COSMOLOGY AND NEUTRINO PROPERTIES

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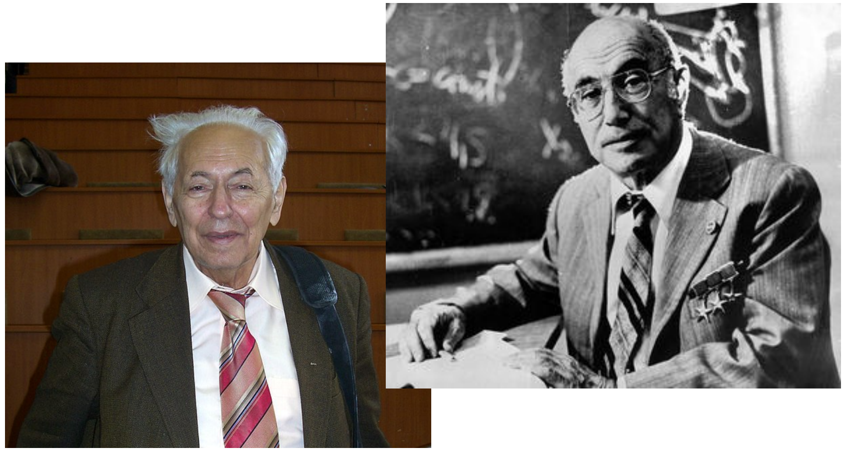
Neutrino Oscillation Workshop 2022

Rosa Marina, September 10th, 2022

COSMOLOGY AND NEUTRINO PROPERTIES



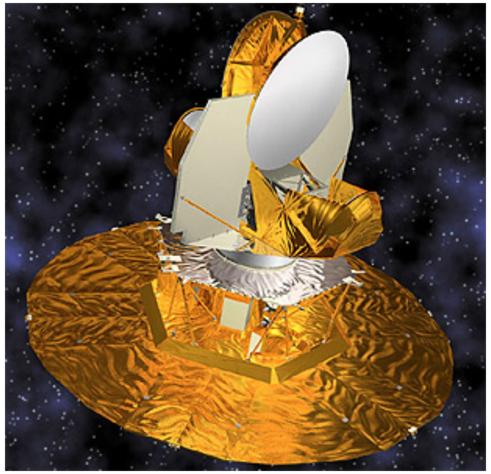
"Rest mass of muonic neutrino and cosmology"
Gershtein & Zel'dovich 1966

$$\Omega_\nu h^2 \simeq \left(\frac{\sum m_\nu}{94\,\mathrm{eV}}\right) \quad \Rightarrow \quad \sum m_\nu \lesssim 94 h^2\,\mathrm{eV}$$

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

Fast forward to 2007:

$\sum m_\nu < 1.8\,\mathrm{eV}^*$ from **WMAP 3yr** (Spergel, 2007)



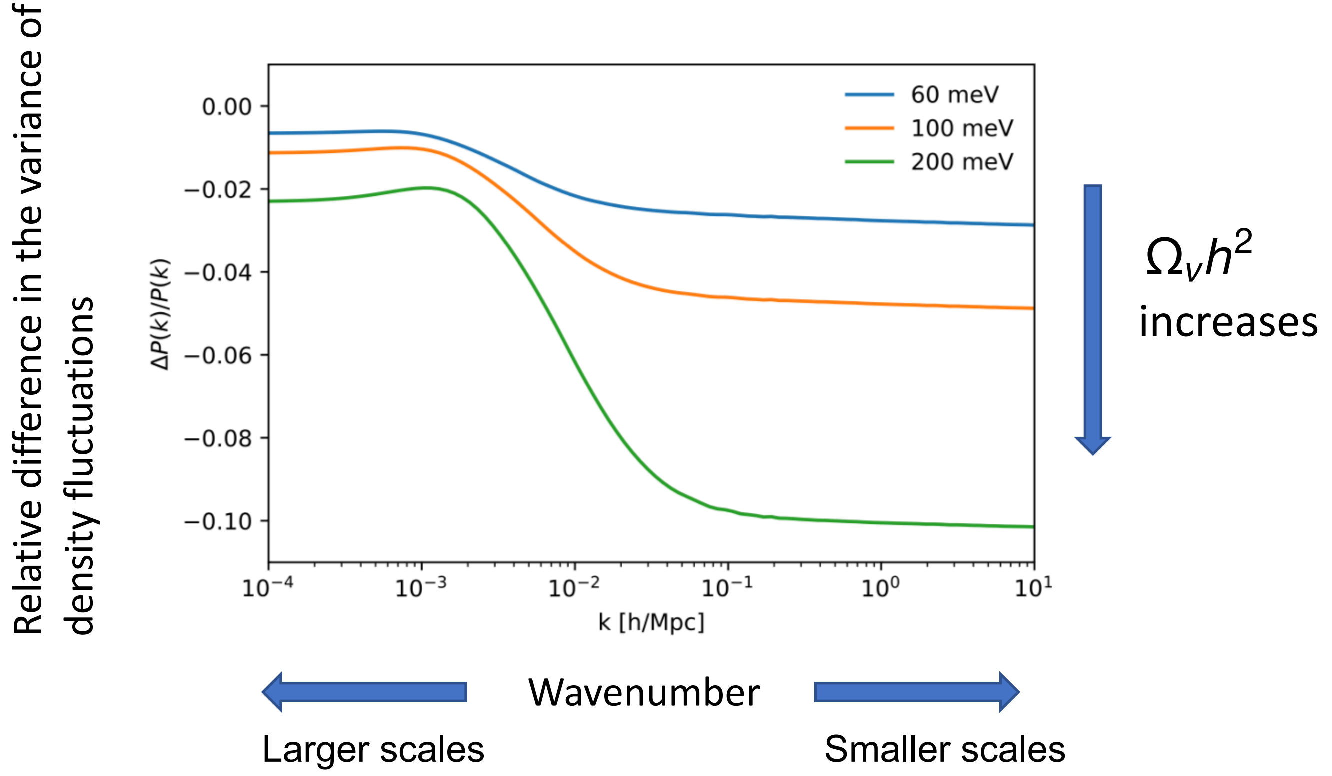
(many independent papers before that, using the 1yr data)

Saturates the hard limit from primary anisotropies (0.6 eV neutrino has m~3T at recombination)

* All one-sided limits in the following are 95% CL

NEUTRINOS AND STRUCTURE FORMATION

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



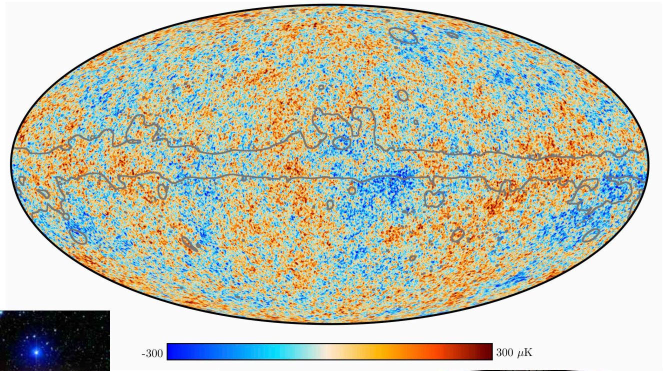
Probes of density fluctuations below the Jeans scale:

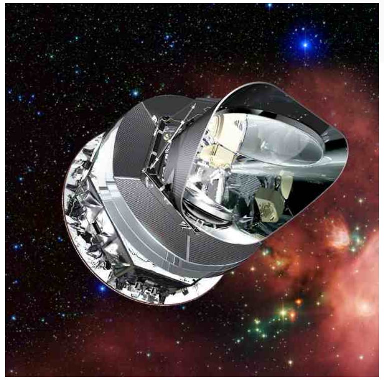
- Gravitational weak lensing of the CMB
- Clustering and weak lensing of galaxies
- Number density of galaxy clusters
- (+ their cross-correlation)

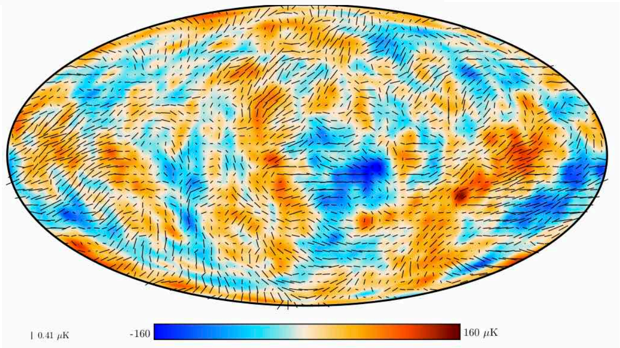
can be used to measure neutrino masses from cosmology.

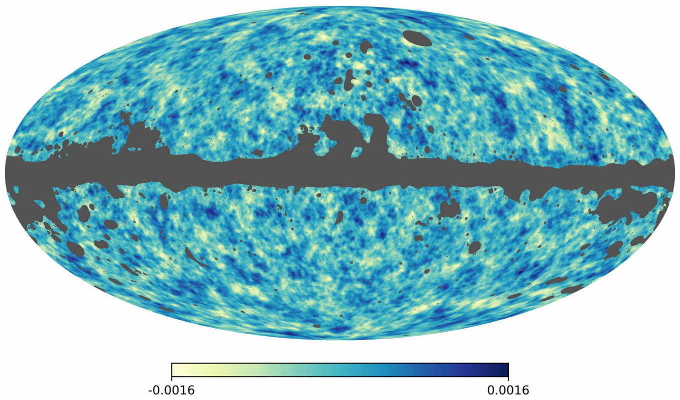
$$\Omega_\nu h^2 = 6.2 \times 10^{-4} \left(\frac{\sum m_\nu}{58\,\mathrm{eV}} \right)$$

NEUTRINO MASSES AFTER PLANCK

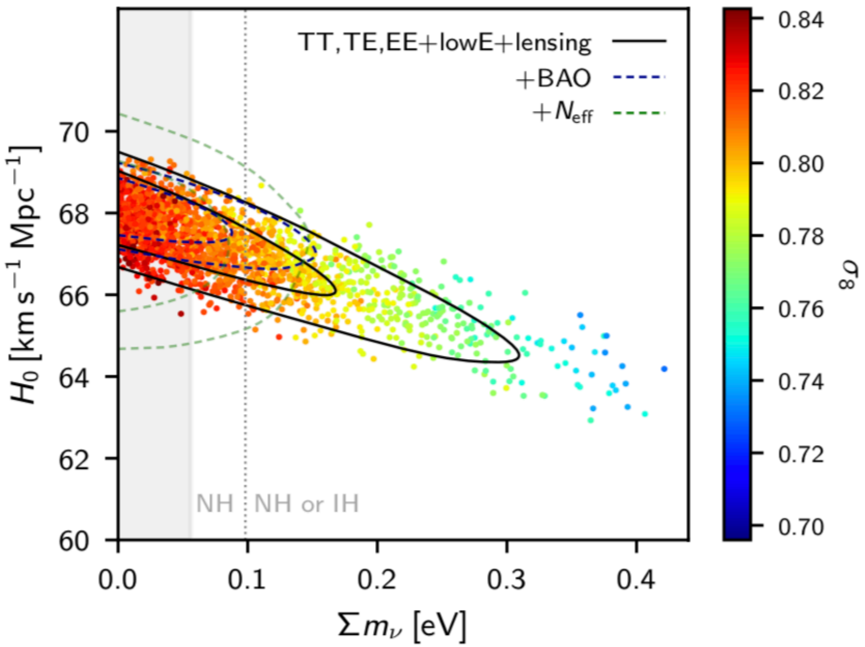








Planck 2018

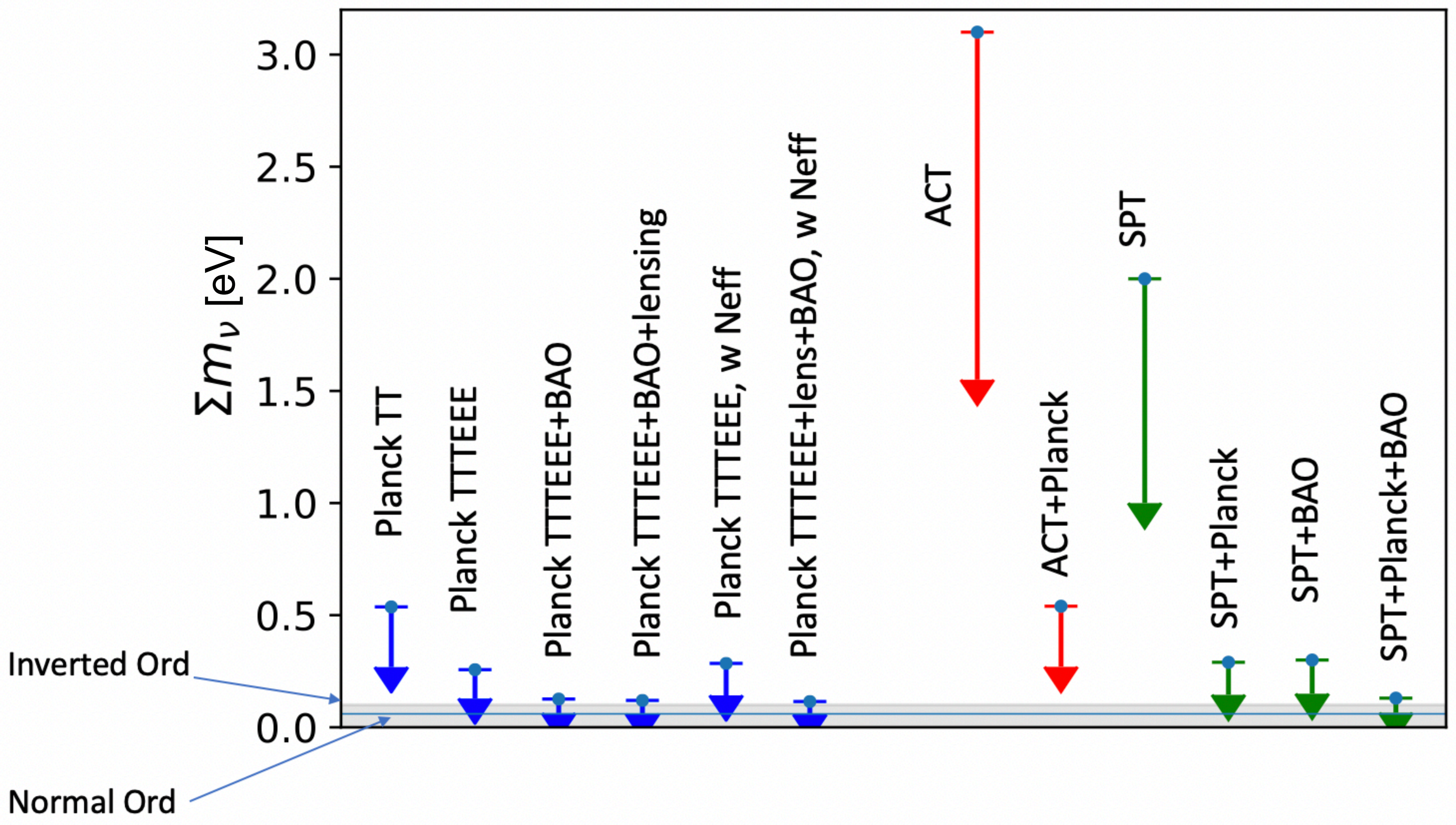


$$\sum m_\nu < 0.24\,\mathrm{eV}$$ (TTTEEE+lowE+lensing)

$$\sum m_\nu < 0.12\,\mathrm{eV}$$ (... + BAO)

(95% CL)

ν MASSES IN ΛCDM: PRESENT STATUS



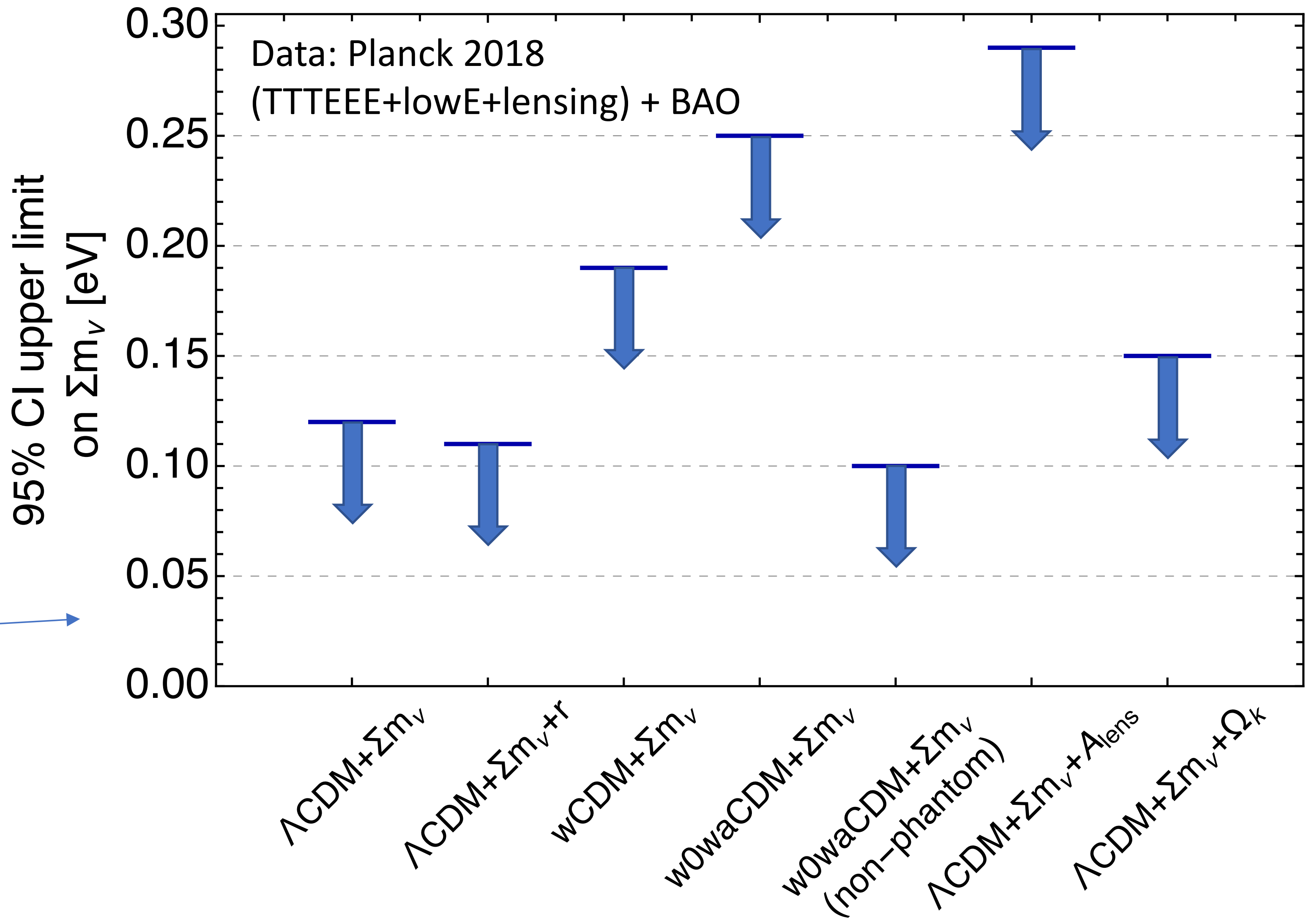
Credit: M. Gerbino

ν MASSES IN ΛCDM EXTENSIONS

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)

based on S. Roy Choudhury & S. Hannestad (2020) arXiv 1907.12598



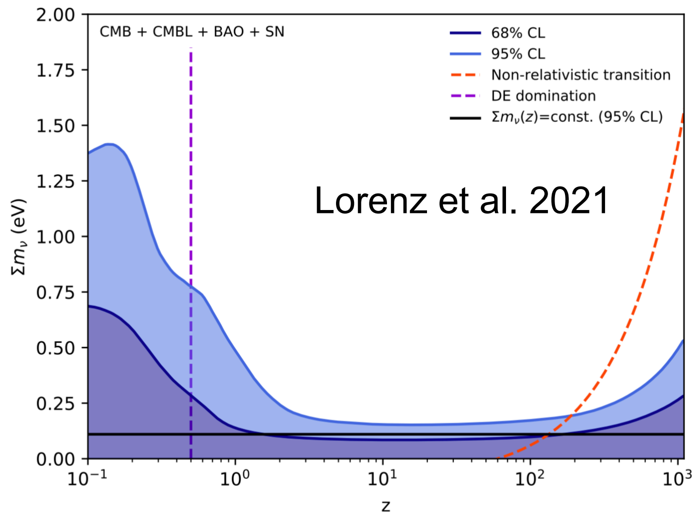
See also Di Valentino et al. [arXiv:1908.01391] $\Sigma m_\nu < 0.52$ eV in a 12-parameters cosmological model

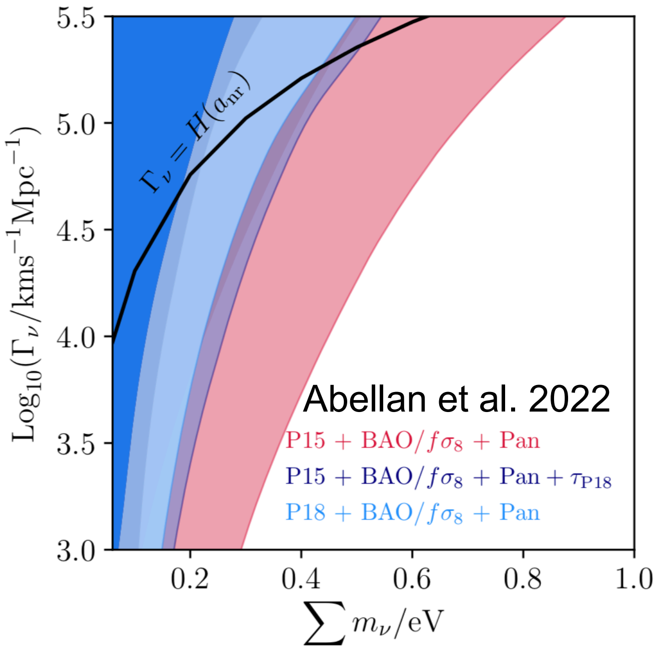
ν MASSES IN ΛCDM EXTENSIONS

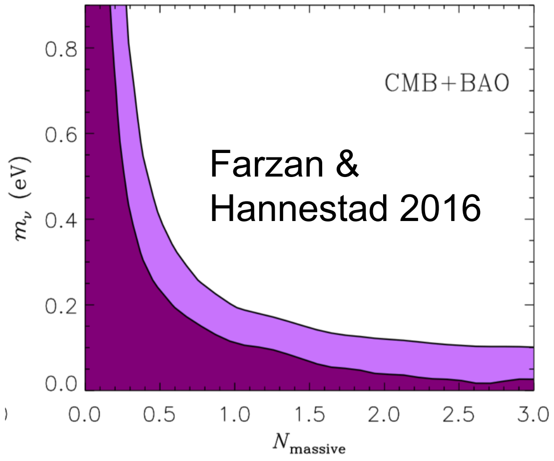
Constraints can be further loosened in alternative models, e.g.

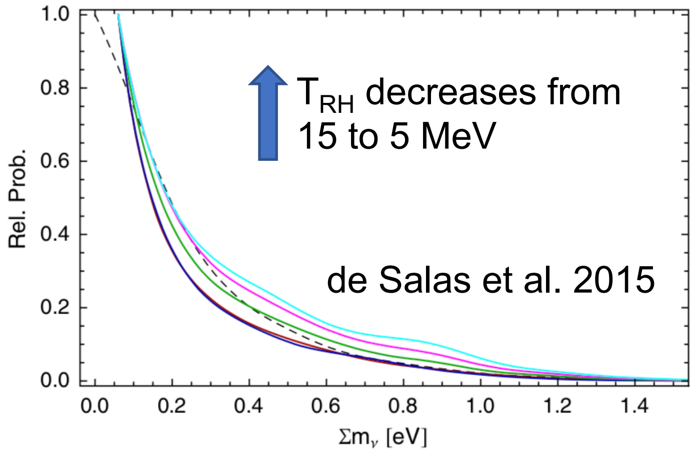
- Neutrino decays
- Late-time phase transitions (mass-varying neutrinos)
- Low-reheating scenarios
- Long-range ν interactions
- Conversion to lighter states

In some cases, this would reopen the window for a detection in KATRIN (see e.g. Alvey et al, 2021)





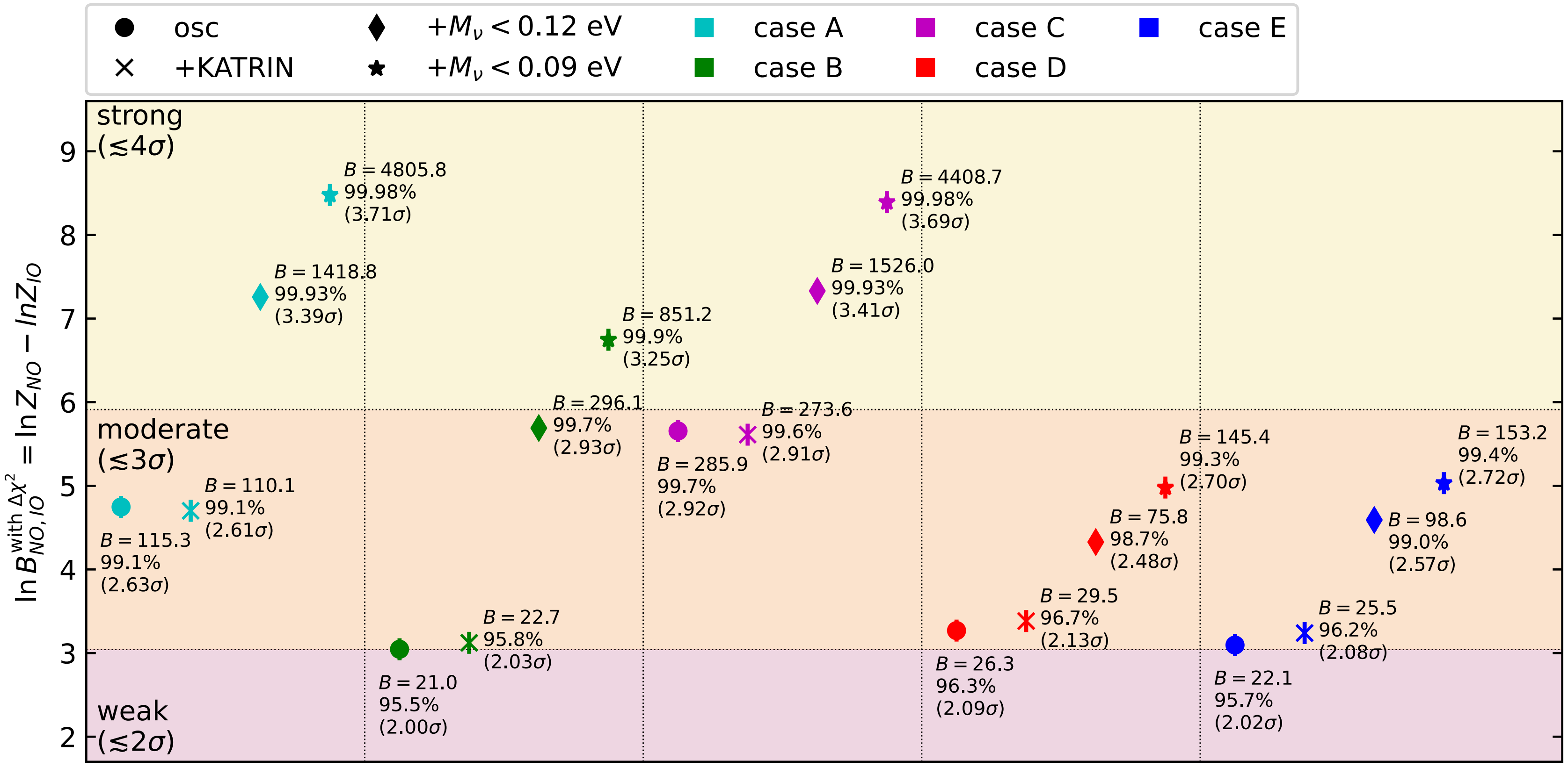




MASS ORDERING FROM COSMOLOGY

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 on neutrino masses.
Case E is more conservative: **moderate evidence** (2.6σ) for NO from cosmo+oscillations.
Cosmo alone (not shown): 1.2σ

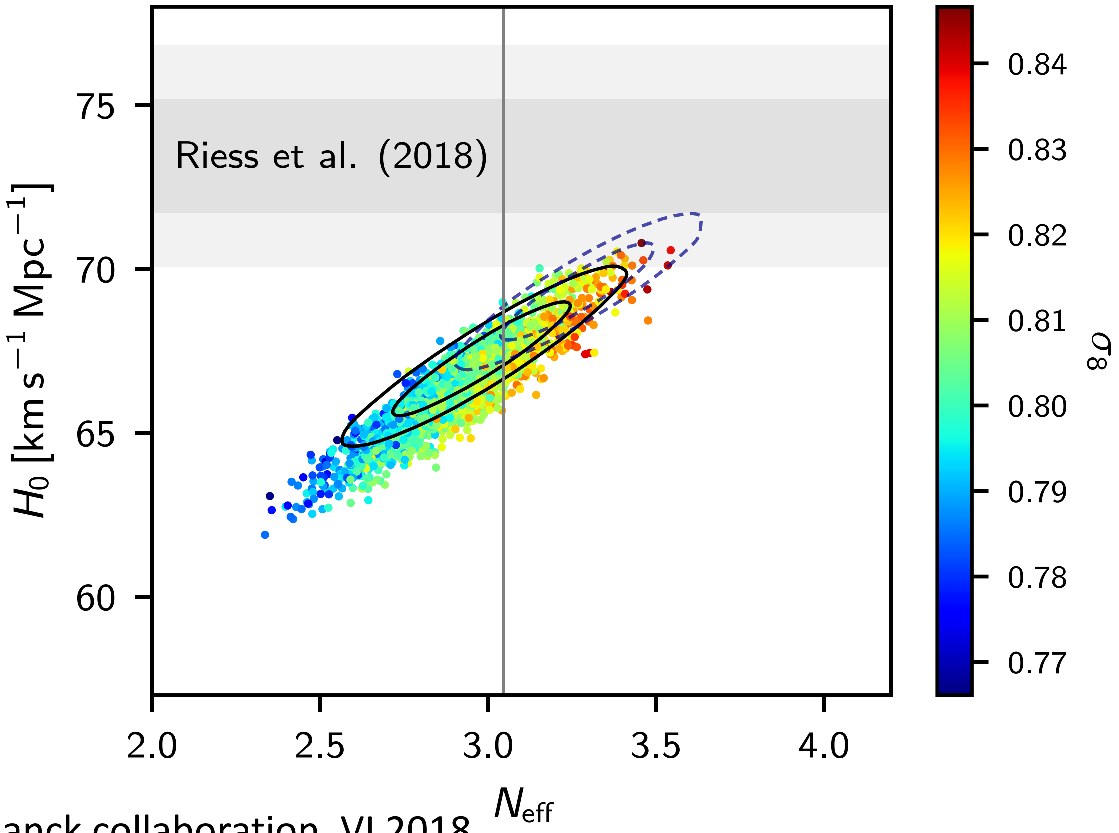


Gariazzo et al (incl ML), arXiv:2205.0219

Results are consistent with previous findings by Jimenez et al. 2022

EFFECTIVE NUMBER OF RELATIVISTIC SPECIES

$$\rho_r \equiv \left[1 + N_{\rm eff} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3}\right] \rho_\gamma$$



Planck collaboration, VI 2018

Theoretical expectation for the three SM neutrinos* :

$$N_{eff} = 3.0440 \pm 0.0002$$

Planck 2018: Neff = 2.89+/- 0.19

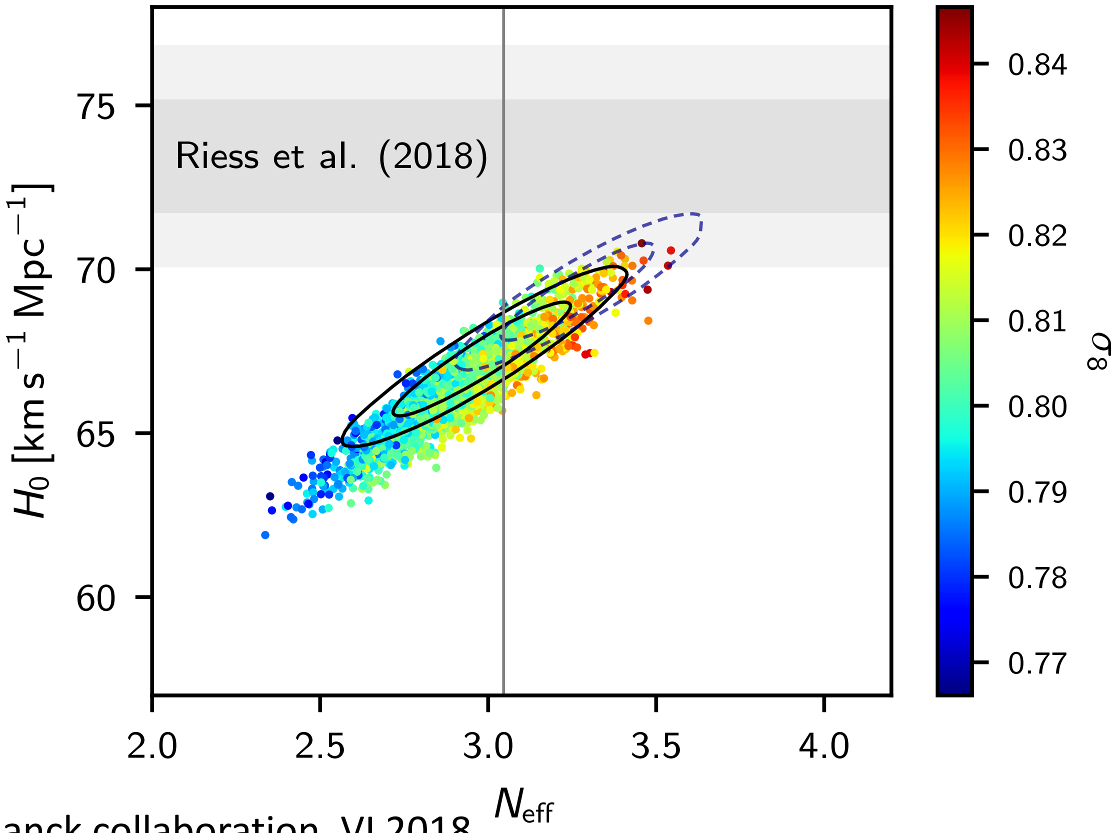
In agreement with the theoretical expectation

Excludes a fourth, light, ***thermalized*** neutrino at more than 5σ

* Dolgov; Mangano+ 2005; ….; Akita&Yamaguchi 2020; Bennett+,2020; Froustey+ 2020

Effective number of relativistic species

$$\rho_r \equiv \left[1 + N_{\rm eff} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3}\right] \rho_\gamma$$



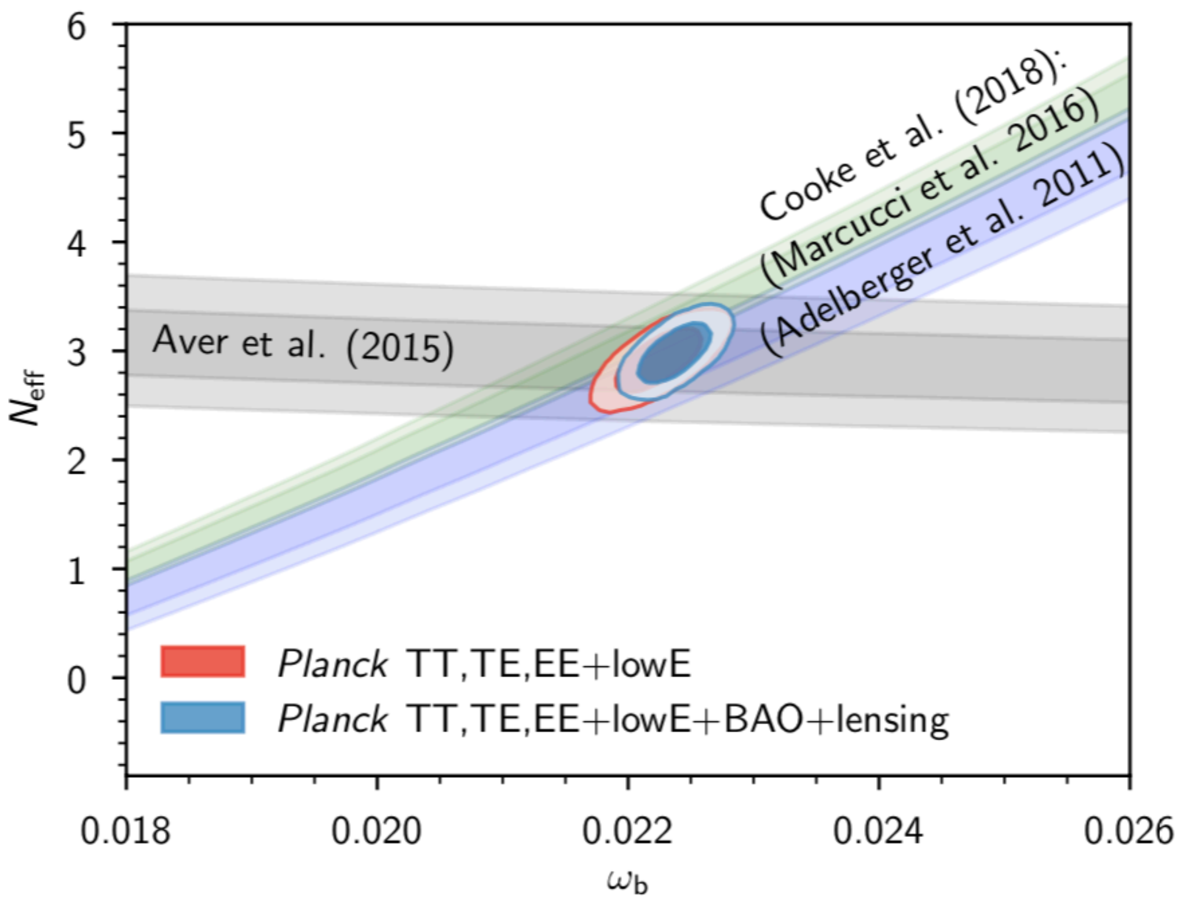
Planck collaboration, VI 2018

A deviation from the standard value might be due to:

- Additional light species (e.g. sterile neutrinos, thermal axions)
- Nonstandard expansion history (e.g. low-reheating temperature scenarios)
- New physics affecting neutrino decoupling (as due e.g. to nonstandard ν-electron interactions)
- Large lepton asymmetry
- …..

In general, the observed $N_{\rm eff}$ puts tight constraints on theories beyond the SM

Effective number of neutrinos and Big Bang Nucleosynthesis



Planck collaboration VI, 2018

The synthesis of light elements is essentially a competition between the nuclear reactions and expansion.
As such, it is pretty sensitive to N_{eff}.

Constraints on the energy density of light species from the abundance of light elements and from CMB observations are in excellent agreement

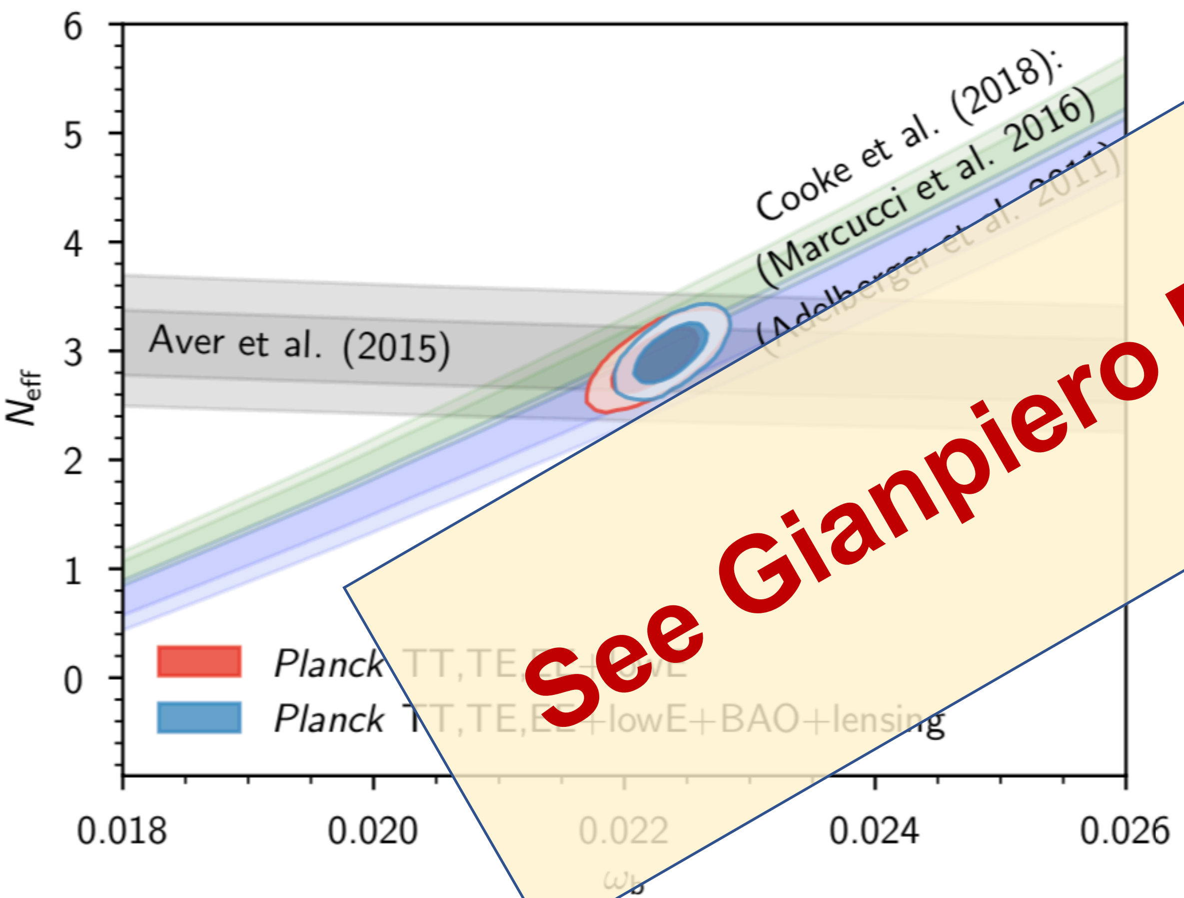
N_{eff} = 2.86 +/- 0.28 [Yp + D/H]

Combining BBN and CMB data:

N_{eff} = 2.88 +/- 0.15 [BBN + CMB]

Pisanti et al, JCAP 2021
Yeh et al., JCAP 2021

Effective number of neutrinos and Big Bang Nucleosynthesis



Planck collaboration VI, 2018

See Gianpiero Mangano's talk!

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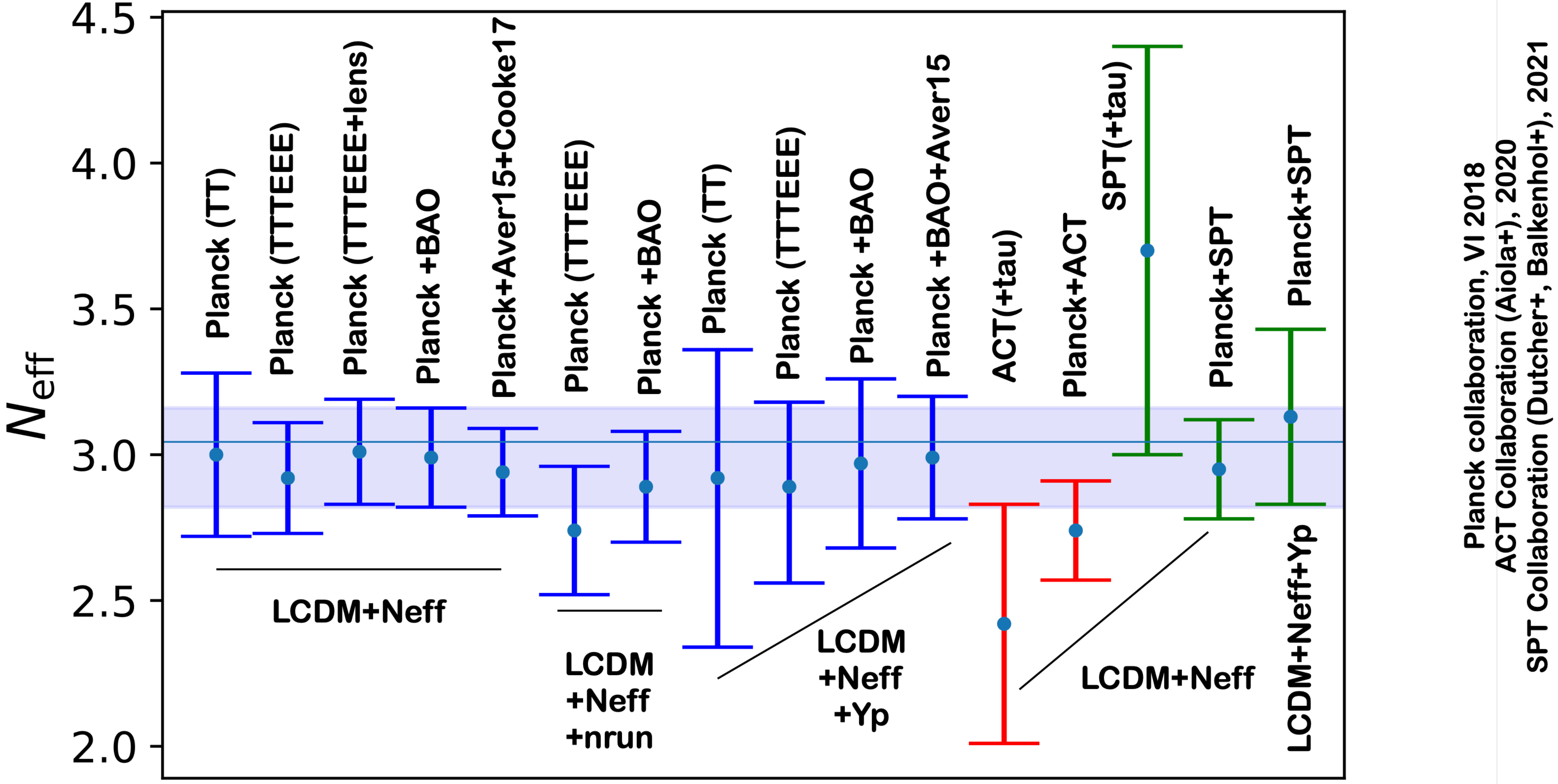
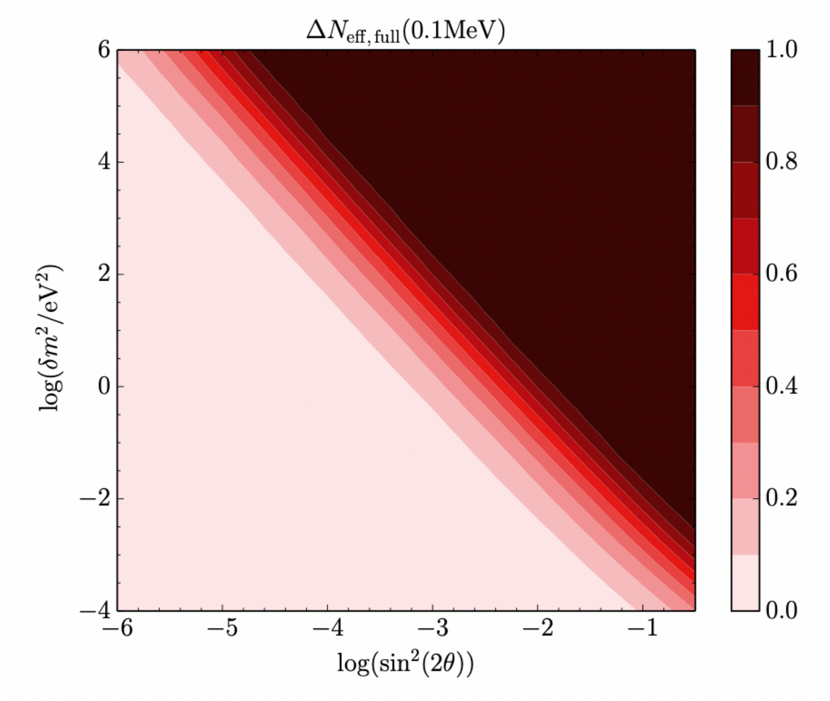
CURRENT LIMITS ON NEFF (68% CL)



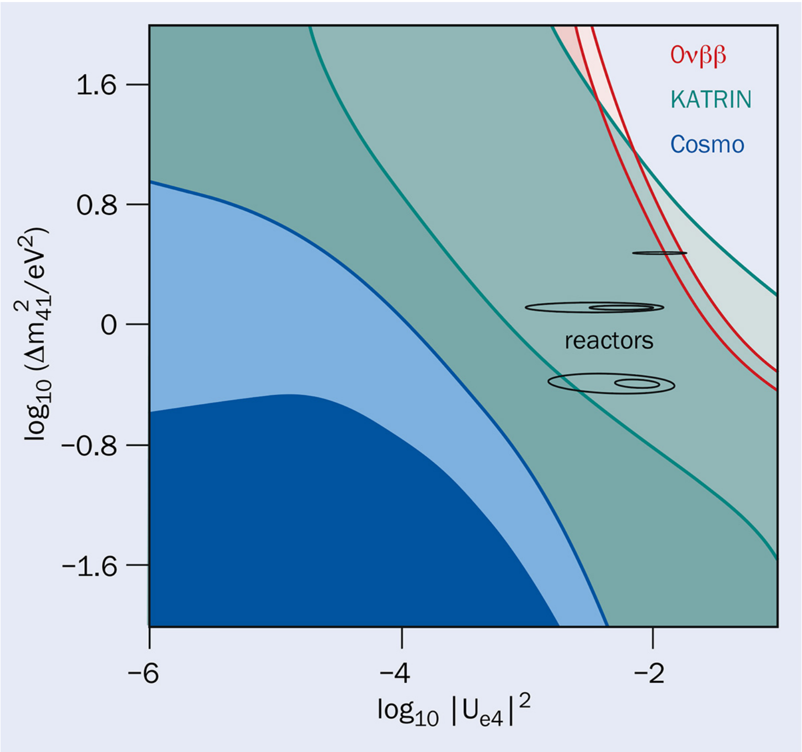
Credit: M. Gerbino

N_{EFF} AND STERILE NEUTRINOS

Neff is a powerful probe of particle interactions
E.g. sterile neutrinos: production from oscillation from active states, final abundance depends on both active-sterile mixing angle and mass difference



Hannestad et al. 2015



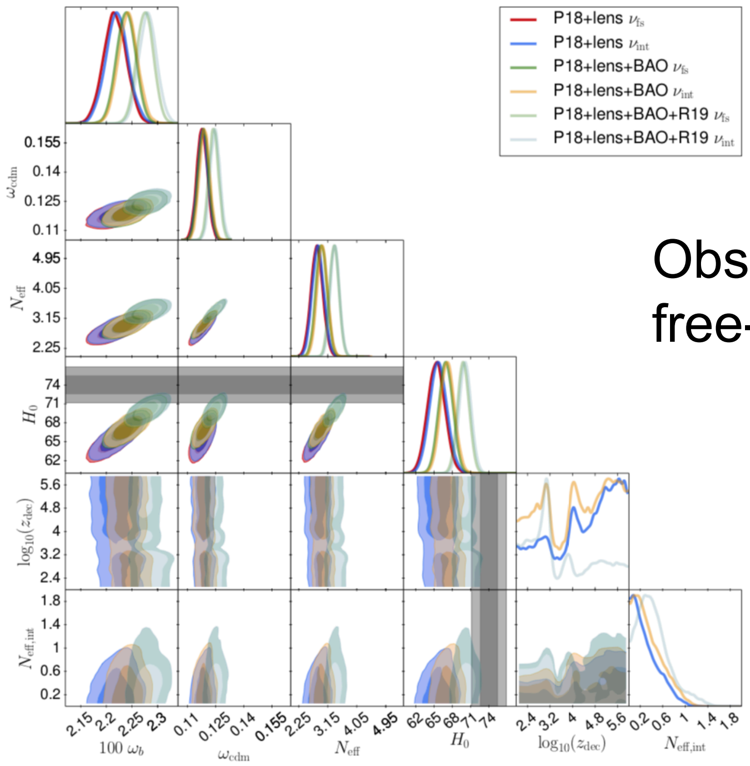
Cosmology robustly exclude region of large sterile mass and mixing params larger than 10^-3 in LCDM extensions

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

See Hagstotz+ (incl ML) 2021

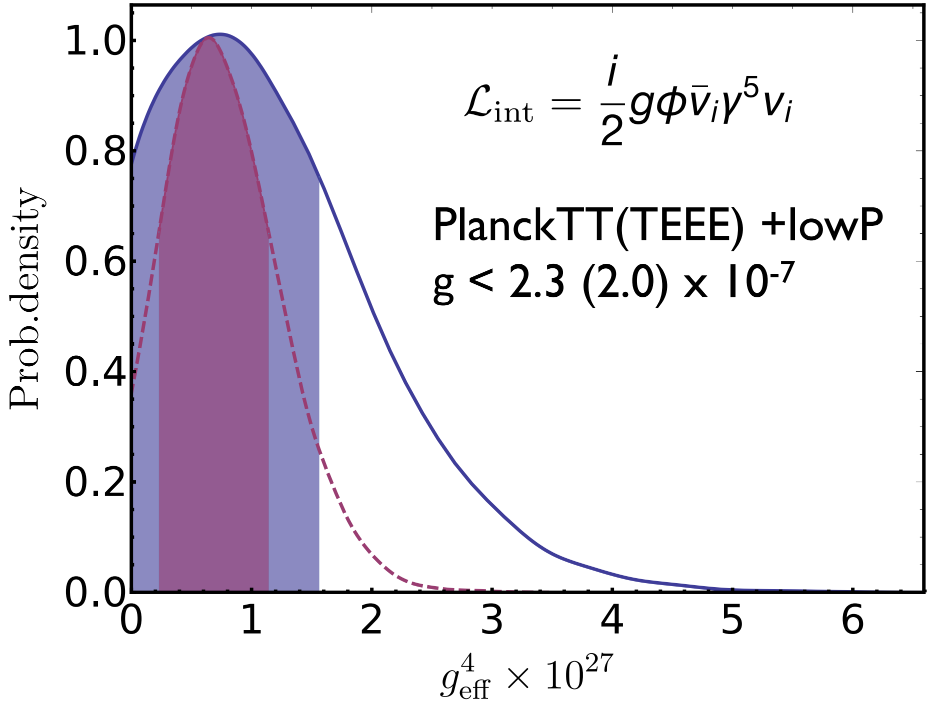
ν NSI IN COSMOLOGY

CMB is also sensitive to the collisional properties of light relics (Bashinsky & Seljak 2004)
Neutrino free streaming can be tested!
E.g. a probe of nonstandard interactions



Brinckmann, Chang, LoVerde, 2021

Observations are consistent with free-streaming neutrinos

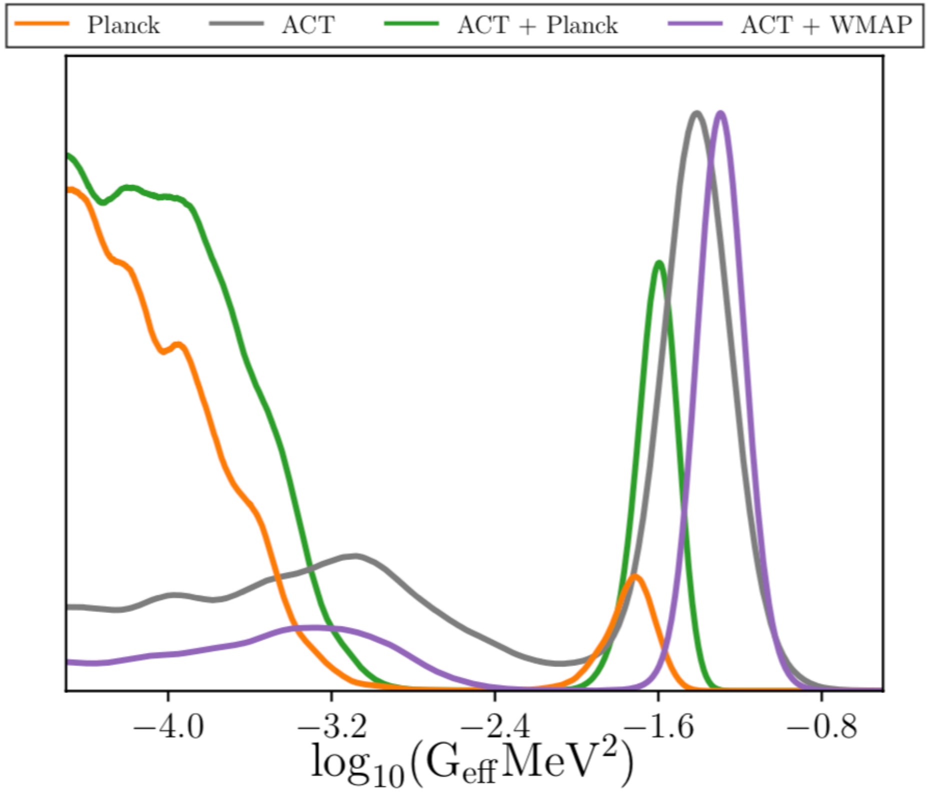


Forastieri, ML, Natoli,, 2019

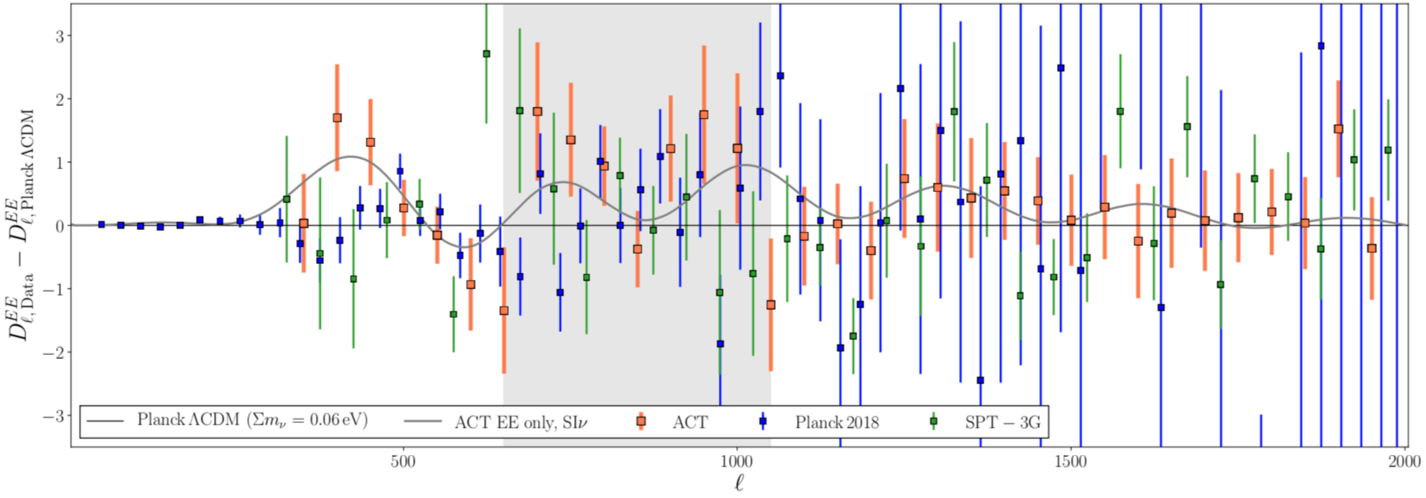
See also Cyr-Racine & Sigurdson 2013, Archidiacono & Hannestad 2013, Forastieri, ML, Natoli 2015, Oldengott et al 2017, Kreisch et al. 2207.03164, Choudhury, Hannestad, Tram 2207.07142

ν NSI IN COSMOLOGY

Preference for delayed onset of neutrino free streaming in the ACT data?

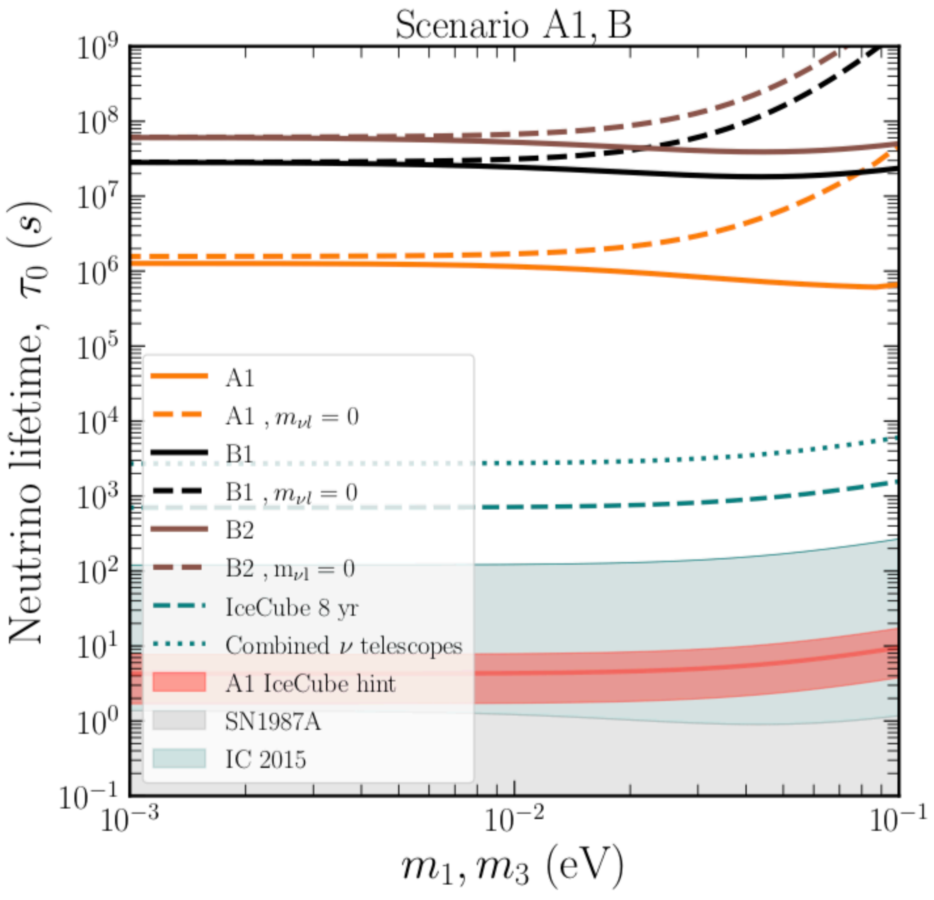


Driven by the ell range 700-1000 in the EE data

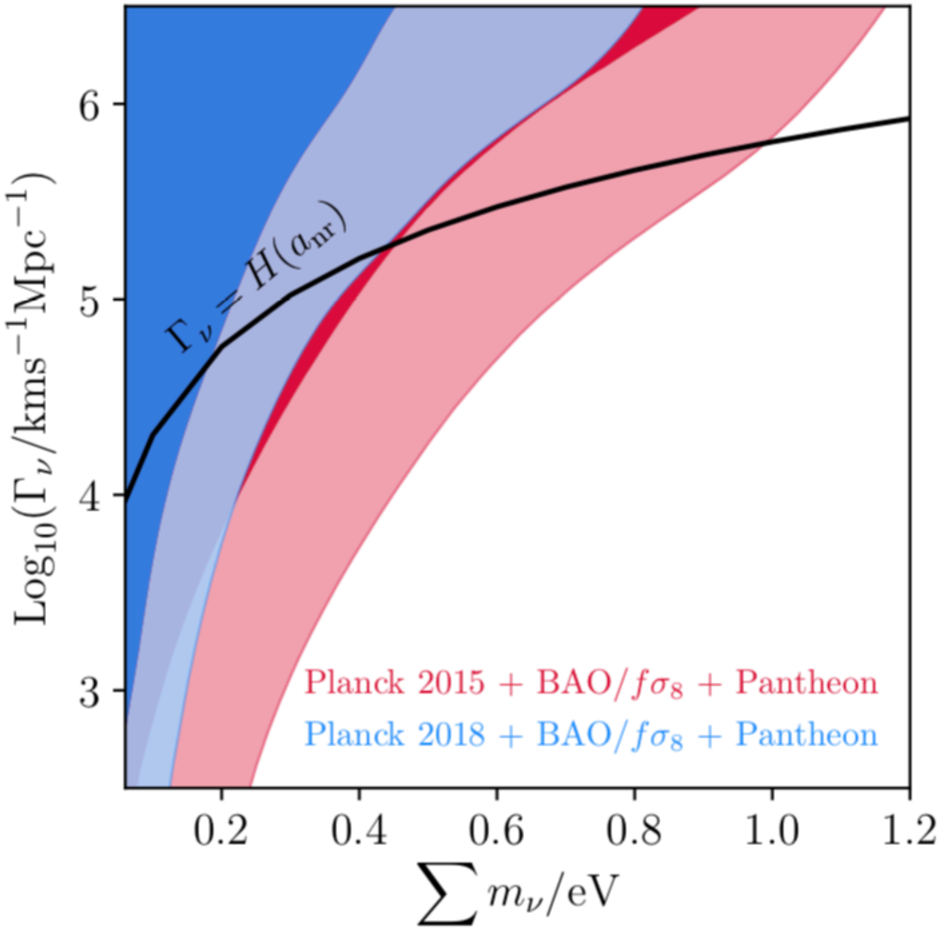


Kreisch et al. 2207.03164

NEUTRINO DECAY

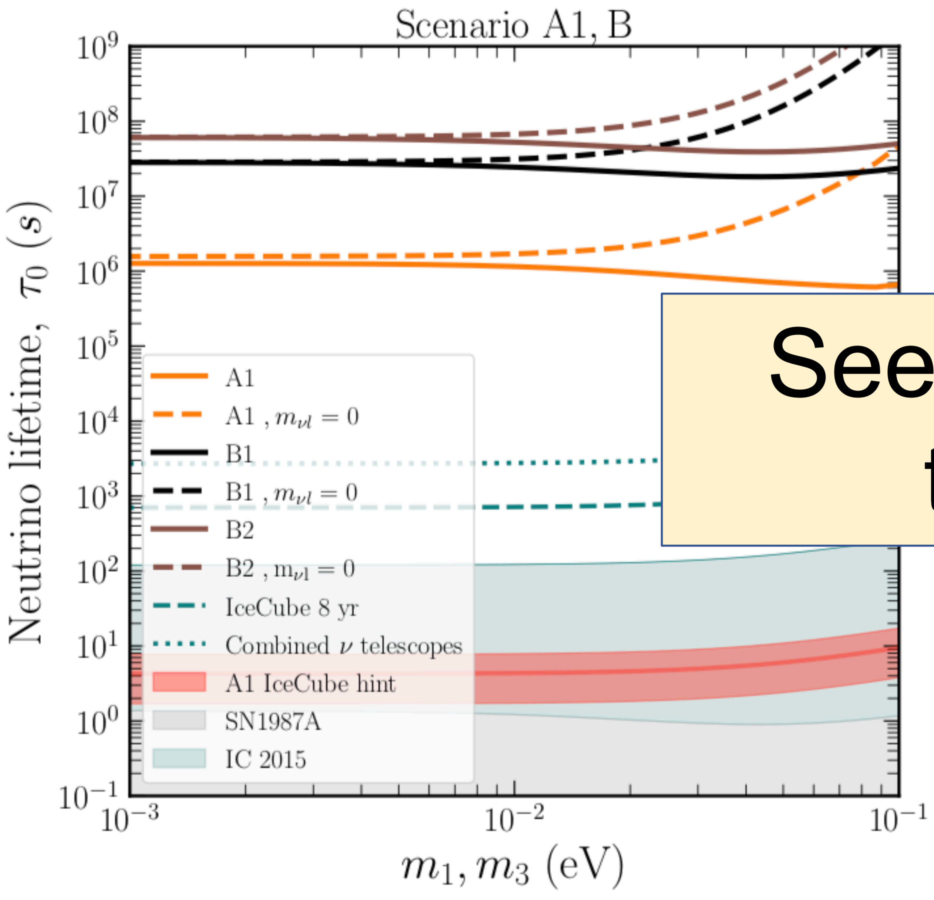


Chen et al. 2016



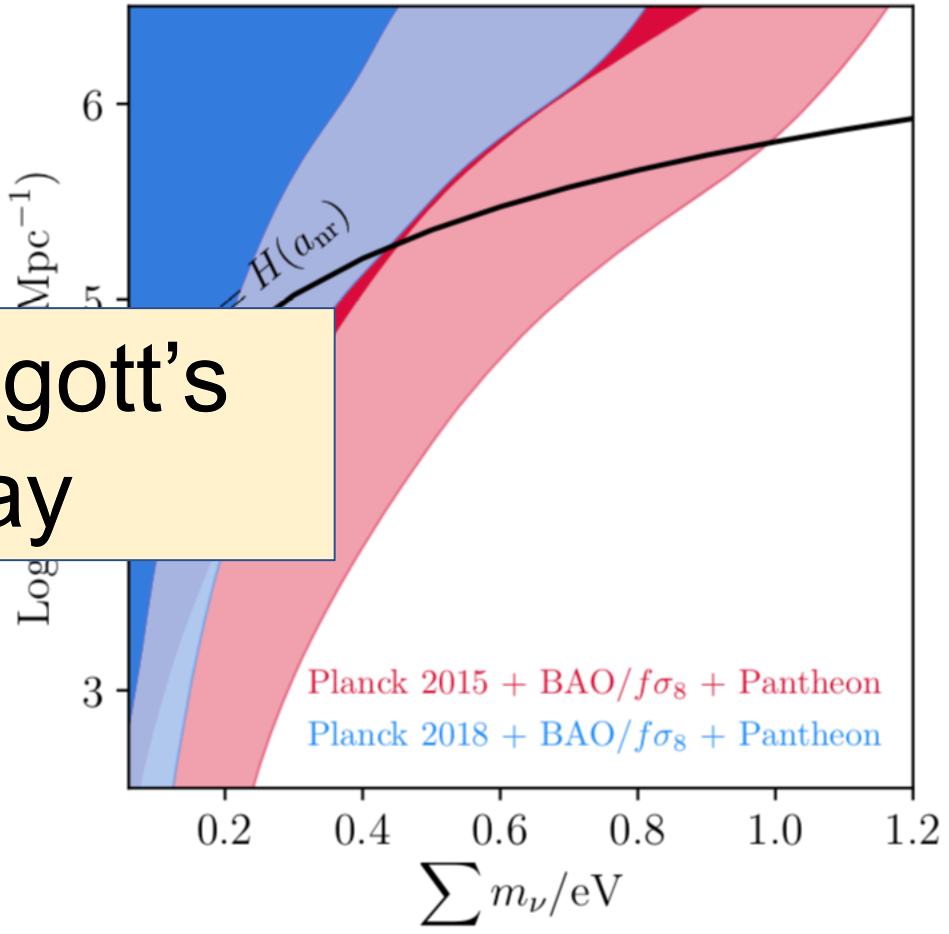
Abellan et al. 2021

NEUTRINO DECAY



Chen et al. 2016

See Isabel Oldengott's talk on Monday



Abellan et al. 2021

Future Prospects

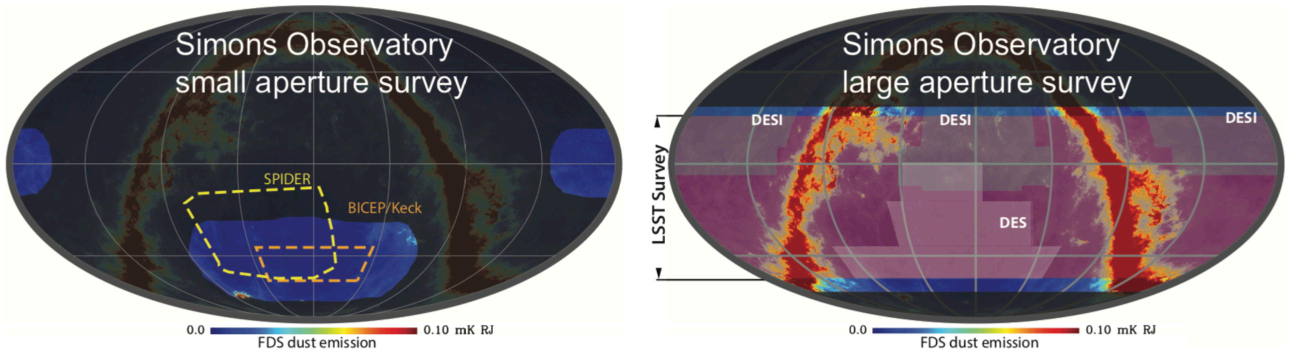
To increase sensitivity to neutrino masses AND reduce model dependency, we need:

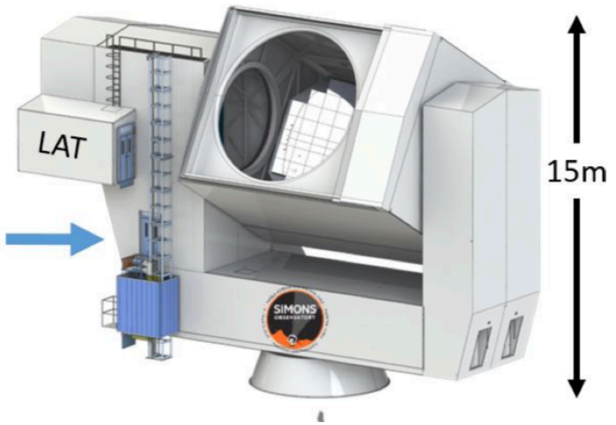
- Precise measurement of the CMB lensing signal (both from 2- and 4-point correlation functions)
- Cosmic variance limited measurement of the reionization optical depth
- other CMB probes of structure formation, e.g. SZ galaxy clusters

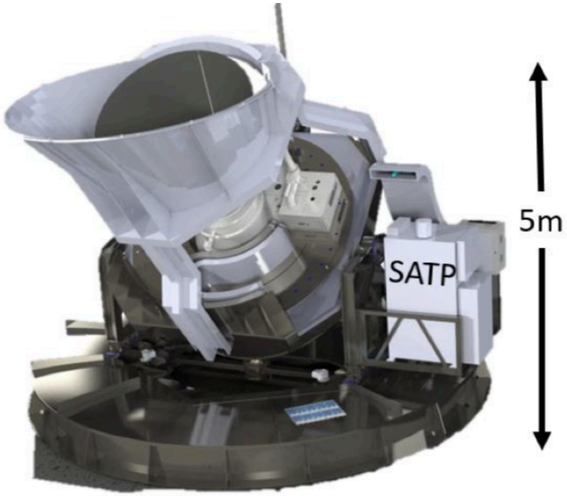
+ non-CMB information

- 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







- Ground-based CMB experiment sited in Cerro Toco in the Atacama Desert in Chile
- 5-yr obs campaing starting in 2023
- 3 Small Aperture (0.4m) Telescopes (SATs) for ‘r science’
- 1 Large Aperture (6m) Telescope (LAT) for small-scale (arcmin) science
- > 60k TES detectors
- 10x sensitivity and 5x resolution wrt Planck
- 6 freq. bands from 27 to 280 GHz

SIMONS OBSERVATORY

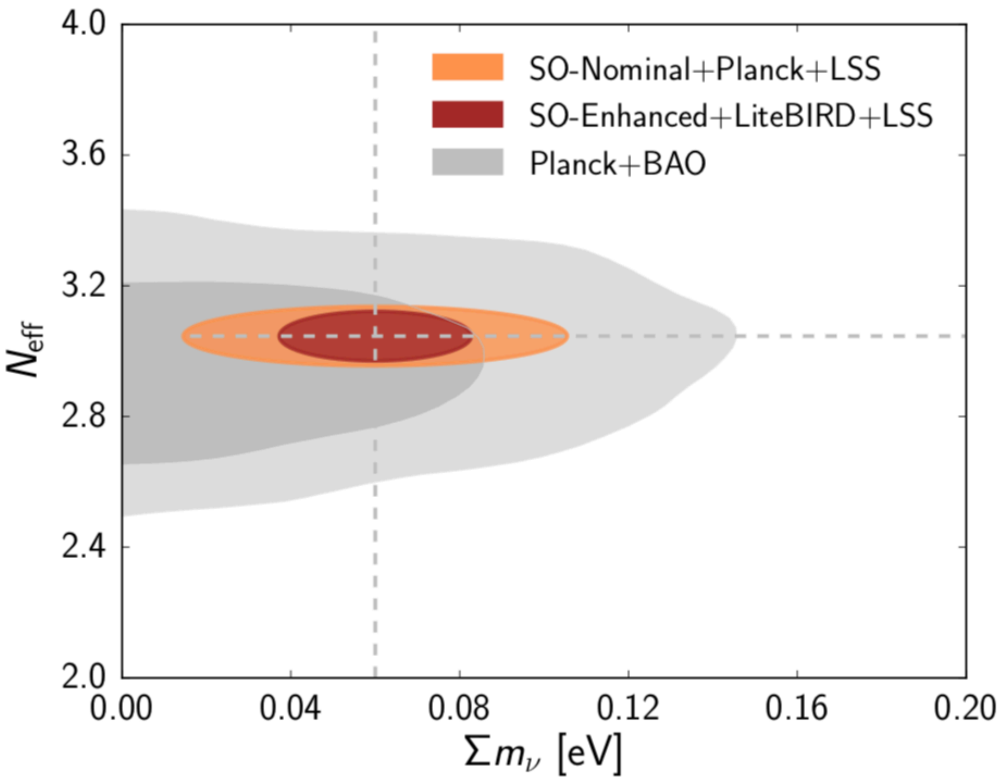


Table 1: Summary of SO-Nominal key science goals[a]

	Current[b]	SO-Nominal (2022-27) Baseline	Goal	Method[d]
Primordial perturbations (§2.1)				
r ($A_L = 0.5$)	0.03	0.003	0.002[e]	BB + external delensing
n_s	0.004	0.002	0.002	TT/TE/EE
$e^{-2\tau}\mathcal{P}(k = 0.2/\text{Mpc})$	3%	0.5%	0.4%	TT/TE/EE
$f_{\text{NL}}^{\text{local}}$	5	3	1	$\kappa\times$ LSST-LSS
		2	1	kSZ + LSST-LSS
Relativistic species (§2.2)				
N_{eff}	0.2	0.07	0.05	TT/TE/EE + $\kappa\kappa$
Neutrino mass (§2.3)				
Σm_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.04	0.03	$\kappa\kappa$ + DESI-BAO
		0.04	0.03	tSZ-N $\times$ LSST-WL
Σm_ν (eV, $\sigma(\tau) = 0.002$)		0.03[f]	0.02	$\kappa\kappa$ + DESI-BAO + LB
		0.03	0.02	tSZ-N $\times$ LSST-WL + LB

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 from LiteBIRD

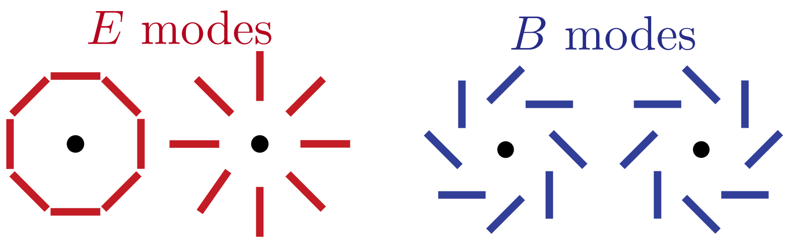
$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

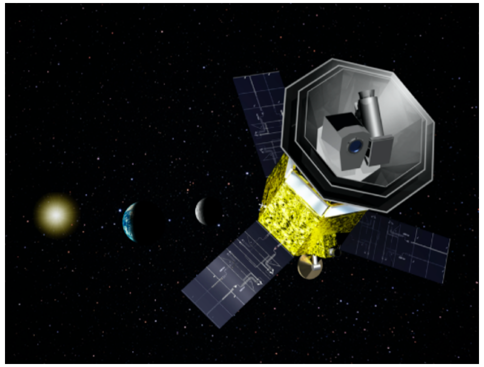
SO Collaboration, 2018

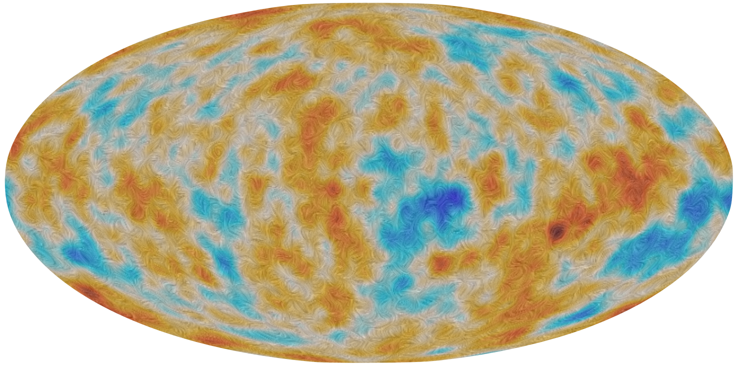

LiteBIRD
A JAXA-led post-Planck space mission for CMB polarization, with participation from US and Europe

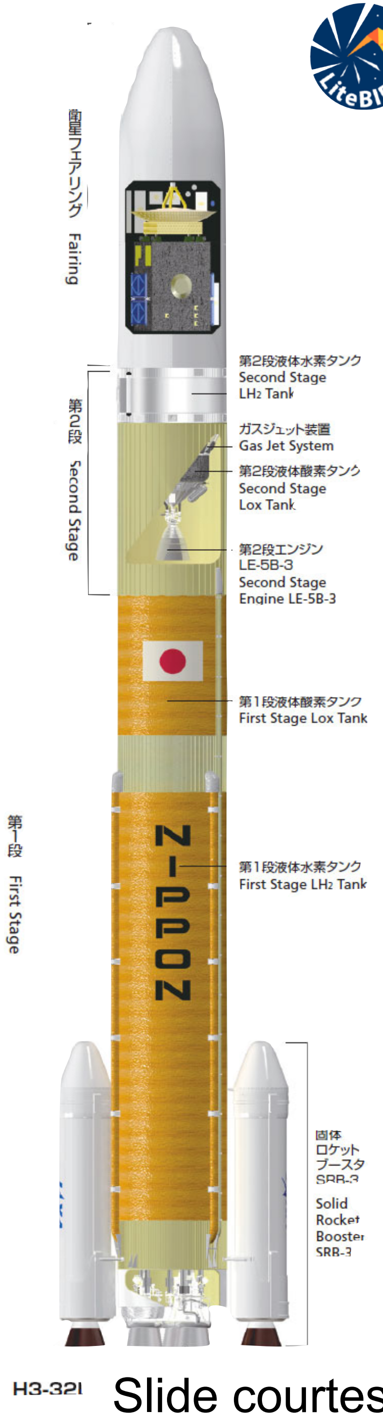
LiteBIRD Overview

- Light satellite for B-modes from Inflation CMB Radiation Observation
- Selected (May 2019) as the next JAXA's L-class mission
- Expected launch in 2029 with JAXA H3 rocket
  - LiteBIRD is the only CMB space mission that can be realized in 2020s
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (40–402 GHz, 15 bands) at 70–18 arcmin
  - three telescopes: LFT, MFT, HFT.
- 4508 TES detectors cooled down to 100 mK read by SQUIDs
- Final combined sensitivity: 2.2 μK arcmin, after component separation





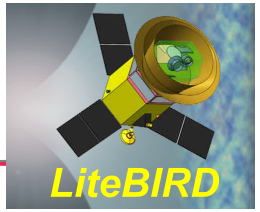




Slide courtesy: G. Signorelli

CMB-S4 - LiteBIRD

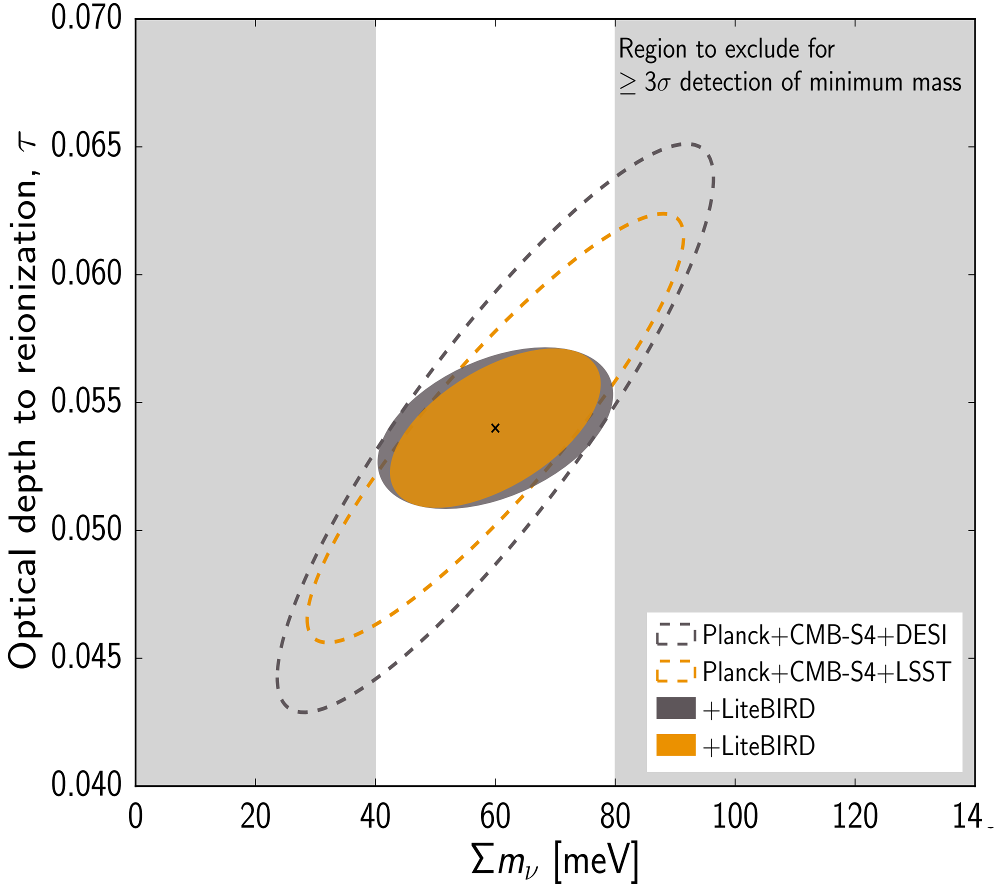
Σm_ν w/ improved τ

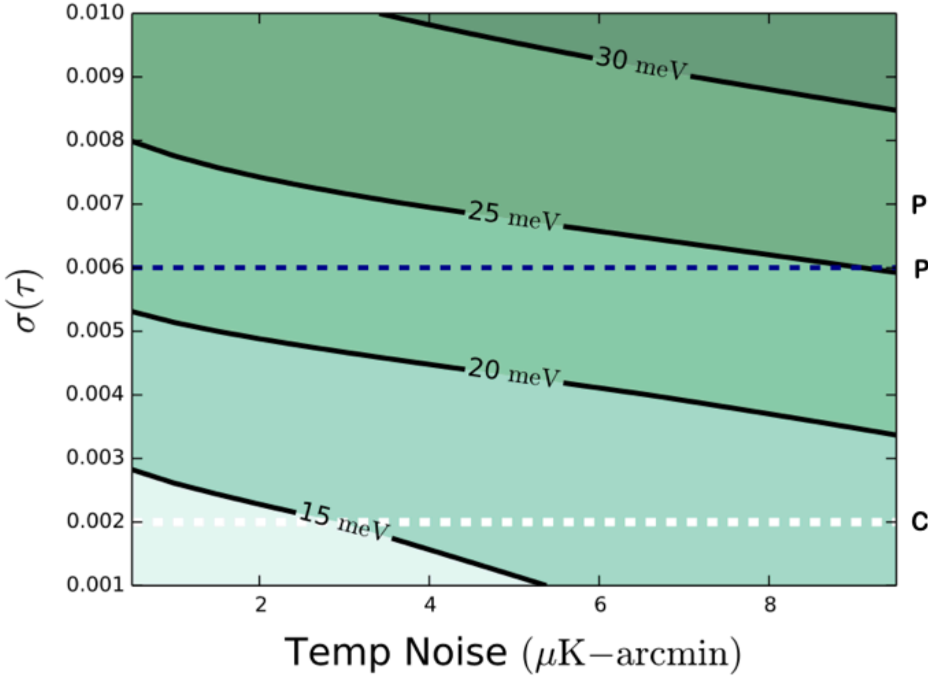


LiteBird Collaboration, arXiv:2202.02773

- $\sigma(\Sigma m_\nu) = 15$ 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.

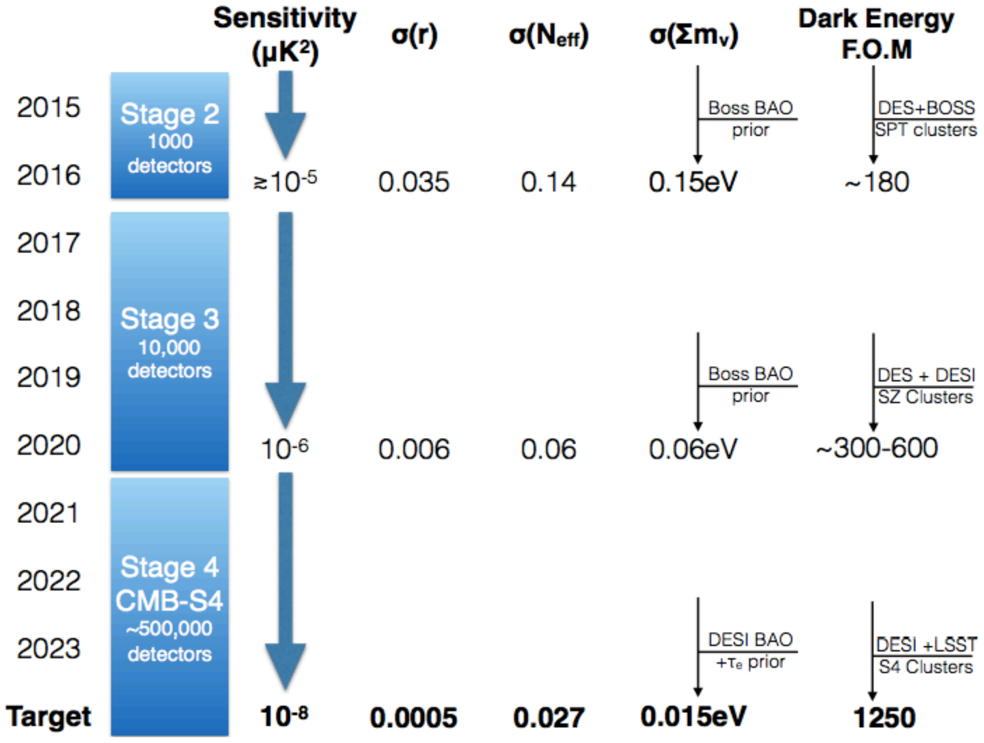




CMB-S4 Collaboration, 2019

CMB Stage-4

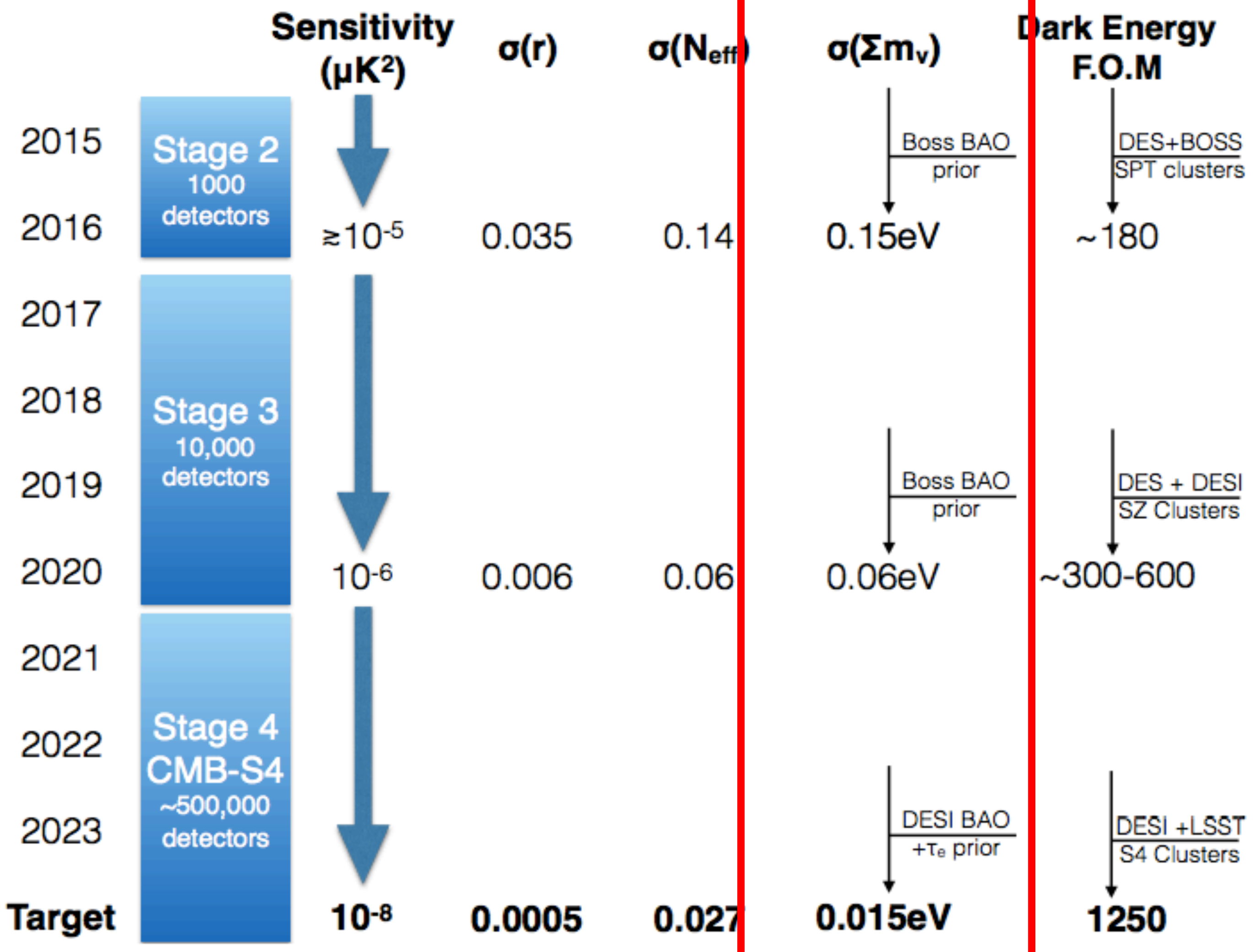
- Definitive ground-bases CMB experiment
- Observing from Atacama Desert and South Pole
- Joint NSF and DOE project
- 7-years obs campaign
- Ultra-deep survey (3% of the sky): 18 SATs + 1 LAT at the South Pole
- Deep and wide survey (60% of the sky): 2 LATs in Chile
- 8 frequency bands between 20 and 280 GHz
- ~ 550K detectors



See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

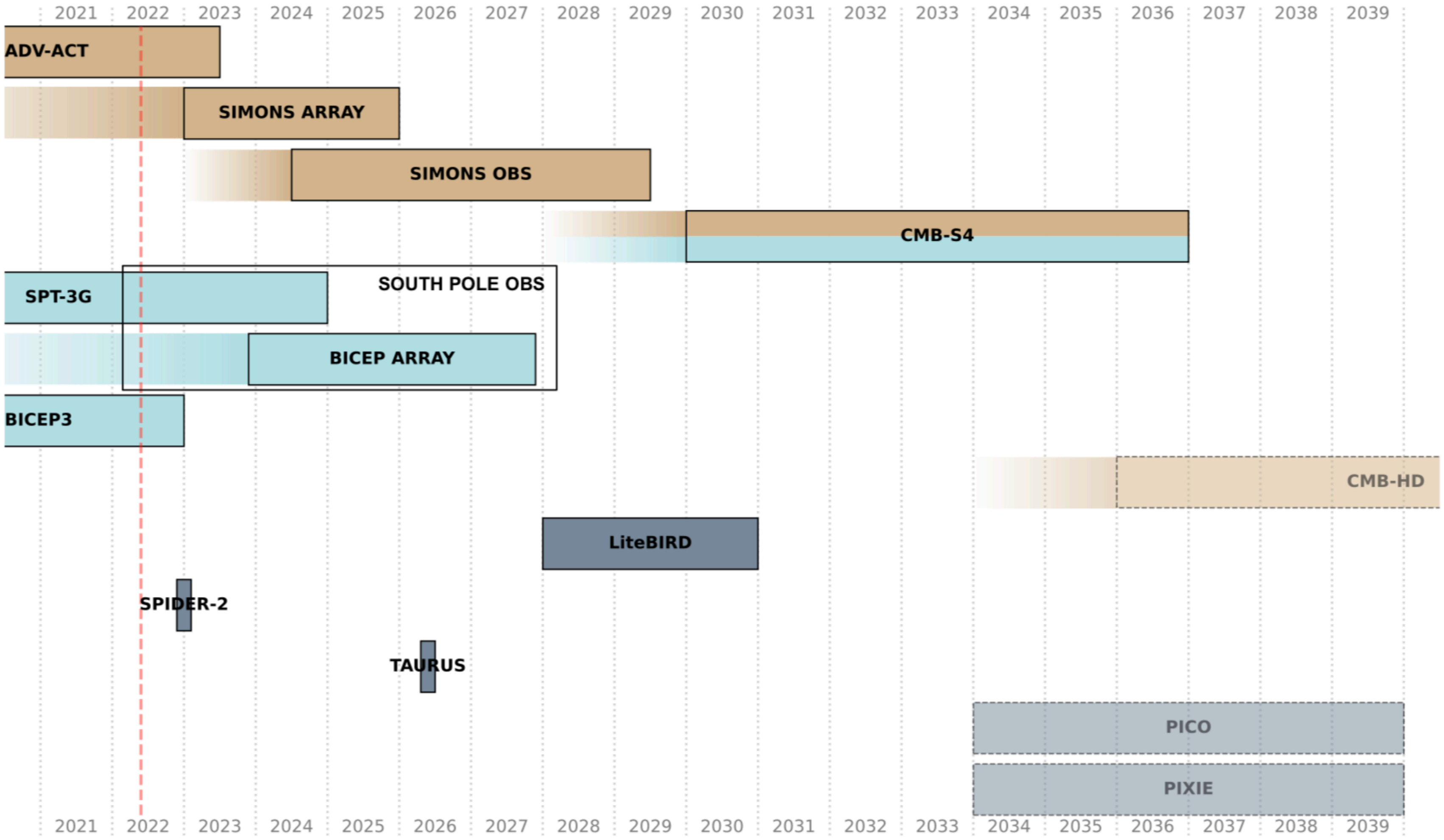
CMB-S4 Science Book (arXiv: 1610:02743)

NEUTRINO PARAMETERS FROM CMB-S4



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

TIMELINE OF CMB EXPERIMENTS



Snowmass2021 Cosmic Frontier: CMB Measurements White Paper
arXiV: 2203.07638

The Euclid Mission

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

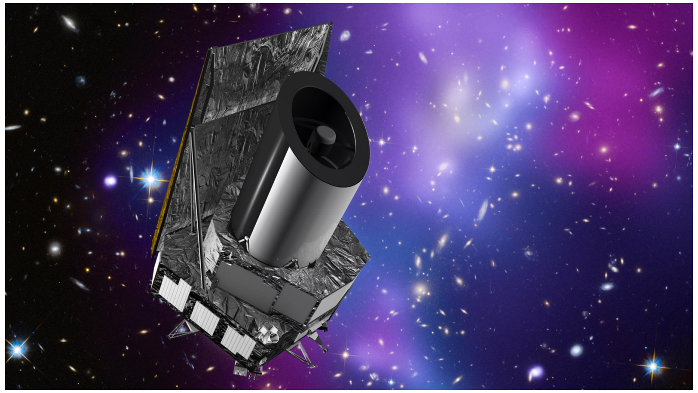
- the origin of the **accelerated expansion** of the Universe
- **Dark energy**, **dark matter** and the behaviour of **gravity at large scales**
- + **neutrino masses, the initial conditions of cosmological evolution, …**

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**

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

(Sprenger et al. 2019)

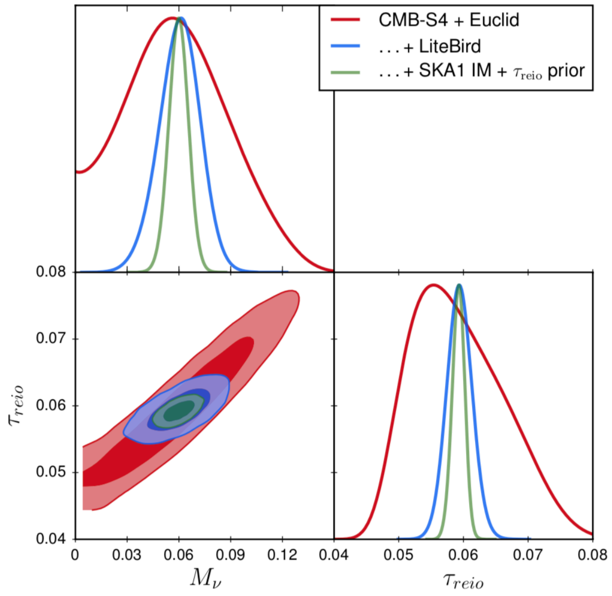


FORECASTS FOR FUTURE CMB+LSS

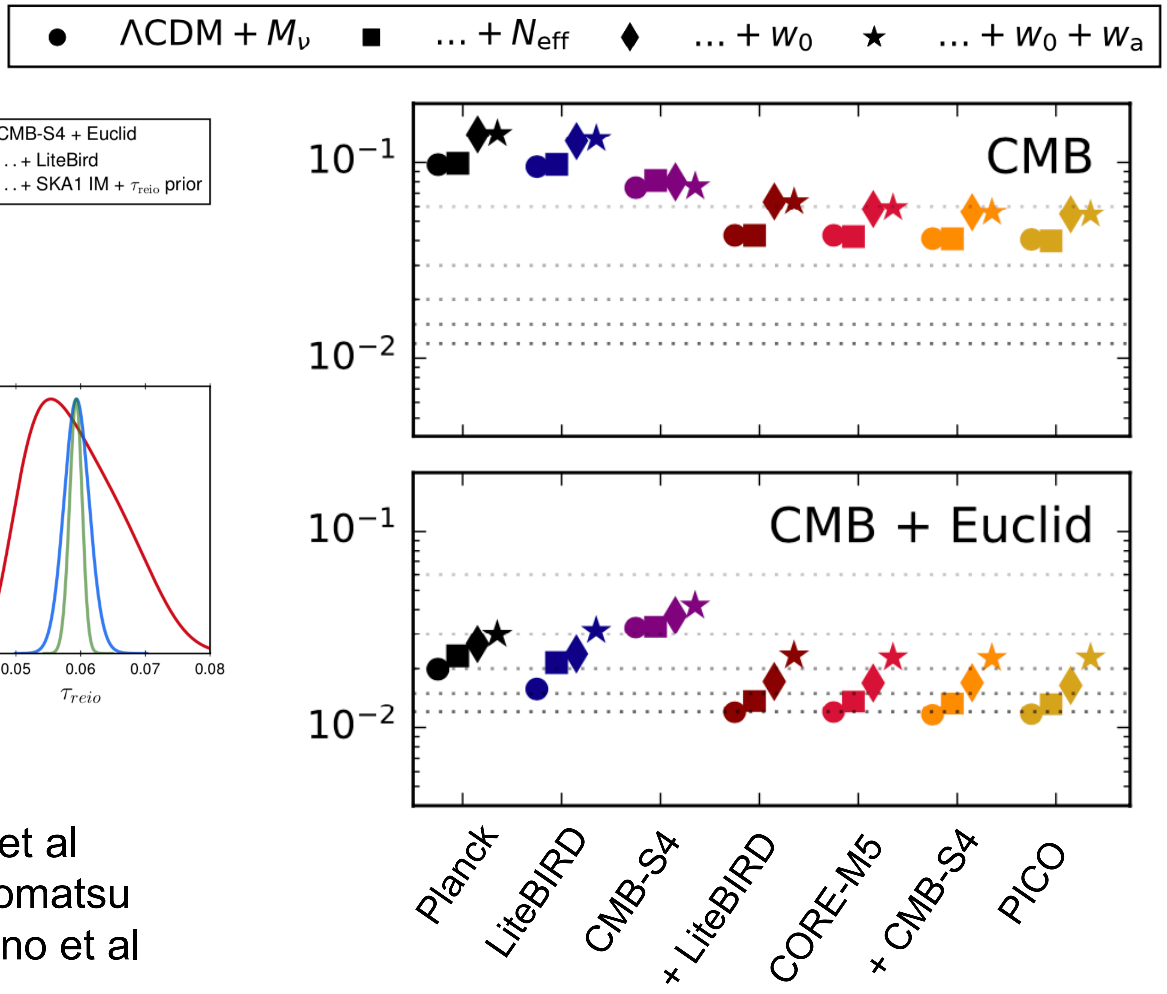
$\sigma(\Sigma m_\nu)$ = 0.04 eV from SO (primary+lensing)
+ DESI BAO
(SO Collaboration 2018)

$\sigma(\Sigma m_\nu)$ = 0.042 eV from LiteBIRD + CMB-S4
= 0.012 eV + Euclid

(0.063 and 0.068 eV in DDE models)
Brinckmann, Hooper,+, JCAP 2019



Brinckmann, Hooper,+, JCAP 2019

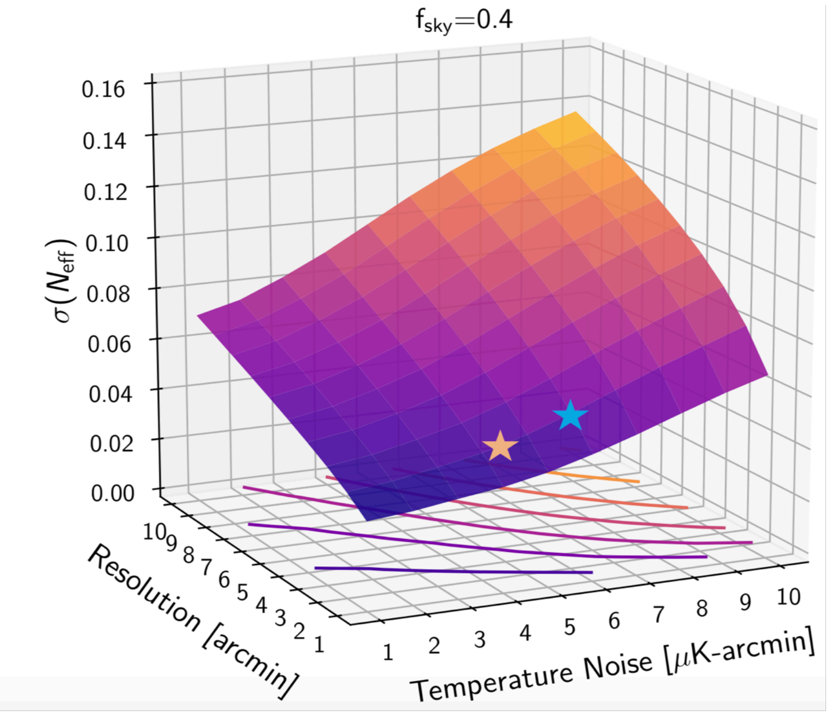


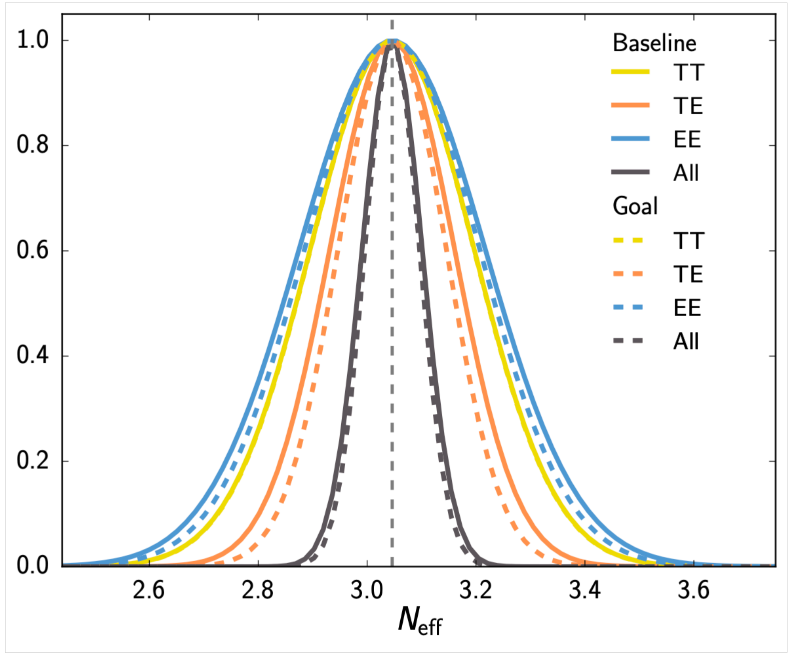
CMB+LSS will provide a statistically significant detection of neutrino masses in ΛCDM (remember $\Sigma m_\nu > 0.06$ eV).

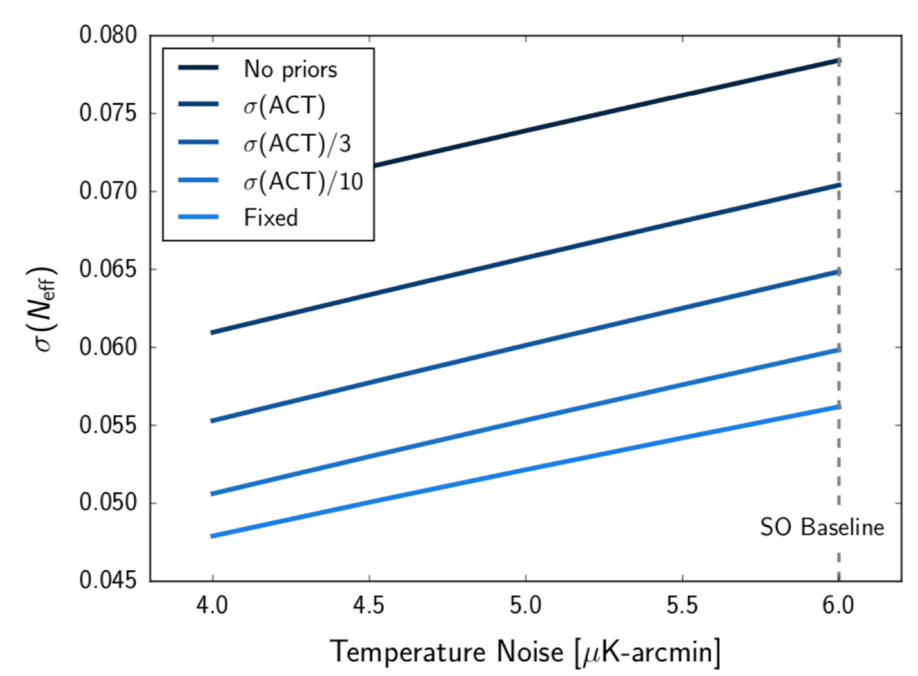
Guaranteed result: either we measure neutrino masses, or we find that the LCDM model has to be amended

See also Allison et al 2015; Boyle & Komatsu 2018; Archidiacono et al 2017.

N_{EFF} FROM SO



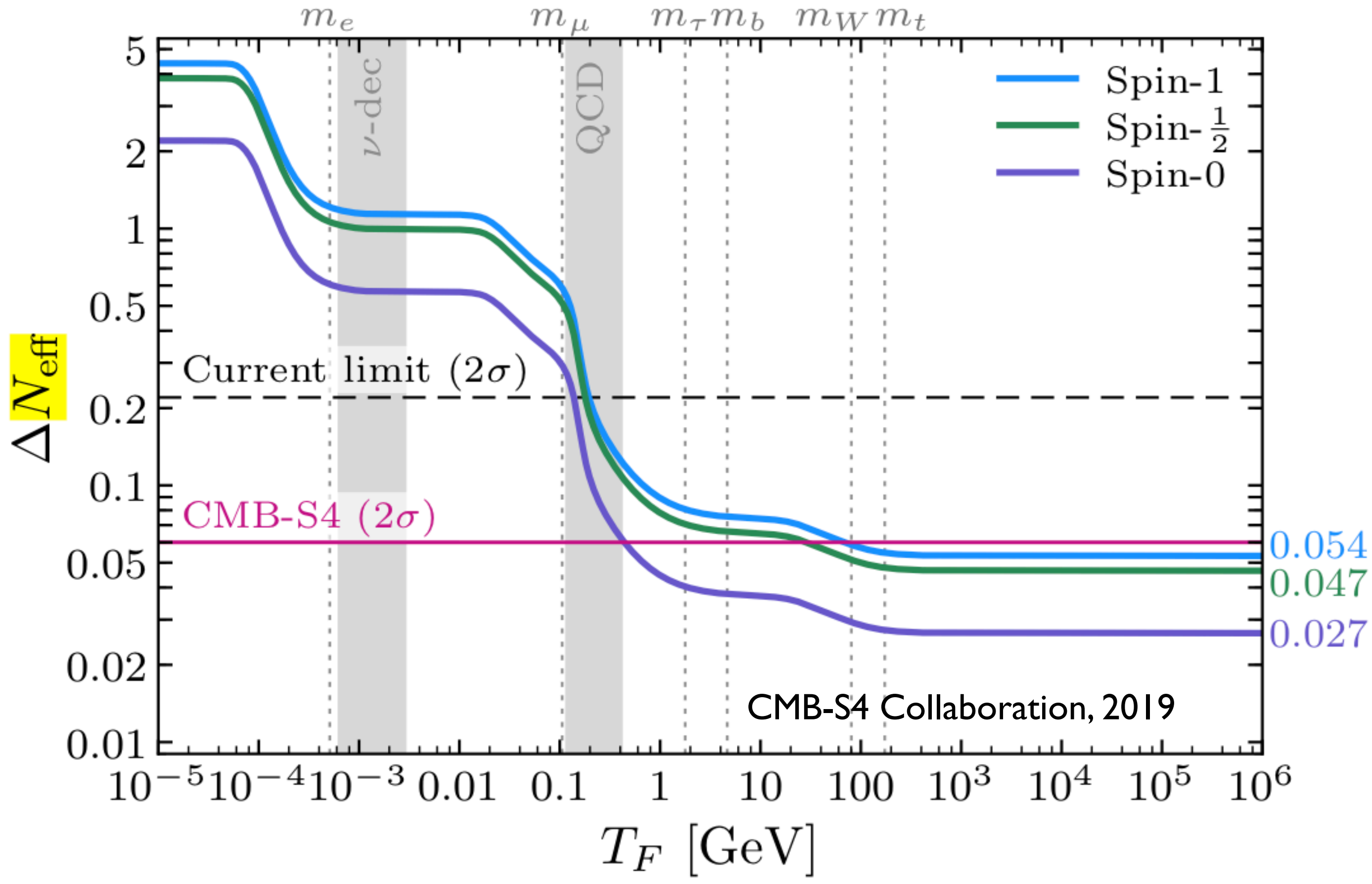




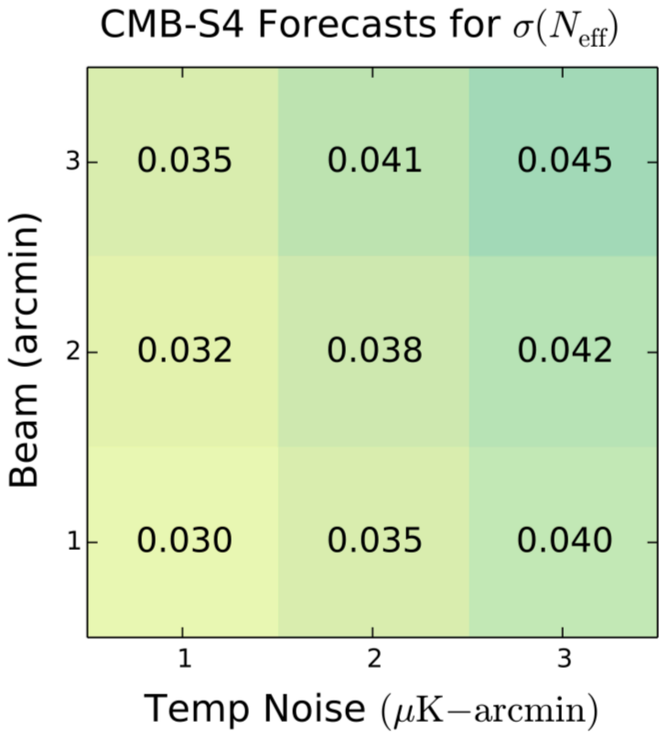
SO collaboration, 2018

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

N_{EFF} FROM CMB-S4



CMB-S4 Collaboration, 2019



CMB-S4 Science Book

SUMMARY

- Current cosmological data provide strong constraints on neutrino properties
- In LCDM, upper bounds are getting close to the minimum value allowed for IO….
- …but limits are somehow relaxed in extended models
- Mild preference for NO
- Strong constraints on BSM neutrino properties (e.g. decay, NSI)
- No convincing evidence for deviations from the standard picture (e.g., non standard Neff, sterile neutrino, NSI…..)
- Combined information from next-generation experiments (CMB from both ground and space, galaxy surveys) will provide a robust, statistically significant measurements of neutrino masses (at least in the framework of the LCDM model)…
- …. Or they will point to the need to revise the standard cosmological model

THANKS!

C. Trillo & E. Breccia, El Peregrino de las estrellas

BACKUP SLIDES

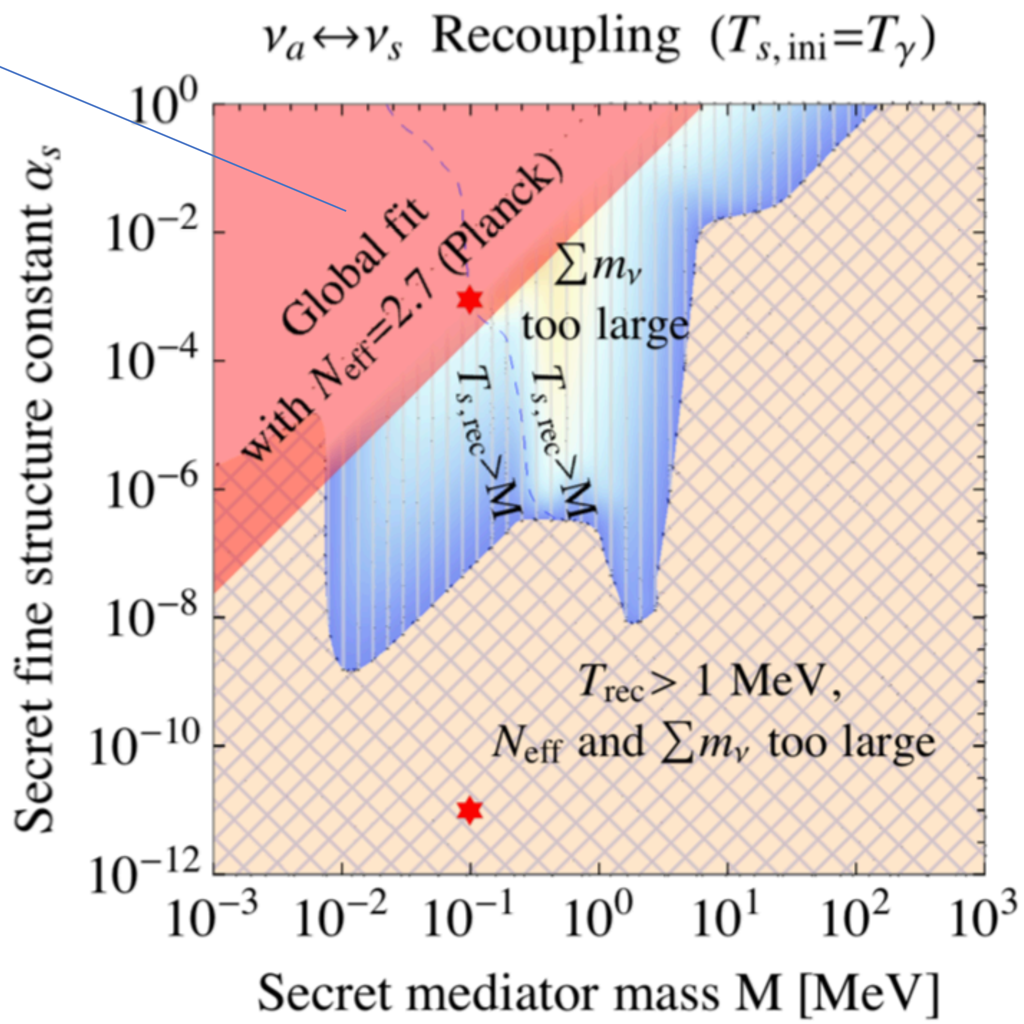
νNSI AND SBL ANOMALIES

Excluded region from Forastieri+ (incl ML) 2017

Catch-22 situation:

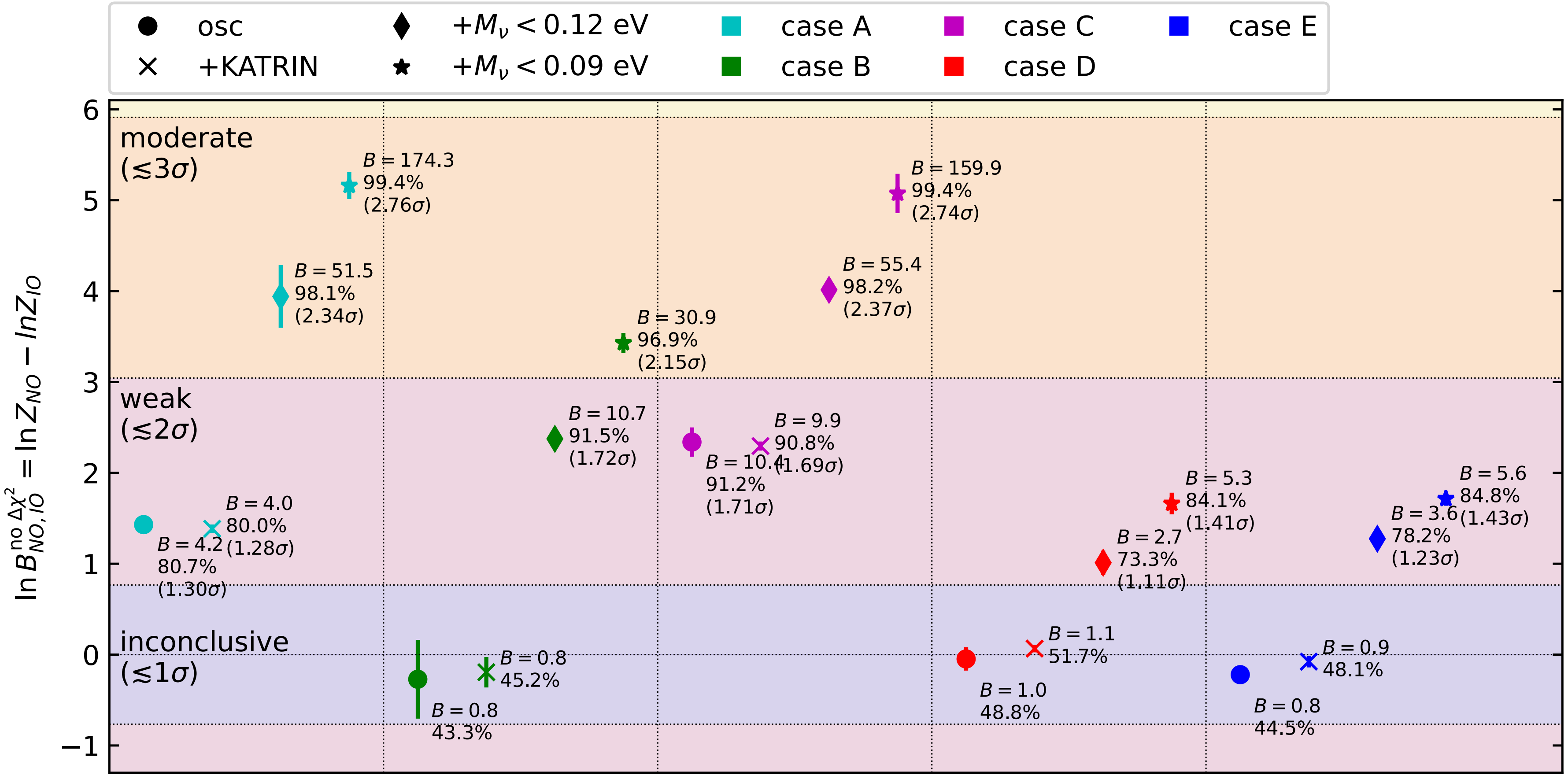
If nonstandard interactions are strong enough to prevent sterile neutrino free-streaming (and erase the neutrino mass bound) then they should leave an observable imprint on CMB anisotropies

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



Plot from Chu et al. 2018

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

Cosmological Constraints on Neutrino Masses

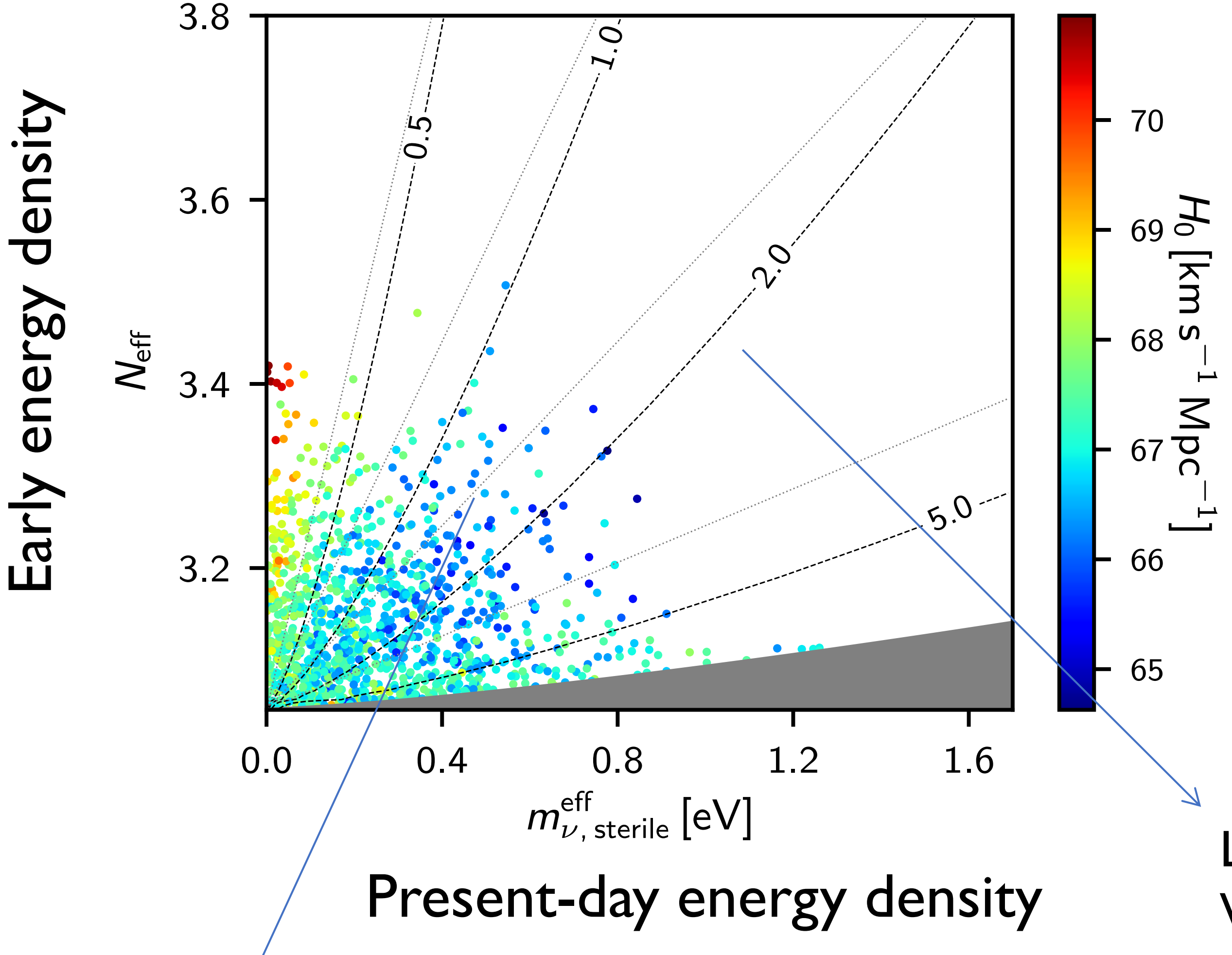
Table 25.2: Summary of $\sum m_\nu$ constraints.

	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

Sterile neutrinos



Planck TT+lowP+ lensing+BAO

$N_{eff} < 3.34$
$m^{eff}{}_{sterile} < 0.23$ 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 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)

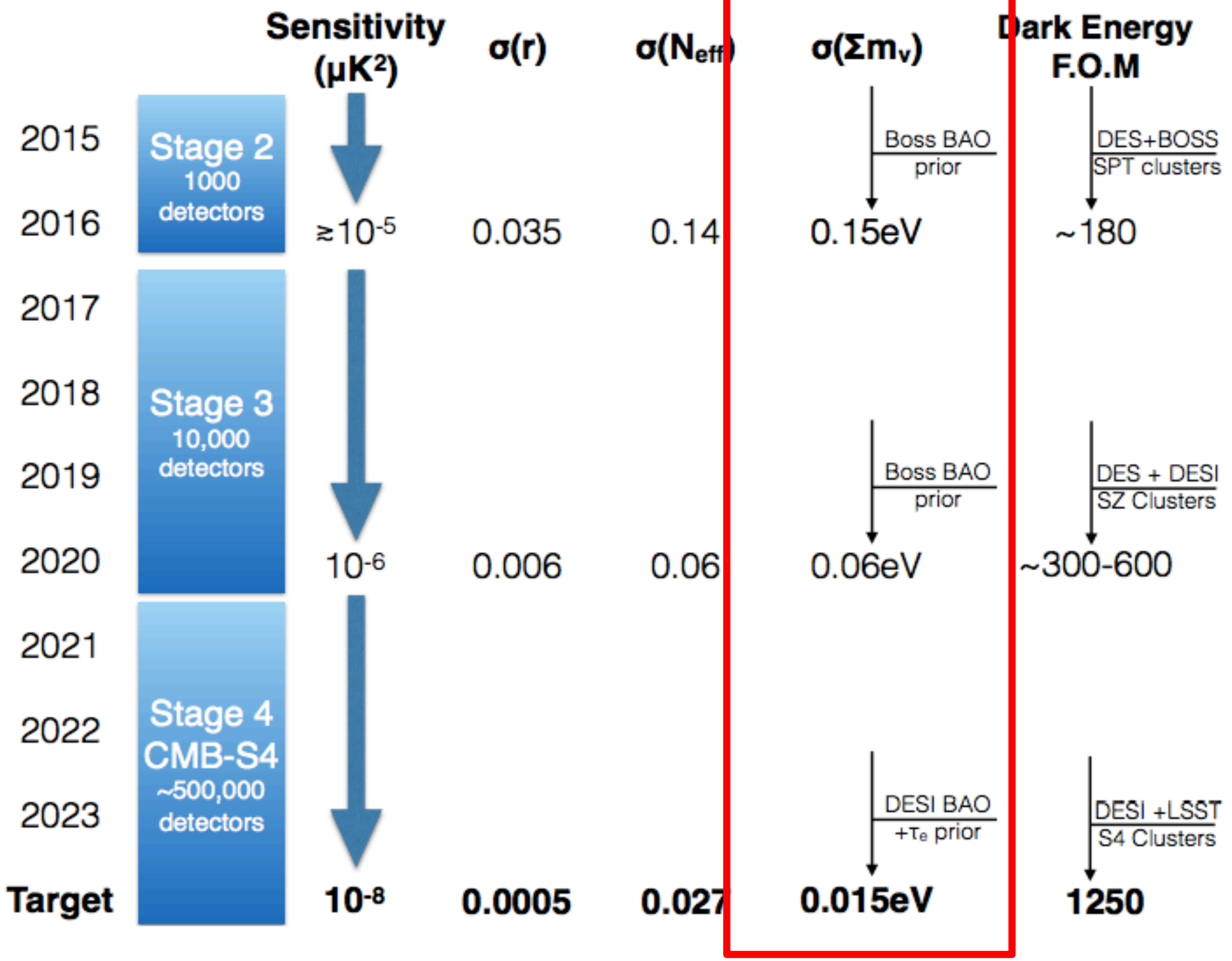
Mass constraints in extended models

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

Extension to ΛCDM	**Σm_ν[meV]**	**Dataset**
$\Lambda\mathrm{CDM} + \Sigma m_\nu$	<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]

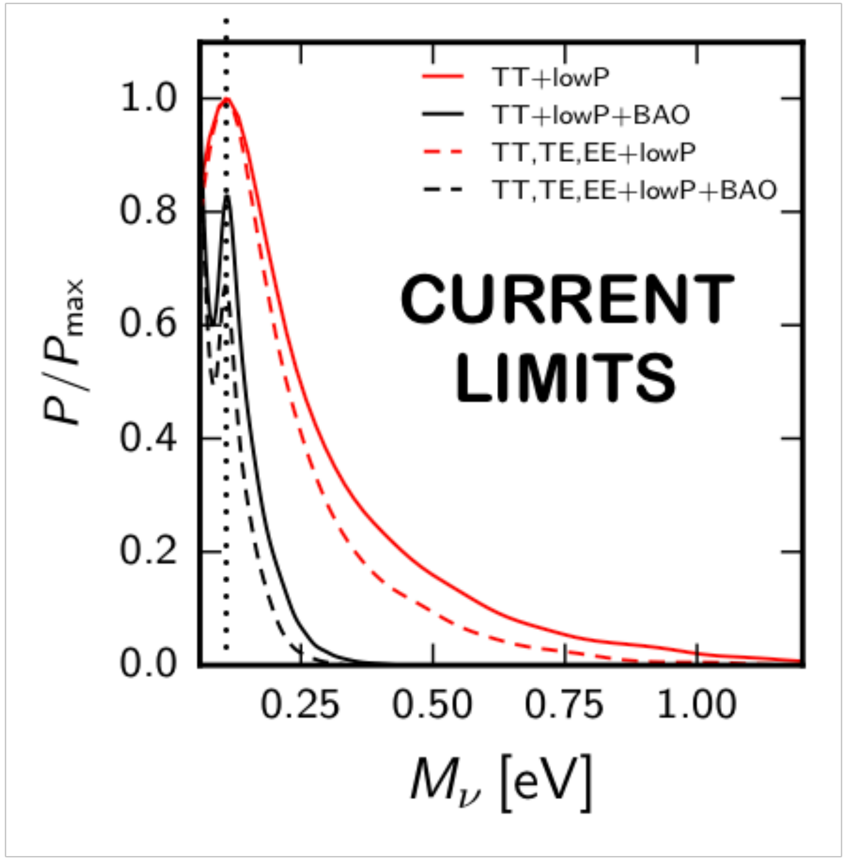
Gerbino & Lattanzi 2018

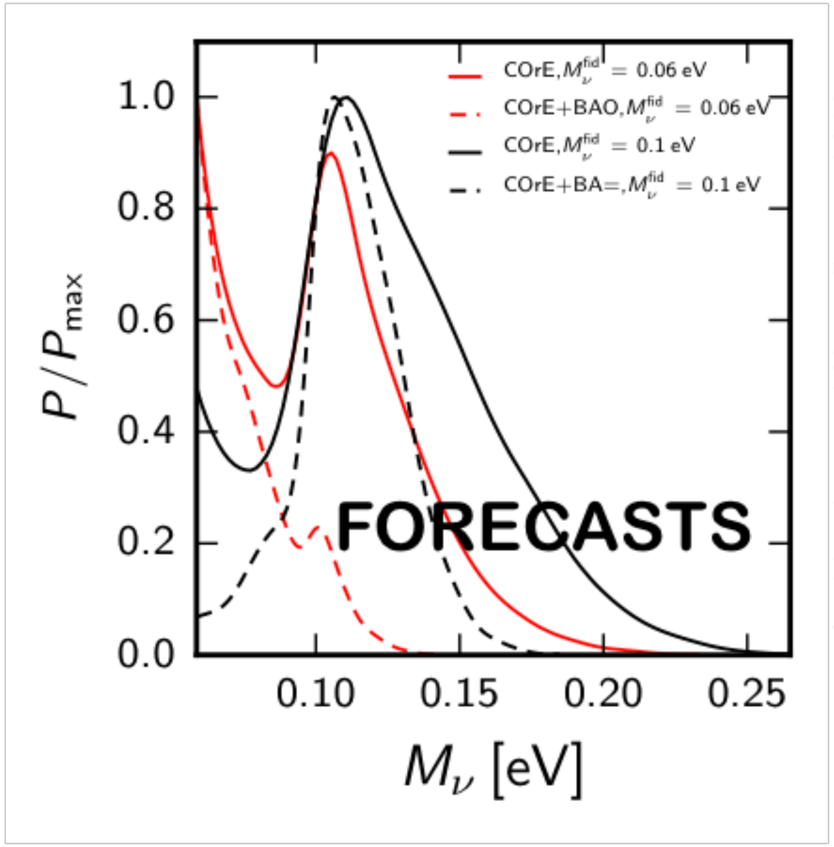
NEUTRINO PARAMETERS FROM CMB-S4



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

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

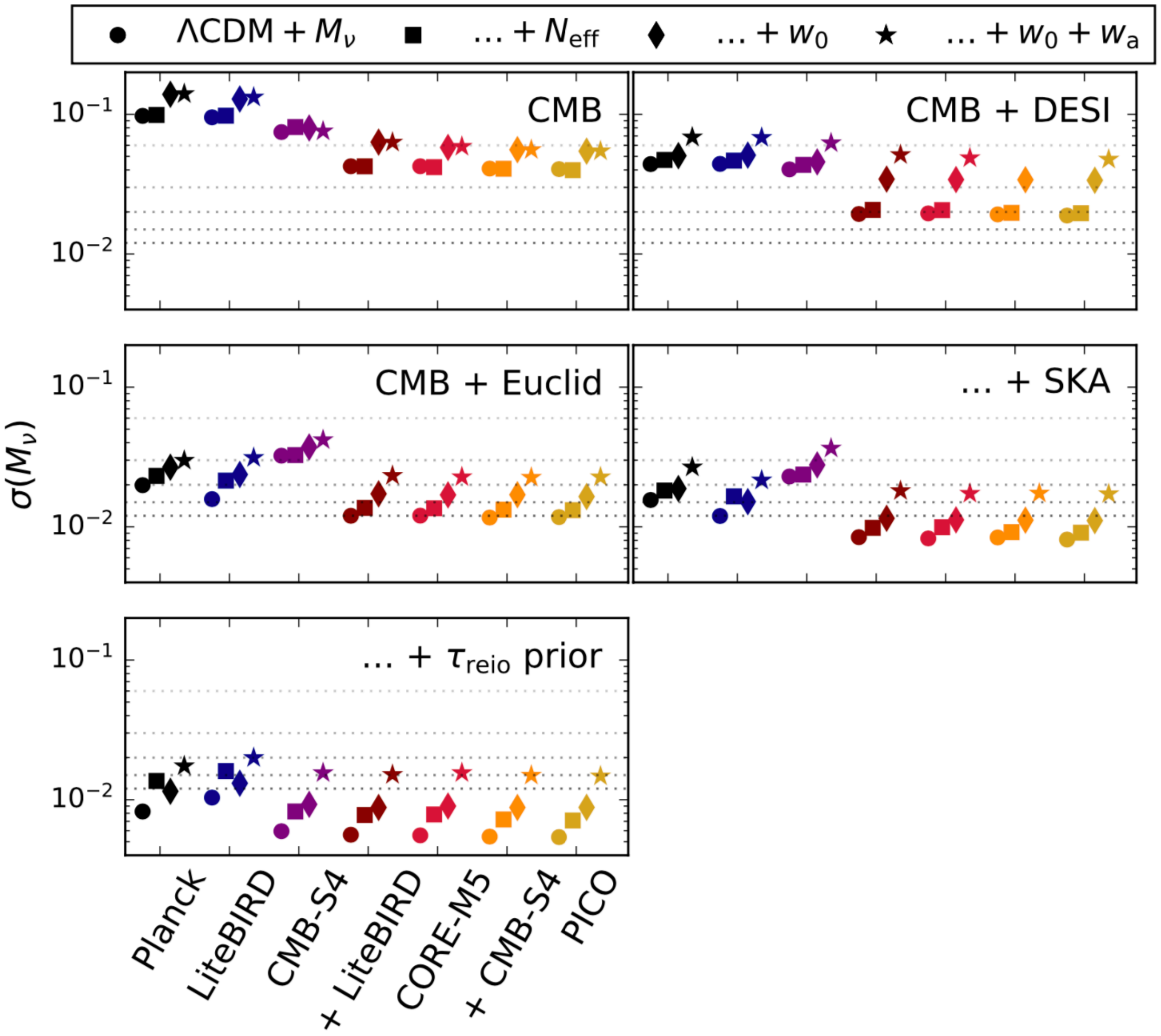
.... 0.06eV mass -> 9:1

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

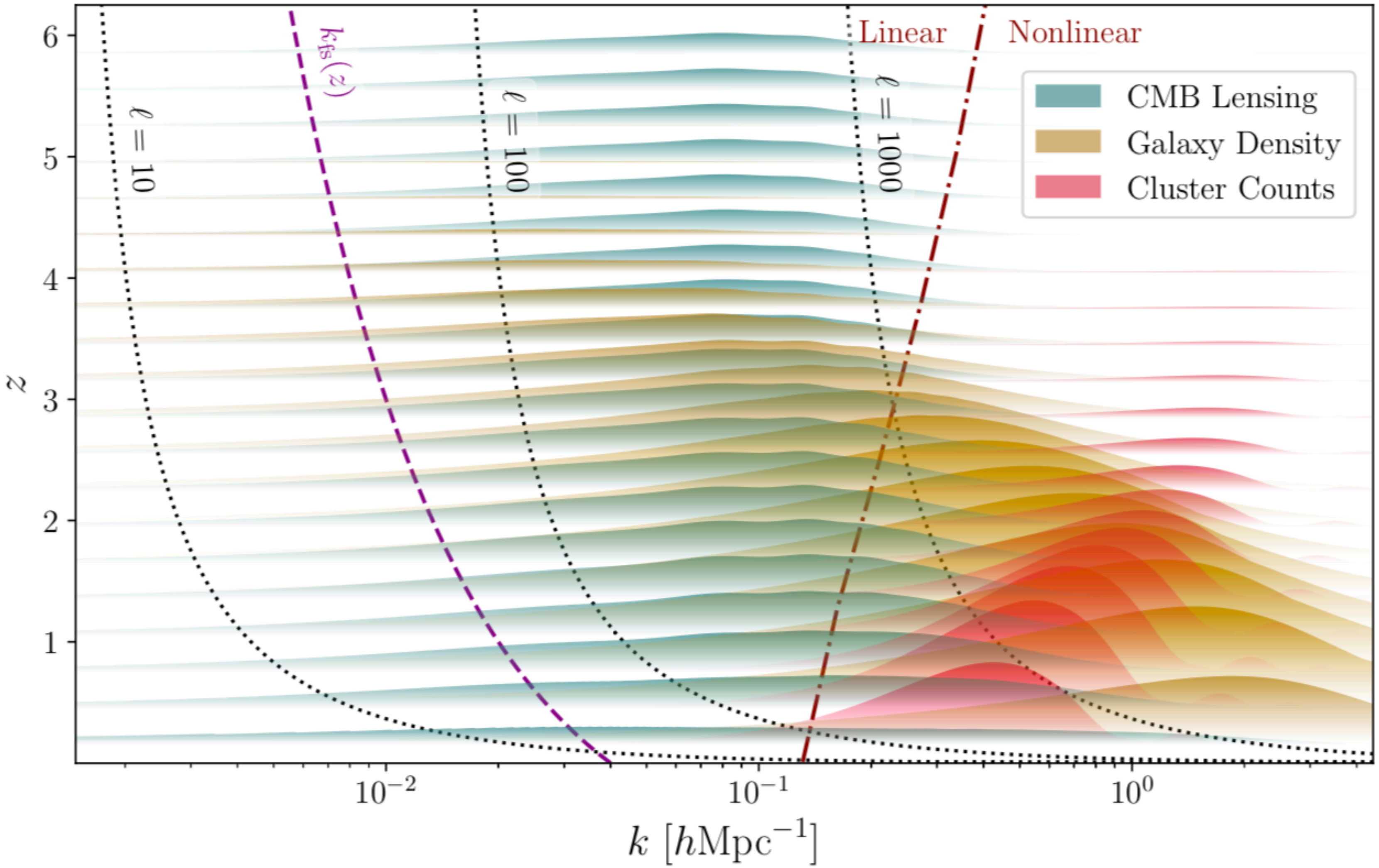
See also Hannestad&Schwetz,2016

NEUTRINO MASS BOUNDS: FUTURE PROSPECTS

Brinckmann+, JCAP 2019



S/N OF FUTURE OBSERVATIONS

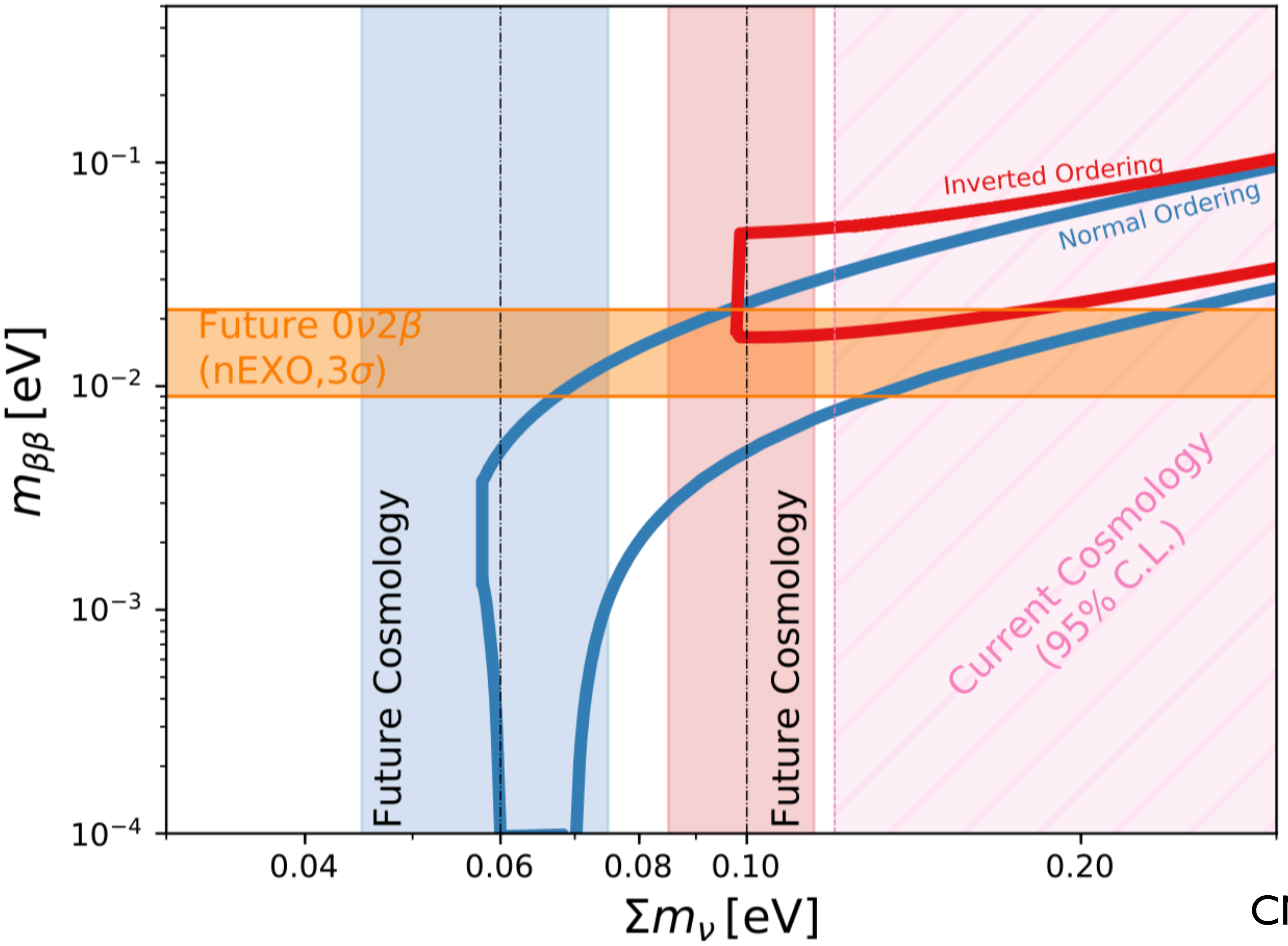


Plot by D. Green & J. Meyers

From the Snowmass white paper

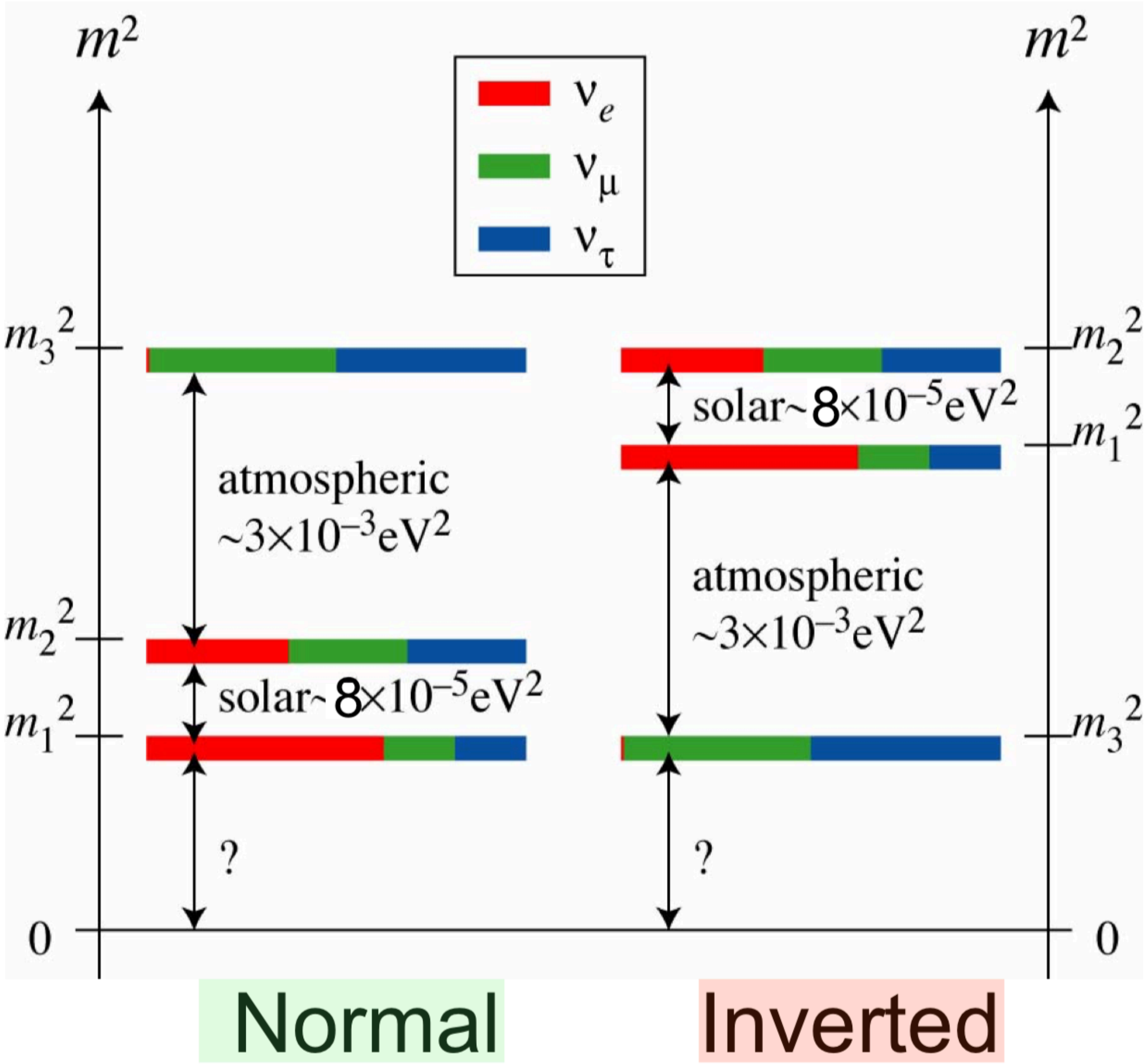
"Synergy between cosmological and laboratory searches in neutrino physics: a white paper" (arXiv 2203.07377)

CMB-S4 - MNU



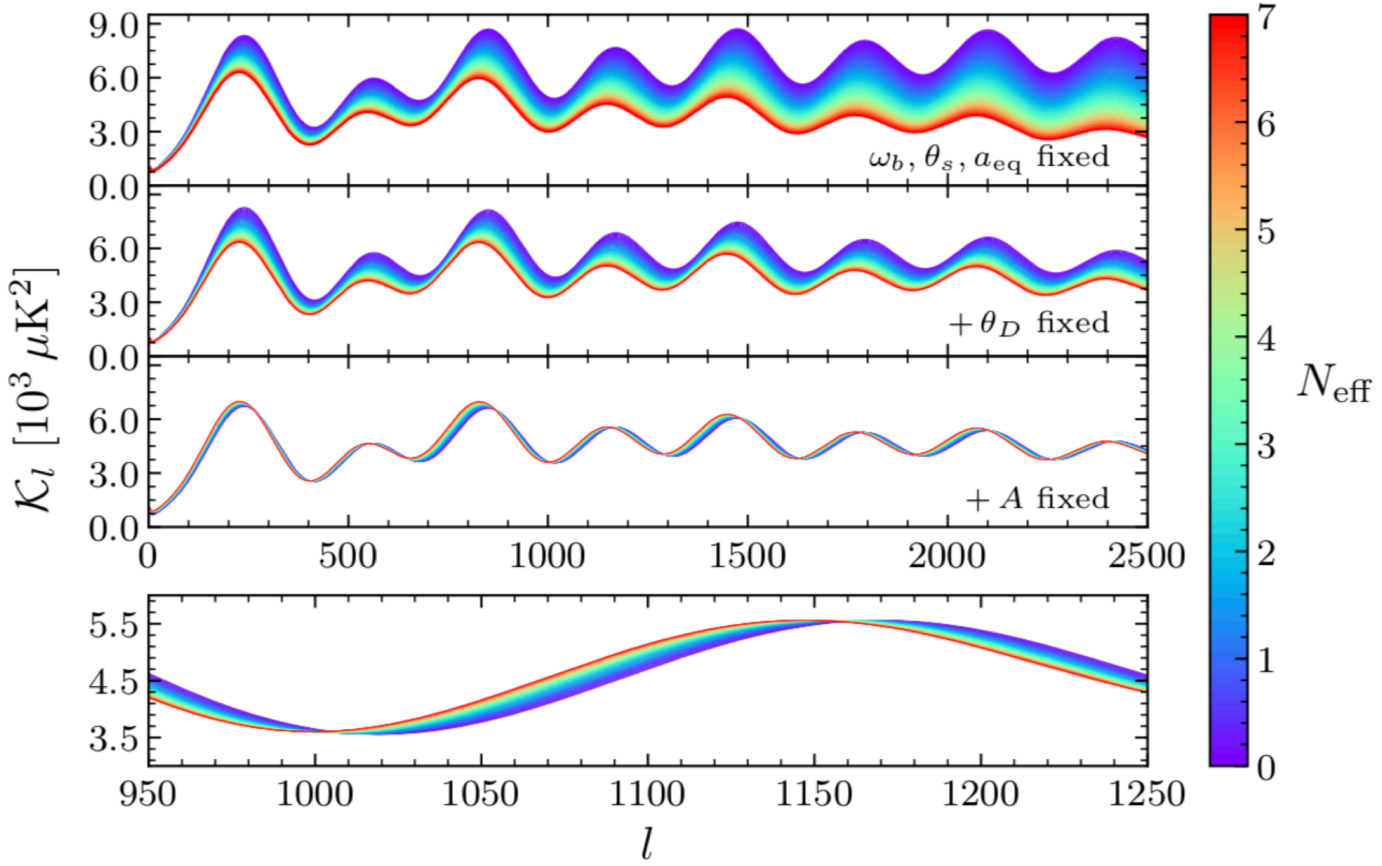
CMB-S4 Collaboration, 2019

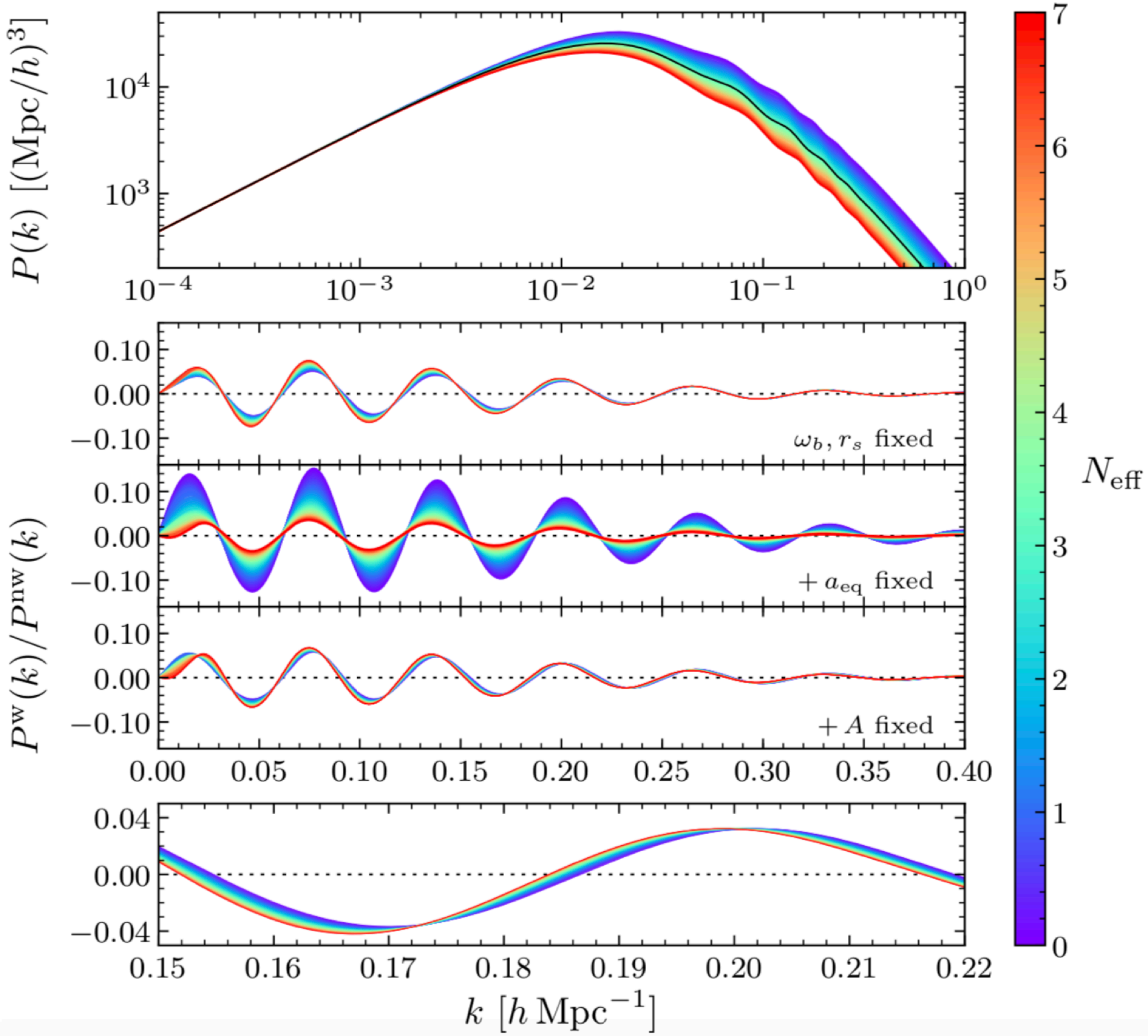
Relic Neutrinos – Present Energy Density



NEFF – PHASE SHIFT

Bashinsky&Seljak, 2004





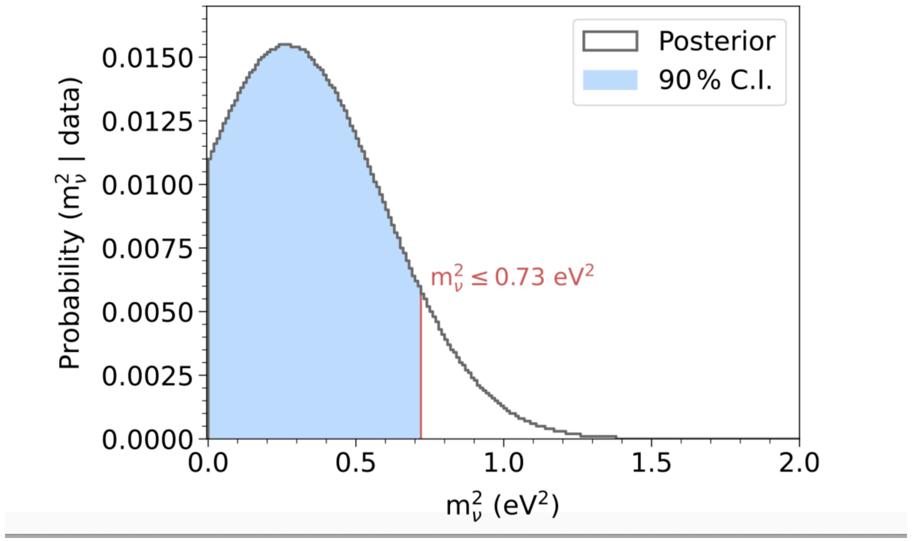
Credts: D. Baumann+, 2018

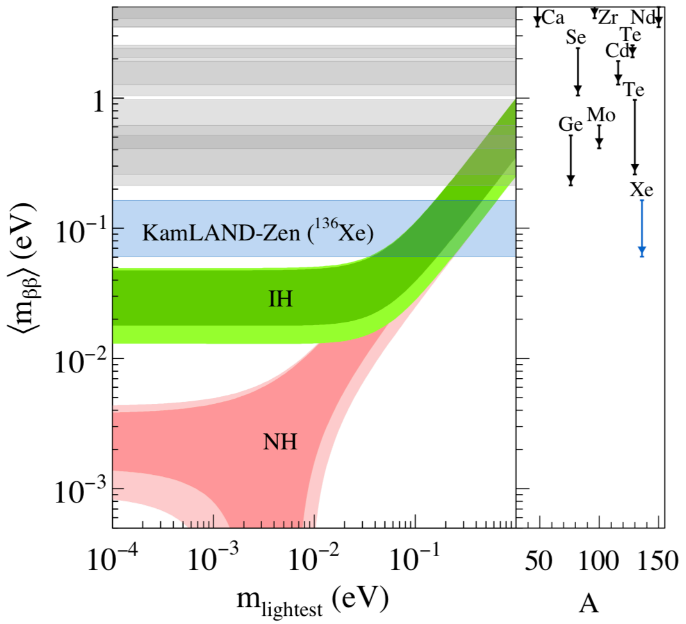
NEUTRINO MASSES FROM THE LAB

Direct mass measurements (end point of β-decay spectrum)

$m_\beta < 0.8\,\mathrm{eV}\;(90\%\,\mathrm{CL})$ (KATRIN coll., 2022)

Target 90% sensitivity: 0.2 eV

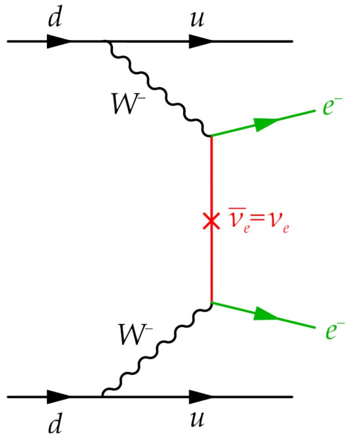




Neutrinoless double β decay (only applies to Majorana ν's)

$m_{\beta\beta} < 0.061 - 0.165\,\mathrm{eV}\;(90\%\,\mathrm{CL})$

(KamLAND-Zen coll., 2016)



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

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

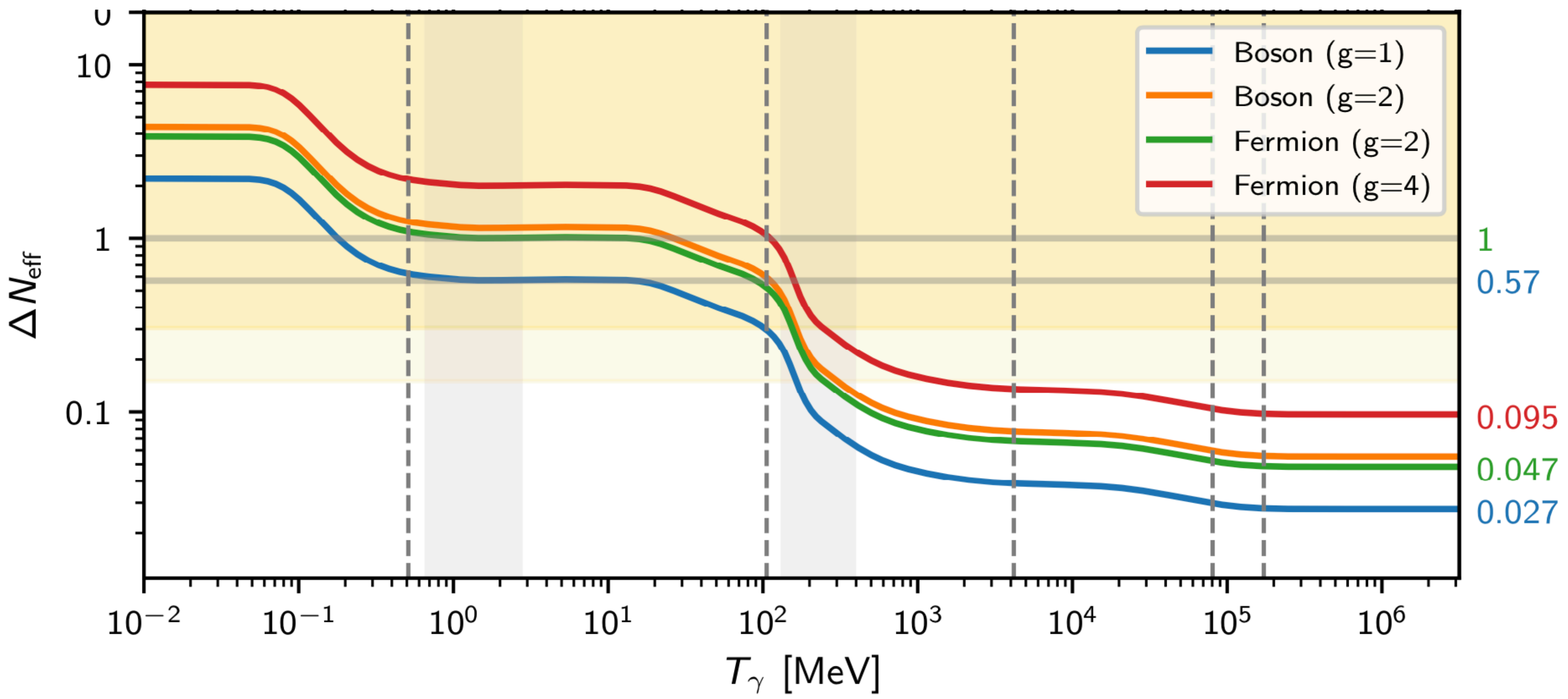
Suppressed growth

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

Acoustic phase shift

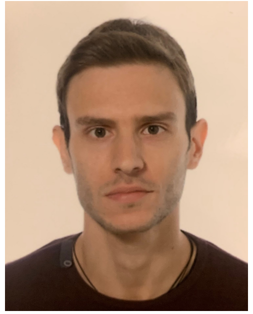
N_{EFF} AND THE DECOUPLING OF SPECIES

For a species that was in thermal equilibrium in the early Universe, ΔN_{eff} is directly related to the decoupling temperature:



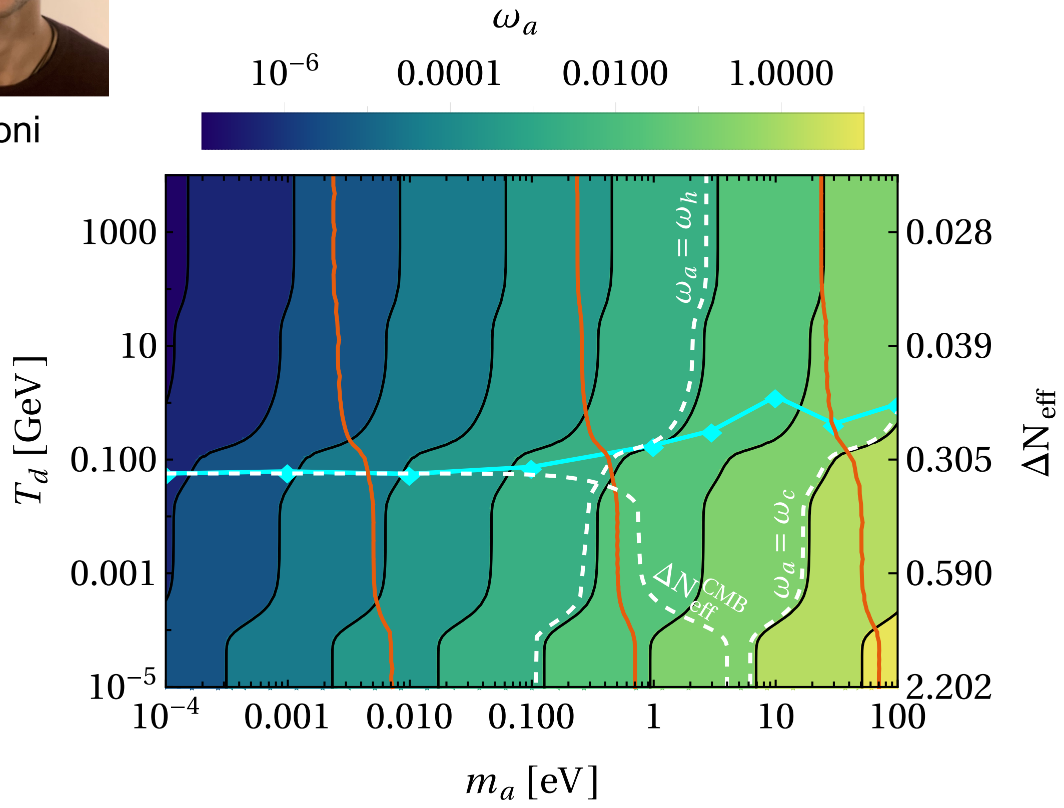
Planck collaboration, VI 2018

N_{EFF} AND THERMAL AXIONS

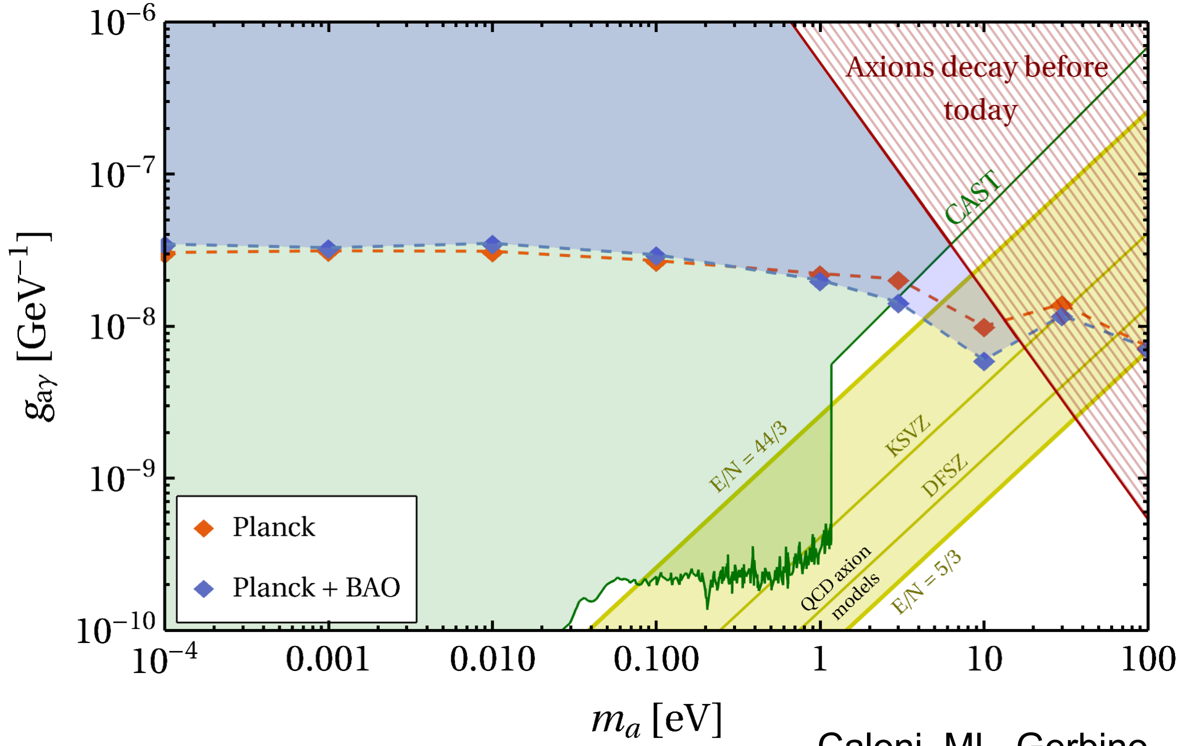


L. Caloni

Axions can be produced thermally in the early Universe through their coupling to **photons** or gluons

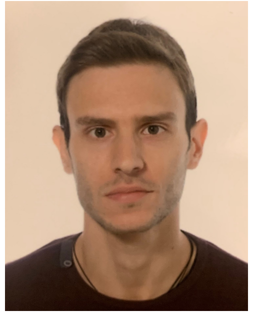


$$\mathcal{L}_{a\gamma} = \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Caloni, ML, Gerbino, Visinelli, 2022

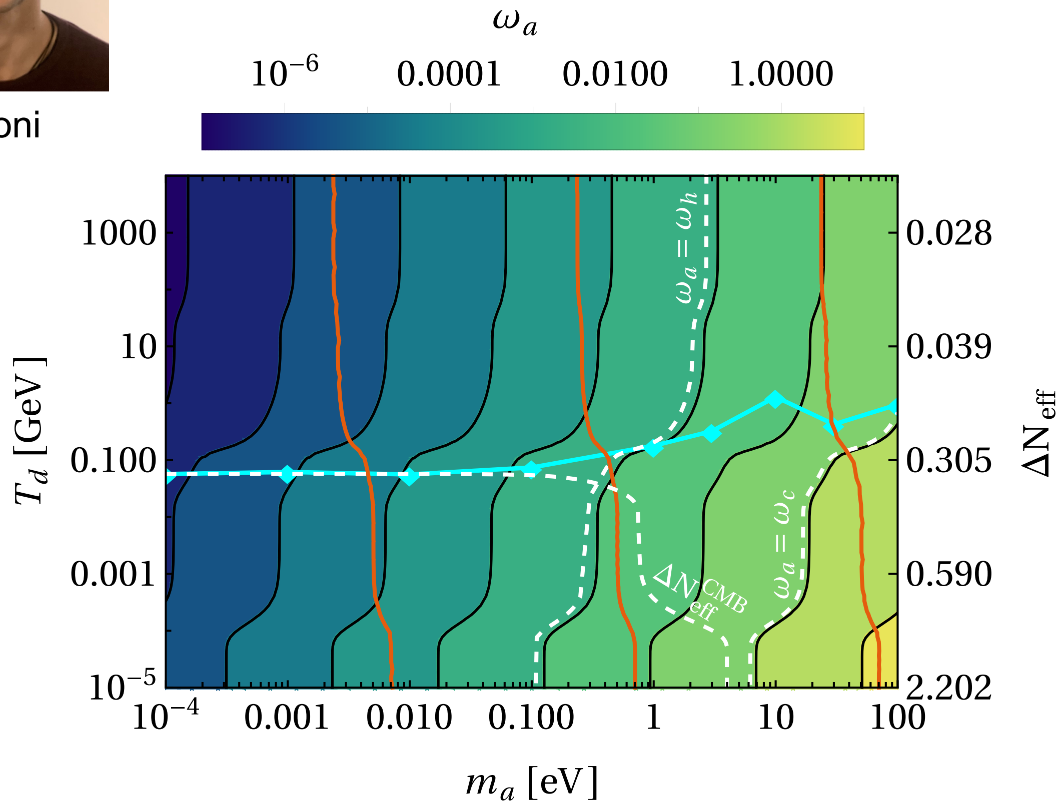
N_{EFF} AND THERMAL AXIONS

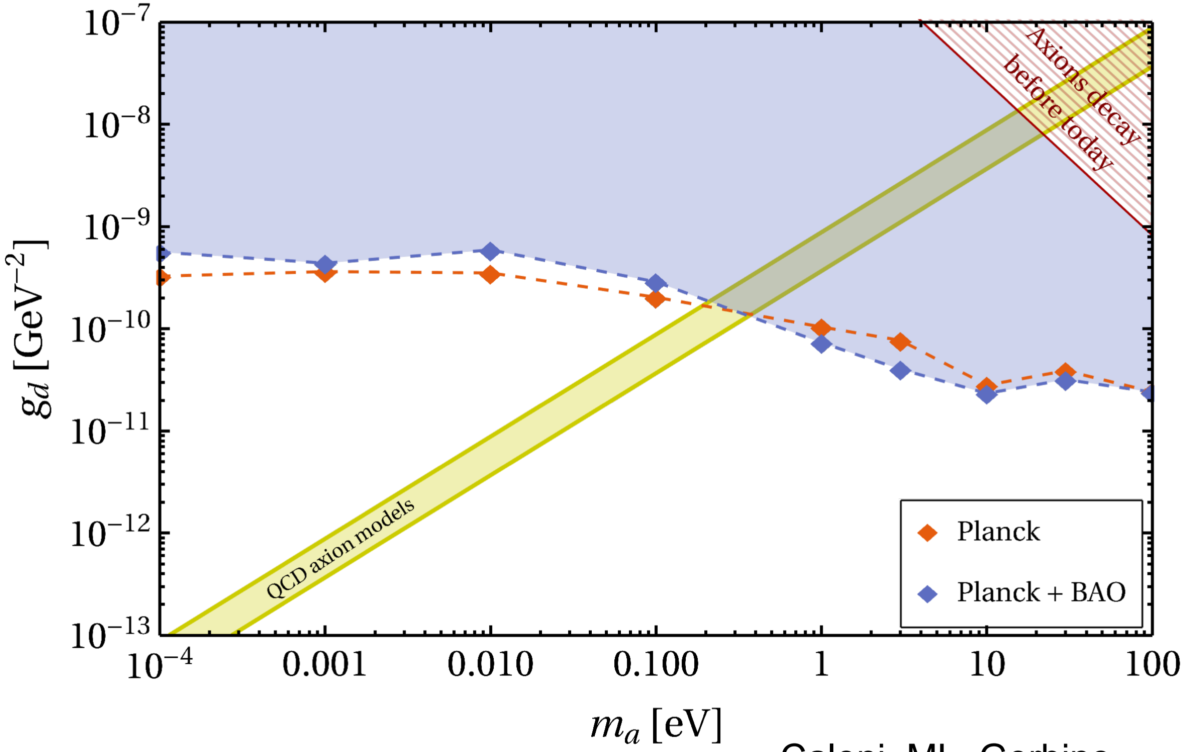


L. Caloni

Axions can be produced thermally in the early Universe through their coupling to photons or **gluons**

$$\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i}$$





Caloni, ML, Gerbino, Visinelli, 2022