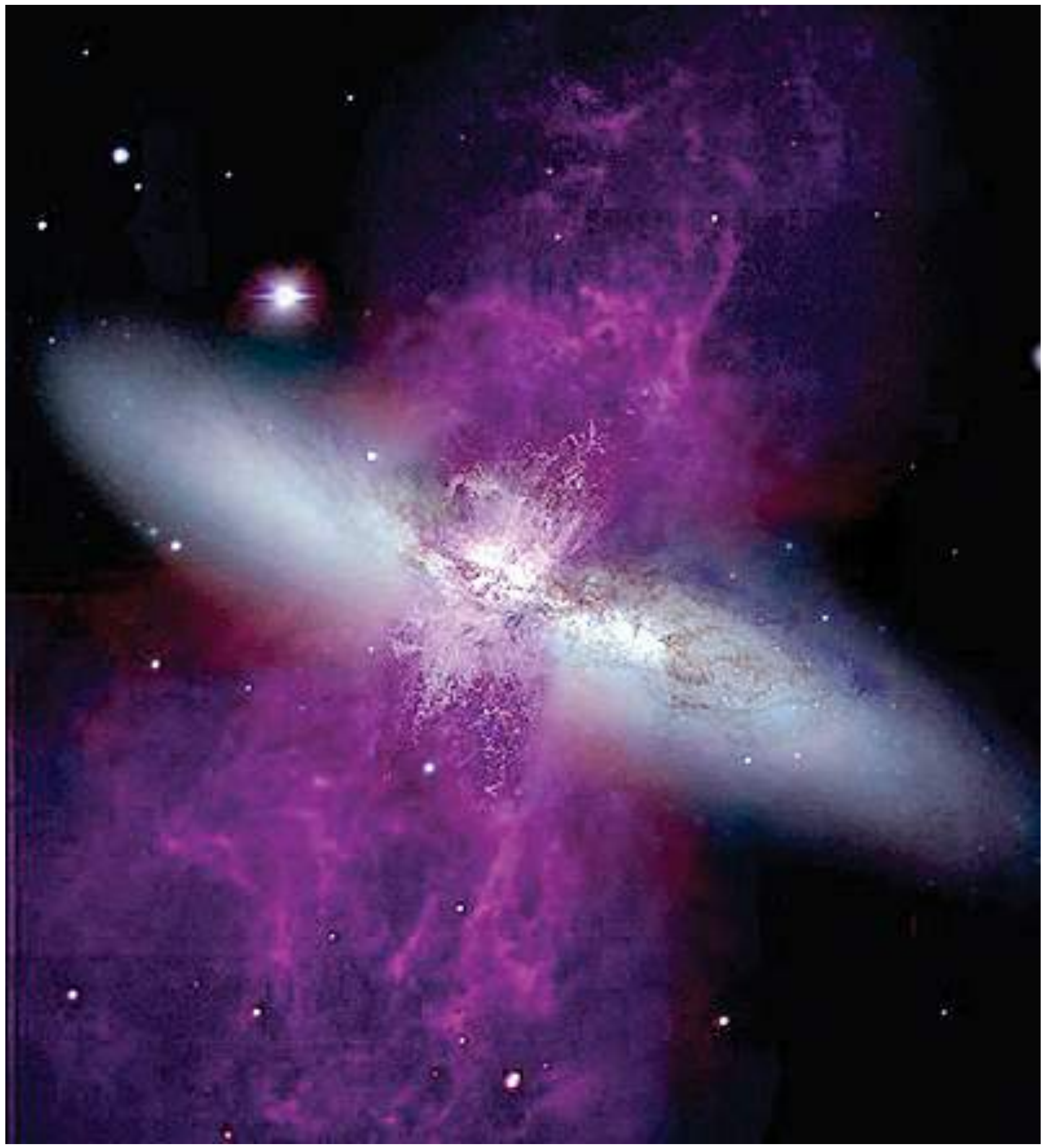
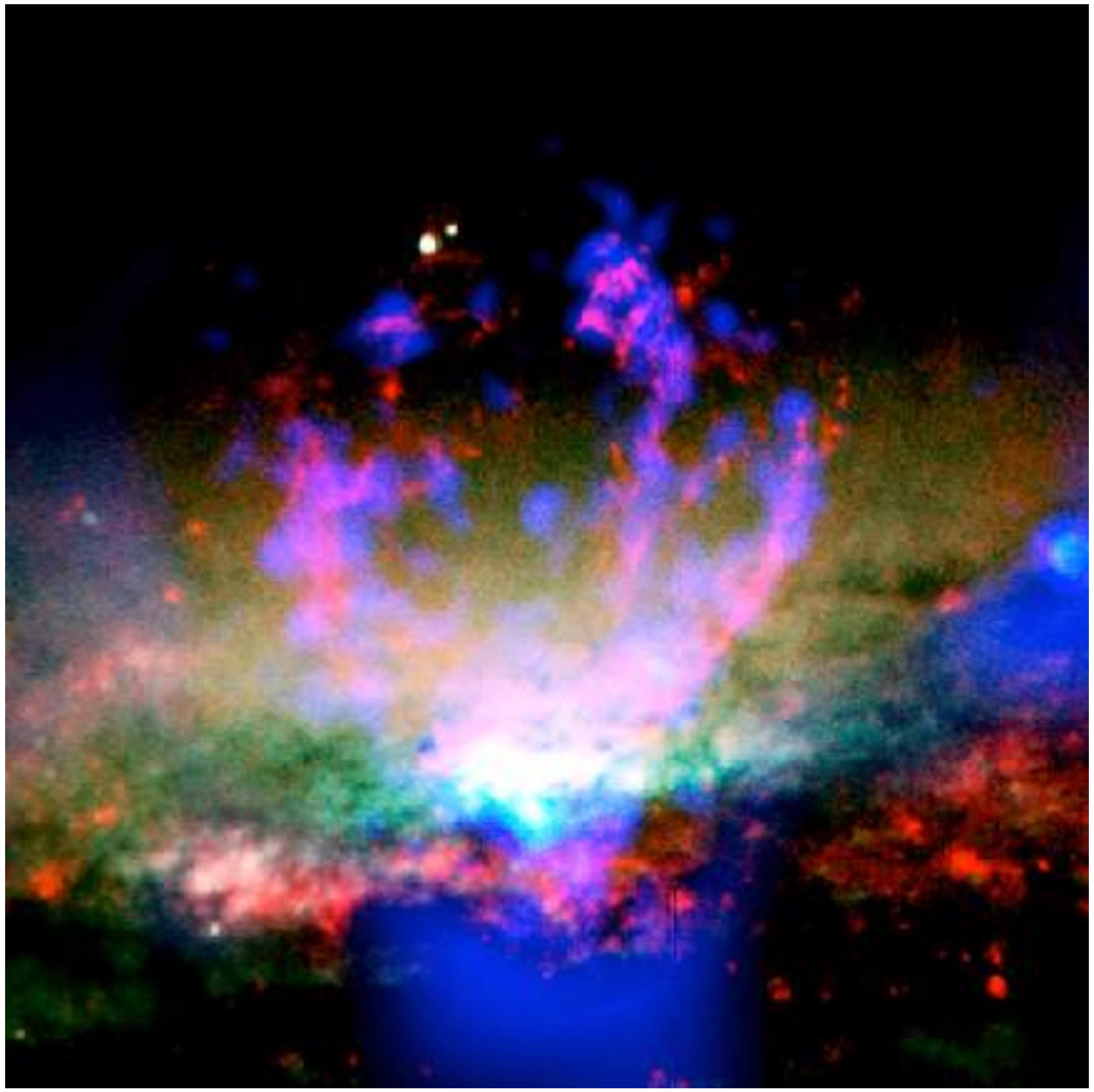
Feedback

Prevalence of Galactic Wind Feedback

-- Pollution of Intergalactic Medium by metals



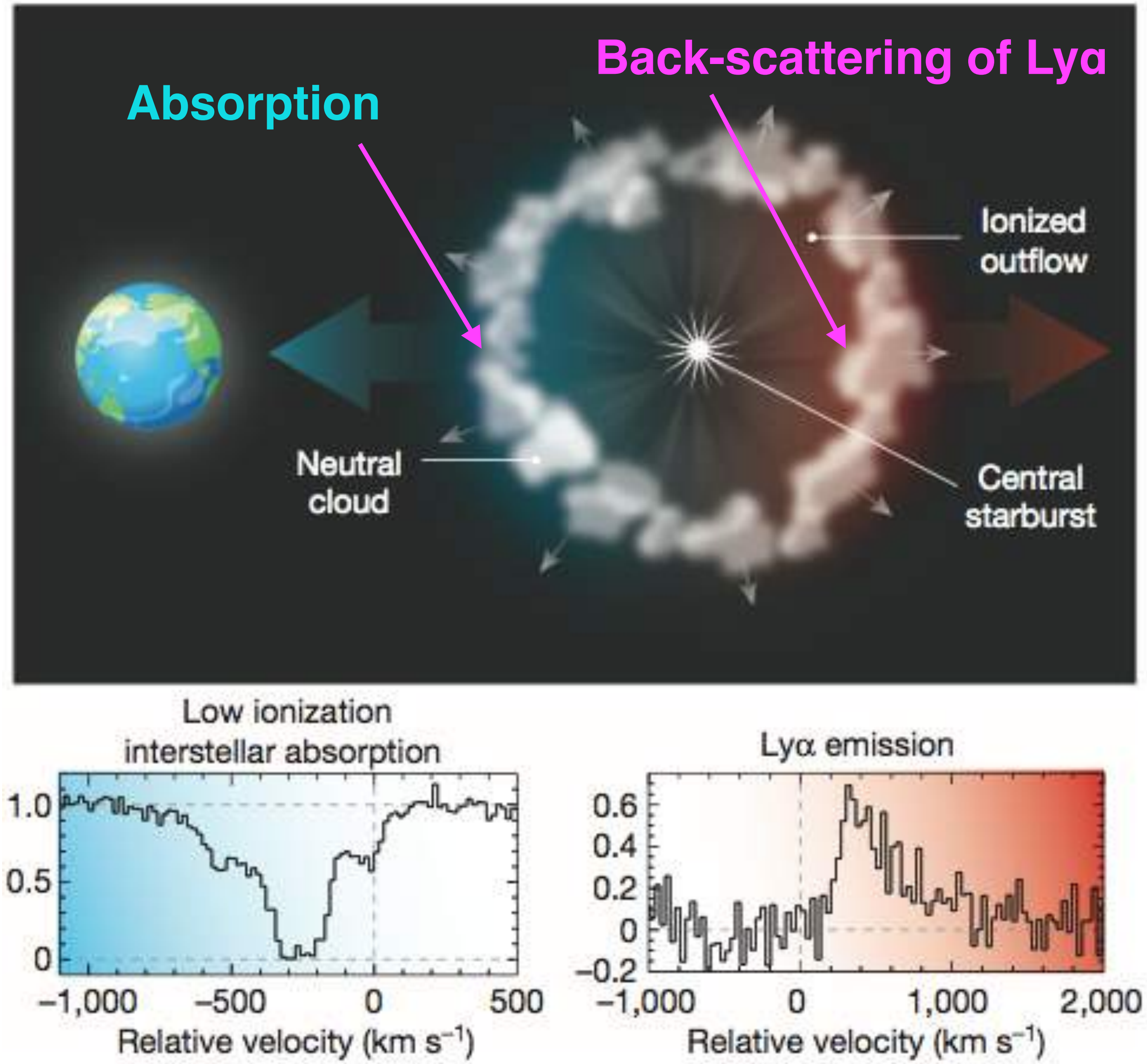
M82 Purple: Hα+N_{II}
Blue: HST, optical



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

Images: Subaru, NASA

Ubiquitous Outflows in High-z SF



~200 km/s

~500 km/s shift

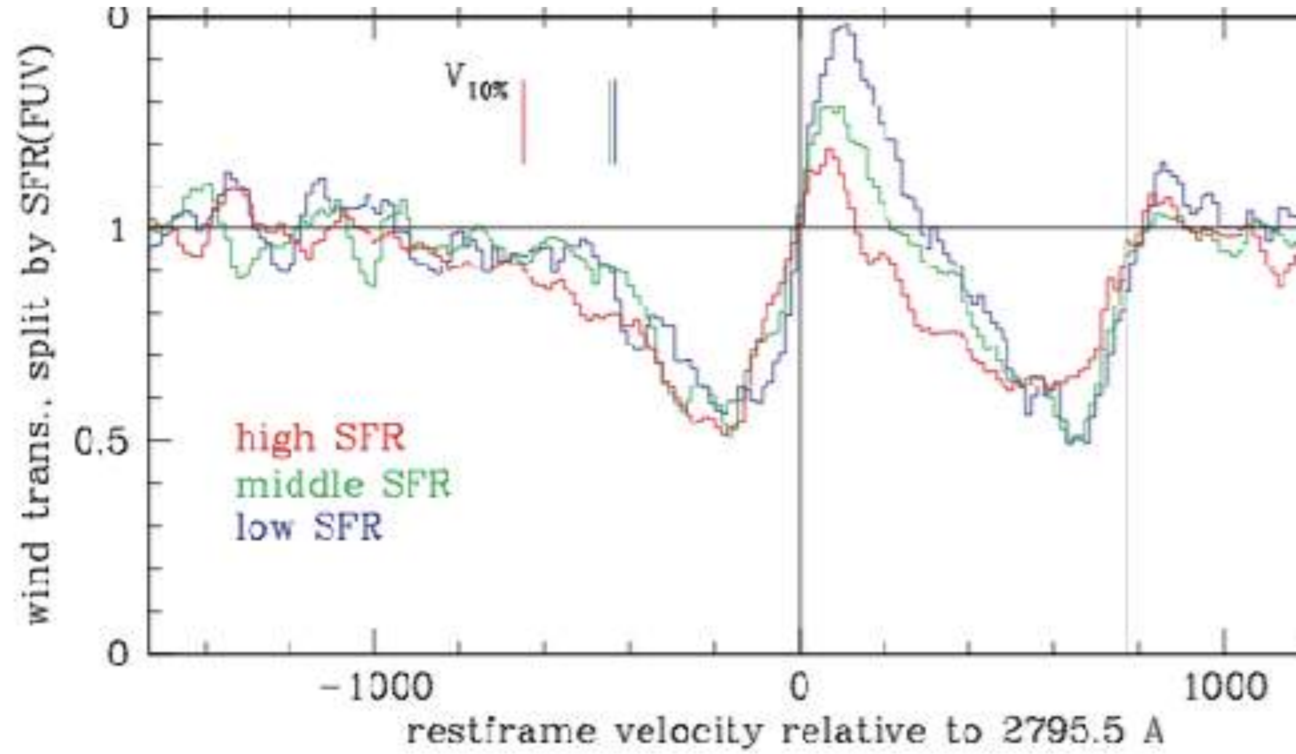
z=2.7 lensed LBG (MS1512-cB58; Pettini+'02)

(Fig. from Erb '15)

(see also Pettini+'01; Shapley+'03)

z~1.4 DEEP2 (1492 gals)

Mg II absorption in co-added spectra

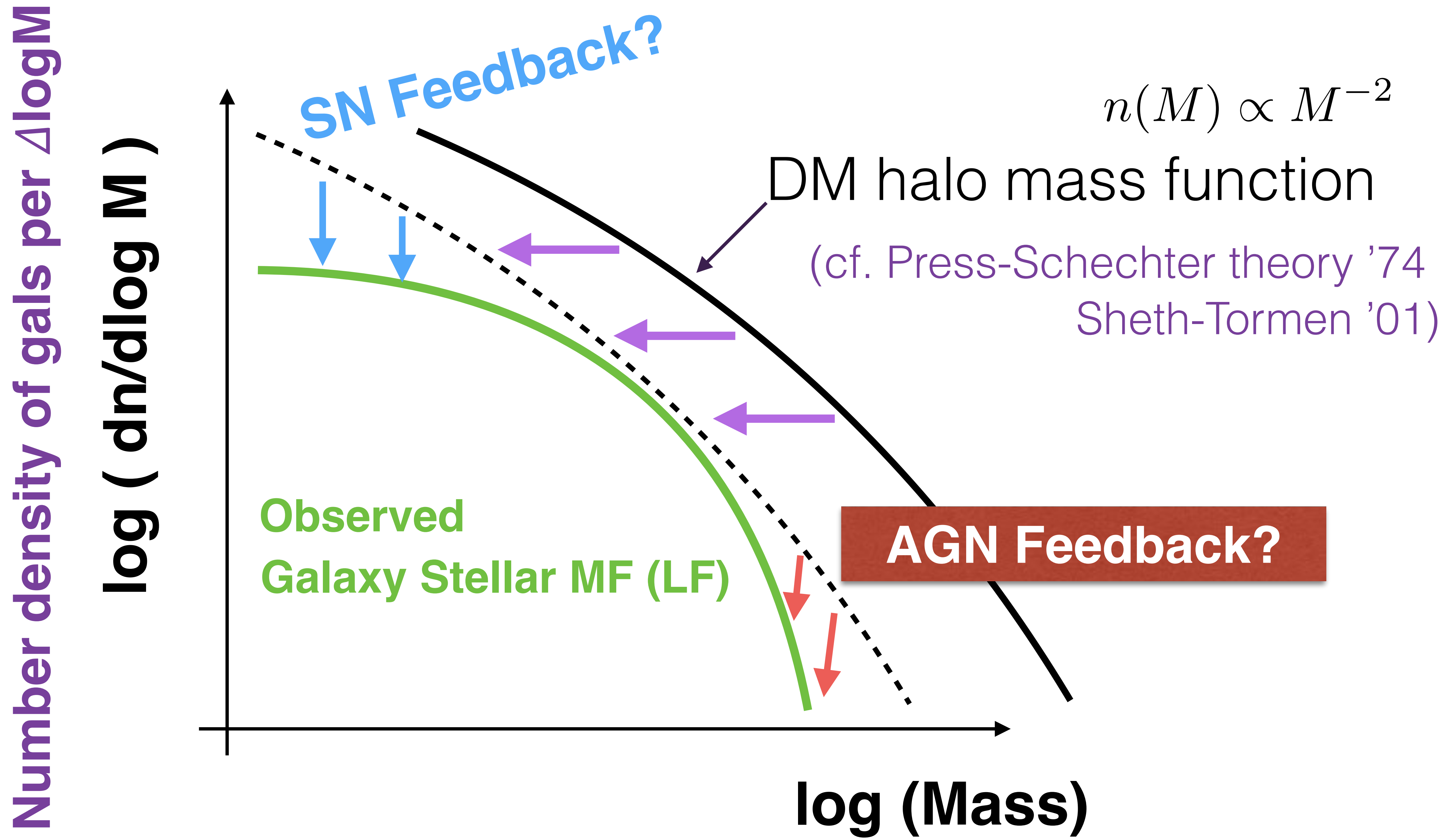


$$V_{wind} \sim \mathrm{SFR}^{0.3}$$ (Weiner+' 09)

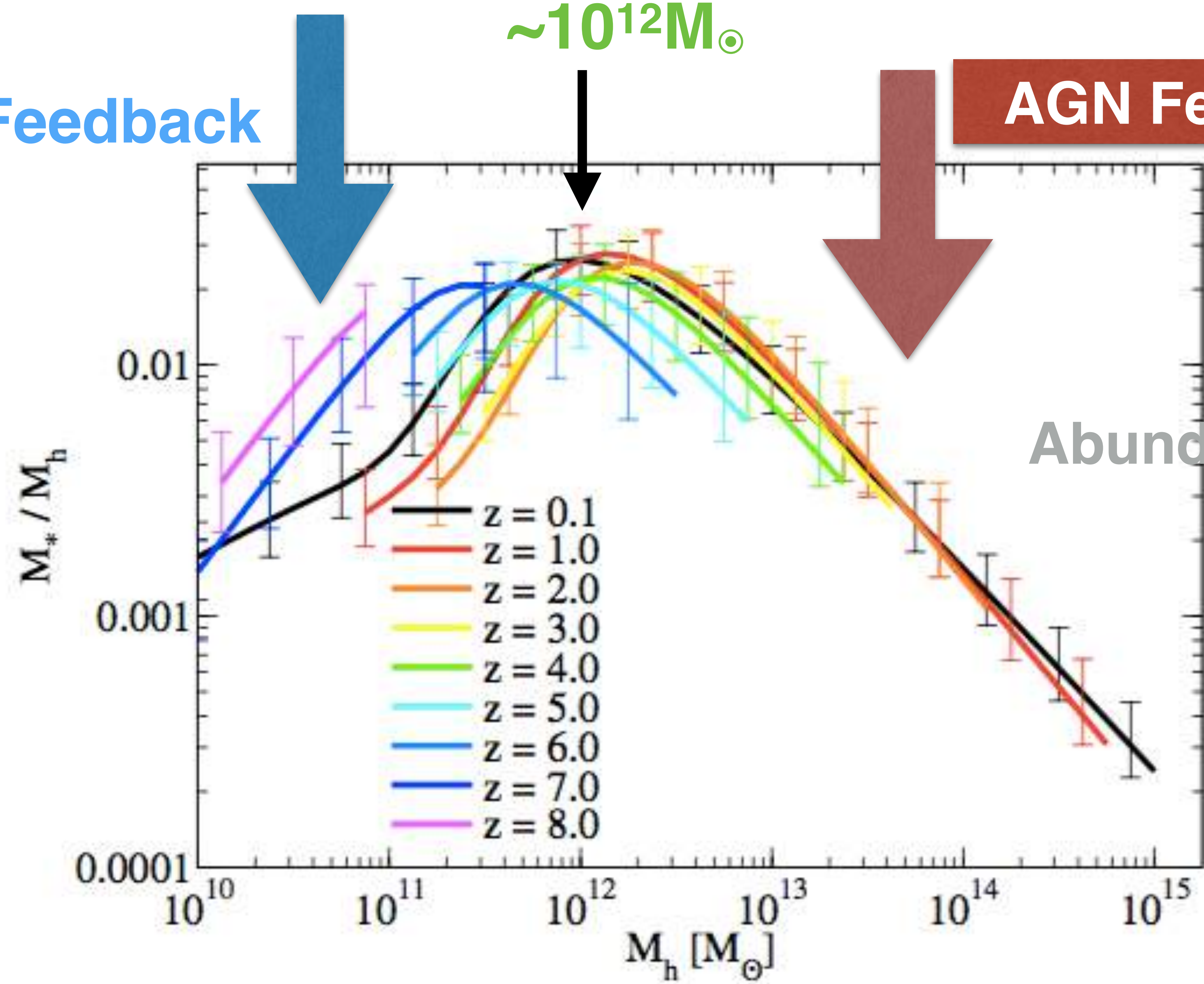
low-z ULIRGs $$\mathrm{V}_{\mathrm{wind}} \sim \mathrm{SFR}^{0.35}$$ (Martin+' 05)

$$\dot{M} \simeq 22 M_{\odot}\ \mathrm{yr}^{-1} \frac{N_H}{10^{20}\ \mathrm{cm}^{-2}} \frac{R}{5\mathrm{kpc}} \frac{v}{300\ \mathrm{km\ s}^{-1}}.$$

Dark Matter Halo —> Galaxies



Stellar-to-Halo Mass Ratio (SHMR)



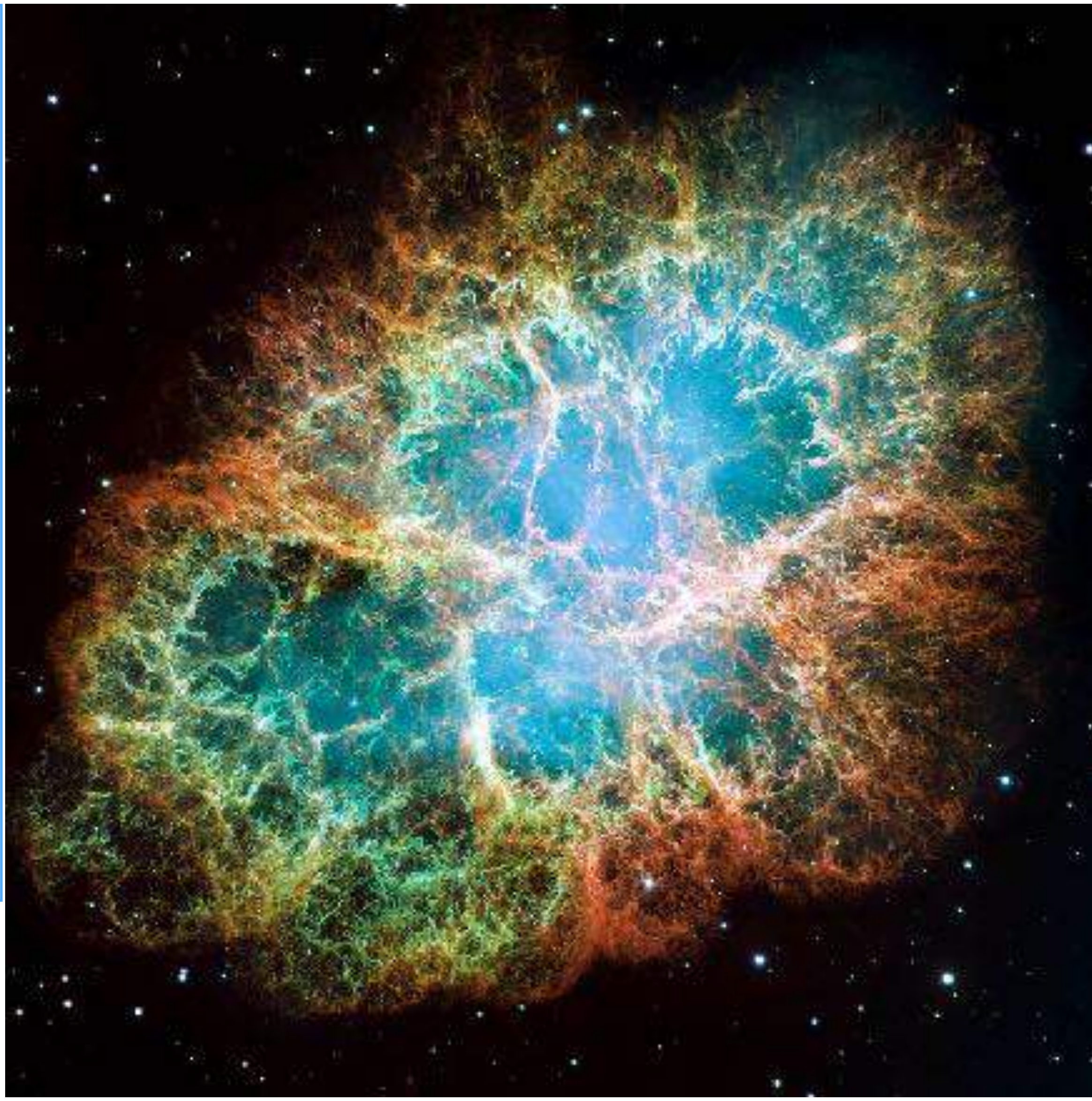
Behroozi+'10, '13, '18

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

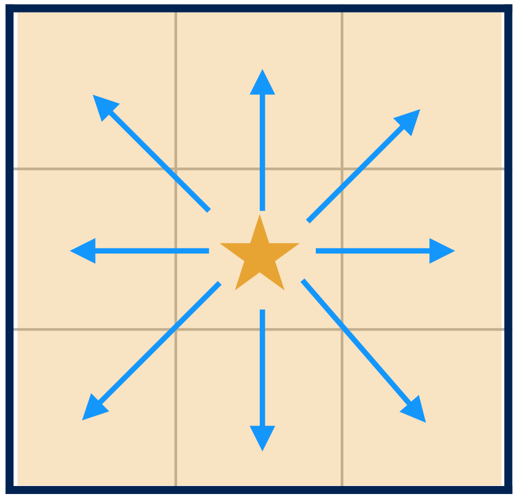
Supernova(SN) Feedback

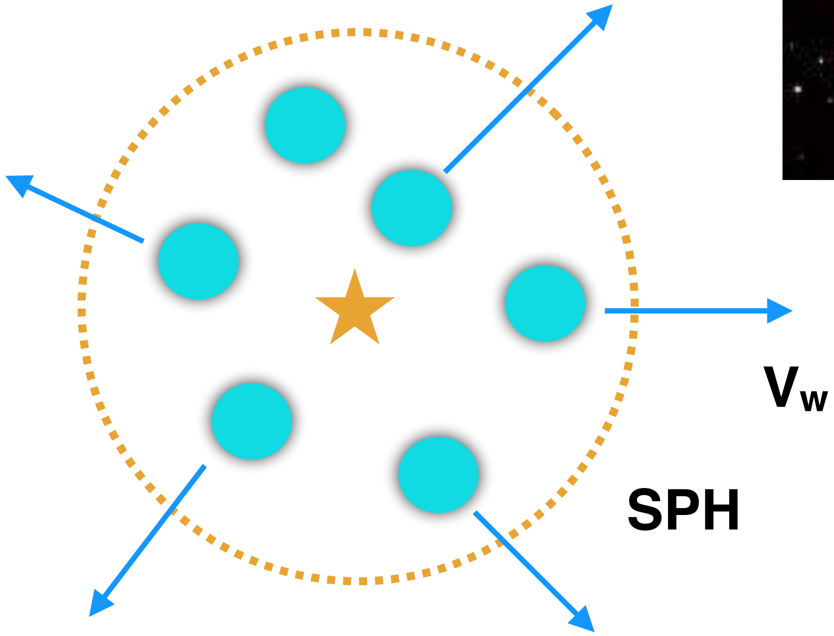
- Source of radiation, metals, cosmic rays; $\mathbf{E_{tot} \sim 10^{53}}$ **erg/SN**
- Total FB energy: $\mathbf{E_{fb} \sim 10^{51}}$ **erg/SN**
  - —> $\mathbf{E_{fb} \sim 10^{48\text{-}49}}$ **erg/M**$_\odot$ (E_k, E_{th})
- Outflows, Suppression of SF

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



Crab Nebula — SN 1054 (NASA, ESA)





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

SN feedback efficiency

Type II SNe: ~ 0.01 SNe per $1\,M_\odot$ of stars (IMF)

$$\boxed{E_{\rm SN} \sim 10^{51}\,\text{erg per SN}}$$ injected into ISM.

~30% of this couples to ISM as kinetic E —> galactic wind

Kinetic energy of GW: $\boxed{E_{\rm w} \sim 10^{51} \times 0.3 \times 0.01 = 3 \times 10^{48}\ \text{erg}\ {M_\odot}^{-1}}$

energy-mass deposition rate

$$\boxed{\begin{aligned} \dot{E}_{\rm w} &= \epsilon_{\rm w} \dot{M}_\star c^2 \\ \dot{M}_{\rm w} &= \eta \dot{M}_\star, \end{aligned}} \longleftrightarrow \boxed{\dot{E}_{\rm w} = \tfrac{1}{2} \dot{M}_{\rm w} v_{\rm w}^2,}$$

$$v_{\rm w} \sim \left(\frac{\epsilon_{\rm w}}{\eta}\right) c \sim 1500\ \text{km s}^{-1}$$

$$\epsilon_{\rm w} = (E_{\rm w}/M_\star c^2) \sim 2 \times 10^{-6}.$$

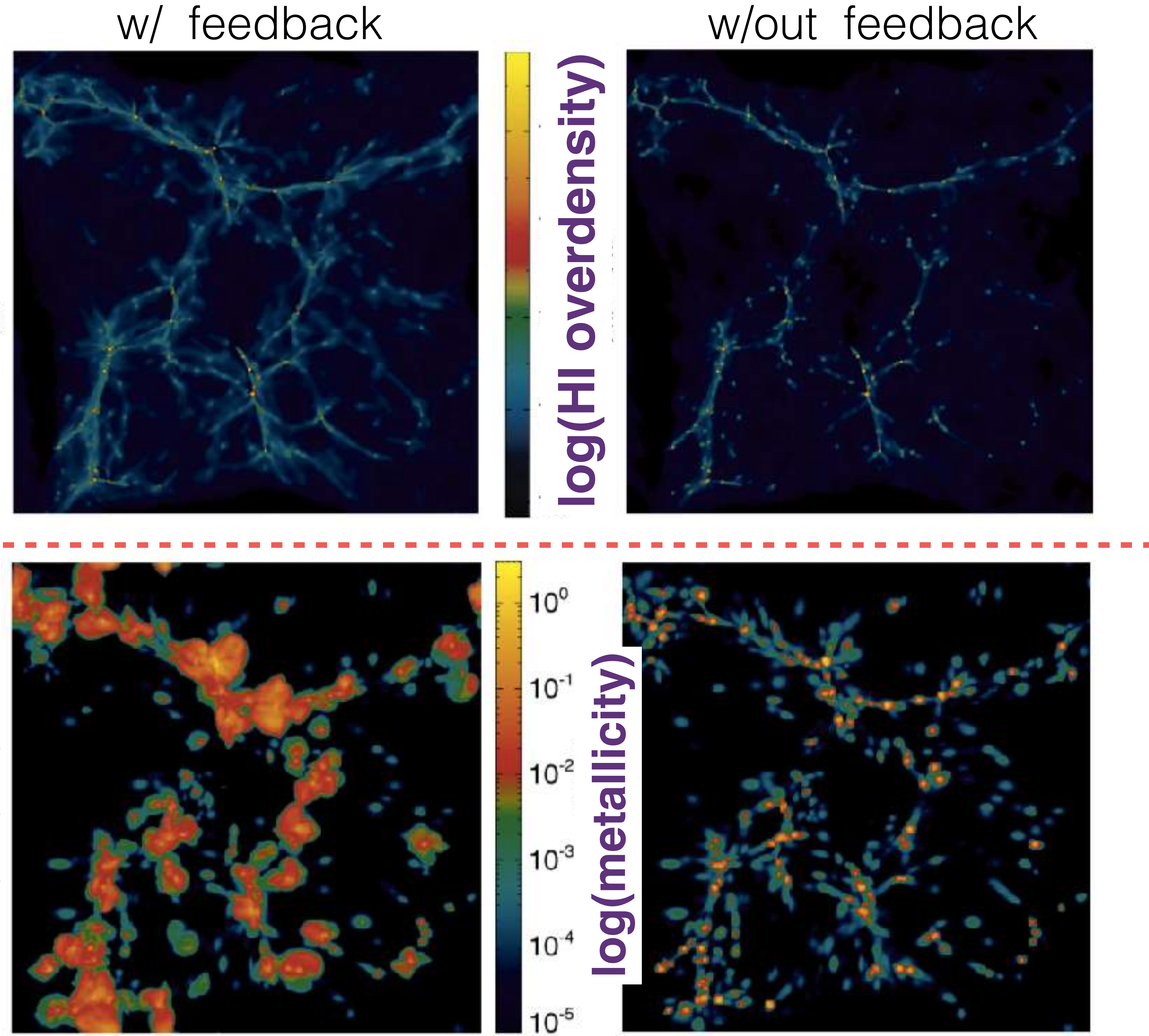
GW velocity:

mass-loading factor $\eta \approx 0.25$

Cen, KN, Ostriker ’05

$\epsilon_{\rm w} = 3 \times 10^{-6}$

$\eta \approx 0.25$

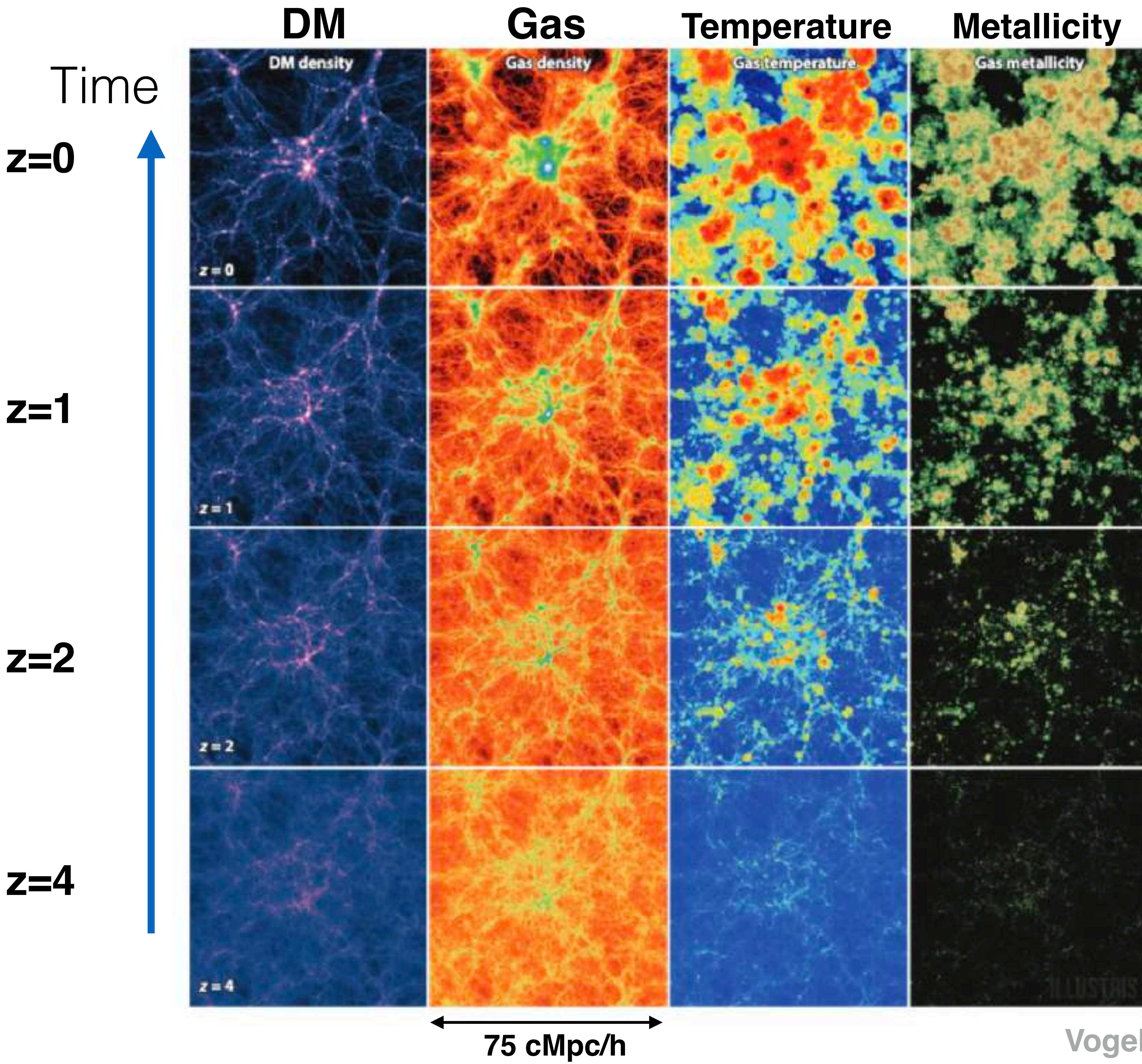


volume filling factor

Z >10^{-3} Zsun : ~6%

Z >10^{-2} Zsun : ~4%

Z >10^{-1} Zsun : ~2%



Vogelsberger+'14

Historical Flow Chart of SN Feedback Treatment

1st phase
'90s

Simple thermal feedback

"Overcooling problem"

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

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

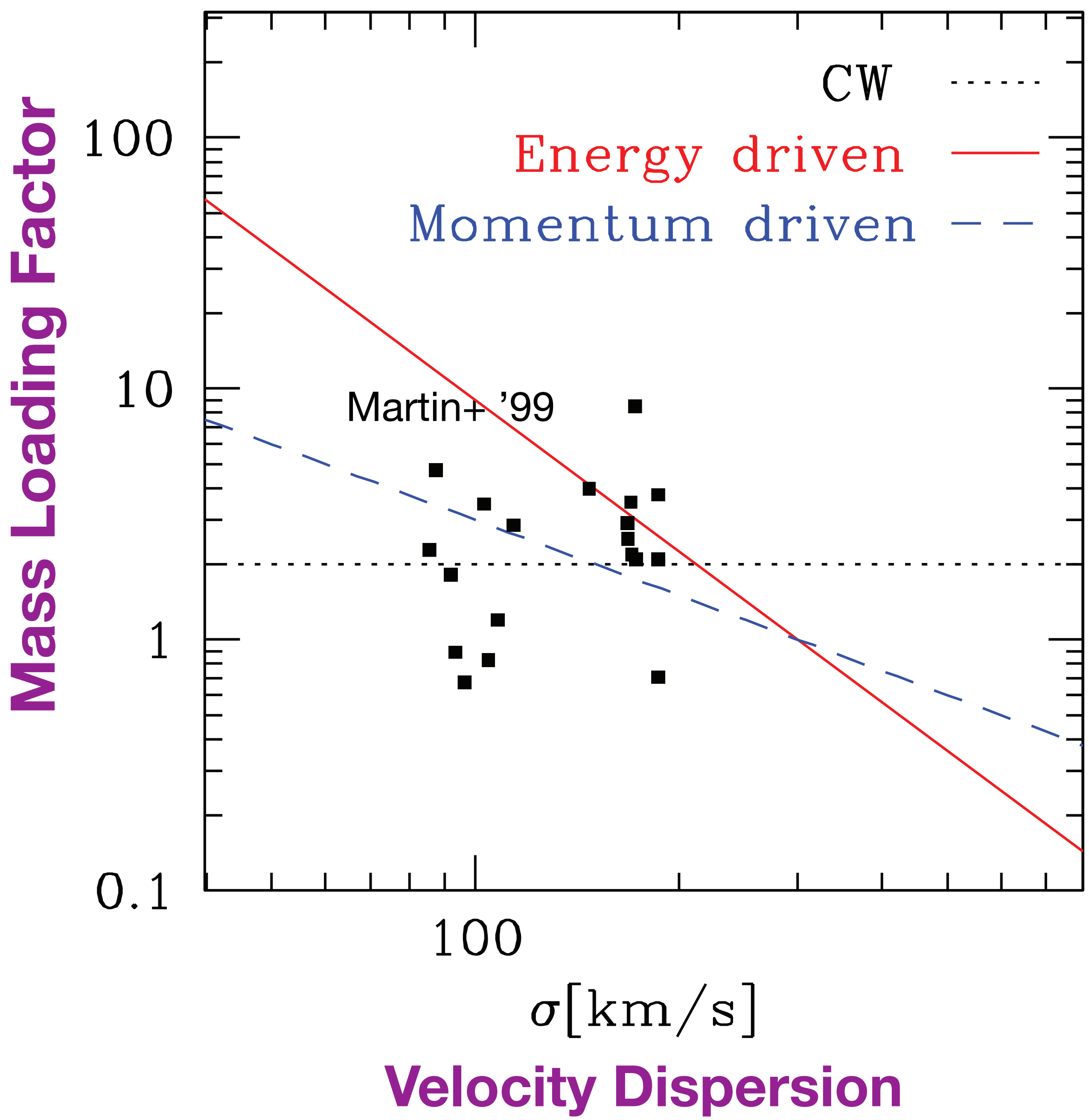
Murray+ '05

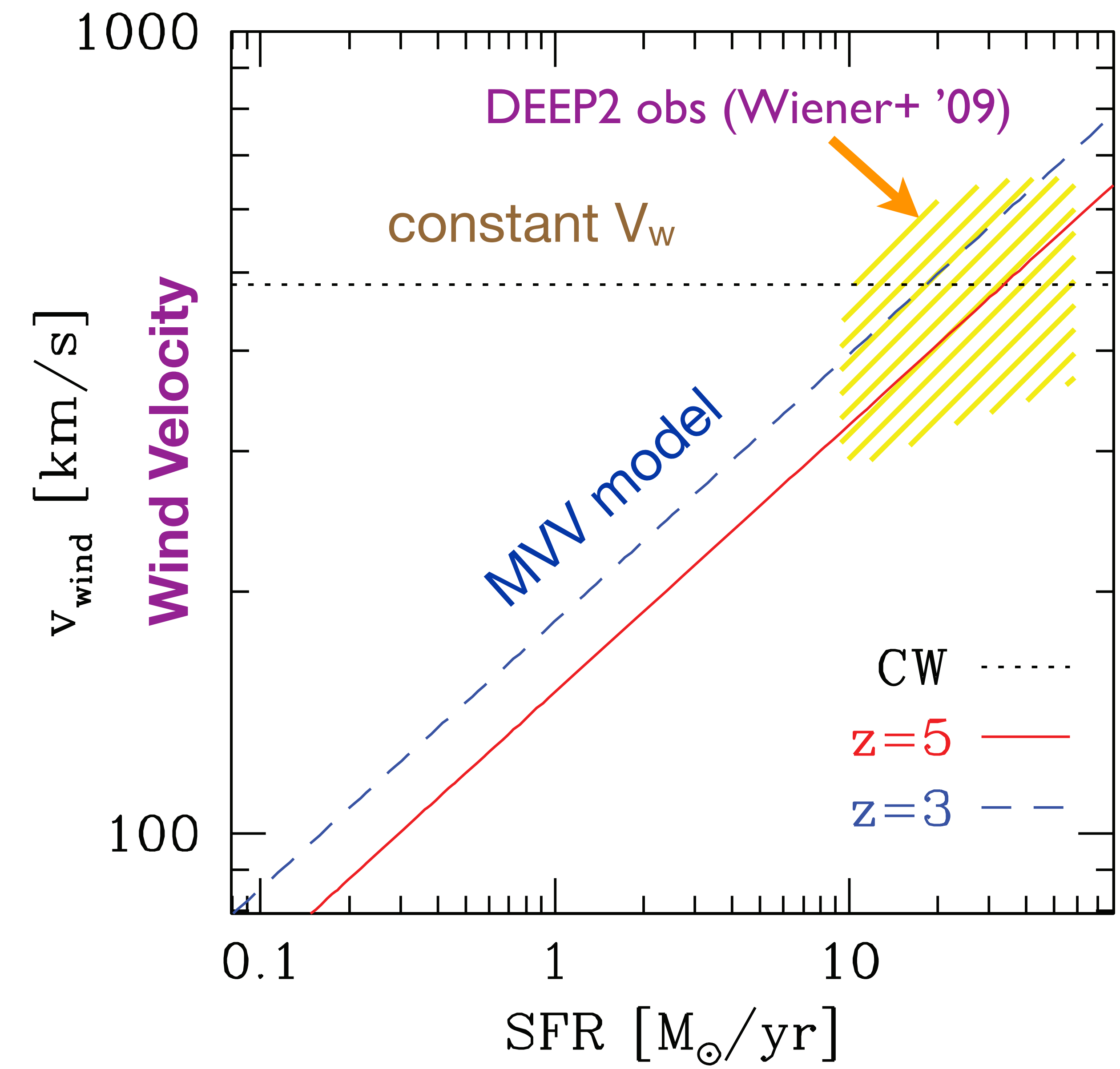
Higher mass-loading factor for lower mass galaxies.

Multicomponent Variable Velocity (MVV) Wind model

Choi & KN '10

$$\eta \equiv \frac{\dot{M}_w}{\dot{M}_\star},$$

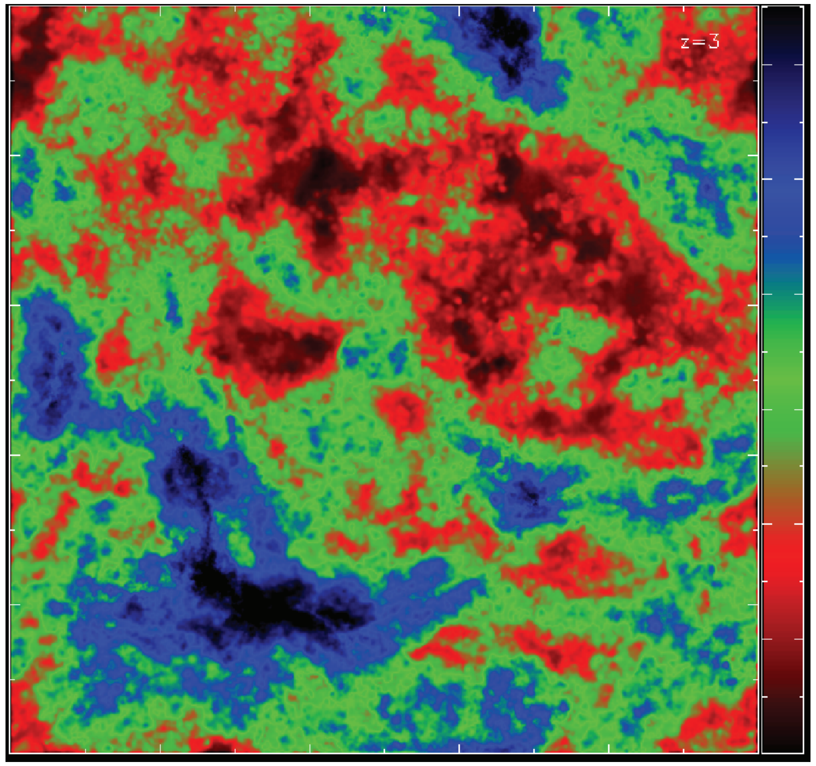




Impact of Momentum-driven Wind on IGM

Temperature

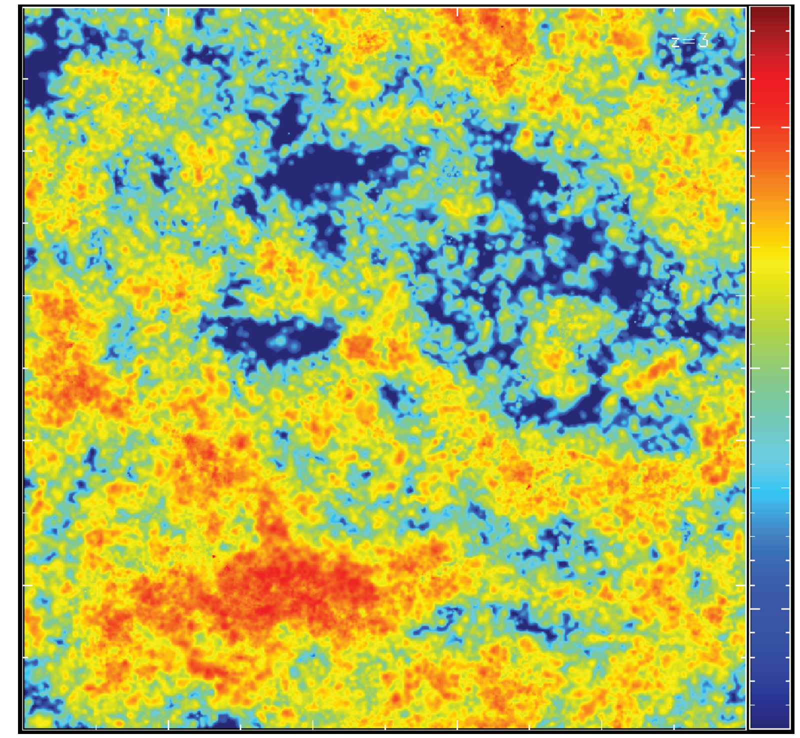
Projected metal density

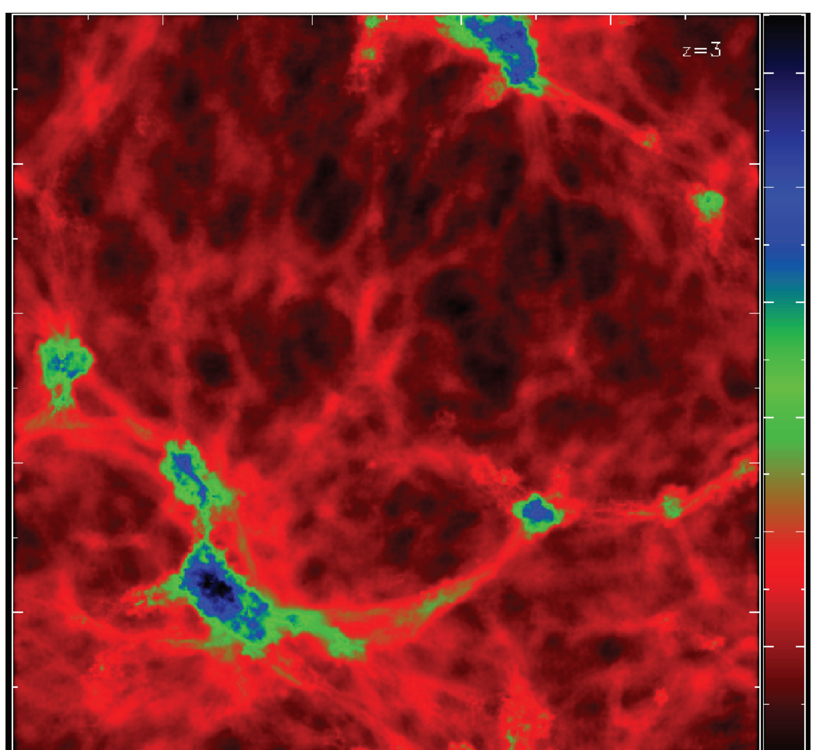


10 Mpc/h

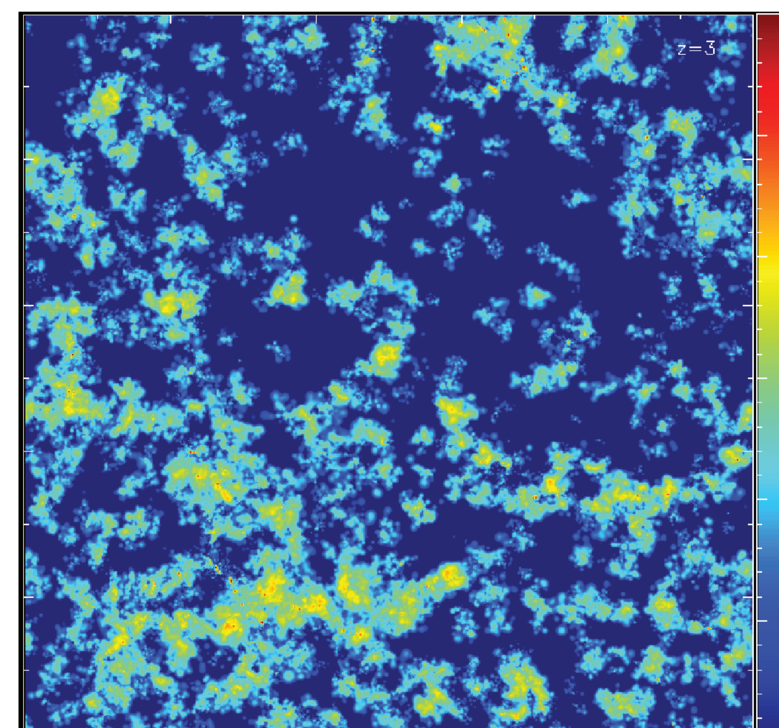
Energy-driven wind (constant V_w)

SH03 model



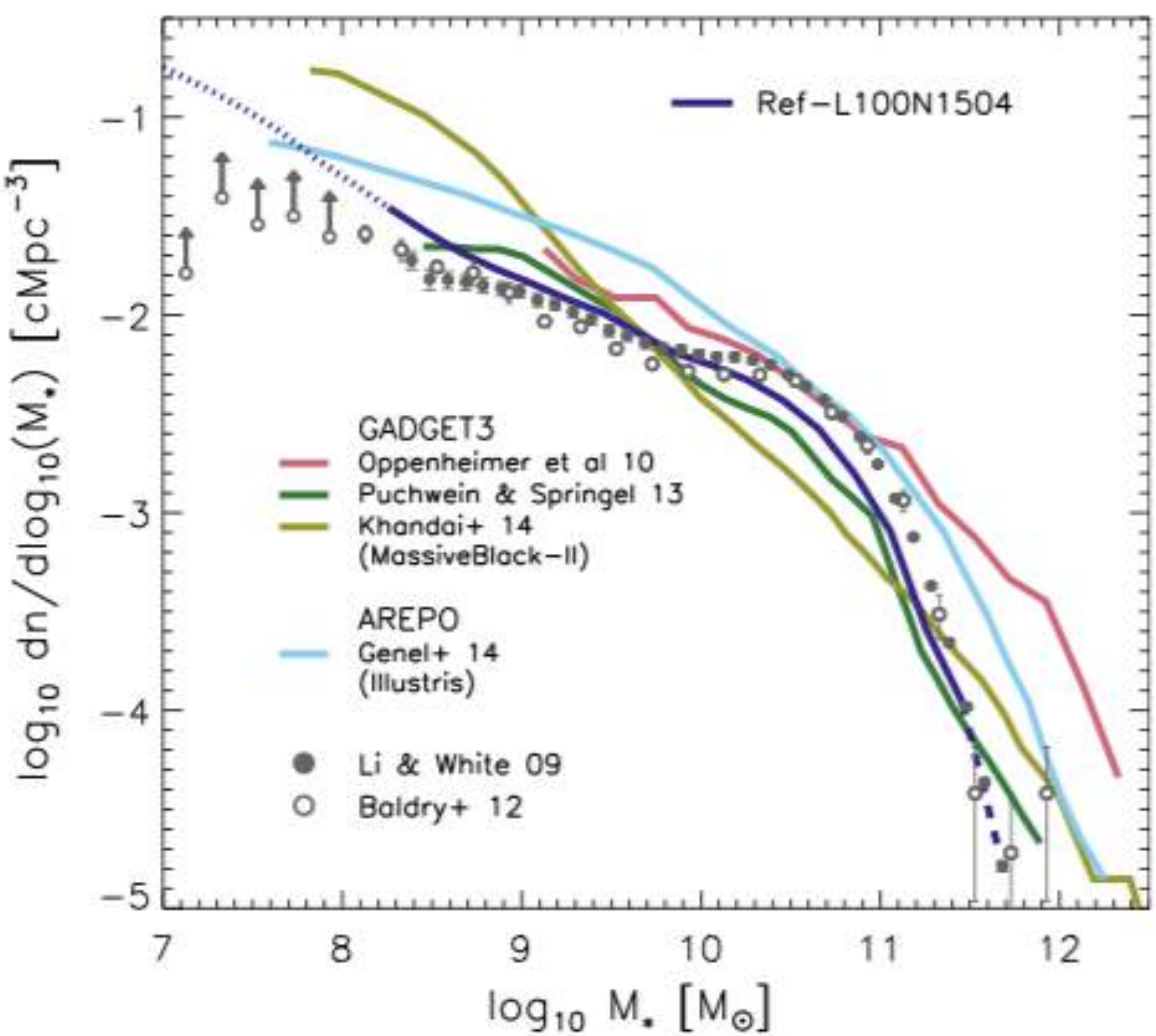


Momentum-driven



Choi & KN '10

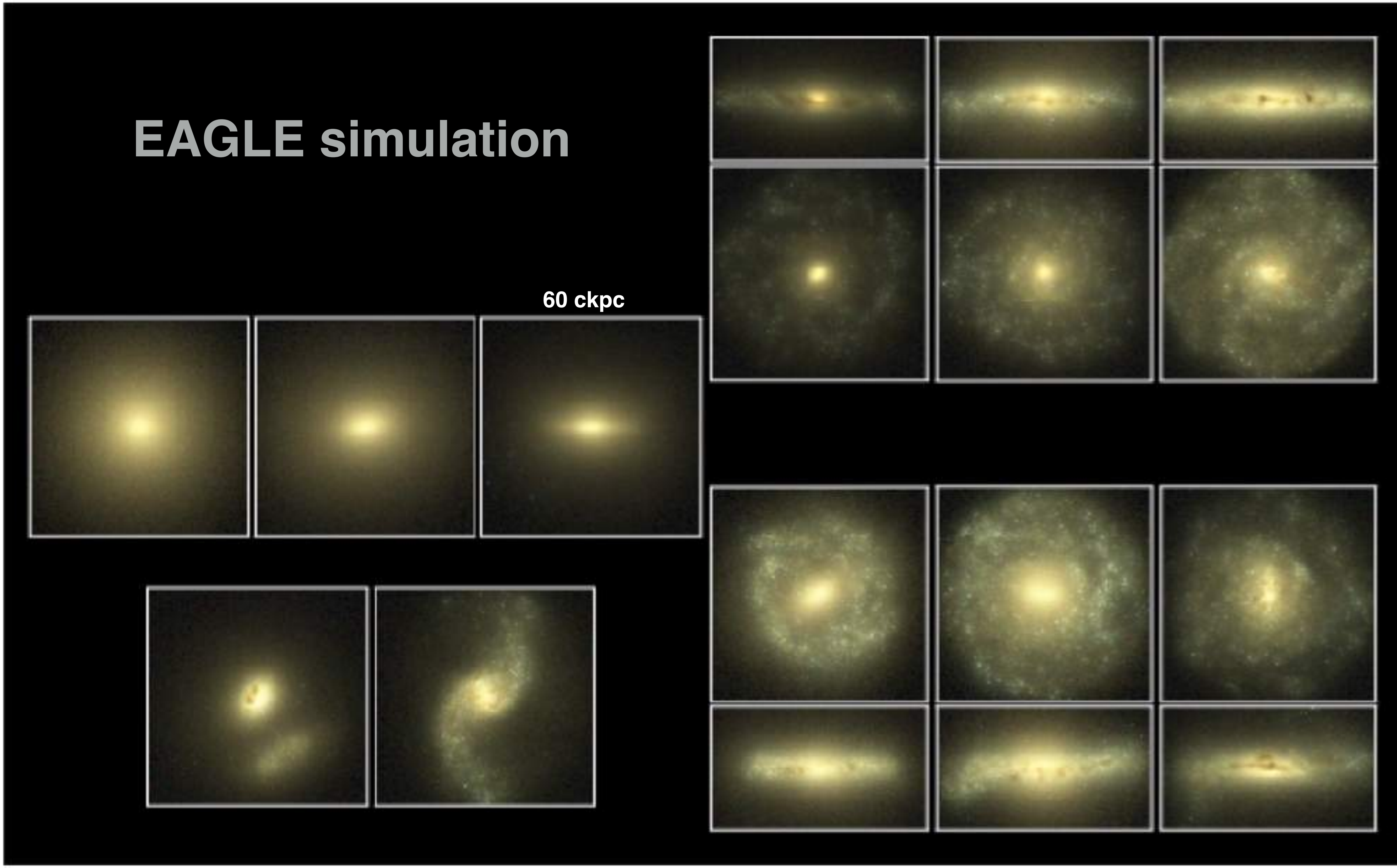
Galaxy Stellar Mass Function (z=0)



Still much variations among sims remain.

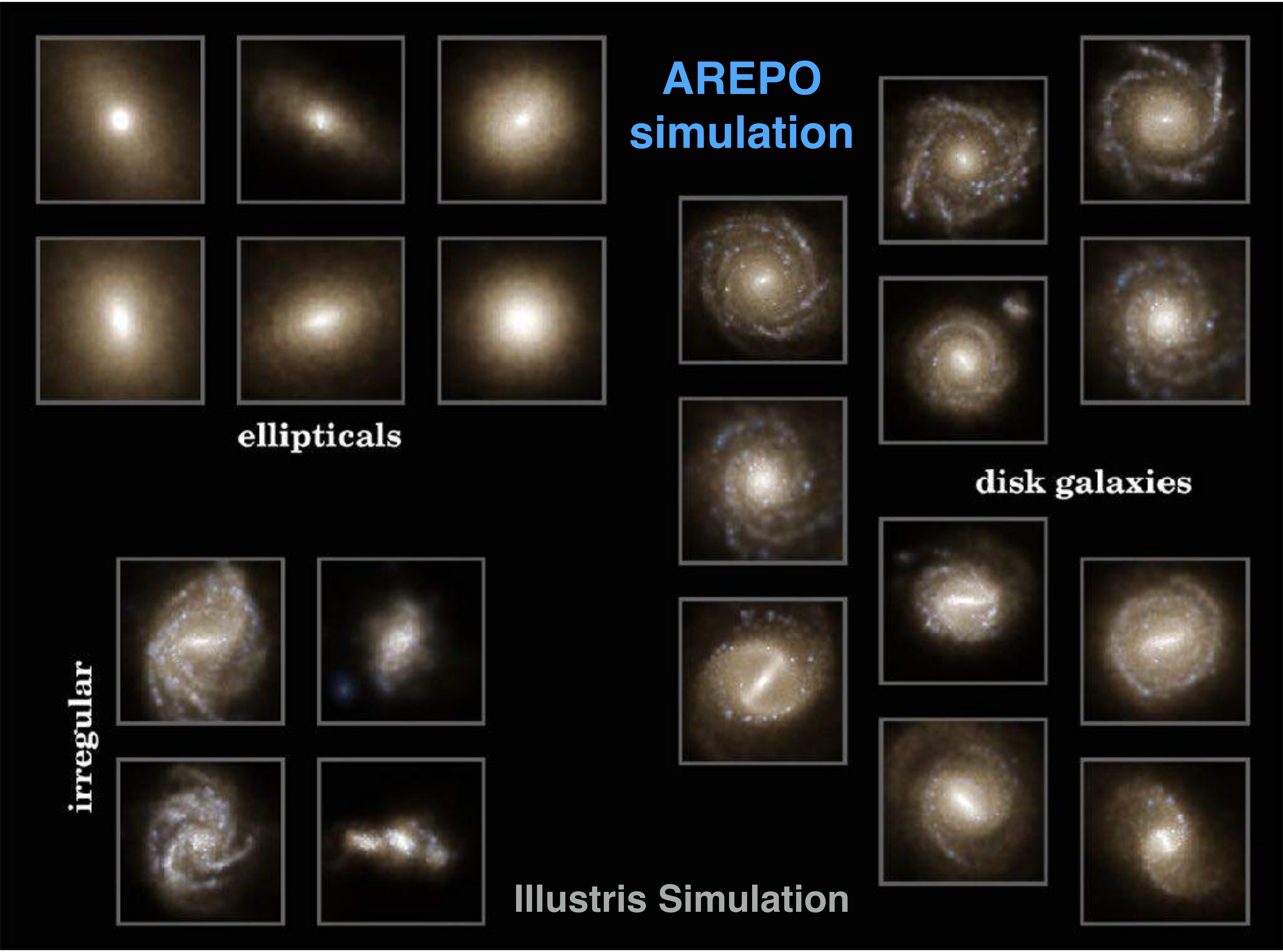
Some FB param tuning is necessary for each resolution.

Schaye+ '15
Crain+ '15



z=0
L100N1504 sim.

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


AREPO
simulation
ellipticals
disk galaxies
irregular
Illustris Simulation

In higher res. zoom-in sims,

Stellar Feedback

(prior 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, ...

Galaxy Merger Simulations

(Springel+ ’05, …, Hopkins+’13)

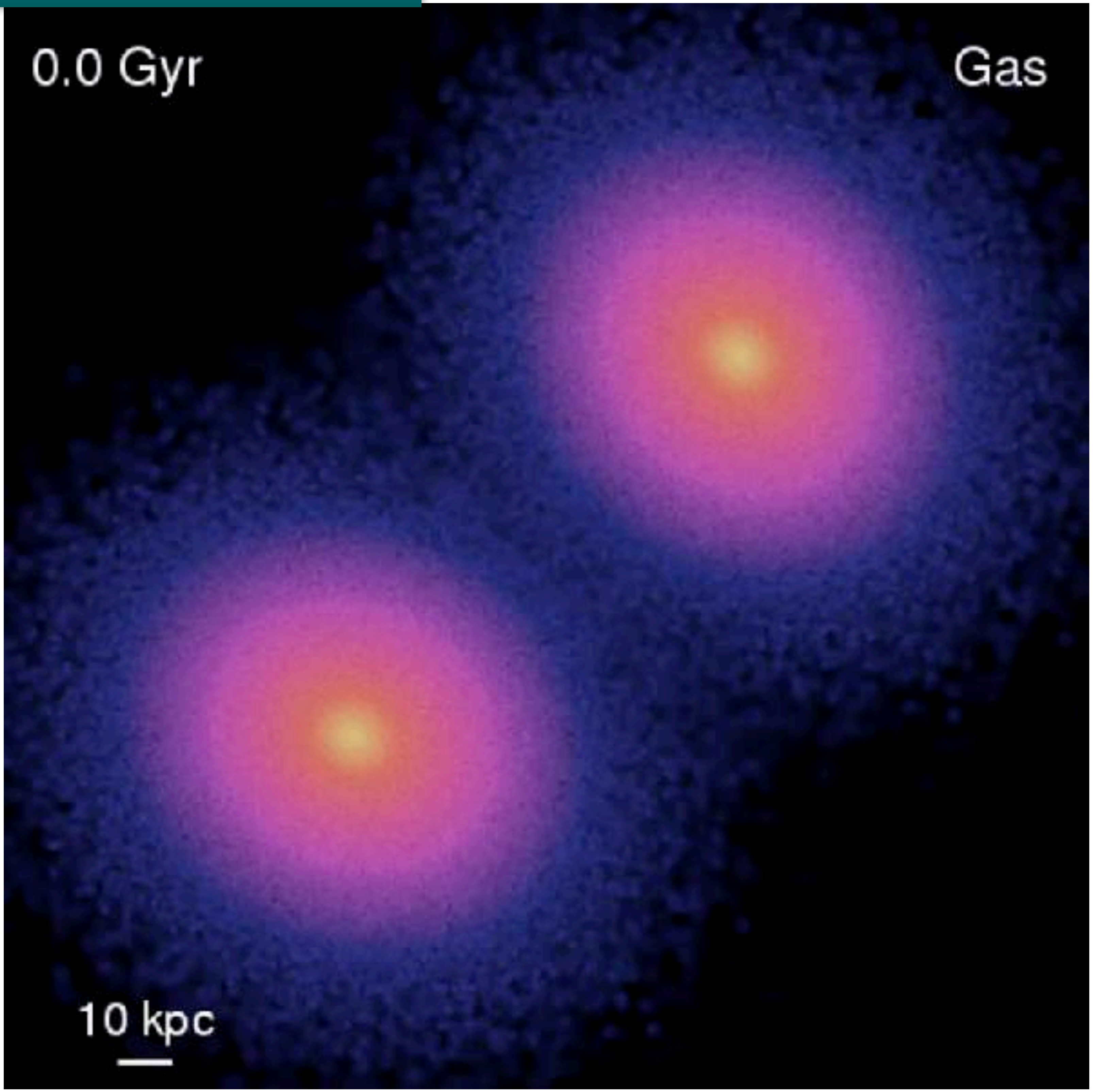
Stellar Feedback:
radiation pressure, direct momentum (stellar wind), photoionization heating

But, this is not in cosmological context.

Resolution:

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

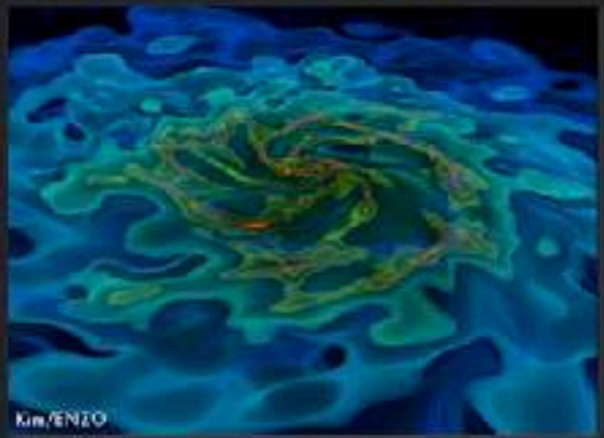
Hopkins+ ’13
(GADGET SPH)



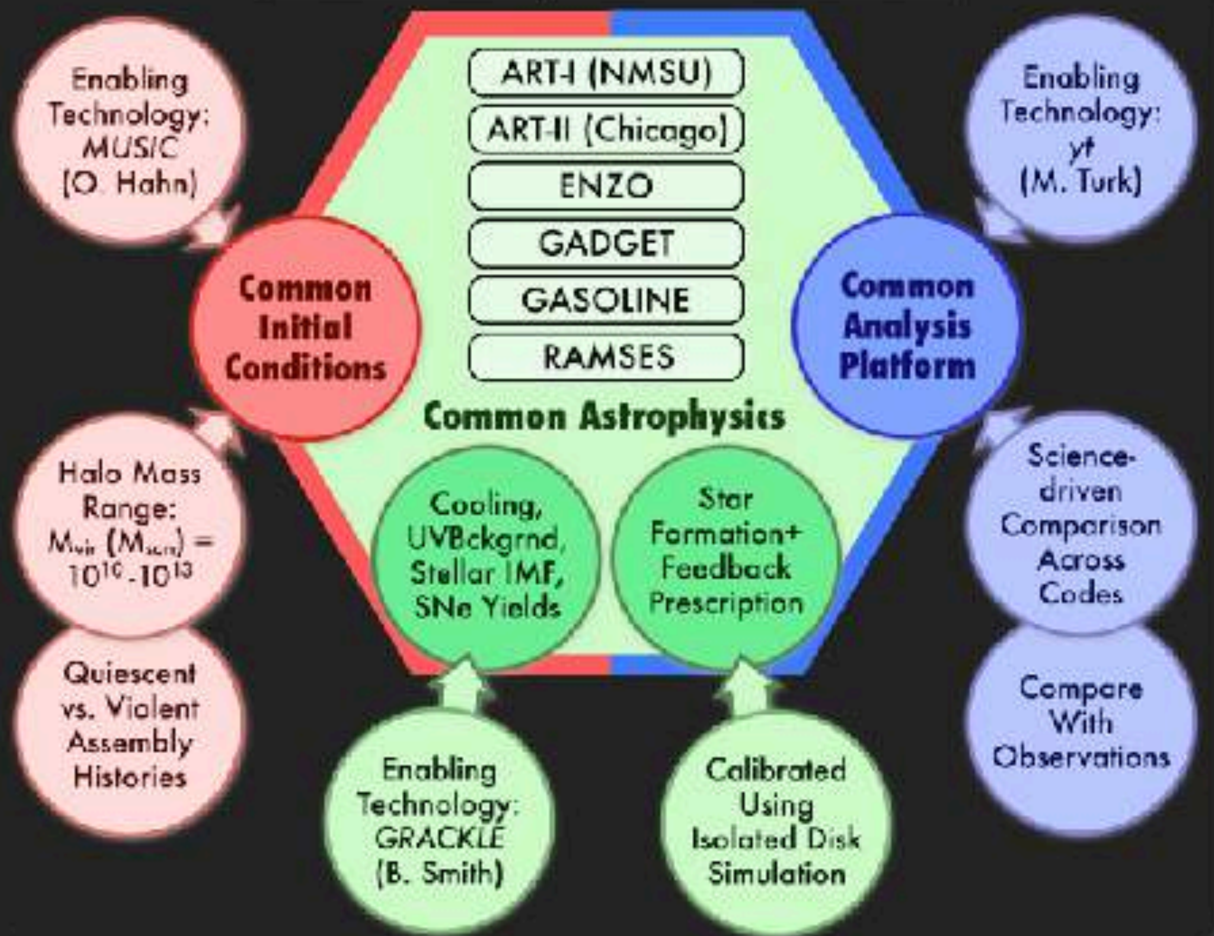
AGORA

A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

High-res Galaxy Simulations



AGORA Comparison Infrastructure



AGORA Goal & Team

- GOAL: A collaborative, multi-platform study to raise the realism and predictive power of galaxy formation simulations
- TEAM: 104 participants from 51 institutions worldwide, Mar. 2014
- DATA SHARING: Simulations outputs and analysis softwares will be shared with the community

- Contact: santacruzgalaxy@gmail.com
- AGORA First light: First paper by Ji-hoon Kim et al. (arXiv:1308.2669)
- Project funded in part by:

Kim+ 14, 16; plus more in prep.

AGN feedback efficiency

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)

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

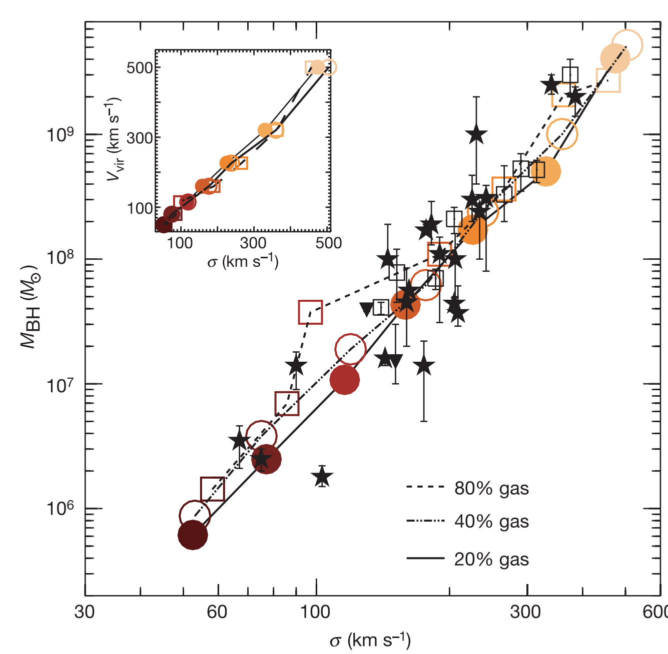
Shakura & Sunyaev ’73

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



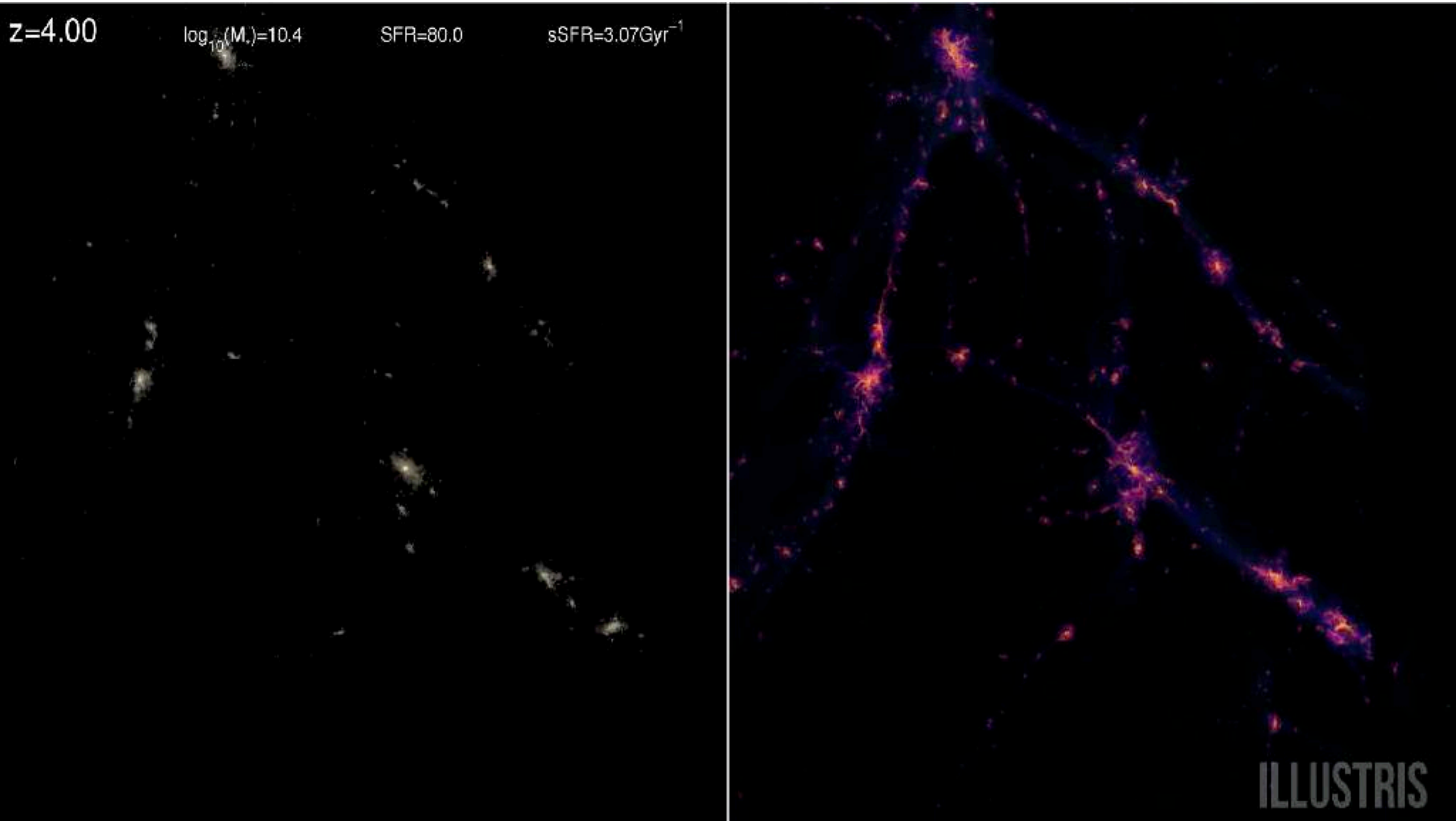
Di Matteo+ ’05

Violent AGN feedback (quasar mode)

Movie

Di Matteo+ ‘05

Stellar Light | Gas Density



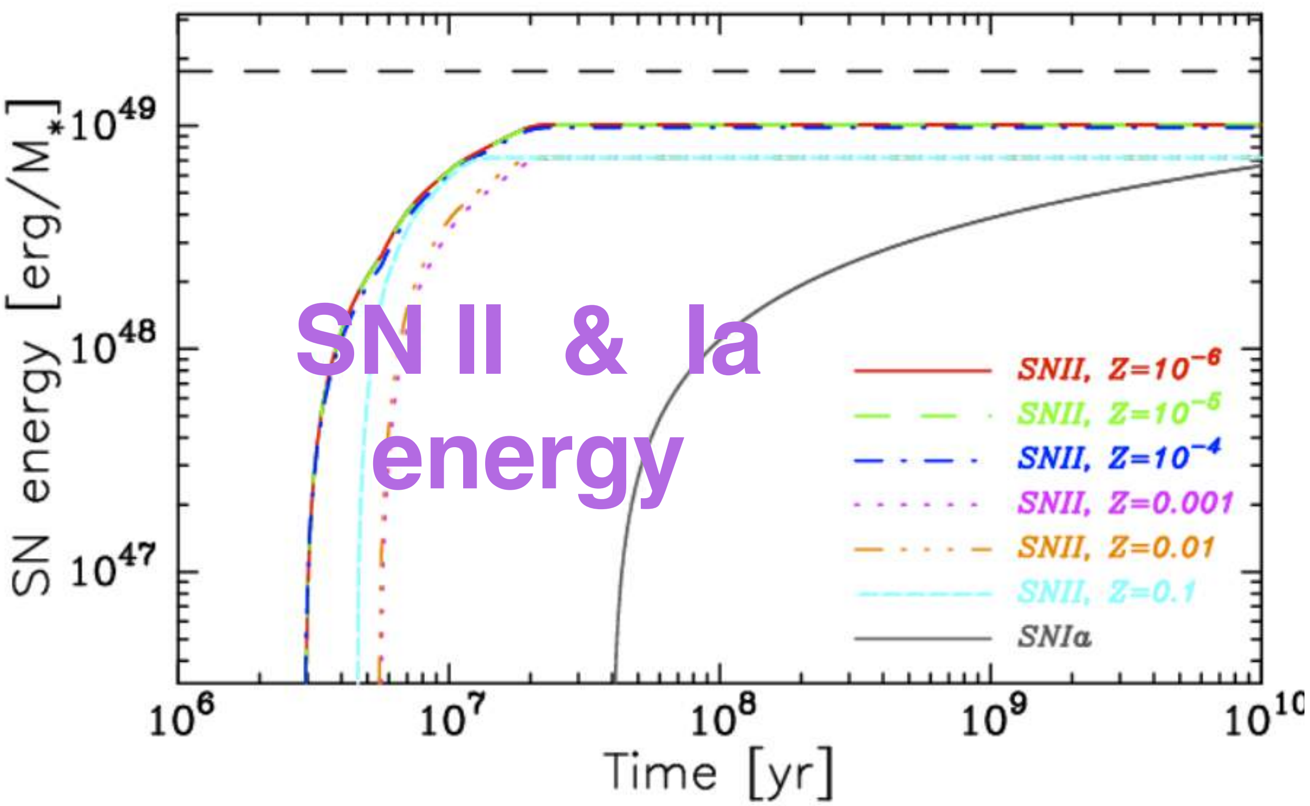
Formation of massive elliptical, “red & dead” gal.

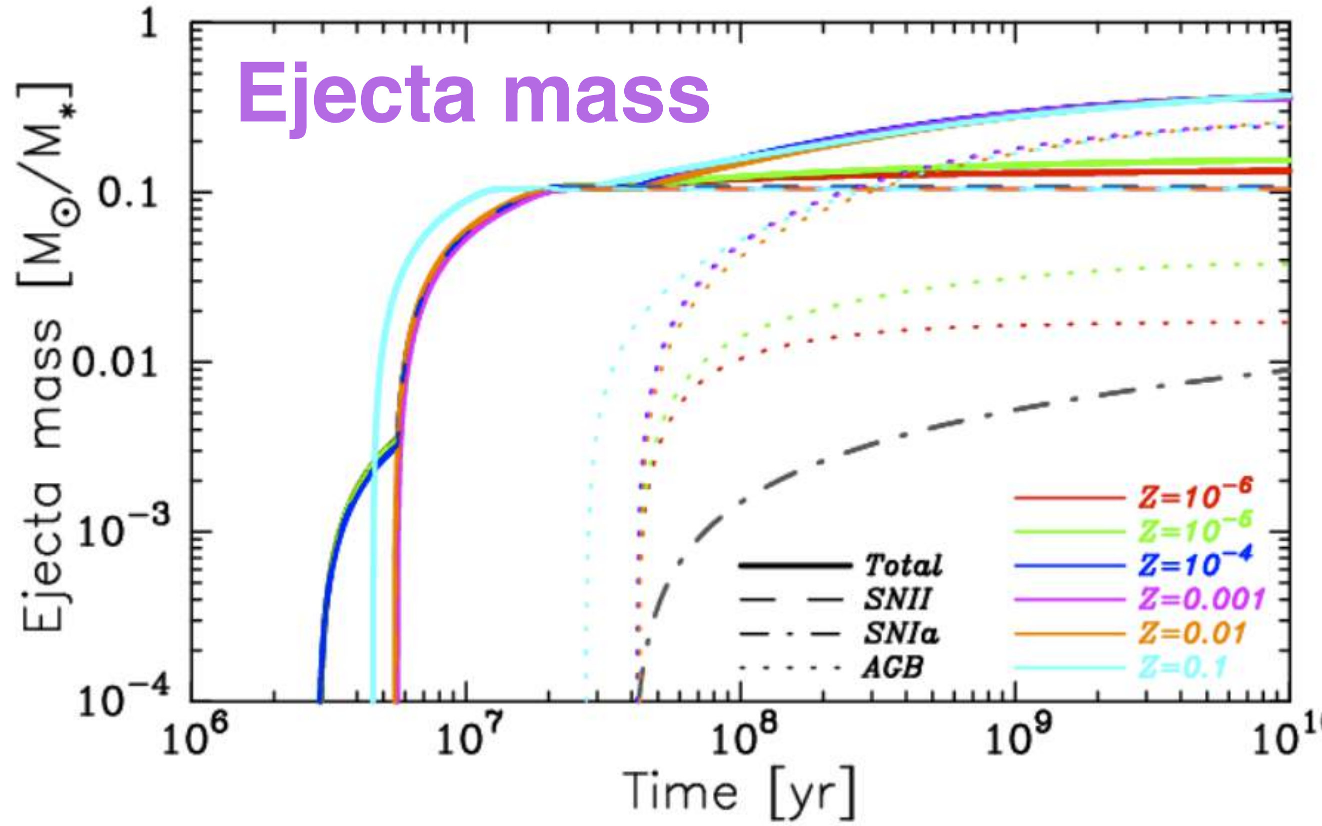
“Recipe” for Galaxy Formation

- ☑ Background Cosmology
- ☑ Gravitational Instability + spherical collapse model
- ☑ N-body dynamics (Dark Matter) — Ch.2 of my book
- ☑ Hydrodynamics — Ch.3 of my book
- ☑ Radiative Cooling of Gas, UVB
- ☑ Star Formation
- ☑ Feedback (SNe, AGNs), Chemical Enrichment

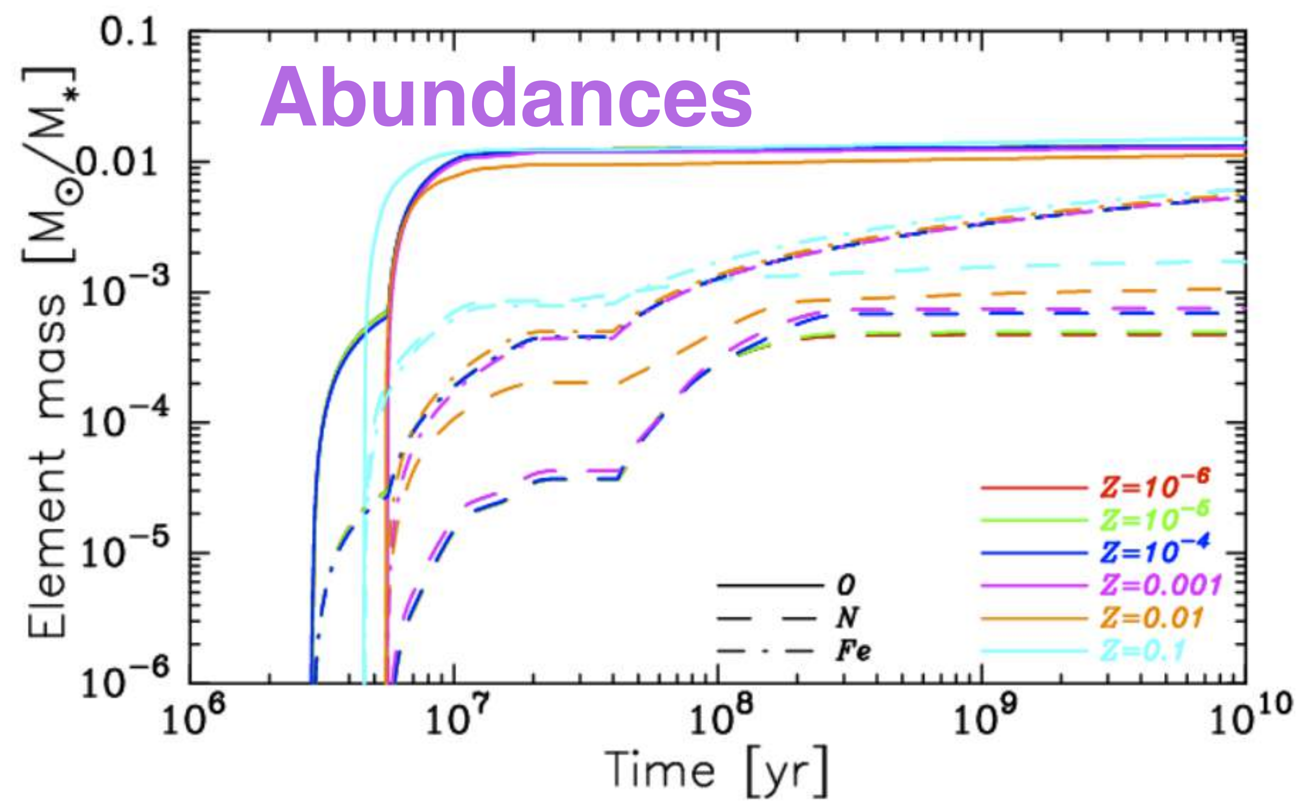
CELib chemical evolution package (Saitoh '17)

https://bitbucket.org/tsaitoh/celib/src/master/





Treating SN-II, Ia, AGB star contrib. separately using `CELib' chemical package (Saitoh '17) w. diff. yield pattern



Gadget3-Osaka simulations

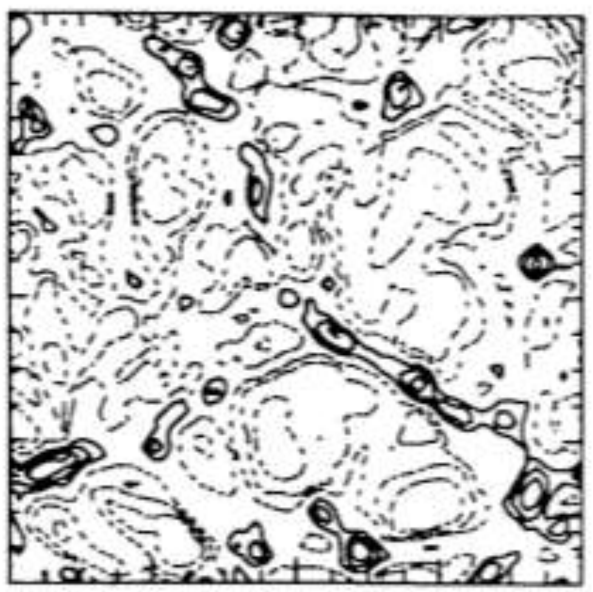
Shimizu, KN+ '19

Part III.3

- zoom-in simulations (movie time!)
- How do galaxies get gas? — cold flow & disk formation
- Escape fraction
- Emission lines from high-z gals.

Three Revolutions in Cosmological Hydro Simulations

1990': 1st Revolution

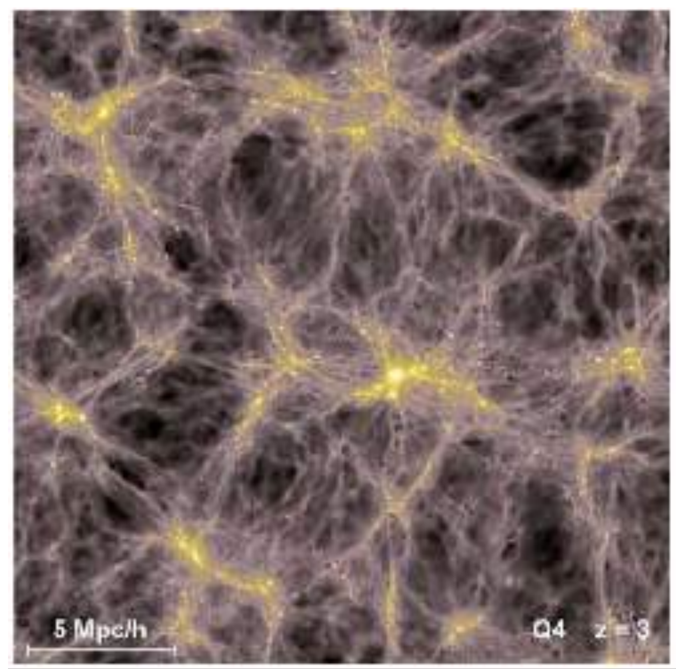


First cosmological, but coarse calculation

Resolution~100 kpc

e.g. Cen, Ostriker '92-'93
Katz+ '96

2001-2011 2nd Rev.

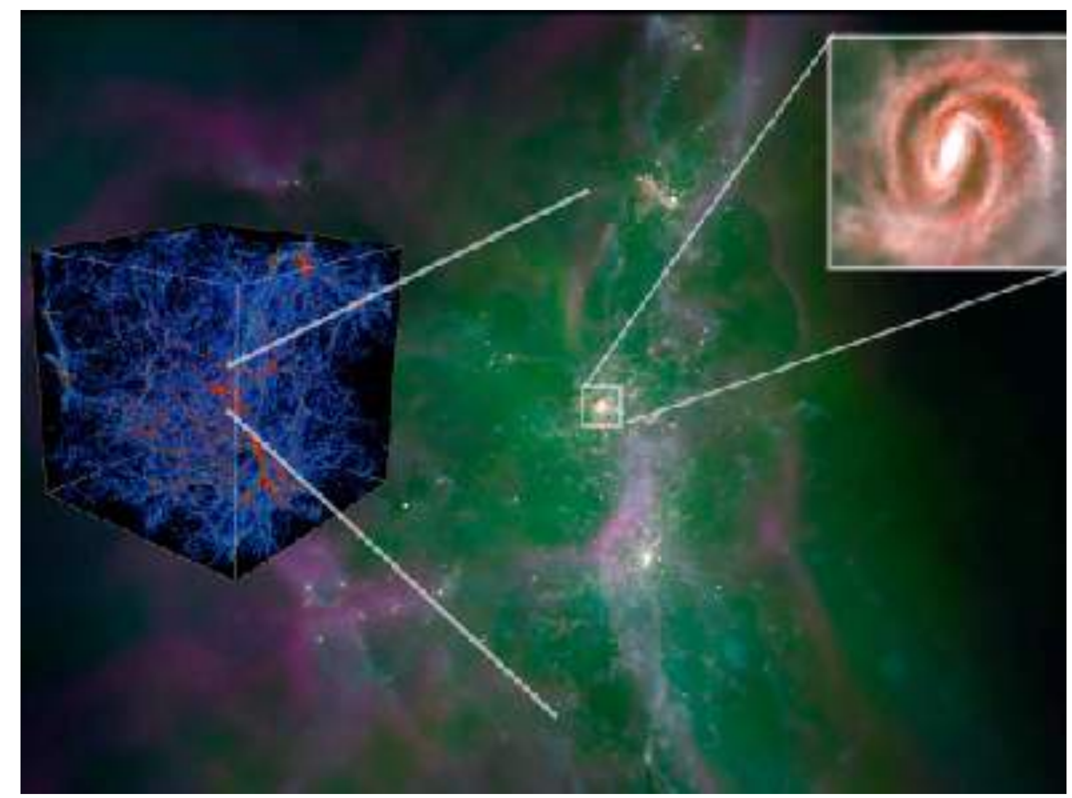


Larger scale, medium resolution **w. subgrid models**

Resolution ~ kpc

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

2012~ 3rd Rev.

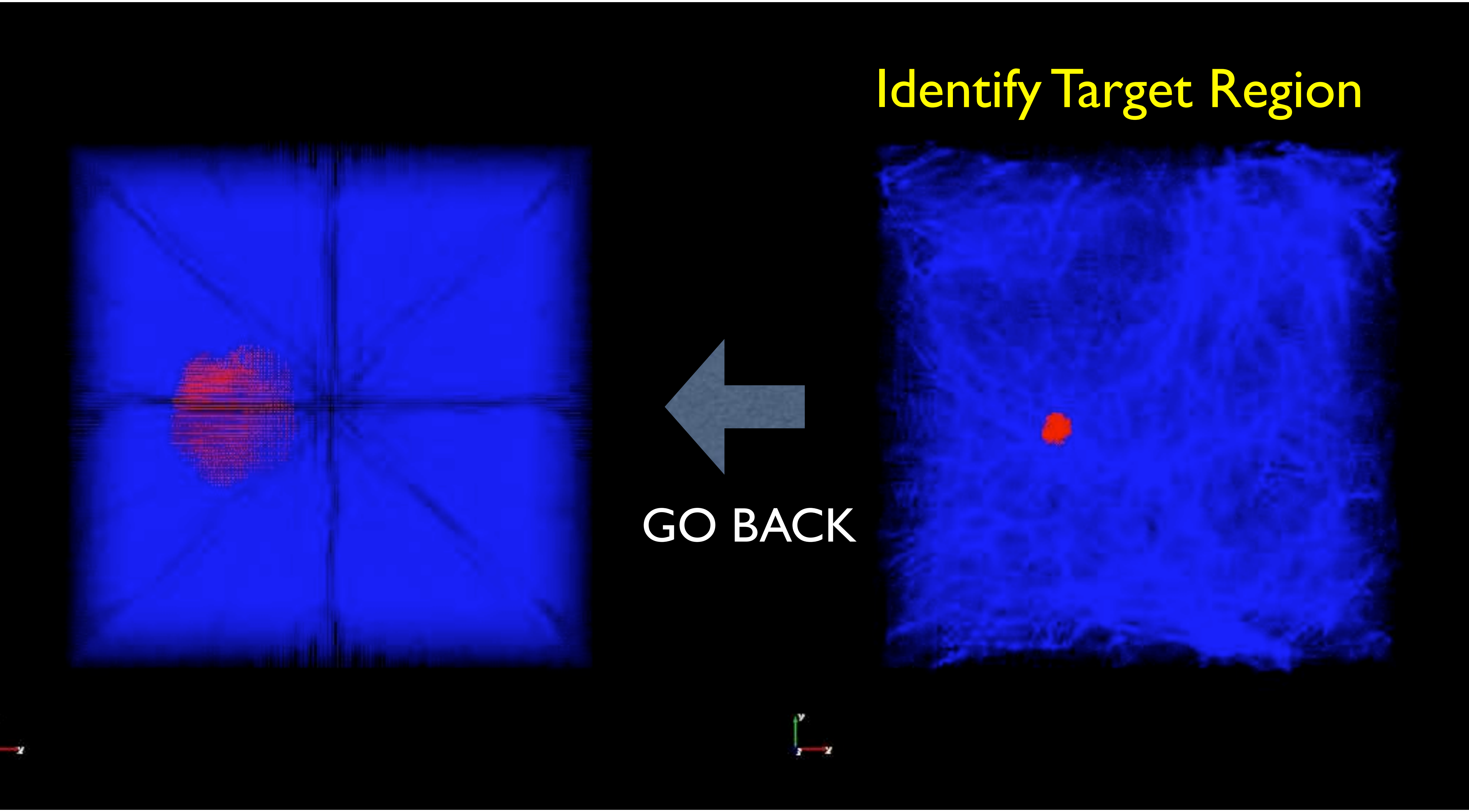


Zoom-in method allows much higher res.

Resolution~ 10-100pc

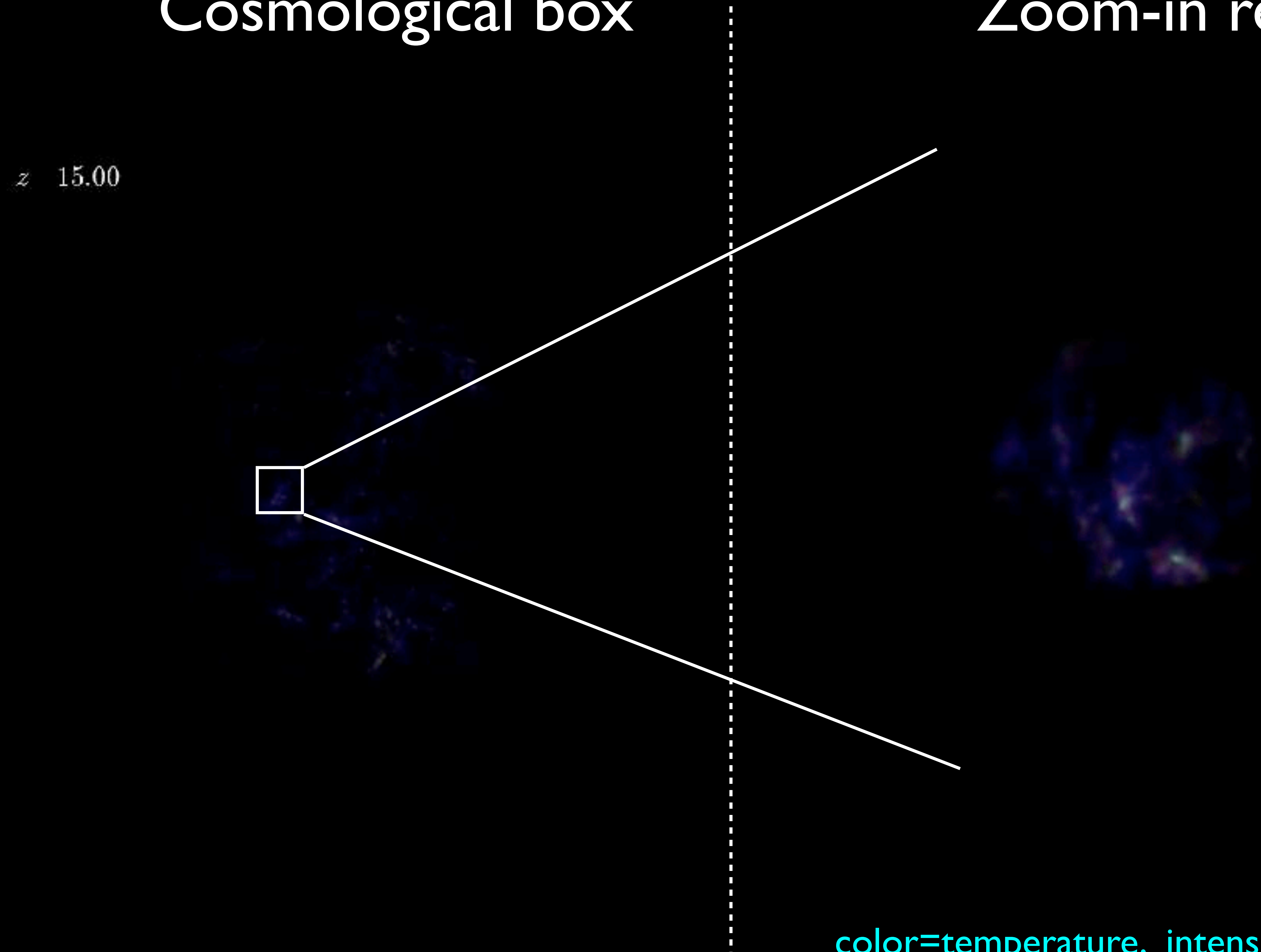
IC code: GRAFIC (Bertschinger)
MUSIC (Hahn & Abel '11)

Setting Up a Zoom-in Simulation



MUSIC (Hahn & Abel '11) + Thompson's SPHGR (python analyses code suite)

Cosmological box | Zoom-in region

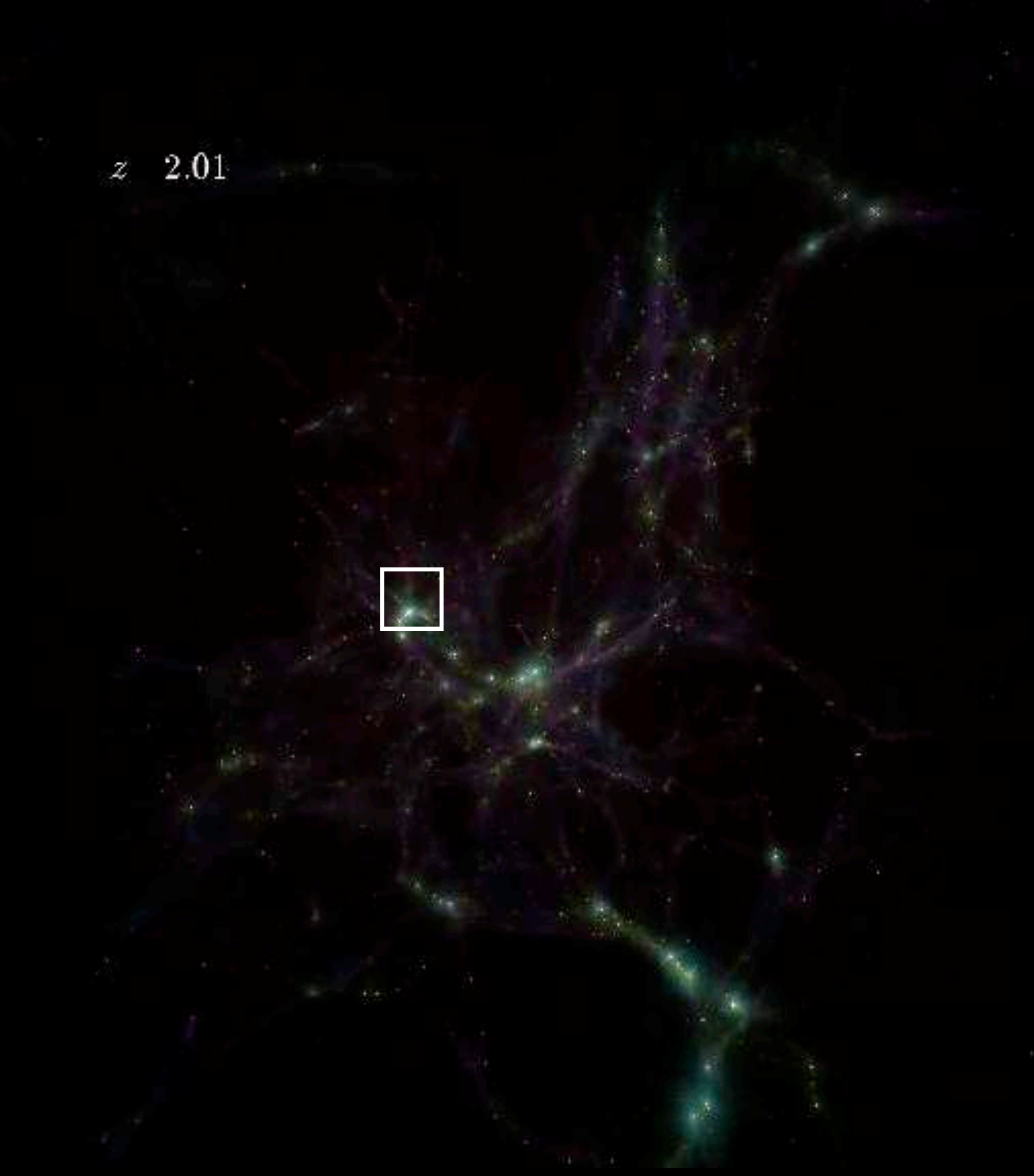


color=temperature, intensity=gas density

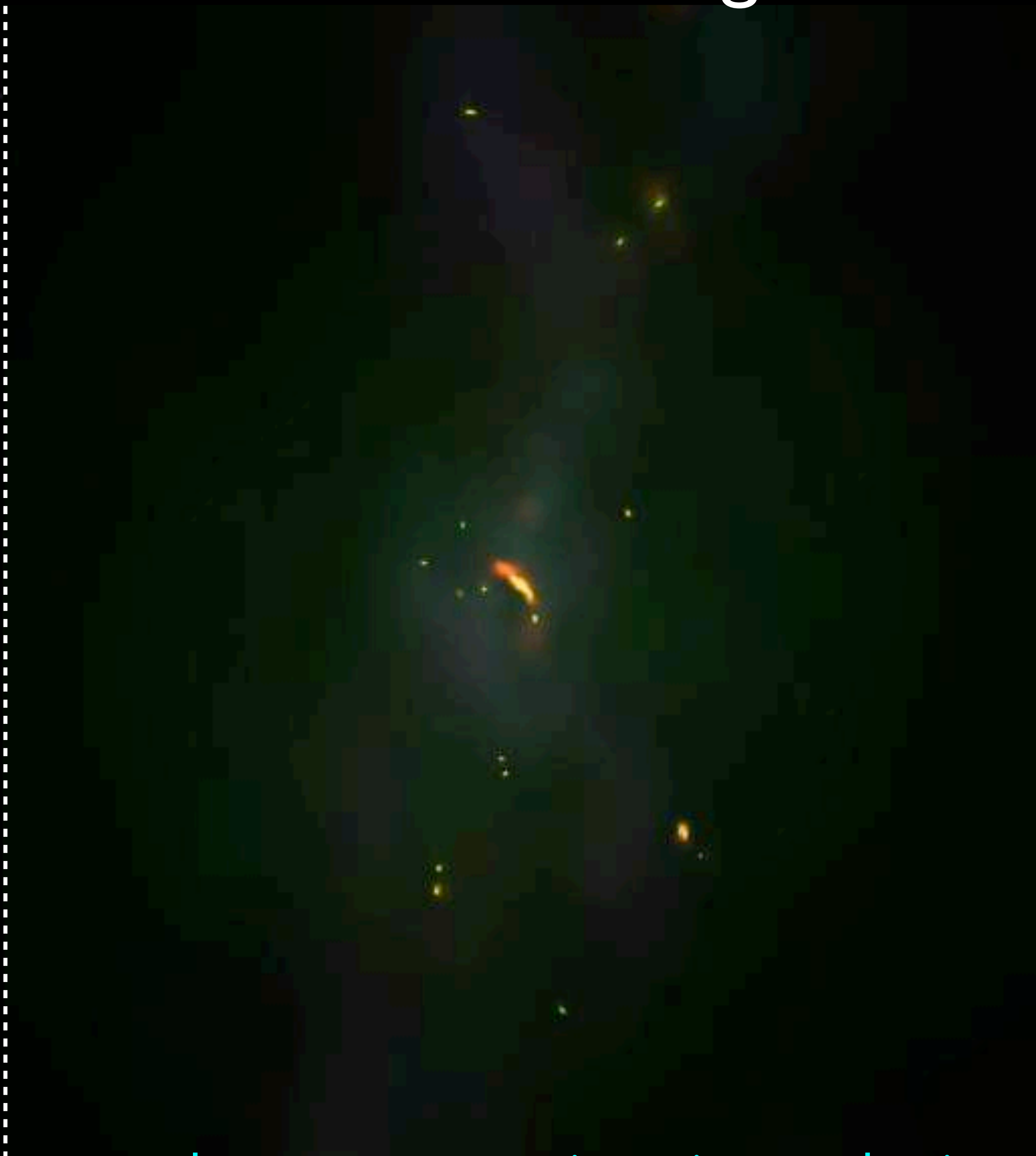
yellow dots = stars

Thompson & KN ’13

Cosmological box



Zoom-in region

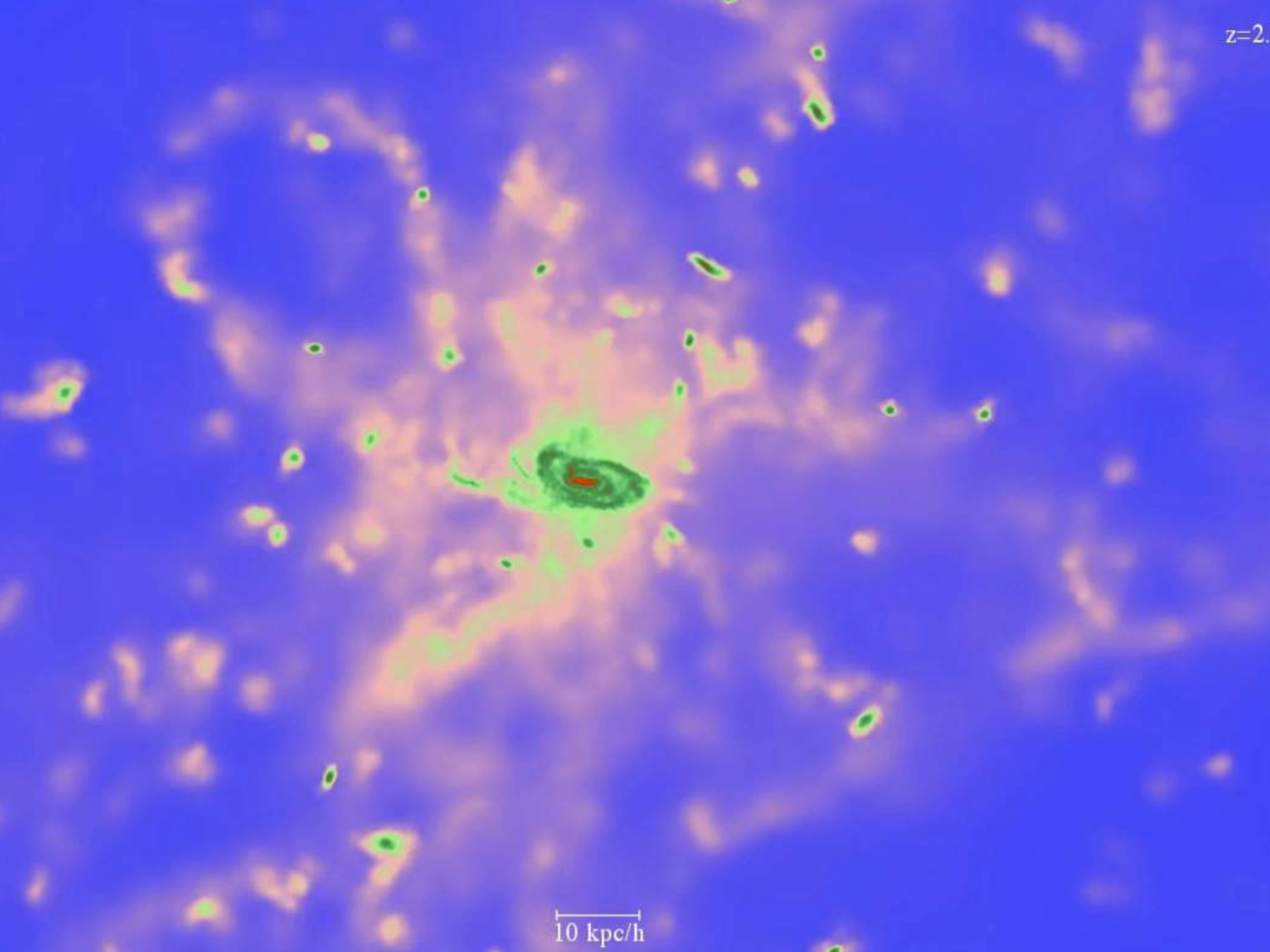


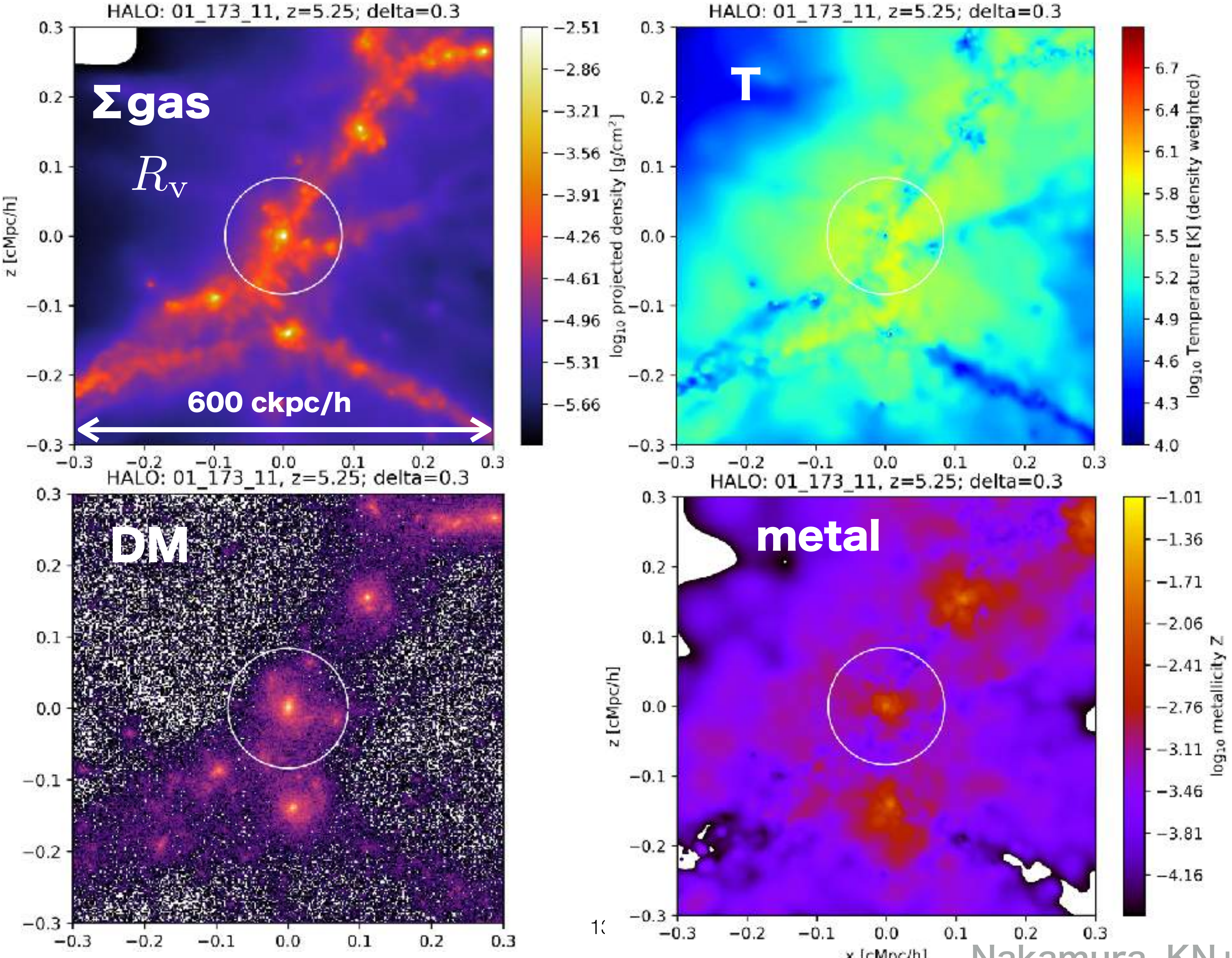
color=temperature, intensity=gas density

yellow dots = stars

Thompson & KN '13

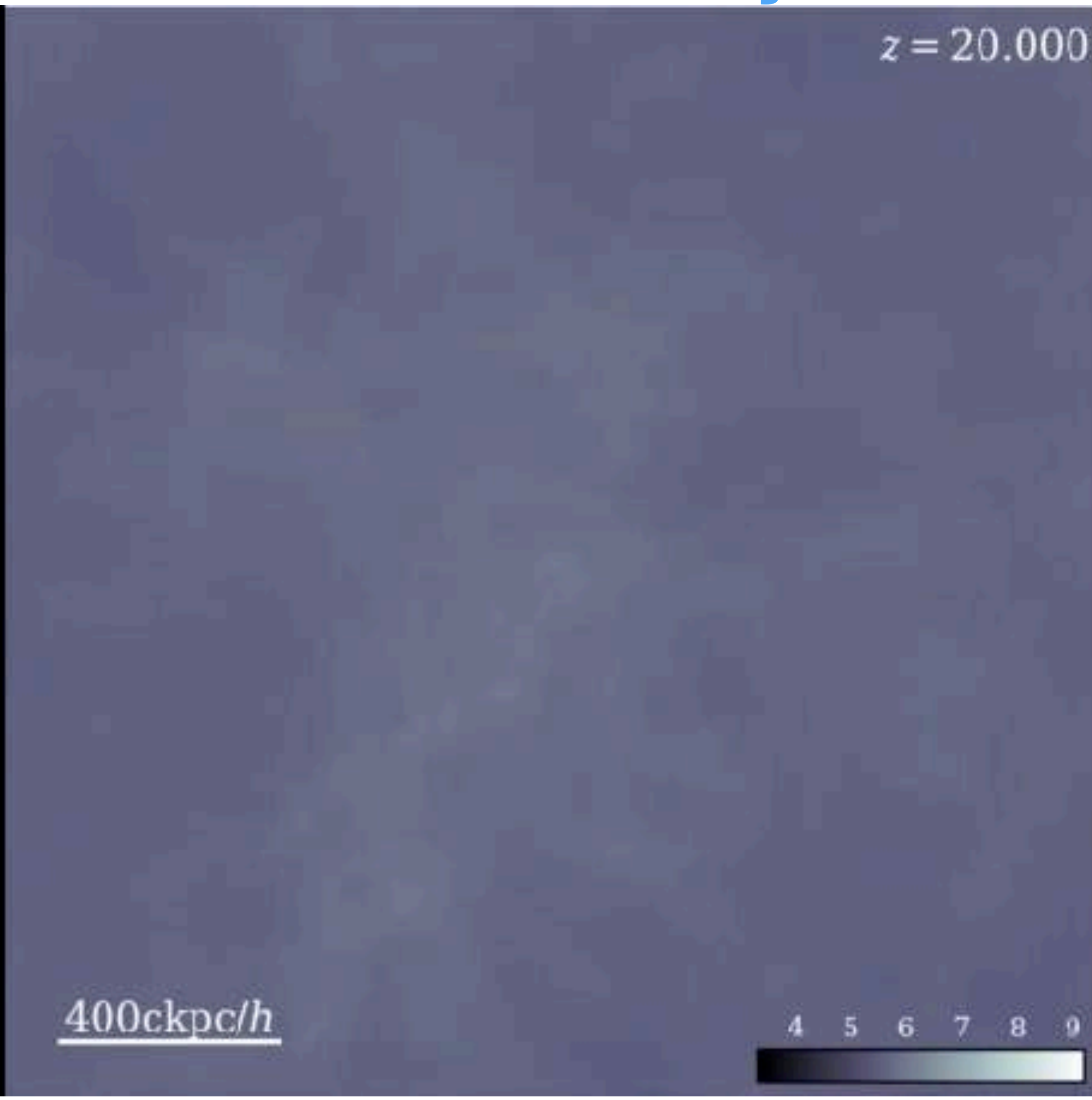

moderate res. zoom sim:
~1.25 ckpc/h
z~2


z=2.
10 kpc/h

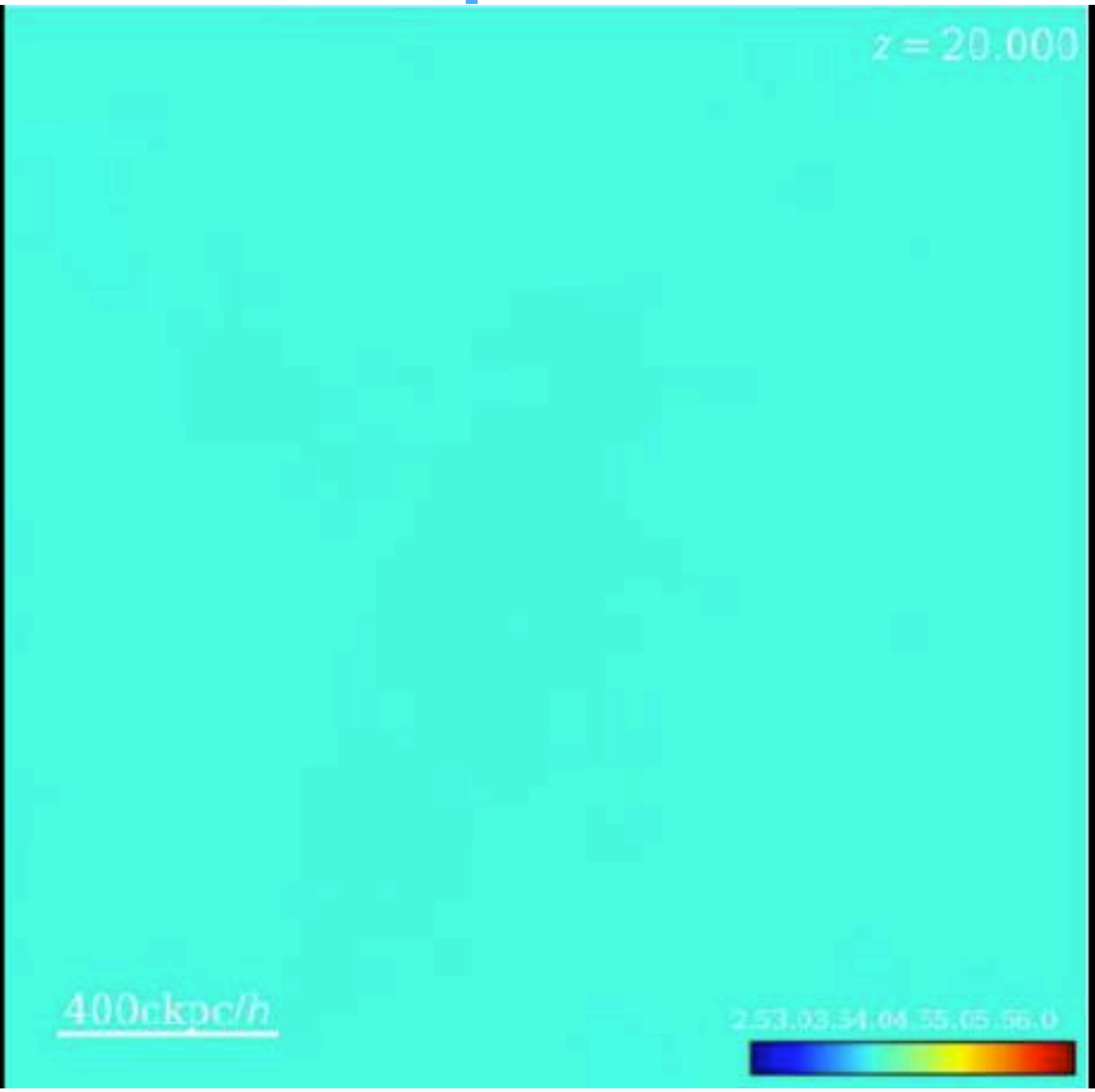

HALO: 01_173_11, z=5.25; delta=0.3
Σgas
R_{v}
600 ckpc/h
log₁₀ projected density [g/cm²]
z [cMpc/h]
T
log₁₀ Temperature [K] (density weighted)
DM
metal
log₁₀ metallicity Z
x [cMpc/h]

Nakamura, KN+

Gas Density



Temperature

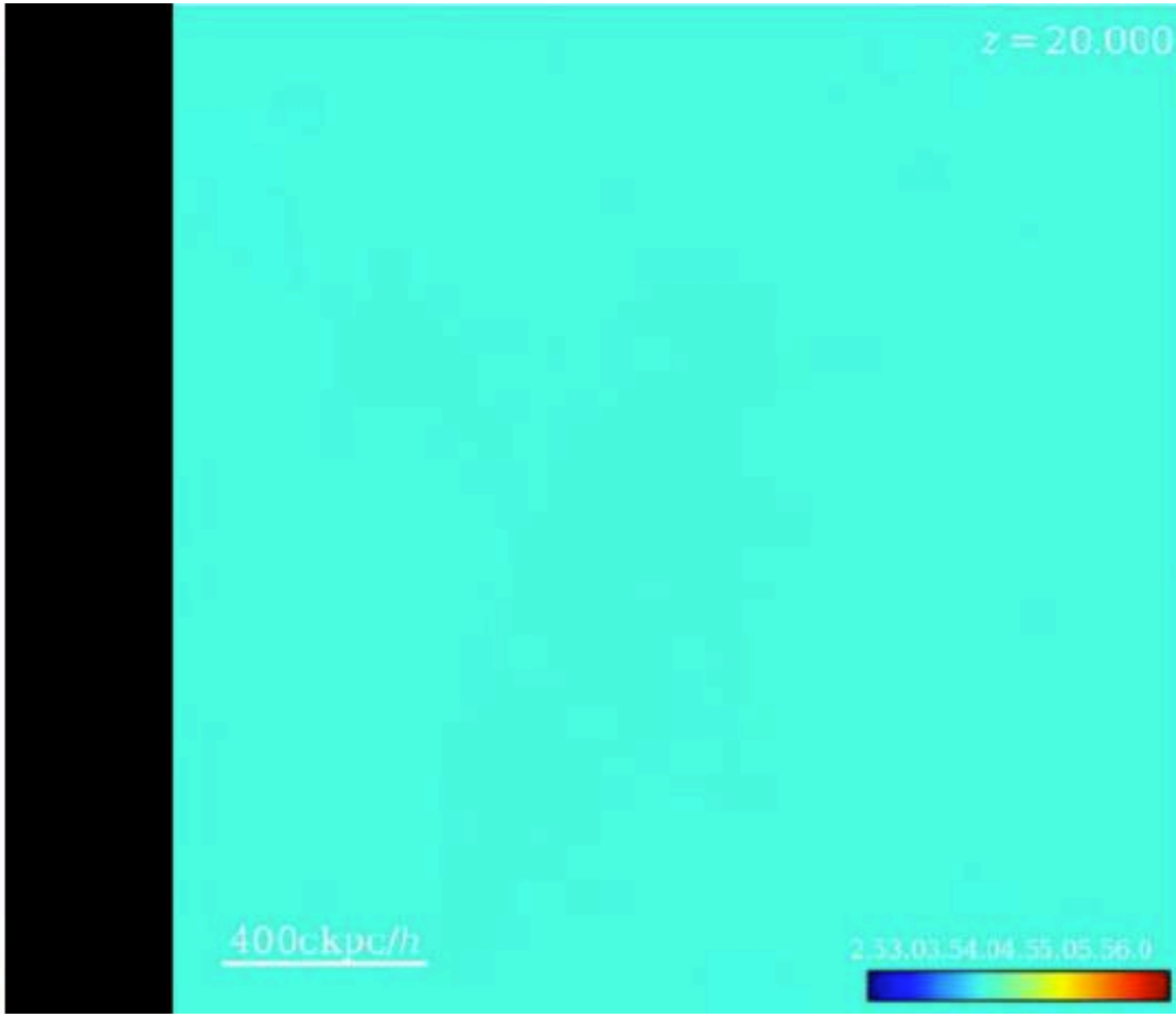


AGORA L12 sim.

Shimizu, KN+

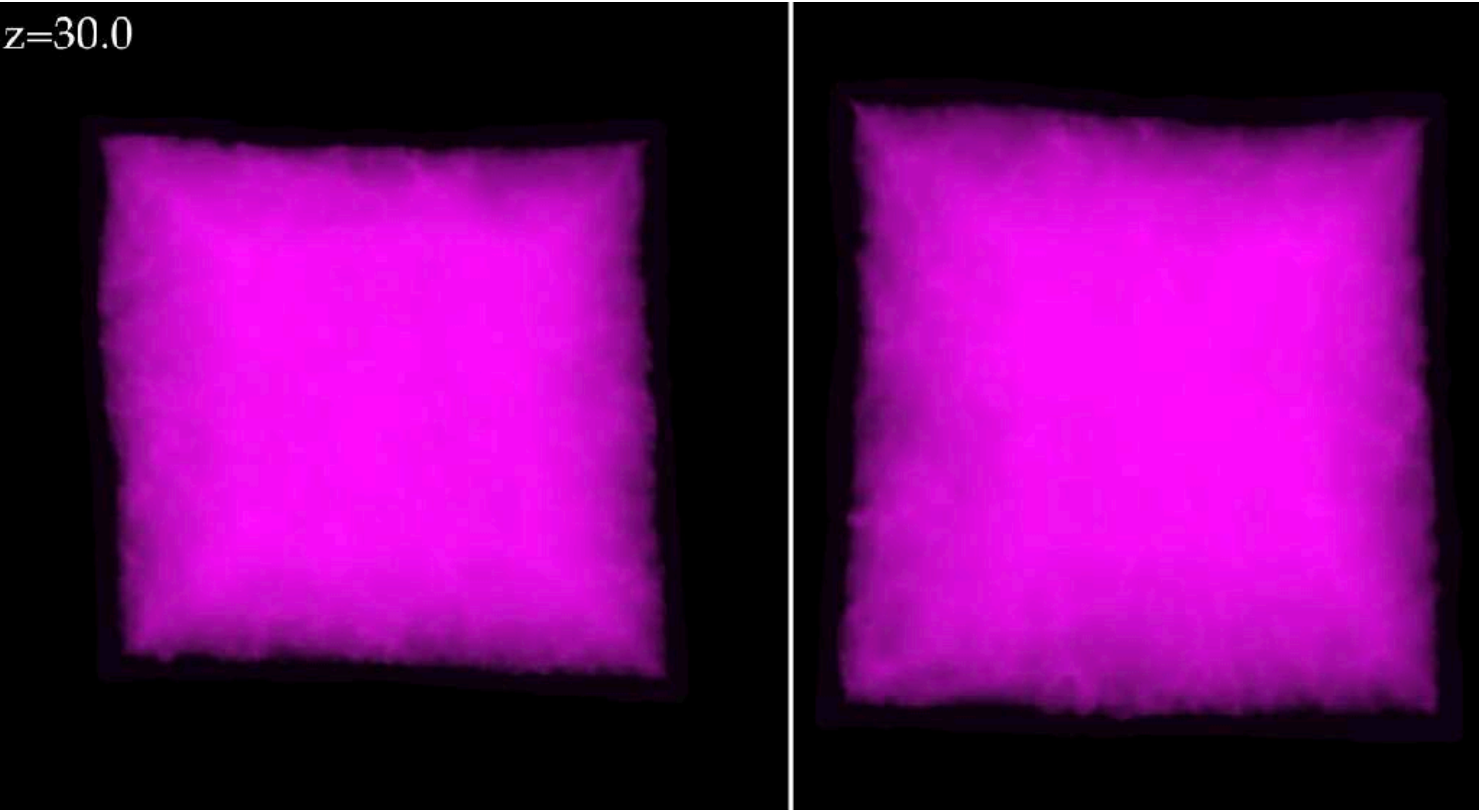
Metallicity

Temperature



AGORA L12 sim.

Shimizu, KN+



m12q FIRE simulation

m_{dm}~2e5 M⊙/h

m_b=5e3 M⊙/h

ϵ_{dm}=100 pc/h

ϵ_b=7 pc/h

Feedback in Zoom-in Cosmo Sim

Models w/ more direct momentum input:

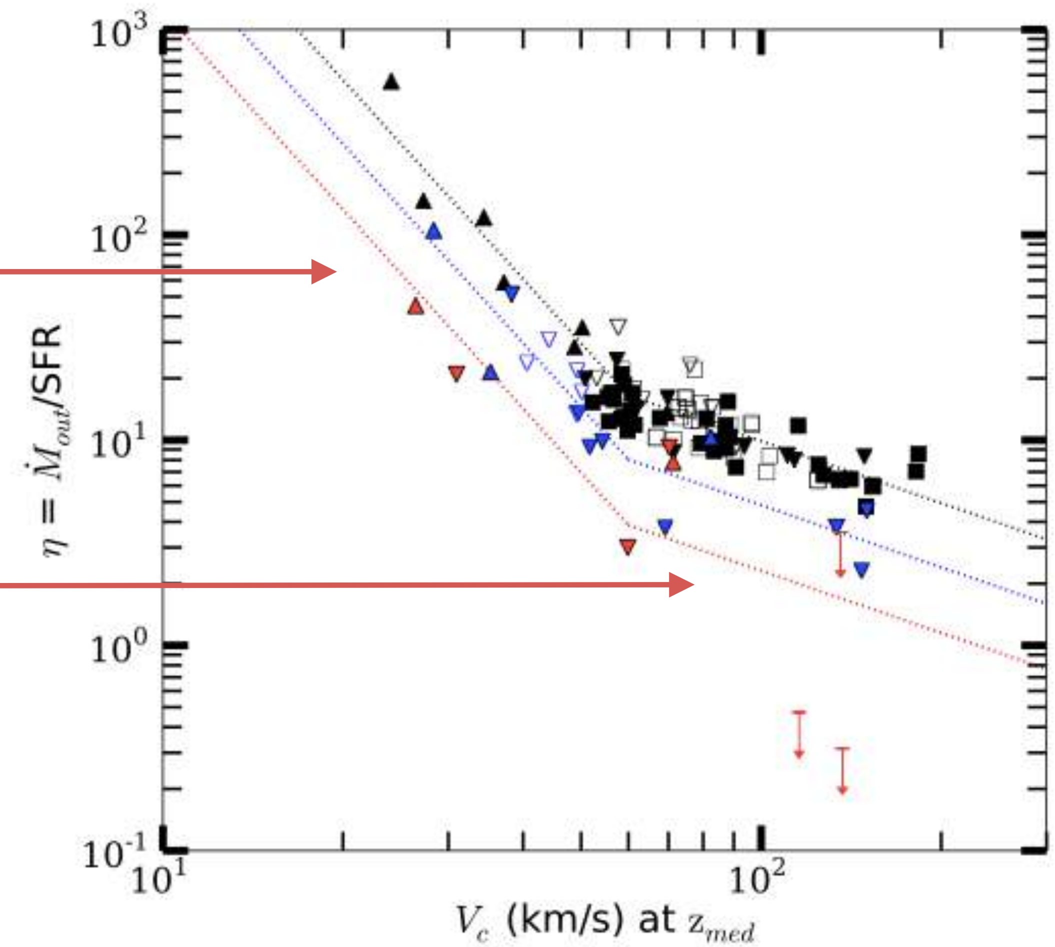
Mass Loading Factor : η

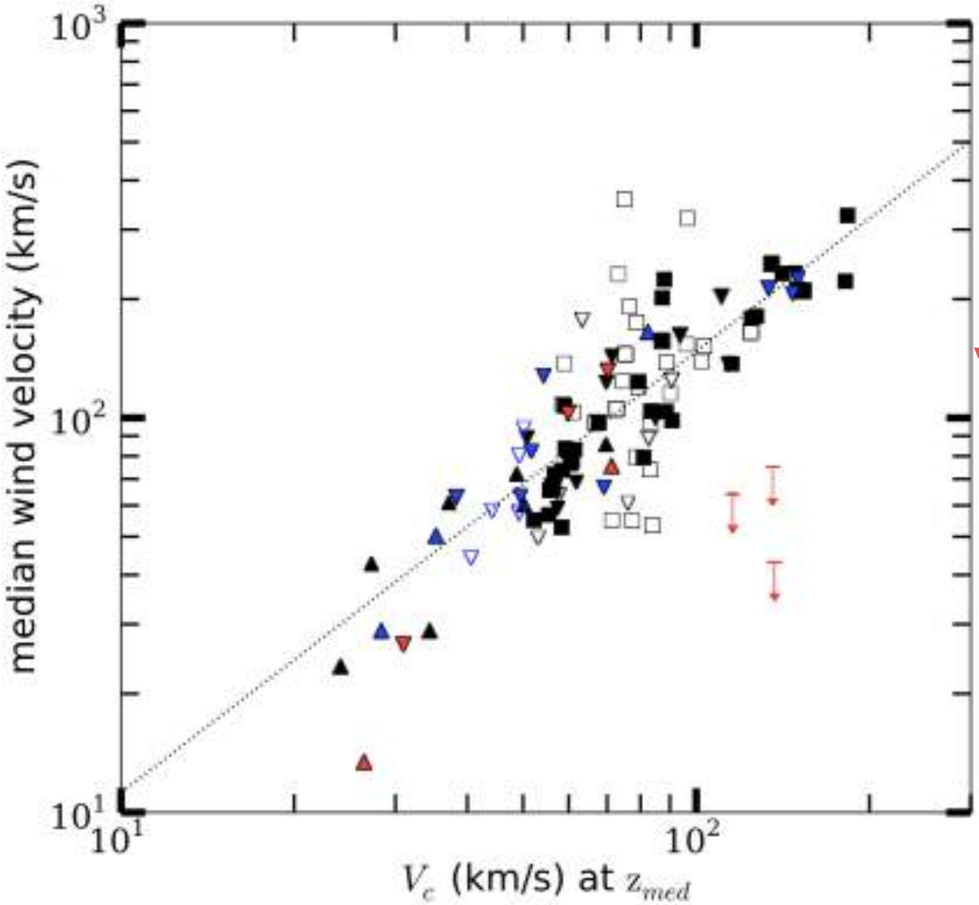
$$\eta = 2.91\,(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-3.22}$$

(steeper than Energy-driven)

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

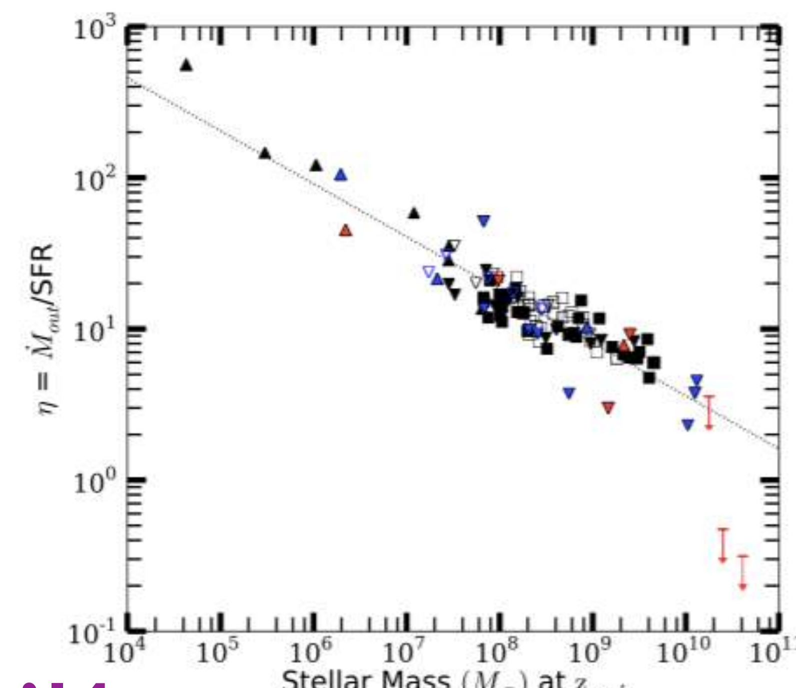
(≈ Momentum-driven)





Wind Velocity

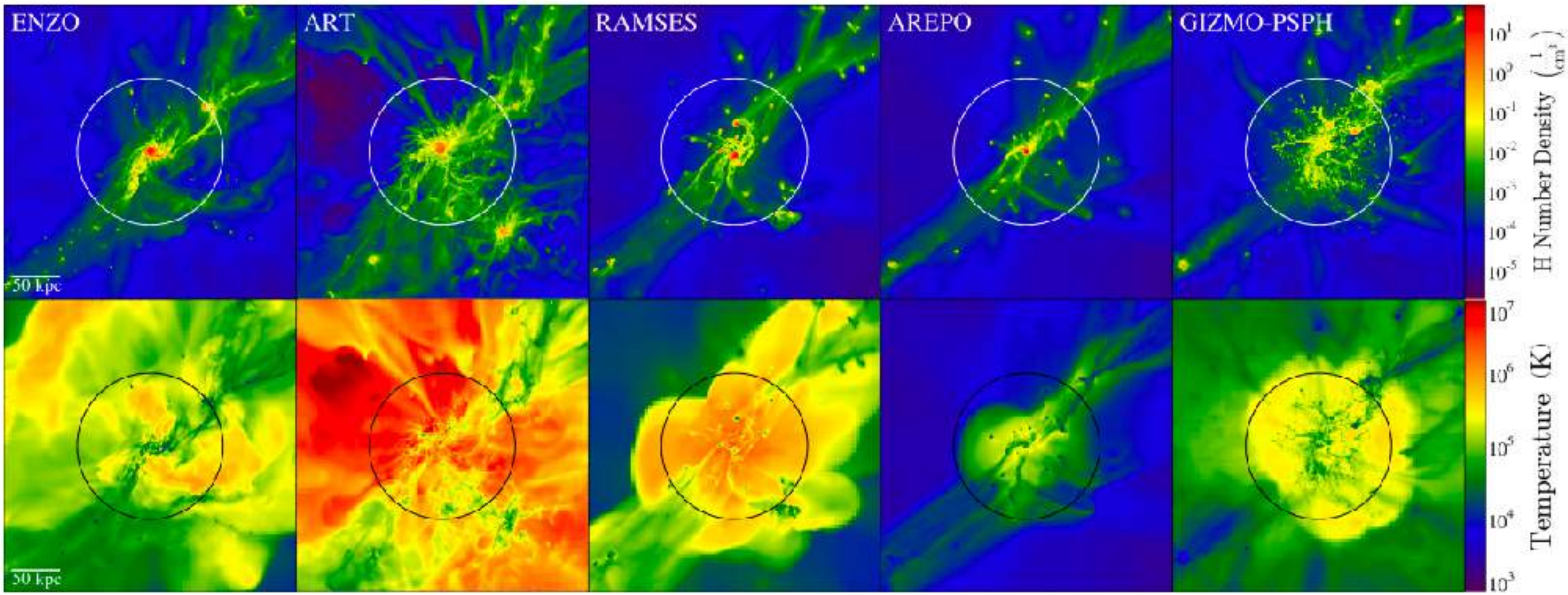
($V_w \sim V_c \sim M_h^{1/3} \sim SFR^{1/2}$)



Hopkins+'13; Muratov+ '14

Cold flow: generic feature of ΛCDM
(accretion)

Enzo ART RAMSES AREPO GIZMO-PSPH

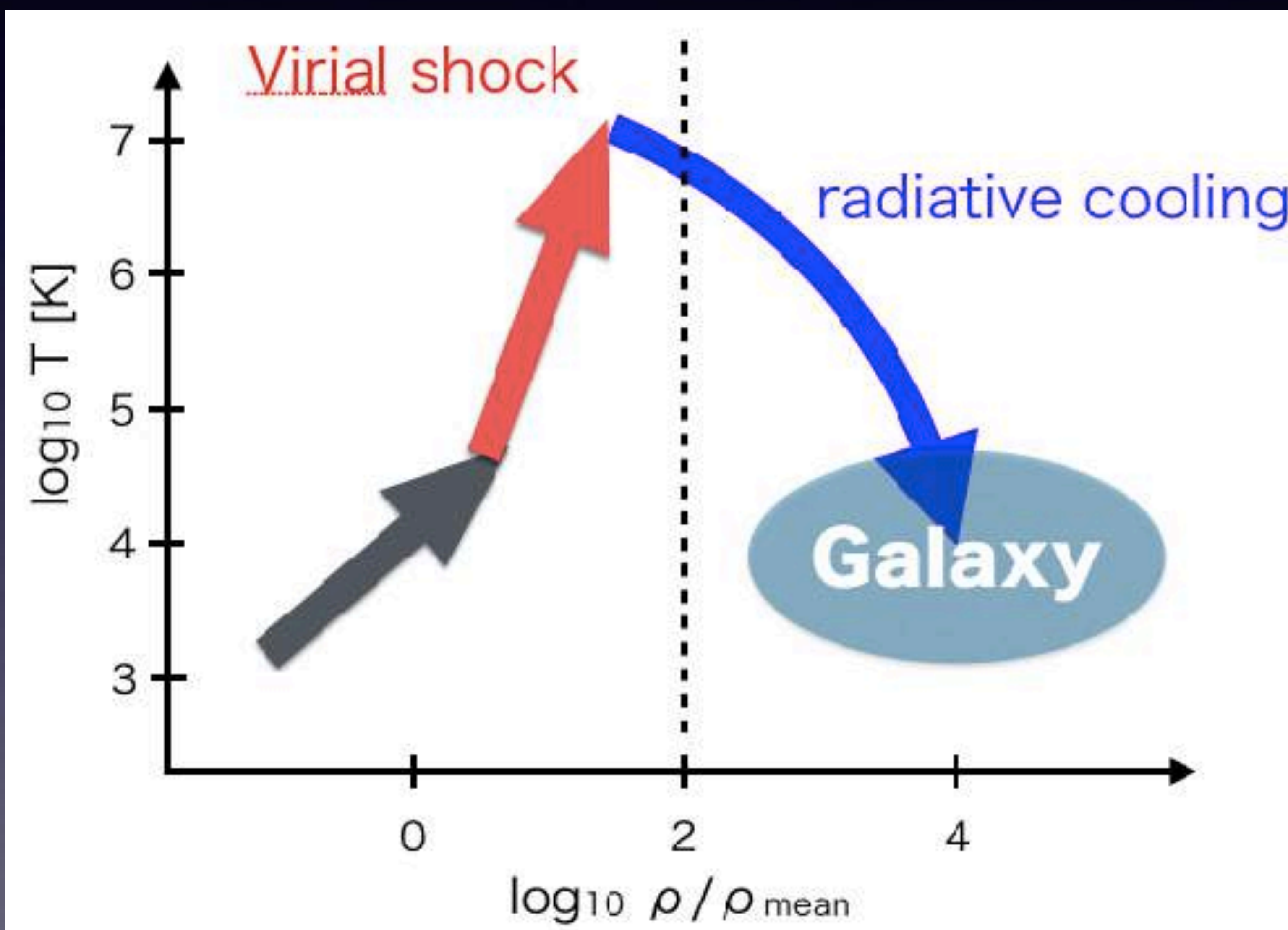


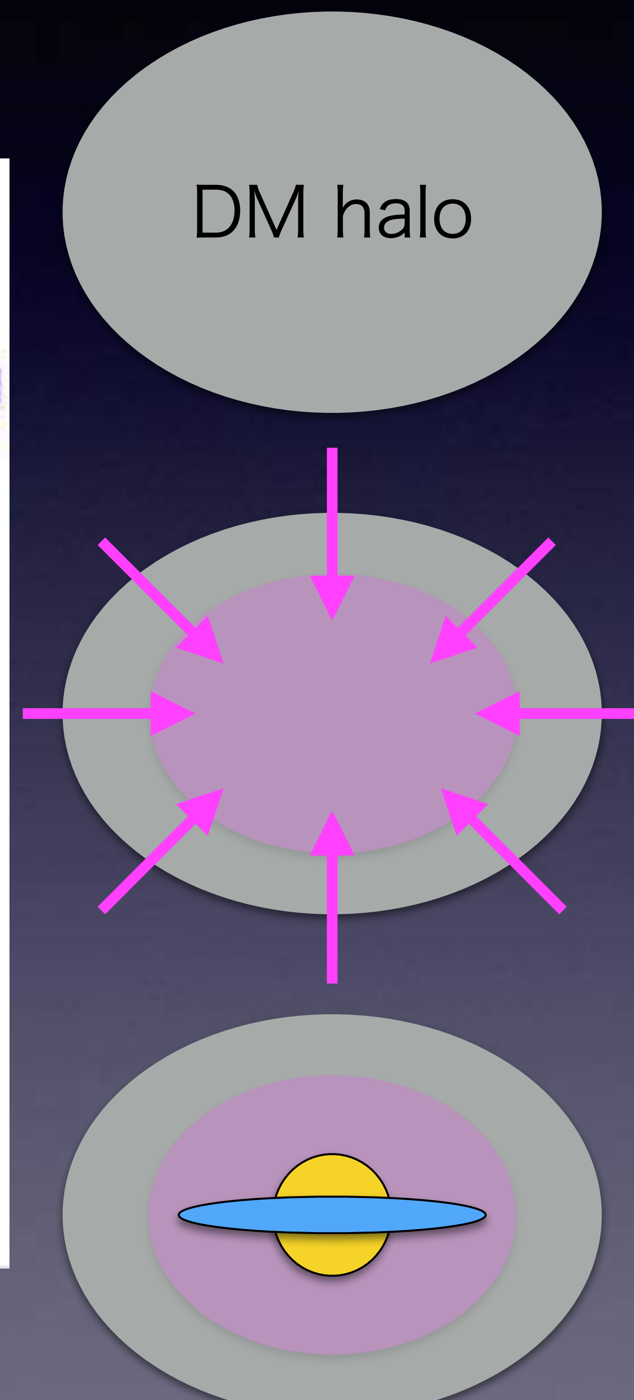
(details of SF & feedback are different in each code)

Stewart+’17

1st-order Galaxy formation

Rees & Ostriker ’77, White & Rees ’78, Fall & Efstathiou ’80, White & Frenk ’91, Mo, Mao & White ‘98



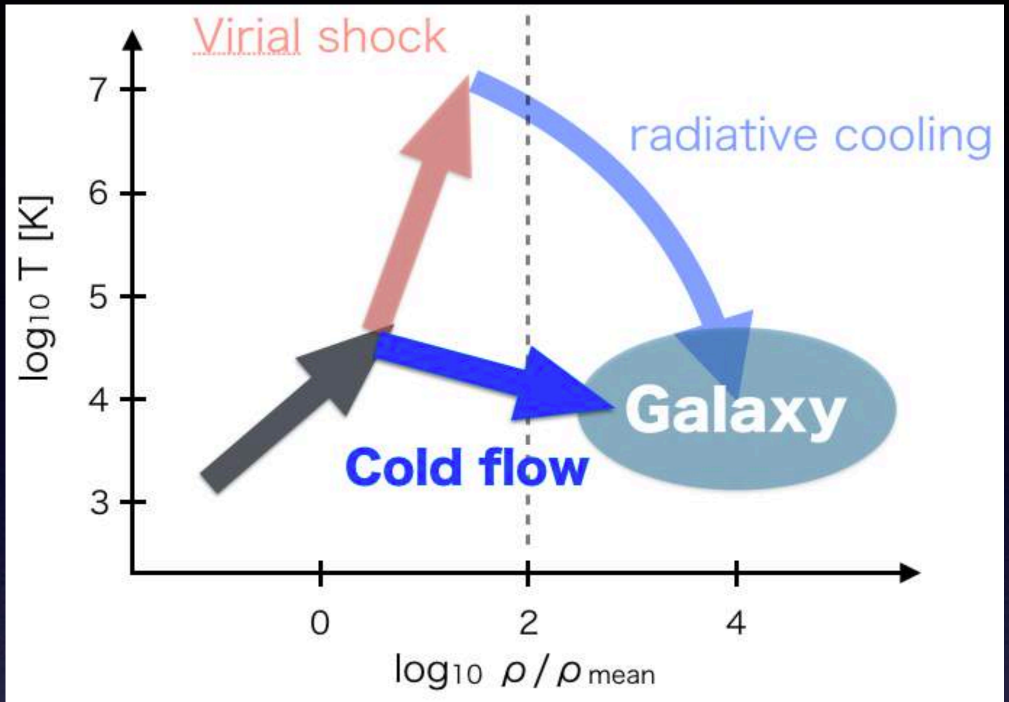


DM halo forms

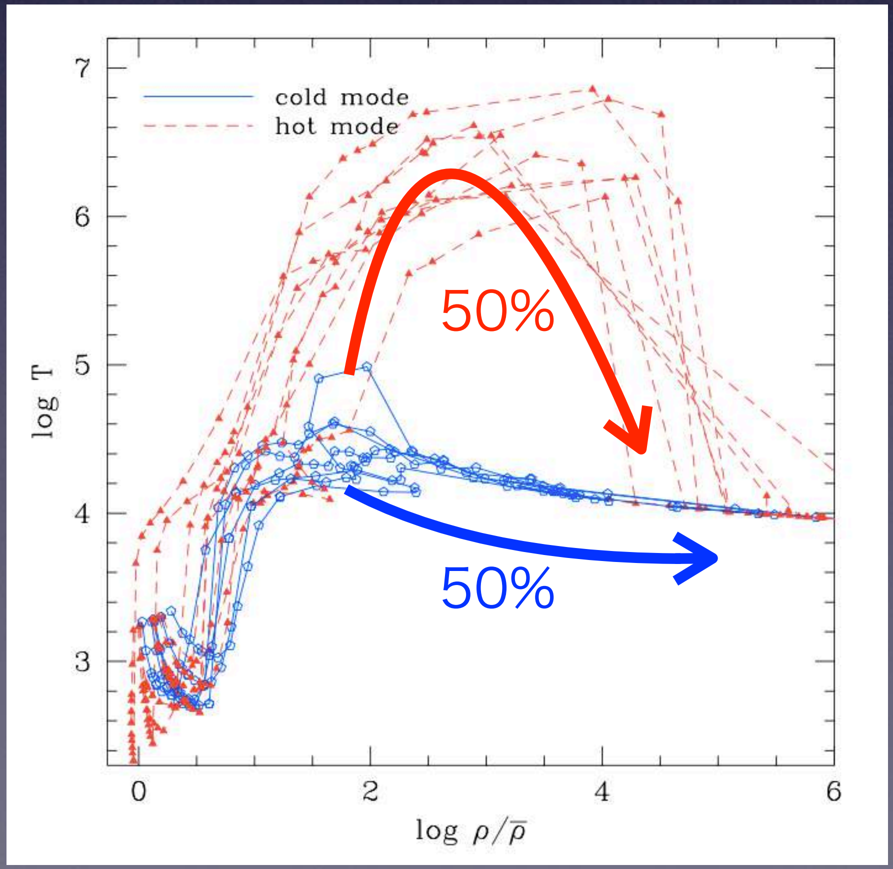
gas accretes & shock-heated

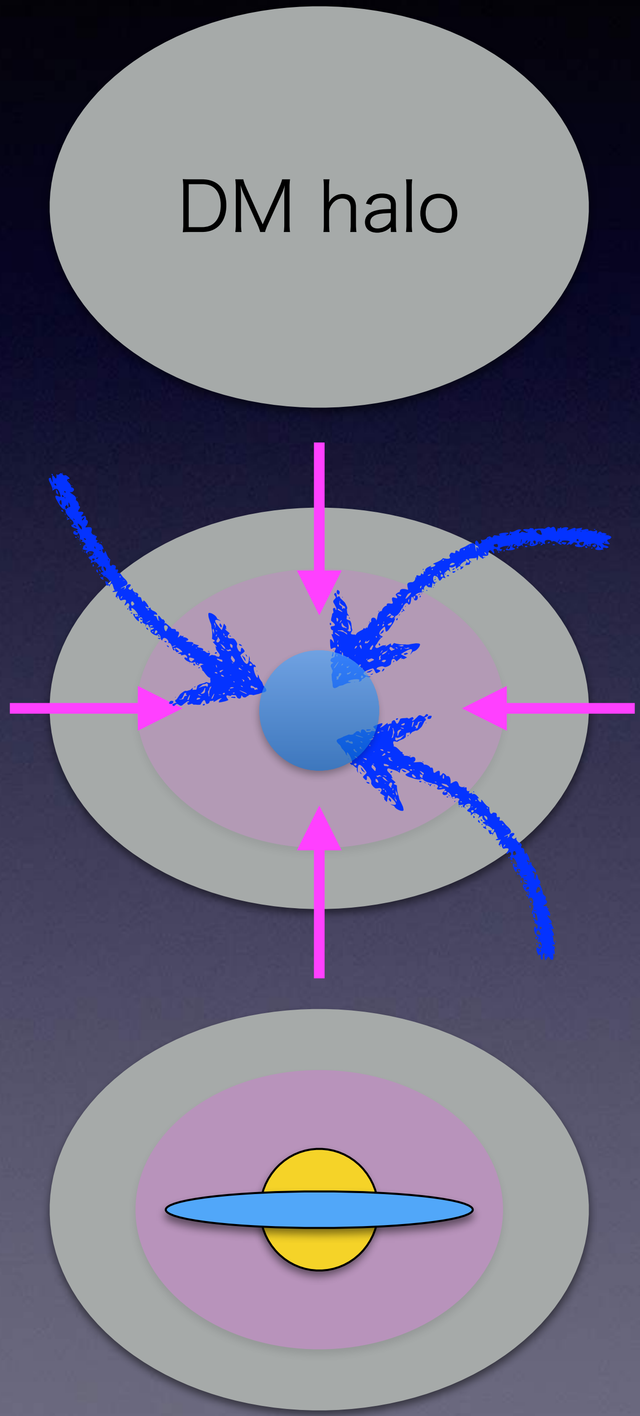
Cooling & disk galaxy forms

Galaxy formation with cold flows



Keres+'05





DM halo forms

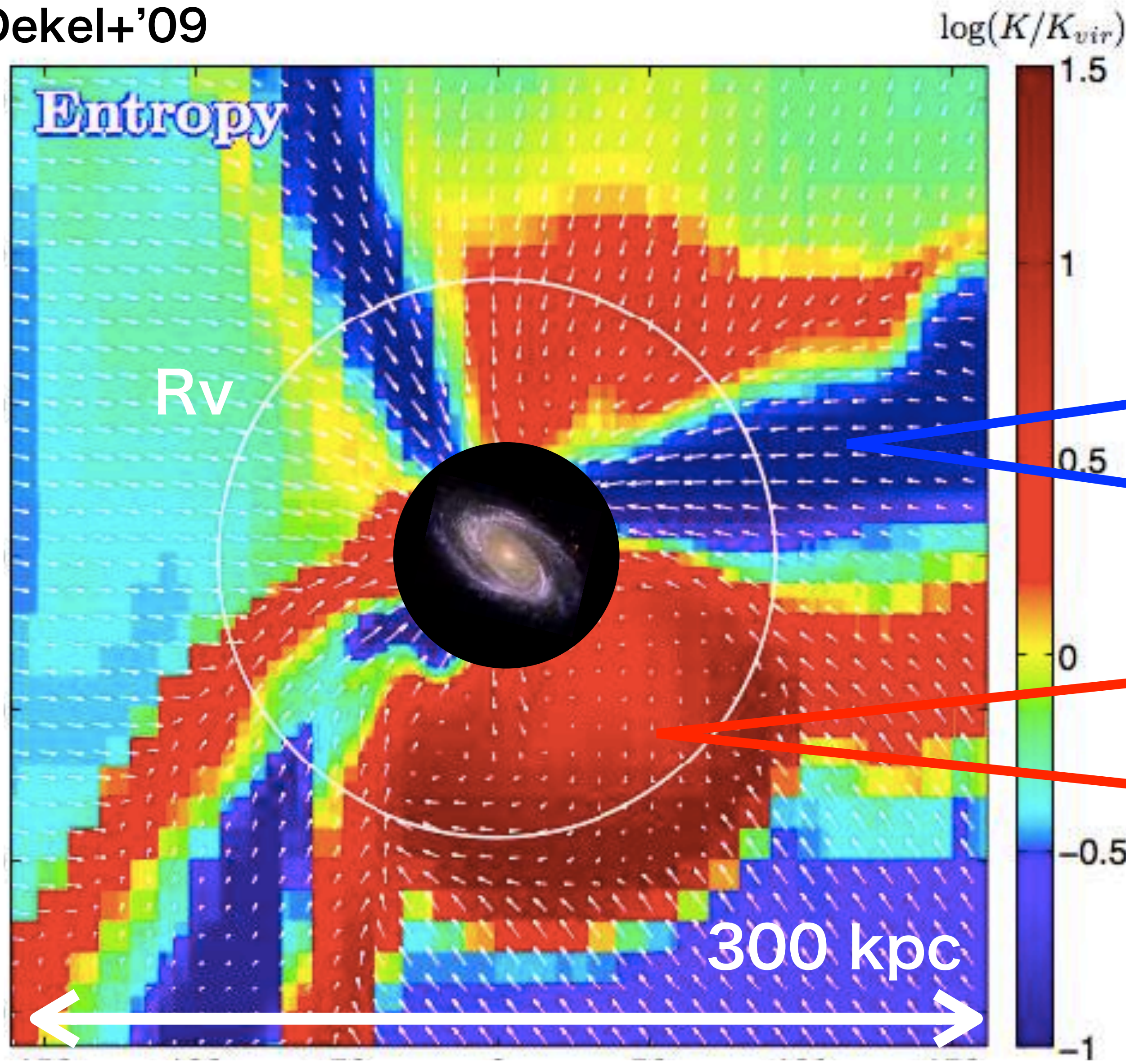
gas accretes spherically & filamentary

Cooling & disk galaxy forms

How do galaxies acquire gas?

Cold Flow & Virial Shock

Dekel+'09



Cold Flow

Efficient inflow of cold gas

Promotes SF

Gas Accretion & **Virial Shock**

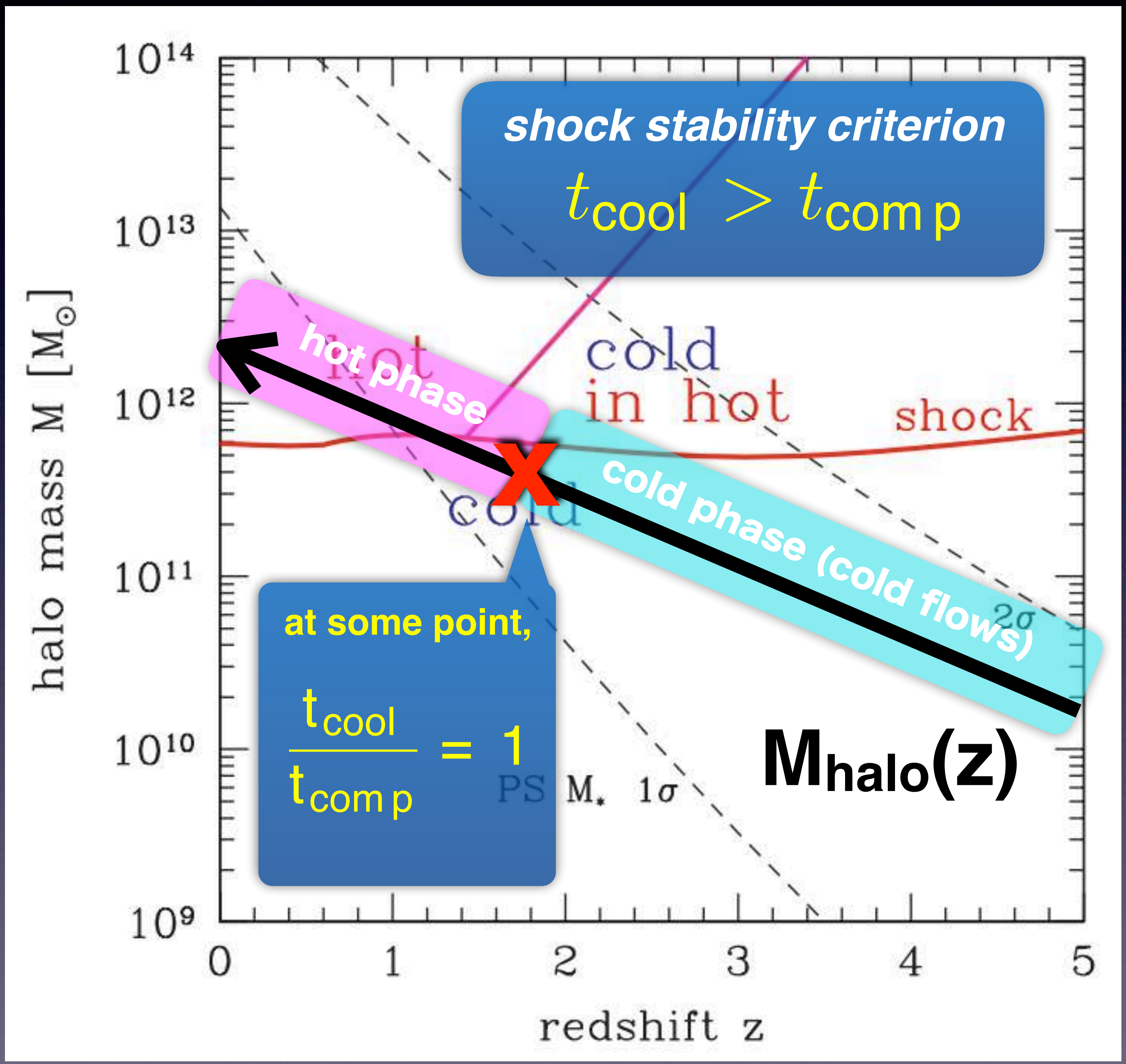
Heating to $\mathbf{T_{vir}}$

Prohibit SF

Birnboim & Dekel '03 :
Keres+'05

t_compression vs. **t_cool**
controls the thermal state of gas.

Criteria for cold flows



$$t_{comp} = -\frac{\Gamma}{\nabla \cdot \mathbf{u}} \sim \Gamma t_{ff}$$

$$t_{cool} = \frac{\frac{3}{2} n k_B T}{n_H^2 \Lambda(T, Z)}$$

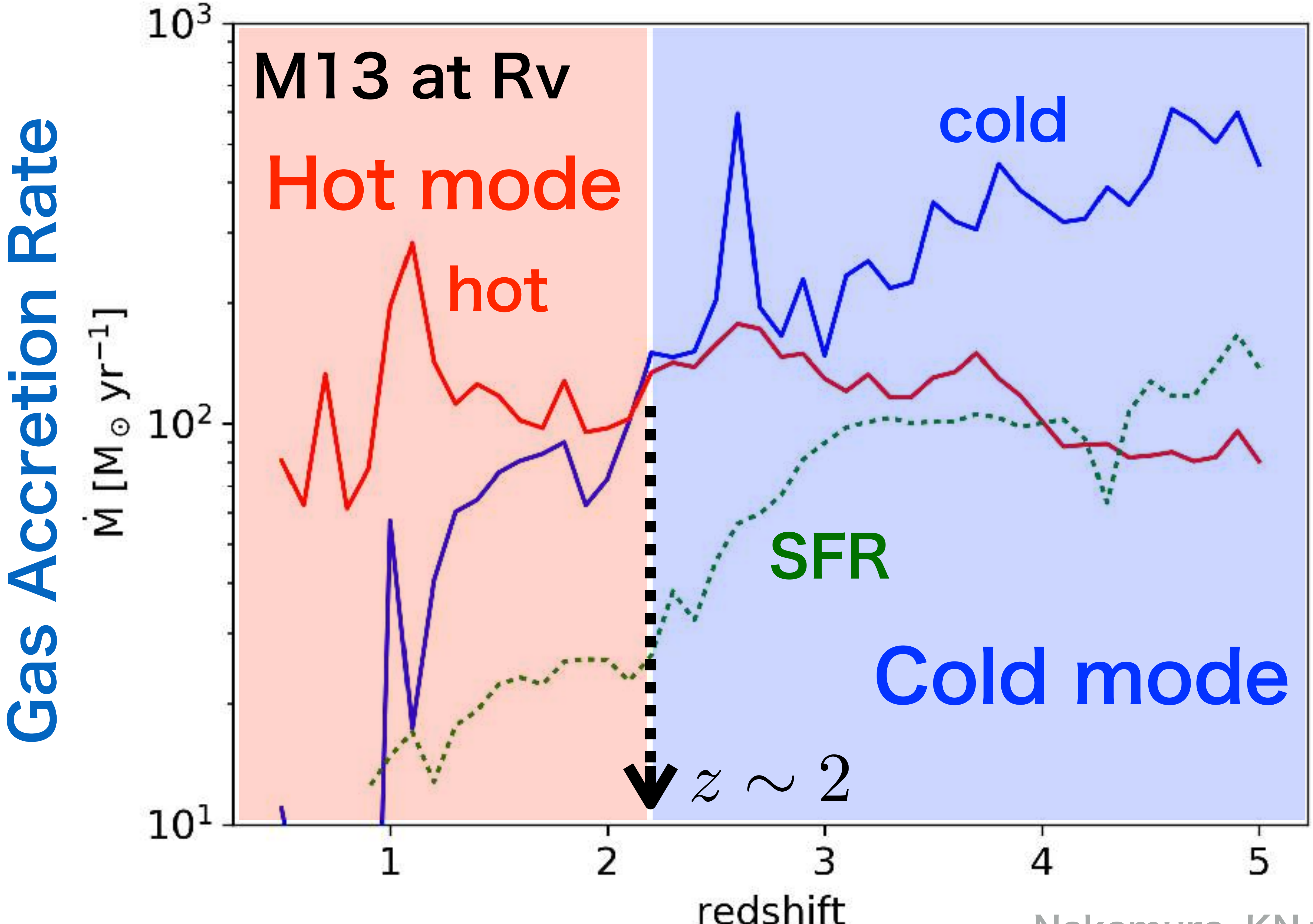
Compute

$$\frac{t_{cool}}{t_{comp}}$$

at Rv and examine the redshift evolution.

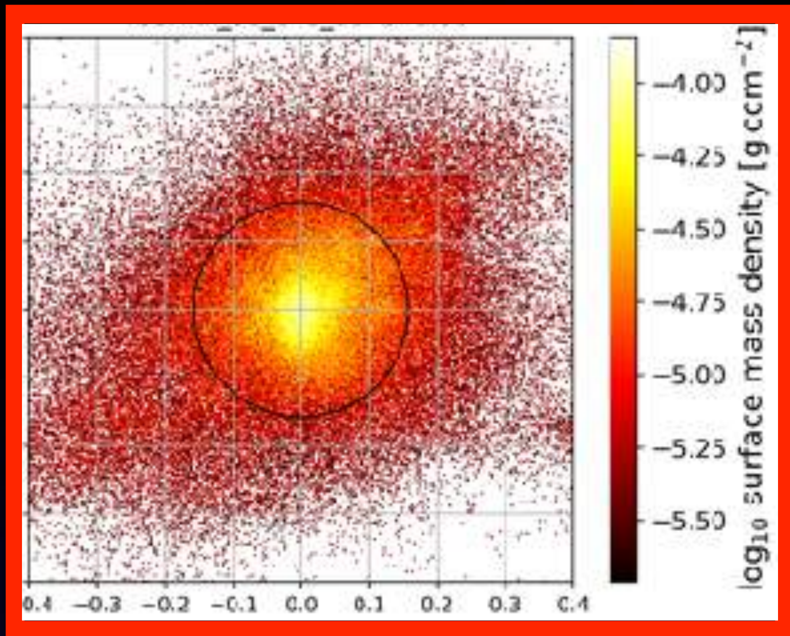
Dekel & Birnboim '06

Transition from Cold to Hot mode



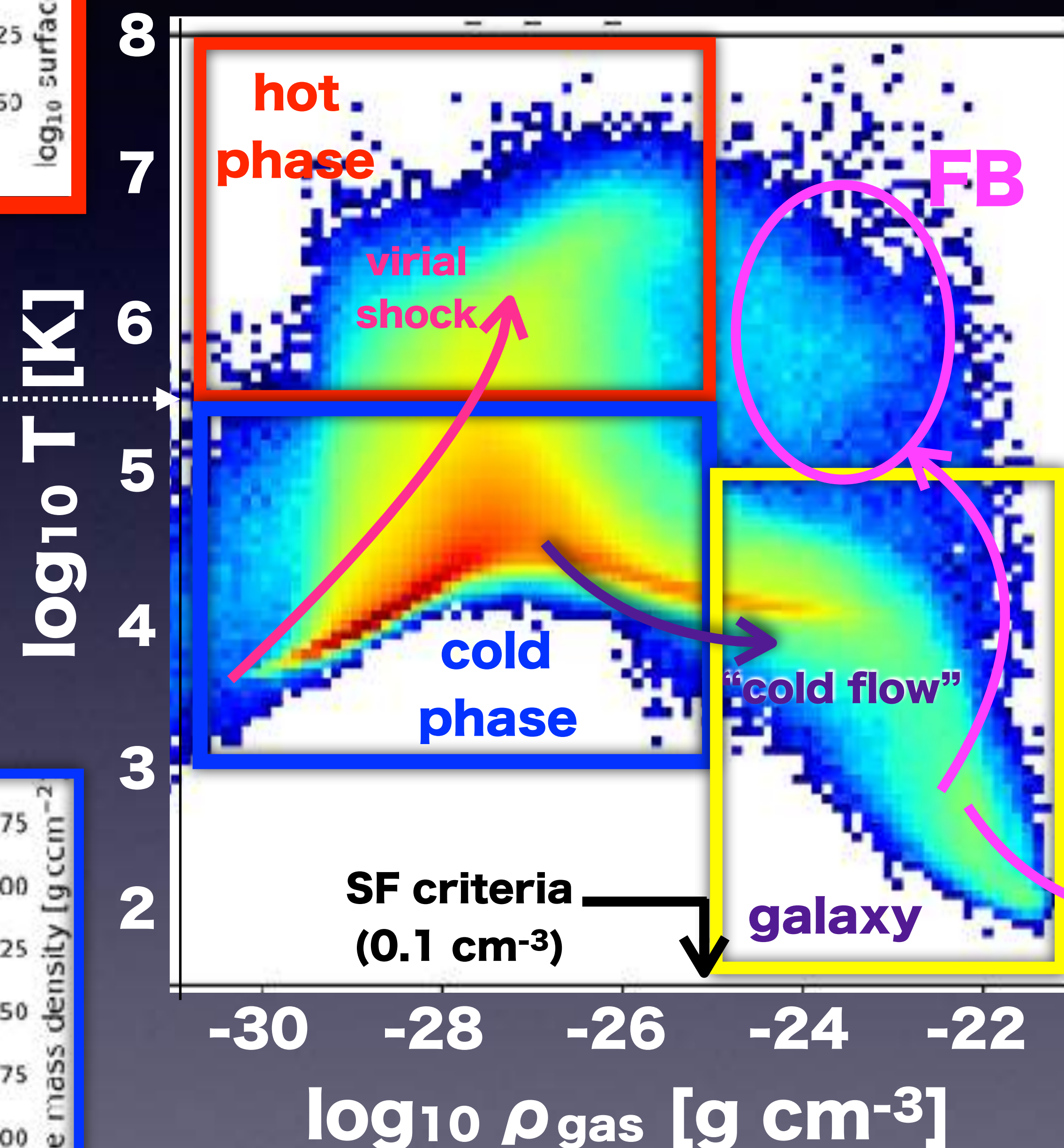
Nakamura, KN+'18

Galaxy Formation in phase diagram

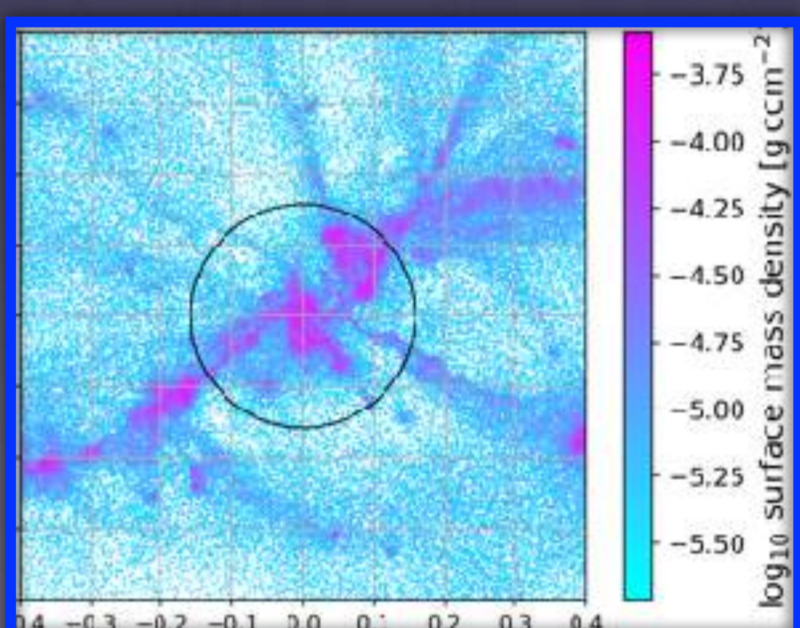


hot diffuse gas
(~ 10^{6-7} K)

$T \sim T_{vir}$



star formation



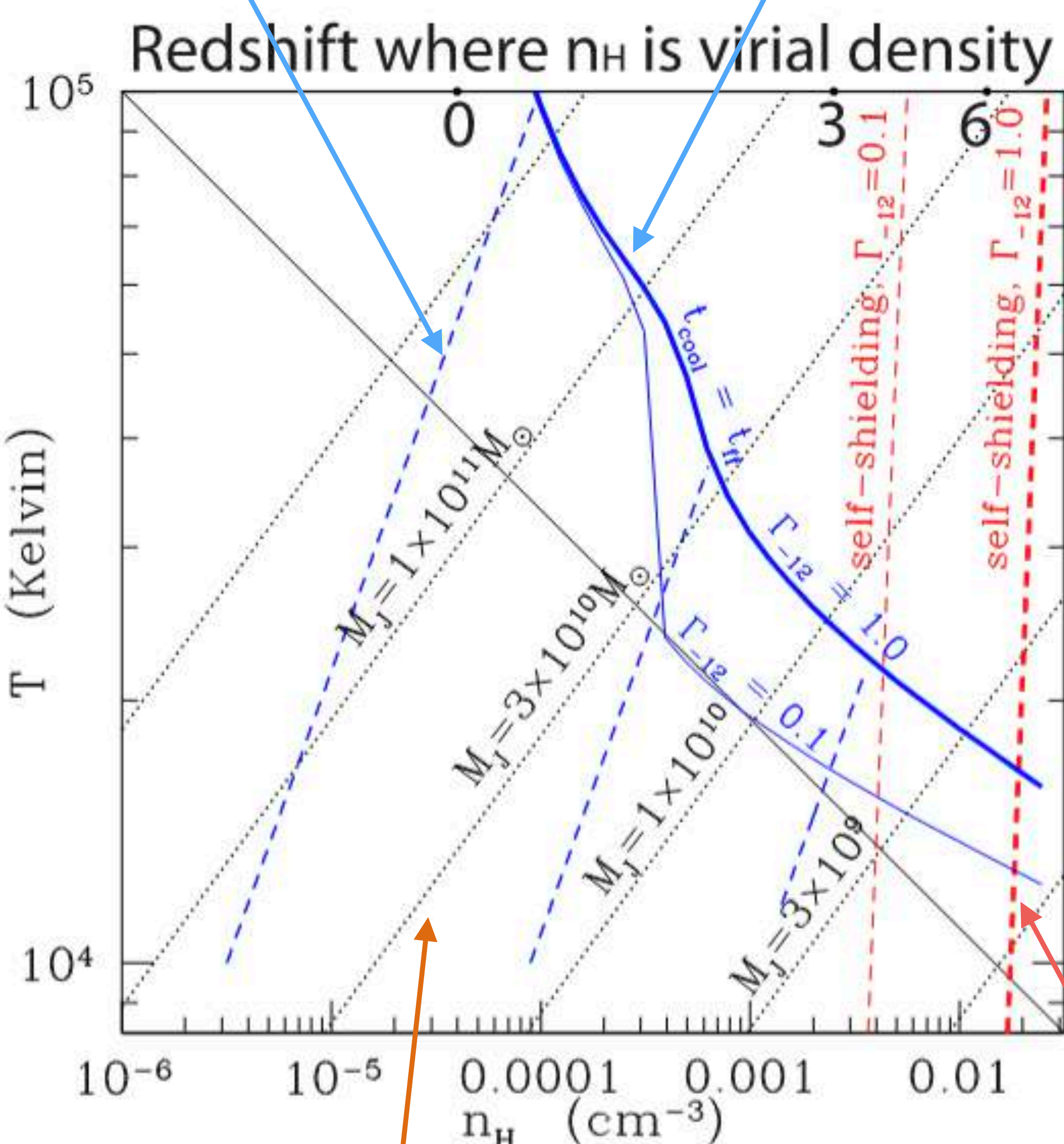
cold gas (filament)
(~ $10^{4-5.5}$ K)

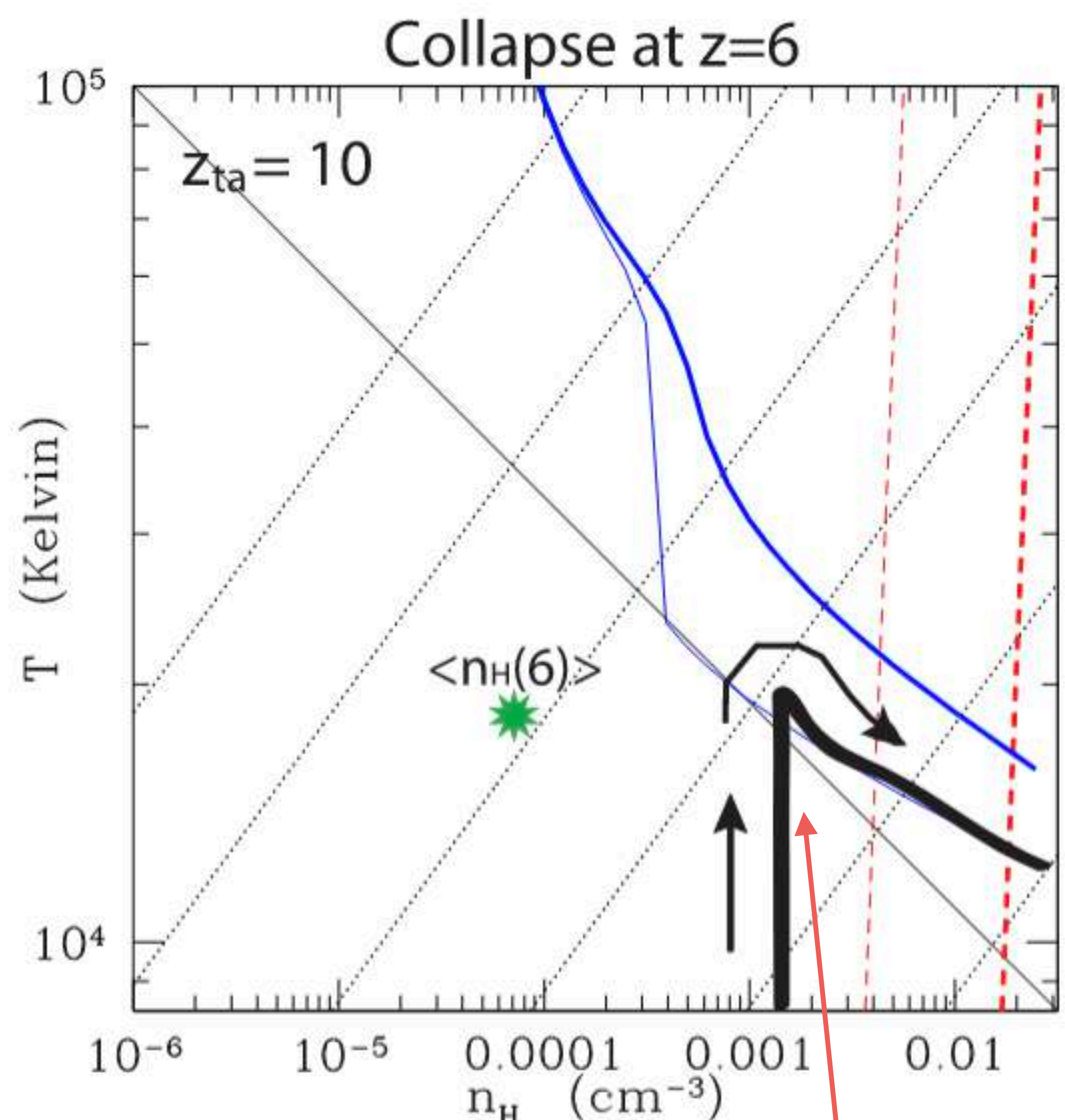
Nakamura, KN+'18

Gas Accretion onto Halos

adiabat ($T \propto n_{\mathrm{H}}^{2/3}$)

equilibrium curve





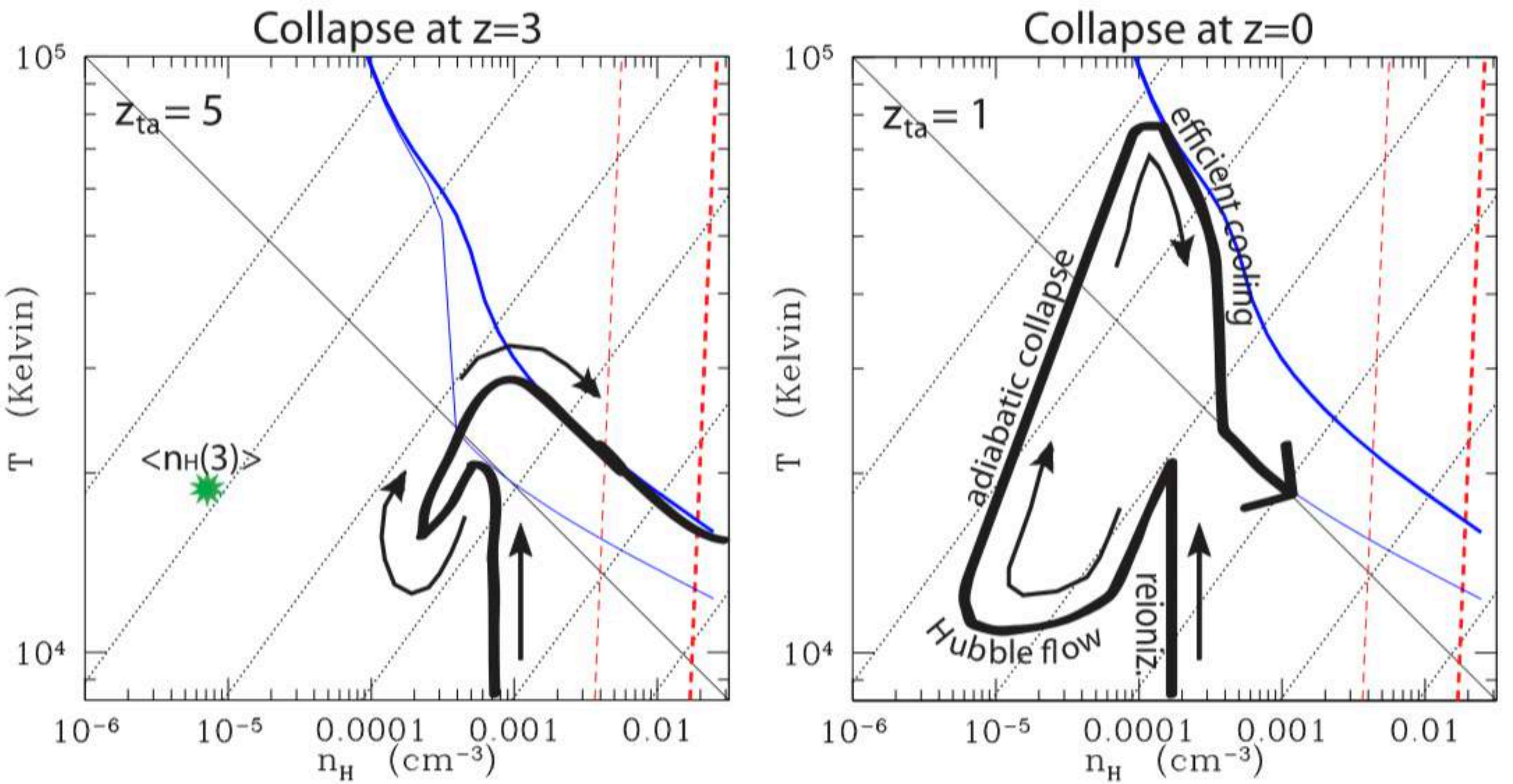
self-shielding threshold

(assuming reionization heating to T=2e4 K @ z=9)

const. Jeans mass

Noh & Mcquinn '14

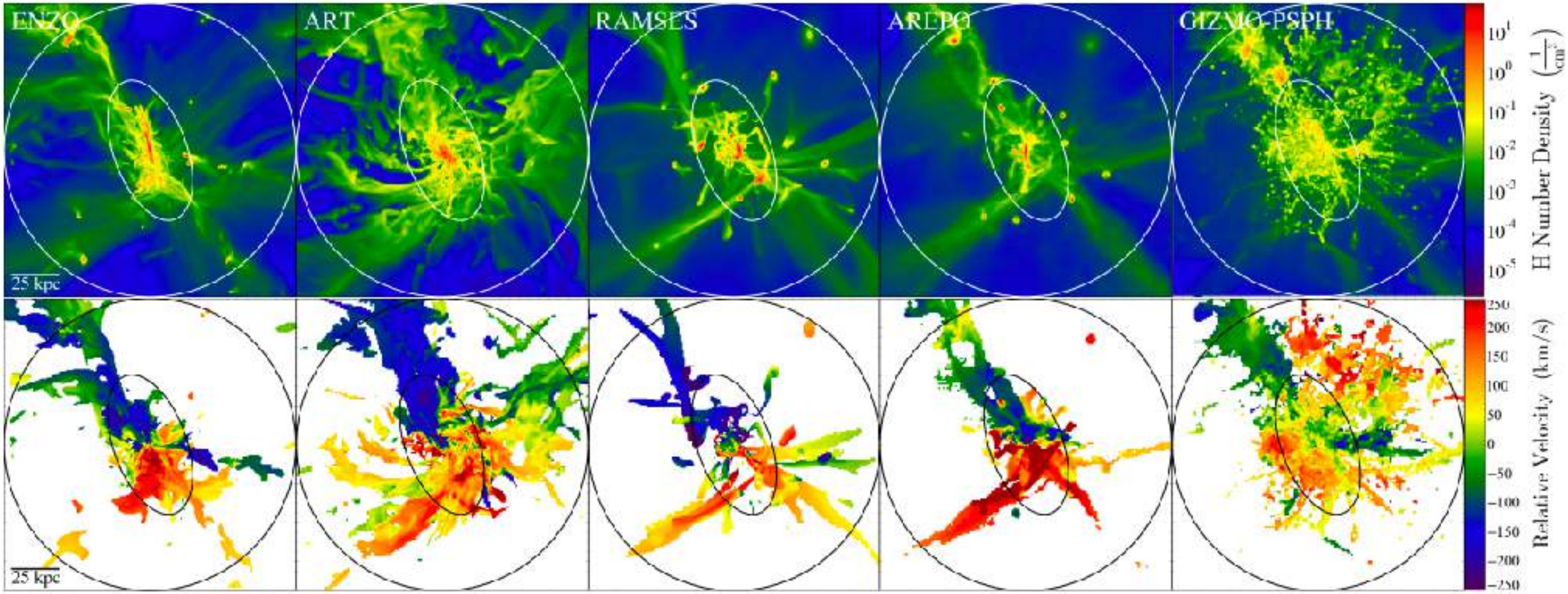
Gas Accretion onto Halos



Noh & Mcquinn ‘14

“Cold Flow Disk”

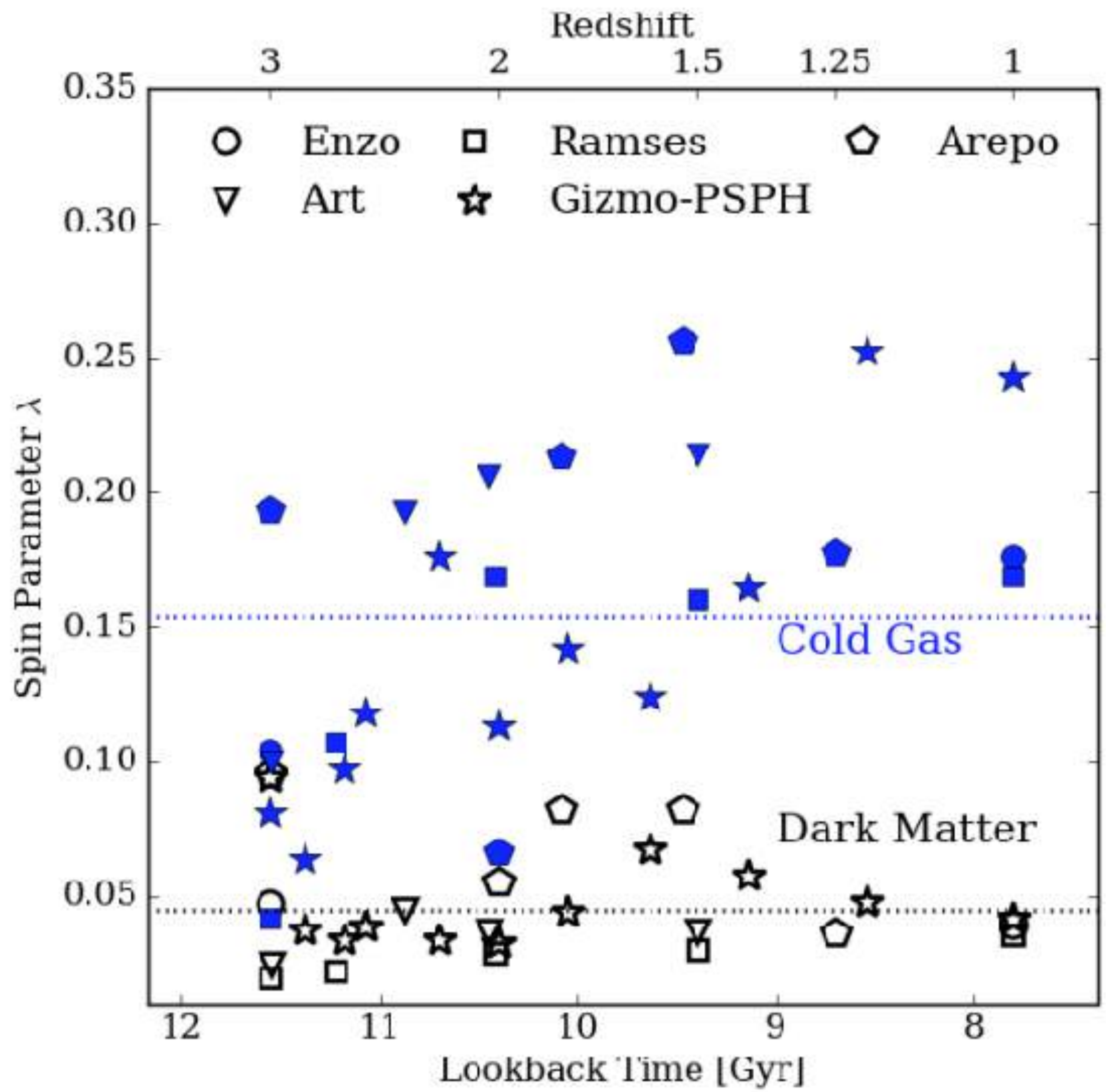
z~3



Extended, flattened rotating structures of high–*J* material.

Stewart+’17

Cold gas in halos have 4x J than dark matter



spin param.

$\lambda_x \equiv j_x / 2V R$

$\boxed{\lambda_{cold} \simeq 0.15}$

$\lambda_{DM} \simeq 0.04$

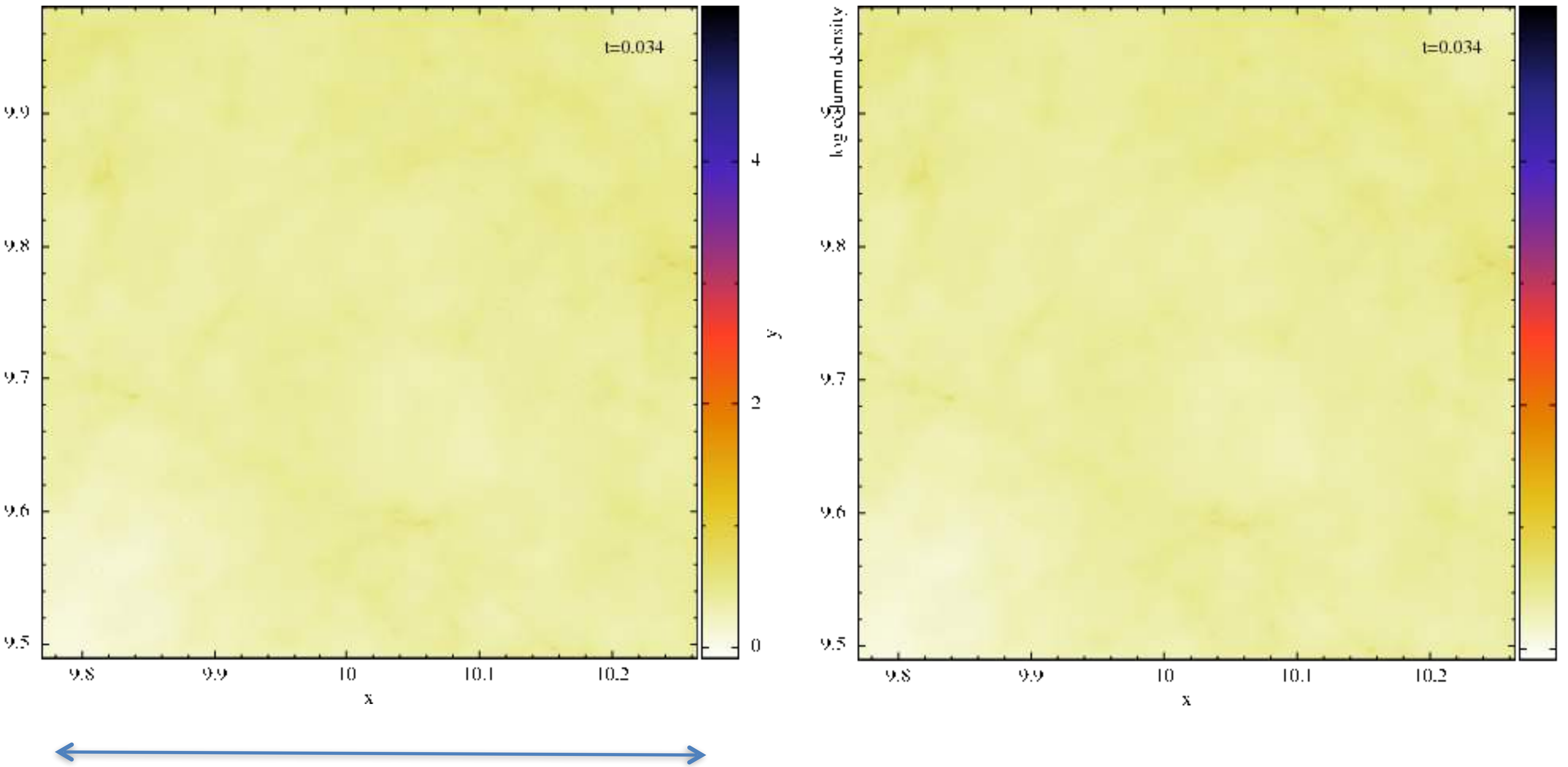
Stewart+'17

Impact of SN feedback on Gas

zoom-in sim: from z=20 to 6, resol. ~ 30 pc @ z~6

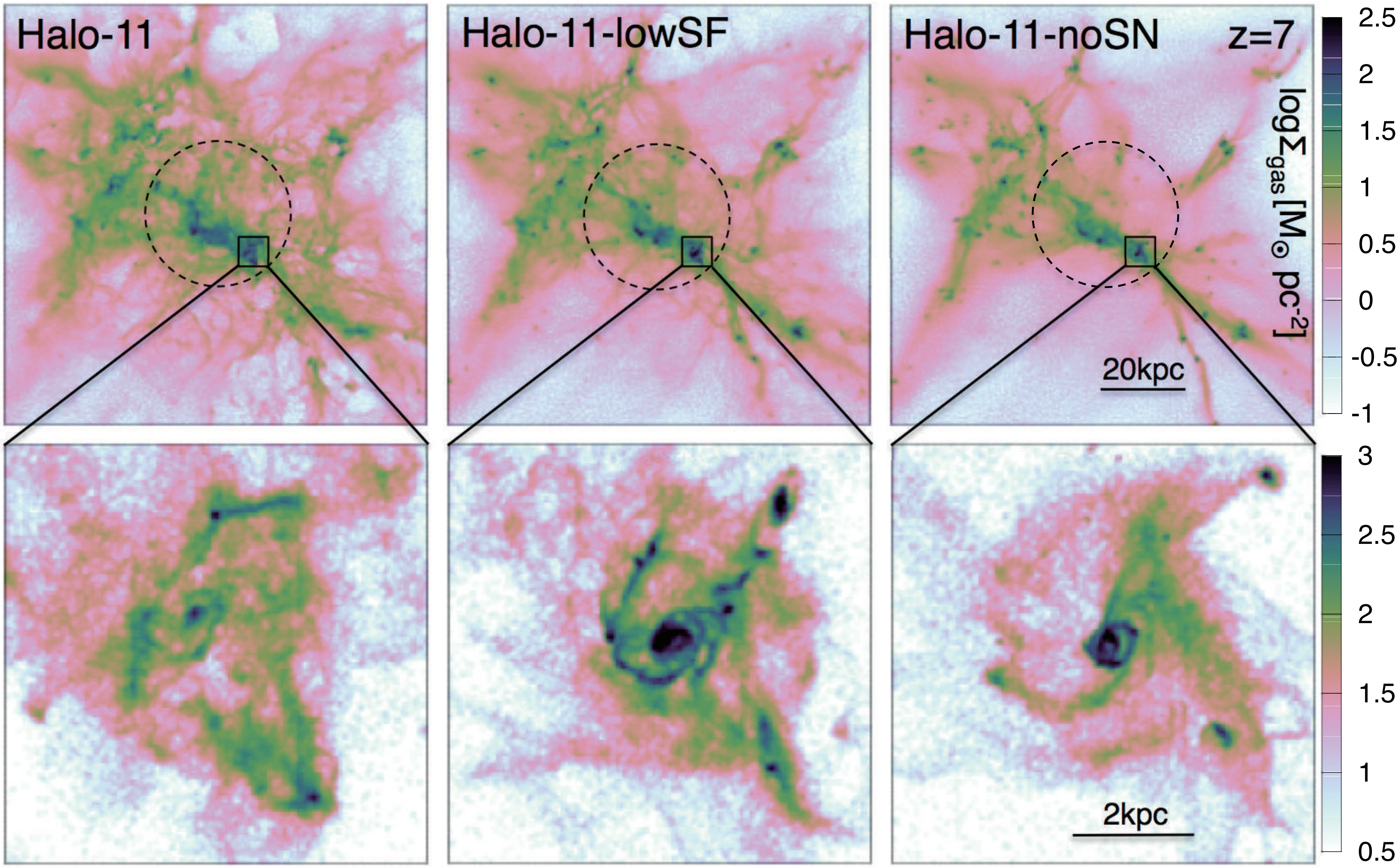
No SN feedback

w. SN feedback



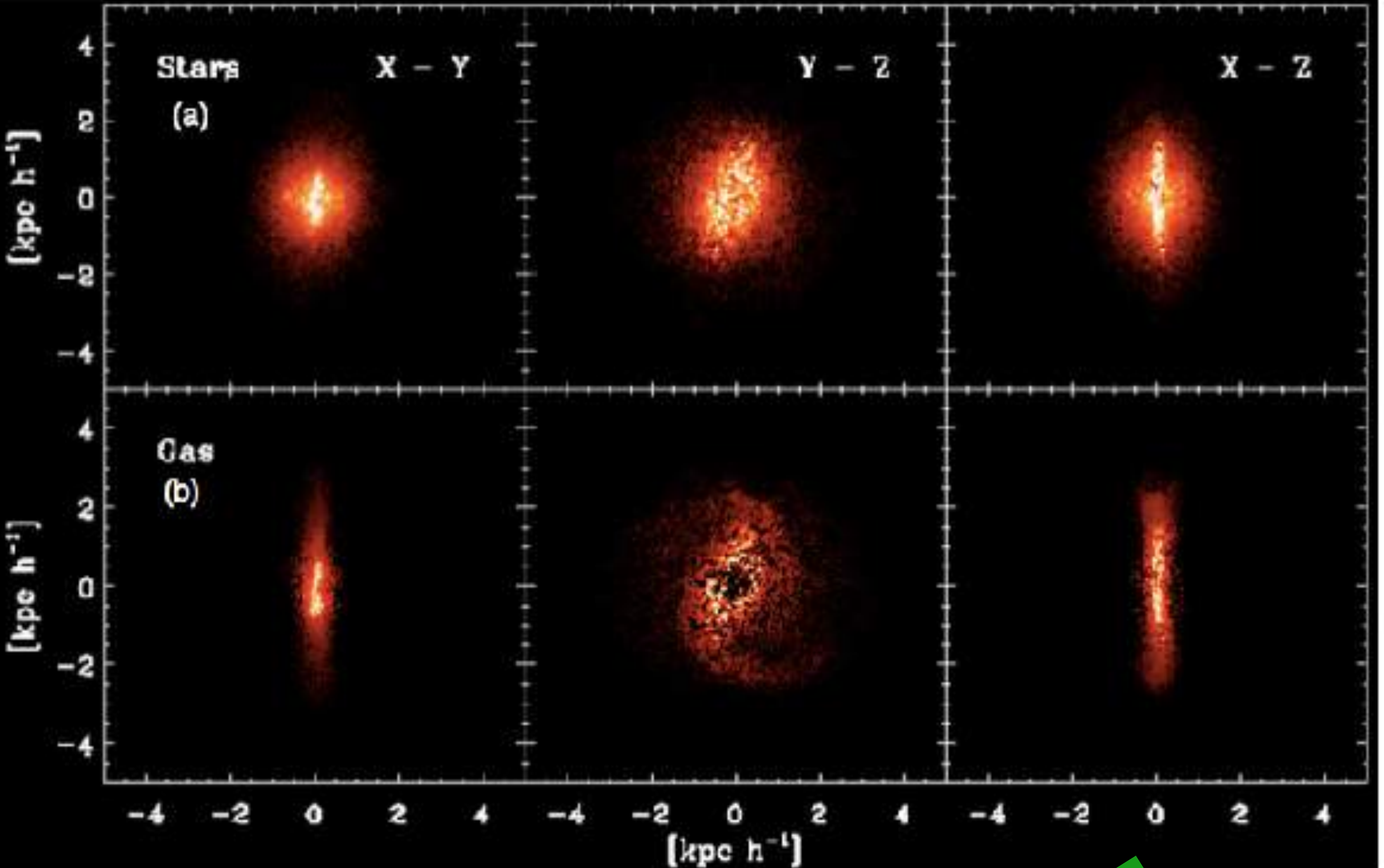
Yajima, KN+ '17

Different morphologies @ z~7 w/ diff. SF & FB models



(zoom-in sim)

Yajima, KN+ '17



z=10.2

Romano-Diaz+ '11

resolution ~ 30 pc (proper), 300 c-pc

Massive disk gal @ z~10

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

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

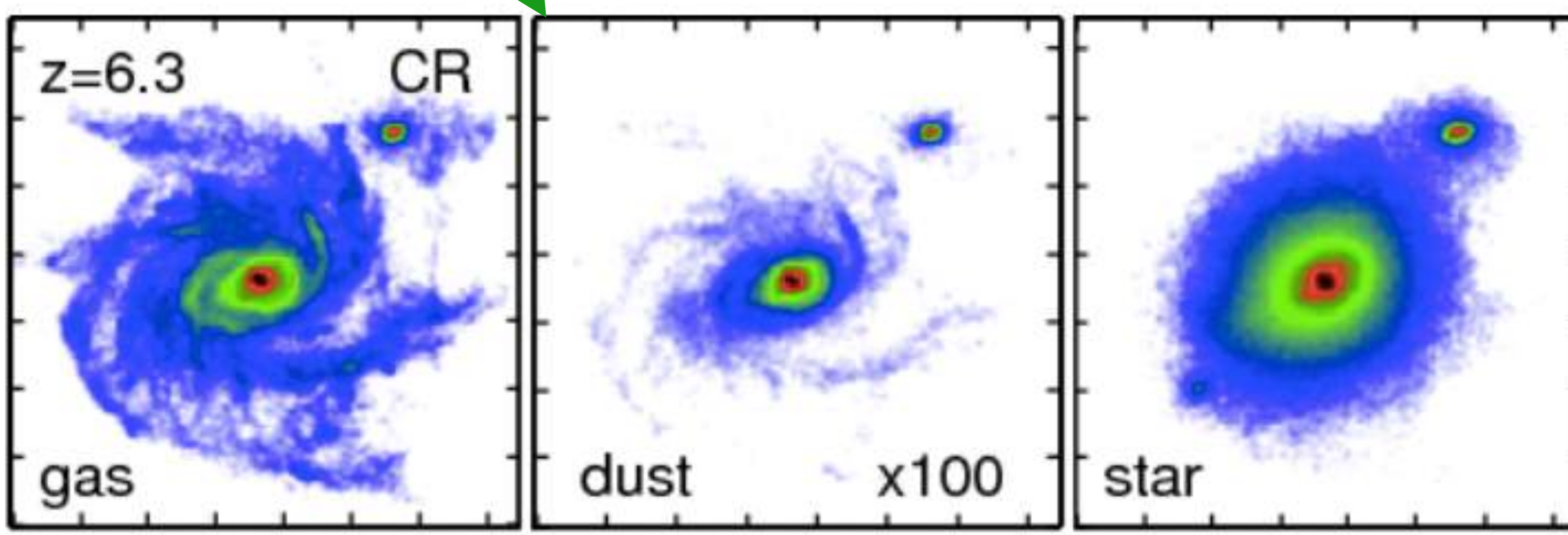
$M_{star,disk} \sim 8 \times 10^{8}\ h^{-1}\ M_\odot$

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

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

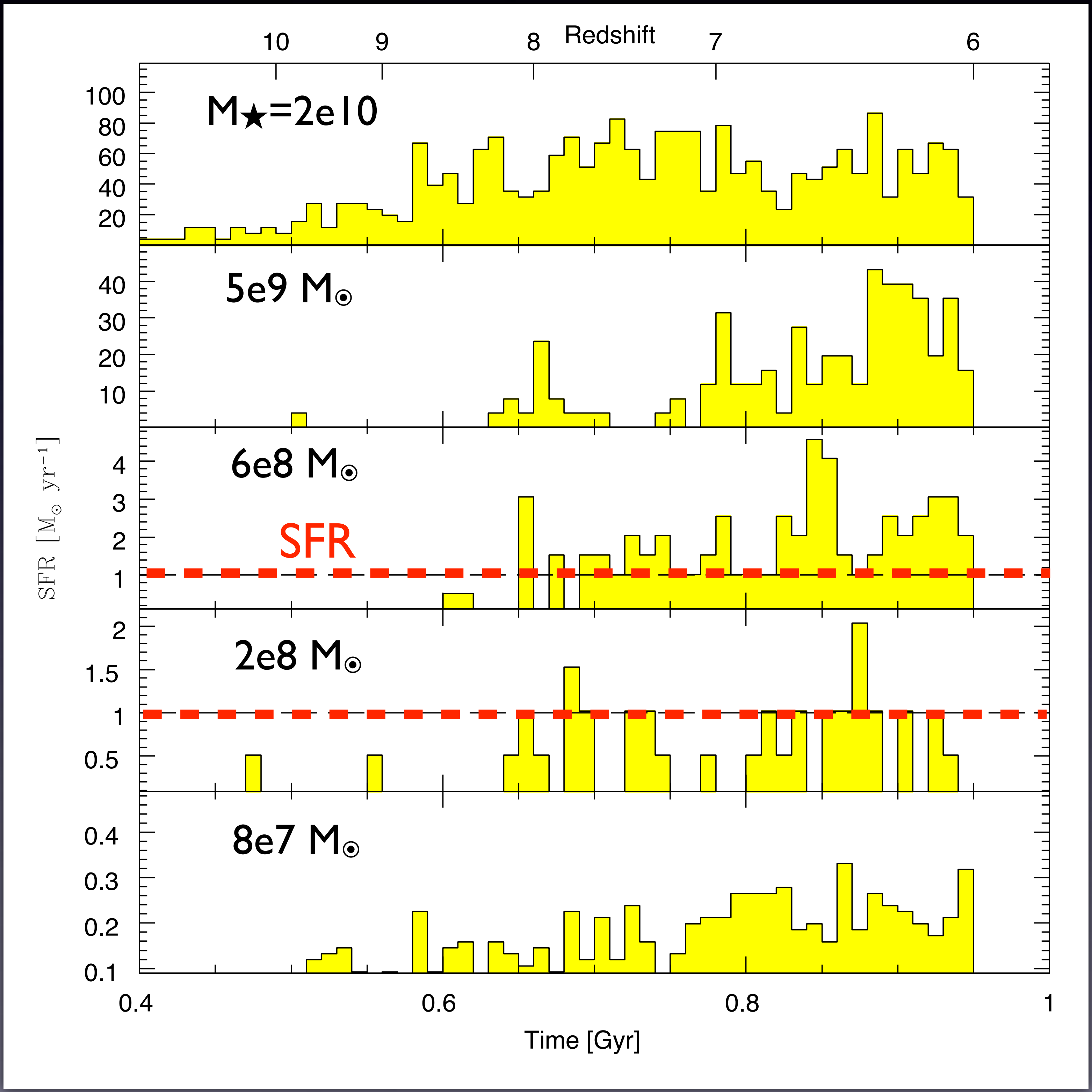
z=6.3

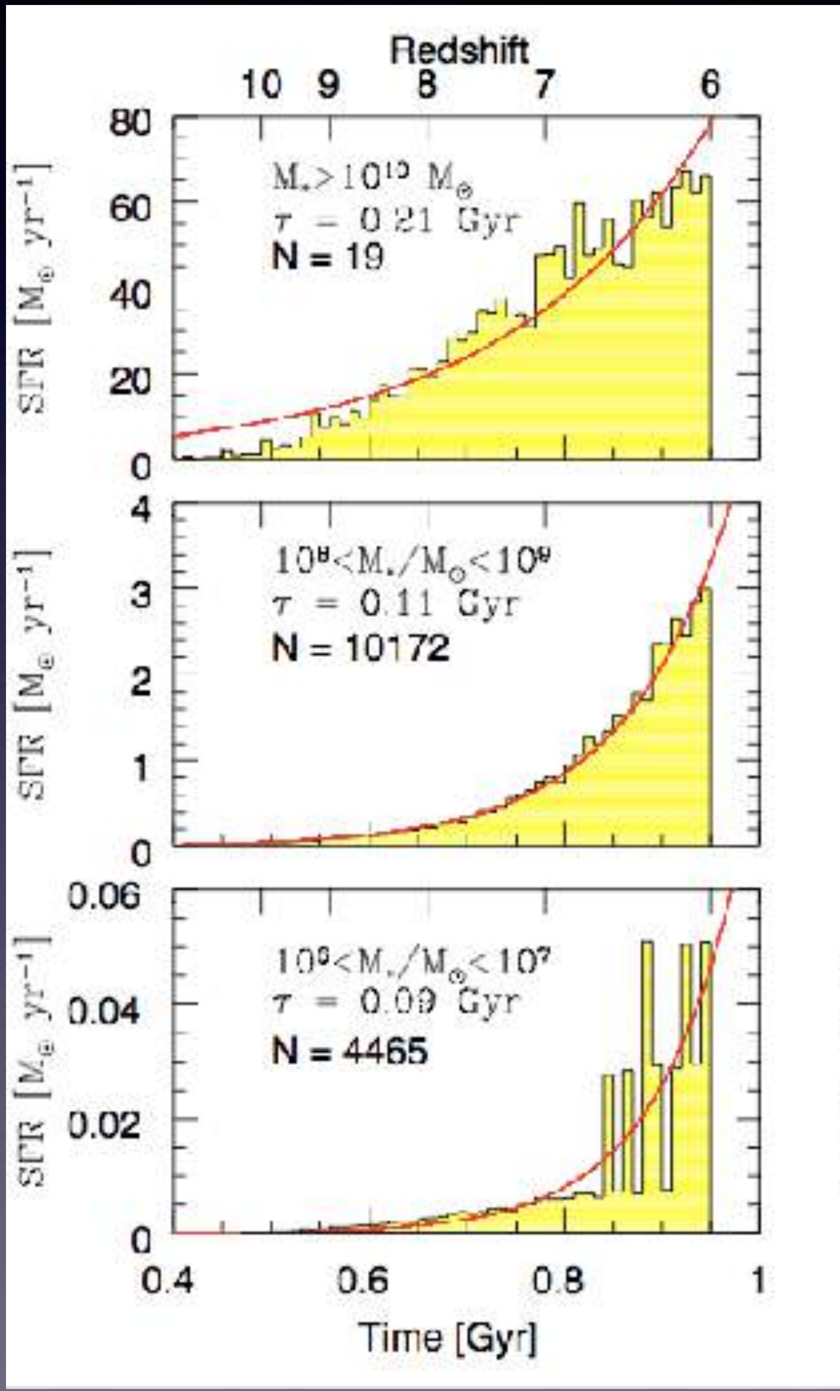
Yajima+ '15



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

Merger or Smooth Accretion?

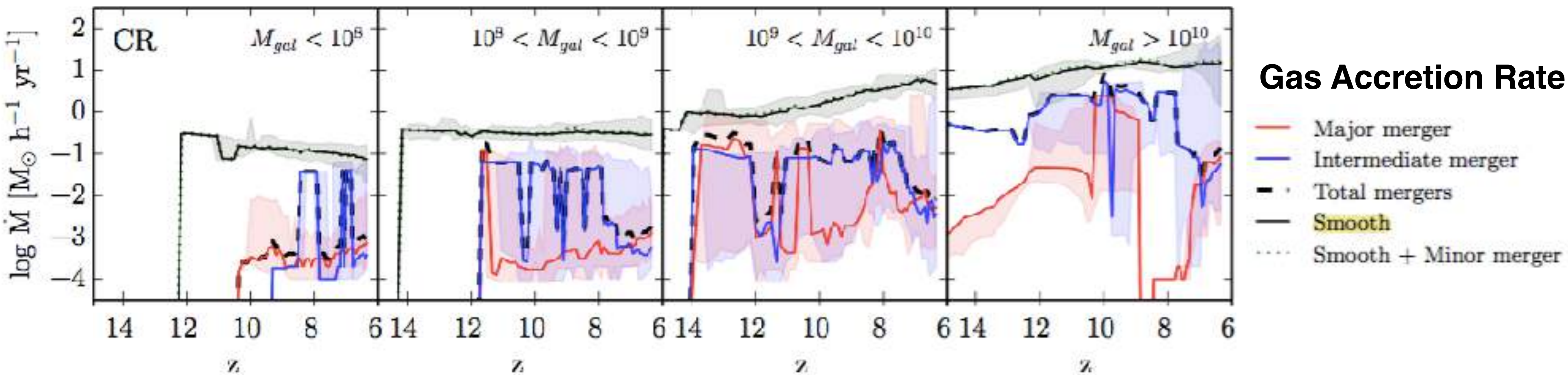


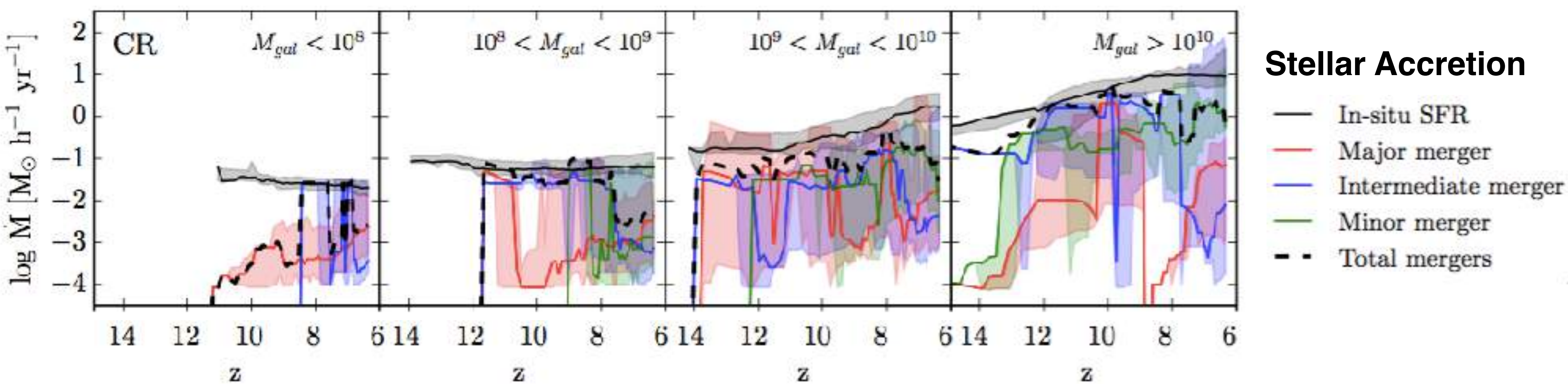


Jaacks, Choi & KN, 12b

Accretion vs. Merger?

Romano-Diaz+ '14

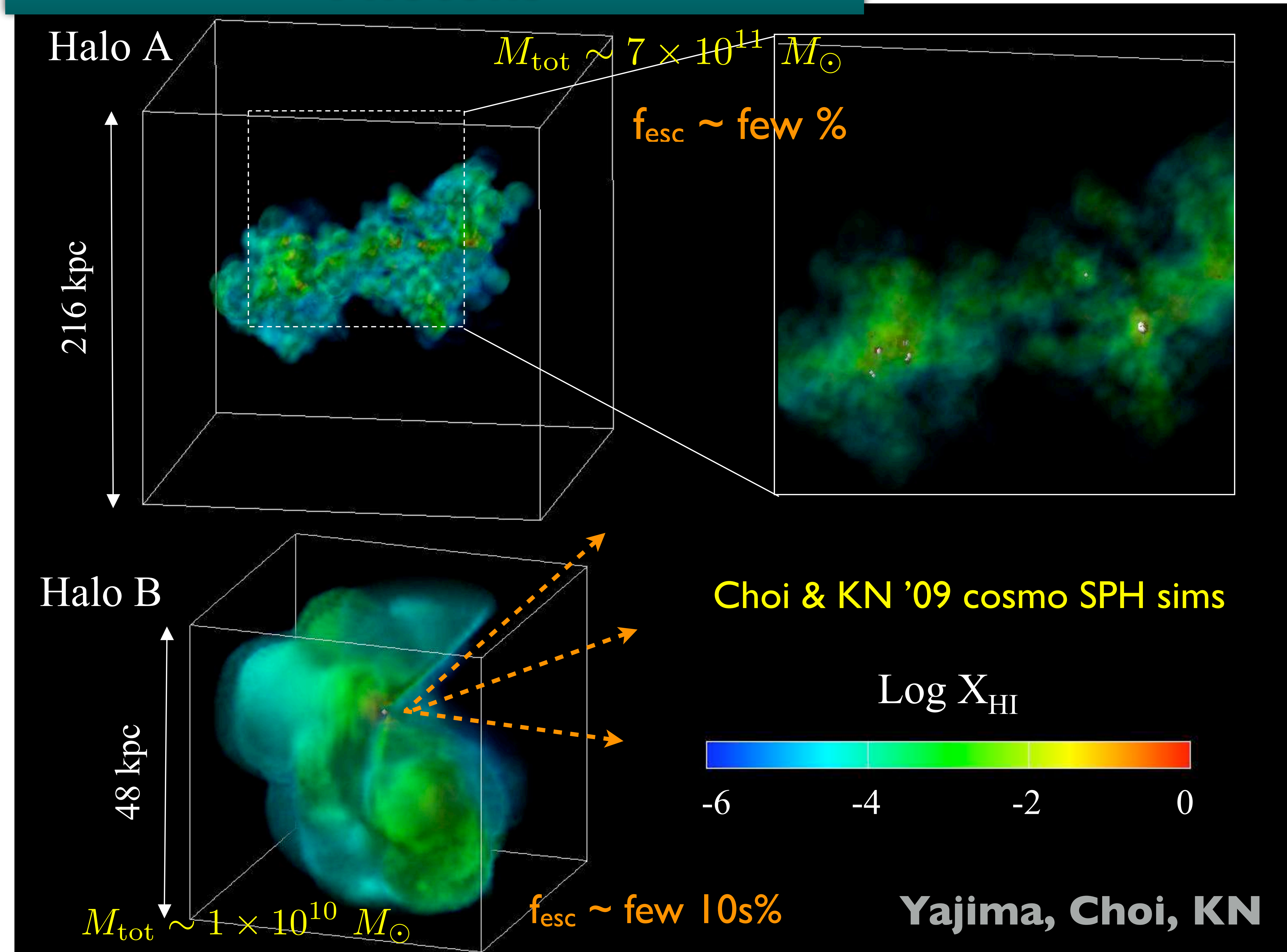




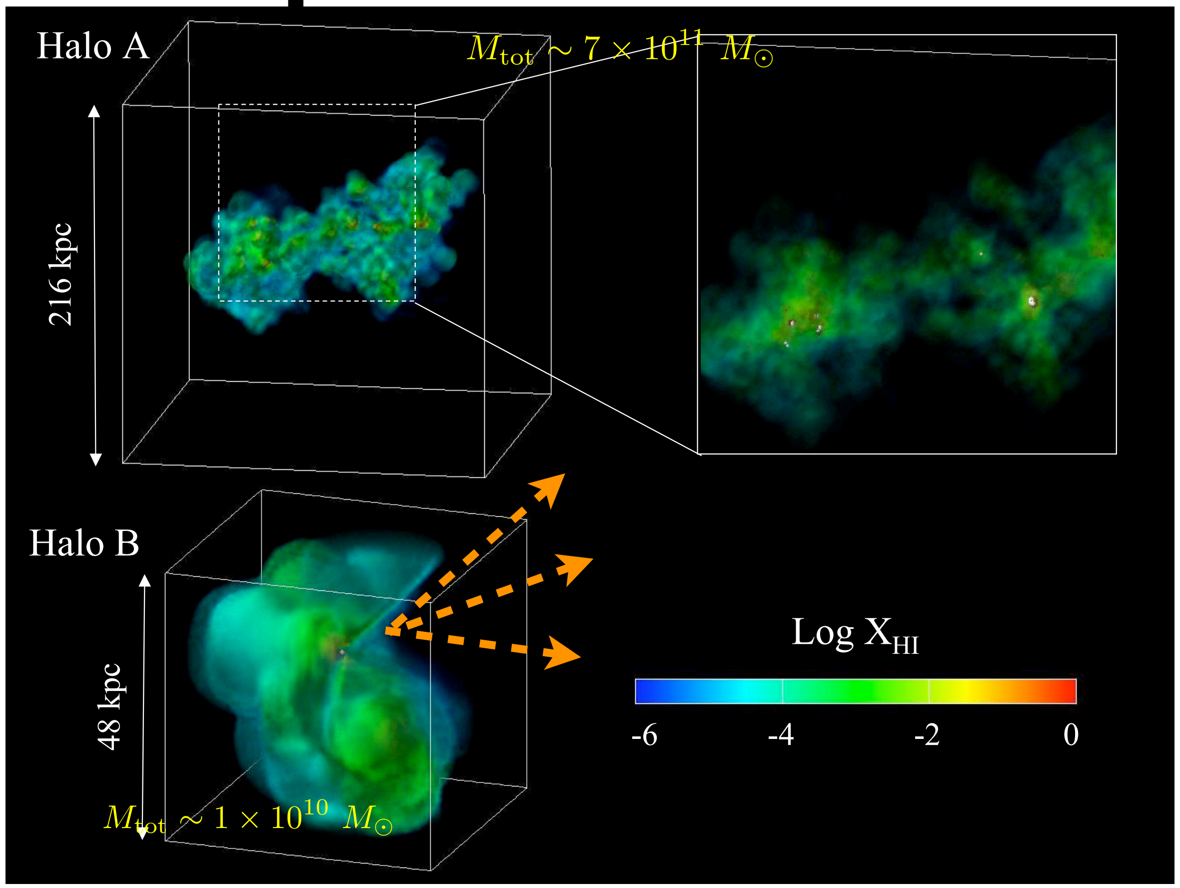
Smooth gas accretion & In Situ SFR >> Mergers

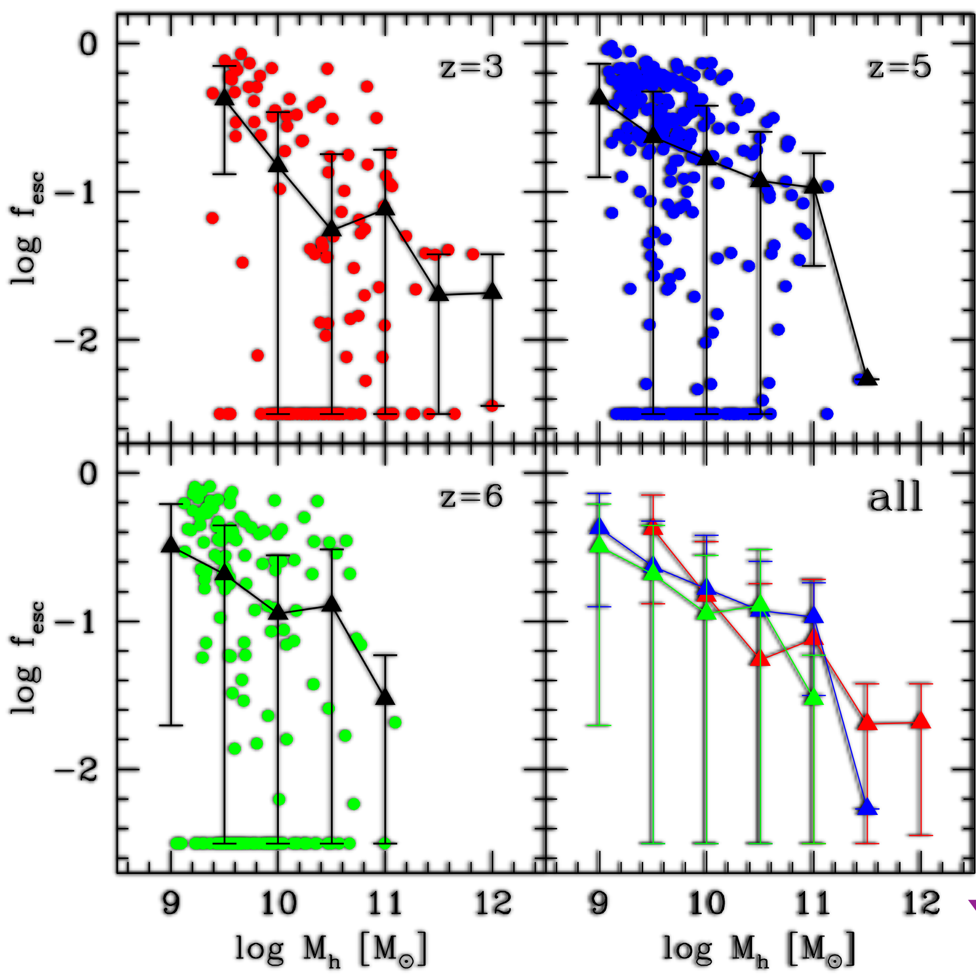
Escape Fraction of Ionizing Photons

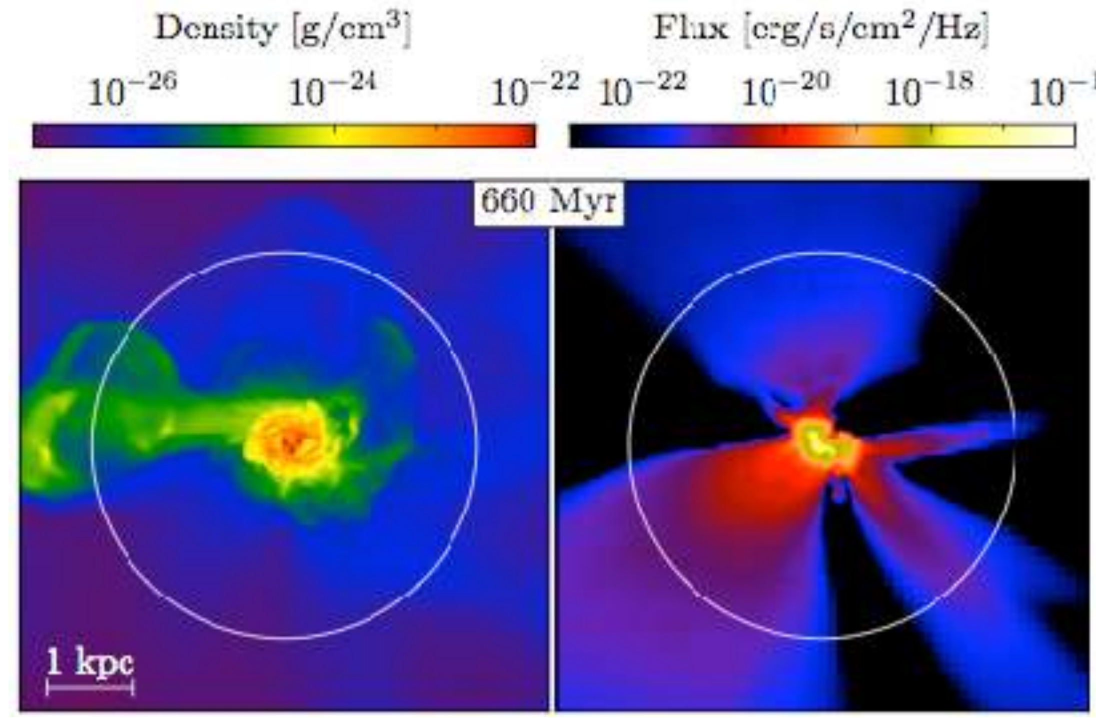
Authentic Ray Tracing method
(Nakamoto+ ’01, Illiev+ ’06, Yajima+ ’09)

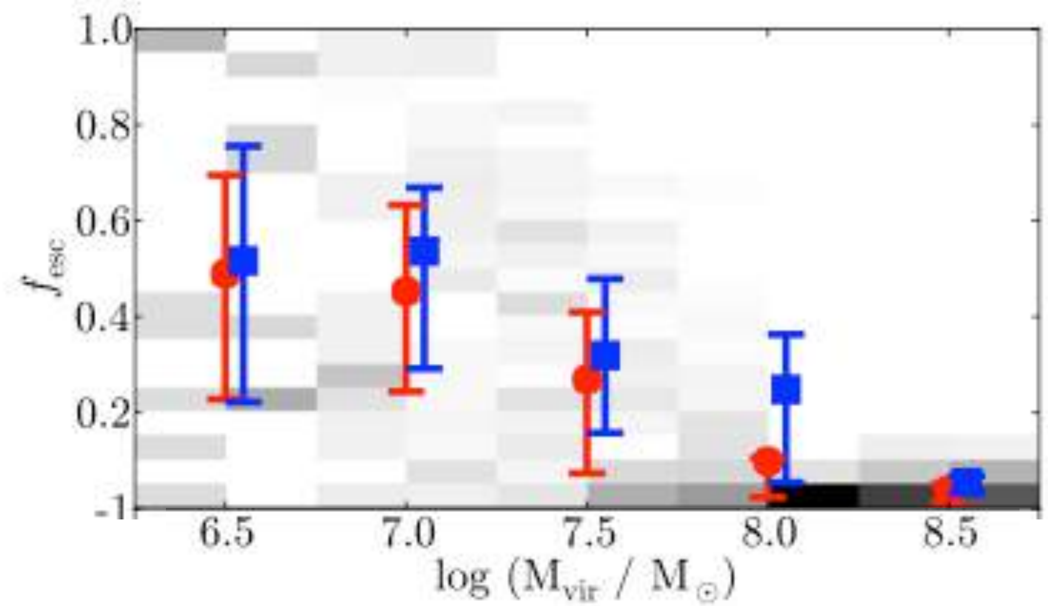


Escape Fraction of Ionizing Photons







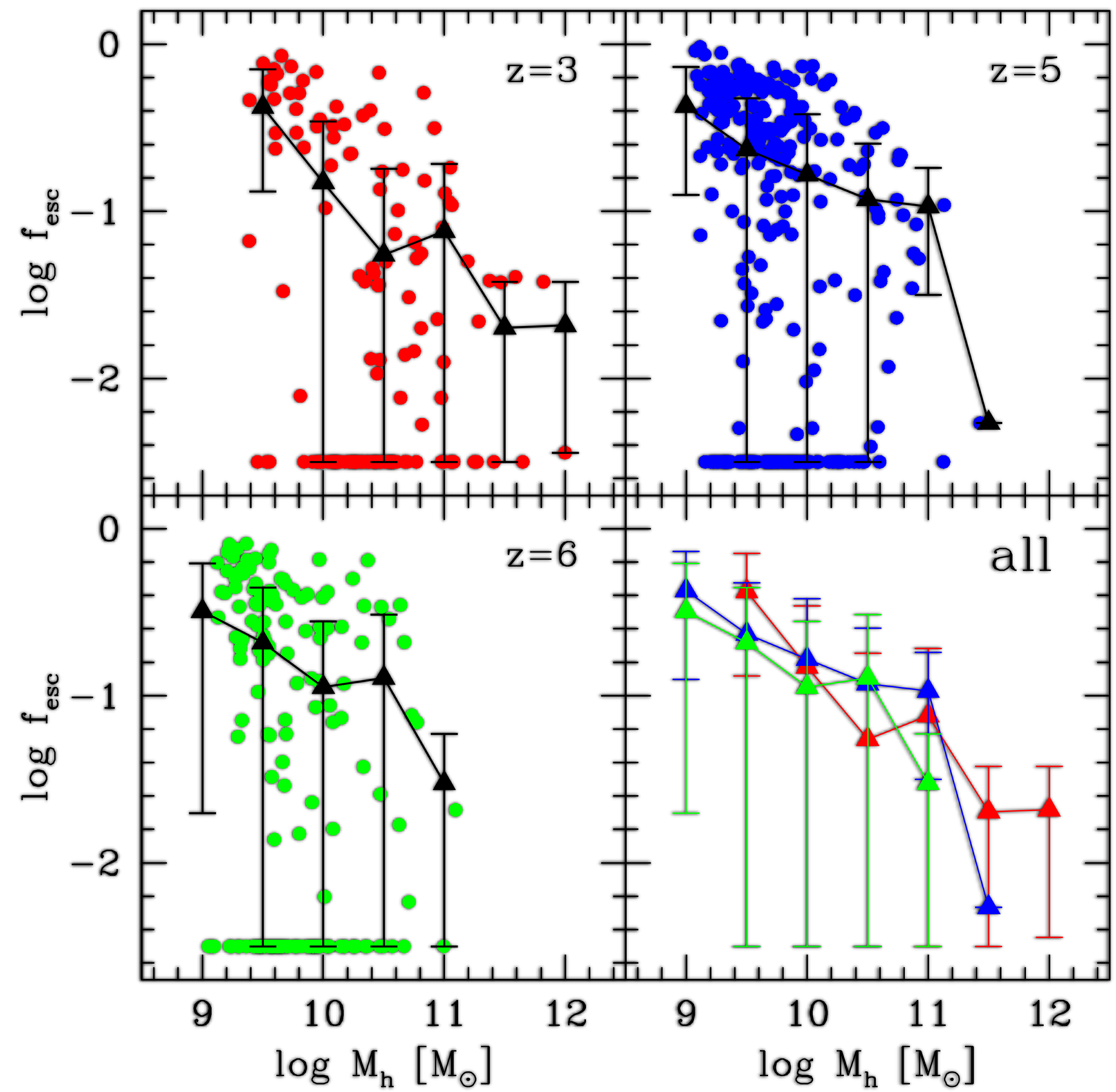


Wise+ '14

Yajima, Choi, KN '11

f_{esc} as a func of M_{halo} & redshift

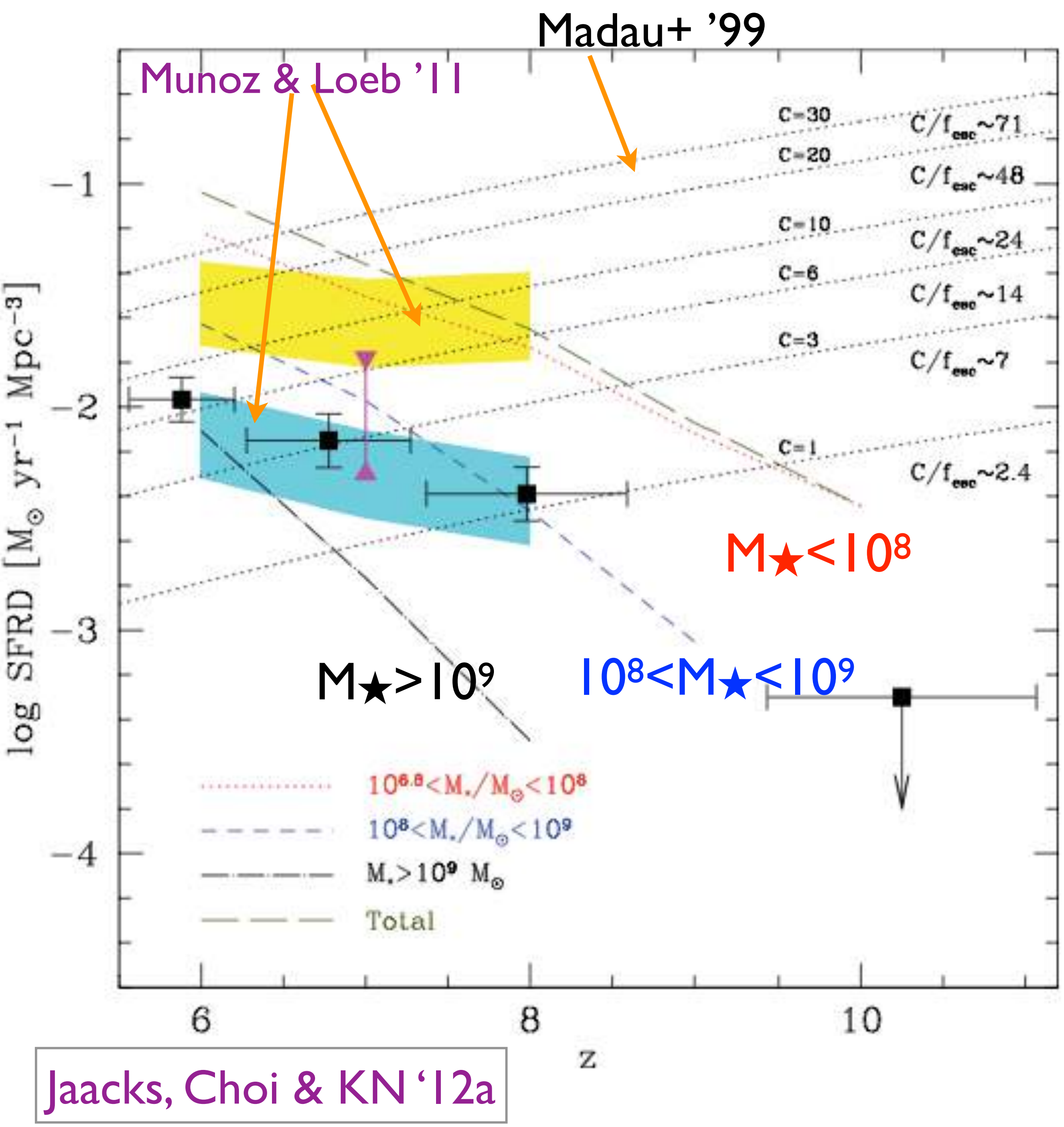
- **Decreasing f_{esc} as a func of M_{halo}** --- roughly consistent with Razoumov+'09; but somewhat different from Gnedin+'09, Wise & Cen '09
- Universe can be reionized by the star-forming galaxies at z=6 if C≤10.
- High f_{esc} for low-mass gals helps.

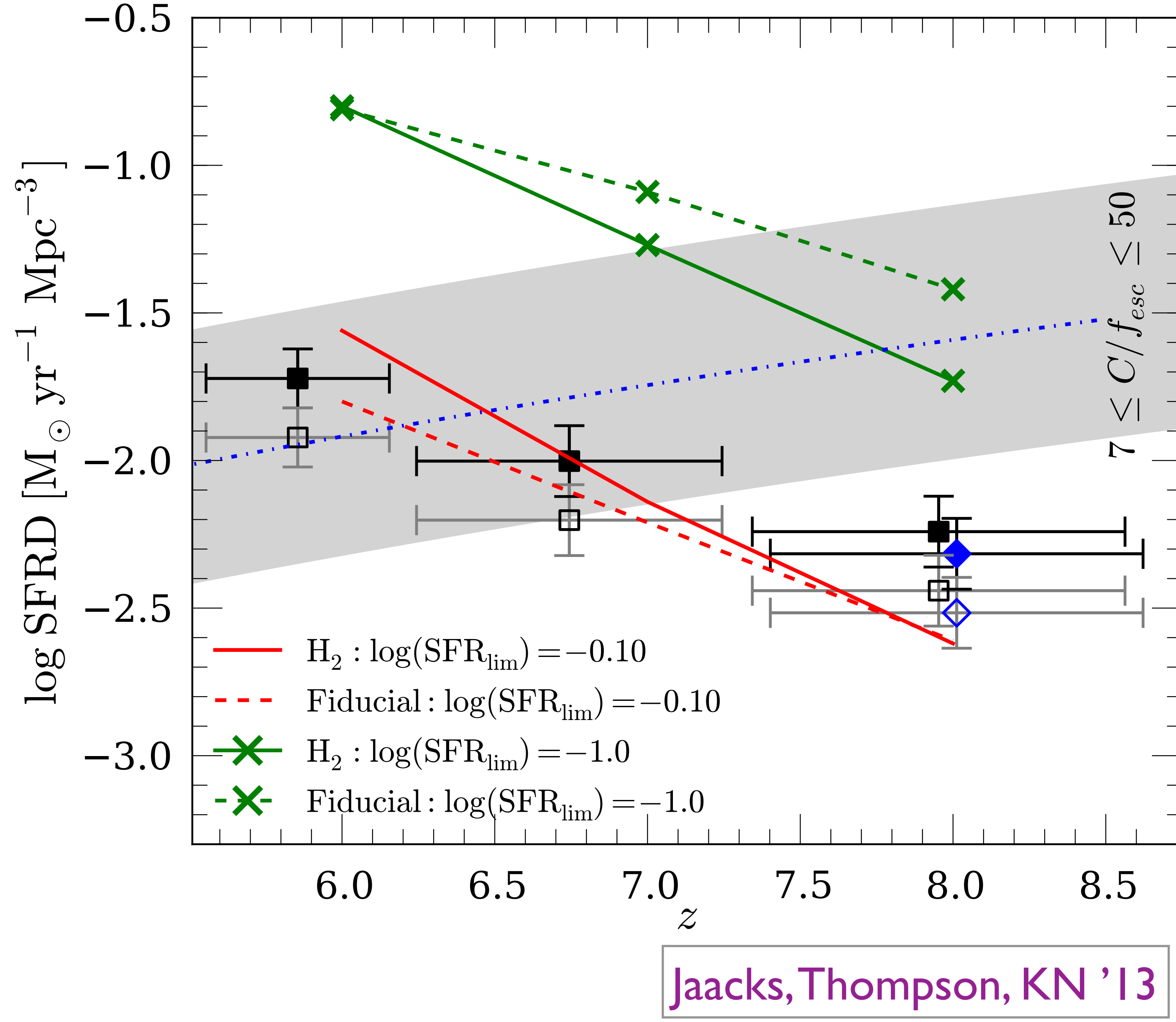


(cf. Gnedin+, Paardekooper+, Razoumov+, Wise&Cen)

Yajima, Choi, KN '11

Reionization of the Universe

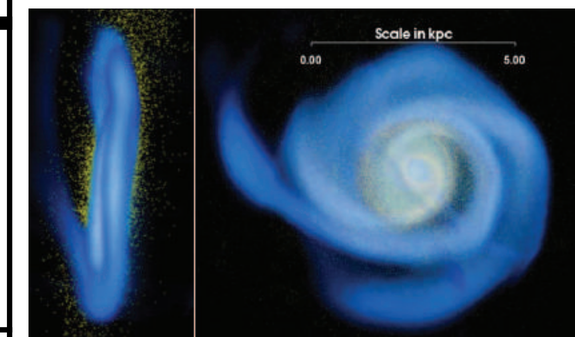


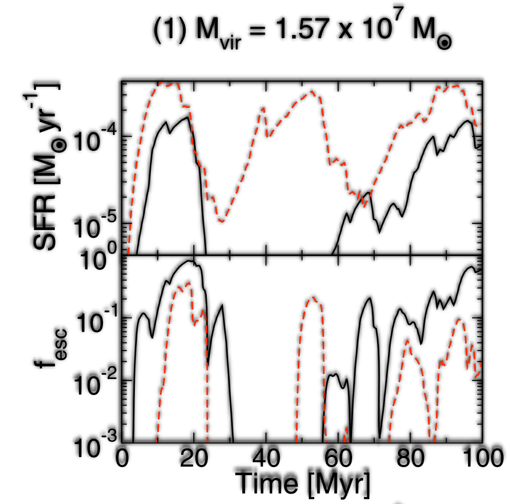


Low mass gals dominate the contrib. to the ionizing photons & they can maintain ionization to z~6

Escape Fraction of Ionizing Photons

Authors	$f_{esc,ion}$ (M_{halo})	Method
Gnedin+ '09	Very low 10^{-5}-10^{-1}, ↗ 10^{11}-10^{12} $M_{\odot}$	AMR, 6Mpc box, 65pc res, OTVET, z=3
Razoumov+'09	1.0-0.0, ↘ 10^{8}-$10^{11}$$M_{\odot}$	SPH, 6Mpc box, ~0.5kpc res, resim 9 gals, z=4-10
Wise & Cen +'09	Large scatter & time evol. 0-0.4, → 10^{6}-$10^{9}$$M_{\odot}$	AMR, 2 & 8Mpc box, 0.1pc res, z=8
Yajima+ '09	0-0.5, ↘ with time	Eulerian (Mori & Umemura '06 sim, single system, t=0-1Gyr)
Yajima, Choi, KN '11	1.0-0.0 ↘ 10^{9}-$10^{12}$$M_{\odot}$	SPH, 10Mpc box, ~0.5kpc res, z=3-6 100s of gals.





Emission lines from high-z galaxies

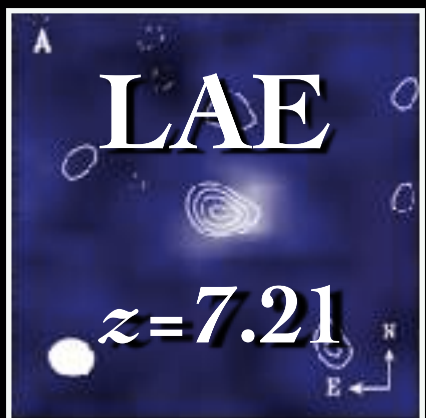
Arata, Yajima, KN+ ’18, 19

Arata, Yajima, KN+ ’19, arXiv:1908.01438

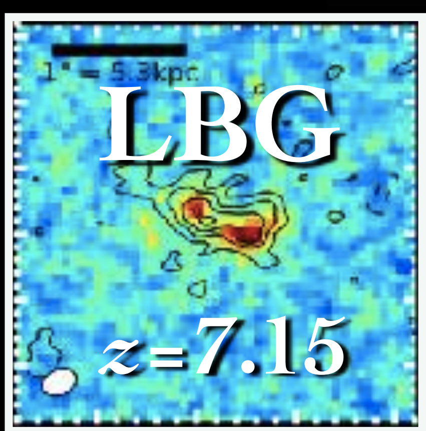
(just posted yesterday!)

(slides from Arata’s IAU presentation)

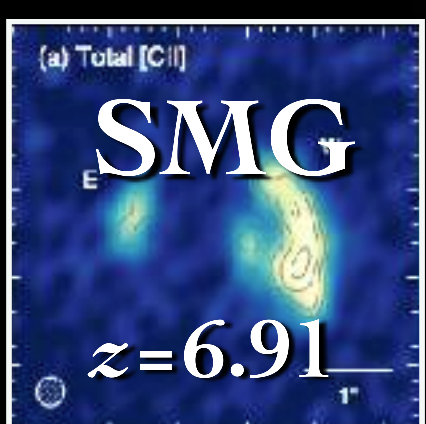
Radiative Properties of the First Galaxies



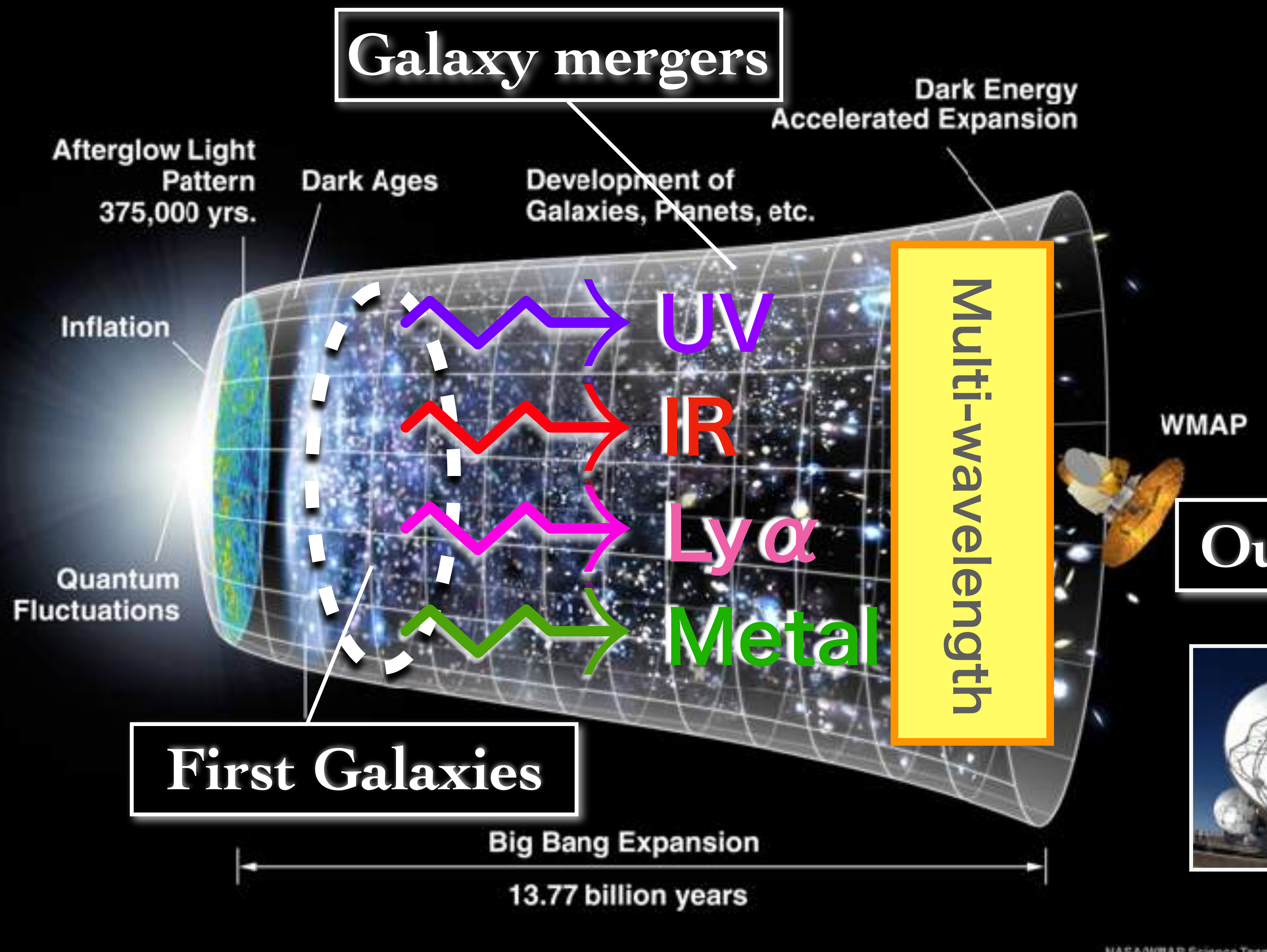
Inoue+16



Hashimoto+18b

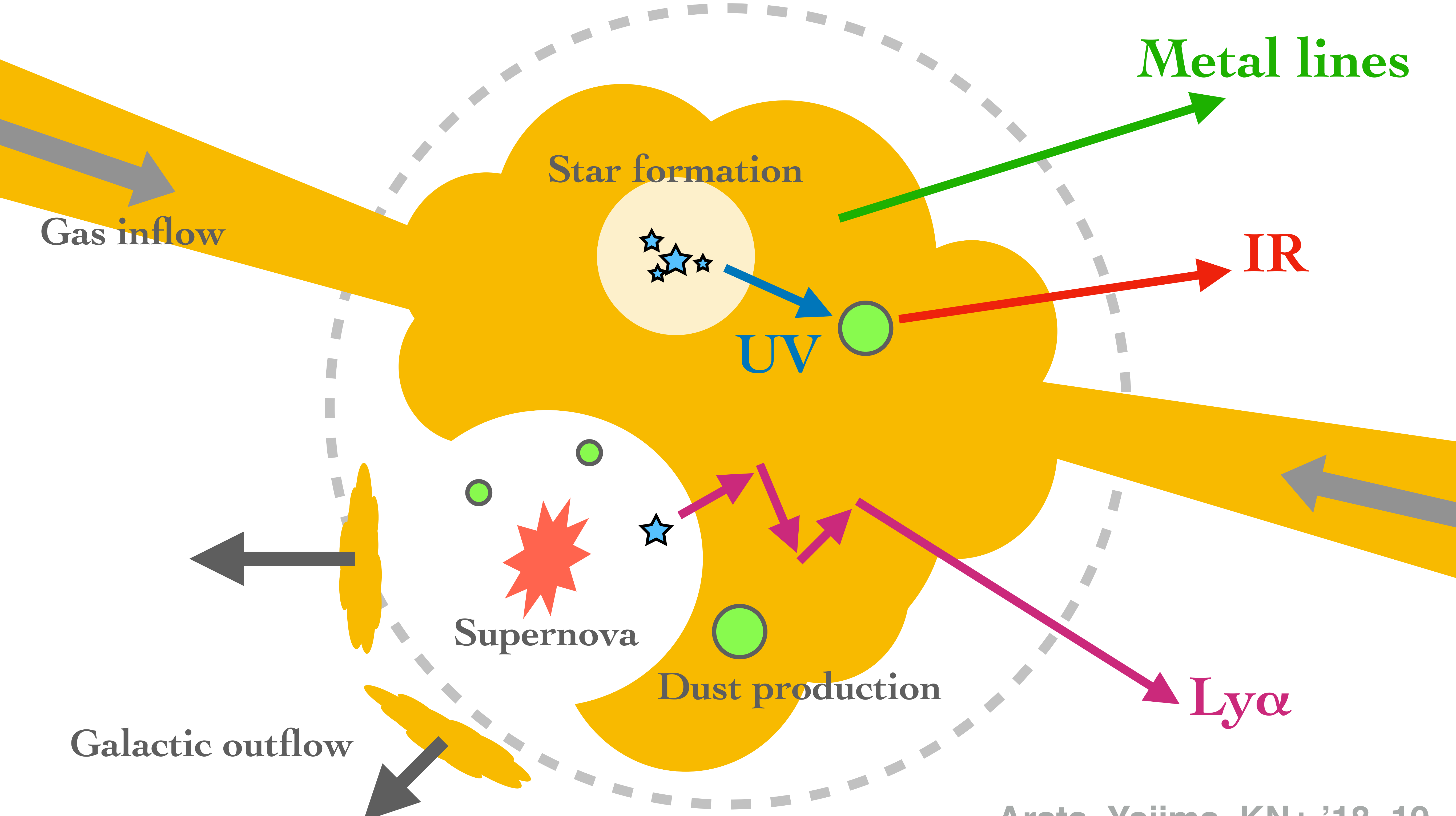


Marrone+18



How does the **wide variety** emerge??

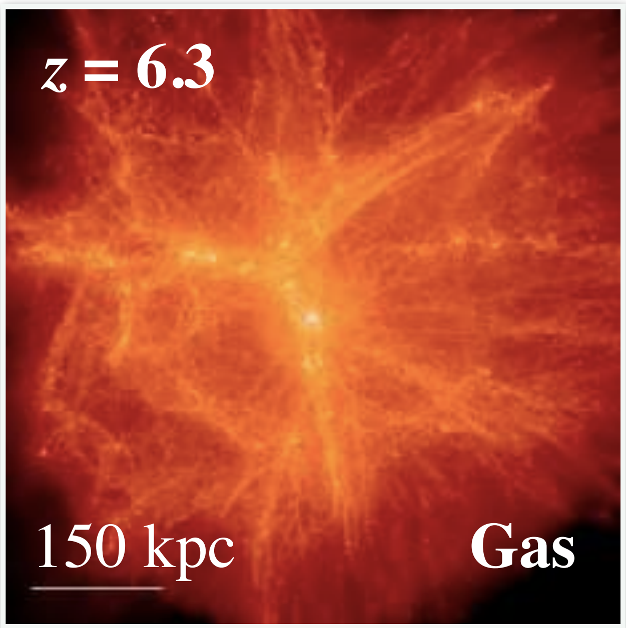
Galaxy Evolution and Radiative Properties



Arata, Yajima, KN+ '18, 19

Previous Works

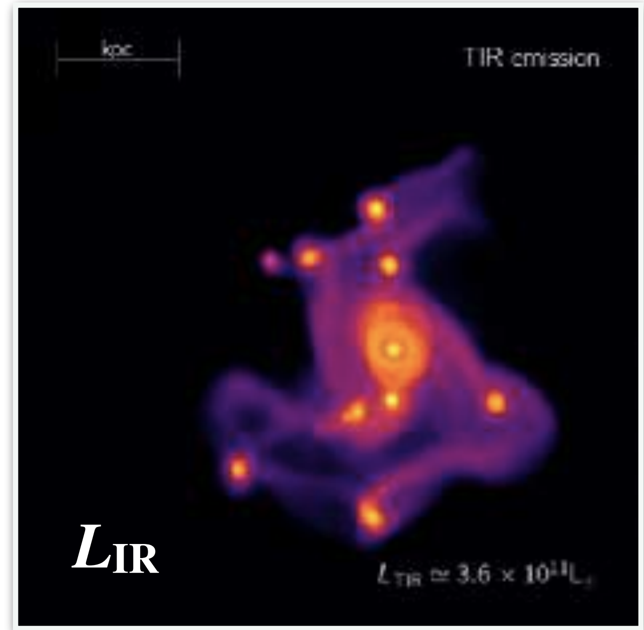
(Cosmological hydro. + Radiative transfer)



Yajima+15

overdense region

UV light is heavily obscured by dust

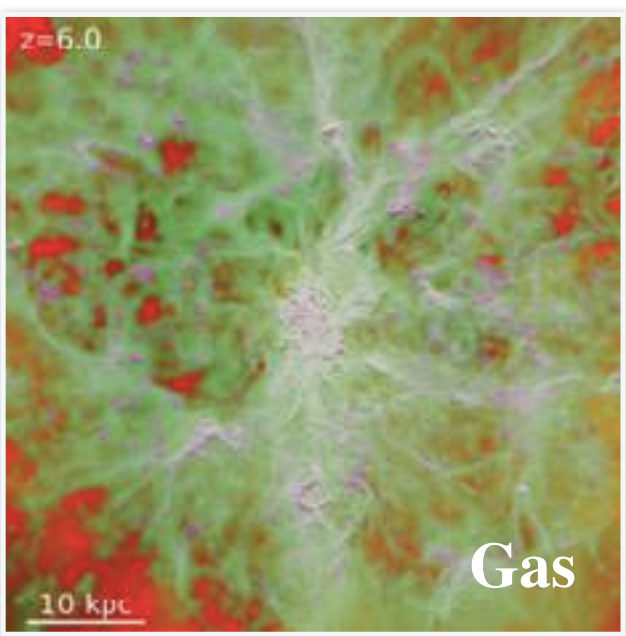


Behrens+18

SMG at z=8.38

(Laporte+17)

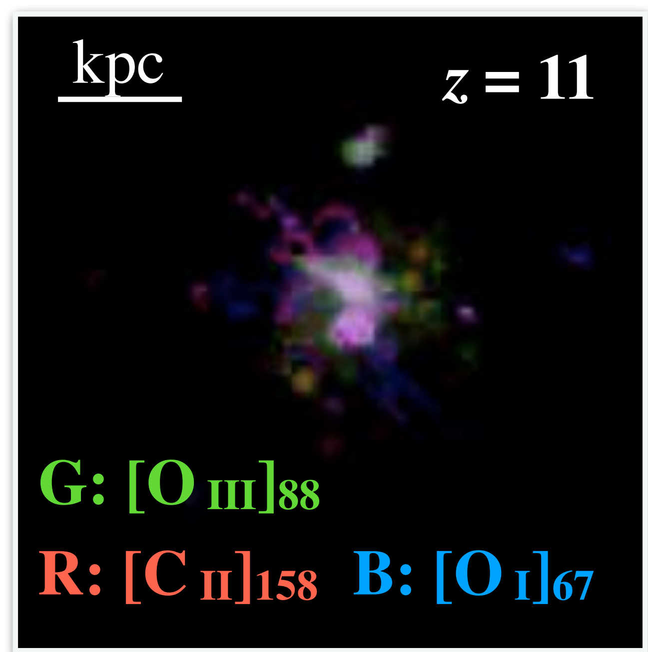
Dust enrichment proceeds rapidly



Ma+15

less massive gals.

Escape fraction of ionizing photons fluctuates



Katz+19

Metal line emitters

Zoom-in sim. can resolve detailed ISM structure

Model & Setup

✦ Cosmological hydrodynamic simulations

code: GADGET-3 developed by *First Billion Years* (FiBY) project (Johnson+13)

z = 6 – 15 Zoom-in method (Yajima+17, Arata+18)

target halo: $M_\mathrm{h} \sim 10^{11}$ Ms (Halo-11), 10^{12} Ms (Halo-12) at z=6

✦ Radiative transfer calculations

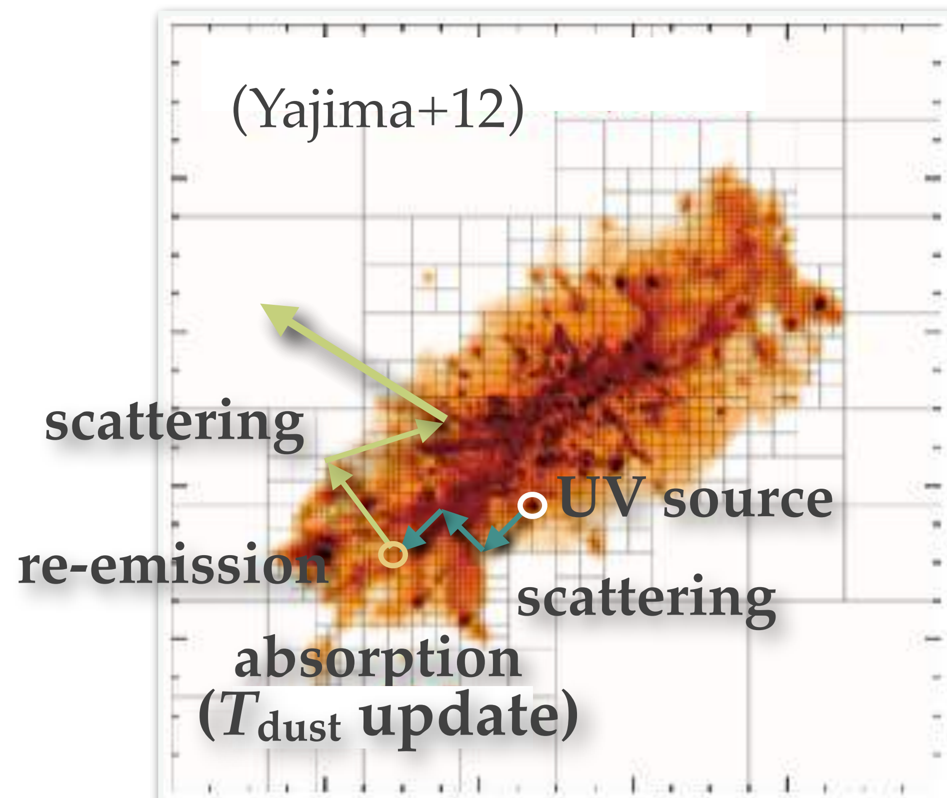
code: ART² (Li+08, Yajima+12)

- Multi-wavelength radiative transfer

  Ionizing / Dust cont. / Lyα / Metal lines

- Adaptive Mesh Refinement (AMR)

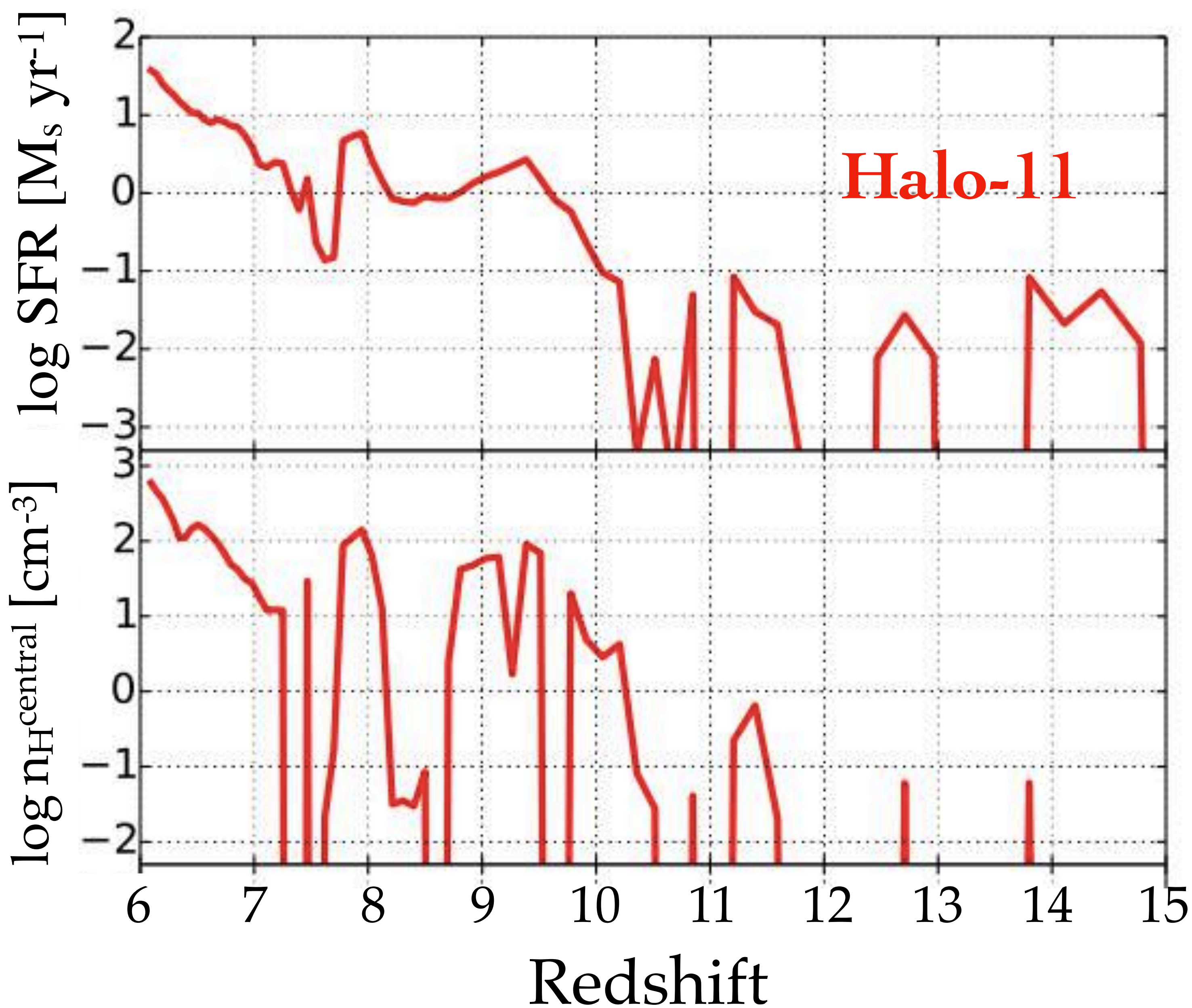
  Dust mass in a cell: $m_\mathrm{d} \approx x_\mathrm{c} \rho_\mathrm{c} V \mathcal{D}_{0.01} \left(\frac{Z}{Z_\odot}\right)$



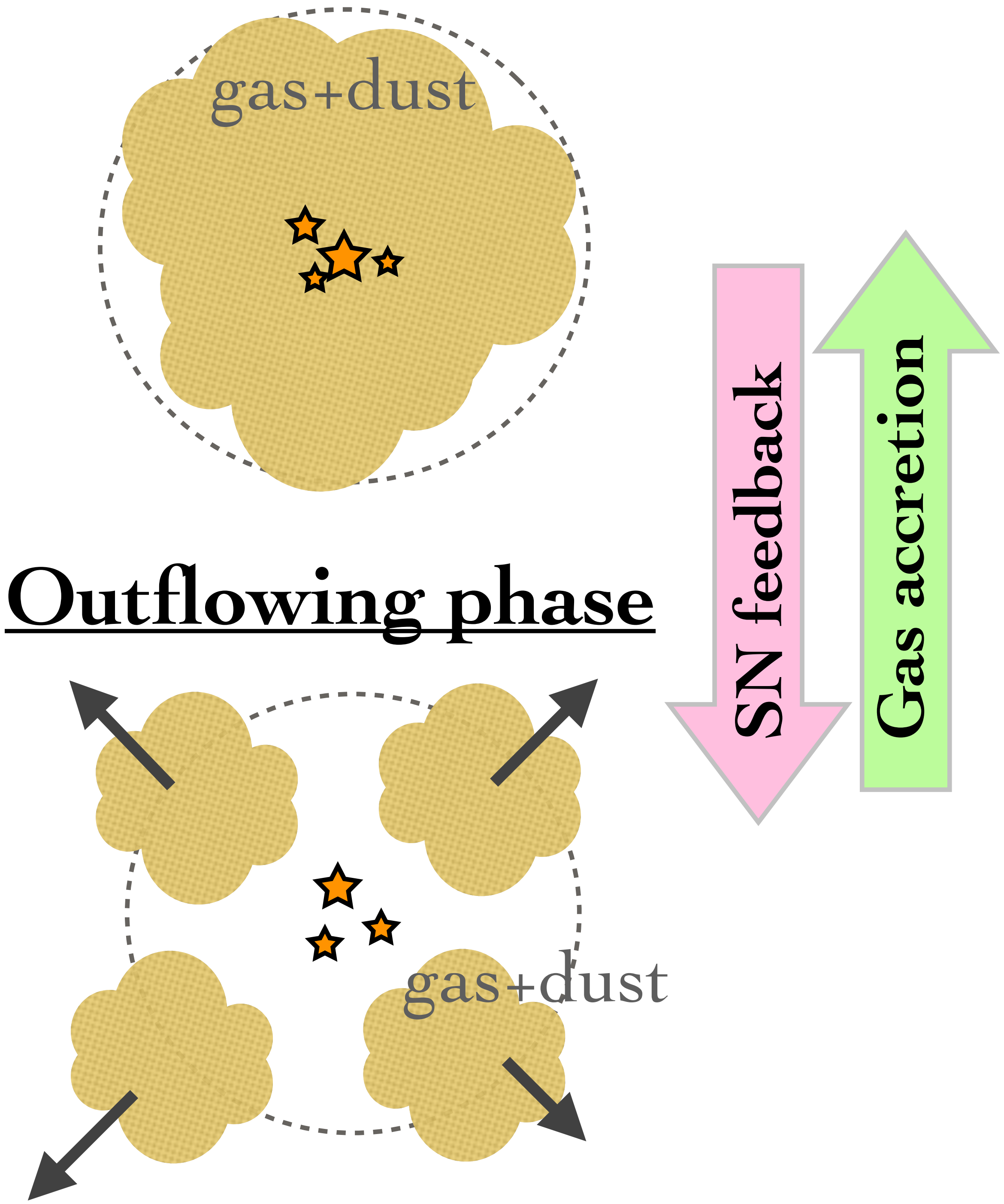
Star Formation

Star formation occurs intermittently

(Yajima+17, see also Kimm & Cen 14)

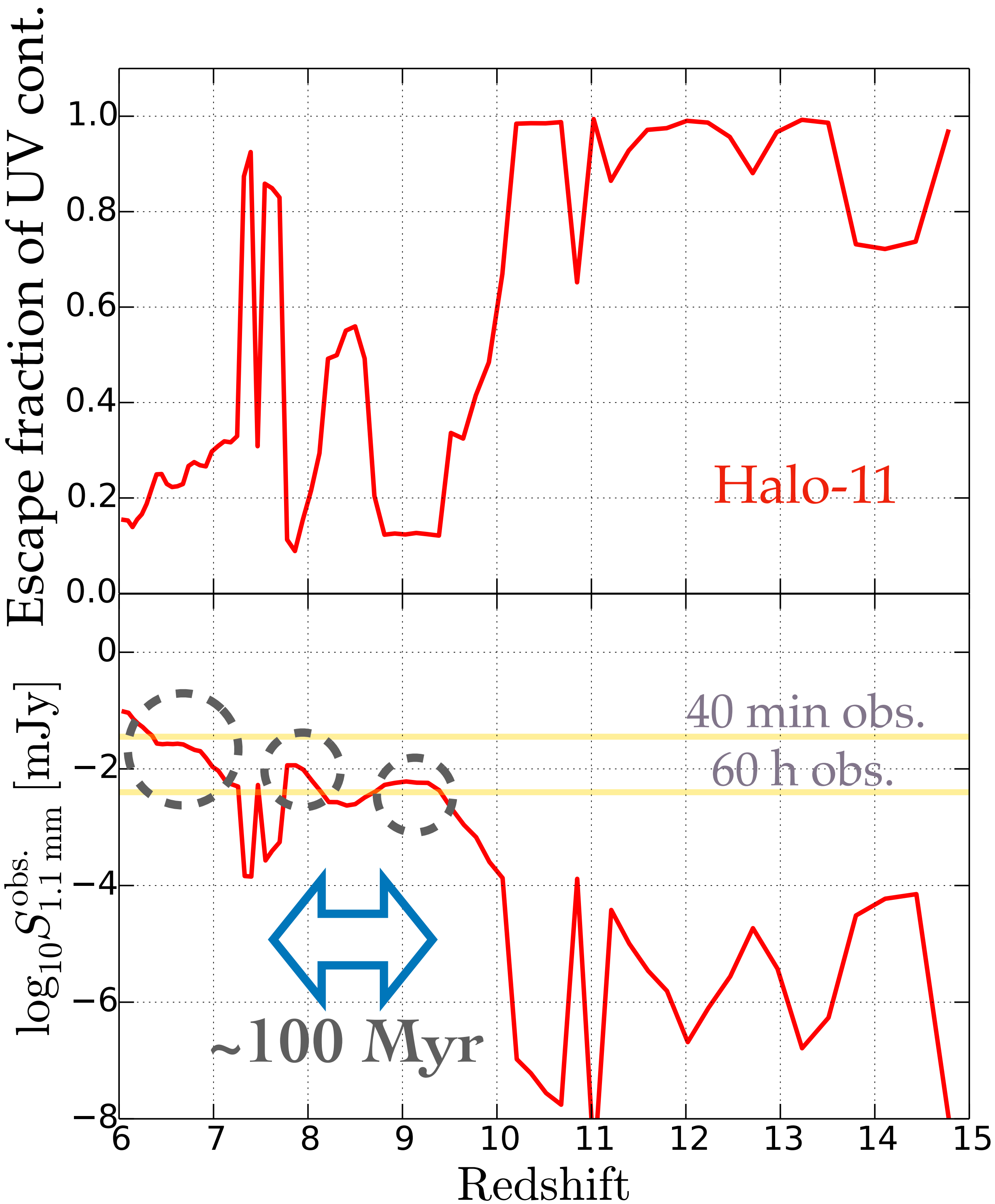


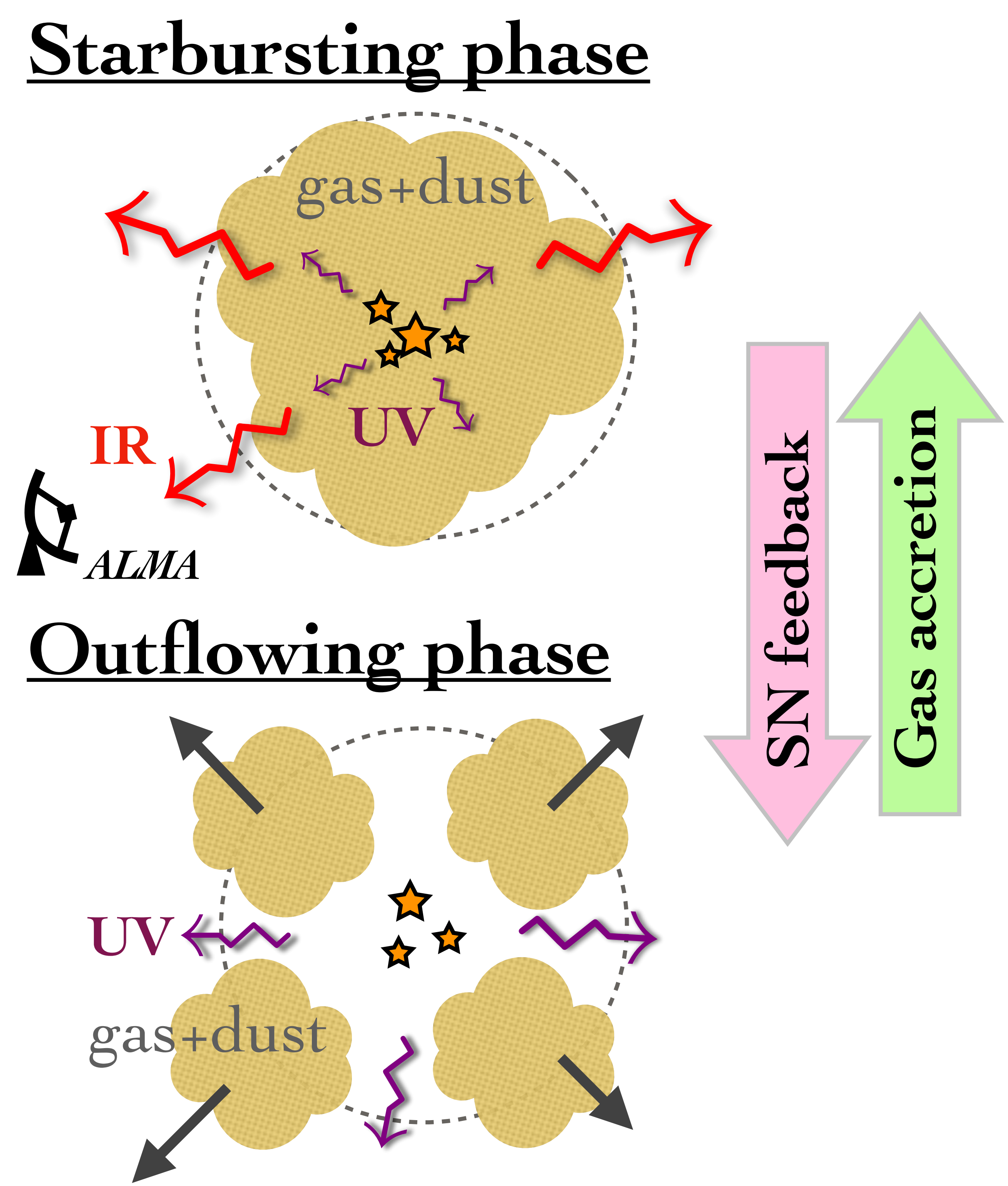
Starbursting phase



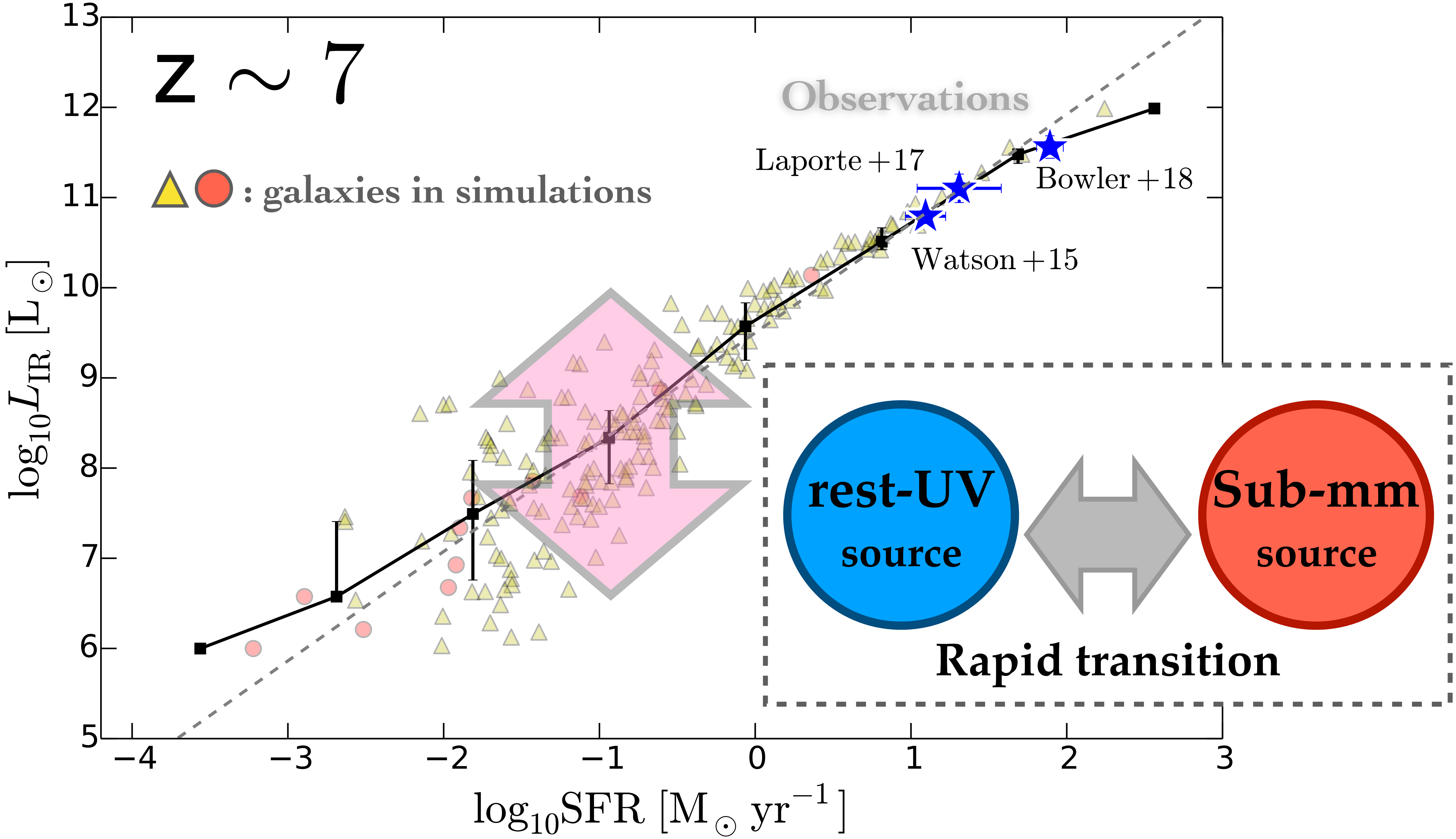
Outflowing phase

Fluctuation of Escape Fraction





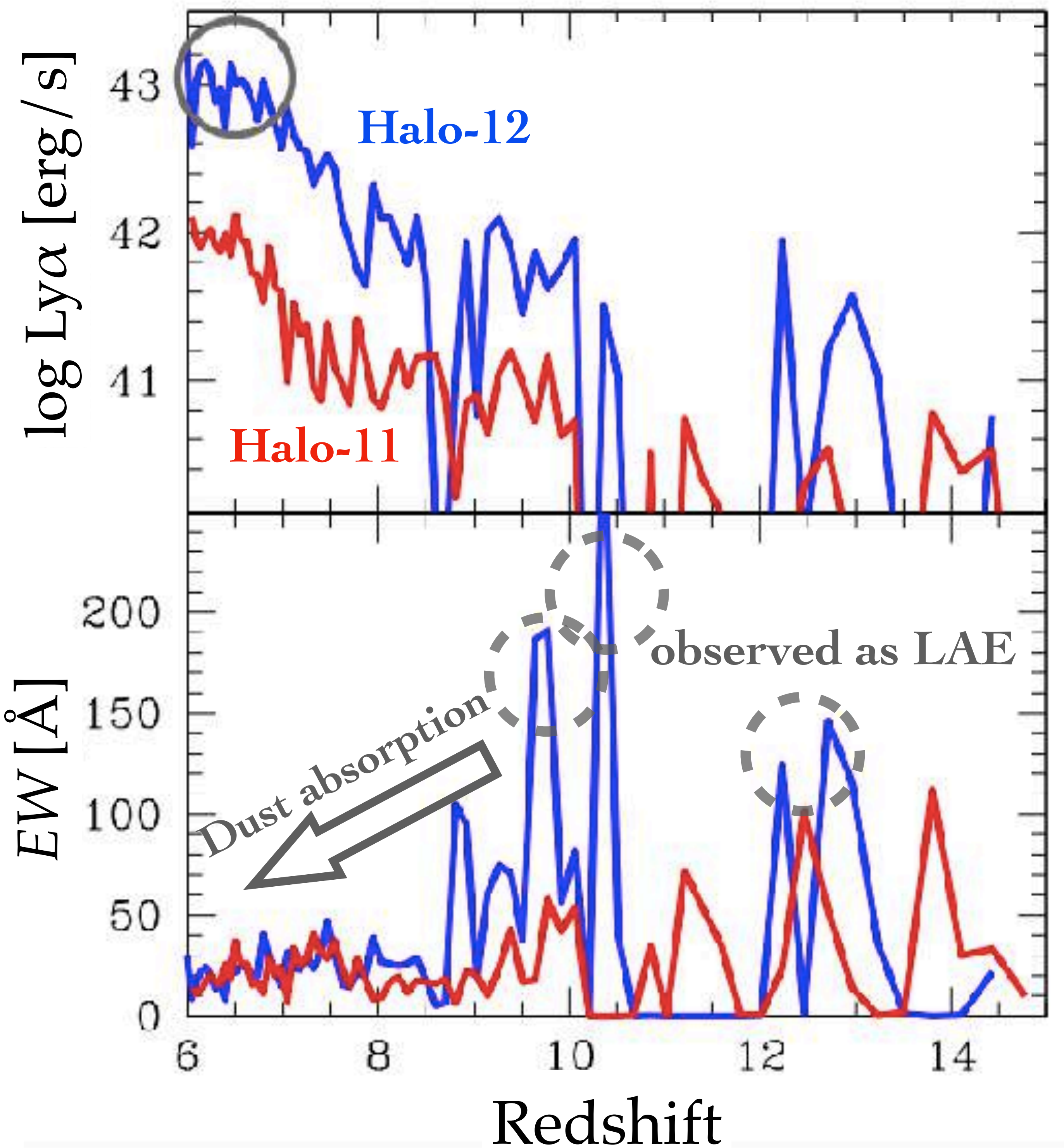
Large Dispersion of IR Luminosity

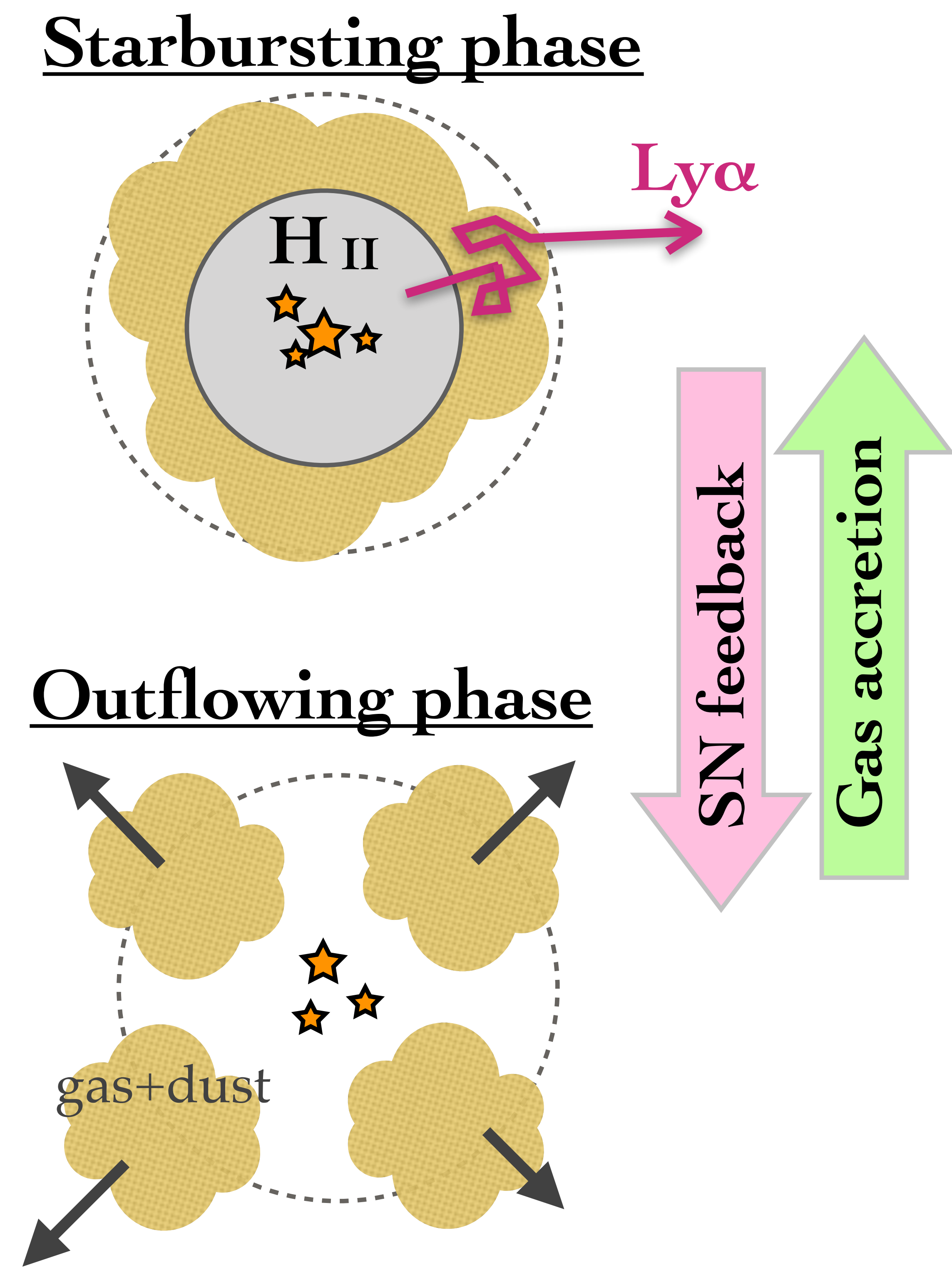


Intermittent SF –> wide variety of radiative properties

Arata+ '18

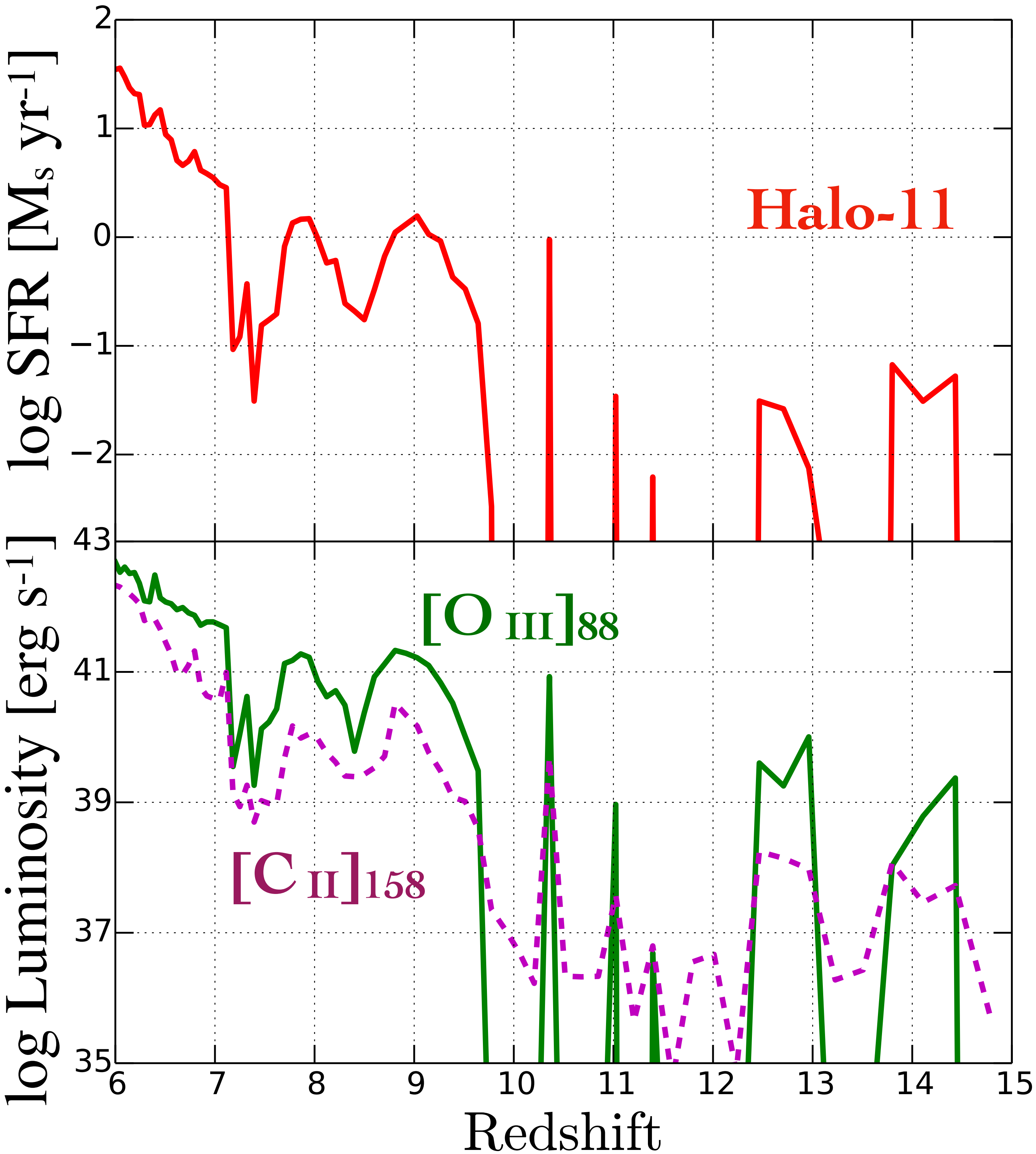
Lyα Luminosity Evolution

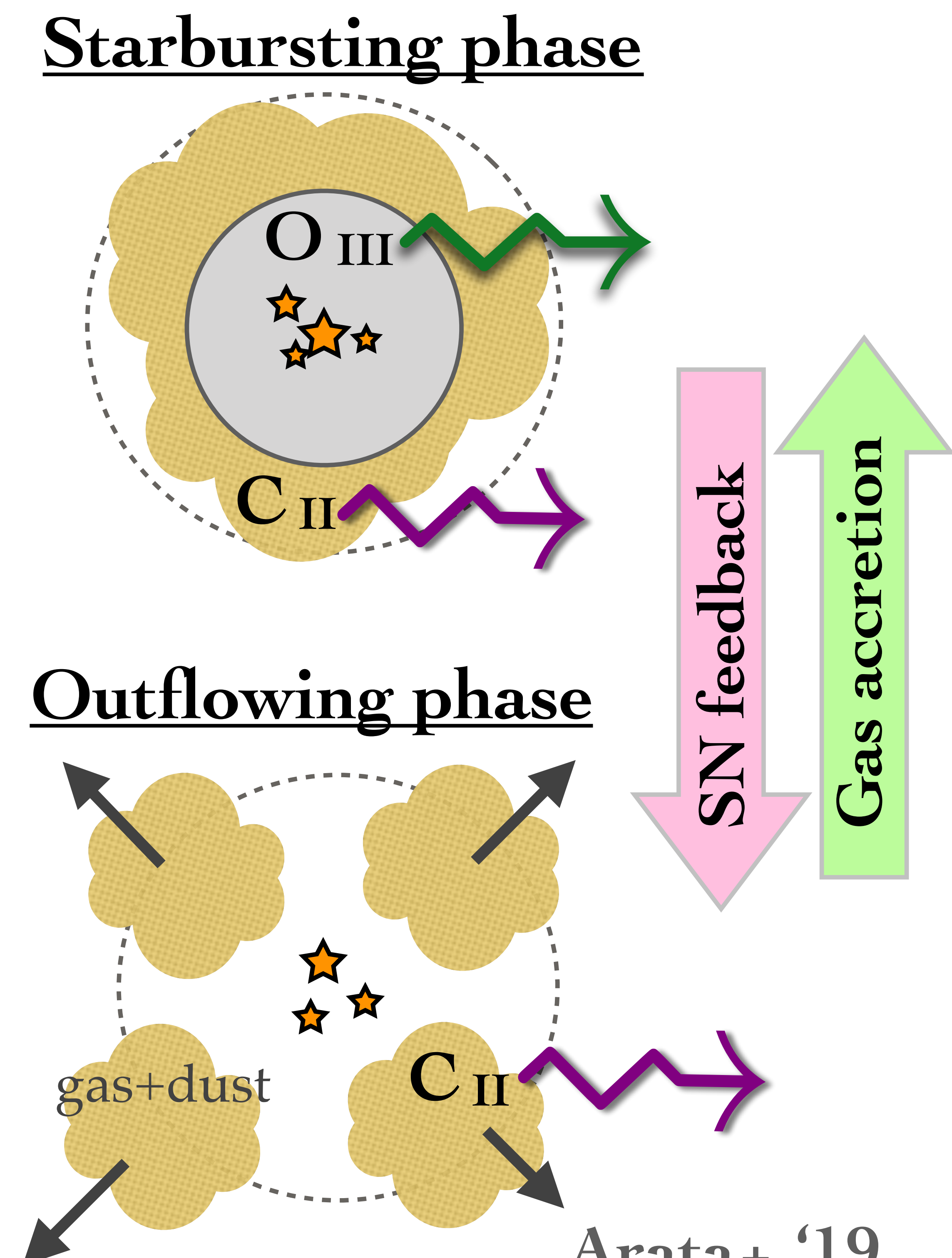




Arata+ '19

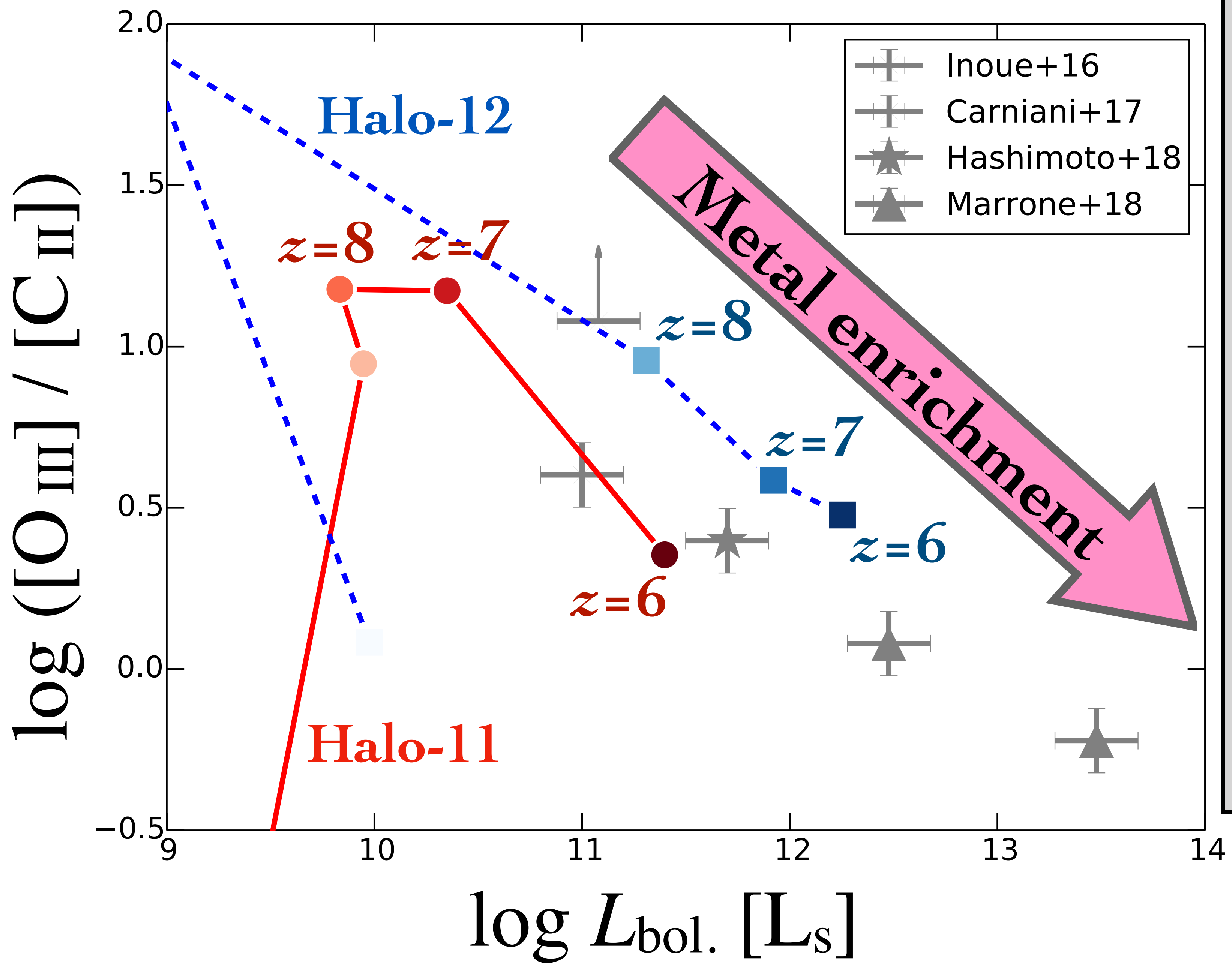
Starbursting [O III] Emissioin Phase and Quiescent [C II] Emission Phase





Arata+ '19

[O III]/[C II] Ratio Evolution



Metal enrichment

- **Suppresses H II region due to dust absorption**

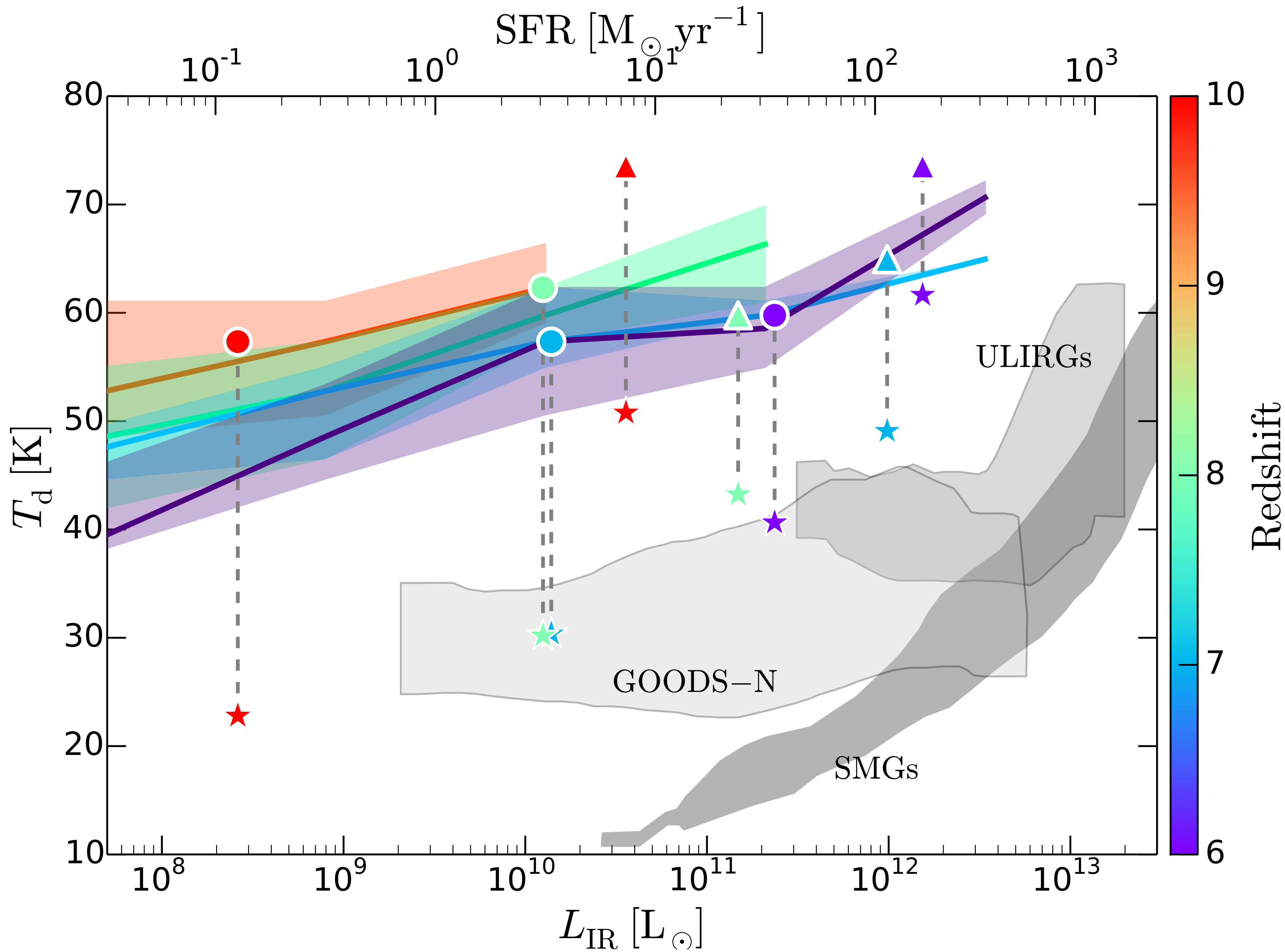
  [O III] ↘

- **Enhances H I cloud formation due to metal cooling**

  [C II] ↗, SFR($L_{\mathrm{bol.}}$) ↗

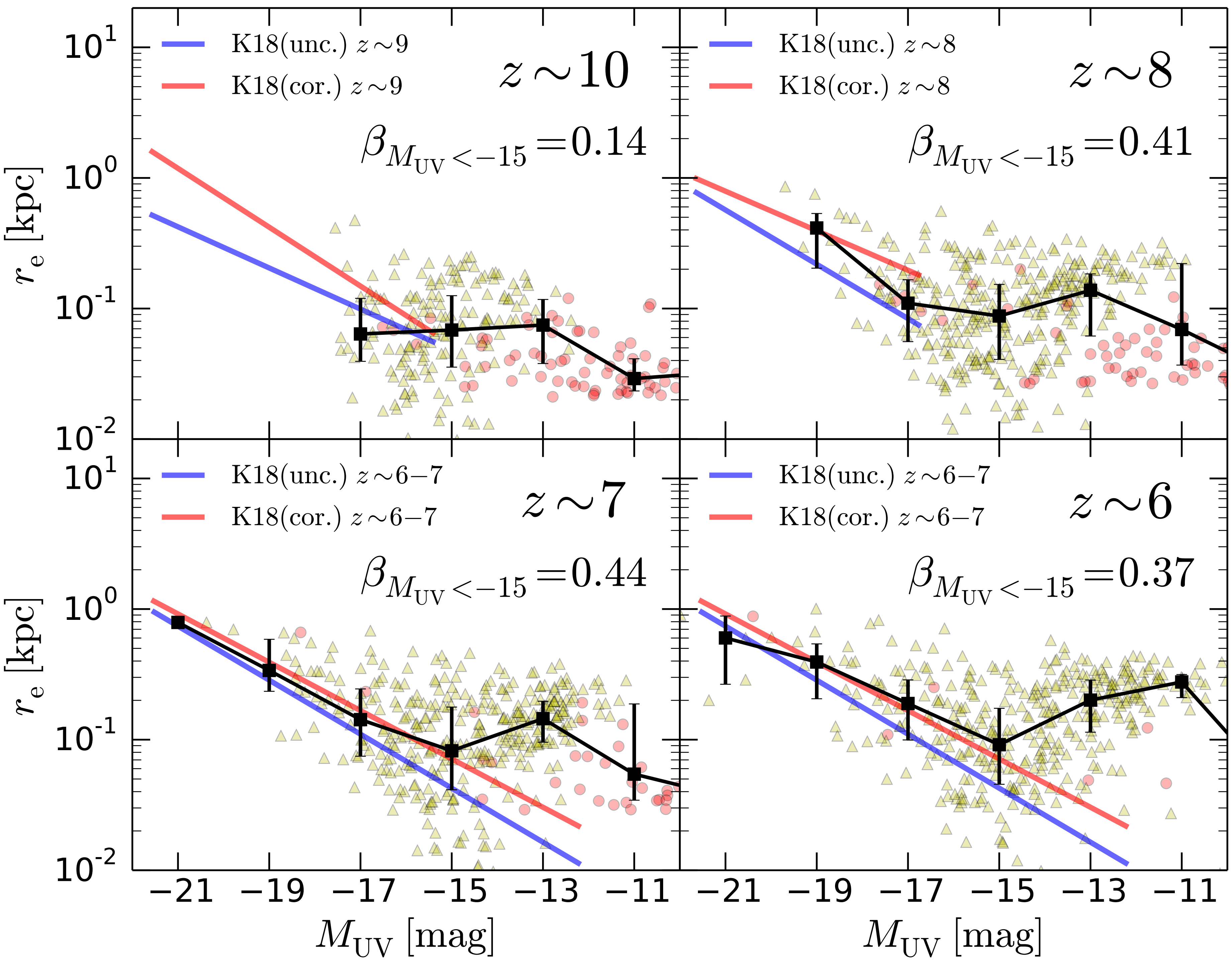
Arata+19

Dust Temperature



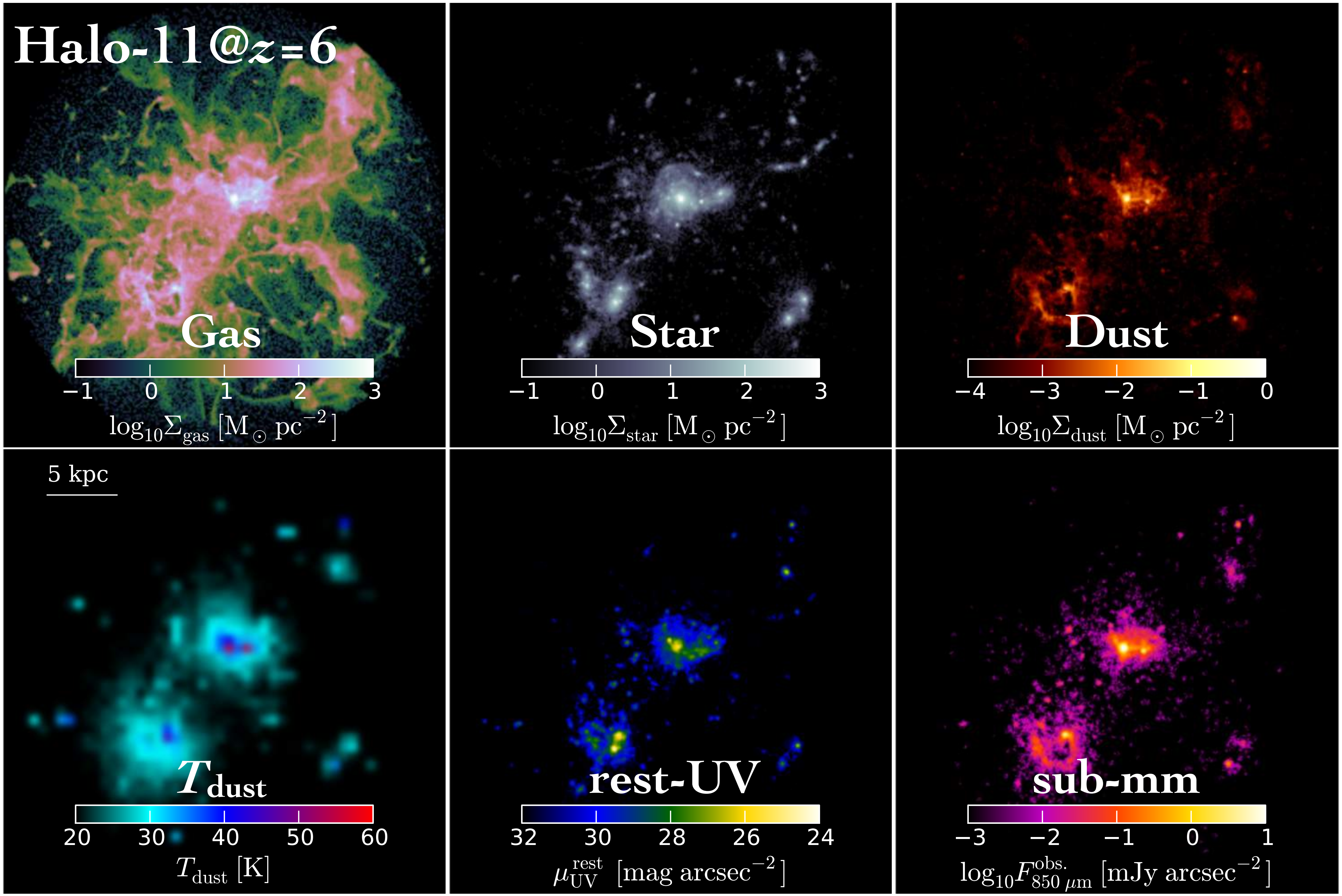
Arata, Yajima, KN+ '18

Galactic Size



Arata, Yajima, KN+ '18

Projected Images



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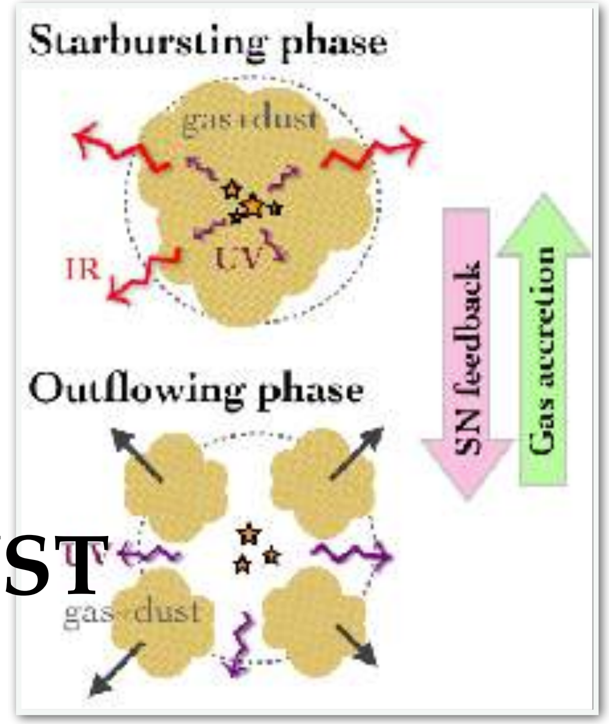
Summary

We studied radiative properties of the first galaxies using cosmological hydrodynamic simulations and multi-wavelength radiative transfer calculations

Intermittent star formation due to SN feedback generates wide variety of radiative properties



- **UV escape fraction fluctuates between 20-80%**
- **Time-scale of color transition is ~100 Myr**
- **$L_{\mathrm{Ly}\alpha}$~10^{42} erg s^{-1} at z~10 might be observed by JWST**
- **[O III]/[C II] ratio declines with metal enrichment**

Arata, Yajima, KN+ '19, arXiv:1908.01438

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It was a great school !!