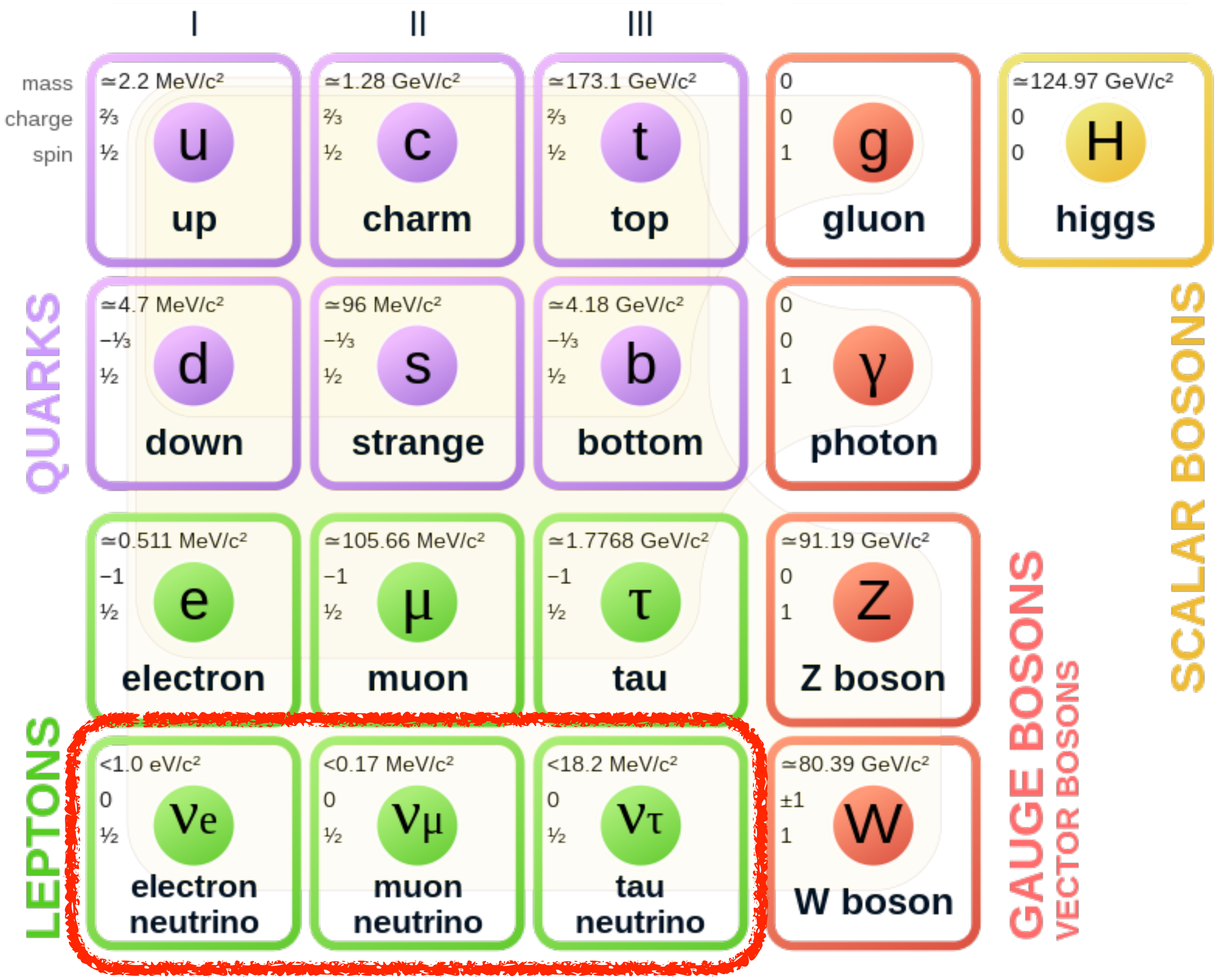
Neutrino masses and structure formation

"Review" + the example of Lyman-alpha forest

Eric Armengaud
Action Dark Energy - Marseille 06/05/2022

Standard Model neutrinos



ν : Lightest + "least" interacting fermions in SM

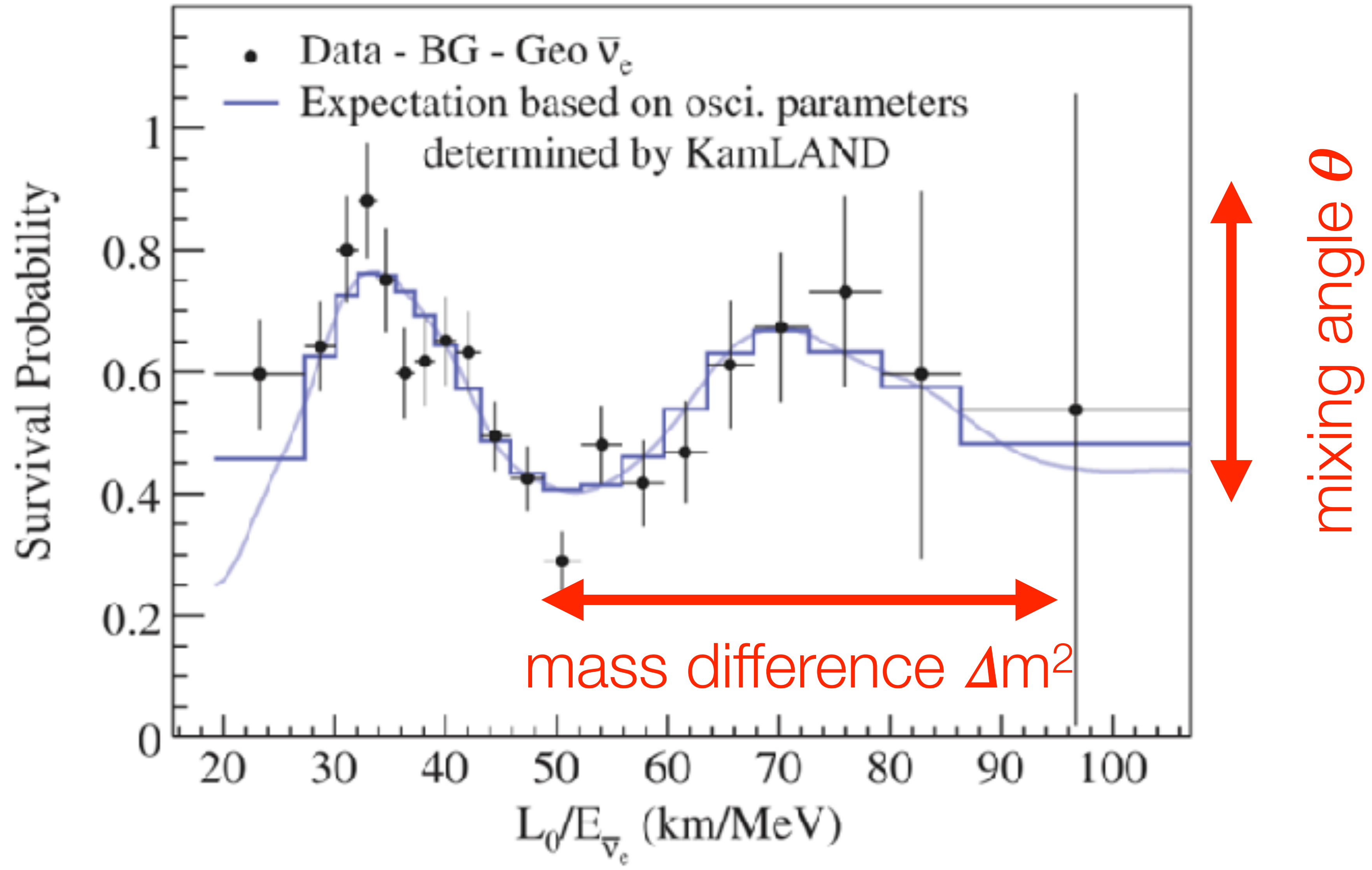
Interact by flavors

Mass terms:

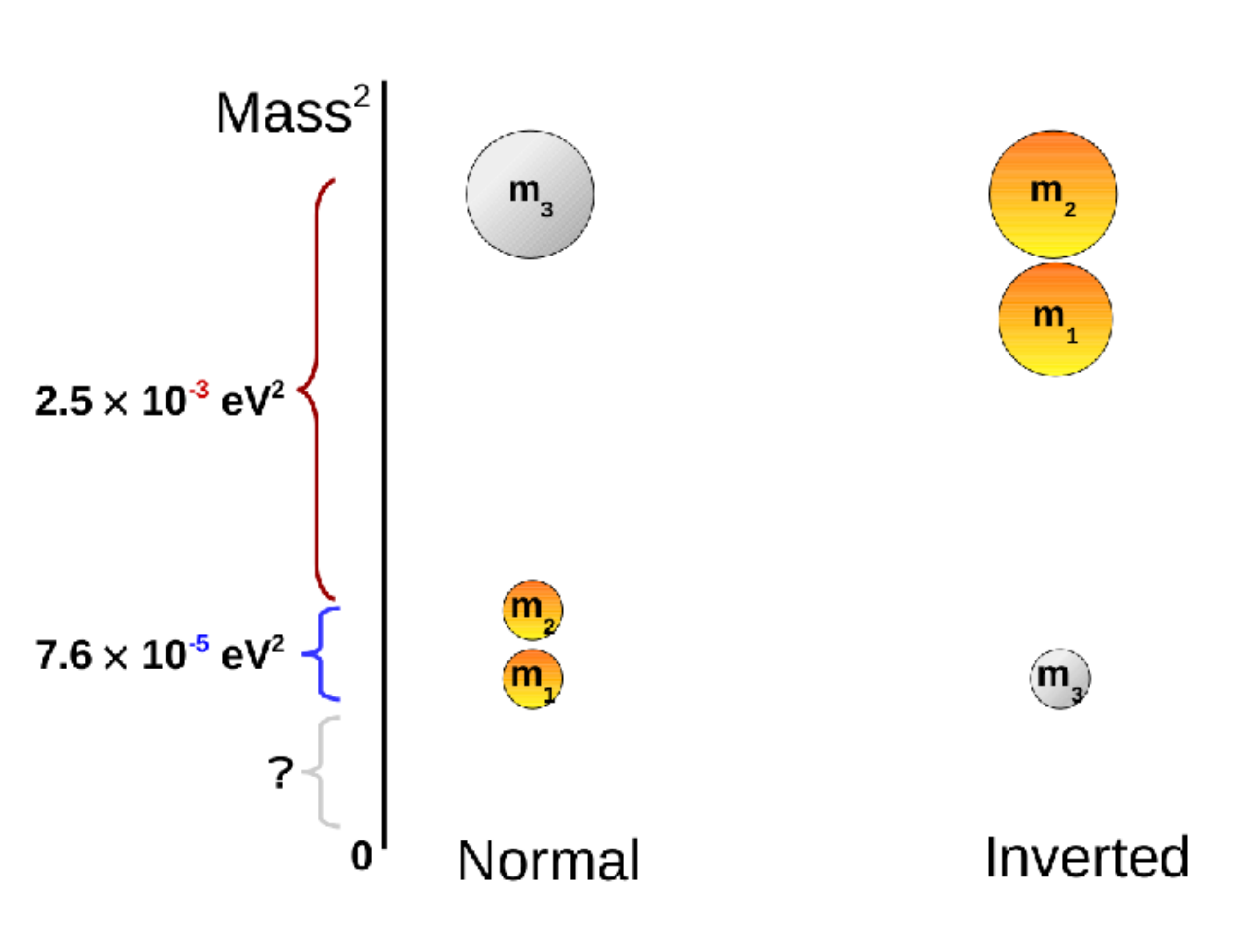
- Dirac (SM-like = Higgs coupling)
- Majorana (permitted, see-saw)

Mass measured: oscillations

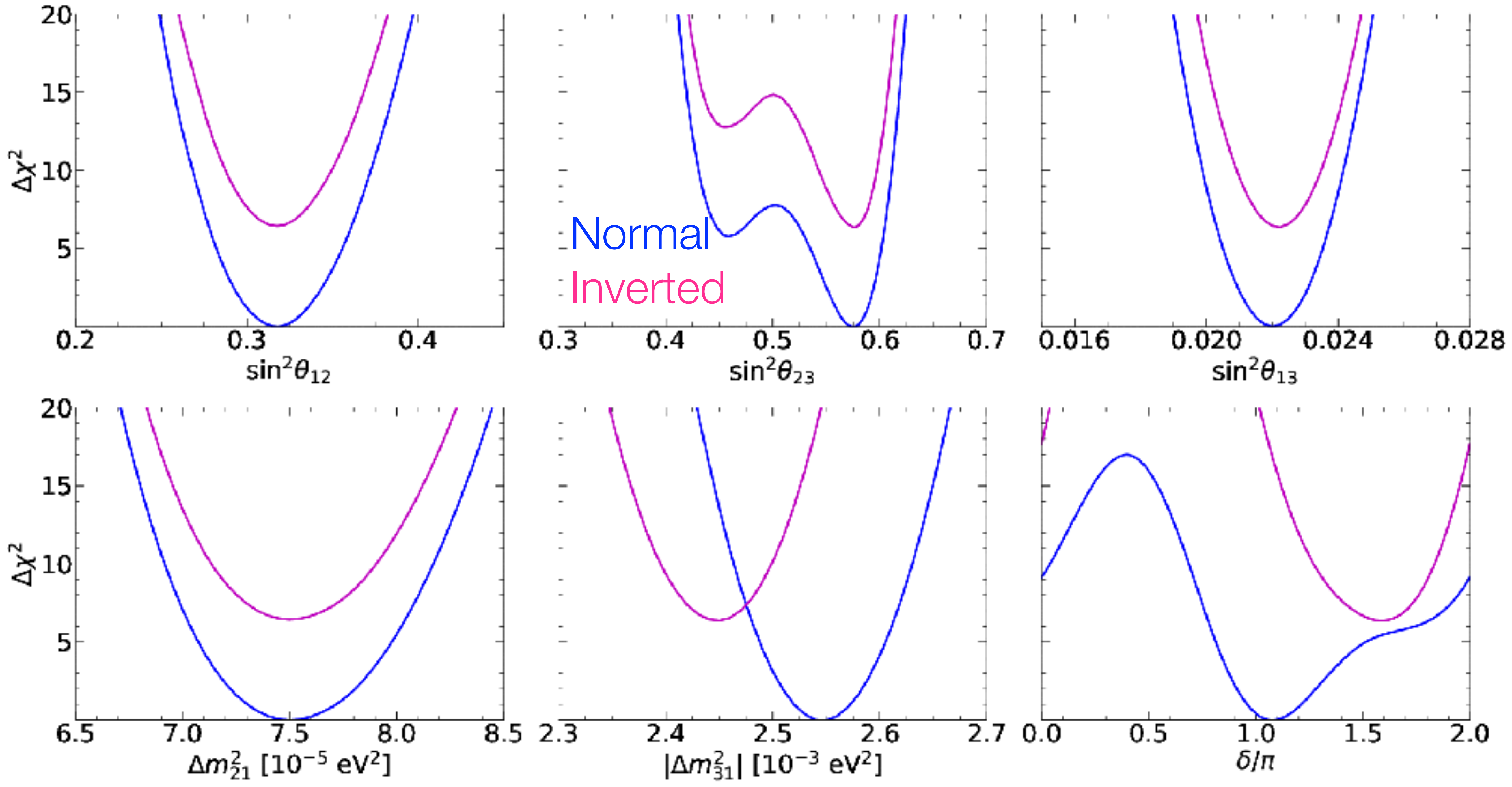
$$P_{osc} = sin^2(2\theta)\, sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Neutrino masses and mass ordering

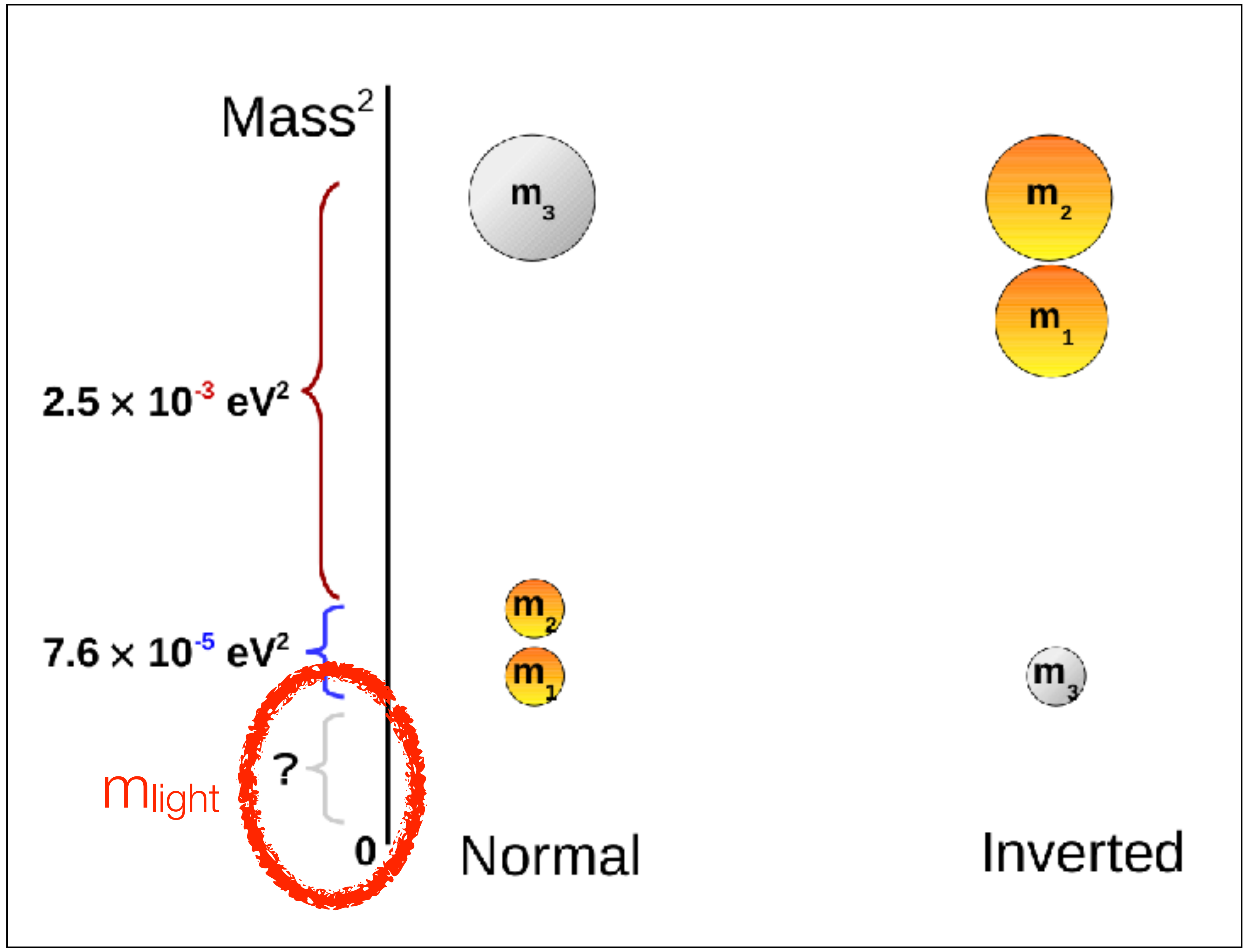


https://globalfit.astroparticles.es $\chi^2(\mathrm{IO}) - \chi^2(\mathrm{NO}) = 6.4$ (~2.5σ)



Upcoming experiments to settle mass ordering - ORCA, JUNO, IceCube, HyperK, DUNE...

Neutrino masses and mass ordering



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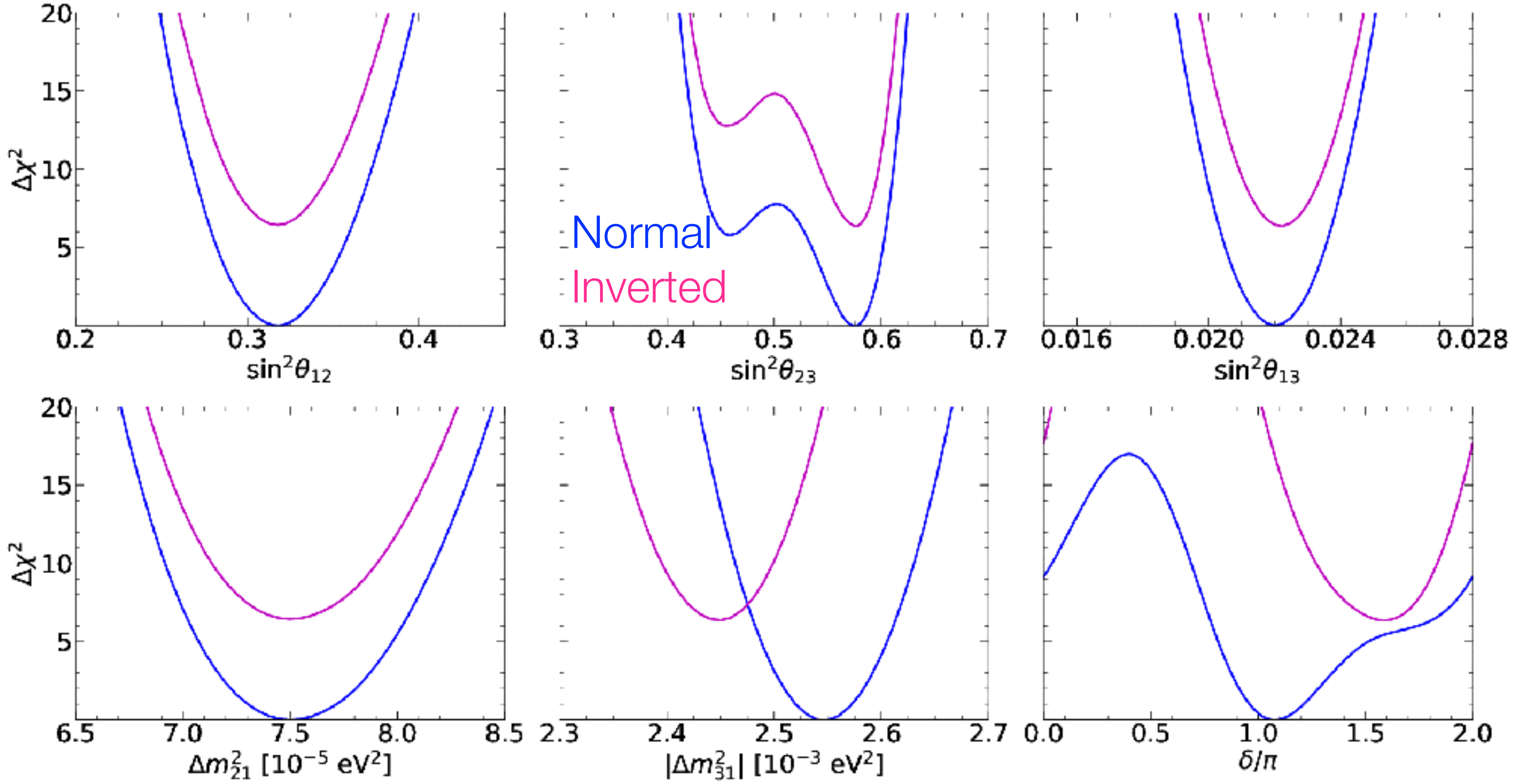


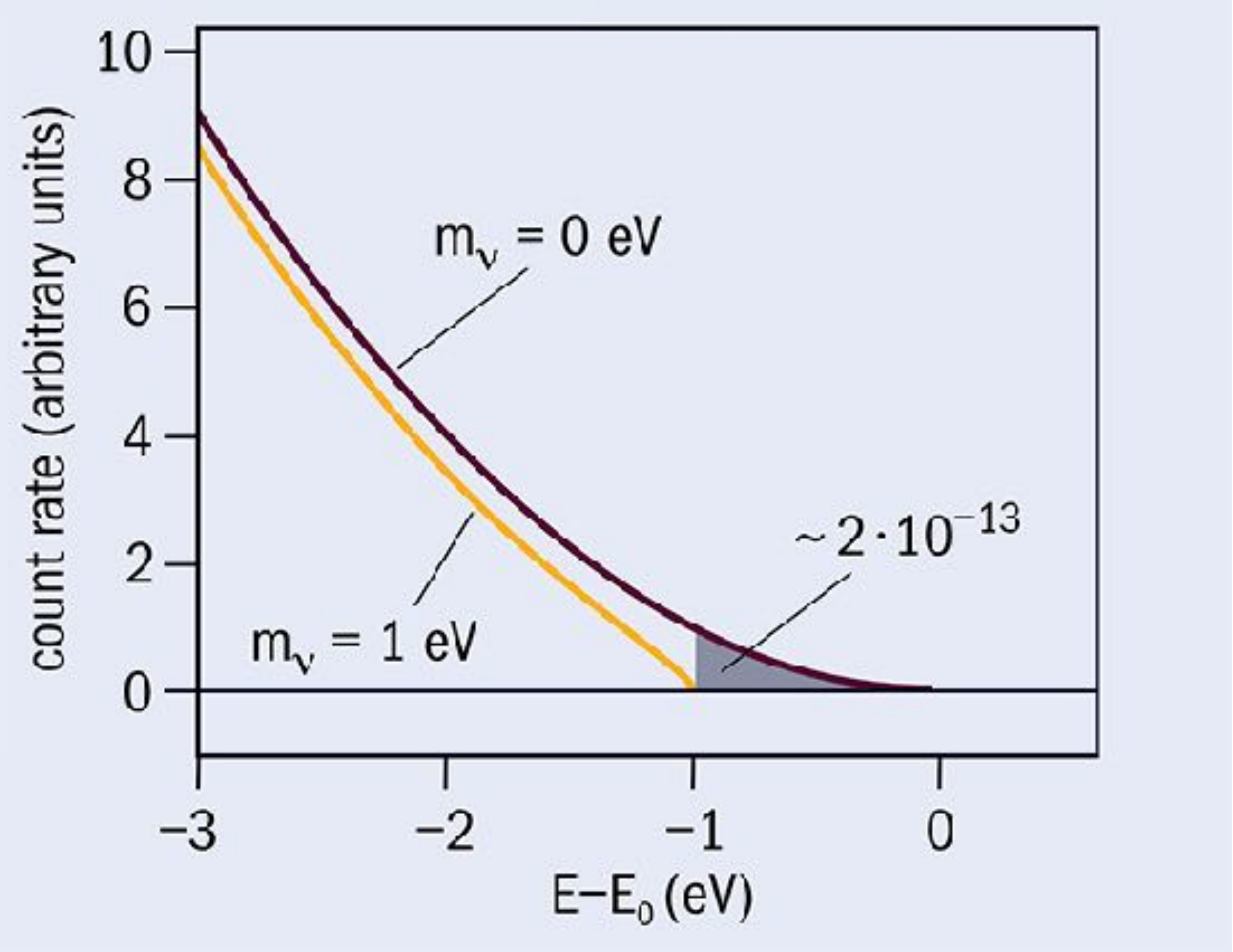
Upcoming experiments to settle mass ordering - ORCA, JUNO, IceCube, HyperK, DUNE...

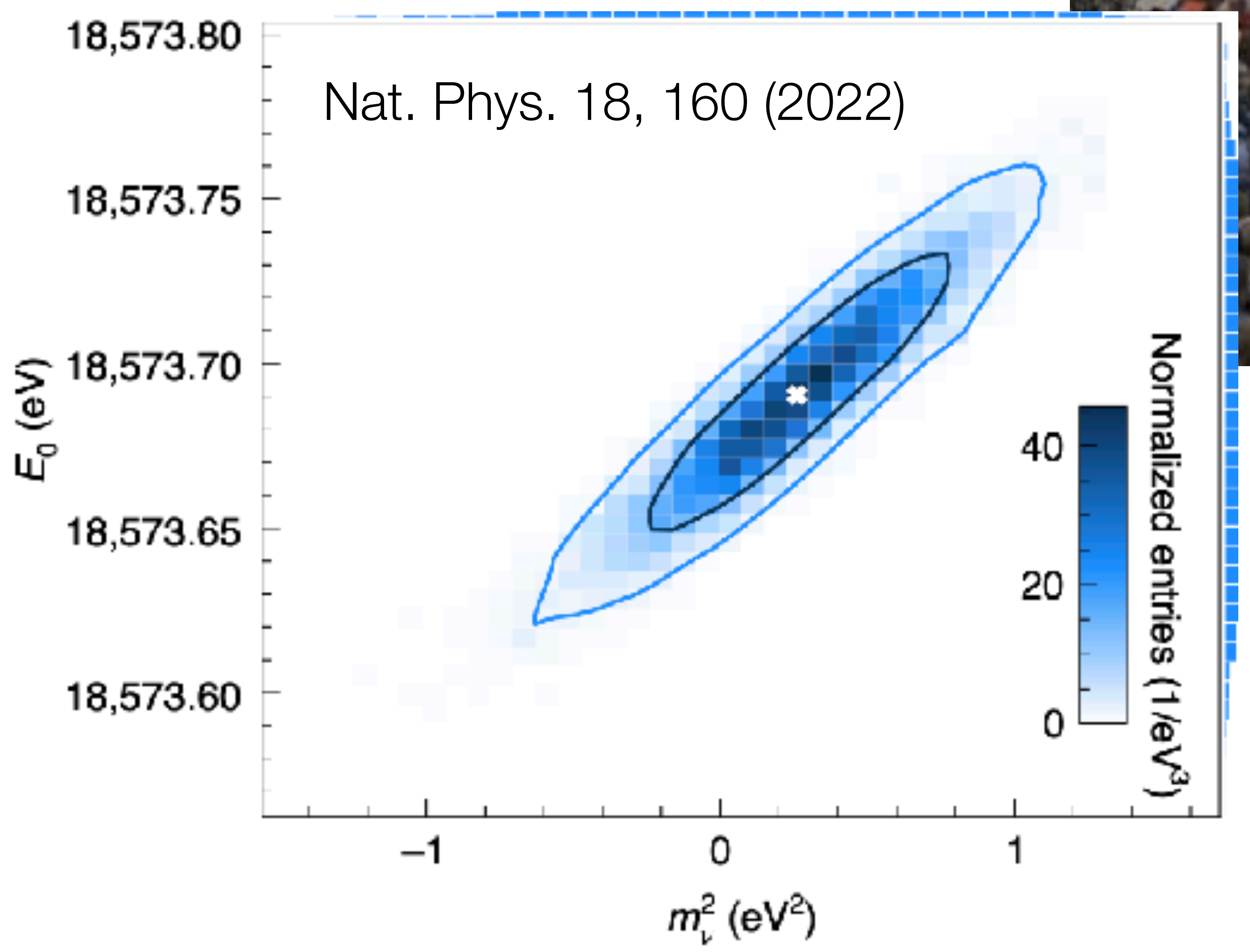
Cosmology: measure Σm_ν = m1 + m2 + m3

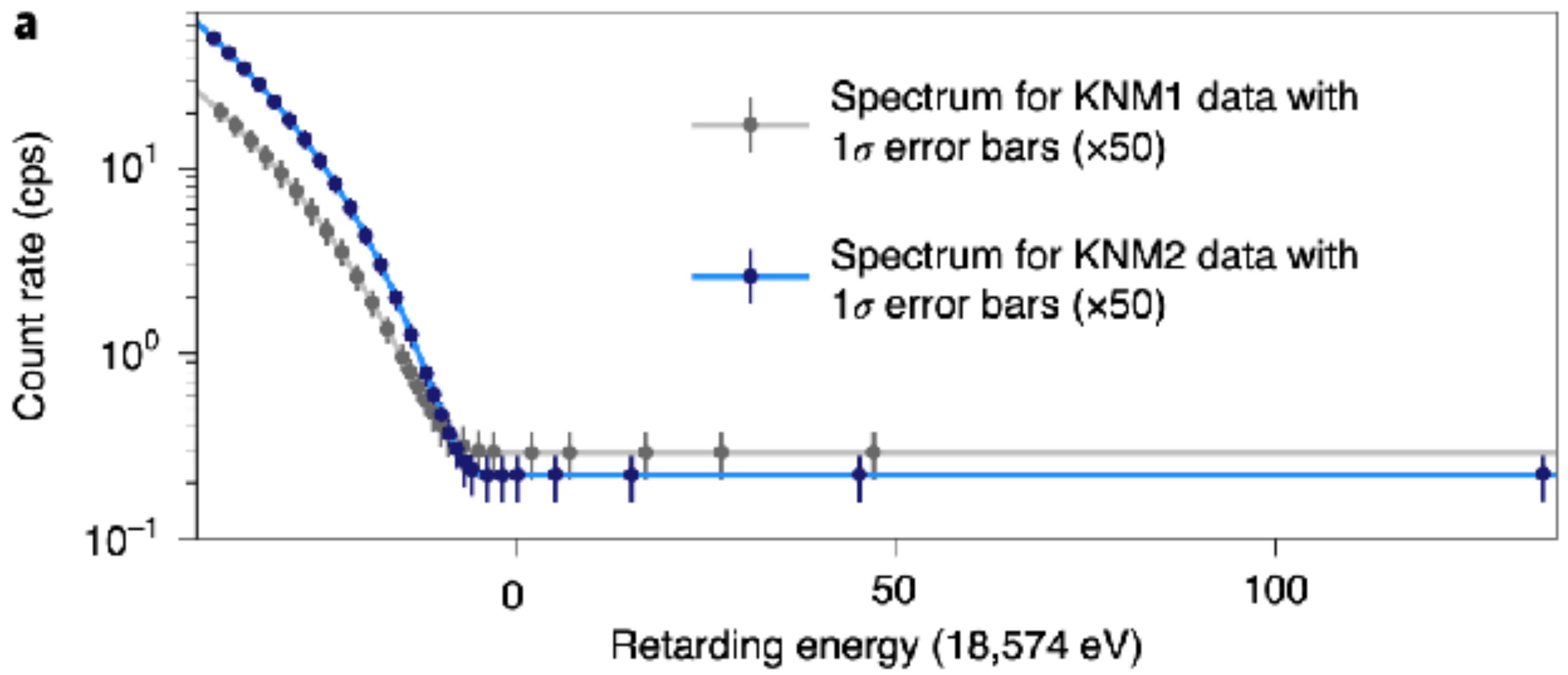
Normal: $\Sigma m_\nu >$ 58 meV Inverted: $\Sigma m_\nu >$ 100 meV

Absolute mass scale: KATRIN

$$T_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$$





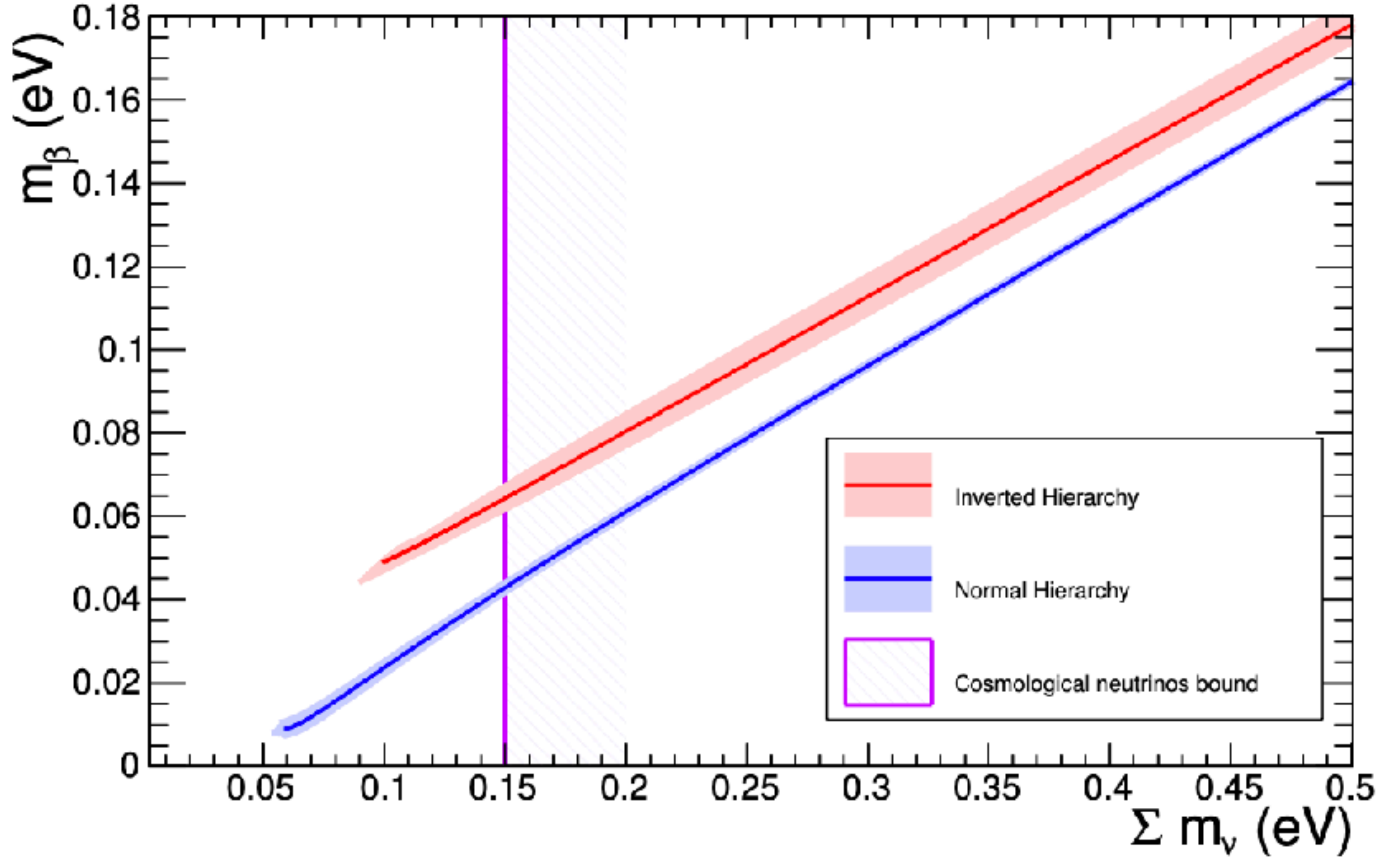


$m_\beta < 0.8$ eV @ 90% CL

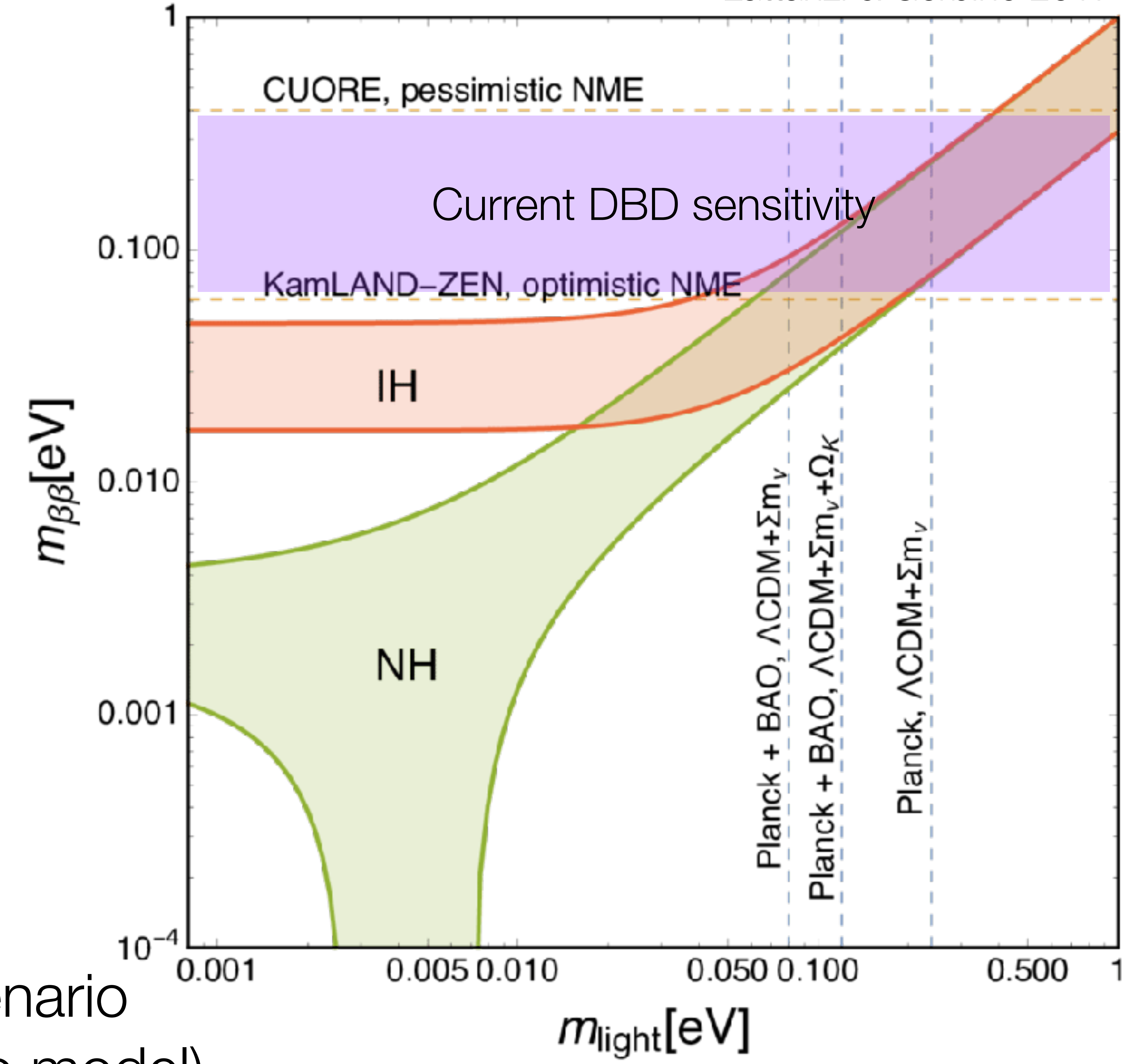
$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

Tritium, neutrinoless double beta decay (DBD), and cosmology

Yèche 2017



Lattanzi & Gerbino 2017



- Different "absolute" neutrino mass scales
- DBD more sensitive than tritium, but only for Majorana scenario
- Cosmology most competitive (with assumptions on cosmo model)

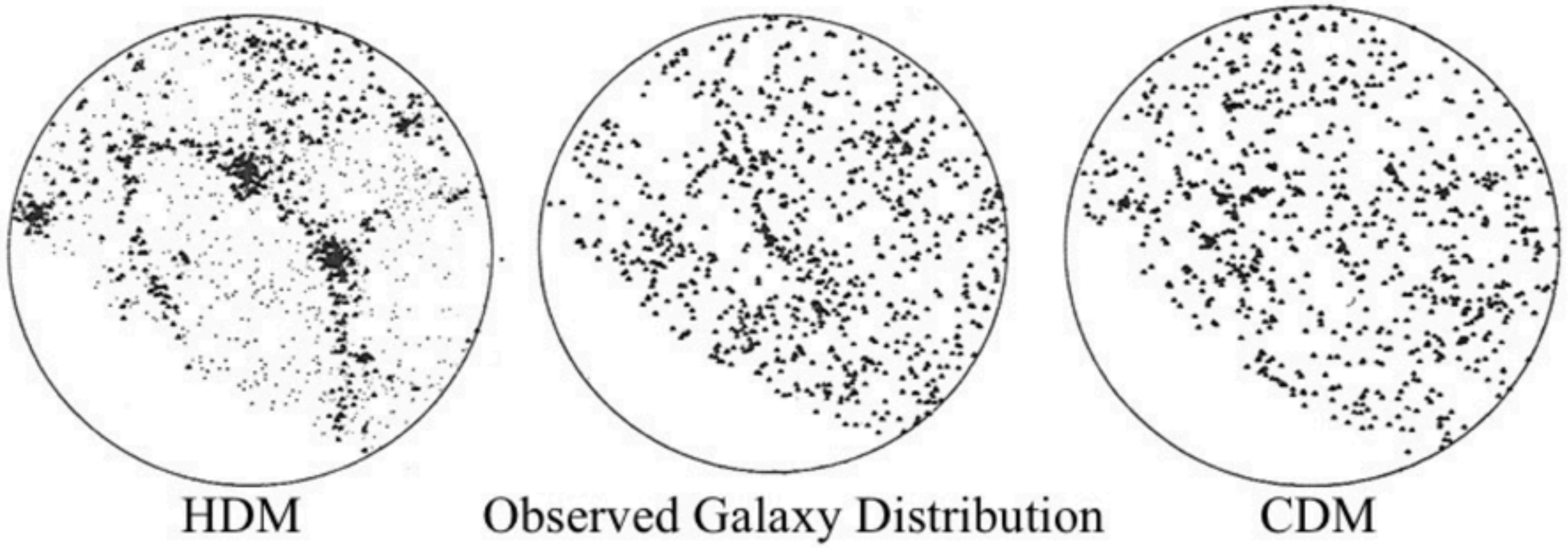
Cosmological neutrinos (CνB)

Very abundant cosmic fluid, well-known (in principle)
Thermal relic (decoupling @ T~MeV)

Transition to non-relativistic regime (at least 2/3): $1 + z_{\rm nr} = 189 \left(\frac{m_\nu}{0.1 \rm eV}\right)$
Hot dark matter (HDM)

Relic energy density: $f_\nu = \frac{\Omega_\nu}{\Omega_m} \simeq 0.023 \left(\frac{\Sigma m_\nu}{0.3\,\rm eV}\right)\left(\frac{0.14}{\omega_m}\right)$

S. White 1986



Back to the 80s... :
DM = neutrinos ?
Needed HDM, m_ν ~ 15 eV

Neutrino free-streaming

Relativistic fluid (not coupled to baryons):

$$\lambda_{\rm fs} \sim \frac{c}{H}$$

Non-relativistic regime:

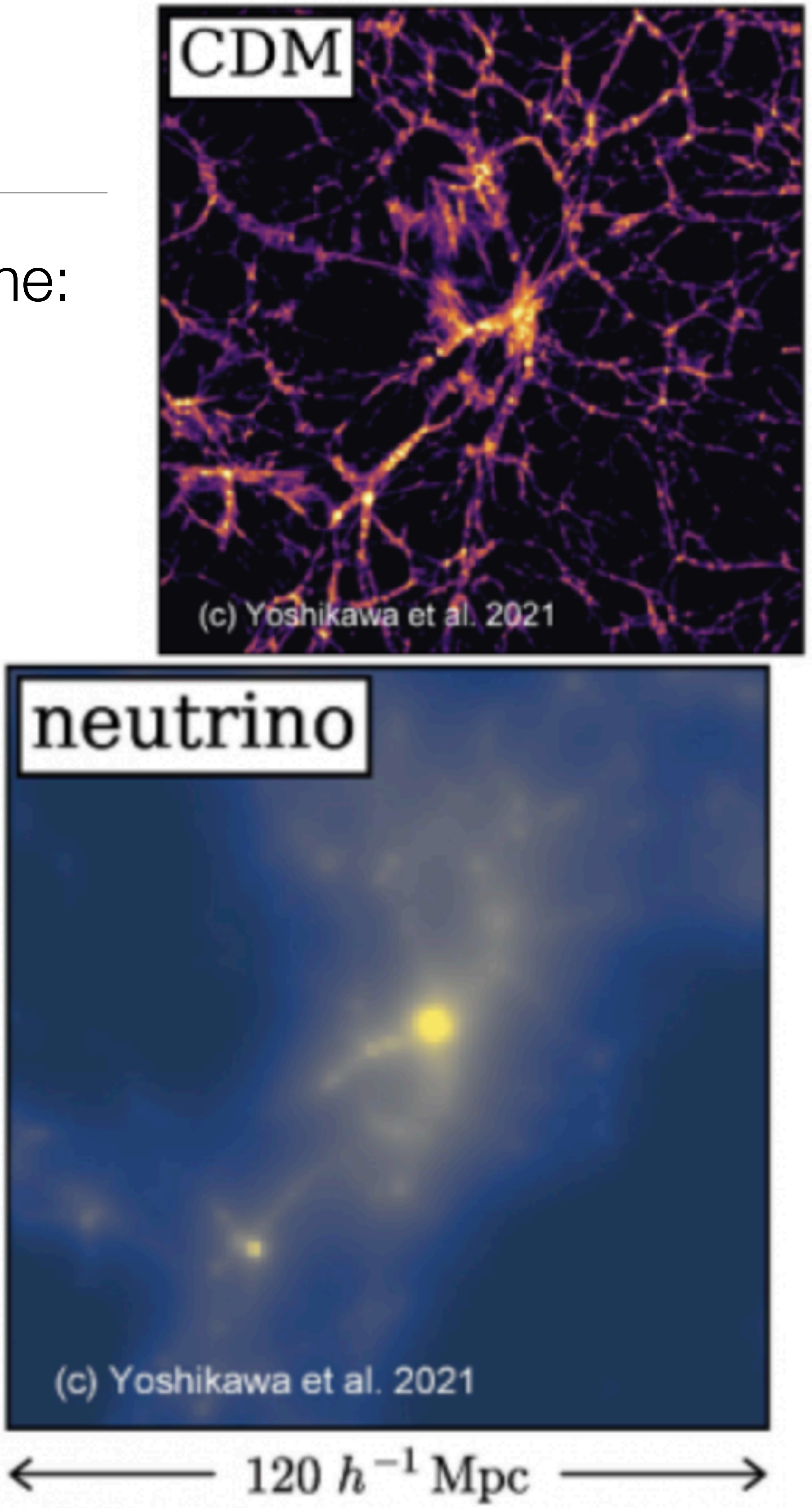
$$\lambda_{\rm fs} \sim \frac{3\,T_\nu^0}{m_\nu}\,\frac{a_0}{aH}$$

⇒ In comoving coordinates : **maximum free-streaming scale @ NR transition**:

$$k_{\rm nr} \simeq 0.002 \left(\frac{\omega_m}{0.14}\right)^{1/2} \left(\frac{m_\nu}{0.1\,{\rm eV}}\right)^{1/2}\ {\rm Mpc}^{-1}$$

k < k$_{\rm nr}$: δ_ν ~ CDM

k >> k$_{\rm nr}$: δ_ν highly damped



Massive neutrinos: impact on matter P(k)

1) Do not contribute to **total** P(k):

$$P_m = P(c+b+\nu) = \langle \delta_c^2 \rangle \quad k < k_{\rm nr}$$
$$= (1-f_\nu)^2 \langle \delta_c^2 \rangle \quad k \gg k_{\rm nr}$$

2) Backreaction on the gravitational potential:

$$\ddot{\delta}_{\rm cdm} + \frac{\dot{a}}{a}\dot{\delta}_{\rm cdm} = 4\pi G a^2 \delta\rho$$

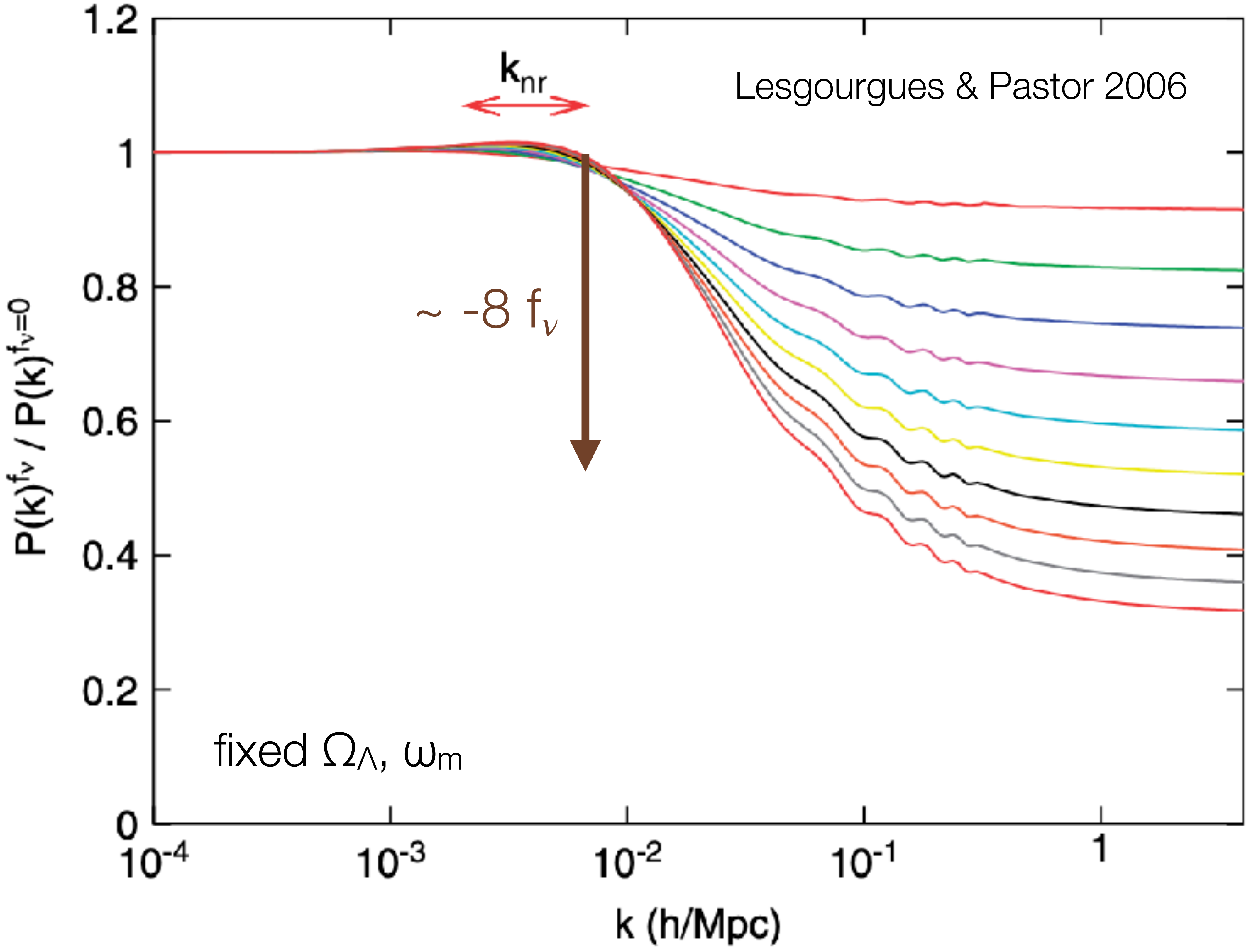
ν contributes

ν does not contribute

$$\Rightarrow \quad \ddot{\delta}_{\rm cdm} + \frac{2}{\tau}\dot{\delta}_{\rm cdm} - \frac{6}{\tau^2}(1-f_\nu)\delta_{\rm cdm} = 0.$$

$$\delta_{\rm cdm} \sim a^{1-3f_\nu/5}$$

$$P_m(k \gg k_{\rm nr}) \sim P_m(f_\nu = 0) \times (1 - 8 f_\nu)$$



Non-linear evolution / simulations

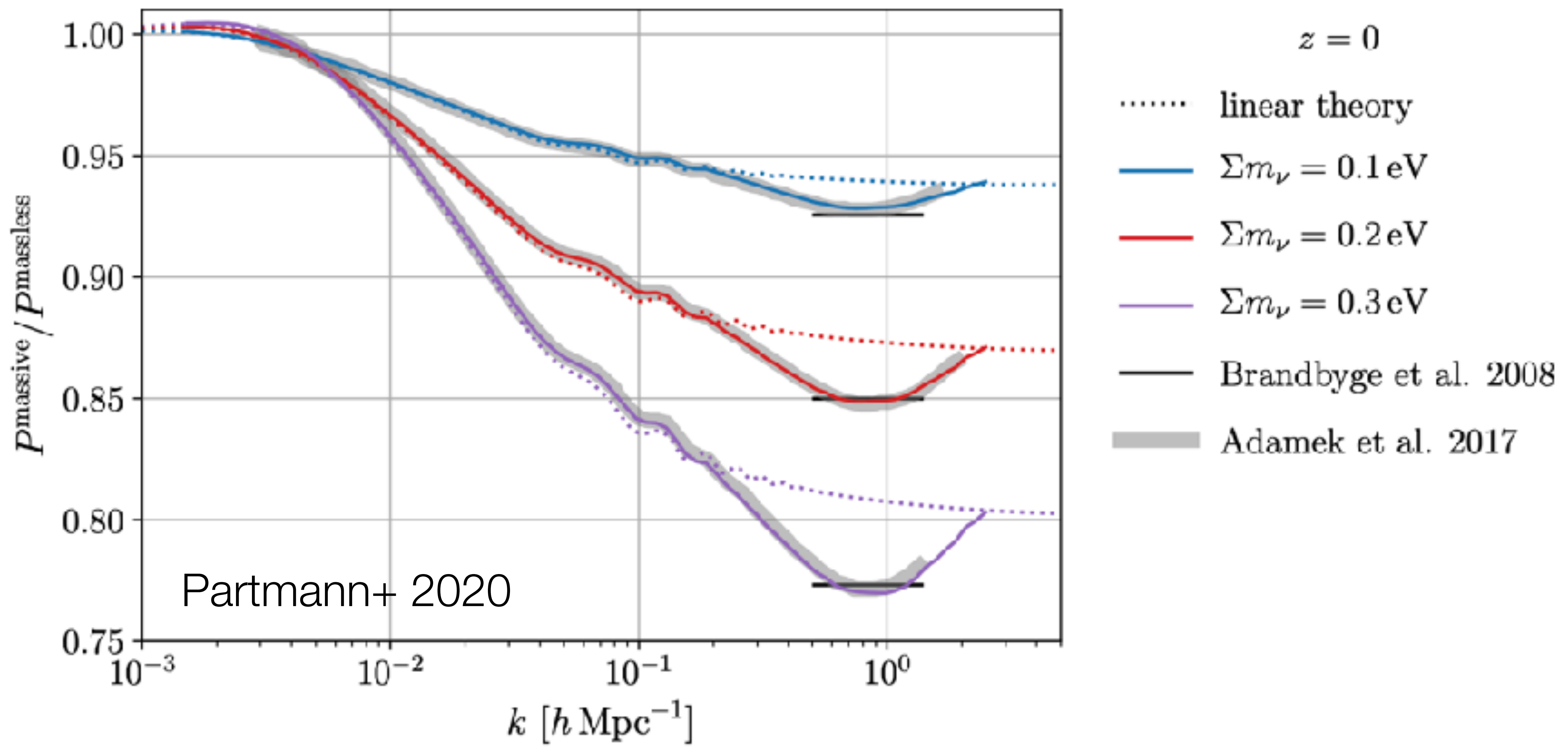
See Julian Adamek's talk

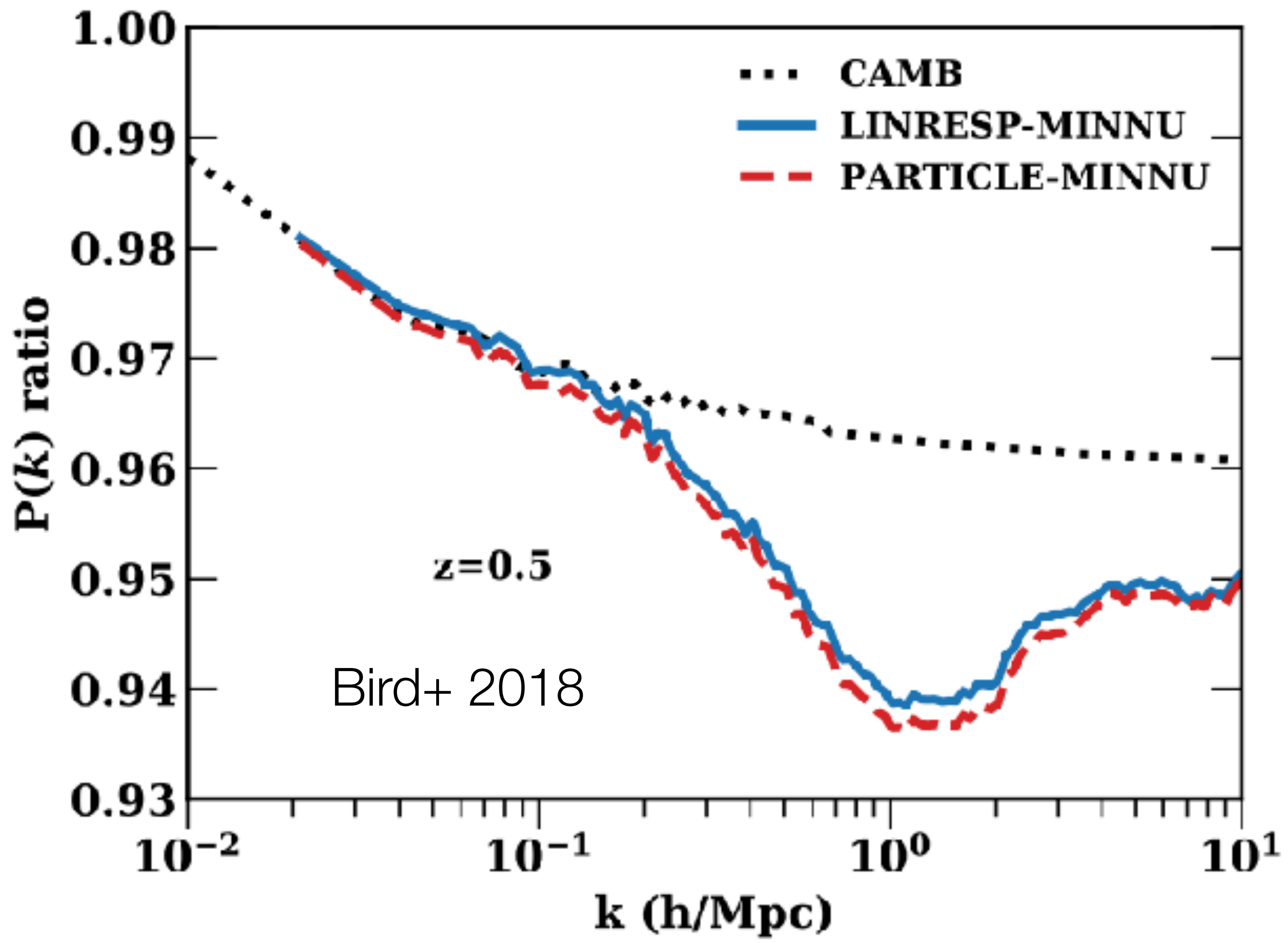
Velocity dispersion
 ⇒ Need more particles than for CDM

Many strategies proposed

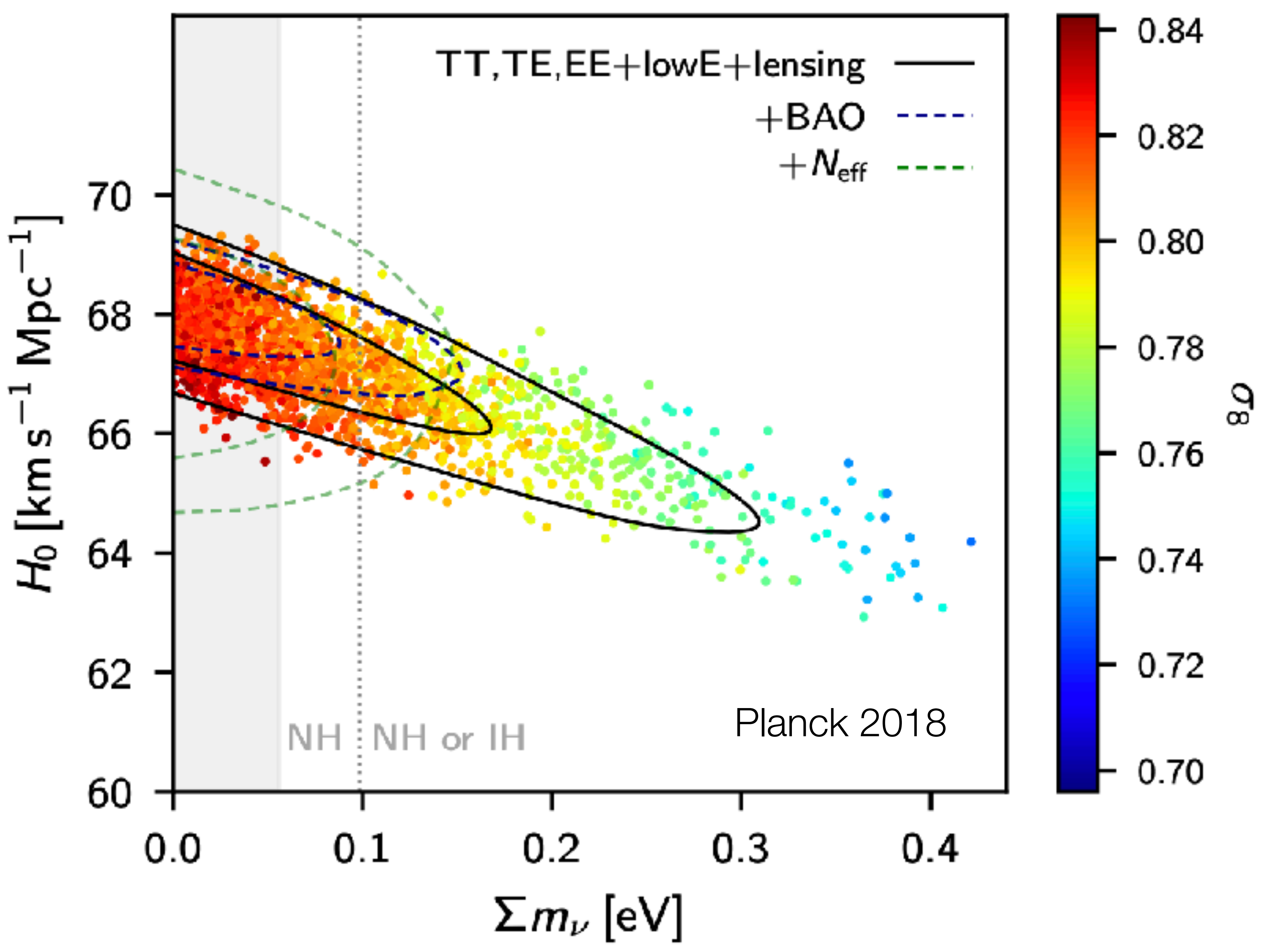
- eg. map with-ν simulations with no-ν simulations, varying cosmo parameters to mimick P_{lin} in RoI ("spoon effect" is not specific to ν)

- eg. linear response approximation

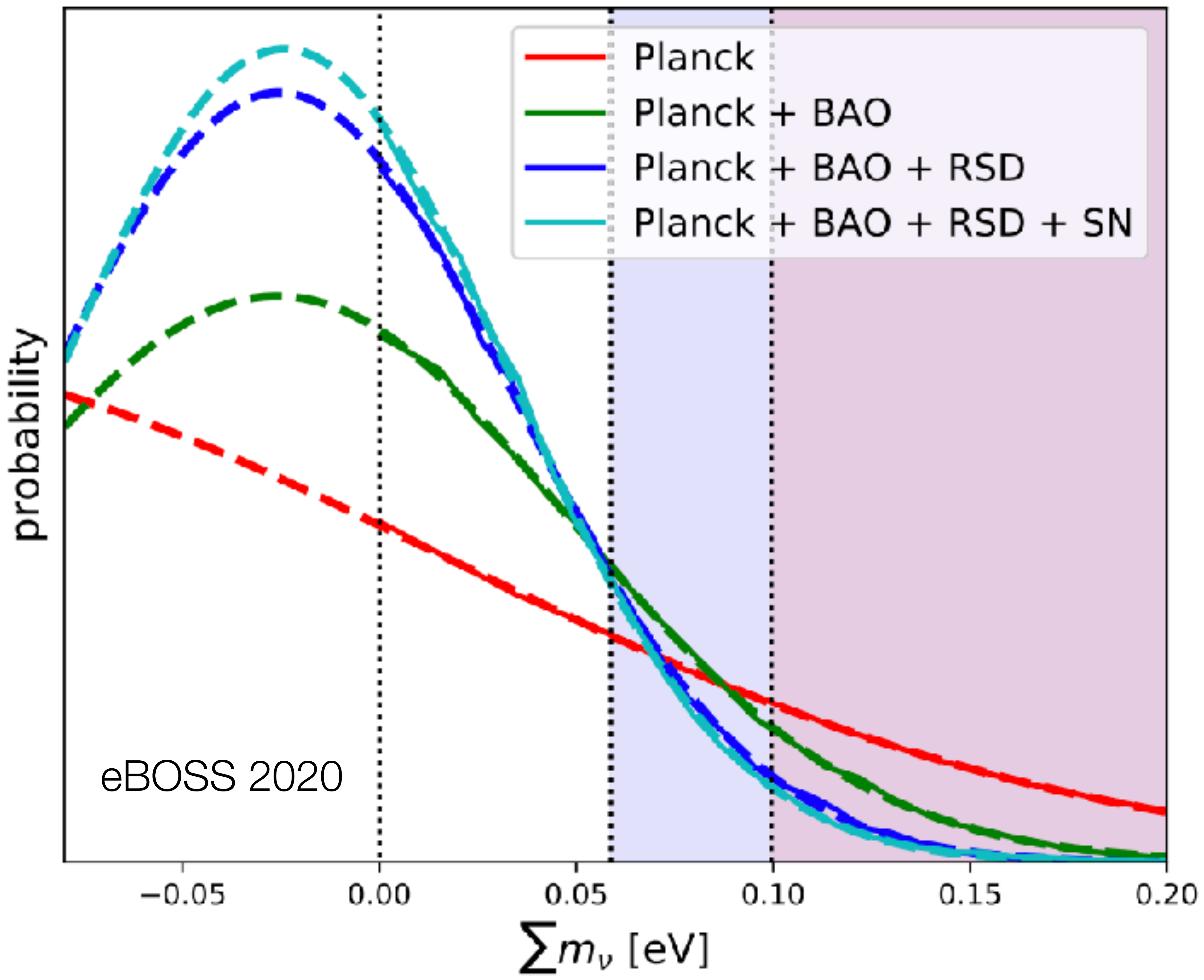




Current CMB + BAO mass bounds



$$\sum m_\nu < 0.26 \text{ eV} \quad (95\,\%,\, \textit{Planck}\ \text{TT,TE,EE+lowE}).$$



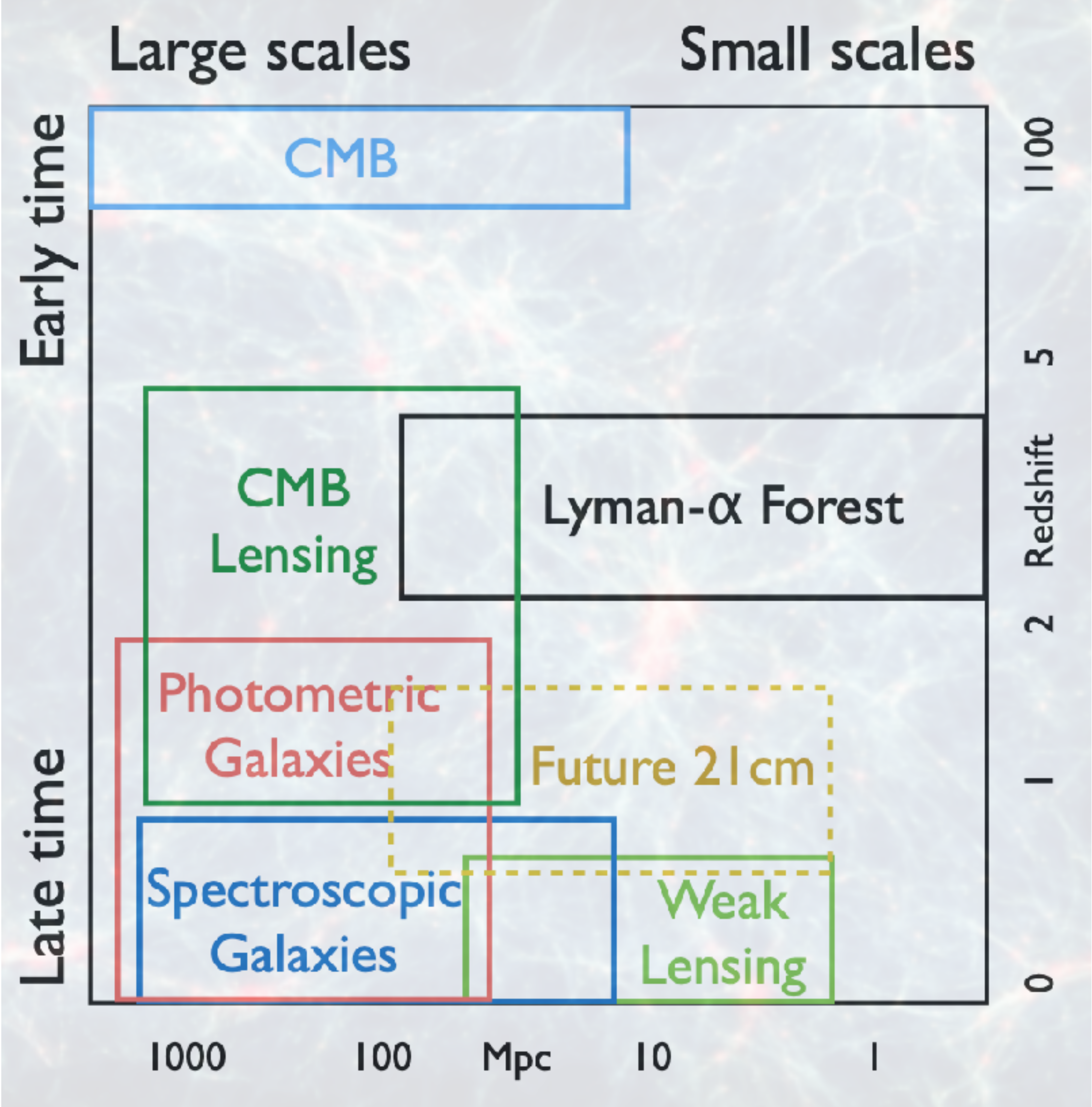
Planck+BAO: Σm_ν < 126 meV

Planck data somewhat favors "unphysical" neutrino mass

Probes of Σm_ν with matter distribution

Many probes in the market
All with sensitivity to Σm_ν
Degeneracies with other cosmo pars
Mitigate impacts of systematics
- NL effects (optimal k / ell range)
- baryons, bias, IA, others ...

CMB lensing
Full-shape P(k) from clustering (incl. RSD)
Galaxy WL statistics
Void properties
Lyman-alpha forest
Cross-correlations
...



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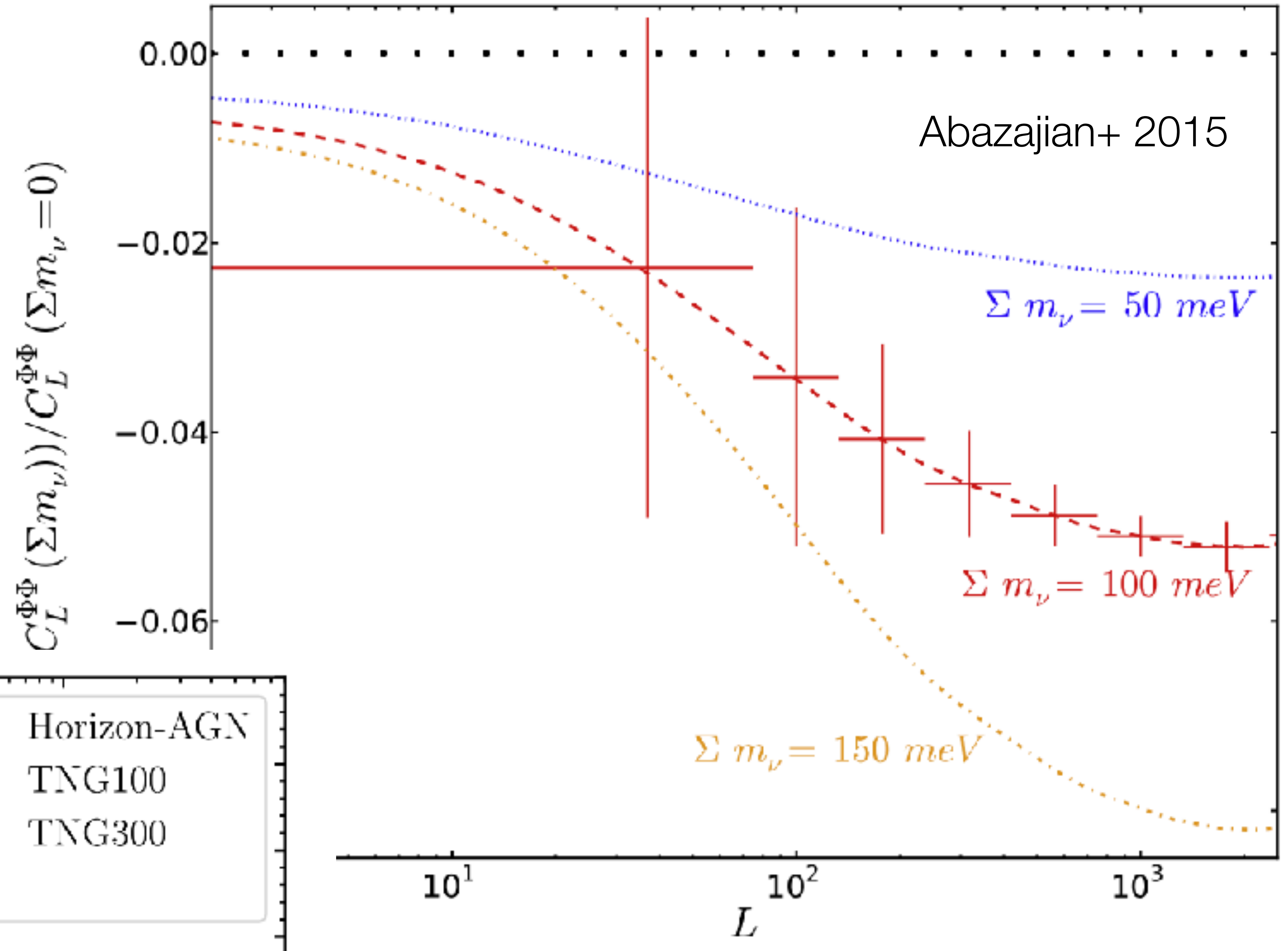

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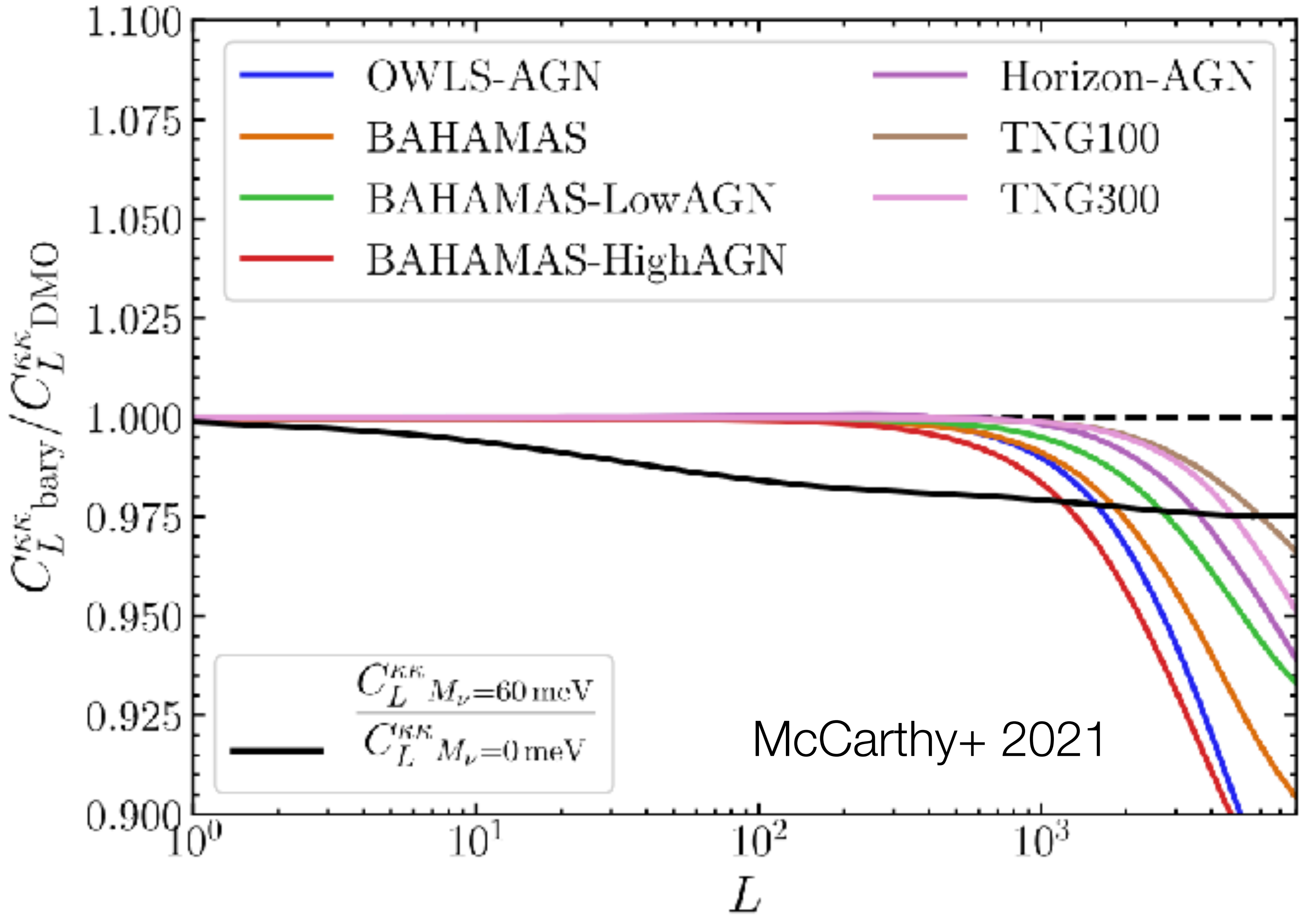

high-ell data contaminated by feedback

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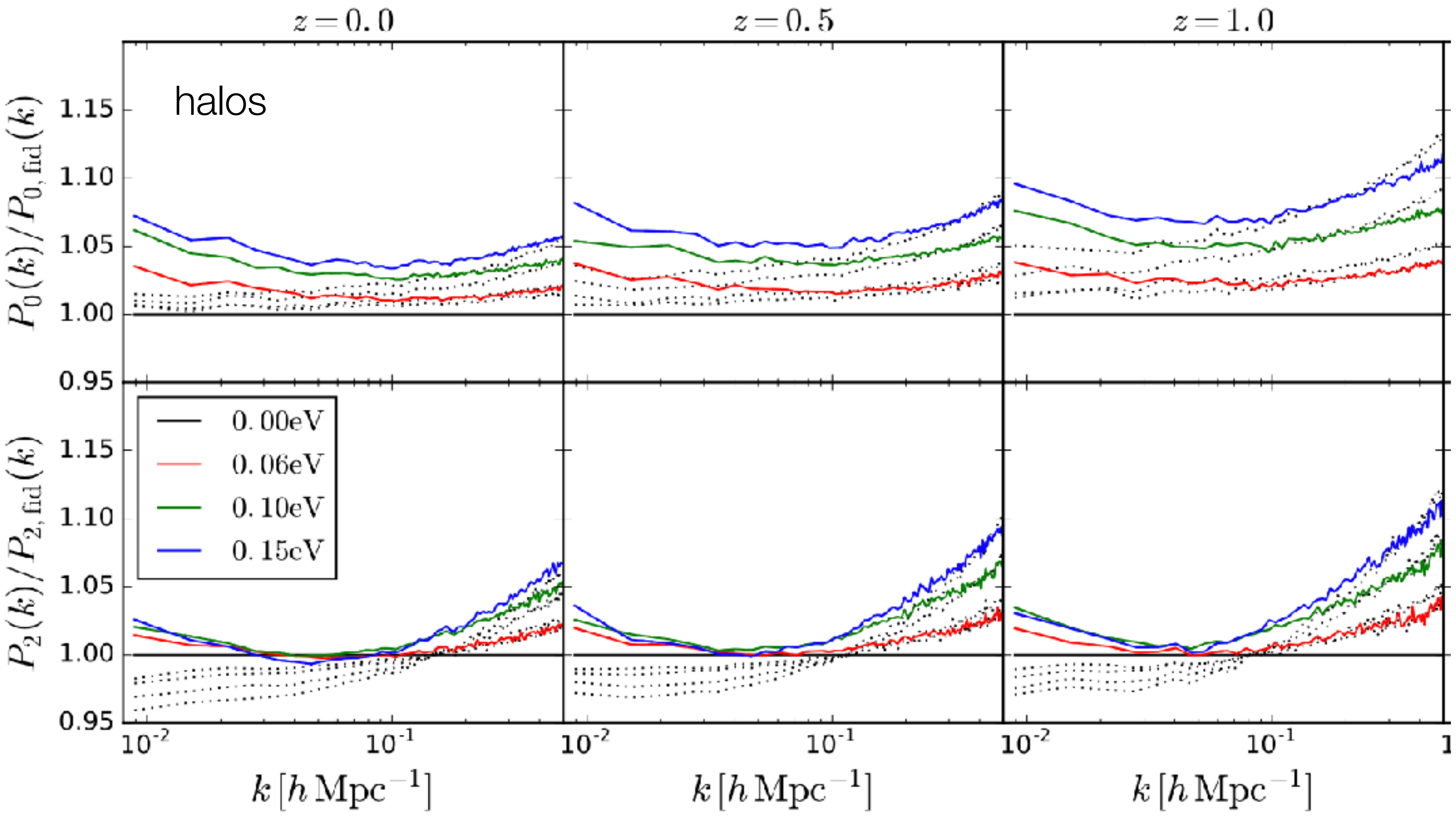

Villaescusa-Navarro+ 2017

subtleties about bias...

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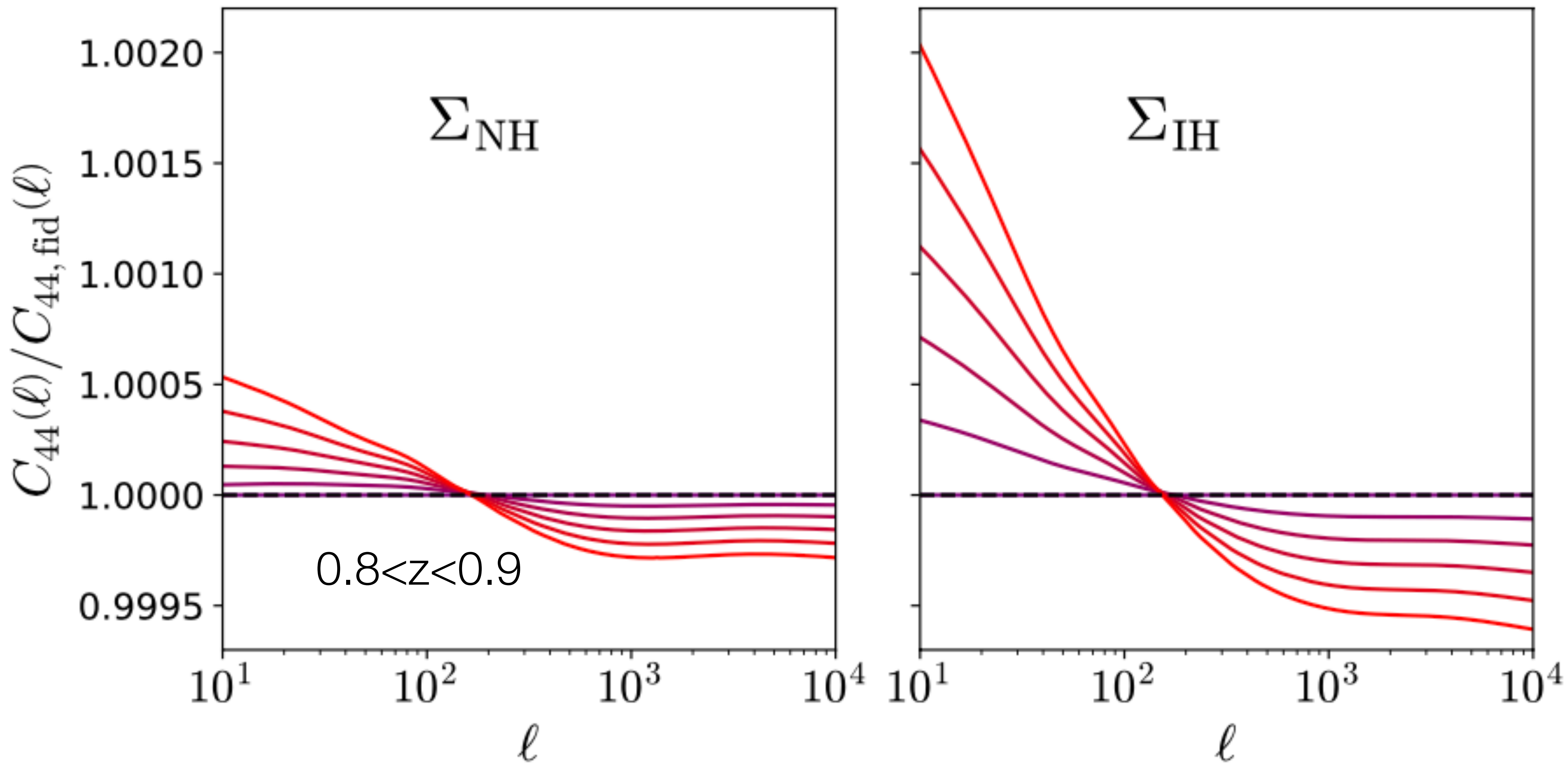
Copeland+ 2019



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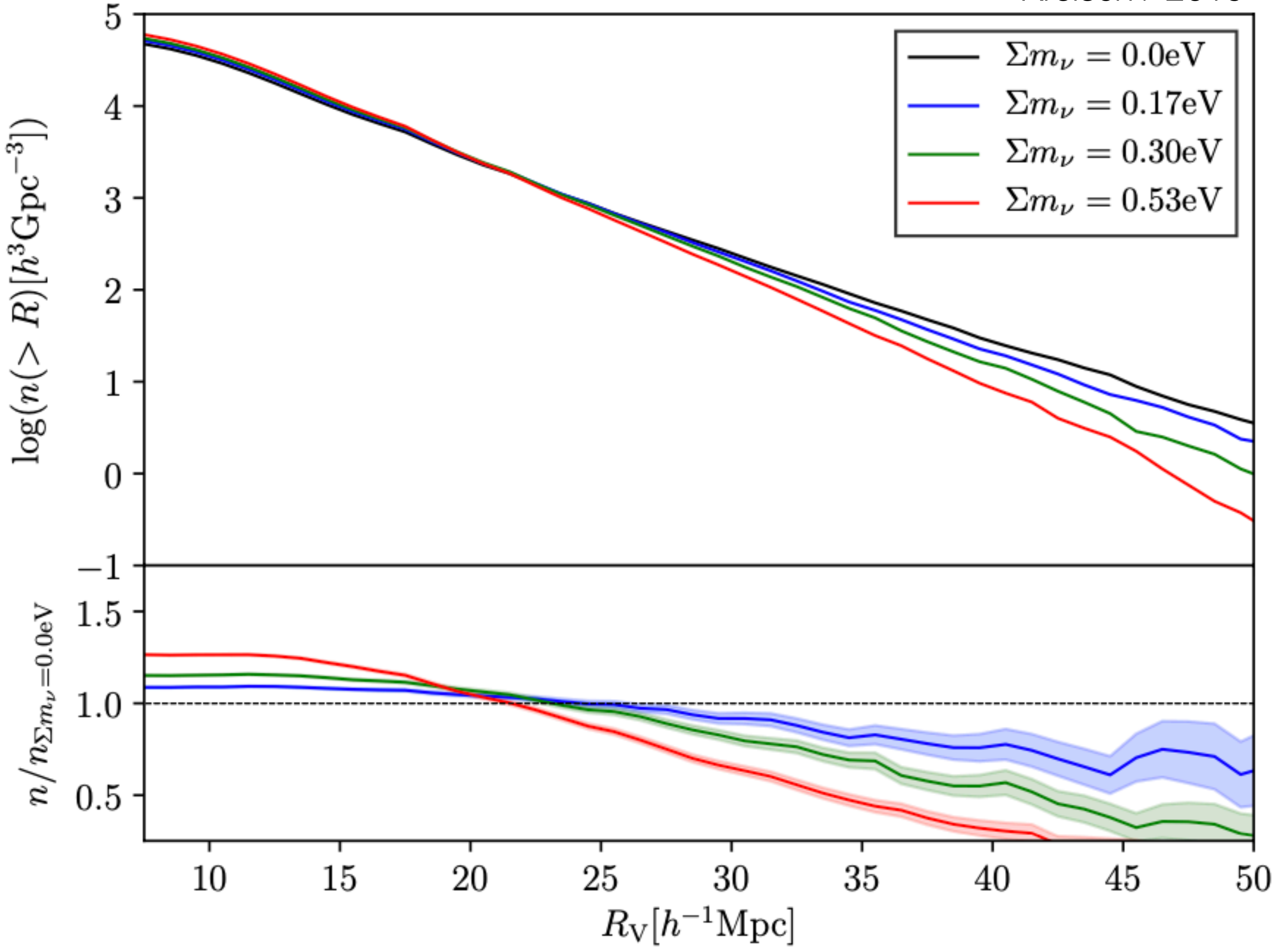
Kreisch+ 2019



Forecast ...

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\rm eff}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\rm max} = 0.1h\,{\rm Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\rm max} = 0.2h\,{\rm Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\rm max} = 0.2$)	0.020	0.062

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

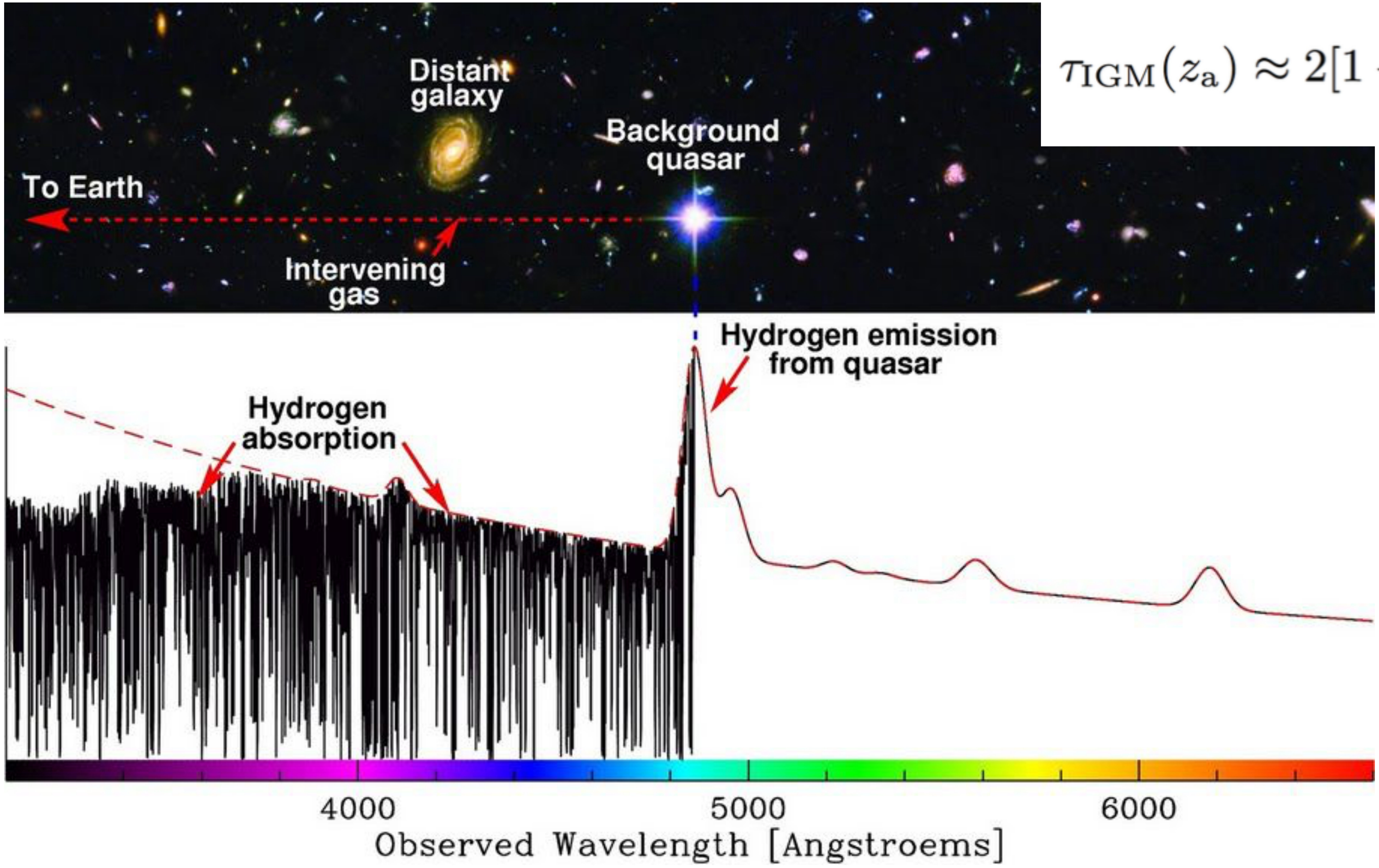
CMB-S4
Next Generation CMB Experiment

Setup	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
S4	73	111	0.79	1.14	2.46
(+ DESI BAO)	29	76	0.48	0.13	0.41
LSST-clustering	69	91	3.33	0.42	1.22
LSST-shear	41	120	2.99	0.19	0.57
LSST-shear+clust	32	72	2.06	0.11	0.33
S4+LSST	23	28	0.49	0.10	0.26
	-	24	0.49	-	-

Setup (+CV-τ)	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
LSST-clustering	69	91	3.3	0.42	1.20
LSST-shear	31	117	2.82	0.18	0.55
LSST-shear+clust	24	72	1.99	0.11	0.31
S4+LSST	14	21	0.49	0.10	0.26
	-	15	0.49	-	-

From C. Yèche, ADE 2019

The example of Lyman-α forest



$$\tau_{\rm IGM}(z_{\rm a}) \approx 2[1+\delta(z_{\rm a})]^2 \frac{\alpha_{\rm rec}(T)}{\Gamma} \left(\frac{1+z_{\rm a}}{4}\right)^{4.5}$$

n_{HI}

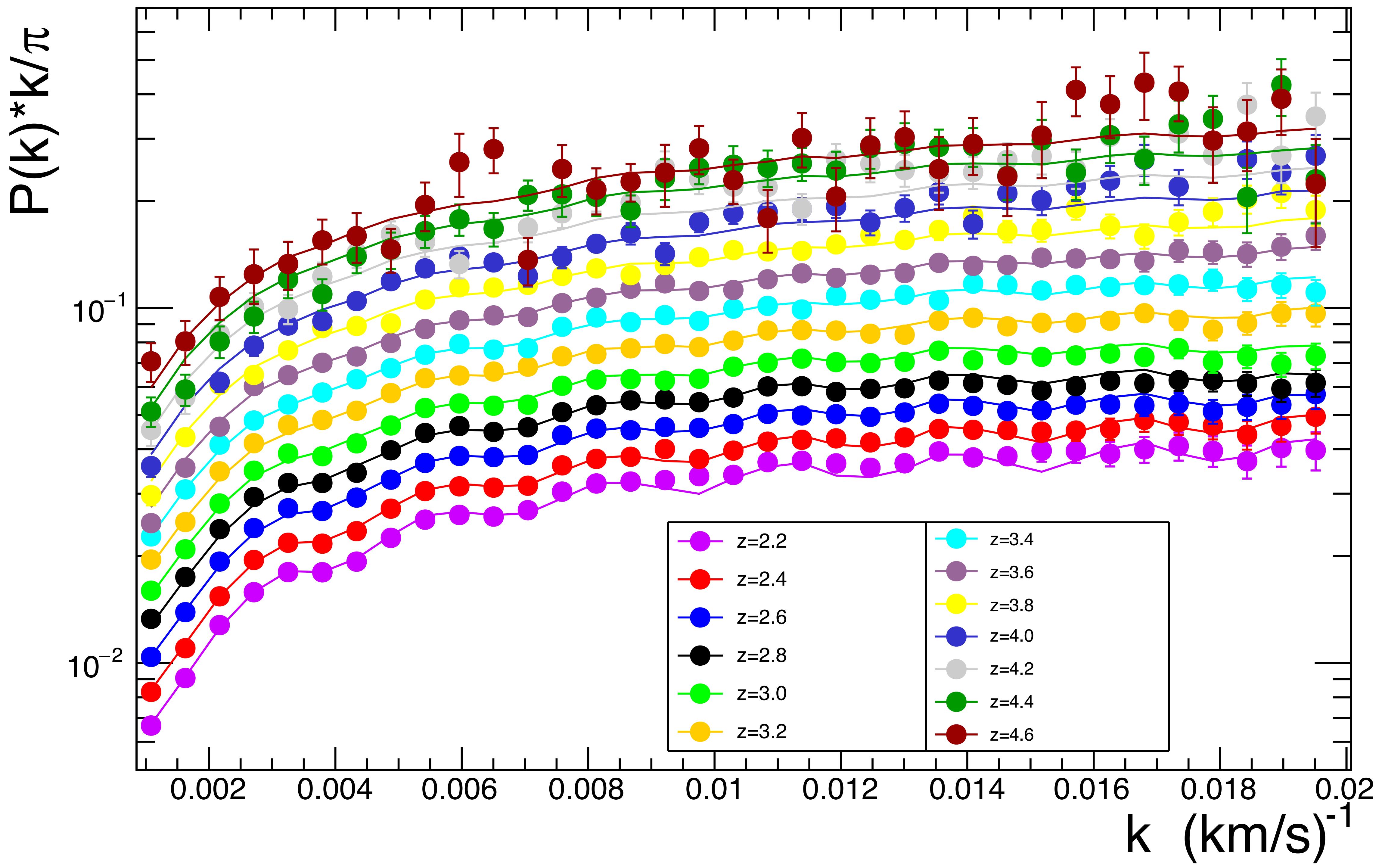
Measure exp(-τ)

τ ~ 1 for **mild density fluctuations in the IGM**

Measured small-scale correlations in Ly-α forest: P1D

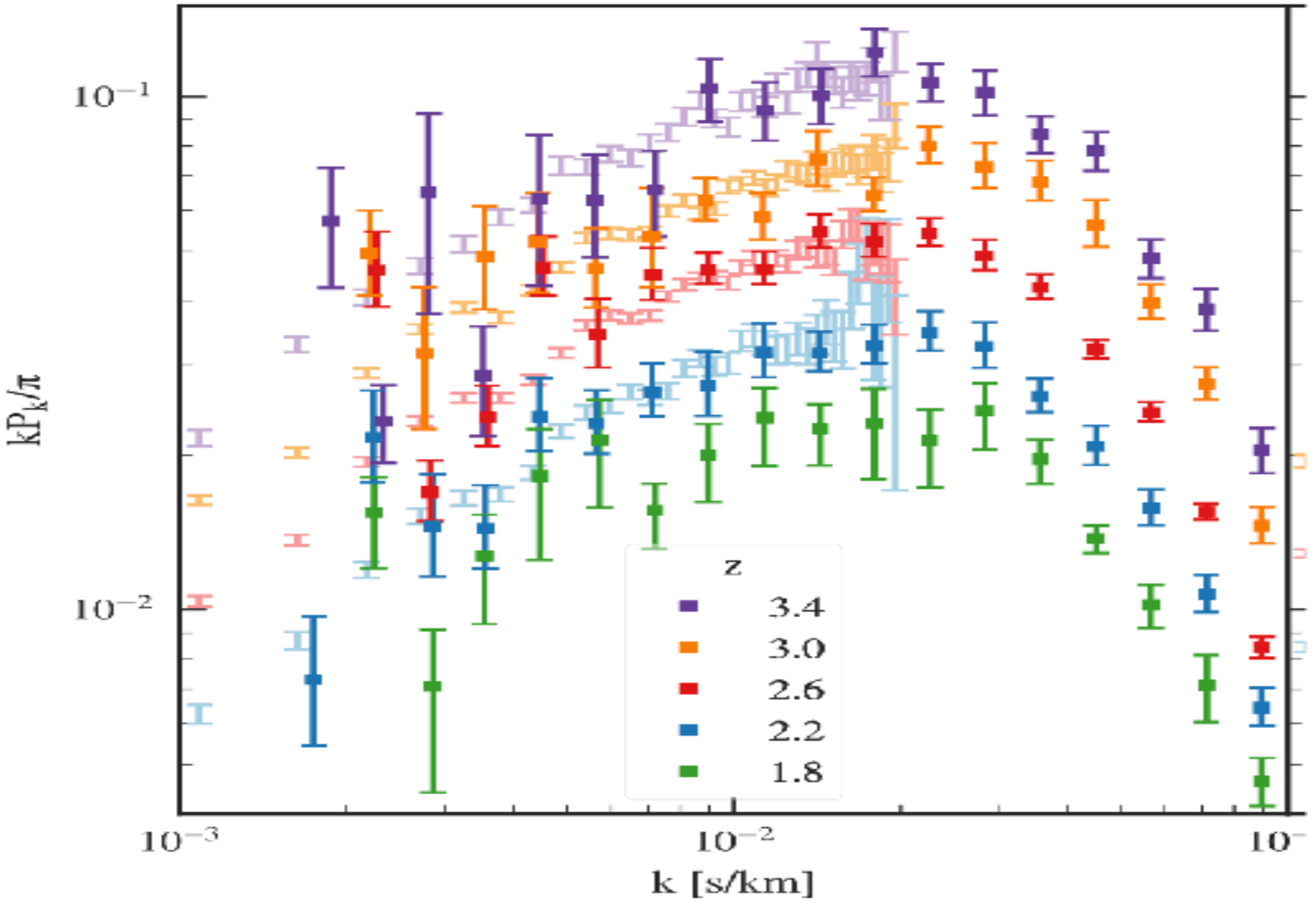
Currently, separation between lines-of-sight >> Mpc
==> measure **1D power spectrum of absorption fluctuations** ~ correlations within individual lines-of-sight

Chabanier+ 2019



eBOSS

Walther+ 2018

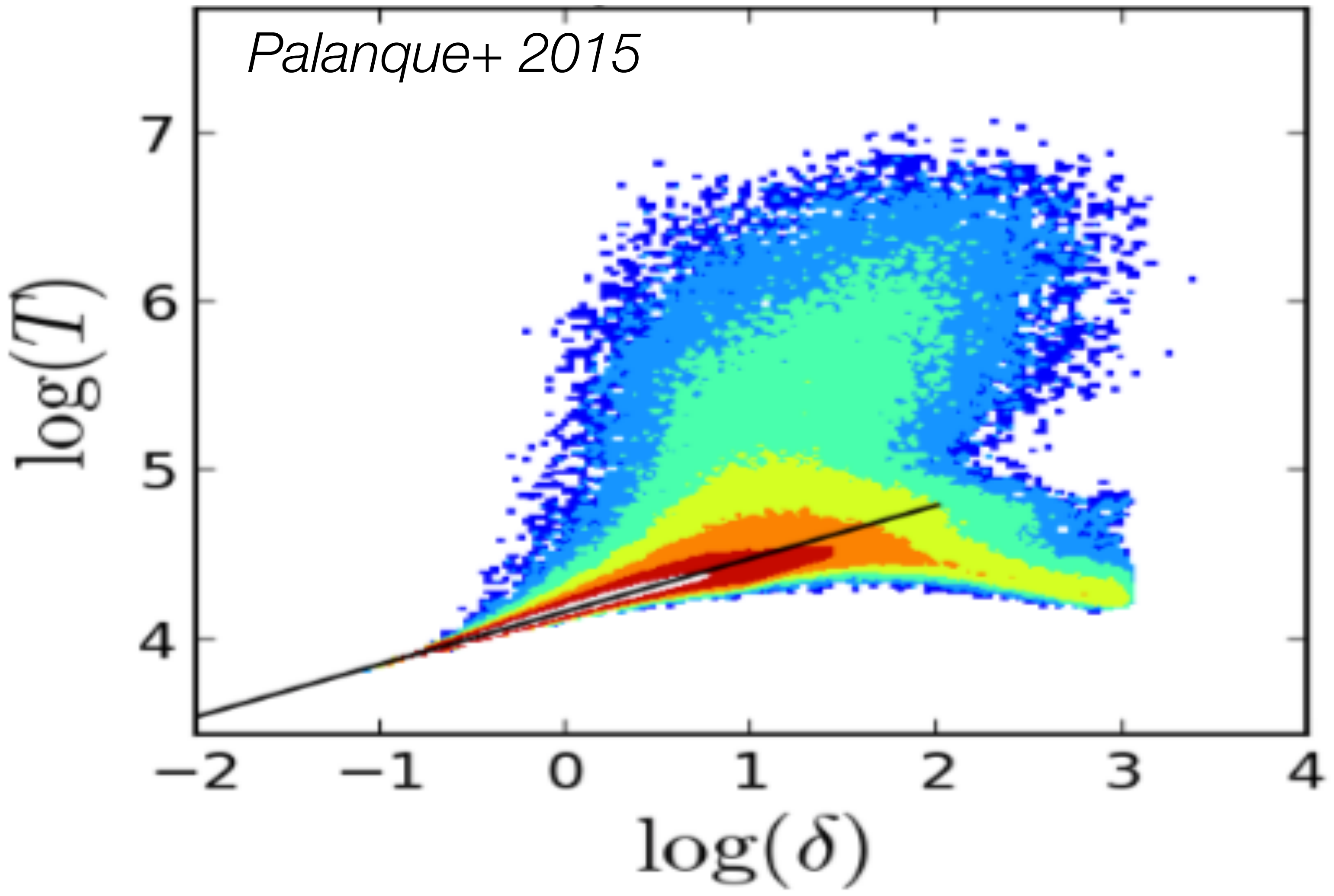


high-resolution

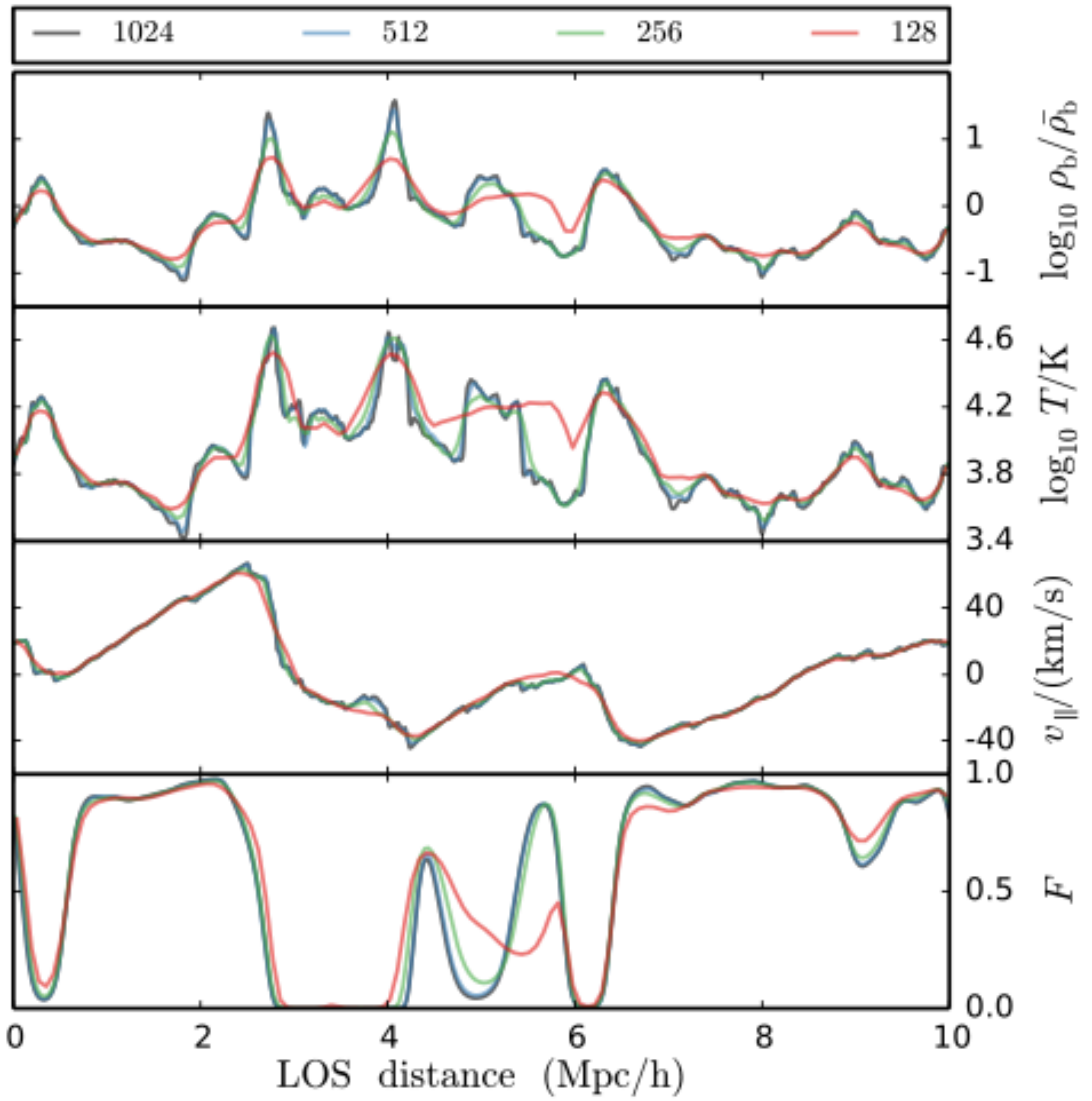
"Full-shape" modelling P1D

Hydro simulations
Gadget (SPH for baryons) with "QUICKLYA" ~ do not model galaxies
Draw skewers through snapshots, compute $(P1D)_{model}$
Box size ~ 100 Mpc
Start simulation @ z=30 (massive neutrinos) !

Grid of cosmology + IGM parameters
"Taylor" interpolation between simulation points



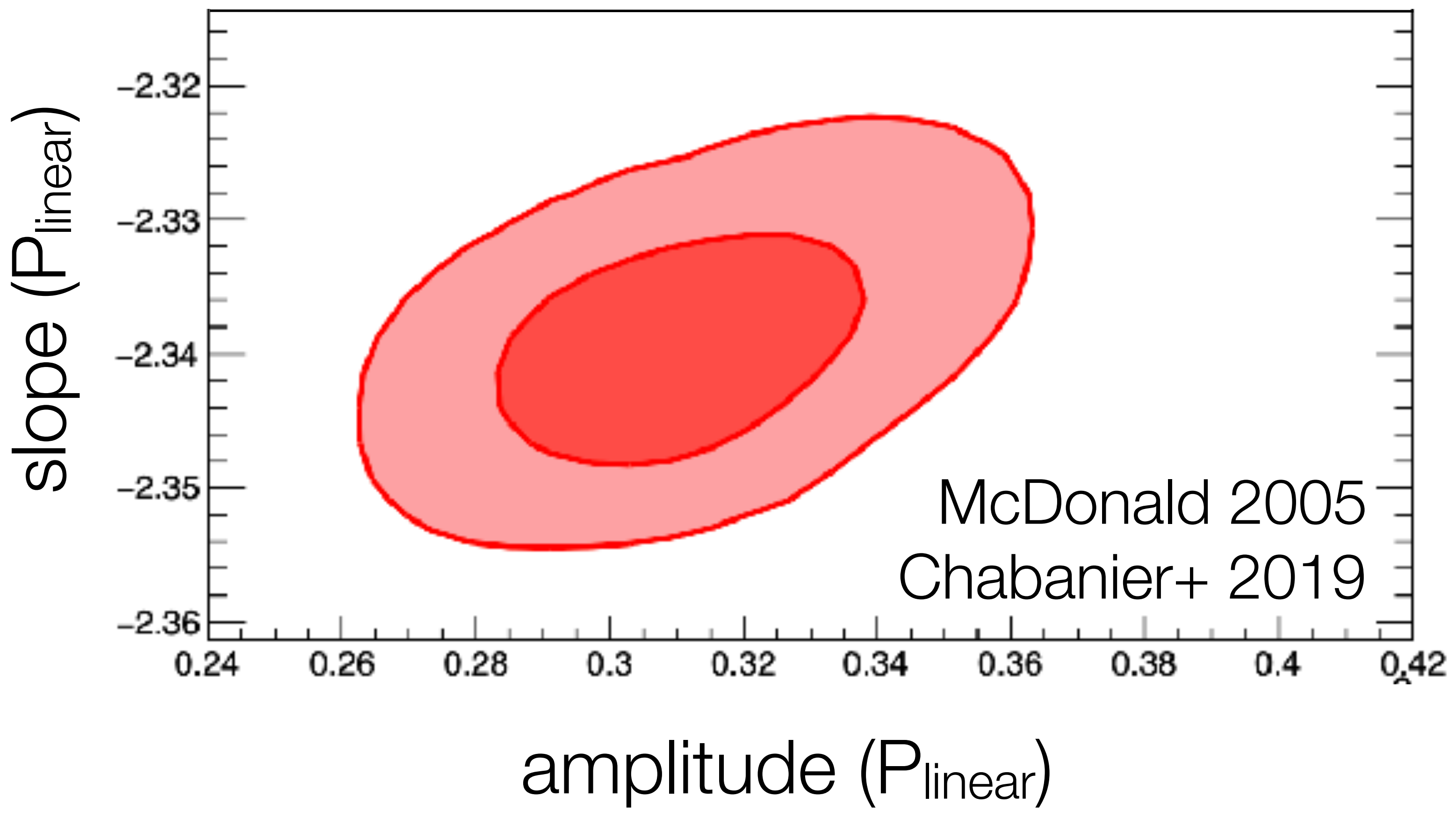
Parameter	Central value	Range
n_s	0.96	± 0.05
σ_8	0.83	± 0.05
Ω_m	0.31	± 0.05
H_0	67.5	± 5
$T_0(z=3)$	14000	± 7000
$\gamma(z=3)$..	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4
$\sum m_\nu$ (eV)	0.0	0.4, 0.8



Σm_ν from P1D

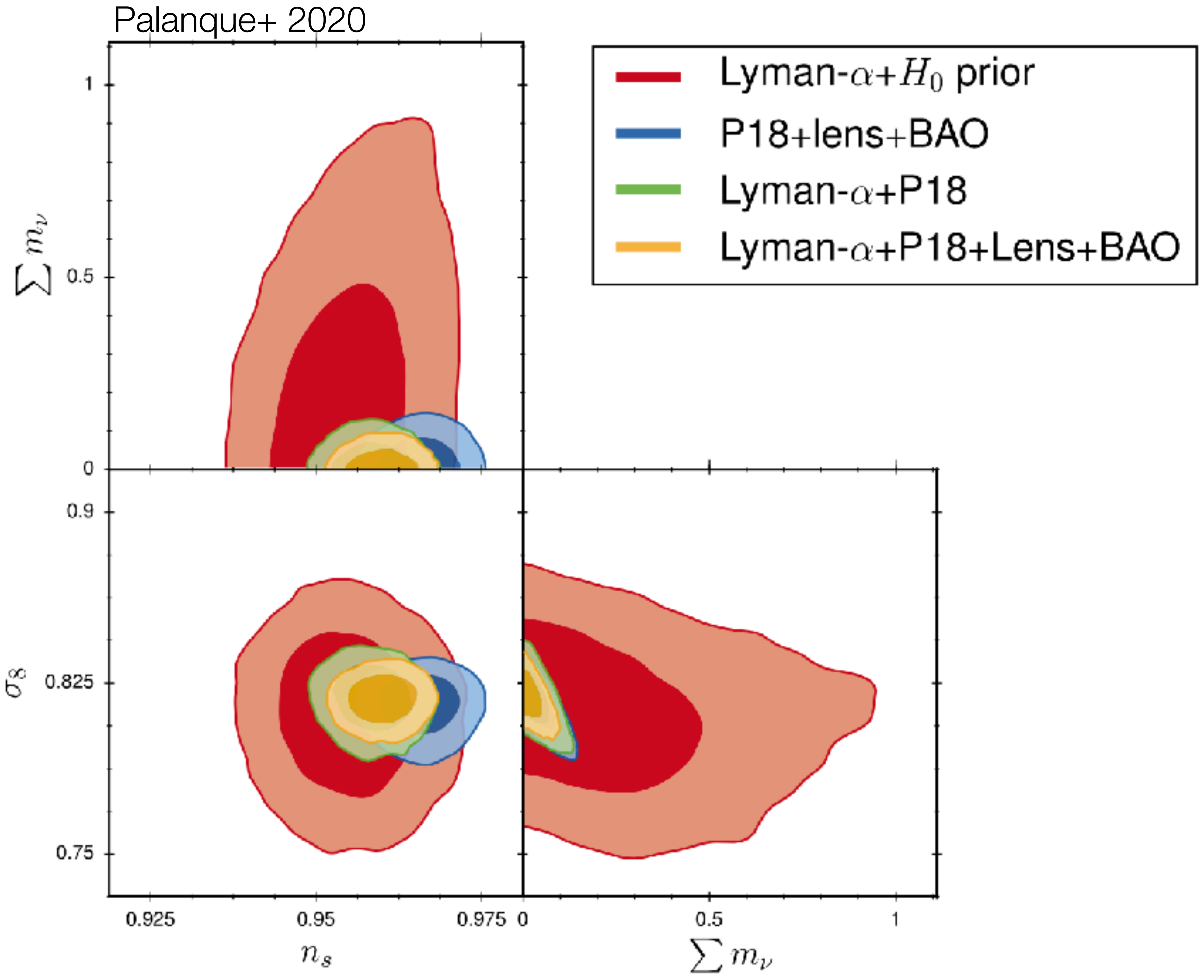
Main "cosmo" information in P1D:

P_{linear} @ (zp, kp) = (3, 0.009 s/km)



nuisance parameters:

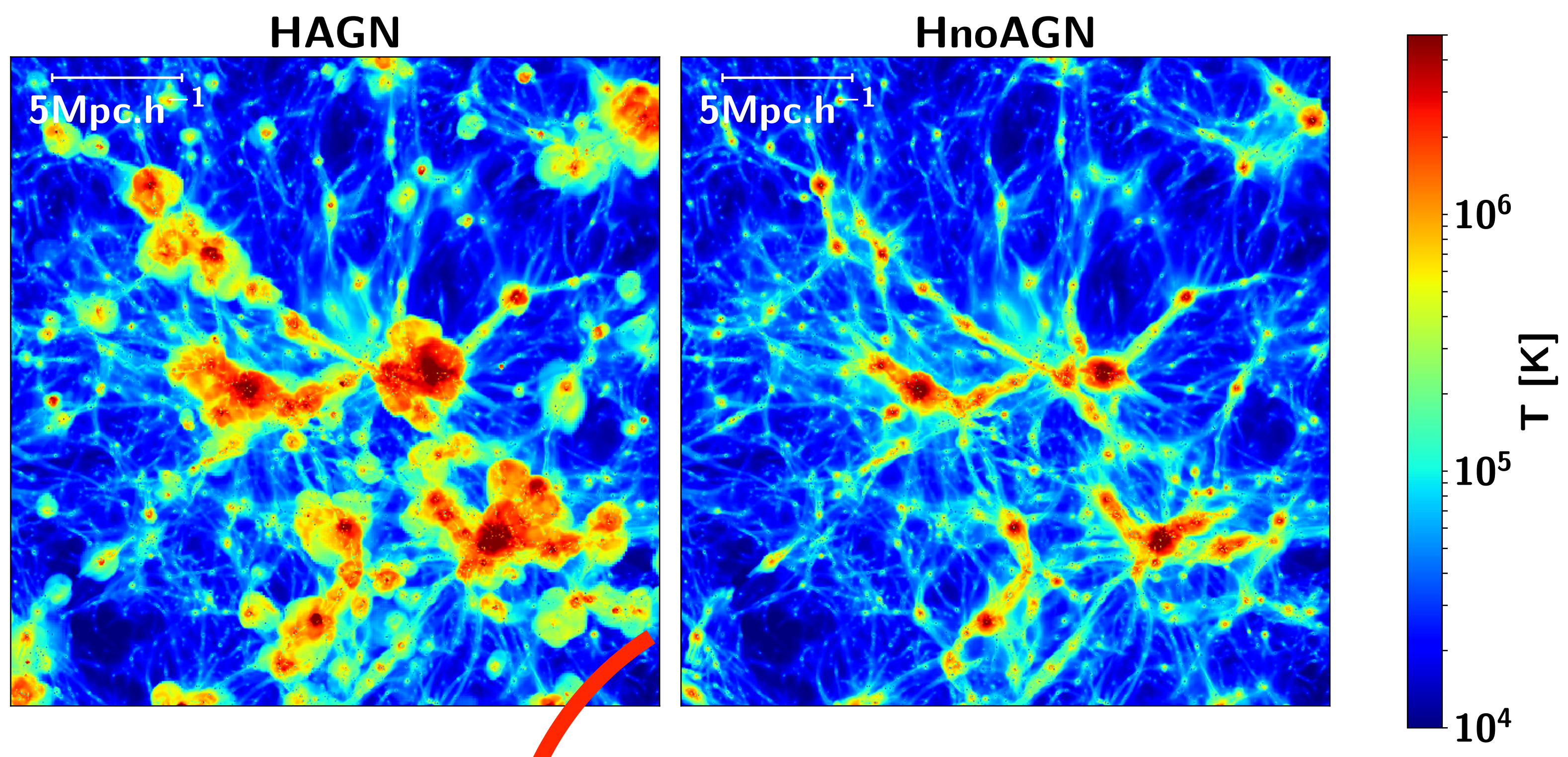
$T_0(z=3)$	Normalization temperature of IGM at $z=3$
$\gamma(z=3)$	Logarithmic slope of δ-dependence of IGM temperature at $z=3$
$\eta^T(z<3)$	Logarithmic slope of z-dependence of T_0 for $z<3$
$\eta^T(z>3)$	Logarithmic slope of z-dependence of T_0 for $z>3$
η^γ	Logarithmic slope of z-dependence of γ
A^τ	Amplitude of the effective optical depth of Lyα absorption $\tau_{\rm eff}$
η^τ	Logarithmic slope of redshift dependence of $\tau_{\rm eff}$
$f_{\rm Si\,III}$	Fraction of Si III absorption relative to Lyα absorption
$f_{\rm Si\,II}$	Fraction of Si II absorption relative to Lyα absorption
$z_{\rm reio}$	Redshift of reionization
$A^{\rm splice}$	Amplitude of splicing correction
$\eta^{\rm splice}$	Small-scale slope of splicing correction
$A^{\rm SN}$	Amplitude of supernova feedback correction
$A^{\rm AGN}$	Amplitude of AGN feedback correction
$A^{\rm UVfluct}$	Amplitude of UV fluctuation correction
$A^{n,i}$	Amplitude of noise power correction for redshift bin i

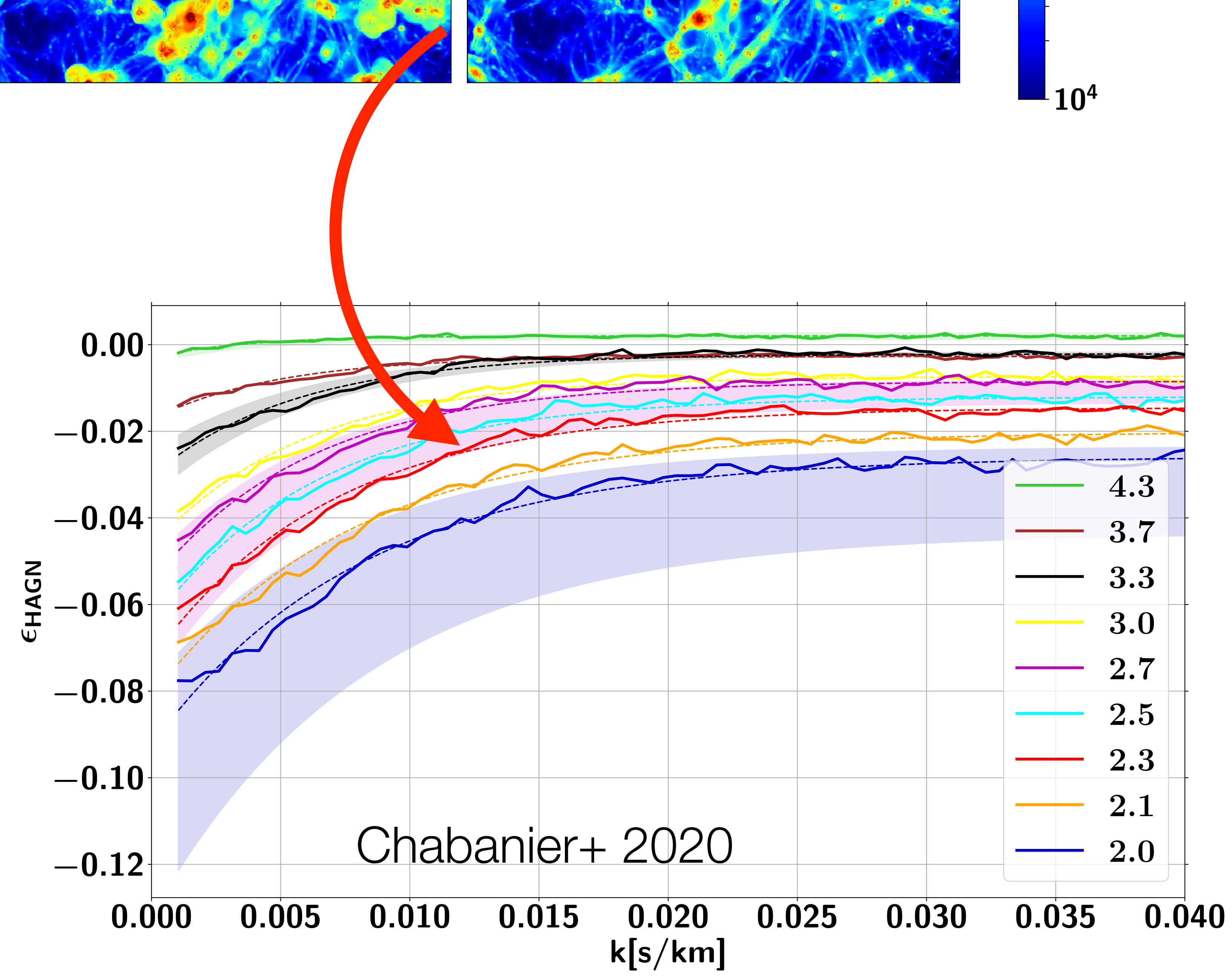


Planck + P1D: Σm_ν < 110 meV

Lyman-α ongoing improvements: modelling

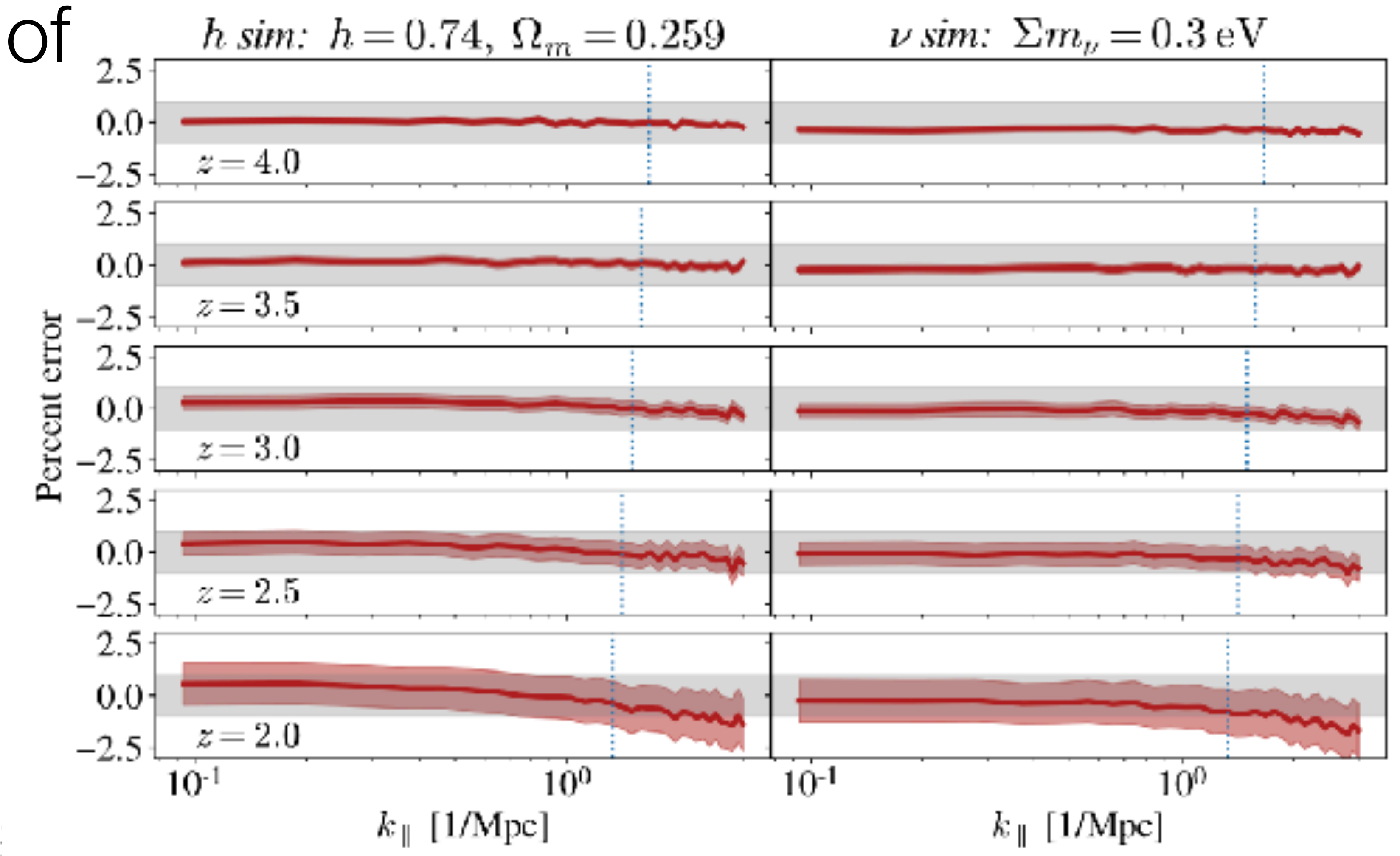
- Quantify feedback, inhomogeneous UV background ...



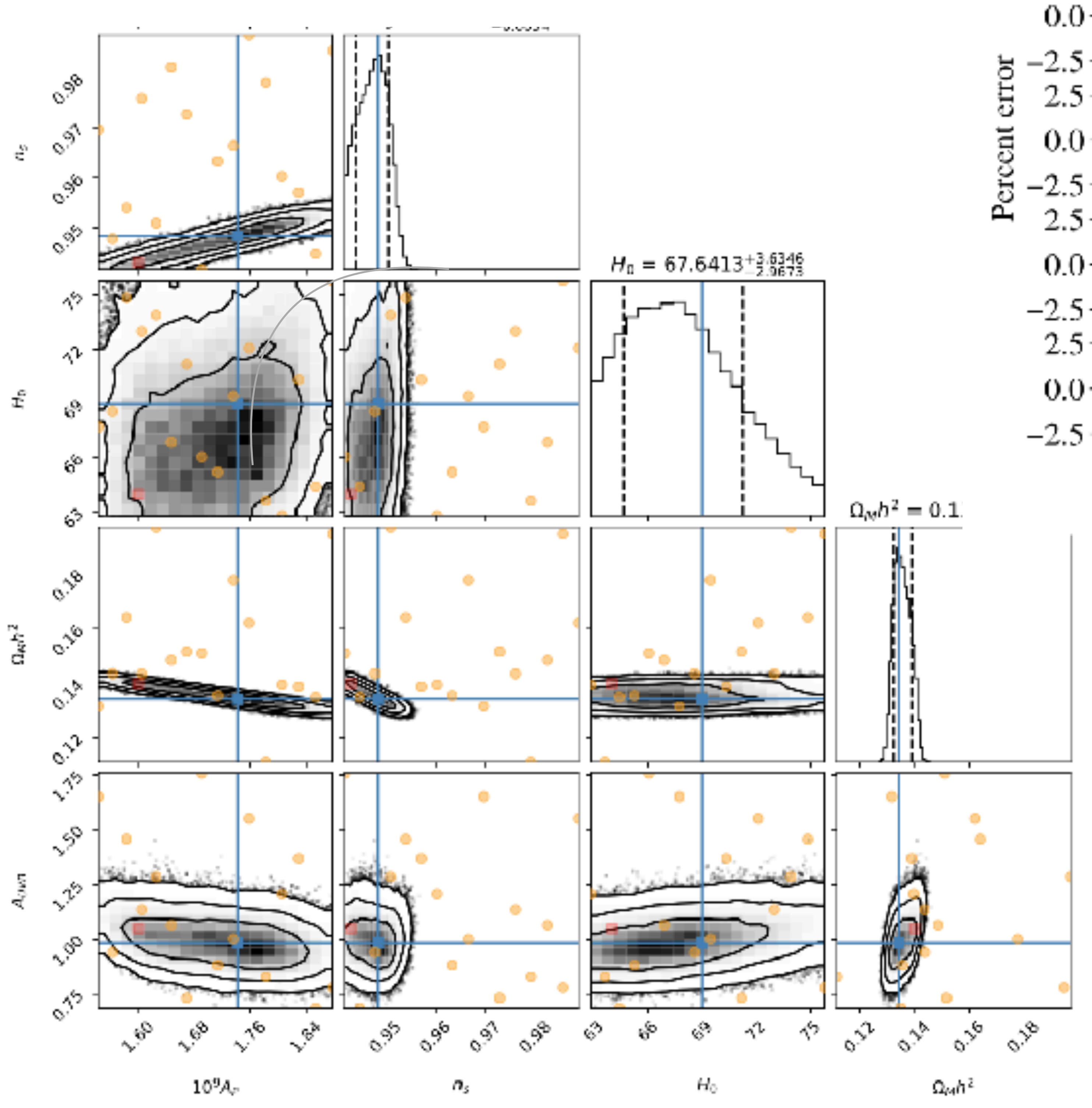


Chabanier+ 2020

- Optimize hydro grid : choice of parameter space, emulator



Pedersen+ 2021



Walther+ 2020

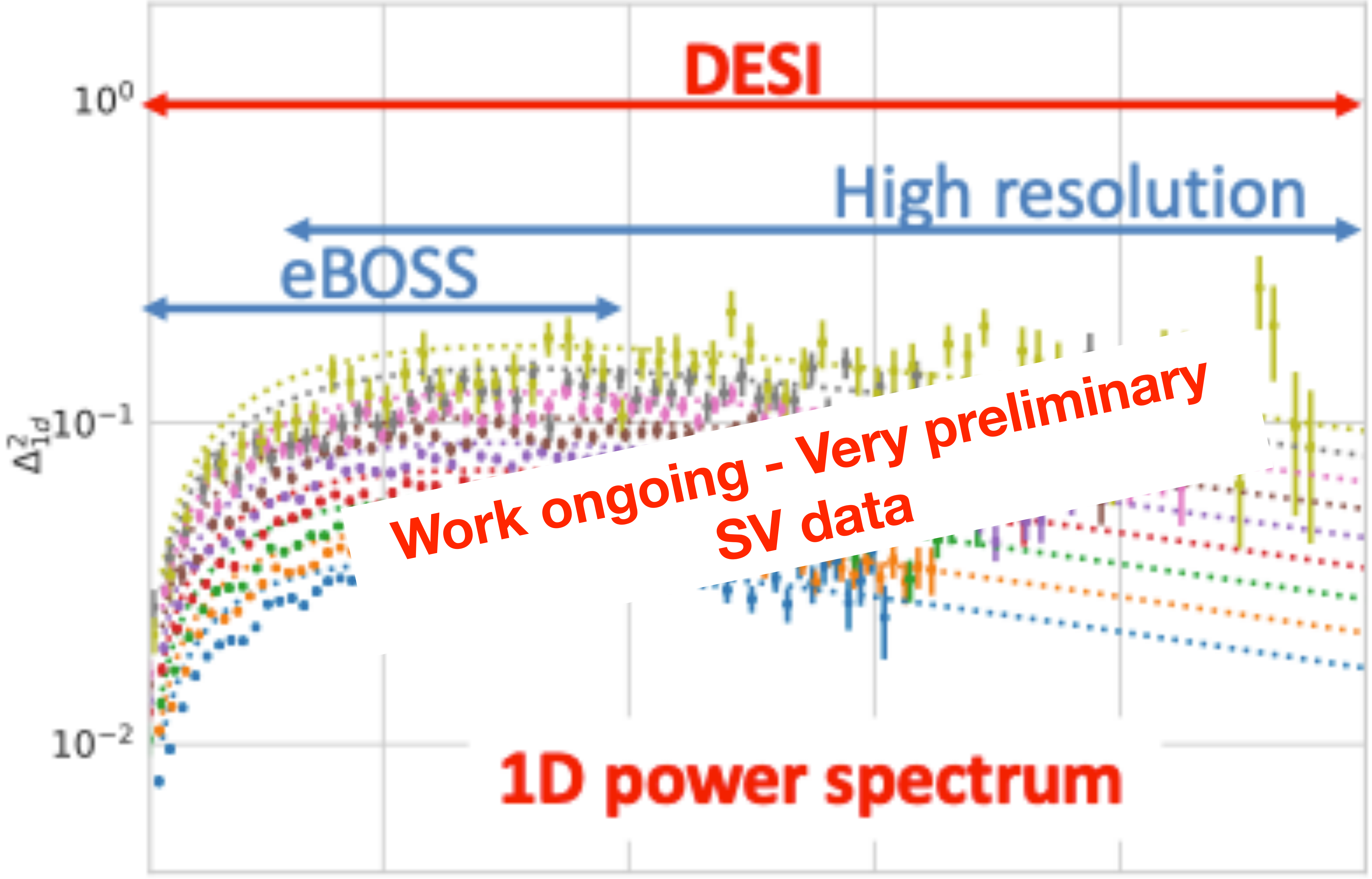
- See also LyAl-Net (Chotipan yesterday), LyMAS (Peirani 2022), ...

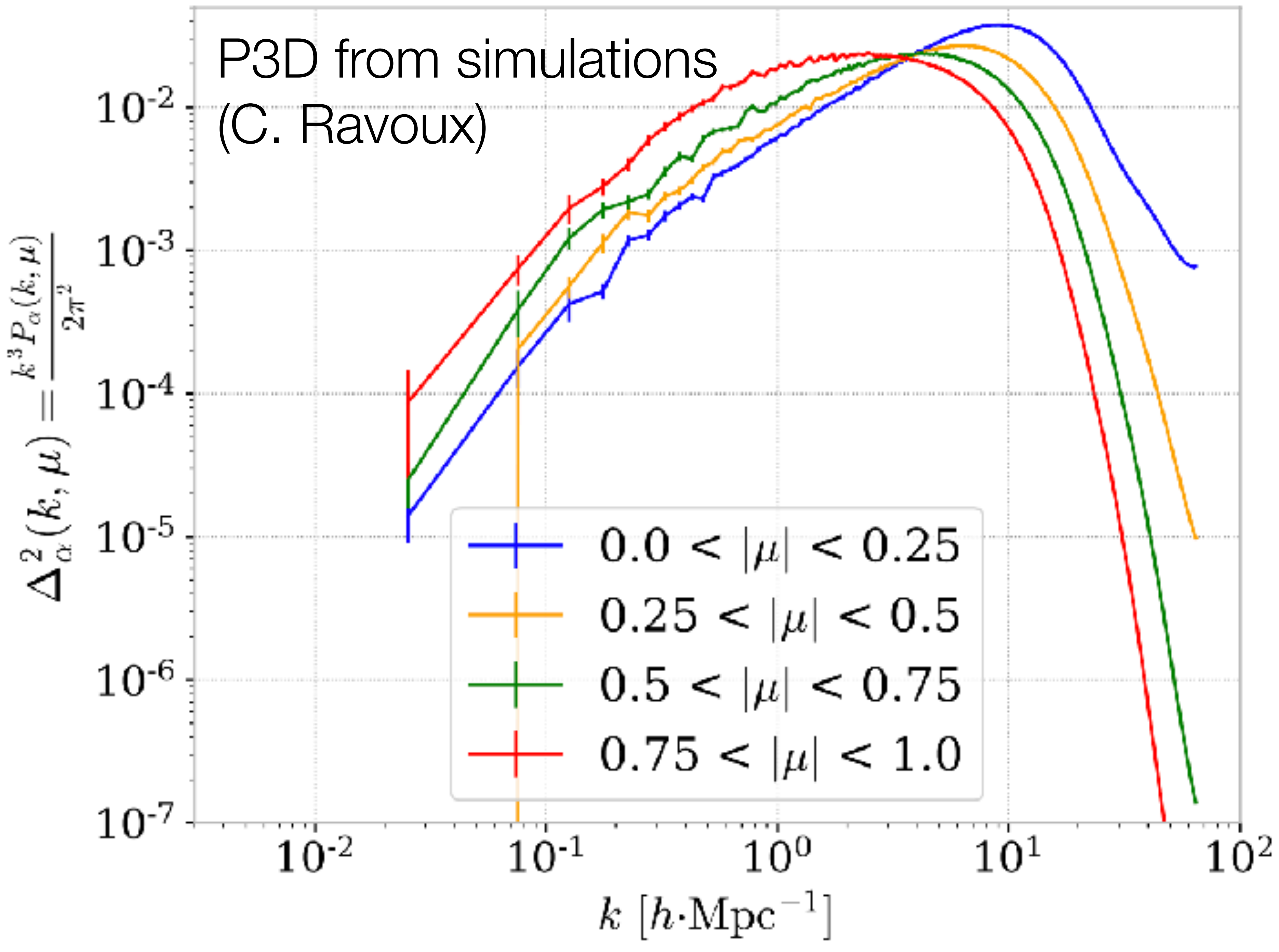
Lyman-α ongoing improvements: data

DESI & WEAVE-QSO : more statistics, higher resolution

Large lines-of-sight density ⇒ measure P3D (improve IGM thermal params) ?

First analysis of DESI-SV ongoing !





Conclusions

- Measuring Σm_ν would be an achievement for "precision cosmology"
  - Short-term ~2025 ? $\sigma(\Sigma m_\nu)$ ~ 20-30 meV, ~3σ detection ?
  - Later ? improved τ measurement ⇒ ~4-5σ ?

- Several probes in the market for small-scale P(k)
  - Have to demonstrate control of their own systematics

- **Other "beyond standard model" neutrino physics with cosmology:**
  - Sterile neutrinos: Neff, P(k) cut-off @ high k
  - New interactions (connection to dark sector): P(k), reionization...