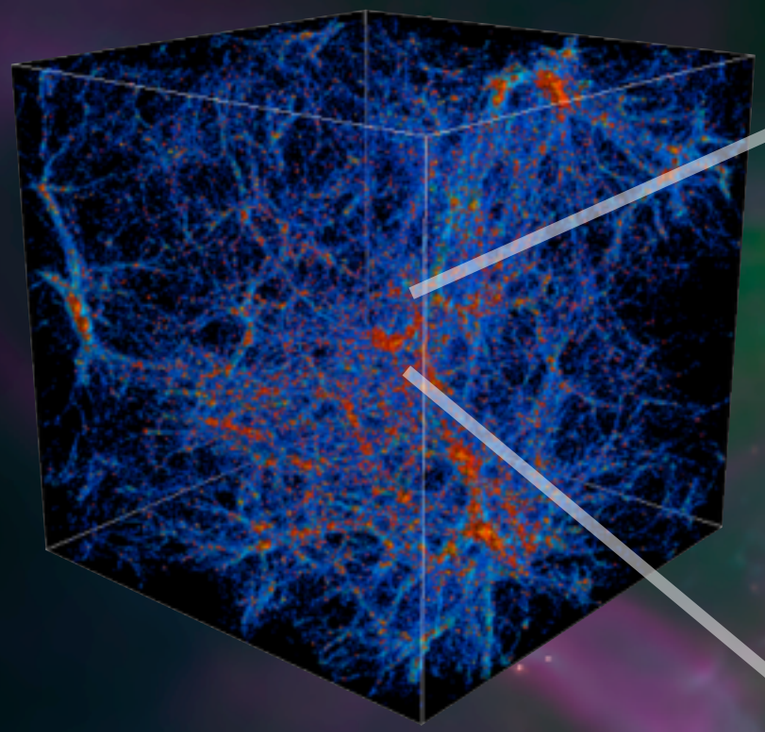
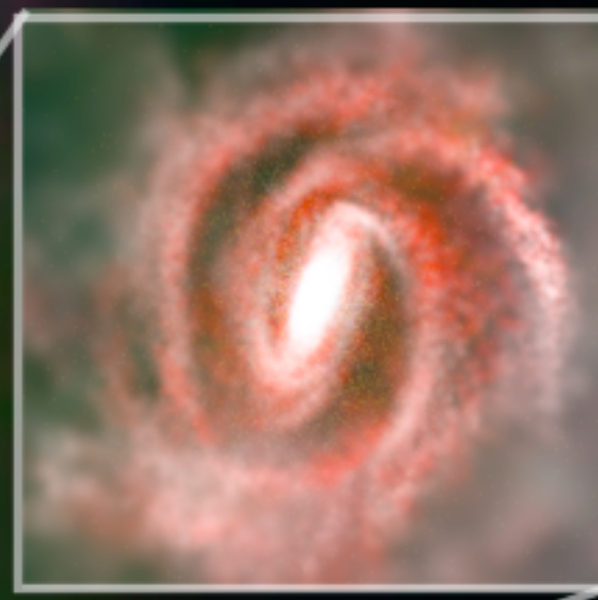
High-z Galaxy Formation and Feedback

「フィードバック機構」



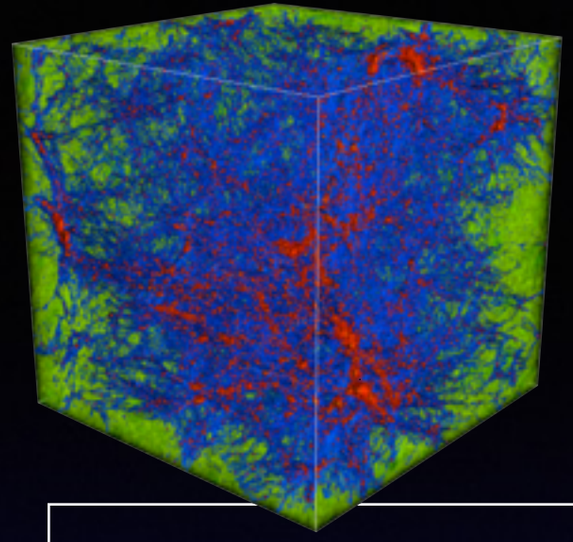


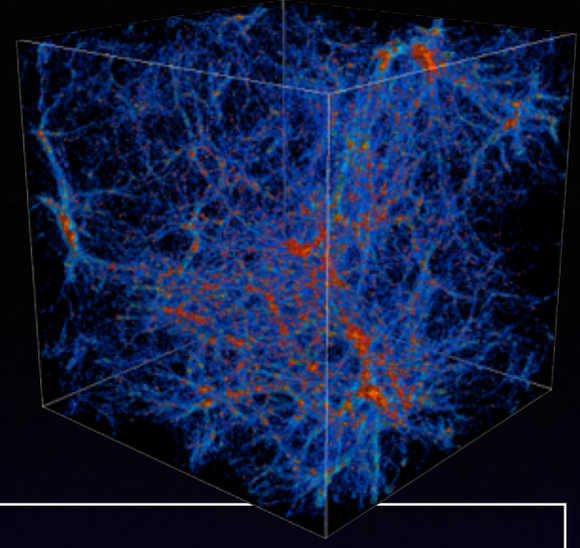
Ken Nagamine
Osaka / UNLV

長峯健太郎
（大阪大学）

Recent Collaborators on this topic:

Jun-Hwan Choi (UT Austin)
Jason Jaacks (UT Austin)
Emilio Romano-Diaz (Bonn)
Isaac Shlosman (Kentucky)
Robert Thompson (W. Cape)
Keita Todoroki (Kansas)
Hide Yajima (Tohoku)





Outline

- フィードバック機構とは？ (by MS, SNe, AGN, ...)
- Effects on Cosmological Quantities
- Effects on Galaxy Statistics
- Downsizing, Galaxy Morphologies, Elliptical Gals.
- Conclusions

フィードバック機構とは？

（銀河形成における）

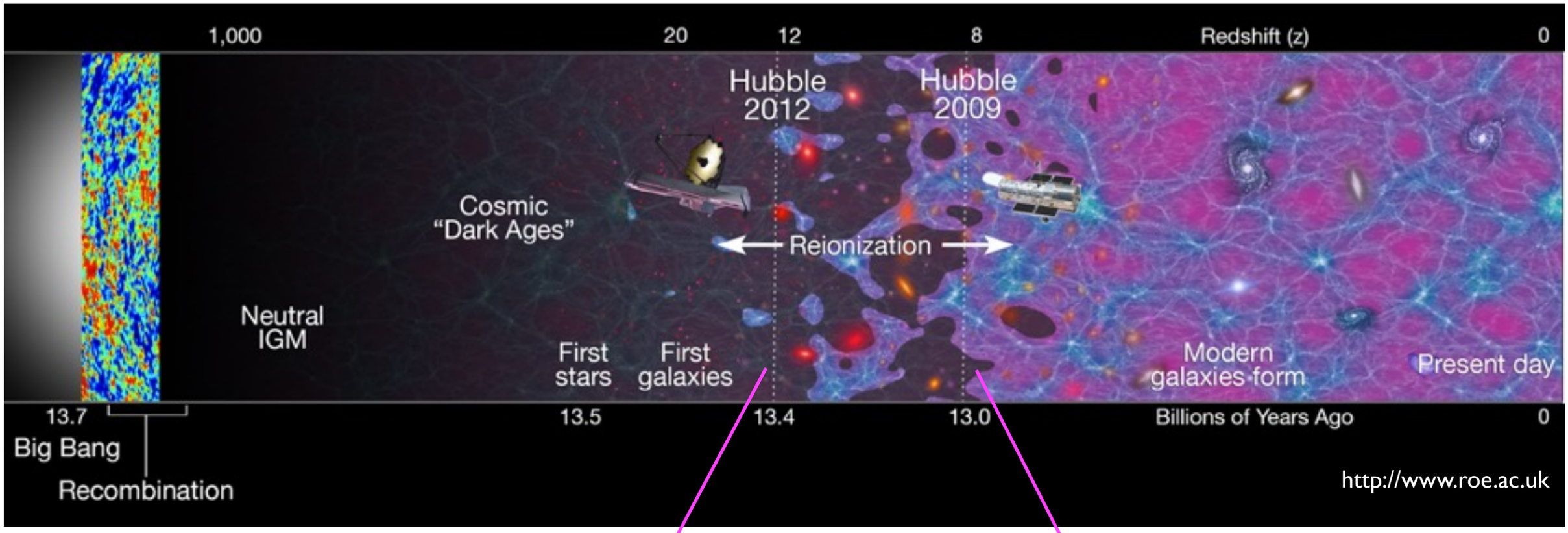
- エネルギー(**光、物質**）が放出され、その後の系の進化に影響を与えること。

- **What, Who, Where, When, Why, How ?**
- Who?：超新星、SMBH (AGN)、大質量星(MS)
- Where? : galaxy, star-forming region, black hole
- **When, Why, How?**

``Concordance ΛCDM model ”

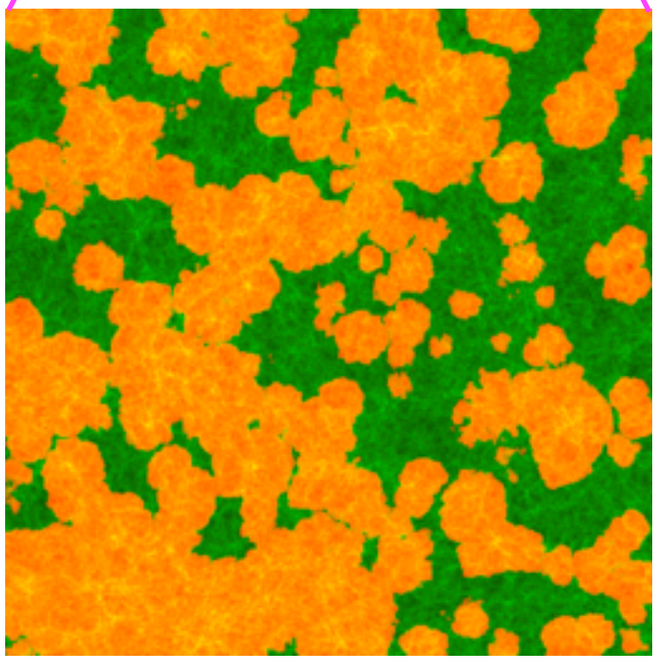
WMAP, Planck:
SN Ia

$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$



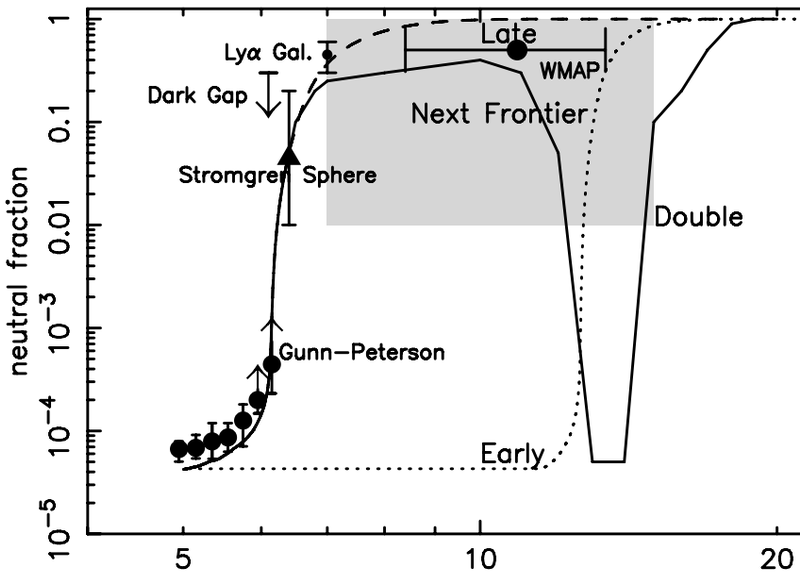
Understand

- Reionization process
- Galaxy Formation
  - statistics (LF, MF)
  - SFRD, SMD
  - Mass-metallicity (Fund. Plane?)
  - Gas fractions
  - …



Illiev+ ’06

neutral fraction

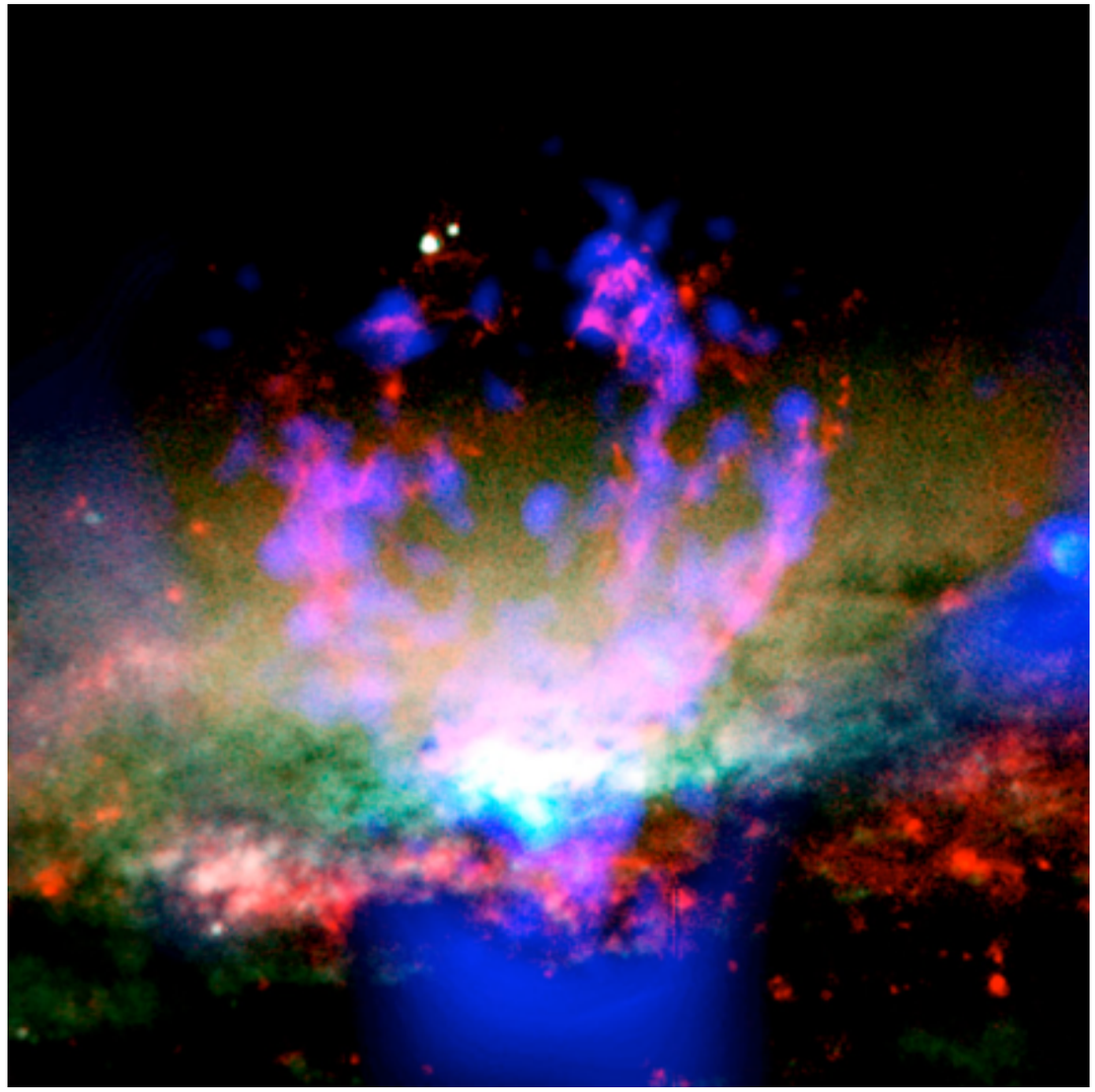


Fan+ ’08

Prevalence of Galactic Wind Feedback

-- Pollution of Intergalactic Medium by metals

M82 Purple: $H\alpha+N_{II}$
Blue: HST, optical



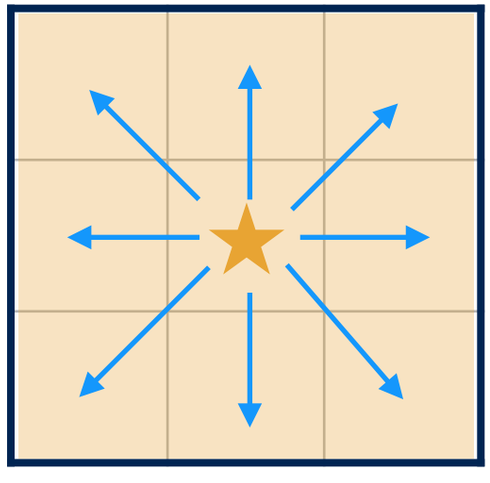
NGC3079
Blue: Chandra (X-ray)
Red Green: HST (optical)

Supernova(SN) Feedback

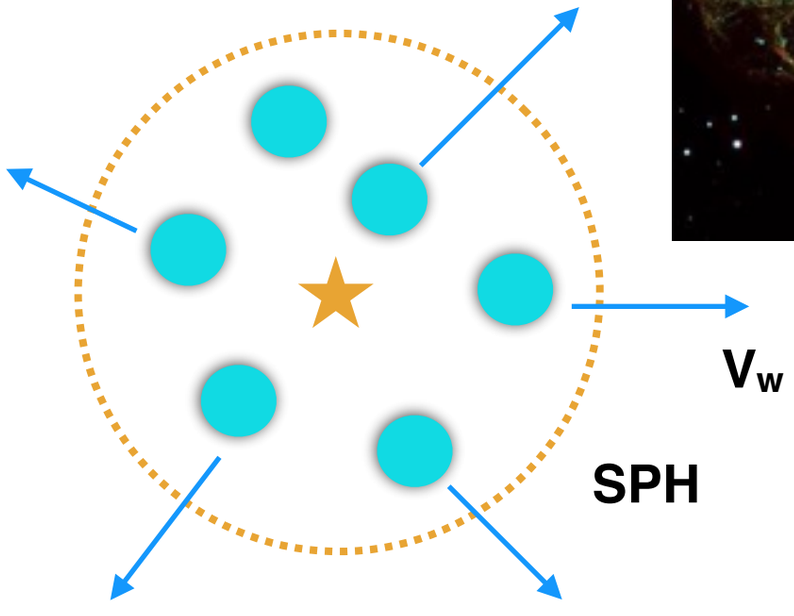
- Source of radiation, metals, cosmic rays
- E_{tot}~10^{51} erg (mostly to "ν")
- —> E_{fb}~10^{49} erg, —> E_k, E_{th}
- Outflows, Suppression of SF

Crab Nebula — SN 1054 (NASA, ESA)

(White & Rees 78; Dekel & Silk '86)



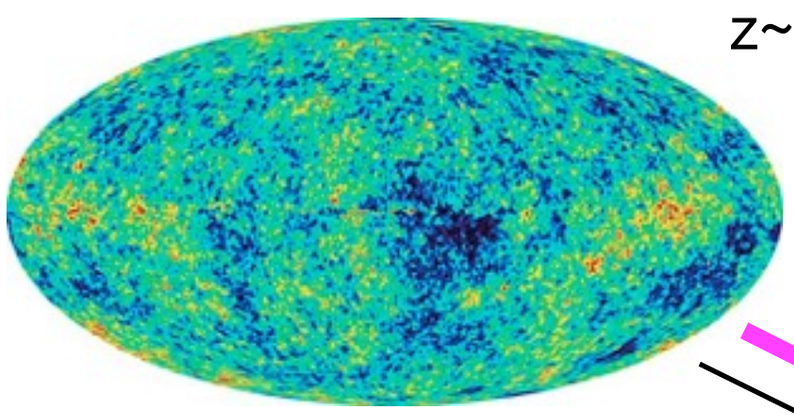
mesh codes



- Kinetic energy & momentum
- Thermal energy
- Type I, II

Computational Cosmology

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



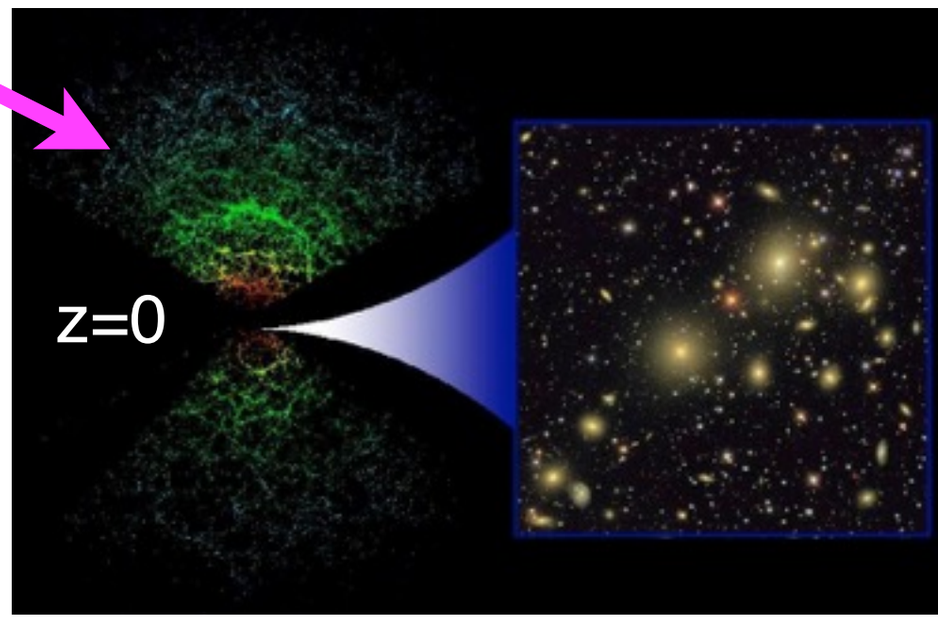
z~1100

z=100

z=10

z=3

z=0

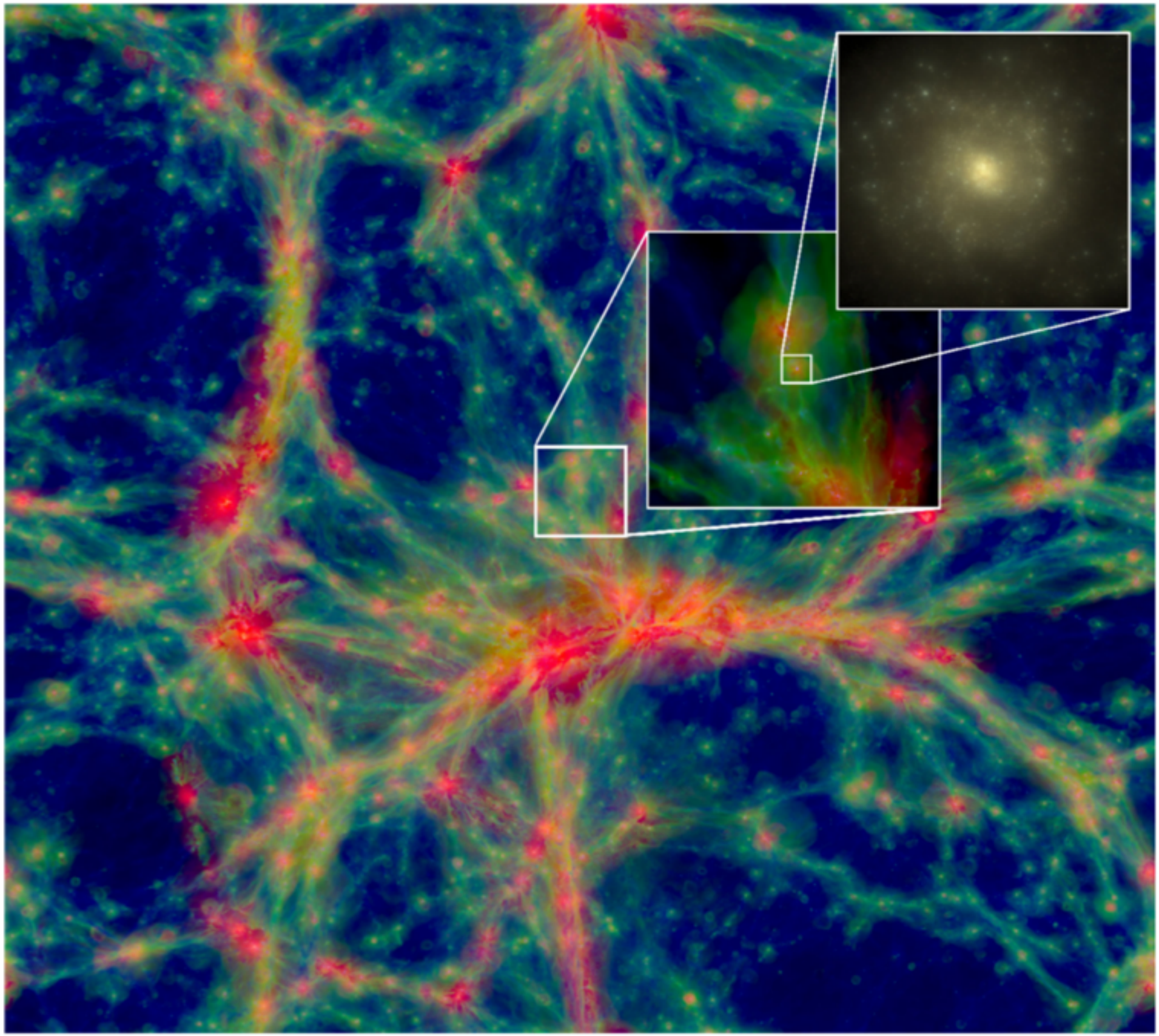


Initial conditions

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

Radiative cooling/heating, Star formation, & Feedback

Gravity + Hydrodynamics



100 cMpc

z=0

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

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

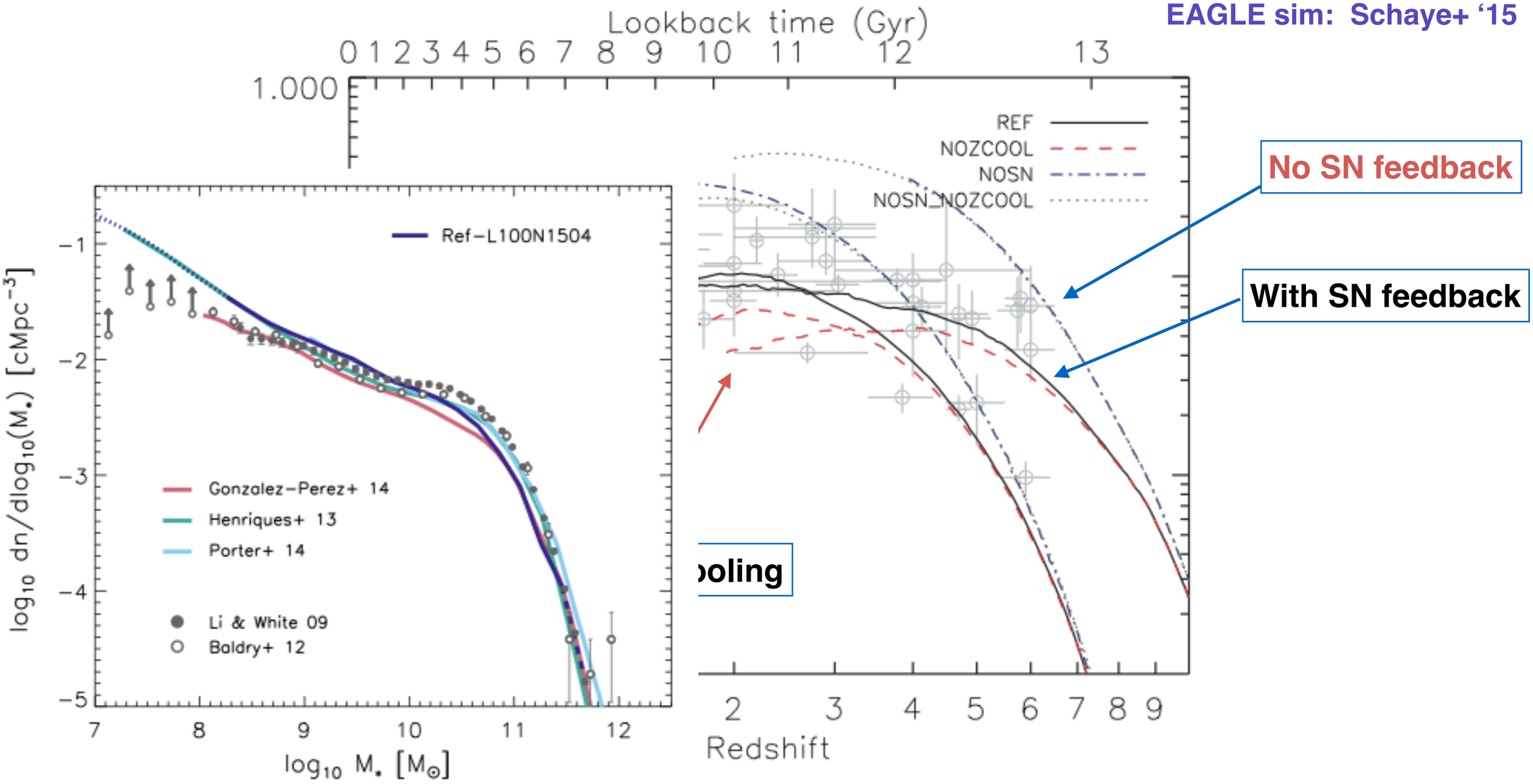
$T > 10^{5.5}$ K (red)

EAGLE sim: Schaye+ '15

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

Cosmic Star Formation History

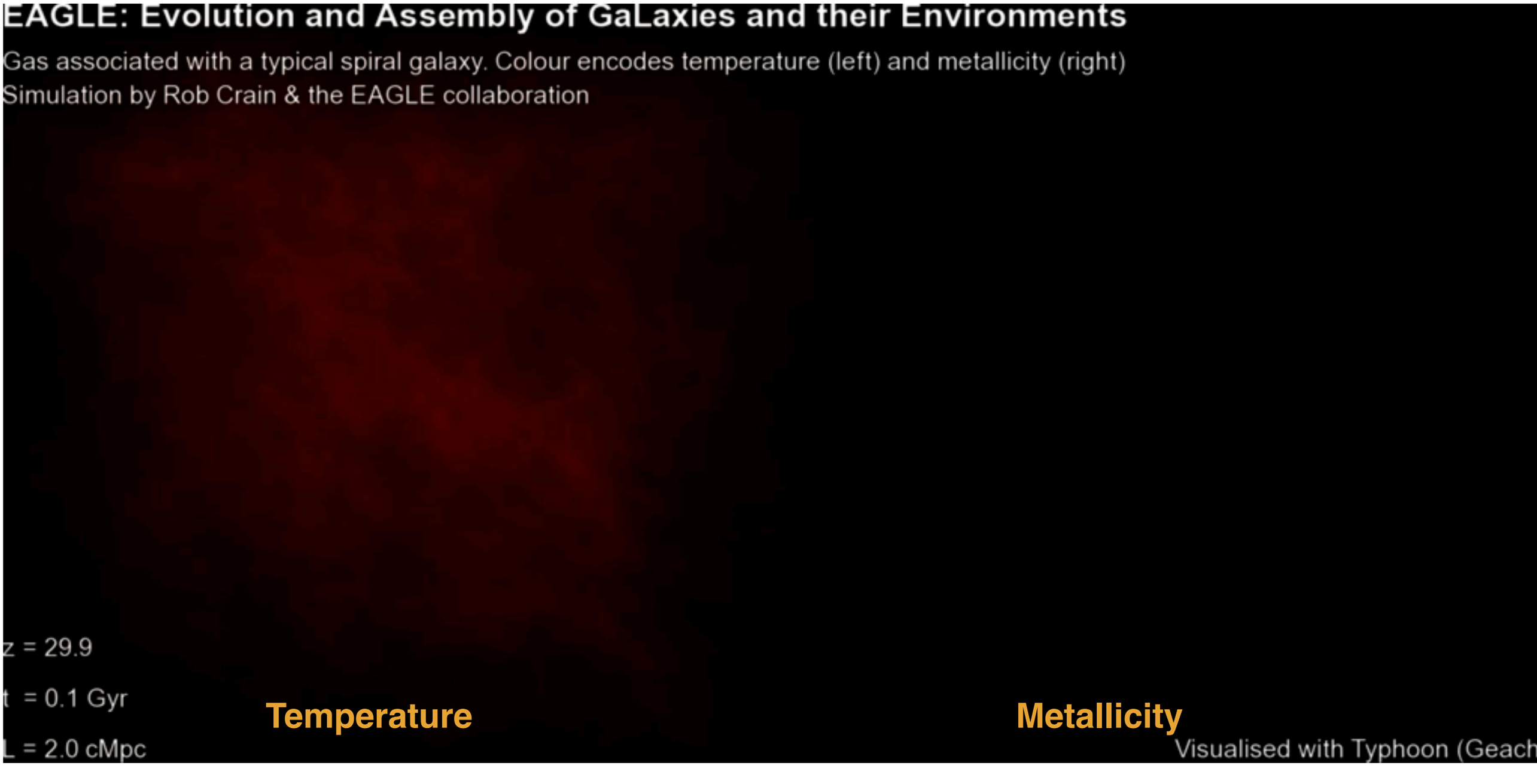
EAGLE sim: Schaye+ '15



Too many stars are produced without SN FB.

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



Galactic Wind (Kinetic) Feedback

Need to specify $\dot{M}_w$ **and** V_w

"Energy-driven" vs. "Momentum-driven"

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

η : mass-loading factor

Energy-driven: $\frac{1}{2}\dot{M}_W V_W^2 \sim \dot{E}_{\rm SN} \sim SFR$

$$\eta = \left(\frac{\sigma_0}{\sigma_{\rm gal}}\right)^2$$

$$V_W \sim V_{\rm esc} \sim \sigma_{\rm gal}$$

$$\sigma_0 \approx 300 \text{ km s}^{-1}$$

Momentum-driven: $\dot{M}_W V_W \sim \dot{P}_{\rm rad} \sim SFR$

$$\eta = \frac{\sigma_0}{\sigma_{\rm gal}}$$

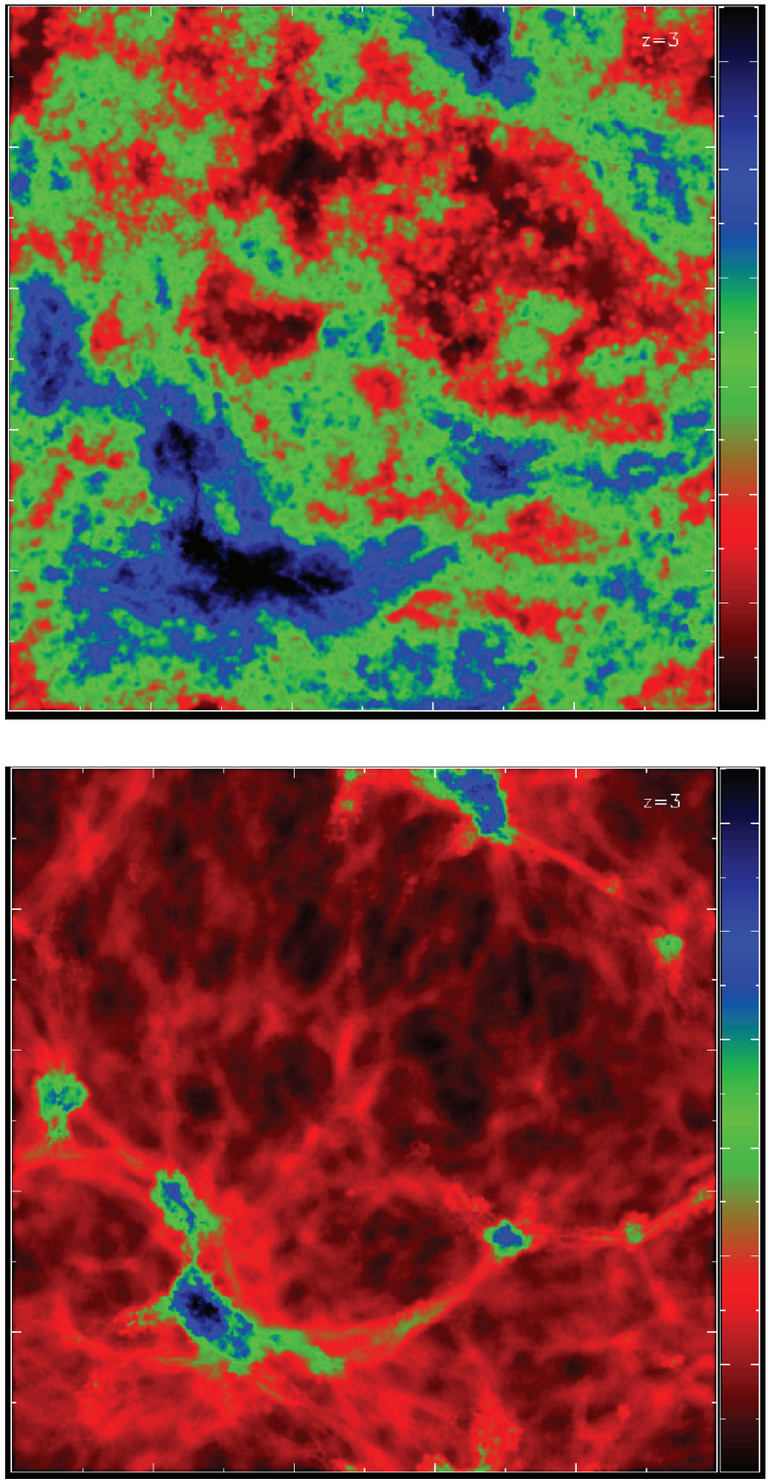
Radiation pressure from massive stars and SNe is applied to the dust particles, which entrains the wind

Murray+ '05

Higher mass-loading factor for lower mass galaxies.

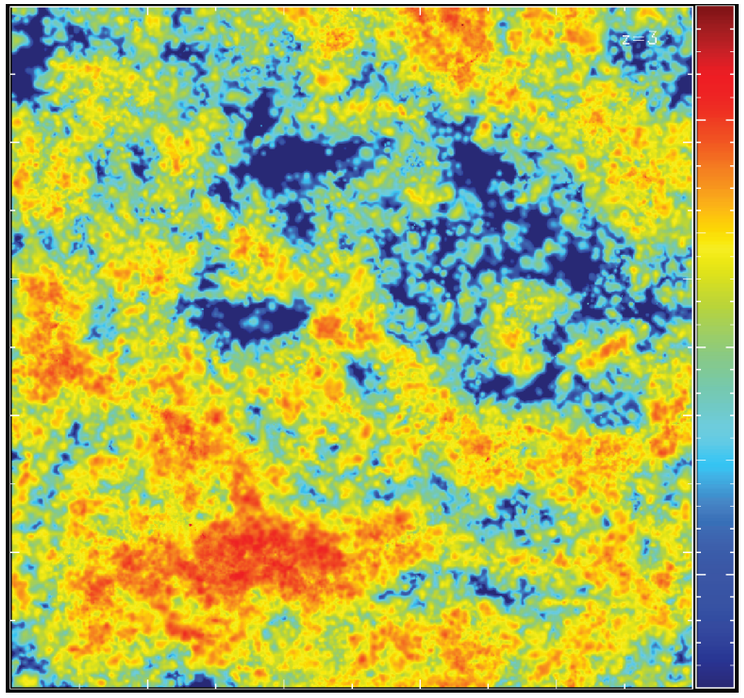
Impact of Momentum-driven Wind on IGM

Temperature



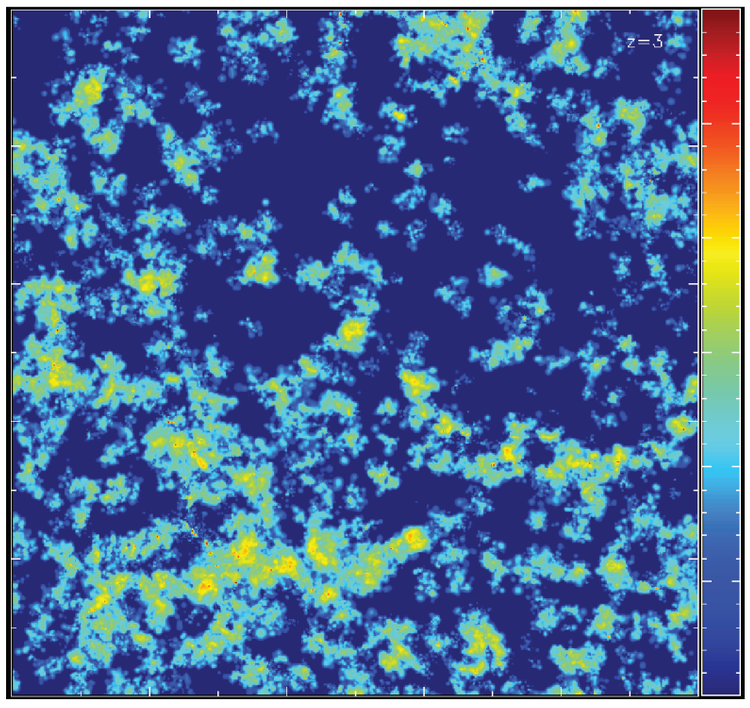
10 Mpc/h

Projected metal density



Energy-driven wind (constant V_w)

Momentum-driven

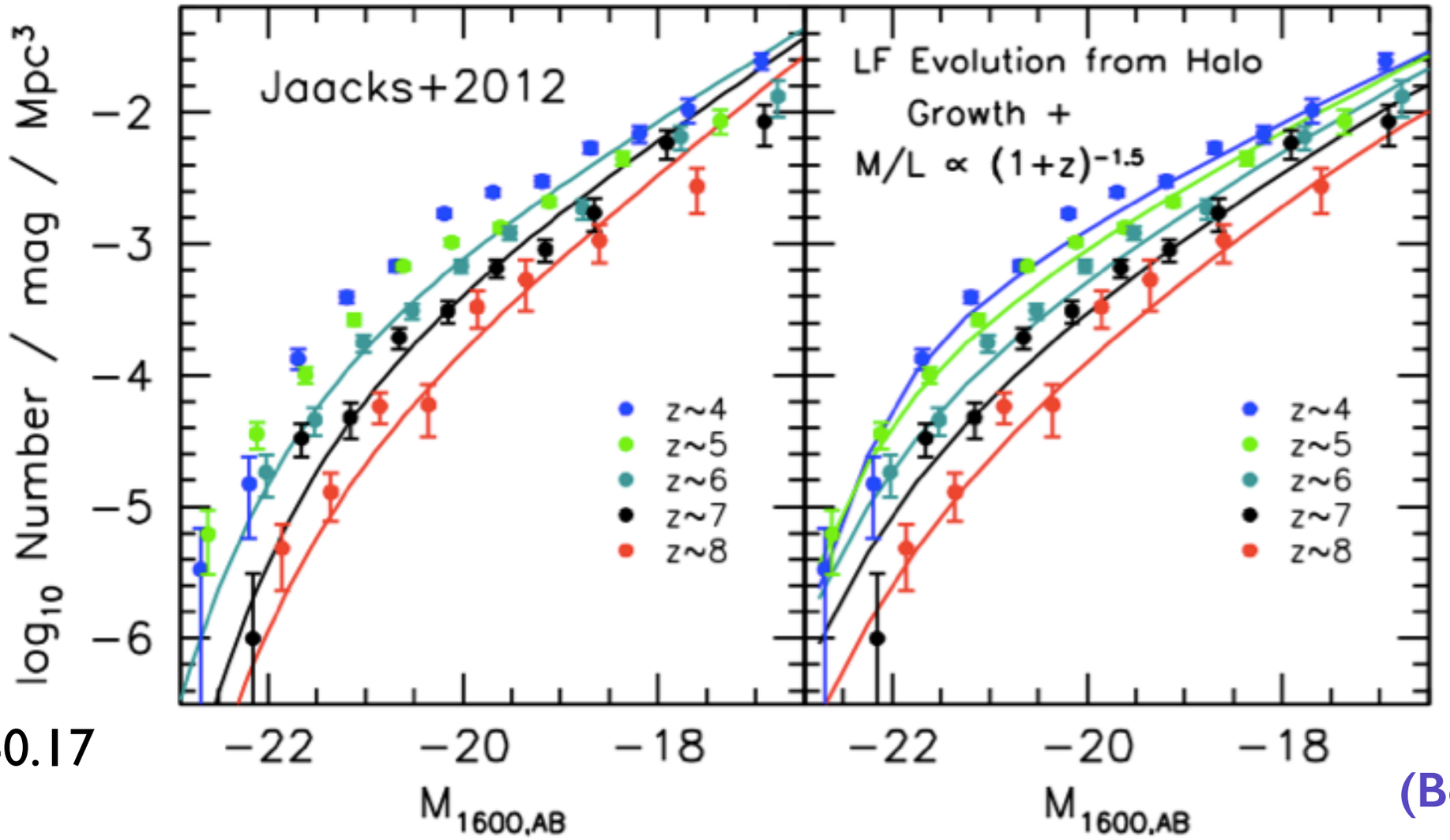


Choi & KN '10

UV LFs at z=4-8: Obs vs. Sim

HUDF09+HUDF12, ERS, CANDELS, BORG/HIPPIES

Simulations **DM halo MF + M/L evol.**



α=-1.64 (z=4)

↓

α=-2.06 (z=6)

dα/dz= -0.17

dα/dz= -0.13

(Bouwens+ '14)

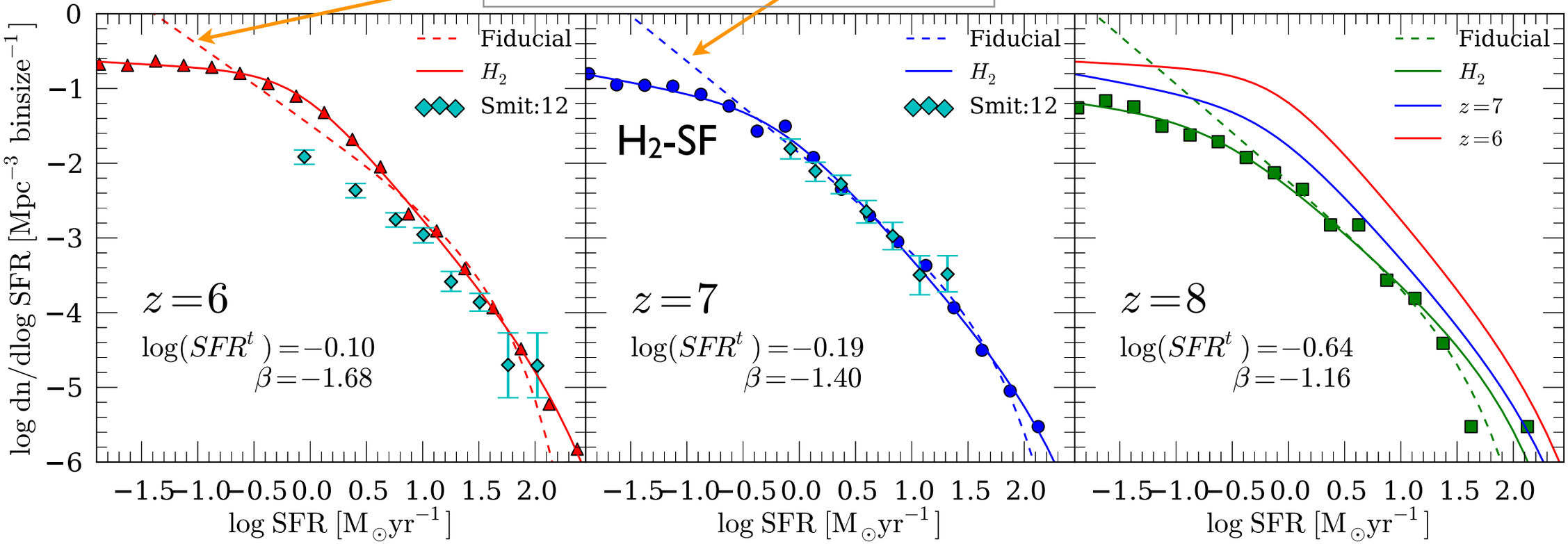
Steepening of the faint-end slope towards high-z even to α≲-2

(cf., Dunlop+, Ellis+, Finkelstein+, McLure+, Oesch+, Ouchi+, Schenker+, Trenti+, etc.)

SFR fcn w/ H_2-SF model

Previous pressure-SF model

Jaacks, Thompson, KN '13



Modified Schechter SFR fcn:

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

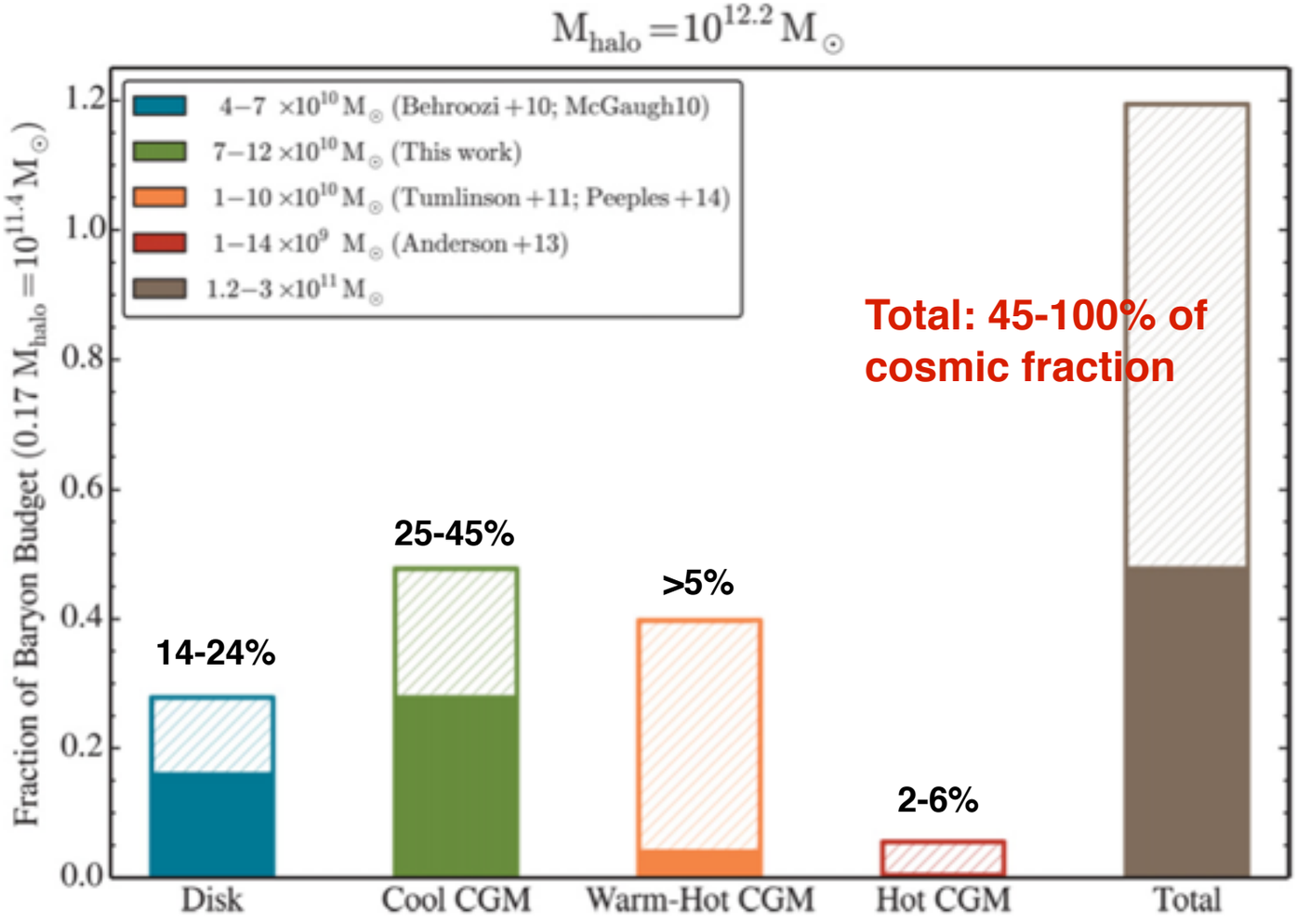
Agrees well with current obs constraints at z=6 & 7 (Smit+ '12).

SFR fcn provides more direct comparison btw sim & obs.

CGM baryon budget

(Circum-galactic Medium)

- HST COS. 44 quasar spectra
- multiphase CGM in L* gal (r<160kpc)
- CLOUDY modelling
- More sophisticated models of stellar FB is needed.



Werk+ '14

Multi-phase CGM in high-z galaxies

Stellar Feedback

(in addition to SN feedback)

- stellar winds from young stars ("early" 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

Galaxy Merger Simulations

(Springel+ '05, …, Hopkins+'13)

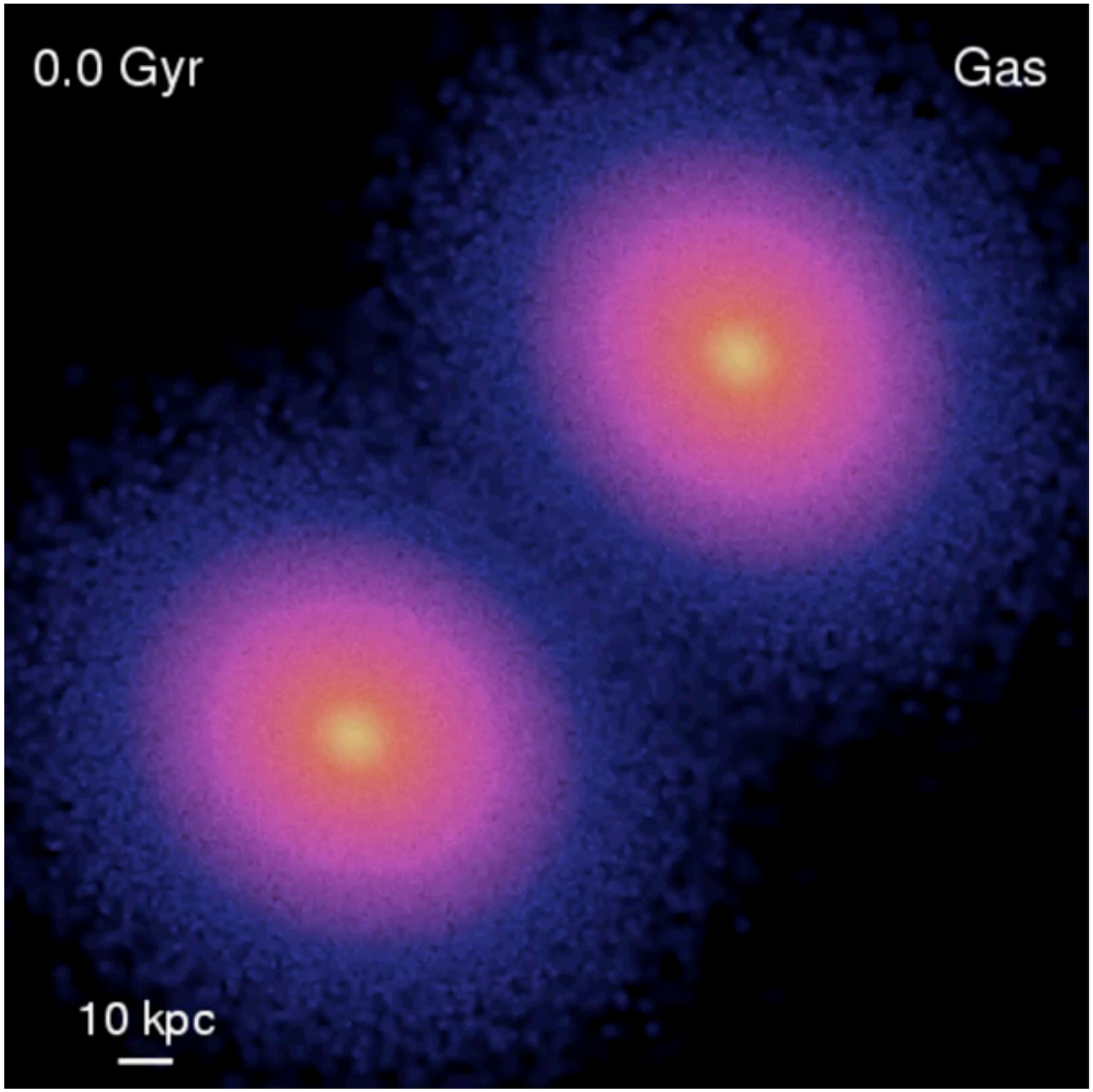
Stellar Feedback:
radiation pressure, direct momentum (stellar wind), photoionization heating

But, this is not in cosmological context.

Resolution:

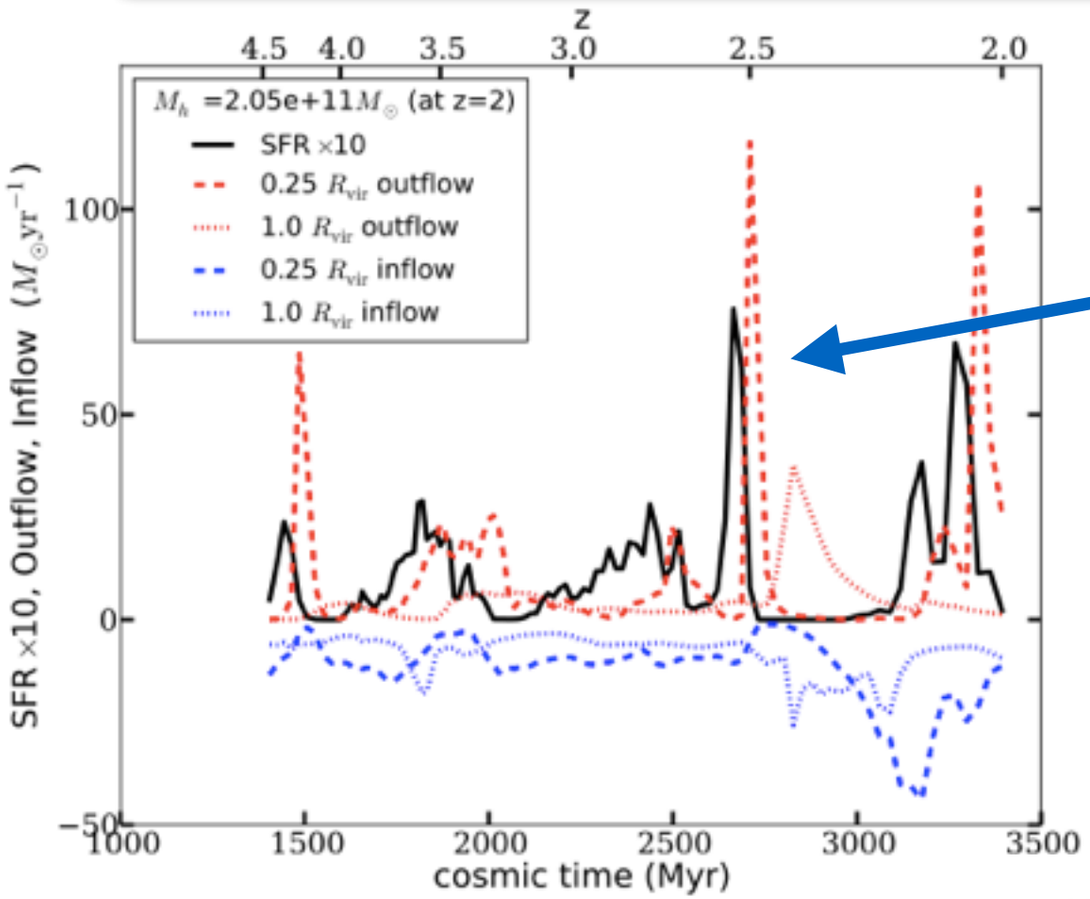
$m_p \lesssim 1000 M_\odot$, $\epsilon \sim 3$pc

Hopkins+ '13
(GADGET SPH)



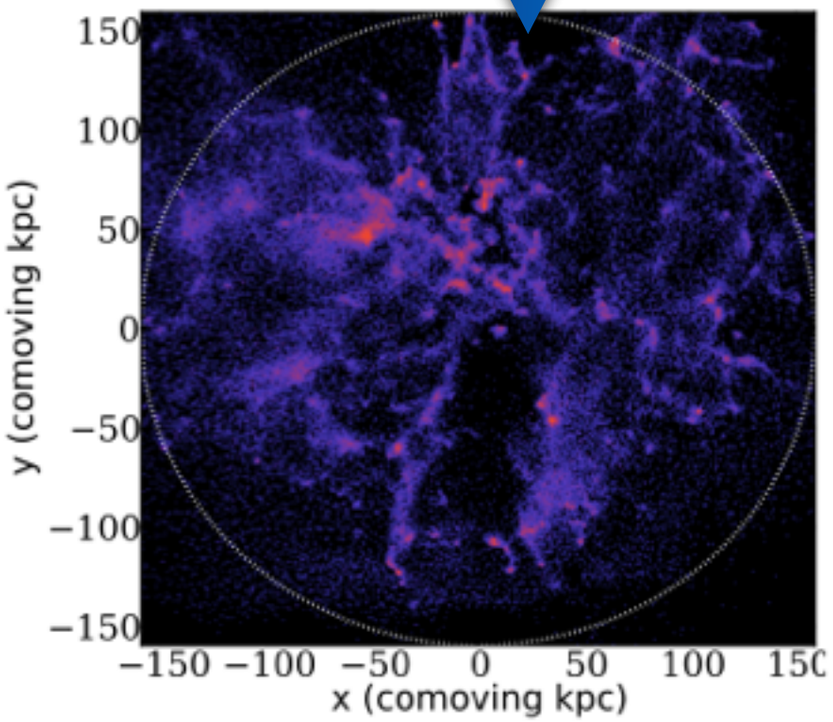
Stellar Feedback in Zoom-in Sim

(Cosmological Initial Condition)

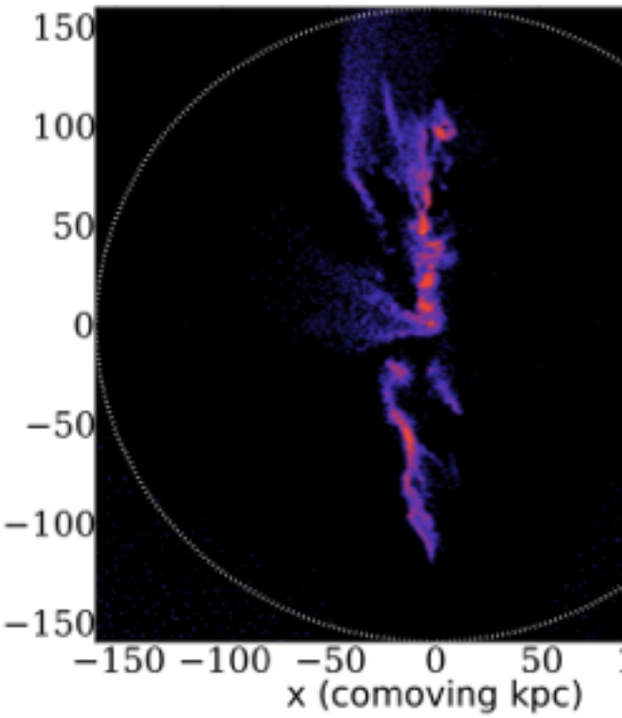


- Star formation is episodic.

- Outflows sweep up CGM.



Inflow



Hopkins+'13; Muratov+ '14

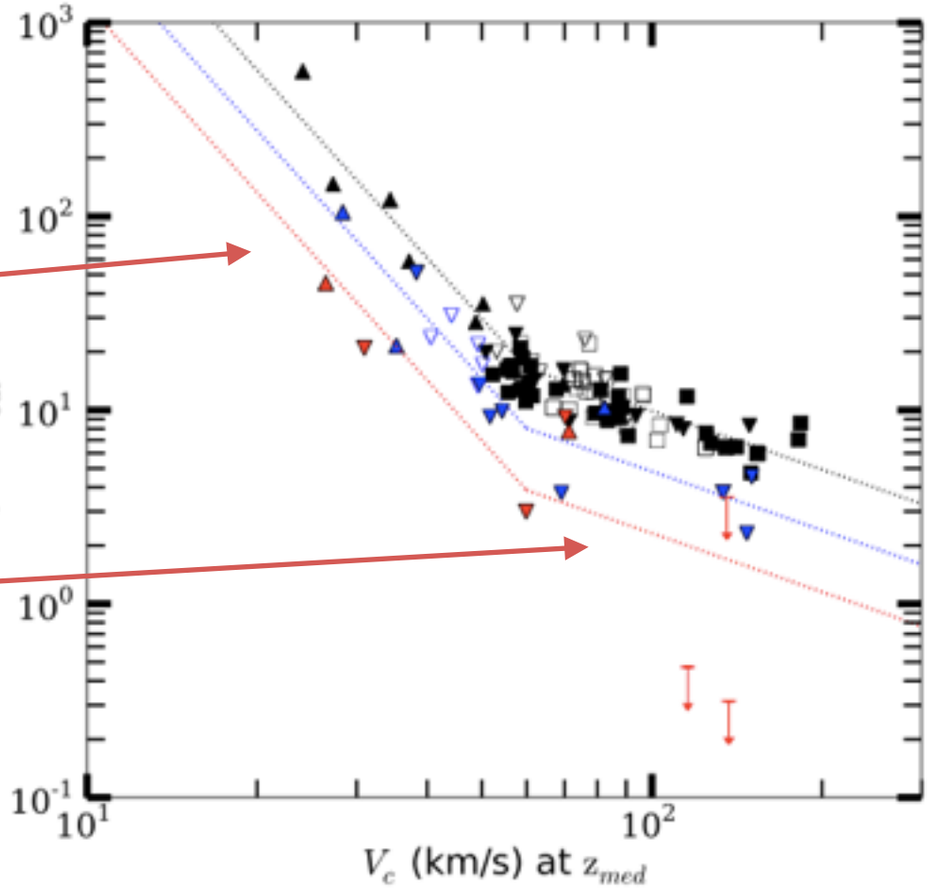
Stellar Feedback in Zoom-in Sim

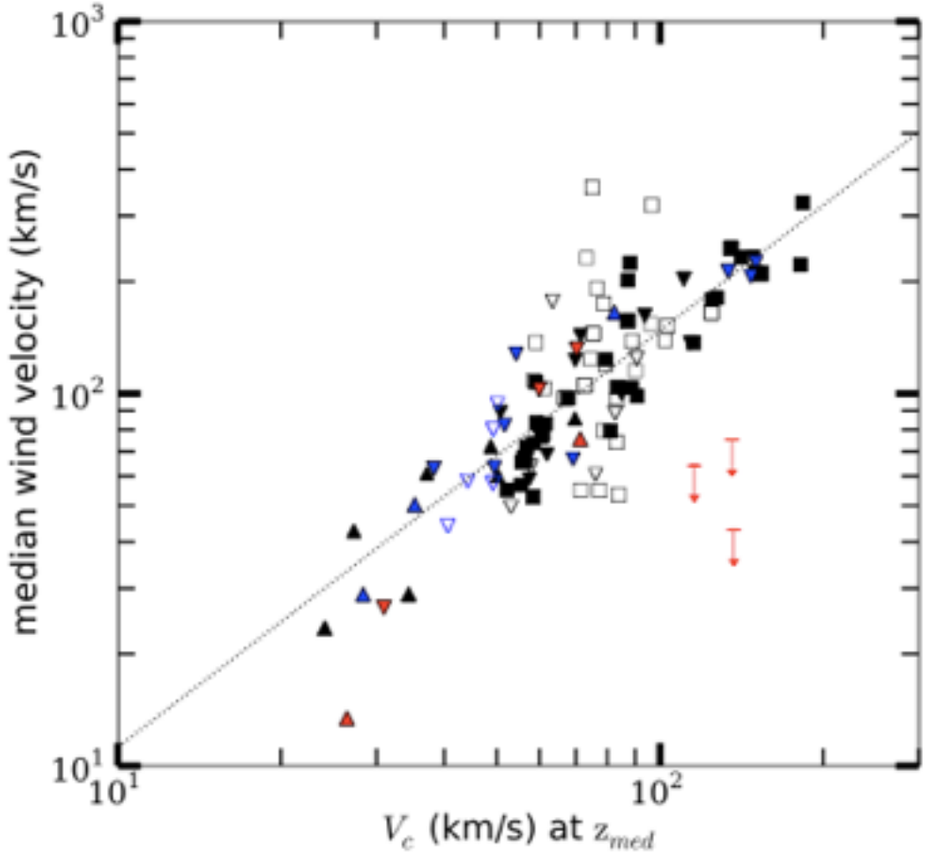
Mass Loading Factor : η

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

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

(≈ Momentum-driven)



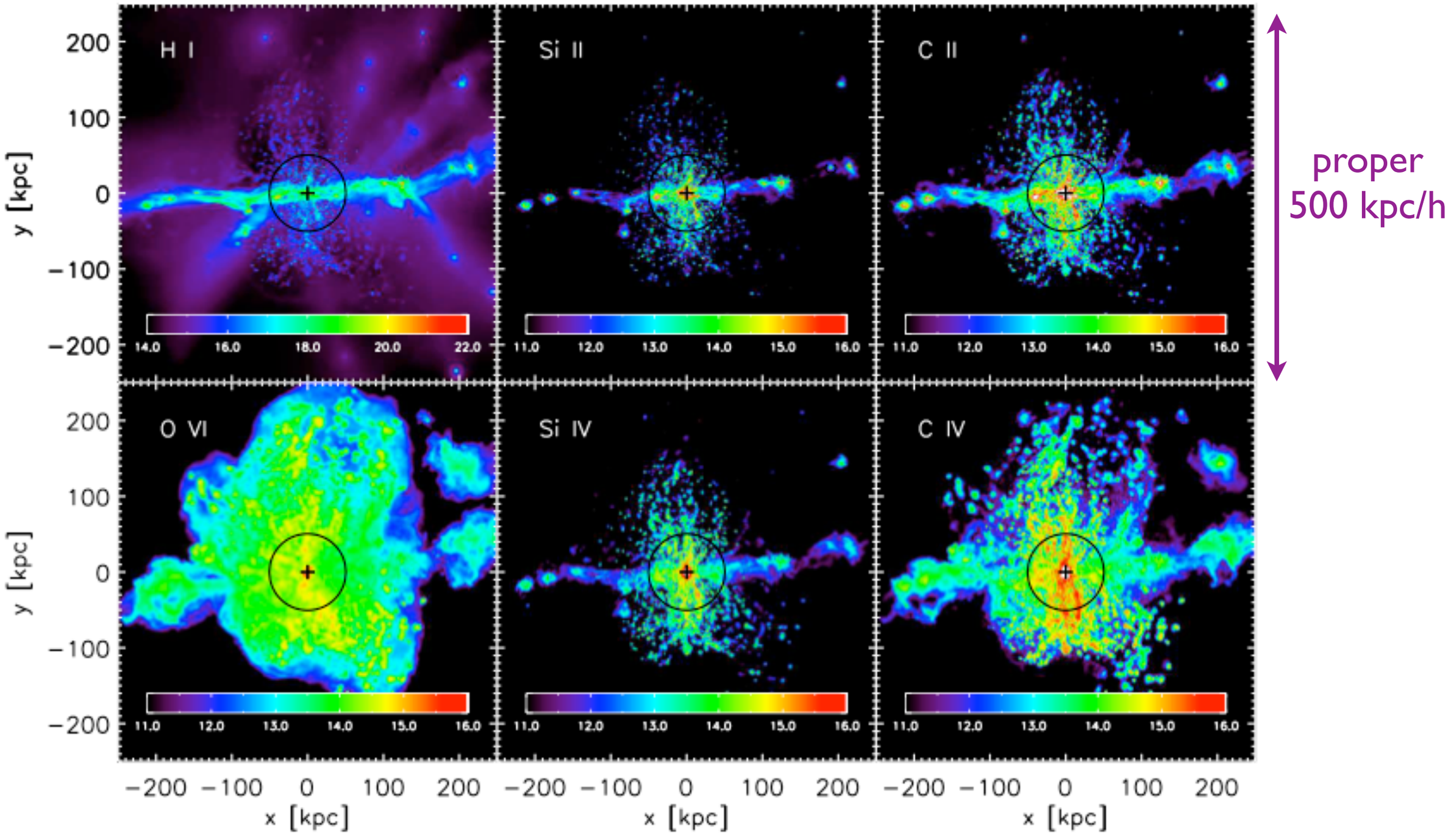


Wind Velocity

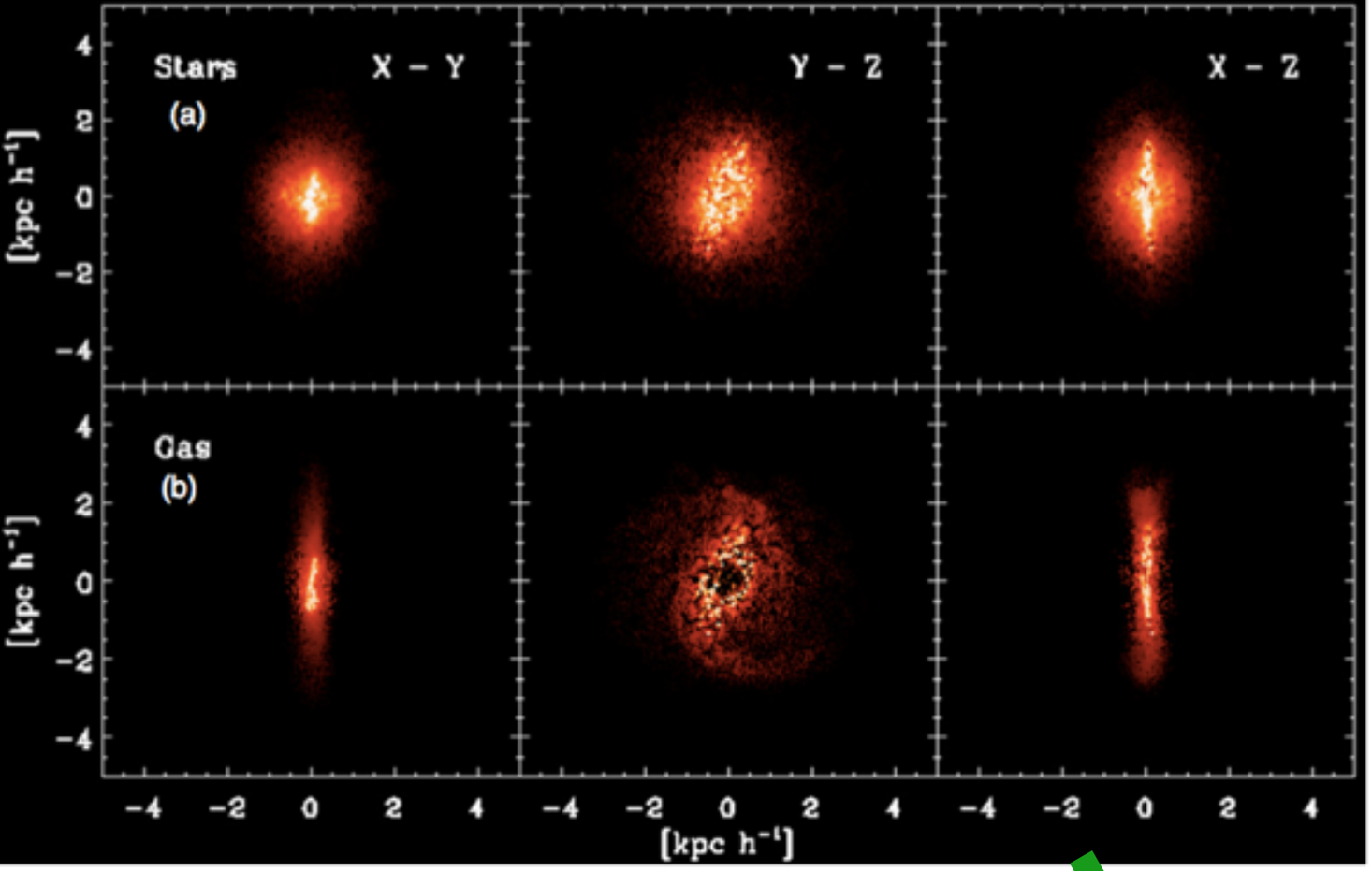
Hopkins+'13; Muratov+ '14

Circum-galactic medium (CGM)

(probed by quasar absorption lines)



z=2.8 Eris2 zoom-in simulation (Shen+ ’13)



z=10.2

Romano-Diaz+ ‘11

resolution ~ 30 pc (proper)

Massive disk gal already at z~10

$M_{tot} \sim 1.1 \times 10^{10}\ h^{-1}\ M_\odot$

total disk mass is $\sim 2.9 \times 10^{9}\ h^{-1}\ M_\odot$

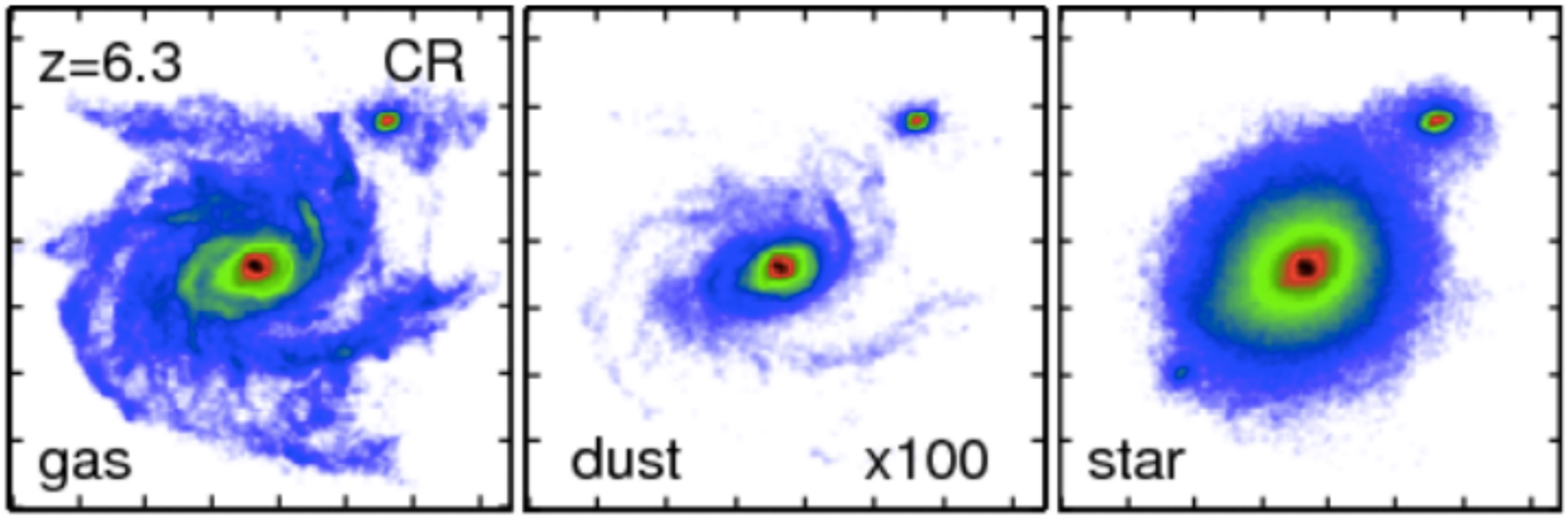
$M_{star,disk} \sim 8 \times 10^{8}\ h^{-1}\ M_\odot$

z=6.3

Yajima+ ‘14

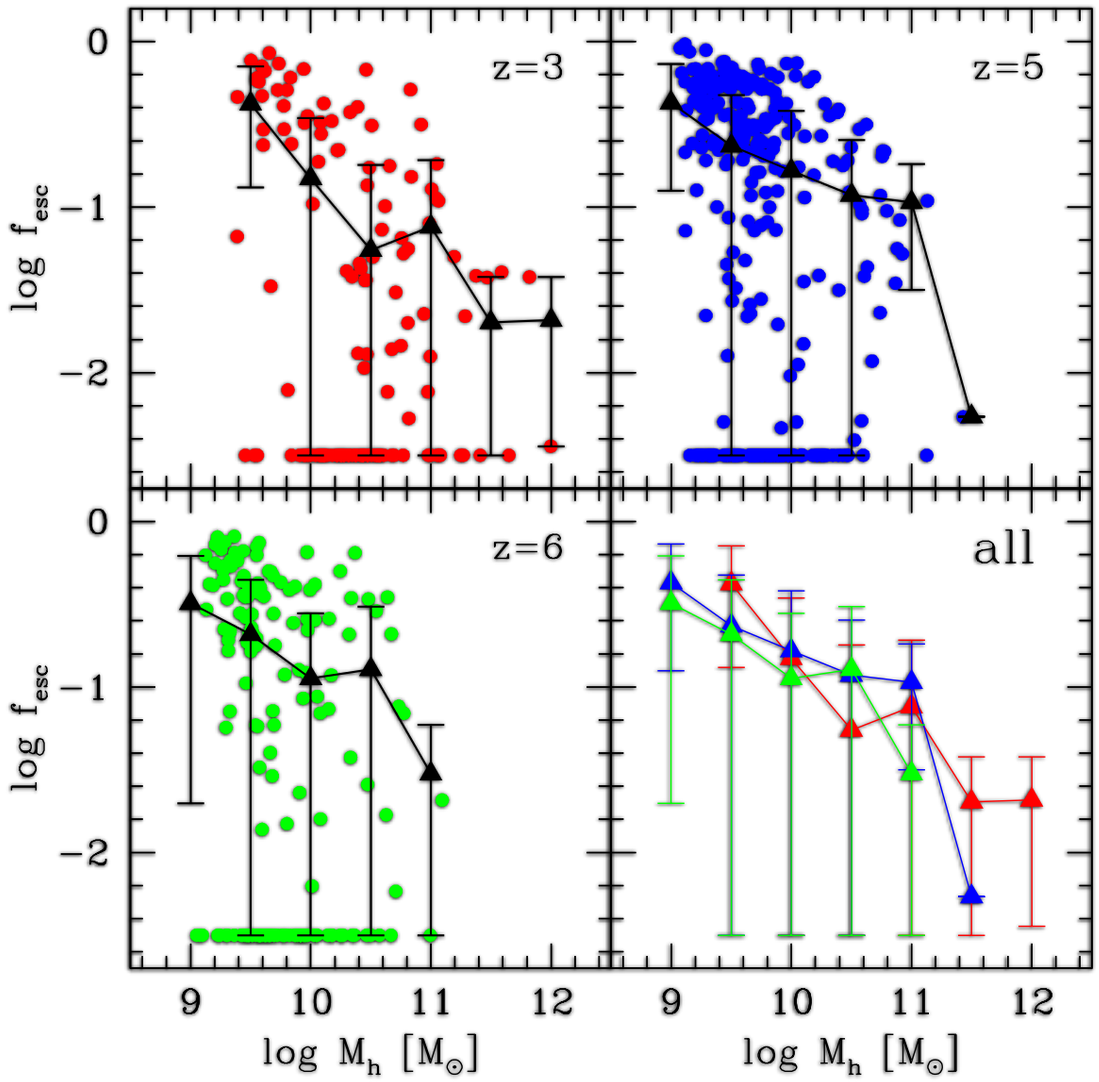
$M_{gas} \sim 4.8 \times 10^{10}\ M_\odot$

$M_{star} \sim 4.1 \times 10^{10}\ M_\odot$

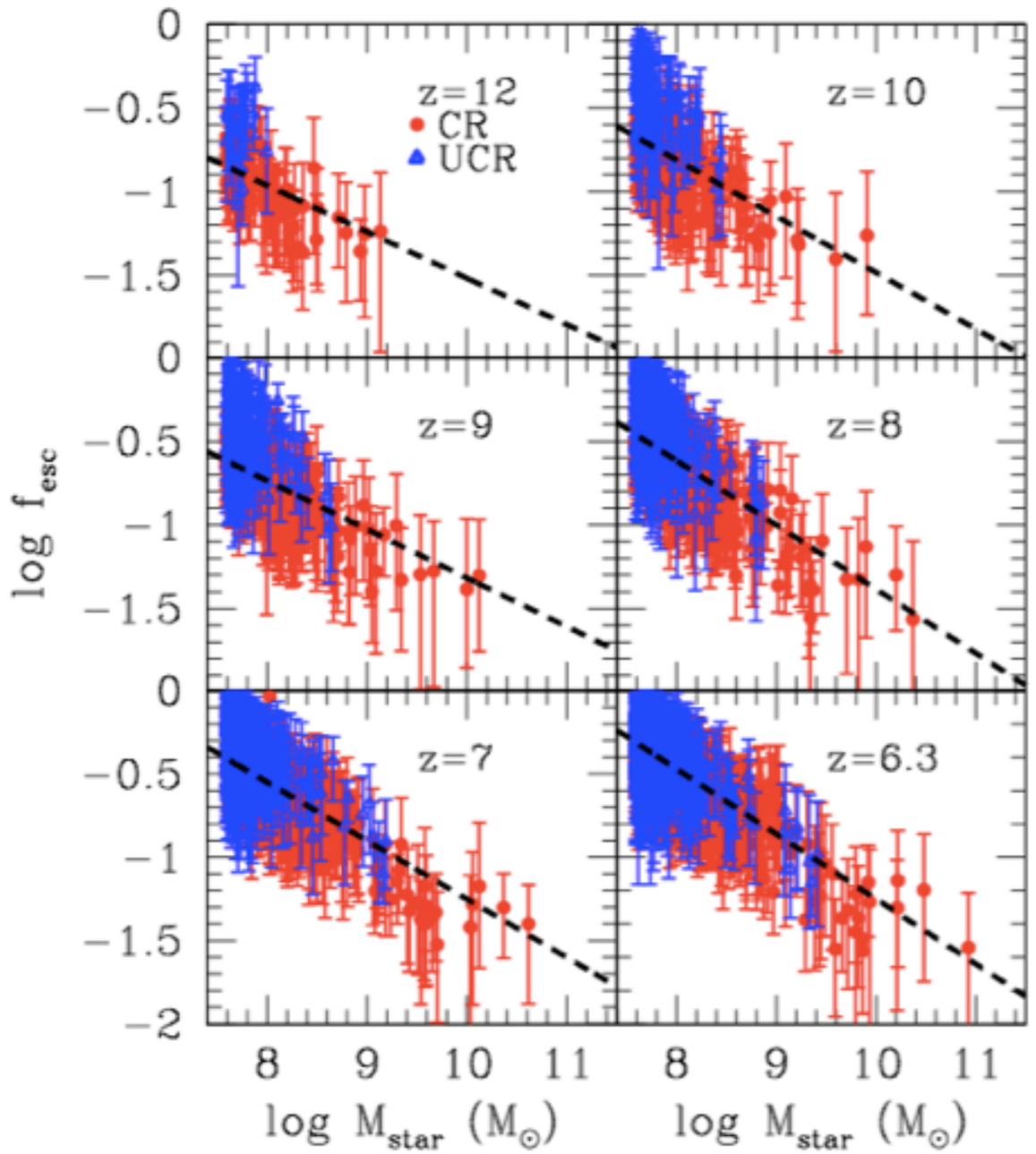


$M_{dust}/M_{metal} = 0.4, \quad$ i.e. $M_{dust} = 0.008\ M_{gas}\ (Z/Z_\odot)$

Escape Fraction of Ionizing Photons



Yajima, Choi, KN '11



Yajima+ '14

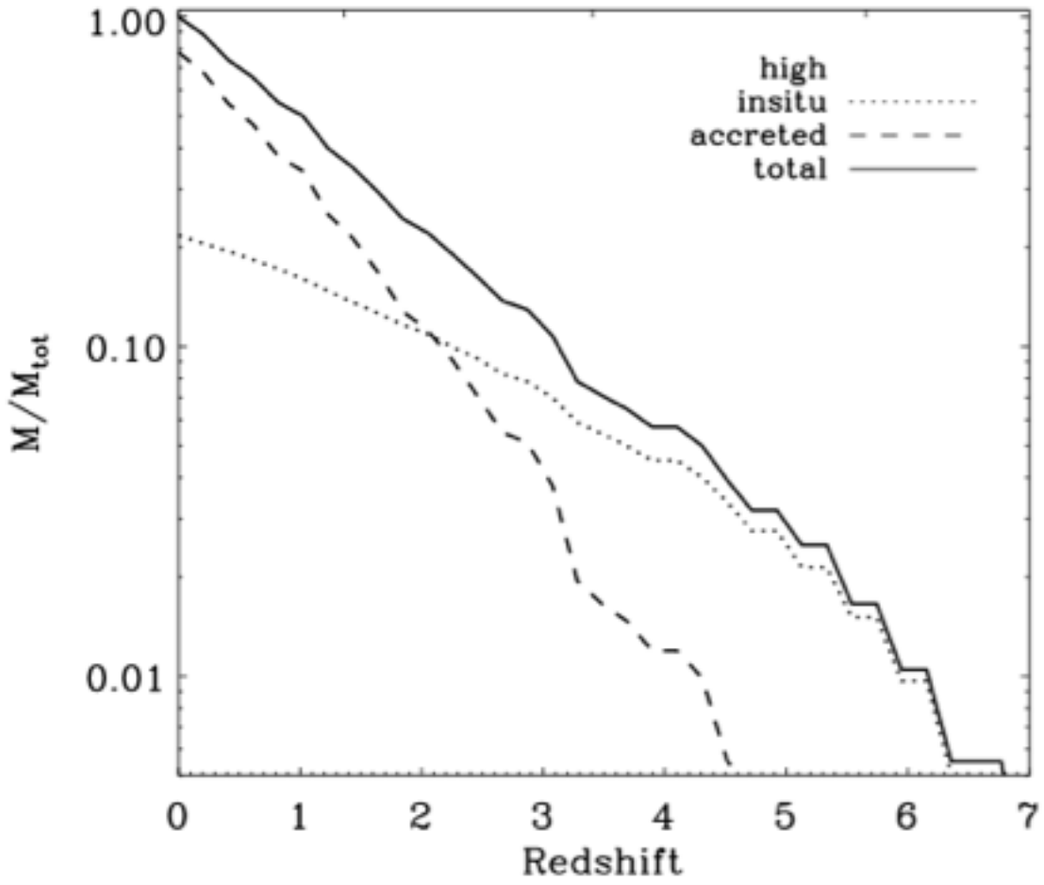
Elliptical Galaxies, Downsizing, & Feedback

Two-phase Formation & Downsizing

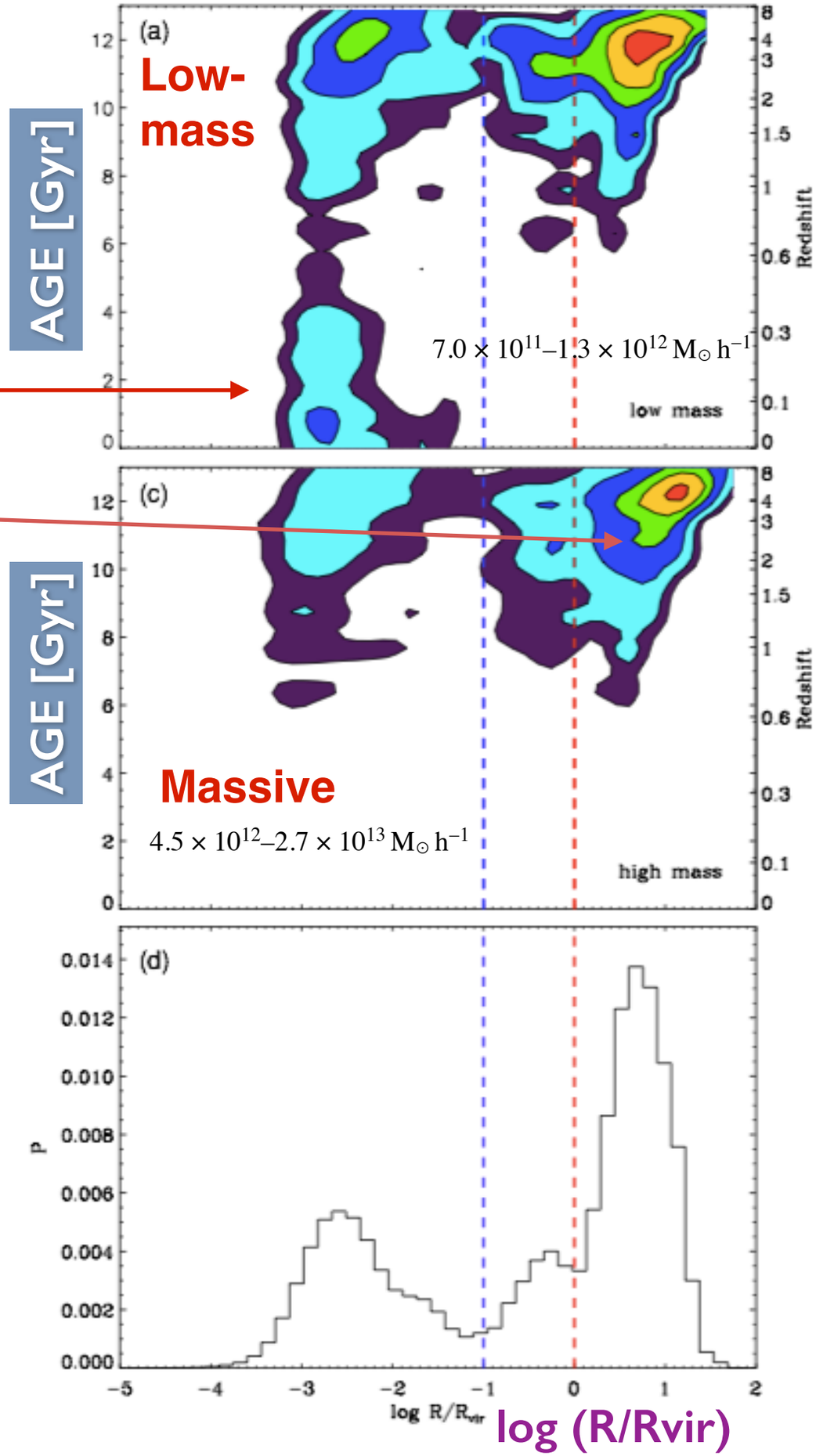
Naab+'12; Oser+'14 : zoom-in cosmo hydro sim

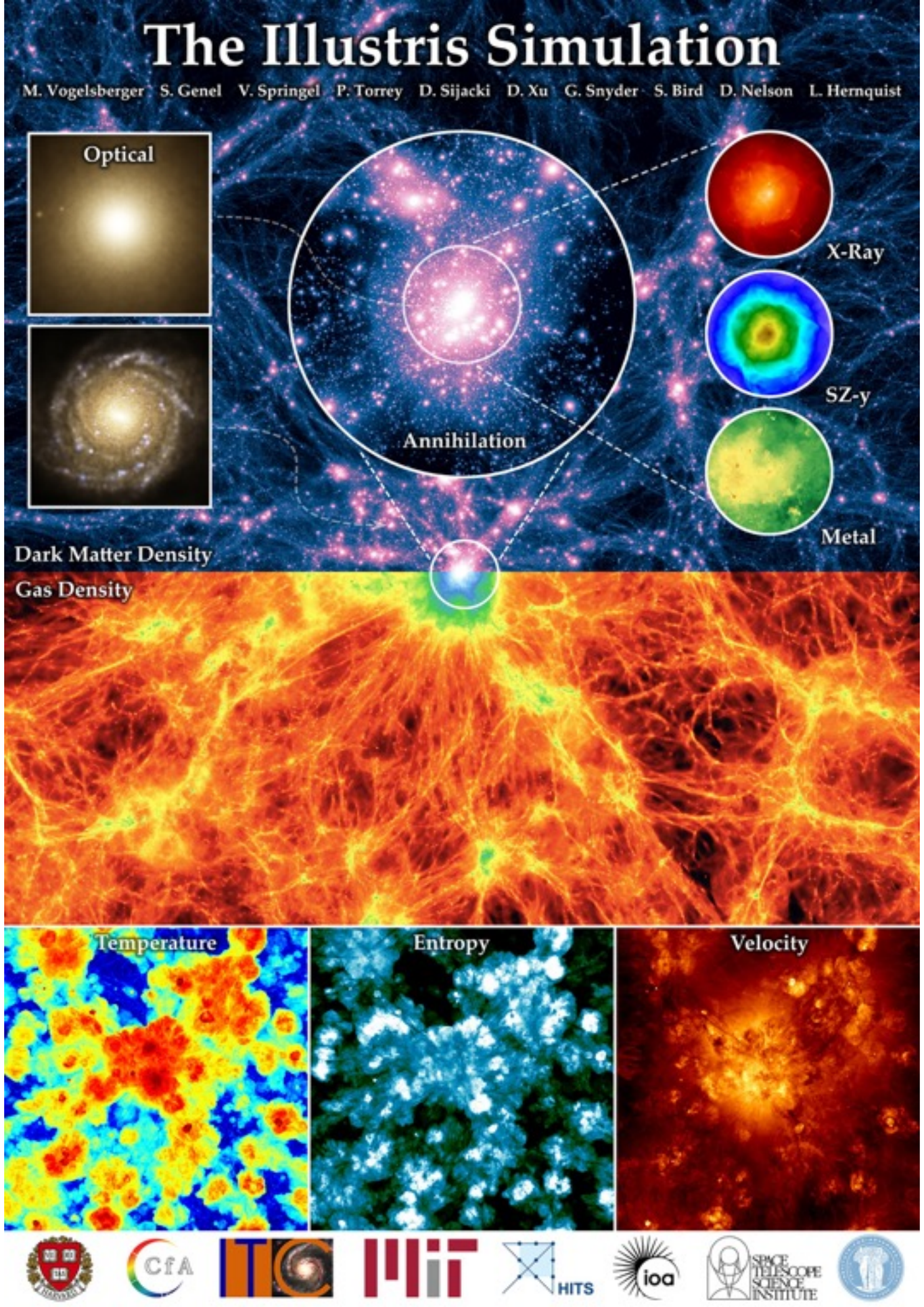
late in-situ SF

Formed at high-z outside, but accreted later on.



In-situ SF dominant @ high-z



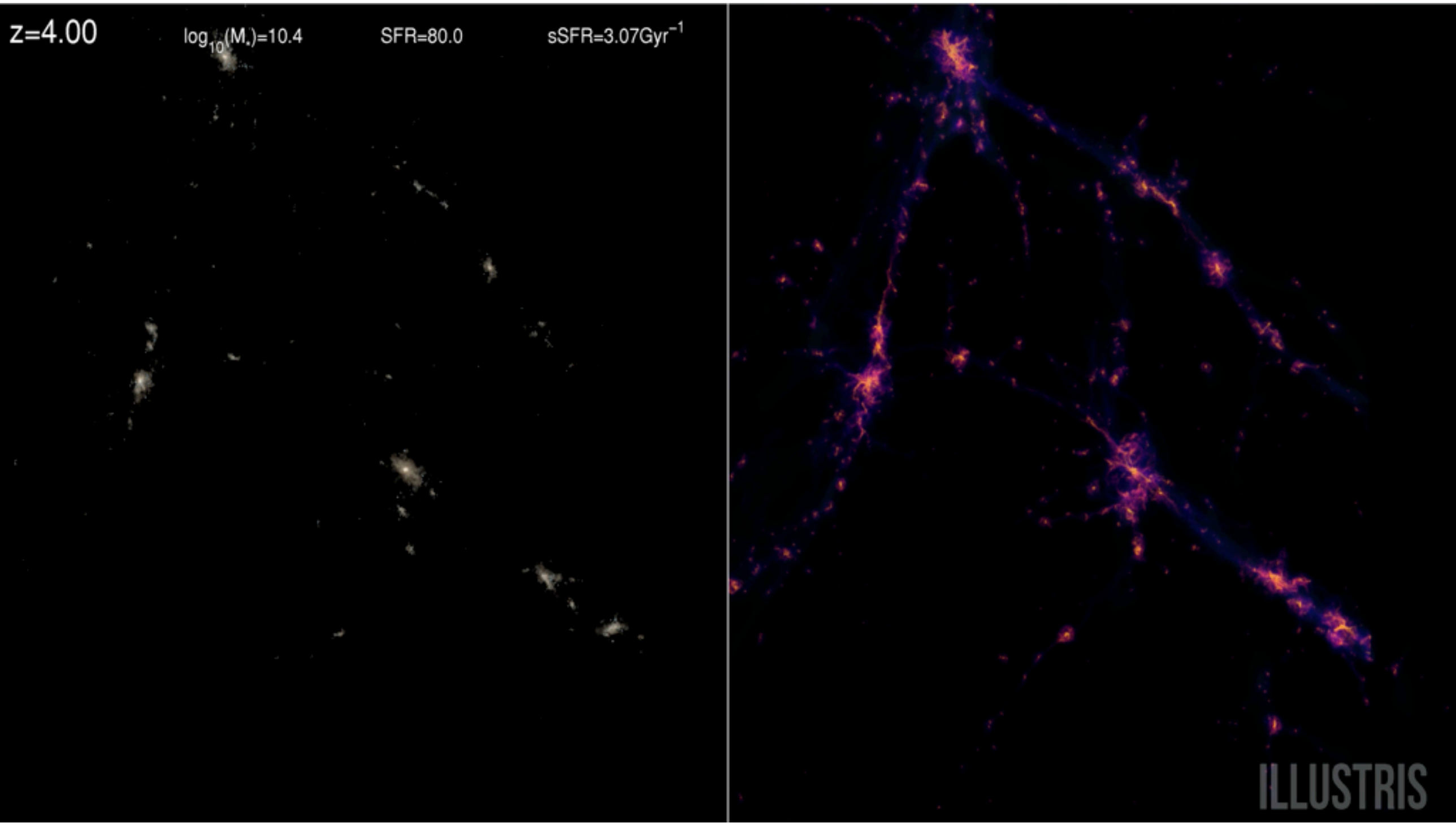


http://www.illustris-project.org/

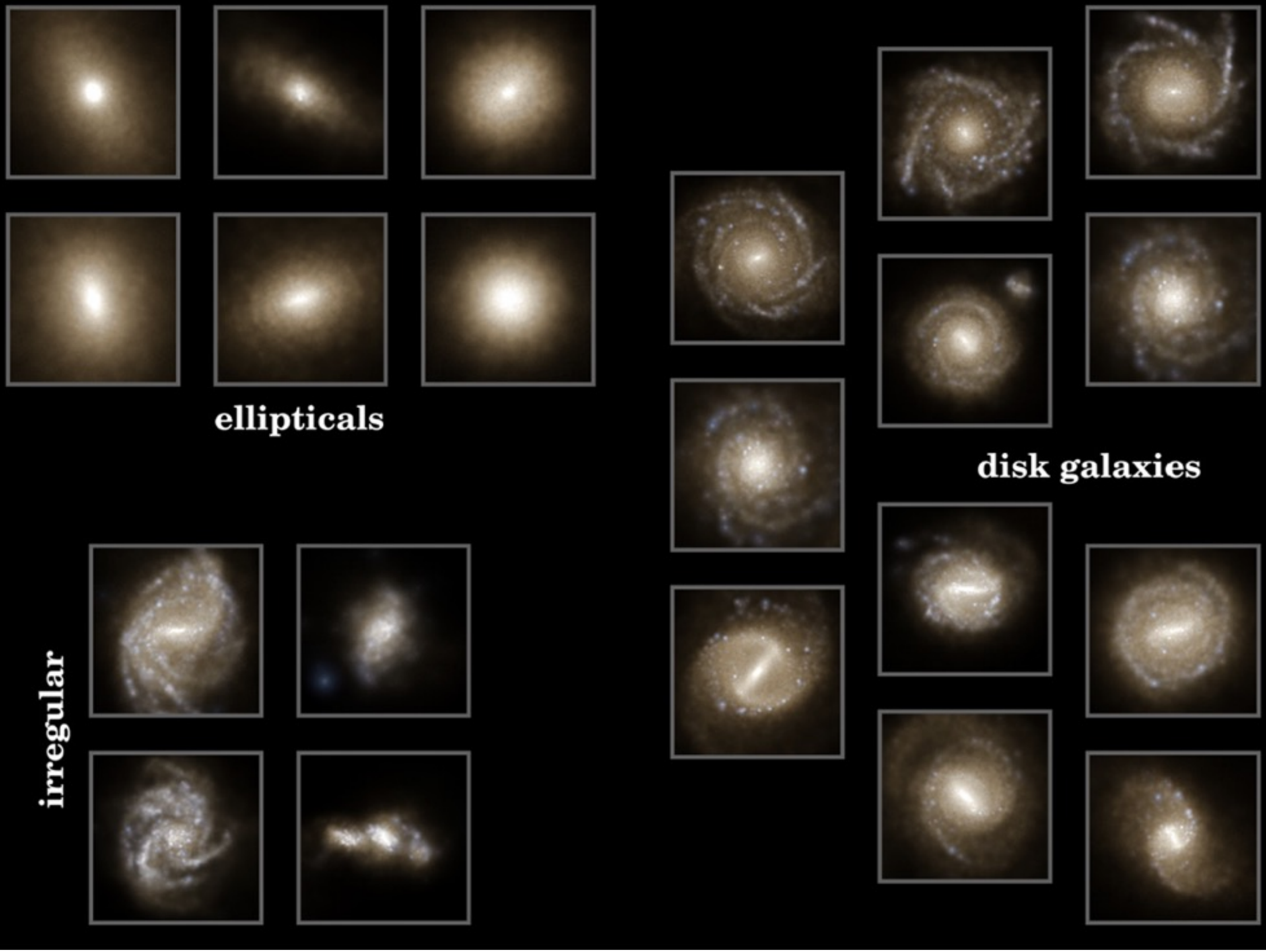
10 cMpc volume; w/ AGN feedback (quasar + radio mode)

Stellar Light

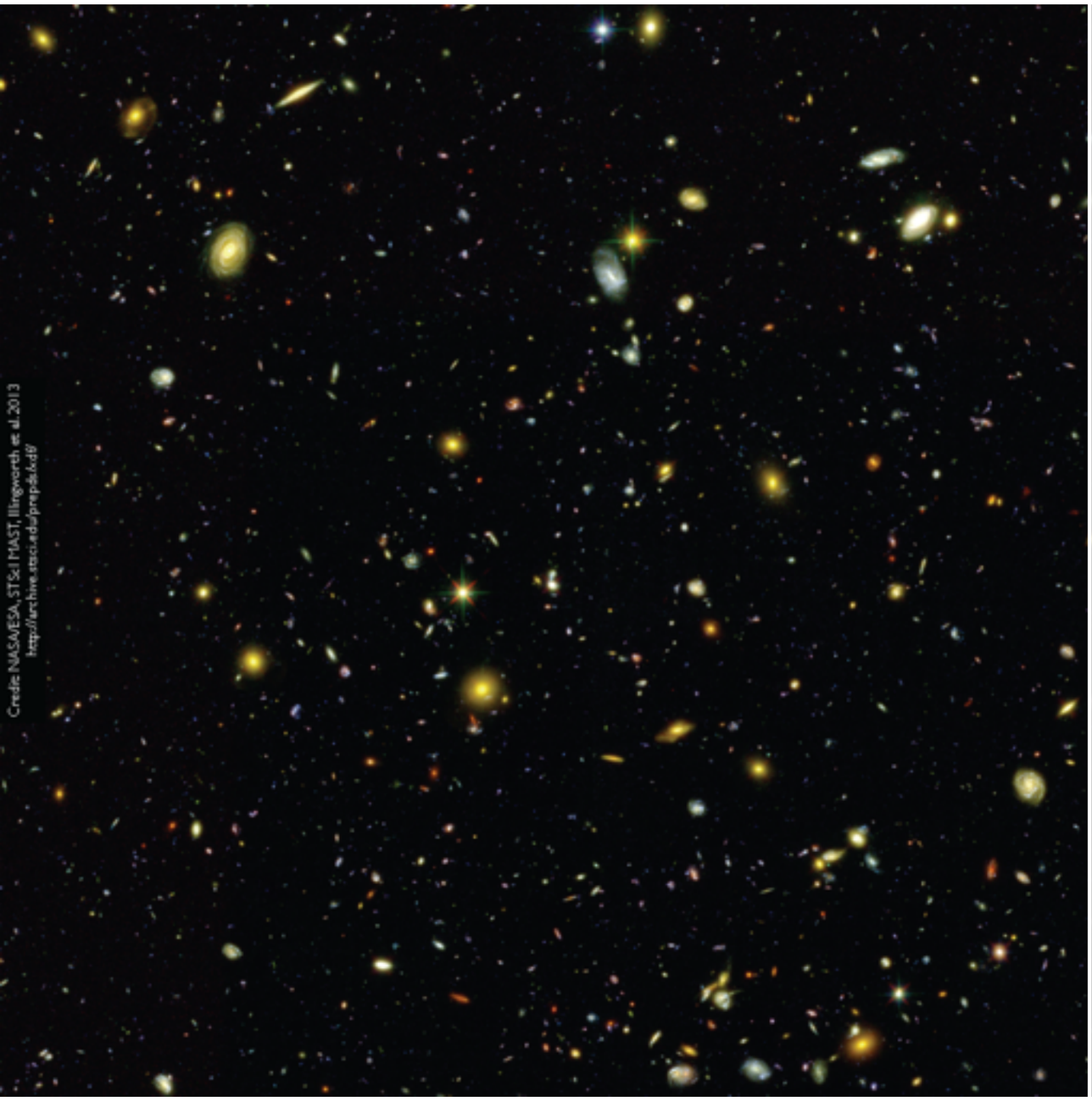
Gas Density

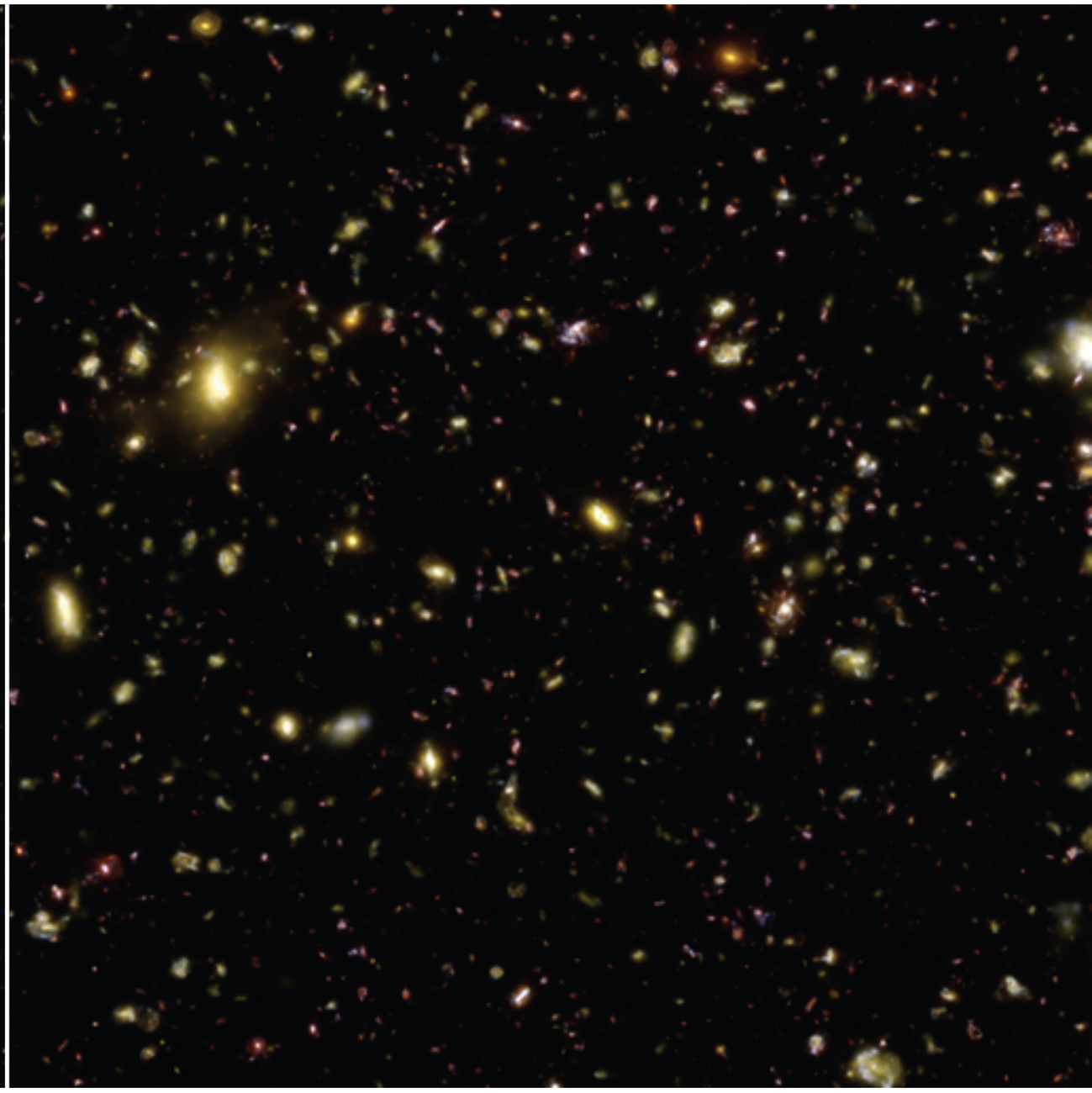


Formation of massive elliptical, “red & dead” gal.


ellipticals
disk galaxies
irregular

Which is the true HUDF observation?





Conclusions, Keywords & Future

- *`Feedback' continues to be the focus of galaxy formation & evolution.*
- *"Early Feedback" from young stars: rad pressure, momentum, thermal energy, photoionization,*
- *Dust! (couple w/ radiation)*
- *Morphology, Downsizing. Color bimodality?*
- *Orientation effect; Escape Fraction; Reionization*
- *AGN FB, gal-SMBH co-evolution.*

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