DARK MATTER AND STRUCTURE FORMATION

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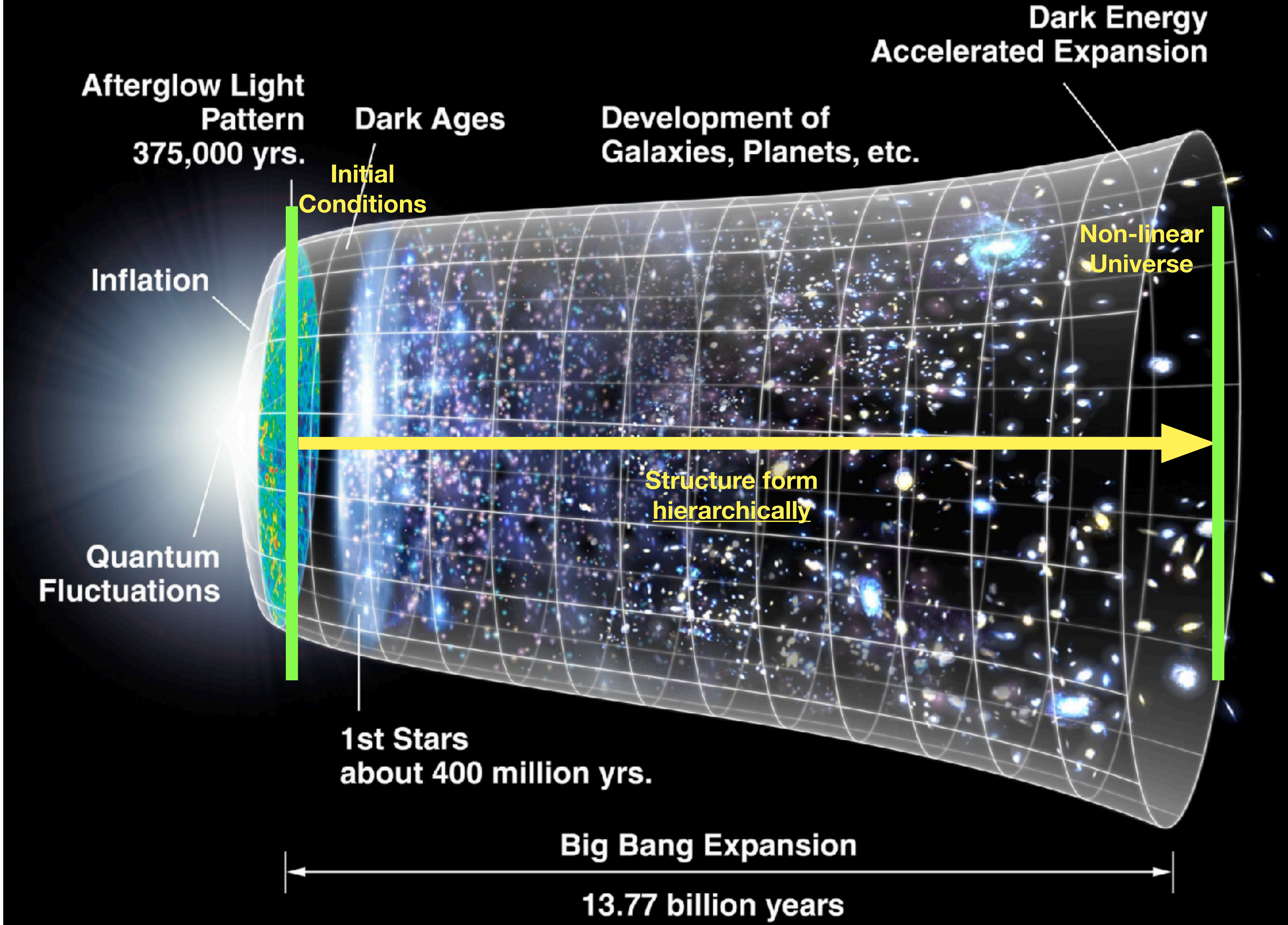
Physics of the flavourful Universe
Portorož 21-09-2021

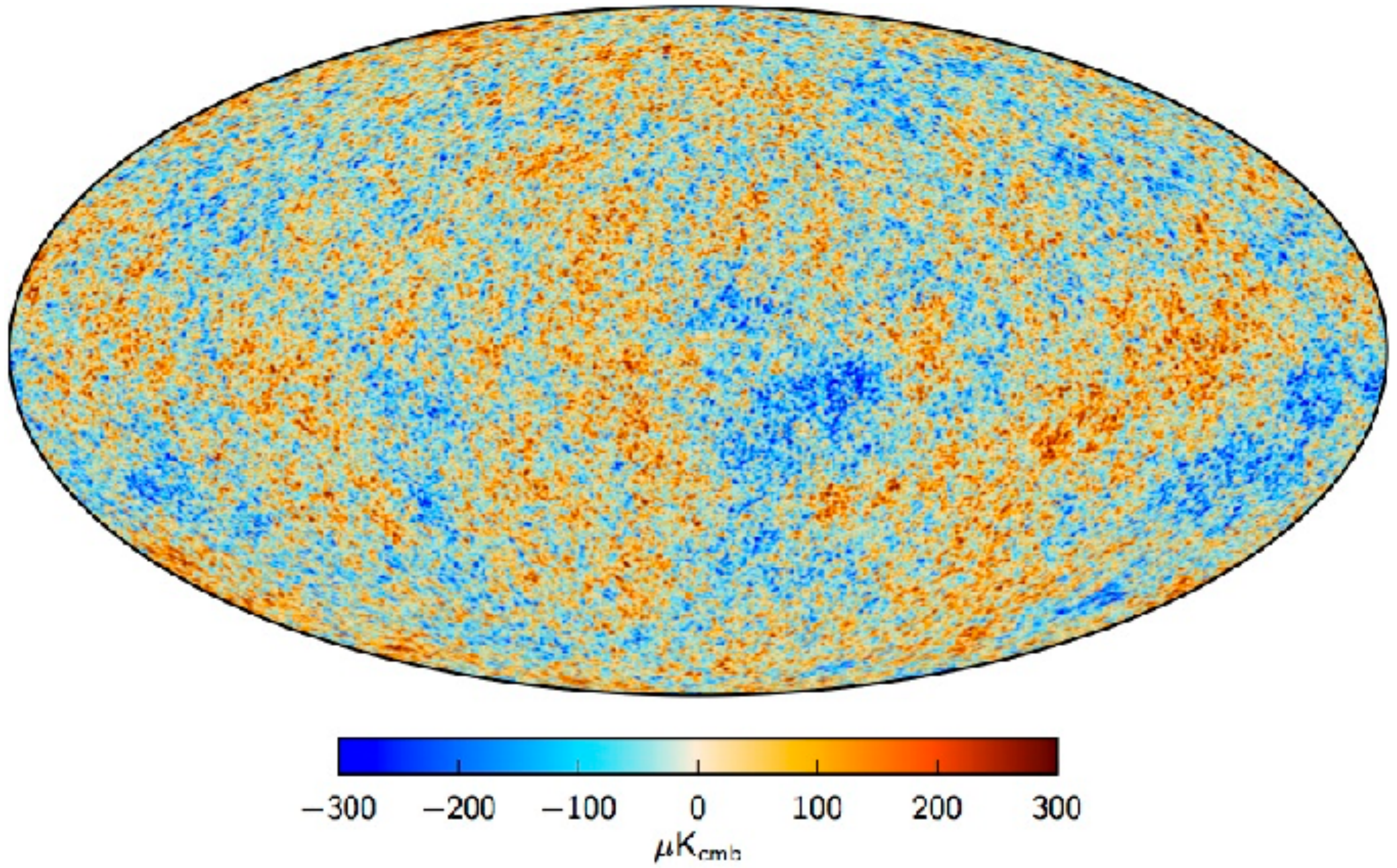
Euclid Flagship
Simulation

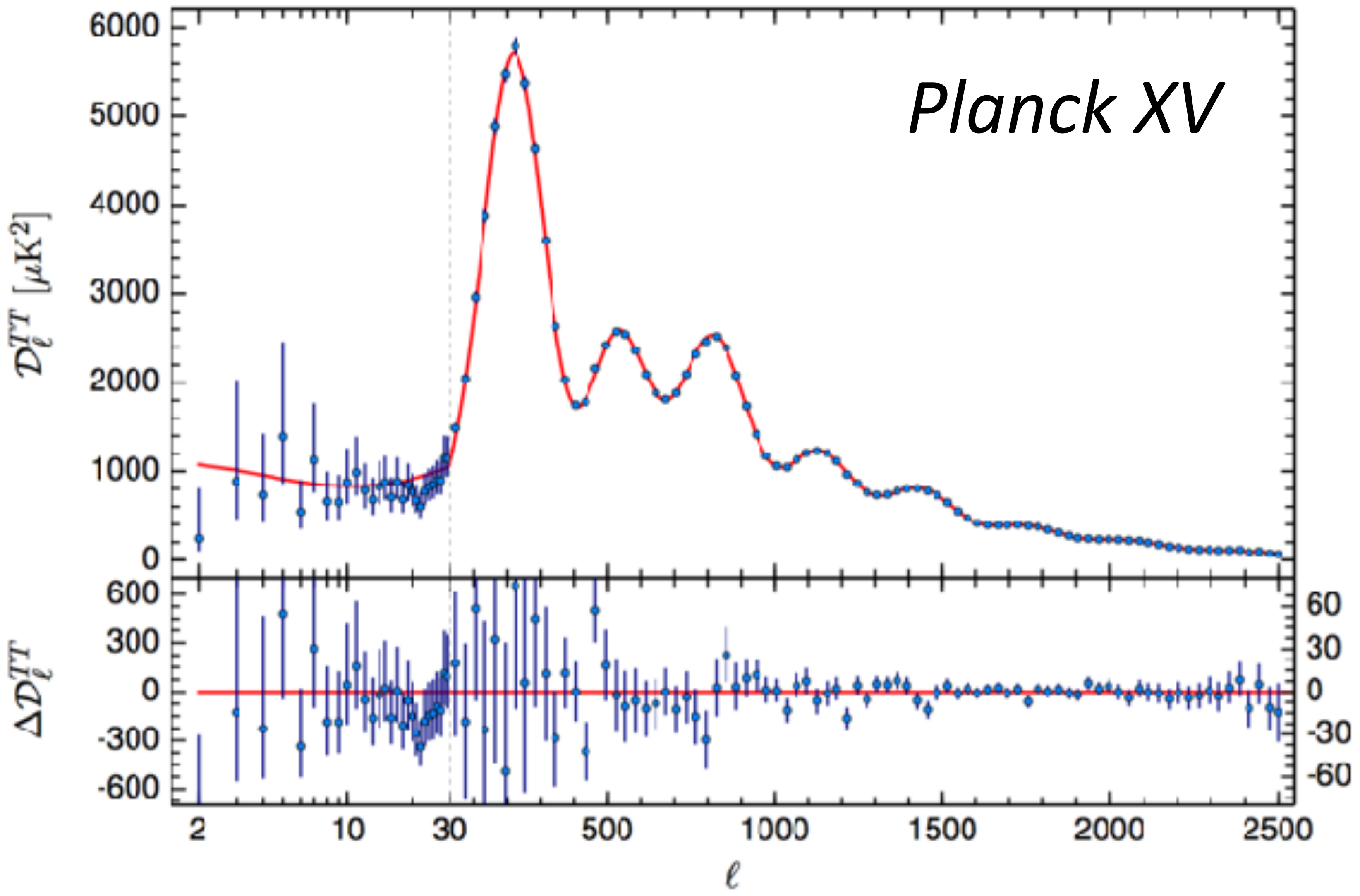
SISSA

- Dark Matter (DM) is the main ingredient at the core of the structure formation process, through **gravity.**
- It shapes the physical properties of **astrophysical objects** from small to large masses and influences the growth of **perturbations.**
- Both linear and non-linear **scales** could be used to infer fundamental properties of the DM.
- Different **redshift** regimes are typically addressed.
- Baryon physics?
- Non-linearities?



The standard ΛCDM model – I: CMB





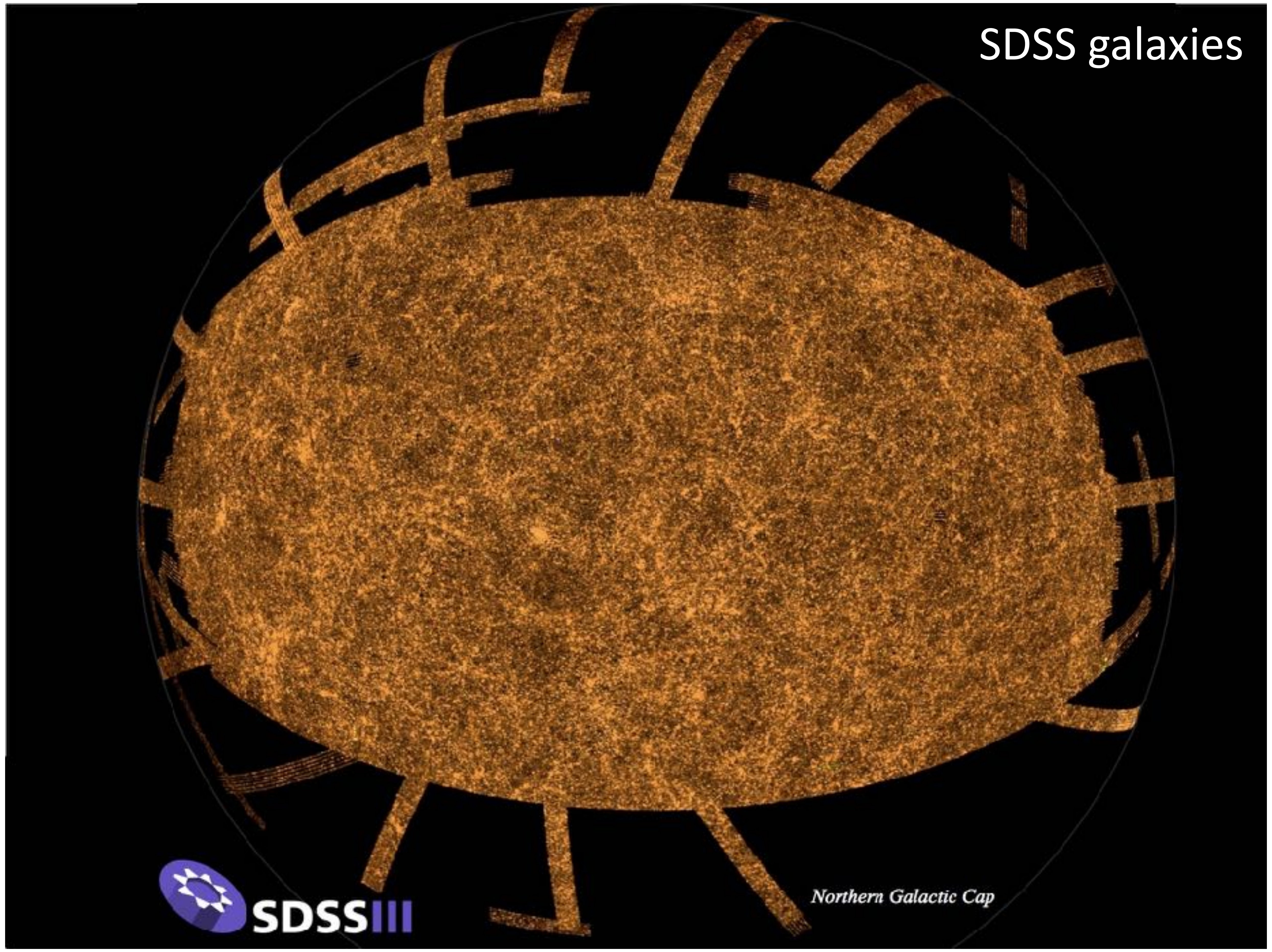
Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012

primary params.

derived params.

- Planck spectacular confirmation of a **6 parameter model.** FRWL metric + linear perturbations of hot plasma (Thomson scattering).
- Non baryonic and baryonic matter fluids required at 80 and 140σ.
- Rich structure full of information on (but not only!) our Universe at z~1100.
- WIMP models constrained from energy injection in the IGM, which modifies reionisation history.

The standard ΛCDM model - II: LSS



- Large Scale Structure (LSS) is a **tracer of the underlying matter** (cold? total?) density field.
- Different redshifts, scales, systematics compared to CMB.
- Most used: **galaxies** red. space distortions, weak lensing.
- Difficulties: **physics not linear** any more. Galaxies are a biased tracer.
- Note: *modelling galaxies as points is* *<u>pointless</u>*.

$$\delta_{\rm tracer} = F(\mathbf{x}, z, environment?\,, physics?\,, luminosity?\, etc.) \times \delta_{CDM}$$

The standard ΛCDM model - III: Mass Functions (and beyond)

Simplest theory to quantitatively address hierarchical structure formation is offered by the *Press-Schechter formalism* –> to use this on real data need to understand **galaxy/DM halo connection**

Filtering of P(k)

$$\sigma^2(R) = \frac{1}{2\pi^2}\int_0^\infty k^3 P(k)\tilde{W}^2(kR)\frac{\mathrm{d}k}{k}$$

Key physical quantity

$$\nu \equiv \delta_c/[D(z)\sigma(M)]$$

Universal Mass Function for DM haloes

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

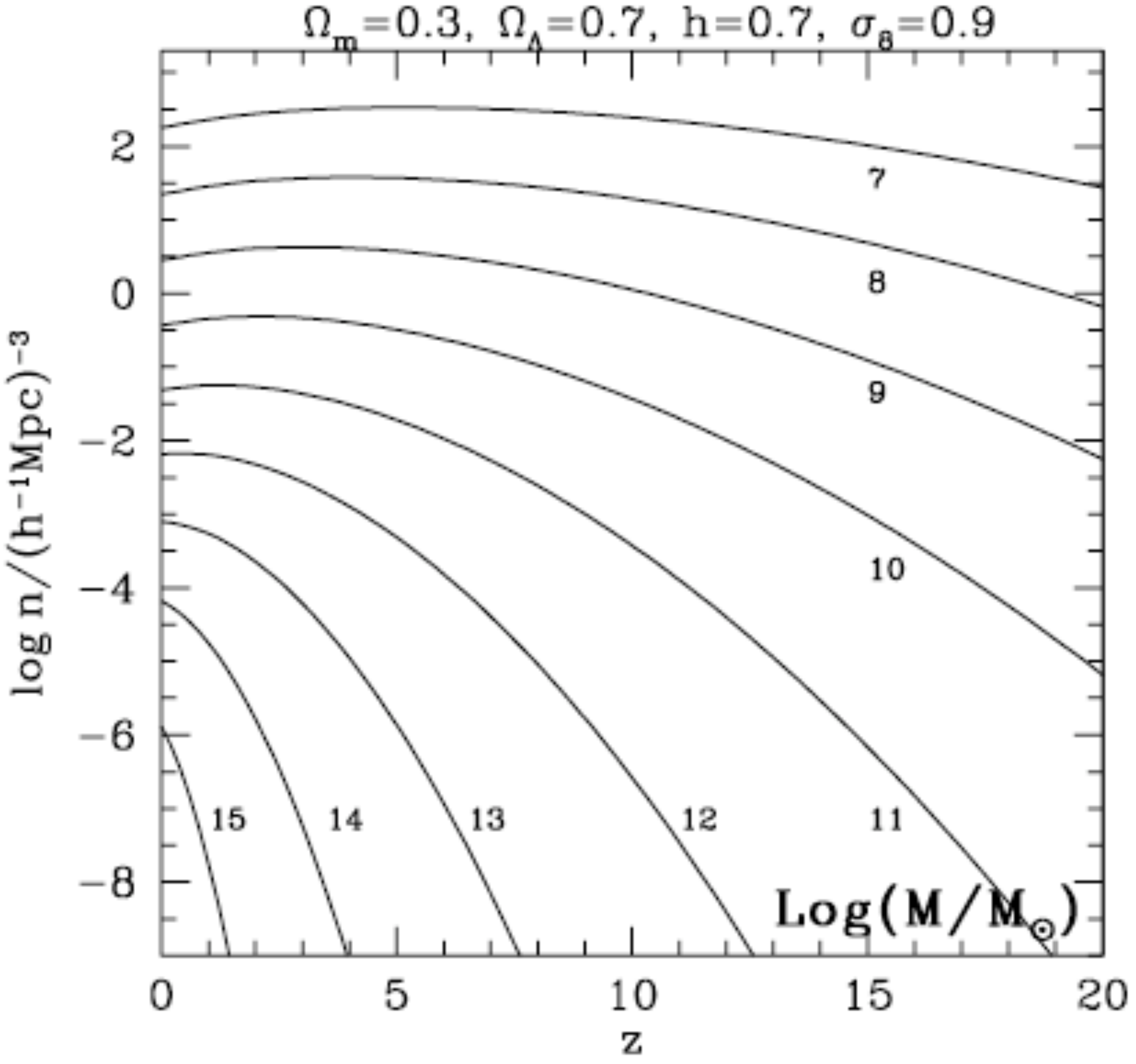
DM halo bias

$$b(M,z) = 1 + \frac{\nu^2(M,z)-1}{\delta_c}$$

DM correlation Function

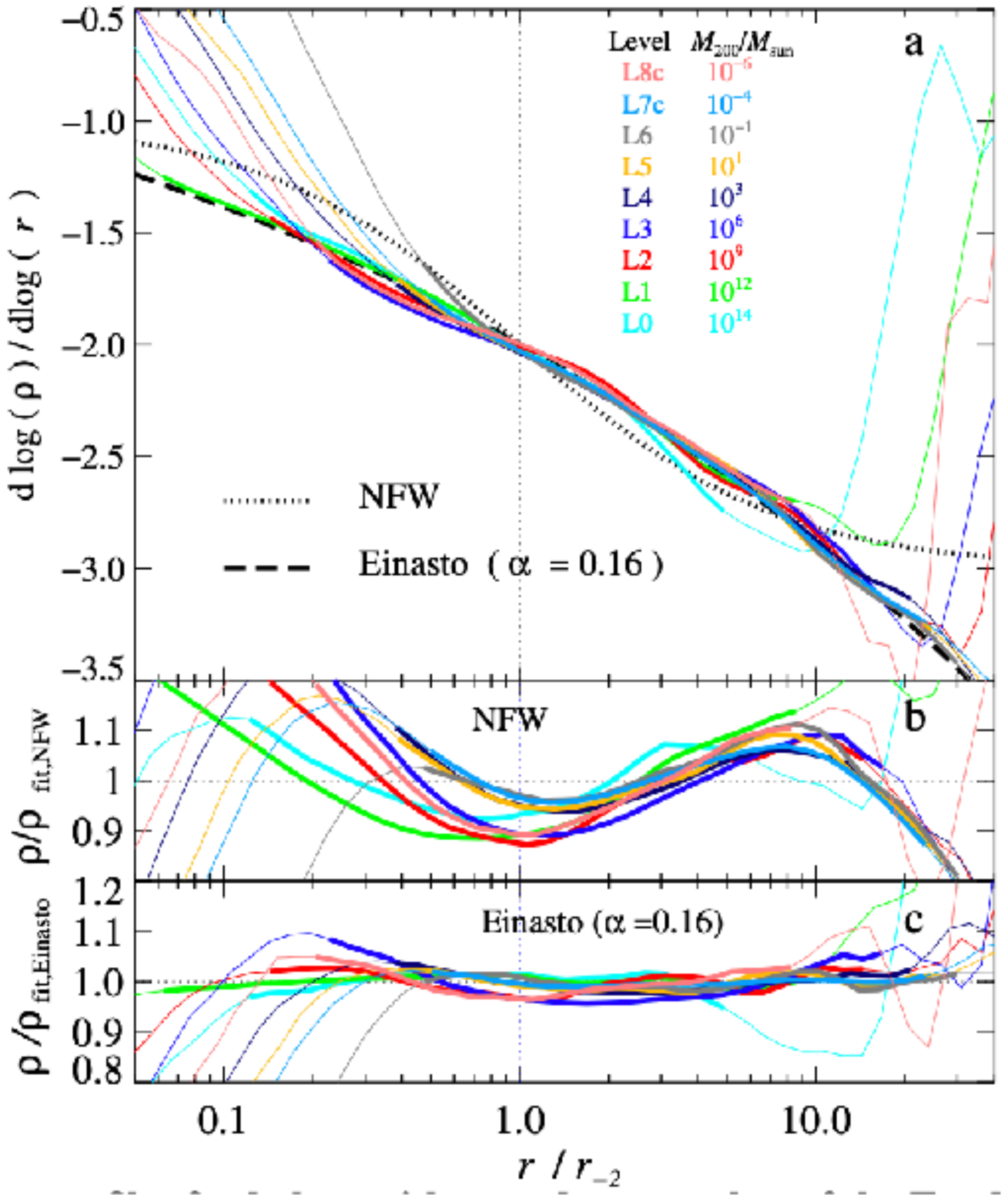
$$\xi_{\rm hh}(r,z) = b^2(M,z)\xi_{\rm mm}(r,z)$$

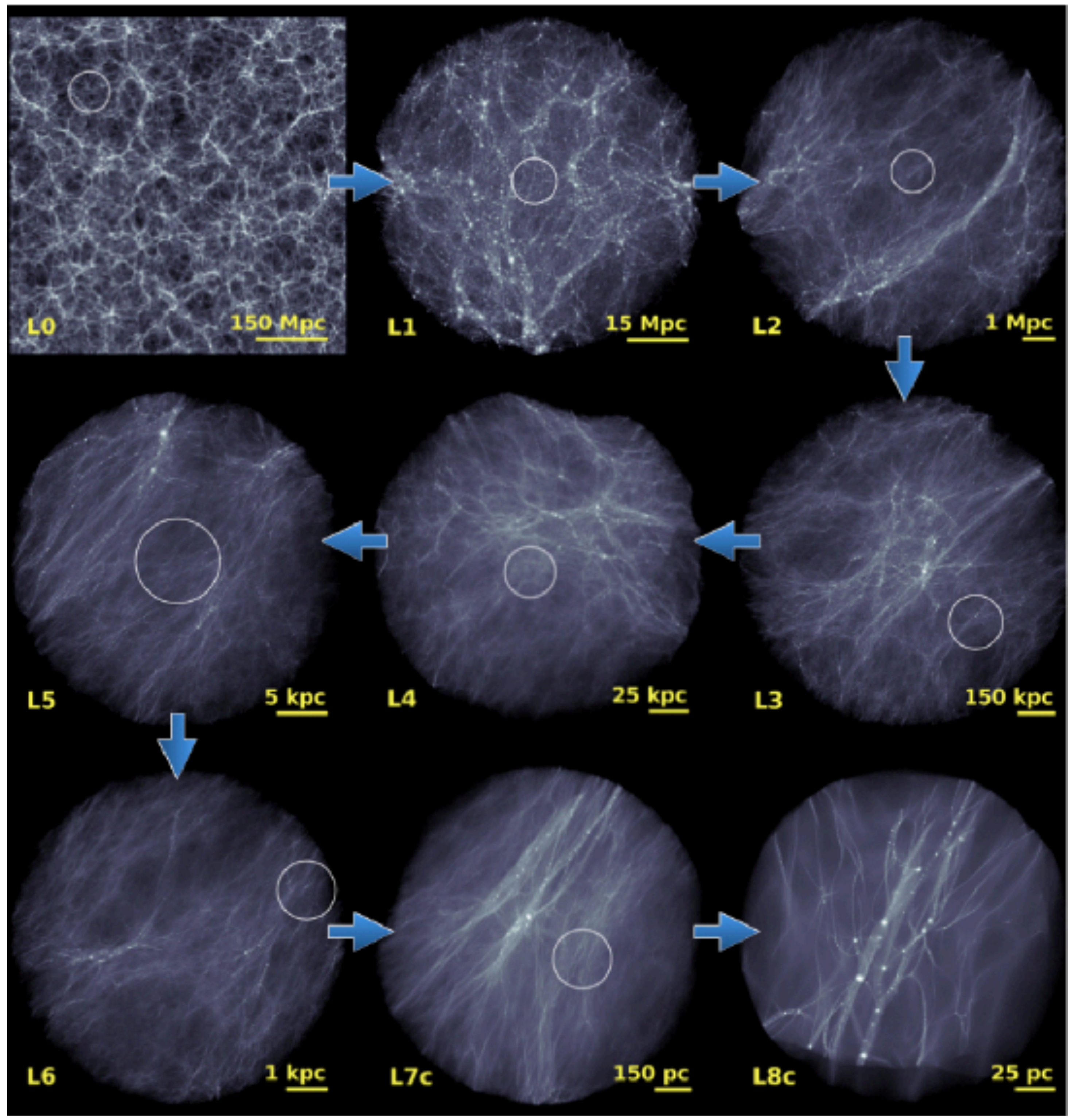
Mo & White 2002



The standard ΛCDM model – V: Non–linearities

- Smooth background NFW (cusped) halo.
- Bound subhaloes with total mass <10% of the host, most massive ~1%, less centrally concentrated than smooth component.
- Tidal (due to tidal stripping) and fundamental streams (due to cold initial conditions).





Wang+20

MeV Dark Matter

keV Dark Matter

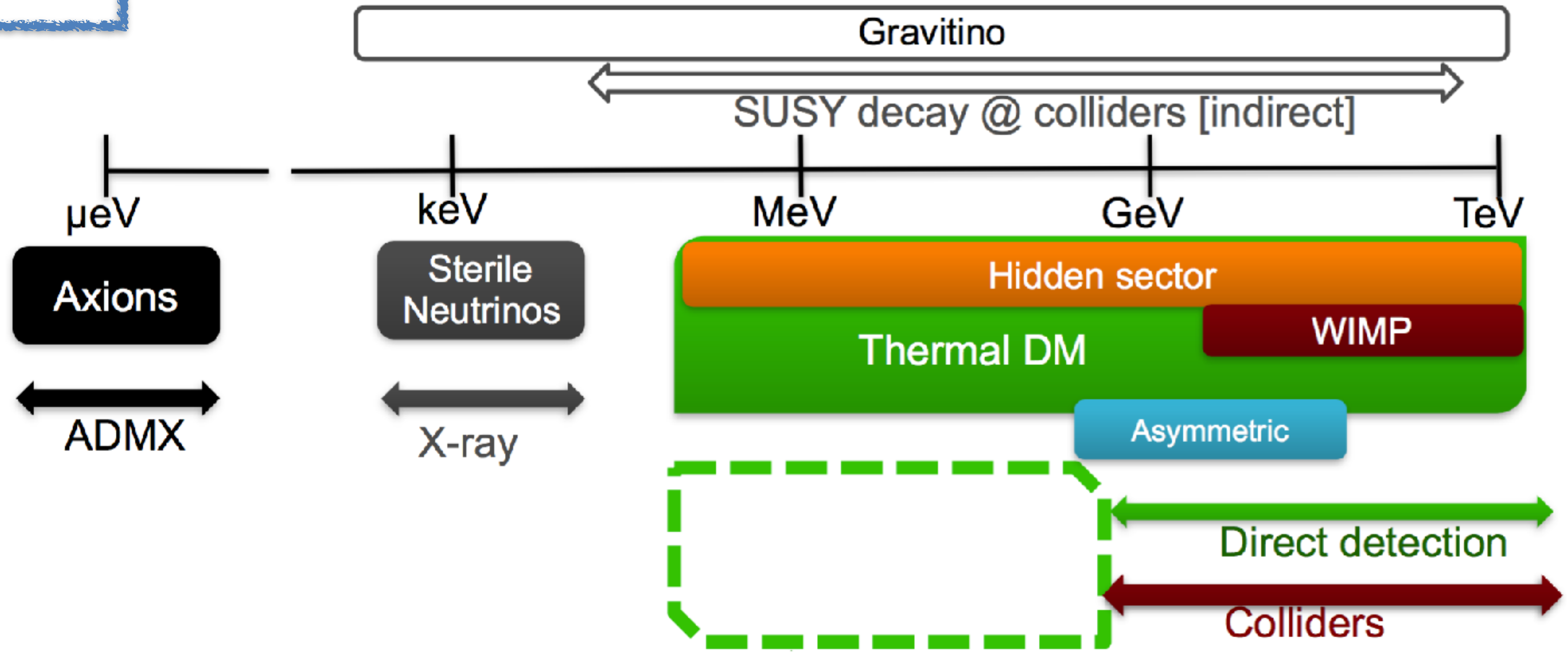
Axions

Primordial BHs

… no stone left unturned

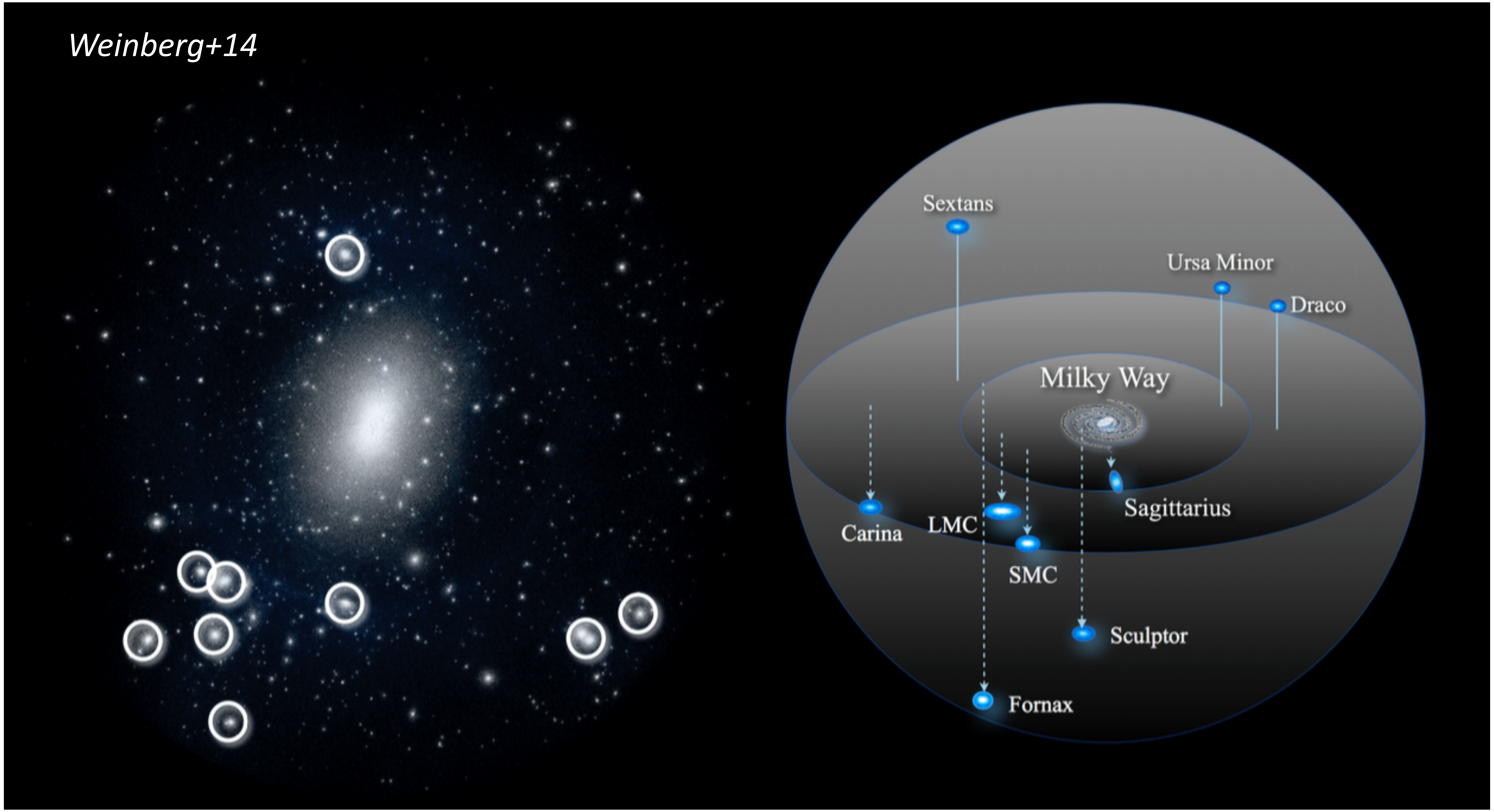
DM as a particle

Loose bounds on dark matter mass an properties e.g.
if fermions Tremaine&Gunn bound > 35 eV
if self-interacting $\sigma/m < 1.25\ cm^2/gr$



Note that in principle there could be WIMPS that behave like warm dark matter: WIMPS generated in non-thermal scenarios (Lin+01) or two WIMPS one-stable and one long-lived and coupled to photons (Profumo+05)

Small scales controversies?



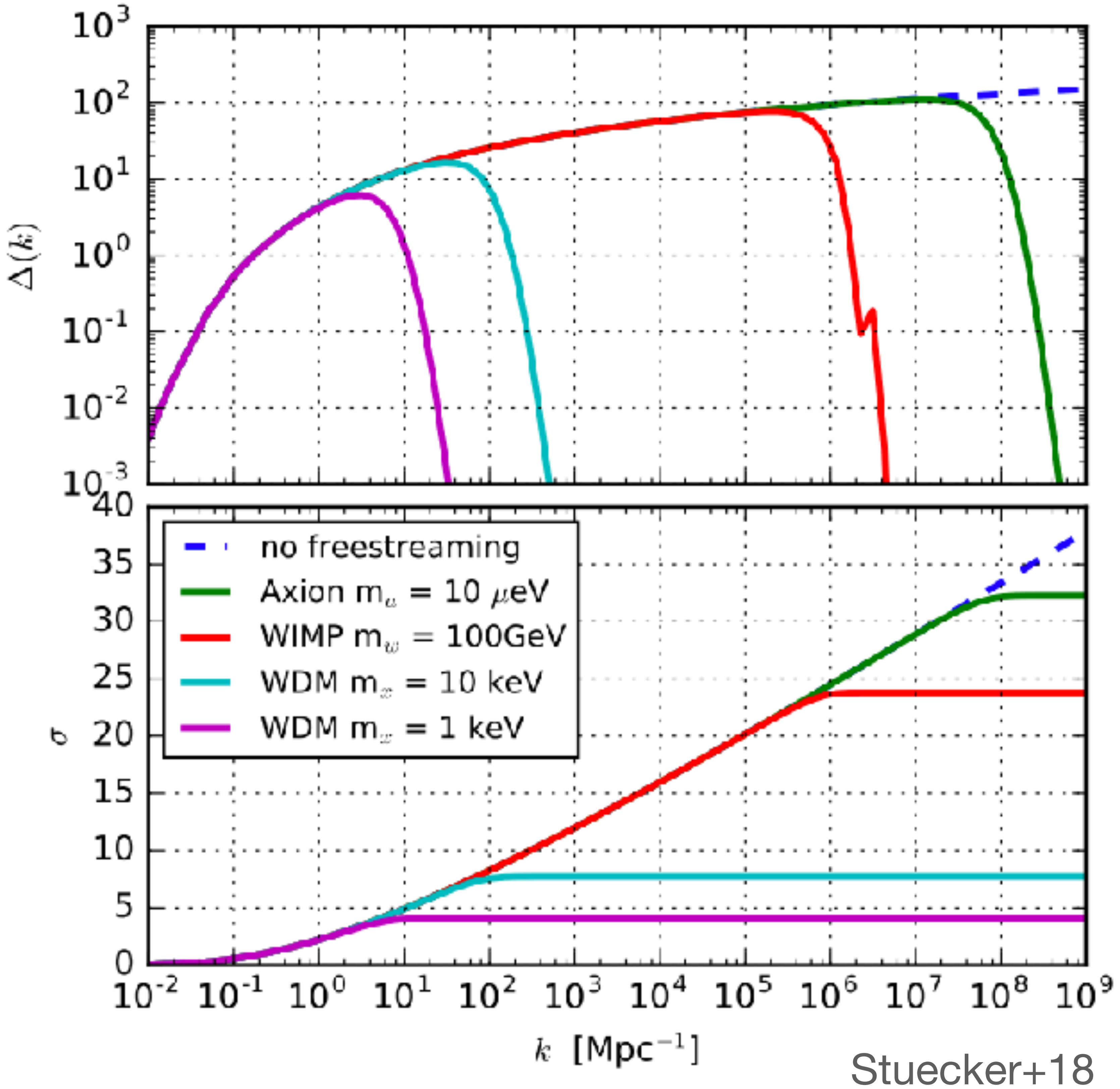
1) Too big to fail problem
2) Missing satellite problem
3) Cusp-core problem
4) Amplitude of power spectrum too low?

Note that baryonic physics (e.g. galactic feedback) could also solve the tension. Contrived to have DM perfectly mimicking baryons (different z-evolution?)

non-CDM at small scales: Power Spectrum

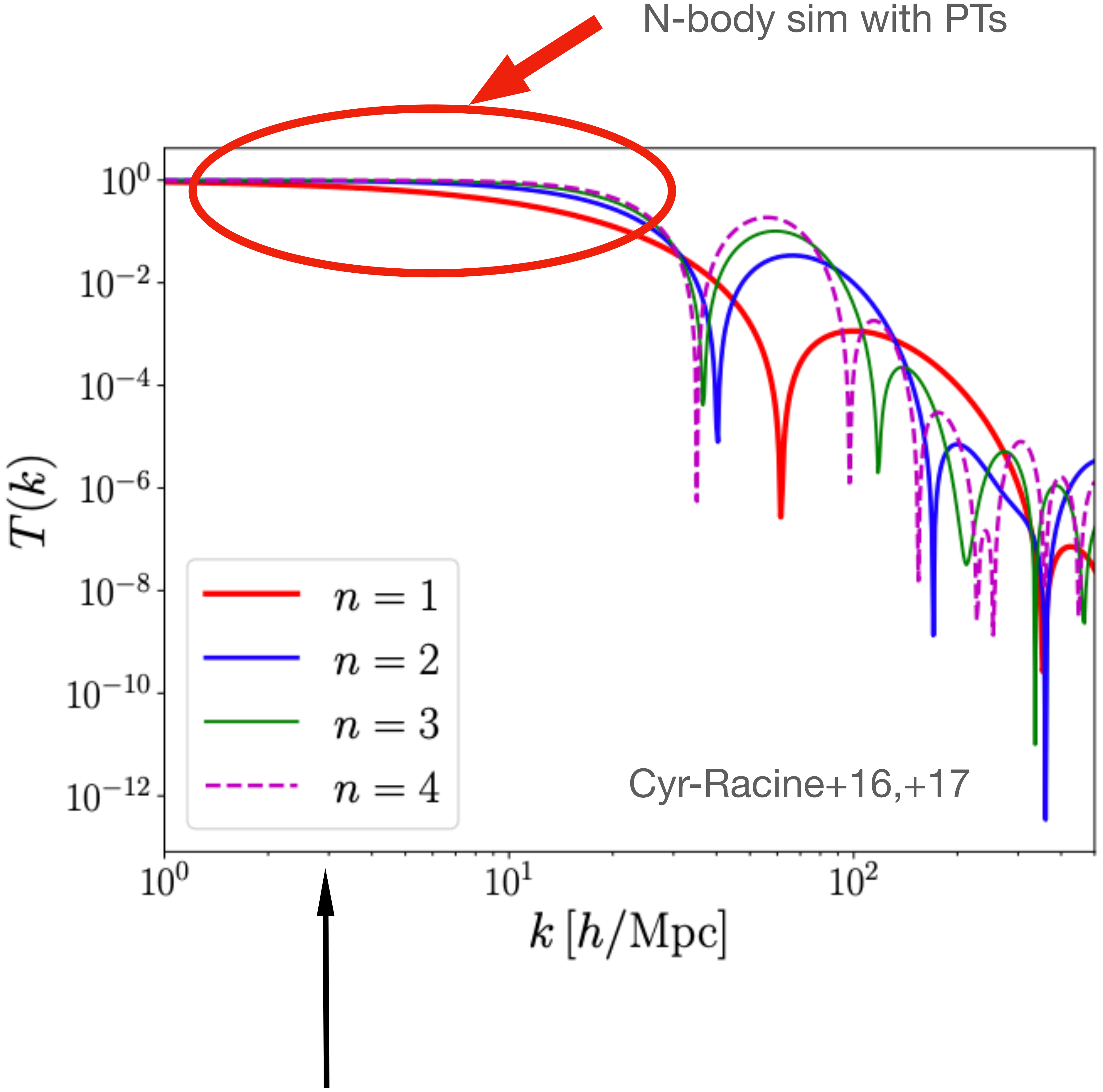
- Cut-off in the linear power spectrum at small scales due to DM physics: non-zero thermal velocities, coupling with dark radiation, charged scalar dark matter, dark matter self-interactions, etc.

Dvorkin+13
Cyr-Racine+16 [ETHOS]



Stuecker+18

Mildly non-linear regime
also potentially interesting
and could be addressed without
N-body sim with PTs

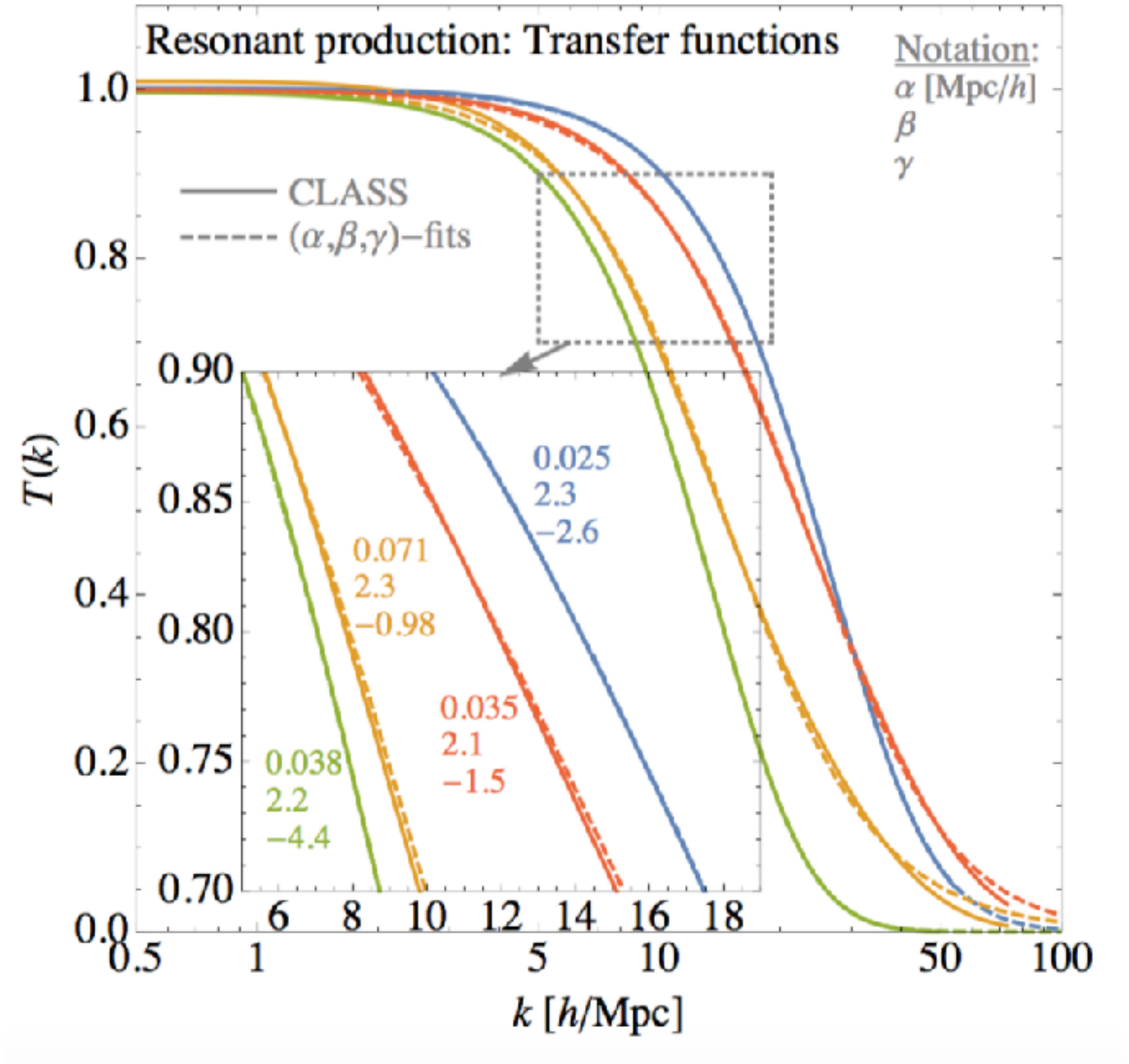


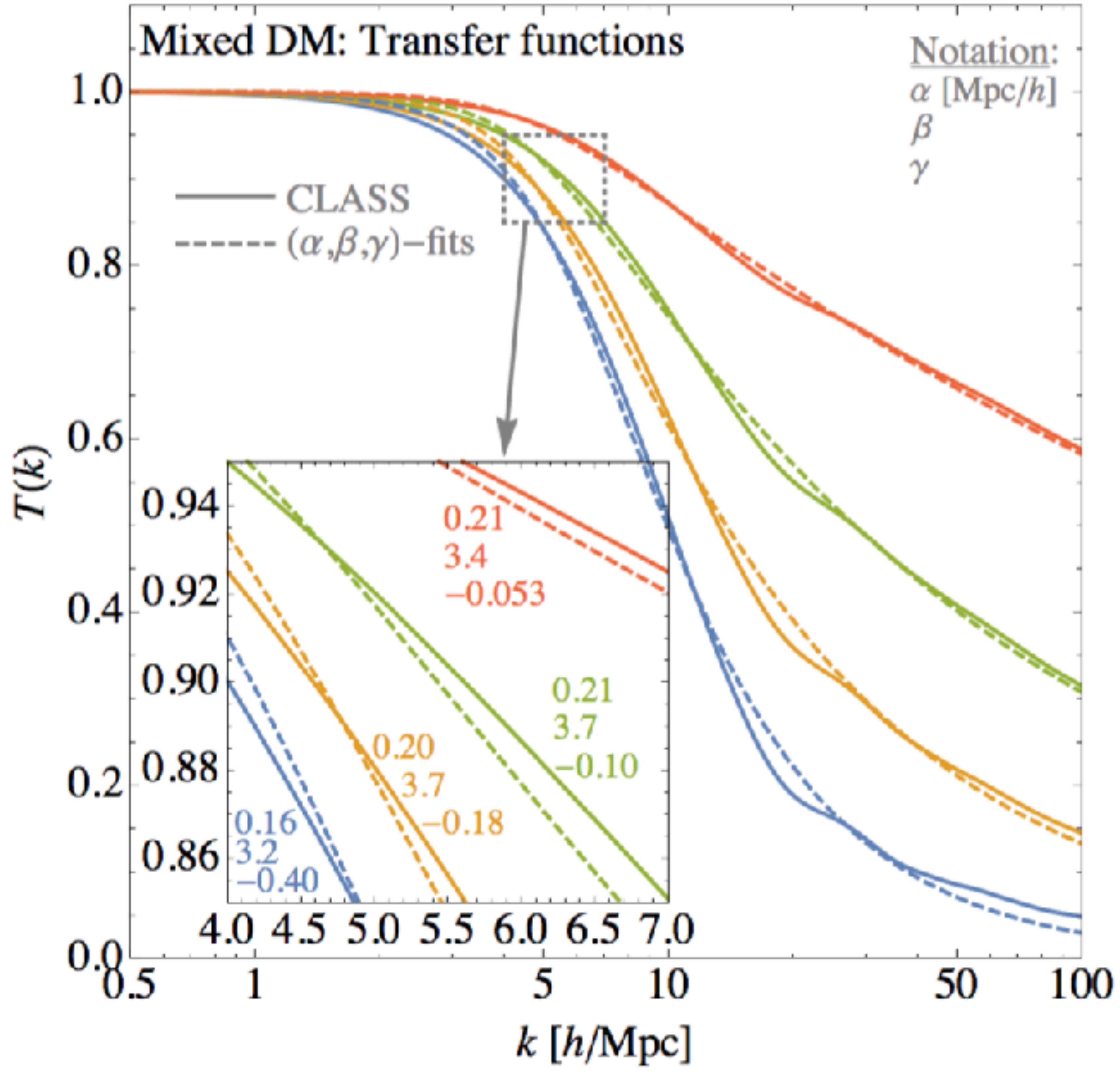
Cyr-Racine+16,+17

DM drag opacity

non-CDM at small scales: Power Spectrum - II

Murgia, Merle, Viel, Totzauer, Schneider 2017





Full CLASS Boltzmann calculation compared
to phenomenological formula

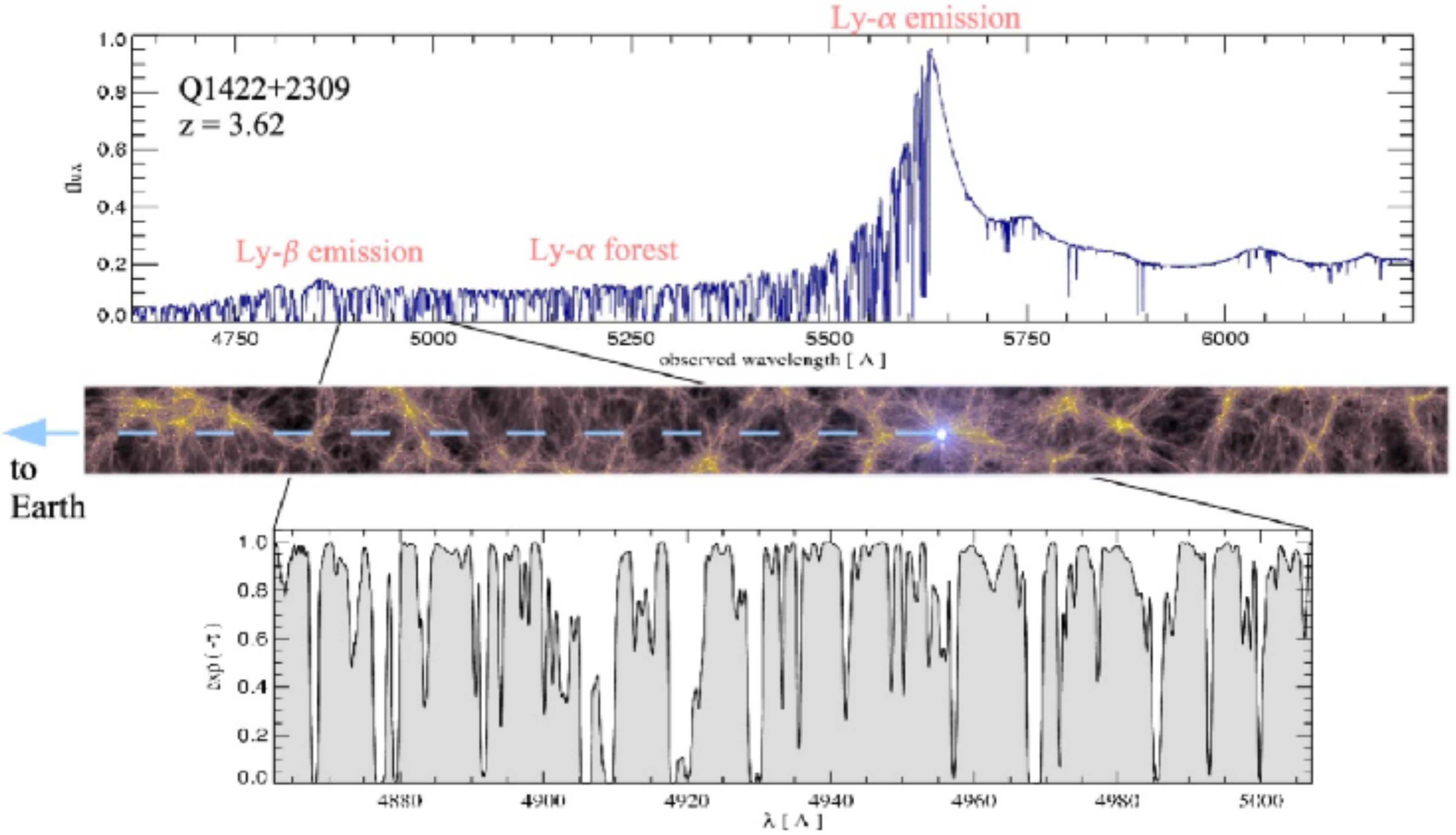
Standard approach $T(k) = [1+(\alpha k)^{2\nu}]^{-5/\nu}$ ⇒ **New general approach** $T(k) = [1+(\alpha k)^{\beta}]^{\gamma}$

Simple parametrization proposed works well for:

- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixed models
- fuzzy dark matter
- ETHOS models

Warm Dark Matter Constraints from the Intergalactic Medium

Viel+05,08,13 - Irsic, MV+16,+17

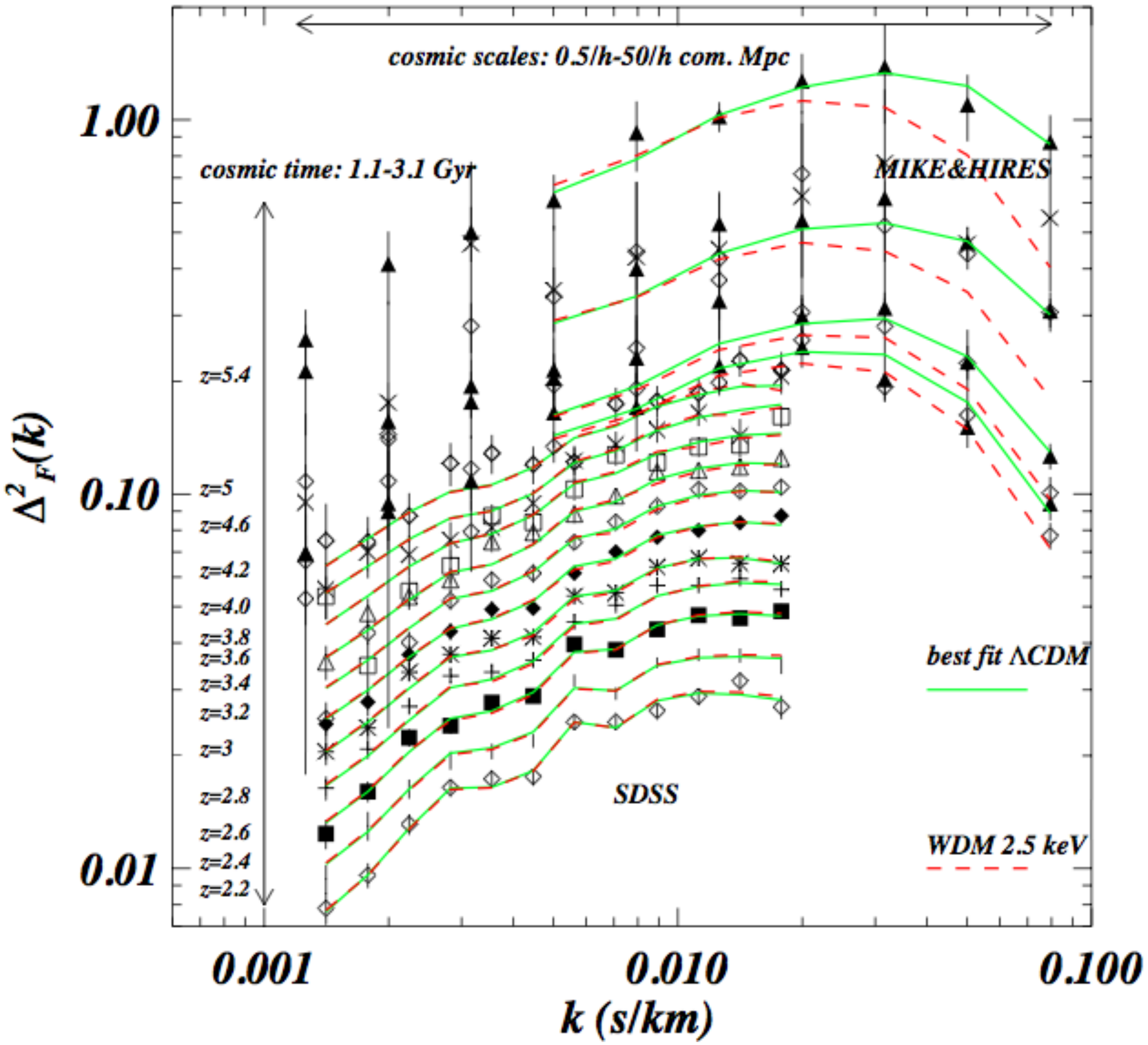


$$P_{3D,\mathrm{dark\,matter}} \rightarrow P_{1D,\mathrm{Ly}\alpha\,\mathrm{flux}}$$

- **Intergalactic medium:** filaments at low density (outside galaxies) - distances spanned 0.1-100 Mpc/h
- Lyman-alpha forest its the main manifestation of the IGM
- High redshift observable, 1D projected power
- Tight constraints on:
  - *thermal warm dark matter*
  - *sterile neutrinos*
  - *ultralight boson dark matter*
- **Results:** masses typically advocated to solve the small scale crisis are at odds with Lyman-alpha forest. Impact on structure formation not distinguishable from LCDM. **Cosmic web is cold.**
- Mixed C+W Dark matter?
  Redshift dependence?
  Note: *other astro signatures*

Warm Dark Matter Constraints from the Intergalactic Medium – II

$M_{\text{thermal WDM}} > 3.5\ \text{keV}\ (2\sigma\ \text{C.L.})$



This lower limit is derived under some assumptions:

- Bayesian analysis with LCDM ref model
- Resolution corrections
- Still somewhat partial covering of Reionization models

however…

Impressive quantitative test of structure formation ***before*** *galaxy form!!!*

DM-Dark Radiation interactions from the Intergalactic Medium

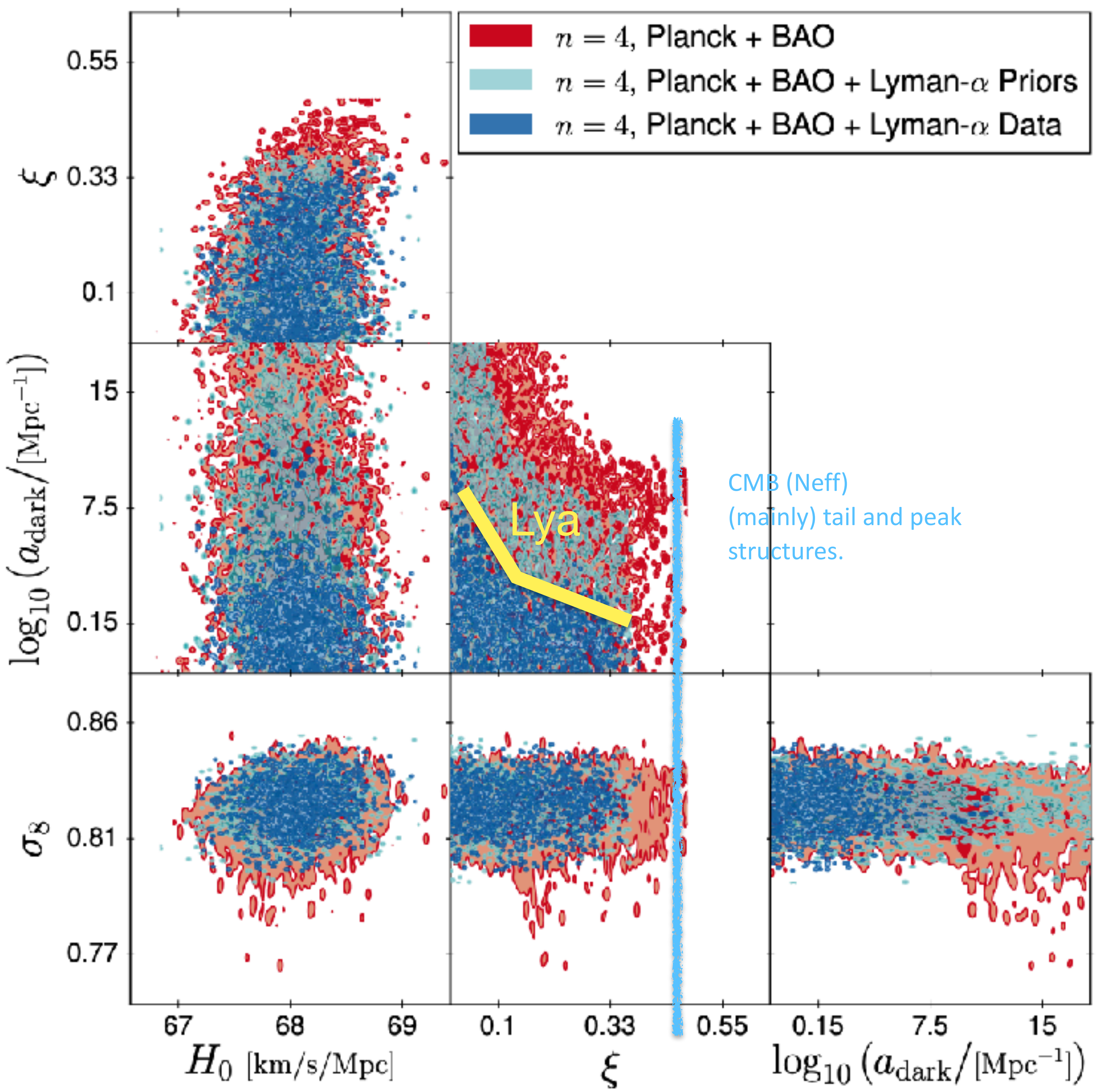
$$\Gamma_{\mathrm{DR-DM}} \propto a_{\mathrm{dark}} T^n$$

$$\xi = T_{\mathrm{DR}}/T_\gamma$$

- Multi-observable approach
- N-body sims designed to explore the parameter space
- Novel likelihood methods that exploit the small scale features in the power spectrum

Archidiacono+19

Interaction Strength



Lya

CMB (Neff)
(mainly) tail and peak
structures.

Amount of DR

Final bounds on physical parameters:

$$\Delta N_{\mathrm{eff}} < 0.23$$

$$a_{\mathrm{dark}}\xi^4 < 30\,\mathrm{Mpc}^{-1}$$

Scalar Dark Matter

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

KG and Einstein equations

$$T^{\phi}_{\mu\nu} = g_{\mu\nu}\left(-\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - \frac{1}{2}m^2\phi^2\right) + \partial_\mu\phi\partial_\nu\phi.$$

Energy momentum tensor
for the scalar field

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)d\boldsymbol{x}^2$$

Metric

$$\phi = \frac{1}{\sqrt{2m}}\left(\varphi e^{-imt} + \varphi^* e^{imt}\right)$$

Oscillating field

$$i\left(\dot{\varphi} + \frac{3}{2}H\varphi\right) = -\frac{\partial^2\varphi}{2a^2 m} + m\Phi\varphi;$$

Dropping higher order and averaging
over one oscillating period:
Schrodinger type eq.

$$\rho_\phi \equiv m\varphi\varphi^*, \quad v_i \equiv \frac{\partial_i\{\arg(\varphi)\}}{am} = -\frac{i}{2am}\left(\frac{\partial_i\varphi}{\varphi} - \frac{\partial_i\varphi^*}{\varphi^*}\right)$$

Defining density and velocities
of the fluid

$$\dot{v}_i + Hv_i + \frac{v_j\partial_j v_i}{a} = -\frac{\partial_i\Phi}{a} + \boxed{\frac{1}{2a^3m^2}\partial_i\left(\frac{\partial^2\sqrt{\rho_\phi}}{\sqrt{\rho_\phi}}\right)}$$

Euler eq. NOTE the pressure term

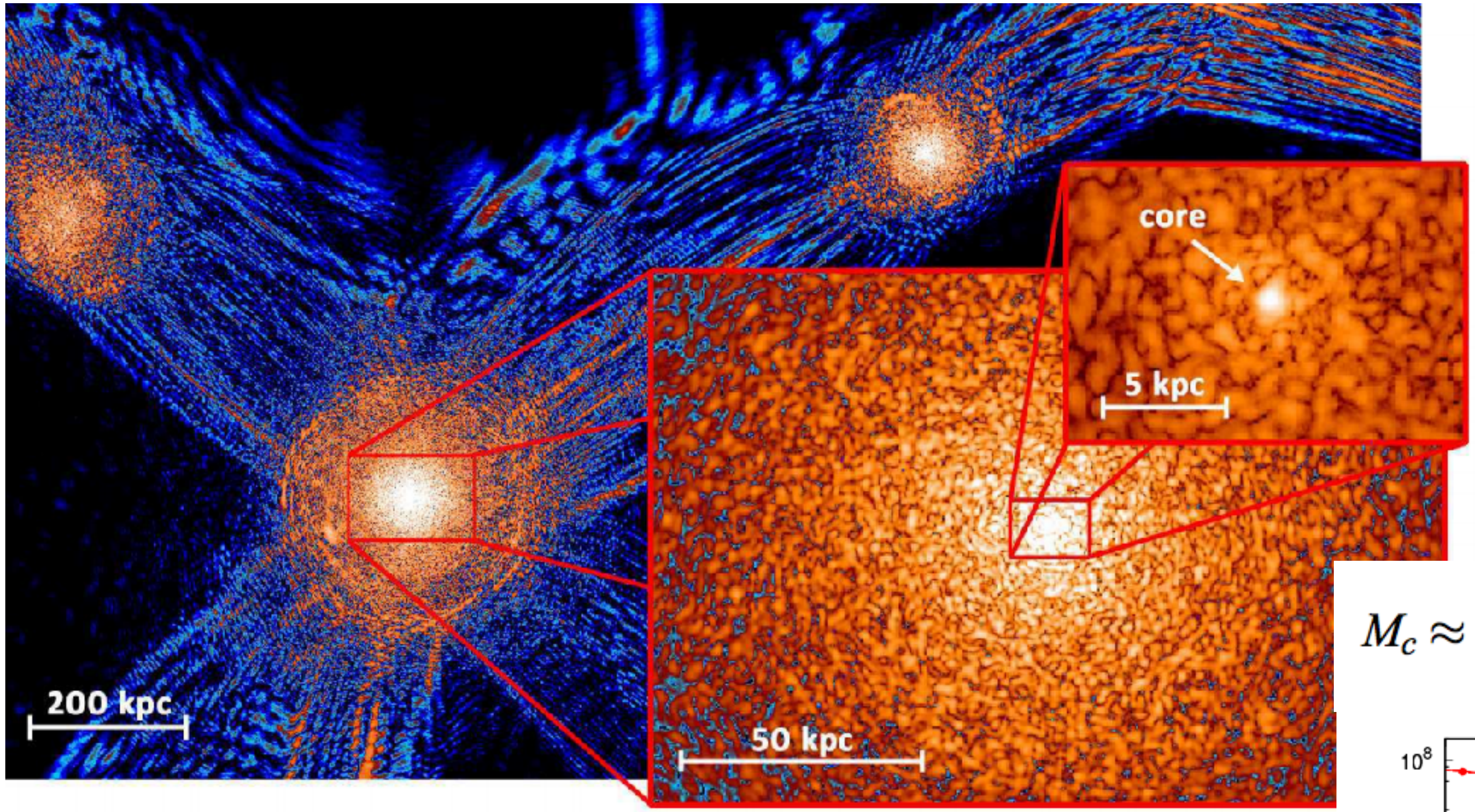
$$\dot{\rho}_\phi + 3H\rho_\phi + \frac{\partial_i(\rho_\phi v_i)}{a} = 0.$$

Continuity

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15, Nori&Baldi 18

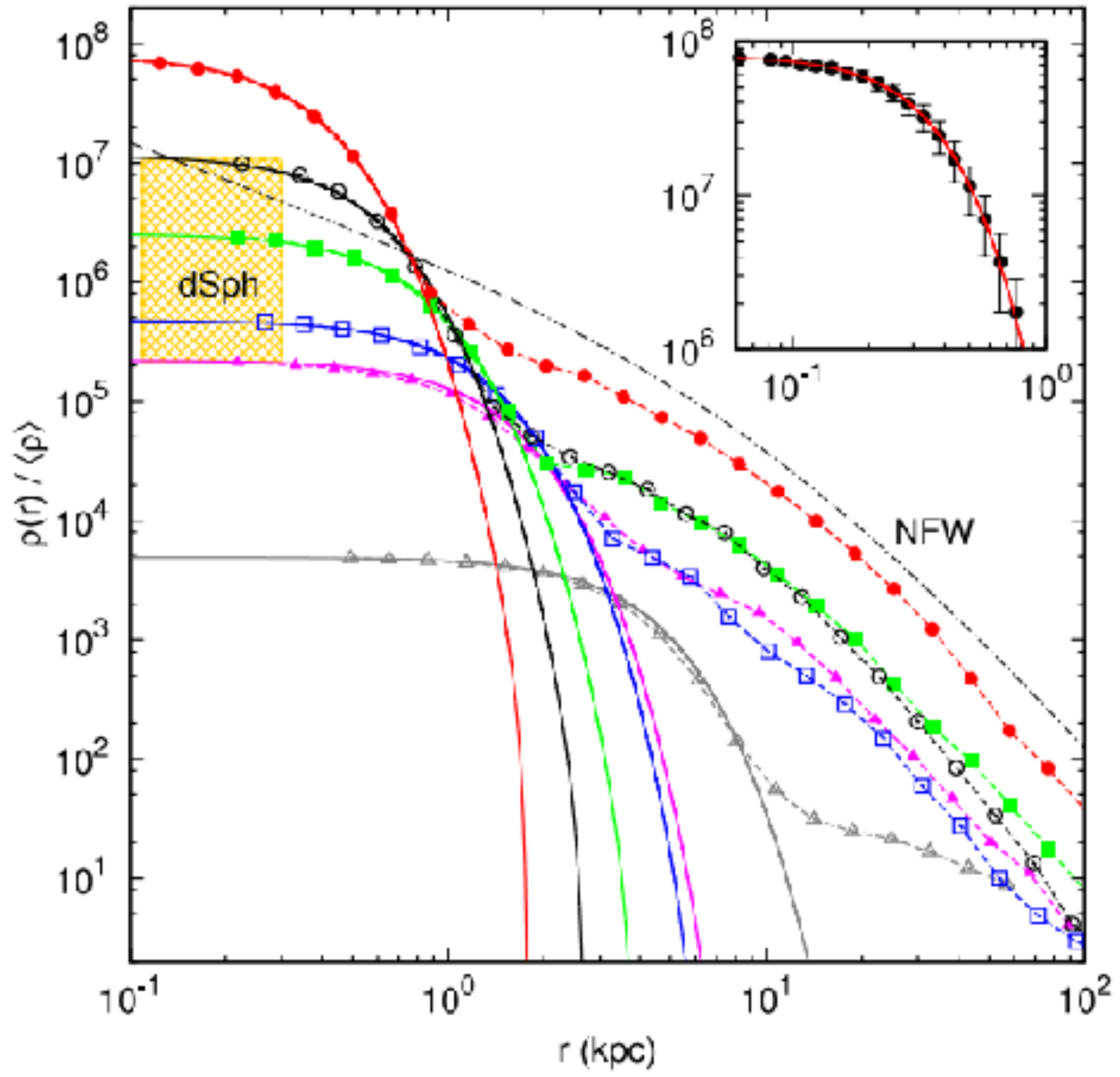
Scalar Dark Matter – II

Schive+ 14



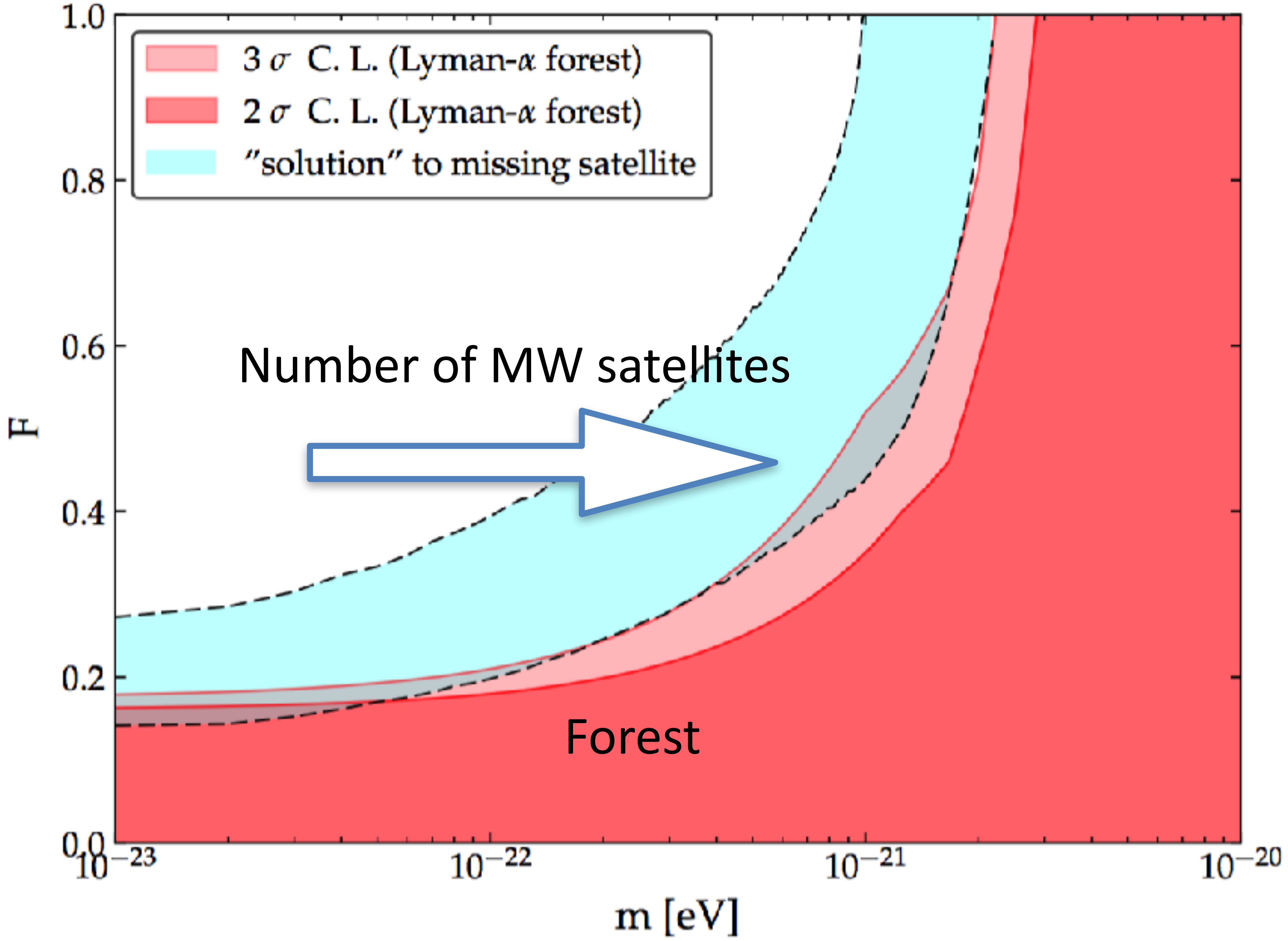
- Very **distintictive prediction: solitonic core** (steep jump in density) with a simple numerical solution (e.g. Mocz+17, Schive+17, Marsh+15).
- Stability of the core over cosmological times still an open issue.
- Size of the core $M_{core} \sim M_{galaxy}^{1/3}$.
- Claimed detection at 10^{-22} eV from Phornax.
- Searched in galaxies but not seen, however baryon might be an issue (Blum+17,+19).

$$M_c \approx \frac{5.5\times10^9}{(m_B/10^{-23}\ \mathrm{eV})^2(\mathrm{r_c}/\mathrm{kpc})} M_\odot$$



Scalar Dark Matter as a fluid contributing to a fraction of Dark Matter

Kobayashi, Murgia+17
Murgia+18



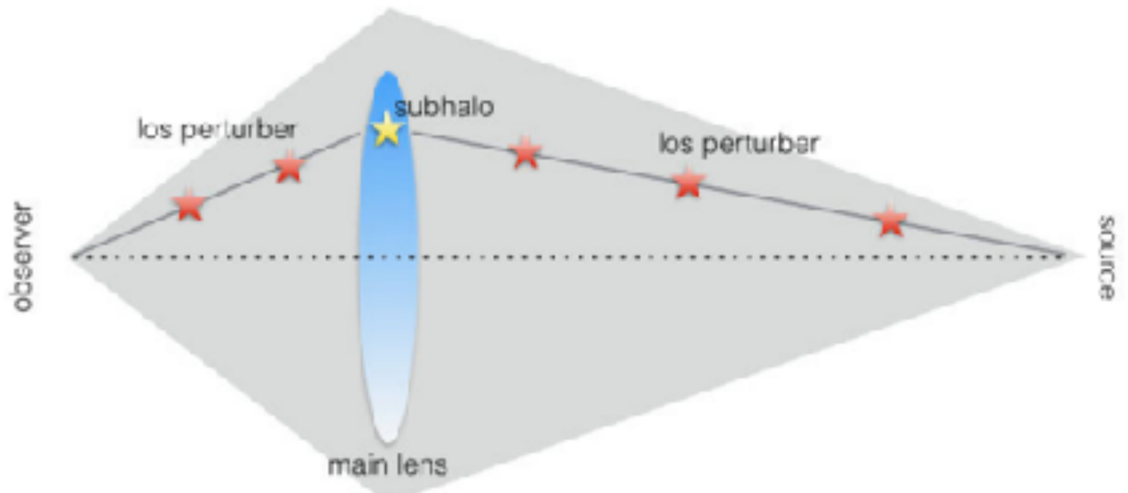
- Use of the mass function to reproduce a number of satellites in the range [20,60] for a MW halo in agreement with observations

- Linear P(k) only input for obtaining both these constraints

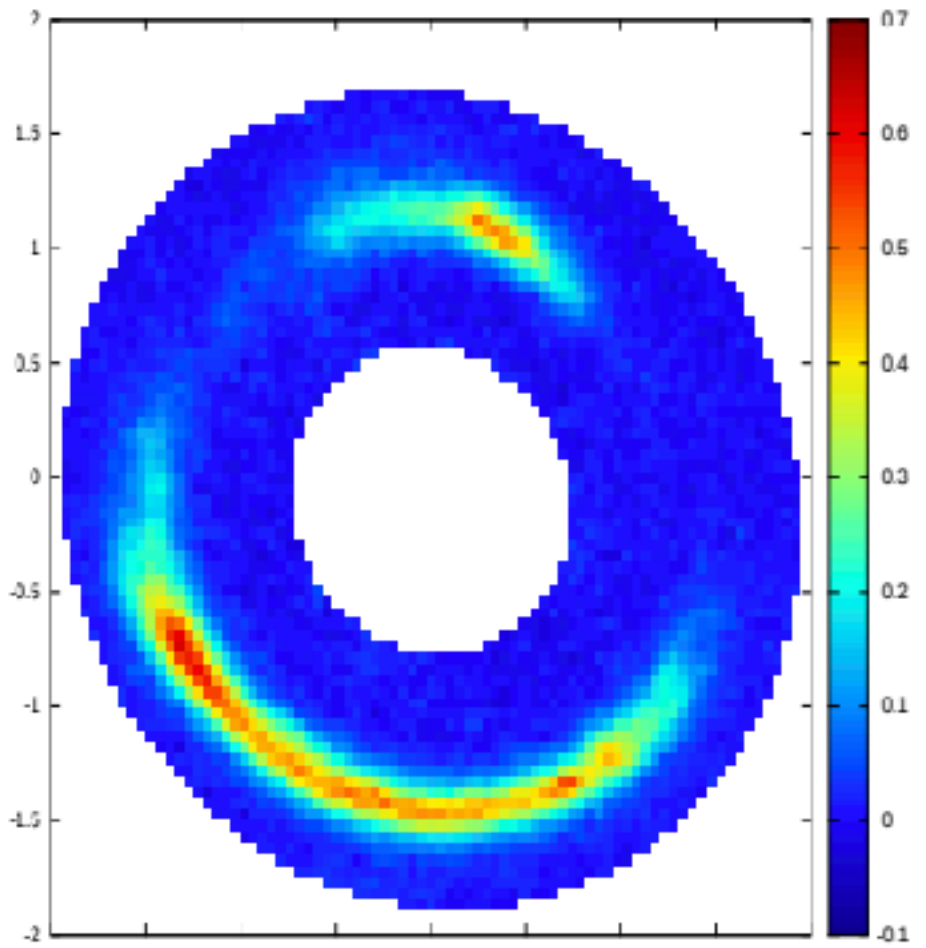
- Little room to solve the small scale crisis unless F~0.2 and mass 1.e-23,1.e-22

Perturbers in strong lensing systems

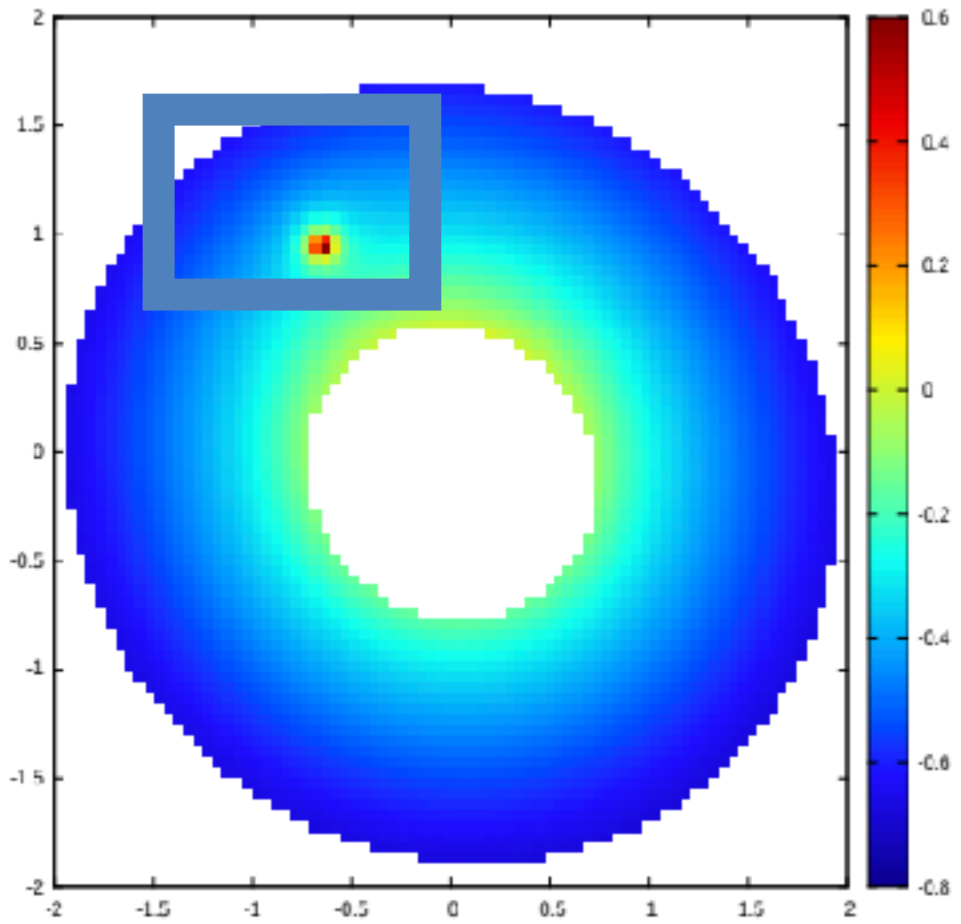
Dark and highly concentrated sub halo discovered Gravitational lens system SDSSJ0946+006 [Vegetti+10,+12] - see also Ostdiek+21



Minor+2021



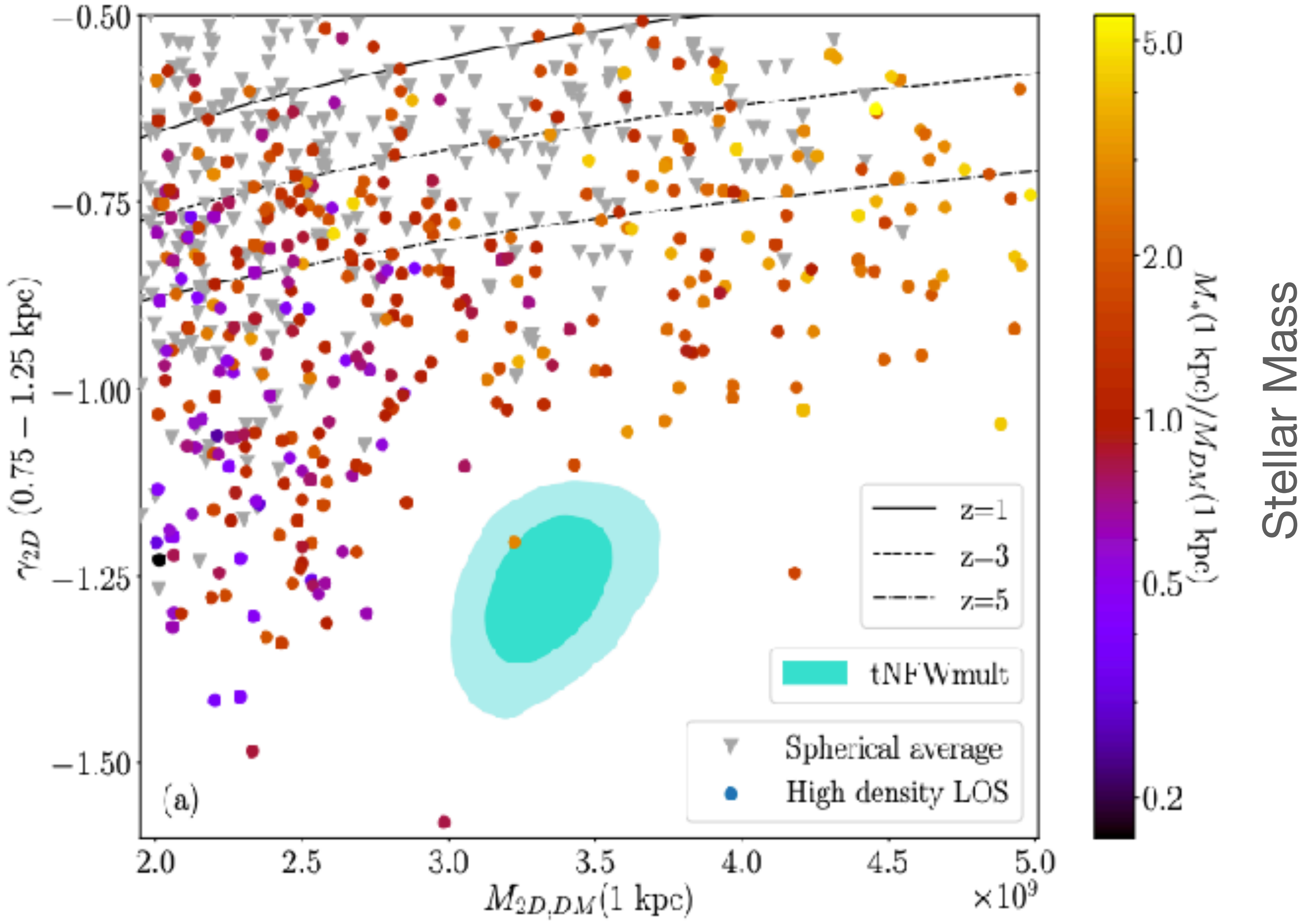
(a) masked HST image



(a) tNFW model

Minor+2021

Density slope



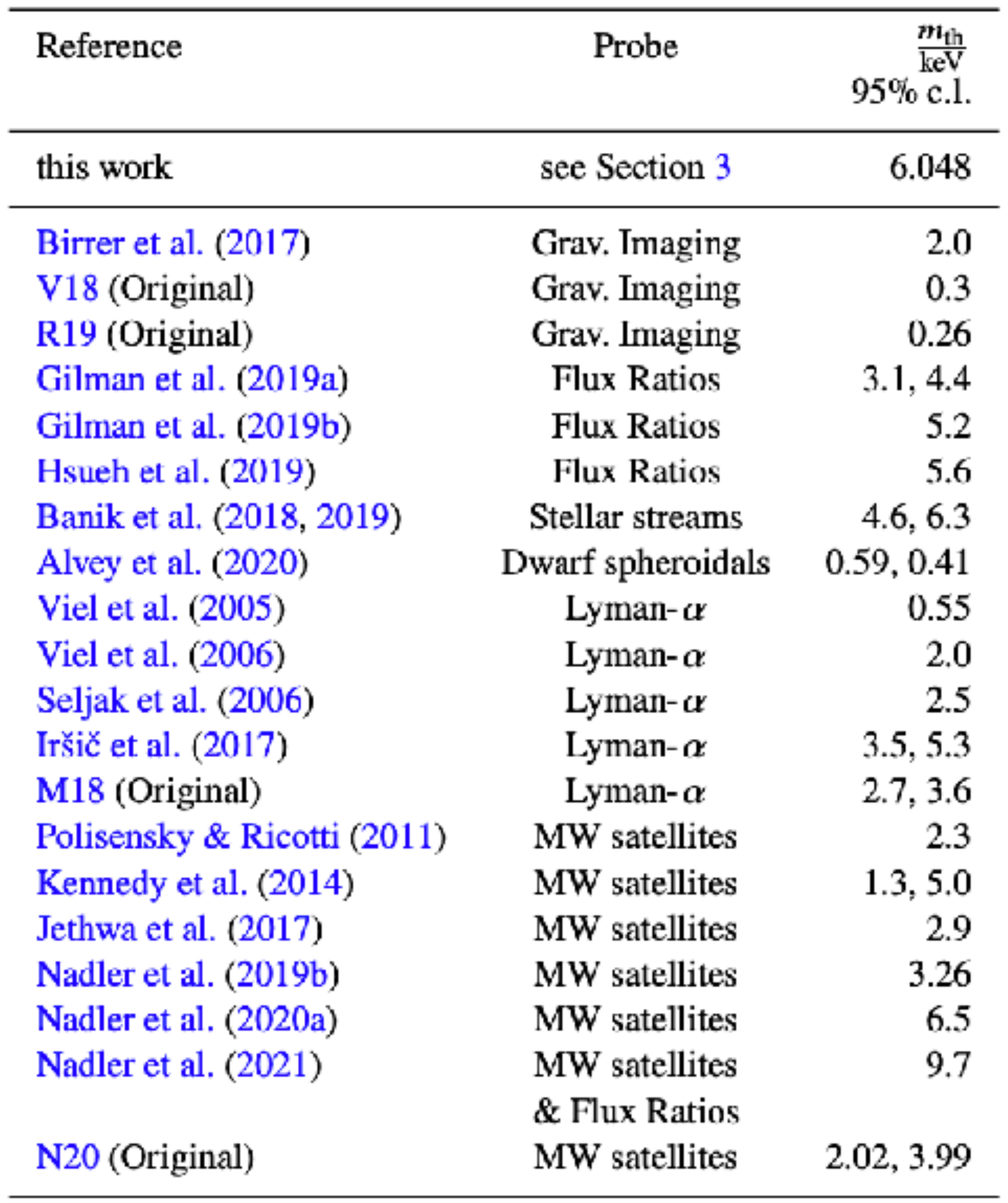
2D mass

A dark, highly concentrated subhalo unexpected in a ΛCDM universe, even when baryons are considered.
Note: *even more unlikely in WDM scenarios!*

Tension with CDM is not significantly reduced if the perturber is assumed to be a line-of-sight structure, rather than a subhalo.

Joint analysis

Thermal WDM lower limit

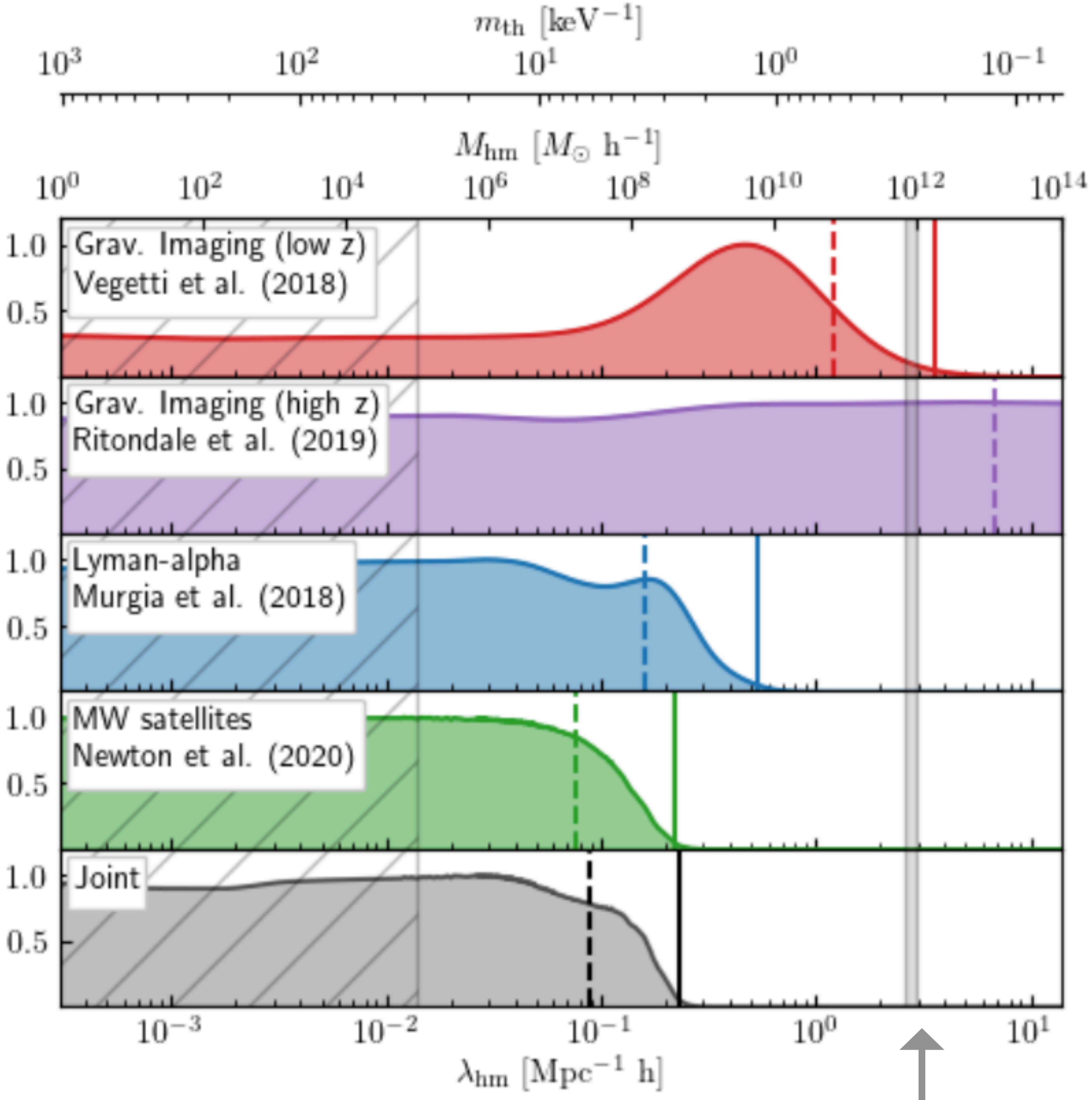


Reference	Probe	$\frac{m_{\mathrm{th}}}{\mathrm{keV}}$ 95% c.l.
this work	see Section 3	6.048
Birrer et al. (2017)	Grav. Imaging	2.0
V18 (Original)	Grav. Imaging	0.3
R19 (Original)	Grav. Imaging	0.26
Gilman et al. (2019a)	Flux Ratios	3.1, 4.4
Gilman et al. (2019b)	Flux Ratios	5.2
Hsueh et al. (2019)	Flux Ratios	5.6
Banik et al. (2018, 2019)	Stellar streams	4.6, 6.3
Alvey et al. (2020)	Dwarf spheroidals	0.59, 0.41
Viel et al. (2005)	Lyman-α	0.55
Viel et al. (2006)	Lyman-α	2.0
Seljak et al. (2006)	Lyman-α	2.5
Iršič et al. (2017)	Lyman-α	3.5, 5.3
M18 (Original)	Lyman-α	2.7, 3.6
Polisensky & Ricotti (2011)	MW satellites	2.3
Kennedy et al. (2014)	MW satellites	1.3, 5.0
Jethwa et al. (2017)	MW satellites	2.9
Nadler et al. (2019b)	MW satellites	3.26
Nadler et al. (2020a)	MW satellites	6.5
Nadler et al. (2021)	MW satellites & Flux Ratios	9.7
N20 (Original)	MW satellites	2.02, 3.99

Flux power spectrum

Sub-halo mass function

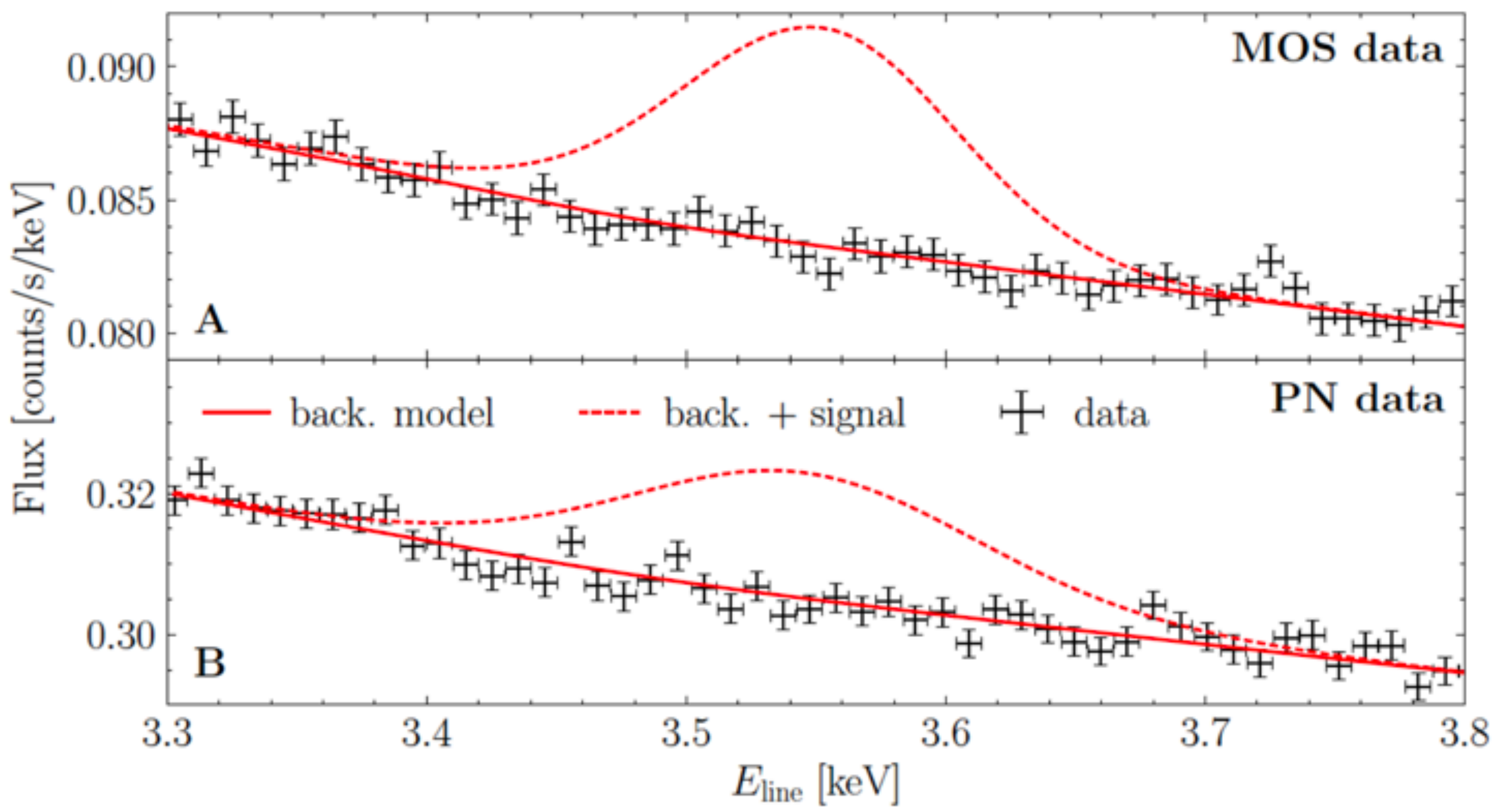
Enzi+21



MW mass

Could DM produce radiation?

Dessert+21



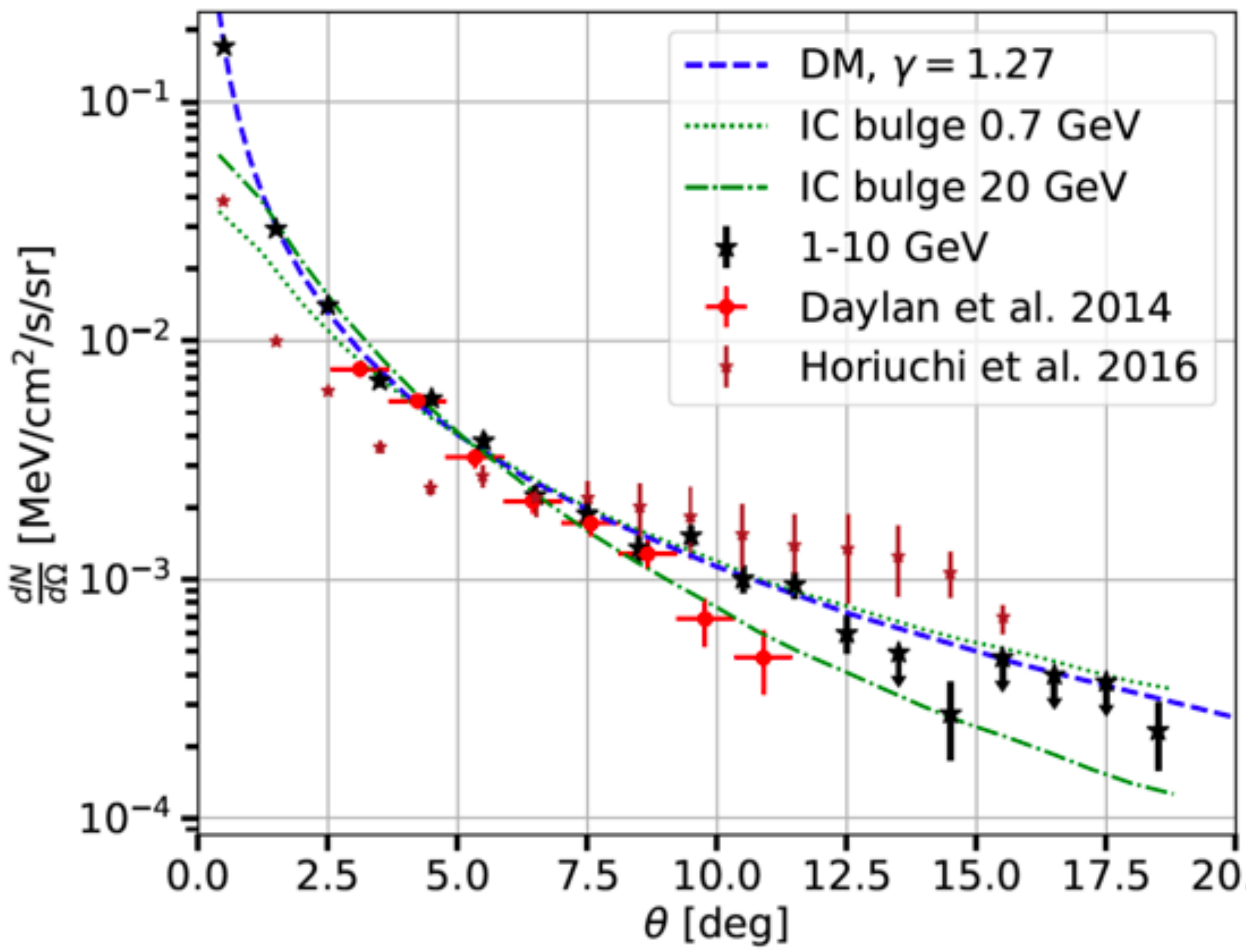
Dark matter decay can produce continuum or line emission. An X-ray line was claimed to be detected at 3.5 keV in galaxy clusters.

Decay of a sterile neutrino of mass 7 keV?

Strongly excluded by non-detection from the MW halo [30Ms observations].

$$L_{halo} \propto M_{halo}$$

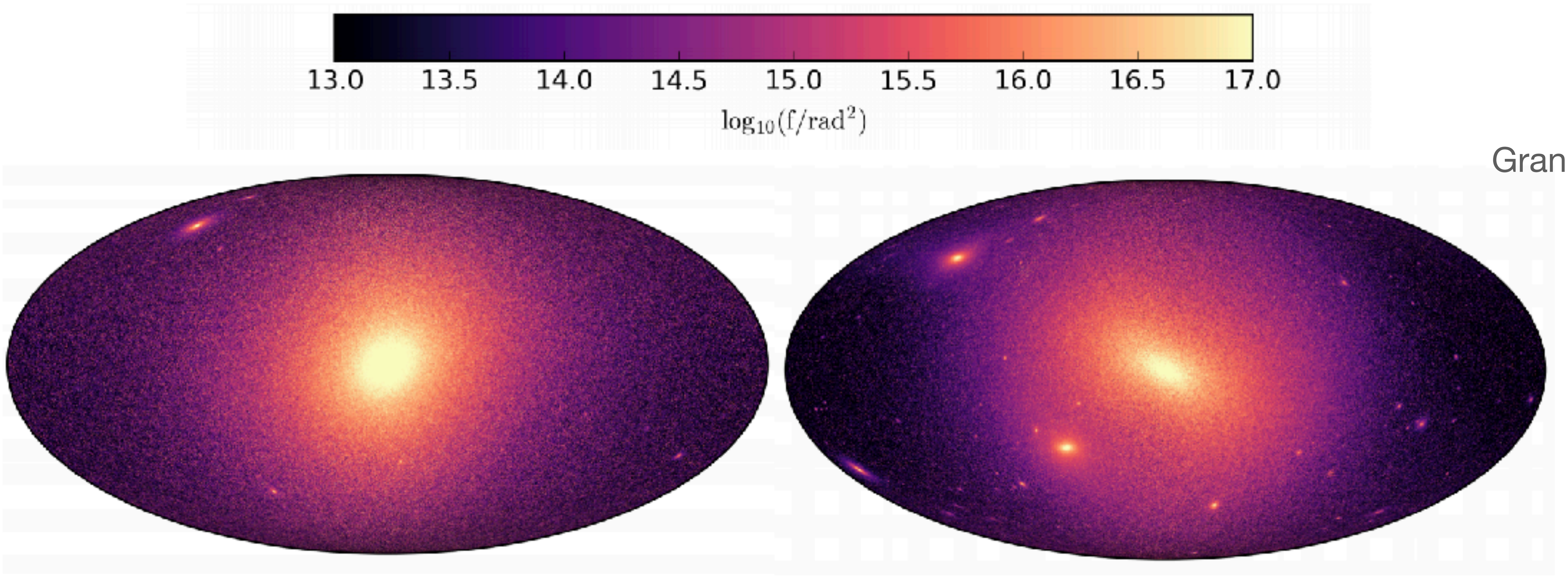
Di Mauro+21



Dark matter annihilation, for example of SUSY WIMPS, could produce continuum or line radiation in the γ-ray range. Possibly detection as an excess at 1 – 10 GeV towards the Galactic bulge. Luminosity biased to high-density (i.e. low- mass?) halos/subhalos

$$L_{halo} \propto \rho_{halo} M_{halo}$$

Could DM produce radiation? - II



Grand&White21

Full baryonic physics

3 times more
luminous than DM only

Dark Matter
Only

- Smooth halo is the dominant contributor to the annihilation flux (sub-haloes contribute <4%).
- Full physics DM halo more concentrated due to baryon adiabatic contraction, sub haloes less luminous in gamma rays.
- Subhaloes much less important than earlier works (e.g. Springel+08) - sub haloes are less concentrated, tidal effects are stronger.
- All but the very brightest objects will be unresolved with the Fermi-LAT. These brightest objects are predicted to be ~ 30 kpc away and to have mass ~ $6 \times 10^8 M_\odot$ in the full-physics case.

Future of DM indirect searches

- large/medium scales:
  - interaction with baryons and/or radiation
  - weak lensing observable
  - galaxy clustering also with perturbation theories

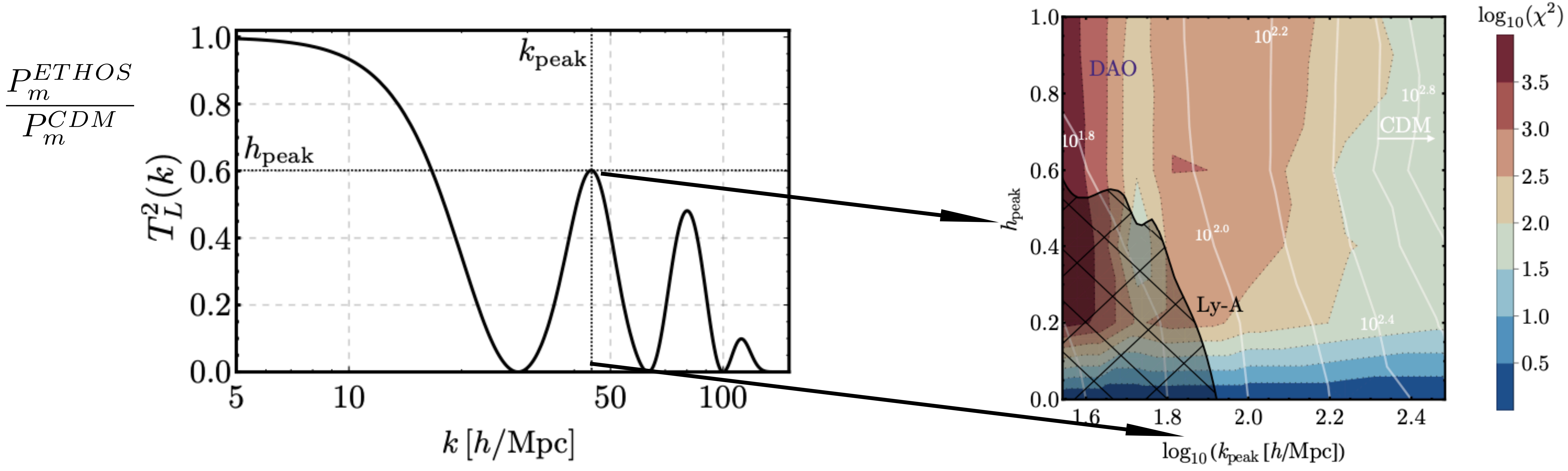
- small/very small scale structures:
  - cold vs warm DM models
  - phase-space density constraints
  - self interaction
  - also via strong lensing and substructures and mass function observations
  - streams, gaps in strong lensing arcs

21cm Intensity Mapping perspectives: ETHOS vs WDM

More than a simple cutoff to be explored at small scales

21cm at cosmic dawn (z=10-30) HERA power spectrum measurements
Could provide such a test and allow to discriminate between different DM
Models

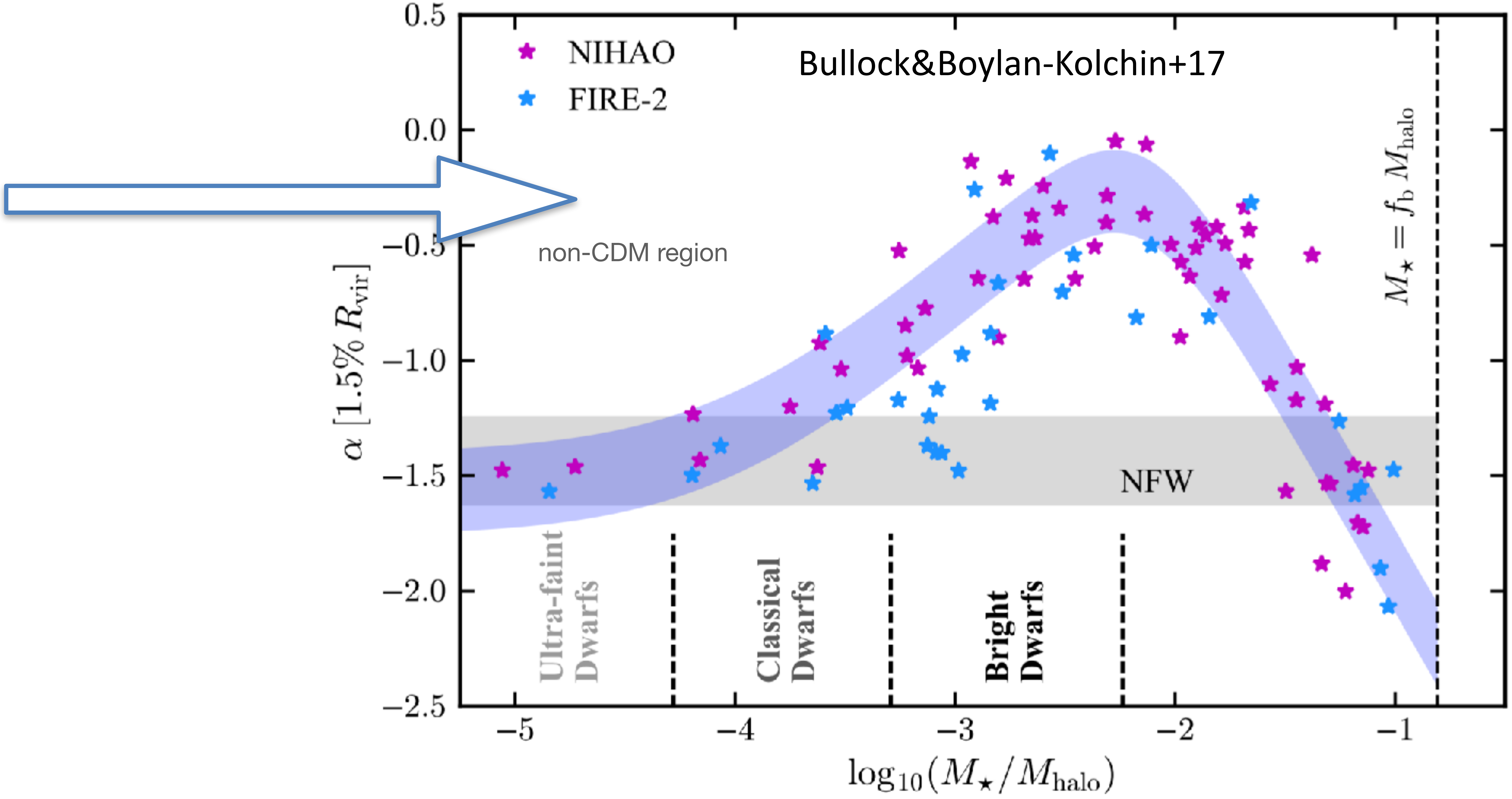
Chi square difference between ETHOS and corresponding WDM



Munoz+2021

Very high redshift regime, close to linear, is promising to probe DM nature

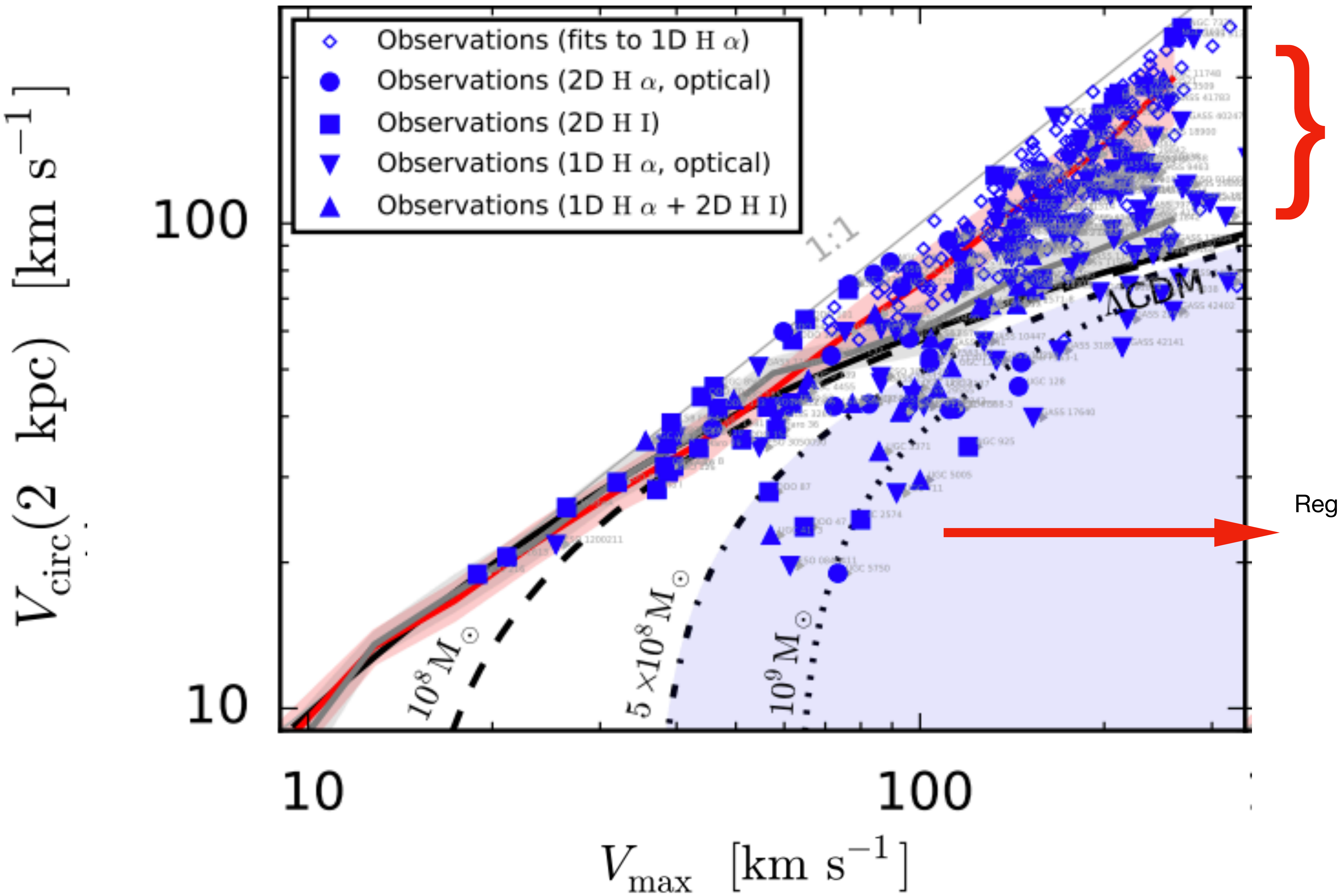
ΛCDM model: core/cusps with feedback



Hydro simulation in LCDM with feedabck predict cored profile for bright dwarfs 10^7-10^9 $M_\star$, and cuspy for classical (10^5-10^7 $M_\star$) and ultra-faint Dwarfs (10^2-10^5 $M_\star$)

Galaxy Rotation Curves

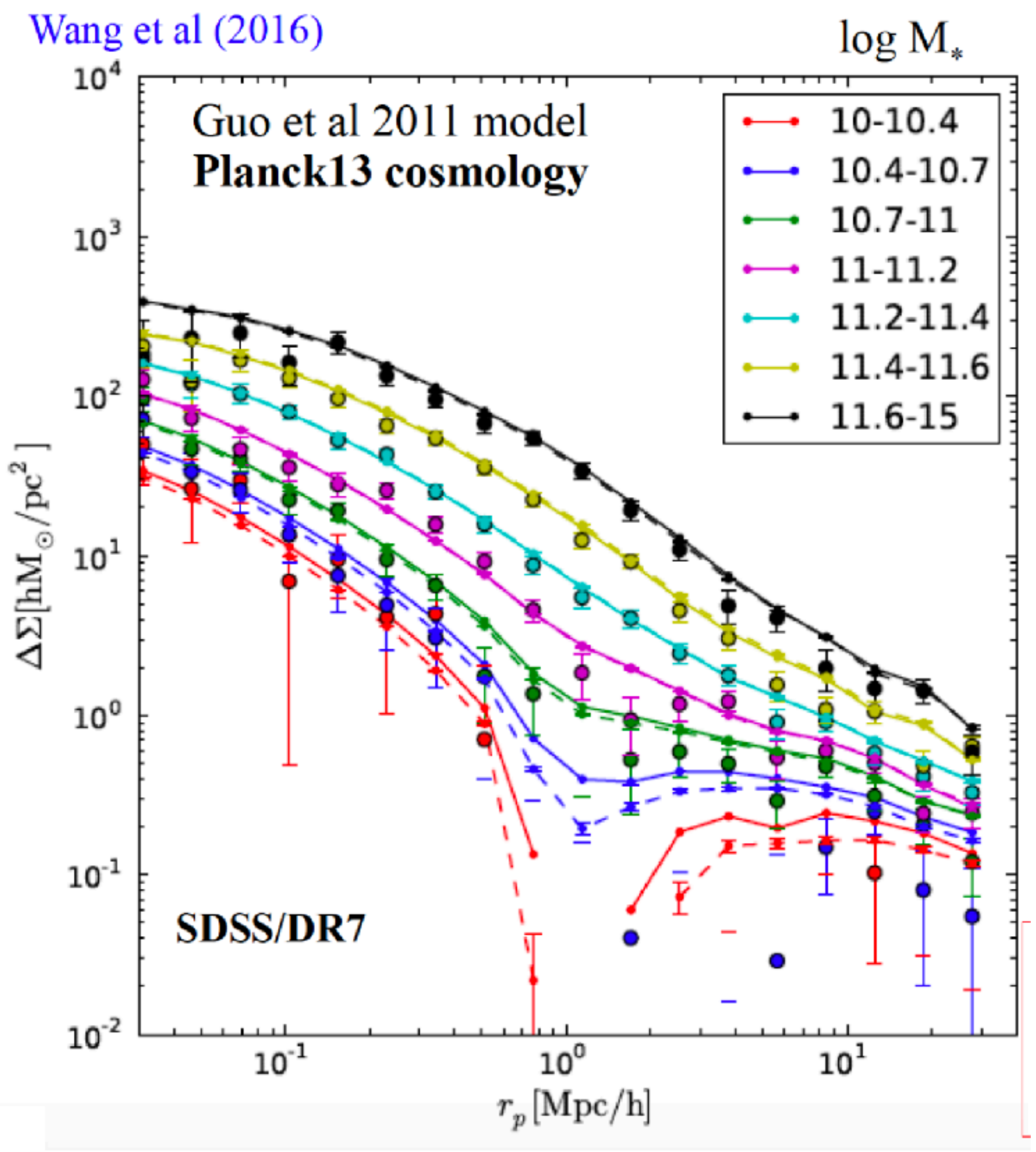
Oman+15



Huge diversity/scatter
not seen in simulations
even when baryons
are included

Region populated by observational
data points
but not by models

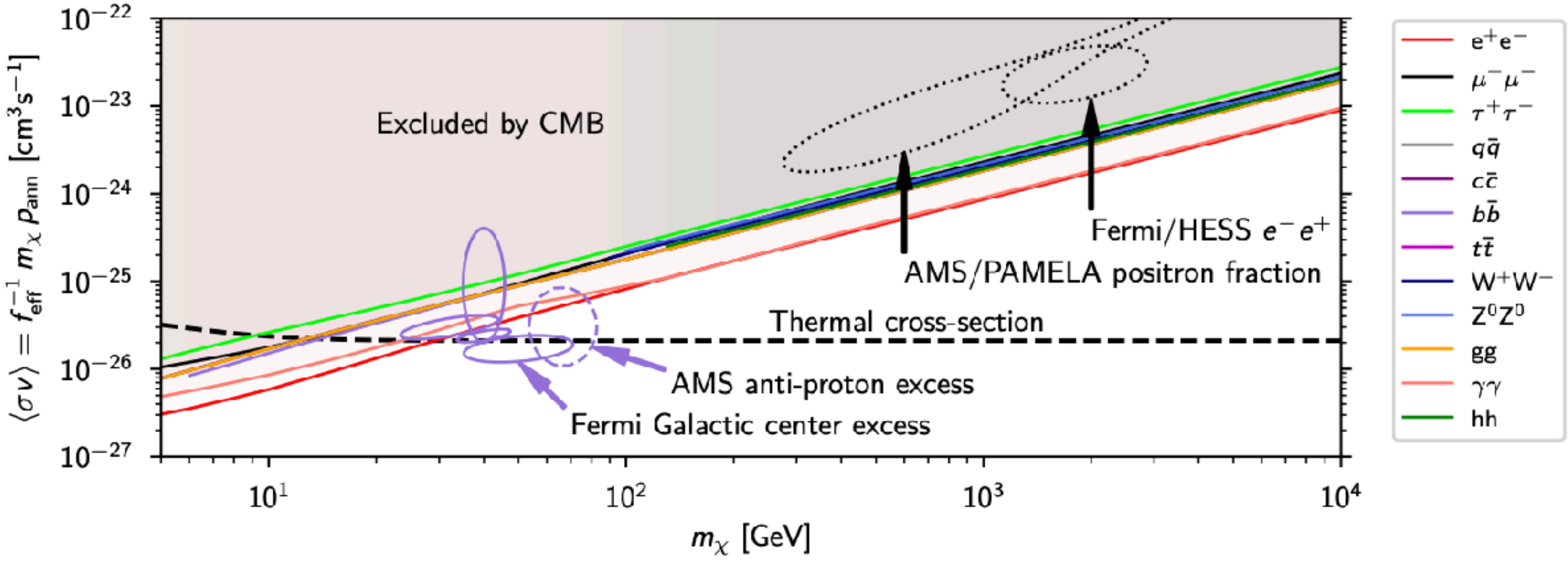
Average mass profile around bright galaxies



- Points are average mass profiles around clusters and bright galaxies Obtained with weak lensing
- Millennium simulation match well
- Galaxy abundance matching only free parameter in the fit

CMB constraints on WIMPs

Planck collaboration 2018

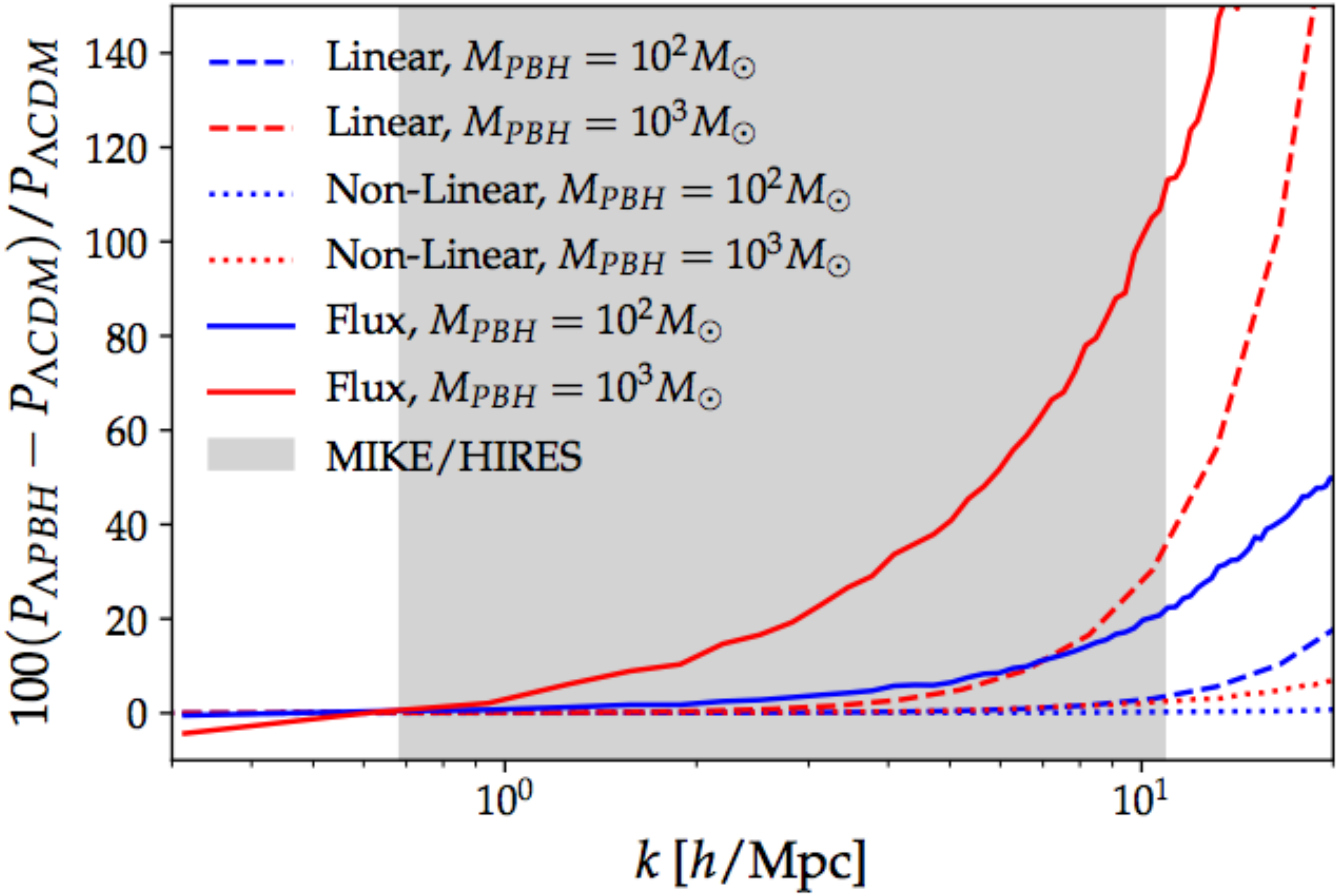


$$p_{\rm ann} \equiv f_{\rm eff}\frac{\langle\sigma v\rangle}{m_\chi}$$

Primordial Black Holes

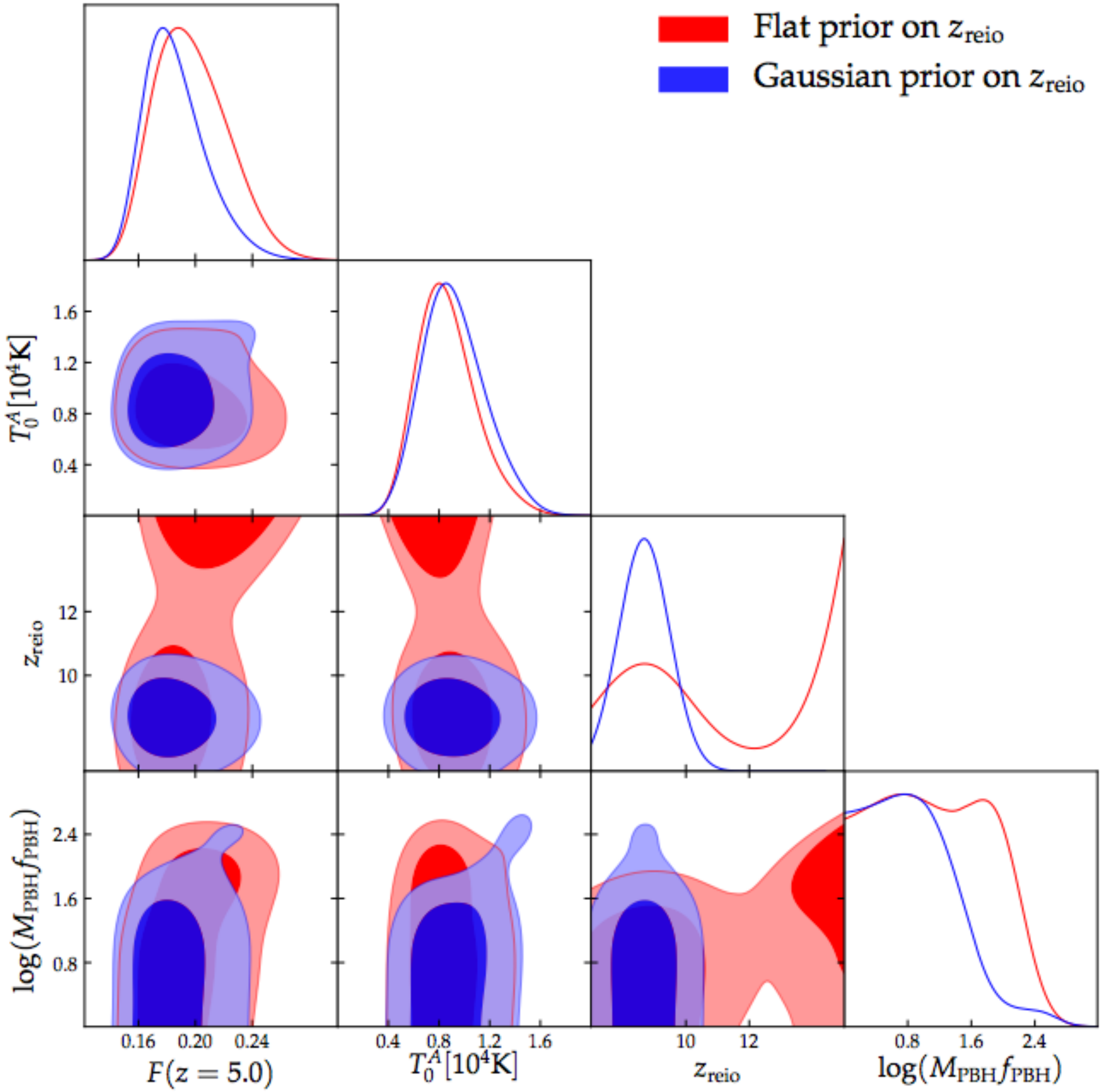
Afshordi, McDonald, Spergel 03

$$P_{\rm CDM}(k,z) = D^2(z)\left(T^2_{\rm ad}(k)P_{\rm ad} + T^2_{\rm iso}(k)P_{\rm iso}\right)$$



Murgia, Scelfo, MV, Raccanelli, PRL, 2019

Primordial Black Holes - II



Primordial Black Holes - III