COSMOLOGICAL CONSTRAINTS ON NEUTRINO MASSES: PRESENT STATUS AND FUTURE PROSPECTS

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NuTs Workshop

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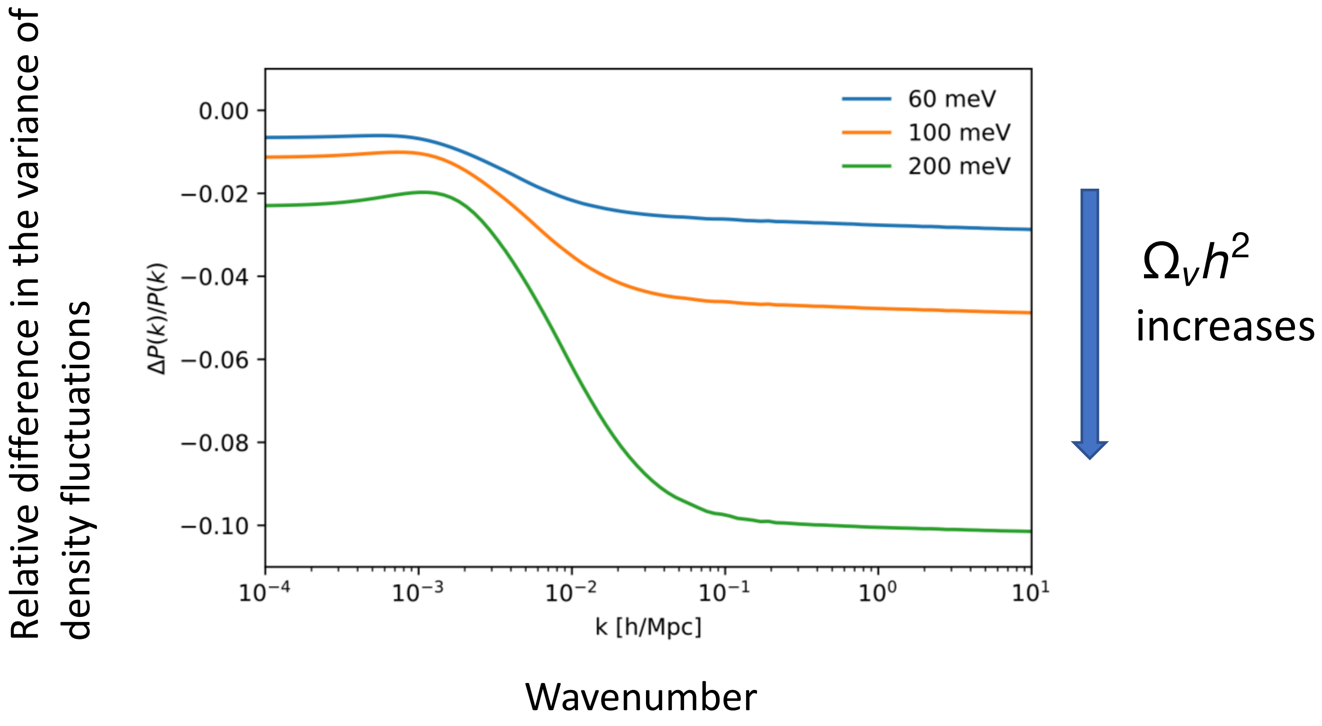
May 16th, 2022

NEUTRINO MASSES IN COSMOLOGY (A CRASH COURSE)

Structure formation below the (effective) Jeans scale is **suppressed** in a Universe with massive neutrinos



Probes of density fluctuations below the Jeans scale:

- Gravitational weak lensing of the CMB
- Clustering and weak lensing of galaxies
- Number density of galaxy clusters
- (+ their cross-correlation)

can be used to measure neutrino masses from cosmology.

$$\Omega_\nu h^2 = 6.2 \times 10^{-4} \left(\frac{\sum m_\nu}{58\,\mathrm{eV}} \right)$$

$$\sum m_\nu \equiv m_1 + m_2 + m_3$$

Weak Lensing of the CMB

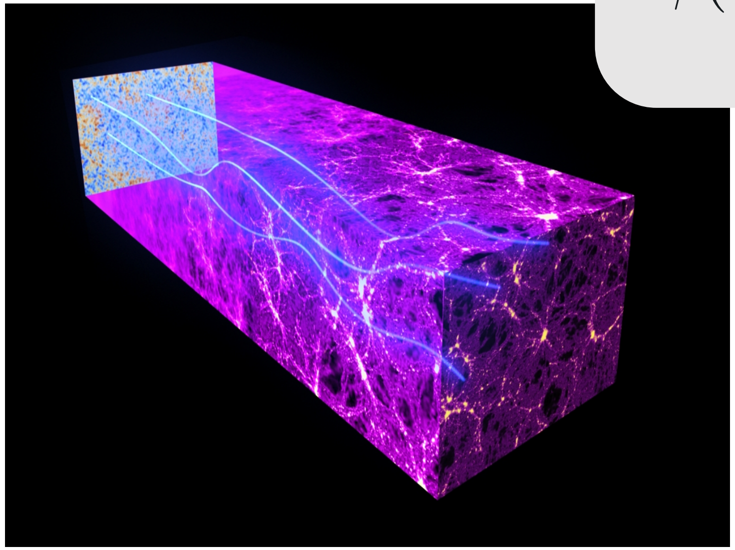
The observed CMB field T^{obs} is displaced wrt to the "unlensed" field T^{unl}, i.e. the one that would be seen in a perfectly homogeneous Universe, due to the lensing effect of intervening structures between us and the LSS:

$$T^{\rm obs}(\vec{n}) = T^{\rm unl}(\vec{n} + \vec{d})$$

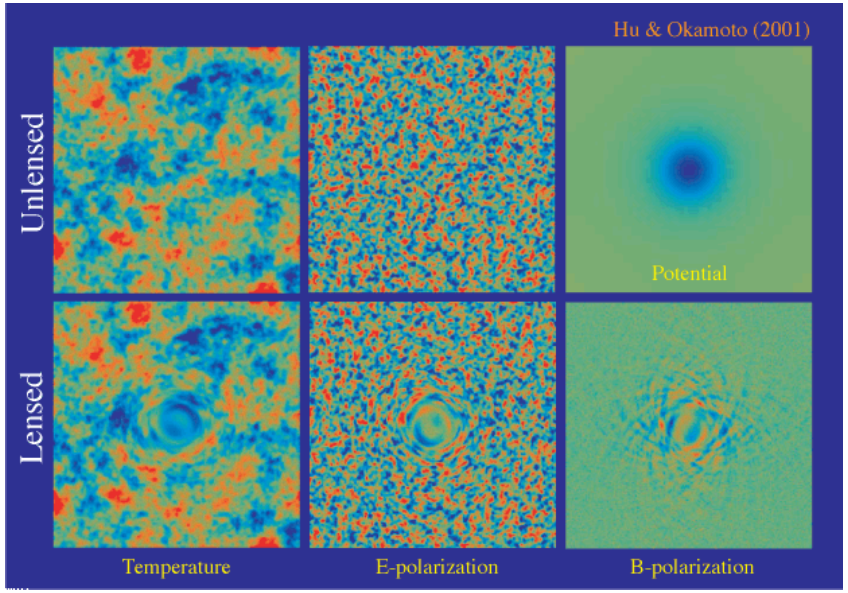
$\vec{d} = \vec{\nabla}\phi$ is the deflection field

Line-of-sight integral of the gravitational potentials

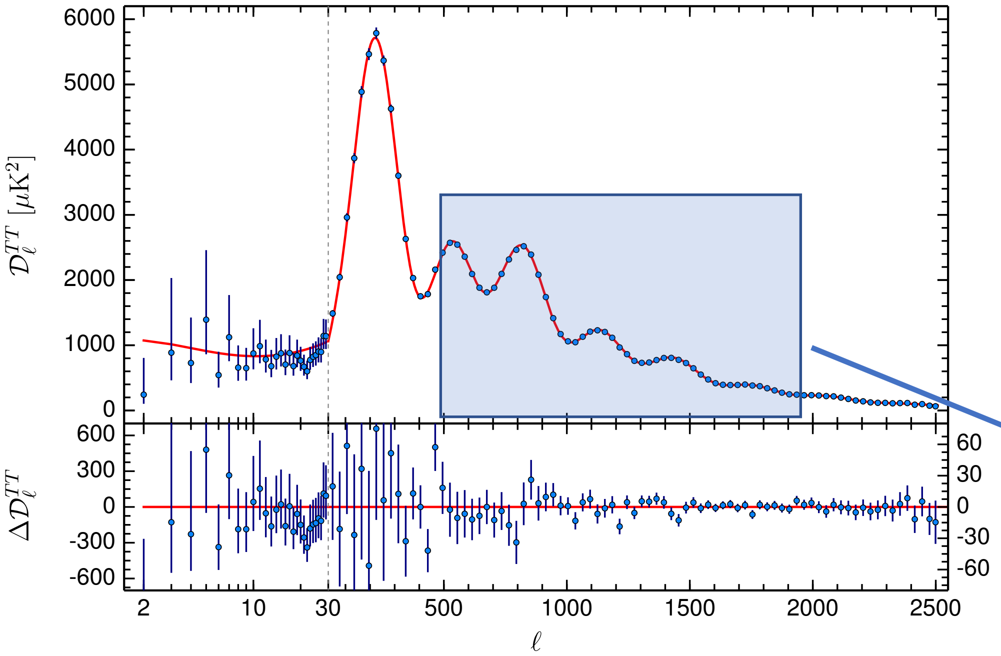
$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$



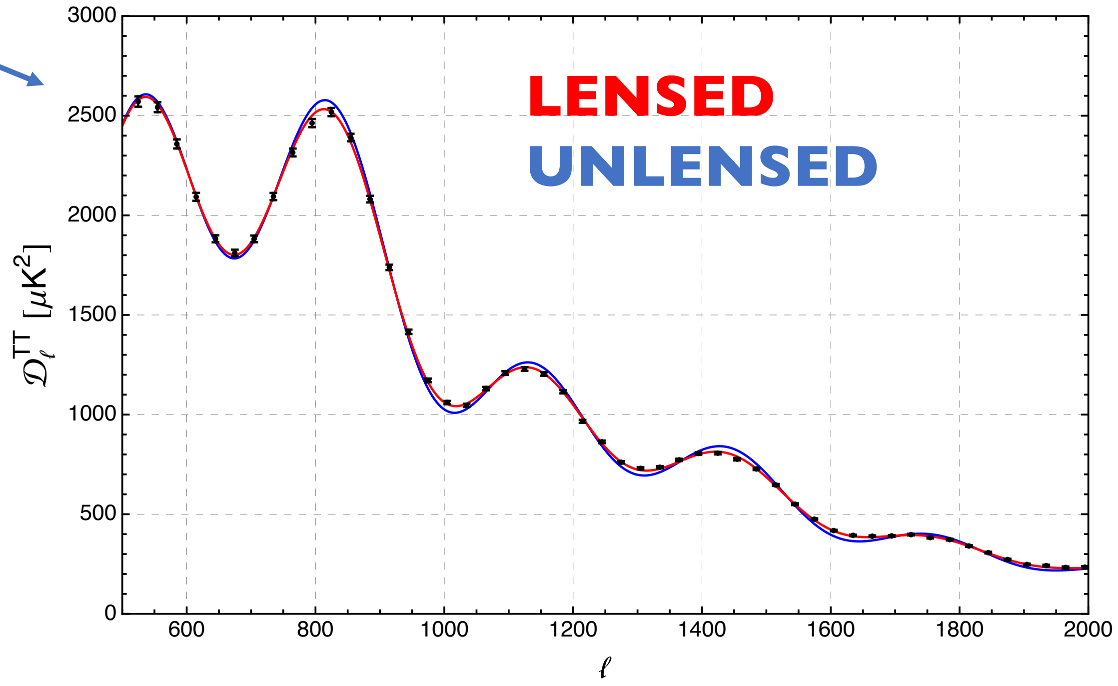
Makes CMB sensitive to the late-time density field, too….



WEAK LENSING OF THE CMB



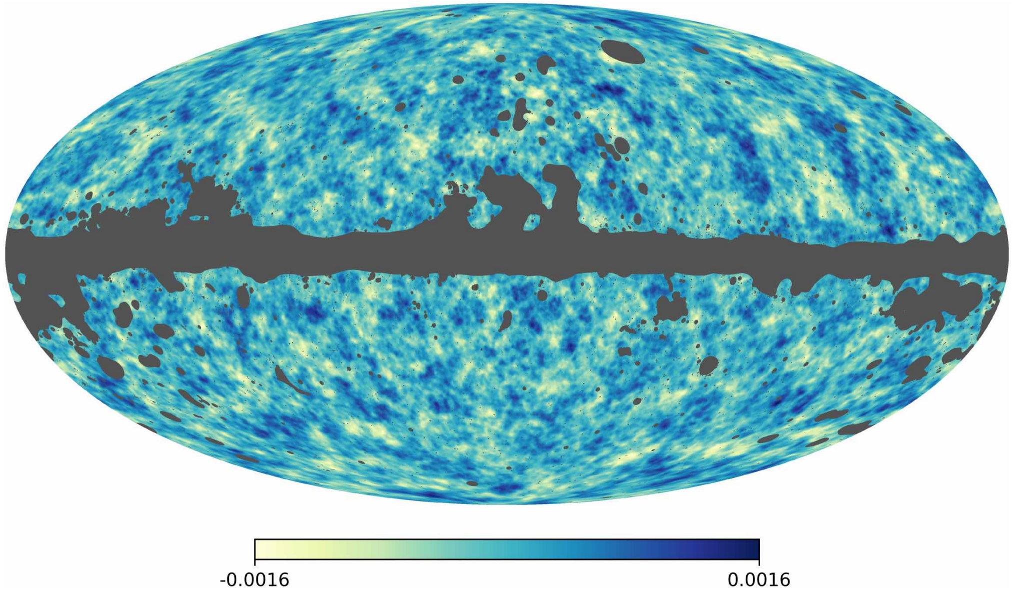
In the power spectrum, lensing causes a smoothing effect at small scales



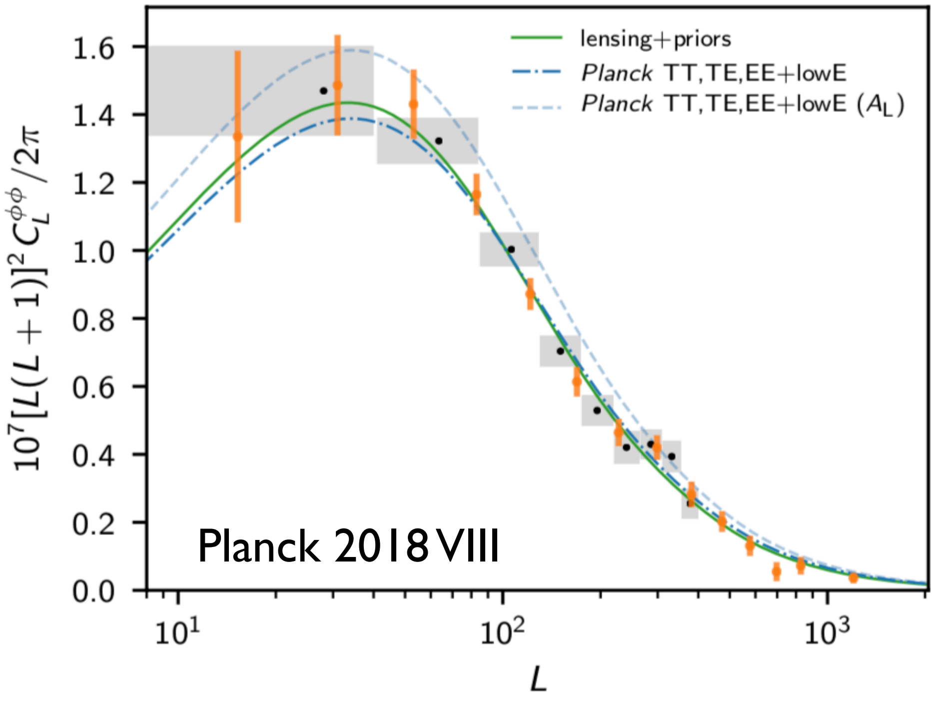
Neutrino free streaming damps matter perturbations and *reduces* lensing

The effect is proportional to the energy density of neutrinos

WEAK LENSING OF THE CMB



The induced nongaussianities can be used to reconstruct the lensing potential field



Map and power spectrum of the lensing potential estimated from the four-point correlation function of the temperature and polarization maps

Observations of Large-Scale Structures

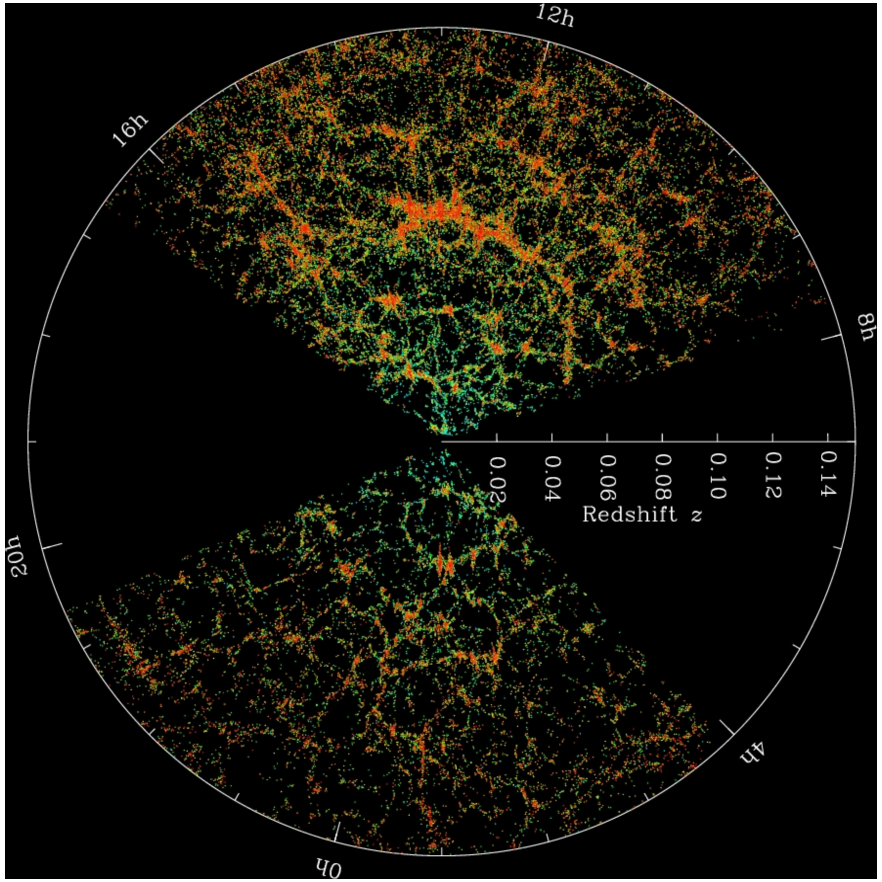


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Fractional density fluctuation:

$$\delta_m(\vec{x}, z) \equiv \frac{\rho_m(\vec{x}, z) - \bar{\rho}_m(z)}{\bar{\rho}_m(z)} = \sum \tilde{\delta}_m(\vec{k}, z) e^{-i\vec{k}\cdot\vec{x}}$$

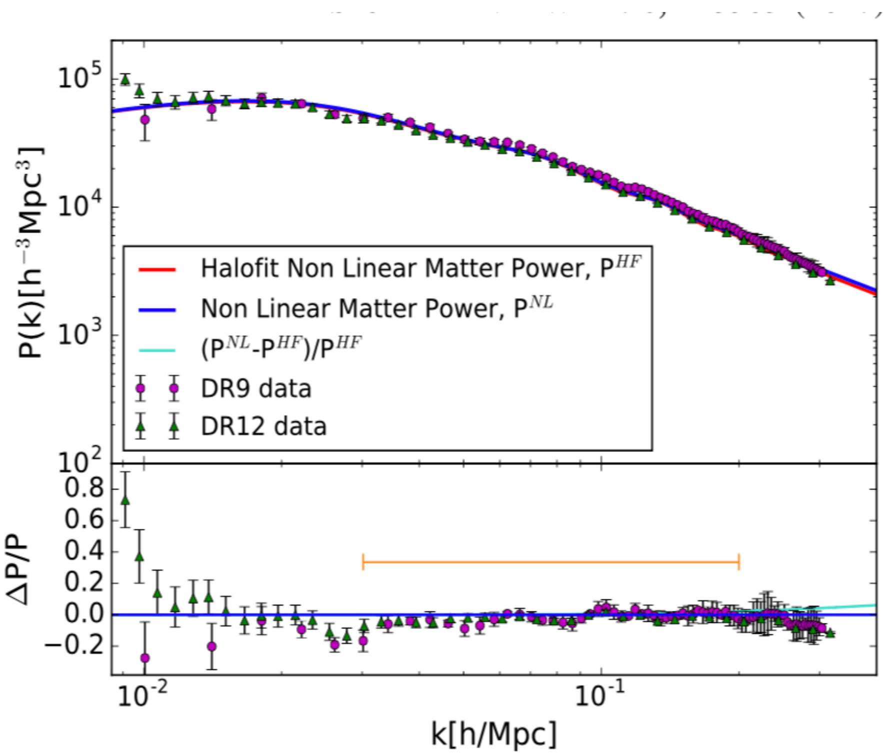
Power spectrum:

$$\left\langle \tilde{\delta}_m(\vec{k}, z)\tilde{\delta}_m(\vec{k}', z) \right\rangle = P_m(k, z)\delta^{(3)}\left(\vec{k} - \vec{k}'\right)$$

The power spectrum is the Fourier transform of the 2-point correlation function:

$$P_m(k) \longleftrightarrow \xi_m(r) \equiv \langle \delta_m(x)\delta_m(x+r)\rangle$$

Observations of Large-Scale Structures



data points from BOSS

Fractional density fluctuation:

$$\delta_m(\vec{x}, z) \equiv \frac{\rho_m(\vec{x}, z) - \overline{\rho}_m(z)}{\overline{\rho}_m(z)} = \sum \widetilde{\delta}_m(\vec{k}, z) e^{-i\vec{k}\cdot\vec{x}}$$

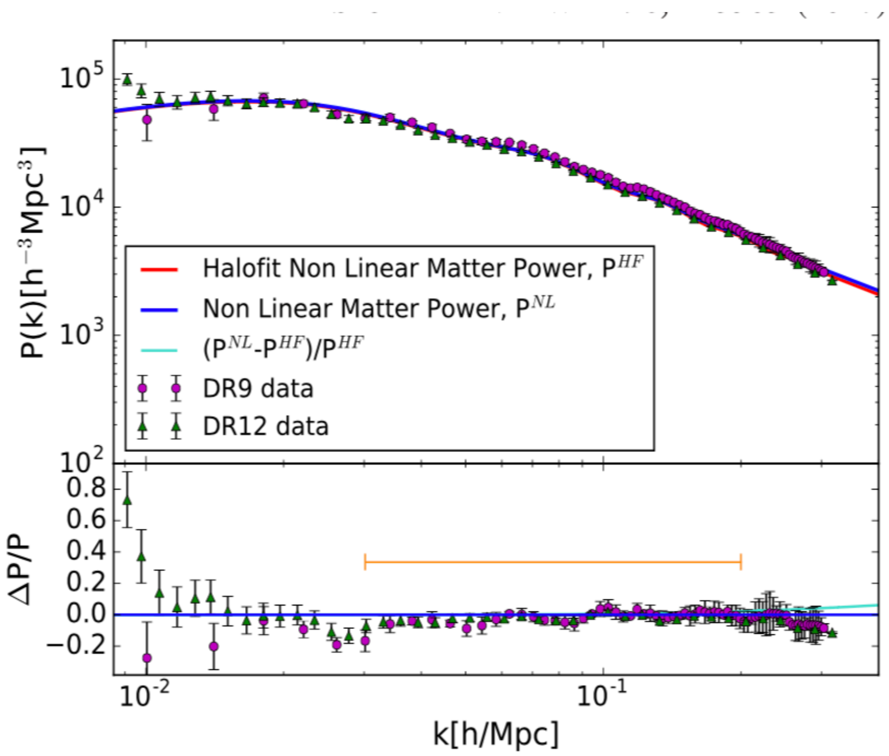
Power spectrum:

$$\left\langle \widetilde{\delta}_m(\vec{k}, z) \widetilde{\delta}_m(\vec{k}', z) \right\rangle = P_m(k, z) \delta^{(3)} \left(\vec{k} - \vec{k}' \right)$$

The power spectrum is the Fourier transform of the 2-point correlation function:

$$P_m(k) \longleftrightarrow \xi_m(r) \equiv \langle \delta_m(x) \delta_m(x + r) \rangle$$

OBSERVATIONS OF LARGE-SCALE STRUCTURES



data points from BOSS

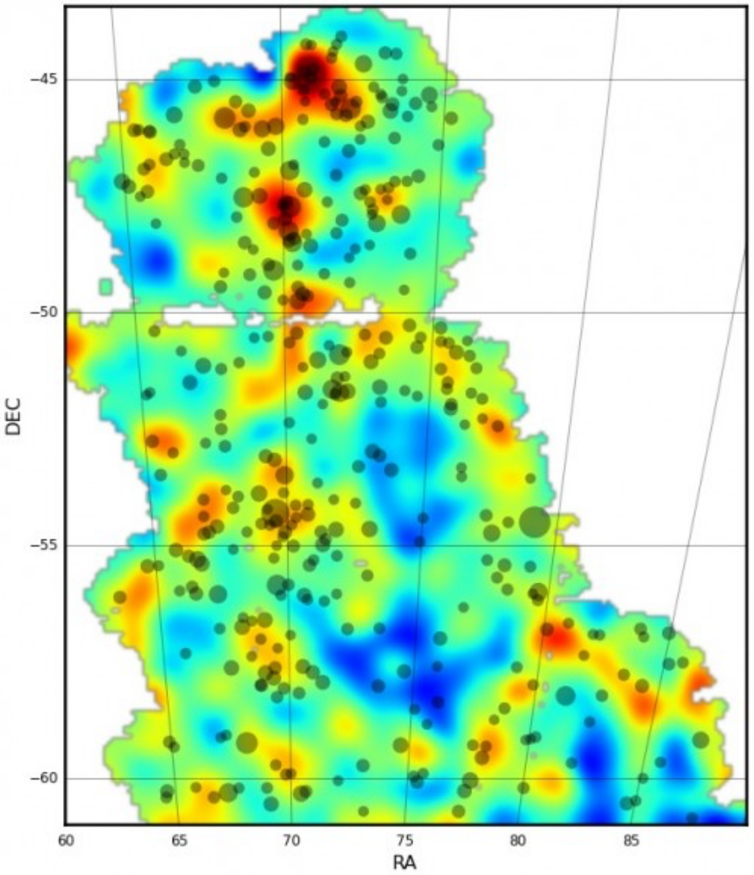
Galaxy surveys measure fluctuations in the galaxy number, $\delta n_g/n_g$.

This is not the same as observing the fluctuations in the total density field, even though the two are related (but the relation is not necessarily simple – e.g. it might be scale-dependent).

In other words, galaxies are a ***biased*** tracer of the underlying density field. This introduces a systematic in P(k) measurements.

Another issue is that small scales are affected by nonlinearities in the evolution of density fluctuations.

OBSERVATIONS OF LARGE-SCALE STRUCTURES



Weak lensing convergence map
from the Dark Energy Survey (DES)

Another option is to look at the distortions in galaxy shapes induced by weak gravitational lensing ("***cosmic shear***")

Cosmic shear is an observational target of future surveys (e.g. Euclid). It requires to measure distortions of order 1% in galaxy ellipticities.

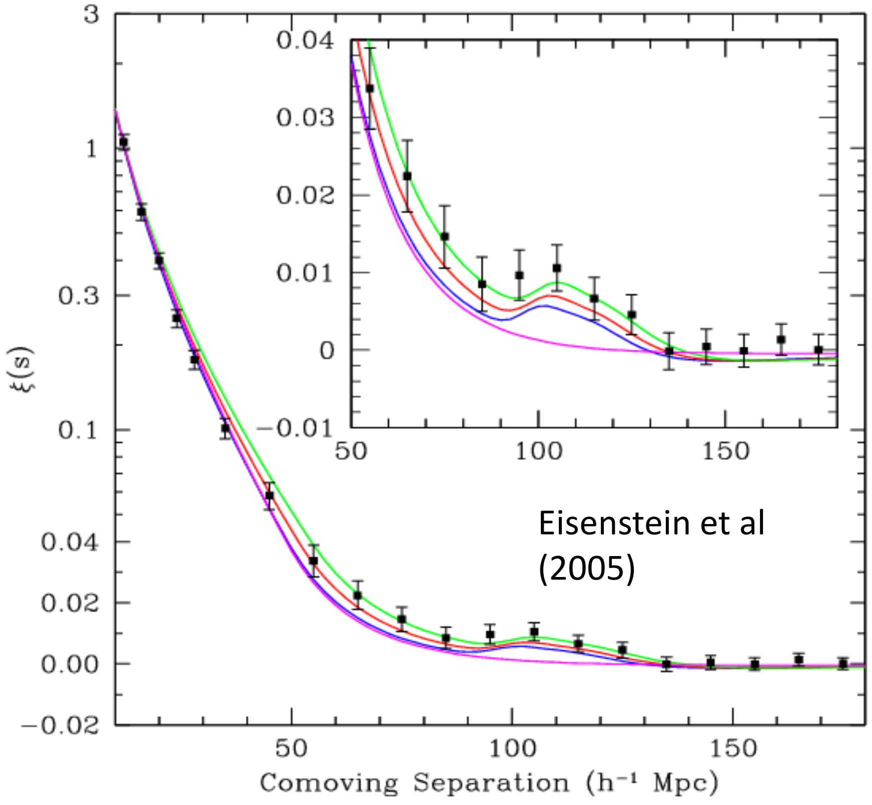
$$\kappa = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_m \int_0^{r_s} dr\, \frac{\delta(r)}{a(r)} \frac{r(r_s - r)}{r_s},$$

Convergence field

This is a more direct probe of matter fluctuations than galaxy number counts, since the lensing potential is produced by all matter components, including dark matter.

However, issues with nonlinearities remain.

Observations of Large-Scale Structures



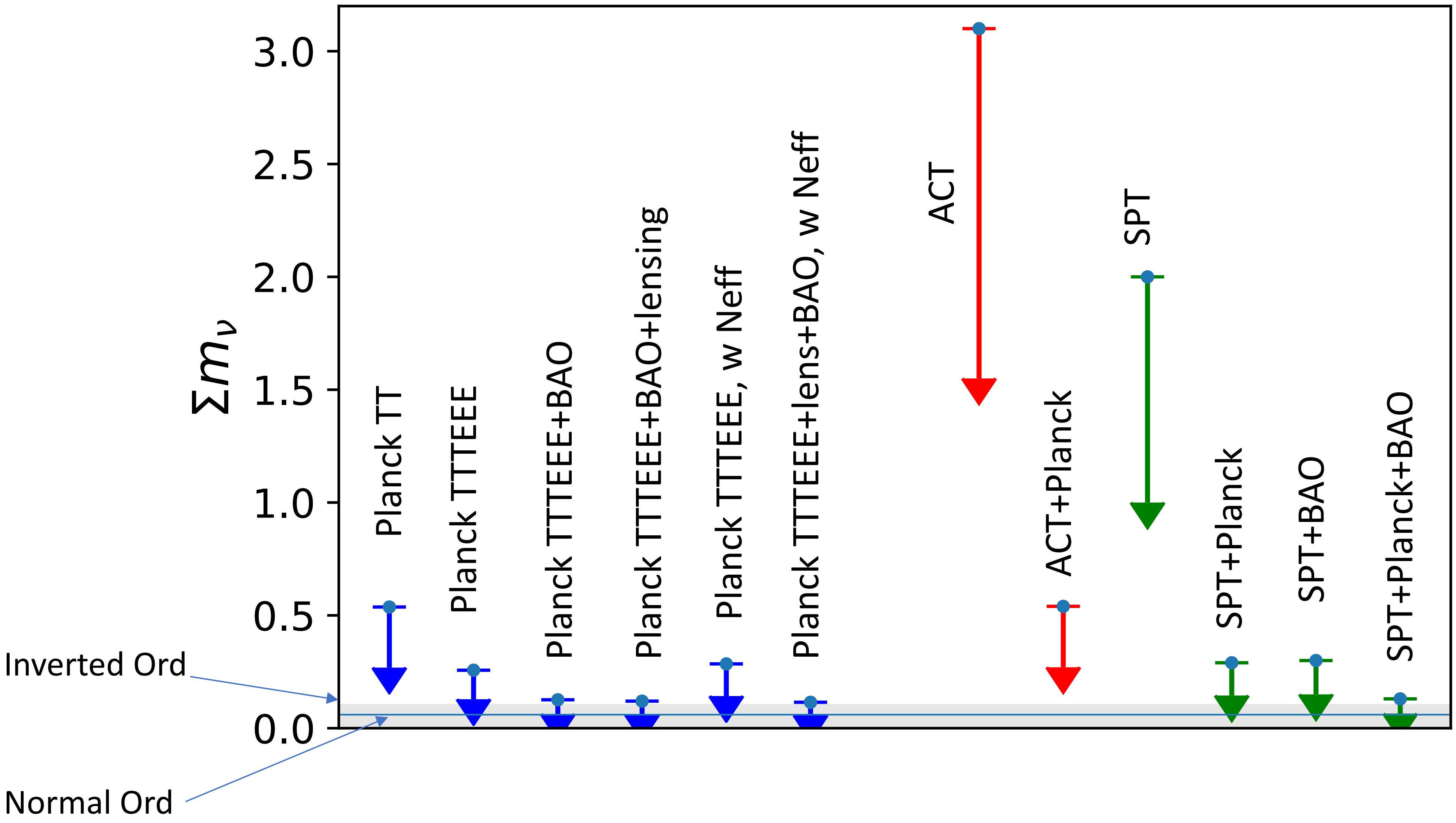
BAO in coordinate space: peak in the 2-point correlation function

Oscillations in the baryon-photon fluid leave their imprint in the matter power spectrum, other than in the CMB power spectrum.
This is visible as a peak in the 2point correlation function, or small wiggles in the power spectrum.

The scale of these ***Baryon Acoustic Oscillations*** (BAO) measures the sound horizon at the so-called drag epoch and can be used as a standard ruler to constrain the expansion history.

BAO allow to solve geometrical degeneracies, and are less affected by systematics (e.g. nonlinear evolution).

CURRENT LIMITS ON MNU (95% CL)



Credit: M. Gerbino

Cosmological Constraints on Neutrino Masses

Table 25.2: Summary of $\sum m_\nu$ constraints.

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[34]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[34]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16	[34]
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[34]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[38]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[34]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[34]
CMB + probes of background evolution + LSS			
Pl18[TT+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[34]
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.12	[34]
Pl18[TT,TE,EE+lowE+lensing] + BAO+Pantheon	ΛCDM+$\sum m_\nu$	< 0.11	[34]

Table from Lesgourgues & Verde
See also Gerbino & Lattanzi

[34] Planck 2018 Parameters paper
[38] Di Valentino et al., 2015

Cosmological Constraints on Neutrino Masses

Inclusion of information on the growth of structures pushes the bounds below the maximum value allowed for inverted ordering, $\Sigma m_\nu = 0.1$ eV. See e.g.

- $\Sigma m_\nu < 0.09$ eV from Planck + SNIa + RSD from SDSS-IV eBOSS (Di Valentino, Gariazzo, Mena 2021)

- $\Sigma m_\nu < 0.09$ eV from Planck + BAO + Lya from BOSS and eBOSS (Palanque-Delabrouille et al., 2020)

Mass constraints in extended models

TABLE 3 | Constraints on Σm_ν from different extensions to the ΛCDM model for the indicated datasets.

Extension to ΛCDM	Σm_ν[meV]	Dataset
ΛCDM $+ \Sigma m_\nu$	<254	Planck TT+lowP+lensing+BAO[a]
ΛCDM $+ \Sigma m_\nu + \Omega_K$	<368	Planck TT+lowP+lensing+BAO[a]
ΛCDM $+ \Sigma m_\nu + w$	<372	Planck TT+lowP+lensing+BAO[a]
ΛCDM $+ \Sigma m_\nu + N_{\rm eff}$	<323	Planck TT+lowP+lensing+BAO[a]
ΛCDM $+ \Sigma m_\nu + A_L$	<413	Planck TT+lowP+lensing+BAO[a]
ΛCDM $+ \Sigma m_\nu$	62 ± 16	CORE TT,TE,EE,PP+BAO [132]
ΛCDM $+ \Sigma m_\nu + \Omega_K$	63 ± 21	CORE TT,TE,EE,PP+BAO [132]
ΛCDM $+ \Sigma m_\nu + w$	48^{+22}_{-17}	CORE TT,TE,EE,PP+BAO [132]
ΛCDM $+ \Sigma m_\nu + N_{\rm eff}$	68^{+15}_{-17}	CORE TT,TE,EE,PP+BAO [132]
ΛCDM $+ \Sigma m_\nu + Y_{\rm He}$	62 ± 16	CORE TT,TE,EE,PP+BAO [132]
ΛCDM $+ \Sigma m_\nu + r$	60^{+15}_{-17}	CORE TT,TE,EE,PP+BAO [132]

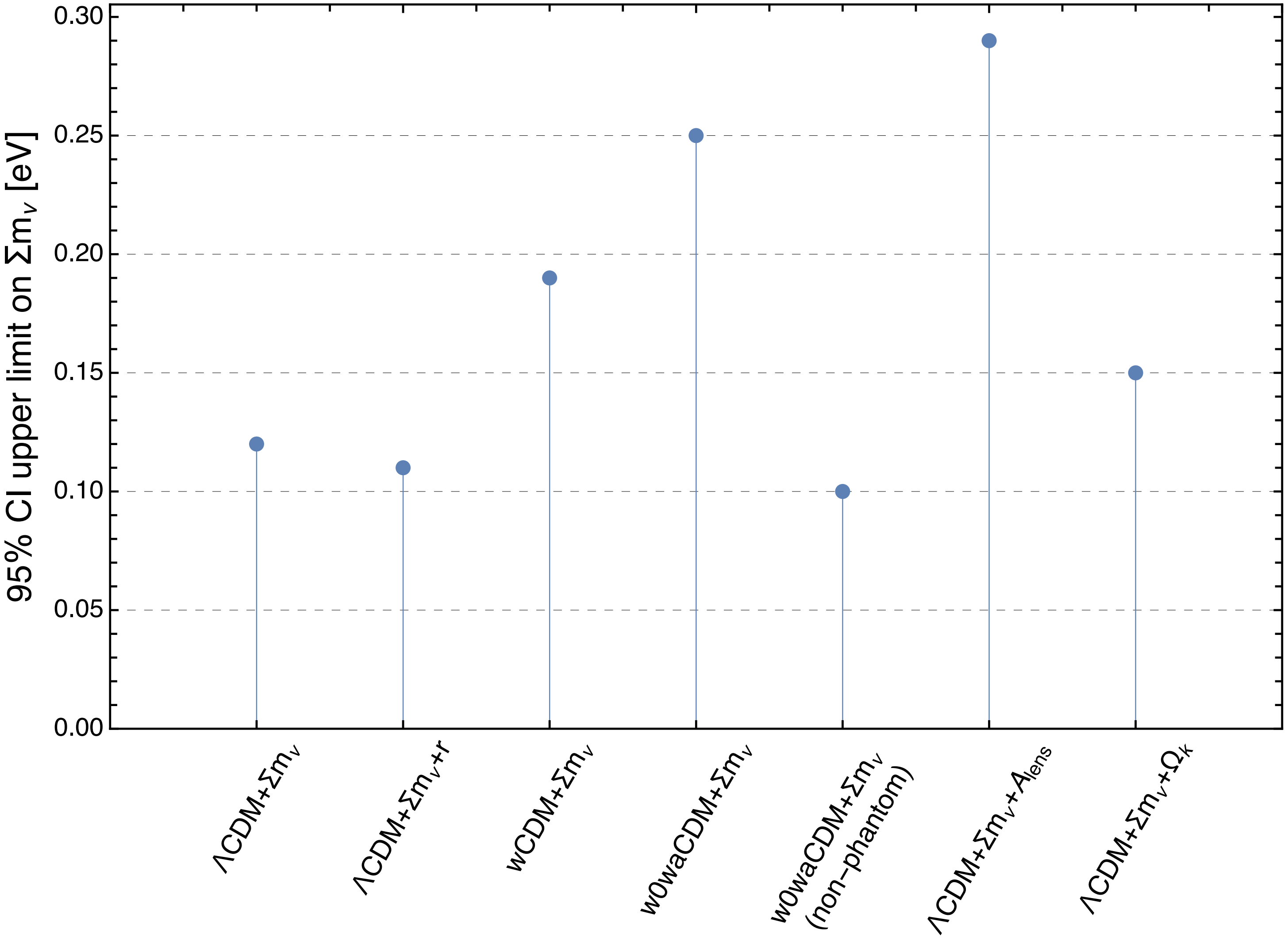
Gerbino & Lattanzi 2018

MASS CONSTRAINTS IN EXTENDED MODELS

It is by now well known that neutrino mass constraints are degraded in:

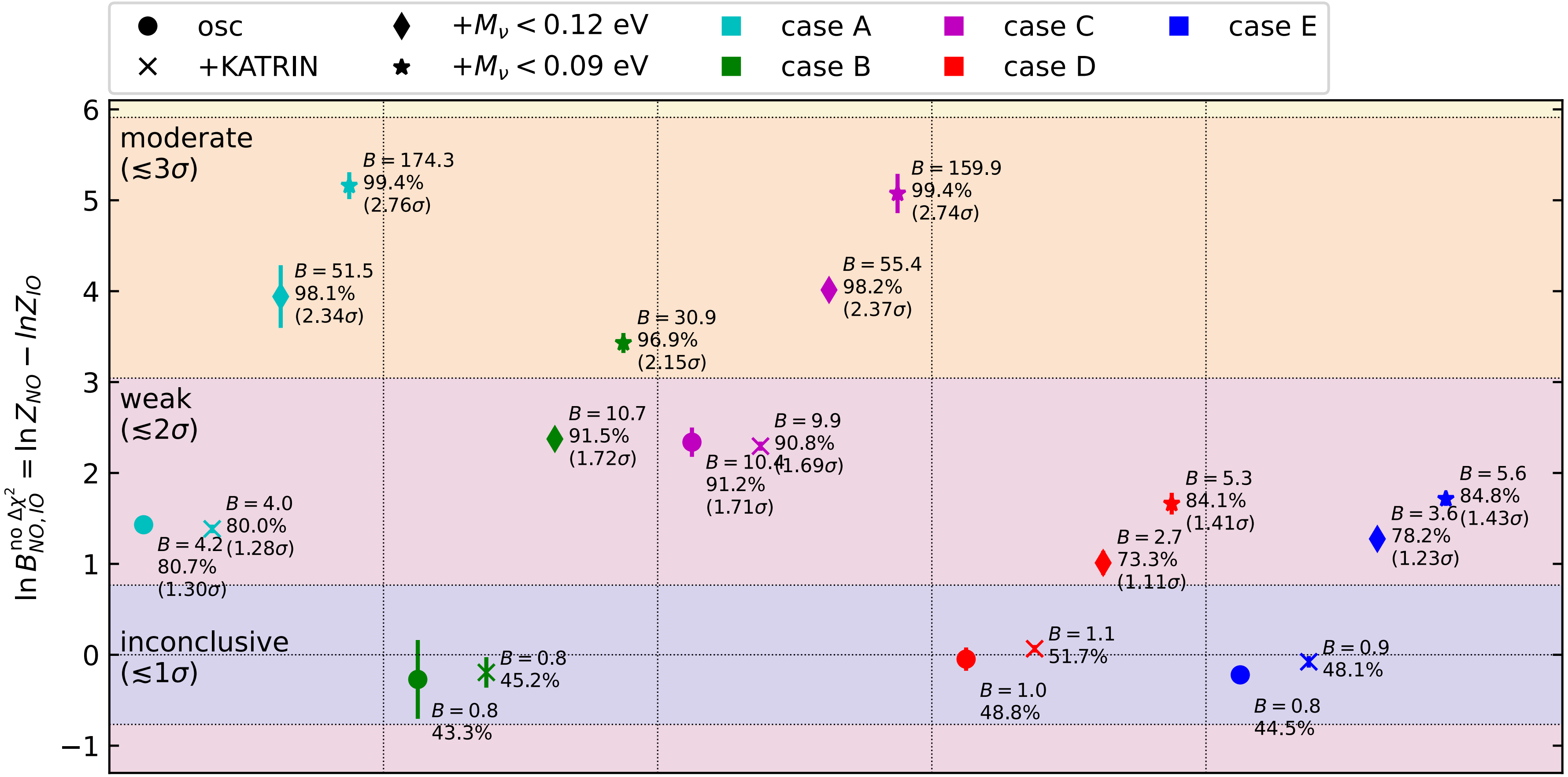
- Dynamical DE models (but only for phantom DE!, see e.g. Vagnozzi et al. 2019)
- Non-flat models
- Models with varying lensing amplitude (which is however not a physical parameter – basically a way to eliminate the information from CMB lensing)

Data: Planck 2018 (TTTEEE+lowE+lensing) + BAO



Plot based on the results of S. Roy Choudhury & S. Hannestad (2020) arXiv 1907.12598

WHICH ORDERING?

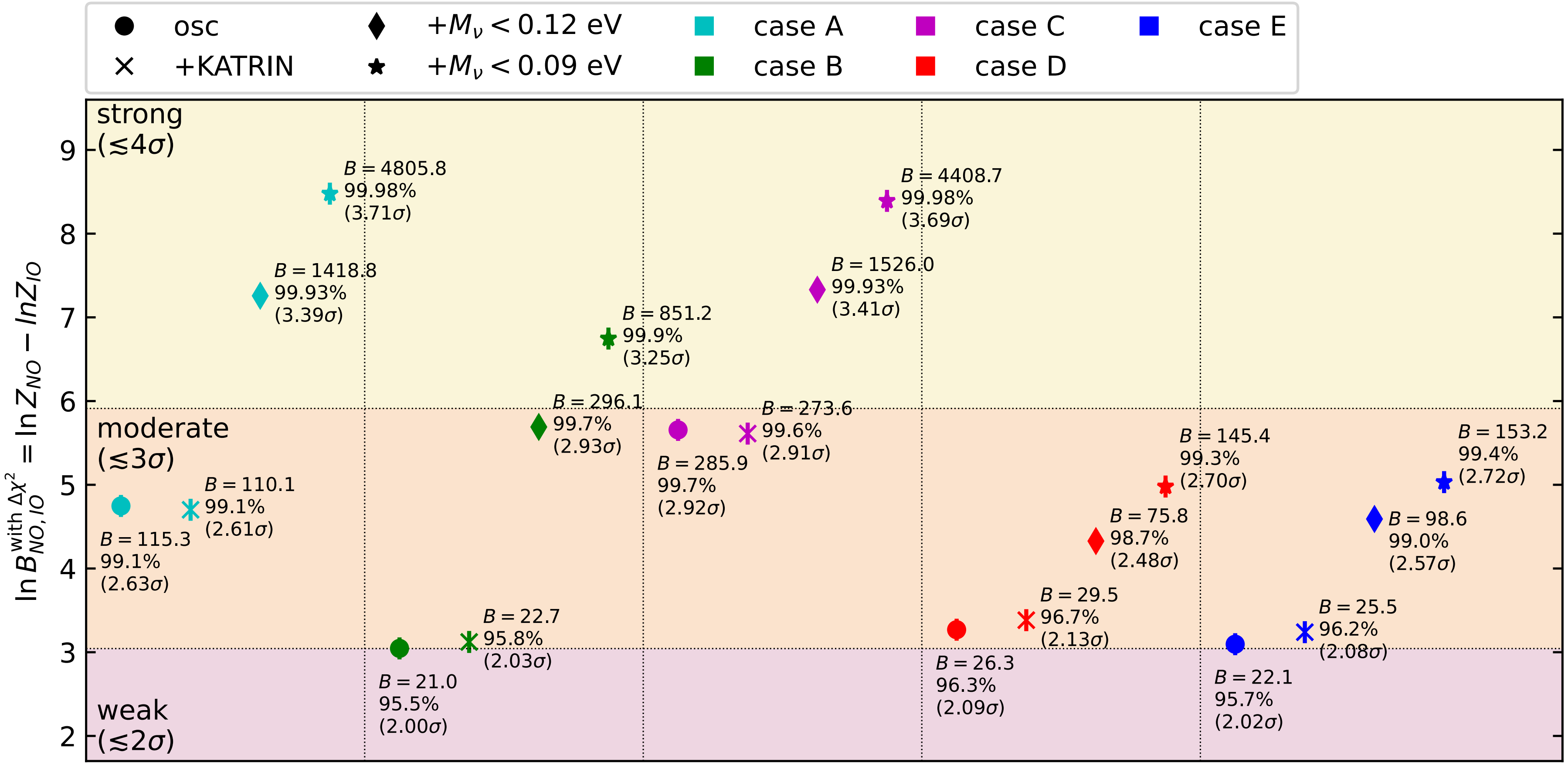


Odds for NO vs IO from oscillation measurements of the mass differences + constraints on the absolute mass scale from beta decay or cosmology.

Shows results for different priors (case E is more conservative)

Gariazzo et al, arXiv:2205.0219

WHICH ORDERING?



This is also factoring the preference for NO coming from oscillation experiments

Gariazzo et al, arXiv:2205.0219

Future experiments

Simons Observatory (2024+): ground-based in Chile; thousand detectors, low noise, high angular resolution; improved measurements of primary CMB in T and P; improved reconstruction of the lensing power spectrum; enhanced cluster science (detection of galaxy clusters via Sunyaev-Zeldovich effect)

CMB-S4 (2029+): ground-based, with large aperture telescope in Chile; SO successor, 10^5 detectors, lower noise, Improved measurements of CMB, lensing, clusters. Ultimate CMB experiment from ground.

LiteBIRD (2029+): satellite; main target: improved polarization measurements for inflationary science and reionization. Better estimates of tau (reionization optical depth) can improve constraints on other parameters

Euclid (2023?+): satellite; galaxy and weak lensing survey for the reconstruction of the matter distribution and Improved measurements of the BAO scale.

DESI (2021+): ground-based, spectroscopic, BAO reconstruction.

Rubin (202x+): ground-based; galaxy and weak lensing survey
Roman (20XX+): satellite; high-z galaxy survey
SPHEREx (202x+): satellite; low-z galaxy survey, all-sky.

FUTURE EXPERIMENTS

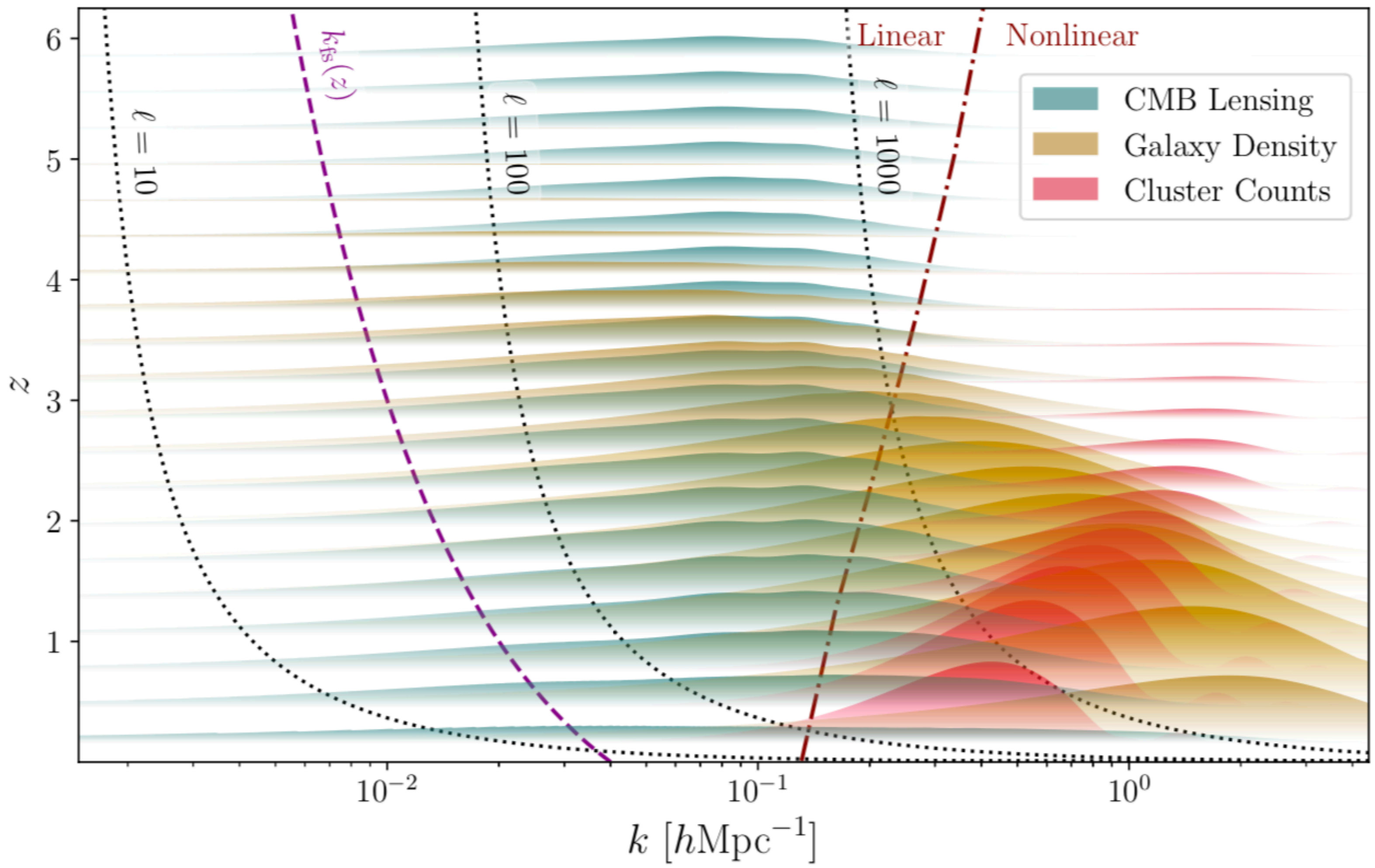
To increase sensitivity to neutrino masses AND reduce model dependency, we need:

- Precise measurement of the CMB lensing signal (both from 2- and 4-point correlation functions)
- Cosmic variance limited measurement of the reionization optical depth (need to go to space!)
- other CMB probes of structure formation, e.g. SZ galaxy clusters

+ non-CMB information

- BAO information to reduce geometrical degeneracies
- Full shape of the matter power spectrum (including control of at least mildly nonlinear scales. EFT of LSS?) possibly up to relatively high redshifts (intensity mapping?)
- CMB/LSS cross correlations

S/N OF FUTURE OBSERVATIONS



Plot by D. Green

From the Snowmass white paper

“Synergy between cosmological and laboratory searches in neutrino physics: a white paper”

Gerbino et al., arXiv 2203.07377

Simons Observatory - Mnu

- CMB lensing from SO combined with DESI BAO

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

- Sunyaev-Zeldovich cluster counts from SO calibrated with LSST weak lensing

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

- thermal SZ distortion maps from SO combined with DESI BAO

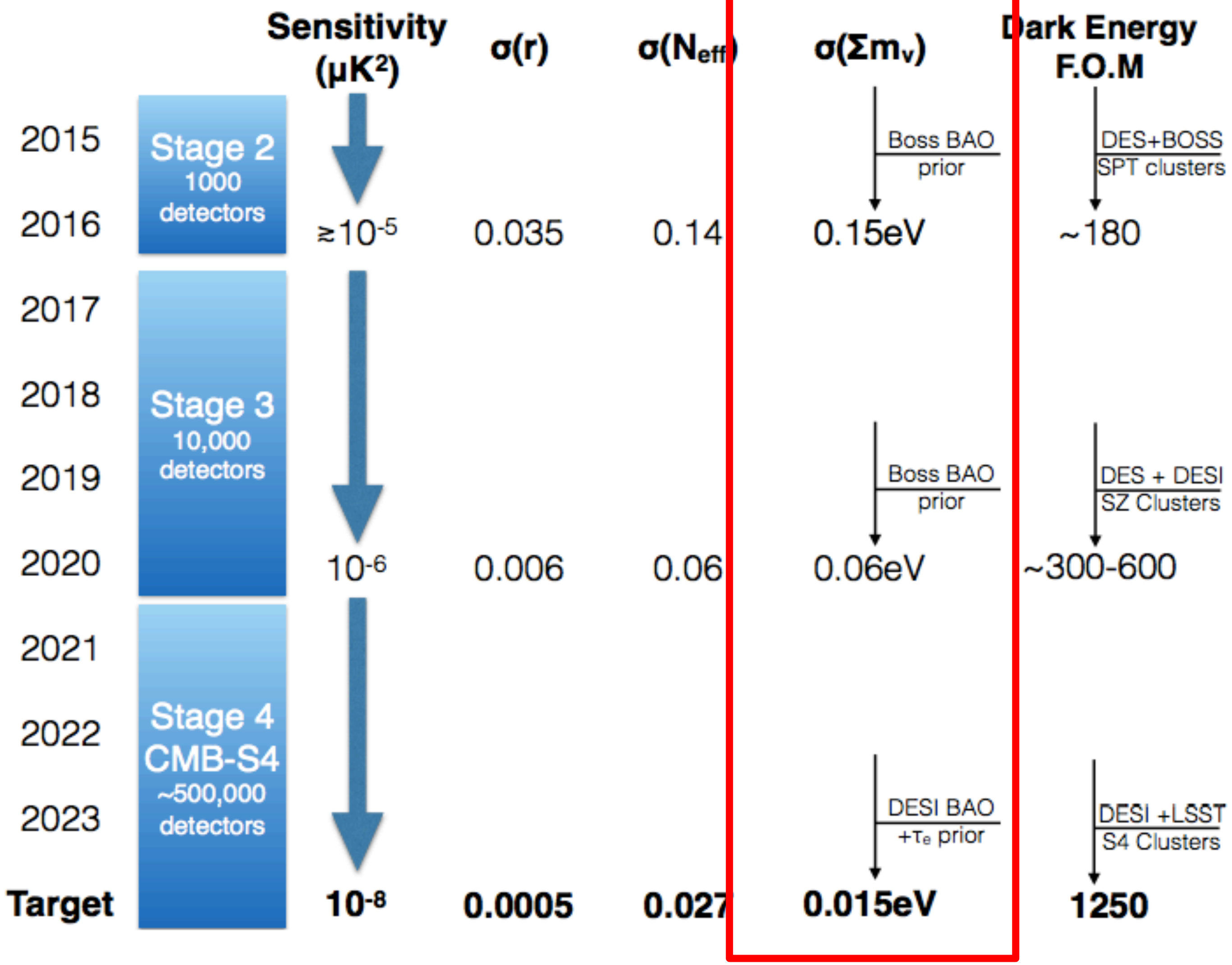
$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

- legacy SO dataset combined with cosmic-variance-limited measurement of reionization optical depth

$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

SO Collaboration, 2018

NEUTRINO PARAMETERS FROM CMB-S4

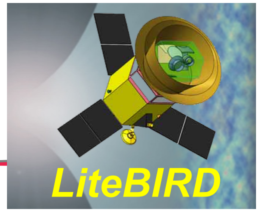


CMB-S4 Science Book (arXiv: 1610:02743)


LiteBIRD
A JAXA-led post-Planck space mission for CMB polarization, with participation from US and Europe

CMB-S4 - LiteBIRD

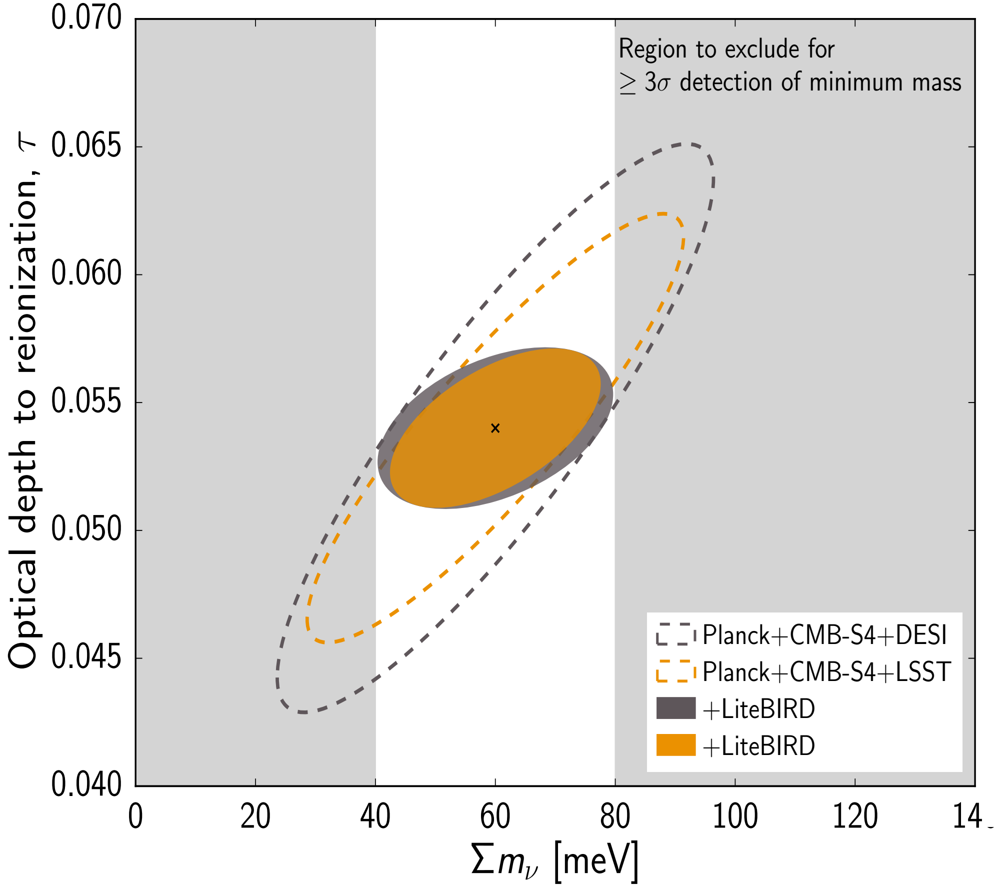
Σm_ν w/ improved τ

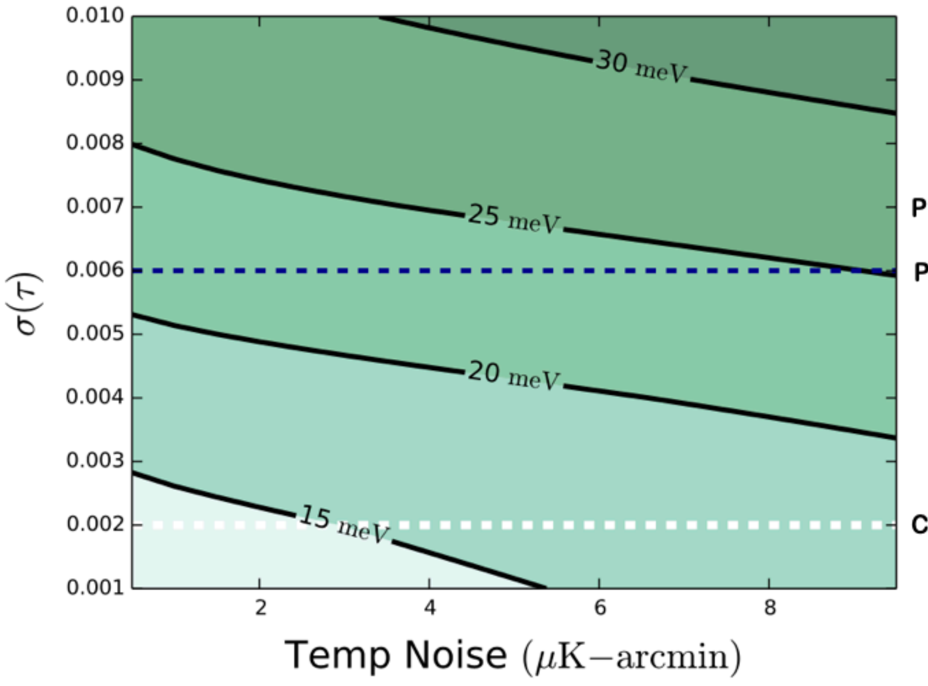


LiteBird Collaboration, arXiv:2202.02773

- $\sigma(\Sigma m_\nu) = 15$ meV
- $\geq 3\sigma$ detection of minimum mass for normal hierarchy
- $\geq 5\sigma$ detection of minimum mass for inverted hierarchy

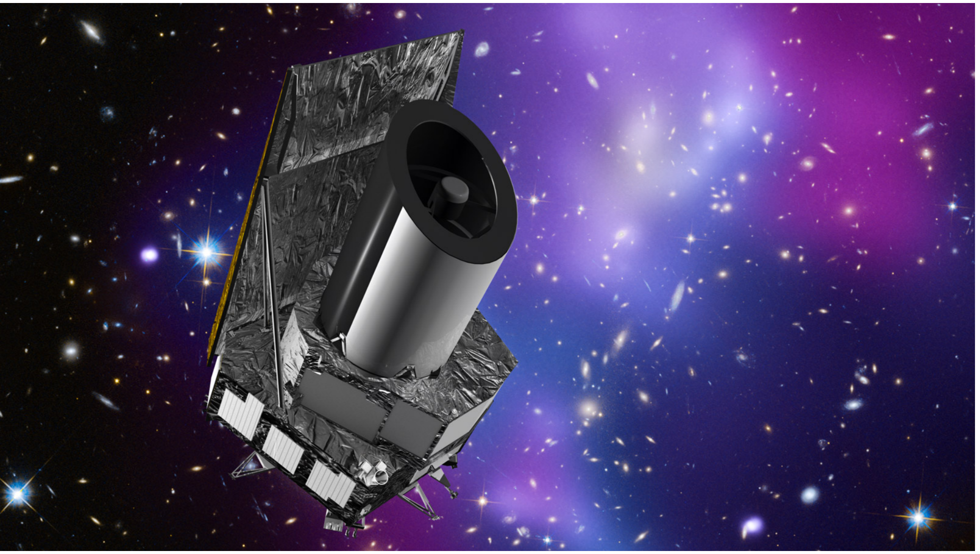
Caveat:
No systematic error included yet.





CMB-S4 Collaboration, 2019

The Euclid Mission



Euclid will measure **weak lensing** and **galaxy clustering** observing 15.000 deg^2 (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg^2)

This will allow to reconstruct the **expansion history** and the **growth of cosmological structuree**

Euclid is an ESA M-class space mission devoted to studying :

- the origin of the **accelareted expansion** of the Universe
- **Dark energy**, **dark matter** and the behaviour of **gravity at large scales**
- + **neutrino masses, the initial conditions of cosmological evolution, …**

$\sigma(\Sigma m_\nu) = 0.020$ eV from Euclid + Planck

(Sprenger et al. 2019)

NEUTRINO MASS BOUNDS: FUTURE PROSPECTS

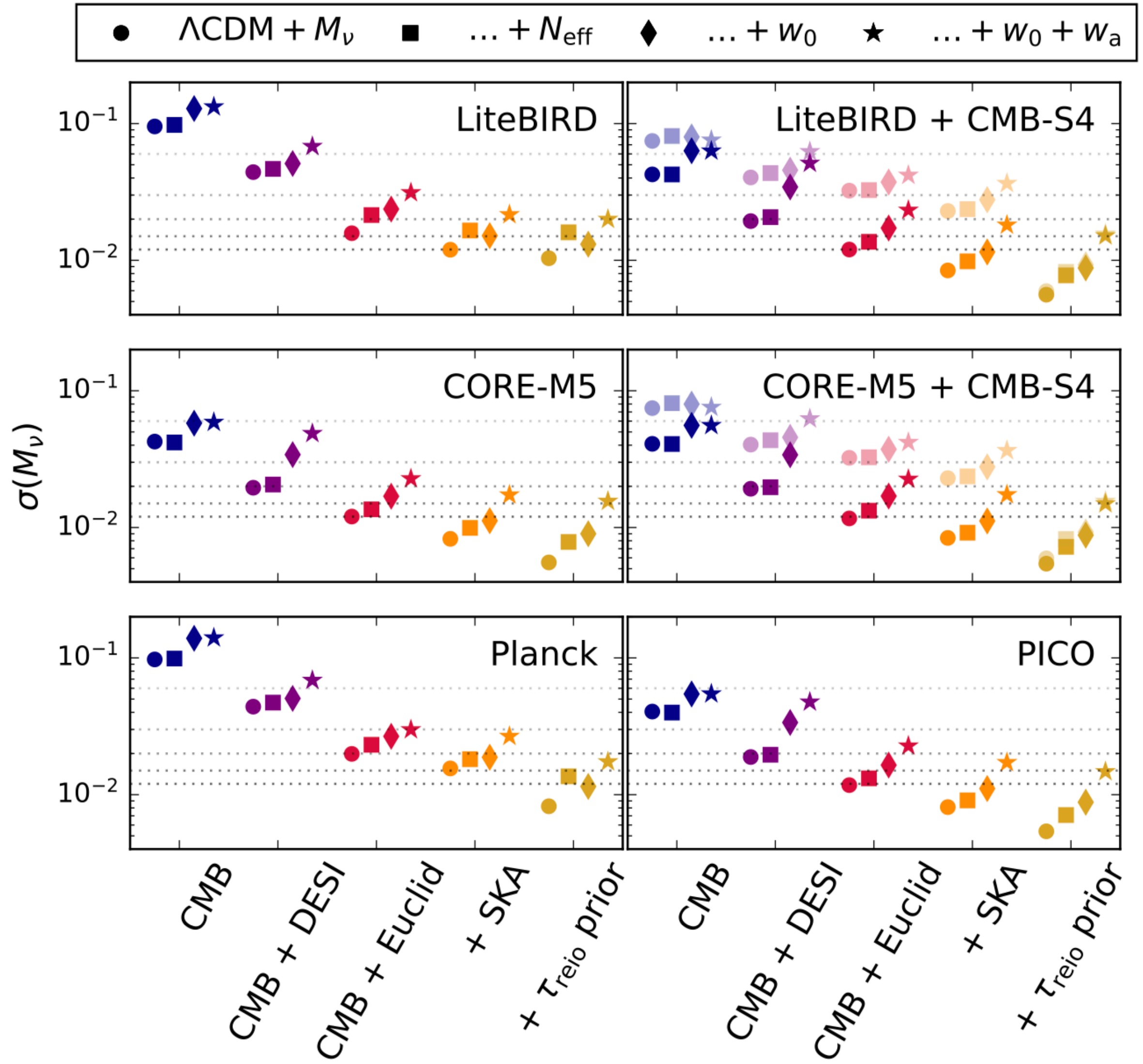
$\sigma(\Sigma m_\nu) = 0.042$ eV from LiteBIRD + CMB-S4

(0.063 eV in DDE models)

Which goes down to

$\sigma(\Sigma m_\nu) = 0.0056$ eV
adding + Euclid + SKA IM + τ from 21cm

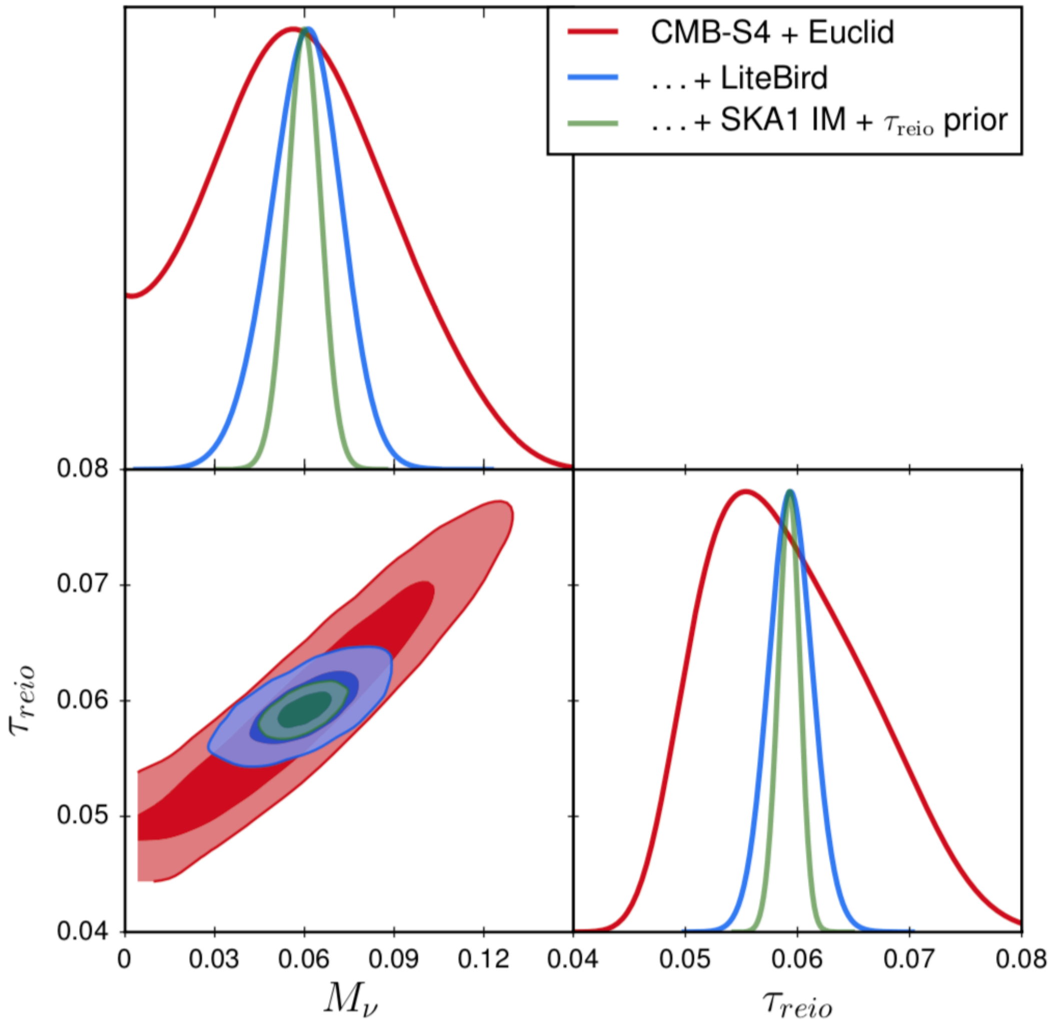
(0.015 in DDE models)



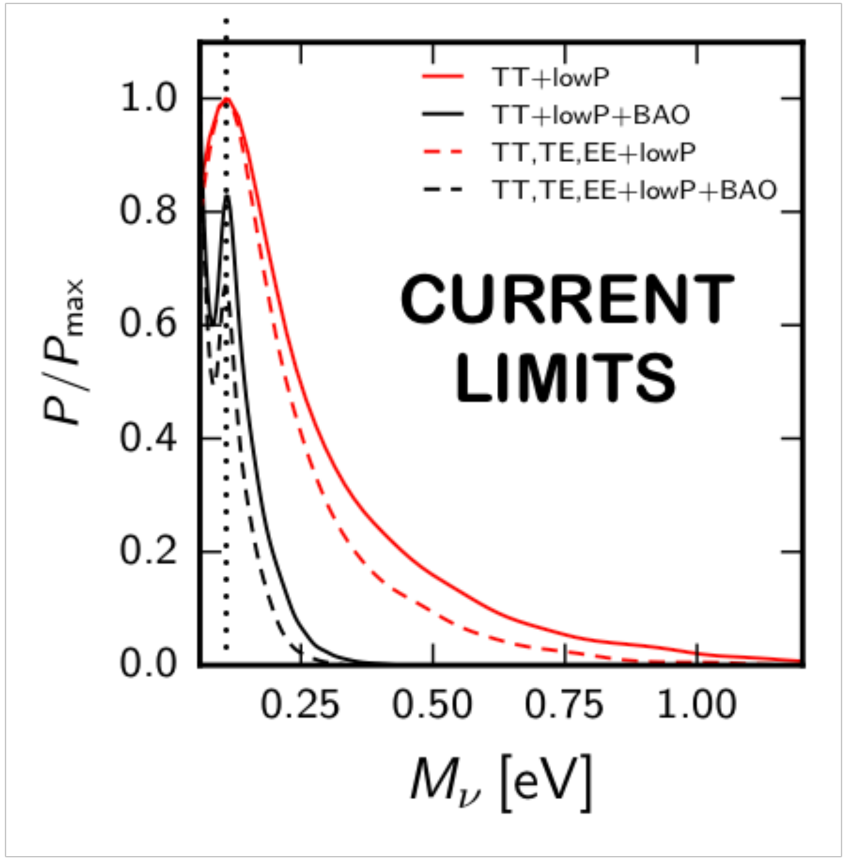
Brinckmann+, JCAP 2019

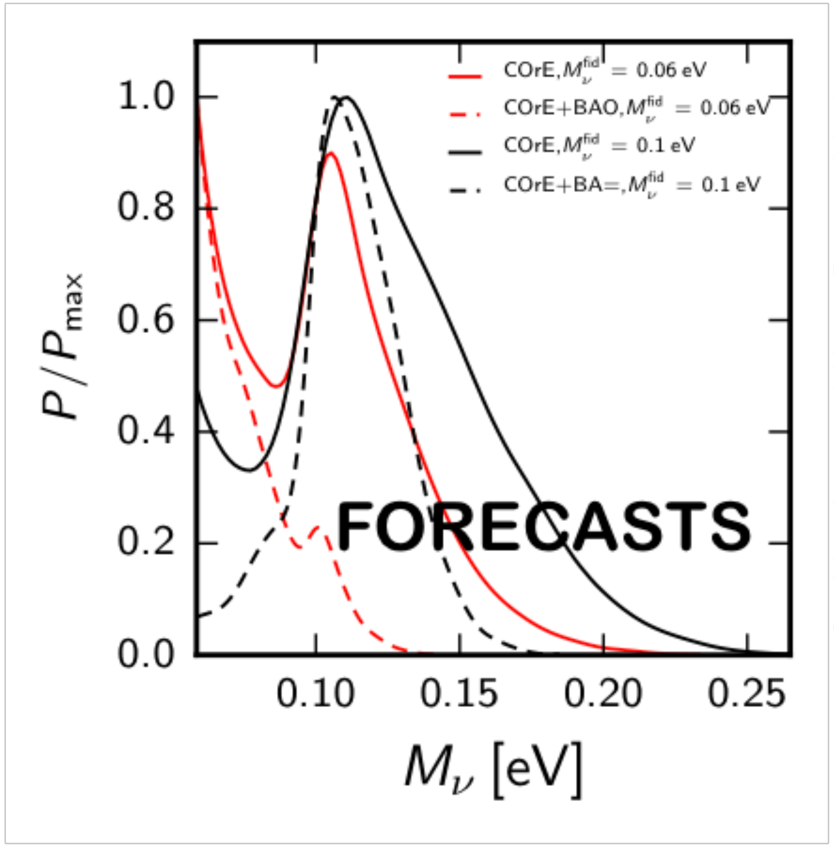
NEUTRINO MASS BOUNDS: FUTURE PROSPECTS

Brinckmann+, JCAP 2019



Sensitivity to the hierarchy





Gerbino,Lattanzi,Mena,Freese 2016

$$\mathcal{P}(h = NH) : \mathcal{P}(h = IH) \qquad \mathcal{P}(h = NH) : \mathcal{P}(h = IH)$$

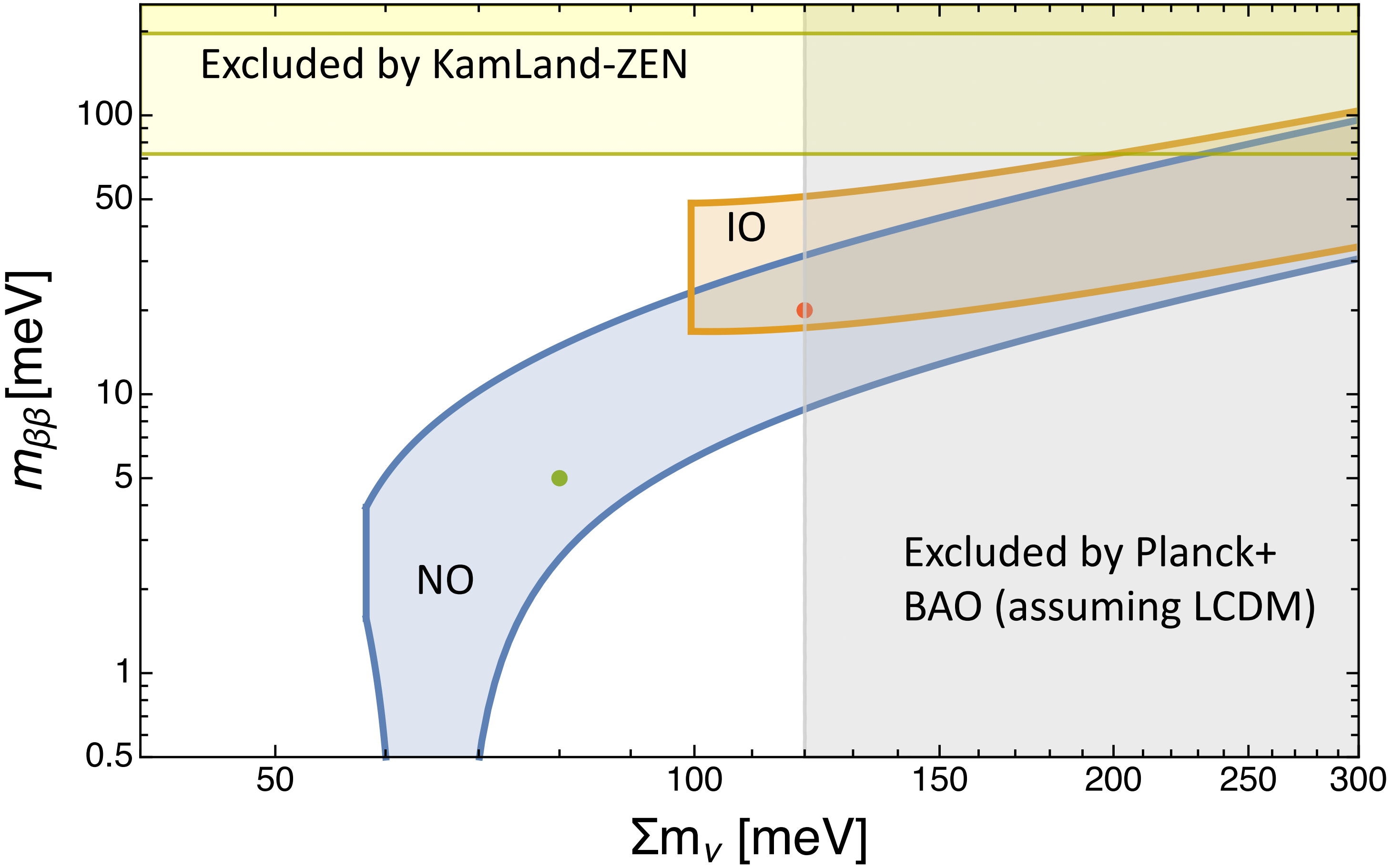
.... **3:2**

.... **0.06eV mass -> 9:1**

.... **0.1eV mass -> 1:1**

See also Hannestad&Schwetz,2016

SYNERGY BETWEEN COSMO AND LAB



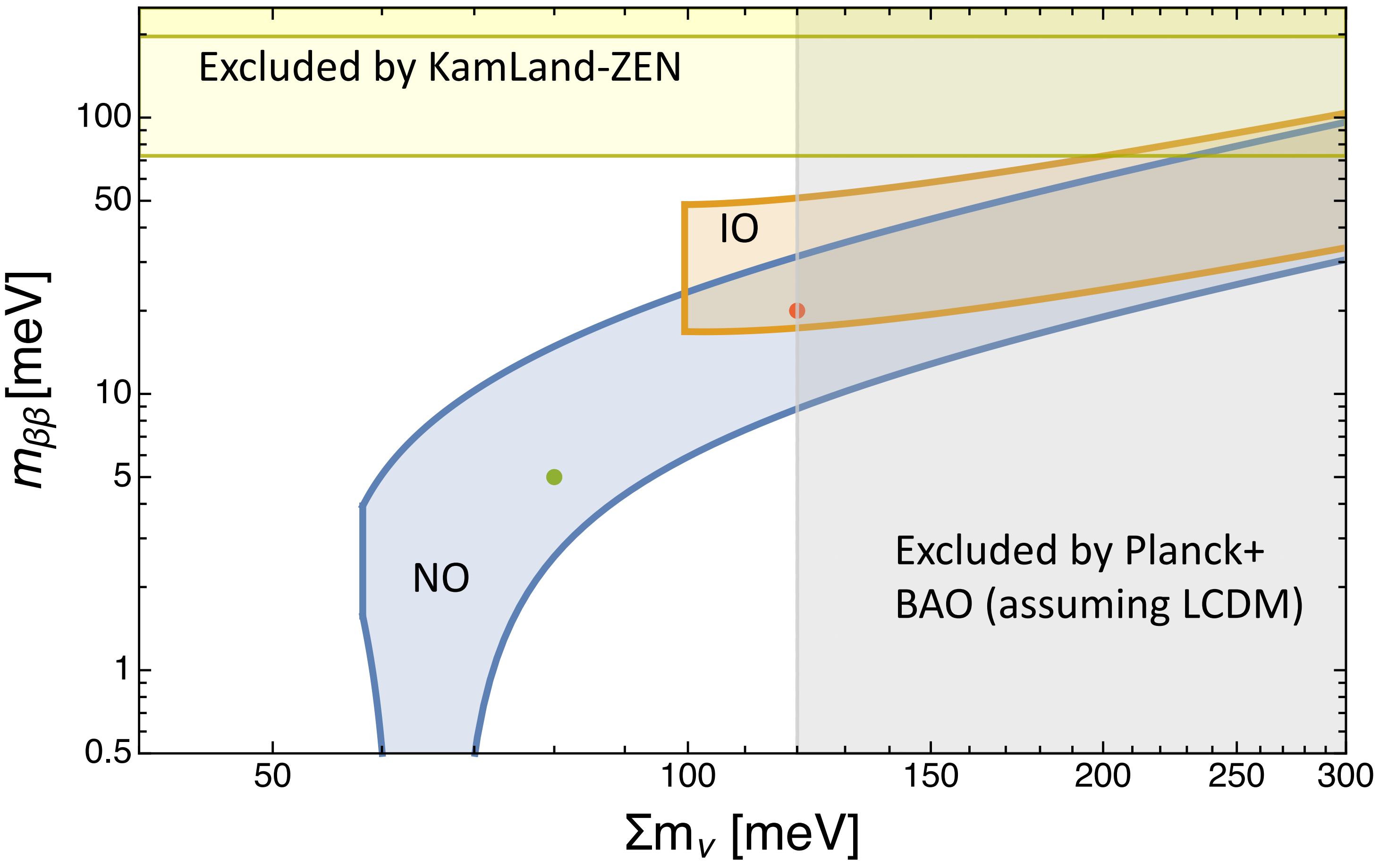
Gerbino et al., arXiv 2203.07377

Concordance 1: Signal in both 0n2B and cosmology. Neutrinos are Majorana. No reason to go beyond LCDM. Standard Neff. Ordering is undetermined, but can be determined through oscillation experimens.

Concordance 2: Signal in cosmology (with "low" mass), but not in 0n2b. Two possibilities: 1) Neutrinos are Dirac,or 2) Neutrinos are Majorana and ordering is normal. Oscillations can break the degeneracy.

In both cases, no need to go beyond LCDM or beyond the mass mechanism for 0nu2b

SYNERGY BETWEEN COSMO AND LAB



Gerbino et al., arXiv 2203.07377

Non concordant scenarios are of course possible (and probably more interesting!), e.g. signal in 0nu2b and not in cosmology, or discordant signals.

Would point to nonstandard scenarios in either the particle physics or cosmological sector, or in both

THANKS!