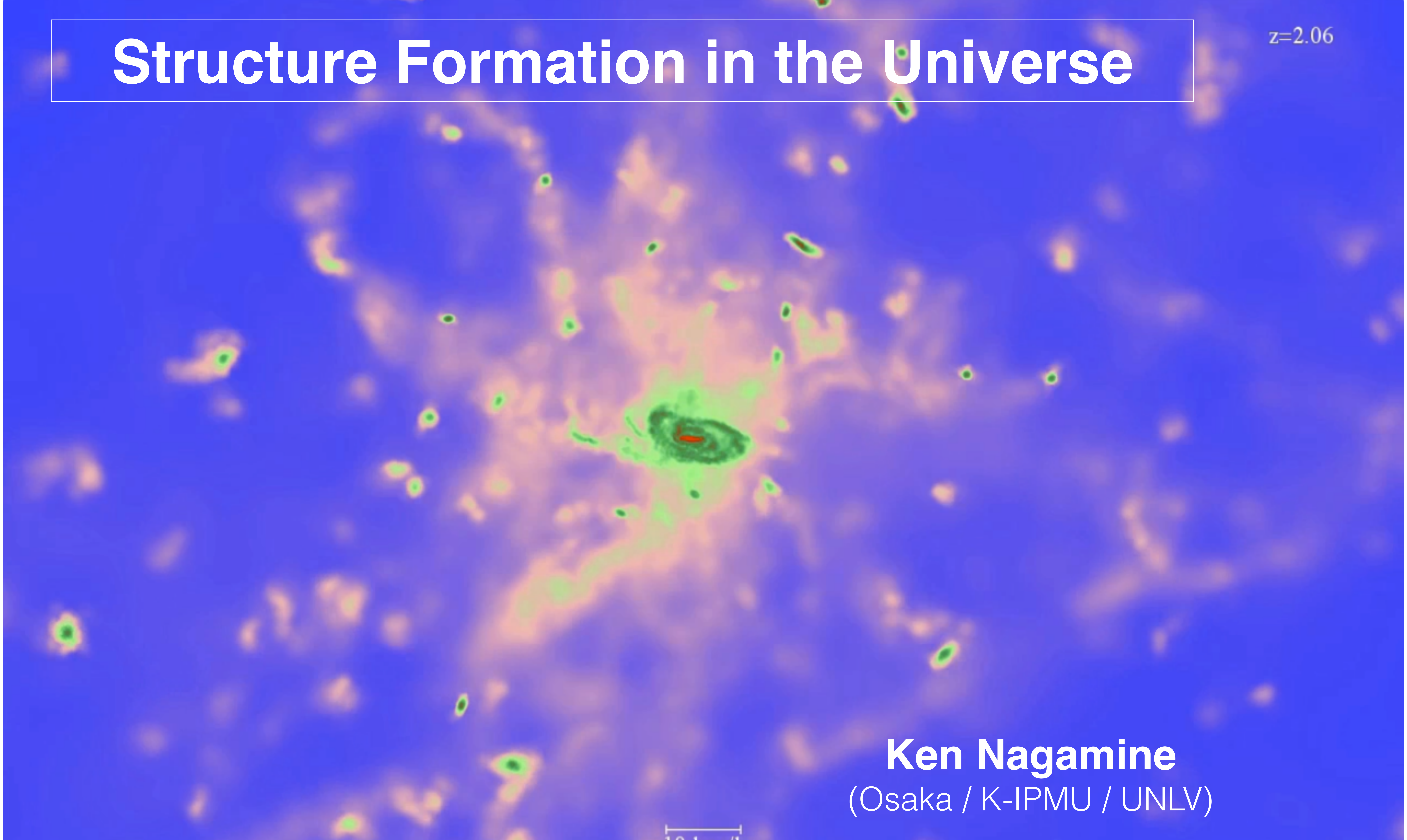
Structure Formation in the Universe

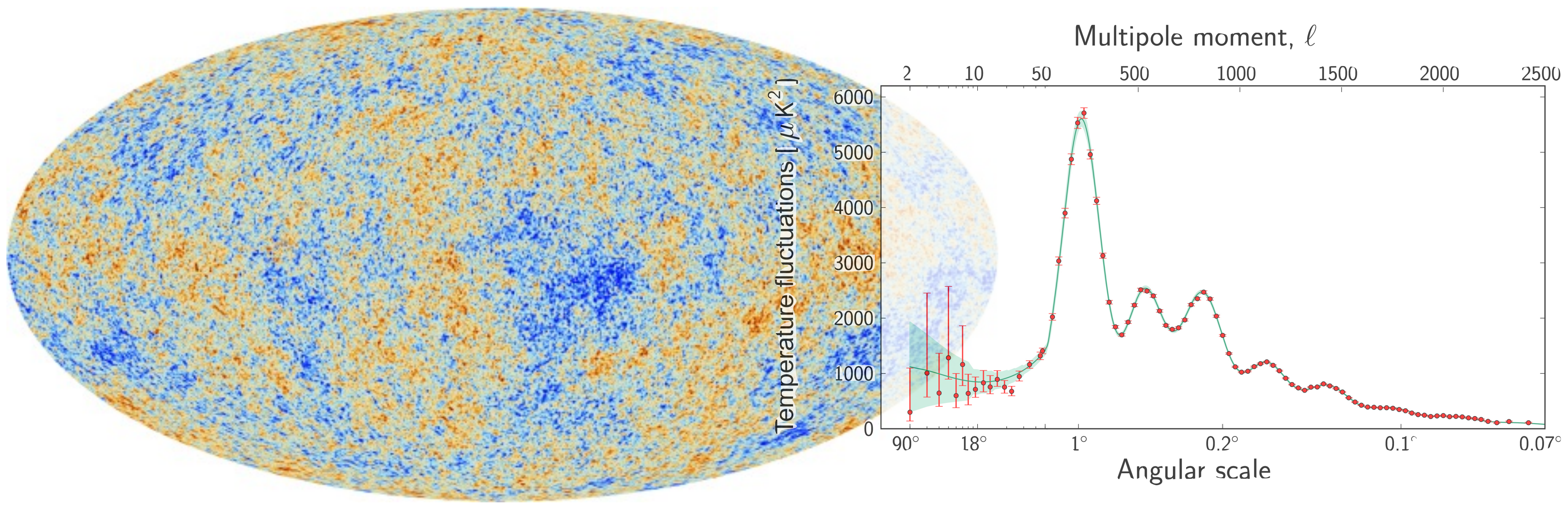


Ken Nagamine
(Osaka / K-IPMU / UNLV)

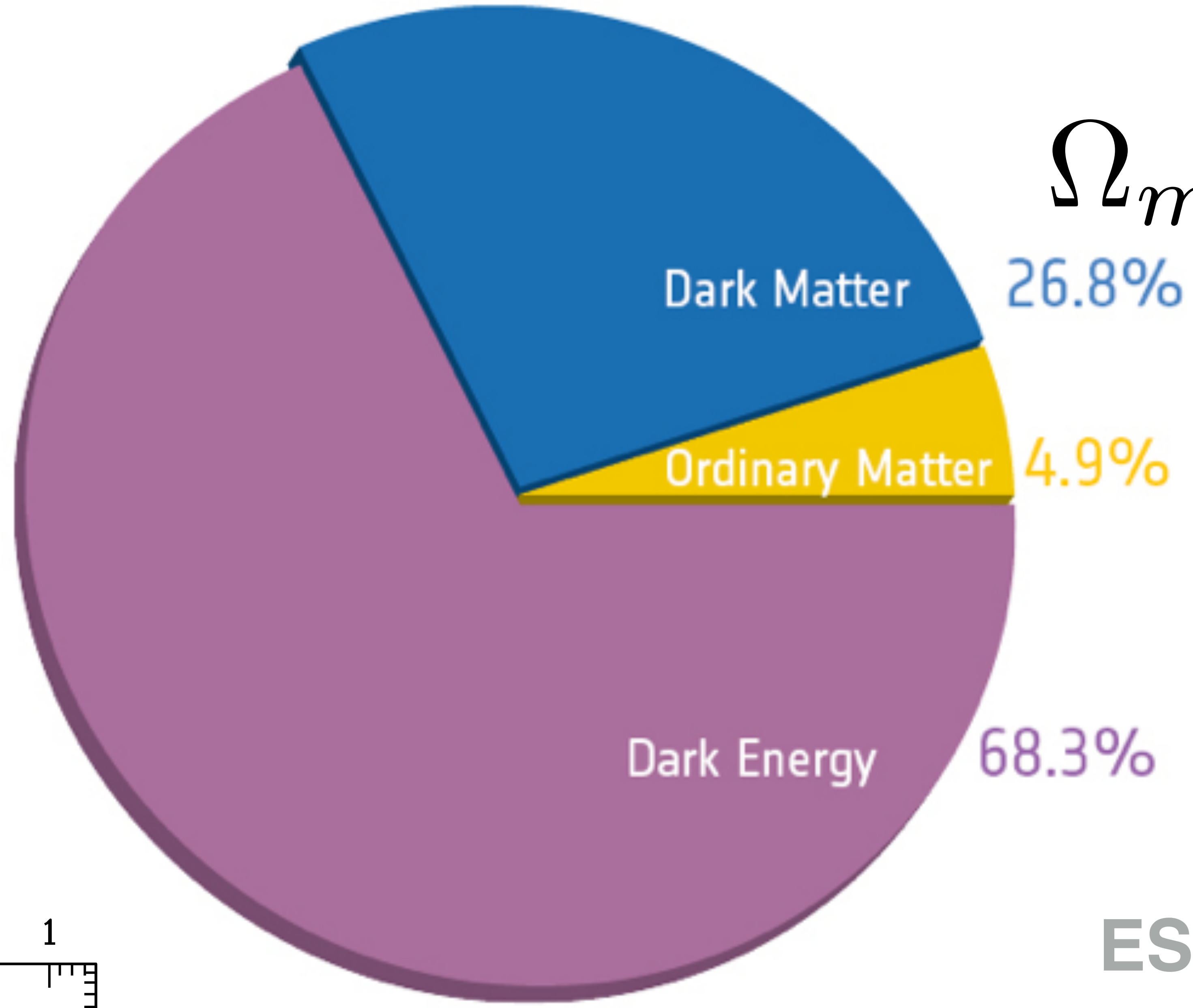
Outline

- **Cosmology & Structure Formation**
- **Dark Matter & Galaxy Formation** (*Supernova* feedback - title of this workshop…) — no more "missing satellite problem"
- ***Baryons*** — High-z galaxies, Local dwarfs, Lya forest
- Recent ***JWST*** discoveries & their implications

``Era of Precision Cosmology"



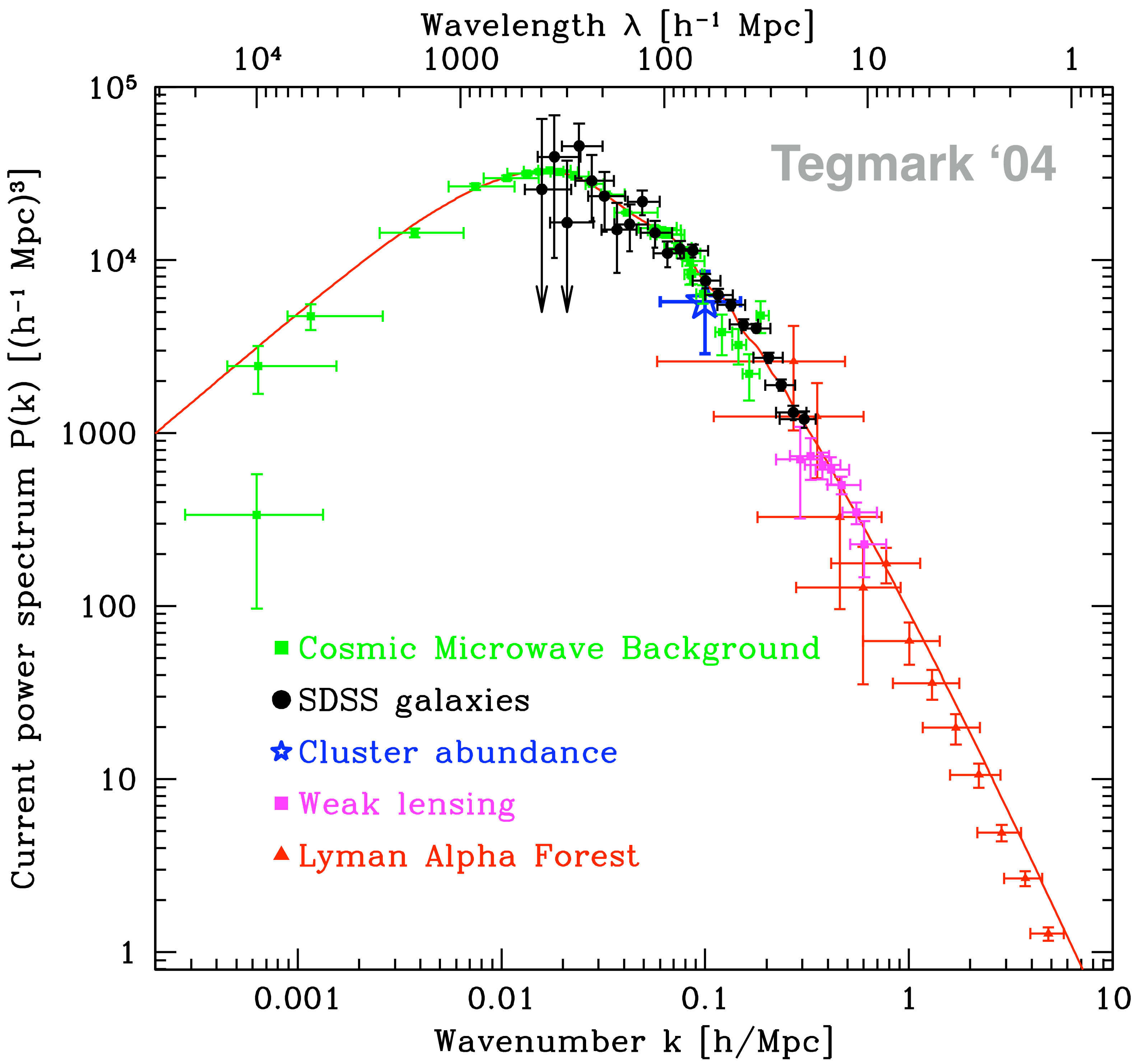
Planck



$\Omega_m \sim 0.3$

ESA '13

Matter power spectrum

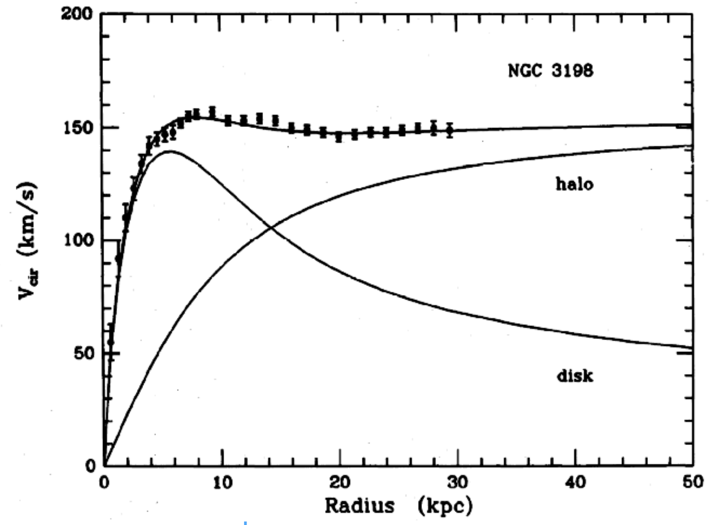


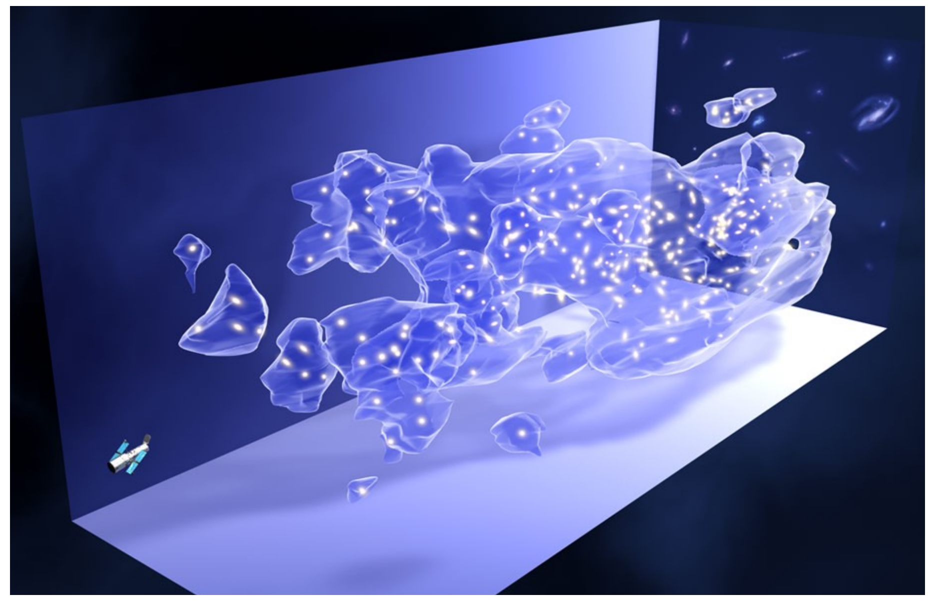
$$\frac{\Omega_{\rm DM}}{\Omega_b} \sim 5$$

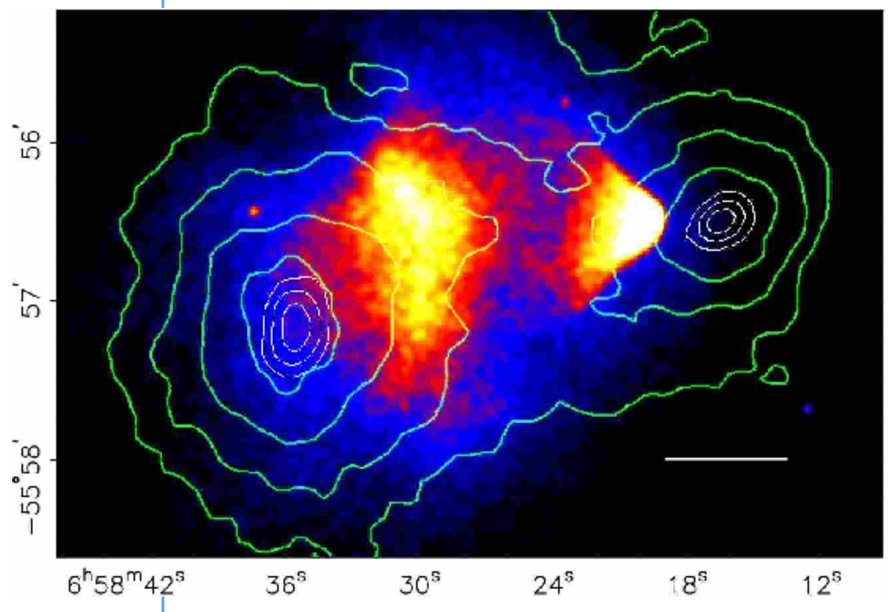
Evidence of Dark Matter

— success of CDM on large scales ($\gtrsim$100 kpc)

- **Stellar motions** Lord Kelvin (1884); Kapteyn '22; Jeans'22; Oort '32
- **Galaxy clusters** — ~80% of mass is dark (Zwicky '33)
- **Galaxy rotation curves** (Rubin & Ford '70)
- **Galactic disk stability** (stellar kinematics; Ostriker & Peebles '74)
- **Cosmic Microwave Background** (CMB) — angular power spec.
- **Structure formation** — P(k), galaxy clustering, Ly-α forest
- **Gravitational lensing** (strong & weak)
- **Bullet Cluster** (Markevich+'02; Clowe+'06)
- ……







``Concordance ΛCDM model ”

WMAP, Planck
SN Ia

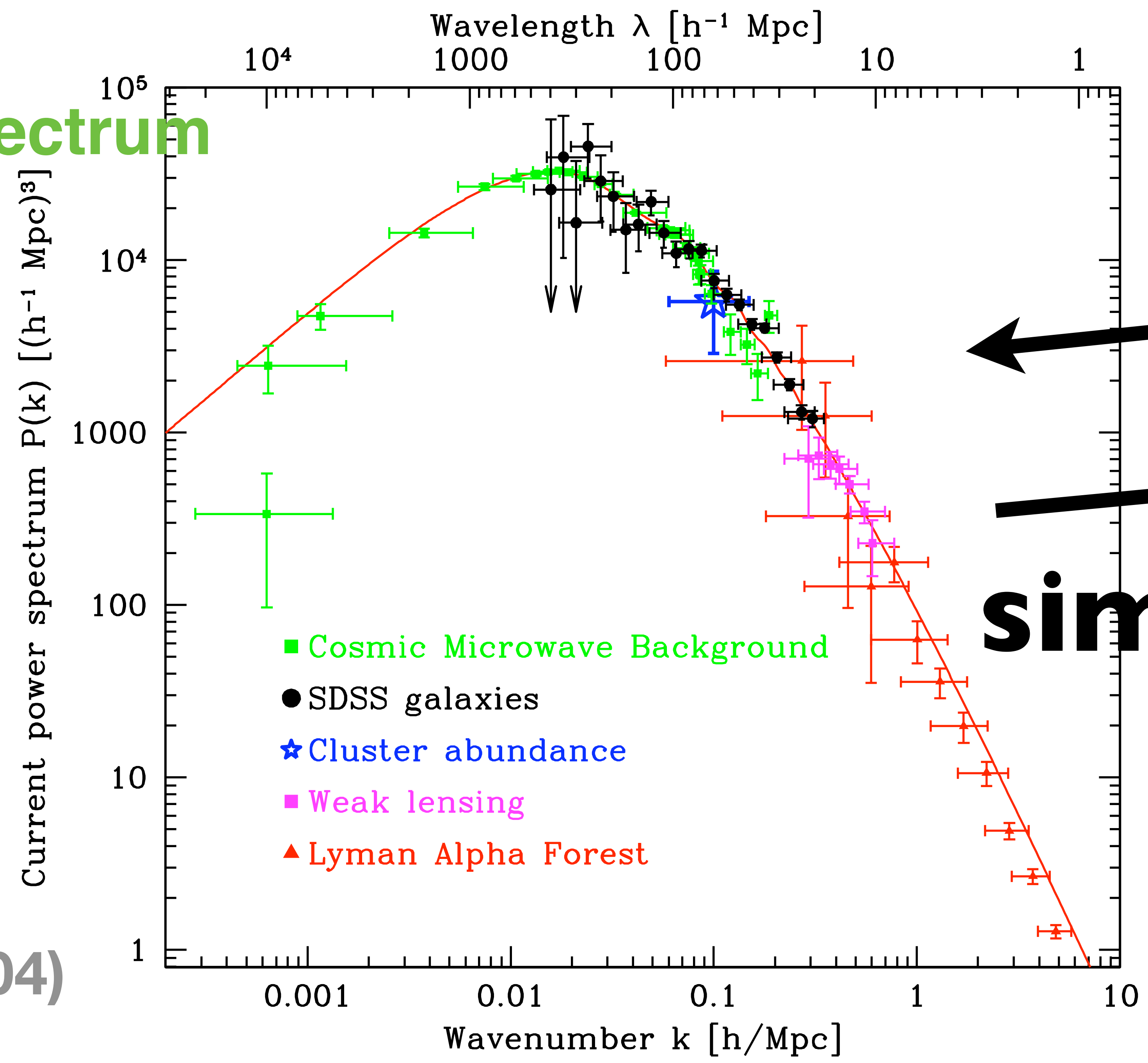
$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

“737 cosmology”

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

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

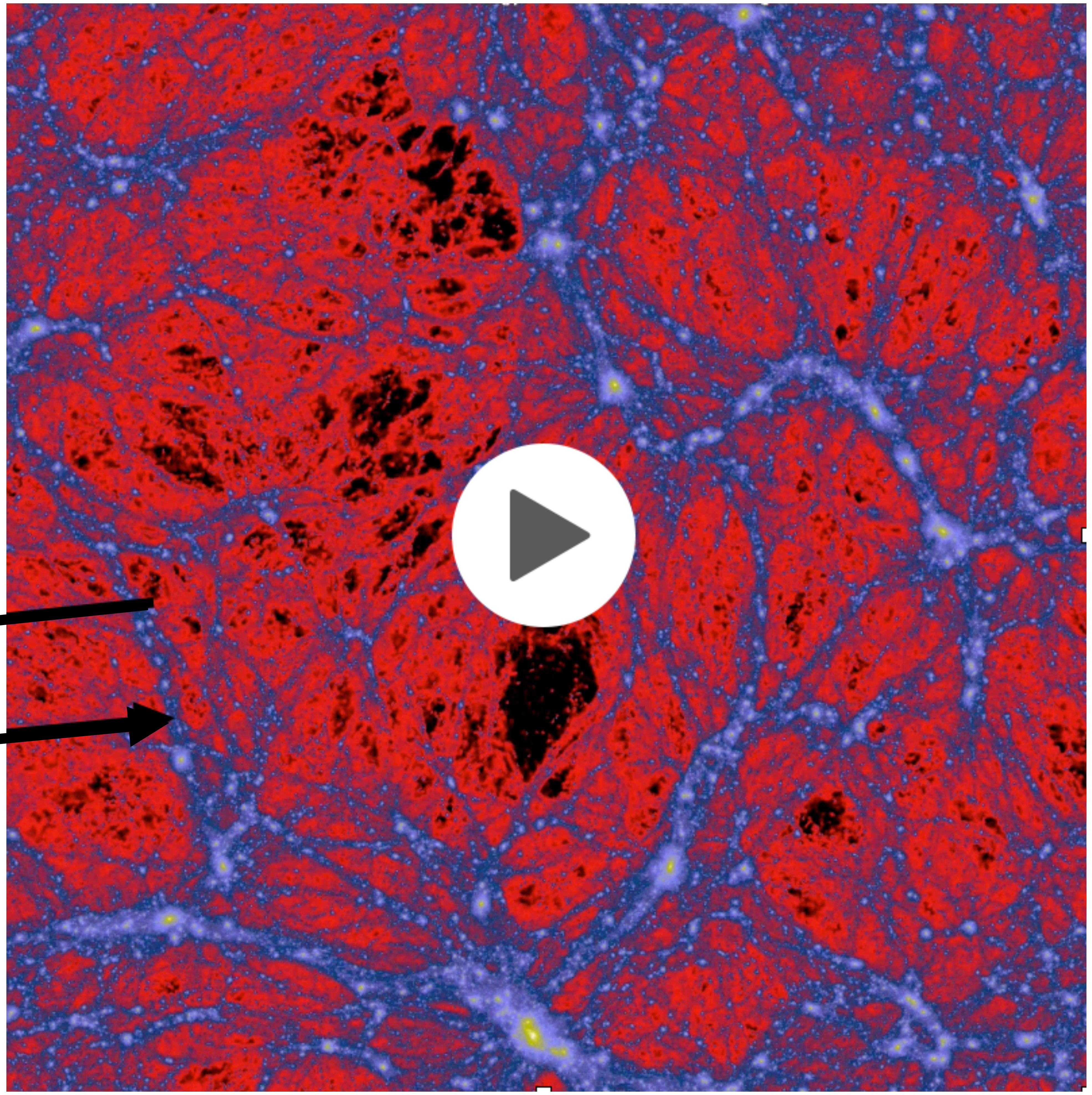
Matter power spectrum



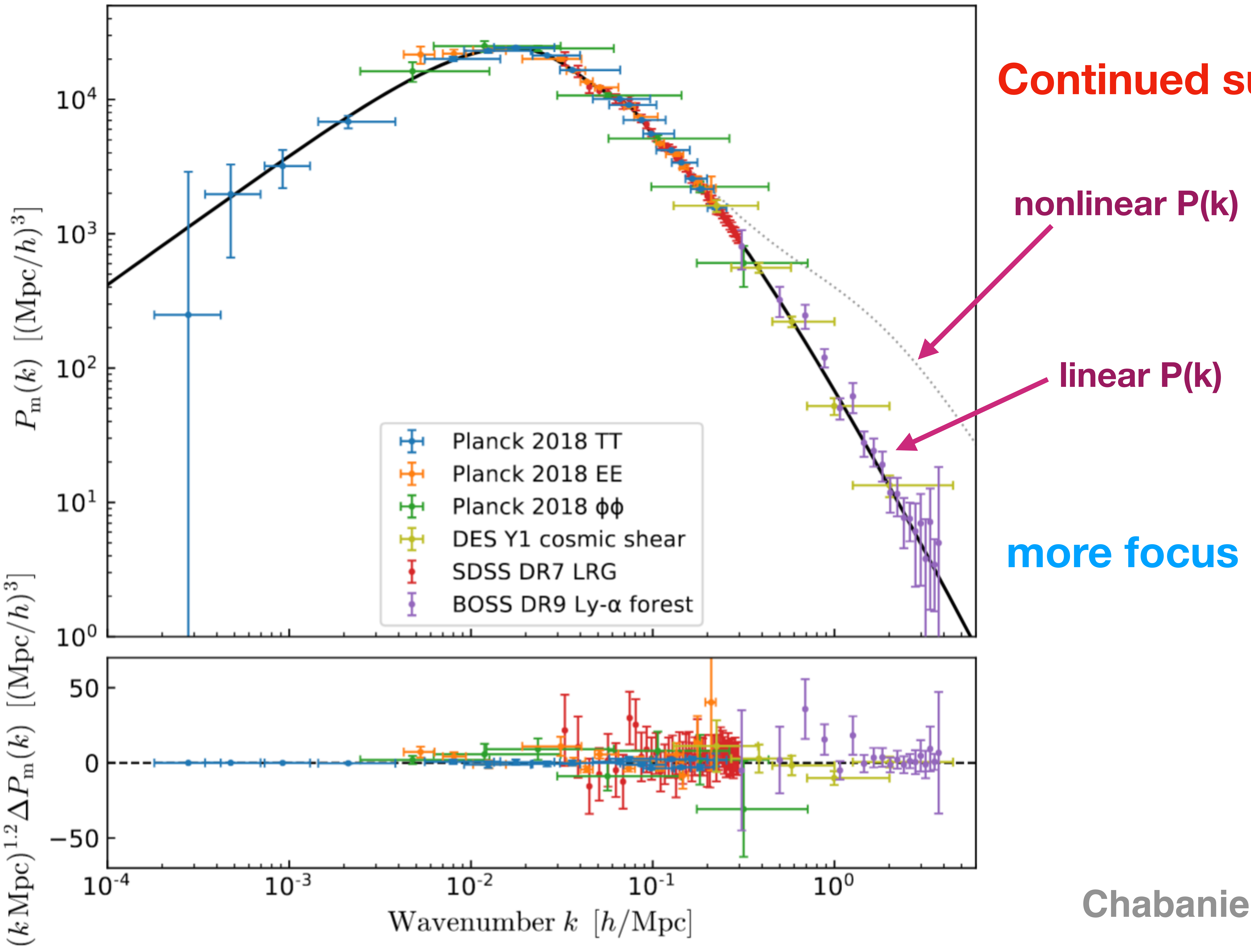
Tegmark+ (2004)

FFT

simulate



“Back-bone of structure”



Continued support for ΛCDM

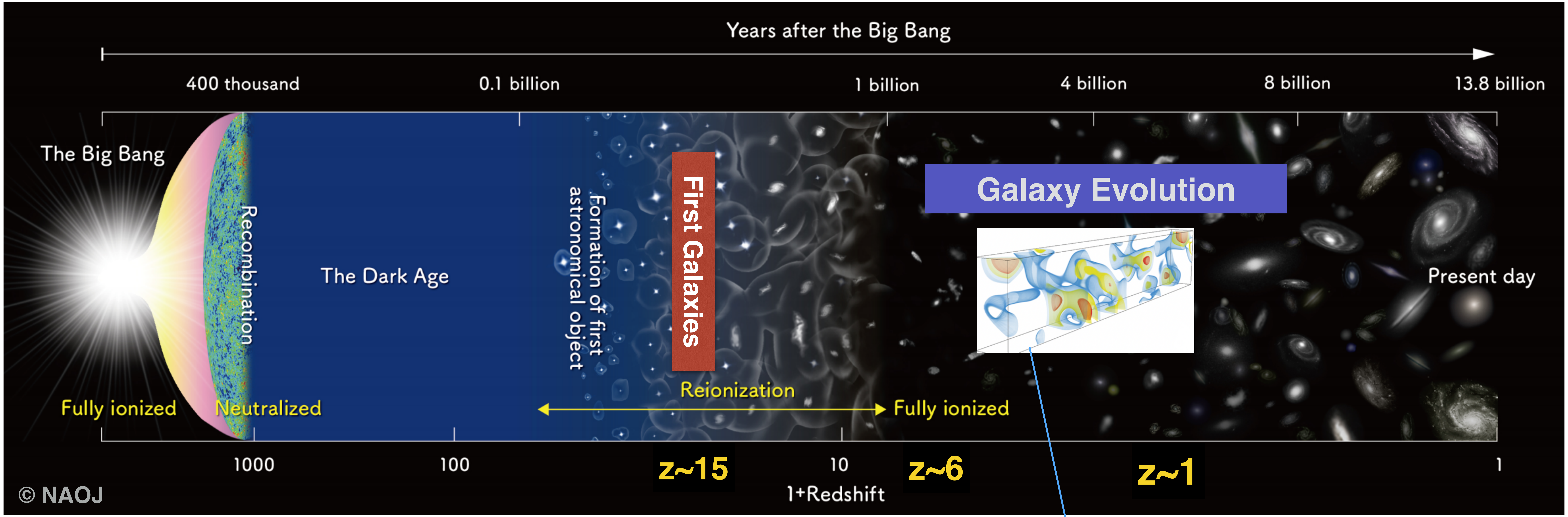
more focus on small scales

Chabanier+'19

`Standard Model' of Cosmic Structure Formation (ΛCDM)

Cosmic time

1 Gyr 6 Gyr 13.8 Gyr



JWST, ELT/TMT

PFS

HSC

~~HST~~

SKA

DES
MOONS
EUCLID…

SDSS, 2dF


1億光年
0.5 億光年
0.1 億光年
10 億光年
Uchuu simulation: Ishiyama+21

Press-Schechter Mass Function (1974)

Ansatz : Probability of $\delta_s > \delta_c(t)$ **==** fraction of mass contained in halos with mass >M

$$\mathscr{P}[>\delta_c(t)] = \frac{1}{\sqrt{2\pi}\sigma(M)} \int_{\delta_c(t)}^{\infty} \exp\left[-\frac{\delta_s^2}{2\sigma^2(M)}\right] d\delta_s = \frac{1}{2} \operatorname{erfc}\left[\frac{\delta_c(t)}{\sqrt{2}\sigma(M)}\right].$$

mass variance: $\sigma^2(M) = \langle \delta_s^2(\mathbf{x};R) \rangle = \frac{1}{2\pi^2} \int_0^{\infty} P(k)\, \widetilde{W}^2(\mathbf{k}R)\, k^2\, dk$

The mass fraction: $F(>M) = \underline{2}\,\mathscr{P}[>\delta_c(t)].$ As $M \to 0$, $\mathscr{P}[>\delta_c(t)] \to 1/2.$

fudge factor

PS mass function:

$$n(M,t)\,dM = \frac{\bar{\rho}}{M} \frac{\partial F(>M)}{\partial M} dM = 2\frac{\bar{\rho}}{M} \frac{\partial \mathscr{P}[>\delta_c(t)]}{\partial \sigma} \left|\frac{d\sigma}{dM}\right| dM$$

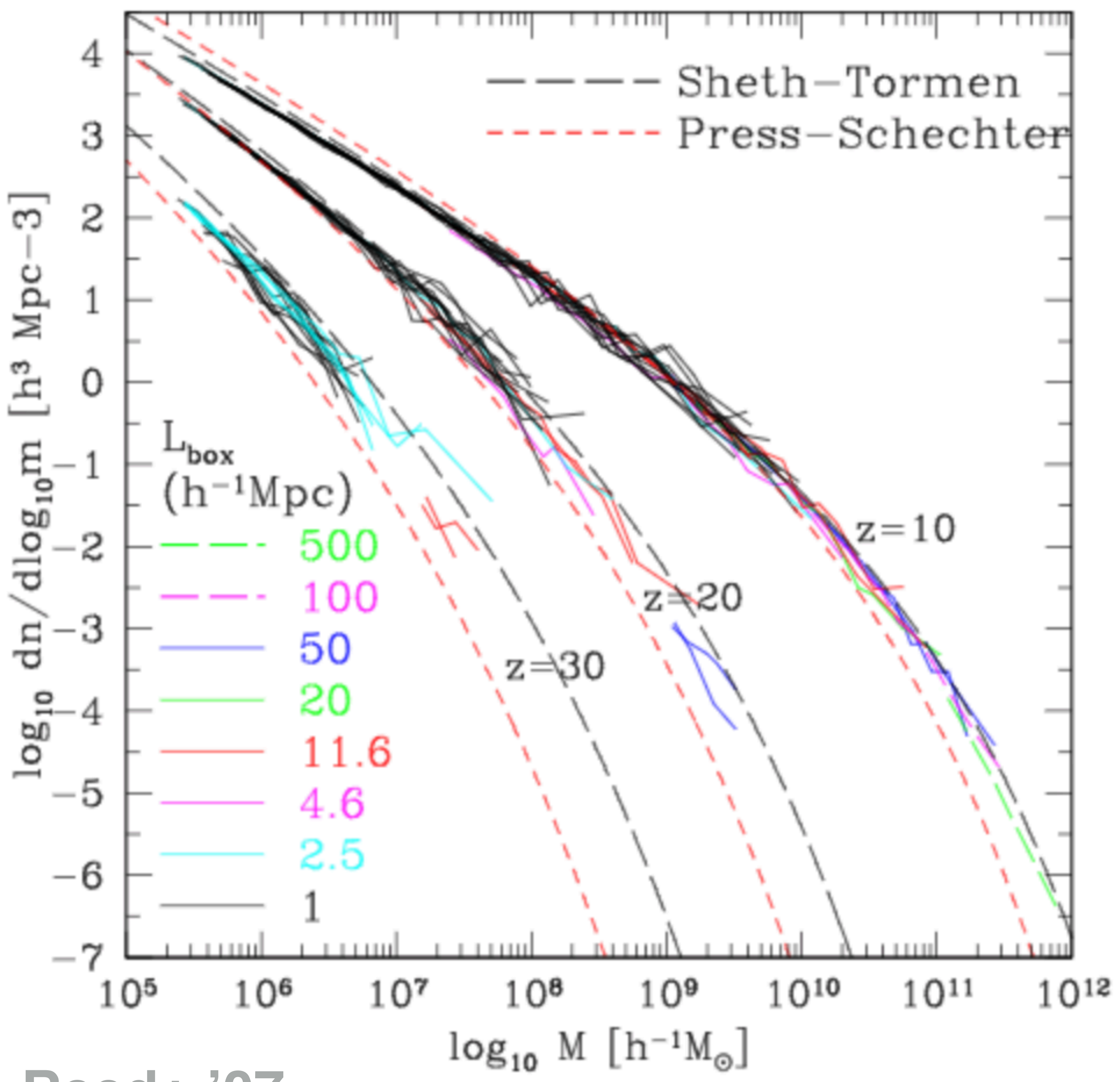
$$= \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M^2} \frac{\delta_c}{\sigma} \exp\left(-\frac{\delta_c^2}{2\sigma^2}\right) \left|\frac{d\ln\sigma}{d\ln M}\right| dM.$$

or,

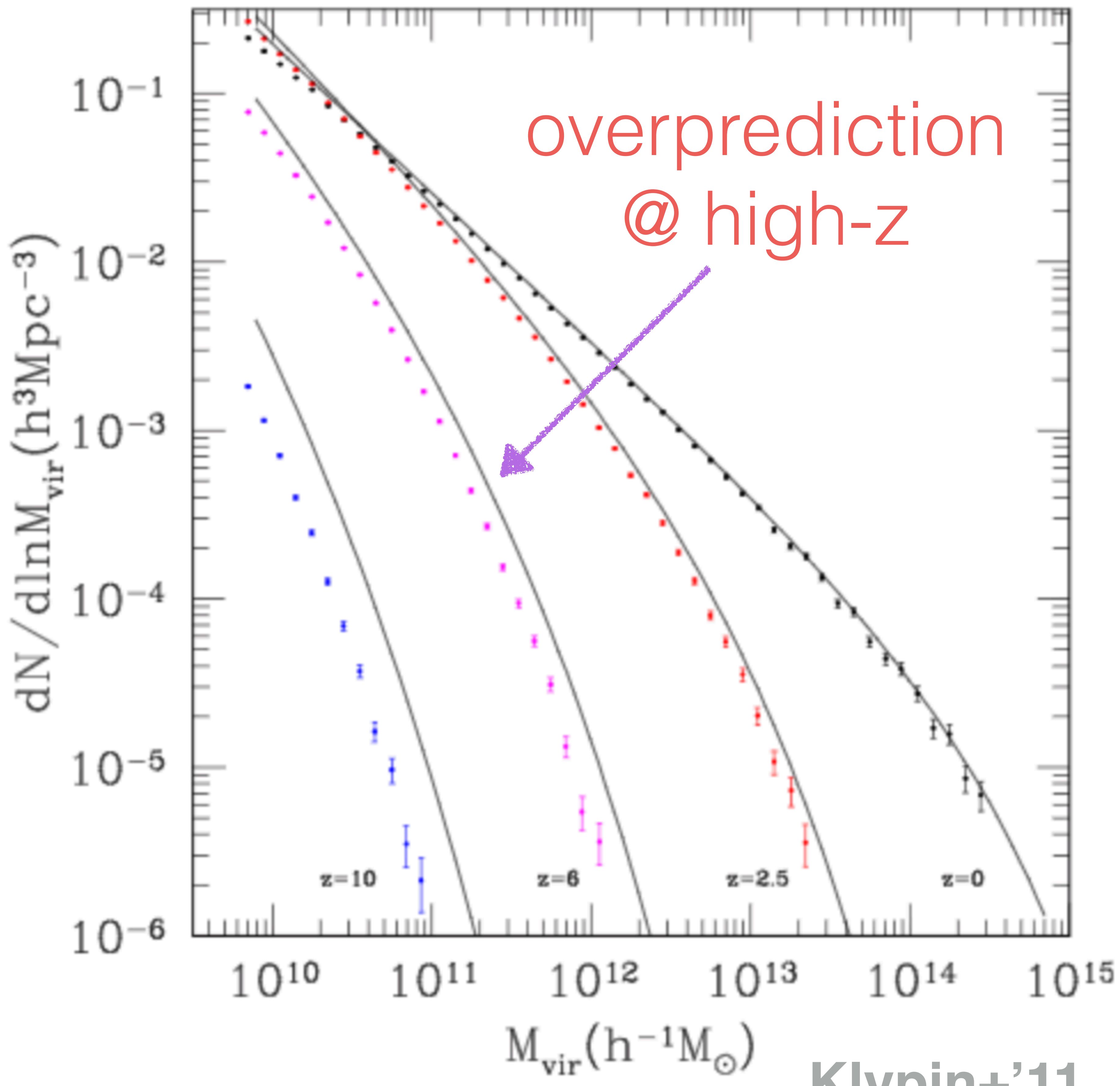
$$n(M_h, z)dM_h = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M_h^2} \nu e^{-\nu^2/2} \left|\frac{d\ln\nu}{d\ln M_h}\right| dM_h,$$

$\nu = \delta_c(t)/\sigma(M)$

Comparison with N-body simulation



Reed+ '07



Klypin+'11

$$n(M,z)\,\mathrm{d}M = A\left(1+\frac{1}{\nu'^{2q}}\right)\sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M}\frac{\mathrm{d}\nu'}{\mathrm{d}M}\exp\left(-\frac{\nu'^2}{2}\right)\mathrm{d}M,$$

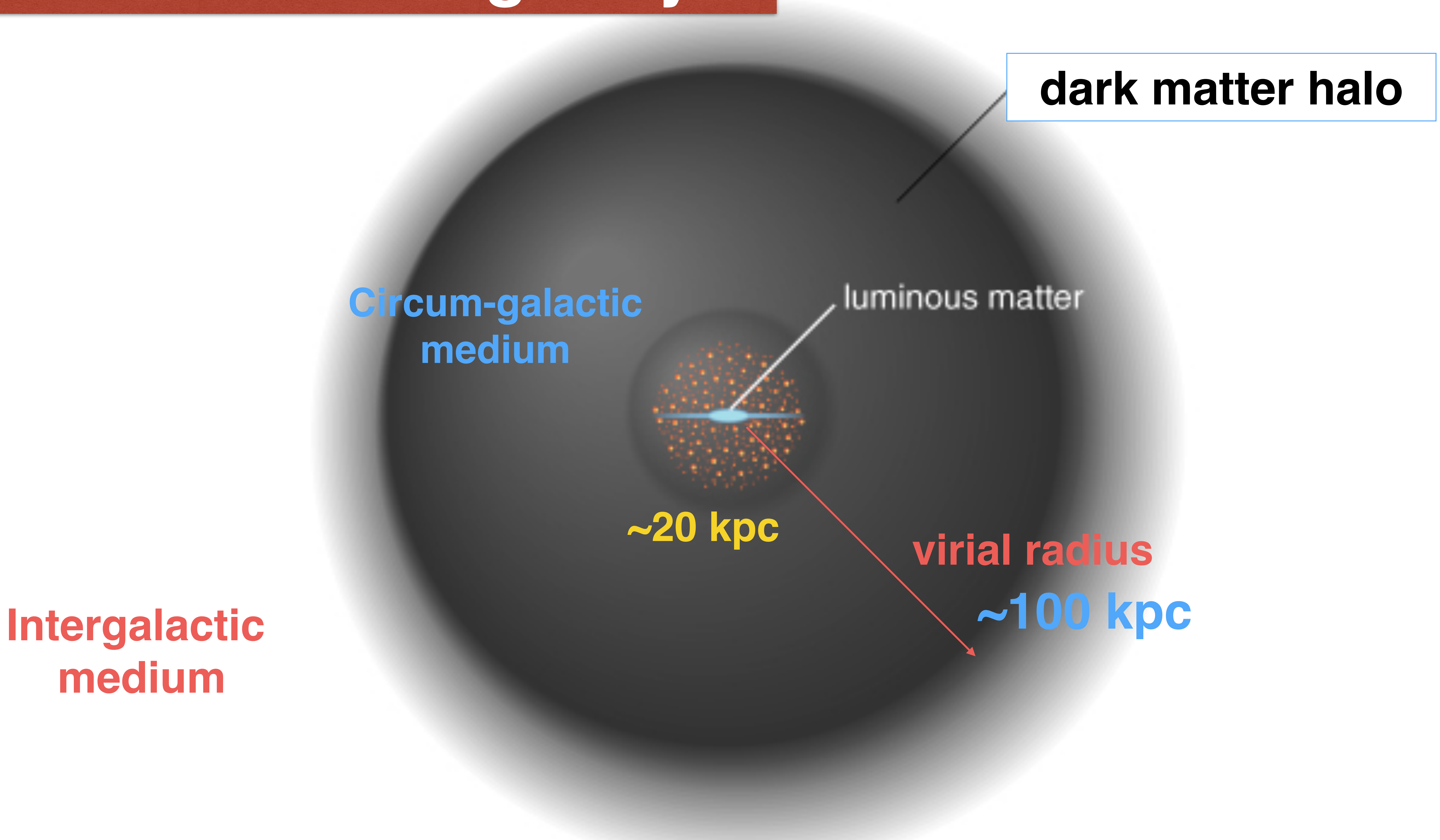
(Sheth & Tormen '99)

ellipsoidal collapse

$$\nu' = \sqrt{a}\,\nu,\ a = 0.707,\ A \approx 0.322\ \text{and}\ q = 0.3.$$

(see also Mo & White '02)

DM halo & central galaxy



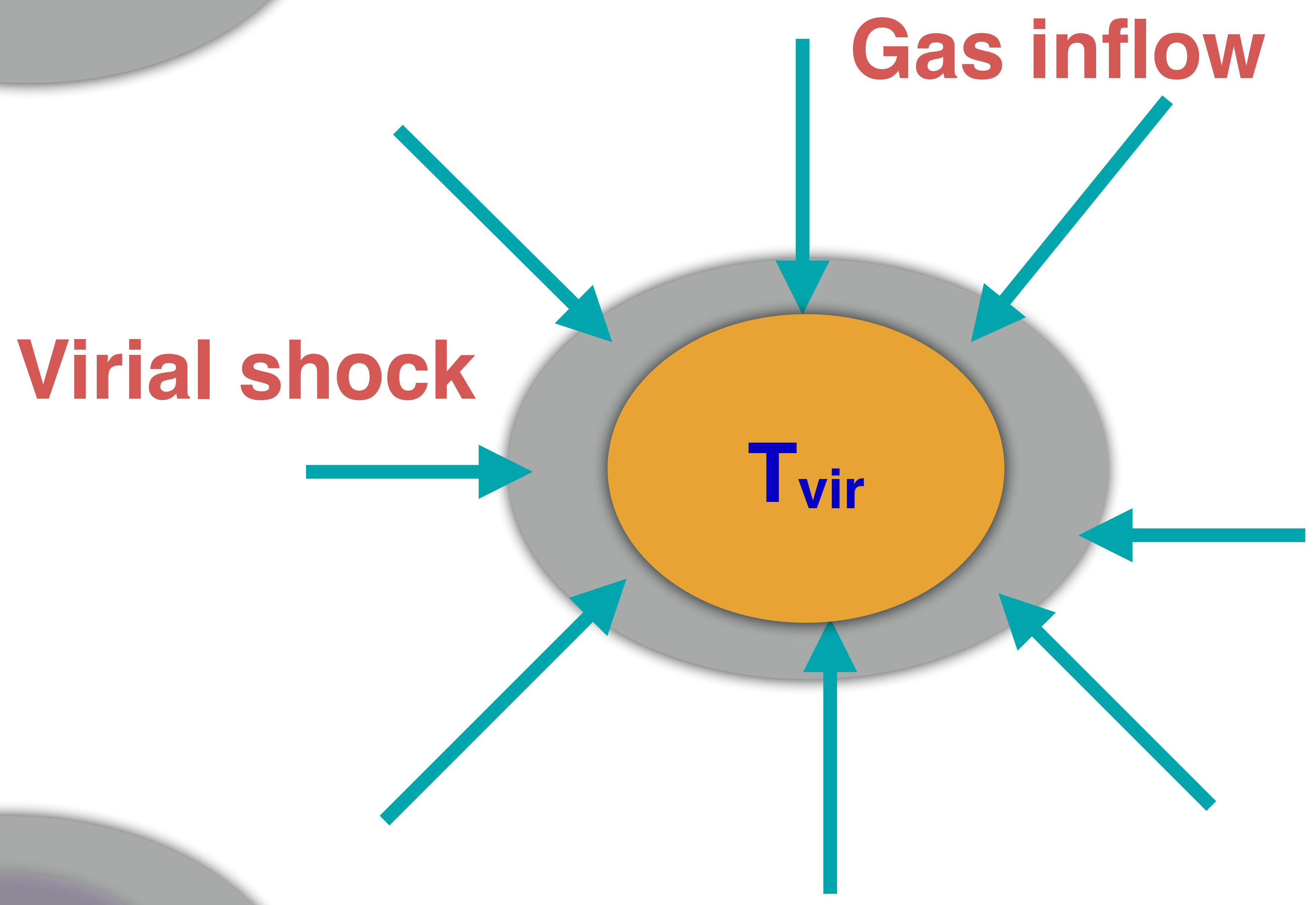
(cf. Spherical collapse model)

1st-order Galaxy Formation

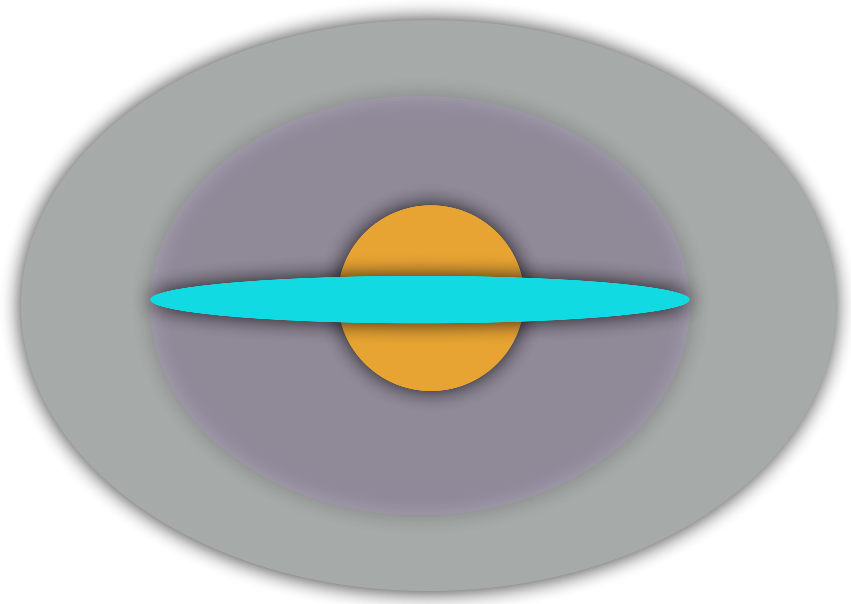
DM halo forms.

“spherical cow”

Gas infall
& shock heating



Gas dissipates,
cools,
& forms a disk.

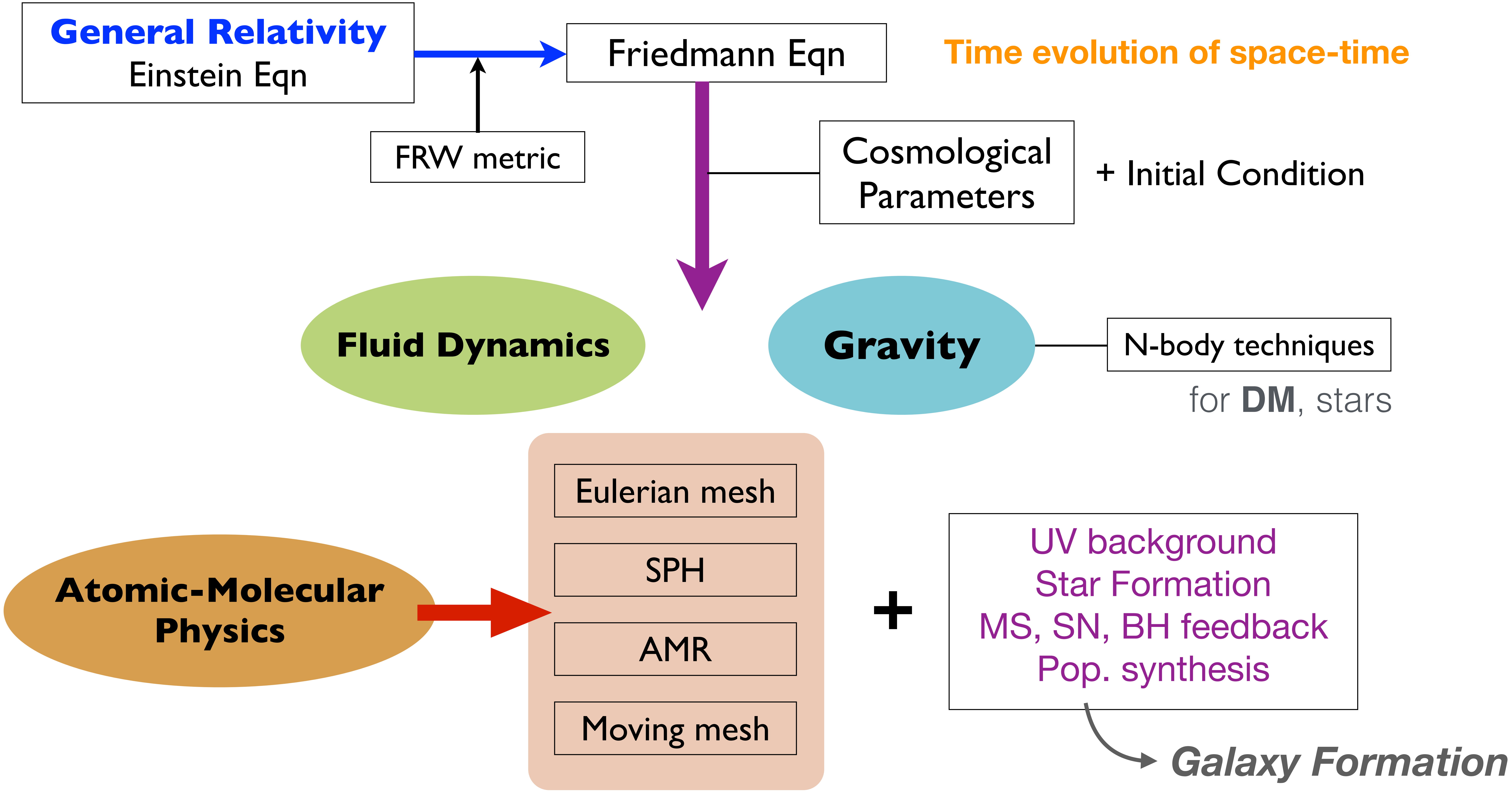


$$R_{\rm d} = \frac{1}{\sqrt{2}}\left(\frac{j_{\rm d}}{m_{\rm d}}\right)\lambda r_{200}$$

Star, Galaxy Formation

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

Framework of Computational Cosmology

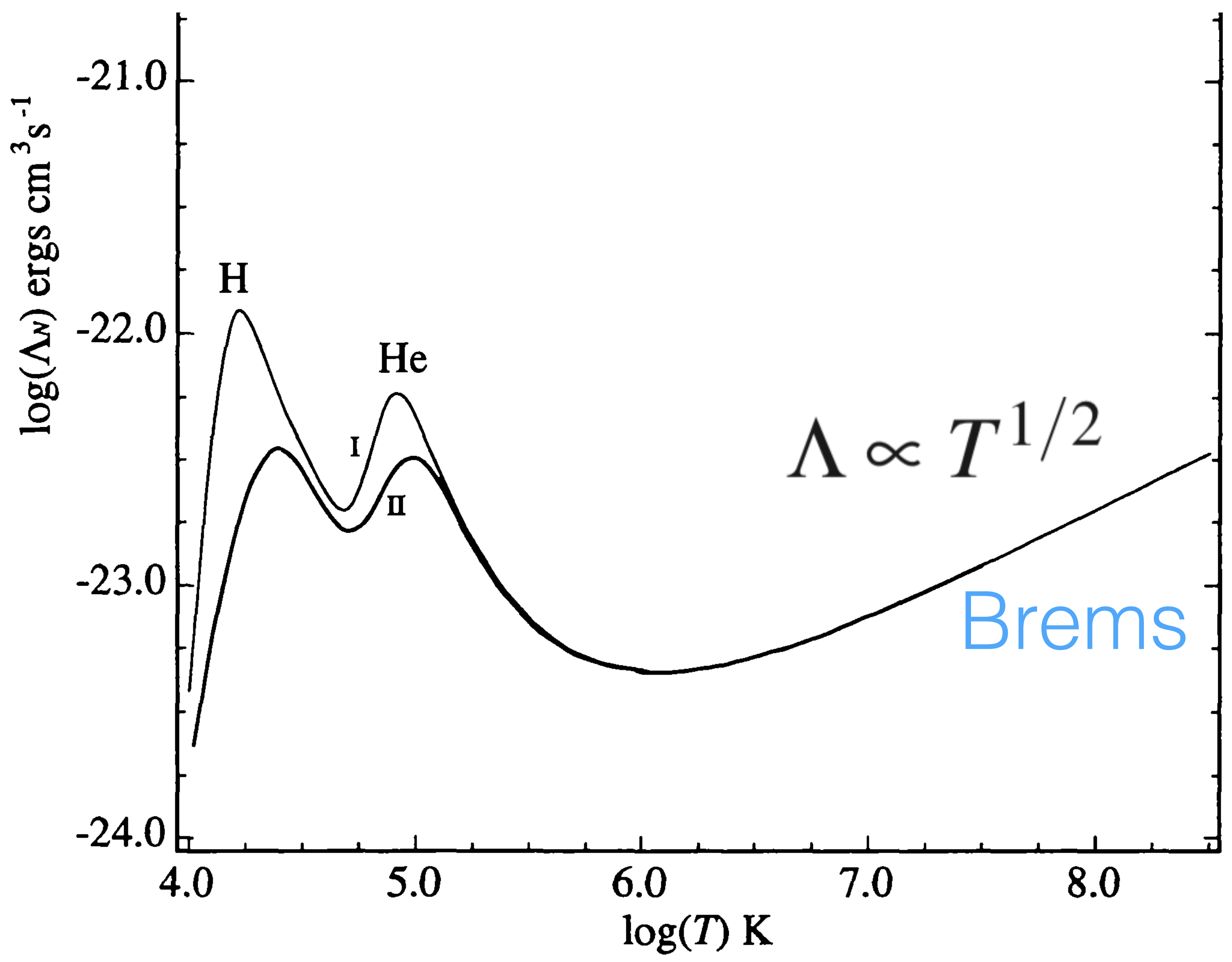


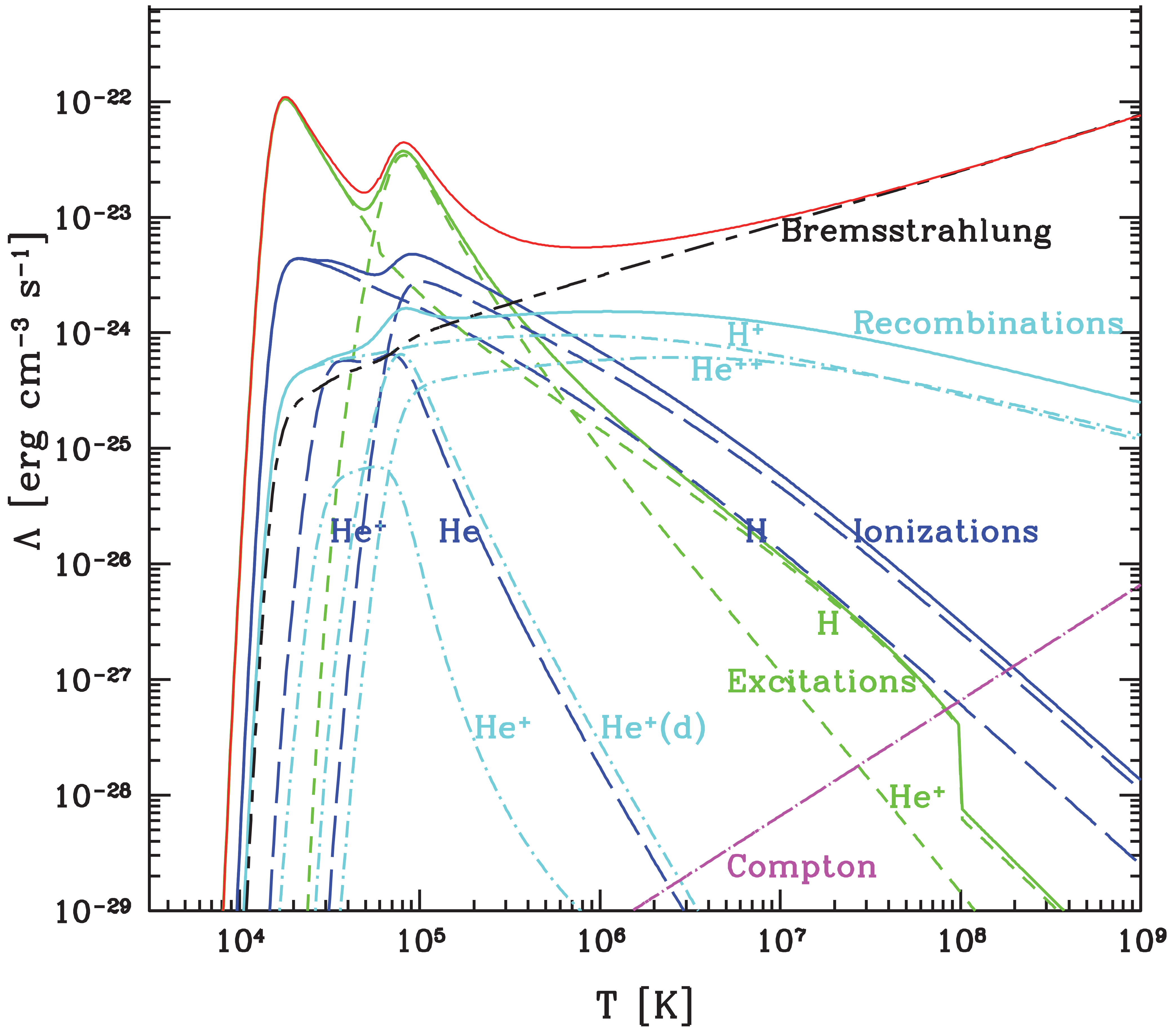
Cooling Curve

(Radiative Cooling Rate/Function)

Primordial Gas — optically thin gas

Sutherland & Dopita '93



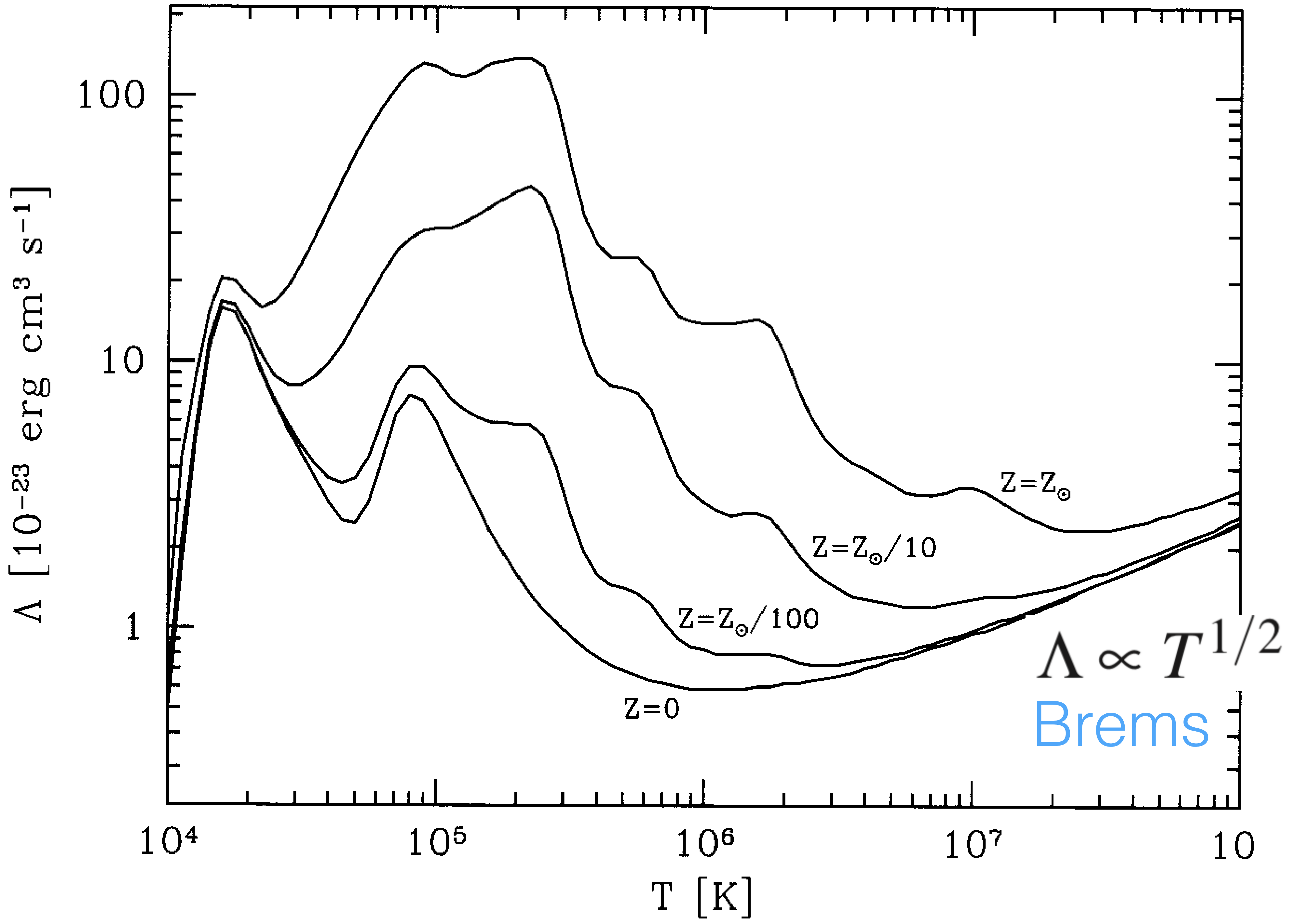


$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\rm H}^2},$$ **[erg cm^3 s^{-1}]**

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

Cen '92; Katz+'96

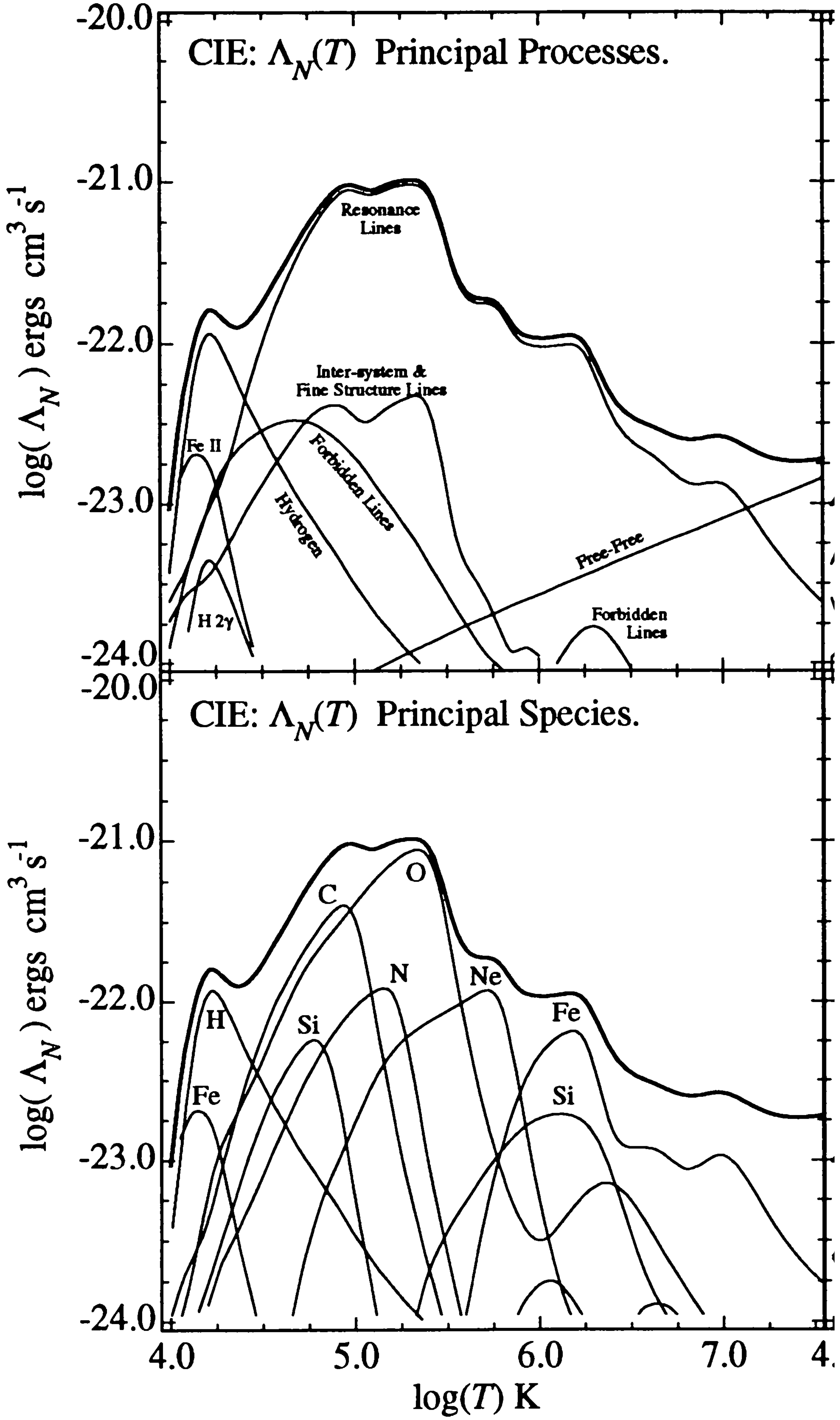
Sutherland & Dopita 1993, ApJS, 88, 253



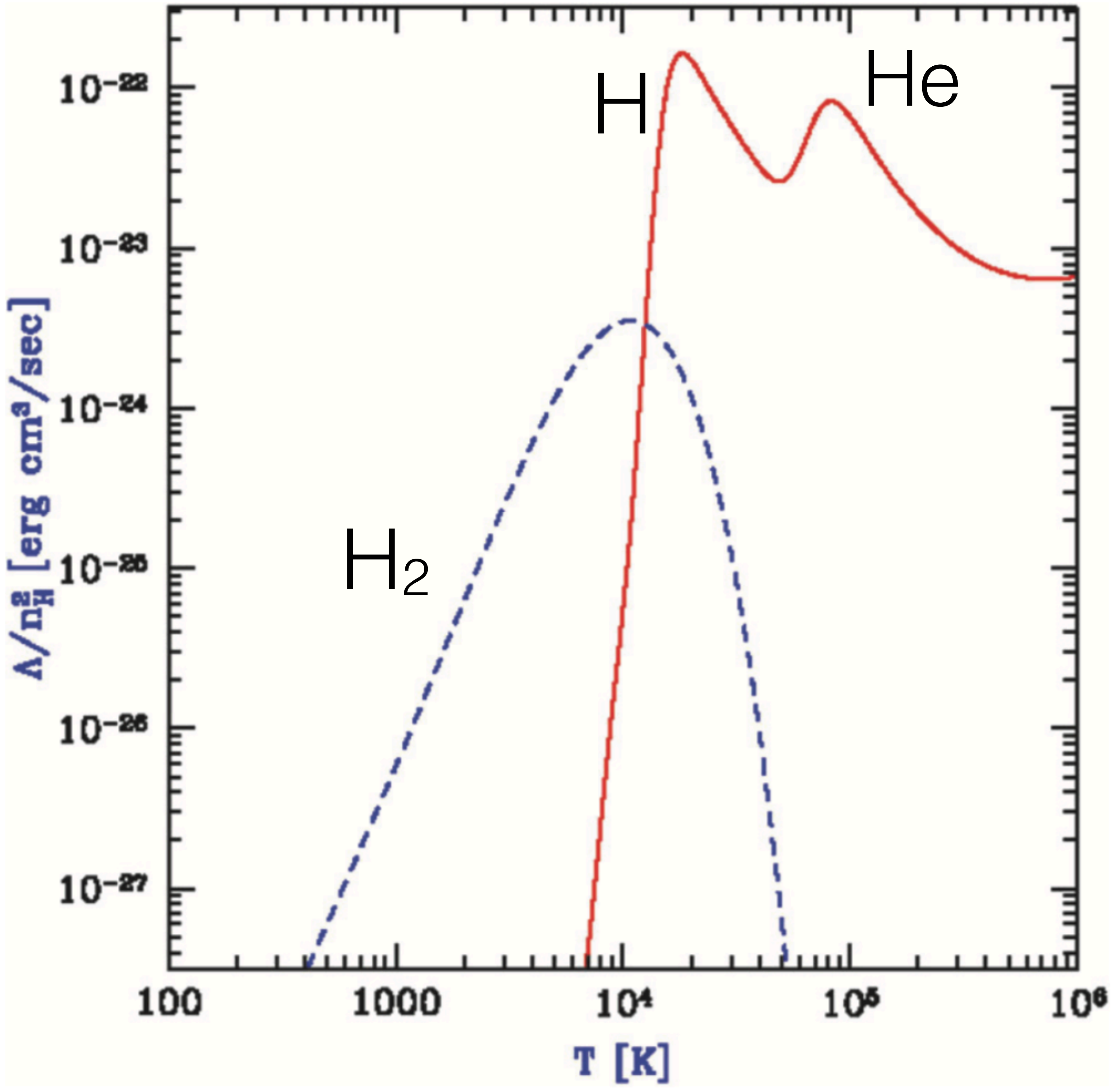
$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\mathrm{H}}^2},$$ **[erg cm³ s⁻¹]**

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

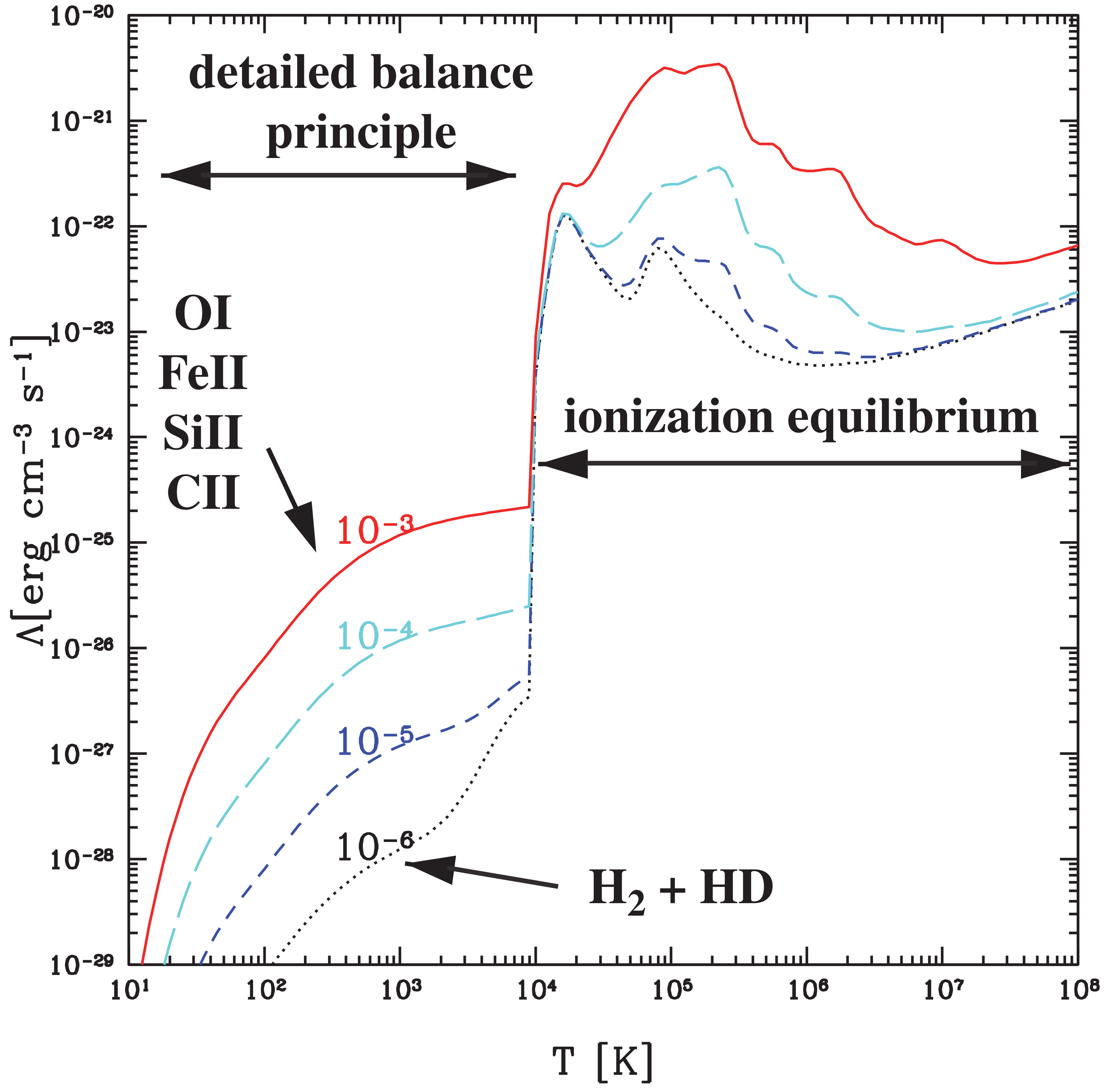
[erg cm⁻³ s⁻¹]



Cooling Curve @ $T<10^4$ K



Barkana & Loeb '01

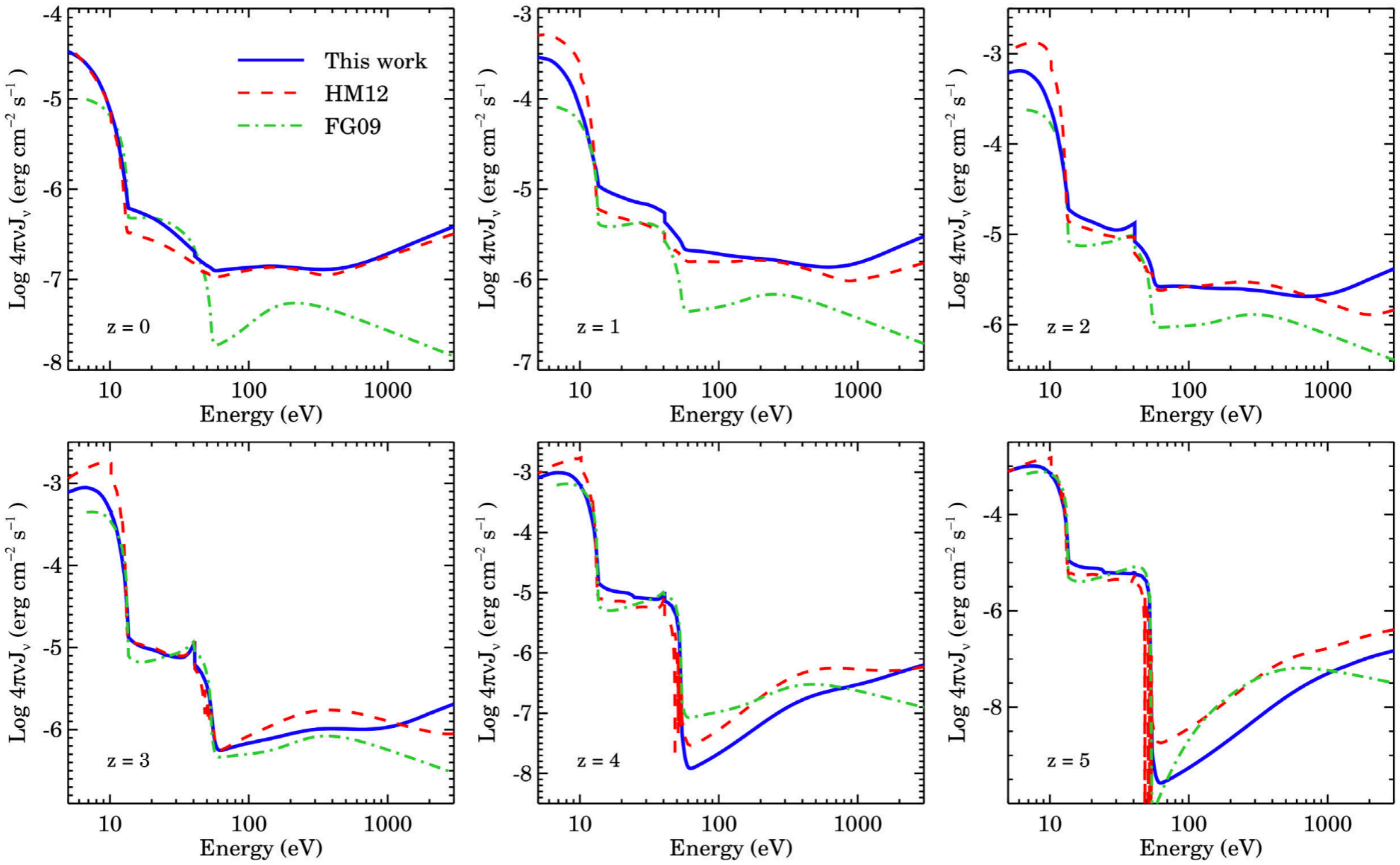


Maio+'07

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

UV background (UVB) radiation

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

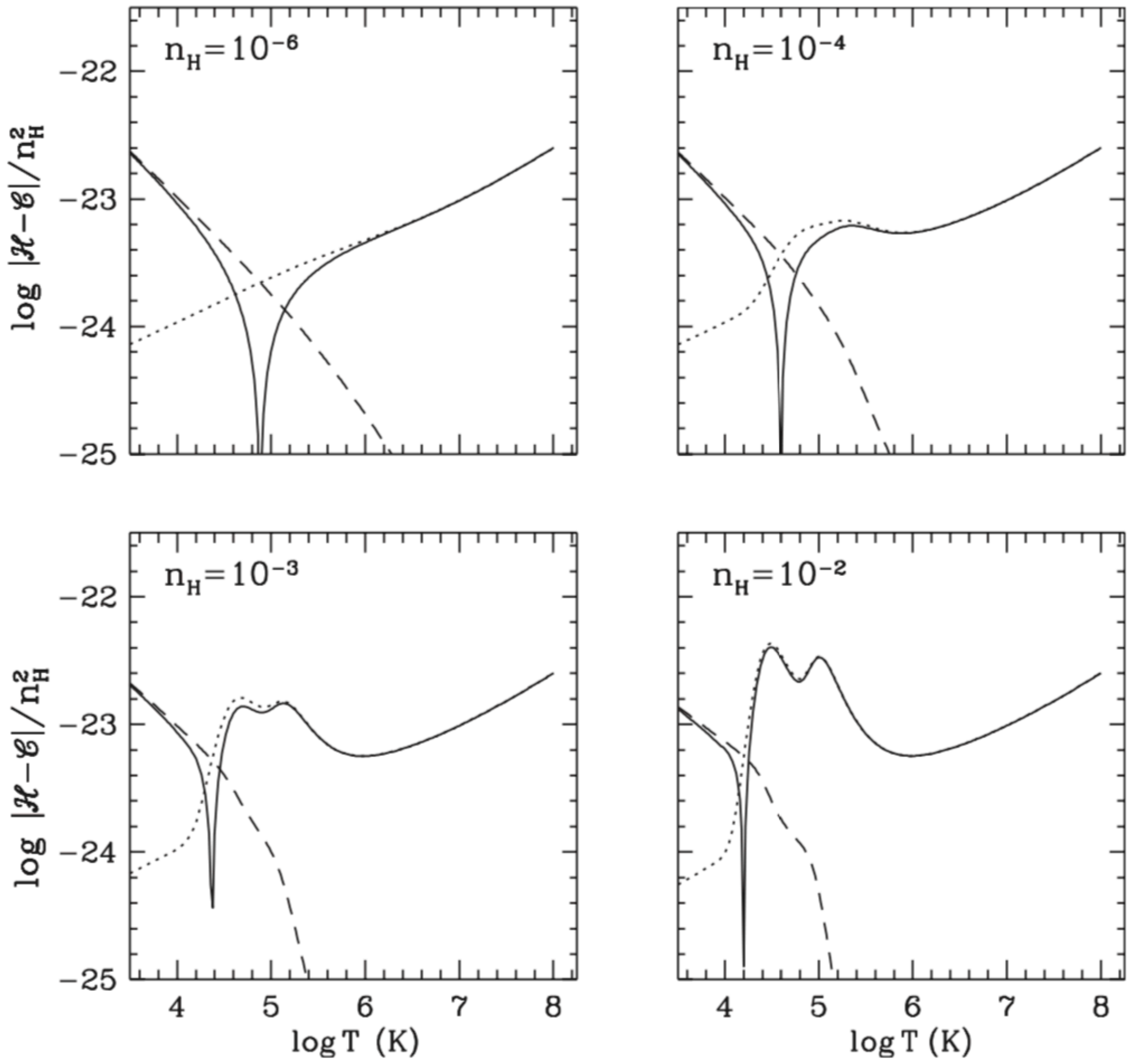


red: HM12 green: FG09

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

Net cooling rate with heating

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



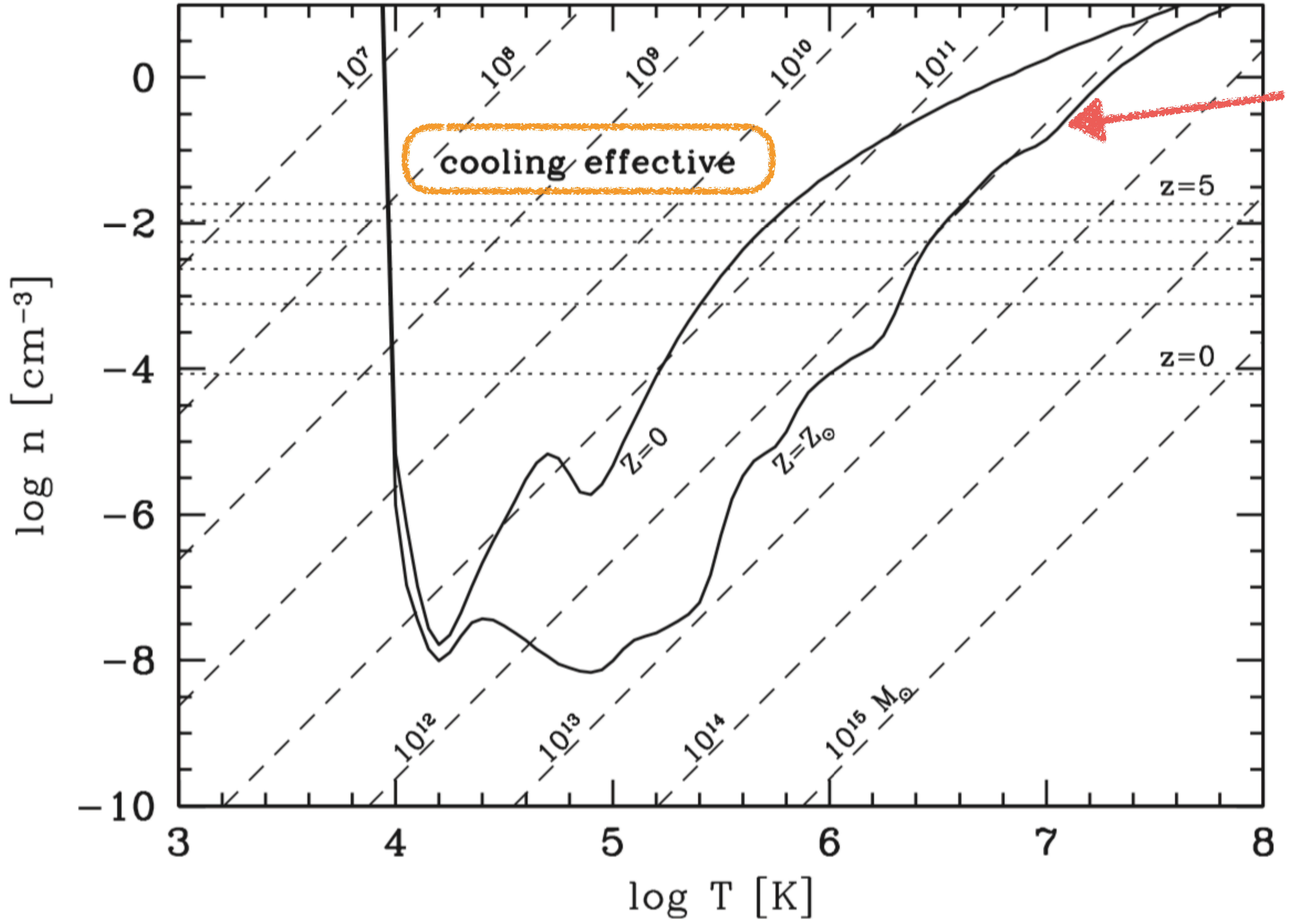
dotted: cooling rate

dashed: photo-ioniz. heating rate

Weinberg+'97

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

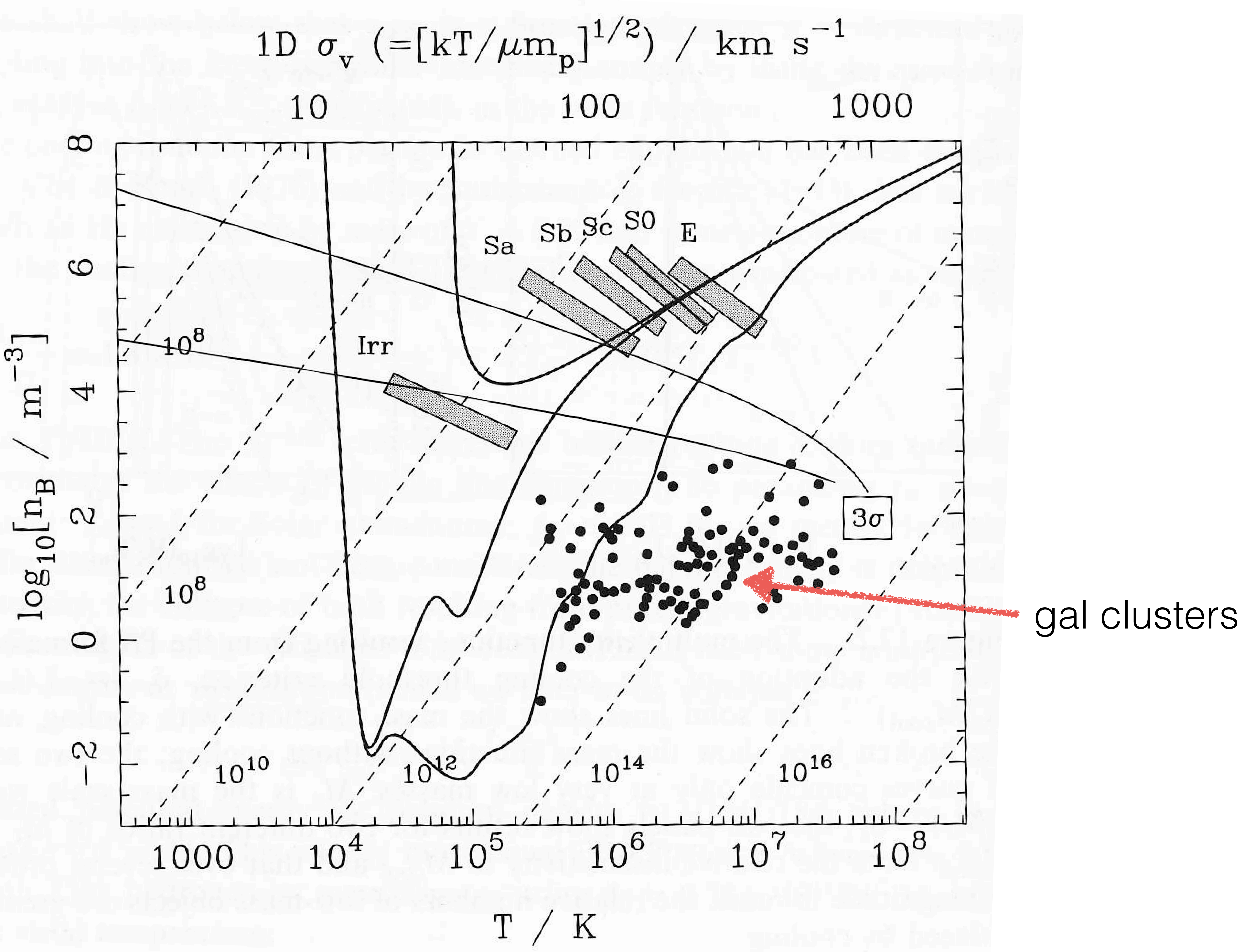
equilibrium curve



$t_{\rm cool} = t_{\rm ff}$

$$t_{\rm cool} \equiv \frac{\rho \mathscr{E}}{\mathscr{C}} = \frac{3nk_{\rm B}T}{2n_{\rm H}^2 \Lambda(T)} \approx 3.3 \times 10^9 \frac{T_6}{n_{-3}\Lambda_{-23}(T)}\,{\rm yr},$$

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}} = \sqrt{\frac{3\pi f_{\rm gas}}{32Gn\mu m_{\rm p}}} \approx 2.1 \times 10^9 f_{\rm gas}^{1/2} n_{-3}^{-1/2}\,{\rm yr}, \qquad \propto \frac{1}{\sqrt{G\rho}}$$

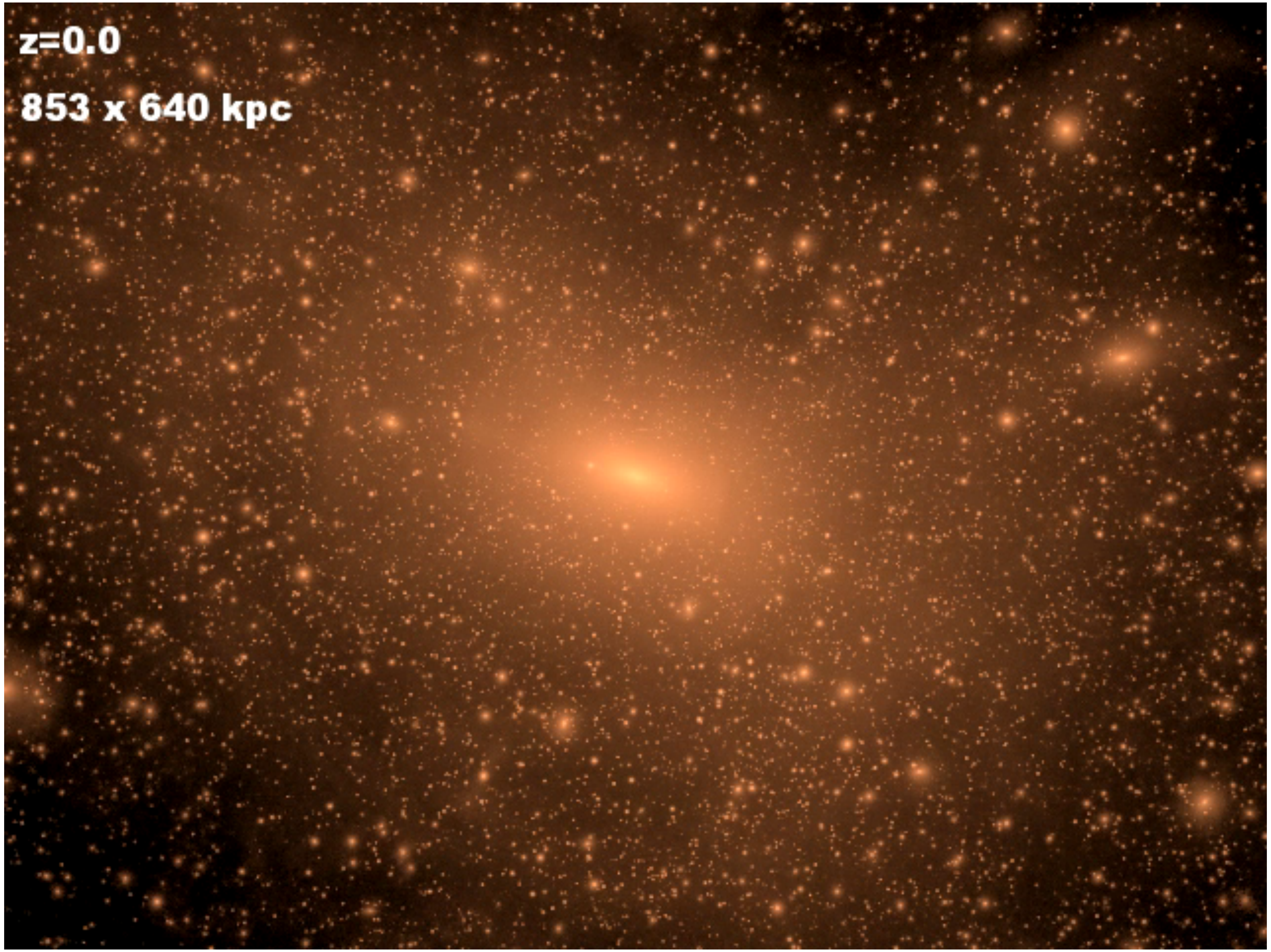


Blumenthal+'84; Peacock textbook, p.572

ΛCDM challenged by small-scale problems?

- **Cusp-Core problem —** simulations predict steeper inner DM halo profile
  Flores & Primack '94; Moore '94
- **Missing satellites problem —** too much substructure?
  Klypin+'99; Moore+'99
- **Too-big-to-fail problem —** overabundance of massive & dense substructures (in CDM) that could host gals after reionization
  Boylan-Kolchin+'11
- **Void phenomenon:** gals in voids are too normal?
  Peebles '01
- **Satellite plane problem:** satellites aligned in a plane for both MW and Andromeda
- ….

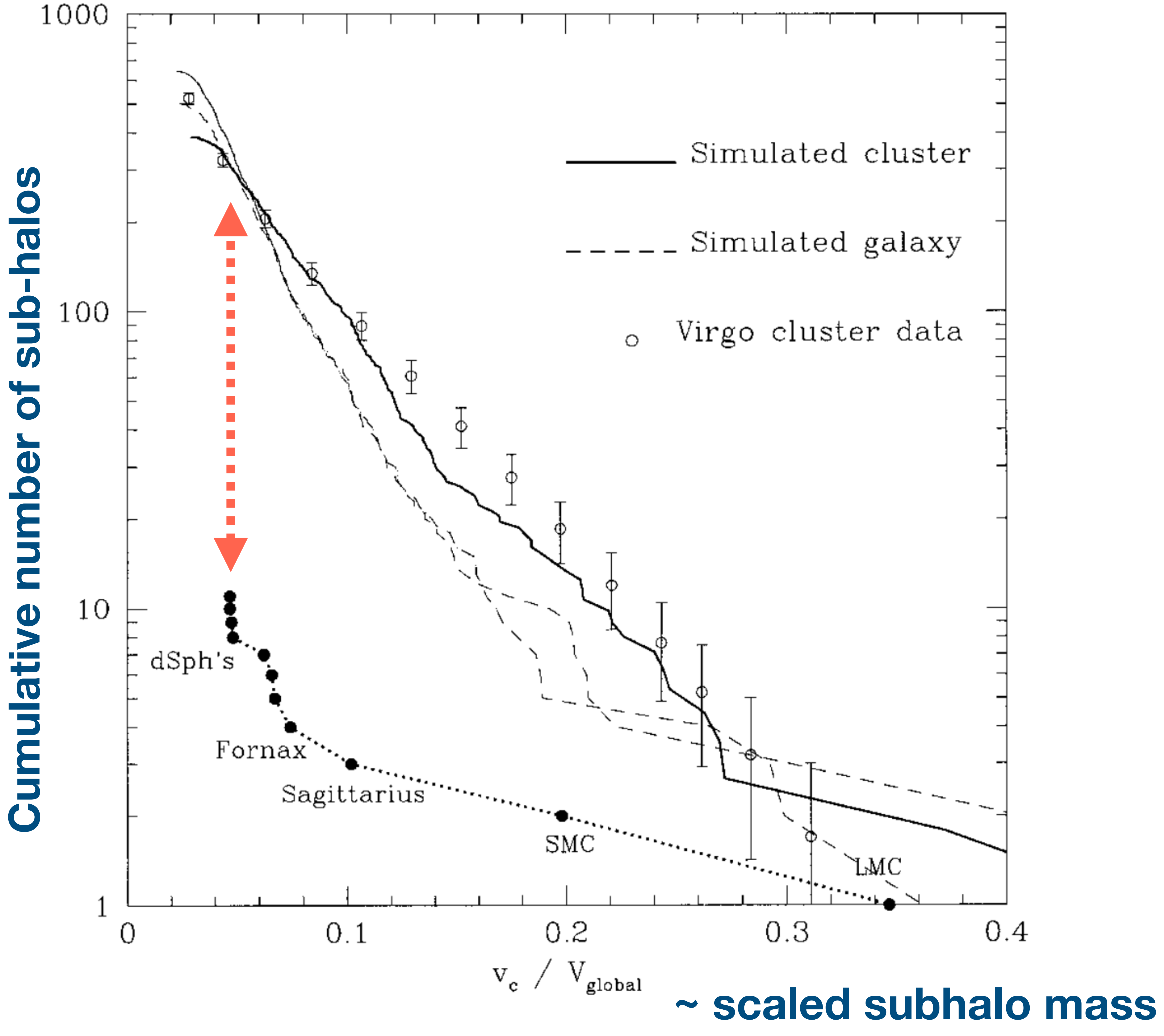
Substructure problem?



Movie

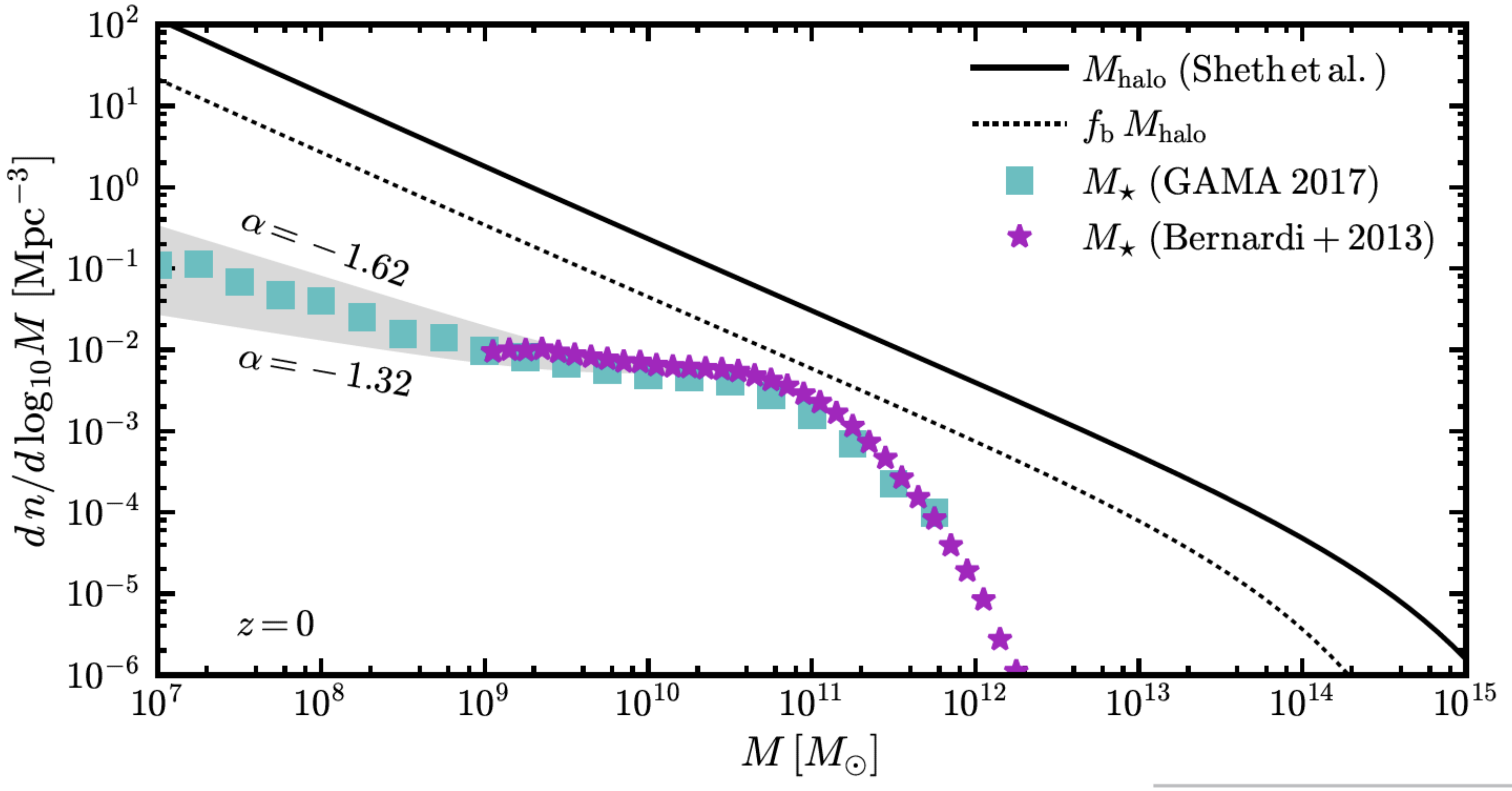
Diemand+'06

Original Substructure Problem



Klypin+'99; Moore+'99

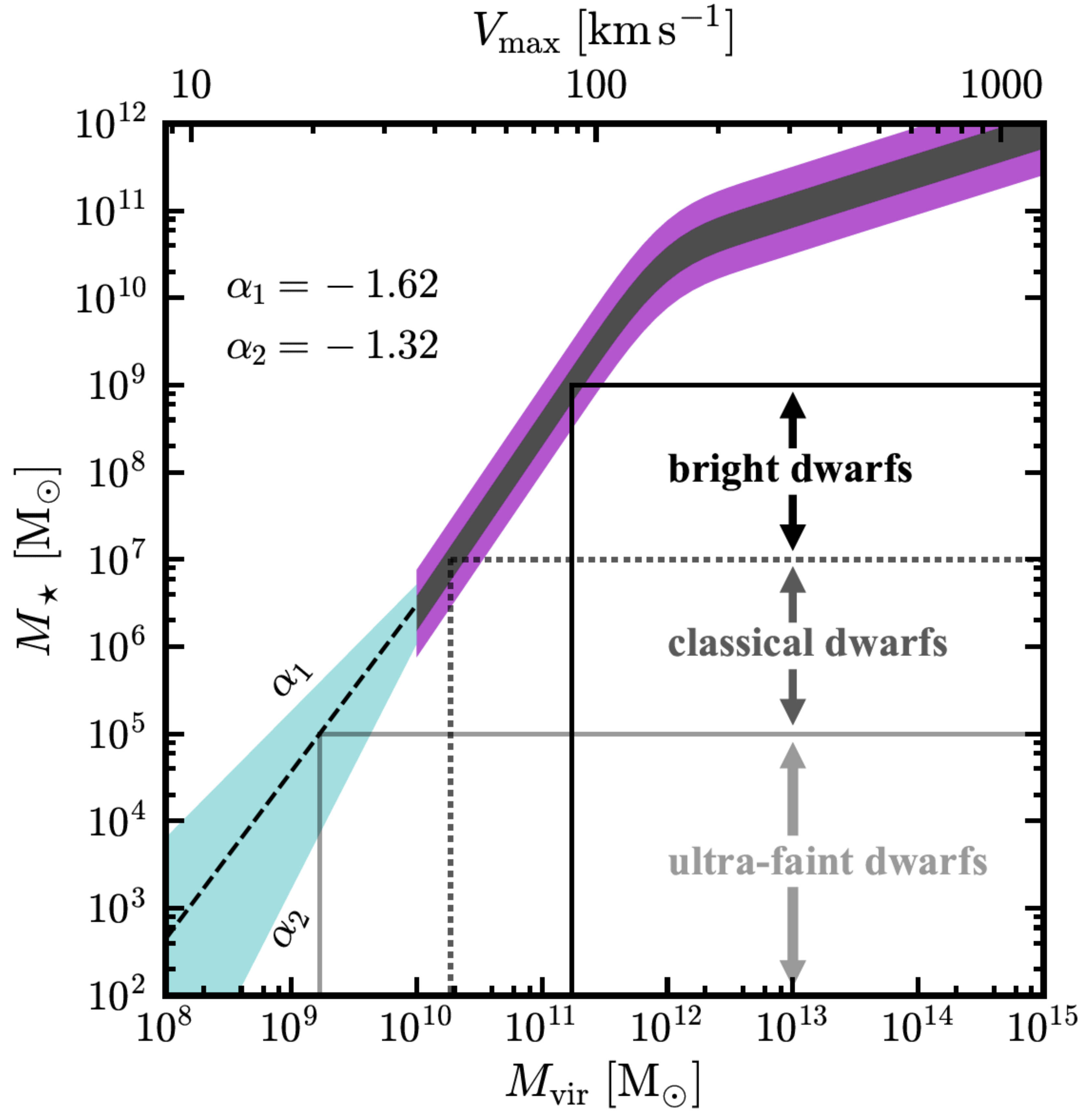
Abundance Matching (AM) technique



Bright Dwarfs:
$M_\star \approx 10^8 M_\odot$
$M_{\rm vir} \approx 10^{11} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-3}$

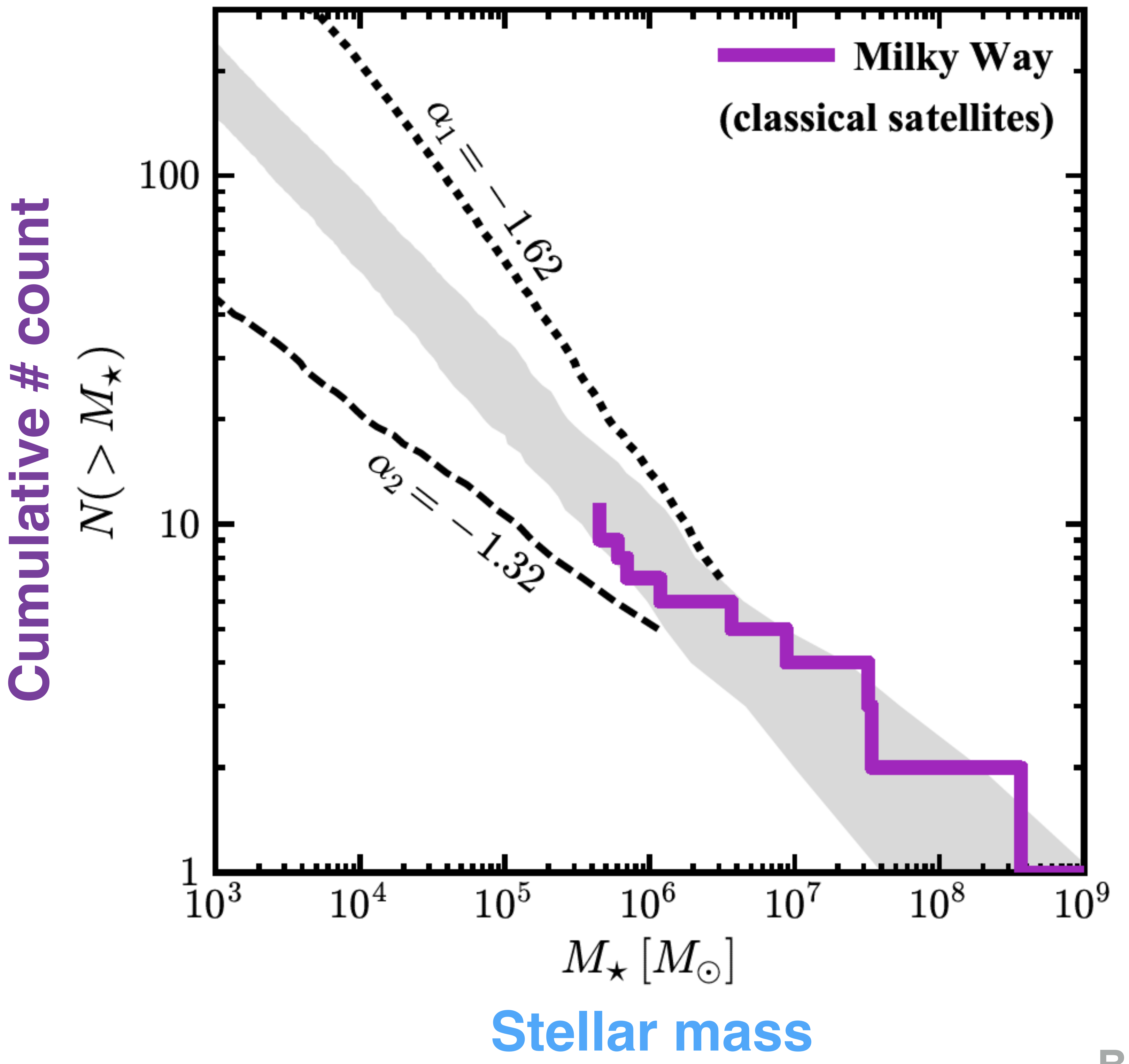
Classical Dwarfs:
$M_\star \approx 10^6 M_\odot$
$M_{\rm vir} \approx 10^{10} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-4}$

Ultra-faint Dwarfs:
$M_\star \approx 10^4 M_\odot$
$M_{\rm vir} \approx 10^9 M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-5}$



Bullock & Boylan-Kolchin '17

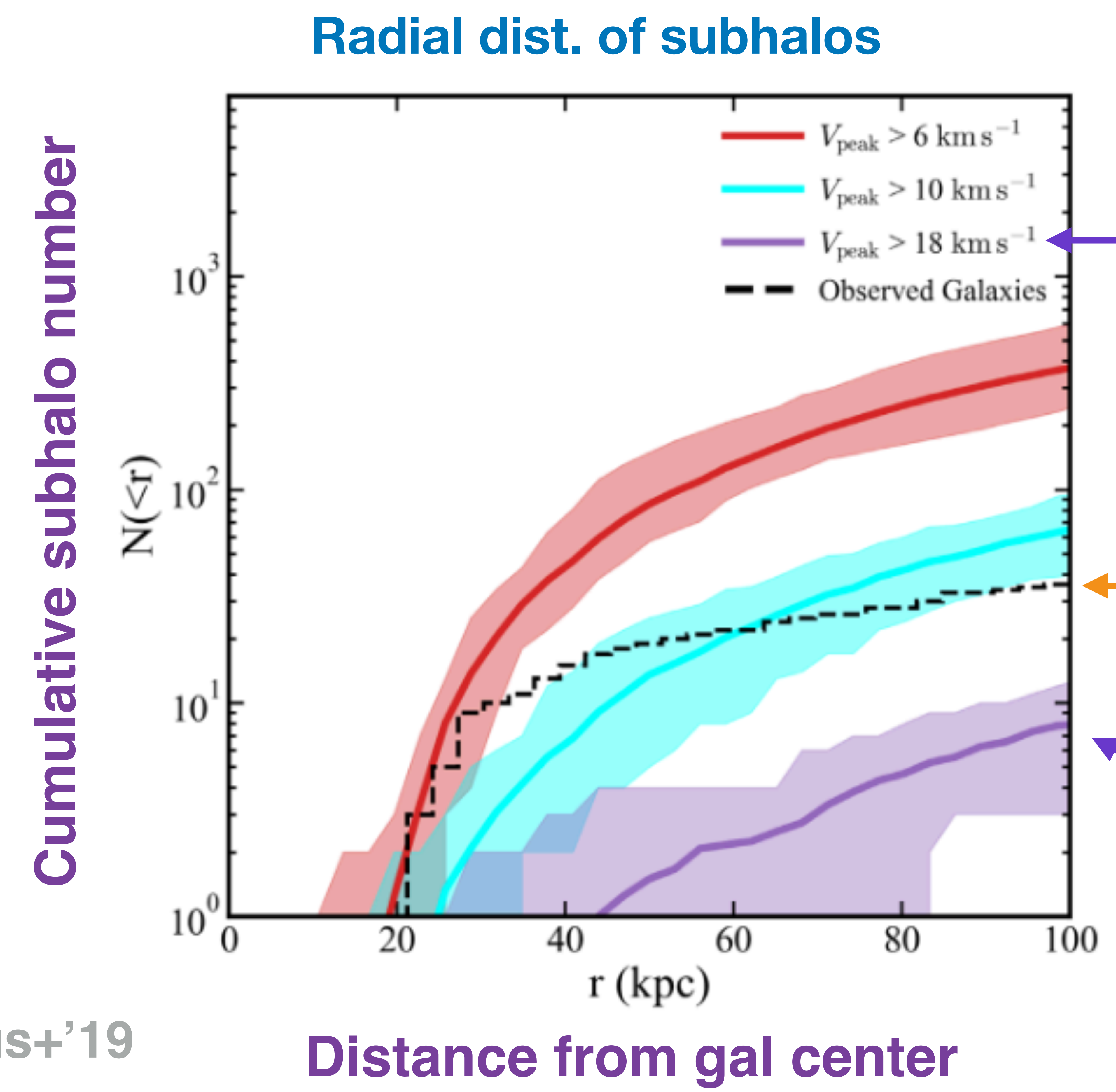
Substructure Problem Solved?



Garrison-Kimmel+'17

Bullock & Boylan-Kolchin '17

No more Missing Satellites Problem??



Graus+'19

~ *reionization suppression scale* ($M_h \sim 10^8\, M_\odot,\ T_{vir} \sim 10^4\, K$)

(subhalos below this mass cannot host UFDs due to photo-heating by UVB)

~40-50 known ultra-faint dwarfs

"Too many satellites problem"

Not enough dwarf gals in hydro sims if you populate only above the reionization suppression scale.

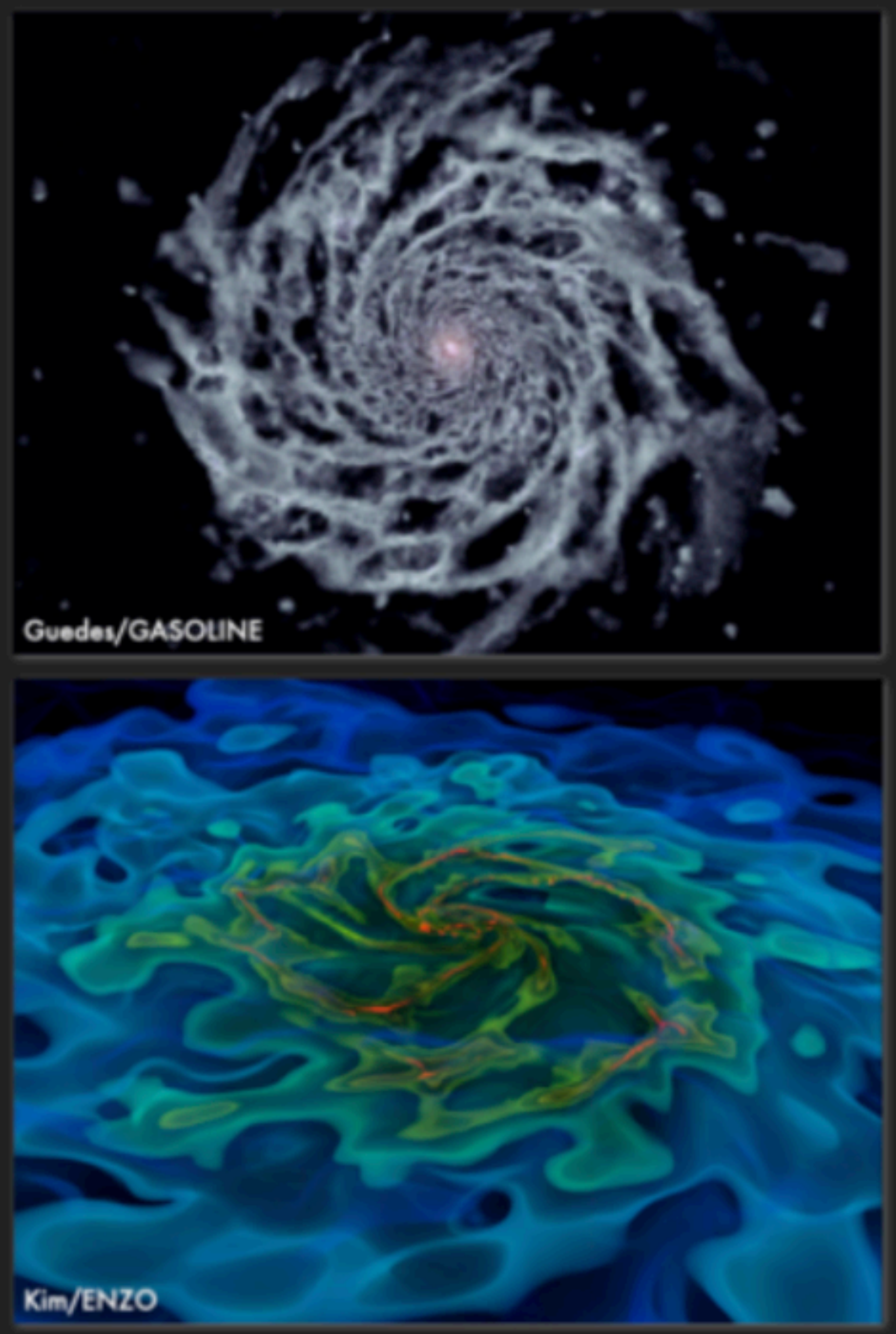
Latest obs by: **SDSS, Pan-STARRS, DES, MagLiteS,…**

cf. Garrison-Kimmel+'17; Jethwa+18; Kim+'18; Li+19 http://agorasimulations.org

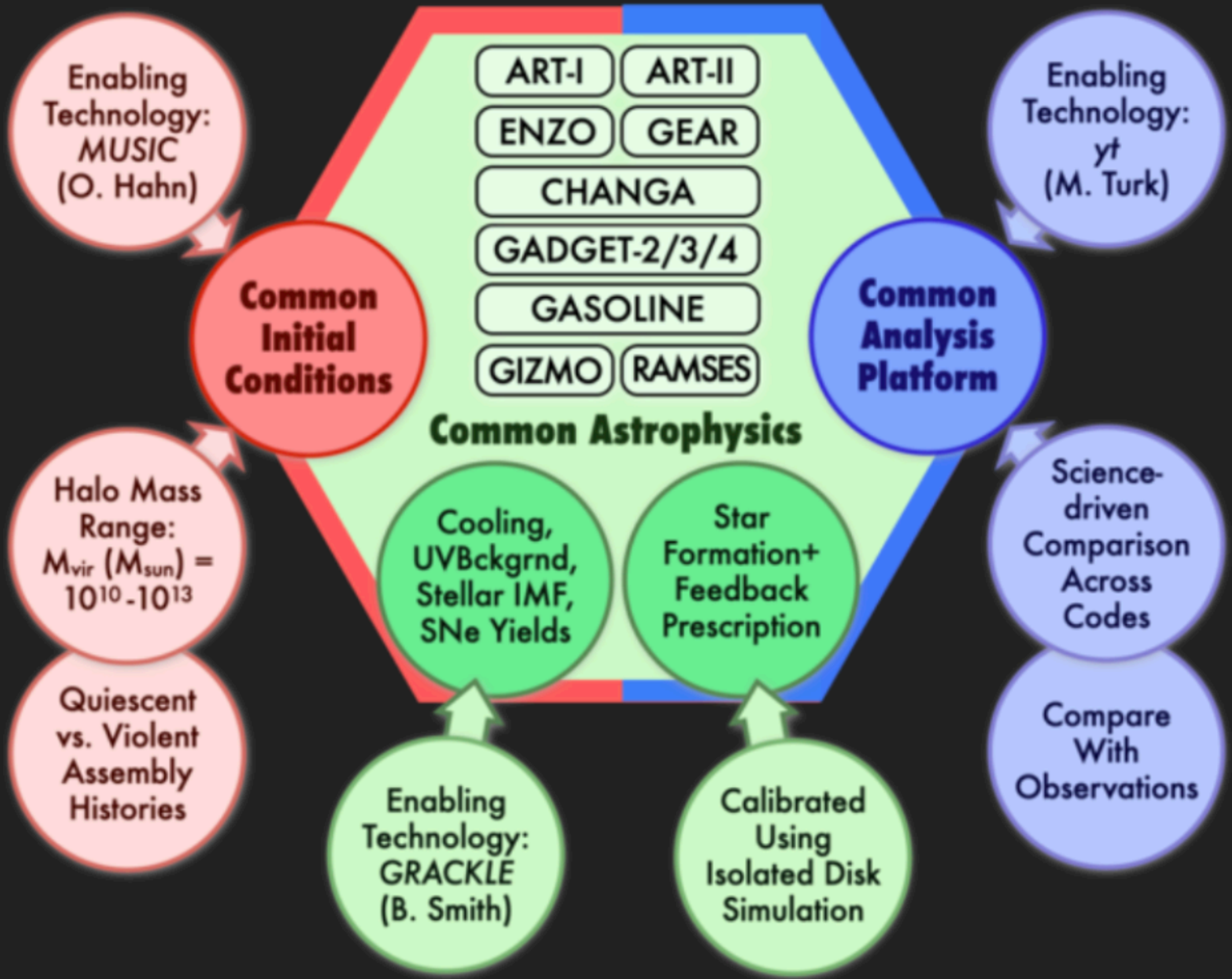
AGORA

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

High-res Galaxy Simulations



AGORA Comparison Infrastructure



AGORA Goal & Team

- GOAL: A collaborative, multi-platform study to raise the realism and predictive power of galaxy formation simulations
- TEAM: 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)

data release on Flathub: http://flathub.flatironinstitute.org/agora

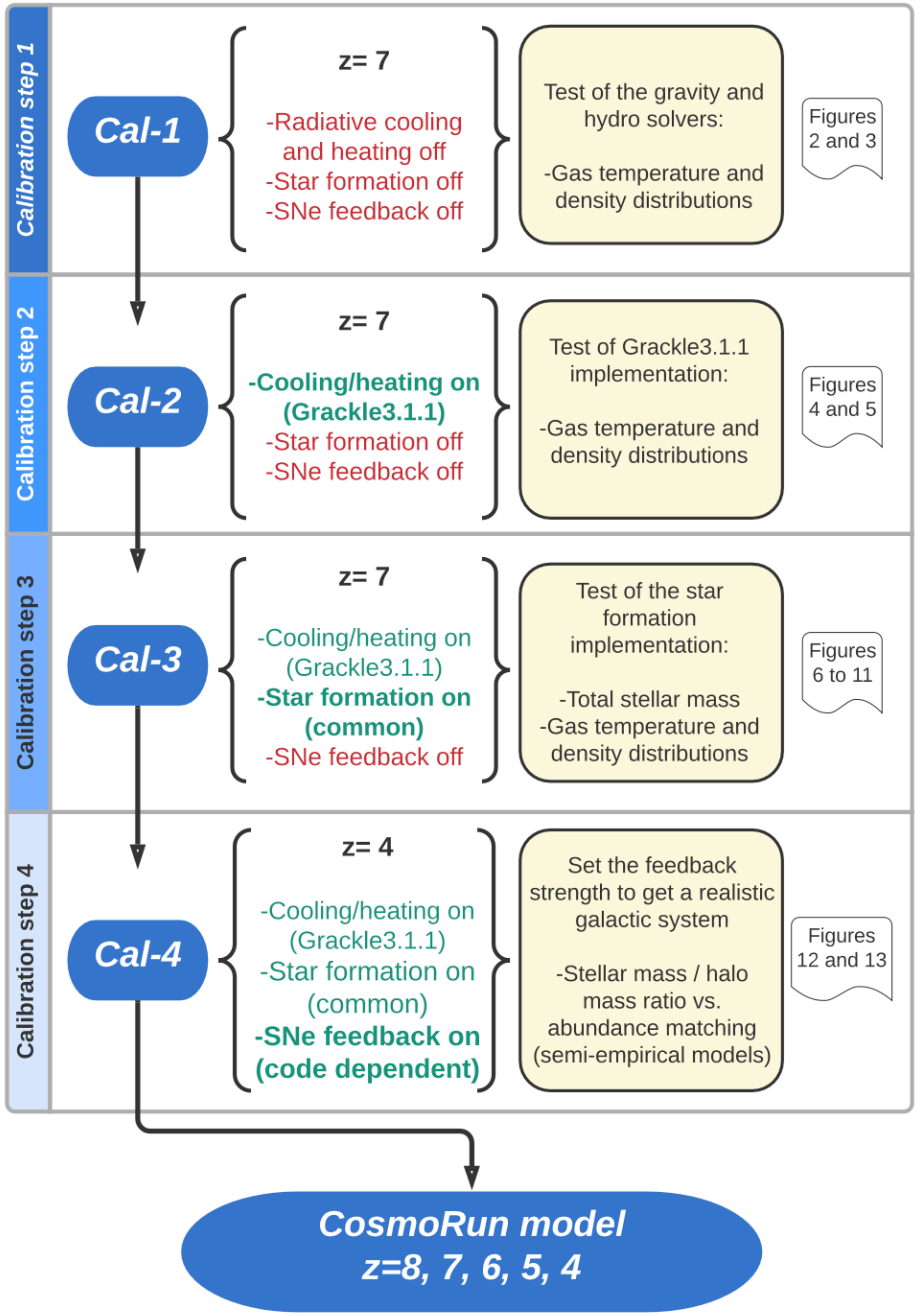
arXiv:2001.04354 (Jan 2020)

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.

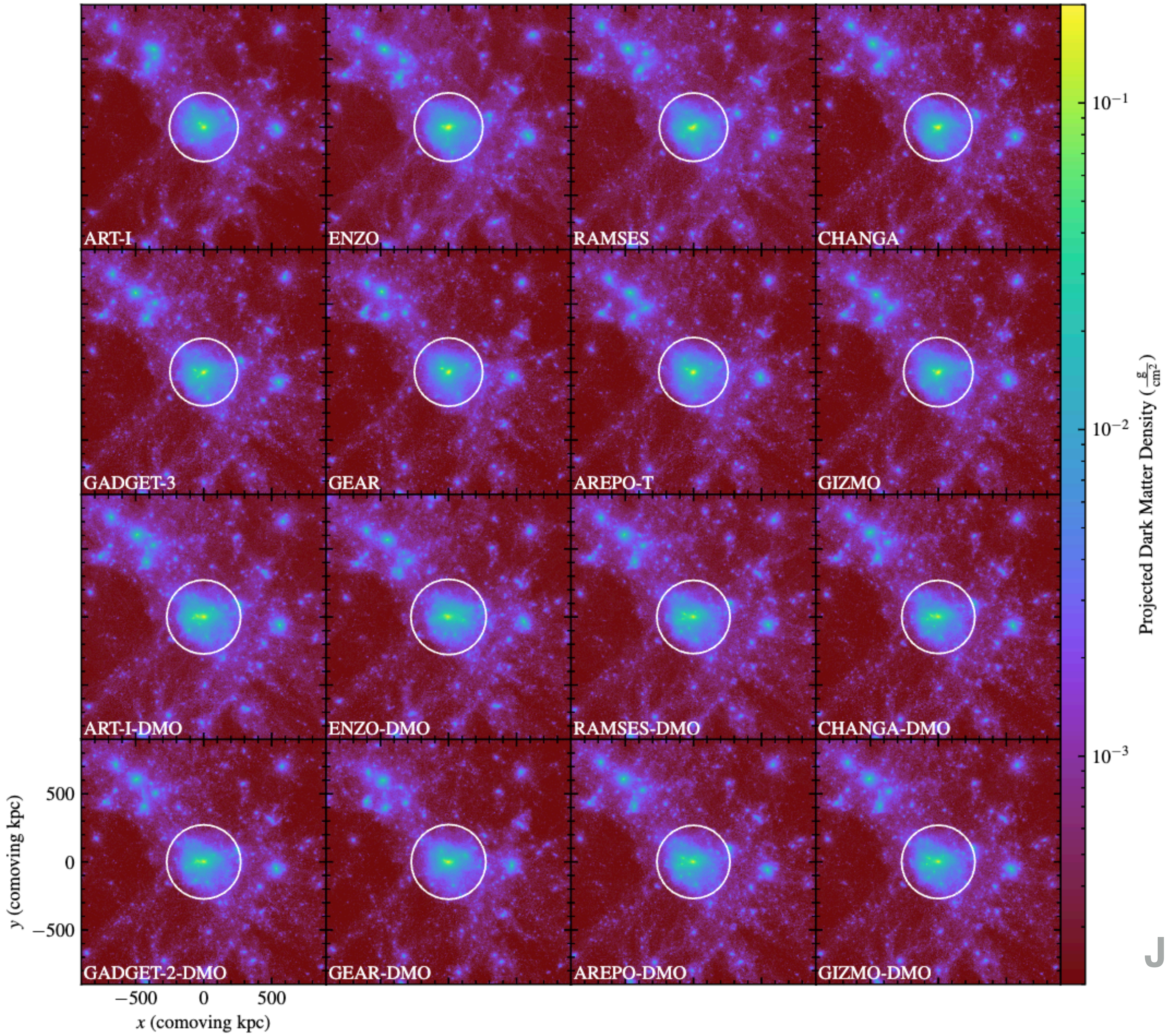
Code	Stellar feedback	SN & metal production model	Effective metal yield	Runtime parameters
ART-I	T+K, RP	SN Type Ia/II, AGB stars*	0.033	$E_{\rm thermal} = 2 \times 10^{51}$ ergs/SN, $p = 3.6 \times 10^6\, {\rm M_\odot\, km\, s^{-1}}$/SN
ENZO	T	SN Type II	0.032	$E_{\rm thermal} = 5 \times 10^{52}$ ergs/SN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

Roca-Fabrega+21



The *AGORA* High-resolution Galaxy Simulations Comparison Project. V: Satellite Galaxy Populations In A Cosmological Zoom-in Simulation of A Milky Way-mass Halo

Minyong Jung,[1] Santi Roca-Fàbrega,[2,3,*] Ji-hoon Kim,[1,4,*] Anna Genina,[5,*] Loic Hausammann,[6,7,*] Hyeonyong Kim,[1,8,*] Alessandro Lupi,[9,10,*] Kentaro Nagamine,[11,12,13,*] Johnny W. Powell,[14,*] Yves Revaz,[7,*] Ikkoh Shimizu,[15,*] Héctor Velázquez,[16,*] Daniel Ceverino,[17,18] Joel R. Primack,[19] Thomas R. Quinn,[20] Clayton Strawn,[19] Tom Abel,[21,22,23] Avishai Dekel,[24] Bili Dong,[25] Boon Kiat Oh,[26,1] Romain Teyssier,[27] and the *AGORA* Collaboration[28,29]



- **8 different Cosmological Hydrodynamic Codes**

  mesh: ART, Enzo, RAMSES

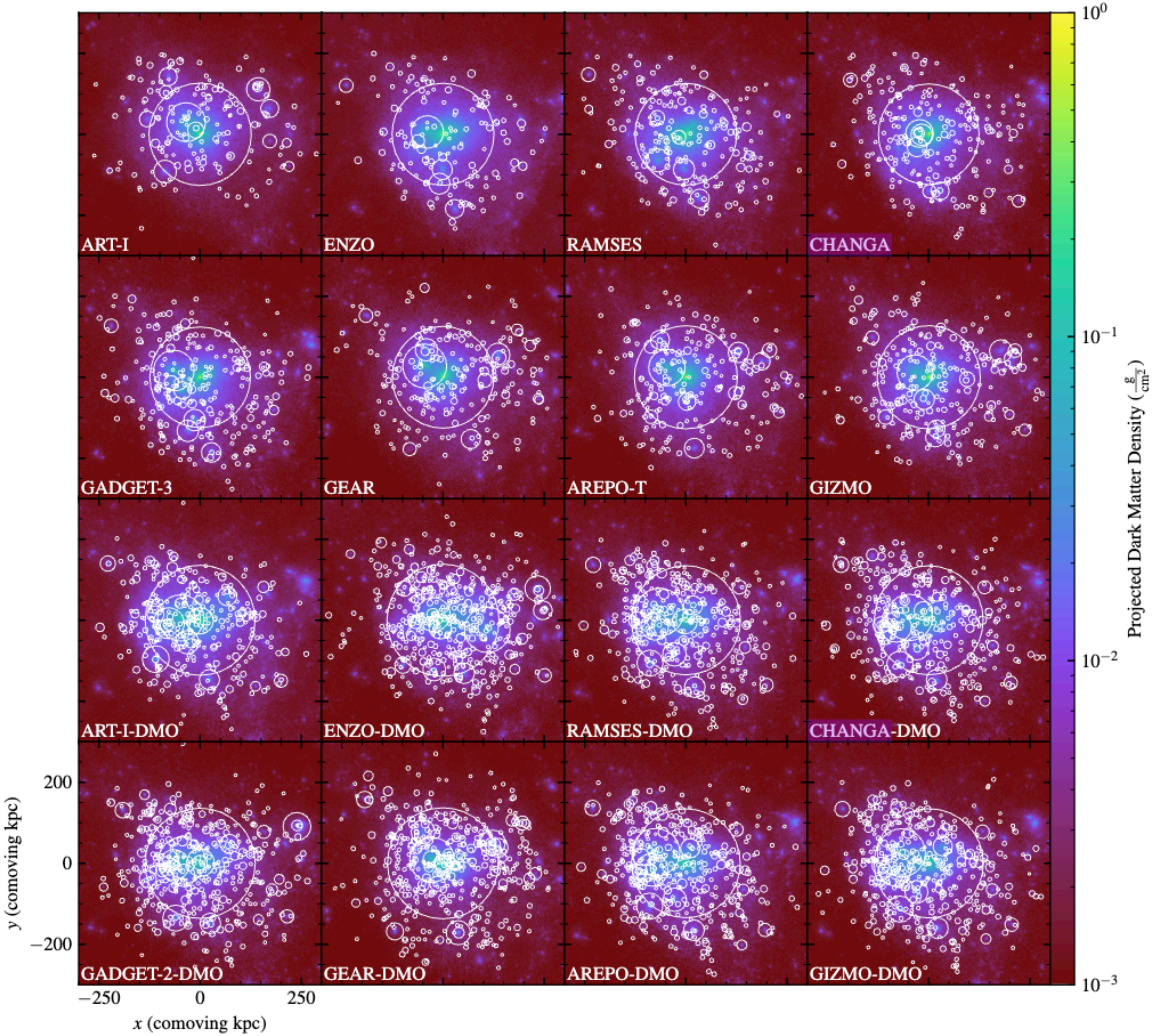
  Lagr. —Eurlerian: AREPO, Gizmo

  SPH: CHANGA, GADGET-3, GEAR

- **Detailed examination of satellites down to z~2 & z~0**

- **Hydro & DM-only runs**

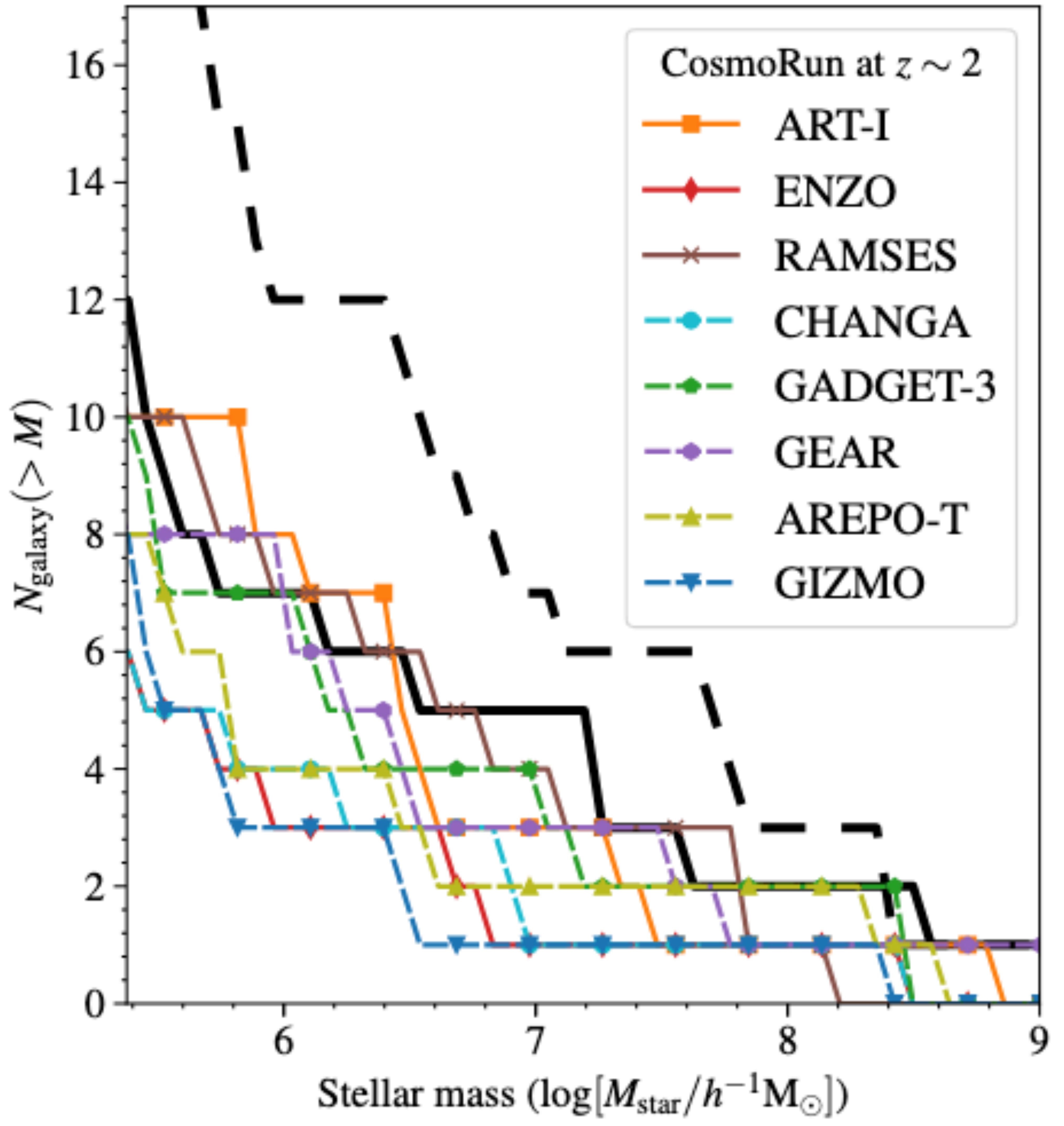
Jung+ (including KN) ’24

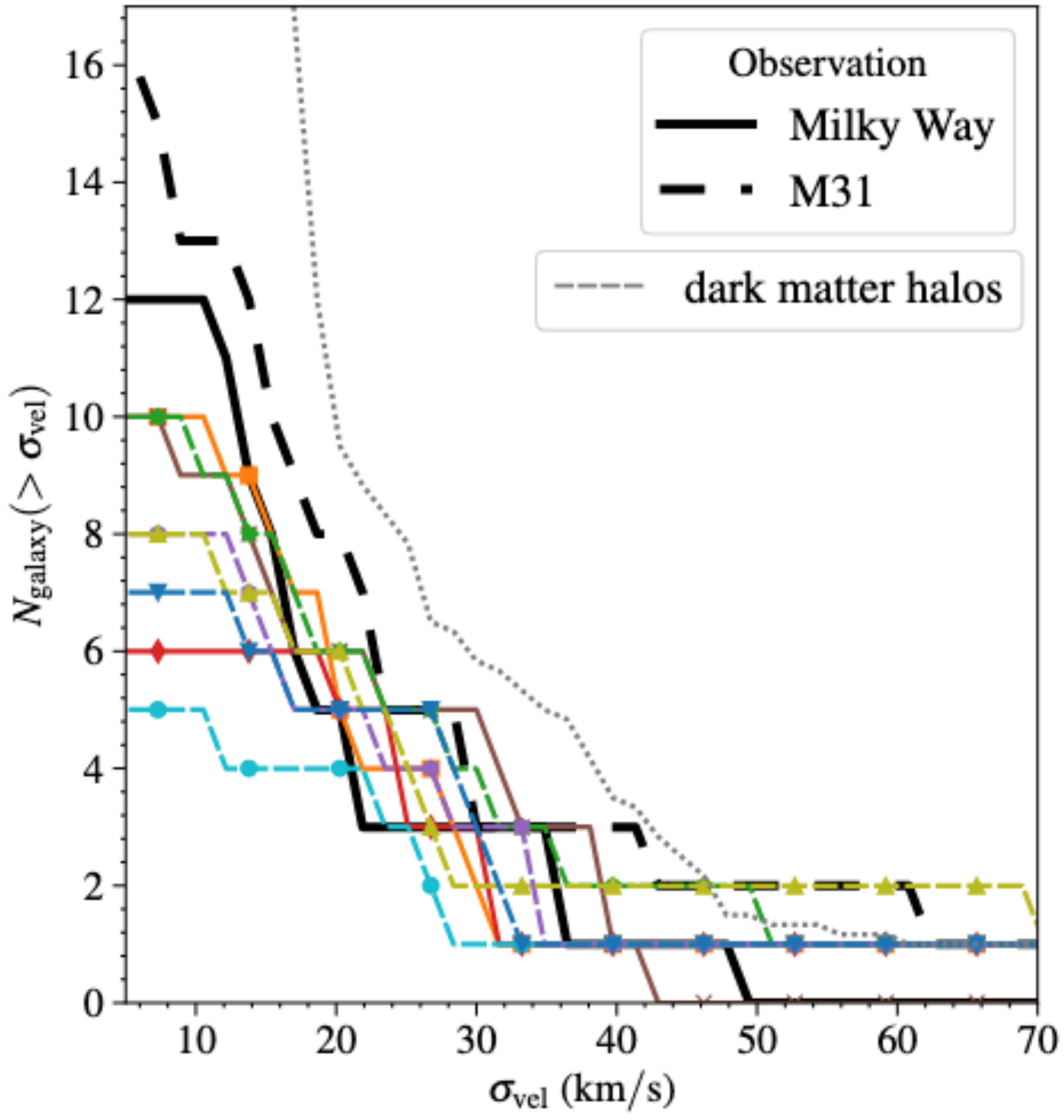


white circles: halos w. $M_h \geq 10^7 M_\odot$ up to 0.5 Rvir

Jung+ (including KN) ’24

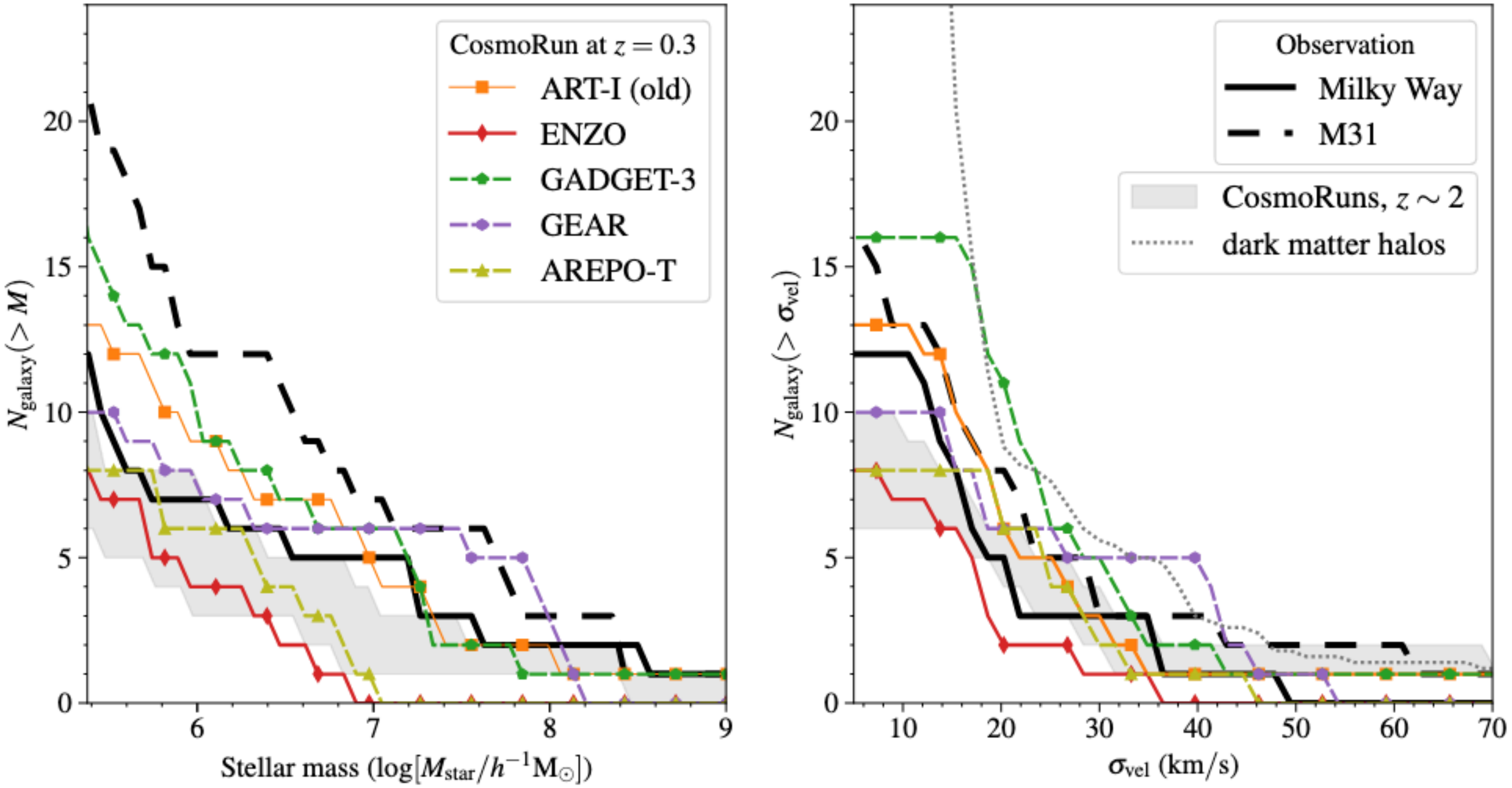
No more "Missing Satellites Problem"



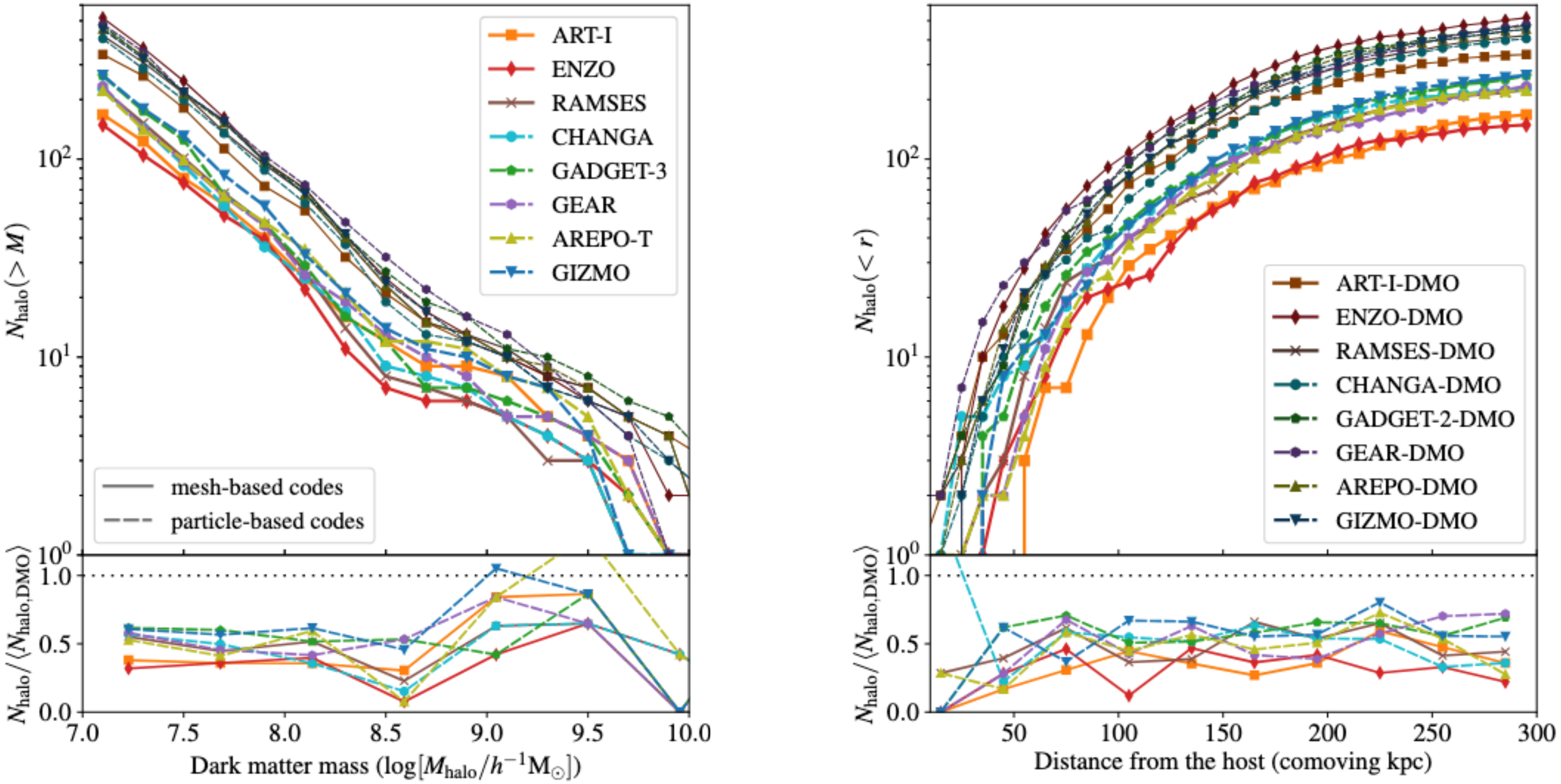


Jung+ (including KN) '24

No more "Missing Satellites Problem"



Jung+ (including KN) '24

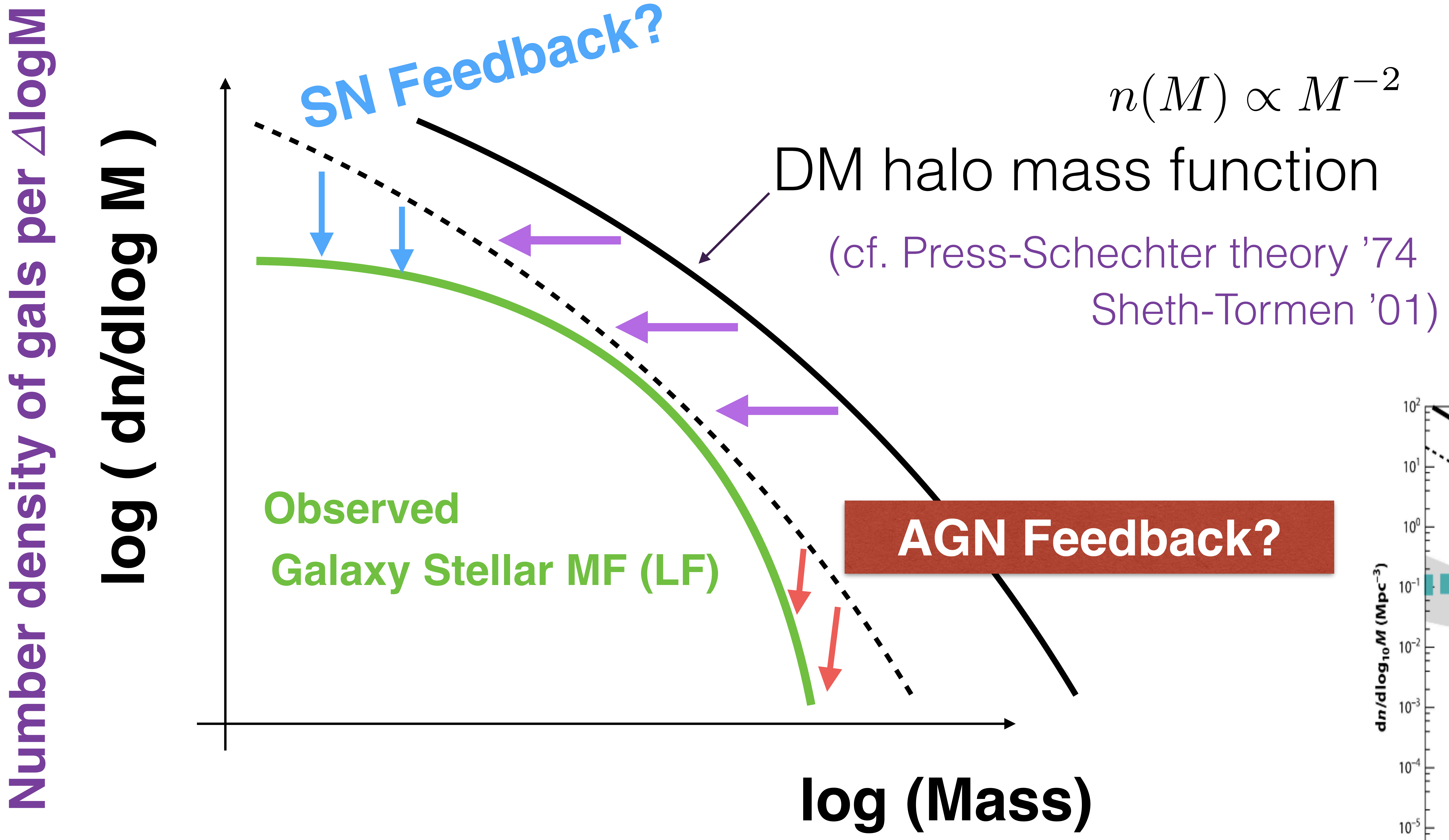


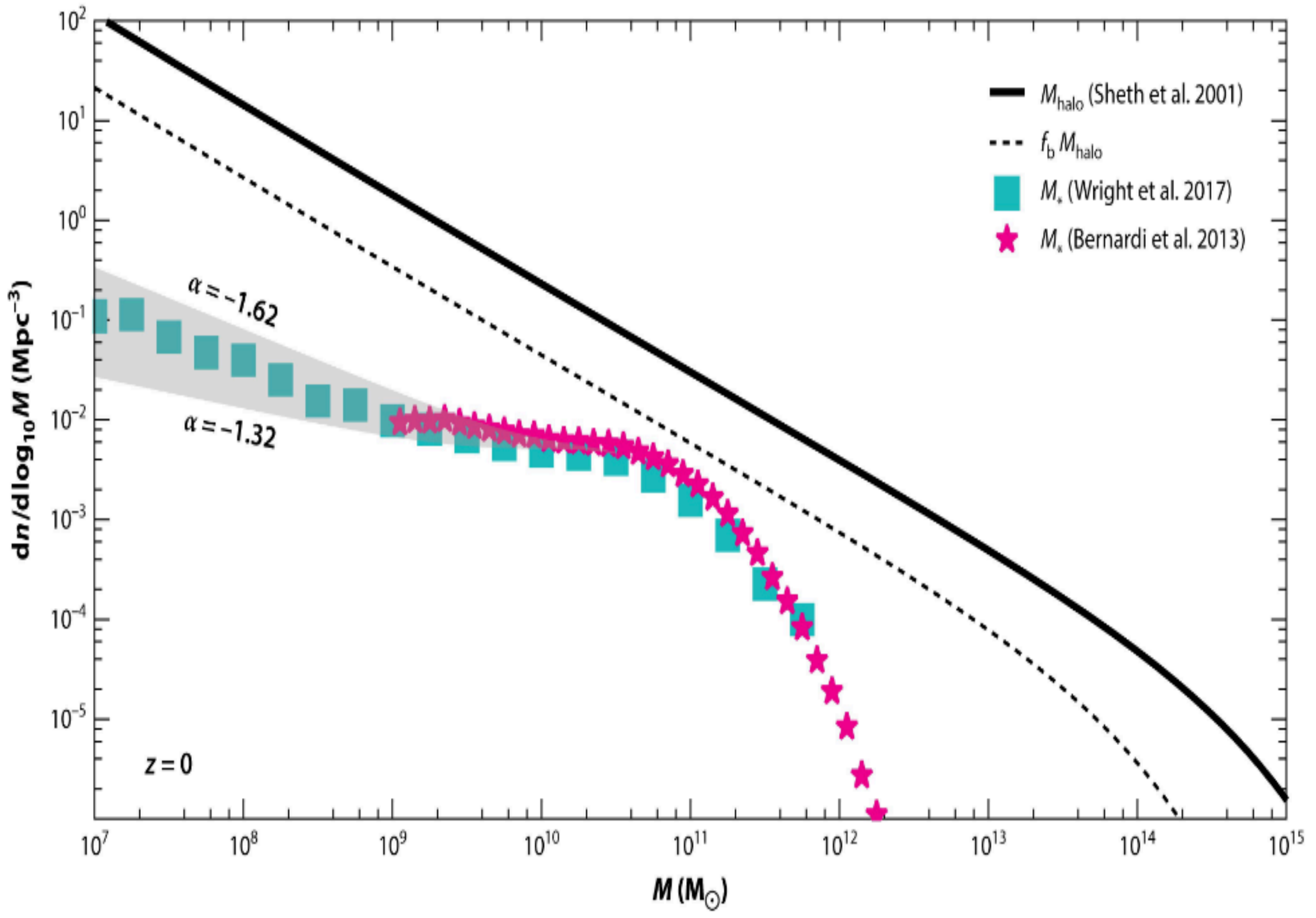
# of satellite halo is less in hydro sims compared to DM-only sim.

Reionization, UV background, ram-pressure/tidal stripping, SN feedback

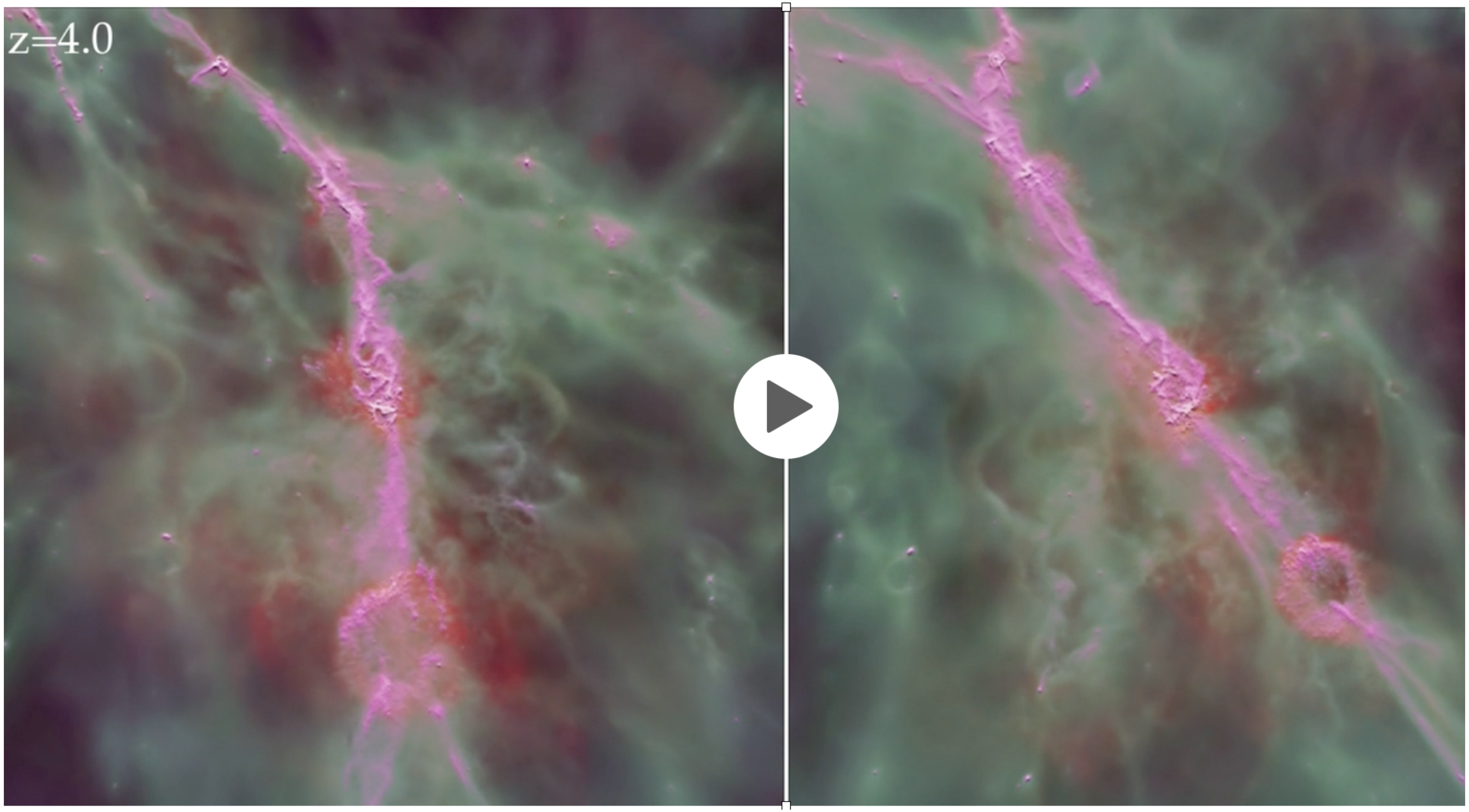
Jung+ (including KN) '24

Dark Matter Halo —> Galaxies





Movie



m12q FIRE simulation

m_{dm}~2e5 M⊙/h

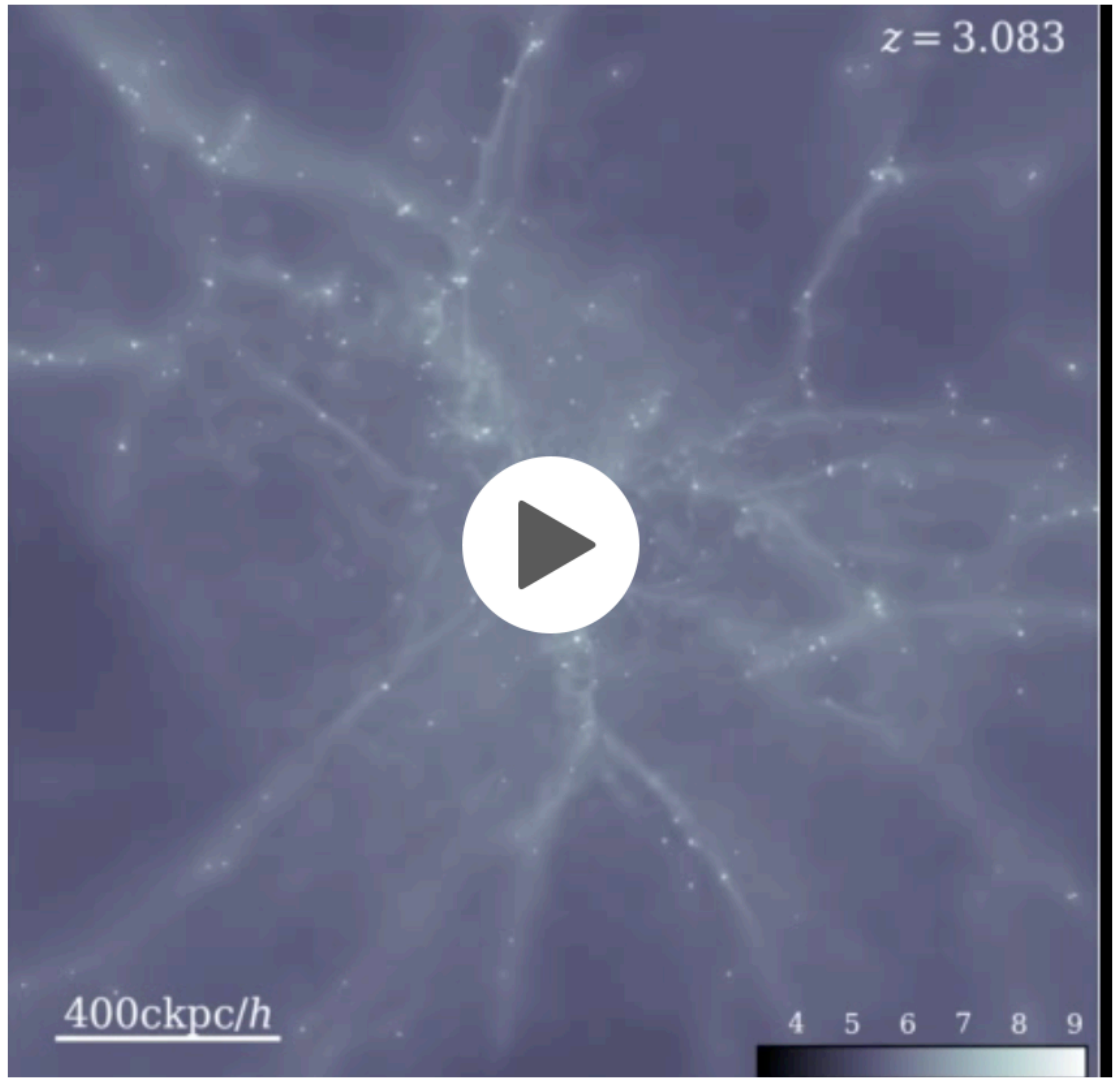
m_b=5e3 M⊙/h

ϵ_{dm}=100 pc/h

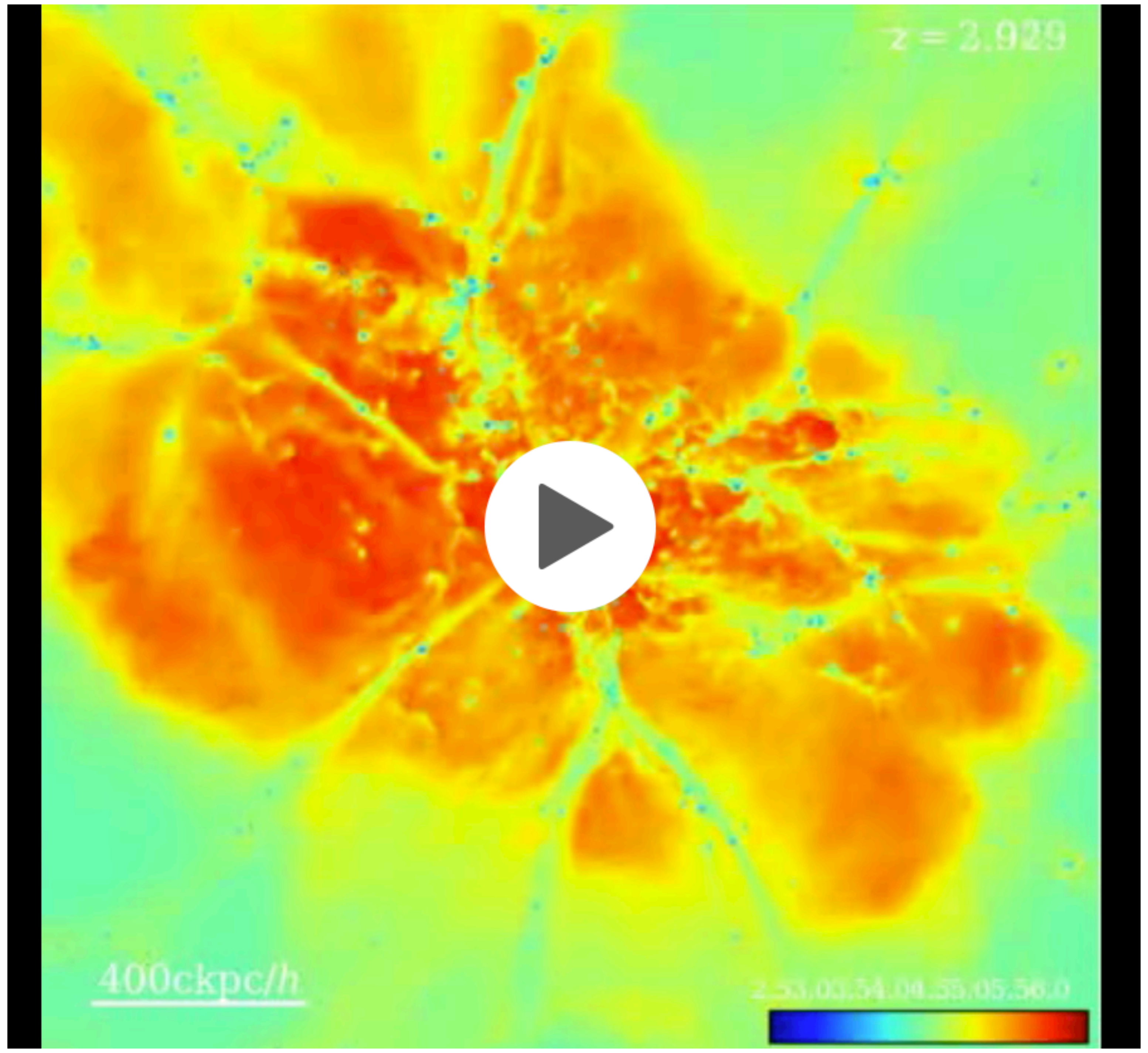
ϵ_b=7 pc/h

Movies: zoom-in sim

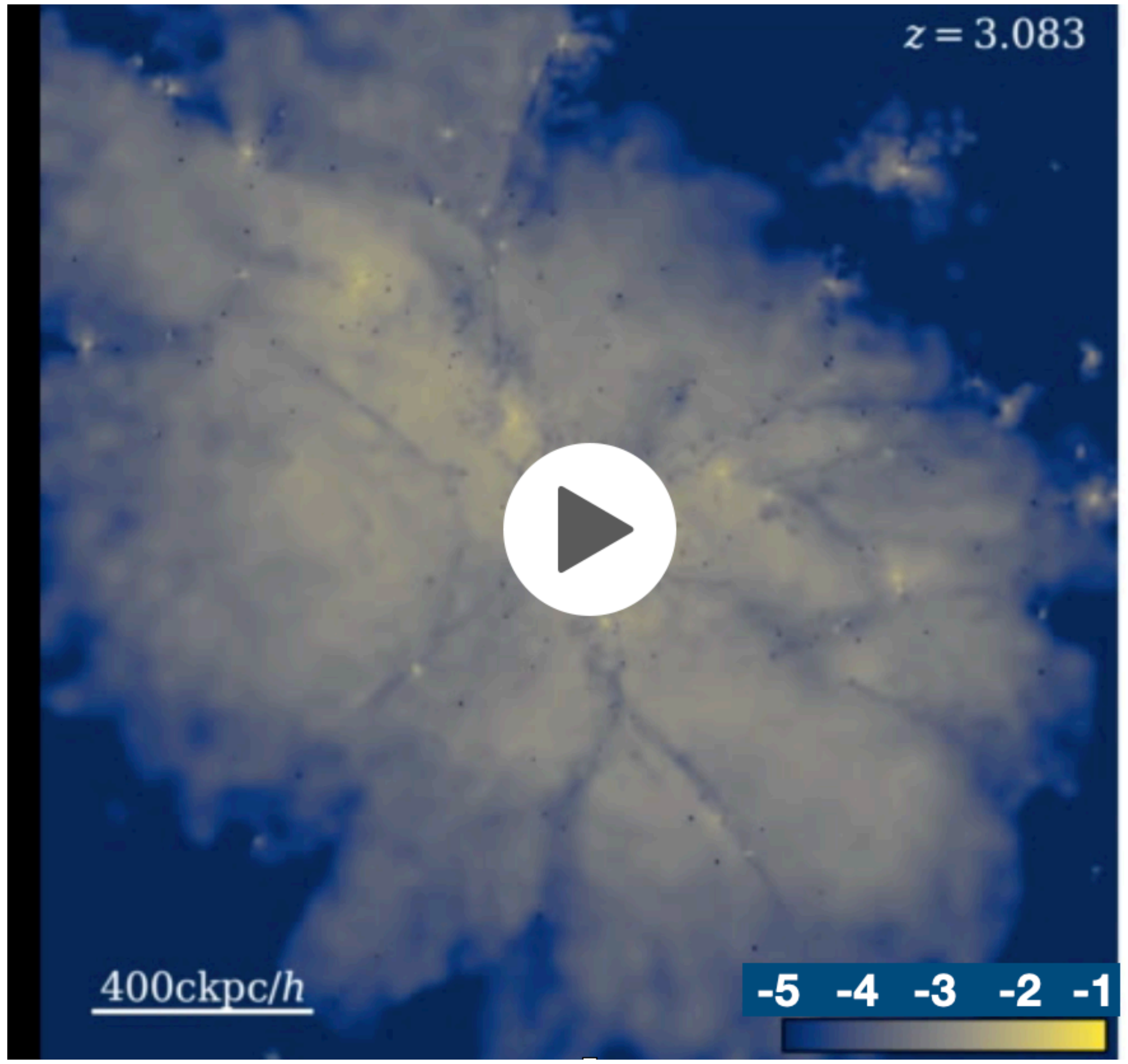
Gas Density



log(Temperature)



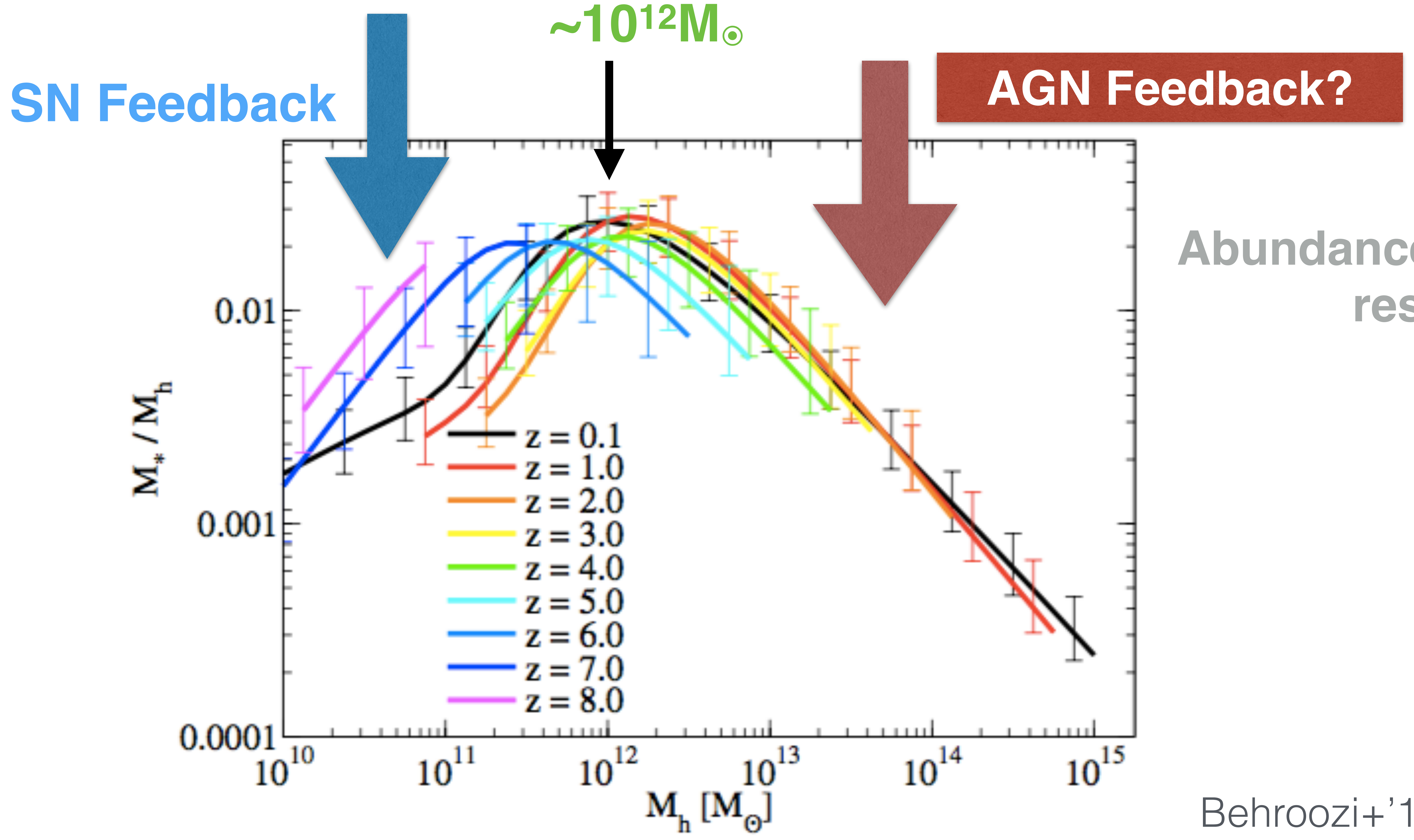
log(Metallicity)



AGORA L12 GADGET3-Osaka sim. Shimizu, KN+19

cf. Roca-Fabrega+21 https://sites.google.com/site/santacruzcomparisonproject/

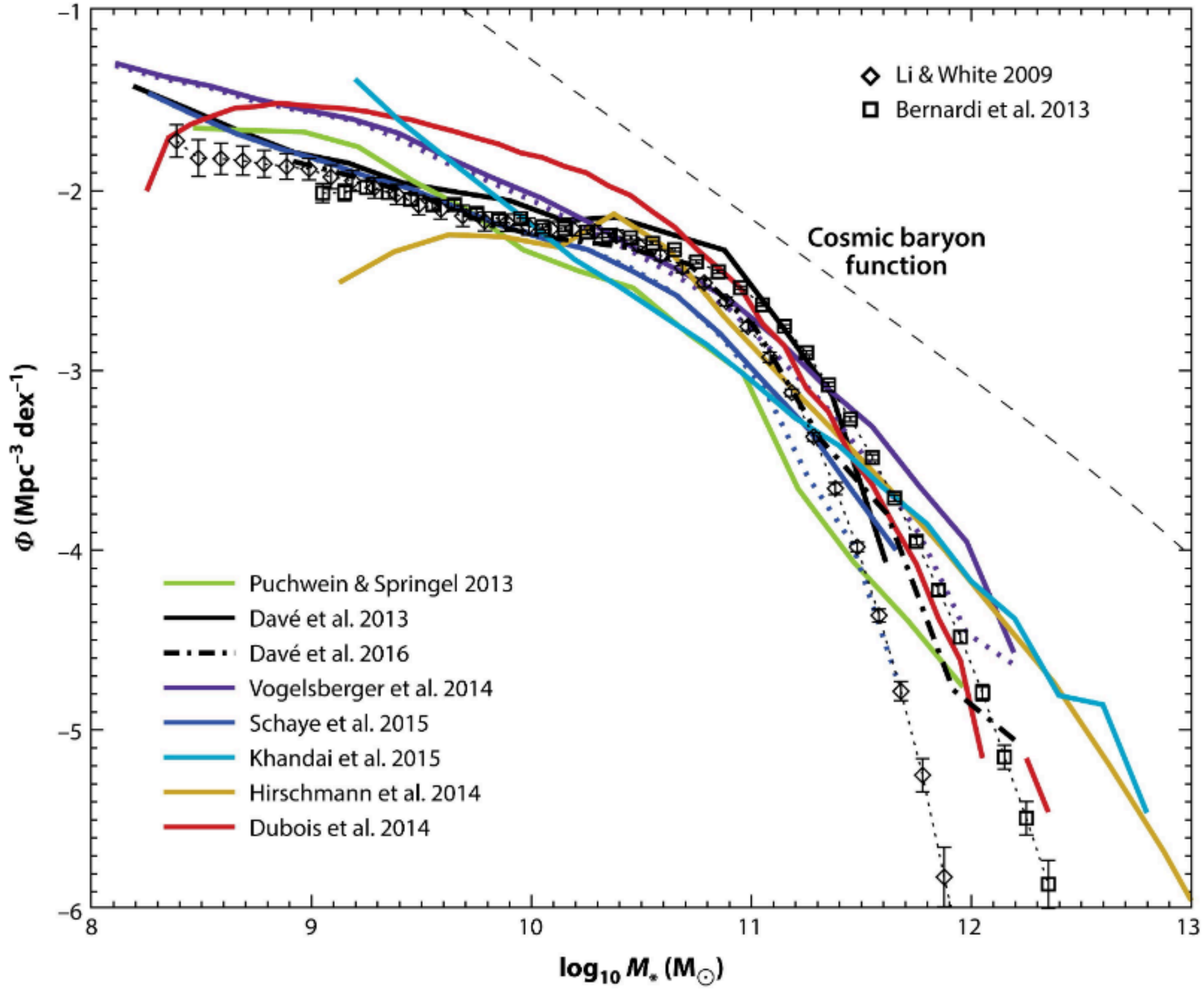
Stellar-to-Halo Mass Ratio (SHMR)



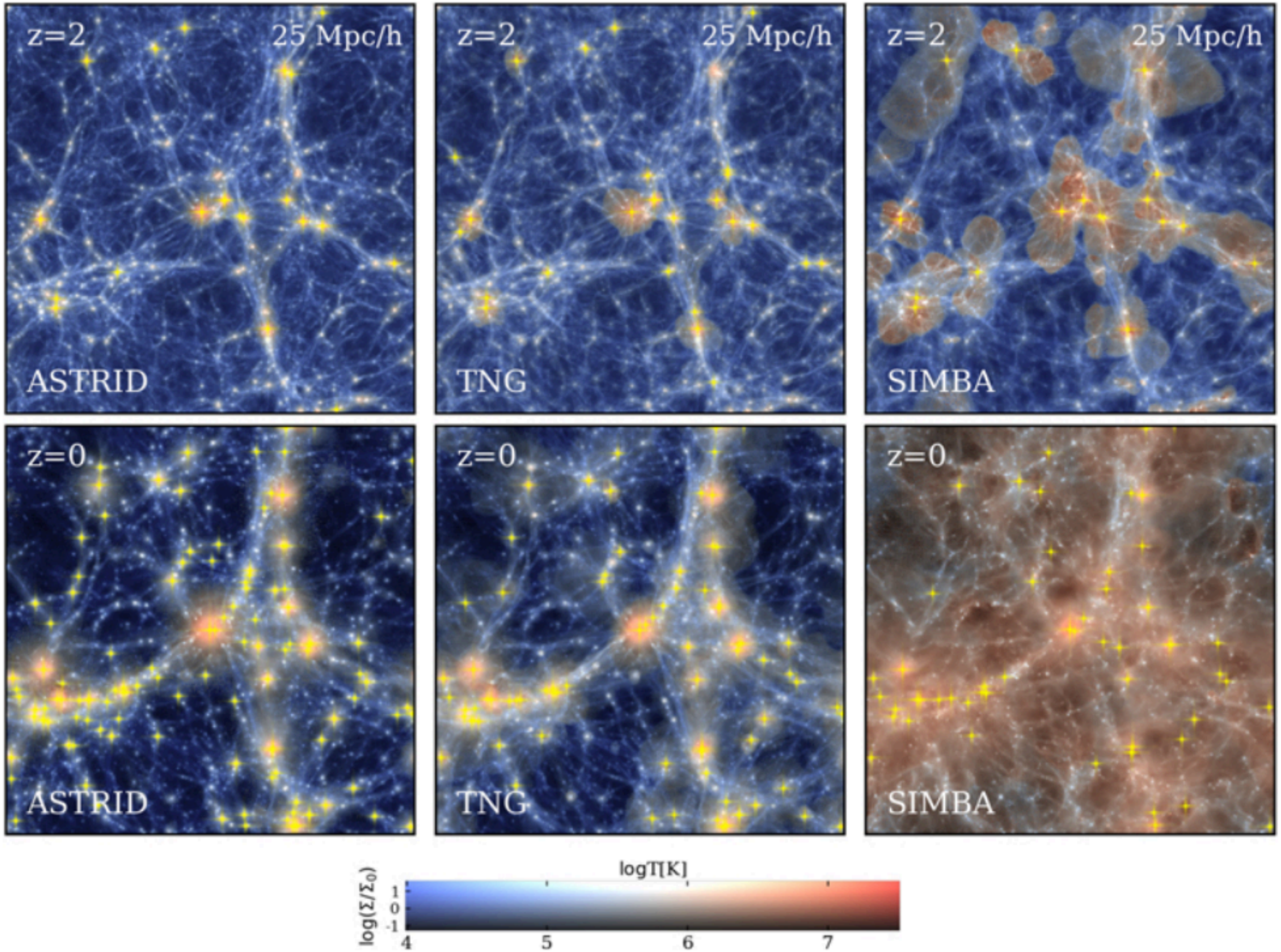
Abundance Matching result

Behroozi+'10, '13, '18

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



Naab & Ostriker '17



Different feedback models

↓

Different CGM/IGM temperatures

Ni+ '21

AGN feedback models

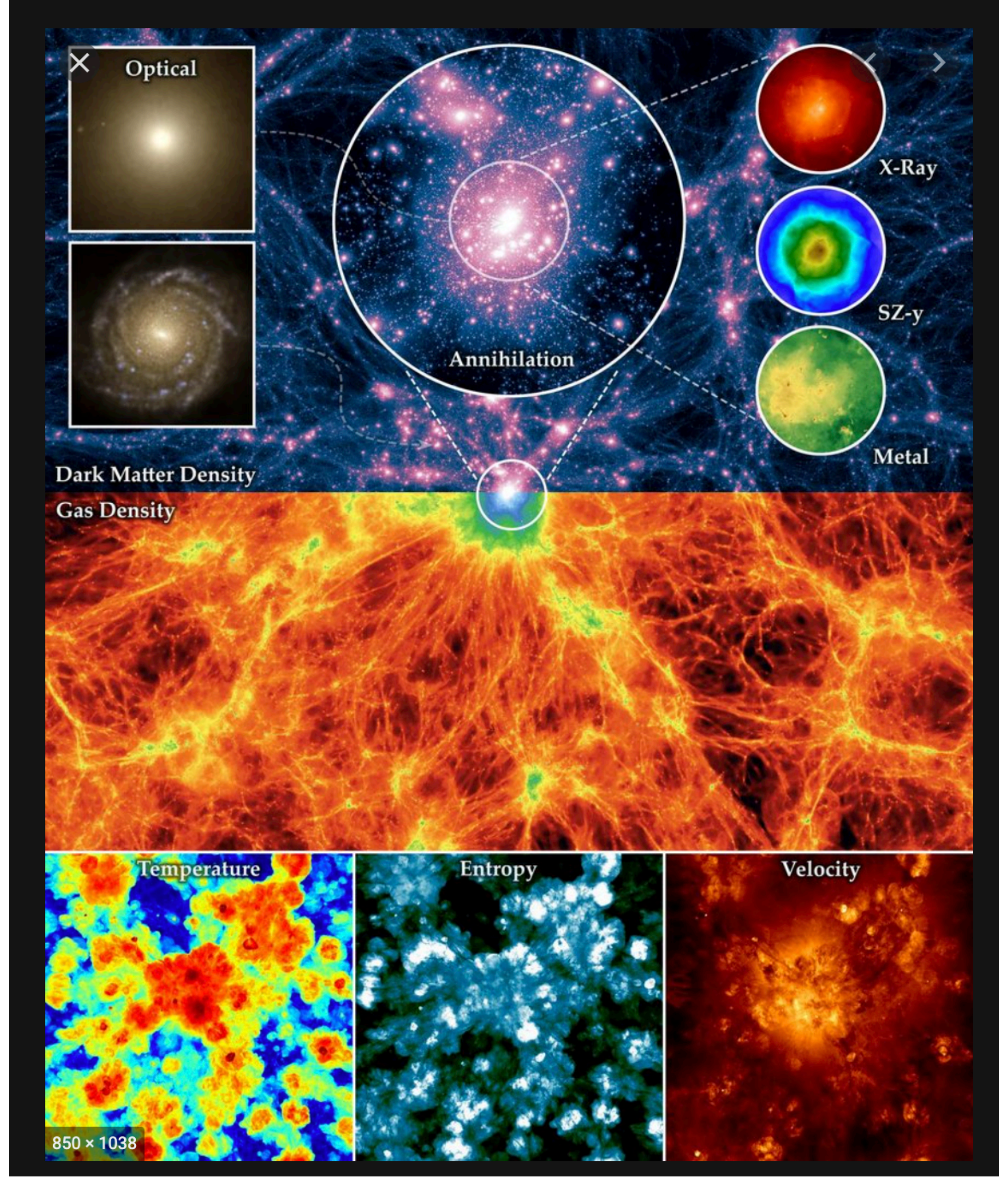
- **Two-mode AGN feedback model**

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

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

IllustrisTNG

AREPO

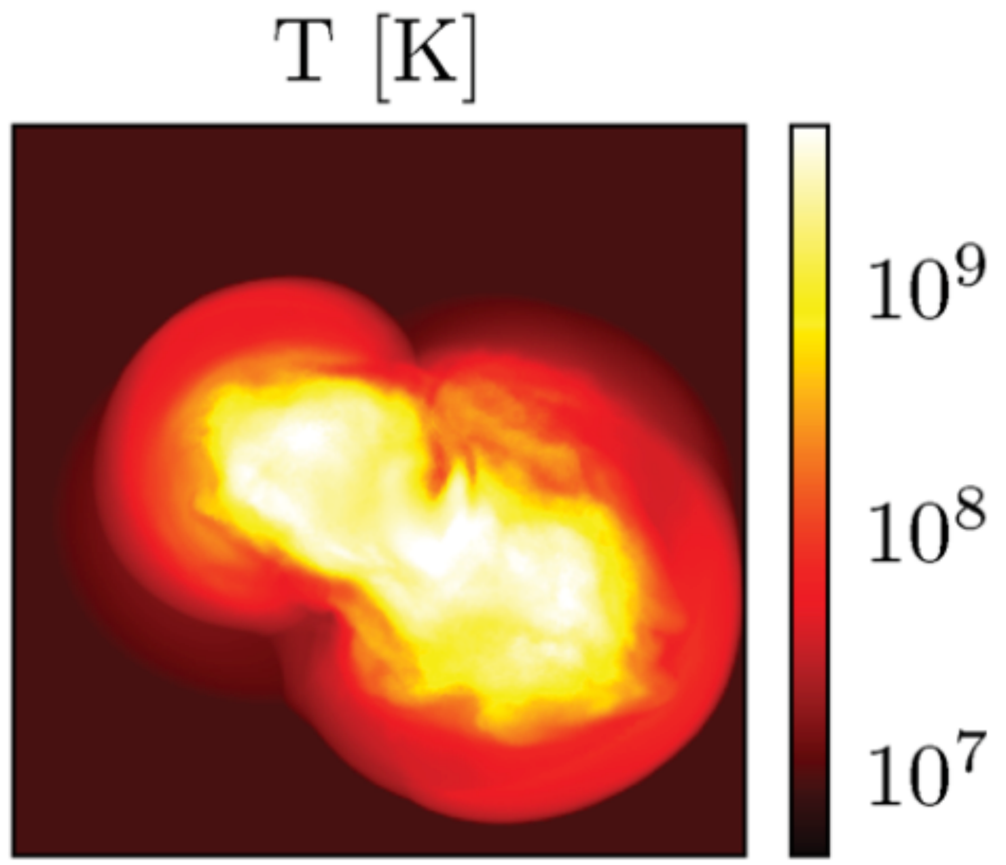


- **Eddington ratio threshold**

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

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

Angular Momentum / Torque model

- **EAGLE** (GADGET-3)

$$\dot{M}_{\rm BH} = \min(\dot{M}_{\rm Bondi} \times \min\left((c_{\rm s}/V_\Phi)^3/C_{\rm visc}, 1\right), \dot{M}_{\rm Edd}),$$

Rosas-Guevara+15,16

V_Φ : average circular speed of gas around BH

C_{visc} : free param for viscosity of subgrid accretion disk

$$\epsilon_r \epsilon_f = 0.1 \times 0.15 = 0.015.$$

Stochastic thermal heating only when sufficient to raise to $\Delta T = 10^{8.5} K$

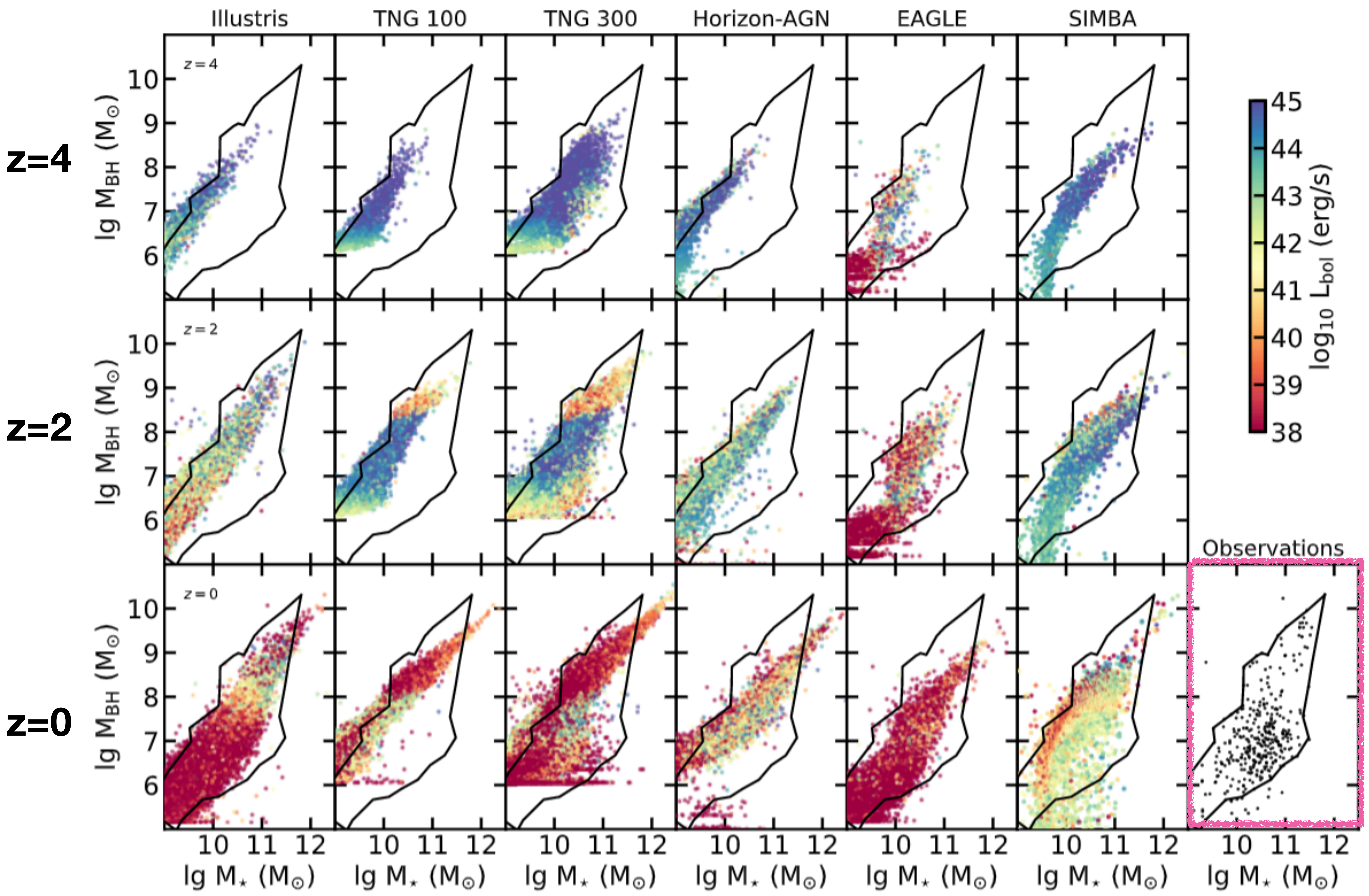
- **SIMBA** (Gizmo)

$$\dot{M}_{\rm BH} = (1-\epsilon_{\rm r}) \left[\min(\dot{M}_{\rm Bondi}, \dot{M}_{\rm Edd}) + \min(\dot{M}_{\rm Torque}, 3\,\dot{M}_{\rm Edd})\right],$$

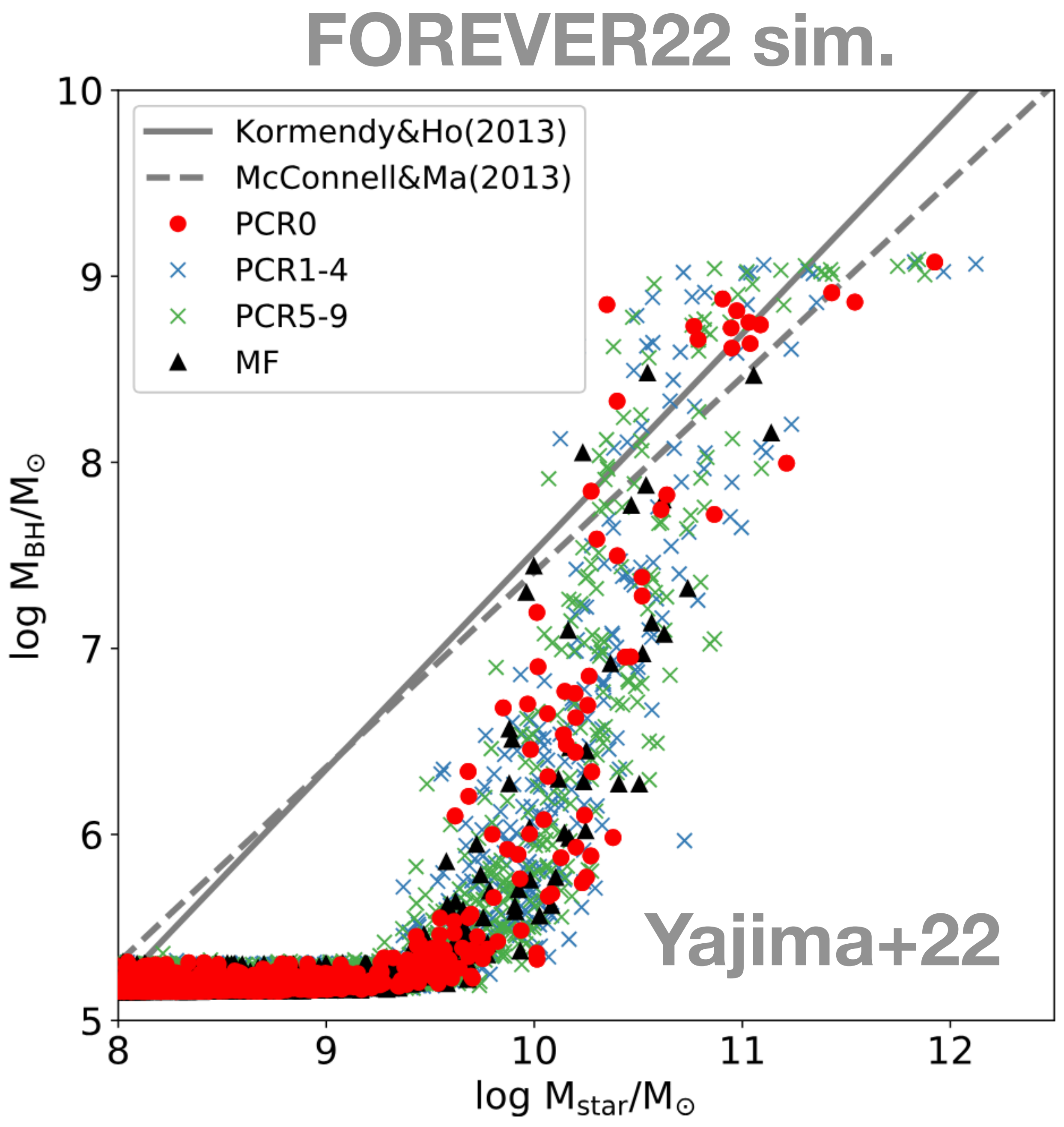
$$\dot{M}_{\rm Torque} = \epsilon_{\rm T}\, f_{\rm d}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/6} \times \left(\frac{M_{\rm enc}(R_0)}{10^9\,{\rm M}_\odot}\right) \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \times \left(1 + \frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M}_\odot/{\rm yr},$$

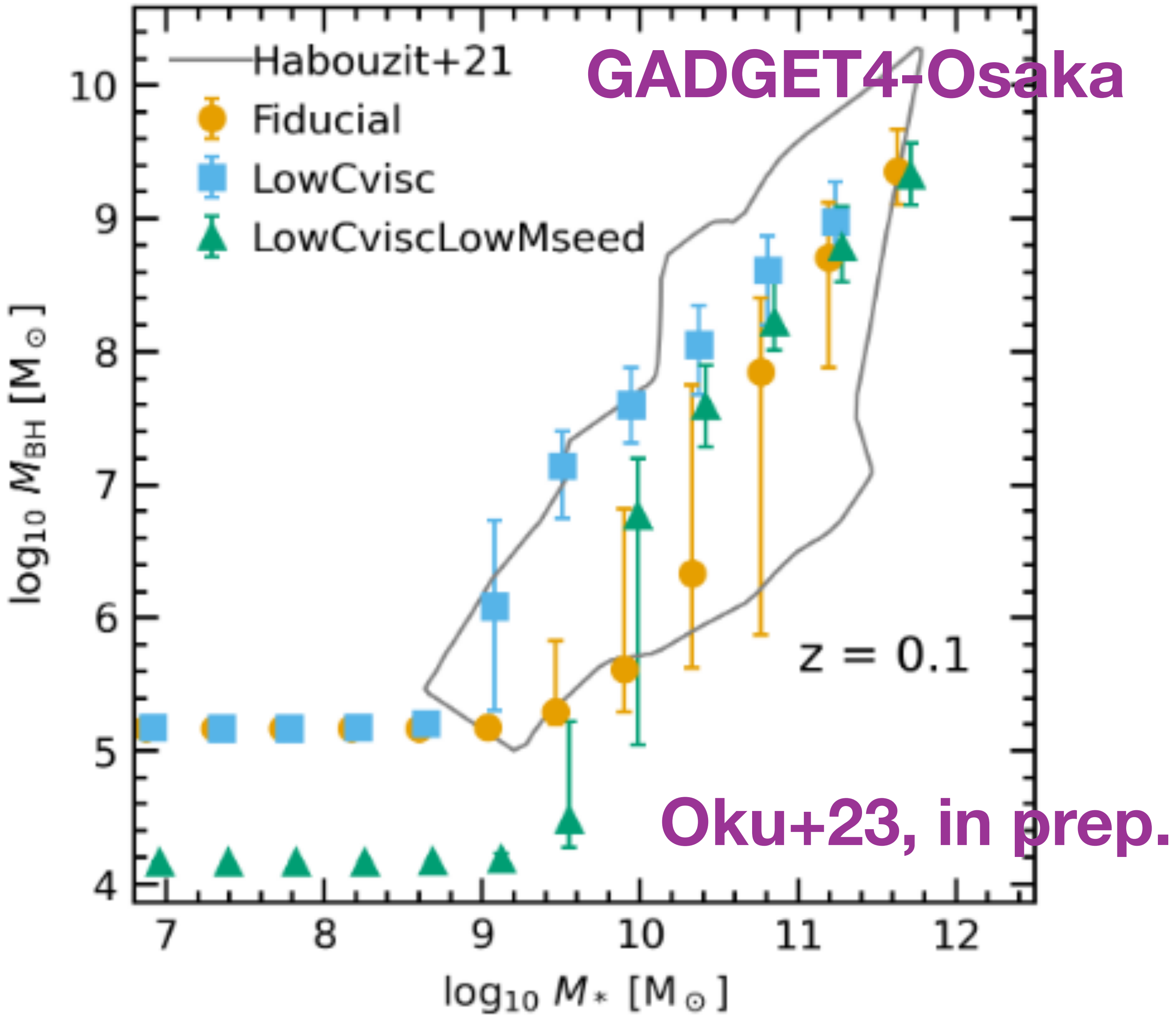
gas inflow rate driven by grav. instabilities from galactic to the accretion disk scale, within $R_0 = 2\, h^{-1}$ kpc
(Hopkins & Quataert '10; Angl´es-Alc´azar+ '15,'17).

M_{BH} — M_* relation



Habouzit+21





Dark matter particle candidates

DM particle mass m_{DM}

GeV-TeV — **CDM** — ***Thermal relic WIMP*** (10GeV ~ 1TeV)

$v_{\mathrm{th}} \approx 0\,\mathrm{km/s}$

(cf. self-interacting DM)

keV — **WDM** — becomes non-relativistic earlier than CDM; suppress perturbation at galactic or smaller scales

$v_{\mathrm{th}} \approx 0.03\,\mathrm{km/s}$

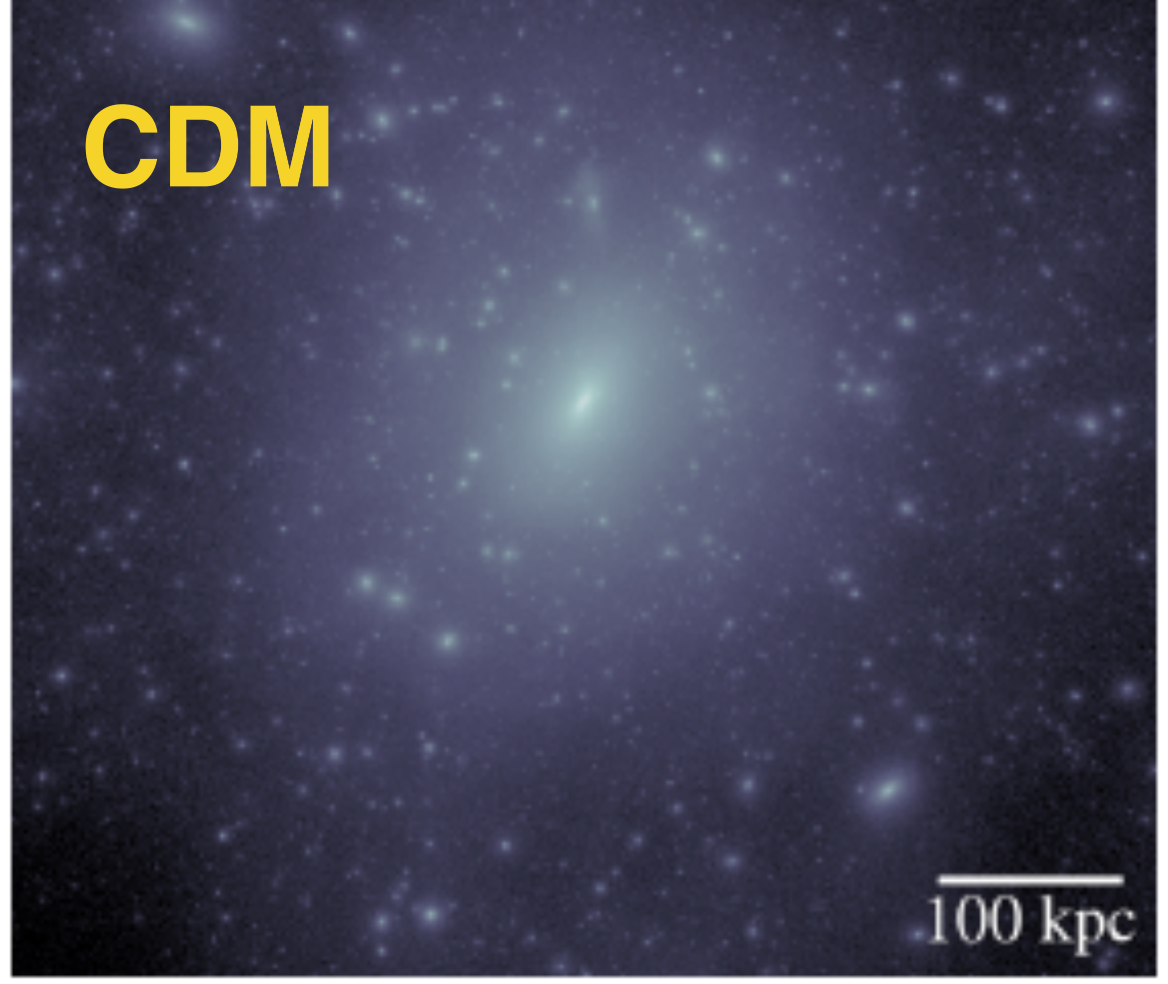
(gravitino, sterile neutrino,…)

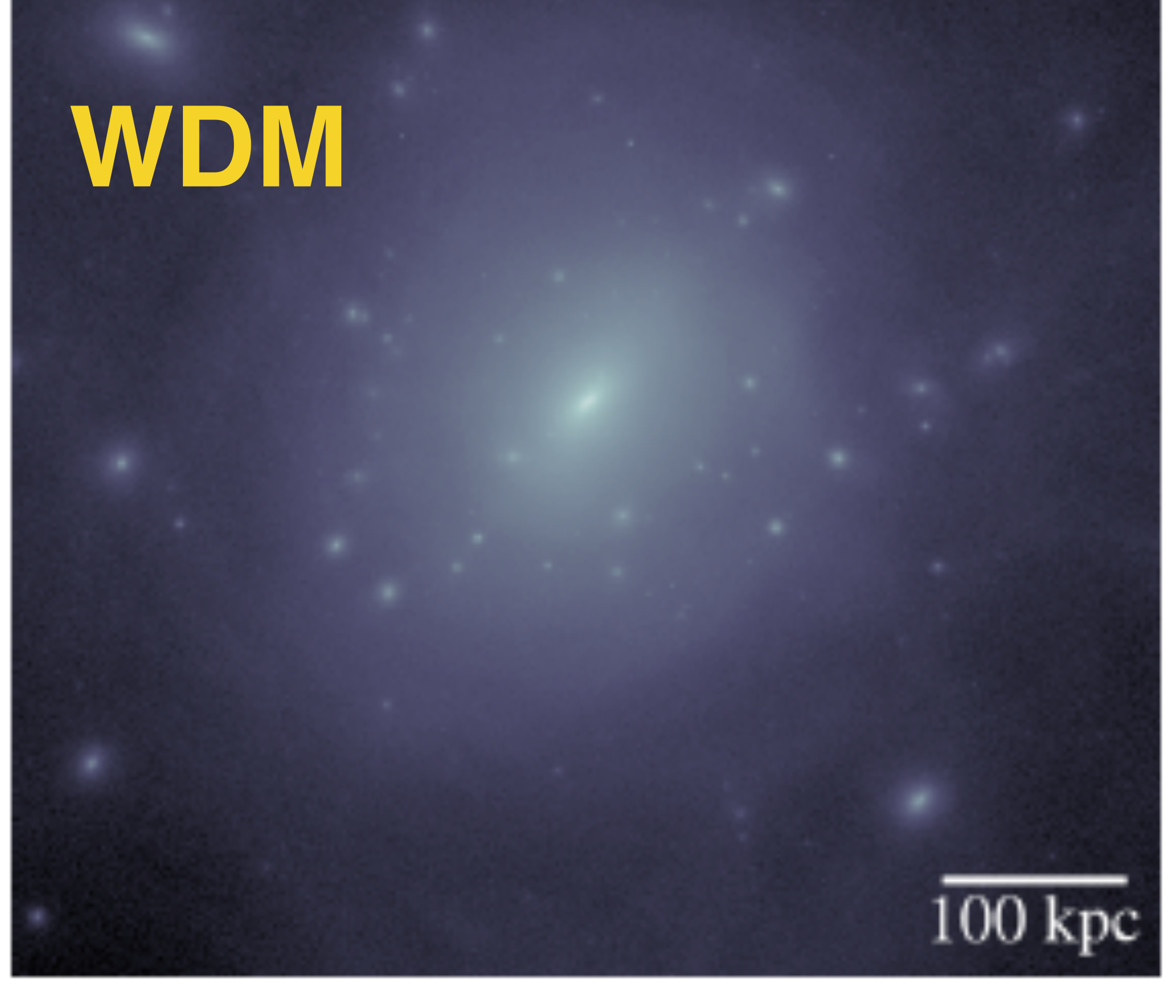
eV — **HDM** — remains relativistic until late time, and erase structures at super-galactic scales. (**ν**,…)

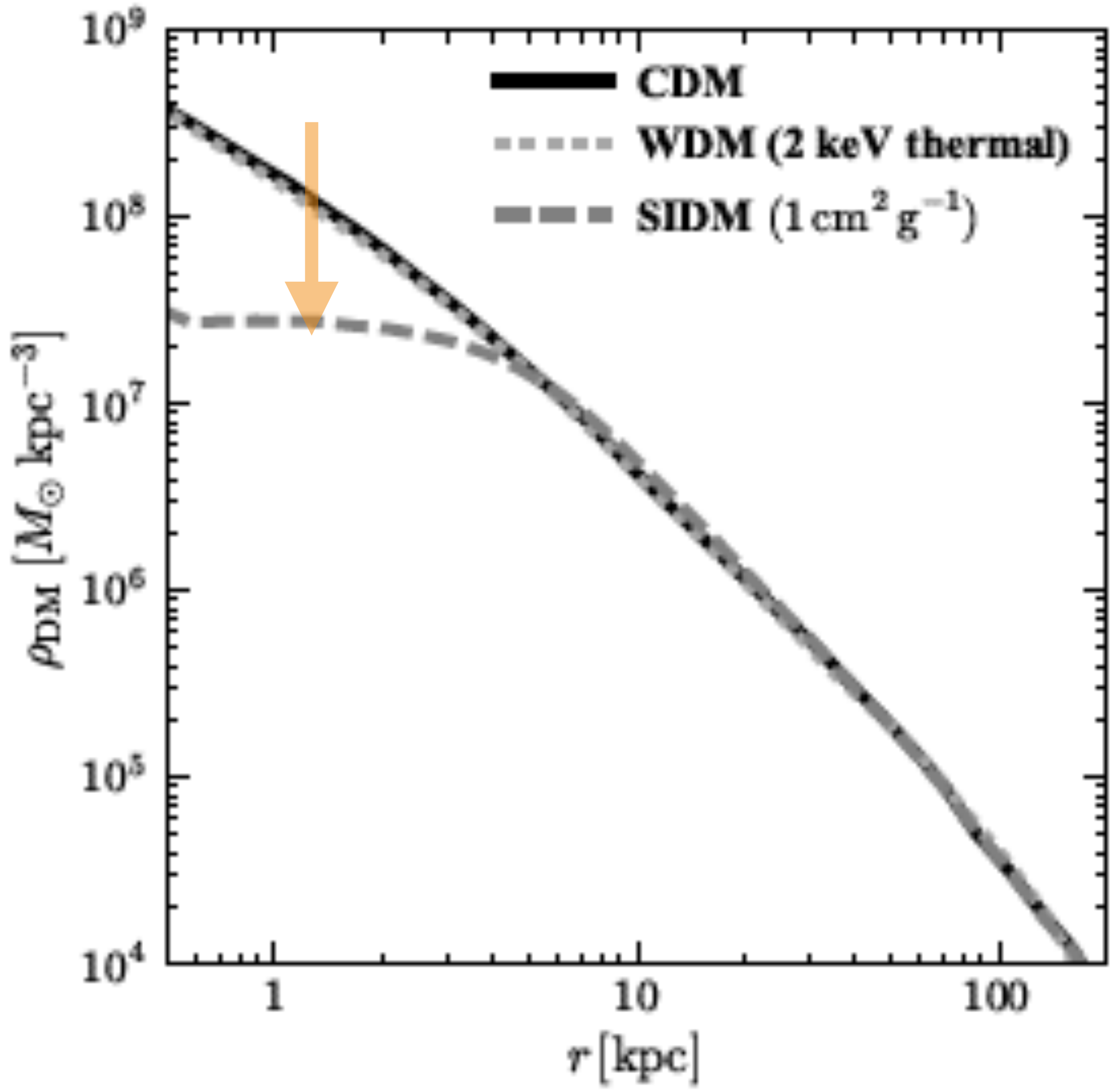
$v_{\mathrm{th}} \approx 30\,\mathrm{km/s}$

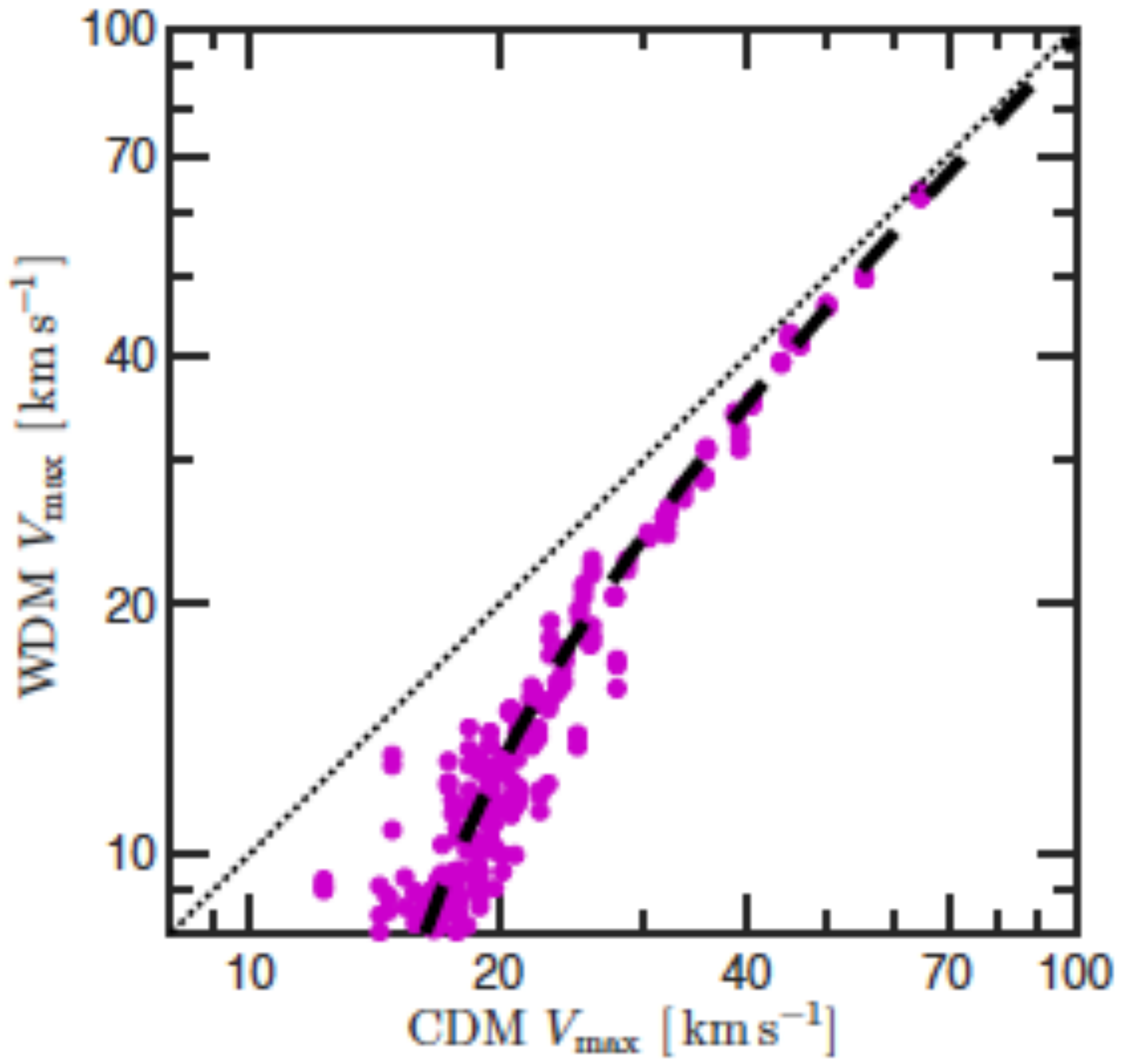
μeV~meV — standard QCD-**axion**

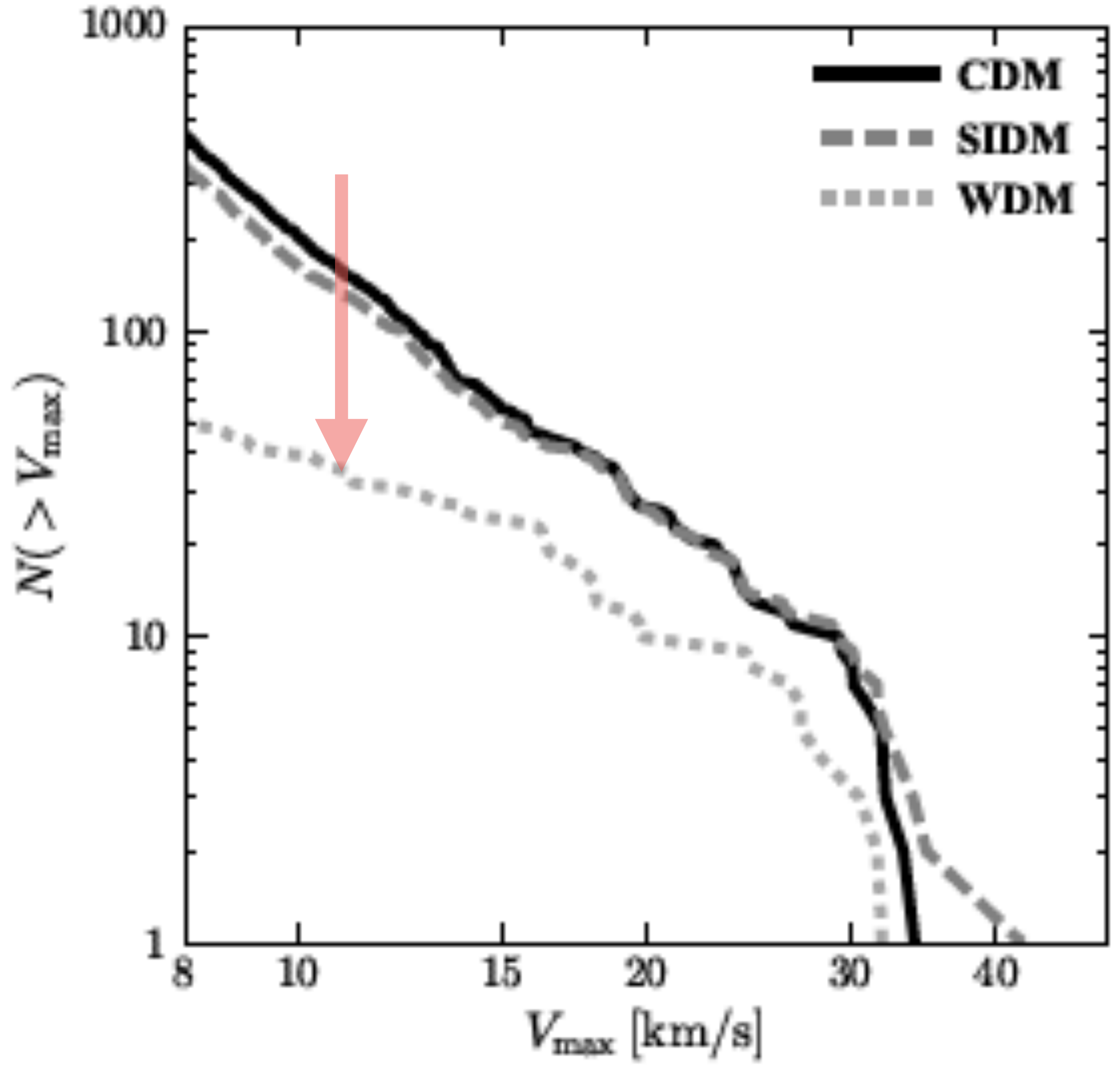
~10^{-22} eV — **FDM** (Fuzzy DM; axion-like, ALP, ULA)











- **WDM** reduces substructure, but **keeps the cusp.**
- **SIDM doesn't reduce substructure, but produces a large core**

Bullock & Boylan-Kolchin '17

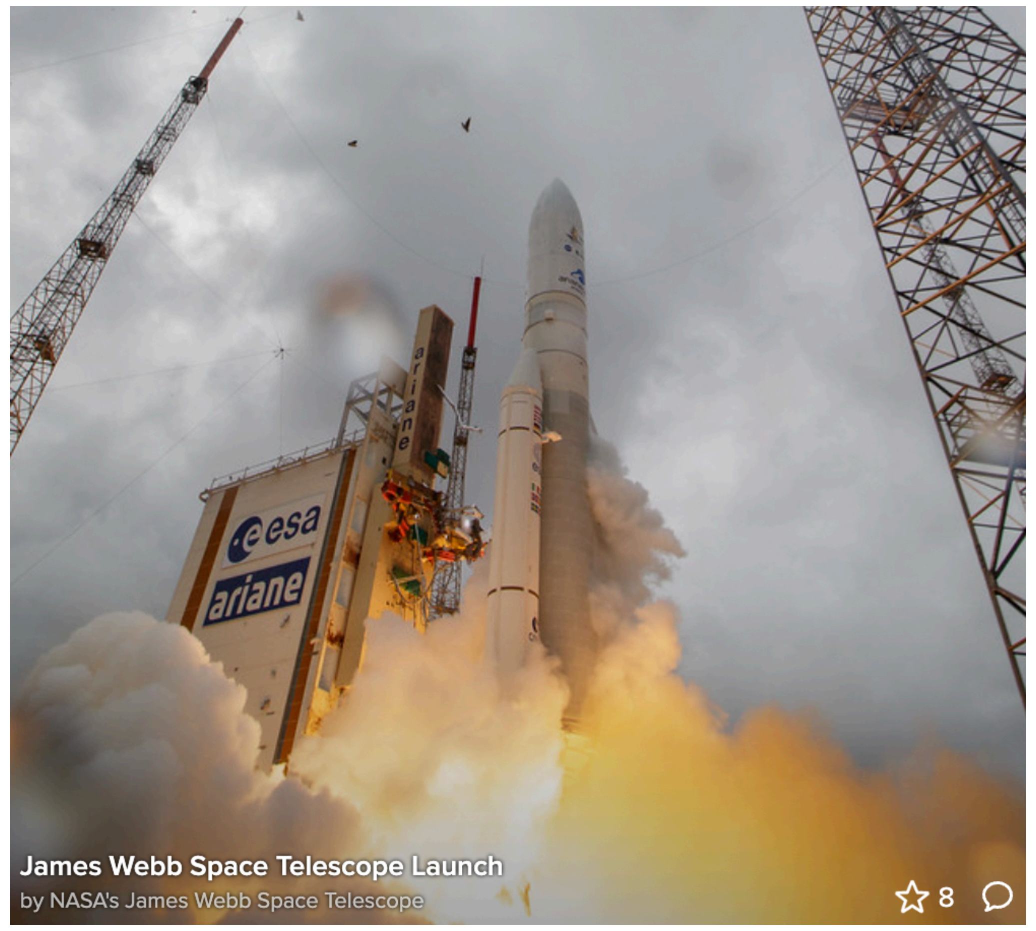
$\sigma/m \sim 0.1 - 100\ \mathrm{cm^2/g}$

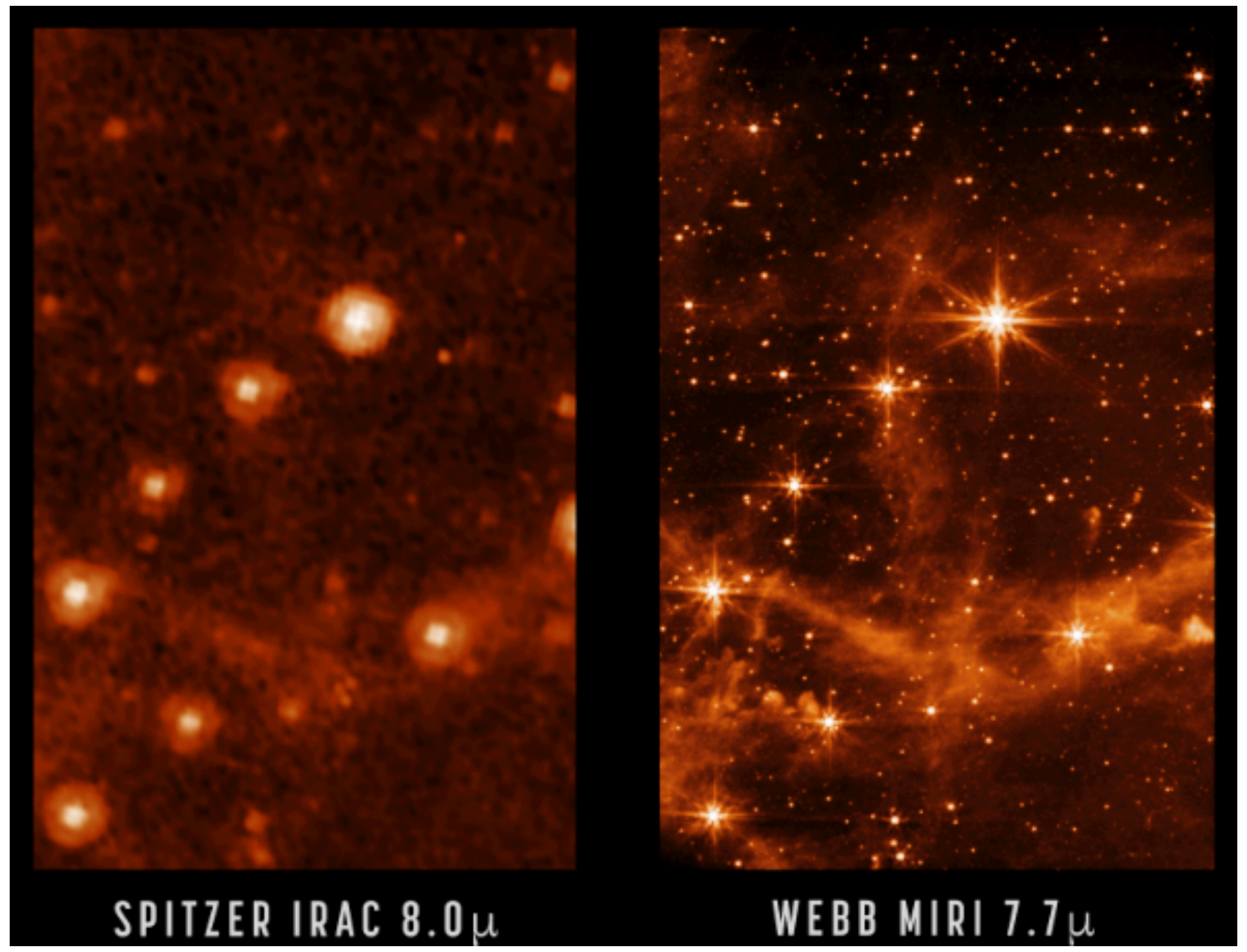
Spergel & Steinhart '00

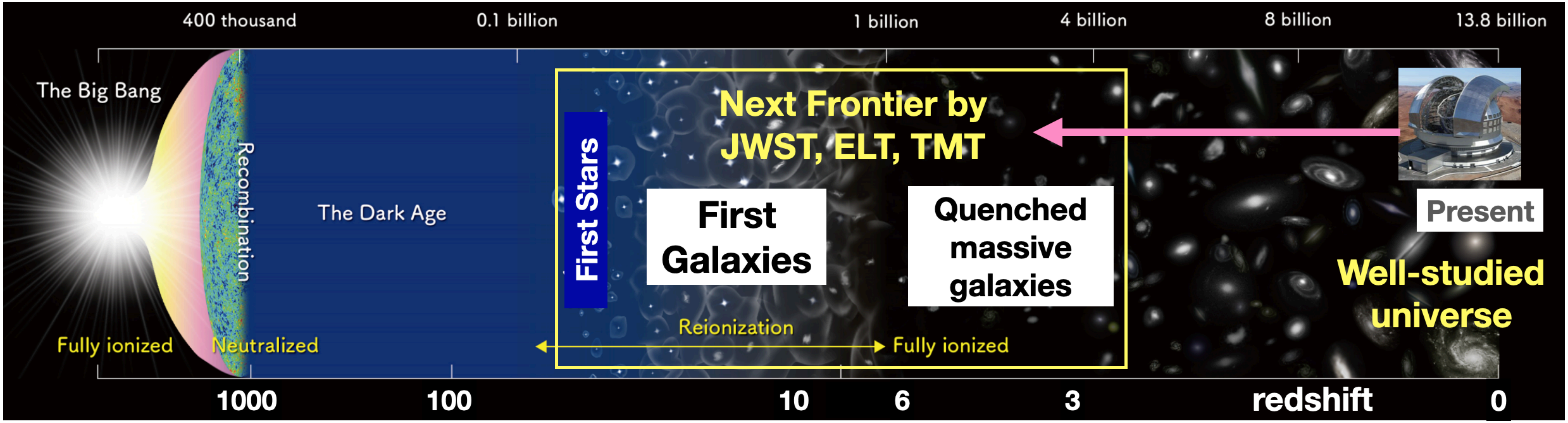
Rocha+'13

Recent JWST discoveries & their implications

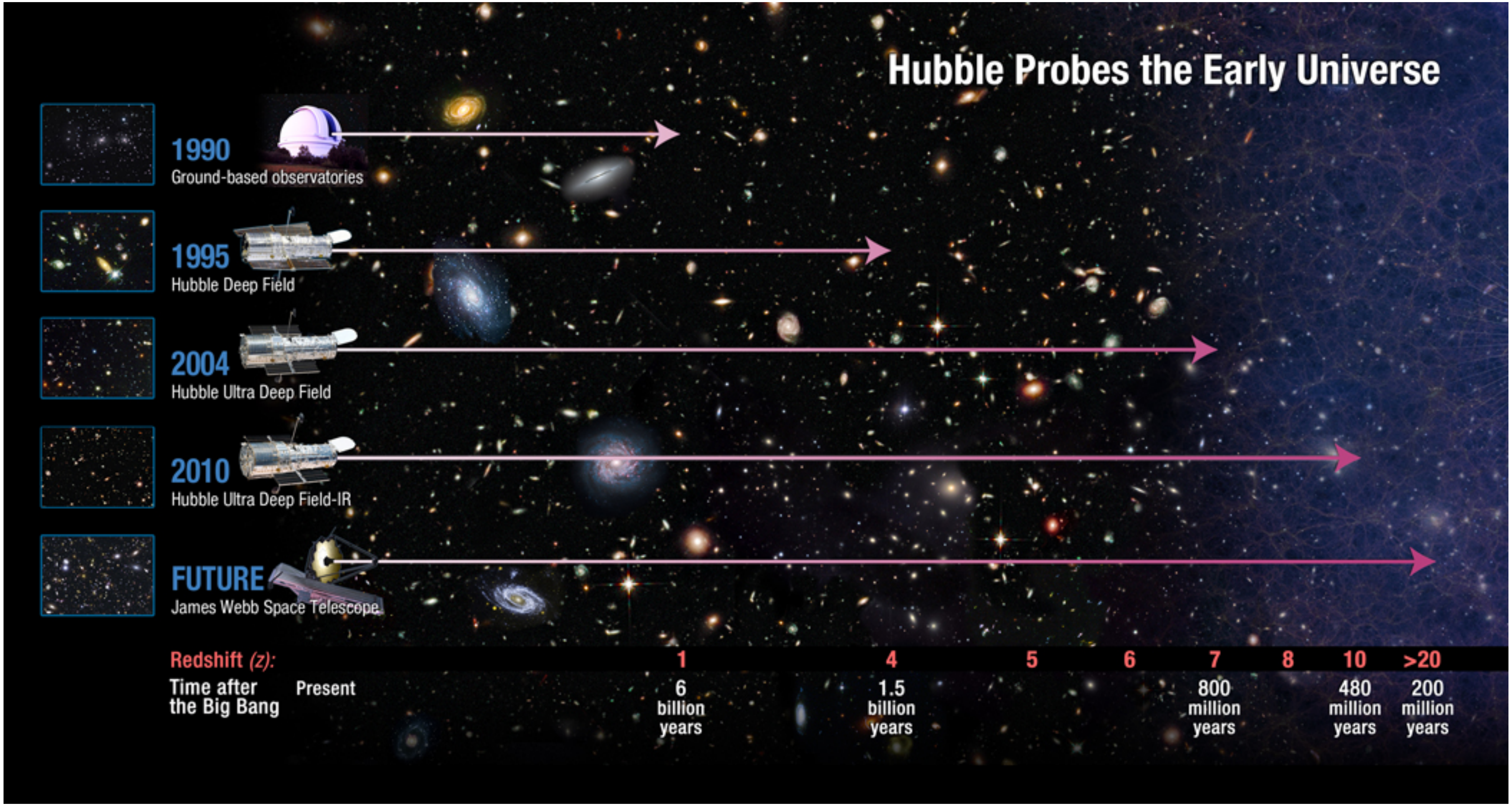
JWST launch
Dec 2021







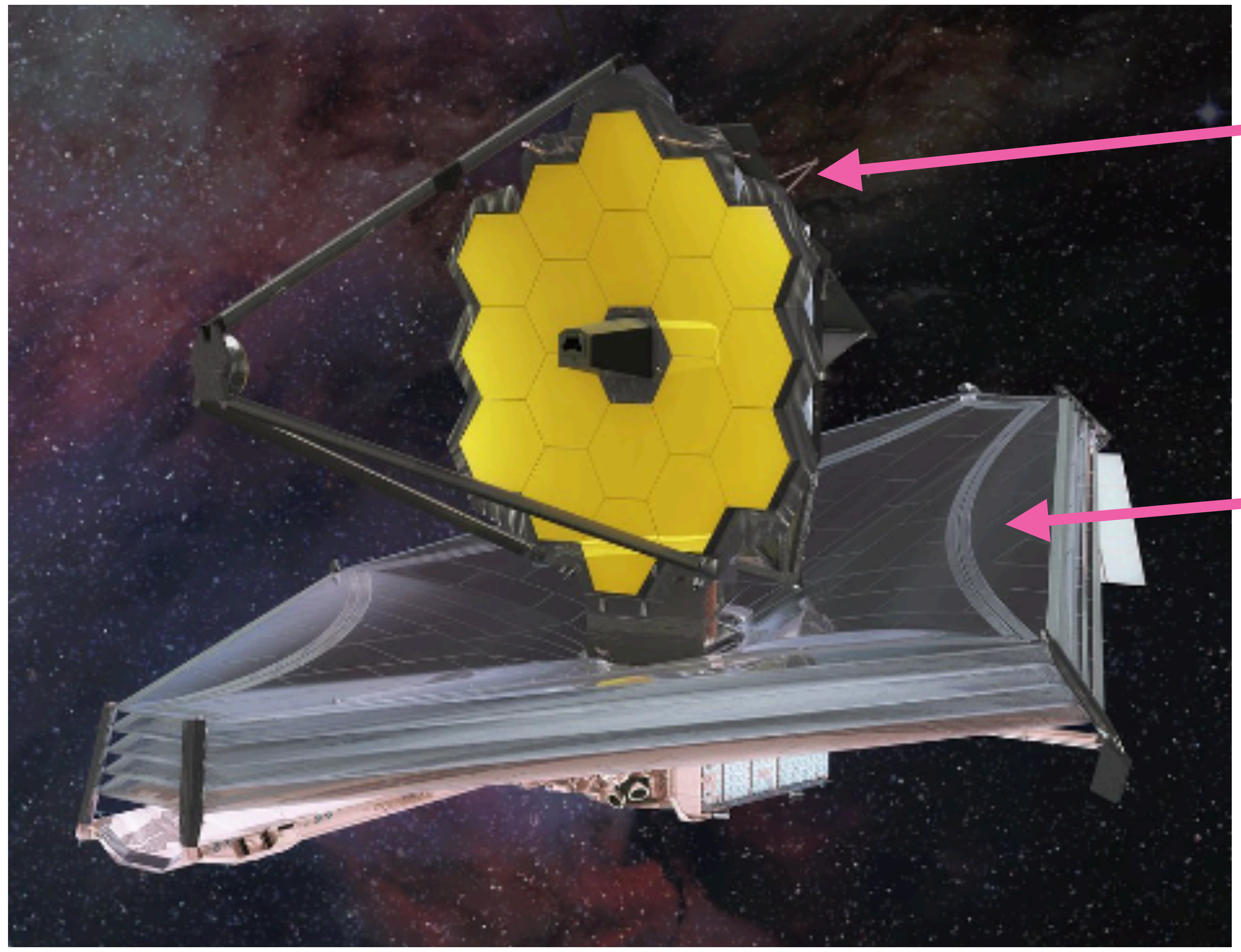
Redshift Frontier



NASA

James Webb Space Telescope (JWST)

- Covering up to IR (0.6 —28.5 micron)
- Segmented mirror (6.5m) @L2 point （cf. Hubble 2.4m)
- ~10B USD project（~1.5兆円）
- Launched on Dec 25, 2021; First image released on July 12, 2022

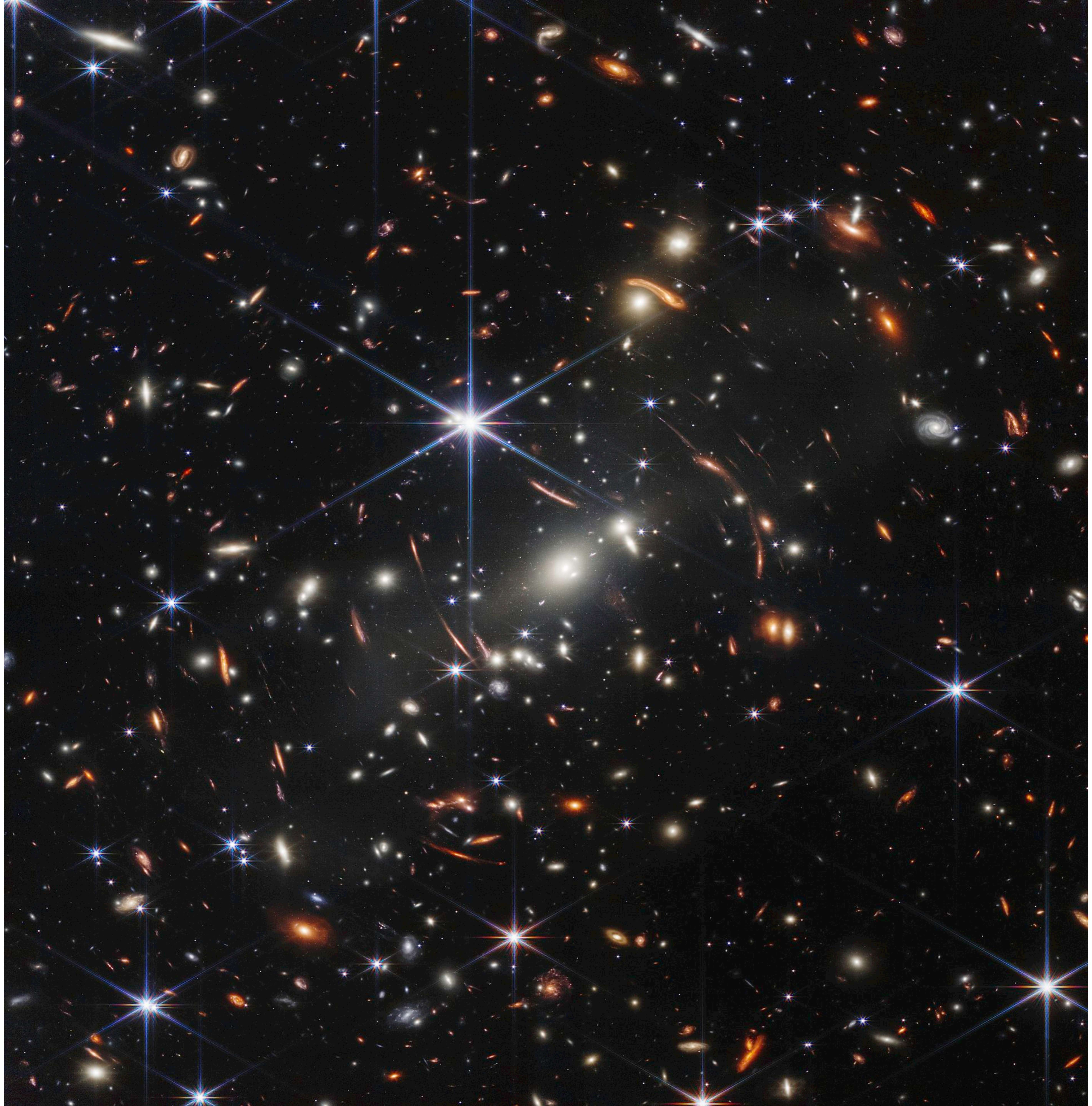


primary mirror（diameter 6.5m)

Sun Shield

keep the telescope at -233°c

ジェームズ・ウェッブ宇宙望遠鏡 (JWST)



Galaxy Cluster SMACS 0723

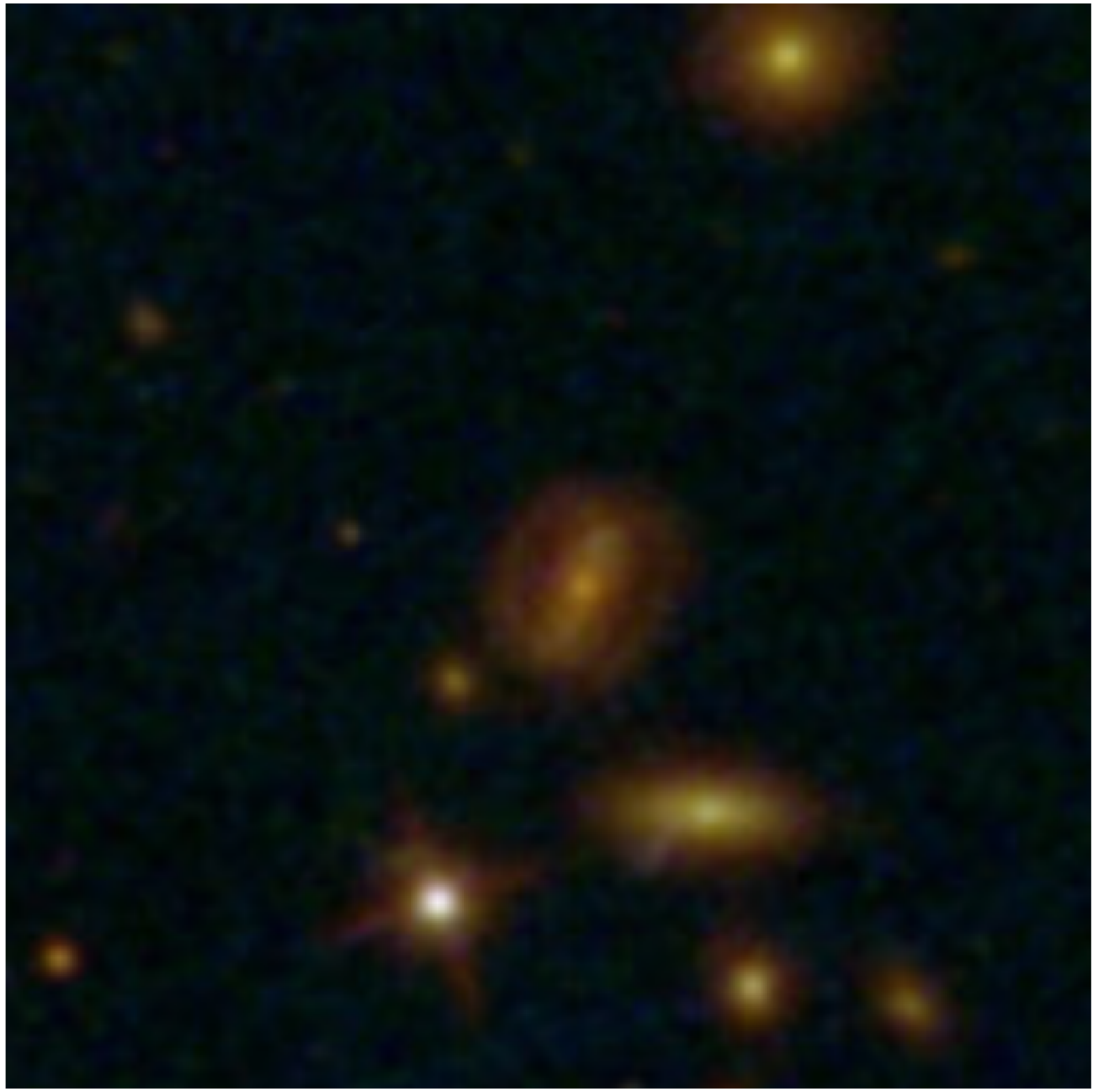
First publicly released JWST image

July 11, 2022

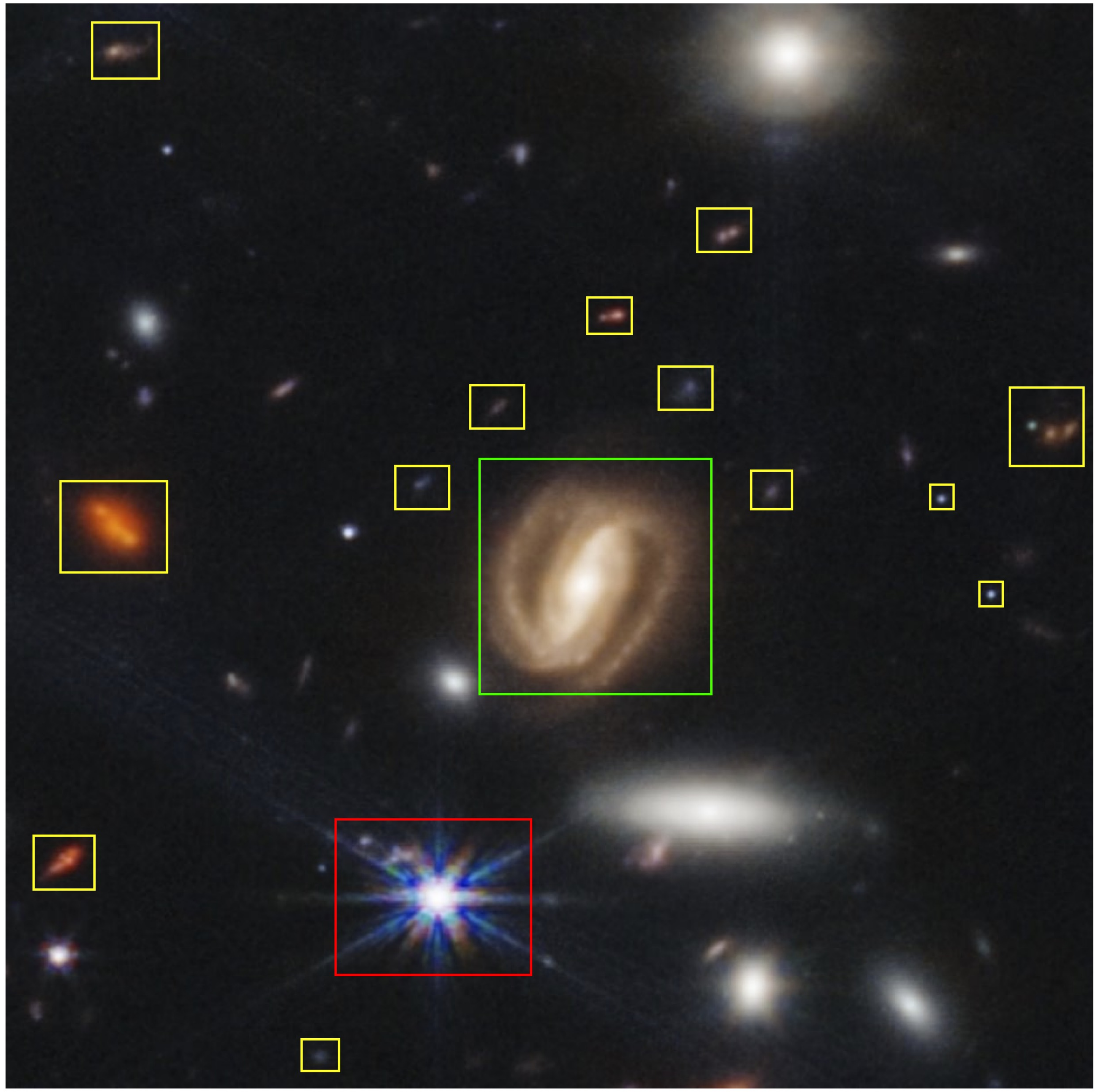
4.6 billion yrs from Earth

z~0.4

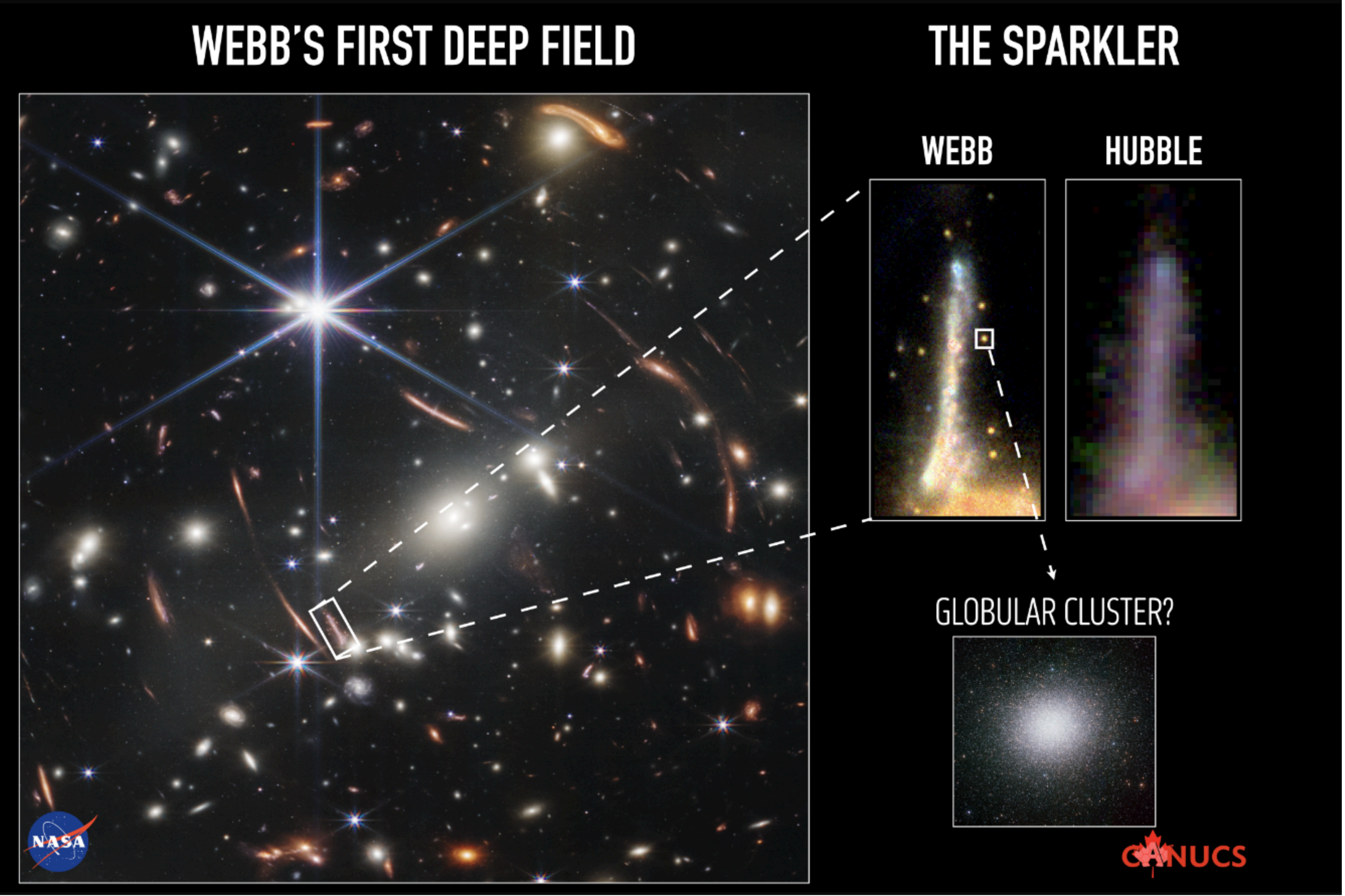
HST



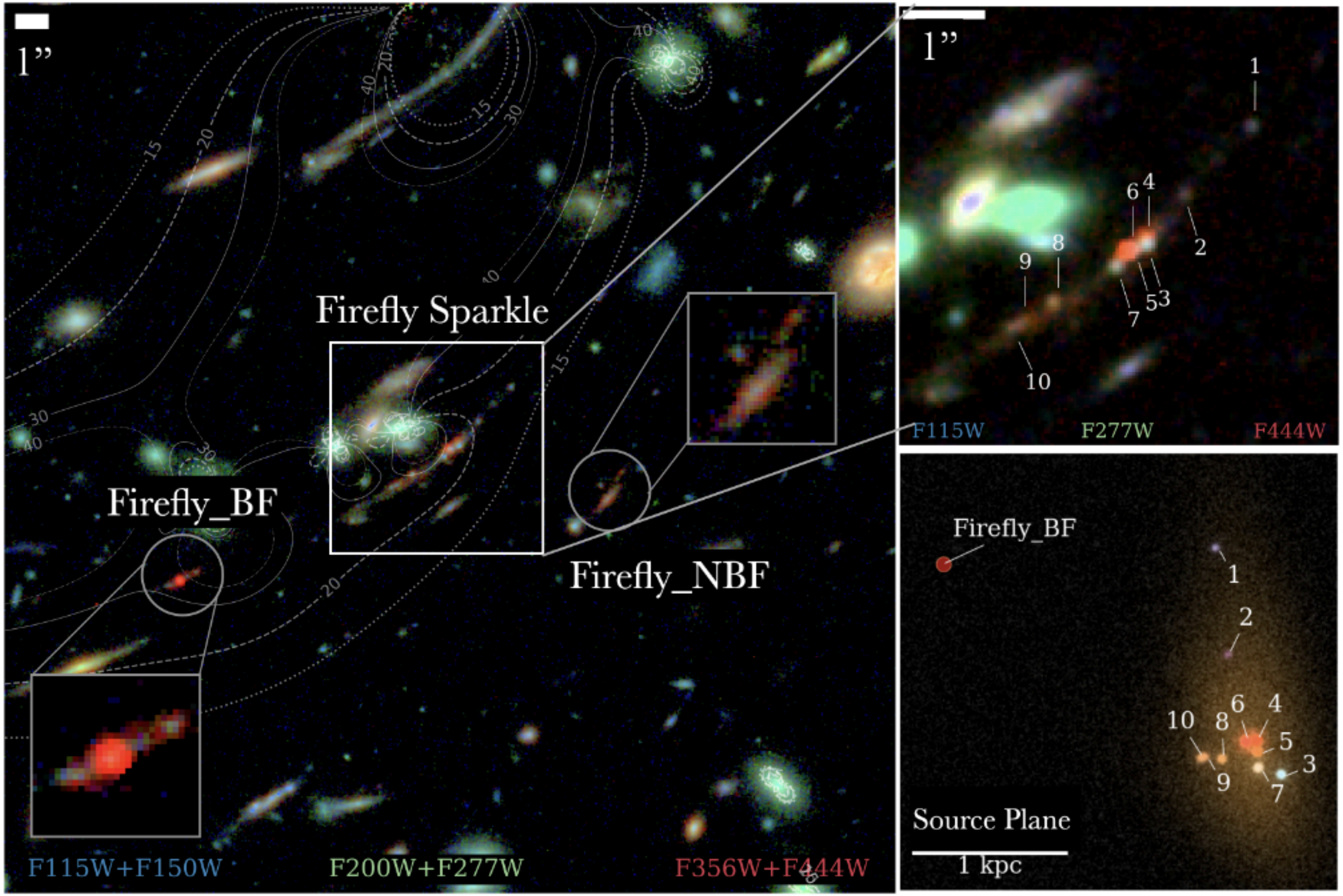
JWST



Galaxy Cluster SMACS 0723


WEBB'S FIRST DEEP FIELD
THE SPARKLER
WEBB
HUBBLE
GLOBULAR CLUSTER?
NASA
CANUCS

9 Gyrs ago…



Grav. lensed gal in MACS J1423:

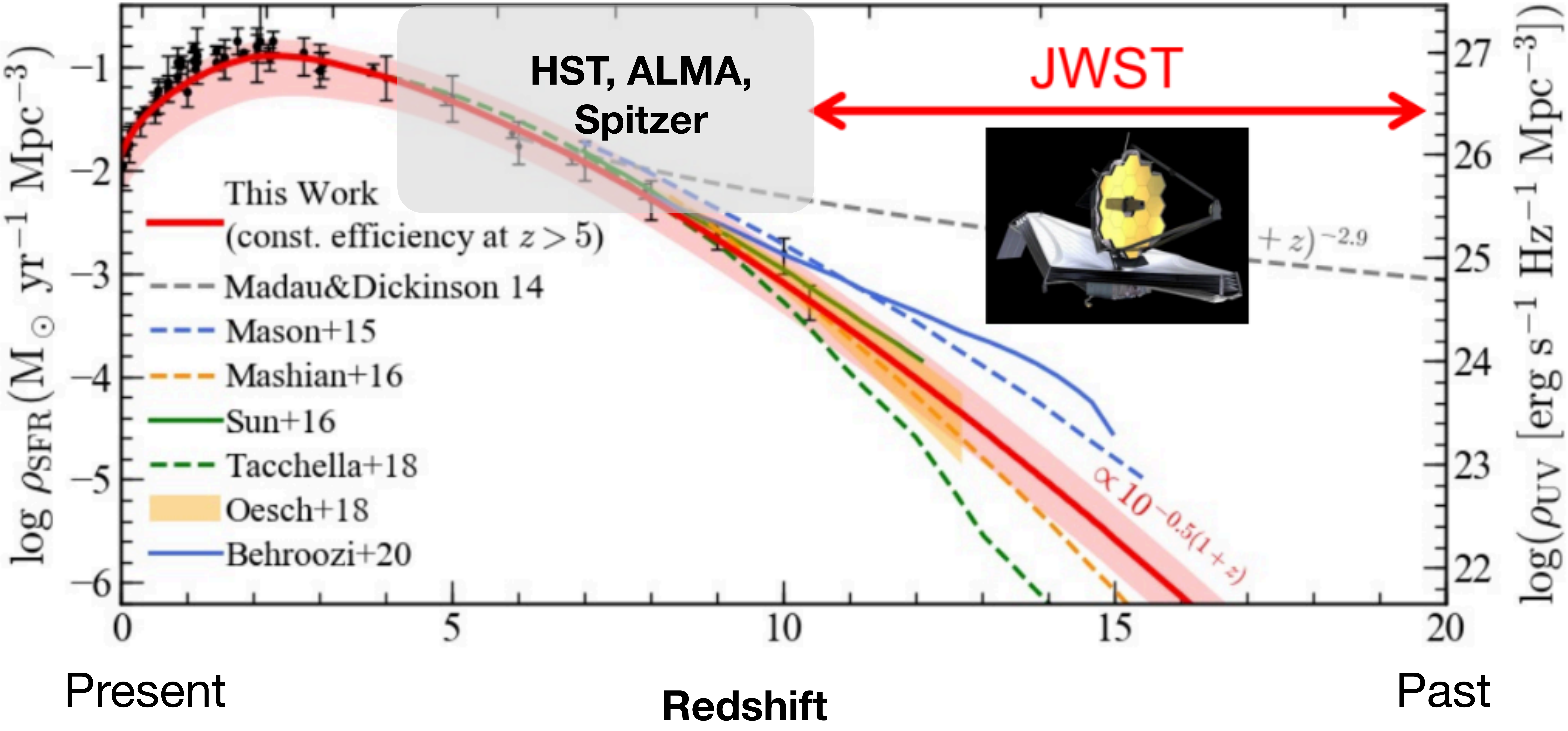
$z_{spec} \sim 8.3$

- **[Oiii] detection**

- **10 star clusters**
- $M_\star \sim 10^5 - 10^6\, M_\odot$
- **nebular dominated spectra —> high** $T_e \sim 4 \times 10^4\, K$
- **top-heavy IMF**

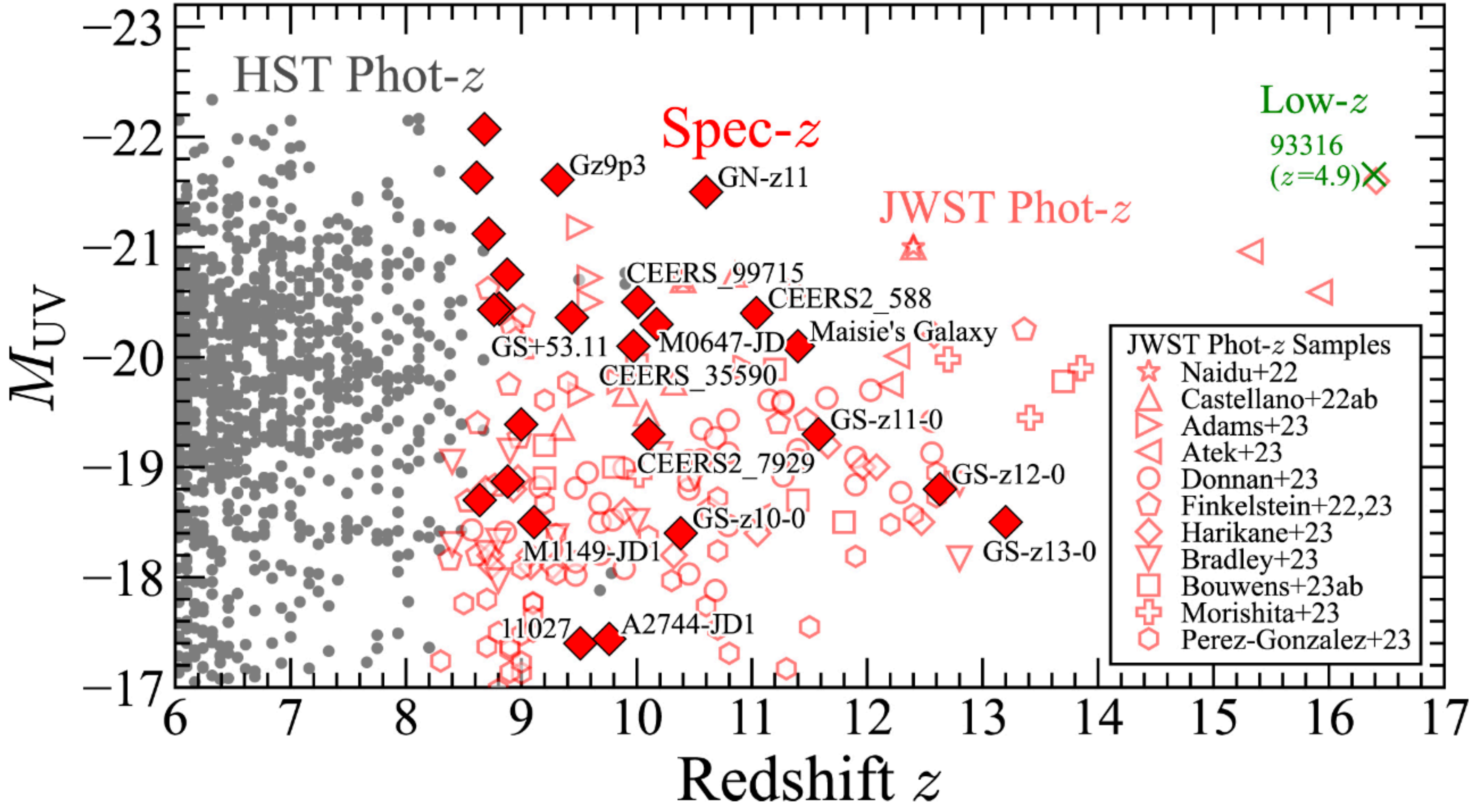
Mowla+'24

Cosmic Star Formation Rate



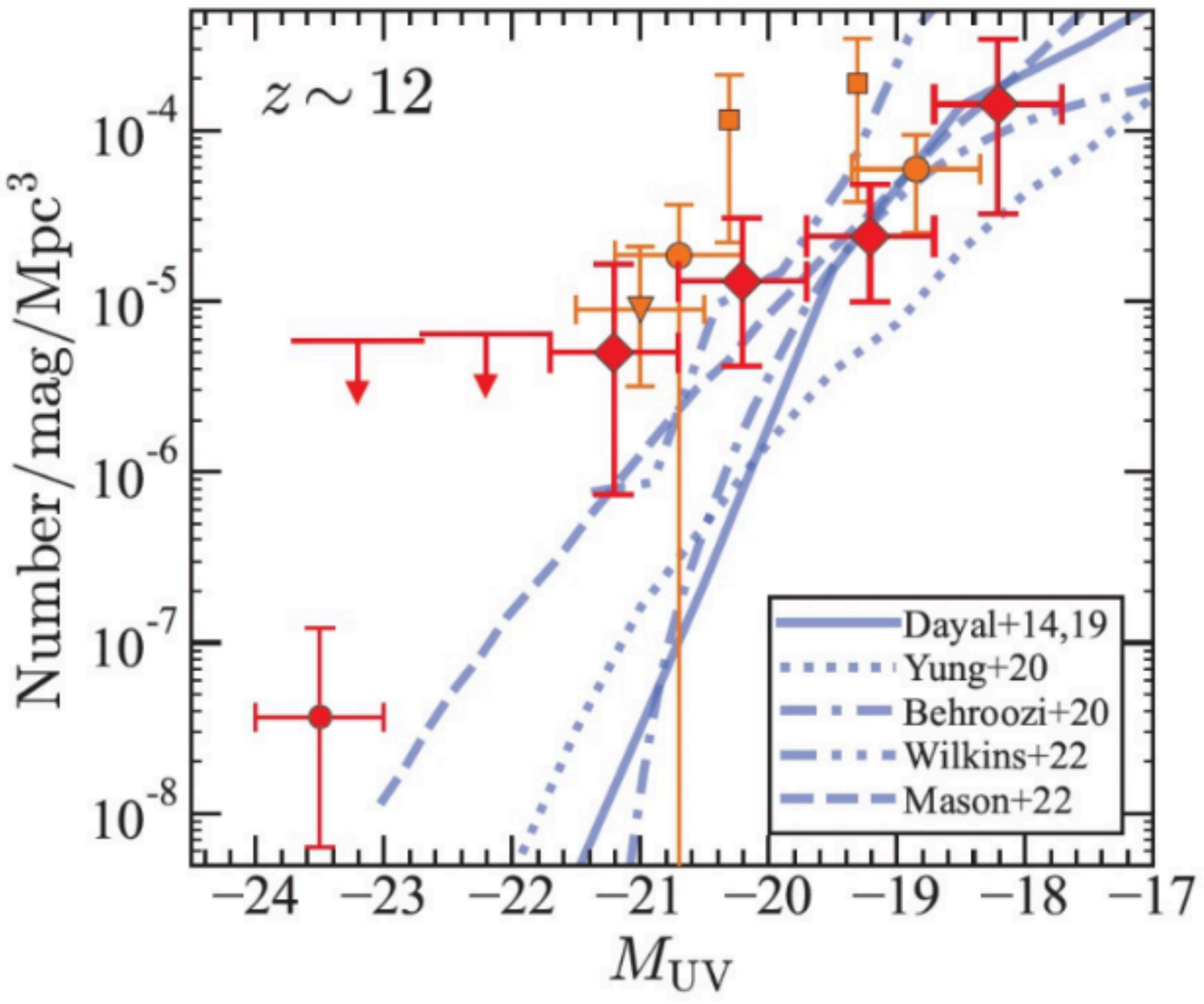
Harikane+23

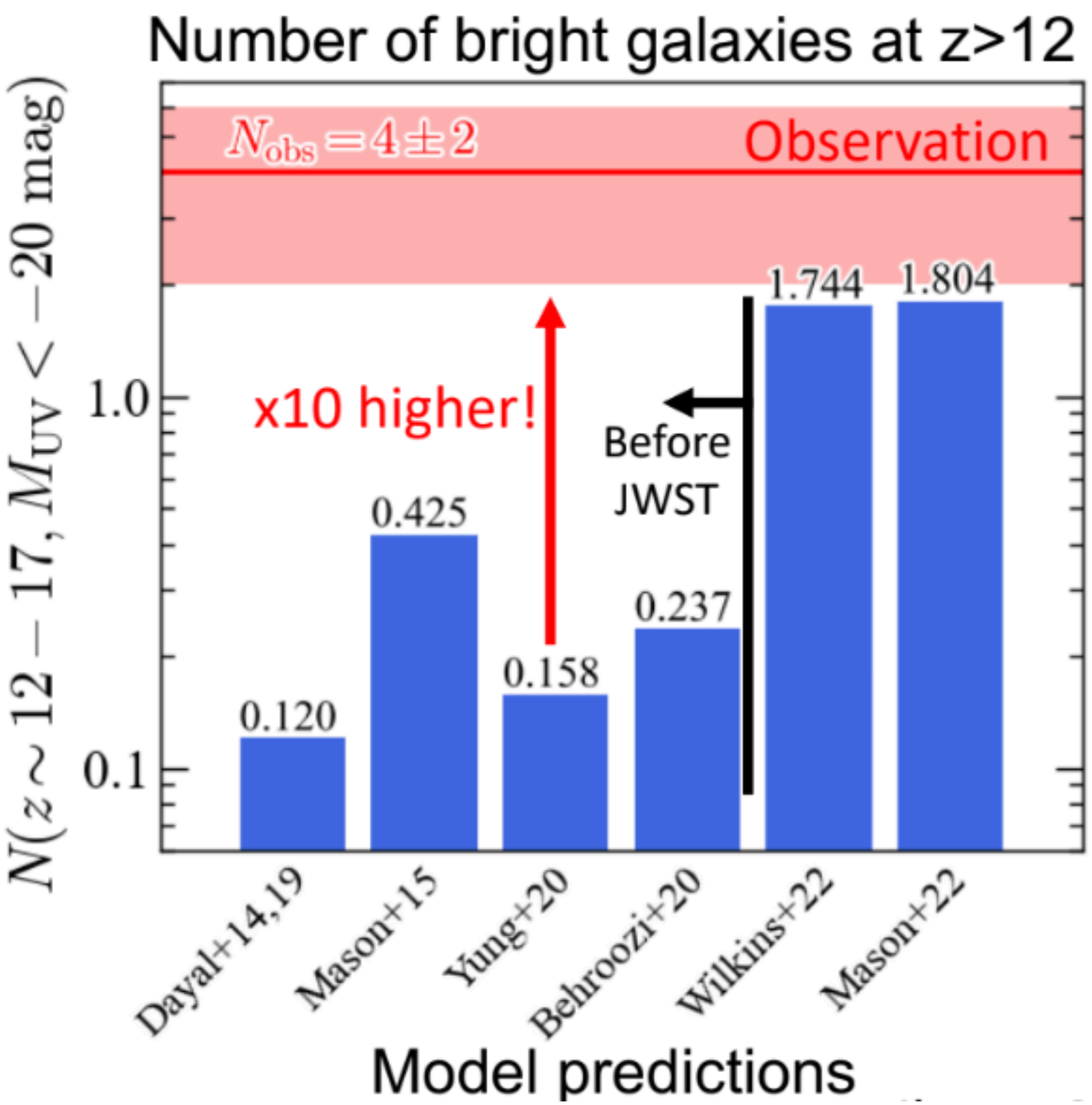
More high-z galaxies



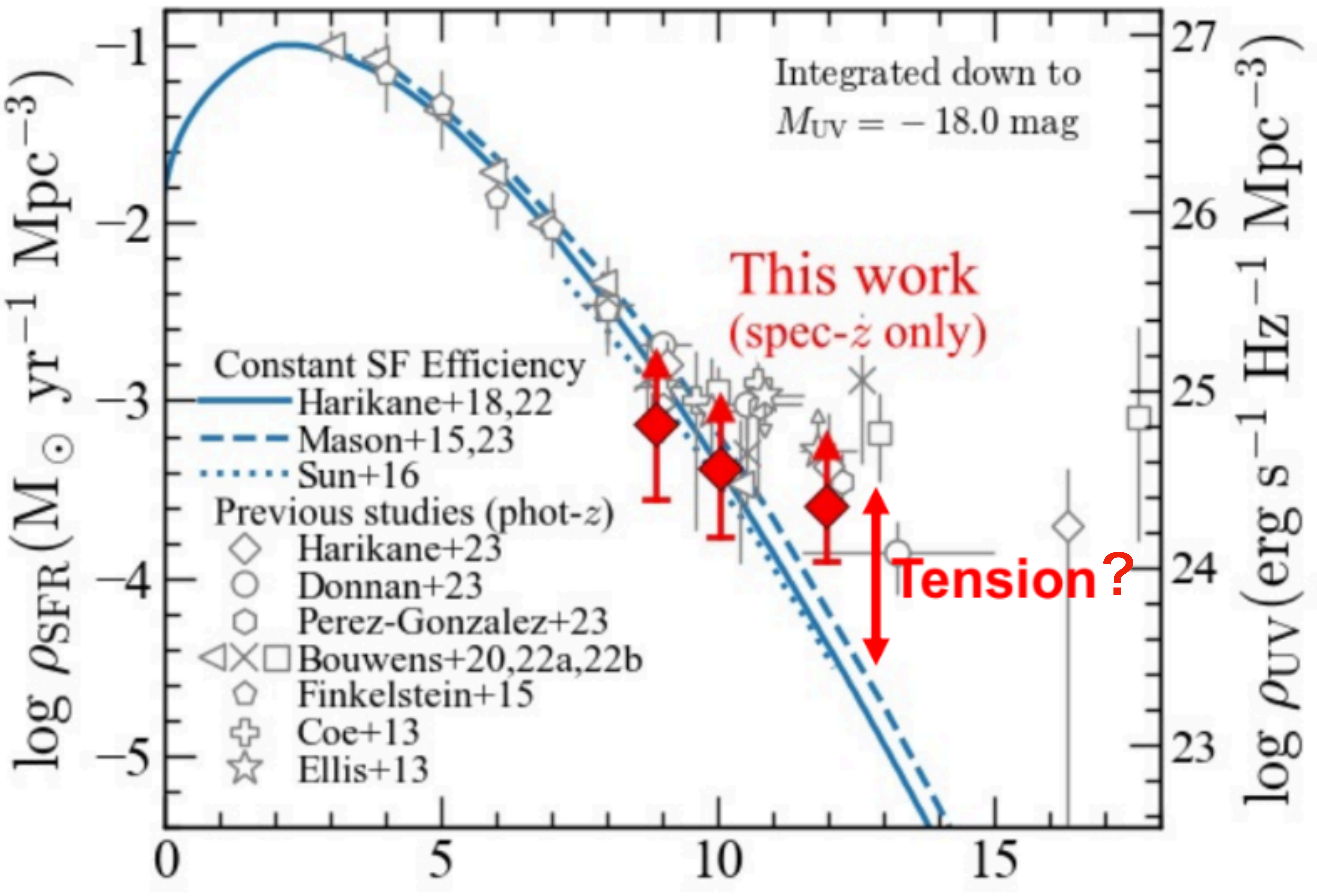
Harikane+'23

Larger number of z>12 gals than in simulations?





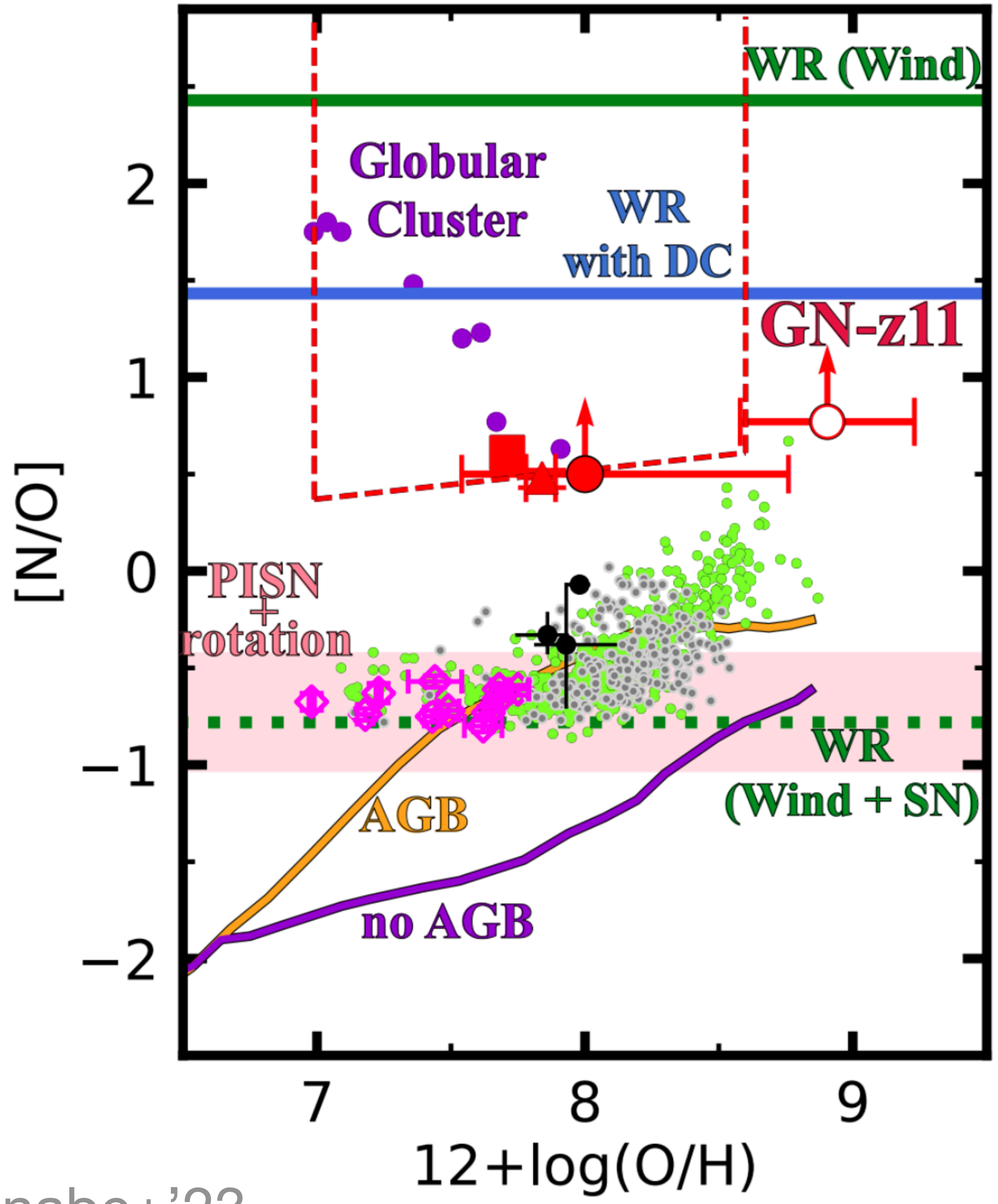
Harikane+'23



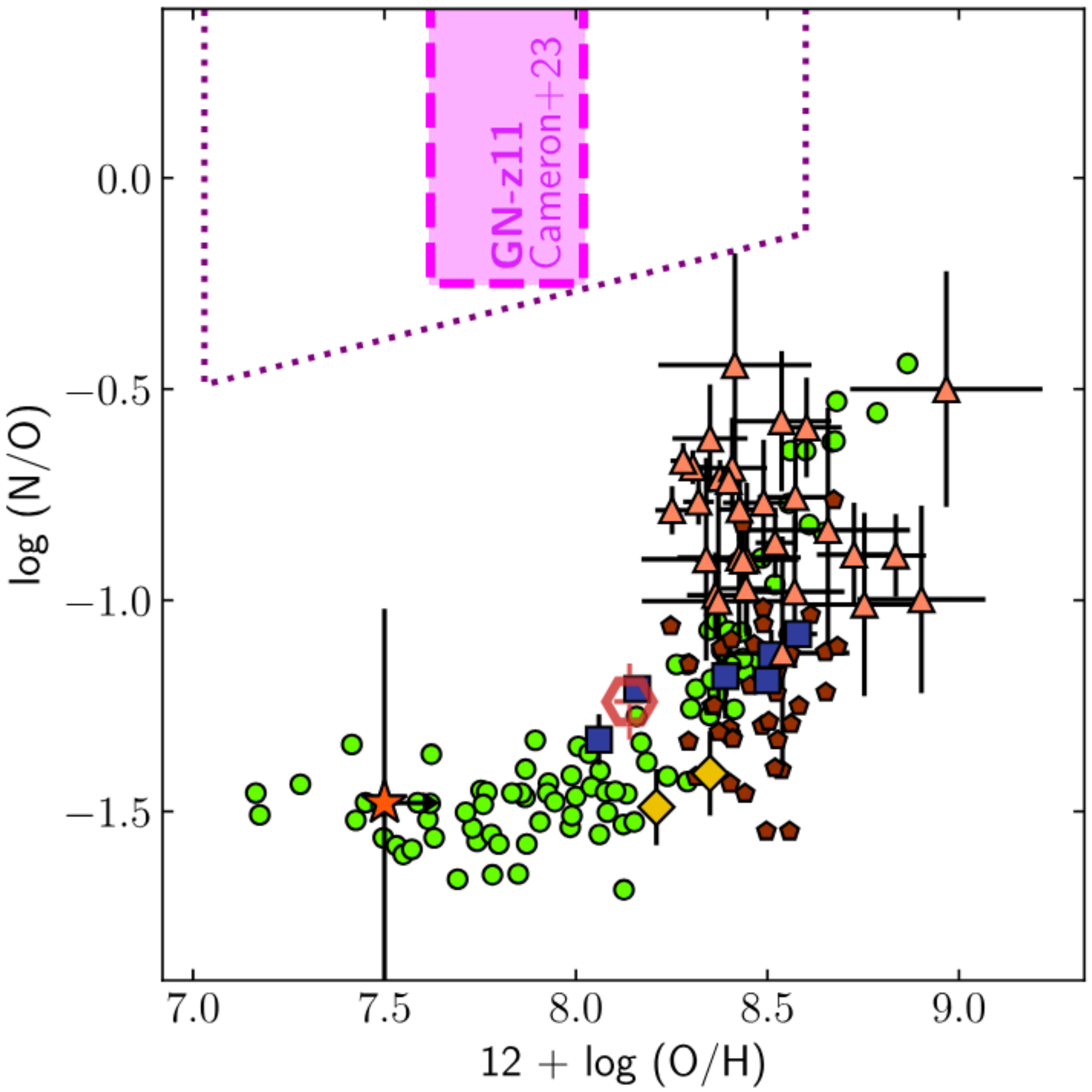
Integrated down to
$M_{UV} = -18.0$ mag
This work
(spec-z only)
Tension?
Constant SF Efficiency
Harikane+18,22
Mason+15,23
Sun+16
Previous studies (phot-z)
Harikane+23
Donnan+23
Perez-Gonzalez+23
Bouwens+20,22a,22b
Finkelstein+15
Coe+13
Ellis+13
$\log \rho_{SFR} (M_\odot \ yr^{-1} \ Mpc^{-3})$
$\log \rho_{UV} (erg \ s^{-1} \ Hz^{-1} \ Mpc^{-3})$
−1
−2
−3
−4
−5
27
26
25
24
23
0
5
10
15

Redshift

Anomalous abundance ratios — top-heavy IMF?

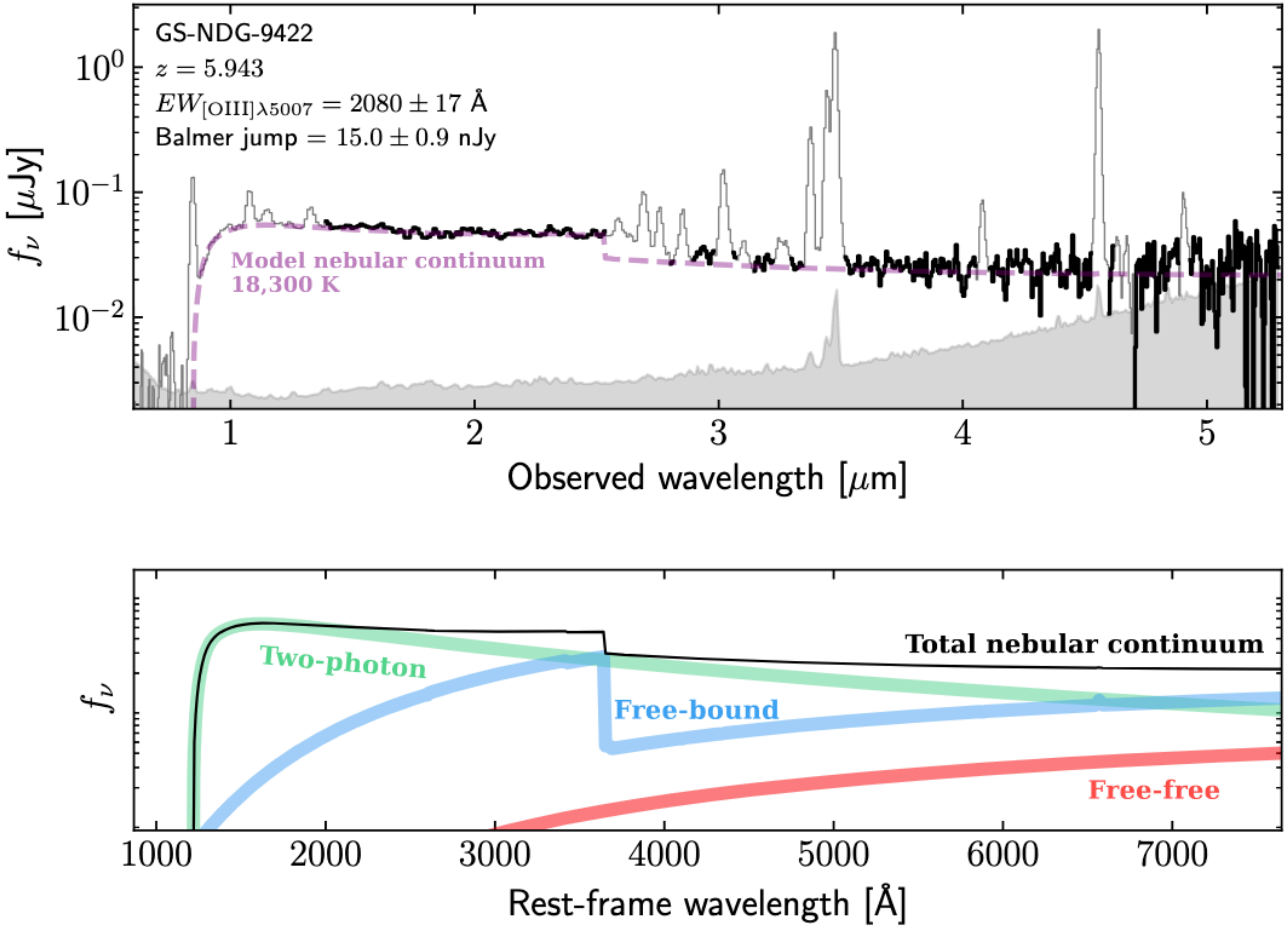


Watanabe+'23



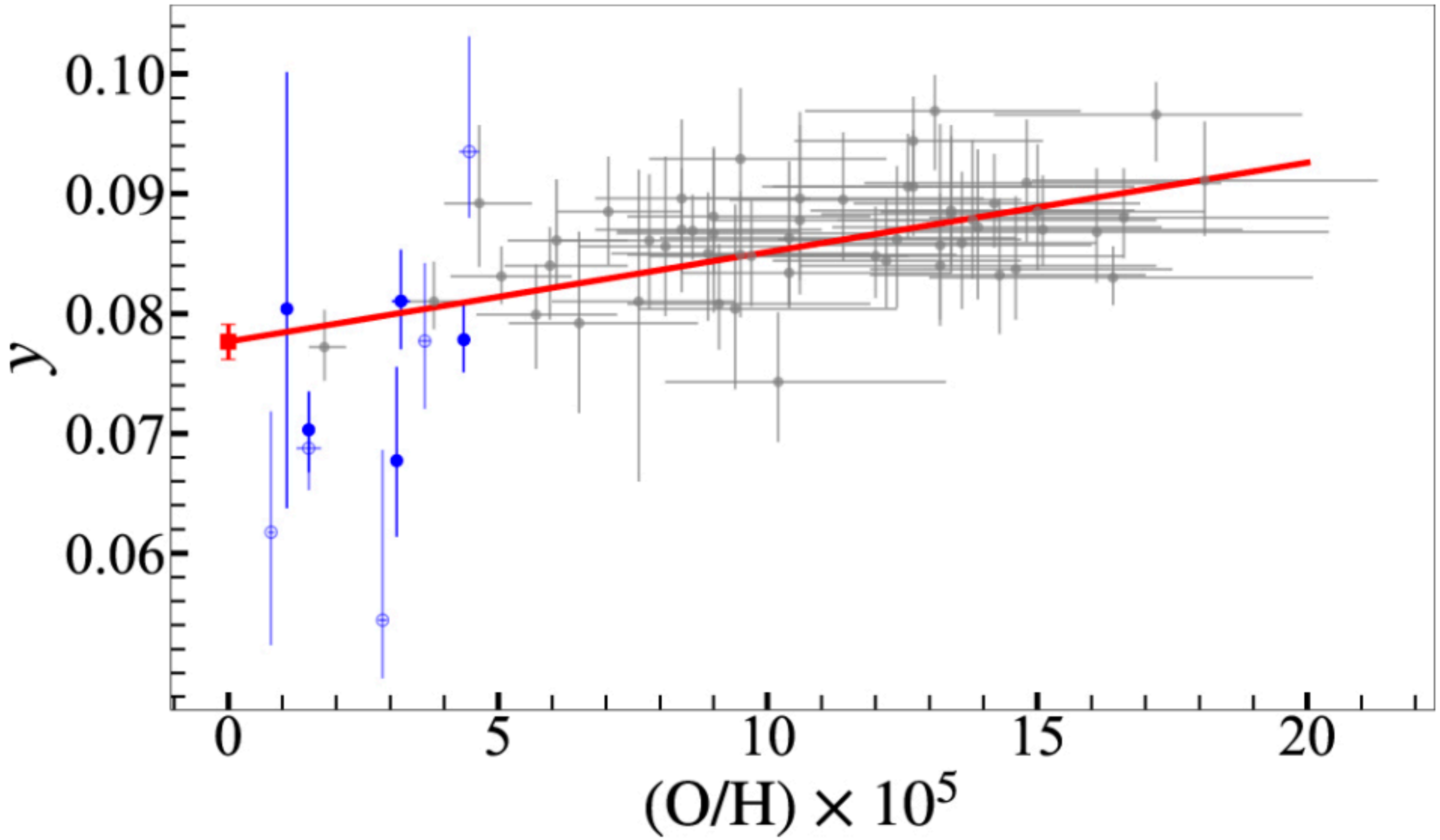
Cameron+'23a

High nebular continuum — top heavy IMF?



Cameron+'23b

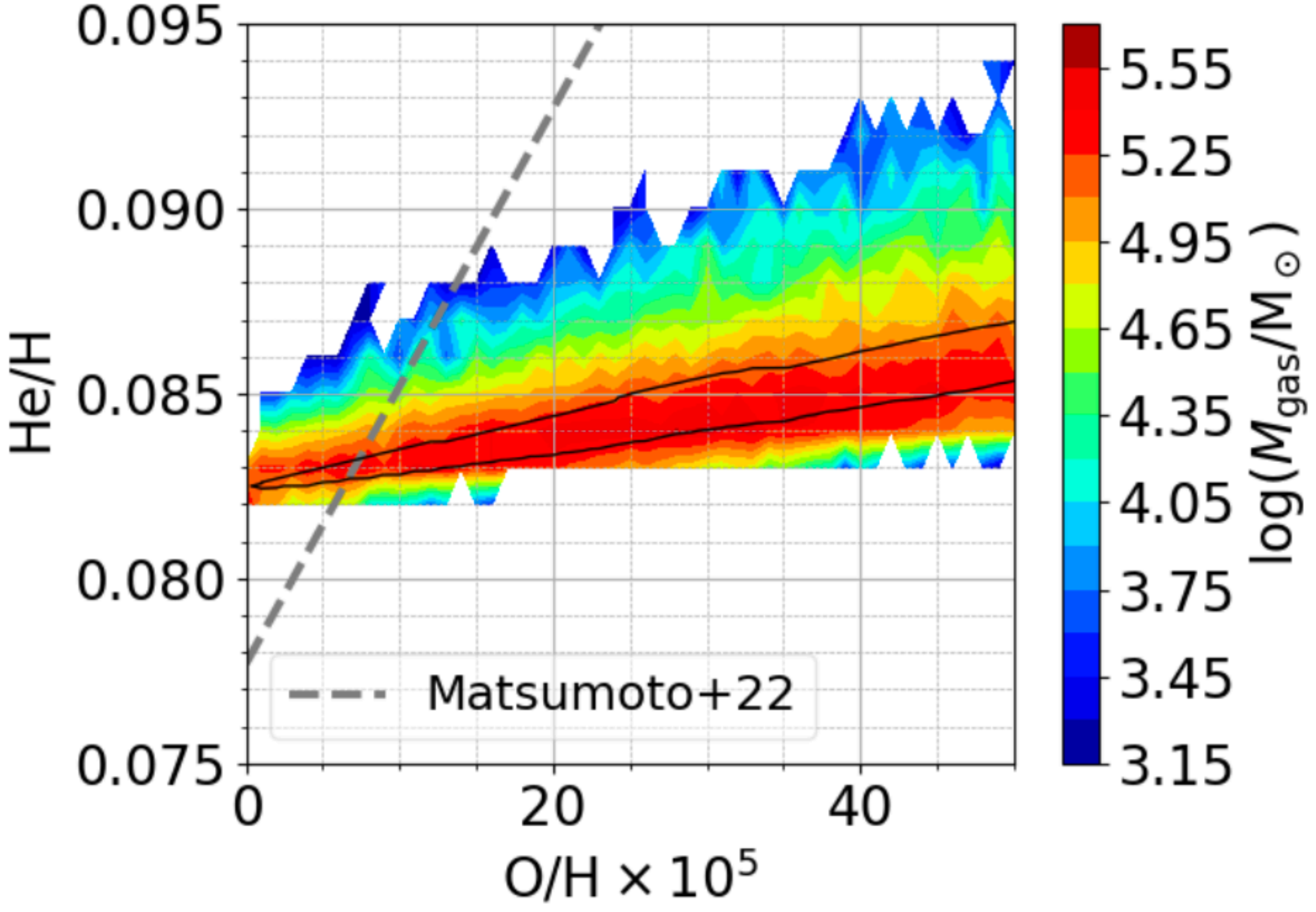
Primordial He abundance from local EMPGs

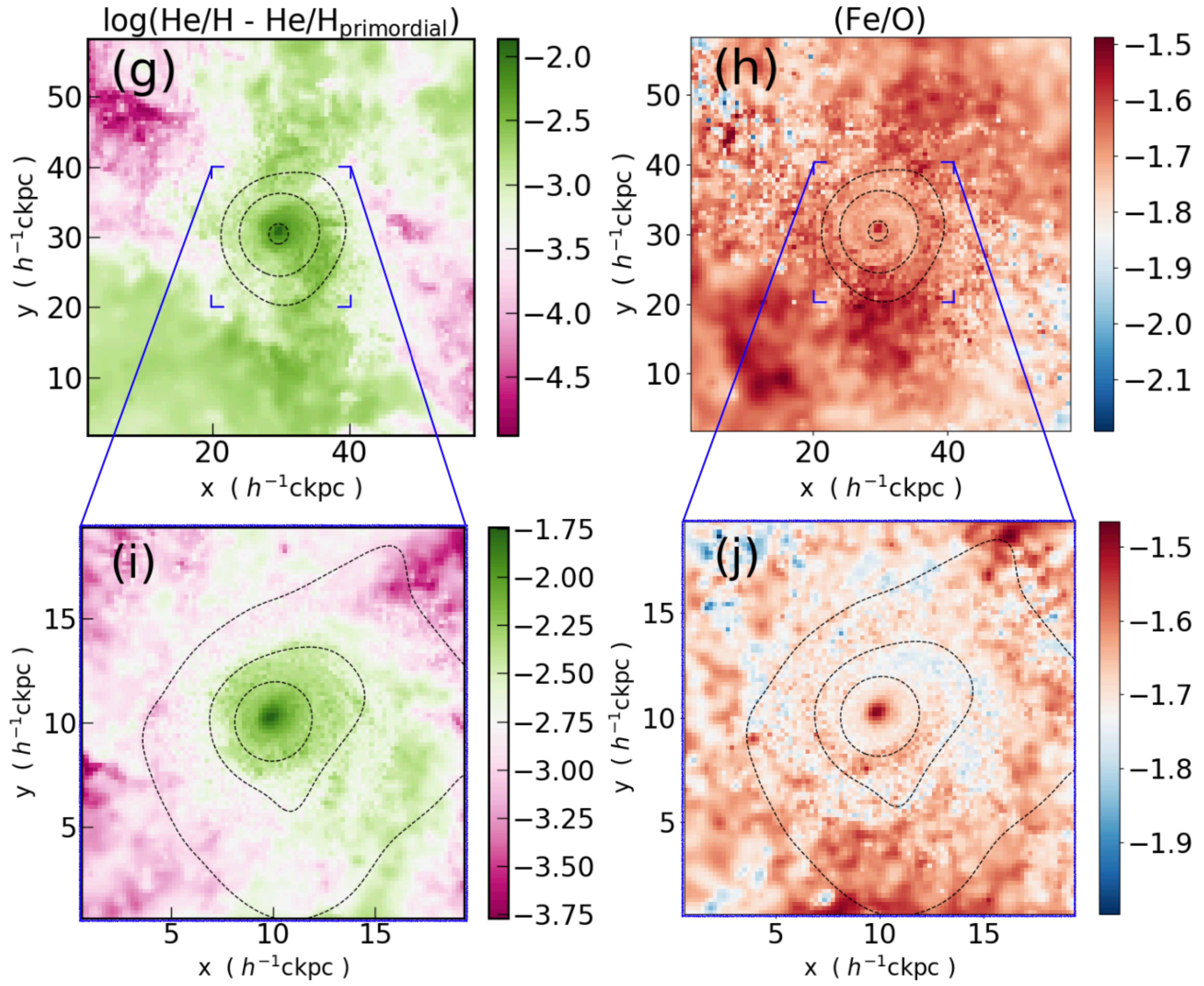


Matsumoto+'23

Probing Chemical Enrichment in Extremely Metal-Poor Galaxies and First Galaxies

Keita Fukushima,[1] Kentaro Nagamine,[1,2,3] Akinori Matsumoto,[4,5] Yuki Isobe,[4,5] Masami Ouchi,[6,4,7]
Takayuki R. Saitoh,[8] and Yutaka Hirai[9,10]





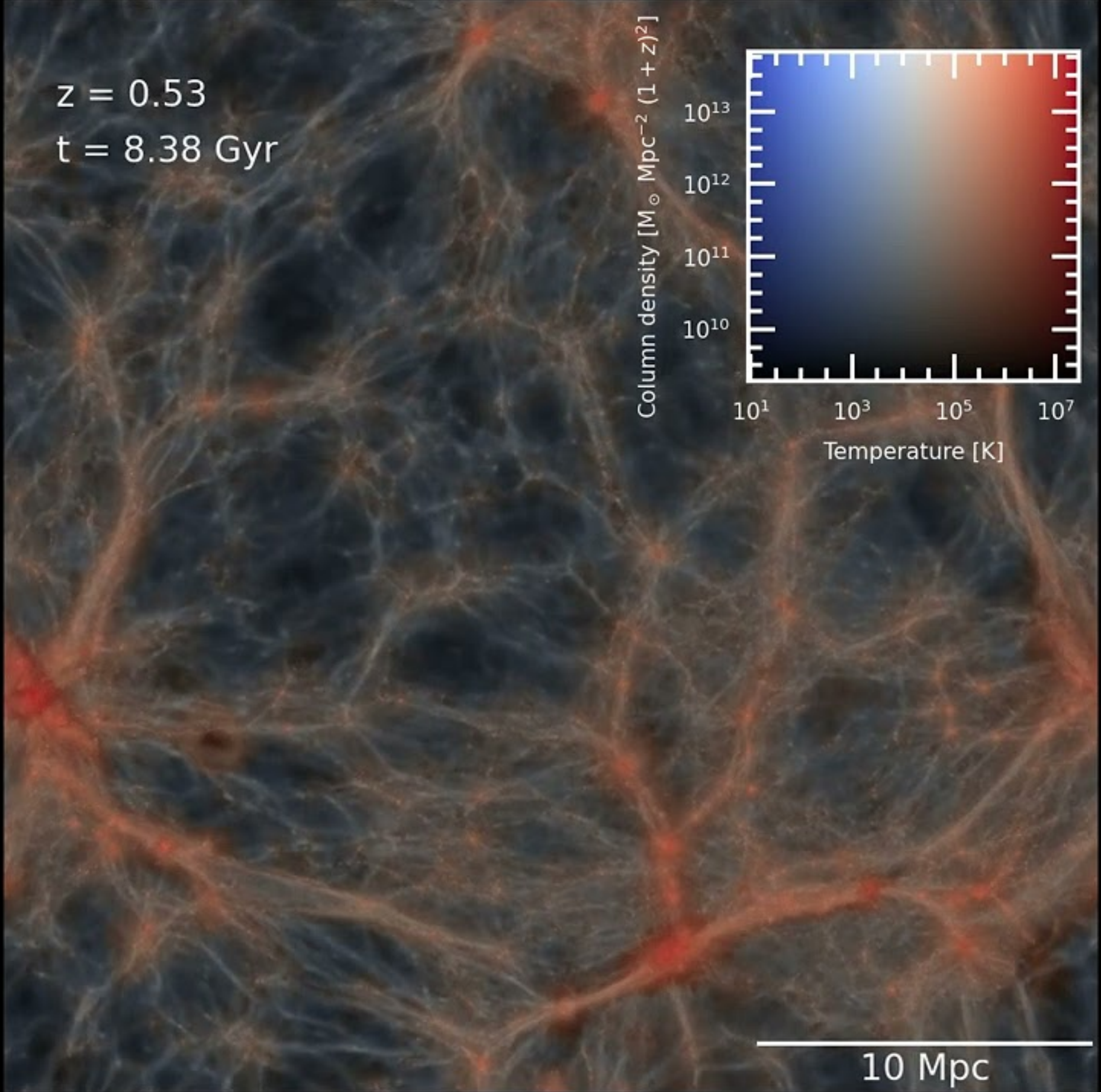
z~10 simulated galaxy

Lya forest & IGM tomography

CROCODILE

simulation

Dr. Wani
@Osaka U.



Understanding the matter distribution:

DM, gas, stars

HI, metals, dust, …

25 & 50 Mpc/h

Star formation

SN & AGN fb

UVB

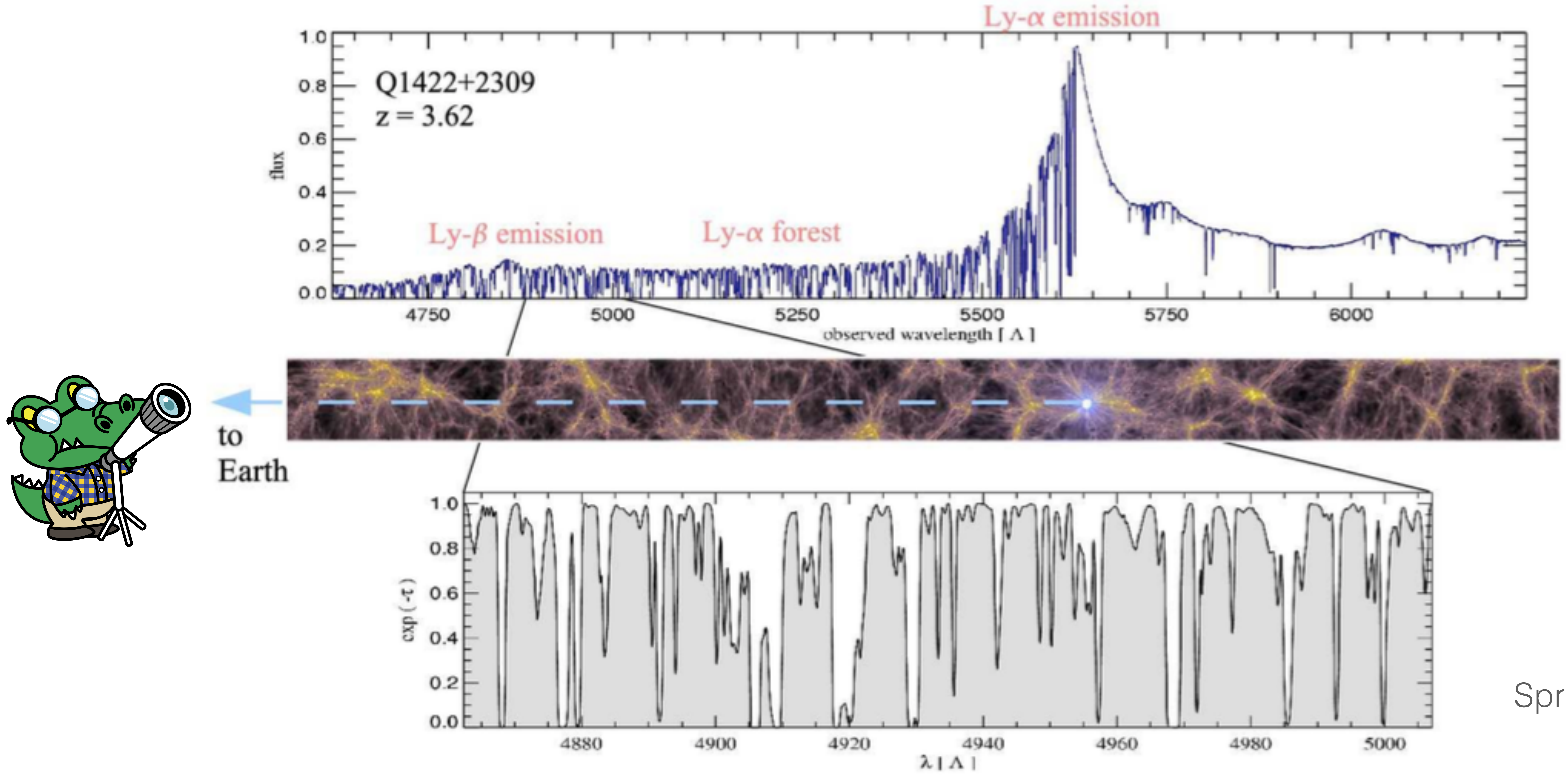
Oku & KN '24

arXiv:2401.06324

Quasar absorption line and Ly-α forest

(a beam of light from a supermassive black hole)

(rest-frame 1216Å)

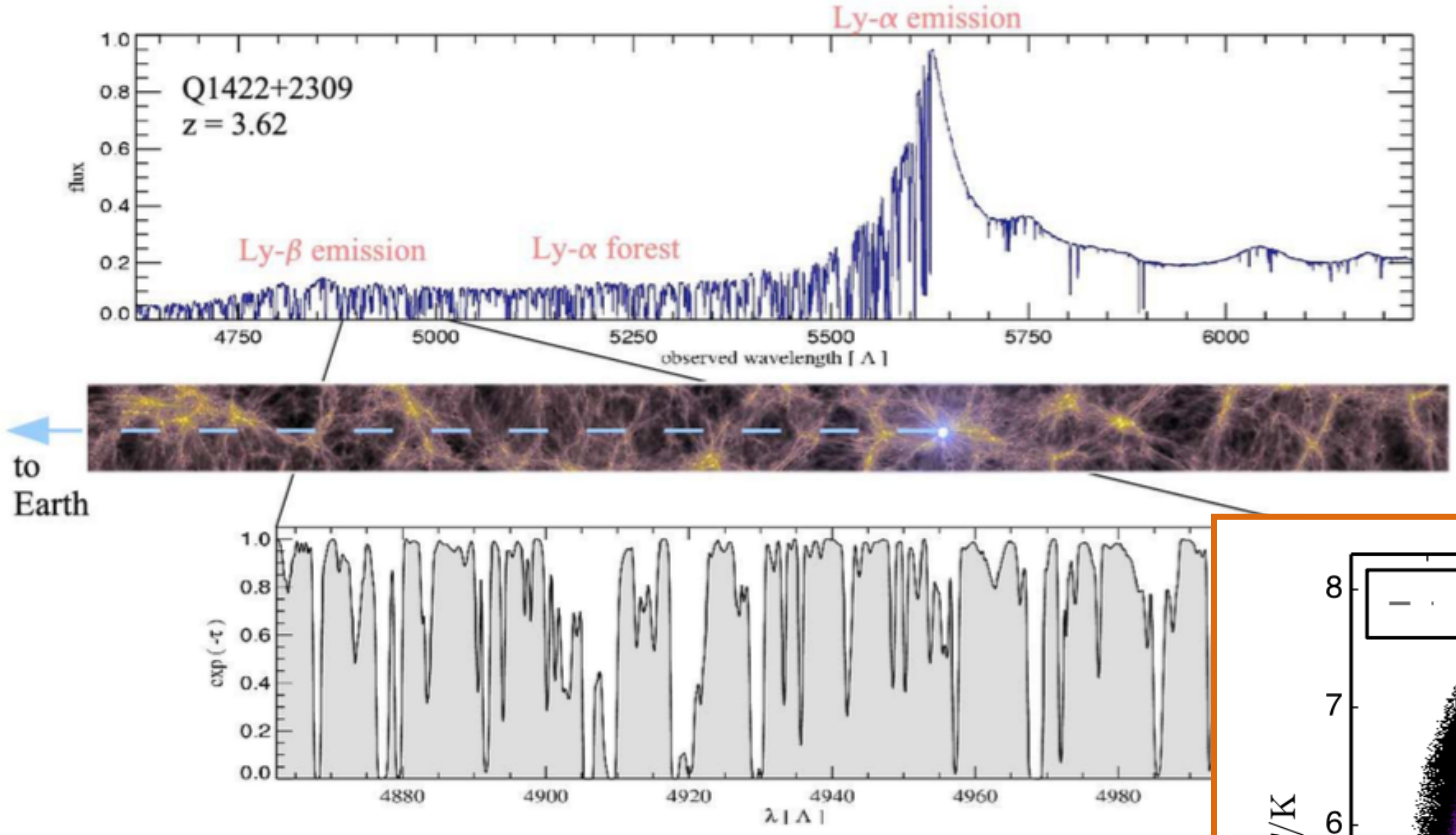


Springel+'05

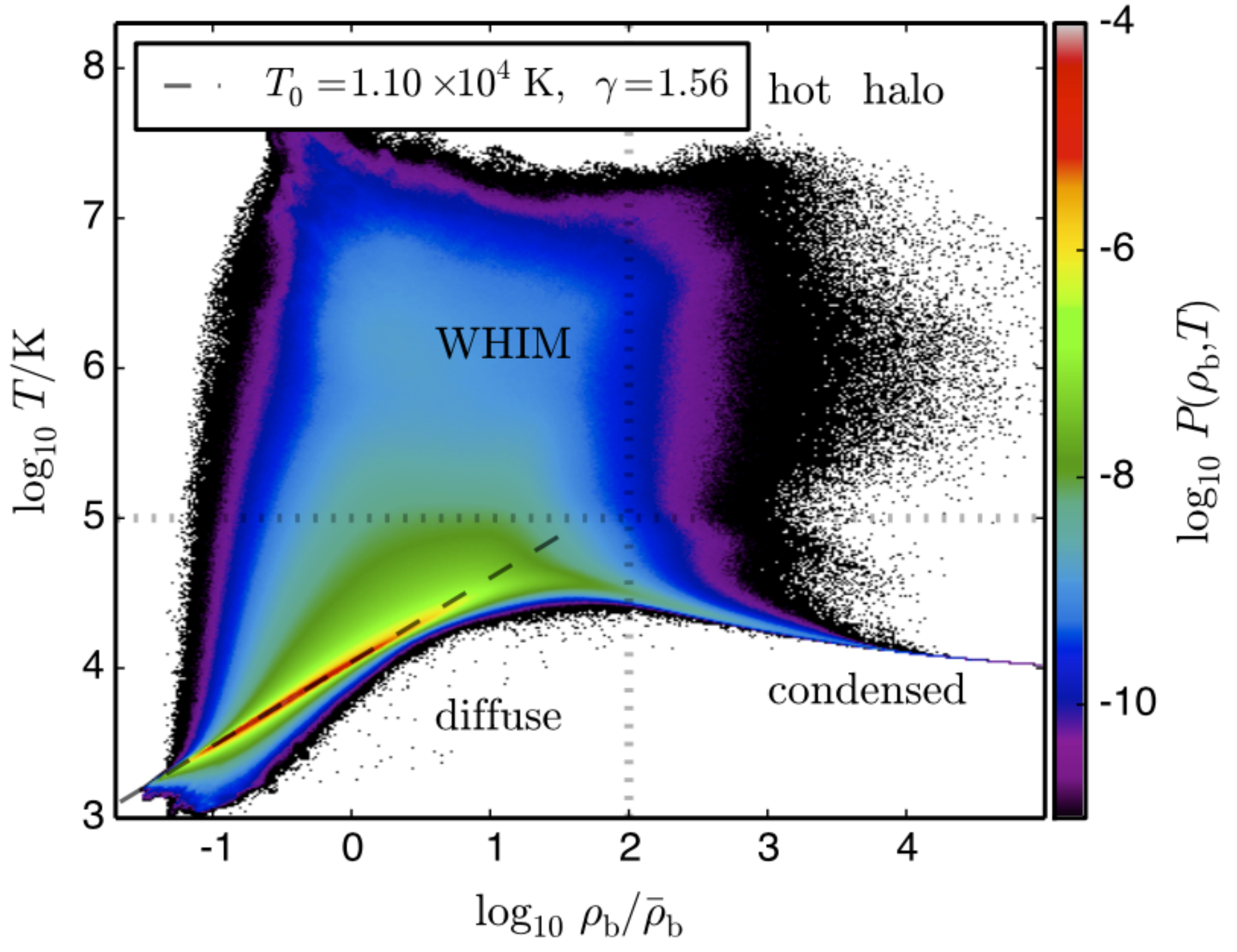
obs: Weymann+81; Cowie+95; Rauch+98

theory: Cen+94; Hernquist+96; Miralda-Escude+96; Croft+98; Zhang+97, 98

Quasar absorption line and Ly-α forest



Springel+'05
(cf. Cen+'94)

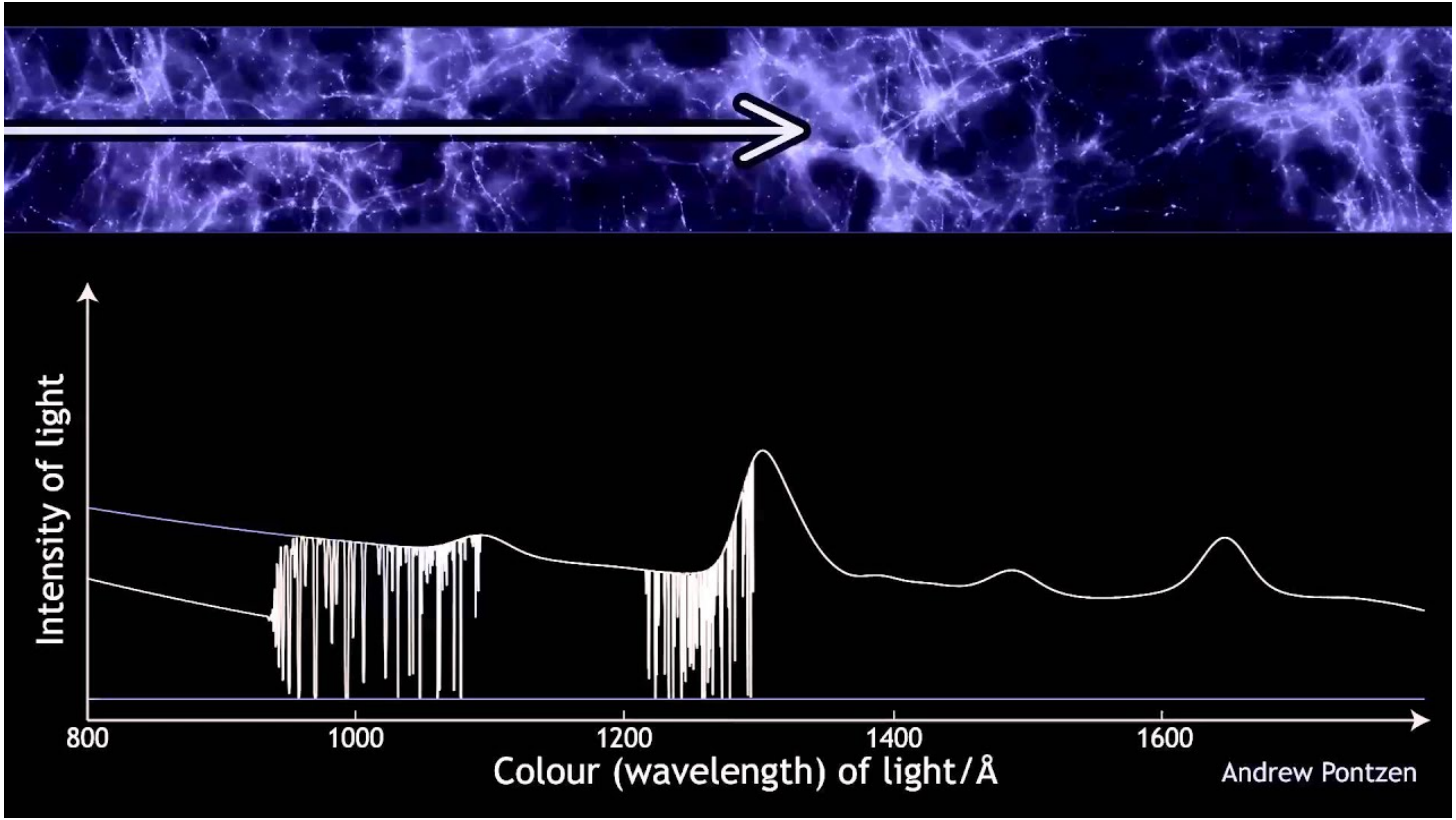


Lukic+16

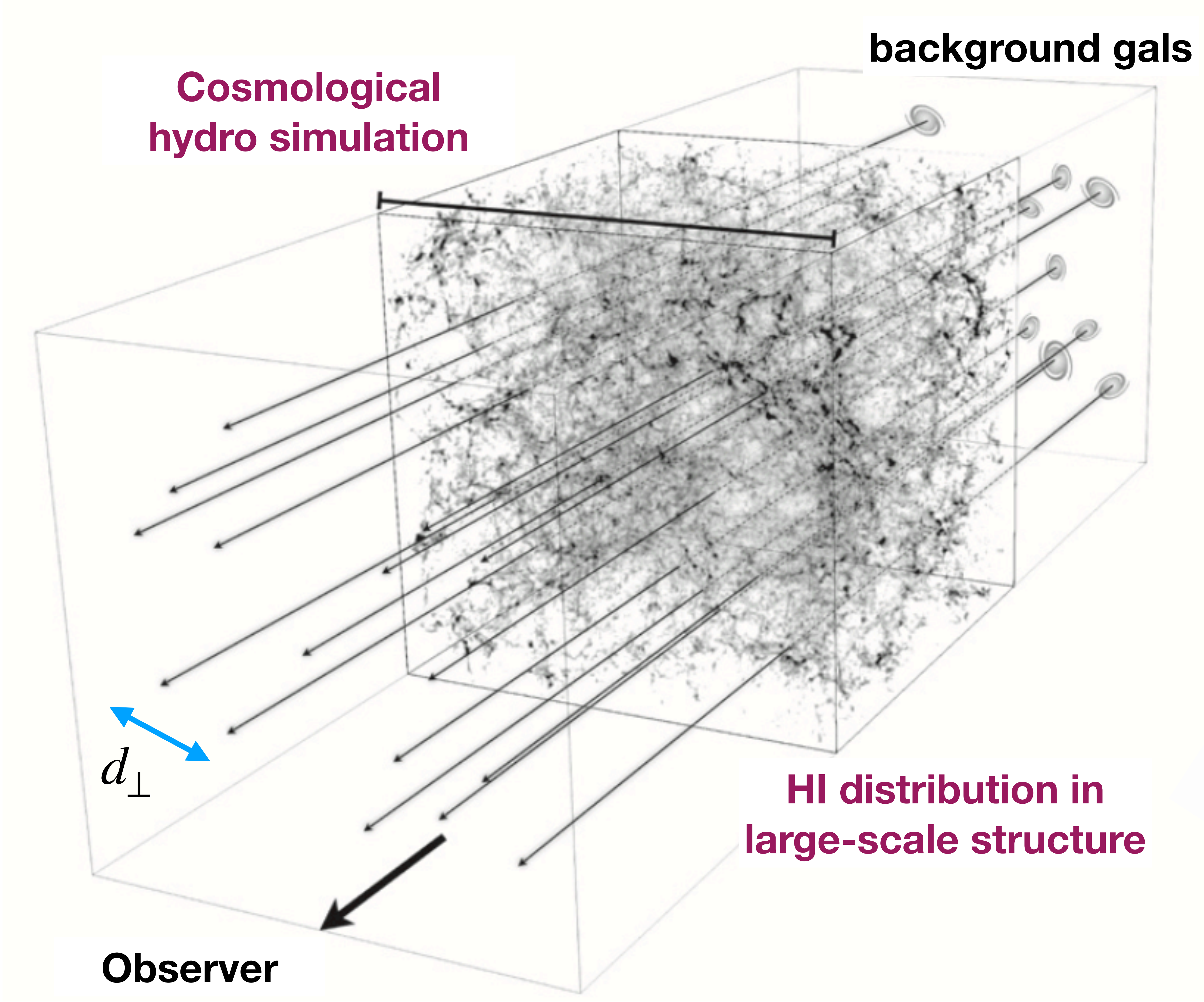
Ly-α forest demonstration movie

Quasar

(very bright SMBH)



IGM tomography

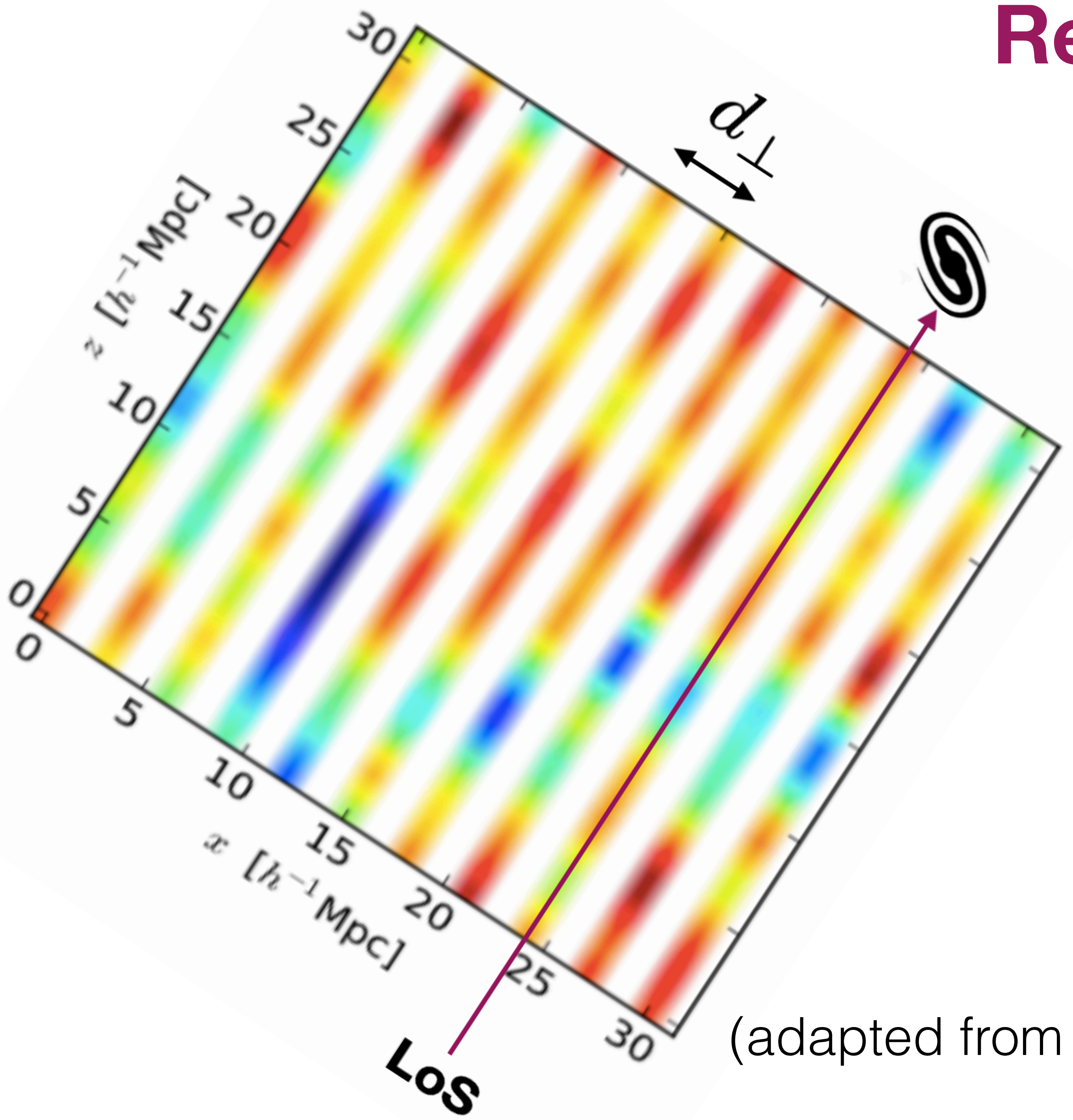


TMT JP Science Book 2020

Numerous background
star-forming galaxies

Many Lyα forest skewers

Reconstruct baryon
density field



(adapted from M. White)

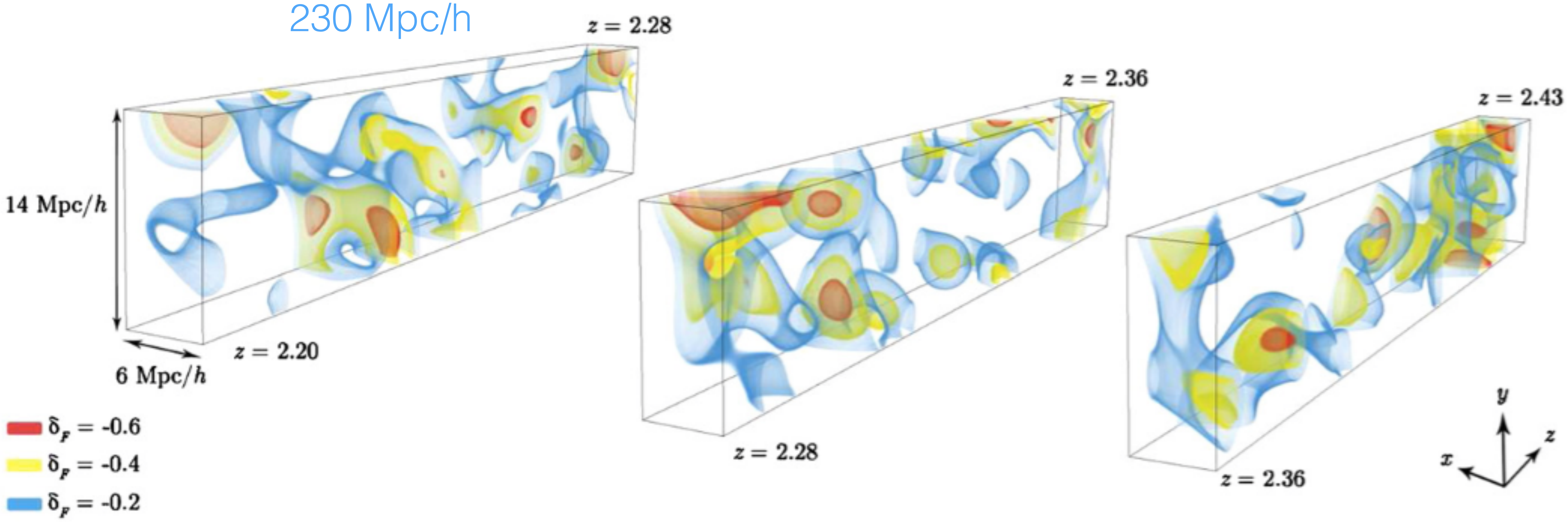
e.g. **CLAMATO** survey

Lee+'14

Tomographic Reconstruction of 3D Lyα forest absorption

24 star-forming gals (SFGs) @ z~ 2.3 - 2.8

230 Mpc/h



Can we learn about feedback from this?

CLAMATO survey **(Lee+ '14)**
(COSMOS Lyα mapping and tomography observations)

$z \sim 2.3$

$g \gtrsim 23$ star-forming gal.

eventually 1 deg²

~1000 SFGs

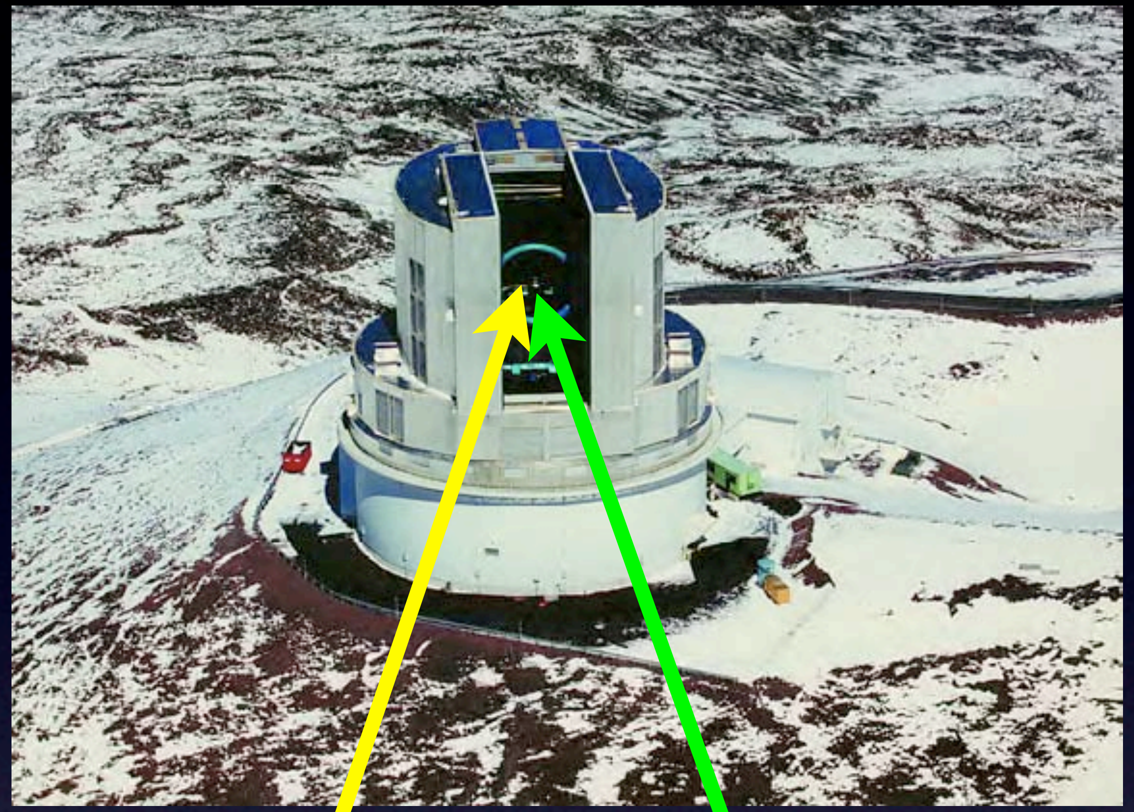
moderate spec res. $R \equiv \frac{\lambda}{\Delta\lambda} \sim 1000$

$\epsilon_{3D} \sim 2 - 5 \text{ Mpc}/h$

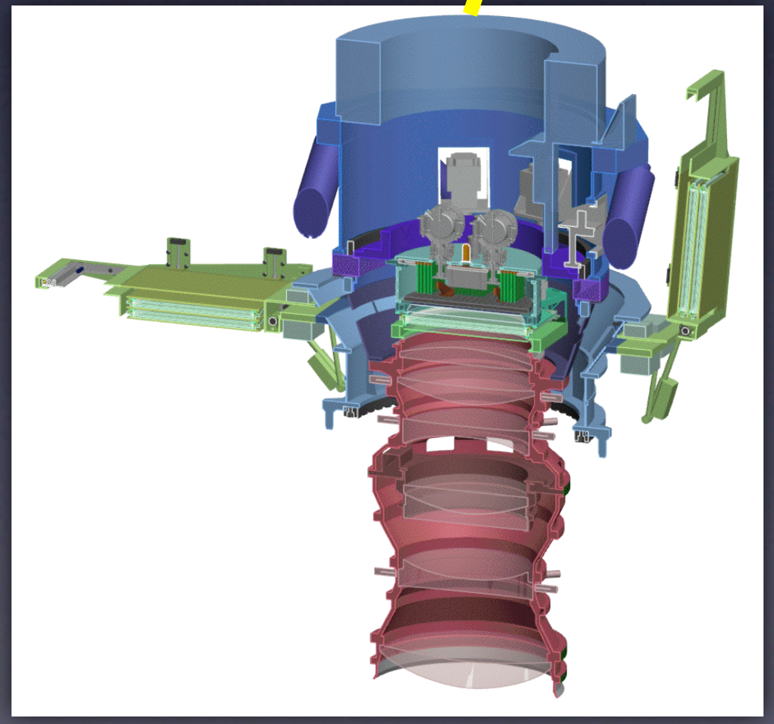
(60Mpc/h)² x 300Mpc/h

SuMIRe /PFS

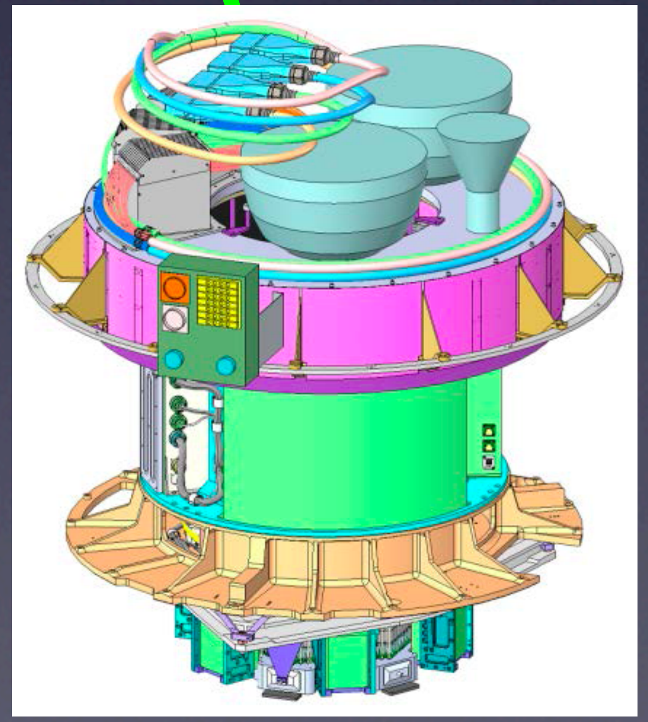
(Subaru Measurement of Images and Redshift)



- a 5+5 year survey program
- exploiting FOV ~1.5° of 8.2m Subaru
- Imaging with Hyper-SuprimeCam (HSC)
  - 870M pixels
  - ~20M galaxy images, 1400 sq. deg.
  - 2014–2019, 300 nights
- spectroscopy with PrimeFocusSpectrograph (PFS) ≠ PSF
  - 2400 optical fibers
  - ~4M redshifts
  - 2024~ 300+ nights
- *like SDSS on 8.2m telescope!*



HSC



PFS

PI: *Murayama)*

Many other surveys:

cf. DESI, Euclid, MOONS, WEAVE-QSO, J-PAS, ...

Green+21, the PFS Galaxy Evolution public doc (arXiv:2206.14908)

Using the light cone to study feedback effects

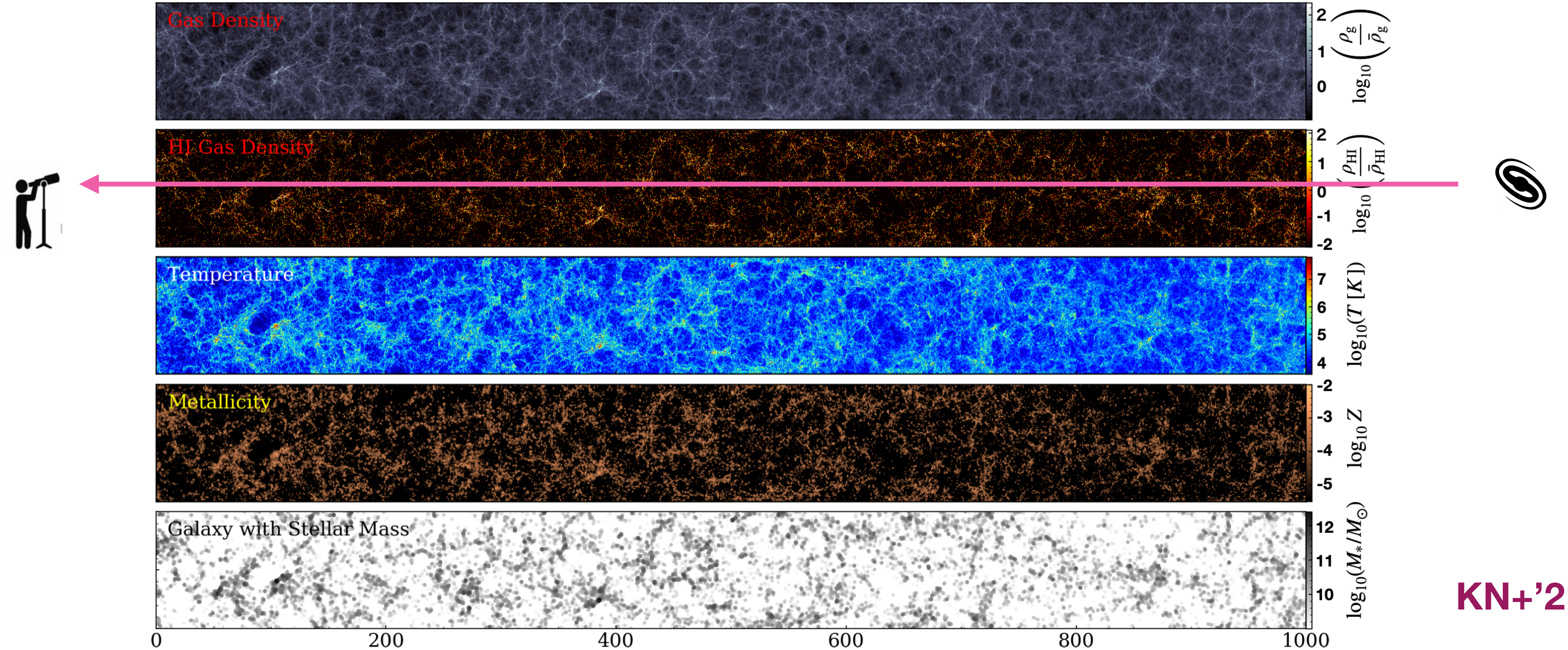
GADGET3-Osaka cosmological simulation: L_{box}= 100 Mpc/h, N= 2 x 512^3

w/ various models

1. No-feedback **2. Const. wind velocity** (Springel & Hernquist '03)
3. Osaka feedback model (Shimizu+'19) **4. FG09 vs. HM12 UVB,** **5. Self-shielding or not.**

(but no AGN FB yet)

Light-cone @ z~2-3, $100\,h^{-1}\mathrm{cMpc}\,(\mathrm{height}) \times 1\,h^{-1}\mathrm{cGpc} \times 10\,h^{-1}\mathrm{cMpc}\ (\mathrm{depth})$



KN+'21

Line-of-sight example (z=2.4 – 2.6)

(~ 2 connected simulation box)

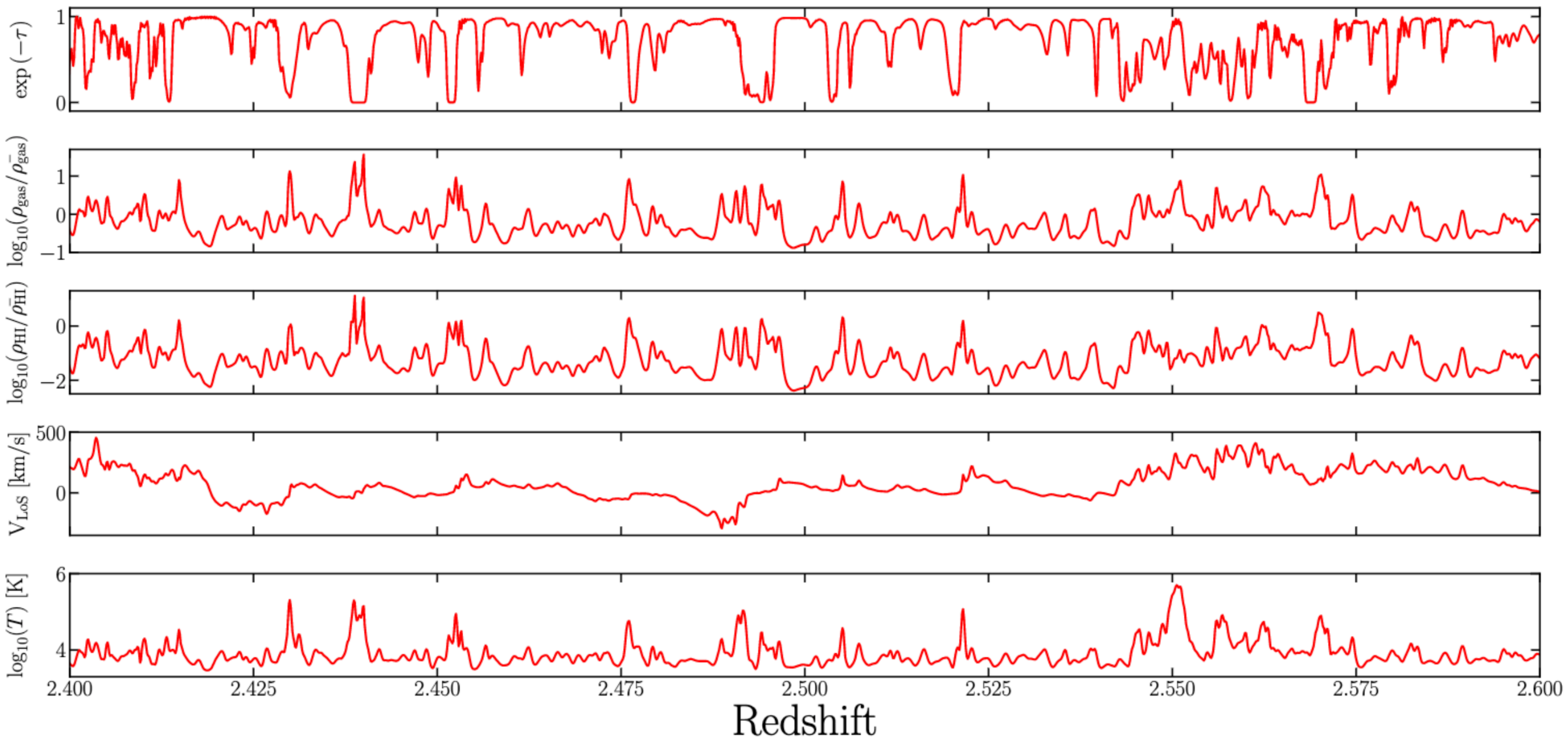
transmission

gas overdensity

HI overdensity

peculiar velocity

temperature

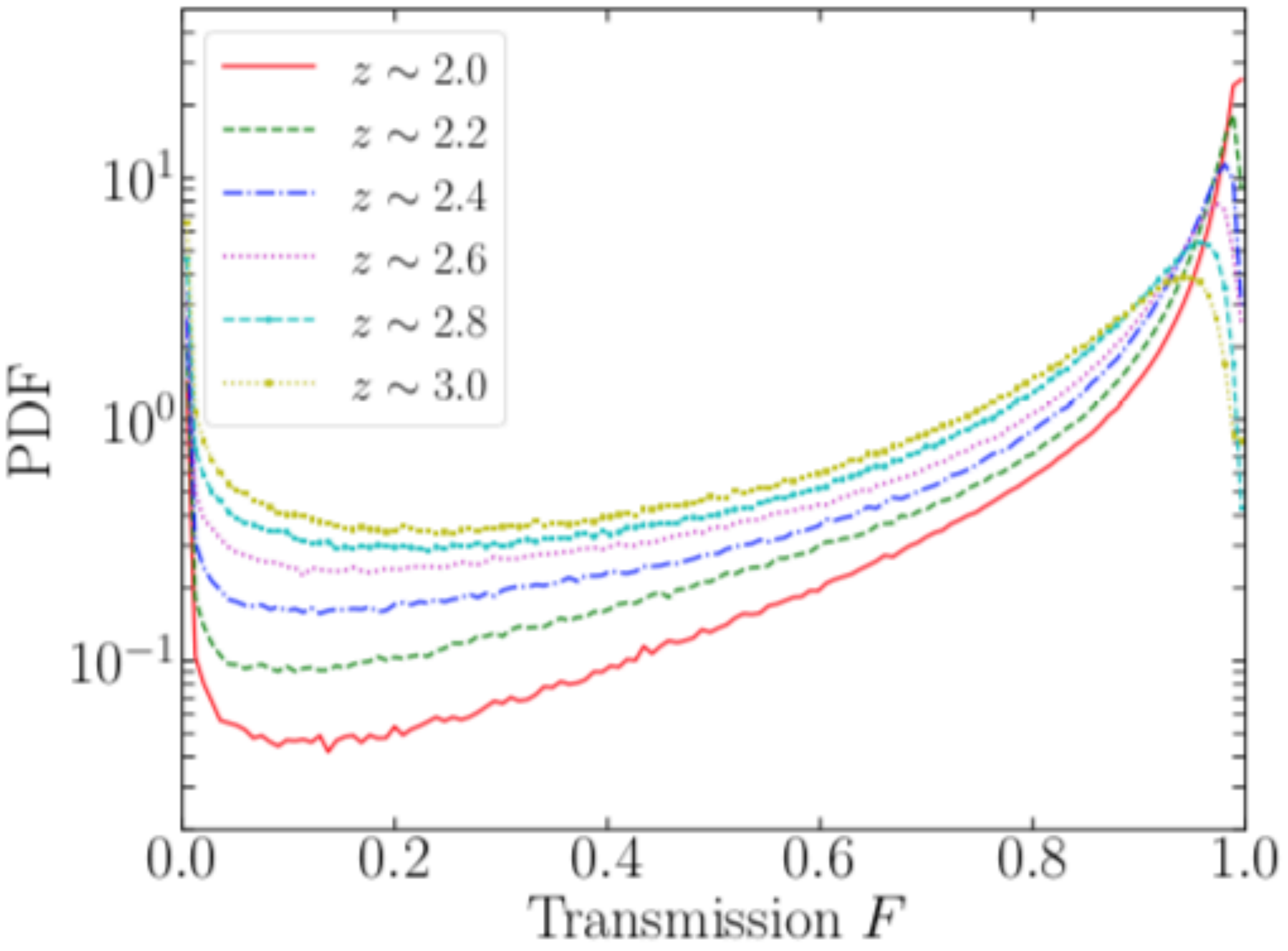


Various statistics can be computed from this: 1. Flux PDF, 2. 1D $P_k(v)$, 3. Flux contrast (1D, 2D)

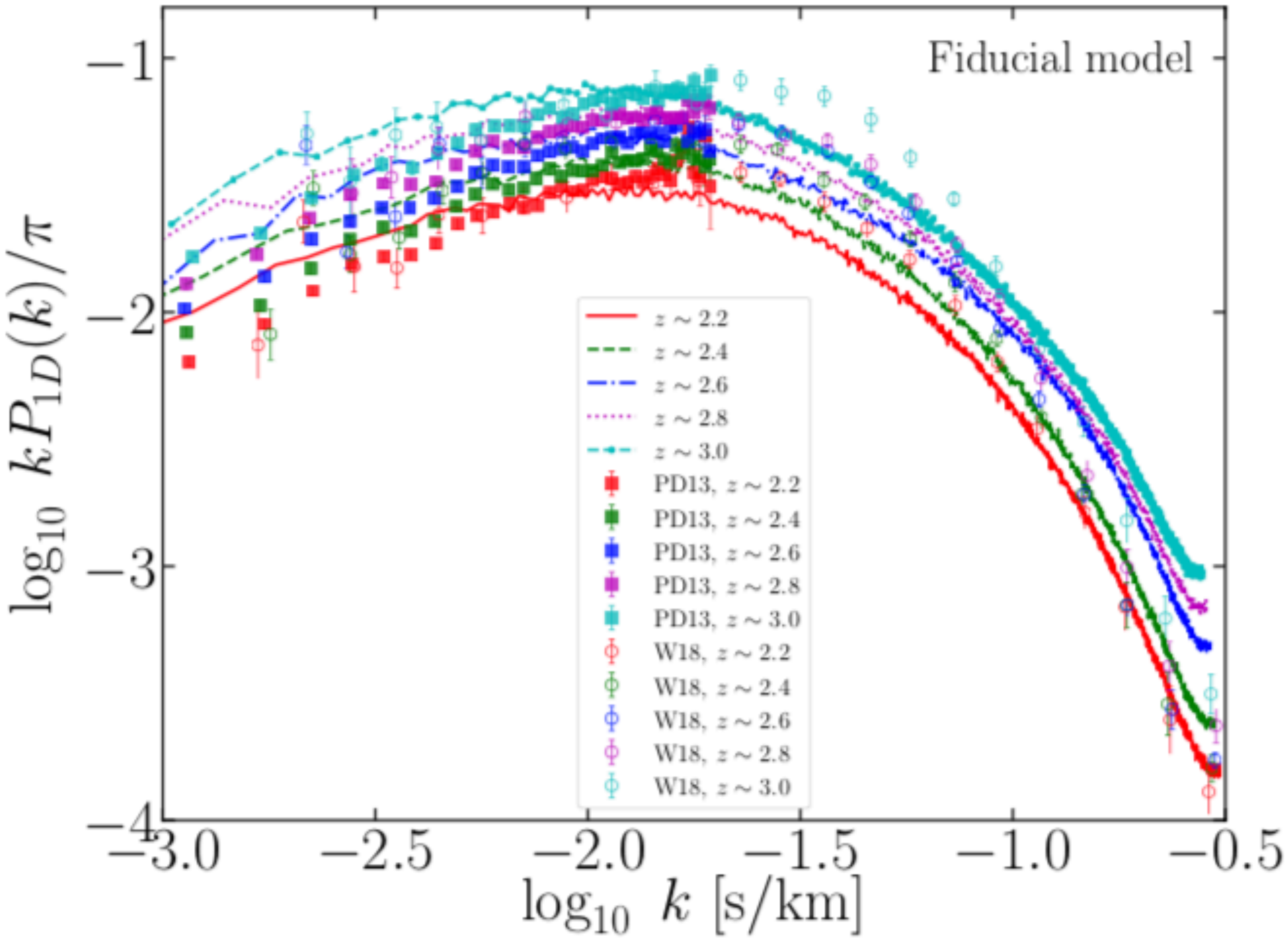
KN+'21

Lyα forest statistics

Flux PDF



1D Ly-a P(k)

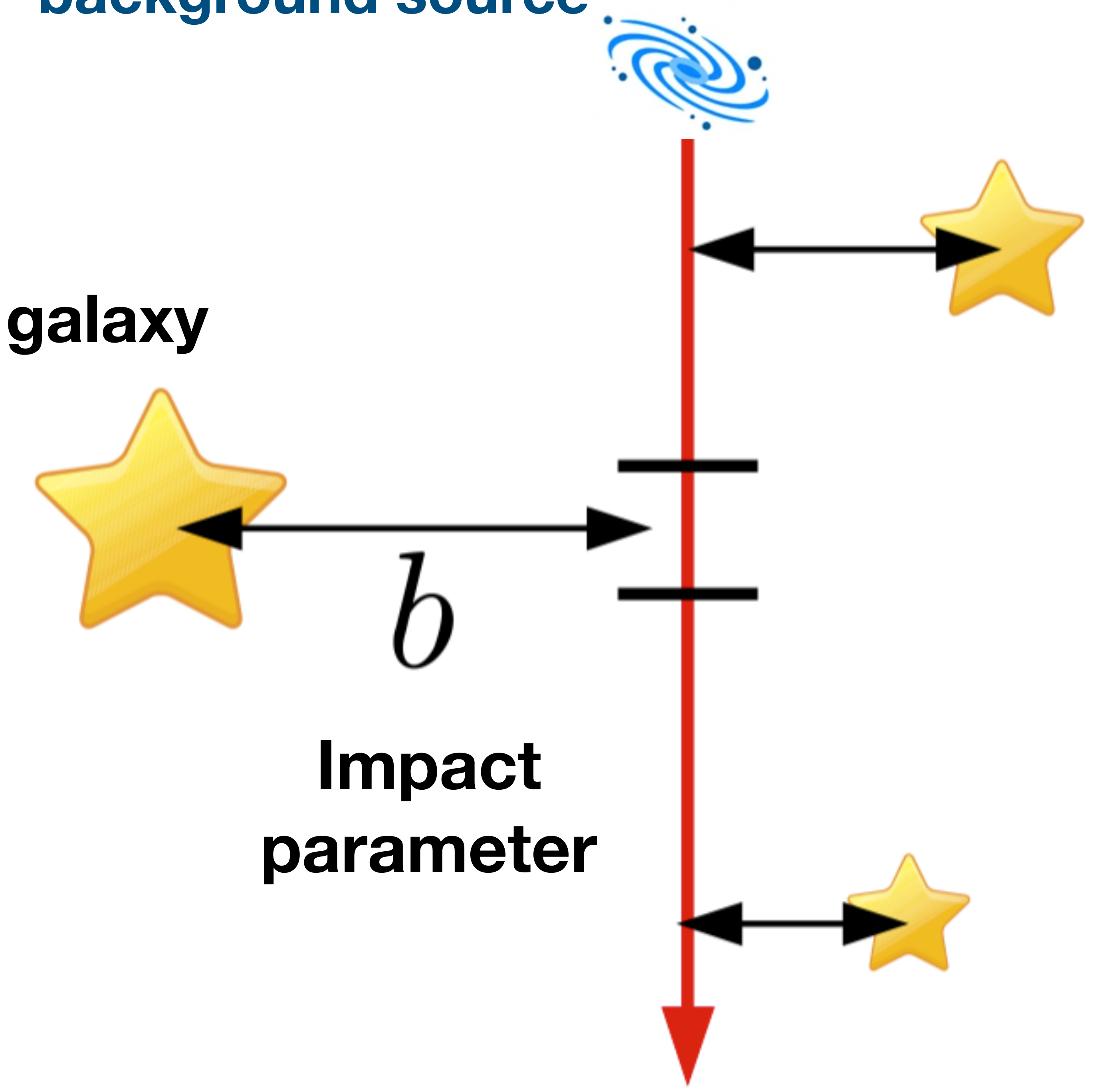


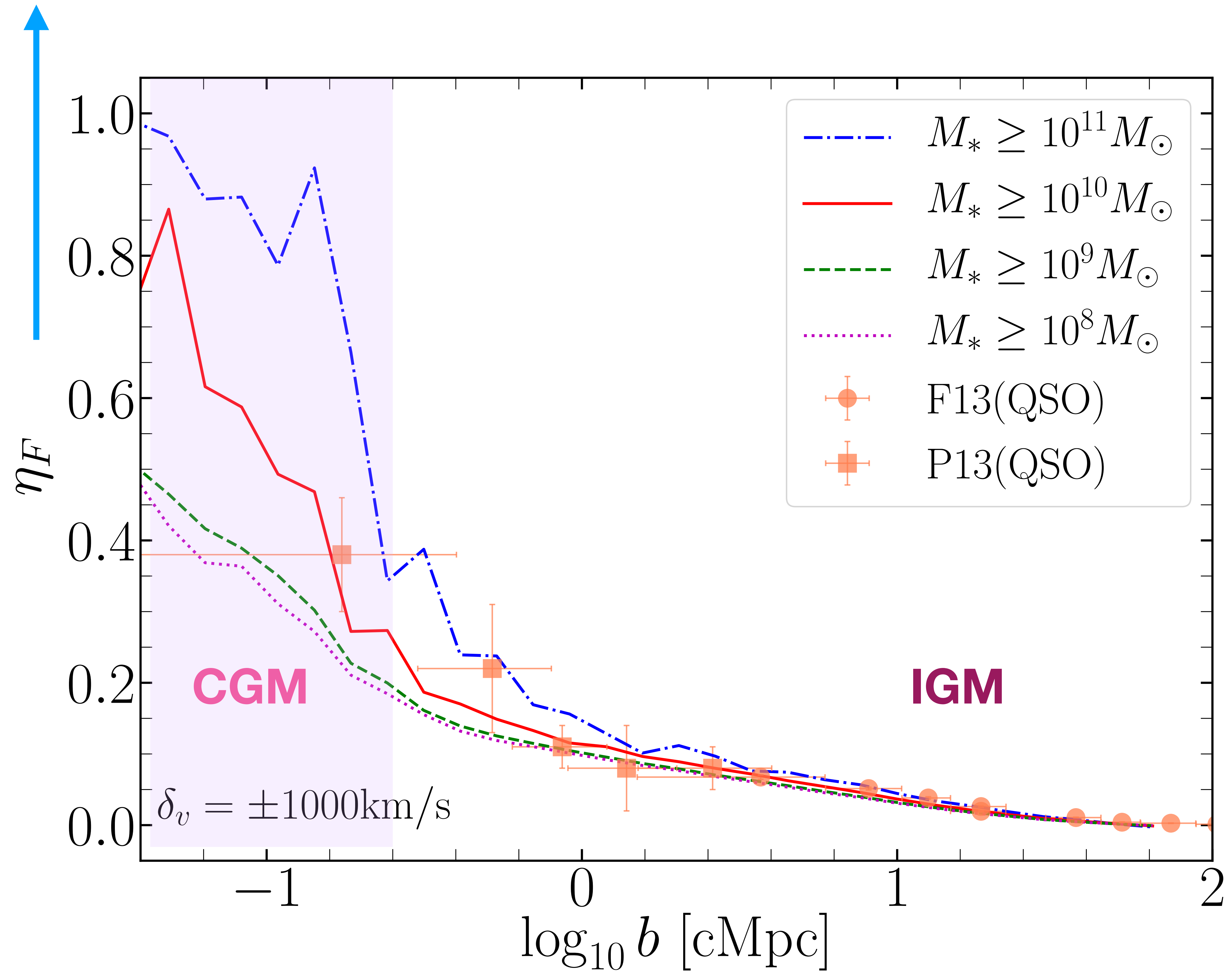
Lyα forest mean flux contrast vs. Impact param.

Flux Contrast

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

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





Impact Parameter from galaxies

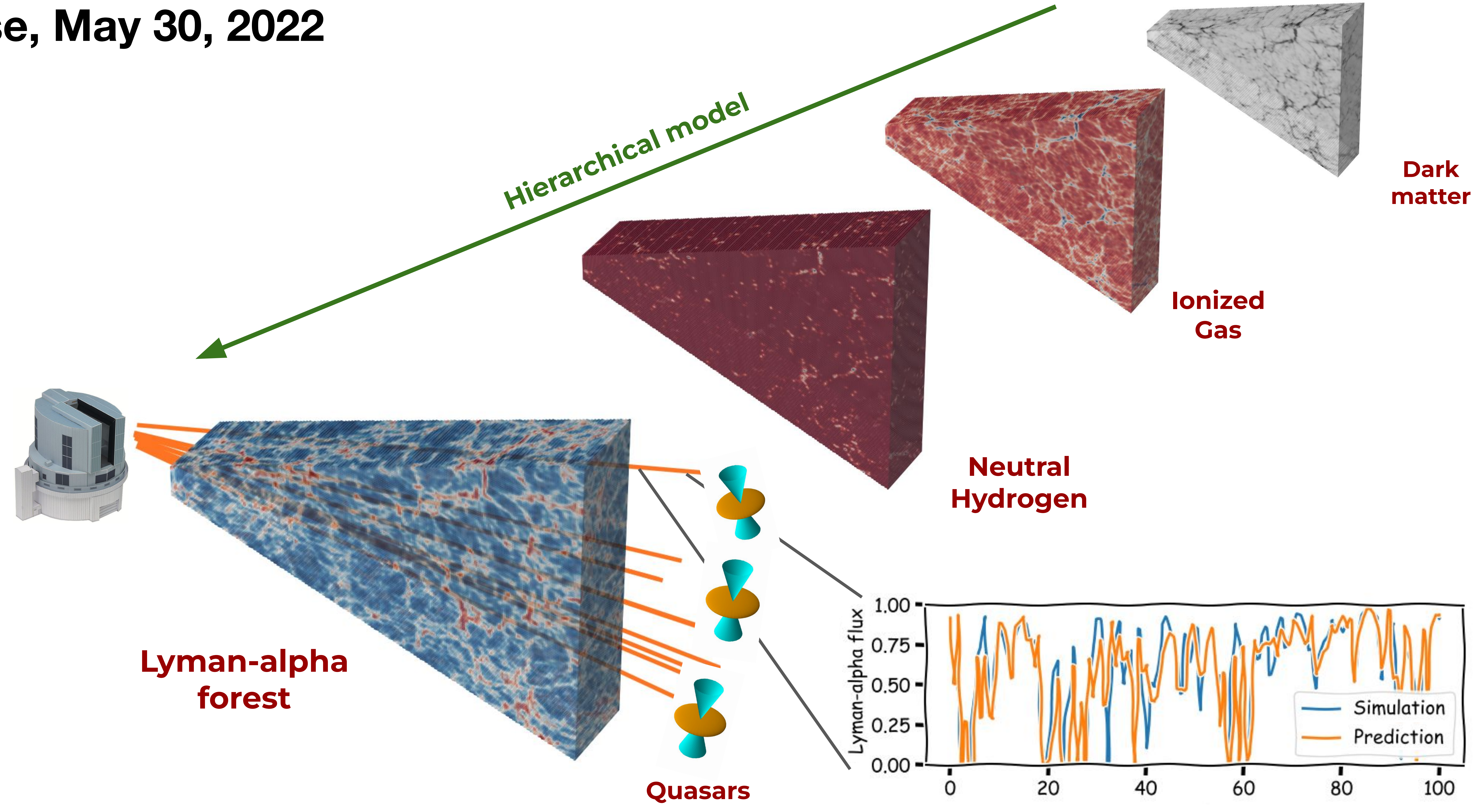
Research at Osaka University ResOU リソウ

10万時間を数秒に! 宇宙の物質分布を高速計算する新アルゴリズムを開発

機械学習的手法が革新する宇宙物理学

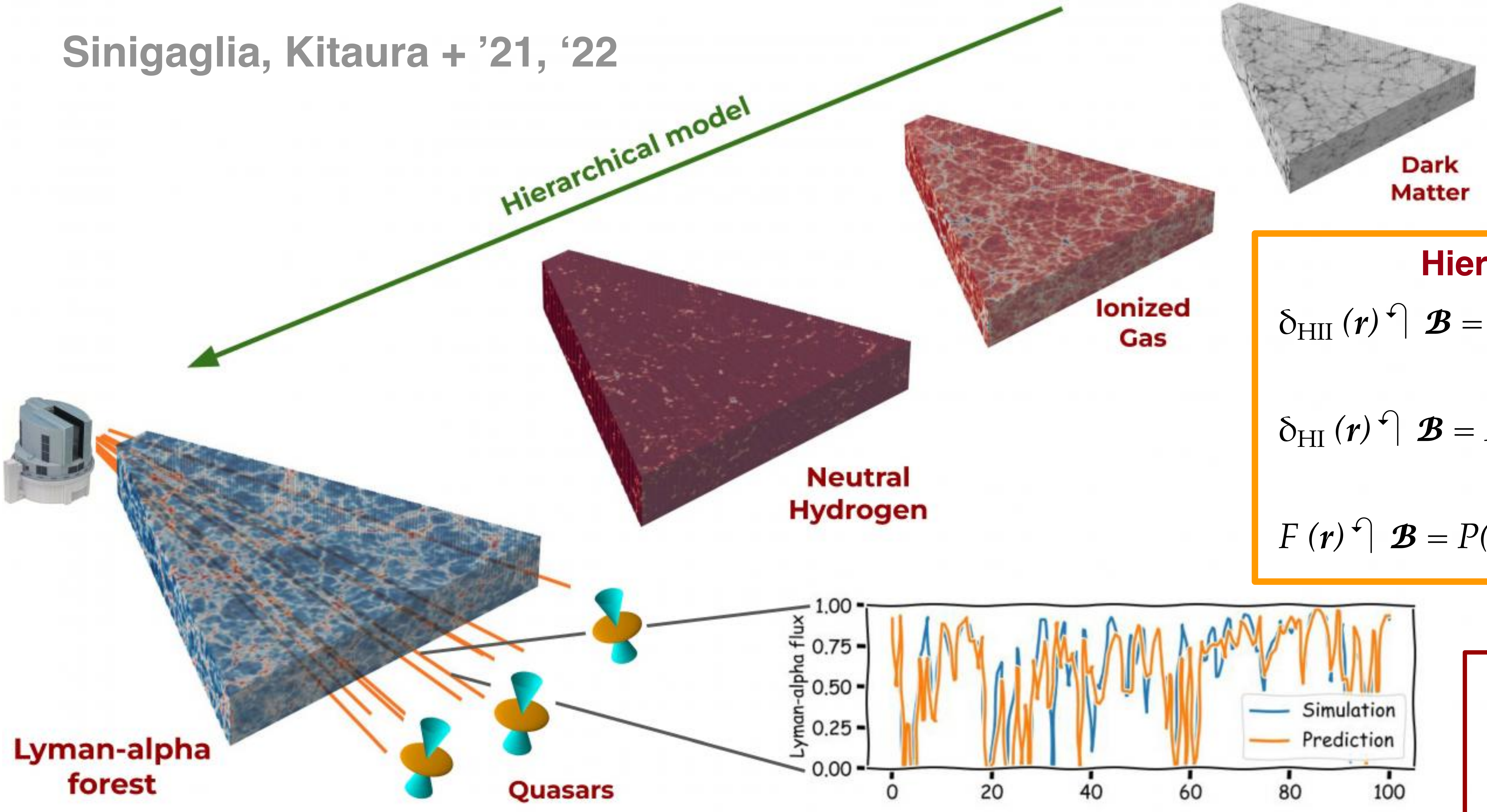
https://resou.osaka-u.ac.jp/ja

Press release, May 30, 2022



Lyα forest via HydroBAM — *hierarchical bias mapping*

Sinigaglia, Kitaura + ’21, ‘22



Hierarchical approach

$$\delta_{HII}(\boldsymbol{r}) \hookleftarrow \mathcal{B} = P(\delta_{HII}(\boldsymbol{r}) \,|\, \Theta\{\delta_{dm}(\boldsymbol{r}) \otimes \mathcal{K}, \text{n.l. terms}\})$$

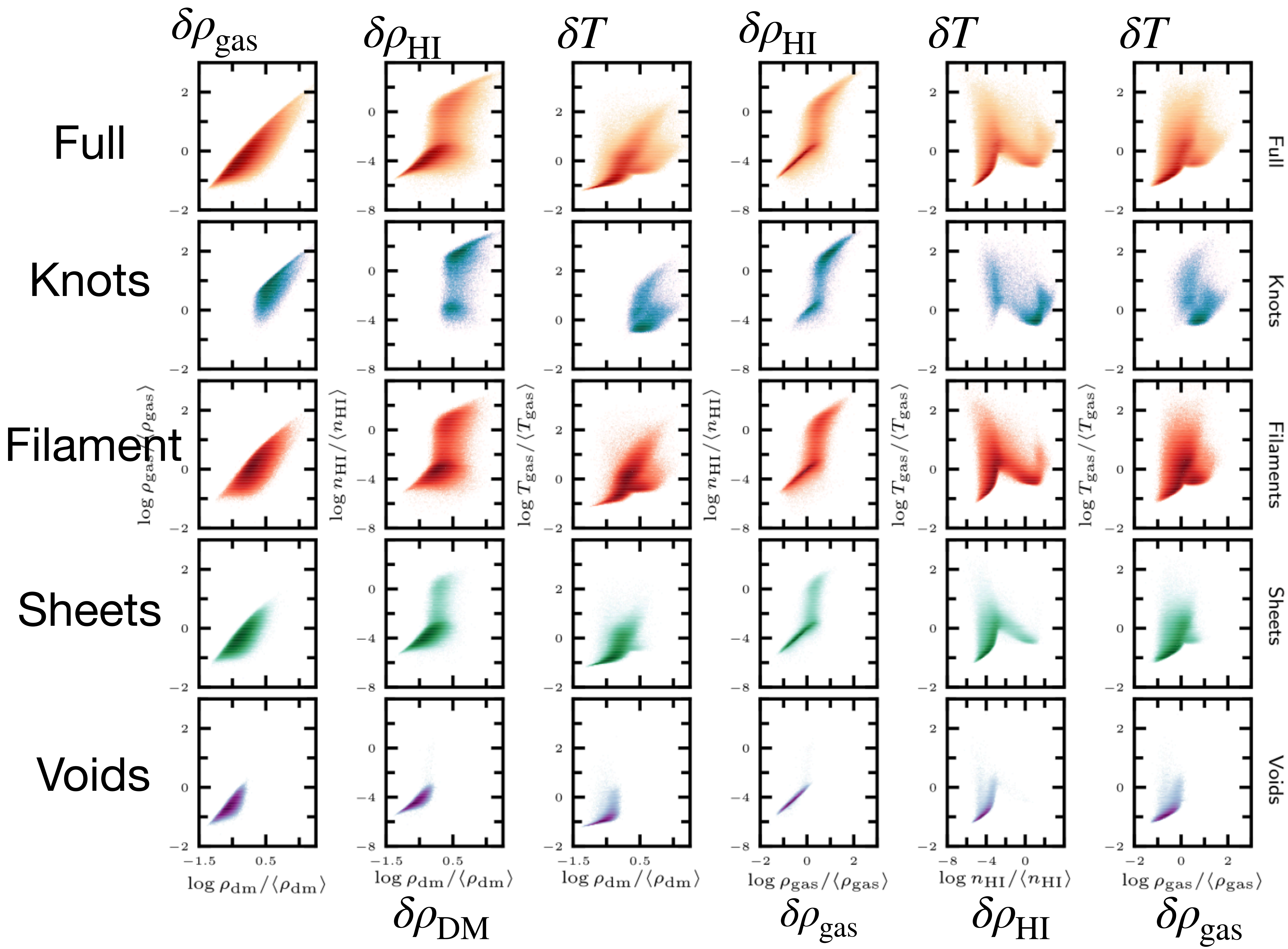
$$\delta_{HI}(\boldsymbol{r}) \hookleftarrow \mathcal{B} = P(\delta_{HI}(\boldsymbol{r}) \,|\, \Theta\{\delta_{HII}(\boldsymbol{r}) \otimes \mathcal{K}, \text{n.l. terms}\})$$

$$F(\boldsymbol{r}) \hookleftarrow \mathcal{B} = P(F(\boldsymbol{r}) \,|\, \Theta\{\delta_{HII}(\boldsymbol{r}) \otimes \mathcal{K}, \delta_{HI}(\boldsymbol{r})\})$$

Training data: GADGET3-Osaka hydro sim. w. SF & Feedback in (100 Mpc h^{-1})^3

Models the Lya forest with accurate summary statistics up to 3-pt

Complexity of Cosmological Baryon Phase Diagrams



Joint Prob. Distribution

$$\mathcal{P}(\eta,\ \{\Theta\}),$$

$$\eta = \rho_{gas},\ \rho_{HI},\ T$$

Measure the bias:

$$\mathcal{P}(\eta|\{\Theta\}).$$

Compute $P_\eta(k)$

& compare with the reference sim.

Sinigaglia+'21

Bias Assignment Method (BAM)

Balaguera-Antolinez+'18,'19
Kitaura+'22
Sinigaglia+'21, '22

First, characterize the DM distribution:

(i) Local property: δ_{DM}

(ii) Non-local property:

e.g., cosmic web classification via

eigen values of tidal field tensor (long range)

T-web $\mathcal{T}_{ij} \equiv \partial_i \partial_j \phi$

cf. Hahn+'07, Ferero-Romero+09, Zhao+15, Libeskind+18

I^{ϕ}-web

Trace: $I_1^{\phi} \equiv \lambda_1 + \lambda_2 + \lambda_3$

$I_2^{\phi} \equiv \lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_1 \lambda_3$

Determinant: $I_3^{\phi} \equiv \lambda_1 \lambda_2 \lambda_3$

Kitaura+20

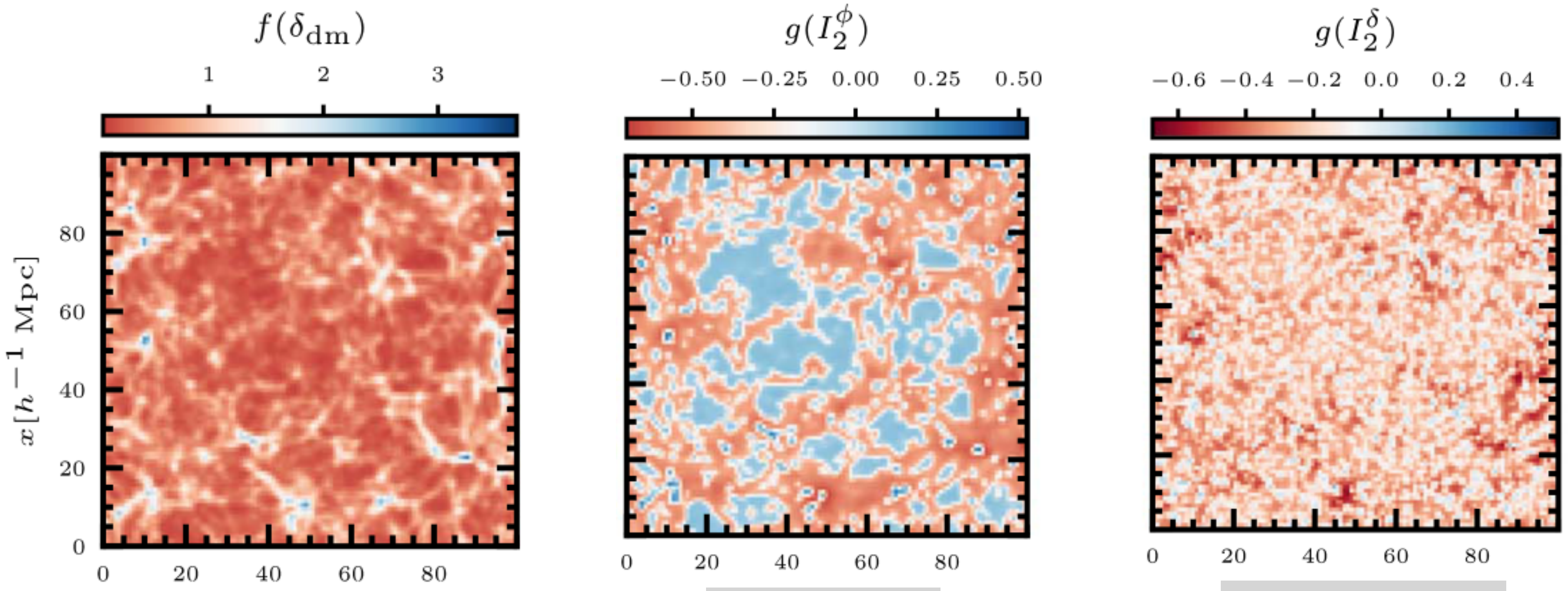
In summary,

1. Local δ: $\{\Theta\} = \{f(\delta)\}$
2. T-web : $\{\Theta\} = \{f(\delta)$, knots, filaments, sheets, voids$\}$
3. I$^{\phi}$-web : $\{\Theta\} = \{f(\delta), g(I_2^{\phi}), g(I_3^{\phi})\}$
4. I$^{\delta}$-web : $\{\Theta\} = \{f(\delta), g(I_1^{\delta}), g(I_2^{\delta})\}$,

$f(x) = \log(2 + x)$ $g(x) = 2(x^{\alpha} - \gamma)/(\eta - \gamma) - 1$

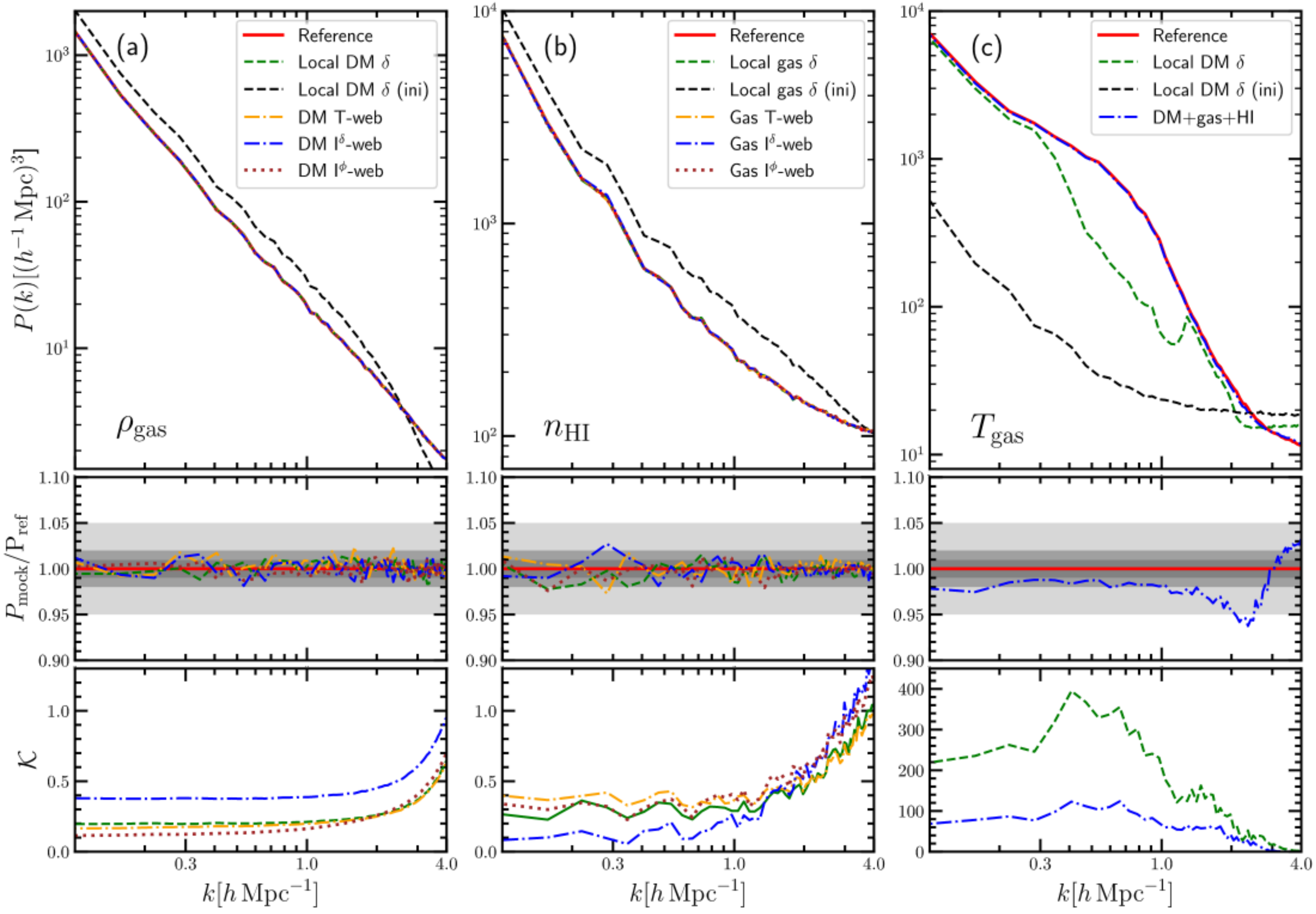
$\gamma \equiv \min(x^{\alpha}), \ \eta \equiv \max(x^{\alpha})$

mapping large range of ***I*** into [-1, 1]



only local nonlocal more local

P(k) as a cost function



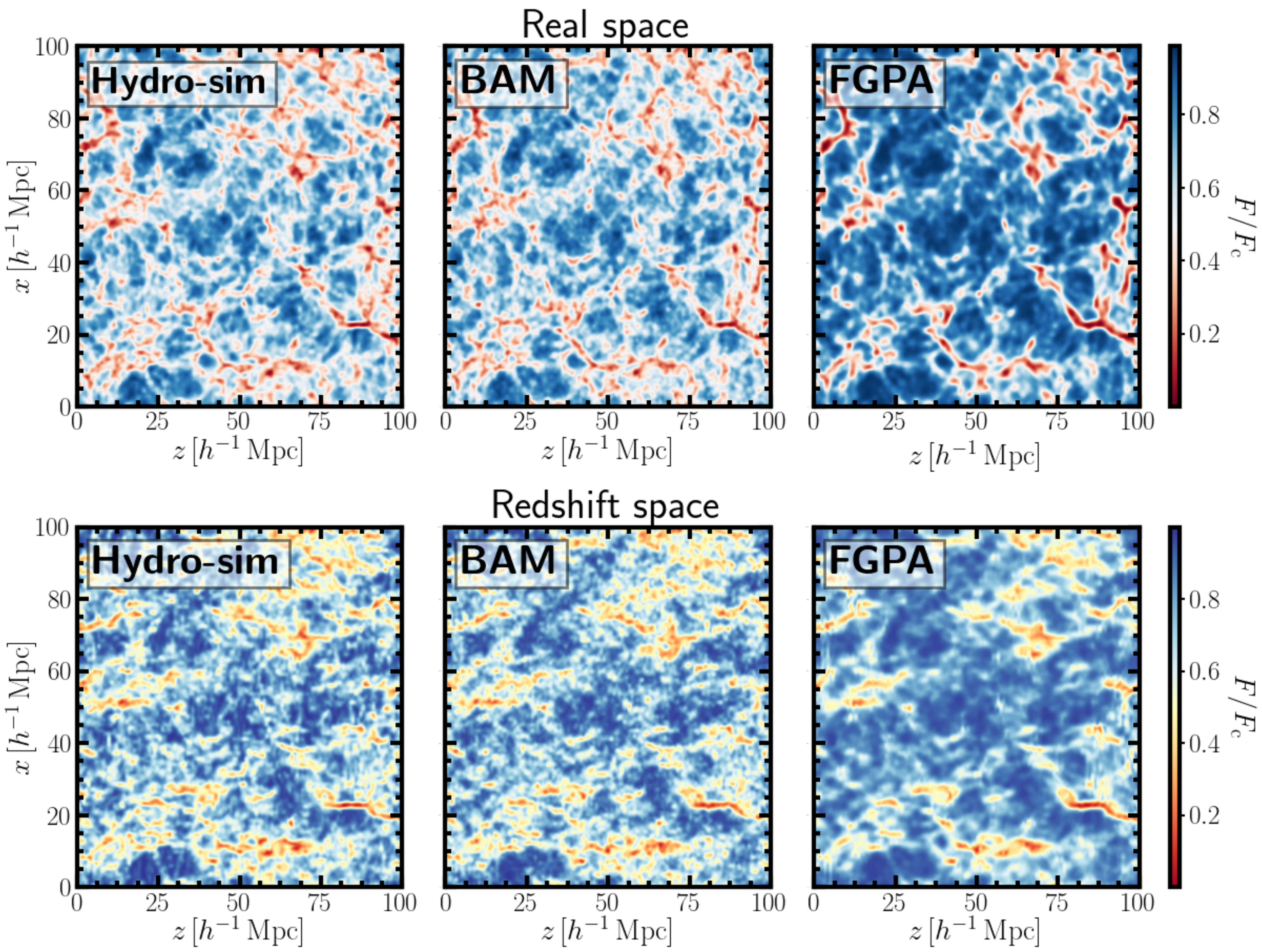
$$T_0(k) \equiv P^{i=0}_{\tilde{\eta}}(k)/P_{\eta}(k),$$

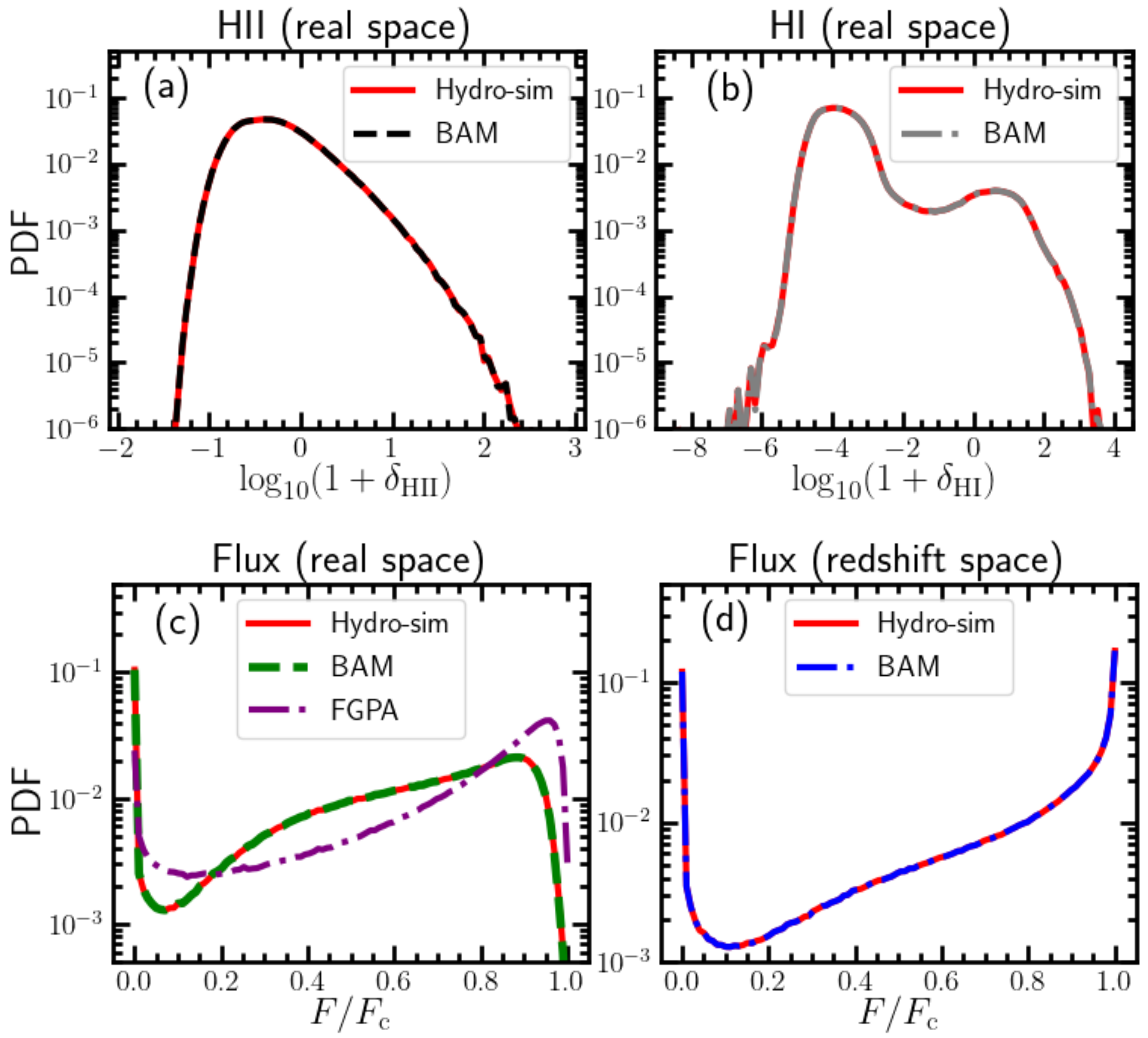
Kernel

$$\bar{\mathcal{K}}(k) \equiv \prod_{j=0}^{i} w_j(k)$$

Sinigaglia+'21

Results: 2D maps & one-point PDF



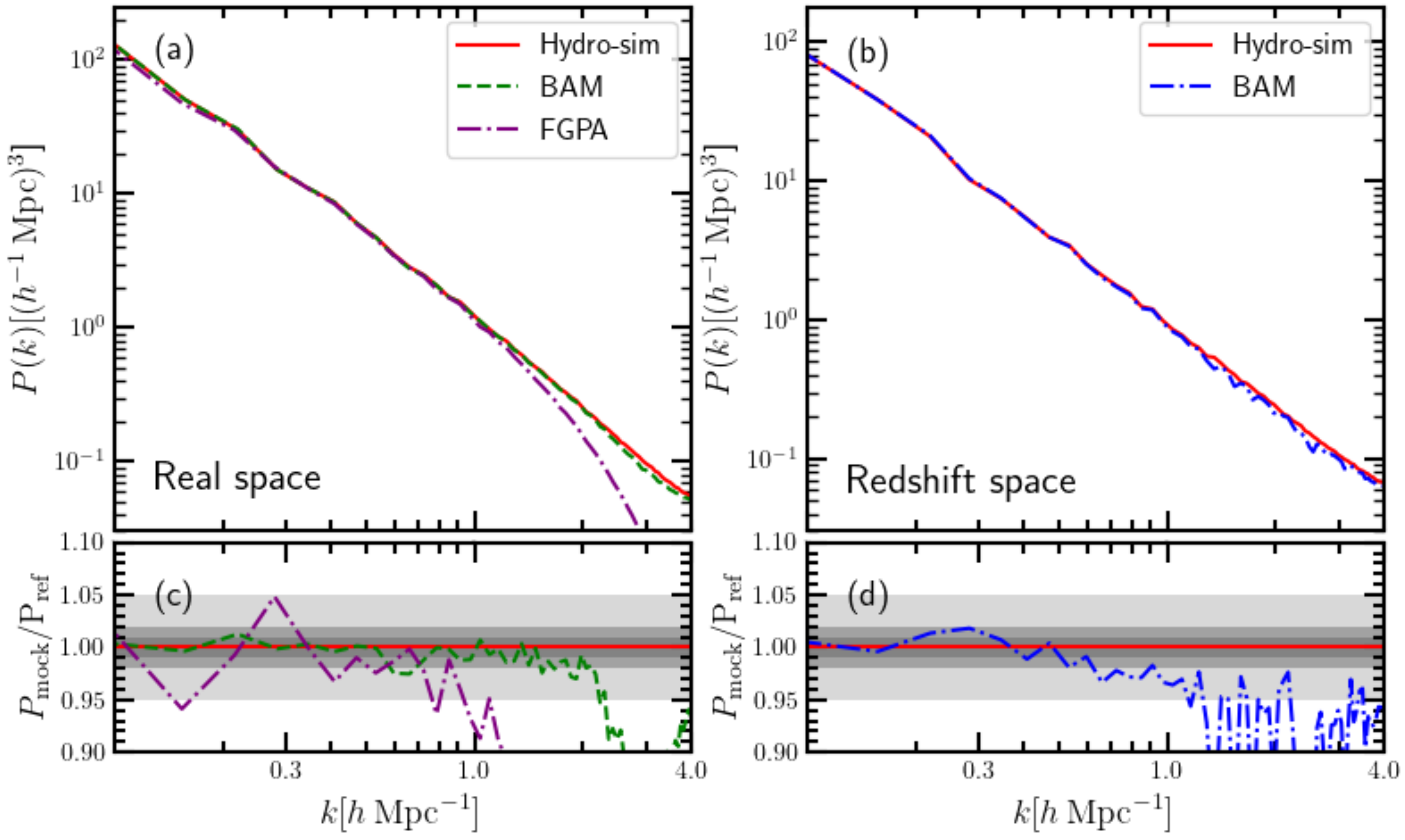


FGPA: $\tau = A\,(1+\delta_{\mathrm{dm}})^{\beta}, \quad F = \exp(-\tau)$

cf. Harrington+21; Horowitz+'21

Sinigaglia+'22

Results: power spectrum



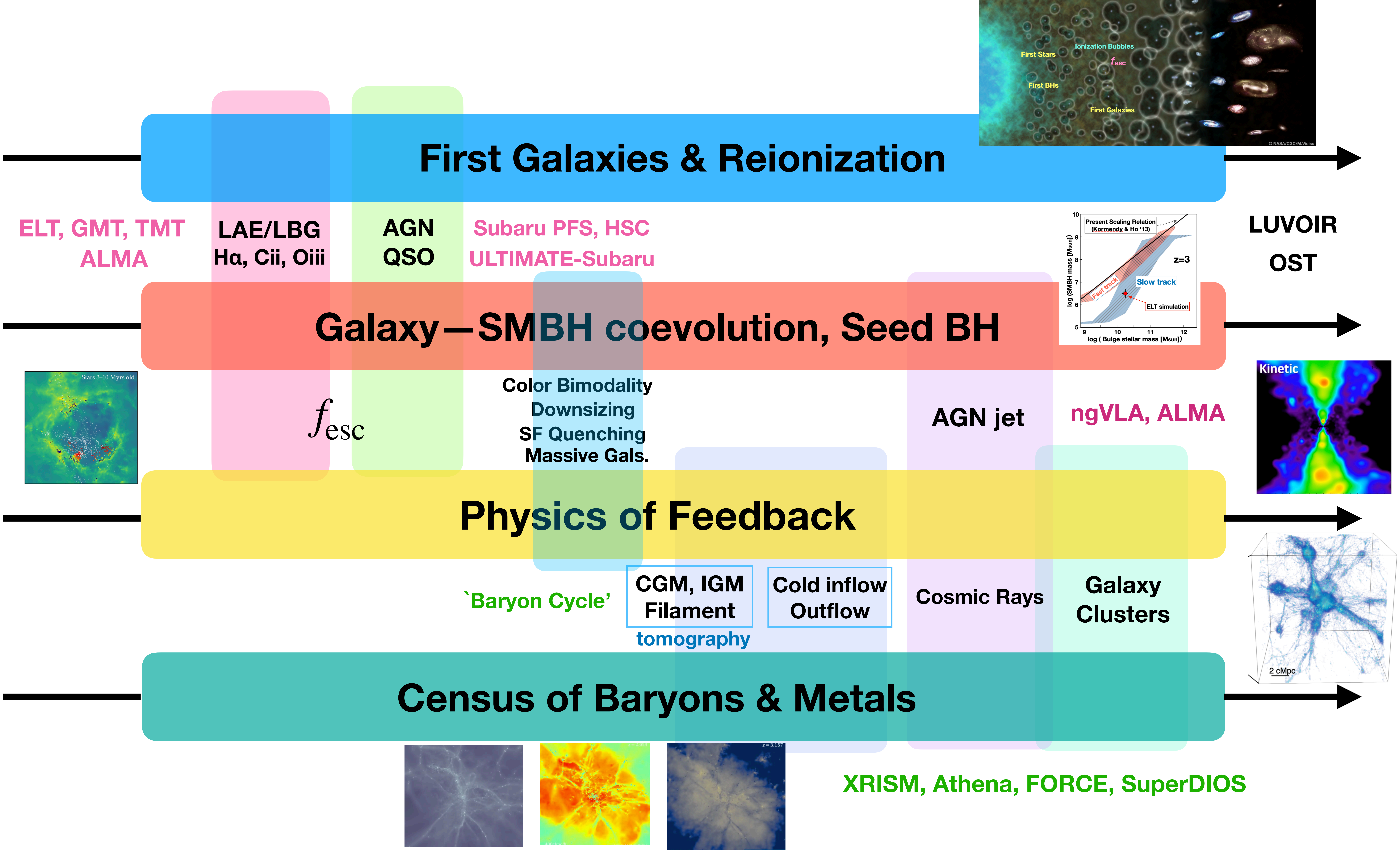
Deviation from reference

BAM: $< 2\%$ up to $k \sim \mathbf{2.0}\, h\, \mathbf{Mpc^{-1}}$ in real space

$< 2\%$ up to $k \sim \mathbf{1.0}\, h\, \mathbf{Mpc^{-1}}$ in redshift space

FGPA: $\sim 5\%$ up to $k \sim \mathbf{1.0}\, h\, \mathbf{Mpc^{-1}}$ in real space

Sinigaglia+'22



First Stars
Ionization Bubbles
f_{esc}
First BHs
First Galaxies
© NASA/CXC/M.Weiss
First Galaxies & Reionization
ELT, GMT, TMT
ALMA
LAE/LBG
Hα, Cii, Oiii
AGN
QSO
Subaru PFS, HSC
ULTIMATE-Subaru
Present Scaling Relation (Kormendy & Ho '13)
z=3
Slow track
Fast track
ELT simulation
log (SMBH mass [Msun])
log (Bulge stellar mass [Msun])
LUVOIR
OST
Galaxy—SMBH coevolution, Seed BH
Stars 3-10 Myrs old
f_{esc}
Color Bimodality
Downsizing
SF Quenching
Massive Gals.
AGN jet
ngVLA, ALMA
Kinetic
Physics of Feedback
`Baryon Cycle'
CGM, IGM
Filament
tomography
Cold inflow
Outflow
Cosmic Rays
Galaxy
Clusters
2 cMpc
Census of Baryons & Metals
XRISM, Athena, FORCE, SuperDIOS

End.