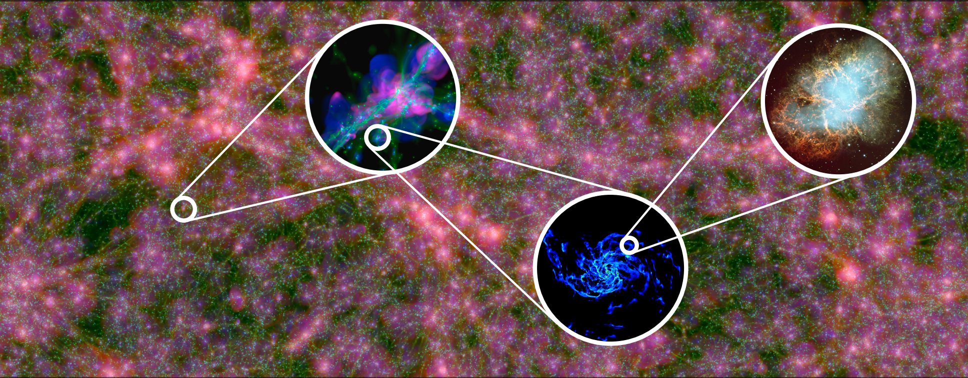
Galaxy formation and evolution
Physical models & Theoretical challenges 3°



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July 2019, Petnica

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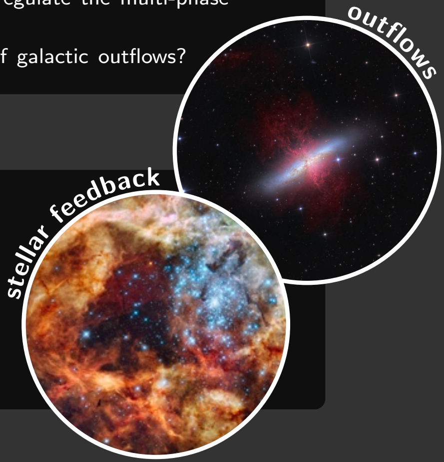
Important processes

- core-collapse explosions
- stellar winds
- radiation
- AGN feedback
- magnetic fields
- cosmic rays ...



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Feedback processes

- stellar feedback
  $\longrightarrow$ stellar winds, photoionization, SNe
- AGN feedback
  $\longrightarrow$ from accreting SMBH
- cosmic rays
- magnetic fields

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  - *solution?*
    - ad hoc tricks
    - add E_{kinetic} ...

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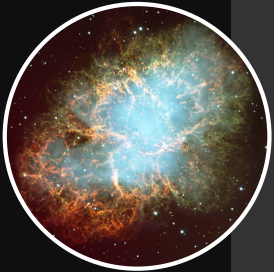

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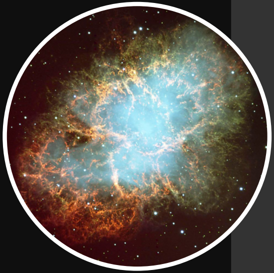

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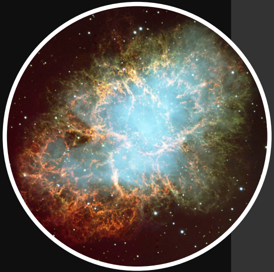

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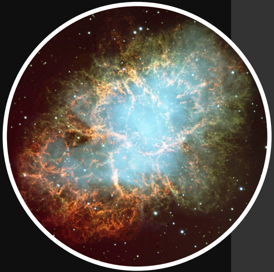

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  - fountains
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- can regulate the scale heights of galactic disks
- can regulate the SFR

Phases of SN blast waves

1. early free expansion phase

Phases of SN blast waves

(1) early free expansion phase

- initial phase of evolution
- ejecta dominate the mass of the swept up material
- ejecta $\longrightarrow$ expand ballistically with $v_{\rm ej} \sim$ const

$$v_{\rm ej} = \sqrt{\frac{2E_{\rm SN}}{M_{\rm ej}}}$$

- ends when $M_{\rm ej} \sim M_{\rm sw}$
- by definition $\longrightarrow$ no momentum transferred

Phases of SN blast waves

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Phases of SN blast waves

1. early free expansion phase
2. energy conserving Sedov-Taylor phase
   - shock heats up the interior
   - hot gas T & P $\longrightarrow$ can become very high
   - expansion into the ambient medium proceeds with negligible cooling
   - ends when cooling $\longrightarrow$ important $\rightarrow$ cooling shell formation
     - cold
     - dense
     - thin

     shell forms
   - shock heats & accelerates the ambient medium
   - momentum at the shell formation:

$$p_{\mathrm{sf}} \propto E_{\mathrm{SN}}^{-0.93} n_0^{-0.13} \qquad \text{(e.g. Draine 2011)}$$

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Phases of SN blast waves

1. early free expansion phase
2. energy conserving Sedov-Taylor phase
3. pressure driven snowplow phase
   - occurs $\Longleftrightarrow$ non-negligible pressure of hot gas interior
   - powered by homogeneous pressure inside the shell
   - shell pushed outward by overpressured hot gas in the interior of the SN remnant
   - eq. of motion of thin shell (idealised):

$$\frac{d}{dt}(M_{\rm shell} v_{\rm snr}) = 4\pi r_{\rm snr}^2 (P_{\rm hot} - P_0)$$

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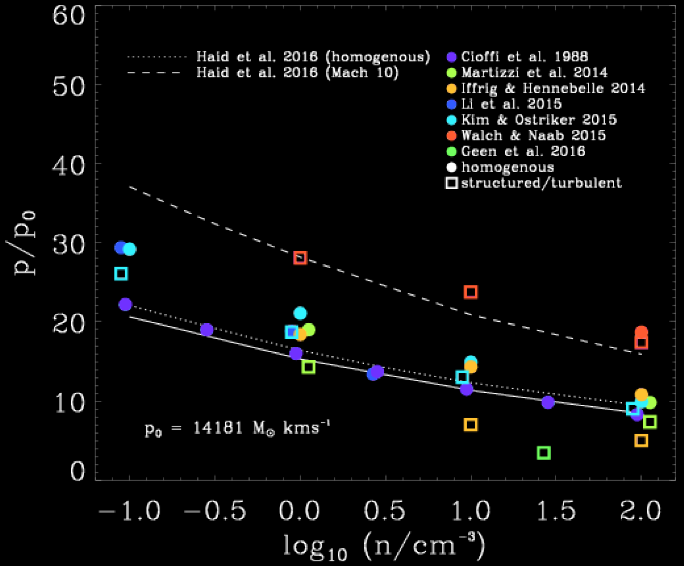
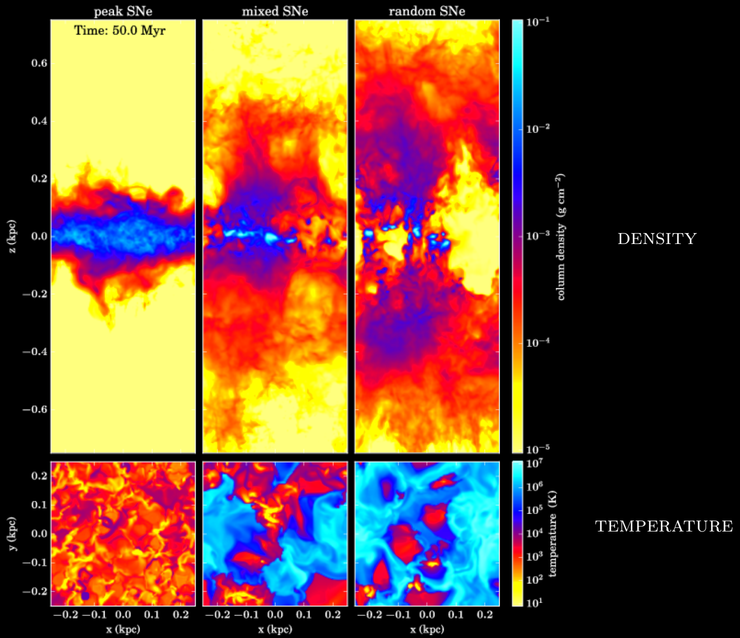
4. momentum conserving snowplow phase

- interior P exhausted $\longrightarrow$ shell continues to
  - expand
  - sweep up ISM mass
- $P_{\mathrm{hot}} \sim P_0 \implies$ constant radial momentum
- all excess E_{therm} radiated away $\rightarrow$ no radial momentum can be generated



from Naab & Ostriker 2017



adapted from Naab & Ostriker 2017

SNe feedback

1. *delayed cooling* models
   (e.g. Gerritsen 1997, Stinson et al. 2006)
   - ad hoc trick
   - E_{thermal} from SNe deposited in ISM

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  - reduced $M_\star$
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- problems
  - significant amount of thermally unstable gas
  - ...?

SNe feedback

(2) *stochastic thermal* feedback
(Dalla Vecchia & Schaye 2012)

- ad hoc trick
- $\mathrm{E}_{\mathrm{thermal}}$ from SNe deposited in ISM in a stochastic way
- jump in T ($\Delta T = 10^{7.5}$ K)

SNe feedback

2. *stochastic thermal* feedback (Dalla Vecchia & Schaye 2012)
   - ad hoc trick
   - $\mathrm{E}_{\mathrm{thermal}}$ from SNe deposited in ISM in a stochastic way
   - jump in T ($\Delta T = 10^{7.5}$ K)
   - guarantees
     $\longrightarrow$ long cooling times
     $\longrightarrow$ onset of Sedov-Taylor phase
     $\longrightarrow$ efficient momentum generation
     $\longrightarrow$ outflows

SNe feedback

3 *non-thermal* heating models (Teyssier et al. 2013)

- ad hoc trick
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   - represents
     - turbulence
     - cosmic rays
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   - E_{thermal} from SNe deposited in non-thermal component of ISM
   - represents
     - turbulence
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   - energy injection in a stochastic way (e.g. Roškar et al. 2014)

SNe feedback

4. *two-phase* approach
   (Scannapieco et al. 2006)
   - ad hoc trick
   - hot & cold gas $\longrightarrow$ evolved separately

SNe feedback

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- hot & cold gas $\longrightarrow$ evolved separately
- E from SNe added to the cold gas
    - stored for a certain time (decoupled from hydrodynamics)
    - released when it becomes hot phase

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- hot & cold gas ⟶ evolved separately
- E from SNe added to the cold gas
    - stored for a certain time (decoupled from hydrodynamics)
    - released when it becomes hot phase
- shown to produce spirals with realistic properties (Aumer et al. 2013)

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5 *wind* feedback

- some fraction of E from SNe
  $\longrightarrow$ injected in the form of E or $\vec{p}$
  $\longrightarrow$ driven away from the SF region

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- observations suggest
  - v_{wind} – increases
  - η – decreases

  in galaxies with higher $M_\star$ and SFR

SNe feedback

(5') *momentum driven* winds
(Oppenheimer & Davé 2006,2009)

- parametrised by
  - $v_{\rm wind} \propto \sigma$
  - $\dot{m}_{\rm wind} v_{\rm wind} \propto \dot{m}_\star$

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  $\Longleftrightarrow$ ensure it leaves the SF region
- success
  - more realistic cosmic SF histories
  - more realistic enrichment histories of galaxies and circum-galactic medium
  - more realistic present day spirals (zoom-in sims)
  - more realistic gas rich massive high-z disks

SNe feedback

5" *energy driven* winds
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- success: better agreement for the MW-like galaxies satellites abundances
  $\iff$ higher η for lower M$_\star$

SNe feedback

6. *hybrid* model
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        - momentum driven wind
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7. updated *decoupled* model
(Davé, Thompson & Hopkins 2016)
- $v_{\rm wind}$
- η

$\longrightarrow$ scalings from high resolution zoom-in simulations

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- radiation driven stellar winds from massive O- and B-stars $\Rightarrow$ bubbles of low ρ around stars

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- more direct momentum injection than SNe
- can reduce star formation process in forming star clusters

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  - launch galactic winds
  - disrupt small clouds on short time-scales
  - also compress over-dense regions into clumps & pillars $\Rightarrow$ further coupling difficult

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HII regions

- around young massive stars
- created by ionizing UV photons by heating the parental cloud from $\lesssim 100$ K to $\sim 10^4$ K
- momentum input by direct absorption of UV photons $\rightarrow$ IR radiation re-emitted + scattered on dust: $\dot{P}_{\rm rad} \sim (1+\tau_{\rm IR})L/c$

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- momentum input required to drive strong outflows disturbs the gas and the resulting stellar disk $\rightarrow$ impossible to retain the disk morphology
(e.g. Roškar et al. 2014, Rosdahl et al. 2015)

Success

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- AGN feedback
  $\longrightarrow$ suppression of the residual SF in the centre

BH growth

- accretion rate:

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  - *torque-limited* accretion (Shlosman et sl. 1989): when $\frac{r_{\rm centrif}}{r_{\rm Bondi}} > 1$ (e.g. Anglés-Alcázar et al. 2016)

AGN feedback

- traditional feedback:

$$\frac{dE_{\rm feed}}{dt} = \epsilon_{\rm f} L_{\rm bol} = \epsilon_{\rm f} \epsilon_{\rm r} \frac{dM_{\rm BH}}{dt} c^2$$

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    (e.g. Sijacki et al. 2007)
  - 'radio' mode: E_{kin} injected into a jet-like bipolar outflow $\sim 10^4$ km/s (e.g. Dubois et al. 2012)
  - helps to prevent the formation of cooling flows $\Rightarrow$ reduction of stellar mass and nuclear SF in massive halos

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- momentum associated with the energy transfer
- spatial direction for the momentum outflow

Solution?

- specify the output per accreted mass matched to observations in
  - mass
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  - mass
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- their coupling
  - thermal
  - mechanical
  - radiative

  to surrounding medium $\rightarrow$ handled by hydrodynamical codes

First attempts

- UV, X-ray emission from accreting BH (e.g. Vogelsberger et al. 2013, Choi et al. 2015, Bieri et al. 2016)
- mechanical & radiative effects included (e.g. Choi et al. 2016, Hopkins et al. 2016)
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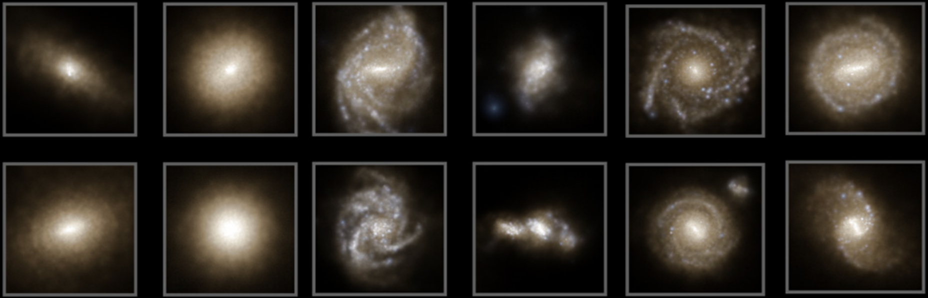
$\Longrightarrow$

- mass growth of BH $\rightarrow$ similar to the 'thermal' feedback
- more extreme fluctuation level of the kinetic feedback ...
- jets leave dramatic imprint, but probably not transferring significant amount of E or $\vec{p}$
- coupling mechanisms (e.g. turbulent mixing, dissipation) $\rightarrow$ studied in high-resolution simulations

Ab initio models

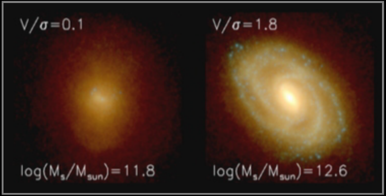
ellipticals irregular disk galaxies

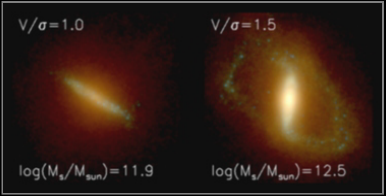


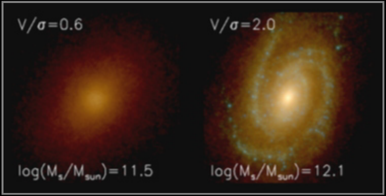
Illustris (Vogelsberger et al. 2014)

see also
Horizon-AGN (Dubois et al. 2014)
Eagle (Schaye et al. 2015)

AGN no AGN AGN no AGN

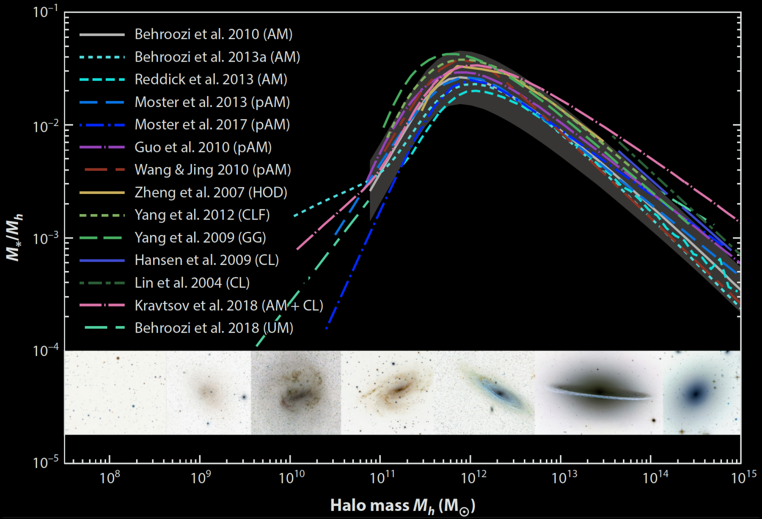






HORIZON-AGN/HORIZON-NOAGN (Dubois et al. 2014, 2016)

Ab initio models



adapted from Wechsler & Tinker 2018

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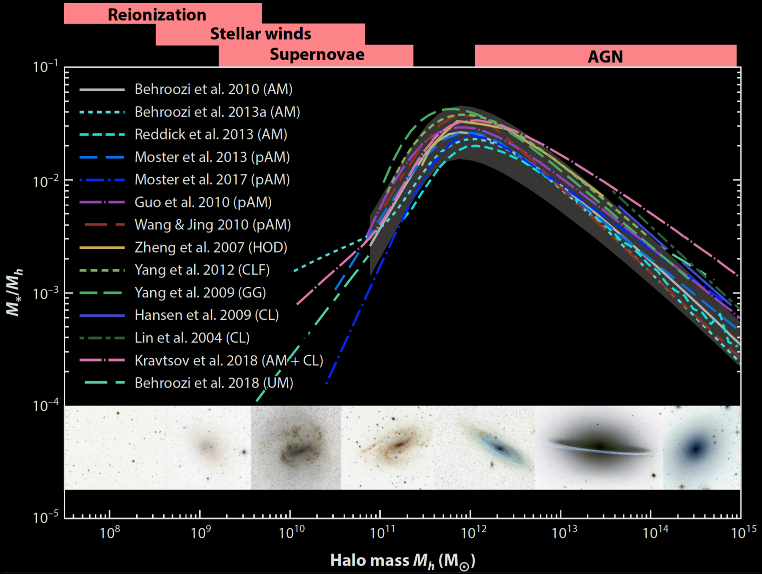

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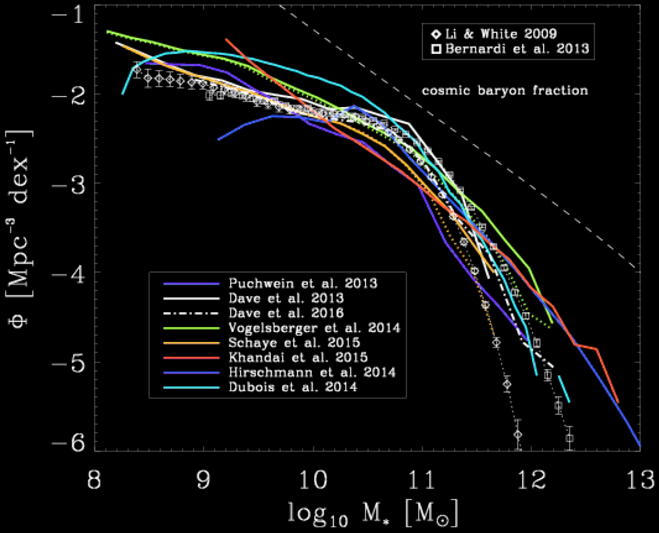
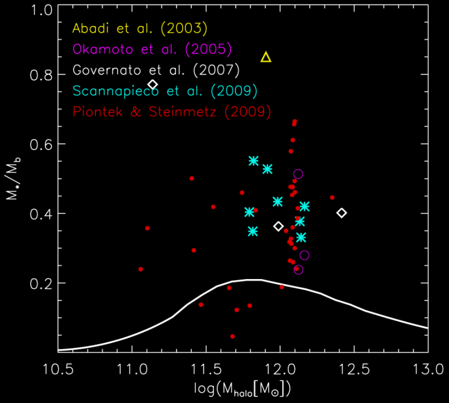
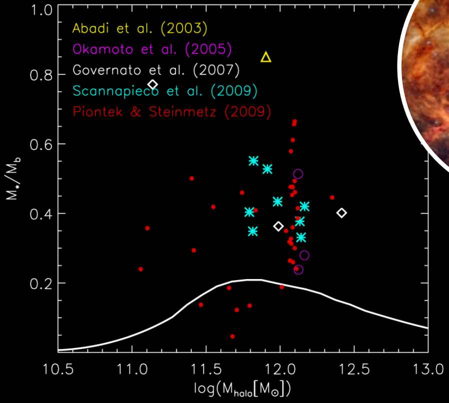


from Naab & Ostriker 2016



Guo et al. 2010



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