NEUTRINO COSMOLOGY AND DARK MATTER

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From Theory to Observations

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LECTURE 3

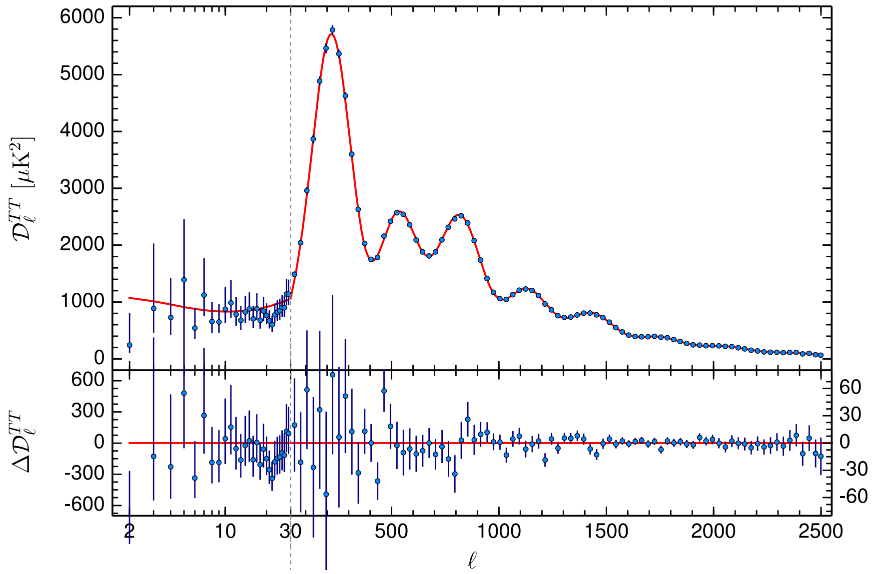
MASSIVE NEUTRINOS AND COSMOLOGICAL OBSERVABLES

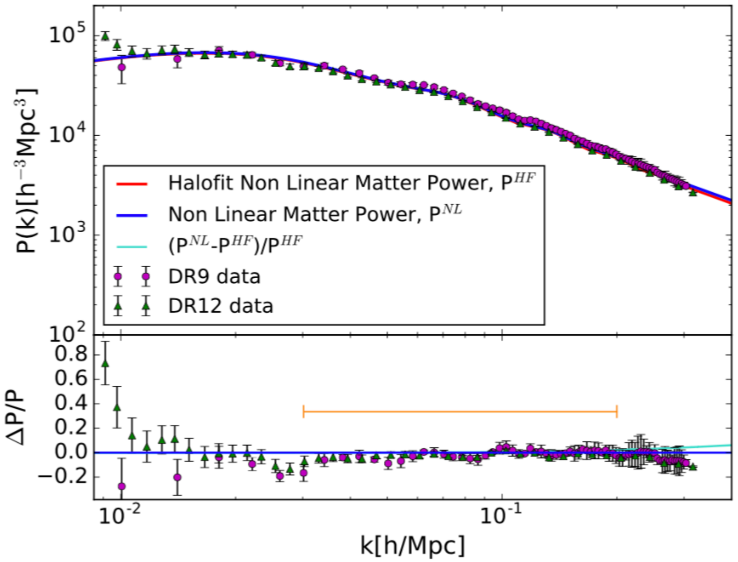
In the standard picture, neutrino abundance (relative to photons) is fixed by GR + SM

The only free parameter is $M_\nu = \Sigma m_i$

that fixes the present energy density:

$$\Omega_\nu h^2 \equiv \frac{\rho_\nu}{\rho_c} h^2 = \frac{M_\nu}{93.14\,\mathrm{eV}}$$





The neutrino energy density affects the expansion history (for example changing the relative abundance of matter and radiation)

This can be however compensated by tweaking other parameters (e.g. the matter density or the present expansion rate)

Most of the cosmological information on neutrino masses comes from their peculiar effect on the evolution of matter perturbations (also seen in the CMB, see below)

MASSIVE NEUTRINOS AND COSMOLOGICAL OBSERVABLES

Assuming *flatness* and a *cosmological constant* (i.e. no dynamical DE), the Friedmann eq. reads:

$$\frac{H(z)^2}{\left(100\,\mathrm{km\,s^{-1}Mpc^{-1}}\right)^2} = (\omega_c + \omega_b)(1+z)^3 + \omega_\Lambda + \omega_\gamma(1+z)^4 + \frac{\rho_\nu(z)}{\rho_{c,0}h^{-2}}$$

Background effects:

The expansion history is the same as the one in a Universe with massless neutrinos and standard N_{eff} as long as $z > z_{nr}$.

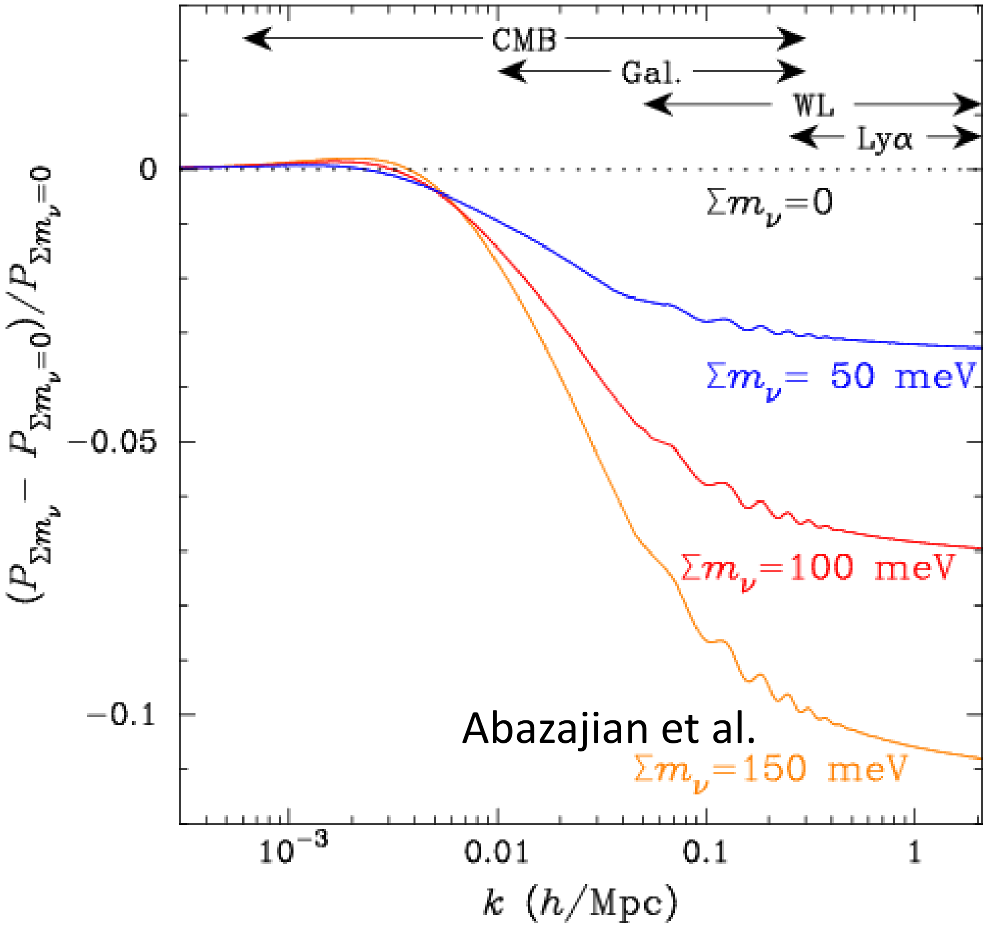
For neutrinos that become NR after decoupling ($m_\nu < 0.6$ eV), this will affect the angular diameter distance to the LSS, and/or the redshift of matter/Lambda equality, z_Λ.

We can tweak the parameters (Ω_Λ and h) to keep $d_a(z_*)$ or z_Λ fixed, but not both.

The data constrain d_a much better than z_Λ (uncertainties are large at small ells due to cosmic variance), so it makes more sense to tweak parameters to keep d_a fixed.

This also implies that constraining power on $m_\nu < 0.6$ eV from background effects is somehow limited.

NEUTRINO FREE-STREAMING: DAMPING OF PERTURBATIONS



Abazajian et al.

In a Universe with neutrinos, small-scale density perturbations are suppressed due to collisionless damping (free-streaming).

Neutrinos are collisionless and have large thermal velocities (they have been relativistic for most of the history of the Universe).

They do not cluster below a critical scale, the free-streaming length (corresponding to the scale of the horizon at the time of the nonrelativistic transition).

At small scales:

$$\frac{P(M_\nu) - P(M_\nu = 0)}{P(M_\nu = 0)} = -8\frac{\Omega_\nu}{\Omega_m}$$

In principle the effect can be seen directly in the matter power spectrum
There are issues however: non-linearities, scale-dependent bias……

MASSIVE NEUTRINOS AND COSMOLOGICAL OBSERVABLES

$$k_{\rm fs} \simeq 0.018\,\Omega_m^{1/2}\left(\frac{m_\nu}{1\,{\rm eV}}\right)^{1/2} h{\rm Mpc}^{-1}$$

Free streaming scale

$$\delta_m(k \gg k_{\rm fs}) \propto a^{1-(3/5)\Omega_\nu/\Omega_m}$$

Suppressed growth

$$k_p r_s + \phi = p\pi$$

Acoustic phase shift

OBSERVATIONS OF LARGE-SCALE STRUCTURES

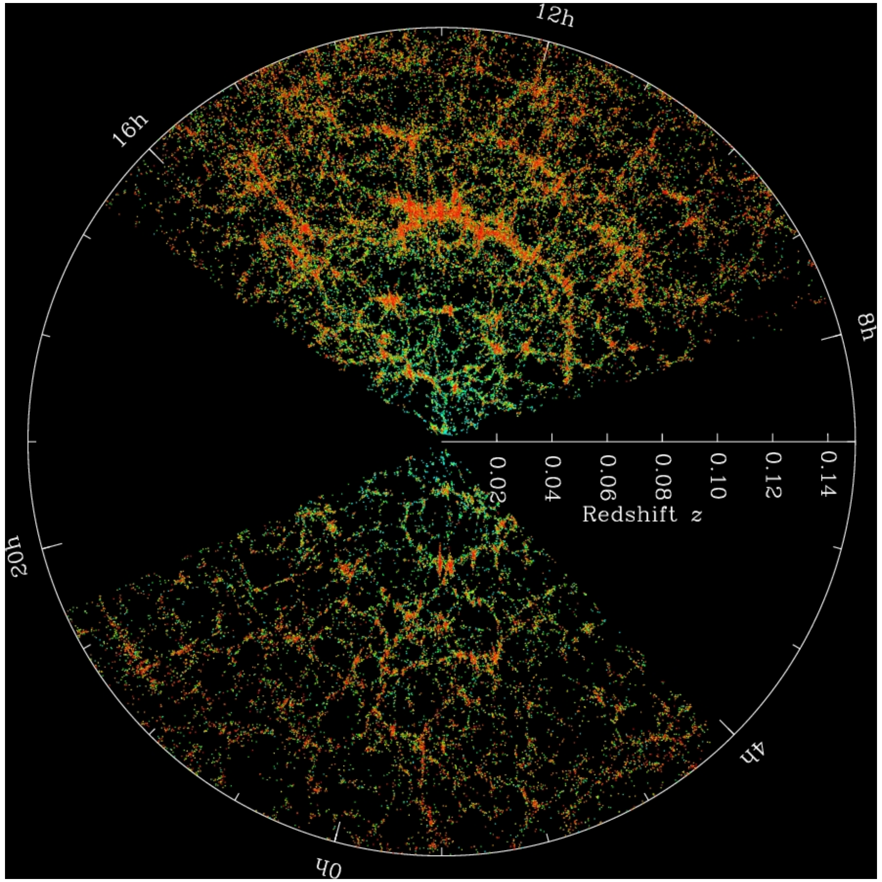


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Fractional density fluctuation:

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

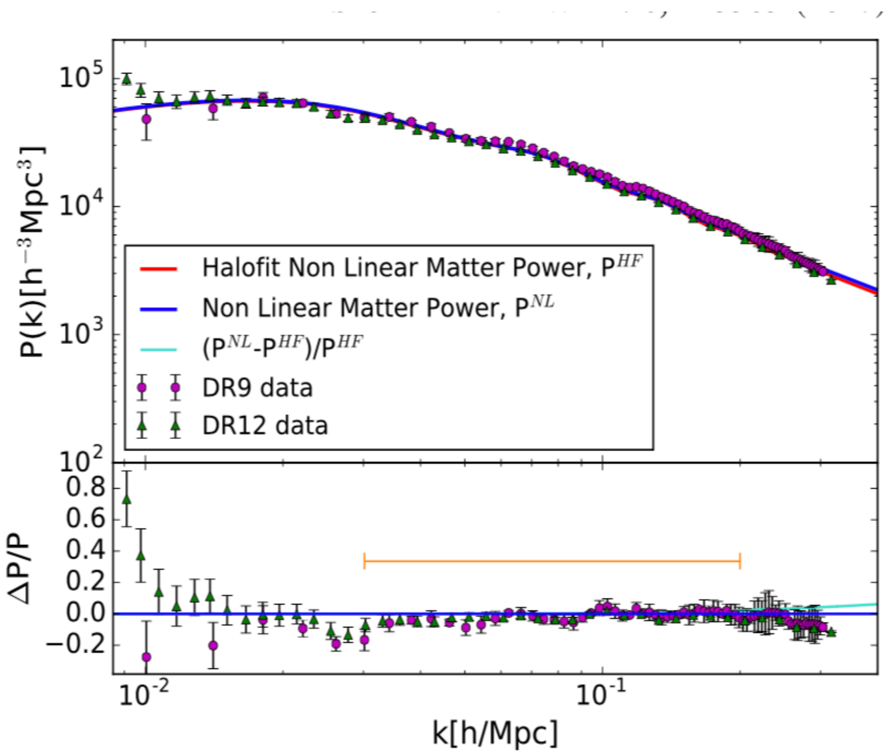
Power spectrum:

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

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:

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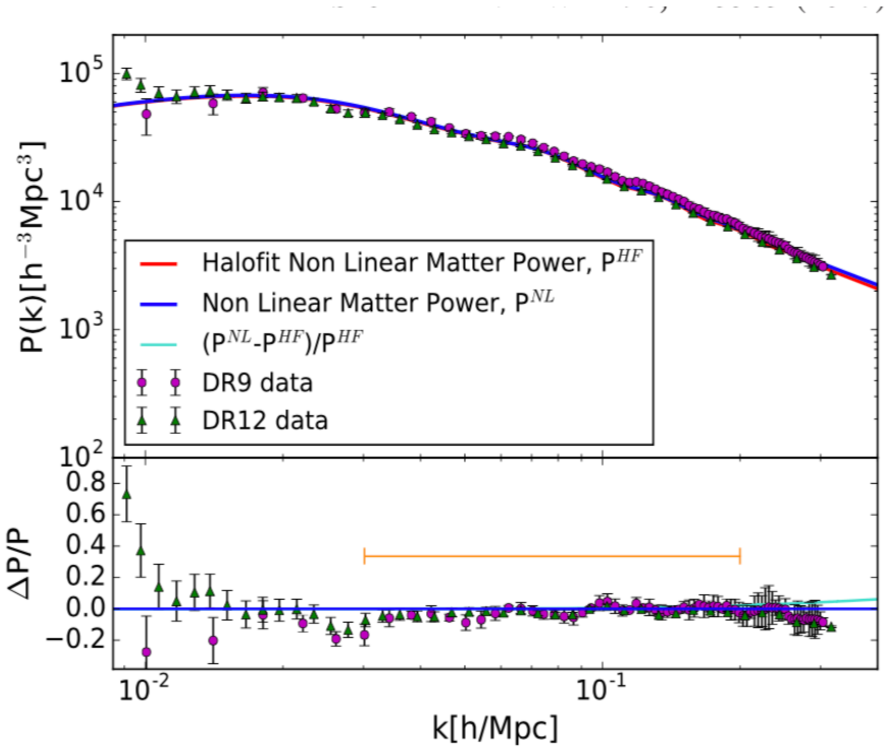
OBSERVATIONS OF LARGE-SCALE STRUCTURES



data points from BOSS

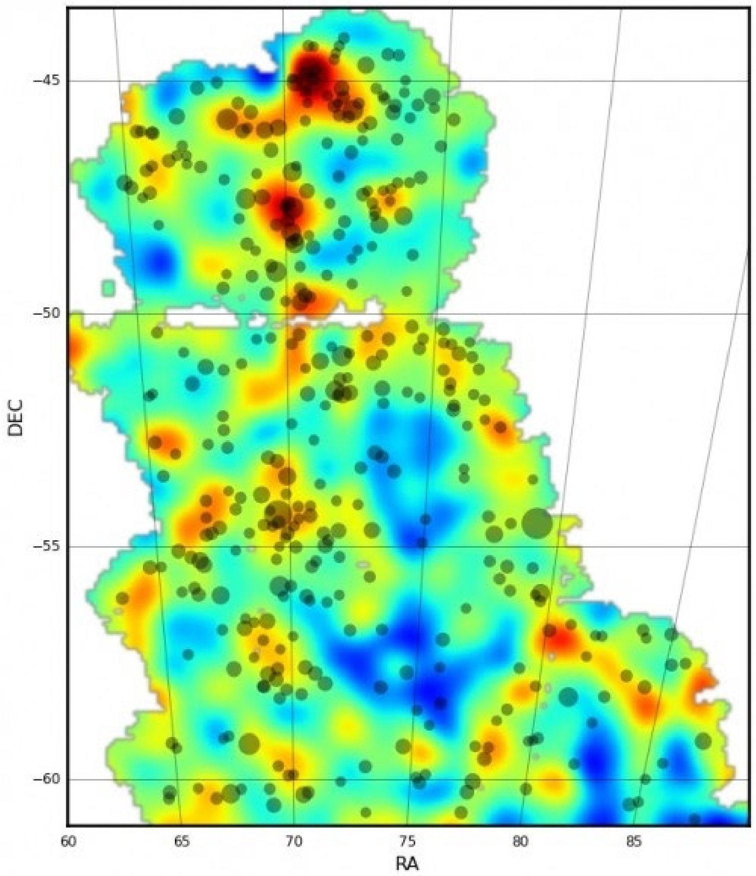
Galaxy surveys measure fluctuations in the galaxy number, $\delta n_g/n_g$.

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.

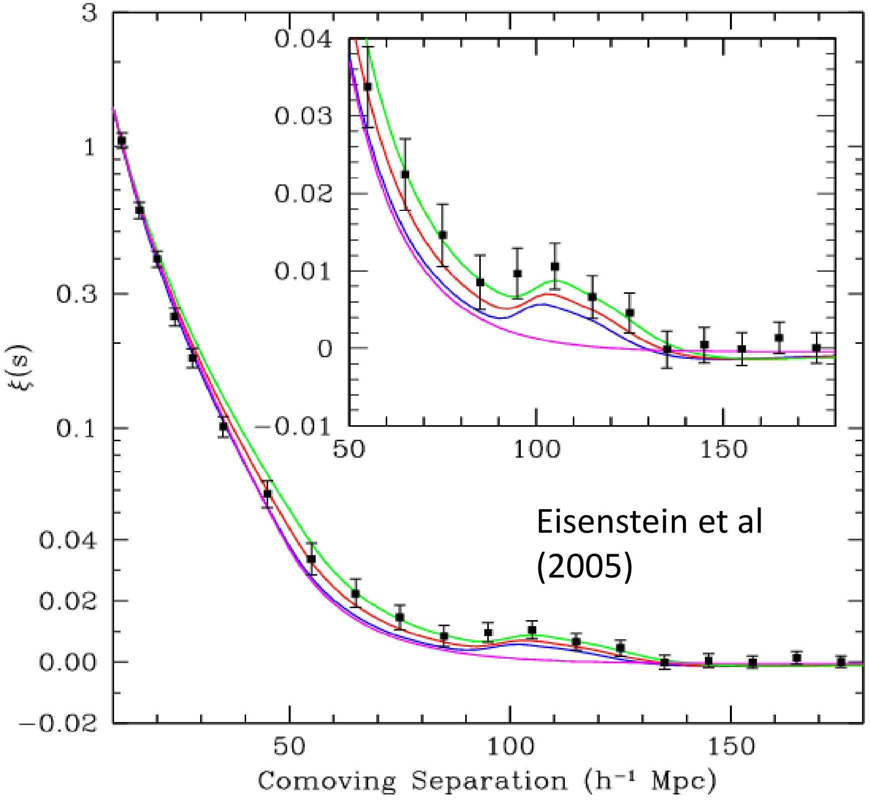
$$\kappa = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_m \int_0^{r_s} dr\, \frac{\delta(r)}{a(r)} \frac{r(r_s - r)}{r_s},$$

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



Eisenstein et al (2005)

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).

WEAK LENSING OF THE CMB

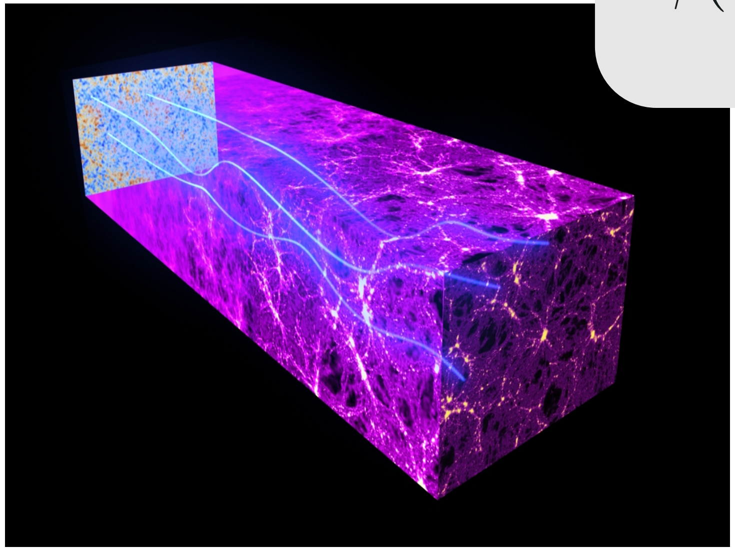
The observed CMB field T^{obs} is displaced wrt to the "unlensed" field T^{unl}, i.e. the one that would be seen in a perfectly homogeneous Universe, due to the lensing effect of intervening structures between us and the LSS:

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

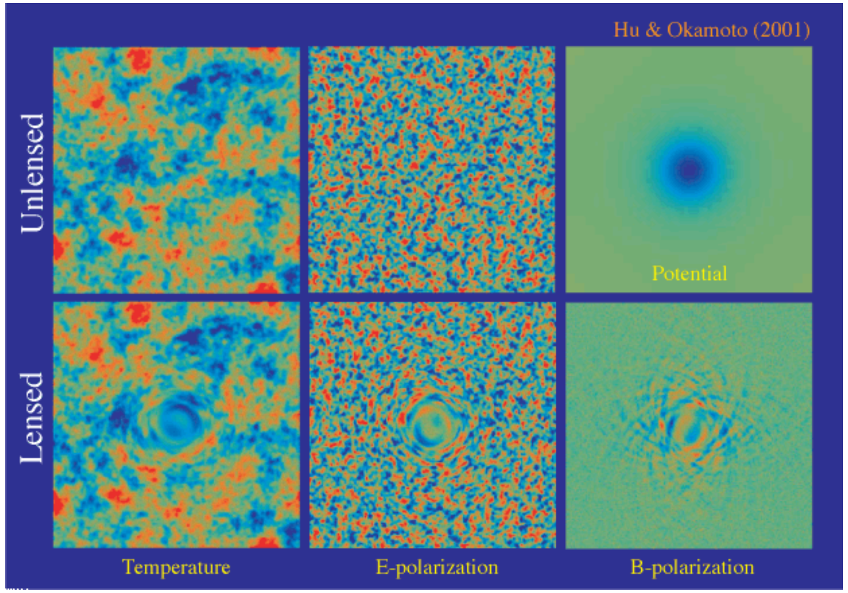
$\vec{d} = \vec{\nabla}\phi$ is the deflection field

Line-of-sight integral of the gravitational potentials

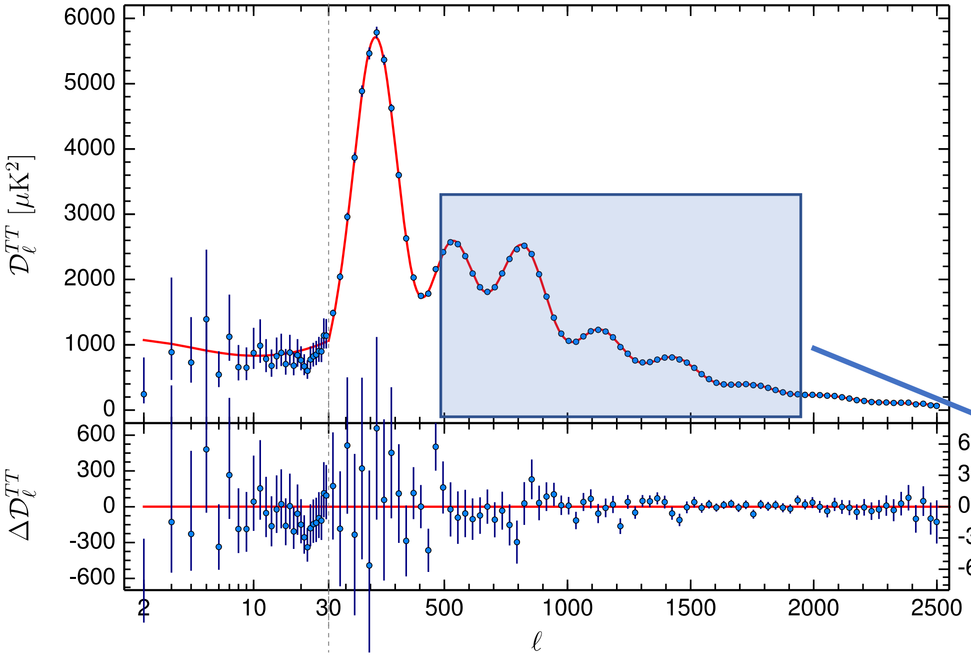
$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$



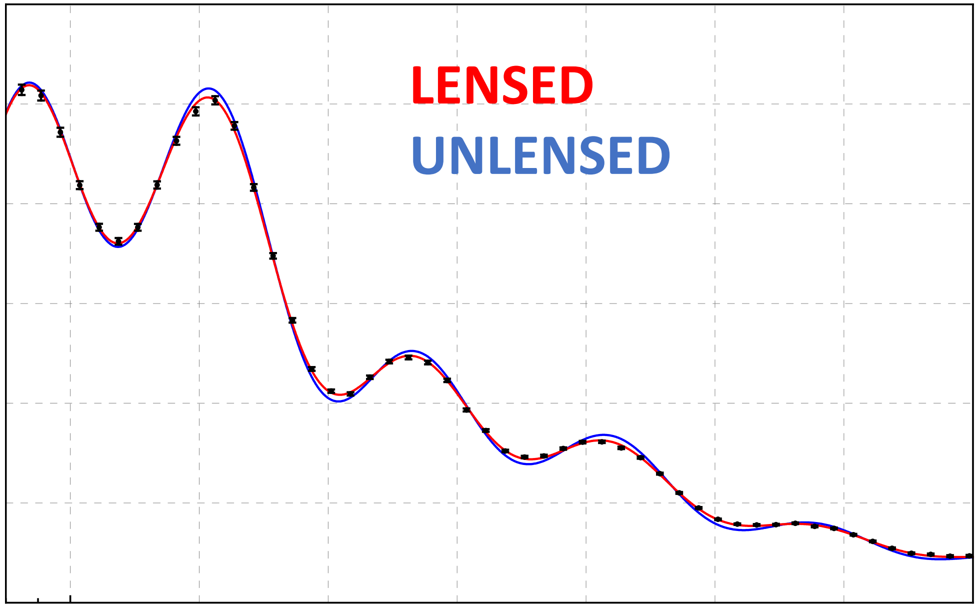
Makes CMB sensitive to the late-time density field, too….



WEAK LENSING OF THE CMB



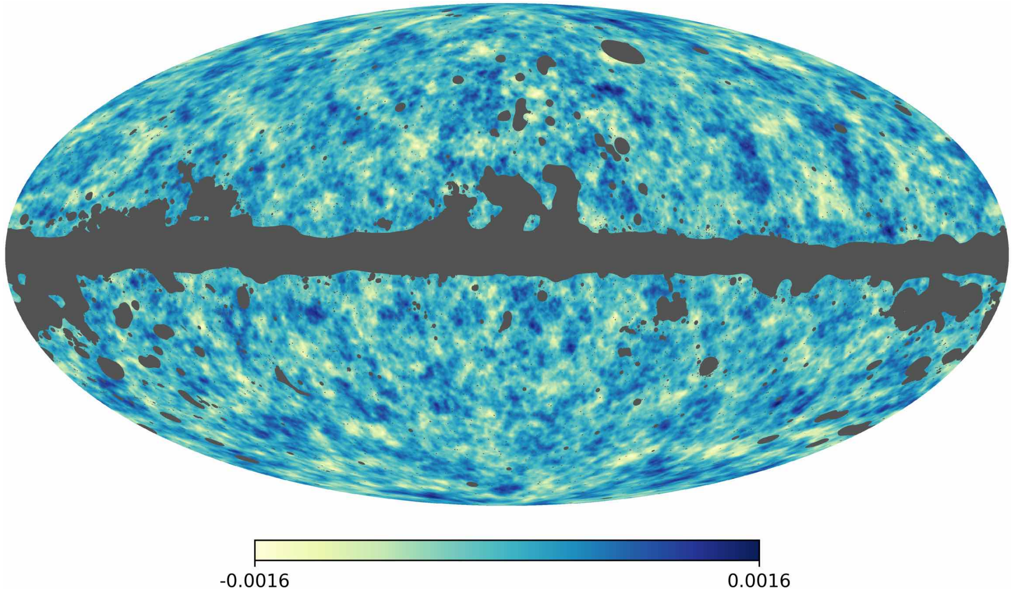
In the power spectrum, lensing causes a smoothing effect at small scales



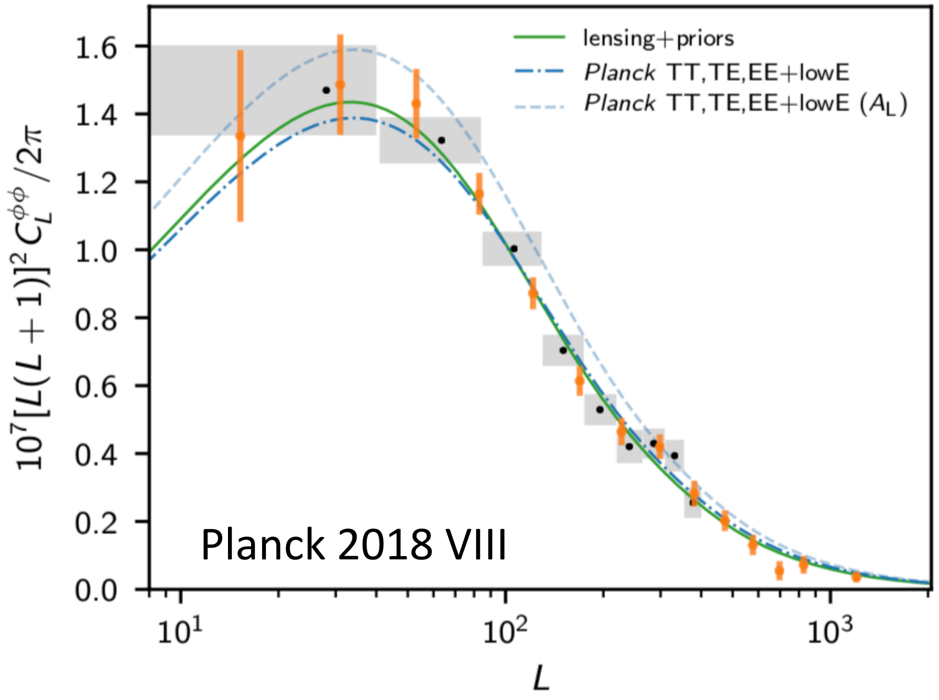
Neutrino free streaming damps matter perturbations and *reduces* lensing

The effect is proportional to the energy density of neutrinos

WEAK LENSING OF THE CMB

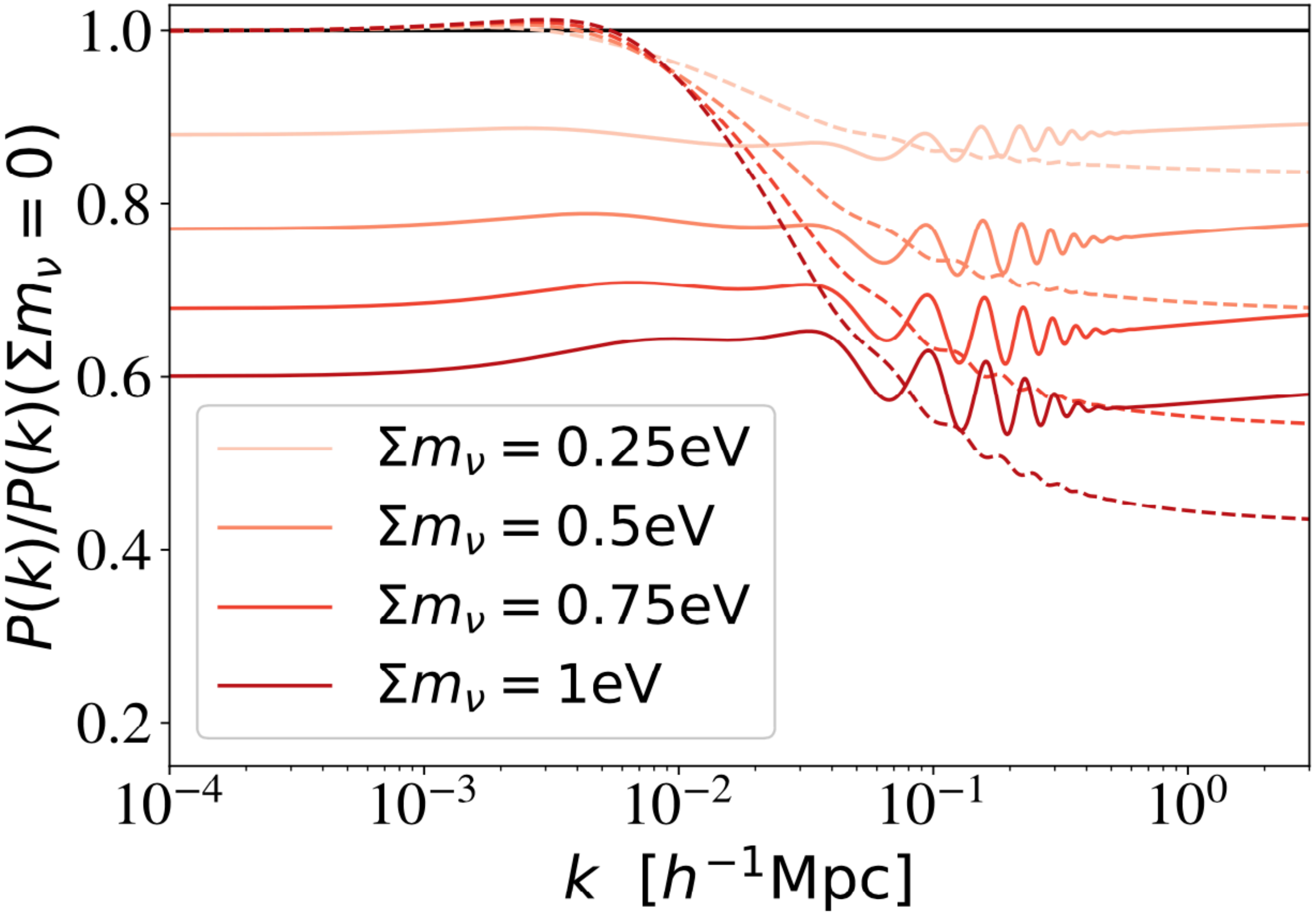


The induced nongaussianities can be used to reconstruct the lensing potential field



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

MATTER POWER SPECTRUM AND MASSIVE NEUTRINOS



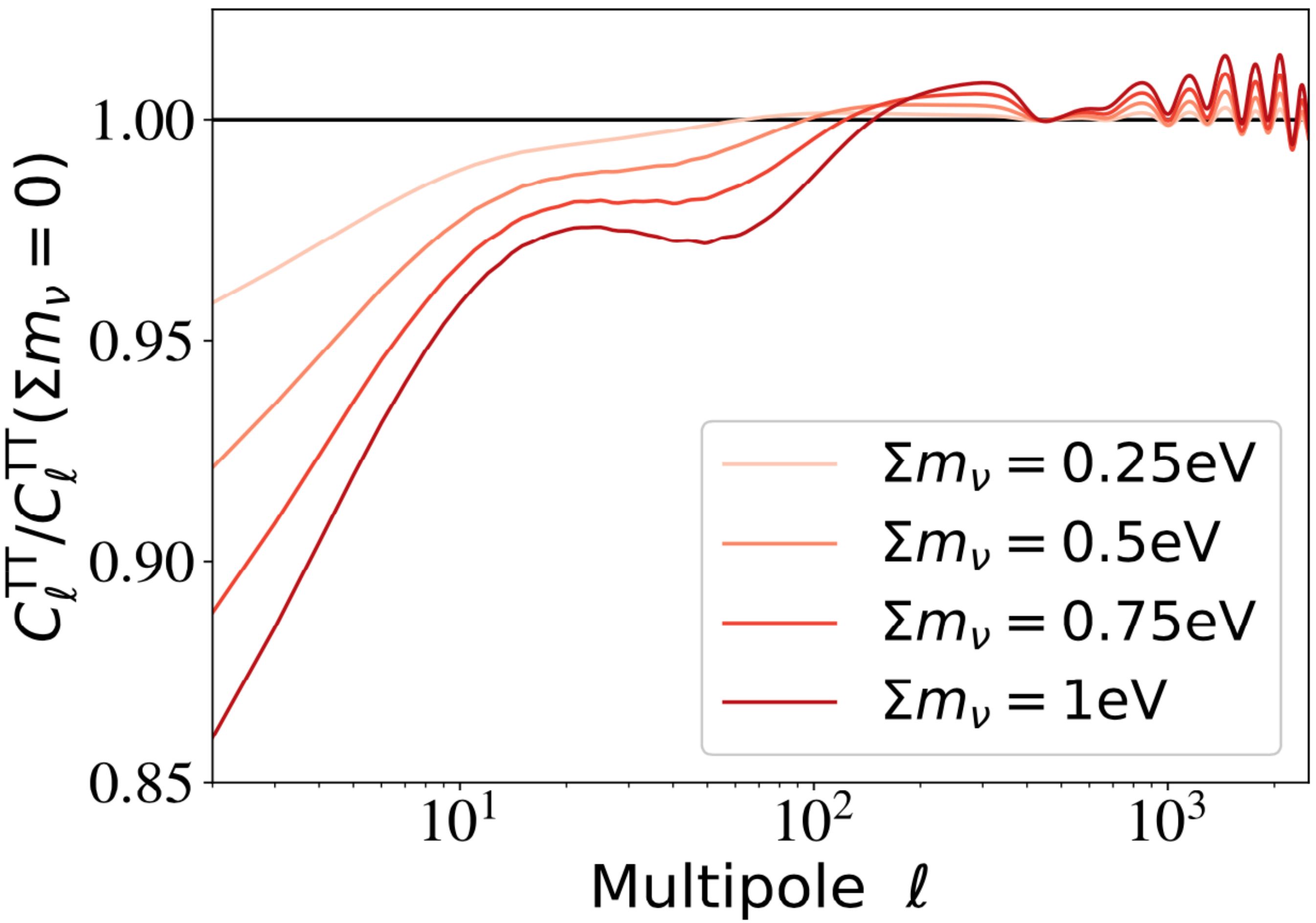
Lesgourgues & Verde, RPP 2019

Dashed curves are for fixed total matter density, so the DM density is adjusted to compensate for the varying neutrino density.

This allows to isolate the characteristic effect of neutrino free-streaming – i.e., power suppression at small scales - in the plot, but would lead to large effects in the CMB power spectrum.

In the case of the solid curves, the other parameters are instead changed to minimize changes in the CMB power spectrum (see discussion in lecture 2).

NEUTRINOS AND THE CMB



Lesgourgues & Verde, RPP 2019

Ratio between CMB spectra with massive neutrinos and the spectrum for massless neutrinos.

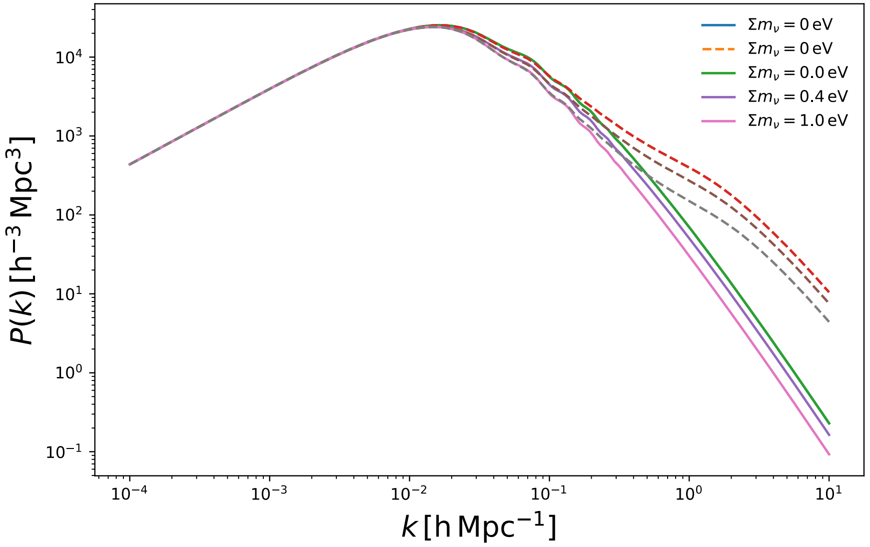
Here the Hubble constant is varied in order to keep constant the angular-diameter distance to the LSS, so that almost all background effects due to massive neutrinos are canceled. This results in degeneracy between M_ν and H_0.

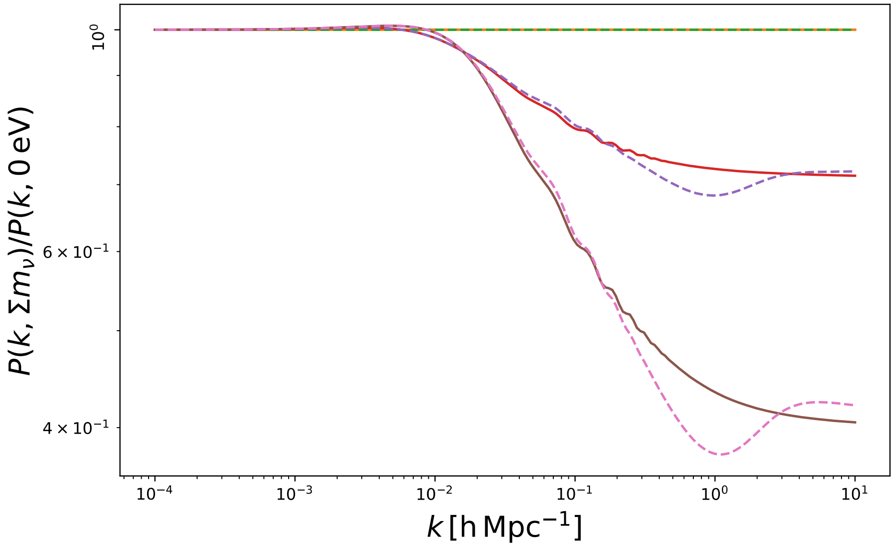
There is a residual effect duo to uncompensated changes in the time of matter-Λ equality (delayed for larger neutrino masses).

This results in smaller power at large scales, where however errors are large, due to a decrease late integrated Sachs-Wolfe effect.

Oscillation at large ell's are mostly due to lensing.

MNU – KEEPING OMEGA MATTER FIXED





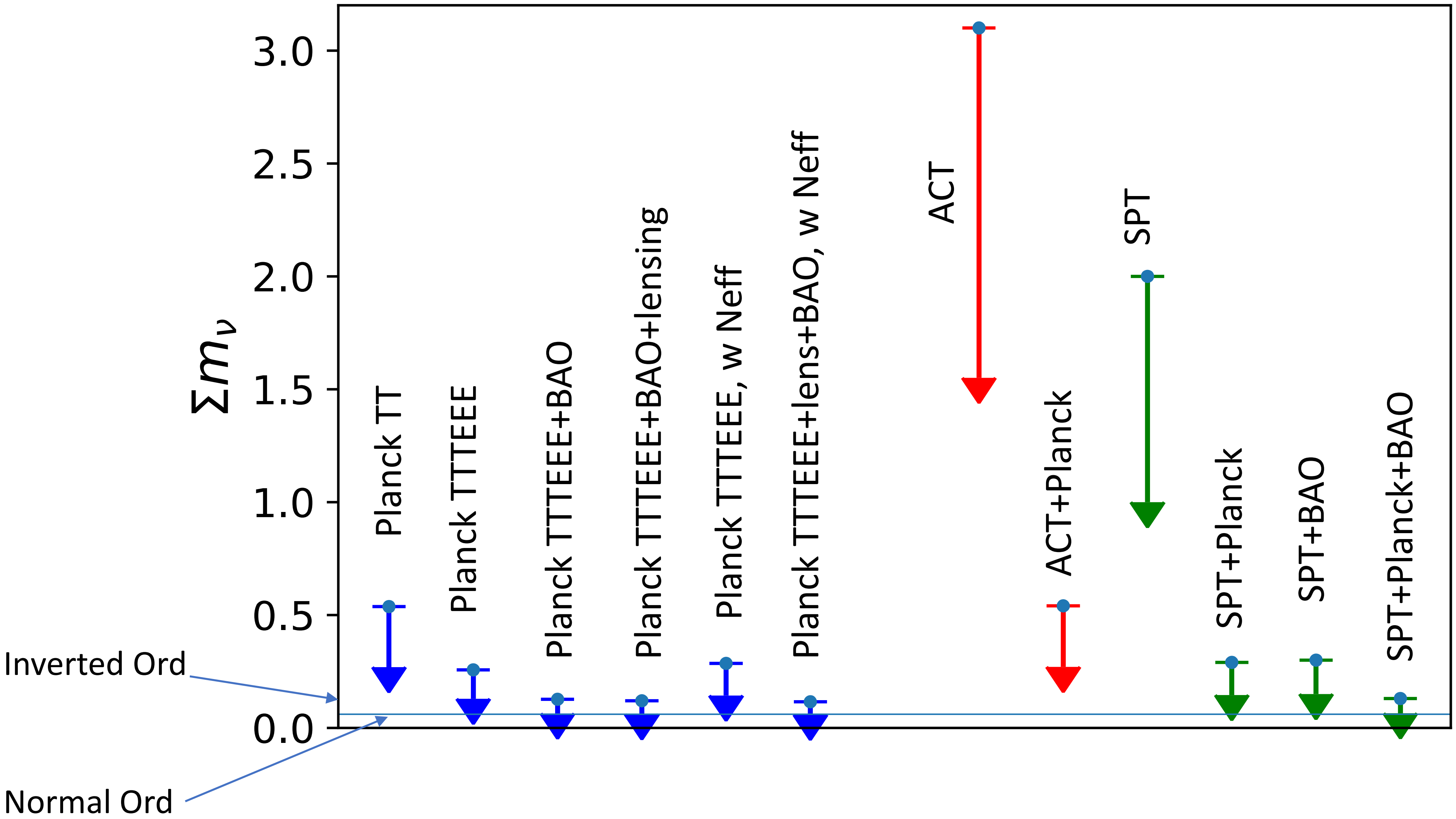
Step-like suppression at small scales:

$$\frac{P(\Sigma m_\nu)}{P(0)} \simeq 1 - 8f_\nu; f_\nu \equiv \Omega_\nu/\Omega_m$$

At $k \gtrsim 0.1h/Mpc$, deviations from linear evolution:
Perturbative approximation does not hold anymore
Need for simulations (N-body)
and/or beyond-perturbative regime (EFT)

In the non-linear case, spoon-like feature at small scales

CURRENT LIMITS ON MNU (95% CL)



Credit: M. Gerbino

COSMOLOGICAL CONSTRAINTS ON NEUTRINO MASSES

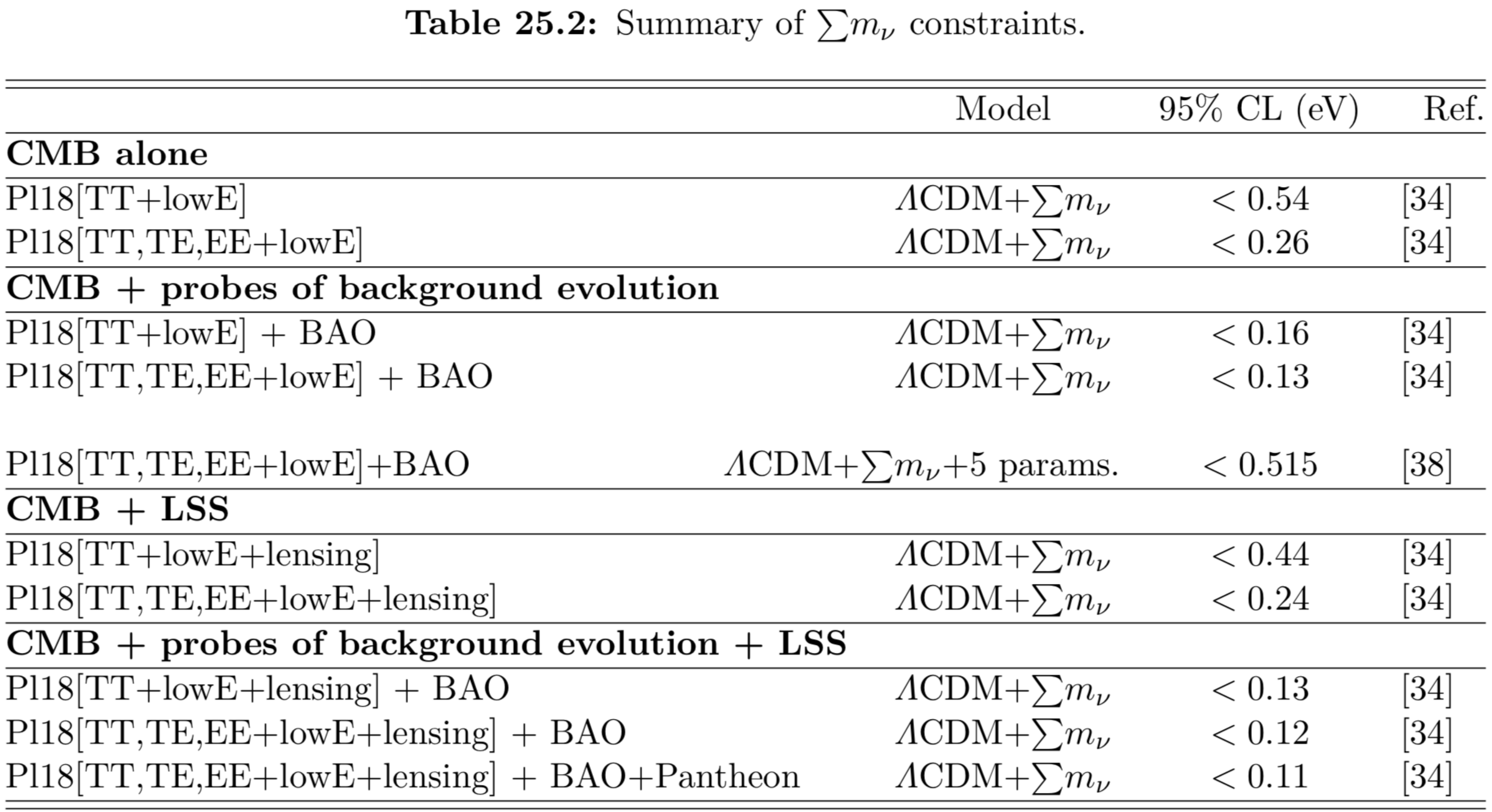


Table 25.2: Summary of $\sum m_\nu$ constraints.

	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

MASS CONSTRAINTS IN EXTENDED MODELS

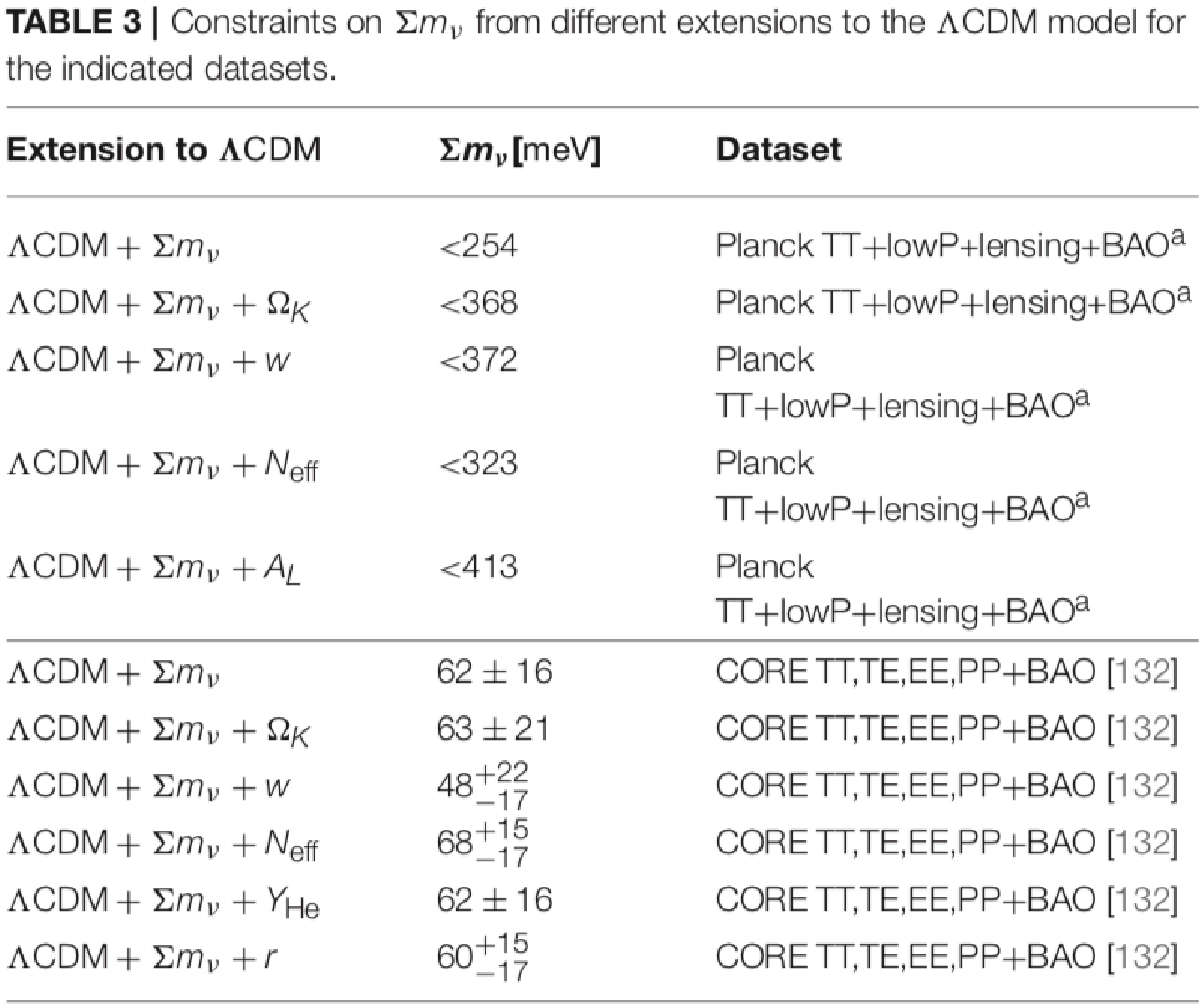


TABLE 3 | Constraints on Σm_ν from different extensions to the ΛCDM model for the indicated datasets.

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

Gerbino & Lattanzi 2018

WHY SHOULD WE MEASURE NEUTRINO MASSES?

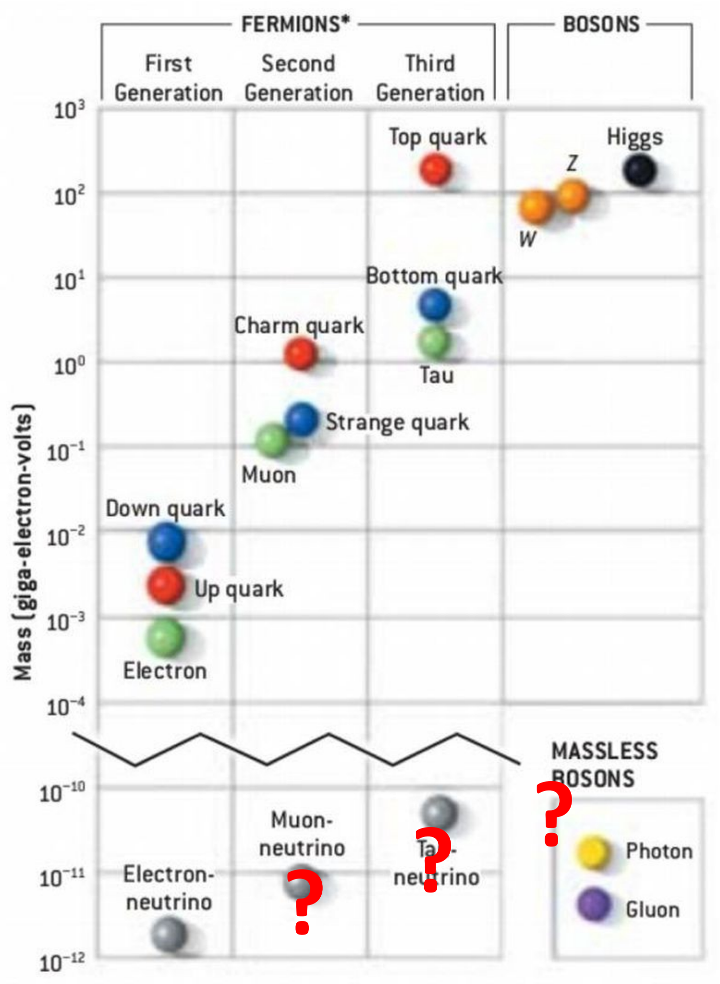


Image credit: G. Kane

Neutrinos are part of the standard model of particle physics….

… however their properties might be related to physics beyond the SM

Many open questions to date:

- absolute mass scale?
- origin of (small) masses?
- origin of mixing pattern?
- mass hierarchy?
- Majorana or Dirac?
- CP violation?

THREE-NEUTRINO MIXING

Neutrino flavour eigenstates are superpositions of the mass eigenstates

$$|\nu_\alpha >= \sum_i U^*_{\alpha i}|\nu_i >$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\times\ \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

PMNS matrix

3 mixing angles
1 CP-violating Dirac phase
2 CP-violating Majorana phases

THREE-NEUTRINO MIXING

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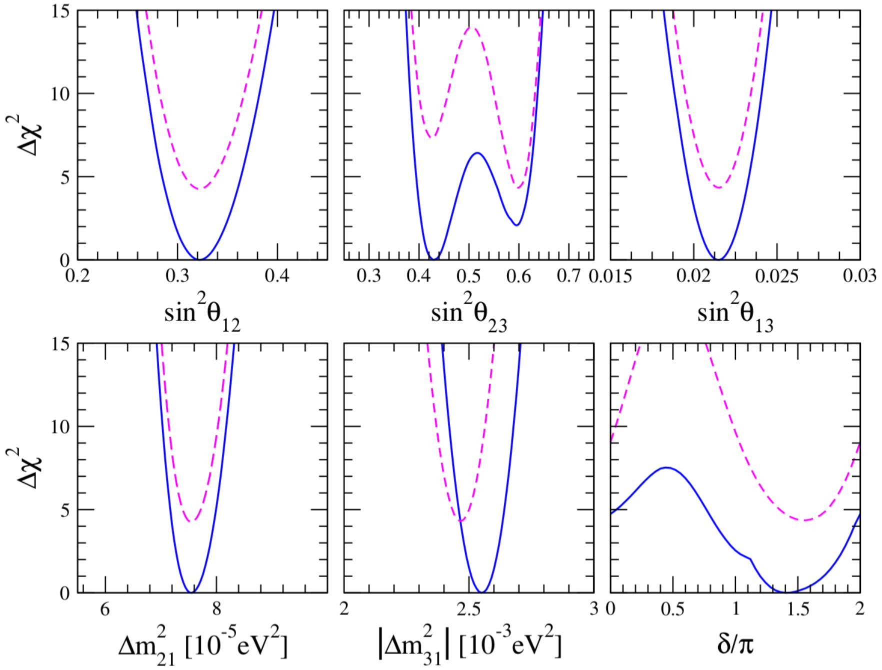
PMNS matrix

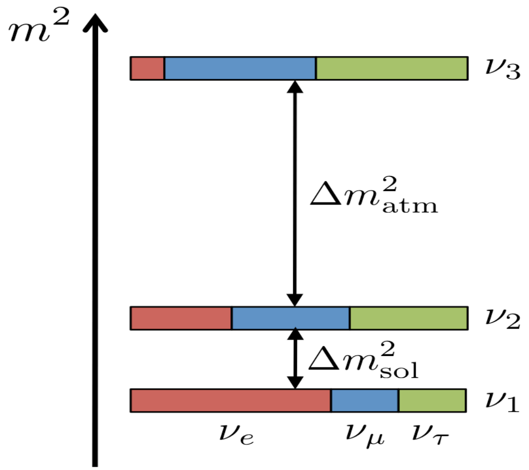
3 mixing angles
1 CP-violating Dirac phase
2 CP-violating Majorana phases

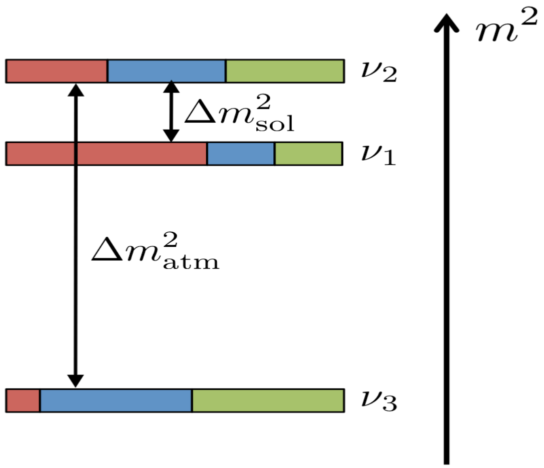
+ 3 masses (1 mass scale, 2 mass differences)



Gariazzo et al. 2018; see also Capozzi et al. 2018; Esteban et al. 2018

normal hierarchy (NH) **vs.** **inverted hierarchy (IH)**





$\Sigma m_\nu > 0.06$ eV

$\Sigma m_\nu > 0.10$ eV

ABSOLUTE MASS SCALE

The **absolute mass scale** can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 0.8 \text{ eV @ } 90\%\text{CL}$$

(KATRIN)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| < 0.06 - 0.16 \text{ eV @ } 90\%\text{CL}$$

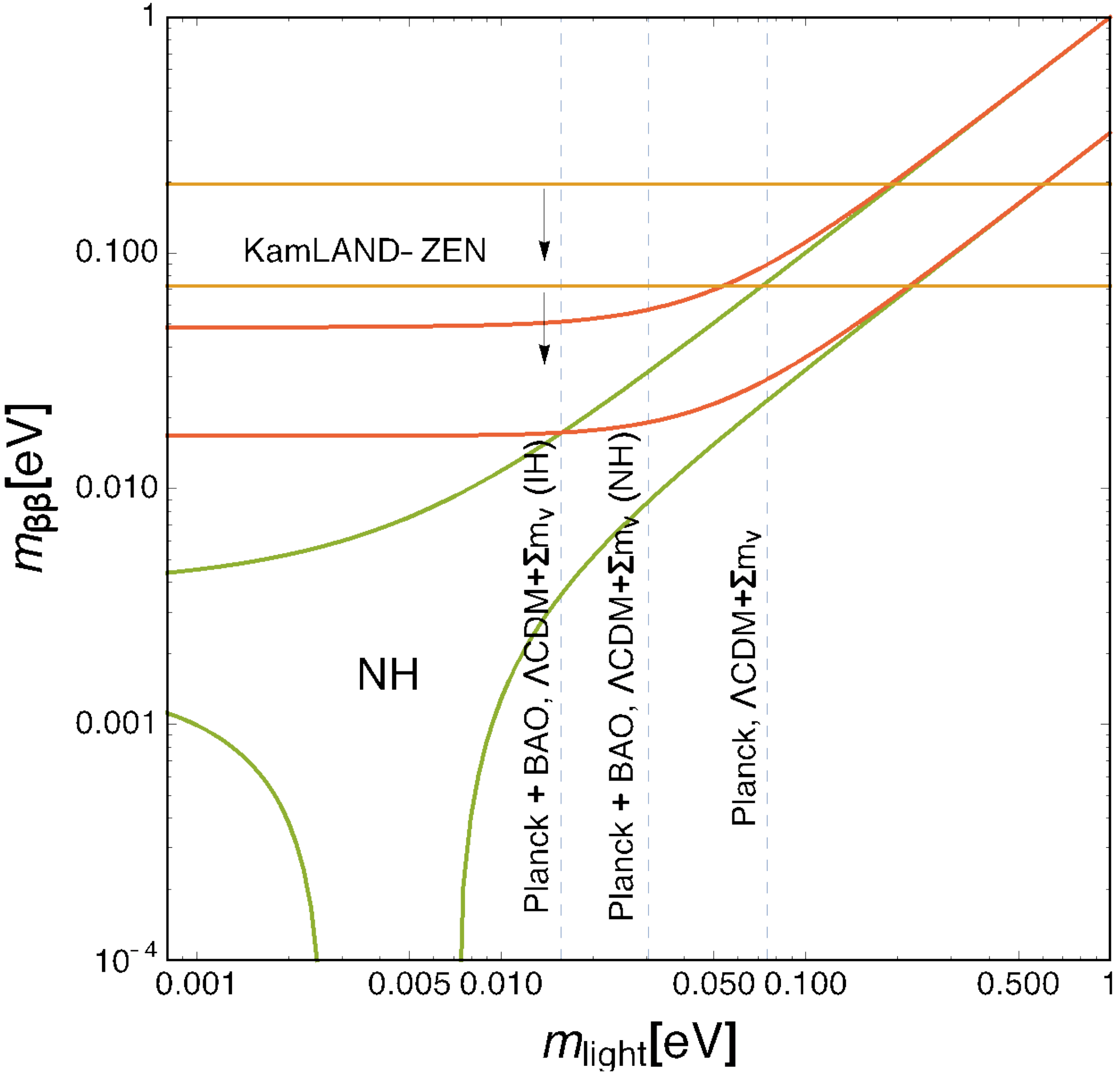
(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i < 0.12 - 0.24 \text{ eV @ } 95\%\text{CL}$$

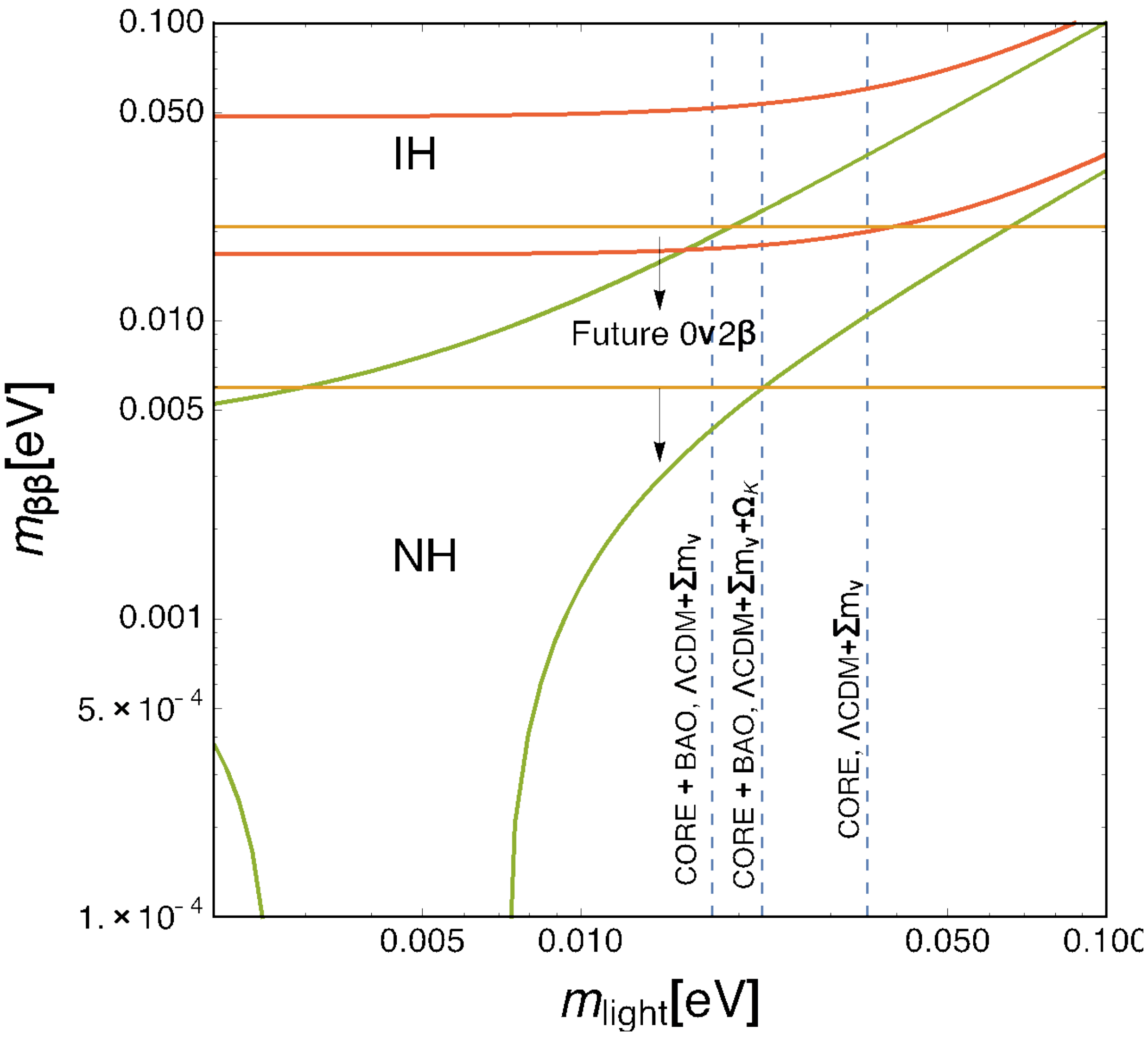
(Planck+…)

COMPLEMENTARITY WITH LAB PROBES



Gerbino & Lattanzi 2018

COMPLEMENTARITY WITH LAB PROBES



Gerbino & Lattanzi 2018

OTHER MASSIVE LIGHT RELICS

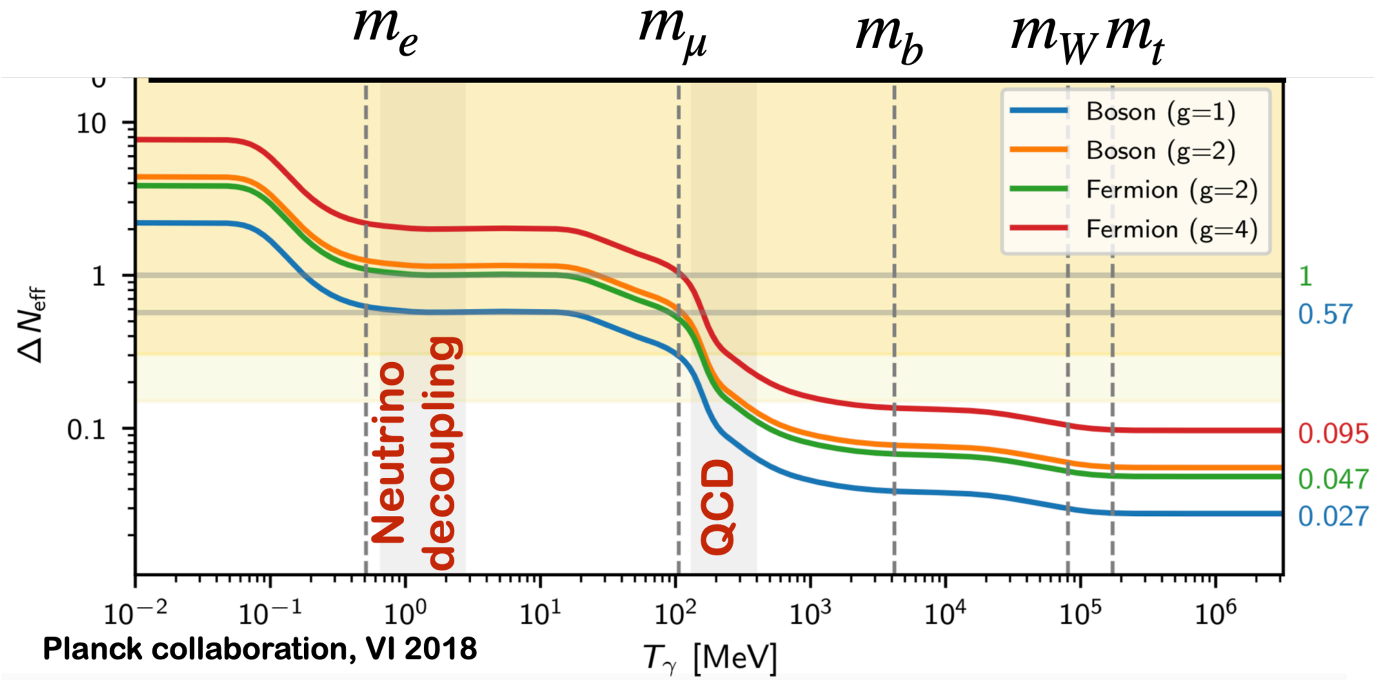
Many extensions of the SM of particle physics predict the existence of new particles species that might contribute to the radiation/matter content of the Universe.
These new species can provide **dark matter** candidates: they can be cold/warm and thus contribute to a large fraction of the matter density of the Universe; or, if they are hot, they can be a subdominant component, like active neutrinos.
Examples include: the **sterile neutrino**, the **axion** (and axion-like particles in general) …..

In the limit of vanishing mass, the effect of these extra species is completely captured by their contribution to N_{eff} (if they are free streaming at the times relevant for cosmological observations).
In this case, the term **dark radiation** is also used.

For a non-vanishing mass, phenomenology depends on whether the species is thermal or not, and on its free-streaming length (for thermal relics, this is basically set by m/T).

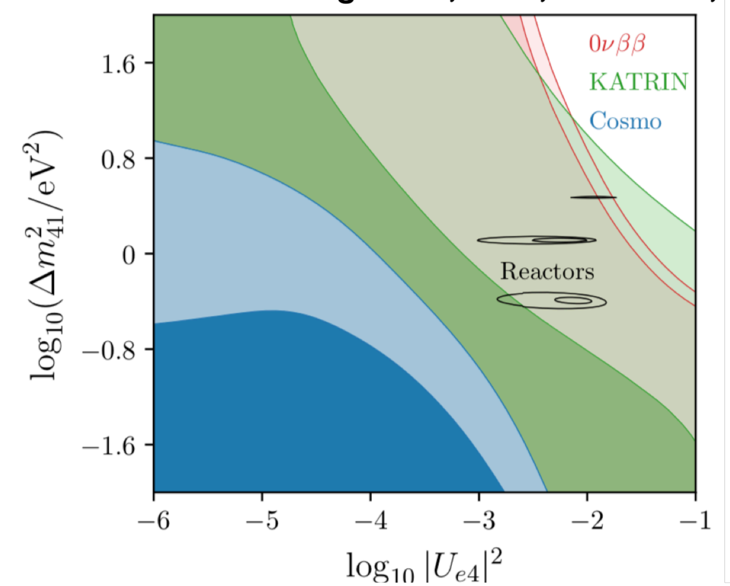
Thermal relics with a m/T ratio similar to active neutrinos have a cosmological phenomenology similar to the one studied so far.
(indeed, for a class of models involving light fermions, there is in fact an ***exact*** mapping – see Colombi, Dodelson and Widrow 1996).

CURRENT LIMITS ON NEFF



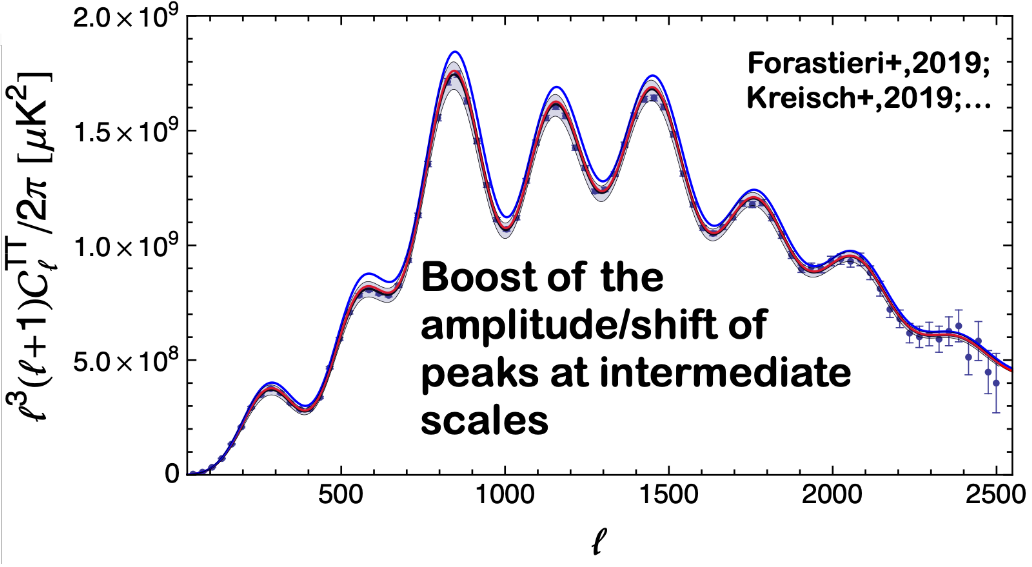
Planck collaboration, VI 2018

Hagstotz+, 2020; Gariazzo+, 2020



Presence of additional fully thermalised species decoupling after QCD phase transition excluded at 95%c.l.

Need to change non-trivially interaction properties to allow for extra radiation

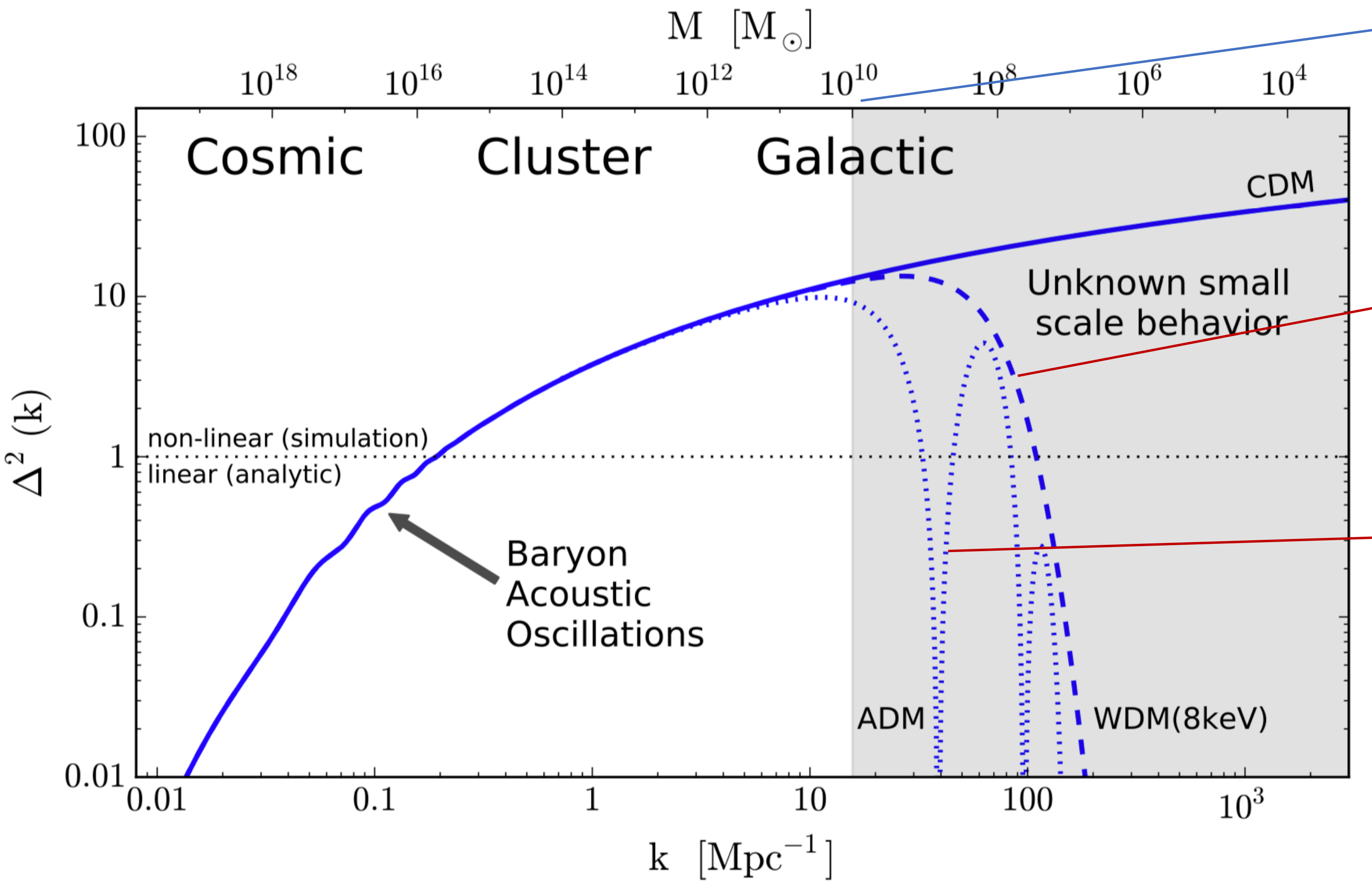


Forastieri+,2019; Kreisch+,2019;…

Boost of the amplitude/shift of peaks at intermediate scales

WARM VS COLD (VS HOT)

Variance of density fluctuations



This mode enters the horizon at T~1 keV

Small-scale cutoff due to free streaming (collisionless damping)

Acoustic oscillations (if DM has pressure)

Perturbation wavenumber (~ 1/length)

Kuhlen, Vogelsberger, Angulo, 2012

STERILE NEUTRINOS

A sterile neutrino is a singlet under the gauge group of the SM. As such, it interacts only gravitationally or through mixing the active neutrinos (parameterized by the mixing angle).

Thus the interaction of a sterile neutrino with the SM is (weak) x (a small mixing angle).

Sterile neutrinos can be produced in the early Universe, for example, through oscillations from active states (Dodelson-Widrow mechanism).
The DW mechanism is now excluded to account for 100% of the DM, but it can still produce a subdominant component.

This mechanism produces a phase-space distribution of the form
(Fermi-Dirac) x (a suppression factor)

COSMOLOGICAL CONSTRAINTS ON STERILE NEUTRINOS

Usin the Colombi-Dodelson-Widrow reparameterization

$$m_s^{\mathrm{eff}} \equiv \left(94.1\,\Omega_s h^2\right)\ \mathrm{eV}$$

Effective mass

(sets non-relativistic energy density)

$$\Delta N_{\mathrm{eff}} = \begin{cases} (T_s/T_\nu)^4 & \text{thermal} \\ \chi_s & \text{DW} \end{cases}$$

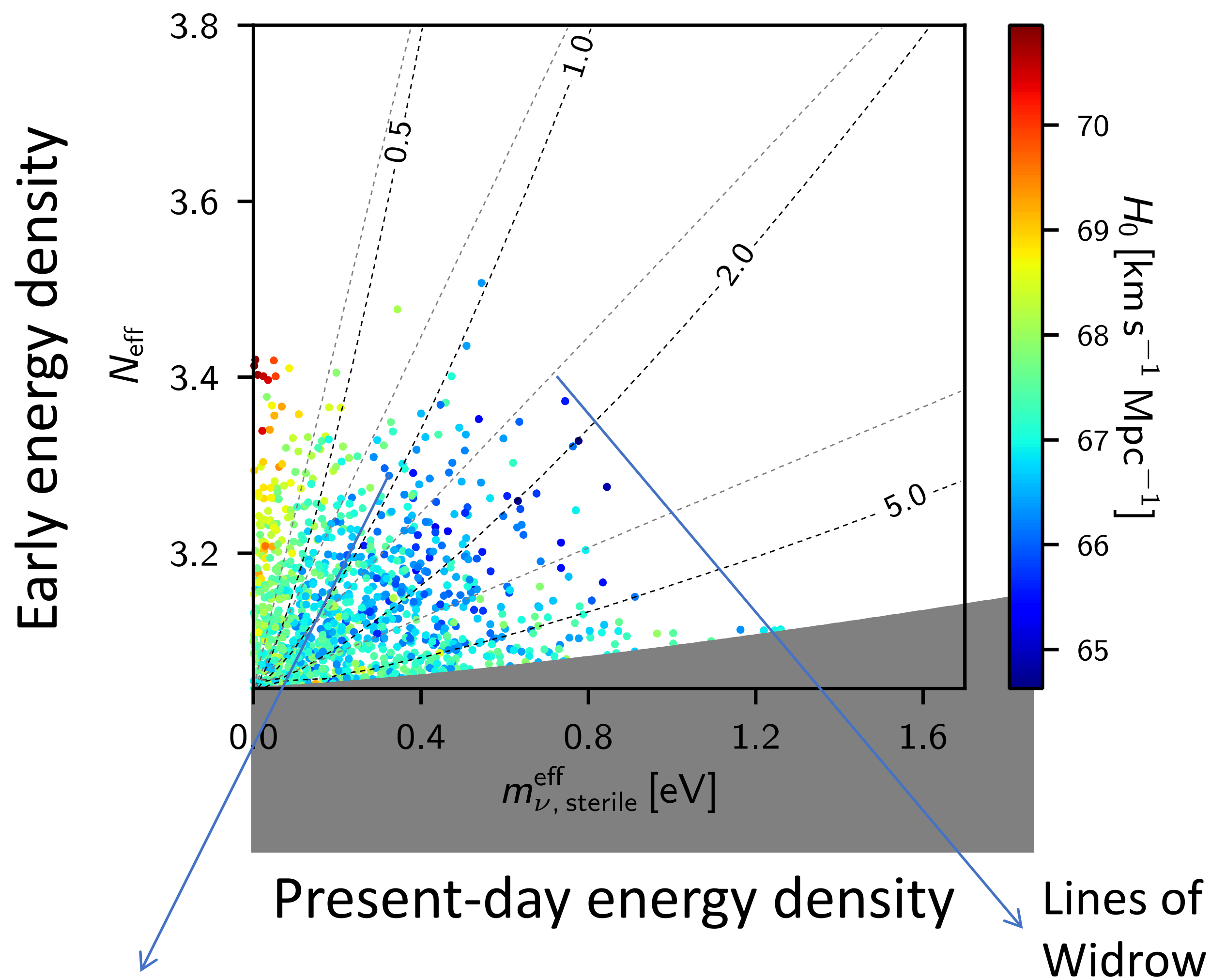
Effective number of degrees of freedom

(sets relavistic energy density)

To get the actual mass:

$$m_s = \begin{cases} m_s^{\mathrm{eff}}\,(T_s/T_\nu)^{-3} = m_s^{\mathrm{eff}}/\Delta N_{\mathrm{eff}}^{3/4} & \text{thermal} \\ m_s^{\mathrm{eff}}/\chi_s = m_s^{\mathrm{eff}}/\Delta N_{\mathrm{eff}} & \text{DW} \end{cases}$$

COSMOLOGICAL CONSTRAINTS ON STERILE NEUTRINOS



Early energy density

Present-day energy density

Planck TT+lowP+
lensing+BAO

$N_{\rm eff} < 3.34$
$m^{eff}_{sterile} < 0.23$ eV

One sterile eigenstate;
total active mass fixed to
0.06 eV

Lines of constant m_s (Dodelson-Widrow sterile nu's)

Lines of constant m_s (thermal sterile nu's)

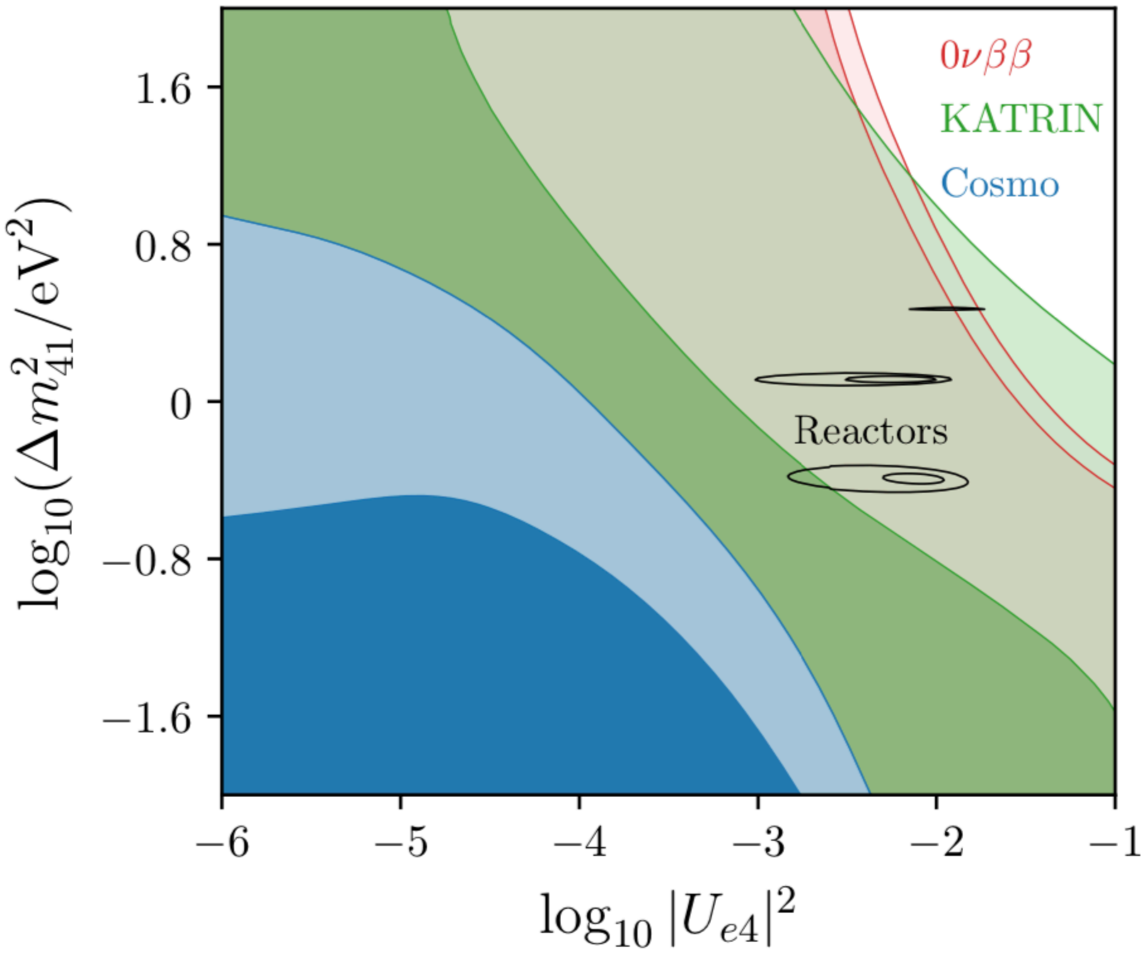
Planck collaboration, VI 2018

COSMOLOGICAL CONSTRAINTS ON STERILE NEUTRINOS

Cosmology robustly exclude region of large sterile mass and mixing params larger than 10^-3 in LCDM extensions

Light sterile solution to short-baseline oscillation anomalies hard to accommodate!

See Hannestad 2014; Hagstotz+ (incl ML) 2021;

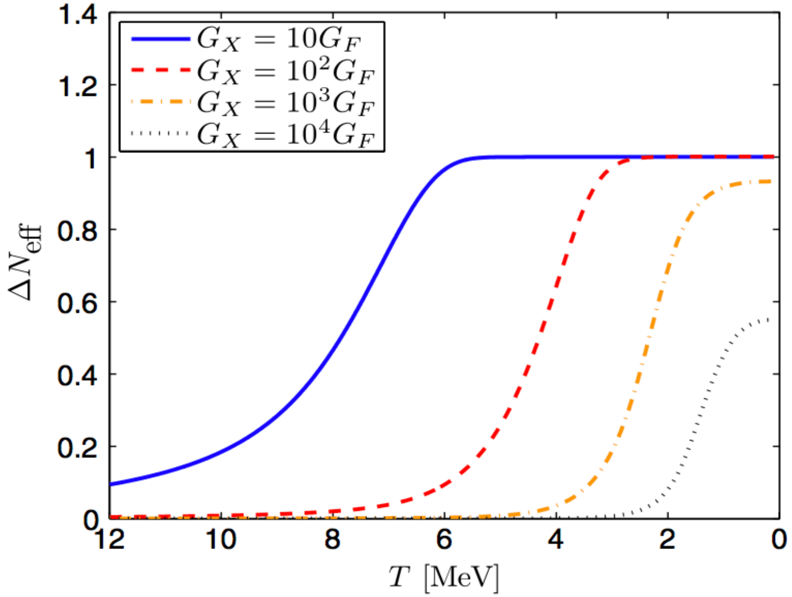


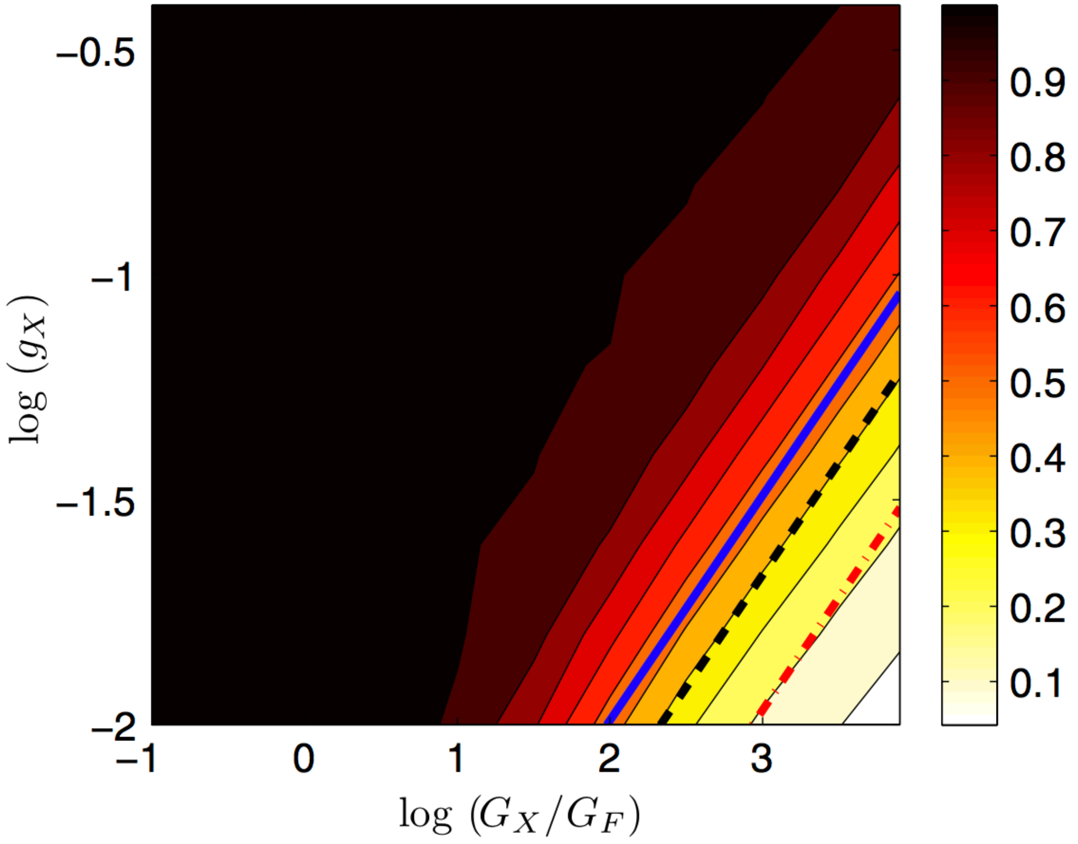
Hagstotz+, 2021

νNSI AND SBL ANOMALIES

A possible solution:
new ("secret") neutrino interactions in the sterile sector can prevent production in the early Universe

$$\mathcal{L}_s = g_X \bar{\nu}_s \gamma_\mu \frac{1}{2} \left(1 - \gamma_5\right) \nu_s X^\mu$$



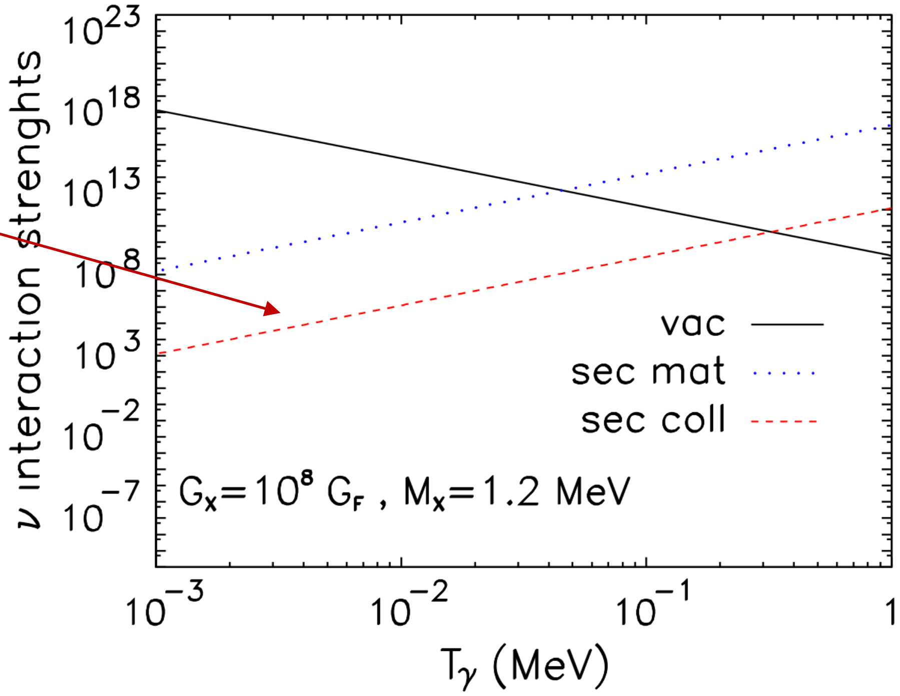


Hannestad et al. 2014; Dasgupta & Kopp 2014; Bringmann et al 2014; Saviano et al 2014; Mirizzi et al 2015; Chu,Dasgupta,Kopp 2015; Chu et al. 2018

νNSI AND SBL ANOMALIES

For $g_X > 10^{-2}$ and $M_X < 10$ MeV, it is still possible to copiusly produce neutrinos at low (T<1 MeV) temperatures, through an interplay between vacuum oscillations and collisions (“*scattering-induced decoherence*”)
(Saviano et al 2014; Mirizzi et al 2015;)
Relaxation rate to chemical equilibrium:

$$\Gamma_t \simeq \langle P(\nu_\alpha \to \nu_s) \rangle_{\rm coll} \Gamma_X .$$



Number conservation and flavour equilibration imply

$n_{s,\rm after} = n_{a,\rm after} = 3/4\ n_{a,\rm before}$

Then collisions lead to thermalization and

$$T_\nu = \left(\frac{3}{4}\right)^{1/3} T_\nu^{\rm std} \longrightarrow N_{\rm eff} = 4 \times \left(\frac{3}{4}\right)^{4/3} \simeq 2.7$$

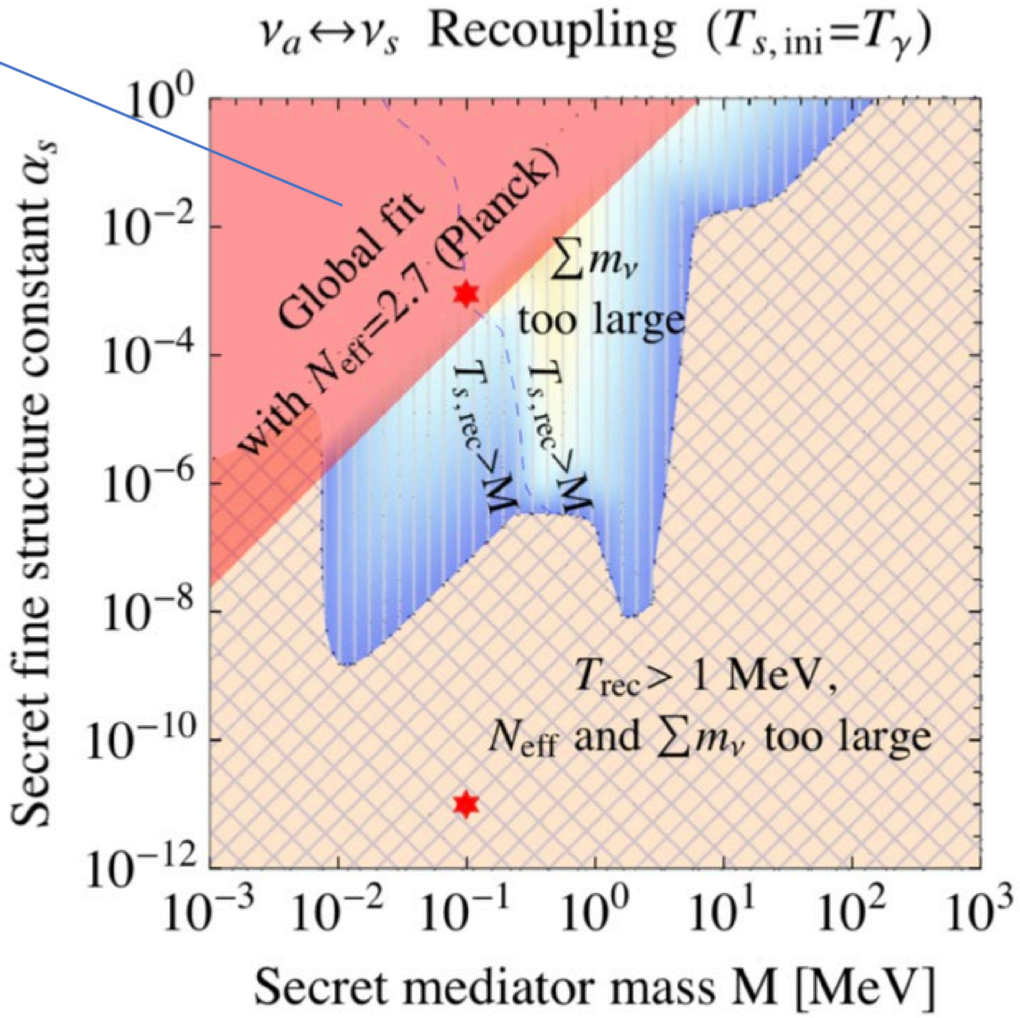
νNSI AND SBL ANOMALIES

Excluded region from Forastieri+ (incl ML) 2017

Catch-22 situation:

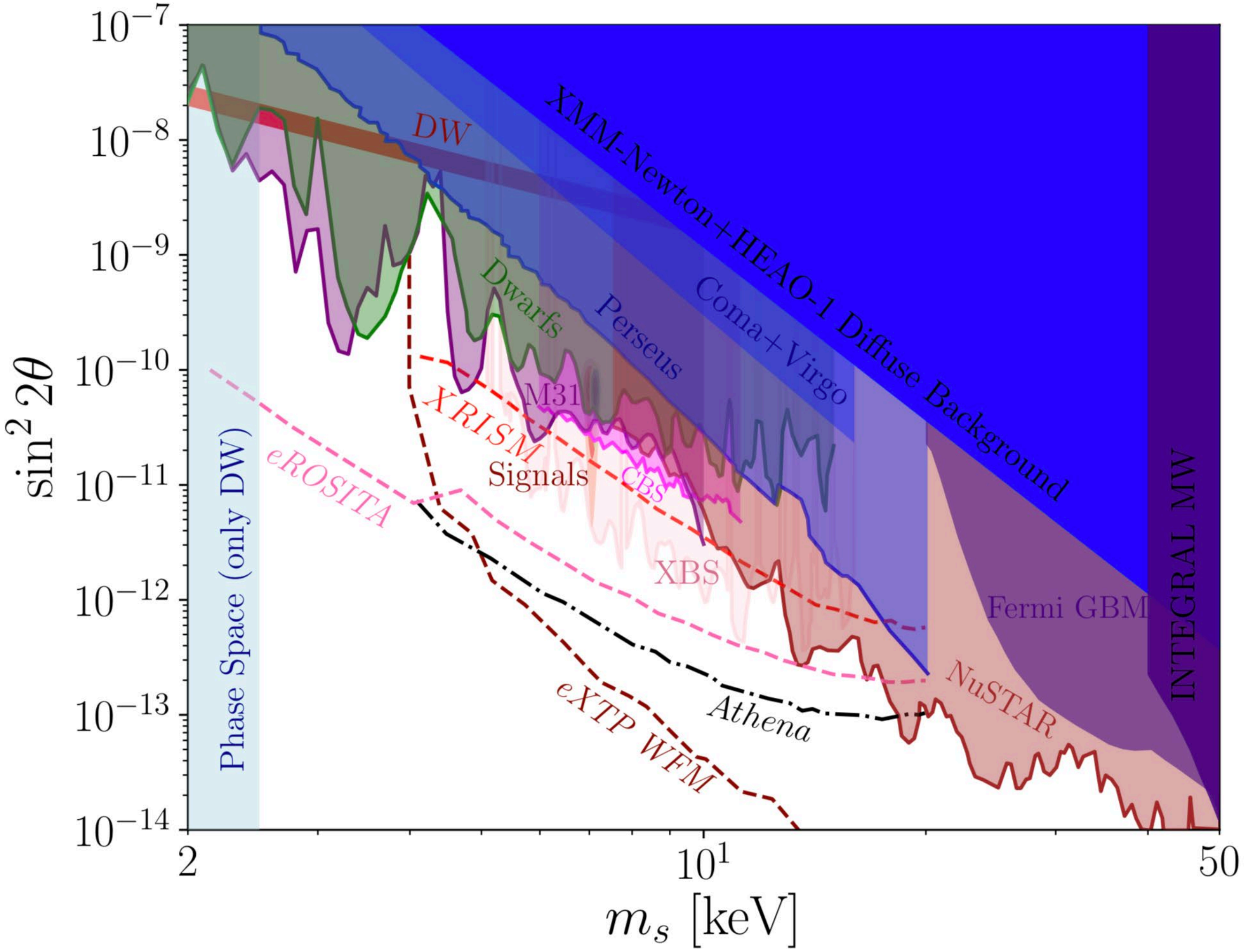
If nonstandard interactions are strong enough to prevent sterile neutrino free-streaming (and erase the neutrino mass bound) then they should leave an observable imprint on CMB anisotropies

In the end, you violate either the mass or the interaction strength bound.



Plot from Chu et al. 2018

CONSTRAINTS ON STERILE NEUTRINO DM



Exclusions assume that sterile nu's make for all the DM

AXIONS

The **QCD axion** is a pseudo Nambu-Goldstone boson that has been proposed to explain the fact that CP is not badly violated by strong interactions.

$$\mathcal{L} = \left(\frac{\phi_a}{f_a} - \bar{\Theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

QCD Axions can be produced in the early Universe by several mechanisms:

- *Thermal production*
 thermal axions behave as hot dark matter and thus can only be a subdominant component

- *Production from string decay*
 After the QCD phase transition, discrete domains form with vacuum angles differing by 2π, and topological defects form at their borders. These decay and radiate axions

- *Misalignment mechanism*
If the field is initially misplaced from the minimum, it exhibits coherent oscillations while rolling towards the bottom of the potential

AXIONS FROM MISALIGNMENT

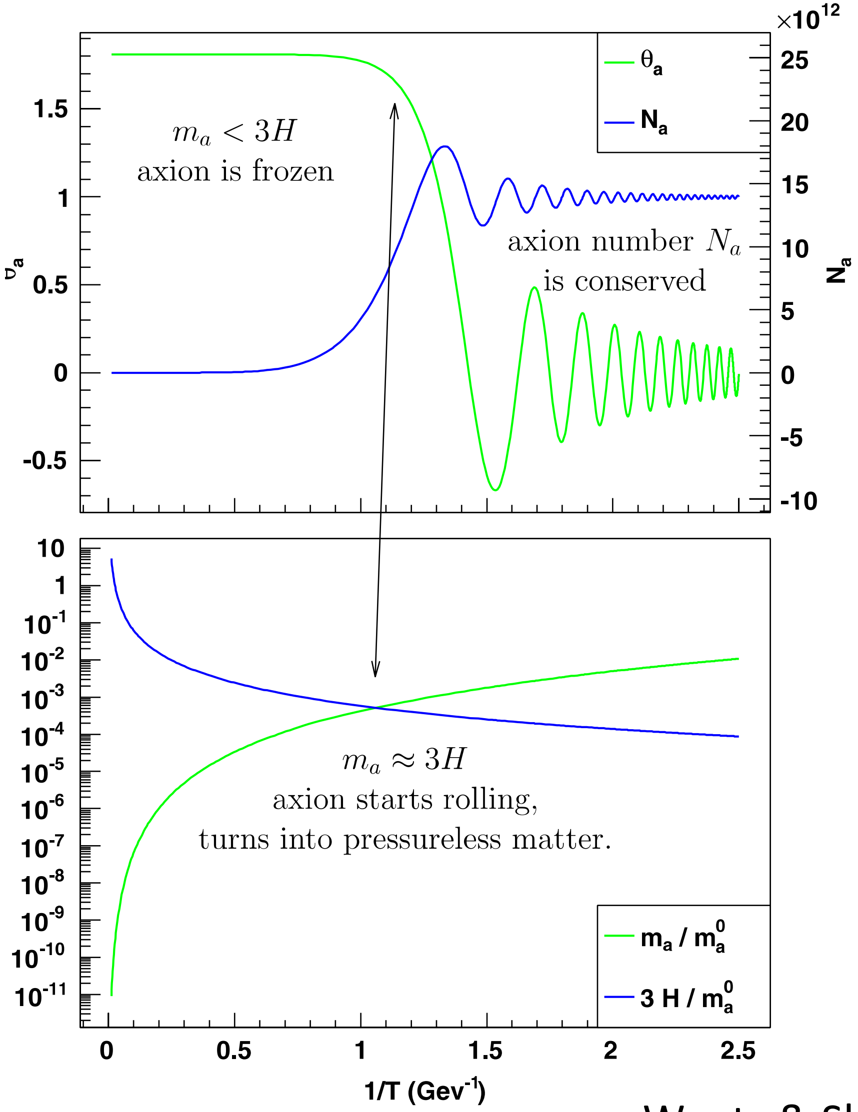
The axion field evolves according to

$$\ddot{\theta} + 3H\dot{\theta}_a + m_a^2(T)\,\sin\theta_a = 0,$$

- As long as its compton wavelength is above the Hubble scale, the axion is effectively massless and q = const.
- At the QCD phase transition, instantons effect generate a mass and when m_a ~ 3H, the axion starts to roll towards its minimum in q = 0
- Shortly after, coherent oscillation set up and the axion behaves as cold dark matter, i.e. $r_a \sim a^{-3}$. The number density when oscillations set up roughly scales as

$$n_a(T_{\rm osc}) \propto m_a(T_{\rm osc}) f_a^2 \theta_i^2$$

- At this point entropy conservation can be used to compute the present density



Wantz & Shelland 2010

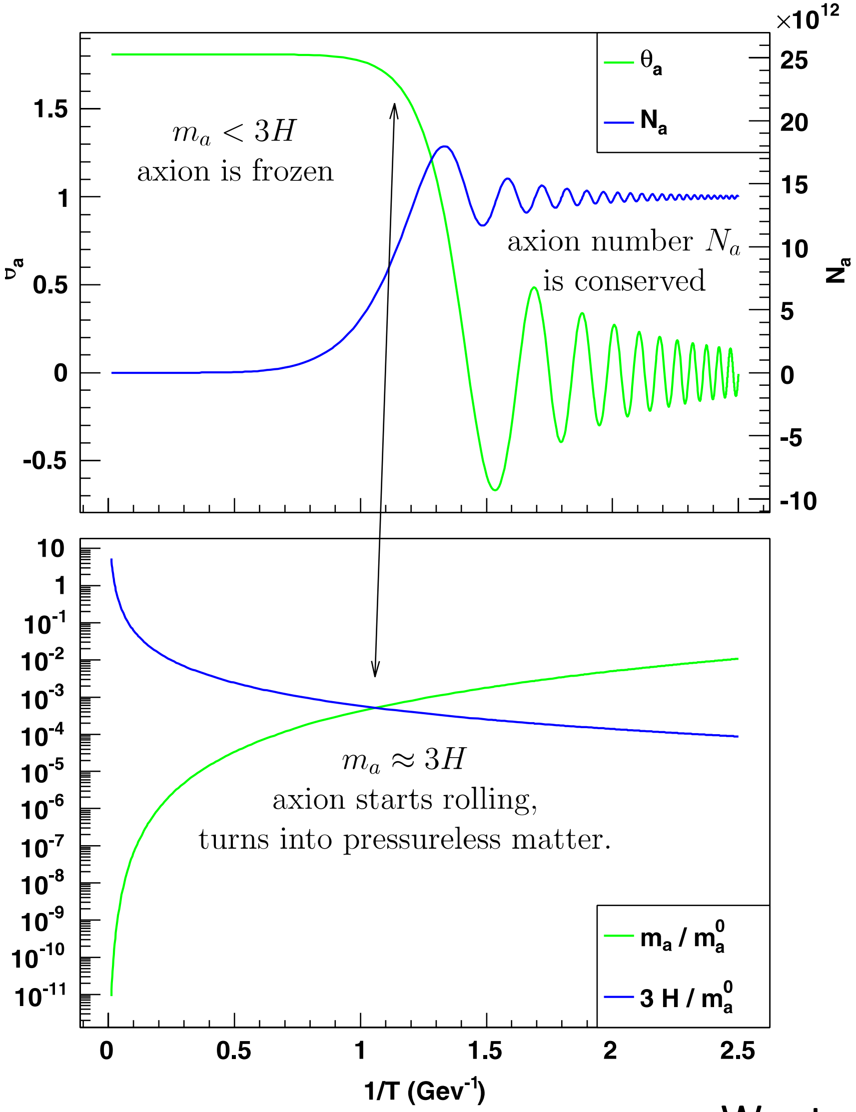
AXIONS FROM MISALIGNMENT

Two main ingredients to obtain Ω_{mis} given the initial misalignment angle θ_i and the PQ scale f_a:

- equation of state (enters in the evolution of the Hubble rate);

- topological susceptibility
  $\chi(T) = m_a^2(T)\, f_a^2$
(needs lattice QCD calculations)

$$\Omega_A^{\rm VR} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ \rm GeV}\right)^{1.165} F\,\Theta_{\rm i}^2$$
$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} F\,\Theta_{\rm i}^2\,,$$



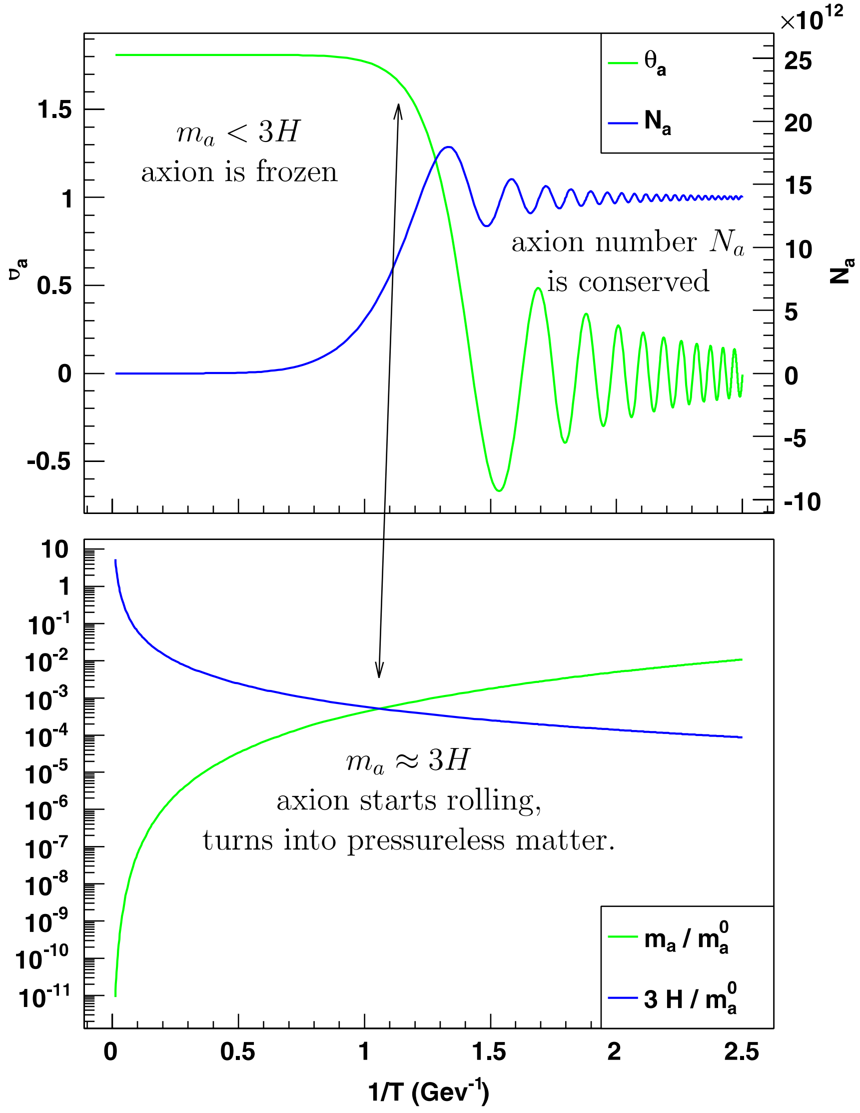
Wantz & Shelland 2010

AXIONS FROM MISALIGNMENT

Two possible scenarios:

- pre-inflationary axion: the PQ symmetry is broken during inflation and not restored afterwards. θ_i is constant across the whole observable Universe (its value being a free parameter of the model).

- post-inflationary: the PQ symmetry is broken after inflation, θ_i^2 should be replaced by its spatial average. Topological defects are produced.



Wantz & Shelland 2010

AXIONS FROM MISALIGNMENT

In the pre-inflationary scenario, θ is a free parameter.
If $\theta = O(1)$, m_a should be > 6 μeV

However, arbitrarily small values of m_a can be made consistent with the observed DM density if θ is small enough ("anthropic" axion window).

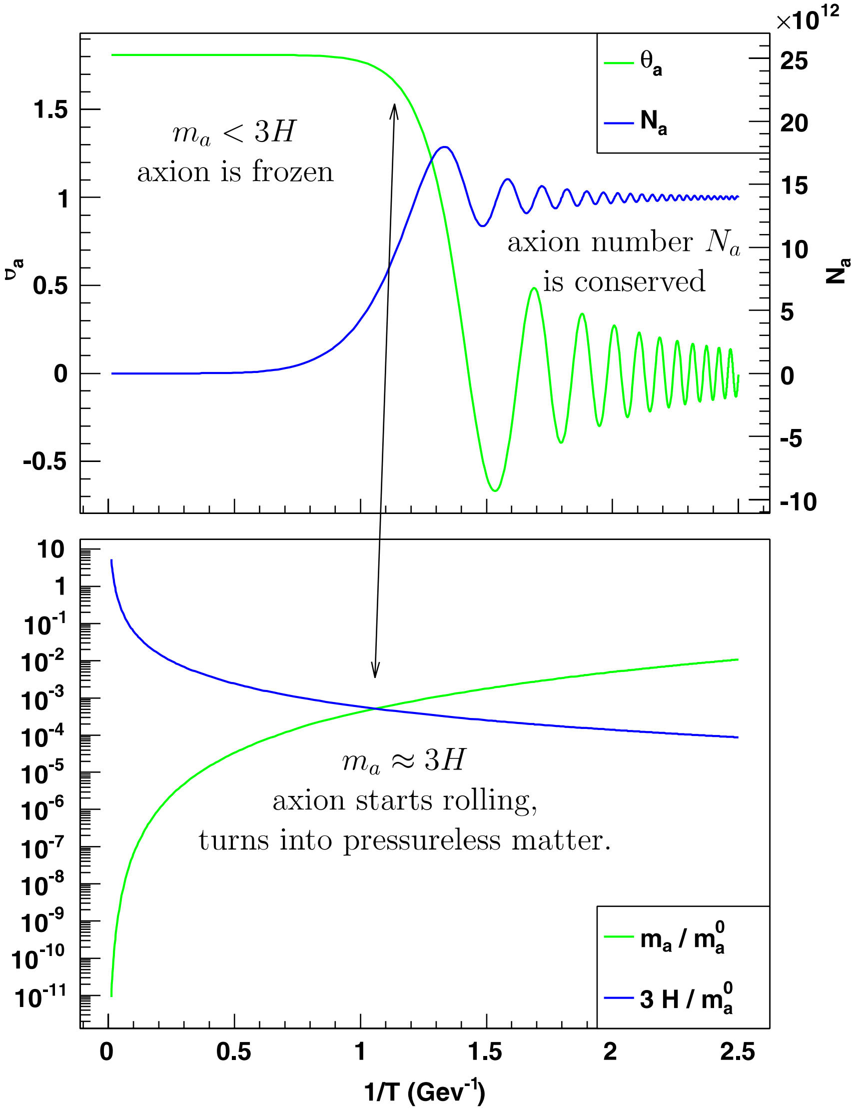
In the pre-inflationary scenario, quantum fluctuations of the axion field lead to isocurvature density fluctuations.

These have not been observed; current constraints from Planck imply that, *if QCD axions make for all the DM,* the expansion rate during inflation should be

$$H_I < 5.7 \times 10^8\,\mathrm{GeV}\left(\frac{5\mathrm{neV}}{m_a}\right)^{0.4175}$$

i.e.,

$$\frac{r}{0.1} \lesssim 3 \times 10^{-11}\left(\frac{5\mathrm{neV}}{m_a}\right)^{0.835}$$



Wantz & Shellard 2010

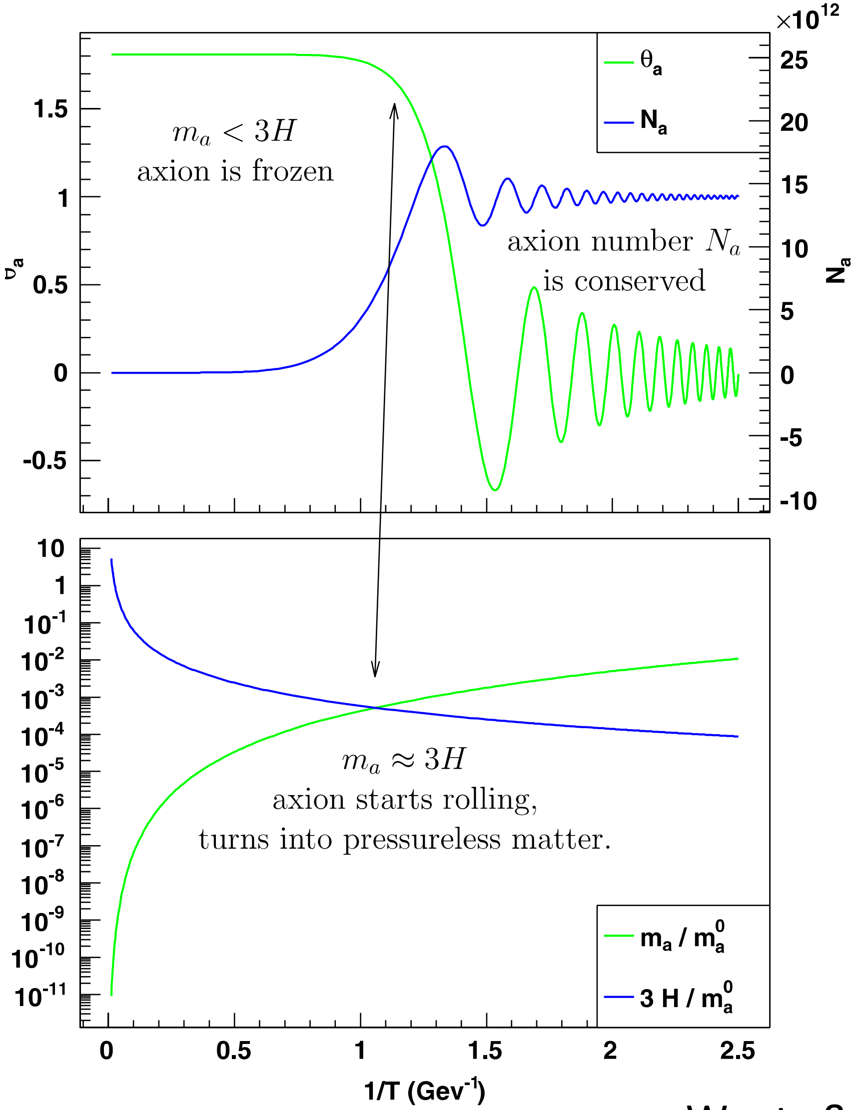
AXIONS FROM MISALIGNMENT

In the post-inflationary scenario, θ should be substituted with its average over the whole observable Universe.
This gives:

$$\Omega_{a,\mathrm{mis}}h^2 = 0.12\left(\frac{30\mu\mathrm{eV}}{m_a}\right)^{1.165}$$

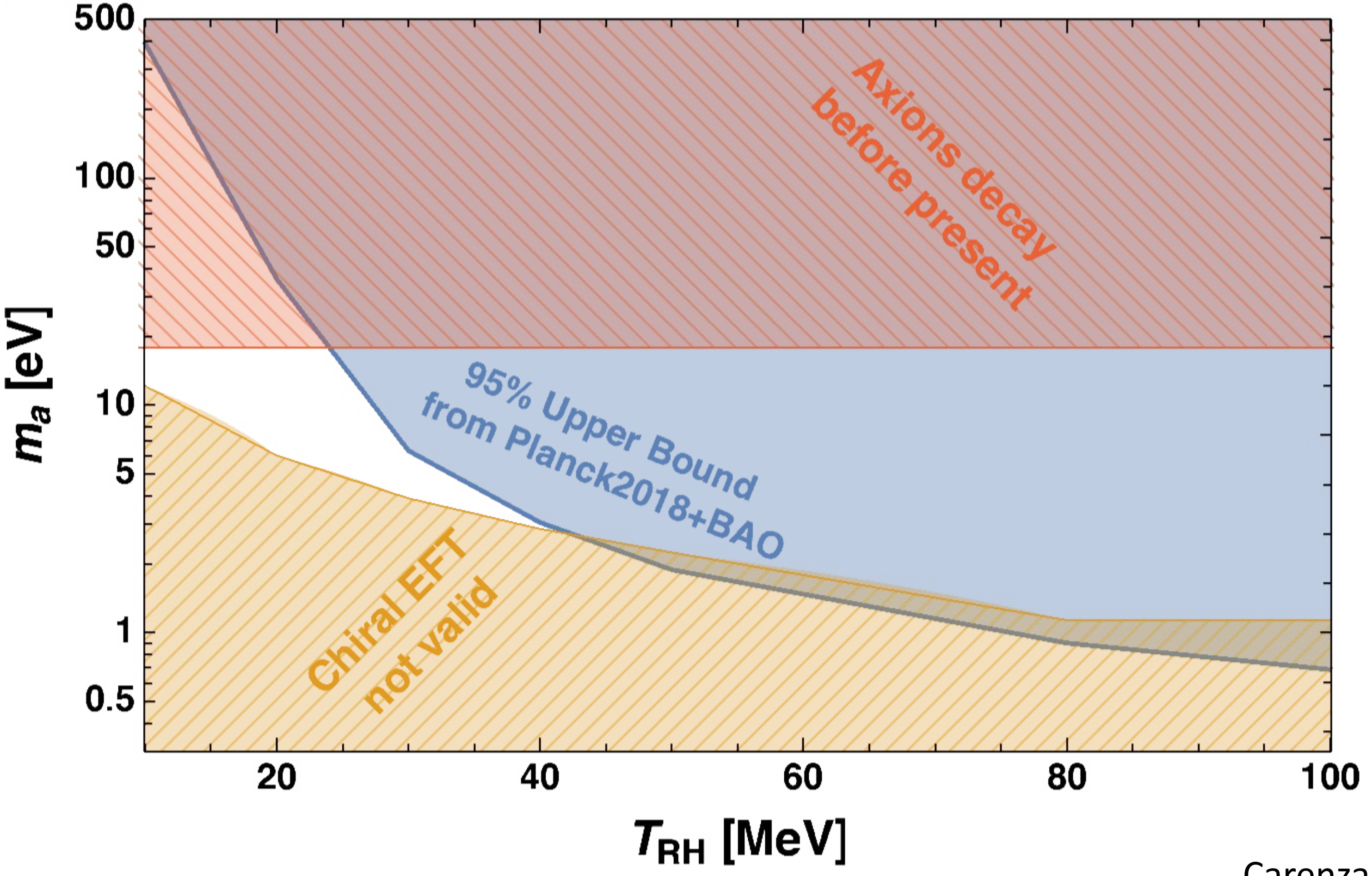
Taking into account also the contribution from the decay of topological defects yields the following range for CDM axion masses:

m_a = 25 μeV – 4.4 meV



Wantz & Shelland 2010

CMB CONSTRAINTS ON THERMAL (HOT) AXIONS



Carenza, ML, Mirizzi, Forastieri, 2021

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 (2022+): satellite; galaxy and weak lensing survey for the reconstruction of the matter distribution and Improved measurements of the BAO scale.

DESI (2020+): 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

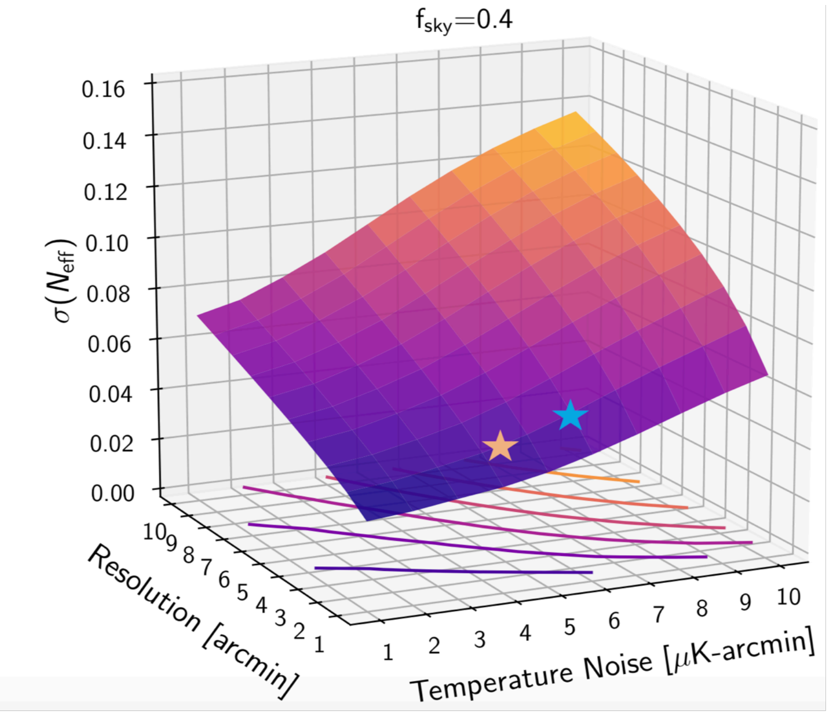
To increase sensitivity to neutrino masses AND reduce model dependency, we need:

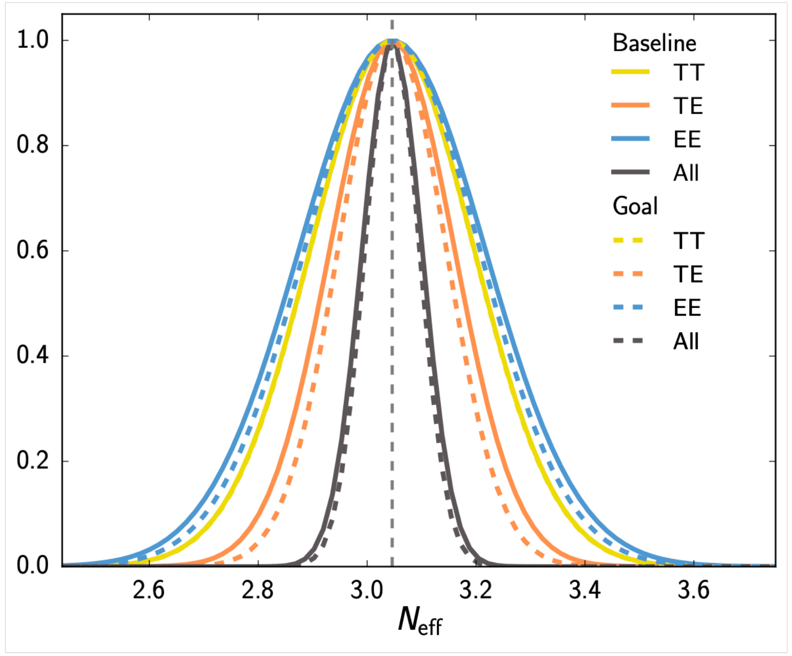
- Precise measurement of the CMB lensing signal (both from 2- and 4-point correlation functions)
- Cosmic variance limited measurement of the reionization optical depth (need to go to space!)
- other CMB probes of structure formation, e.g. SZ galaxy clusters

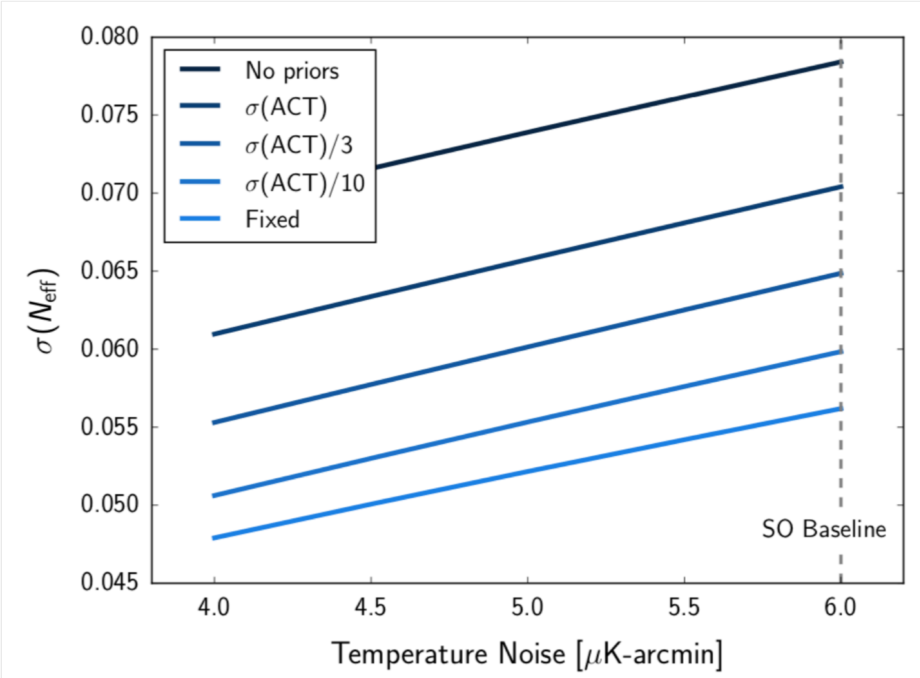
+ non-CMB information

- 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

SIMONS OBSERVATORY - NEFF







SO collaboration, 2018

$$\boxed{\sigma(N_{\rm eff}) = 0.07\ [0.05]}$$

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

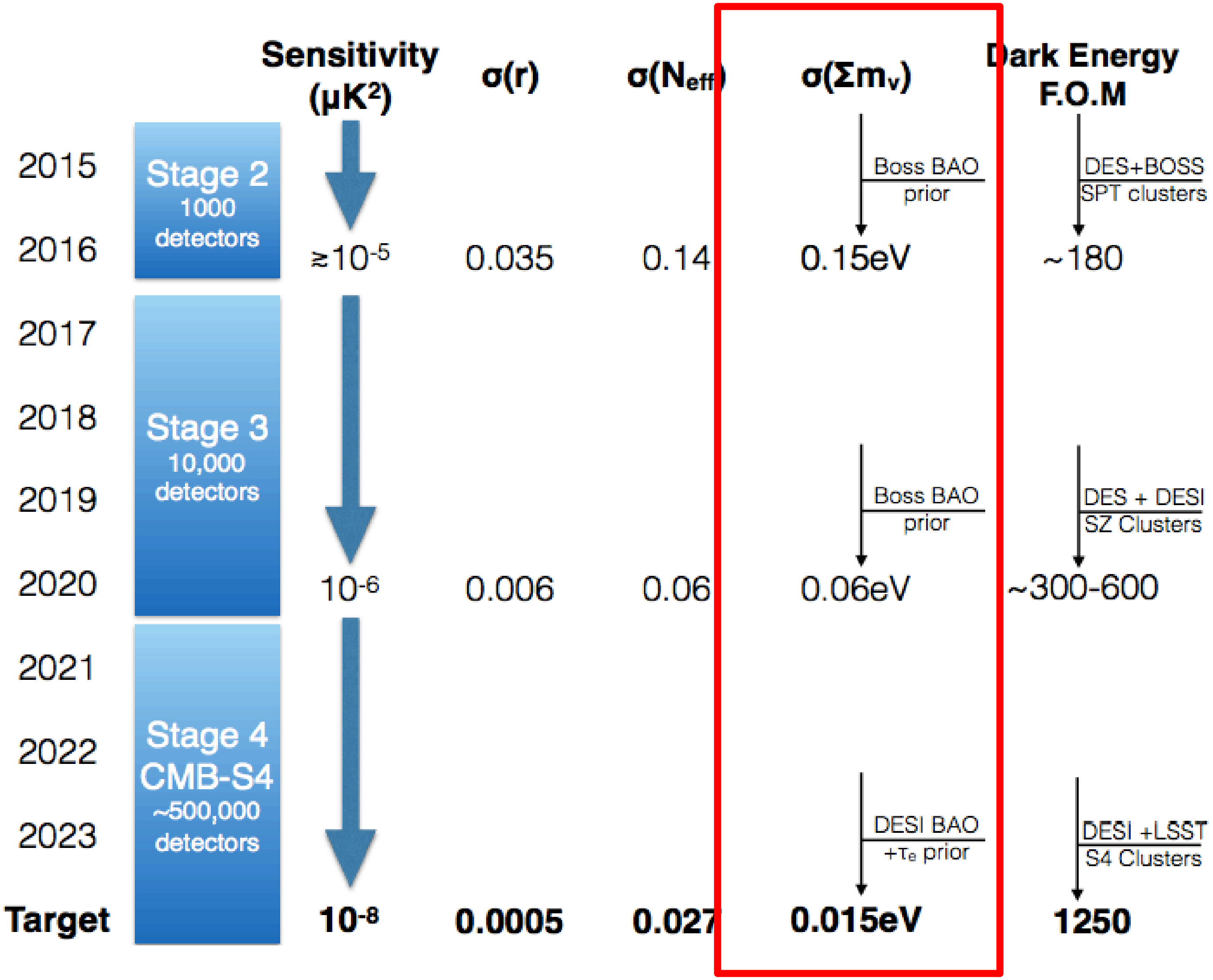
$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

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

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

SO Collaboration, 2018

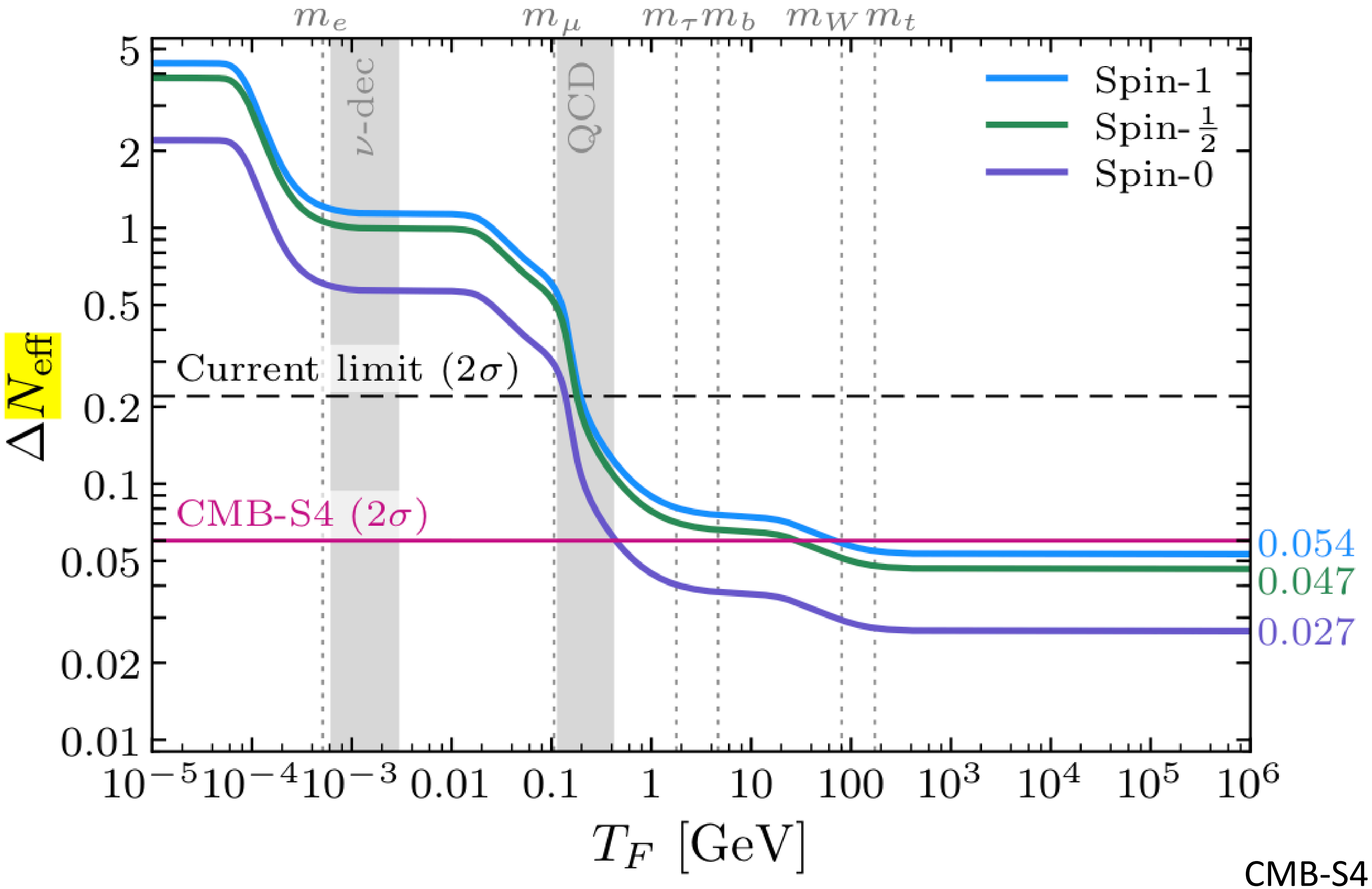
NEUTRINO PARAMETERS FROM CMB-S4



		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO +τ_e prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

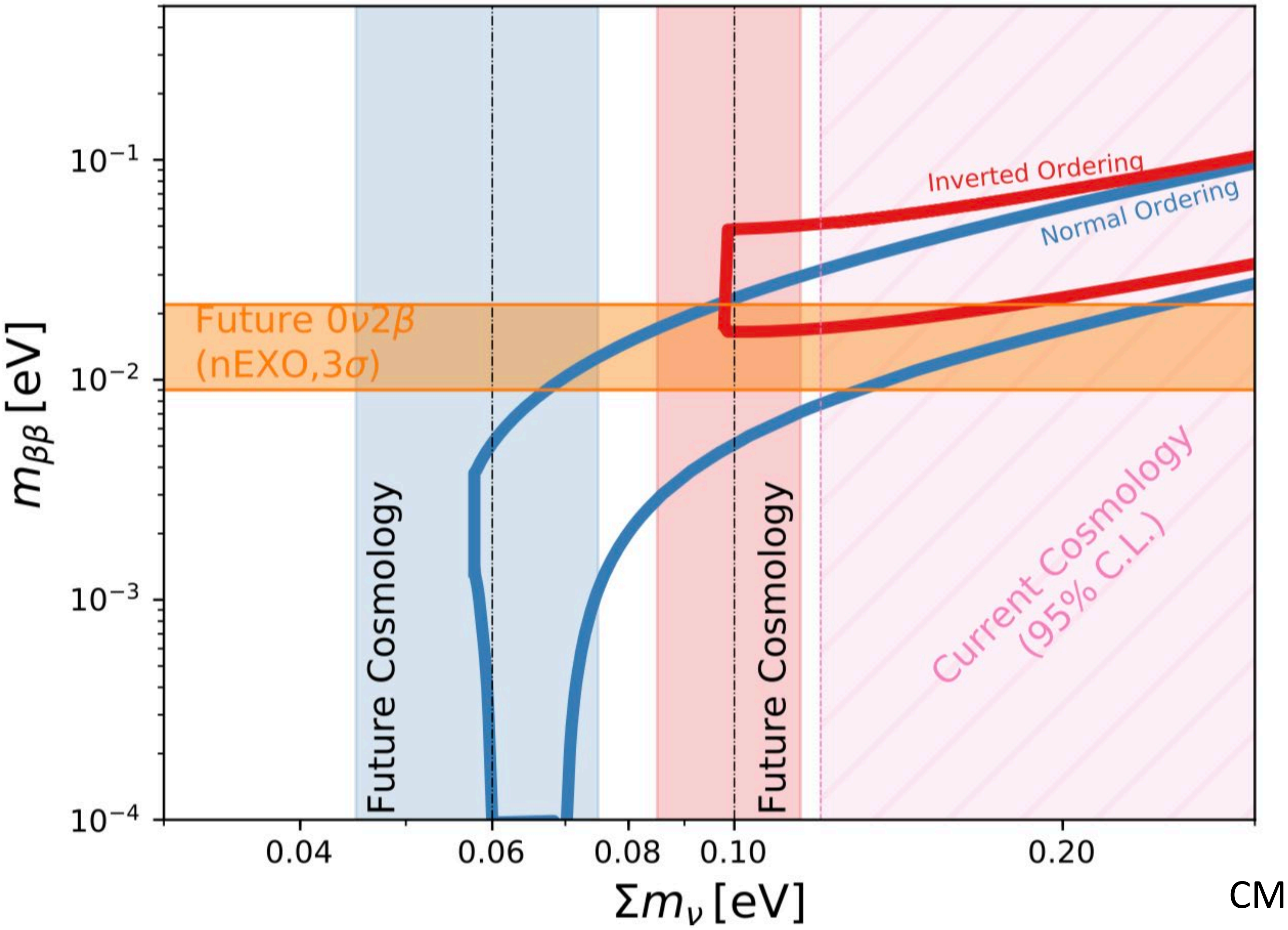
CMB-S4 Science Book (arXiv: 1610:02743)

CMB-S4 - NEFF



CMB-S4 Collaboration, 2019

CMB-S4 - MNU



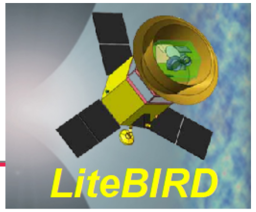
CMB-S4 Collaboration, 2019

LiteBIRD

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

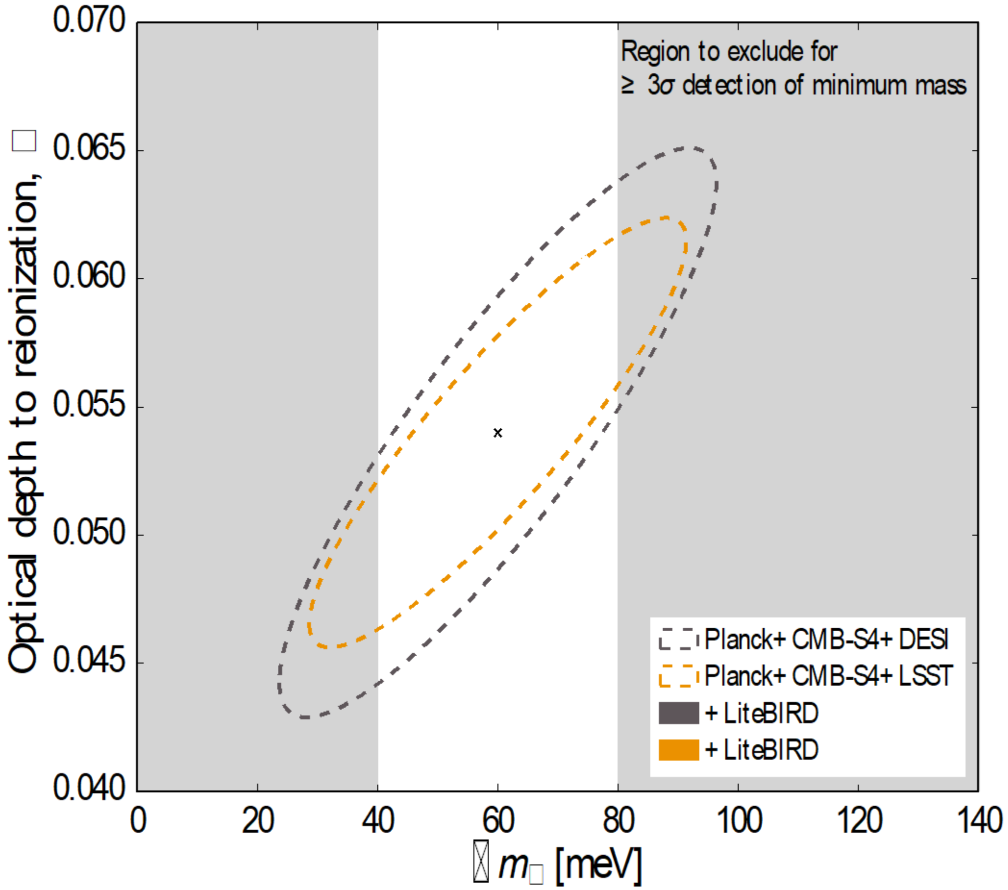
CMB-S4 - LITEBIRD

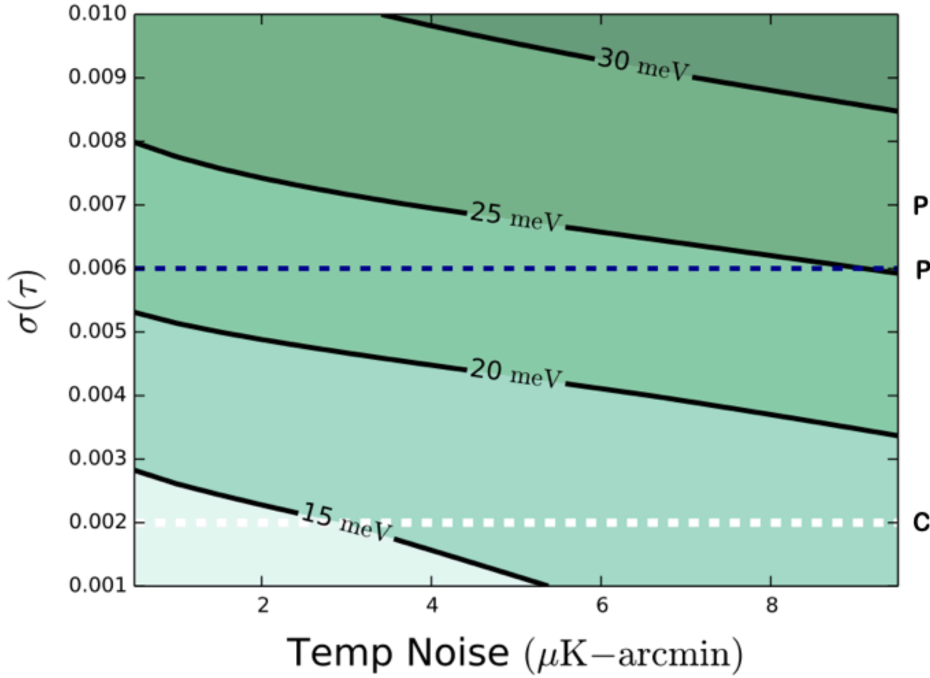
Σm_ν w/ improved τ



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

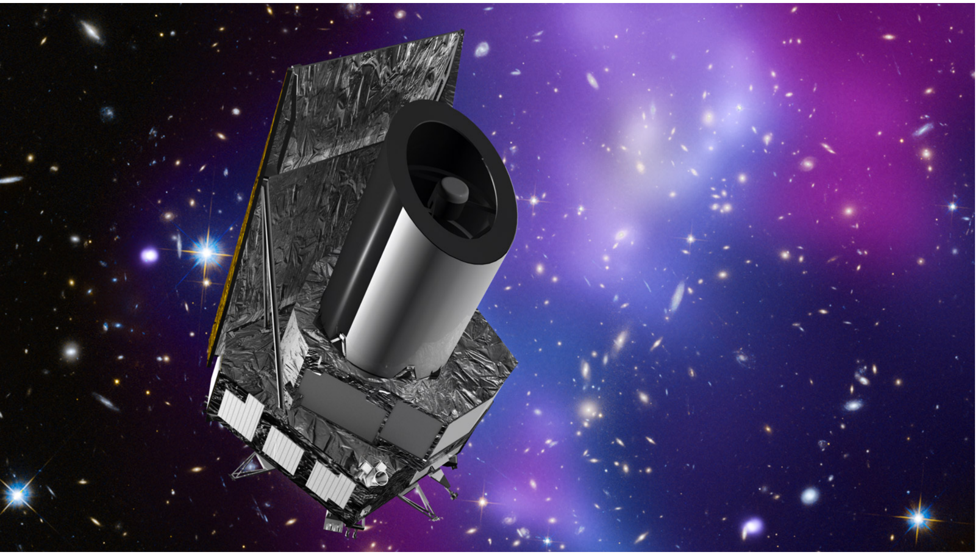
Caveat:
No systematic error included yet.





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**

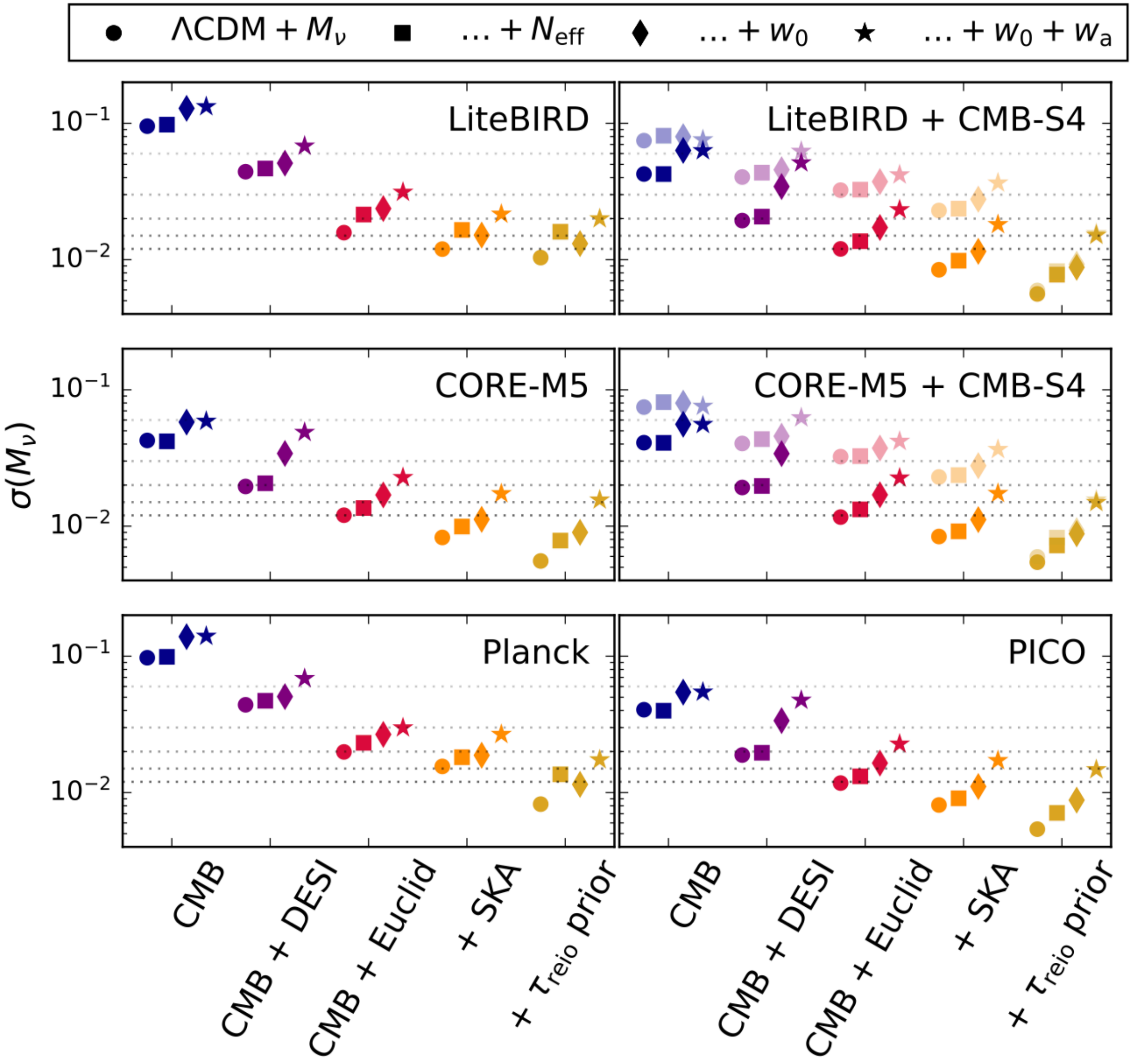
Euclid is an ESA M-class space mission devoted to studying :

- 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, …**

Launch scheduled in early 2023!

NEUTRINO MASS BOUNDS: FUTURE PROSPECTS

Brinckmann+, JCAP 2019



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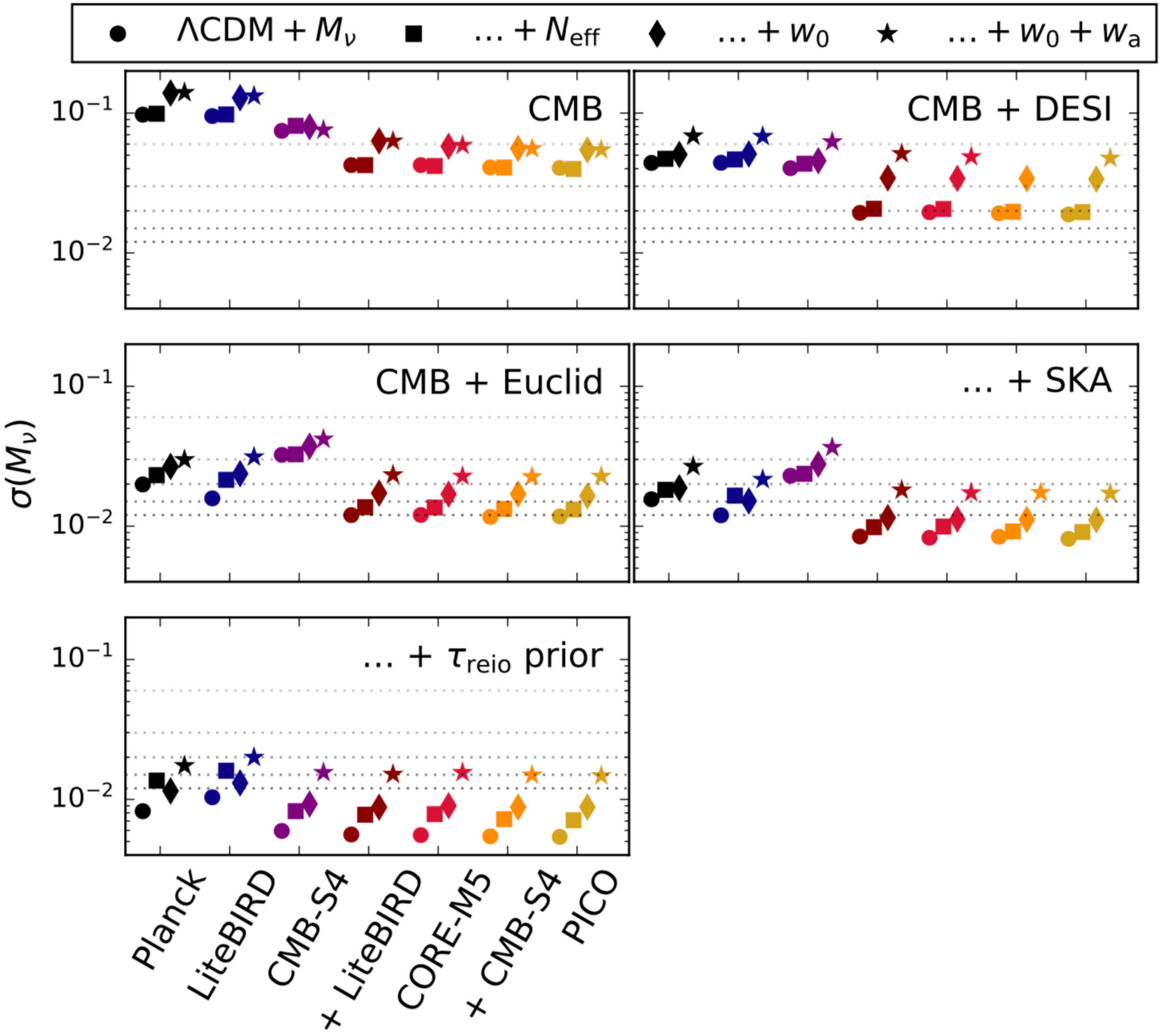
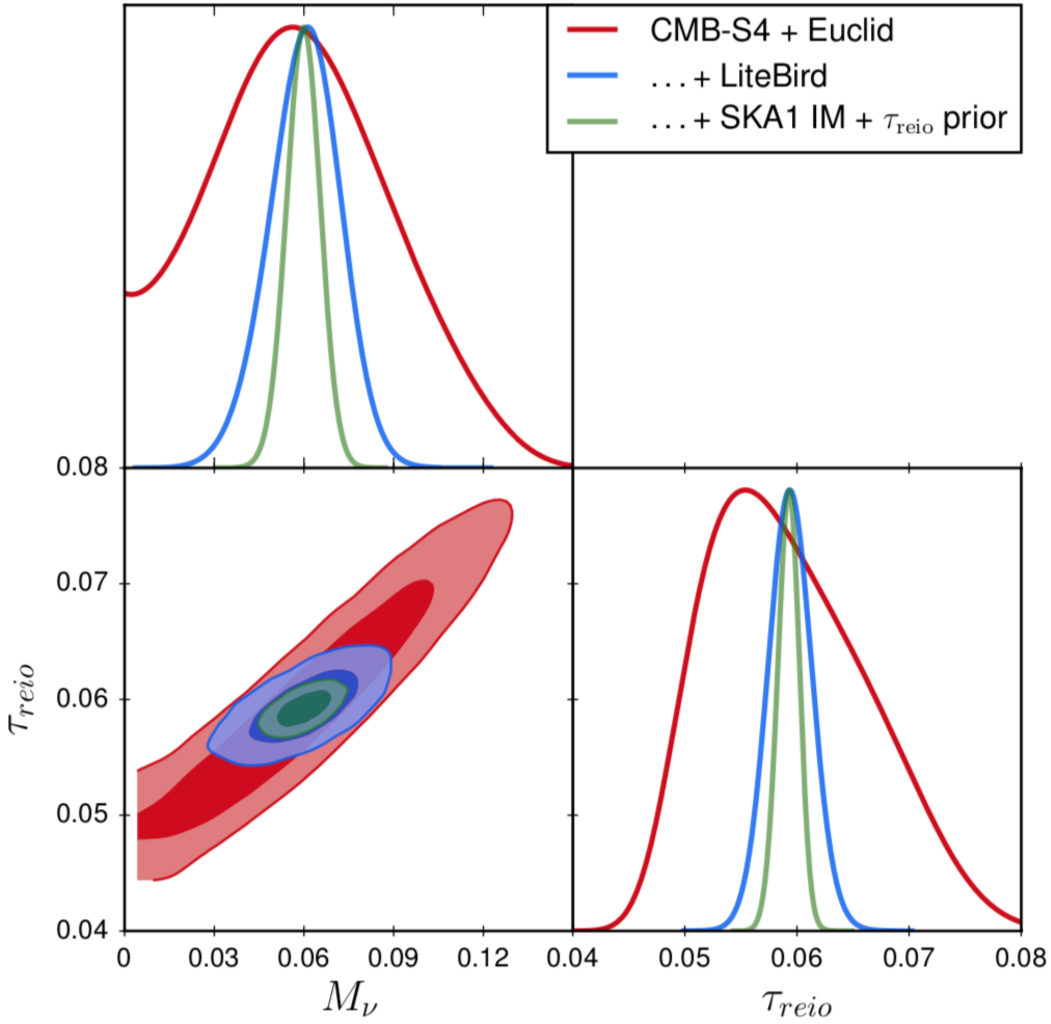


NEUTRINO MASS BOUNDS: FUTURE PROSPECTS

Brinckmann+, JCAP 2019



THANKS!