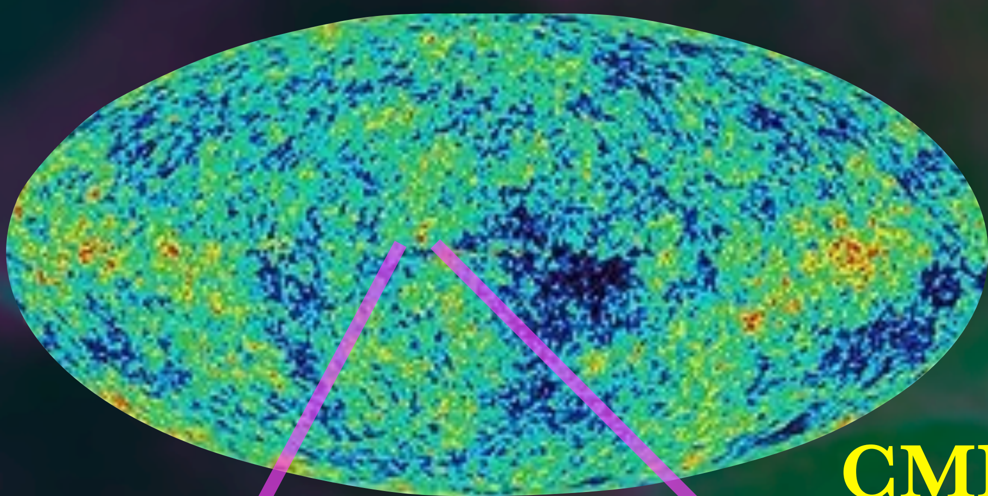
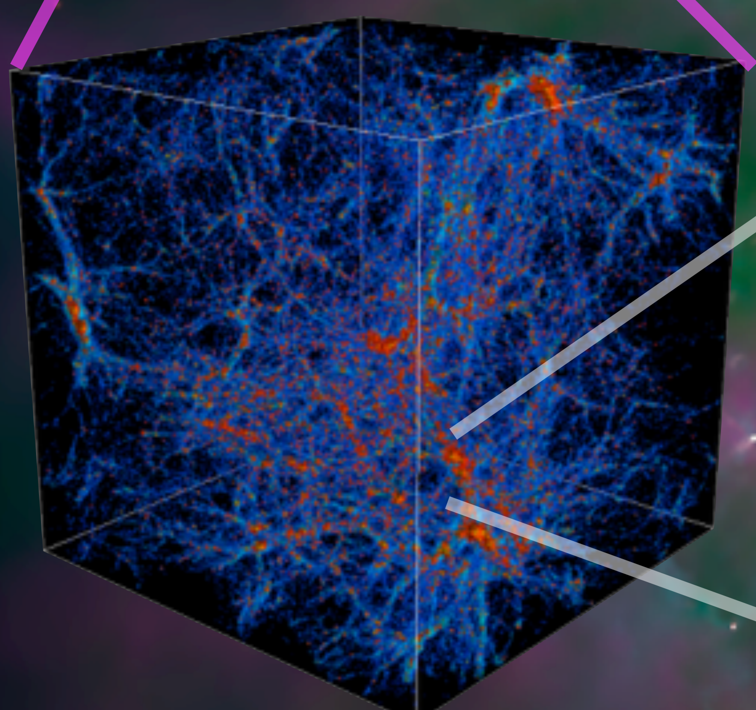
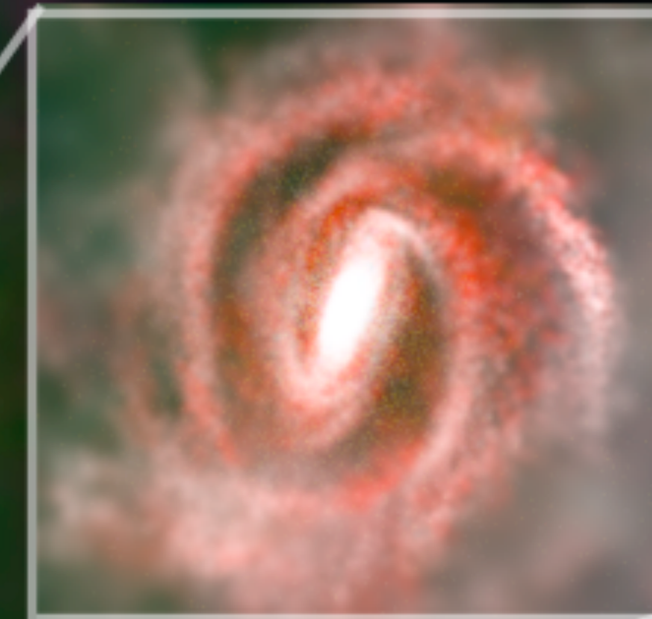
Recent Progress in Numerical Cosmology & Galaxy Formation



CMB



Large Scale Structure



Galaxy Formation

Ken Nagamine
Osaka / UNLV

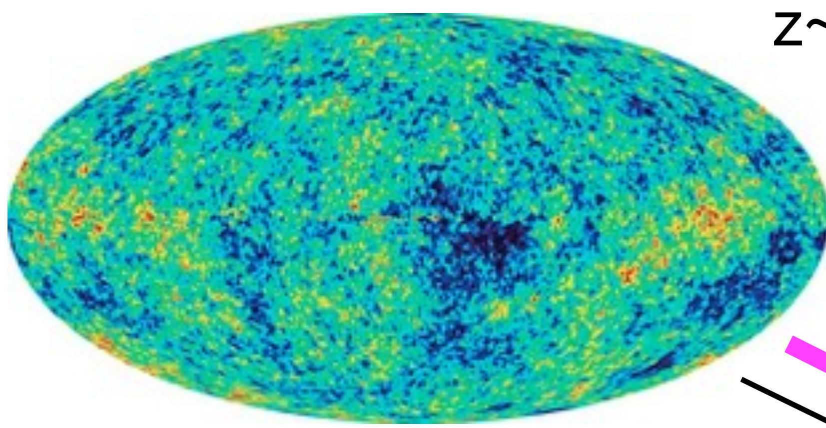
Recent Collaborators :

J.-H. Choi (UT Austin)
J. Jaacks (UT Austin)
E. Romano-Diaz (Bonn)
I. Shlosman (Kentucky/Osaka)
R. Thompson (NCSA)
K. Todoroki (Kansas)
Hide Yajima (Tohoku)
S. Aoyama, Y. Luo, I. Shimizu (Osaka)

Computational Cosmology in a ΛCDM Universe

Self-consistent galaxy formation scenario from first principles (as much as possible)

z~1100



Initial conditions

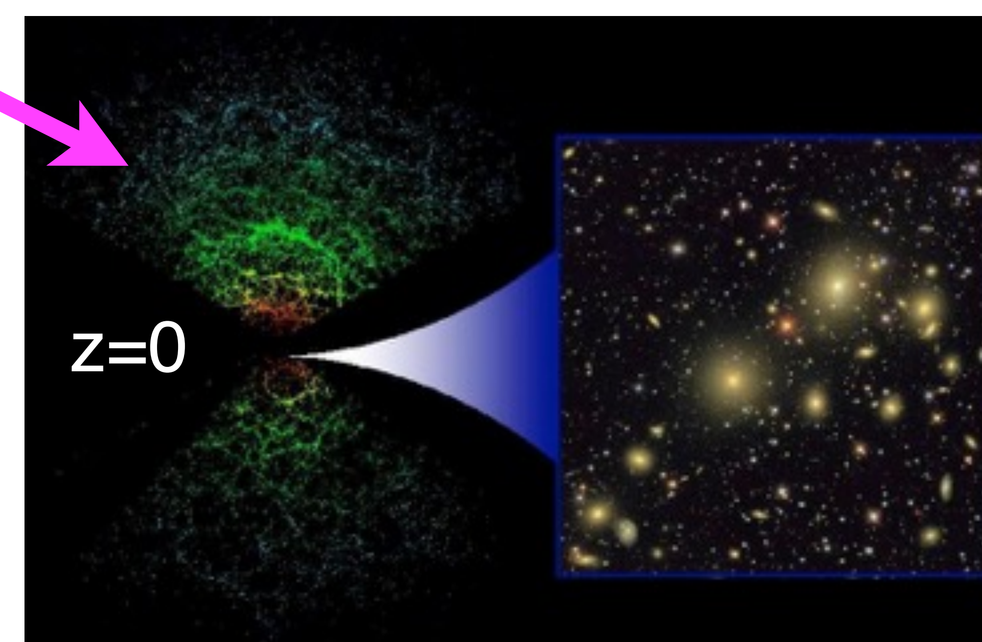
Cosmological params,
Dark energy, Dark matter,
Baryons
(+expanding universe)

z=100

z=10

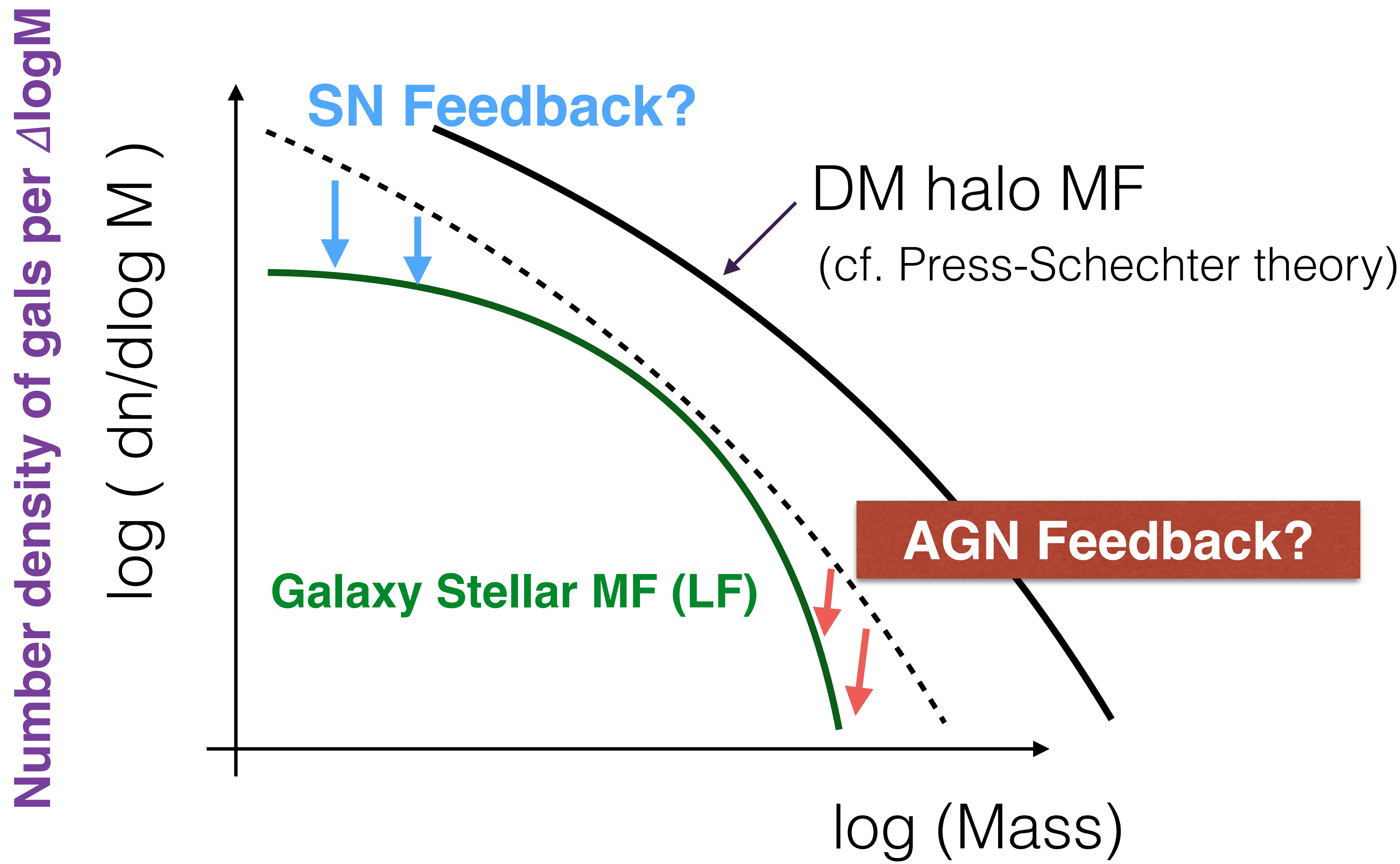
z=3

Radiative heating/cooling,
Star formation,
& Feedback

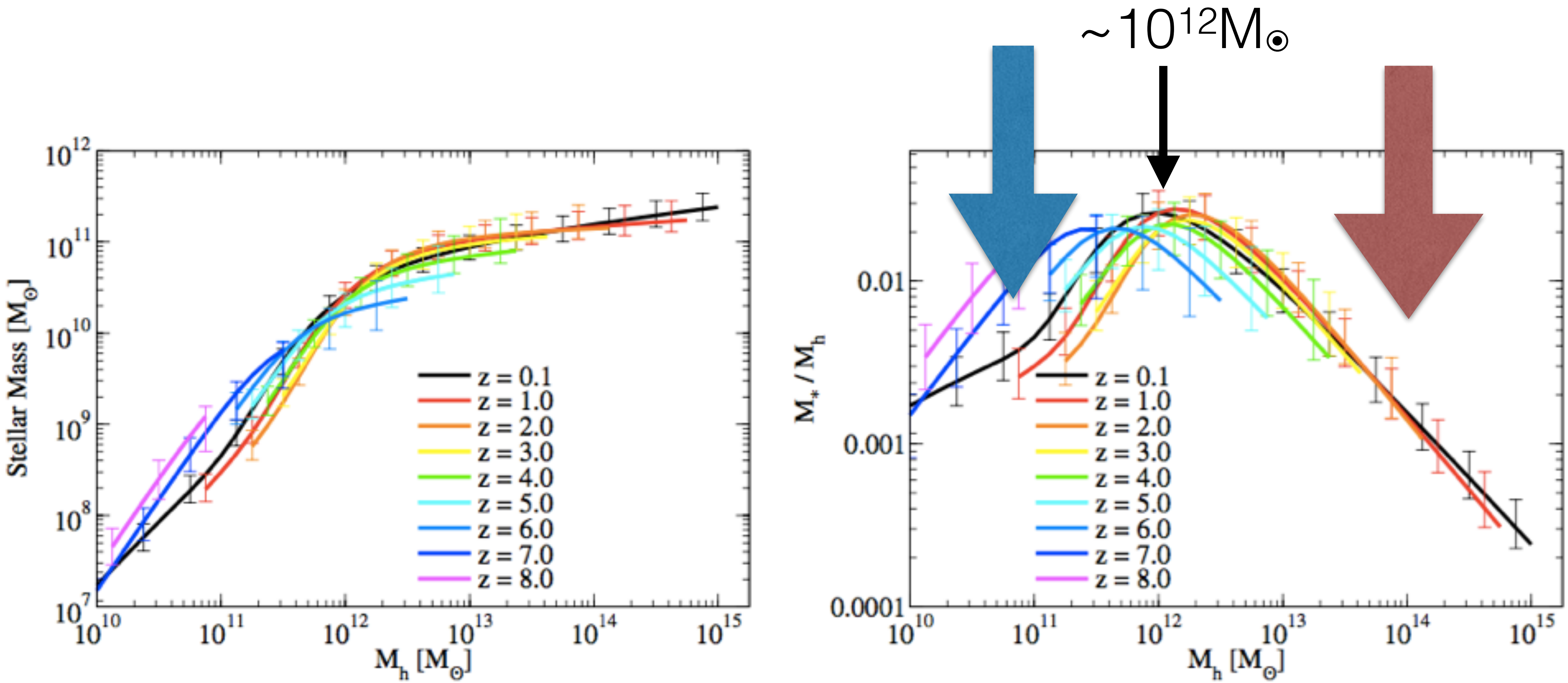


Gravity + Hydrodynamics

Dark Matter Halo —> Galaxies



Stellar-to-Halo Mass Ratio (SHMR)



Behroozi+'10, '13

(cf. Ilbert+'10; George+'11; Leauthaud+'12)

Historical Flow Chart of SN Feedback Treatment

1st phase
'90s

Simple thermal feedback

↓

2nd phase
'00-'10

Phenomenological subgrid model (thermal + kinetic) based on galactic properties (SFR, M_{star}, M_{halo})

Multi-phase ISM model

↓

3rd phase
'10~
(w/ zoom sim)

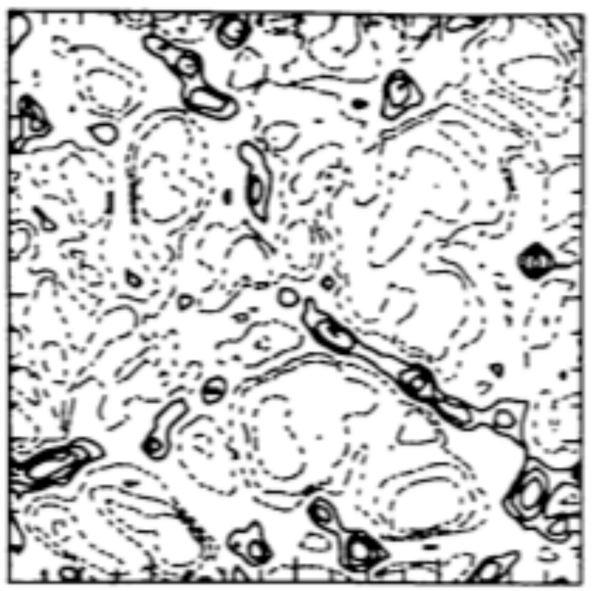
More direct, local, thermal+kinetic +radiative feedback models

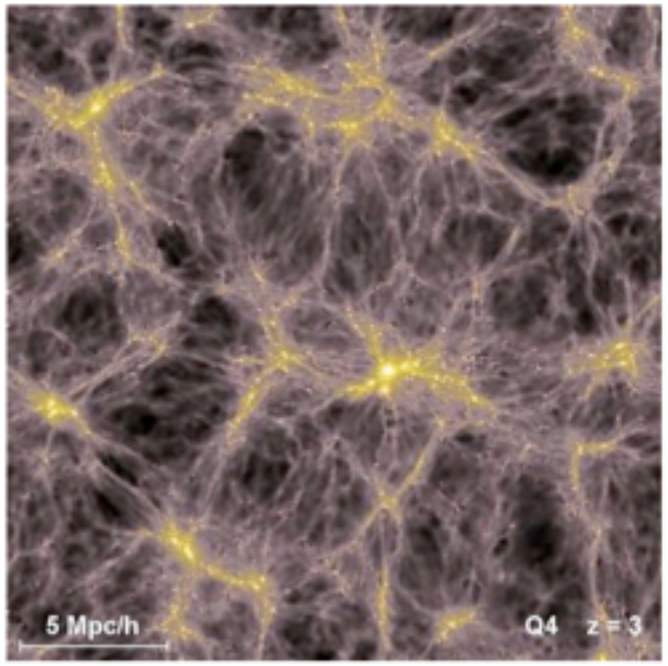
Three Revolutions in Cosmological Hydro Simulations

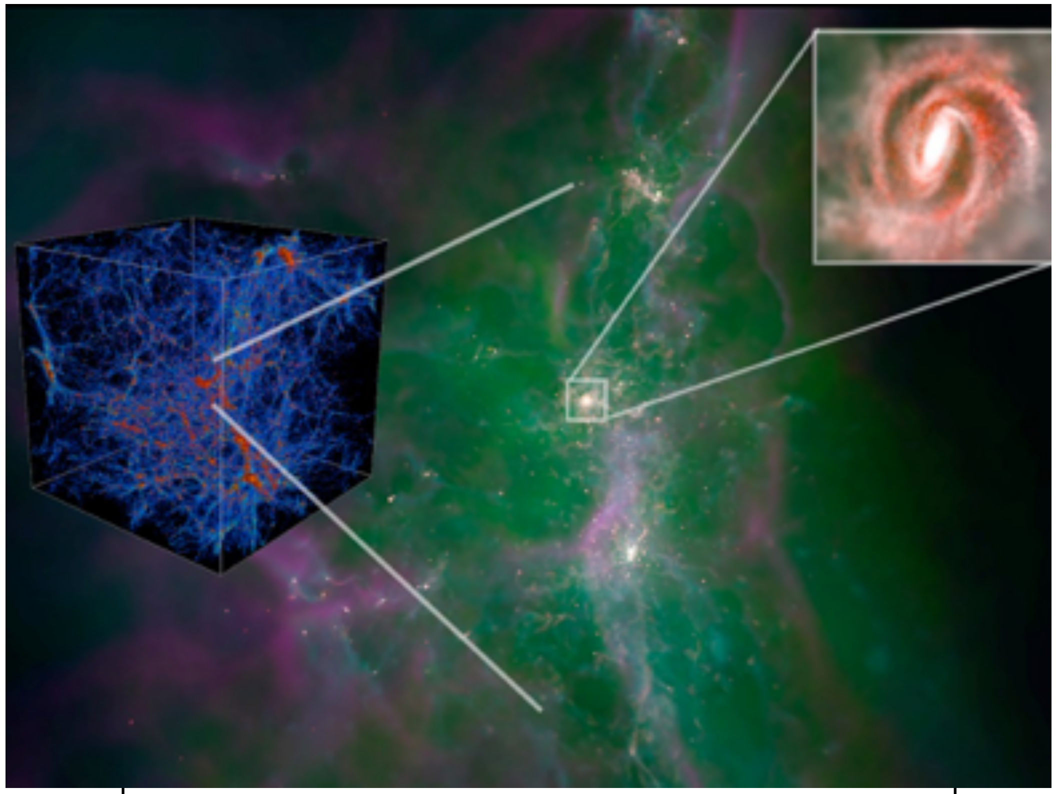
1990': 1st Revolution

2001-2011 2nd Rev.

2012~ 3rd Rev.







First cosmological, but coarse calculation

Resolution~100 kpc

e.g., Cen '92
Katz+ '96

Larger scale, medium resolution **w. subgrid models**

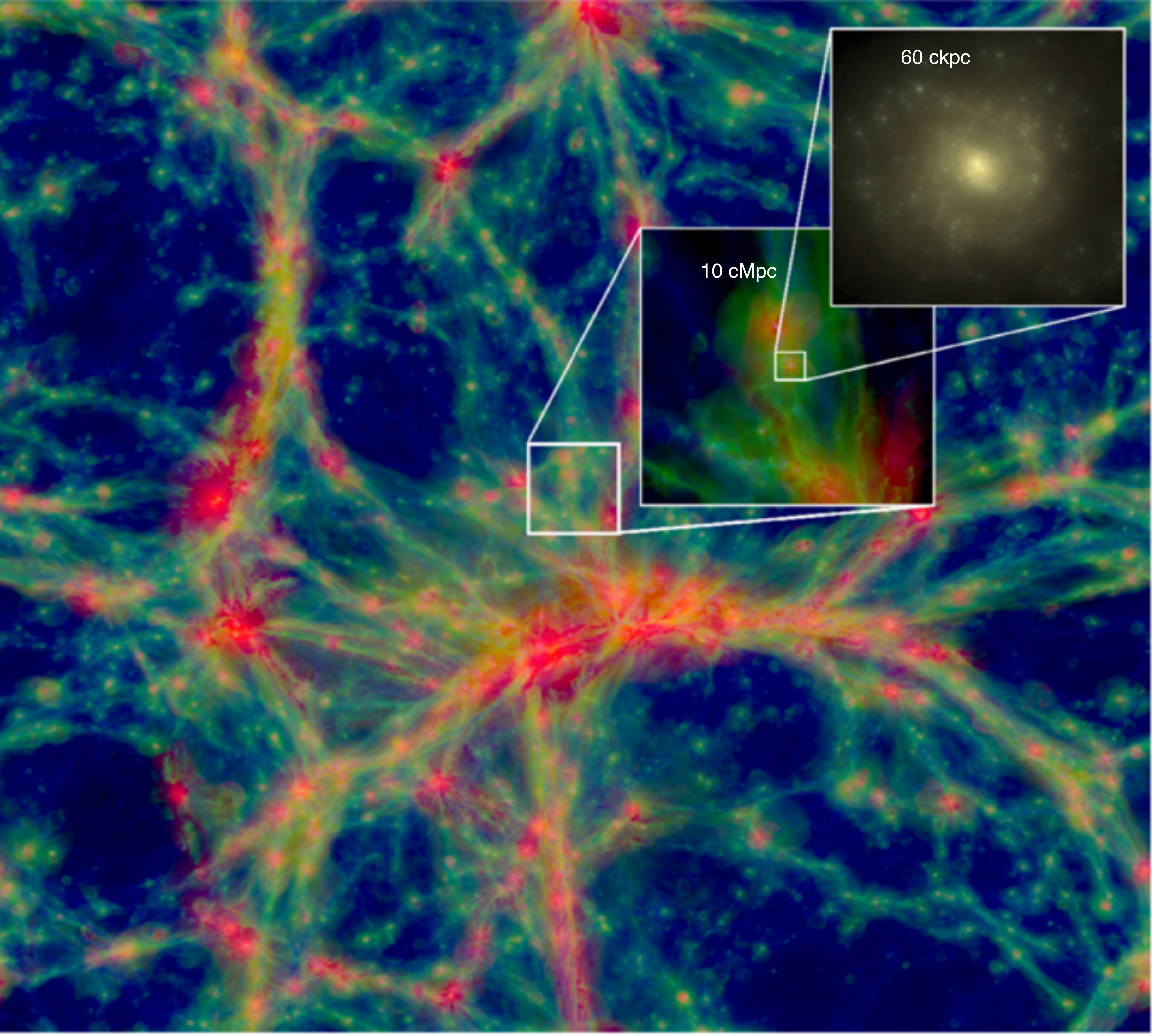
Resolution ~ kpc

e.g., KN+ '01, 04, 06
Springel & Hernquist '03

Zoom-in method allows much higher res.

Resolution~ 10-100pc

e.g. MUSIC (Hahn & Abel '11)



EAGLE sim (Schaye+ '15)

- Pressure SF model (Schaye & Dalla Vecchia '08)
- Stochastic thermal FB w/ ΔT, $f_{th}(n, Z)$ params (Dalla Vecchia & Schaye '08) — reserve E_{th} for 3e7 yr.
- Mass-loss (Wiersma+'09) — AGB, Type Ia & II SN, MS winds (Margio '01; Portinari+'98)

z=0

100 cMpc

$T < 10^{4.5}$ K (blue)

$10^{4.5}$ K $< T < 10^{5.5}$ K (green)

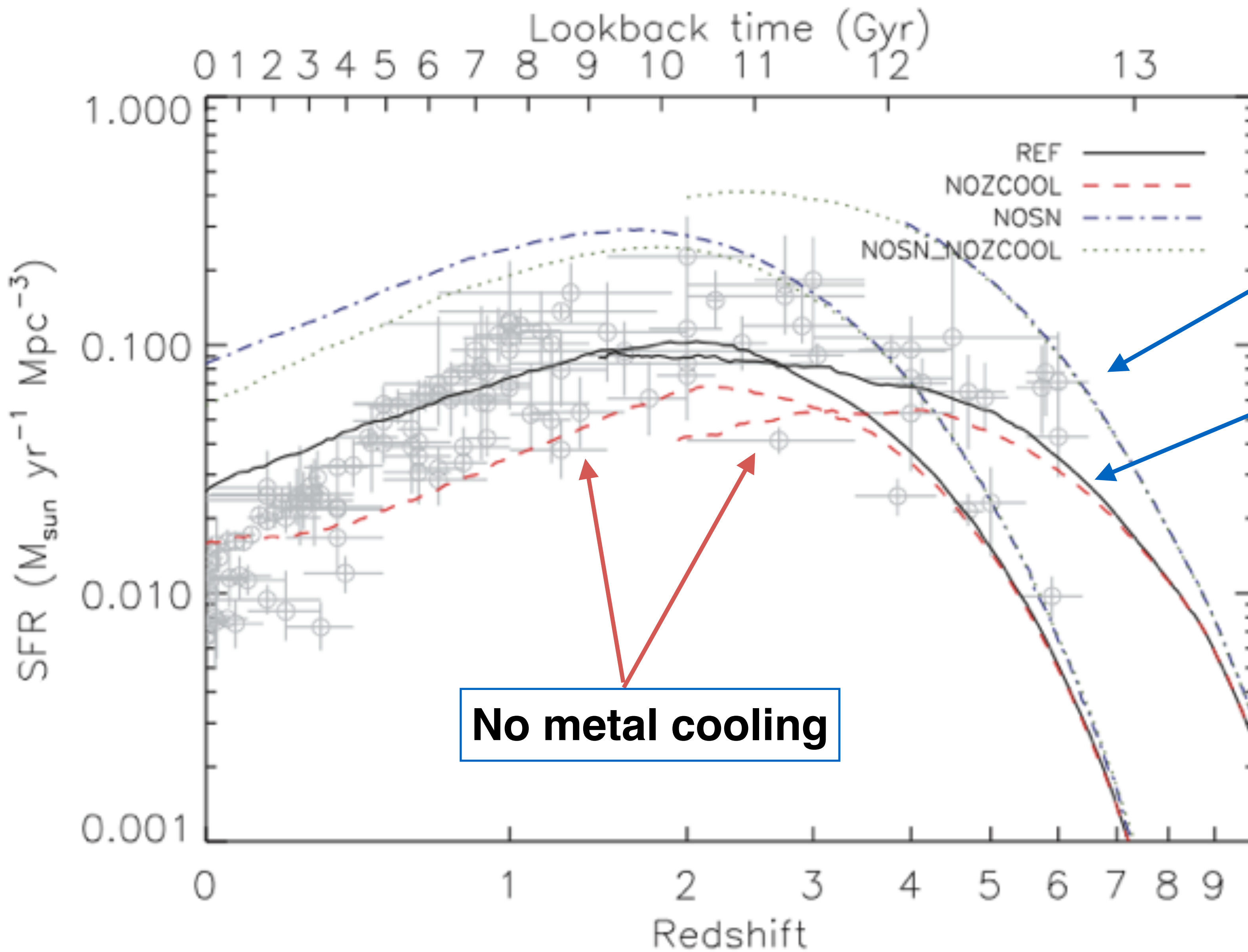
$T > 10^{5.5}$ K (red)

Name	L (cMpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (comoving kpc)	ϵ_{prop} (pkpc)
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

- **(Still, f_{gas} & T for gal clusters may be too high)**

Cosmic Star Formation History

EAGLE sim: Schaye+ '15

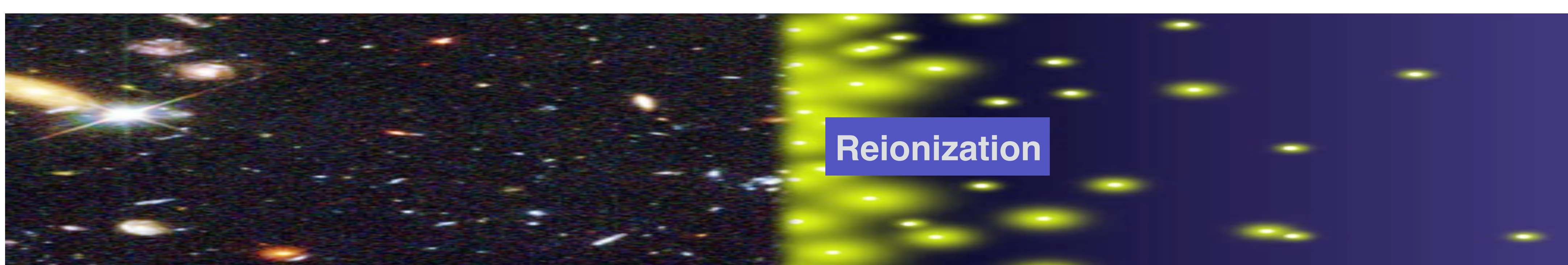


No SN feedback

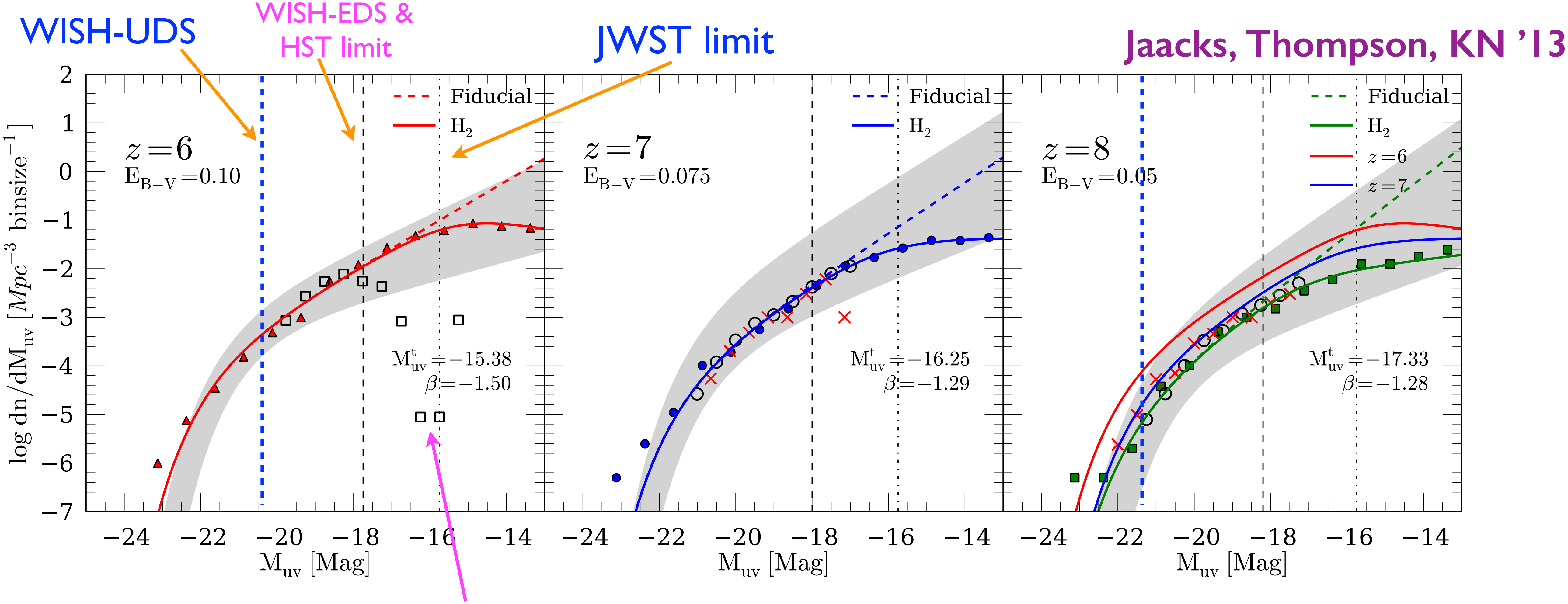
With SN feedback

No metal cooling

Too many stars are produced without SN FB.



LFs with H_2-SF model



(cf. O'Shea, KN+'05: Enzo-Gadget comparison)

Modified Schechter Func.

$$\Phi(L) = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \left[1 + \left(\frac{L}{L^t}\right)^{\beta}\right]^{-1},$$

(cf. Loveday+ '97)

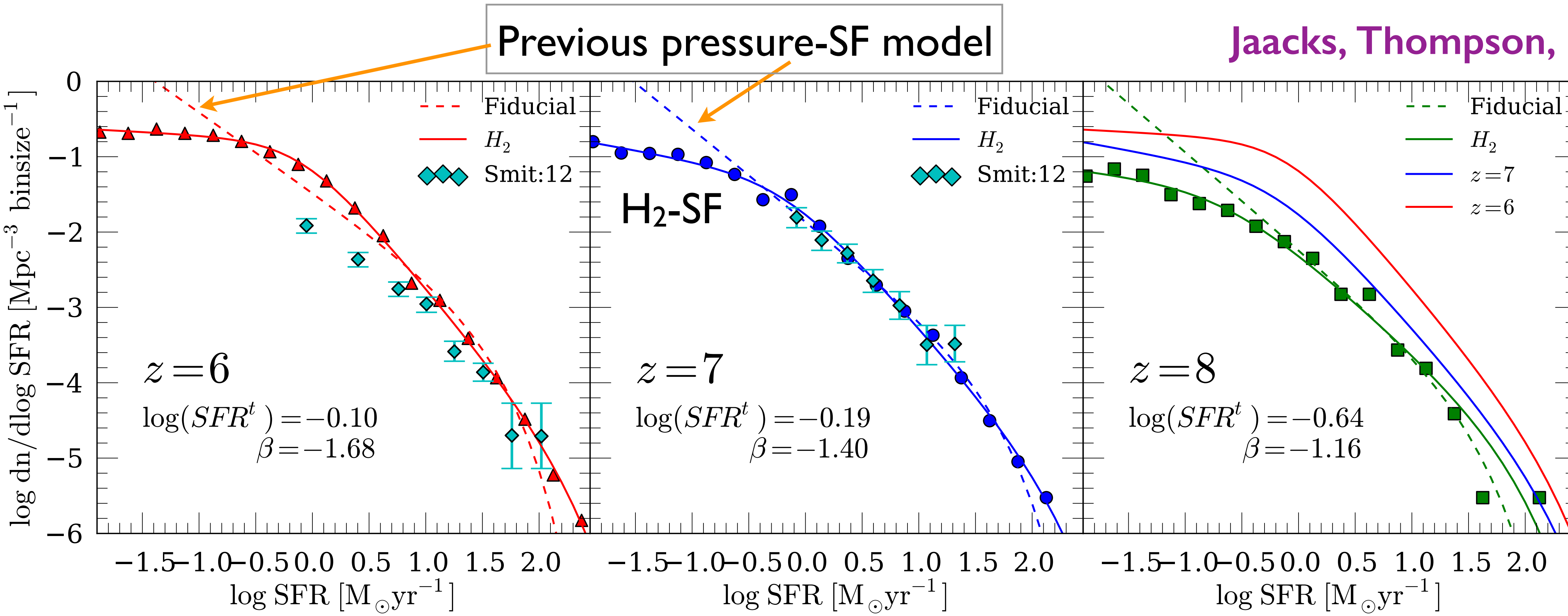
# of low-mass gals is significantly reduced at M_{uv}>-16

Future test with JWST.

(cf. O'Shea+ '15)

SFR fcn w/ H_2-SF model

Jaacks, Thompson, KN '13



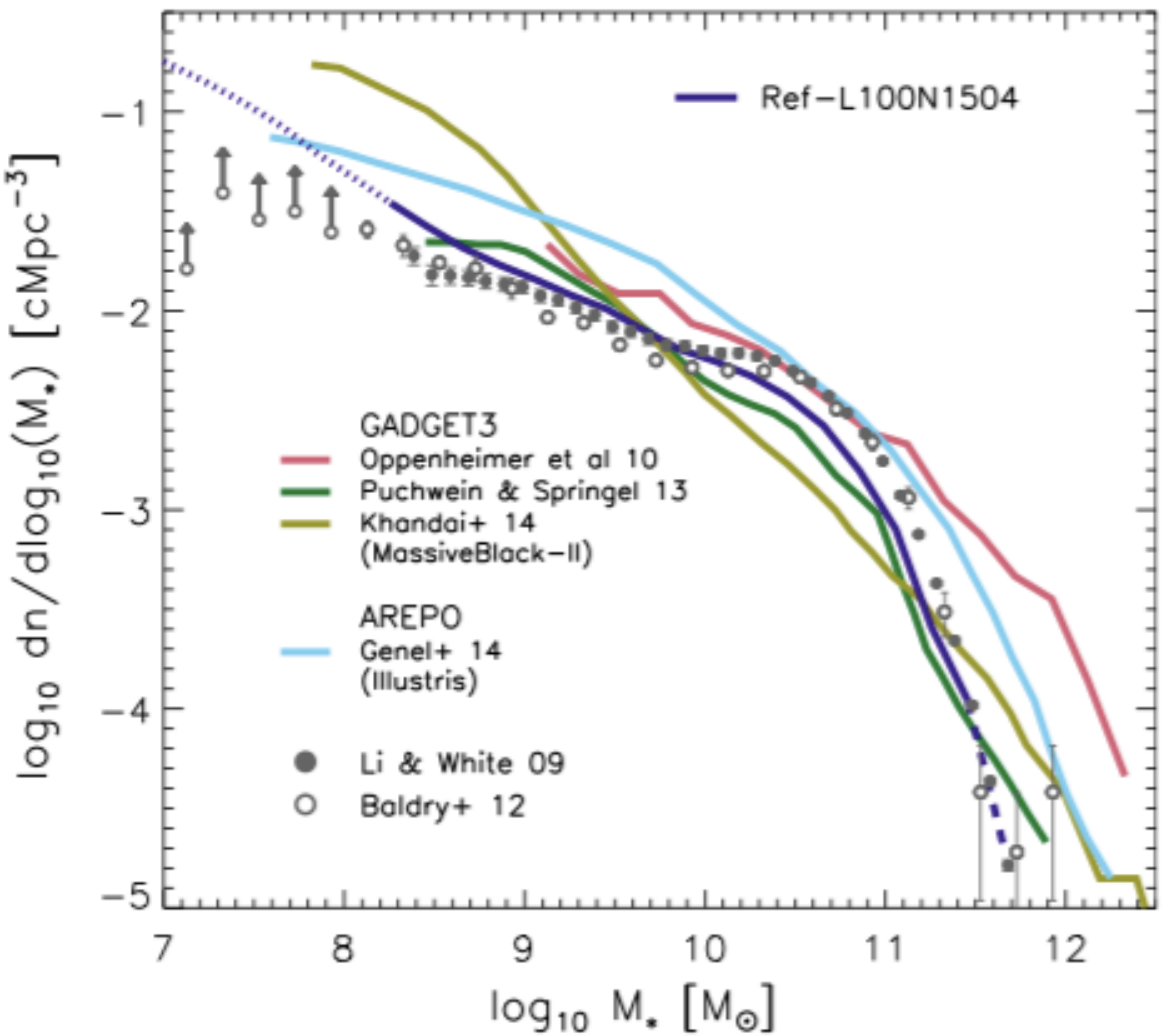
Modified Schechter SFR fcn:

$$\phi(\mathrm{SFR}) = \ln(10)\phi^* \left(\frac{\mathrm{SFR}}{\mathrm{SFR}^*}\right)^{(1+\alpha)} \exp\left(-\frac{\mathrm{SFR}}{\mathrm{SFR}^*}\right) \times \left[1 + \left(\frac{\mathrm{SFR}}{\mathrm{SFR}^t}\right)^{\beta}\right]^{-1},$$

Agrees well with current obs constraints at z=6 & 7 (Smit+ '12).

SFR fcn provides more direct comparison btw sim & obs.

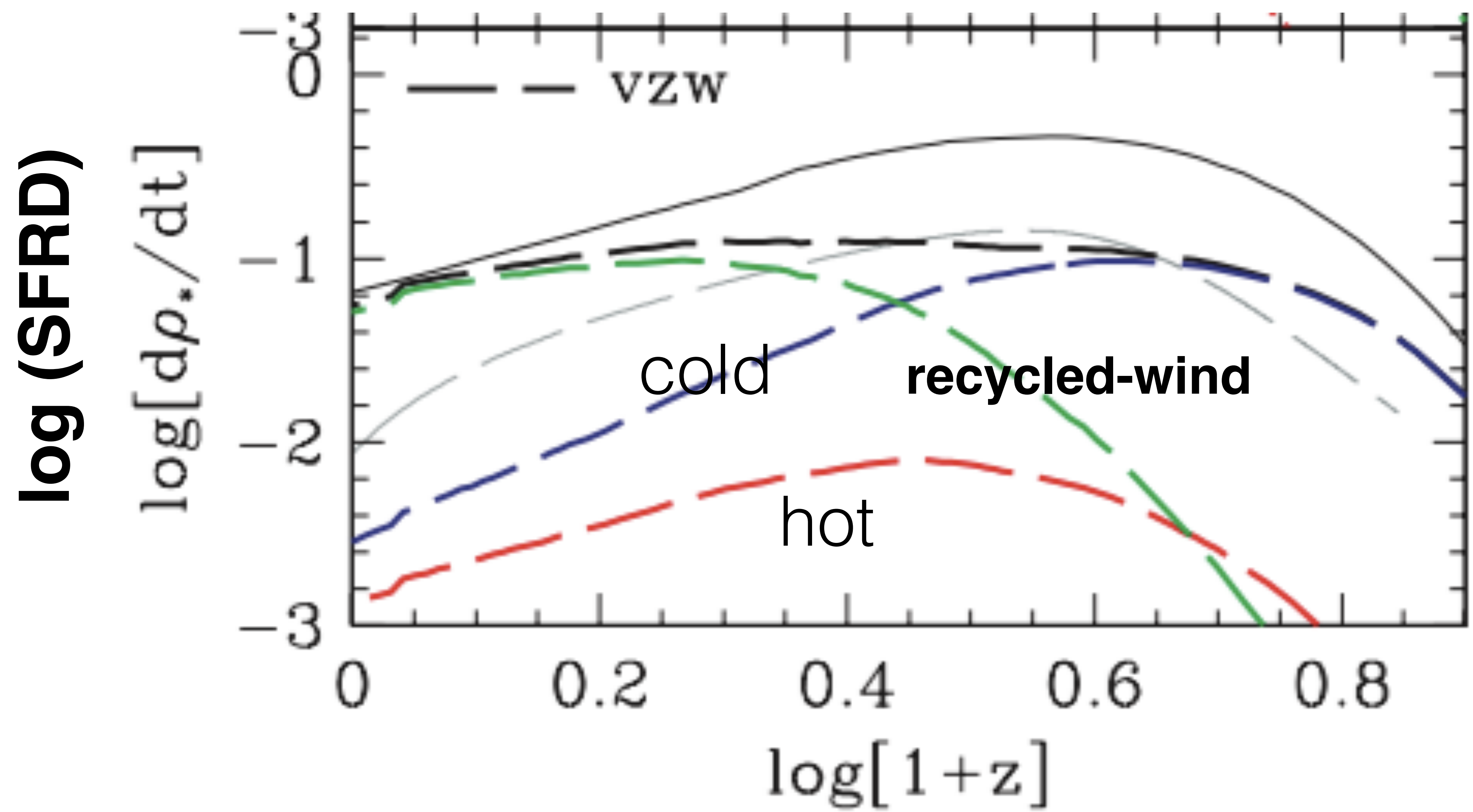
Galaxy Stellar Mass Function (z=0)



Still much variations among sims remain, & some FB param tuning is necessary for each resolution.

EAGLE sim:
Schaye+ '15
Crain+ '15

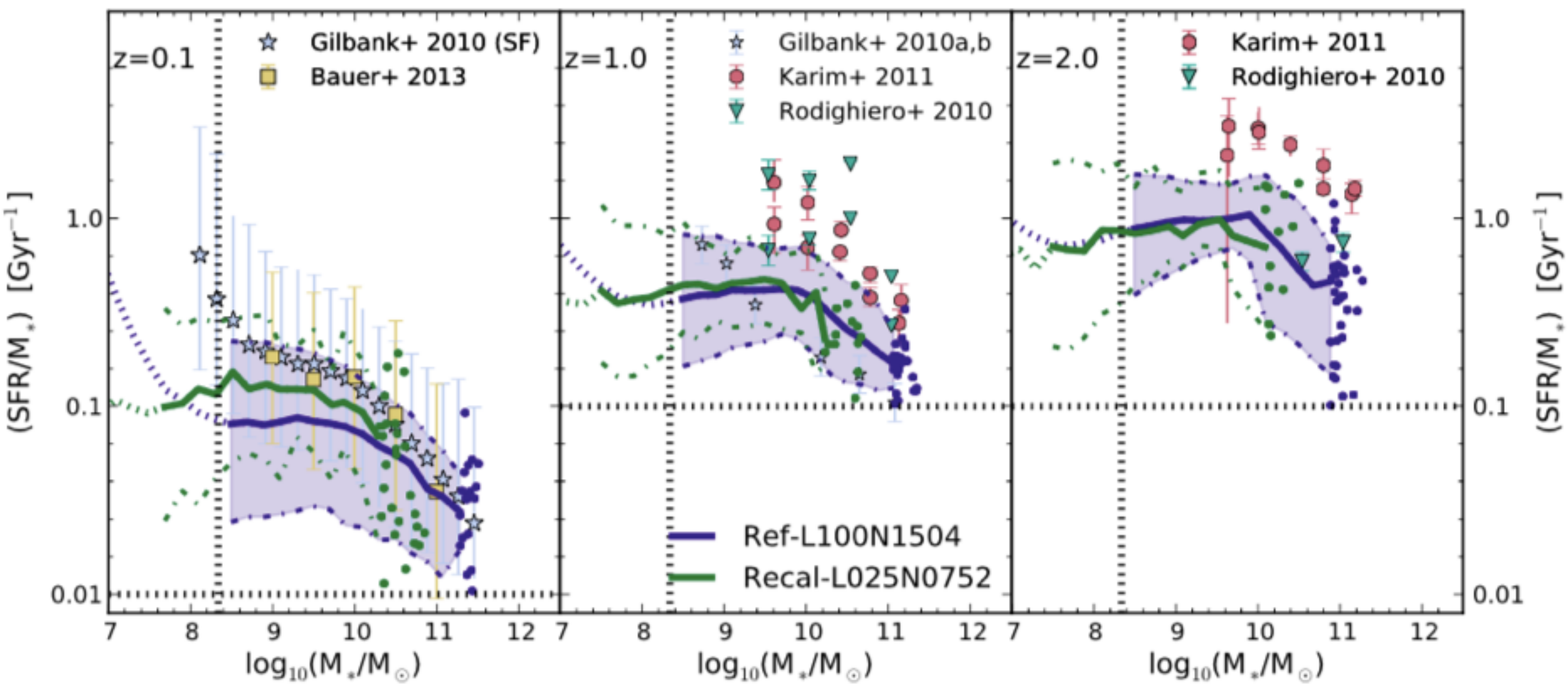
Star Formation via Recycled Wind Gas



Shape of GSMF controlled by outflows via wind-recycling?

Oppenheimer+ '10

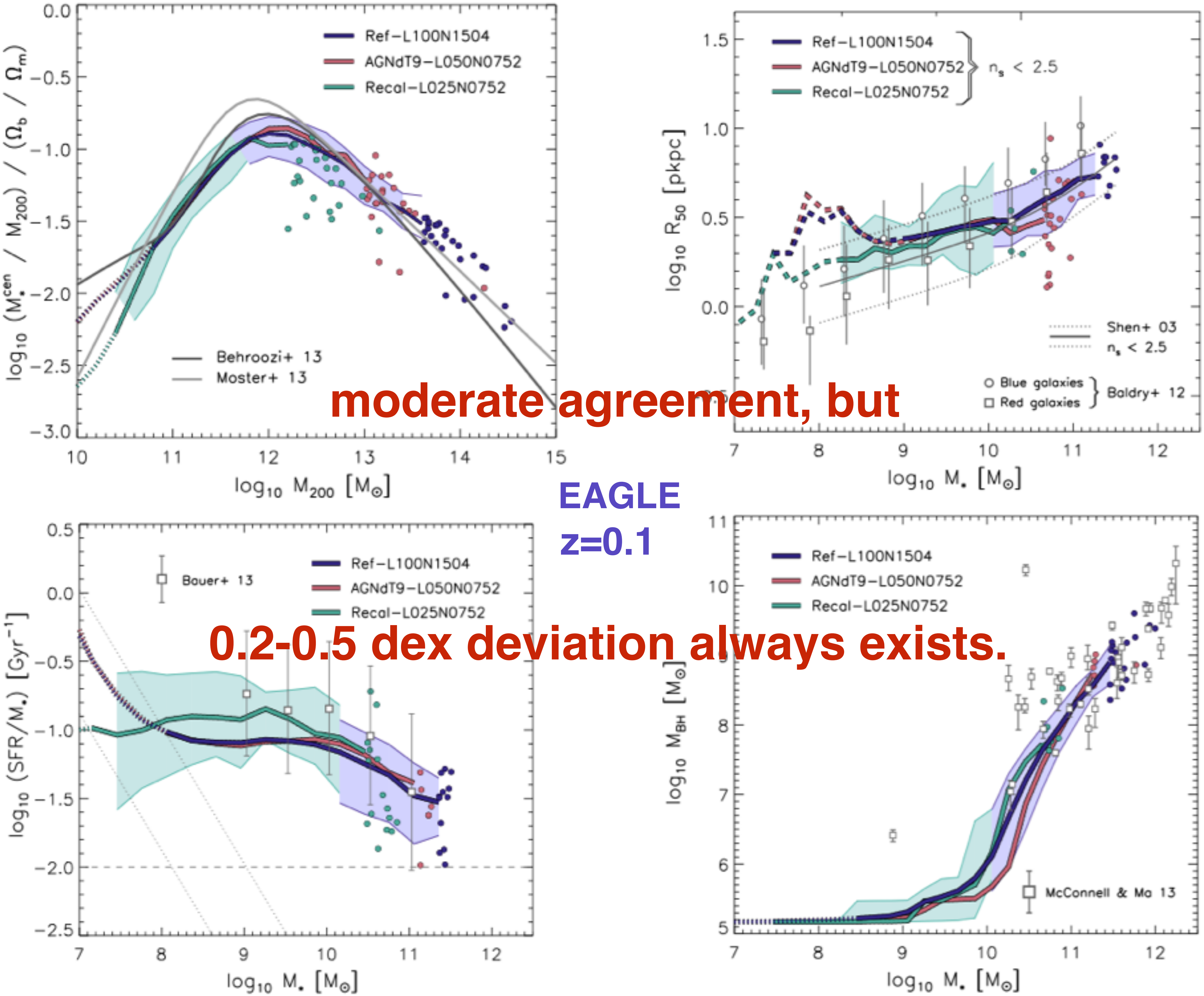
Matched the GSMF at z~0, but then….



Simulation systematically lower by ~0.3 dex off than obs.

Feedback too efficient?

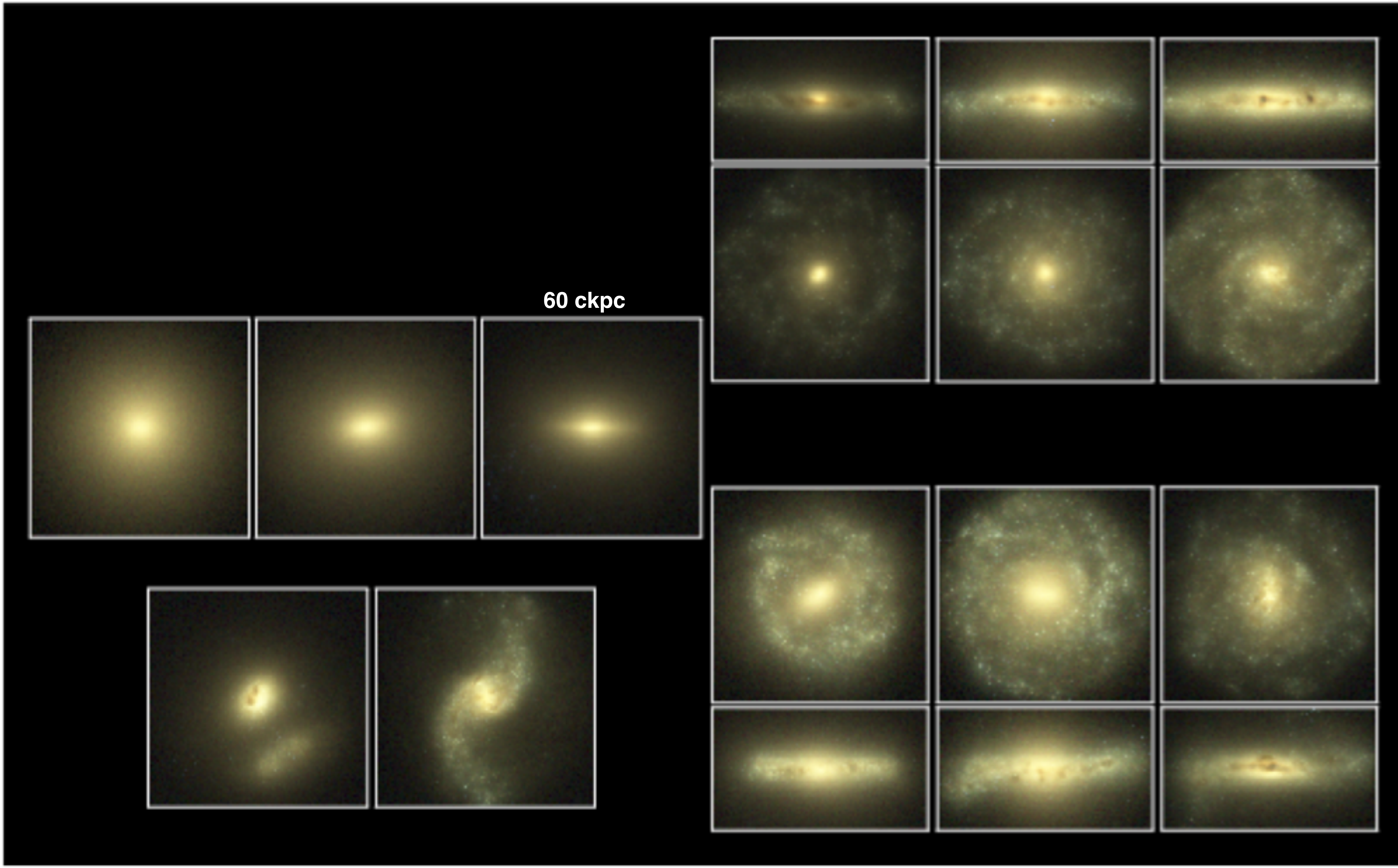
EAGLE sim.
Furlong+'15



moderate agreement, but

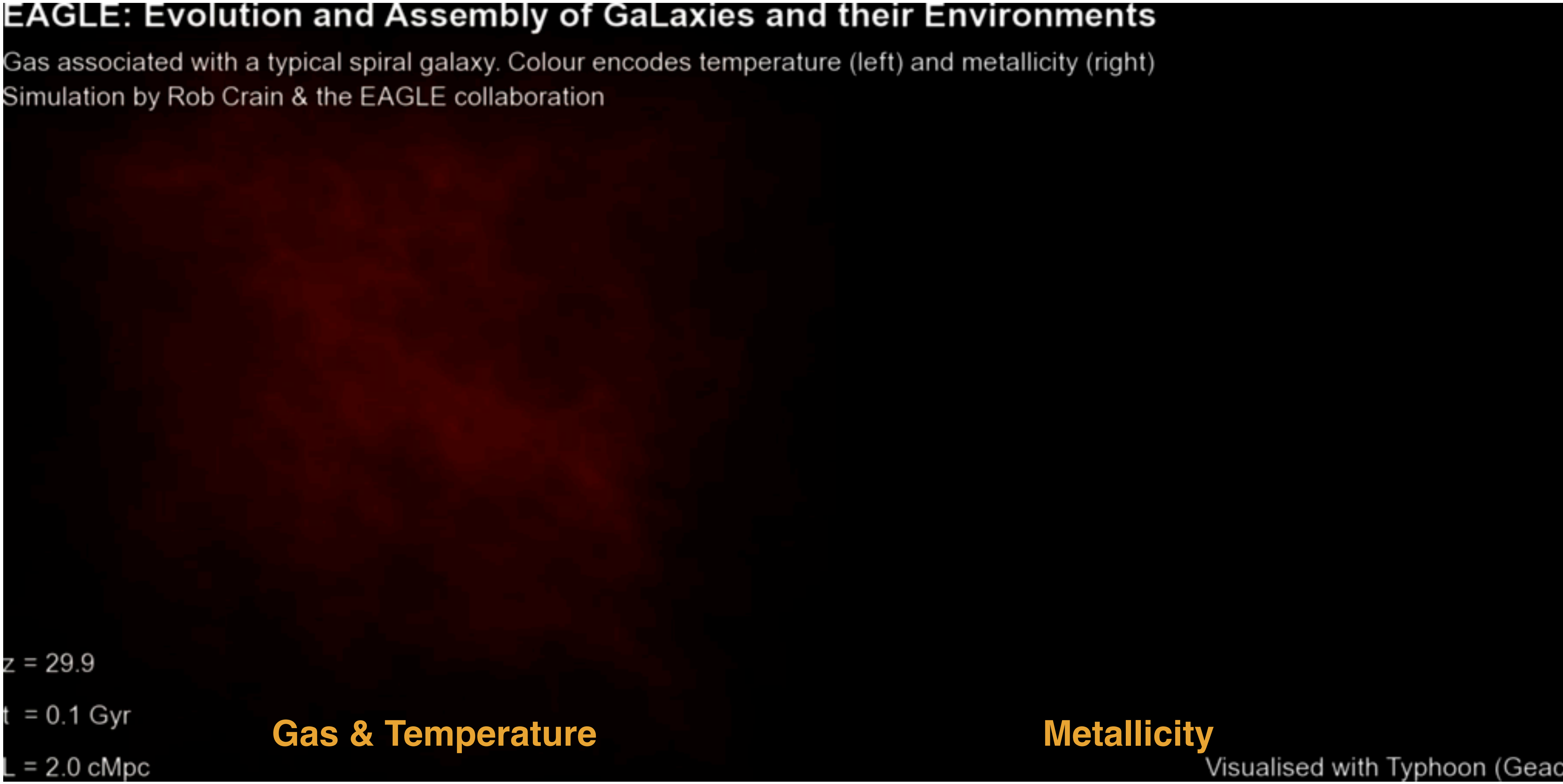
EAGLE
z=0.1

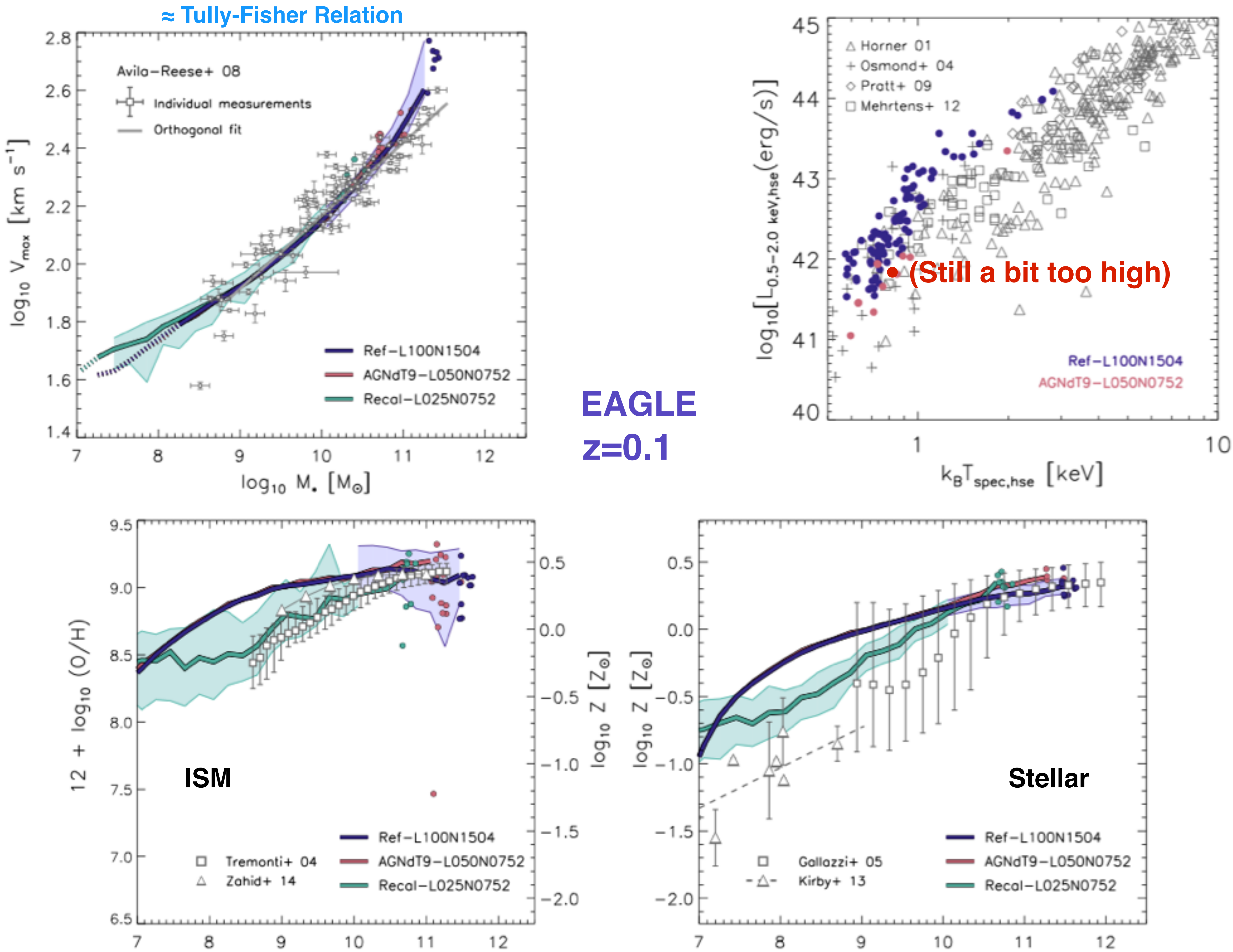
0.2-0.5 dex deviation always exists.



z=0
L100N1504 sim.

u, g, r - composite image
SKIRT (Baes+ ’11) RT code


EAGLE: Evolution and Assembly of GaLaxies and their Environments
Gas associated with a typical spiral galaxy. Colour encodes temperature (left) and metallicity (right)
Simulation by Rob Crain & the EAGLE collaboration
z = 29.9
t = 0.1 Gyr
L = 2.0 cMpc
Gas & Temperature
Metallicity
Visualised with Typhoon (Geach



≈ Tully-Fisher Relation
Avila-Reese+ 08
Individual measurements
Orthogonal fit
Ref-L100N1504
AGNdT9-L050N0752
Recal-L025N0752
log10 Vmax [km s^-1]
log10 M* [M⊙]
Horner 01
Osmond+ 04
Pratt+ 09
Mehrtens+ 12
(Still a bit too high)
Ref-L100N1504
AGNdT9-L050N0752
log10[L0.5-2.0 keV,hse(erg/s)]
kBTspec,hse [keV]
EAGLE
z=0.1
ISM
Tremonti+ 04
Zahid+ 14
Ref-L100N1504
AGNdT9-L050N0752
Recal-L025N0752
12 + log10 (O/H)
log10 Z [Z⊙]
Stellar
Gallazzi+ 05
Kirby+ 13
Ref-L100N1504
AGNdT9-L050N0752
Recal-L025N0752
log10 Z [Z⊙]

In more higher resol. zoom-in simulations,

Stellar Feedback

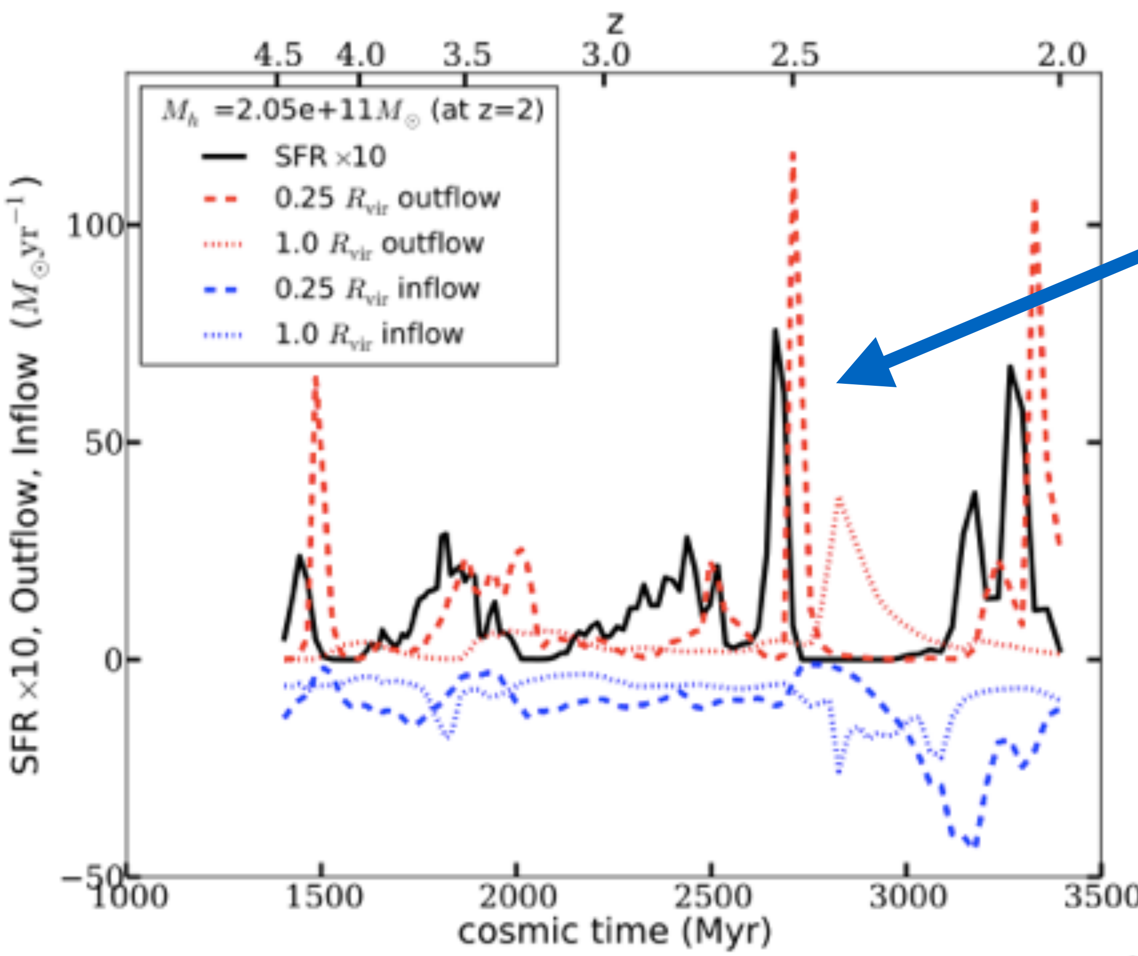
(in addition to standard SN feedback)

- stellar winds from young stars ("Early" stellar FB)
- radiation pressure $\dot{P}_{\rm rad} \approx (1 - \exp(-\tau_{\rm UV/optical}))\,(1 + \tau_{\rm IR})\,L_{\rm incident}/c$
  - dust absorption of UV —> IR emission
- photo-ionization + photo-electric heating
  (alters future heating/cooilng rates)

$$1 + \tau_{\rm IR} = 1 + \Sigma_{\rm gas}\,\kappa_{\rm IR}$$

Hopkins+ '13, …

Stellar Feedback in Zoom-in Sim



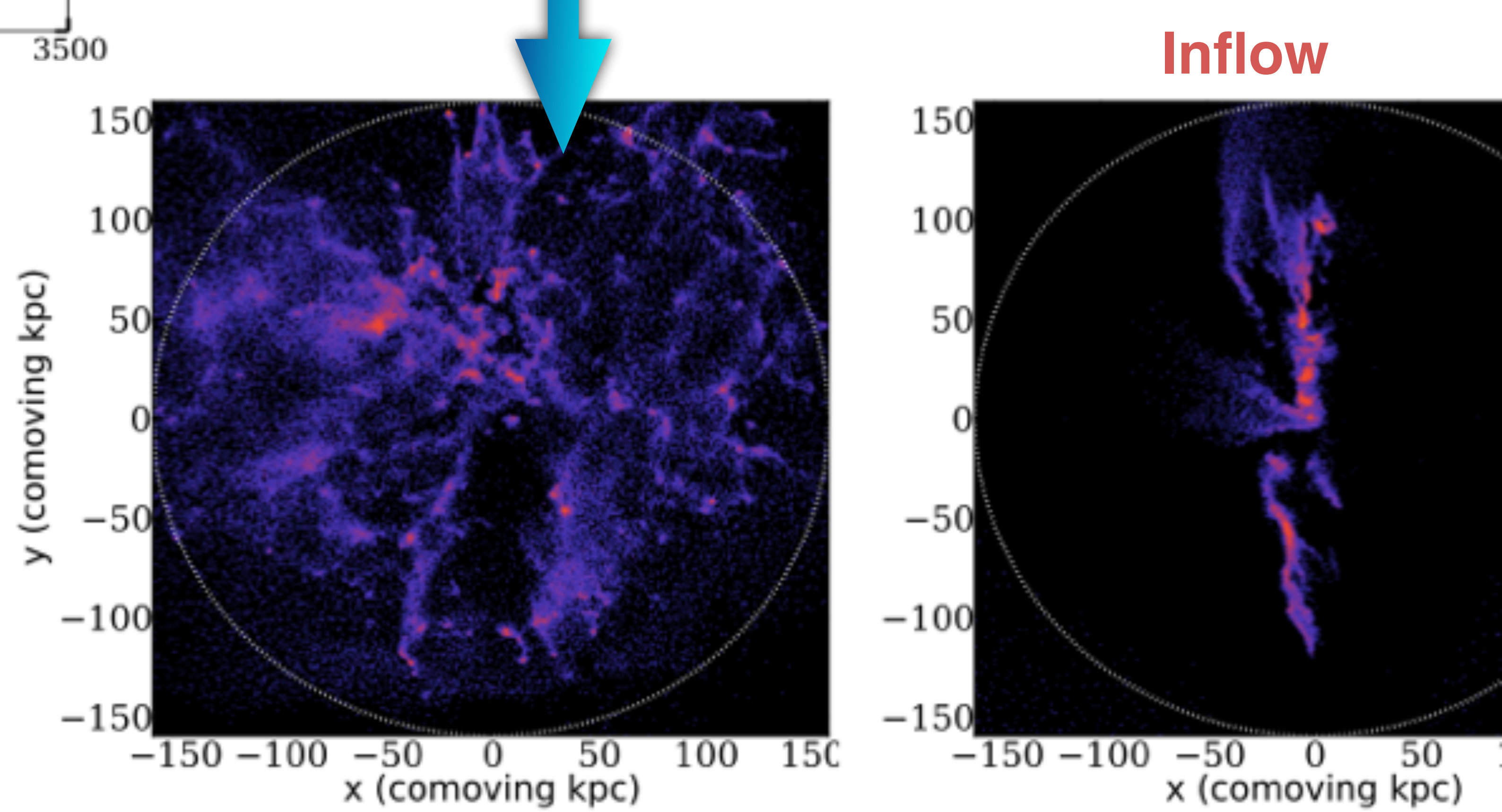
(Cosmological Initial Condition)

- Stochastic SF history

(cf. KN+'05; Jaacks+'12)

Important for the variance of SF main sequence.

- Outflows sweep up CGM.



But over-FB would eject too much gas.

FIRE simulations:
Hopkins+'13; Muratov+ '14

Stellar Feedback in Zoom-in Cosmo Sim

$$\dot{M}_W = \eta \dot{M}_\star,$$

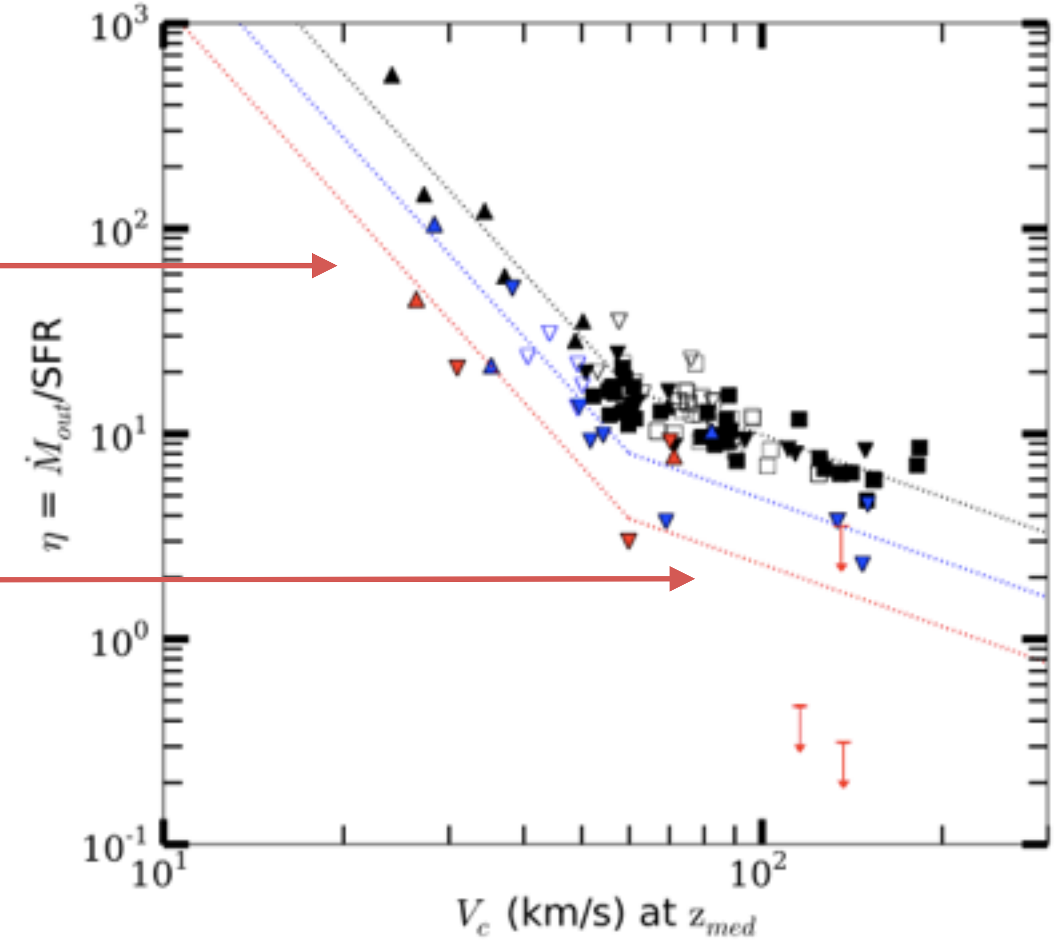
Mass Loading Factor : η

$$\eta = 2.91\,(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-3.22}$$

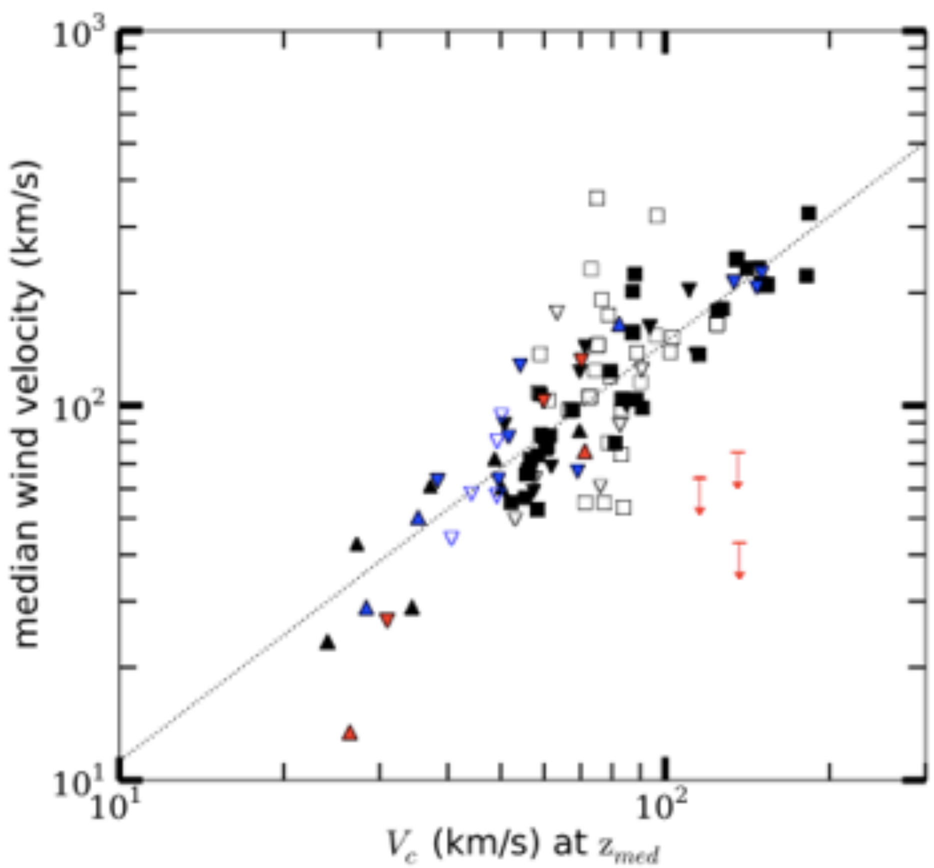
(steeper than Energy-driven)

$$\eta = 2.91\,(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-1.00}$$

(≈ Momentum-driven)



(Hopkins+'13; Muratov+ '14)



Wind Velocity

$V_W \sim V_c \sim M_h^{1/3} \sim SFR^{1/2}$ (Choi & KN '10)

Super-bubble Feedback model

(Keller+ '14)

simple SF law:
(no `early stellar FB')

$$\dot{\rho}_* = c_* \frac{\rho_{gas}}{t_{ff}}$$

$c_* = 0.1,$

$\rho = M_{gas}/\epsilon^3 = 9.3\ \mathrm{cm}^{-3}$

Basically an extended multiphase ISM treatment of SH03:

Hot phase

vs.

Cold phase

$$m = m_{\rm hot} + m_{\rm cold} \qquad E = u_{\rm hot} m_{\rm hot} + u_{\rm cold} m_{\rm cold}$$

$$\frac{P}{\rho} = \frac{(\gamma - 1)E}{m}$$

$$\rho_{\rm cold} = \frac{P}{(\gamma - 1) u_{\rm cold}} \qquad \rho_{\rm hot} = \frac{P}{(\gamma - 1) u_{\rm hot}}$$

When PdV work is done to a multiphase particle, it is shared between the two phases weighted by their respective fraction of the total energy E:

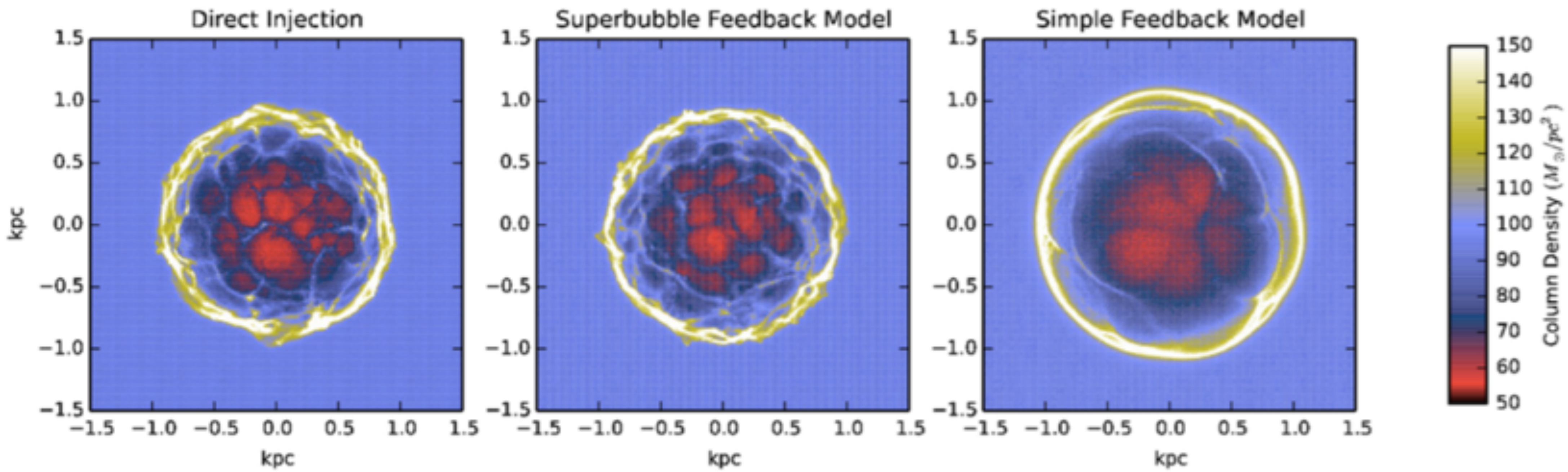
(cf. Mac Low & McCray '88)

Mass flux between the hot and cold phase is computed.

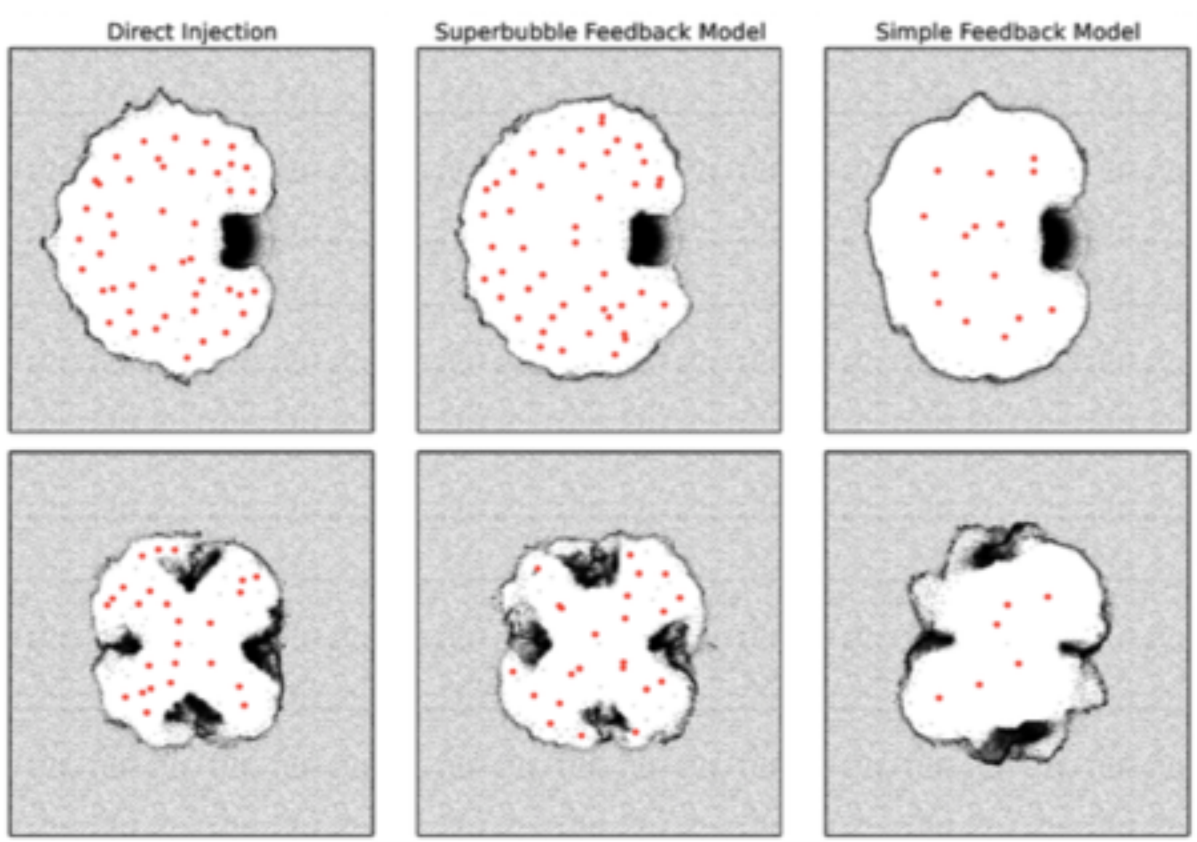
(via thermal conduction between the dense shell and the hot interior.)

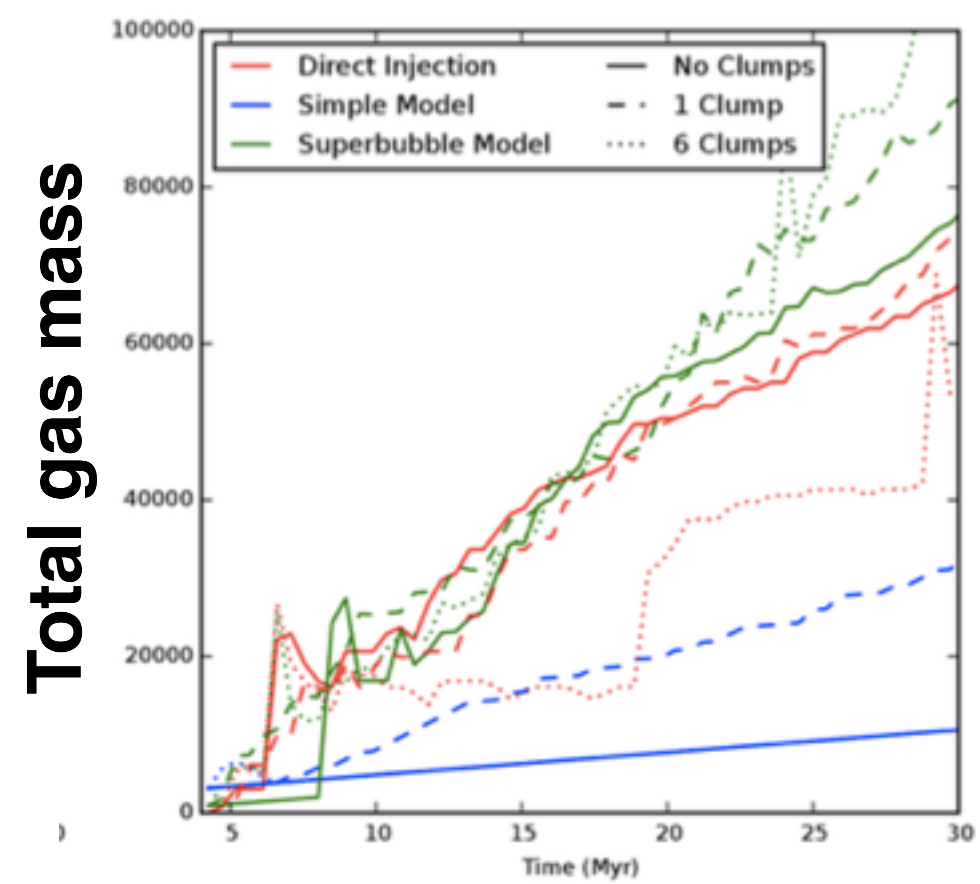
(cf. Mac Low & McCray '88)

Single central star cluster

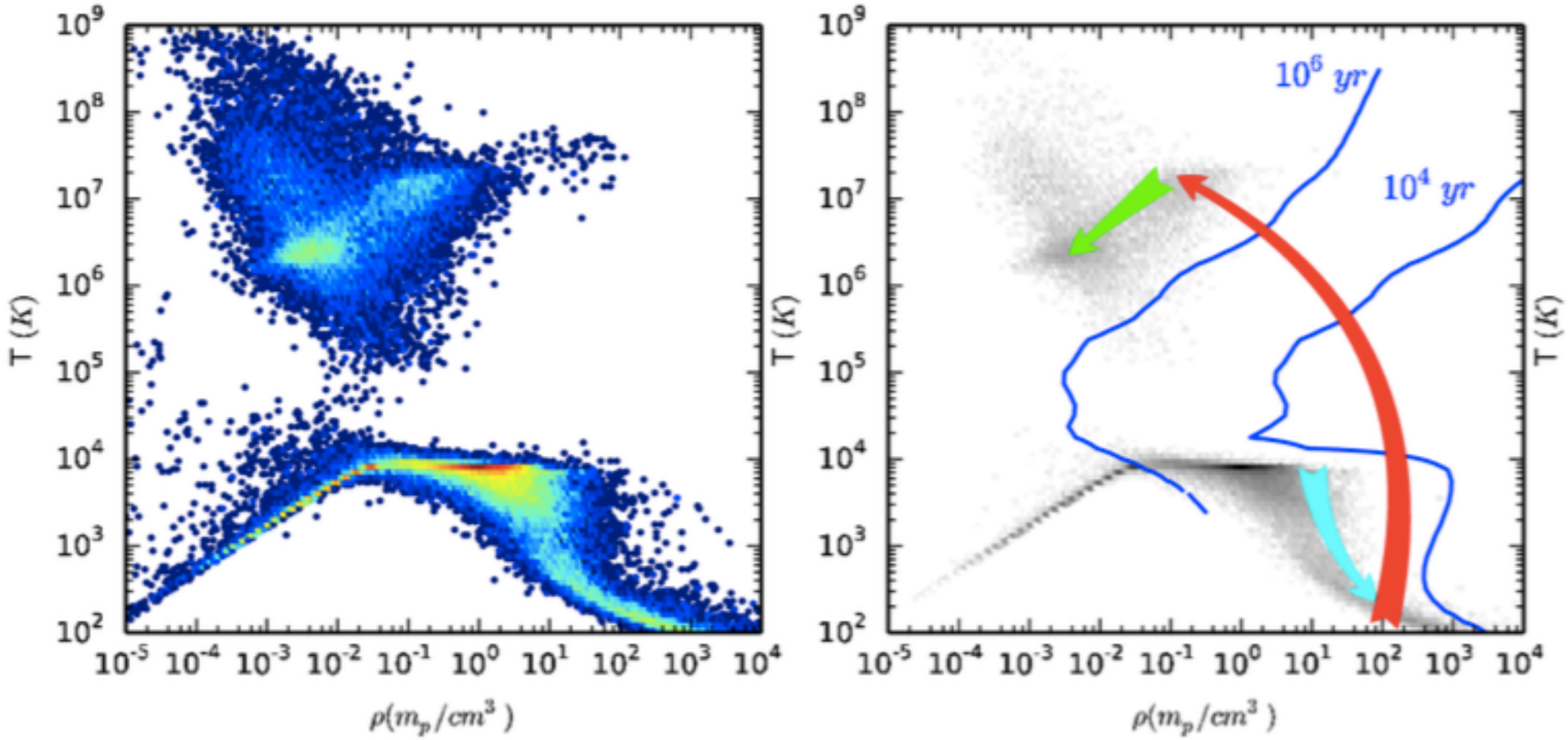


Clumpy ISM

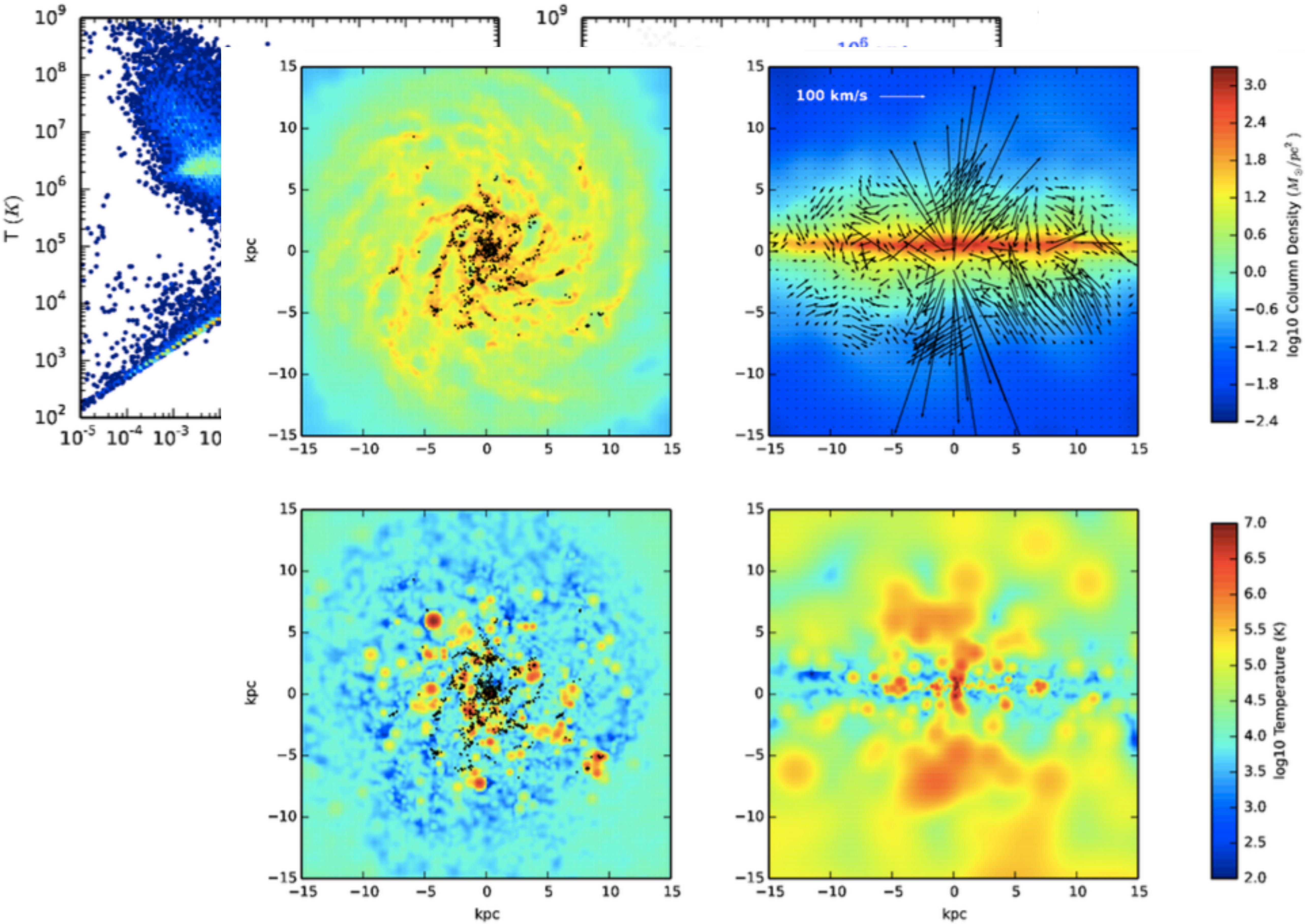


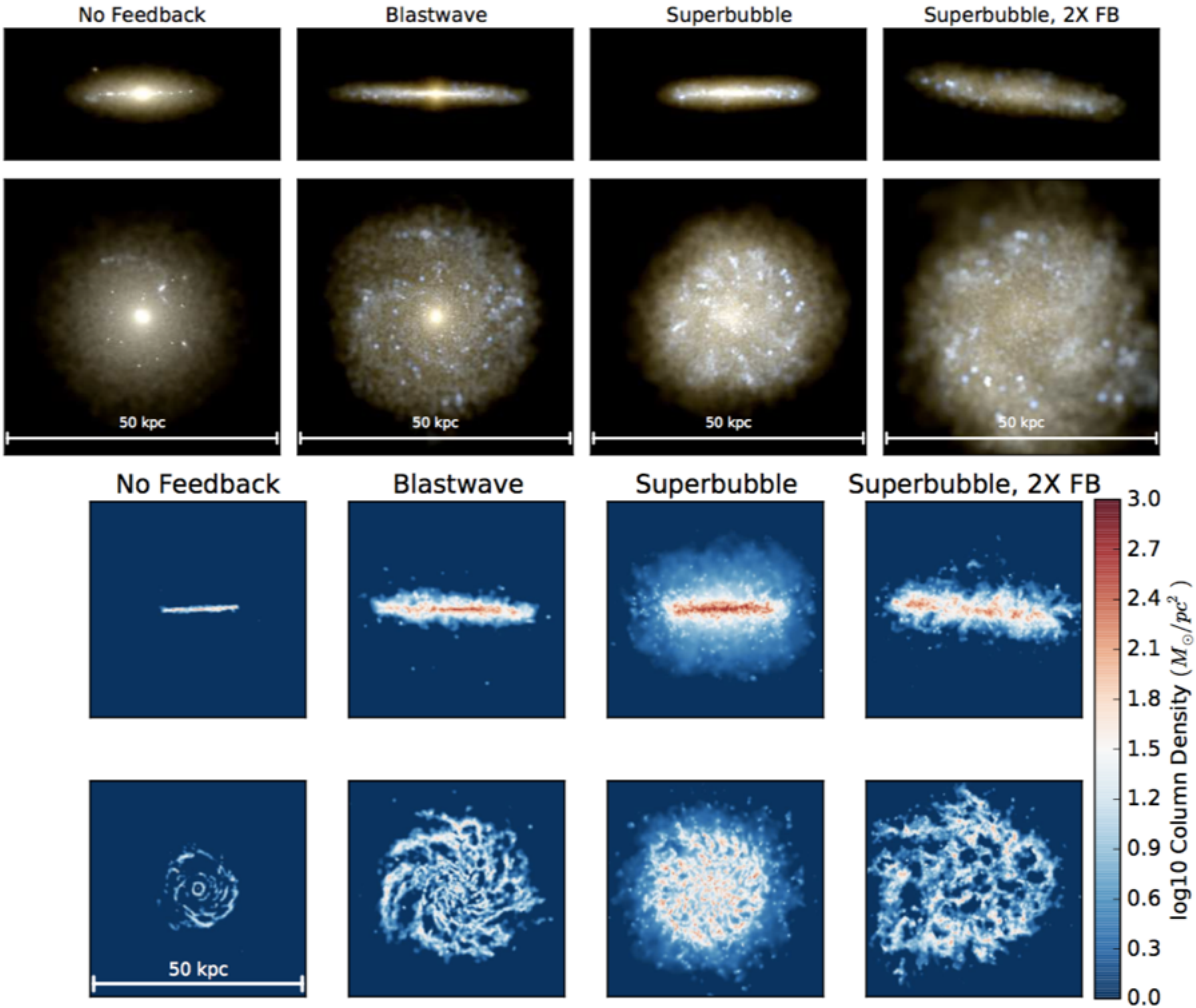


Test with AGORA iso gal model:



Test with AGORA iso gal.





No Feedback
Blastwave
Superbubble
Superbubble, 2X FB
50 kpc
50 kpc
50 kpc
50 kpc
No Feedback
Blastwave
Superbubble
Superbubble, 2X FB
50 kpc
log10 Column Density ($M_\odot/pc^2$)
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0

Assumptions in Cosmo. Sims.

Bondi-Hoyle-Lyttleton mass accretion rate

$$\dot{m}_a = \alpha \frac{4\pi G M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \quad \& \quad \alpha \sim 100$$

Radiative output from accretion

$$L_{\rm a} = \epsilon_{\rm r} c^2 \dot{M}_{\rm a},$$

radiative efficiency $\epsilon_{\rm r}$ (rest-mass energy conversion)

$$\epsilon_r \approx 10^{-1}$$

Shakura & Sunyaev '73

Feedback efficiency $\epsilon_{\rm f}$

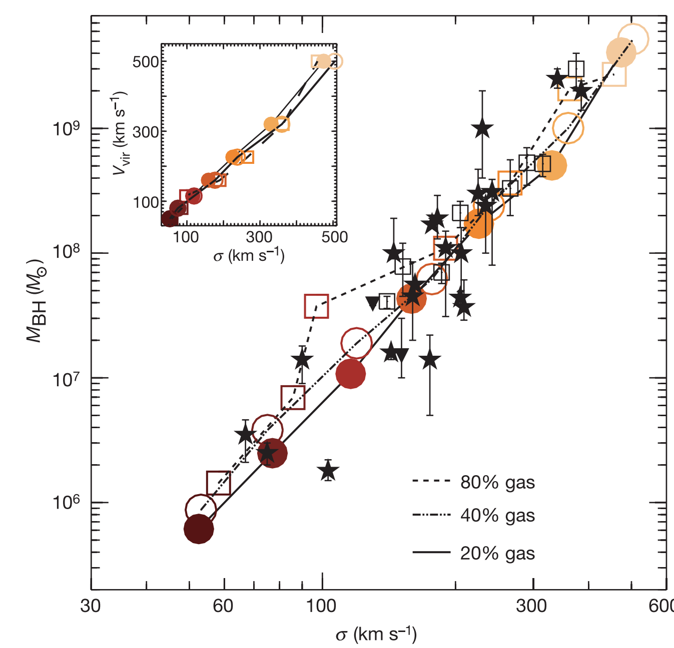
$$\dot{E}_{\rm f} = \epsilon_{\rm f} L_a = \epsilon_{\rm f} \epsilon_{\rm r} \dot{M}_a c^2$$

Requirement from M_{BH}-σ rel.

$\epsilon_{\rm f} = 0.05$ Springel, Di Matteo+ '05

$\epsilon_{\rm f} = 0.15$ Booth & Schaye '09; Dubois+ '12

$\epsilon_{\rm f} \sim 10^{-3}$ Bellovary+ '10



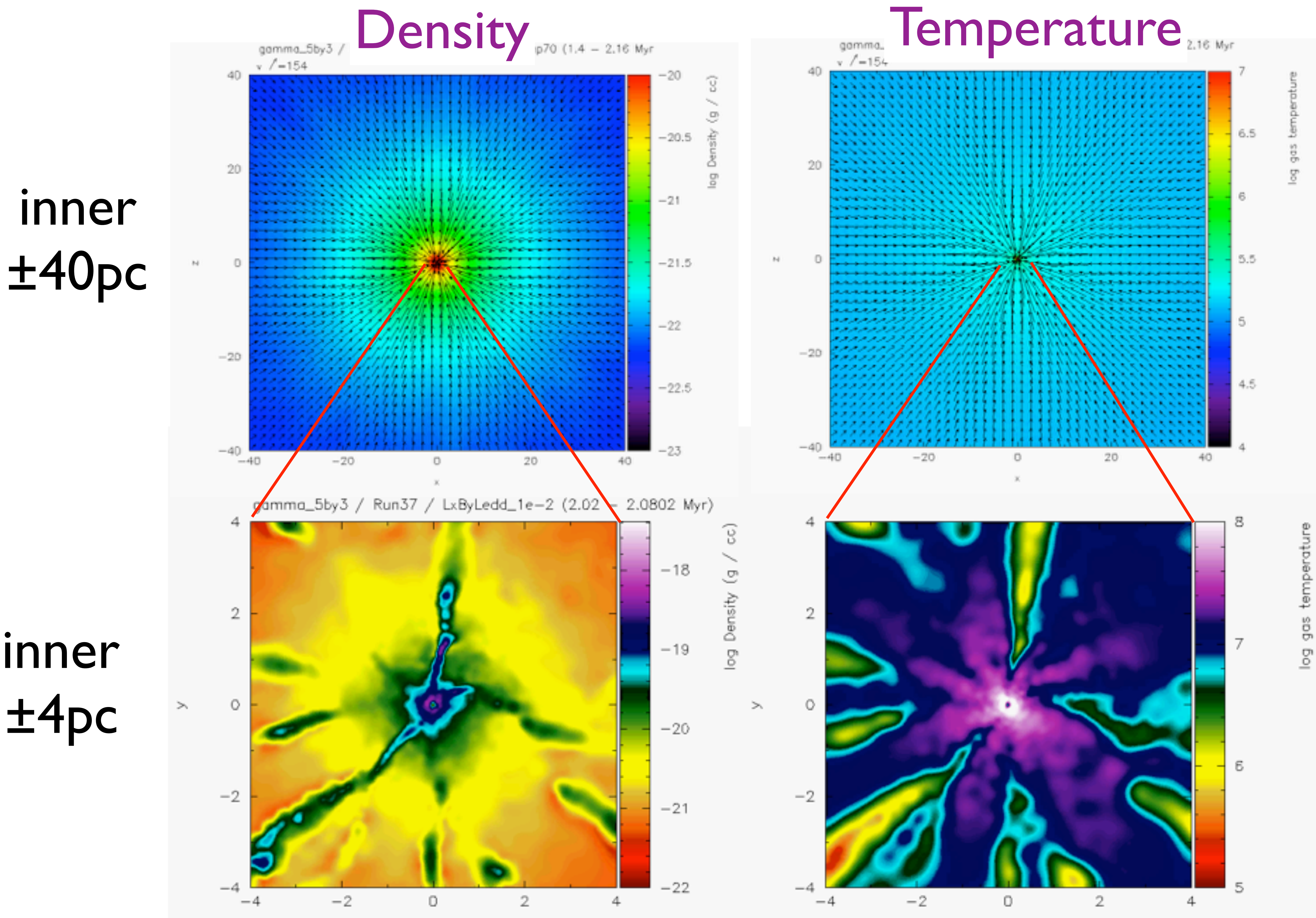
Di Matteo+ '05

Non-spherical inflow:

due to rad. feedback

Run 26: r_{out}=200pc, Lx/L_{Edd}=0.01

Barai, Proga, KN '11



Non-spherical outflow:

due to rad. feedback

Run 27: r_{out}=200pc, Lx/L_{Edd}=0.02

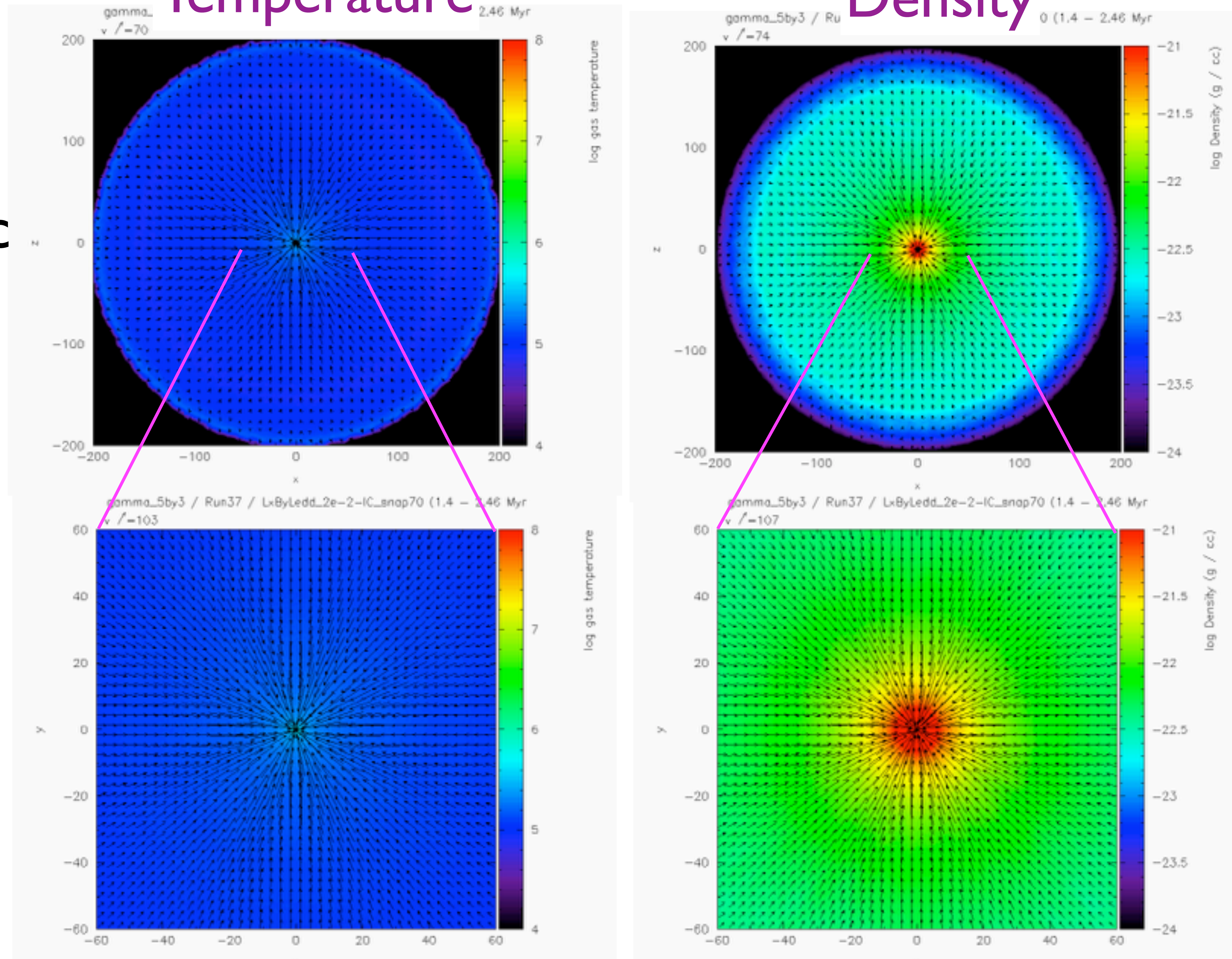
Barai, Proga, KN '11

Temperature

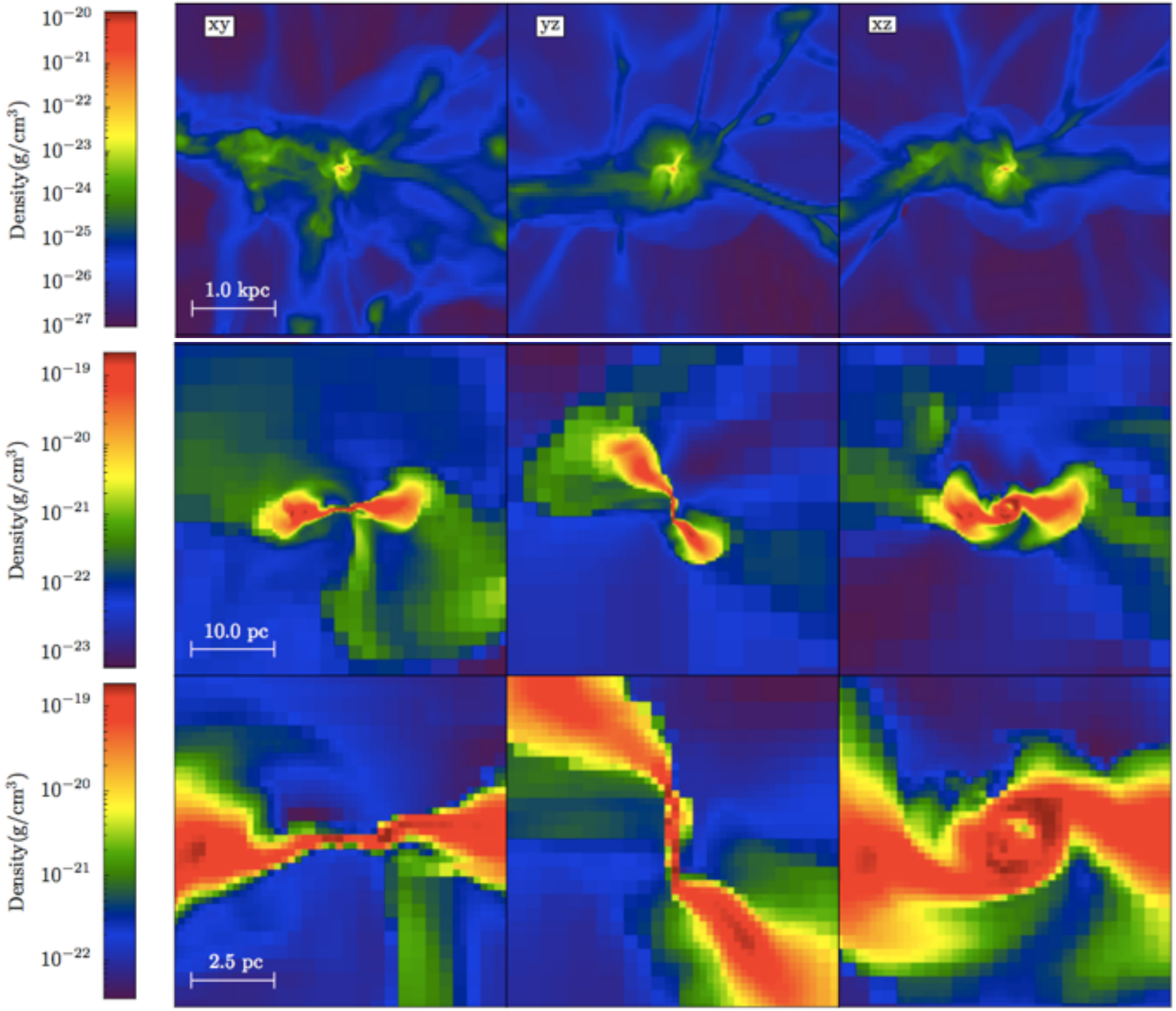
Density

± 200pc

inner
±60pc



SMBH seed formation at high-redshift



Always involves a disk, and Bondi is not a good model.

Shlosman, Choi, Begelman, KN '15

Summary

- *FEEDBACK continues to be the focus of galaxy formation & evolution research — shape of GSMF not fully understood.*
- *"Early Feedback" from young stars: rad pressure, momentum, thermal energy, photoionization*
- *But simpler models (e.g. superbubble-only) might be adequate w/ limited resolution*
- *Dust & Radiation Transfer*
- *Beginning to resolve Galactic Morphology better*
- *Bigger problems: Downsizing, Color bimodality, AGN FB efficiency, SMBH-gal co-evolution, ….*
- *AGN Feedback: maybe ~~Bondi models~~ not enough —> ??*