Testing alternative DM models via structure formation in the universe

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Uchuu simulation: Ishiyama+21

https://www.cfca.nao.ac.jp/en/pr/20210910

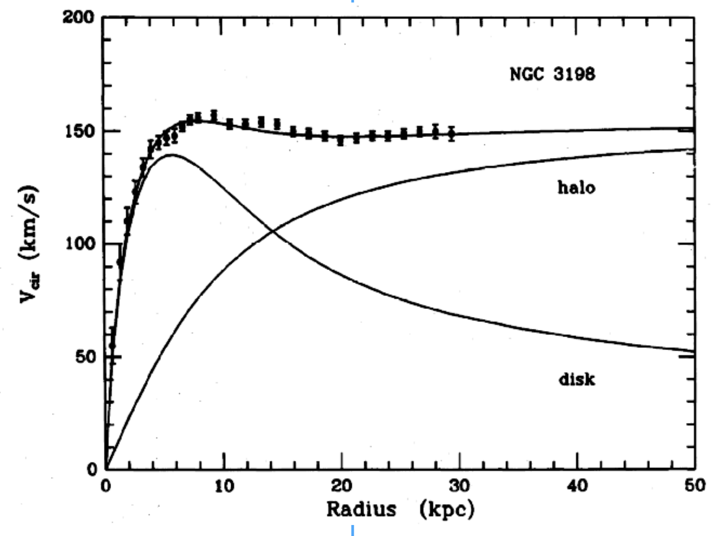
Outline

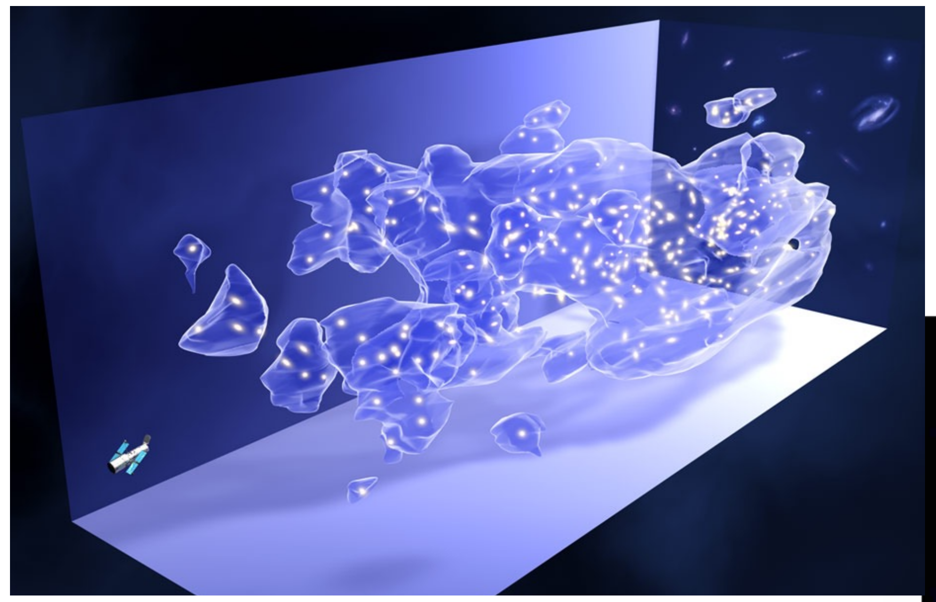
- Success of **ΛCDM** & "**small-scale crisis**"
- **Alternatives: WDM, SIDM, FDM, ….**
- **Probing via Structure Formation — Lya forest, High-z galaxies, Local ultra-faint dwarfs**

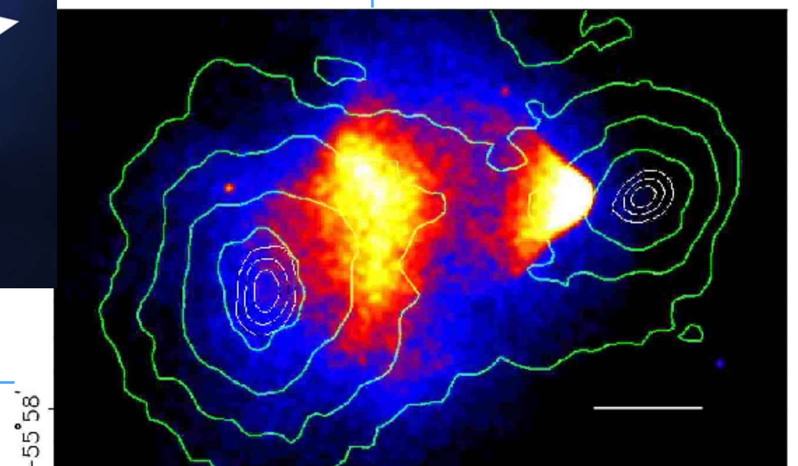
Evidence of Dark Matter

— success of CDM on large scales (≳100 kpc)

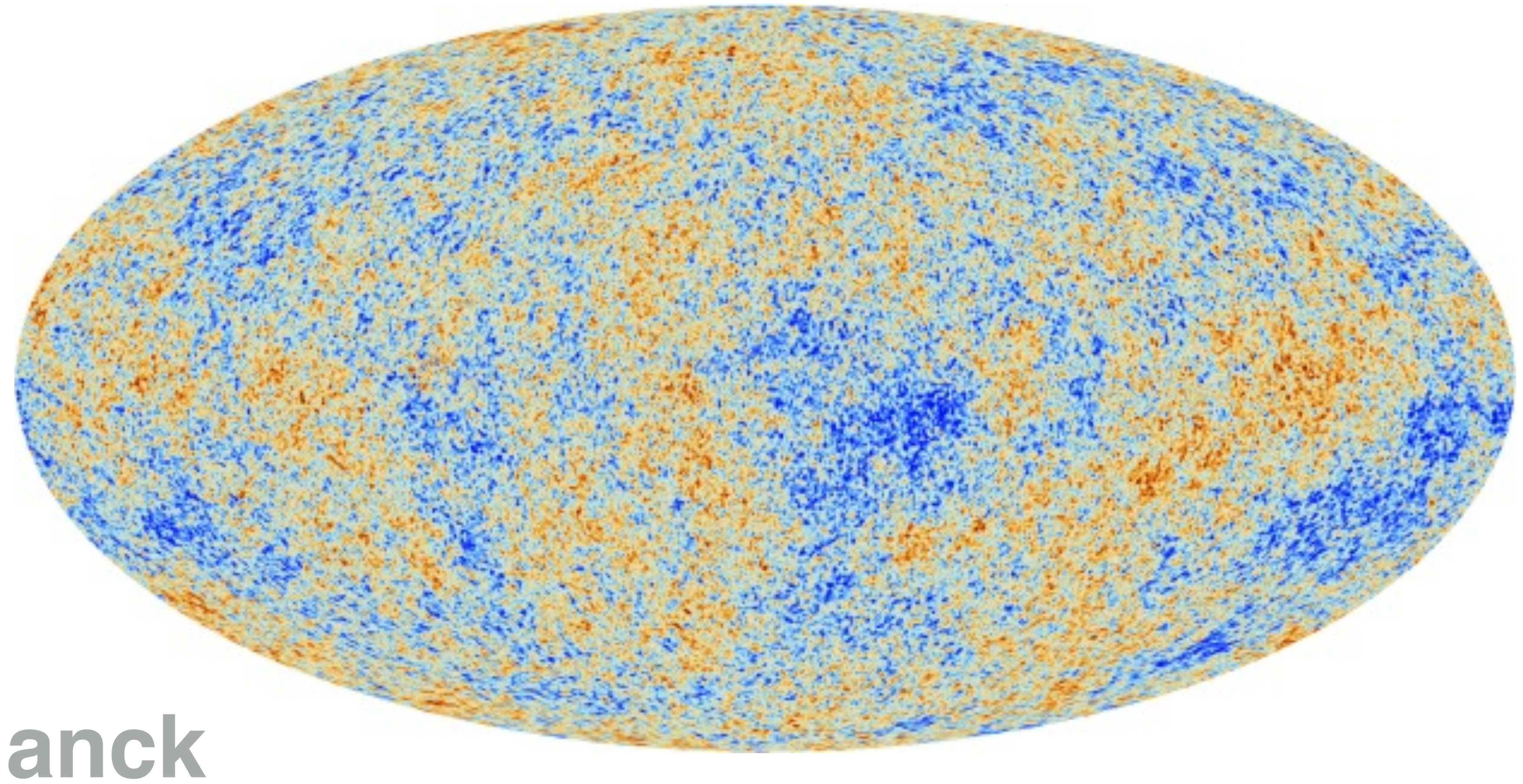
- **Stellar motions** Lord Kelvin (1884); Kapteyn '22; Jeans'22; Oort '32
- **Galaxy clusters** — ~80% of mass is dark (Zwicky '33)
- **Galaxy rotation curves** (Rubin & Ford '70)
- **Galactic disk stability** (stellar kinematics; Ostriker & Peebles '74)
- **Cosmic Microwave Background** (CMB) — angular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



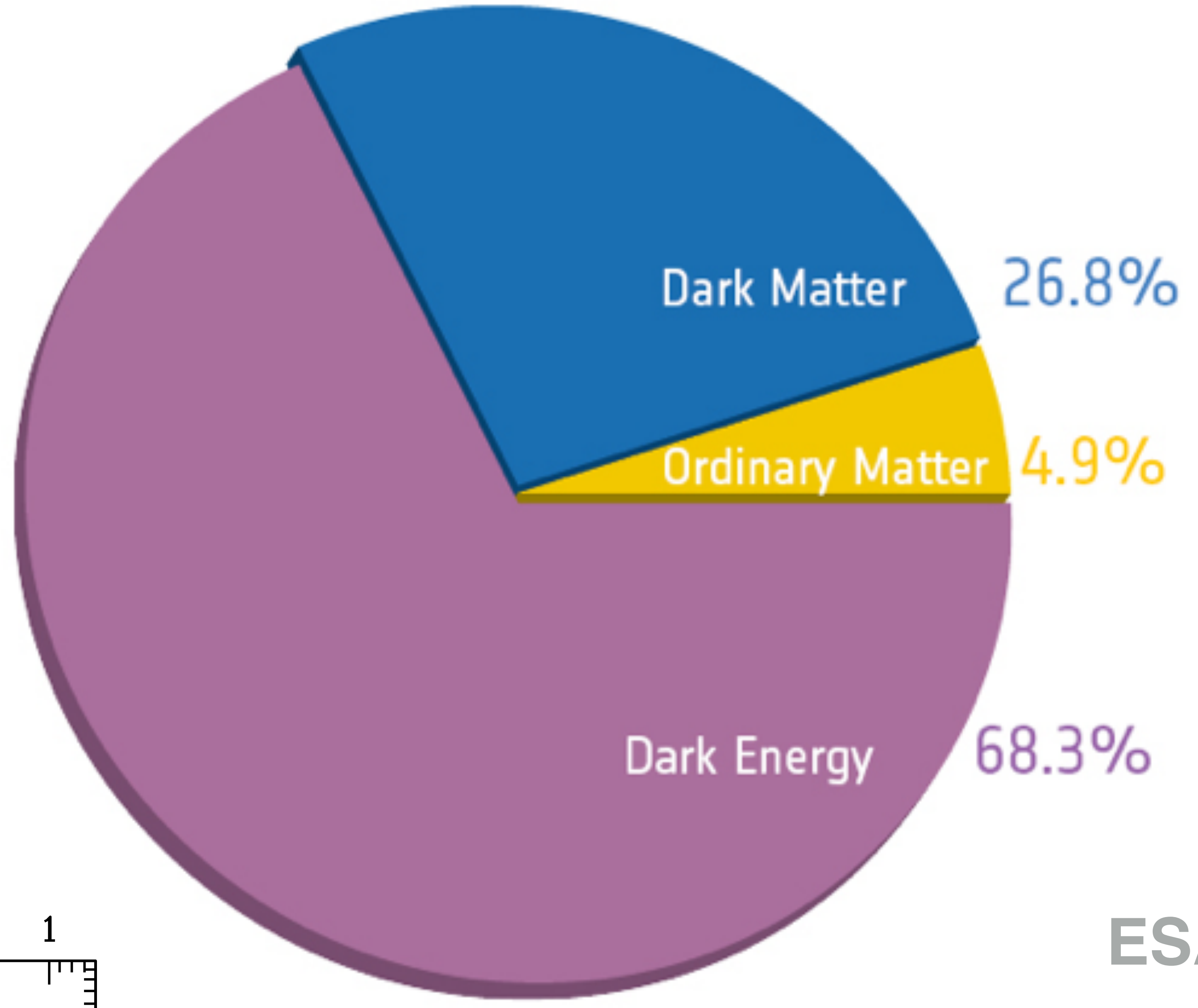




``Era of Precision Cosmology"

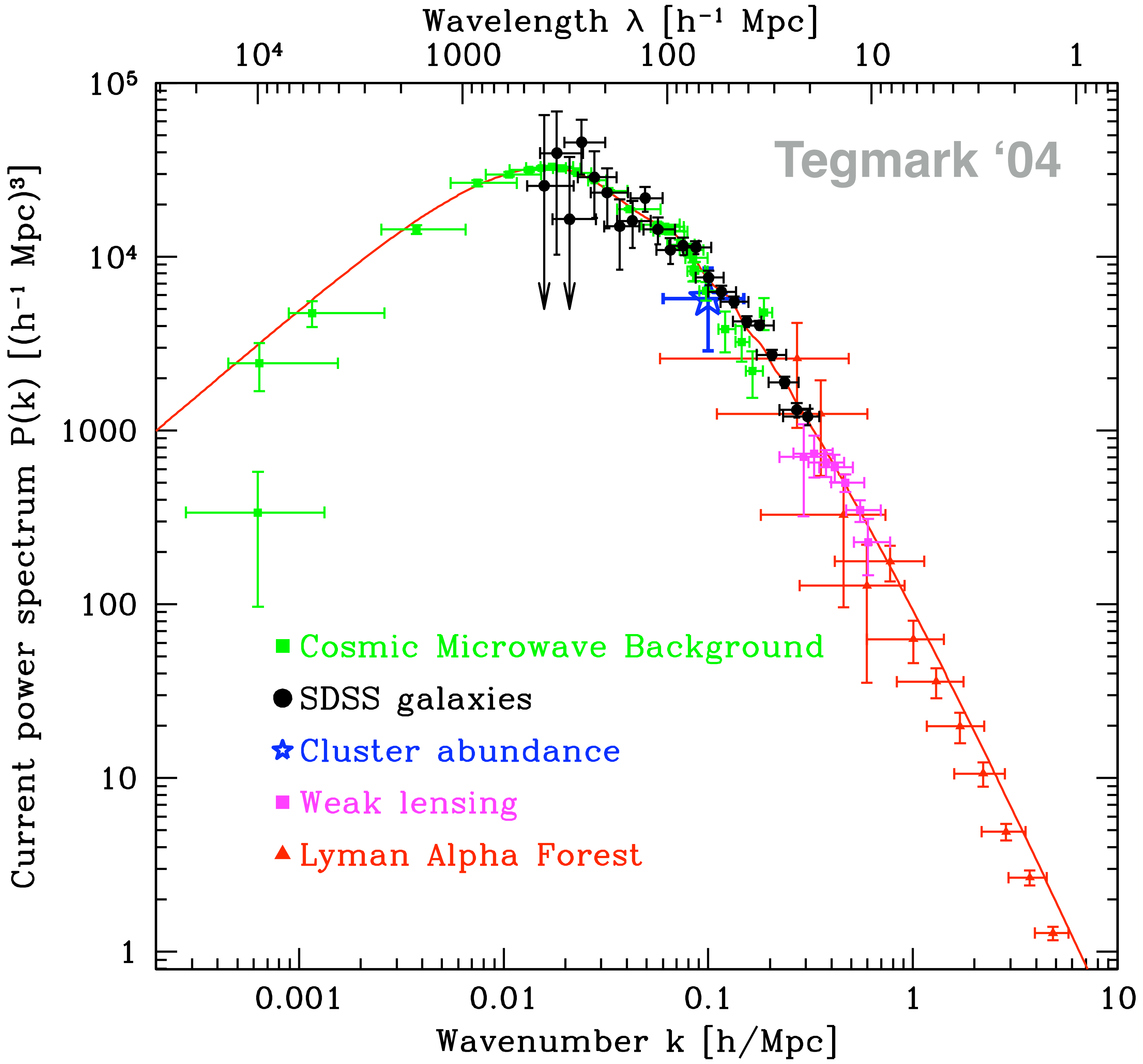


Planck

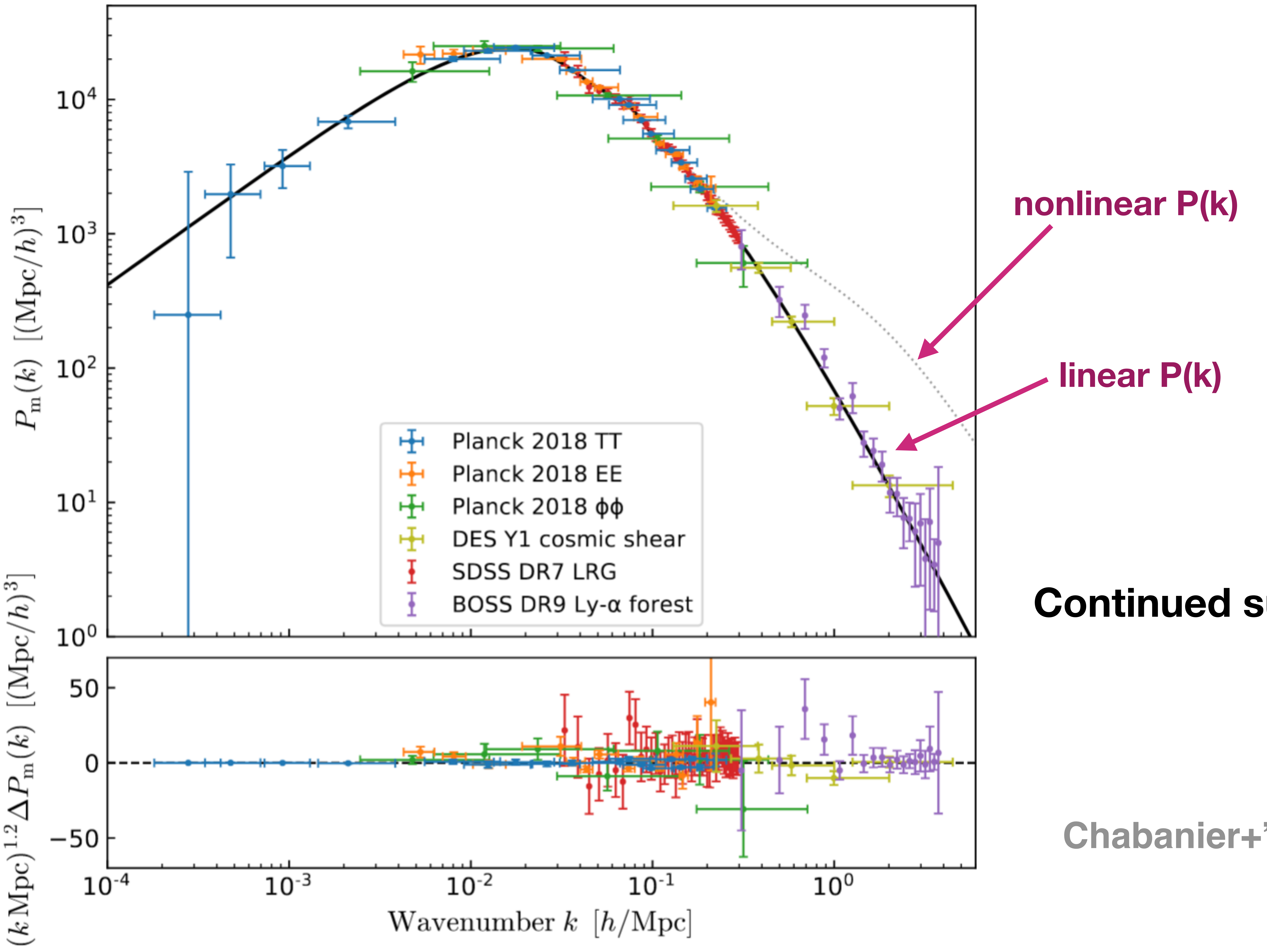


ESA '13

Matter power spectrum



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



Continued support for ΛCDM

Chabanier+'19

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 —** over-abundance of massive & dense substructures (in CDM) that could host gals after reionization

  Boylan-Kolchin+'11

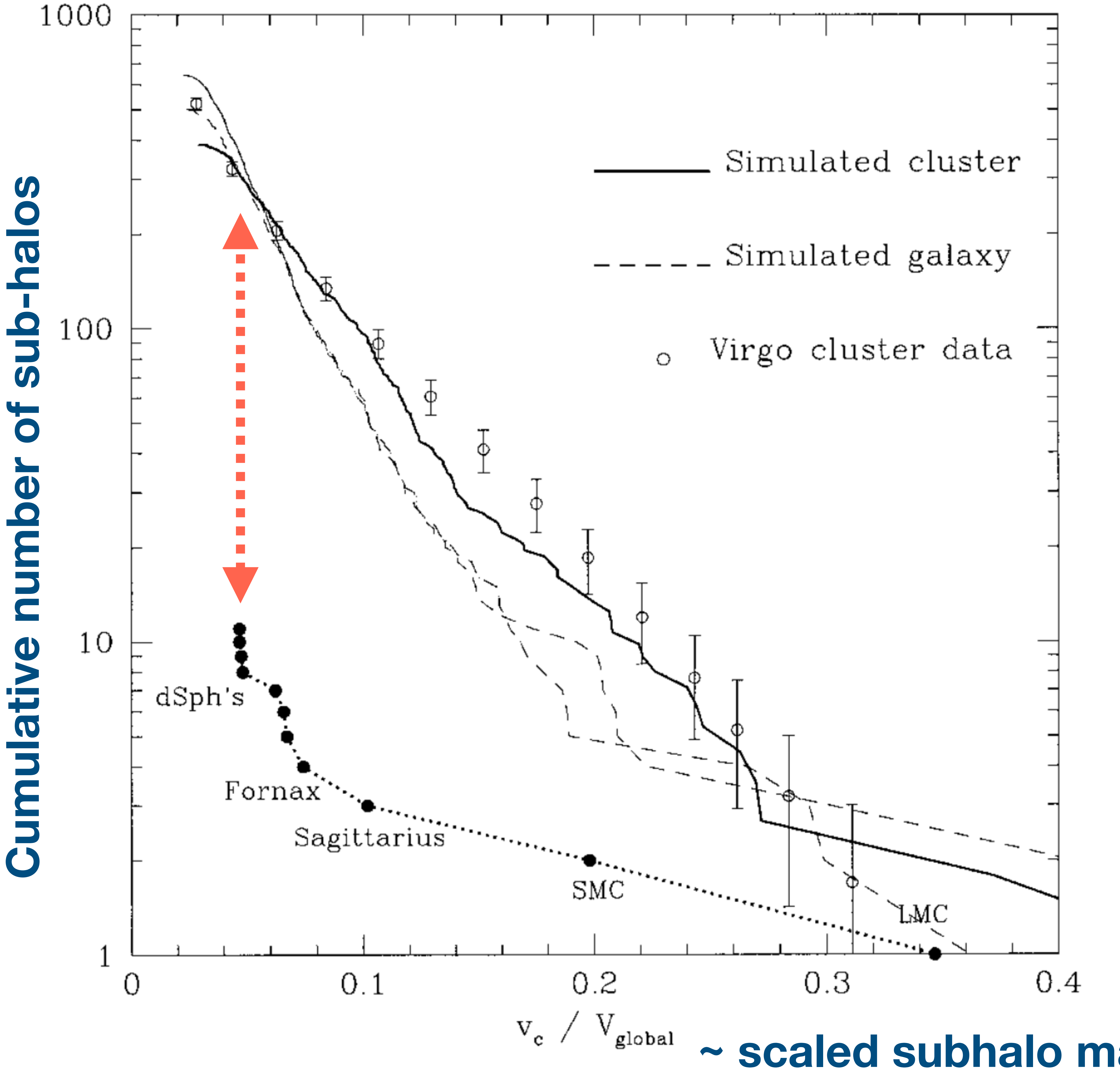
- **Void phenomenon:** gals in voids are too normal?

  Peebles '01

- **Satellite plane problem:** satellites aligned in a plane for both MW and Andromeda

- ….

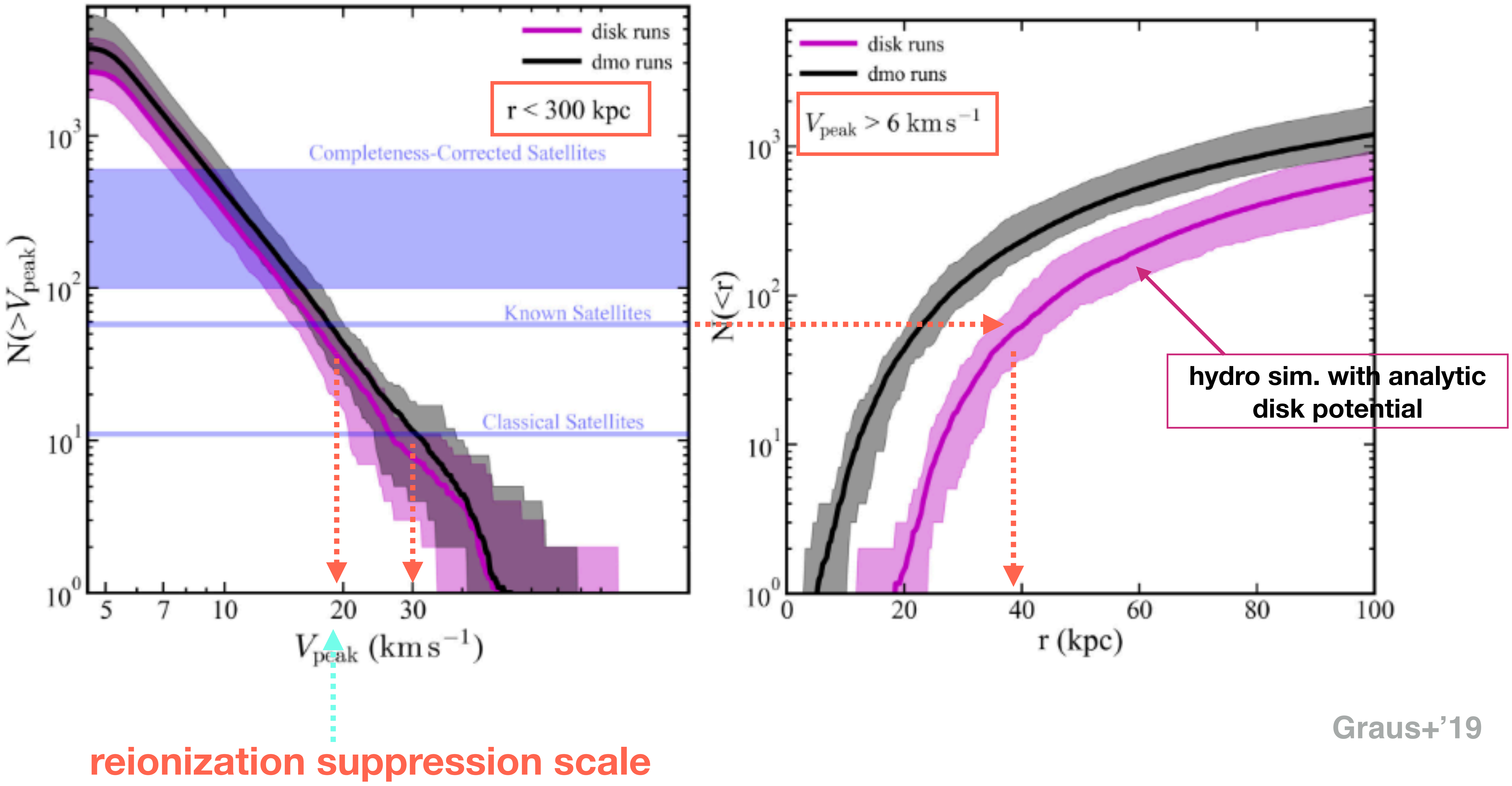
Original Substructure Problem



Cumulative number of sub-halos

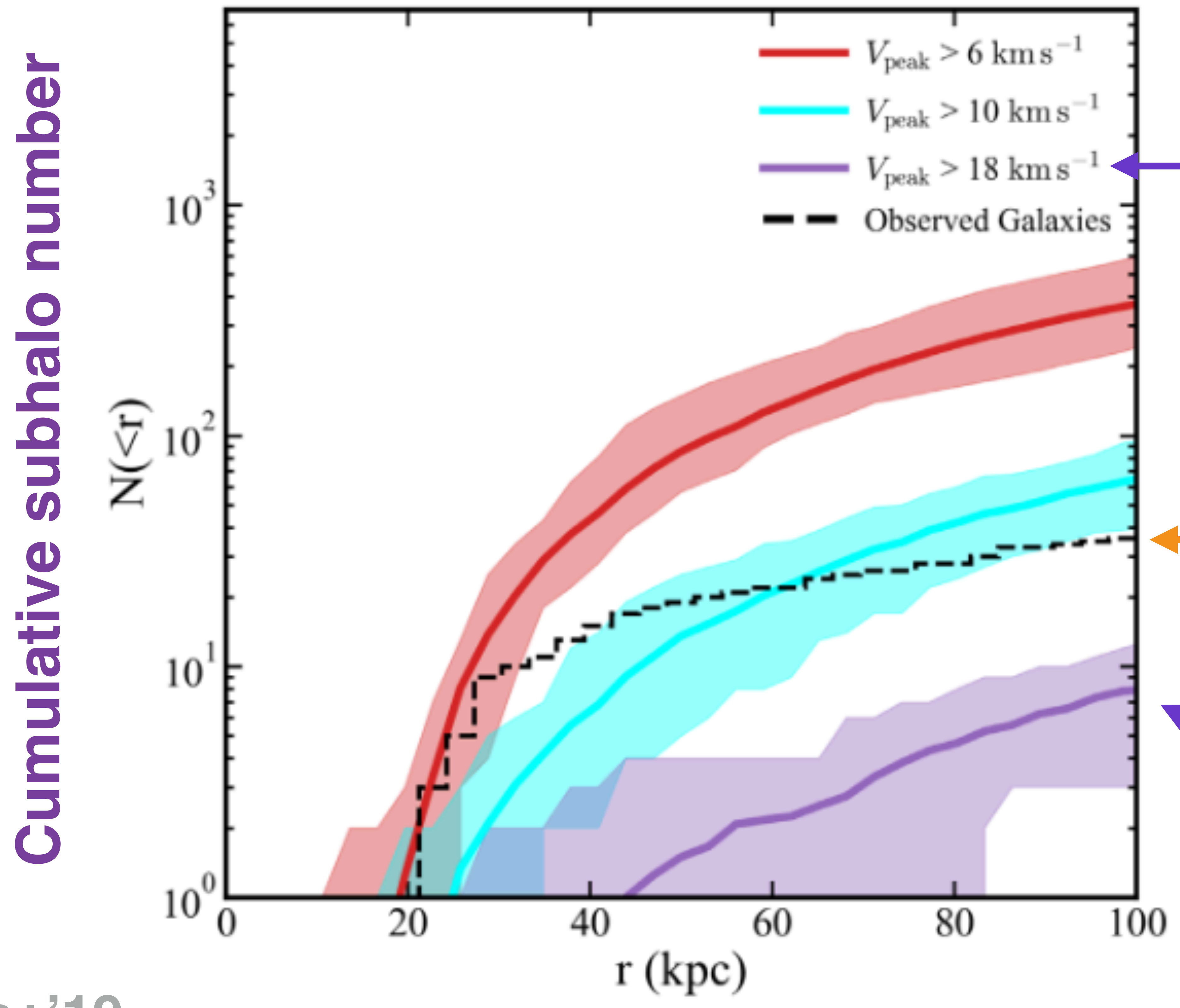
~ scaled subhalo mass

Klypin+'99; Moore+'99


disk runs
dmo runs
r < 300 kpc
Completeness-Corrected Satellites
Known Satellites
Classical Satellites
N(>V_peak)
V_peak (km s^-1)
disk runs
dmo runs
V_peak > 6 km s^-1
N(<r)
r (kpc)
hydro sim. with analytic disk potential
reionization suppression scale
Graus+'19

No Missing Satellites Problem??

Radial dist. of subhalos with



Graus+'19

Distance from gal center

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 few dwarf gals in hydro simulations 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

No Missing Satellites Problem

high-resolution zoom-in simulation

CHANGA code (Gasoline + Charm++)

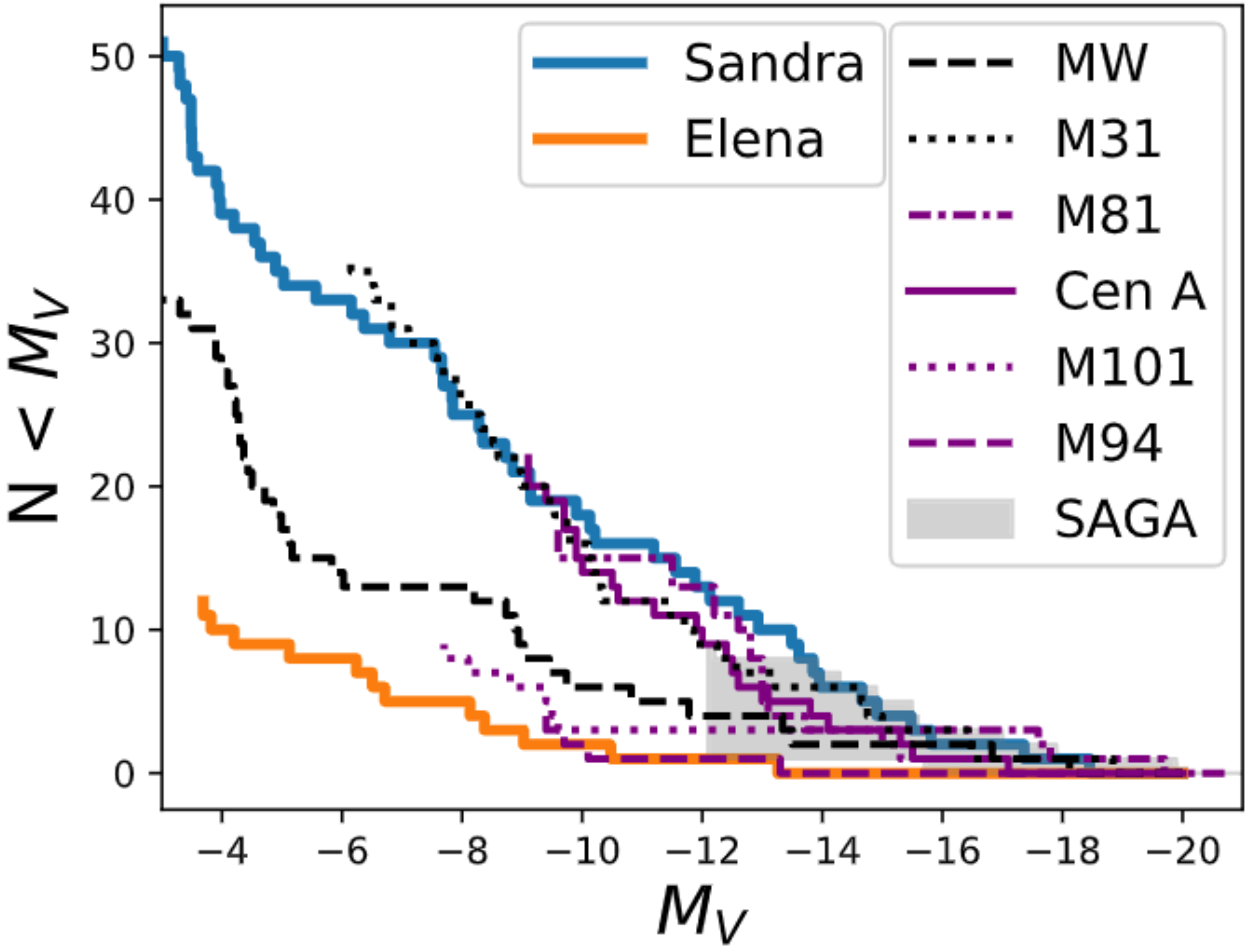
$$\epsilon_g = 87\,\mathrm{pc}$$

$$h_{\mathrm{sml}} = 11\,\mathrm{pc}$$

$$m_{\mathrm{dm}} = 1.8e4\,M_\odot$$

$$m_{\mathrm{gas}} = 3.3e3\,M_\odot$$

$$m_* = 994\,M_\odot$$



Applebaum+21

cf. Garrison-Kimmel+'17; Graus+18; Kim+'18

Dark matter ptcl candidates

DM particle mass scale

$m_{\rm DM}$

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

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

(cf. self-interacting DM)

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

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

(gravitino, sterile neutrino,…)

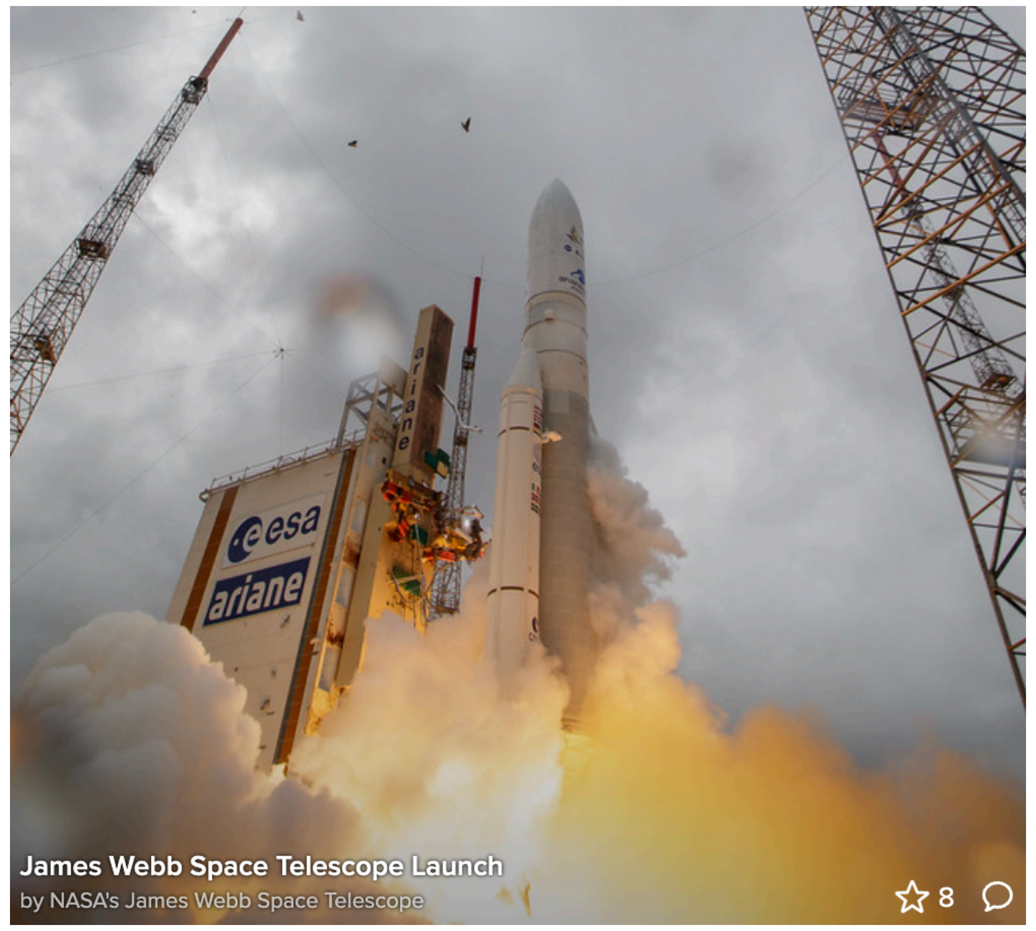
eV — **HDM** — remains relativistic until late time, and erase structures at super-galactic scales. (ν,…)

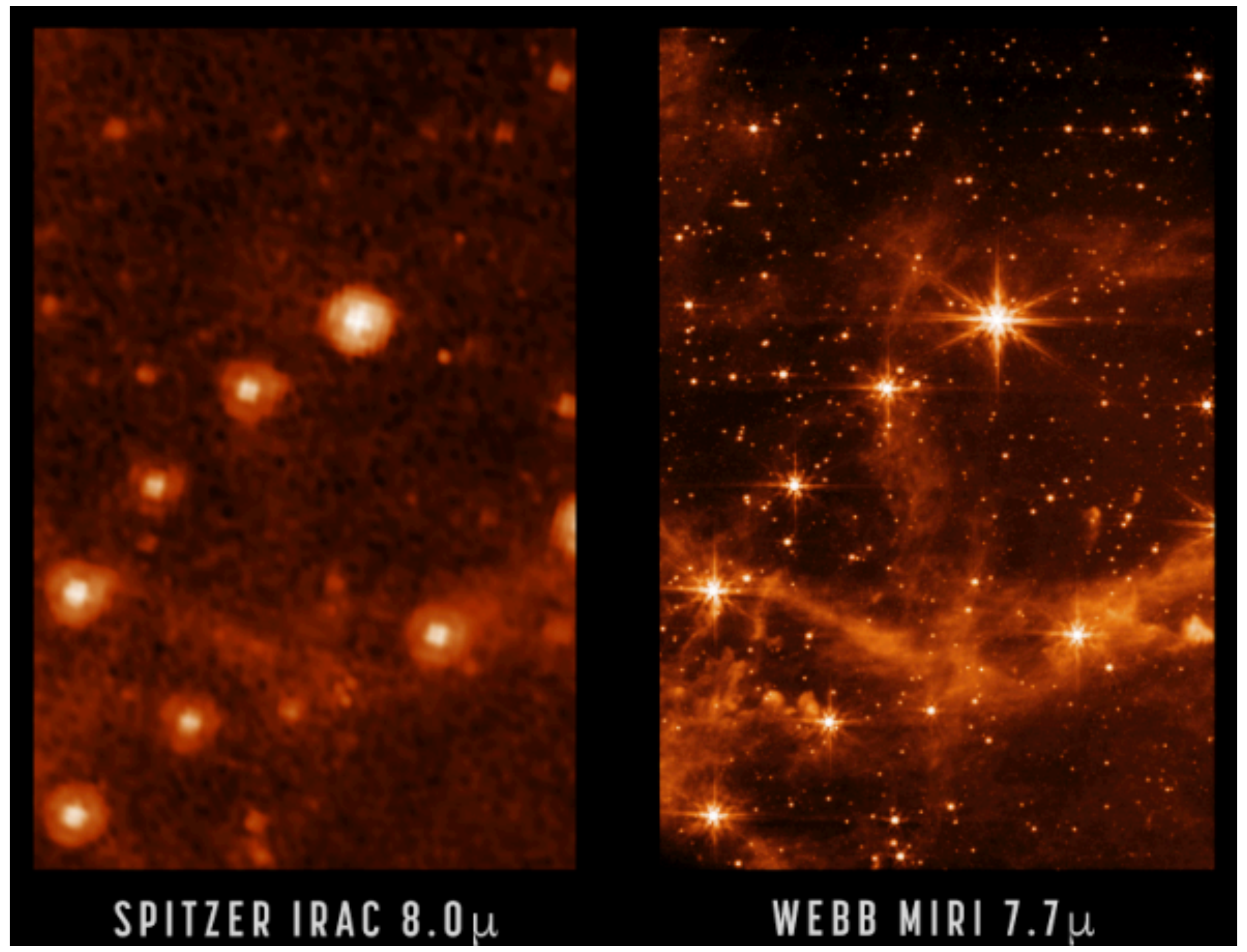
$v_{\rm th} \approx 30\,{\rm km/s}$

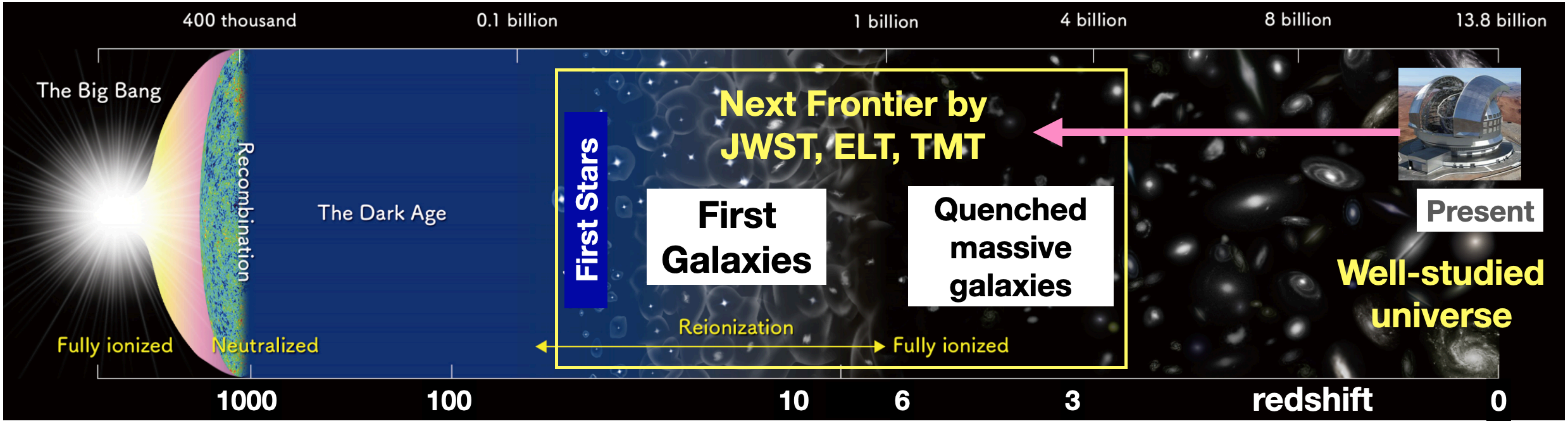
μeV~meV — standard QCD-**axion**

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

JWST launch
Dec 2021







Fuzzy Dark Matter (FDM)

Ultra Light Bosons, Wave-like, Axion-like

- non-thermal scalar boson field, non-rela, low-momentum state as a cold **B.E.C.** (i.e. “BECDM”)
- **$m \sim 10^{-22}$ eV**, $\lambda_{\text{de Broglie}} \sim$ **1kpc**
- suppression of halos at $\lesssim$ **10^{7}-10^{10} $M_{\odot}$**
- quantum pressure —> central **soliton** core
- on large-scales, ≈ CDM

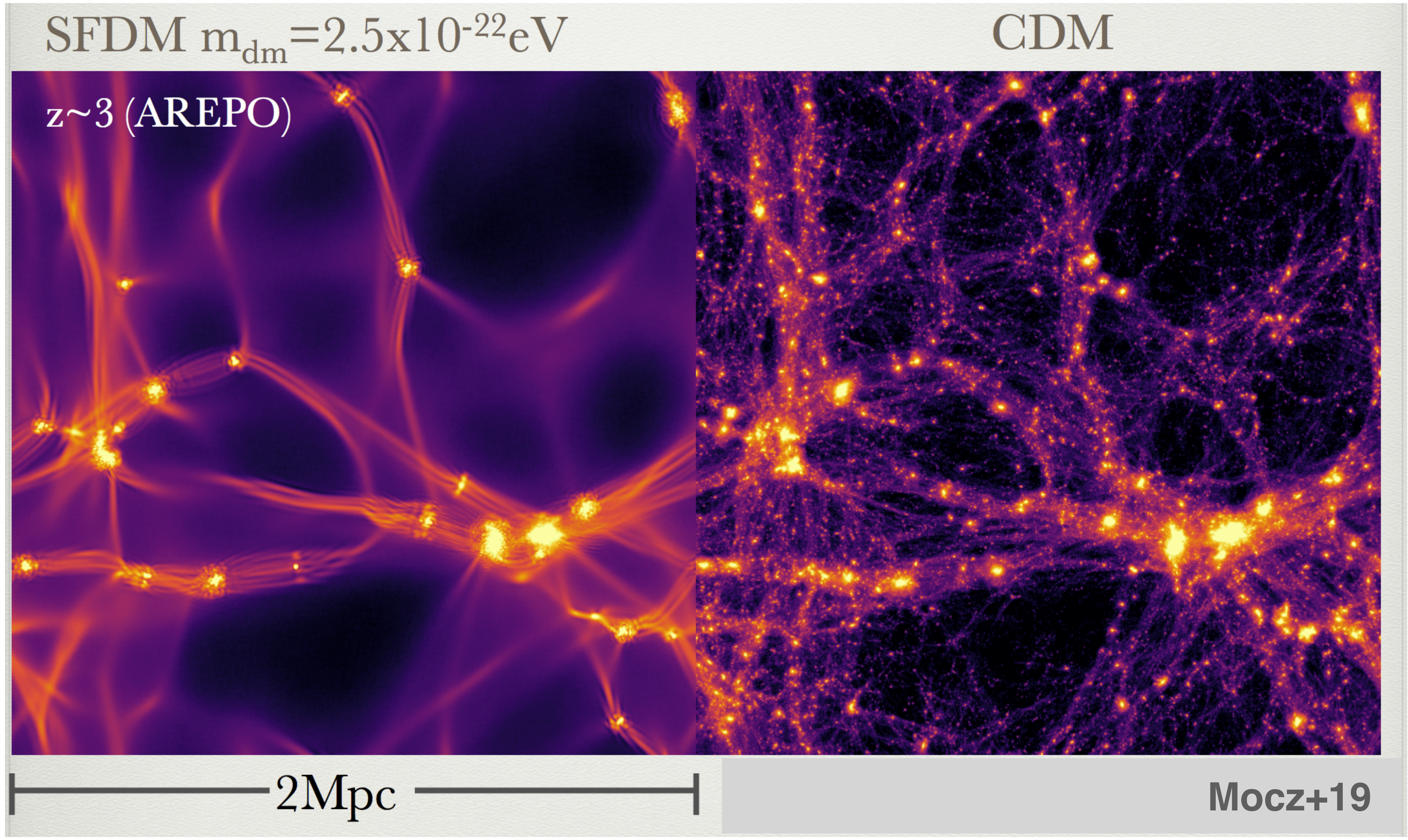
Baldeschi+83; Kim ’87; Sin+94; Hu+00; **Marsh+14; Schive+14,16; Hui+17; Mocz+17; Robles+18; Zhang+18; Mocz+19, ….**

Schrödinger-Poisson eq.

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\Psi + Vm\Psi$$

$$\nabla^2 V = \frac{4\pi G}{a}(\rho - \overline{\rho})$$

$$\rho = |\Psi|^2$$



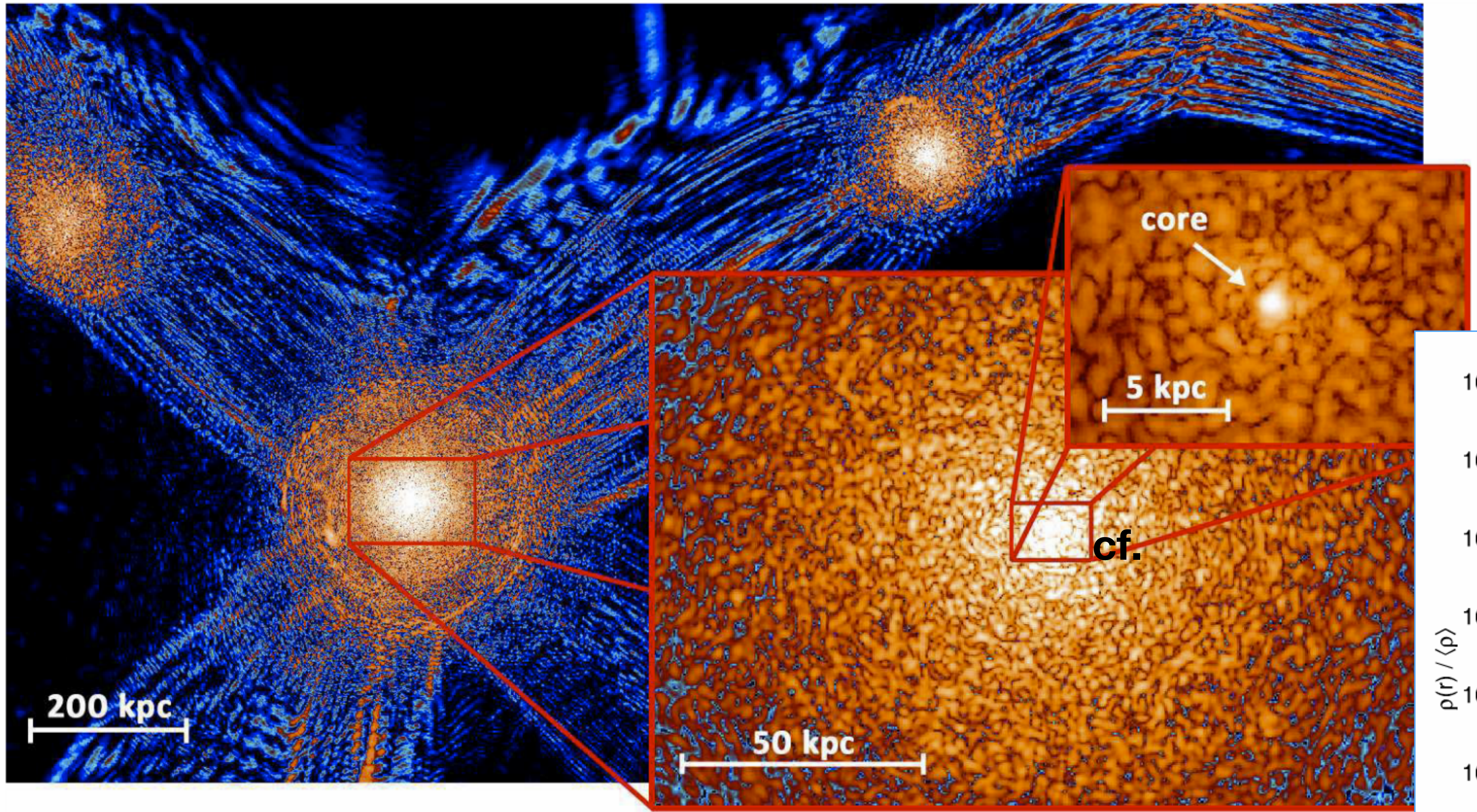
- Uncertainty principle counteracts gravity below Jeans scale

- **quantum pressure** from uncertainty principle — **solitonic core**

- constraints from Lyα P(k): $m > 2 \times 10^{-21}$ eV   Irsic+17

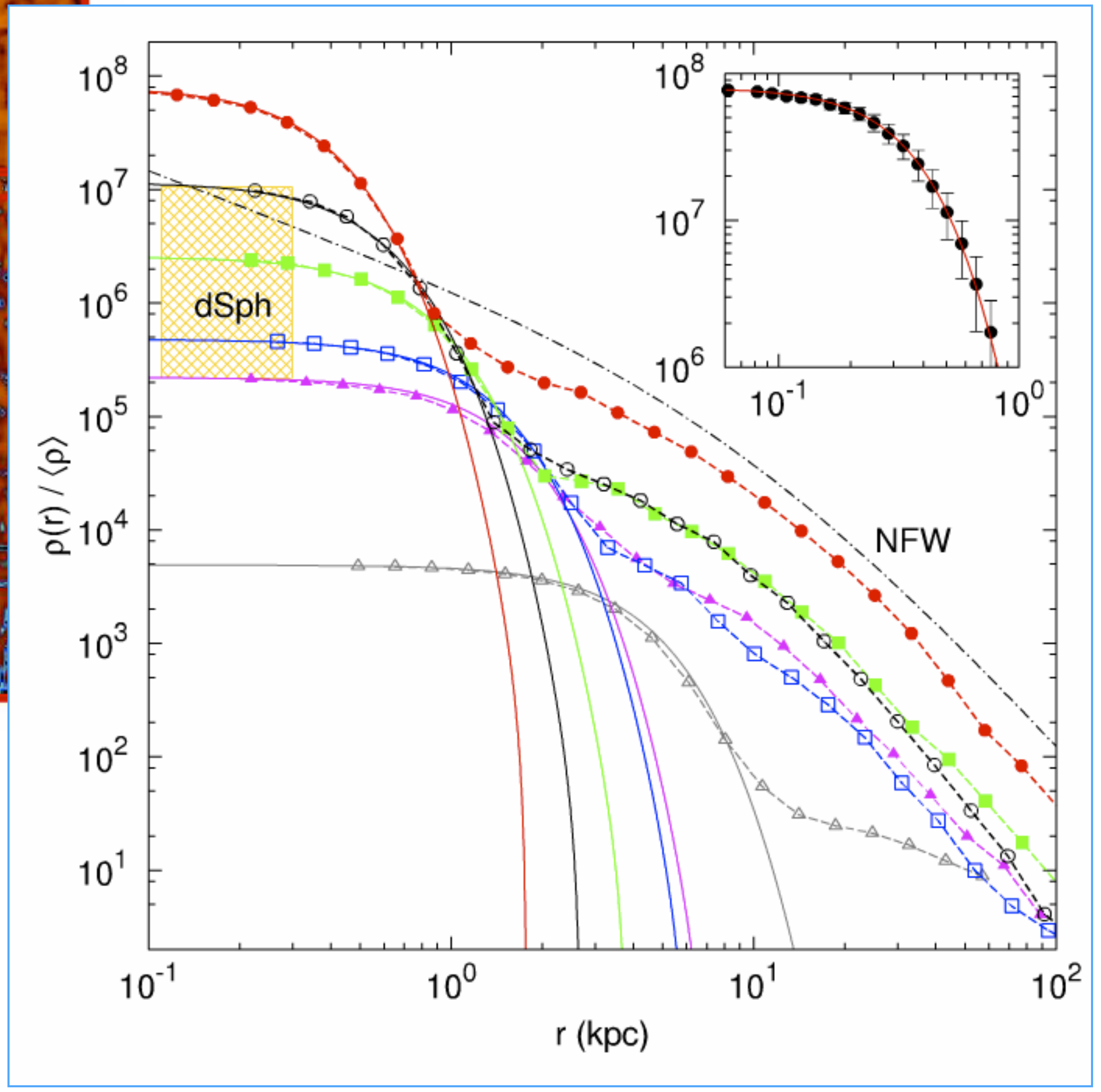
(Not much room for ULA?)

Solitonic Core of FDM simulation



Schive+14, Nature

gravitationally bound solitonic core



e.g. $m_B = (8.1^{+1.6}_{-1.7}) \times 10^{-23}$ eV

for Fornax dSph gal.

$M_s \propto M_{gal}^{1/3}$

$M_s \simeq 2 \times 10^9 \, M_\odot$ for MW core

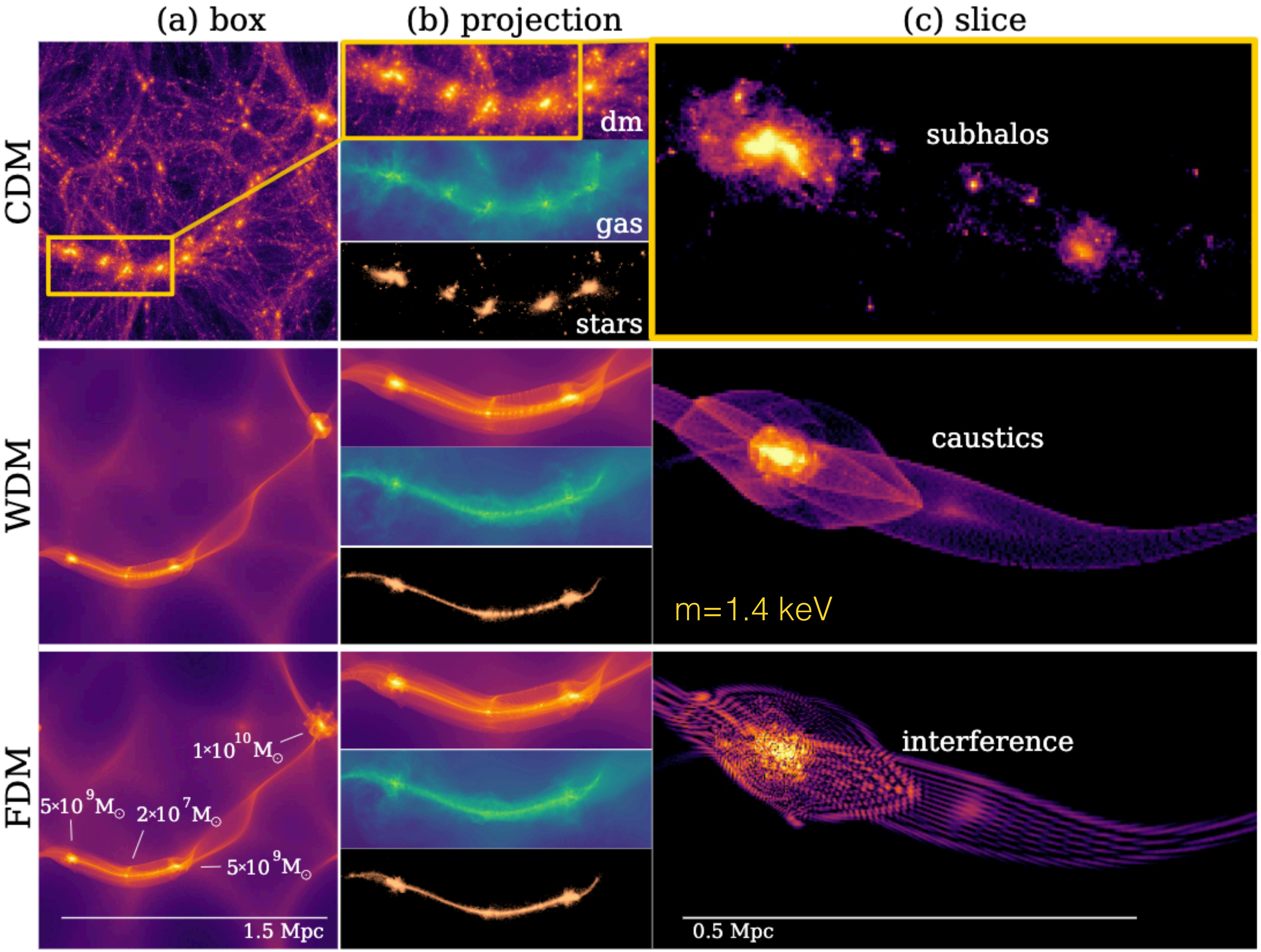
$m_{FDM} \gtrsim 10^{-21}$ eV

Hayashi+21

CDM

WDM

FDM

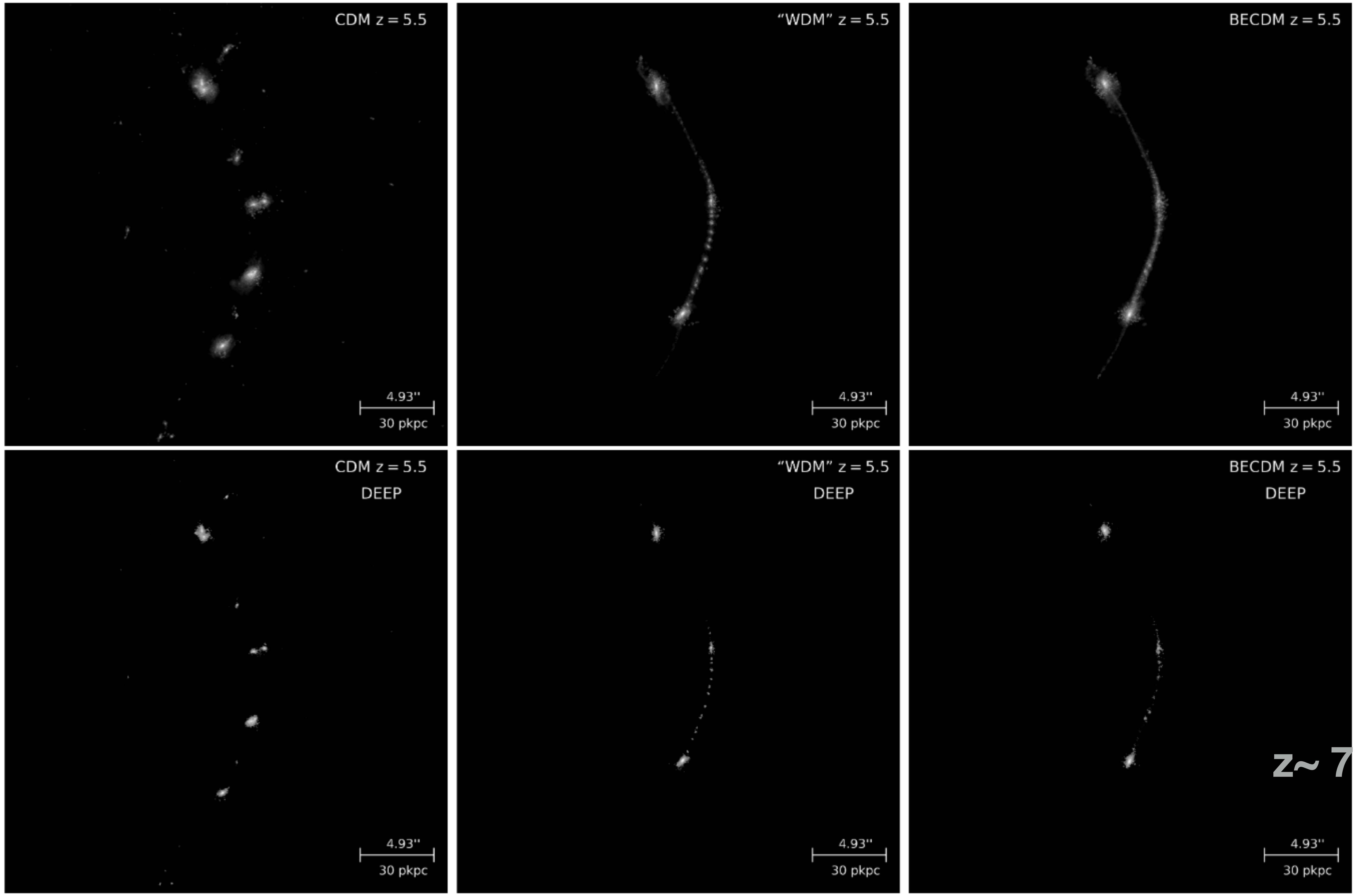


z~ 7

Mocz+ ‘21

JWST mock observation

CDM WDM FDM



z~ 7

original raw image

(no surface brightness limit)

w/ realistic surface brightness limit:

$\sim 0.0013\,\mathrm{MJy\,sr^{-1}}$

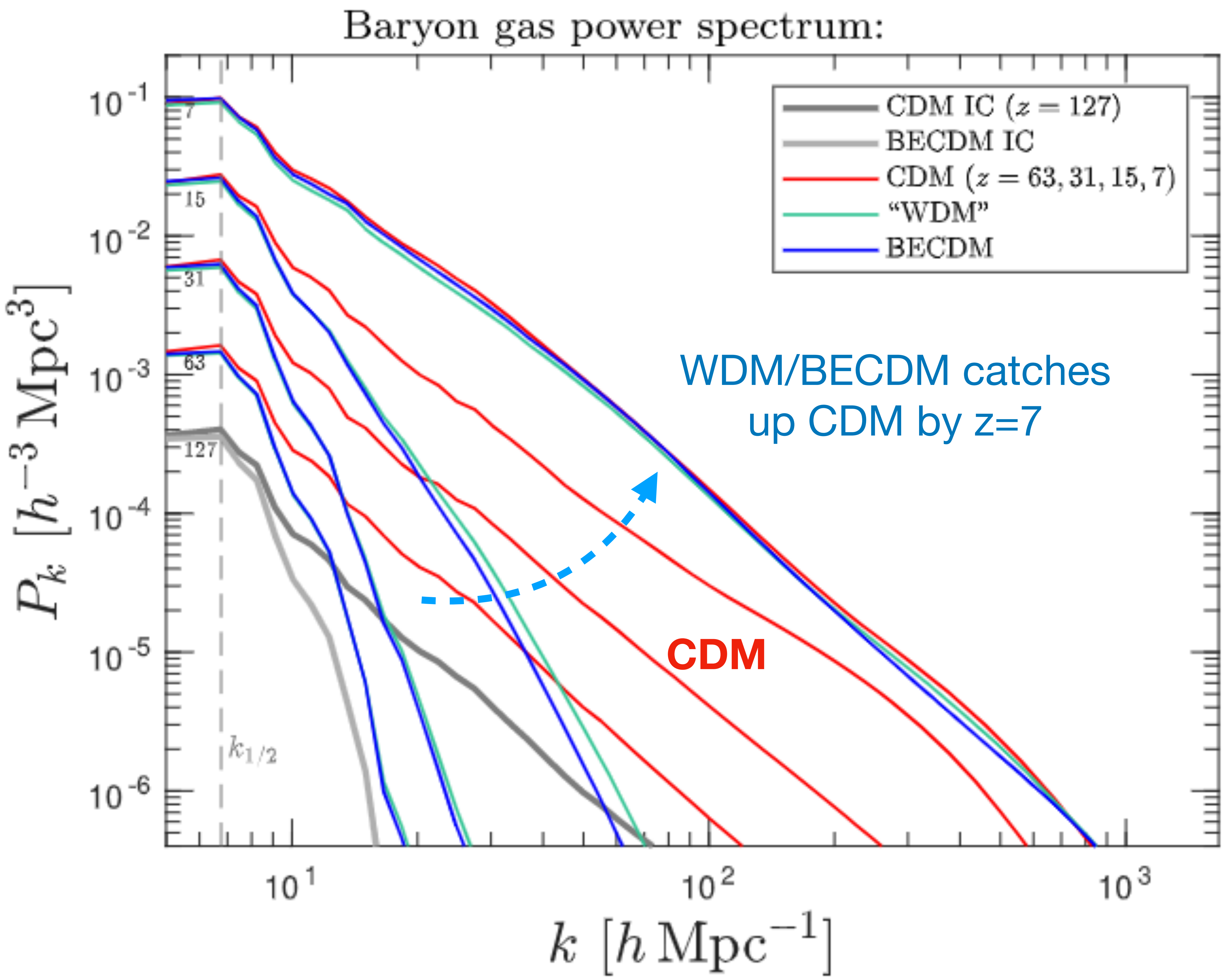
$27.7\,\mathrm{ABmag/arcsec^2}$

(~50 times deeper than the actual)

filamentary stellar distr. is barely visible.

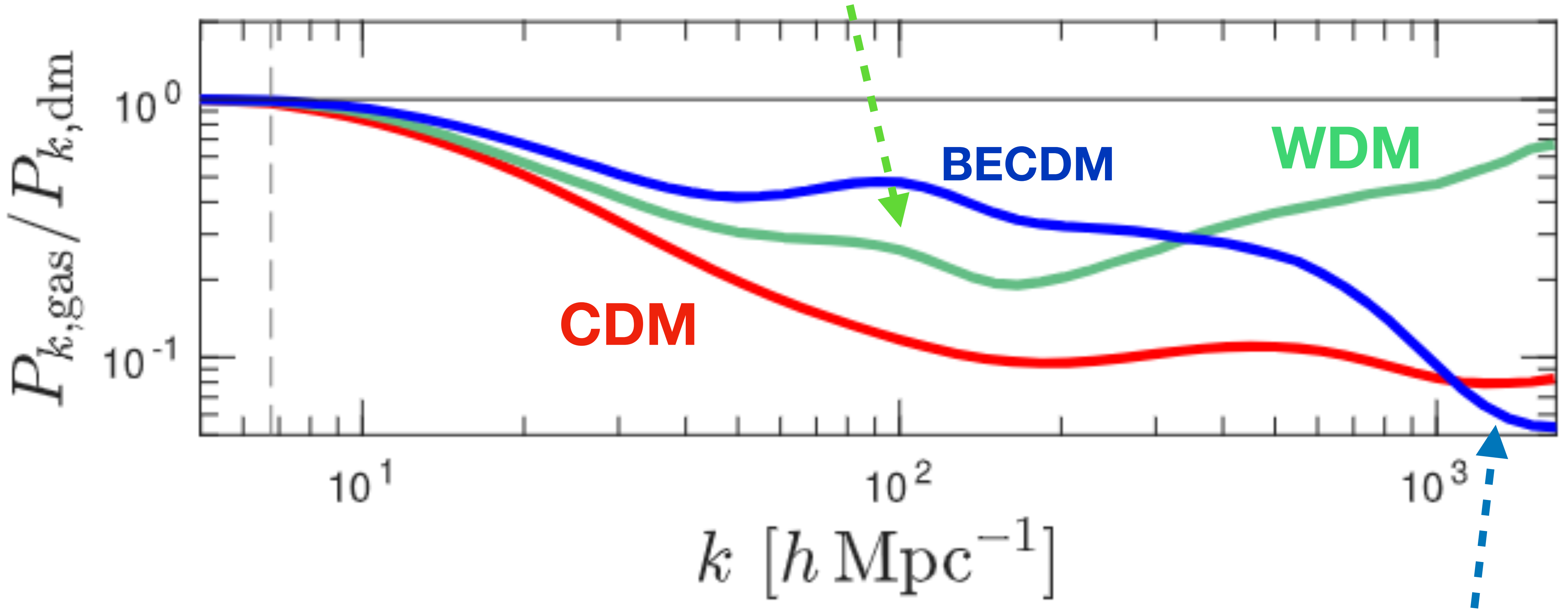
ELT / TMT obs. with AO + grav lensing

Mocz+ '21



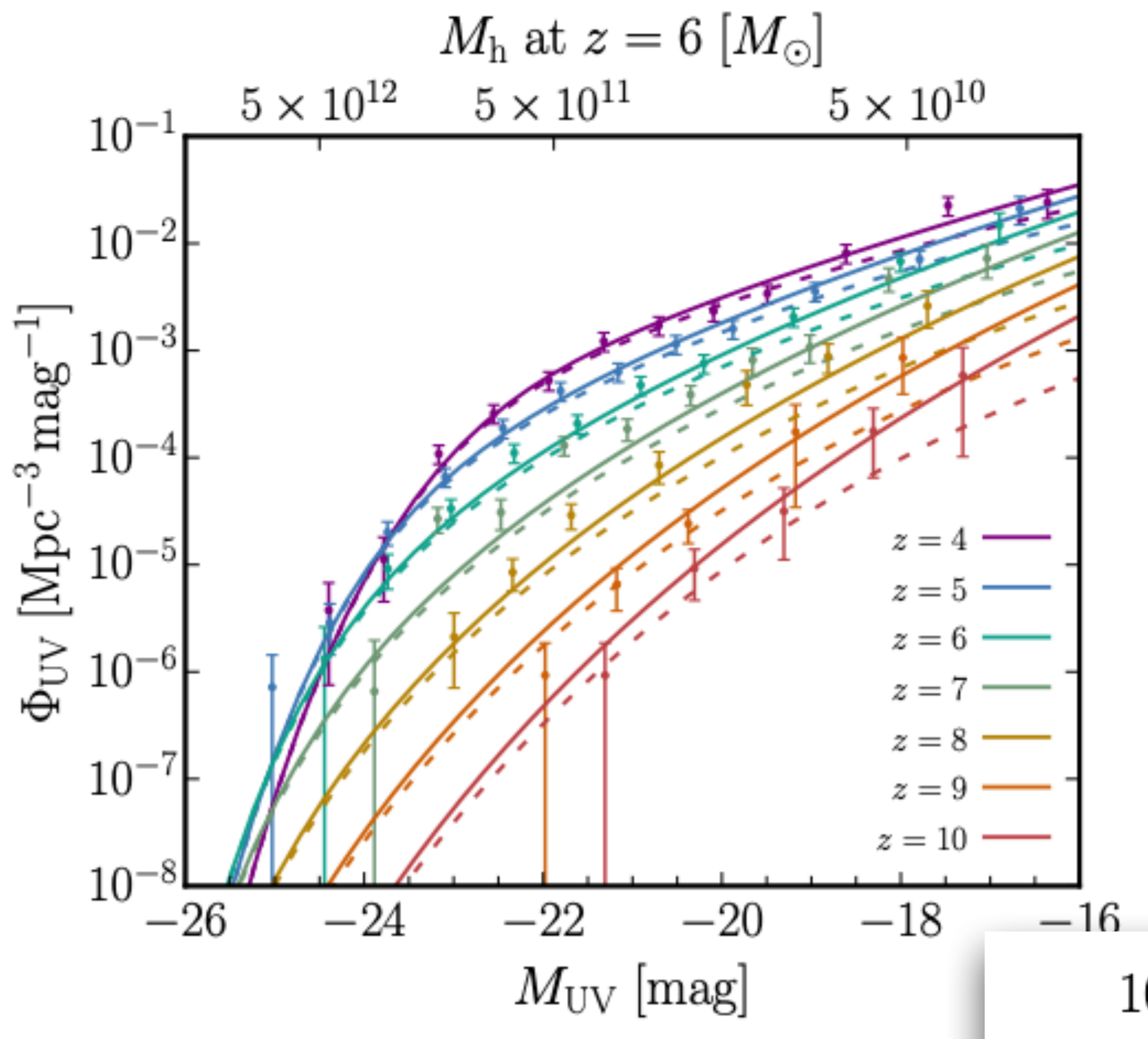
WDM & BECDM are smoother than CDM (i.e. closer to DM distr.)

z~ 7

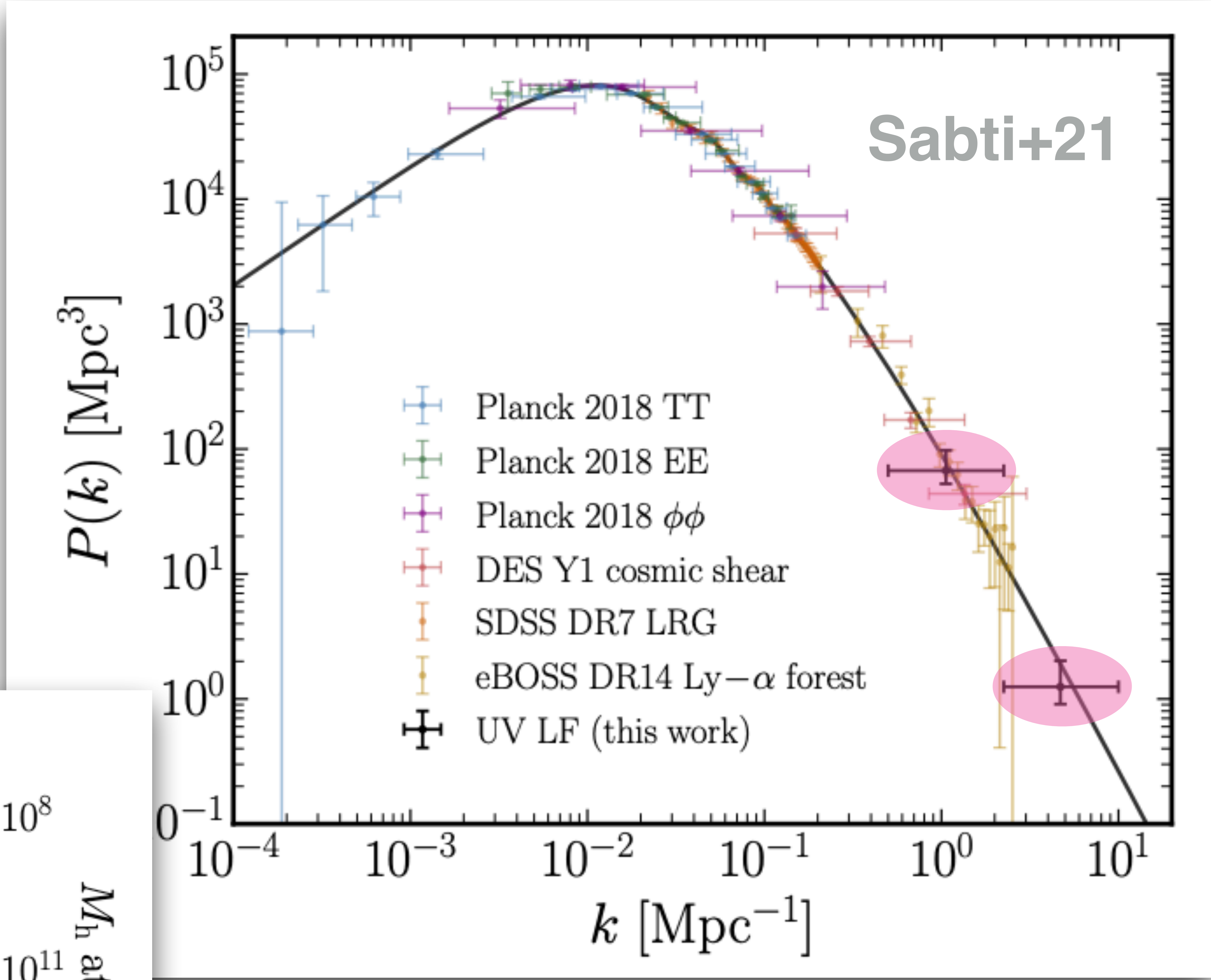


Drop of power in BECDM due to interference pattern (not imprinted on baryons)

UV Luminosity Function as a Probe of DM & P(k)

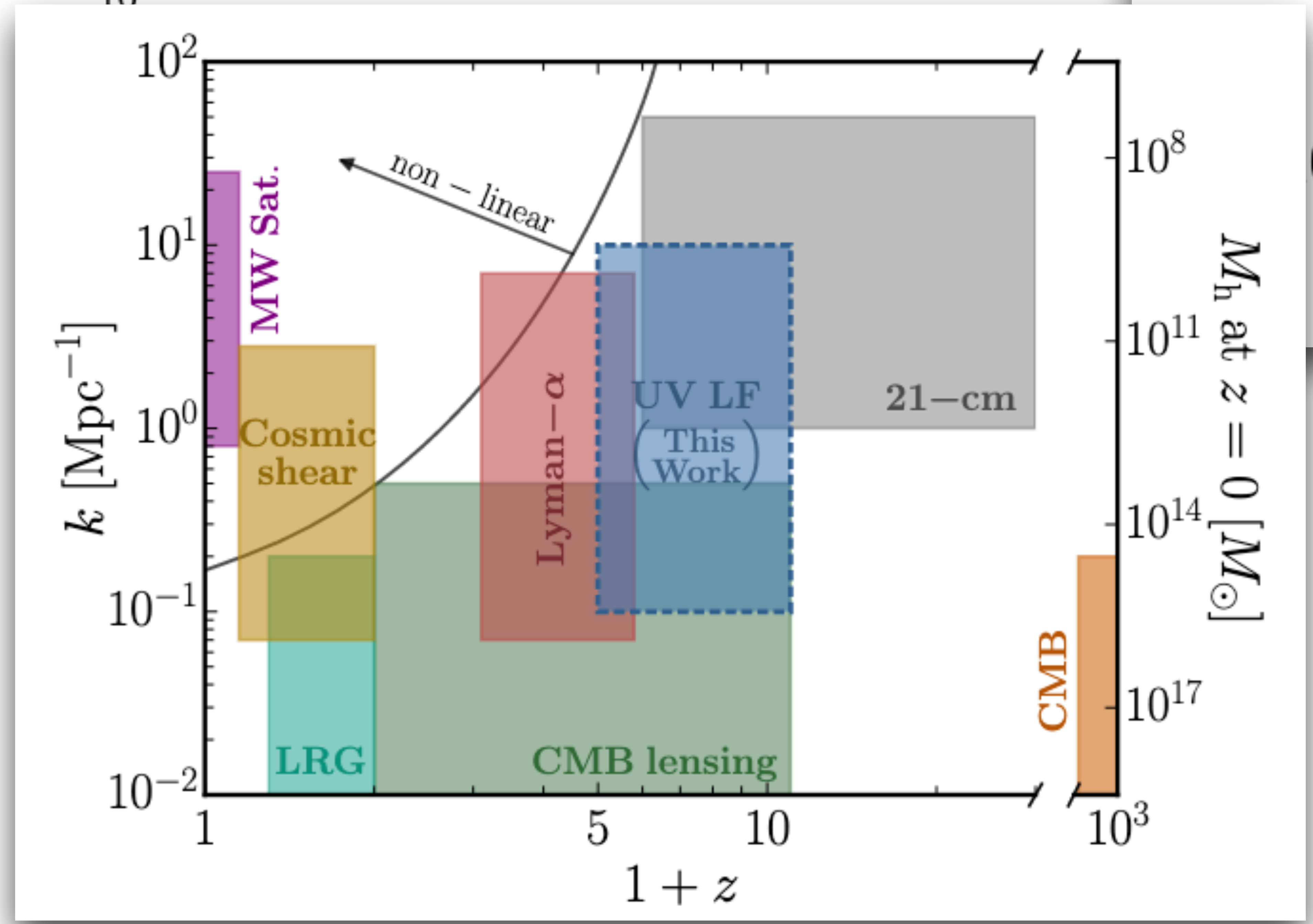


Oesch+18
Bouwens+21
Bechtol+22



$$\Phi_{UV} = \frac{dn}{dM_h} \times \frac{dM_h}{dM_{UV}}$$

(halo occupation = 1)

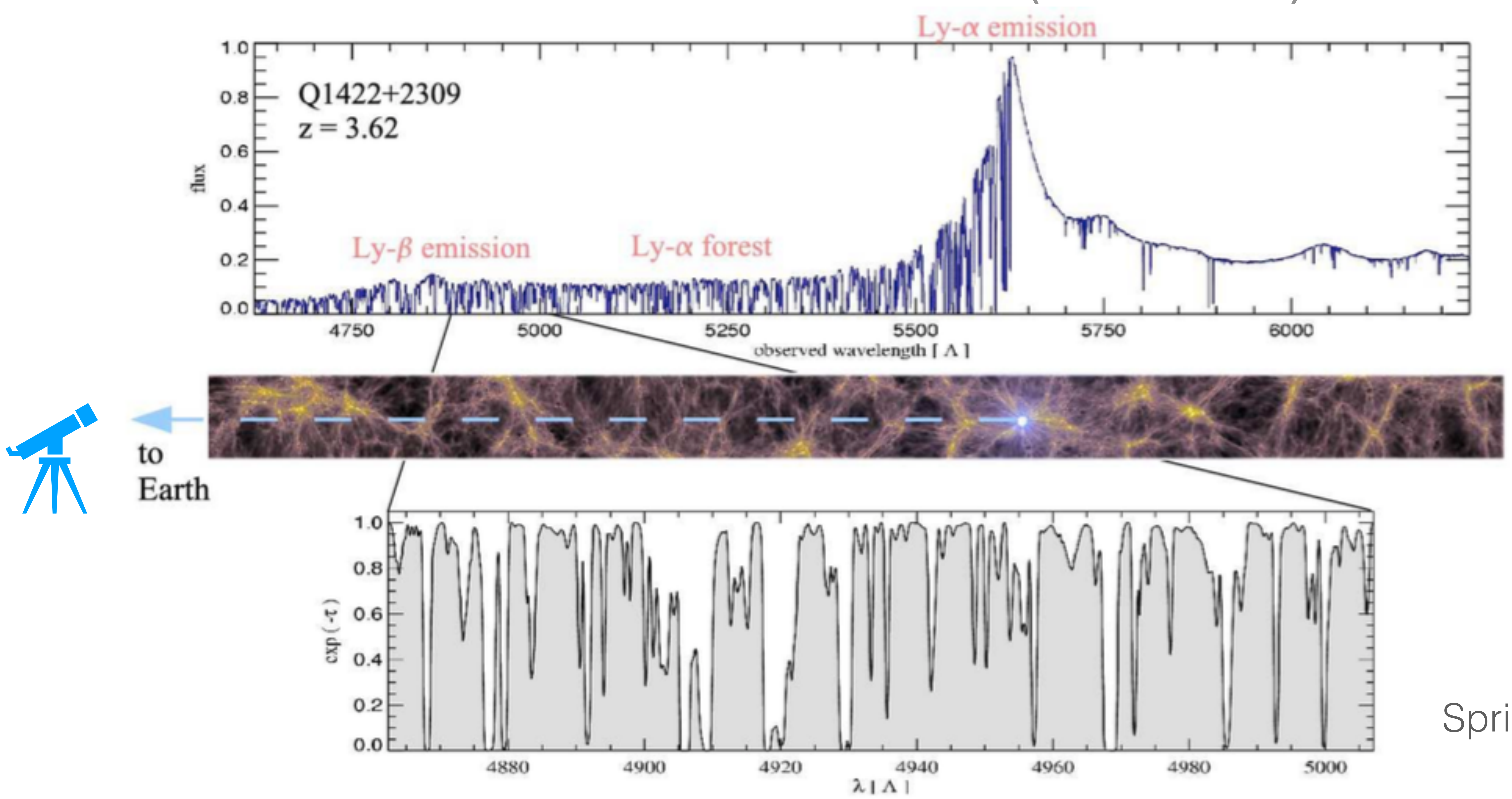


$$\tilde{f}_* = \frac{\dot{M}_*}{\dot{M}_h} = \frac{\epsilon_*}{\left(\frac{M_h}{M_c}\right)^{\alpha_*} + \left(\frac{M_h}{M_c}\right)^{\beta_*}},$$

$$\dot{M}_h = -\sqrt{\frac{2}{\pi}} \frac{(1+z)H(z)M_h}{\sqrt{\sigma^2_{M_h}(Q) - \sigma^2_{M_h}}} \frac{1.686}{D^2(z)} \frac{dD(z)}{dz}$$

Quasar (QSO) absorption line and Ly-α forest

(a beam of light from a supermassive black hole)



Springel+'05

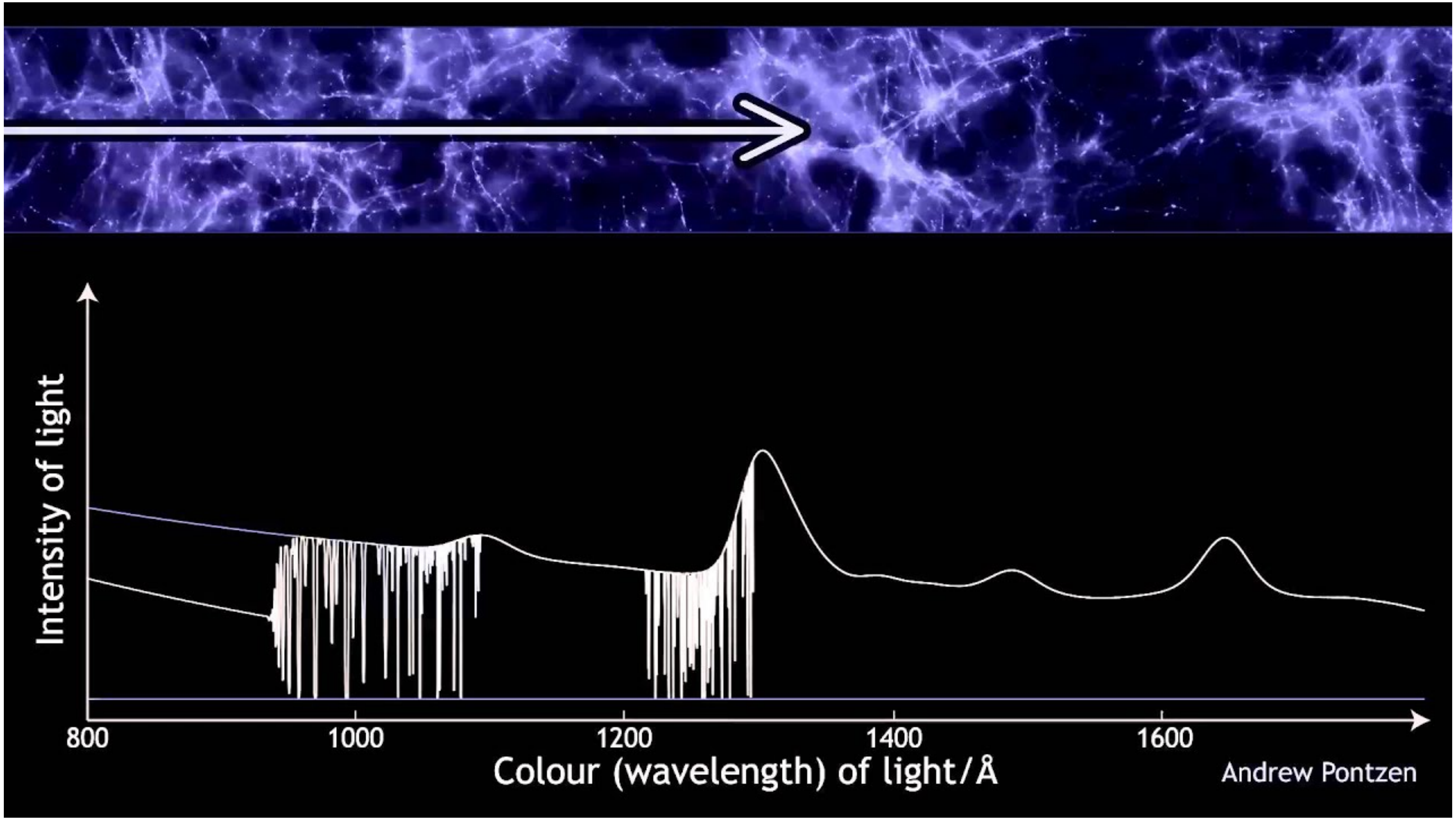
obs: Weymann+81; Cowie+95; Rauch+98

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

Ly-α forest demonstration movie

Quasar

(very bright SMBH)



Producing light-cone data

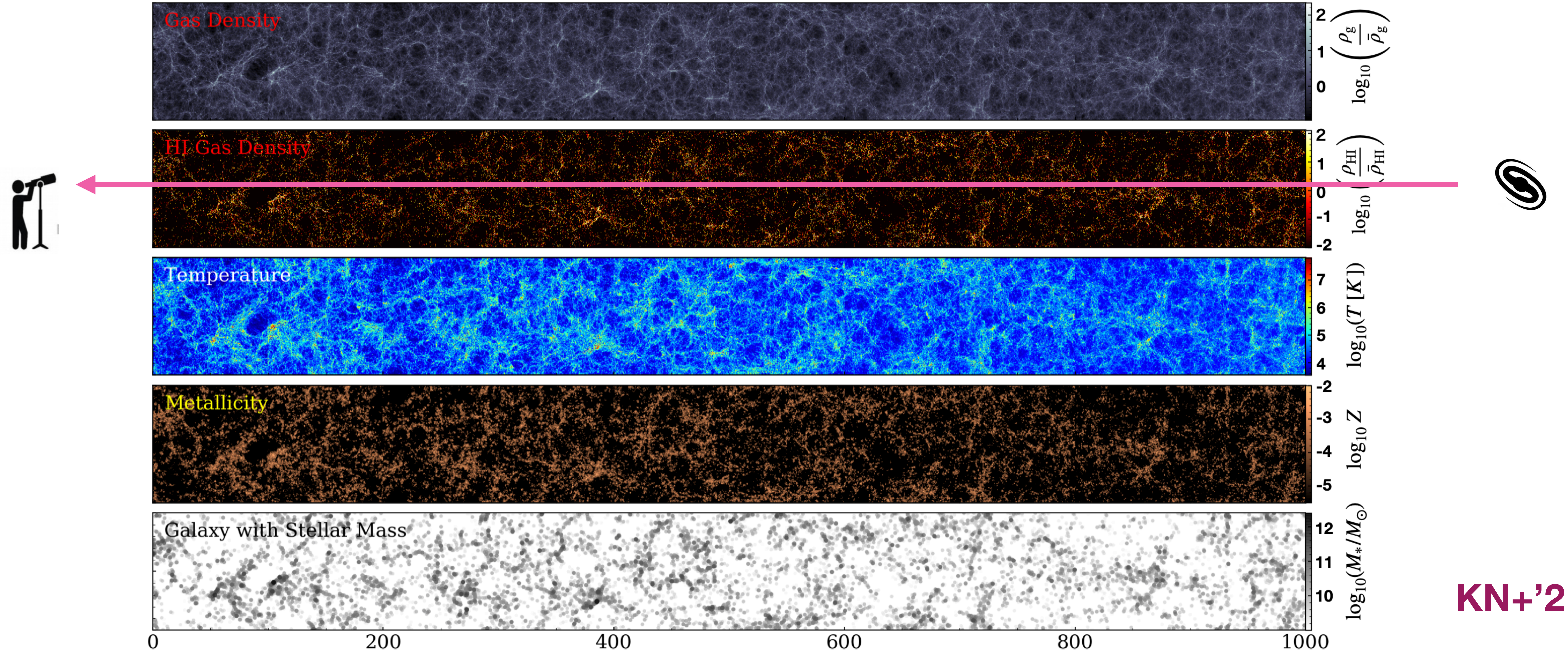
GADGET3-Osaka cosmological simulation (L_{box}= 100 Mpc/h, N= 2 x 512^3)

Model variations:

- **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)

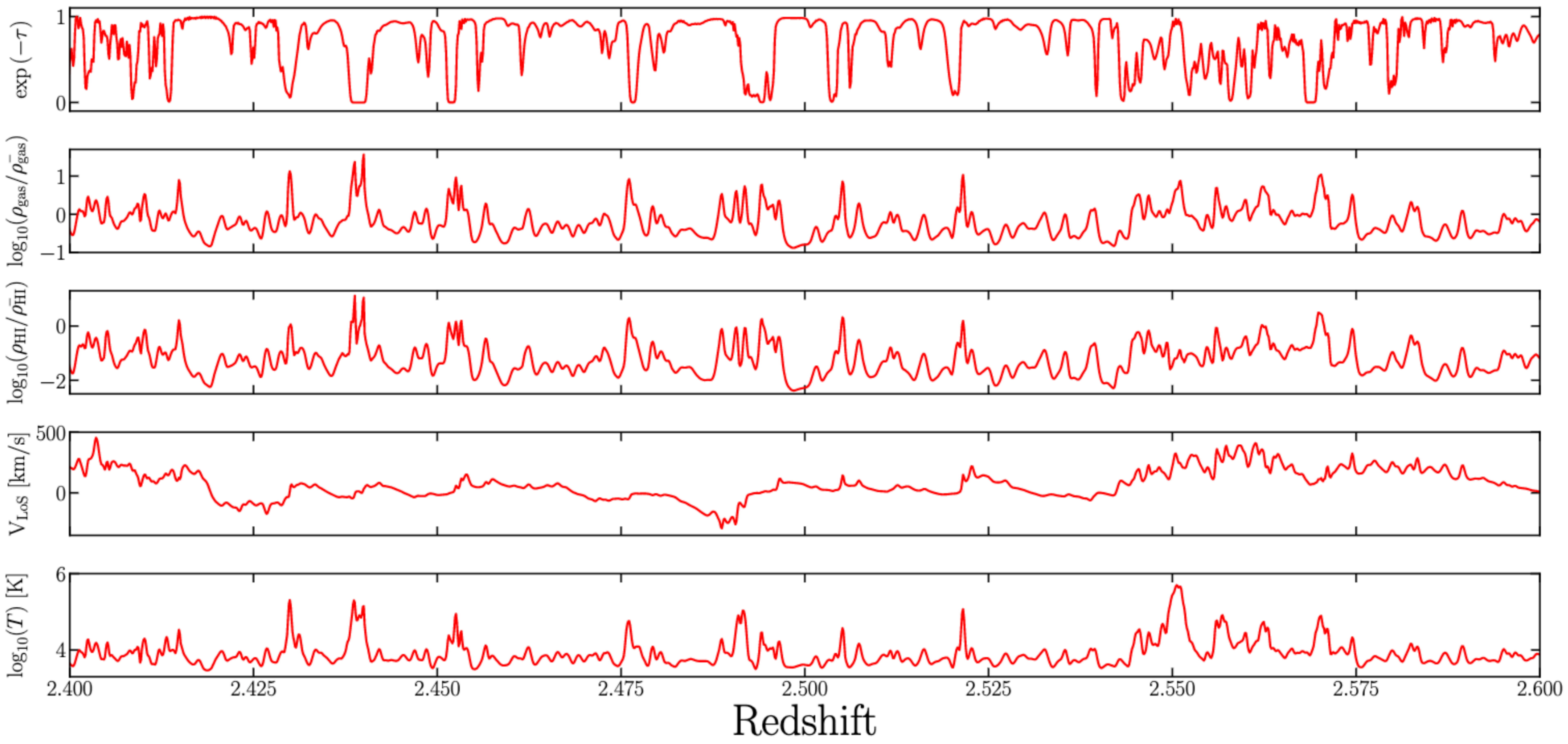
transmission

gas overdensity

HI overdensity

peculiar velocity

temperature

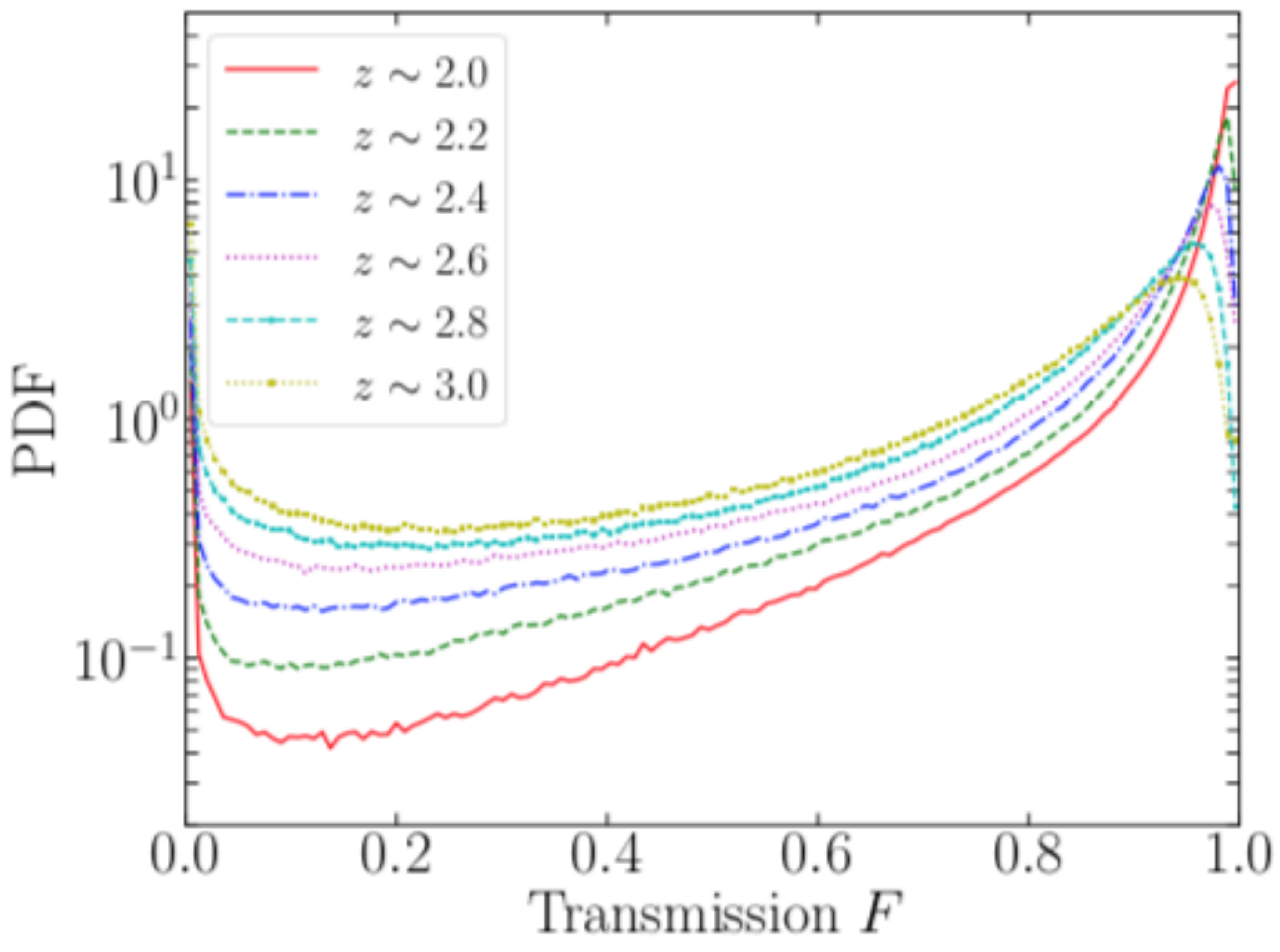


Various statistics can be computed from this: **1. Flux PDF,** **2. 1D $P_k(v)$,** **3. Flux contrast (1D, 2D)**

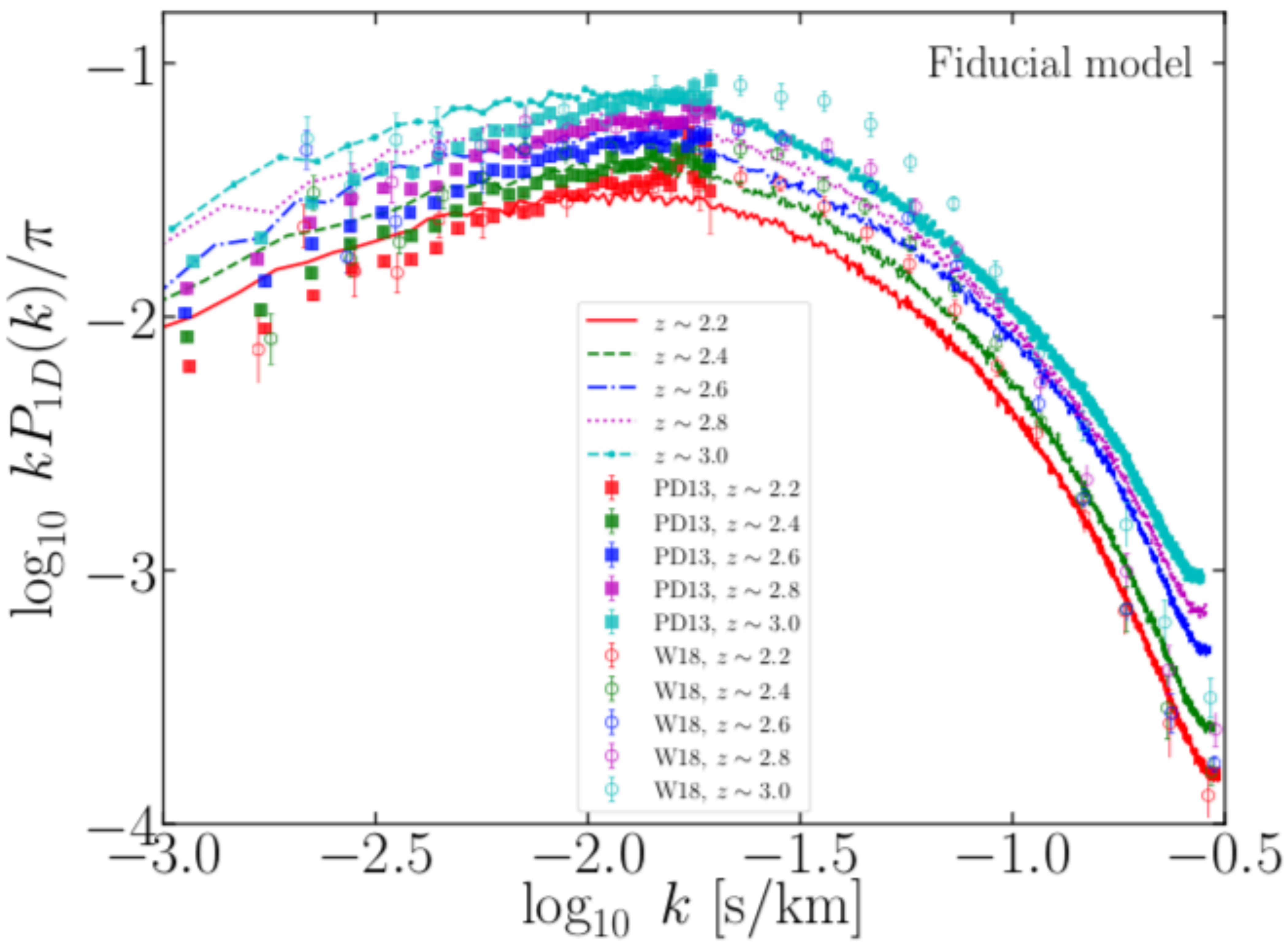
KN+'21

Lyα forest statistics

Transmitted flux PDF



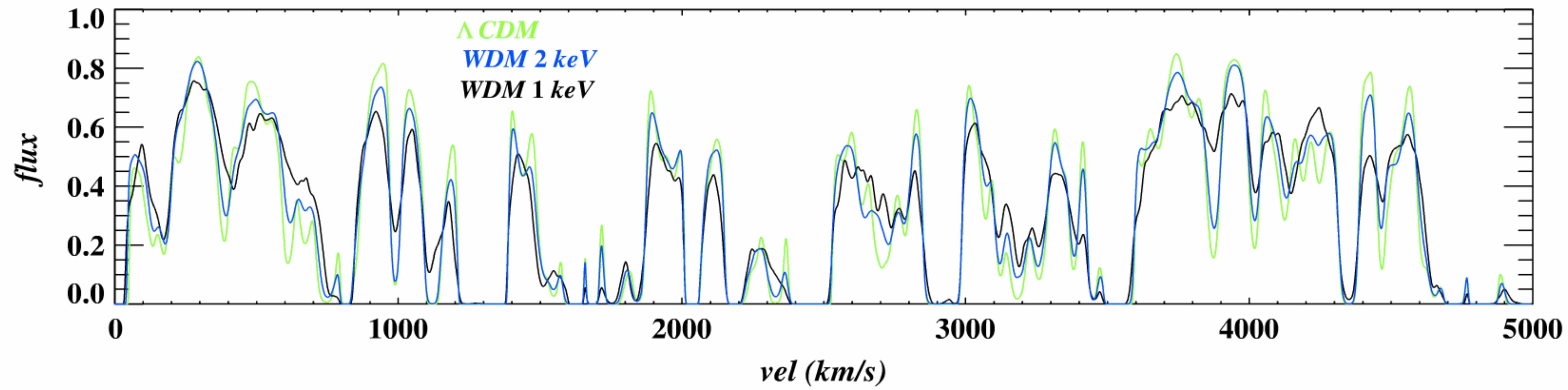
1D Ly-a P(k)



~30% effect of baryonic physics difference

KN+’21

Ly-α forest constraint via WDM/FDM simulation

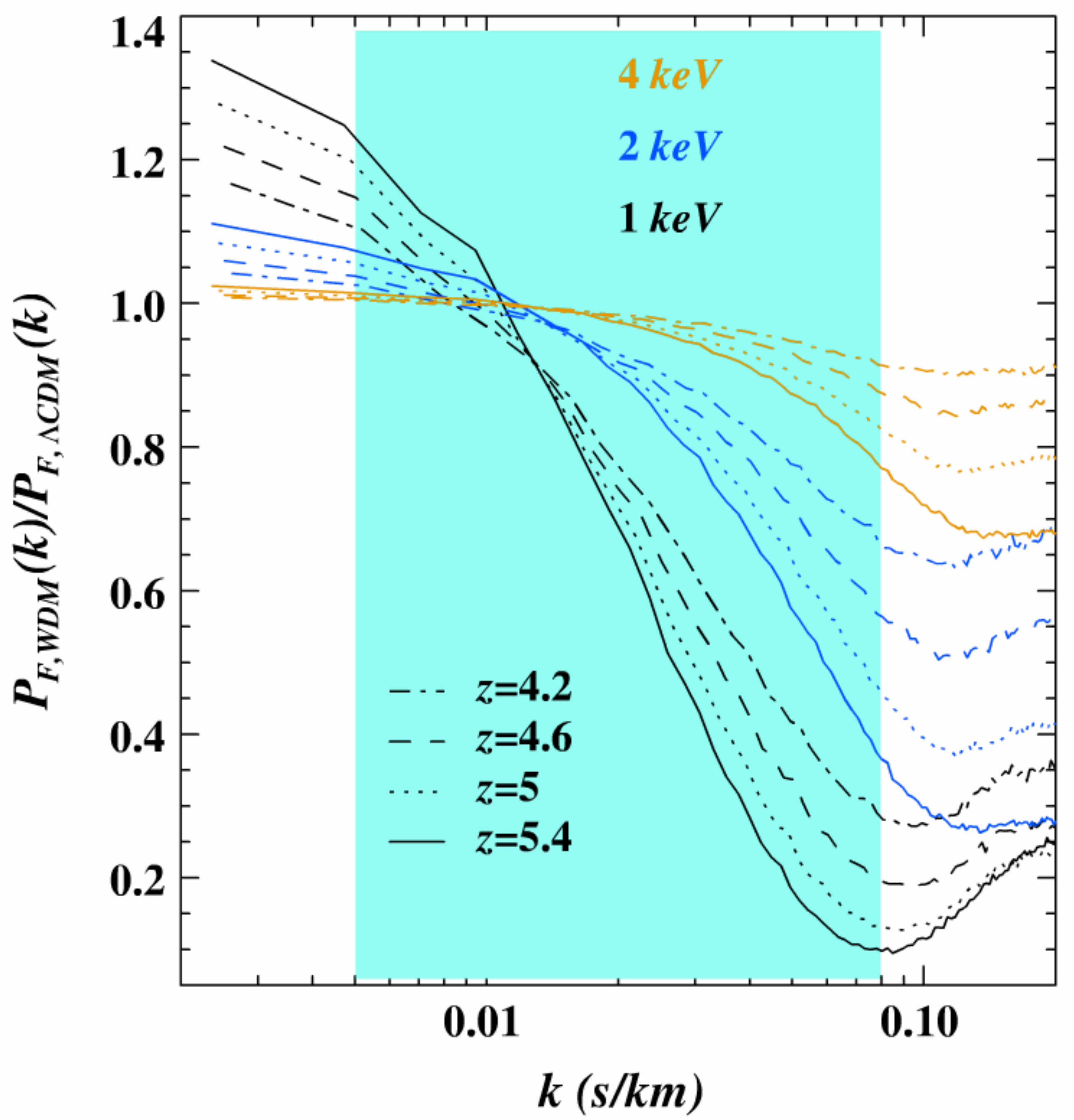


assume

$T = T_0(1+\delta)^{\gamma-1}$

1D flux power spec

$\delta_F = F/\langle F\rangle - 1$



marginalize over cosmo params, & $\mathbf{T_0}$, **γ** using COSMOMC against obs.

m>3.3 keV (2-σ), **$M_{h,min}$~2e8 $M_\odot$**

Viel+'13; Baur+'16

$m > 2 \times 10^{-21}$ eV

cf. Irsic+17; Armengaud+17; Zhang+17

WDM conclusions

- WDM w/ m $\lesssim$ 3keV have been explored — viable, strong alternative to CDM
- $m_{wdm} \gtrsim$ a few keV more likely than < 1keV.
- **Viel+13, Ly-a forest:** **m>3.3 keV** (2-σ), **$M_{h,min}$~2e8 $M_\odot$**

  Baur+16: m>2.96 eV (for thermal relic)
- Further study needed with high-res. and feedback —
  e.g. impact of AGN feedback on small-scale power
  (van Daahlen+’11; Semboloni+’11)

— Concluding remarks —

- **“Small-scale problem”** — might exist, but astrophysics can solve them.
- **“Missing satellite problem” seems to be disappearing**
—> ``Too many satellites problem” ?
- But still interesting to consider alternatives to CDM
- Lyα forest & High-z gals — strong constraints. (statistics)

$$m_{wdm} \gtrsim 3\,\mathrm{keV}$$
$$m_{FDM} \gtrsim 10^{-21}\,\mathrm{eV}$$

- Better understanding of feedback is needed.
- **FDM** vs. **WDM** — interesting differences on small scales.
- stellar kinematics — non-spherical models w/ anisotropic σ

(e.g. **Hayashi+; Goldstein+22** — $m \gtrsim 10^{-20}\,\mathrm{eV}$)