An overview of AGN implementations in cosmological simulations

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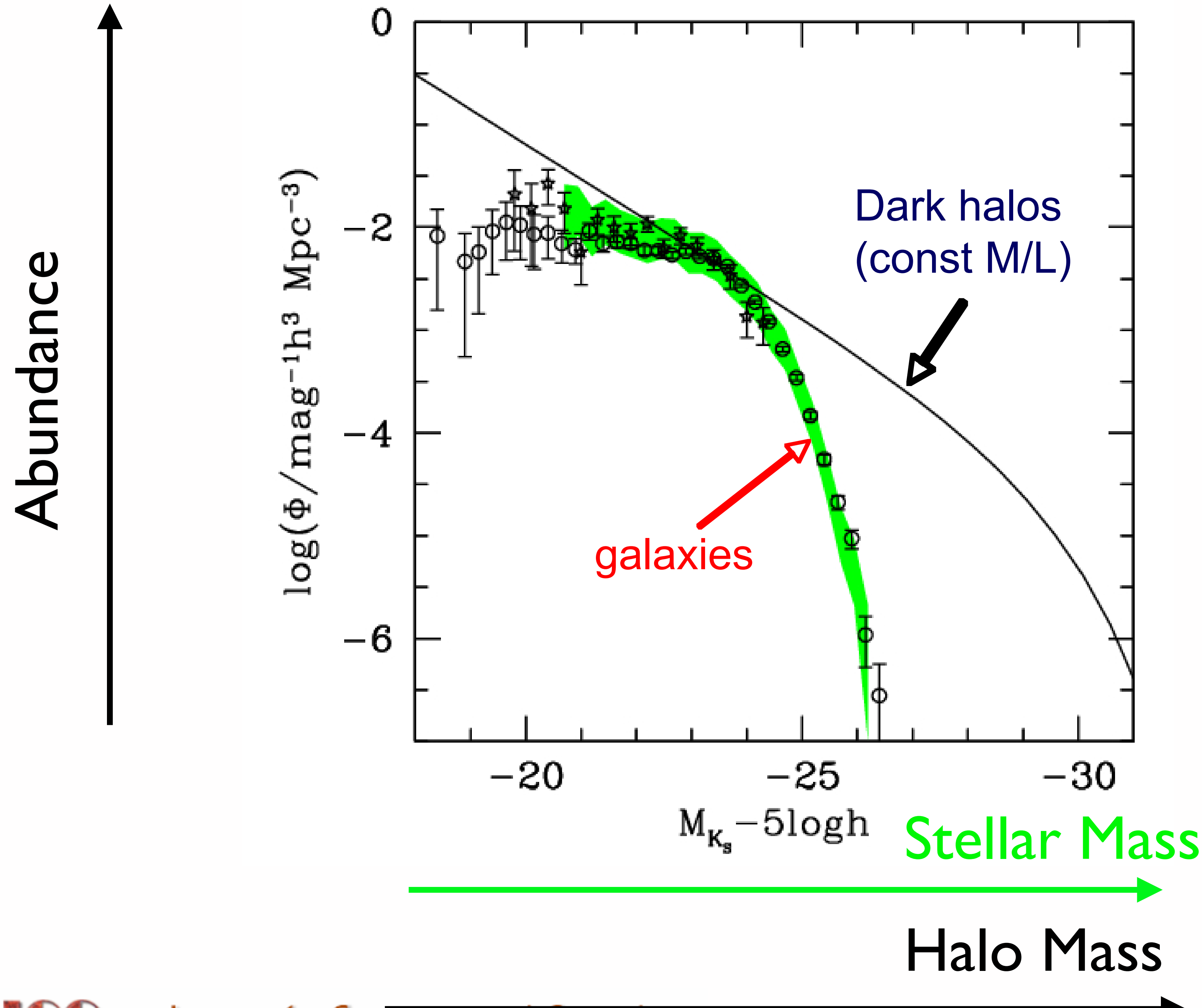
Menu:

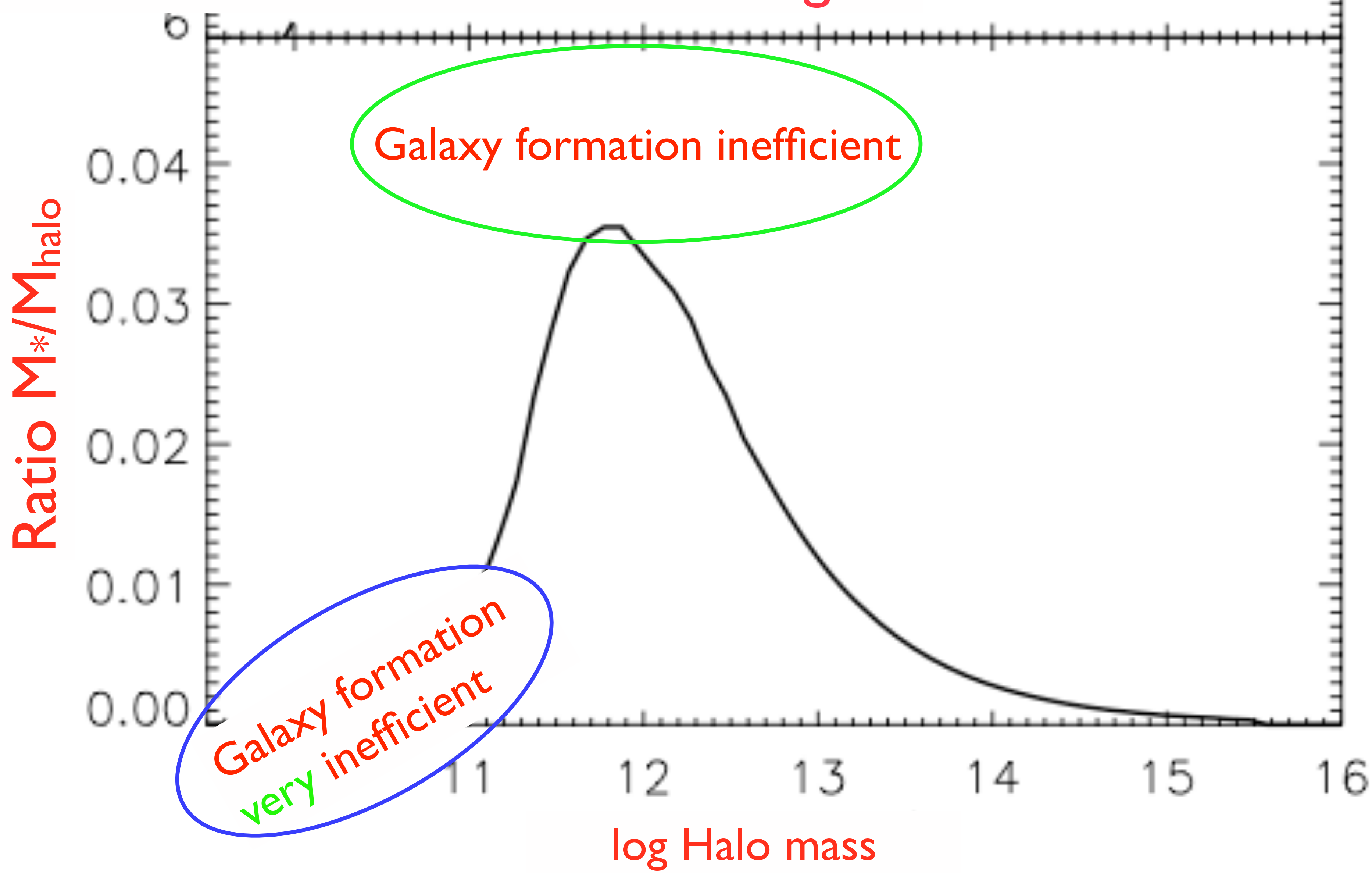
- Need for AGN in cosmological simulations
  apart from the fact that black holes are there
- Implementation: Physics versus subgrid physics
  - Seeding
  - Feeding and merging
  - Feedback(ing)
- What can we learn from such simulations?

Galaxy stellar mass function versus dark matter halo mass function

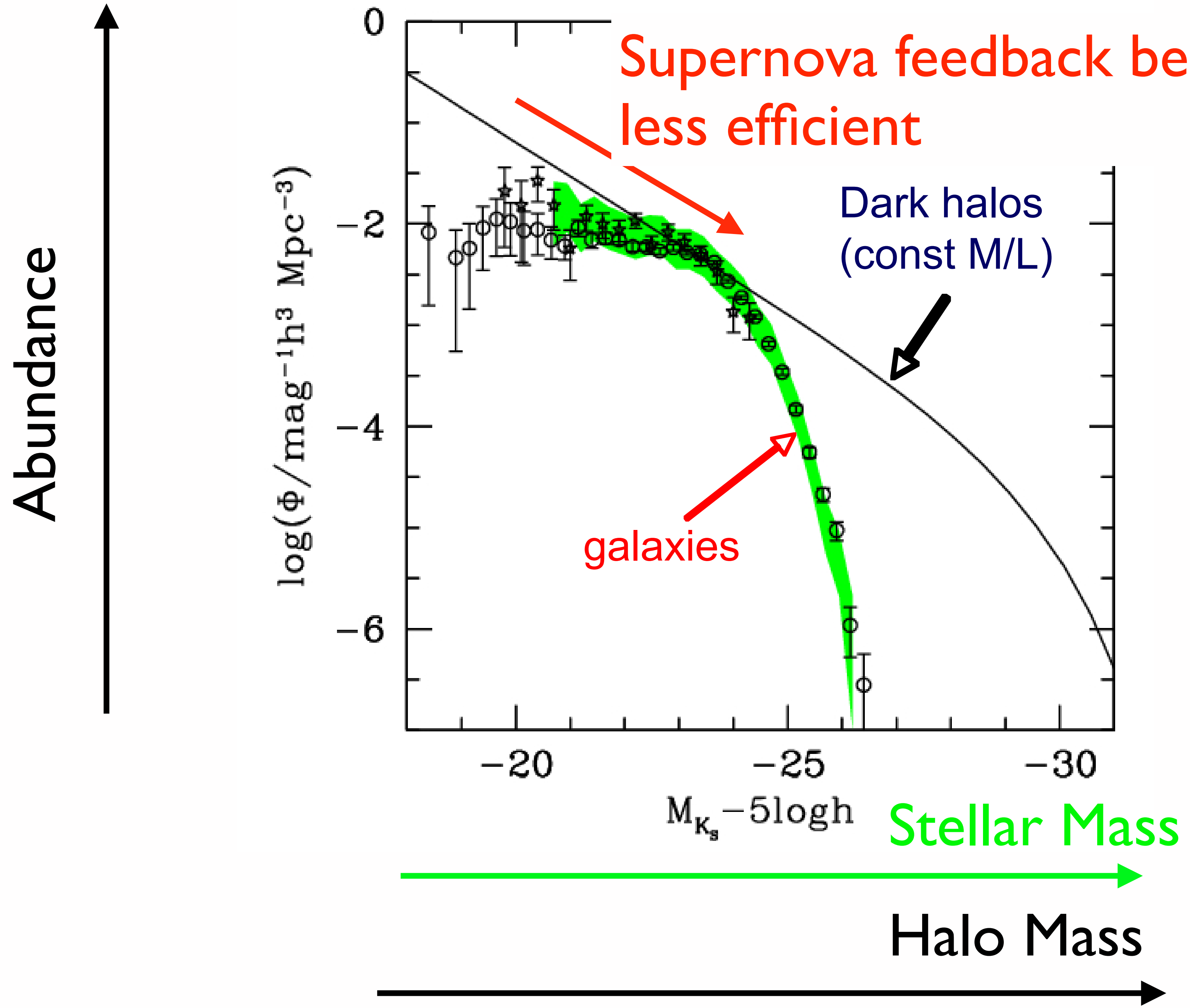


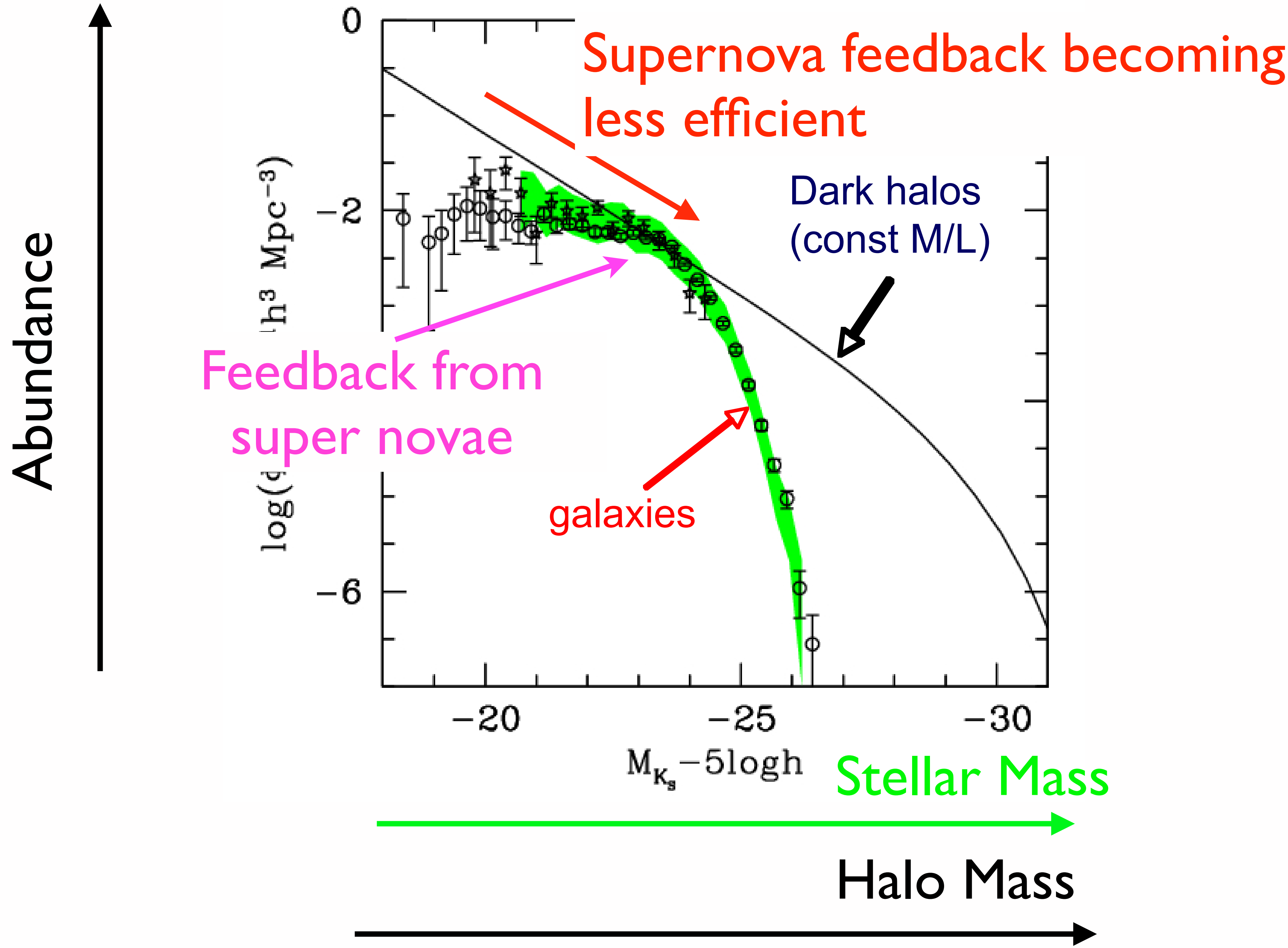
Bower+06

… in terms of abundance matching

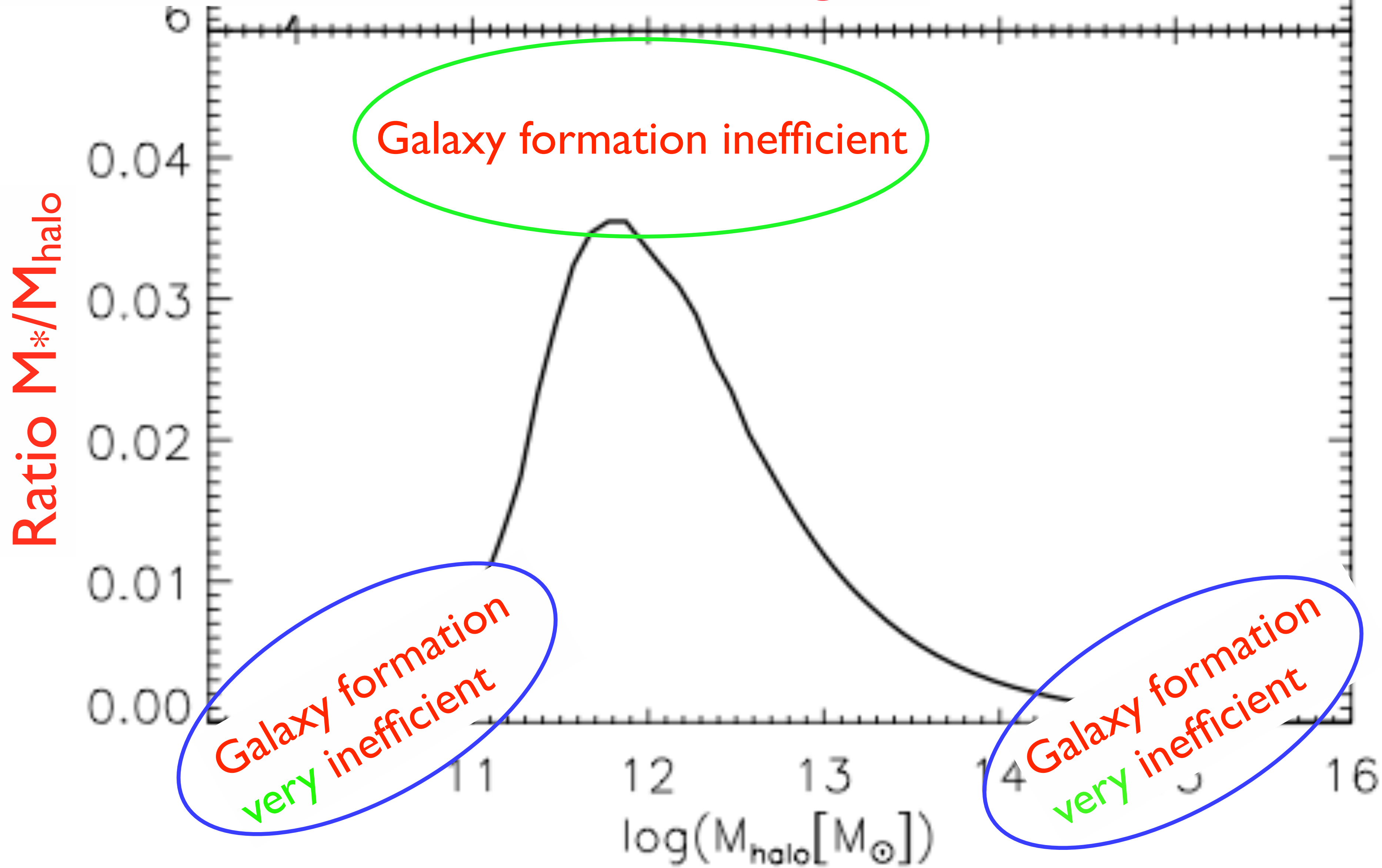


Qi+10,Behroozi+, Leauthaud+


Abundance
log(Φ/mag⁻¹h³ Mpc⁻³)
0
−2
−4
−6
Supernova feedback becoming less efficient
Dark halos (const M/L)
galaxies
−20
−25
−30
M_Ks −5logh
Stellar Mass
Halo Mass

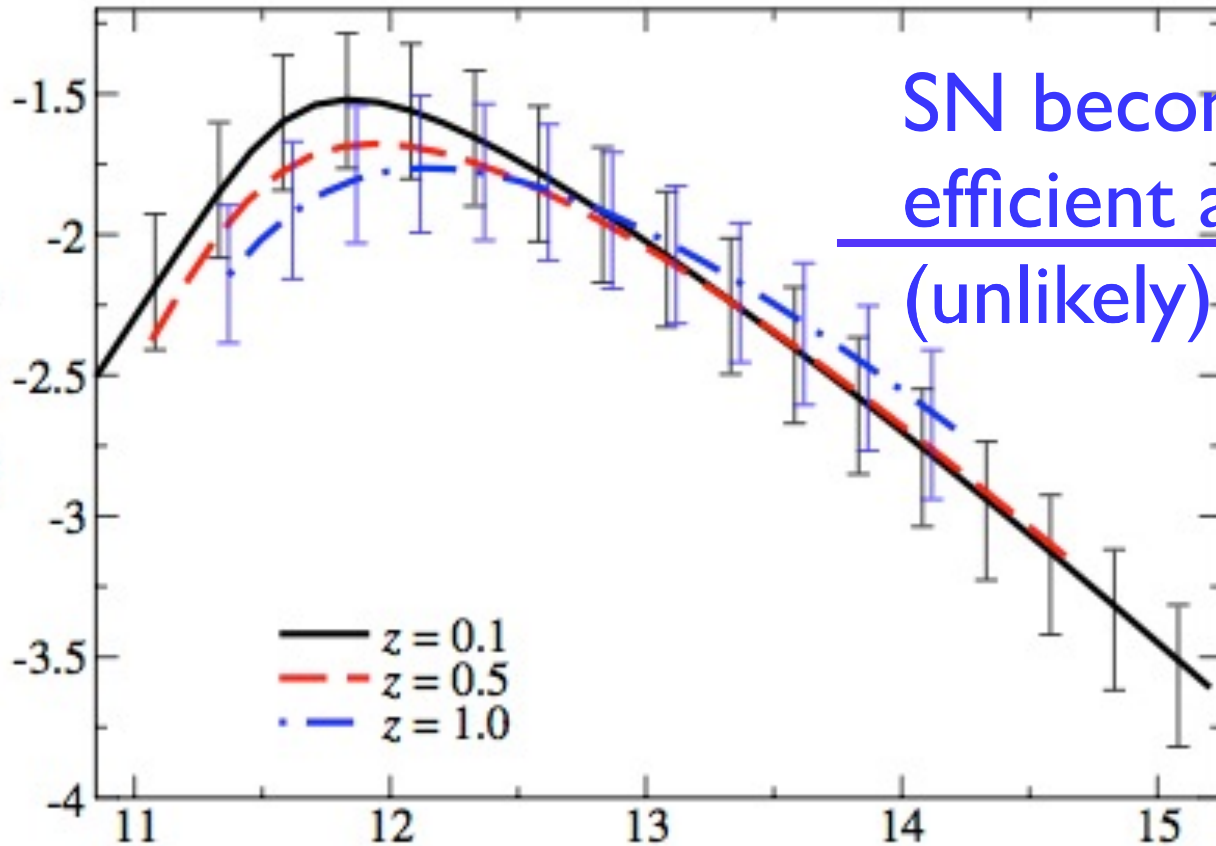

Abundance
0
−2
−6
Supernova feedback becoming less efficient
Dark halos (const M/L)
Feedback from super novae
galaxies
−20
−25
−30
M_Ks −5logh
Stellar Mass
Halo Mass

… in terms of abundance matching



Qi+10,Behroozi+, Leauthaud+

Supernova feedback becomes increasingly inefficient



SN become more efficient again? (unlikely)

Log stellar / halo mass

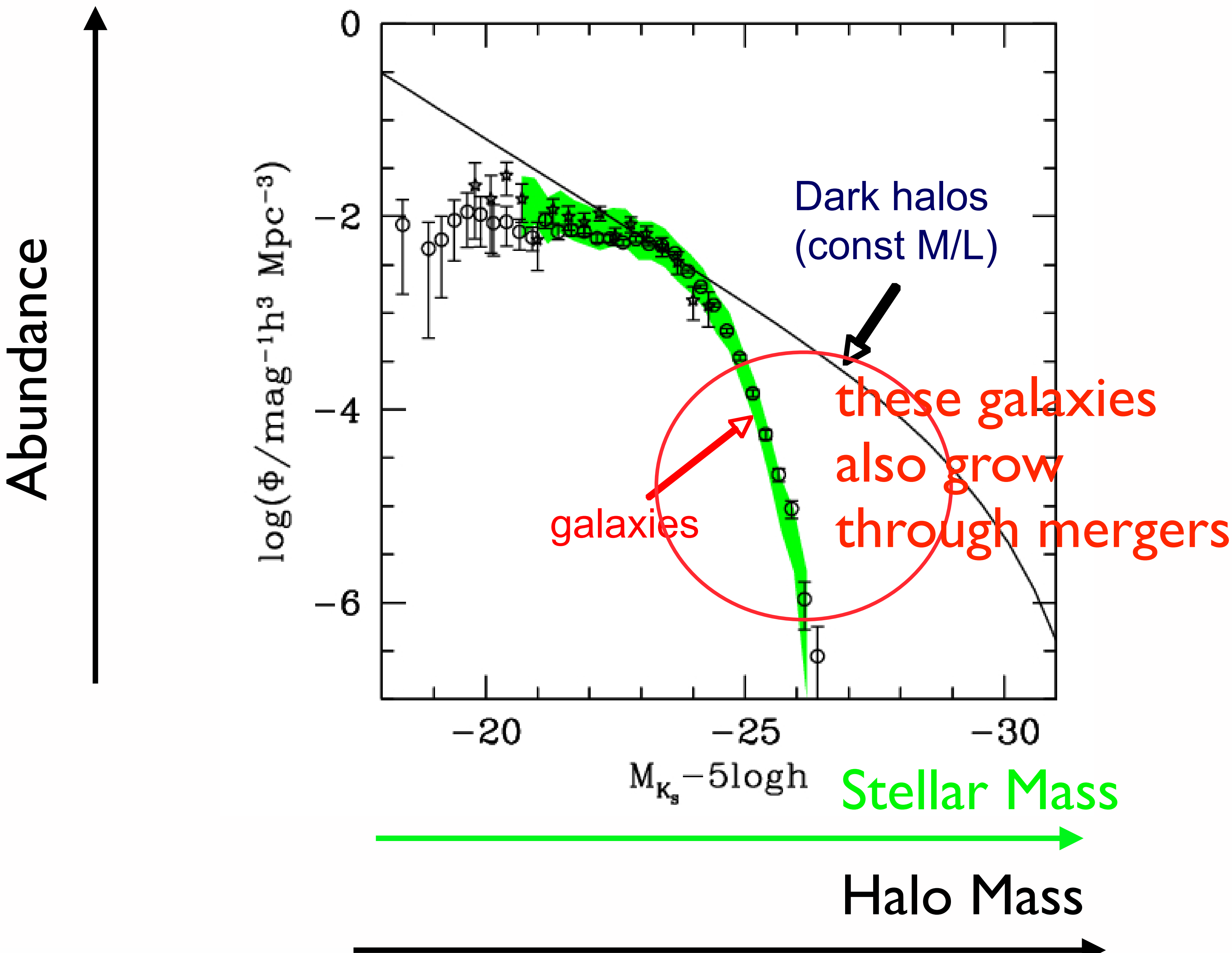
Log Halo Mass

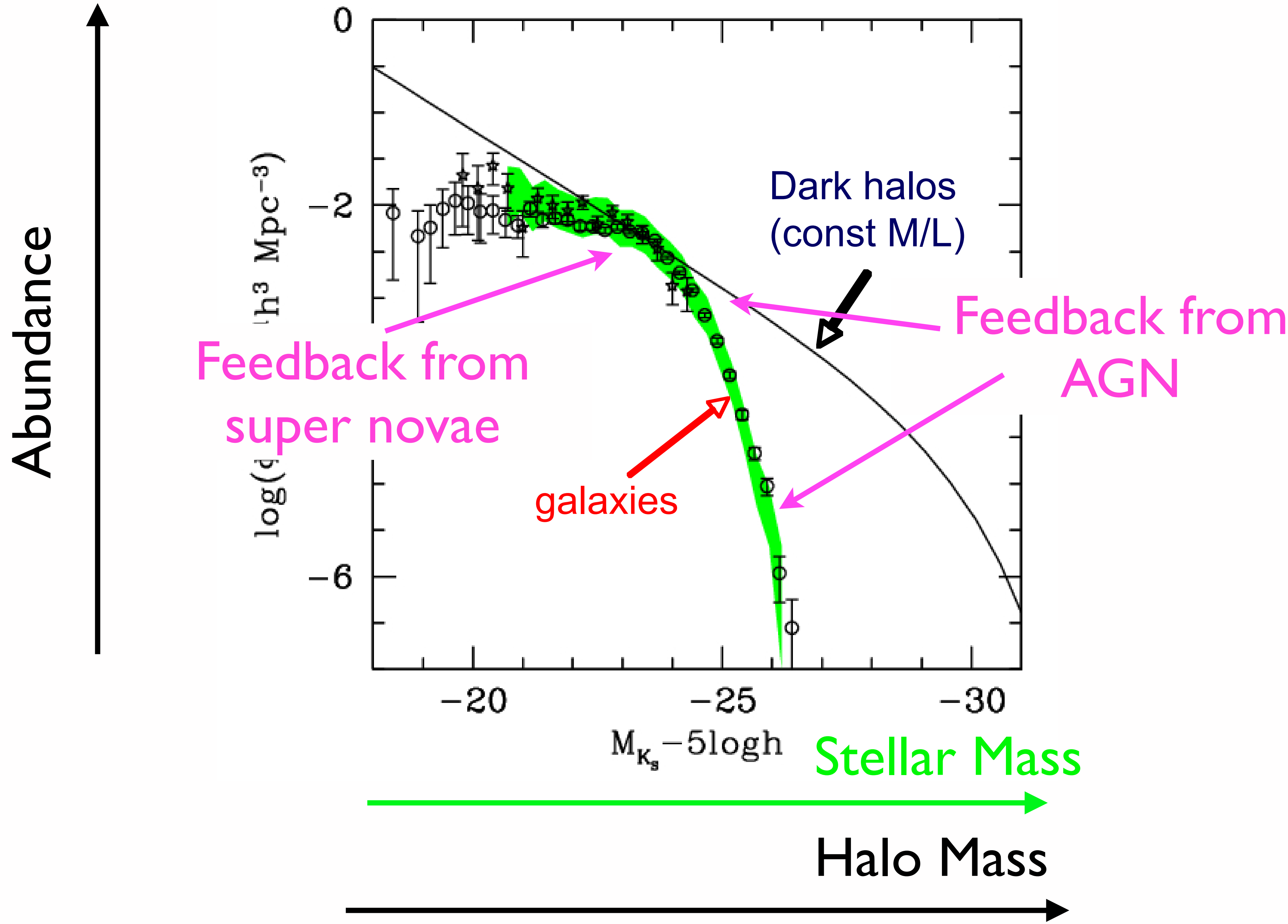
Behroozi+10

Need for AGN in cosmological simulations:

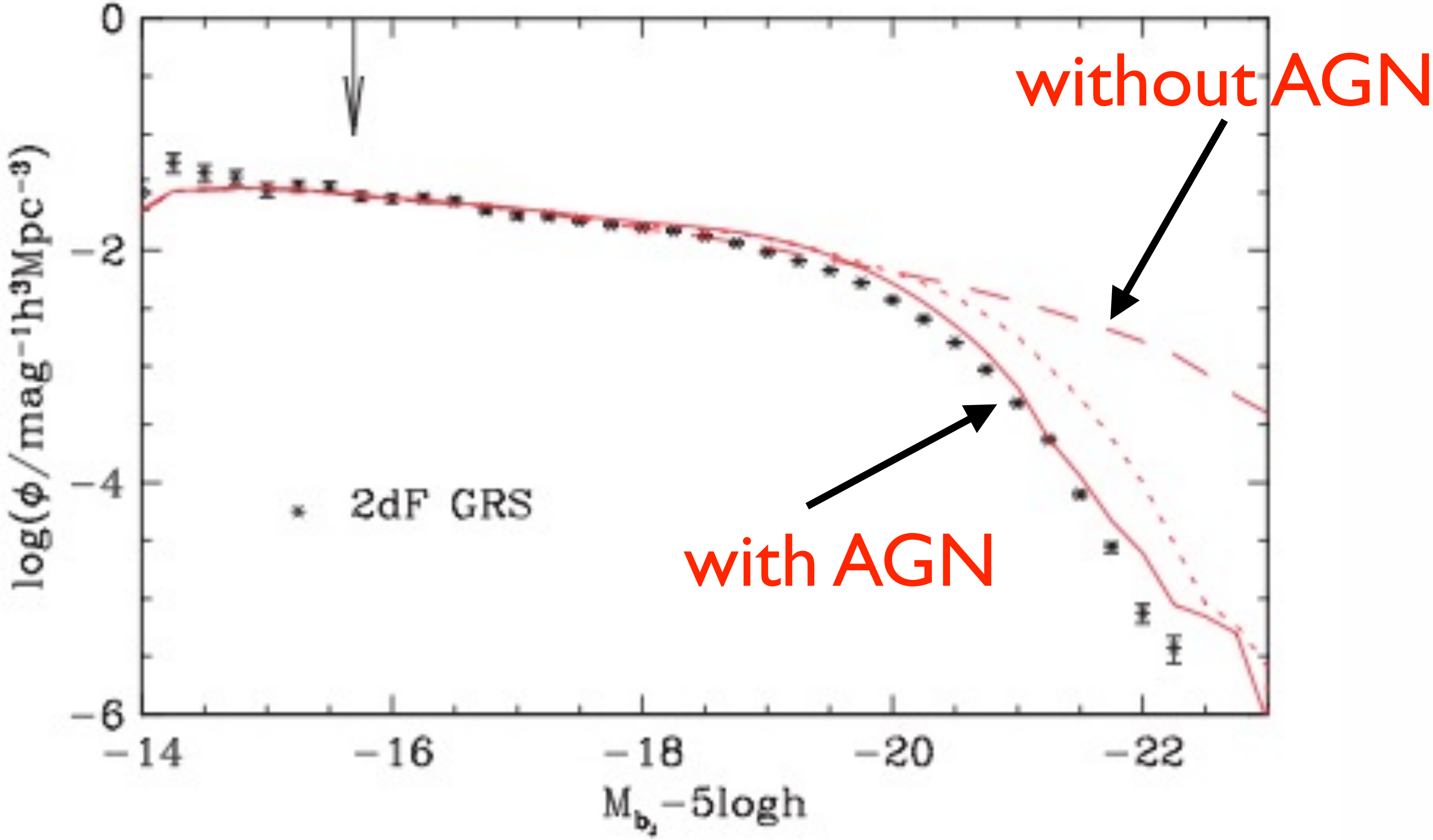
Without some additional mechanism massive galaxies:

1. Are too massive
2. Are forming stars at a too high rate


Abundance
0
−2
−4
−6
log(Φ/mag⁻¹h³ Mpc⁻³)
Dark halos
(const M/L)
these galaxies
also grow
through mergers
galaxies
−20
−25
−30
$M_{K_s} - 5\log h$
Stellar Mass
Halo Mass

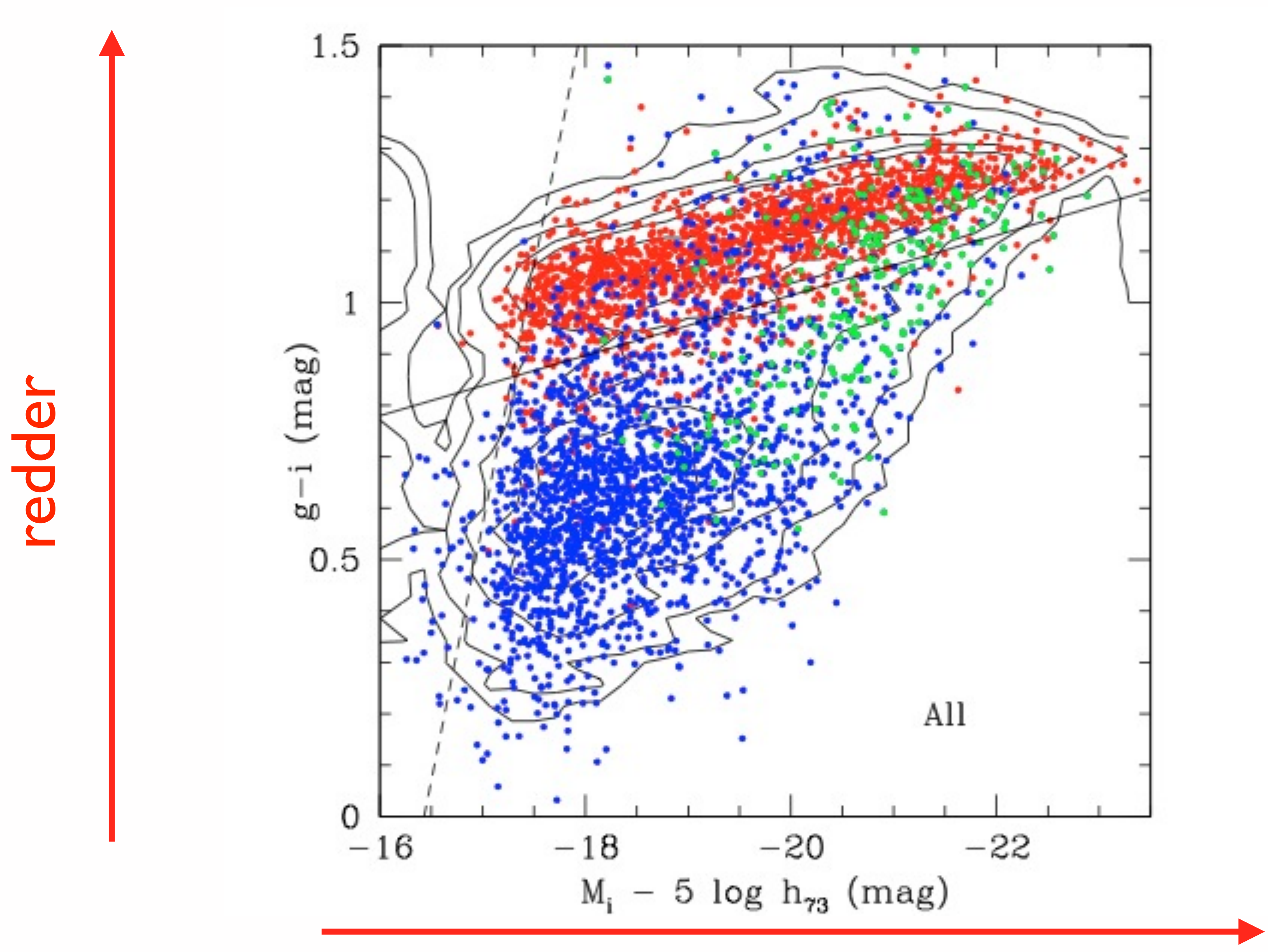

Abundance
0
−2
−6
log(φ h³ Mpc⁻³)
−20
−25
−30
$M_{K_s} - 5\log h$
Dark halos
(const M/L)
Feedback from
super novae
Feedback from
AGN
galaxies
Stellar Mass
Halo Mass

Semi-analytics: AGN causes exponential break

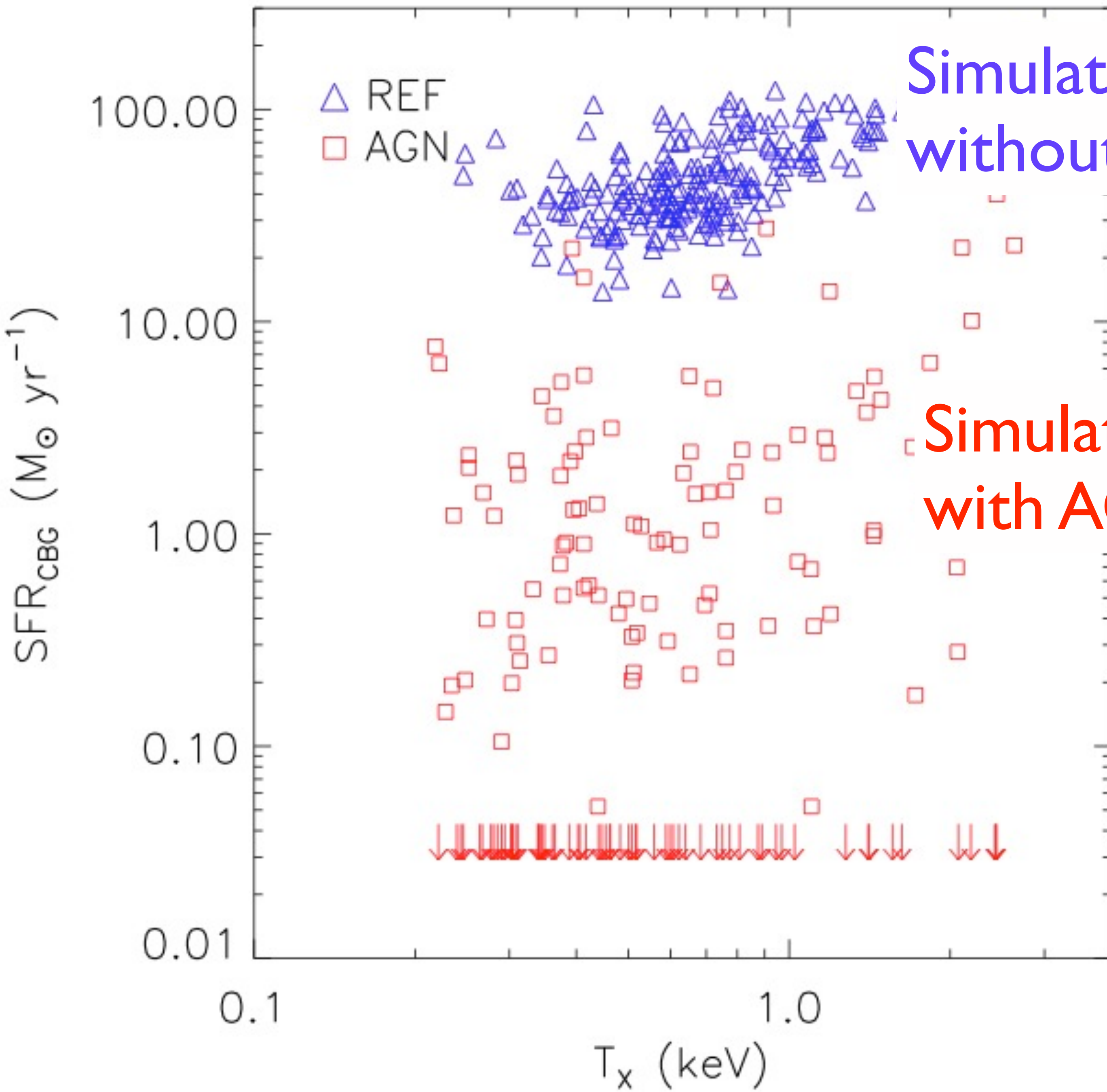


Bower+06, Croton+06

massive galaxies have low star formation rates



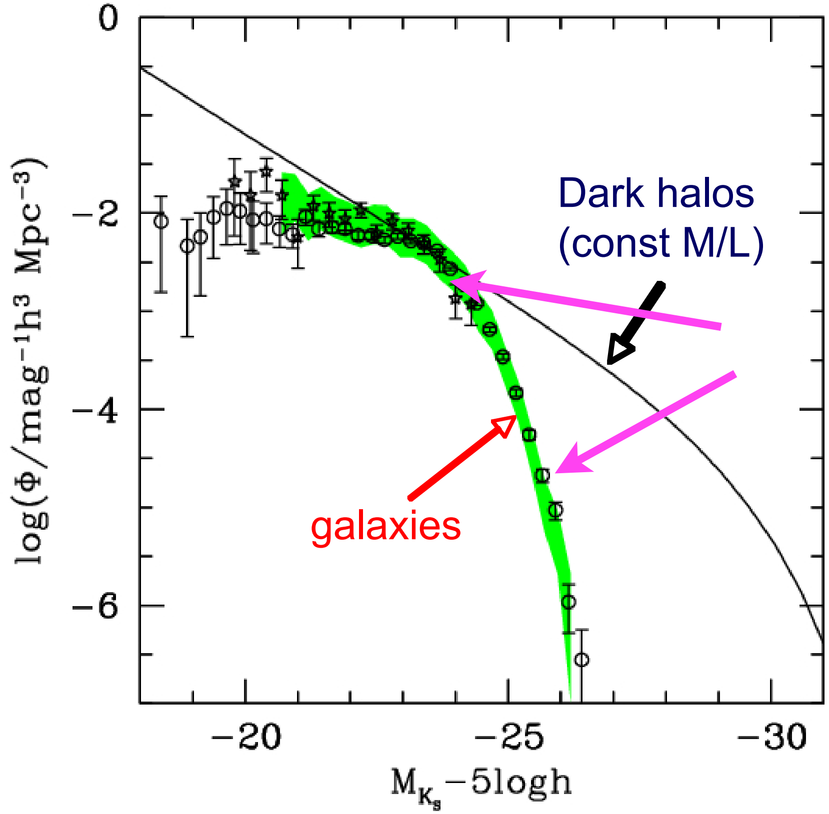
SFR in BCG too high - and not enough scatter



Simulation without AGN

Simulation with AGN

OWLS sims, McCarthy + 10



Feedback from AGN

Mission (impossible) for AGN:

1. quench star formation in galaxies of low-enough stellar mass
2. keep it quenched in those more massive

Menu:

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  - (in addition to BHs being there!)
- Implementation: Physics versus subgrid physics
  - Seeding
  - Feeding and merging
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nt cosmological simulations and their AGN feedback implemen

Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe

Mark Vogelsberger[1], Shy Genel[2], Volker Springel[3,4], Paul Torrey[2], Debora Sijacki[5], Dandan Xu[3], Greg Snyder[6], Dylan Nelson[2] , and Lars Hernquist[2]

The EAGLE project: Simulating the evolution and assembly of galaxies and their environments

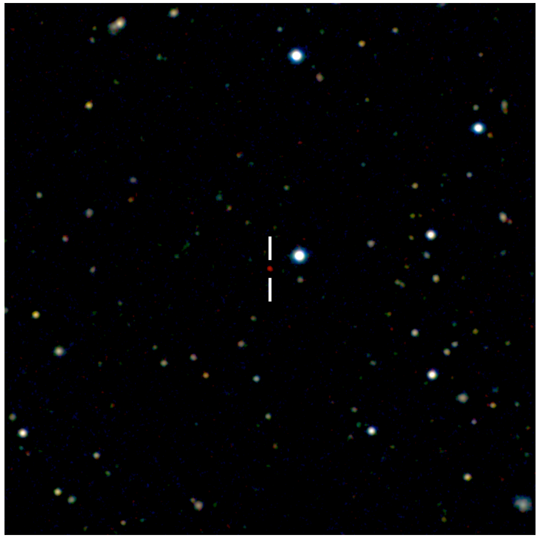
Joop Schaye,[1*] Robert A. Crain,[1] Richard G. Bower,[2] Michelle Furlong,[2] Matthieu Schaller,[2] Tom Theuns,[2,3] Claudio Dalla Vecchia,[4,5] Carlos S. Frenk,[2] I. G. McCarthy,[6] John C. Helly,[2] Adrian Jenkins,[2] Y. M. Rosas-Guevara,[2] Simon D. M. White,[7] Maarten Baes,[8] C. M. Booth,[1,9] Peter Camps,[8] Julio F. Navarro,[10] Yan Qu,[2] Alireza Rahmati,[7] Till Sawala,[2] Peter A. Thomas,[11] James Trayford[2]

The MassiveBlack-II Simulation: The Evolution of Halos and Galaxies to $z \sim 0$

Nishikanta Khandai[1], Tiziana Di Matteo[2], Rupert Croft[2], Stephen Wilkins[3], Yu Feng[2], Evan Tucker[2], Colin DeGraf[4], Mao-Sheng Liu[2]

All inspired by Springel+05

Black hole seeding



ULAS J1120 ukirt/eso

$M_{BH}=10^9\ M_{sun}$

$z=7,\ t=1$Gyr

Mortlock+11

472 REES

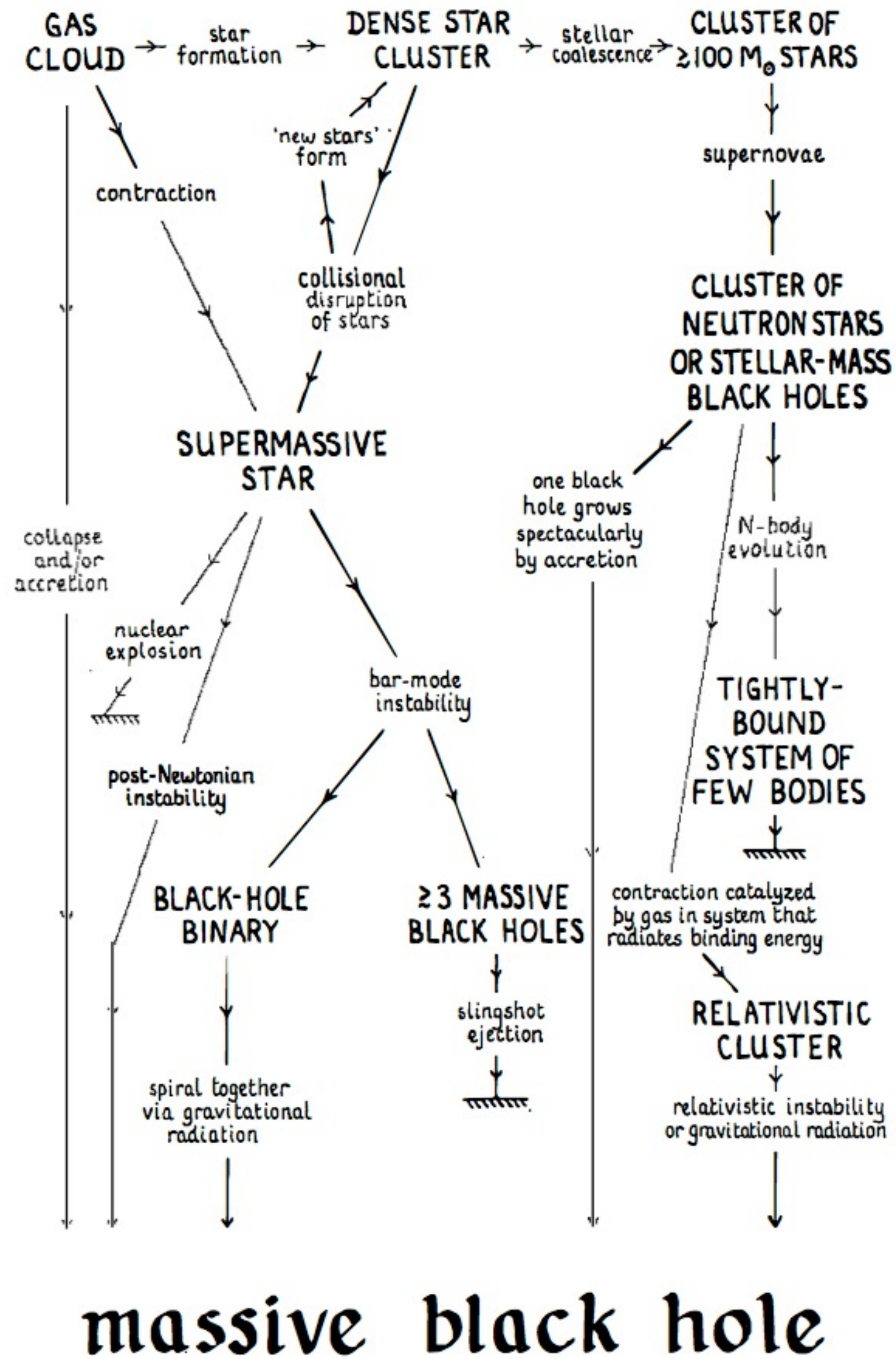
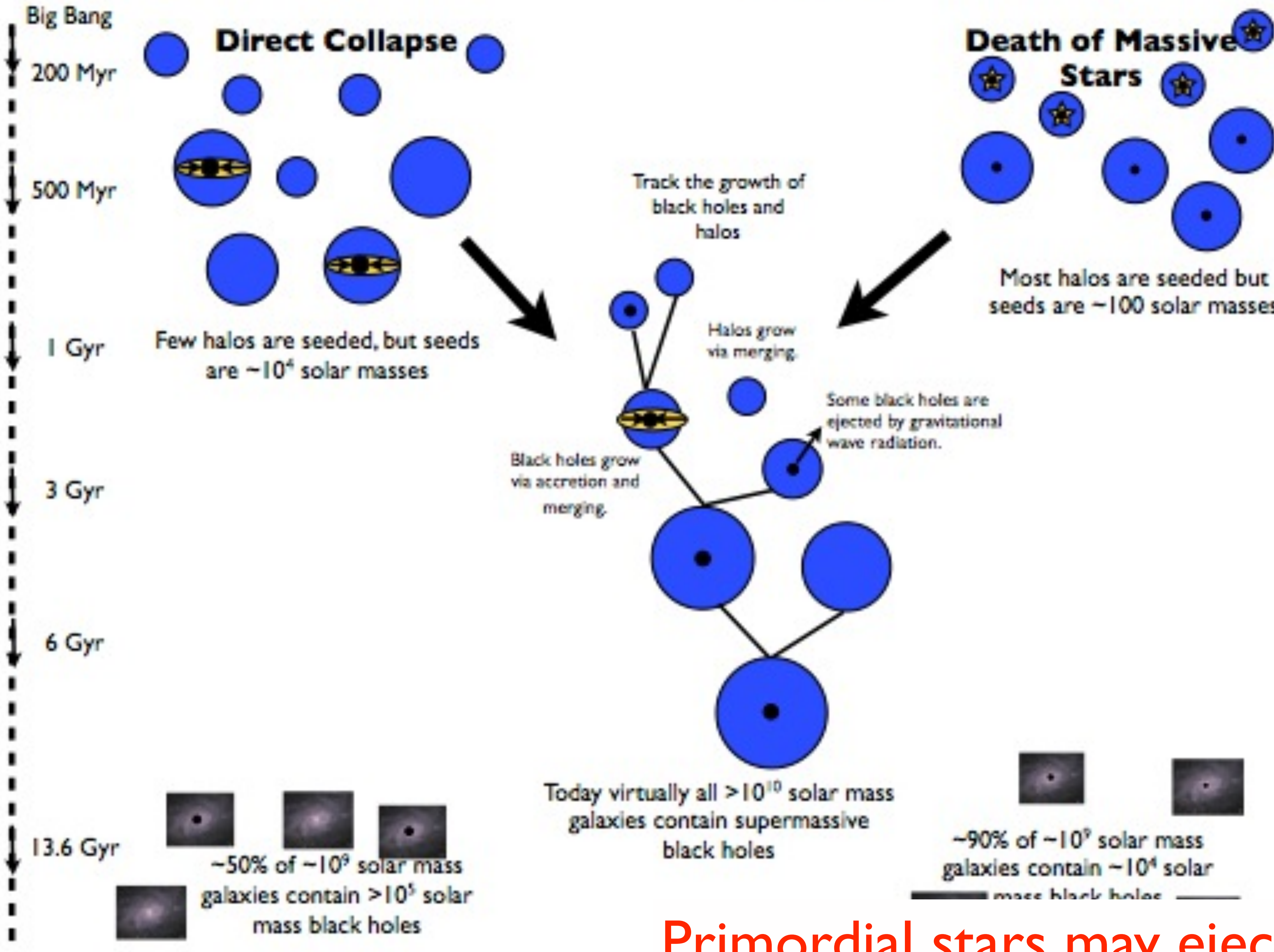


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Rees 84, Kocsis & Loeb 13



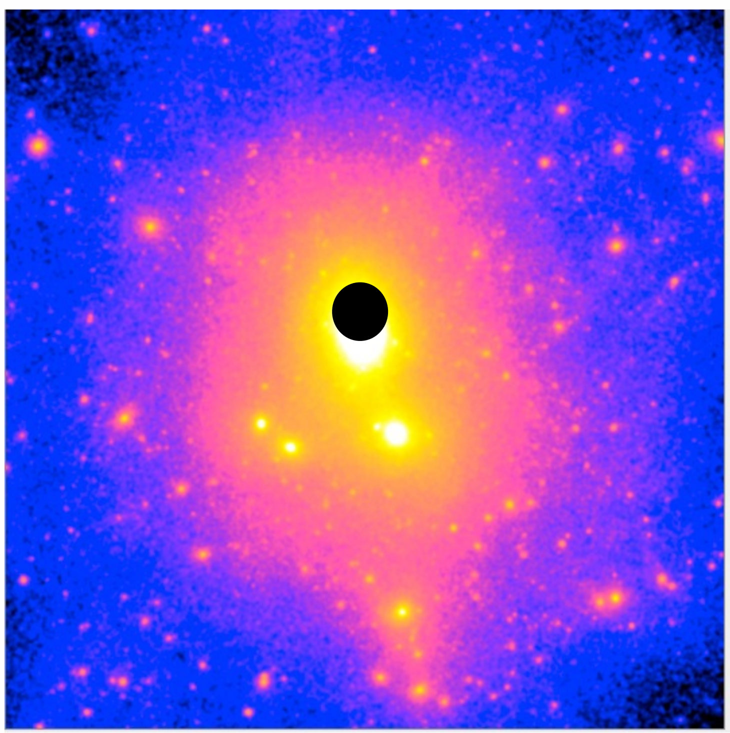
Primordial stars may eject all gas out of mini-halo .. and can't grow

Why does collapsing gas not simply make stars?

Greene 12

Black hole seeding

Simulation	FoF Mass $10^{10} h^{-1} M_\odot$	Gas mass $10^6 h^{-1} M_\odot$	BHS seed mass $10^5 h^{-1} M_\odot$
Eagle	1	1.2	1
Illustris	5	1.2	1
Massive Black	5	2.2	5



dark matter halo

- BH probably only can start accreting when in dark matter halo of a galaxy, i.e. with virial temperature $> 10^4$K - not so bad?
- BH seed mass comparable to or less than particle mass! Hence need subgrid BH mass
- no dynamical friction: put BH at centre by hand

Black hole accretion

$$\dot{M}_{\rm Bondi} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

$$r_{\rm Bondi} = \frac{G M_{\rm BH}}{c_s^2}$$

$$\dot{M}_{\rm BH} = (1 - \epsilon_r)\dot{M}_{\rm Bondi}$$

*

*: typically, rate is multiplied by large factor, 100-3000

Black hole accretion

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$$r_{\rm Bondi} = \frac{G M_{\rm BH}}{c_s^2}$$

$$\dot{M}_{\rm BH} = (1 - \epsilon_r) \dot{M}_{\rm Bondi}$$

Accretion rate* - limit by Eddington

Bondi radius

Rate of increase in BH mass

gas density

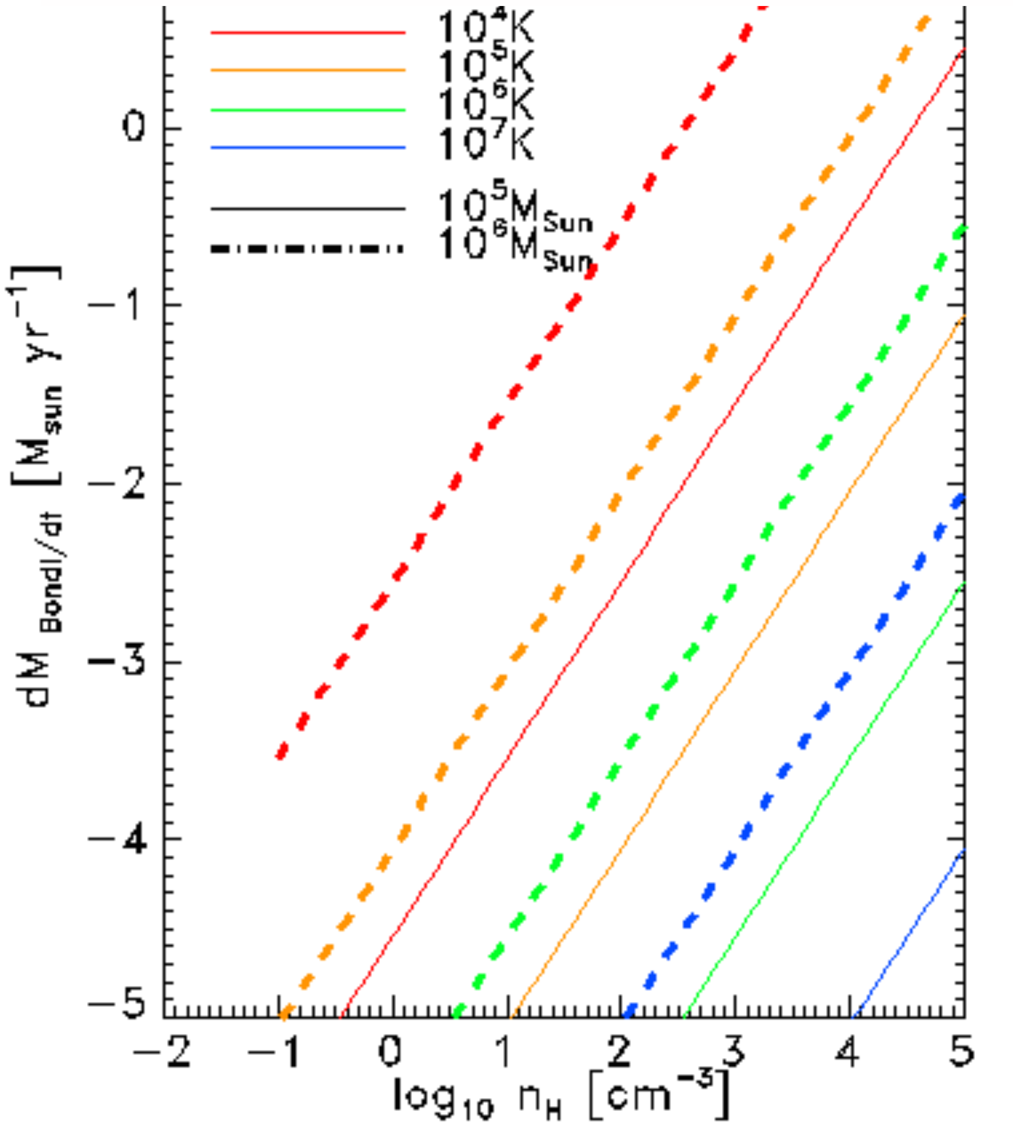
most neglect reduction due to radiative efficiency

sound speed

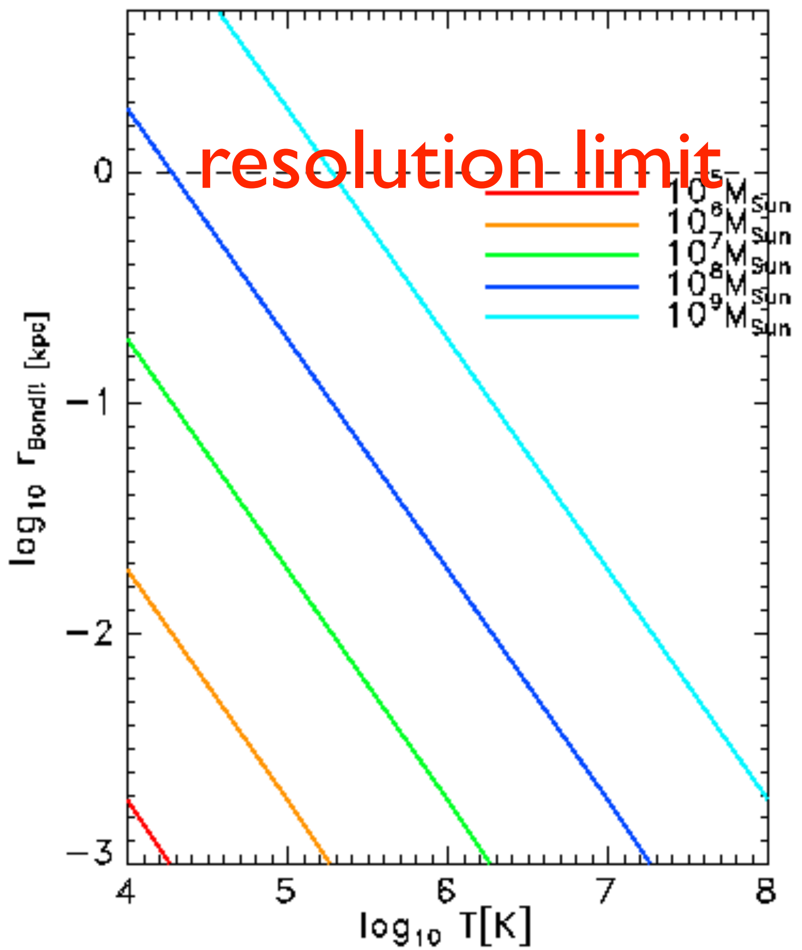
relative velocity gas-BH

*: typically, rate is multiplied by large factor, 100-3000

Accretion rate [log M_sun/yr]



Bondi radius [log kpc]



The ISM stirred by super novae

Temperature

density

velocity

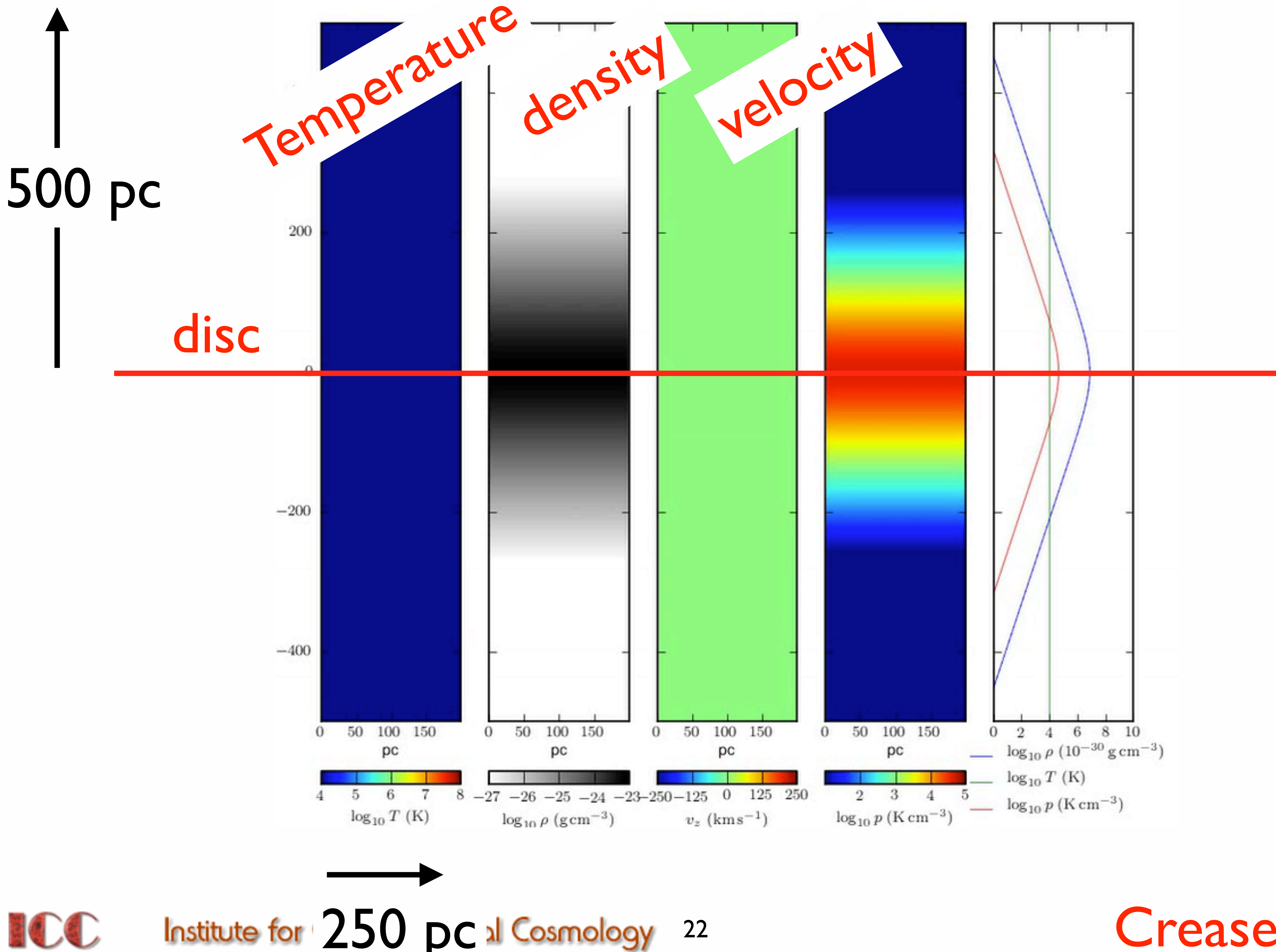
500 pc

disc

250 pc

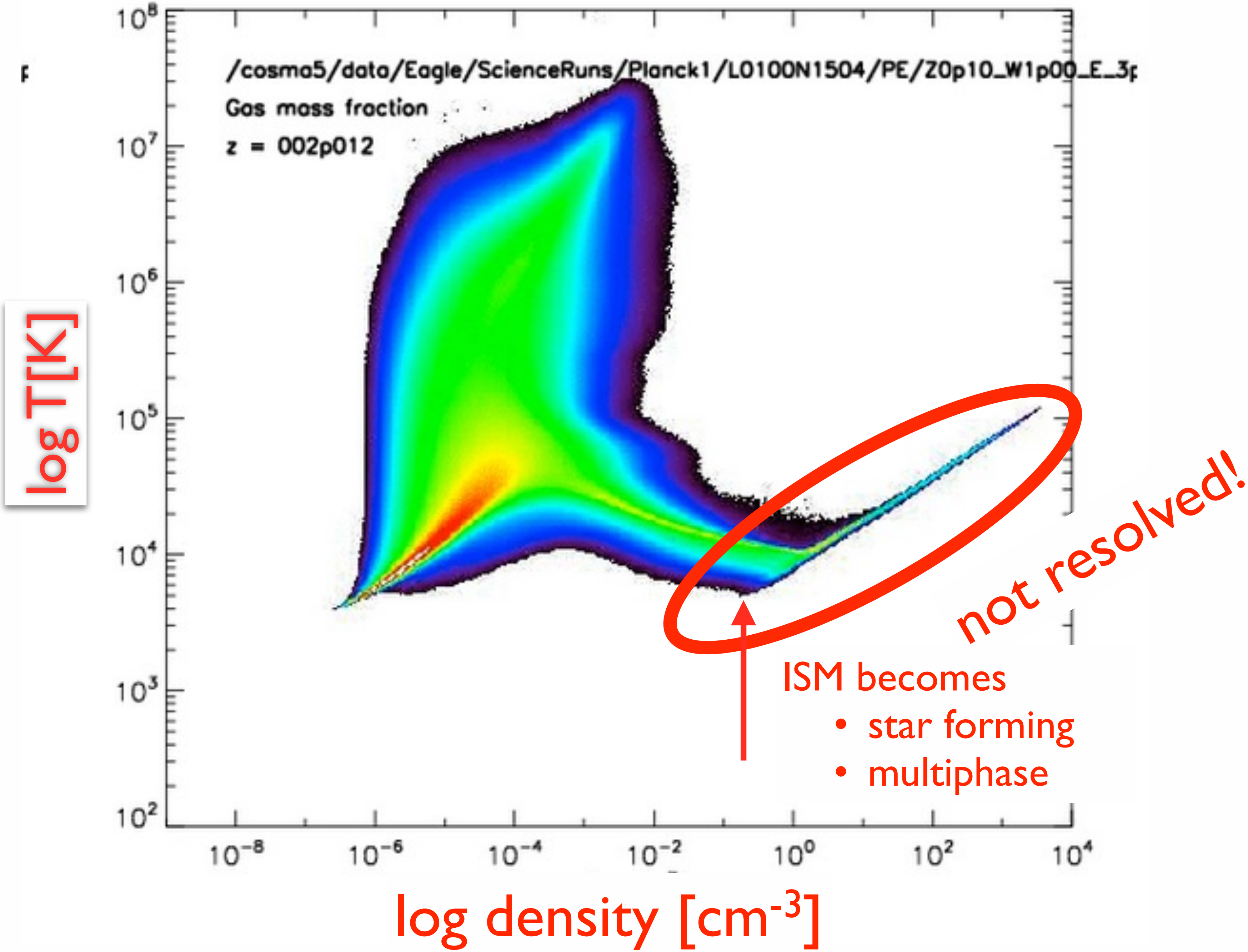
Creasey+13

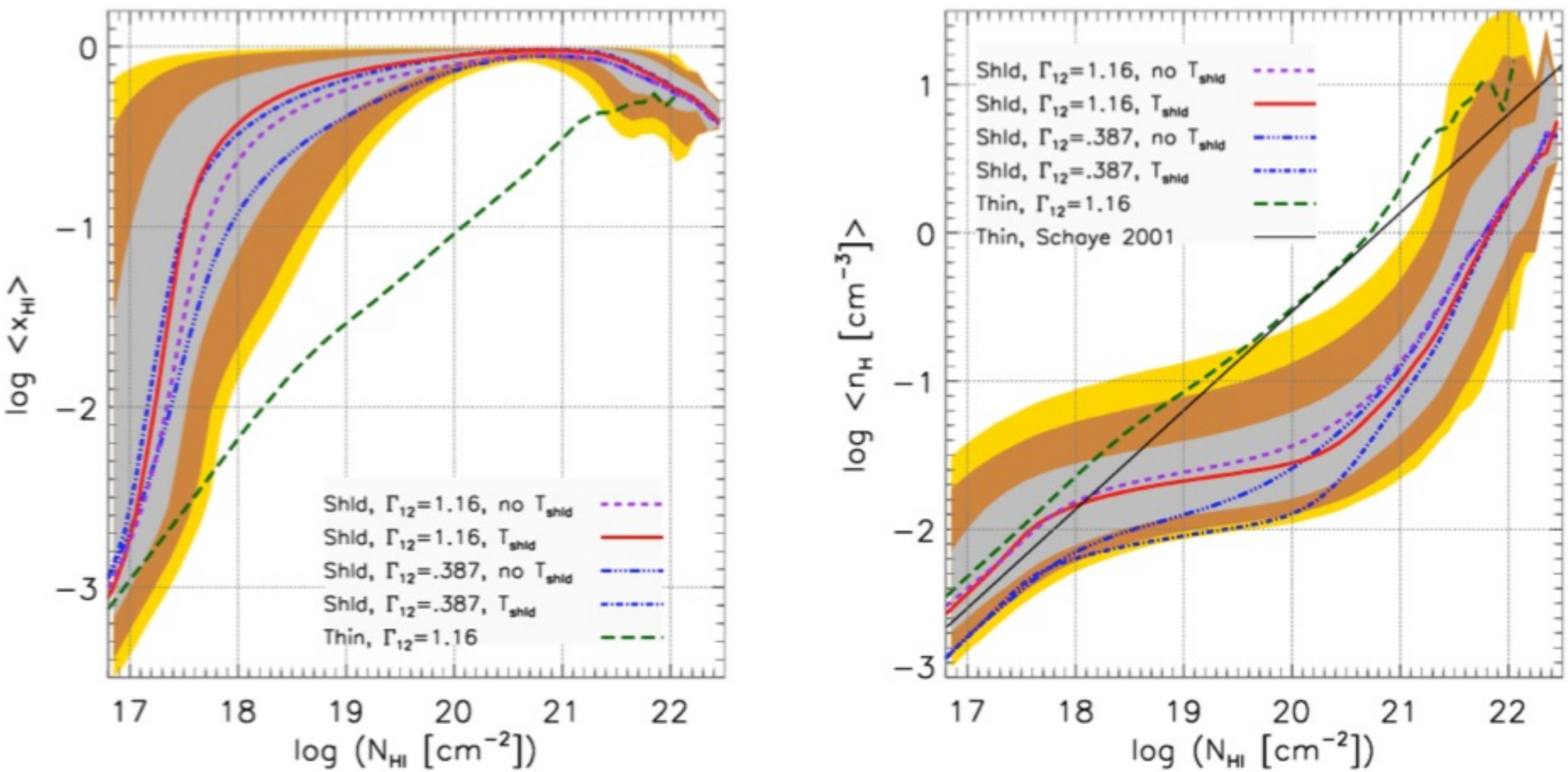
The ISM stirred by super novae



Creasey+13

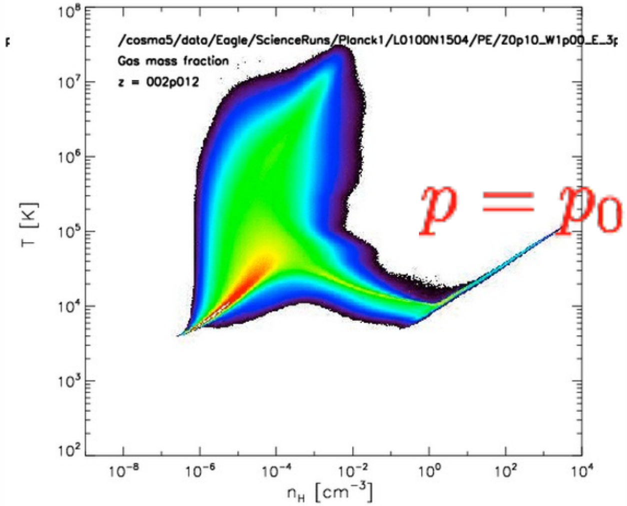
Temperature-density relation in cosmological volume





log <x_HI>
log (N_HI [cm^-2])
Shld, Γ12=1.16, no T_shld
Shld, Γ12=1.16, T_shld
Shld, Γ12=.387, no T_shld
Shld, Γ12=.387, T_shld
Thin, Γ12=1.16
log <n_H [cm^-3]>
Thin, Schaye 2001

Altay+11



$$p = p_0 \left(\frac{\rho}{\rho_0}\right)^\gamma$$

$$\lambda_{\rm Jeans} \propto \left(\frac{c_s^2}{\rho}\right)^{1/2} \propto \rho^{\frac{(\gamma-2}{2})} \propto \rho^{-1/3} \quad \text{for } \gamma = 4/3$$

$$\text{spatial resolution} \propto \rho^{-1/3}$$

$$\dot{M}_{\rm Bondi} \propto \rho^{1/2}$$

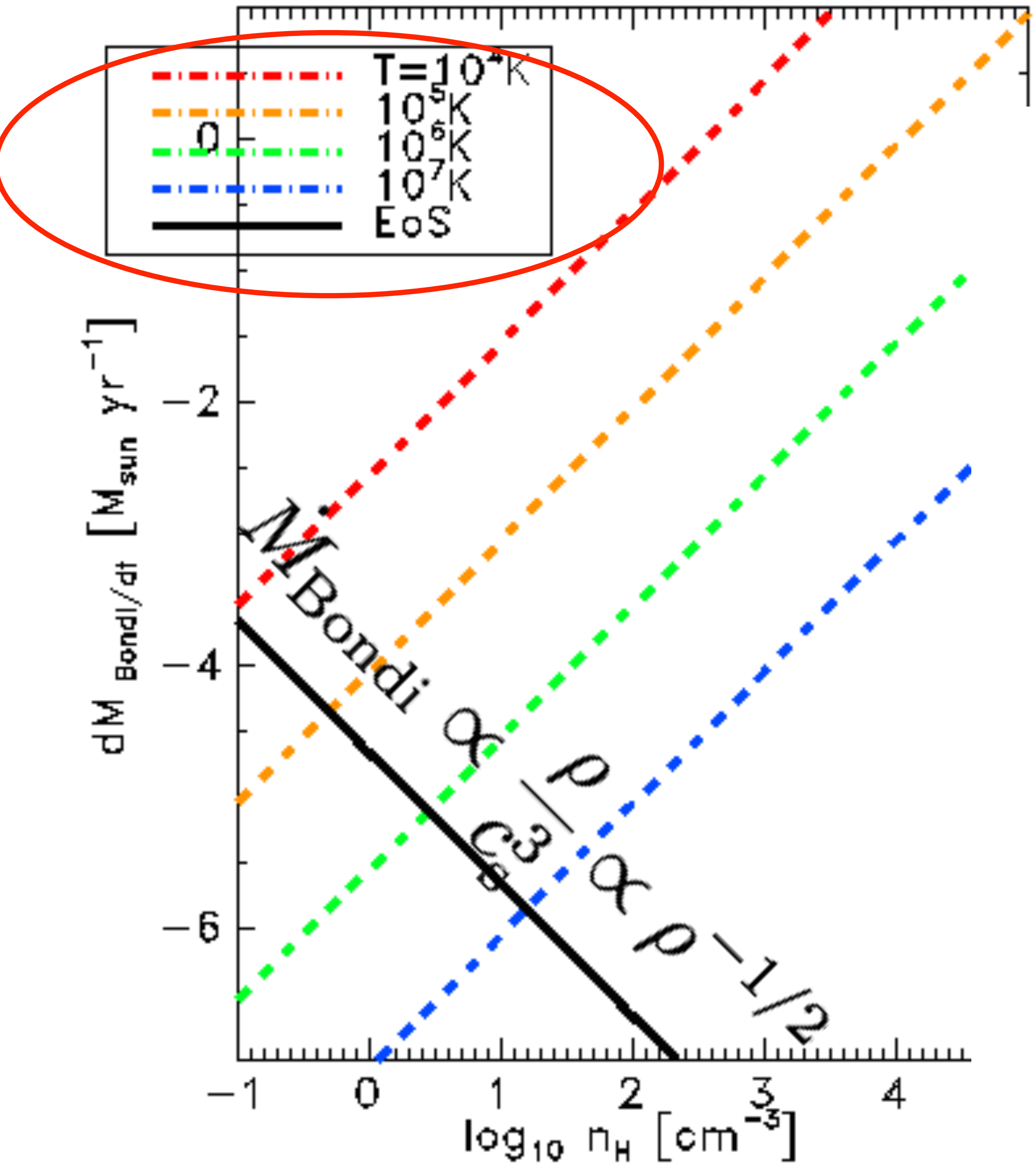
$$r_{\rm Bondi} \propto \rho^{-1/3} \propto \text{spatial resolution}$$

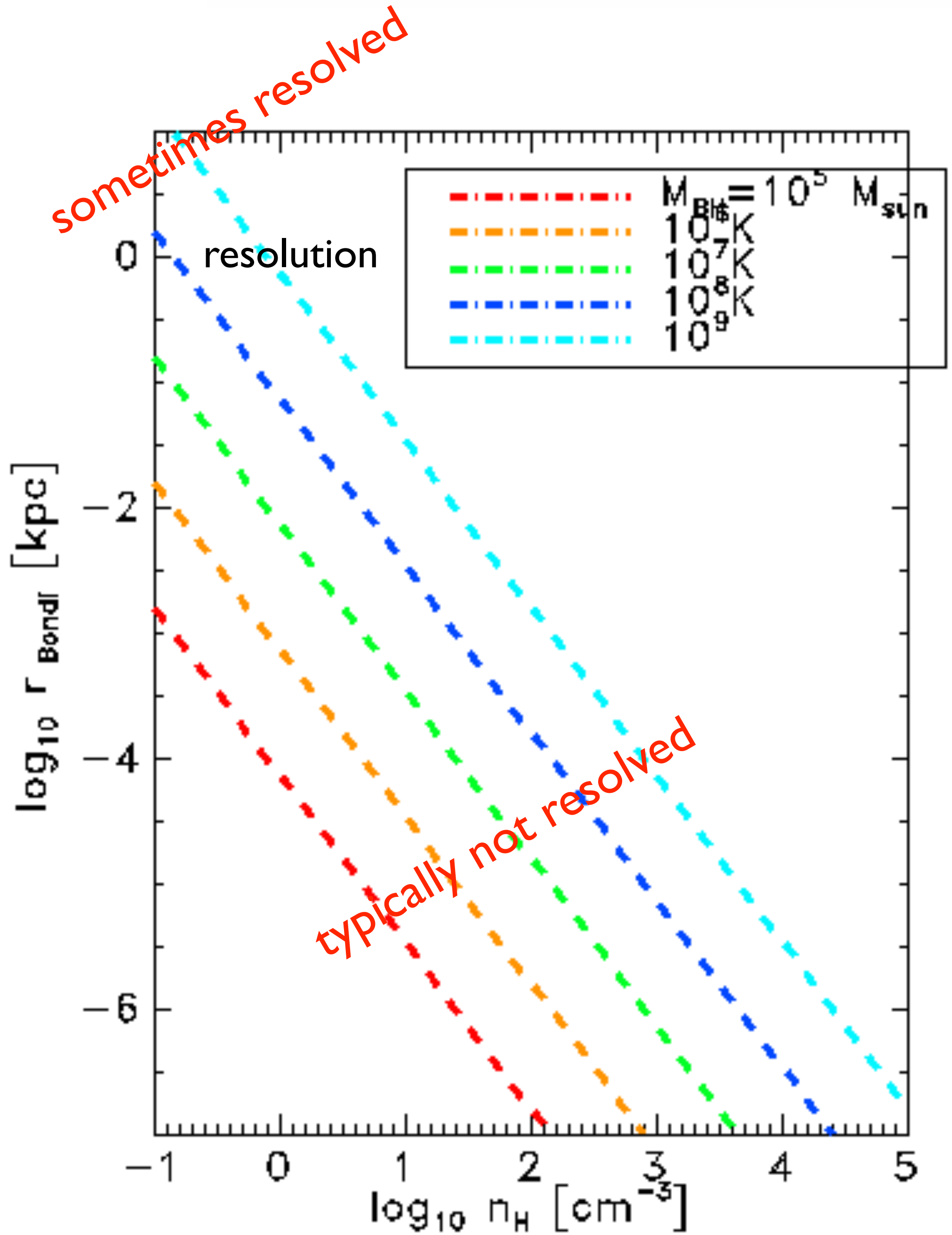
If you "resolve" the Jeans mass, you can "resolve" accretion

Booth & Schaye 09

when not, scale accretion rate to account for insufficient resolution

Accretion rate on the EoS





accretion rate implemented using a stochastic approach (subgrid mass versus particle mass):

- subgrid mass increases given calculated accretion rate
- particle masses follows subgrid mass by swallowing particles stochastically

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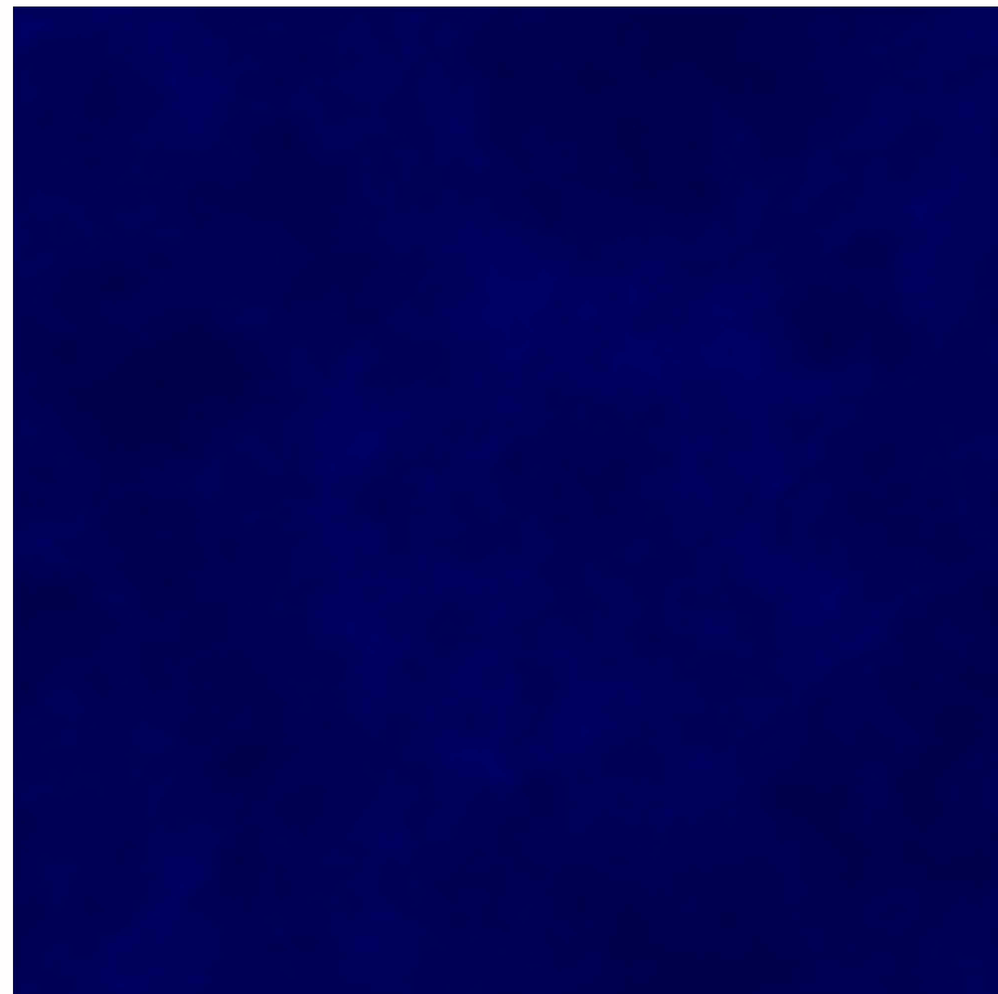
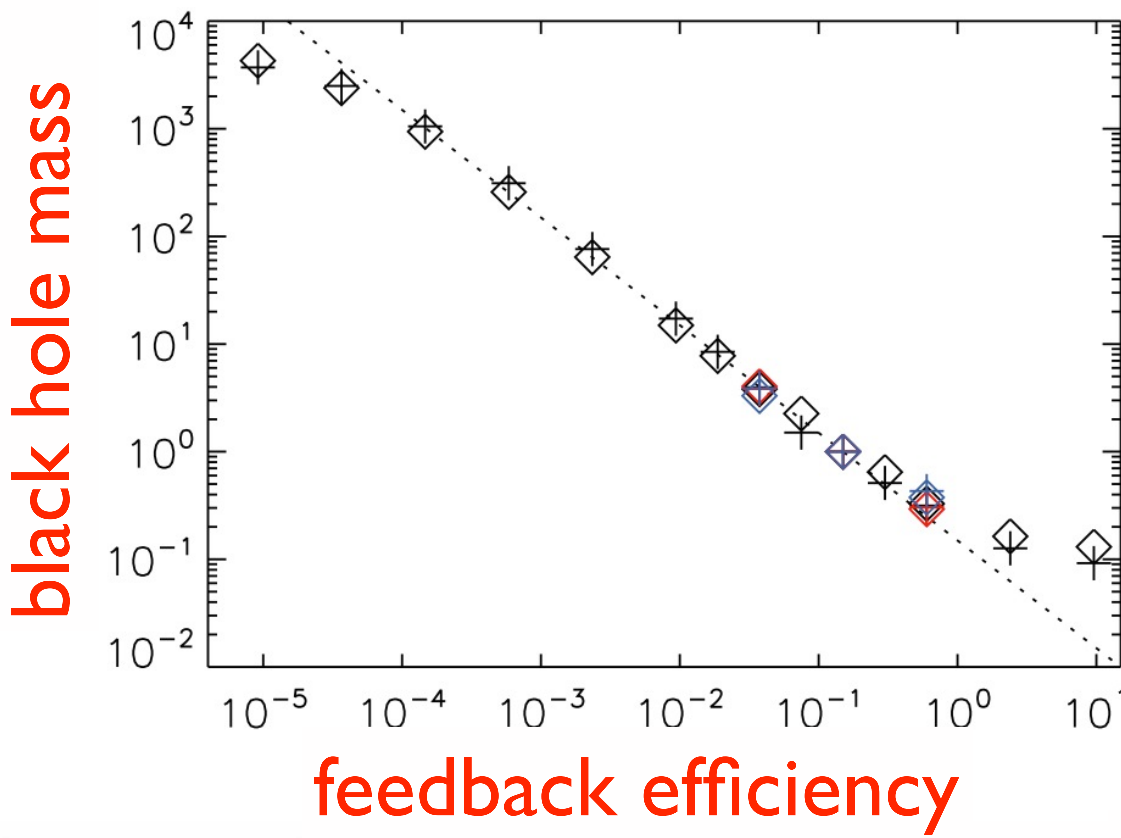


- Bondi radius, and hence Bondi accretion rate typically not resolved
    - subgrid model?
- Effect of angular momentum (Richard Bower's talk)

The impact of angular momentum on black hole accretion rates in simulations of galaxy formation

Y. M. Rosas-Guevara [1] *, R. G. Bower [1] †, J. Schaye [2], M. Furlong [1], C. S. Frenk [1], C. M. Booth [3], R. Crain [2], C. Dalla Vecchia [4], M. Schaller [1], T. Theuns [1,5].

however: rate of increase of BH is mostly set by feedback efficiency, rather than accretion rate *once it is self-regulating*



Booth & Schaye 10

Black hole feedback

$$\dot{E} = \epsilon_f \, \epsilon_r \dot{M}_{\rm acr} c^2$$

↖ couples to ISM

- *if* BH self regulates, injects an amount of energy that balances accretion rate *onto halo*
- *parameter* ϵ_f *determines black hole mass - but not their feedback suppression*
    - *black hole masses cannot be predicted: calibrate* ϵ_f

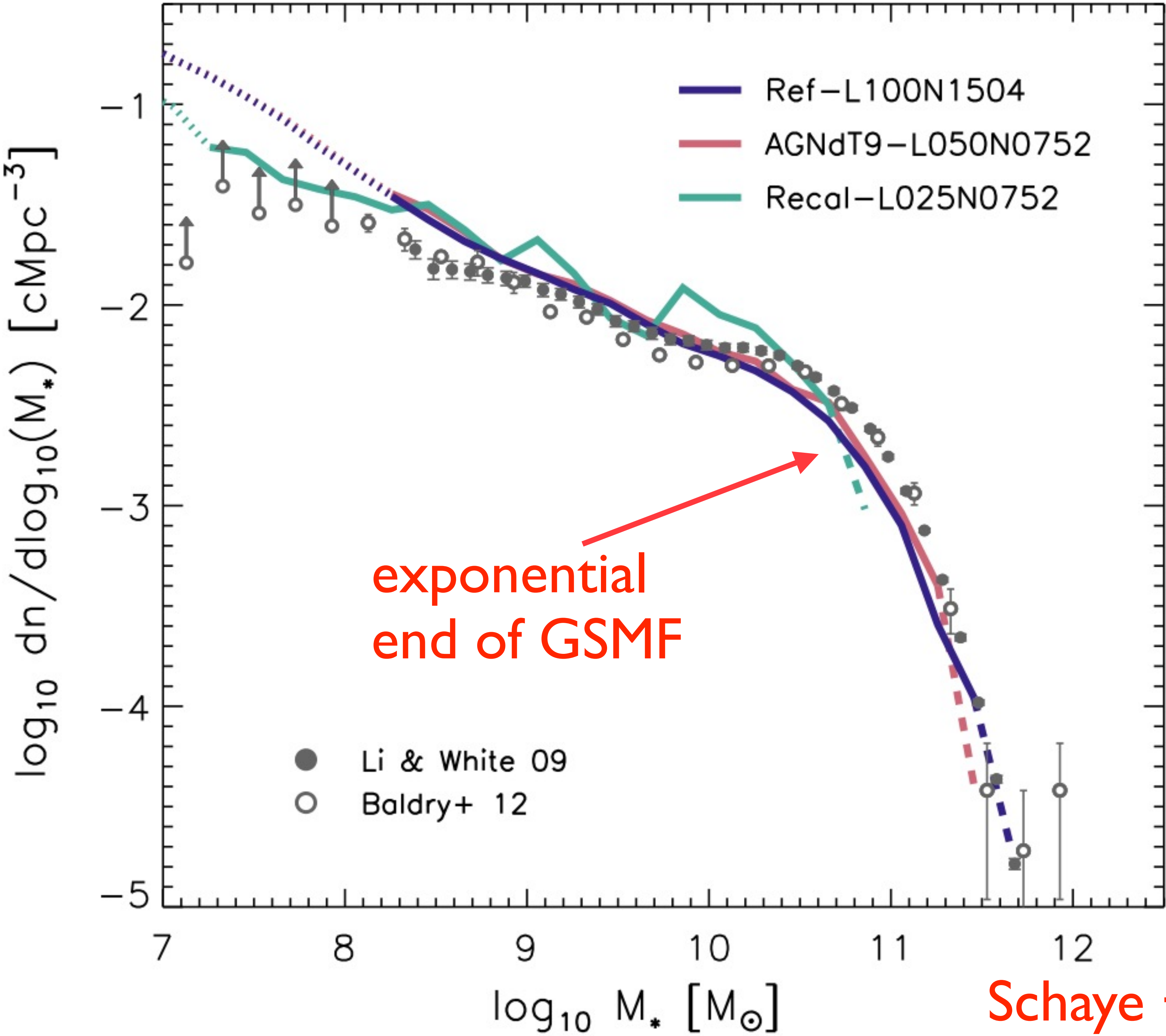
crucial aspect: how to transfer $\dot{E}$ to gas?

Eagle: heat gas to fixed temperature, T = $10^{7.5}$K, probabilistically

$$\text{probability} = \frac{\int_{t_1}^{t_2} \dot{E} dt}{(k_{\rm B}T/m_{\rm h})\, M_{\rm SPH}}$$

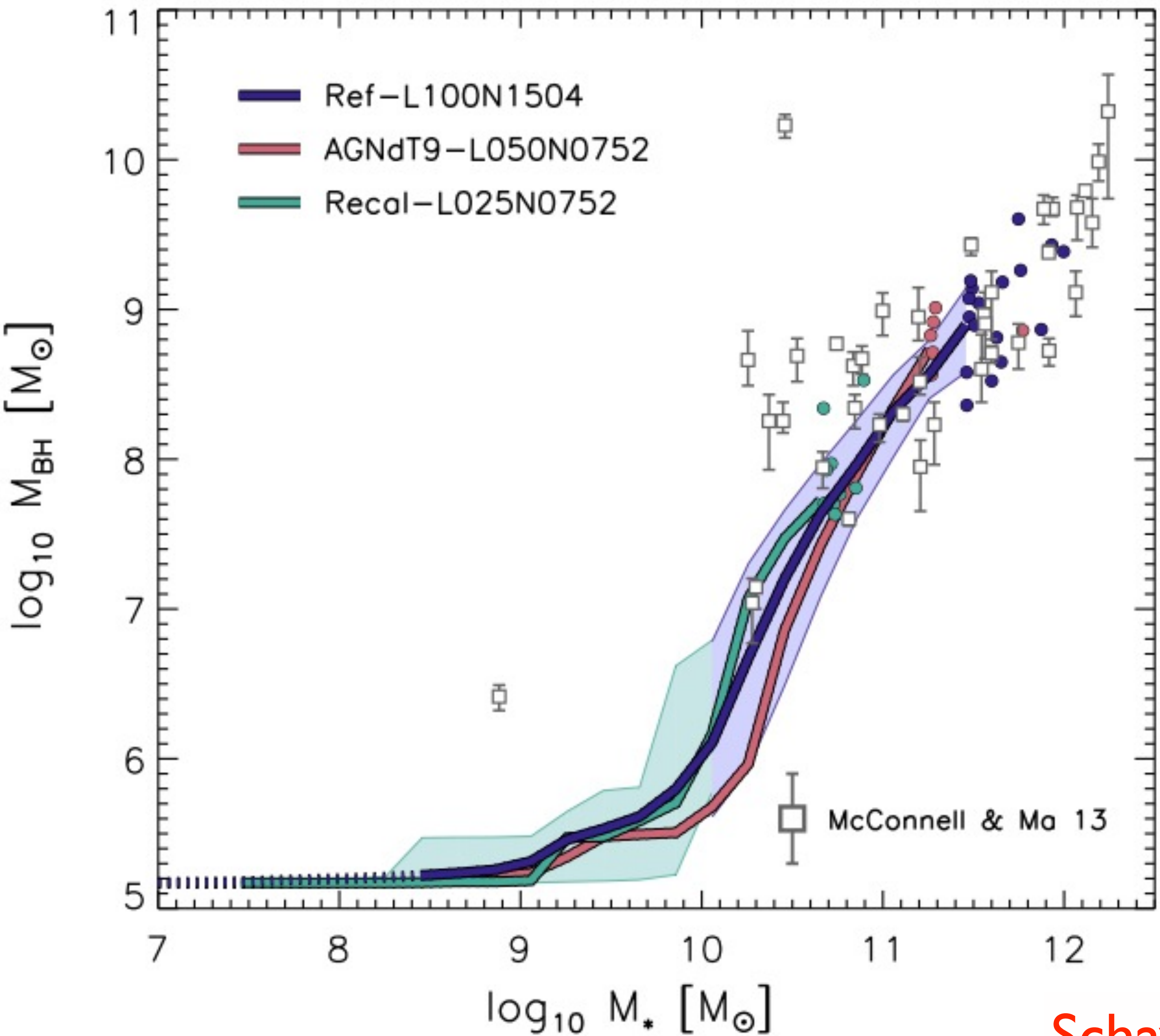
- gas always heats to high temperature: minimise radiative losses
- use reservoir to store energy if not used
- introduces stochasticity

- works well
- massive clusters: need higher heating temperature



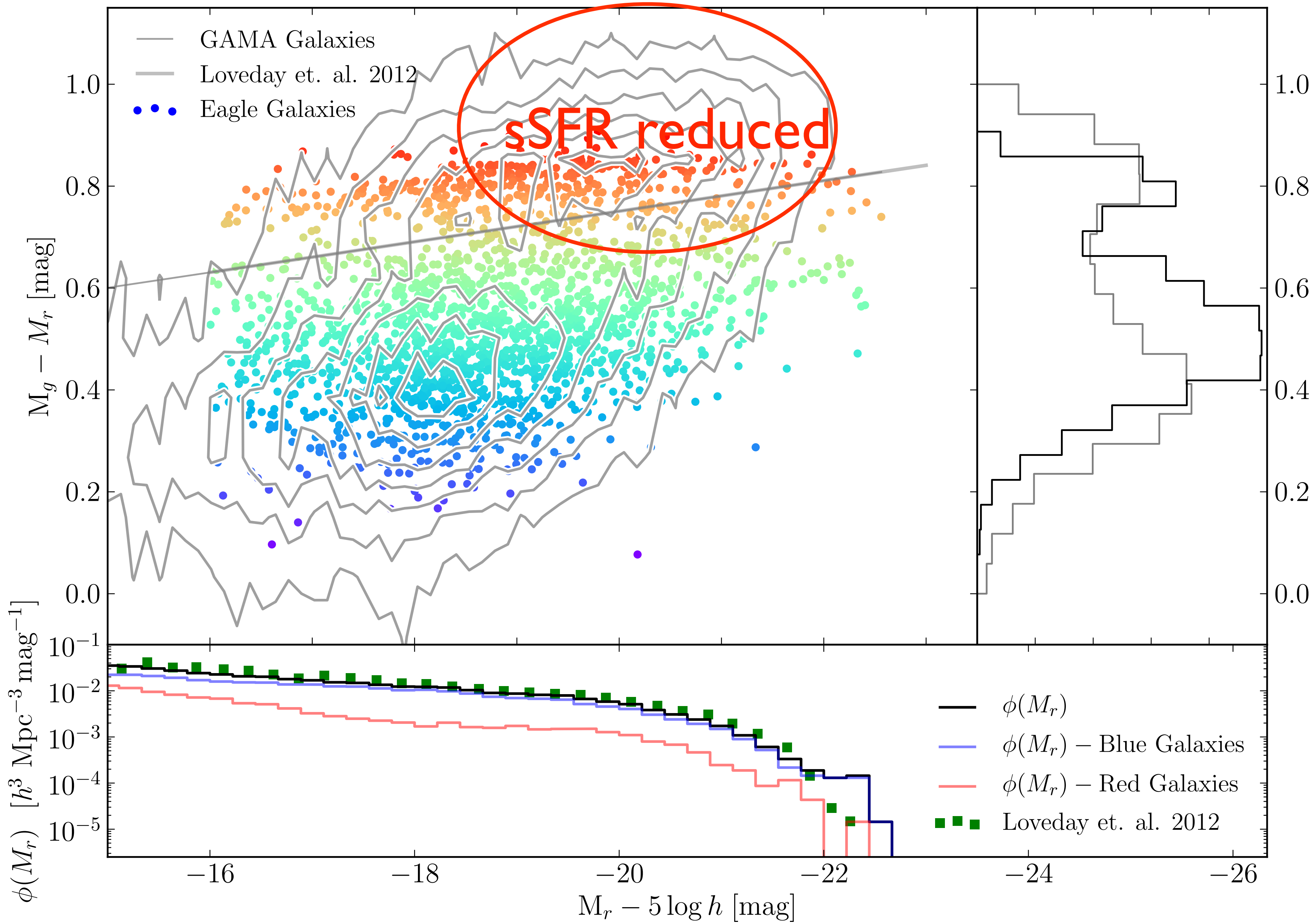
Ref−L100N1504
AGNdT9−L050N0752
Recal−L025N0752
Li & White 09
Baldry+ 12
exponential end of GSMF
log10 dn/dlog10(M*) [cMpc−3]
log10 M* [M⊙]
−1
−2
−3
−4
−5
7
8
9
10
11
12

Schaye +14


Ref−L100N1504
AGNdT9−L050N0752
Recal−L025N0752
McConnell & Ma 13
$\log_{10} M_{BH}$ [$M_\odot$]
$\log_{10} M_*$ [$M_\odot$]
5
6
7
8
9
10
11
7
8
9
10
11
12

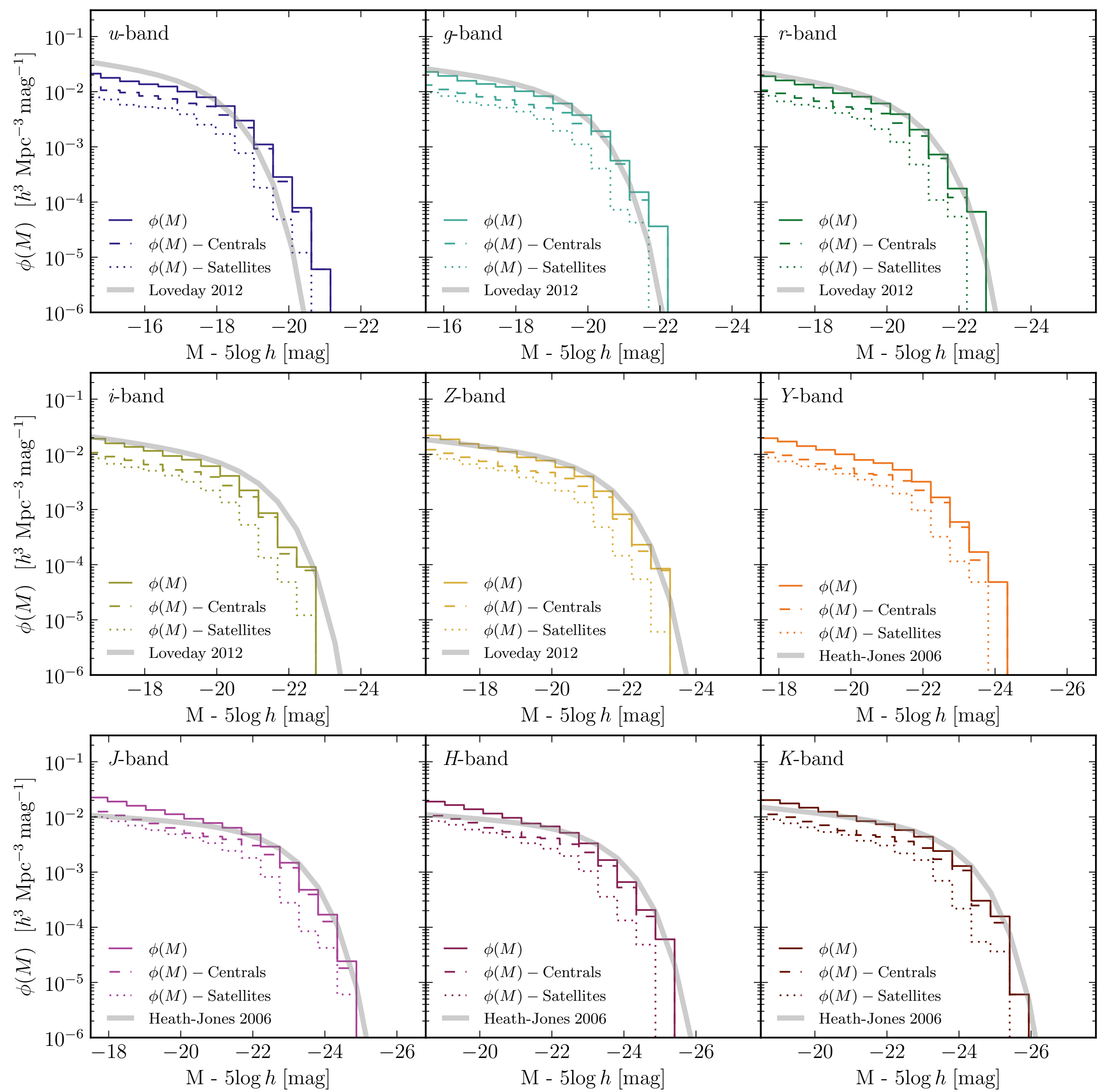
Schaye +14

z=0 colour-magnitude diagram vs GAMA



Trayford +14

z=0 luminosity function



Trayford +14

Illustris: (Springel+05, ++)

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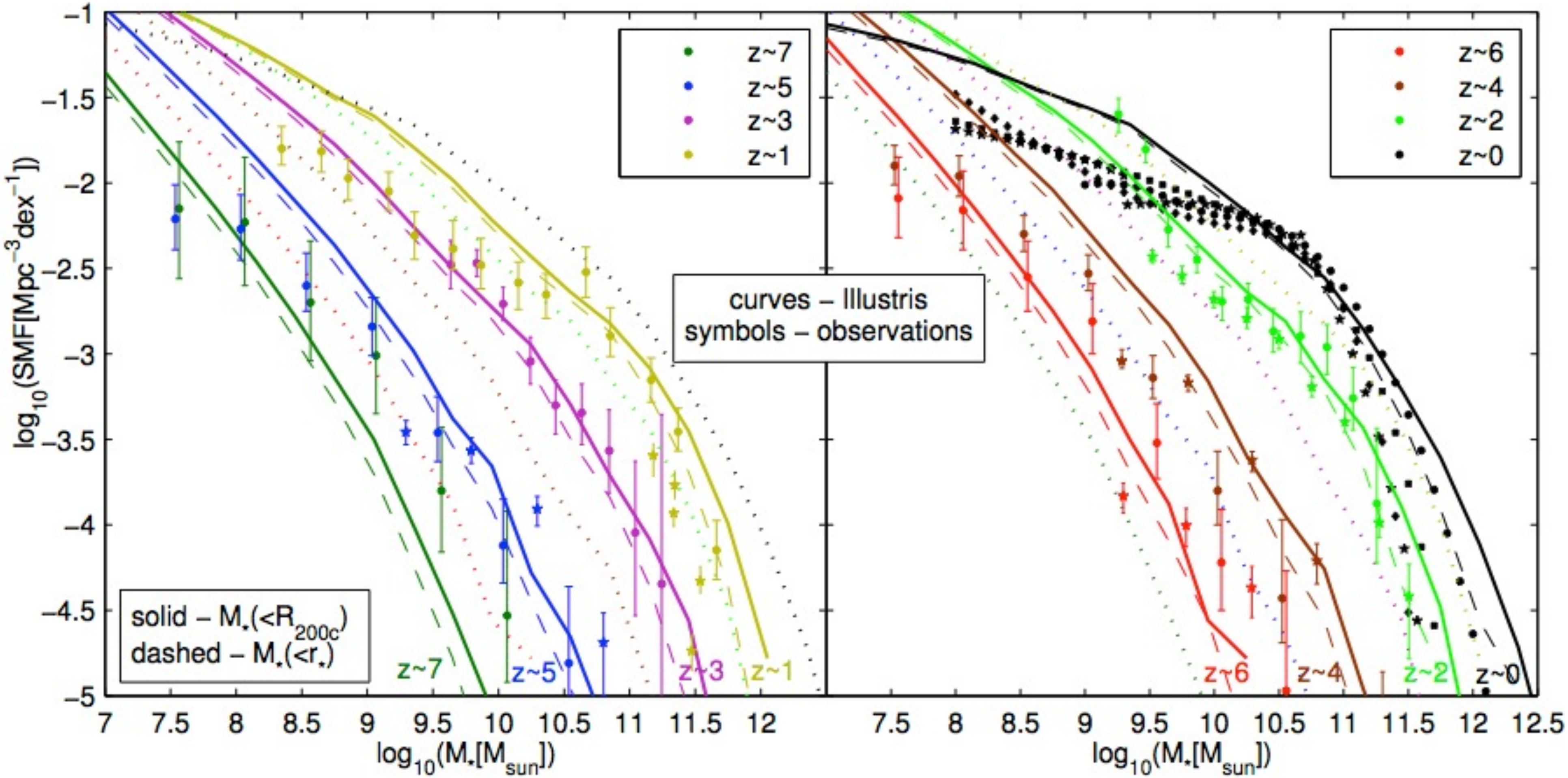
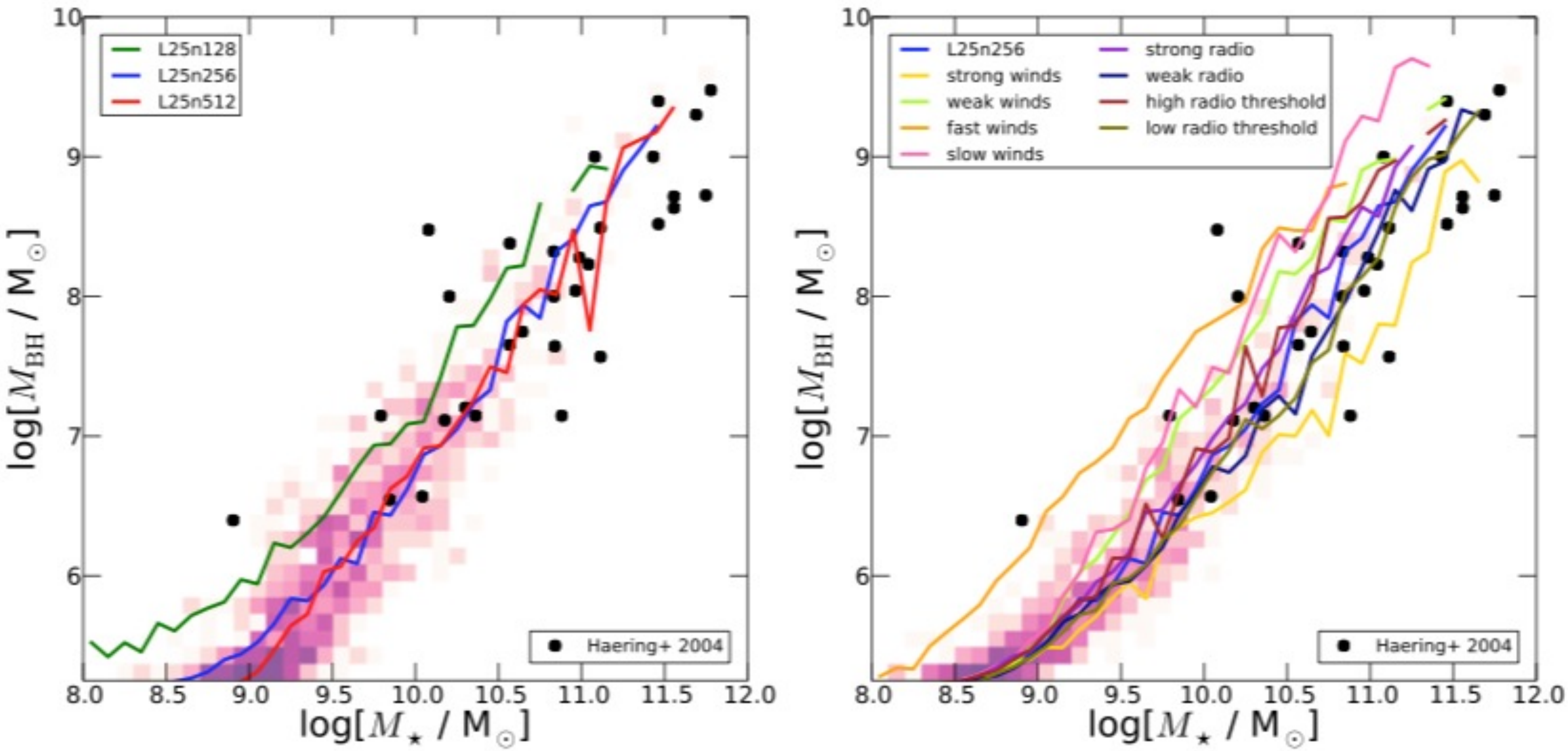
- QSO mode at high accretion rate
  - heats surrounding gas
- Radio mode at low accretion rate
  - inflate bubbles thermally
    - parameters: radius, energy, trigger, location
- Radiative feedback
    - active BH ionizes gas, suppressing cooling
      requires non-equilibrium calculations

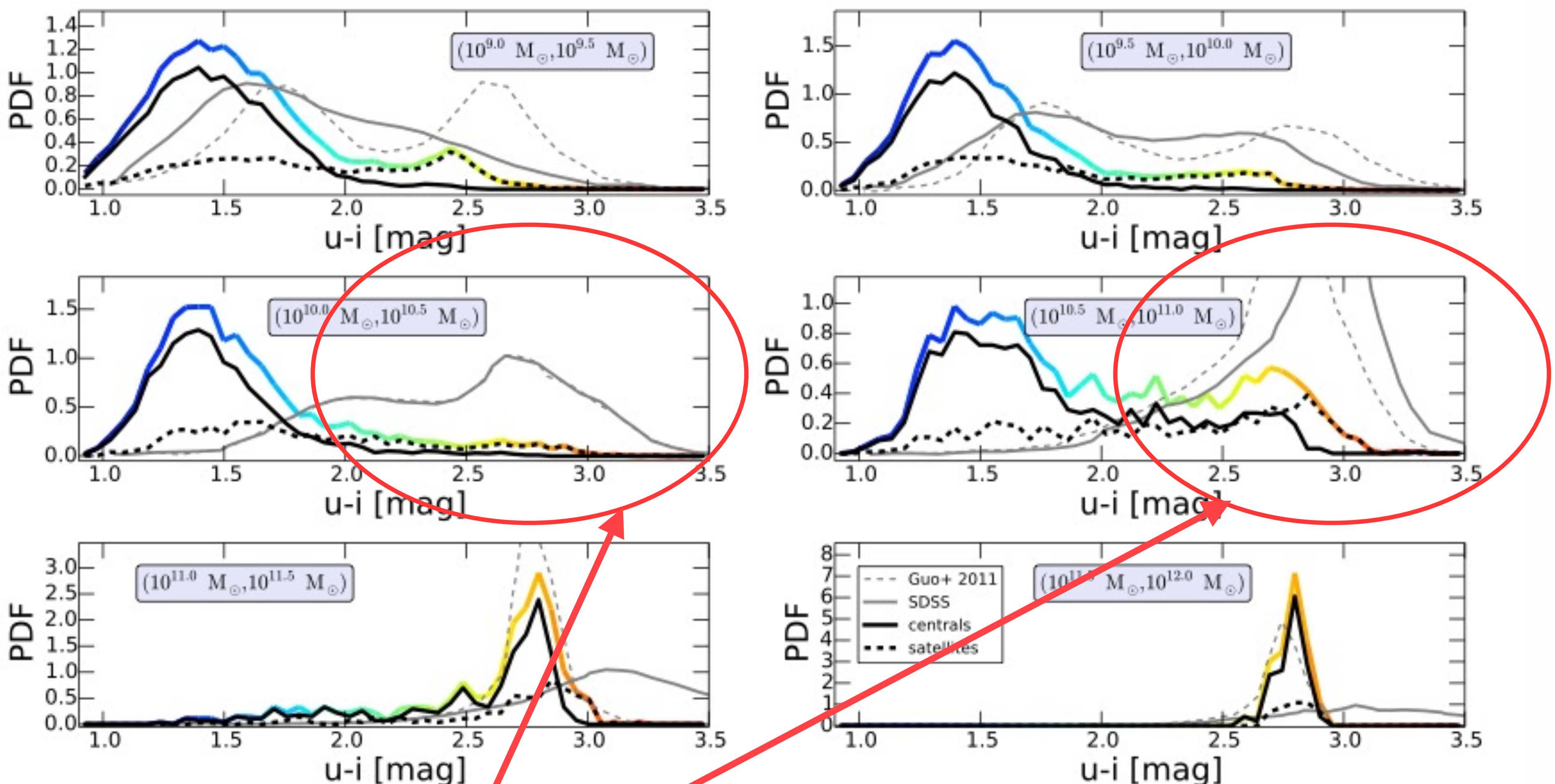

z~7
z~5
z~3
z~1
curves – Illustris
symbols – observations
solid – M*(<R200c)
dashed – M*(<r*)
z~6
z~4
z~2
z~0
log10(SMF[Mpc^-3dex^-1])
log10(M*[Msun])

Genel+14



Vogelsberger +13

colour cuts



too little quenching?

Vogelsberger +14

Massive Black:

The MassiveBlack-II Simulation: The Evolution of Halos and Galaxies to $z \sim 0$

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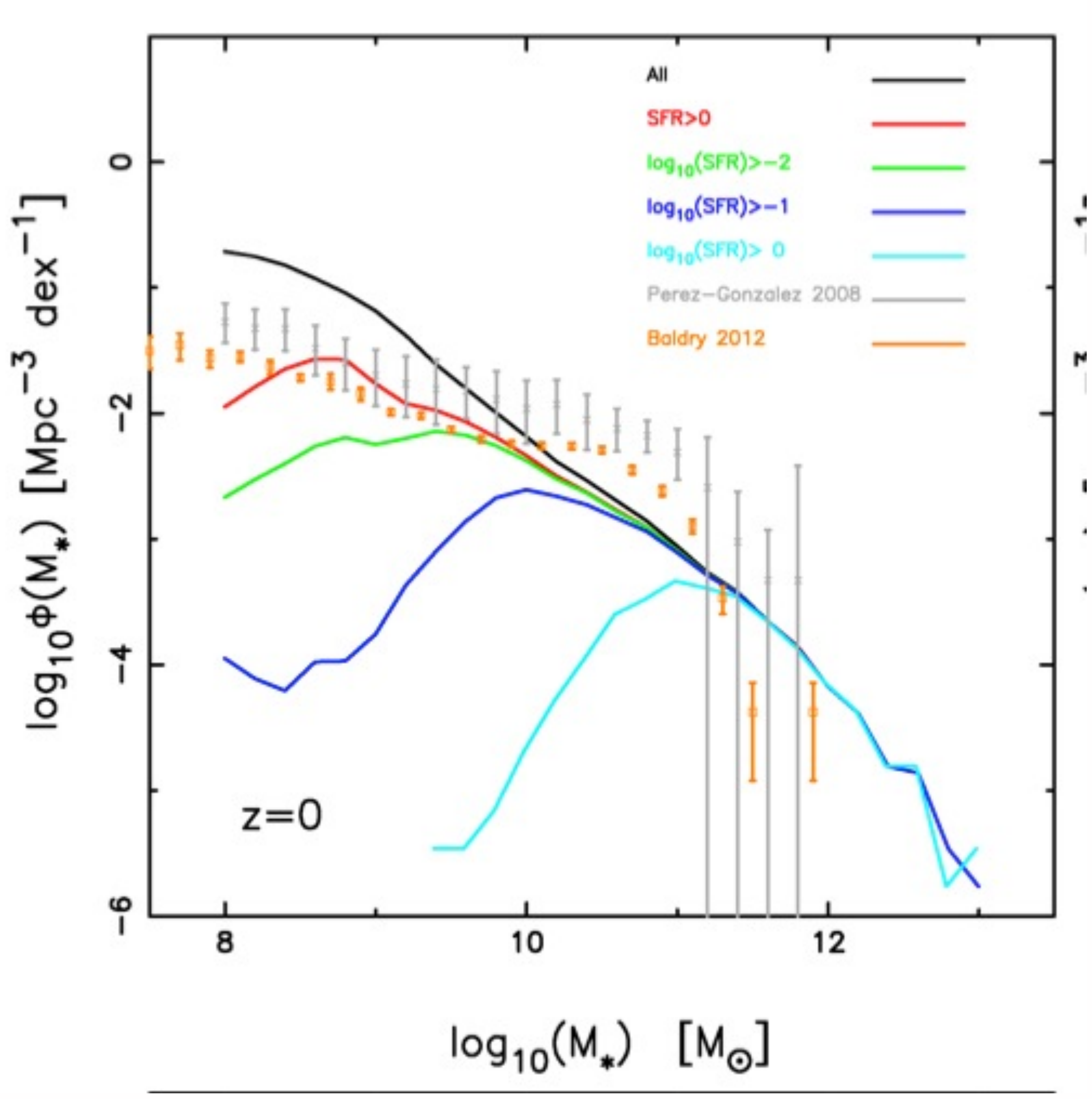
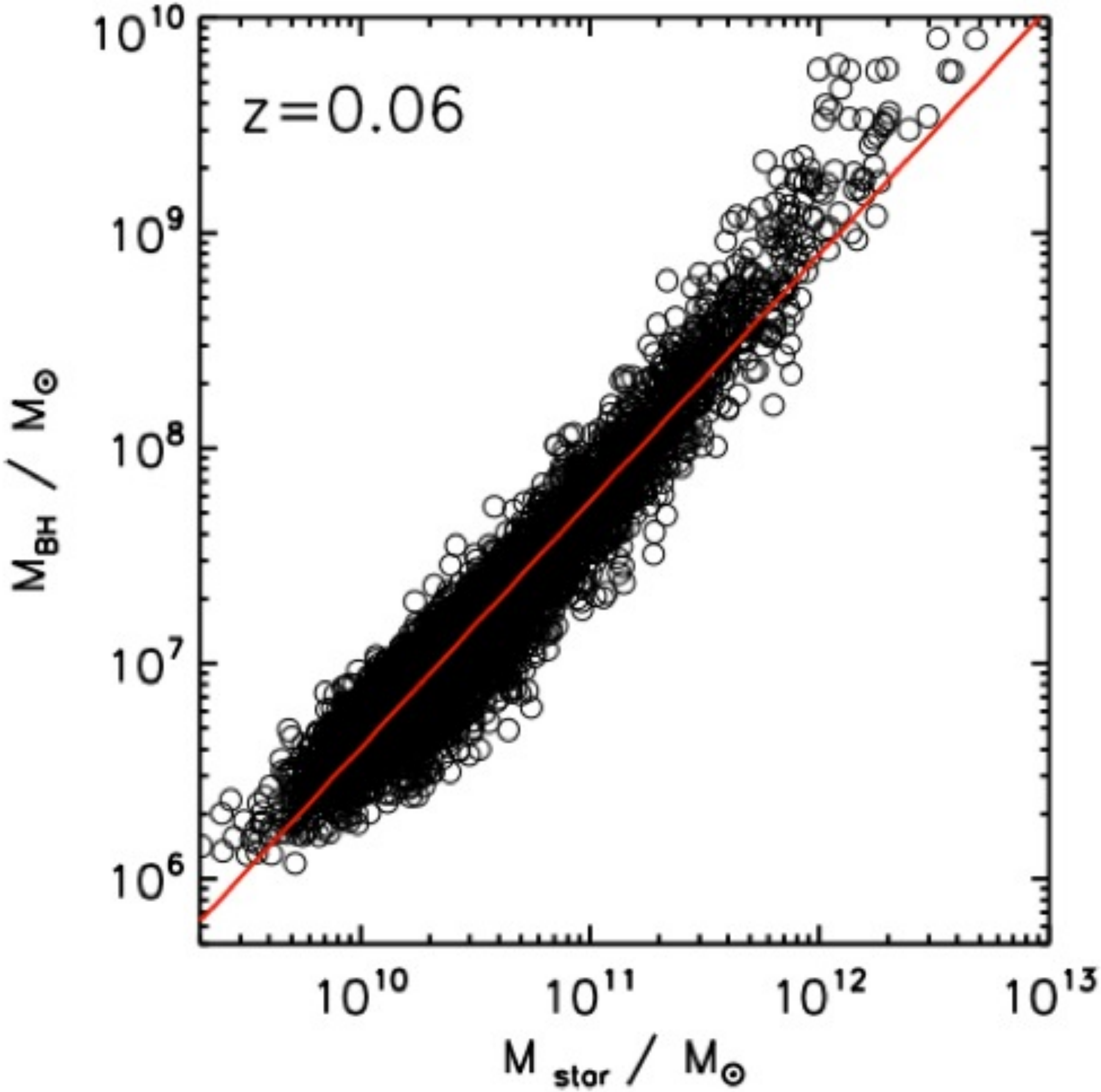
  - heats surrounding gas

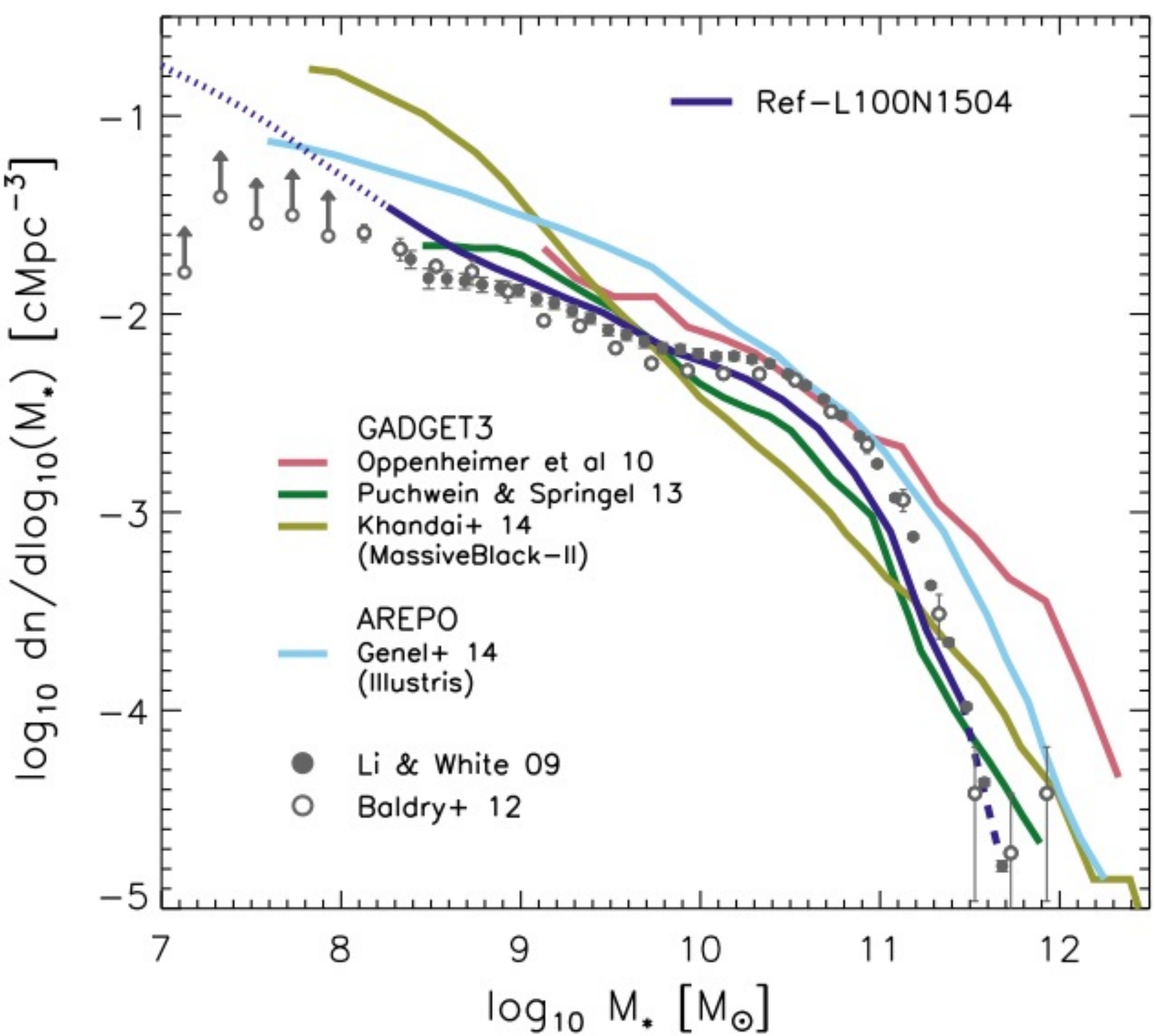

All
SFR>0
log10(SFR)>−2
log10(SFR)>−1
log10(SFR)> 0
Perez−Gonzalez 2008
Baldry 2012
z=0
log10Φ(M*) [Mpc−3 dex−1]
log10(M*) [M⊙]
0
−2
−4
−6
8
10
12

Khandai+14

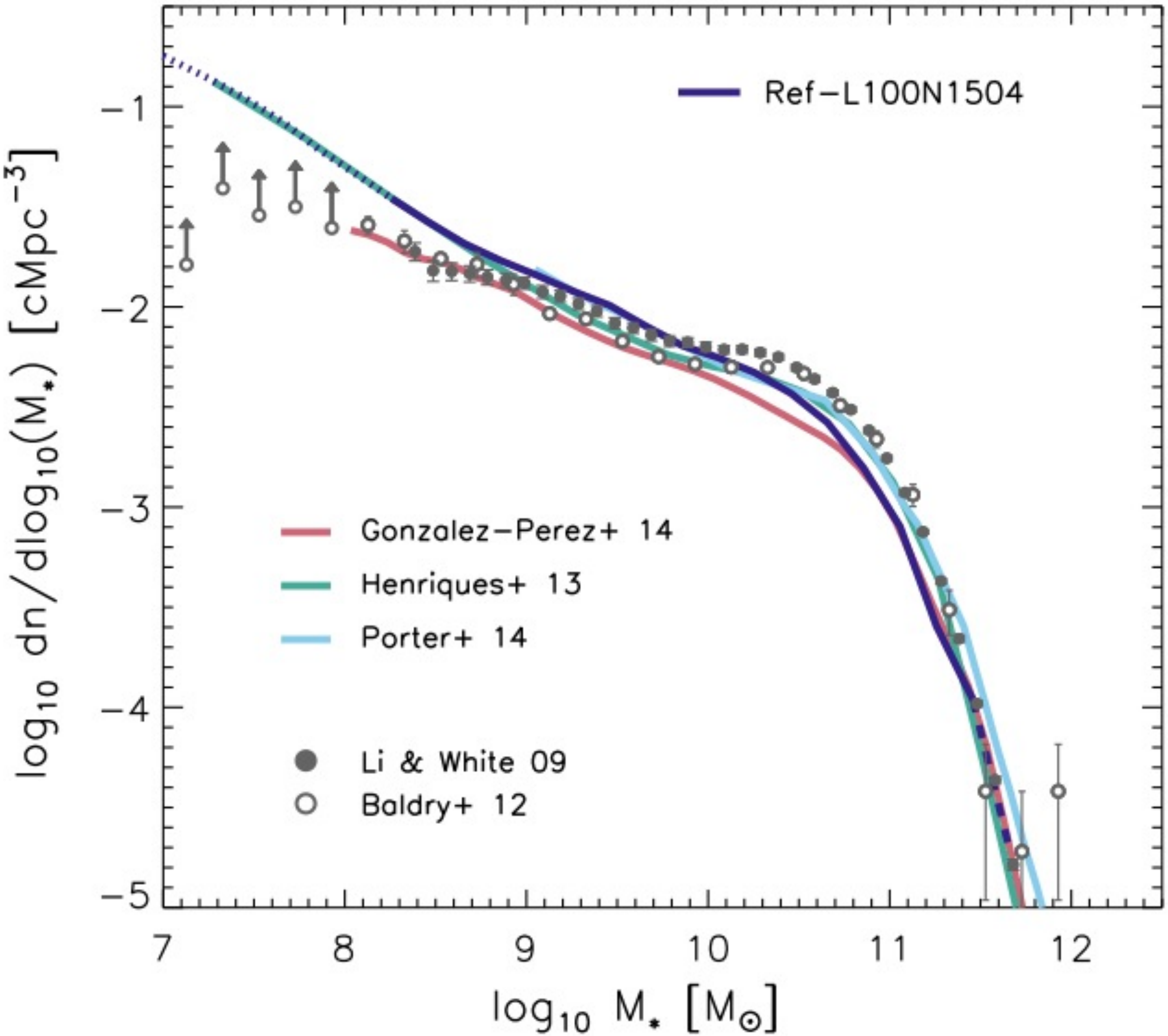

z=0.06
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
M_{BH} / $M_{\odot}$
10^{10}
10^{11}
10^{12}
10^{13}
M_{star} / $M_{\odot}$

Khandai+14

Comparison: hydro simulations



Comparison: Eagle vs semi-analytics



Menu:

- Need for AGN in cosmological simulations
    - (in addition to black holes existing!)
- Implementation: Physics versus subgrid physics
  - Seeding
  - Feeding and merging
  - Feedback(ing)
- What can we learn from such simulations?

(Eagle centric view of)

What we can learn from such simulations.

- SN feedback efficiency sets stellar mass at low mass
    - galaxy stellar masses cannot be predicted
- AGN feedback efficiency sets accretion rate
    - BH masses cannot be predicted

… when self-regulating

- not true for stellar mass at high z
- not true for BH at low BH mass

- No need for selecting 2 feedback "modes" by hand

What we can learn from such simulations.

- It was not obvious that a relatively simple subgrid model would work
- No obvious inconsistencies with data so far
    - mass-metallicity relations most discrepant
- Use simulations to investigate evolution
    - mergers vs in-situ SF, interaction IGM-galaxies, interaction AGN-SF
- Experiments: variation of parameters, degeneracies
    - good agreement suggest model reasonably realistic
- Use simulations to check for (self)-consistency of data

An overview of AGN implementations in cosmological simulations

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