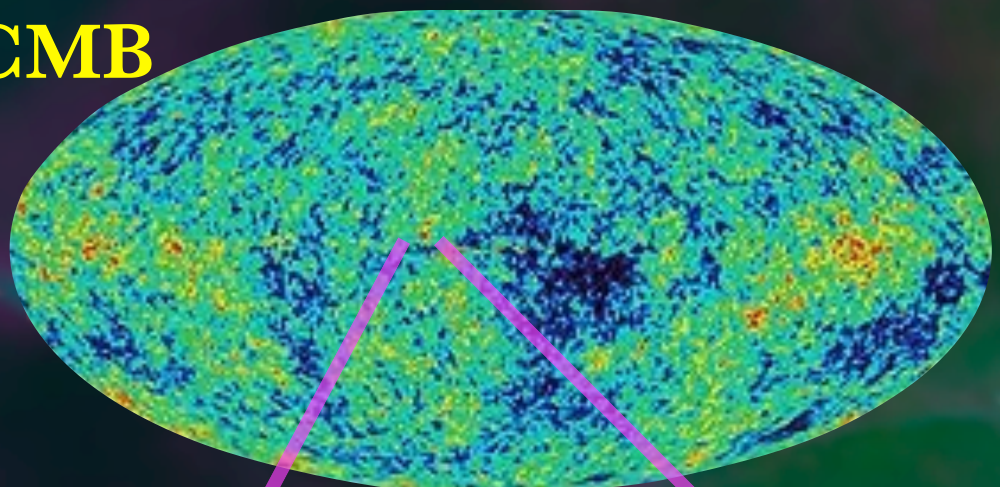
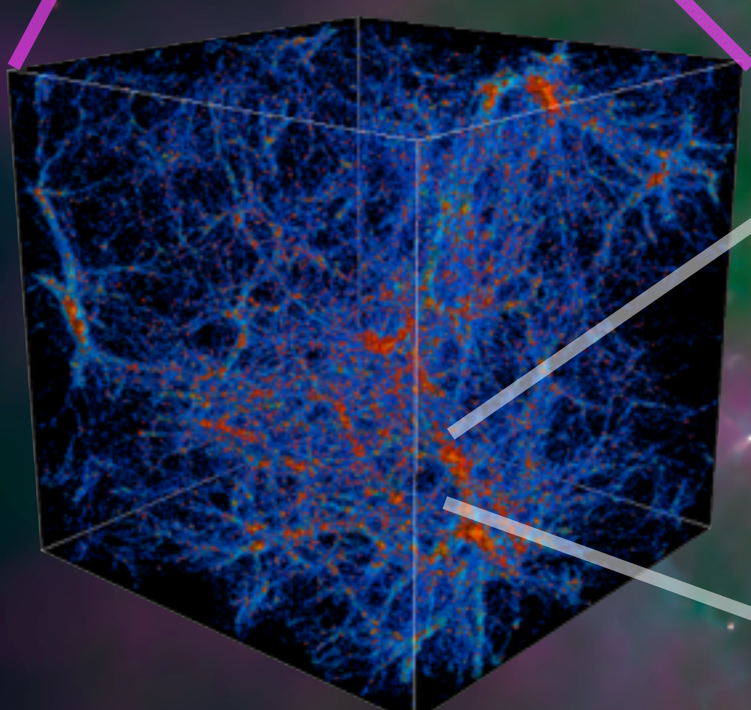
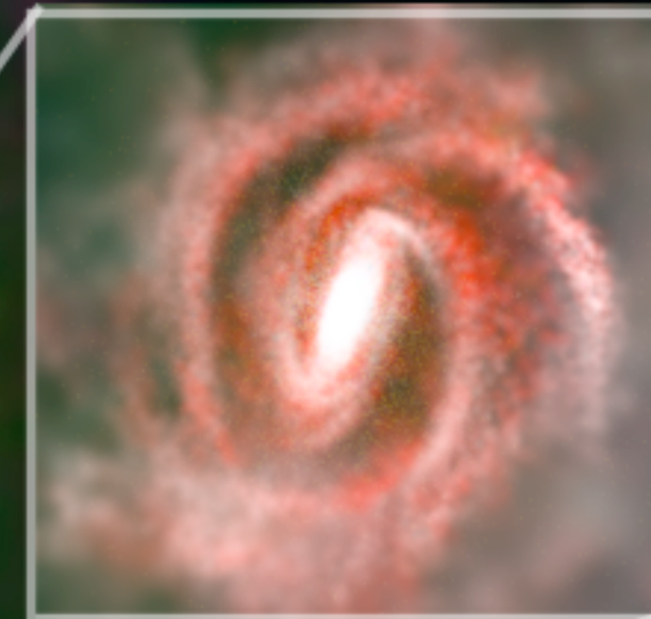
Recent Development in Numerical Cosmology & SWIMS

CMB





Large Scale Structure



Galaxy Formation

Ken Nagamine
Osaka / UNLV

Recent Collaborators :

J.-H. Choi (UT Austin)
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K. Todoroki (Kansas)
Hide Yajima (Tohoku)

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I. Shimizu (Osaka)

TAO-SWIMS

Simultaneous-color **W**ide-field **I**nfrared **M**ulti-object **S**pectrograph

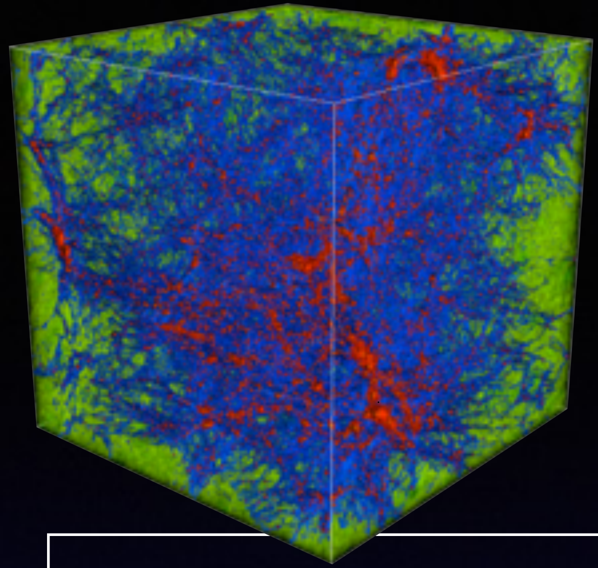
Spec & Plans

- NIR multi-object spectrograph / imager for TAO6.5m
- max 9.6arcmin FOV (6.6x3.3arcmin on Subaru)
- λ = 0.9 - 2.45 μm
- Photometry, Multi-object spectrograph (R~1000)
- Simultaneous 2-band obs (0.9-1.4 and 1.4-2.45μm)
- Early 2016: to Subaru
- Aim: In 2018, first light on TAO6.5m, Chile

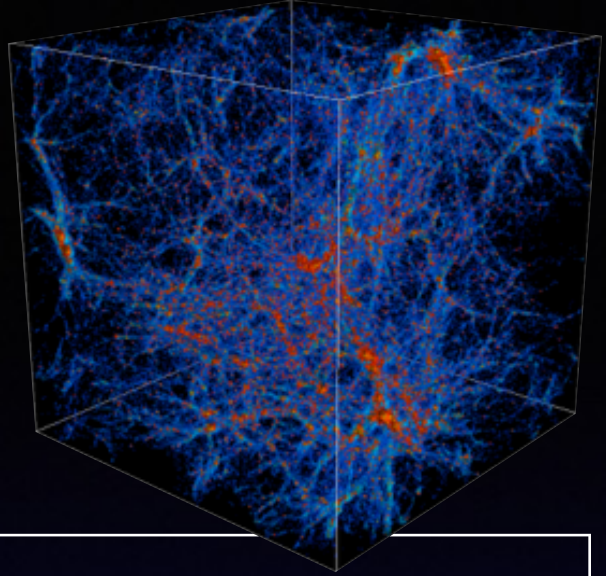
- **Detailed investigation of galaxies at $1<z<5$ (peak of formation)**
- **Use IFU and study galactic structures at $1<z<5$**
- **Internal structures of dusty gals (ULIRG/LIRG; e.g. Pa-α)**

What do theory & numerical simulations tell us?

Remaining issues in simulations — What can SWIMS do?



Outline



- Introduction
- Numerical Cosmology: Cosmological Hydrodynamic Simulations
- the 3rd Revolution: Zoom-in Cosmo Hydro Sims.
- Key Physical Processes for Feedback: Stellar, SN, AGN
- Remaining Issues?

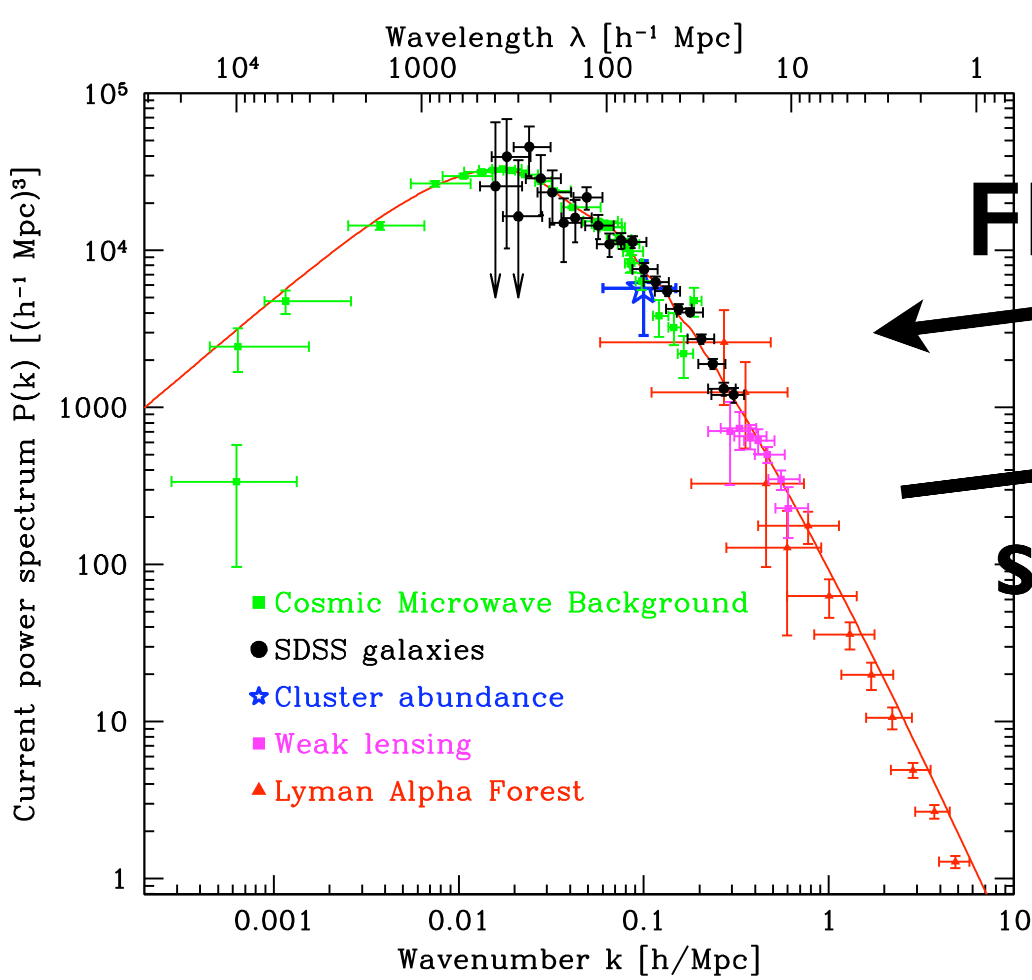
``Concordance ΛCDM model ”

WMAP, Planck
SN Ia

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

$$\Omega_{DM} \approx 0.26$$

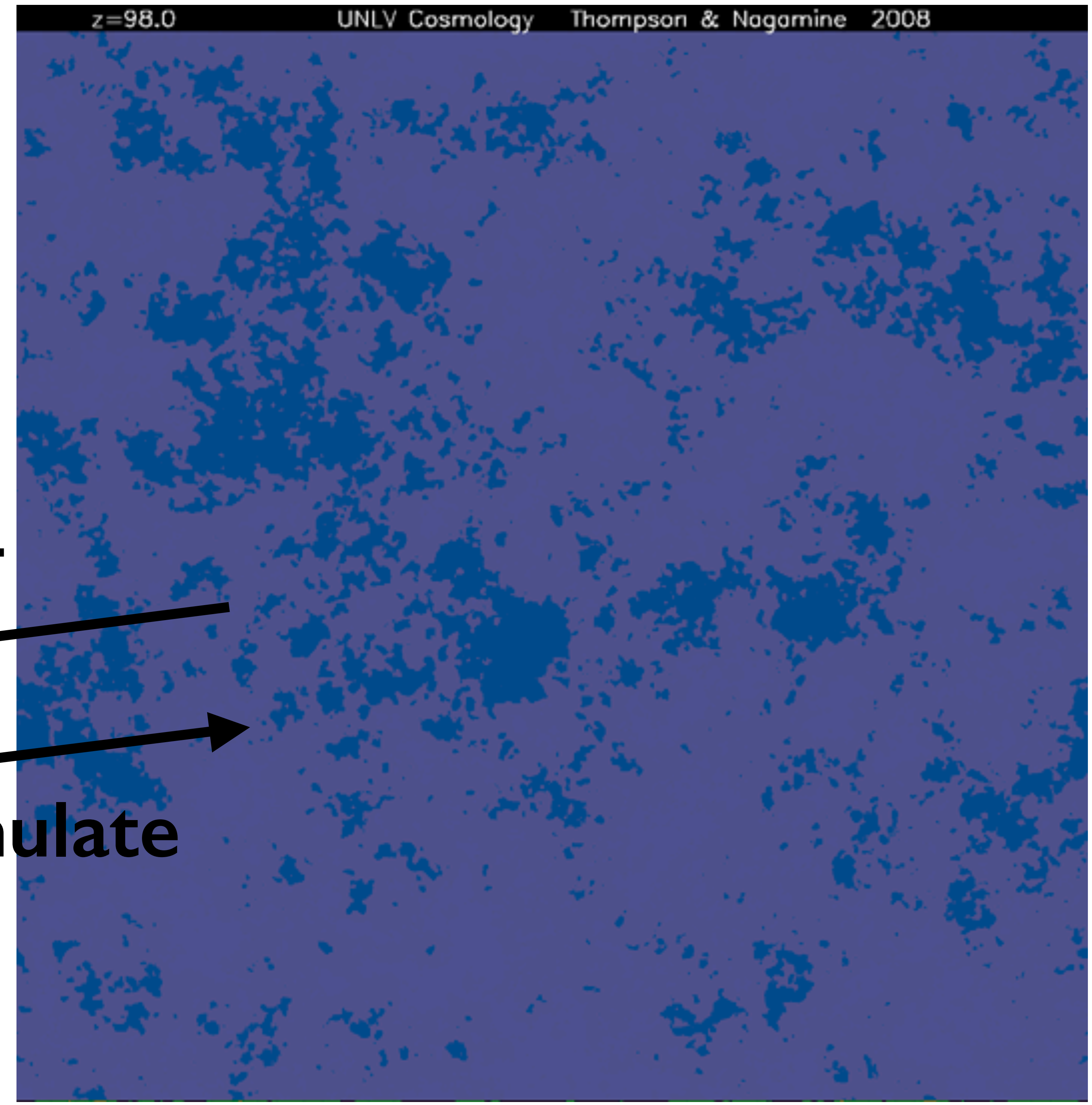
- Successful on large-scales (>1Mpc)
- Can we understand galaxy formation in this context?



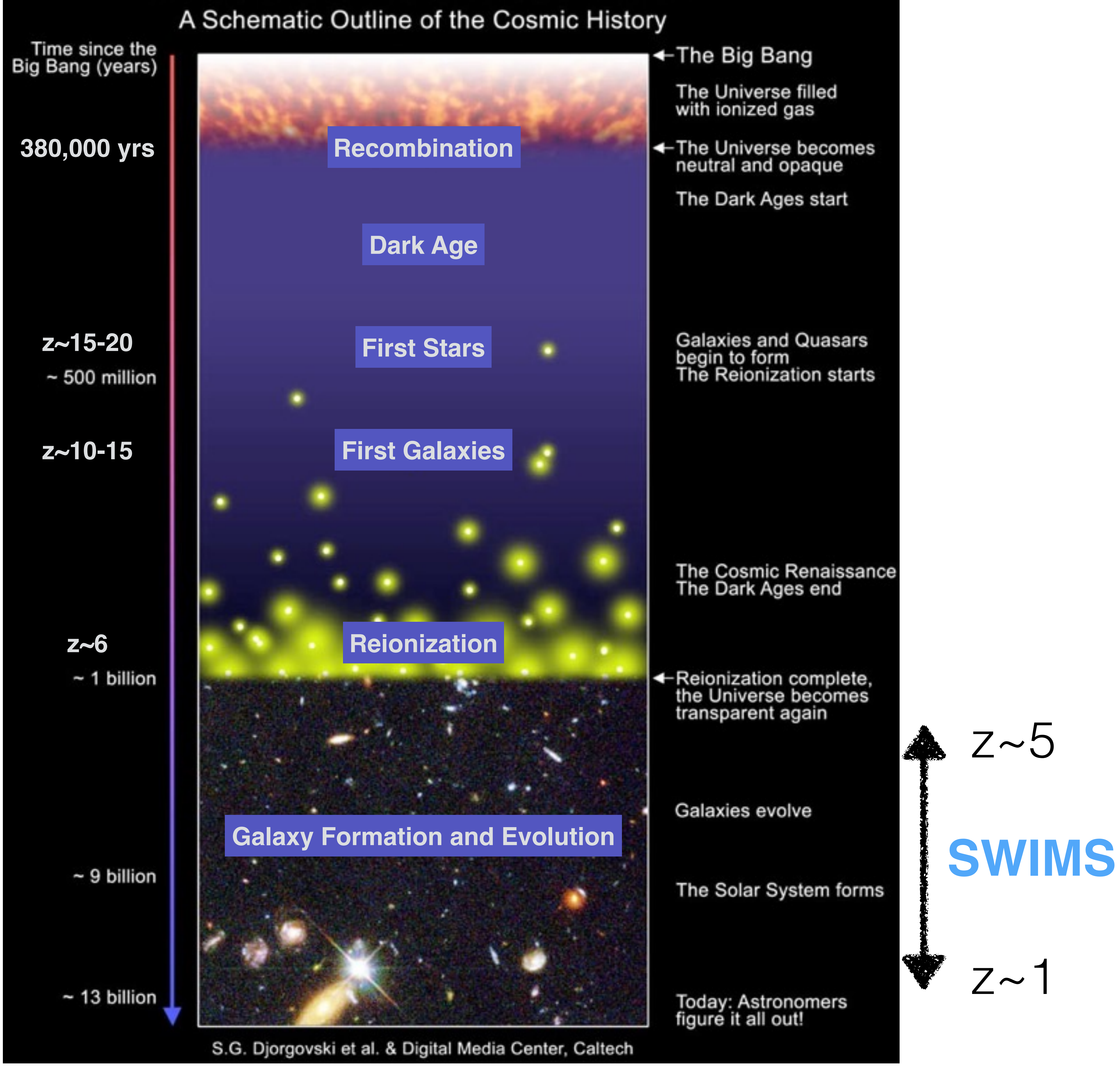
Tegmark+ (2004)

FFT

simulate



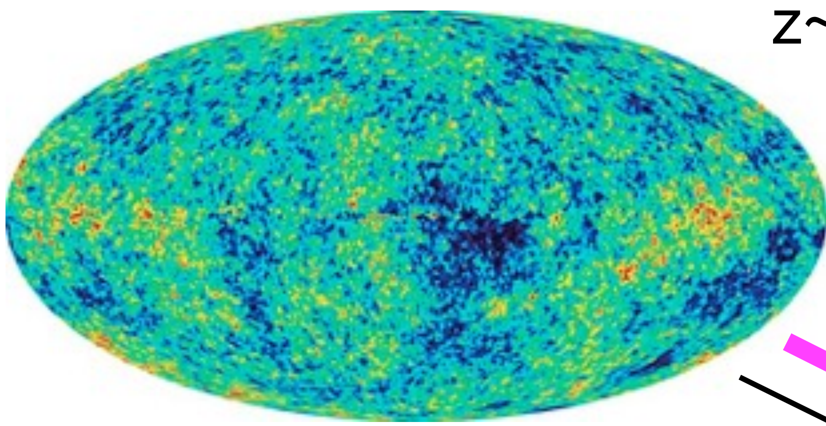
“Back-bone of structure”



A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
380,000 yrs
z~15-20
~ 500 million
z~10-15
z~6
~ 1 billion
~ 9 billion
~ 13 billion
Recombination
Dark Age
First Stars
First Galaxies
Reionization
Galaxy Formation and Evolution
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech
z~5
SWIMS
z~1

Computational Cosmology

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



z~1100

Initial conditions

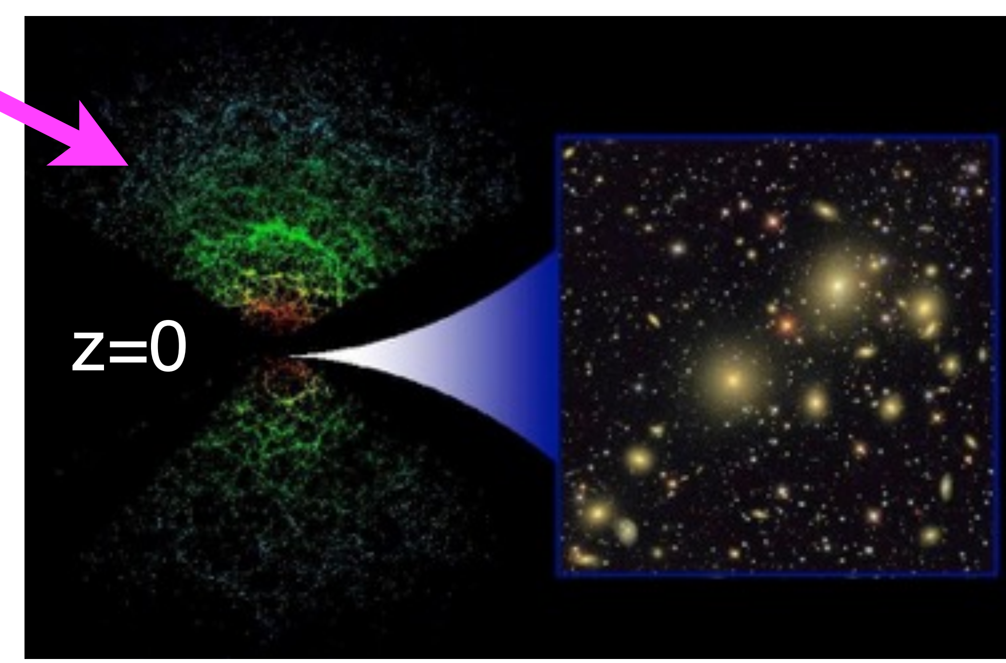
z=100

z=10

z=3

Radiative cooling/heating, Star formation, & Feedback

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



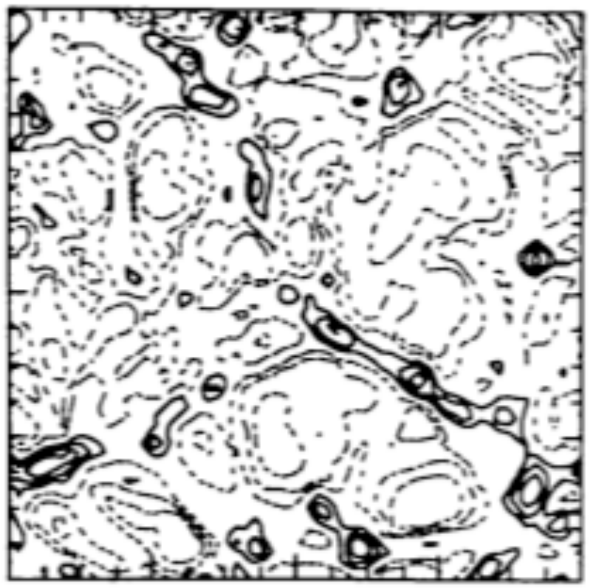
Gravity + Hydrodynamics

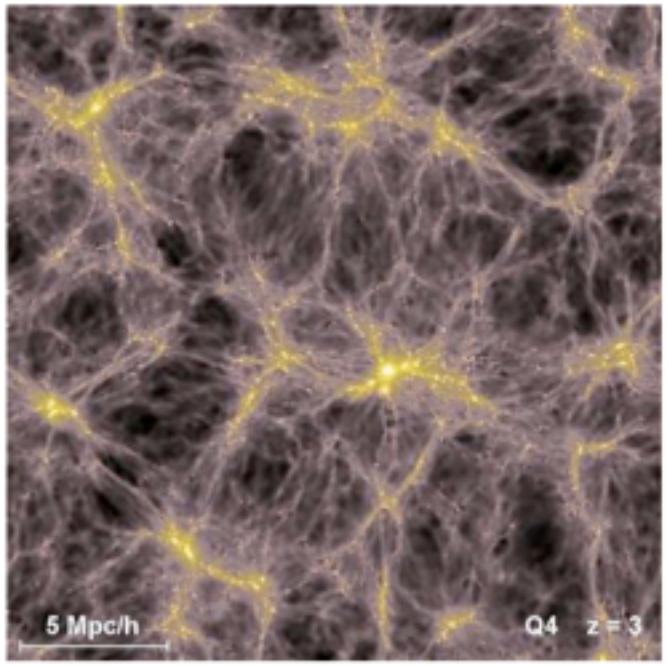
Three Revolutions in Cosmological Hydro Simulations

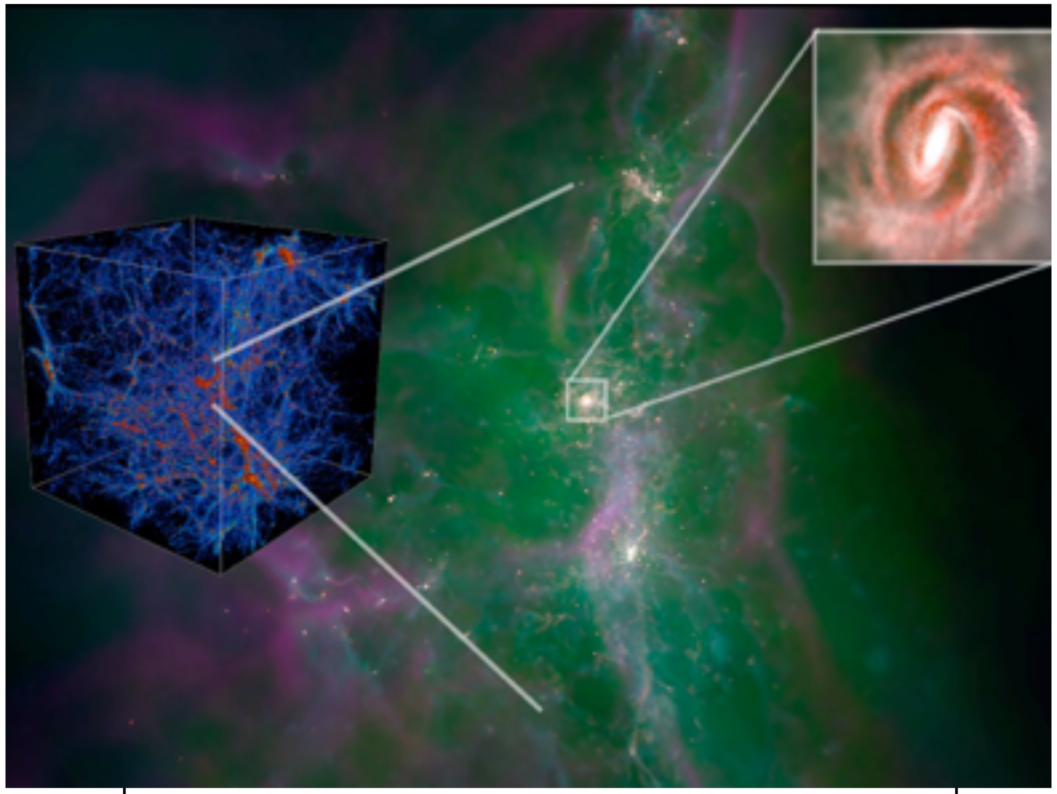
1990': 1st Revolution

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

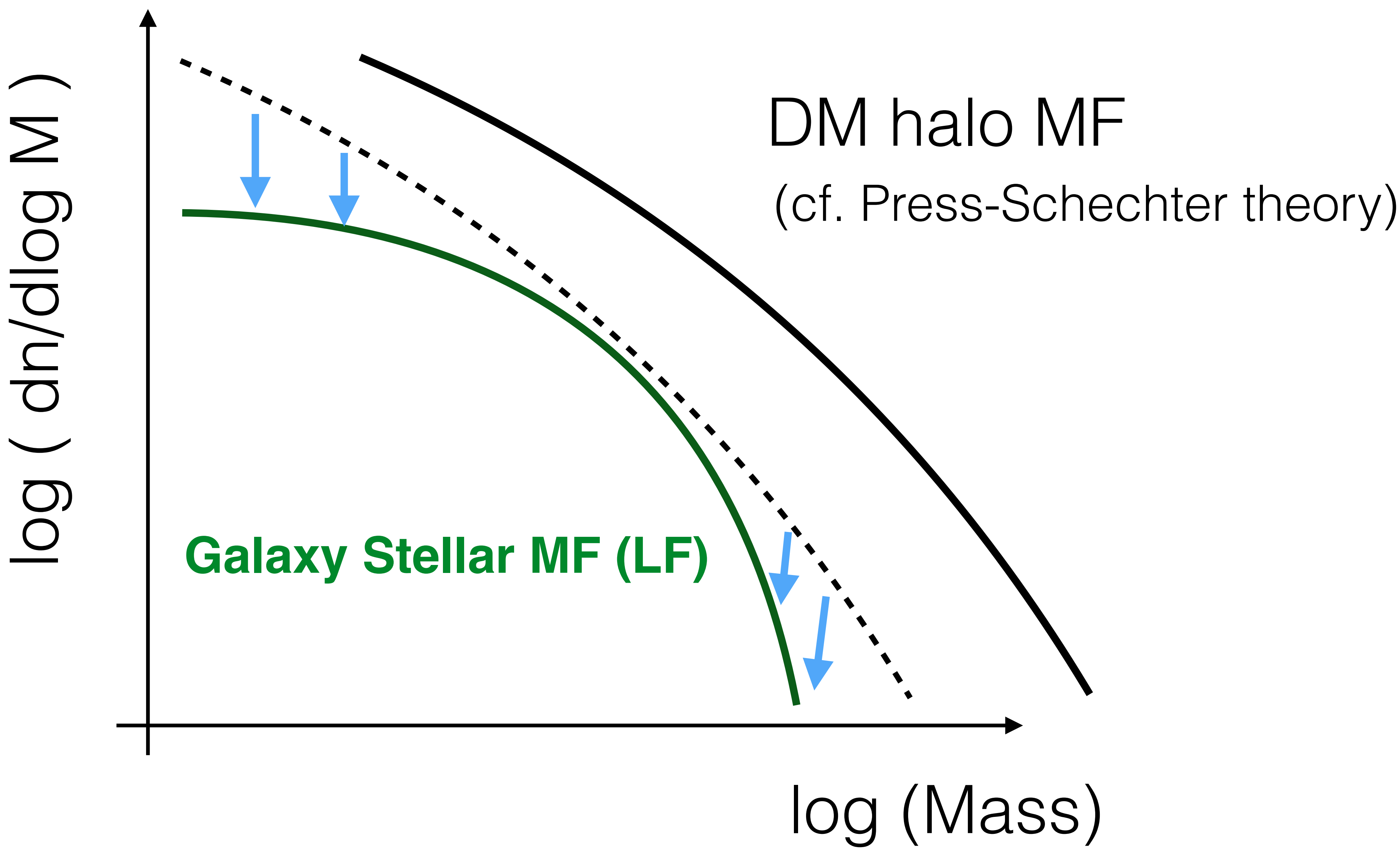
e.g., KN+ '01, 04, 06
Springel & Hernquist '03

Zoom-in method allows much higher res.

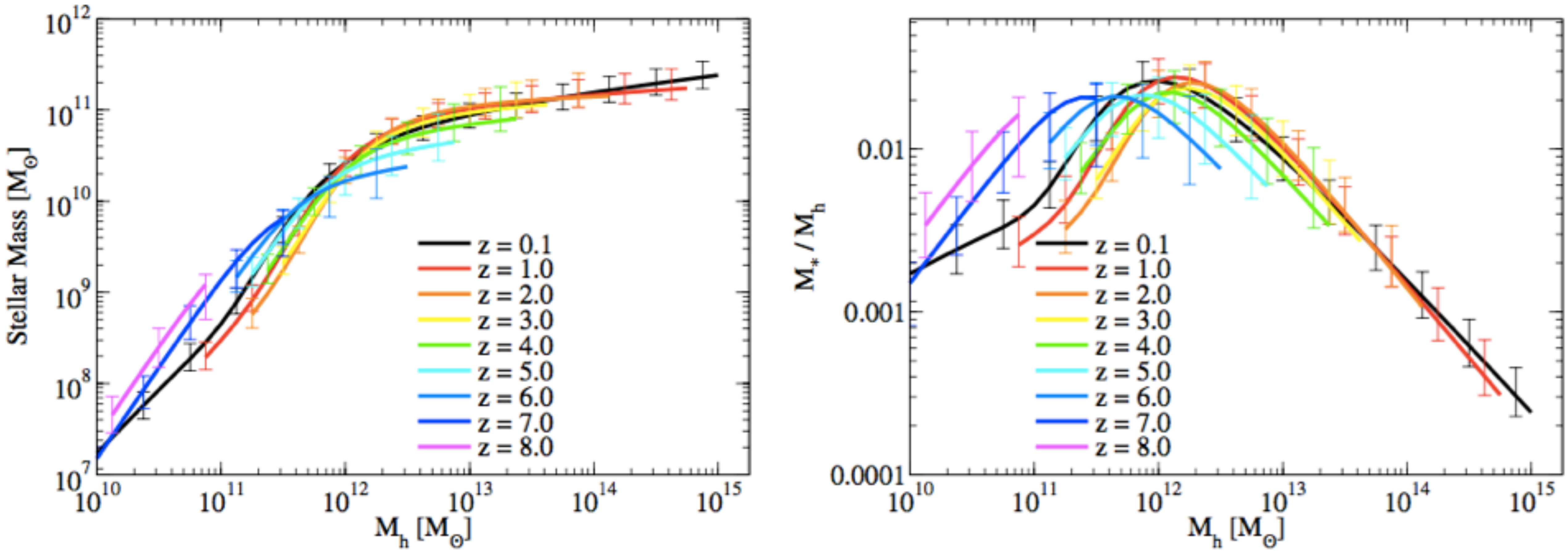
Resolution~ 10-100pc

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

Dark Matter Halo —> Galaxies



Stellar-to-Halo Mass Ratio (SHMR)



Behroozi+'10, '13

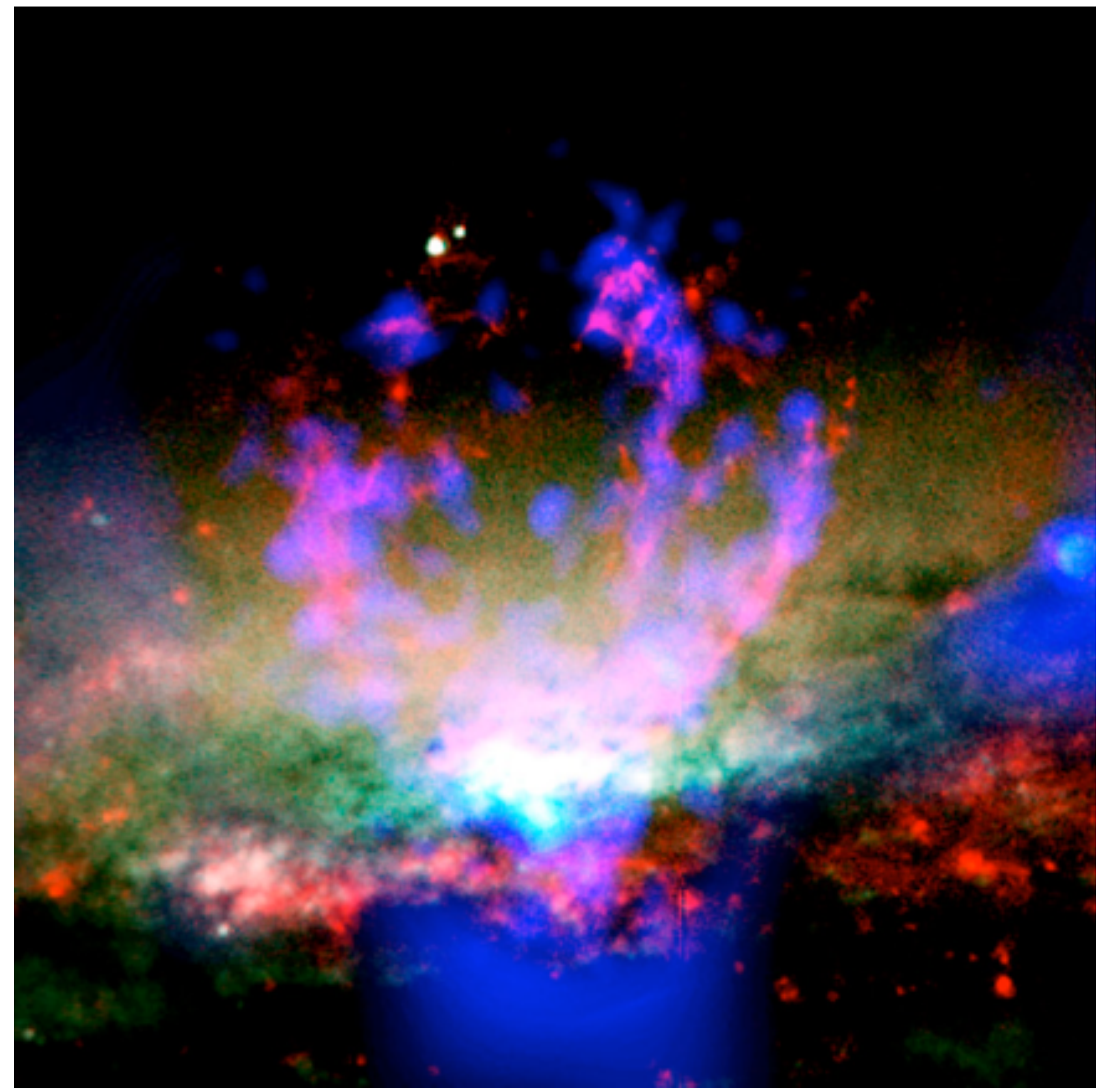
(cf. Ilbert+'10; George+'11; Leauthaud+'12)

"FEEDBACK" has been the KEY

- Energy(Light, Mass) is ejected, and affect later evolution of the system.
- What, Who, Where, When, Why, How ?
- What? : Radiation, Mass (gas, dust)
- Who? : SNe, SMBH(AGN), Massive Stars(MS)
- Where? : galaxy, star-forming region, black hole
- When, Why, How?

Prevalence of Galactic Wind Feedback

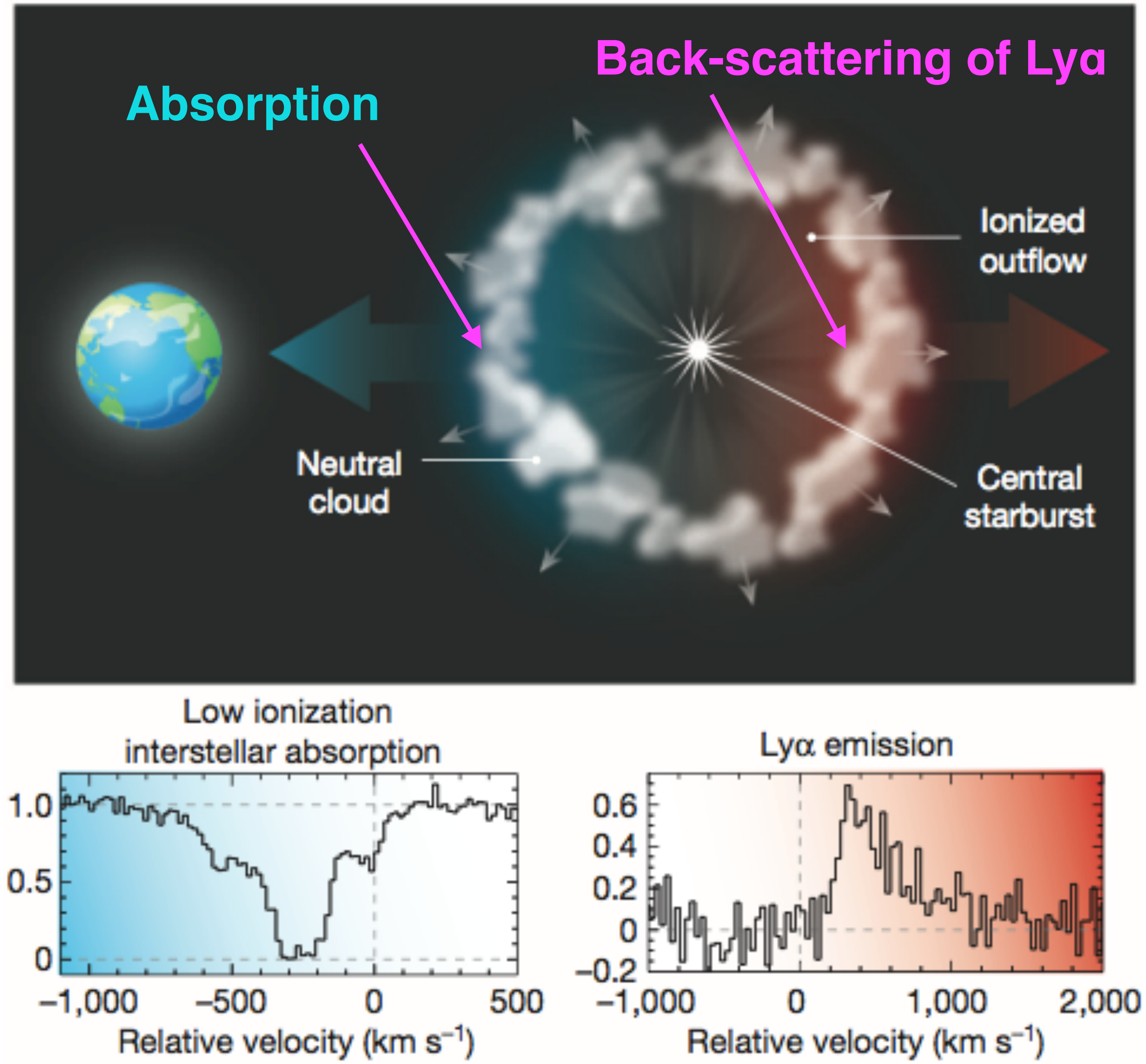
-- Pollution of Intergalactic Medium by metals



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

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

Ubiquitous Outflows in High-z SF Galaxies



~200 km/s

~500 km/s shift

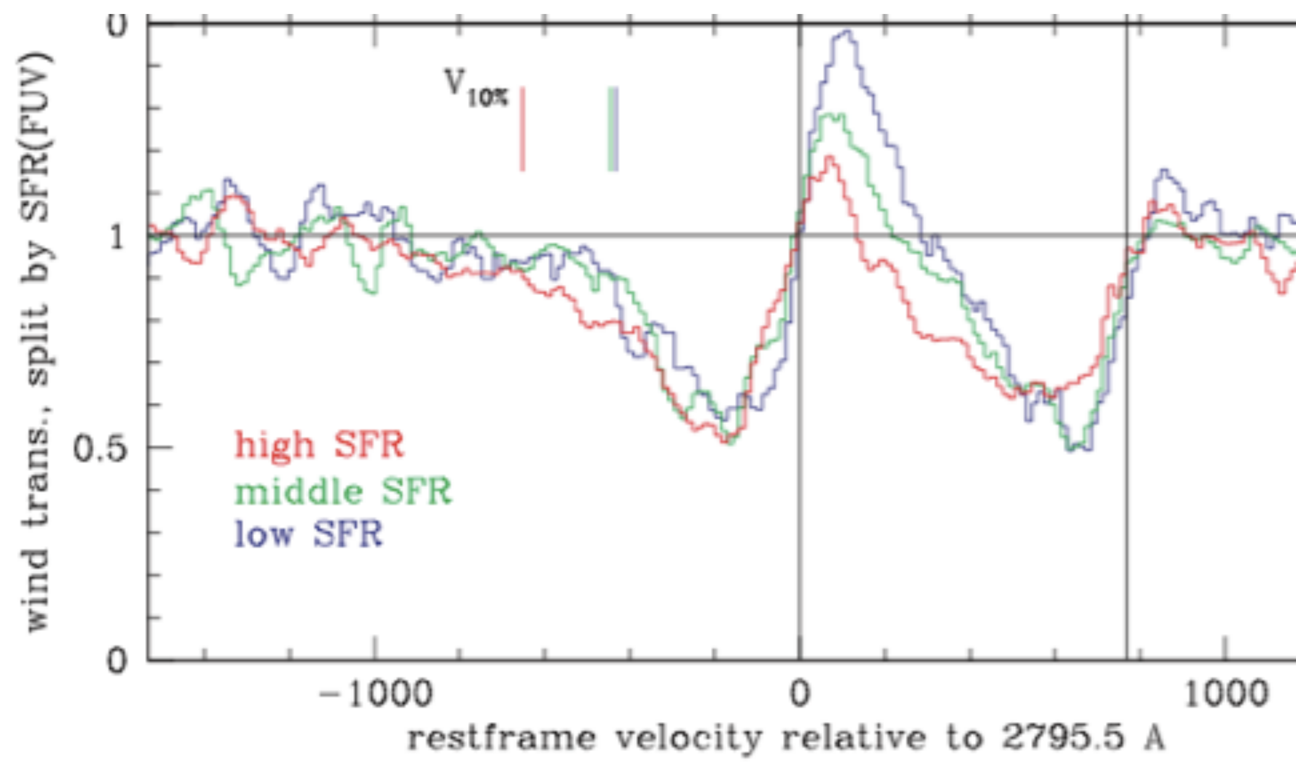
z=2.7 lensed LBG (MS1512-cB58; Pettini+'02)

(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 $$V_{\rm wind} \sim \mathrm{SFR}^{0.35}$$ (Martin+' 05)

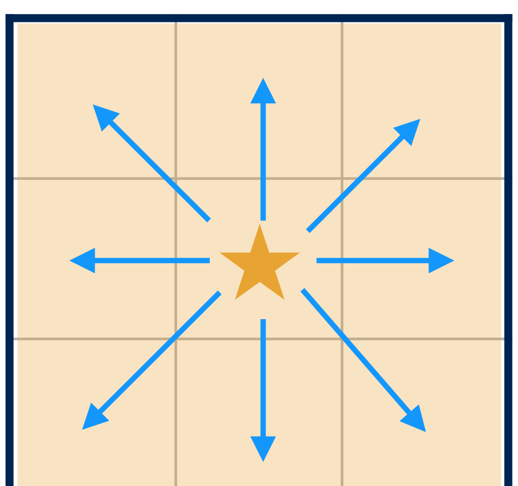
$$\dot{M} \simeq 22 M_\odot \,\mathrm{yr}^{-1} \frac{N_H}{10^{20}\,\mathrm{cm}^{-2}} \frac{R}{5\mathrm{kpc}} \frac{v}{300\,\mathrm{km\,s}^{-1}}.$$

Supernova(SN) Feedback

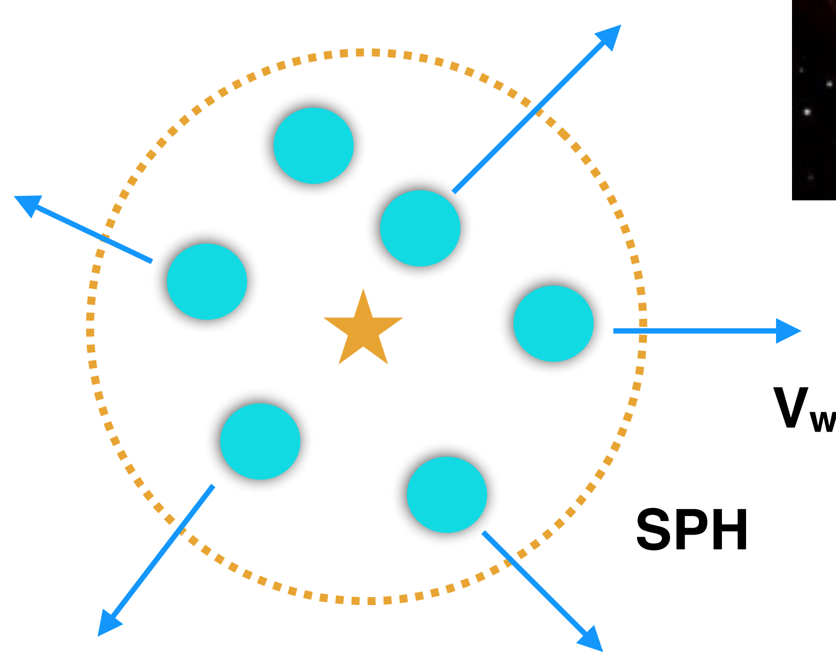
- Source of radiation, metals, cosmic rays; $E_{tot} \sim 10^{53}$ erg/SN
- Total FB energy: $E_{fb} \sim 10^{51}$ erg/SN
  - —> $E_{fb} \sim 10^{48\text{-}49}$ erg/$M_\odot$ (E_k, E_{th})
- Outflows, Suppression of SF

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

Crab Nebula — SN 1054 (NASA, ESA)



mesh codes



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

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})

↓

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

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

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

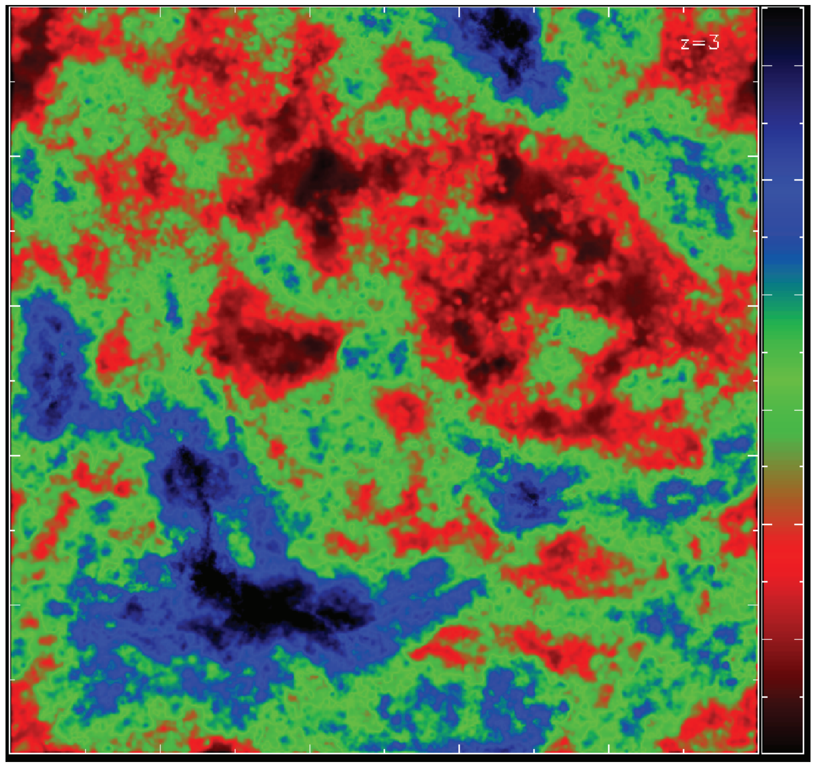
Murray+ '05

Higher mass-loading factor for lower mass galaxies.

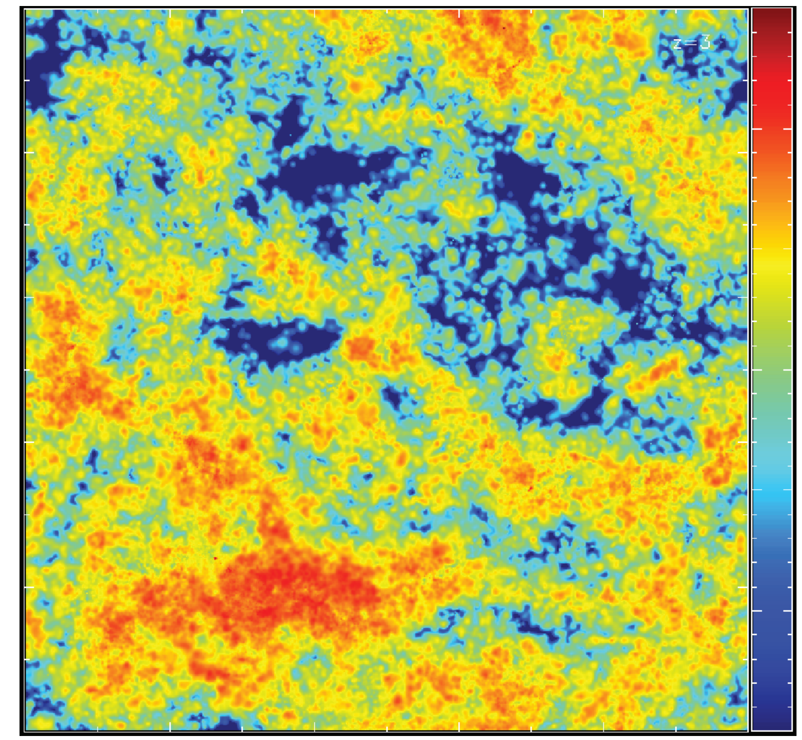
Impact of Momentum-driven Wind on IGM

Temperature

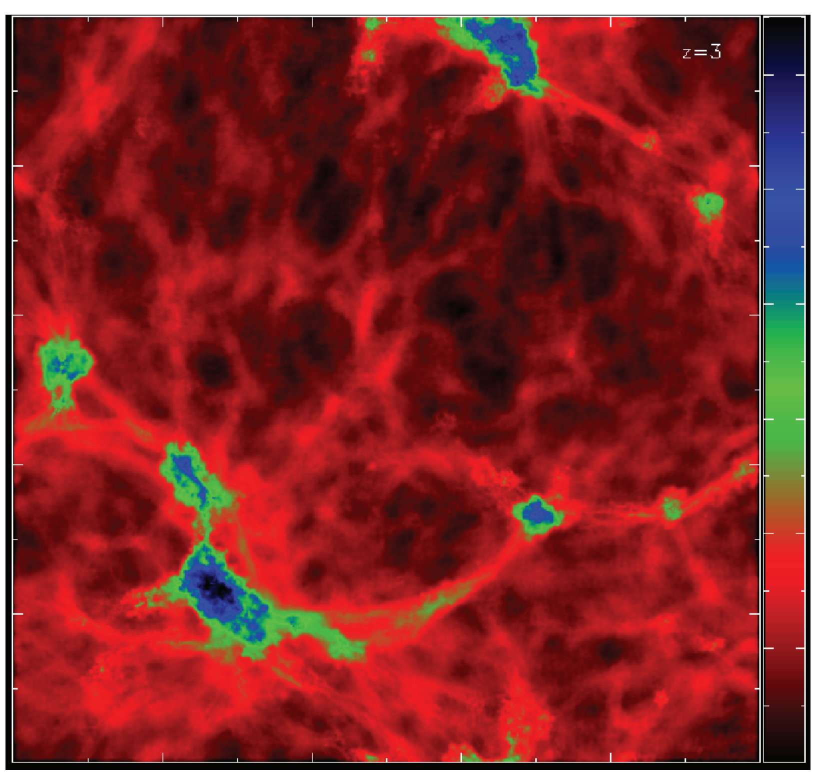
Projected metal density

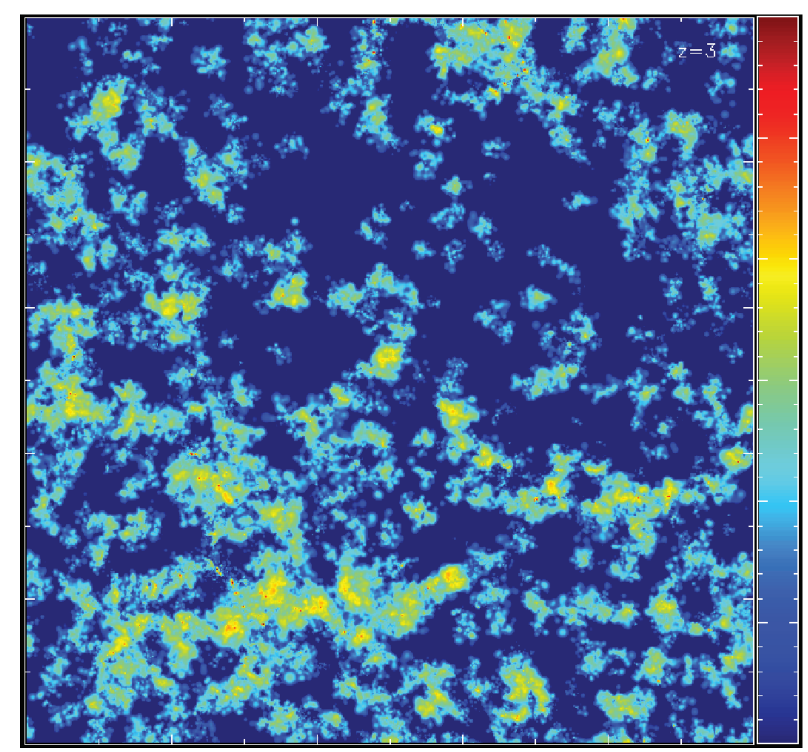


10 Mpc/h



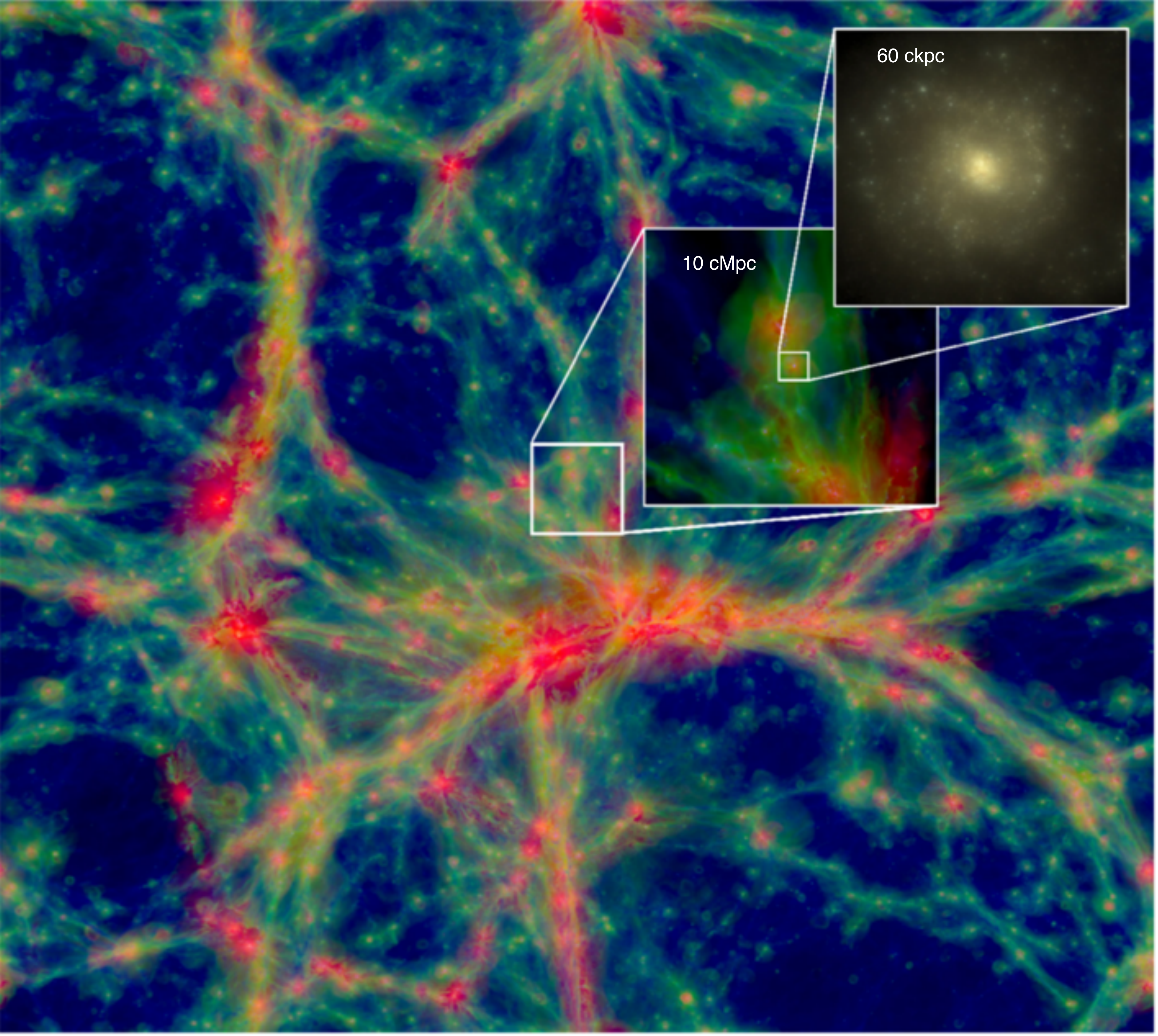
Energy-driven wind (constant V_w)





Momentum-driven

Choi & KN '10



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) — but no turning-off hydro force for winds, but instead reserve E_{th} until 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)

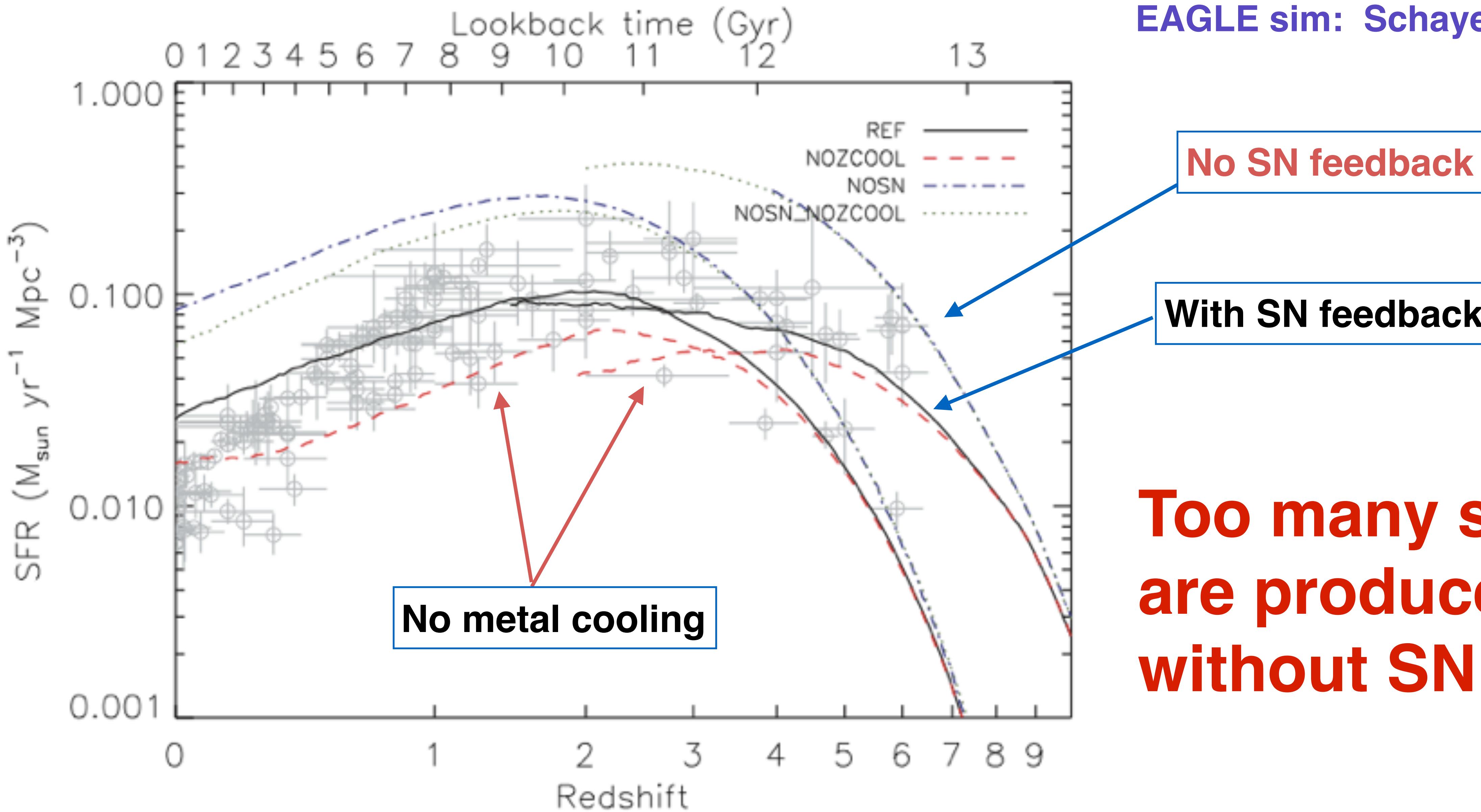
$T > 10^{5.5}$ K (red)

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

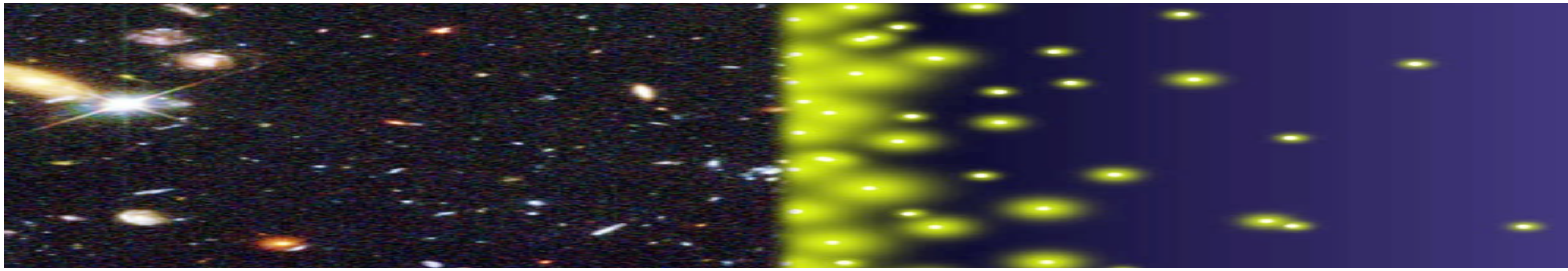
- **(Still, f_{gas} & T for gal clusters may be too high)**

Cosmic Star Formation History

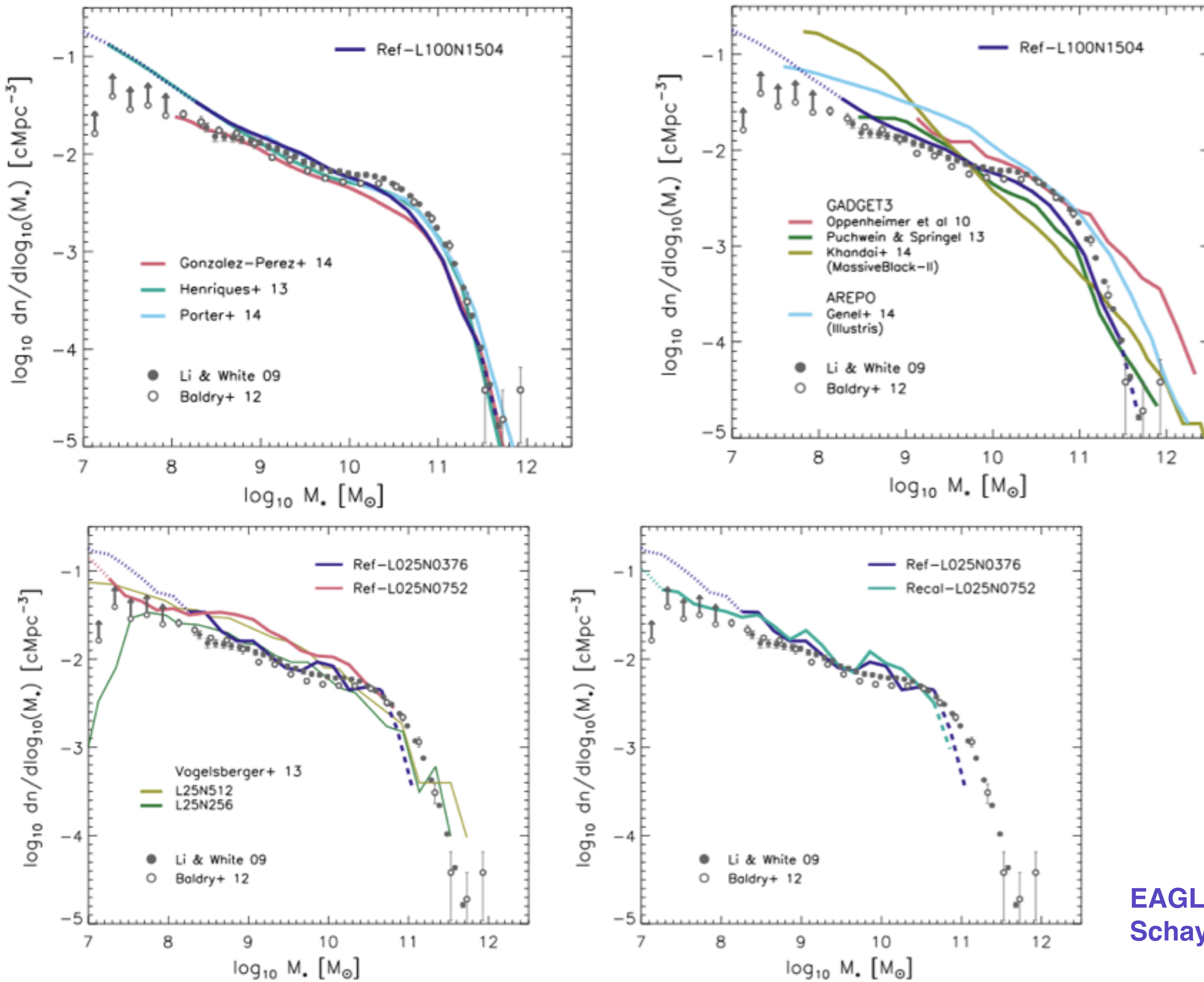
EAGLE sim: Schaye+ '15



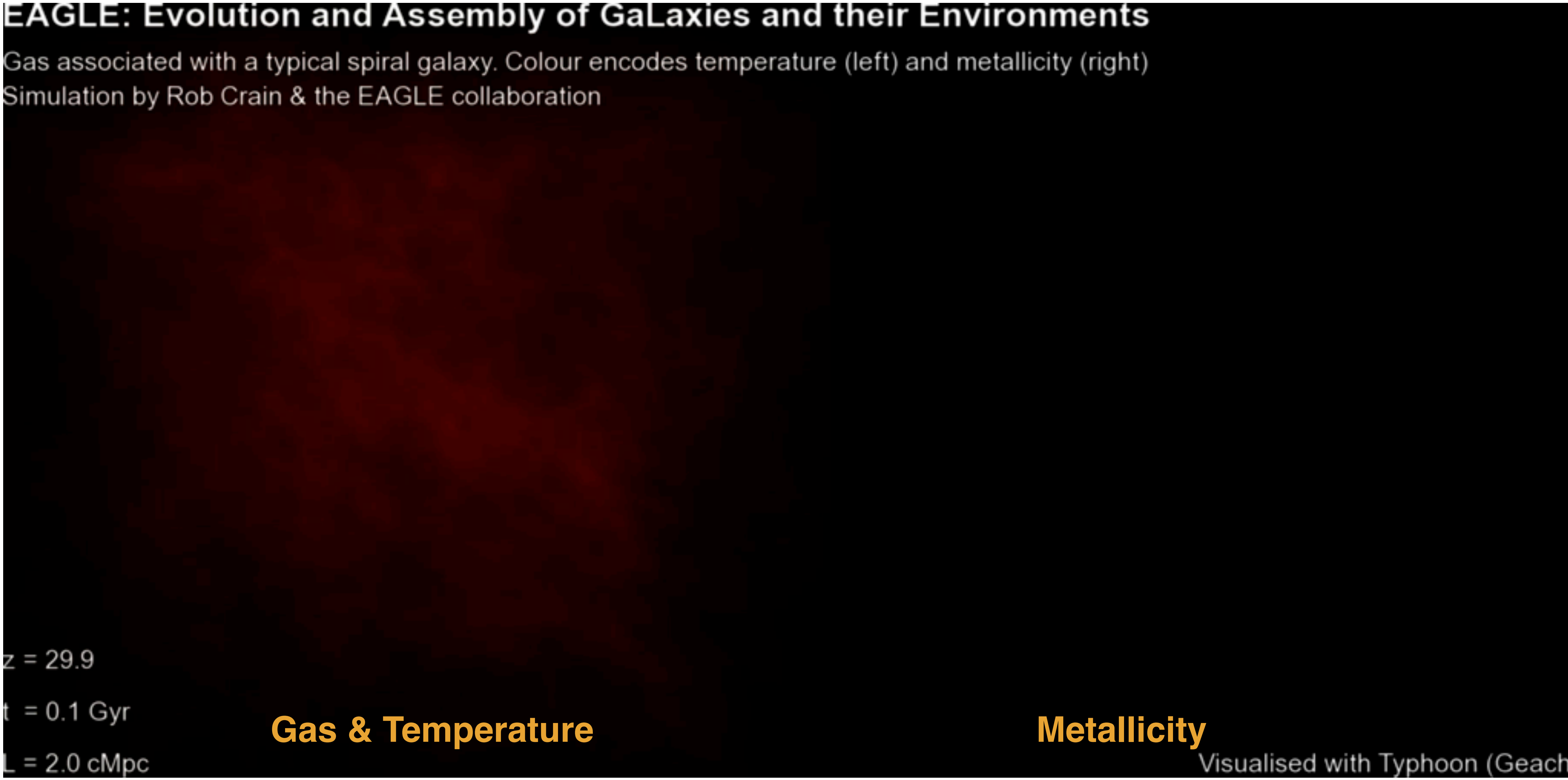
Too many stars are produced without SN FB.

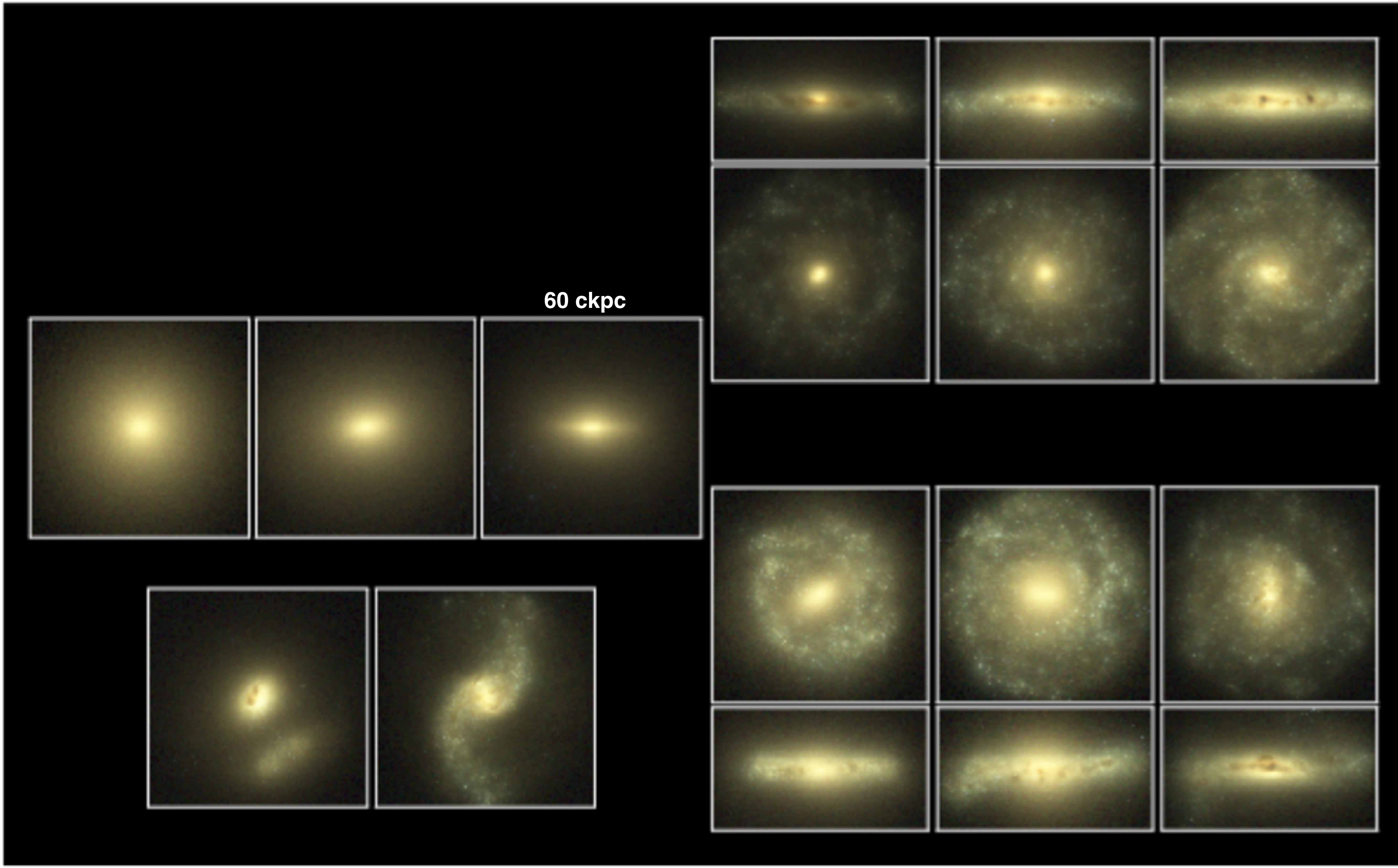


Galaxy Stellar Mass Function



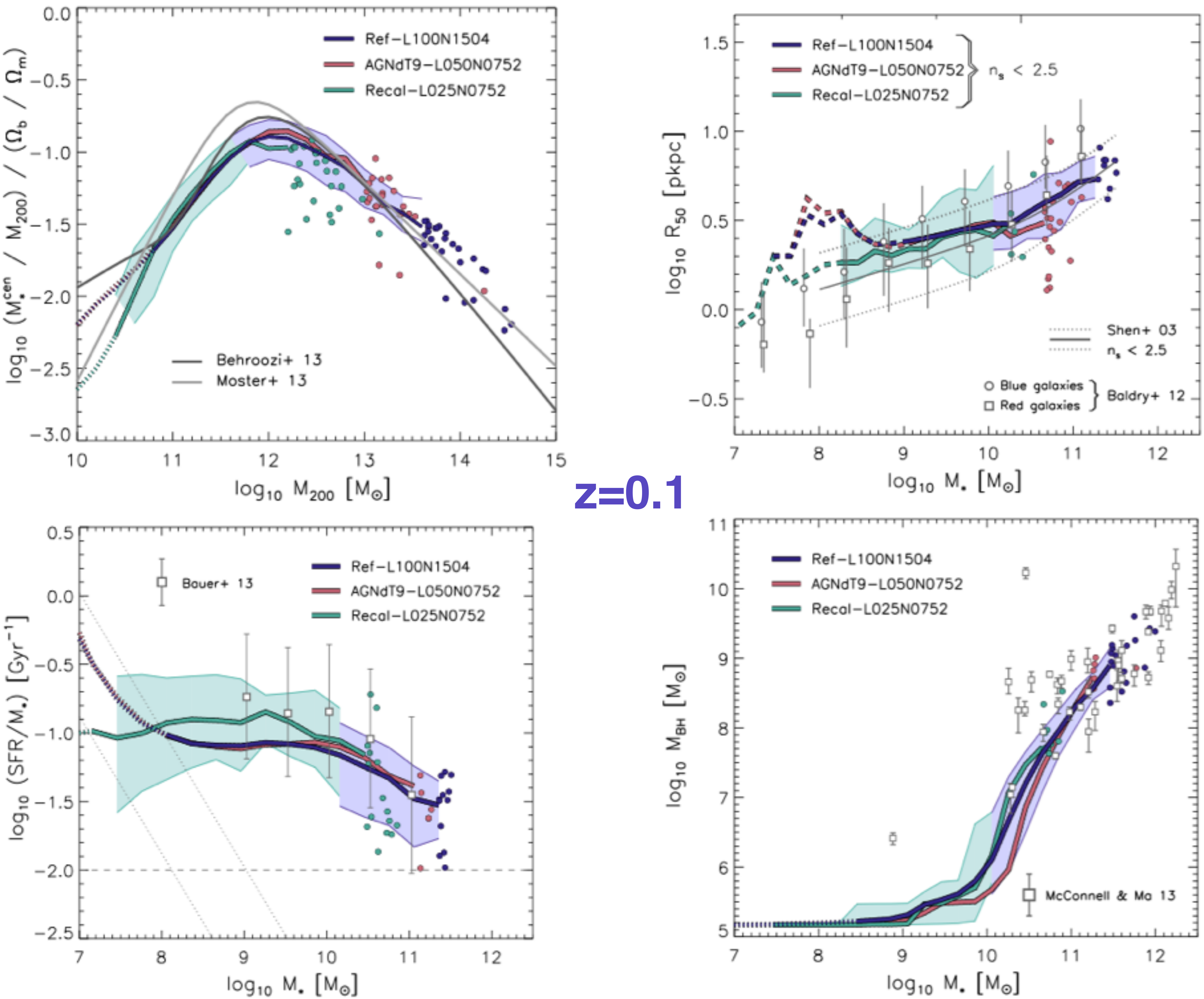
EAGLE sim: Schaye+ '15

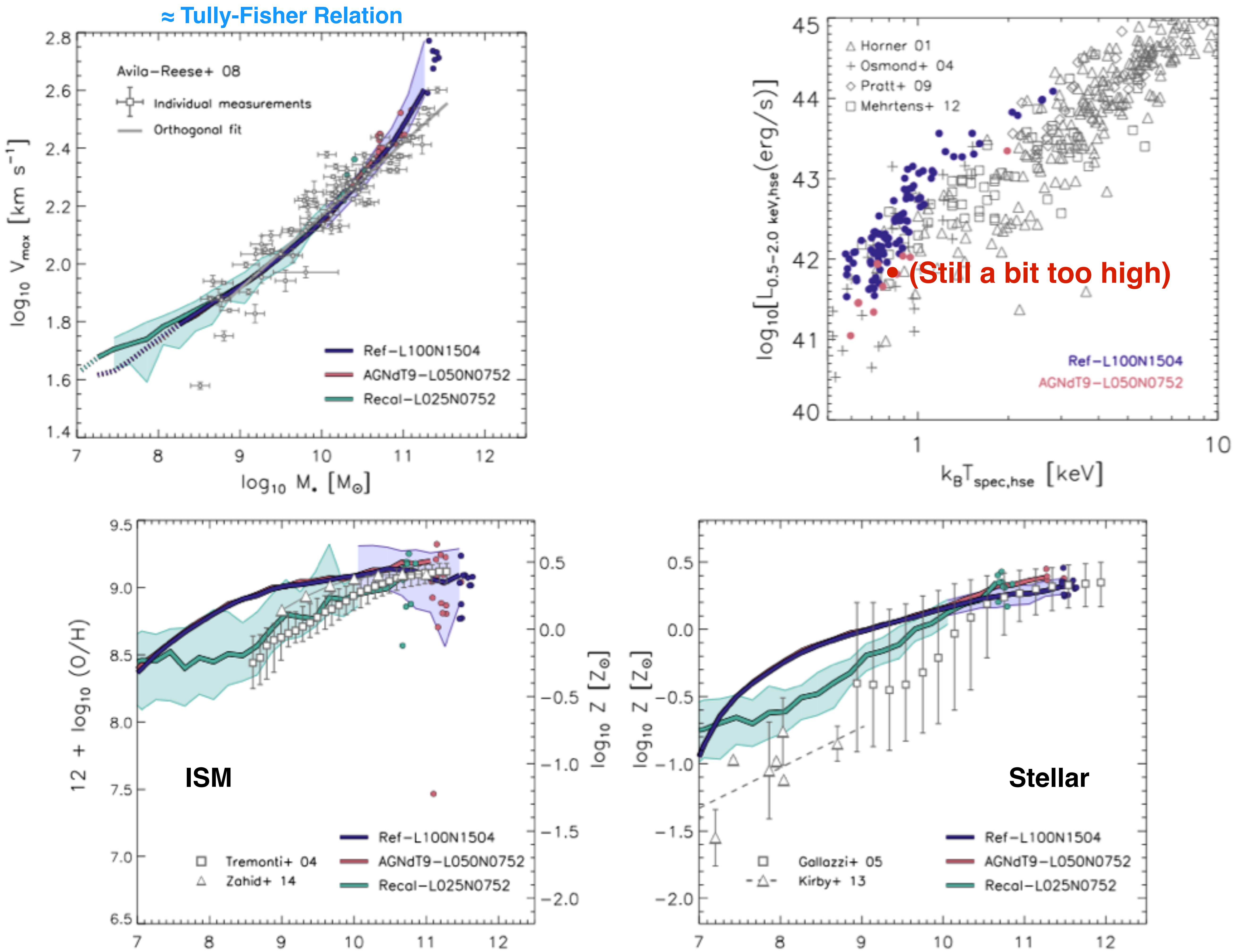

EAGLE: Evolution and Assembly of GaLaxies and their Environments
Gas associated with a typical spiral galaxy. Colour encodes temperature (left) and metallicity (right)
Simulation by Rob Crain & the EAGLE collaboration
z = 29.9
t = 0.1 Gyr
L = 2.0 cMpc
Gas & Temperature
Metallicity
Visualised with Typhoon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



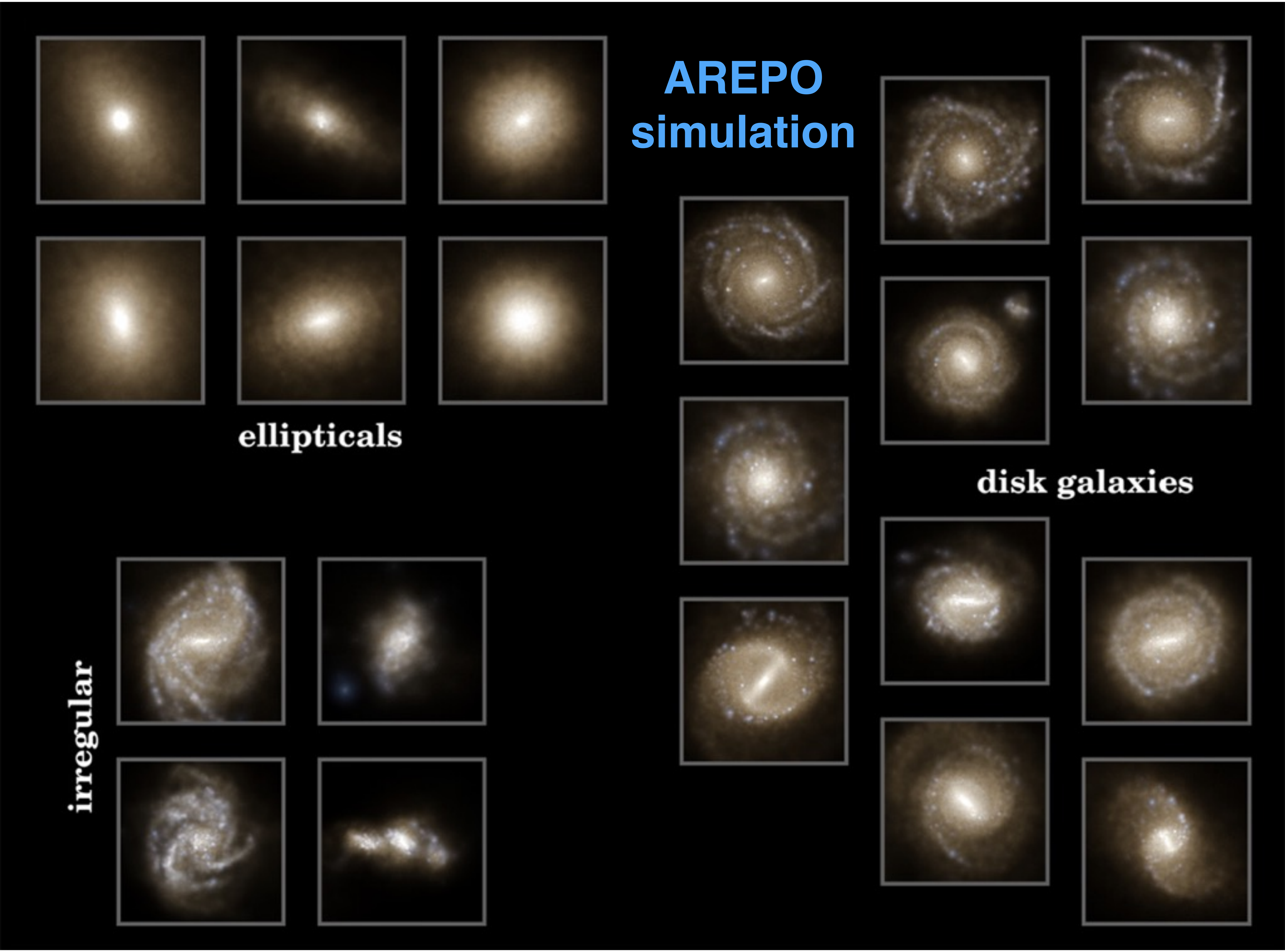
z=0
L100N1504 sim.

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


Ref−L100N1504
AGNdT9−L050N0752
Recal−L025N0752
Behroozi+ 13
Moster+ 13
log10 (M*cen / M200) / (Ωb / Ωm)
log10 M200 [M⊙]
ns < 2.5
Shen+ 03
Blue galaxies
Red galaxies
Baldry+ 12
log10 R50 [pkpc]
log10 M* [M⊙]
z=0.1
Bauer+ 13
log10 (SFR/M*) [Gyr−1]
McConnell & Ma 13
log10 MBH [M⊙]



≈ 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]
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☉]


AREPO
simulation
ellipticals
disk galaxies
irregular

Stellar Feedback

(in addition to SN feedback)

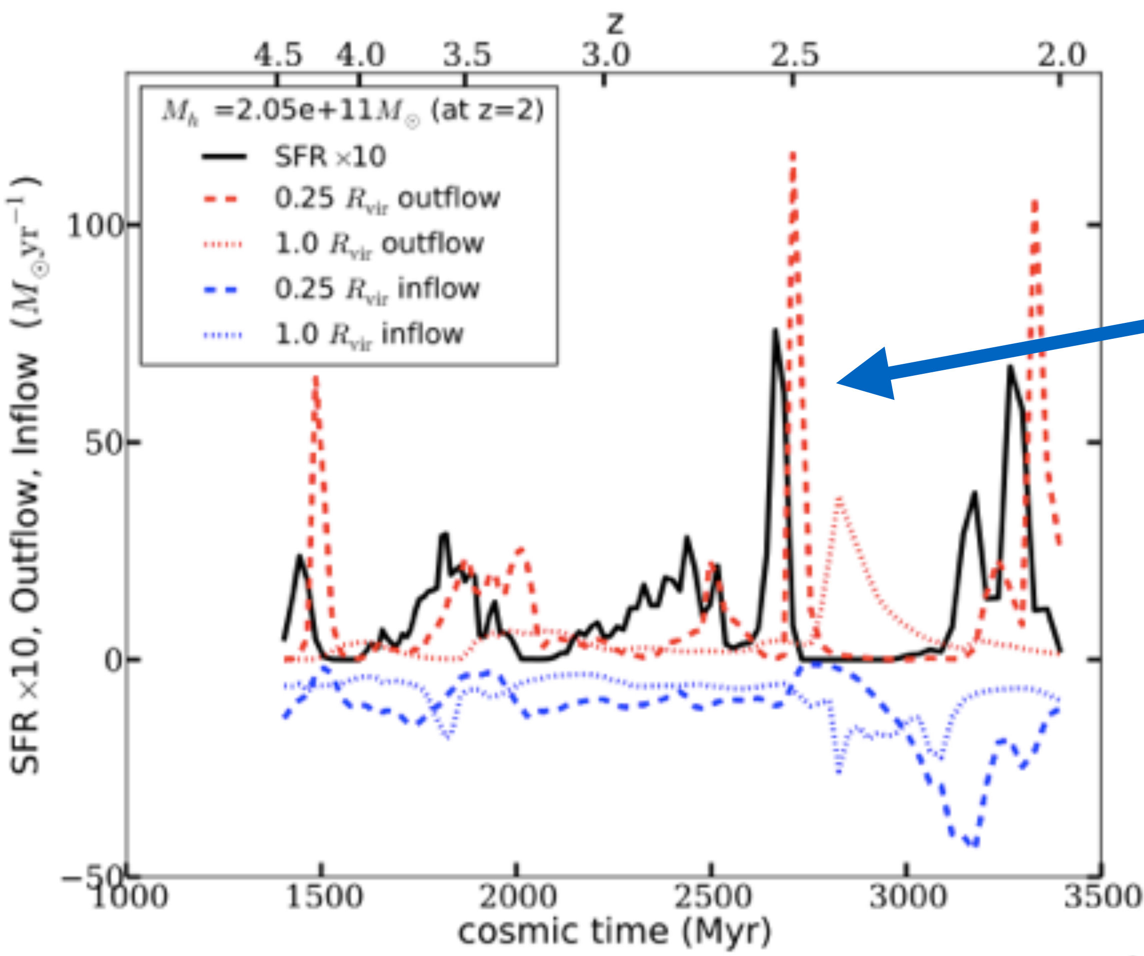
- stellar winds from young stars (“Early” stellar FB)
- radiation pressure $\dot{P}_{\rm rad} \approx (1 - \exp(-\tau_{\rm UV/optical}))\,(1 + \tau_{\rm IR})\,L_{\rm incident}/c$
  - dust absorption of UV —> IR emission
- photo-ionization + photo-electric heating
  (alters future heating/cooilng rates)

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

Hopkins+ ’13, …

Stellar Feedback in Zoom-in Sim

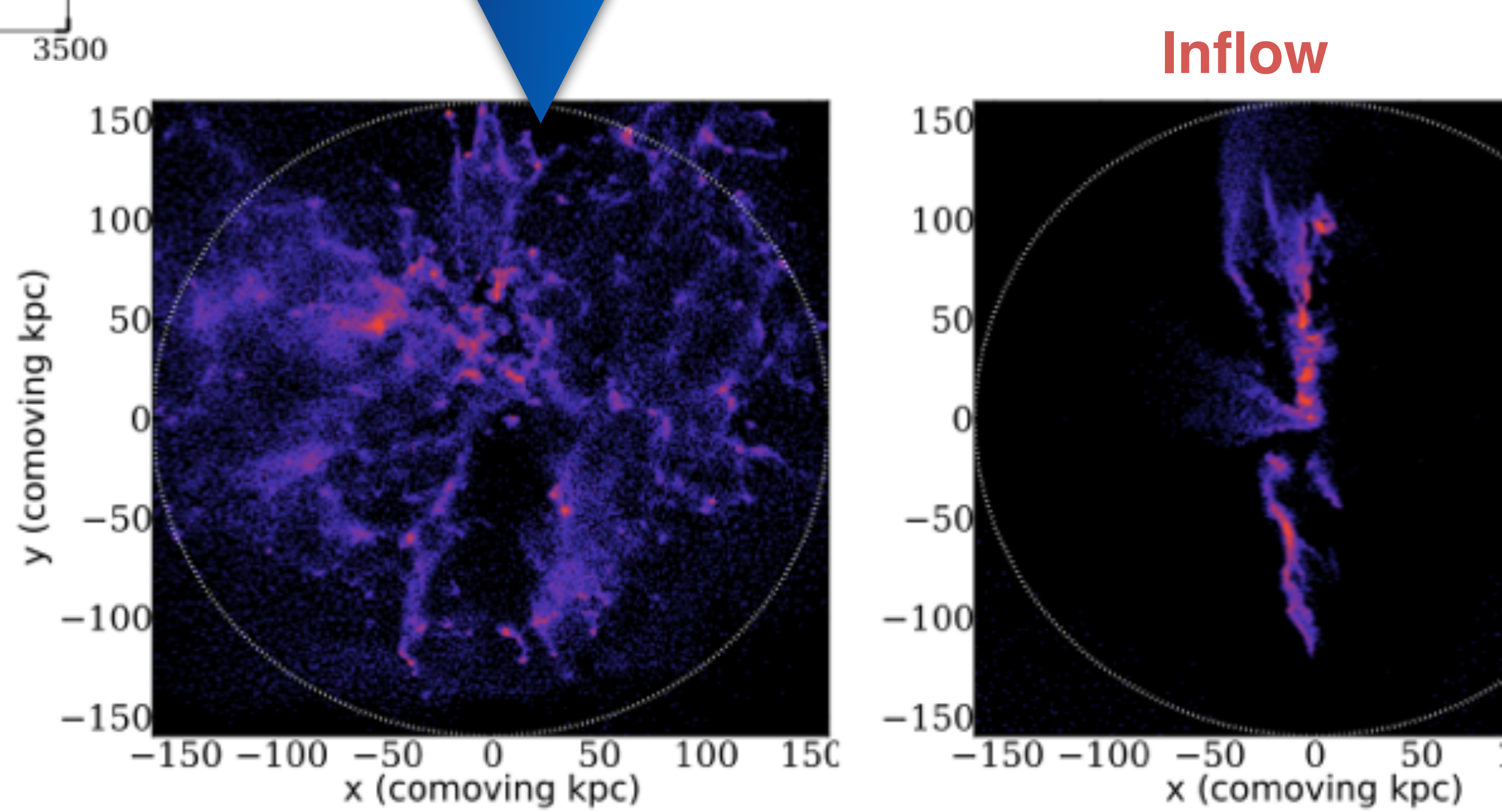
(Cosmological Initial Condition)



- Star formation is episodic.

(KN+'05; Jaacks+'12)

- 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

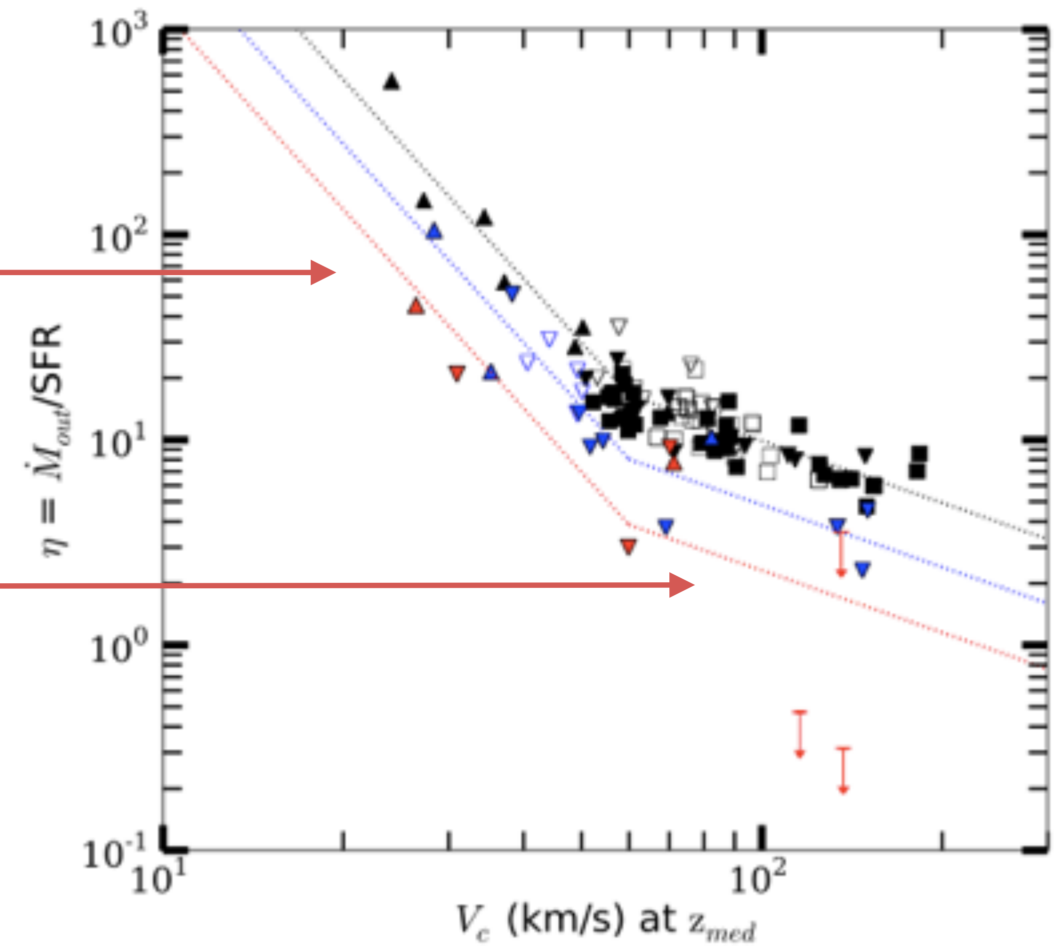
Mass Loading Factor : η

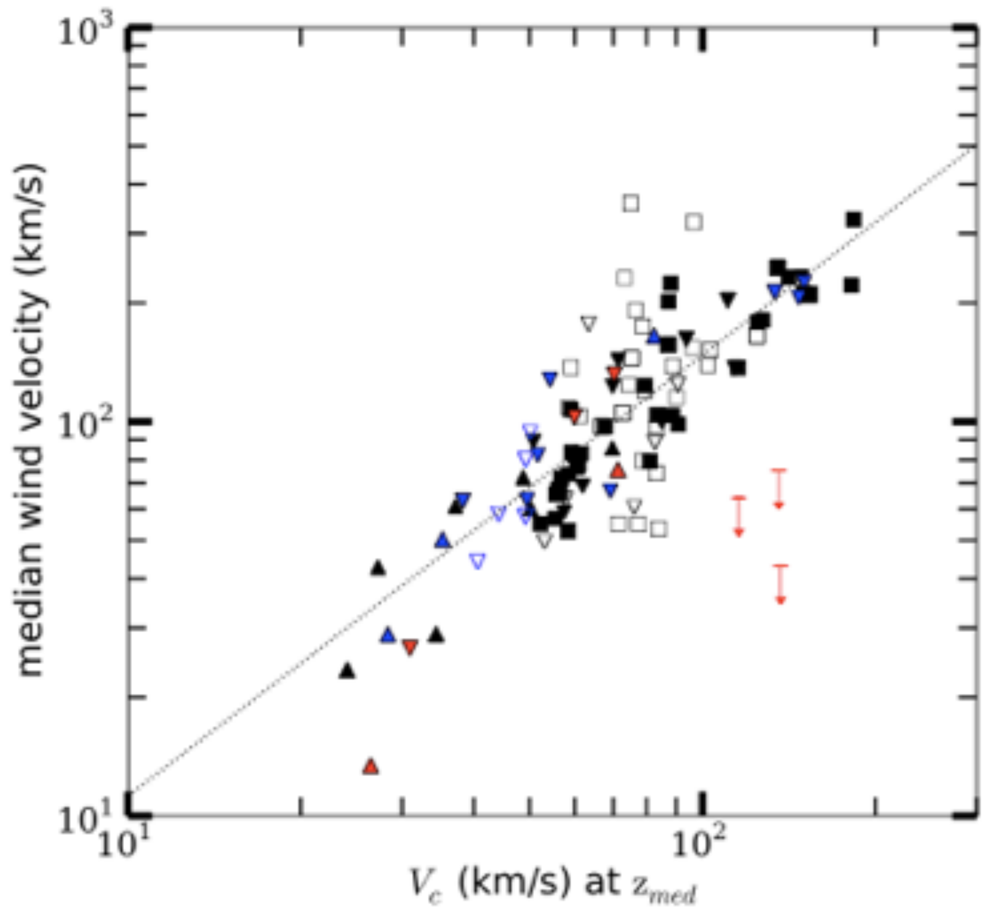
$$\eta = 2.91\,(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-3.22}$$

(steeper than Energy-driven)

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

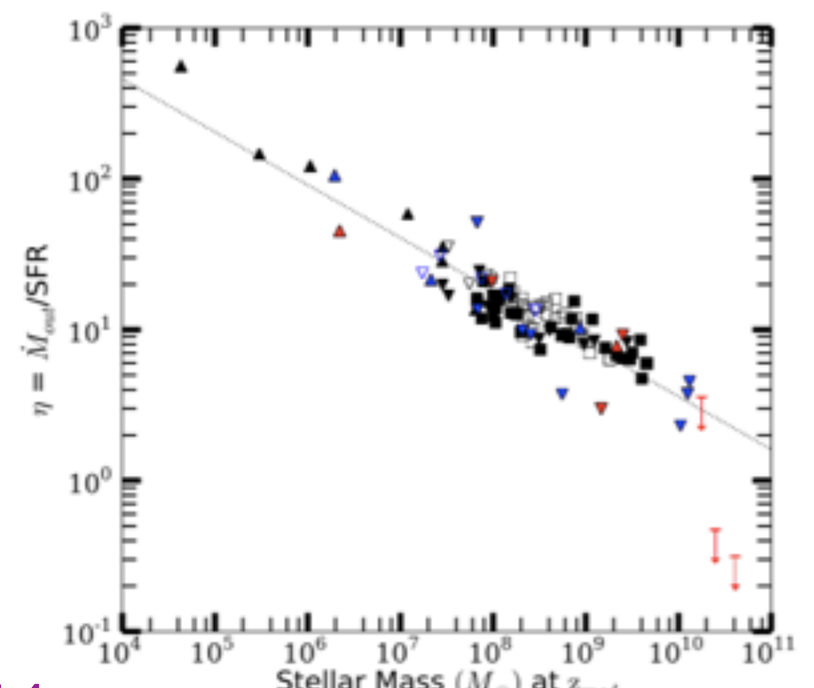
(≈ Momentum-driven)





Wind Velocity

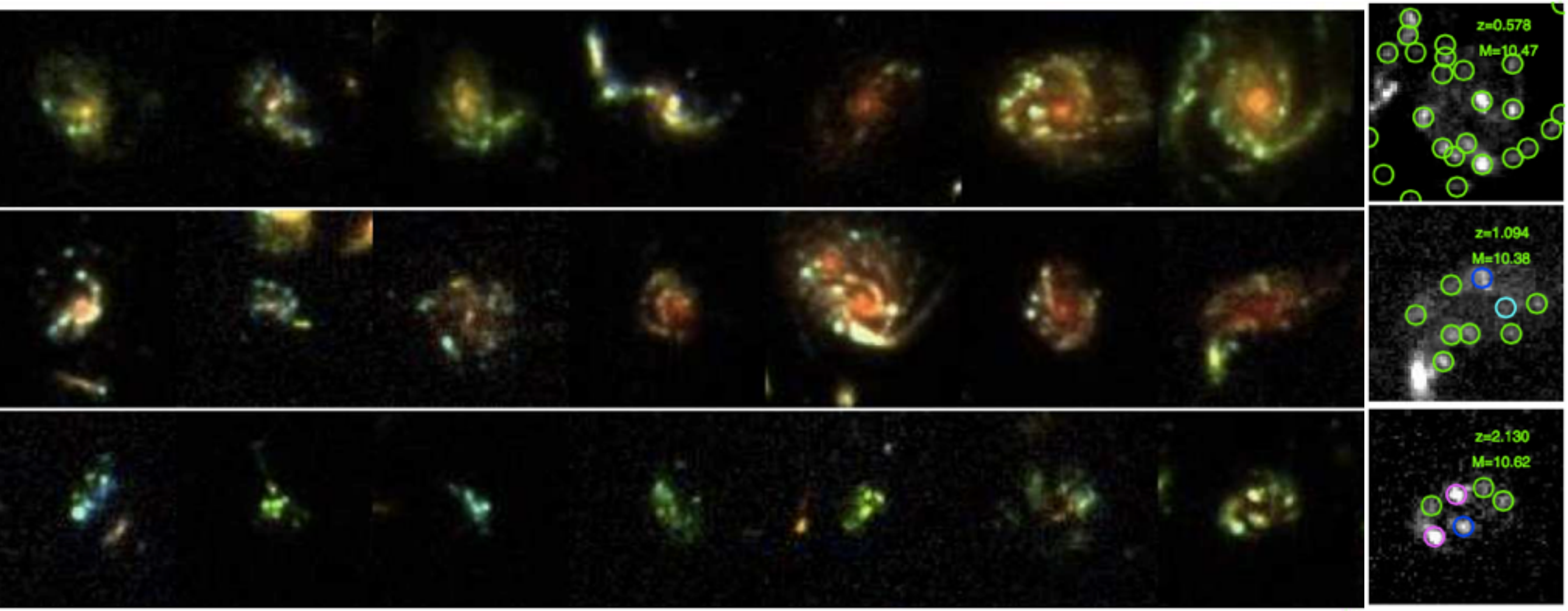
($V_w \sim V_c \sim M_h^{1/3} \sim SFR^{1/2}$)



Hopkins+'13; Muratov+ '14

Clumpy High-z Galaxies

CANDELS (Guo+'15)

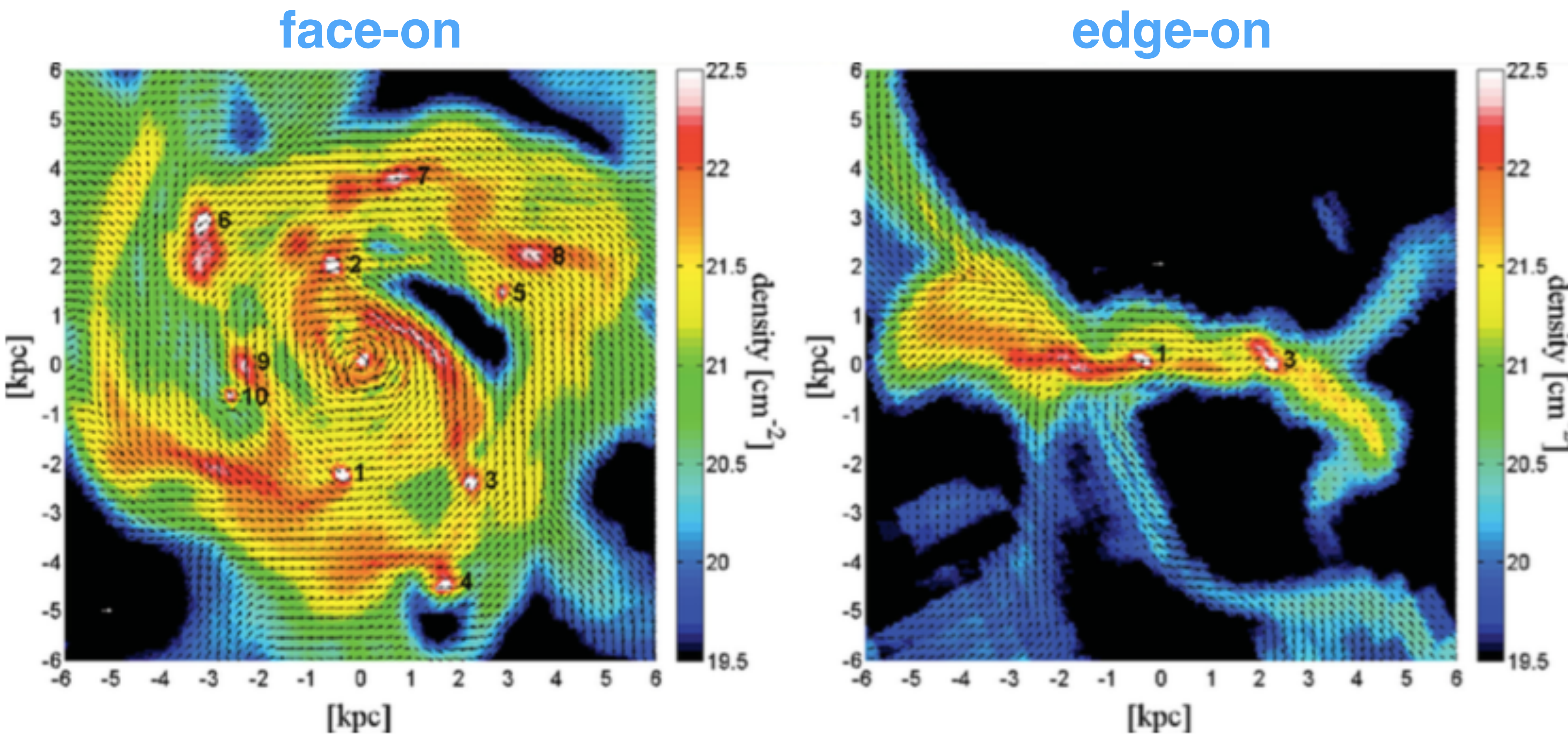


- f_{clump}~60% @ z=0.5-3 for $\log M_* < 10$
- Clumps contribute ~4-10% of total SFR

(cf. Colley+ '96, '97)

Clumpy High-z Galaxies in Simulations

Violent, turbulent, warped disks

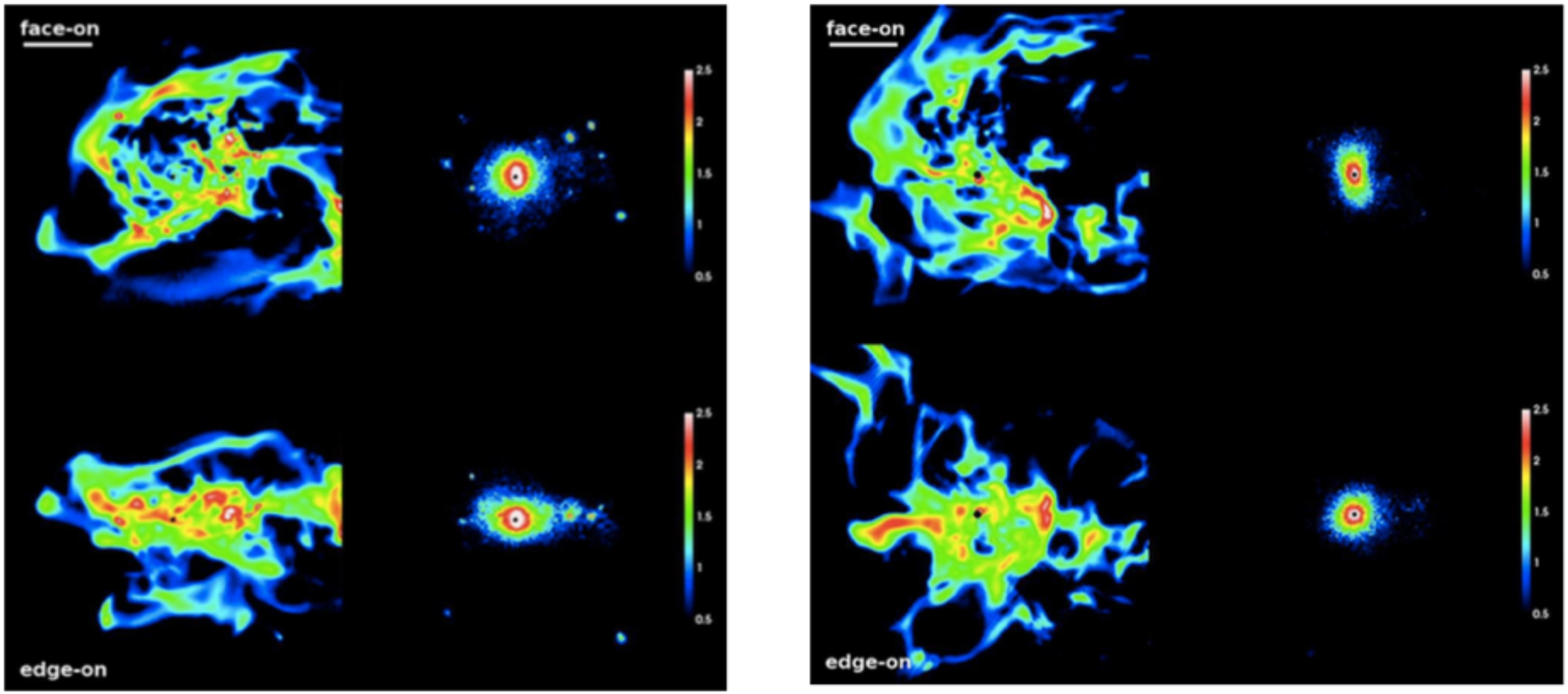


Clump themselves seem to be in Jeans equilibrium.

Ceverino+ '12

Radiation Pressure & Clumpy High-z Galaxies

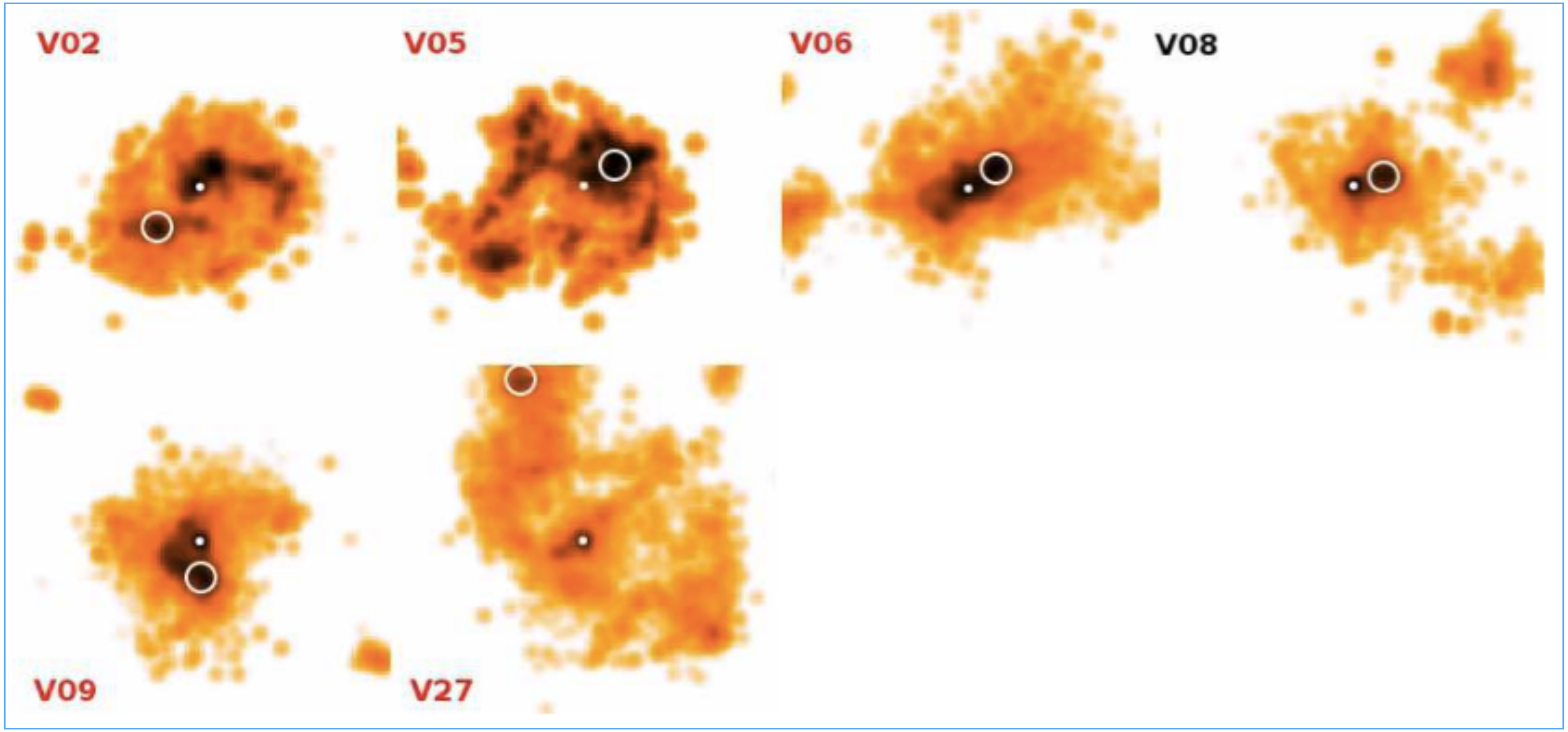
W/out P_{rad} With P_{rad}



- High-ρ clumps disappeared due to P_{rad}.
- More extended gas envelopes.

Ceverino+ '14

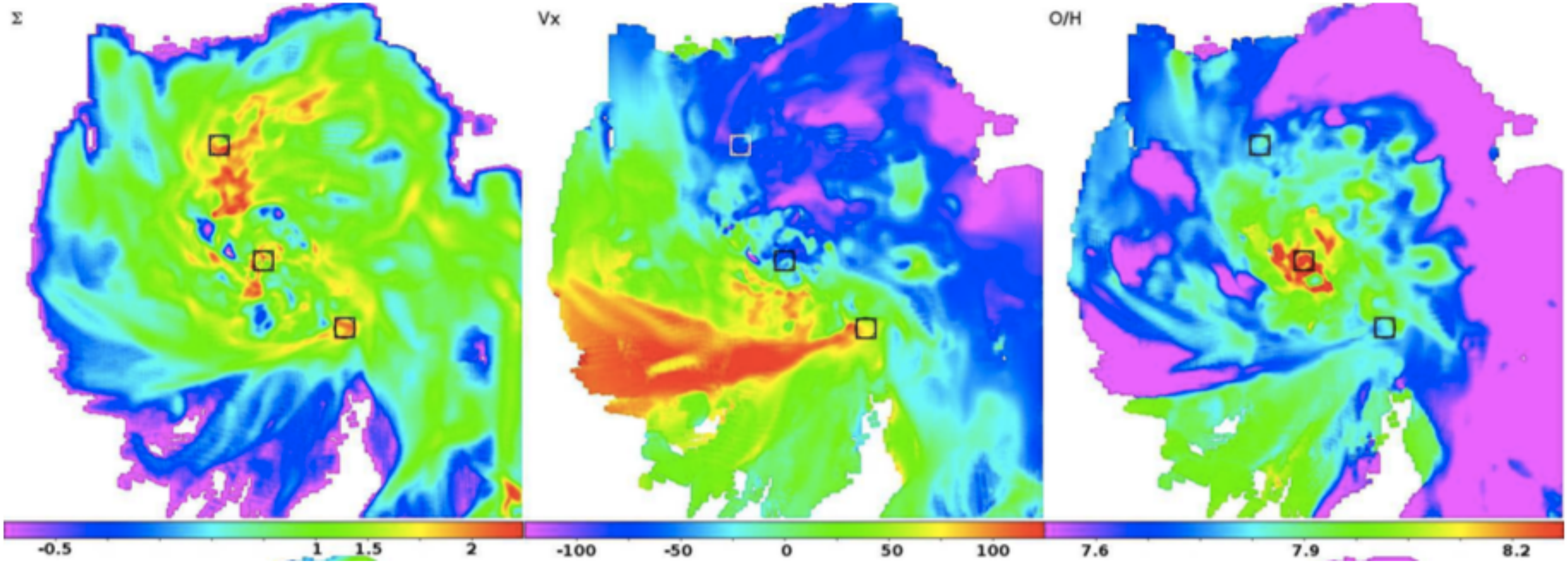
Same sims viewed in Hα (i.e. SFR)



(but no treatment of dust extinction & rad. transfer yet.)

Ceverino+ '15

Velocity Fields (for IFU)

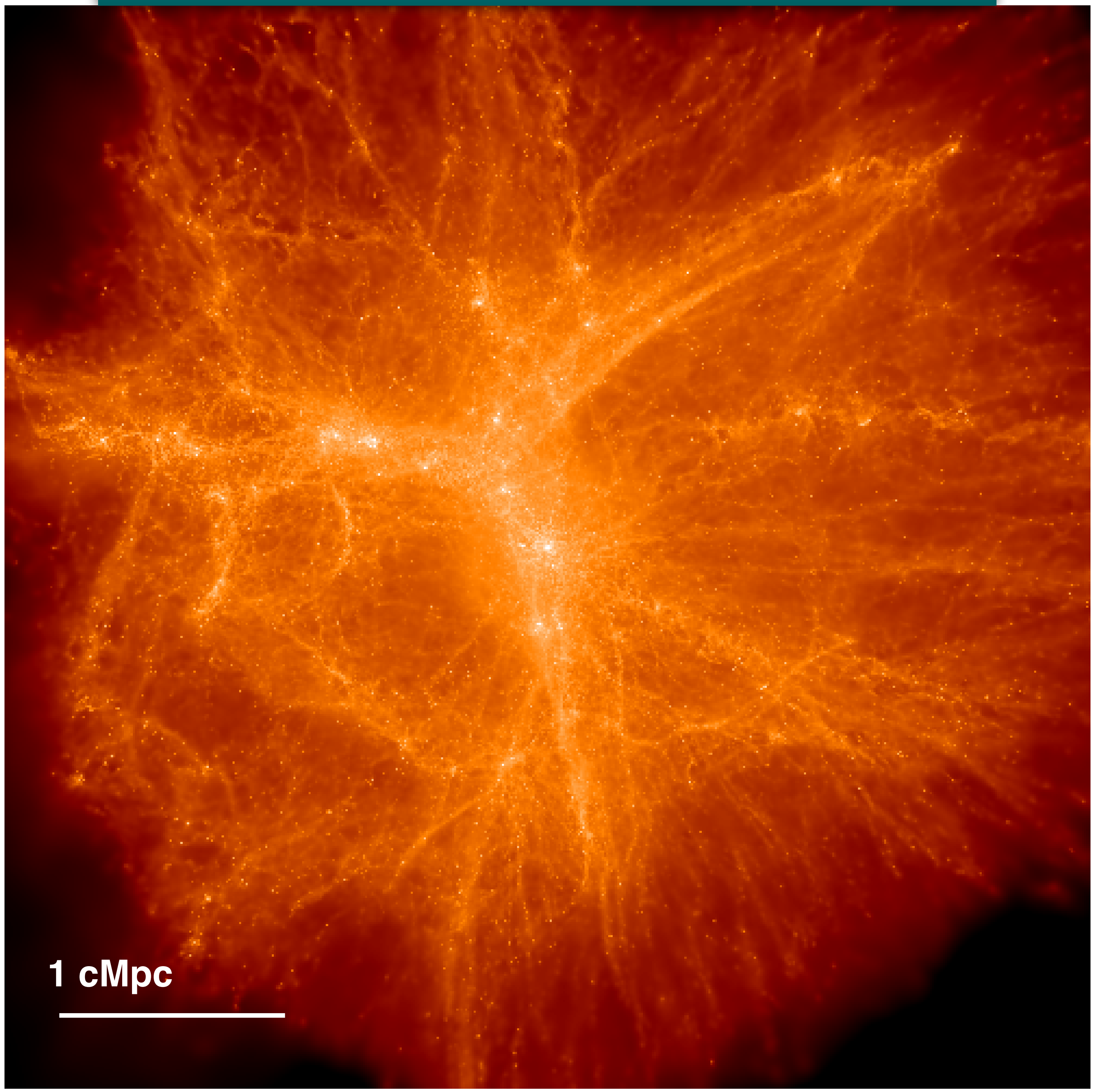


Low metallicity inflow penetrates into high-z disk, then forms Hα bright clump.

Ceverino+ '15

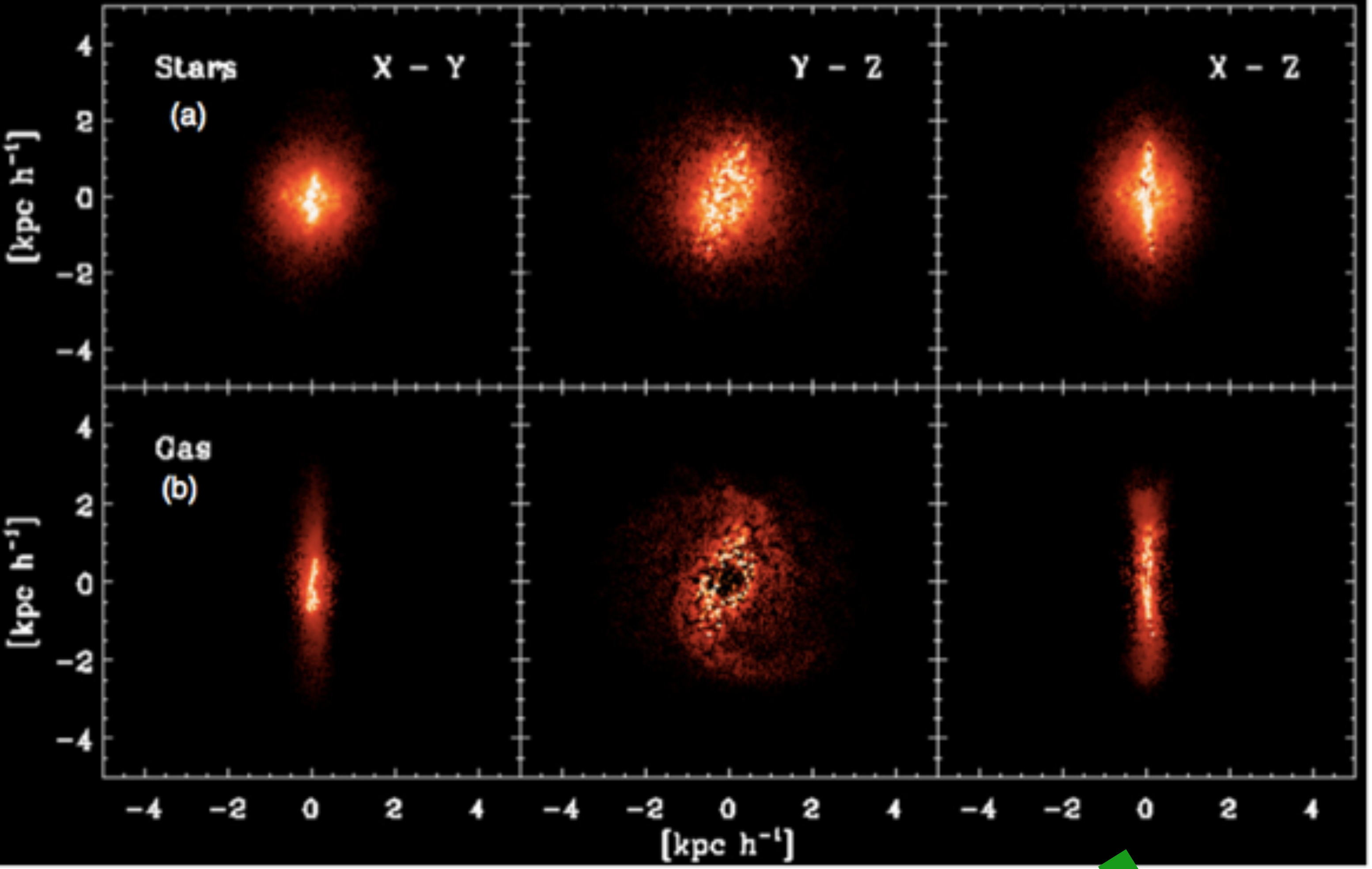
Another Example of Zoom-in Sim

Constrained Realization



(Romano-Diaz+'11, '13 sim)

- `Quasar host'-like 5-σ region (20 cMpc/h)
- 3.5 cMpc/h zoom-in region
- ϵ=300 com pc; ~30pc (proper @z~10)
- m_{dm}~5e5 $M_\odot$
- m_{gas}~1e5 $M_\odot$



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 $\sim 2.9 \times 10^{9}\ h^{-1}\ M_\odot$

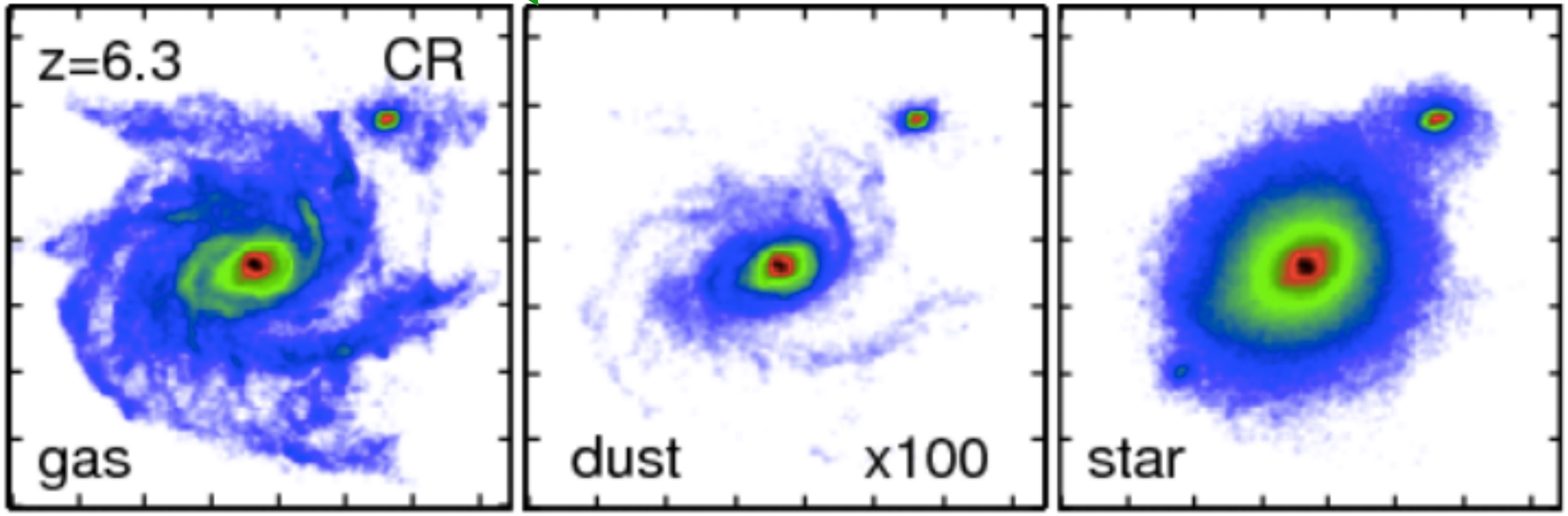
$M_{star,disk} \sim 8 \times 10^{8}\ h^{-1}\ M_\odot$

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

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

z=6.3

Yajima+ '15



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

Very high SFR

The most massive galaxy:

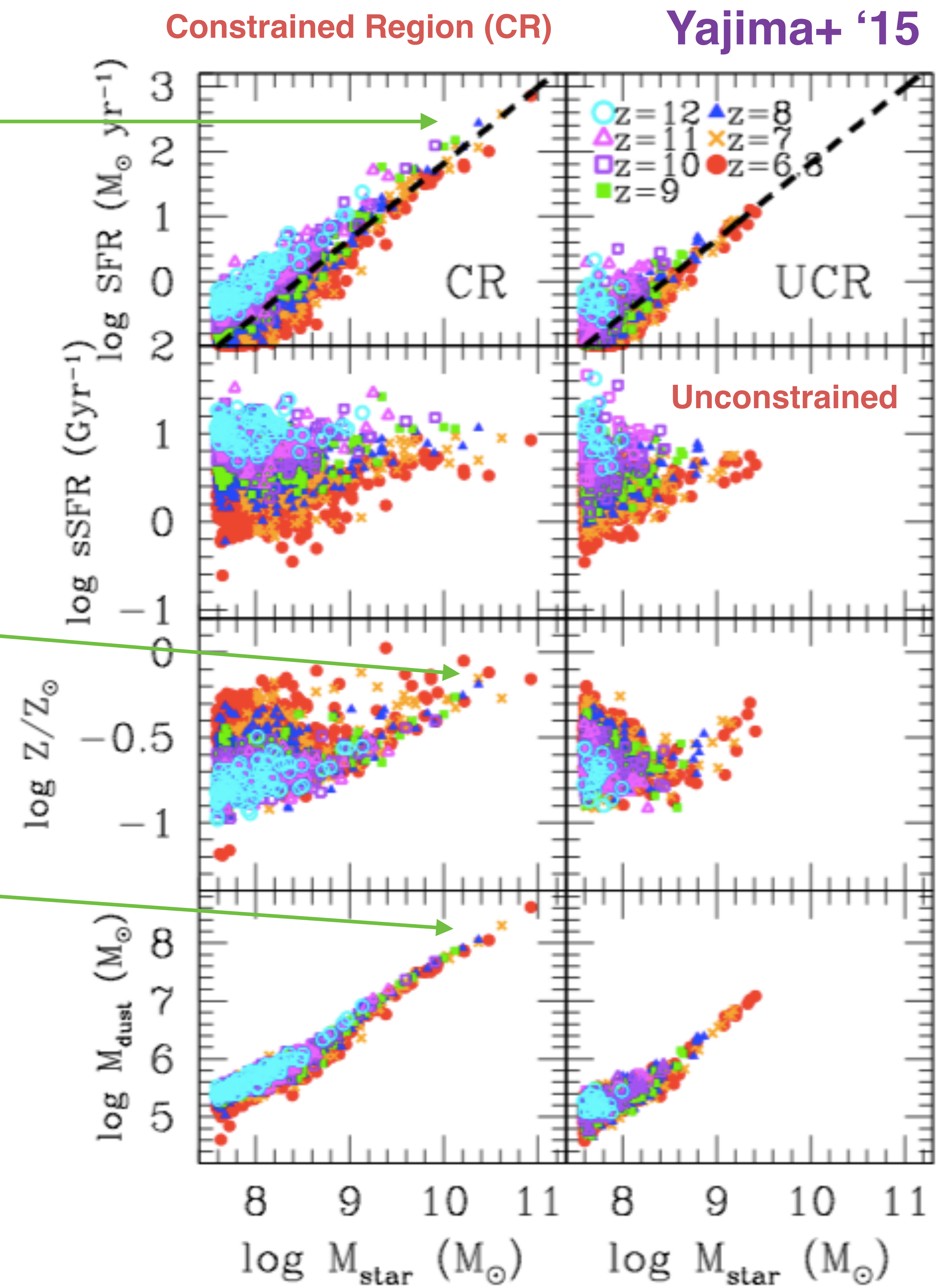
Mstar ~ 8.4×10^{10} $M_{\odot}$,

Mdust ~ 4.1×10^{8} $M_{\odot}$,

SFR ~ 745 $M_{\odot}$ yr^{-1} (z=6.3)

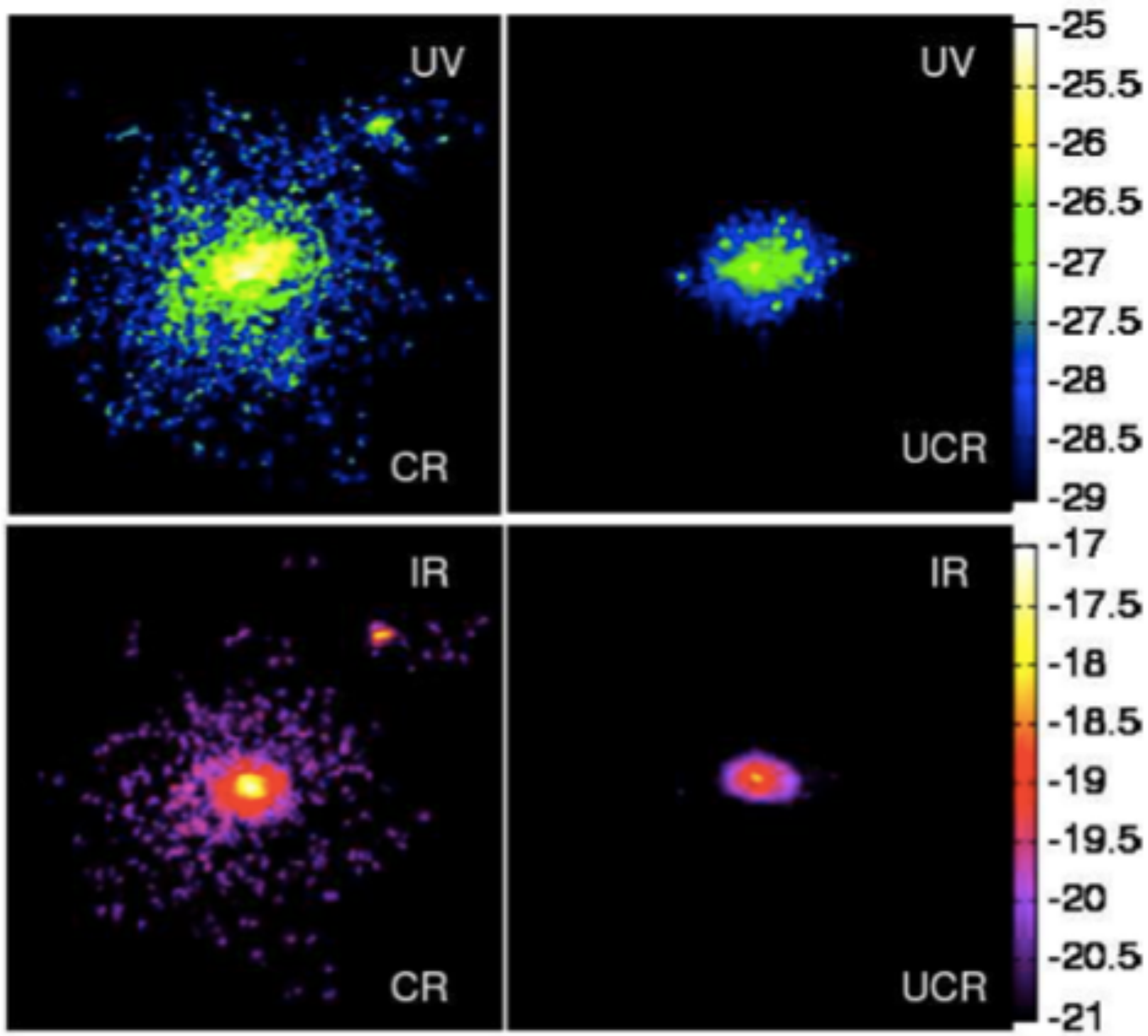
Close to solar metallicity

Large amount of dust in massive gals



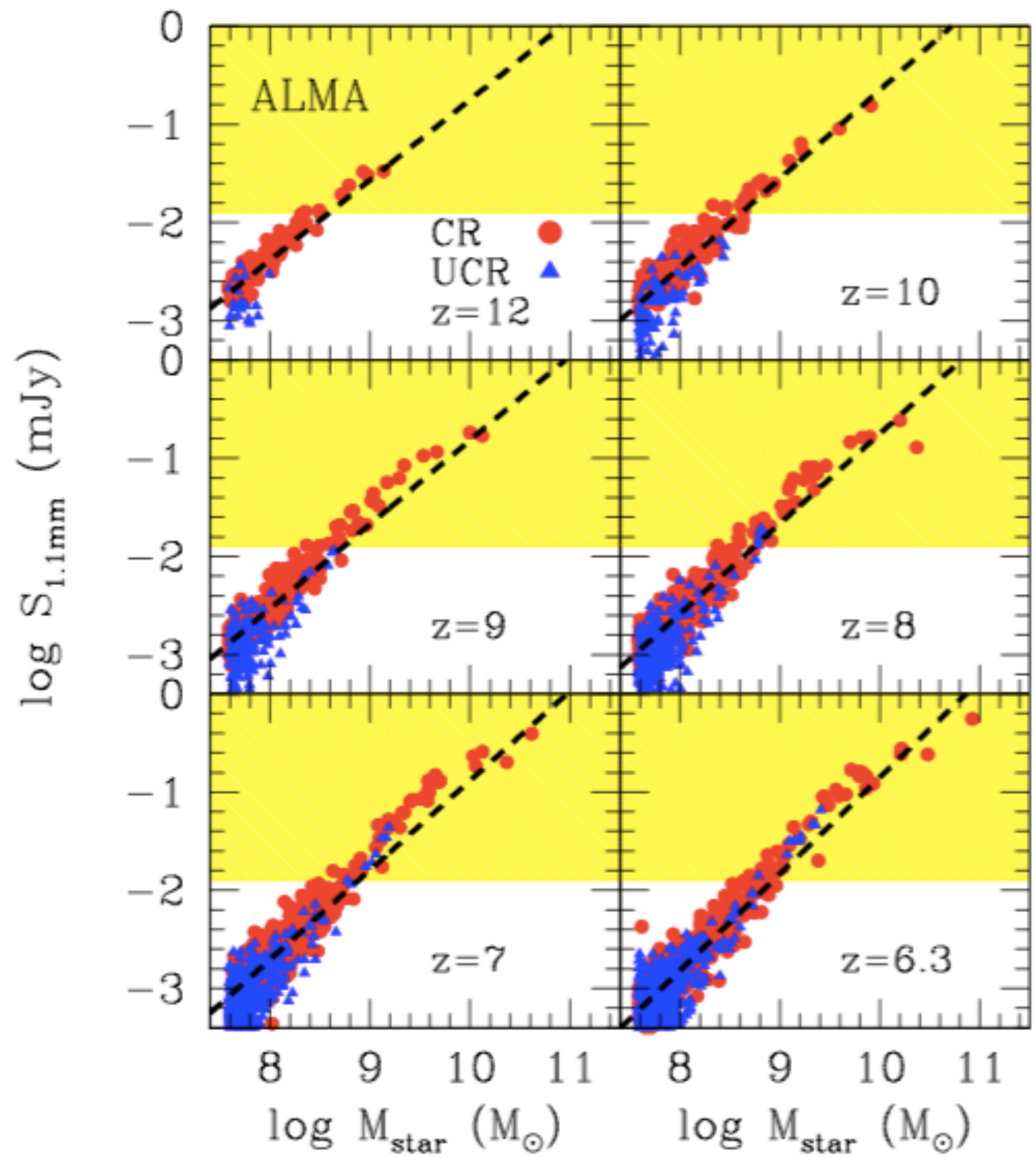
ALMA Observability

UV: 1600 A rest-frame



IR: 106 μm rest (850 μm obs)

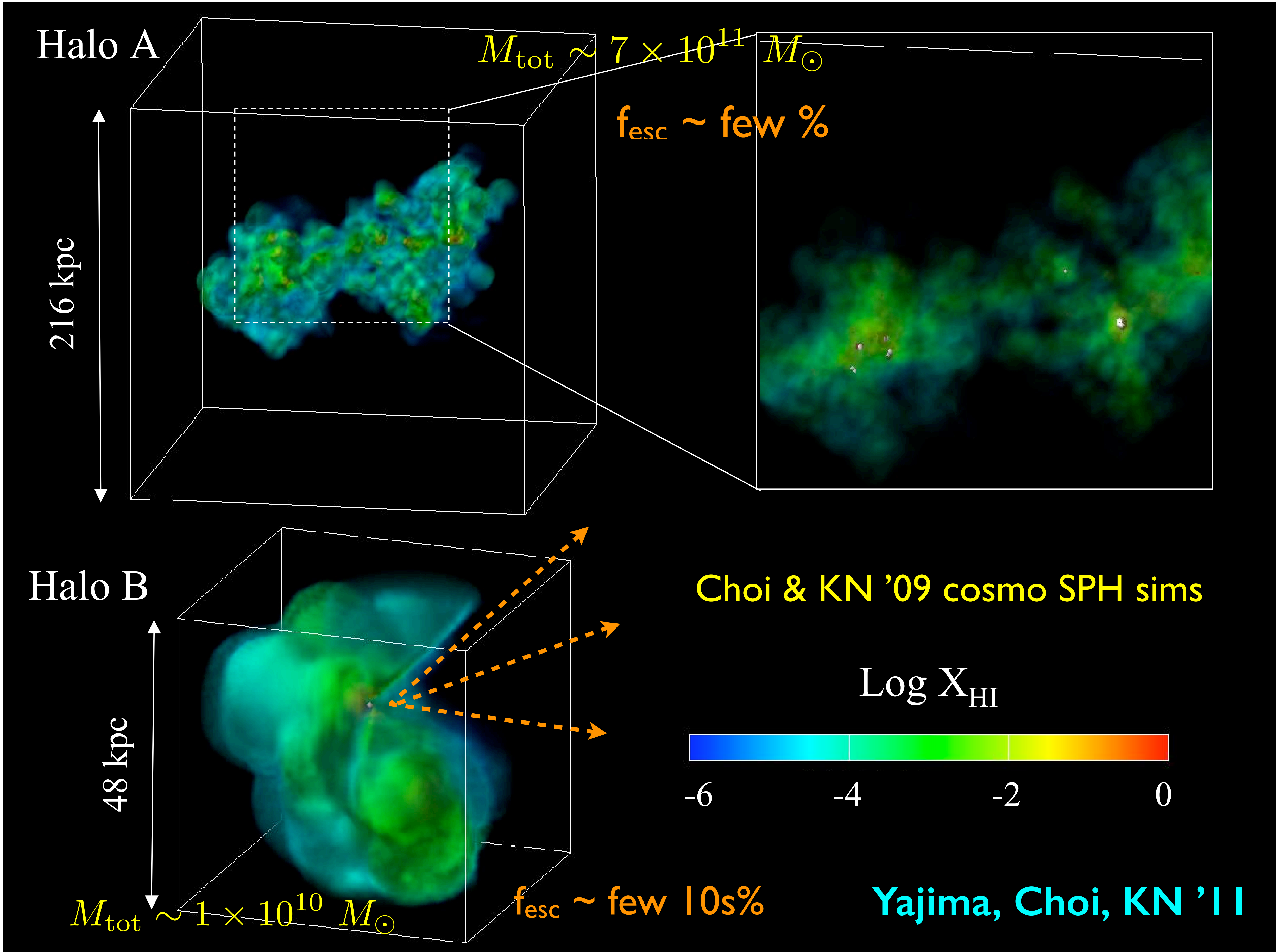
surface brightness in the log scale in units of [erg s^{-1} cm^{-2} Hz^{-1} $arcsec^{-2}$]



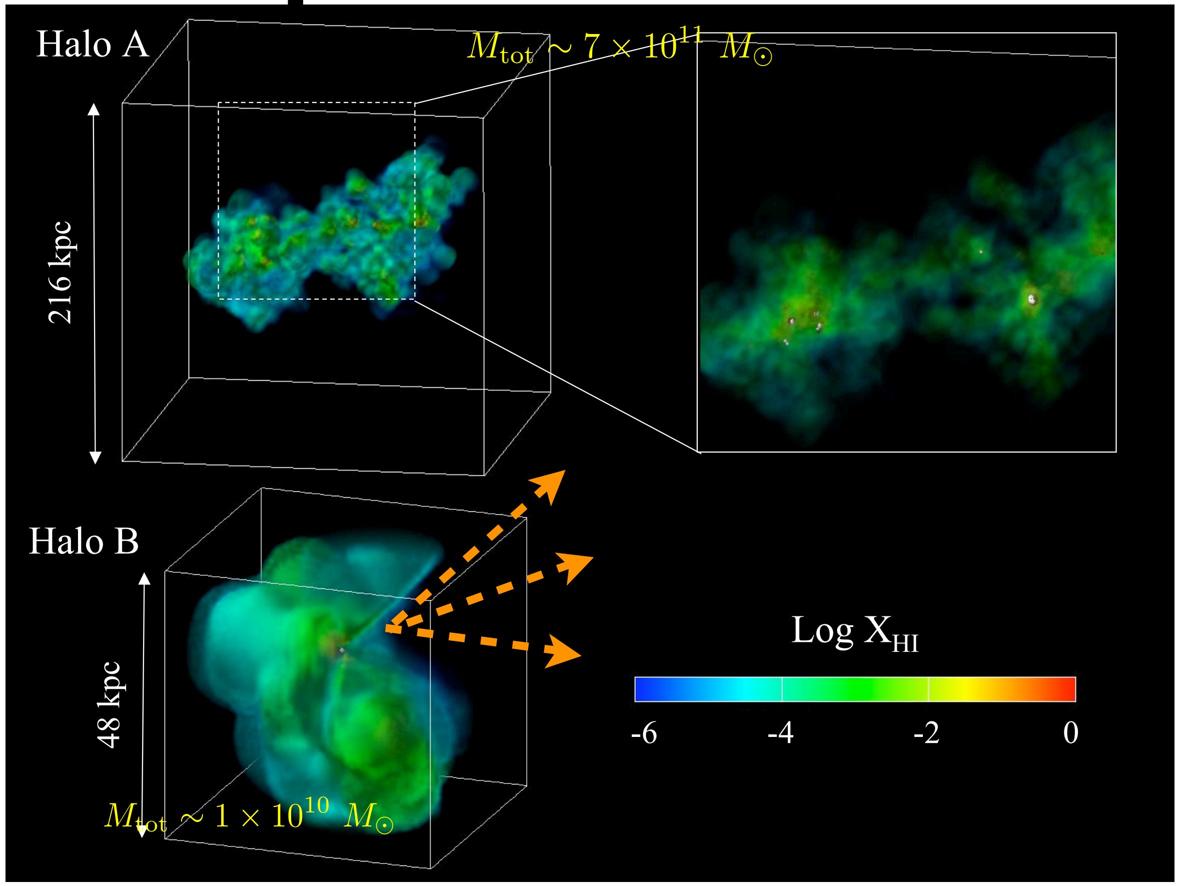
Yajima+ '15

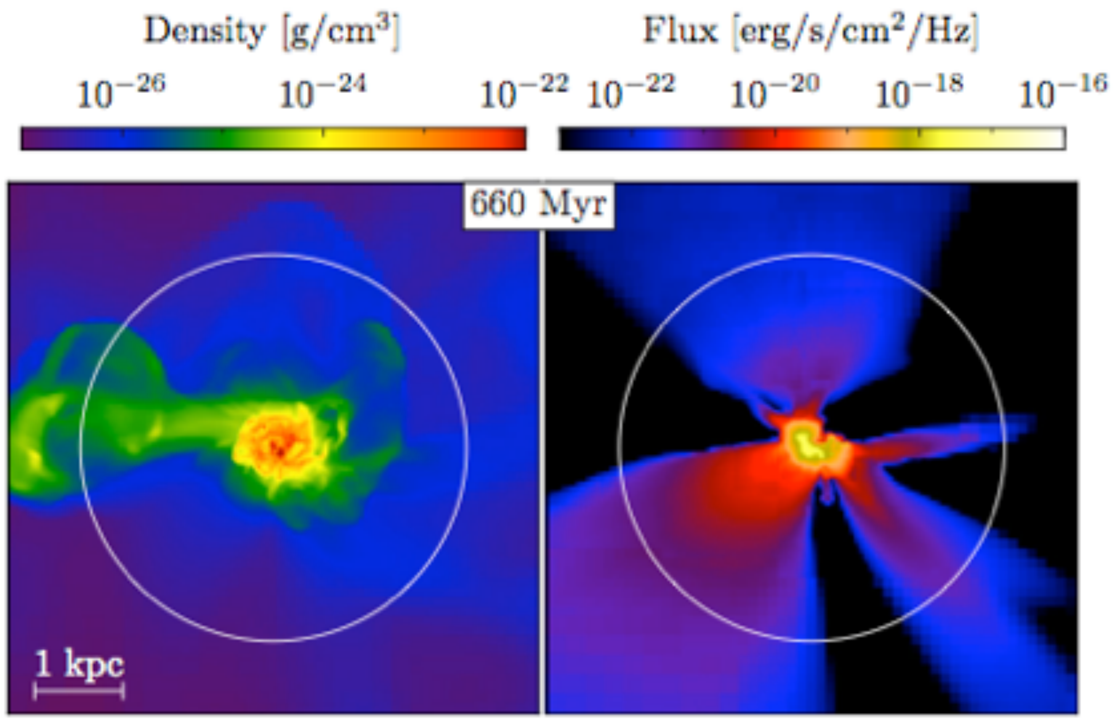
Escape Fraction of Ionizing Photons

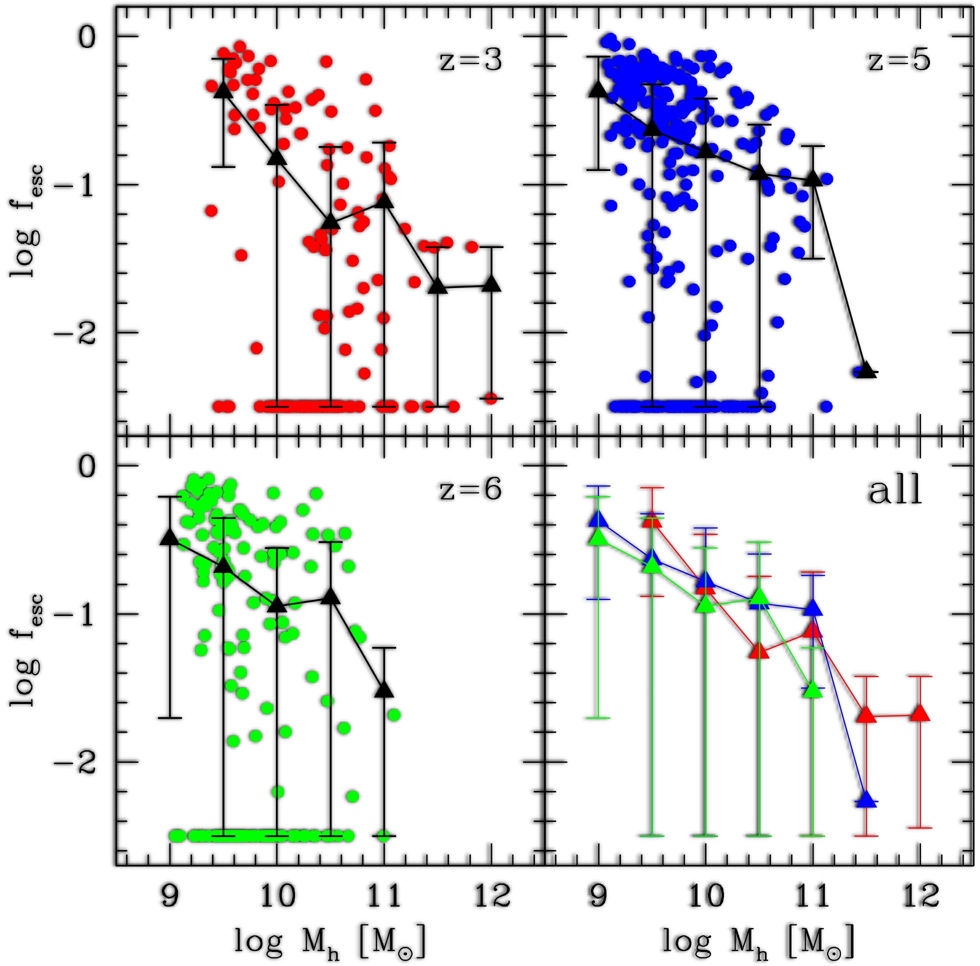
Authentic Ray Tracing method
(Nakamoto+ '01, Illiev+ '06, Yajima+ '09)

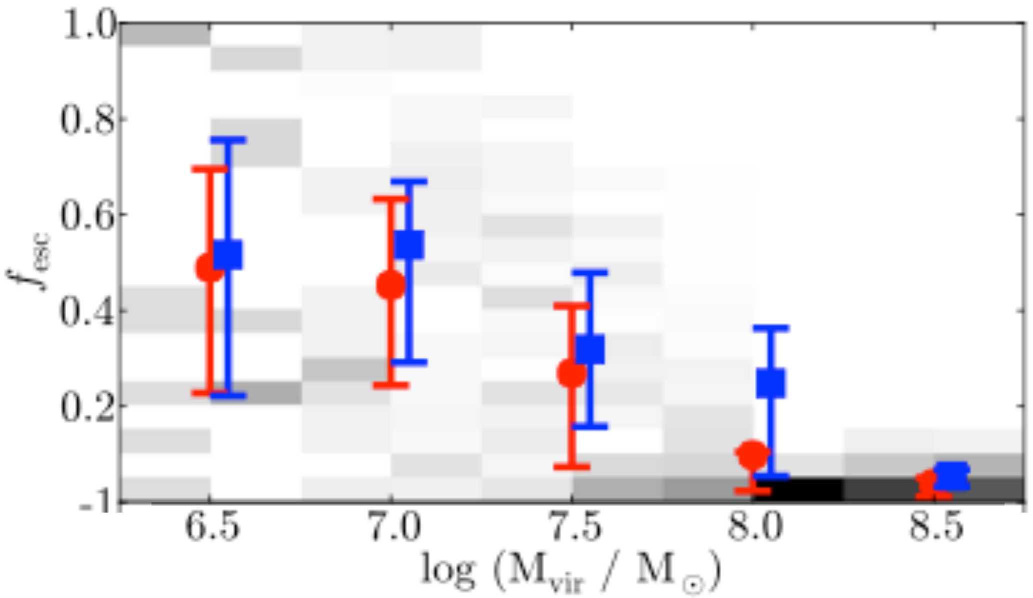


Escape Fraction of Ionizing Photons







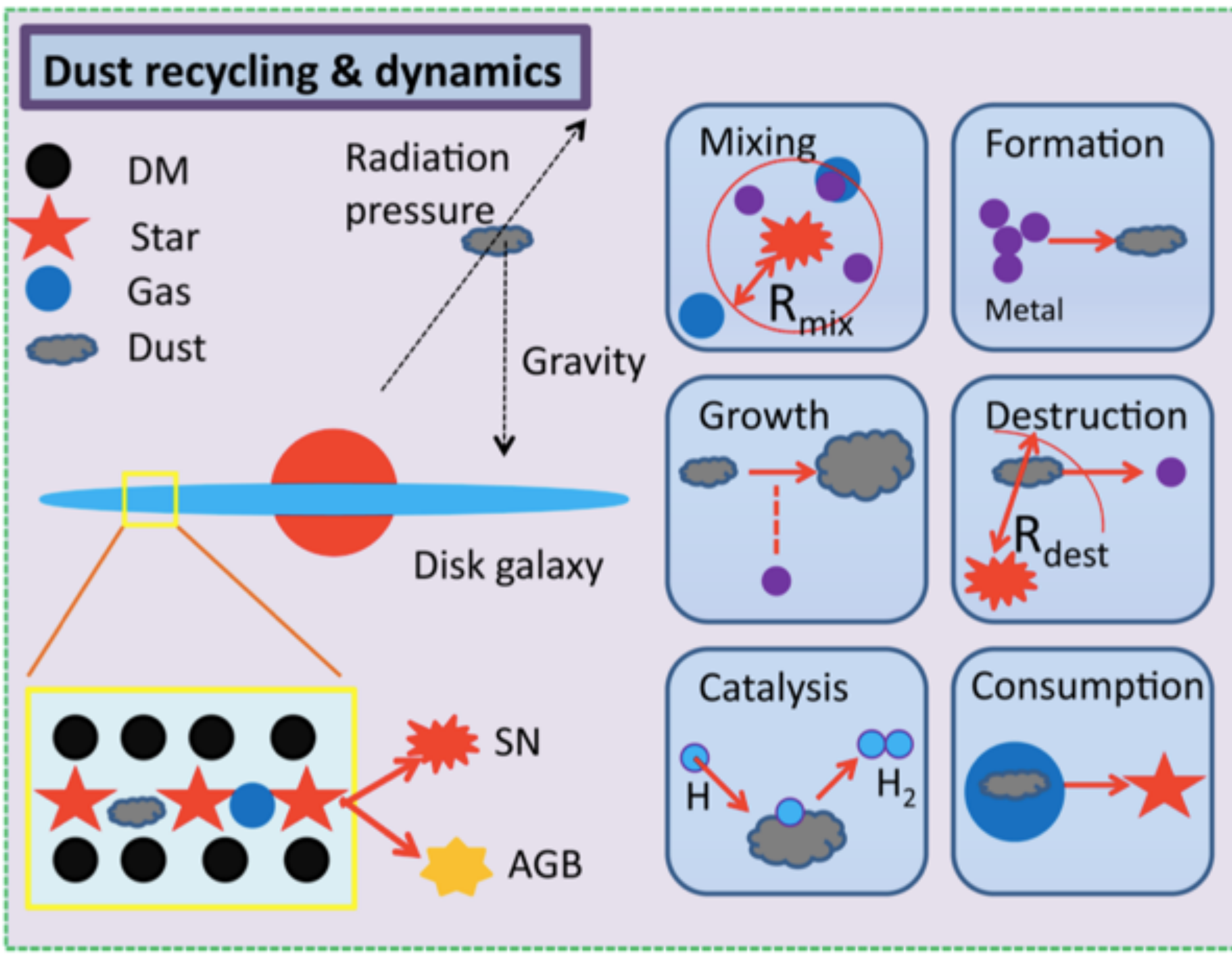


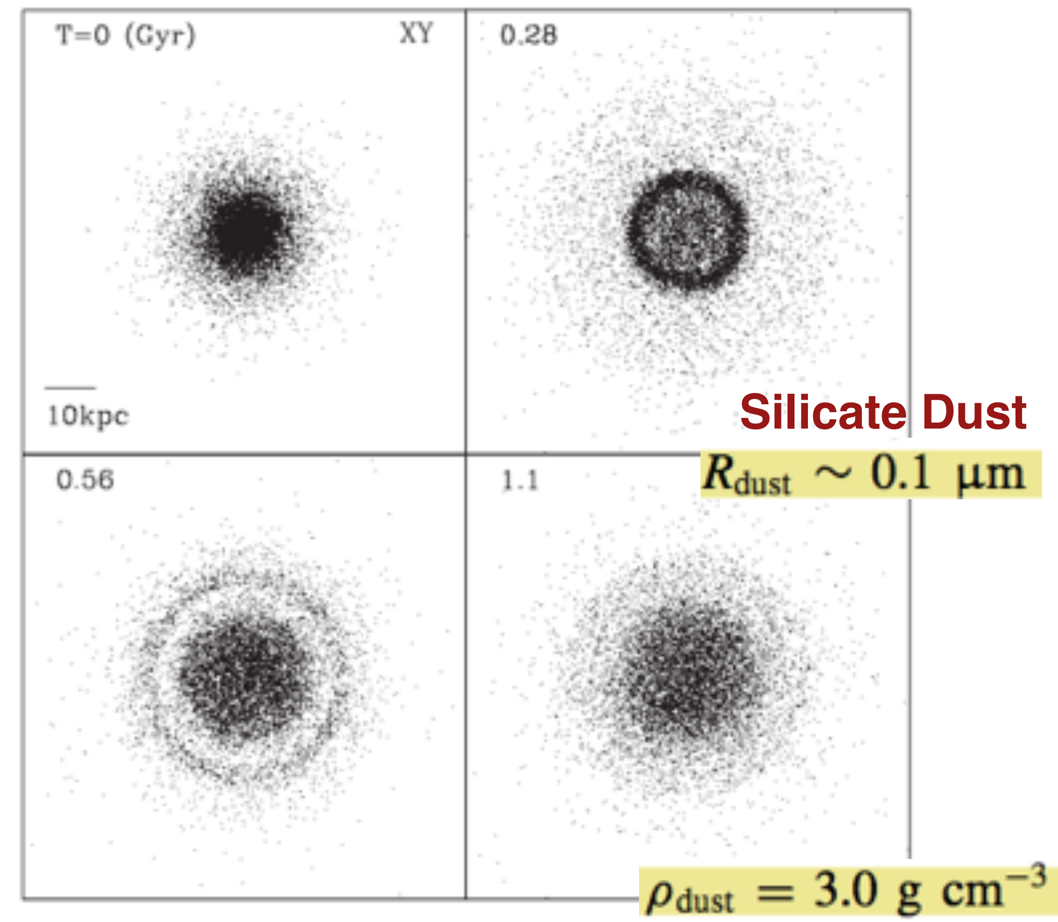
Wise+ ’14

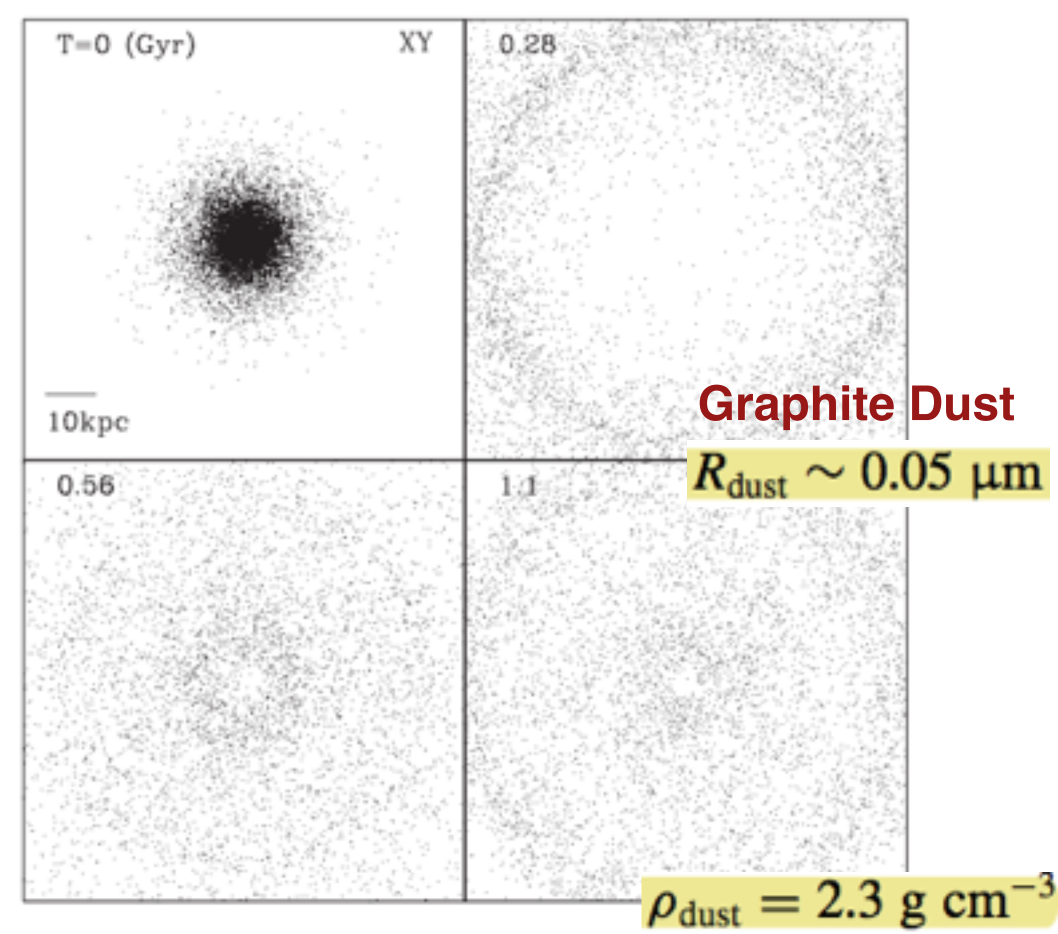
Yajima, Choi, KN ’11

Dust models - 1.

- **Bekki'15:** live dust ptcls in SPH. 4 component model.
  - Tests on isolated MW gal model. Diff softening for each component. Δt=1.4e6 yr.

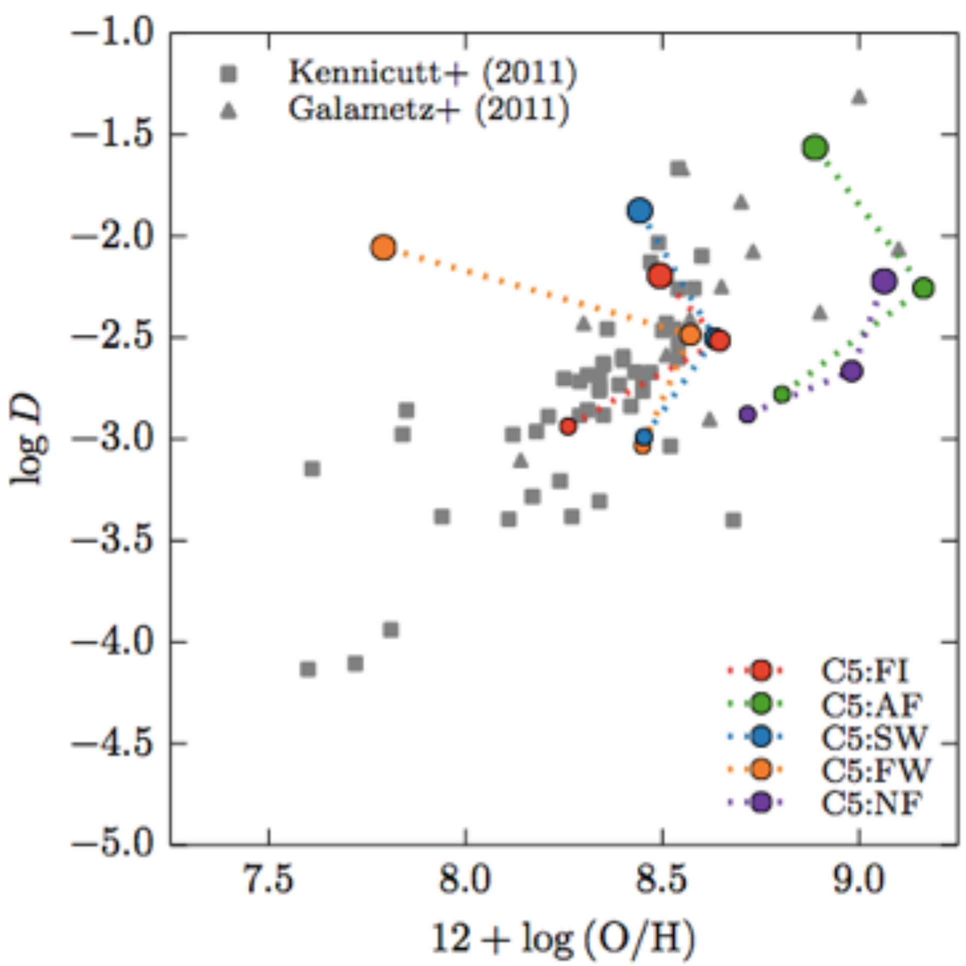


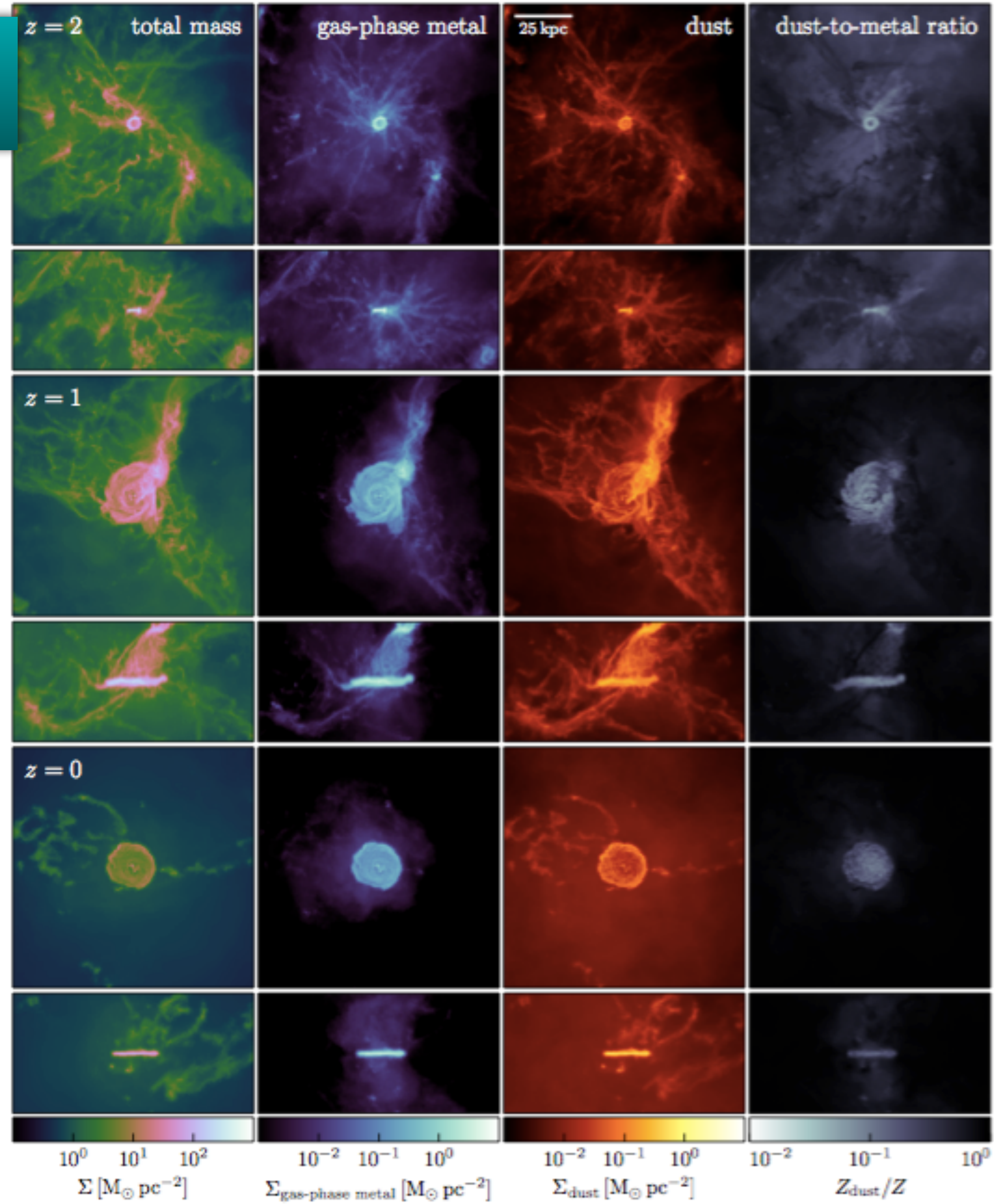




Dust models - II.

- McKinnon'15: AREPO cosmo zoom-in





Dust models - III.

The production/destruction processes of Dust in ISM
(e.g. Asano+ ‘13a, Hirashita ‘15 etc.)

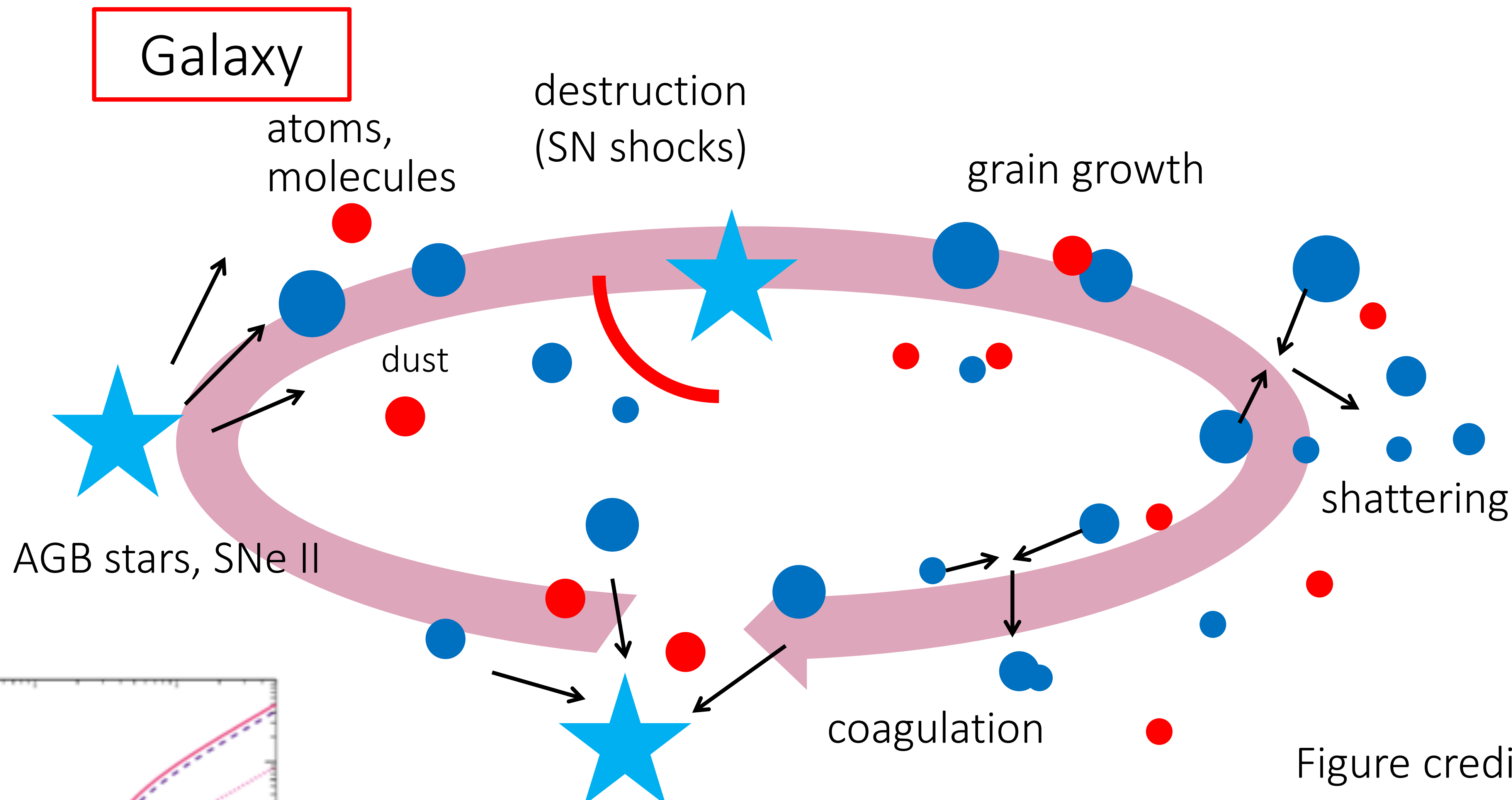
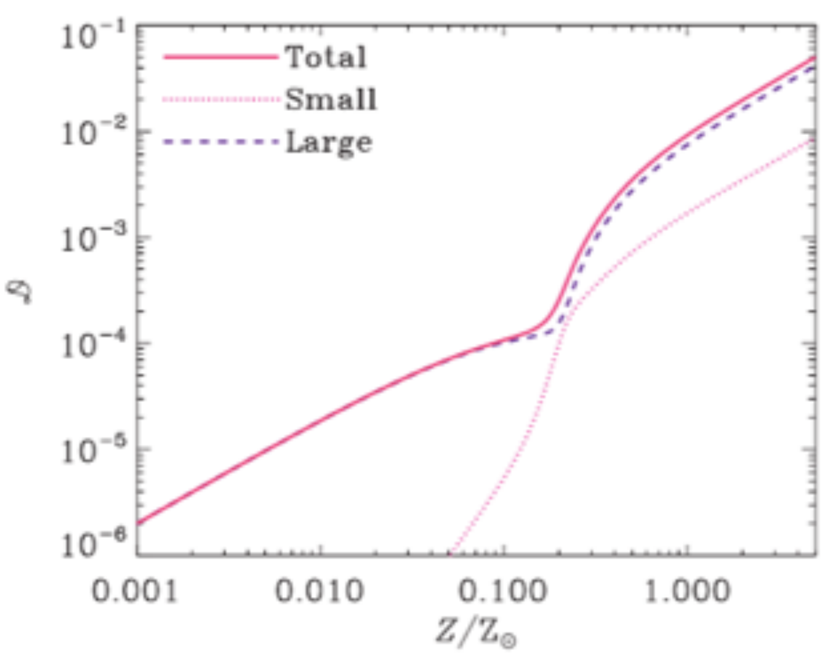
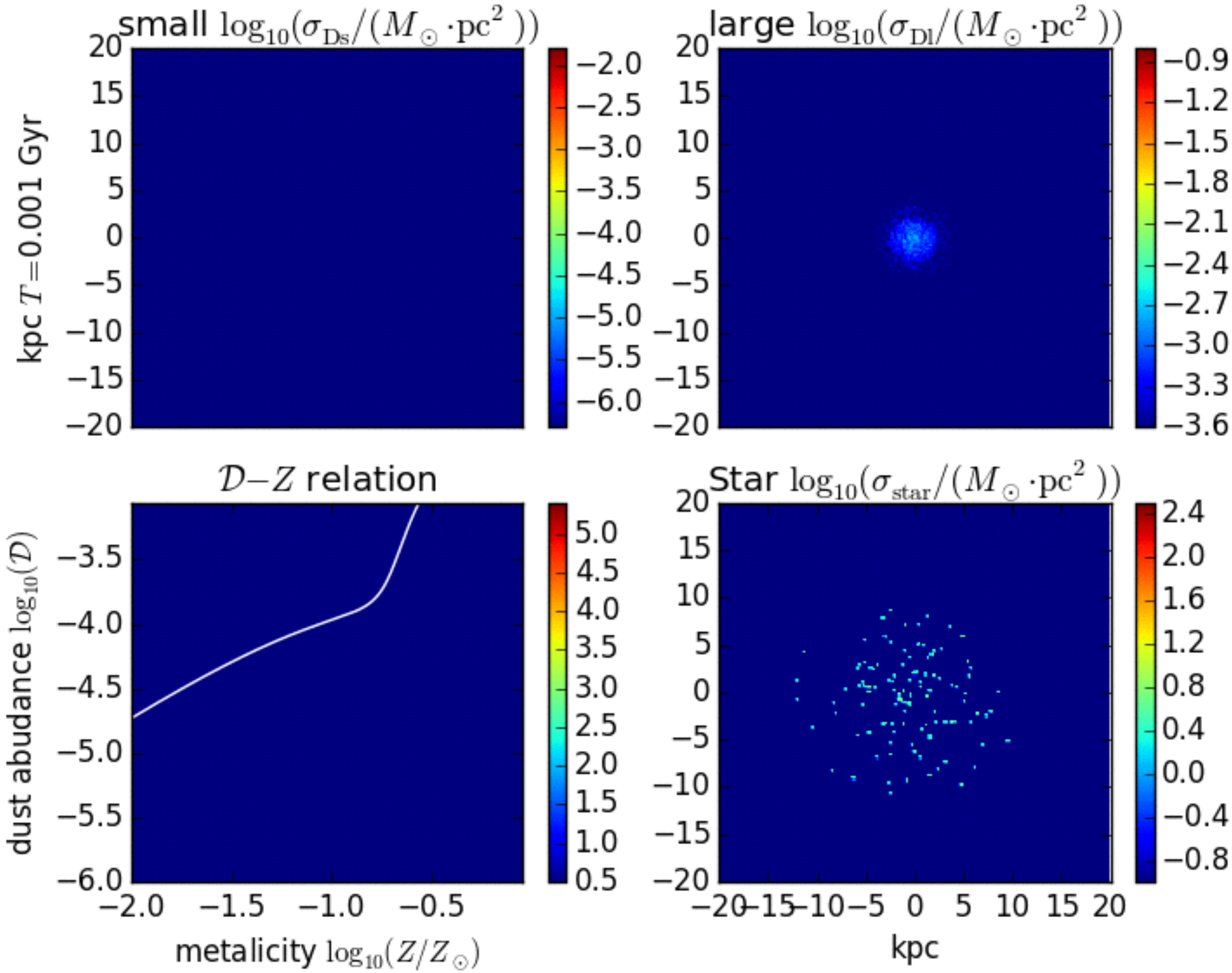


Figure credit :Asano



Process[a]	Small grains[b]	Large grains[b]	Total
Stellar ejecta	△	↗	↗
Shock destruction	↘	↘	↘
Accretion	↗	△	↗
Coagulation	↘	↗	→
Shattering	↗	↘	→

Isolated gal. w/ 2-component dynamical dust model



(Aoyama, Hou+’15, in prep.)

Summary

- *FEEDBACK, Feedback, feedback….. continues to be the focus of galaxy formation & evolution.*
- *"Early Feedback" from young stars: rad pressure, momentum, thermal energy, photoionization,*
- *Radiation Transfer, Dust*
- *Beginning to resolve Galactic Morphology better*
- *Downsizing, Color bimodality, ….*
- *AGN FB, gal-SMBH co-evolution.*