Galaxy Formation: theory

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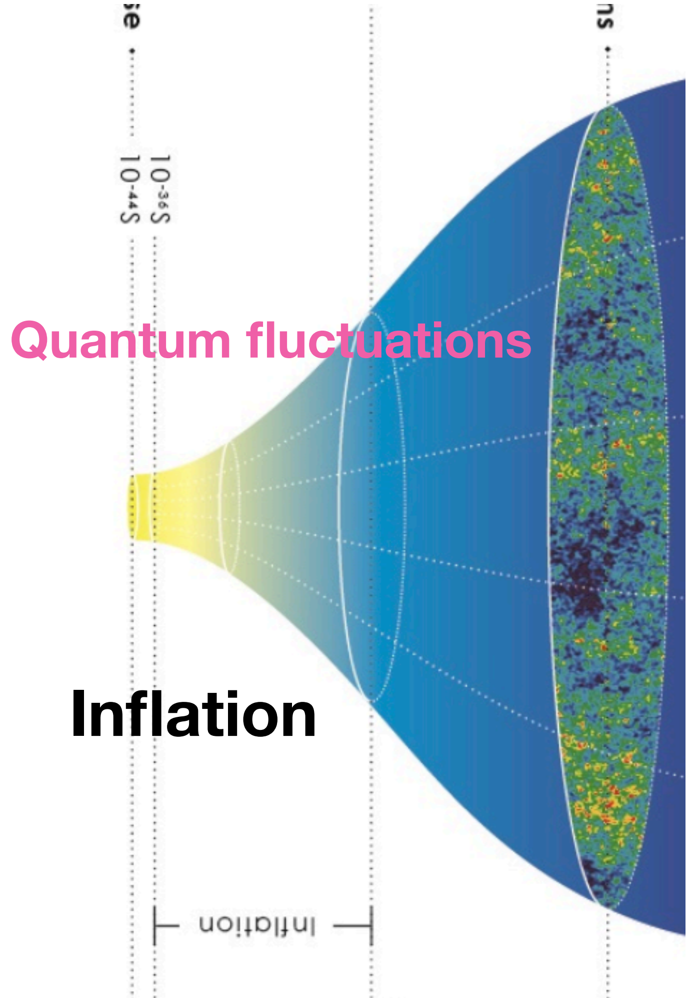
Contents

How to make a galaxy?

- **1st order**: background cosmology, perturbation, dark matter, hierarchical formation, radiative cooling

- **2nd: the Frontier & central issues**
  - anisotropic cold/hot in/outflow, angular momentum
  - star formation & feedback, quenching, downsizing → Morishita review
  - anisotropic, inhomogeneous radiation

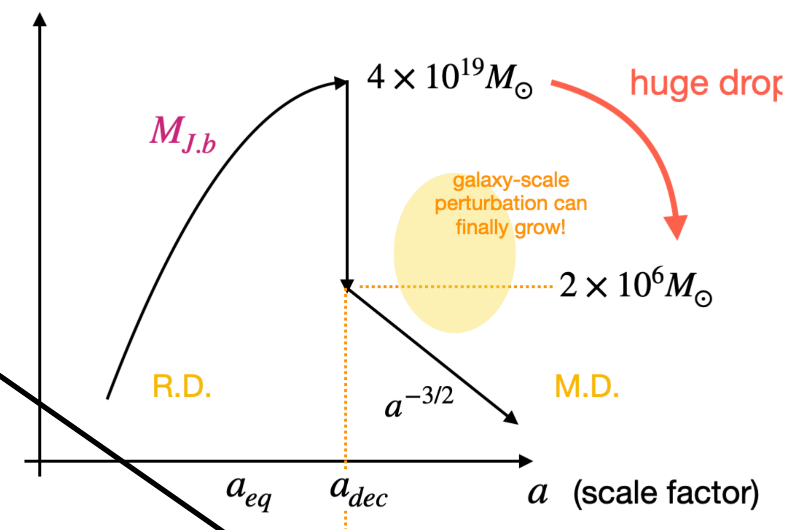
- **3rd: Good Tests**
  - high-z galaxy formation, CGM/IGM cf. Kakiichi, Momose review
  - environment: proto-clusters vs. field

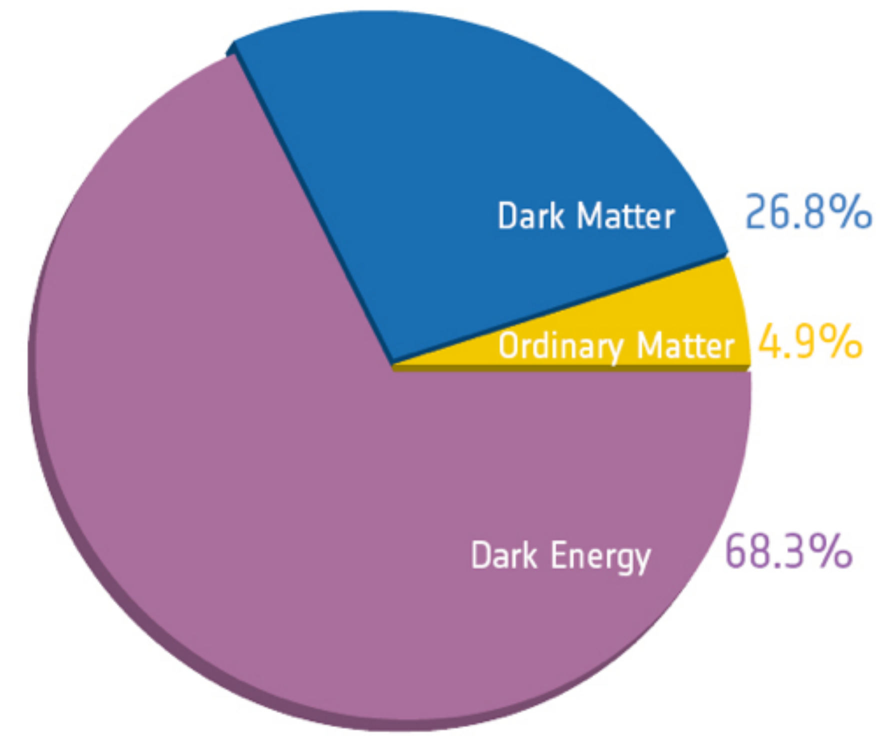


homogeneous & isotropic

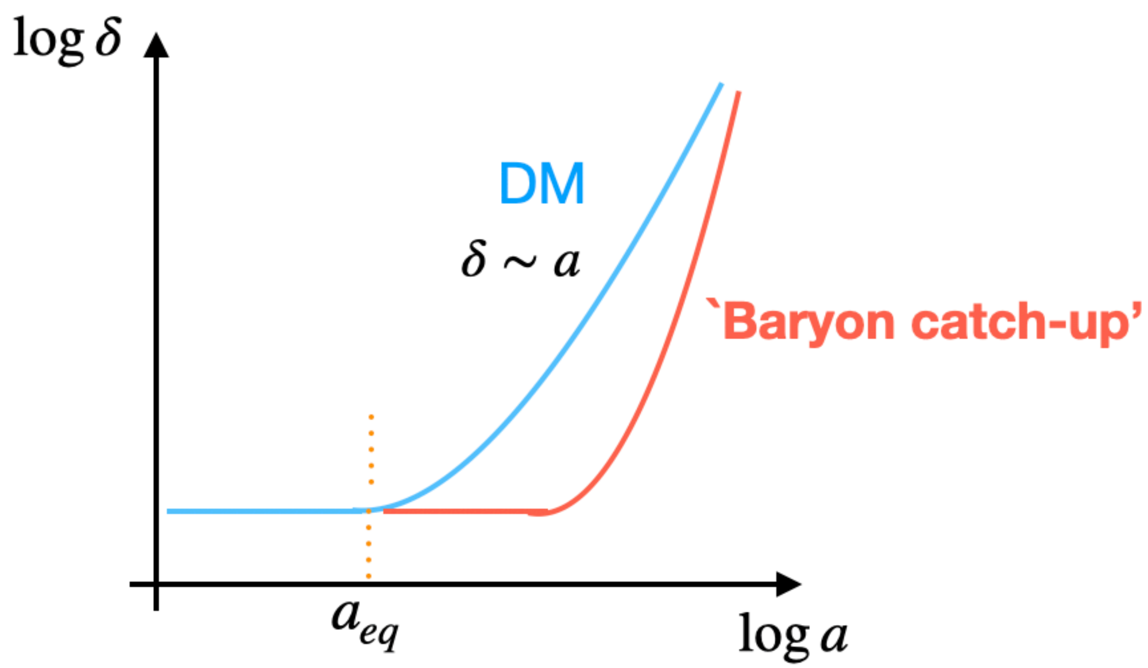
FRW universe

$$\frac{\delta\rho}{\rho} \sim 10^{-5}$$

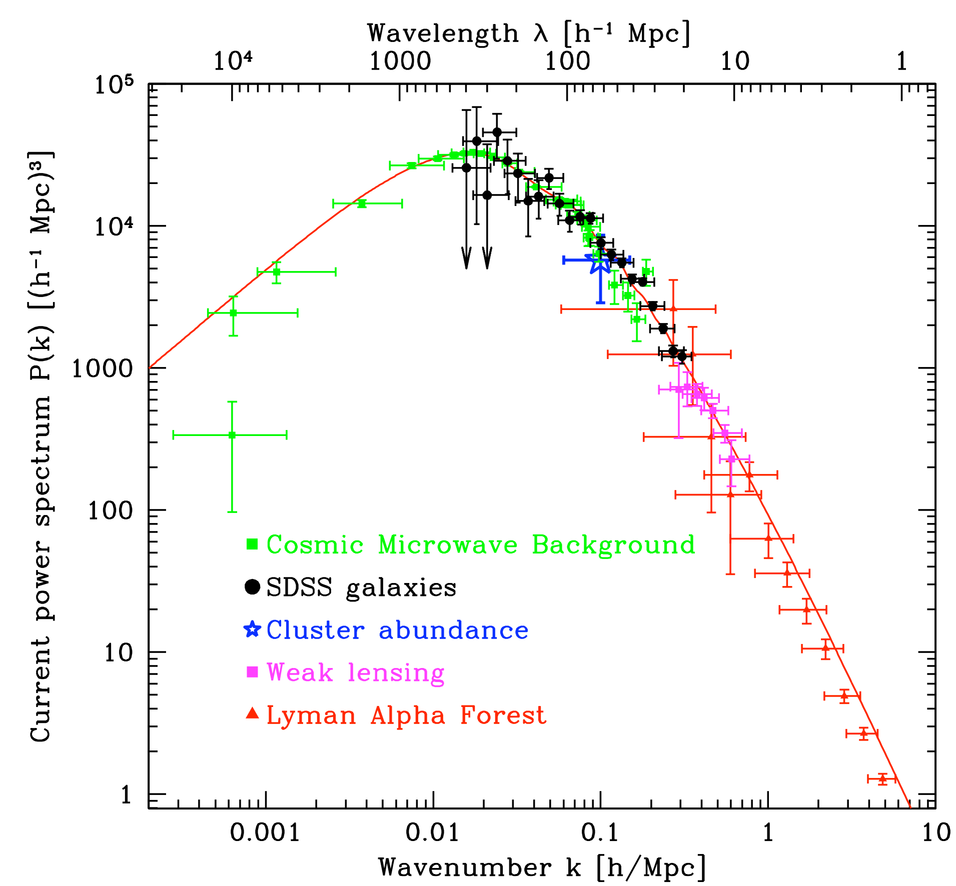




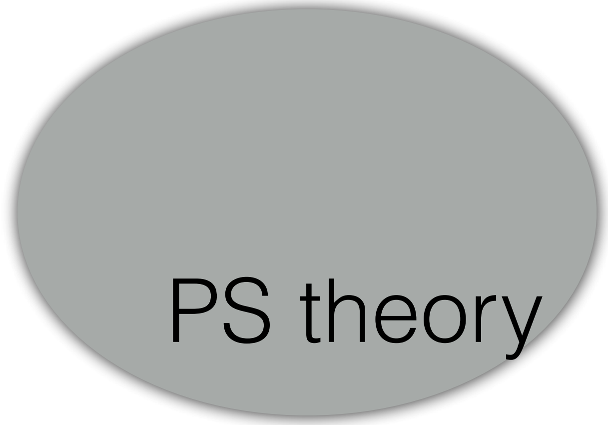
Linear Perturbation Theory



Present-day Matter Fluctuation

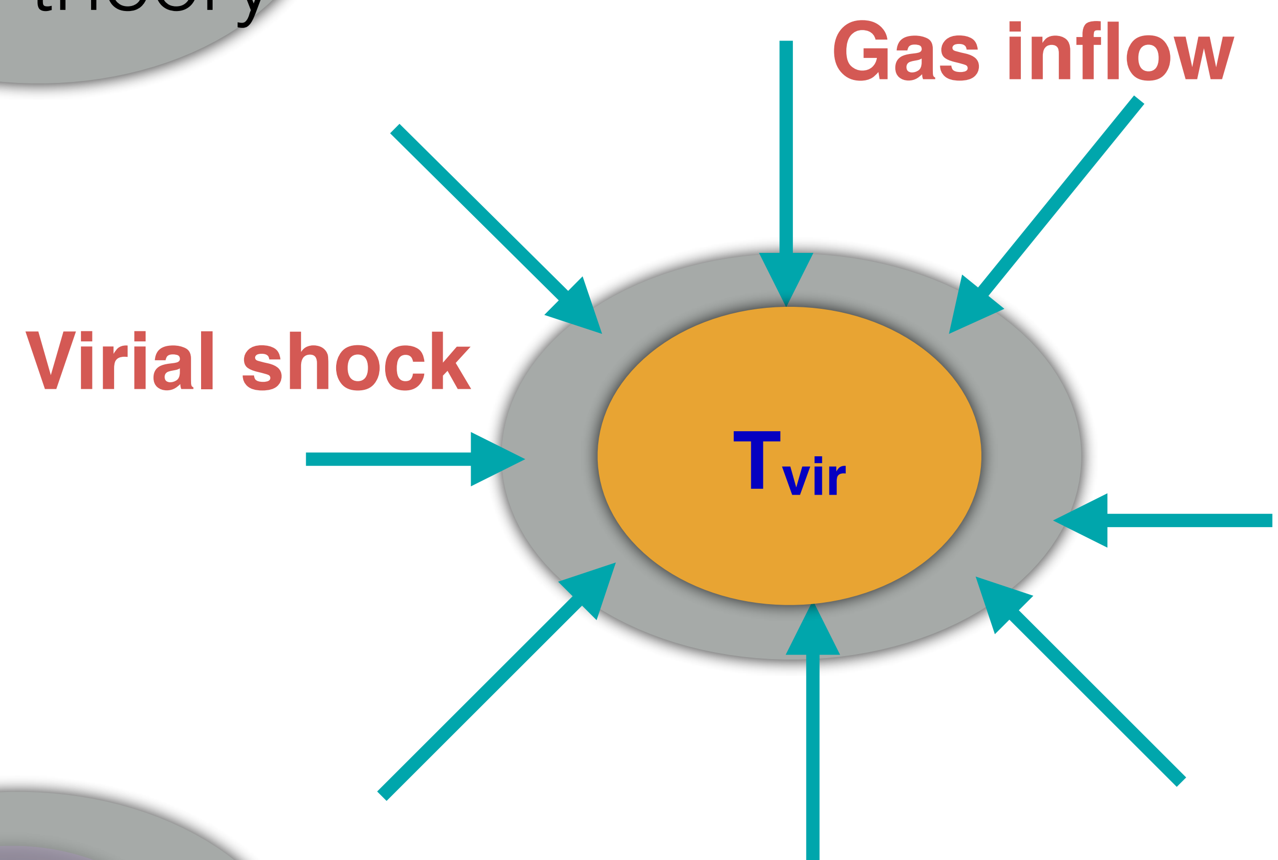


"1st-order" Galaxy Formation



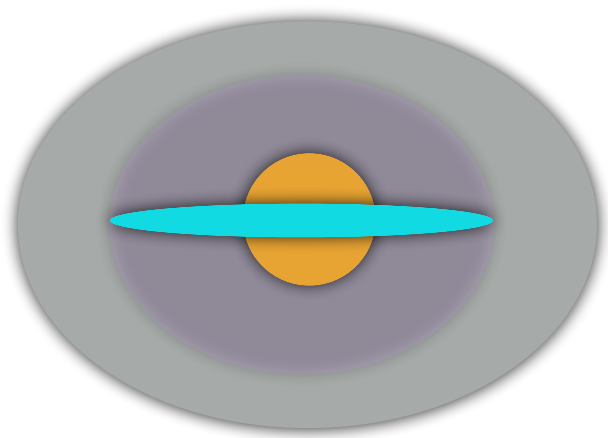
"spherical cow"

DM halo forms.



Gas infall
& shock heating

Gas dissipates,
cools,
& forms a disk.



Star, Galaxy Formation

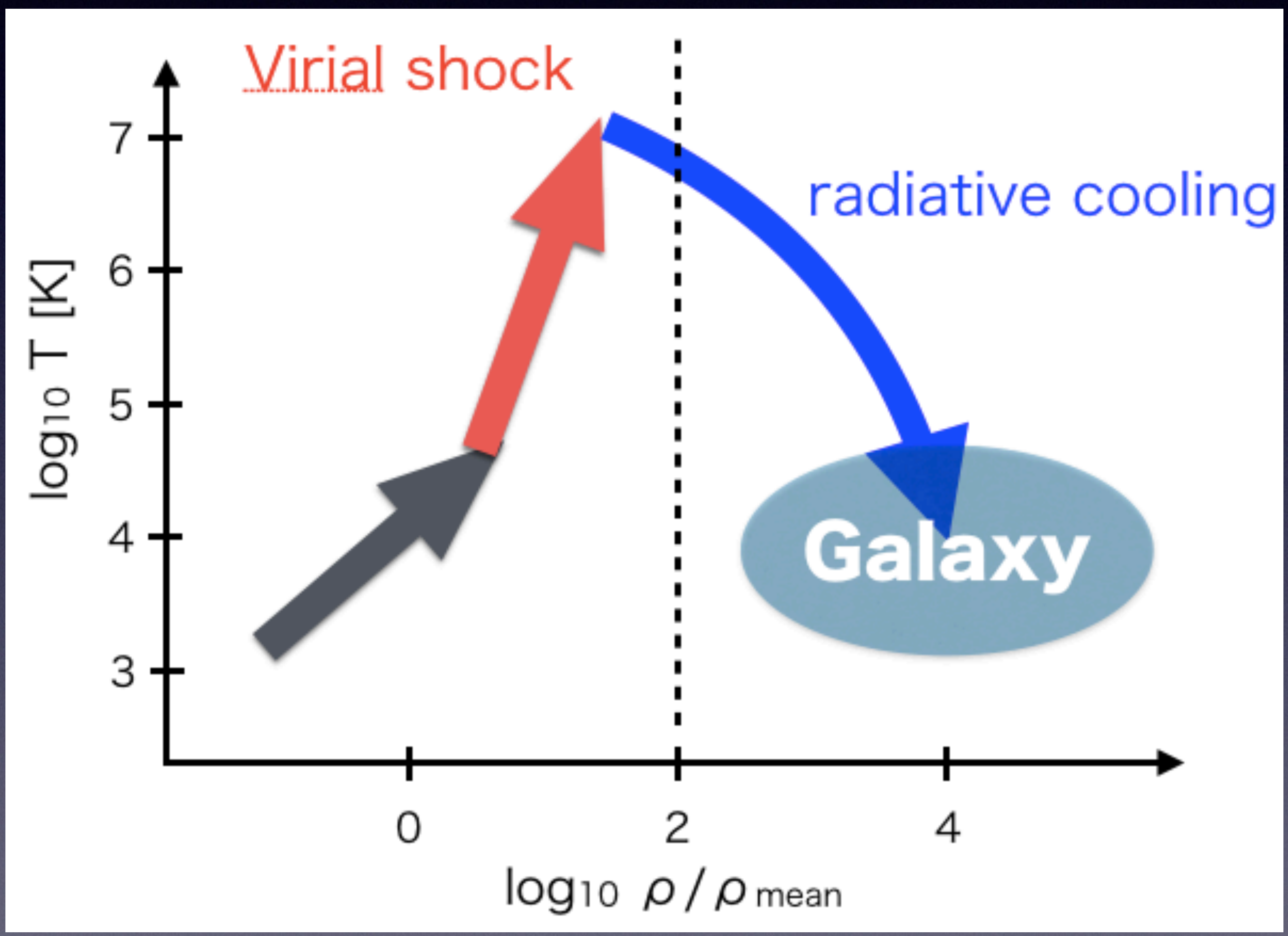
$$R_d = \frac{1}{\sqrt{2}}\left(\frac{j_d}{m_d}\right)\lambda r_{200}$$

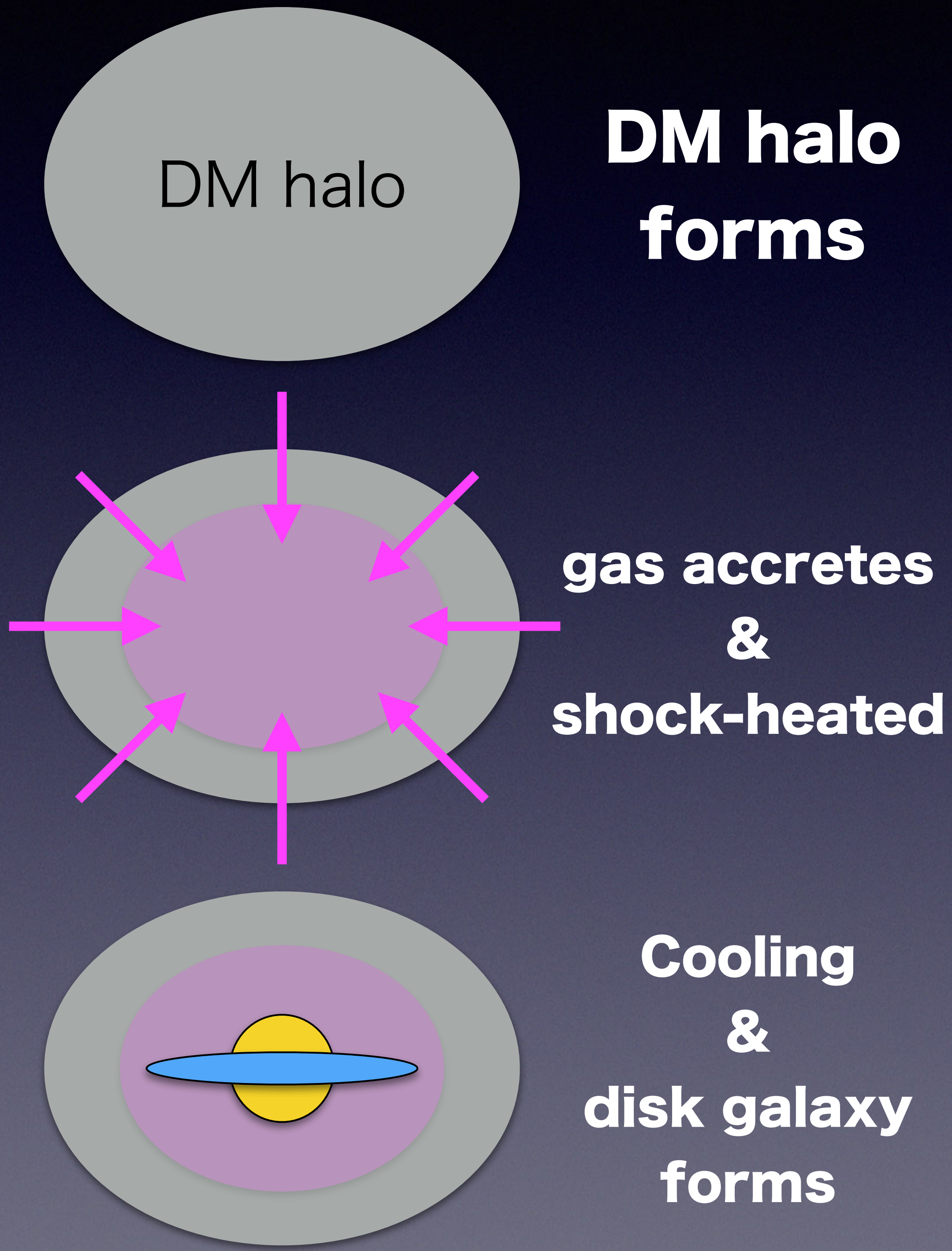
Rees & Ostriker '77
White & Rees '78
Fall & Efstathiou '80
White & Frenk '91
Mo, Mao & White '98

1st-order Galaxy formation

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

Phase Diagram



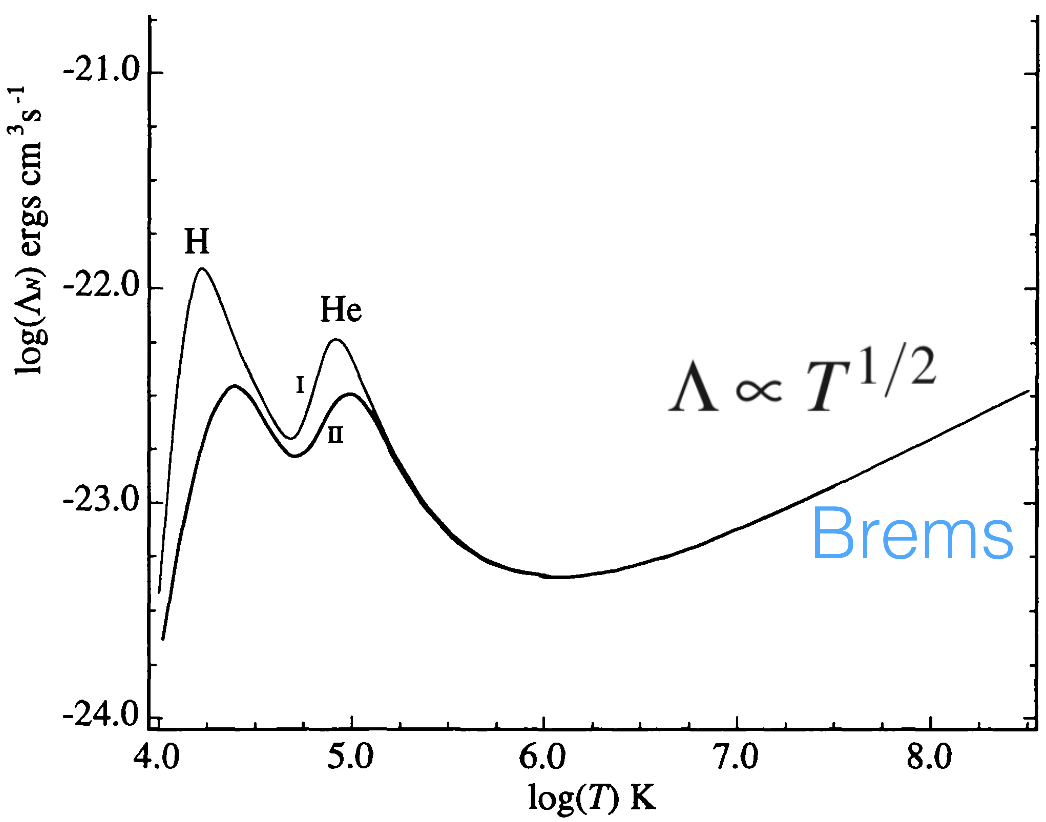


Cooling Curve

(Radiative Cooling Rate/Function)

Primordial Gas — optically thin gas

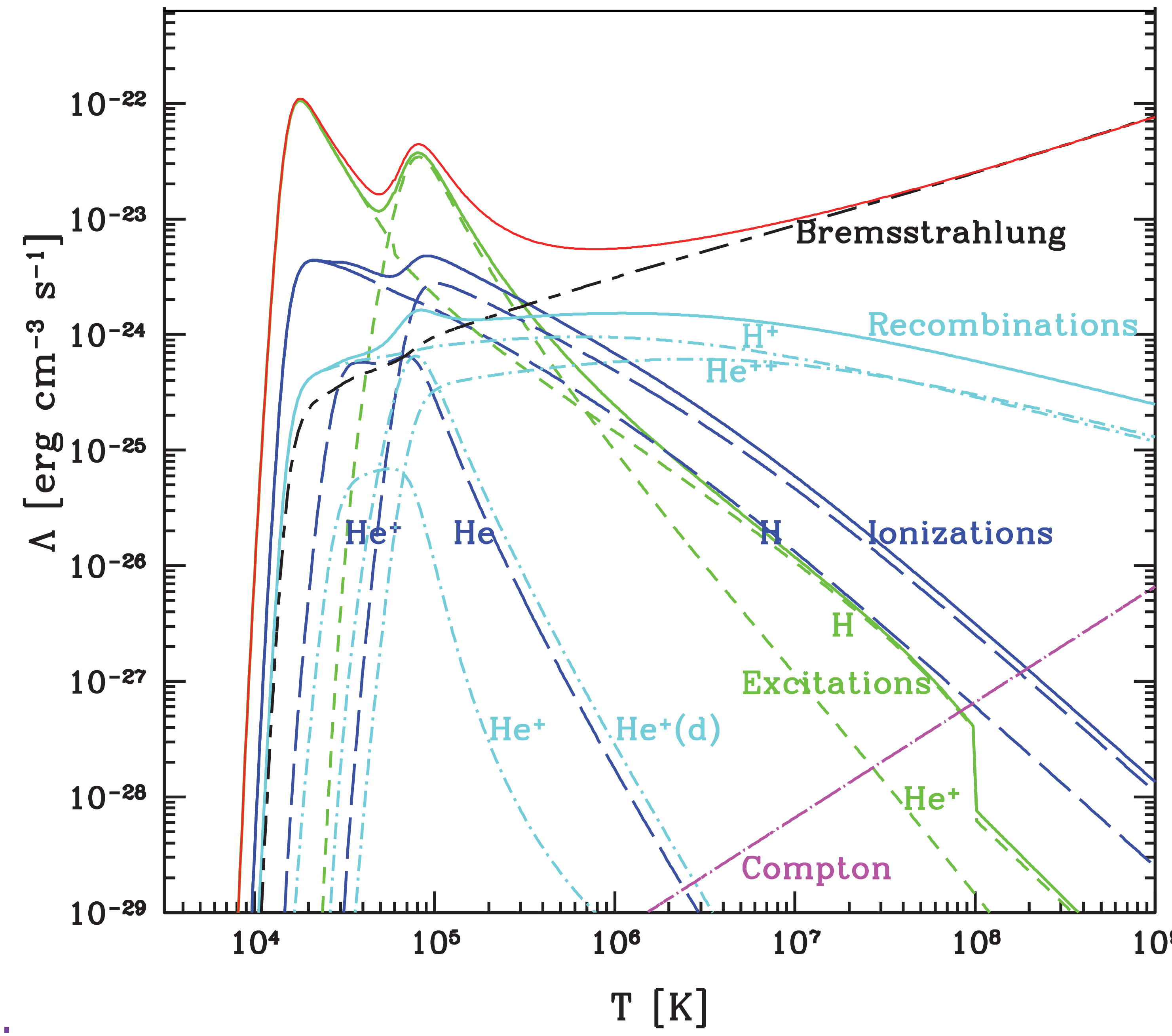
Sutherland & Dopita '93



$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_H^2}, \quad [\mathrm{erg\ cm^3\ s^{-1}}]$$

$\mathscr{C}$: cooling rate per unit vol.

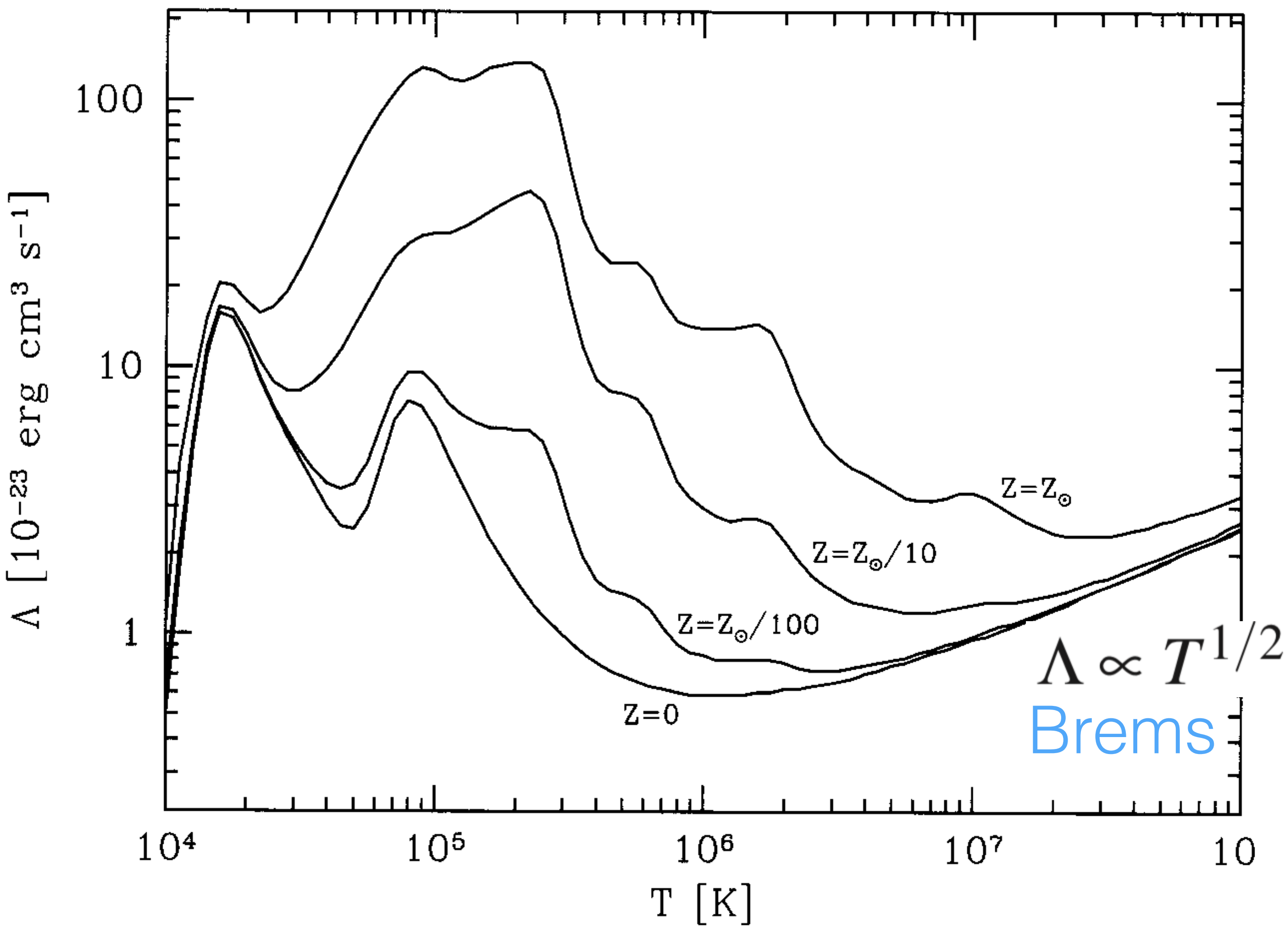
$[\mathrm{erg\ cm^{-3}\ s^{-1}}]$



Cen '92; Katz+'96

With Metal-line Cooing

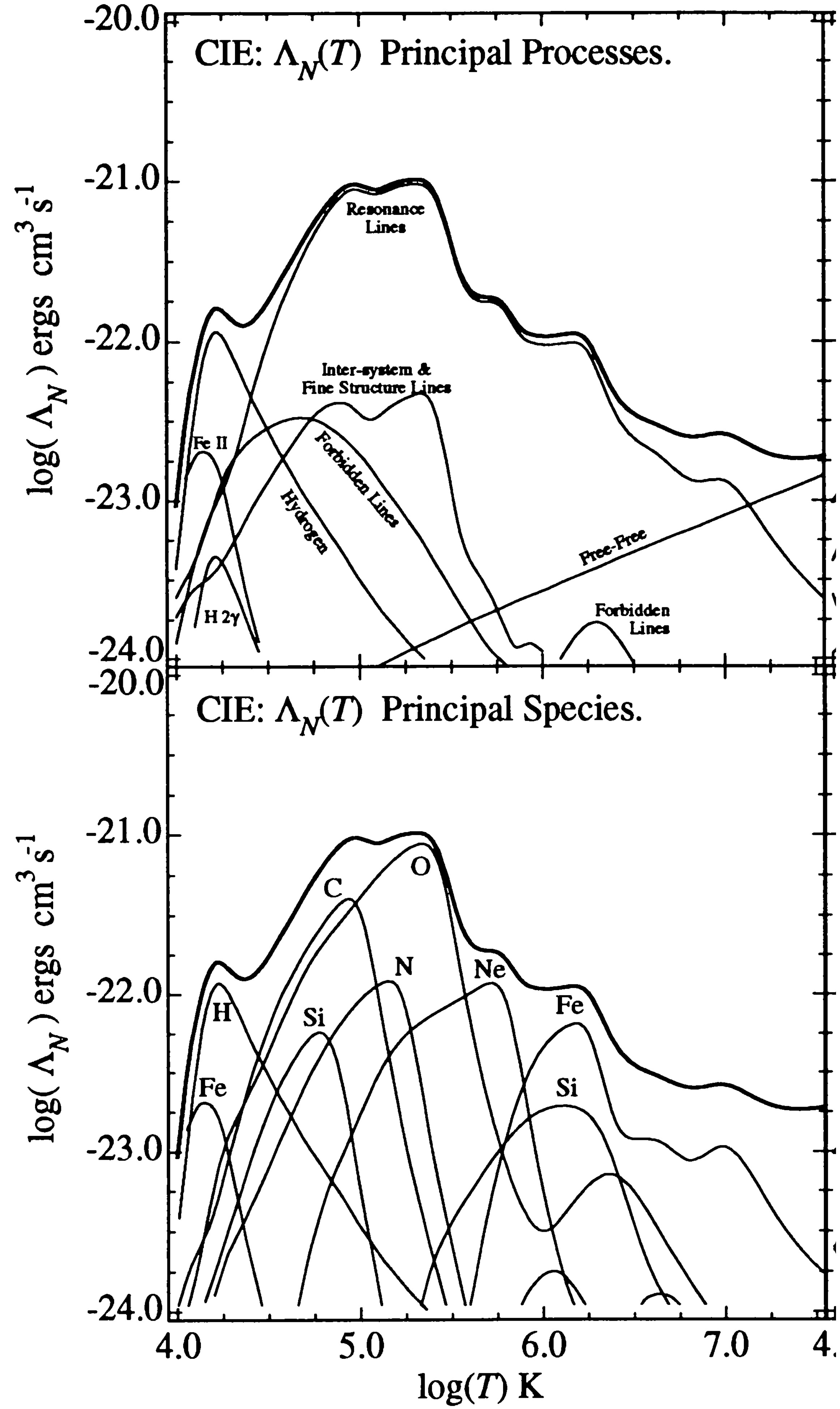
Sutherland & Dopita 1993, ApJS, 88, 253



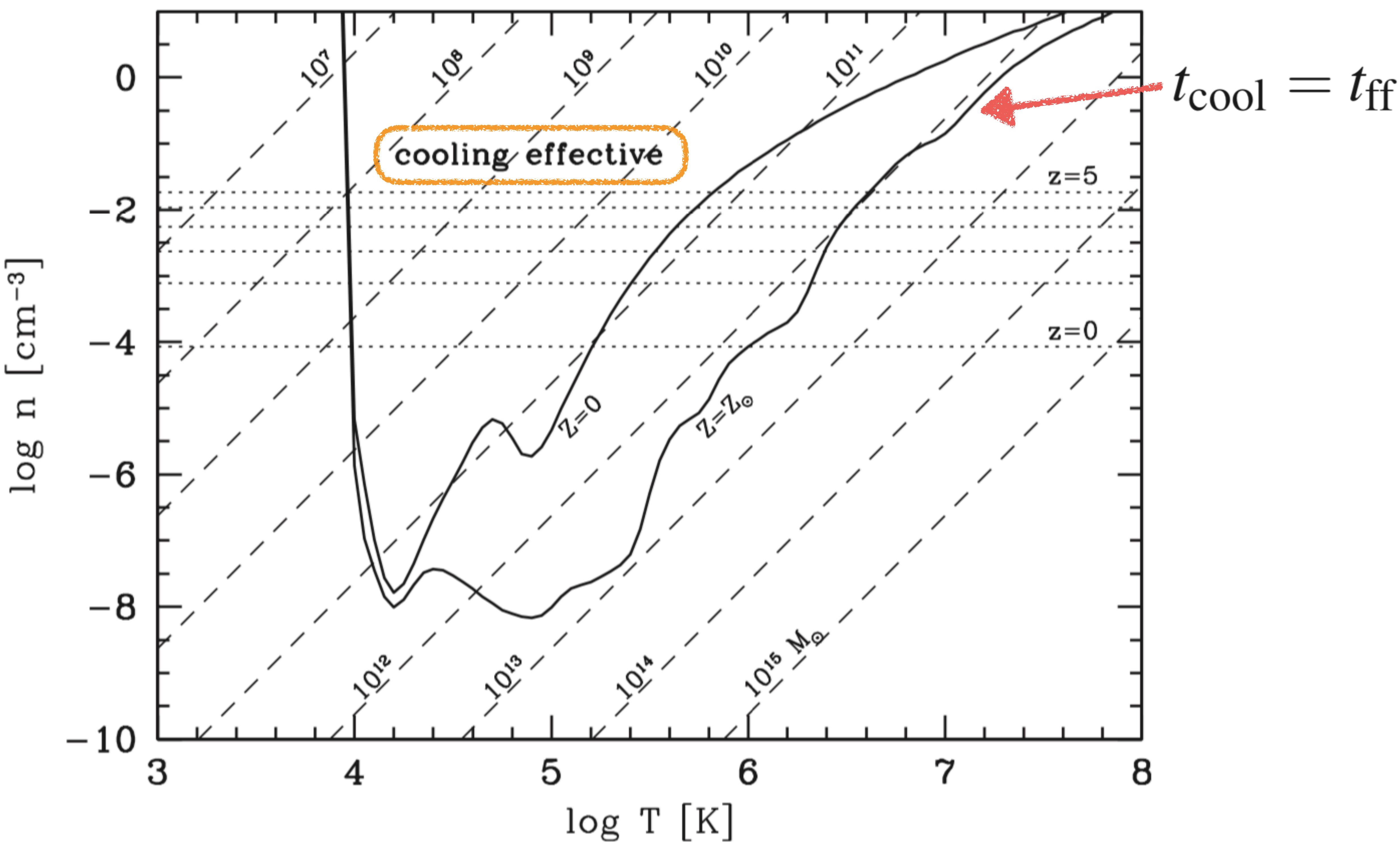
$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\rm H}^2},$$ **[erg cm³ s⁻¹]**

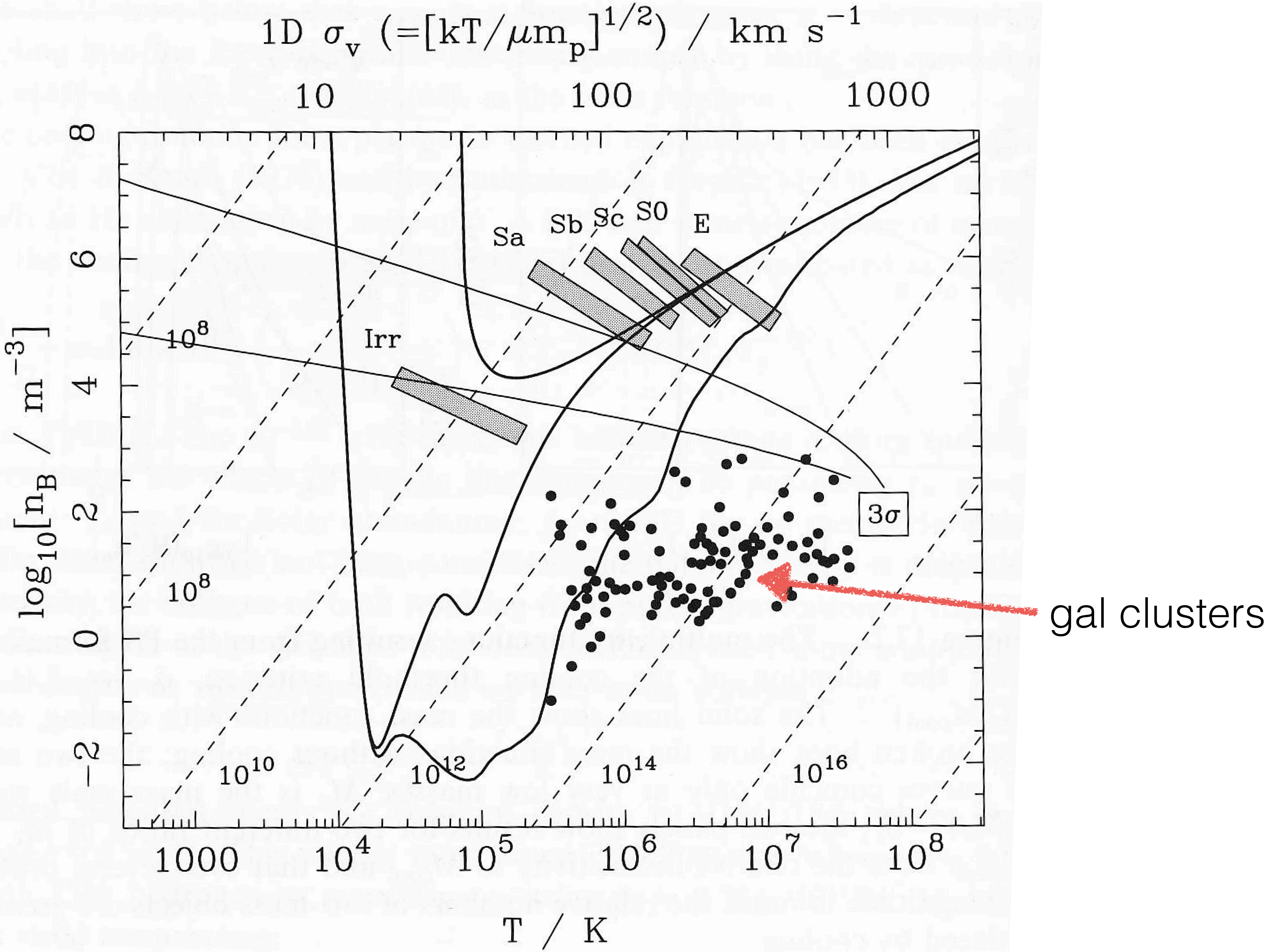
$\mathscr{C}$: cooling rate per unit vol.

[erg cm⁻³ s⁻¹]



equilibrium curve

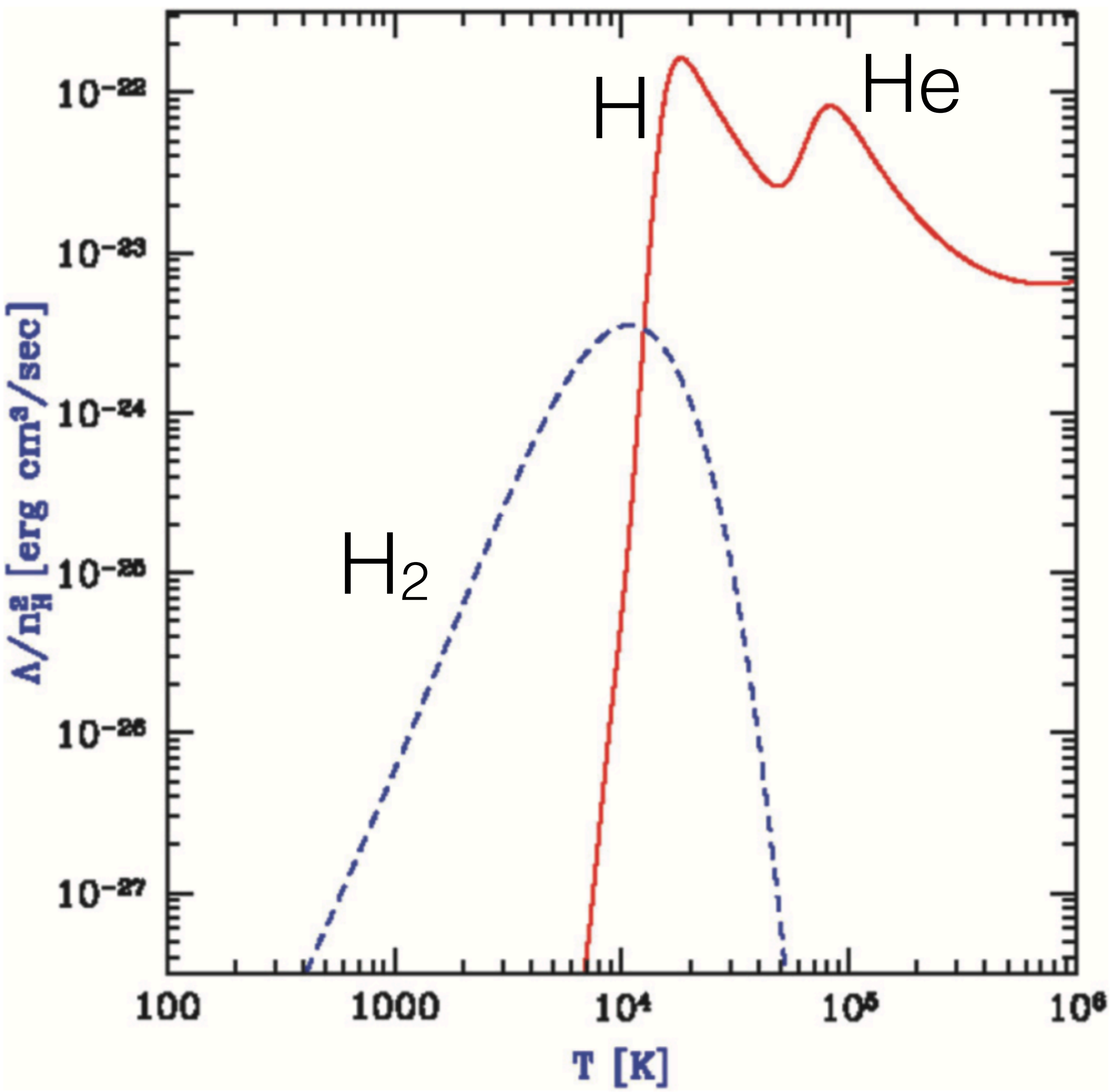




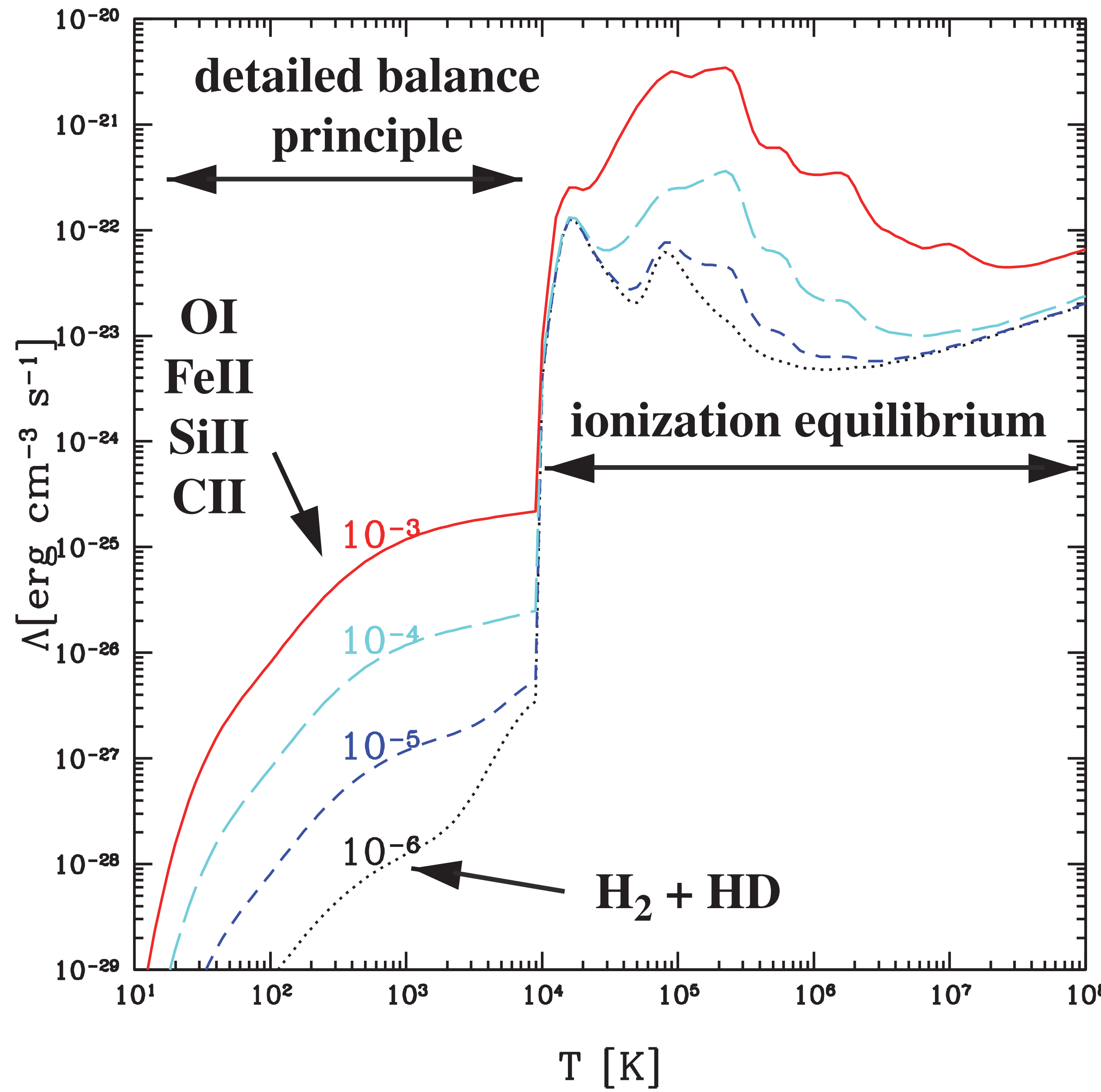
Blumenthal+'84; Peacock textbook, p.572

Cooling Curve @ T<10^4 K

(for higher redshift, lower mass halos, or for star formation)



Barkana & Loeb '01

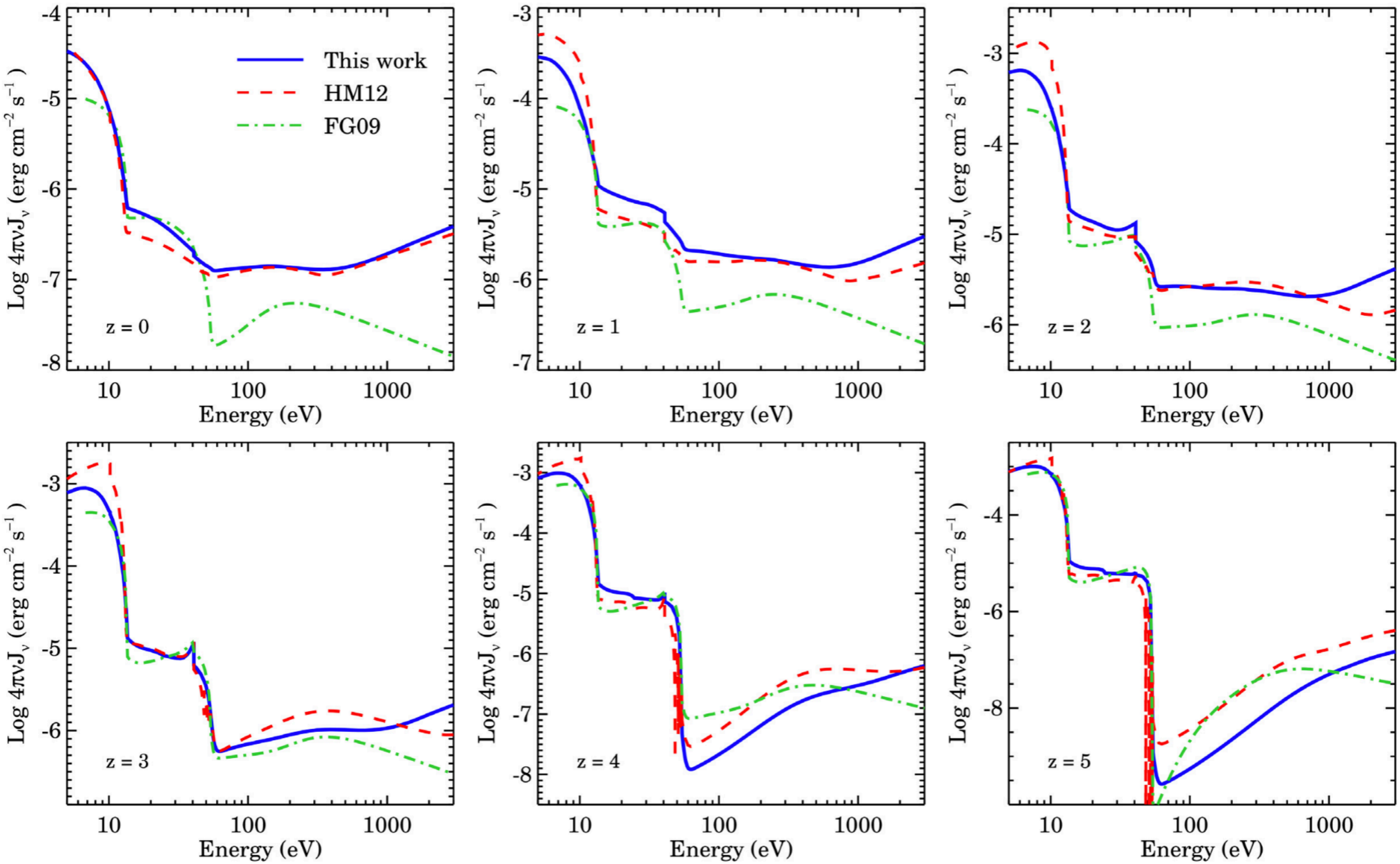


Maio+'07

cf: **T_{vir} ~ 10^4 K** for atomic cooling halo of **M_h~10^8 $M_\odot$**

UV background (UVB) radiation

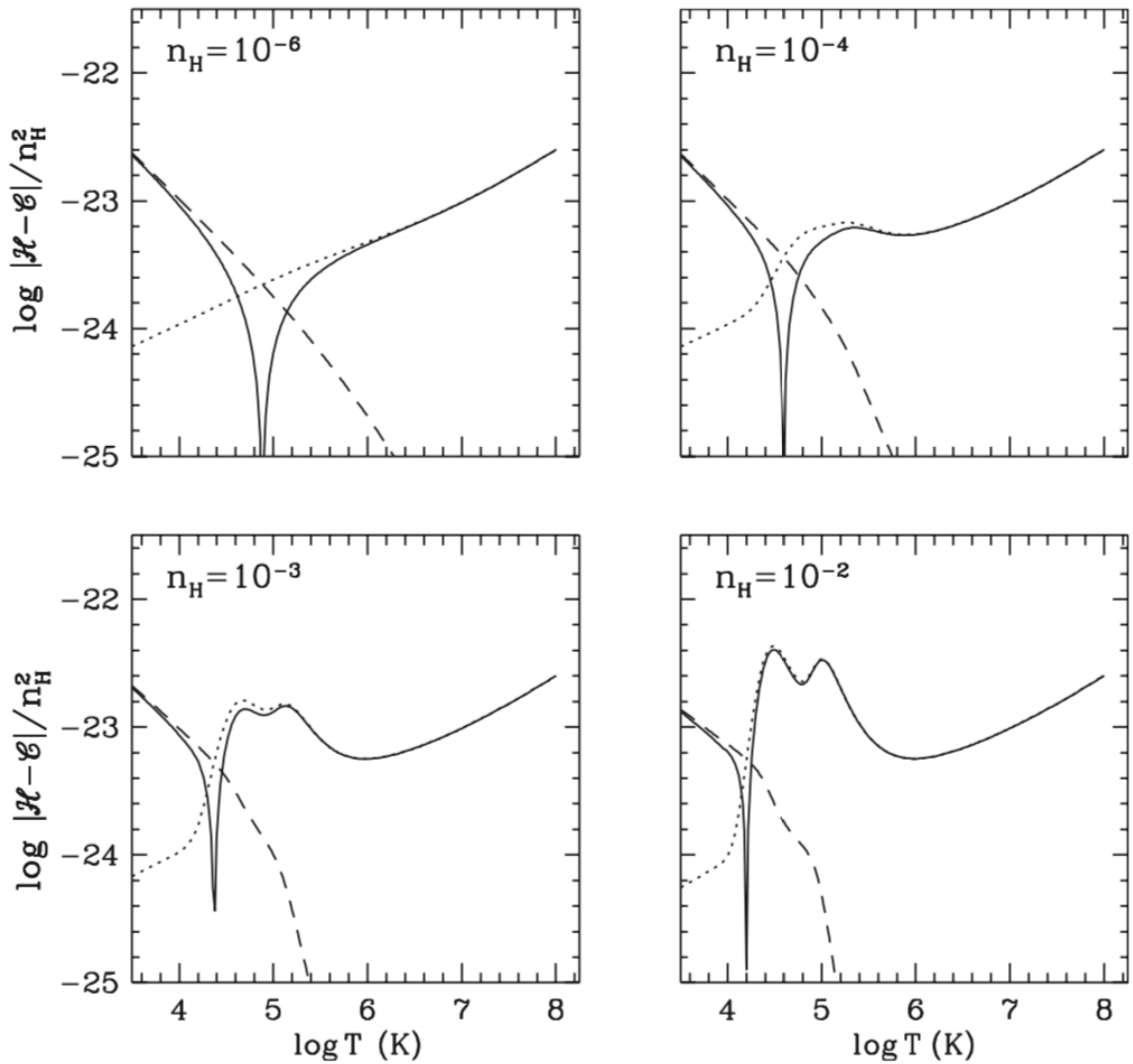
specific intensity: $$J_{\nu_0}(z_0) = \frac{c}{4\pi}\int_{z_0}^{\infty} \mathrm{d}z\, \frac{(1+z_0)^3\,\epsilon_\nu(z)}{(1+z)\,\mathrm{H}(z)}\, \mathrm{e}^{-\tau_{\rm eff}(\nu_0,\, z_0,\, z)}.$$



Haardt & Madau ’96, ’12; Faucher-Giguere+’09; Khaire & Srianand ’19; …

Net cooling rate with heating

solid line:
net rate
[erg cm^3 s^{-1}]



dotted:
cooling rate

dashed:
photo-ioniz.
heating rate

Weinberg+'97

With UVB: $J(\nu) = 10^{-22}(\nu_{\rm H}/\nu)\,\mathrm{erg\,s^{-1}\,cm^{-2}sr^{-1}Hz^{-1}}$.

Useful code packages for cooling

Grackle : https://grackle.readthedocs.io/en/grackle-3.1.1/

(taken out of Enzo AMR simulation)

by B. Smith

KROME: http://www.kromepackage.org/

by Grassi, Bovino+

Cloudy: https://www.nublado.org/

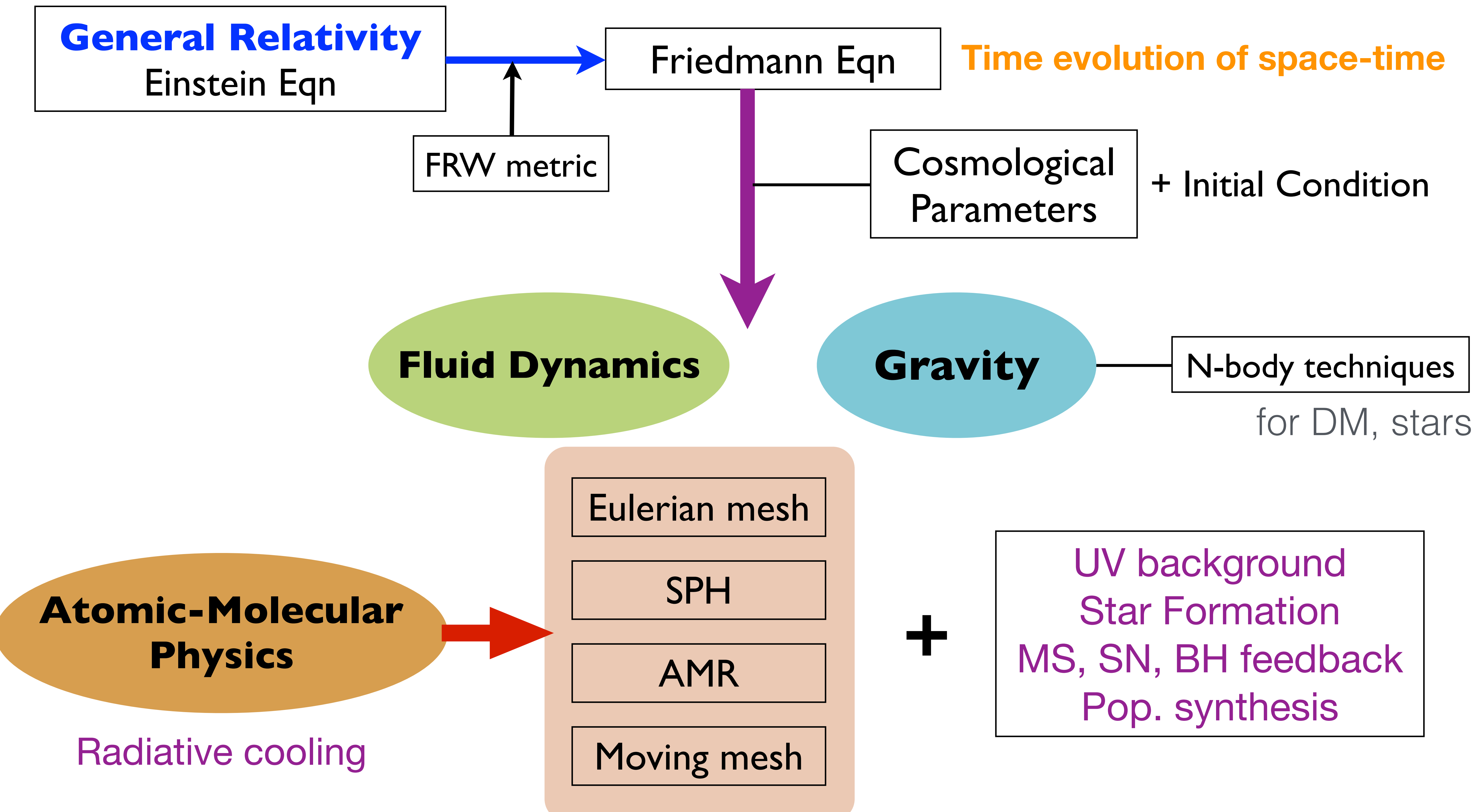
by G. Ferland+

MAPPINGS III: http://cdsweb.u-strasbg.fr/~allen/shock.html

by Allen+

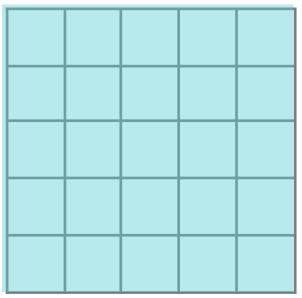
shock & photo-ionization model

Framework of Computational Cosmology



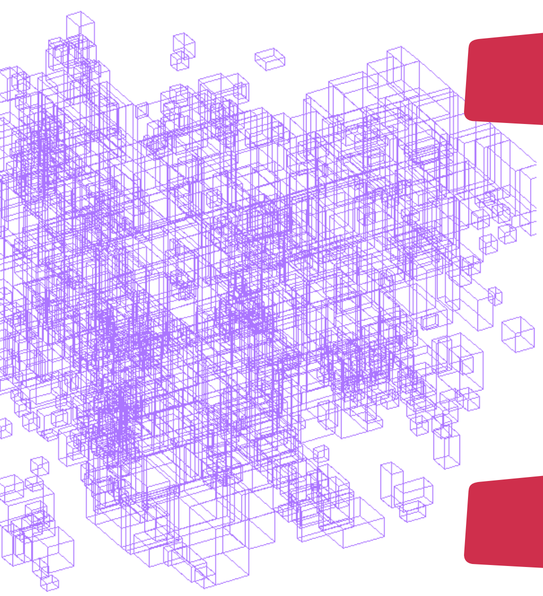
(Ch.2 of Encyclopedia of C.)

Cosmological Hydro Codes



Eulerian mesh (e.g. Cen & Ostriker ’92; KN+’01)

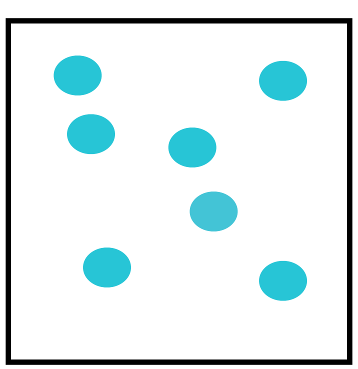
- Eulerian mesh, PM gravity solver, shock capturing hydro
- fast; good baryonic mass resolution at early times
- low final spatial resolution in high-ρ regions, but good at low-ρ regions



AMR (adaptive mesh refinement: e.g. Enzo, RAMSES, etc.)

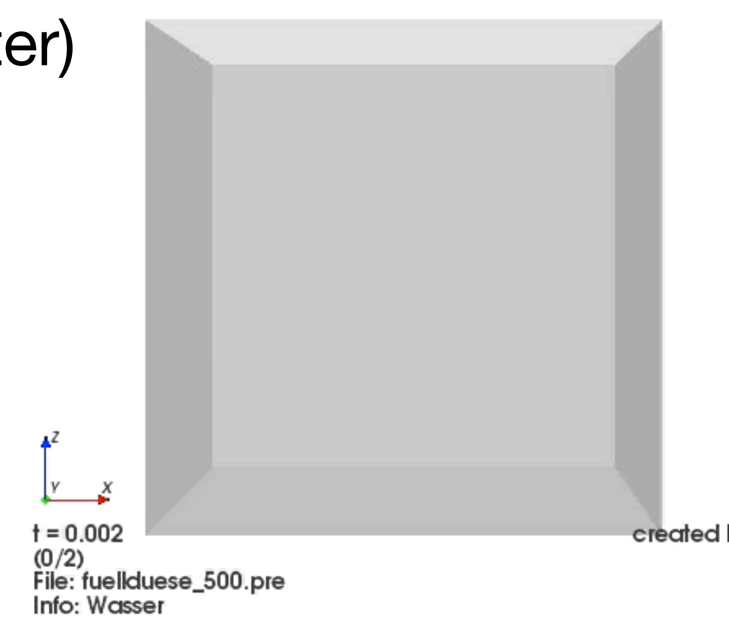
- Eulerian root grid, refine as necessary
- multi-grid PM gravity solver, ZEUS hydro, PPM hydro
- high dynamic range, but slower

AMR-SPH comparison:
O’Shea, KN+ ‘05



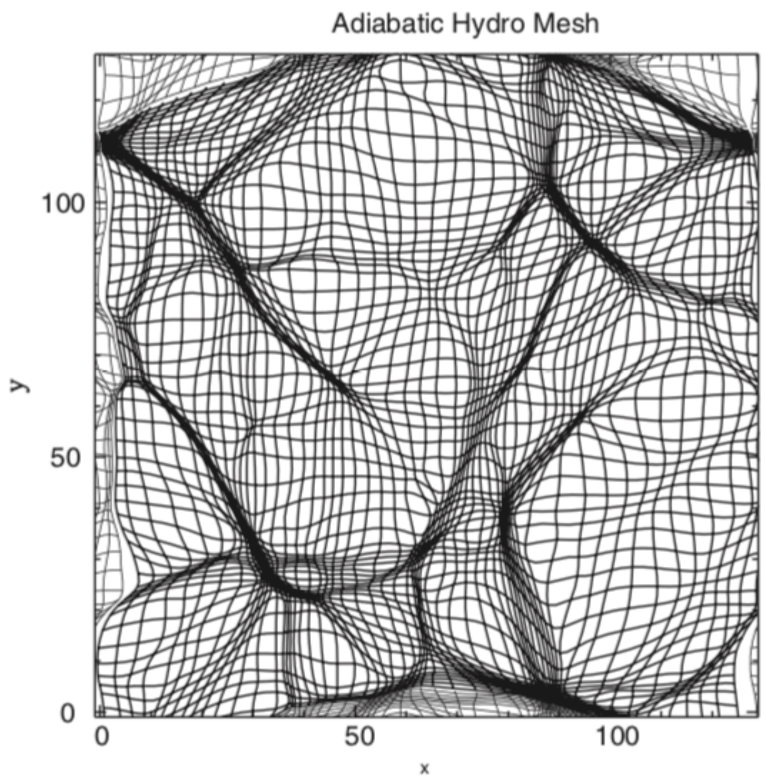
SPH (Smoothed Particle Hydrodynamics: e.g. GADGET, GASOLINE, etc.)

- Lagrangian, particle-based (both gas & dark matter)
- Tree-PM for gravity
- SPH for hydro
- fast; good spatial resolution in high-ρ region, but
  not so good in low-ρ region



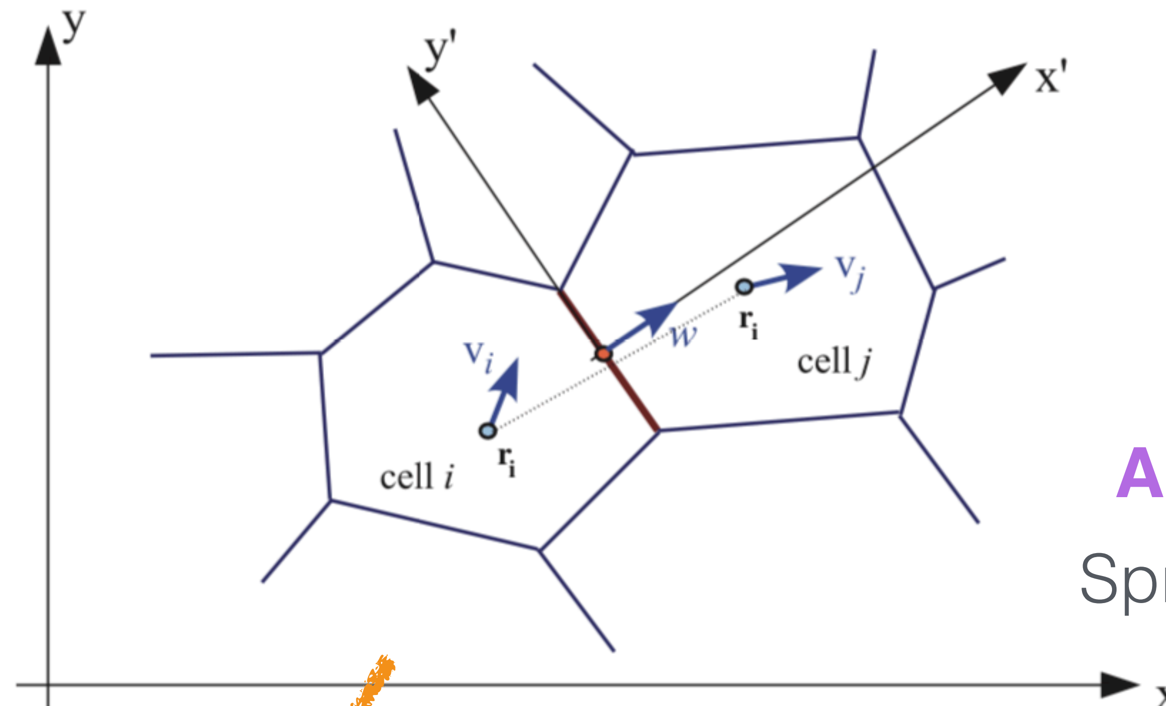
Furthermore,

Moving mesh method:



Pen ‘98

Voronoi tesselation



AREPO

Springel ‘10

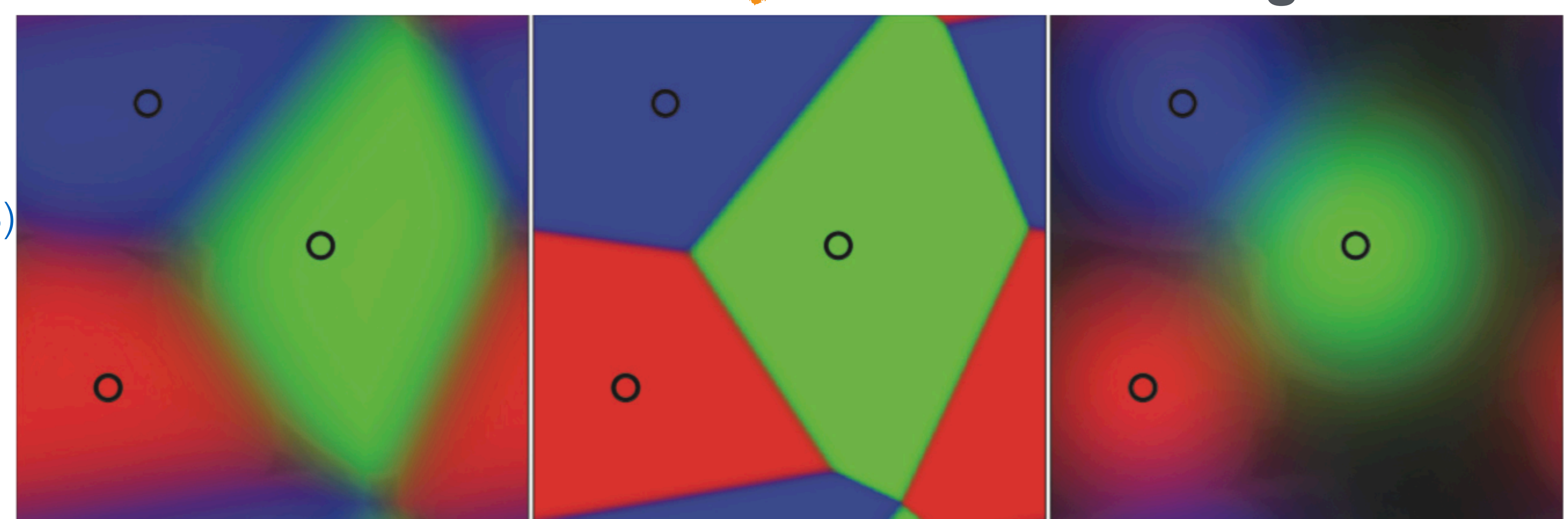
Mesh-less method:

regular SPH

Gizmo

(based on GADGET-3)

Hopkins ‘12



New Meshless Methods Here (MFV, MFM) Unstructured / Moving–Mesh Methods Smoothed–Particle Hydrodynamics

Cosmological Hydrodynamics

Mass consv.

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho u_k) = 0 \,,$$

ρ : comoving density

u : proper peculiar vel.

Momentum consv.

$$\frac{\partial \rho u_i}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho u_i u_k + P\delta_{ik}) = -\frac{\dot{a}}{a}\rho u_i \,,$$

Energy consv.

$$\frac{\partial E}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}[(E + P)u_k] = -\frac{2\dot{a}}{a}E \,.$$

where $E \equiv P/(\gamma - 1) + \frac{1}{2}\rho u_k^2$

total specific energy per comoving vol.

Plus

1. The gravitational source term in the comoving coordinates.
2. The Compton cooling (or heating) term due to interactions of free electrons with the diffuse microwave background radiation field and the diffuse X-ray background radiation field.
3. The integrated radiative cooling-heating term due to hydrogen and helium, which includes electron bremsstrahlung cooling, hydrogen and helium recombination cooling, helium dielectronic recombination cooling, hydrogen and helium collisional ionization cooling, hydrogen and helium collisional excitation cooling, and photoionization heating.
4. Numerical diffusion terms and terms induced from them.

Cen '92; Cen & Ostriker '93~; …

H, He, Hii, Heii, ….

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho u_k - D_{\rho k}) = 0\,, \tag{4a}$$

$$\frac{\partial \rho_{\mathrm{H\,I}}}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho_{\mathrm{H\,I}} u_k - D_{\rho_{\mathrm{H\,I}} k}) = n(e)(f_{\mathrm{H}}\rho - \rho_{\mathrm{H\,I}})\alpha_{\mathrm{H\,II}}(T) - n(e)\rho_{\mathrm{H\,I}}\beta_{\mathrm{H}}(T) - \rho_{\mathrm{H\,I}}\int_{\nu_0(\mathrm{H})}^{\infty} 4\pi\sigma_\nu(\mathrm{H})\,\frac{i(\nu)}{h\nu}\,d\nu\,, \tag{4b}$$

$$\frac{\partial \rho_{\mathrm{He\,I}}}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho_{\mathrm{He\,I}} u_k - D_{\rho_{\mathrm{He\,I}} k}) = n(e)\rho_{\mathrm{He\,II}}[\alpha_{\mathrm{He\,II}}(T) + \xi_{\mathrm{He\,II}}(T)] - n(e)\rho_{\mathrm{He\,I}}\beta_{\mathrm{He\,I}}(T) - \rho_{\mathrm{He\,I}}\int_{\nu_0(\mathrm{He\,I})}^{\infty} 4\pi\sigma_\nu(\mathrm{He\,I})\,\frac{i(\nu)}{h\nu}\,d\nu\,, \tag{4c}$$

$$\begin{aligned}\frac{\partial \rho_{\mathrm{He\,II}}}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}[\rho_{\mathrm{He\,II}} u_k - D_{\rho_{\mathrm{He\,II}} k}] &= n(e)[(1 - f_{\mathrm{H}})\rho - \rho_{\mathrm{He\,I}} - \rho_{\mathrm{He\,II}}]\alpha_{\mathrm{He\,III}}(T) - n(e)\rho_{\mathrm{He\,II}}\beta_{\mathrm{He\,II}}(T)\\ &\quad - \rho_{\mathrm{He\,II}}\int_{\nu_0(\mathrm{He\,II})}^{\infty} 4\pi\sigma_\nu(\mathrm{He\,II})\,\frac{i(\nu)}{h\nu}\,d\nu - n(e)\rho_{\mathrm{He\,II}}[\alpha_{\mathrm{He\,II}}(T) + \xi_{\mathrm{He\,II}}(T)]\\ &\quad + n(e)\rho_{\mathrm{He\,I}}\beta_{\mathrm{He\,I}}(T) + \rho_{\mathrm{He\,I}}\int_{\nu_0(\mathrm{He\,I})}^{\infty} 4\pi\sigma_\nu(\mathrm{He\,I})\,\frac{i(\nu)}{h\nu}\,d\nu\,,\end{aligned} \tag{4d}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}(\rho u_i u_k + P\delta_{ik} - D_{ik}) = -\frac{\dot a}{a}\rho u_i - \frac{1}{a}\rho\frac{\partial \phi}{\partial x_i} + \frac{1}{a}\frac{u_i}{u^2}D_{\rho k}\frac{\partial \phi}{\partial x_k}\,, \tag{5}$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\frac{\partial}{\partial x_k}[(E + P)u_k - D_{Ek}] = -\frac{2\dot a}{a}E - \frac{1}{a}\rho u_k\frac{\partial \phi}{\partial x_k} + \frac{1}{a}D_{\rho k}\frac{\partial \phi}{\partial x_k} - \Lambda_{\mathrm{net}}\,, \tag{6}$$

radiation

$$\frac{\partial i(\nu)}{\partial t} = \frac{\dot a}{a}\left[\nu\frac{\partial i(\nu)}{\partial \nu} - 3i(\nu)\right] + c[j_{\mathrm{ff}}(\nu) + j_{\mathrm{fb,H\,II}} + j_{\mathrm{fb,He\,II}} + j_{\mathrm{fb,He\,III}} - \kappa(\nu)i(\nu)]\,, \tag{7}$$

EOS

$$P = \frac{1}{m_P}\left(\rho_{\mathrm{H\,I}} + \rho_{\mathrm{H\,II}} + \frac{\rho_{\mathrm{He\,I}} + \rho_{\mathrm{He\,II}} + \rho_{\mathrm{He\,III}}}{4} + \rho_{\mathrm{H\,II}} + \frac{\rho_{\mathrm{He\,II}}}{4} + \frac{\rho_{\mathrm{He\,III}}}{2}\right)kT\,, \tag{8}$$

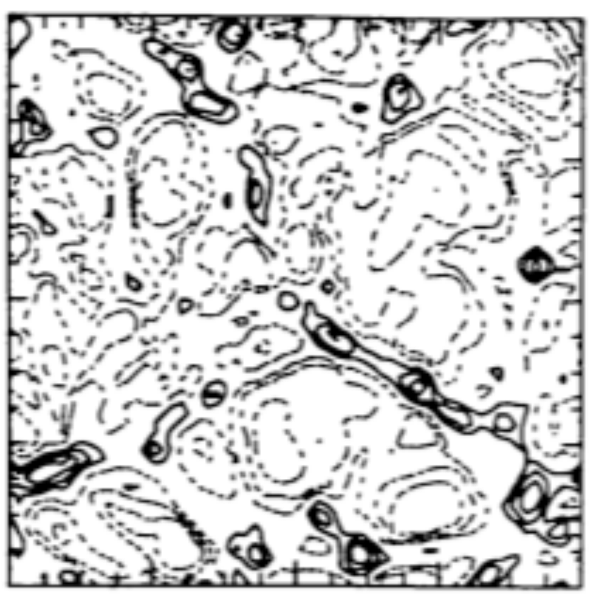
Cen ’92

“Recipe” for Galaxy Formation

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

Three Revolutions in Cosmological Hydro Simulations

1990': 1st Revolution

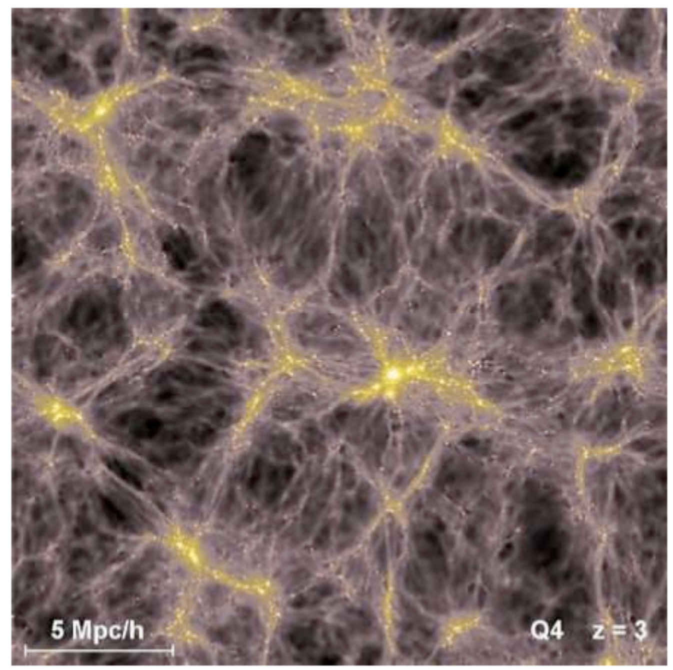


First cosmological, but coarse calculation

Resolution~100 kpc

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

2001-2011
2nd Rev.

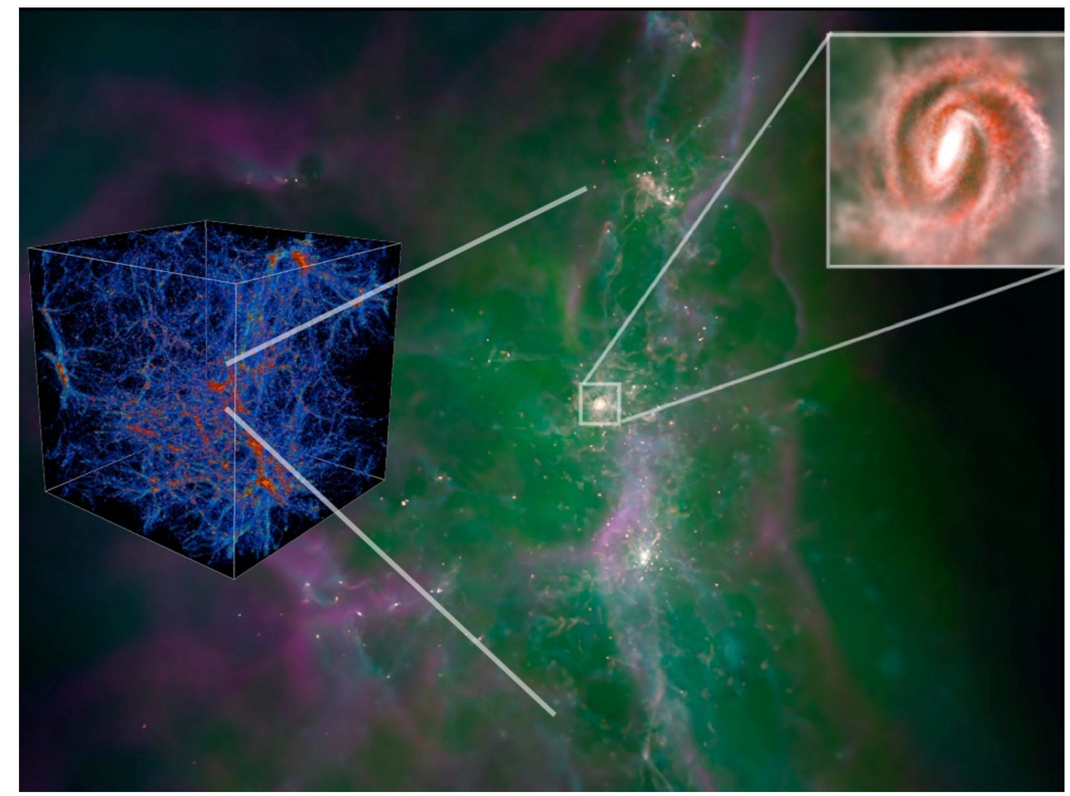


Larger scale, medium resolution **w. subgrid models**

Resolution ~ kpc

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

2012~
3rd Rev.

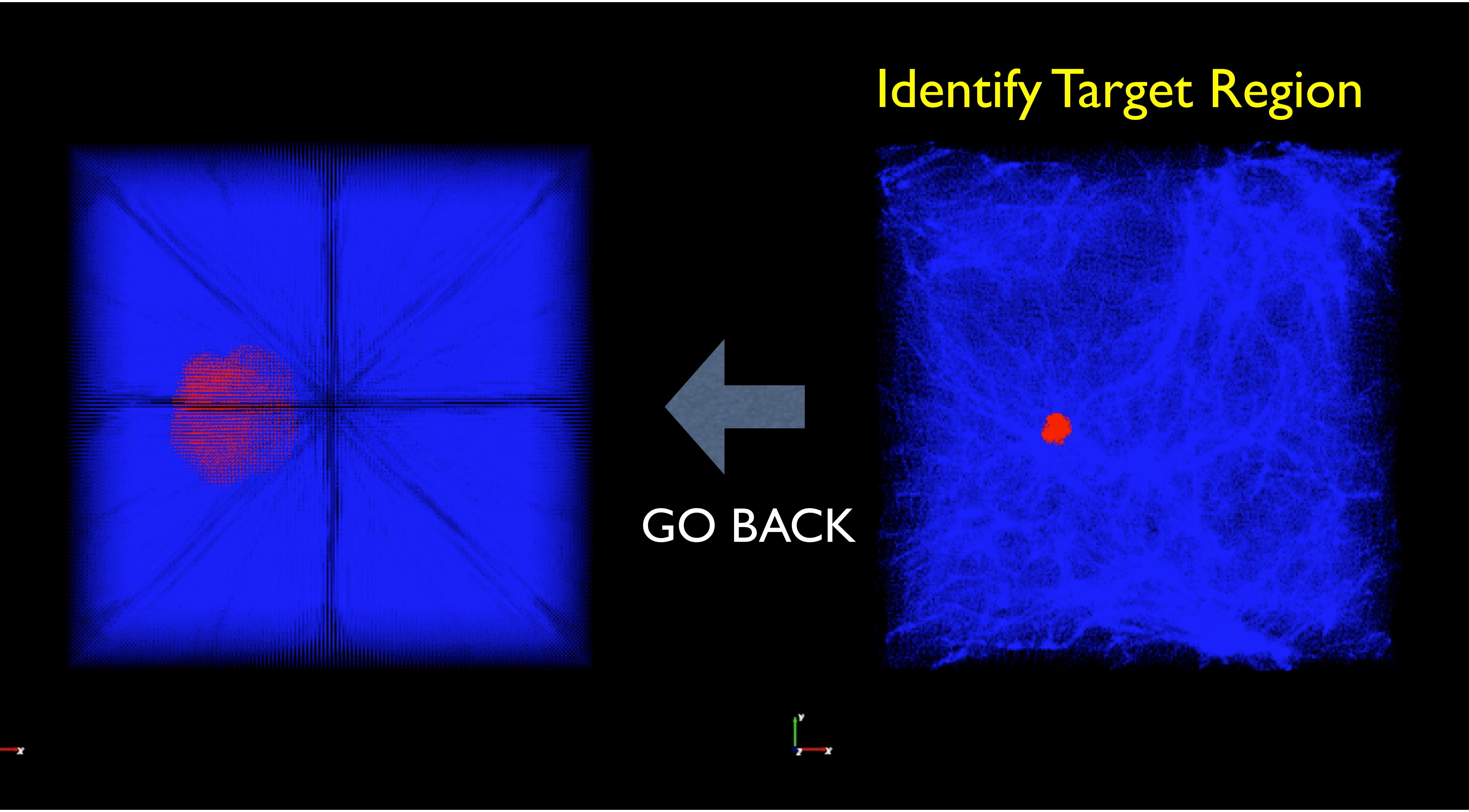


Zoom-in method allows much higher res.

Resolution~ 10-100pc

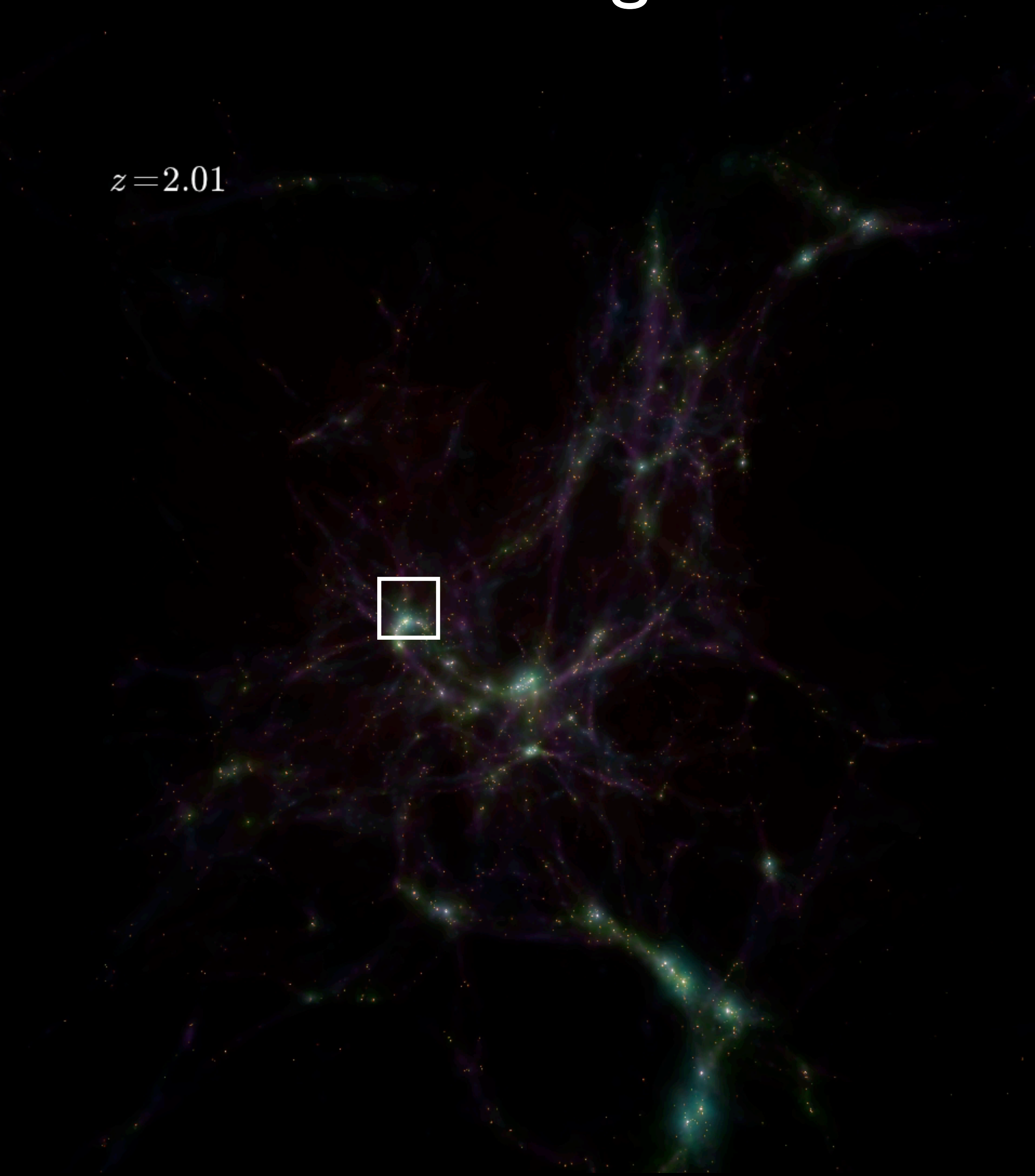
IC code: GRAFIC (Bertschinger)
MUSIC (Hahn & Abel '11)

Setting Up a Zoom-in Simulation

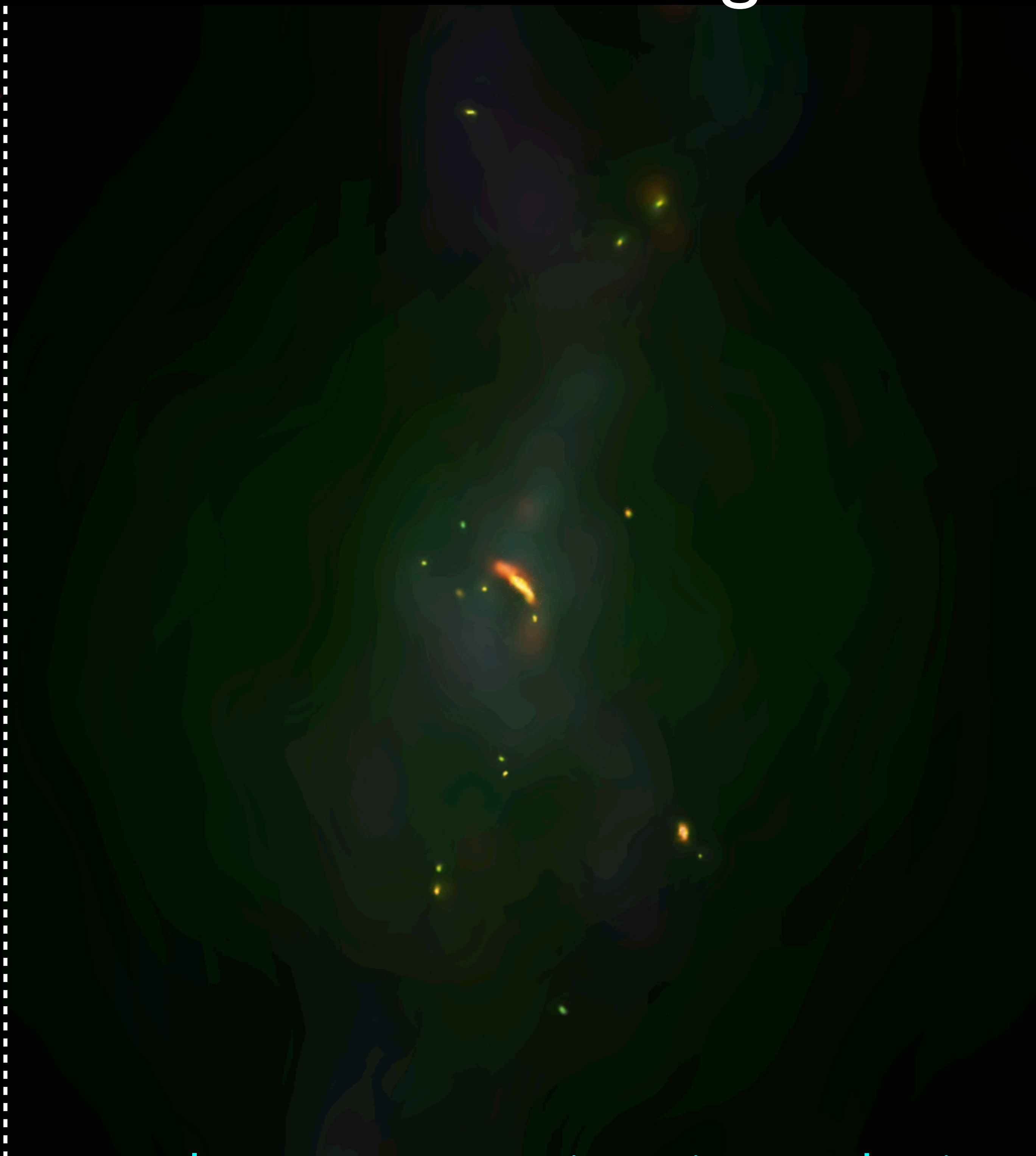


MUSIC (Hahn & Abel '11) + Thompson's SPHGR (python analyses code suite)

Cosmological box



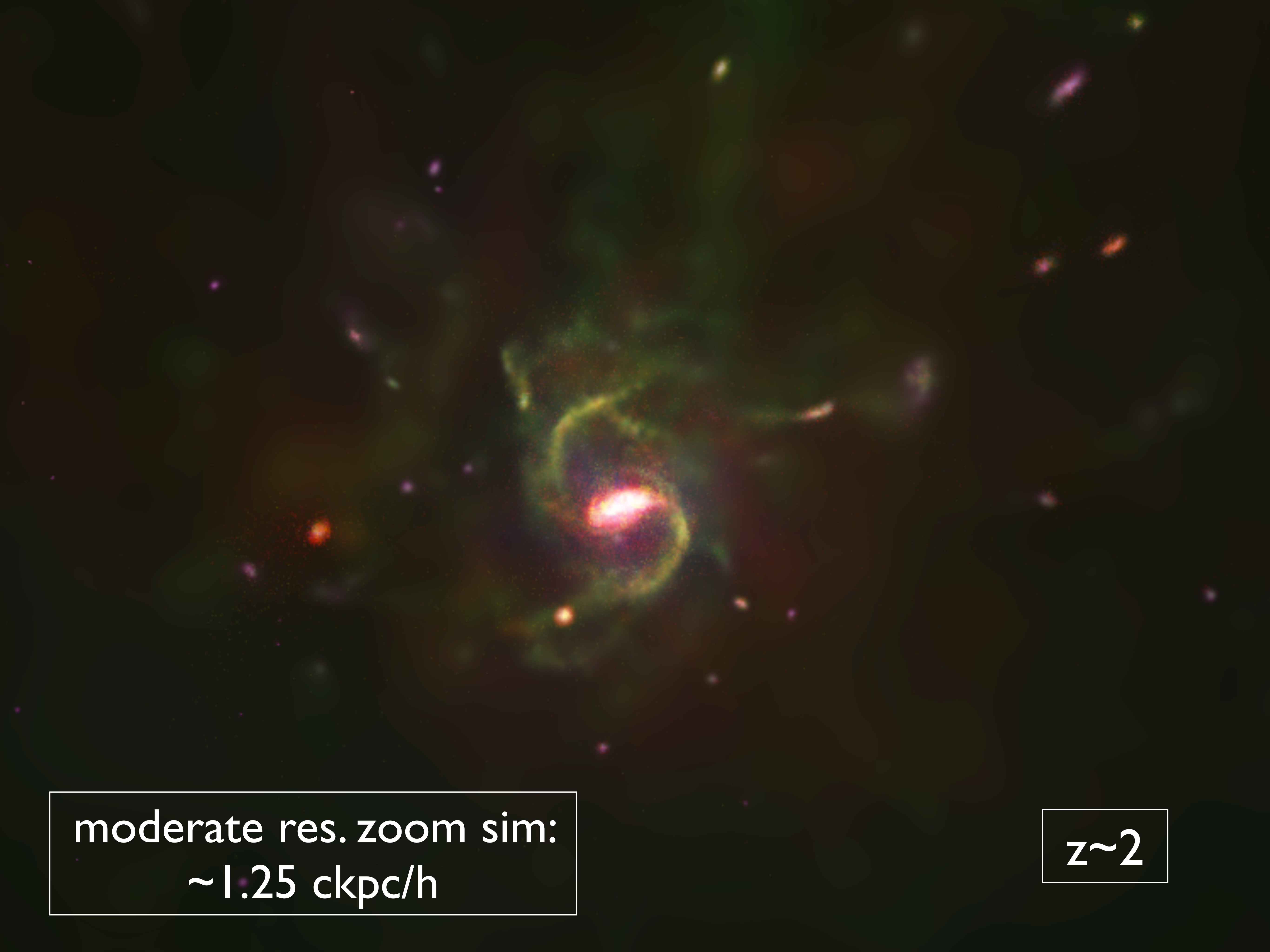
Zoom-in region



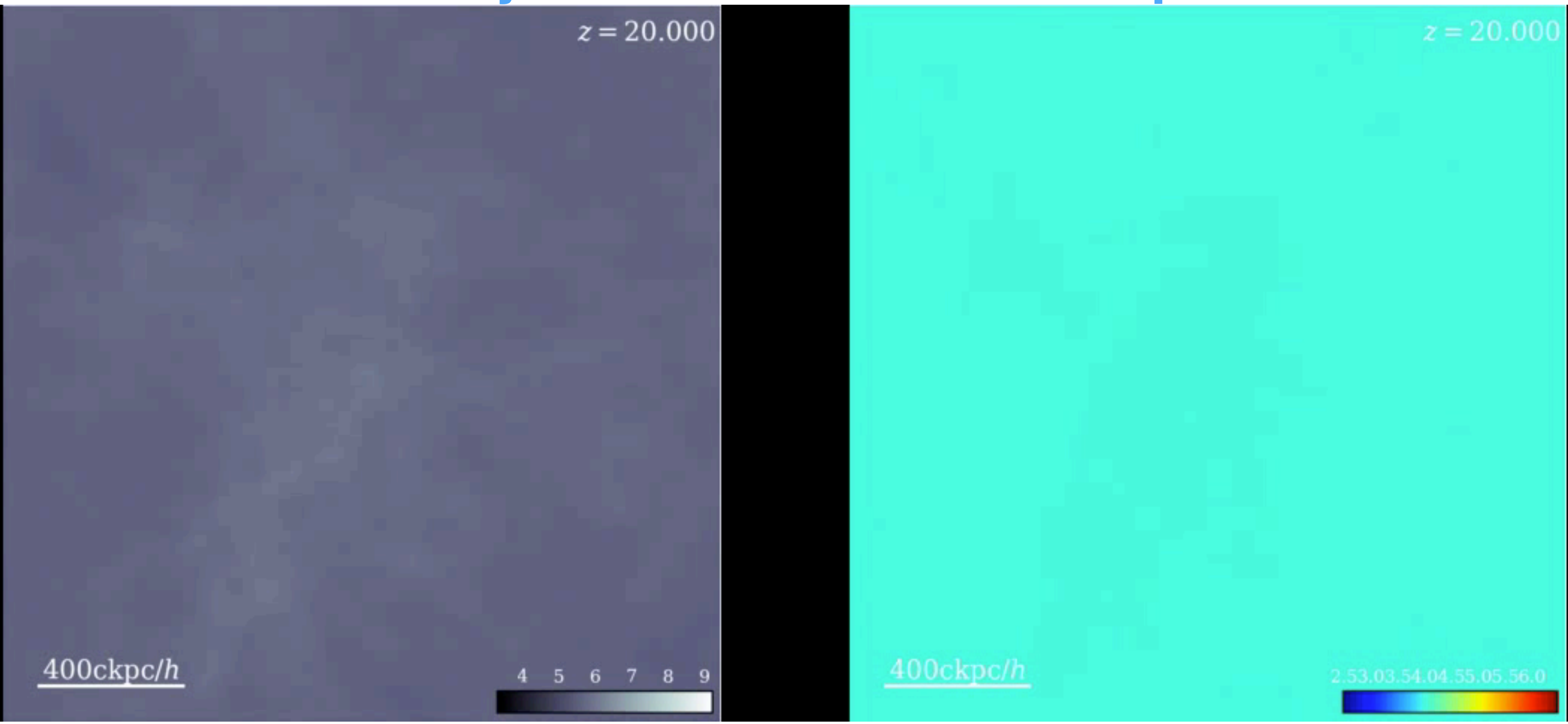
color=temperature, intensity=gas density

yellow dots = stars

Thompson & KN '13


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

Gas Density | Temperature

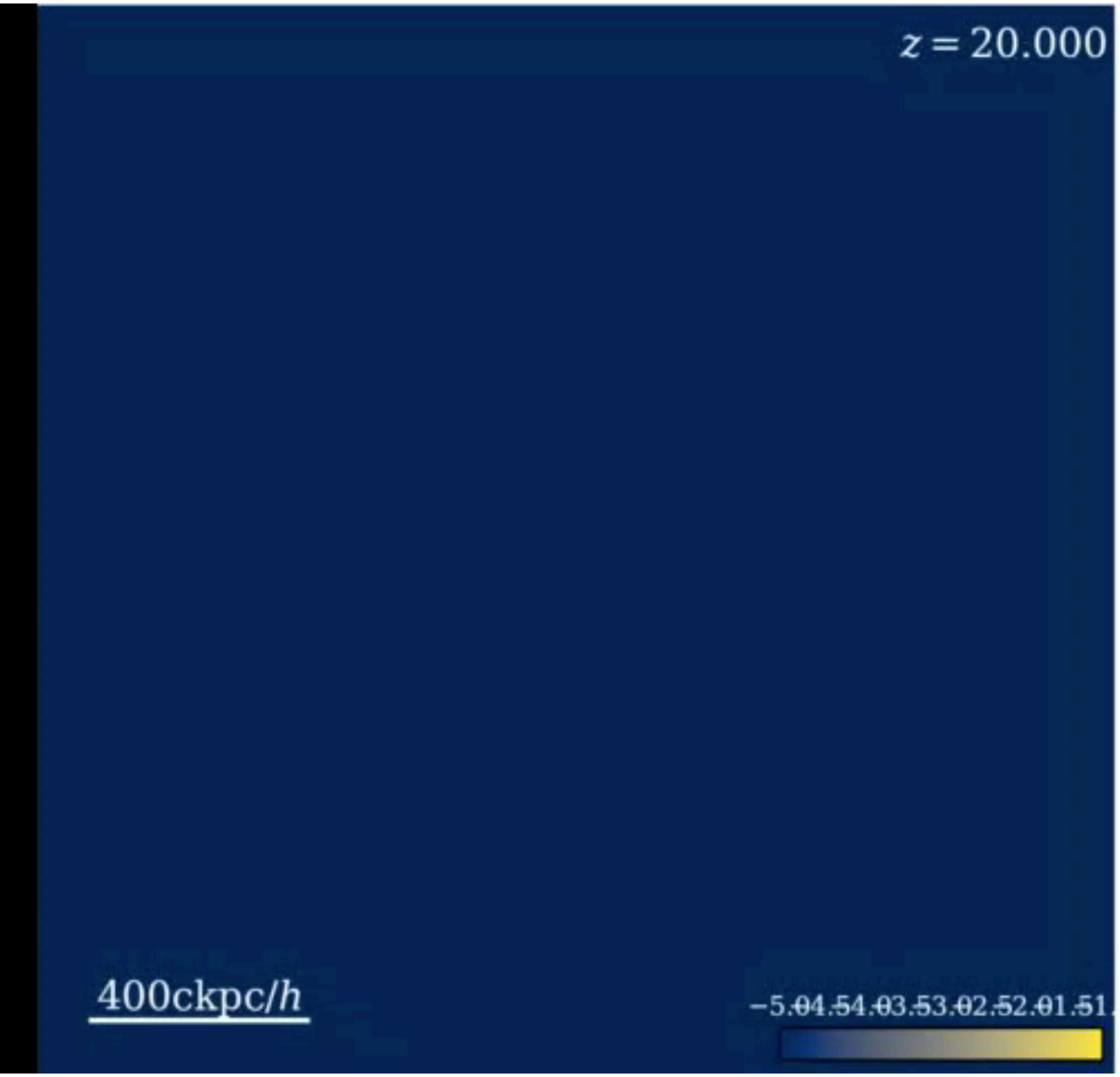


AGORA L12 sim. Shimizu, KN+19

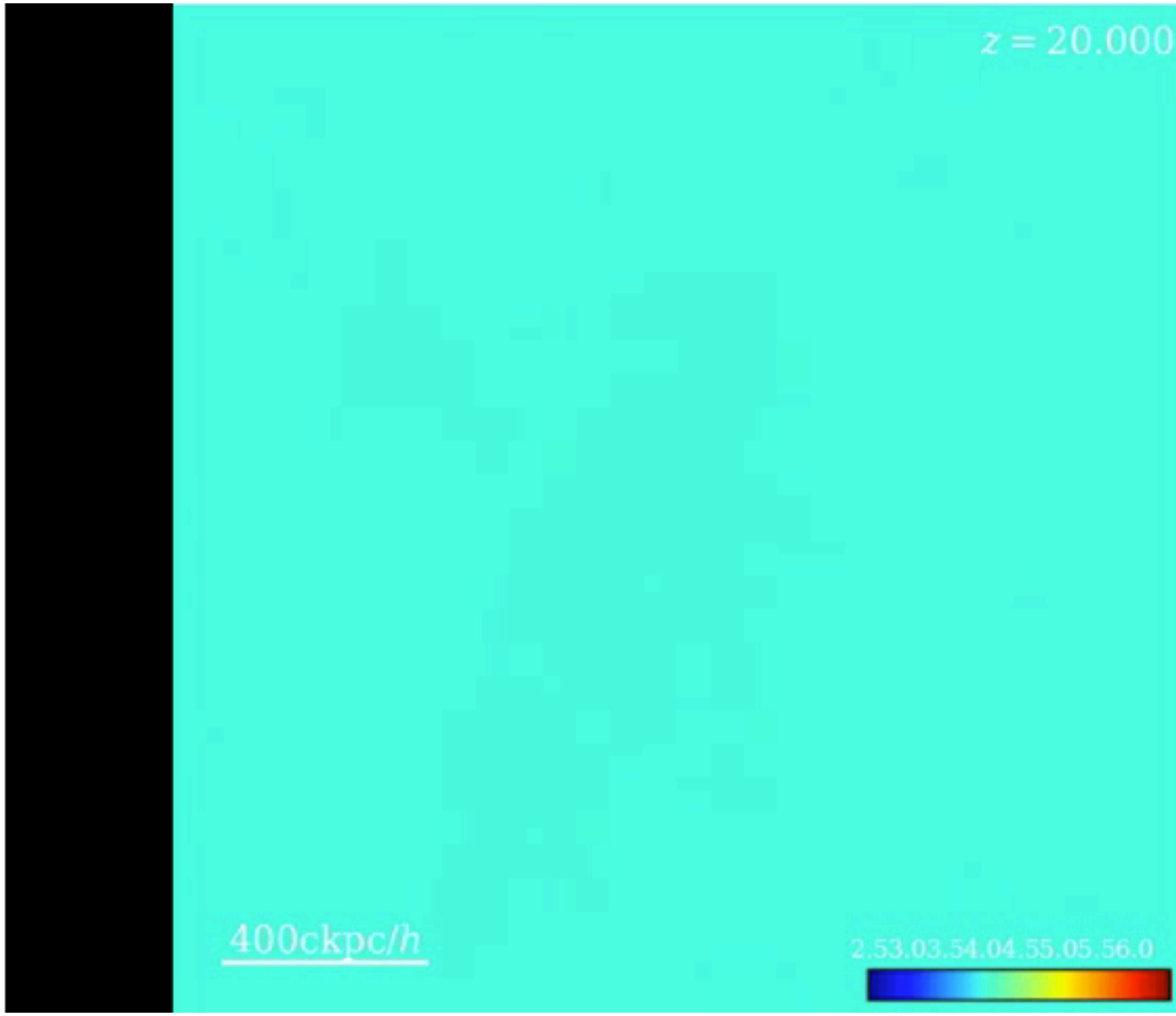
movie available in keynote and pptx here:

https://www.dropbox.com/sh/ebocq9px5fyelwk/AAAHMhQsukOhsVJR7miESjama?dl=0

Metallicity



Temperature



AGORA L12 sim. Shimizu, KN+19

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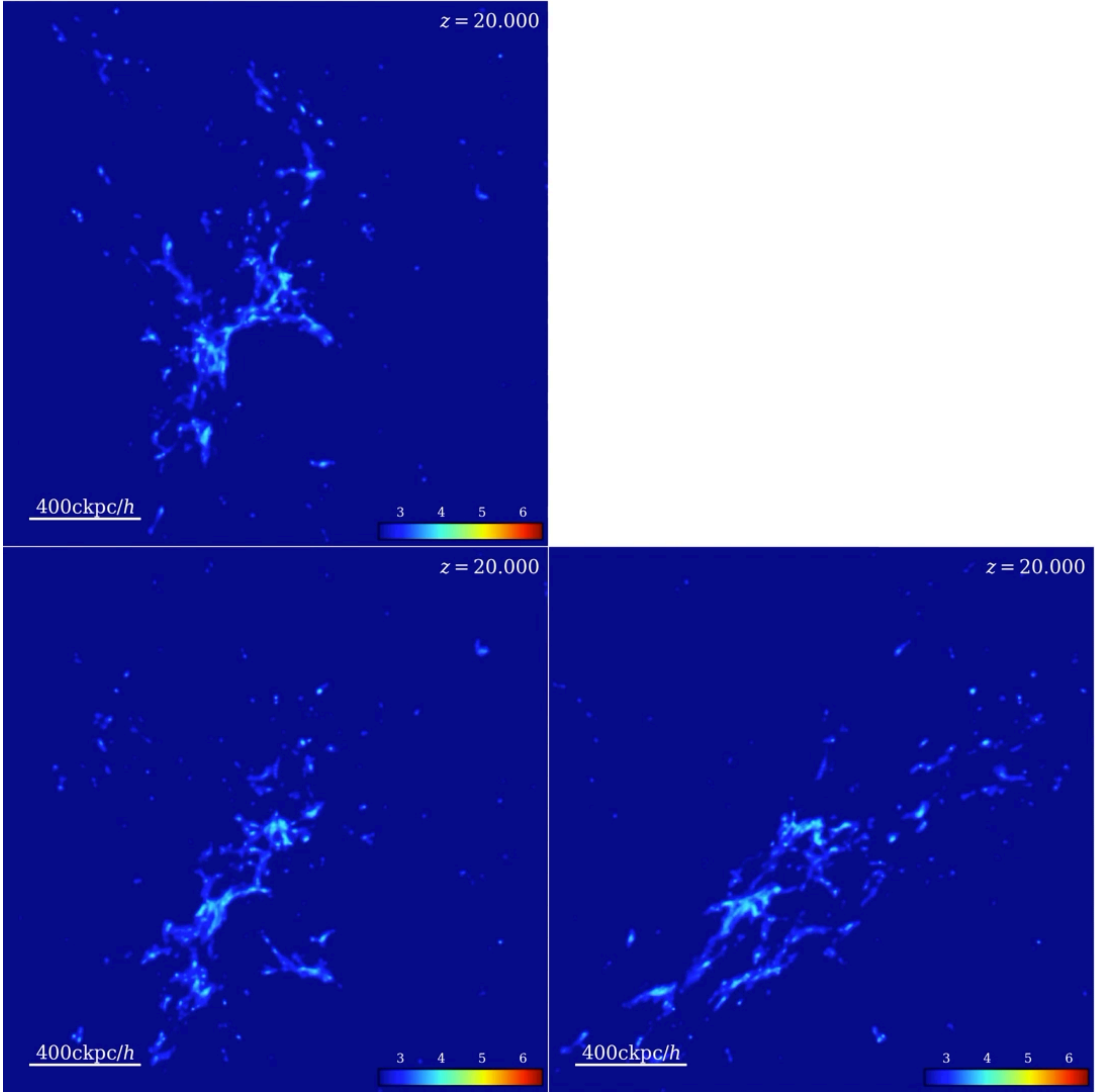
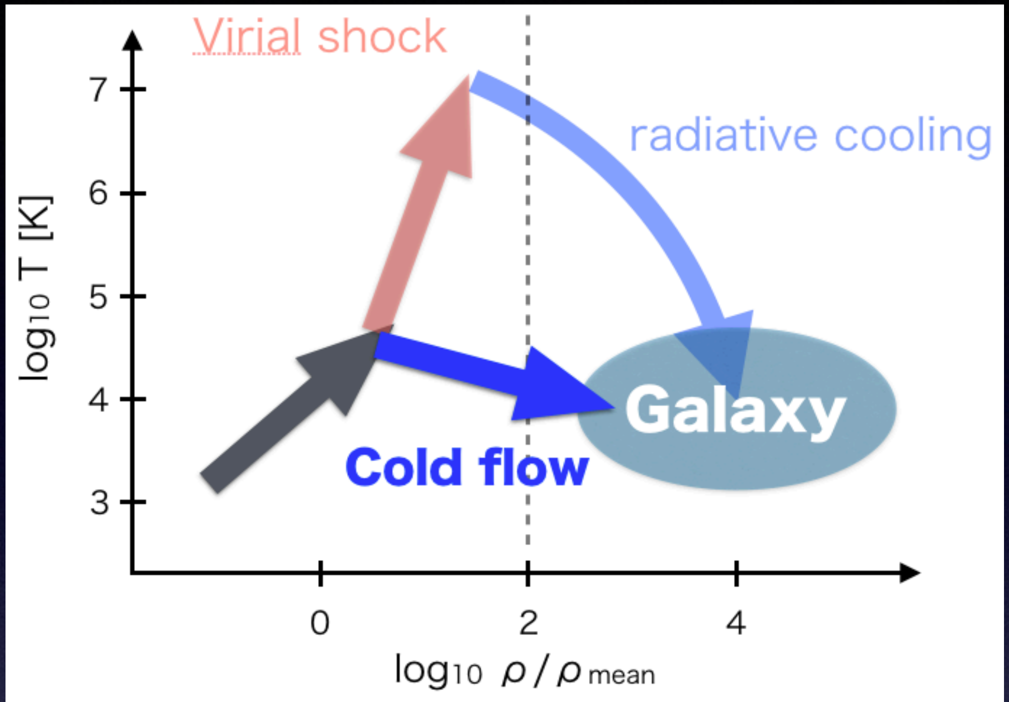
https://www.dropbox.com/sh/ebocq9px5fyelwk/AAAHMhQsukOhsVJR7miESjama?dl=0

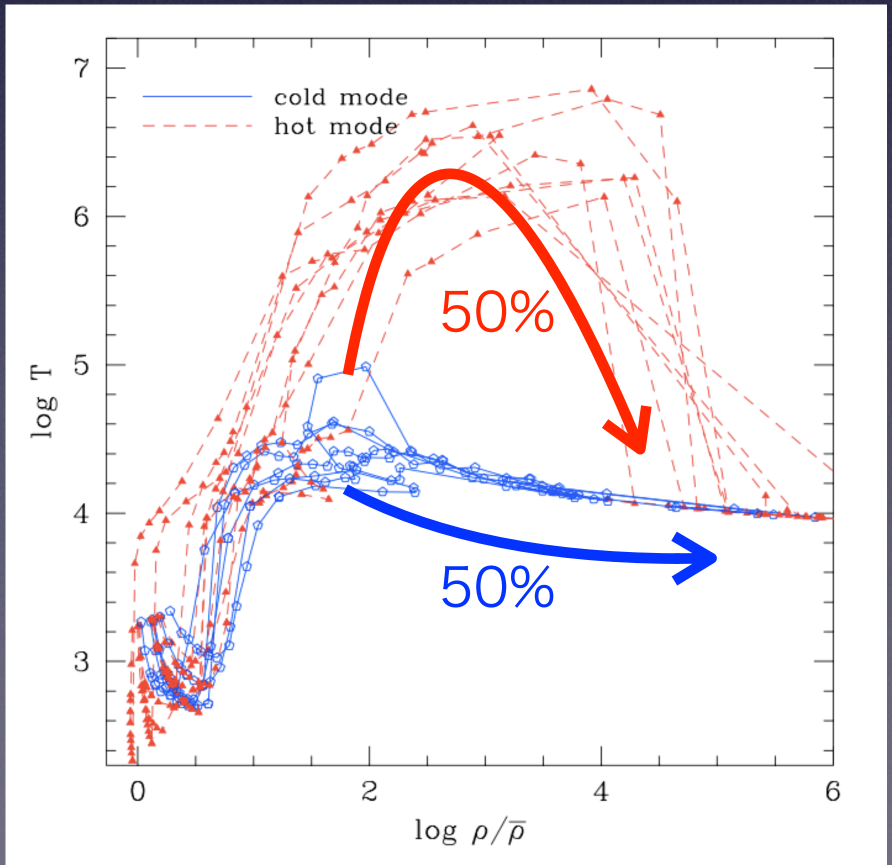


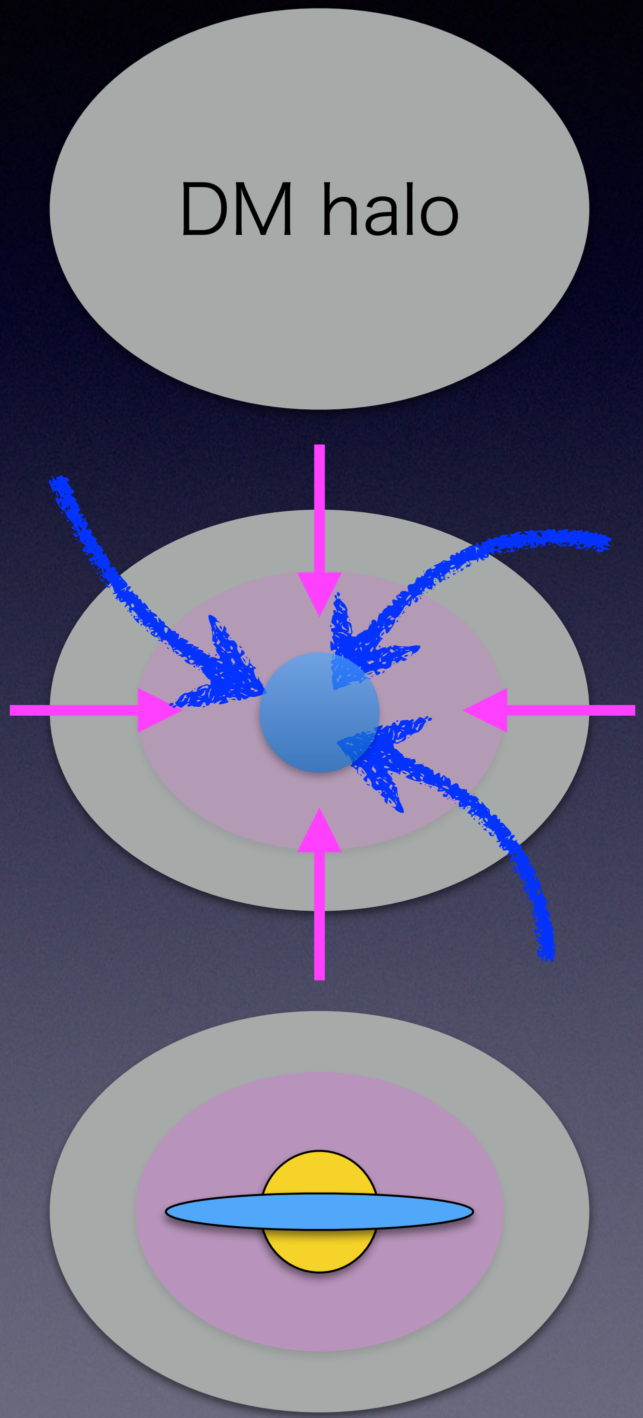
$z = 20.000$
400ckpc/h
3
4
5
6
$z = 20.000$
400ckpc/h
3
4
5
6
$z = 20.000$
400ckpc/h
3
4
5
6

Galaxy formation with cold flows



Keres+'05





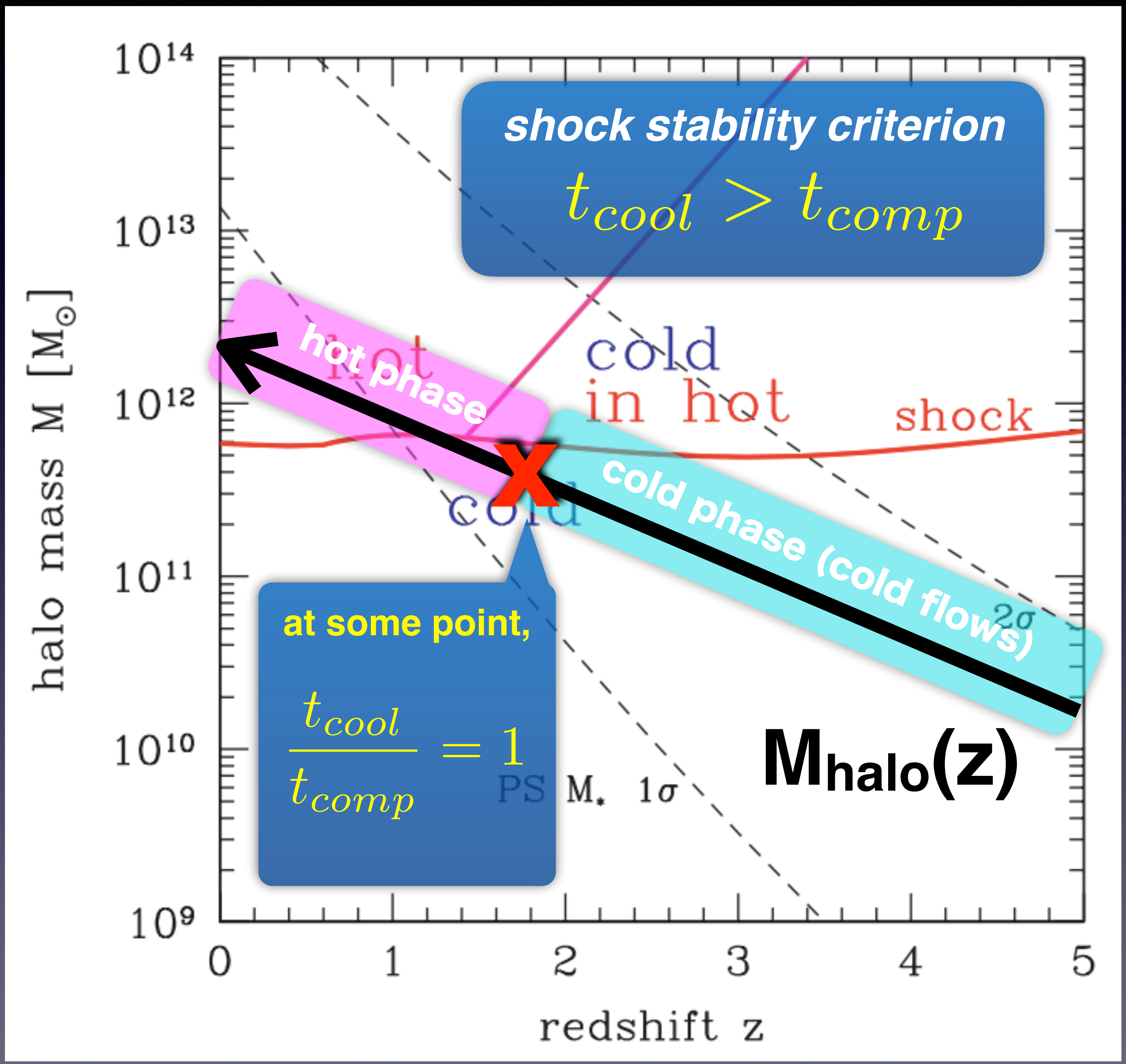
DM halo forms

gas accretes spherically & filamentary

Cooling & disk galaxy forms

cf. Kosei Matsumoto talk

Criteria for cold flows



Dekel & Birnboim '06

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

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

Compute

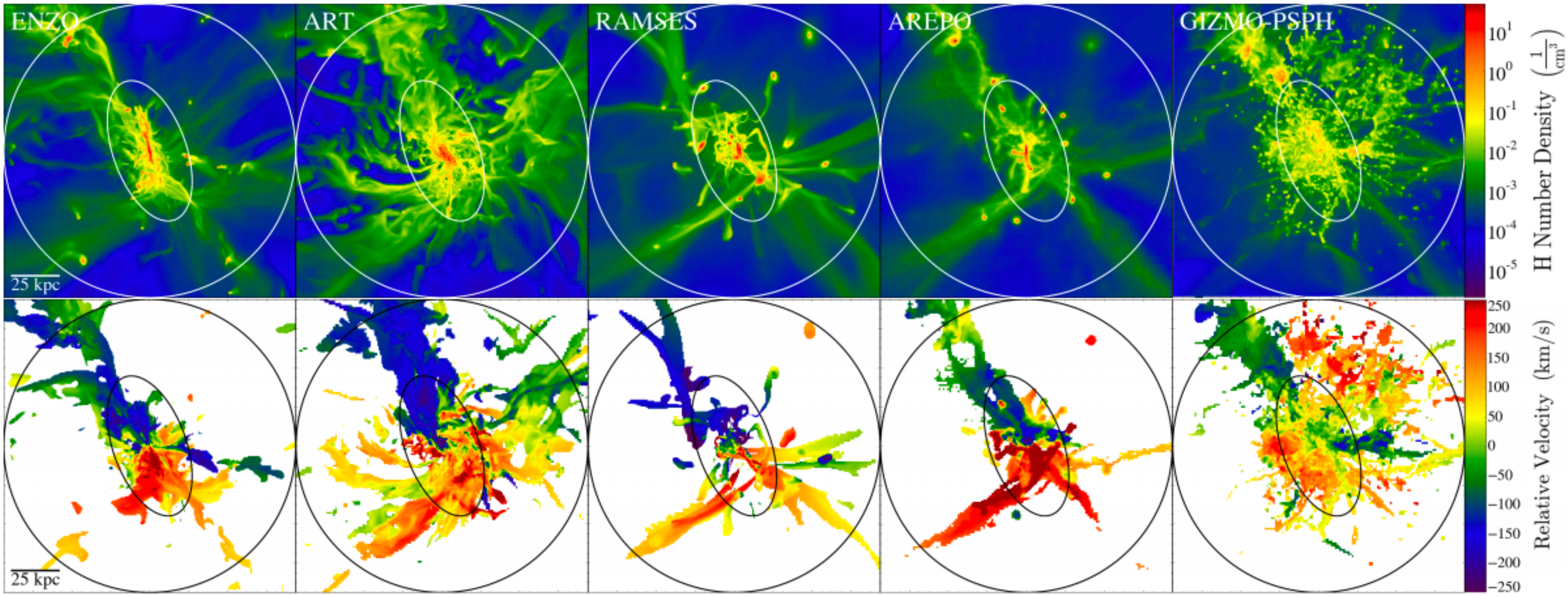
$$\frac{t_{cool}}{t_{comp}}$$

at Rv and examine the redshift evolution.

cf. Kosei Matsumoto talk

“Cold Flow Disk”

z~3

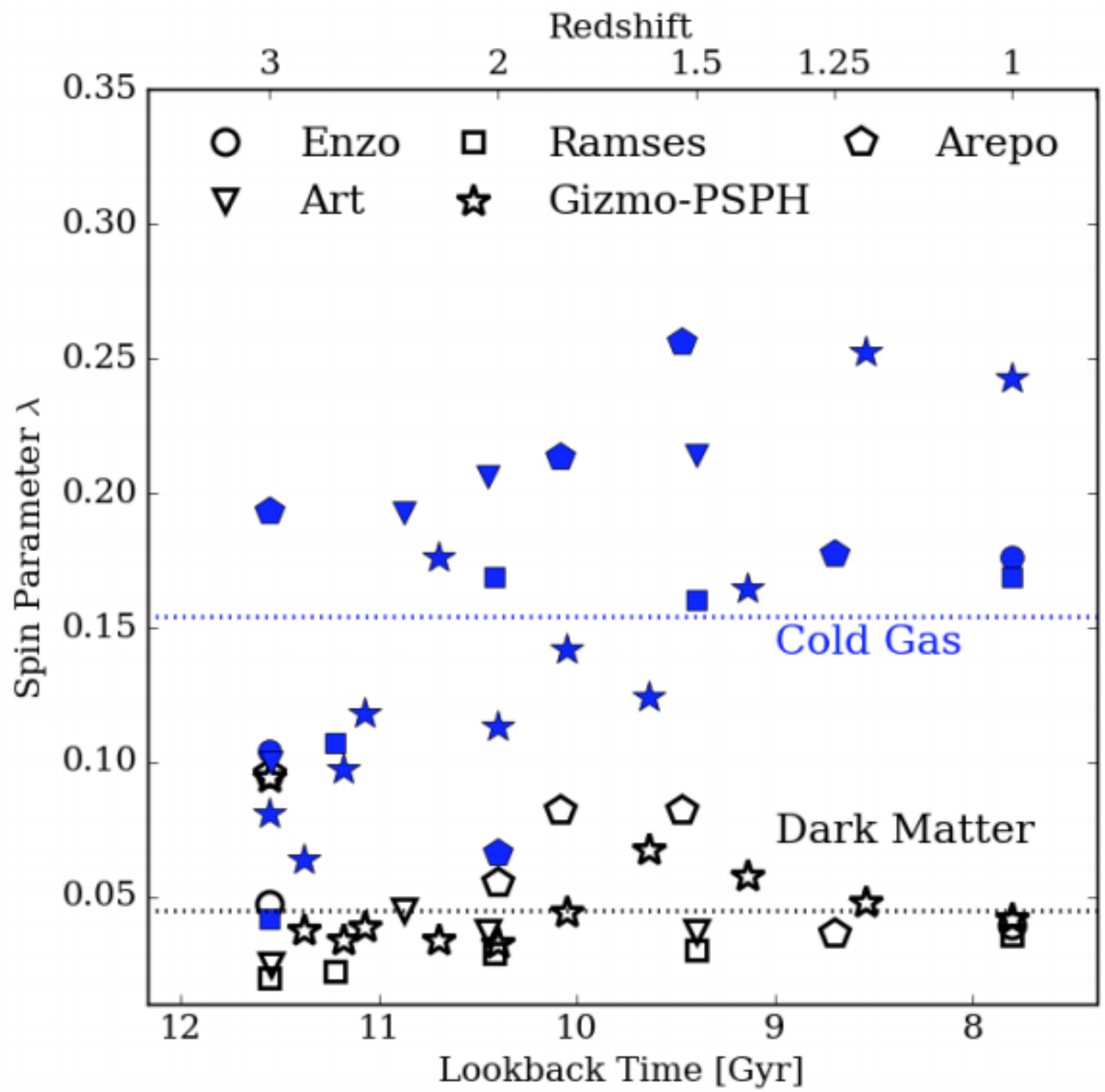


Extended, flattened rotating structures of high–*J* material.

Stewart+’17

Cold gas in halos have 4x *J* than dark matter

Stewart+'17



spin param.

$\lambda_x \equiv j_x / 2V R$

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

$\lambda_{DM} \simeq 0.04$

cf. angular momentum catastrophe in '90s (Steinmetz, …)

History 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

cf. Yuri Oku's talk

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 (GW)

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

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

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

GW velocity

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

mass-loading factor $\eta \approx 0.25$

Galactic Wind (Kinetic) Feedback

Need to specify $\dot{M}_w$ and V_W

cf. Choi & KN '10

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

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

η : mass-loading factor

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

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

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

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

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

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

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.

Feedback in Zoom-in Cosmo Sim

Models w/ more direct momentum input:

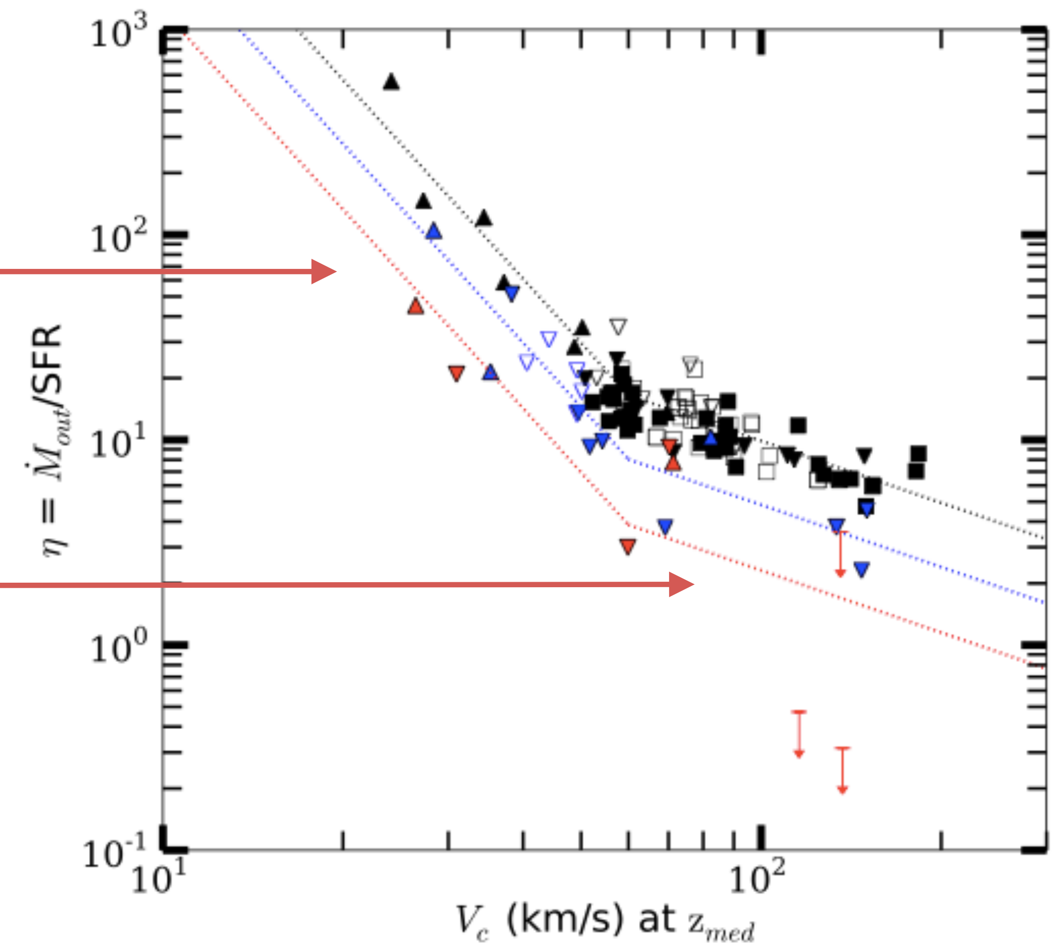
Mass Loading Factor : η

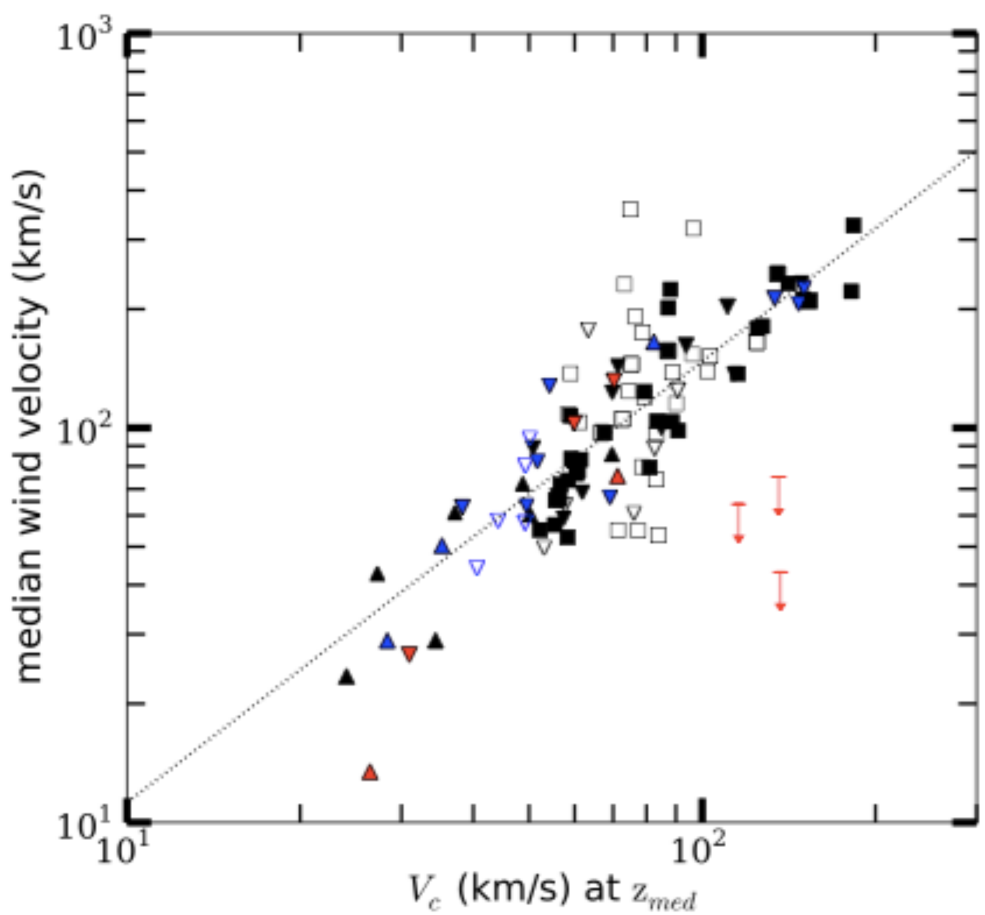
$$\eta = 2.91\,(1+z)^{1.25}\left(\frac{v_c}{60\mathrm{km/s}}\right)^{-3.22}$$

(steeper than Energy-driven)

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

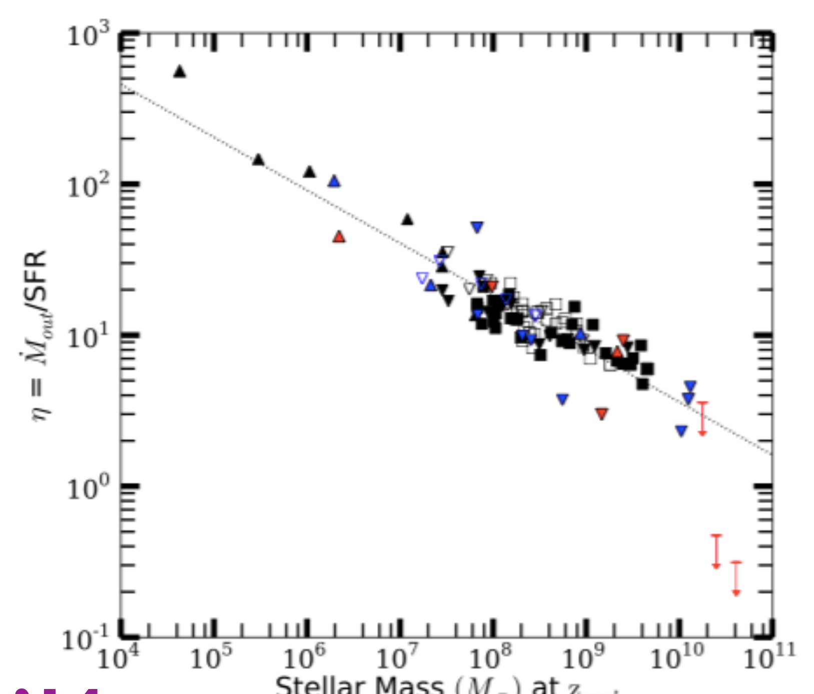
(≈ Momentum-driven)



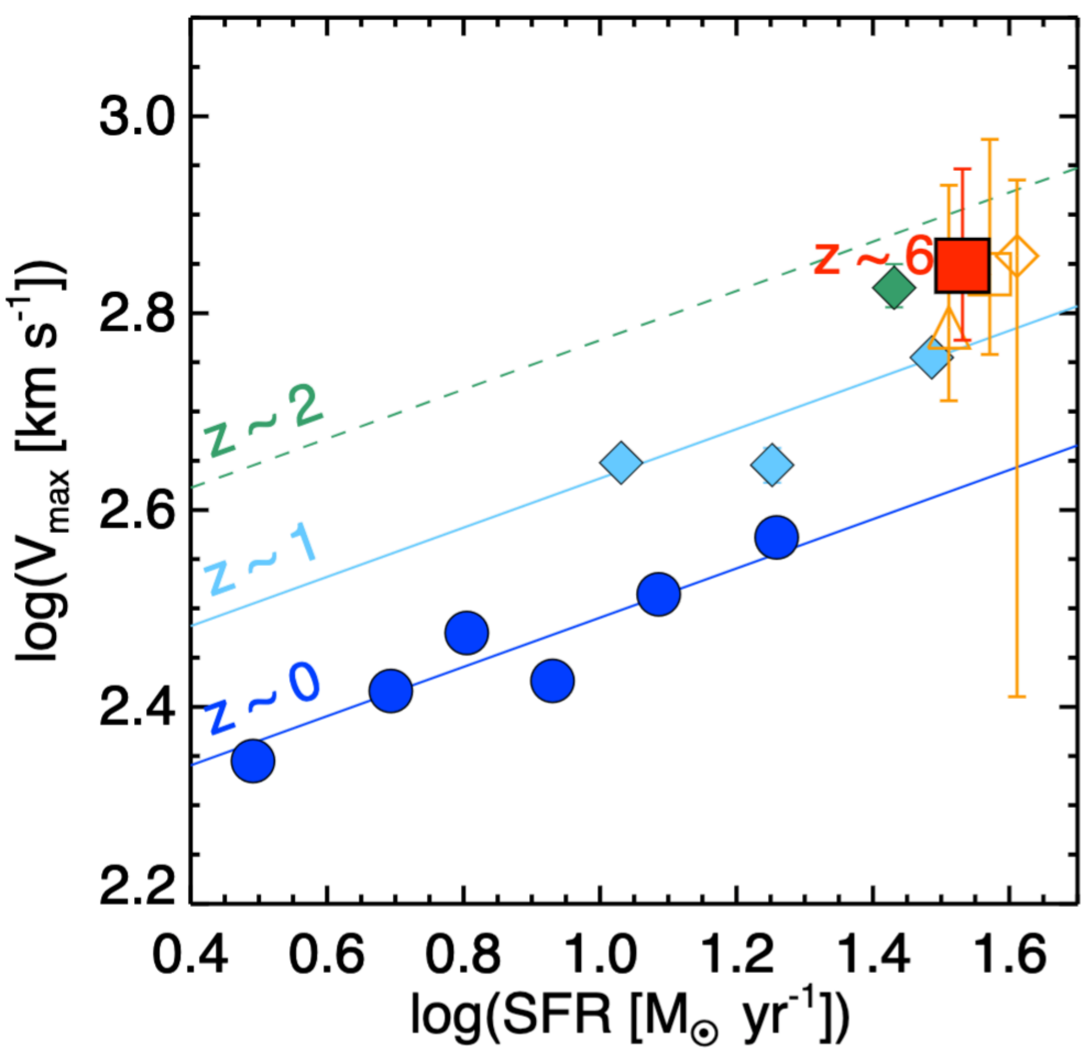


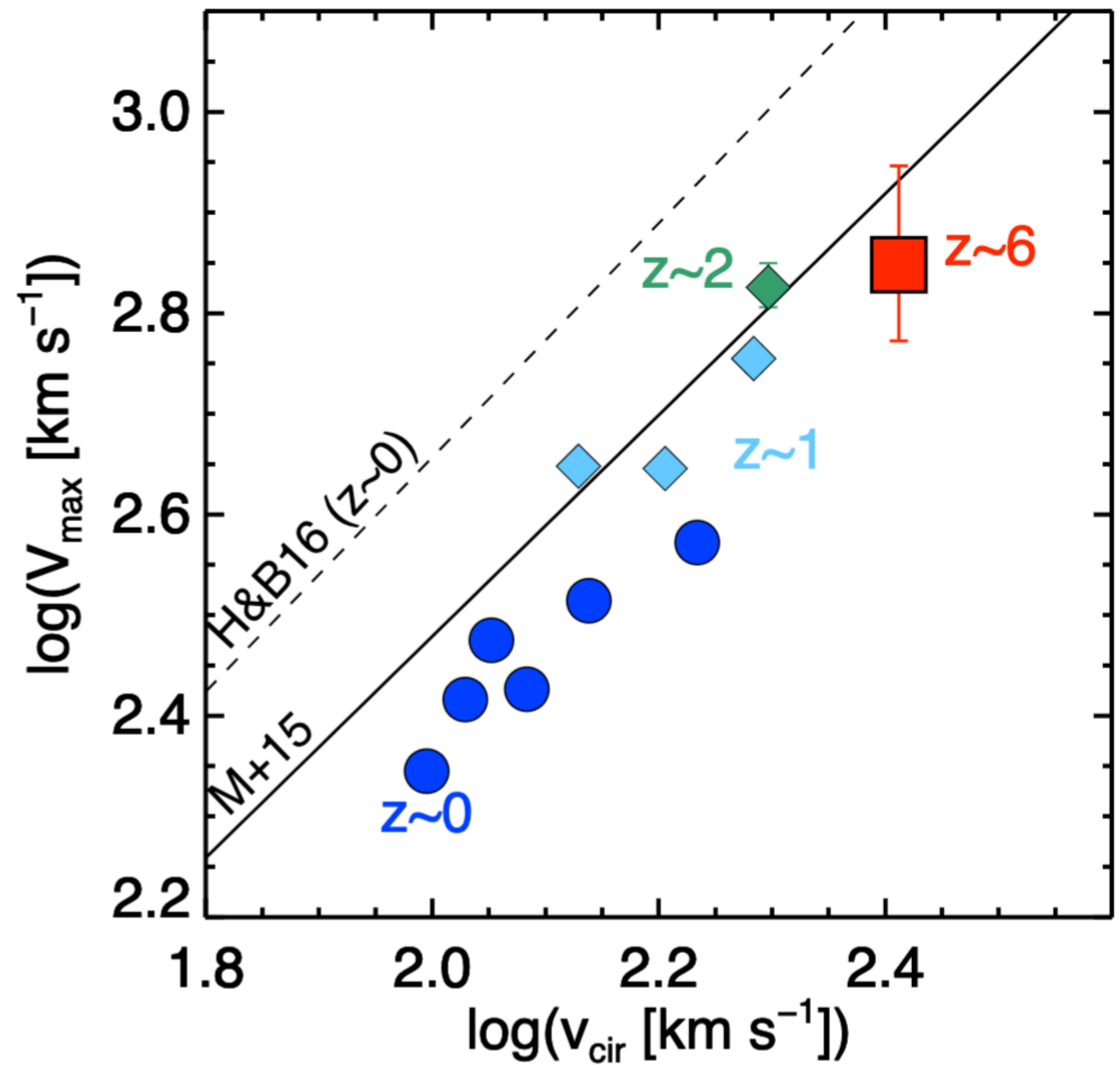
Wind Velocity

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



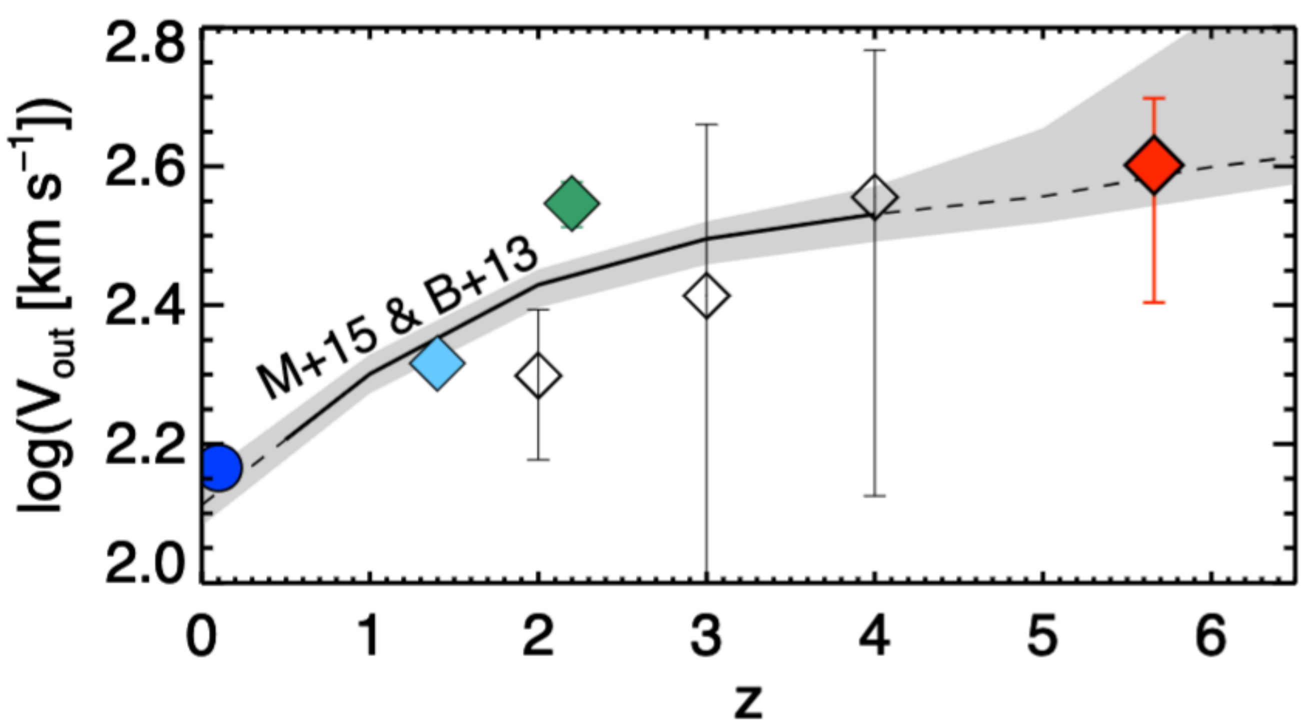
Hopkins+'13; Muratov+ '14





Using blue-shifted absorption lines

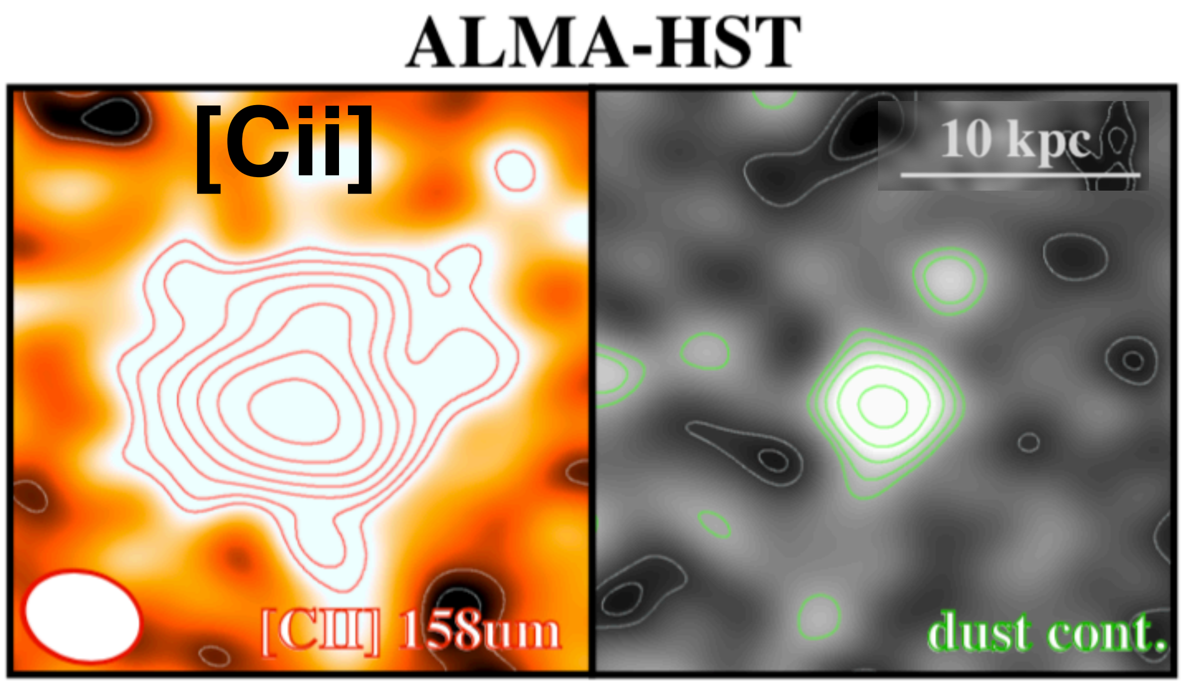
Si II λ1260
C II λ1335
Si IV λ1394, 1403



Sugahara+19

Extended [CII] emission profile

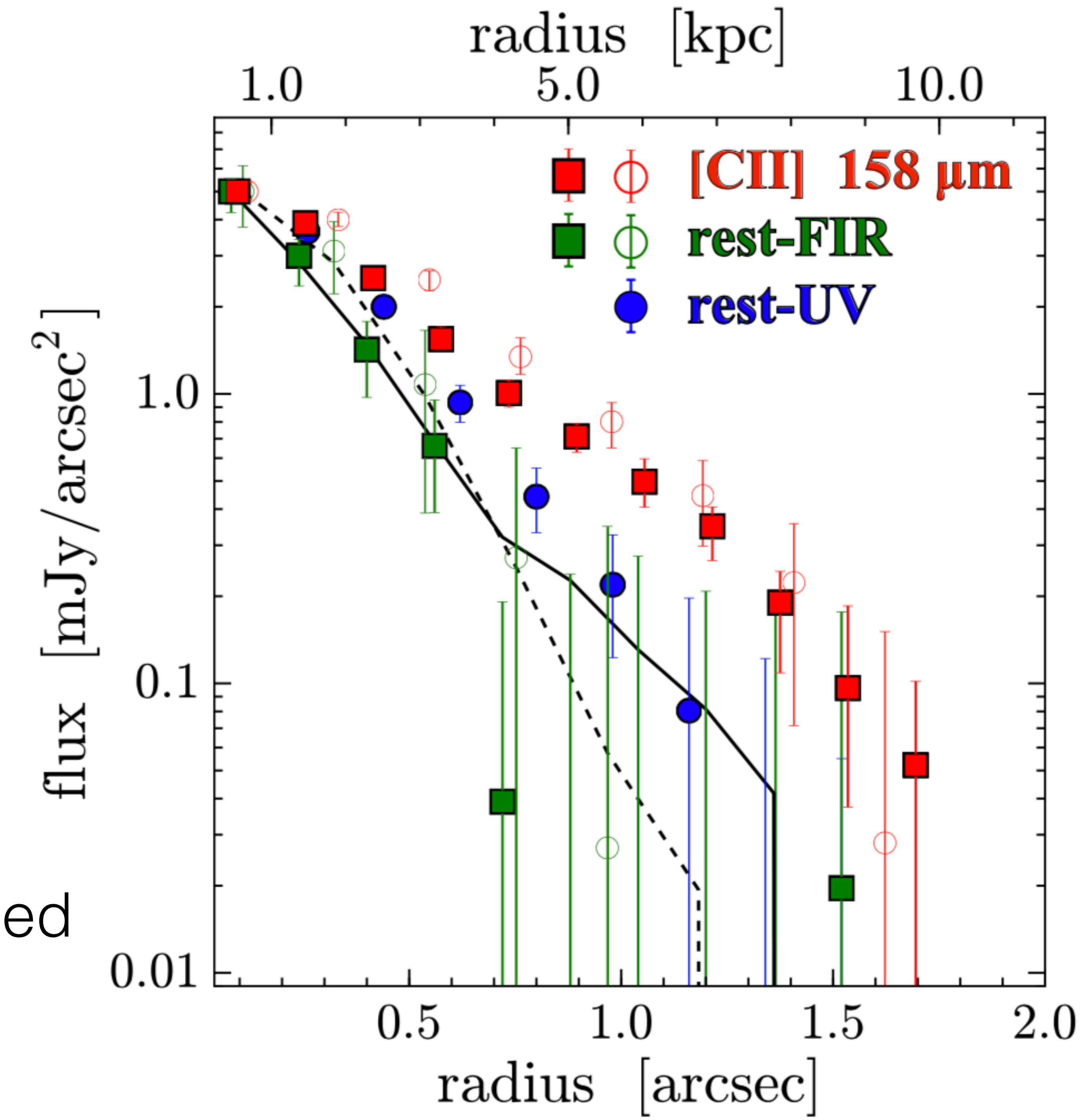
from stacking ALMA & HST data



4'' x 4''

Fujimoto+ '19

lines: synthesized beam profile

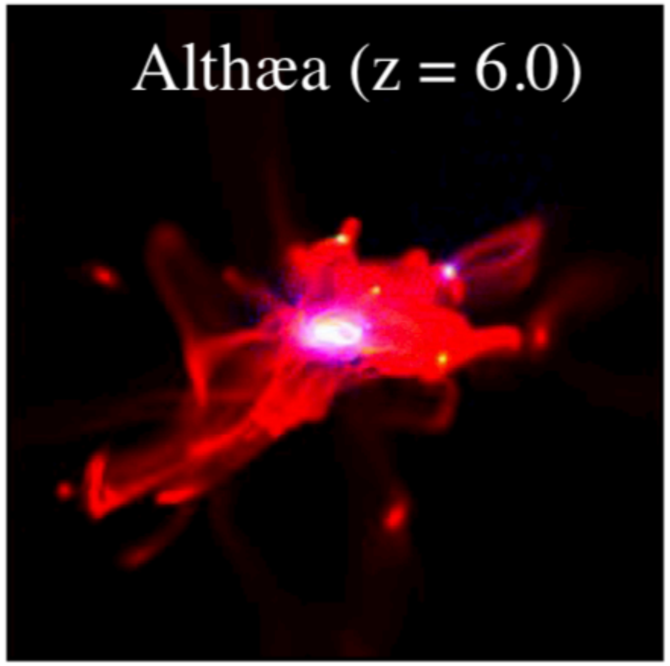


NAOJ press-release on Dec 16, 2019

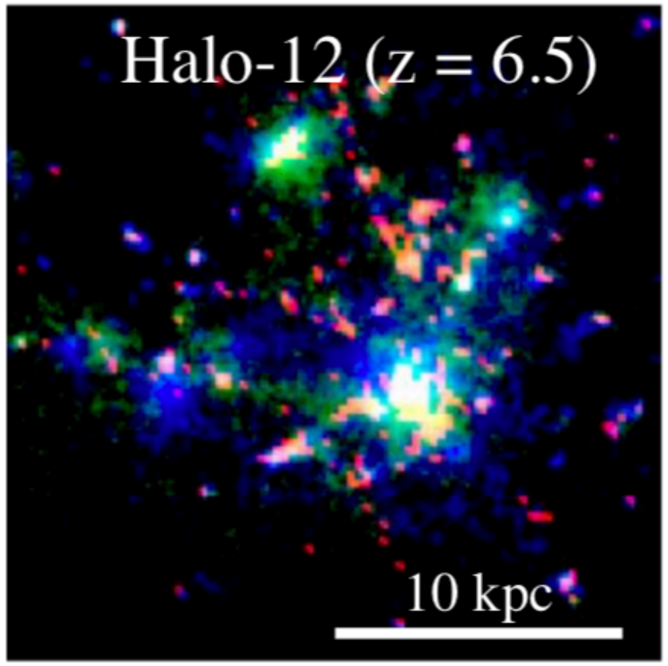
[C II] profile: comparison w. simulation

4”x4” sim image

[CII] 158 µm
rest-FIR
rest-UV

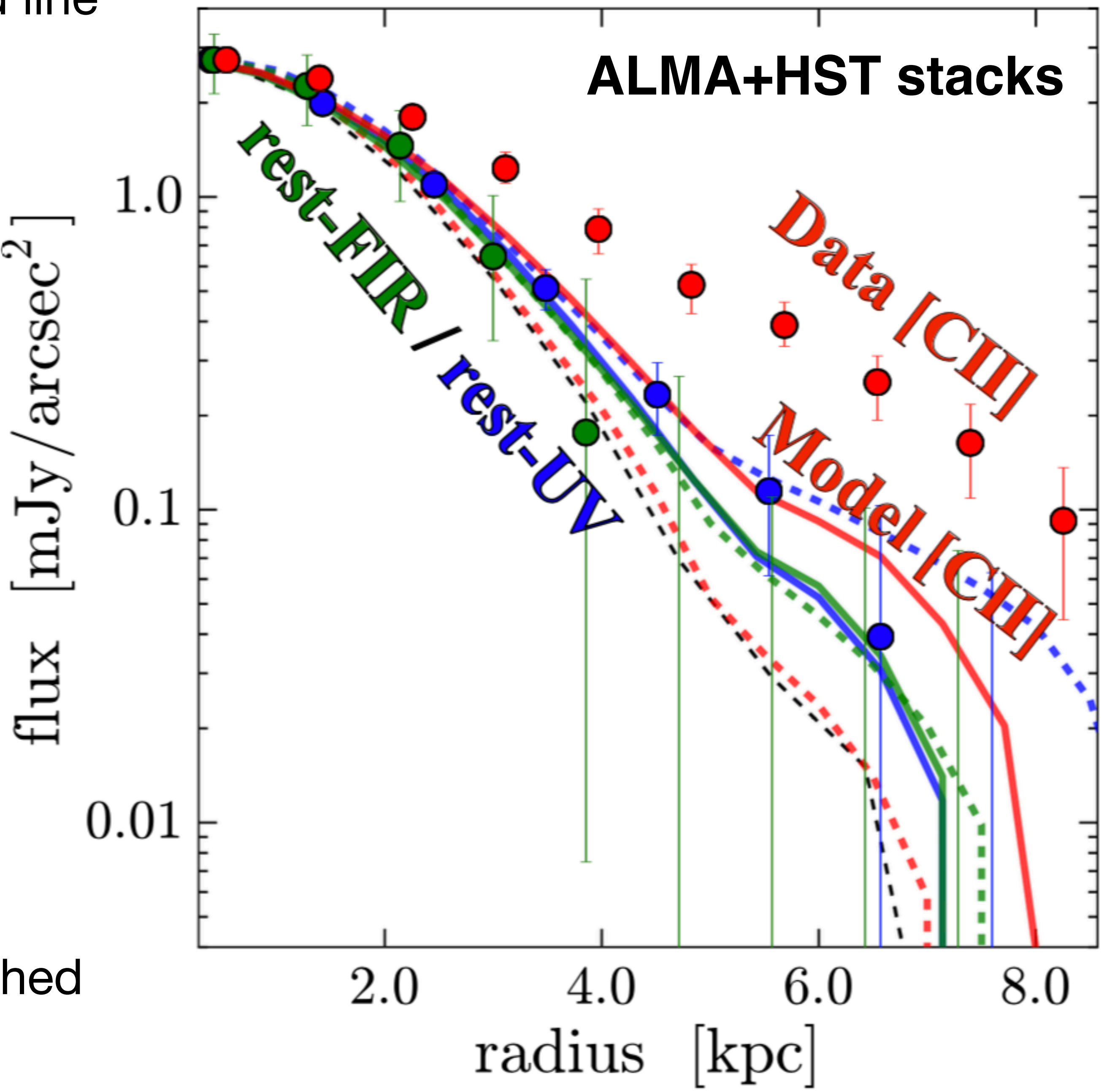


solid line



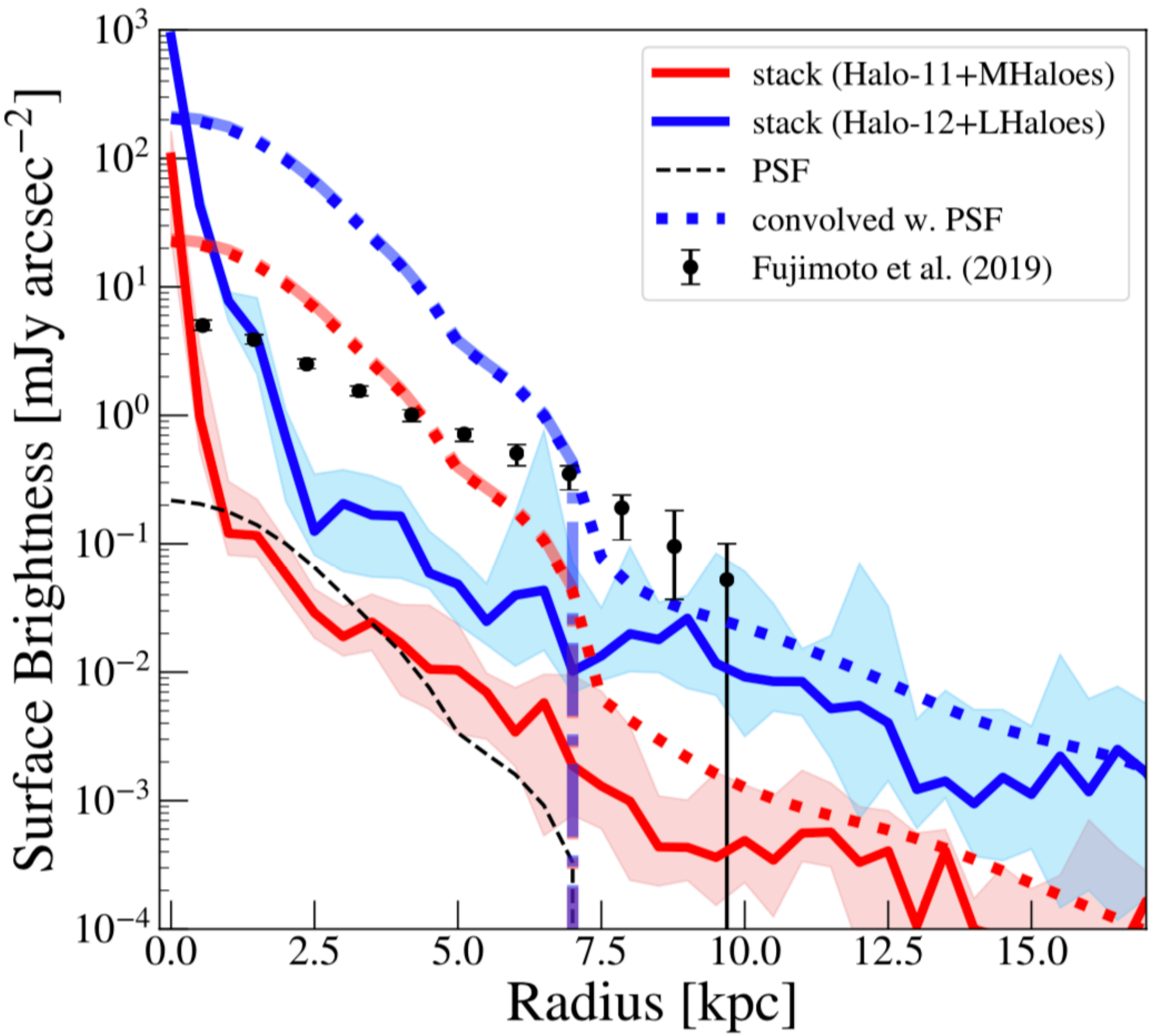
dashed

Fujimoto+19



- How does carbon enrichment happens so widely in the early universe?
- What powers the emission?

[C II] intensity profile & ALMA PSF

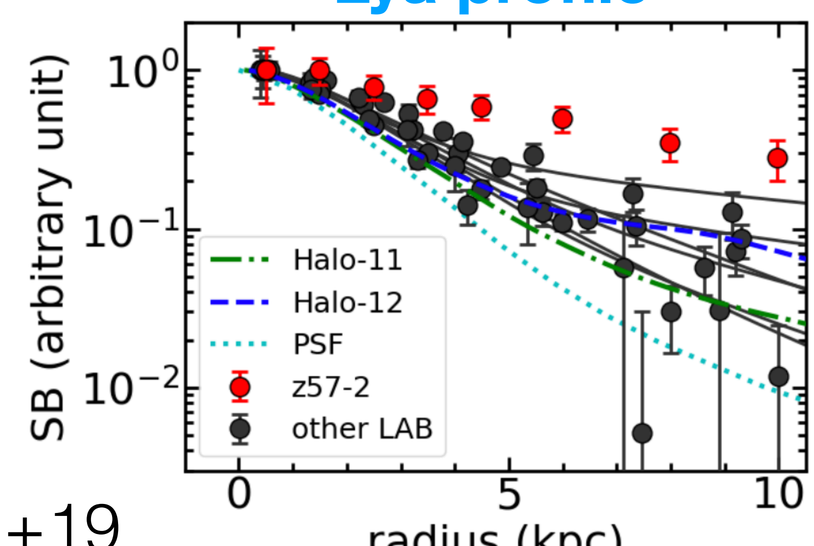


Arata, Yajima, KN+'18, '20

Sim. profile is ***steeper*** near the center.

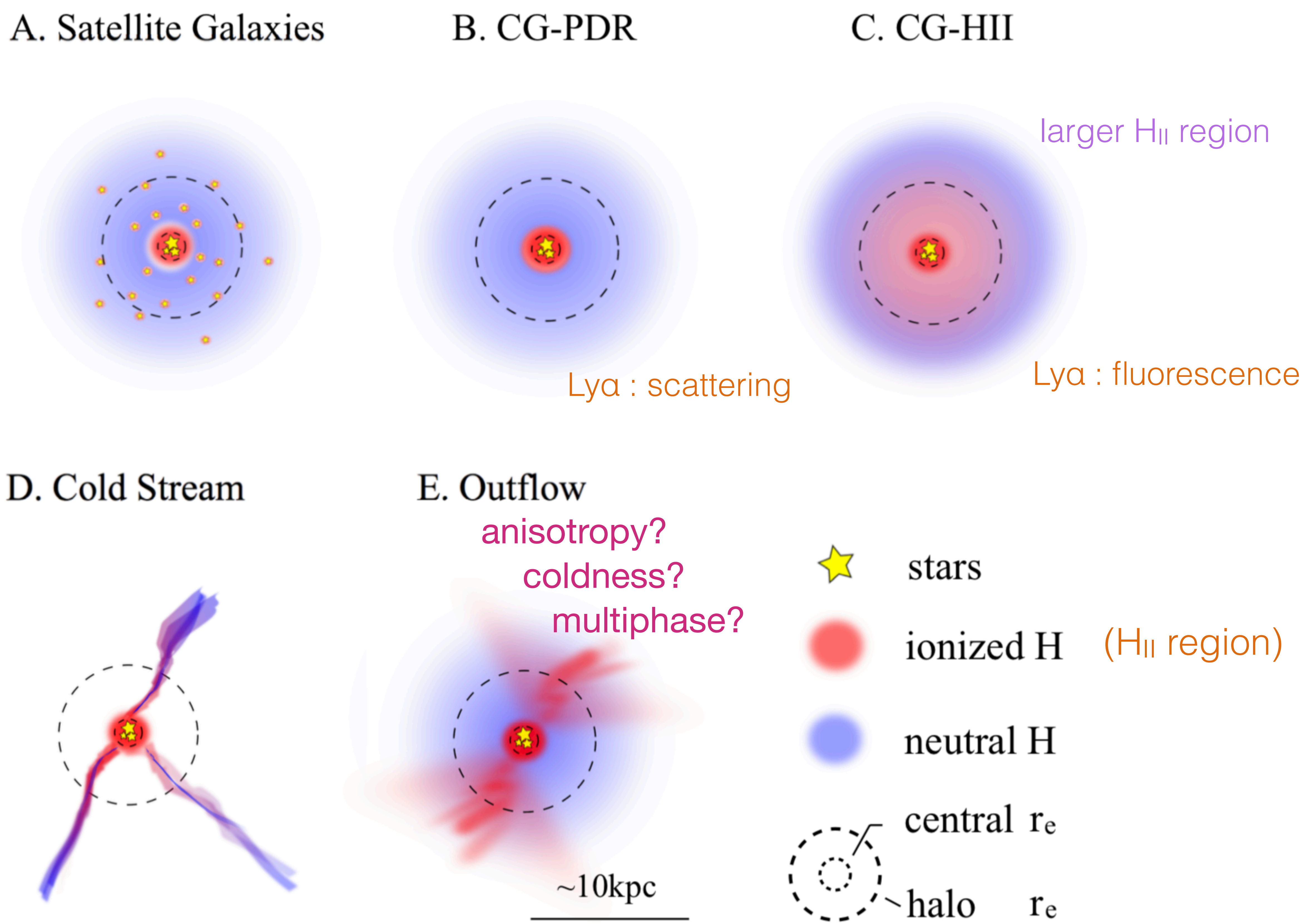
More massive halo —> more extended profile.

Lya profile



cf. Zhang+19

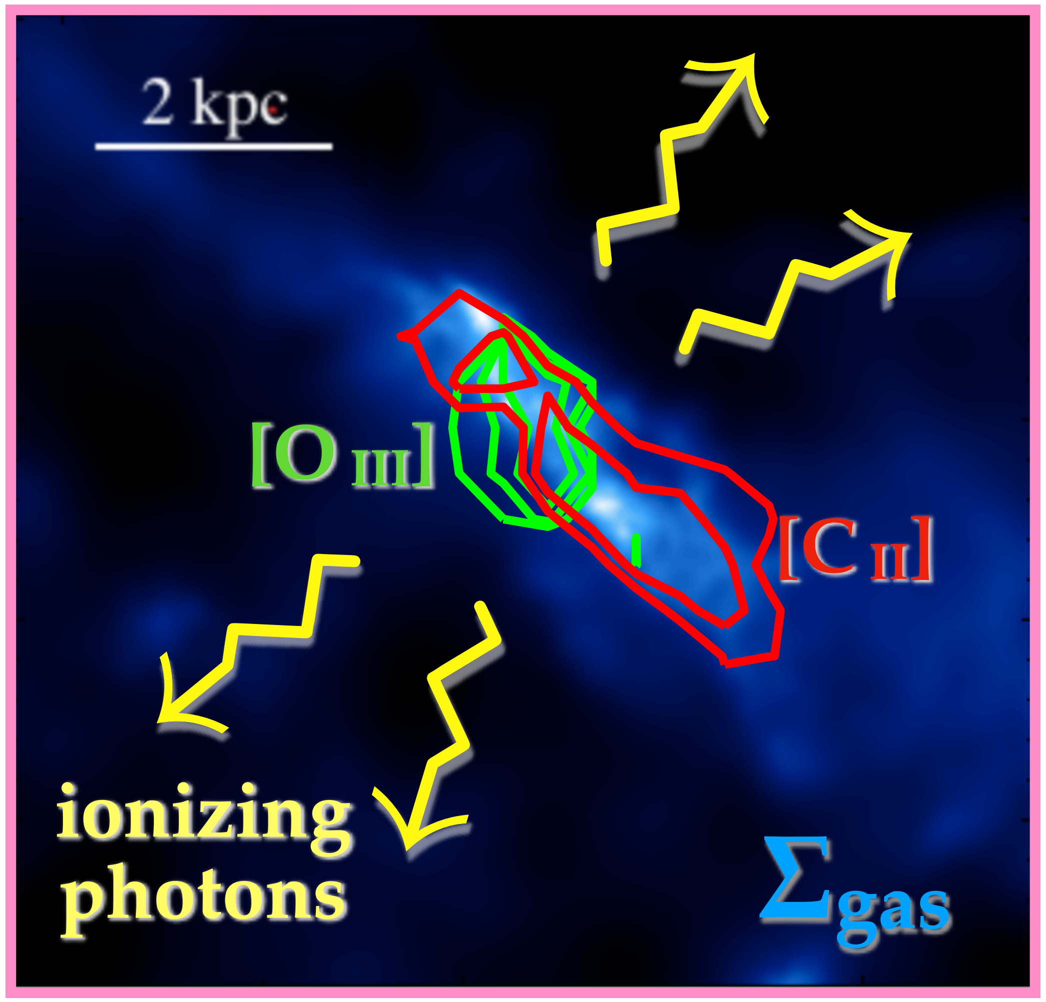
Different possibilities of [CII] halo



Fujimoto+19

Offset between [O III] and [C II]

Halo-11 @z = 11



Ionizing photons escape
perpendicular to filament

⇒ Reionization

Combined obs of [O III] and [C II]
will reveal ionizing structure
of reionization

cf. Vallini+15; Pallottini+14,15,17,19; Moriwaki+18;
Katz+19; …

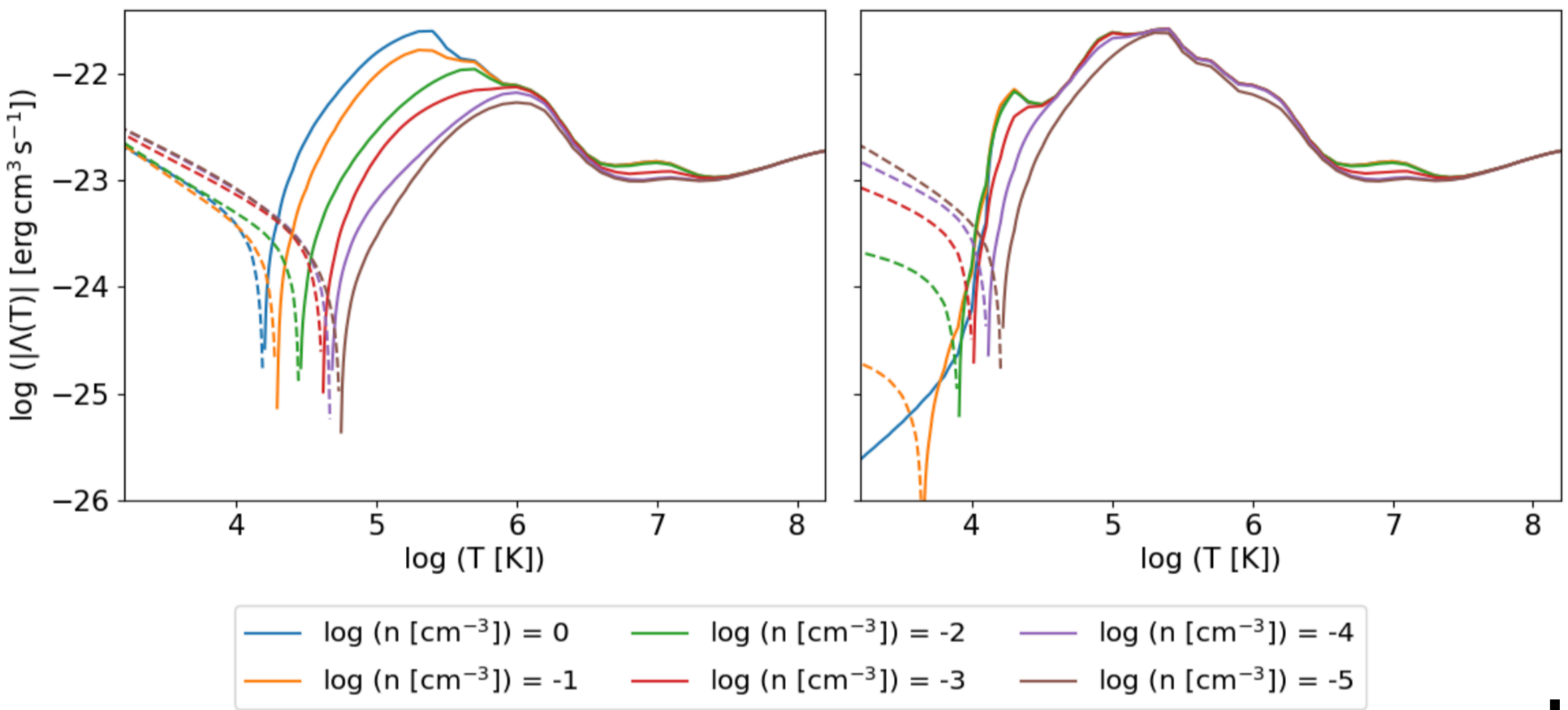
Arata+'20

1D Cold Outflow model

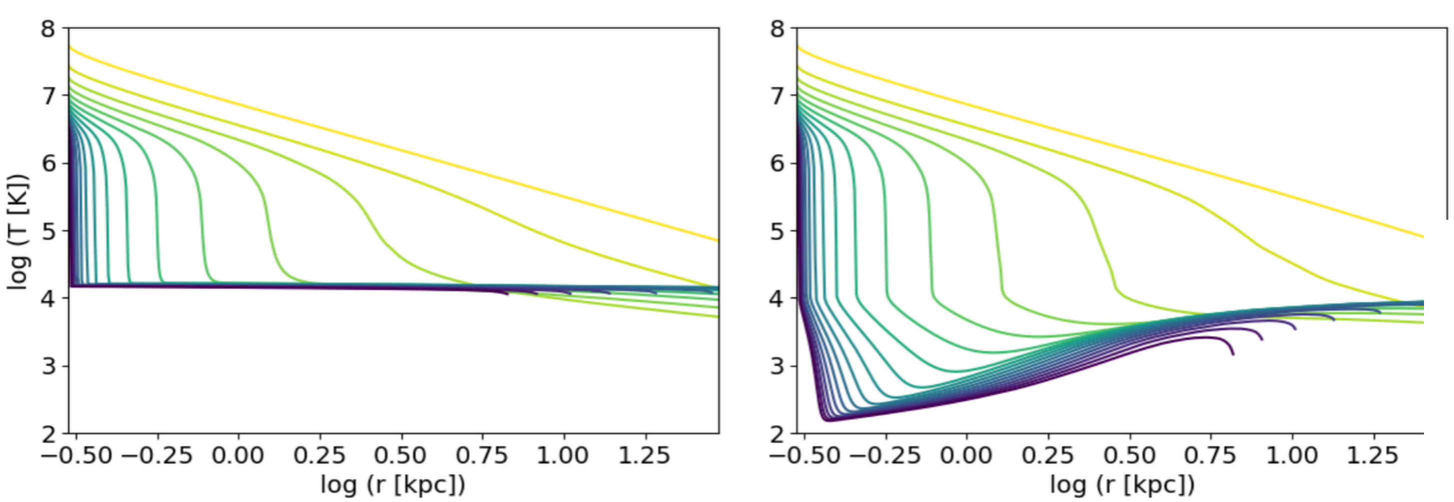
Pizzati+20

net cooling rate

$f_{esc} = 0.2$ $\qquad$ $f_{esc} = 0.0$



Temperature



Galactic flux based on

Salpeter IMF

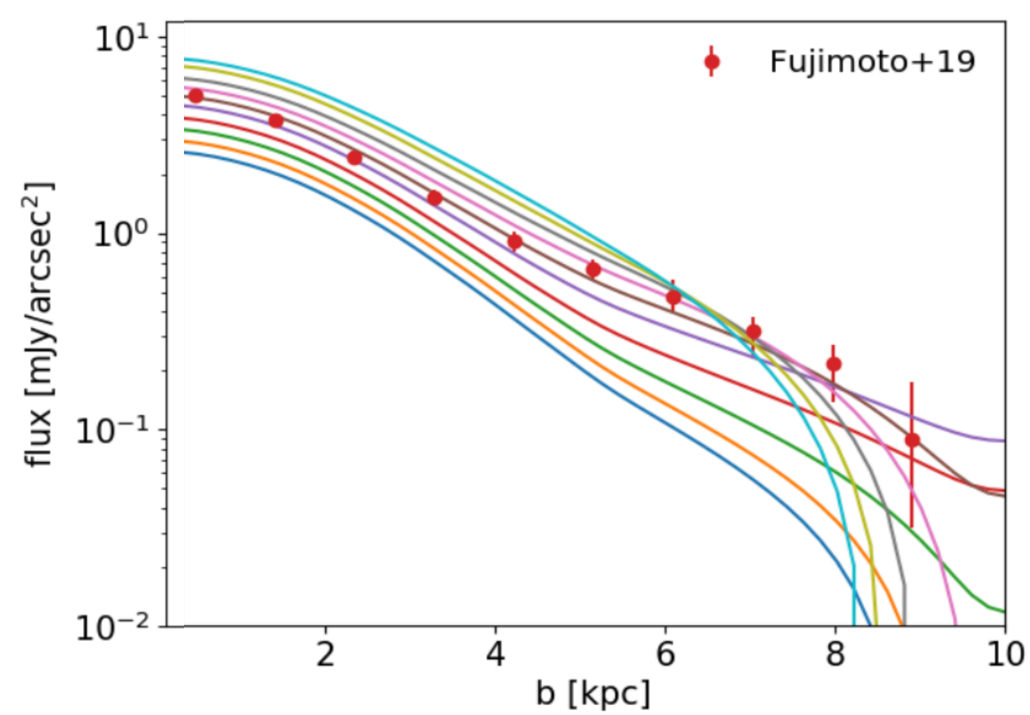
const SFR=50 $M_\odot$ yr^{-1}

best-fit : $\eta \sim 3$

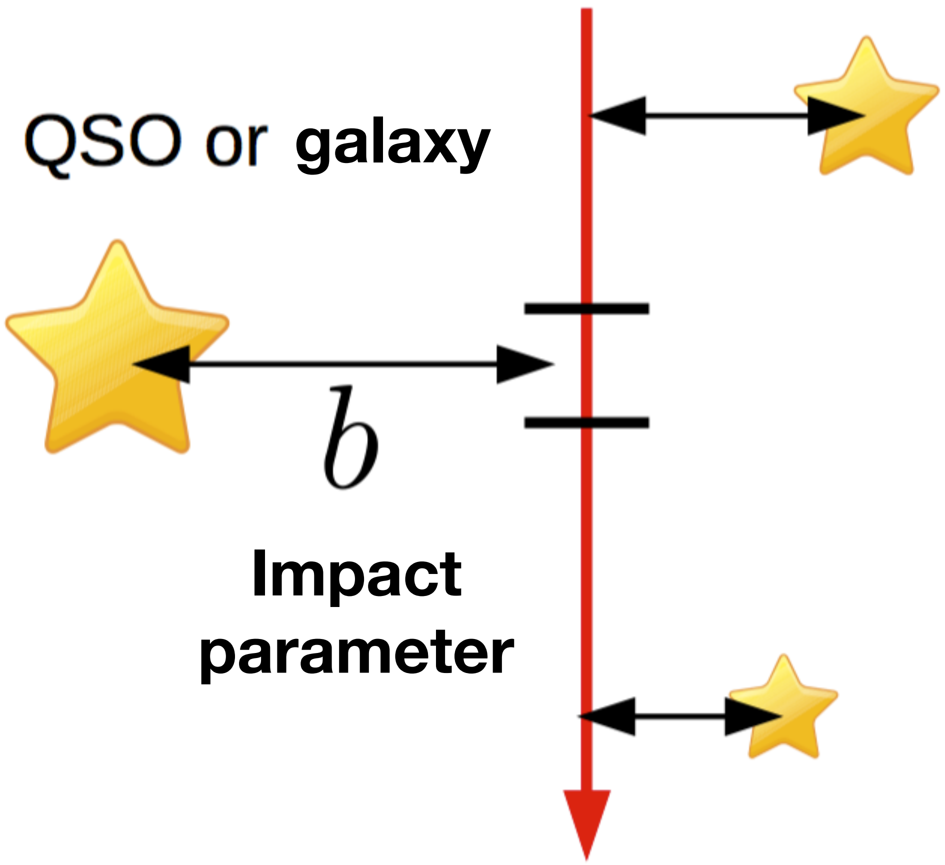
$v_{\rm circ} \sim 170\,{\rm km\,s^{-1}}$

$\dot{M}_{\rm out} \sim 130\,M_\odot\,{\rm yr^{-1}}$

$v_{\rm out} \sim 300 - 500\,{\rm km\,s^{-1}}$



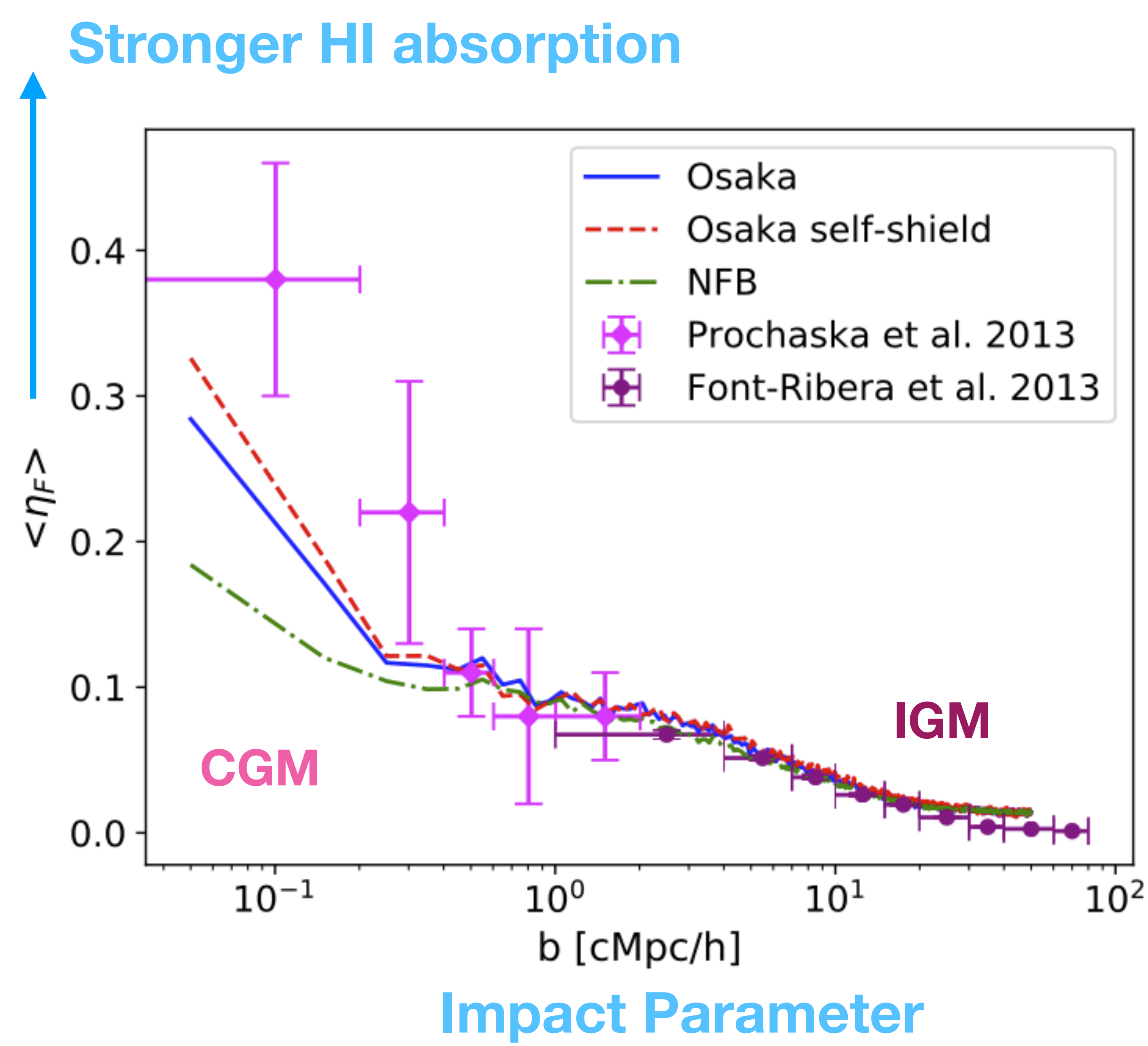
Lyα forest mean flux contrast vs. Impact param.



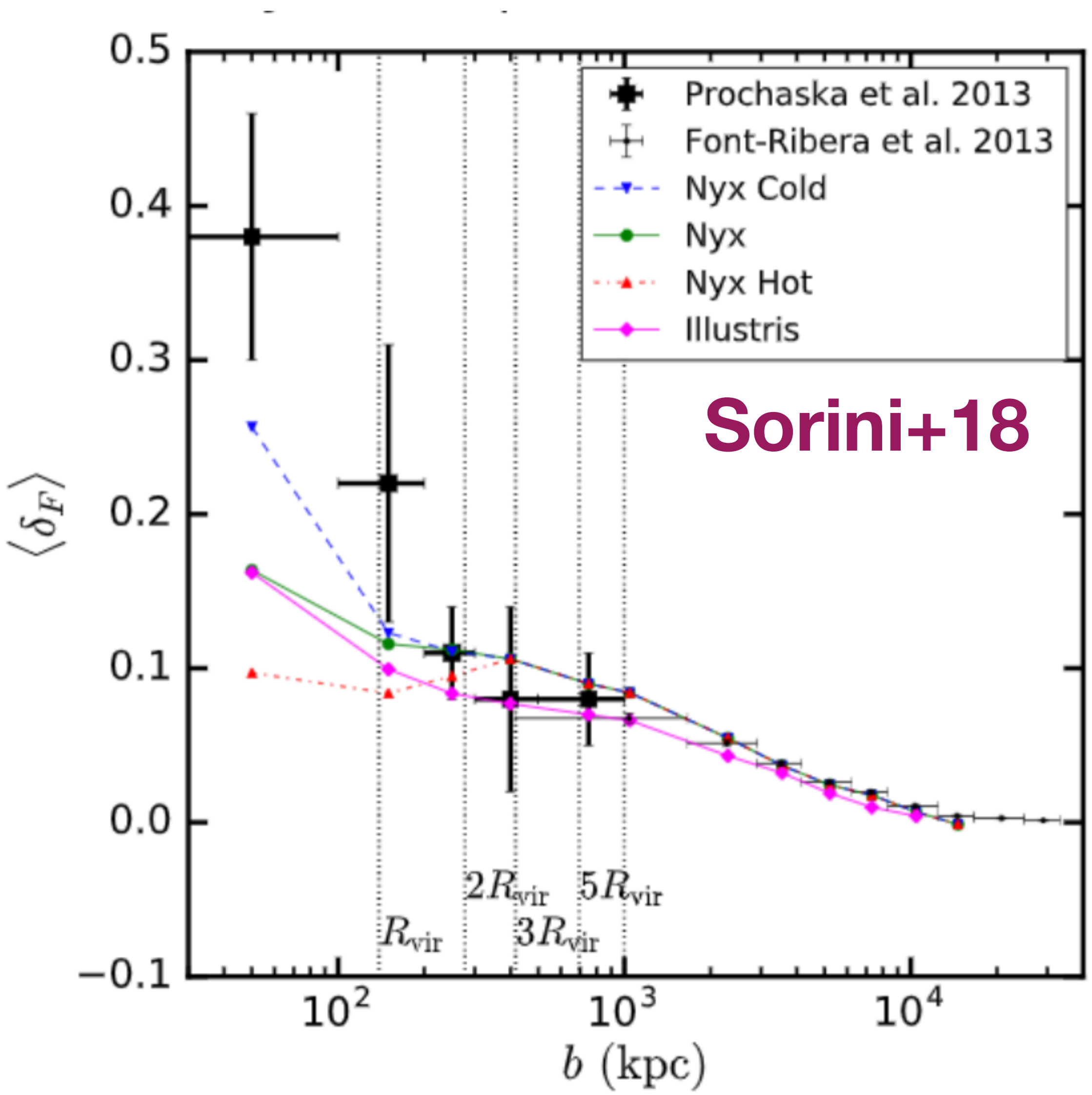
Flux Contrast

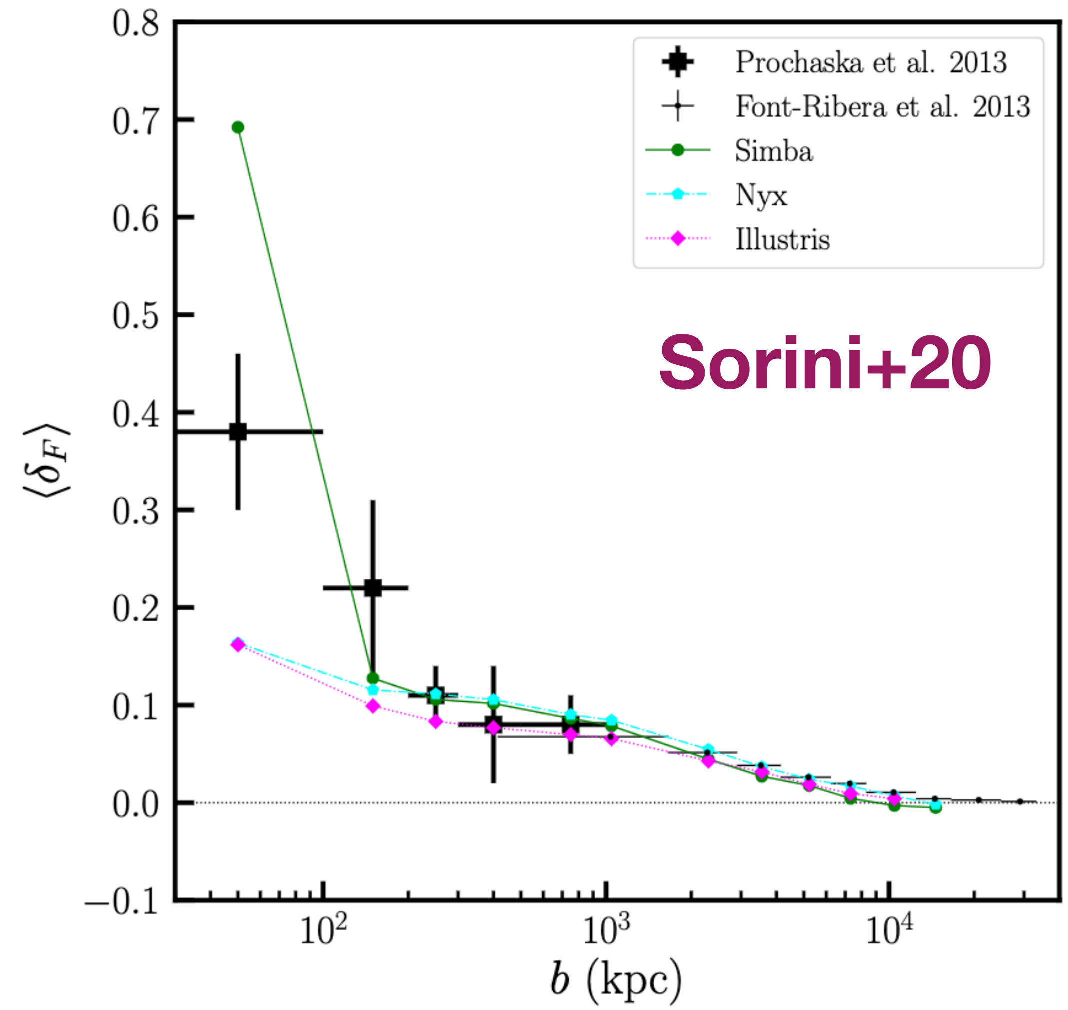
$$\eta_F \equiv -\delta_F = 1 - \frac{F}{\langle F \rangle}$$

$$F = e^{-\tau}$$



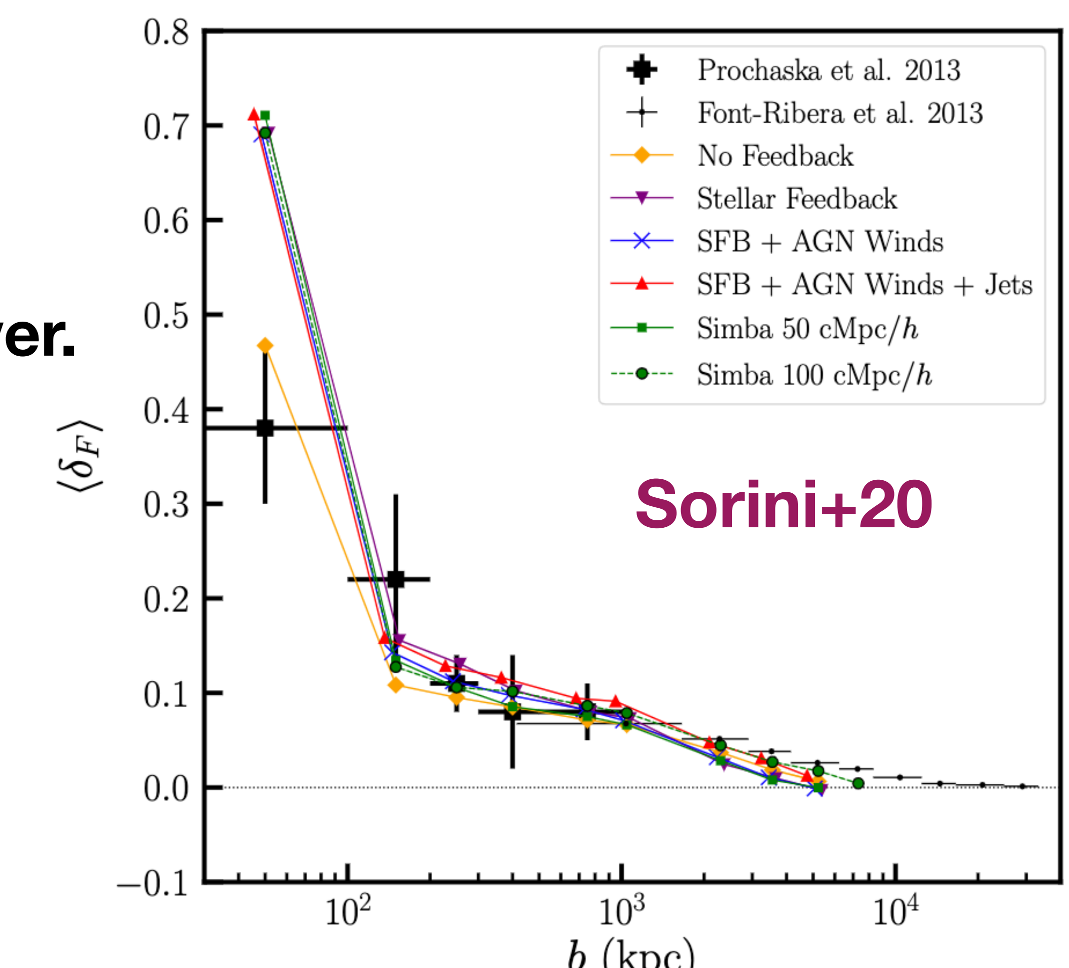
K. Fujita+'19 M-thesis (cf. Sorini+)



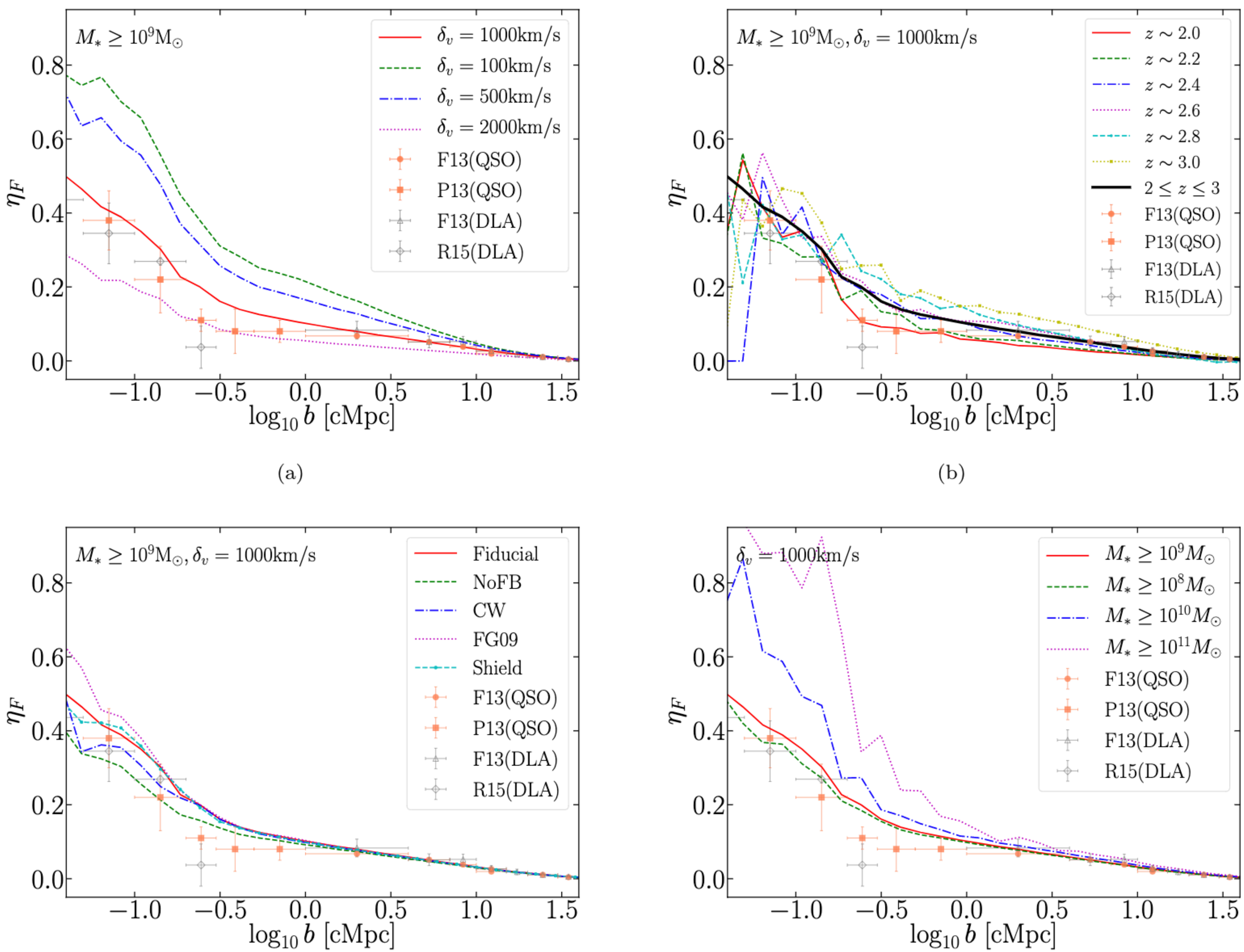


Stellar feedback is the dominant driver.

(AGN subdominant.)



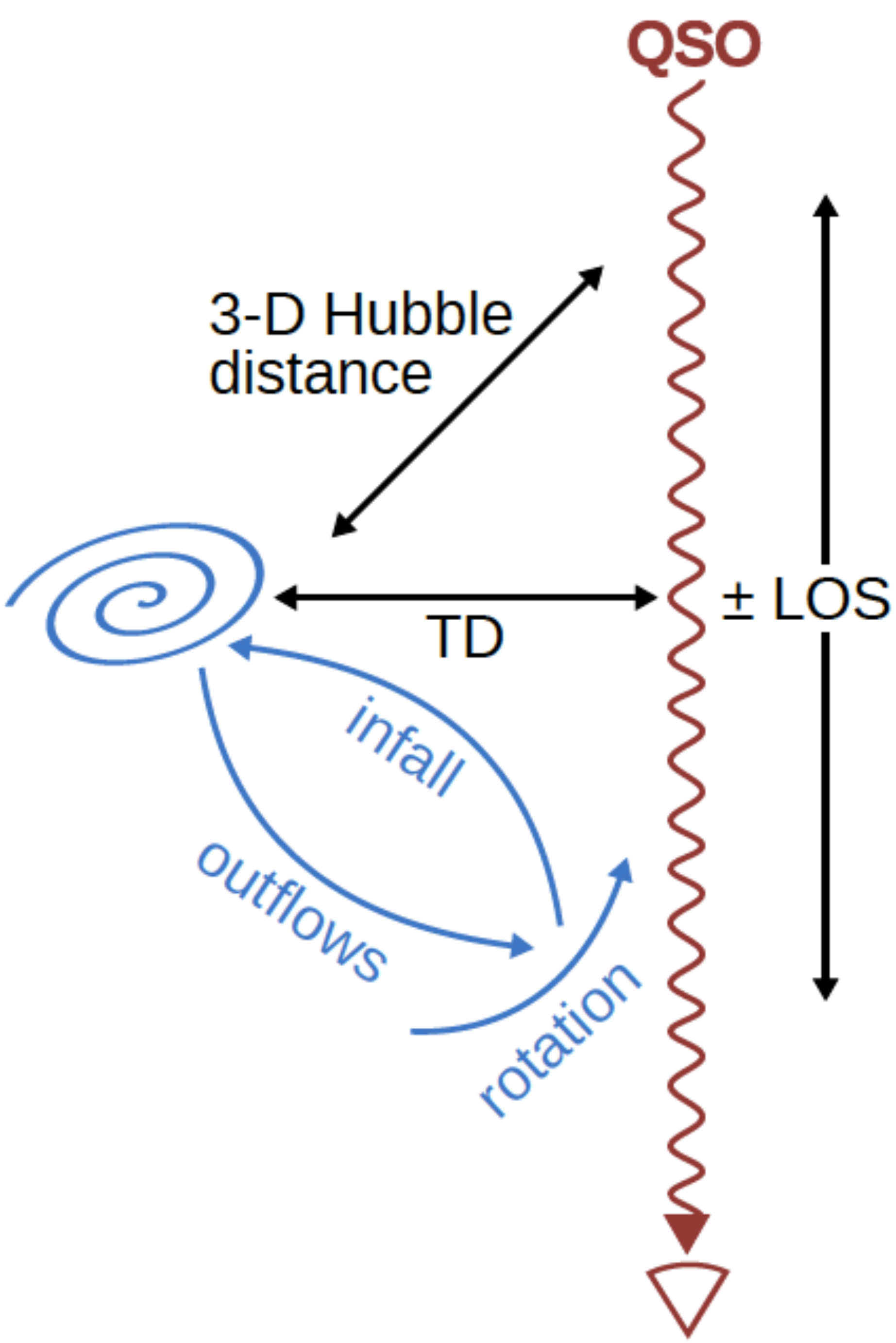
Flux Contrast : updated results

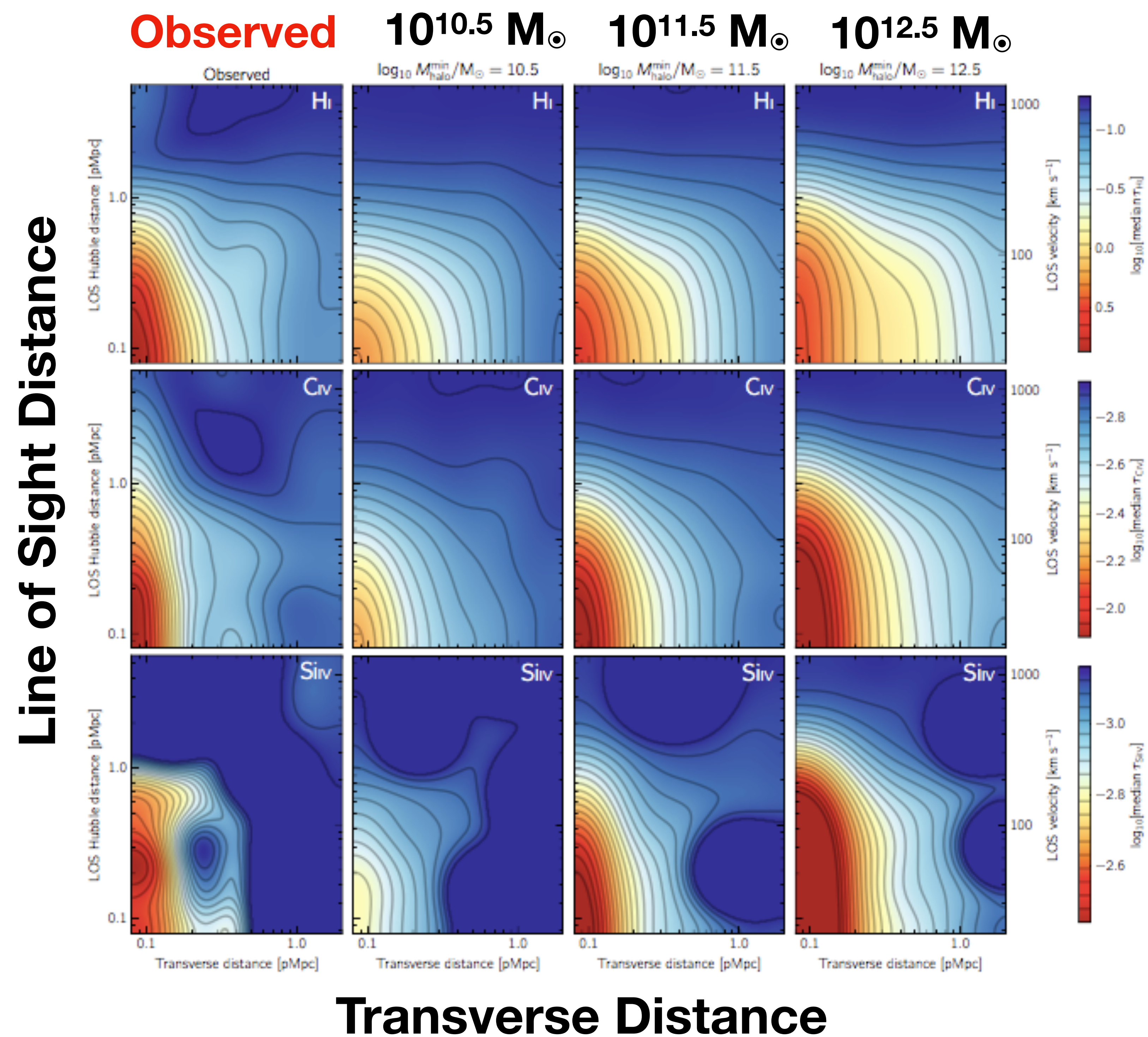


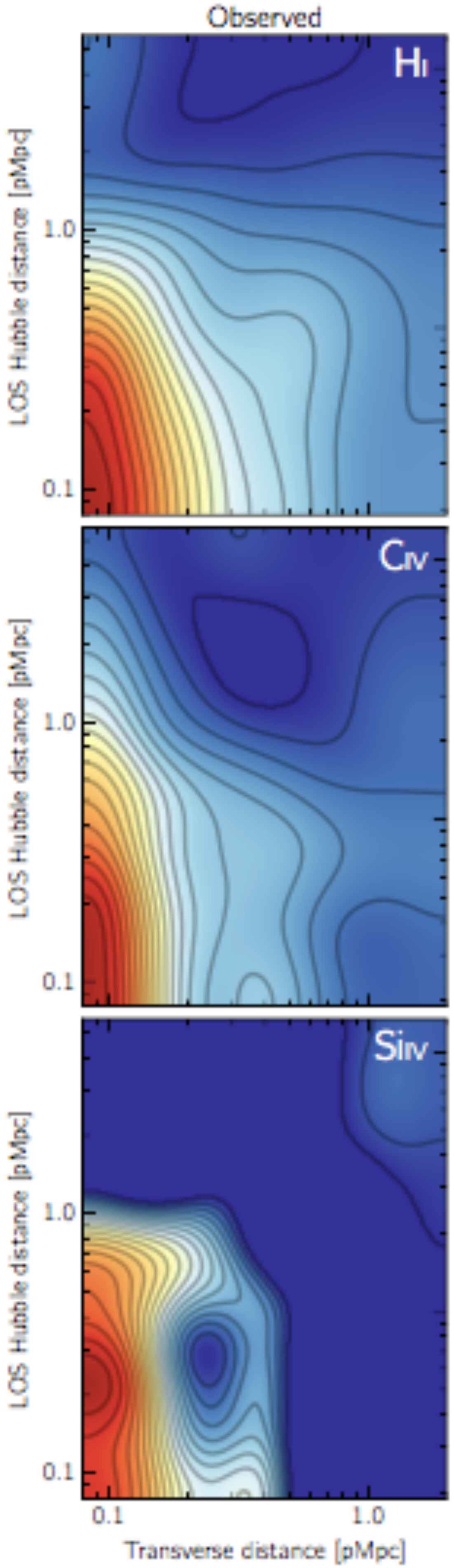
KN+'20, submitted

2D Velocity Structure

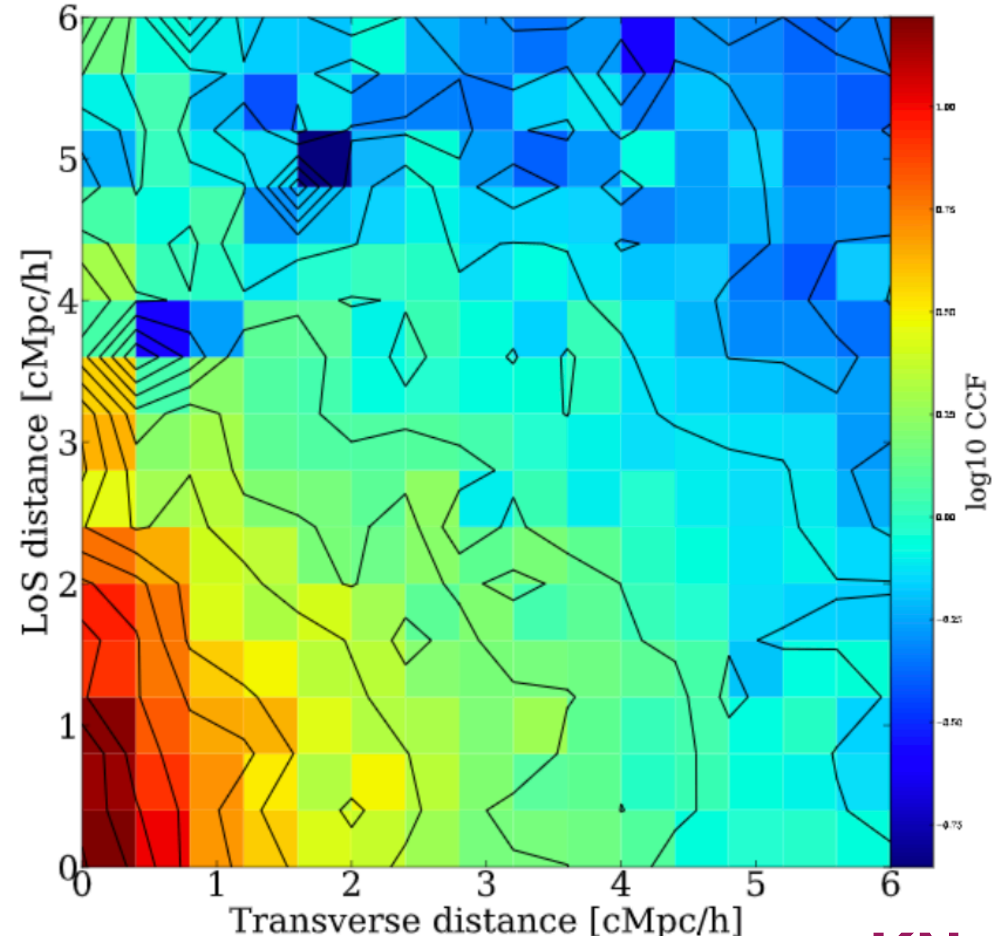
Turner+'17 (KBSS): log(τ) in color



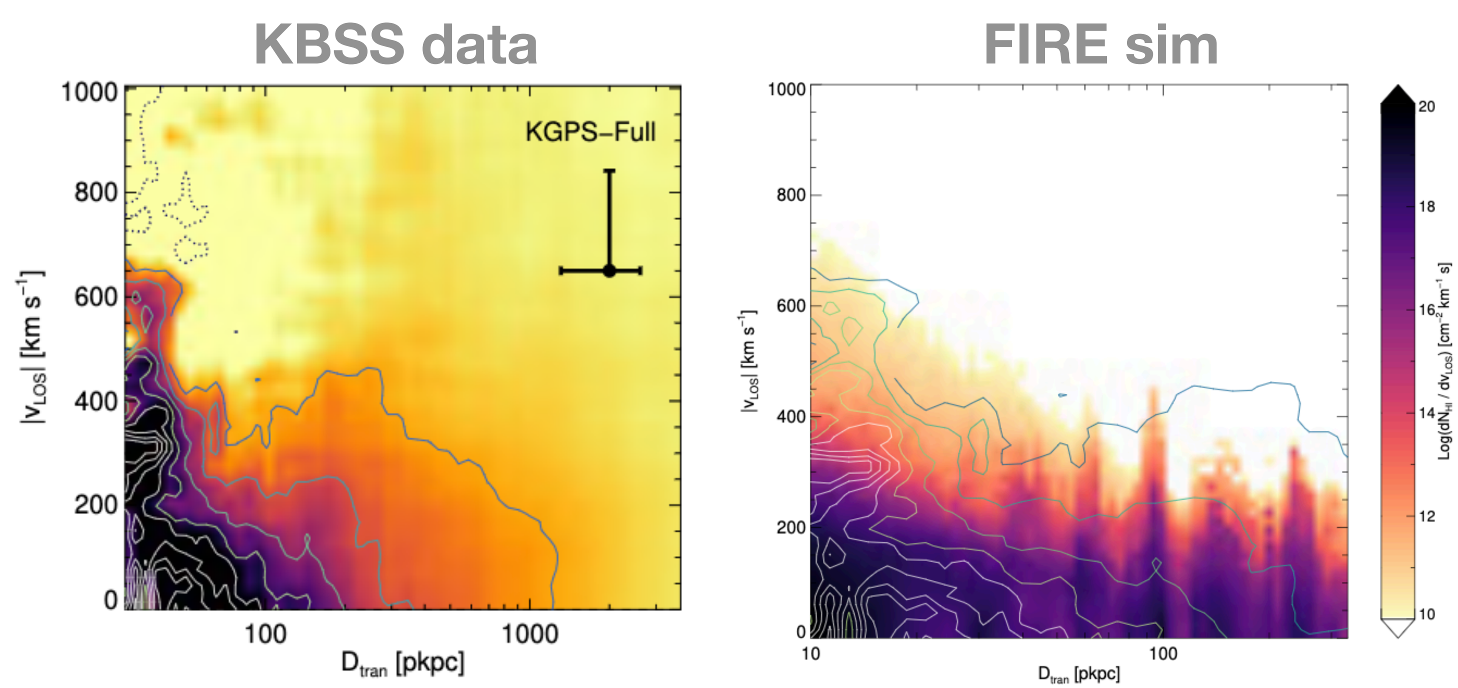




Turner+17



KN+'20, submitted



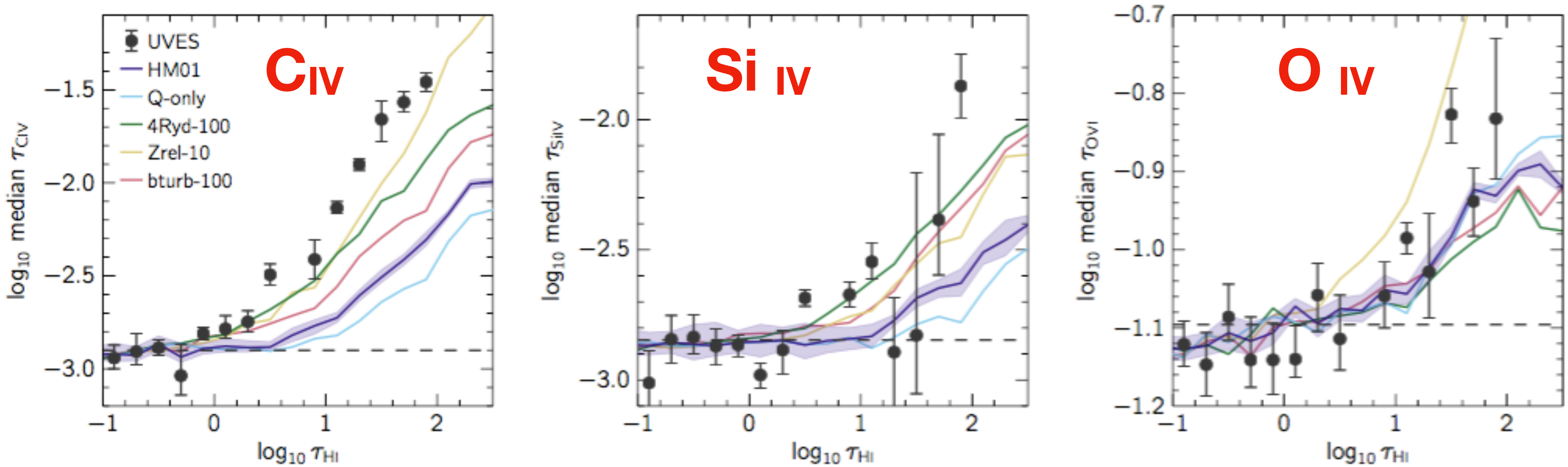
cf. Chen+20

Sim. underpredicts $\tau_{CIV}(\tau_{HI})$ significantly.

8 QSOs, <z>~3.75

(comparison btw obs. & **EAGLE** sim.)

(but **O$_{IV}$** better agreement)



Possible solutions?

(a) different models for the ionizing background radiation;

(b) simulations run at a higher resolution;

(c) inclusion of additional line broadening due to unresolved turbulence;

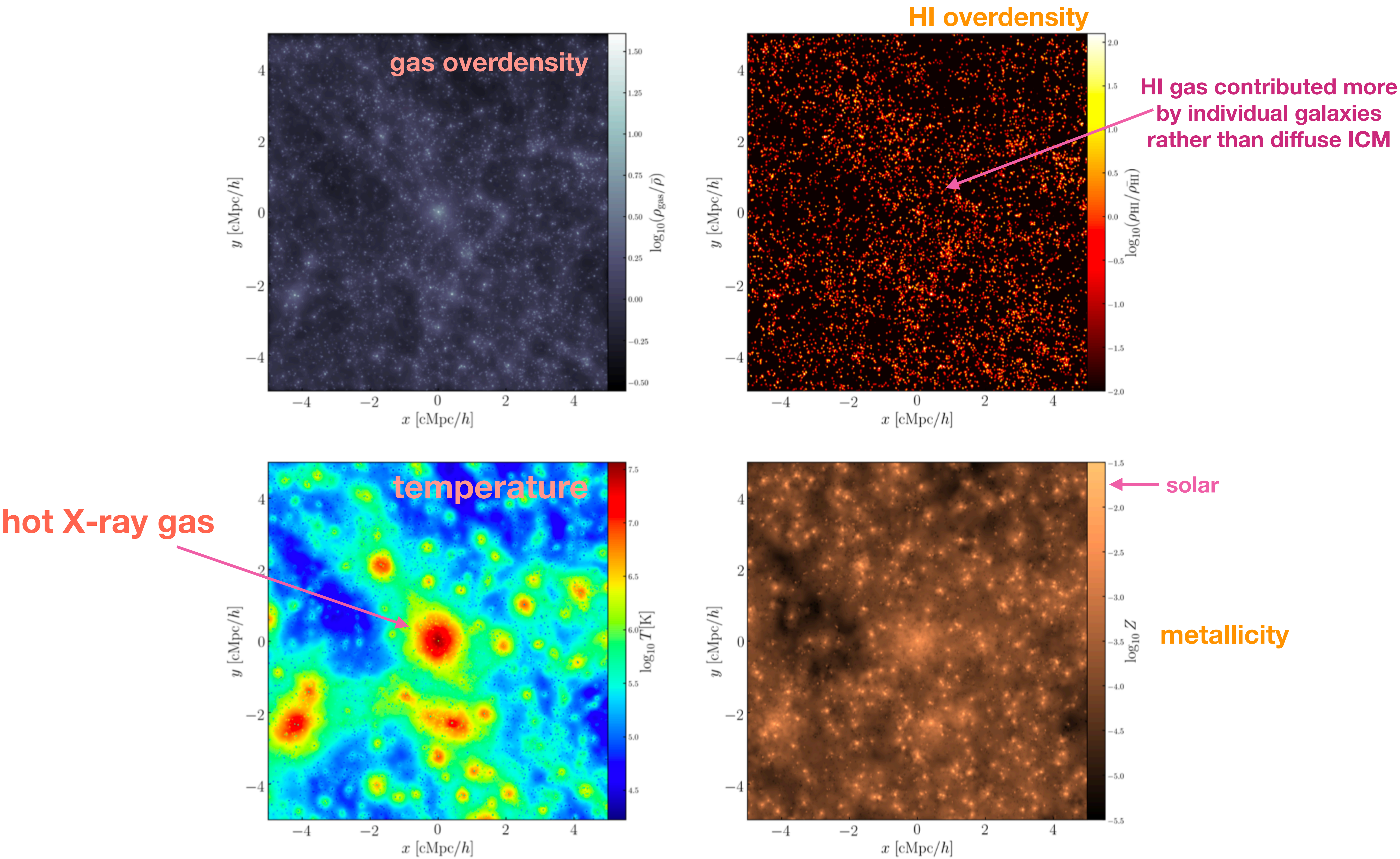
(d) increased elemental abundances.

Outflows need to entrain more cold gas w. metals?

cf. similar suggestion from [Cii] obs.

Turner+’15

Protocluster @ z~2.1

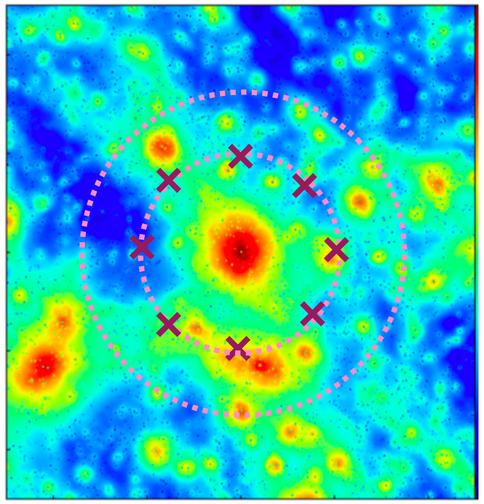


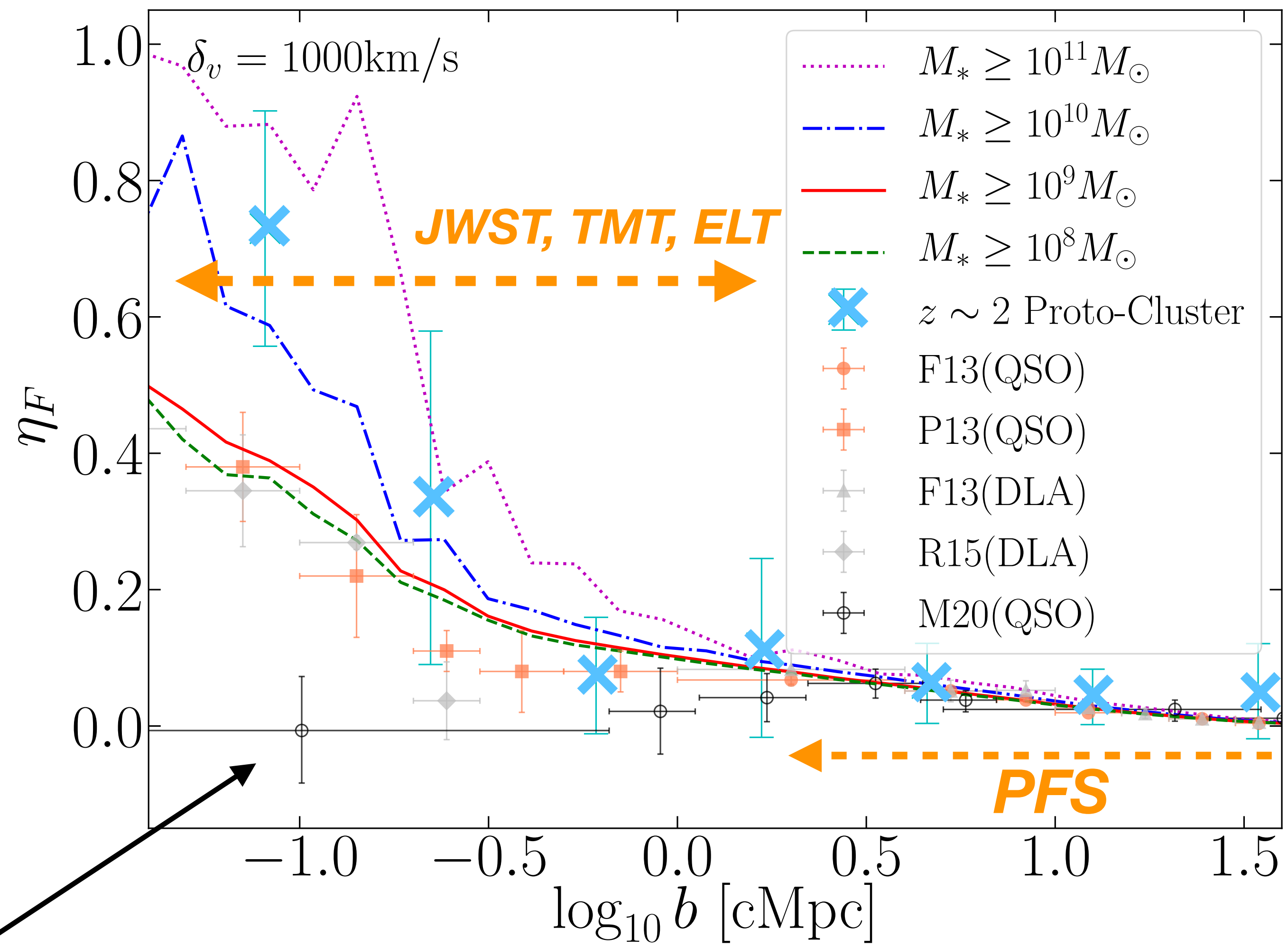
cf. Keita Fukushima talk

KN+'20, submitted

Flux contrast of a protocluster

z~2.2





KN+'20

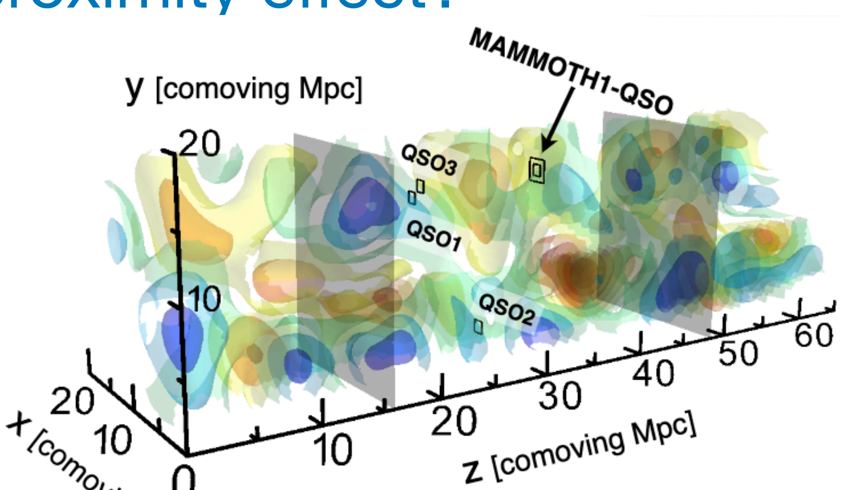
asymptote to cosmic IGM

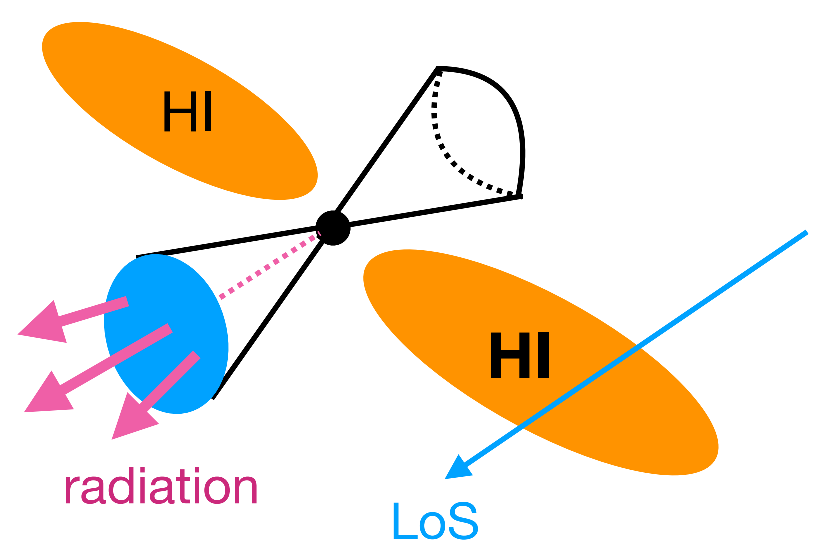
consistent w/ Sorini+'18

Mukae+'20

MAMMOTH QSO region

proximity effect?





→ support for ΛCDM

cf. Prochaska+13; Lee+14; Cai+16, 17; Liang+20; Miller+19

Summary

- High-z gal. formation: good testing lab of ***ΛCDM paradigm***
- ***Interplay btw SF & Cold flow, multiphase outflow***
  — gal. growth & quenching (→ Morishita review)
- *IR lines* — extended [Cii], Lyα, Hα profiles — stronger cold outflow? (kinetic FB & thermal instability? cosmic rays?)
- Lyα flux contrast, IGM tomography (PFS) — ISM/CGM/IGM
  (→ Kakiichi, Momose review)
- Proto-cluster flux contrast → *PFS, FOREVER22*
- AGN feedback (→ Kohno, Sugimura review)

課題（銀河理論）

- M_{BH}ー σ（M_{BH} ーM_{bulge}) 関係をもとに銀河とSMBHは共進化したと言われているが、 そもそも本当にM_{BH}ー σ 関係は存在するのだろうか。 本当に銀河とSMBHは共進化したのだろうか。これらを反証するには どのような観測やシミュレーション研究を行えば良いだろうか。 It is often said that galaxies co-evolved with SMBH based on M_{BH}ーσ relation, but does the correlation really exist, and did they co-evolve? What kind of obs. & simulations shall we carry out to disprove it?
- 銀河の成長を制御していると言われている超新星・AGNフィードバックモデルを制限するためには、どのような観測やシミュレーション研究を行えば良いだろうか。 それぞれ考えてプロジェクトを提案せよ。可能な限り具体的なパラメータなども示せ。 What kind of obs. & simulations shall we carry out to constrain SN & AGN feedback models? Propose some comparison projects with concrete parameters as much as possible.