ICRR共同利用小研究会

「高エネルギー現象で探る宇宙の多様性I」

宇宙の大規模構造形成・銀河形成の観点から

Anatomy of Cosmic Gas

— gal. cluster, SN / AGN / CR feedback

Ken NAGAMINE
(Osaka / K-IPMU / UNLV)

長峯　健太郎

Keywords:

「多波長・マルチメッセンジャー天文学」

「幅広いスケールの分野」

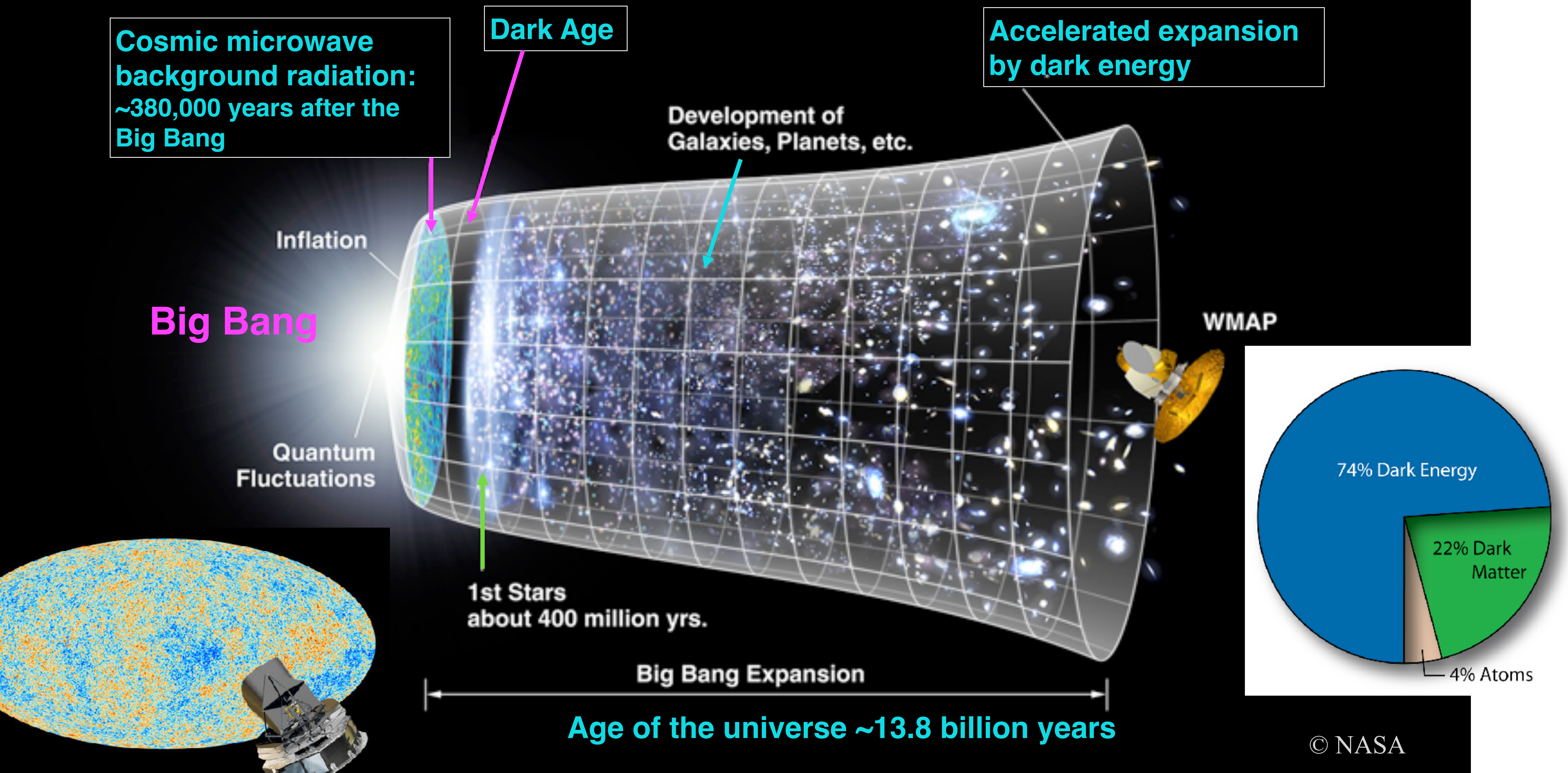
「多角的な視点」

Outline

- Cosmological Structure Formation — halo formation, nonlinear P(k) 10min
- Distribution of Cosmic Gas — shock heating, cold flow, gal. cluster 10min
- **SN & AGN feedback** — SF quenching, metal enrichment, top-heavy IMF at high-z, SMBH—gal co-evolution 15min 15min
- **Cosmic Ray Feedback** 15min
- おまけ（宣伝） 2min

~65min

History of Structure Formation in the Big Bang Universe



``Concordance ΛCDM model ”

WMAP, Planck
SN Ia

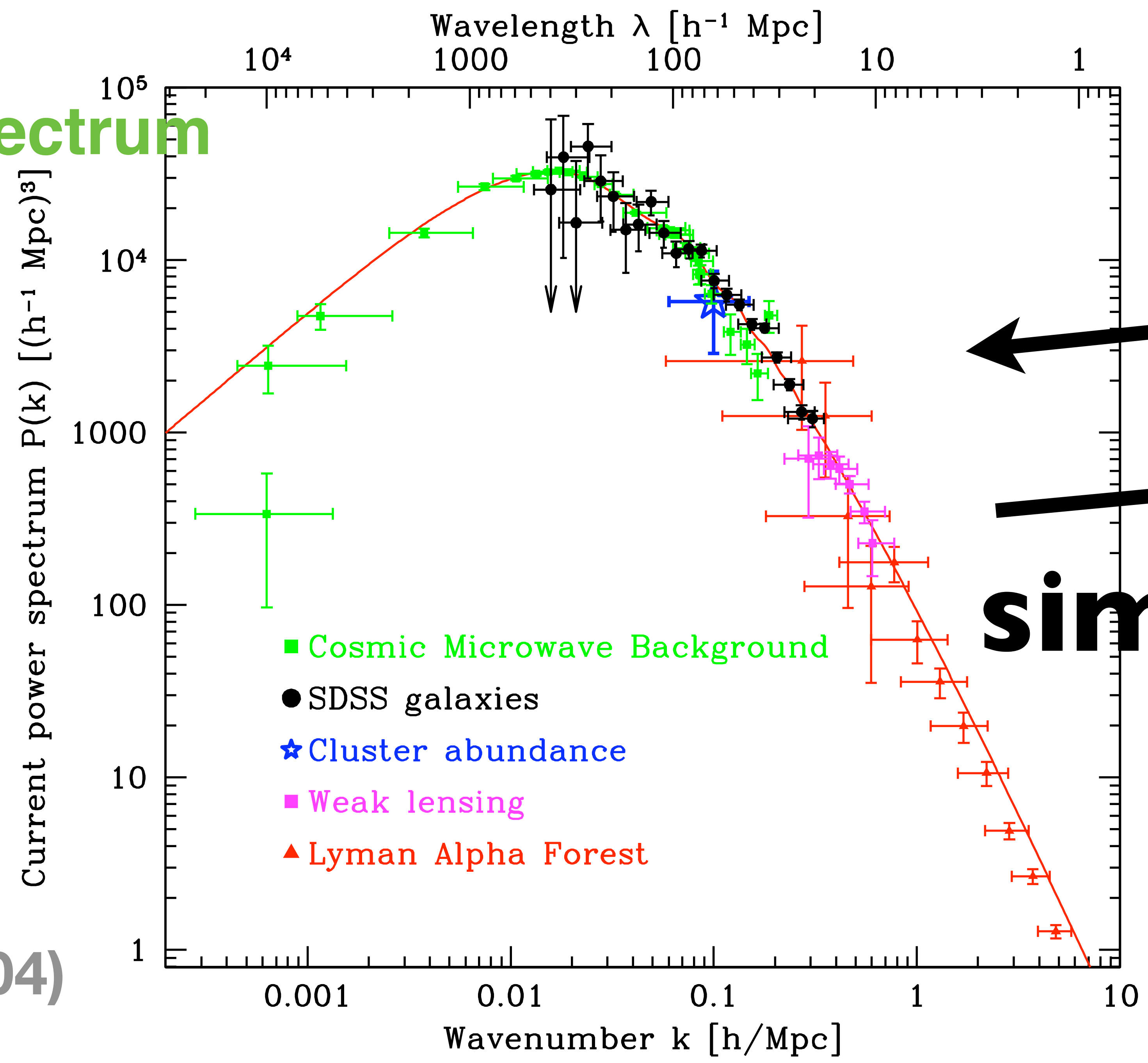
$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

(the so-called “737 cosmology”)

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

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

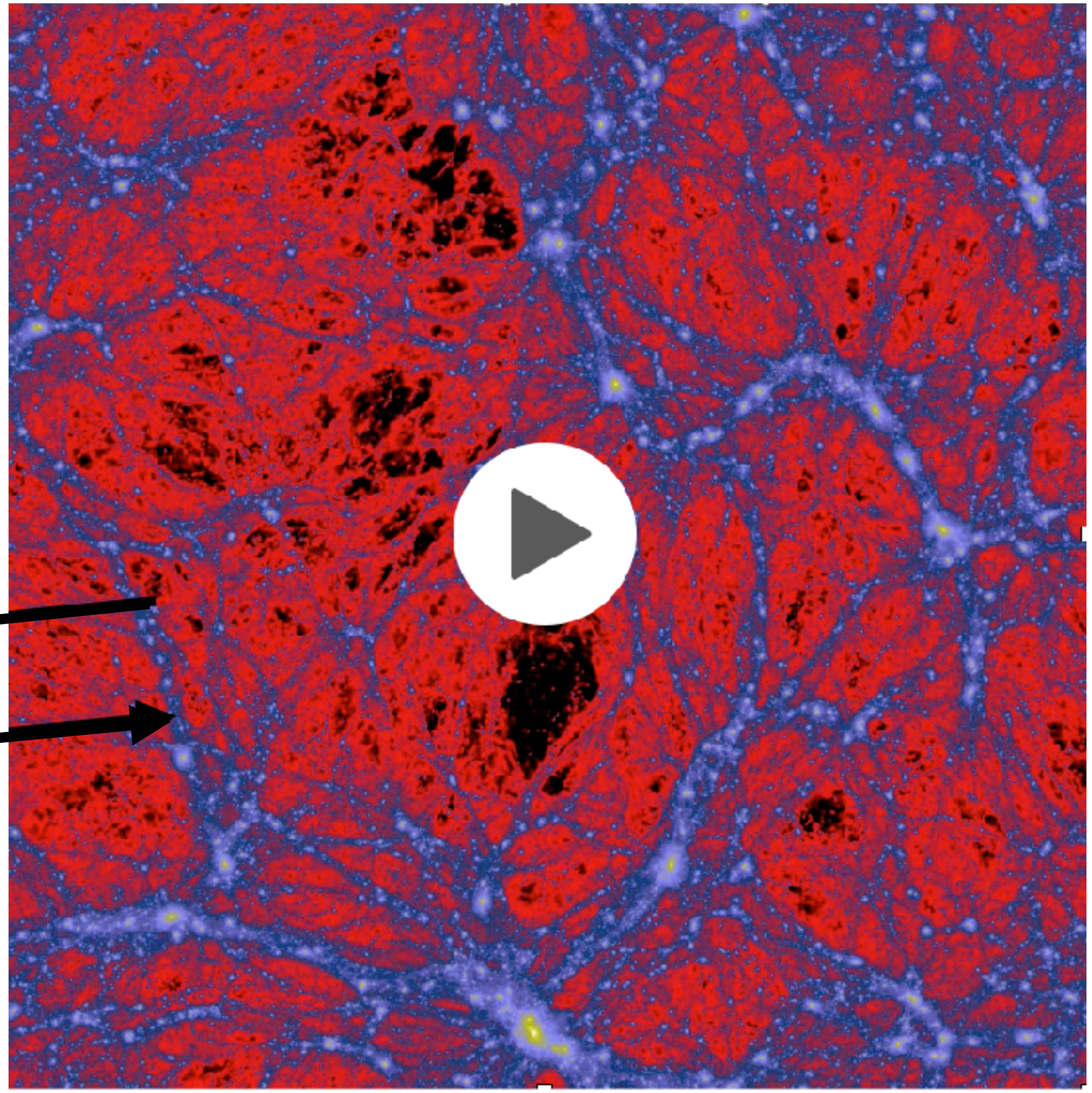
Matter power spectrum



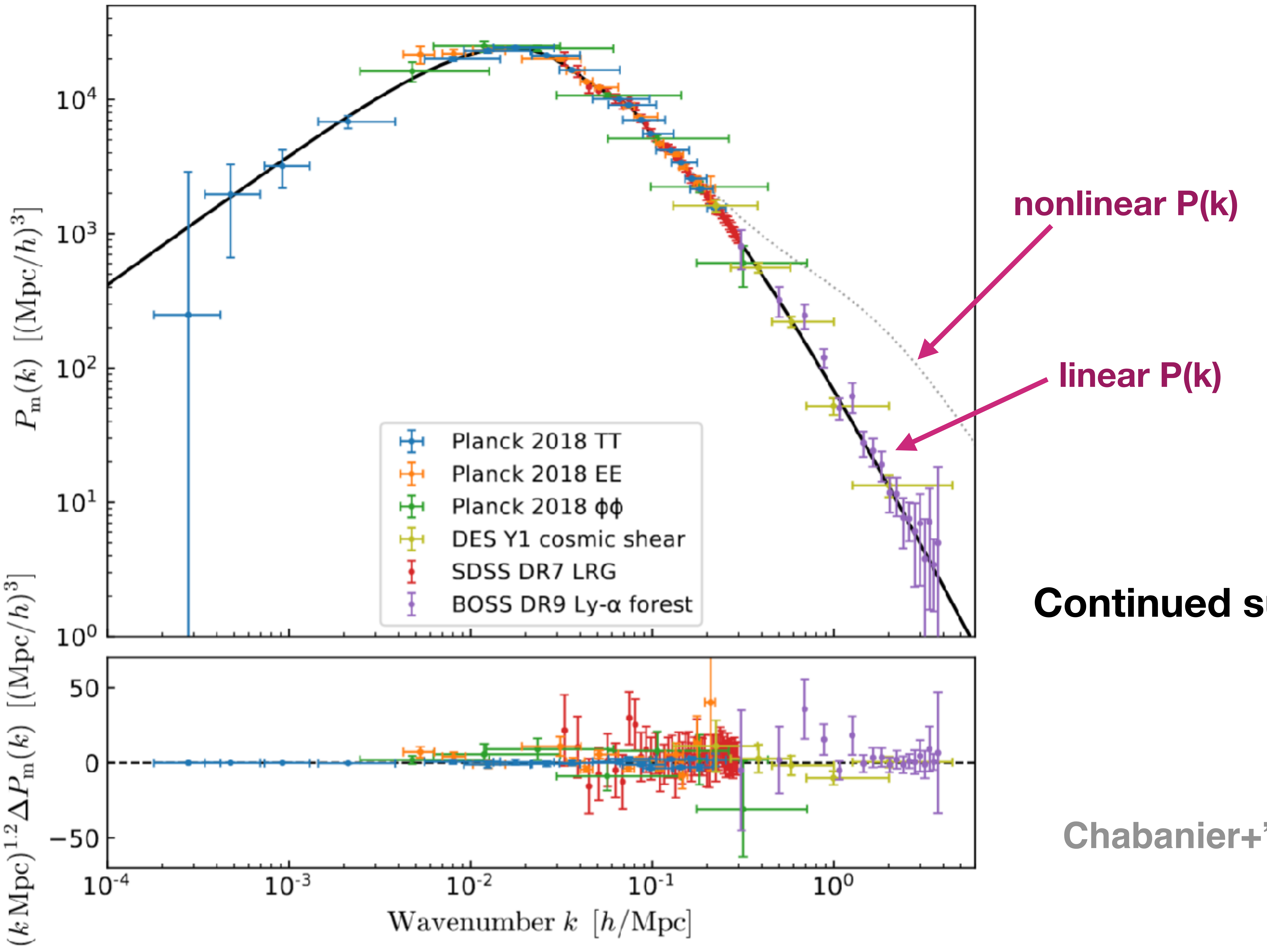
Tegmark+ (2004)

FFT

simulate

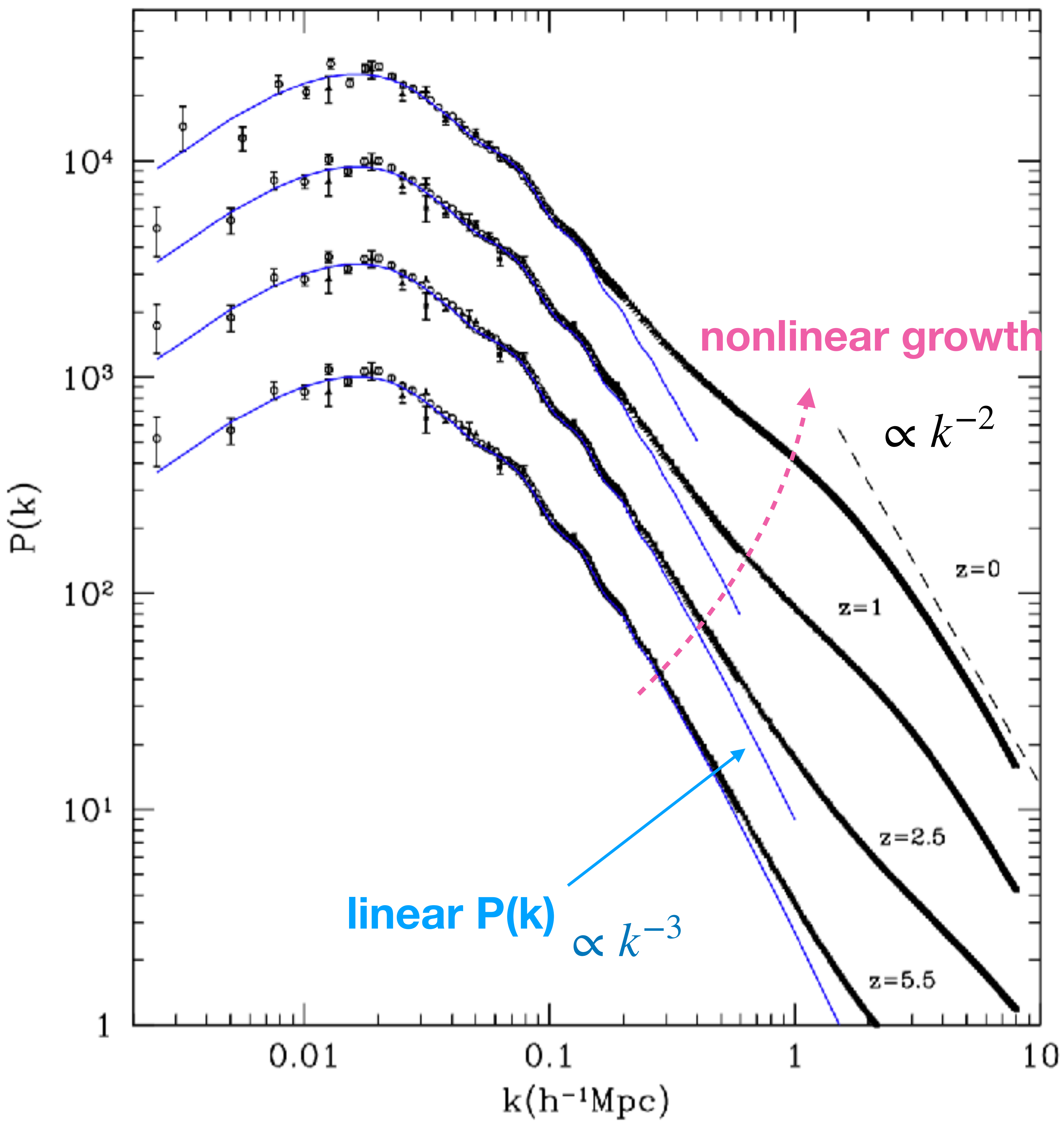


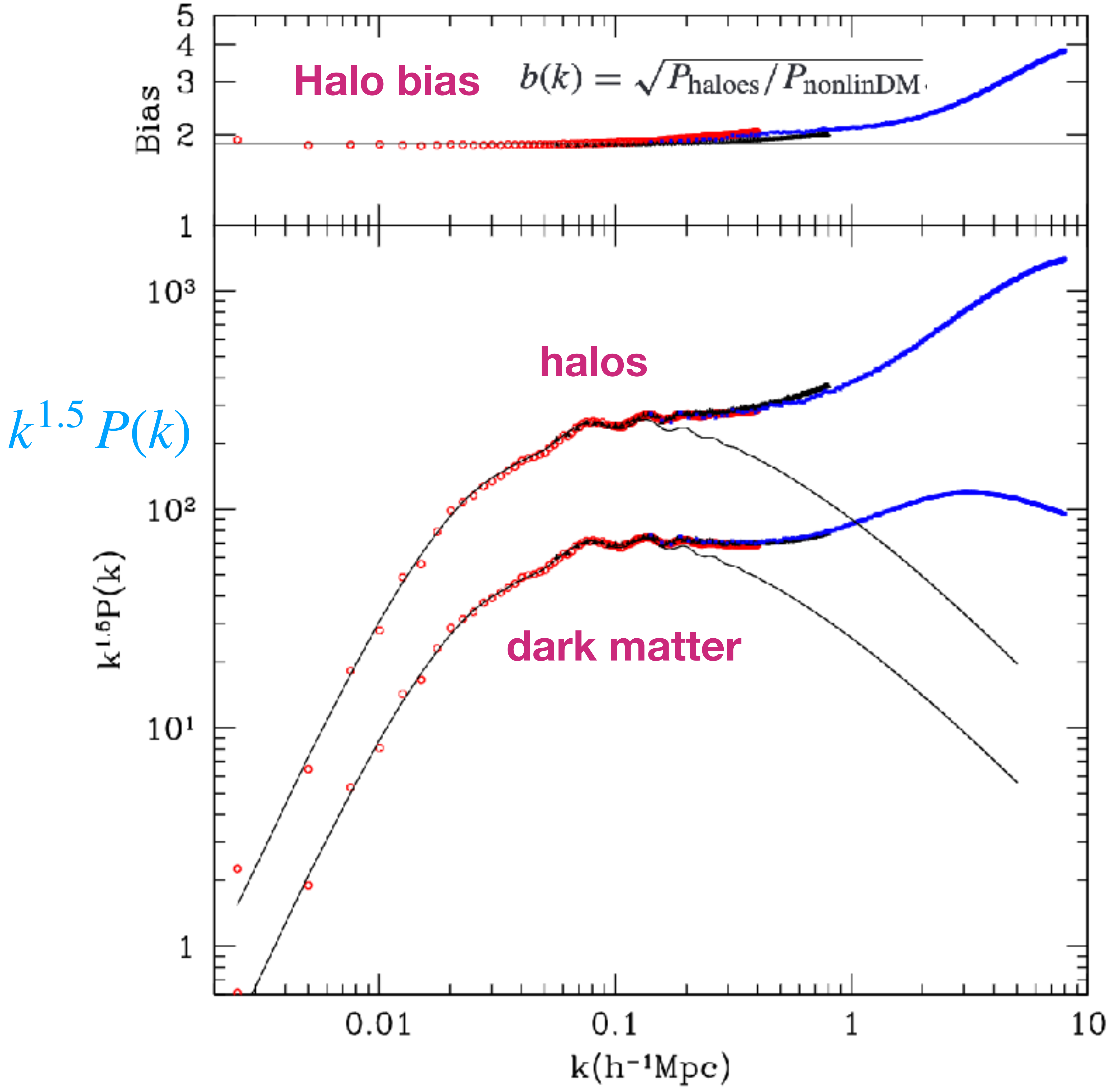
“Back-bone of structure”



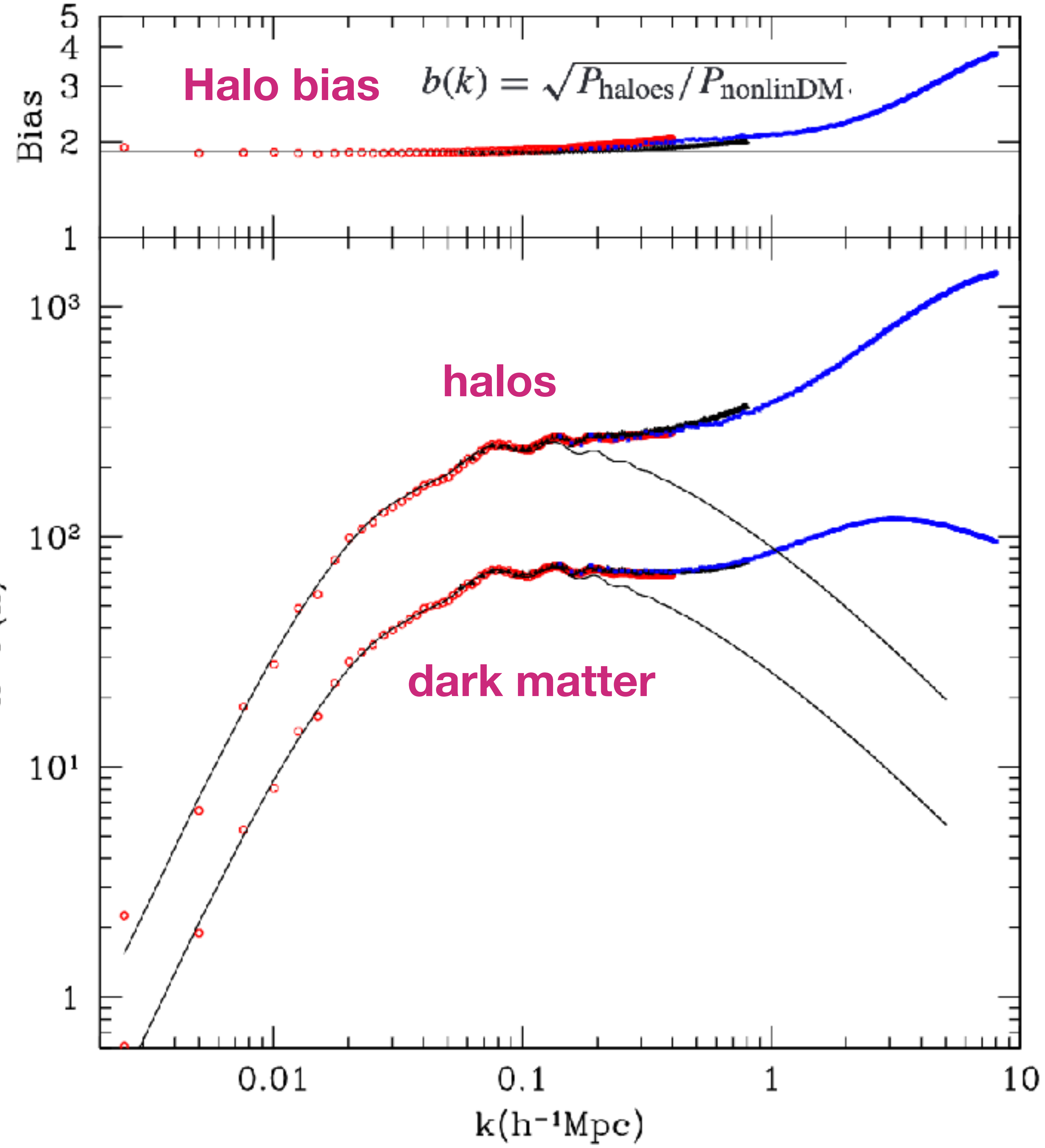
Continued support for ΛCDM

Chabanier+'19

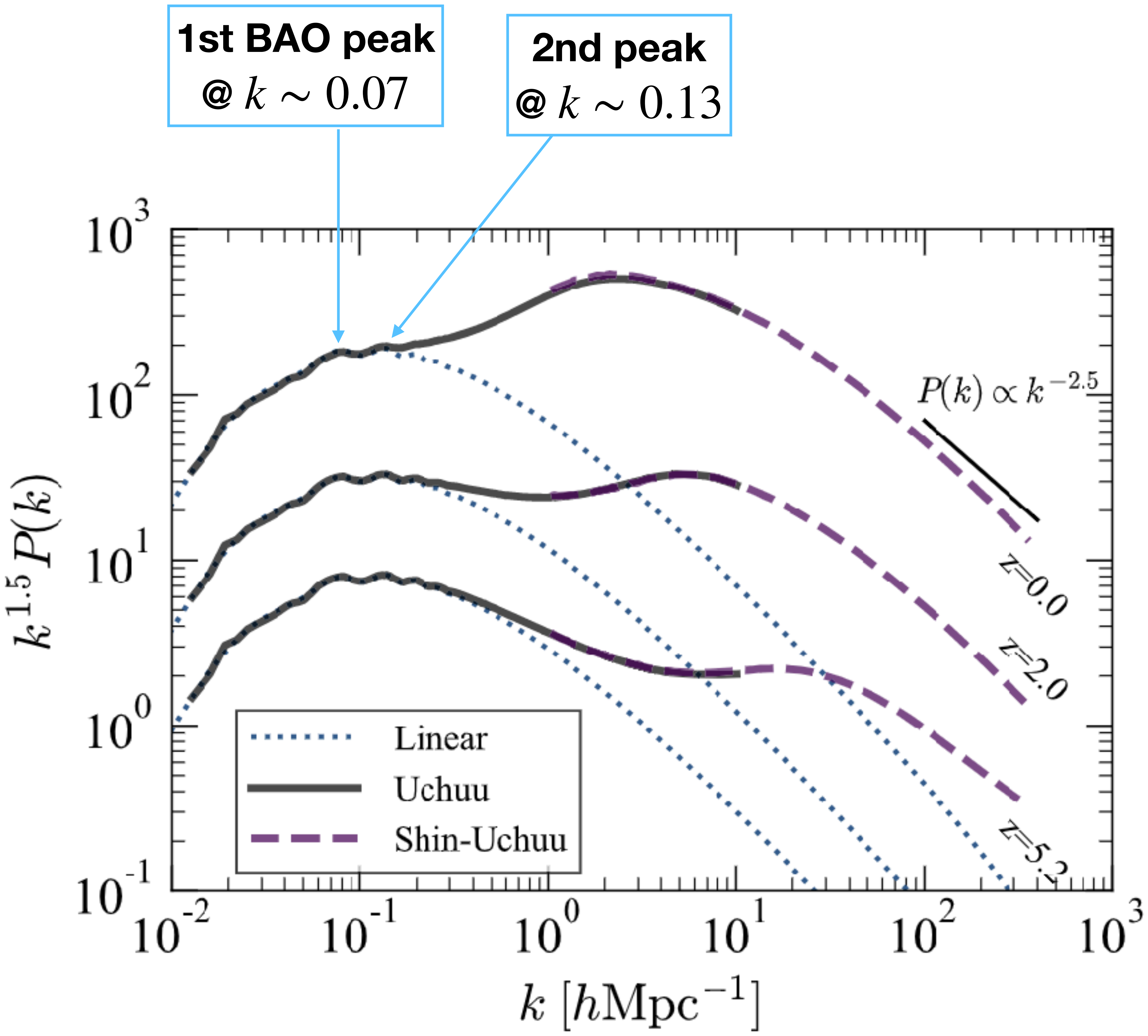




MultiDark sim. Klypin+'16



Klypin+'16

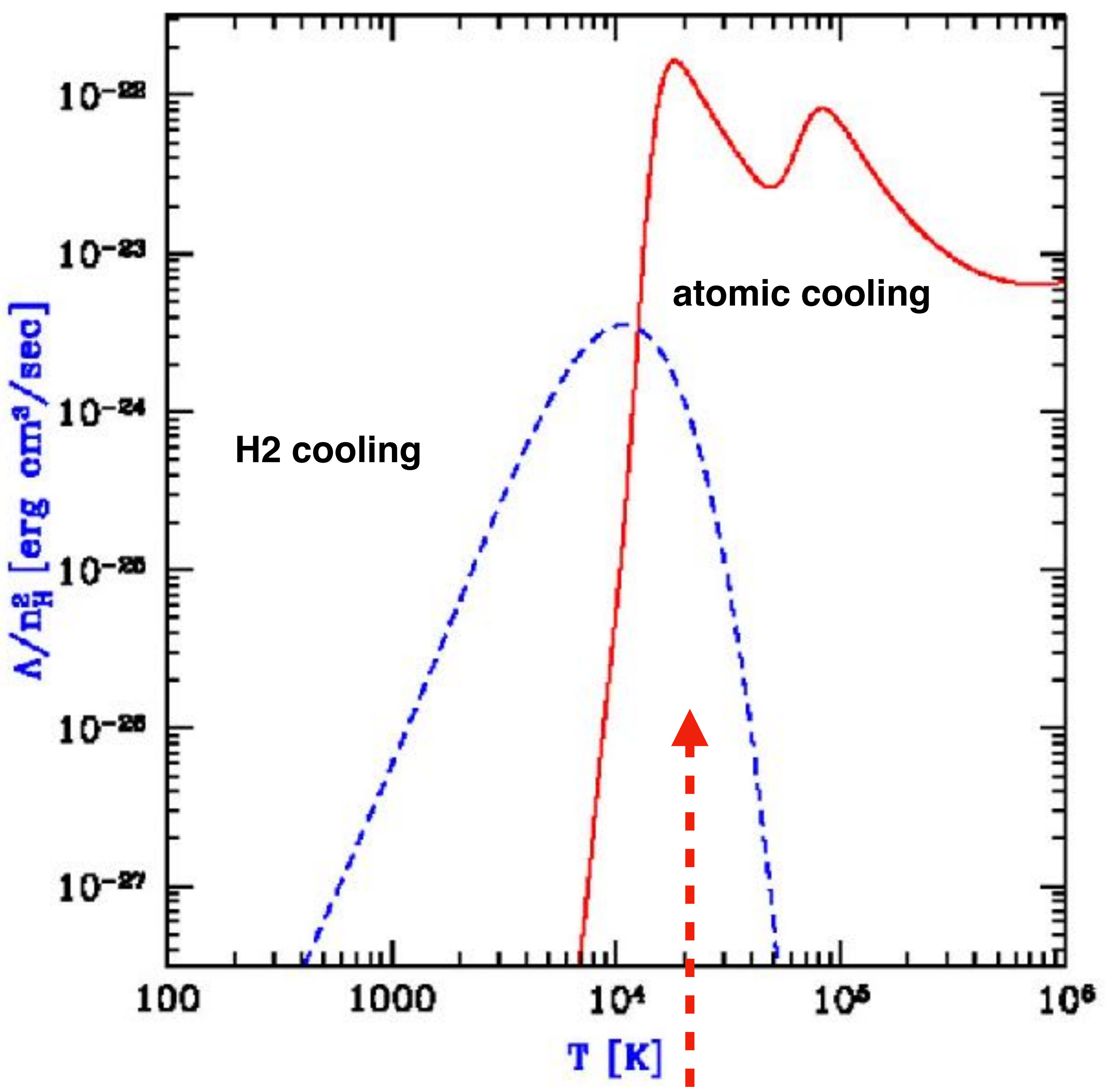


Ishiyama+21

The Uchuu（宇宙）simulation

First Galaxy Formation in Atomic Cooling Halos

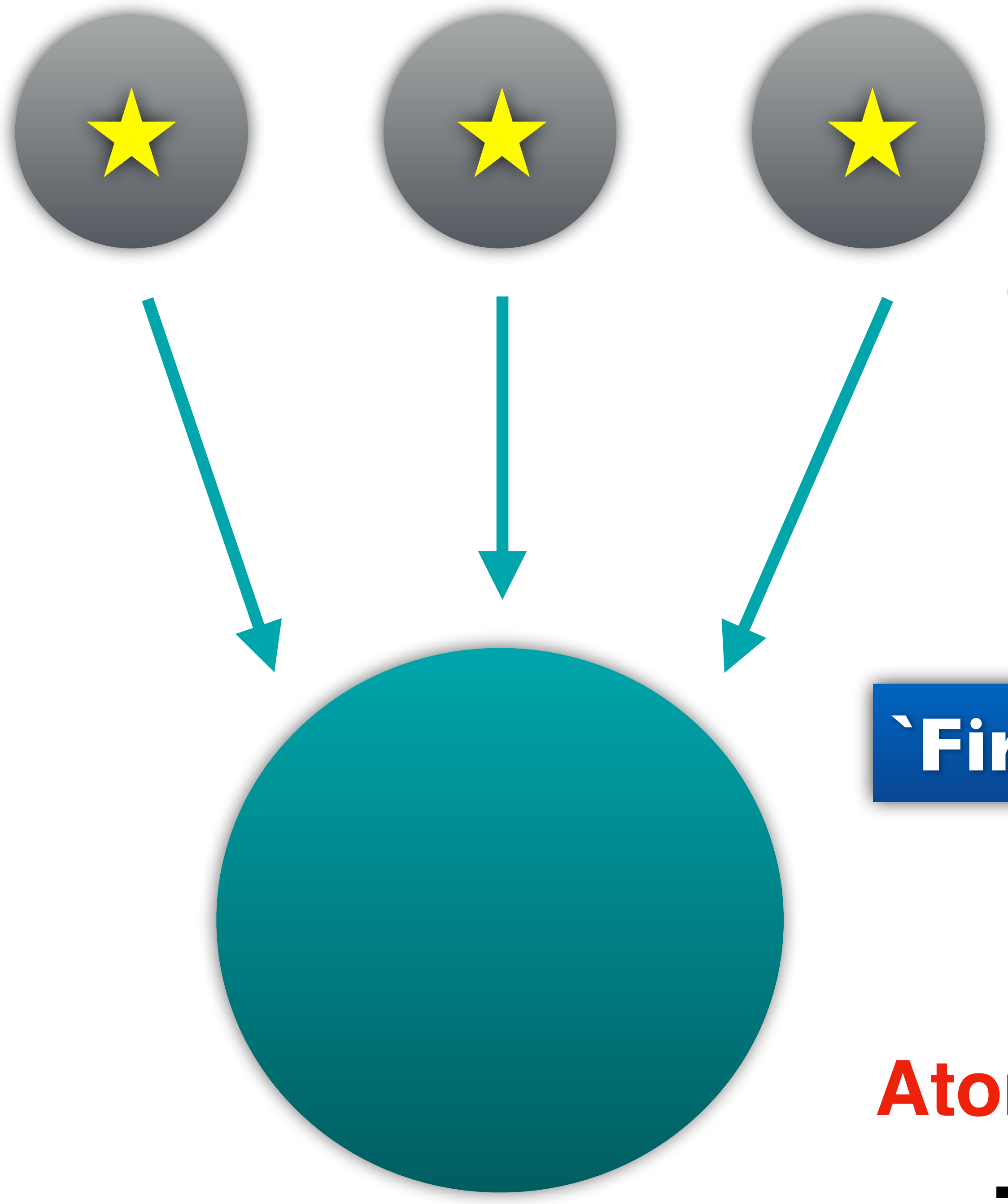
Cooling Rate



`First Star' DM Halo

~10^6 $M_\odot$

(SF via H_2 cooling)



`First Galaxy' Halo

~10^8 $M_\odot$

Atomic Cooling Halo

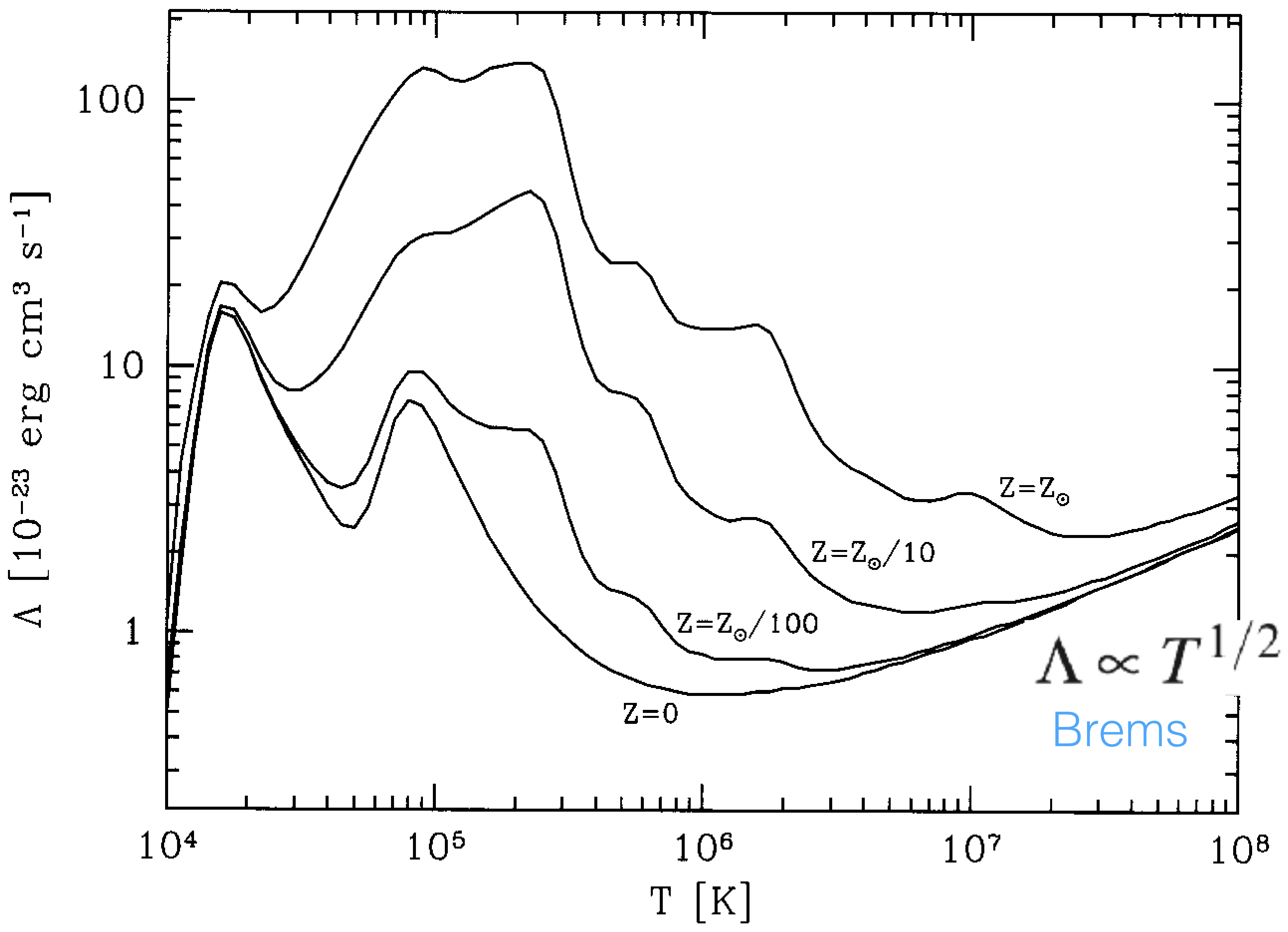
T_{vir} ~ 10^4 K

$$T_{\rm vir} = \frac{\mu m_{\rm H} V_c^2}{2k_{\rm B}} \simeq 10^4 \left(\frac{\mu}{0.6}\right)\left(\frac{M}{10^8 M_\odot}\right)^{2/3}\left[\frac{\Delta_c}{18\pi^2}\right]^{1/3}\left(\frac{1+z}{10}\right) \text{ K},$$

Bryan & Norman '98

cf. $T_{\rm vir} \sim 10^8\,K$ **for** $M = 10^{14}\,M_\odot$ (galaxy clusters)

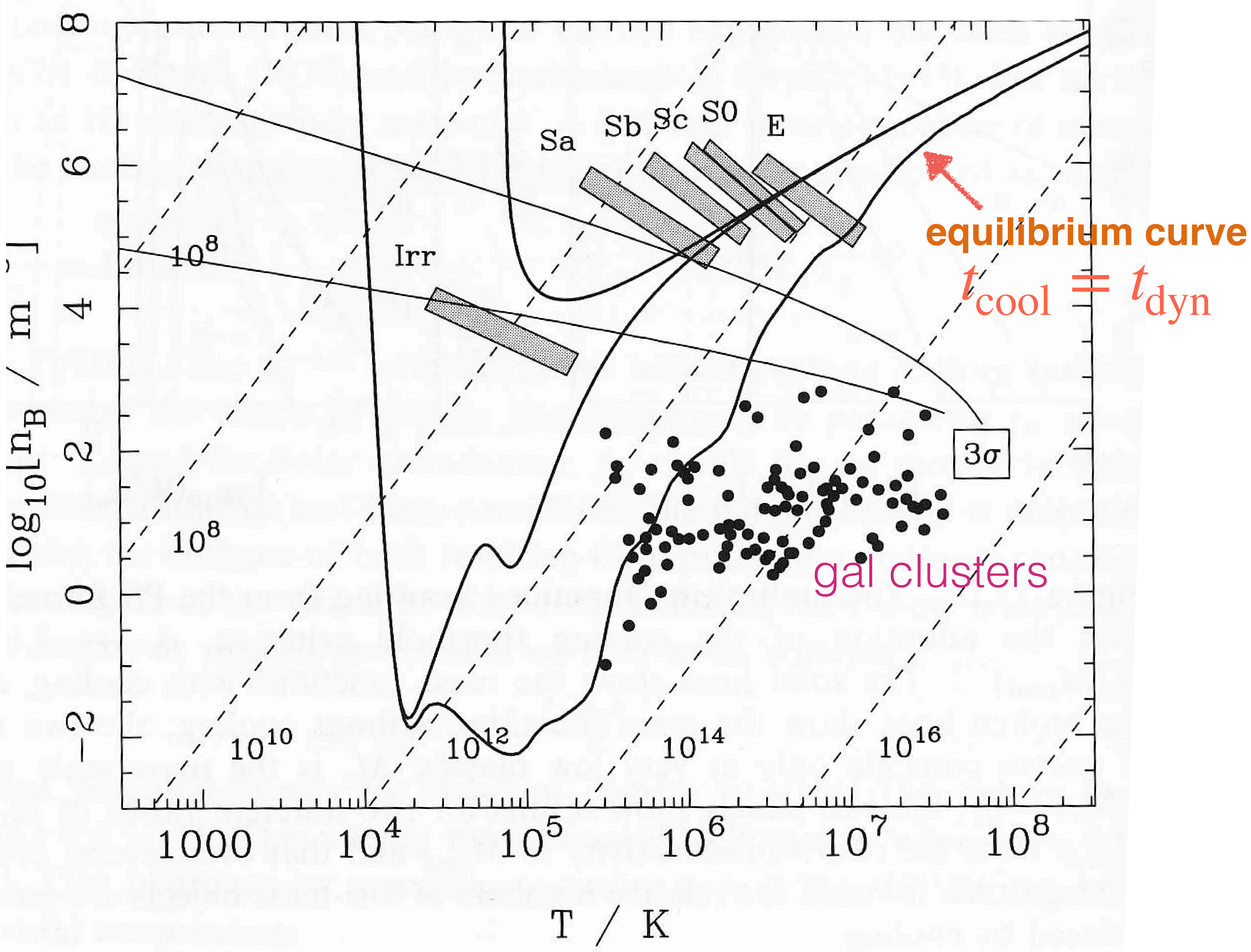
Cooling Function



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

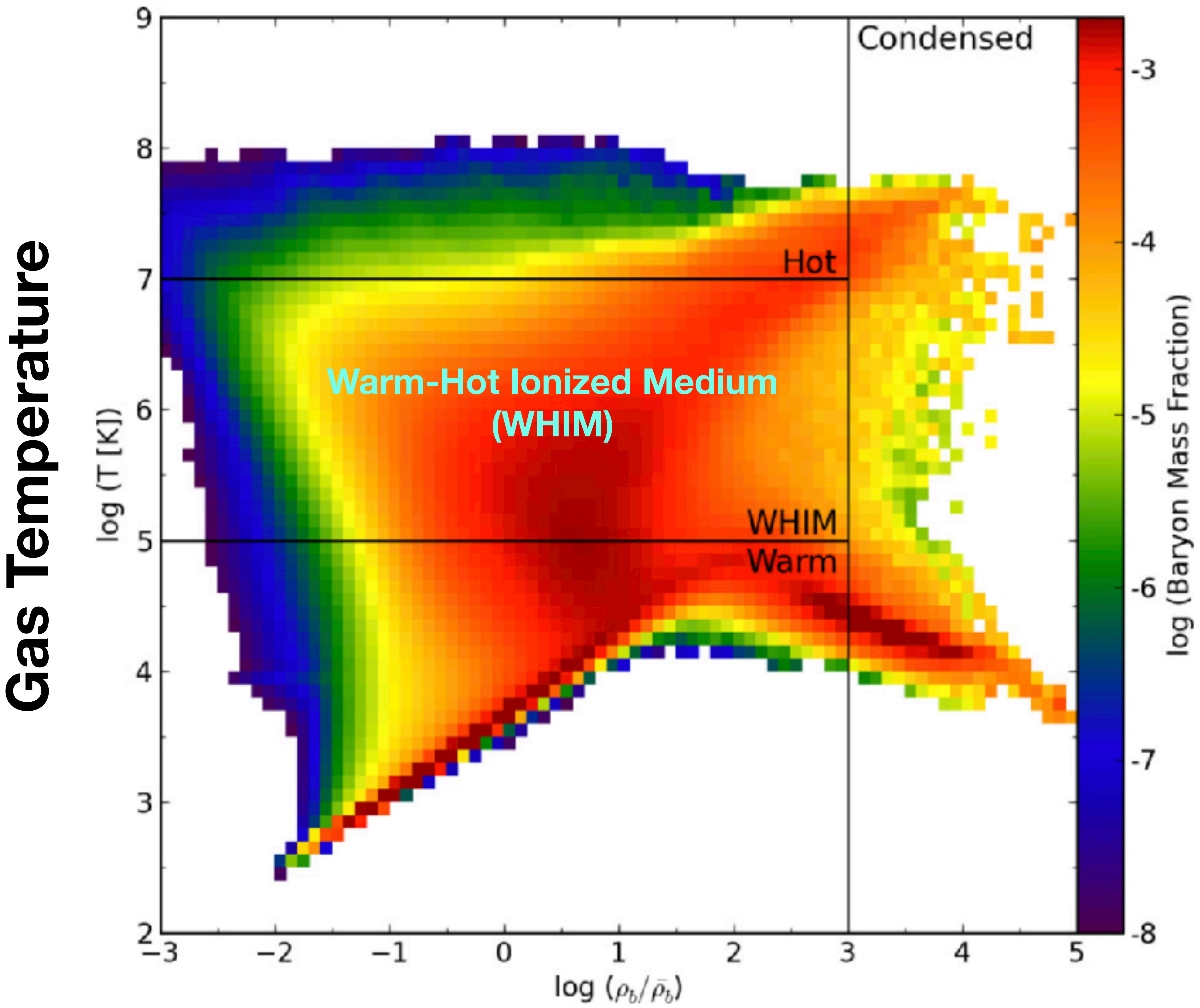
$\mathscr{C}$: cooling rate per unit vol. [erg cm^{-3} s^{-1}]

Mass-scale of Galaxies, Clusters



Blumenthal+'84; Peacock textbook, p.572

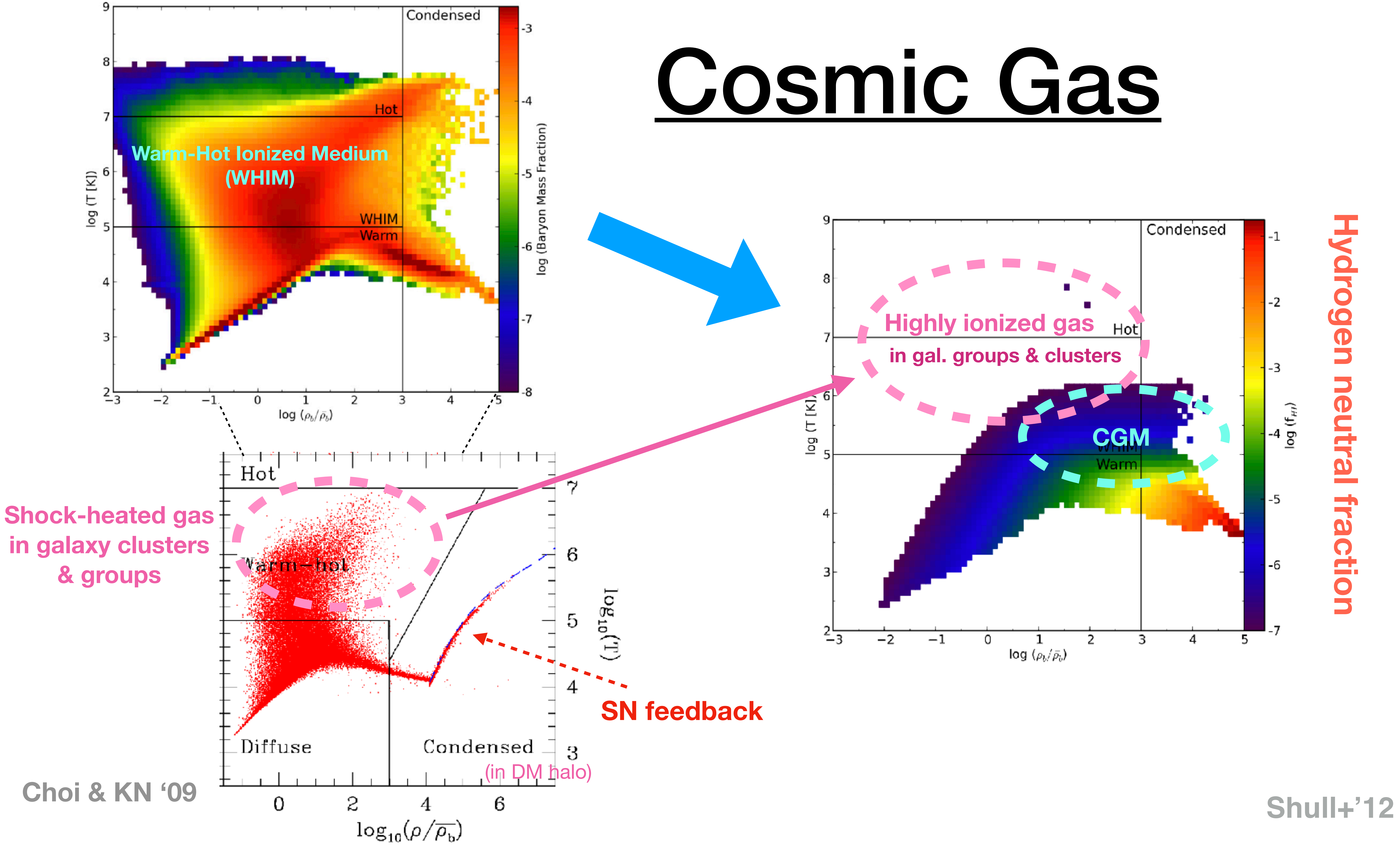
Cosmic Gas : phase diagram



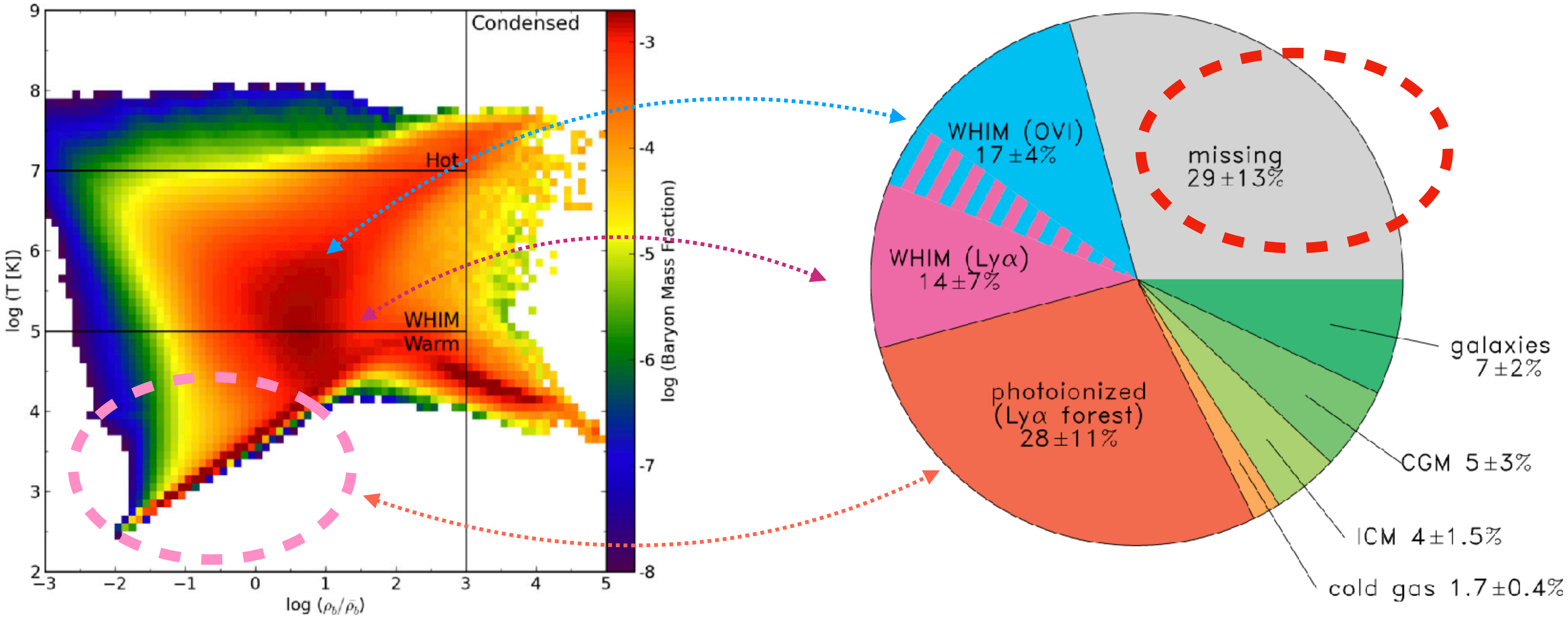
Baryon overdensity

Shull+'12

Cosmic Gas


Condensed
Hot
Warm-Hot Ionized Medium
(WHIM)
WHIM
Warm
log (T [K])
log $(\rho_b/\bar{\rho}_b)$
log (Baryon Mass Fraction)
Hot
Warm−hot
Diffuse
Condensed
(in DM halo)
$\log_{10}(\rho/\overline{\rho_b})$
$\log_{10}(T)$
Shock-heated gas
in galaxy clusters
& groups
SN feedback
Choi & KN '09
Highly ionized gas
in gal. groups & clusters
CGM
Condensed
Hot
WHIM
Warm
log (T [K])
log $(\rho_b/\bar{\rho}_b)$
log (f_{HI})
Hydrogen neutral fraction
Shull+'12

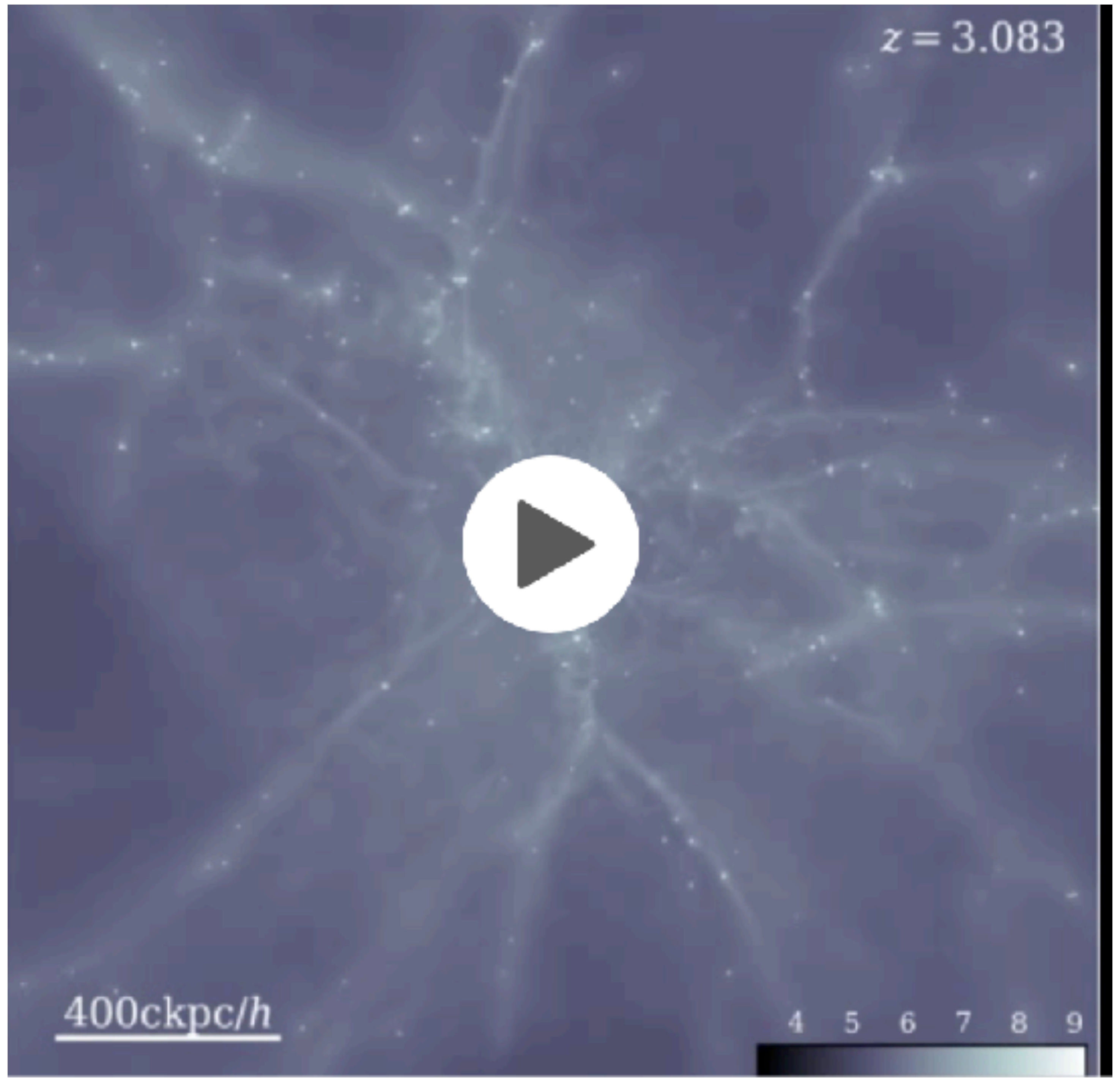
Missing Baryon Problem



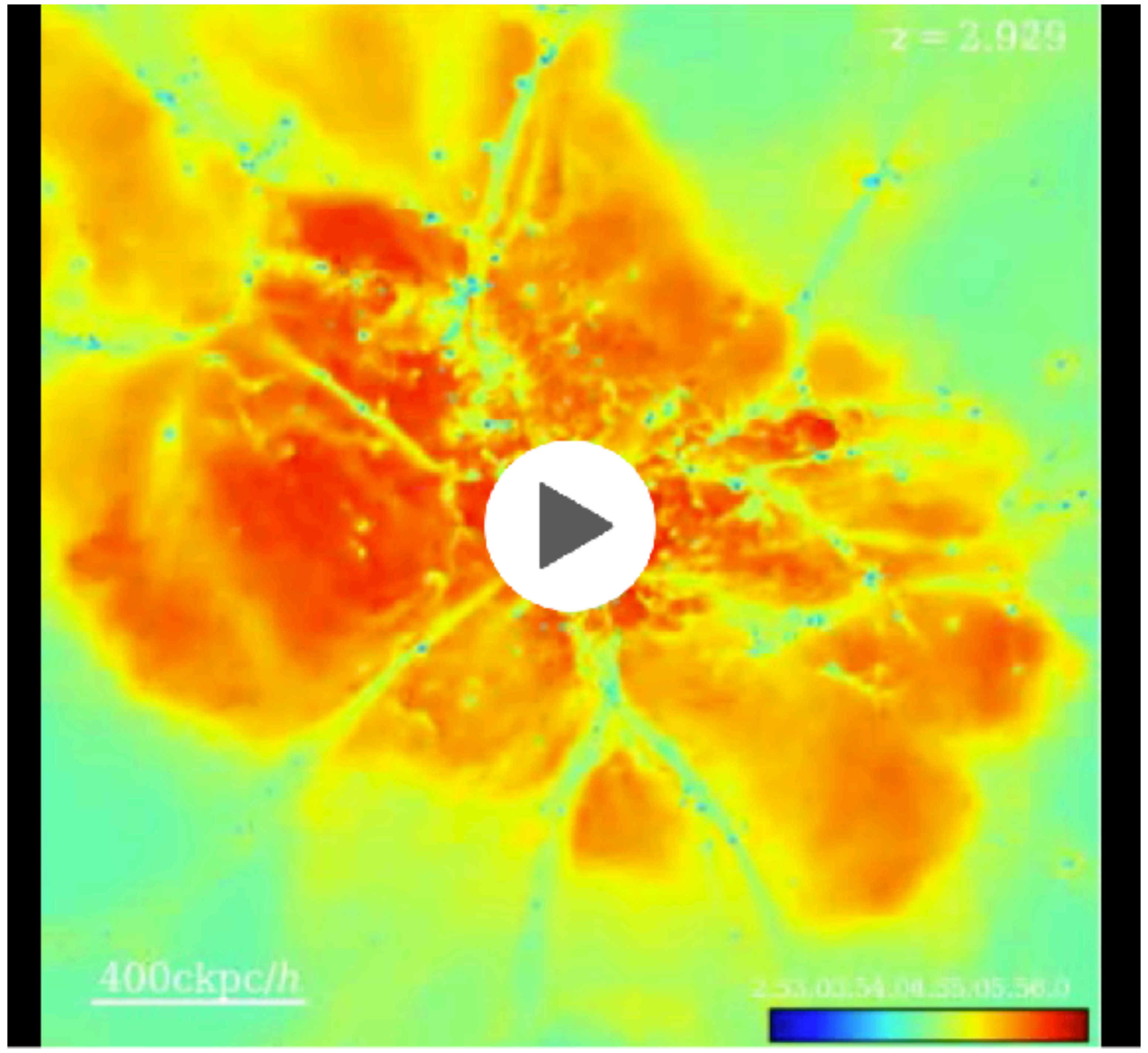
Shull+'12

Movies: zoom-in sim

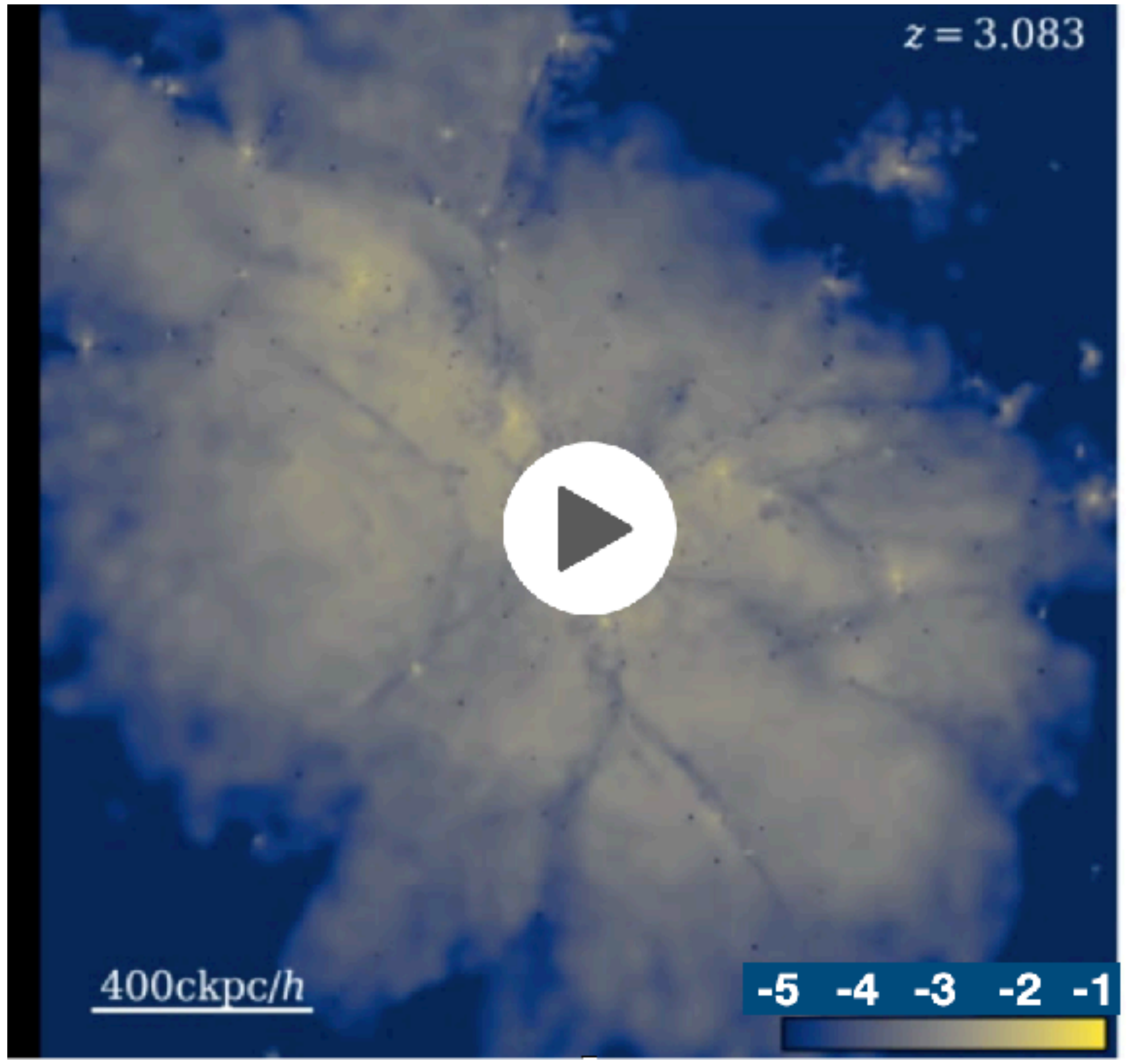
Gas Density



log(Temperature)



log(Metallicity)



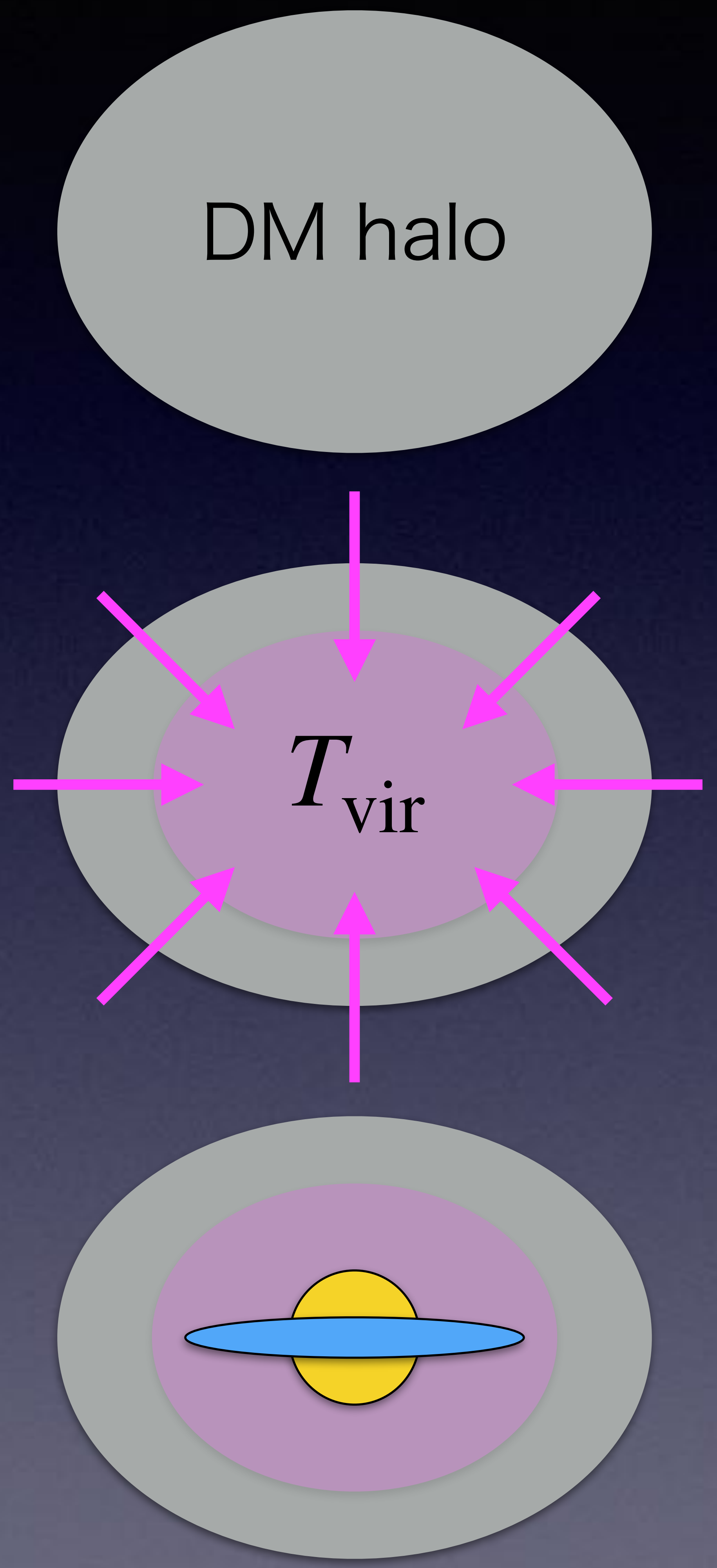
AGORA L12 GADGET3-Osaka sim.

Shimizu, KN+19

cf. Roca-Fabrega+21

https://sites.google.com/site/santacruzcomparisonproject/

1st-order Galaxy formation

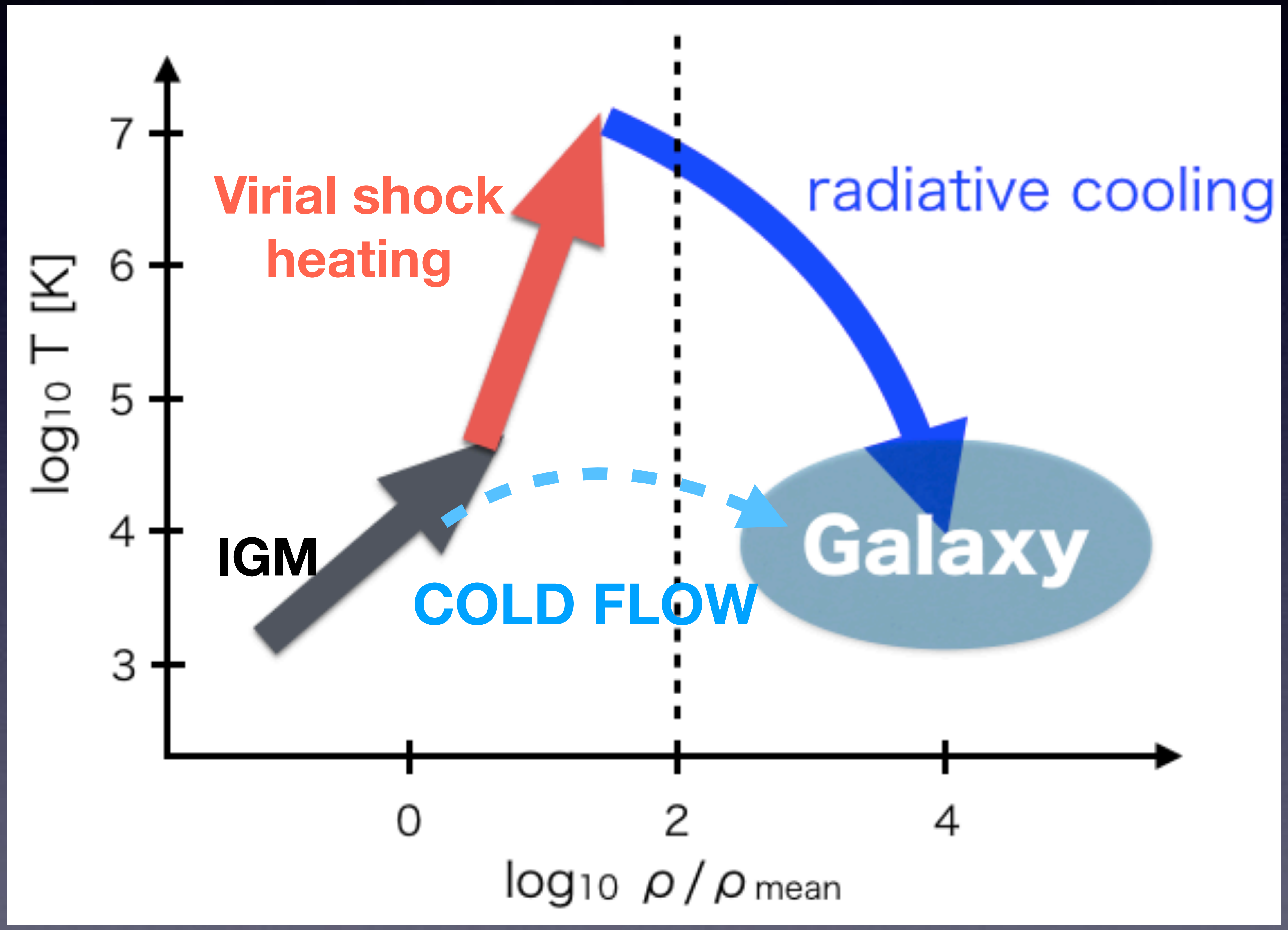


DM halo forms.

gas accretion & shock-heating

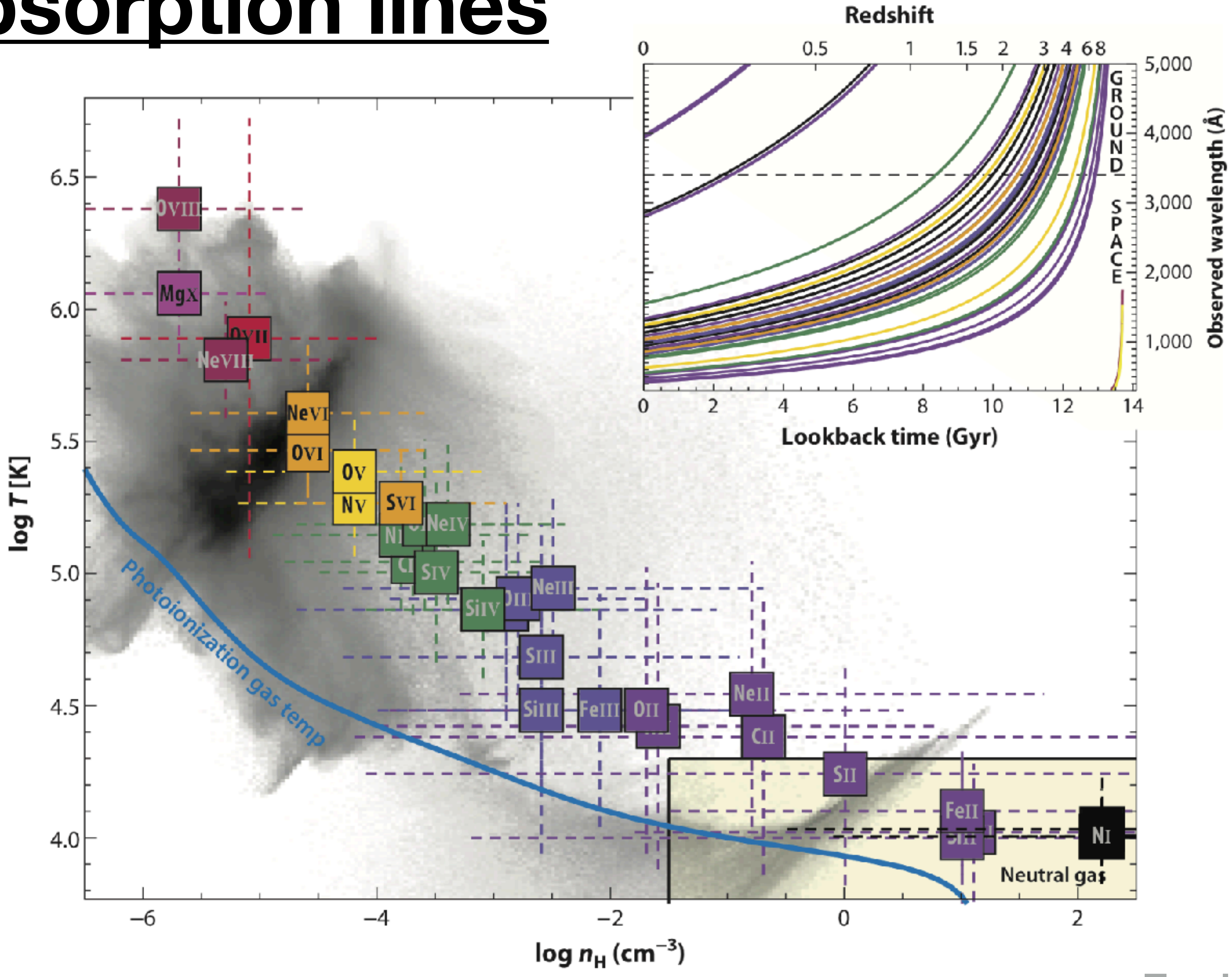
Cooling, dissipation, & disk galaxy forms

Phase Diagram



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

Metal absorption lines

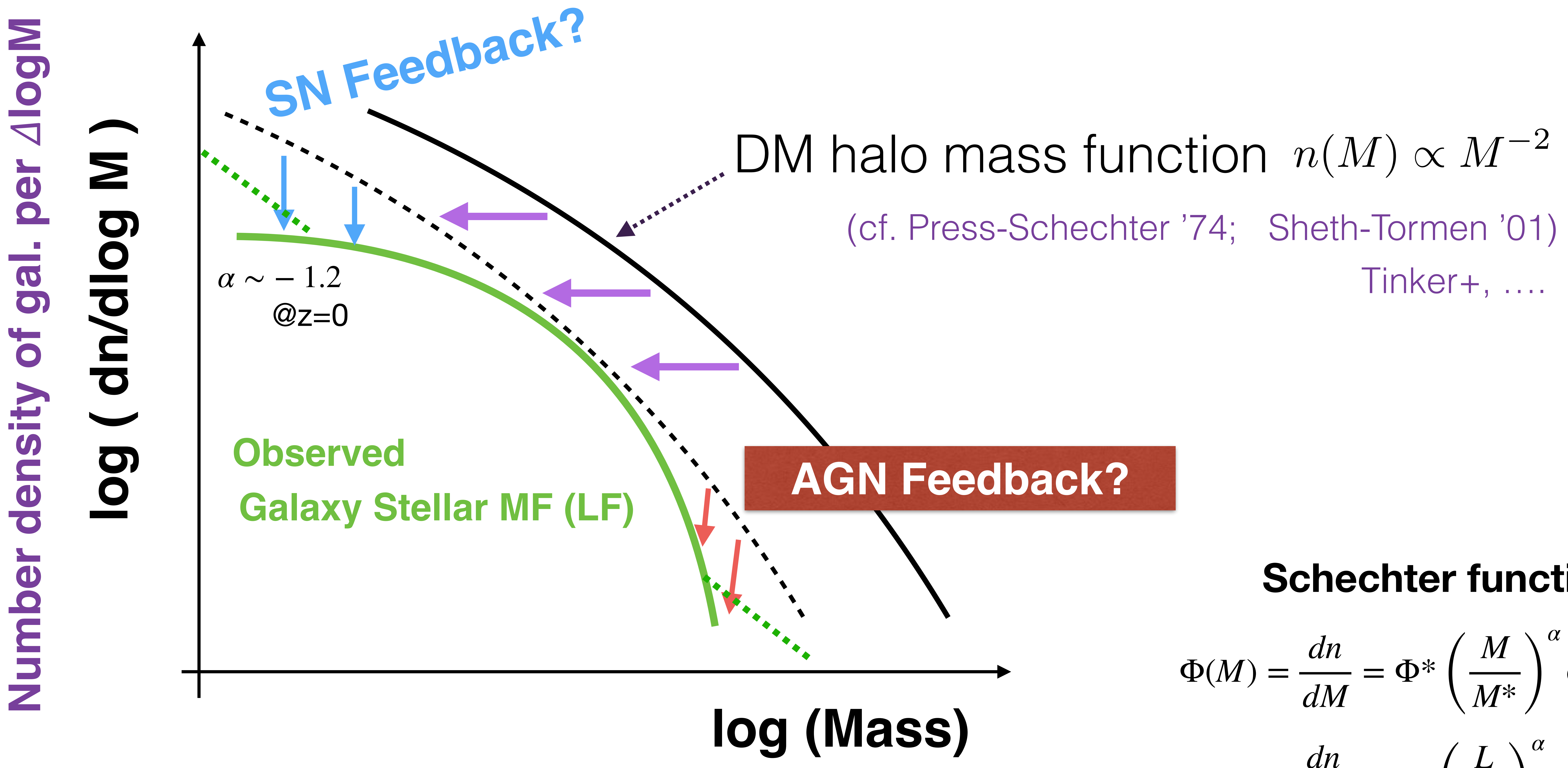


Tumlinson+'17, ARAA

Necessity of Feedback

SNe & AGN

Shaping Galaxy Mass Function via Feedback

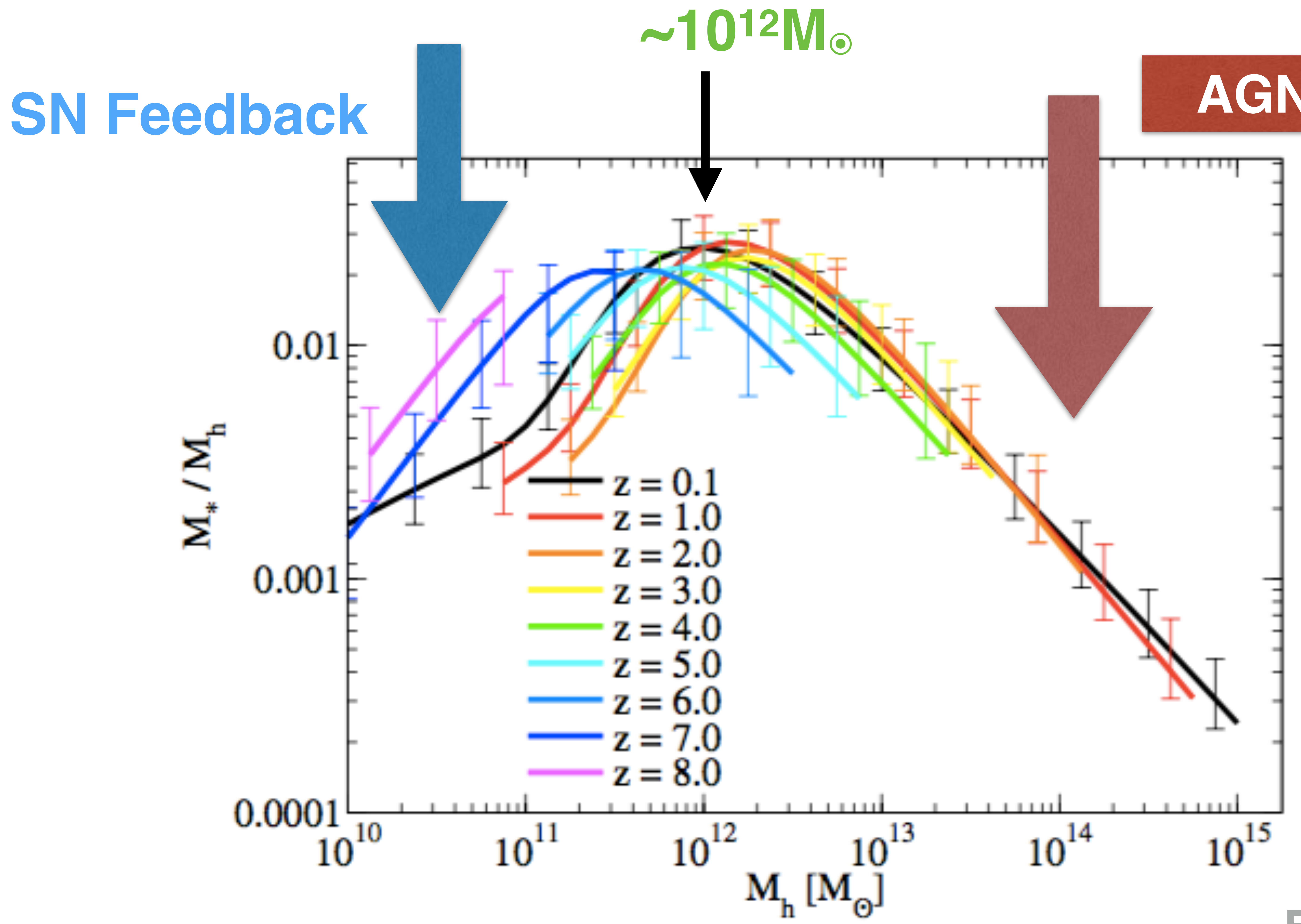


Schechter function

$$\Phi(M) = \frac{dn}{dM} = \Phi^* \left(\frac{M}{M^*}\right)^{\alpha} \exp\left(-\frac{M}{M^*}\right)$$

$$\Phi(L) = \frac{dn}{dL} = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)$$

Stellar-to-Halo Mass Ratio (SHMR)



Abundance Matching

Behroozi+'10, '13, '18

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

SN feedback efficiency

CC SNe: ~ 0.01 SNe per $1\,M_\odot$ of stars **(IMF)** **&** $E_{\rm SN} \sim 10^{51}$ erg per SN

~30% of this couples to ISM as kinetic E. of **galactic wind (GW)**

$$E_{\rm w} \sim 10^{51} \times 0.3 \times 0.01 = 3 \times 10^{48} \text{ erg } {M_\odot}^{-1}$$

energy—mass deposition rate

$$\dot{E}_{\rm w} = \epsilon_{\rm w} \dot{M}_\star c^2$$
$$\dot{M}_{\rm w} = \eta \dot{M}_\star,$$

$$\dot{E}_{\rm w} = \frac{1}{2} \dot{M}_{\rm w} v_{\rm w}^2,$$

GW efficiency: $\epsilon_w \sim 10^{-6}$

mass-loading factor: $\eta \sim 2$

$$v_w = \left(\frac{2\epsilon_w}{\eta}\right)^{1/2} c \sim 300 \text{ km s}^{-1}$$

e.g. Springel & Hernquist (2003)
Cen, KN, Ostriker (2005)

SN vs. AGN (SMBH) feedback

E_K per SN II ~ 1 foe ~ 10^{51} erg $\qquad$ ($E_{tot,II}$ ~ 100 foe ~ 10^{53} erg)

Type II SN occurs ~0.01 per $M_\odot$ of SF for an IMF → **10^{48} — 10^{49} erg / (1$M_\odot$ of SF)**

$$\epsilon_{K,SN} \sim \frac{10^{48} - 10^{49}}{M_\odot c^2} \sim \frac{10^{48} - 10^{49}}{10^{33+21}} \sim 10^{-6} - 10^{-5}$$ **(per 1$M_\odot$ of SF)**

AGN: 10% of $\dot{M}_{\rm acc} c^2$ & feedback efficiency ~0.1 & $\frac{M_{\rm BH}}{M_\star} \sim 10^{-3}$

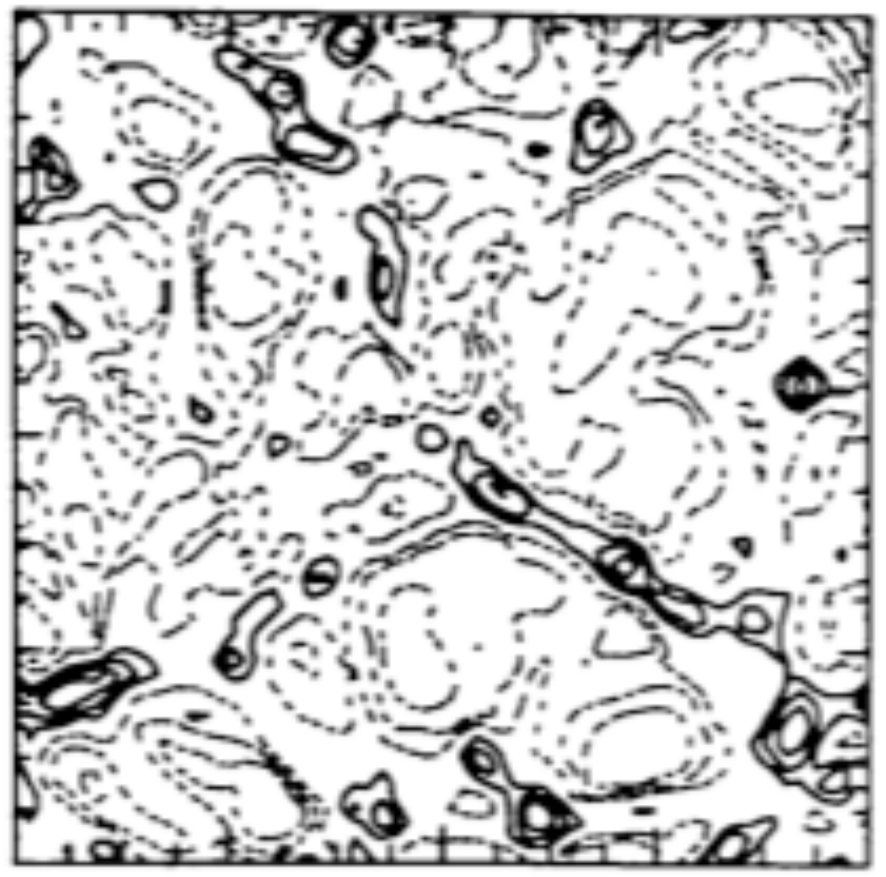
$$\epsilon_{K,AGN} \sim 0.1 \times 0.1 \times 10^{-3} \sim 10^{-5}$$ **(per 1$M_\odot$ of SF)**

Probably depends on various other factors:

$$\chi \equiv \left(\frac{\epsilon_{K,SN}}{\epsilon_{K,AGN}} \right) = \chi(z, M_{\rm halo}, M_*, M_{\rm BH}, SFR, C, \cdots)$$

Three Revolutions in Cosmological Hydro Simulations

1990': 1st Revolution

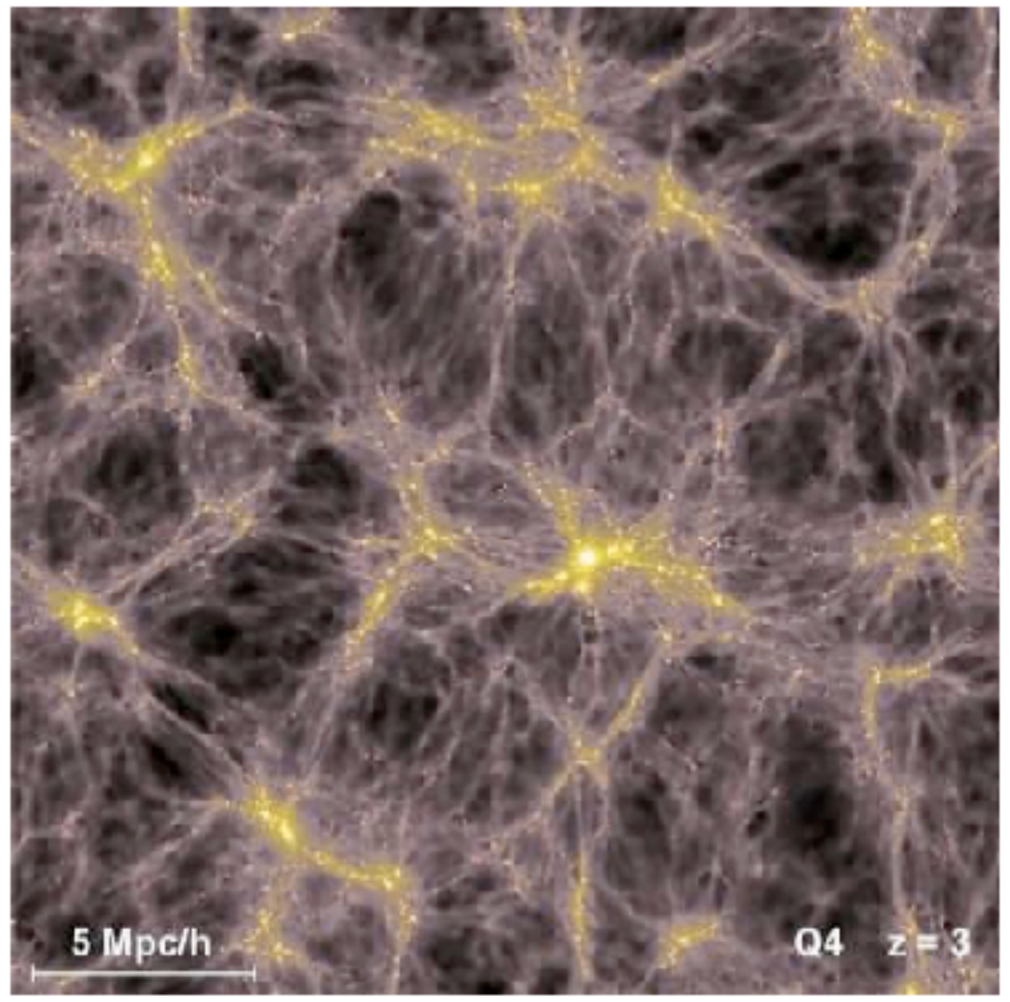


First cosmological, but coarse calculation

Resolution ~100 kpc

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

2000~ 2nd Rev.

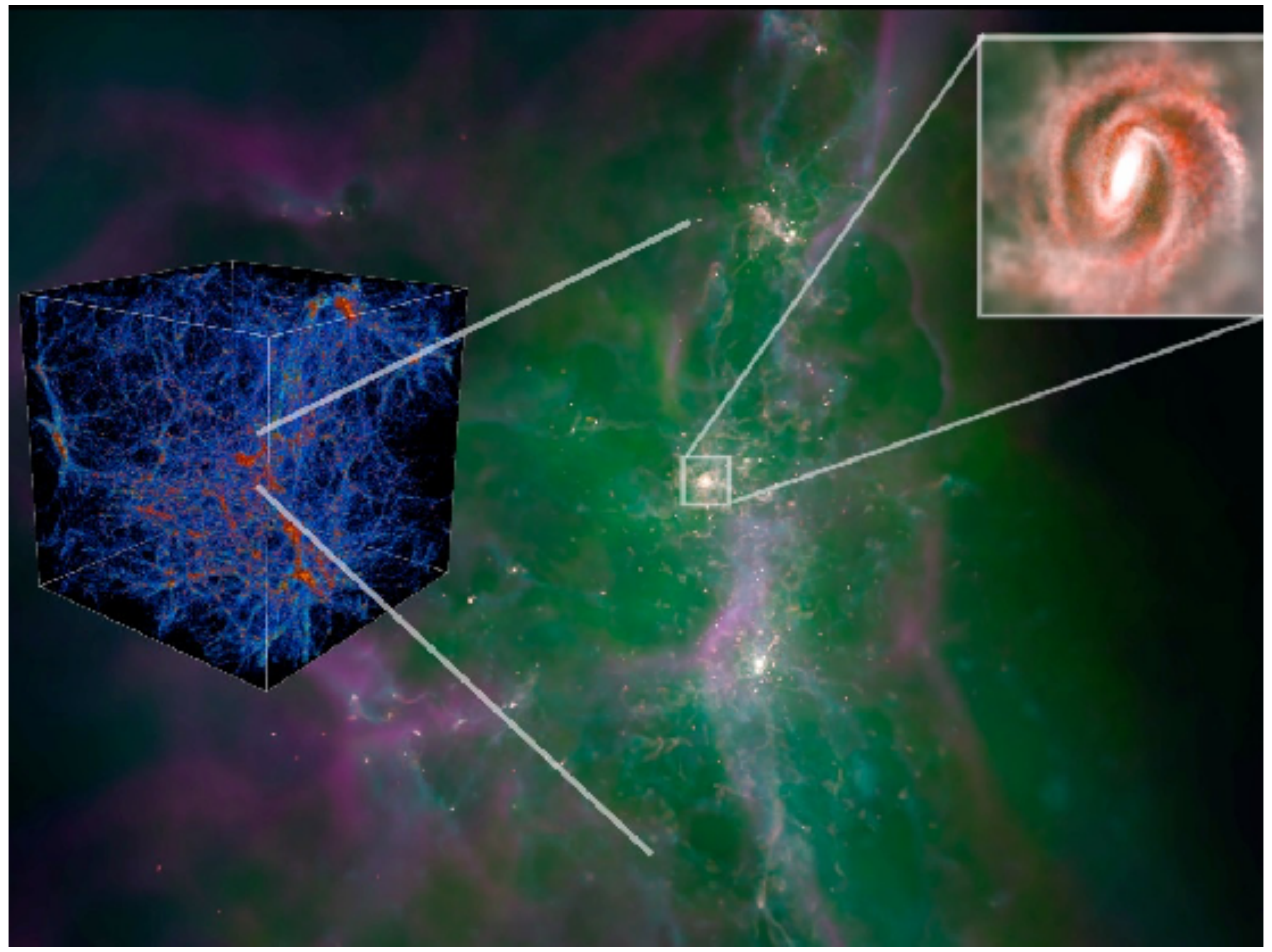


Larger scale, medium resolution
w. subgrid models

Resolution ~ kpc

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

2012~ 3rd Rev.



Zoom-in cosmo. sims. w. better sub grid models

Resolution ~ 10-100pc

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

力学的/熱的 フィードバック

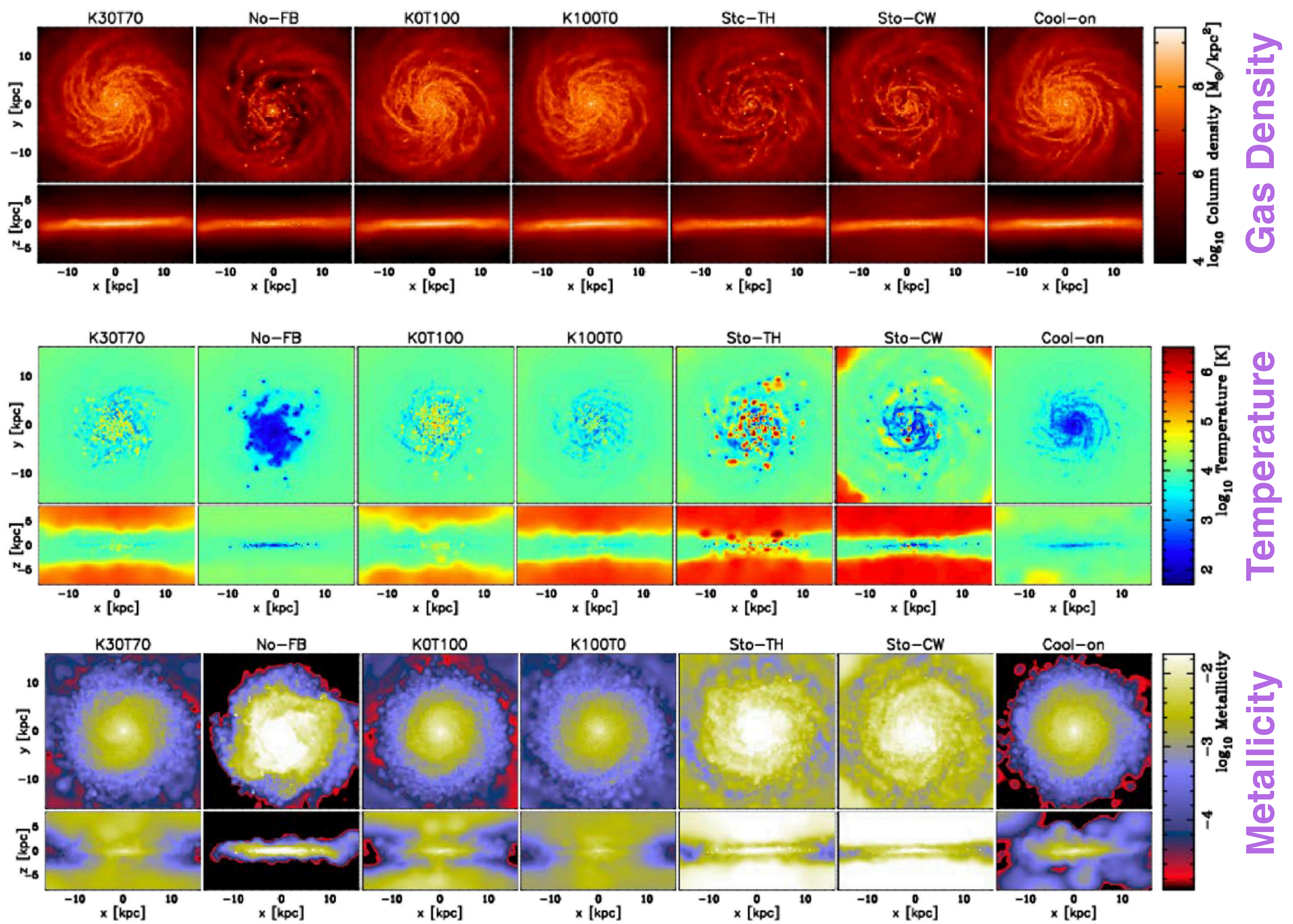
	力学的フィードバック	熱的フィードバック
物理的意味	超新星残骸から ISM への運動量注入	衝撃波加熱
役割	乱流の駆動、 アウトフローの駆動	高温 ($> 10^6$ K) アウトフローの駆動 重金属を銀河外へ拡散
低分解能での問題	冷却長が分解不能 ➡ 超新星残骸の時間発展を解けない (空間分解能の不足)	冷却質量が分解不能 ➡ 熱が直ちに放射される (質量分解能の不足)
先行研究	Springel & Hernquist (2003); Kimm & Cen (2014); Hopkins et al. (2018)	Stinson et al. (2006); Dalla Vecchia & Schaye (2012); Keller et al. (2014)

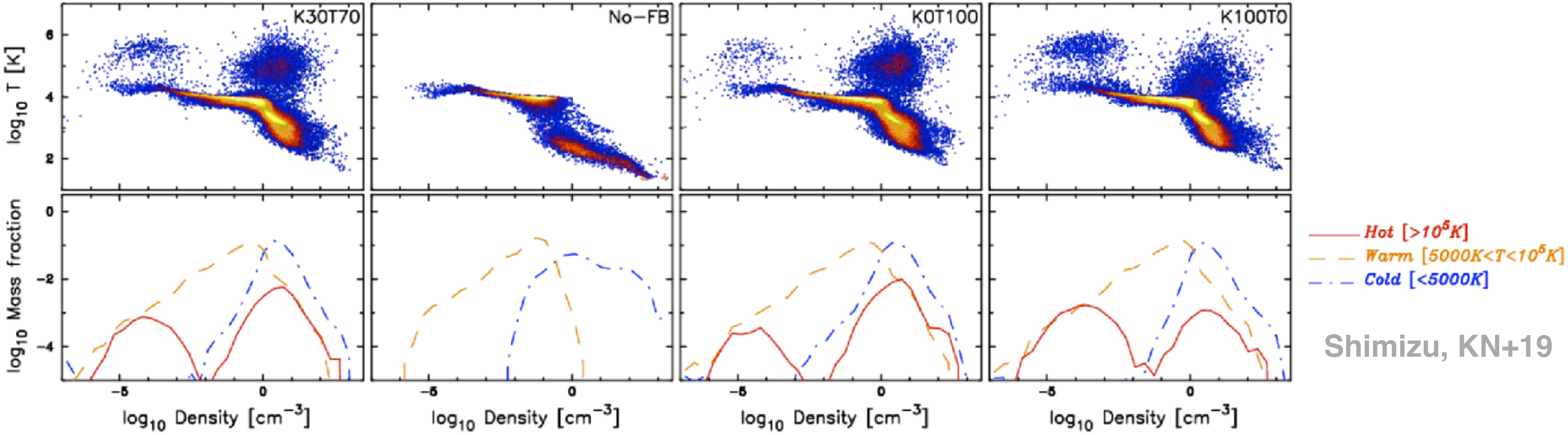
本研究の目標:

- 力学的、熱的 の両方を考慮したフィードバックモデルを構築する。
- まず、pc スケールの高分解能シミュレーションに基づいてモデル化する。
- 次に、モデルを実装して孤立銀河シミュレーションで検証する。

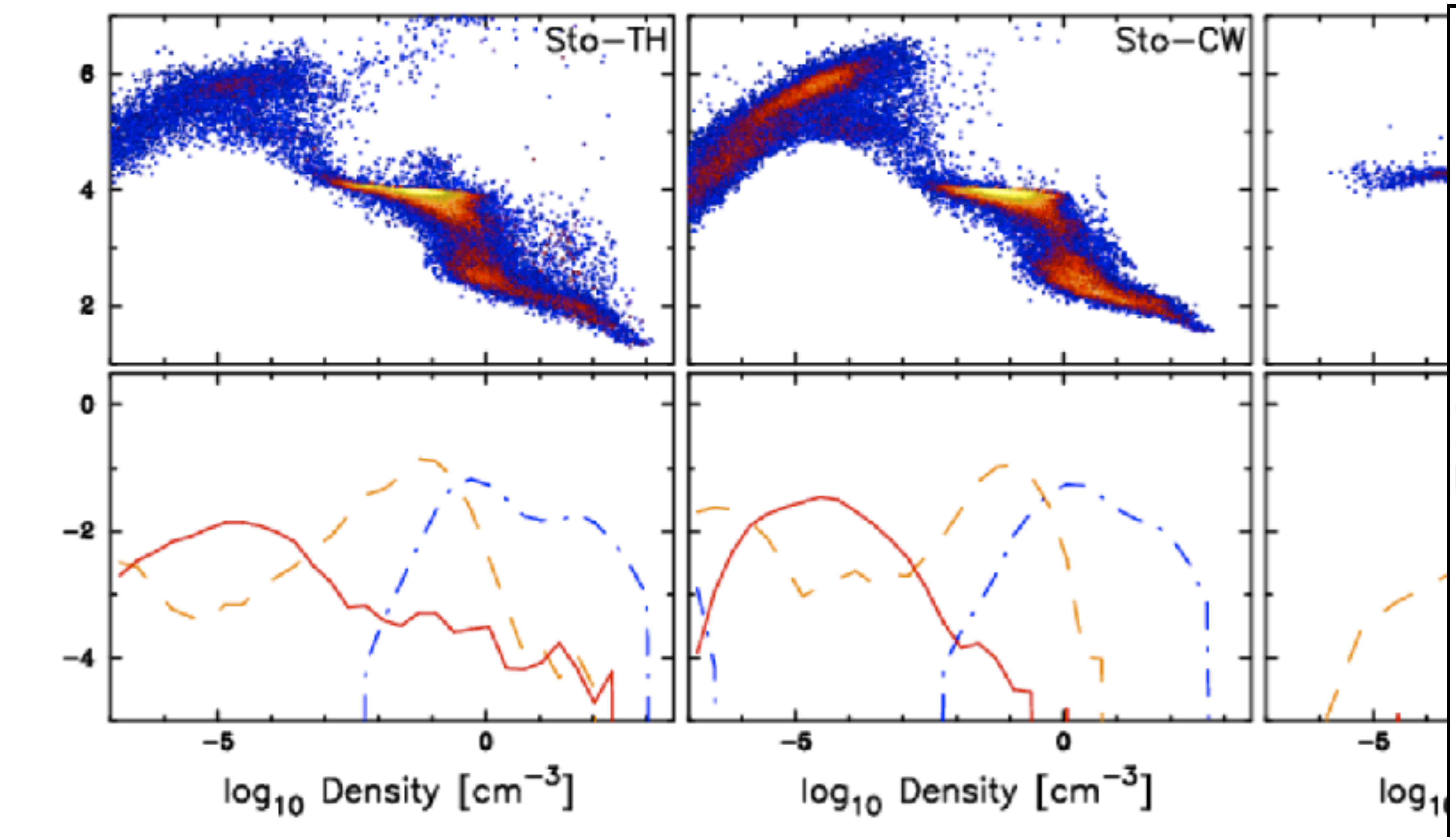
Isolated Galaxy Tests

t=0 to 1 Gyr

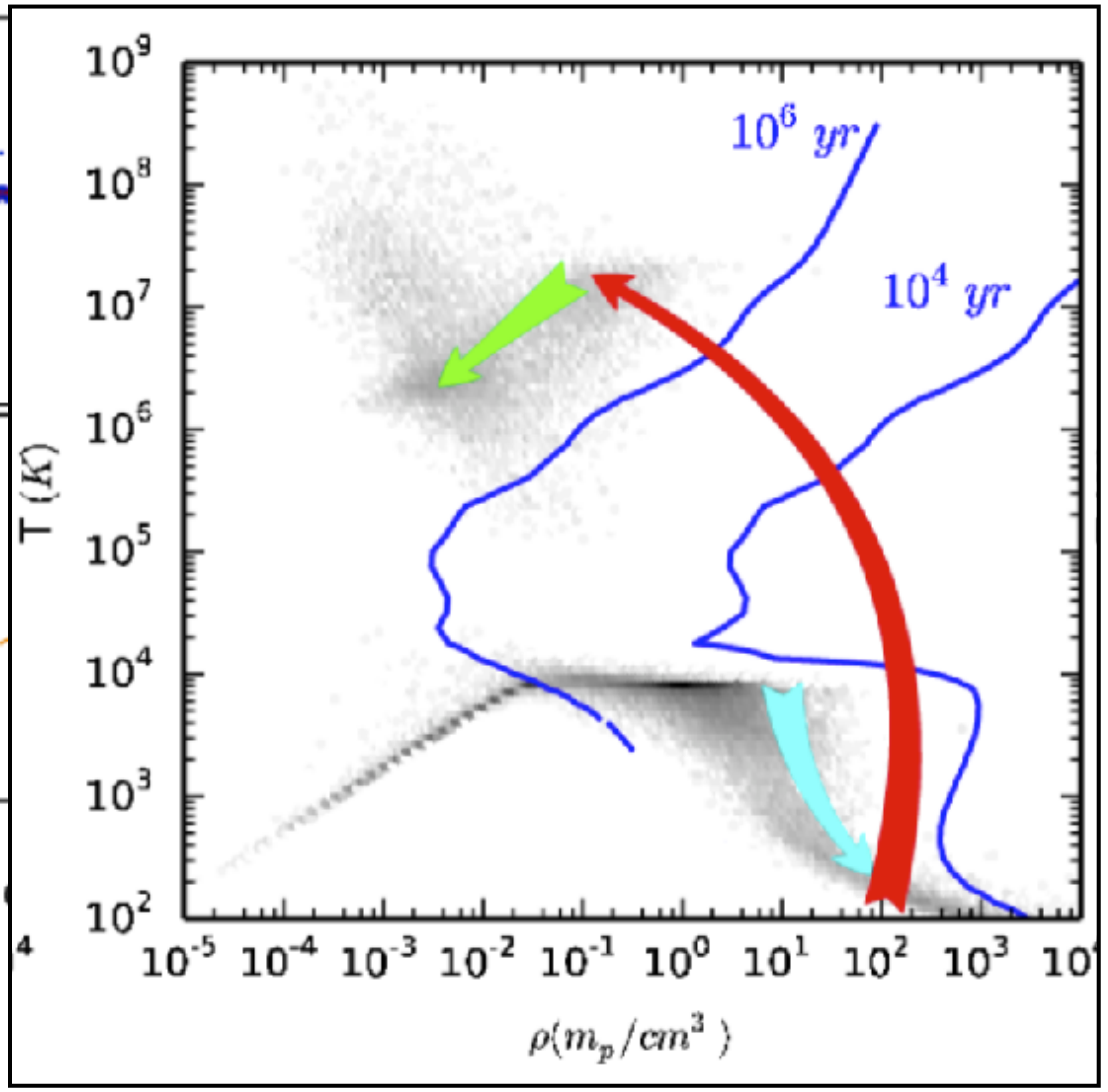




Shimizu, KN+19



Shimizu, KN+19



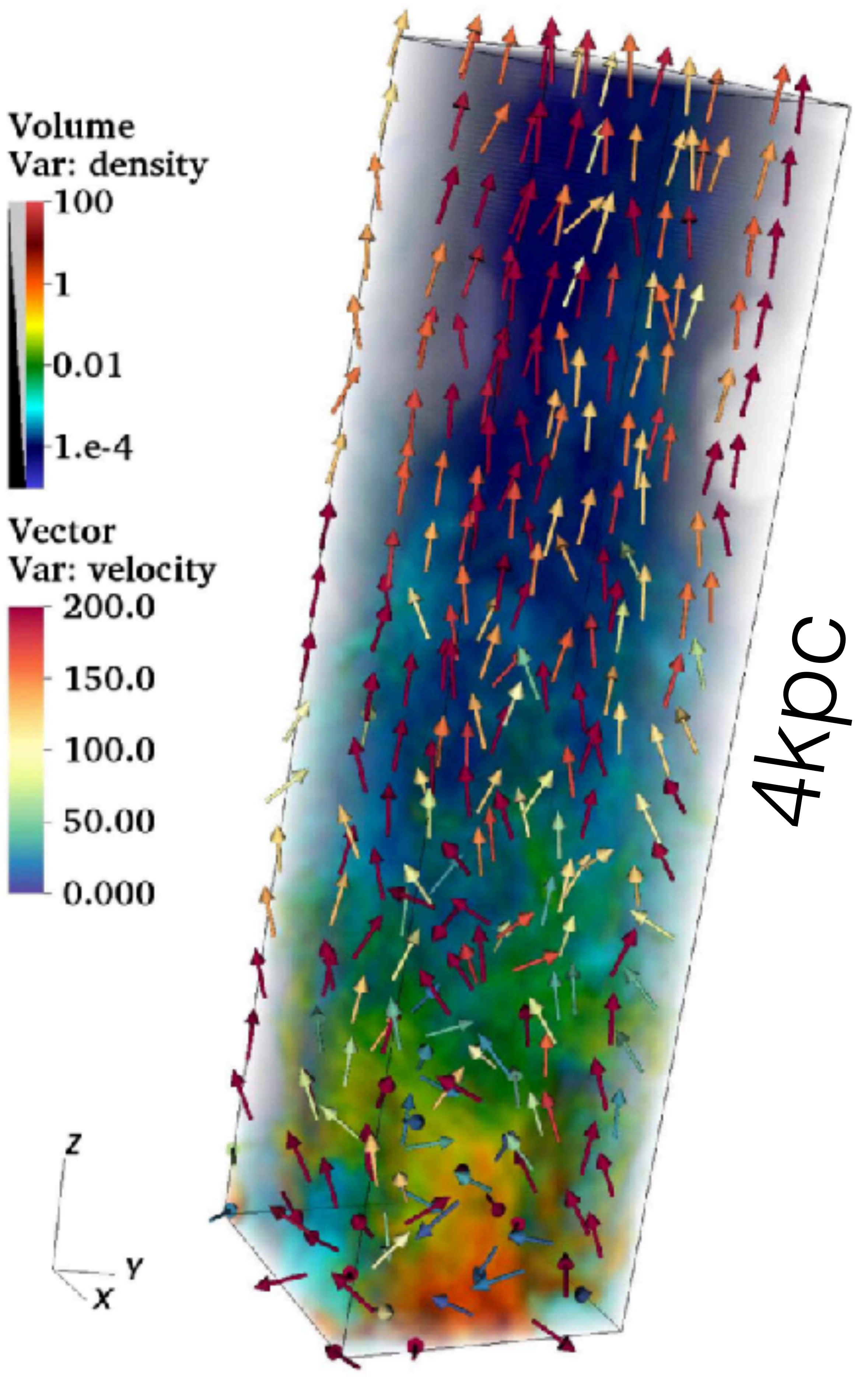
Keller & Wadsley '14

Issues with GW Feedback

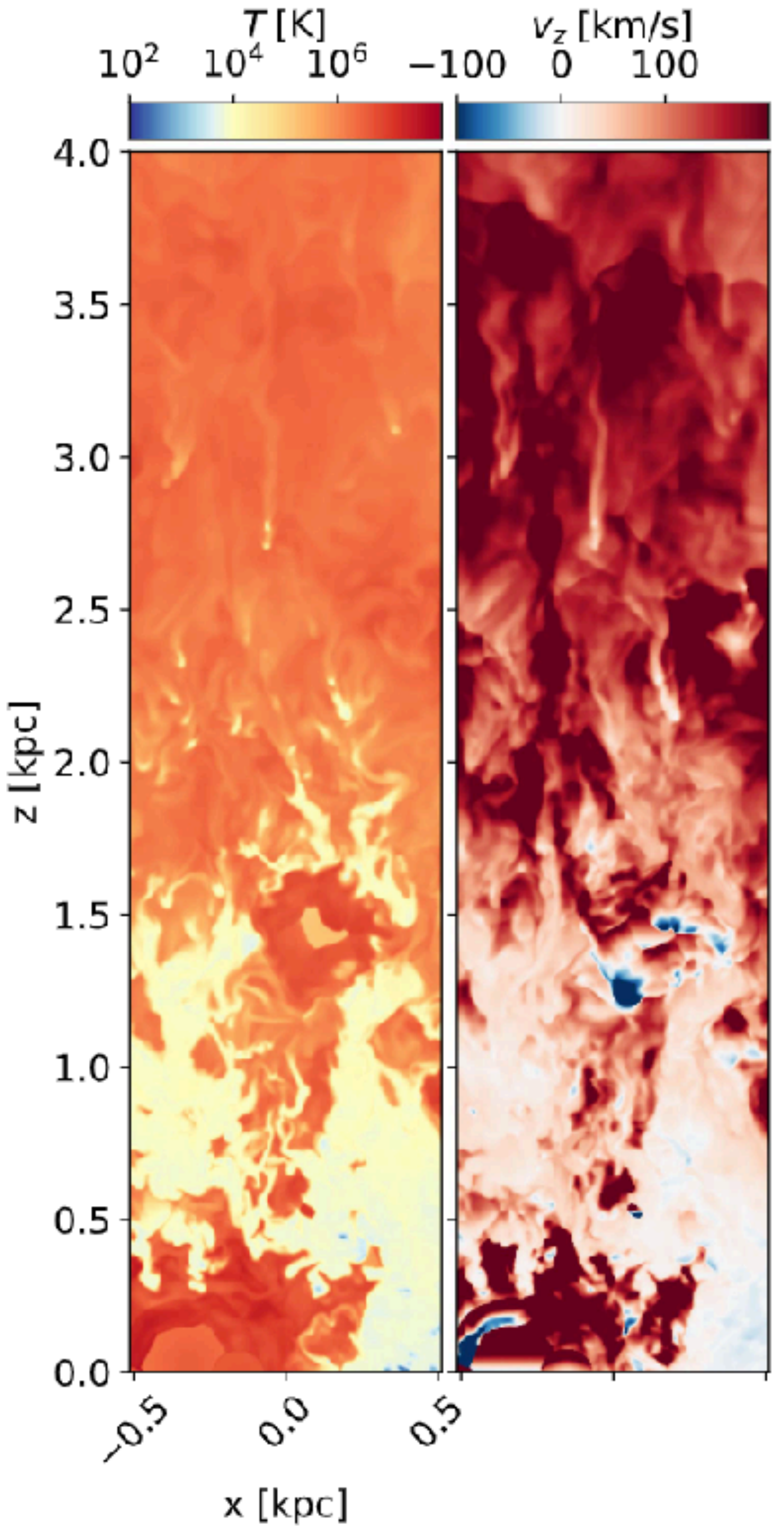
- **Physical state** of outflowing gas (multi-phase, ρ, T, vel., M, p, E)
- **Acceleration sites** (disk? near SNe? above mid-plane? CGM?)
- Ultimate fate of outflows (unbound? recycled?)
- Morphologies (biconical, spherical, filamentary, clumpy)
- **Acceleration mechanism** (mechanical, radiation, CR)

Multi-phase outflow from galactic plane: cut-out sim.

fast-moving,
low-density outflow



as well as warm fountain
(fall-back)



Athena MHD code

1 x 1 x 9 kpc domain

$\Delta x = 4$ pc

Kim & Ostriker '18

Resolved SN-driven winds

GADGET-3 sim.

dwarf gal.

$M_{\rm vir} = 10^{10}\, M_\odot$

$R_{\rm vir} = 44\,{\rm kpc}$

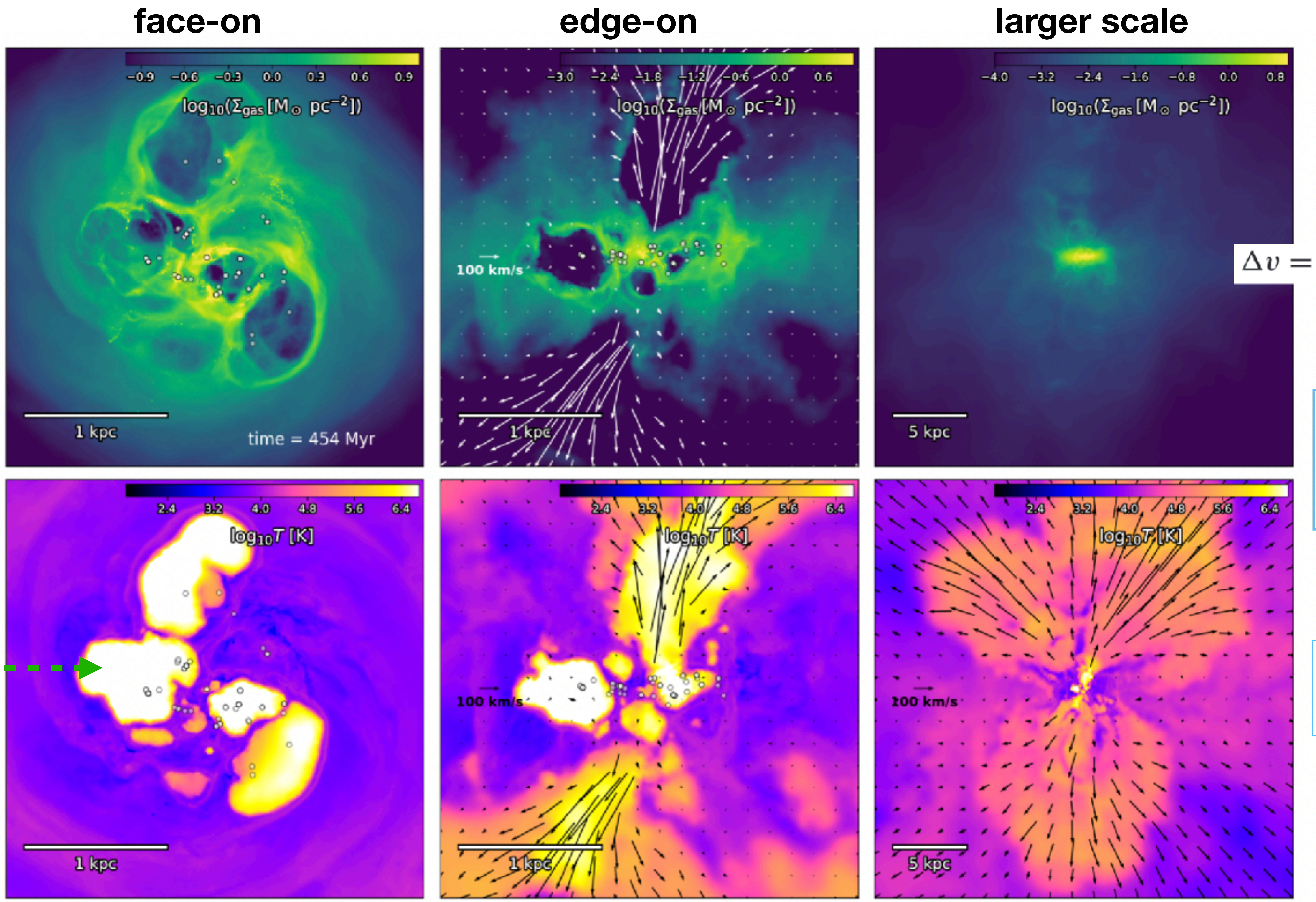
$c = 17$

$m_{\rm gas} = 1\, M_\odot$

$\epsilon_{\rm g},\, h_{\rm s} = 0.3\,{\rm pc}$

$\sim 10^6\, K$

Hu '19



$E_{\rm SN} = 10^{51}$ erg for each SN,

$e_{\rm k} = 0.28 E_{\rm SN} N_{\rm inj}^{-1}$

$N_{\rm inj} = 96$ gas particles

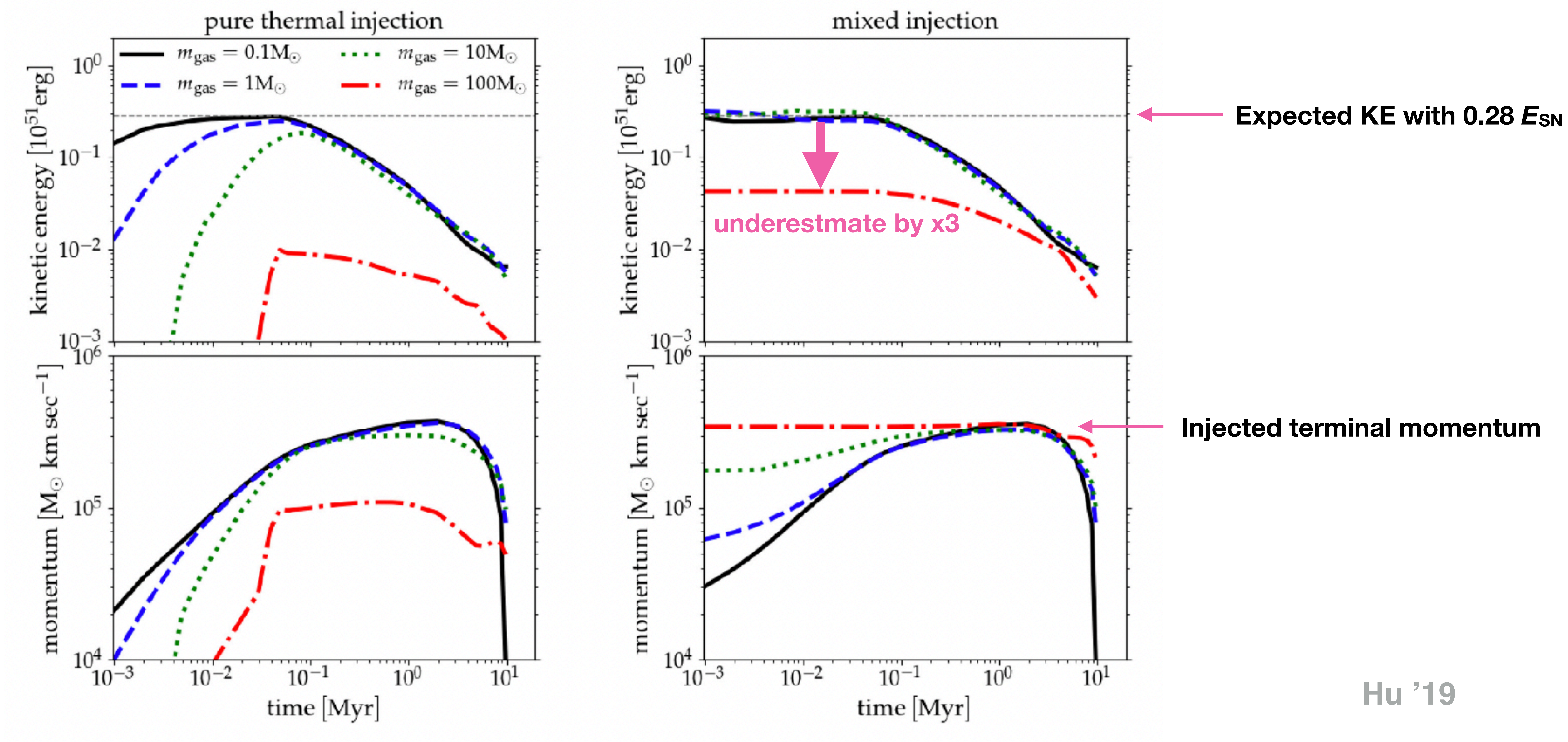
$\Delta v = \sqrt{2e_{\rm k}/m_{\rm gas}} \approx 541\ {\rm km\ s^{-1}} (m_{\rm gas}/{\rm M_\odot})^{-0.5}$

Superbubbles of ~few 100pc break out from the disk & expands.

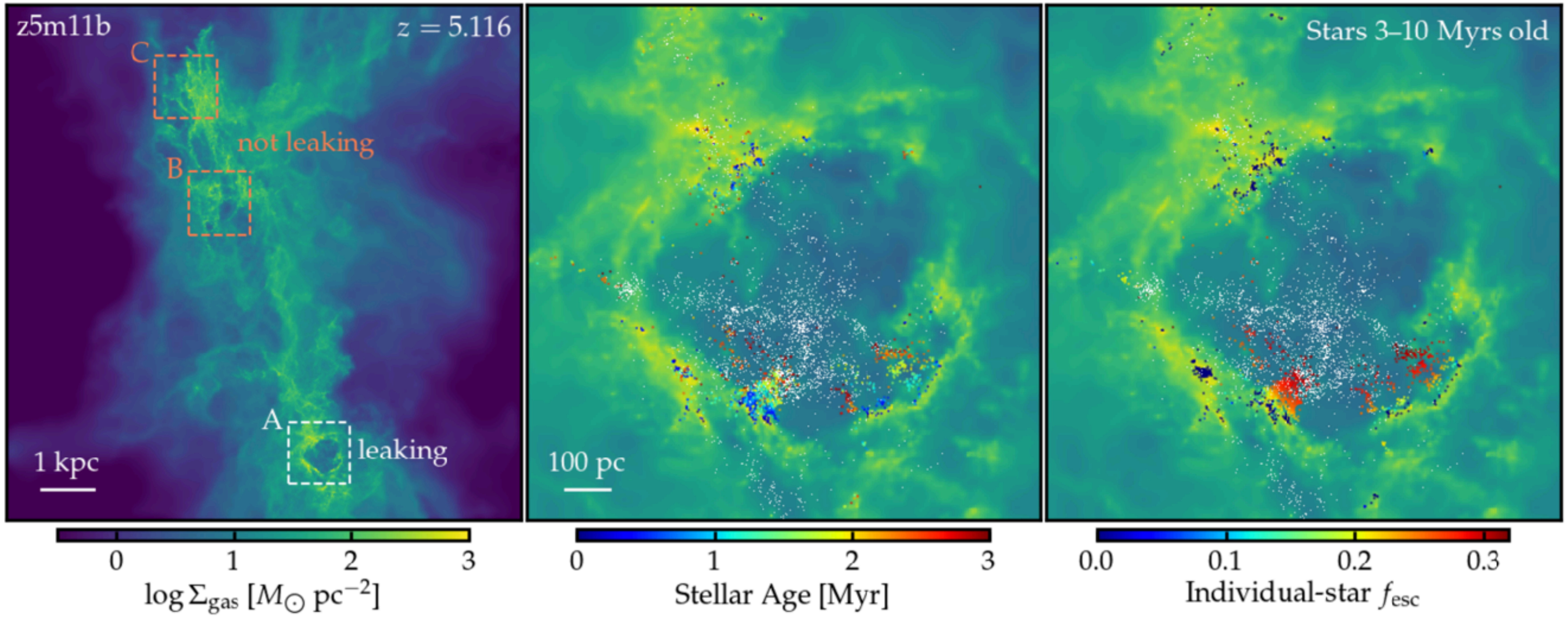
Predicted winds are weaker than in cosmo. simulations.

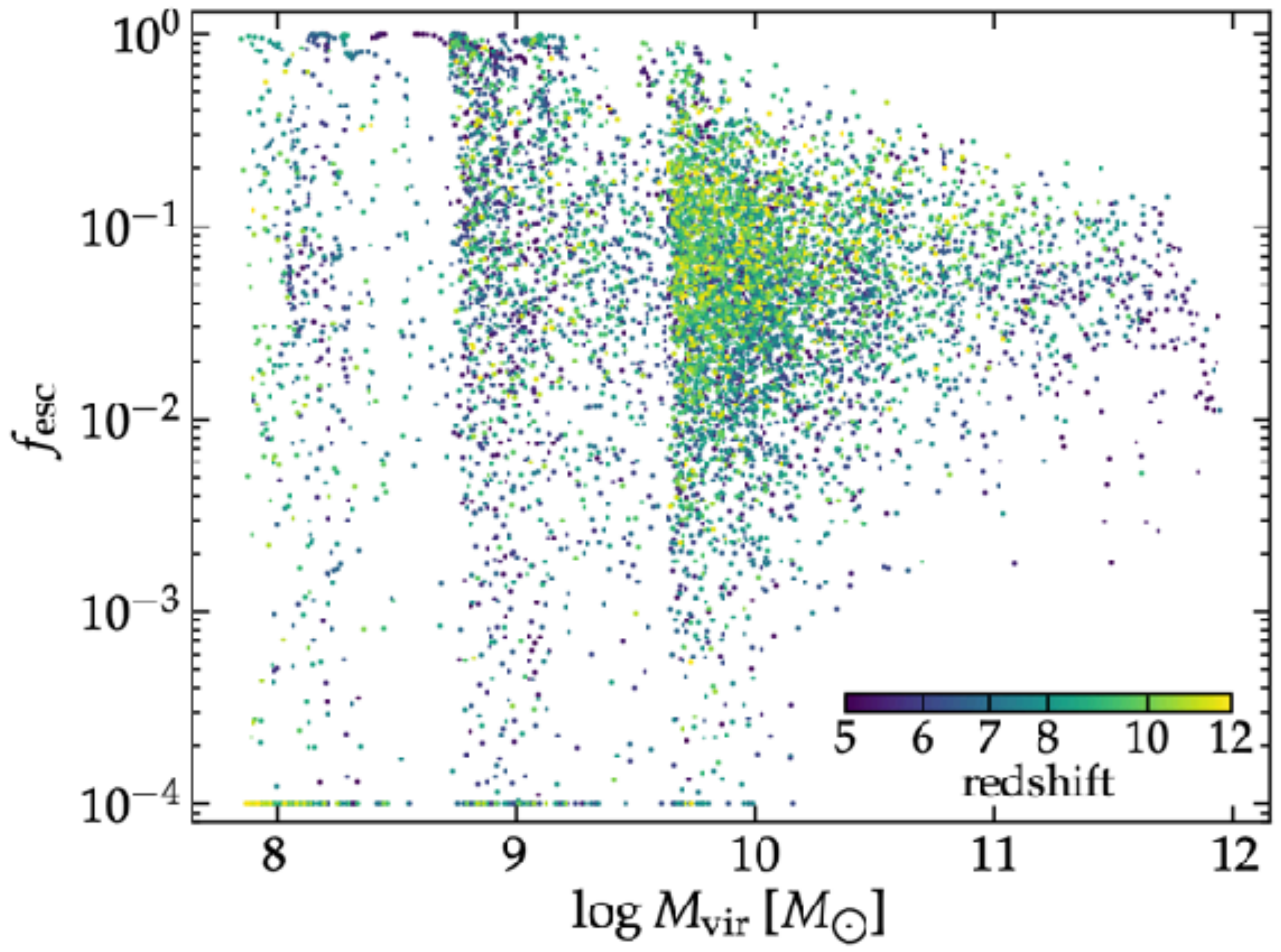
cf. Hill+12; Girichidis+16; Martizzi+16; Gatto+17; Hu+16,17; Li+17; Kim & Ostriker '18

Convergence of resolved sim



Hu '19





$$M_{\rm vir} = 3.7 \times 10^{10}\, M_{\odot}\ (M_{*} = 1.5 \times 10^{8}\, M_{\odot})$$

SPH mass resolution: 100, 900, 1000 $M_{\odot}$

spatial resolution: ~ pc

kpc-scale superbubble

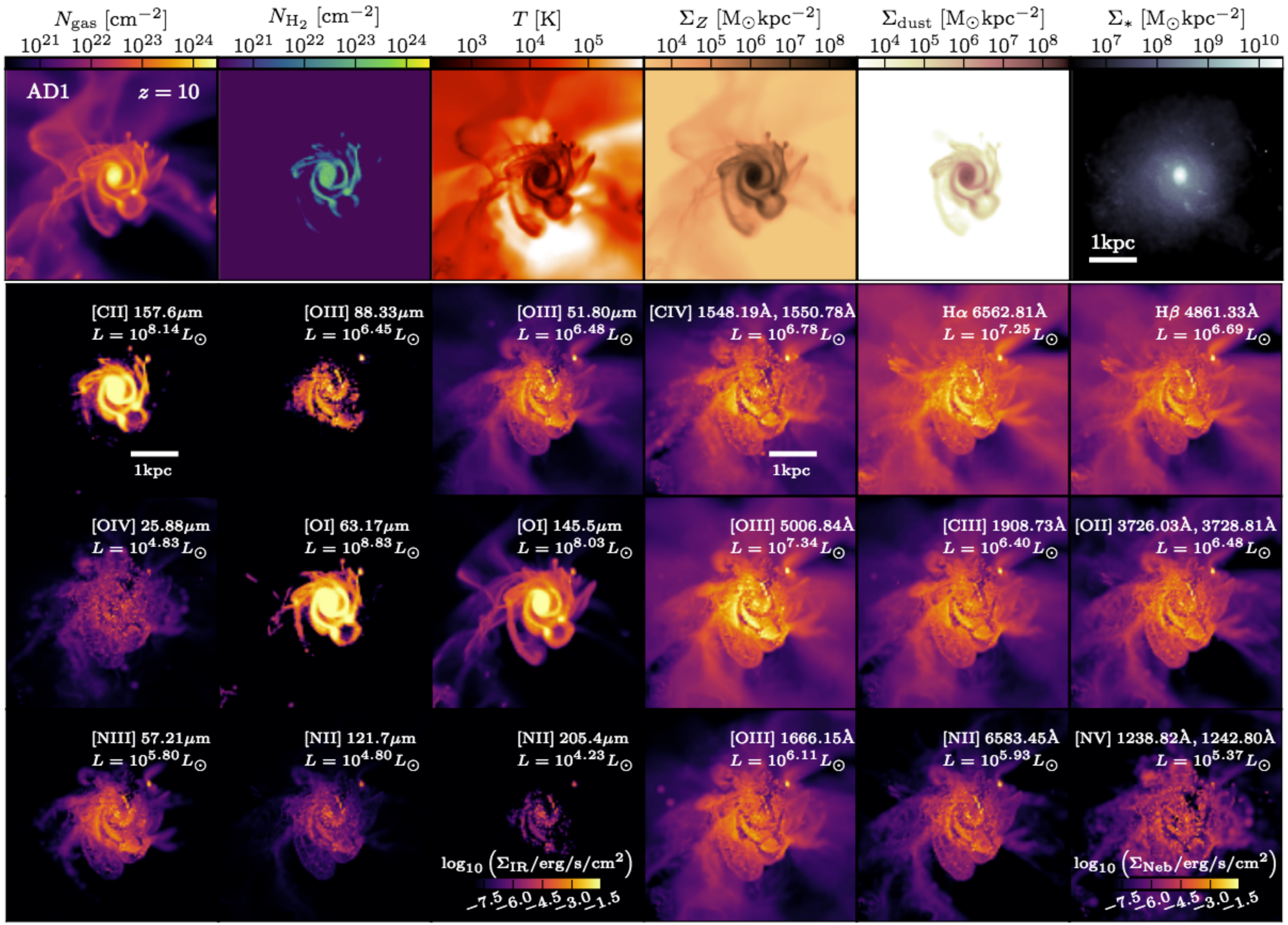
$f_{\rm esc} \sim 0.2$

GIZMO SPH FIRE-2 simulation (Ma+20)

RAMSES-RT SPHINX simulation

Katz+19, 21

- **importance of low-Z CCSN**
- **top-heavy IMF w. reduced [C/O]**
- **[O I] could be useful too.**
- **PDR & clumpy ISM are still unresolved.**



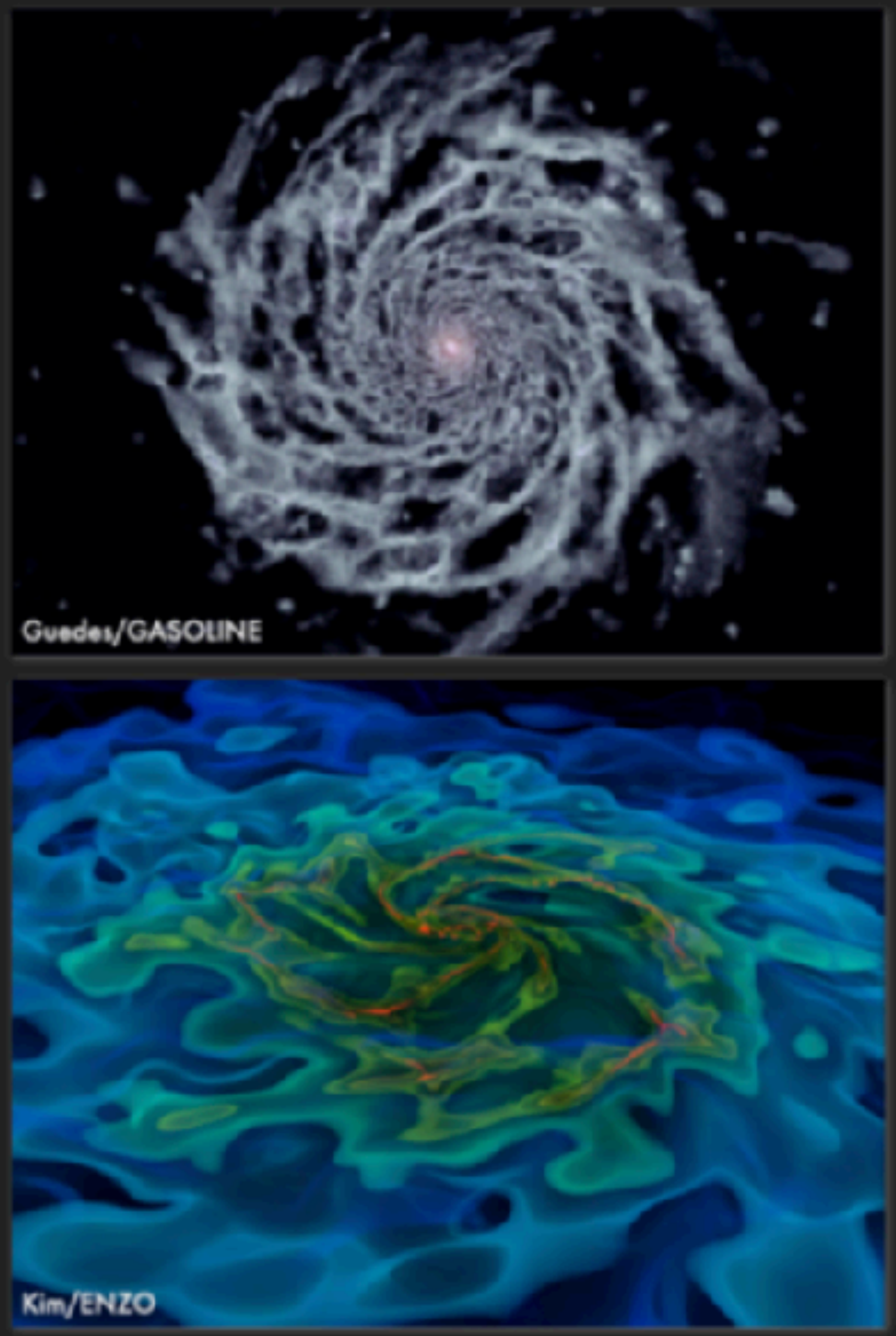
cf. Vallini+15; Pallottini+14,15,17,19; Moriwaki+18; Arata+20 …

AGORA

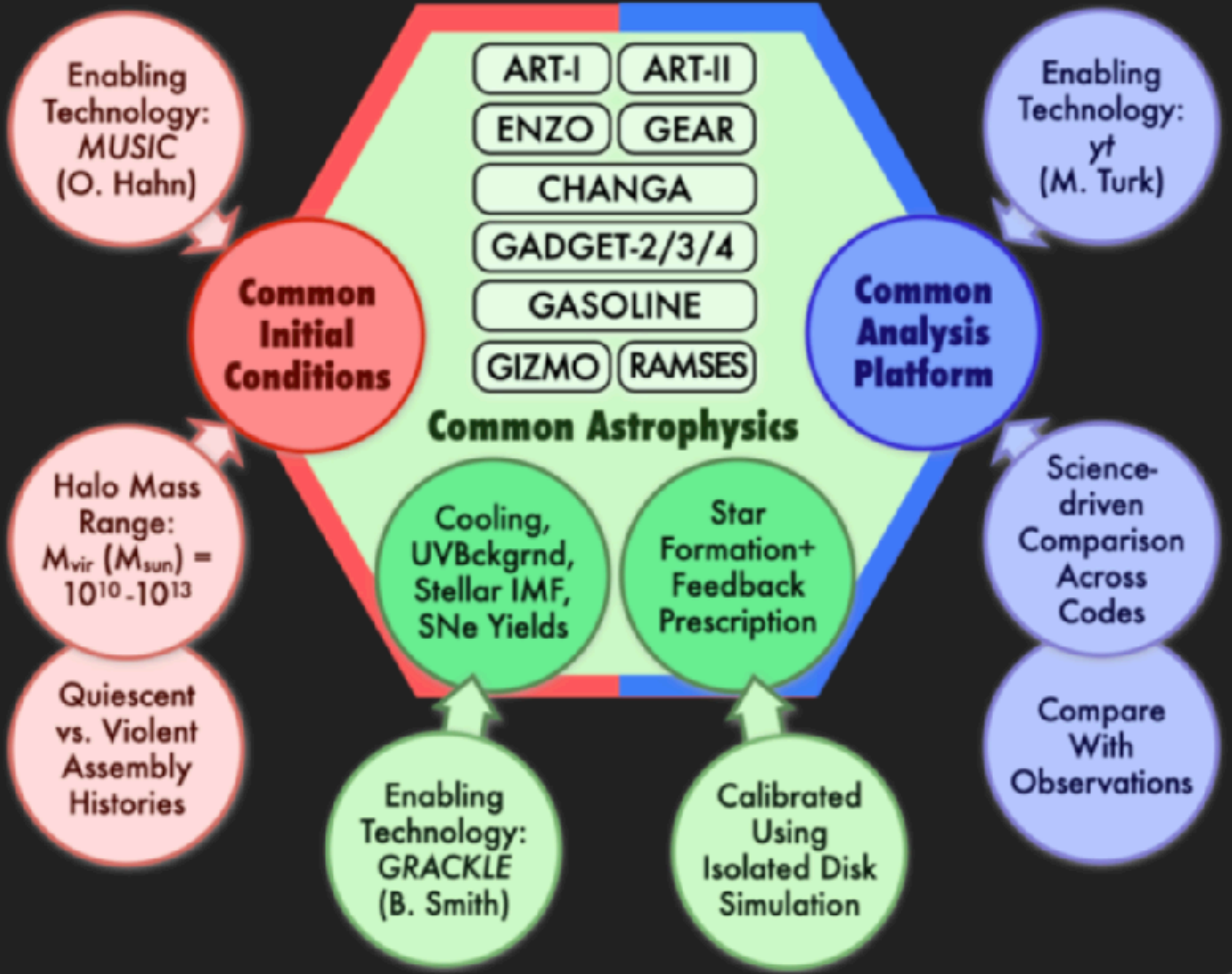
A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

http://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: 160+ participants from 60+ institutions worldwide, representing 9+ codes as of 2021
- DATA SHARING: Simulations outputs and analysis softwares will be shared with the community

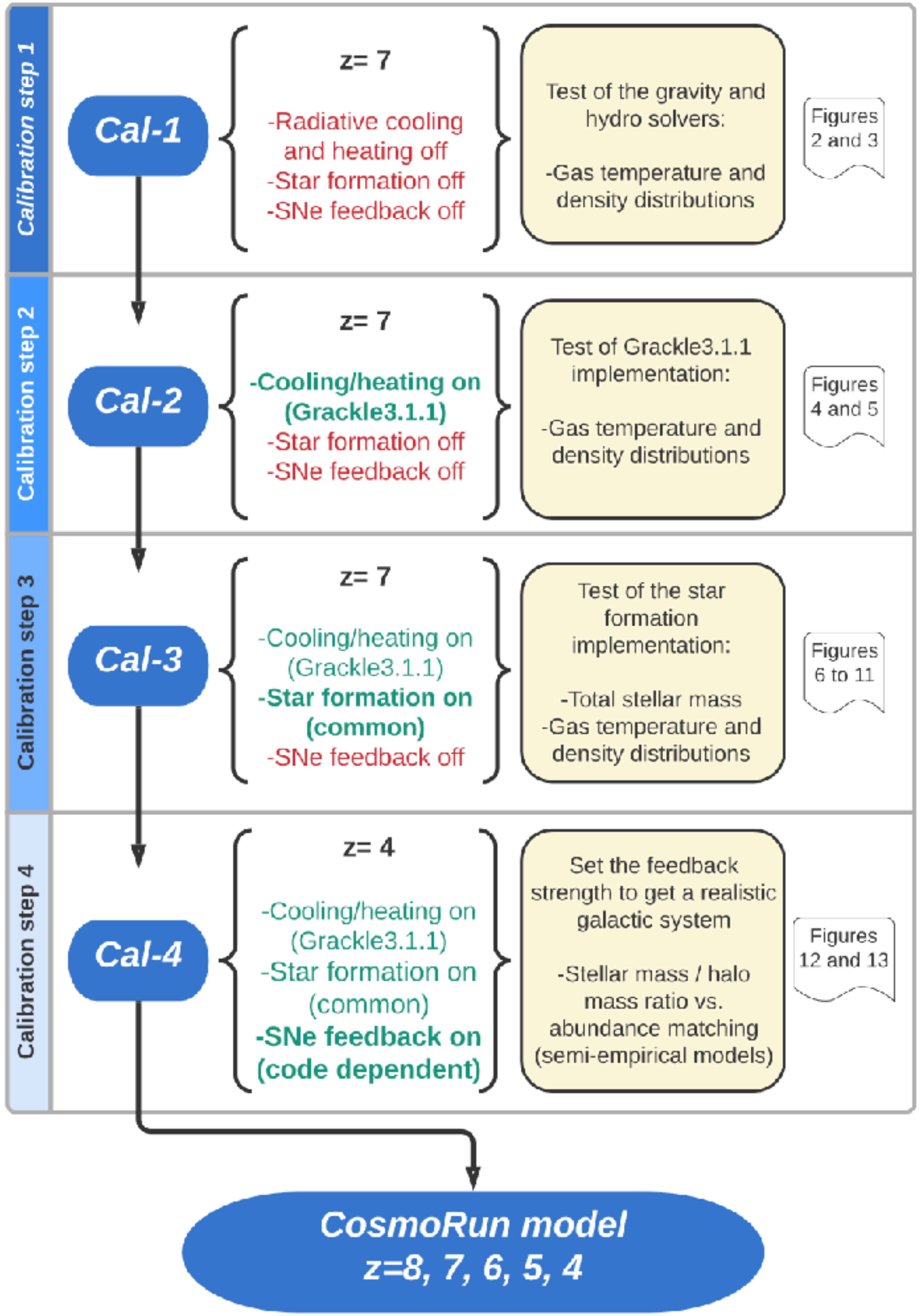
- Contact: santacruzgalaxy@gmail.com
- Flagship paper by J. Kim et al. (2014), 2nd paper by J. Kim et al. (2016), 3rd paper by S. Roca-Fabrega et al. (2021)

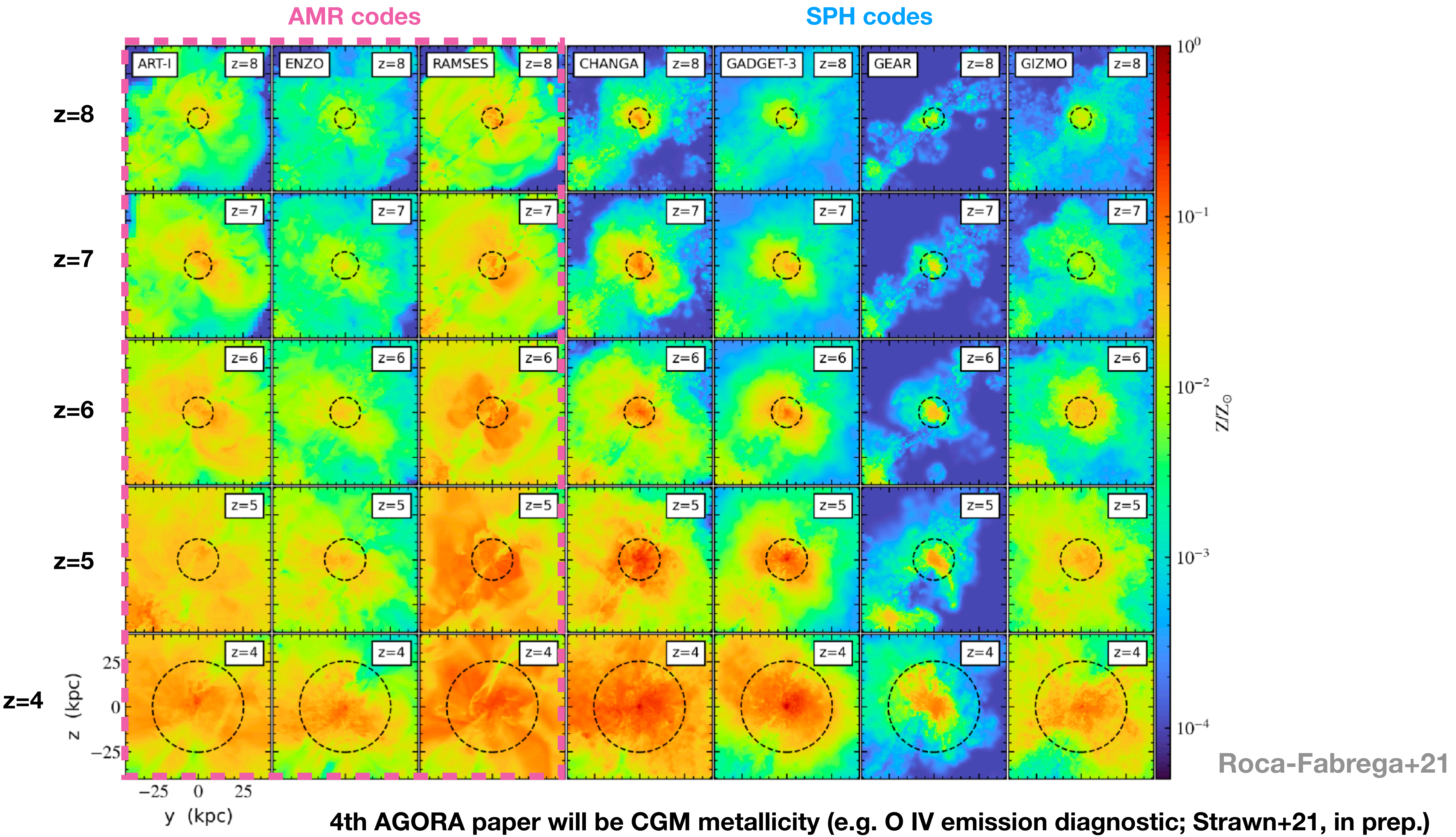
AGORA Paper III: Cosmo-Run

- 4 calibration steps
- only in the 4th step, we turn on our favorite SN feedback model.
- the only constraint: $M_\star \sim (1-5)\times 10^9\, h^{-1} M_\odot$ targeting the abundance matching result at z=4.

Code	Stellar feedback	SN & metal production model	Effective metal yield	Runtime parameters
ART-I	T+K, RP	SN Type Ia/II, AGB stars*	0.033	$E_{\rm thermal} = 2\times10^{51}$ ergs/SN, $p = 3.6\times10^{6}\,{\rm M_\odot\,km\,s^{-1}}$/SN
ENZO	T	SN Type II	0.032	$E_{\rm thermal} = 5\times10^{52}$ ergs/SN
RAMSES	T, DC	SN Type II	0.033	$E_{\rm thermal} = 4\times10^{51}$ ergs/SN, $\sigma_{\rm min} = 100\,{\rm km\,s^{-1}}$, $T_{\rm delay} = 10$ Myr
CHANGA	T+S	SN Type Ia/II, AGB stars**	0.032	$E_{\rm thermal} = 5\times10^{51}$ ergs/SN
GADGET-3	T+K, RP, DC	SN Type Ia/II, AGB stars	0.025	$E_{\rm SN} = 4\times10^{49}$ ergs/$M_\odot$, $T_{\rm delay} = t_{\rm hot}$ (see Section 3.2.5)
GEAR	T, DC	SN Type Ia/II	0.024	$E_{\rm thermal} = 4.5\times10^{51}$ ergs/SN, $T_{\rm delay} = 5$ Myr
GIZMO	T+K	SN Type II	0.033	$E_{\rm SN} = 5\times10^{51}$ ergs/SN

Roca-Fabrega+21



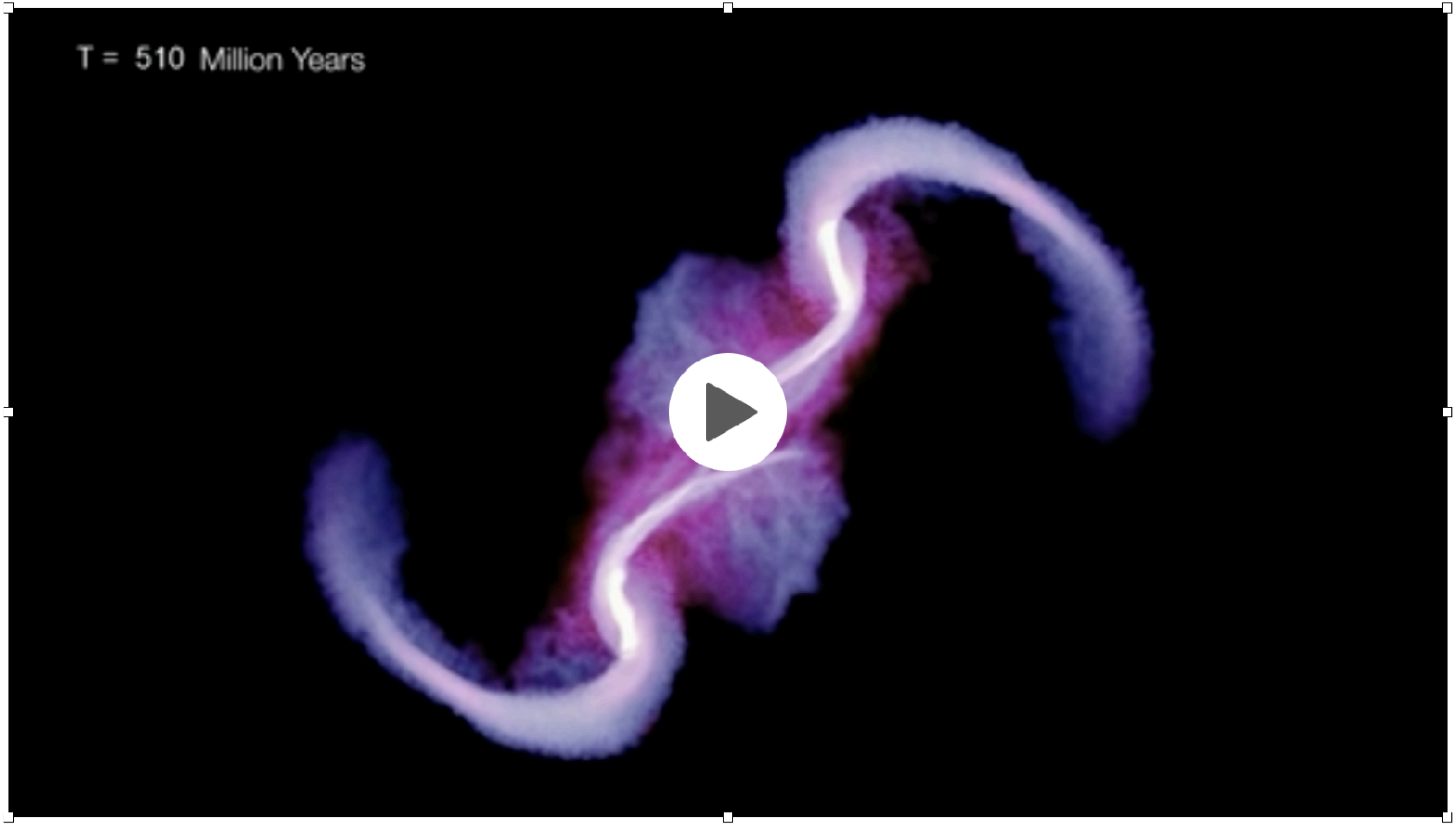


4th AGORA paper will be CGM metallicity (e.g. O IV emission diagnostic; Strawn+21, in prep.)

AGN feedback

(Active Galactic Nuclei)

Violent AGN feedback (quasar mode)



Di Matteo+ '05

AGN feedback efficiency

Bondi-Hoyle-Lyttleton mass accretion rate:

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

Some early work with

$$\alpha \sim 100$$

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

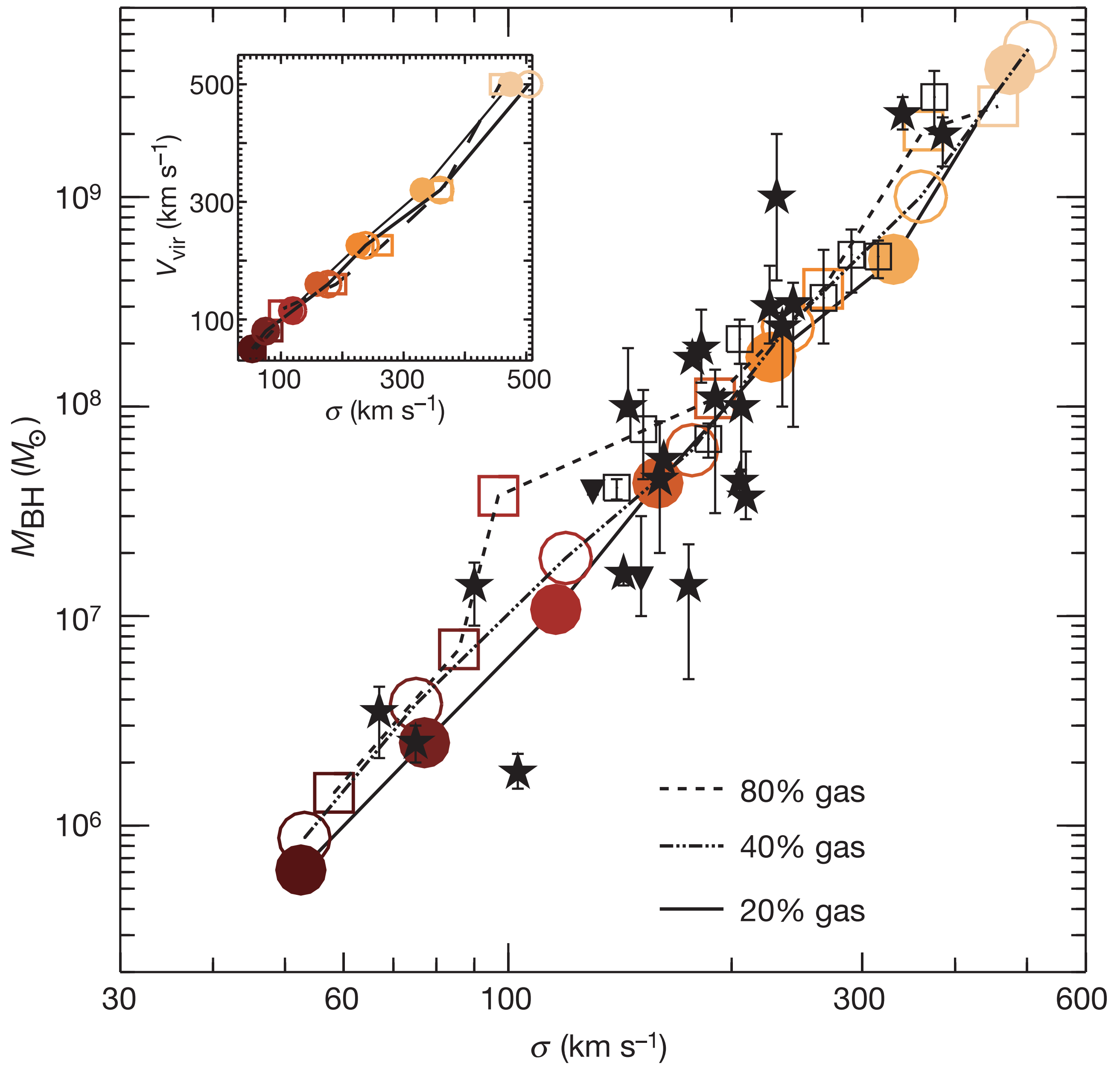
Feedback efficiency $\epsilon_{\rm f}$

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

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

M_{BH}-σ relation



Di Matteo+ '05

AGN feedback energy

Radiative luminosity: $L = \epsilon_r \dot{M}_{acc} c^2 \sim 6 \times 10^{45} \left(\frac{\epsilon_r}{0.1}\right) \left(\frac{\dot{M}_{acc}}{1\, M_\odot\, \mathrm{yr}^{-1}}\right) \mathrm{erg\, s^{-1}}$

Feedback Energy: $E_f = \int \dot{E}_f\, dt = \epsilon_f\, \epsilon_r c^2 \int \dot{M}_{acc} dt$

E.g., growth to 10^8 $M_\odot$ SMBH: $E_f = 2 \times 10^{61} \epsilon_f \left(\frac{\epsilon_r}{0.1}\right) \left(\frac{M_{BH}}{10^8\, M_\odot}\right) \mathrm{erg}$ (cumulative feedback energy)

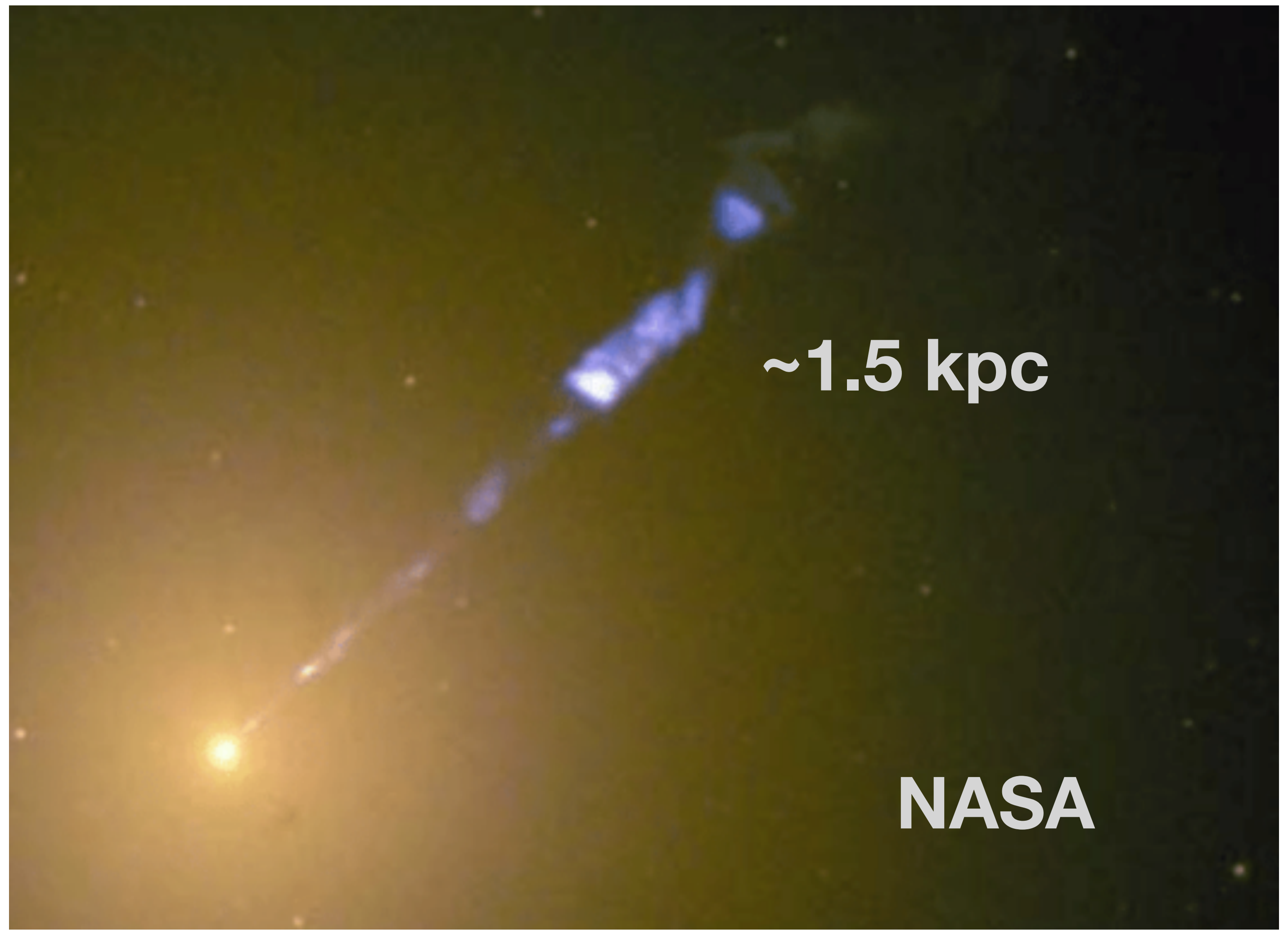
Bulge potential energy: $\mathrm{E_{bulge}} \sim M_{\mathrm{bulge}}\, \sigma_*^2 \sim 2 \times 10^{59} \left(\frac{M_{\mathrm{bulge}}}{10^{11} M_\odot}\right) \left(\frac{\sigma_*}{300\, \mathrm{km\, s^{-1}}}\right)^2 \mathrm{erg}$

So, $\epsilon_f > 0.01$ can give $E_f > E_{\mathrm{bulge}}$

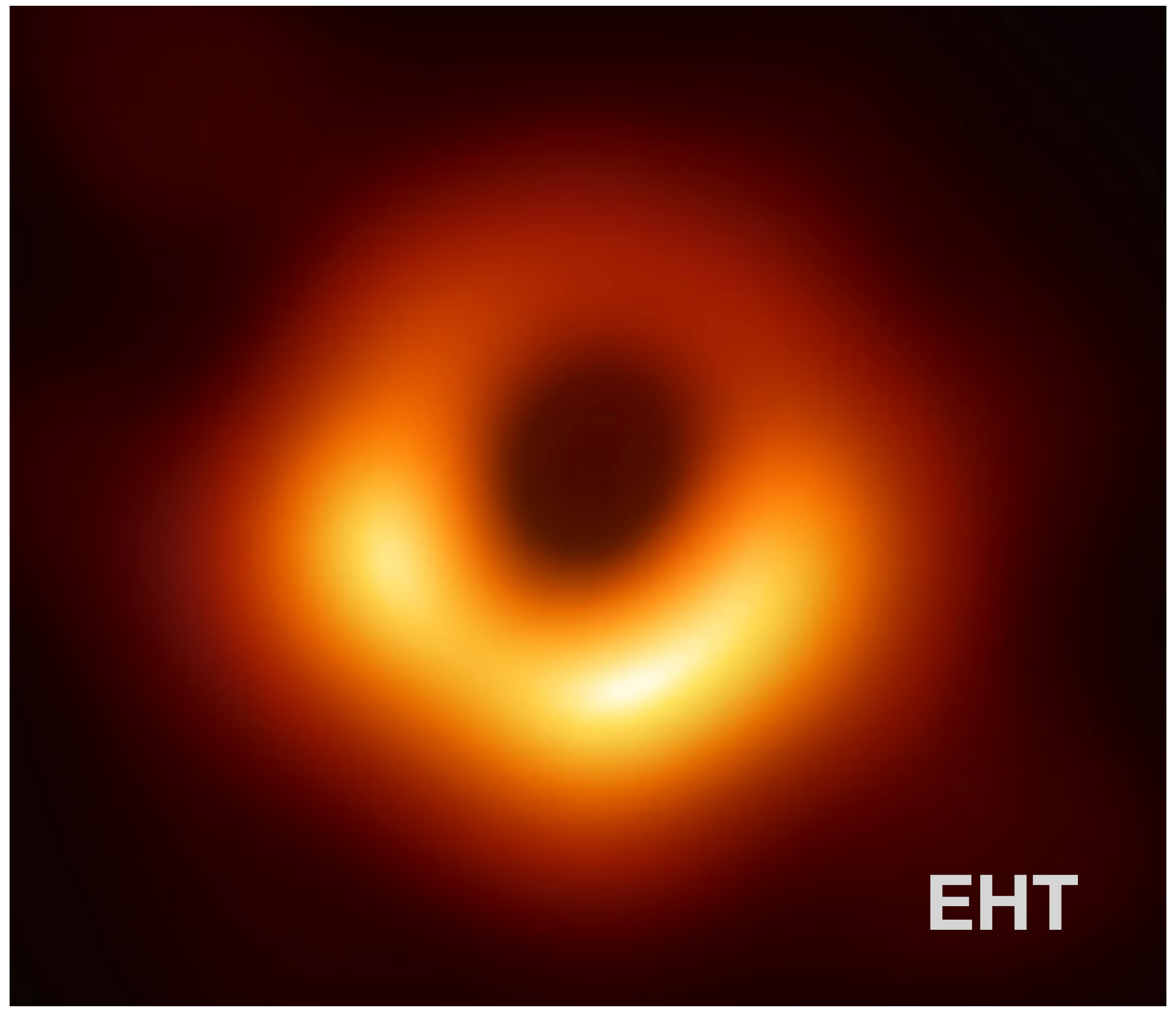
$\frac{M_{\mathrm{bulge}}}{M_{\mathrm{BH}}} \sim 10^{-3}$

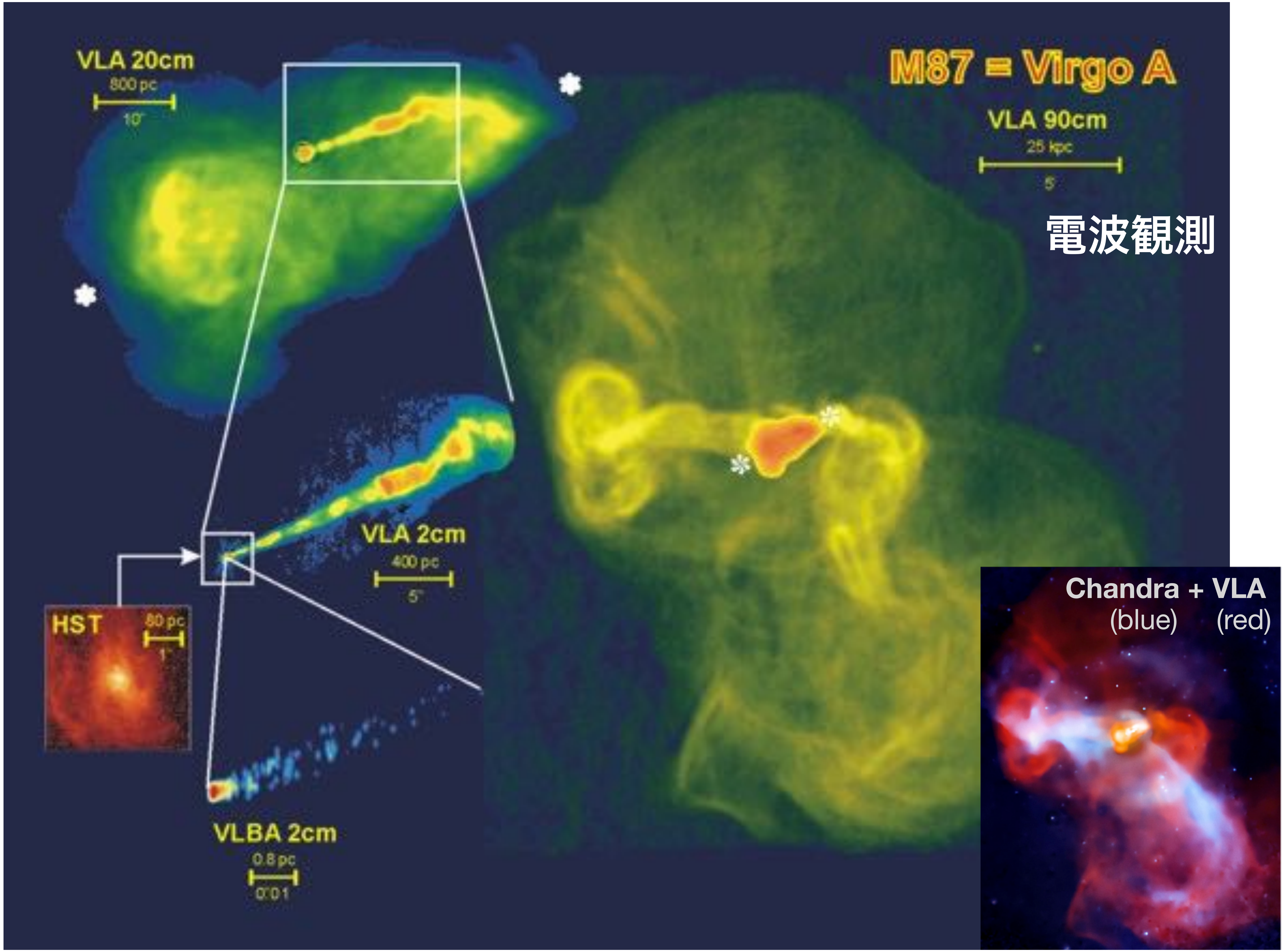
Ferrarese & Meritt '00

AGN jet



$$M_{\mathrm{BH}} \sim 6.5 \times 10^9 M_\odot$$

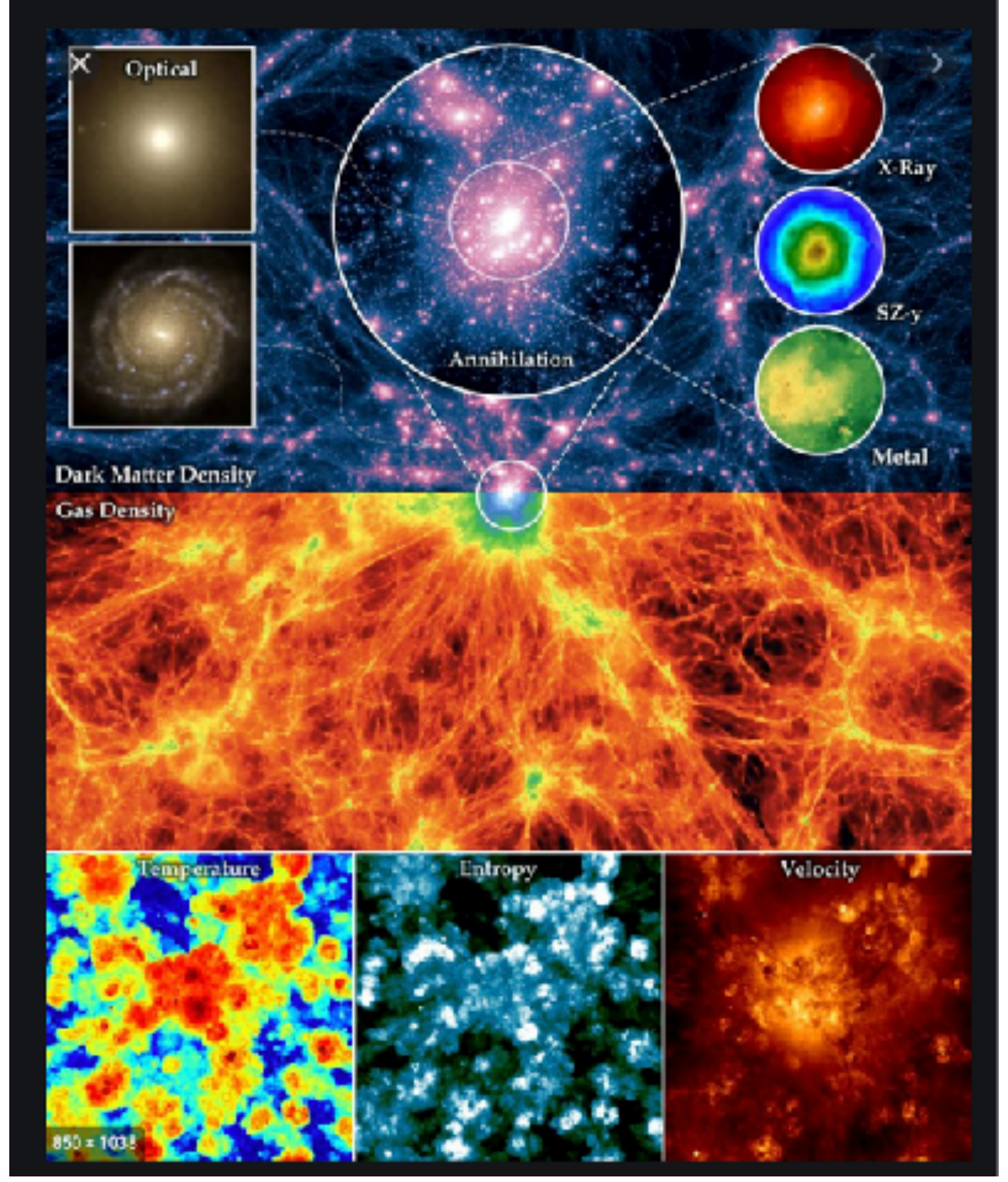




https://www.sciencesource.com/archive/Supergiant-Elliptical-Galaxy--M87--NGC-4486-SS2712619.html

IllustrisTNG

AREPO code — voronoi tessellation



Two-mode AGN feedback model

Eddington-limited accretion: $\dot{M} = \min\left(\dot{M}_{\rm Bondi}, \dot{M}_{\rm Edd}\right),$

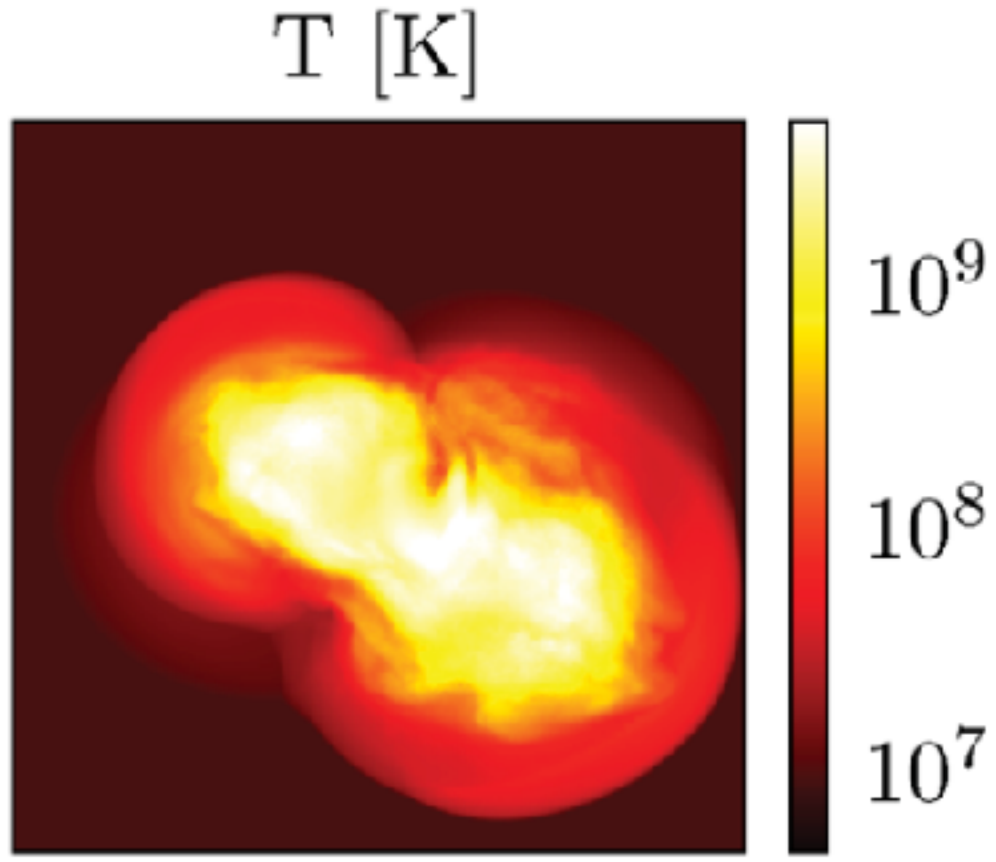
$$\dot{M}_{\rm Bondi} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{c_s^3}, \qquad \dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_{\rm T}} c,$$

Eddington ratio threshold

$$\chi = \min\left[0.002\left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^2, 0.1\right],$$

high → $\dot{E}_{\rm therm} = 0.02\,\dot{M}\,c^2,$ thermal (quasar) mode

low → $\dot{E}_{\rm kin} = \epsilon_{f,\rm kin}\,\dot{M}\,c^2,$ kinetic (jet) mode (maintenance mode)



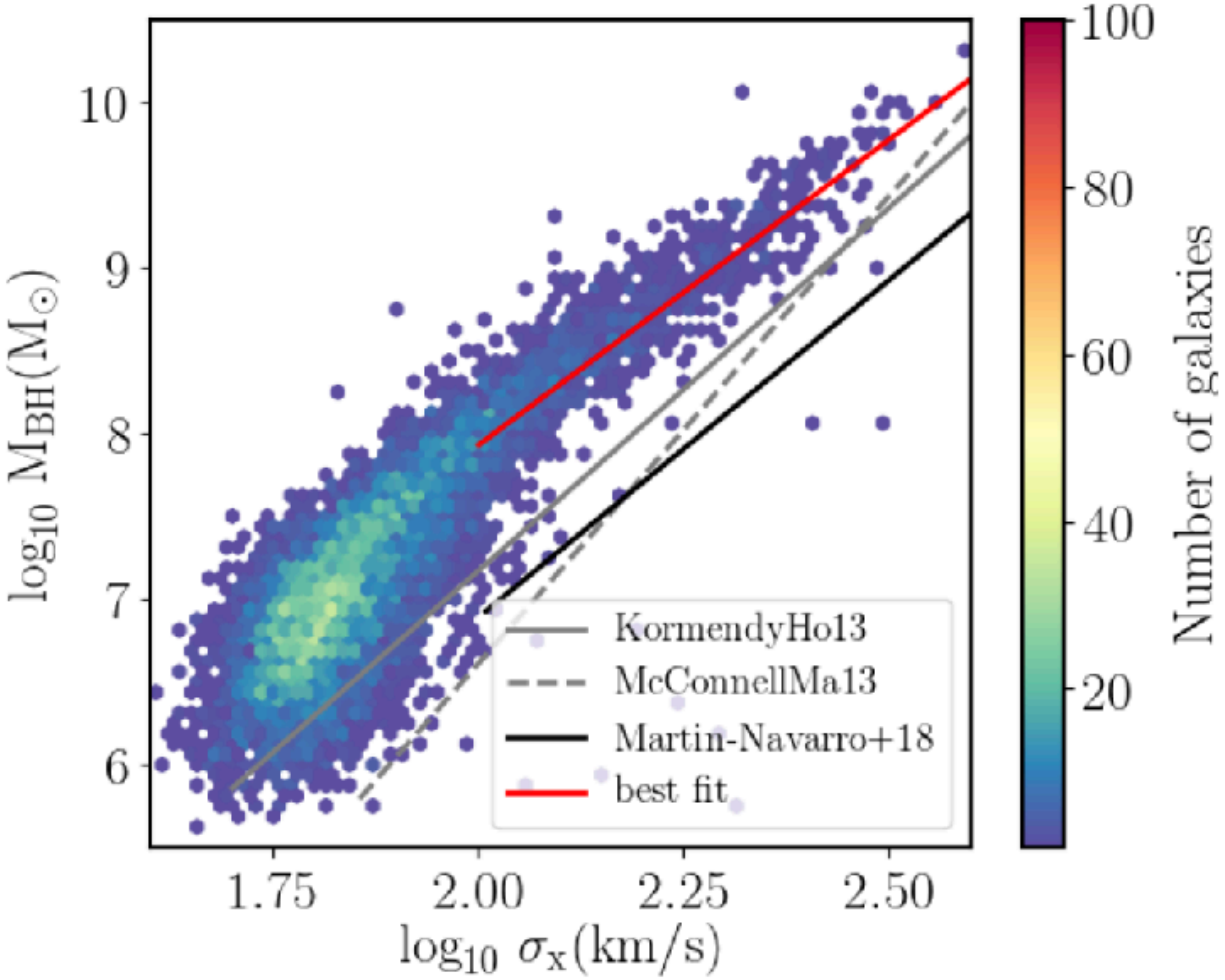
$$\epsilon_{f,\rm kin} = \min\left(\frac{\rho}{0.05\,\rho_{\rm SFthresh}}, 0.2\right),$$

weaker coupling in low-ρ environment

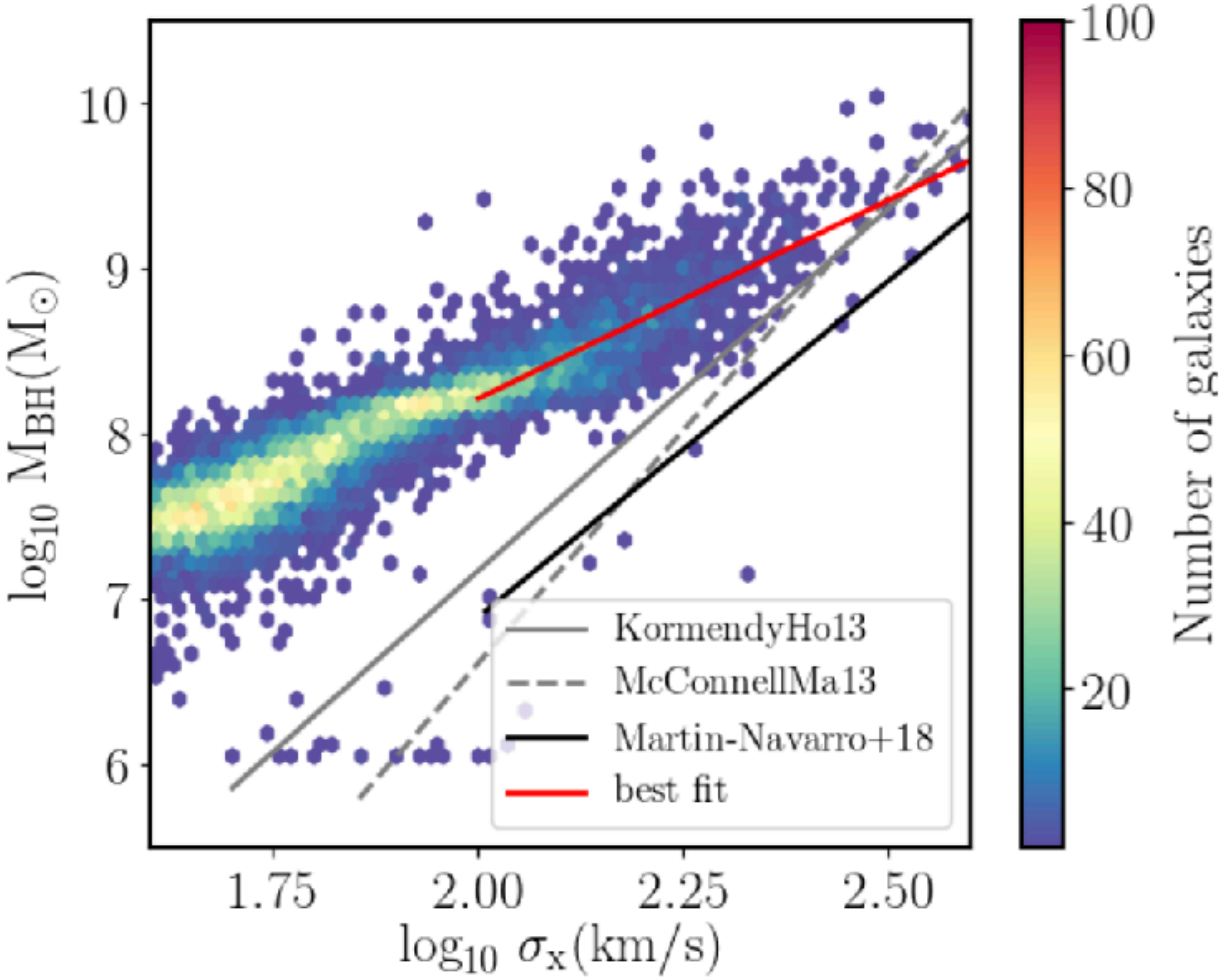
Weinberger+'18

M_{BH} — σ relation

Illustris **(M_{seed} ~ 10^5 $M_\odot/h$)**



TNG **(M_{seed} ~ 10^6 $M_\odot$)**

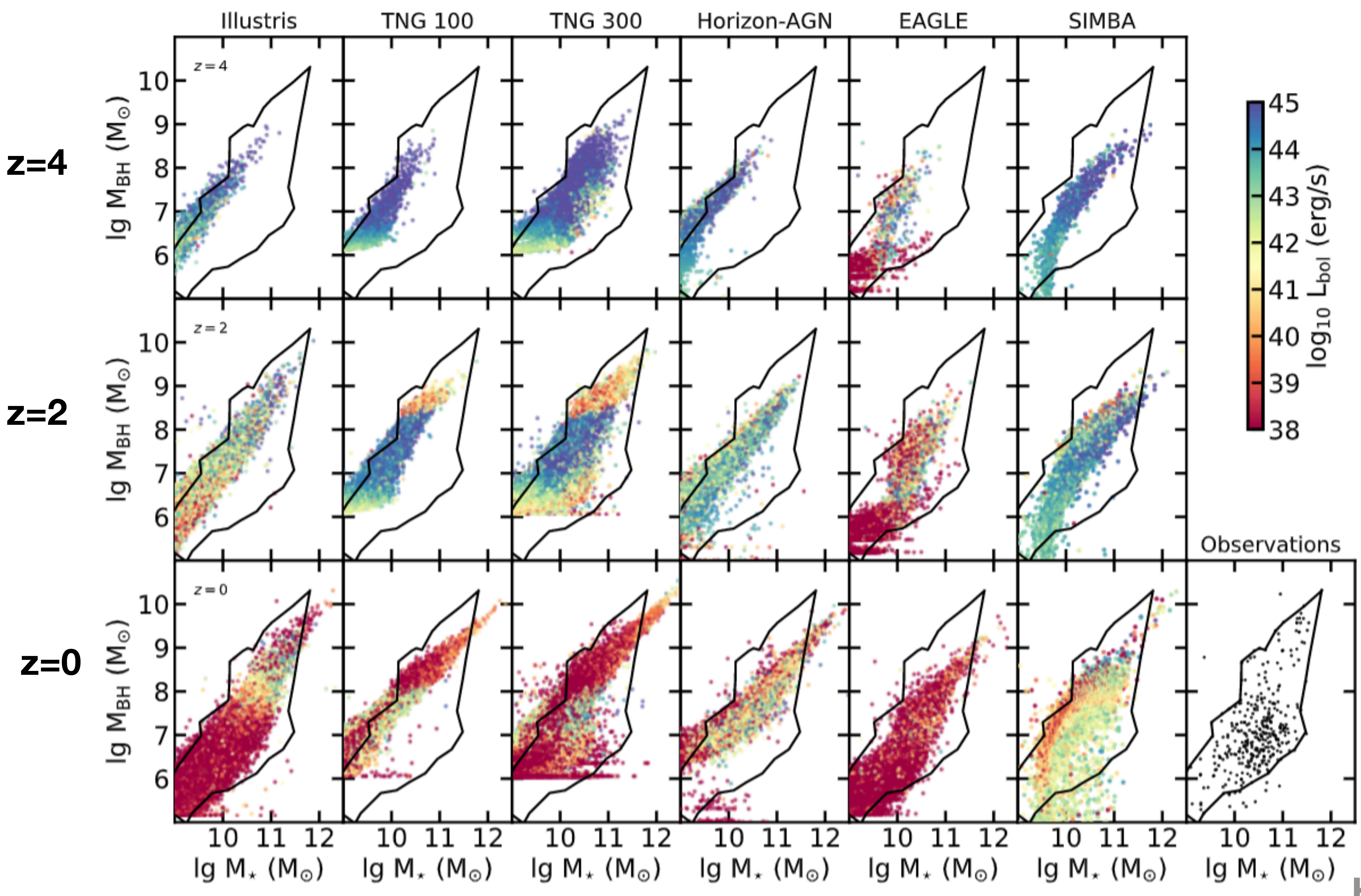


Too small σ in simulations?

Or, too massive seed + too efficient growth?

Li+'19

(at low-mass end)



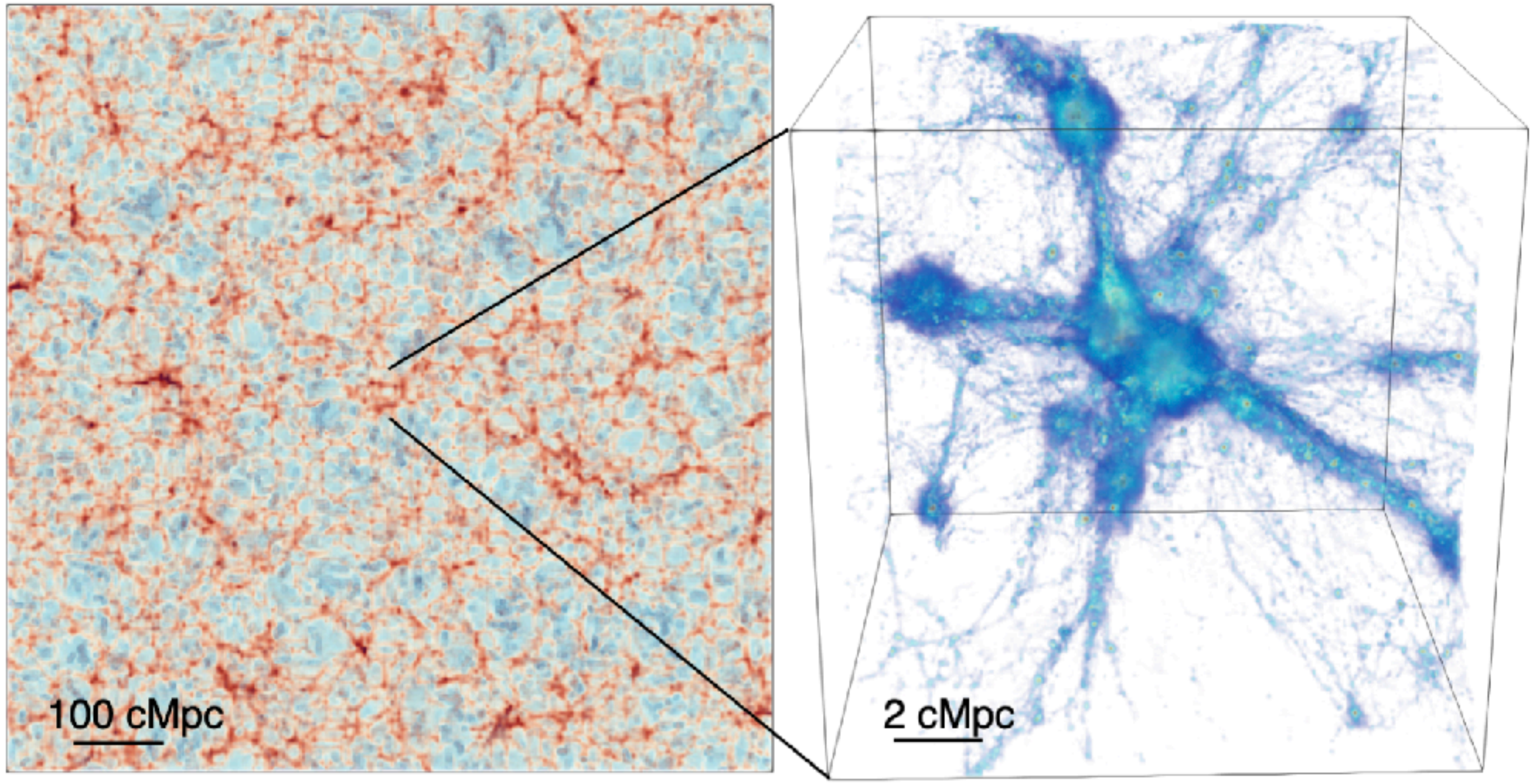
Illustris
TNG 100
TNG 300
Horizon-AGN
EAGLE
SIMBA
z=4
z=2
z=0
z = 4
z = 2
z = 0
lg M_BH (M_⊙)
lg M_⋆ (M_⊙)
log10 L_bol (erg/s)
Observations

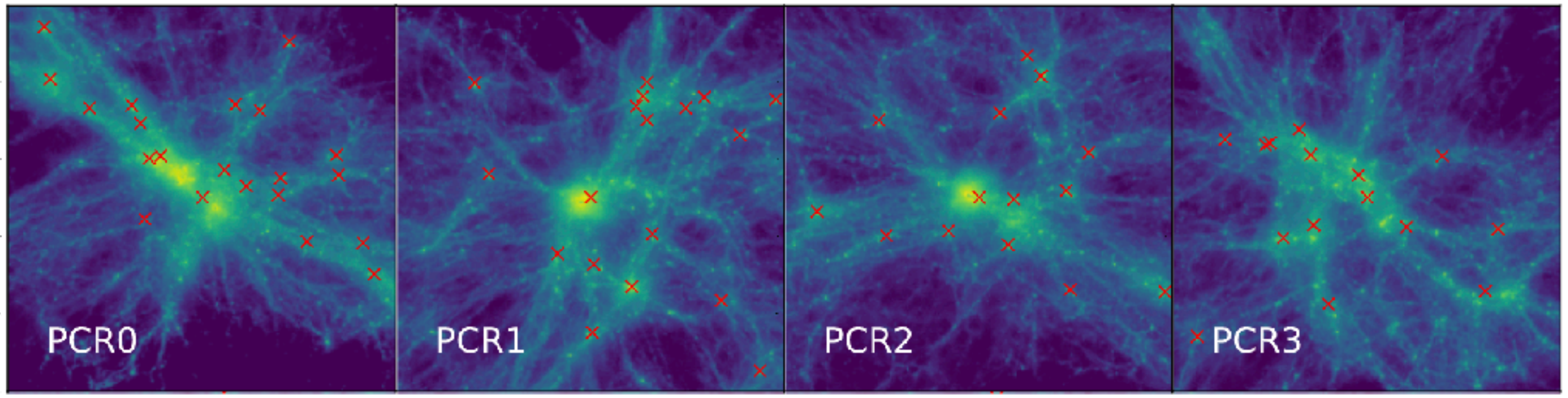
Habouzit+21

	Illustris	TNG100	TNG300	Horizon-AGN	EAGLE	SIMBA
Cosmology						
Ω_Λ	0.7274	0.6911	0.6911	0.728	0.693	0.7
Ω_m	0.2726	0.3089	0.3089	0.272	0.307	0.3
Ω_b	0.0456	0.0486	0.0486	0.045	0.0483	0.048
σ_8	0.809	0.8159	0.8159	0.81	0.8288	0.82
n_s	0.963	0.9667	0.9667	0.967	0.9611	0.97
H_0 (km s^{-1} Mpc^{-1})	70.4	67.74	67.74	70.4	67.77	68
Resolution						
Box side length (cMpc)	106.5	110.7	302.6	142.0	100.0	147.1
Dark matter mass reso. (M$_\odot$)	6.26×10^6	7.5×10^6	5.9×10^7	8×10^7	9.7×10^6	9.6×10^7
Baryonic mass reso. (M$_\odot$)	1.26×10^6	1.4×10^6	1.1×10^7	2×10^6	1.81×10^6	1.82×10^7
Spatial resolution (pkpc)	0.71	0.74	1.48	1.0	0.7	
Gravitational softening (ckpc)	1.4	1.48 ($z \geqslant 1$) /0.74 pkpc	2.96 ($z \geqslant 1$) /1.48 pkpc		2.66 ($z \geqslant 2.8$) / max 0.7 pkpc	0.74
Baryonic softening (ckpc)	1.4 ckpc ($z \geqslant 1$) /0.7 pkpc	1.48 ($z \geqslant 1$) /0.74 pkpc	2.96 ($z \geqslant 1$) /1.48 pkpc		2.66 ($z \geqslant 2.8$) / max 0.7 pkpc	
Seeding						
BH seed mass (M$_\odot$)	1.42×10^5	1.18×10^6	1.18×10^6	10^5	1.48×10^5	1.49×10^5
Seeding prescriptions	$M_h/M_\odot \geqslant 7.1 \times 10^{10}$	$M_h/M_\odot \geqslant 7.4 \times 10^{10}$	$M_h/M_\odot \geqslant 7.4 \times 10^{10}$	$n \geqslant 0.1$ H/cm^3 $\sigma \geqslant 100$ km/s	$M_h/M_\odot \geqslant 1.48 \times 10^{10}$	$M_\star/M_\odot > 10^{9.5}$
Radiative efficiency ϵ_r	0.2	0.2	0.2	0.1	0.1	0.1
Accretion						
Model	Bondi	Bondi + mag. field	Bondi + mag. field	Bondi	Bondi + visc.	Bondi + torques
Boost factor	$\alpha = 100$	-	-	density-dependent	-	$\alpha = 0.1$
SN feedback						
Model	kinetic	kinetic	kinetic	kinetic/thermal	thermal	kinetic
AGN feedback						
Single or 2 modes	2 modes	2 modes	2 modes	2 modes	single mode	2 modes
High acc rate model	isotropic thermal	isotropic thermal	isotropic thermal	isotropic thermal	isotropic thermal	kinetic
Feedback efficiency	$0.05 \times 0.2 = 0.01$	$0.1 \times 0.2 = 0.02$	$0.1 \times 0.2 = 0.02$	$0.15 \times 0.1 = 0.015$	$0.1 \times 0.15 = 0.015$	$0.03 \times 0.1 = 0.003$
Low acc rate model	thermal hot bubble	pure kinetic winds	pure kinetic winds	kinetic bicanonical winds	-	kinetic/ X-ray
Feedback efficiency	$0.35 \times 0.2 = 0.07$	$\leqslant 0.2 \times 0.2 = 0.04$	$\leqslant 0.2 \times 0.2 = 0.04$	$1 \times 0.1 = 0.1$	-	$0.3 \times 0.1 = 0.03$
Transition btw. modes	$f_{Edd} = 0.05$	$\min\left(0.002 \left(\frac{M_{BH}}{10^8\,M_\odot}\right)^2, 0.1\right)$	$\min\left(0.002 \left(\frac{M_{BH}}{10^8\,M_\odot}\right)^2, 0.1\right)$	0.01	-	0.2

Habouzit+21

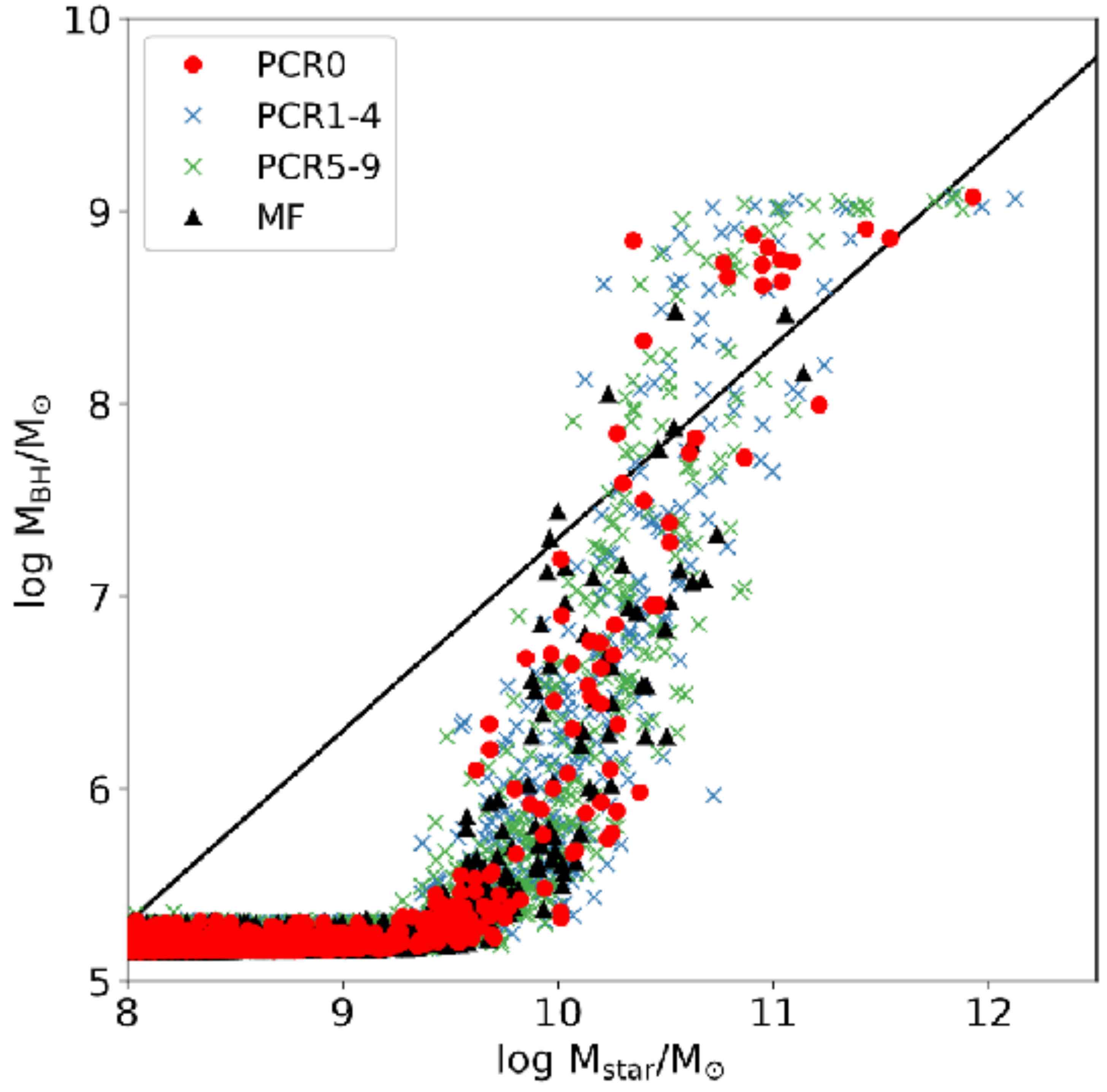
FOREVER22 project

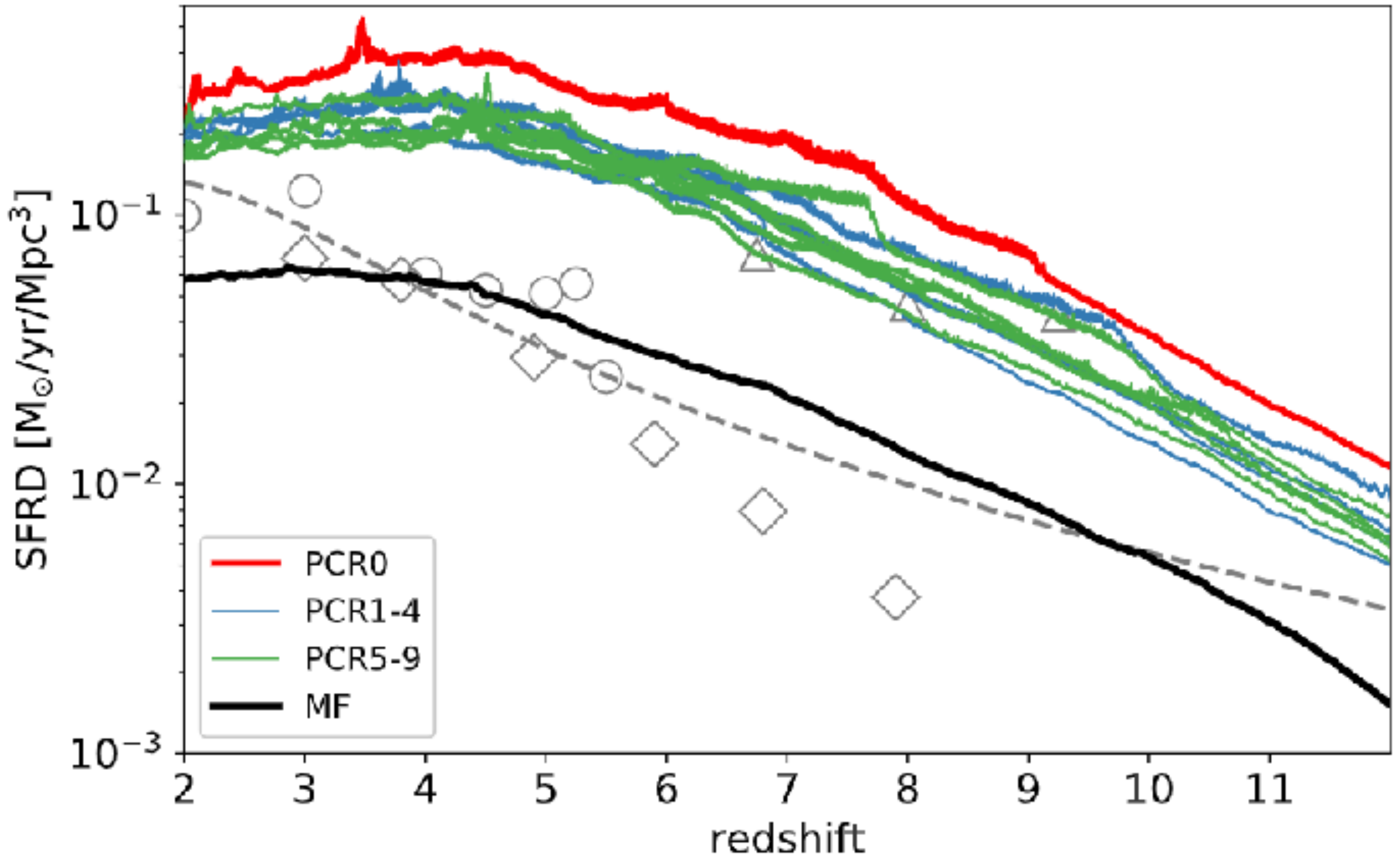




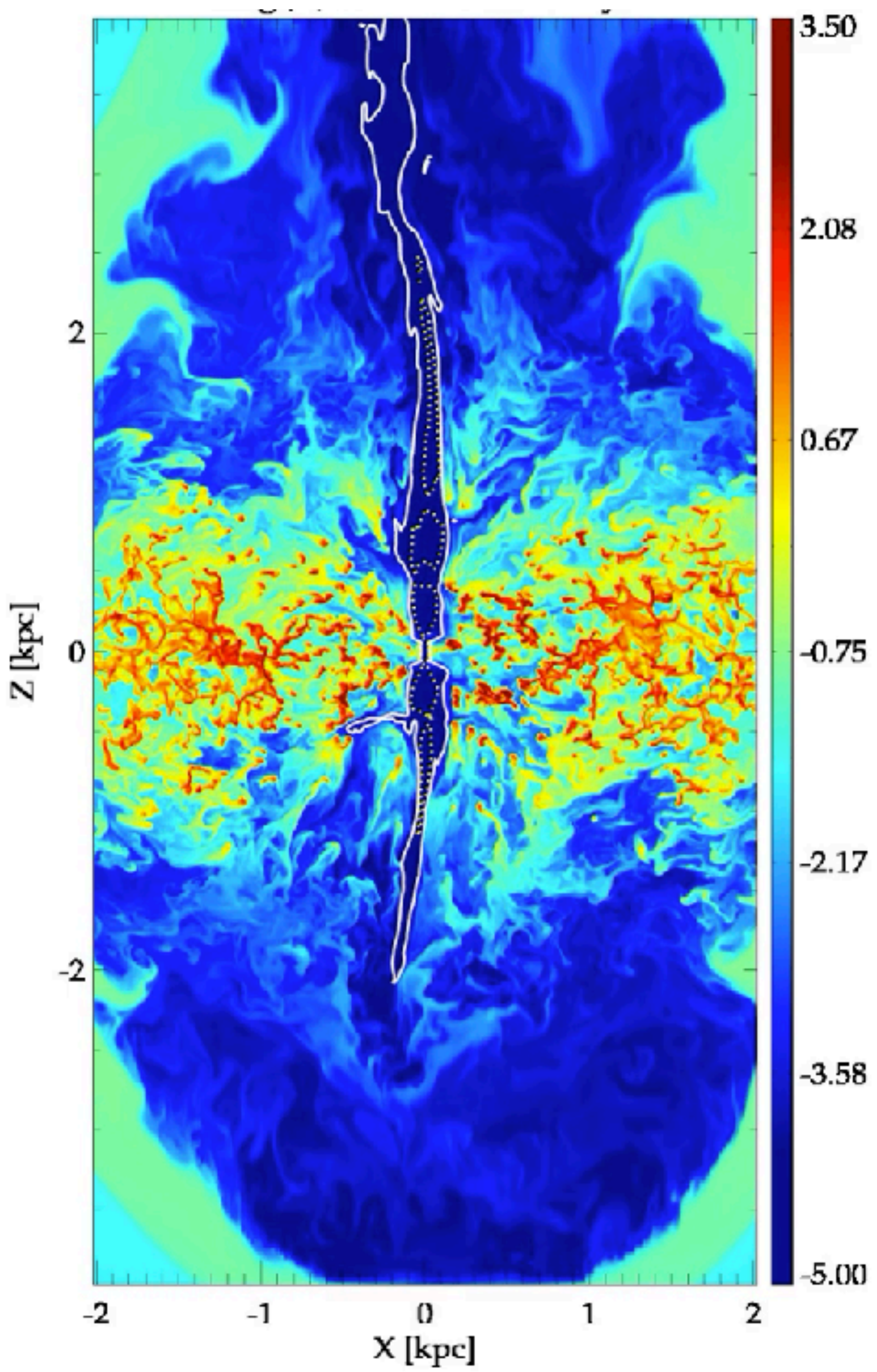
z=3 10 cMpc PCR regions

Yajima+21

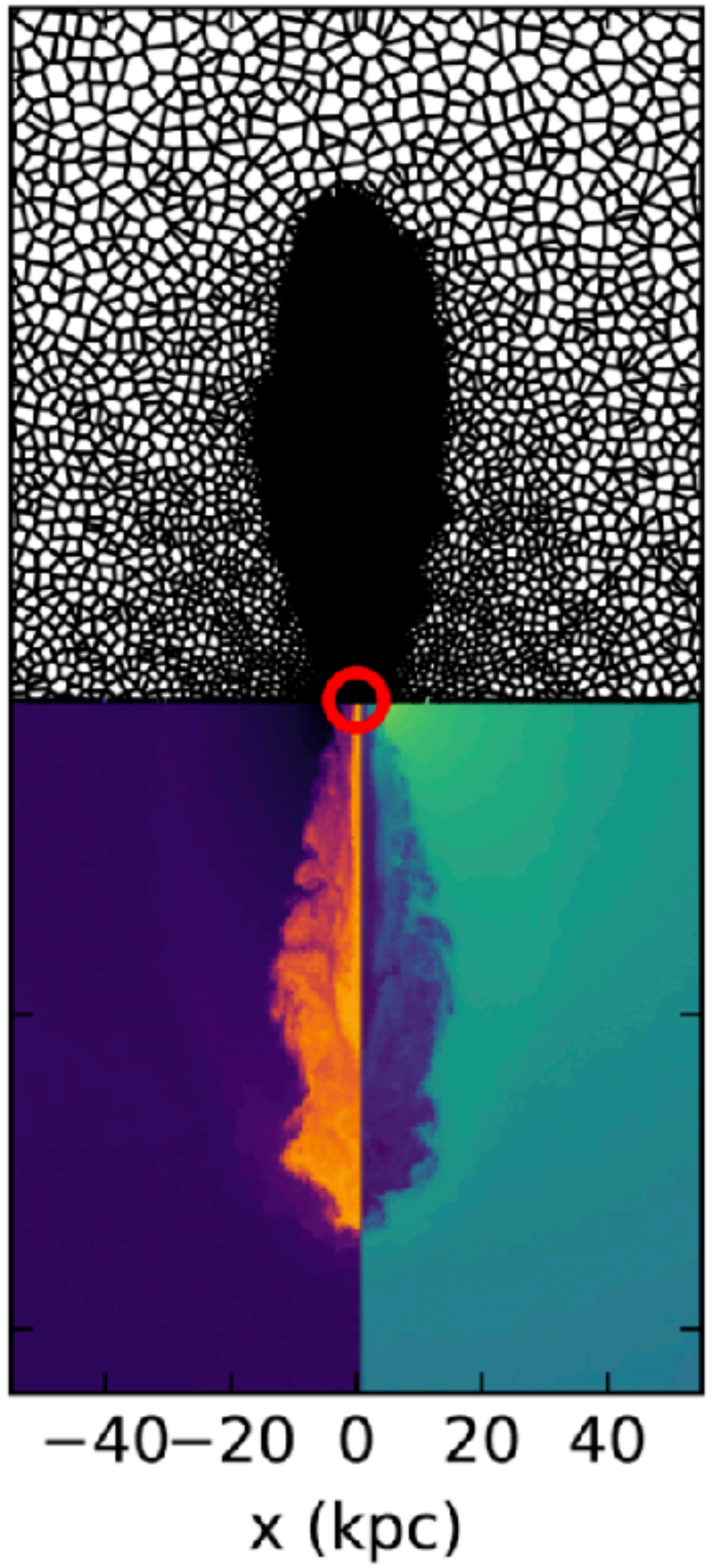




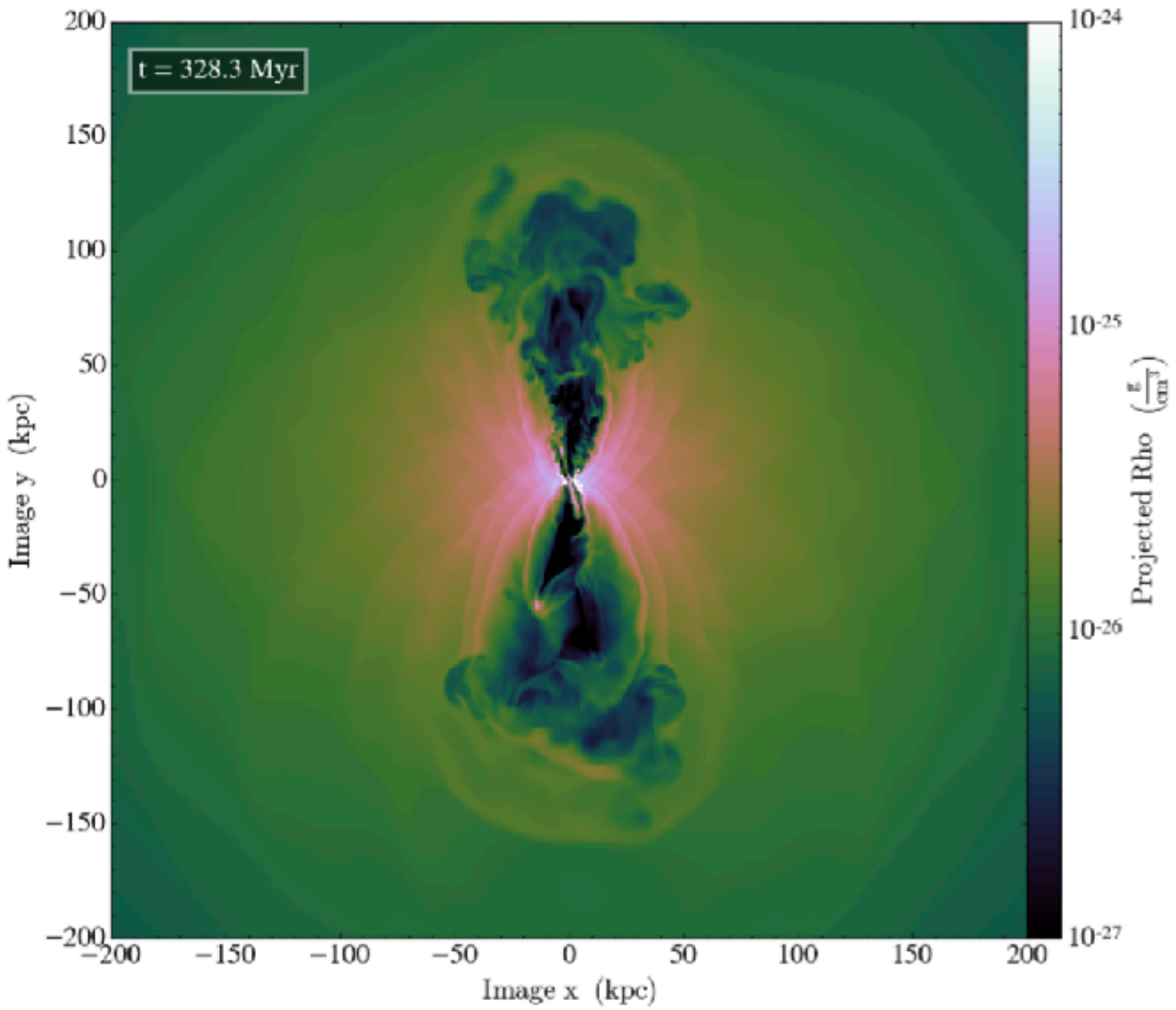
High-res. jet models



Mukherjee, Wagner+18
Jet-ISM interaction



Bourne & Sijacki '17
AREPO



Martizzi+19 ~200 pc
Athena

cf. 大須賀さんtalk

CR feedback

(Cosmic Ray)

CR feedback

- non-thermal component — comparable *E*-density to E_{th}, E_{mag}, E_{turb}
- transport mechanism, interaction with EM waves — coupling with thermal plasma
  (e.g. Zweibel '13,17; Amato & Blasi'18)
- Sources of scattering? — streaming instability, background turbulence
  —> CR m.f.p. Kulsrud & Pearce'69 Yan & Lazarian '02
- Confine, and isotropize the CR distribution
- Can provide significant pressure in CGMs
- Earlier work: effective diffusion, grey, steady approximations

Analytic: Ipavich '75; Boulares & Cox 90; Breitschwerdt+91; Everett+08; Socrates+08; Mao & Ostriker'18; ….

Simulation: Booth+13; Pakmor+16; Ruszkowski+17; Wiener+17; Chan+19; Hopkins+20; Ji+20; Su+20; Hopkins+21; ….

FIRE-2 MHD sim. + CR — w. diffusion, streaming

in dwarf, L* galaxies

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \otimes \boldsymbol{v} + P_T \mathbb{I} - \boldsymbol{B} \otimes \boldsymbol{B}) = 0,$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot [(\rho e + P_T)\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}] = P_{\rm cr} \nabla \cdot \boldsymbol{v} + \Gamma_{\rm st} + S_{\rm g} - \Gamma_{\rm g},$$

cooling

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\mathbf{v} \otimes \boldsymbol{B} - \boldsymbol{B} \otimes \mathbf{v}) = 0,$$

$$\frac{\partial e_{\rm cr}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\rm cr} = \boldsymbol{v} \cdot \nabla P_{\rm cr} - \Gamma_{\rm st} + S_{\rm cr} - \Gamma_{\rm cr},$$

CR loss

$P_{\rm T}$ **: total pressure (thermal + magnetic + CR)**

$P_{\rm cr} = (\gamma_{\rm cr} - 1)\, e_{\rm cr}$ **CR pressure**

$\Gamma_{\rm st} = -\boldsymbol{v}_{\rm st} \cdot \nabla P_{\rm cr}$ (>0) **Streaming loss**

$$(c_s^2)_{\rm eff} = \partial P / \partial \rho = (c_s^2)_{\rm gas} + \gamma_{\rm cr} P_{\rm cr}/\rho,$$

$\gamma_{\rm cr} = 4/3$

$$\boldsymbol{F}_{\rm cr} = (e_{\rm cr} + P_{\rm cr})(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) + \boldsymbol{F}_{\rm di}$$

CR energy flux

advection & streaming

$$\boldsymbol{F}_{\rm di} = -\kappa \hat{\boldsymbol{B}} \otimes \hat{\boldsymbol{B}} \cdot \nabla e_{\rm cr}$$

pure diffusion (zeroth moment)

(—> later expanded to "two moment")

κ : **effective diffusion coefficient**

Lagrangian, finite-volume form:

$$\frac{DE_{\rm cr}}{Dt} = -\int_\Omega d^3\boldsymbol{x} \left\{ P_{\rm cr}(\nabla \cdot \boldsymbol{v}) + \Gamma_{\rm st} + \nabla \cdot \tilde{\boldsymbol{F}}_{\rm cr} \right\},$$

adiabatic term

$$\tilde{\boldsymbol{F}}_{\rm cr} \equiv \boldsymbol{F}_{\rm cr} - \boldsymbol{v}(e_{\rm cr} + P_{\rm cr}) = \boldsymbol{v}_{\rm st}(e_{\rm cr} + P_{\rm cr}) + \boldsymbol{F}_{\rm di}.$$

$$E^i_{\rm cr} = \int_{\Omega_i} e_{\rm cr}\, d^3\boldsymbol{x}$$

conserved total CR energy

Chan+19

CR energy injection: $\Delta E_{\rm cr} = \epsilon_{\rm cr} E_{\rm SNe}$

$\epsilon_{\rm cr}$ (=0.1, default)

$$\boldsymbol{F}_{\rm cr} \to \boldsymbol{F}_{\rm cr} + \Delta \boldsymbol{F}_{\rm cr}$$

$$\Delta \boldsymbol{F}_{\rm cr} = \Delta e_{\rm cr}\, \tilde{c}\, \hat{\boldsymbol{r}}$$

Hadronic & Coulomb losses:

$$\Gamma_{\rm cr} = \tilde{\Lambda}_{\rm cr}\, e_{\rm cr}\, n_{\rm n} = (\tilde{\Lambda}_{\rm cr,had} + \tilde{\Lambda}_{\rm cr,\,Cou})\, e_{\rm cr}\, n_{\rm n}$$
$$= 5.8 \times 10^{-16}\,(1 + 0.28\, x_e) \left(\frac{e_{\rm cr}}{\rm erg\, cm^{-3}}\right) \left(\frac{n_{\rm n}}{\rm cm^{-3}}\right) \;{\rm erg\, cm^{-3} s^{-1}},$$

(Volk+96; Ensslin+97; Guo & Oh '08)

Volumetric gas heating:

$$S_{\rm gas} = 0.98 \times 10^{-16}\,(1 + 1.7\, x_e) \left(\frac{e_{\rm cr}}{\rm erg\, cm^{-3}}\right) \times \left(\frac{n_{\rm n}}{\rm cm^{-3}}\right) {\rm erg\, cm^{-3}\, s^{-1}}.$$

Update CR flux as

$$\boldsymbol{F}_{\rm cr} \to \boldsymbol{F}_{\rm cr}(1 - \tilde{\Lambda}_{\rm cr}\, n_{\rm n} \Delta t).$$

Rather than setting $\tilde{\boldsymbol{F}}_{\rm cr} = -\kappa\, \nabla e_{\rm cr}$,

2-moment method: explicitly solve

$$\frac{1}{\tilde{c}^2}\left[\frac{\partial \tilde{\boldsymbol{F}}_{\rm cr}}{\partial t} + \nabla \cdot (\boldsymbol{v} \otimes \tilde{\boldsymbol{F}}_{\rm cr})\right] + \nabla_{\parallel} P_{\rm cr} = -\frac{(\gamma_{\rm cr}-1)}{\kappa^*}\, \tilde{\boldsymbol{F}}_{\rm cr},$$

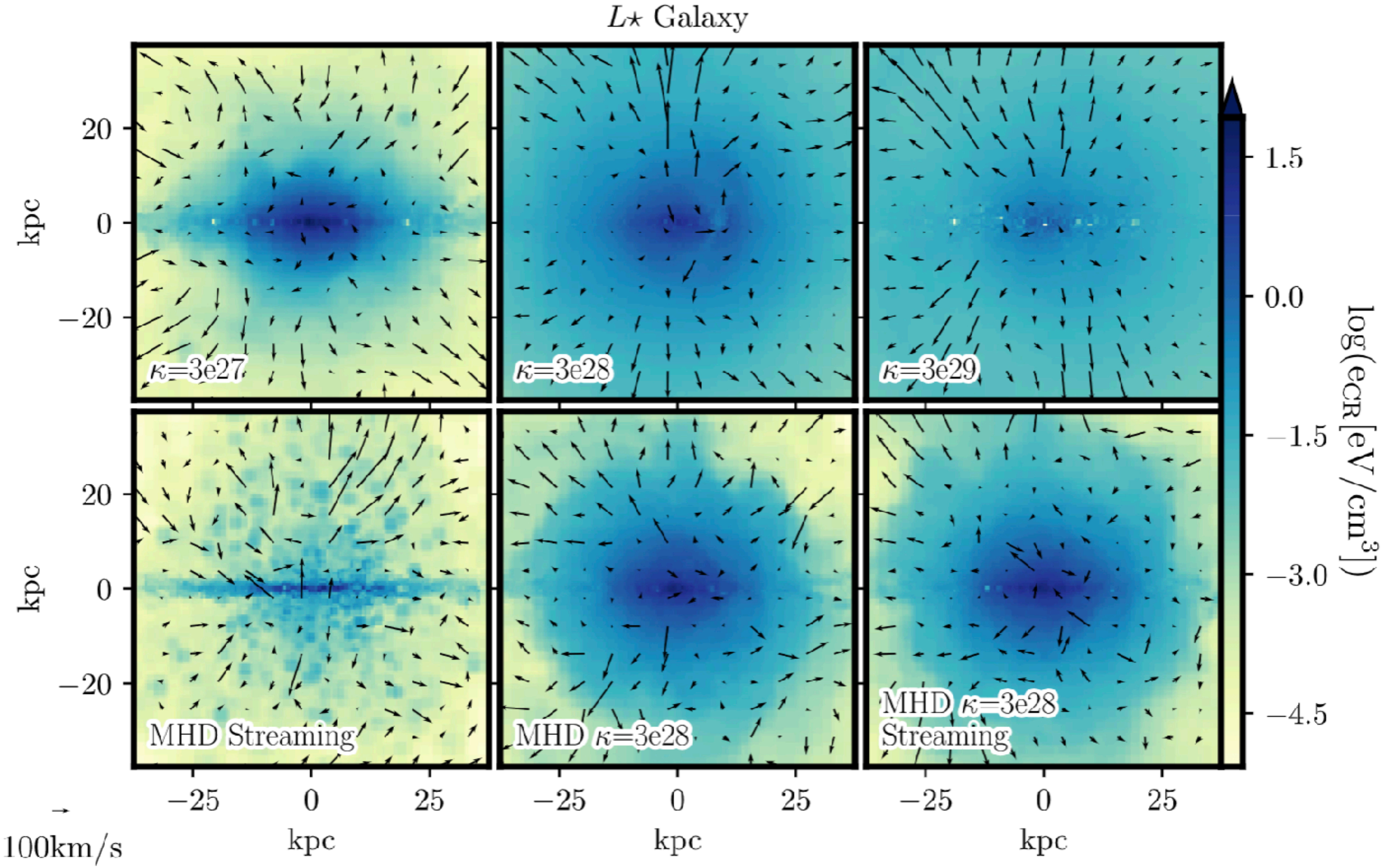
$$\nabla_{\parallel} P_{\rm cr} \equiv \hat{\boldsymbol{B}} \otimes \hat{\boldsymbol{B}} \cdot \nabla P_{\rm cr},$$

Composite parallel (B-field aligned) diffusion coeff:

$$\kappa^* = \kappa + \frac{v_{\rm st}(e_{\rm cr} + P_{\rm cr})}{|\hat{\boldsymbol{B}} \cdot \nabla e_{\rm cr}|},$$

(Snodin+06; Jiang & Oh '08; Thomas & Pfrommer '19)

Chan+19



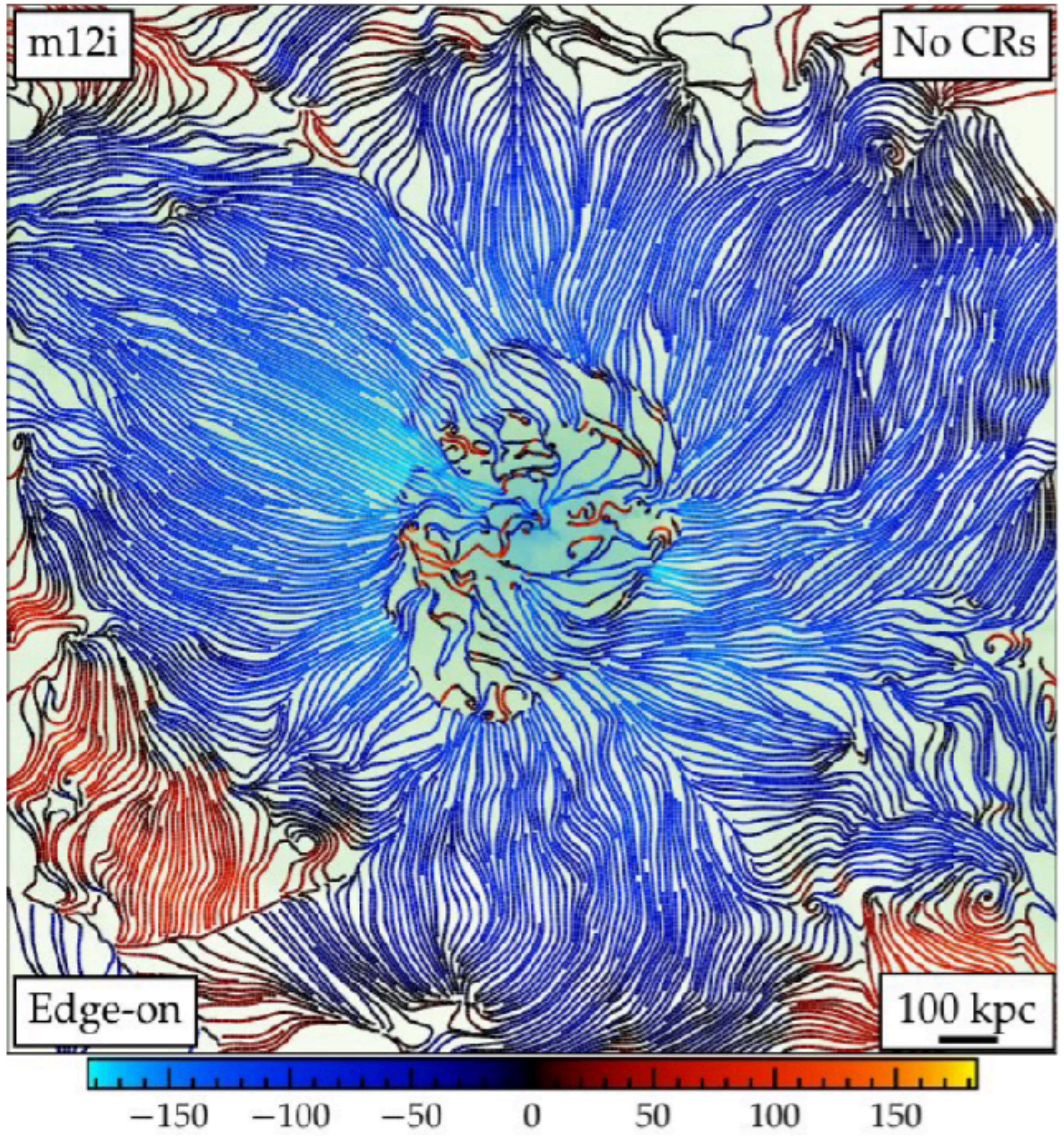
Chan+19

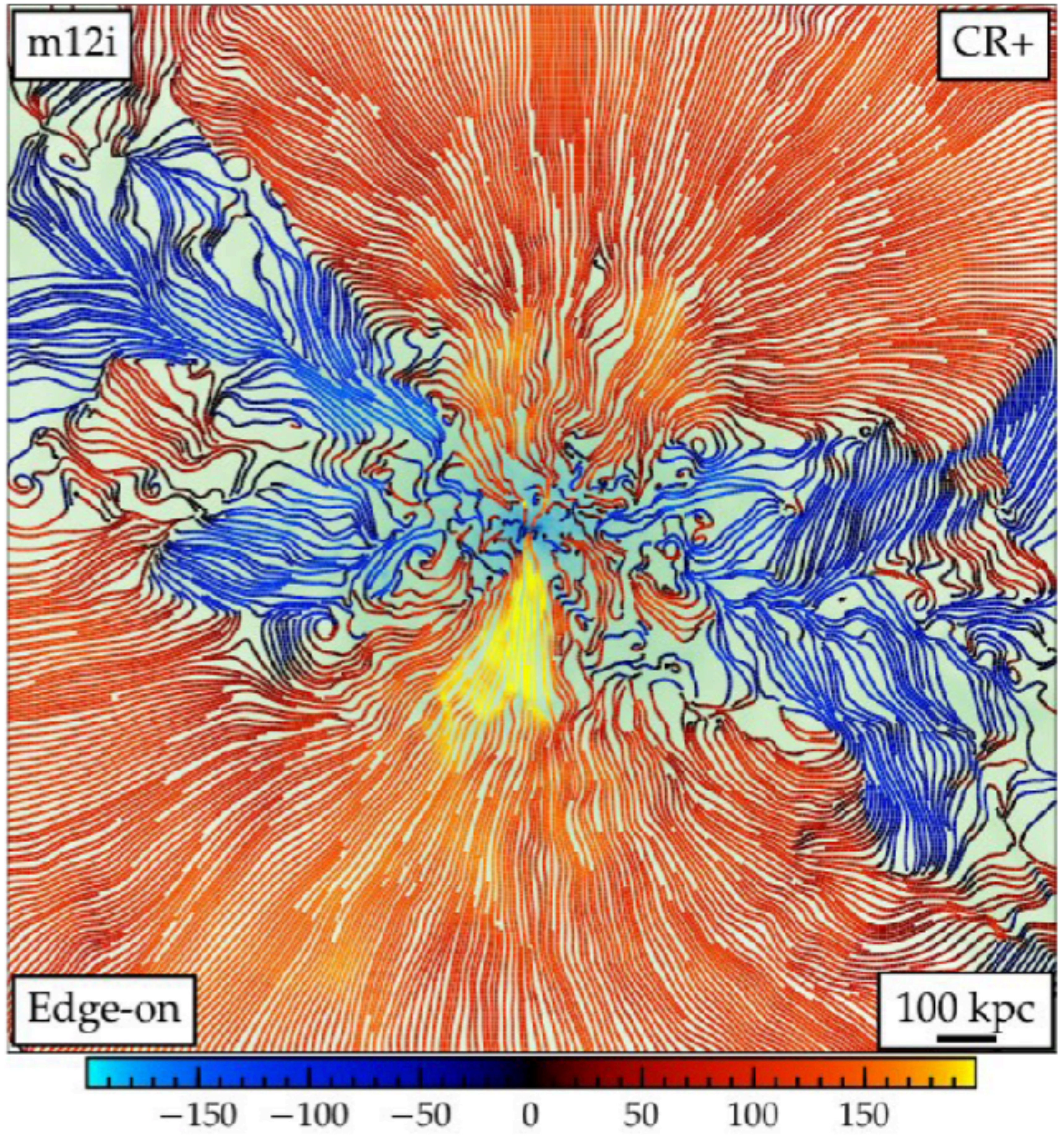
Hopkins+20

Isotropic diffusion coeff. $\kappa \sim 3 \times 10^{29}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ **is favored against γ-ray obs.**

(cf. Quartaert+21) (cf. Lacki+11; …)

FIRE-2 MHD cosmo sim. + CR : follow-up to Chan+19





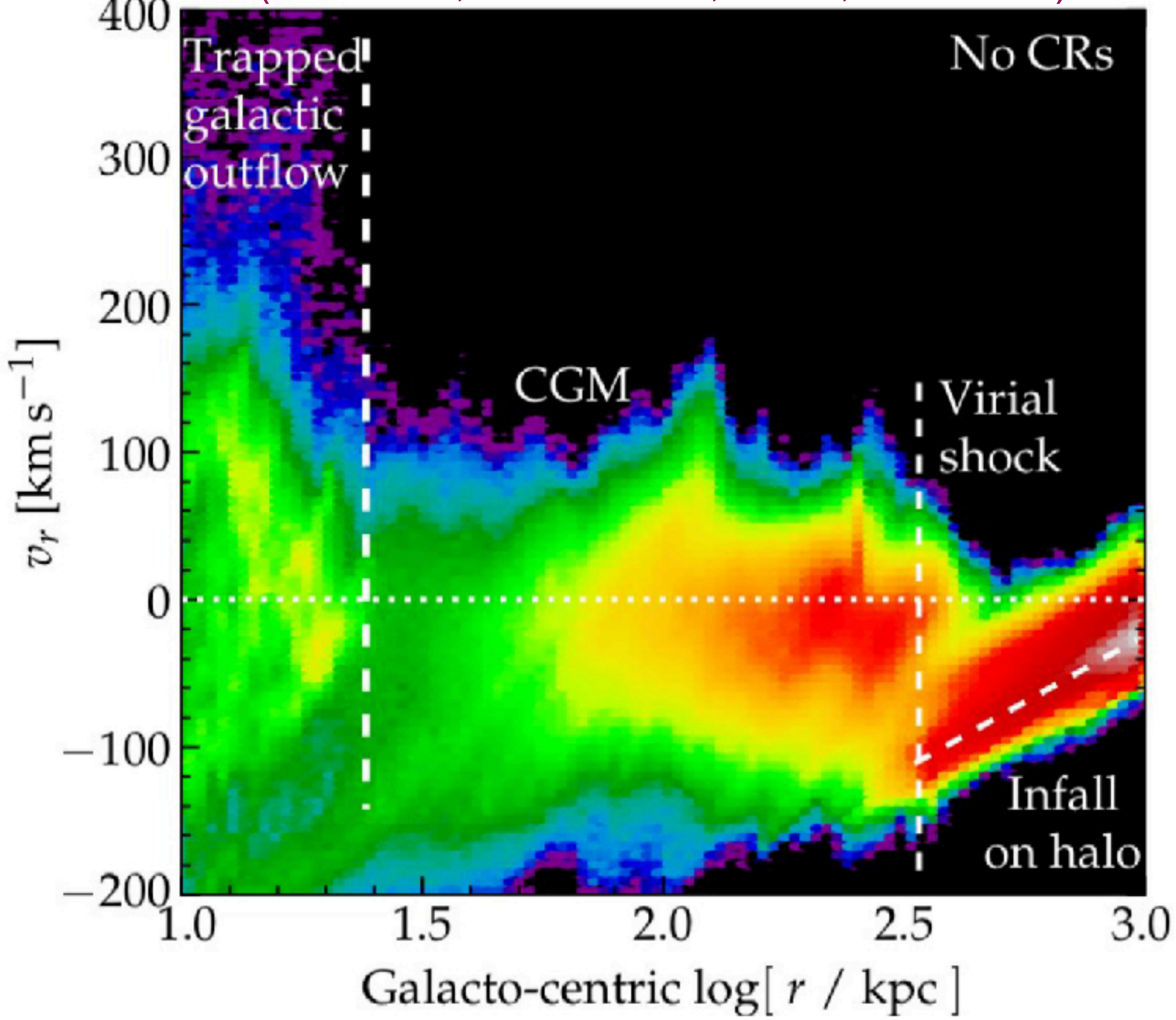
$$\mathbf{v}_{\rm stream} = -v_{\rm stream}\,\hat{\mathbf{B}}\,(\hat{\mathbf{B}}\cdot\hat{\nabla}P_{\rm cr}) \qquad v_{\rm stream} = 3\,v_{\rm A}$$

Hopkins+21

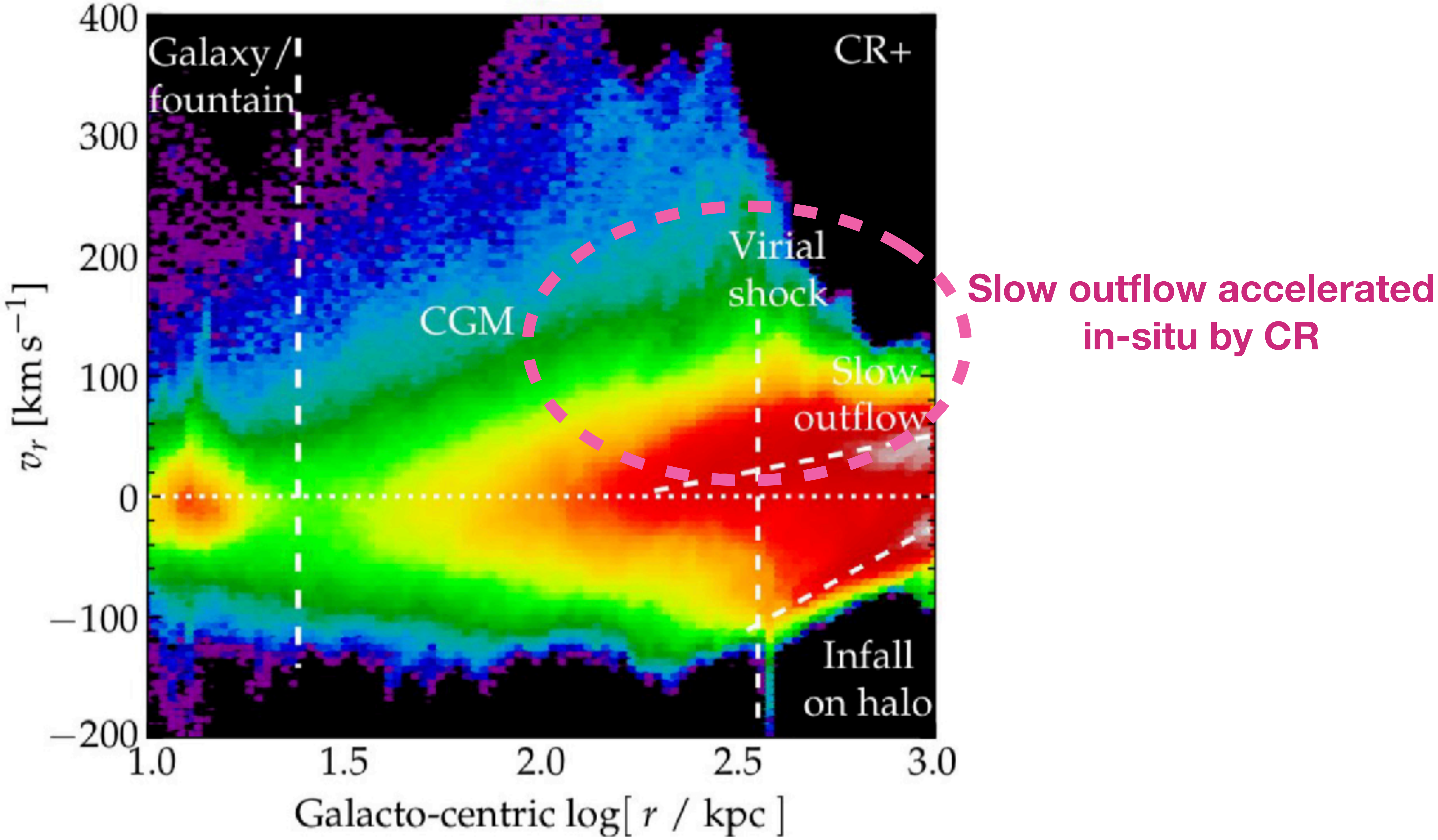
Slow outflow produced by CR

No CR

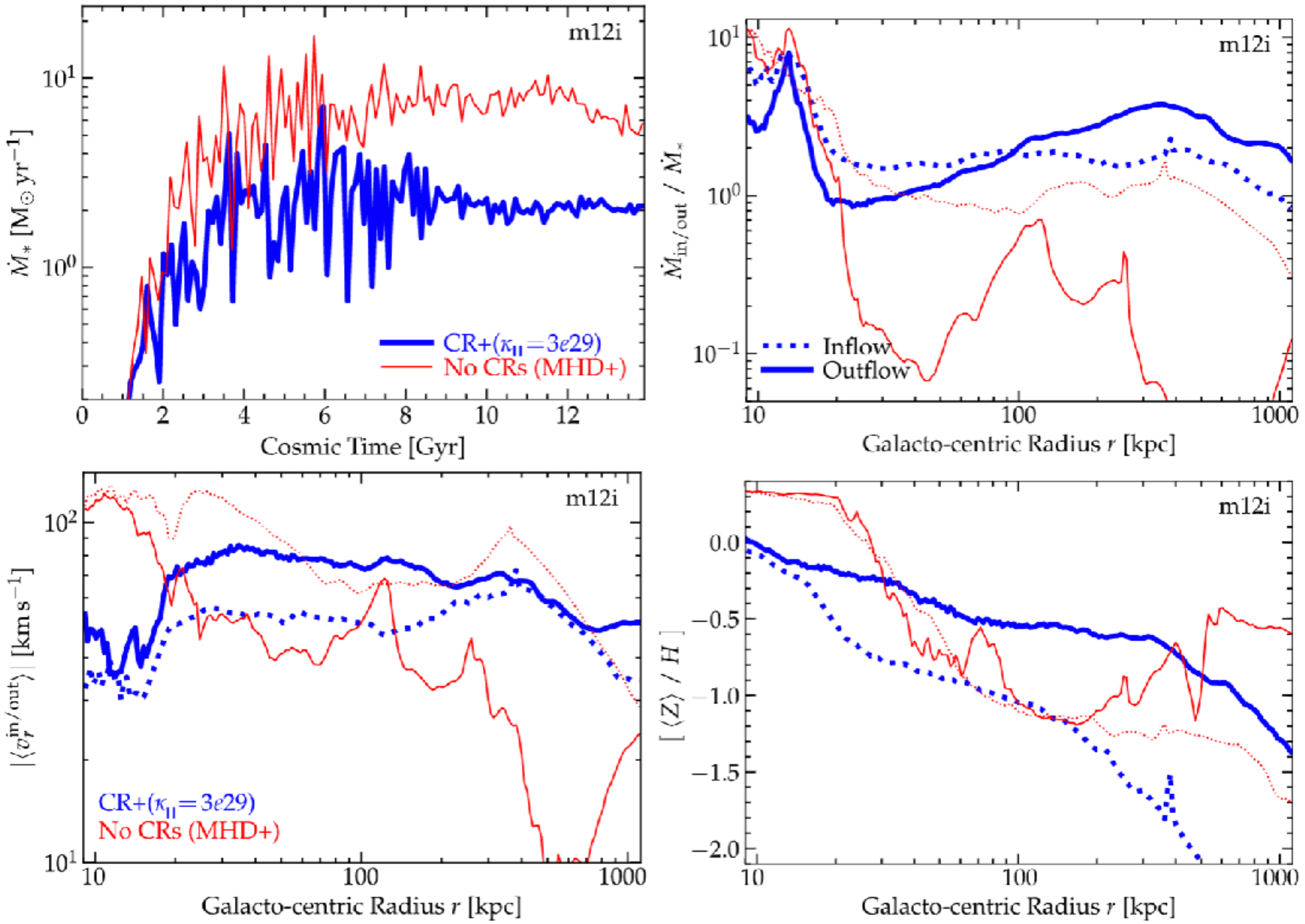
(but + rad, conduction, MHD, stellar FB)

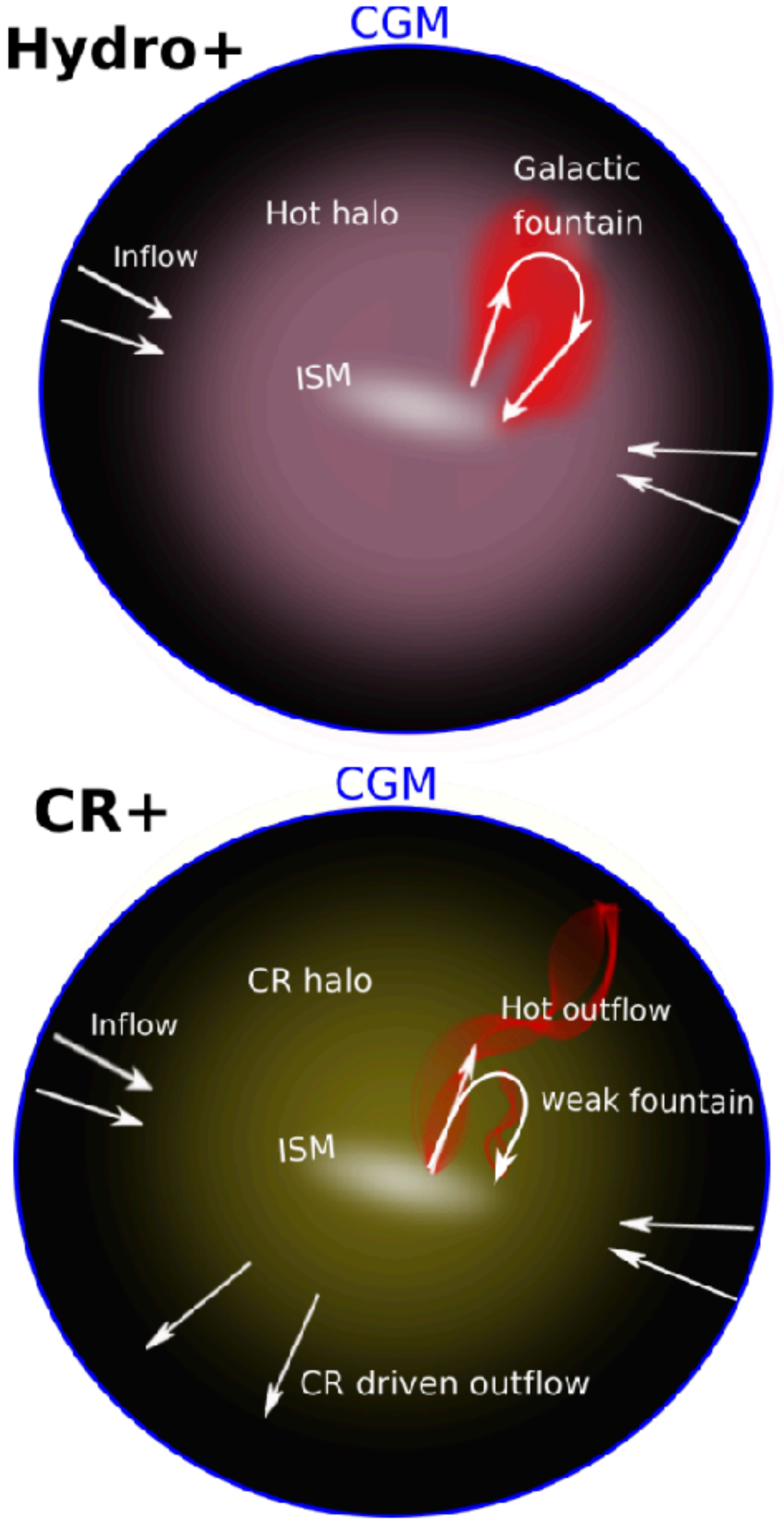


With CR



FIRE-2 sim. Hopkins+21

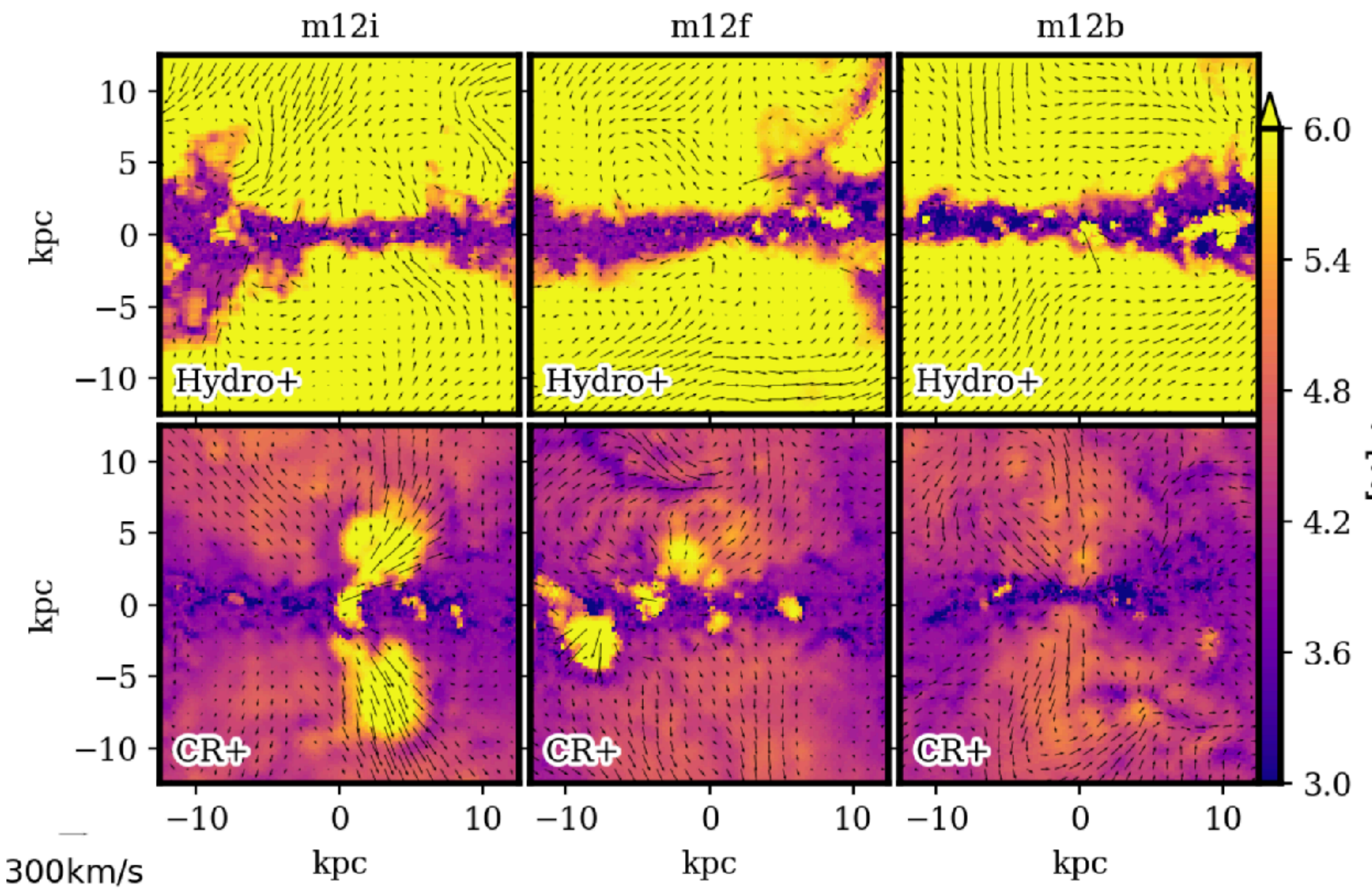




FIRE-2 sim. Hopkins+21

Chan+21

Temperature structure above disk plane



Chan+21

Hot infall ($T \gtrsim 10^5\,K$, ~50 km/s) w.out CR

Warm slow ($T \gtrsim 10^4\,K$, <200 km/s) CR-driven outflow

- weaker adiabatic losses
- do not suffer from rad. cooling
- P_{CR} slows down the infall
- lowers post-shock T

MHD with CRs

$$\frac{\partial \boldsymbol{U}}{\partial t} + \nabla \cdot \mathbf{F} = \boldsymbol{S},$$

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \varepsilon \\ \varepsilon_{\rm cr} \\ \boldsymbol{B} \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^{\rm T} + P\mathbf{1} - \boldsymbol{B}\boldsymbol{B}^{\rm T} \\ (\varepsilon + P)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{v}\cdot\boldsymbol{B}) \\ \varepsilon_{\rm cr}\boldsymbol{v} + (\varepsilon_{\rm cr} + P_{\rm cr})\boldsymbol{v}_{\rm st} - \kappa_\varepsilon \boldsymbol{b}\left(\boldsymbol{b}\cdot\nabla\varepsilon_{\rm cr}\right) \\ \boldsymbol{B}\boldsymbol{v}^{\rm T} - \boldsymbol{v}\boldsymbol{B}^{\rm T} \end{pmatrix},$$

KE-weighted spatial diffusion coefficient

$$\boldsymbol{S} = \begin{pmatrix} 0 \\ \mathbf{0} \\ P_{\rm cr}\nabla\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr} + \Lambda_{\rm th} + \Gamma_{\rm th} \\ -P_{\rm cr}\nabla\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr} + \Lambda_{\rm cr} + \Gamma_{\rm cr} \\ \mathbf{0} \end{pmatrix}, \quad (2)$$

Heaviside-Lorentz system of units.

Pressure

$$P = P_{\rm th} + P_{\rm cr} + \frac{\boldsymbol{B}^2}{2},$$

Energy density

$$\varepsilon = \varepsilon_{\rm th} + \frac{\rho \boldsymbol{v}^2}{2} + \frac{\boldsymbol{B}^2}{2}.$$

(w.out ϵ_{cr})

Streaming vel.

$$\boldsymbol{v}_{\rm st} = -\boldsymbol{v}_{\rm A}\,{\rm sgn}(\boldsymbol{B}\cdot\nabla P_{\rm cr}) = -\frac{\boldsymbol{B}}{\sqrt{\rho}}\frac{\boldsymbol{B}\cdot\nabla P_{\rm cr}}{|\boldsymbol{B}\cdot\nabla P_{\rm cr}|},$$

EOS:

$$P_{\rm th} = (\gamma_{\rm th} - 1)\,\varepsilon_{\rm th}, \qquad \gamma_{\rm th} = 5/3$$

$$P_{\rm cr} = (\gamma_{\rm cr} - 1)\,\varepsilon_{\rm cr}, \qquad \gamma_{\rm cr} = 4/3$$ (in rela. limit)

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \nabla\cdot\left[\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) - \kappa_\varepsilon \boldsymbol{b}\left(\boldsymbol{b}\cdot\nabla\varepsilon_{\rm cr}\right)\right] = -P_{\rm cr}\nabla\cdot(\boldsymbol{v} + \boldsymbol{v}_{\rm st}) + \Lambda_{\rm cr} + \Gamma_{\rm cr}.$$

(Enslin+07; Kulsrud & Pearce'69; Wiener+13,16)

AREPO; Pfrommer+17

Spectrally resolved CR

AREPO MHD sim.

- accurate CR cooling
- E-dep. spatial diffusion

- grey CR
- diffusive transport
- effective cooling

Girichidis+20, 21

Fokker-Planck eq.

$$\frac{\partial f}{\partial t} = \underbrace{-\boldsymbol{v}\cdot\nabla f}_{\text{advection}} + \underbrace{\nabla\cdot(\mathbf{D}_{xx}\cdot\nabla f)}_{\text{diffusion}} + \underbrace{\frac{1}{3}(\nabla\cdot\boldsymbol{v})\,p\frac{\partial f}{\partial p}}_{\text{adiabatic process}}$$

$$+ \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(b_l f + D_{pp}\frac{\partial f}{\partial p}\right)\right]}_{\text{other losses and Fermi II acceleration}} + \underbrace{j}_{\text{sources}},$$

$$f = f(\boldsymbol{x}, p, t) = \mathrm{d}^6 N/(\mathrm{d}^3 x\, \mathrm{d}^3 p)$$

Piecewise power-law ptcl distrib:

$$f(p) = \sum_{i=0}^{N_{\rm spec}} f_i(p)$$

$$= \sum_{i=0}^{N_{\rm spec}} f_{i-1/2}\left(\frac{p}{p_{i-1/2}}\right)^{-q_i}\theta\left(p - p_{i-1/2}\right)\theta\left(p_{i+1/2} - p\right)$$

Number & E density

$$n_i = \int_{p_{i-1/2}}^{p_{i+1/2}} 4\pi p^2 f(p)\,\mathrm{d}p,$$

$$e_i = \int_{p_{i-1/2}}^{p_{i+1/2}} 4\pi p^2 f(p) T(p)\,\mathrm{d}p.$$

$$T(p) = \sqrt{p^2c^2 + m_{\rm p}^2 c^4} - m_{\rm p}c^2$$

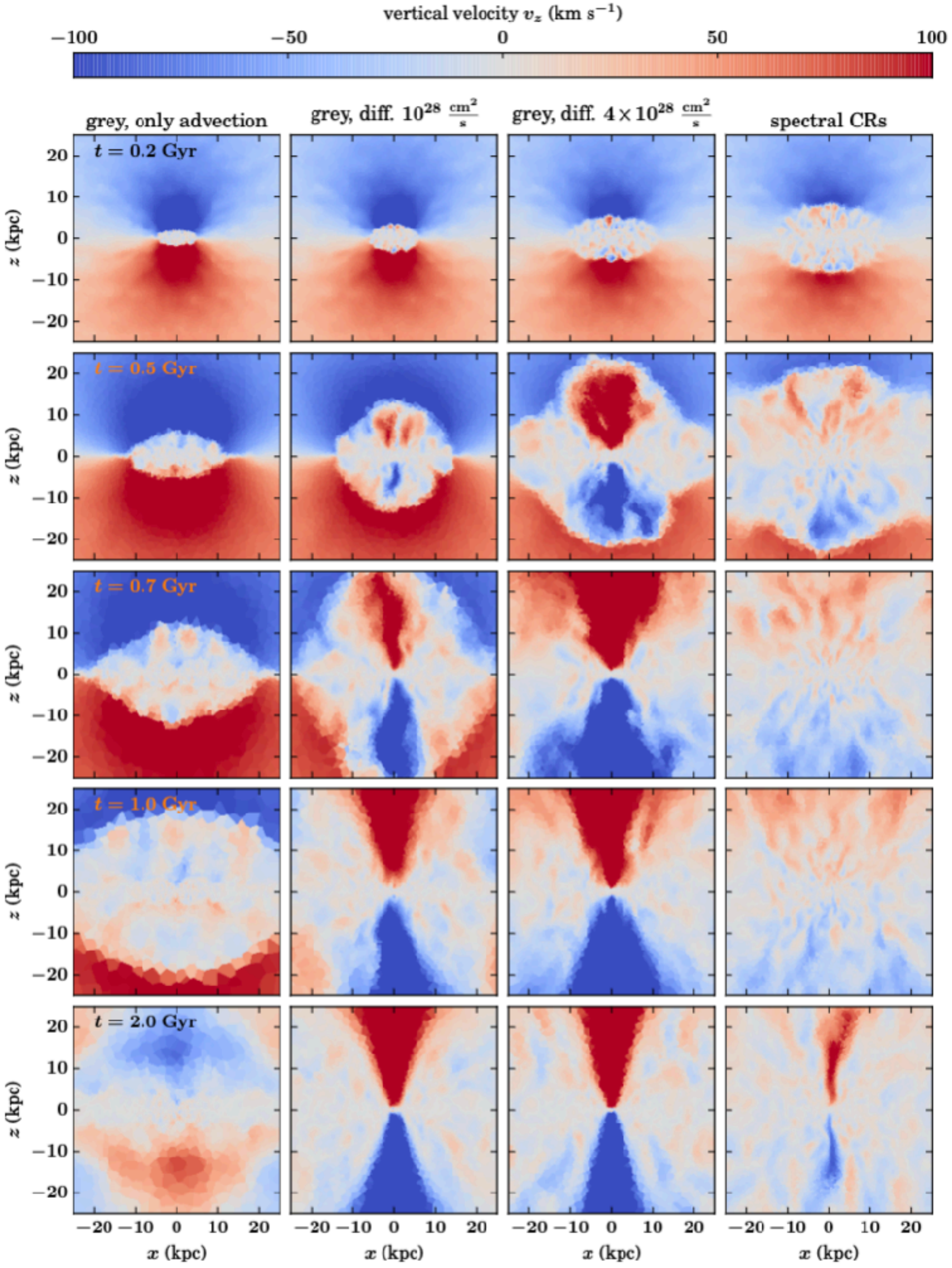
CR pressure

$$P_{\rm cr} = \int_0^\infty \frac{4\pi}{3} c\, p^3 \beta(p) f(p)\,\mathrm{d}p,$$

$$P_{\rm cr} = \sum_{i=1}^{N_{\rm spec}} P_{{\rm cr},i} = \frac{4\pi}{3}\sum_{i=1}^{N_{\rm spec}} \int_{p_{i-1/2}}^{p_{i+1/2}} \frac{f_i(p)\, p^4 c^2}{\sqrt{m_{\rm p}^2 c^4 + p^2 c^2}}\,\mathrm{d}p.$$

cf. Miniati+01; Yang & Ruszkowski'17; Ogrodnik+21

Spectrally resolved
CR

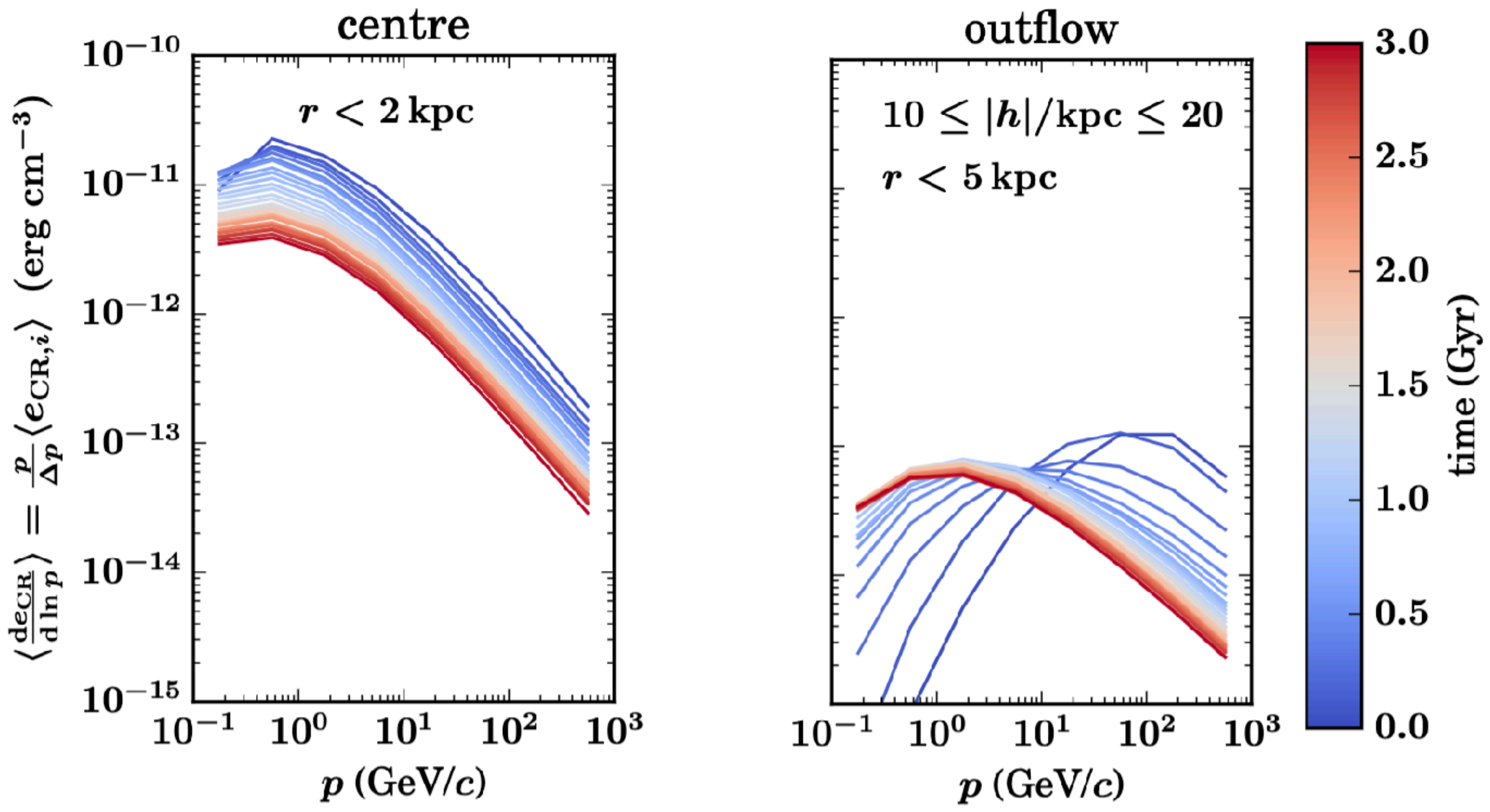


initial outflow front by CRs w. 200 - 600 Gev/c

subsequent outflow by ~10 Gev/c

Girichidis+21

Temporally & Spatially varying CR spectrum



Girichidis+21

Summary & Issues

- Multi-scale, multi-phase structures in the universe.
- **SNe, AGN, CR** feedback: all seems relevant for **galactic wind**
- **SN FB model**: rapidly improving at $\lesssim$pc level — **clustered SNe**
- **AGN FB** model : still highly uncertain; intermittent / two phase growth of SMBH?
- **CR** FB model: details of **propagation** model — diffusion coefficient, scattering, subgrid turbulence, spectral decomposition

追加情報（おまけ）

特別南部コロキウム

10/23 (土)

13:00 - 15:40

オンライン講演会

(無料で登録できます)

参加登録

https://www.phys.sci.osaka-u.ac.jp/nambu/#Section4

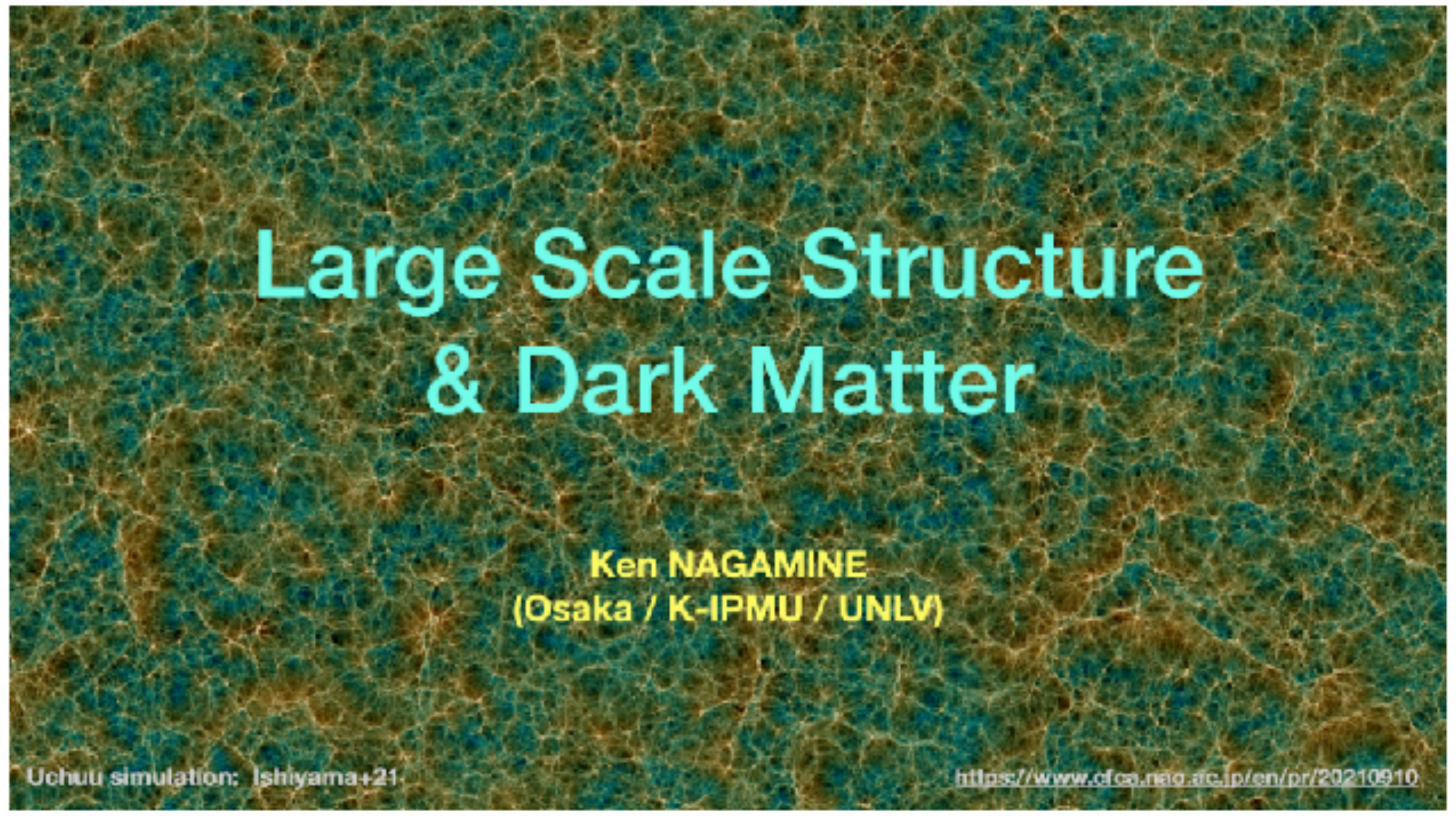
暗黒物質分布セミナーseries

https://sites.google.com/view/dmseminars

暗黒物質の質量分布や速度分布には、観測・理論・シミュレーションから様々な示唆が与えられています。これらは直接検出実験・間接検出実験に影響し、素粒子実験・理論などの隣接領域でも重要です。暗黒物質分布についての知見を広げ、各自の研究分野にフィードバックすることを目的として、セミナーシリーズを開催することになりました。

林航平（一関高専）、東野聡（神戸大学）、身内賢太朗（神戸大）、長尾桂子（岡山理科大）、中竜大（東邦大）

林さん、岡本さんのセミナーに続き、



第３回

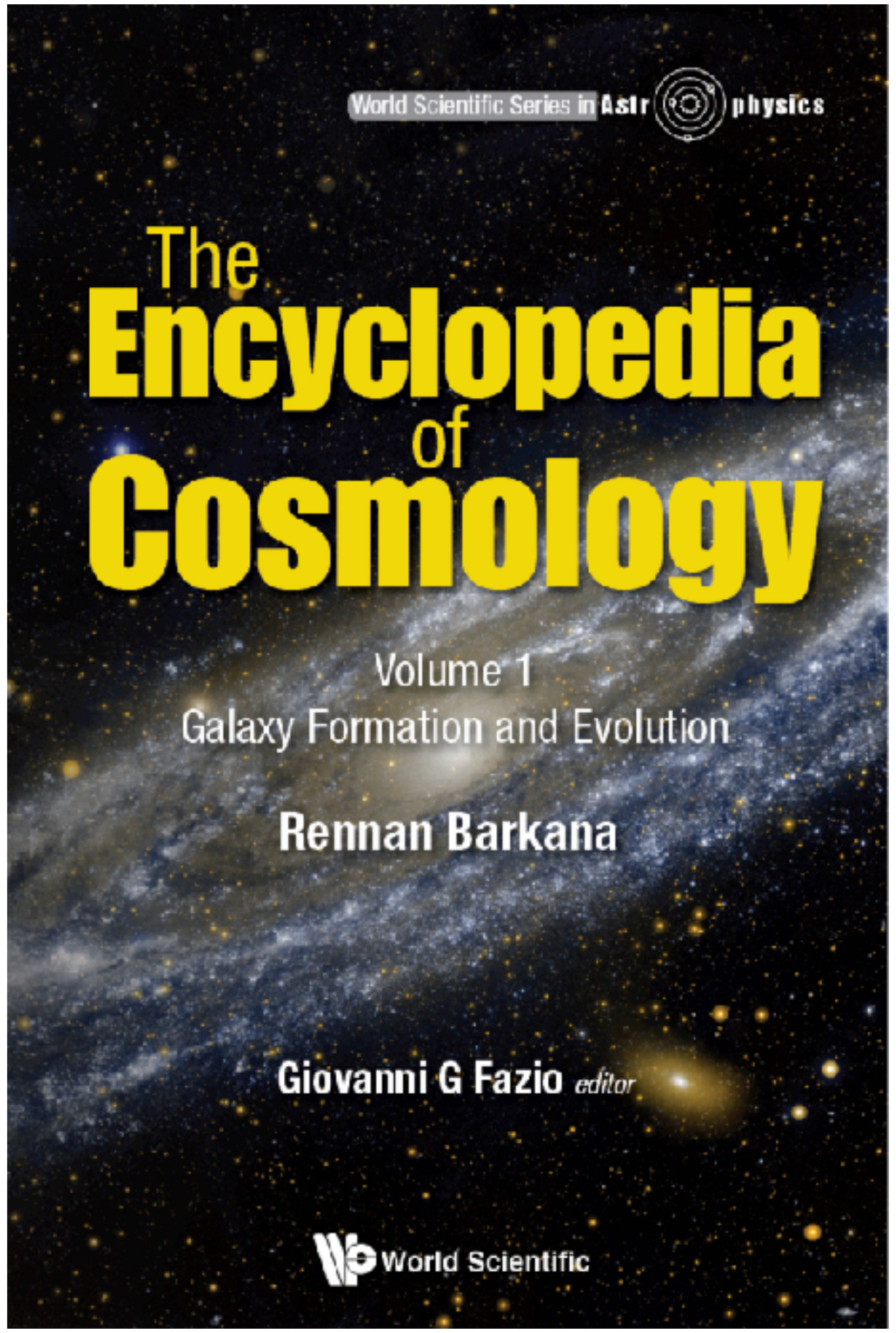
長峯 健太郎（大阪大学）

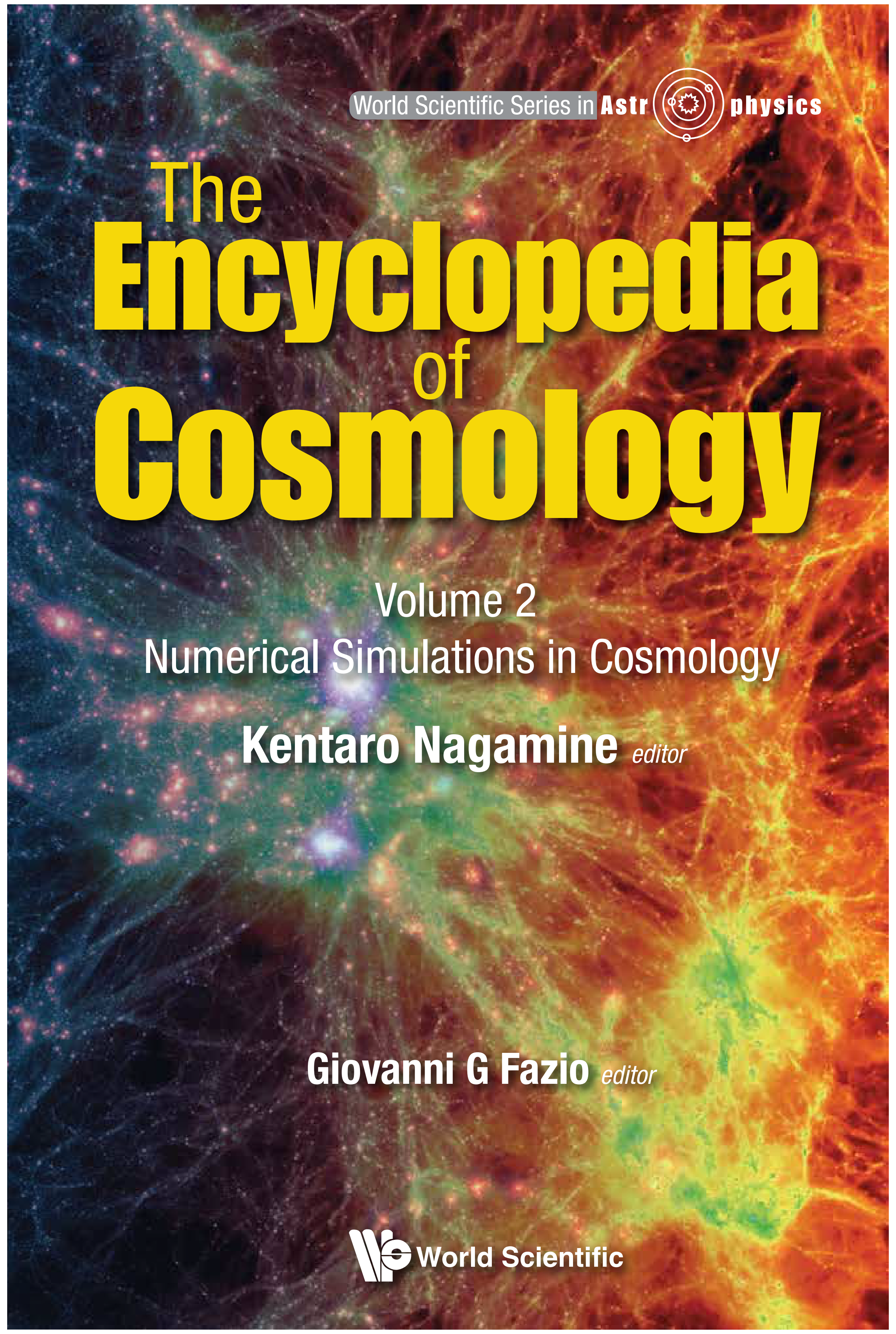
〇日時：2021年10月1日（金）14:00-16:00

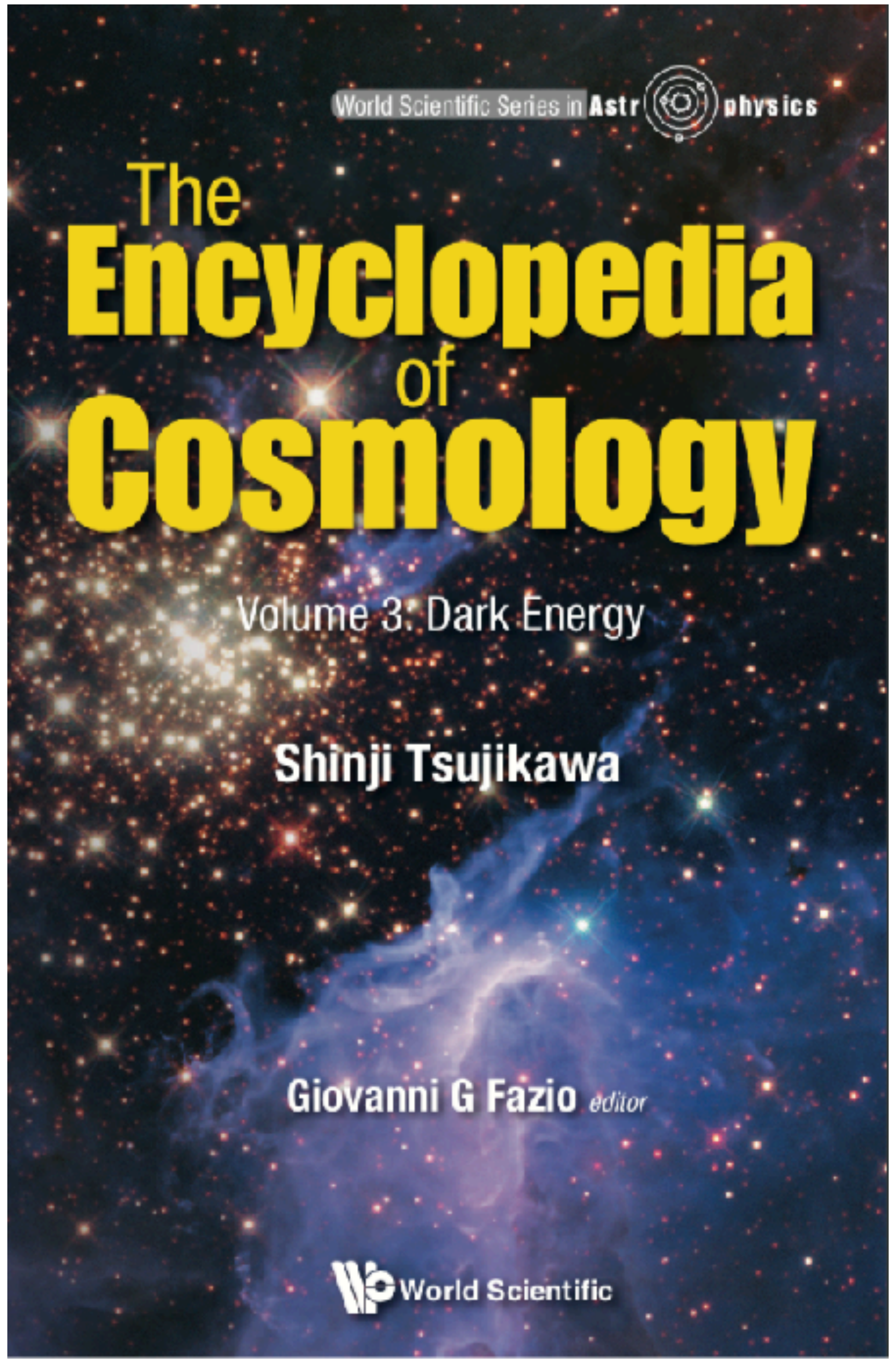
〇タイトル：宇宙の大規模構造とダークマター

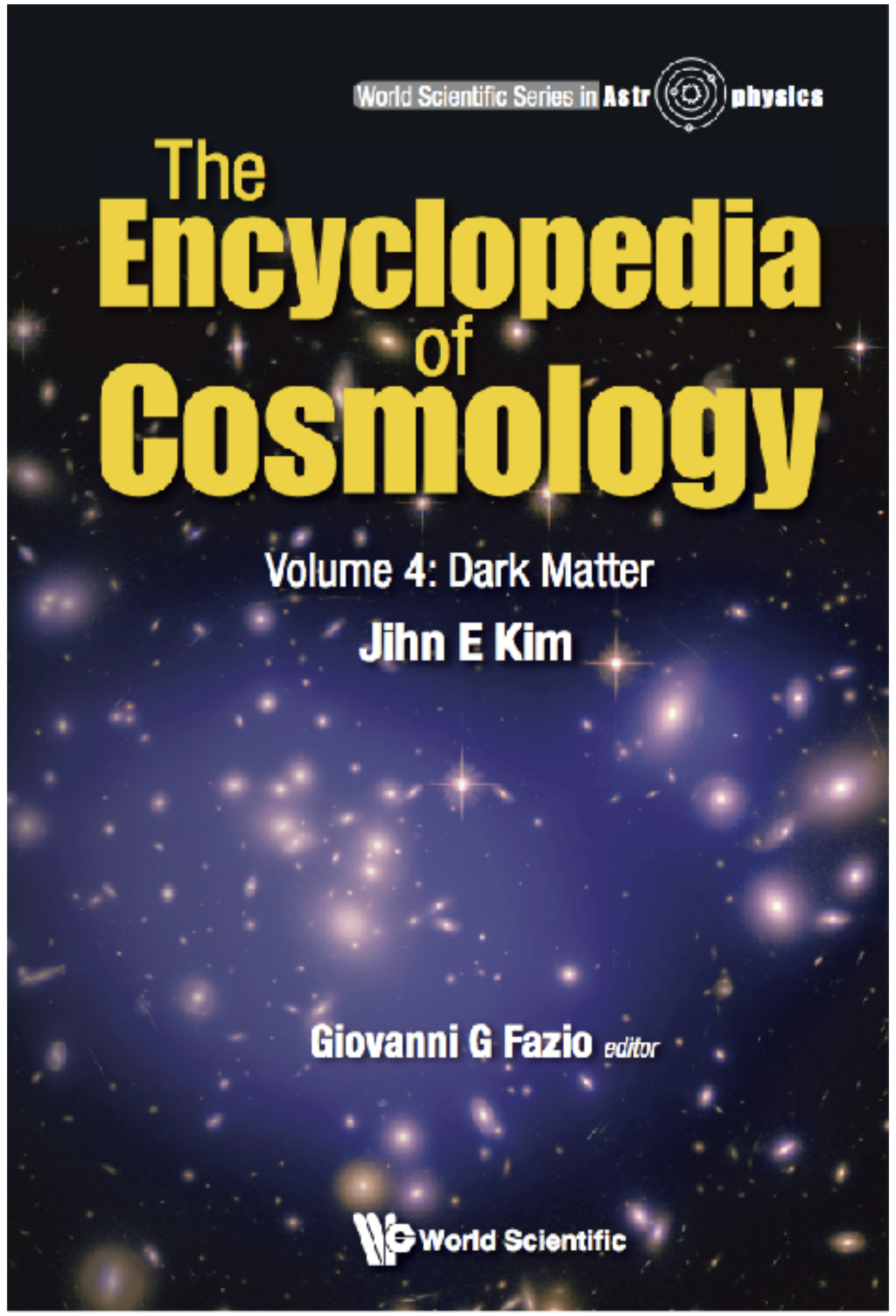
〇概要：

前２回の講演ですでに銀河スケールでの諸問題はかなりカバーされているので、今回は主に宇宙の大規模構造の観点からダークマターについて議論する。空間スケールとしては、100kpc から200Mpc 程が対象となる。トピックとしては、大規模構造形成でダークマターが果たす役割、銀河









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