PARTICLE AND ENERGY COMPOSITION OF THE UNIVERSE: NEUTRINOS, LIGHT RELICS AND DARK MATTER

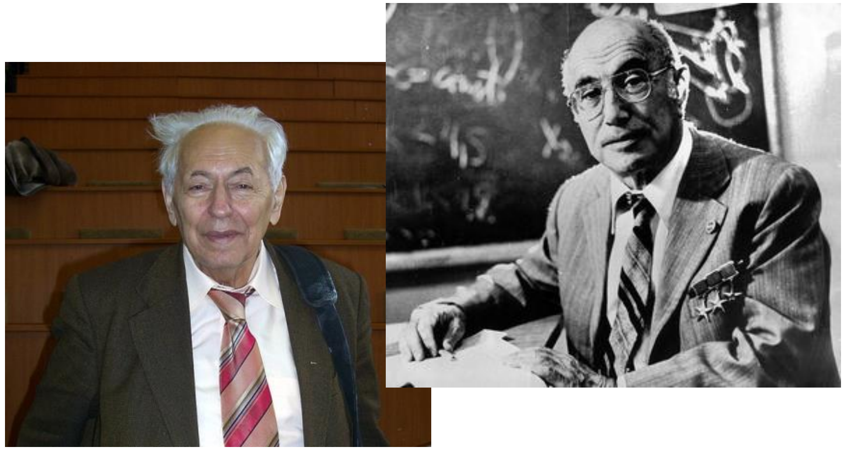
MASSIMILIANO LATTANZI

INFN, sezione di Ferrara

From Planck to the future of the CMB

Ferrara, May 24th, 2022

COSMOLOGY AND NEUTRINO MASSES



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

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

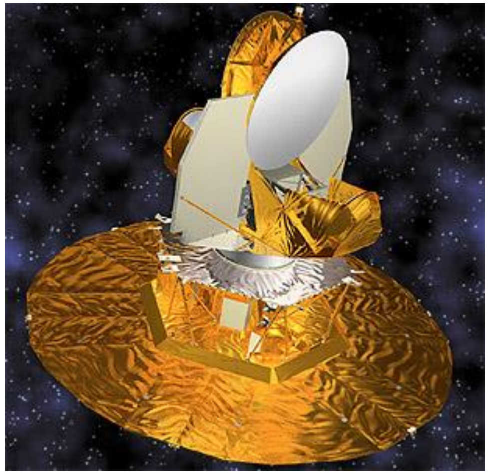
$$\sum m_\nu \equiv m_1 + m_2 + m_3$$

Fast forward to 2007:

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

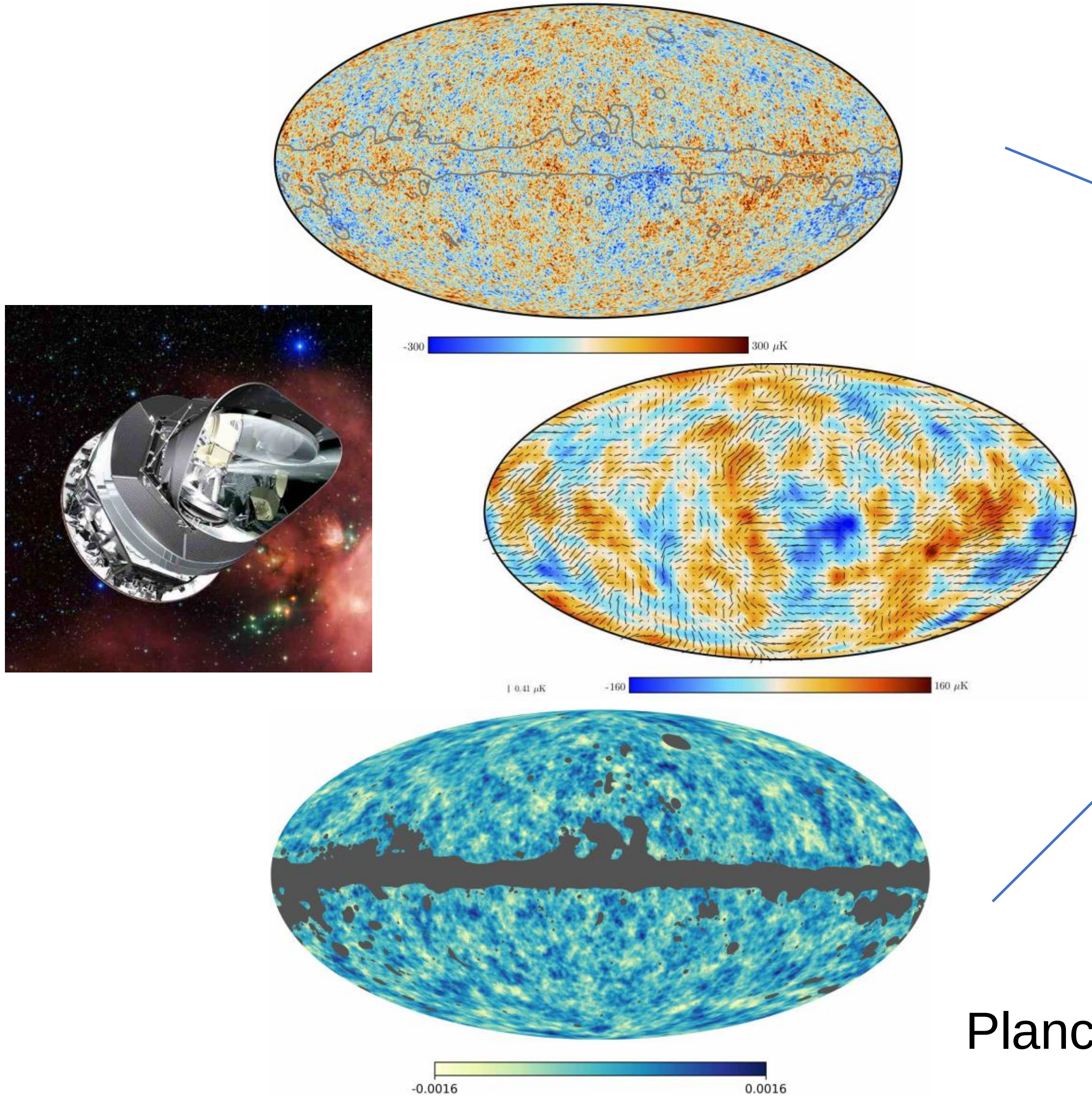
(many independent papers before that, using the 1yr data)

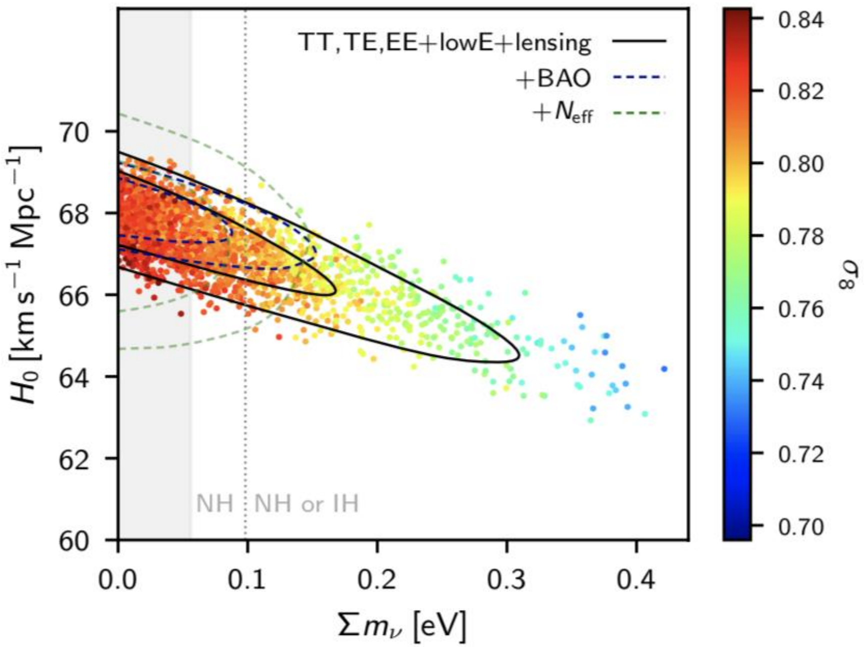
Saturates the hard limit from primary anisotropies (0.6 eV neutrino has m~3T at recombination)



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

Neutrino masses after Planck





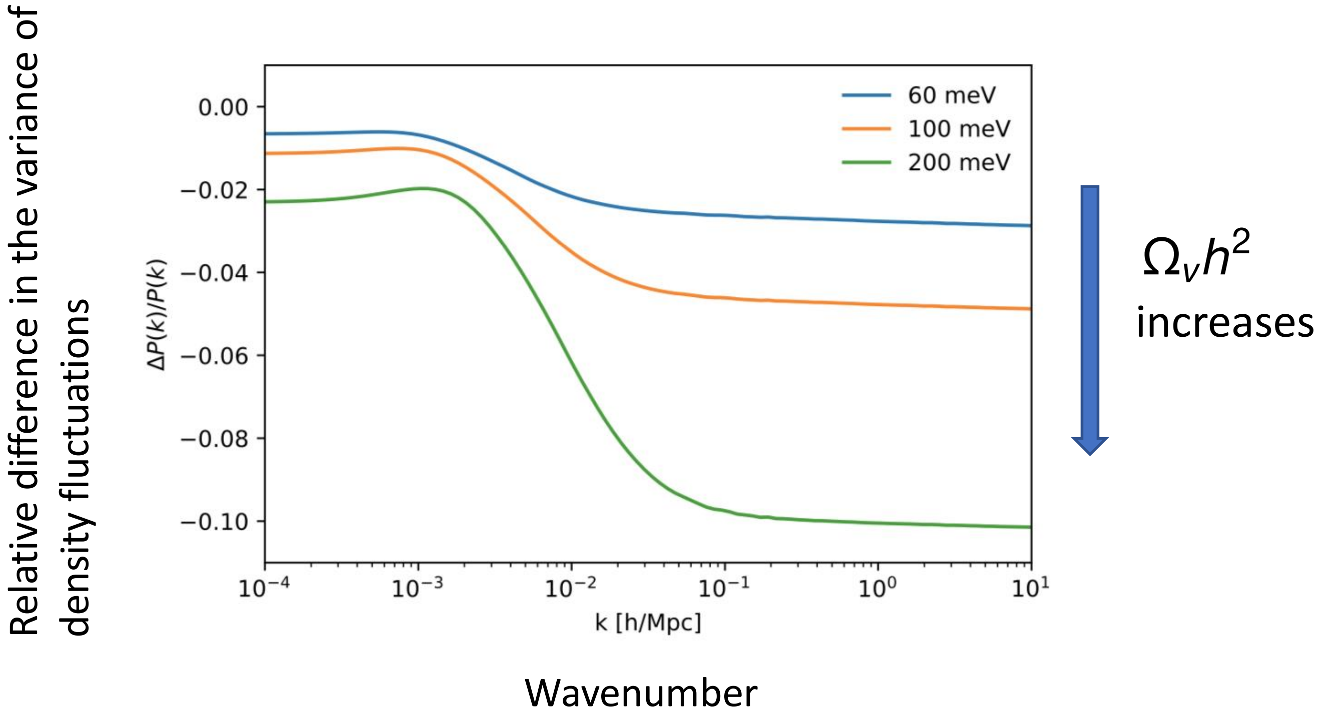
$$\sum m_\nu < 0.24\,\mathrm{eV}$$ (TTTEEE+lowE+lensing)

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

Planck 2018

NEUTRINOS AND STRUCTURE FORMATION

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



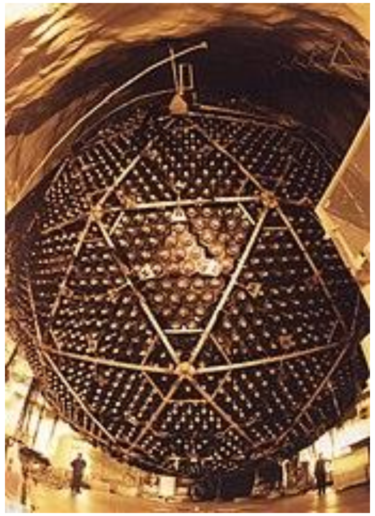
Probes of density fluctuations below the Jeans scale:

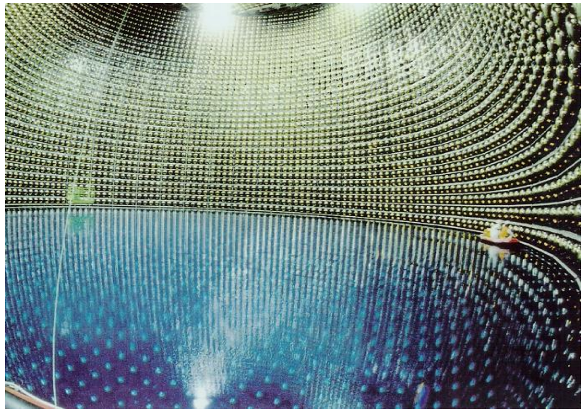
- Gravitational weak lensing of the CMB
- Clustering and weak lensing of galaxies
- Number density of galaxy clusters
- (+ their cross-correlation)

can be used to measure neutrino masses from cosmology.

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

NEUTRINO MASSES FROM THE LAB



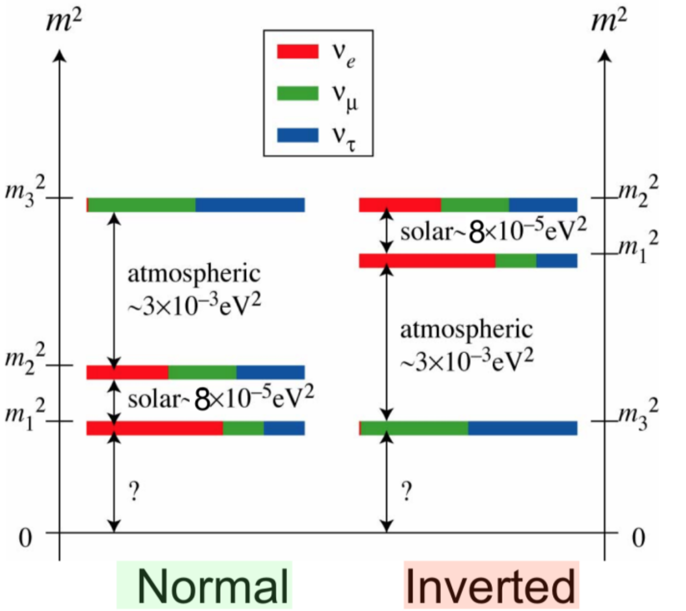


Evidence of neutrino oscillations from **Super-Kamiokande** (1998) and **SNO** (2001).

Neutrinos have a mass!

Nobel prize to Kajita & McDonald in 2015

$\sum m_\nu > 0.06\,\mathrm{eV}$ $\sum m_\nu > 0.10\,\mathrm{eV}$



Nowadays, oscillation parameters (including mass differences) are very well measured.

We still don't know:

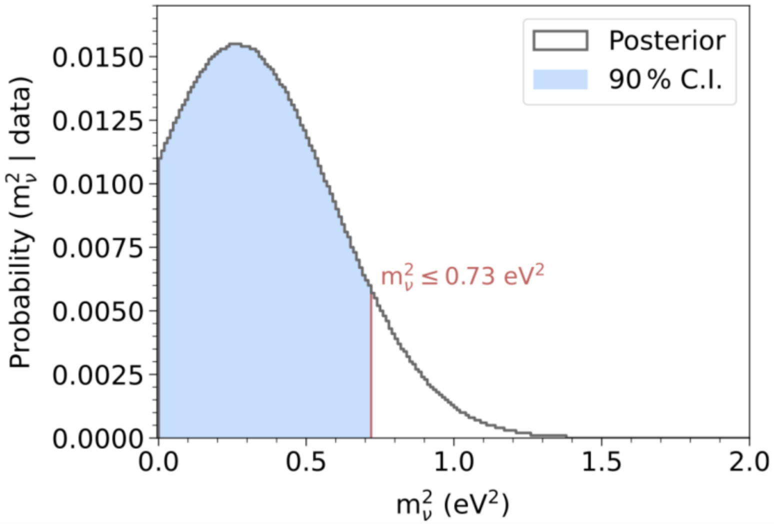
- absolute mass scale
- mass ordering
- Dirac of Majorana?

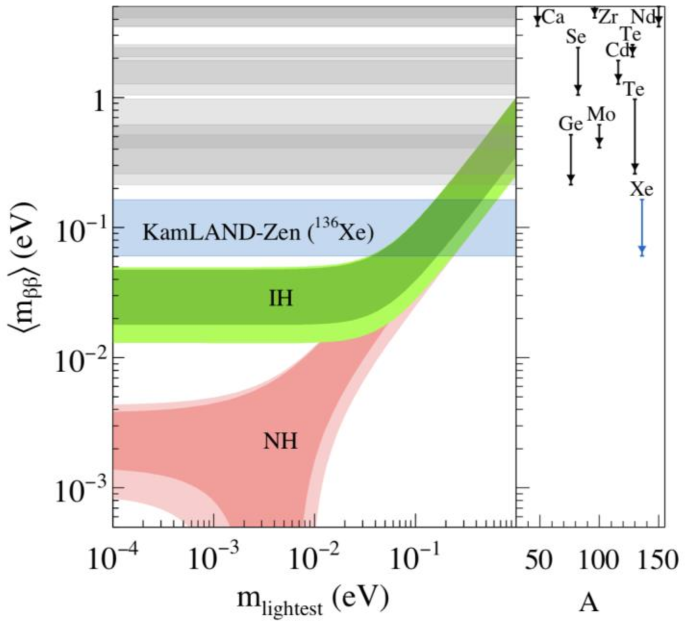
NEUTRINO MASSES FROM THE LAB

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

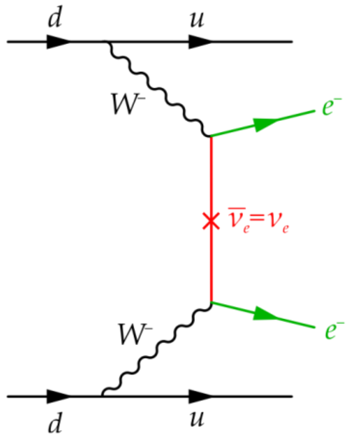




Neutrinoless double β decay (only applies to Majorana ν□s)

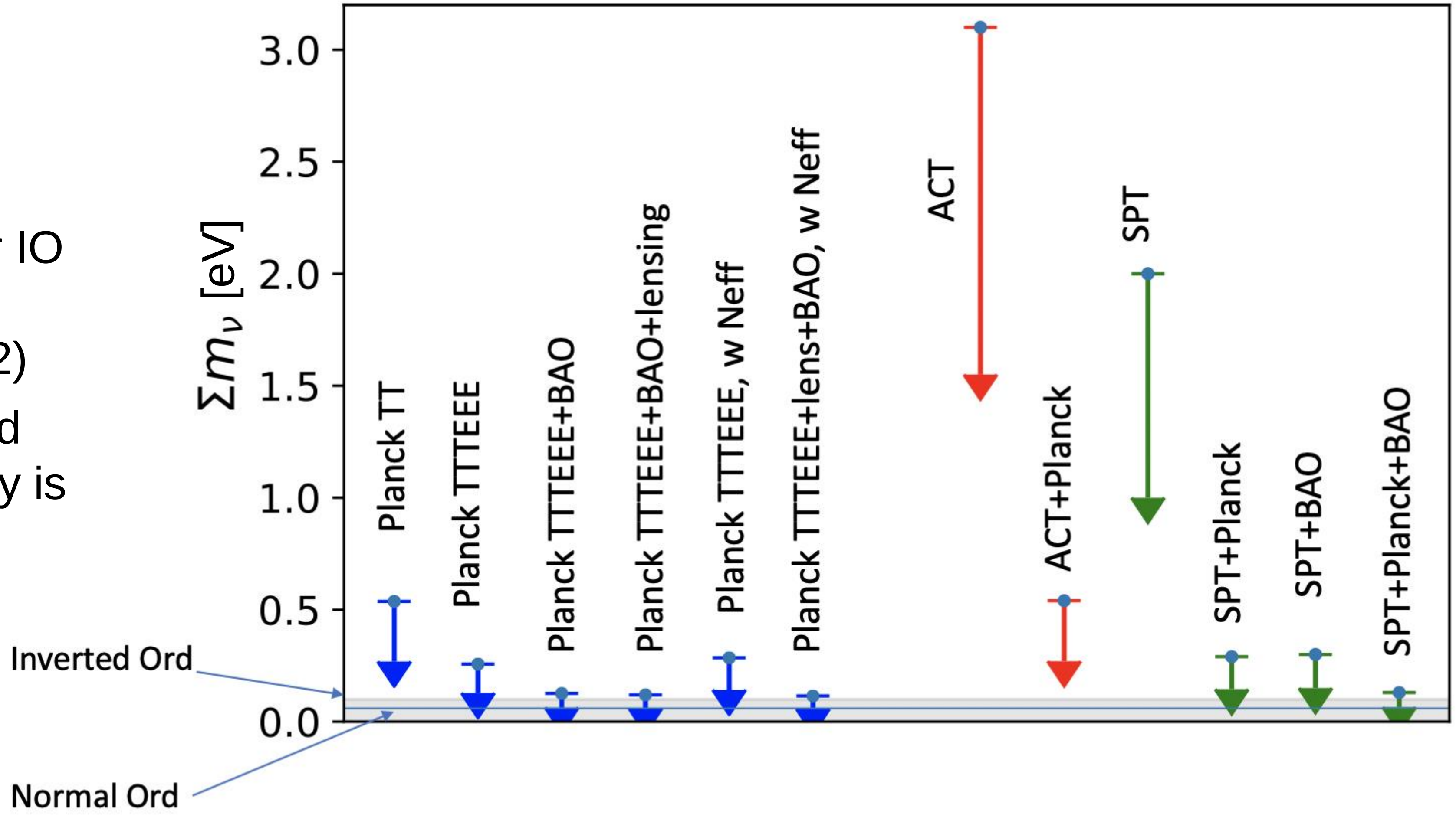
$m_{\beta\beta} < 0.061 - 0.165\,\mathrm{eV}\ (90\%\ \mathrm{CL})$

(KamLAND-Zen coll., 2016)



ν MASSES IN ΛCDM: PRESENT STATUS

- Conservative analysis yield moderate evidence (2.6σ) for IO from cosmo + oscillations (Gariazzo et al (incl ML) 2022)
- … **but:** so far I have assumed that the underlying cosmology is LCDM



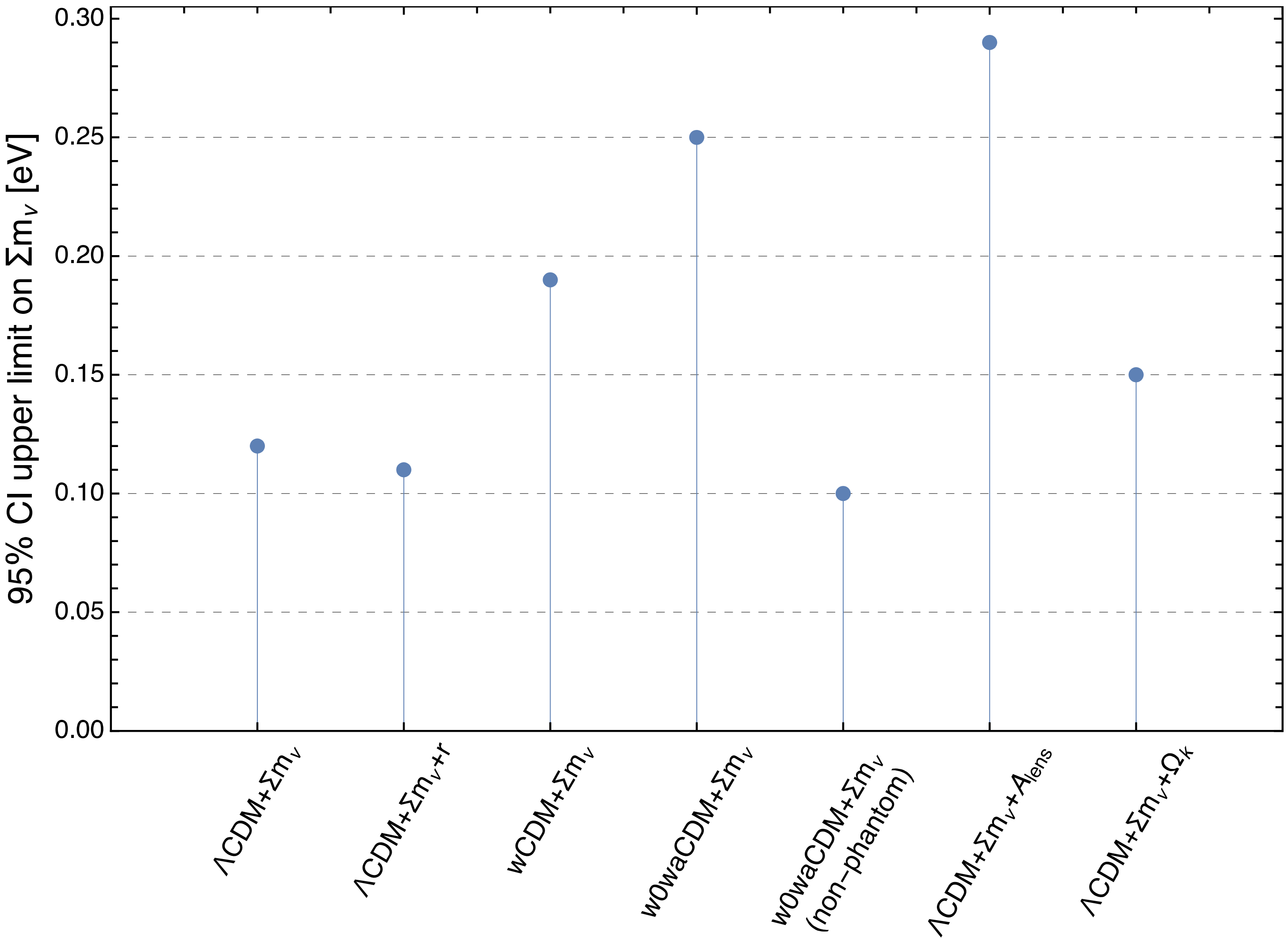
Credit: M. Gerbino

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)

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



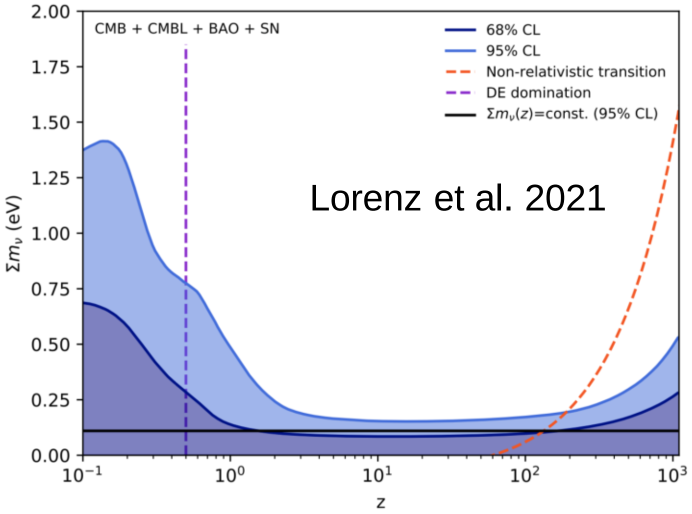
Plot based on the results of S. Roy Choudhury & S. Hannestad (2020) arXiv 1907.12598

ν MASSES IN ΛCDM EXTENSIONS

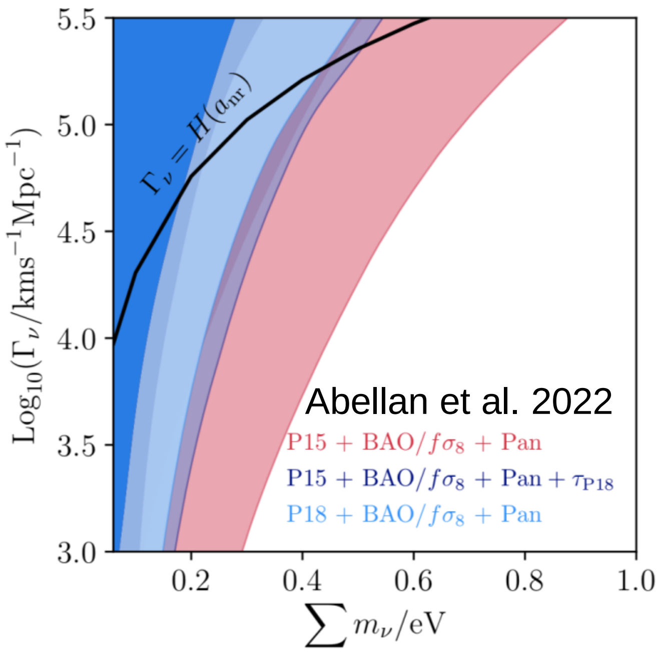
Constraints can be further loosened in alternative models, e.g.

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

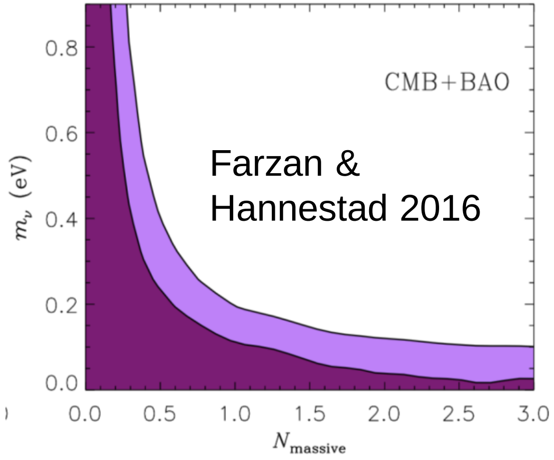
In some cases, this would reopen the window for a detection in KATRIN



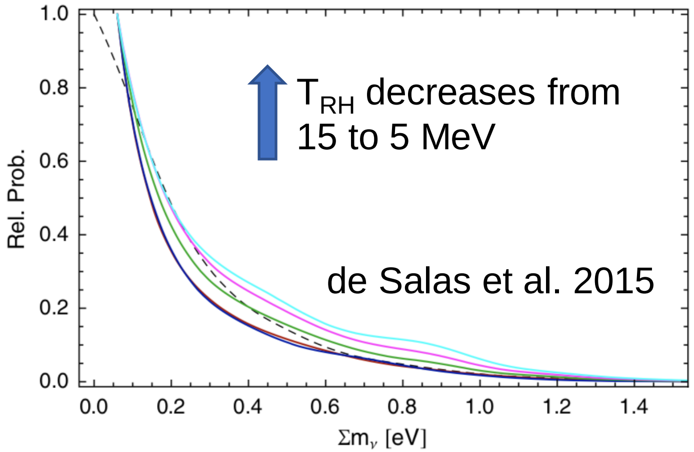
Lorenz et al. 2021



Abellan et al. 2022



Farzan & Hannestad 2016



T_{RH} decreases from 15 to 5 MeV

de Salas et al. 2015

FUTURE PROSPECTS

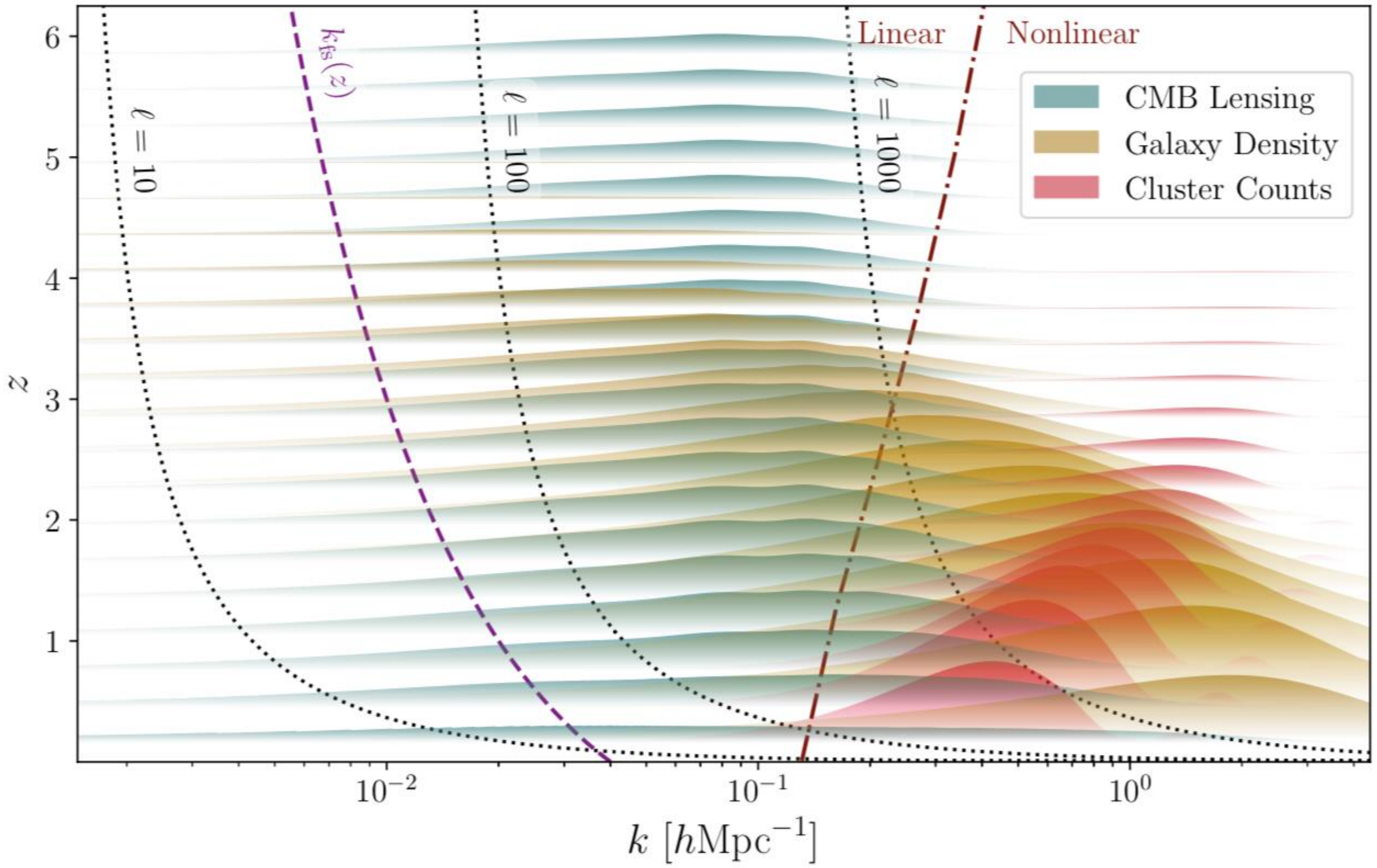
To increase sensitivity to neutrino masses AND reduce model dependency, we need:

- 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

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)

FORECASTS FOR FUTURE CMB+LSS

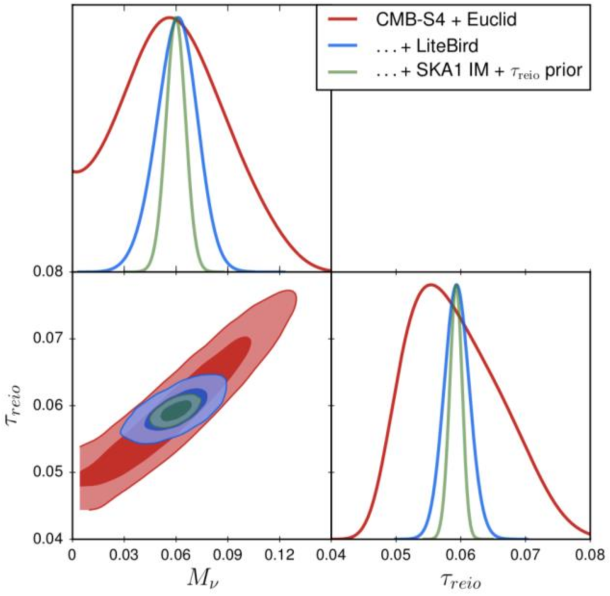
$\sigma(\Sigma m_\nu) = 0.04$ eV from SO (primary+lensing)
+ DESI BAO
(SO Collaboration 2018)

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

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

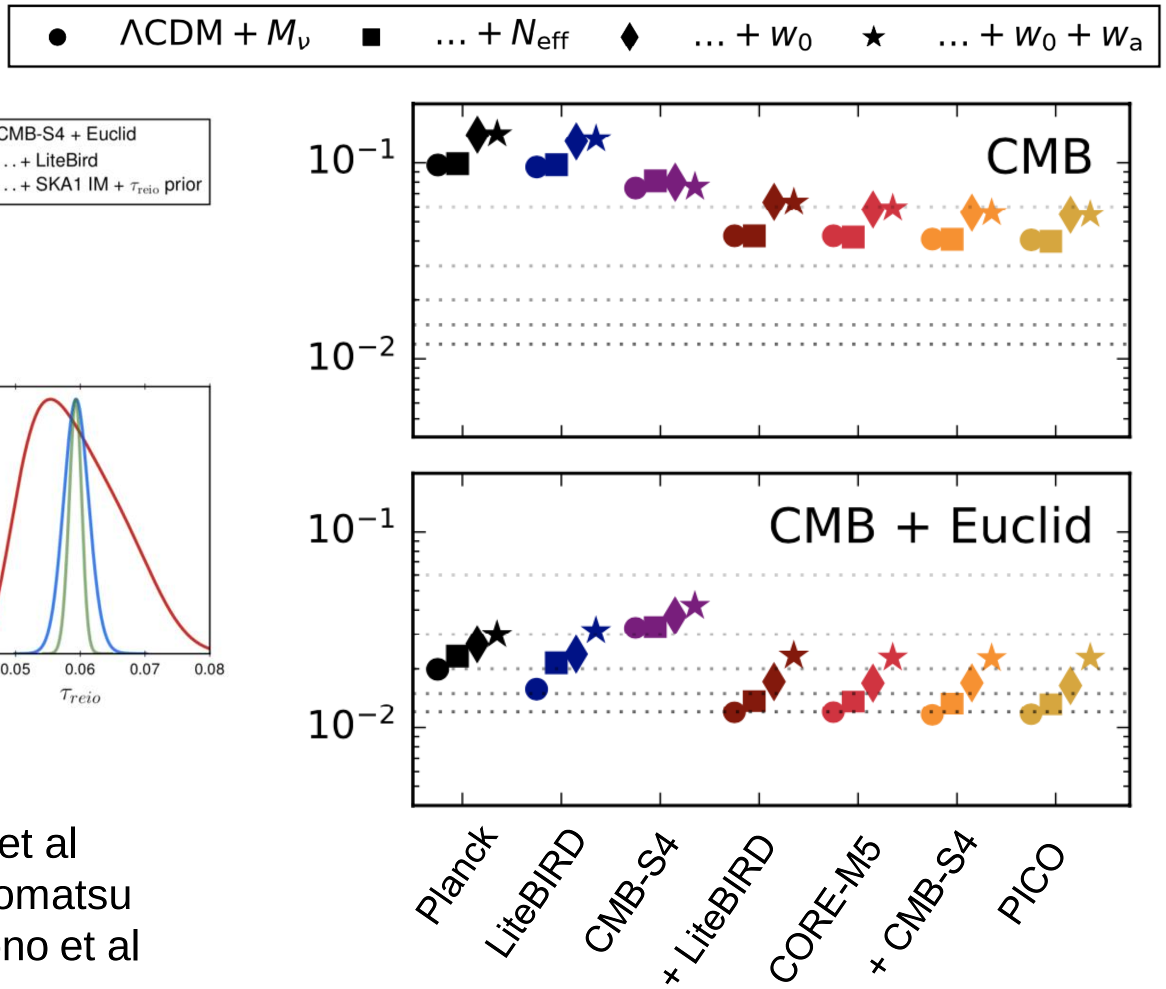
CMB+LSS will provide a statistically significant detection of neutrino masses in ΛCDM (remember $\Sigma m_\nu > 0.06$ eV).

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

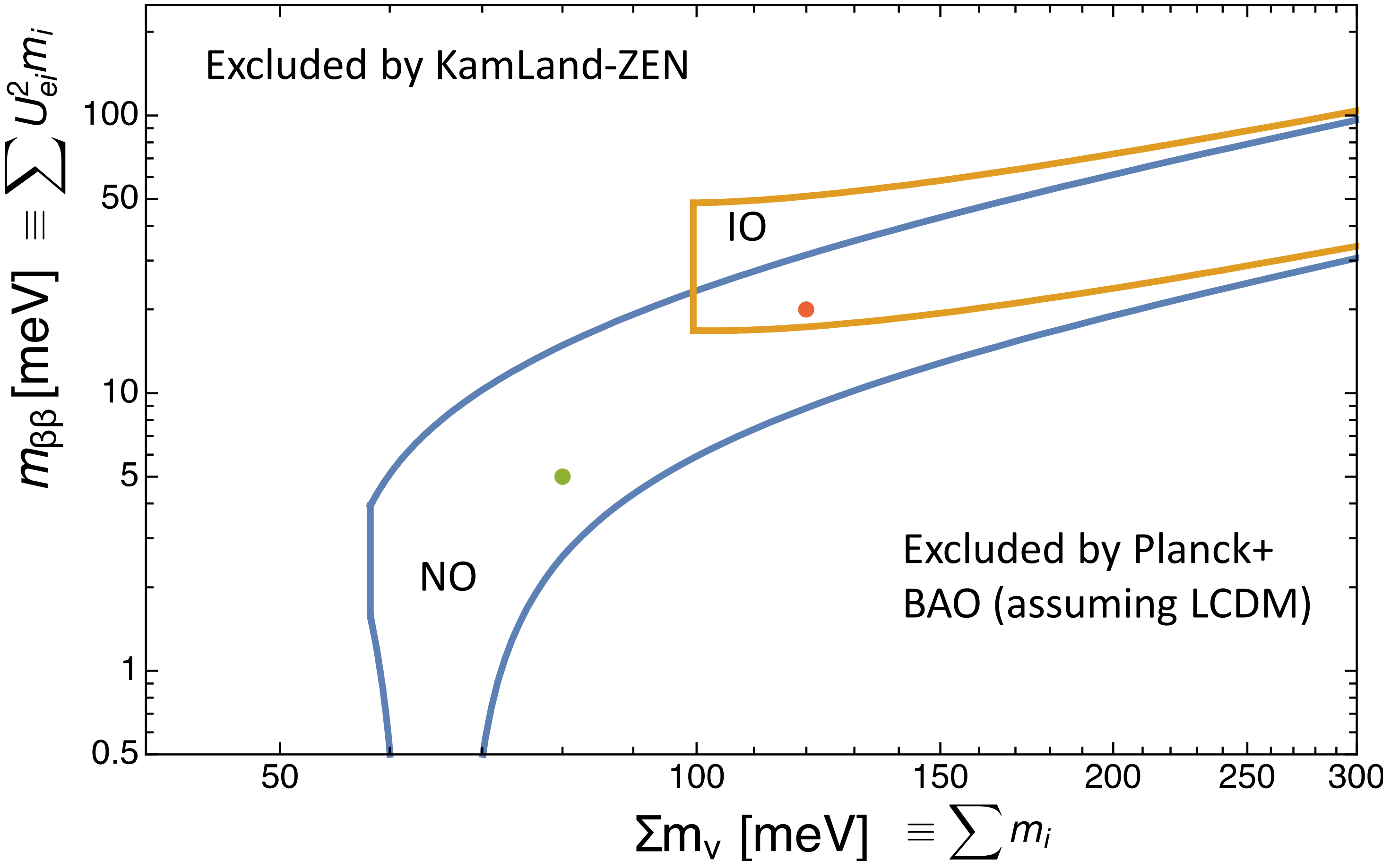


See also Allison et al 2015; Boyle & Komatsu 2018; Archidiacono et al 2017.

Brinckmann, Hooper,+, JCAP 2019



SINERGY BETWEEN COSMO AND LAB



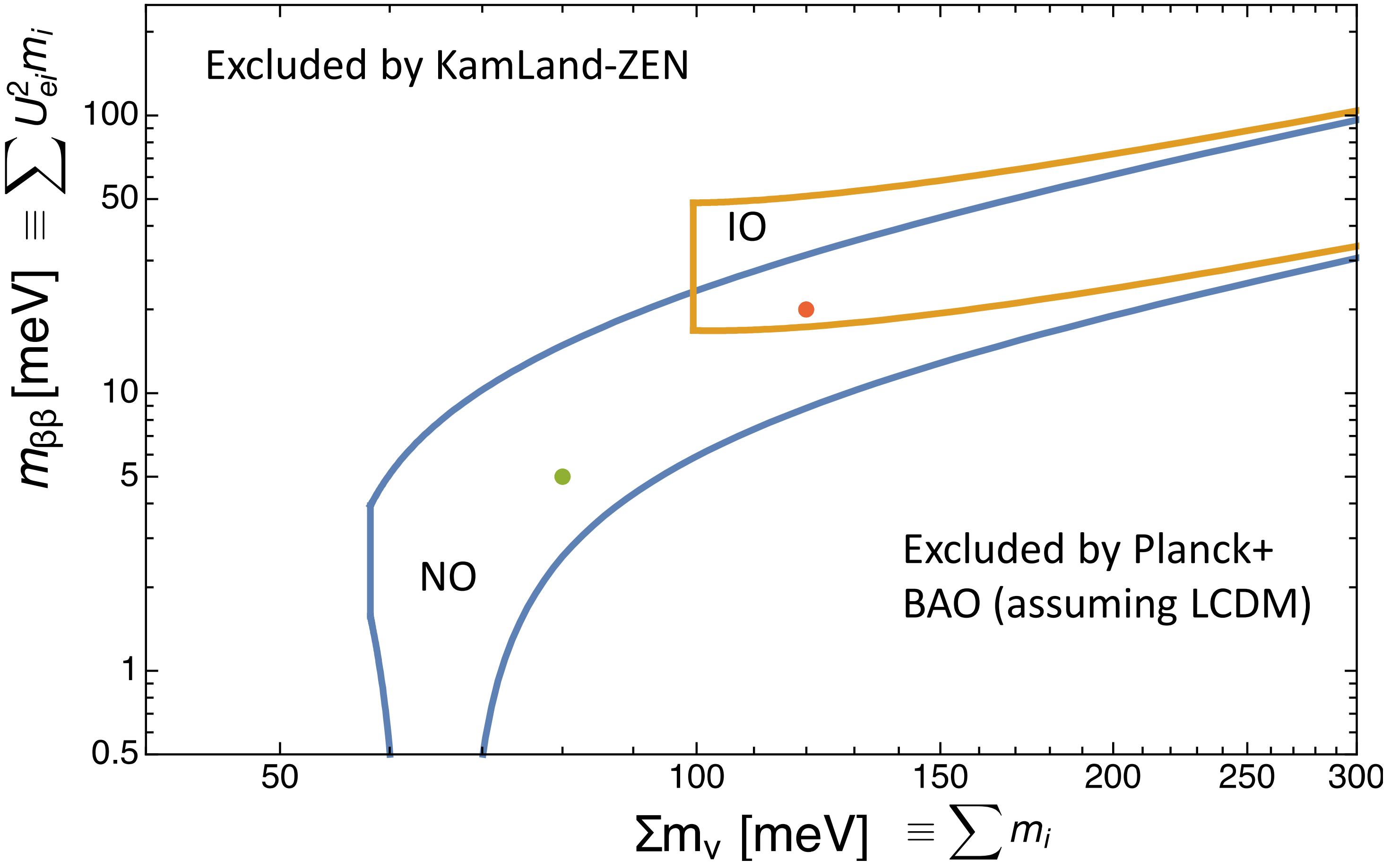
Gerbino et al., arXiv 2203.07377

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 experiments.

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

SINERGY BETWEEN COSMO AND LAB



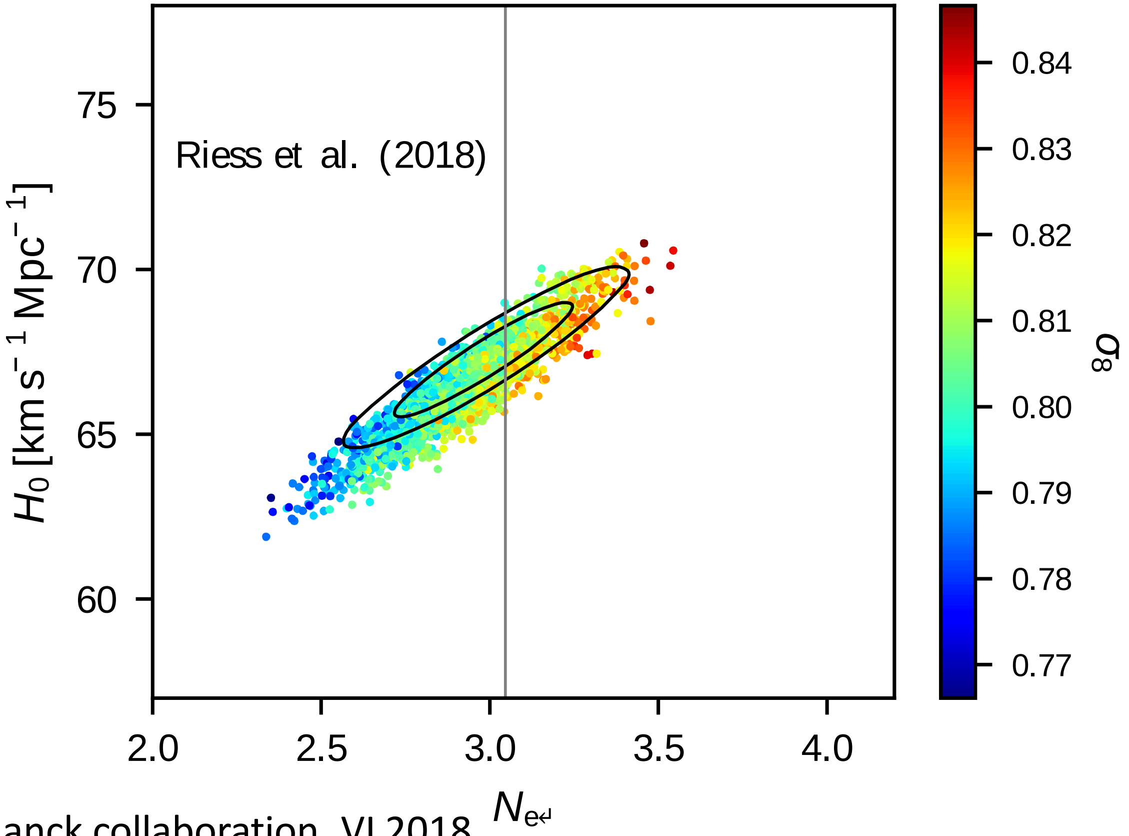
Gerbino et al., arXiv 2203.07377

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

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

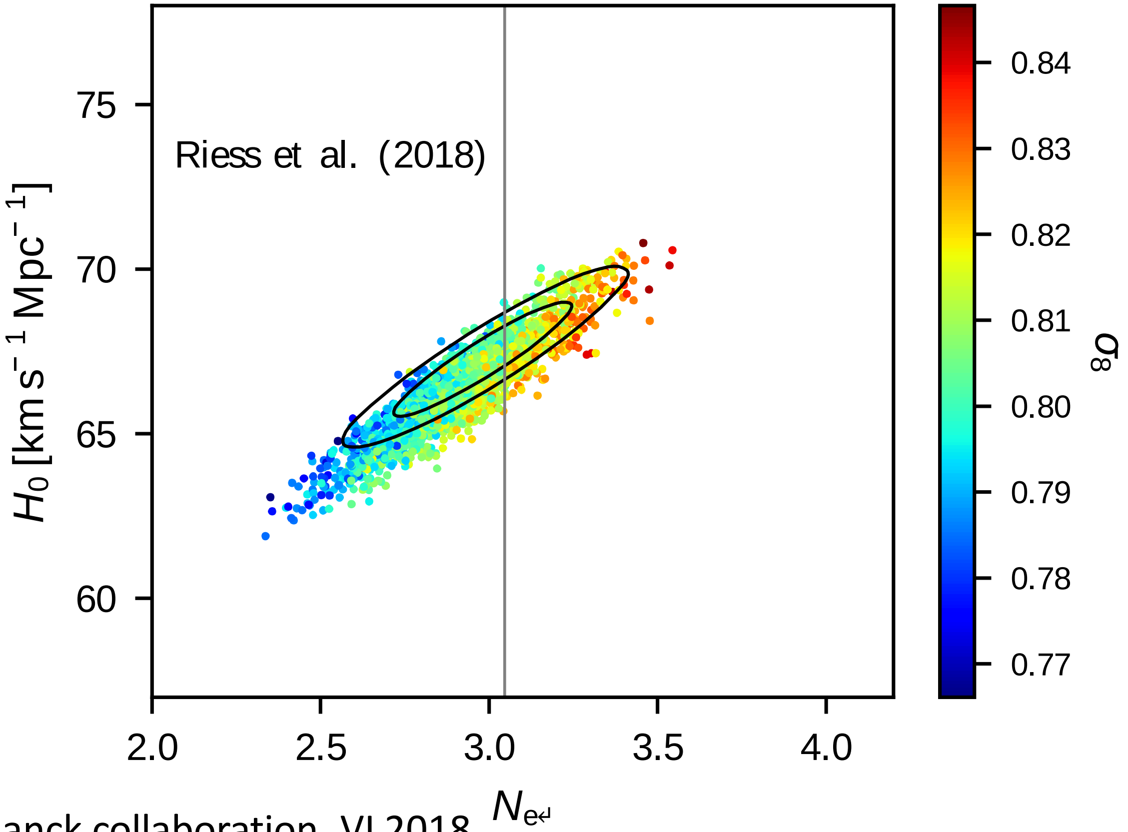
In agreement with the theoretical expectation

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

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

EFFECTIVE NUMBER OF RELATIVISTIC SPECIES

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



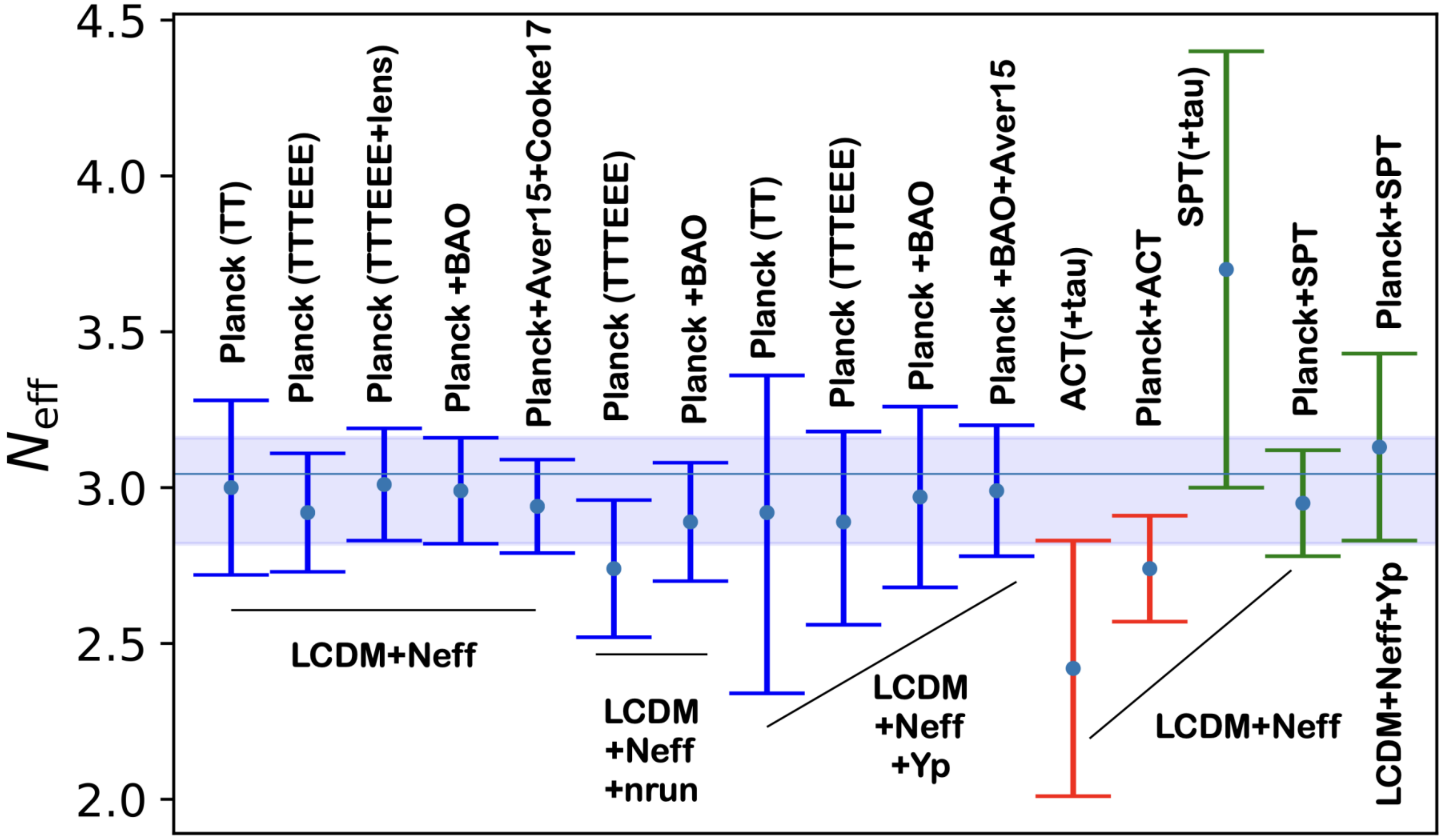
Planck collaboration, VI 2018

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

CURRENT LIMITS ON NEFF (68% CL)

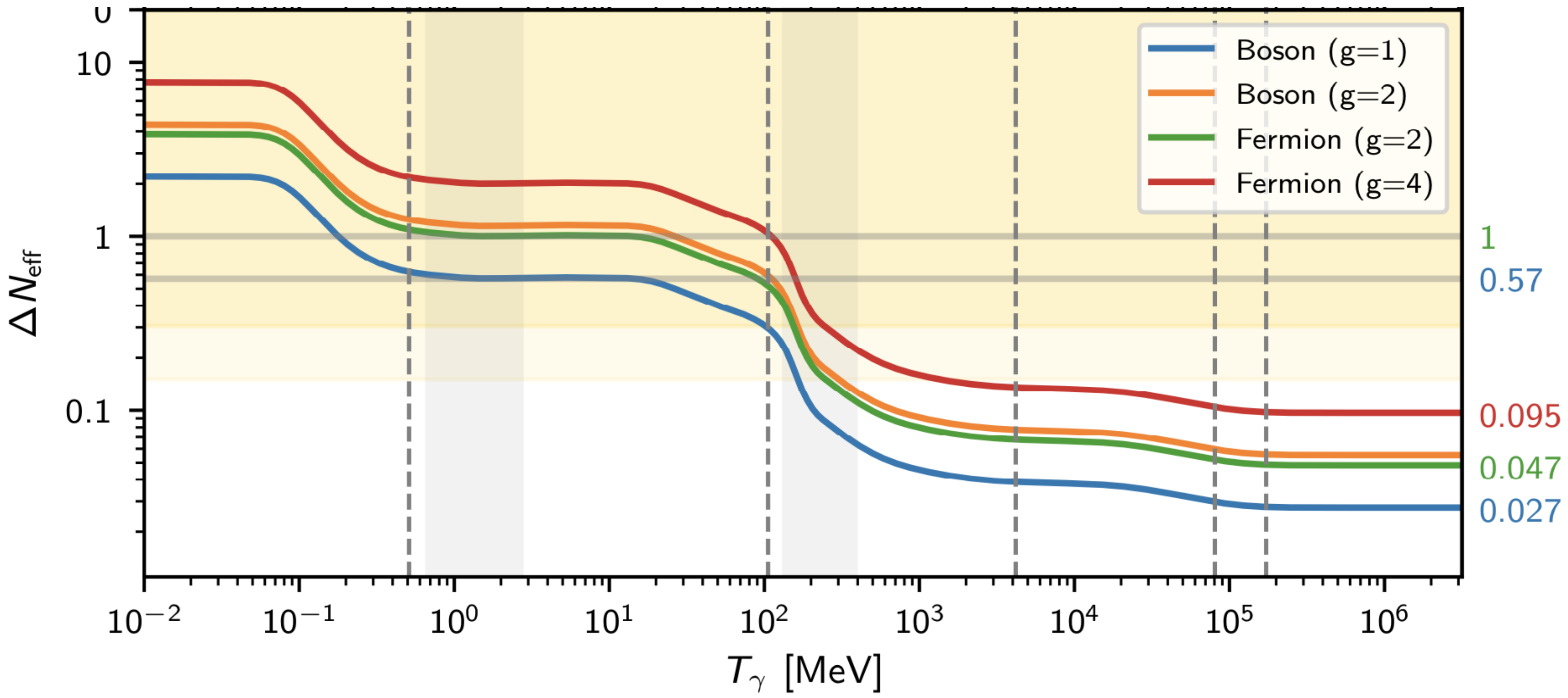


Planck collaboration, VI 2018
ACT Collaboration (Aiola+), 2020
SPT Collaboration (Dutcher+, Balkenhol+), 2021

Credit: M. Gerbino

N_{EFF} AND THE DECOUPLING OF SPECIES

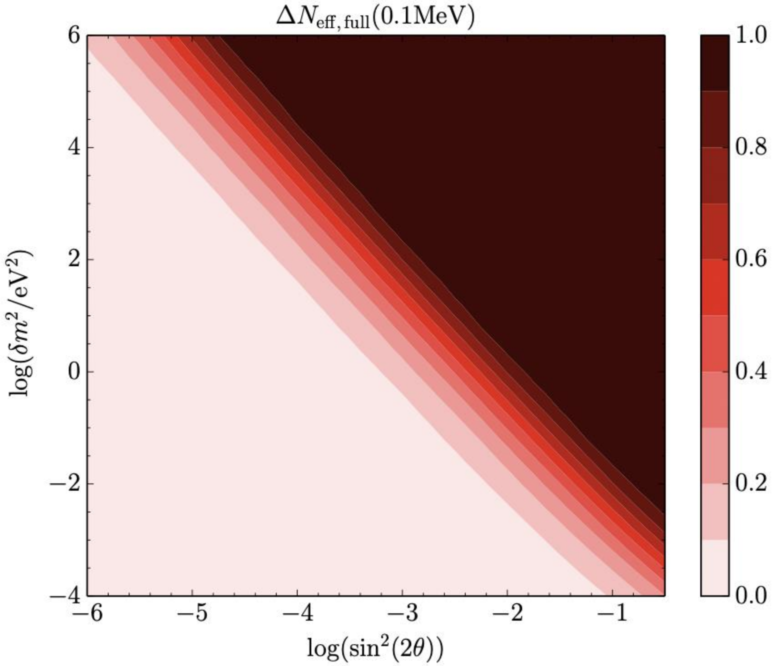
For a species that was in thermal equilibrium in the early Universe, $\Delta N_{\rm eff}$ is directly related to the decoupling temperature:



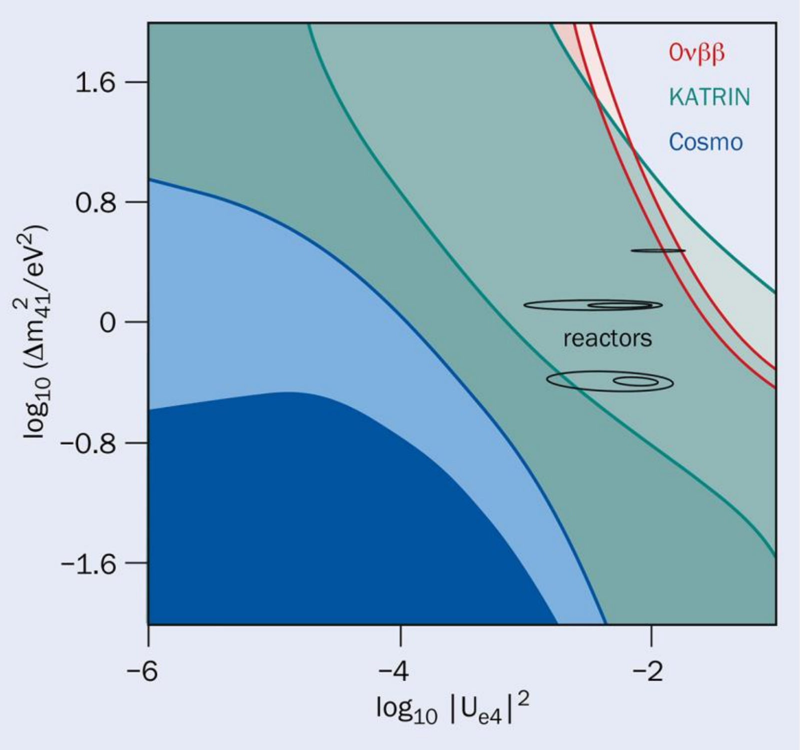
Planck collaboration, VI 2018

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



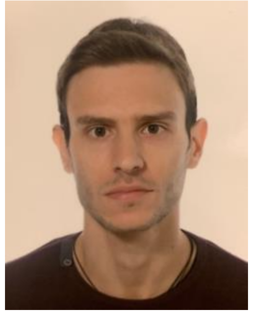
S. Hagstotz

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

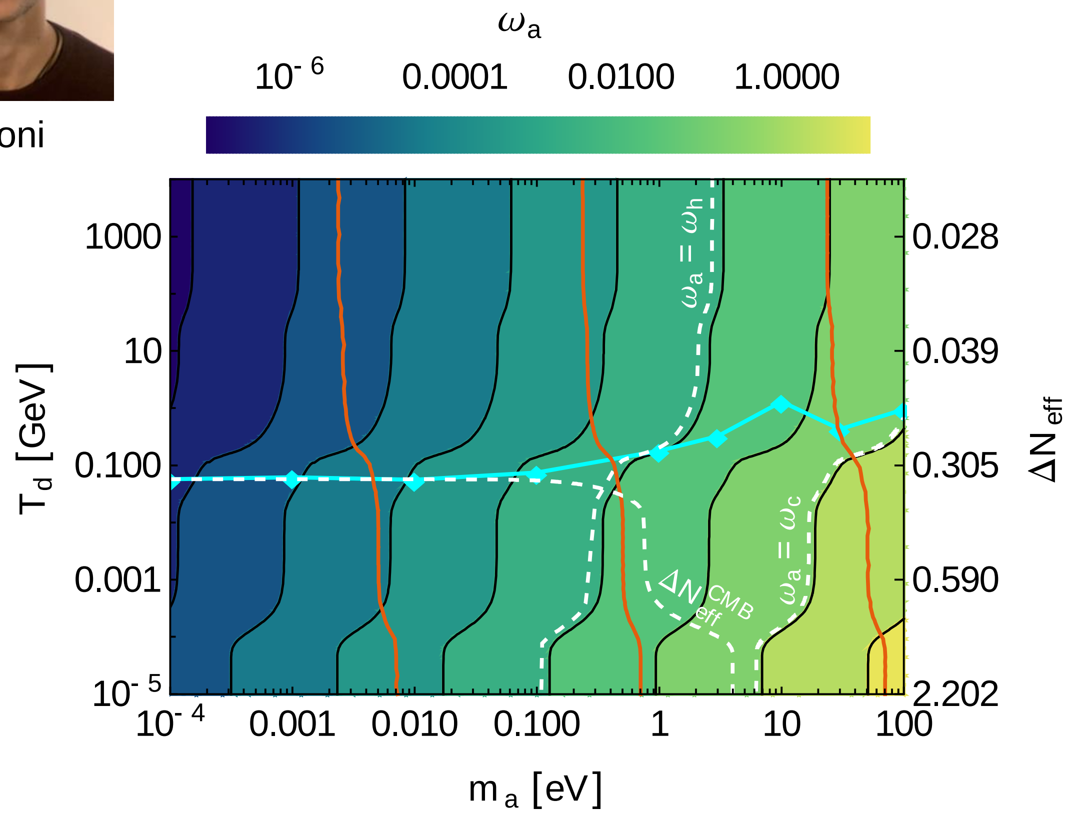
N_{EFF} AND THERMAL AXIONS

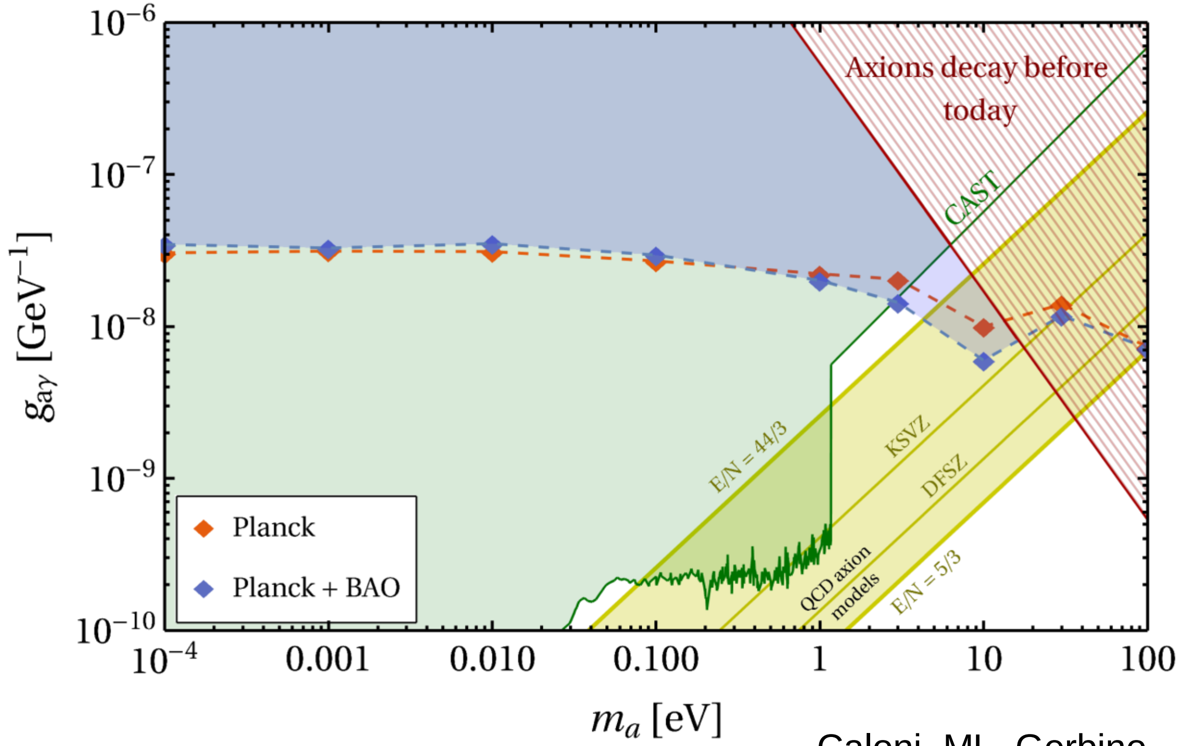


L. Caloni

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

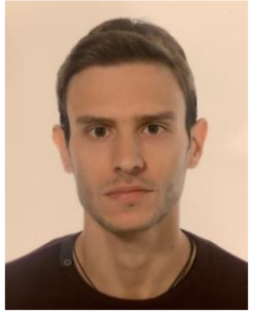
$$\mathcal{L}_{a\gamma} = \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$





Caloni, ML, Gerbino, Visinelli, 2022

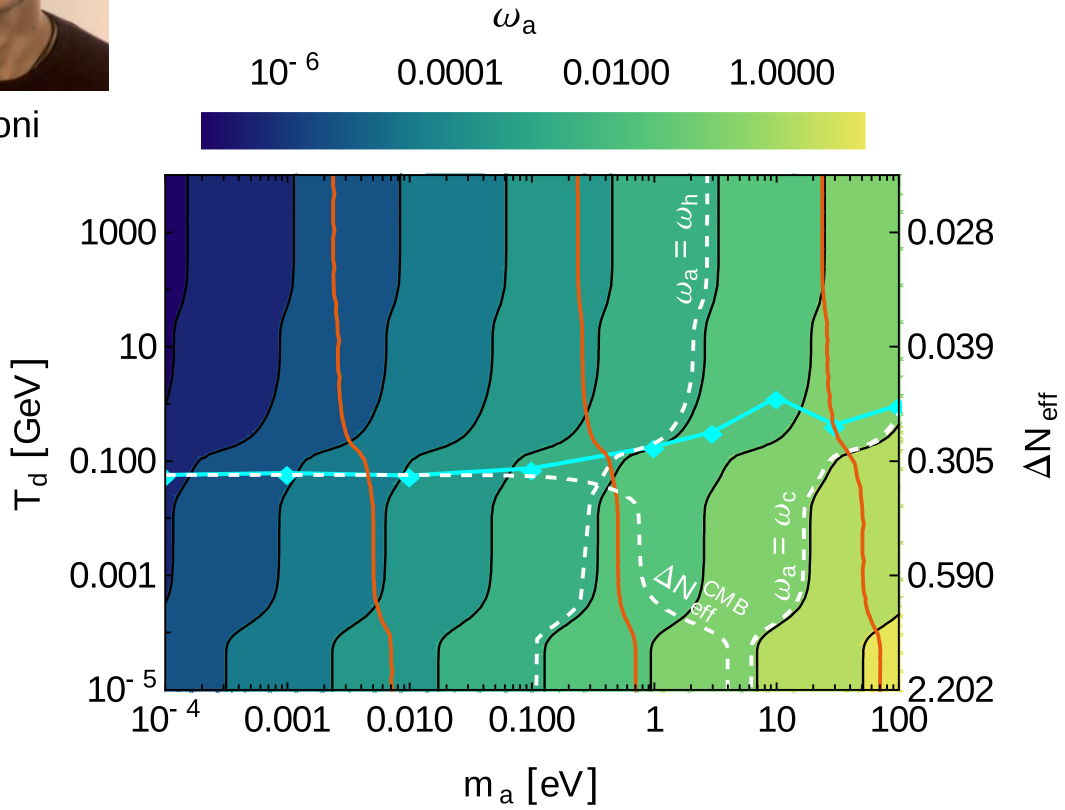
N_{EFF} AND THERMAL AXIONS

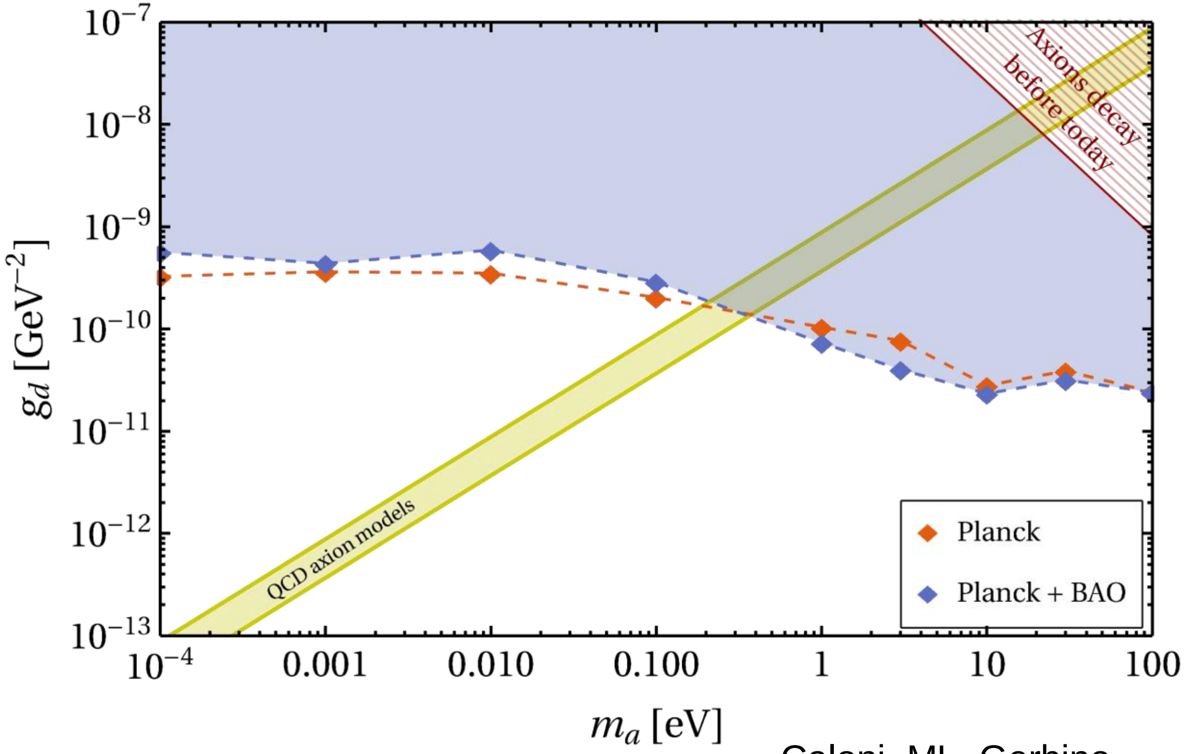


L. Caloni

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

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



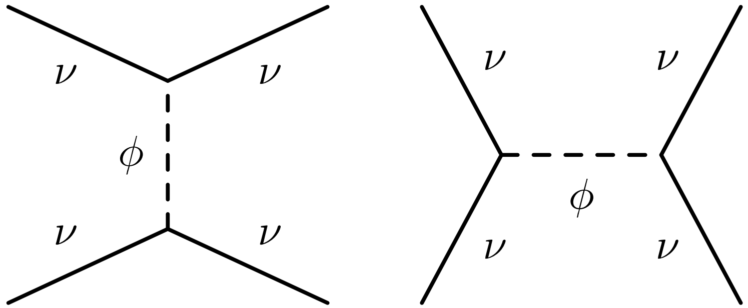


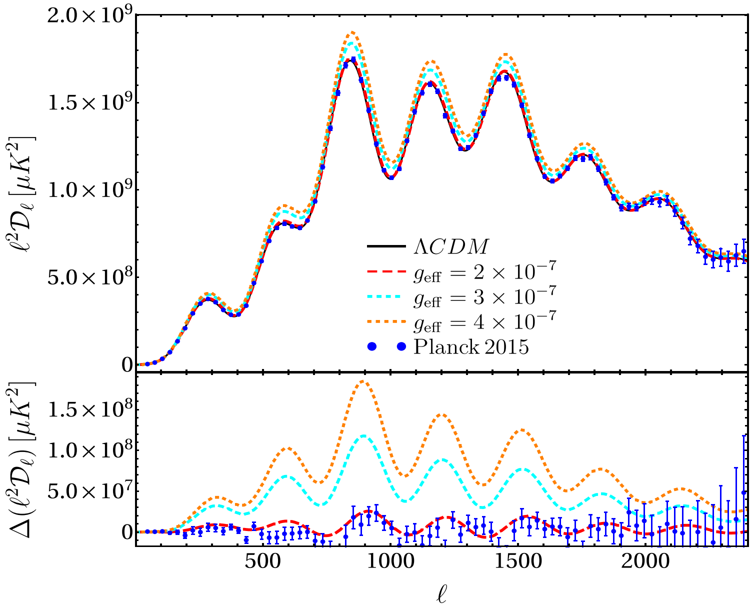
Caloni, ML, Gerbino, Visinelli, 2022

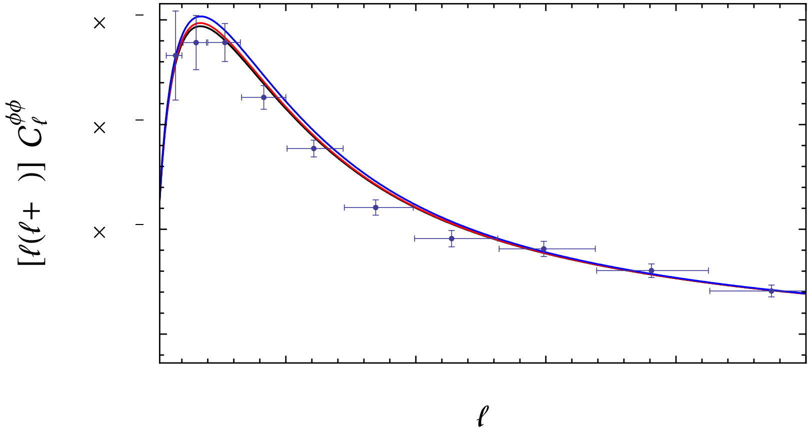
ν NONSTANDARD INTERACTIONS

CMB is also sensitive to the collisional properties of light relics (Bashinsky & Seljak 2004)
E.g. in models of neutrino nonstandard interactions:

$$\mathcal{L}_{\rm int} = \frac{i}{2} g\phi\bar{\nu}_i\gamma^5\nu_i$$



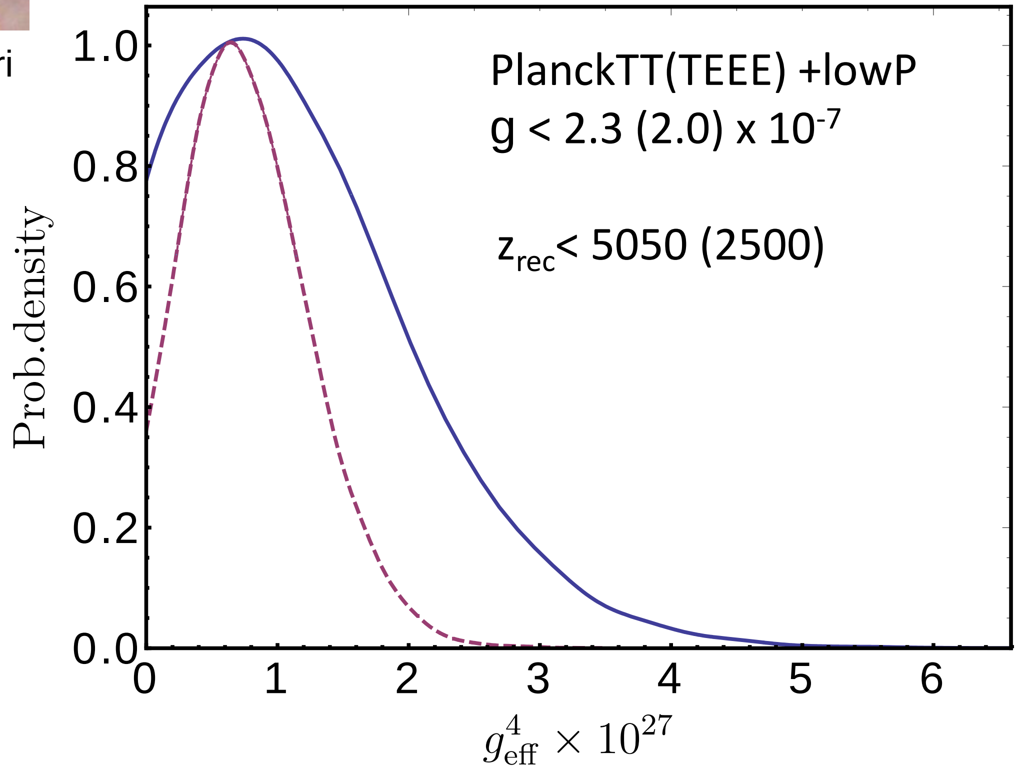




ν NONSTANDARD INTERACTIONS

Forastieri, ML, Natoli, PRD 2019

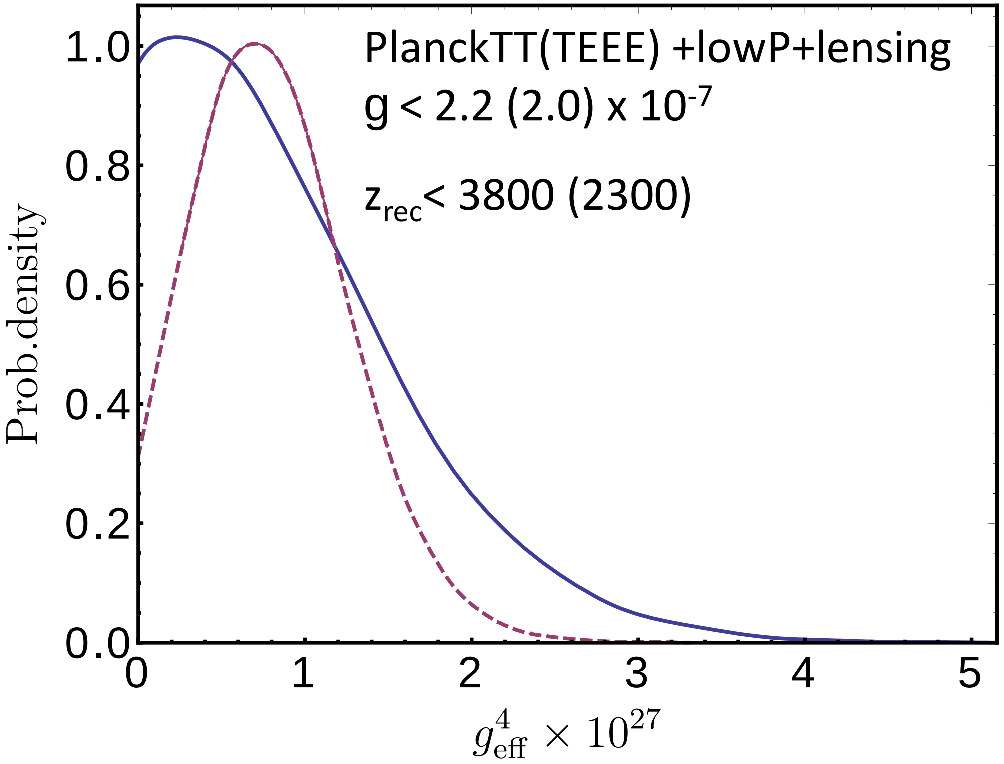
F. Forastieri



PlanckTT(TEEE) +lowP

g < 2.3 (2.0) x 10^{-7}

z_{rec}< 5050 (2500)

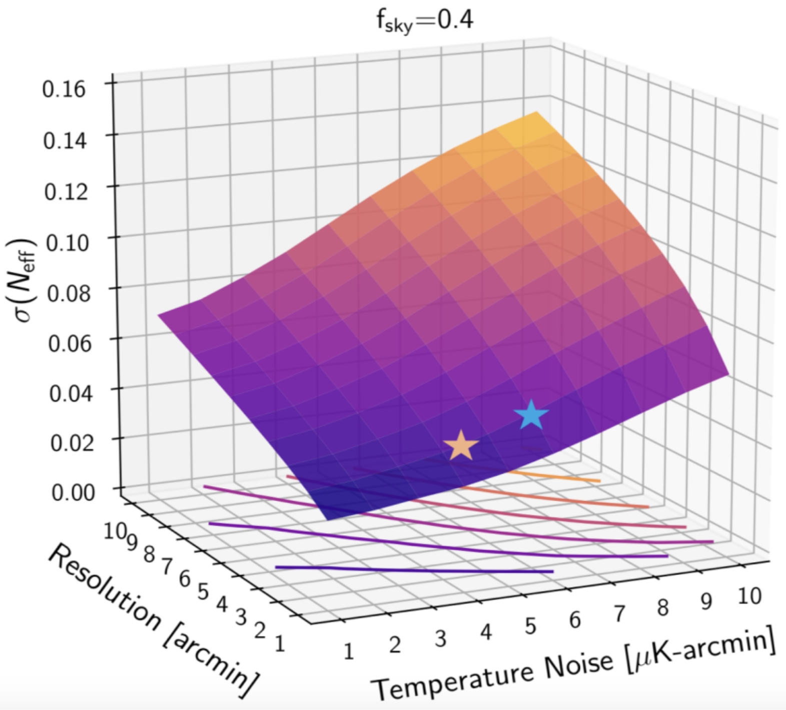


PlanckTT(TEEE) +lowP+lensing

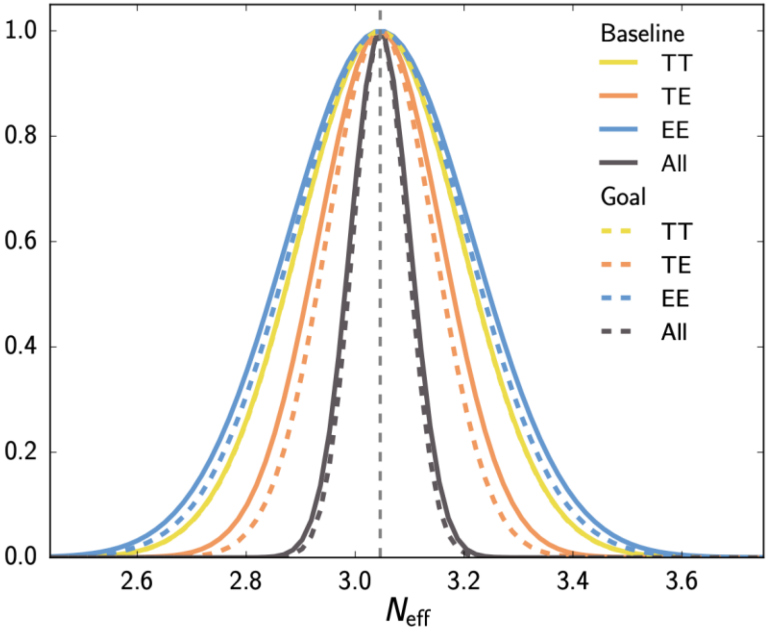
g < 2.2 (2.0) x 10^{-7}

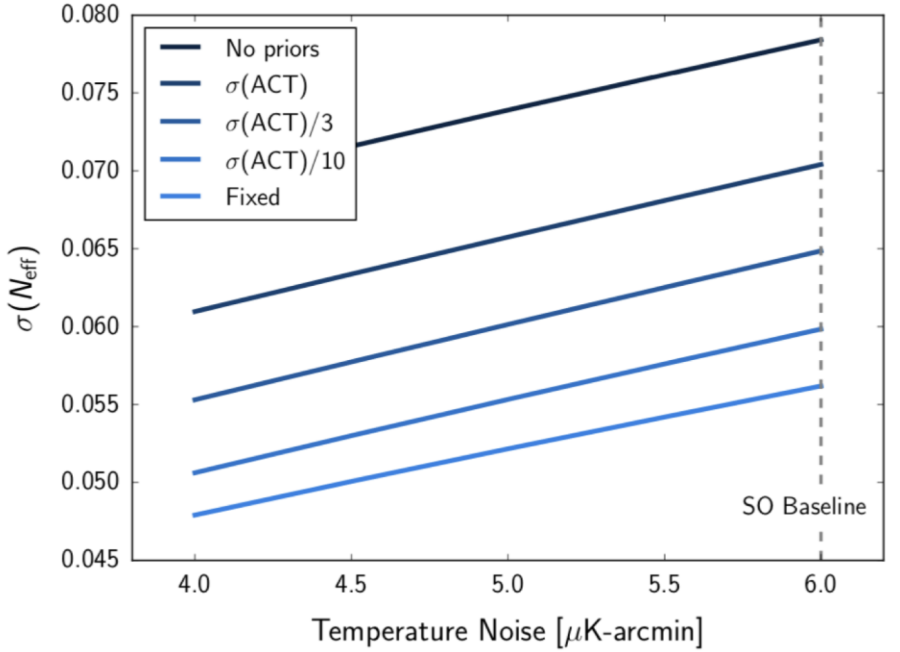
z_{rec}< 3800 (2300)

N_{EFF} FROM SO



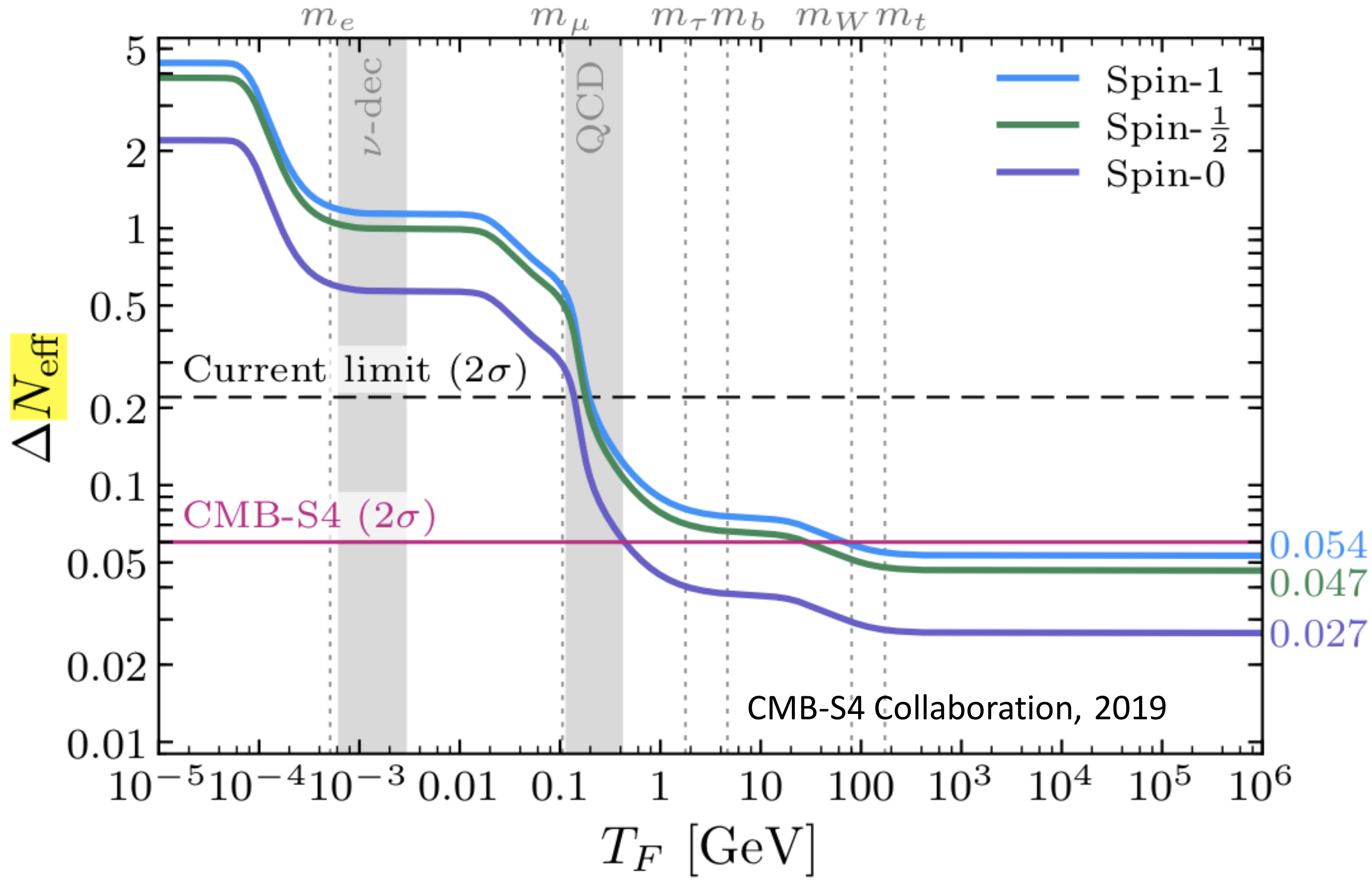
SO collaboration, 2018



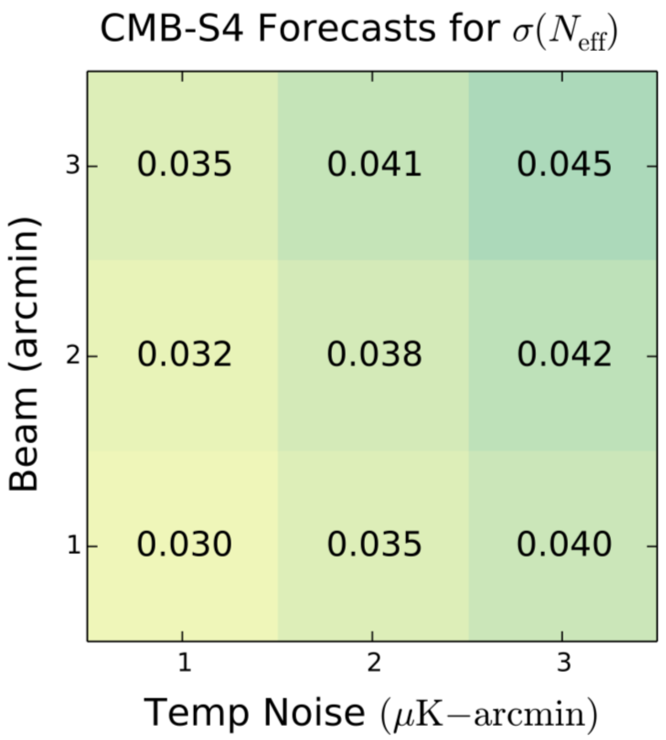


$$\boxed{\sigma(N_{\rm eff}) = 0.07\ [0.05]}$$

$N_{\rm EFF}$ FROM CMB-S4



CMB-S4 Collaboration, 2019


CMB-S4 Forecasts for $\sigma(N_{\rm eff})$

Beam (arcmin) \ Temp Noise (μK$-$arcmin)	1	2	3
3	0.035	0.041	0.045
2	0.032	0.038	0.042
1	0.030	0.035	0.040

CMB-S4 Science Book

DARK MATTER

Observations of CMB anisotropies provide a precise determination of the dark matter density

$$\Omega_c h^2 = 0.1200 \pm 0.0012$$

PlanckTTTEEE + lowE
+ lensing

This measurement already puts constraints on possible models.

However we are still far from characterizing the DM properties, and in particular its (nongravitational) interactions.

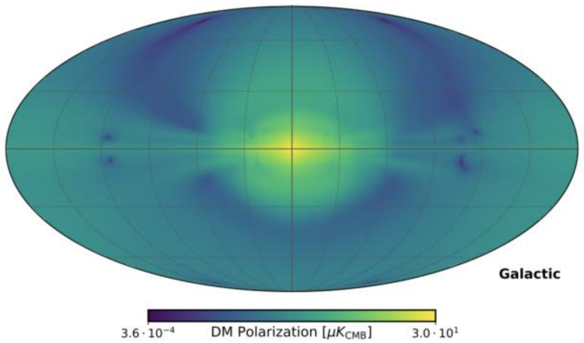
Open questions:

- is DM a single species?
- is it cold/warm?
- is it stable?
- how does it interact with the SM?

DM DECAYS AND ANNIHILATIONS

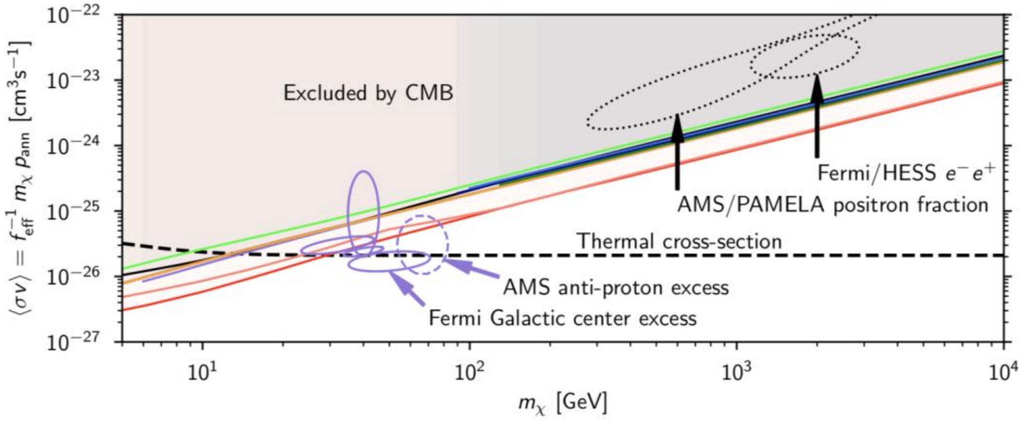
Dark matter decays and/or annihilations can inject energy at different times in the cosmic history

- Prerecombination (CMB spectral distortions)
- ~ recombination (CMB anisotropies)
- ~ dark ages (21cm)
- ~ reionization (CMB anisotropies)
- ~ now in our local environment (observations of the radio sky)



Synchrotron emission at 30 GHz due to DM annihilation to e+e- (Manconi et al. arXiv 2204.04232)

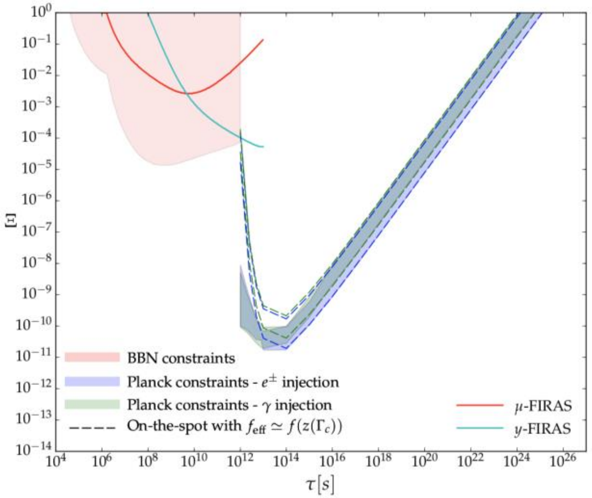
Annihilation cross-section



DM mass

Planck 2018 VI

Efficiency of energy injection

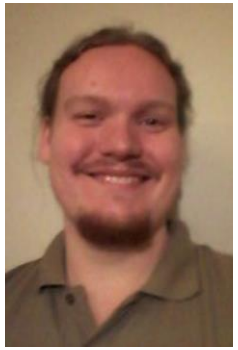


DM lifetime

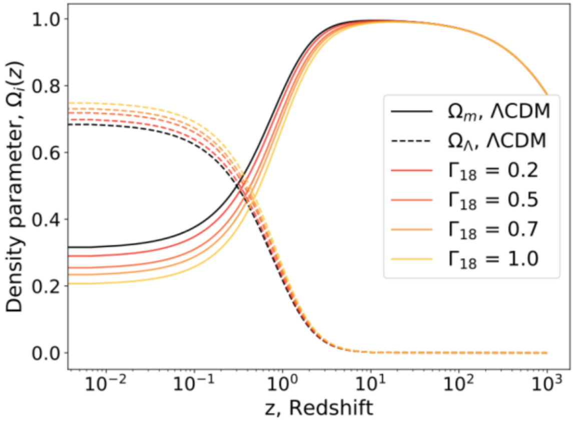
Poulin et al. 2017

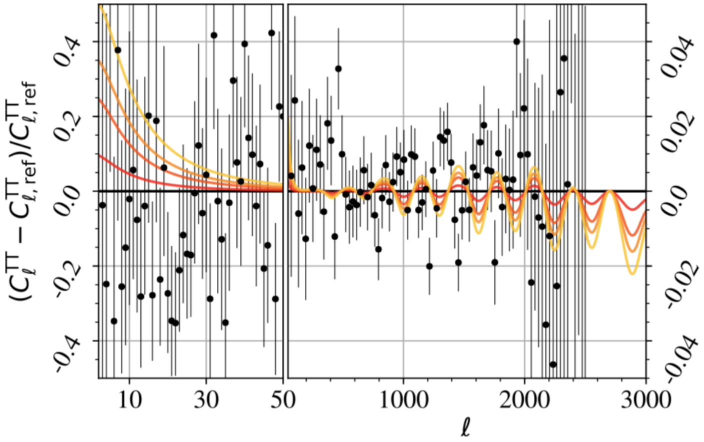
DM LATE INVISIBLE DECAYS

S. Alvi



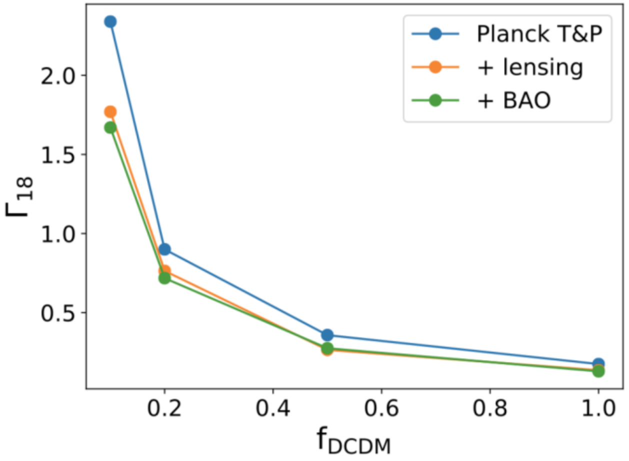
T. Brinckmann

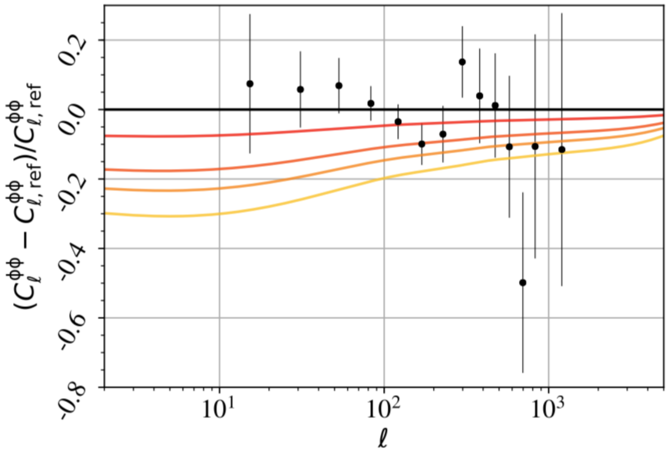




CMB anisotropies can probe invisible DM decays (e.g. to neutrinos)

- Larger late ISW due to variation in gravitational potentials
- Smaller lensing due to suppression of fluctuations





$$\tau_{\rm CDM} > 246\,{\rm Gyr}$$

from Planck+BAO

Alvi+, arXiv:2205.0563

A DARK CRYSTAL?

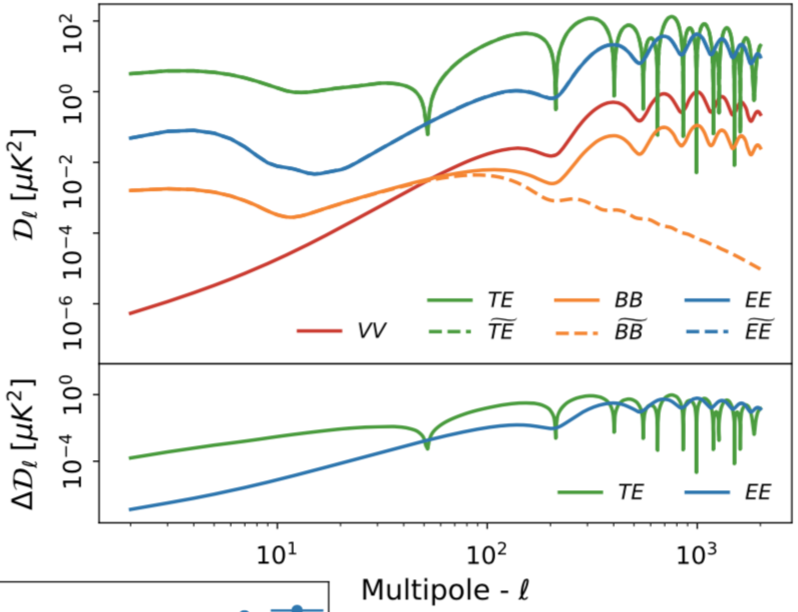
M. Lembo

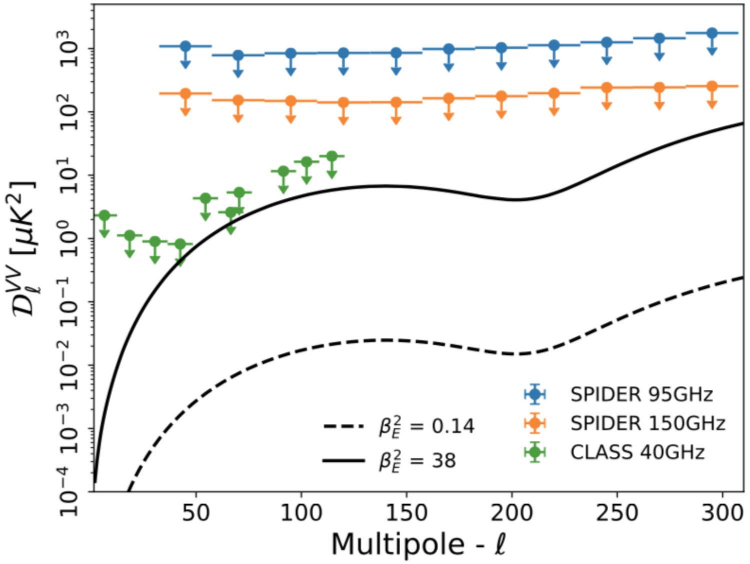
CMB is the farthest light that we can observe.

We can use its polarization to look for deviations from propagation *in vacuo* and constraint its optical properties.

This is an indirect probe of the composition of the Universe

$$\chi = \begin{pmatrix} \chi_{xx} & i\chi_{xy} & -i\chi_{xz} \\ -i\chi_{xy} & \chi_{yy} & i\chi_{yz} \\ i\chi_{xz} & -i\chi_{yz} & \chi_{zz} \end{pmatrix}$$





Lembo et al., 2021

The “Heavenly Lab” has gifted us with many information on the properties of elementary particles….

… and will keep on giving in the future!

We will have a detection of neutrino masses OR an indication from new physics (on the cosmo or particle side, or both)

Future cosmological observations will further constrain the properties of light relics and dark matter, and particle physics models in general.

THANKS!