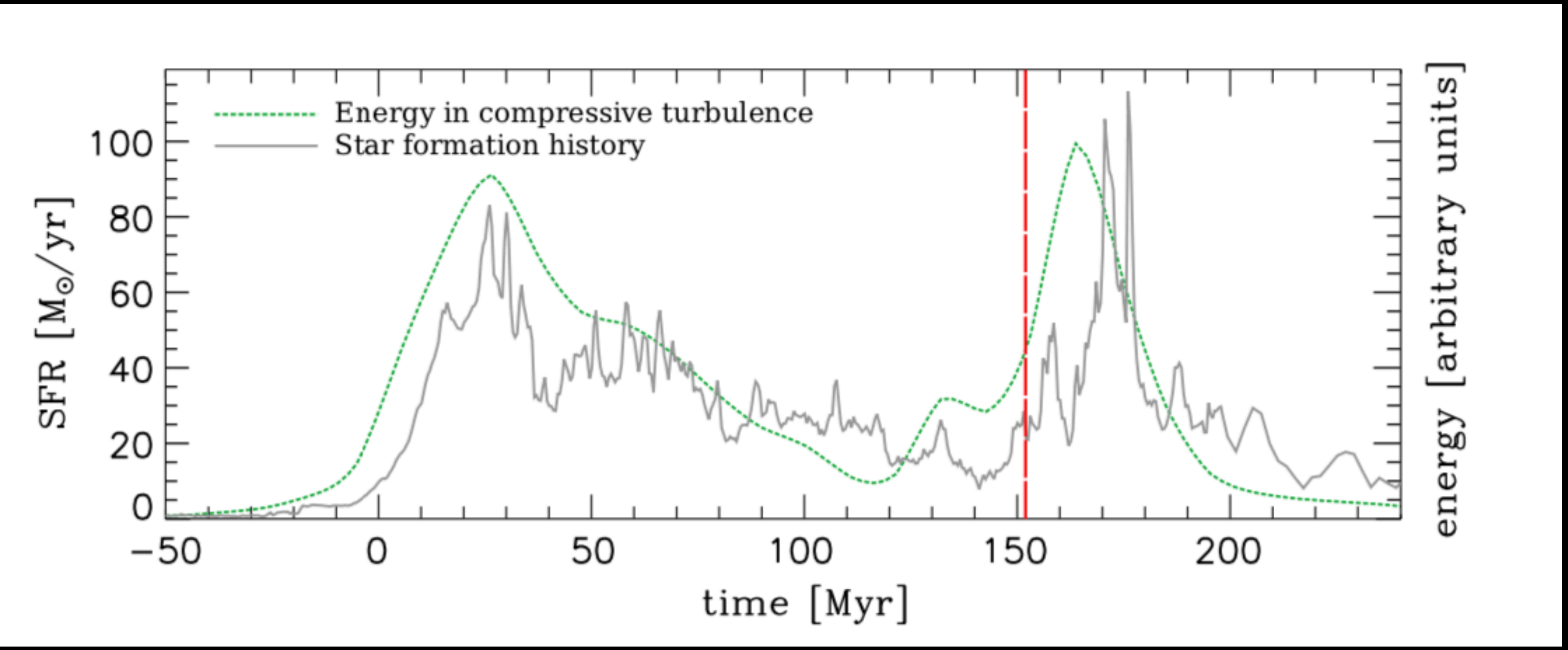
Dusty star-forming galaxies at high-z are crucial for understanding of galaxy evolution.
Why?
Because they are progenitors of local elliptical galaxies !!!

Credit: Toft et al. 2014

3. Important results and challenges: star-formation histories

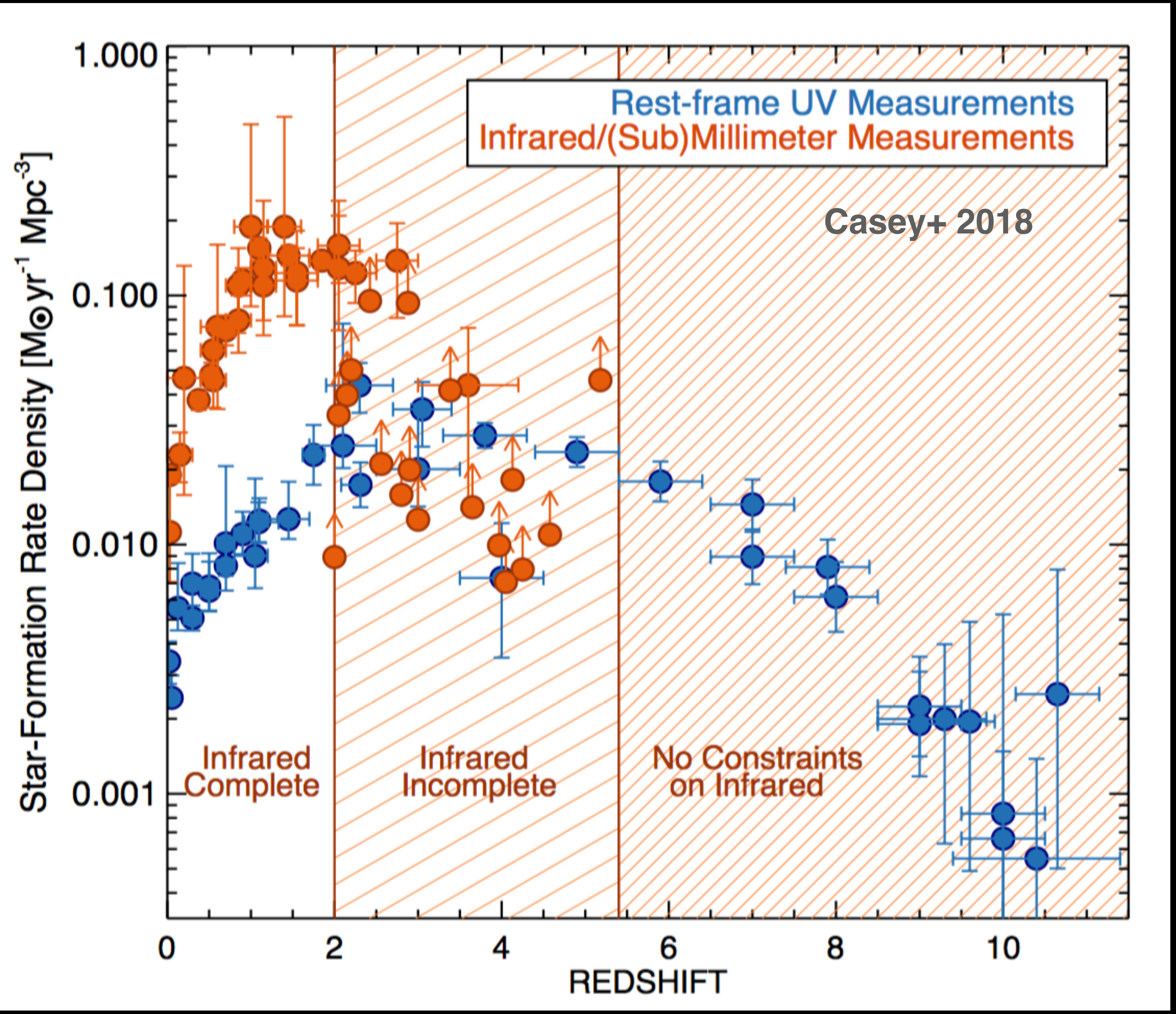


Milky Way



Arp220

3. Important results and challenges: cosmic star formation density



$$\rho_*(z) = \frac{\sum SFR_{IR}}{\frac{4\pi}{3}\int_{z=4}^{z=5} \frac{c/H_0}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}dz}$$

SFR (from UV)

$$\mathrm{SFR_{tot}} = K_{\mathrm{UV}} \times L_\nu(\mathrm{UV})$$

But needs dust correction

Ideally (UV+IR)

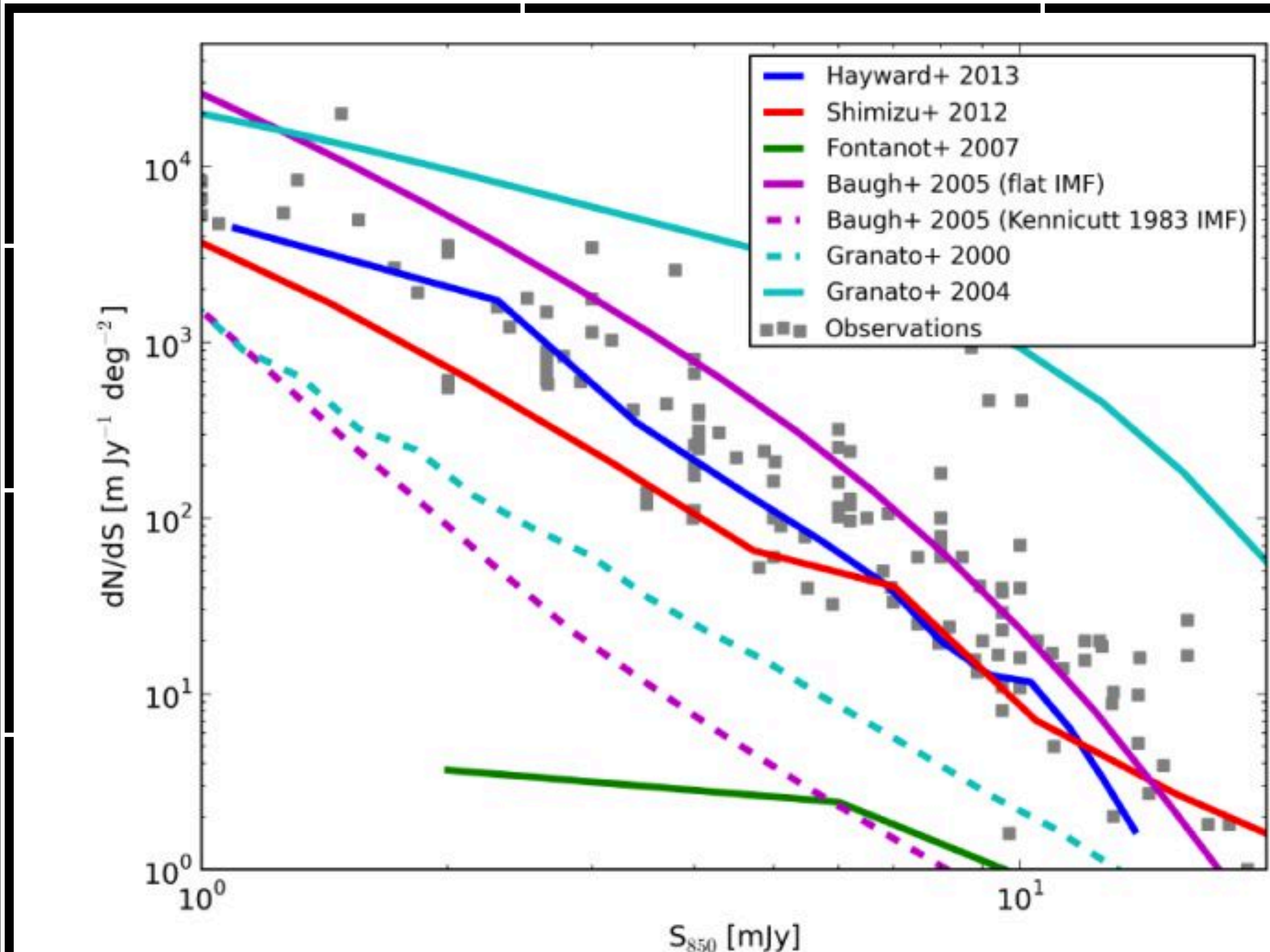
$$\mathrm{SFR_{tot}} = K_{\mathrm{UV}} \times L_\nu(\mathrm{UV}) + K_{\mathrm{IR}} \times L_\nu(\mathrm{IR})$$

3. Important results and challenges: modelling

SAM	Cosmological simulations	Hybrid simulations	Phenomenological models
+ Fast/ Statistics achievable	+ Ab initio, no fine tunning	+ great resolution	**Match number counts and redshift distribution**
- Physics is "tunned" to match with observations	- Expensive, small statistics	- no good recipes for environmental effects, no statistics	extrapolation of locally calibrated SEDs & $L_{(IR)}$
GALFORM, Santa Cruz, L-Galaxies (Munich)	***EAGLE, Illustris, Blue Tides***	***e.g. Hayward+, 13***	***Bethermin+, '17*** ***Casey+, '18*** ***Schreiber+, '16*** ***Mancuso+, '16***
Cannot simultaneously explain number density and redshift distribution of most extreme DSFGs + strongly disagree about merger contribution			

3. Important results and challenges: modelling

SAM	Cosmological simulations	Hybrid simulations	Phenomenological models
			Match number counts and redshift distribution
			extrapolation of locally calibrated SEDs & $L_{(IR)}$
			Bethermin+, '17 ***Casey+, '18*** ***Schreiber+, '16*** ***Mancuso+, '16***



3. Important results and challenges: modelling

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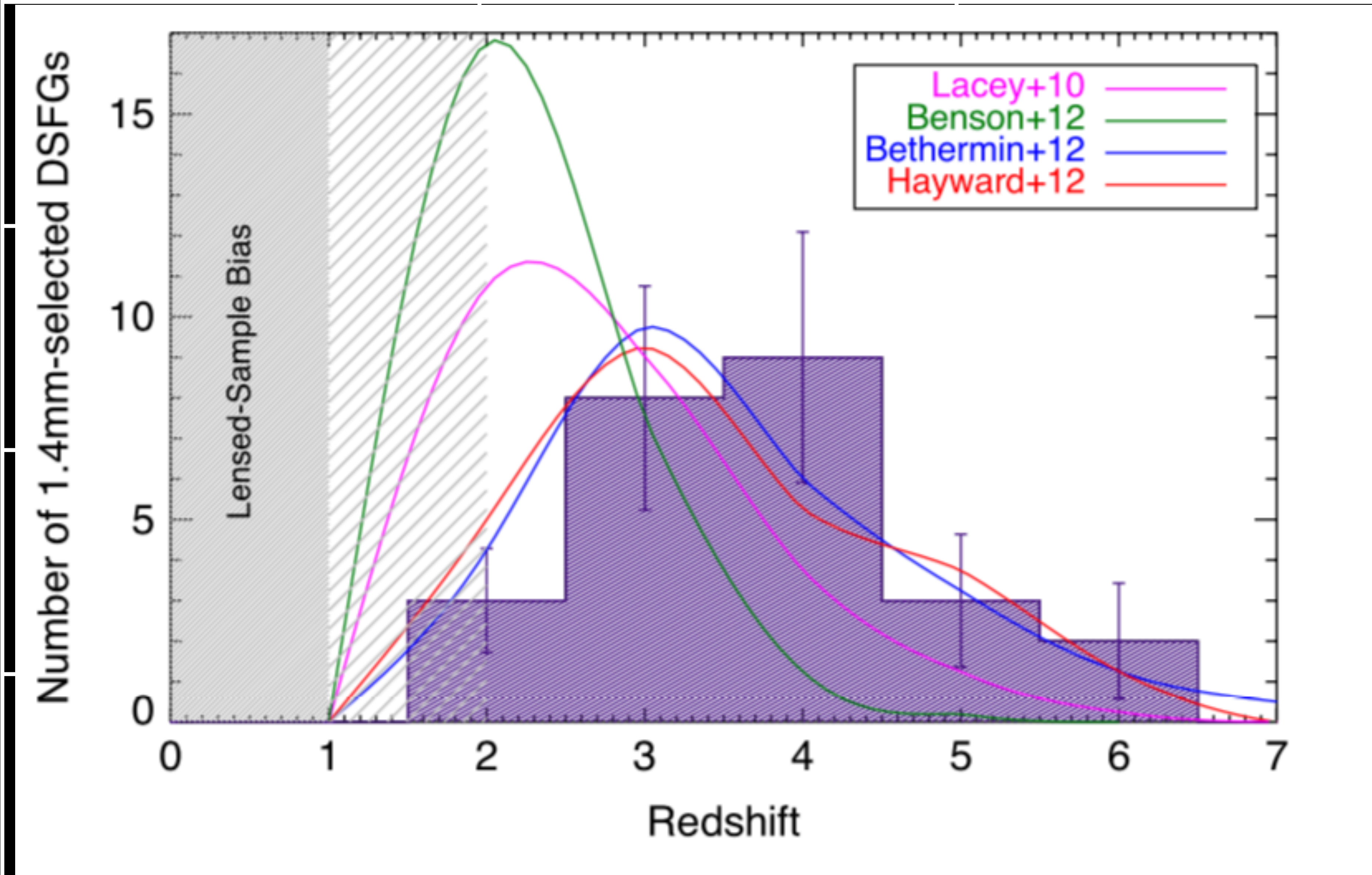
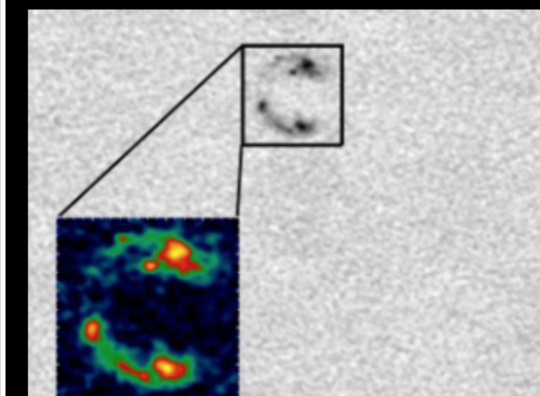


3. I The extreme nature of early DSFGs
(view from simulations)

1. Strong lensing
(e.g. Negrello et al. 2017)

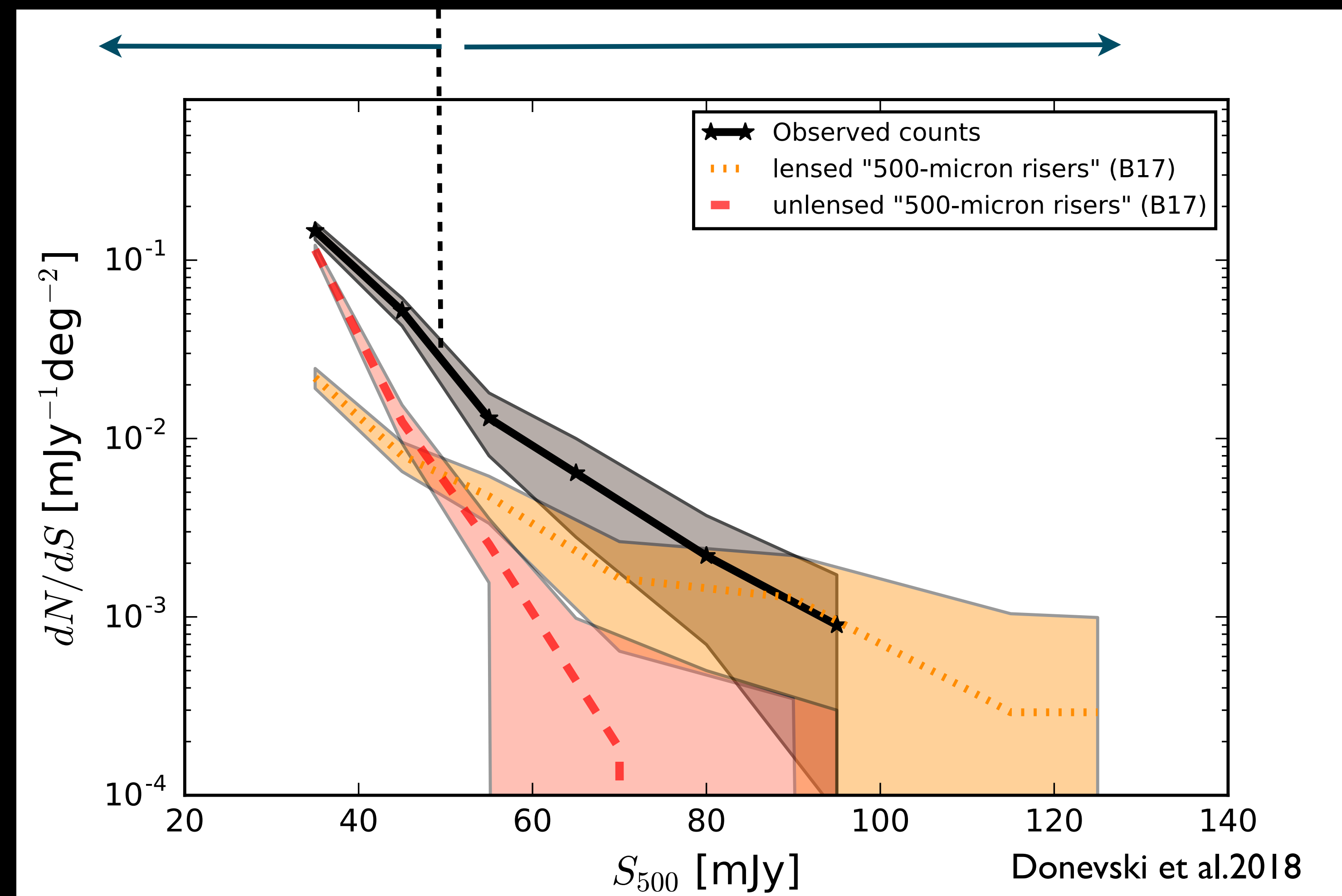
2. Source multiplicity
(e.g. Hayward et al. 2013)

Clustering?
(Donevski et al. 2018)



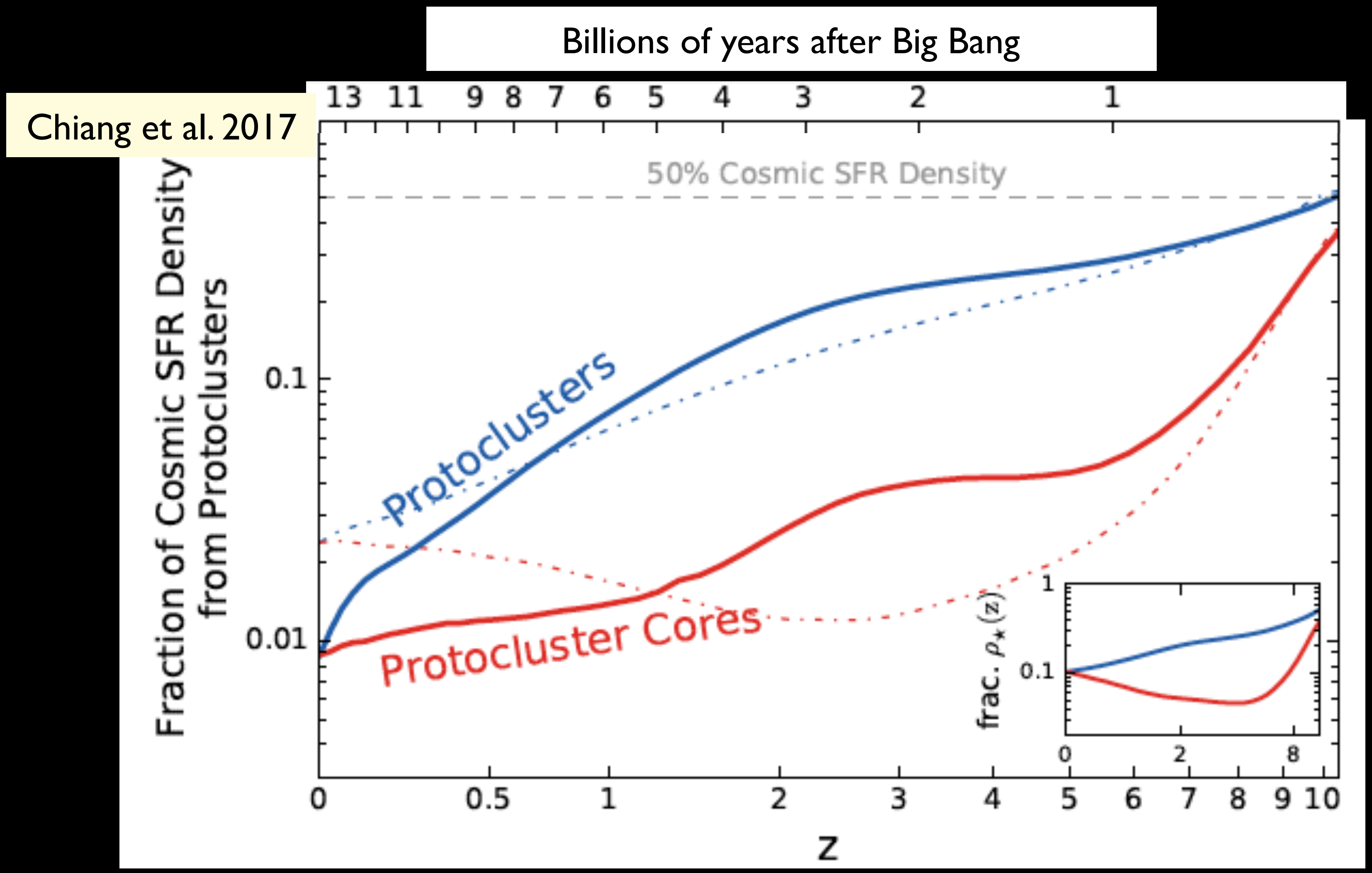
mostly unlensed

lensing dominated



When we correct for all biases, there is still small offset of intrinsicaly bright DSFGs

3.1 Protoclusters and DSFGs: why worrying?



- Fractional volume increases 1000 times from z=0 to z=7
- Contribution to SFRD at z > 4 -10 significant
- Early galaxy growth and star formation dominated by protocluster cores !

Crucial laboratories for studying early growth of massive structures
(after virialisation, their history erased)

3.2 How to locate the most distant protoclusters in the Universe?

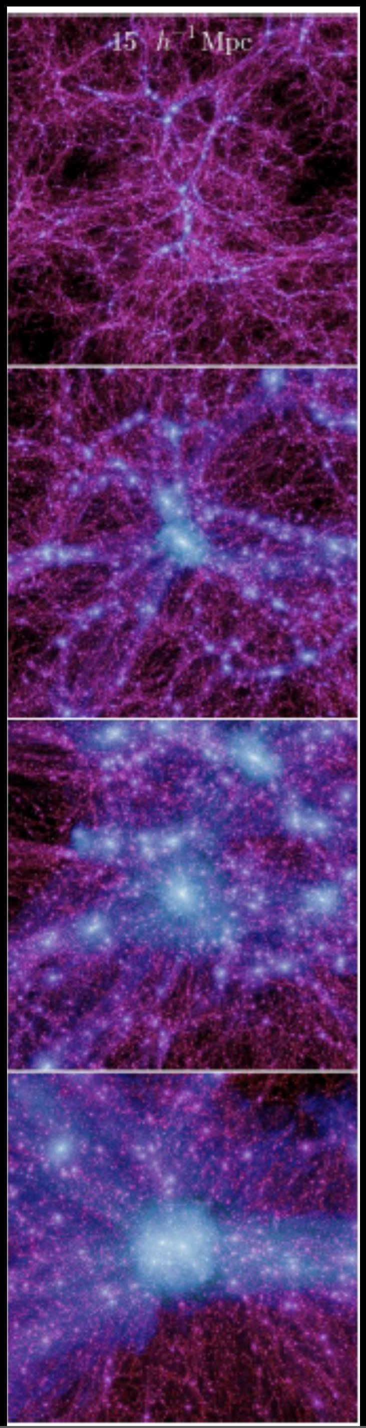
1. Strong lensing (e.g. Negrello et al. 2017)	
2. Source multiplicity (e.g. Hayward et al. 2013)	
Clustering? (Donevski et al. 2018)	

z=6

z=2

z=1

z=0.1

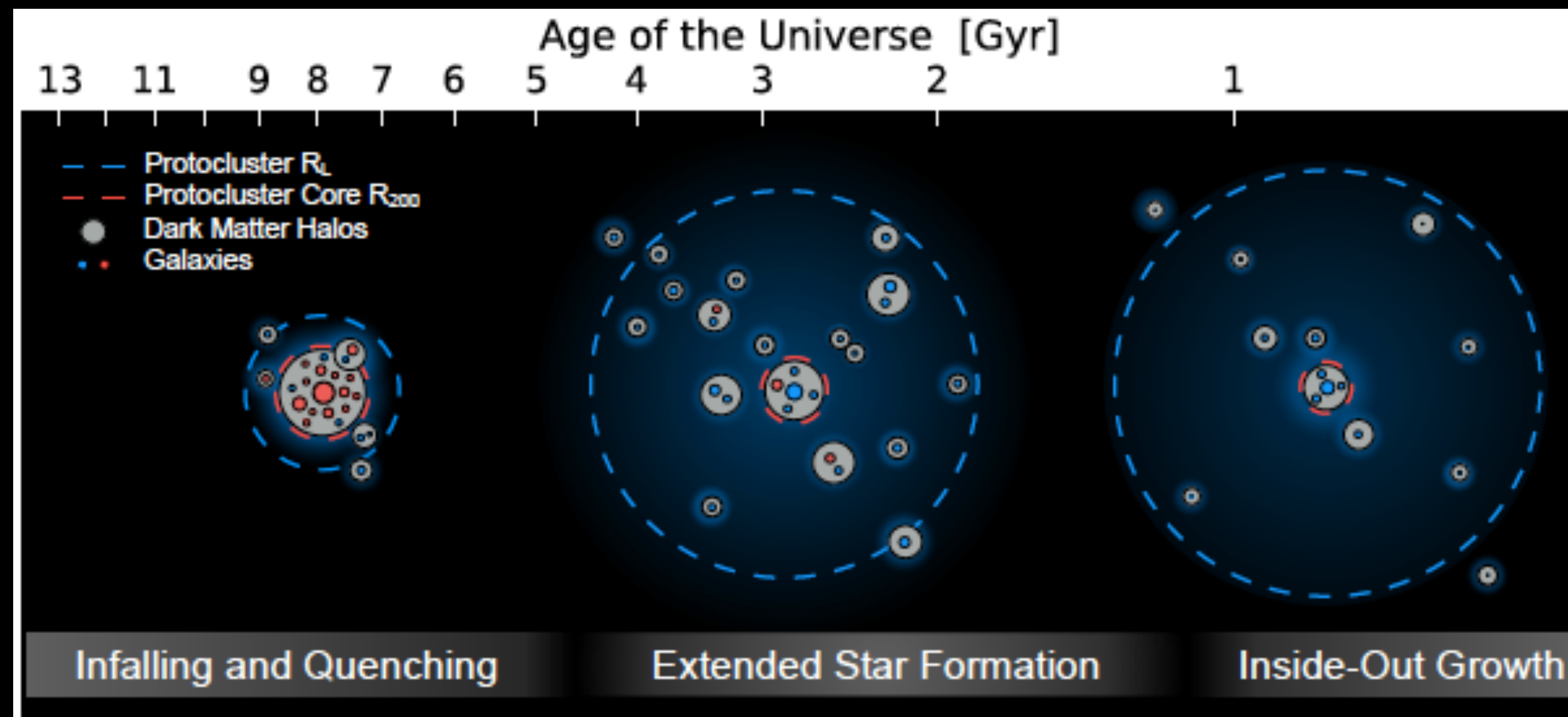


Protoclusters can be spotted even at z ~6-7 if we can find their baryon locators

Overzier et al. 2016 (Milenium II simulation)

3.2 How to locate the most distant protoclusters in the Universe?

1. Strong lensing (e.g. Negrello et al. 2017)	
2. Source multiplicity (e.g. Hayward et al. 2013)	
Clustering? (Donevski et al. 2018)	



z=0.1 z=2 z=6

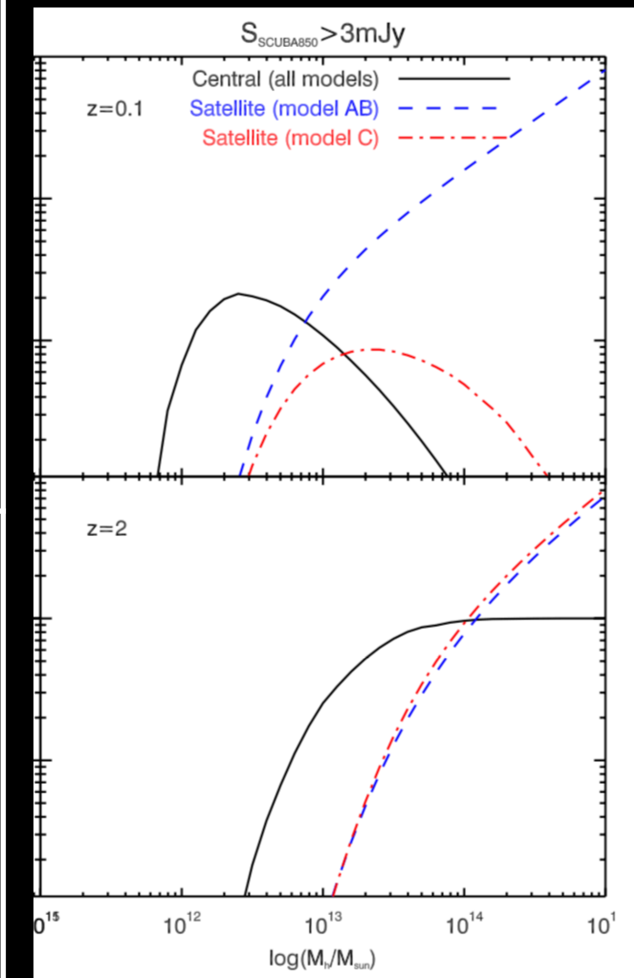
OBSERVATIONAL PROBLEMS:
- **No defined red sequence**
- **Small overdensity due to faint members**
- **Selection from optical is limited / ALMA small FoV**
- **Spectroscopic campaigns targeted a lot of overdensities…**

3.2 How to locate the most distant protoclusters in the Universe?

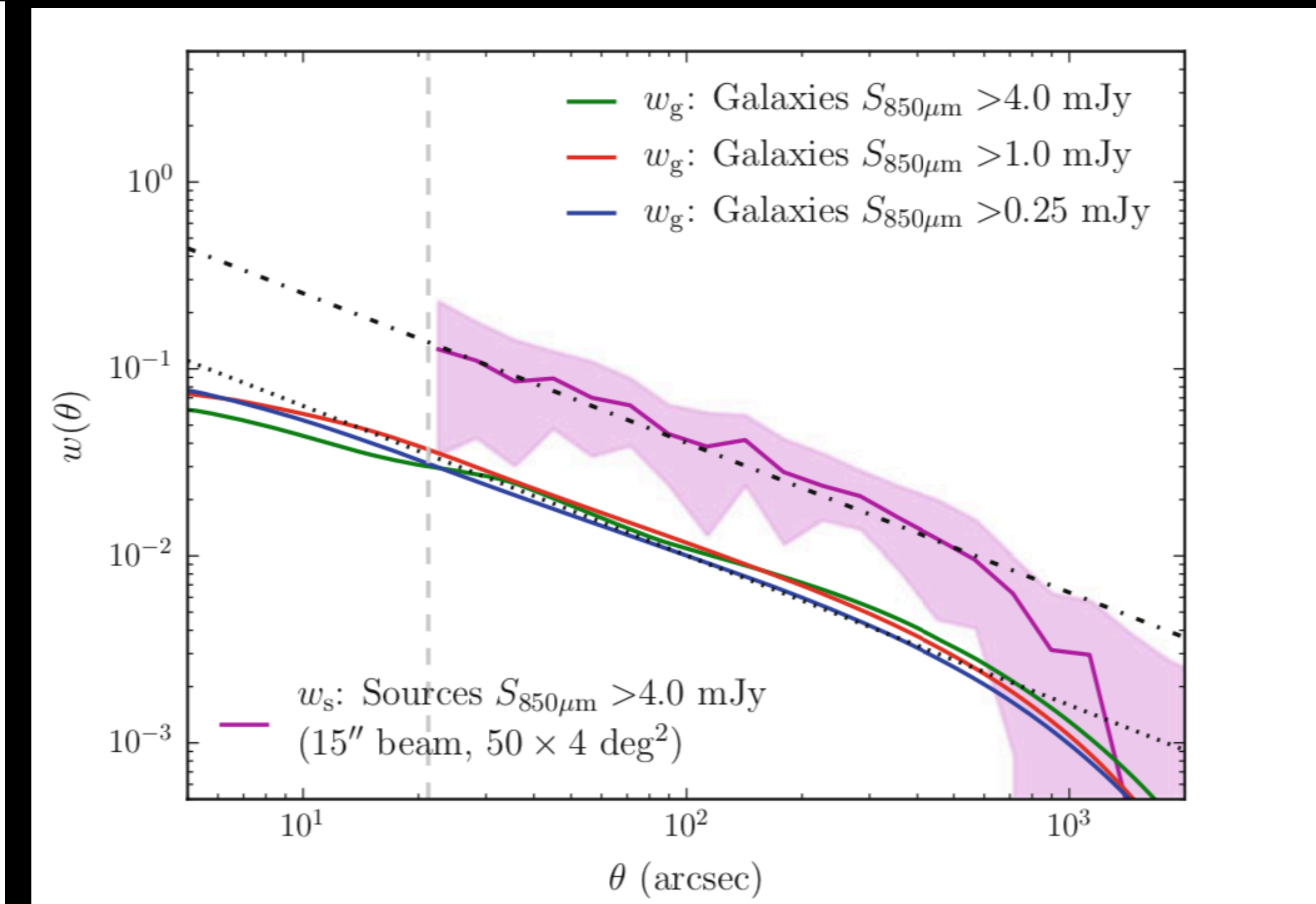
1. Strong lensing
(e.g. Negrello et al. 2017)

2. Source multiplicity
(e.g. Hayward et al. 2013)

Clustering?
(Donevski et al. 2018)

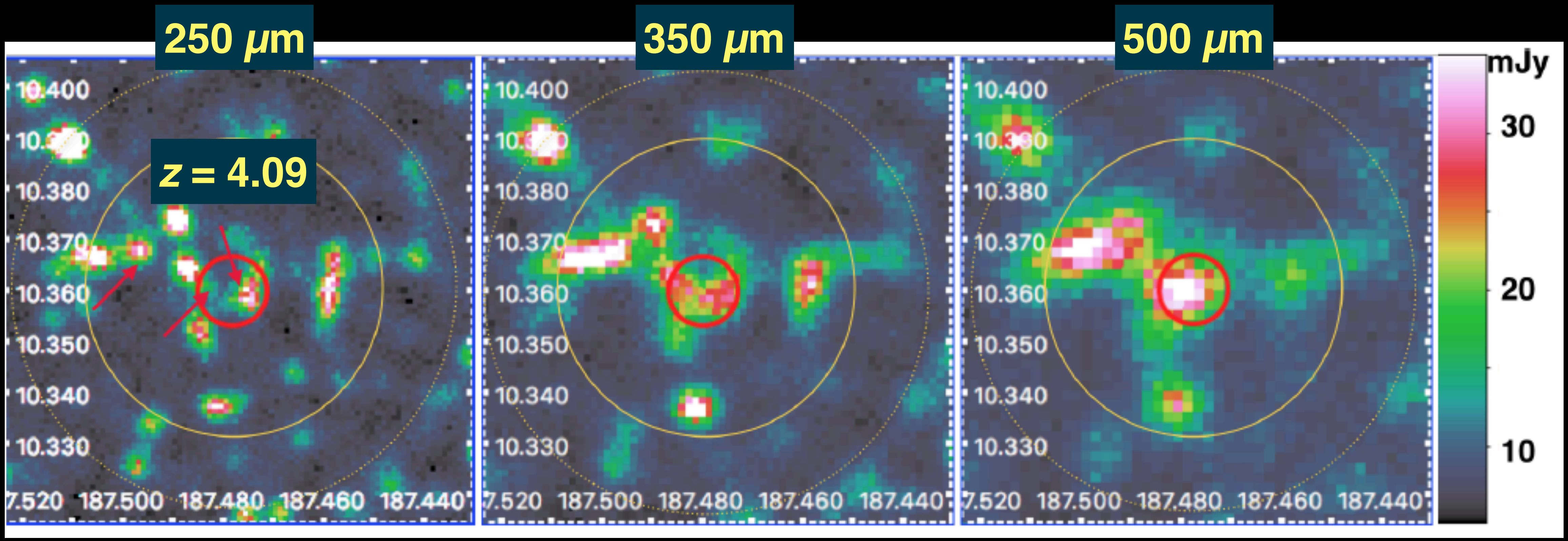


HOD
(Bethermin 2014)



Angular clustering [simulations vs. observations]
(Cowley 2017)

3.3 Signposting early protoclusters with red DSFGs



Simulation

- **Abundance matching methodology**

- **DM halos from Bolshoi-Plank simulation (1.9 deg^2, from z=0 up to z=8)**
- **Galaxy properties (SFR, Lir) modelled based on two models (Bethermin '17 and Schreiber '16)**

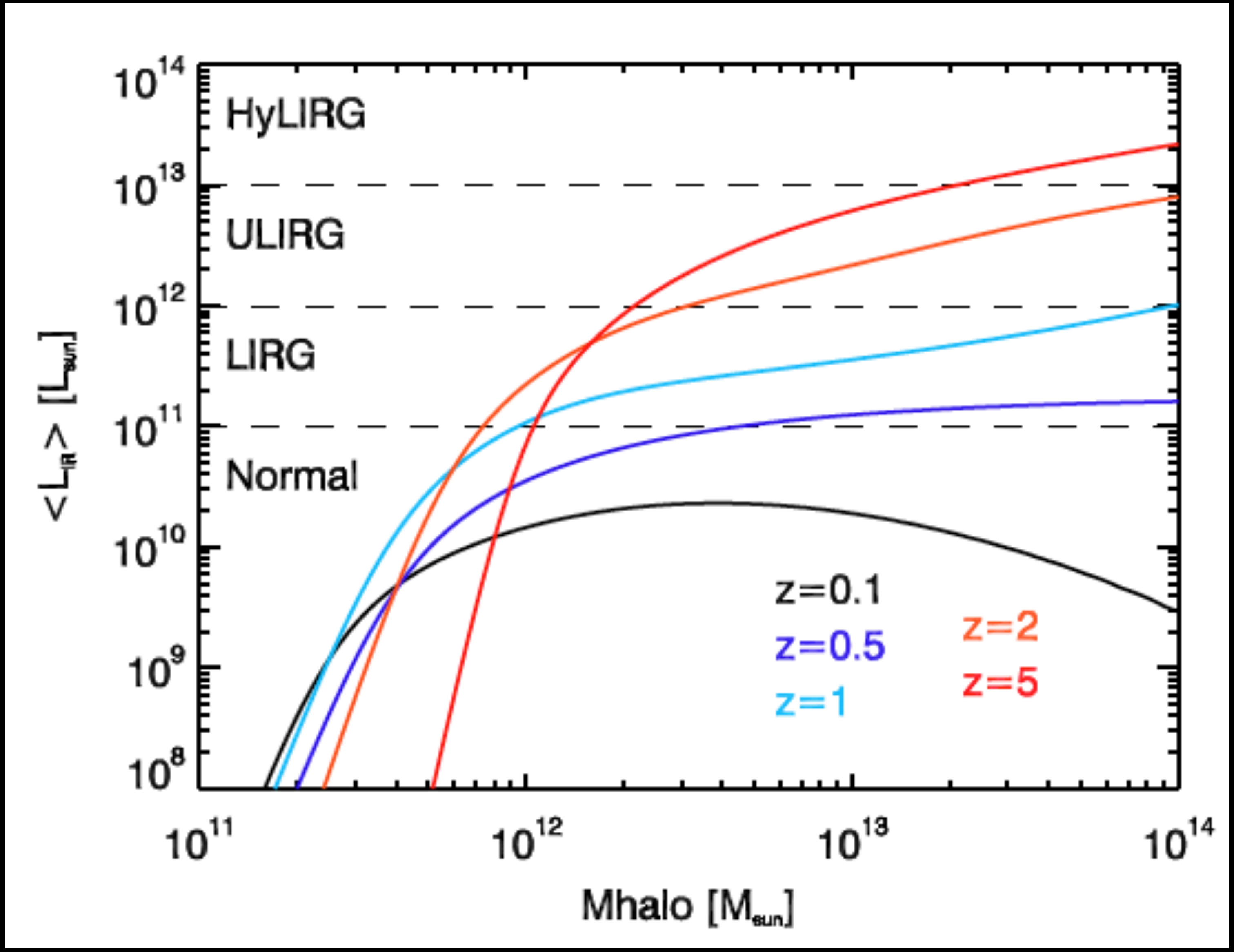
- **RESULT: One extreme overdensity of DSFGs in 2arcmin scale (protocluster core) found at z~4.**

3.2 How to locate the most distant protoclusters in the Universe?

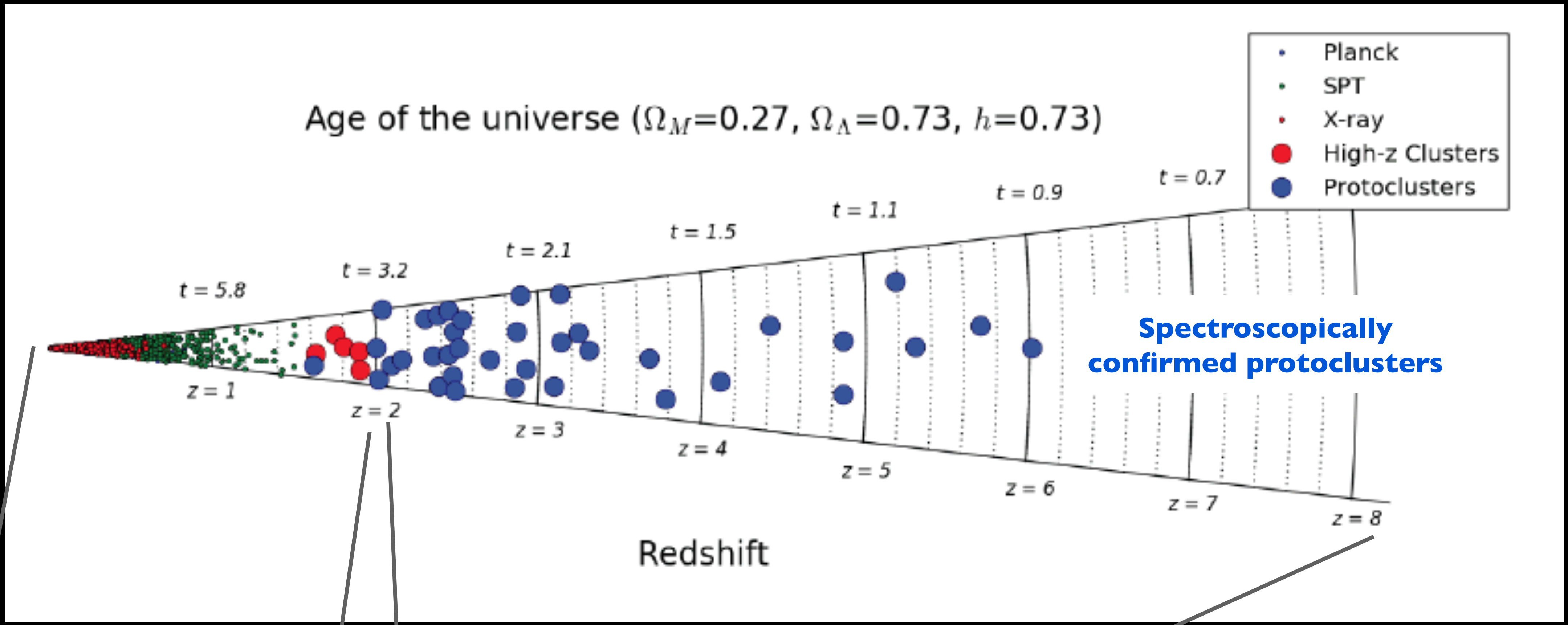
1. Strong lensing
(e.g. Negrello et al. 2017)

2. Source multiplicity
(e.g. Hayward et al. 2013)

Clustering?
(Donevski et al. 2018)

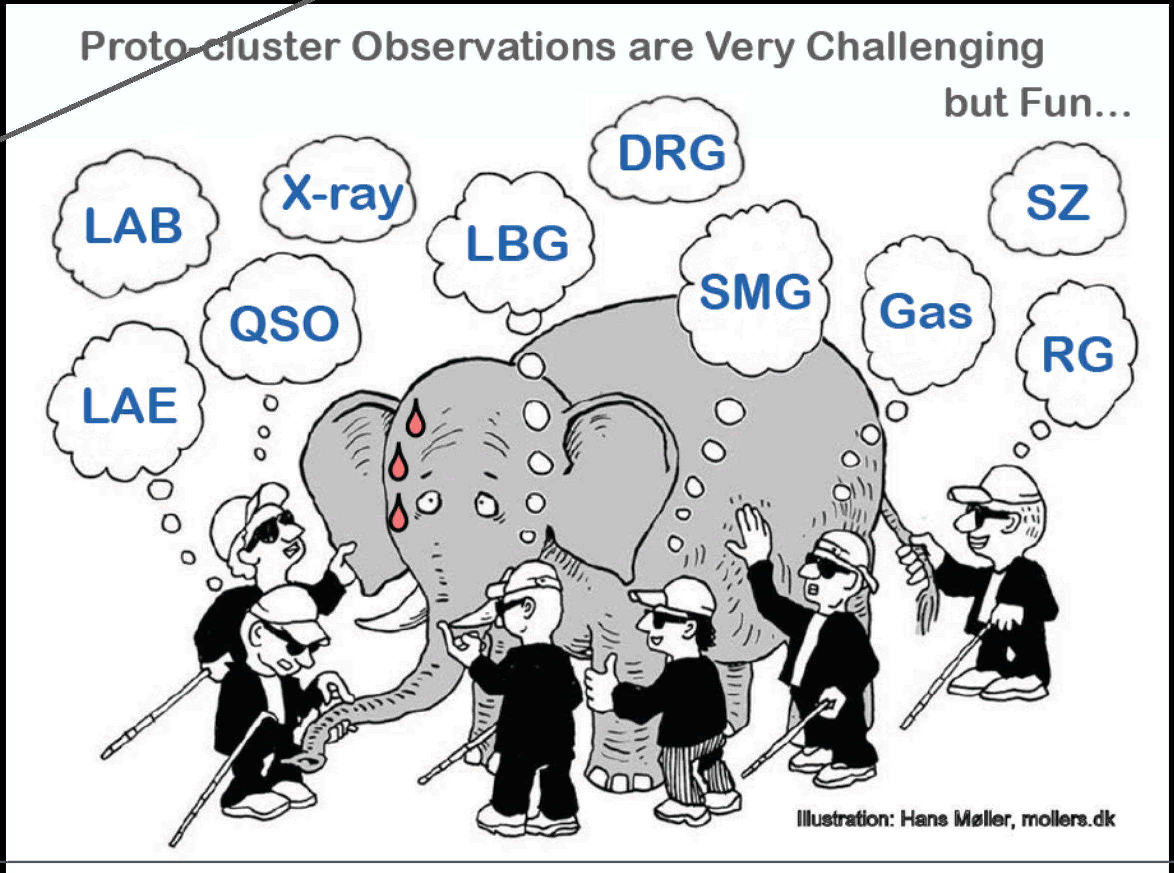


3.2 How to locate the most distant protoclusters in the Universe?



Galaxy Clusters
(M > 10^14 Ms)

Protoclusters



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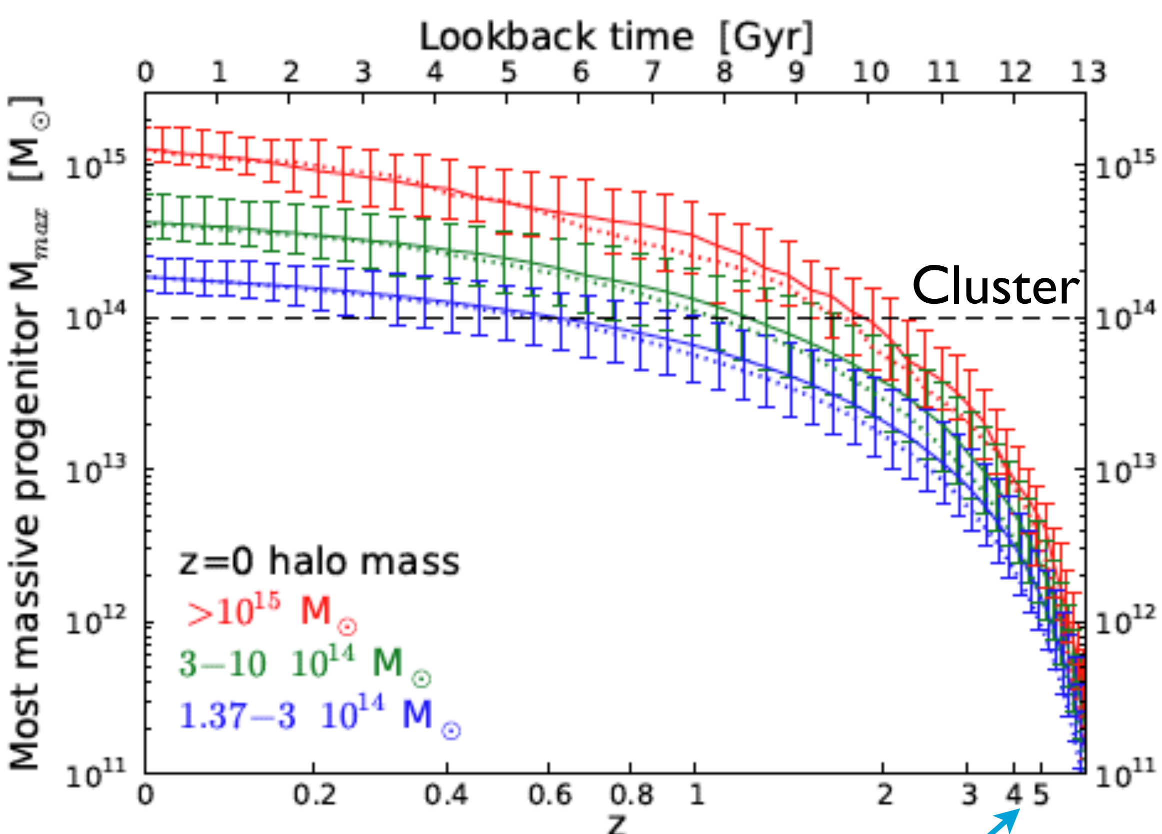
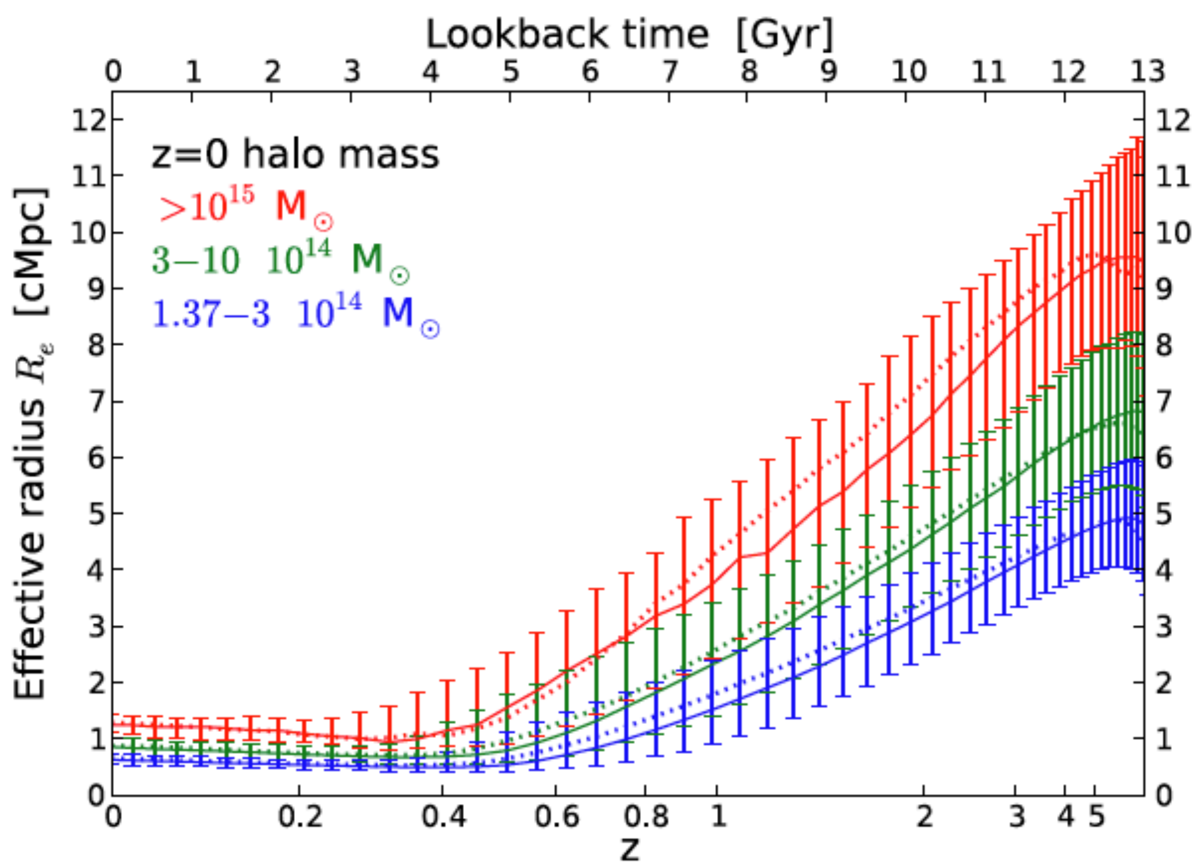


(Chiang et al. 2013)

Modelled DM halo masses of cluster progenitors



Predicted sizes of cluster progenitors

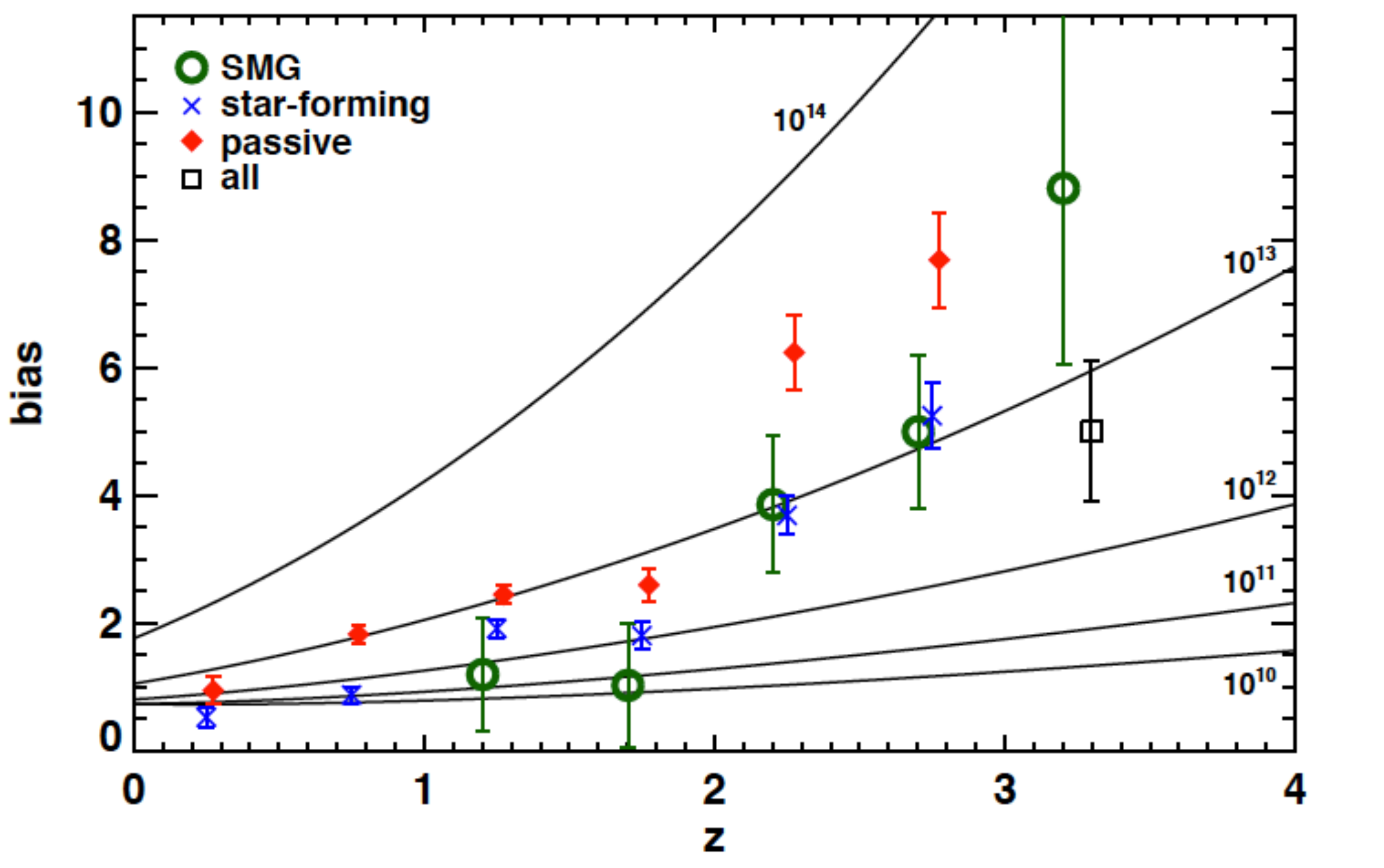
--> We need large surveys that can find rare signposts and inspect larger angular scale environments ! (not only few arcmin)

3.3 Signposting early protoclusters with red DSFGs

Clustering signal of DSFGs is redshift-dependent

QUESTION:

How complete tracers at all redshifts (halo masses) DSFGs are?



(Wilkinson et al. 2017)

"cosmic downsizing" ?

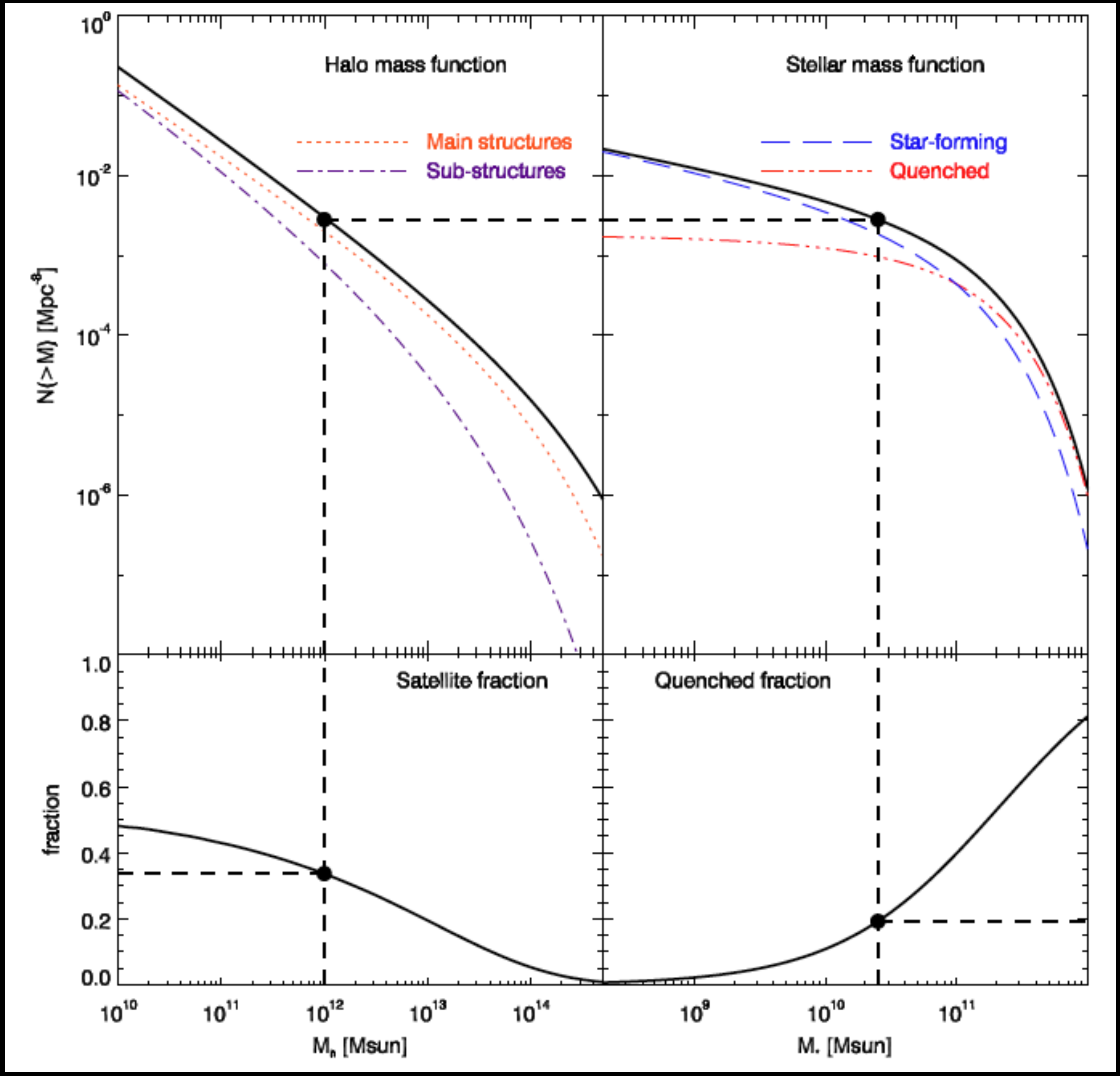
$$w_{\rm obs}(\theta) = b^2 \times w_{\rm dm}(\theta)$$

3.3 Signposting early protoclusters with red DSFGs

Clustering signal of DSFGs is redshift-dependent

QUESTION:

How complete tracers at all redshifts (halo masses) DSFGs are?



3.3 Signposting early protoclusters with red DSFGs

1. Strong lensing
(e.g. Negrello et al. 2017)

2. Source multiplicity

(e.g. Hayward et al. 2013)

3. Clustering?

(Chiang +, 2017
Bethermin +, 2017
Donevski +, to be submitted)

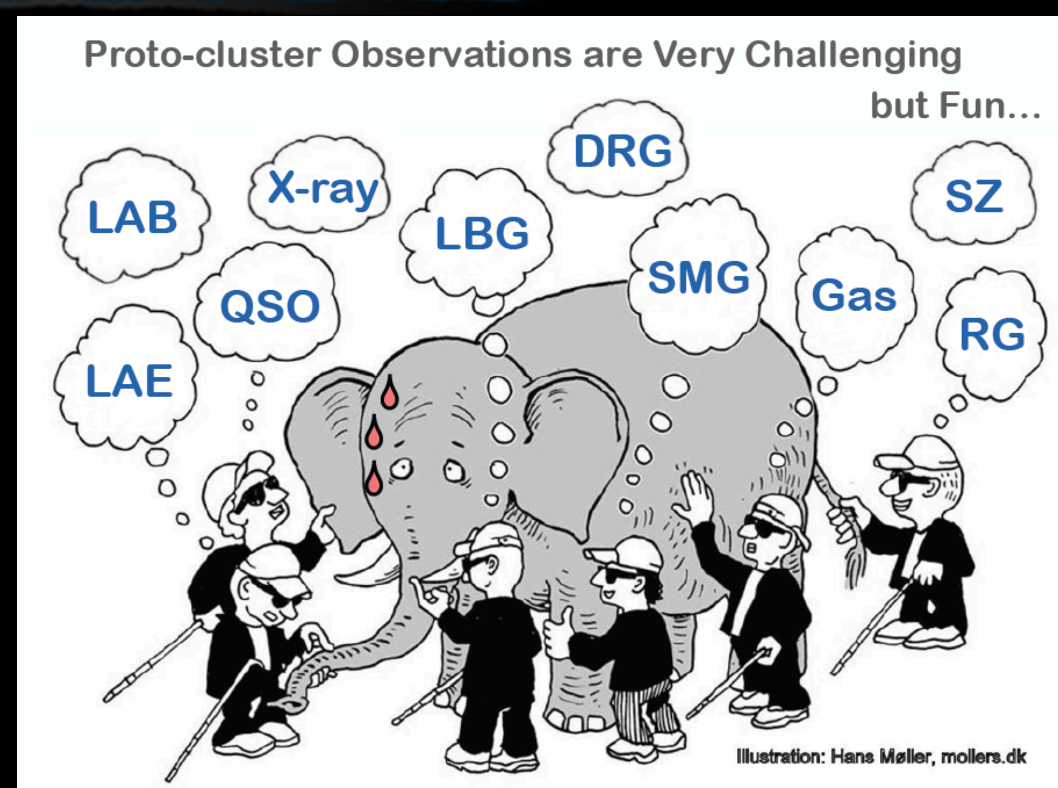
MESSAGE

IMPORTANCE OF FINDING THEM

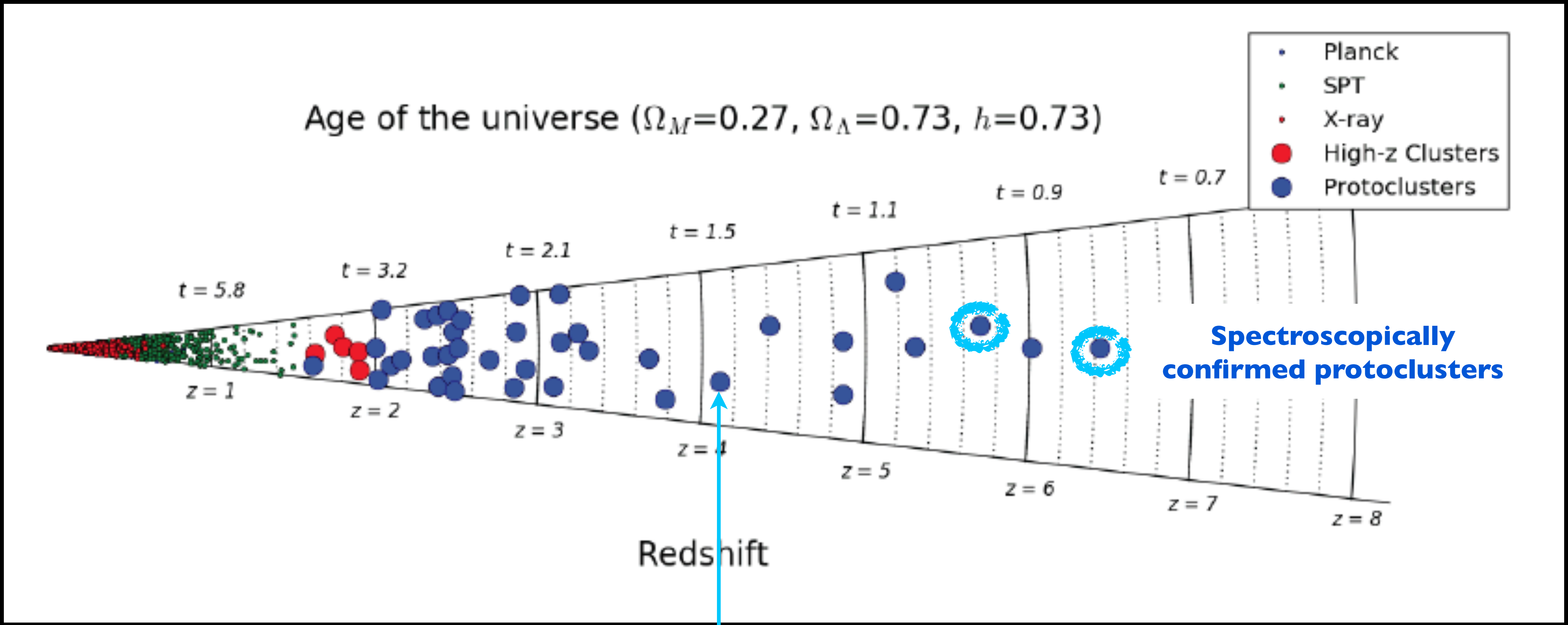
- Fractional volume increases 1000 times from z=0 to z=7 **(e.g. Overzier 2016).**
- Contribution to SFRD at z > 4 -10 significant **(e.g. Chiang +, 2017).**
- Early galaxy growth and star formation dominated by protocluster cores ! **(e.g. Chiang+, 2017, Miller+, 2018, Oteo+, 2018, Harikane+, 2019)**

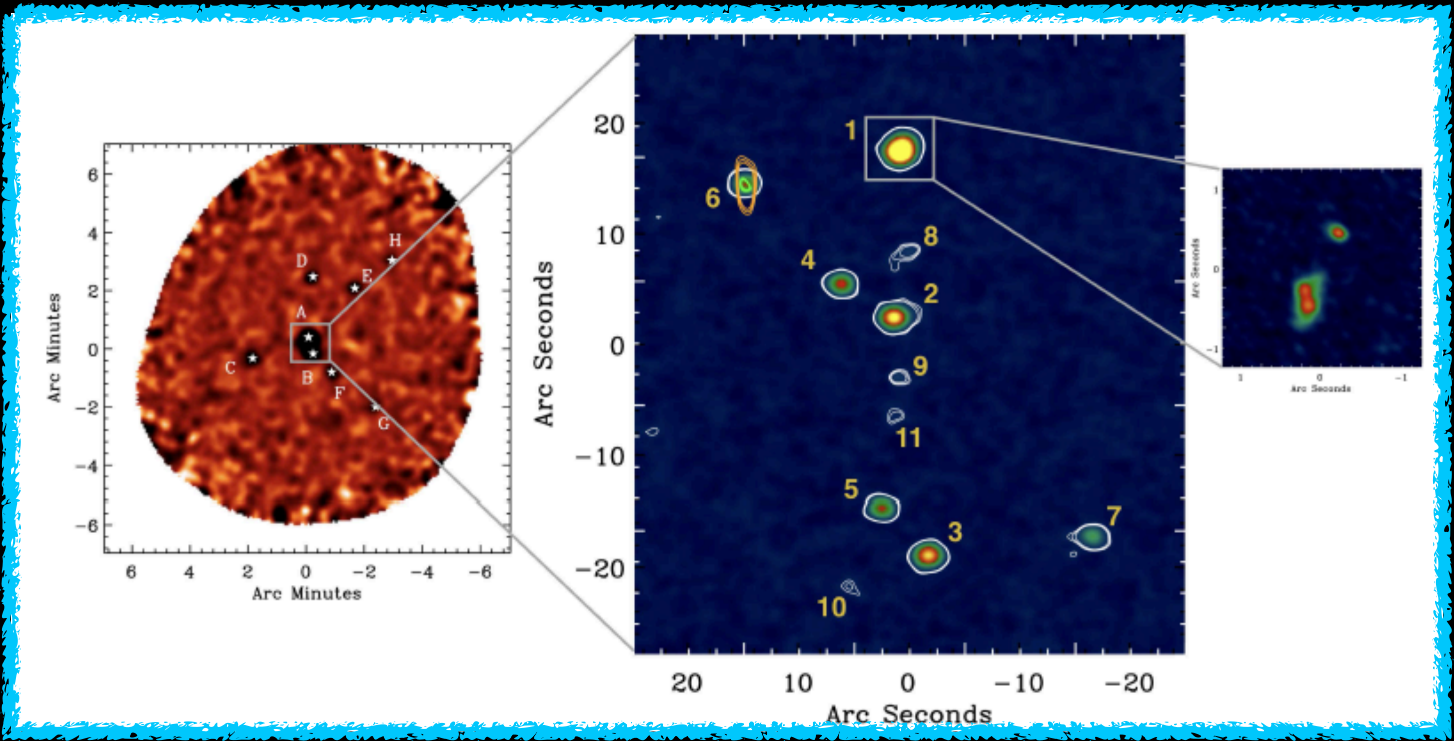
OBSERVATIONAL CHALLENGES:

- No defined red sequence
- Small (observed) overdensity due to faint members
- Selection from optical is limited
- ALMA —> small FoV
- SPIRE —> noise



3.3 Signposting early protoclusters with red DSFGs





The most dense protocluster core of DSFGs

- **z=4.003 (Oteo et al. 2018)**
- **12 galaxies within only 40 sq. arcsec**

But, deficit of low-mass galaxies
No, Ly-alpha emission ...

3.3 Signposting early protoclusters with red DSFGs

Subaru/SCUBA2/ALMA protocluster project (with Uni.Tokyo, Japan)

Goal: Finding and understanding the most distant overdensities in the Universe

OPTICAL-NIR

Mauna Kea... Mirror: 8.2m

HyperSuperCam: 900 Mpix, FoV: 1.5x1.5°

Resolution: 0.25”

SUBMM (850um)

Mauna Kea... Mirror: 15m

FoV: 5’x5’

Resolution: 14”

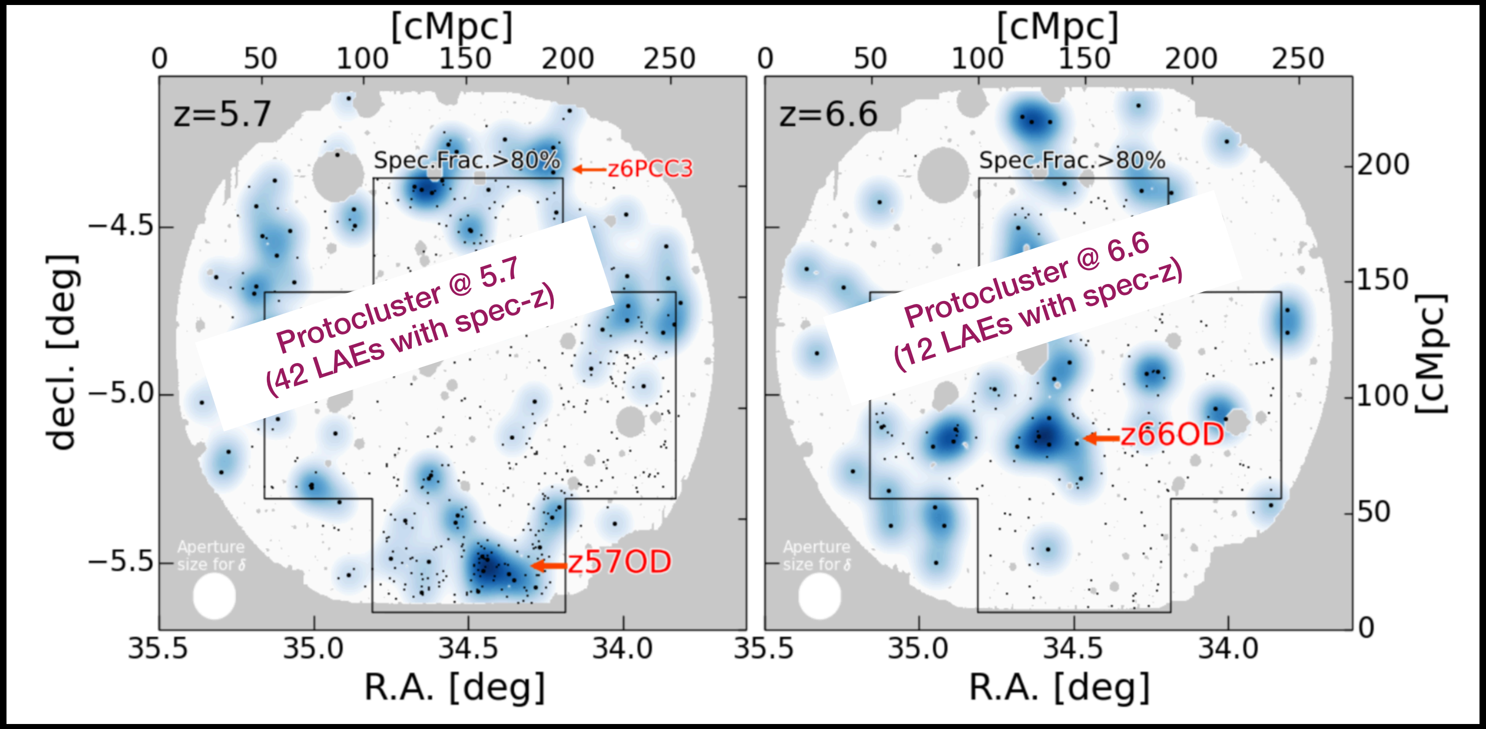
4.3 Discovery of the most distant protoclusters (z ~ 6)

GOAL: Identifying high-z candidate DSFGs in protocluster fields

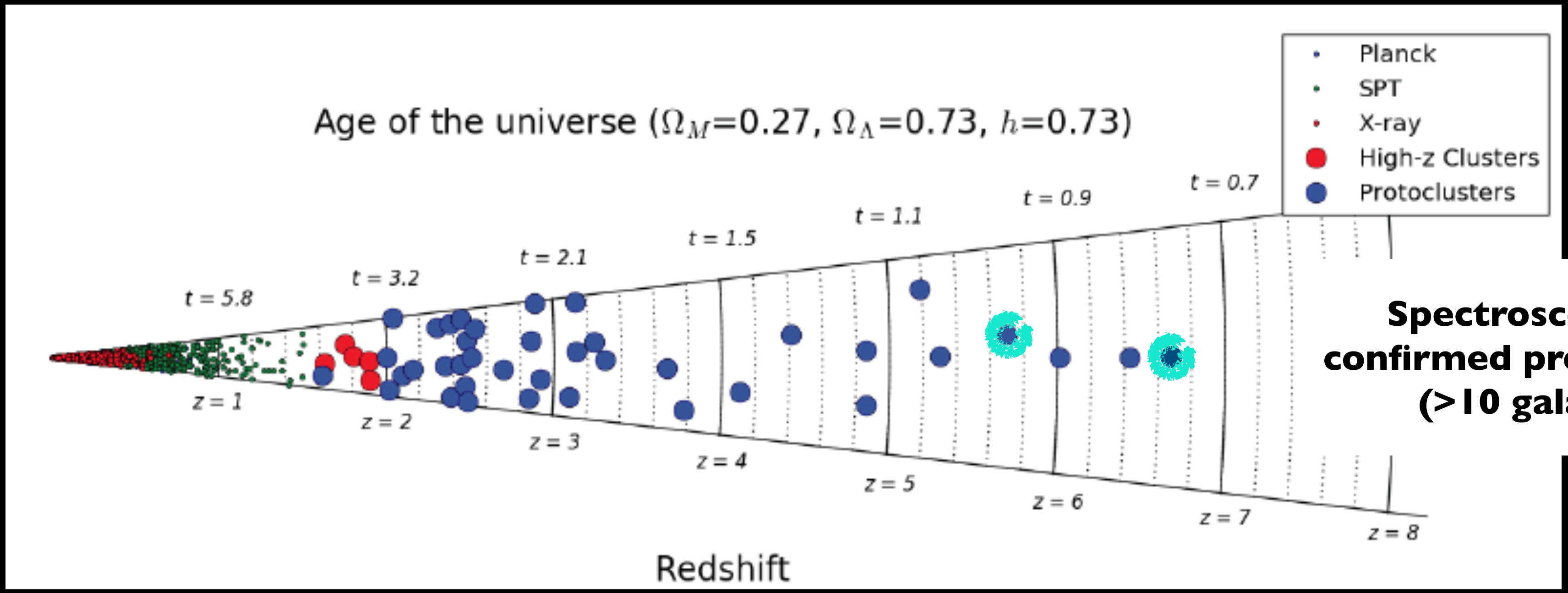
Protocluster of galaxies selected with Ly-α emitters (SILVERRUSH: PI: Ouchi)

Observed area:
3D maps (200 x 200 x 80 cMpc^3) at z=5.69 and z=6.64

e.g. 6’x6’ (=14cMpc x 14cMpc at *z*=5)



(The most distant protocluster confirmed to date, z = 6.67)
Harikane, Ouchi, Ono, Fujimoto, Donevski +., ApJ, 2019



Spectroscopically confirmed protoclusters (>10 galaxies)

4.3 Discovery of the most distant protoclusters (z ~ 6)

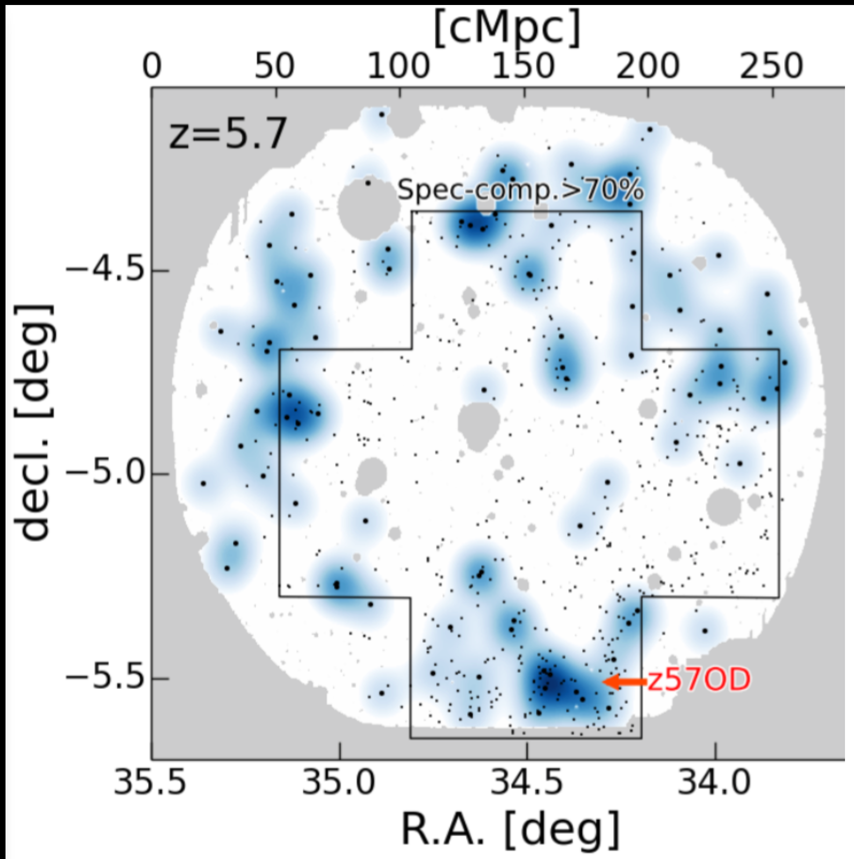
MAIN RESULTS:

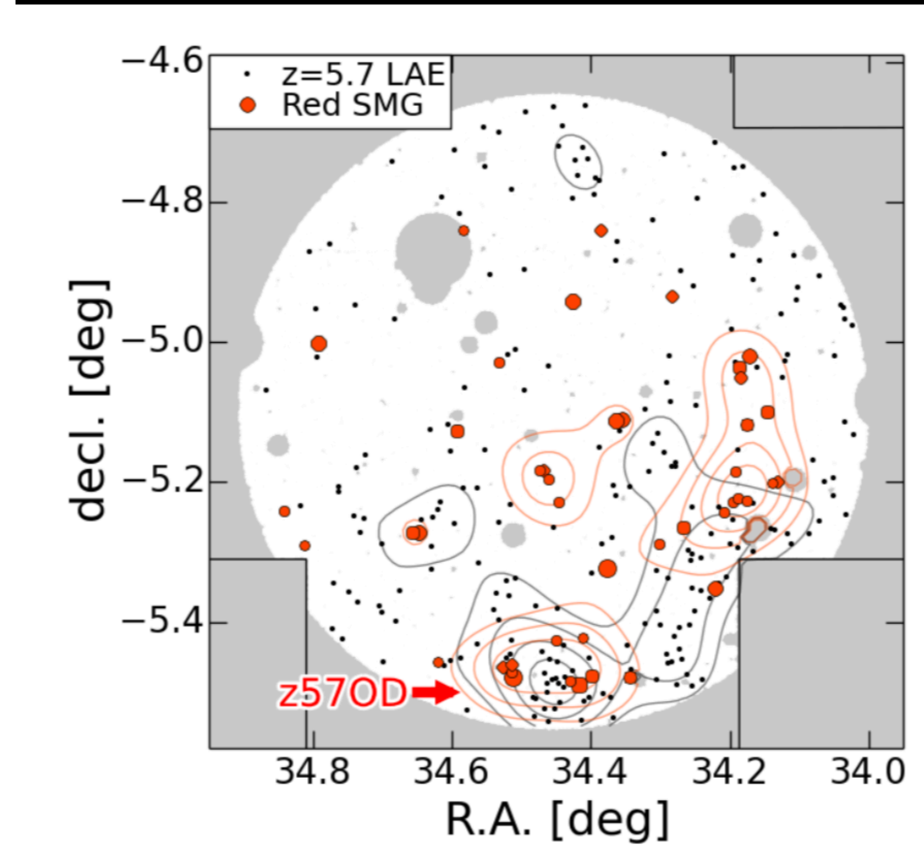
1. The most distant protocluster (z=6.67)

2. Strong clustering of DSFGs found in SCUBA2/SPIRE+ALMA data (red) with LAEs (black).

➡ Synchronous growth of two distinct galactic populations.

(large scale accumulation of baryons within DMhalo)





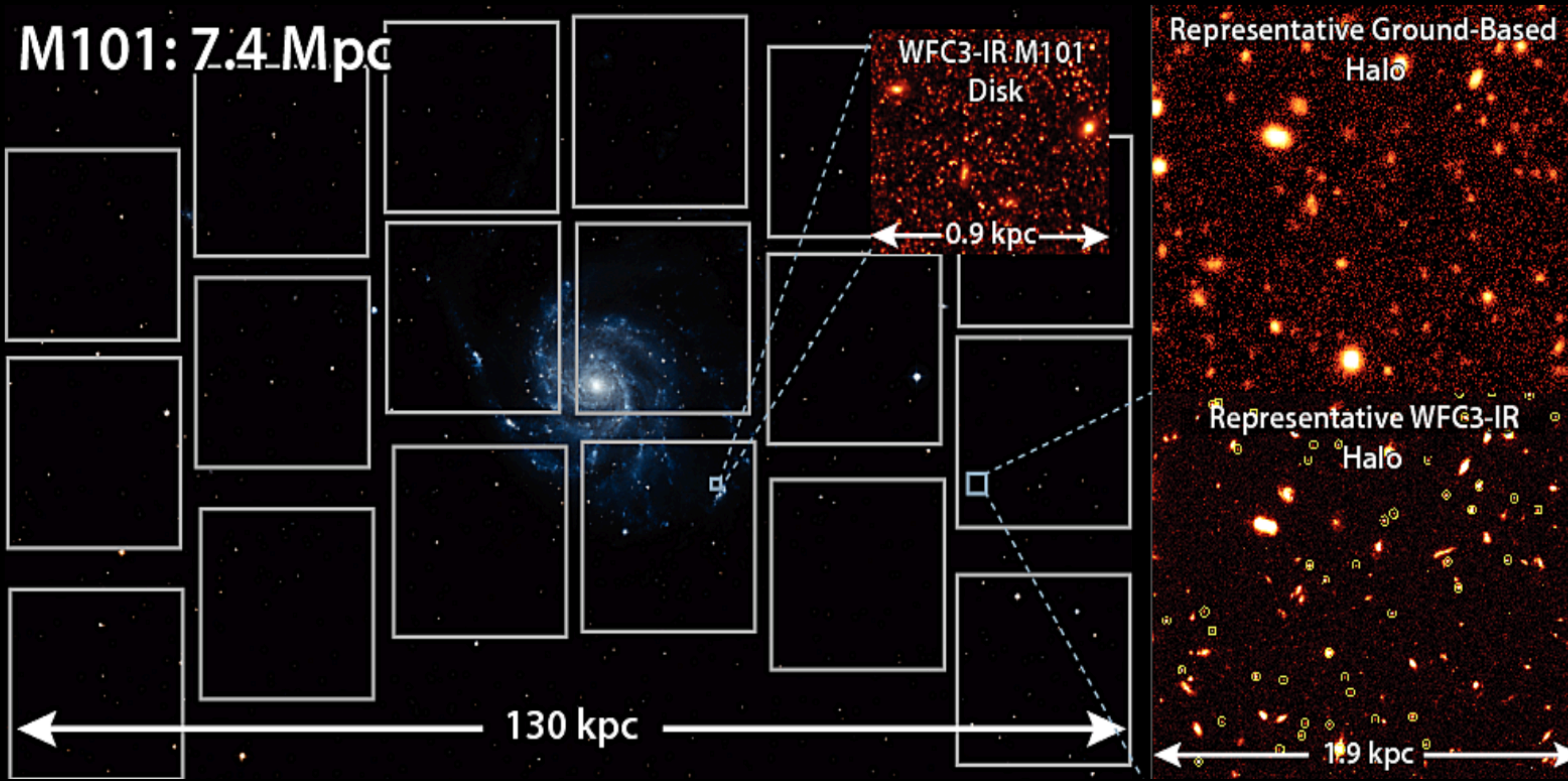
Strong angular cross-correlation between DSFGs and LAEs (Harikane+, 2019)

Future: ALMA C[II] program

Redshifts —> SFRD ?
Gas mass —> depletion time ?

but…
depletion time uncertain if there is ongoing mass accretion !

4. Future surveys



Remarks

A selection of rare IR sources lead to fresh samples of candidate z > 4 DSFGs.

We learn that distant overdensities (protoclusters) of DSFGs have important role in early star-formation even when Universe was less than 1Gyr old at $z \sim 6$.

New quests:

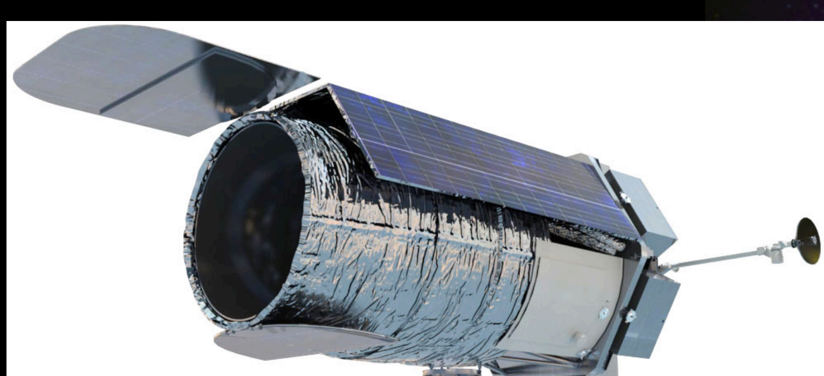
How to systematically inspect the fraction of star-formation in different environments as a function of cosmic time ?

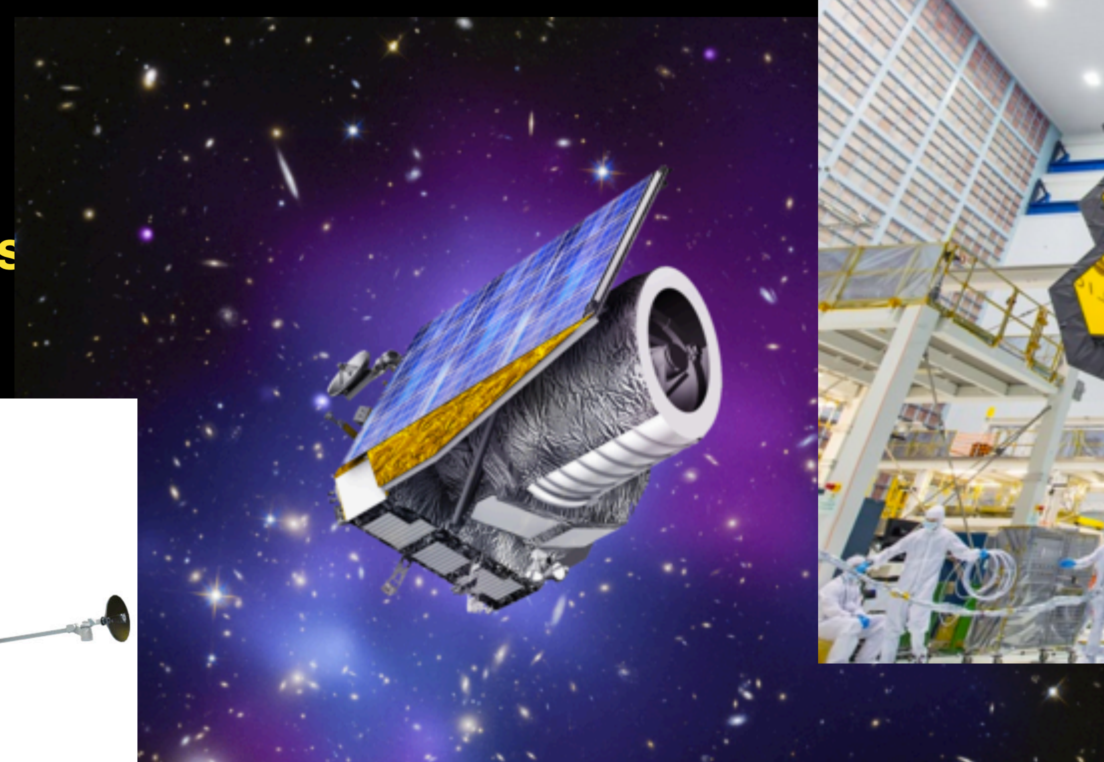
(near) future

• NIKA2 camera
(mm, 30m telescope)

\+ Euclid
(optical, 0.43 deg FoV)

\+ James Webb Space Teles
(NIR/mid-IR)





Send me your questions/comments !

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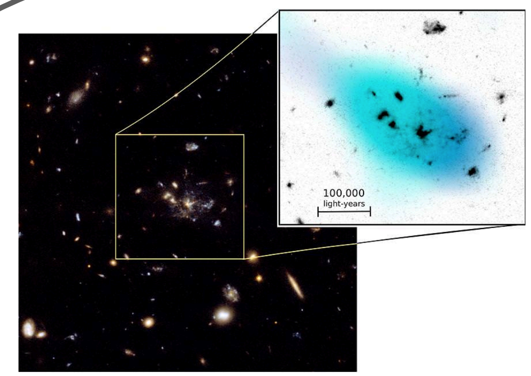
email: darko.donevski@sissa.it

Formation of dust

Dense ISM

Dust growth



t ~ 10-30 Myr

Accretion of metals in cold ISM (metal rich/ molecular H2)

$$\dot{M}_{j,\mathrm{dust}} = \dot{M}^{\mathrm{produced}}_{j,\mathrm{dust}} + \dot{M}^{\mathrm{growth}}_{j,\mathrm{dust}} - \dot{M}^{\mathrm{destruct}}_{j,\mathrm{dust}} - \dot{M}^{\mathrm{SF}}_{j,\mathrm{dust}} + \dot{M}^{\mathrm{infall}}_{j,\mathrm{dust}} - \dot{M}^{\mathrm{out}}_{j,\mathrm{dust}},$$

EJECTA

AGB stars

CC SNe

t ~ few Myr to Gyr

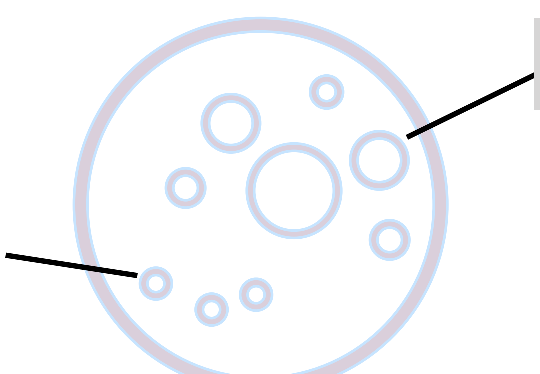
t ~ 1e4 yr

Dust destruction

SNe shocks and collisions

Deriving dust properties of DSFGs

Carbon grains



Silicate grains

ISRF = Diffuse ISM + PDR

$$\frac{\mathrm{d}M_{\mathrm{dust}}}{\mathrm{d}U} = \{(1-\gamma)M_{\mathrm{dust}}\delta(U-U_{\mathrm{min}}) + \gamma M_{\mathrm{dust}}\frac{\alpha-1}{U_{\mathrm{min}}^{1-\alpha}-U_{\mathrm{max}}^{1-\alpha}}U^{-\alpha},$$

$$\langle U\rangle = \frac{L_{\mathrm{dust}}}{P_0 M_{\mathrm{dust}}},$$

<U> ~ SFE/Z