# Dark Matter
# Overview

- Lecture 1&2: Evidence, Properties and Candidates
- Lecture 3&4: Search strategies: Direct and Indirect detection and colliders

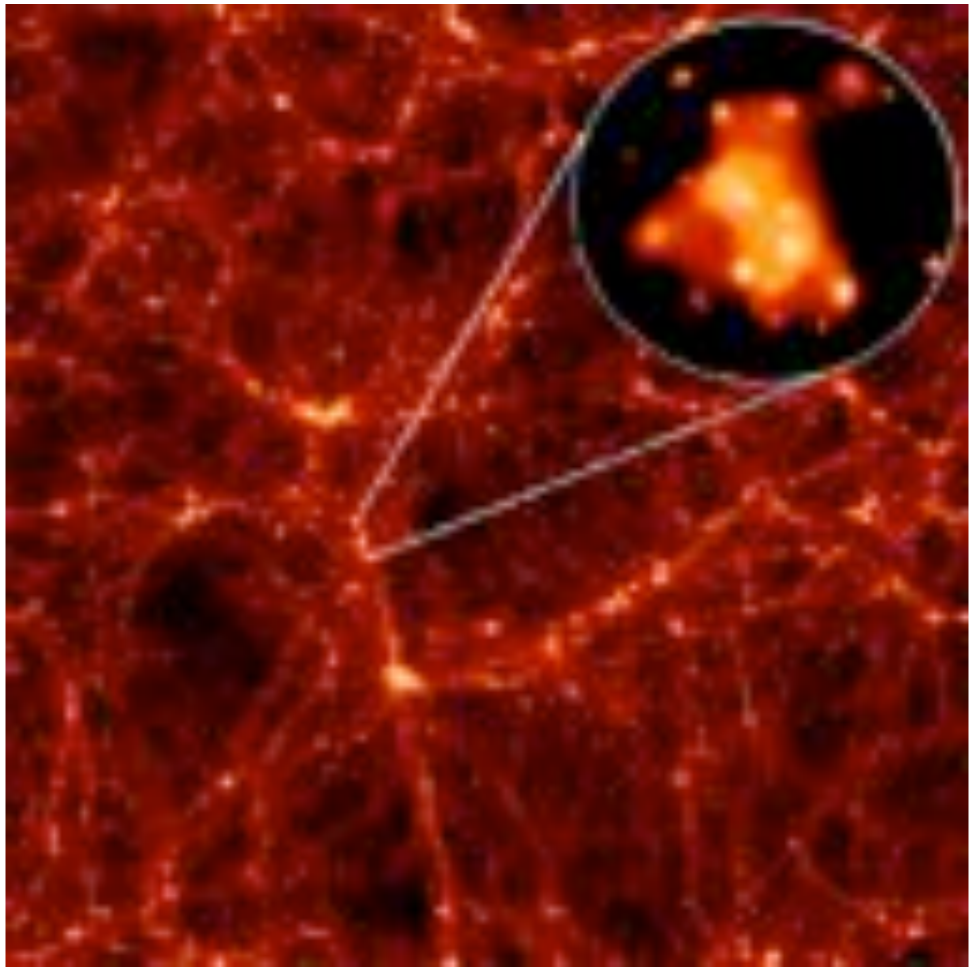
# Dark Matter
# Additional material

- Lectures @ ICTP schools (some material also here):
  - Marco Cirelli, 2012: http://cdsagenda5.ictp.trieste.it/askArchive.php?base=agenda&categ=a11178&id=a11178s0t8/lecture_notes
  - Alejandro Ibarra, 2013: http://cdsagenda5.ictp.trieste.it/full_display.php?ida=a12185
- Reviews: Particle Dark Matter: Evidence, Candidates and Constraints

  Gianfranco Bertone, Dan Hooper, Joseph Silk http://arXiv.org/abs/hep-ph/0404175
- Books: Kolb&Turner, 'Early Universe'

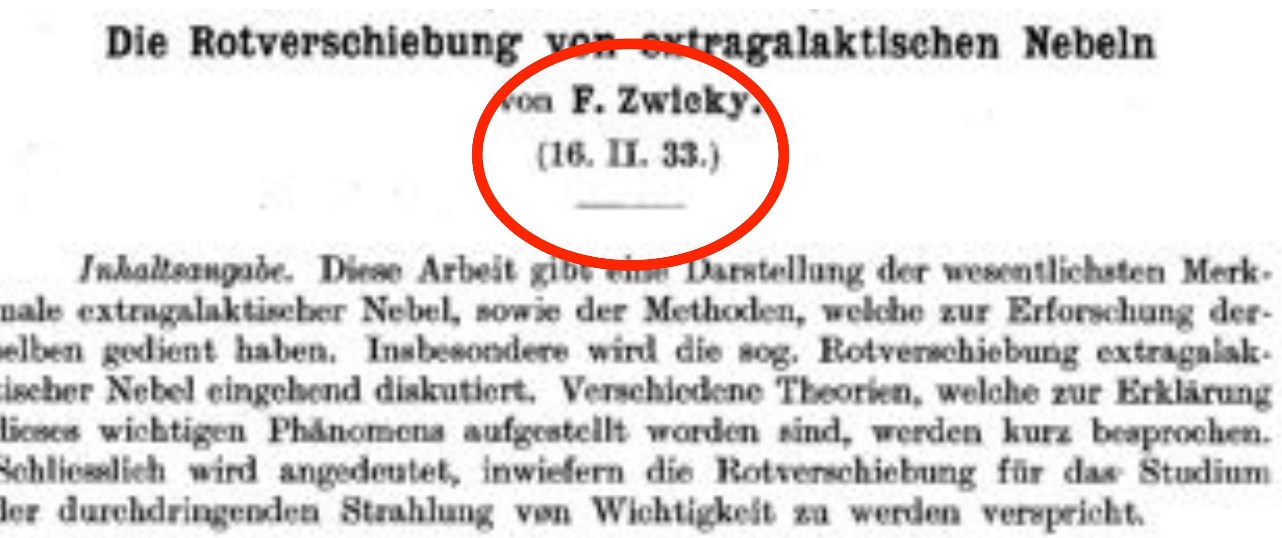
- First evidence in the 30's by measuring the temperature of the gas in Galaxy clusters

- The largest gravitationally bound structures!



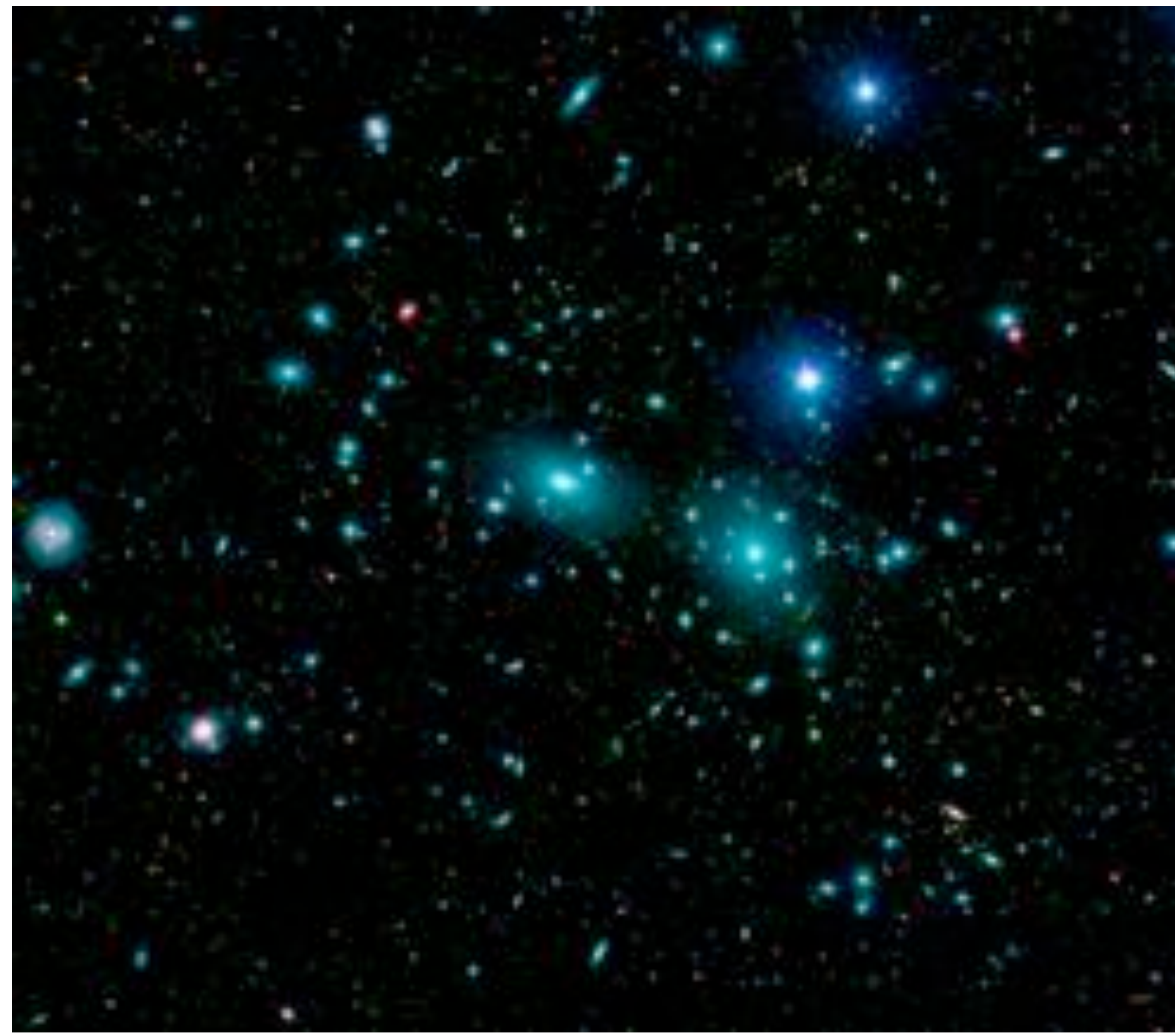
**Virgo Galaxy Cluster**: the closest cluster of galaxies to our Milky Way Galaxy It contains ***over 100 galaxies bound by gravity.*** Pictured above, the center of the Virgo cluster might appear to some as a human face, NASA, astronomy picture of the day, 02/05.

- First evidence in the 30's by measuring the temperature of the gas in Galaxy clusters: 01) motions of galaxies in clusters


Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.
(16. II. 33.)

*Inhaltsangabe.* Diese Arbeit gibt eine Darstellung der wesentlichsten Merknale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derelben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalakischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung lieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium ler durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

**'Dunkel Materie'**



Coma cluster (spans 2$^{o}$ on the sky)

- First evidence in the 30′s by measuring the temperature of the gas in Galaxy clusters: 01) motions of galaxies in clusters

- Zwicky used measurement of a Doppler shift of Galaxies to infer their velocities

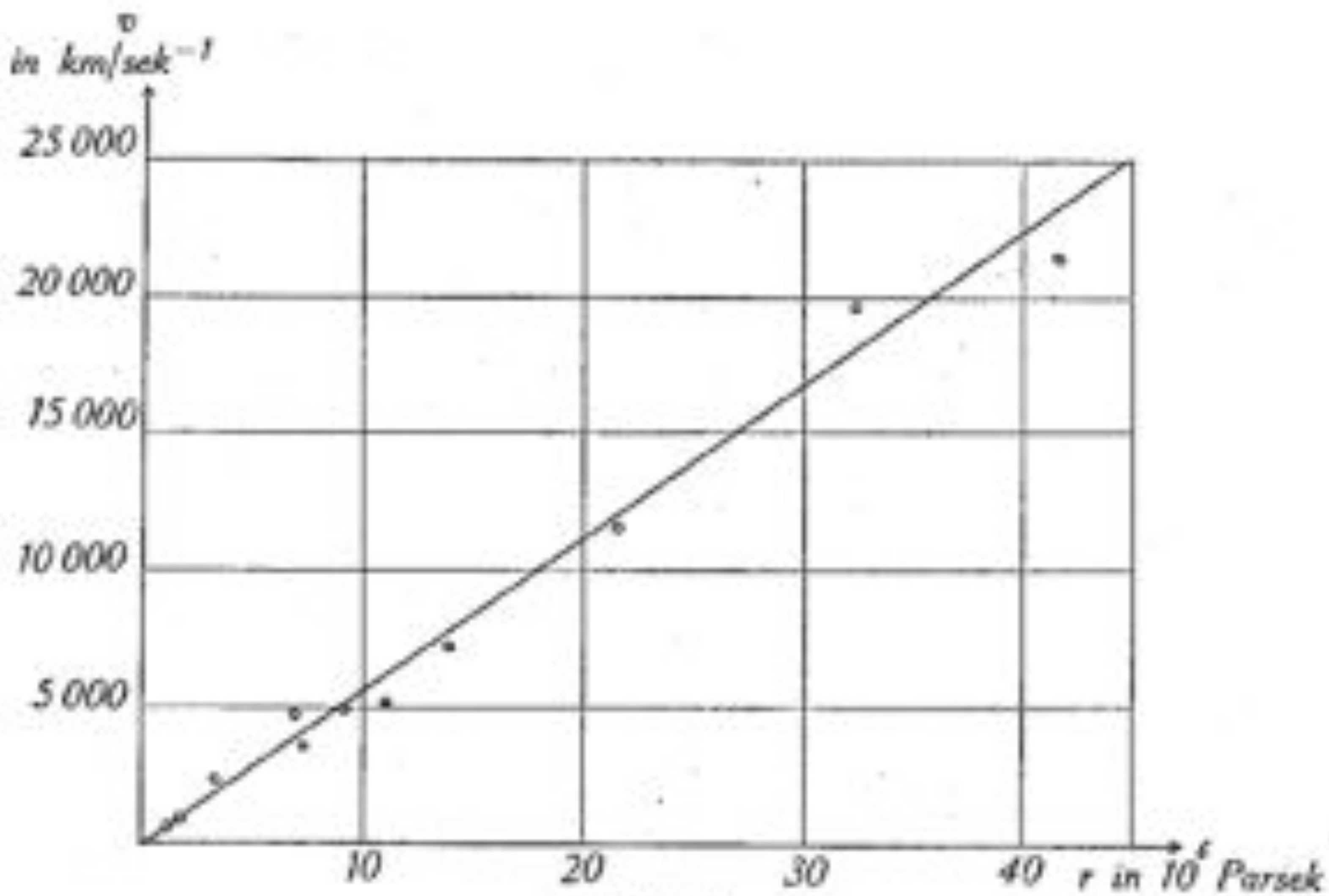



Fig. 2.

- First evidence in the 30′s by measuring the temperature of the gas in Galaxy clusters: 01) motions of galaxies in clusters

For an isolated self-gravitating system,

$$2K + U = 0$$

$$K = \frac{1}{2} M \langle v^2 \rangle \qquad U = -\frac{\alpha G M^2}{\mathcal{R}}$$

$$M = \frac{\langle v^2 \rangle \mathcal{R}}{\alpha G}$$

$$\boxed{\mathcal{M} > 9 \times 10^{46} \mathrm{gr}}$$

Total mass which determines speed of Galaxies!

- First evidence in the 30's by measuring the temperature of the gas in Galaxy clusters: 01) motions of galaxies in clusters

**luminous**

2- Count the number of galaxies (~1000) and calculate the average mass

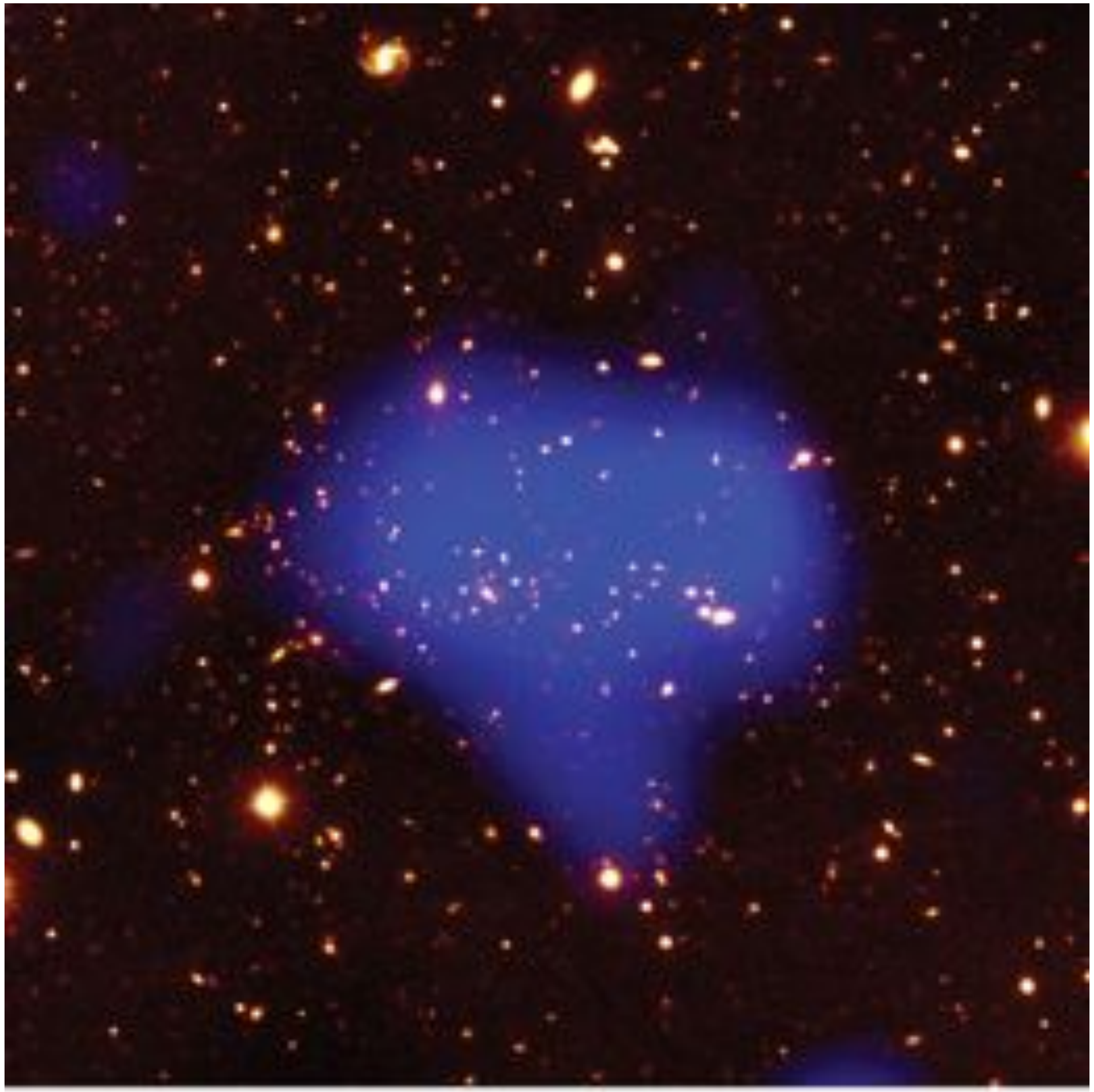
$$\boxed{\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about $8.5 \times 10^7$ suns. According to (36), the conversion factor $\gamma$ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 \,, \tag{37}$$

- Correct result is in fact <<, closer to 50...

- Further evidence from Galaxy clusters: 02) temperature of the hot gas

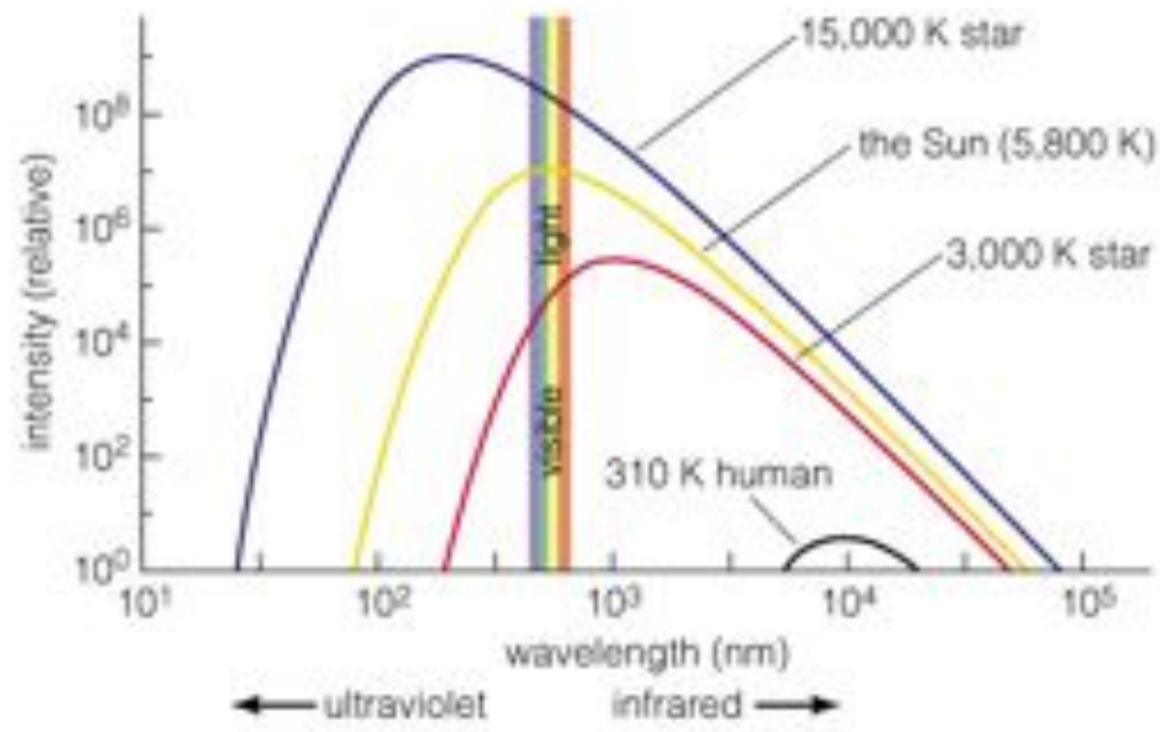


2) Clusters contain large amounts of gas. The gas is extremely hot (100 million Kelvin) and it therefore emits very energetic, X ray photons:

A distant cluster of Galaxies in both, visible, and X-ray light (the blue overlay).

- Further evidence from Galaxy clusters: 02) temperature of the hot gas

*Radiation of a hot gas* tells us cluster mass. How does that work:




Thermal radiation spectrum

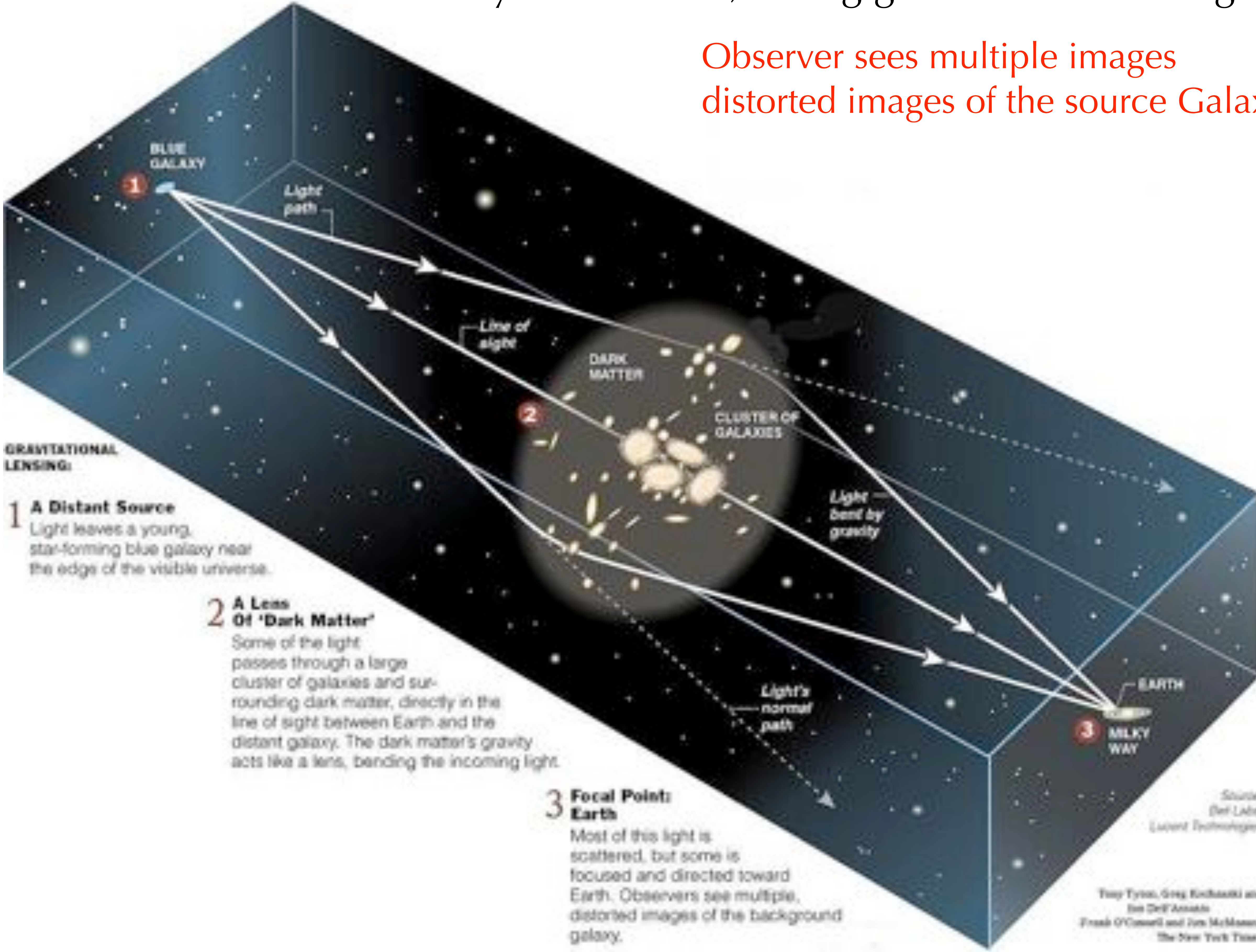
How fast molecules of gas are moving is connected to the amount of gravity they feel: ***stronger the gravity, faster the gas is moving and hotter it is.***

And, we can measure its *temperature* by measuring the *spectrum of photons* the gas emits!

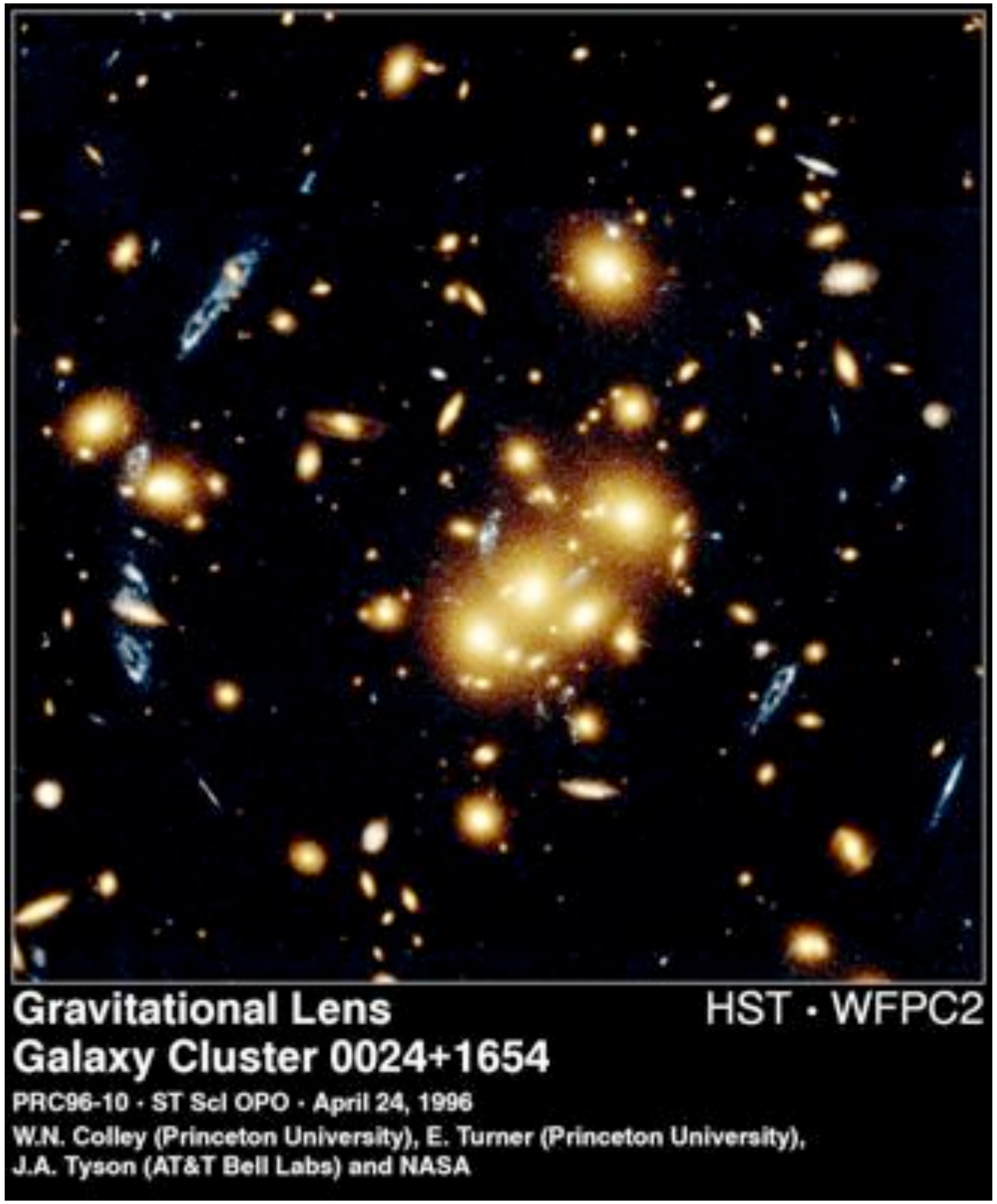
**And again, it turns out, dark matter has to be around.**

- Further evidence from Galaxy clusters: 03) strong gravitational lensing

Observer sees multiple images distorted images of the source Galaxy.



- Further evidence from Galaxy clusters: 03) gravitational lensing




The cluster galaxies are the yellowish ones.

The faint blue galaxies are distant high-redshift galaxies that are lensed by the cluster (this radiation is redshifted to appear blue to us).

Four multiple images of a Blue Source Galaxy!

A great concentration of dark matter in the cluster centers is required to give these dramatic lensing events.

All three methods of measuring cluster mass indicate similar amounts of dark matter ~85%

The same is true in galaxies!

- Evidence at Galaxy scales: rotational curves

Vera Rubin (1928 -)

In the 1970's performed Doppler observations of the orbital speeds in spiral galaxies and produced clear observational evidence that finally convinced astronomers in the existence of DM.

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

*Received 1969 July 7; revised 1969 August 21*

ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm$^{-1}$. Radial velocities, principally from H$\alpha$, have been determined with an accuracy of $\pm 10$ km sec$^{-1}$ for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

For the region interior to 3 kpc where no emission regions have been identified, a narrow [N II] $\lambda$6583 emission line is observed. Velocities from this line indicate a rapid rotation in the nucleus, rising to a maximum circular velocity of $V = 225$ km sec$^{-1}$ at $R = 400$ pc, and falling to a deep minimum near $R = 2$ kpc.

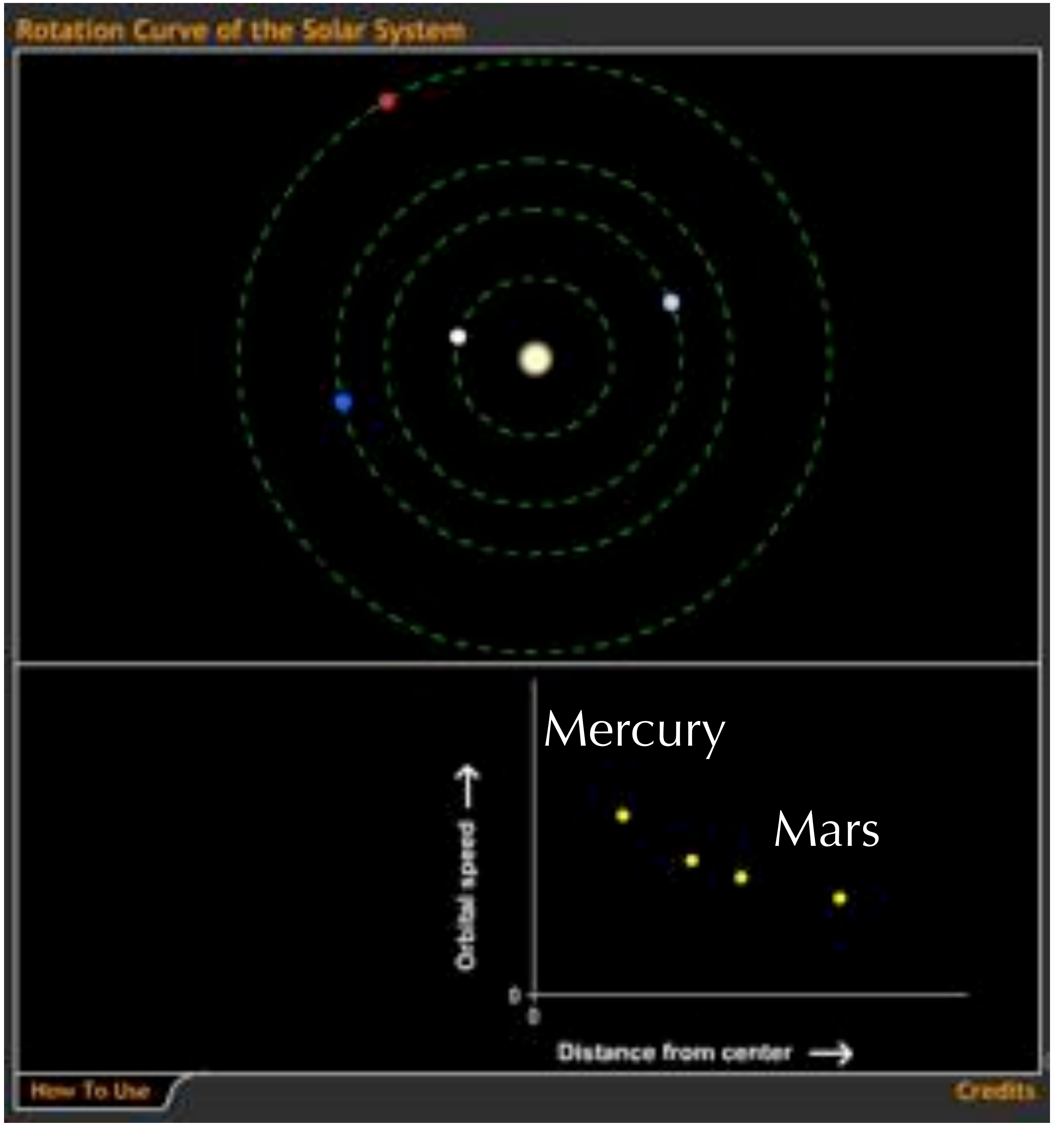
From the rotation curve for $R \leq 24$ kpc, the following disk model of M31 results. There is a dense, rapidly rotating nucleus of mass $M = (6 \pm 1) \times 10^9 M_\odot$. Near $R = 2$ kpc, the density is very low and the rotational motions are very small. In the region from 500 to 1.4 kpc (most notably on the southeast minor axis), gas is observed leaving the nucleus. Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11} M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

The optical velocities, $R > 3$ kpc, agree with the 21-cm observations, although the maximum rotational velocity, $V = 270 \pm 10$ km sec$^{-1}$, is slightly higher than that obtained from 21-cm observations.

- Evidence at Galaxy scales: rotational curves

In our Solar System orbital speed declines with a distance to the Sun because Sun has almost all the mass.

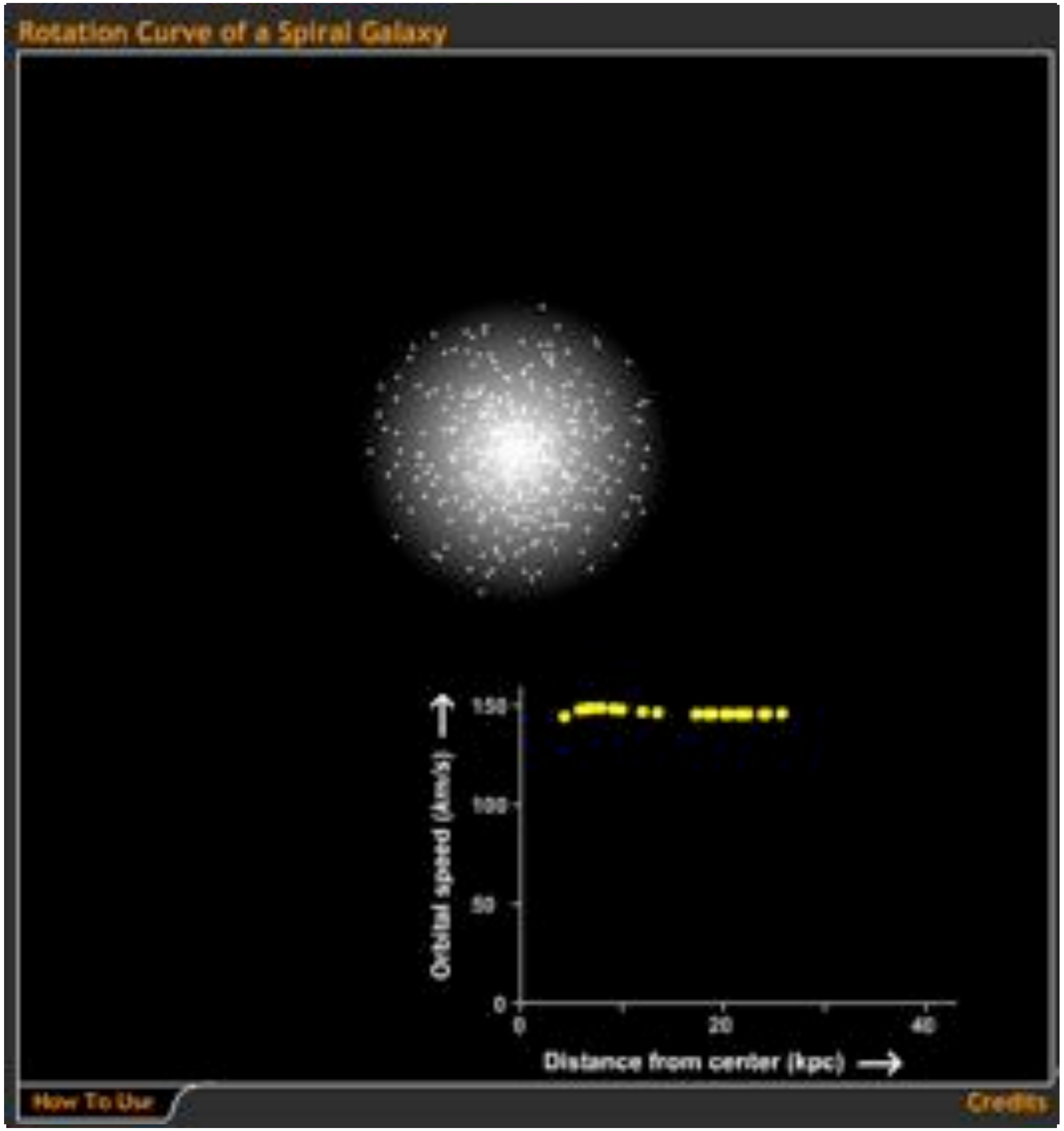
The gravitational force goes as the inverse of radius squared. So as you go further away from a mass, the force decreases by the square of your distance. Since the force goes down, the velocity goes down as well.



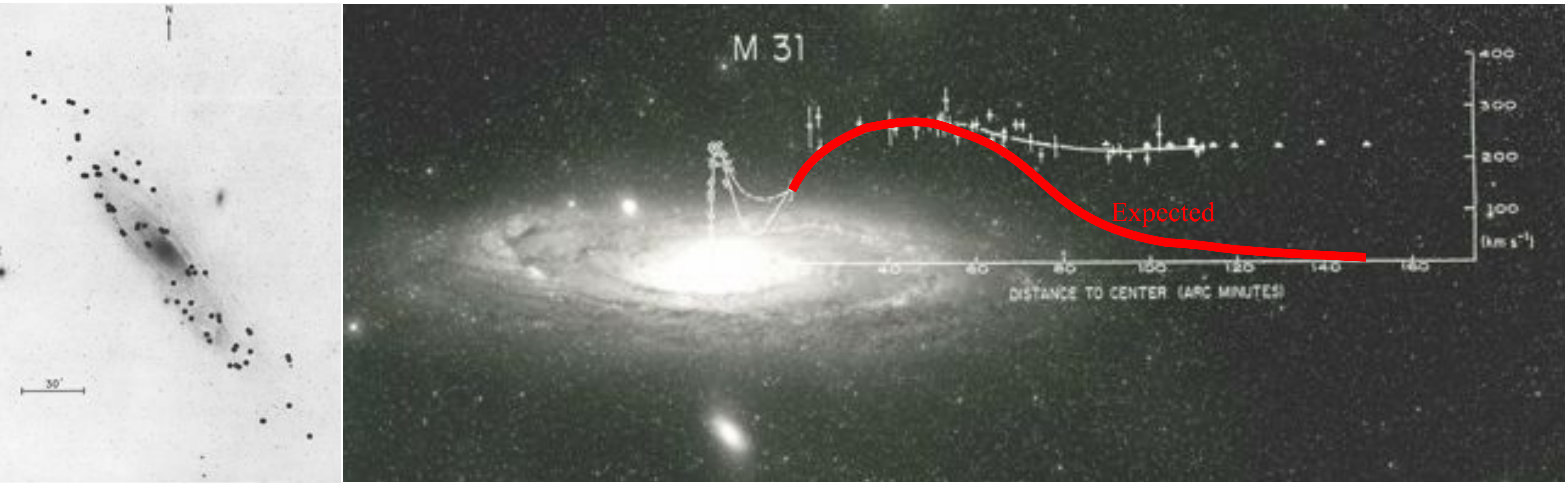
- Evidence at Galaxy scales: rotational curves

Vera Rubin measured in the 1970's that stars orbiting the outside of a galaxy traveled just as fast as those orbiting closer to the center.

→ There should be some huge, invisible mass exerting the gravitational force necessary for those outer stars to stay in orbit.

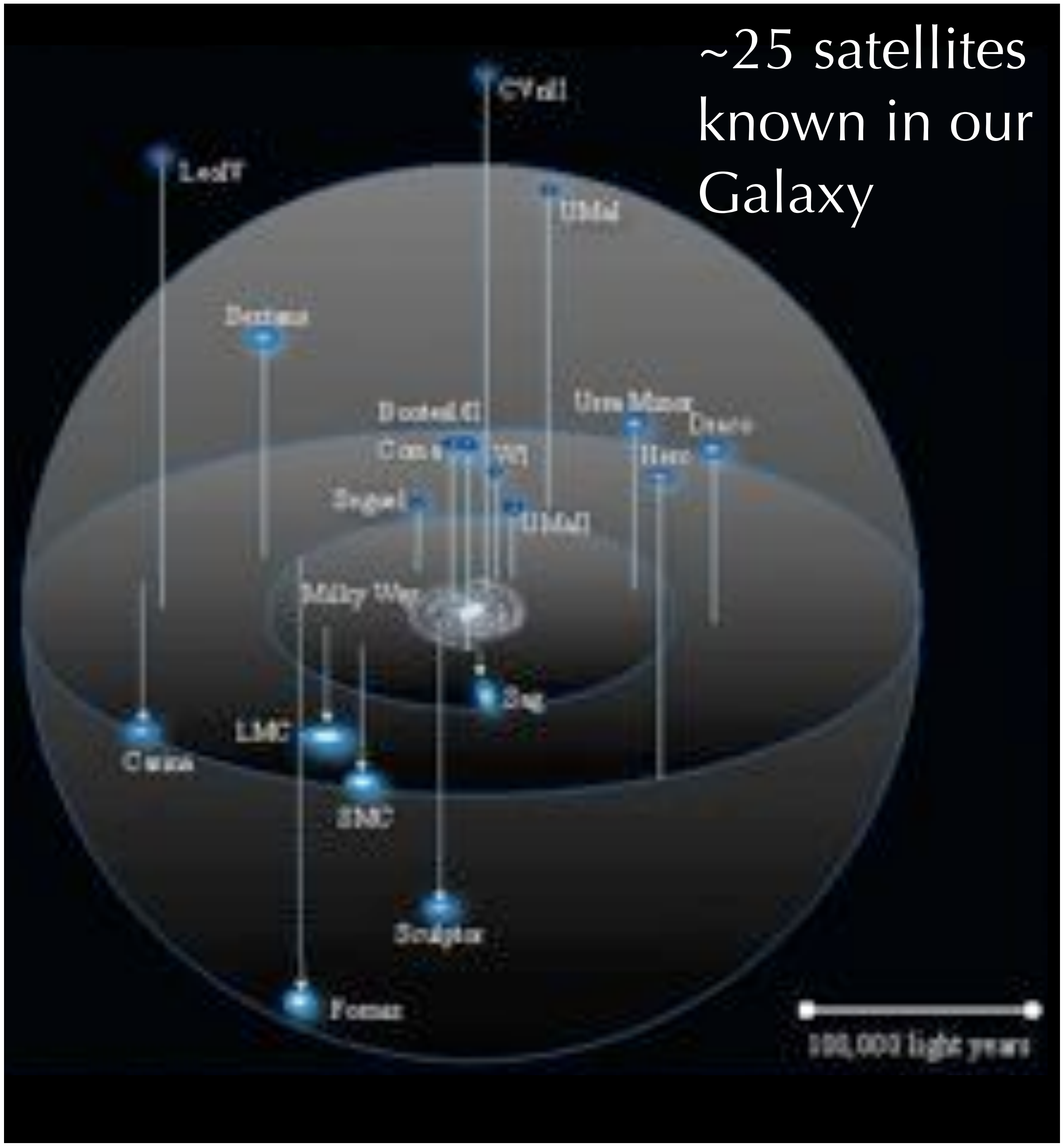


• Evidence at Galaxy scales: rotational curves




→ The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

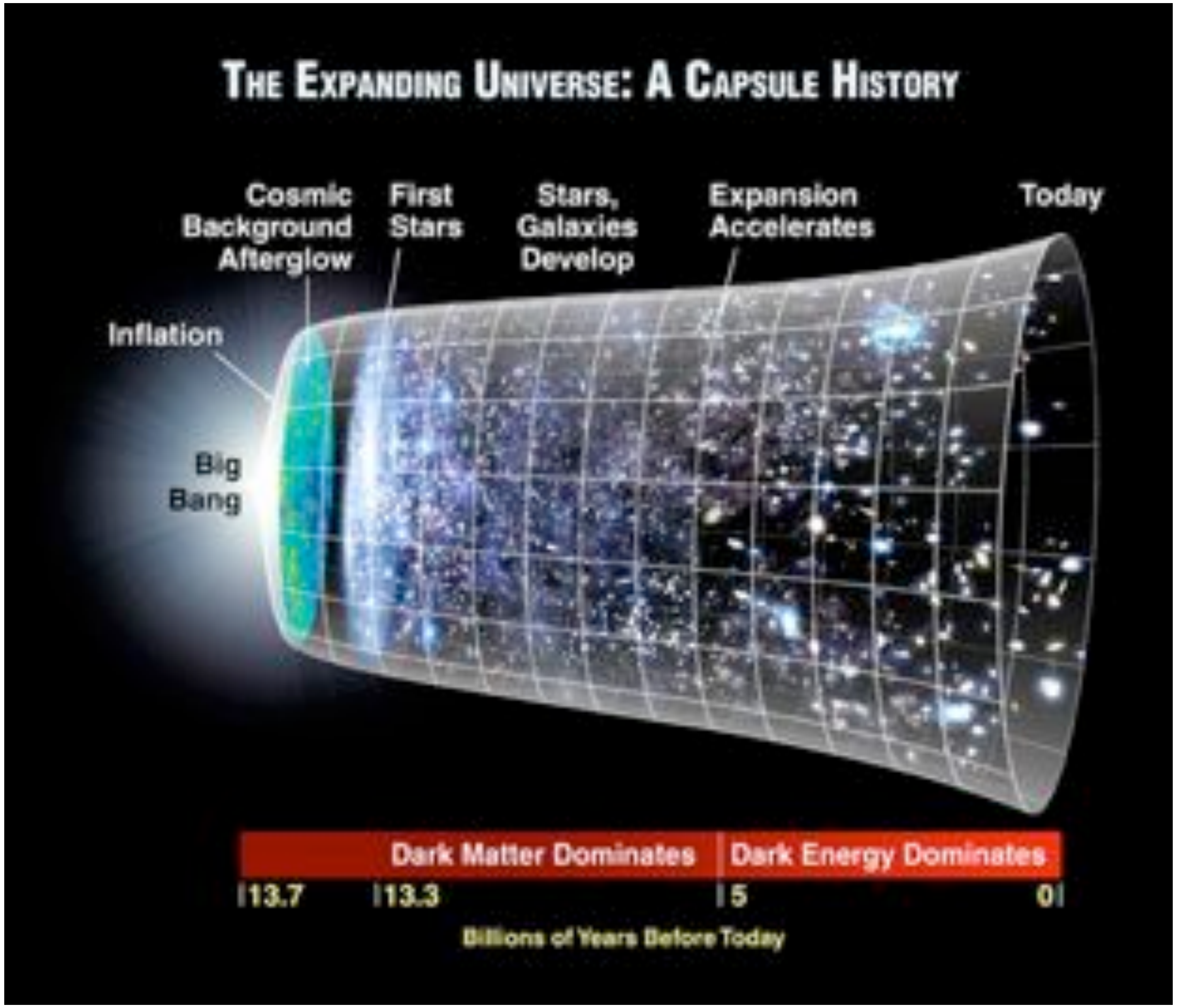
- Evidence at scales of Galaxy satellites: velocity dispersion of satellite Galaxies of our Milky Way.




- Each of them few (~100, 1000) stars, 'miniature galaxies'
- Total mass ~$10^6$ Msol
- we today know **M/L~100** →DM dominated systems!

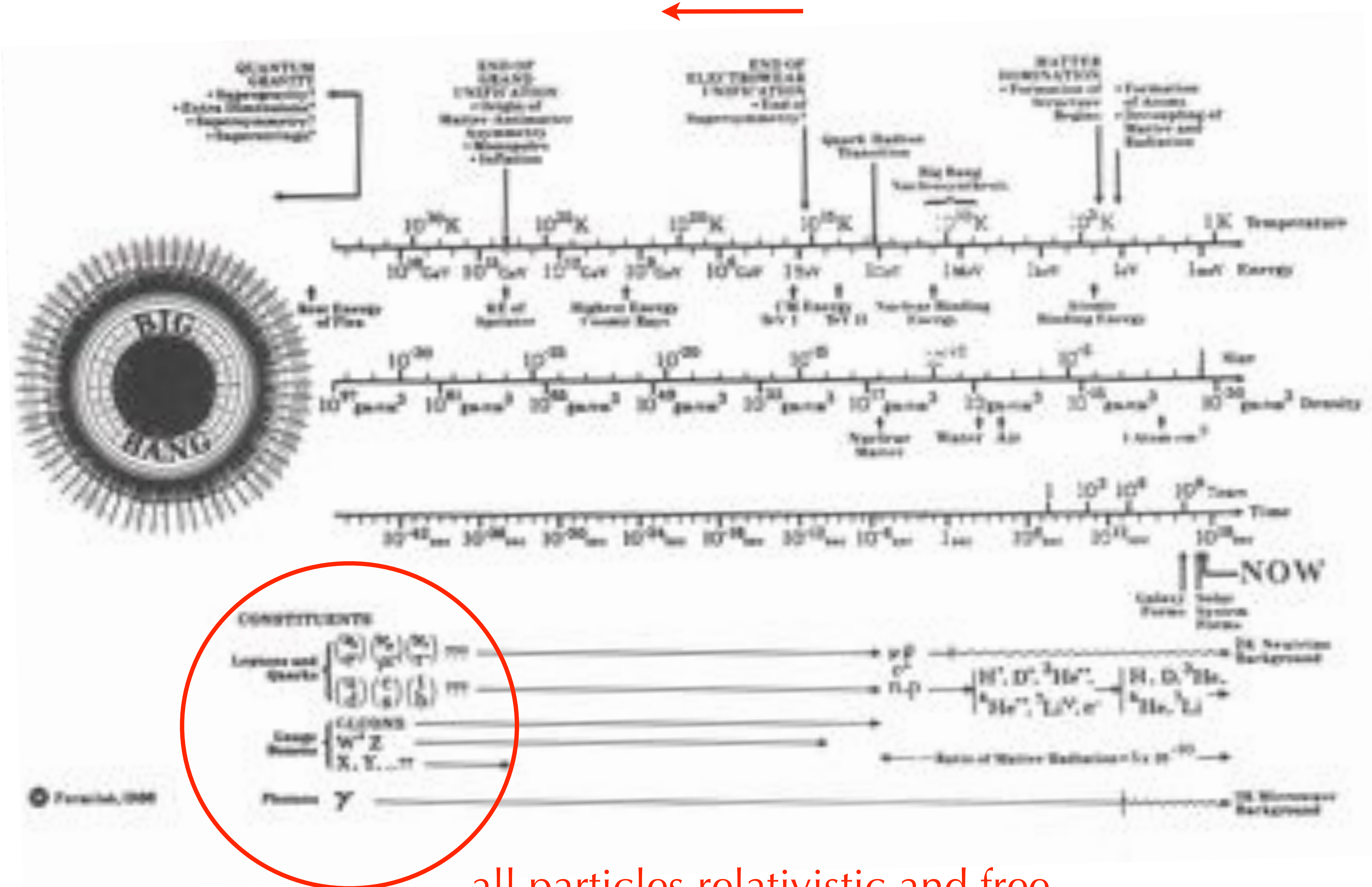
Leo IV Galaxy, discovered in the Sloan data.

- How about ***large*** scales or ***early*** Universe?
- Because most of the matter in the Universe is dark matter, **its characteristics have a great effect on how the Universe evolves and on how structures are formed**.
- it is the key component in our modern story of how we got here: the standard cosmological model "Lambda Cold Dark Matter".



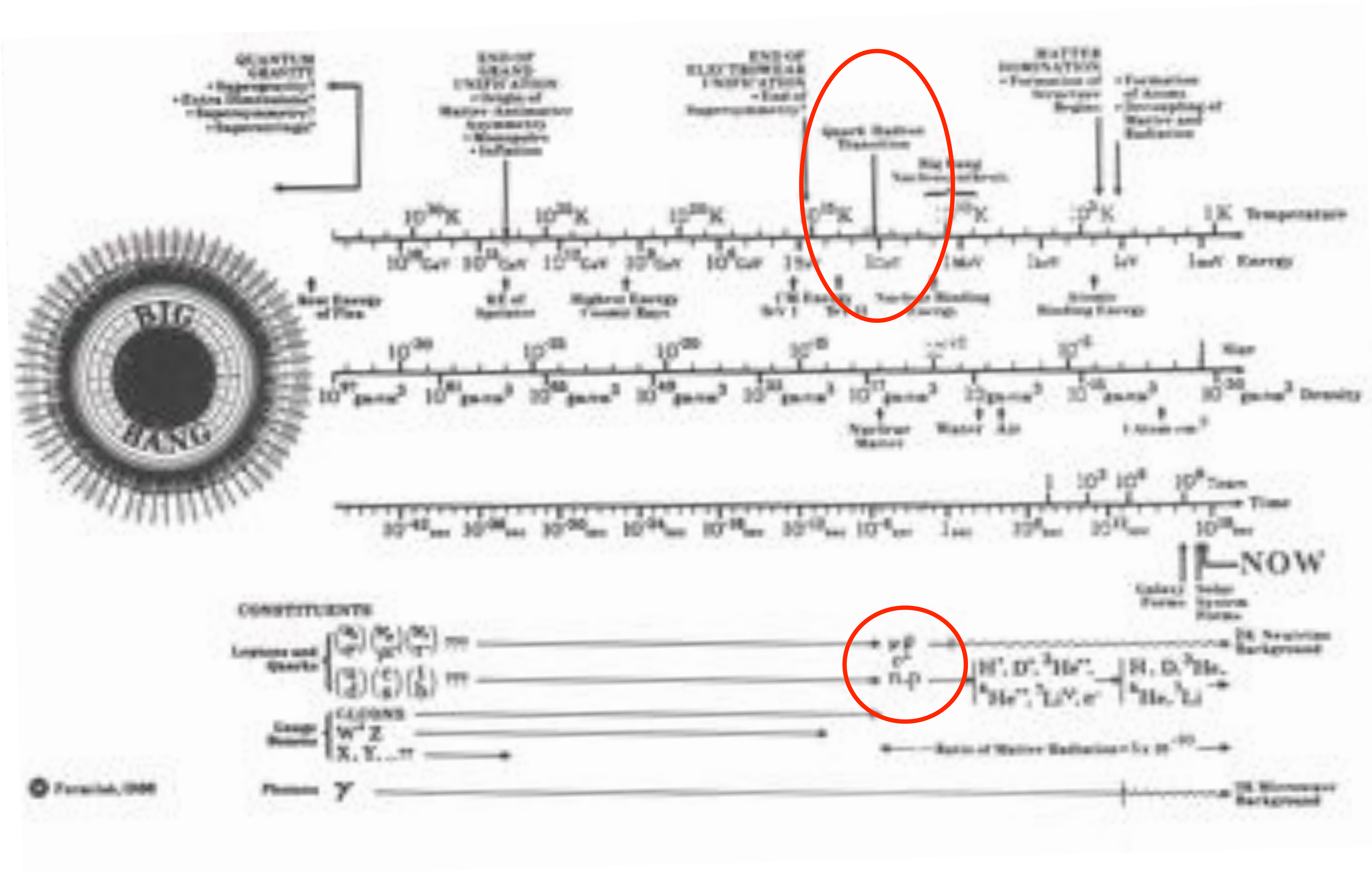
- a (veeery) brief history of the Universe:

<~ 1TeV Standard Model



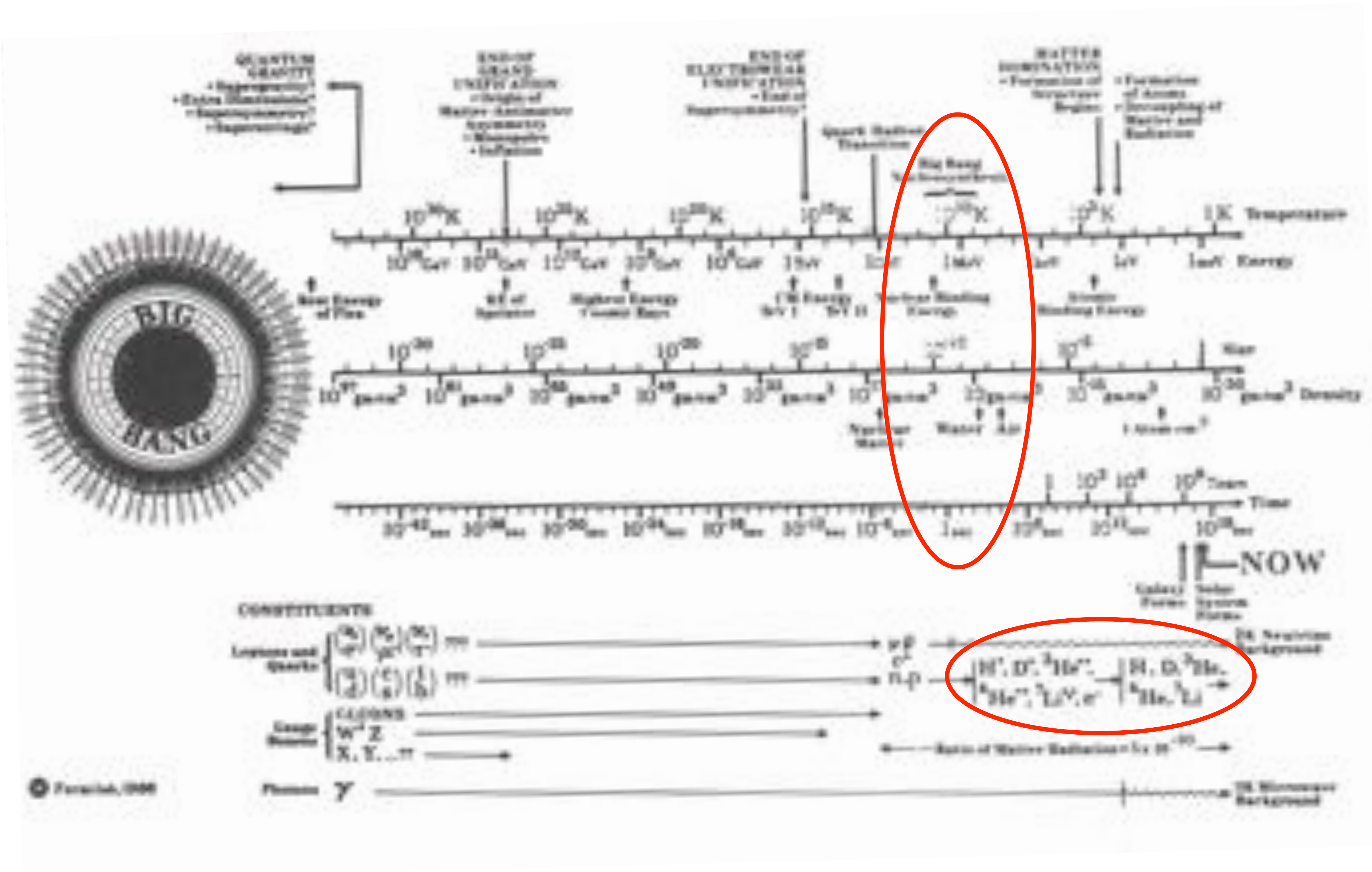

all particles relativistic and free

- a (veeery) brief history of the Universe:



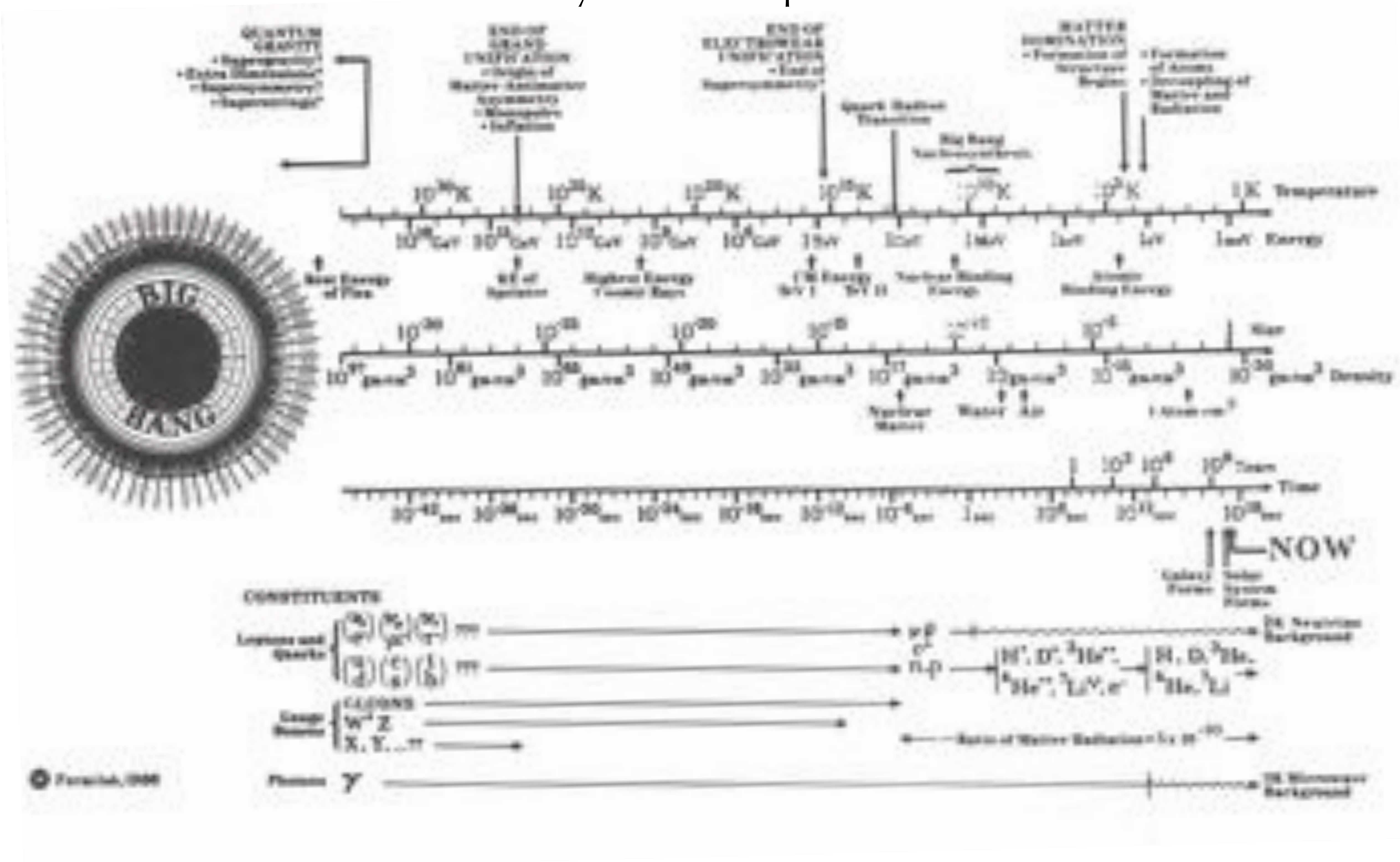
- a (veeery) brief history of the Universe:

Big Bang Nucleosynthesis: all light elements formed!



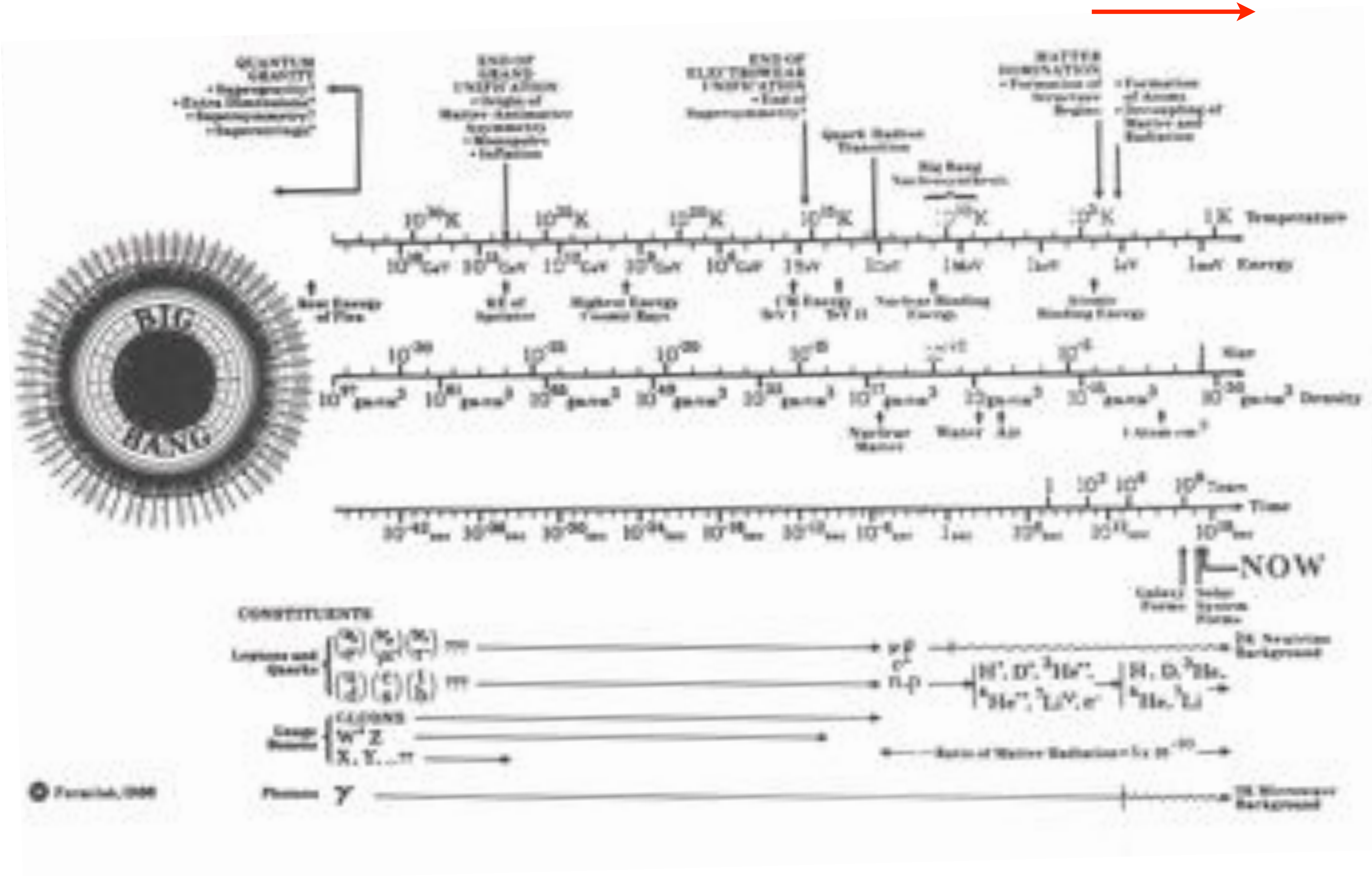
- a (veeery) brief history of the Universe:

Radiation domination : energy density in the Universe dominated by relativistic particles



- a (veeery) brief history of the Universe:

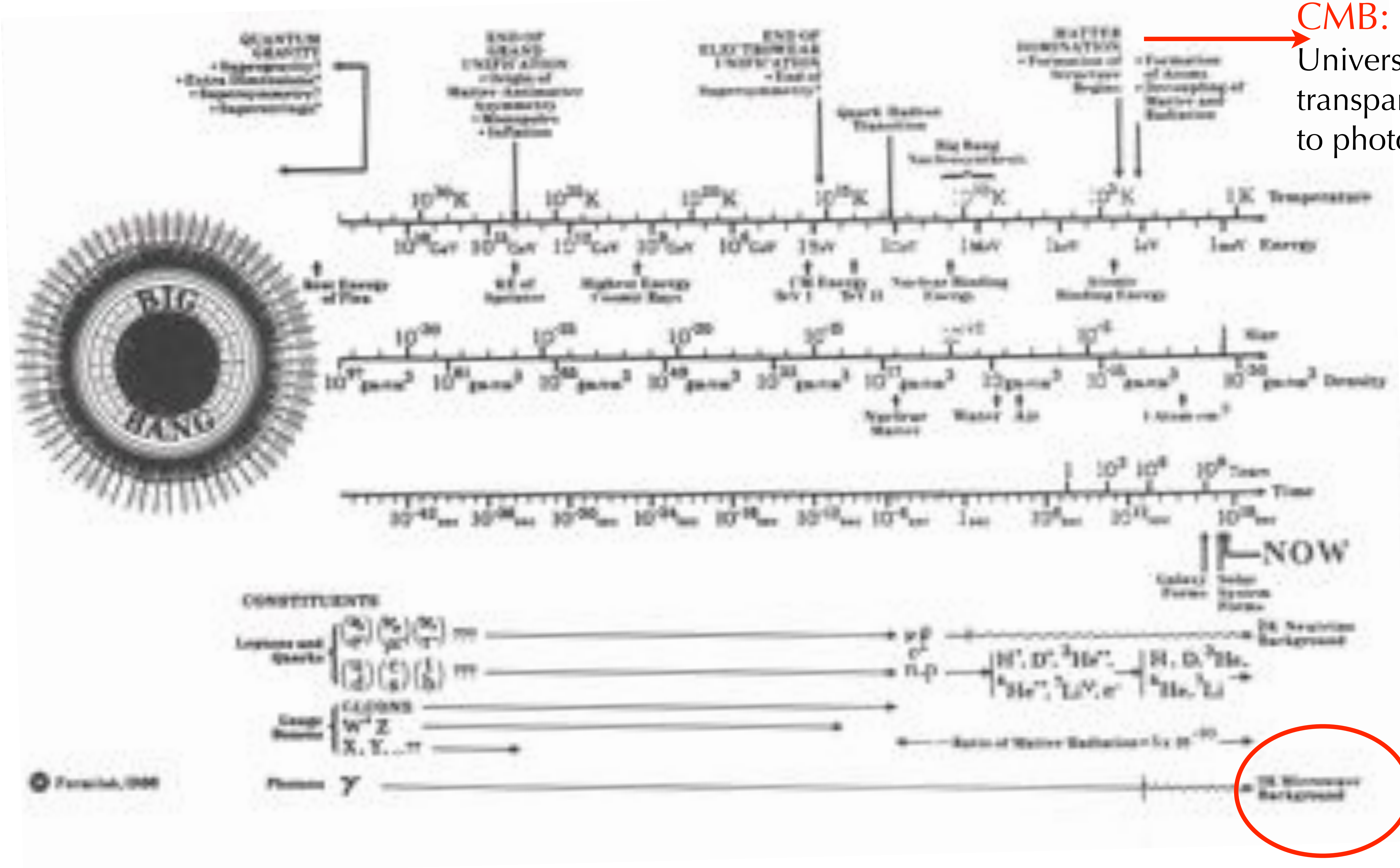
Matter domination :
structures start to form!



- a (veeery) brief history of the Universe:

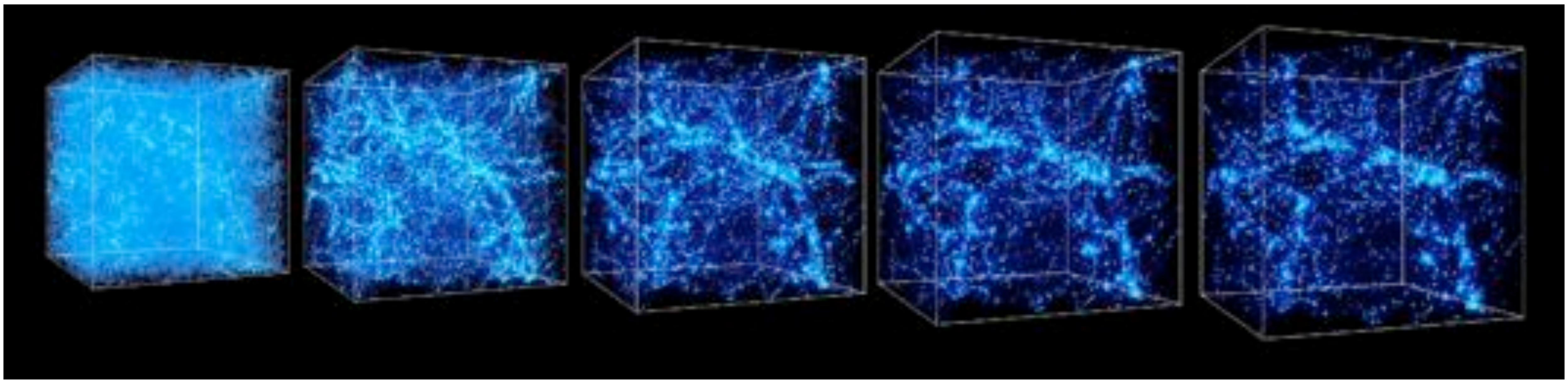
Matter domination : structures start to form!

CMB: Universe transparent to photons!

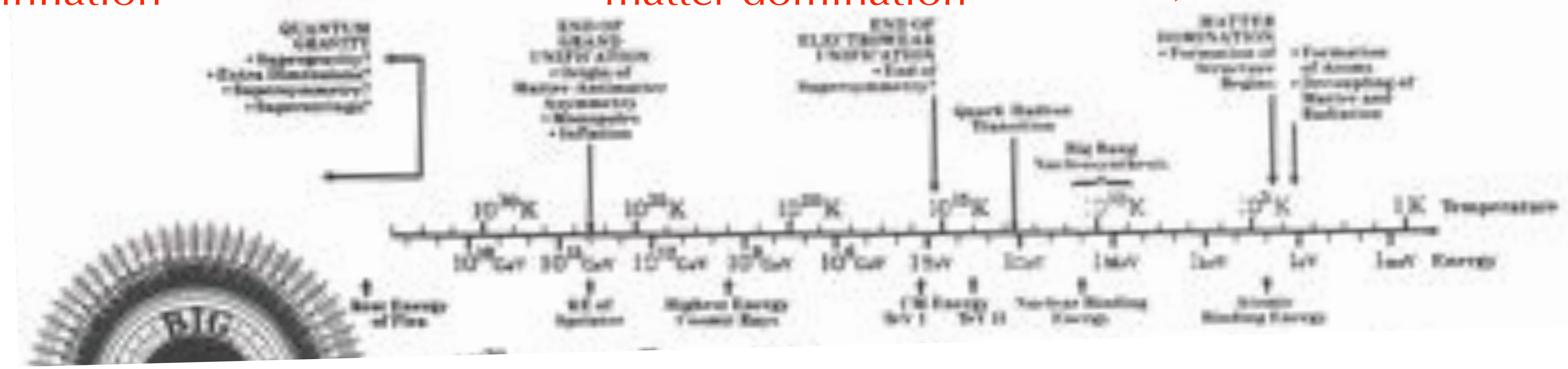


- a (veeery) brief history of the Universe:

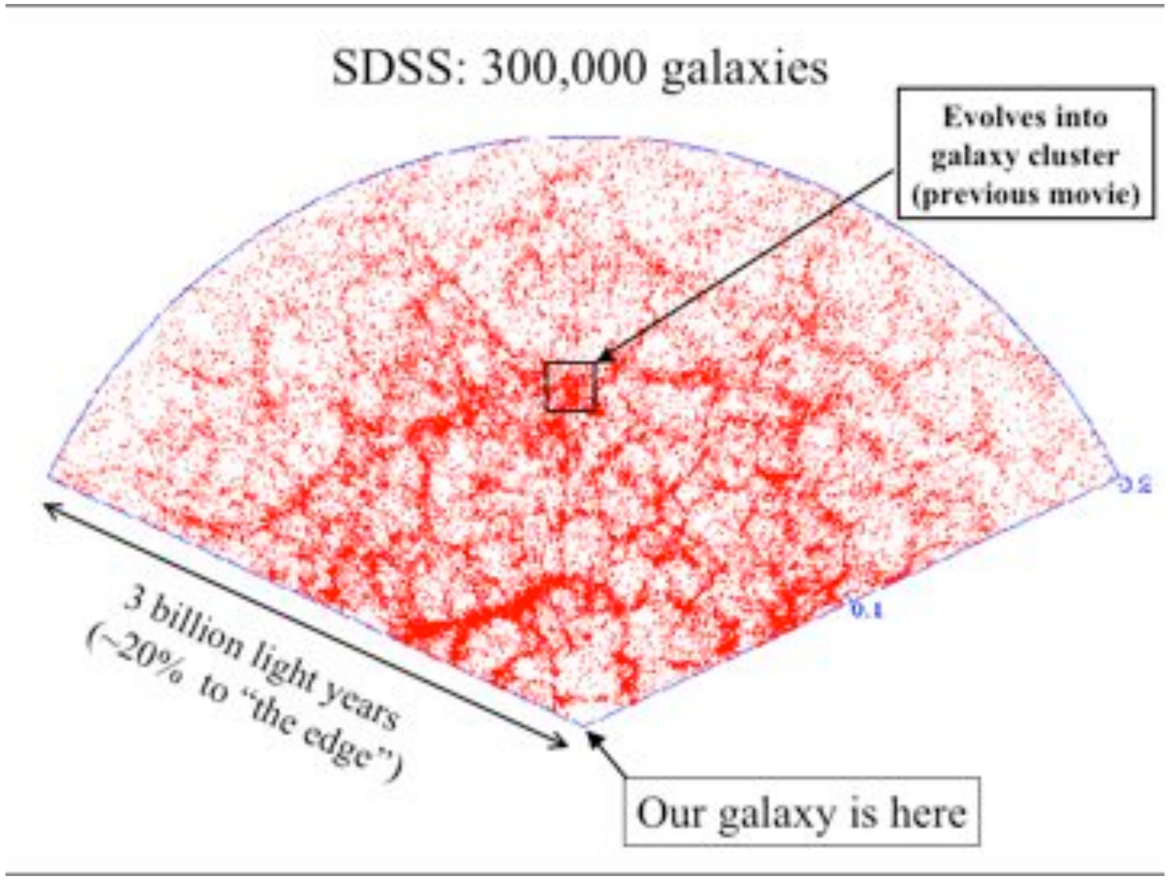
(quantum) overdensities... ... grew to large structures we observe today!



inflation matter domination →



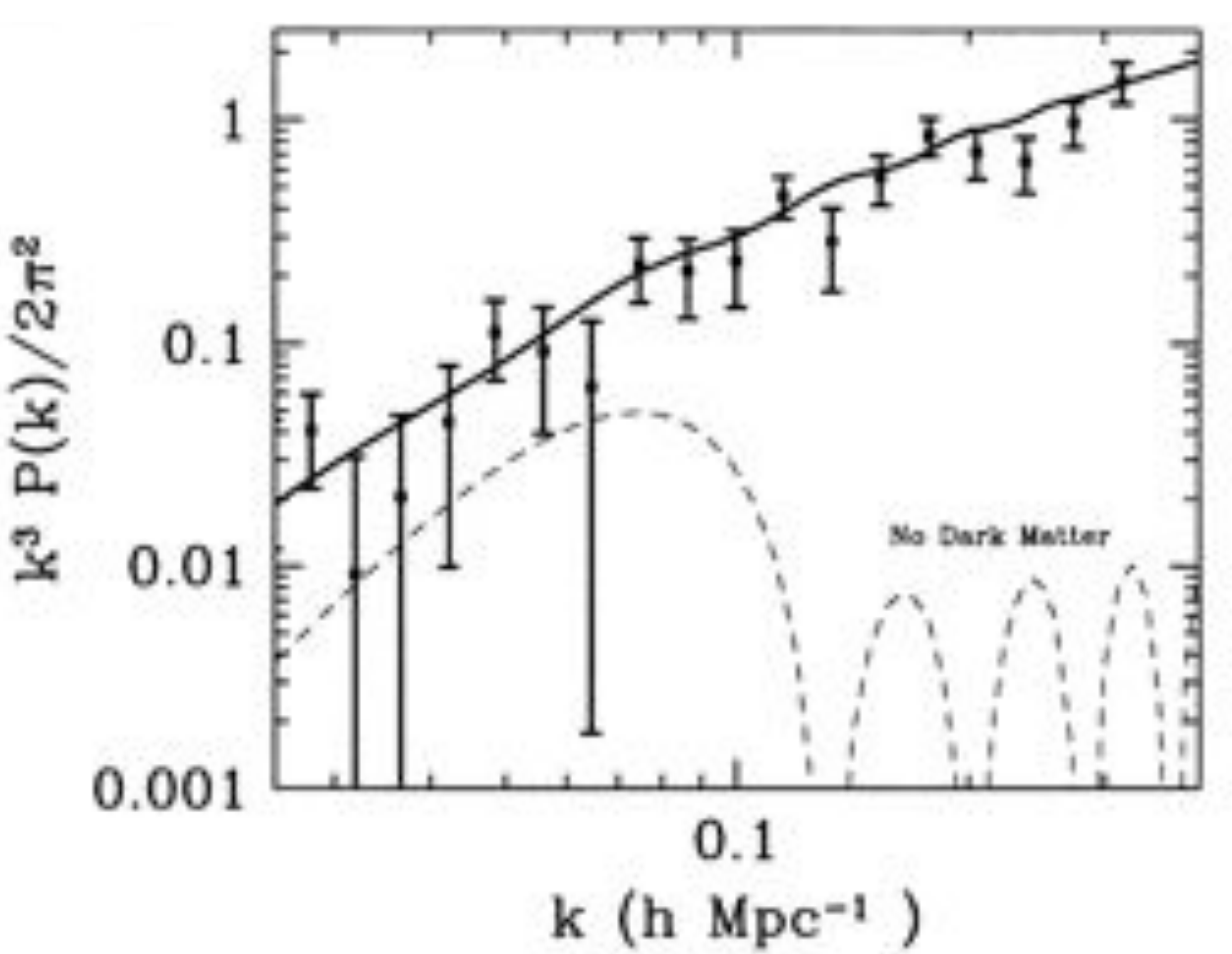
- but the story holds together only if dark matter is also present!




**matter power spectrum**:
'amount' of clustering at different scales

large scales

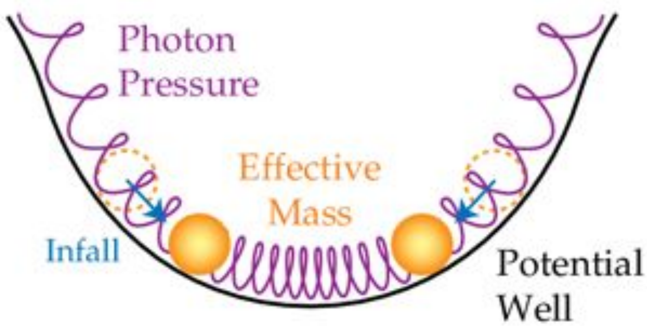
small scales



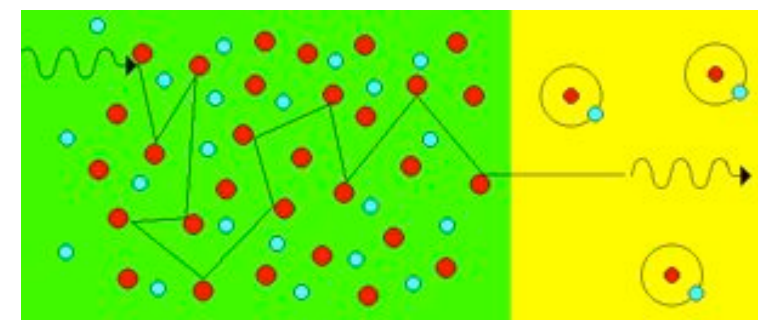

Significant power on small scales! Not possible without DM.

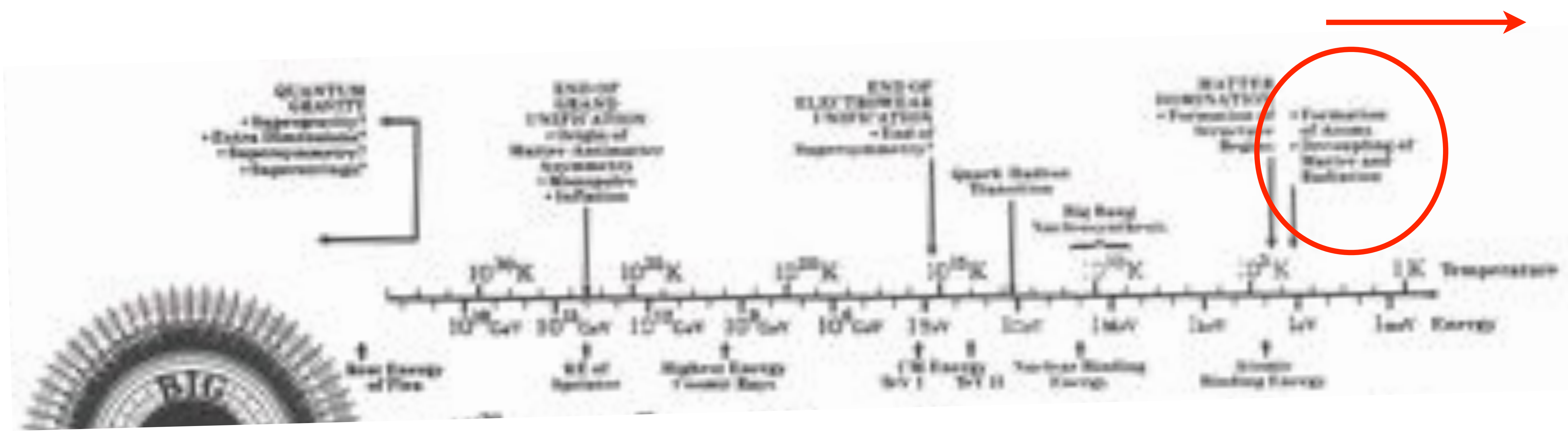
- (veeery) brief history of the Universe:

- When matter starts collapsing to form structures ('gravitational wells') baryon/photon fluid bounces back and forth due to the photon pressure!




Credit: Wayne Hu



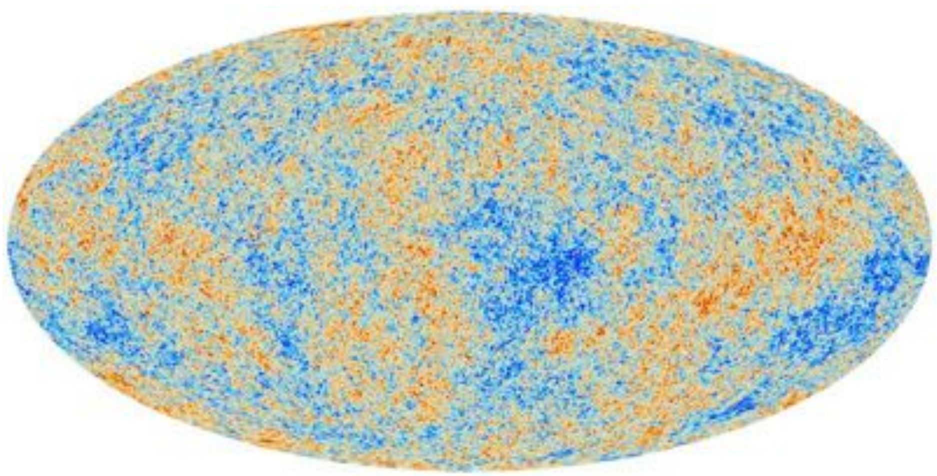


- (veeery) brief history of the Universe:

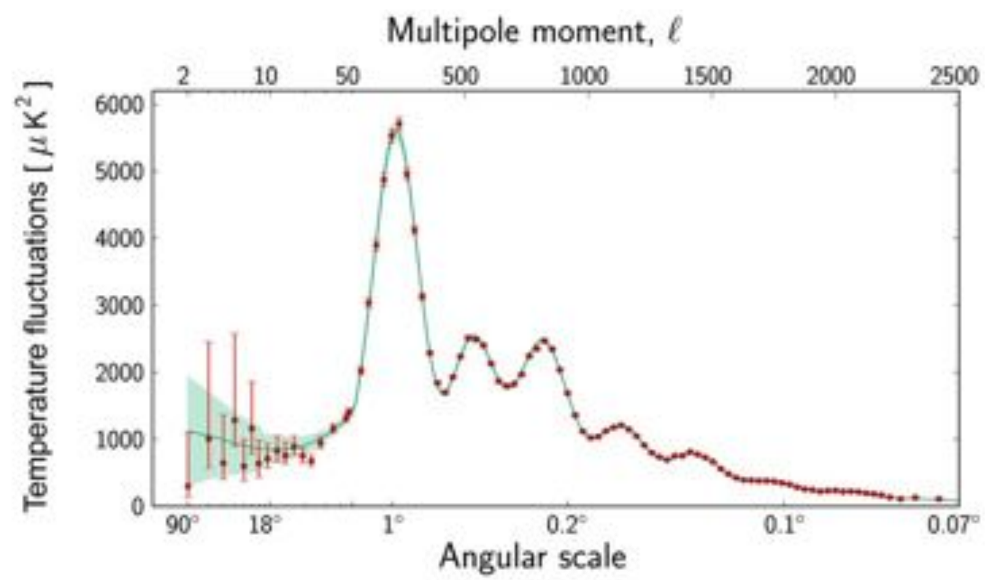
inhomogenity in photon temperature reflects potential wells at time of recombination.

**ΔT/T angular power spectrum**:

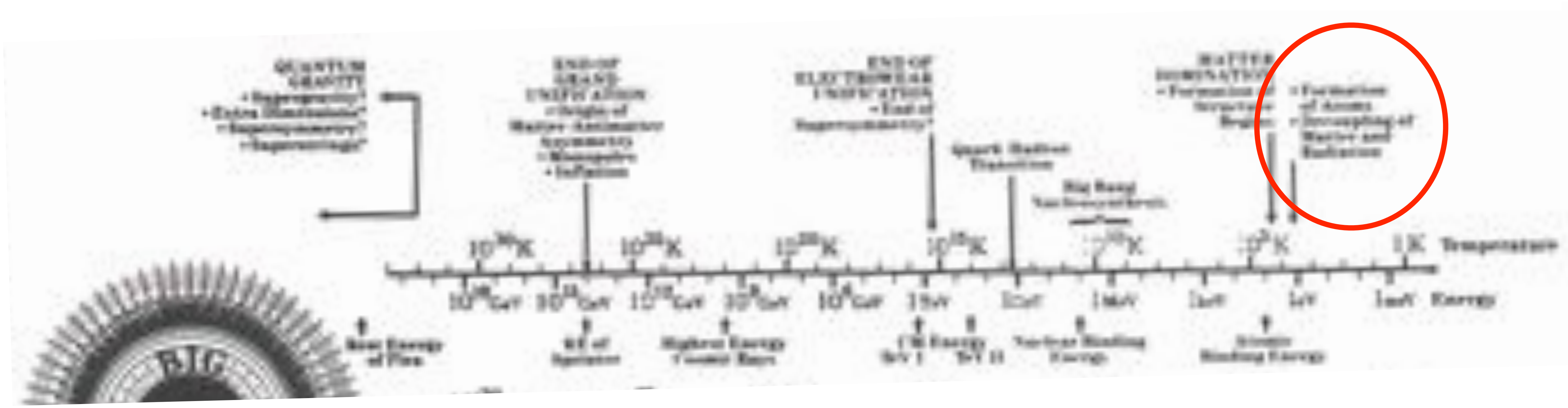
*Cosmic microwave background anisotropies*



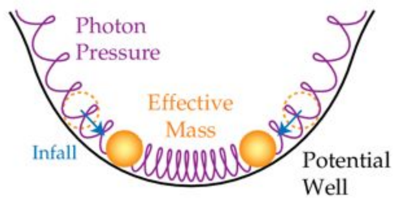
Planck Mission




Planck Mission

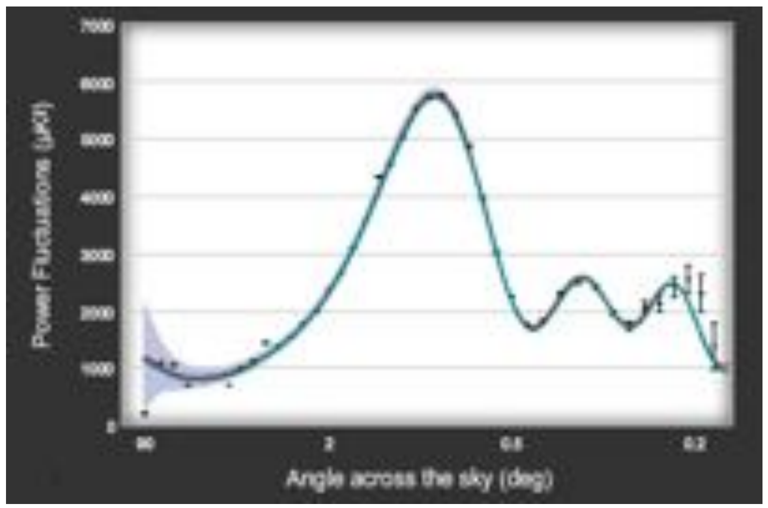


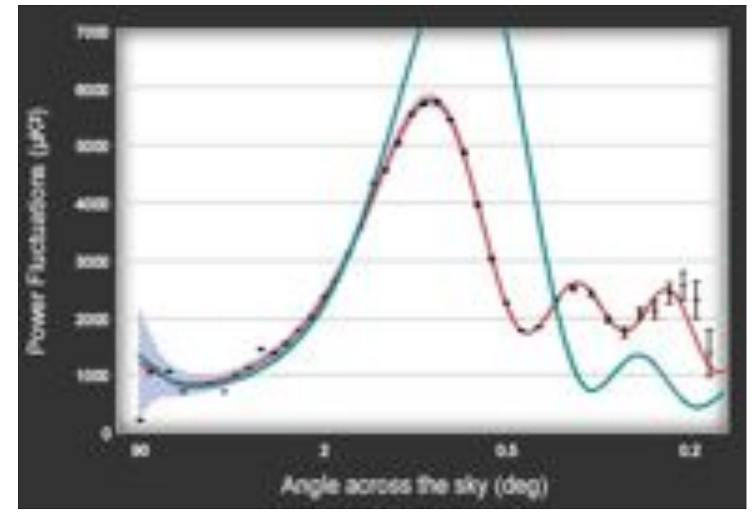
- again, without DM CMB measurement would look very different!

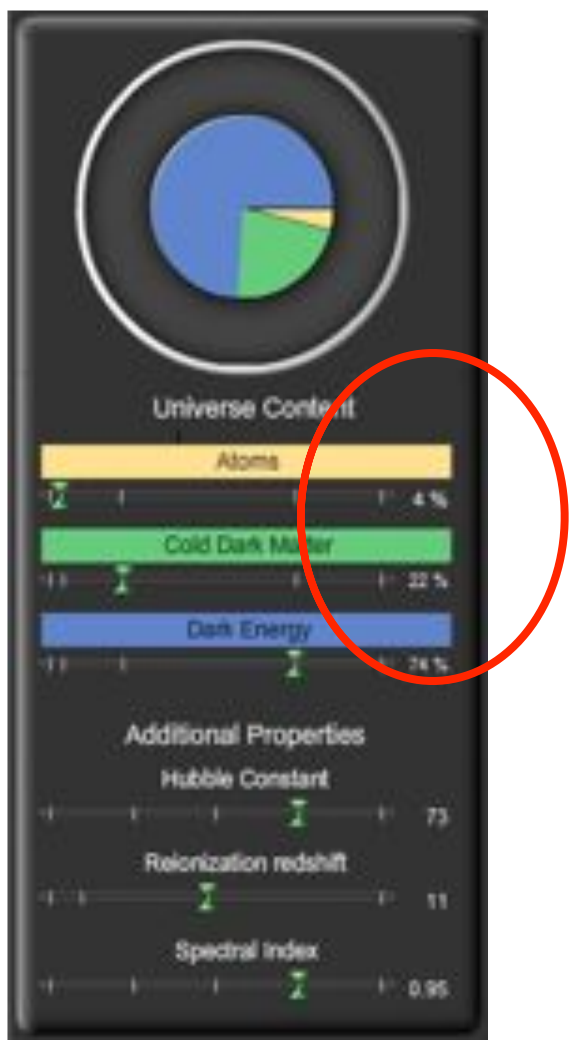


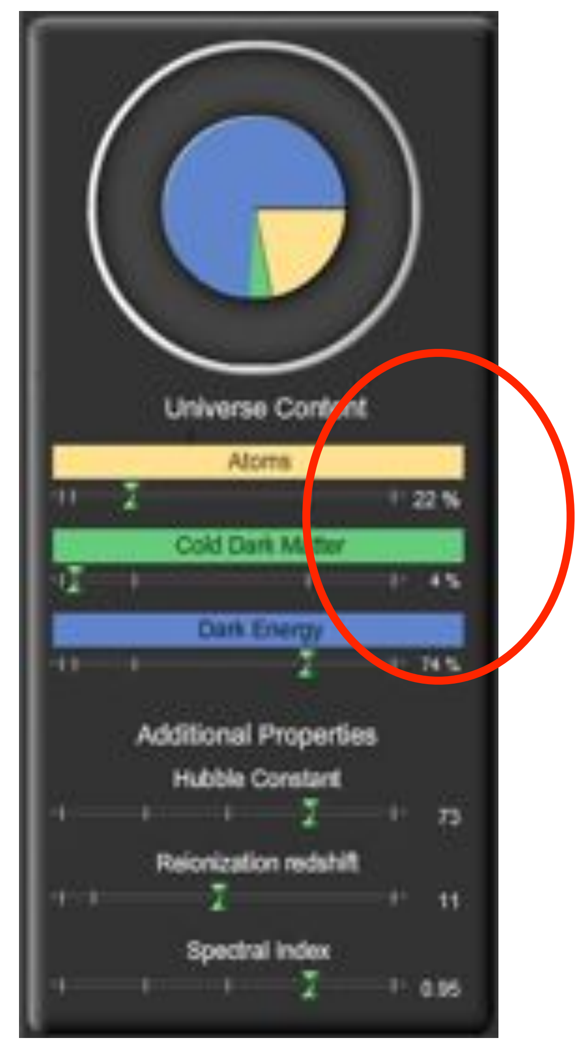

Credit: Wayne Hu

http://lambda.gsfc.nasa.gov/education/cmb_plotter/



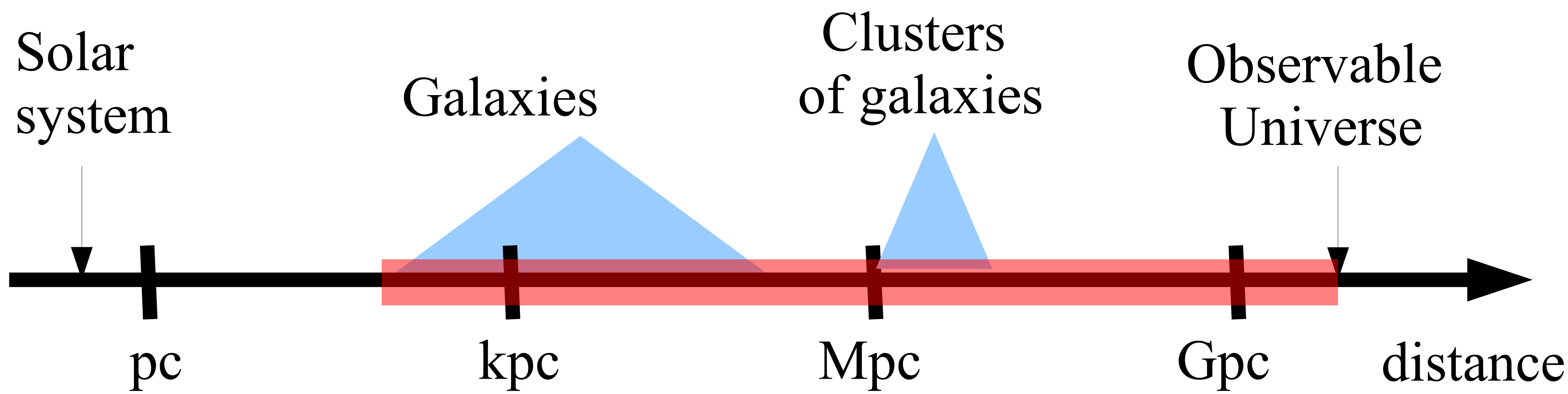



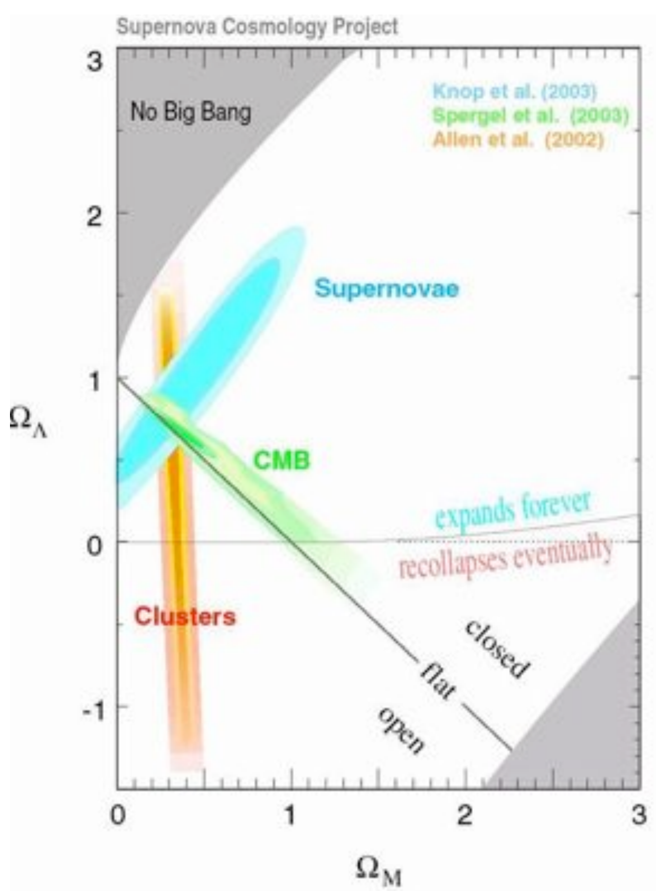



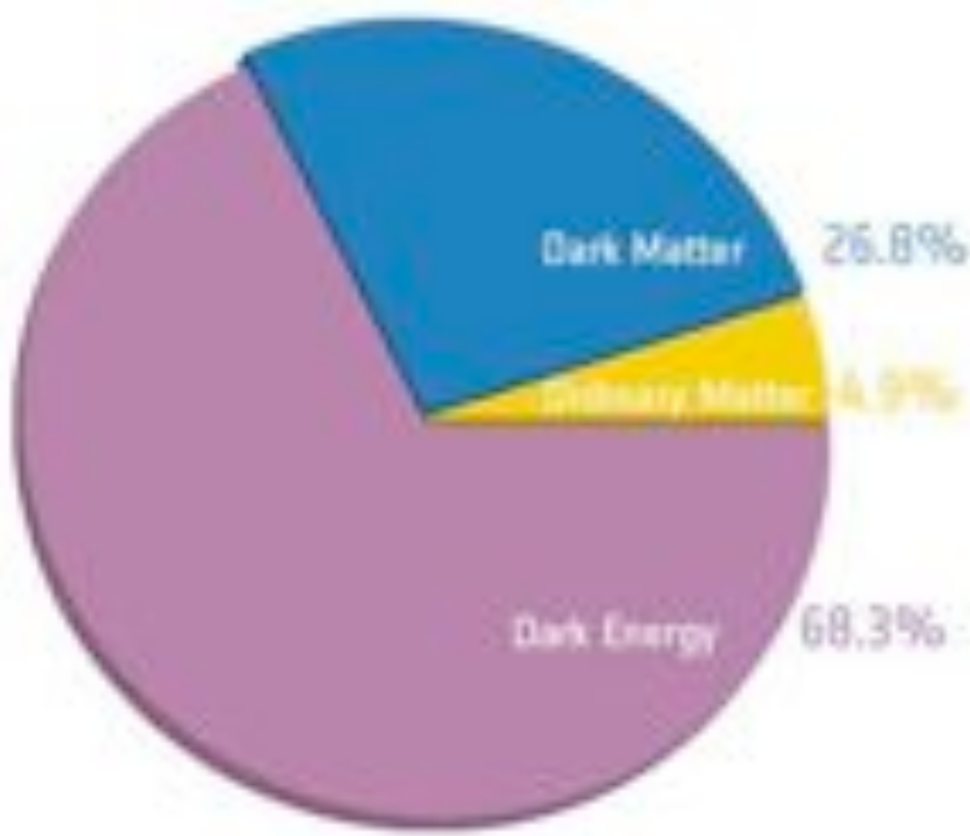



Summary:

- evidence for presence on a wide range of scales: from dwarf galaxies ($10^6$ Msol) to clusters ($10^{15}$ Msol) -- local Universe.
- and throughout the history of the Universe: CMB, large scale structures!



# Our options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction

2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

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Dark Matter
or MOND?
(MOdified Newtonian Dynamics)
or the relativistic generalization TeVeS?
(scalar-vector-tensor MOdified Gravity)

- proposed in the 80’s to explain the galaxy rotation problem
- Milgrom noted that Newton's law for gravitational force has been verified only where gravitational acceleration is large, and suggested that for extremely small accelerations the theory may not hold.

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15


A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
*Received 1982 February 4; accepted 1982 December 28*

I have considered the possibility that Newton’s second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0)\boldsymbol{a} = \boldsymbol{F}, \qquad (1)$$

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

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replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

$$\frac{GM}{r^2} = \frac{a^2}{a_0}$$

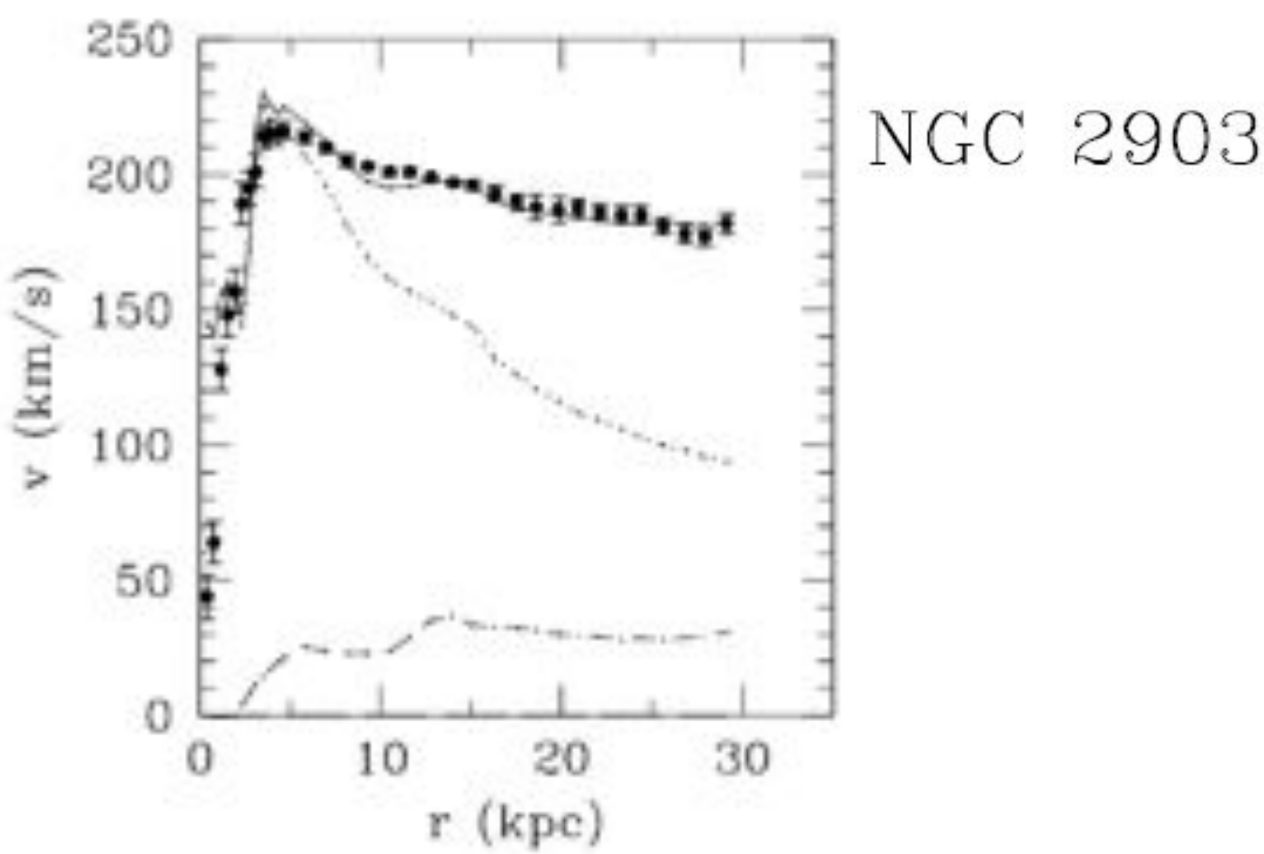
$$a = \frac{v^2}{r} = \frac{\sqrt{GMa_0}}{r}$$

- proposed in the 80's to explain the galaxy rotation problem
- Milgrom noted that Newton's law for gravitational force has been verified only where gravitational acceleration is large, and suggested that for extremely small accelerations the theory may not hold.

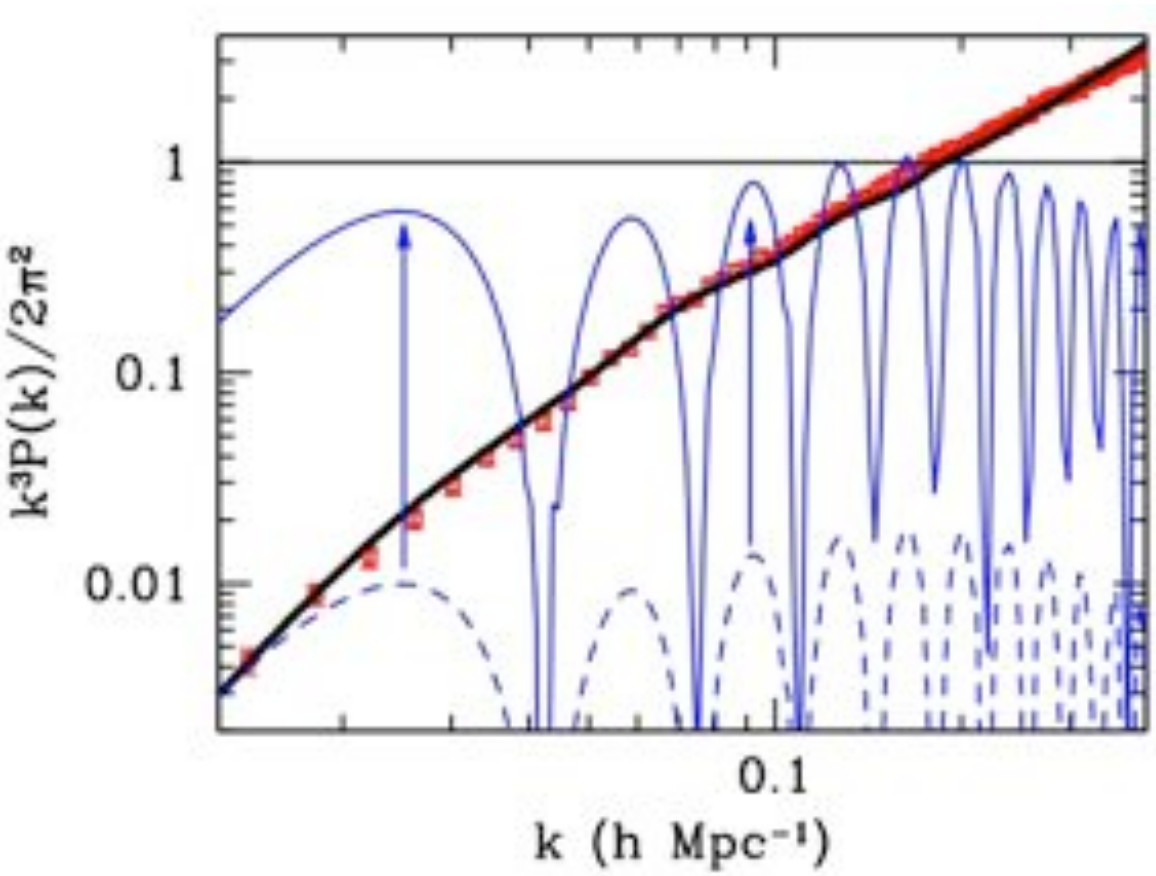
$$v = \sqrt[4]{GMa_0}$$

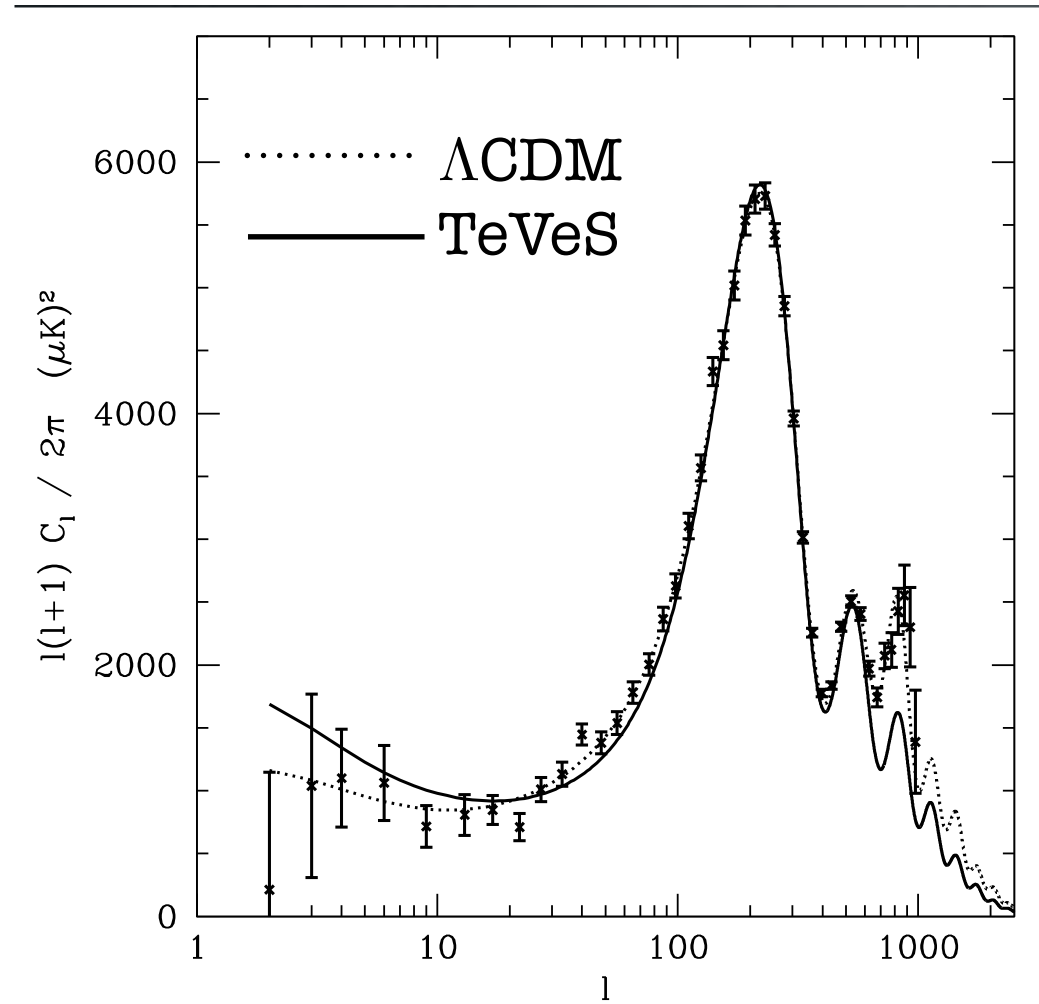
- obtains constant velocity!

$$\boxed{a_0 \simeq 10^{-8}\ \mathrm{cm\,s^{-2}}}$$



- However, evidence for DM collected on a **large span of scales**!
- and it cannot explain large scale (clustering) behavior LSS *and* CMB.




C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)

- Scott Dodelson, 'The real problem with MOND', http://arxiv.org/abs/1112.1320.

- en plus, the Bullet cluster!

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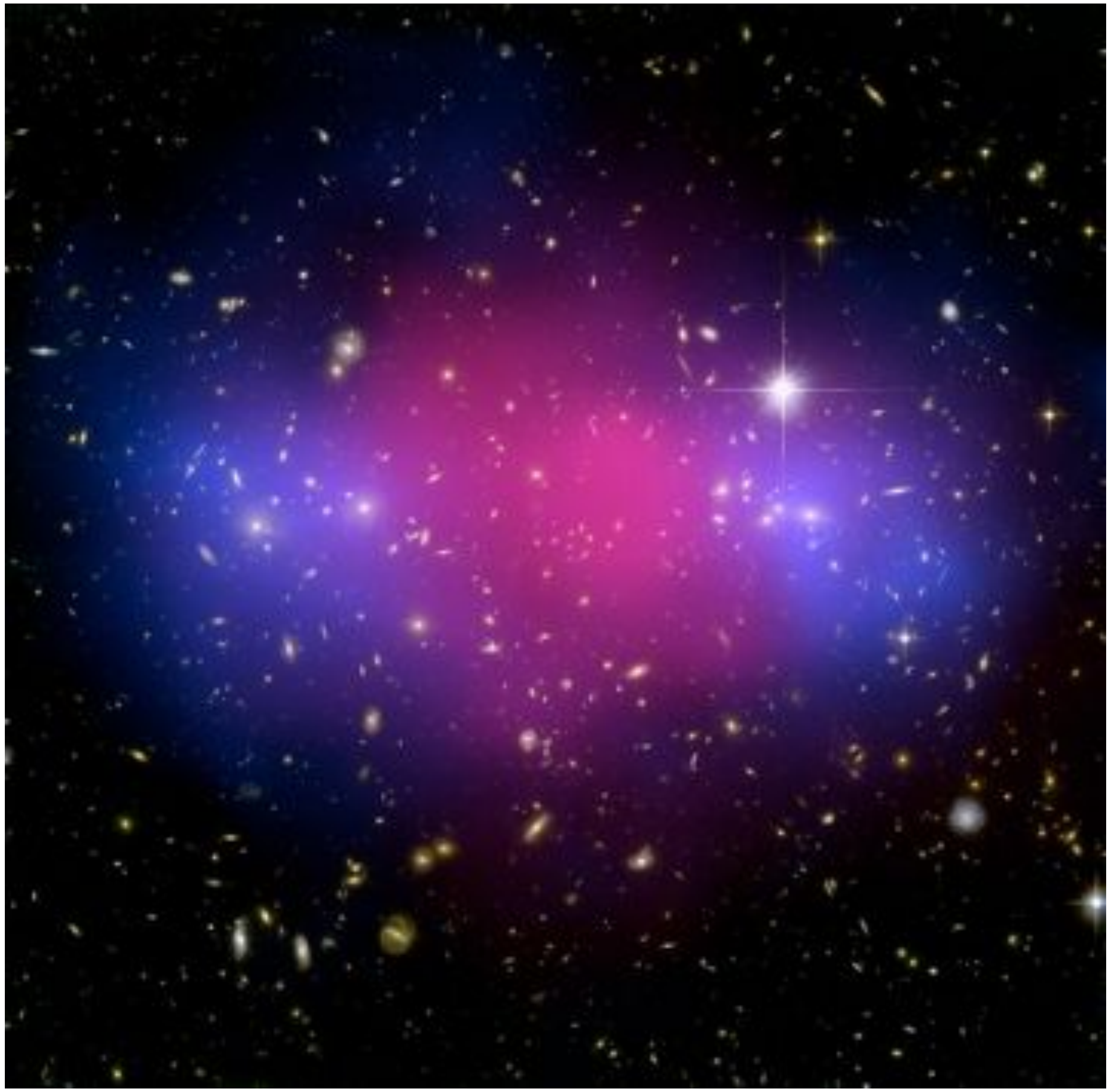
- en plus, the Bullet cluster!

  - Chandra X-ray telescope observation of shocked gaseous atoms. bow shock wave in the gas of the smaller Bullet cluster (pink on right), allowed determination of the velocity of the cluster (4500 km/s) and its direction of motion.

- en plus, the Bullet cluster! - MOND does not predict an offset between mass and light!

- dark matter didn't experience the drag of the collision! The critical evidence is that the (pink) **gas clouds are not centered with cluster masses** as would be expected if the clusters were composed of ordinary atoms and other standard matter!



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Abell 520

# Our options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction

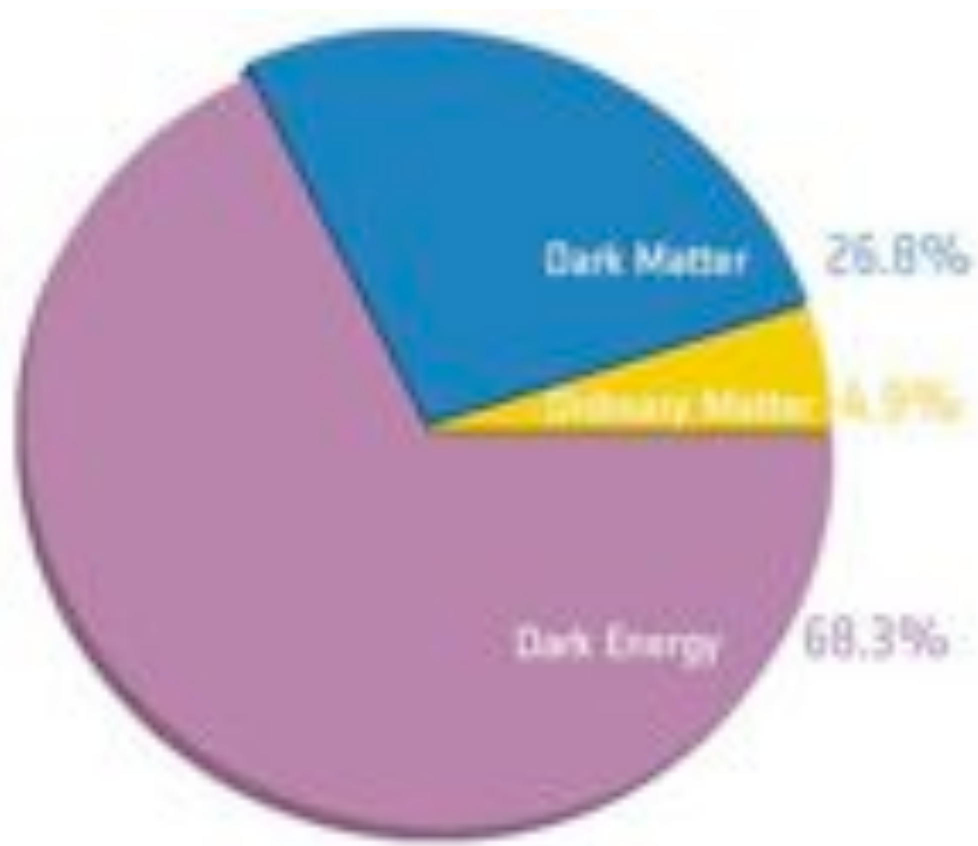
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

# Break?

# Dark Matter
# Properties

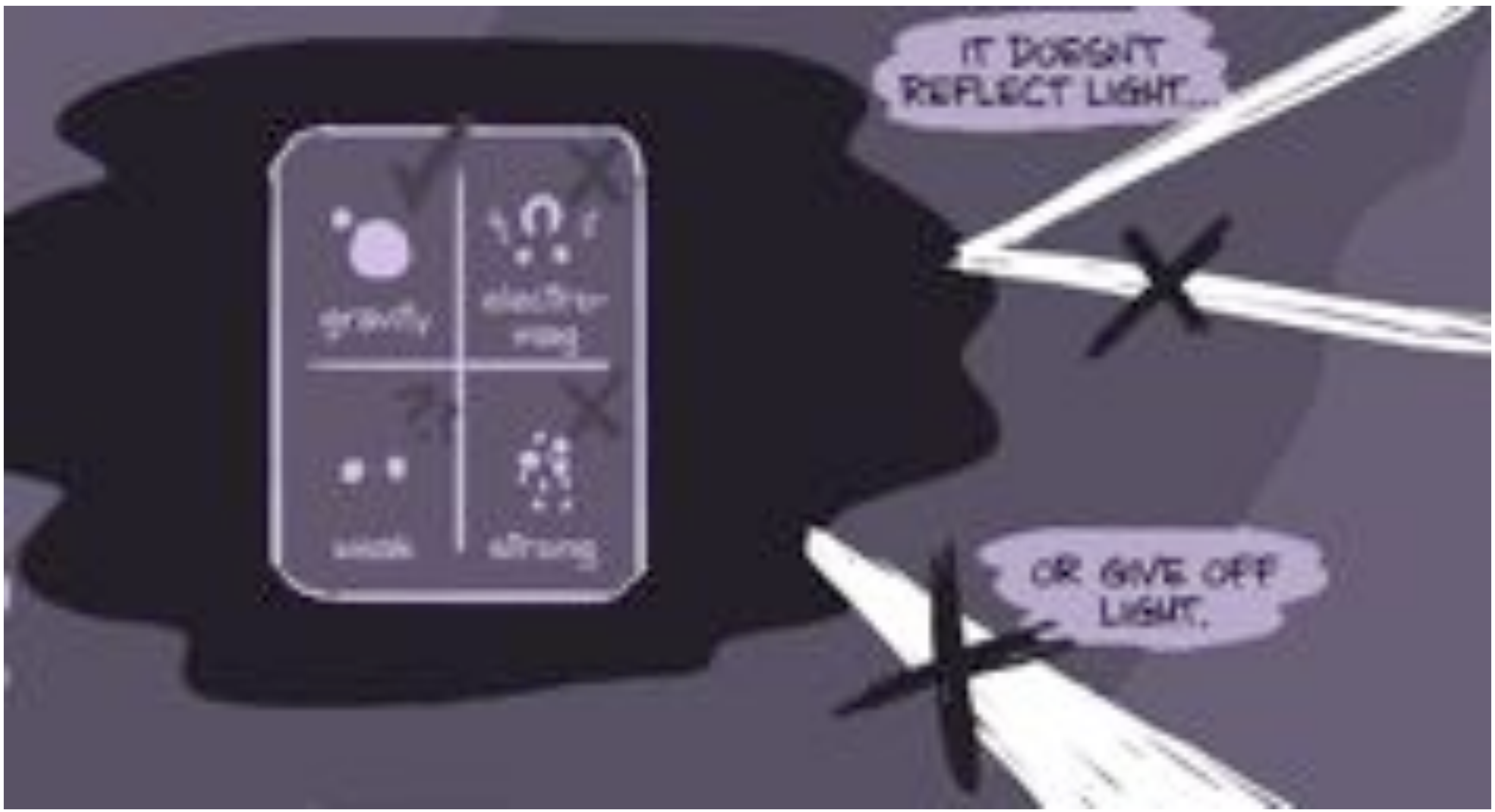
- What do we know about DM?

1. stable particle (life time at least age of the Universe)
2. Its amount $\Omega_{CDM} \sim 0.26$ (Planck)



# • What do we know about DM?

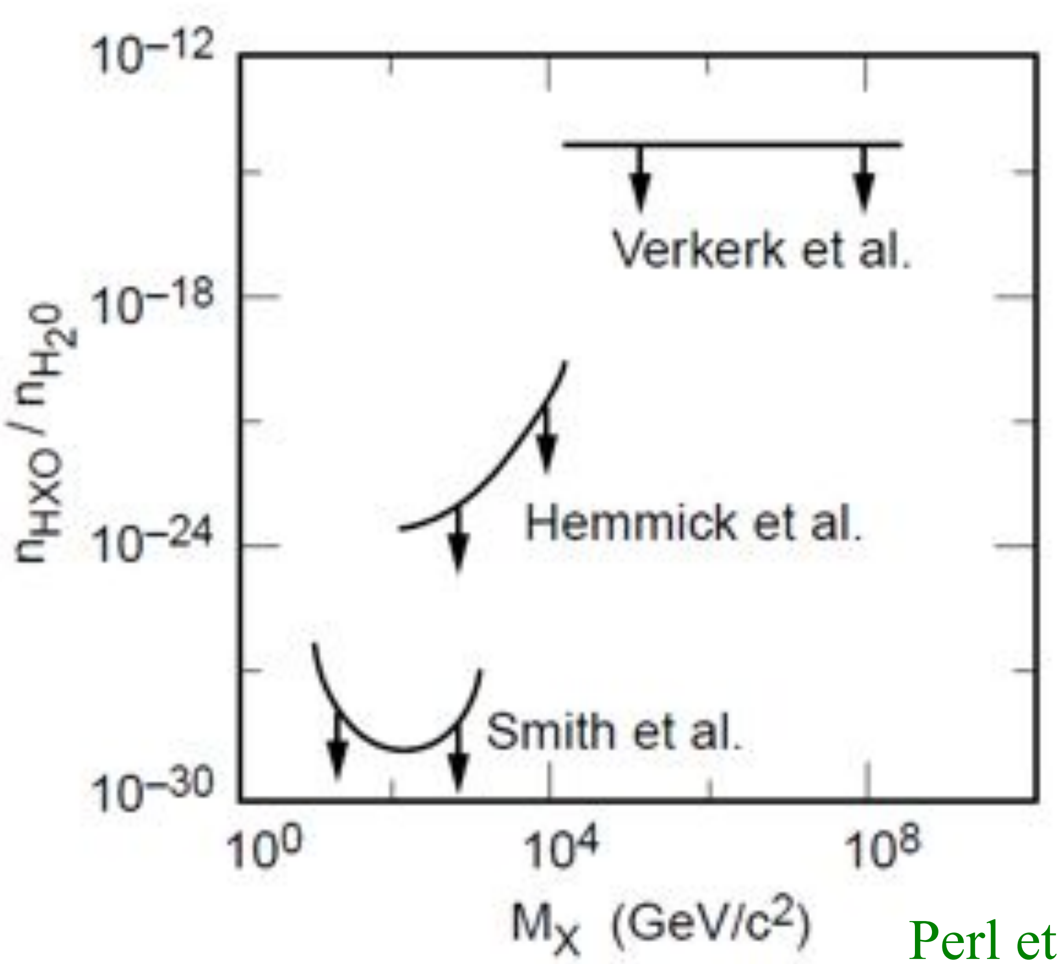
3. electrically neutral: if not, it would interact with photons! (photons couple to charge) DM would not be ‘dark’ i.e. ‘invisible’!



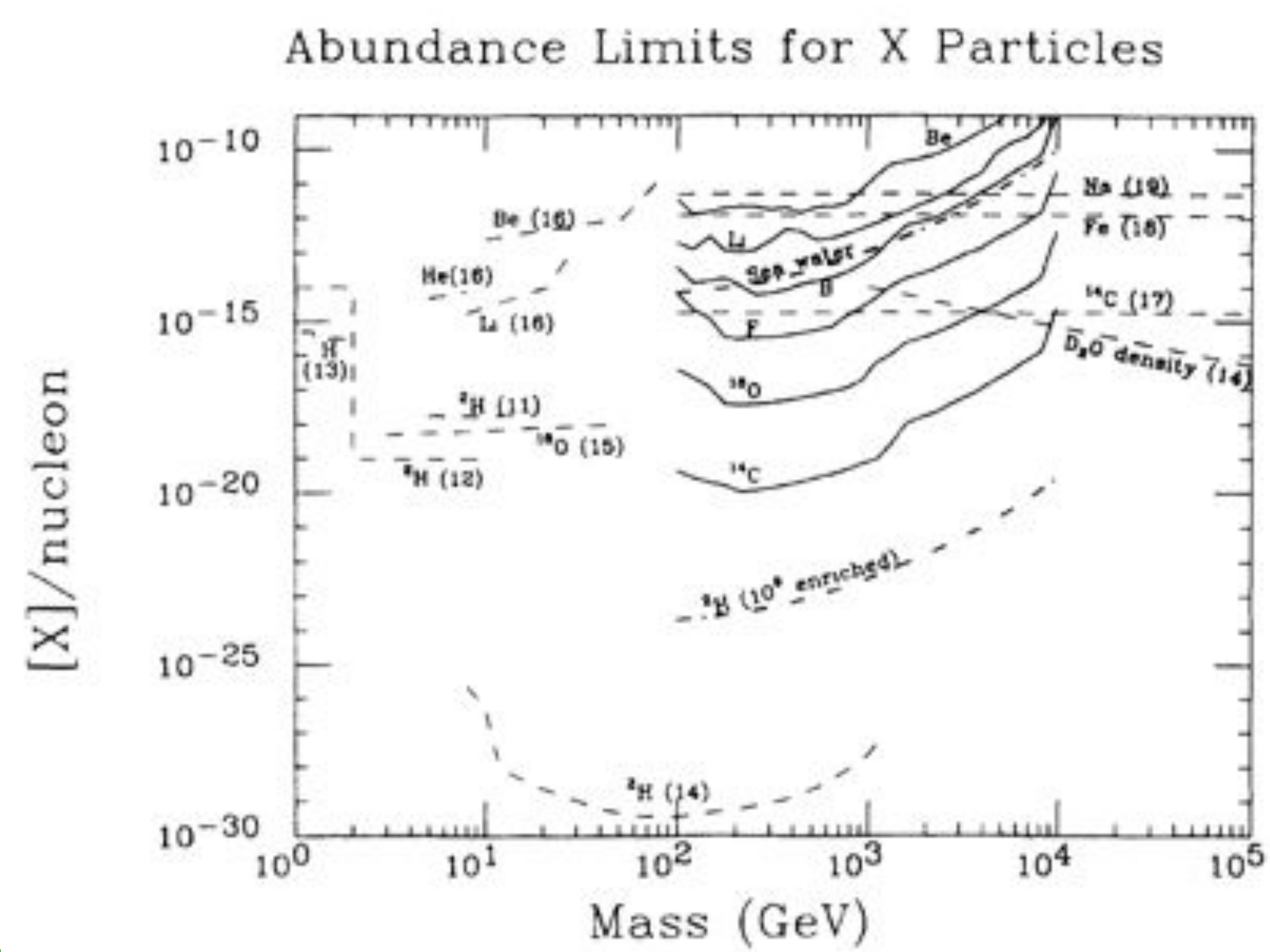
# • What do we know about DM?

3. electrically neutral:

- it could bind with other charged particles (and form neutral systems), but strong limits on exotic atoms!
- if **X+**, bound states with electron ~**heavy Hydrogen**!
- if **X-** bound to nuclei- **anomalous isotopes**

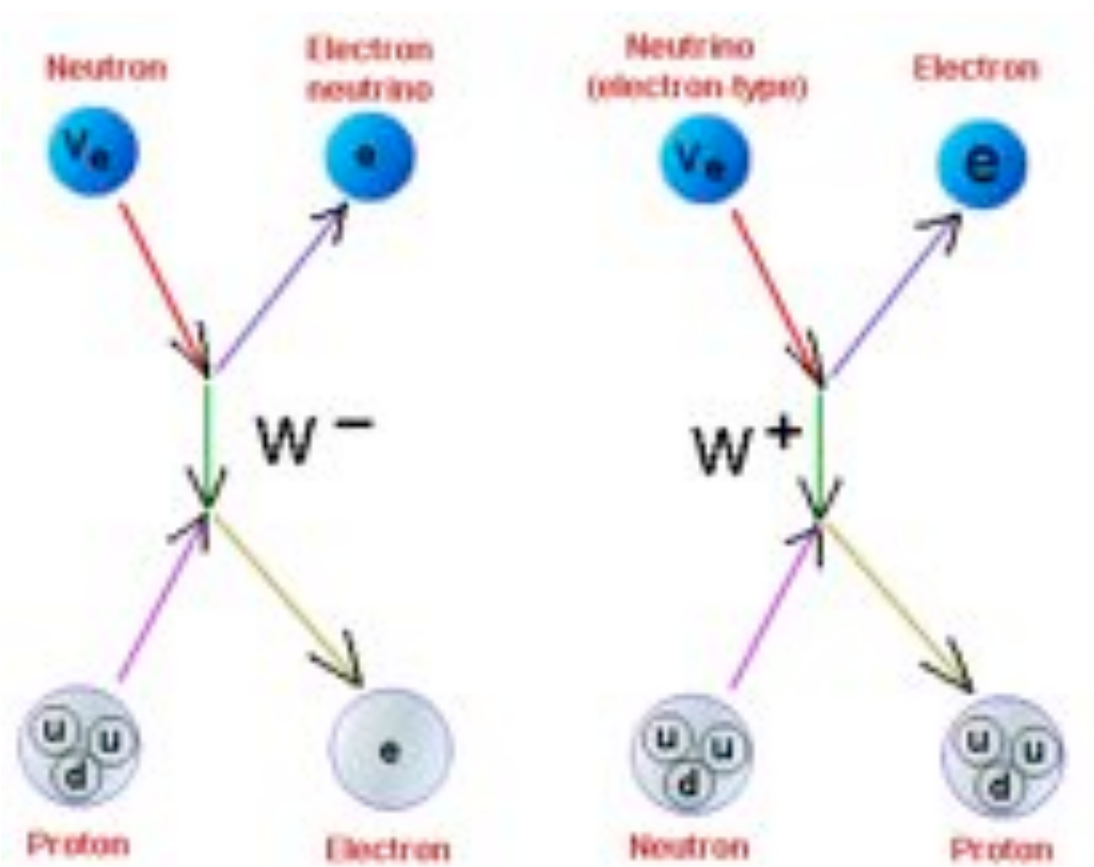


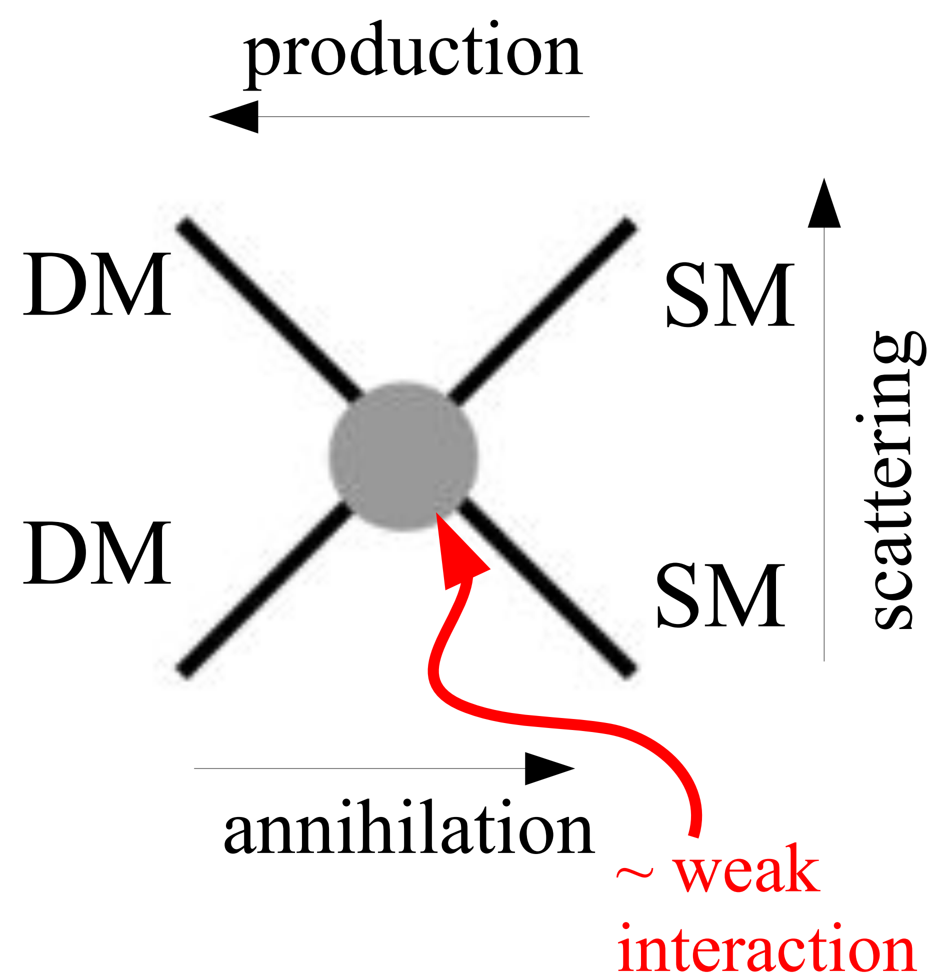

Perl et al.



# • What do we know about DM?

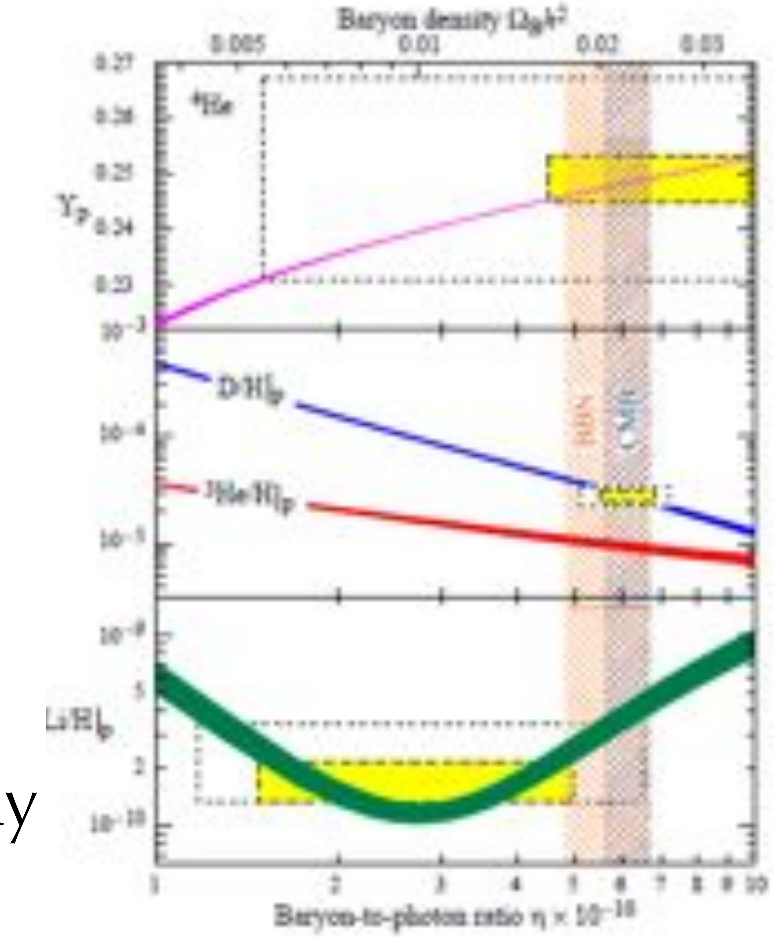
4. *if* it has non gravitational interactions they must be '**weak**':
   - genuine weak interactions, exchange W or Z
   - here means generally just un-observably week



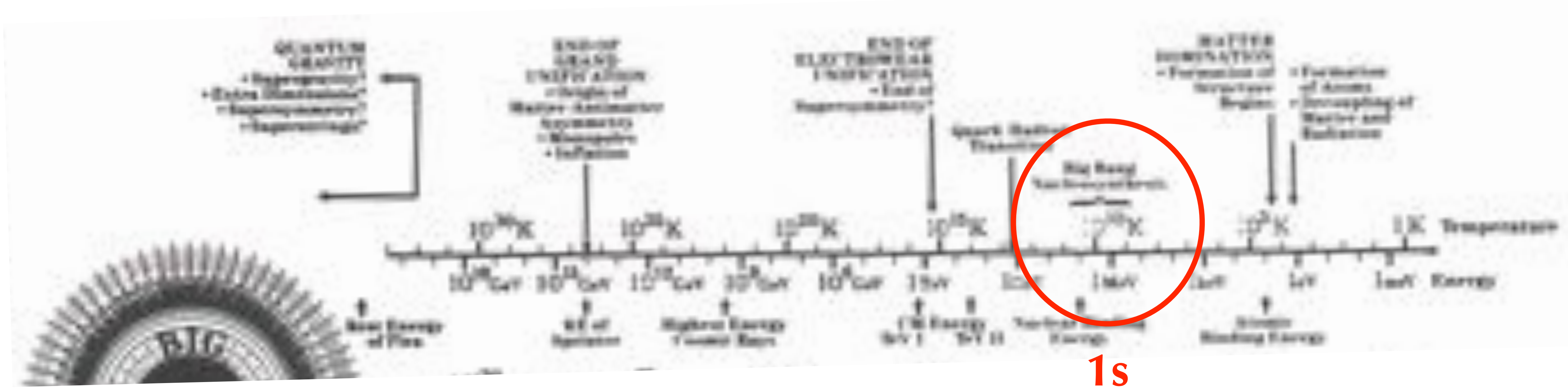



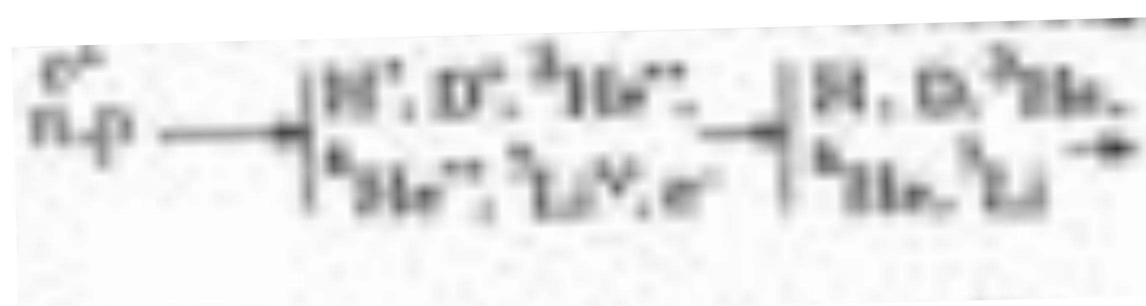
- What do we know about DM?

5. ‘non-baryonic’: does not form atoms and does not dissipate energy like baryons - strong limits from BBN.




From what we know about nuclear physics we can very well predict the sequence of events in which proton, neutron and electrons bound to form H+, D+, He++, Li+++...
**DM did not participate in this process!** i.e. DM cannot be baryonic, otherwise the abundances of elements measured today would be quite different than what calculated!

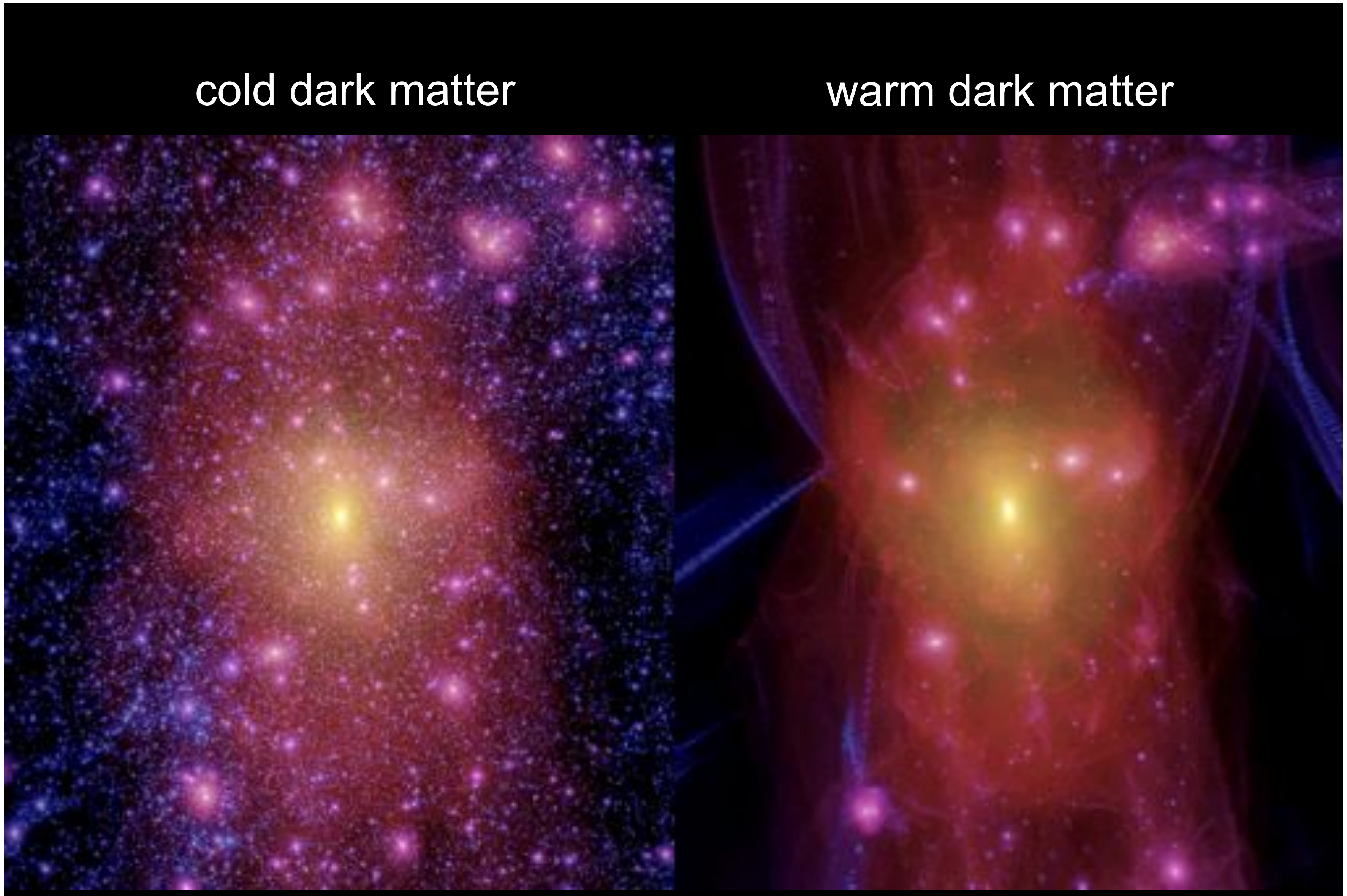


- What do we know about DM?

6. it was slow (non relativistic) at the time of formation of first structures (*if in thermal equilibrium*)

N-body simulations find that if DM would be lighter than keV small structures would have been erased!




Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

# DM check list:

- ☑ stable
- ☑ $\Omega_{CDM} \sim 0.26$
- ☑ electrically neutral
- ☑ ‘weakly’ interacting
- ☑ does not affect BBN
- ☑ non-relativistic at structure formation

# *Two Basic Options*

1. Something we know:

   - Ordinary ***Objects*** (**MACHOS**):

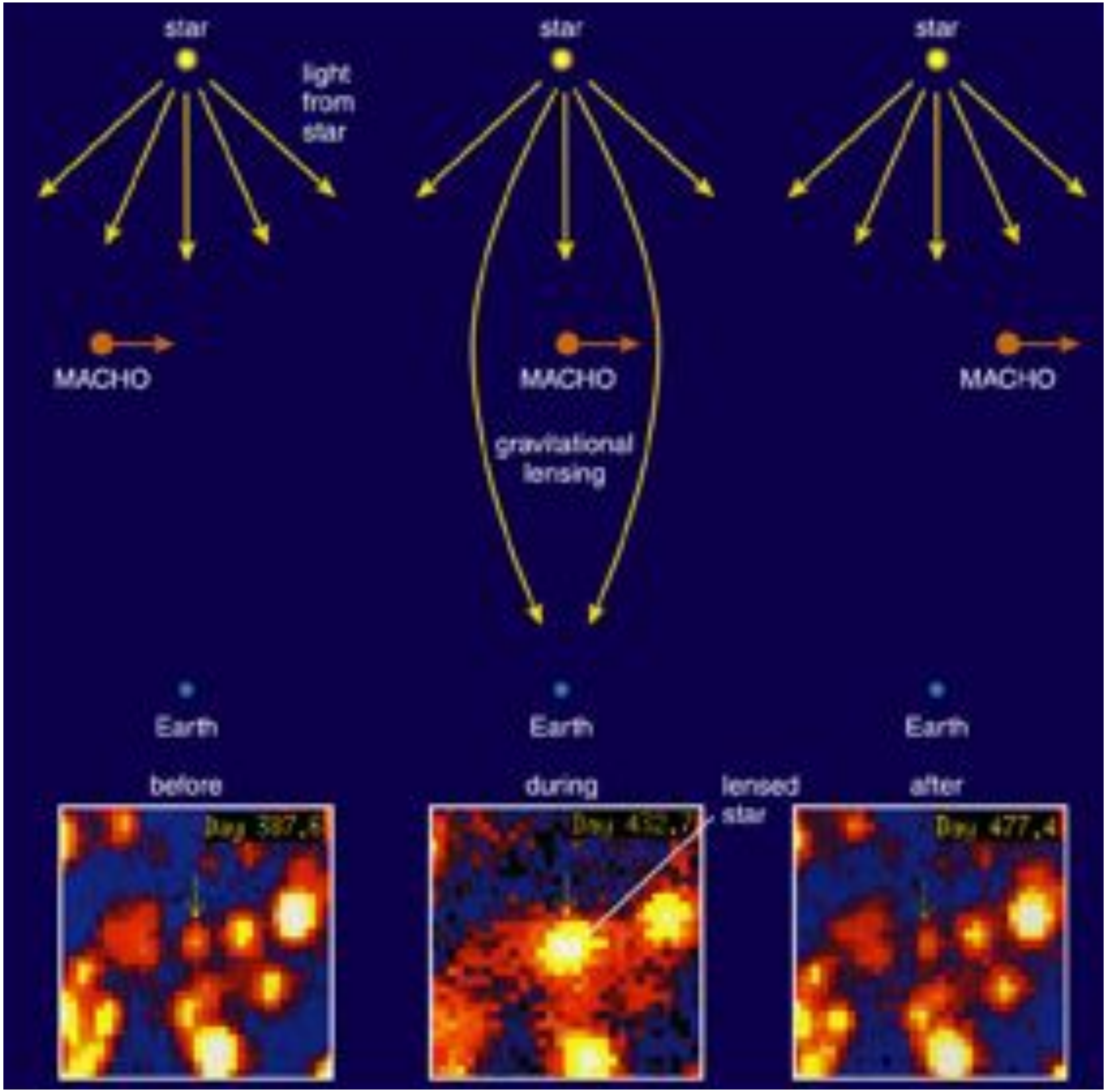
   Massive Compact Halo Objects: small bodies as *dead stars* (white dwarfs), *neutron stars, black holes, large Jupiter like planets…*

   - Standard model ***particle***: weakly interacting ***neutrinos***

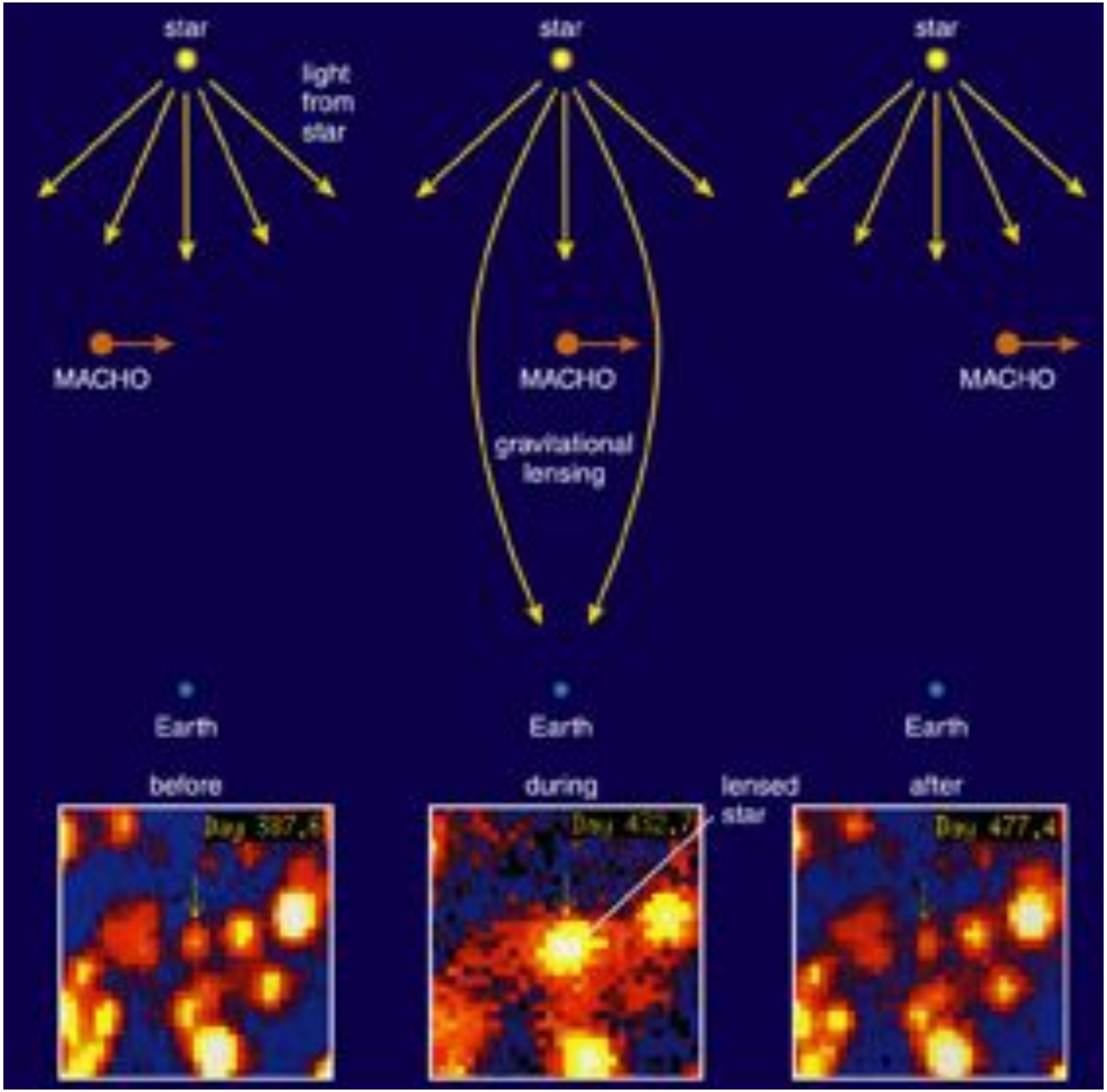
2. Some particle we do not know:

   - ***Weakly Interacting Massive Particles*** (**WIMPS**)

   very general category, some particle which is massive and interacts weakly

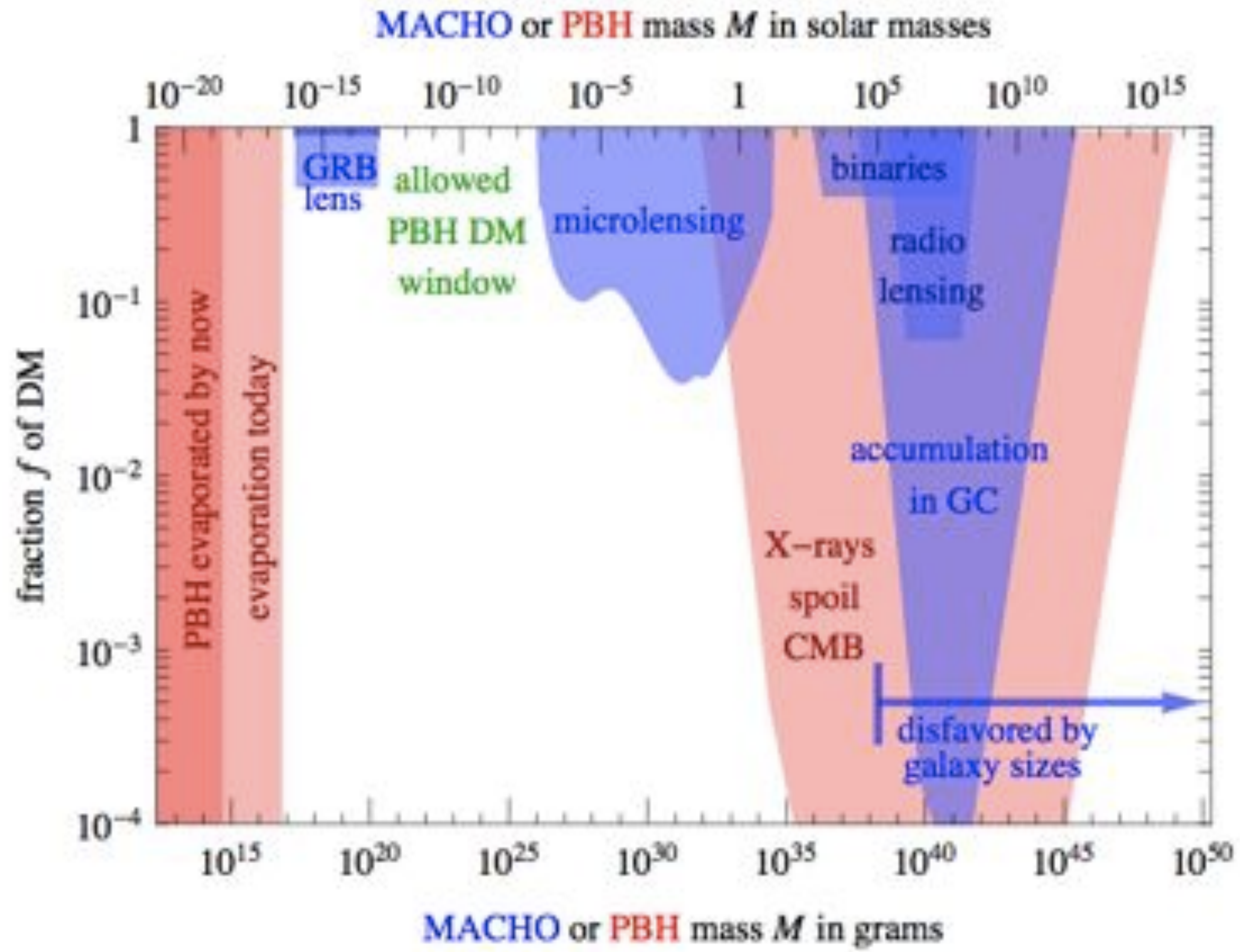



- **MACHO**s occasionally make other stars appear brighter because it focuses light through lensing




- **MACHOs** occasionally make other stars appear brighter because it focuses light through lensing

… but ***not enough lensing*** events are observed to explain dark matter




Standard inflation predicts a nearly scale-invariant (Harrison- Zel′dovich) Gaussian spectrum of perturbations.

The presence of additional power on some ‘small’ scale may have led structures of a size corresponding to that scale to collapse far earlier than in the canonical scenario.

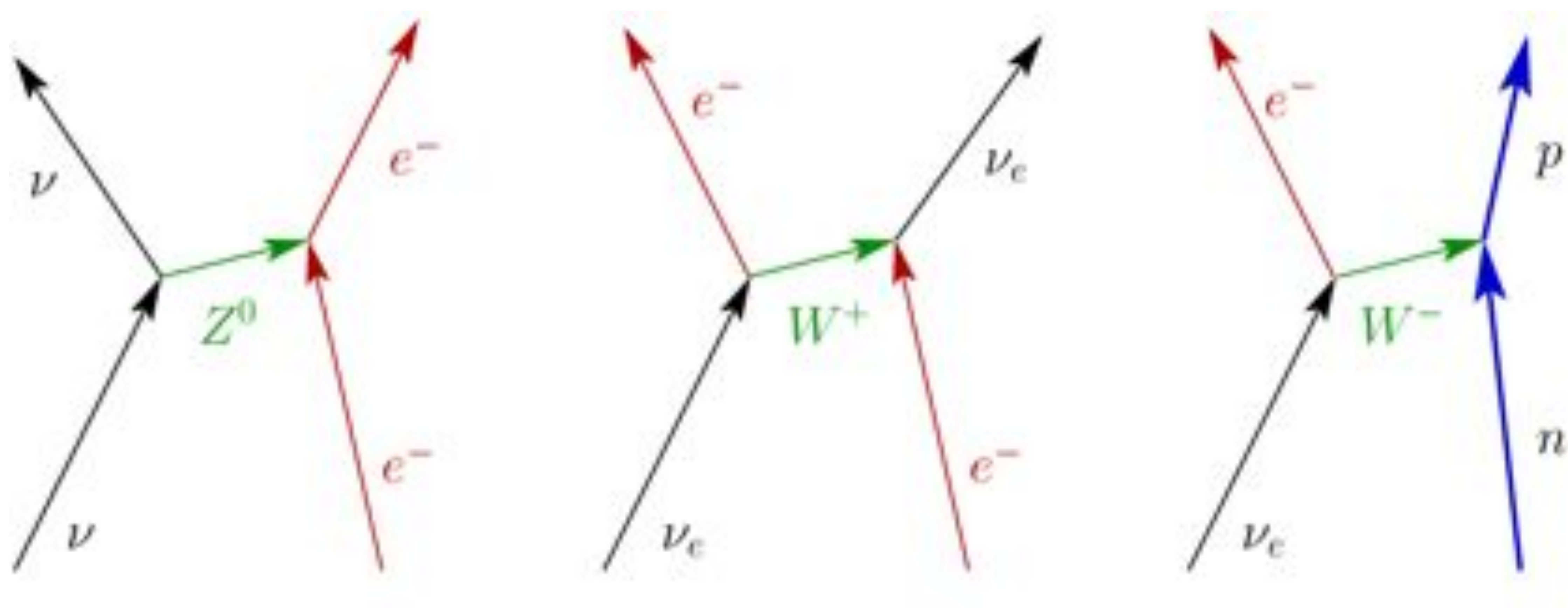
- **Primordial black holes**: perturbation enters the horizon with such a **large am- plitude** ($\delta \sim 0.3 - 0.7$) that a substantial fraction of the horizon volume collapses directly to a black hole.
- **Ultracompact primordial minihalos**:somewhat smaller power, so no black hole collapse.

What about neutrinos?

They are part of a standard model - i.e. exist!

- ☑ neutral
- ☑ and genuinely weakly interacting (W and Z boson exchange)
- ☐ But, they are too light!

Weak interactions




Neutral current

Charged current

Why neutrinos cannot make DM?

(In some more details)

Step back: **thermal decoupling in the Early Universe**

**Boltzmann equation** for number density n of DM particles in the expanding Universe (expanding with a rate H=1/a da/dt):

$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)}$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

when interaction rate is high, particles are in **thermal/kinetic equilibrium**, and their **number density** is given by:

$$n = \frac{g}{(2\pi)^3}\int f(\vec{p})d^3p \qquad f(\vec{p}) = [\exp((E-\mu)/T) \pm 1]^{-1}$$

Why neutrinos cannot make DM?

(In some more details)

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when interaction rate is high, particles are in **thermal/kinetic equilibrium**, and their **number density** is given by:

for **relativistic** species m<< T

$$n = \begin{cases} (\zeta(3)/\pi^2) g T^3 & \text{(BOSE)} \\ (3/4)(\zeta(3)/\pi^2) g T^3 & \text{(FERMI)}, \end{cases}$$

for **non relativistic** species m>> T

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} \exp[-(m-\mu)/T]$$

Why neutrinos cannot make DM?

(In some more details)

Step back: **thermal decoupling in the Early Universe**

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$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)}$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ **(thermal average)**

**Rule of thumb**: Interaction freezes-out at a temperature at which **interaction rate becomes comparable to the expansion rate of the Universe**.

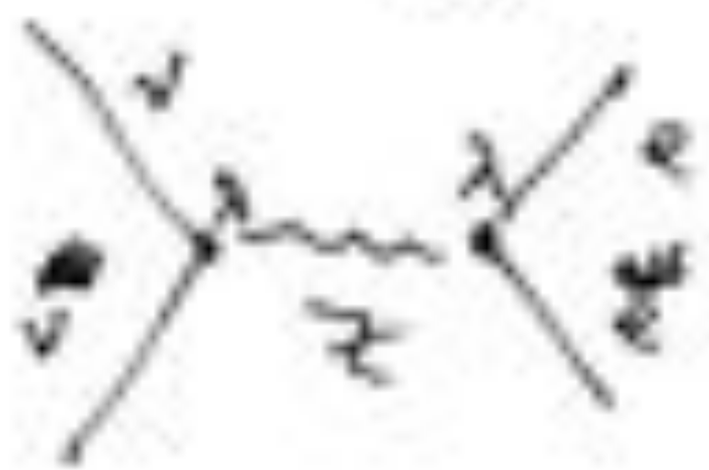
$$n\sigma \sim H$$

Why neutrinos cannot make DM?

(In some more details)

Step back: **thermal decoupling in the Early Universe**

for neutrinos:




$$\sigma(E) \sim \underbrace{E^2}_{\text{phase-space factor}} |A|^2 \sim E^2 \left(\frac{\lambda^2}{p^2+m_Z^2}\right)^2$$

$$p \sim E \,, \ll m_Z \sim 90\,\mathrm{GeV} \quad \Rightarrow \quad \sigma(E) \sim E^2 \, \frac{\lambda^4}{m_Z^4} \simeq E^2 G_F^2$$

Why neutrinos cannot make DM?
(In some more details)
Step back: **thermal decoupling in the Early Universe**

for neutrinos:

$$\Rightarrow \begin{cases} \sigma(T) \sim G_F^2 T^2 \\ v \sim c = 1 \\ n \sim \dfrac{\zeta(3)\, g}{\pi^2} T^3 \simeq 1.3\, T^3 \end{cases}$$

[illegible]

$$\boxed{\Gamma_{(T)} = n\langle\sigma v\rangle \sim 1.3\, G_F^2 T^5}$$

Why neutrinos cannot make DM?

(In some more details)

Step back: **thermal decoupling in the Early Universe**

for neutrinos:

$$\Rightarrow \left[ \frac{\Gamma}{H} \simeq 0.2 \cdot \frac{1}{4}\, T^3 \left(\frac{m_{pl}}{G_F^{-2}}\right) \sim \left(\frac{T}{1.4\,\mathrm{MeV}}\right)^3 \right]$$

$$\Omega_\nu h^2 = \frac{\rho_\nu h^2}{\rho_{crit}} \simeq \frac{m\, n}{\rho_{crit}} \simeq \left(\frac{m}{10\,\mathrm{eV}}\right)$$

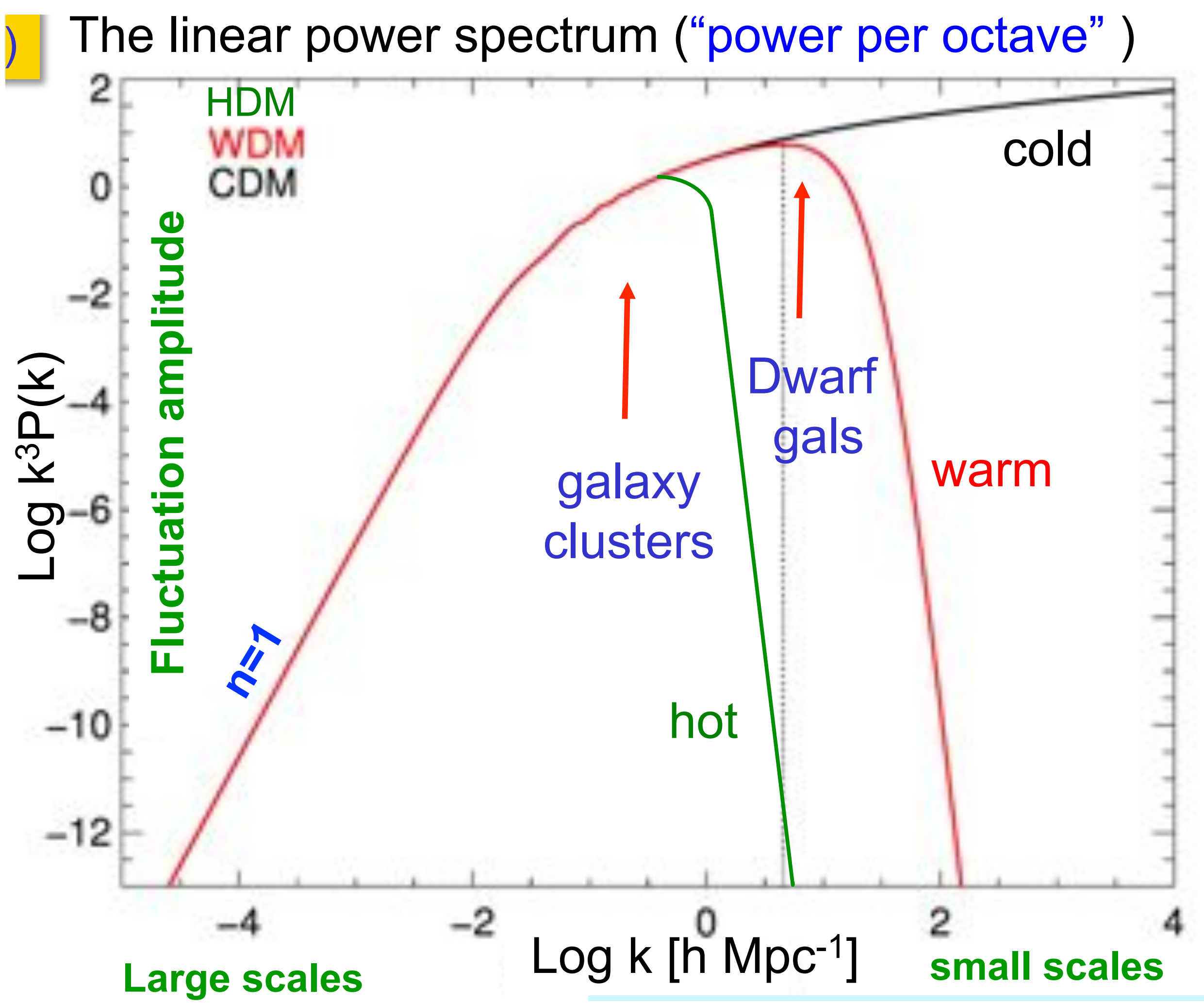
**m<~0.23 eV, cannot make up all DM!**

Why neutrinos cannot make DM?

(In some more details)

Step back: **thermal decoupling in the Early Universe**

for neutrinos:




In addition, they are **relativistic at structure formation**, small satellite Galaxies would not form!

# *Two Basic Options*

1. Something we know:

   - Ordinary ***Objects*** (**MACHOS**):

   Massive Compact Halo Objects: small bodies as dead stars (white dwarfs), neutron stars, black holes, large Jupiter like planets…

   - Standard model ***particle***: weakly interacting **neutrinos**

**Turns out this doesn't work!**

2. Some particle we do not know:

   - ***Weakly Interacting Massive Particles*** (**WIMPS**)

   very general category, some particle which is massive and interacts weakly

# Dark Matter
# Connection with particle physics

Mz

Standard Model

Standard Model of particle physics:

works amazingly well in explaining the observed particle content.

However remaining puzzles:

neutrino masses

dark matter

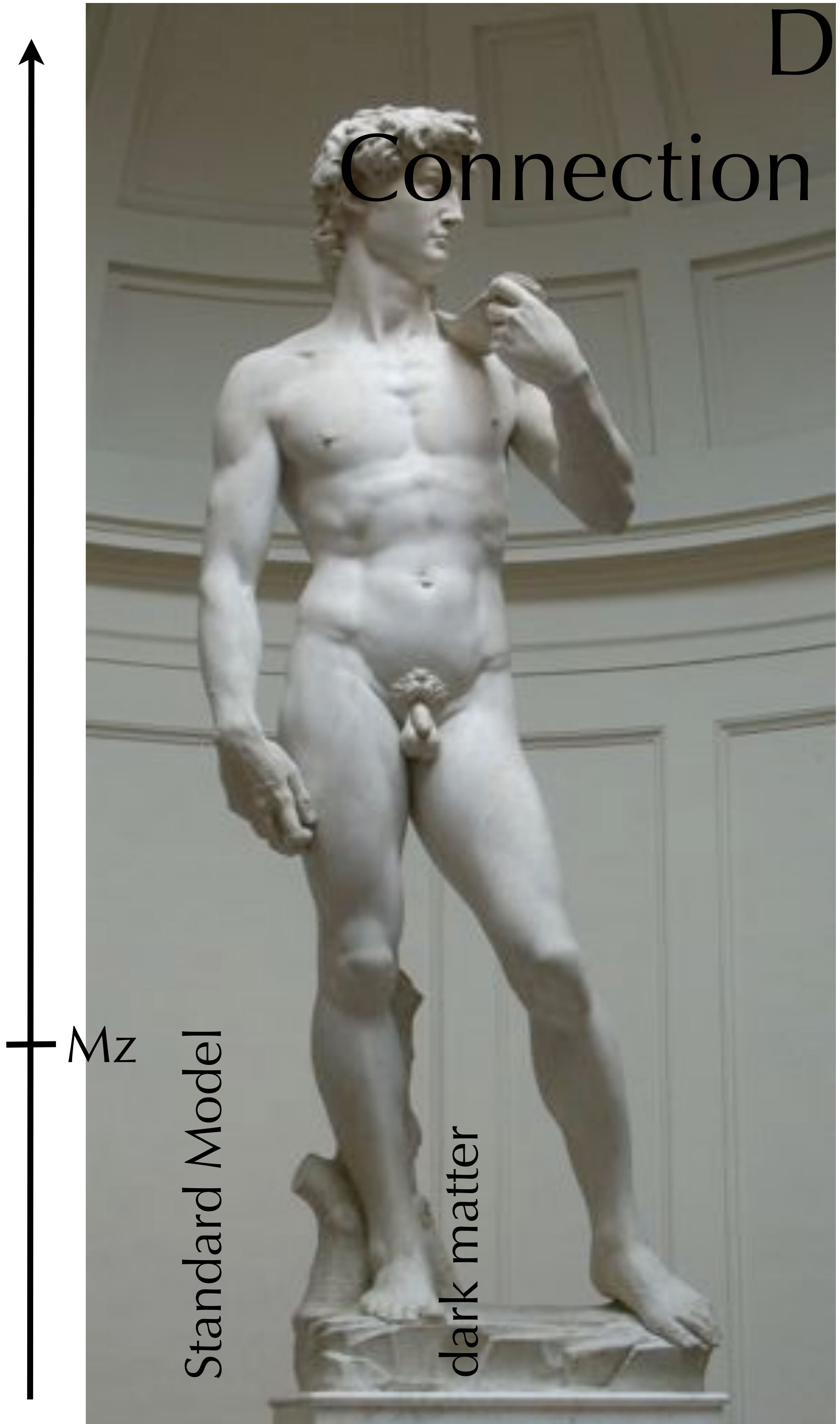
(quantum gravity, dark energy....)

# Dark Matter
# Connection with particle physics

Mz

dark matter

# Dark Matter
# Connection with particle physics




New physics:

The hope is that dark matter (and other signs of new physics) will shine light on a more complete theory at higher energies.

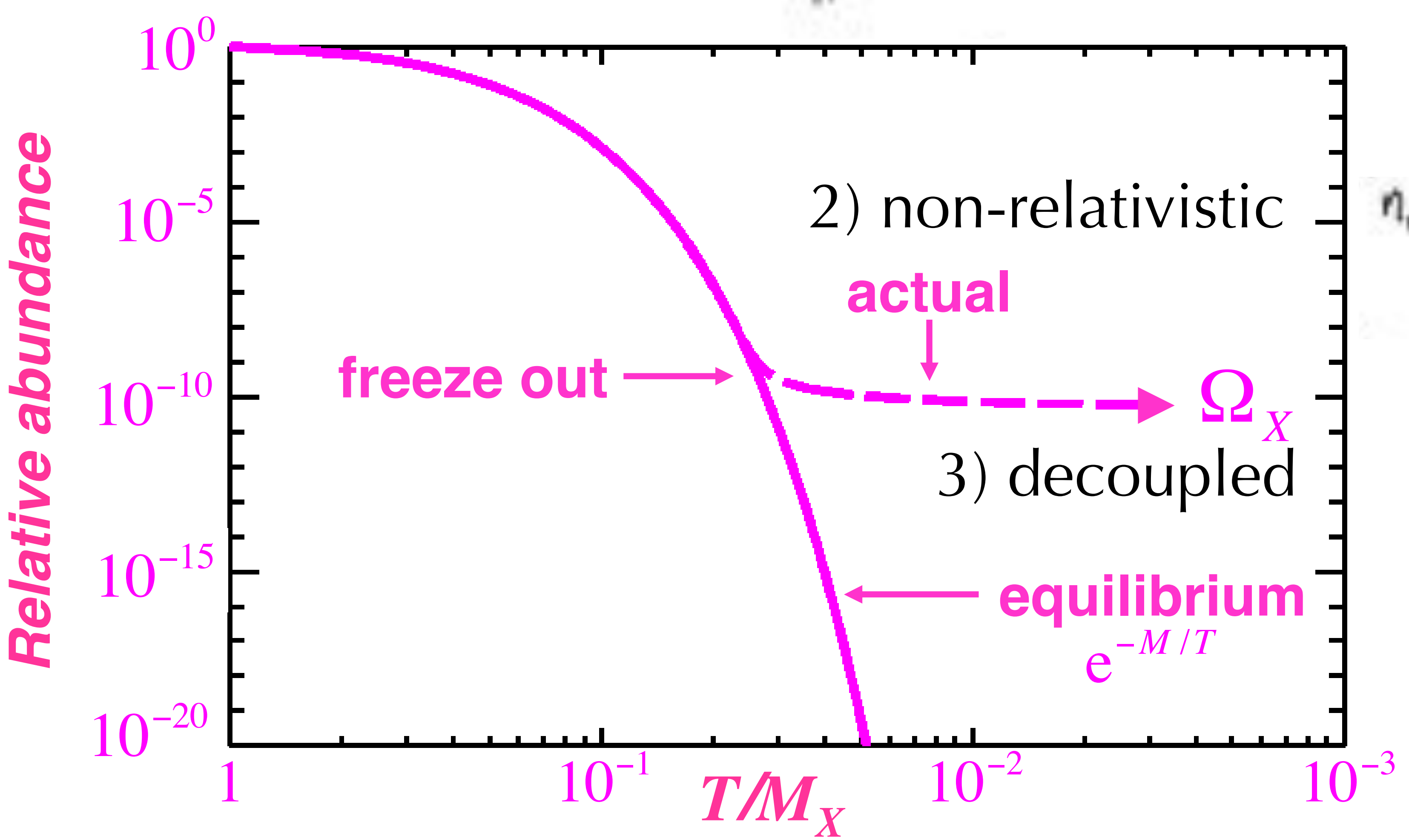
Idea: J. Redondo

# Dark Matter
# WIMPs
# (Weakly Interacting Massive Particles)

# Dark Matter
# WIMPs

- Decoupling from a 'thermal bath' in the Early Universe:

1) relativistic $n = g \frac{\zeta(3)}{\pi^2} T^3$




$n_w = g_w \left(\frac{m T}{2\pi}\right)^{3/2} \exp\left[- m_w / T\right]$

$\Omega_X \propto \sigma_A^{-1}$ ***(independent of mass)*** $\quad M_X \lesssim 200$ TeV

- decoupling when:

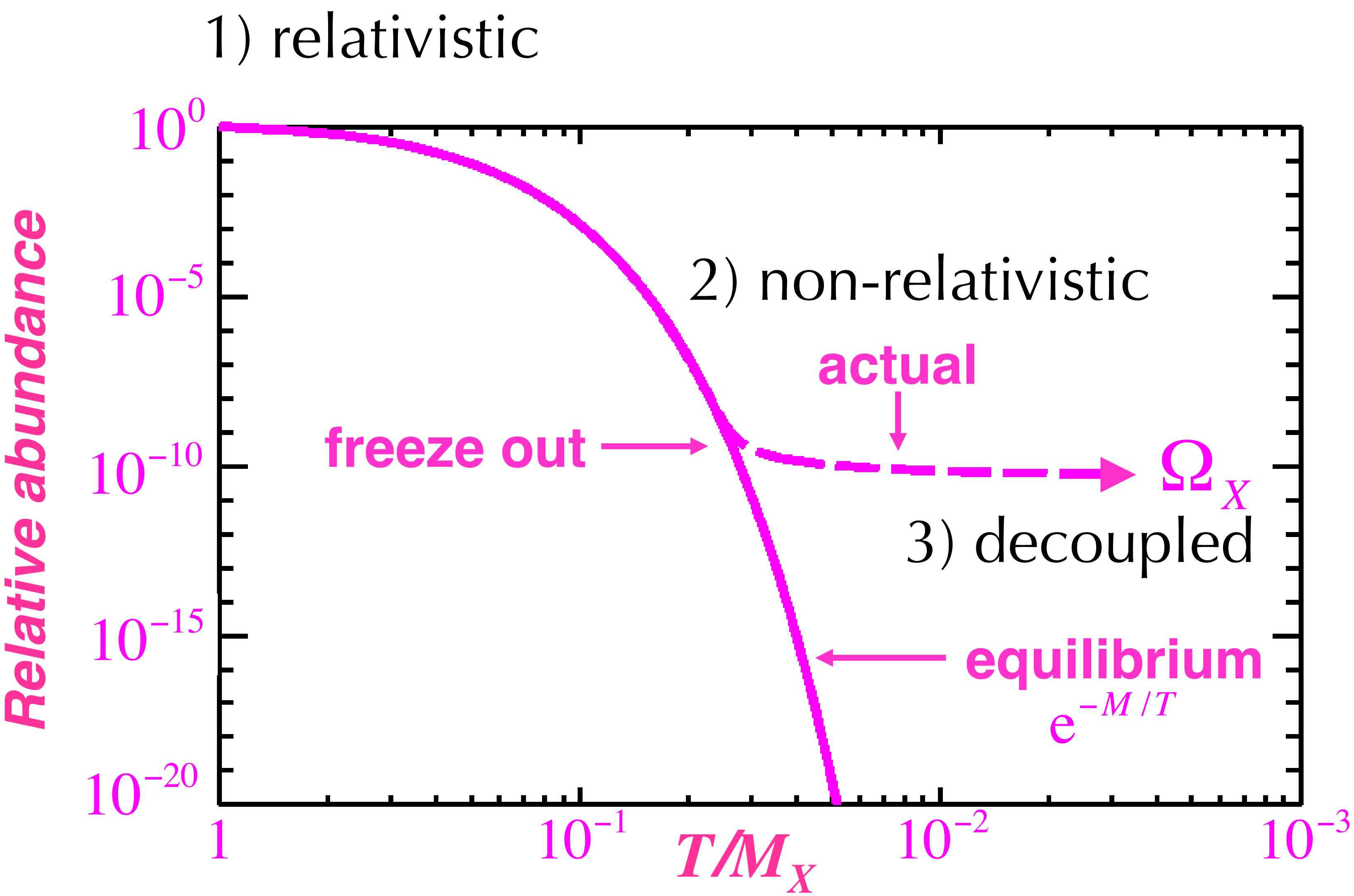
$n \sigma \sim H$

- from here decoupling temperature is:

$\frac{m}{T_{dec}} = 15.2 + 3 \ln\left(\frac{m}{1\,GeV}\right)$

# Dark Matter
# WIMPs

- Decoupling from a 'thermal bath' in the Early Universe:




$\Omega_X \propto \sigma_A^{-1}$ ***(independent of mass)*** $M_X \lesssim 200$ **TeV**

- and final abundance turns out to be:

$$\boxed{\Omega h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v \rangle_{\rm freeze}}{3 \times 10^{-26}\ {\rm cm^3 s^{-1}}}\right)^{-1}}$$

# Dark Matter
# WIMPs

- Decoupling from a 'thermal bath' in the Early Universe:

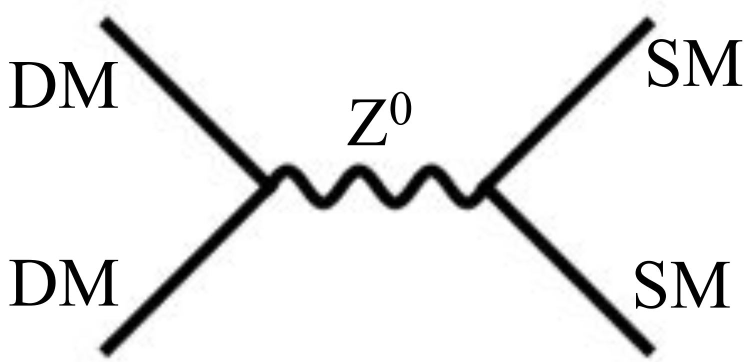
Correct relic density if

$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb} \cdot c}$$

$$\boxed{\Omega h^2 \simeq 0.1 \times \left( \frac{\langle \sigma v \rangle_{\mathrm{freeze}}}{3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}} \right)^{-1}}$$

$$\sigma(E) \sim \underbrace{E^2}_{\text{phase-space factor}} |A|^2 \sim E^2 \left( \frac{\lambda^2}{p^2 + m_*^2} \right)^2$$

- **WIMP miracle!**




$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

$$\boxed{m_{\mathrm{DM}} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}}$$

(provided $g \sim g_{\mathrm{weak}} \sim 0.1$)

# Dark Matter
# WIMPs

- Decoupling from a 'thermal bath' in the Early Universe:

Correct relic density if

$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb}\cdot c}$$

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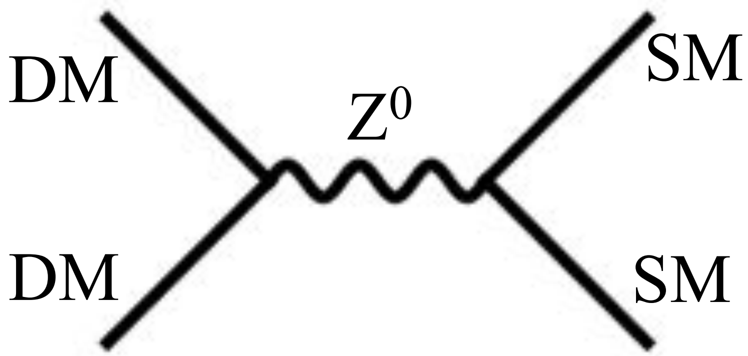



$$\sigma \sim \frac{g^4}{m_{\rm DM}^2} = 1\,\mathrm{pb}$$

$$\boxed{m_{\rm DM} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}}$$

(provided $g \sim g_{\rm weak} \sim 0.1$)

- **WIMP miracle!**
- **It is 'miraculously' easy to get these cross sections:** a typical gauge coupling of order one and a new particle in the TeV range!
- **However,** it is **hard(er) to make these new particles stable**!

# Dark Matter
# WIMPs

- Why WIMPs?

1. we obtain ***DM abundance from simple thermal production!*** (known to work also for standard model particles)

2. DM with a mass $\sim M_Z$ ***clusters in a way confirmed by observations*** (true for $m_{DM} >\sim 1$ MeV)

3. as a bonus, ***any theory which tries to explain the origin of EW mass, generally introduces new (stable) EW mass particles***.

# Dark Matter
# WIMPs: some theory ideas
# SUper SYmmetry

In the Standard Model: bosons are the mediators of interactions, fermions are the constituents of matter. SUSY: a symmetry which relates them, thus providing a sort of **“unified” picture of matter and interactions**.

**Hierarchy problem**: Higgs (scalars) receive quadratic corrections from new physics; Postulate the existence of new particles with similar masses but with spin different by one half to cancel quadratic divergencies, and explain why mH~mZ!

$$\delta m_s^2 \sim \left(\frac{\alpha}{2\pi}\right)\left(\Lambda^2 + m_B^2\right) - \left(\frac{\alpha}{2\pi}\right)\left(\Lambda^2 + m_F^2\right) = \left(\frac{\alpha}{2\pi}\right)\left(m_B^2 - m_F^2\right).$$

# Dark Matter
# WIMPs: some theory ideas
# SUSY

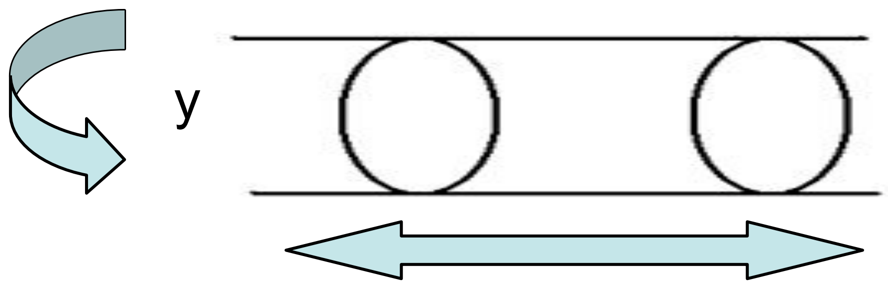
In some SUSY models (**MSSM**) a new symmetry, **R-parity is conserved**: all of the Standard Model particles have R-parity R = 1 and all sparticles (i.e. superpartners) have R = −1. Thus, sparticles can only decay into an odd number of sparticles (plus Standard Model particles). **The lightest sparticle (dubbed the LSP, for Lightest Super- symmetric Particle) is, therefore, stable** and can only be destroyed via pair annihilation, making it an excellent dark matter candidate.

The usual suspect the lightest **neutralino**: a mix of binos, winos, and higgsinos.

# Dark Matter
# WIMPs: some theory ideas
# Universal Extra Dimensions

The picture is that our familiar large 3 + 1 dimensions may be supplemented with more spacelike directions.In many extra-dimensional models, the 3+1 dimensional spacetime we experience is a structure called a **brane**, which is embedded in a $(3 + \delta + 1)$ spacetime called the **bulk**.

- How to define a model with extra dimensions..
  - Number of Extra Dimensions
  - Topology: Line, circle, torus,…
  - Geometry : Flat, warped,…



# Dark Matter
# WIMPs: some theory ideas
# Universal Extra Dimensions

- To begin with, imagine our extra dimension is a circle ($S^1$).
- This requires wave functions of any states to be periodic as one traverses the extra dimension.
- Mathematically, this is the particle-in-a-box problem familiar from basic Quantum Mechanics.
- The 5th component of Momentum ($p_5$) is quantized in units of 1 / R:

$$p_0^2 - \vec{p}^{\,2} - p_5^2 = 0 \quad \Longrightarrow \quad p_0^2 - \overrightarrow{p^2} = p_5^2 = m_{eff}^2$$

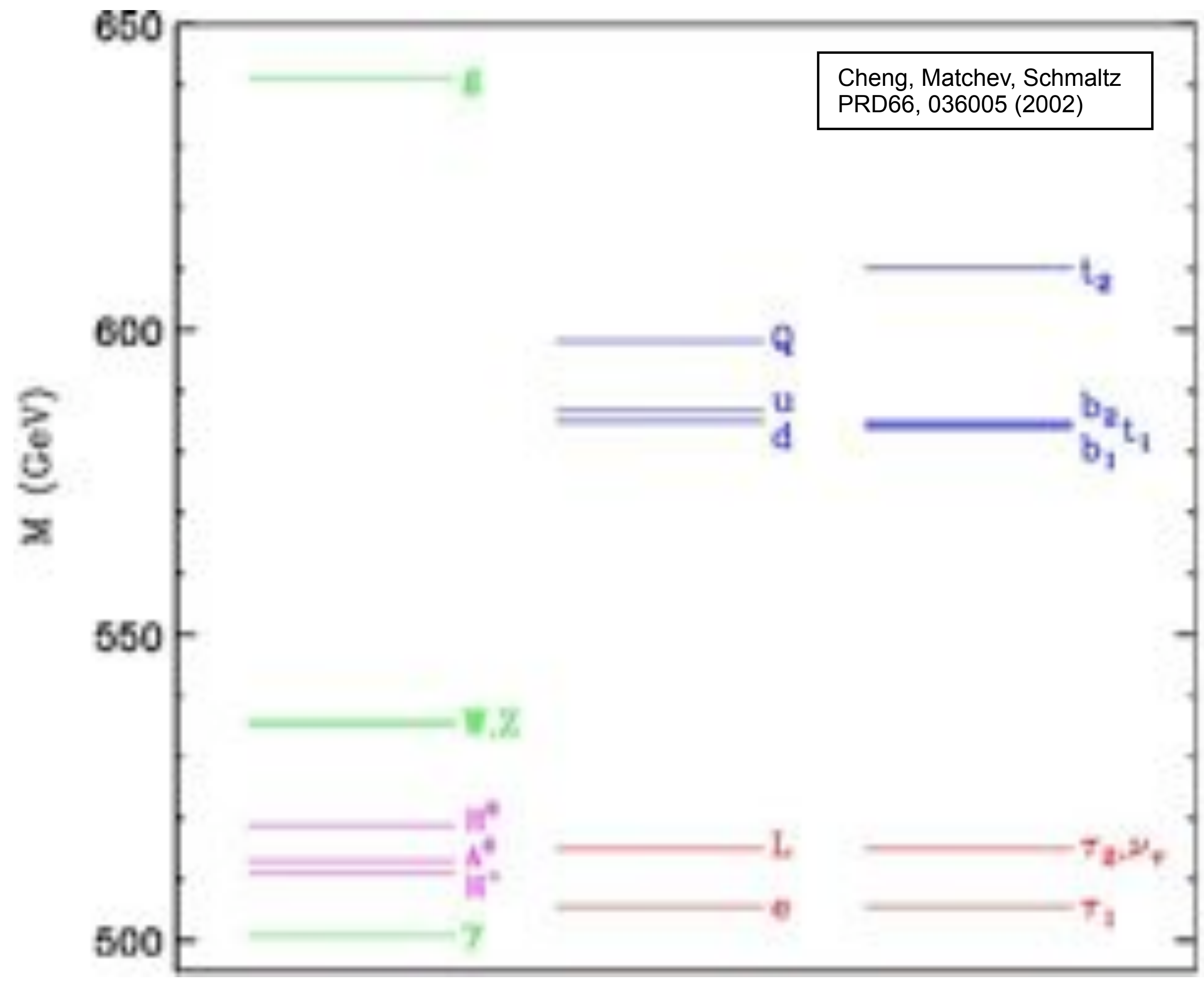
- States with $p_5$ different from zero appear massive to an observer who does not realize the extra dimension is there.
- We (and all low energy physics) are composed of the lowest modes.
- Each field has a tower of massive states with the same charge and spin as the zero mode, but with masses given by n / R.

# Dark Matter
# WIMPs: some theory ideas
# UED

Scenarios in which **all fields** are allowed to propagate in the bulk are called **Universal Extra Dimensions** (UED)

(first level) KK state in these models is stable and associated with the first KK excitation of the **photon**, or more precisely the first KK excitation of the hypercharge gauge boson.

It is stable, neutral, massive... a good DM candidate.



# Dark Matter

# WIMPs: some theory ideas

## Axions

Strong CP problem: Experimental constraints on the currently unobserved **neutron's electric dipole** moment imply that **CP violation arising from QCD must be extremely tiny** and thus Θ must itself be extremely small or absent-> a naturalness problem for the standard model.

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \mathrm{tr} \left\{ G_a^{\mu\nu} \widetilde{G}_{a\mu\nu} \right\} \theta$$

The idea is to add **a new global symmetry** (called a Peccei–Quinn symmetry) to the standard model that becomes **spontaneously broken** and drives Θ eff dynamically to zero.

Instanton effects spoil the Peccei–Quinn symmetry explicitly and provide **a small mass for the axion**.

# Dark Matter
# WIMPs: some theory ideas
# Axions

$$m_a \simeq 6\,\mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$

Its mass related to the coupling -> **one parameter problem**

Though light it is a '**cold dark matter**' as it is produced non thermally! (it was **never in thermal equilibrium** - does not share T of the Universe! and so the free streaming argument does not apply).

(**zero momentum condensate** and so constitutes cold dark matter.)

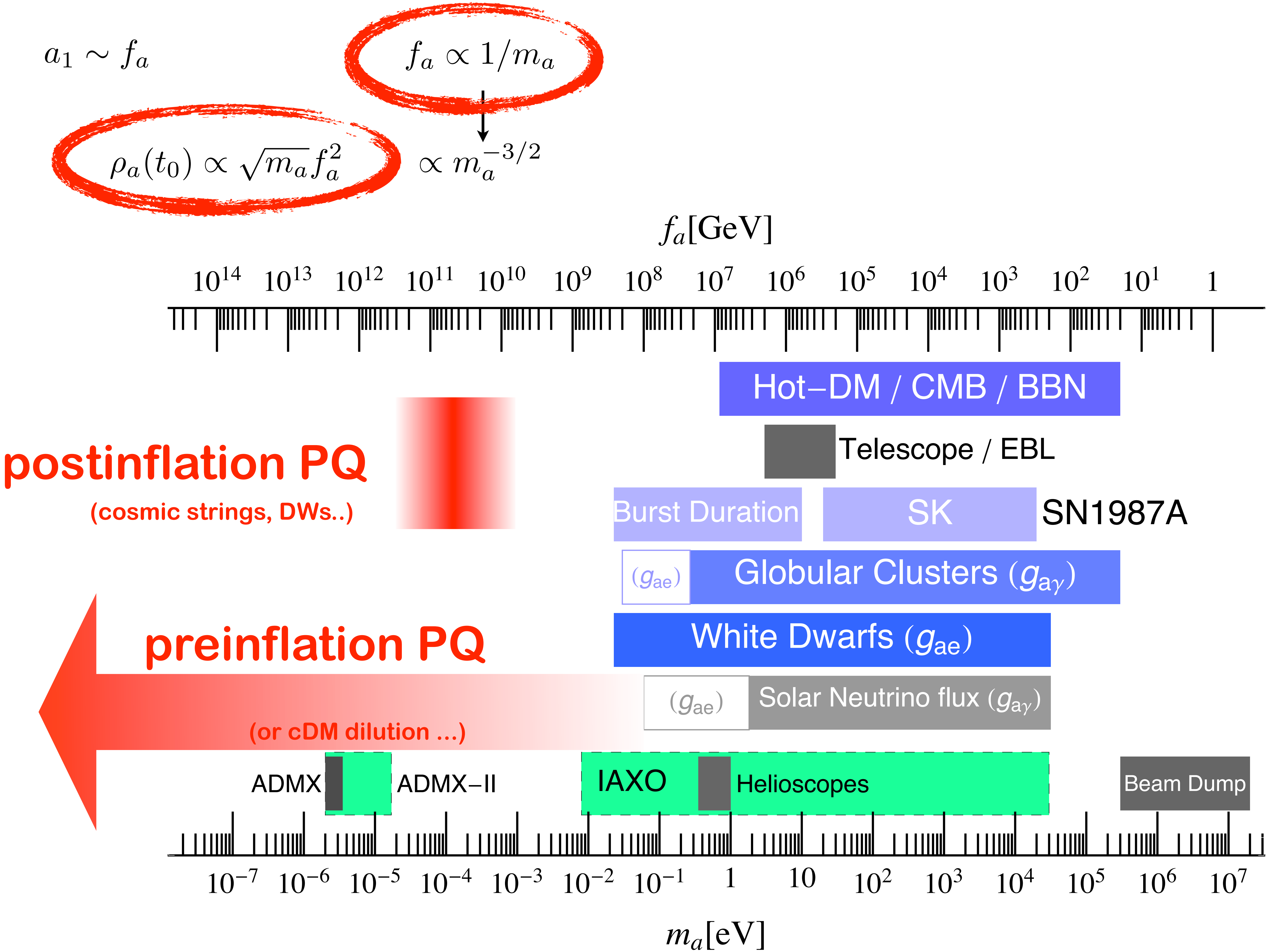
$$\mathcal{L}_I = \frac{g_{a\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu} a = -g_{a\gamma}\mathbf{B}\cdot\mathbf{E}\,a$$

Observational strategy: mix with photons in mag fields.

# Dark Matter
# Connection with particle physics

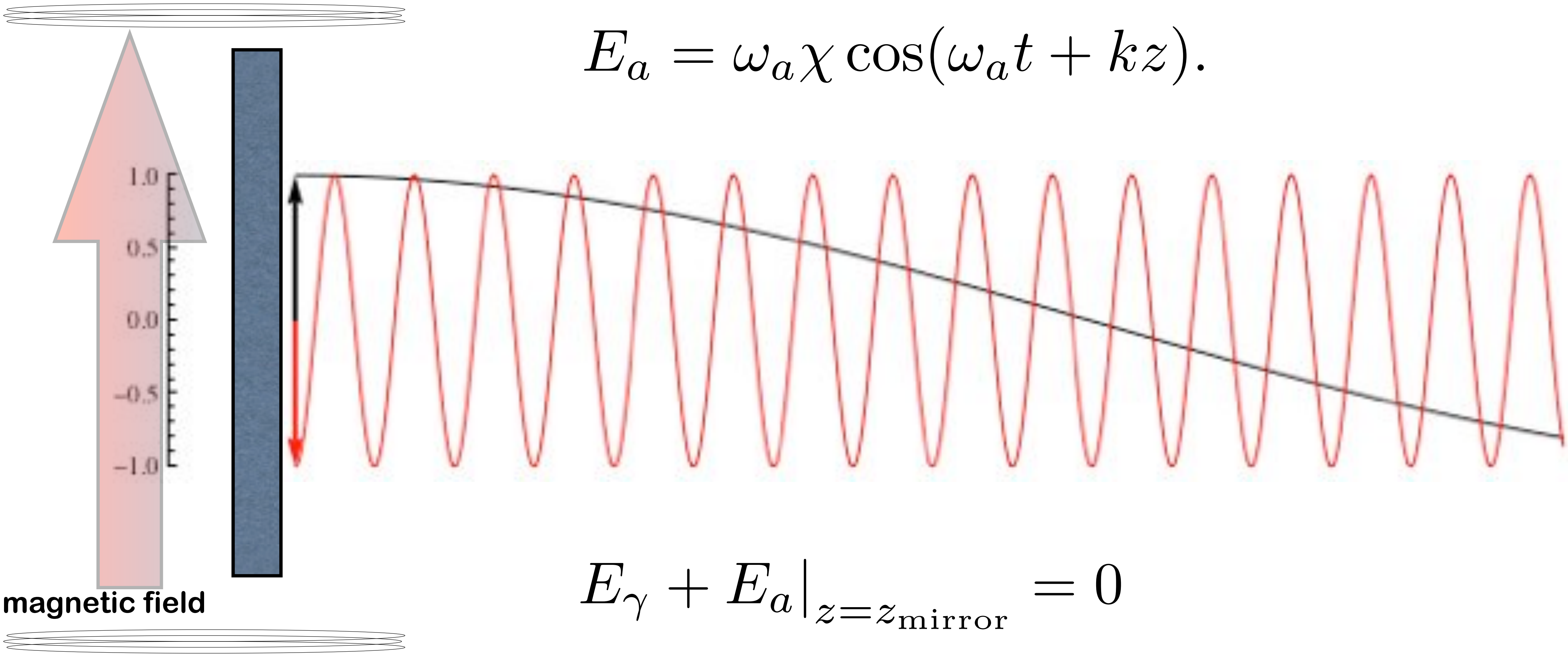
Bottom-line…

# Extra slides



$a_1 \sim f_a$
$f_a \propto 1/m_a$
$\rho_a(t_0) \propto \sqrt{m_a} f_a^2$
$\propto m_a^{-3/2}$
$f_a$[GeV]
$10^{14}$ $10^{13}$ $10^{12}$ $10^{11}$ $10^{10}$ $10^{9}$ $10^{8}$ $10^{7}$ $10^{6}$ $10^{5}$ $10^{4}$ $10^{3}$ $10^{2}$ $10^{1}$ 1
Hot–DM / CMB / BBN
Telescope / EBL
postinflation PQ
(cosmic strings, DWs..)
Burst Duration
SK
SN1987A
($g_{ae}$)
Globular Clusters ($g_{a\gamma}$)
White Dwarfs ($g_{ae}$)
preinflation PQ
($g_{ae}$)
Solar Neutrino flux ($g_{a\gamma}$)
(or cDM dilution ...)
ADMX
ADMX–II
IAXO
Helioscopes
Beam Dump
$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1 10 $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$ $10^{6}$ $10^{7}$
$m_a$[eV]

$$E_a = \omega_a \chi \cos(\omega_a t + kz).$$




$$E_\gamma + E_a|_{z=z_{\rm mirror}} = 0$$

$$E_\gamma = -\omega_a \chi \cos(\omega_\gamma (t - z)).$$

**Photons radiated from the mirror with** $\omega_\gamma = \omega_a = m_a(1 + v^2/2)$

# Dark Matter
# Overview

- Lecture 1&2: Evidence, Properties and Candidates
- Lecture 3&4: Search strategies: Direct and Indirect detection and colliders

# Dark Matter
# The (WIMP) hunt

# Dark Matter
## DM density

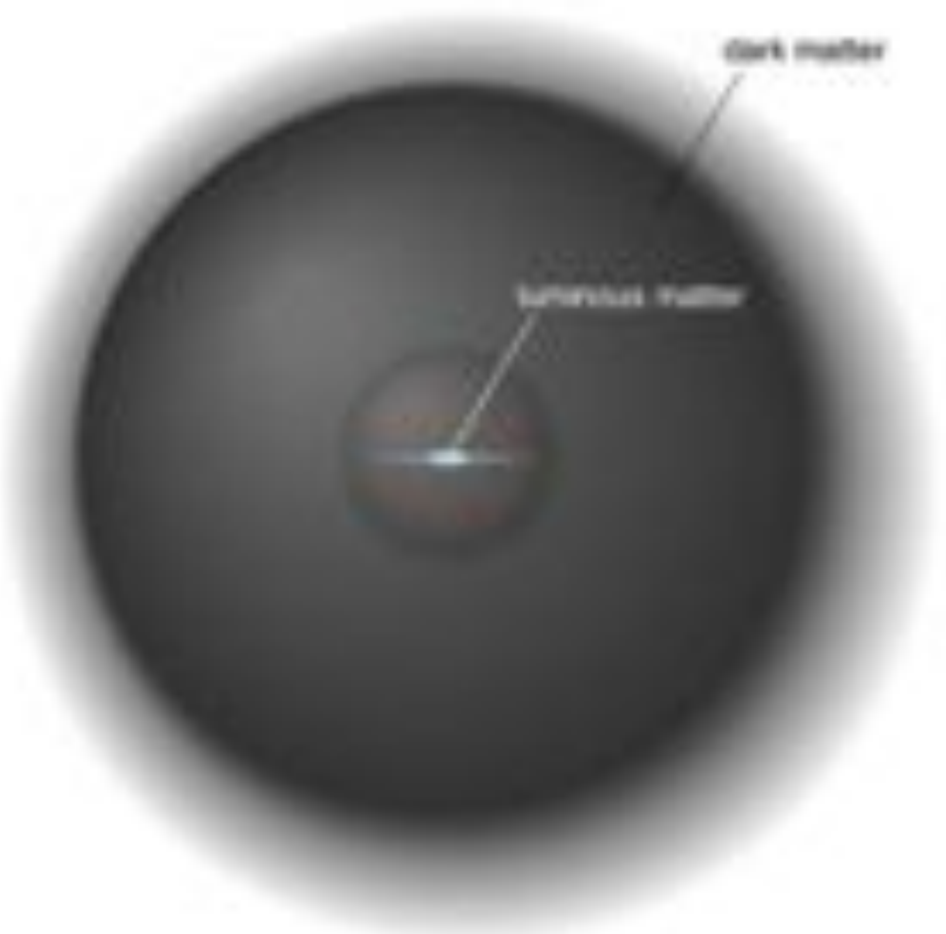
# Dark Matter
# DM density

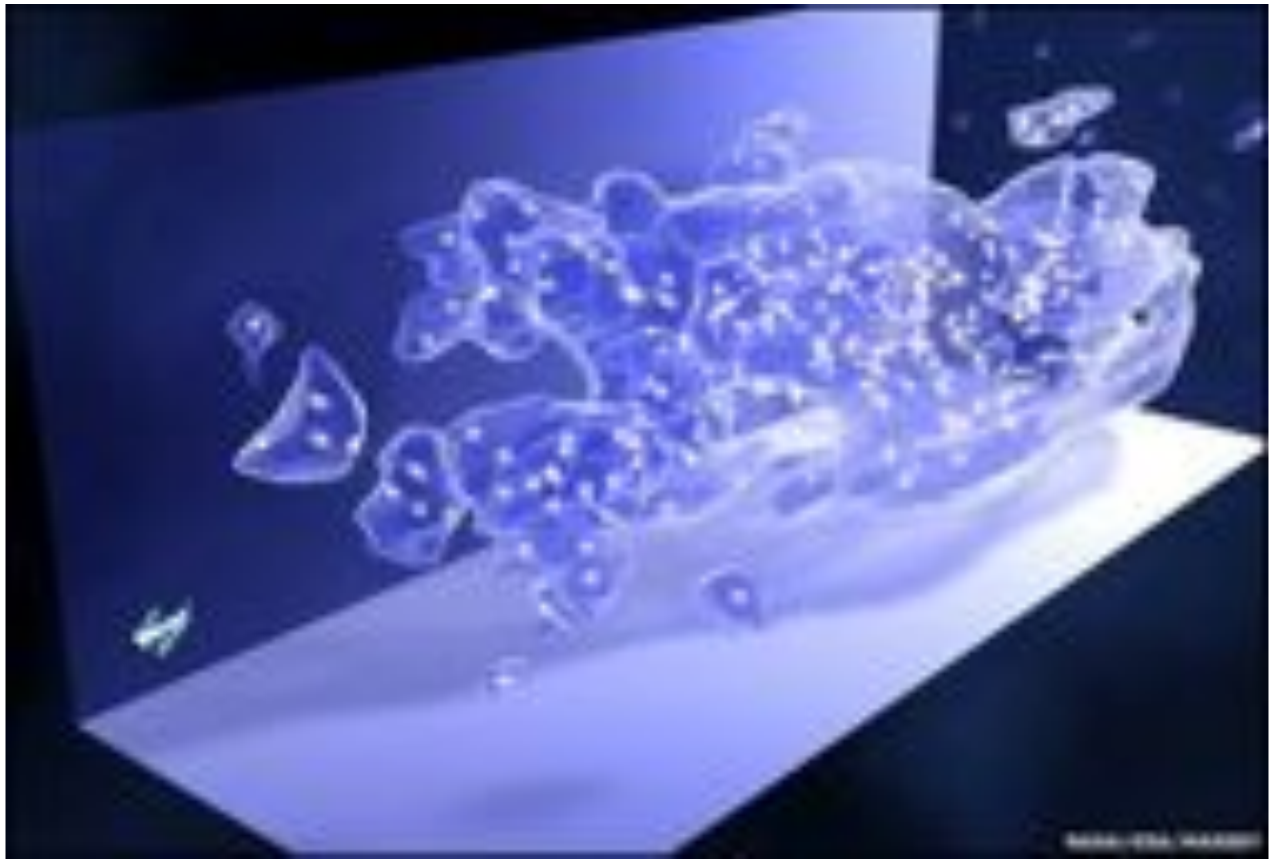
Determined two ways:

- N body simulations
- astrophysical observations of tracers of gravitational potential (rotational curves etc)

How is DM distributed:

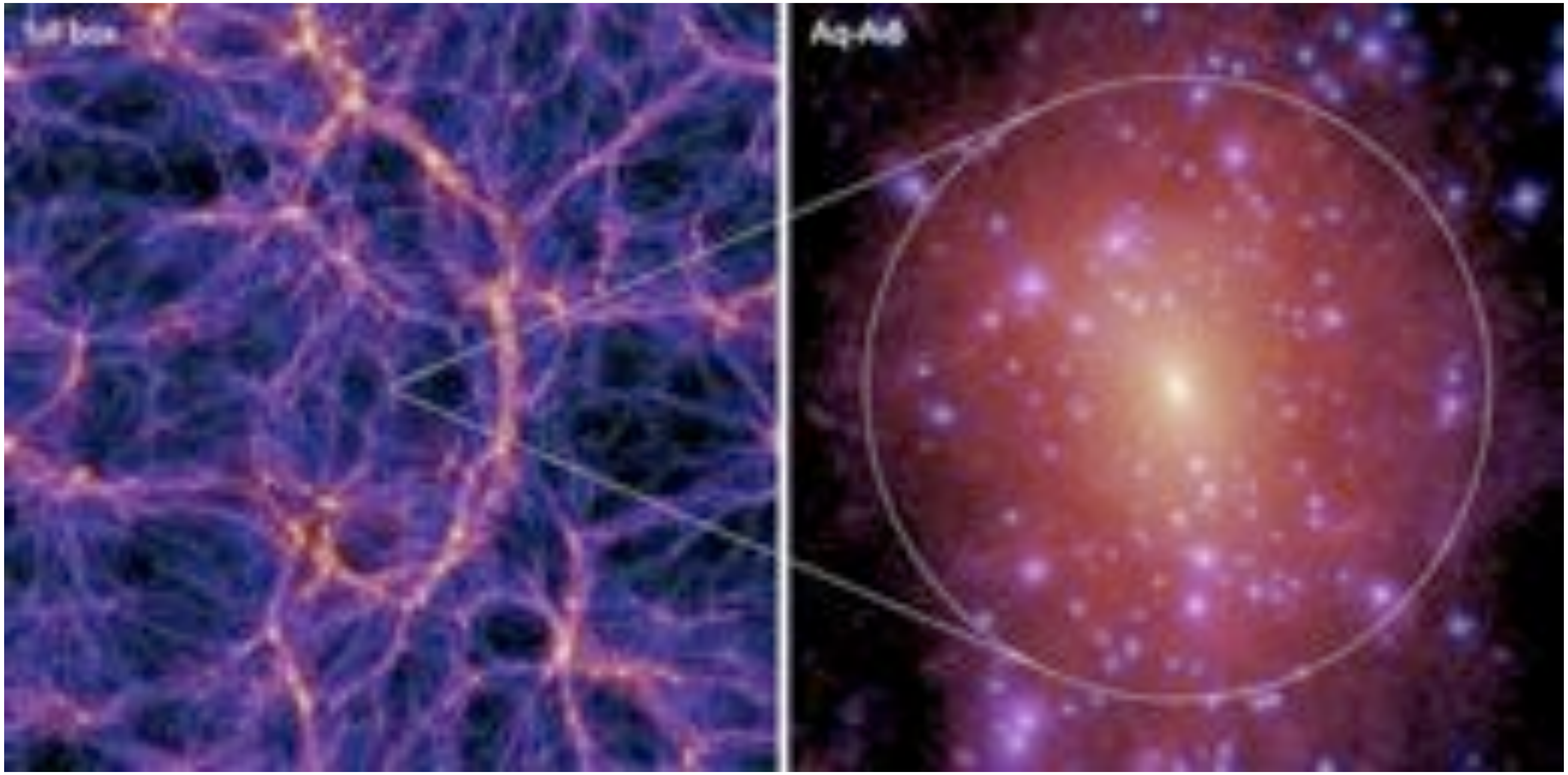
- it is around Galaxies and Clusters of Galaxies.



How is DM distributed:

- DM halos form **filamentary structures** on large scales
- DM halos have **numerous substructure**. Some of it has stars (as satellites of Milky Way) and some is dark.



Millennium simulation suite

N body simulations find that the DM density distribution within each DM halo is scale invariant, and that it follows **cuspy NFW** or **Einasto** density profile.

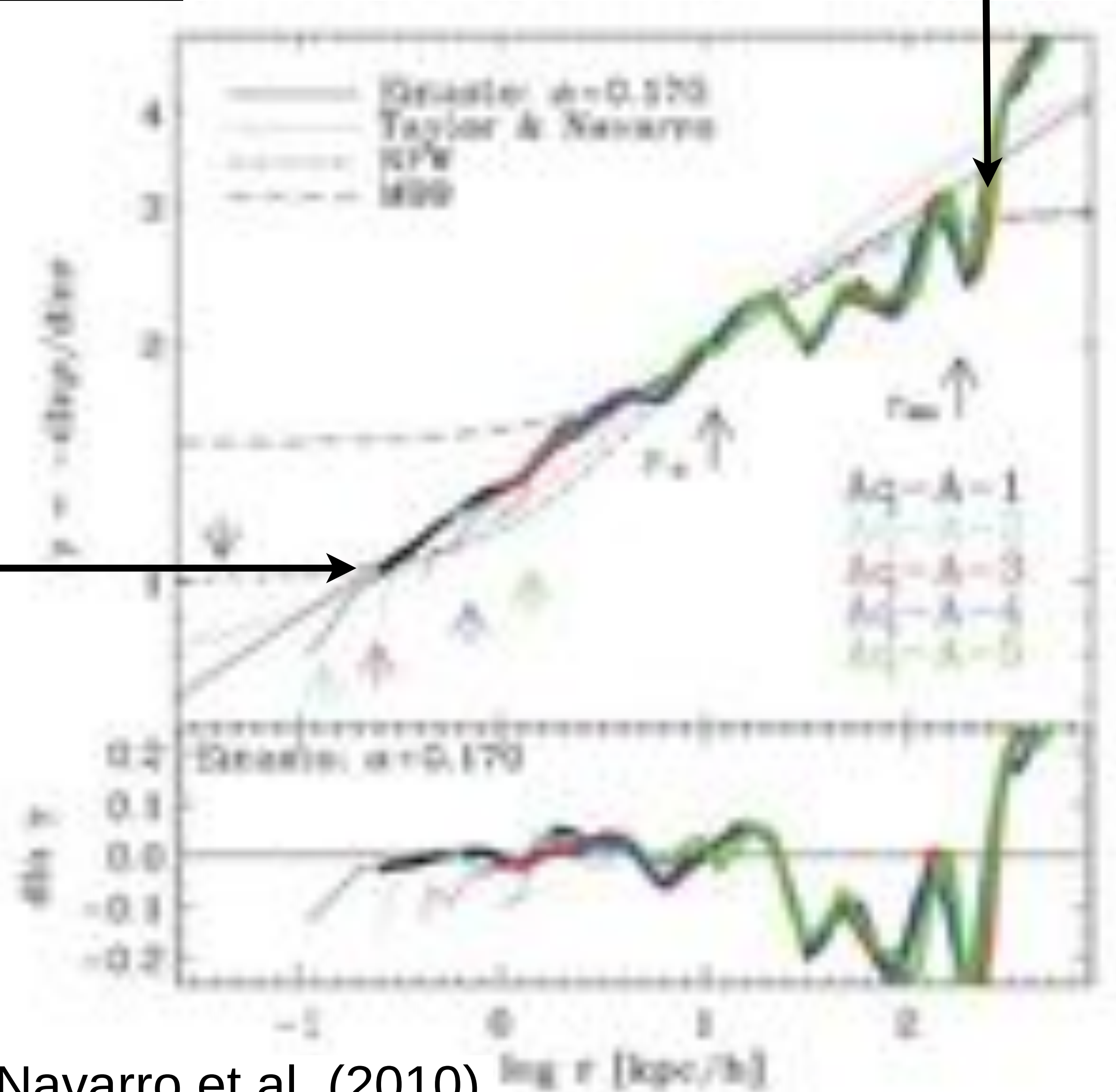
DM-only N-body simulations predict cuspy density profiles: $\gamma \equiv -\dfrac{d\ln\rho}{d\ln r} \lesssim 1$

$$\rho(r) = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2} \quad \text{(NFW)}$$

$$\ln\frac{\rho(r)}{\rho_s} = -\frac{2}{\alpha}\left[(r/r_s)^\alpha - 1\right] \quad \text{(Einasto)}$$

~200 kpc, halo size

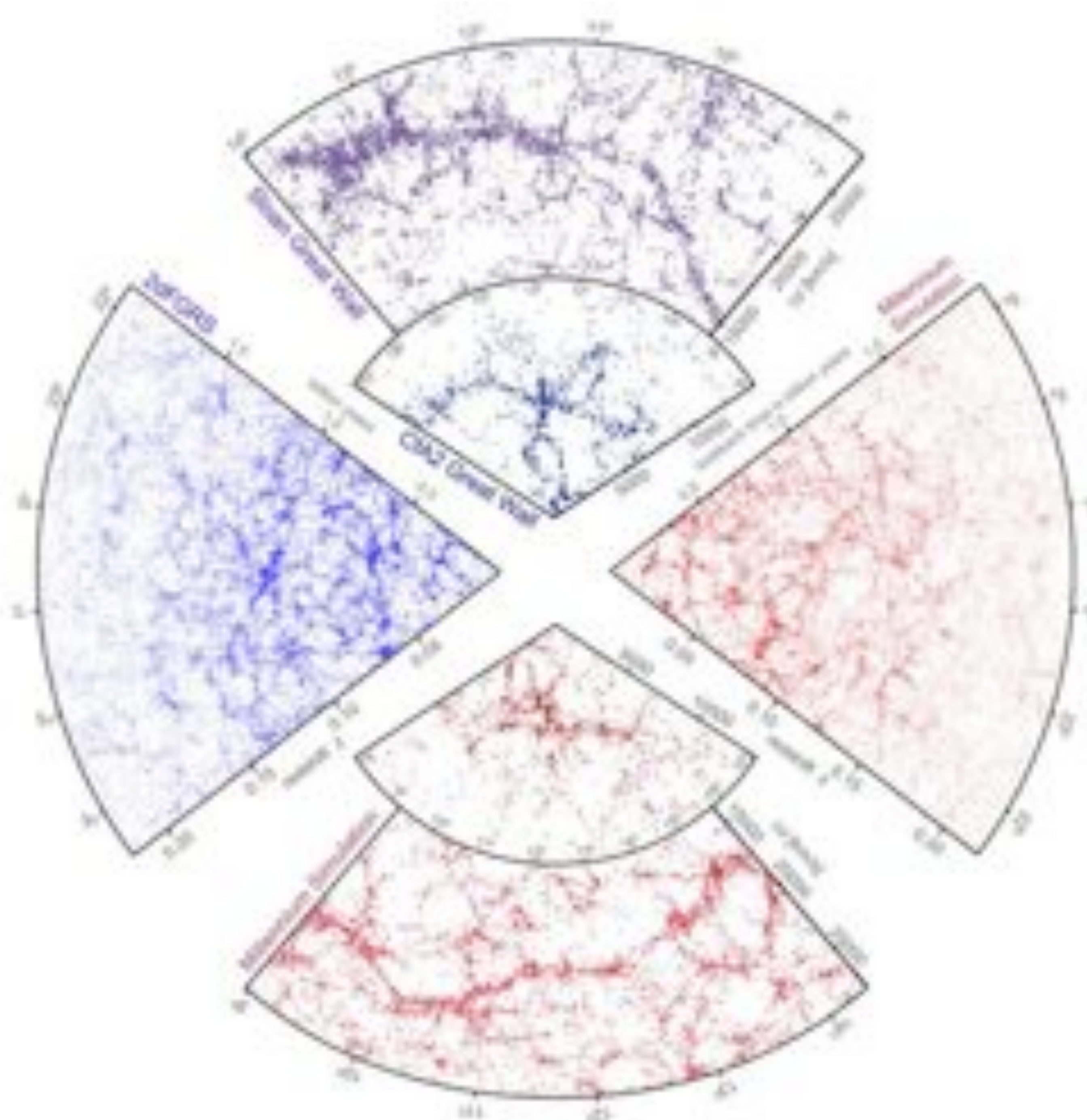
resolution limit, 500 pc




Navarro et al. (2010)

**cuspy: ρ→1/r (r→0) NFW**

Great agreement between N-body simulations and observations, at large scales!



Also, NFW or Einasto DM profiles fit well the profiles of Galaxy Clusters.

But at **small scales** or in **baryon dominated** regions DM density is highly uncertain!

In simulations:

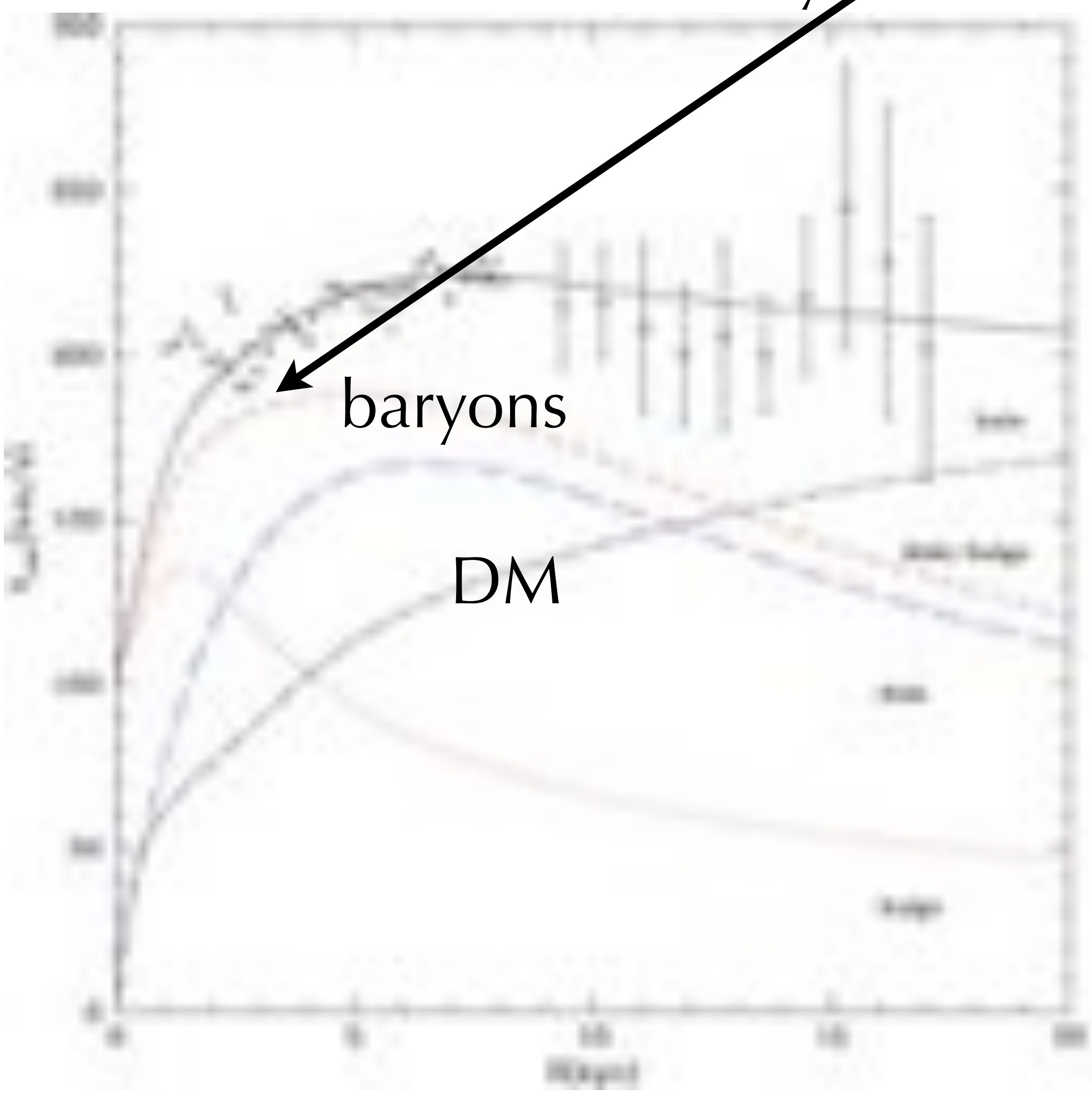
- because of limited resolution: not enough particles in small halos or centers of halos
- and baryonic physics cannot yet be reliably included.

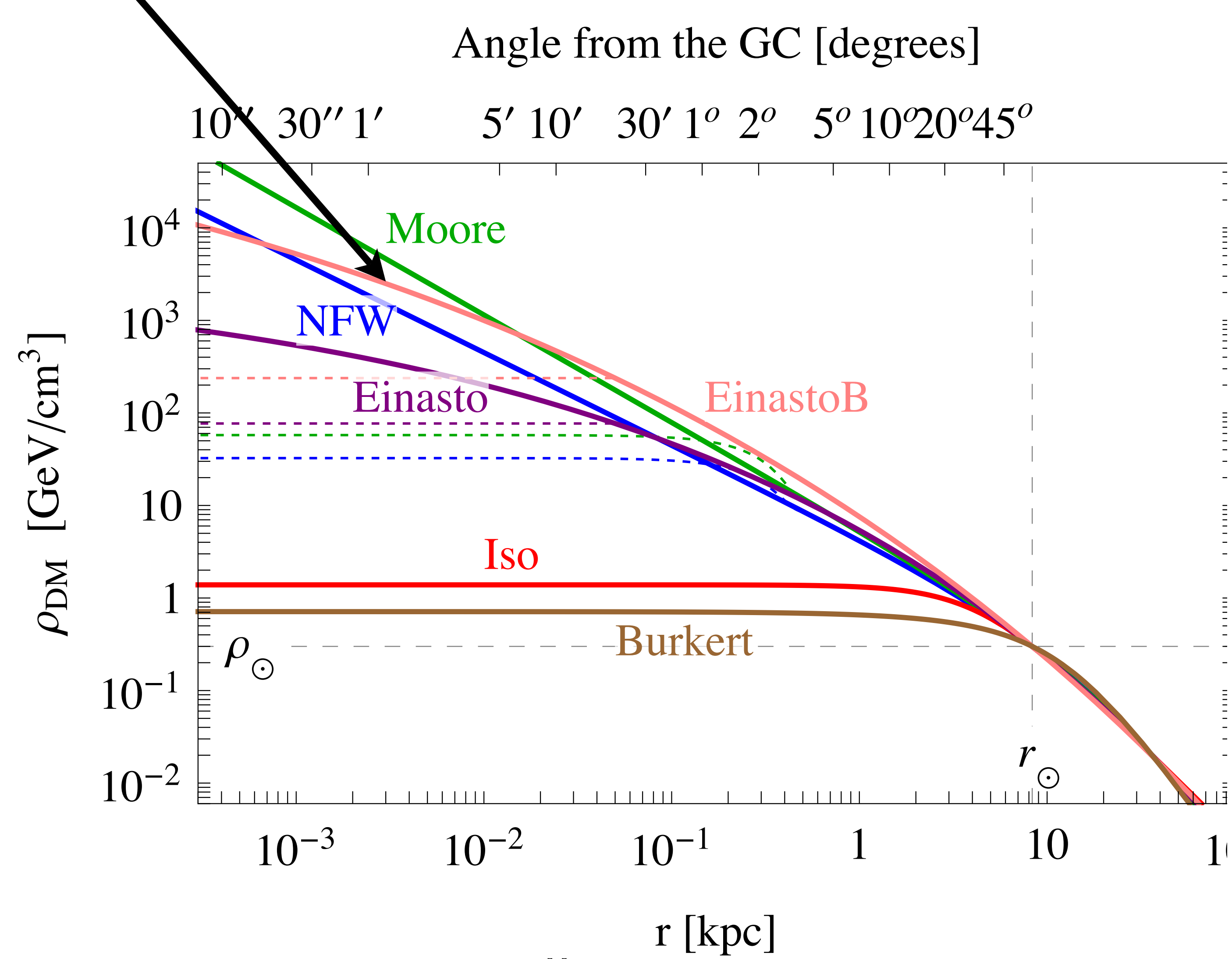
In astrophysical observations:

- close to halo centers gravitational potentials often dominated by baryons
- for very small halos not enough stars to reconstruct the potential

Baryon dominated in inner few kpc! Large uncertainties!

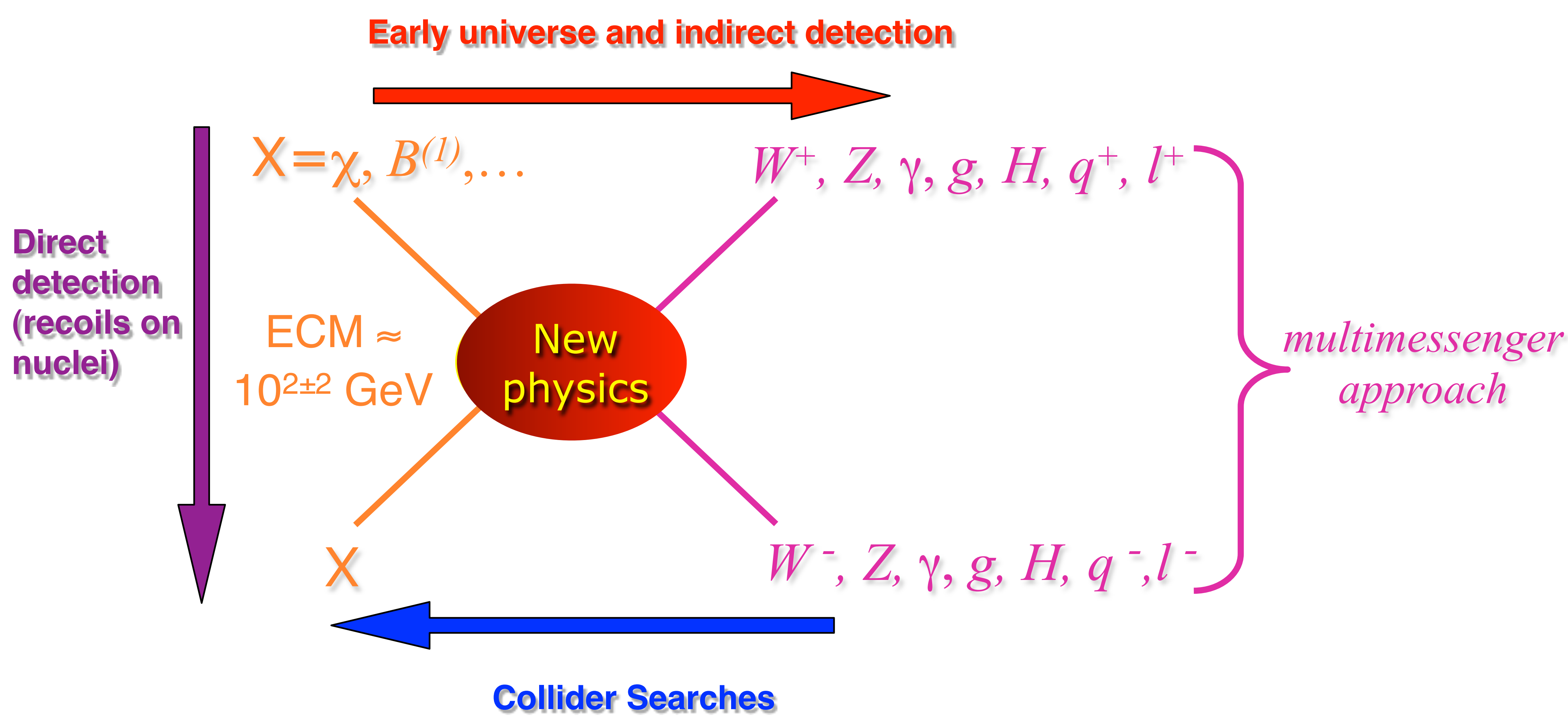
rotational curve Galaxy



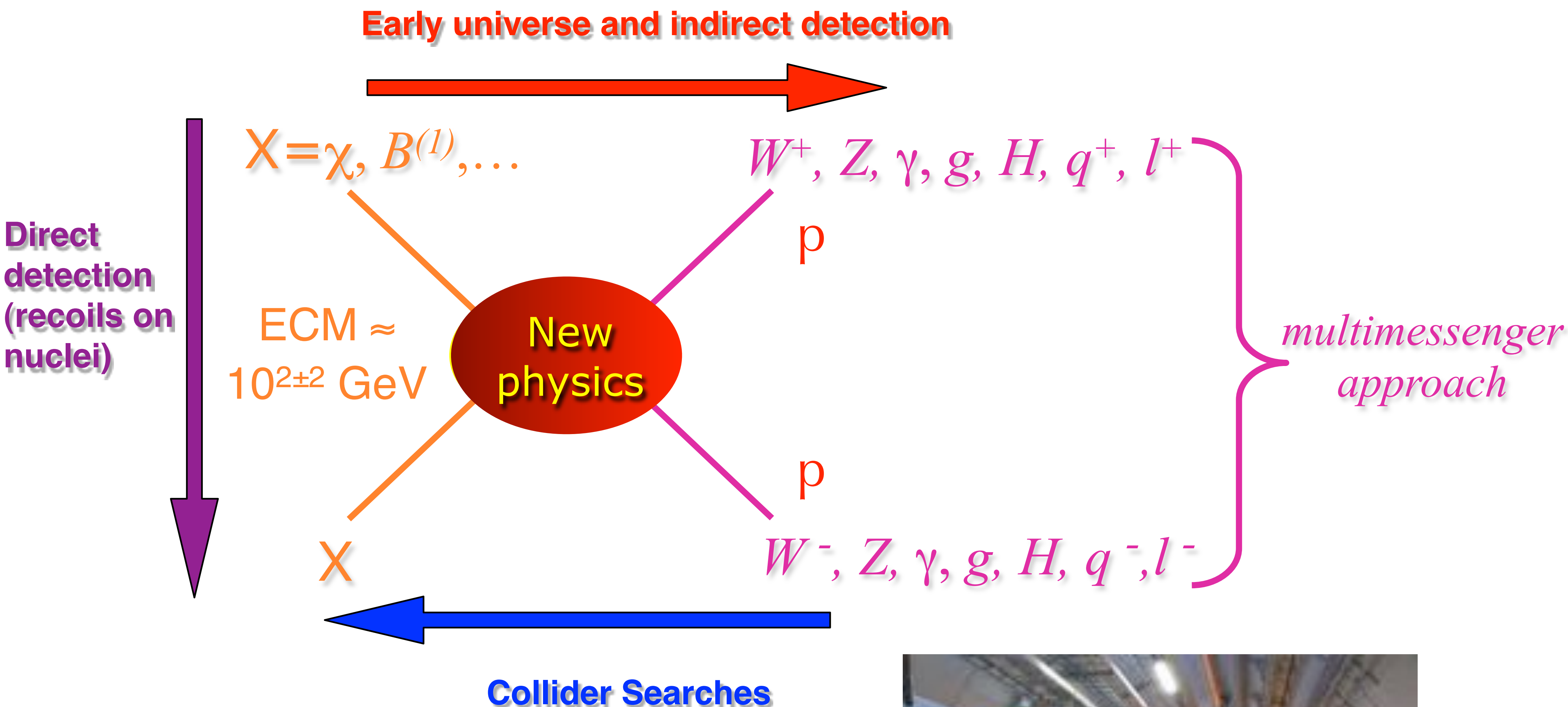



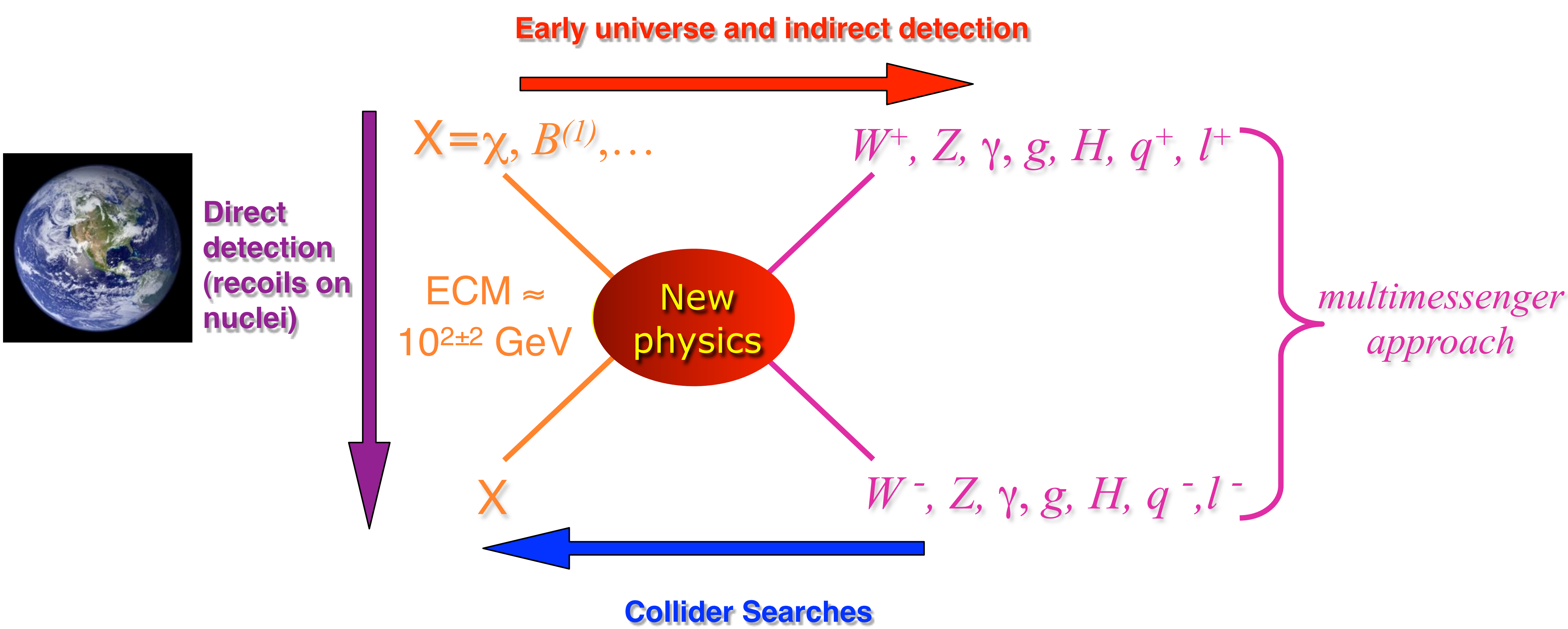

[Cirelli, M.+, JCAP, 2011.]

# Dark Matter Strategies

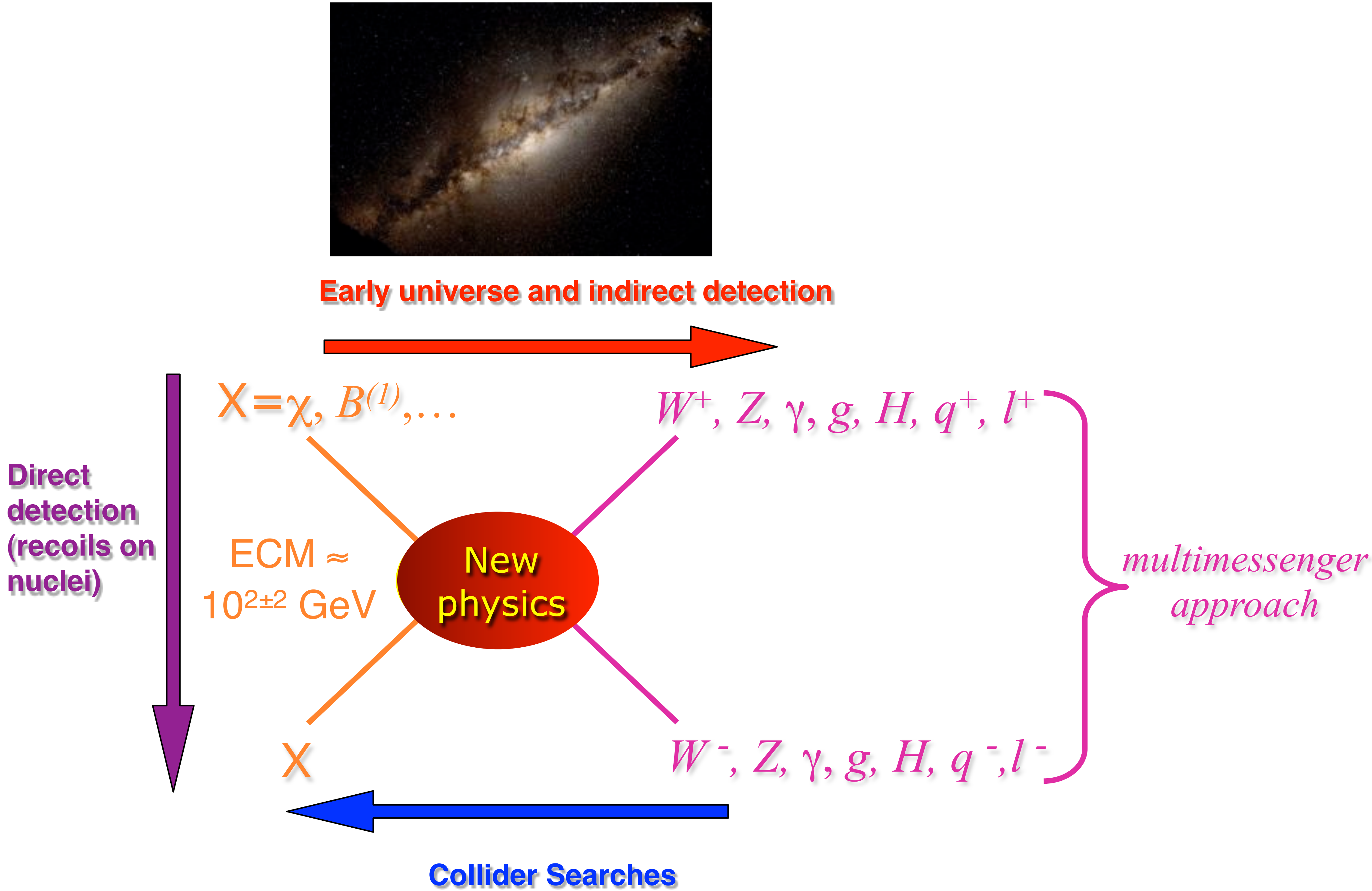



Note: I focus here at $10^{2\pm2}$ GeV mass particle interacting with 'weak' like cross sections. While this is well motivated other mass/cross sections ranges are possible, with different search strategies (axions).


Early universe and indirect detection
X=χ, B^(1),…
W⁺, Z, γ, g, H, q⁺, l⁺
Direct detection (recoils on nuclei)
p
ECM ≈ 10^(2±2) GeV
New physics
multimessenger approach
p
X
W⁻, Z, γ, g, H, q⁻, l⁻
Collider Searches




Elastic scattering rates with detectors, sensitive to the local value of DM density!




Today DM does not annihilate on cosmological scales (average densities too low)

→ its total amount remains ~constant!

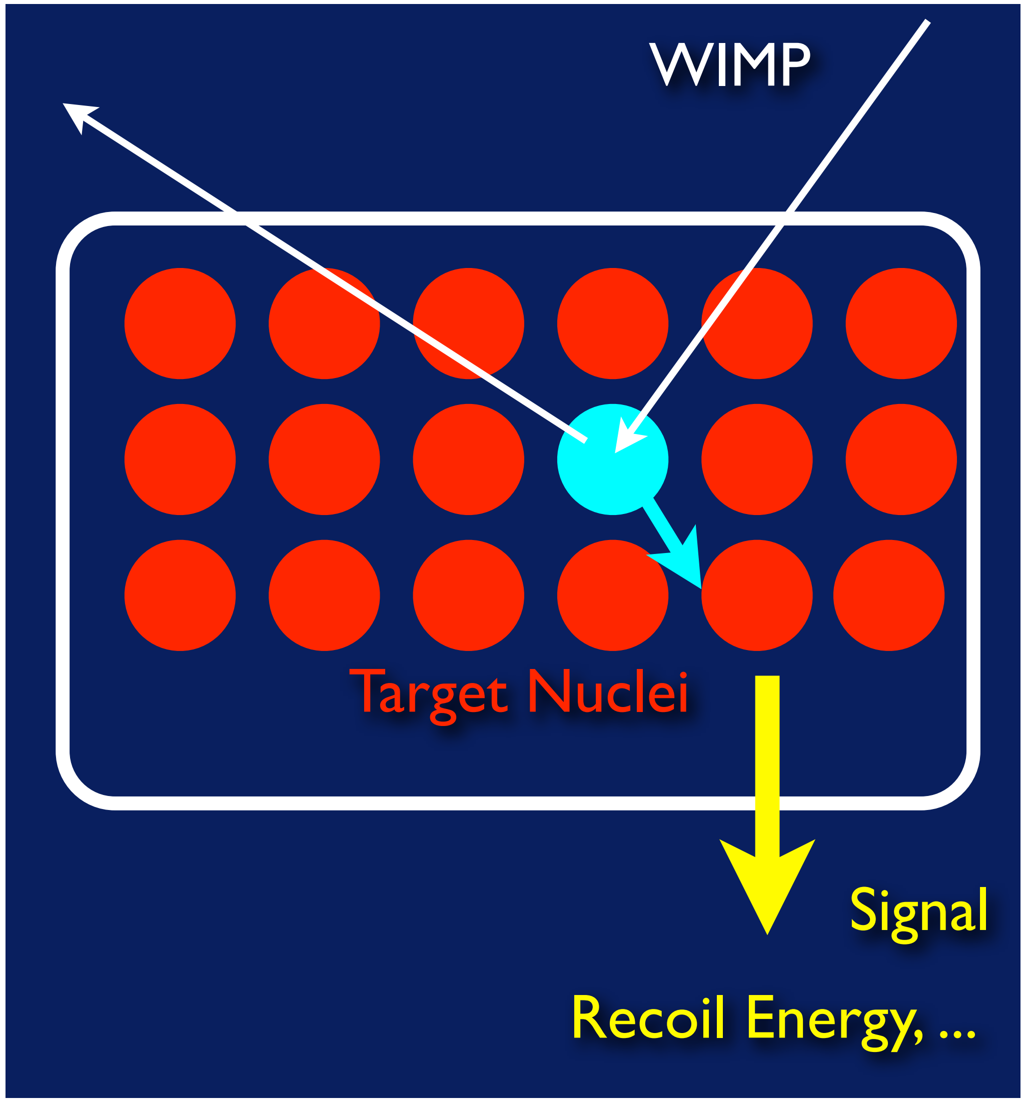
However in astrophysical systems, where it is concentrated annihilation densities are higher/ potentially detectable! - important to know the DM distribution!

**Note: We assume that DM particle is its own anti-particle (i.e. Majorana particle) or if made of particles and anti-particles (Dirac) that they are present in an equal amount!**

# Dark Matter
# Direct detection

# Dark Matter
# Direct detection

The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when a WIMP hits it.




as simple as that ....

Next few slides:

1. theoretical expectations for a signal
2. challenges -> backgrounds!

# Theory:

velocity distribution of DM

$$\frac{dR}{dE_R} = N_T\, n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}|\, f(\vec{v})\, g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

Number of target nuclei
(mass of the detector, A)

scattering cross section with a nucleus of mass A

$n_X = \dfrac{\rho_0}{m_\chi} = 0.4\ \mathrm{GeV/cm^3}/m_x$

Number of DM particles

Theory: $$\frac{dR}{dE_R} = N_T\ n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}|\ f(\vec{v})\ g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

- **f(v): velocity distribution** of DM

Often a truncated Maxwellian distribution is assumed:

$$f_{\mathrm{gal}}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\mathrm{esc}} \\ 0 & v > v_{\mathrm{esc}} \end{cases}$$

$$\bar{v} \simeq 220\,\mathrm{km/s} \qquad v_{\mathrm{esc}} \simeq 550\,\mathrm{km/s}$$

(corresponds to an iso-thermal sphere)

# Theory:

$$\frac{dR}{dE_R} = N_T\ n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}|\ f(\vec{v})\ g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

**cross section with a nuclei A:**

- for **spin independent interactions** and the same for protons and neutrons, the low energy scattering amplitude from a nucleus with mass number A is a coherent sum of A single nucleon scattering amplitudes.

$$\frac{\sigma_{XA}^{SI}}{\sigma_{Xp}^{SI}} = \left(\frac{\mu(A)}{\mu(p)}\right)^2 A^2$$

also depends on the reduced mass, through the phase space.

$$\mu = \frac{M_A M_B}{M_A + M_B}$$

- for **spin dependent** interactions the scattering amplitude changes sign with the spin orientation. Paired nucleons therefore contribute zero to the scattering amplitude

$$\frac{\sigma_{XA}^{SD}}{\sigma_{Xp}^{SD}} = \left(\frac{\mu(A)}{\mu(p)}\right)^2 \frac{[\lambda^2 J(J+1)]_A}{[\lambda^2 J(J+1)]_p} \left(\frac{C_{XA}}{C_{Xp}}\right)^2$$

➡ There is no $A^2$ enhancement in this case! **Limits typically weaker.**

# Theory:

$$\frac{dR}{dE_R} = N_T \; n_X \int_{v_{min}}^{v_{esc}} d\vec{v} \; |\vec{v}| \; f(\vec{v}) \; g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

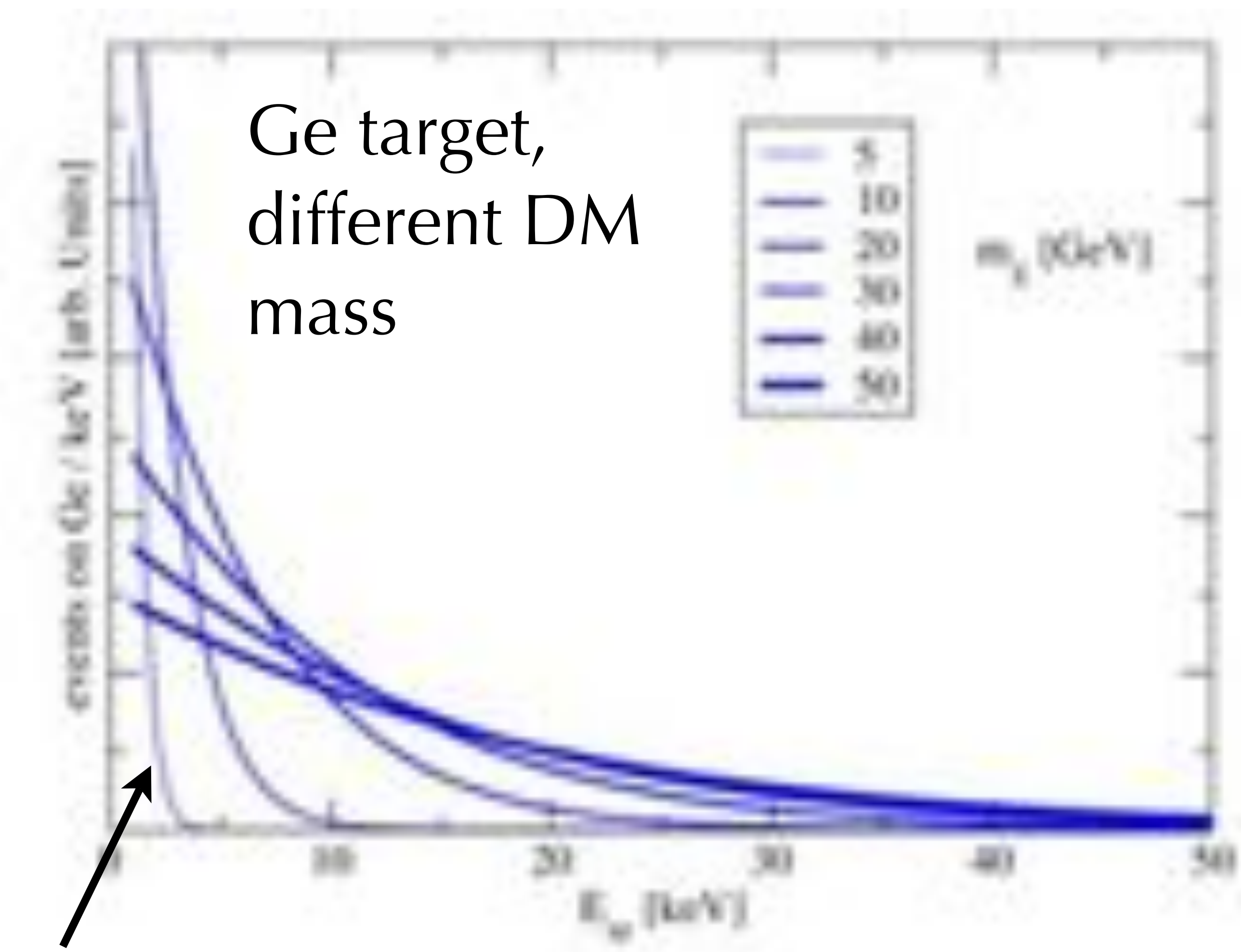
- **recoil energy and vmin:** depends on the mass of DM and target nucleus and DM velocity

$$E_R = \frac{4m_A \; m_X}{(m_A + m_X)^2} (\frac{1}{2} m_X v_X^2) \left( \frac{1 - \cos\theta_{CM}}{2} \right)$$

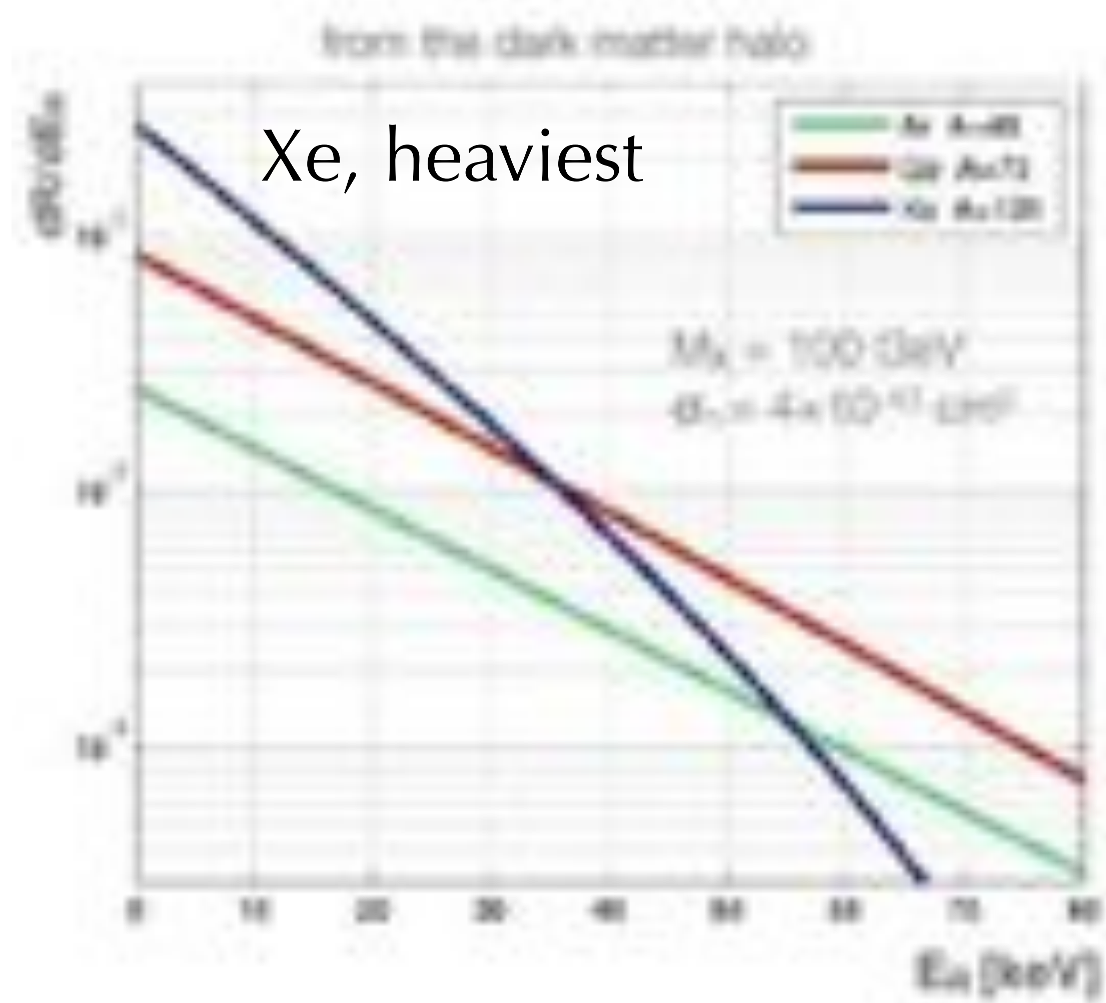
Each detector has an energy threshold -> **there exist a min velocity which ca produce an observable recoil!** Example: A = 16, m = 1 GeV and an energy threshold of 600 eV, the minimal DM velocity to produce a detectable recoil is vmin = 680 km/s.

$$v_{\mathrm{min}} = \sqrt{\frac{E_R m_A}{2\mu^2}}$$

# WIMP Recoil Spectra




lightest




→expect different rates for different targets (cross checks!)

→rate scales with $A^2$ → heaviert targets favored (for scalar couplings)

→ spectrum rises exponentially → low detector threshold desired

→ low-mass WIMPs → lighter target and/or low threshold necessary

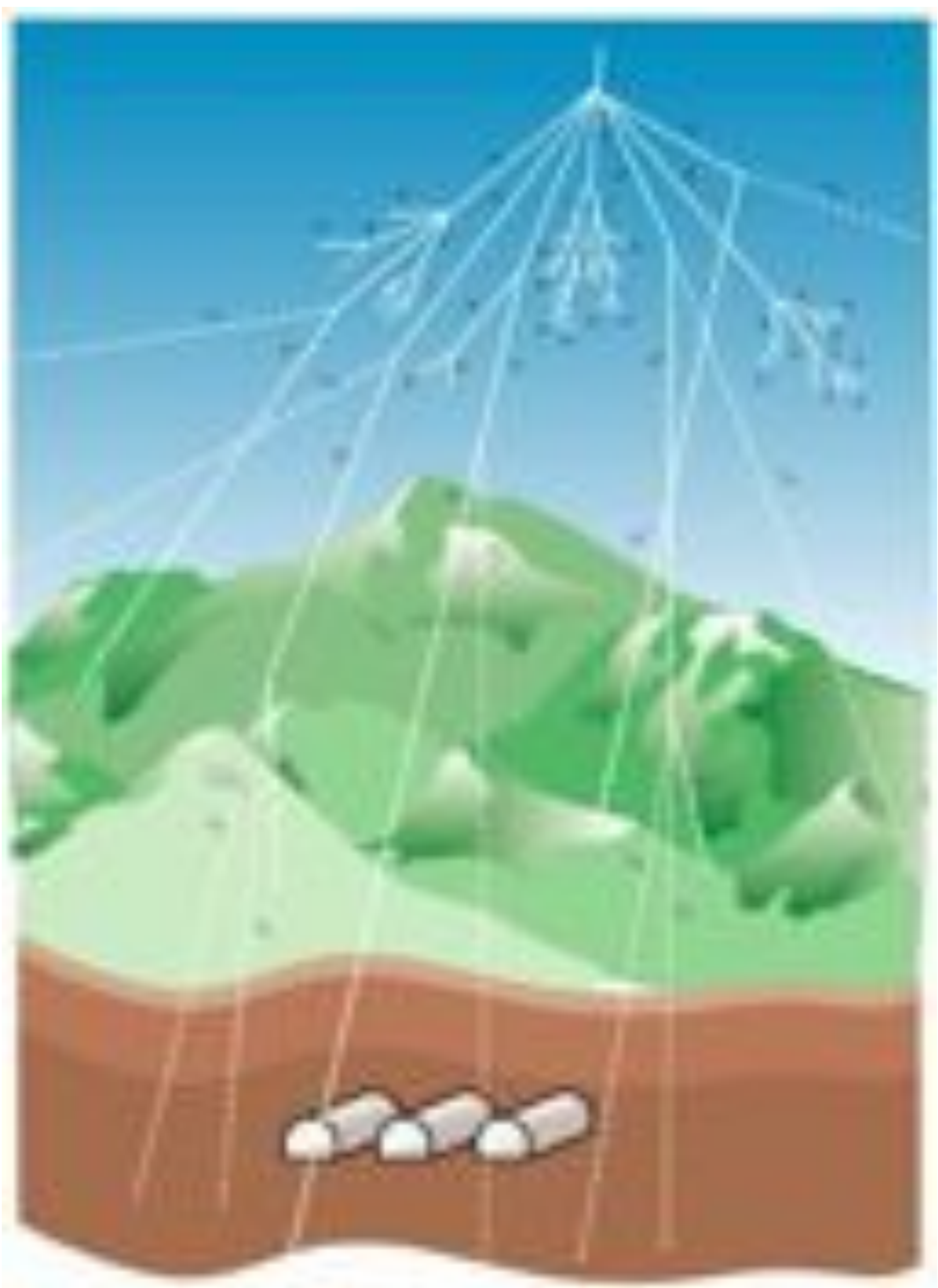
from Schumann, M., 2013.

**Expected rates: <0.1 events /kg/day!**

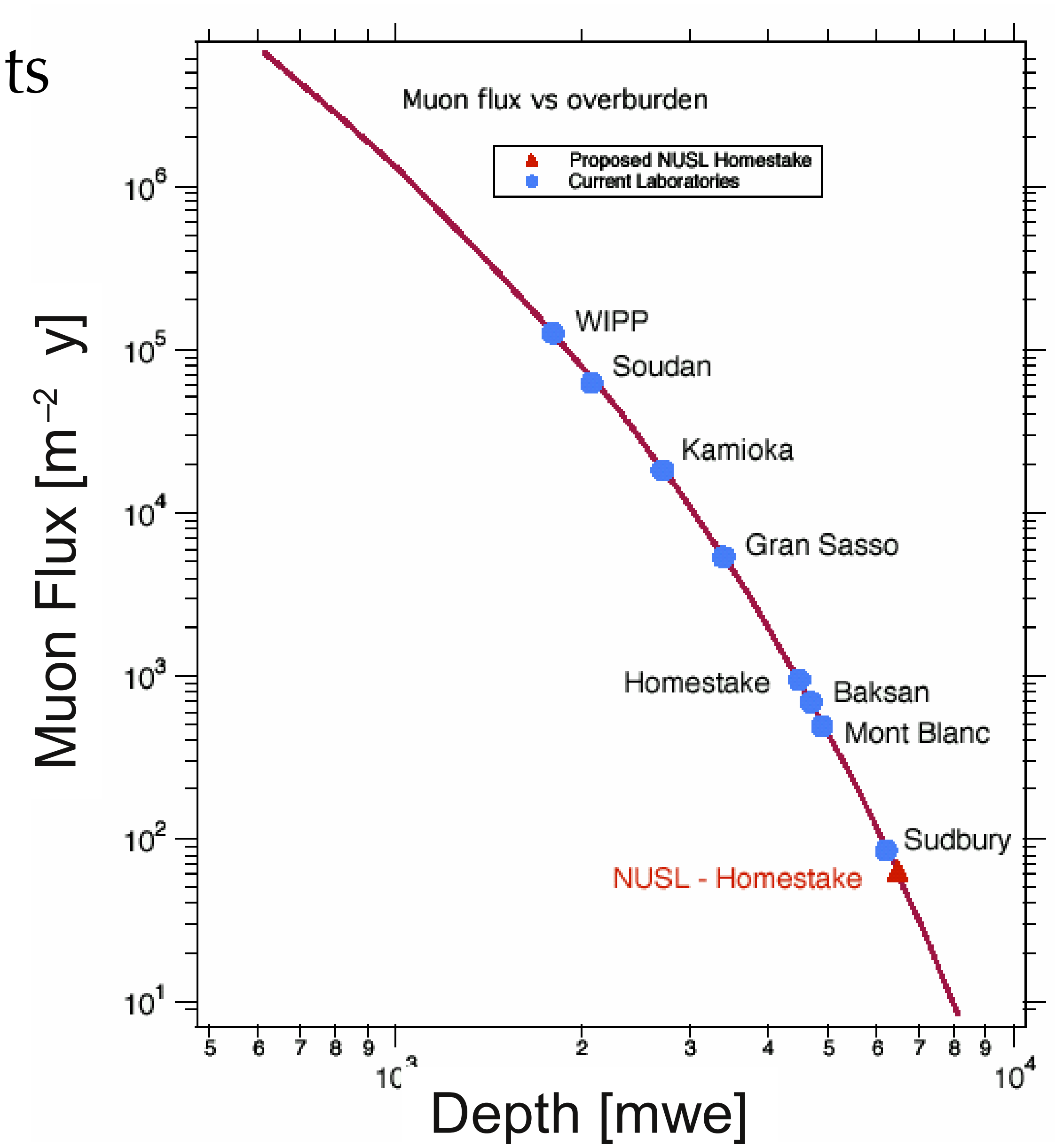
Natural radioactivity: 1 banana ~1M decays/day

Backgrounds: electrons, neutrons, neutrinos: from cosmic rays and natural radioactivity!

Strategy 01: go deep! (get as much shielding as possible)

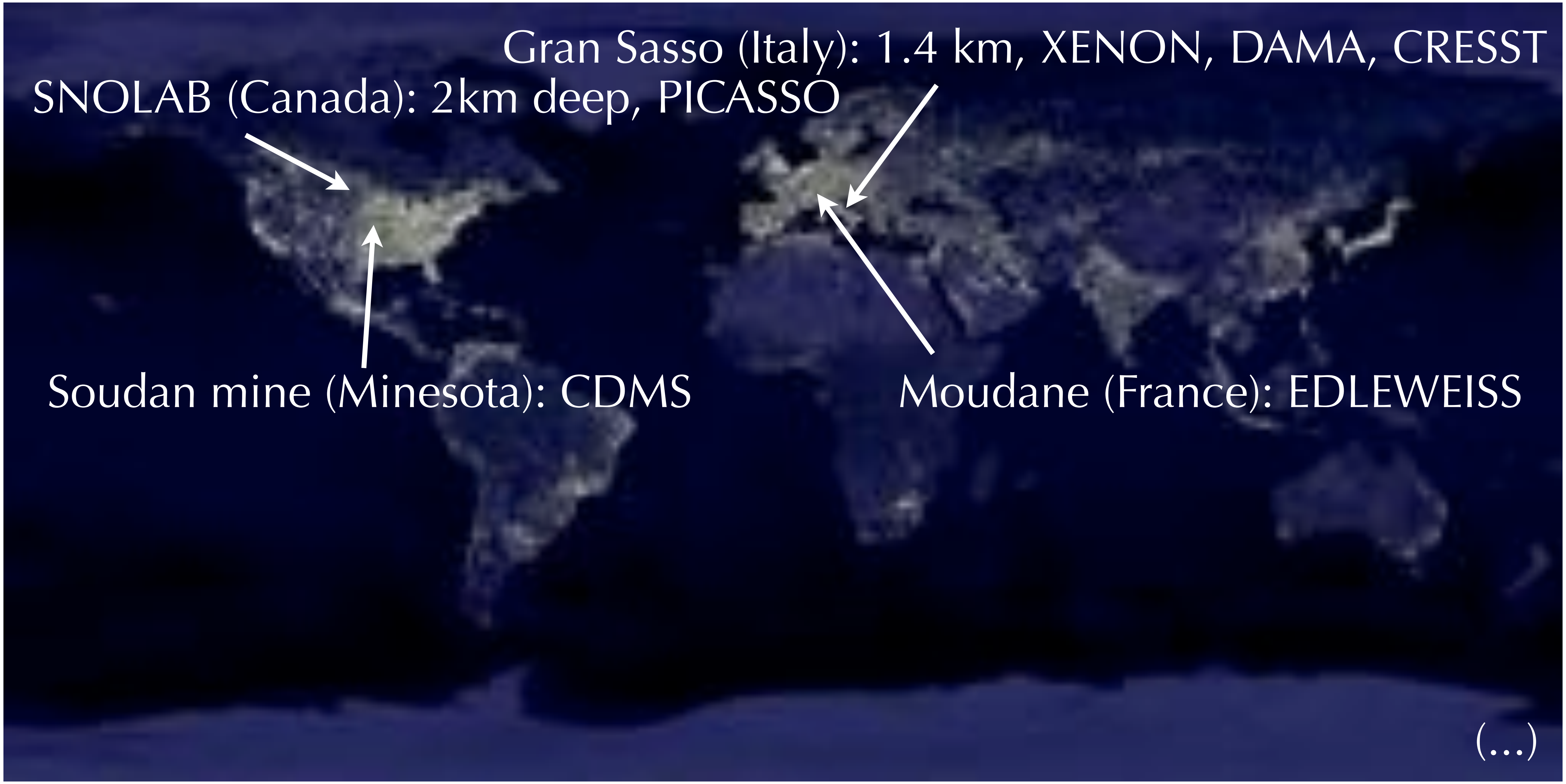


experiments located ~>1km deep



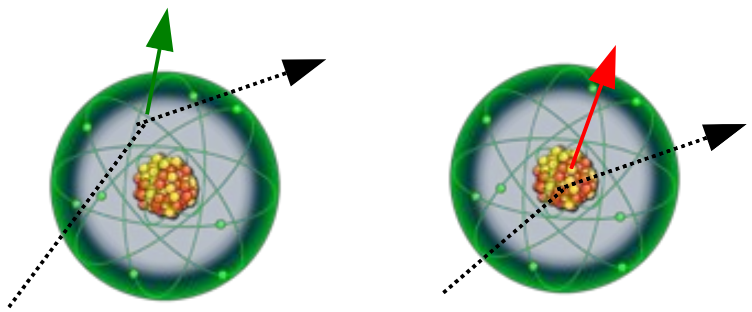
Strategy 01: go deep! (get as much shielding as possible)

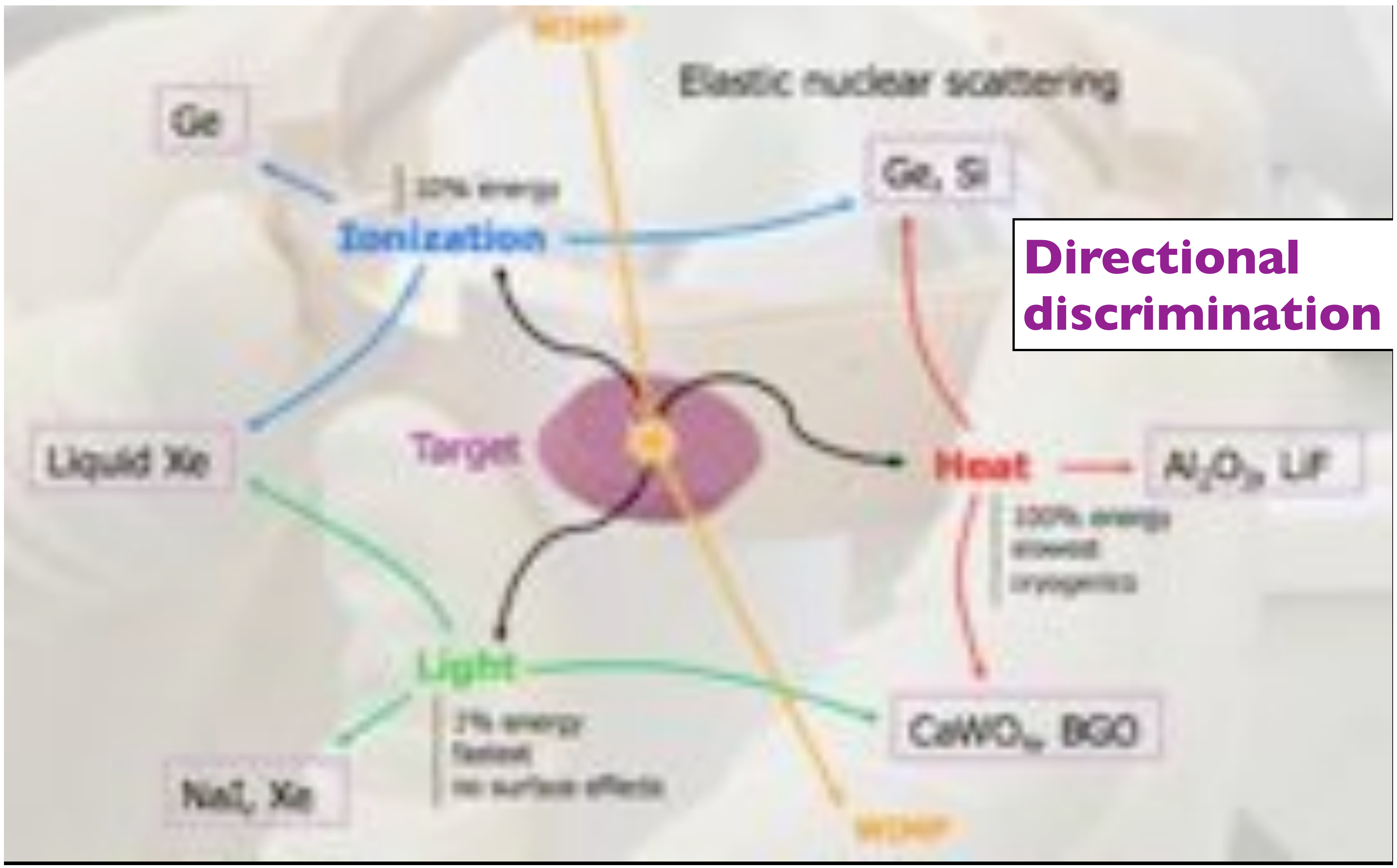
Several current labs:

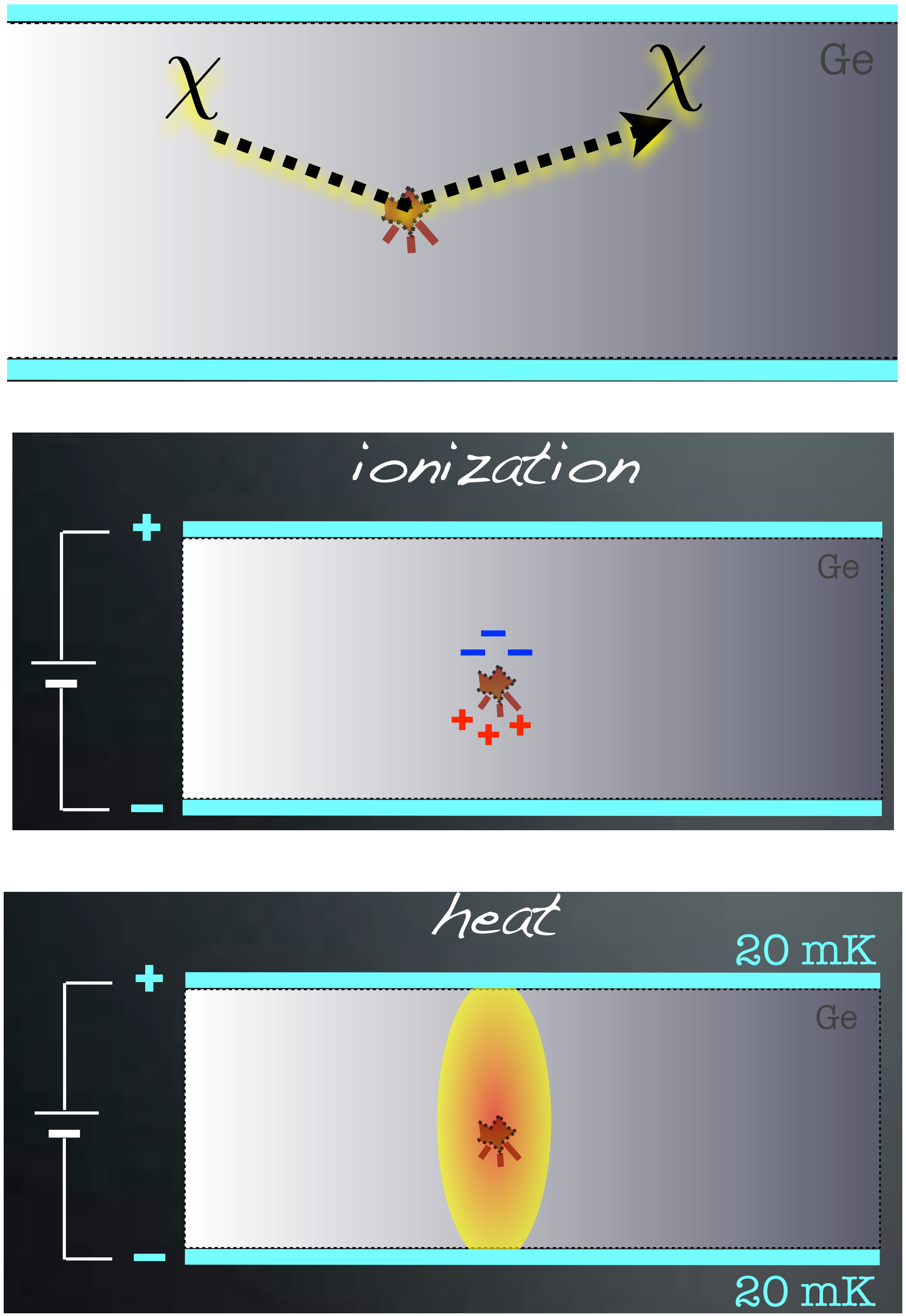


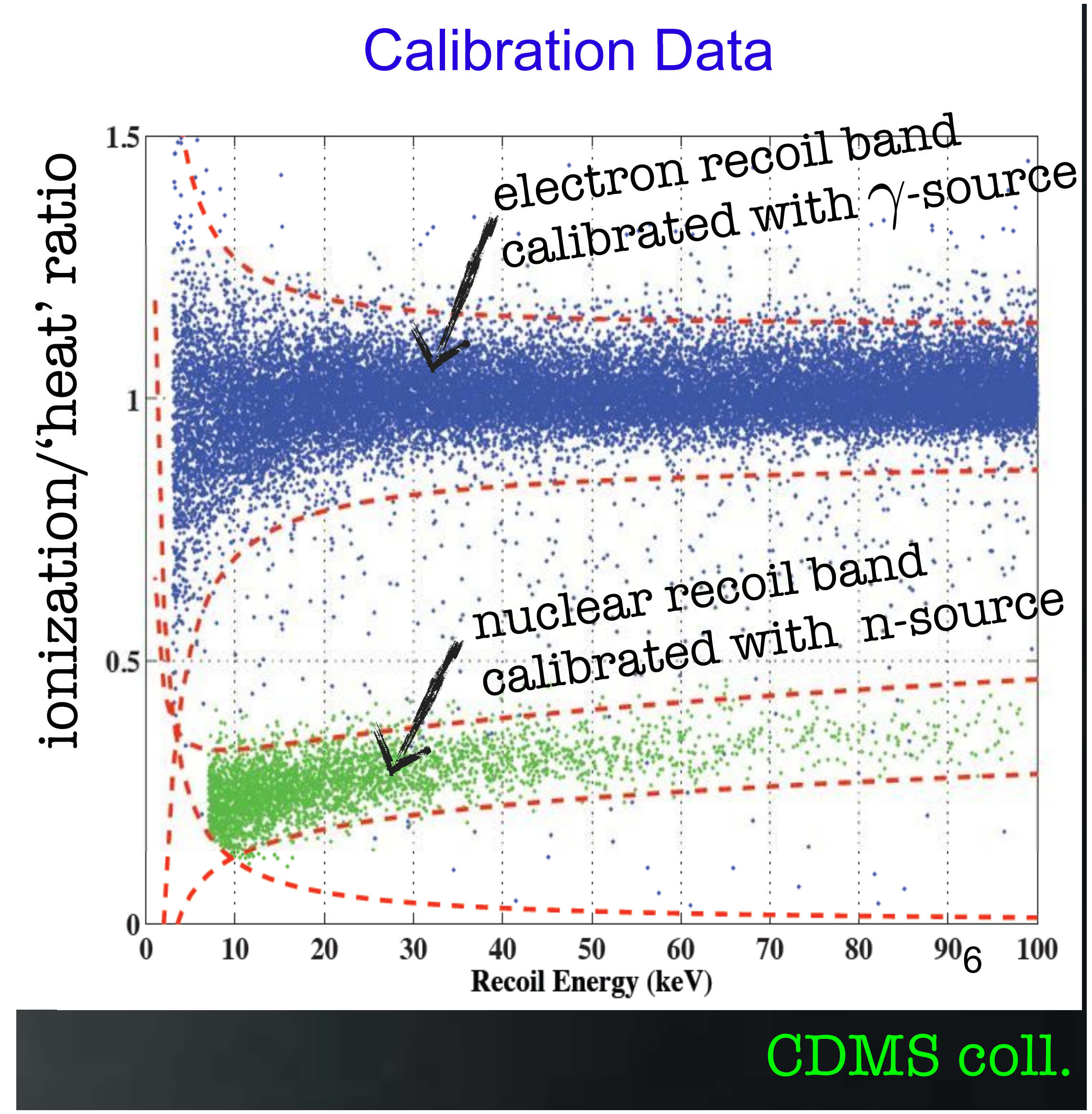
Strategy 02: use double handle! measure two signals to discriminate signal from background, on event-by-event basis.

- WIMPs (and neutrons) scatter off nuclei
- γ and β backgrounds scatter off electrons
- energy loss process different for these two types of recoil



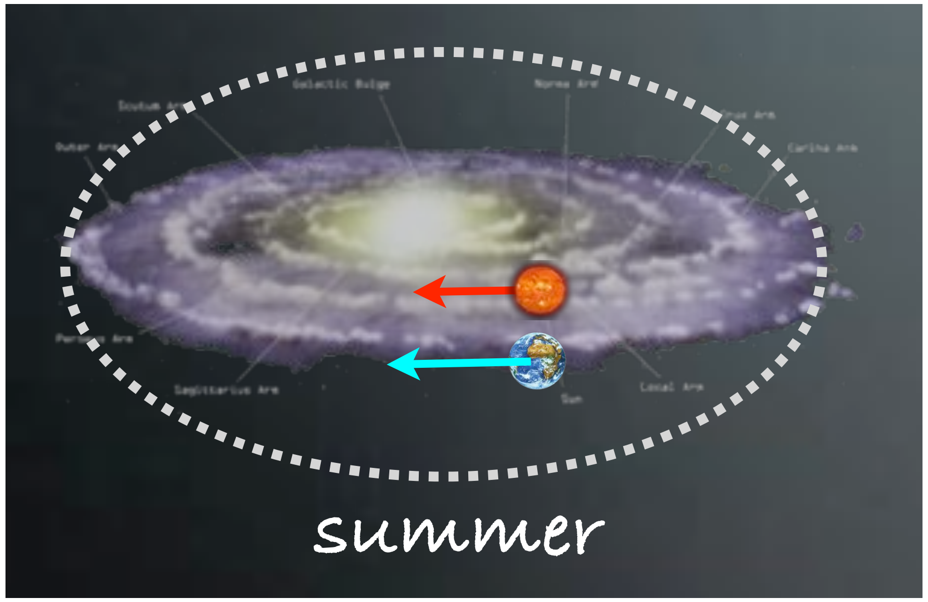


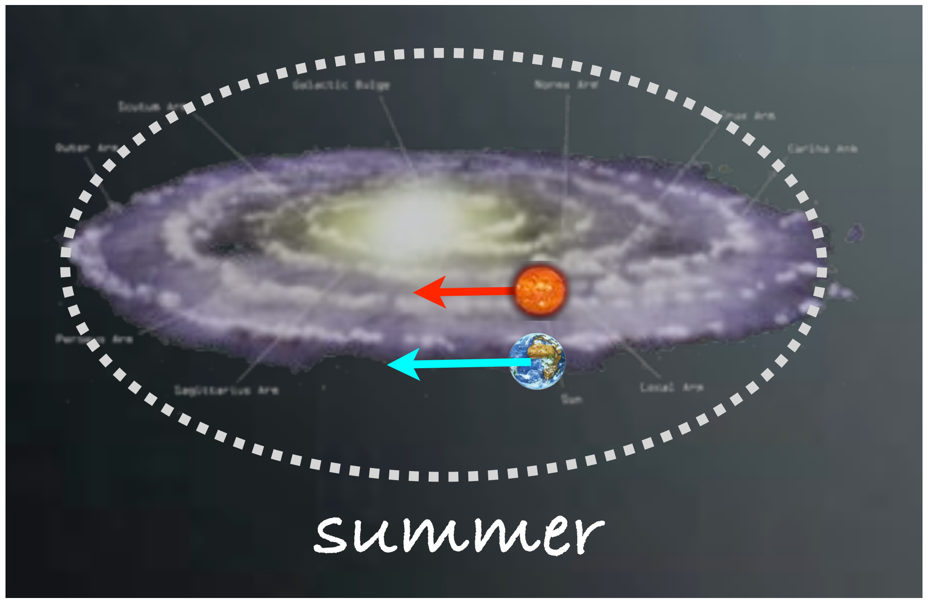

Single scatter interactions from neutrons cannot be distinguished from WIMP signals. Controlling Neutrons:

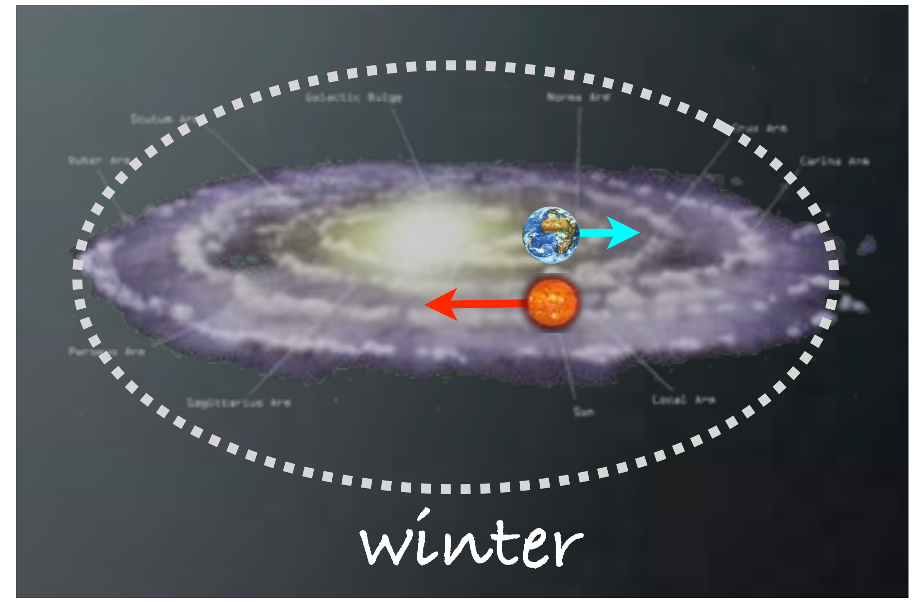
- go deep
- run simulations
- Use Event Topology (n might double scatter)
- self shielding

Strategy 03: or look for specific annual variations (characteristic for DM)!

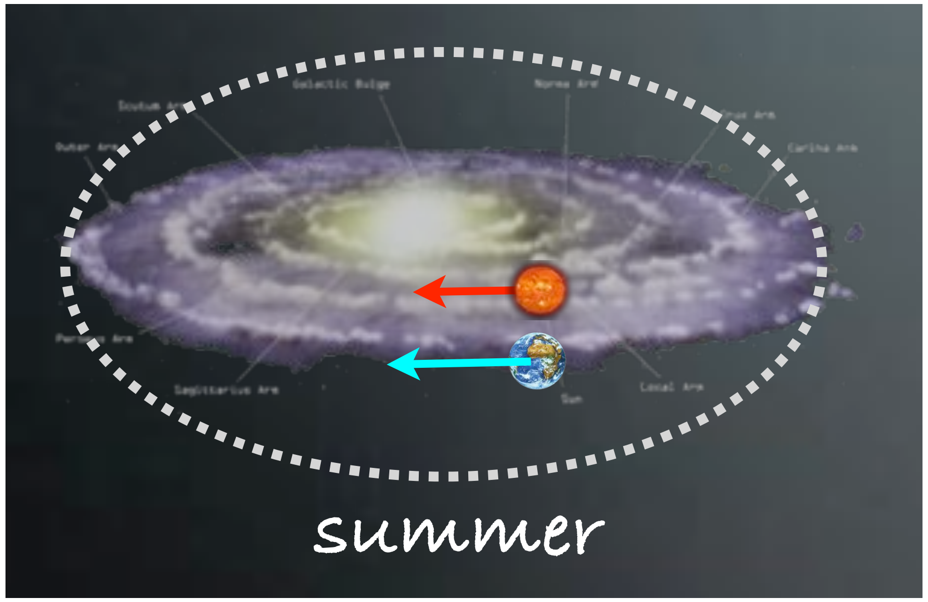


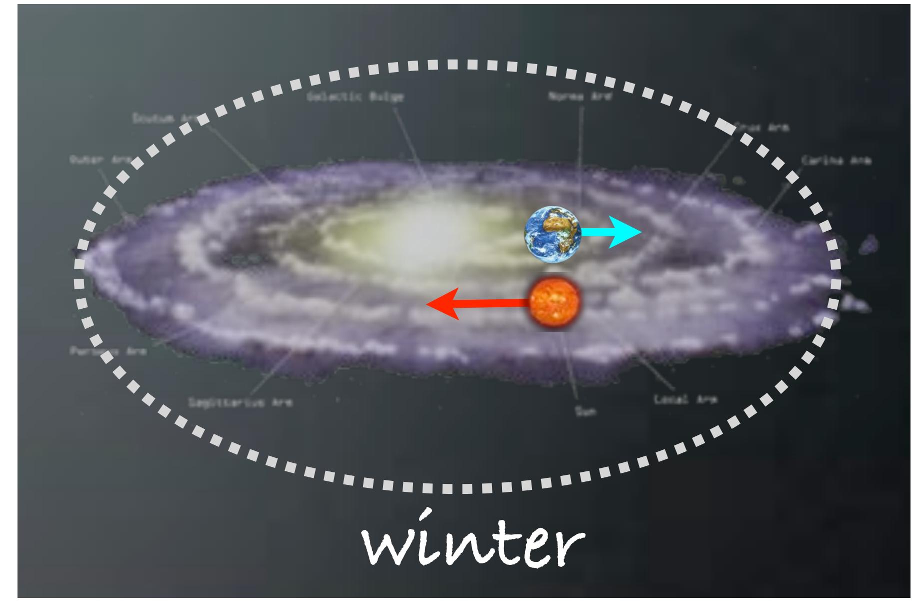
Strategy 03: or look for specific annual variations (characteristic for DM)!

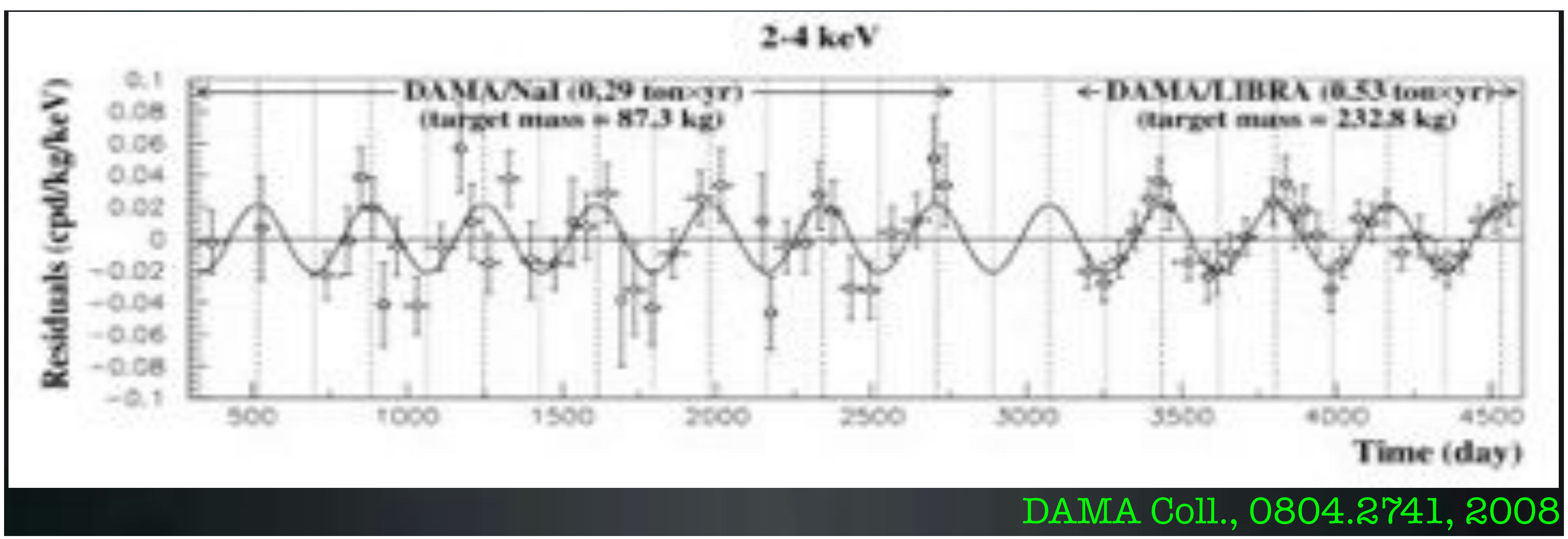


Strategy 03: or look for specific annual variations (characteristic for DM)!




**DAMA collaboration actually observed a signal at >~10 sigma!**

It, however, appears to be ruled out by other experiments.

# How to check the DAMA signal:

## Possible Sources of Annual Modulation

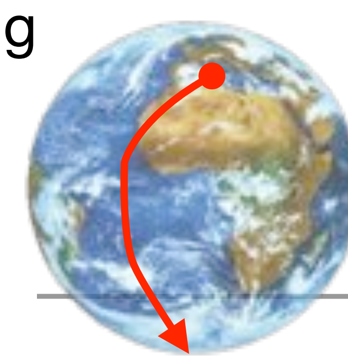
- **Environmental Effects/Backgrounds**
  - Ambient temperature variation
  - Muon flux depend on temperature/pressure in the upper atmosphere
  - Spallation neutrons from muons interaction in rock
  - Radon diffusion from rocks may be varying with time
  - detector and lab maintenance timing

Many of these factors tend to have periodicity of 1 year

- **Detector Effects**
  - quenching factor
  - channeling
  - Xenon scintillation function
  - "Nygren effect"

- **Astrophysical Uncertainties?**
  - f(v)? $v_{esc}$? $v_0$? co-rotating?

- **Dark Matter Physics**
  - inelastic scattering
  - iso-spin violation



**Repeat experiment in different environment. Look for annual modulation with NaI(Tl) in Southern Hemisphere.**

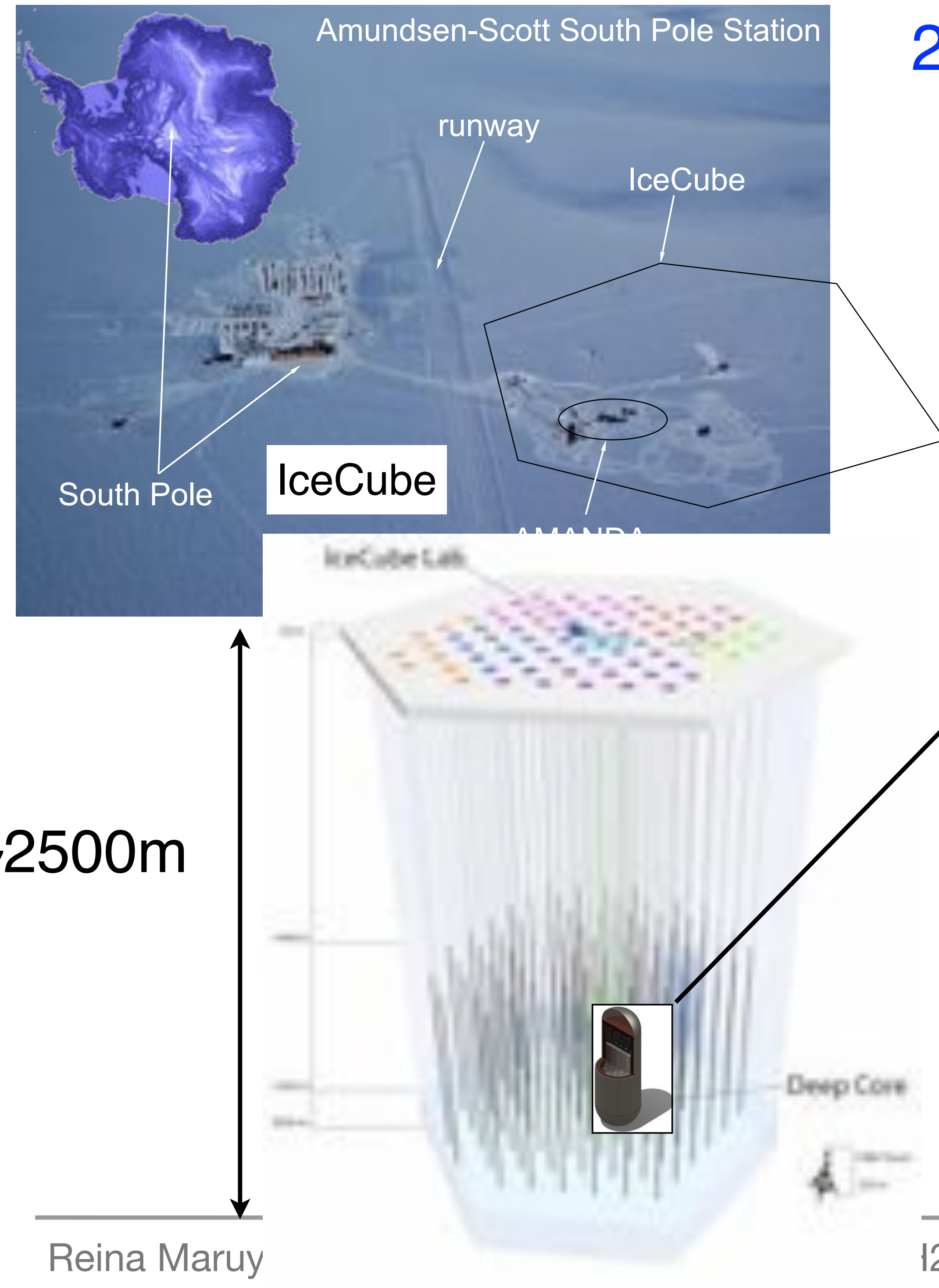
# How to check the DAMA signal:

## Why South Pole?

- The phase of the dark matter modulation is the same.
- Many environmental variations are either opposite in phase (e.g. muon rate) or absent (e.g. temperature, neutrons).
- > 2500 m.w.e. of overburden with clean ice.
  - Clean ice → no lead/copper shielding necessary. No radons.
  - Ice → neutron moderator.
  - Ice as an insulator → No temperature modulation.
- Existing infrastructure
  - NSF-run Amundsen-Scott South Pole Station
  - Ice drilling down to 2500 m developed by IceCube
  - Muon veto by IceCube/DeepCore
  - Infrastructure for construction, signal readout, and remote operation

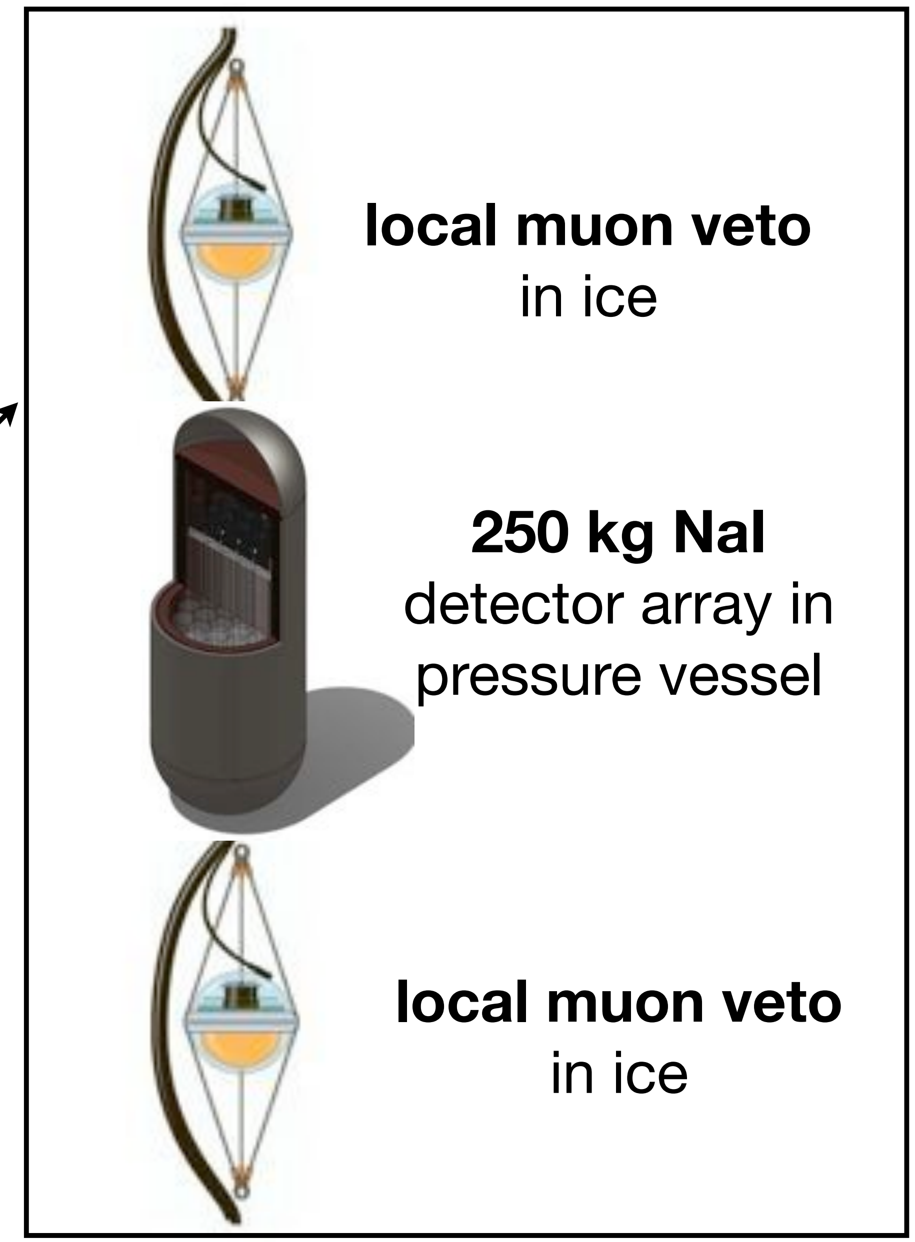
# How to check the DAMA signal:

## DM-Ice 250 kg Concept




~2500m

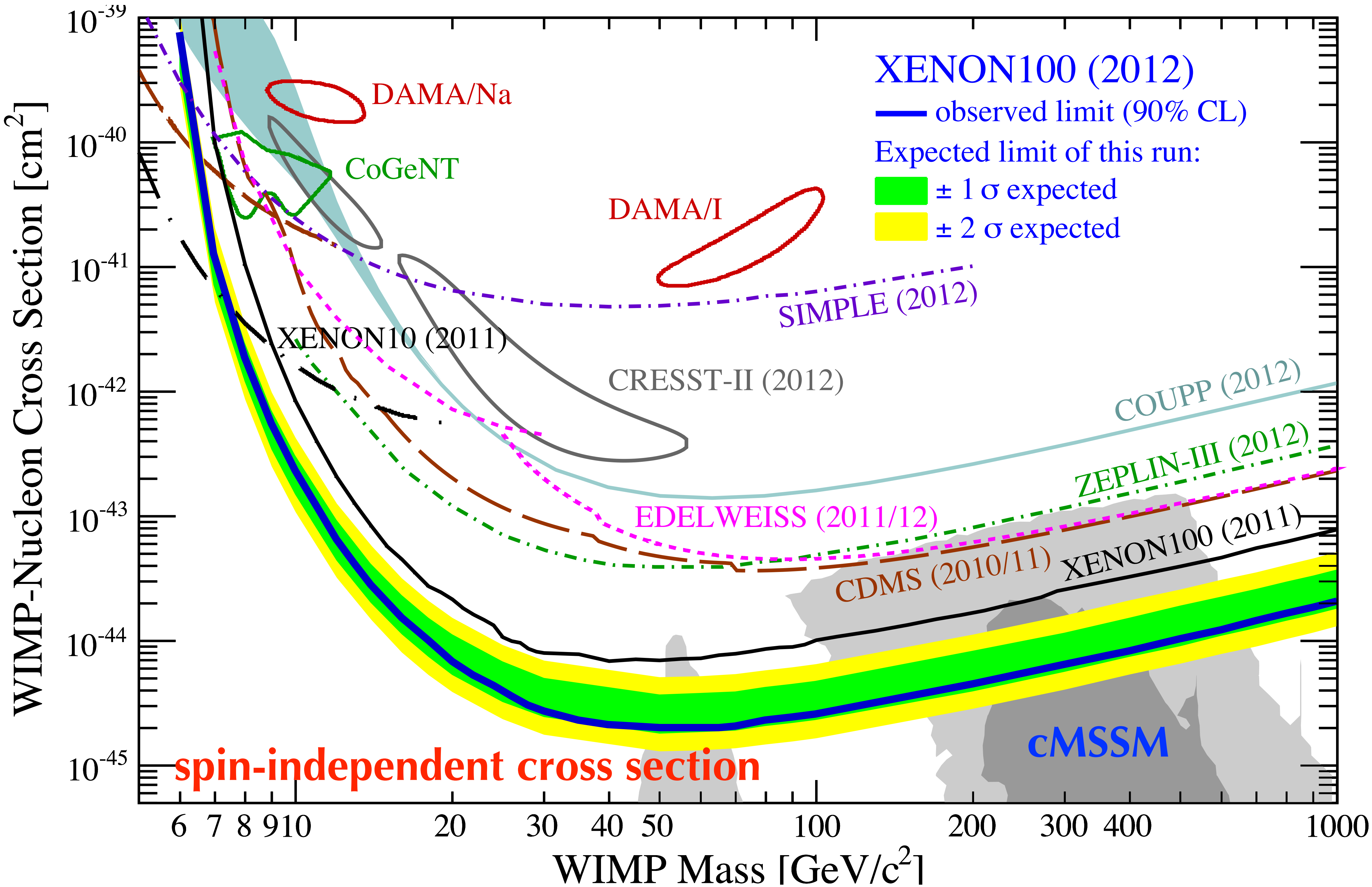
250kg NaI Detector Array Deep in the Ice



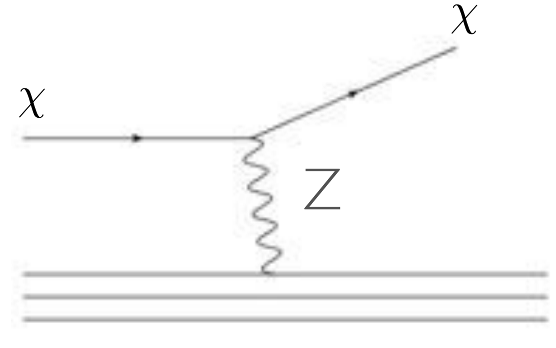

arXiv:1106.1156

# The Status: many experiments constantly pushing the sensitivity!

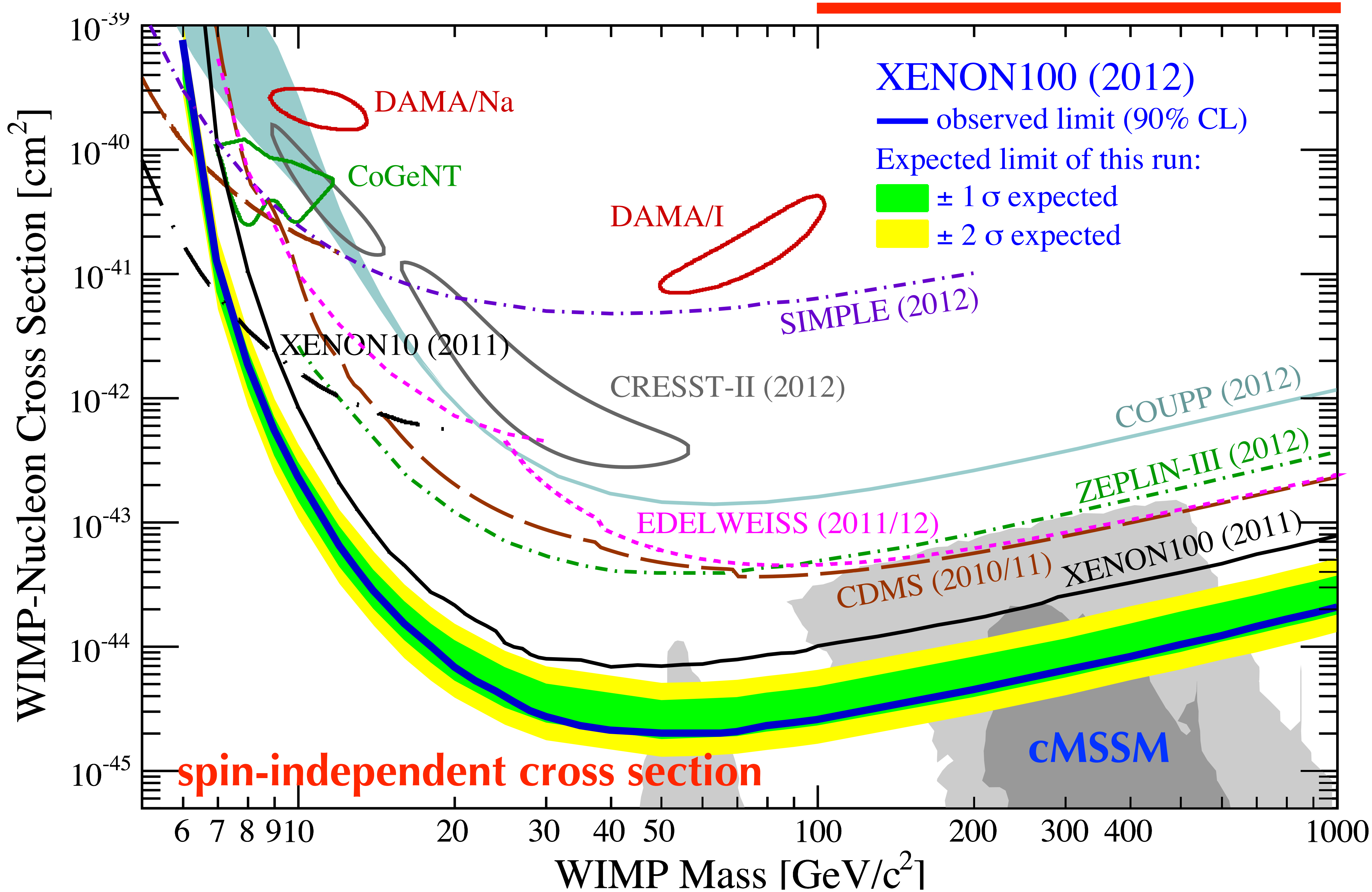
but what are the reference cross section values?



# The Status:




$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39}\mathrm{cm}^2$$



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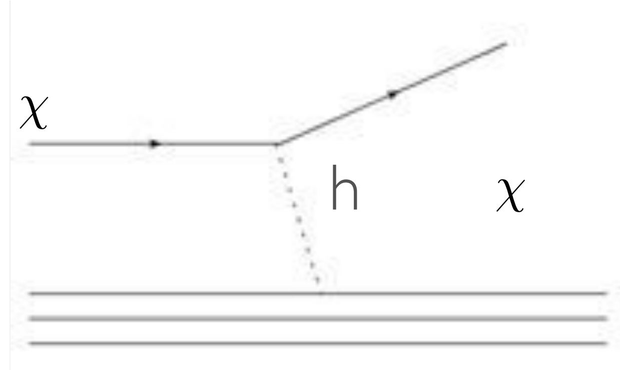
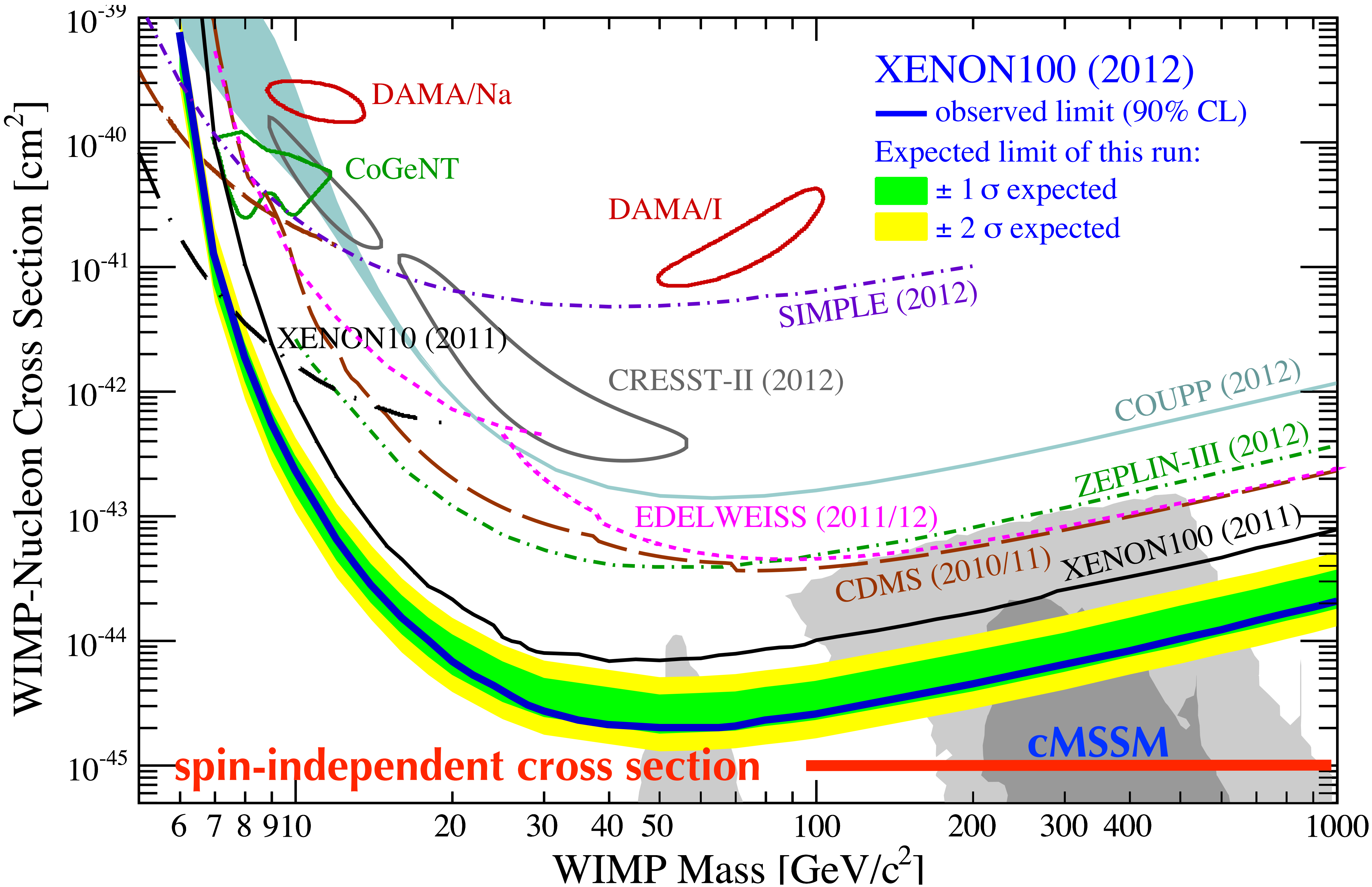



$$\sigma_0 \sim 10^{-39}\mathrm{cm}^2 \times 10^{-6}$$
$$\sim 10^{-45}\mathrm{cm}^2$$



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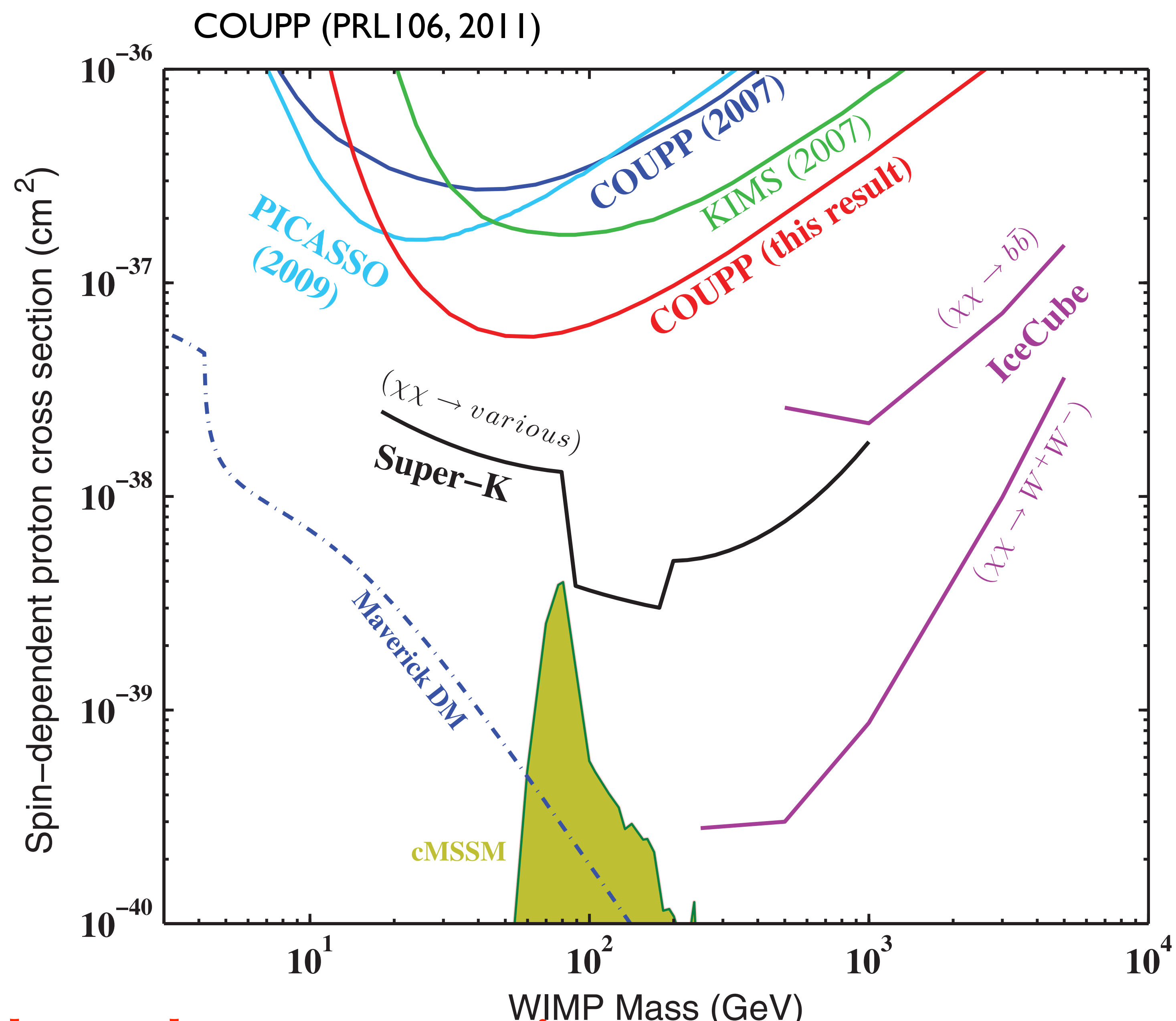
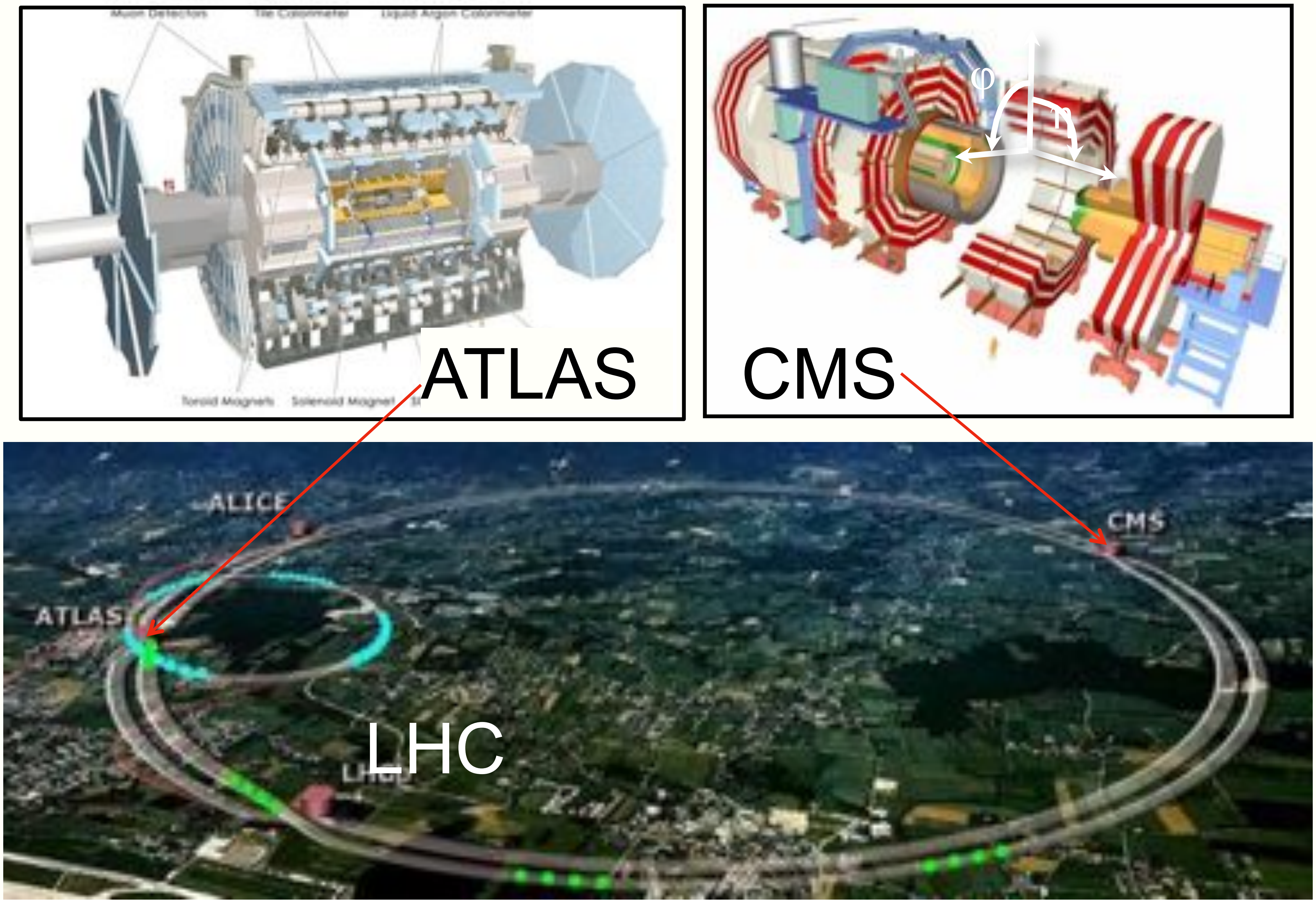



spin-dependent cross section

# Dark Matter
# Collider searches

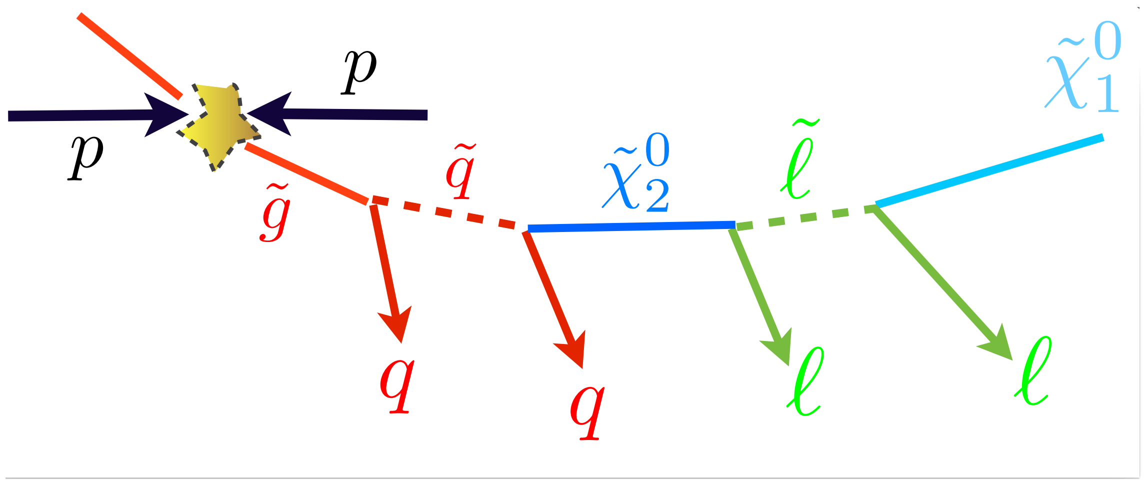
Current big player the LHC, CoM energy 7 TeV! (14 TeV after the close down)

# The Large Hadron Collider



What can collider tell us about DM:

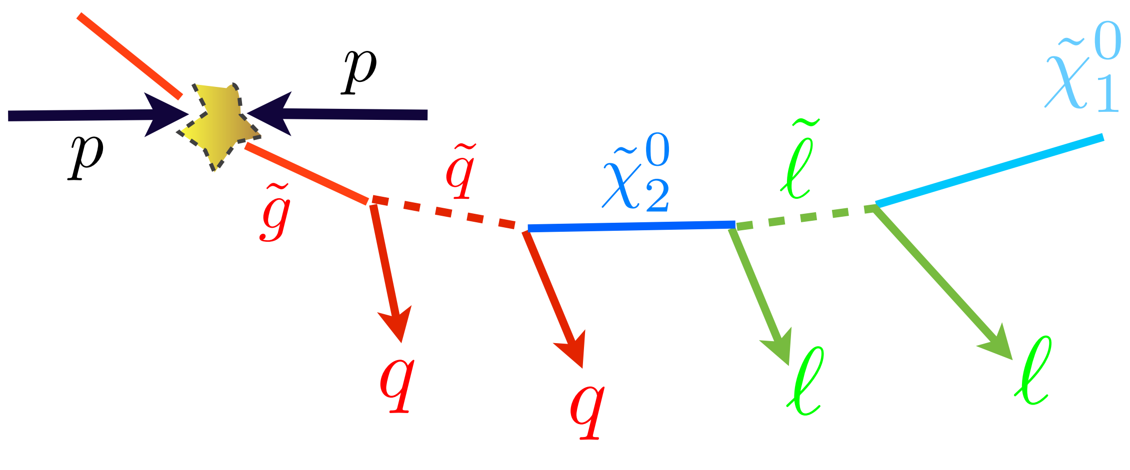
Search strategy 1. **look for a specific signatures of a given model** (SUSY, UED...):



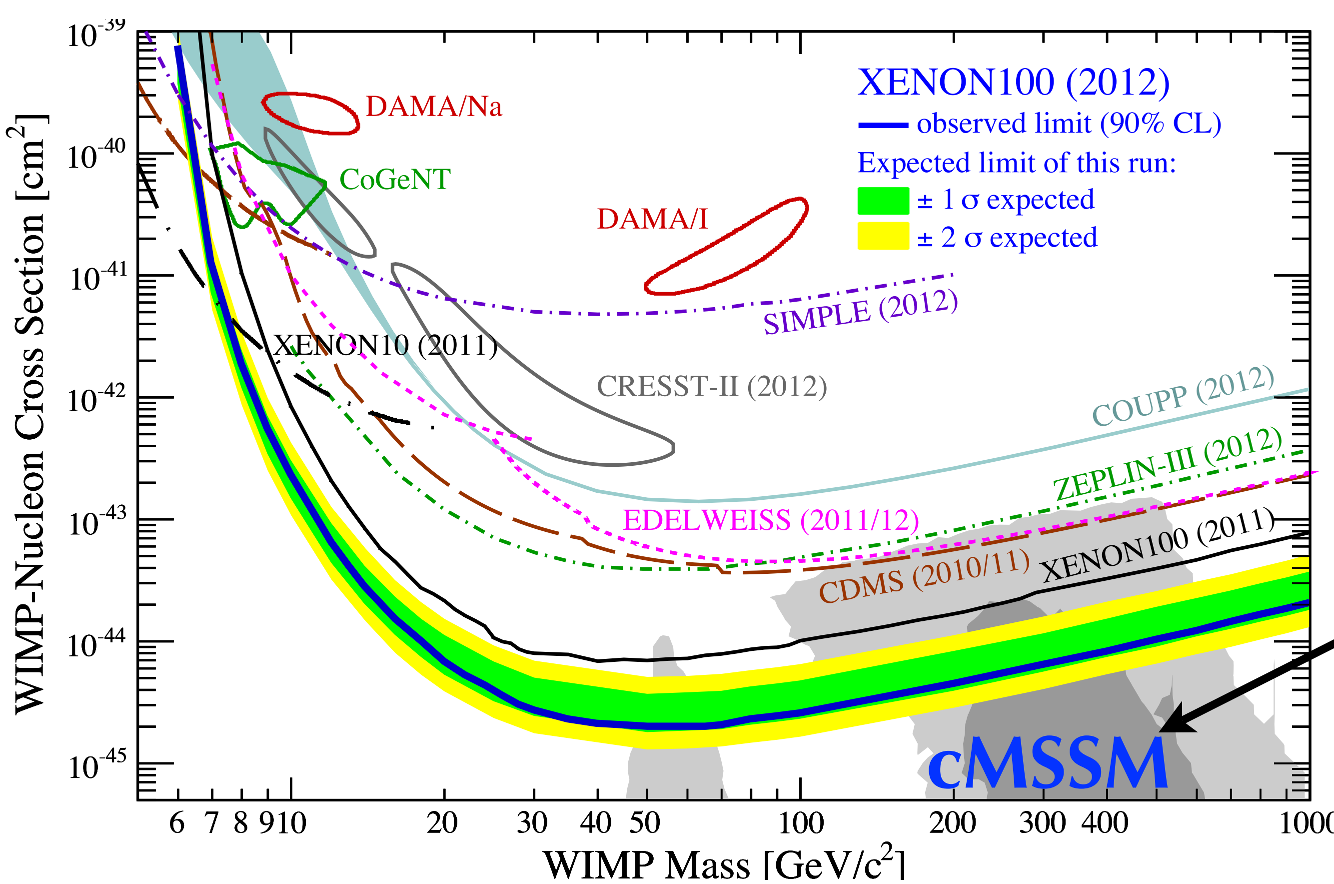

e.g. look for a 4jets+4lepton+MET

What can collider tell us about DM:

Search strategy 1. **look for a specific signatures of a given model** (SUSY, UED...):




e.g. look for a 4jets+4lepton+MET




However, one might want to use a more model independent search!

Within fixed theoretical frameworks it is not simple to gain physical insight to many questions.

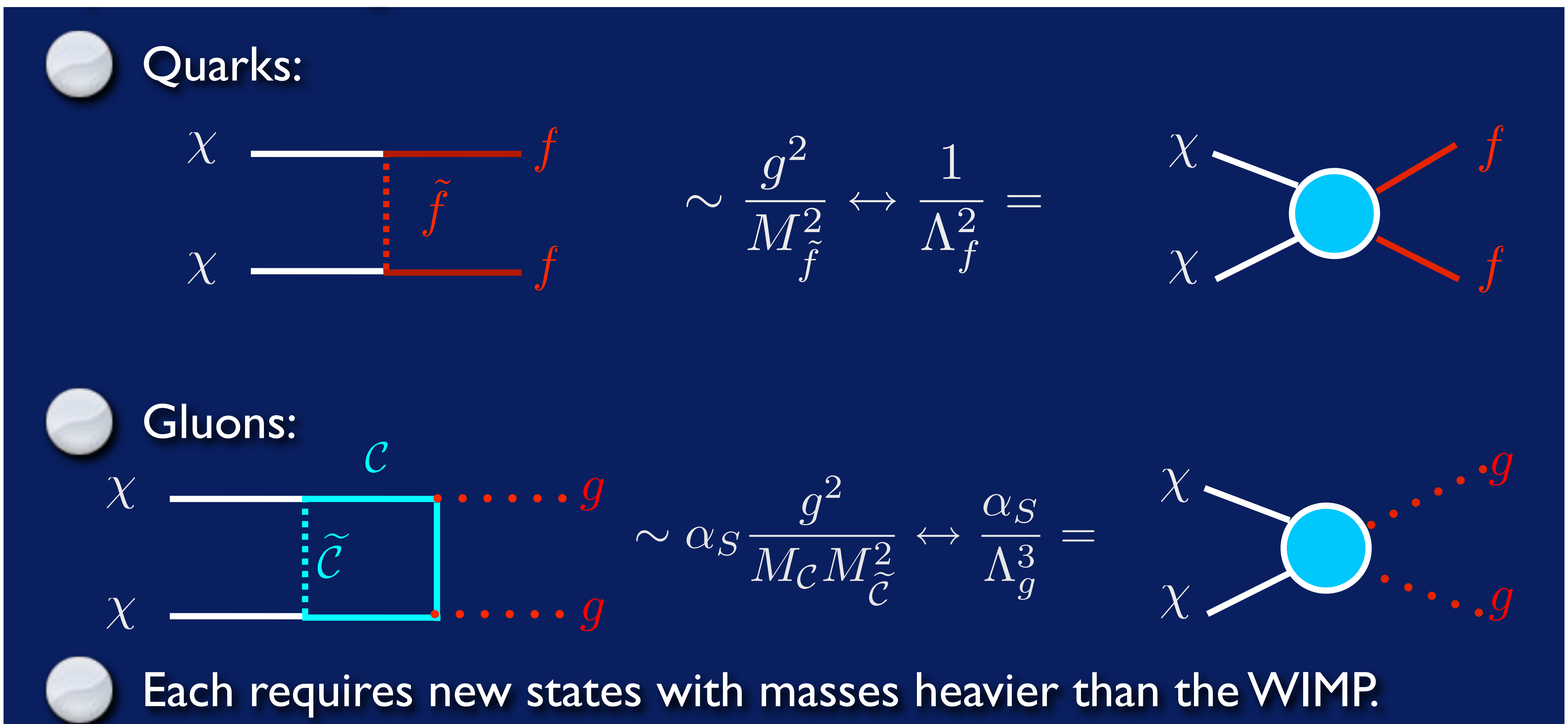
for example

'What happens to this point if we raise stop mass by 5 GeV'? (T. Tait, 2010)

Strategy 02. or use **Effective Field Theory** (EFT) approach!

Ignore degrees of freedom at shorter distances (or, equivalently, at higher energies)

Relevant degrees of freedom consist of the Standard Model + the WIMP (and nothing else...). **New physics parametrized by the cut-off energy scale**.



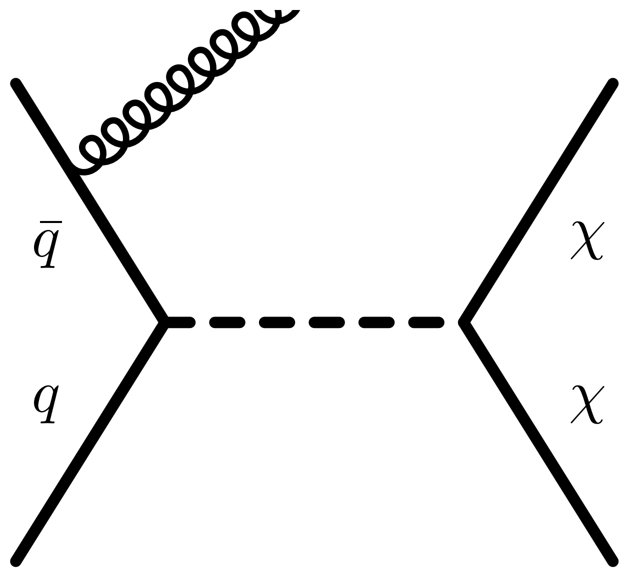
Strategy 02. or use **Effective Field Theory** (EFT) approach!

Not fully model independent, 'type' of interaction needs to be assumed.

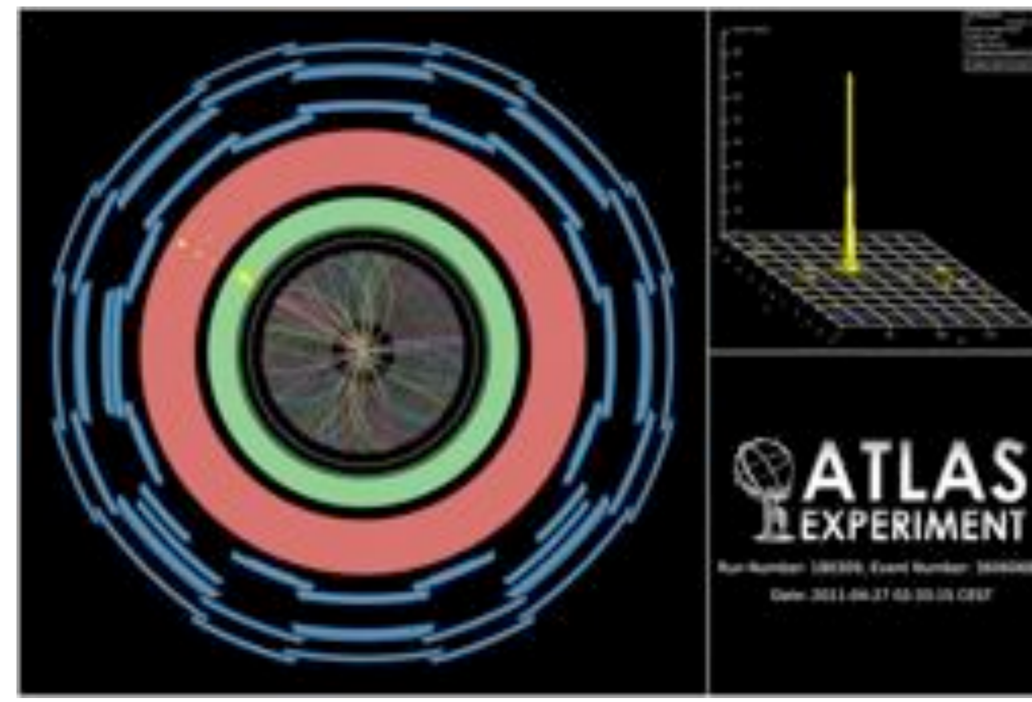
| Name | Operator | Coefficient |
|---|---|---|
| D1 | $\bar{\chi}\chi\bar{q}q$ | $m_q/M_*^3$ |
| D2 | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $im_q/M_*^3$ |
| D3 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $m_q/M_*^3$ |
| D5 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D6 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D7 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| D8 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| D9 | $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$ | $1/M_*^2$ |
| D10 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$ | $i/M_*^2$ |
| D11 | $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^3$ |
| D12 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D13 | $\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D14 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $\alpha_s/4M_*^3$ |
| D15 | $\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$ | $M$ |
| D16 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

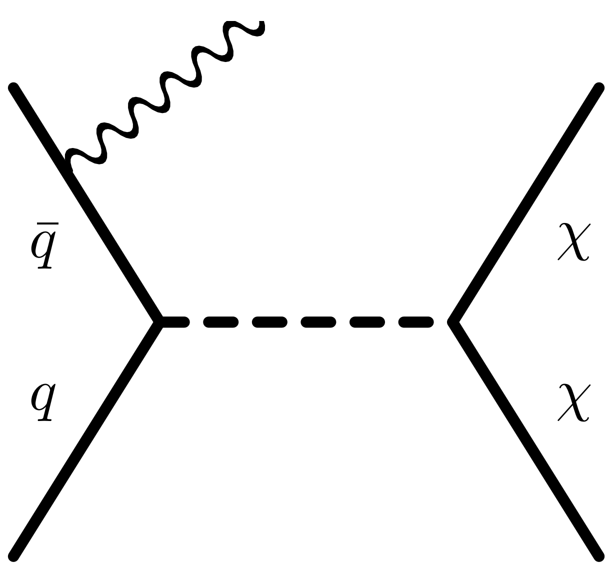
Strategy 02. use **Effective Field Theory** (EFT) approach!

+ **Look for generic collider signatures of DM**: DM is long lived, escapes from a detector carrying missing energy! Only processes followed by mono-jet or mono-photon can be observed  (leave trace in a detector).



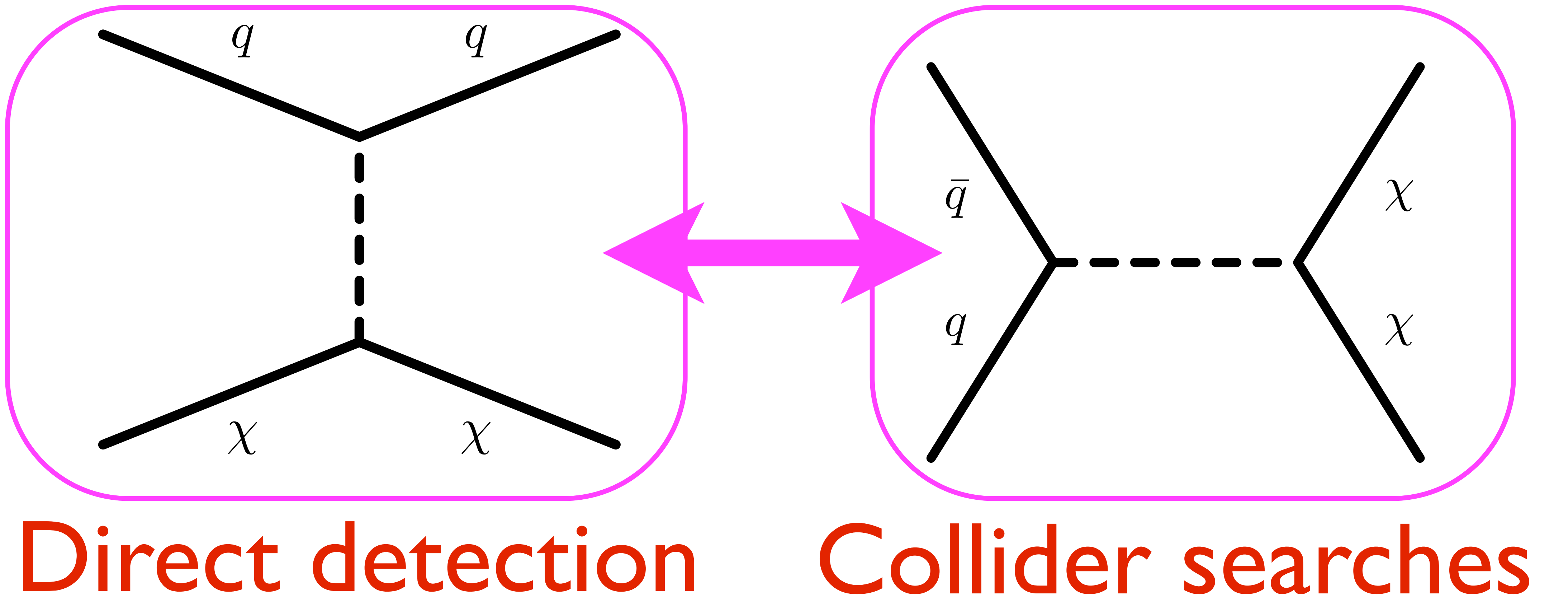

"Monojets"




"Monophotons"

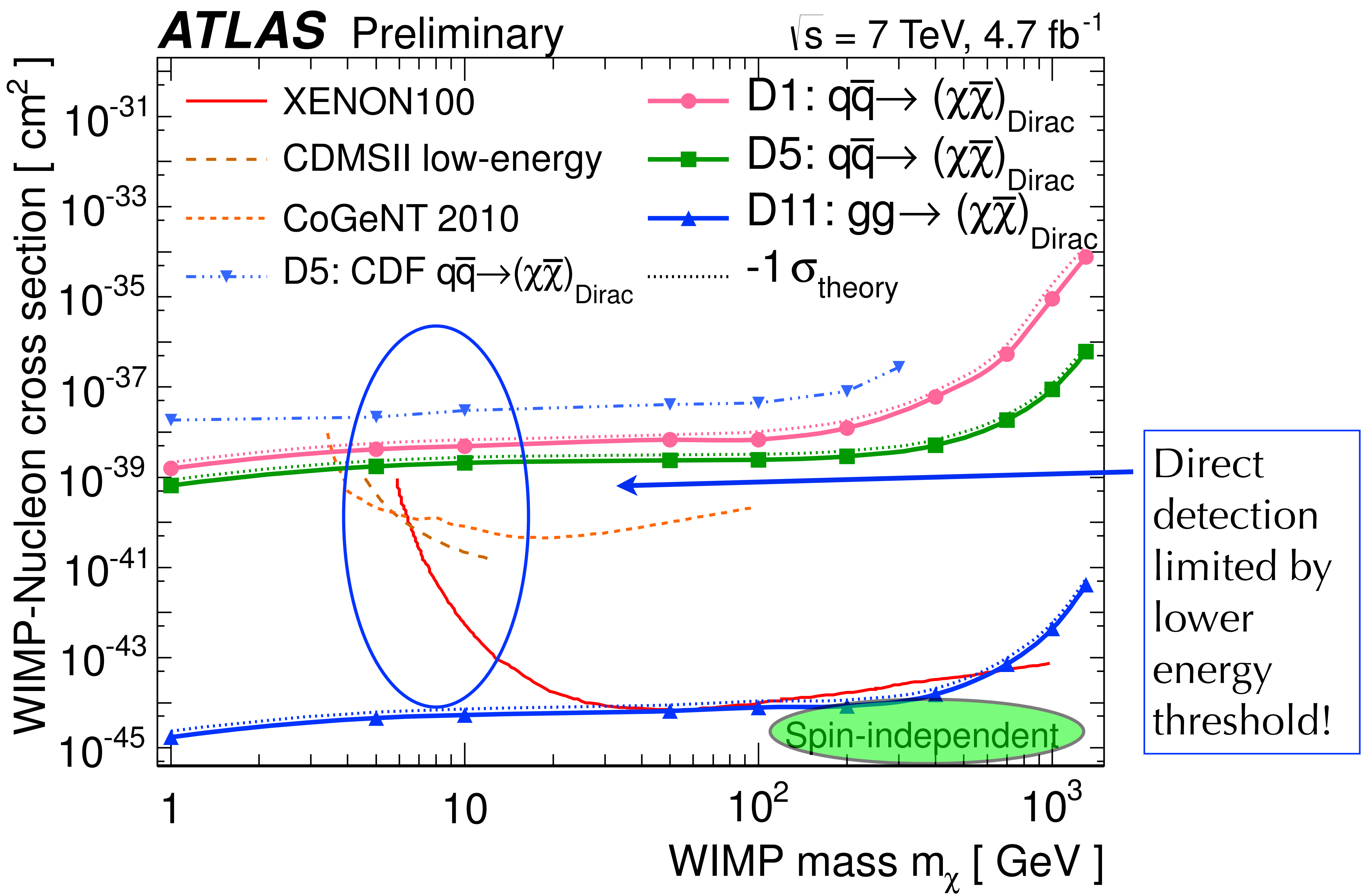
# Synergy: moreover one can use EFT to relate production cross sections with elastic scattering ones.



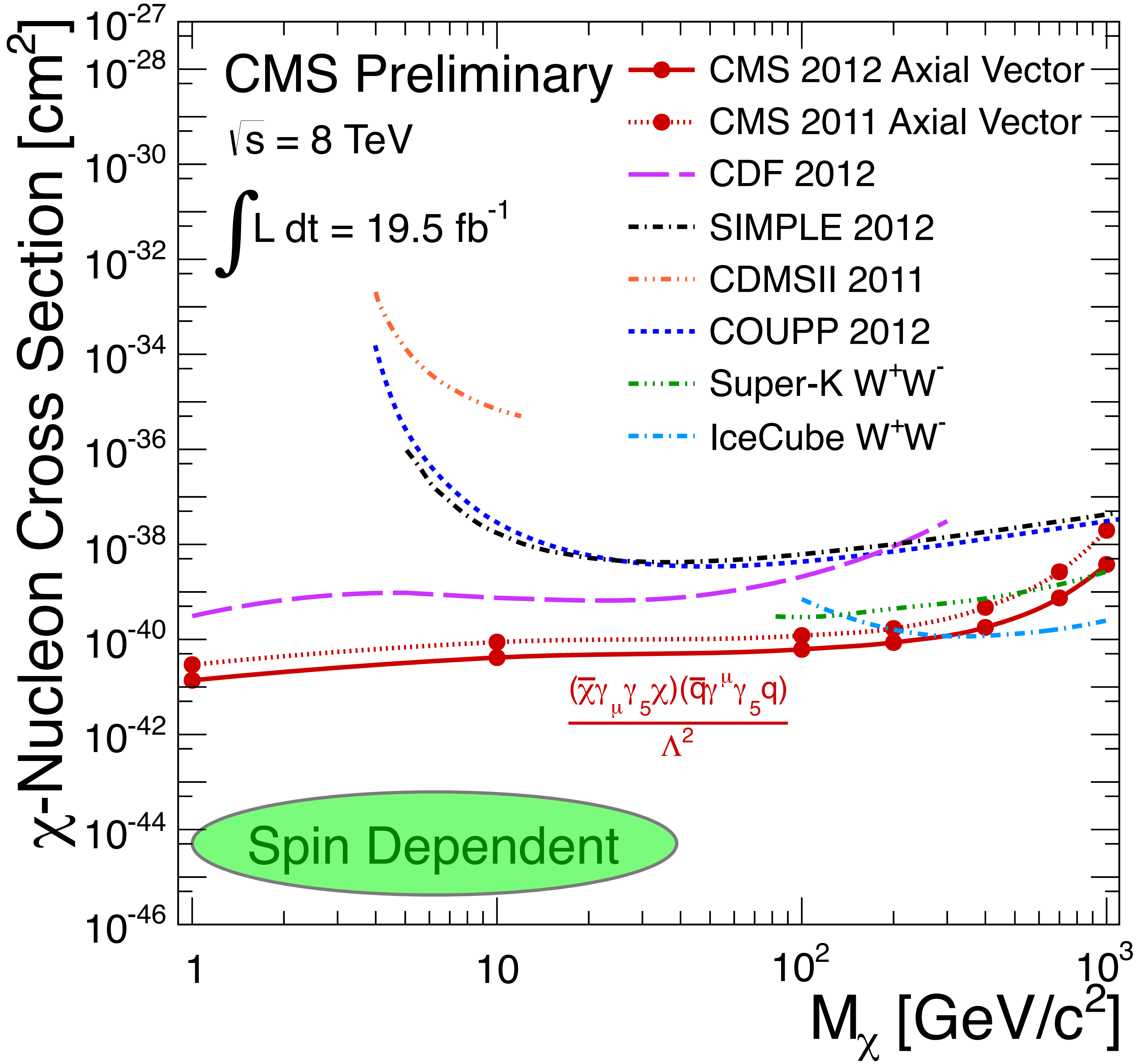

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2 \qquad \sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

both signals depend on the 'cut-off' scale M (above which the details of new physics become important and the effective theory breaks), and therefore can be directly compared!

# monojets: collider constraints are very strong for lighter dark matter and fall off when the dark matter mass exceeds the typical energy reach of the collider.



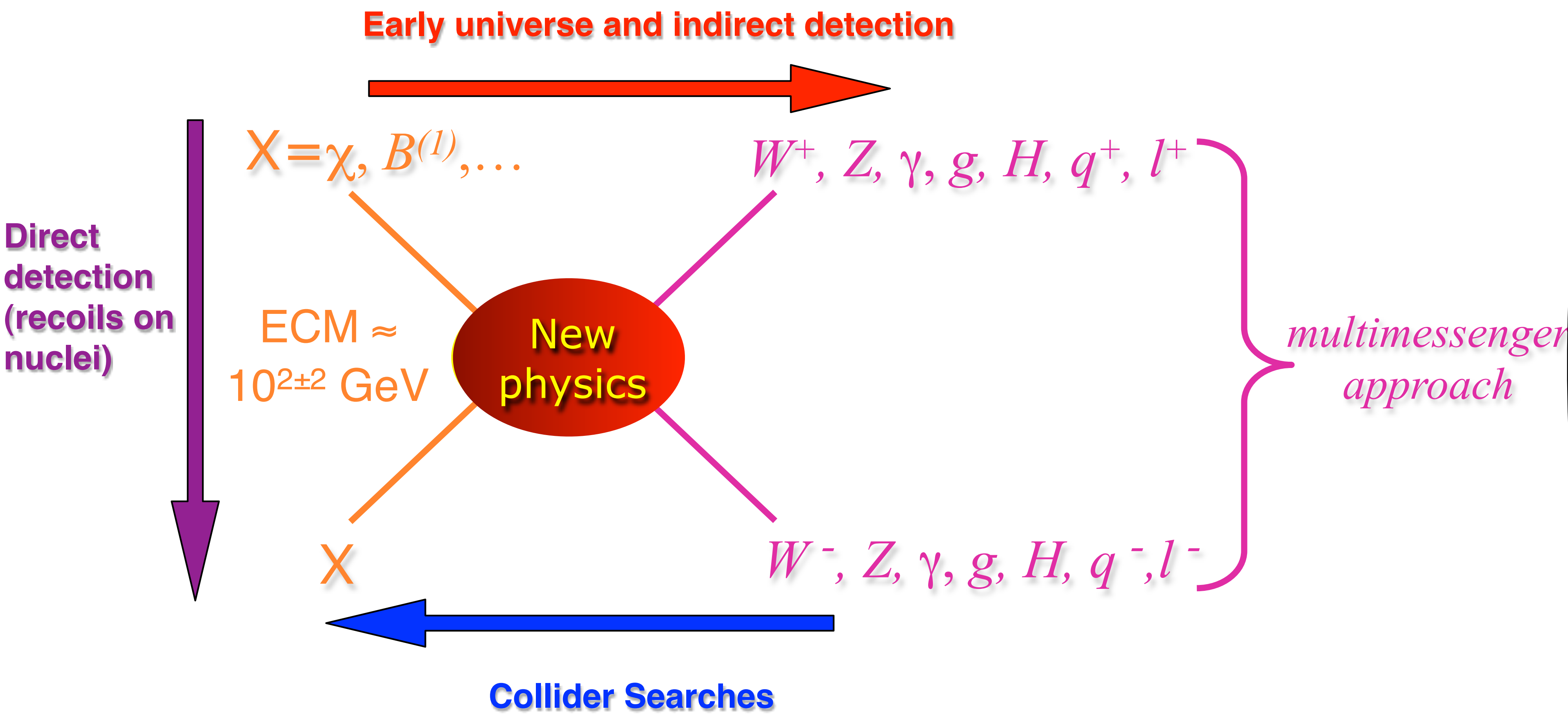
# monojets: collider constraints are very strong for lighter dark matter and fall off when the dark matter mass exceeds the typical energy reach of the collider.



# Break?

# Dark Matter
# Indirect searches

# • How to test the WIMP hypothesis?



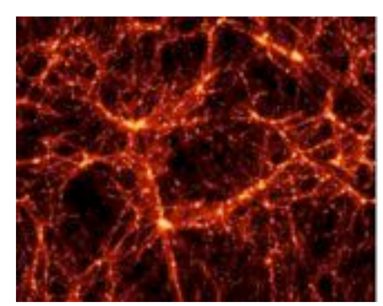

'indirect' detection

*decay* → $\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$ ($D^{-}$)

@ $M_Z$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations ($\sigma$).

*Today, DM expected to annihilate with the same* $\sigma$*, in places where its density is enhanced!*



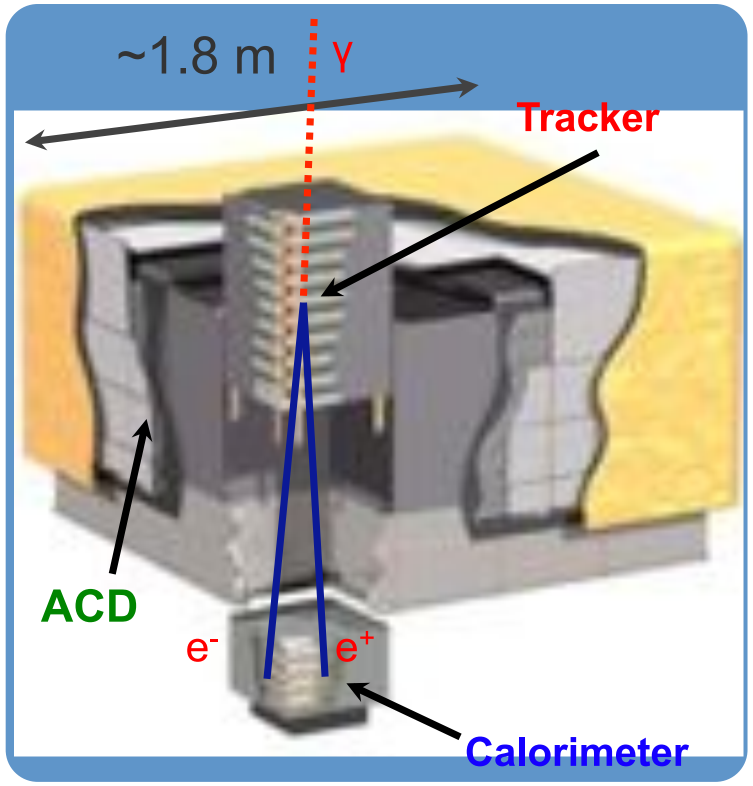
in astrophysical systems - *remotely*

## Astrophysical experiments:

- plus:
  - multipurpose experiments (rich scientific program)

- minus:
  - different priorities,
  - not optimized for DM searches
  - ‘backgrounds’ are astrophysics! not a ‘controlled’/lab system

- messengers ($\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$, $D^{-}$) /experiments (@~Mz range):
  *gamma rays: photons with energy >~ 1 MeV.*
  - satellites (Fermi LAT, AGILE):

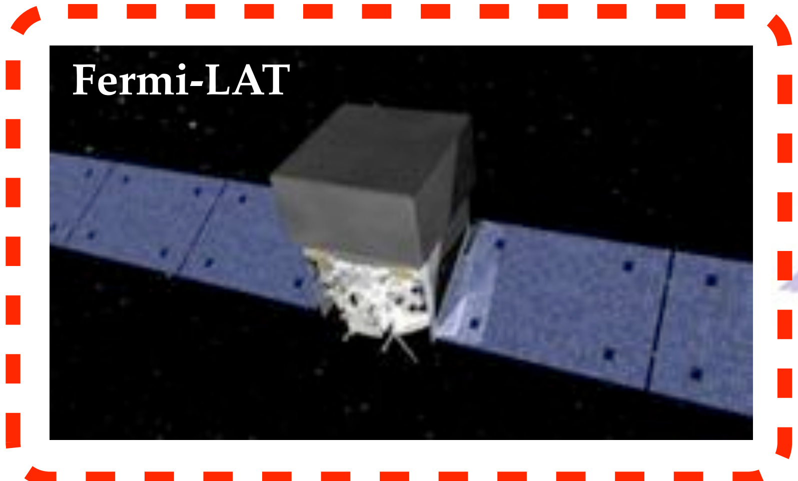




Atwood et al., ApJ 697, 1071 (2009)

  - a pair conversion instrument
  - anti-coincidence system →good charge particle rejection → LAT can ***identify*** the relatively rare gamma rays

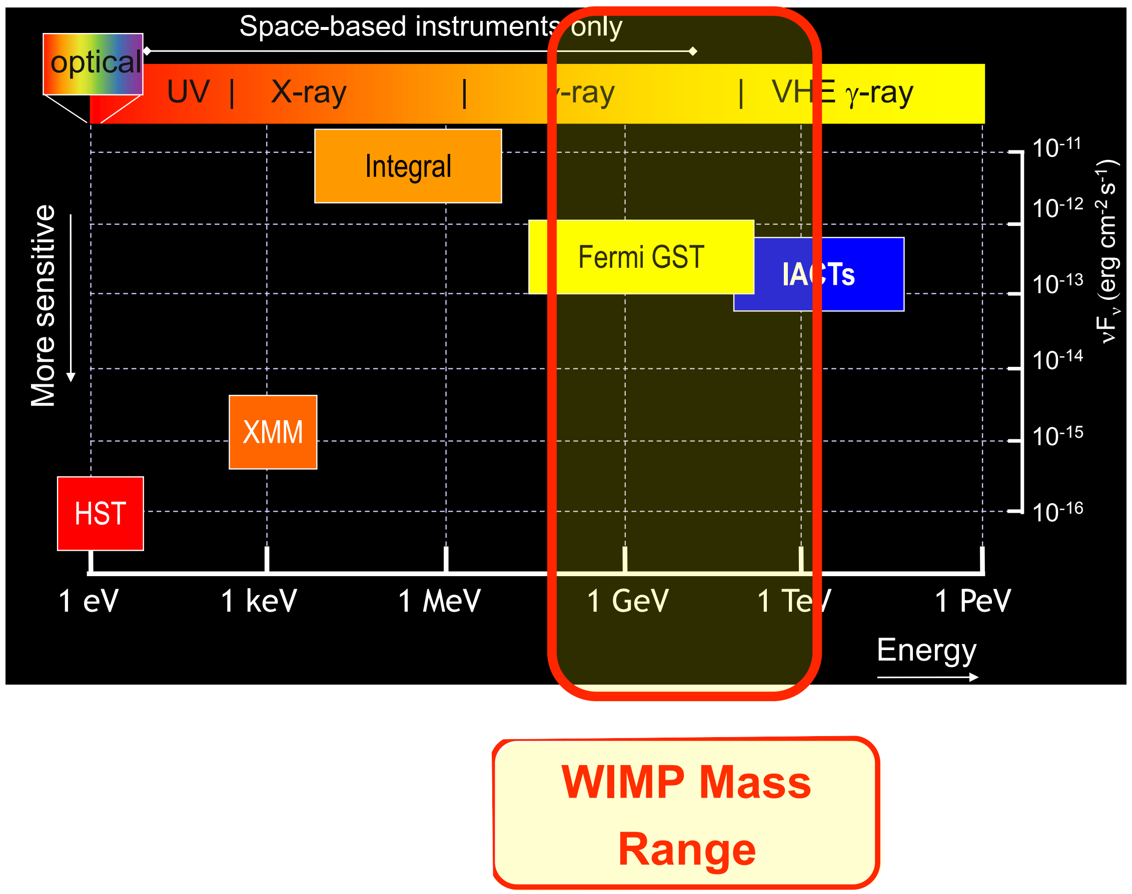
# Key features

Large field of view: 20% of the sky at any instant!




Every ~3 Hours

Energy range: 20 MeV to >300 GeV (~$M_Z$, ideally suited for WIMP searches).

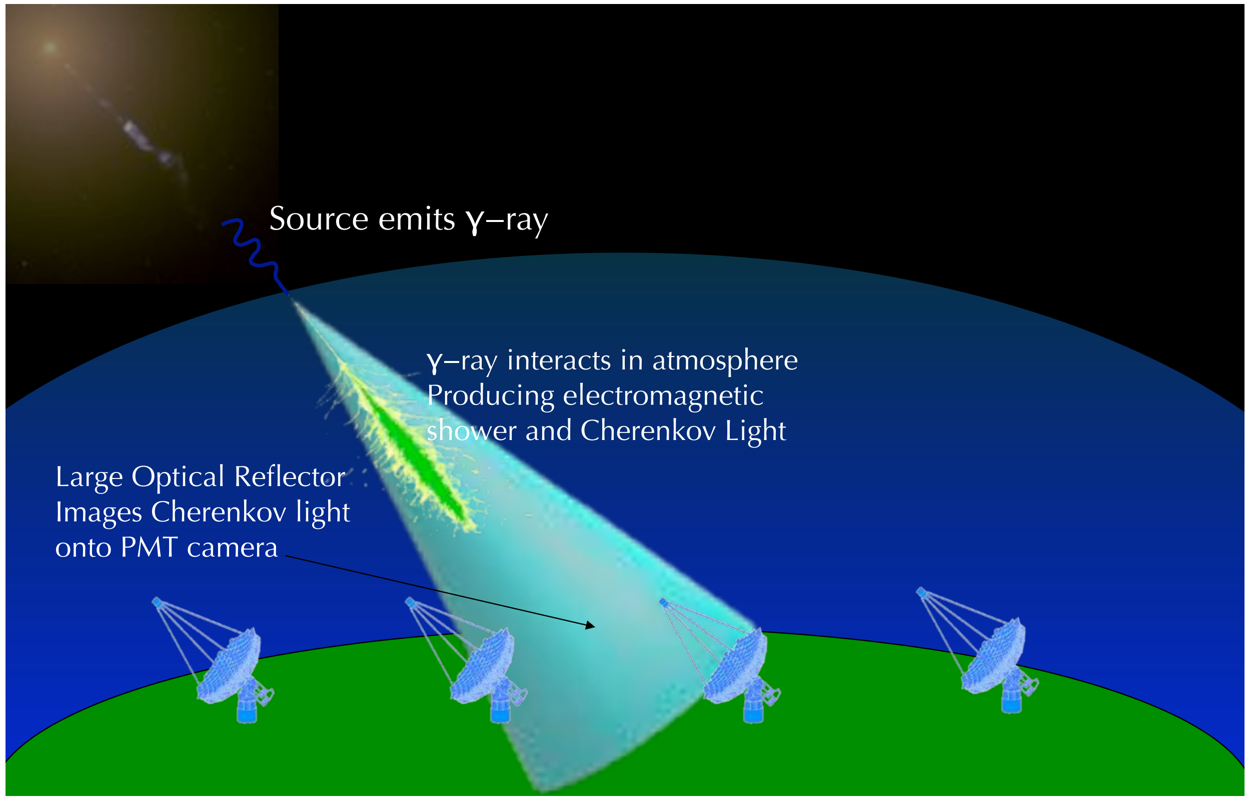


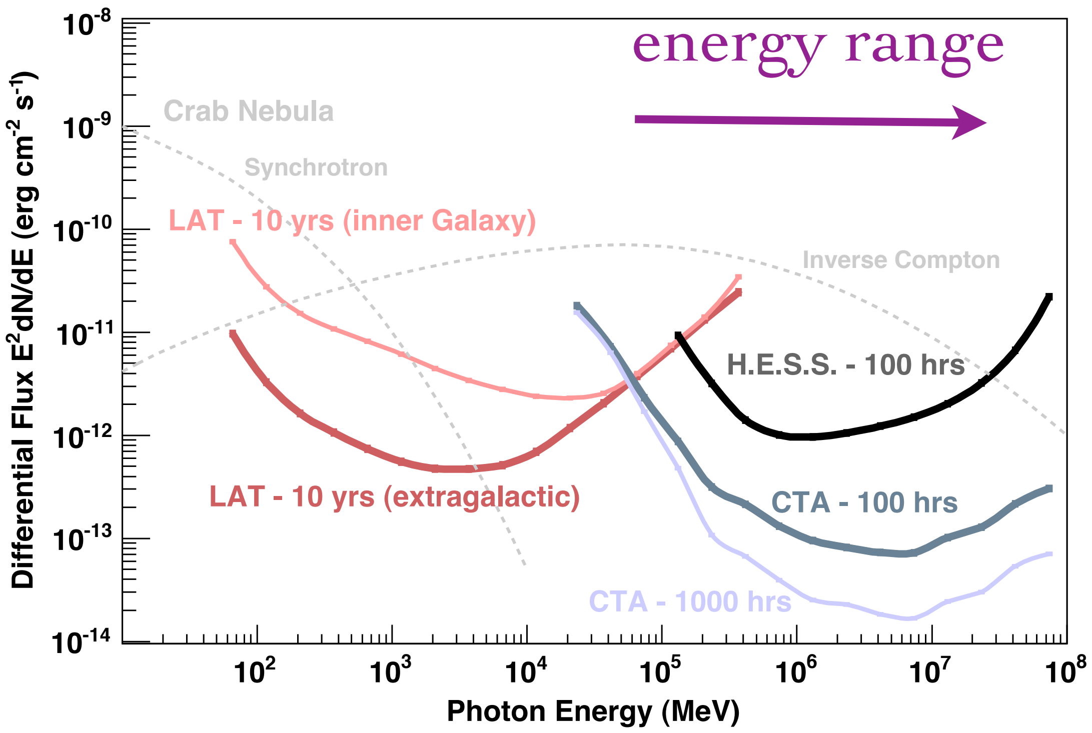

Good angular resolution ~ 0.1 deg; and charged particle vs gamma separation...

(http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)

- messengers (γ, ν, e±, p±, D⁻ ) /experiments (@~Mz range):
  - Imaging Atmospheric Cherenkov telescopes (HESS, MAGIC, VERITAS, TACTIC, CANGAROO III,...)

cover higher energy range

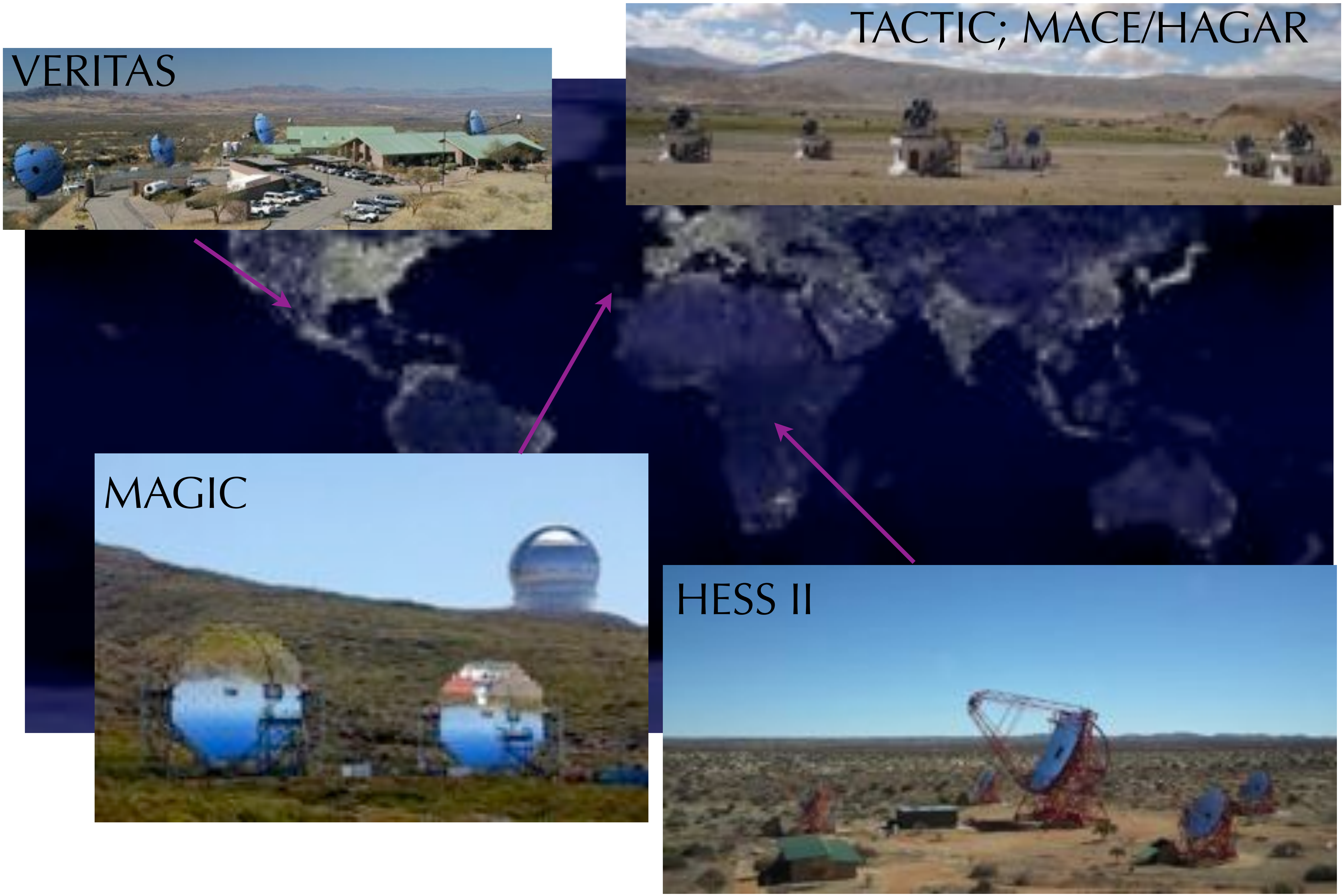



- use atmosphere as a calorimeter (increase detection area high energies)!
- → higher energy range (***100 GeV-100 TeV***); smaller field of view (***2°-5°***), large effective area (***$10^5$ m²***).
- but, have no anti-coincidence detector: ***irreducible charged particle contamination***
- ***complementarity*** between the two techniques!


ground based gamma ray telescopes are pointing, ~few degree field of view.

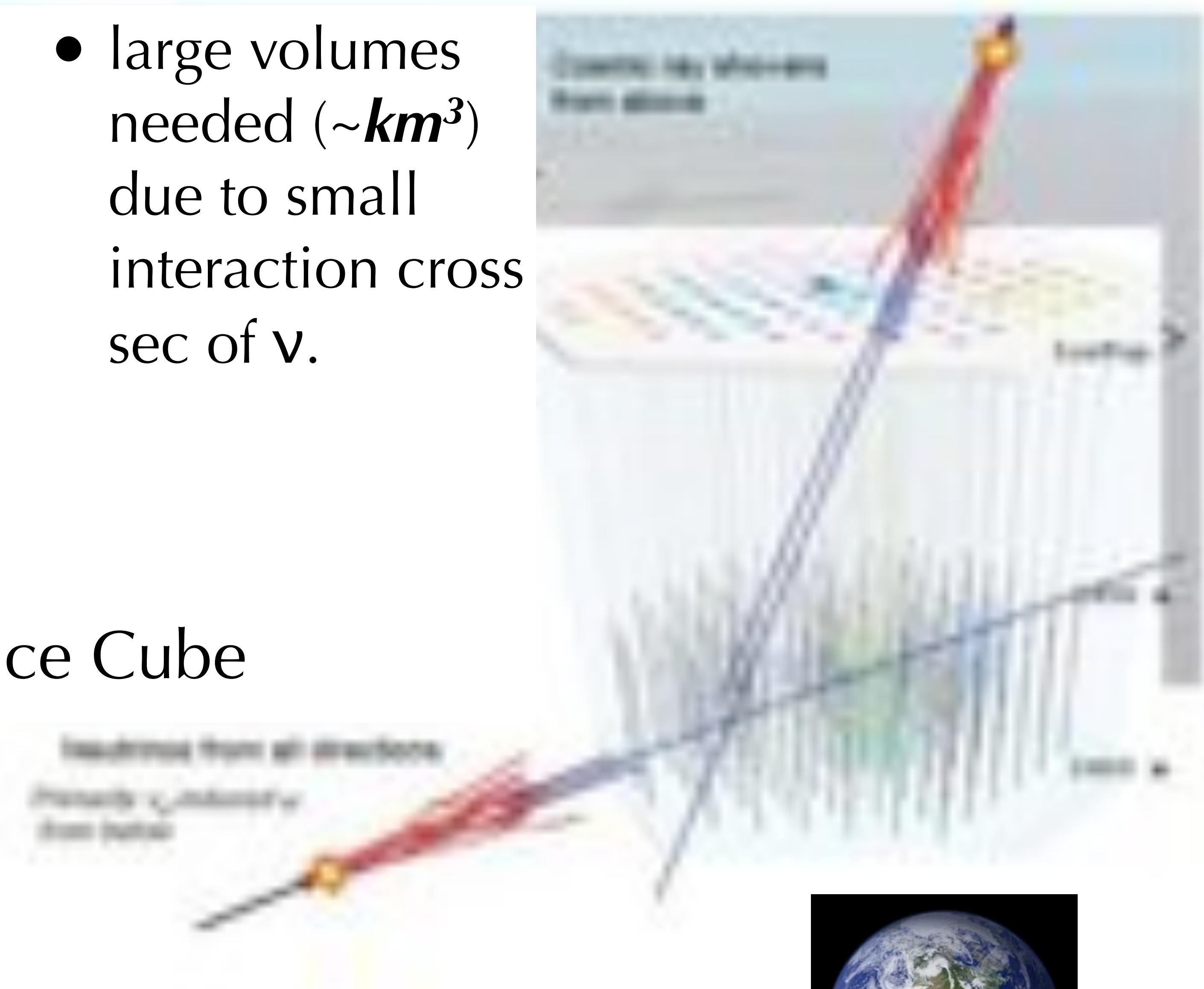
- messengers ($\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$, $D^{-}$) /experiments (@~Mz range):
  - IACTs (current: HESS, MAGIC, VERITAS,...):



- messengers ($\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$, $D^{-}$ ) /experiments (@~Mz range):
  - ICE CUBE, ANTARES, Baikal

- *>~**1 TeV*** (>~ 10 GeV Deep Core)
- muons produced in charged current interactions emit Cerenkov light (in ice/water) → detected by strings of photomultiplier tubes.
- background: *CR muons* → select upward going events or use detector edge as an anticonicidence detector or *atmospheric neutrinos*.

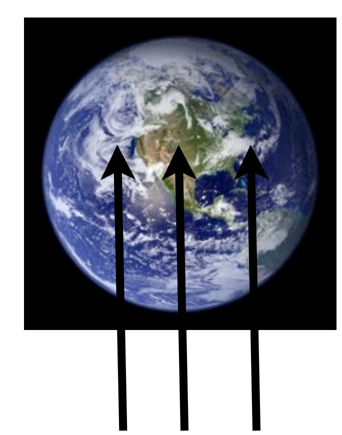
- large volumes needed (~***km³***) due to small interaction cross sec of $\nu$.



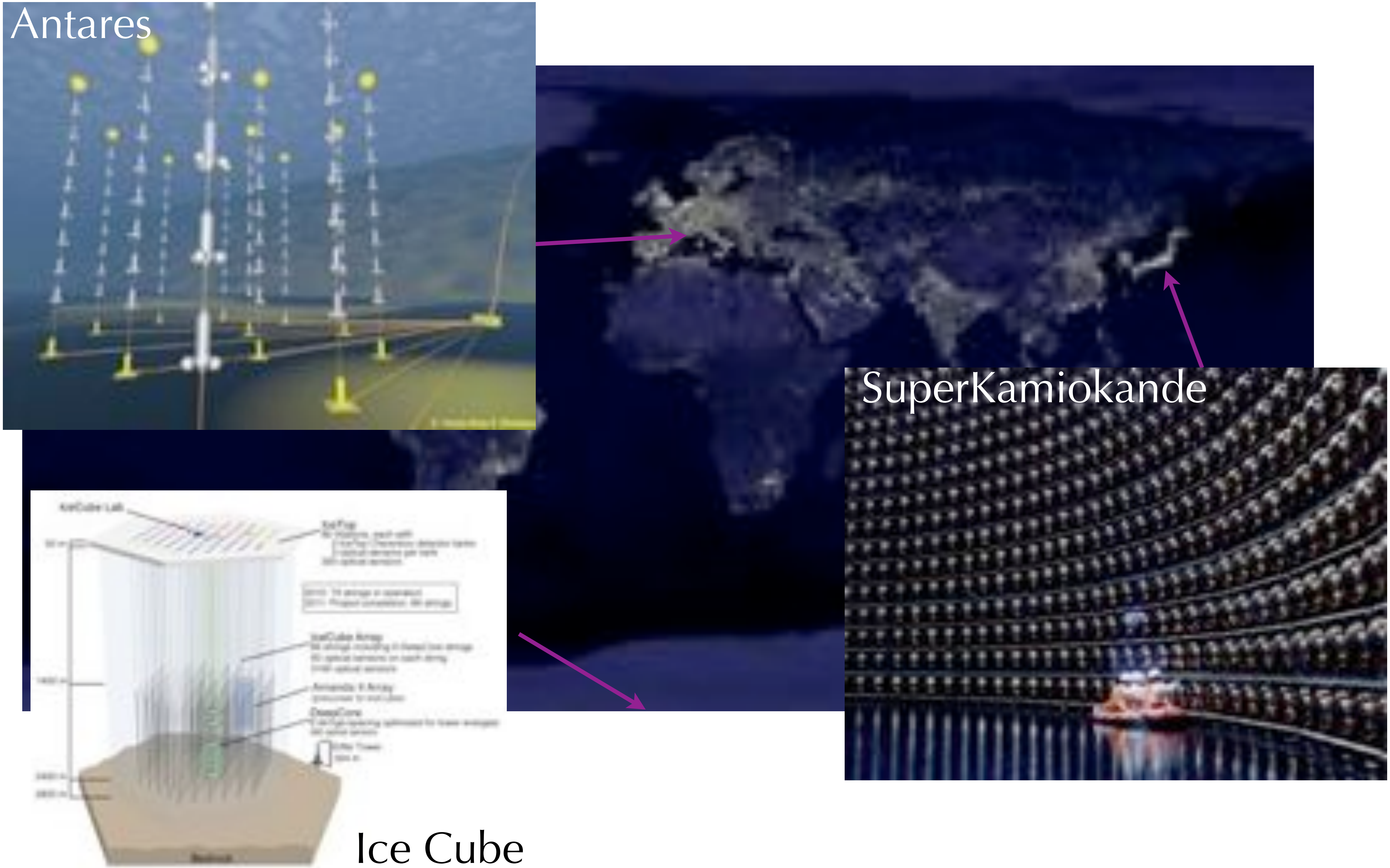
Ice Cube

upward going events

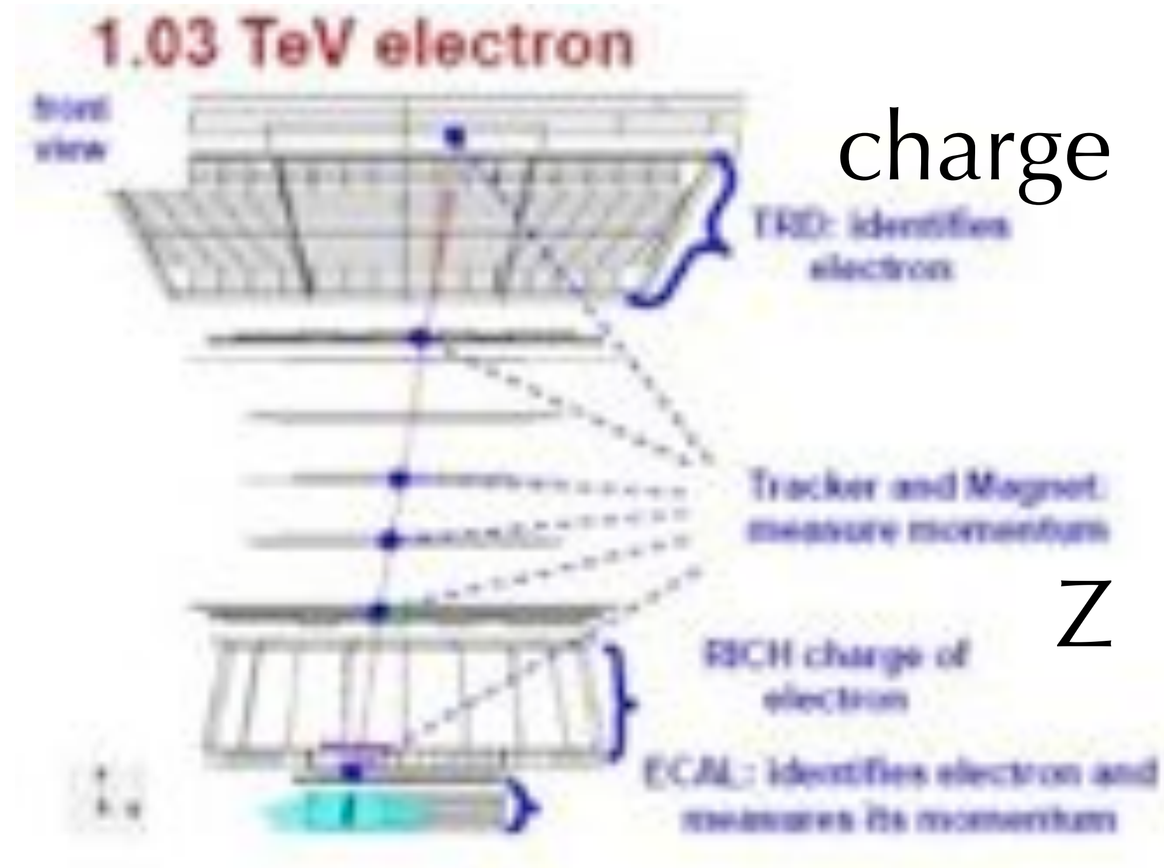
use all Earth for shielding of CRs



- messengers ($\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$, $D^{-}$ ) /experiments (@~Mz range):
  - Super Kamiokande, ICE CUBE, ANTARES



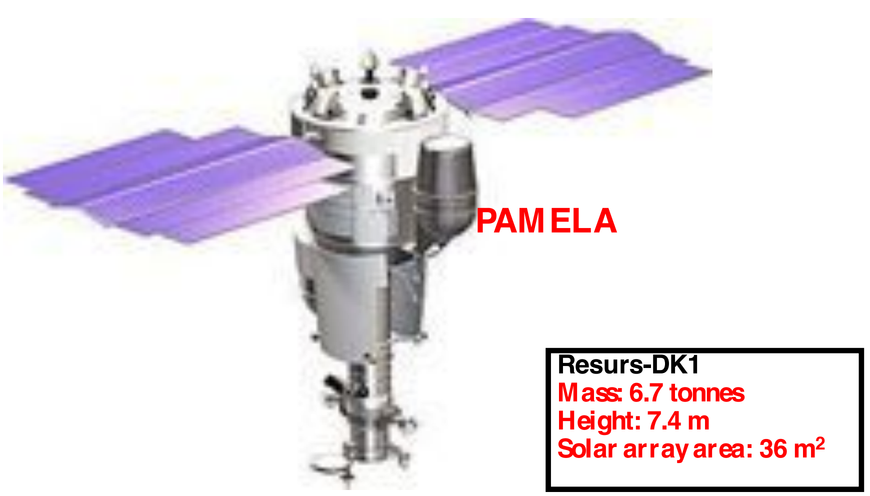
- messengers ($\gamma$, $\nu$, $e^{\pm}$, $p^{\pm}$, $D^{-}$,...) /experiments (@~Mz range):
  - satellites (PAMELA, AMS, ...)/balloons (CREAM, ATIC...):


charge

Z

energy




- unlike gamma-ray experiments, ***magnets*** and are further optimized to distinguish charge and Z study $e^{+}/e^{-}$; $p^{+}/p^{-}$
- AMS, launched May 16, 2011, operating at the ISS,
- PAMELA in orbit till the end of 2013.

- The signal:

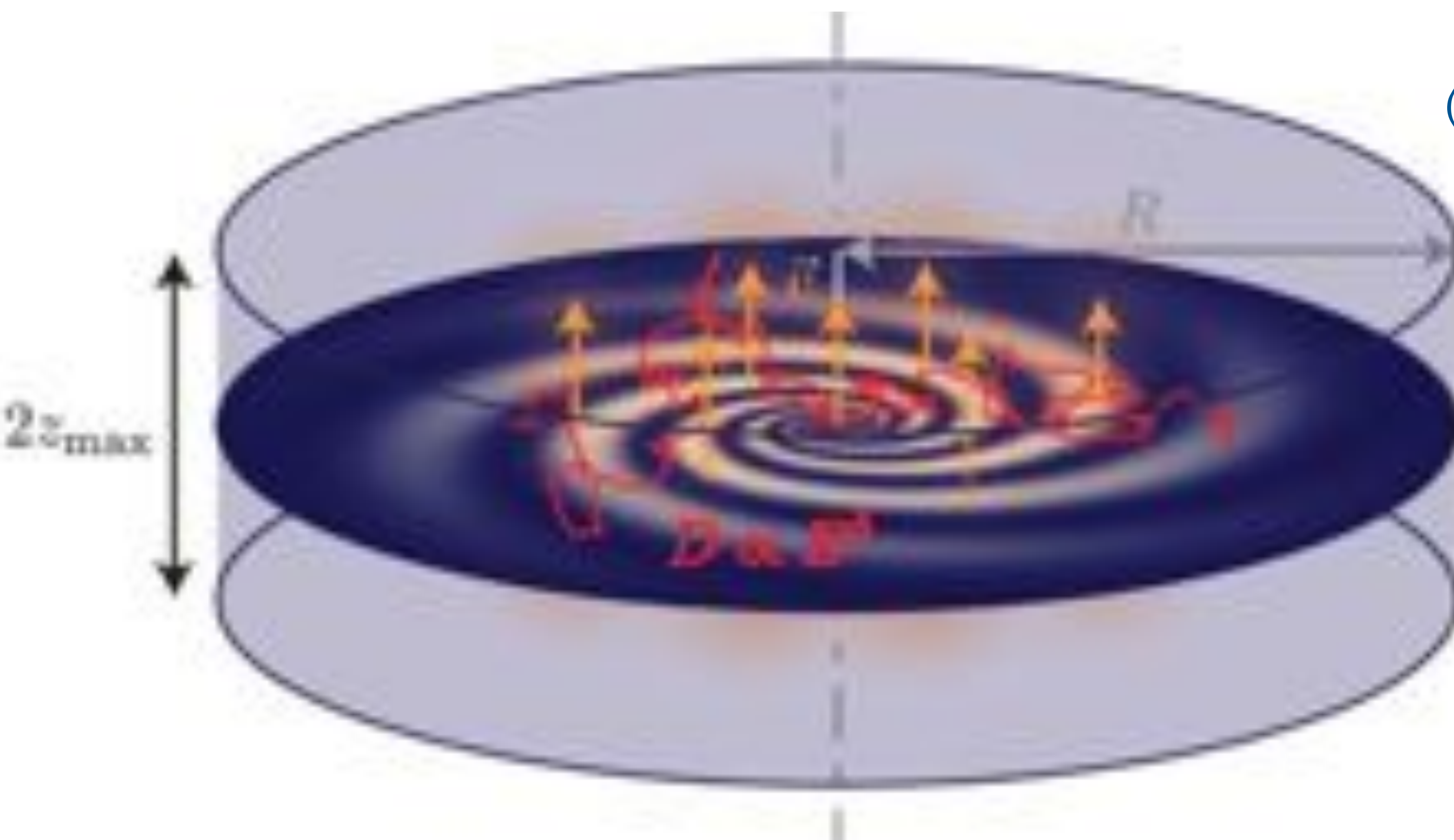
- γ and ν propagate in a straight line, unaffected by Galaxy

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}} \times \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \times \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

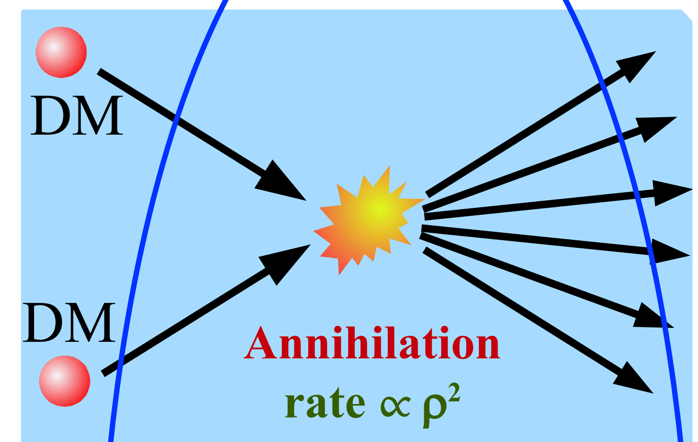
Particle physics: sets **spectrum** and **overall normalization**

DM clustering: **morphology** and **overall normalization**

- charged CR:
  - a more complicated story/ less ‘clean’ channel: CRs propagate diffusively, entangled in Galactic magnetic fields.




(P. Mertsch)

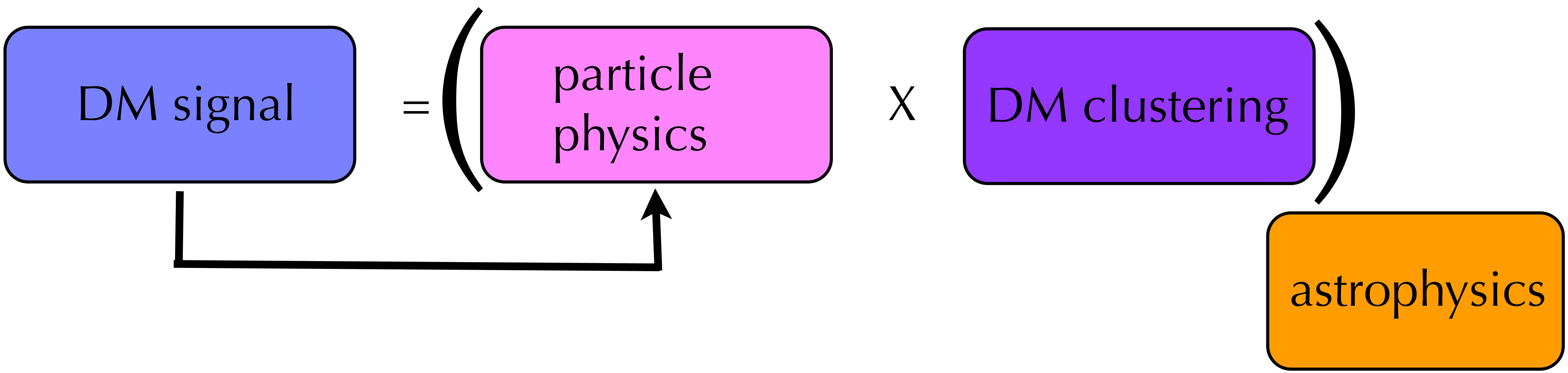



$$Q(E,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\rm DM}^2}\langle\sigma v\rangle\frac{dN}{dE}$$

CR density | Diffusion | Galactic winds | energy losses | re-acceleration | primary and secondary sources

$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p}b_{\rm loss}\psi - \frac{\partial}{\partial p}K\frac{\partial}{\partial p}\psi = q_{\rm source}$$

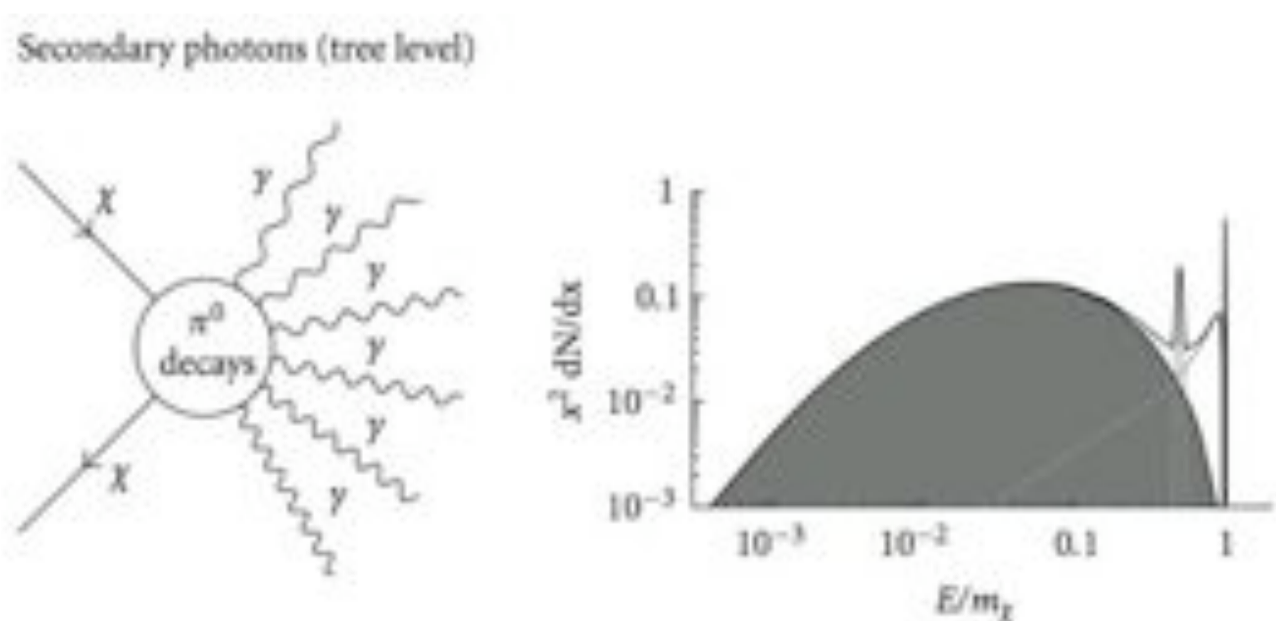
- charged CR:
  - a more complicated story/ less ‘clean’ channel: CRs propagate diffusively entangled in Galactic magnetic fields.
  - signal depends also on conventional astrophysics → *diffusion/energy losses/* in the Galaxy.



- Particle physics part:

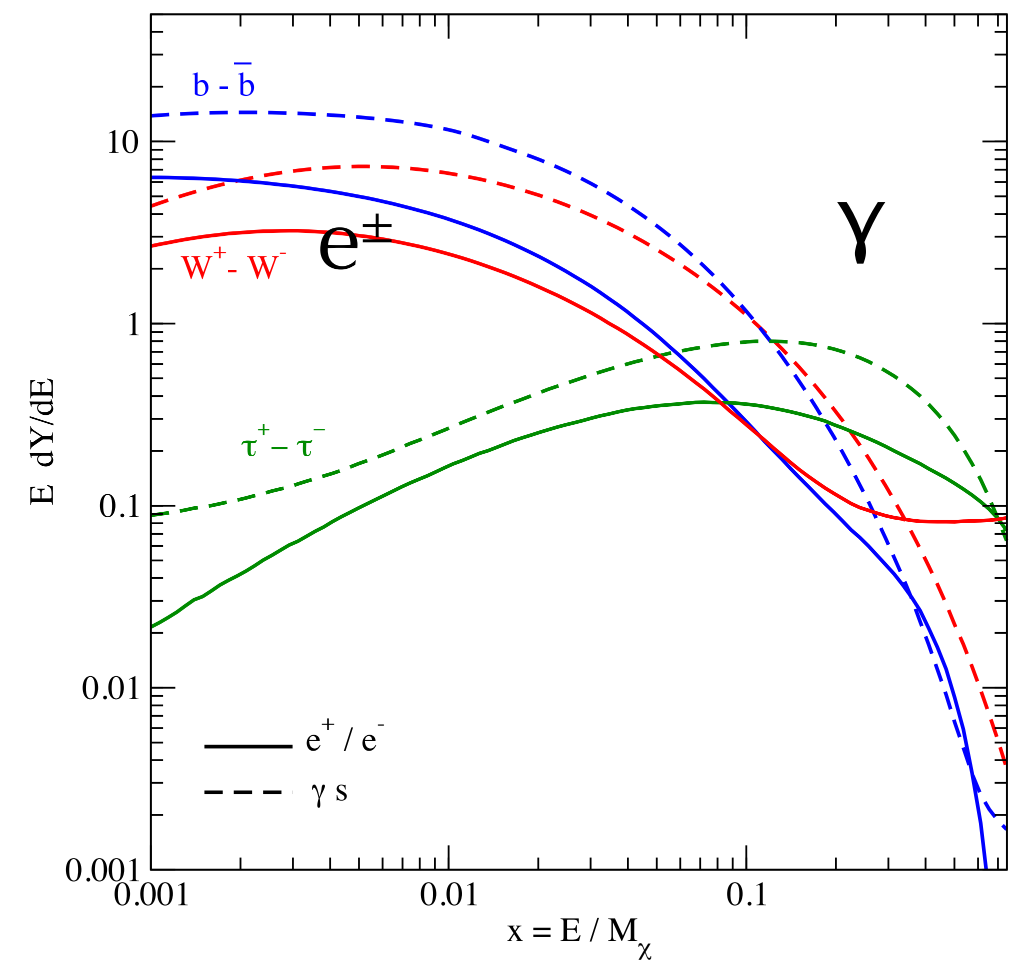
$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}\ \mathrm{X}\ \boxed{\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}}\ \mathrm{X}\ \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\,\rho^2(s,\Omega)$$

- *The (prompt) spectrum of SM particles* resulting from DM annihilation/decay→ Fixed when ***DM mass*** and ***branchings*** are set!
  - featureless 'bump-like' spectrum: ***quasi-universal*** spectra as a result of fragmentation/hadronization and subsequent pion decays.




[M. Kuhlen, AA, 2010.]

***neutrinos***: $\pi^- \rightarrow e\nu$; & (semi) leptonic decays.

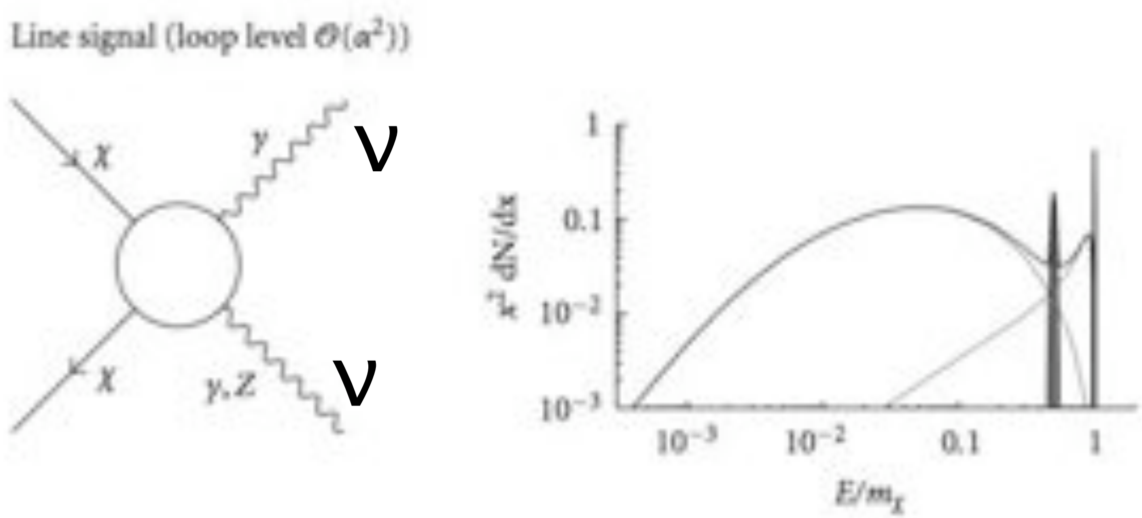


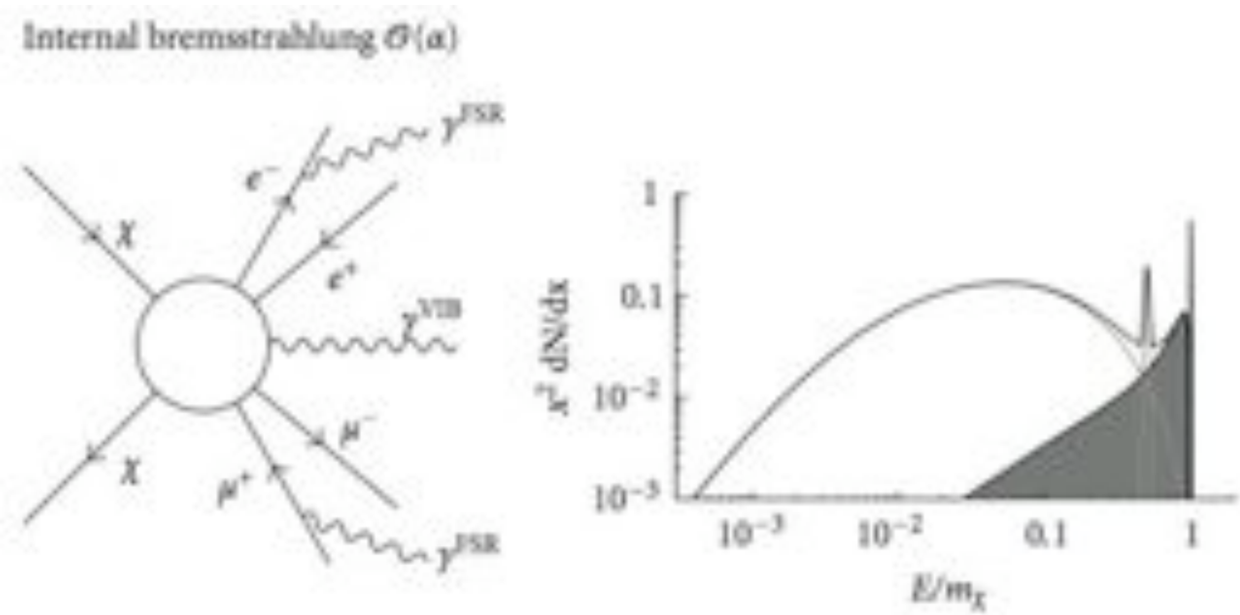

[Regis+, PRD 2008, 0802.0234.]

- Particle physics part:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2} \times \boxed{\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}} \times \int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)$$

- *The (prompt) spectrum of SM particles* resulting from DM annihilation/decay→ Fixed when ***DM mass*** and ***branchings*** are set!
  - feature-full: characteristic line (γ, ν) or internal bremstrahlung gamma ray signals.



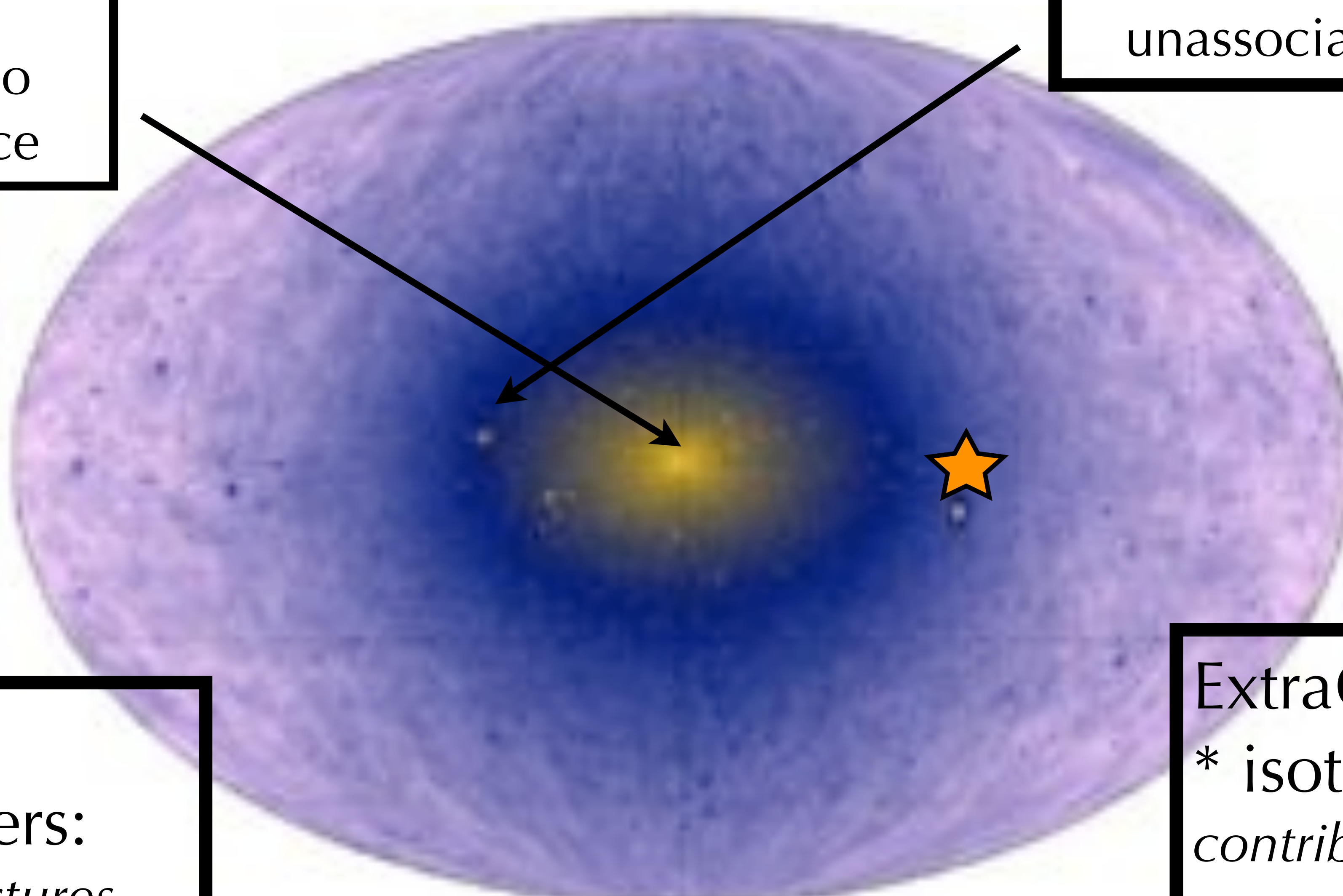

[M. Kuhlen, AA, 2010.]

# • Where to look?

- γ and ν propagate in a straight line, unaffected by Galaxy;
- DM clustering map (N-body simulations) is a good guide of observational targets.

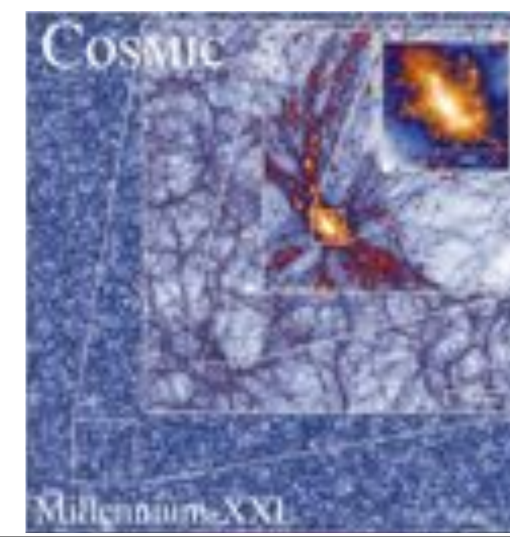
• **Inner Galaxy:**
∗*brightest spot on the DM sky*
∗appears 'diffuse' because we are so close to the source

Map of our Galaxy from Via Lactea N-body simulation



• **Dwarf Galaxies**
*largest Galactic subhalos*
• **Dark subhalos:** in a set of unassociated sources.


ExtraGalactic:
* Galaxy Clusters:
*Most massive structures yet to form*




ExtraGalactic:
* isotropic emission:
*contribution from unresolved halos at all redshifts.*

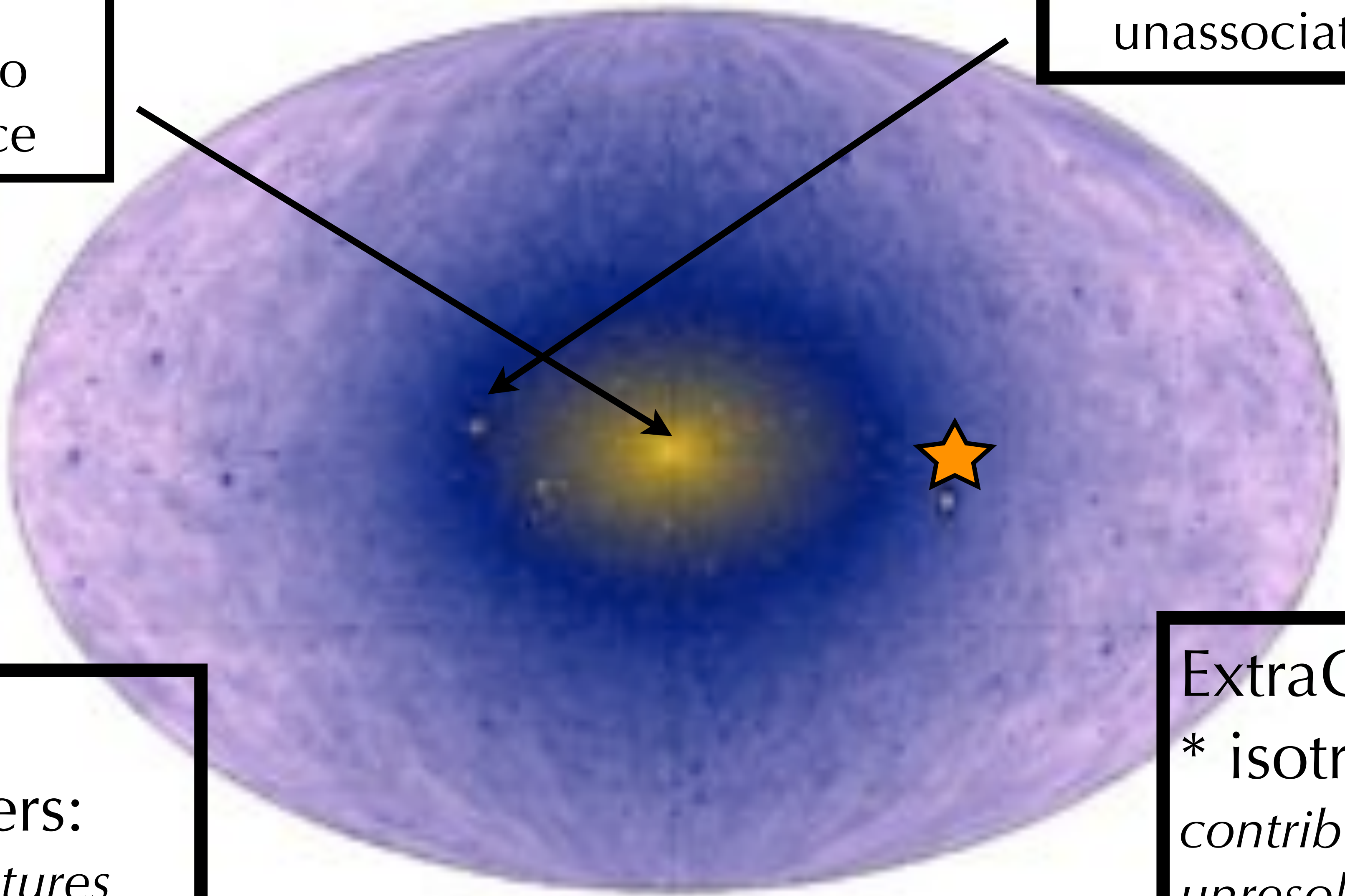
# • Where to look?

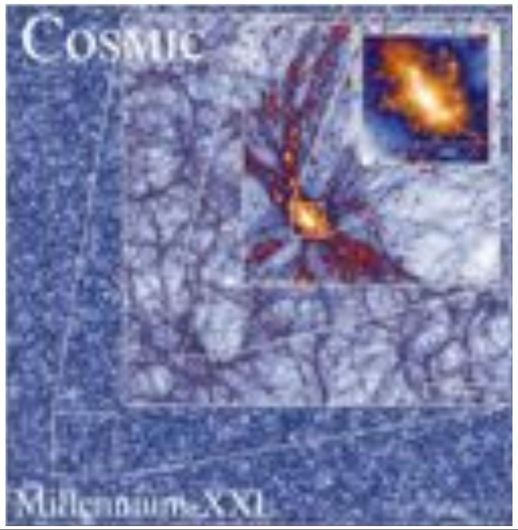
- in addition ν can also escape from systems in which other messengers are trapped. i.e. Sun or Earth!

- **Inner Galaxy:**
  - *brightest spot on the DM sky*
  - appears ‘diffuse’ because we are so close to the source

Map of our Galaxy from Via Lactea N-body simulation

- **Dwarf Galaxies**
  *largest Galactic subhalos*
- **Dark subhalos:** in a set of unassociated sources.



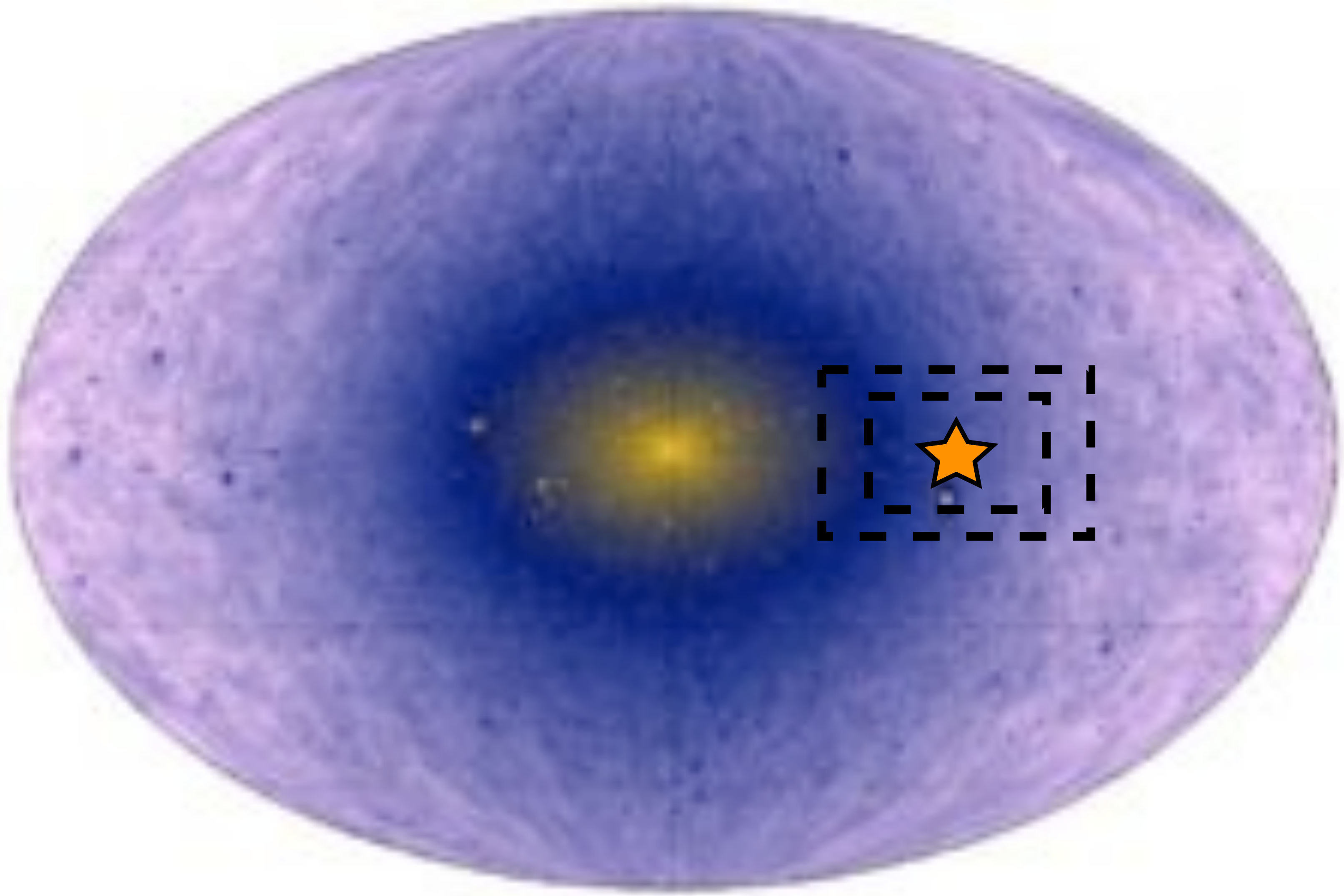

ExtraGalactic:
* Galaxy Clusters:
*Most massive structures yet to form*

ExtraGalactic:
* isotropic emission:
*contribution from unresolved halos at all redshifts.*

# • Where to look?

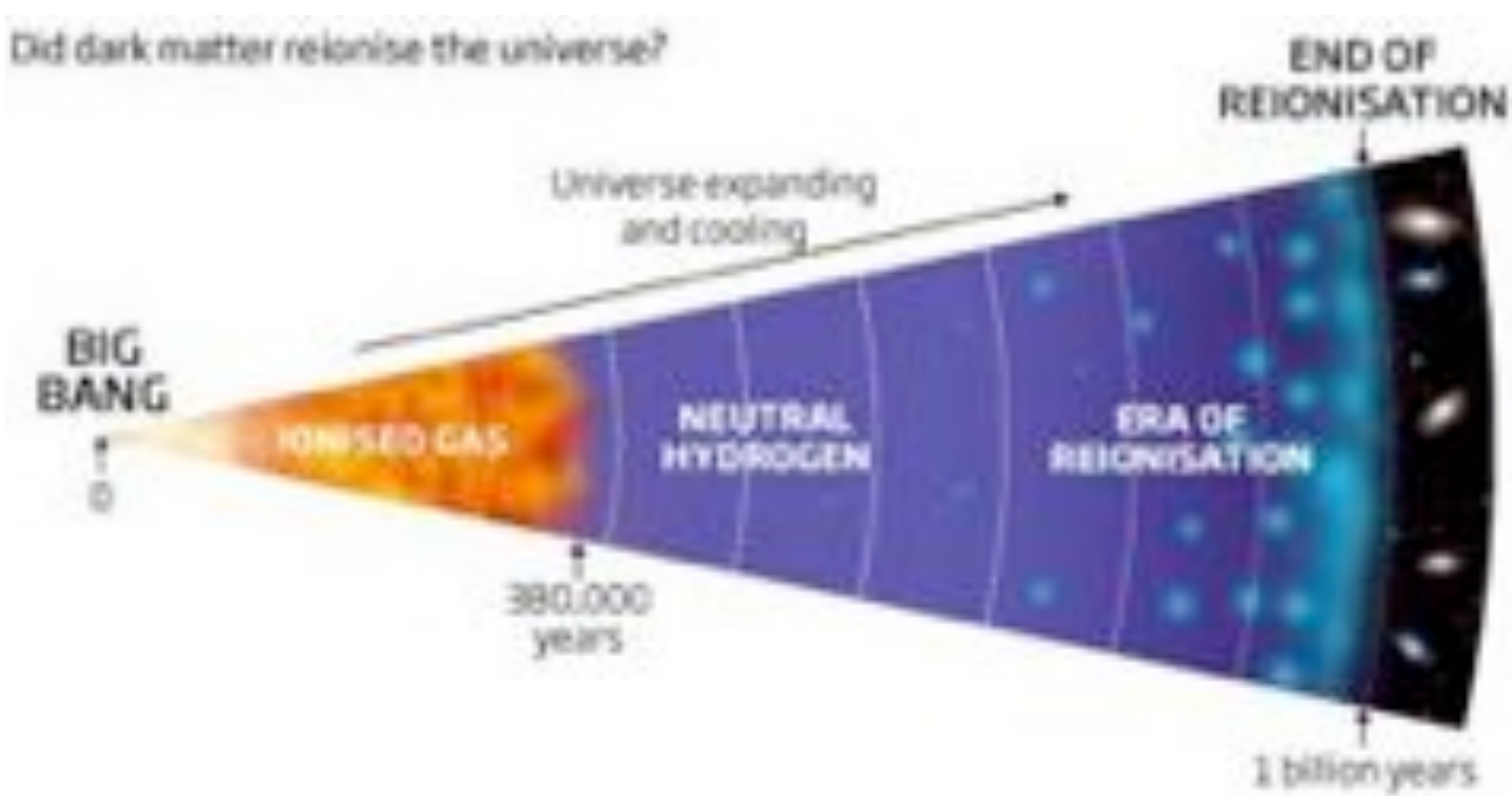
- while charged CR diffuse in the Gal halo and probe (en dependent) local volume.

Map of our Galaxy from Via Lactea N-body simulation



- Where to look?

- back in time! DM ann/decays could affect the early universe evolution:
  - ***BBN*** (T~1 MeV): energy injections destroy formed nuclei
  - ***CMB*** (z ~ 1000): The increased ionization fraction leads to a broadening of the last scattering surface.
  - ***re-ionization*** (6 < z < 20): ionization and heating after recombination and during the epoch of structure formation affect optical depth of the Universe.



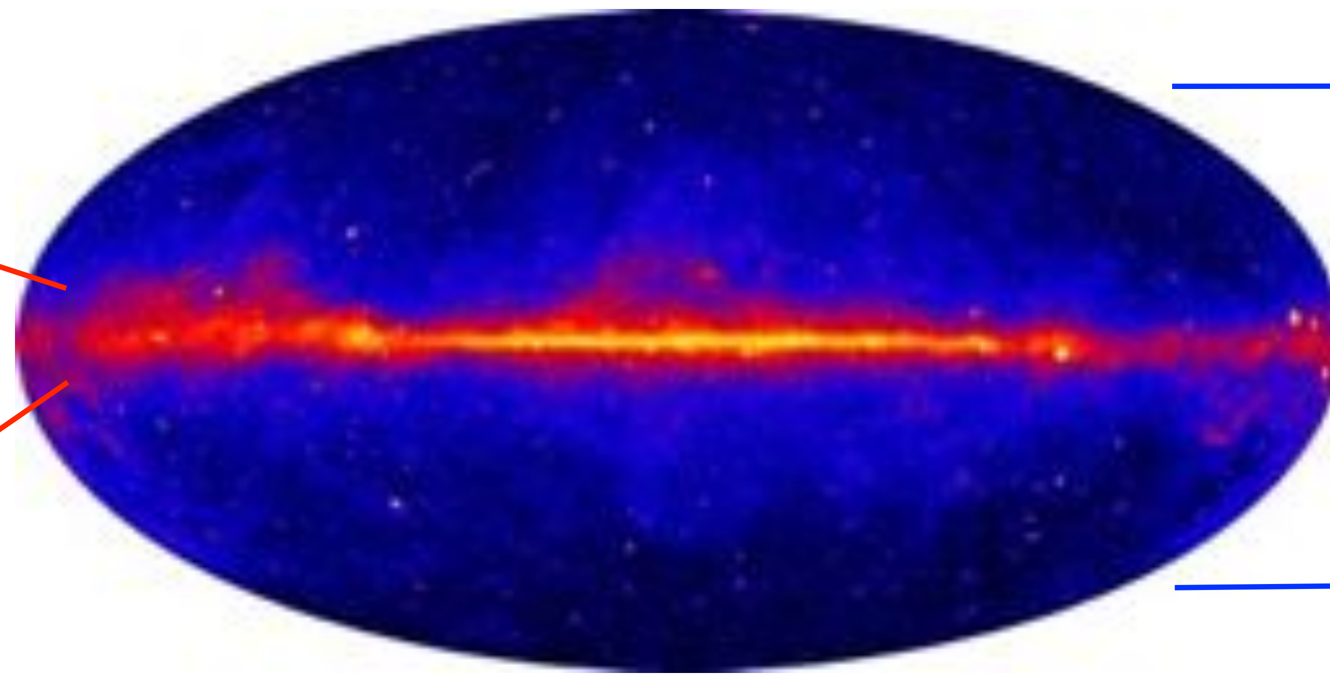
# Backgrounds/astrophysics:

# How does gamma ray sky look like, at 1 GeV?

## 1) Diffuse emission: ~90% LAT photons.

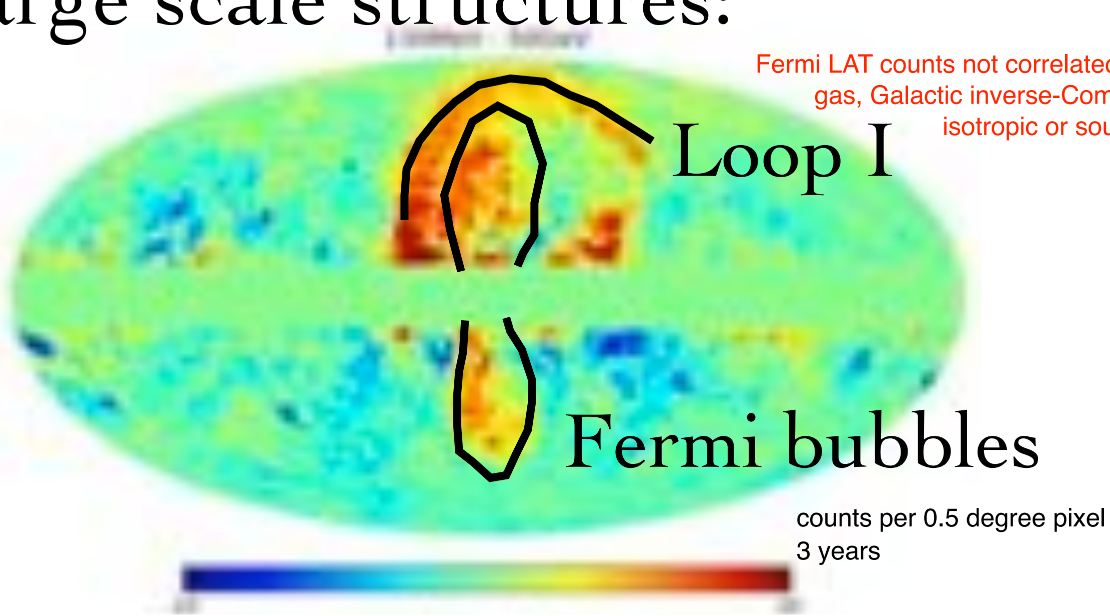
Fermi LAT three year sky map.

**Galactic emission:** **Charged CR** interact with the **interstellar medium** (gas, star light, ...)->$\gamma$



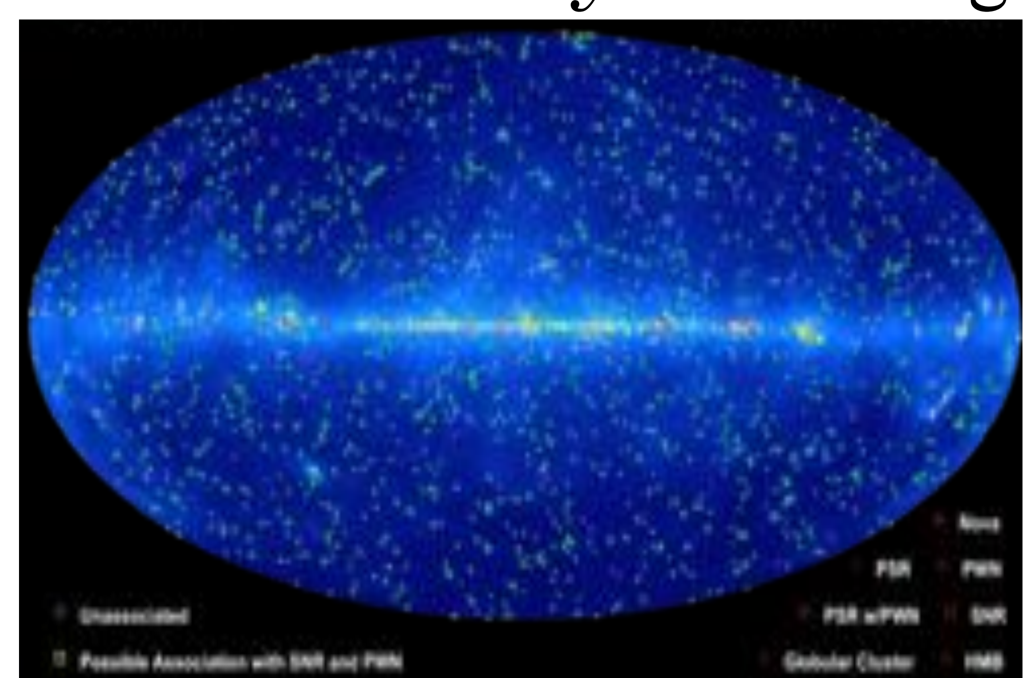
**extra-Galactic**: (high latitude, 'isotropic' emission). Made up by e.g. sources too faint to be resolved individually.

## 2) Large scale structures:




[Casandjian, Gamma2012]

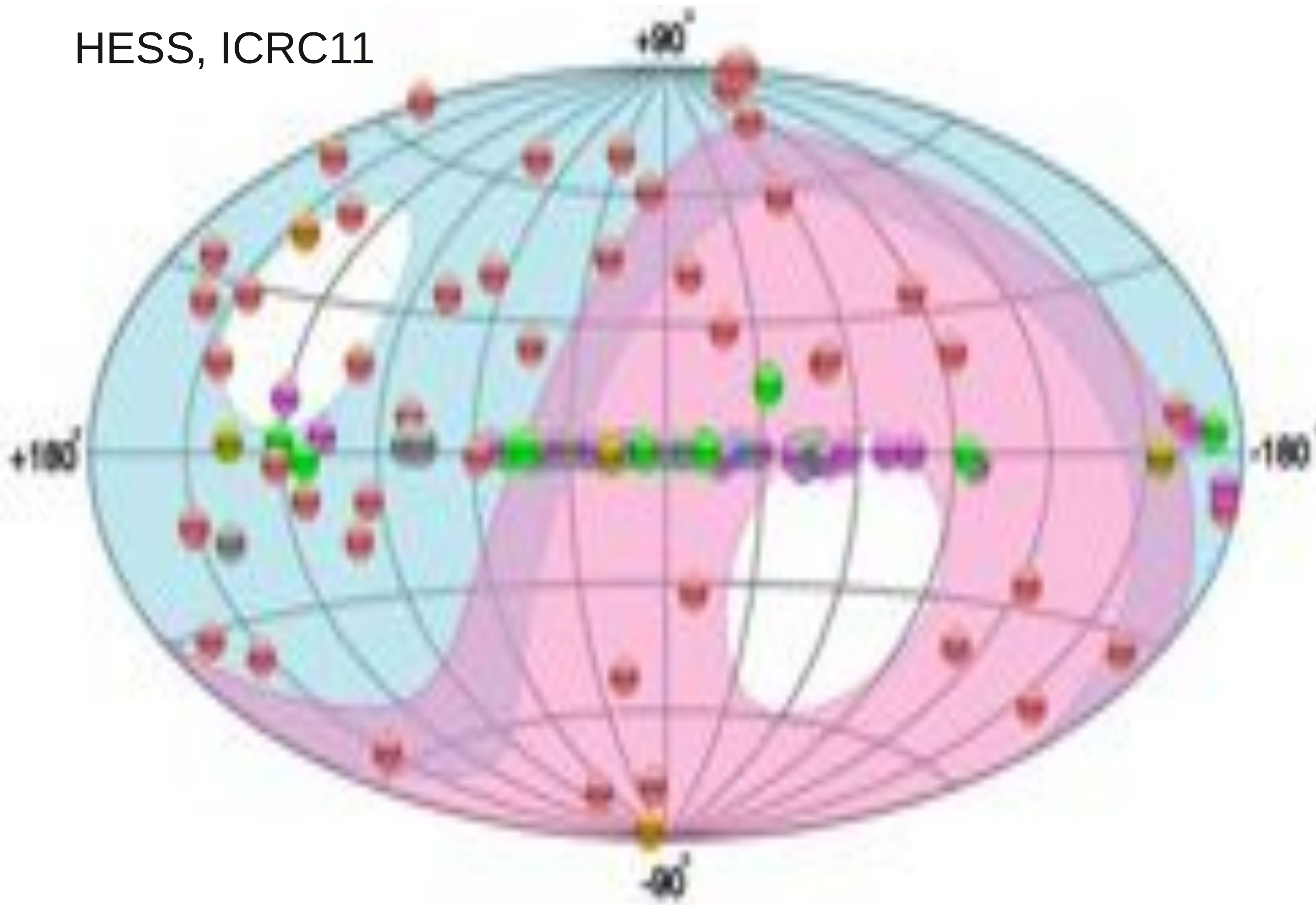
## 3) ~1900 sources in the 2 year catalog



# And at TeV?

Pointing telescopes, mainly point sources!

HESS, ICRC11




http://tevcat.uchicago.edu/

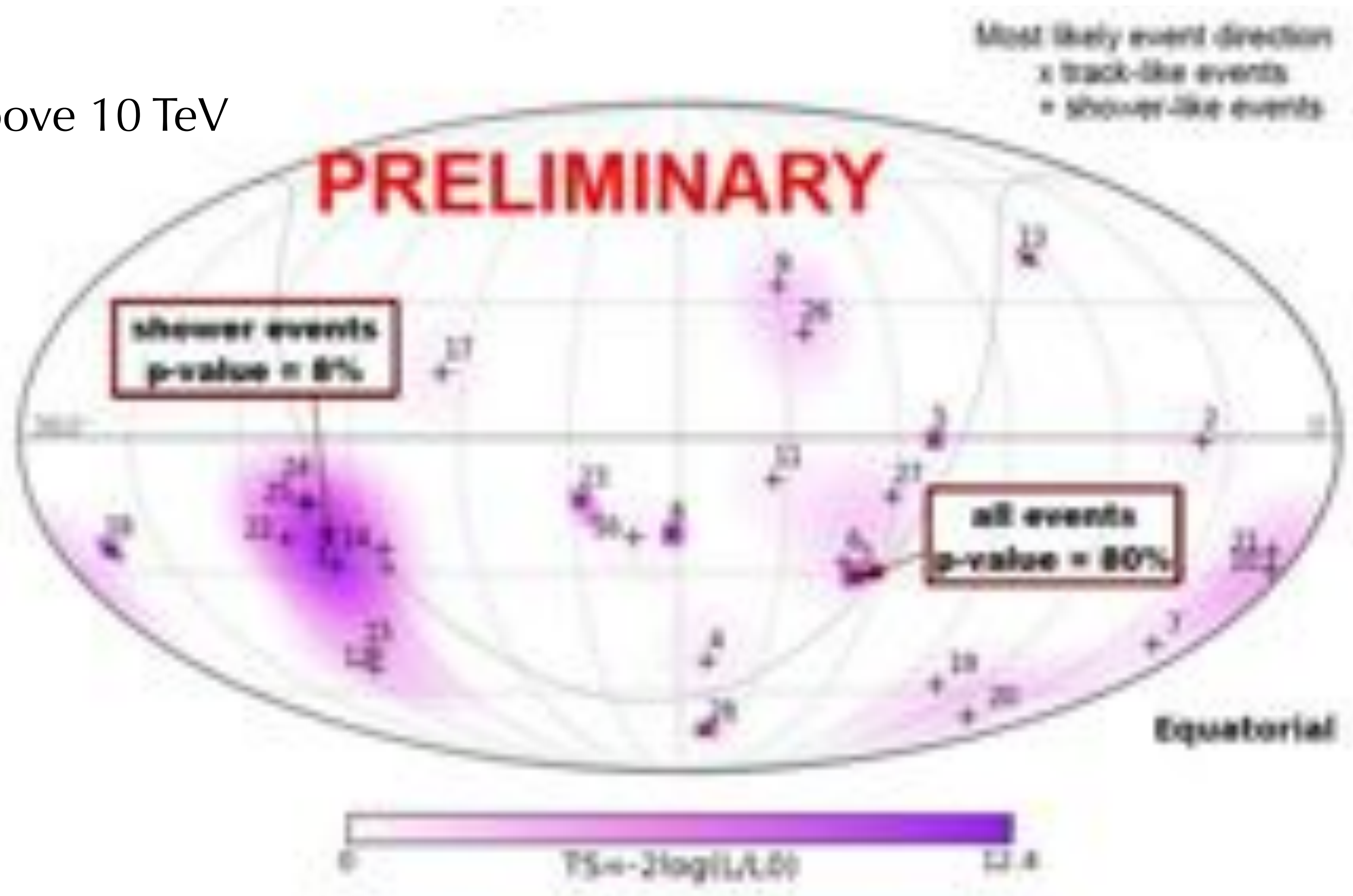
=

# How does neutrino sky look like?

Up to recently only atmospheric or solar neutrinos detected.

Recently, **first detection of astrophysical neutrinos!**

above 10 TeV

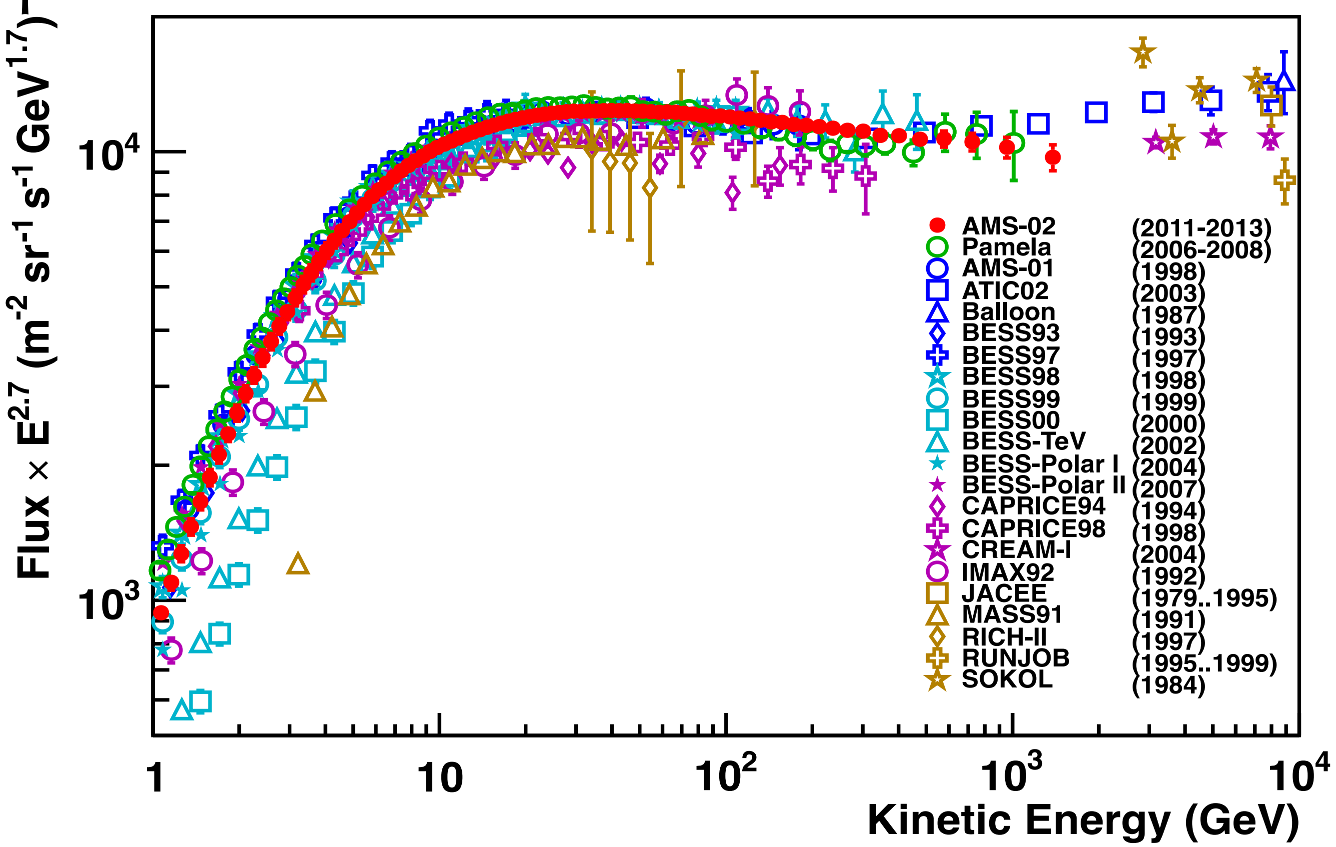



[F. Halzen, ICRC 2013]

# and locally measured cosmic ray fluxes?

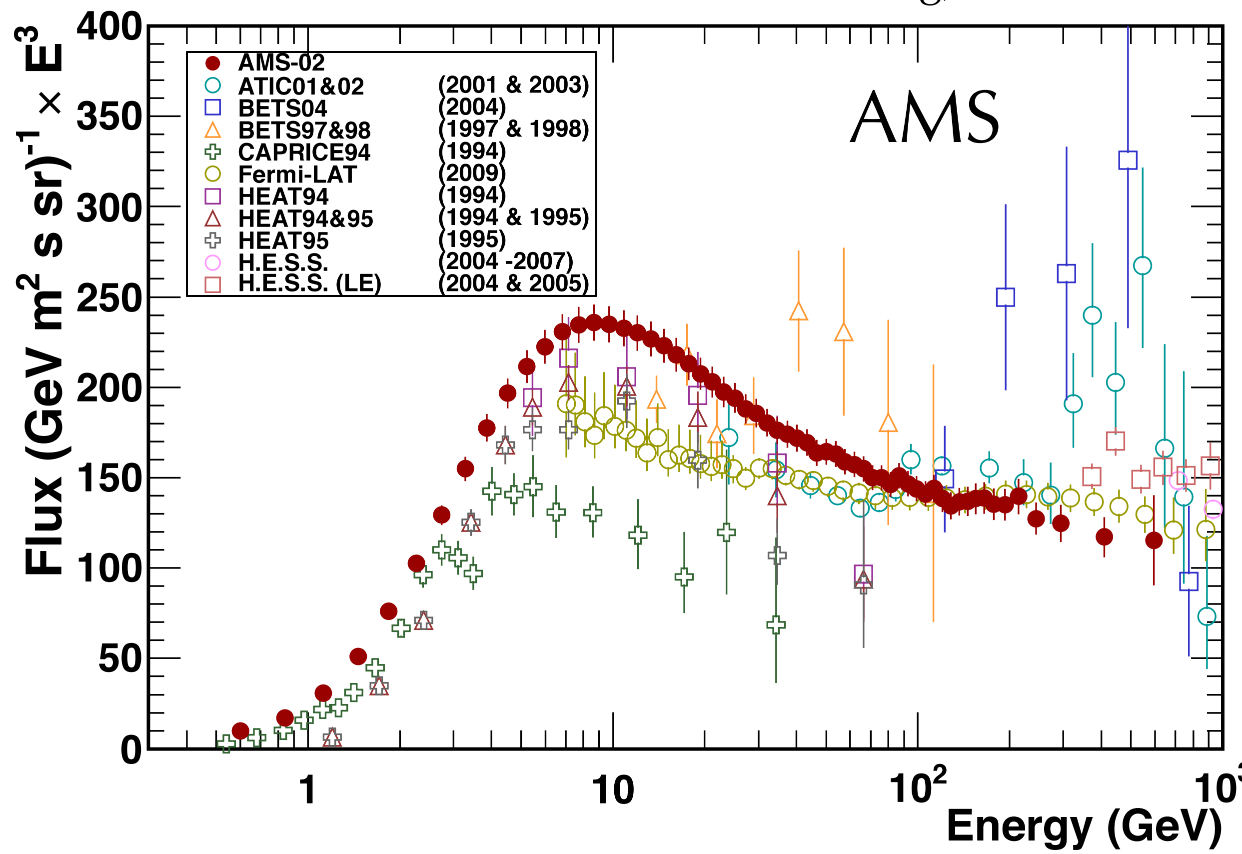
two satellites provided very precise measurements recently:

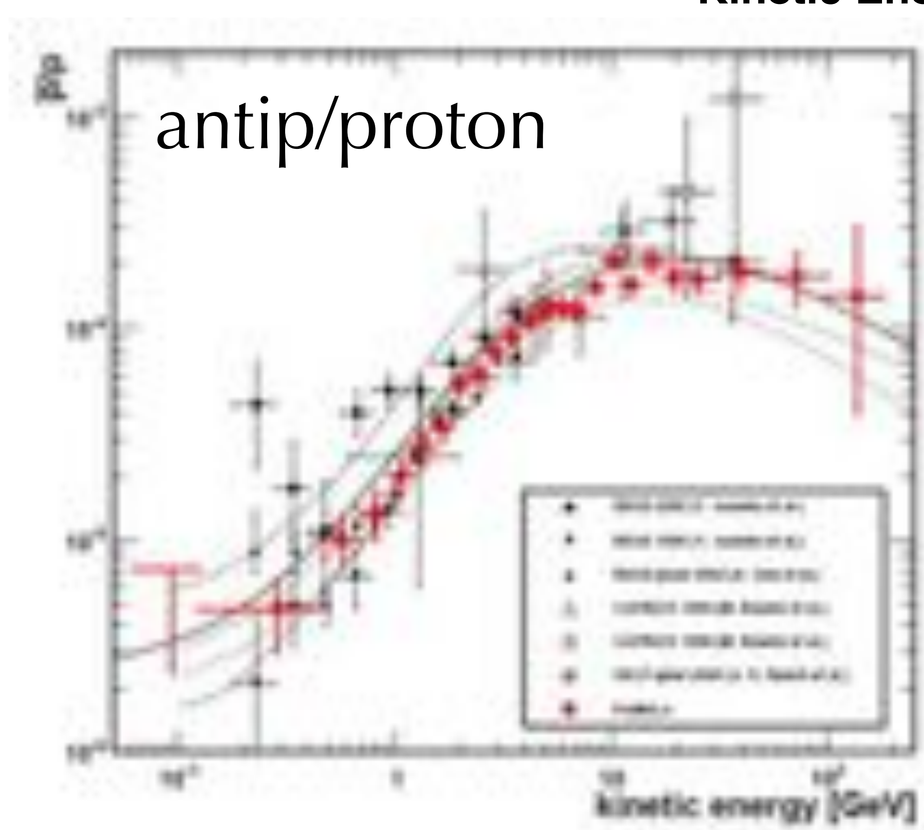
proton flux



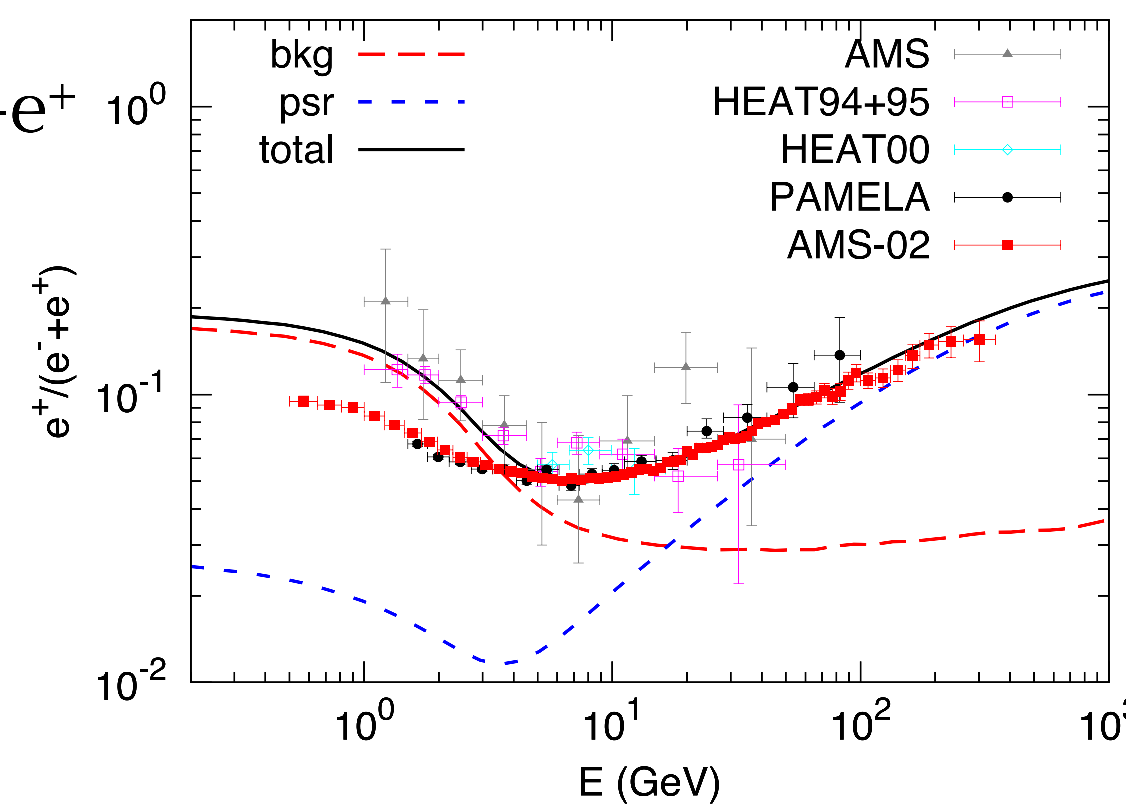

$e^- + e^+$

[S. Ting, ICRC 2013]



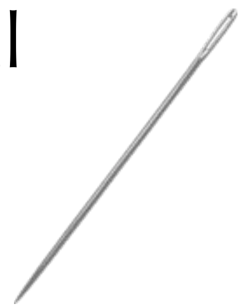




$e^+ / e^- + e^+$



## Challenge:

look for an uncertain signal swapped in the uncertain backgrounds.







[J. Siegal-Gaskins talk@Sackler colloquium 2012]

# Detection paths:

A) look for ***smoking guns***:

➡ 'zero' astro backgrounds, but need luck -- expected signals (for vanilla DM) low

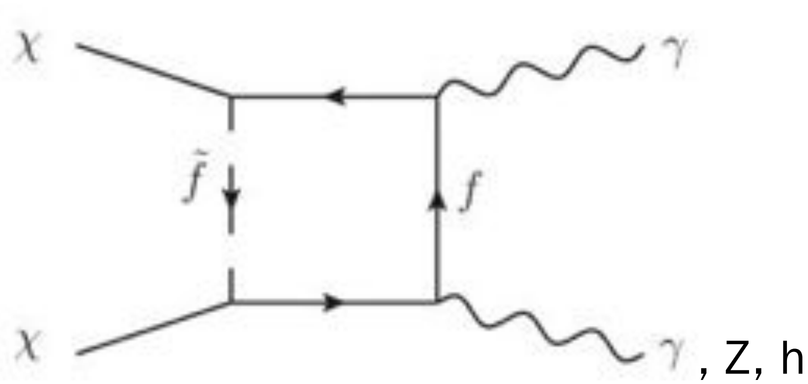
- spectral line features
- dwarf galaxies
- anti-deuterium
- (Sun (neutrinos) - elastic cross section)

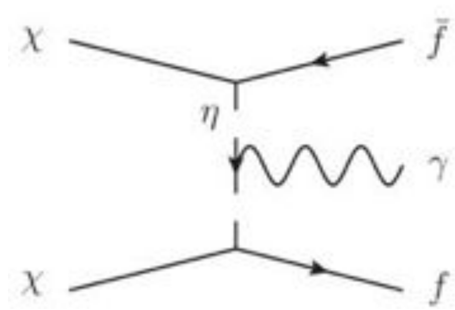
B) search for **standard WIMP signatures** and **use rich astro data to model the backgrounds**

➡ current experimental sensitivity in the right ballpark for vanilla models, but due to the confusion with astro backgrounds possible hints NEED confirmation across the range of ***wavelengths/messengers/targets***

- raising positron fraction;
- Galactic Center gamma ray data

# Gamma ray line:

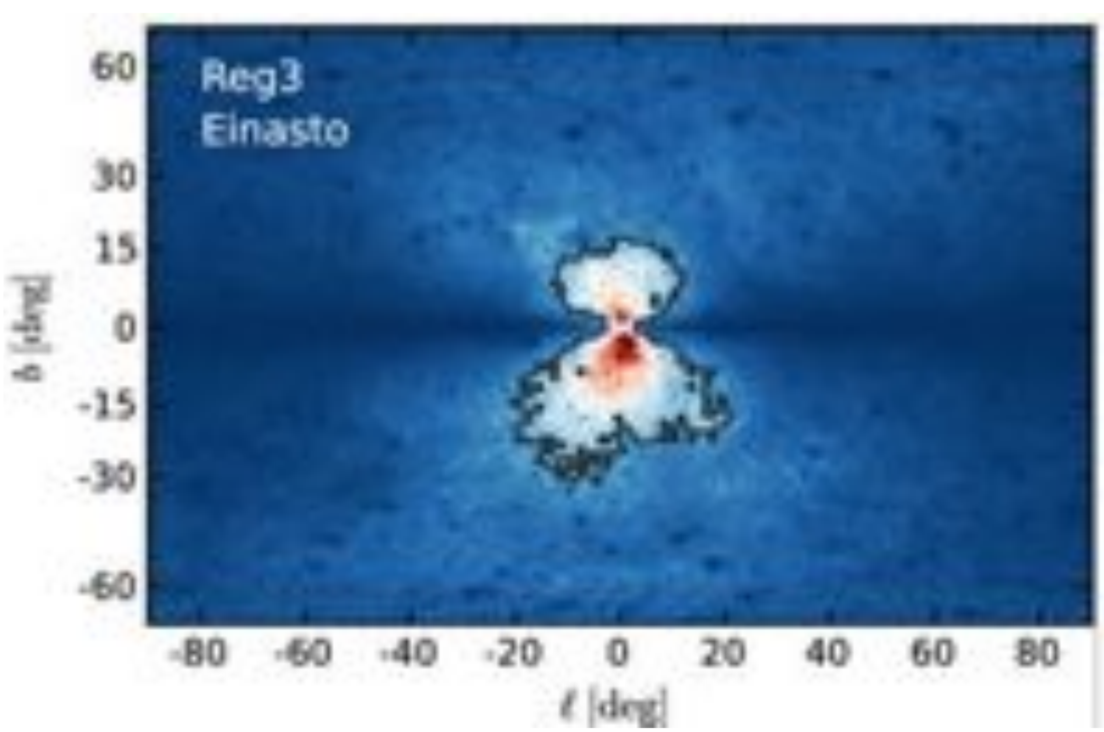



t-channel annihilation

How to look for a spectral feature?

## I) Identify target region




blind or maximize S/N assuming a DM density profile

## II) Spectral analysis


extrapolate measured spectrum from a larger energy range and look for 'line-like' features.

# Gamma ray line

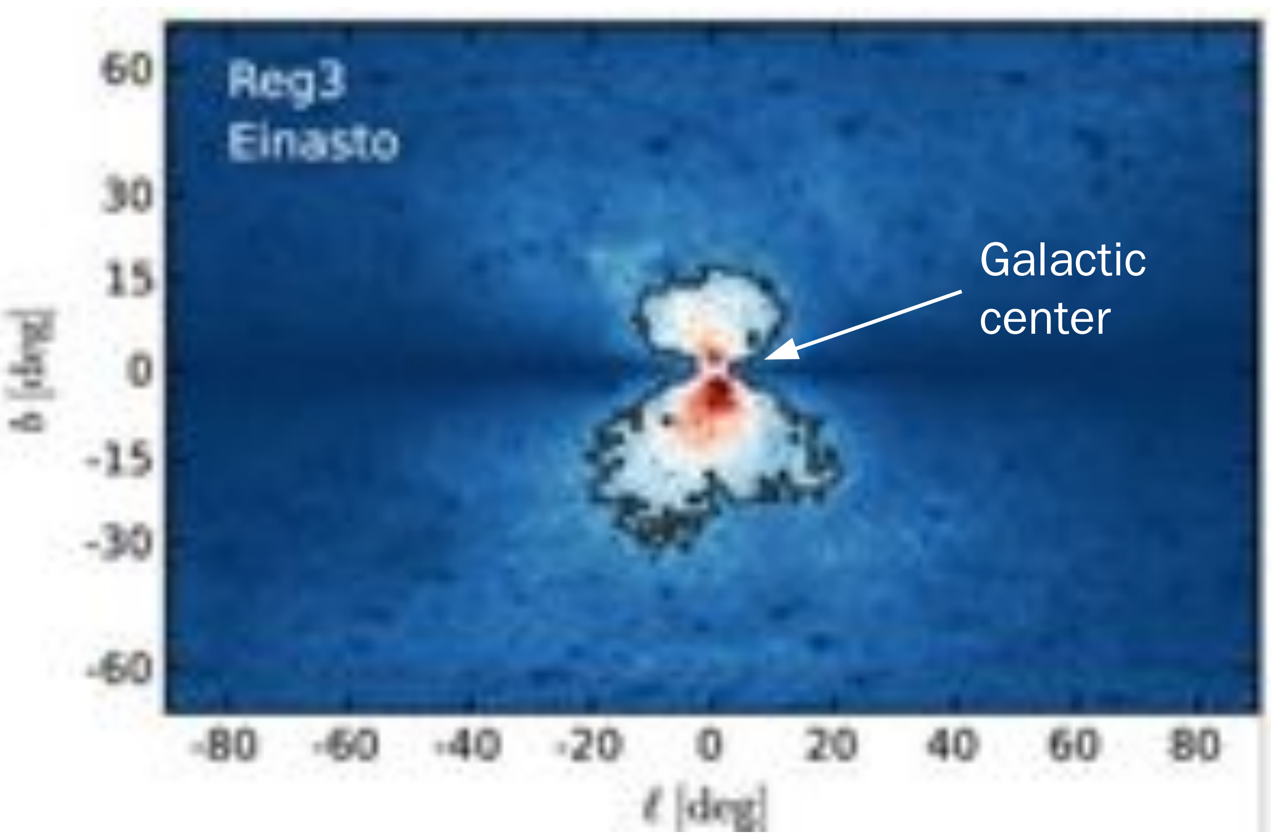
Weniger+ 2012:

Evidence for a narrow spectral feature in 3.5 yr data near 130 GeV in optimized ROIs near the Galactic center.

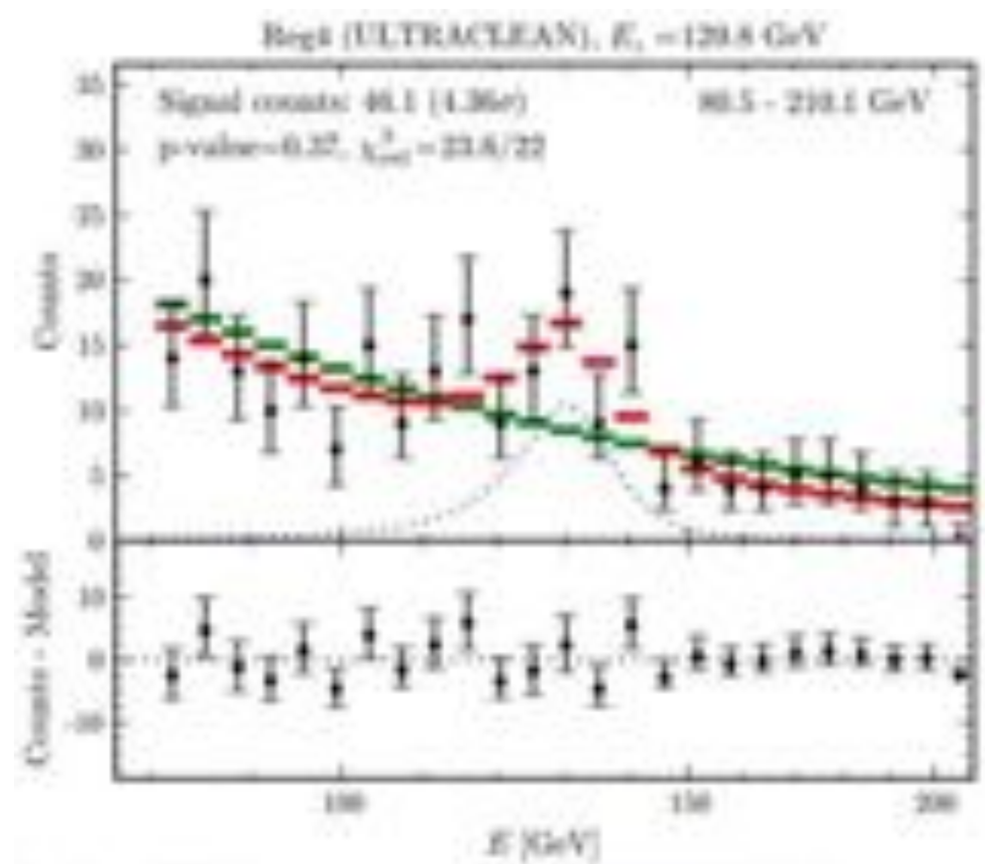
Some indication of double line (111 &130 GeV), Su+, 2012.

- Signal is particularly strong in 2 test regions (cuspier profiles) with S/N> 30%-60%.

Region of interest:




Spectrum:



C. Weniger JCAP 1208 (2012) 007, 1204.2797

# Gamma ray line

**Fermi LAT's line search**

(1305.5597)

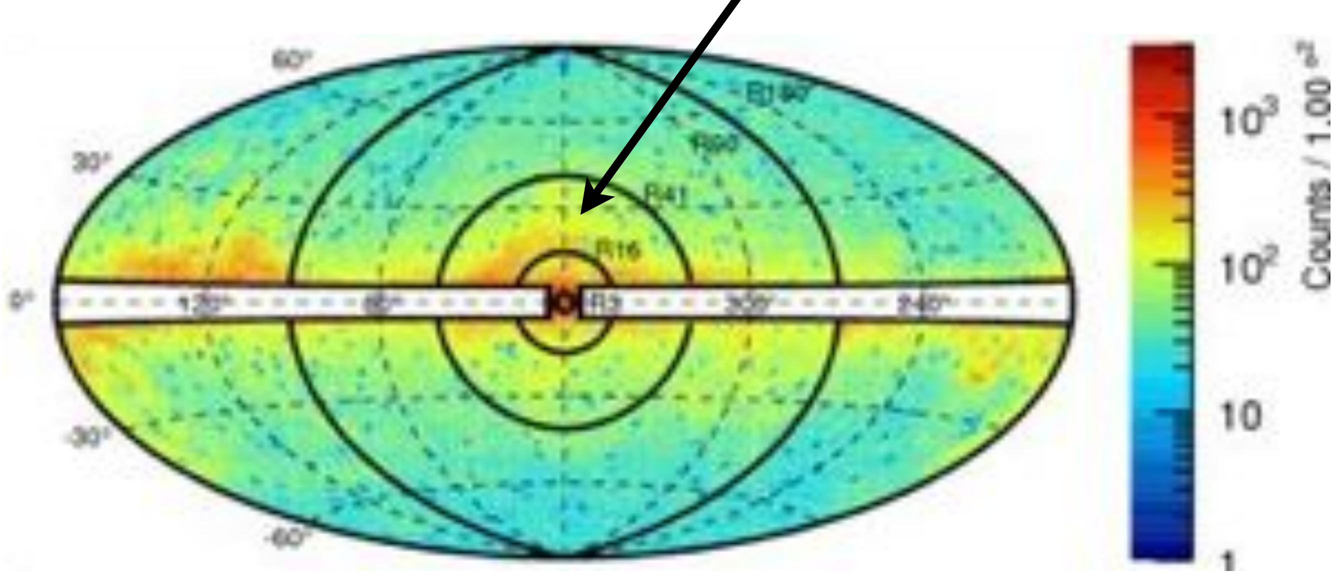
1) Optimize ROI

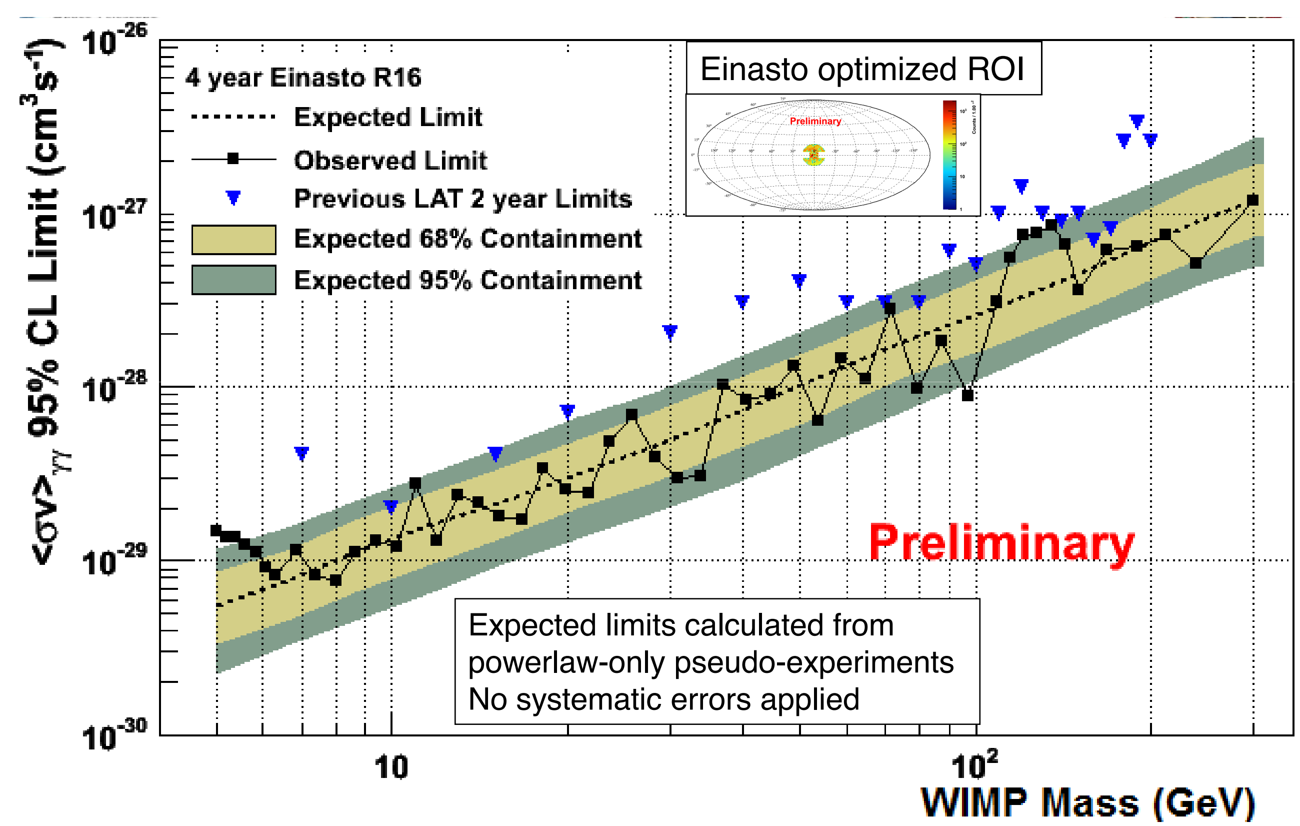
2) Improved Energy Resolution Model

3) Data Reprocessed with Updated Calibrations

**No signal found in a blind search.**

Einasto profile



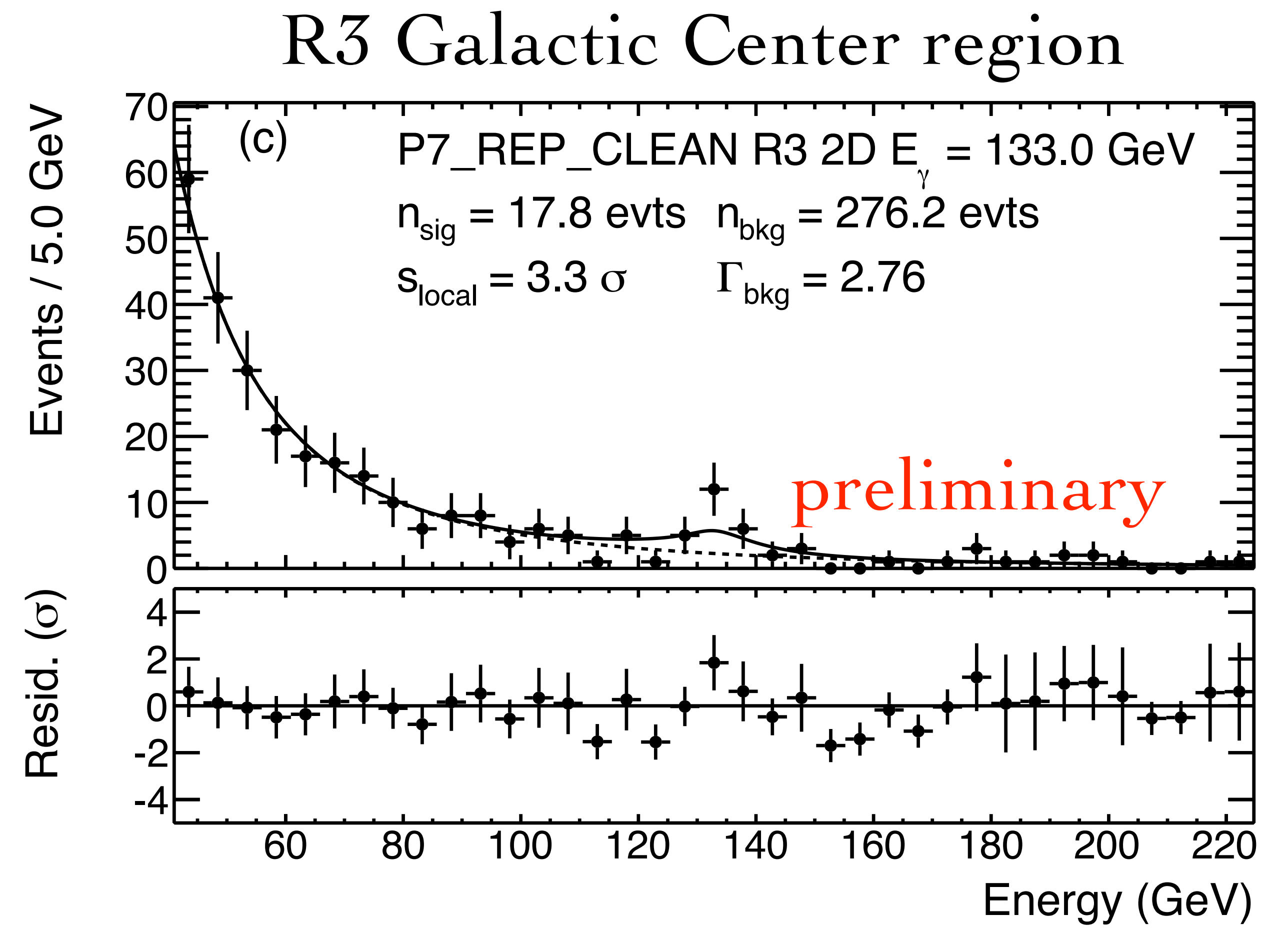




Weniger+ signal not ruled out by 95% CL on $\Phi_{\gamma\gamma}$.

# Gamma ray line

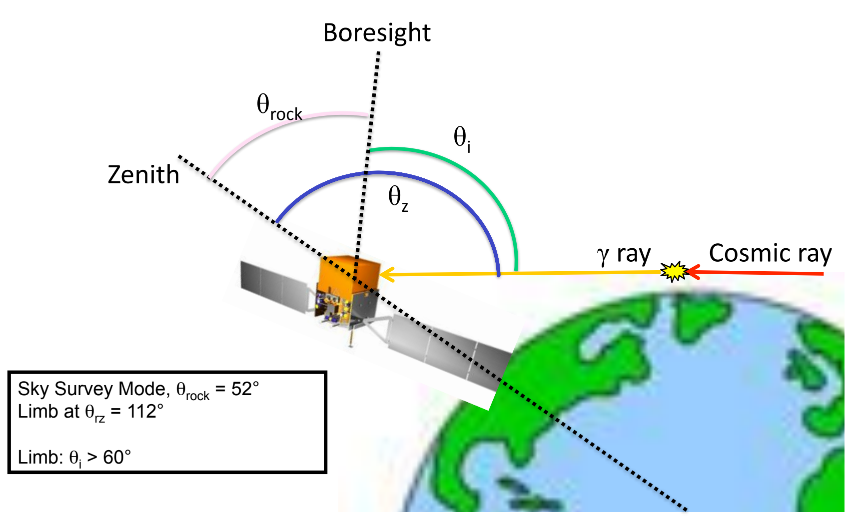
## Fermi LAT's line search

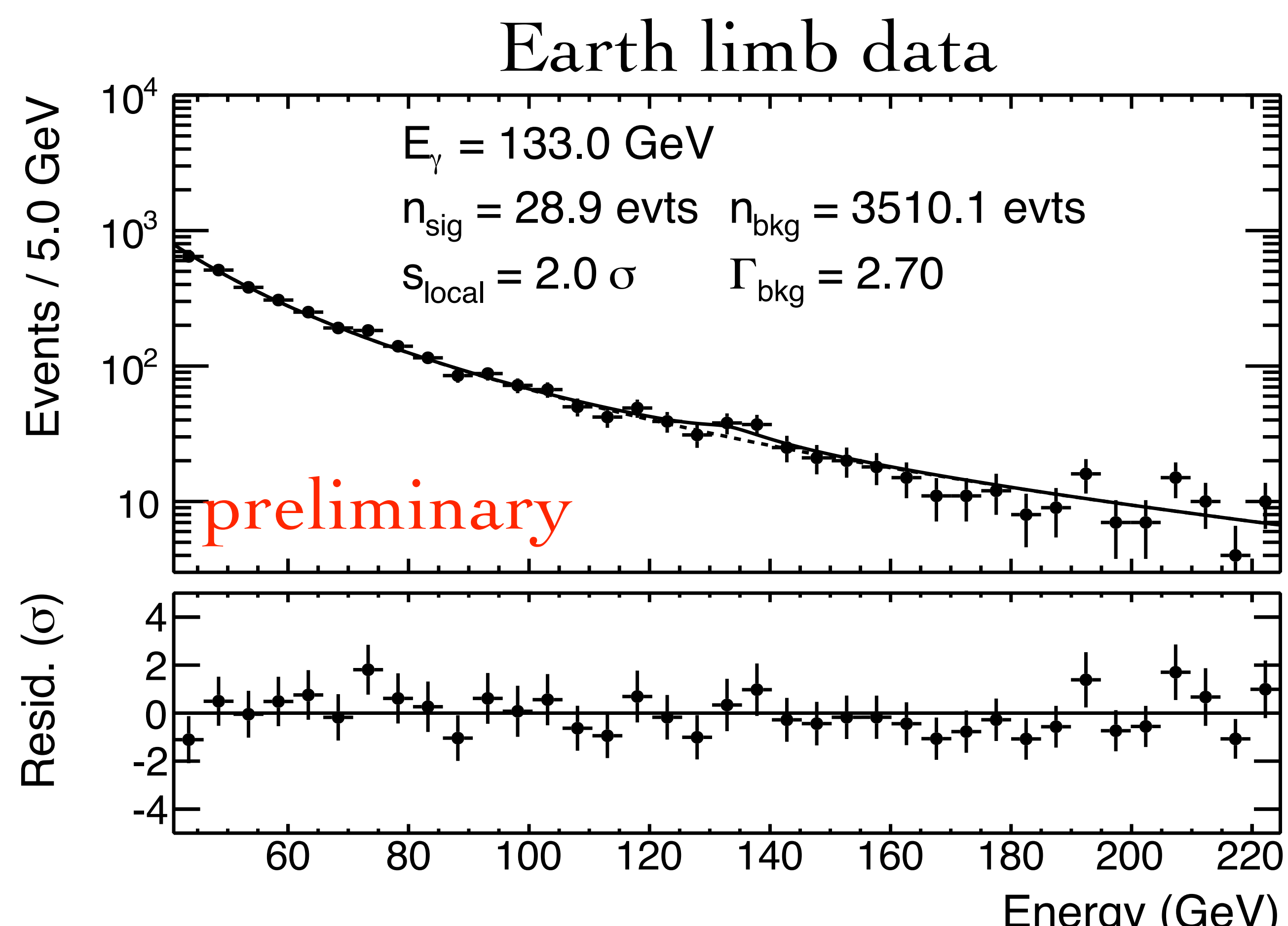
Inspection of a signal @ 133 GeV: 3.3σ (local) <2σ global significance after trials factor; S/N~60%




In addition, weak hint of a spectral line in the limb data, S/N~30%.

Red flag for an instrumental effect.

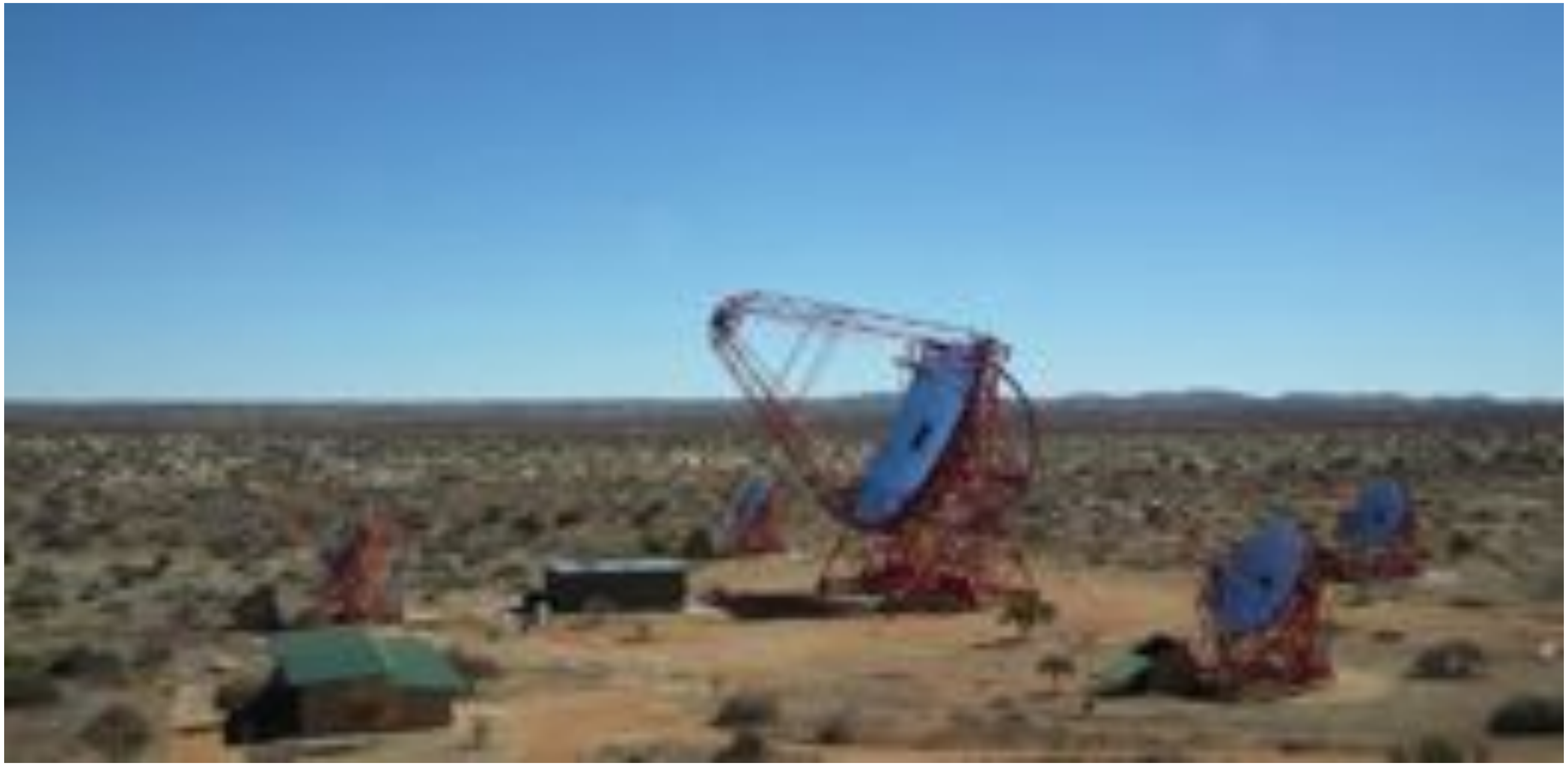


# Gamma ray line

Jury still out:

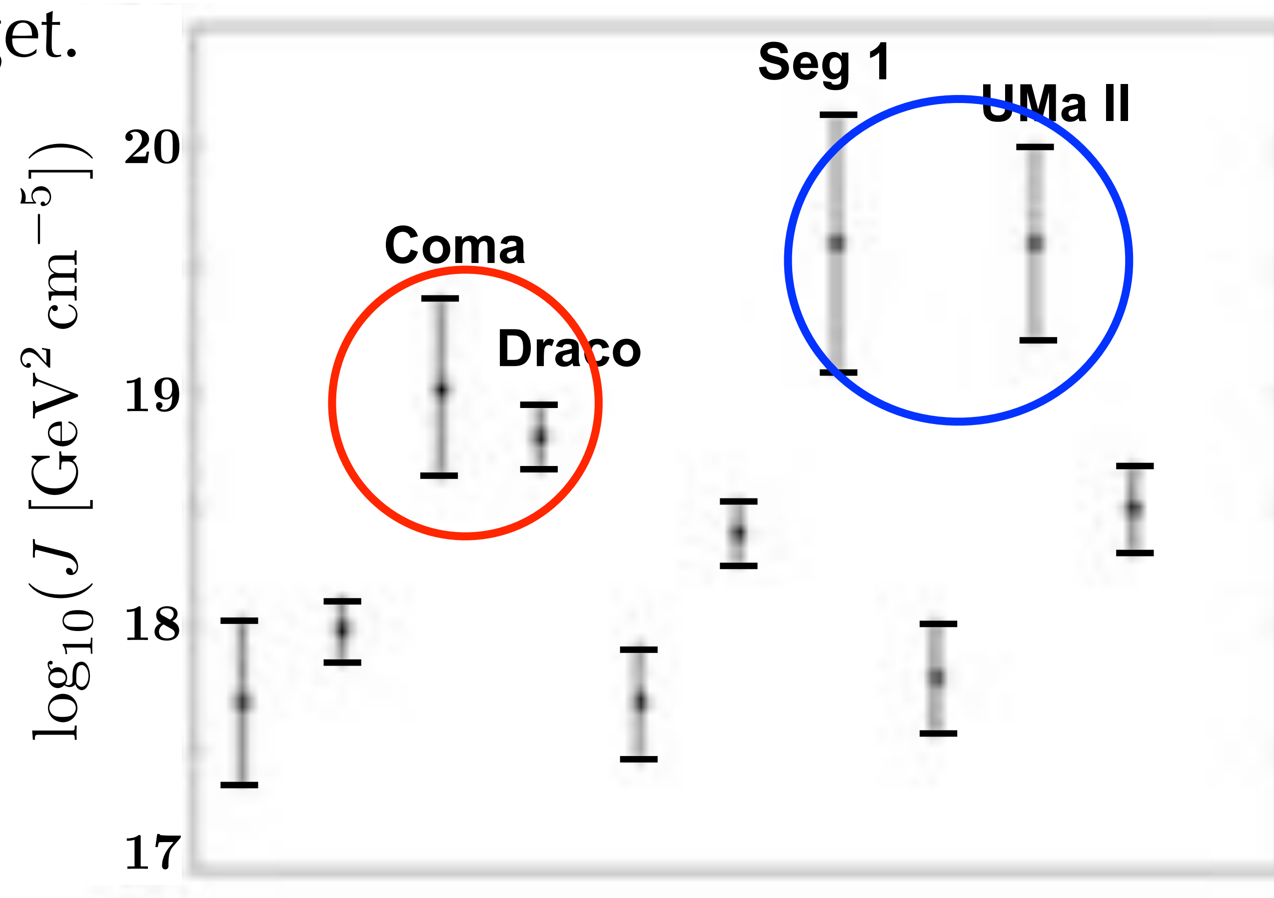
- Fermi LAT scheduled weekly limb observation, to examine a possible instrumental effect. :
  - proposed changes in observational strategy (favor GC region) being reviewed AND
- other experiments: HESS 2 taking data! 50 hours of GC observation enough to rule out signature or confirm it at 5 sigma (if systematics are under control)



# Dwarf spheroidal satellite Galaxies

- Not yet observed in gamma rays! No recent star formation and little gas to serve as target material for cosmic-rays.
- Dark matter dominated systems, mass-to-light ratio up to a few hundreds & close by, within ~ 100 kpc of the Earth

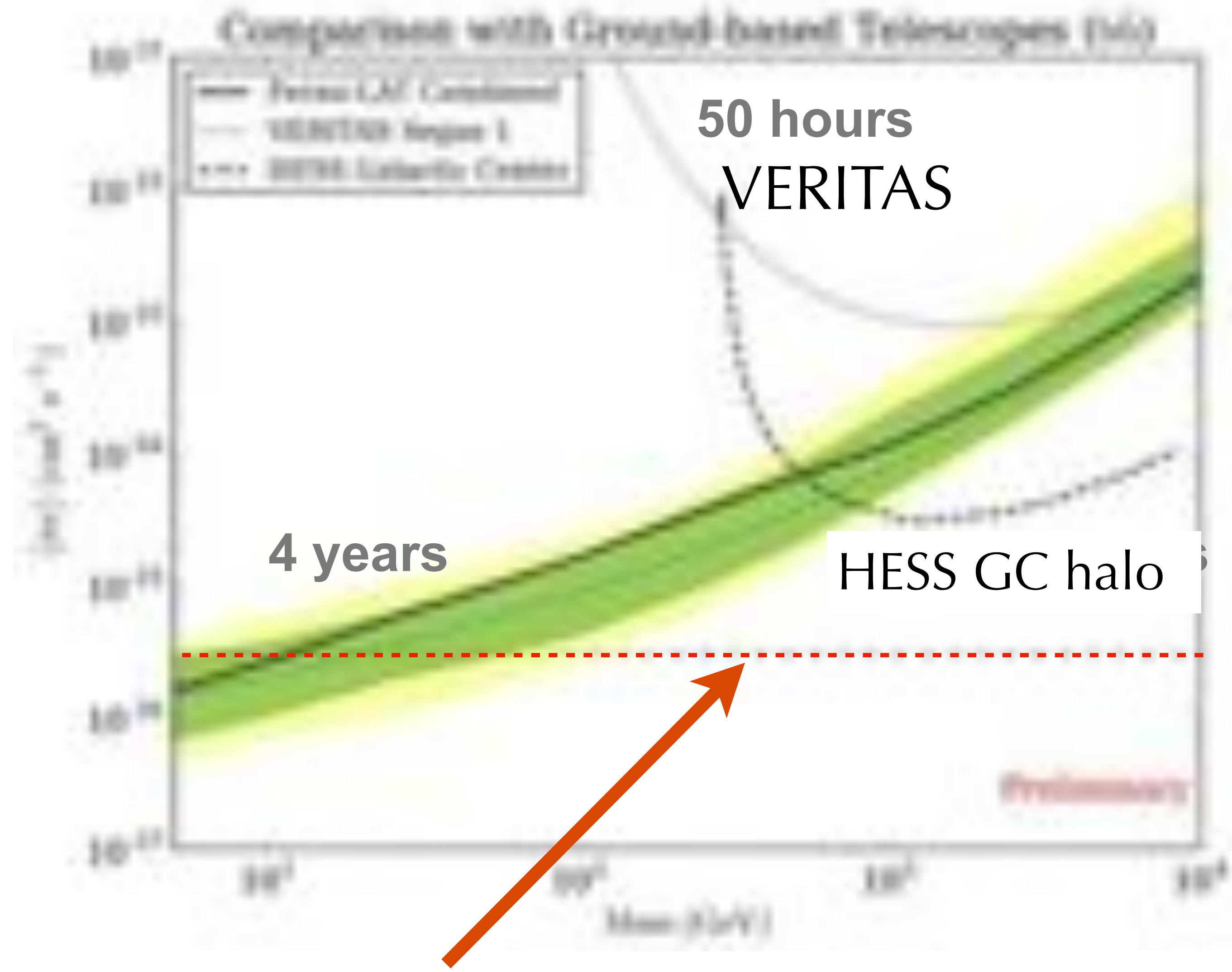
- DM content determined from stellar velocity dispersion
  - – Classical dwarfs: thousand stars
  - – Ultra-faint dwarfs: <~ 100 stars -- considerable uncertainties
  - -> the biggest uncertainty for this target.




[A. Drlica-Wagner, Fermi Symposium 2012]

# Dwarf spheroidal satellite Galaxies

- Fermi LAT analysis of 10 dsph Galaxies using a joint likelihood approach.
- *systematics* ***(due to determination of DM content of dwarf Galaxies) folded in the limits!***




**Thermal Relic Cross Section**

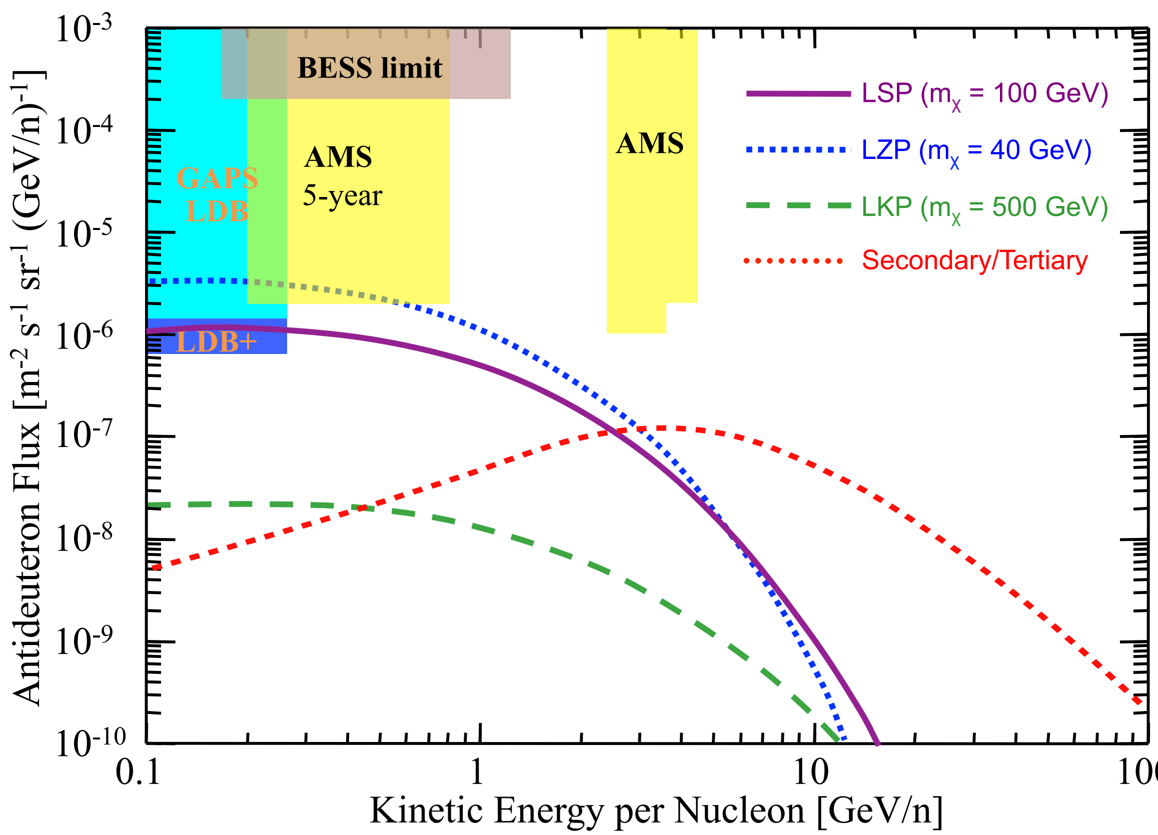
$\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$

**One of the strongest limits on generic WIMPs to date:** Constrain the conventional thermal relic cross section for a WIMP with mass < 30. GeV annihilating to $b\bar{b}$ or $\tau^+\tau^-$.

[A. Drlica-Wagner, Fermi Symposium 2012]
(see also Geringer-Sameth+, 1108.2914 Strigari+, 0902.4750, 1007.4199; Magic coll., 1103.0477; HESS coll., 1012.5602)

# anti-deuterons ($\bar{p}\ \bar{n}$)

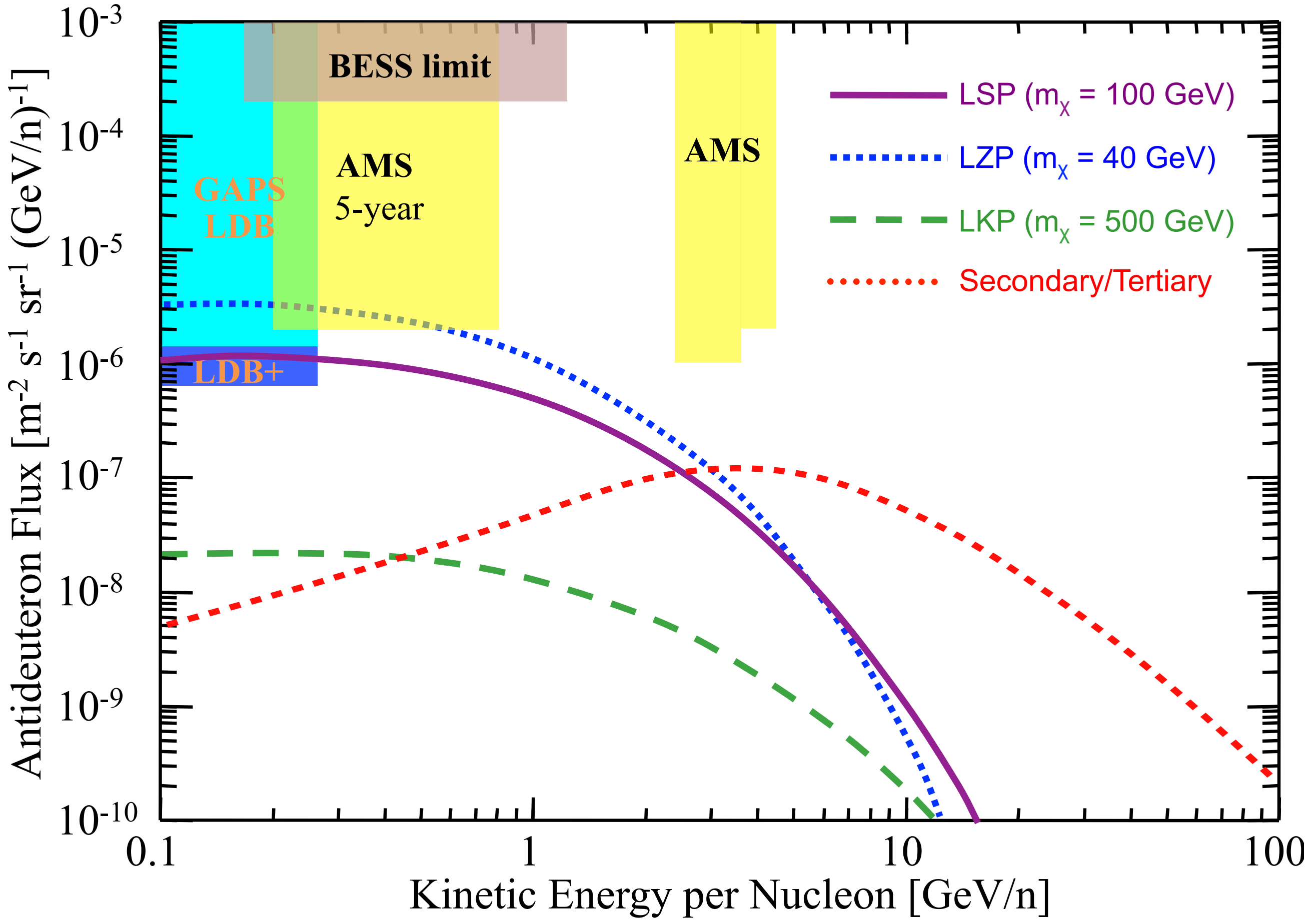
- not detected yet;
- in DM ann/decays produced via the coalescence of anti-p and anti-n originating from an annihilation event
- astro: spallation of high energy cosmic ray protons on the interstellar gas at rest pH or pHe
- ***DM signals*** flatter than astro backgrounds for ***<2,3 GeV/n***: detection of ~1 pn at <1 GeV a smoking gun -- A generic signature with essentially zero conventional astrophysical background




[Ibarra+, 1301.3820, Fornengo+, 1306.4171]

- AMS in its second year & pGAPS finished a prototype flight! Plan for an initial GAPS flight in winter 2017/2018.
- Exciting time coming up for anti-deuteron searches!

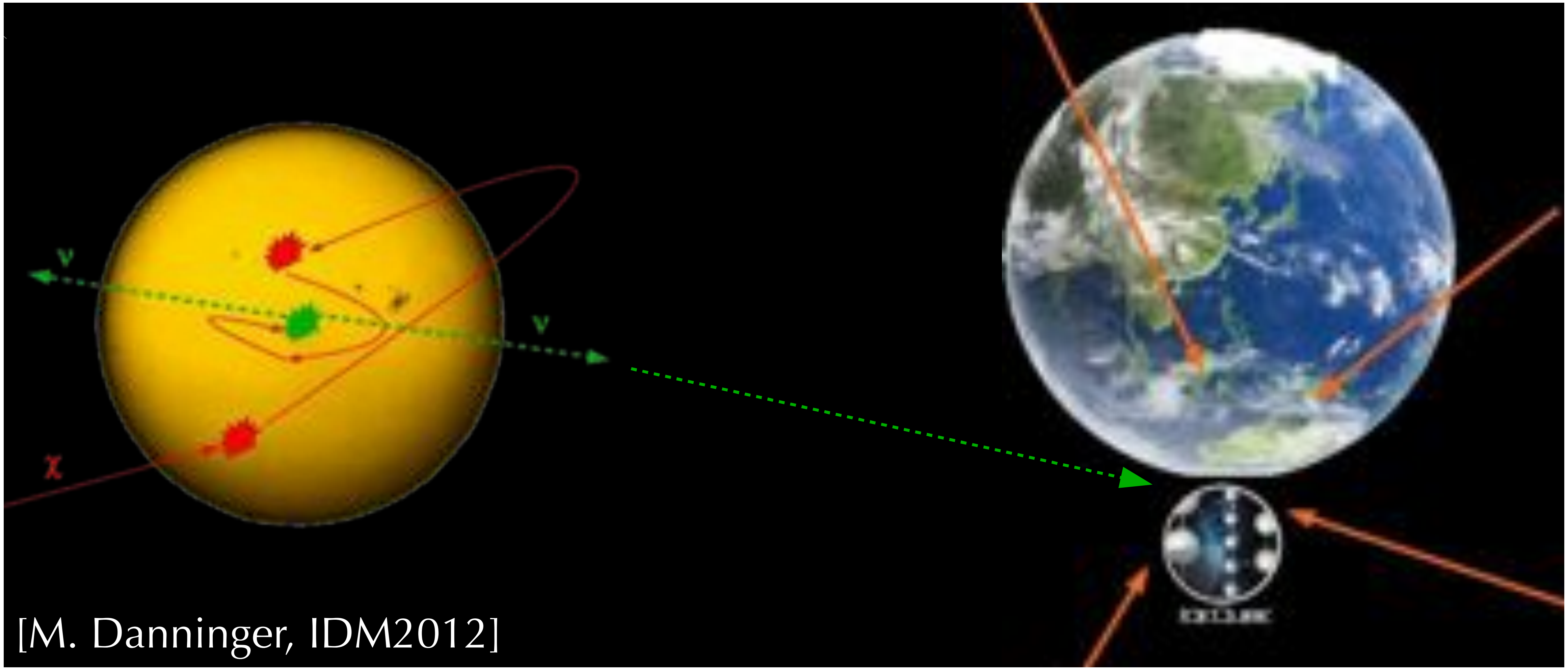






[K. Perez's talk at ICRC & arXiv:1303.1615]

# high energy neutrinos from annihilation in the Sun




$$\dot{N} = C - C_A N^2$$

$$\xrightarrow{\text{eq}} \Gamma_A = \frac{C_A}{2} {N_{\text{eq}}}^2 = \frac{C}{2}$$

In equilibrium all captured DM particles annihilate, by measuring $\Gamma_A$ we constrain elastic cross sections!

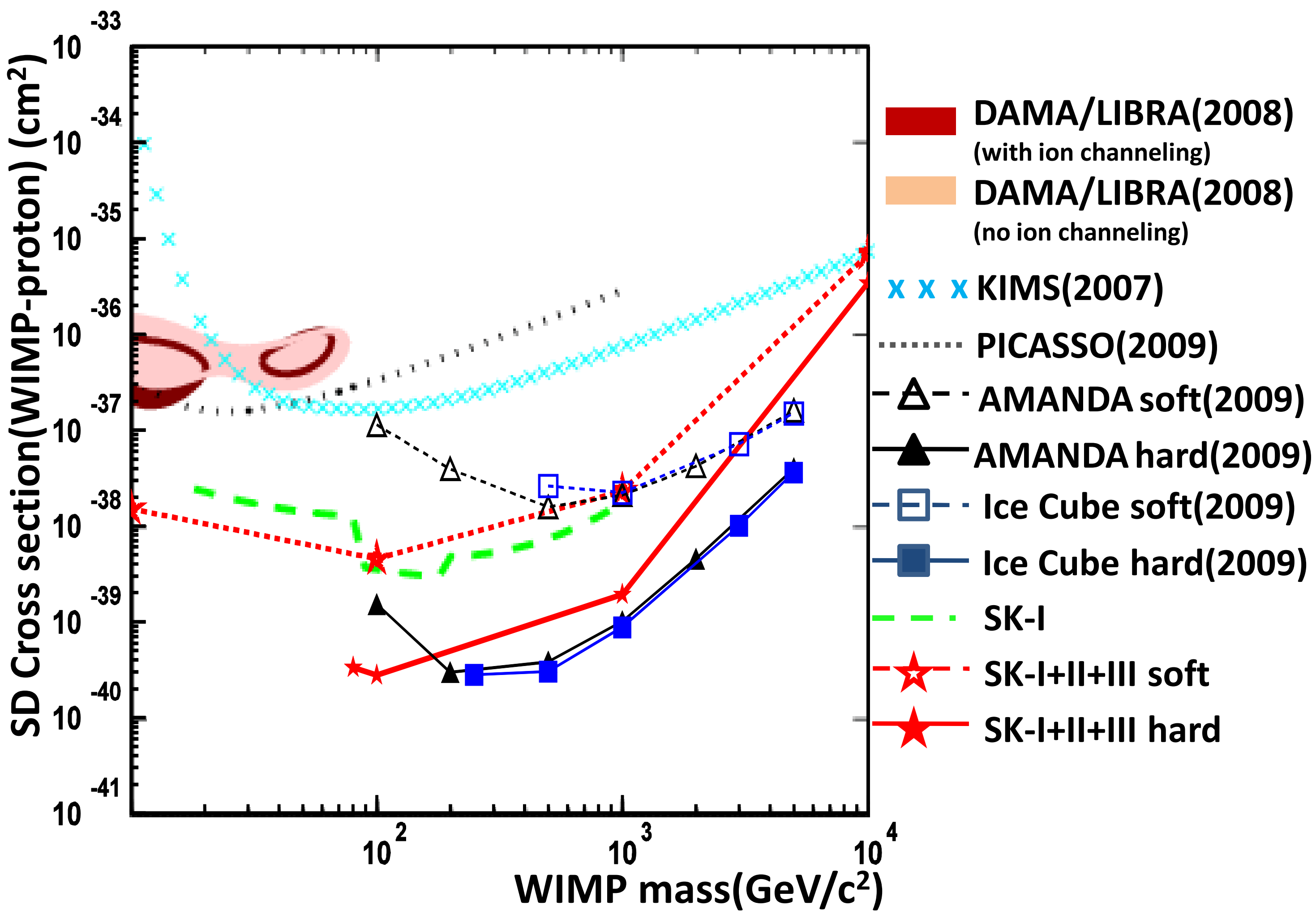
neutrinos from nuclear fusion processes @ low <1 GeV energies -> observation of >10 GeV neutrinos a smoking gun of DM!

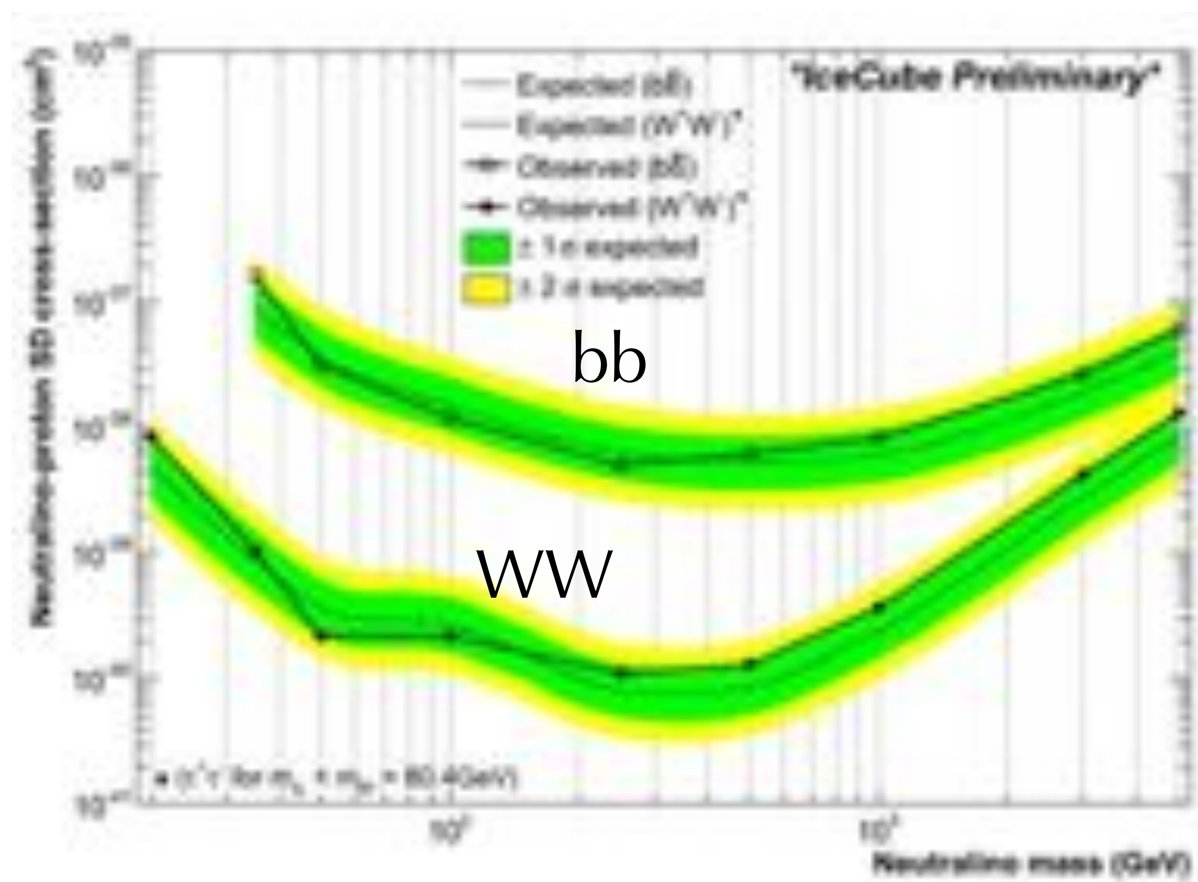
# high energy neutrinos from annihilation in the Sun

Sun is made of p! Limits on spin dependent cross section stronger wrt DD experiments (A LOT of p in the Sun!).

- New results from ***79-string*** data (~1y livetime)
- First Dark Matter analysis including ***DeepCore***
- First ***full year***-round IceCube solar Dark Matter search

SD scattering




[M. Danninger, IDM2012]
[see also 0905.2316, ANTARES.]

**2.** When astrophysics (can) mimics DM signal:

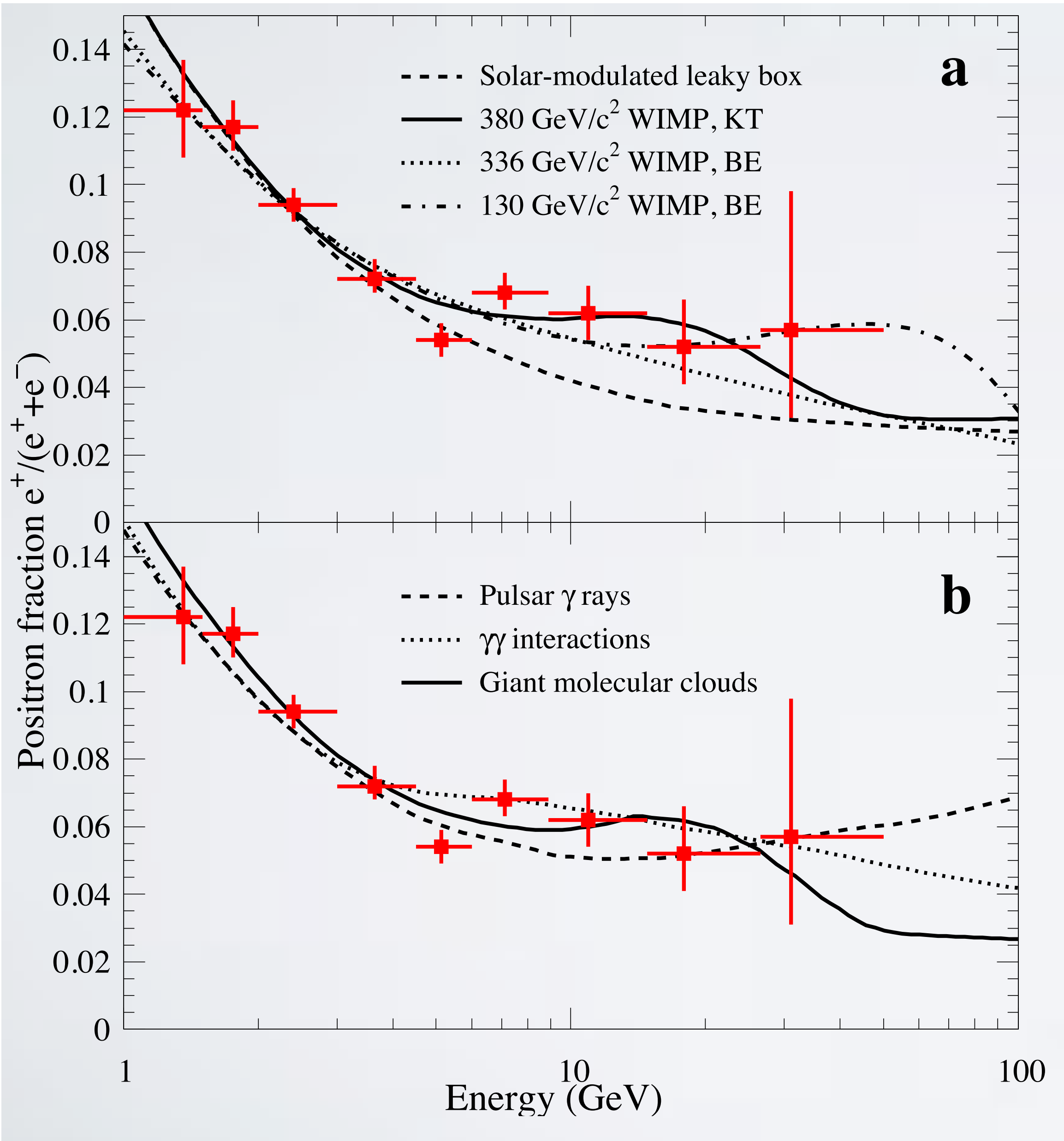
New experiments often reveal ***residuals*** with respect to commonly assumed backgrounds.

Some resemble a DM signal (as we witnessed in recent years).

Rely on multi-wavelength/messenger/target cross checks:

- example: a positron fraction rise.
- review most stringent constraints on WIMP models and illustrate ***complementarity*** of various indirect detection strategies in testing the DM discovery hints.

- Measurement: positron fraction.




Positrons very rare as they are assumed NOT to be produced directly in cosmic ray sources.

Positron fraction is usually measured (by means of canceling instrumental uncertainties):

e+/(e++e-)

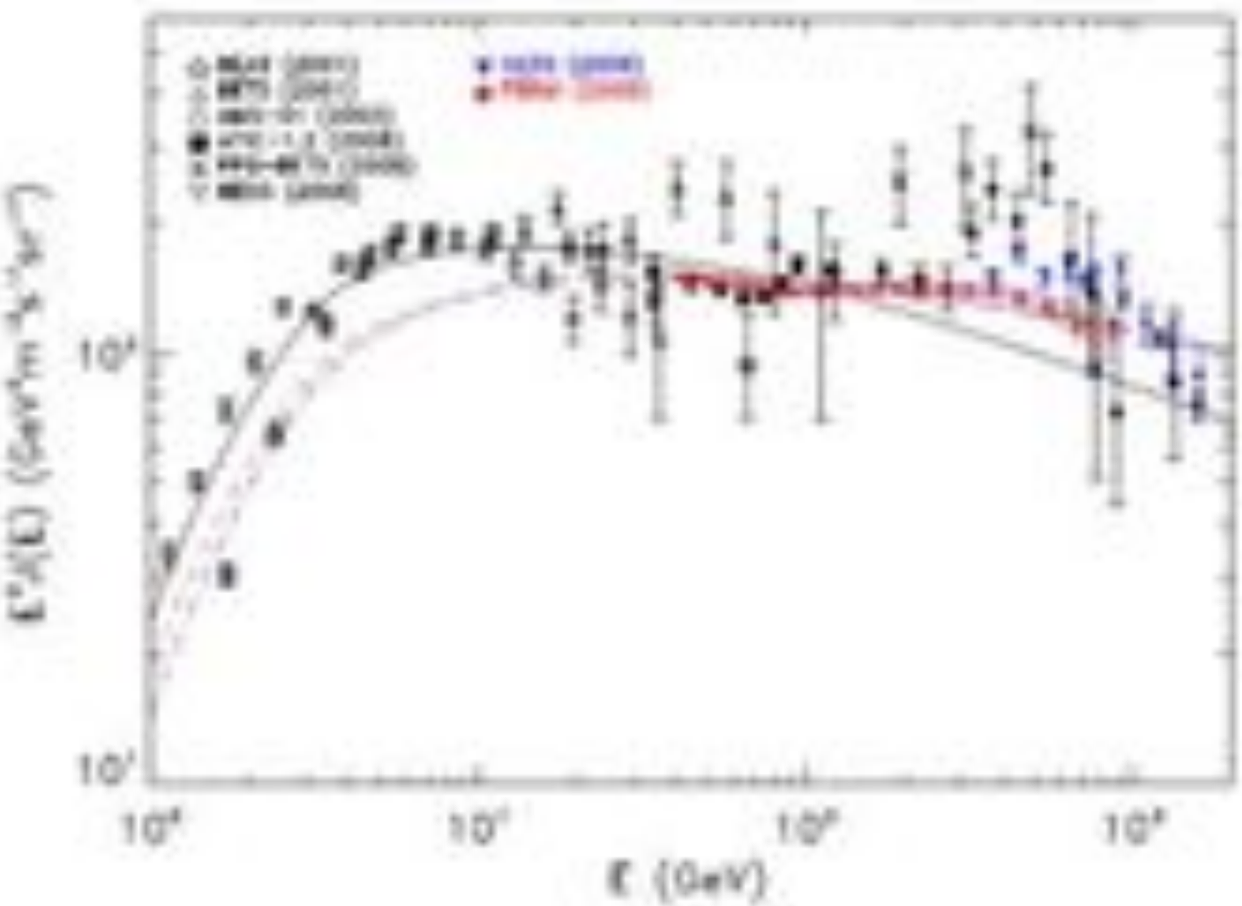
A surprising hint of a rise in a positron fraction in the 90′ after the measurement by the HEAT experiment (Coutu et al, ′99).

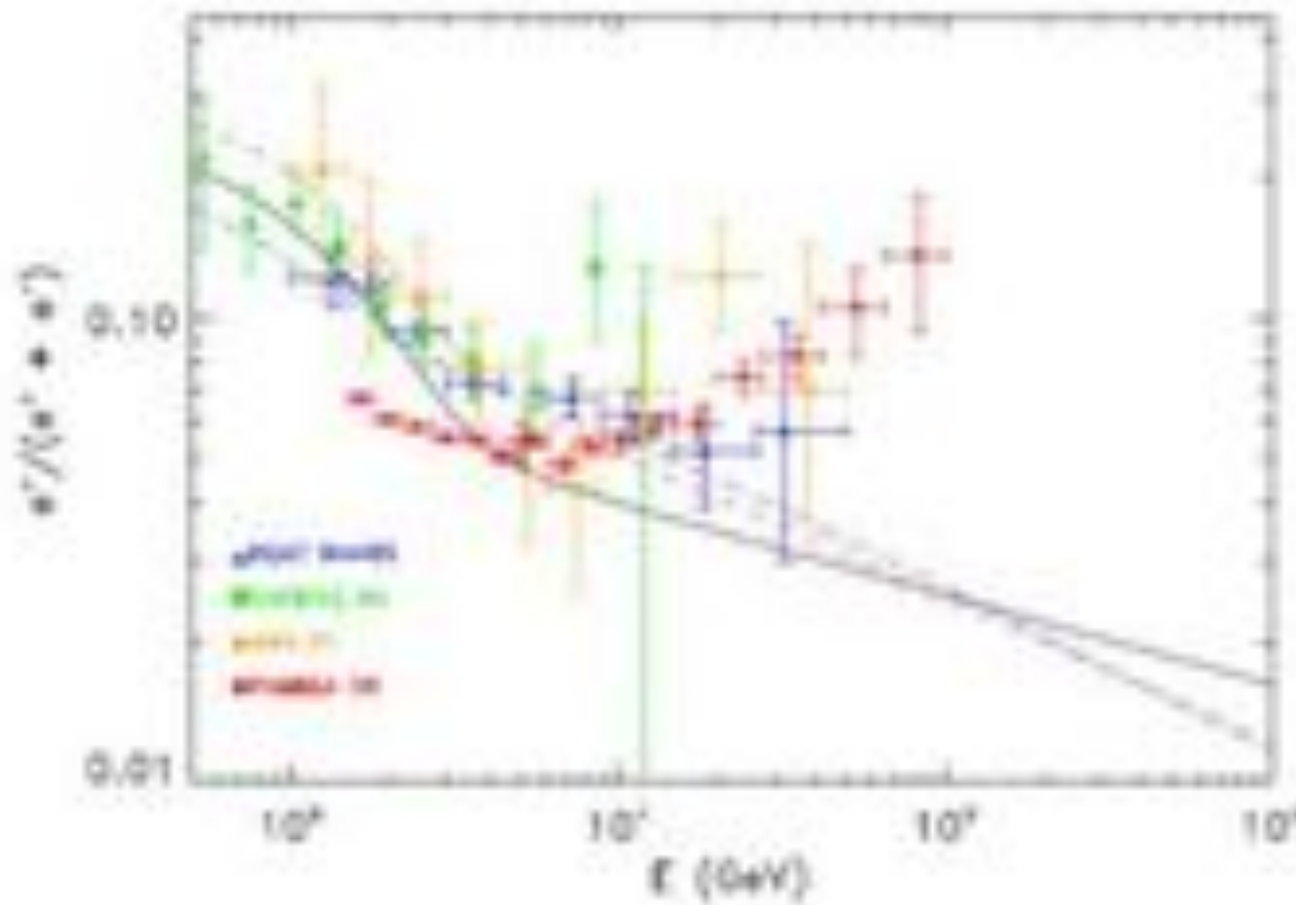
It was showed already then that to explain the rise on needs a **NEW source of positrons**:

DM

or pulsars

## Present situation:



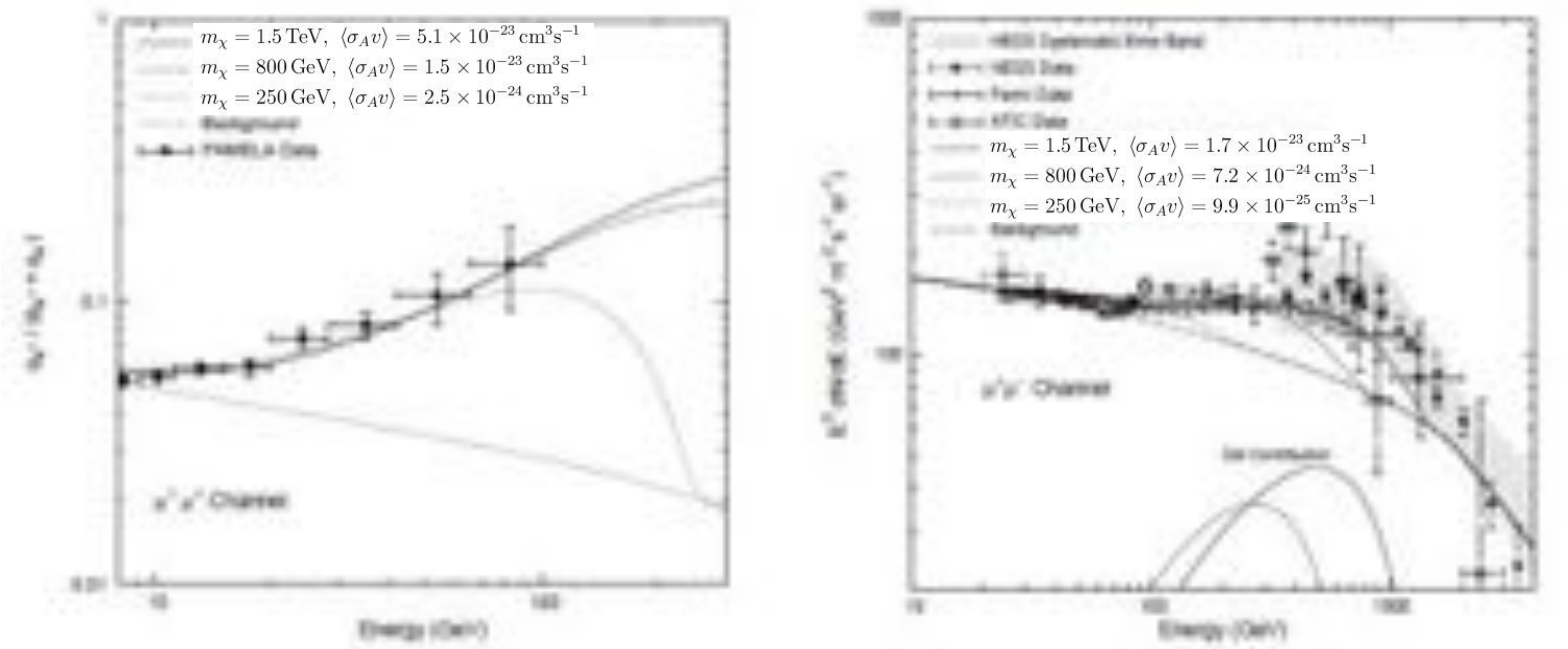




**Evidence for a primary component of positrons**
**(possibly accompanied by electrons)**

# Dark matter interpretation

An electron/positron excess could arise from dark matter annihilations ...

$$\chi\chi \rightarrow \mu^+\mu^-$$



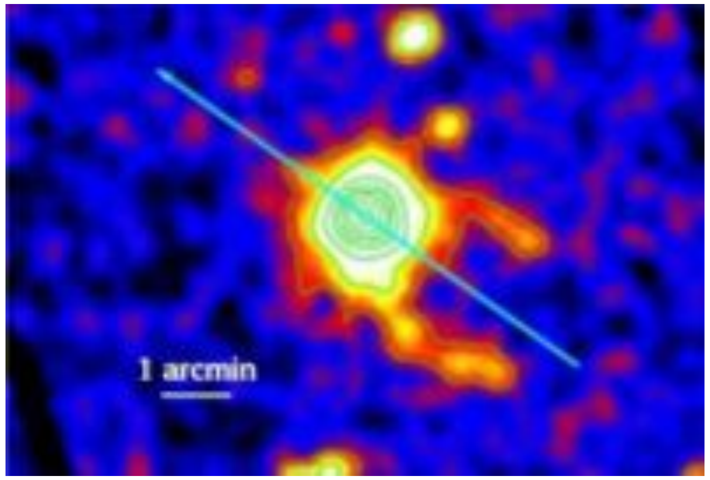

Cholis et al.
arXiv:0811.3641

Is this the first non-gravitational evidence of dark matter?

But, beware of **conventional astrophysics**!!!

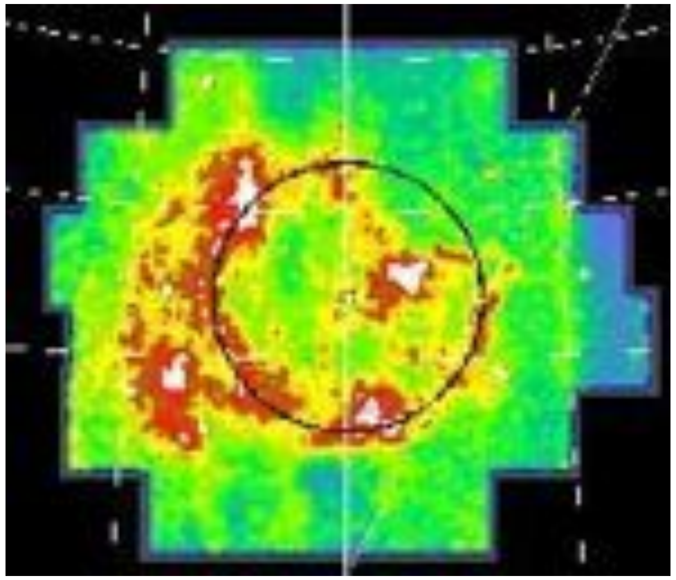
Pulsars are also sources of electrons and positrons! Are we seeing a contribution from nearby pulsars?

## Pulsar explanation I: Geminga + Monogem




Geminga

T=370 000 years
D=157 pc



Monogem (B0656+14)

T=110 000 years
D=290 pc

Now how can we tell which source is causing this rise?

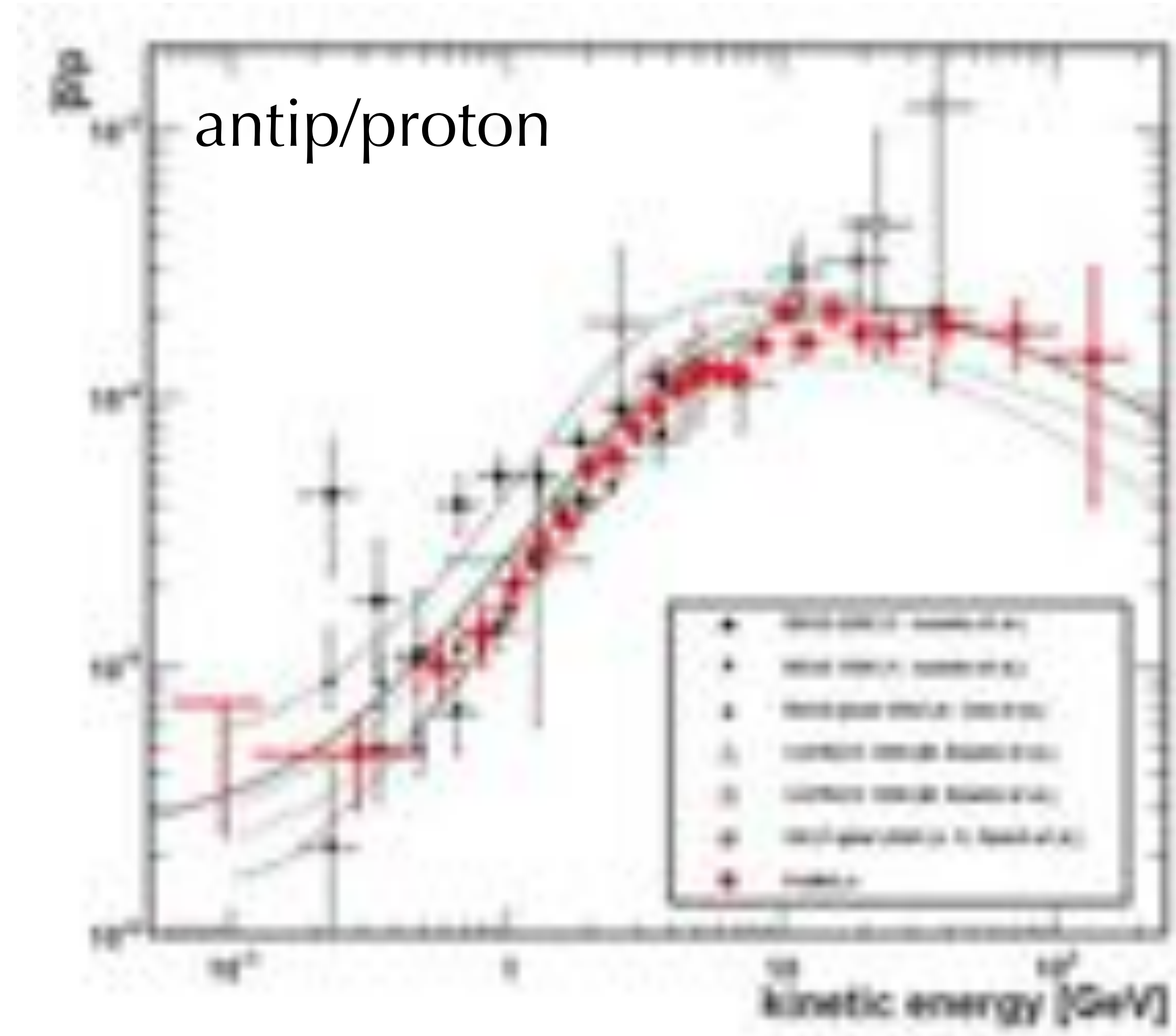
**Check other channels and targets**!!!

- if DM produces electrons/positrons it should produces protons/**antip** too!
- if it produces lots of electrons locally it should produce them **also in other places**, for example close to the Galactic Center, can we look there and test?

- Other channel and targets: CR (anti)protons
    - measurements consistent with purely secondary production of antiprotons in the galaxy
        - tight constraints set on DM annihilation

If it is to explain the e+ data DM would have to be:

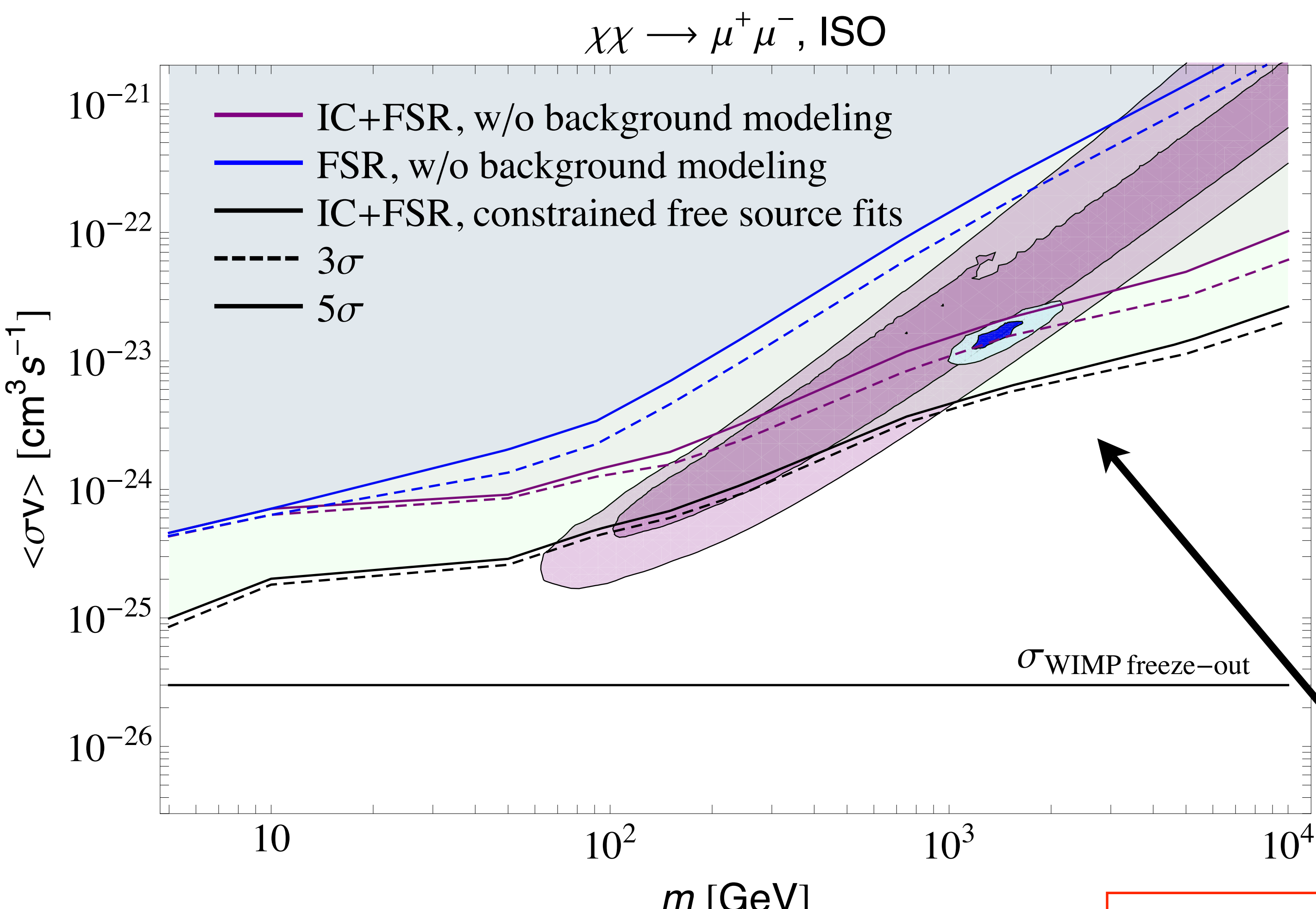
- **leptophilic (i.e. to produce ONLY leptons)**
- **have enhanced cross section, BF~1000.**

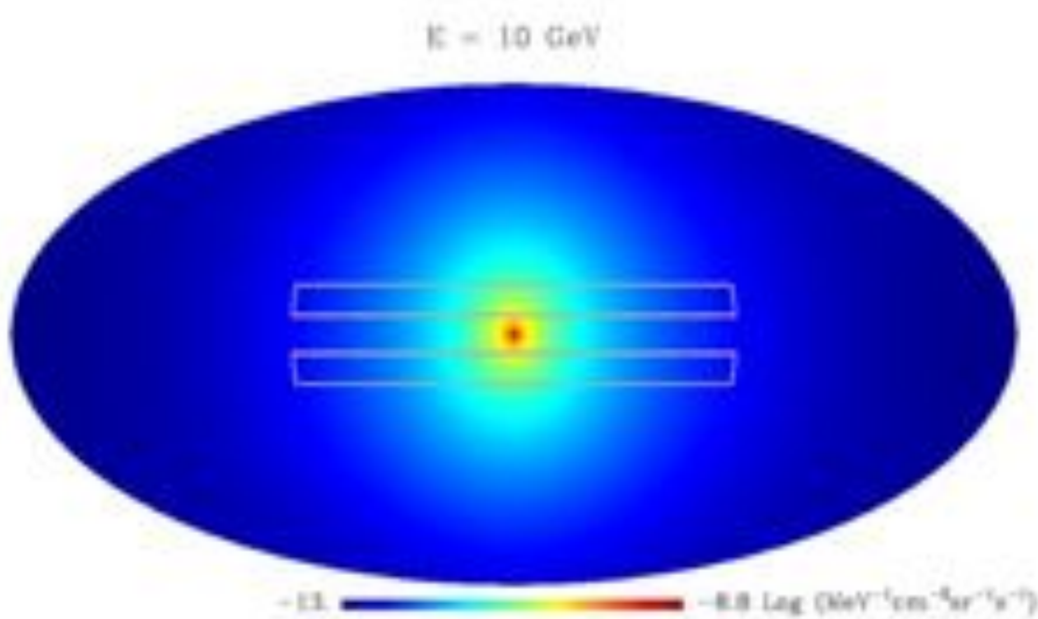



suspicious but we should keep our mind open!

[Cirelli+, 1301.7079] (see also Evoli+, 1108.0664 , Donato+, PRL09; Bringmann, 0911.1124...)

- Other channel and targets: gamma-rays: Fermi LAT/MW halo
    - if DM annihilates dominantly to leptons with high sigma-> **strong Inverse Compton emission in the inner galaxy**
    - by measuring gamma rays we constrain the IC emission from DM produced leptons and indirectly test the DM origin of the positron rise

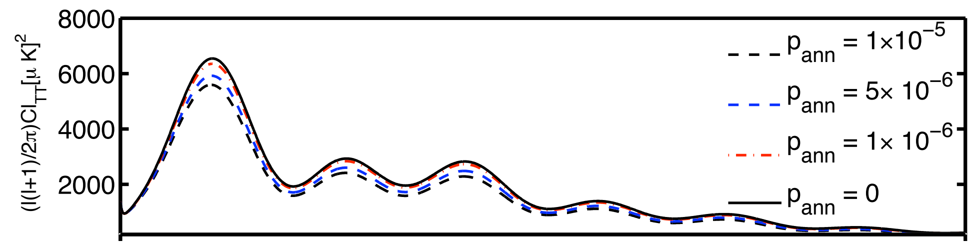


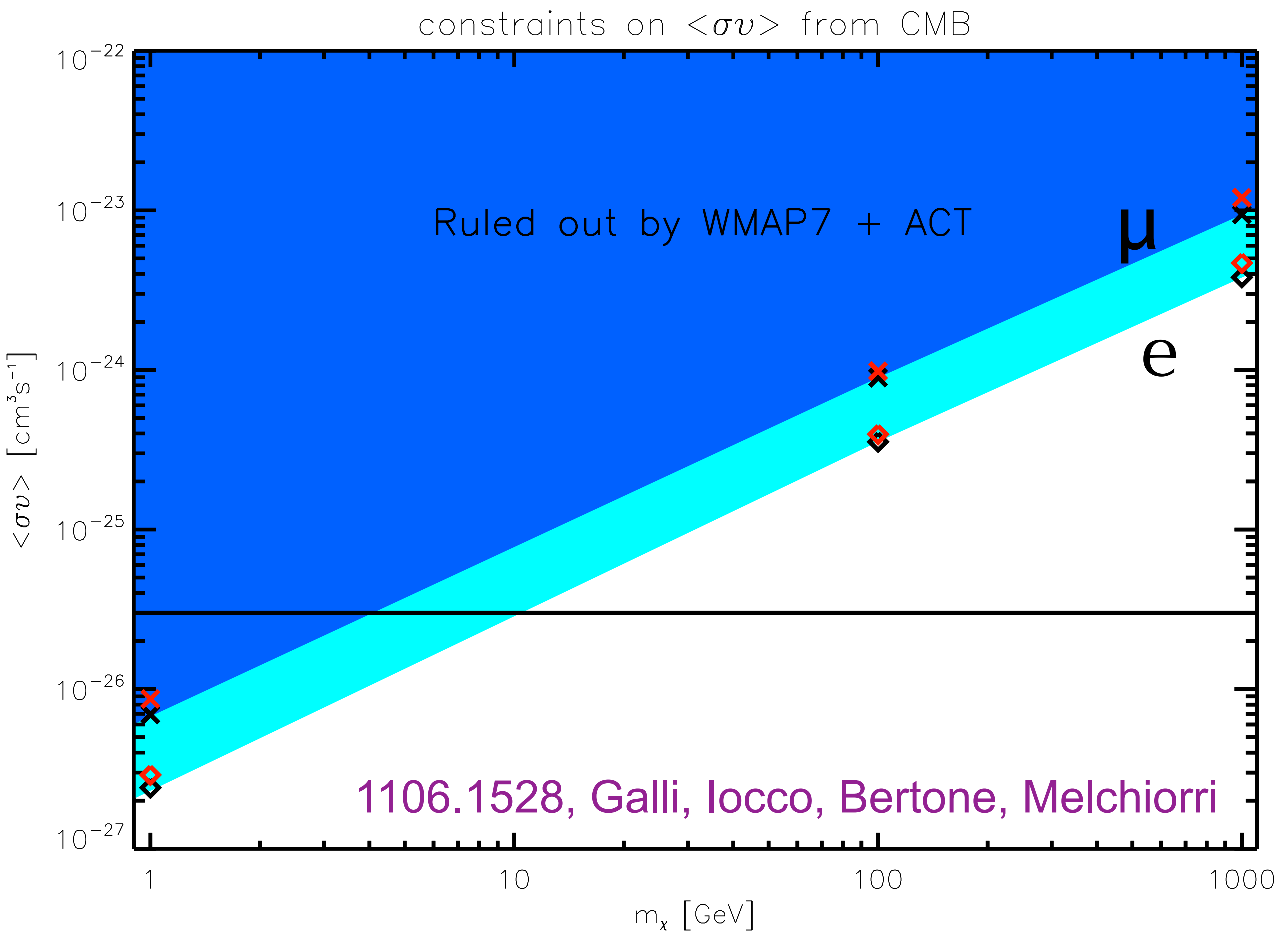
[Ackermann+, APJ 2012, 1205.6474]
(see also Cirelli+, 0912.0663; Papuci+,0912.0742; Baxter+,1103.5779)

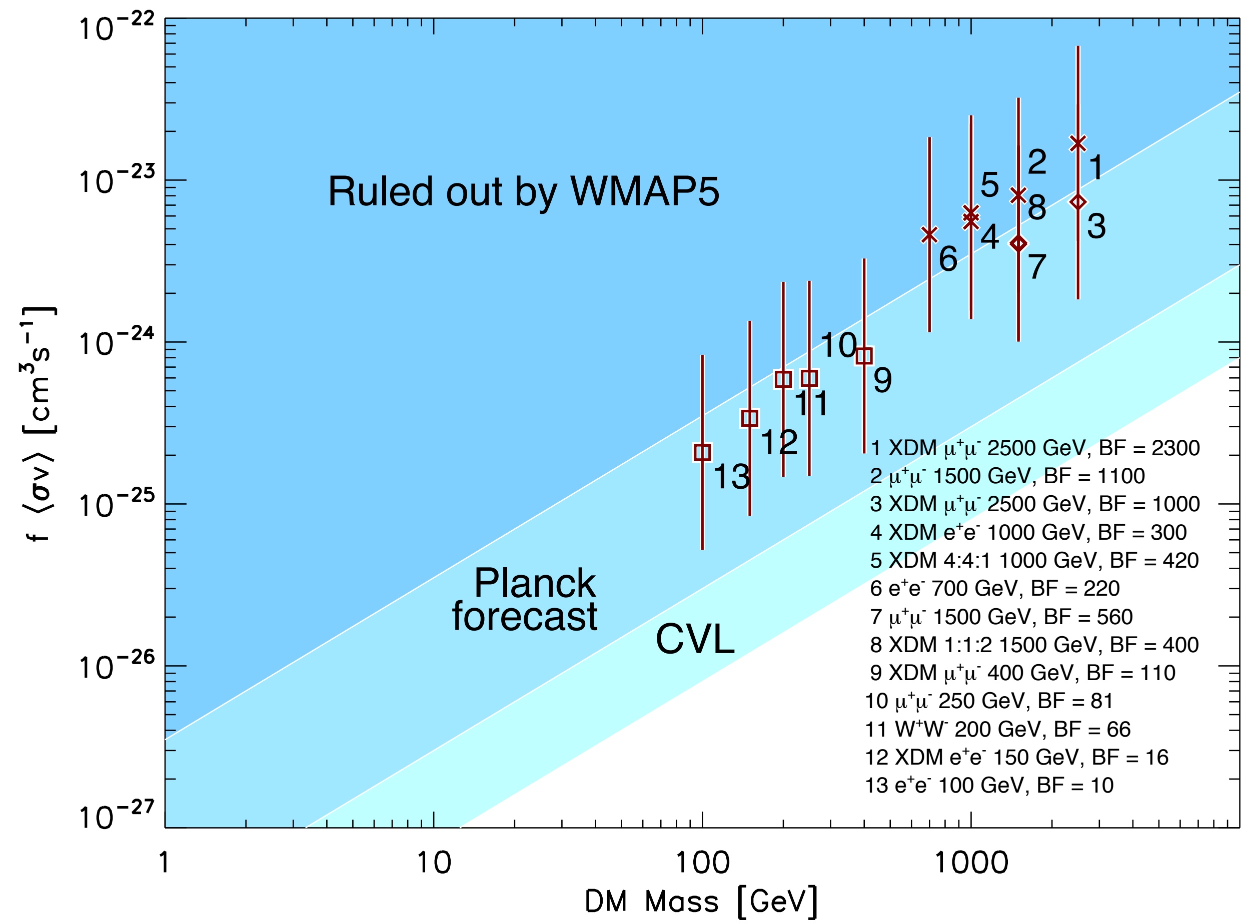
DM interpretation of the rise strongly challenged

- DM constraints: CMB
  - DM annihilations inject energy and energetic particles in the primordial medium, and therefore affect its evolution (i.e. fraction of free electrons).
  - DM in the linear regime/*robust to DM clustering uncertainties*!




CMB anisotropy for different DM annihilation power.




[Slatyer+, PRD 2009, 0906.1197, (see also Cline & Scott, '13; Weniger et al. `13)]

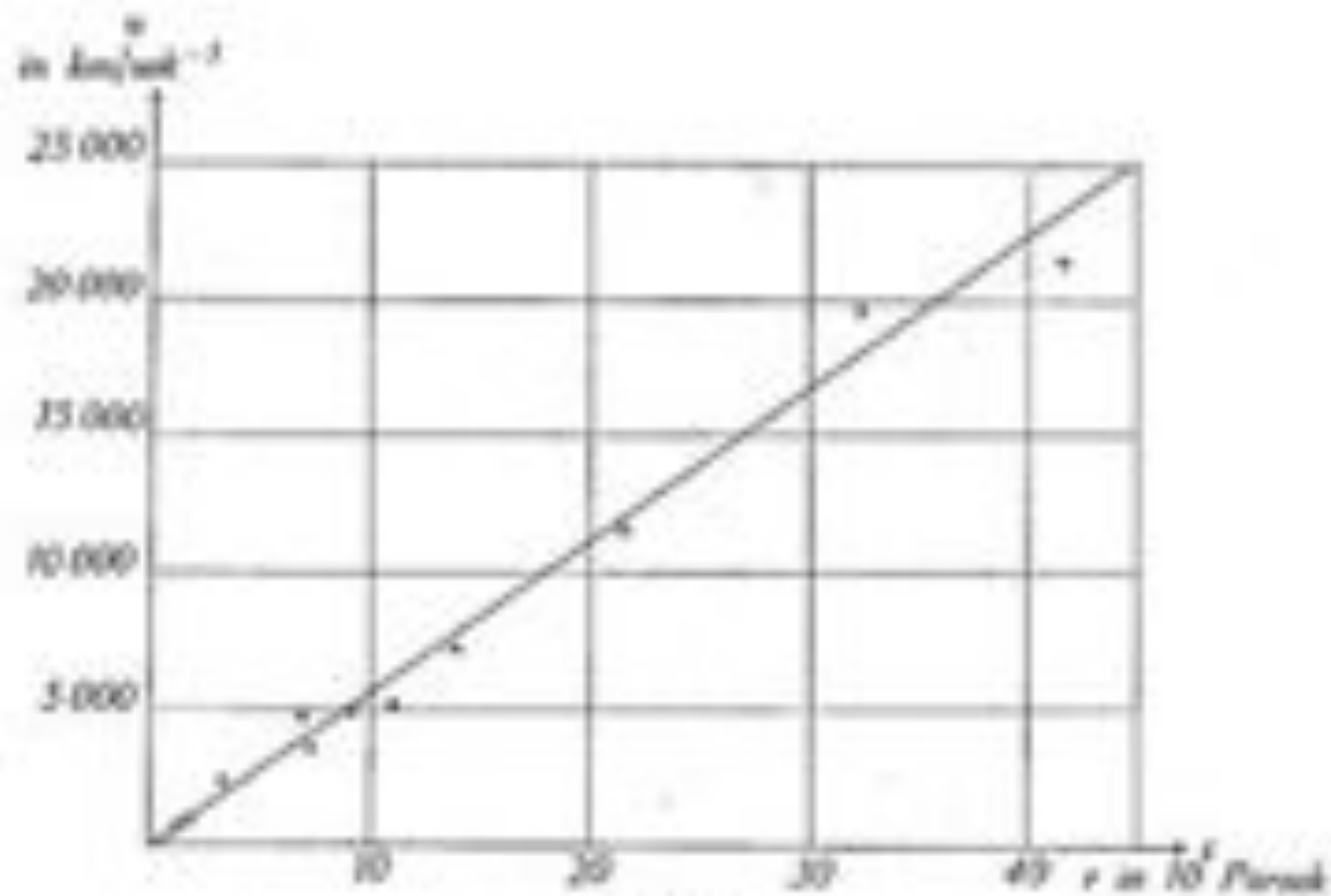
# Summary:

- DM signals can be mimicked by backgrounds (instrumental or astrophysical)
- any hints have to be cross checked with different experiments, targets and messengers.
- and keep looking for smoking guns!

# Summary:

- ~80 years after Zwicky's evidence for DM we still do not know what is it made of
- it took us 45 yrs to discover the Higgs and we knew 'exactly' where to look.
- Most importantly this is a special time… **we have lots of data! and lots of means to cross check our signals or to test models!**

velocity

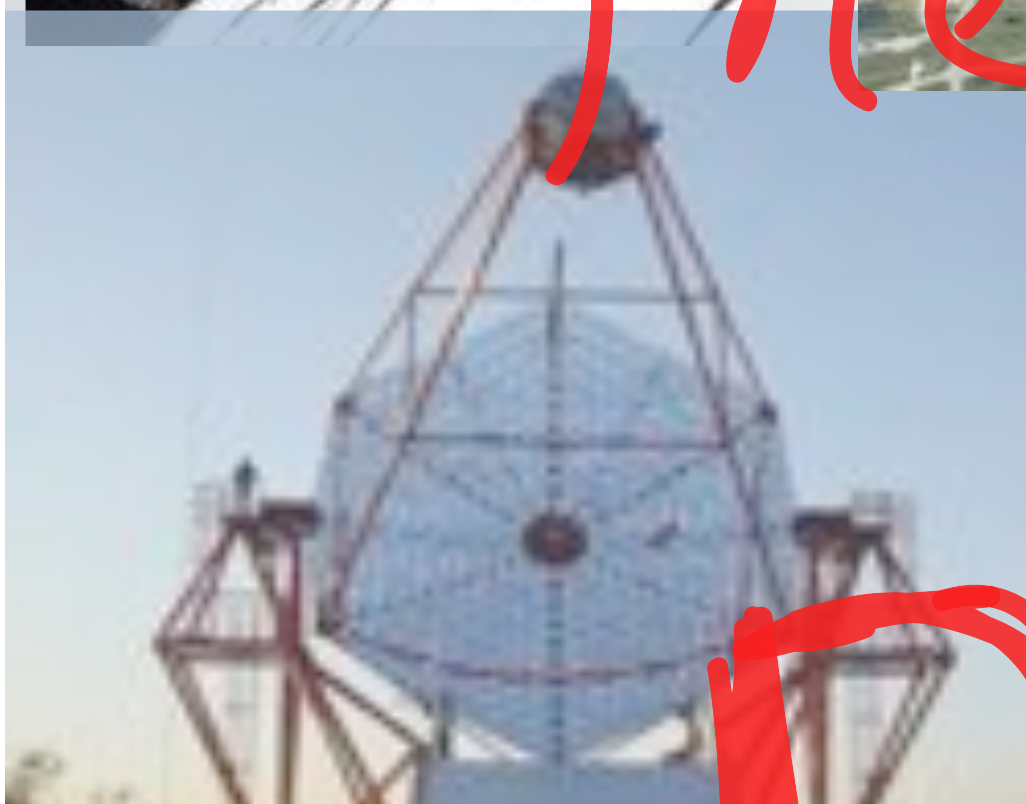



radius

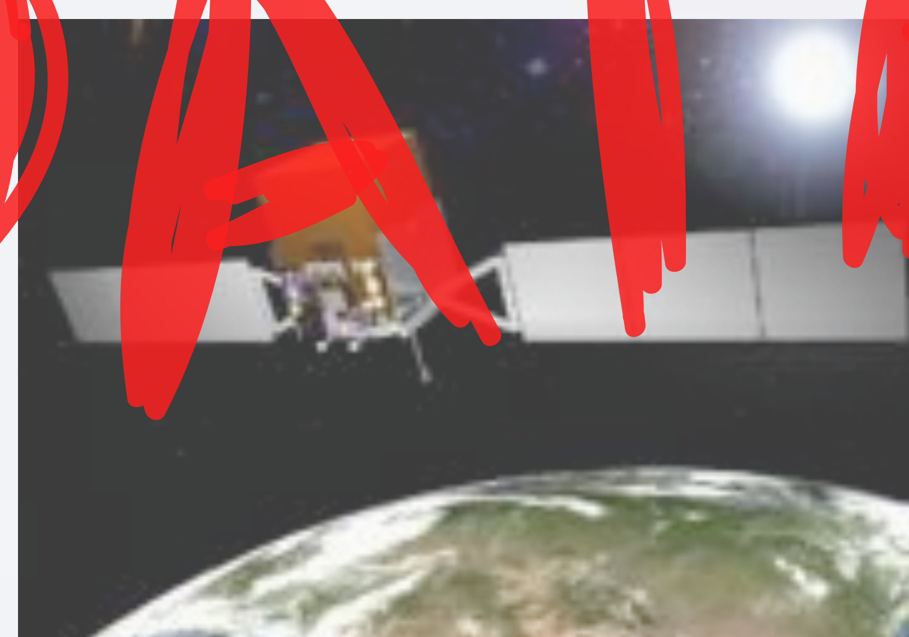
Fig. 2.

# The Era of DATA







[from N. Weiner]