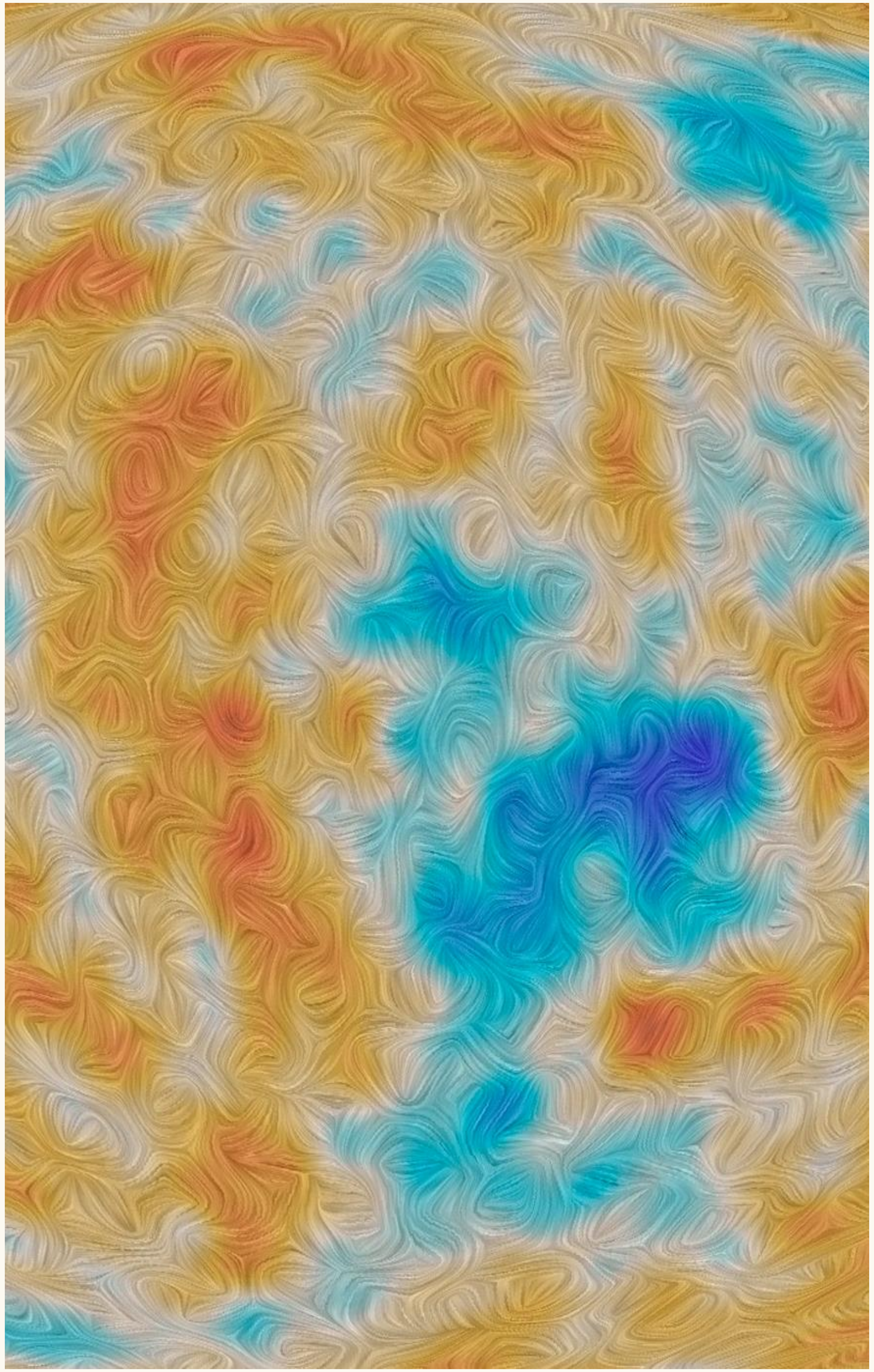


LIGHT RELICS

MASSIMILIANO LATTANZI

INFN, sezione di Ferrara

CMB @60

Panel 9 – Fundamental physics and anomalies

Torino, May 30th, 2025

LIGHT RELICS

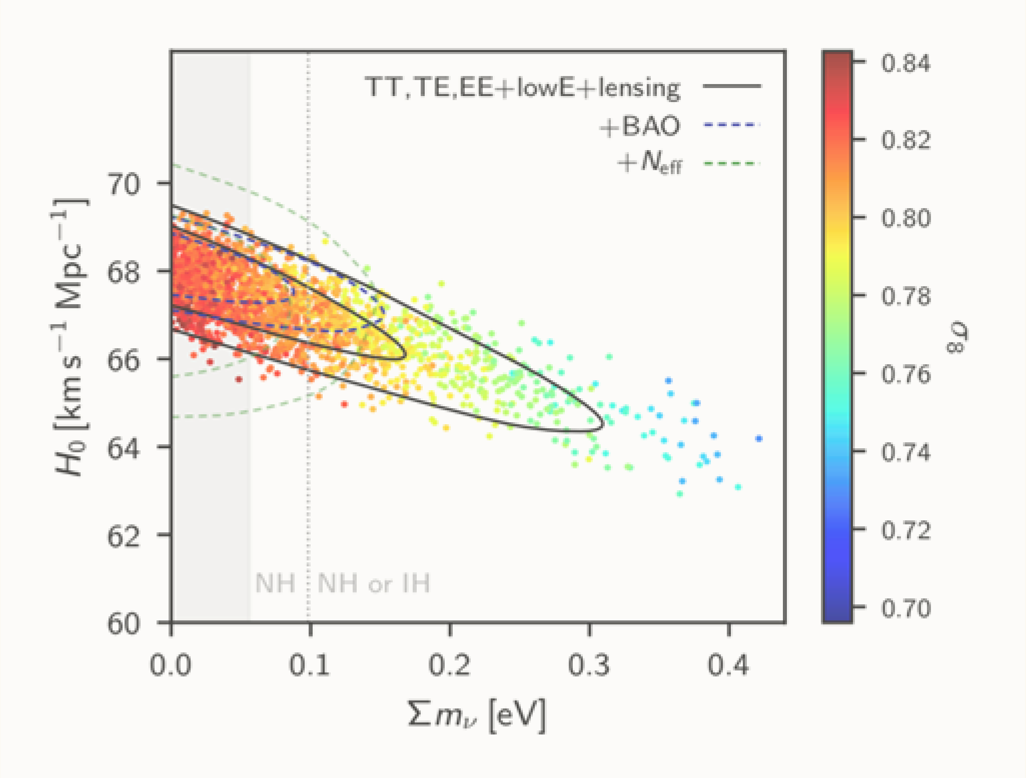
for our (i.e. CMB) purpose, sub-eV-mass particles produced in the early Universe with weak or weaker-than-weak interactions with the standard model sector

Examples: ***active neutrinos***, sterile neutrinos, axions, axion-like particles (ALPs), dark photons, ...
(all of them in some part of their parameter space)

* See also: dark radiation, FIMPs, WISPs, hot dark matter....

Active neutrinos

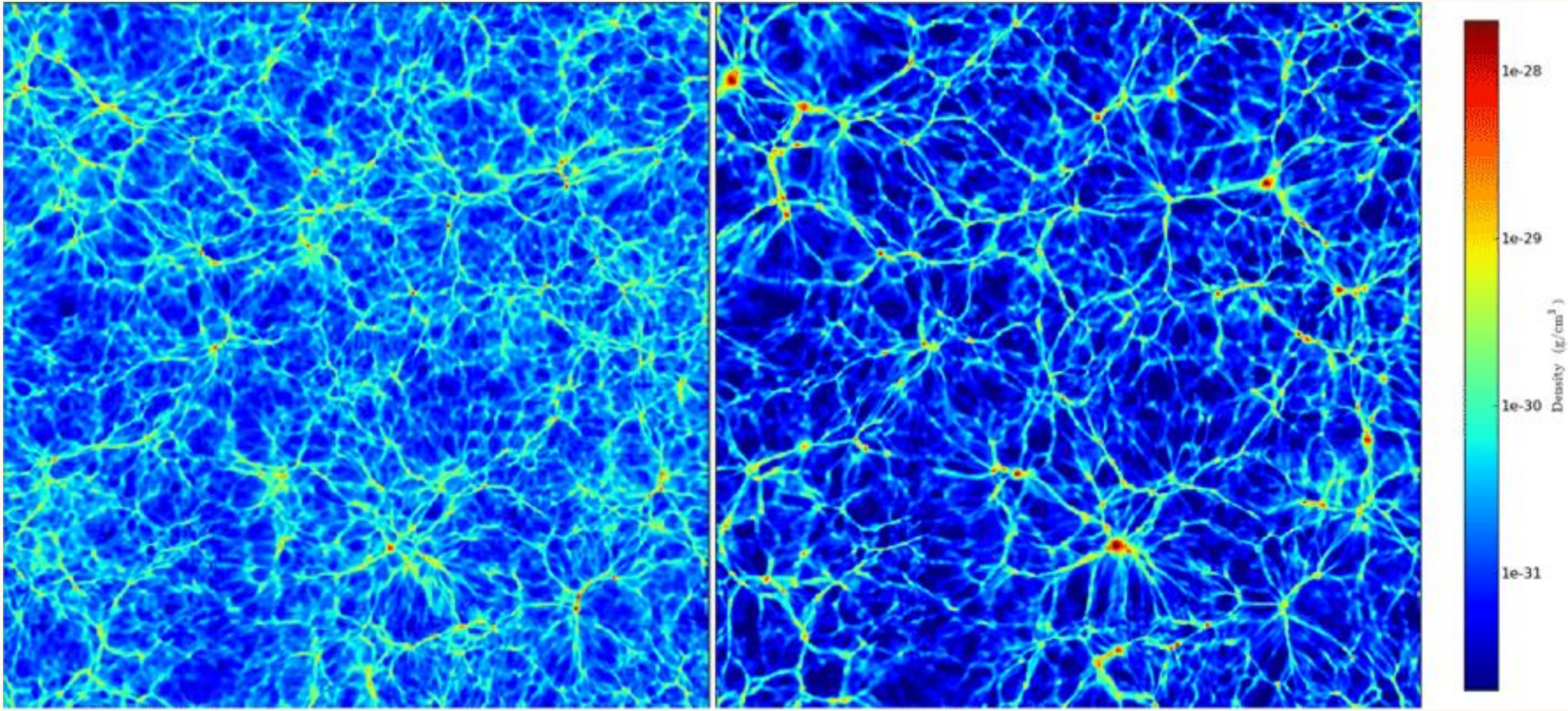
CMB+BAO:
$\Sigma m_\nu = m_1+m_2+m_3 < 0.08 - 0.12$ eV (95% CL)



$\sum m_\nu = 1.9\,\mathrm{eV}$

No neutrinos

Credit: Agarwal & Feldman

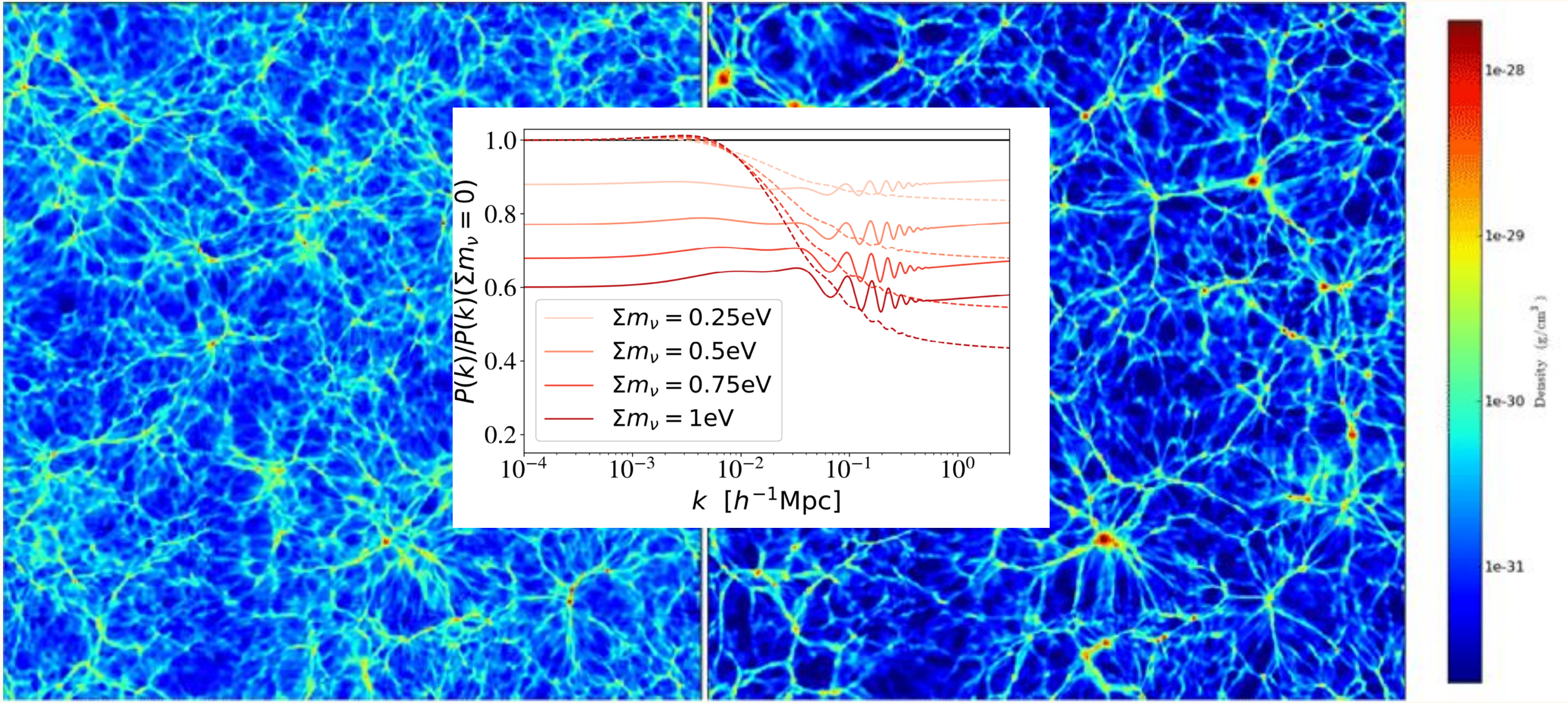


1.5 million lightyears

$\sum m_\nu = 1.9\,\mathrm{eV}$

No neutrinos

Credit: Agarwal & Feldman

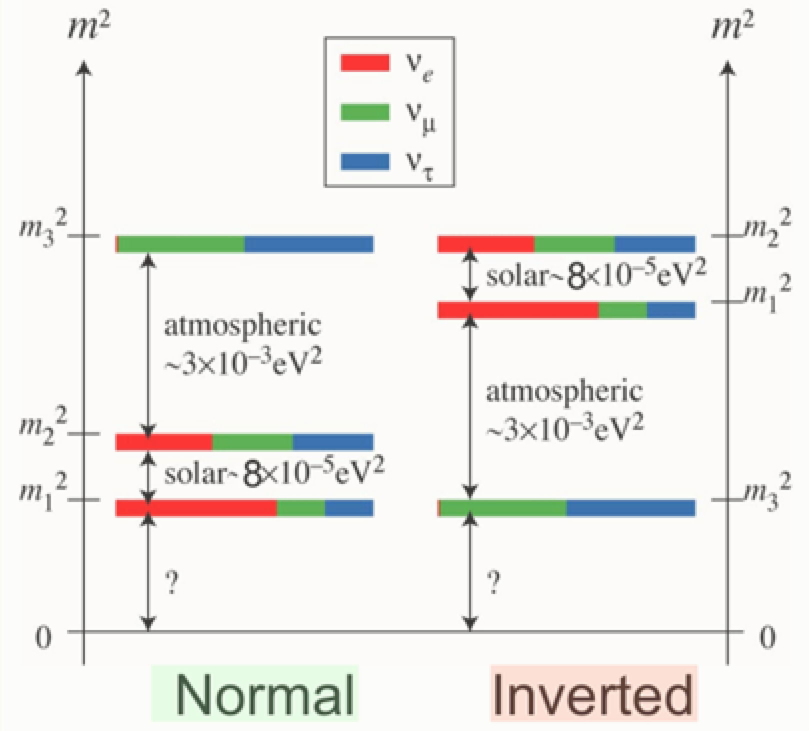


1.5 million lightyears

Active neutrinos

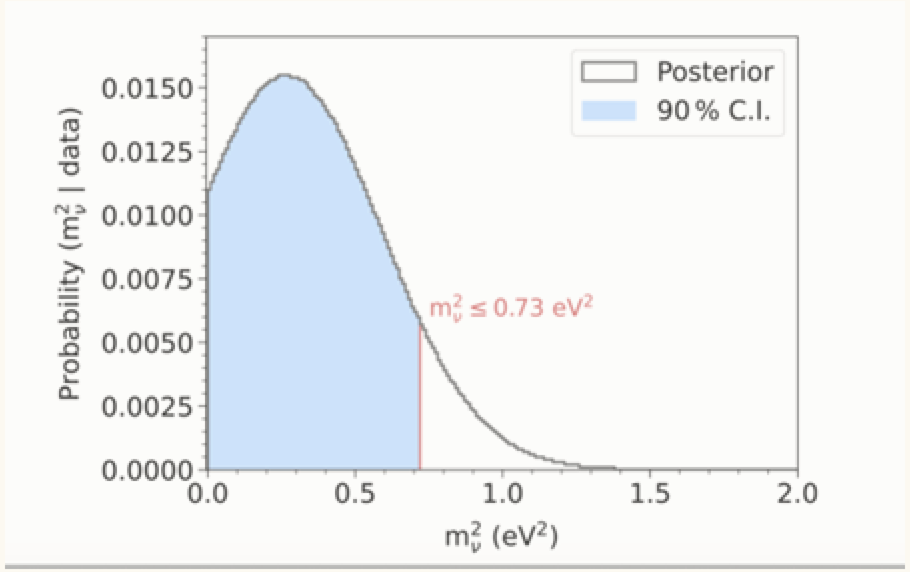
Flavour oscillation experiments

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



End point of tritium b-decay spectrum

Σm_ν < 1.35 eV (KATRIN)



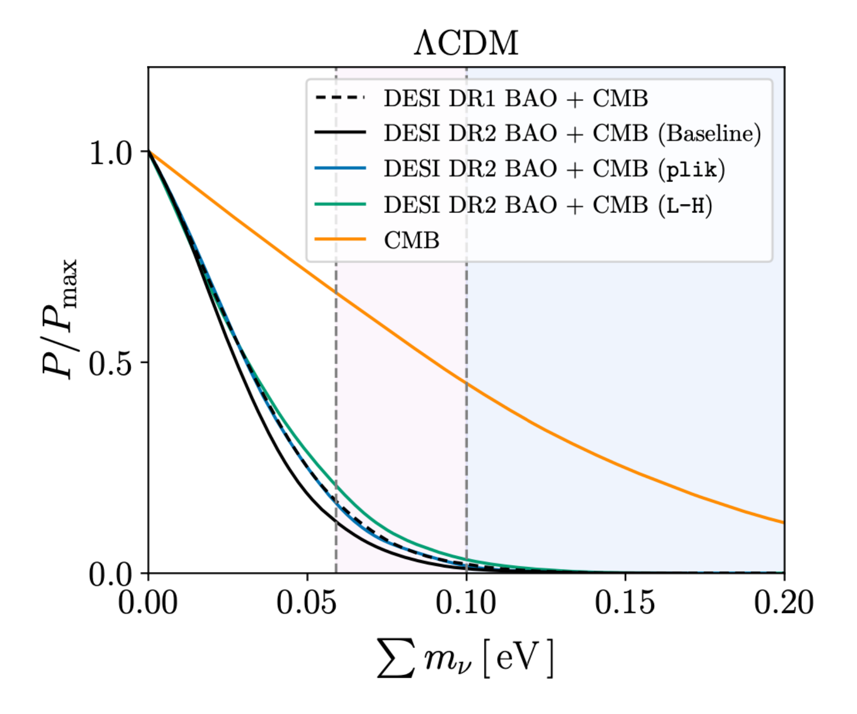
ACTIVE NEUTRINOS

Tension between cosmo and osciillation data?

Planck+ACT+DESI BAO
Preference for vanishing neutrino masses

Σm_ν < 0.064 eV @95% CL

- Hinting at new physics in the neutrino sector (decay, annihilation…) or elsewhere?
- Bound weakens including dynamical DE



DESI Collaboration, arXiv:2503.14744

Effective number of neutrinos

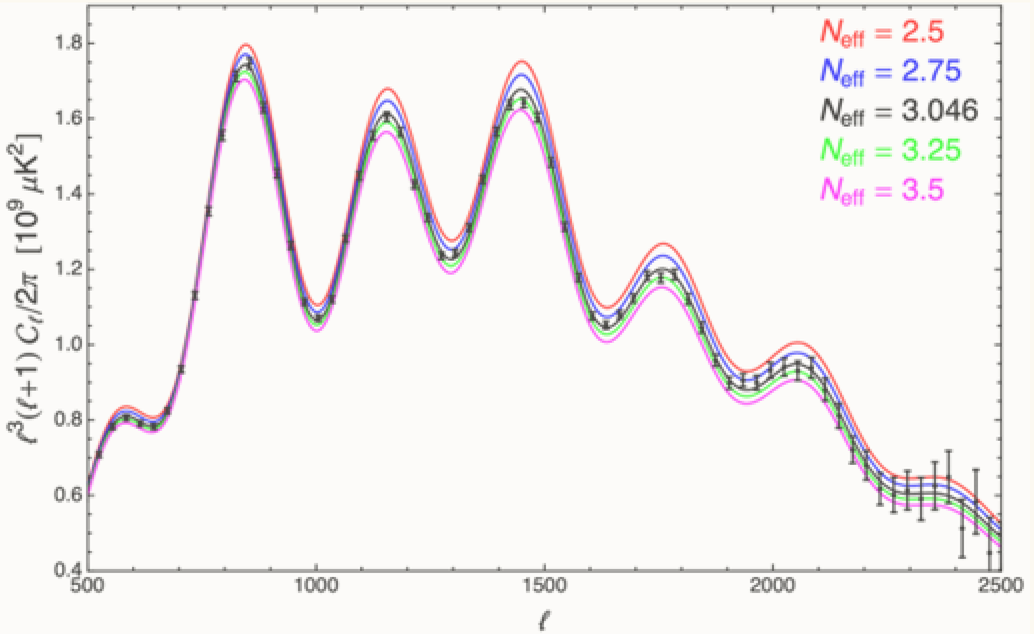
$$\rho_r \equiv \left[1 + N_{\rm eff} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3}\right] \rho_\gamma$$

Theoretical prediction $N_{eff} = 3.0440 \pm 0.0002$
(3 SM neutrinos)

is a probe for

- Additional light species
- Nonstandard thermal history
- physics of neutrino decoupling
- lepton asymmetry
- …..

Affects the damping tail



EFFECTIVE NUMBER OF NEUTRINOS

Currently measured with ~5% precision:

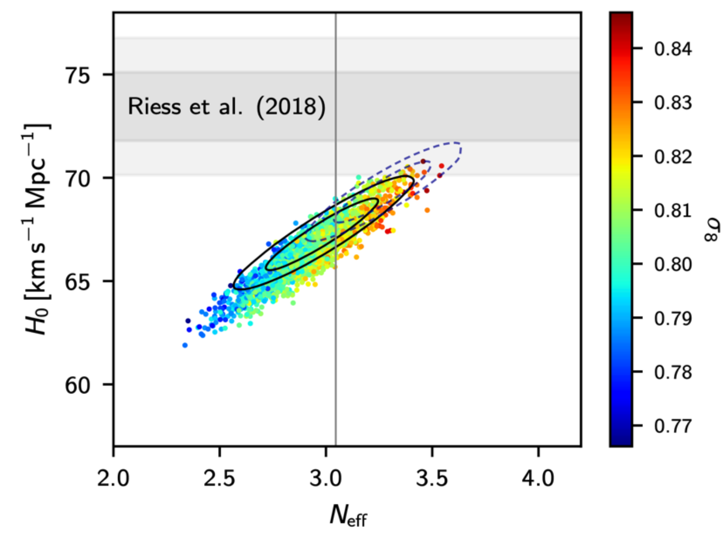
Planck 2018

N_{eff} = 2.89+/- 0.19

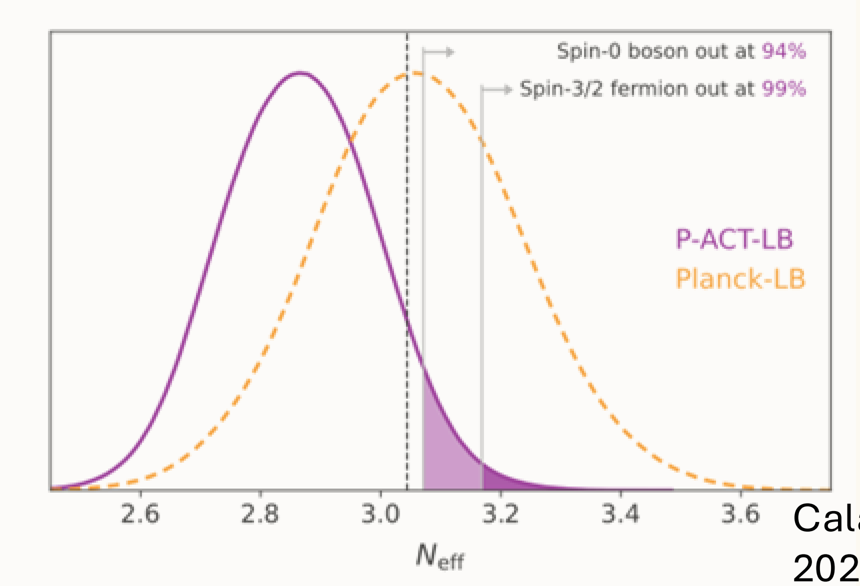
Planck+ACT+BAO:

N_{eff} = 2.86 +/- 0.13

Consistent with the Standard Model prediction

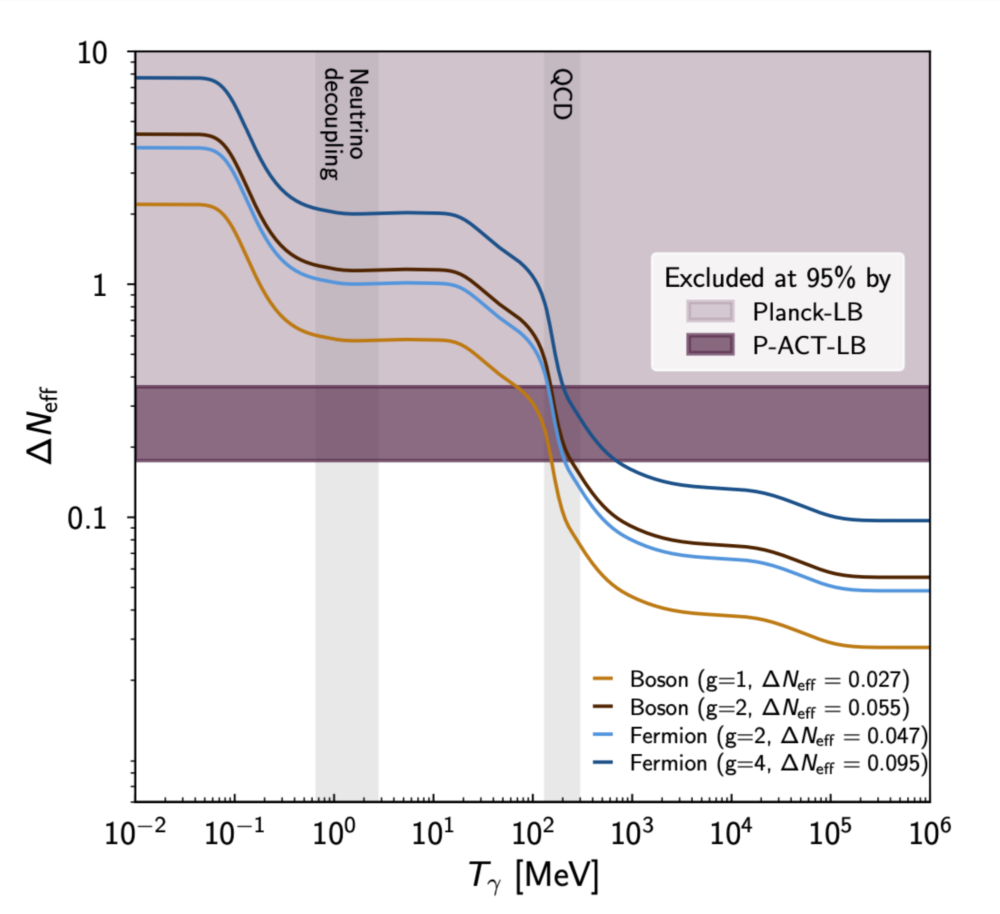


Planck collaboration, VI 2018



Calabrese et al. (ACT coll.) 2025,

EFFECTIVE NUMBER OF NEUTRINOS



Calabrese et al. (ACT coll.) 2025,

- Contribution of extra species *in thermal equilibrium* to Neff is inversely proportional to their decoupling temperature….
- … which is in turn inversely proportional to their (effective) coupling to the SM*
- Decoupling after the QCD phase transition (T~100 MeV) is excluded by present cosmological data

*E.g. for a four point interaction:

$$T_d \sim \left(\frac{1}{G_X^2 m_{\rm pl}}\right)^{1/3} \quad \text{with} \quad G_X = \frac{g^2}{m_X^2}$$

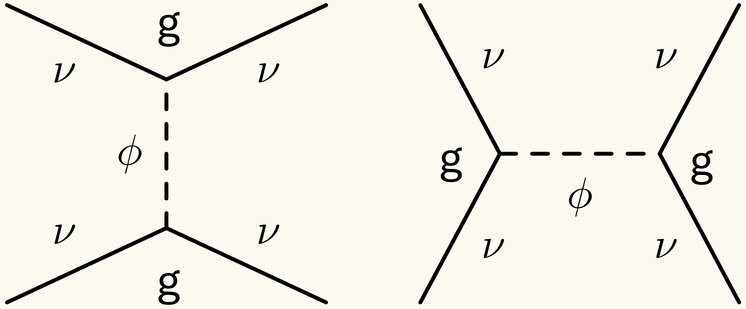
coupling (g)

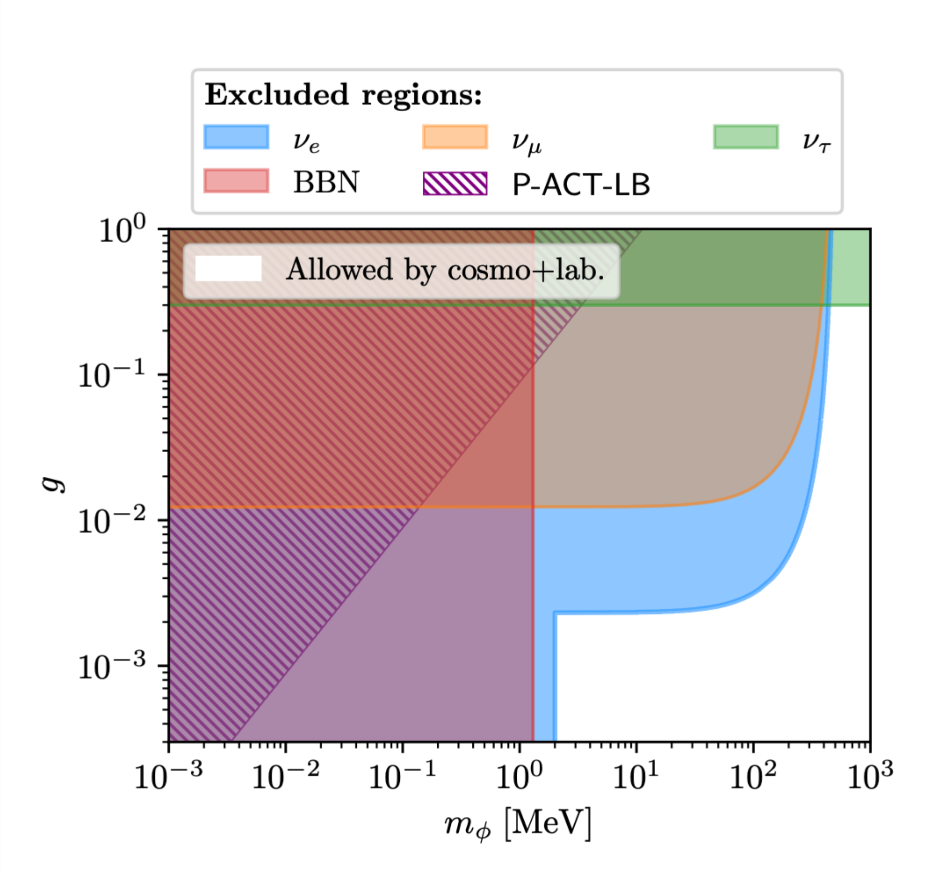
mediator mass (m_X)

Neutrino interactions

CMB is sensitive to the collisional properties of light relics (extra power at intermediate/small scales + phase shift)

E.g. neutrino nonstandard interactions (nuNSI)



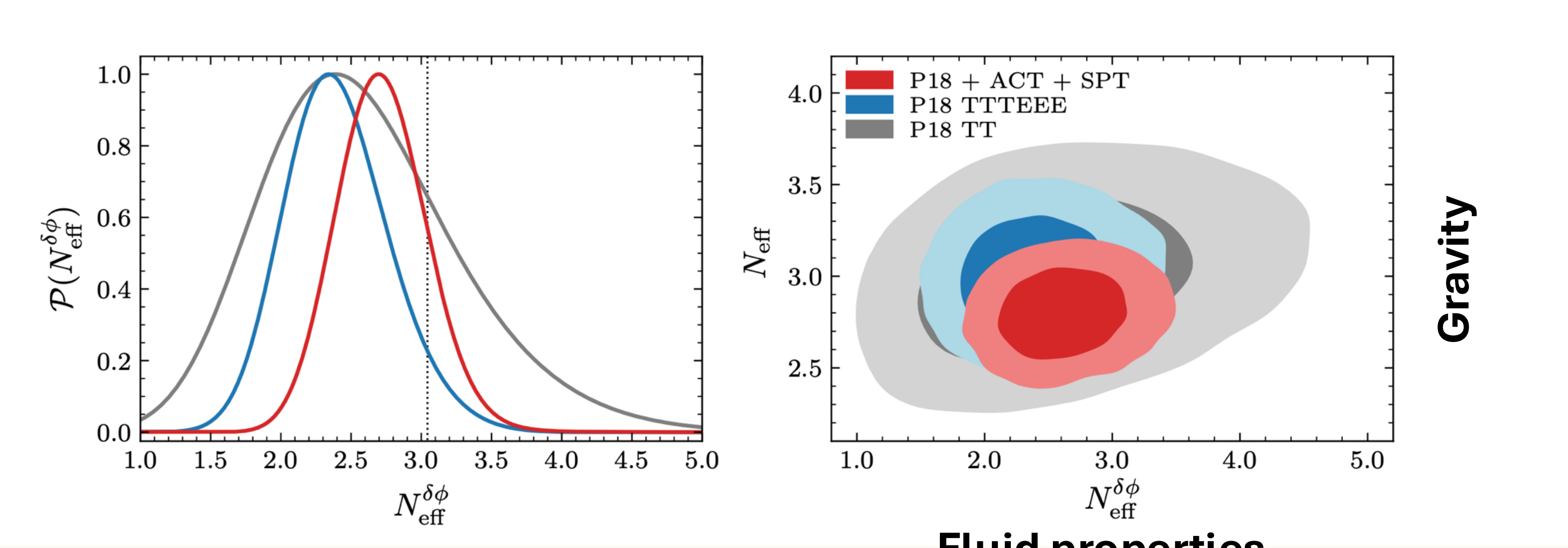


Calabrese et al. (ACT coll.) 2025

Currently no evidence for nuNSI

NEUTRINO INTERACTIONS

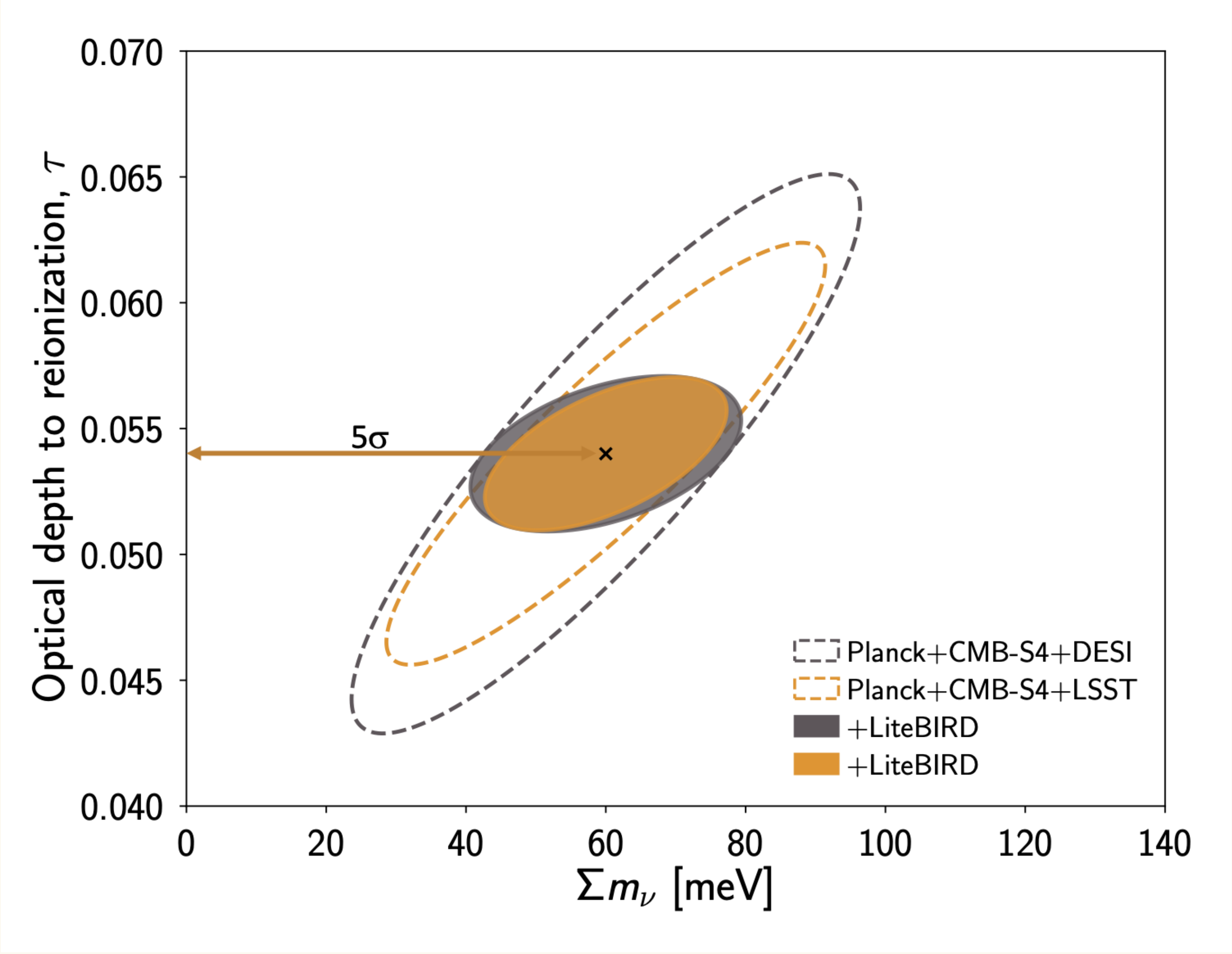
CMB is sensitive to the collisional properties of light relics
(extra power at intermediate/small scales + phase shift)
Phenomenological analysis from Montefalcone, Wallisch, Freese 2025



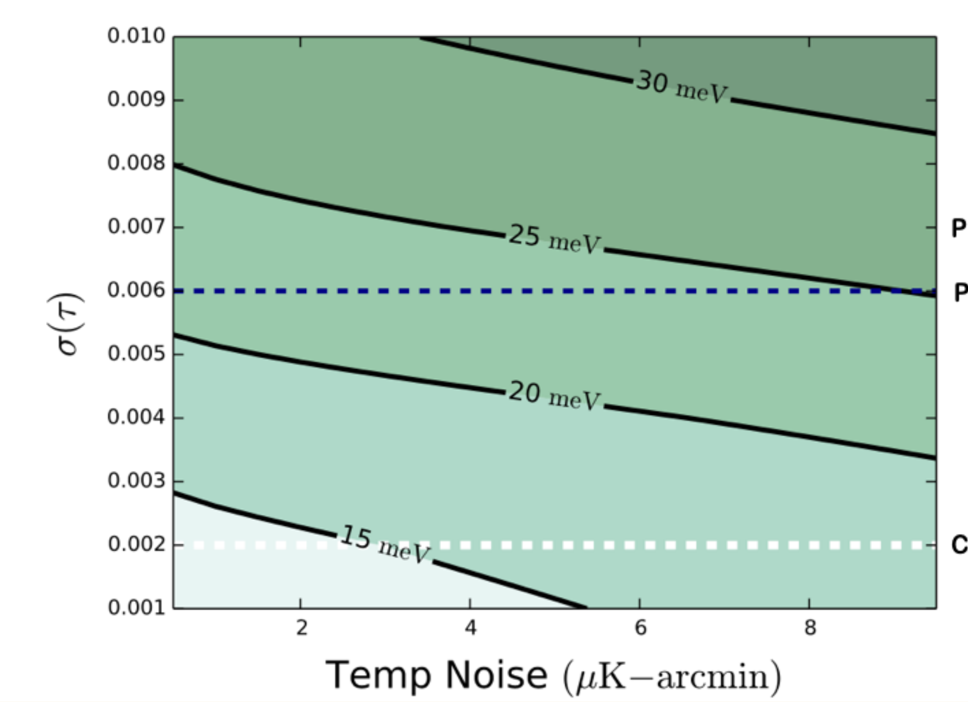
Fluid properties

Also in this case, no evidence for deviation from free streaming behaviour

LITEBIRD+CMB-S4+DESI/LSST



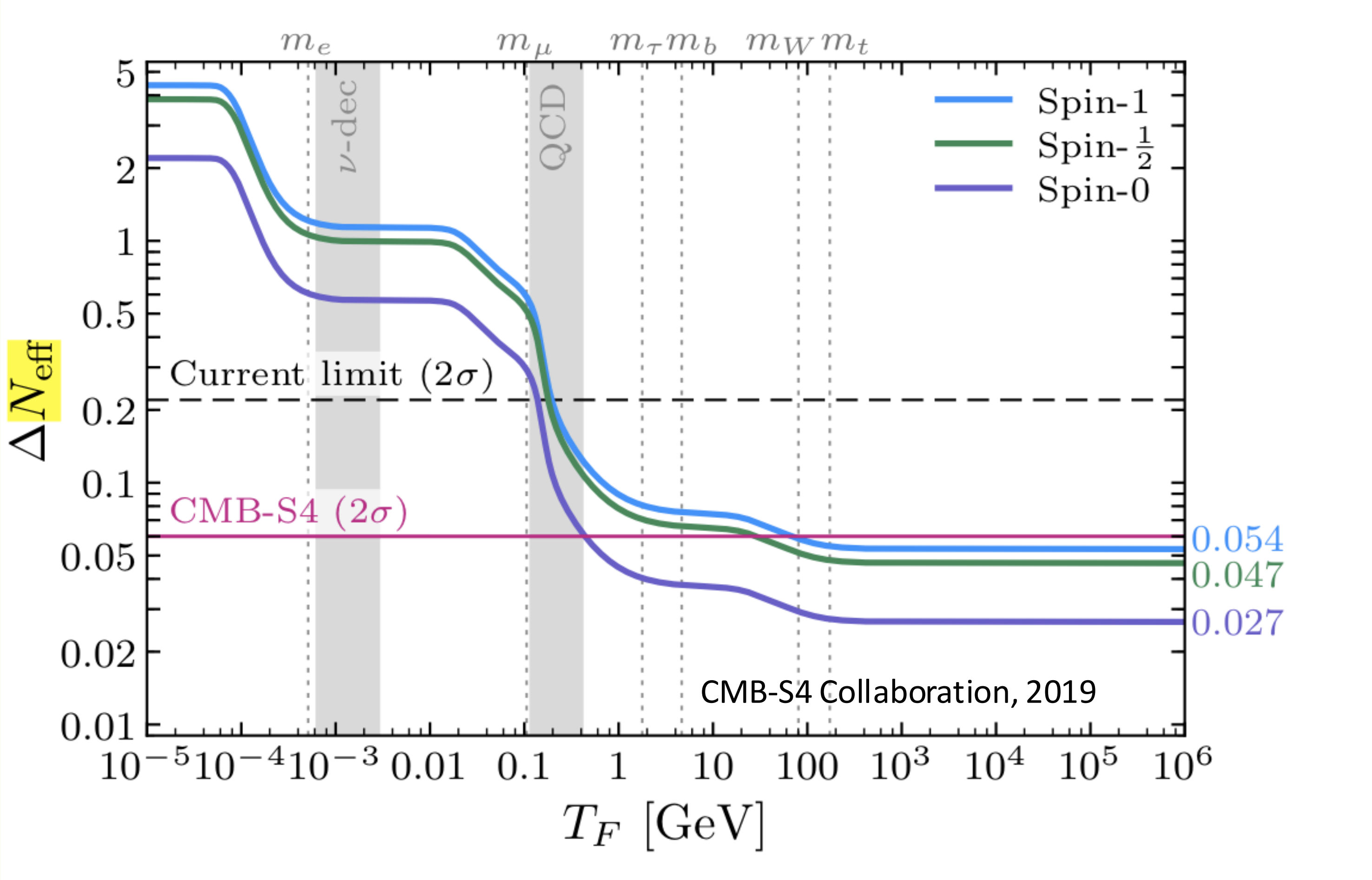
LiteBird Collaboration, arXiv:2202.02773

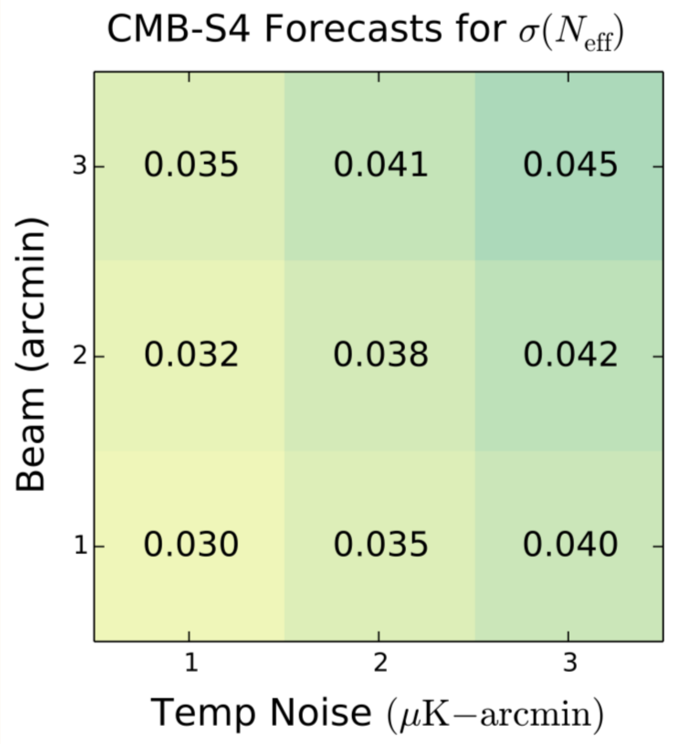


CMB-S4 Collaboration, 2019

N_{EFF} FROM CMB-S4

Contribution of extra species in thermal equlibrium



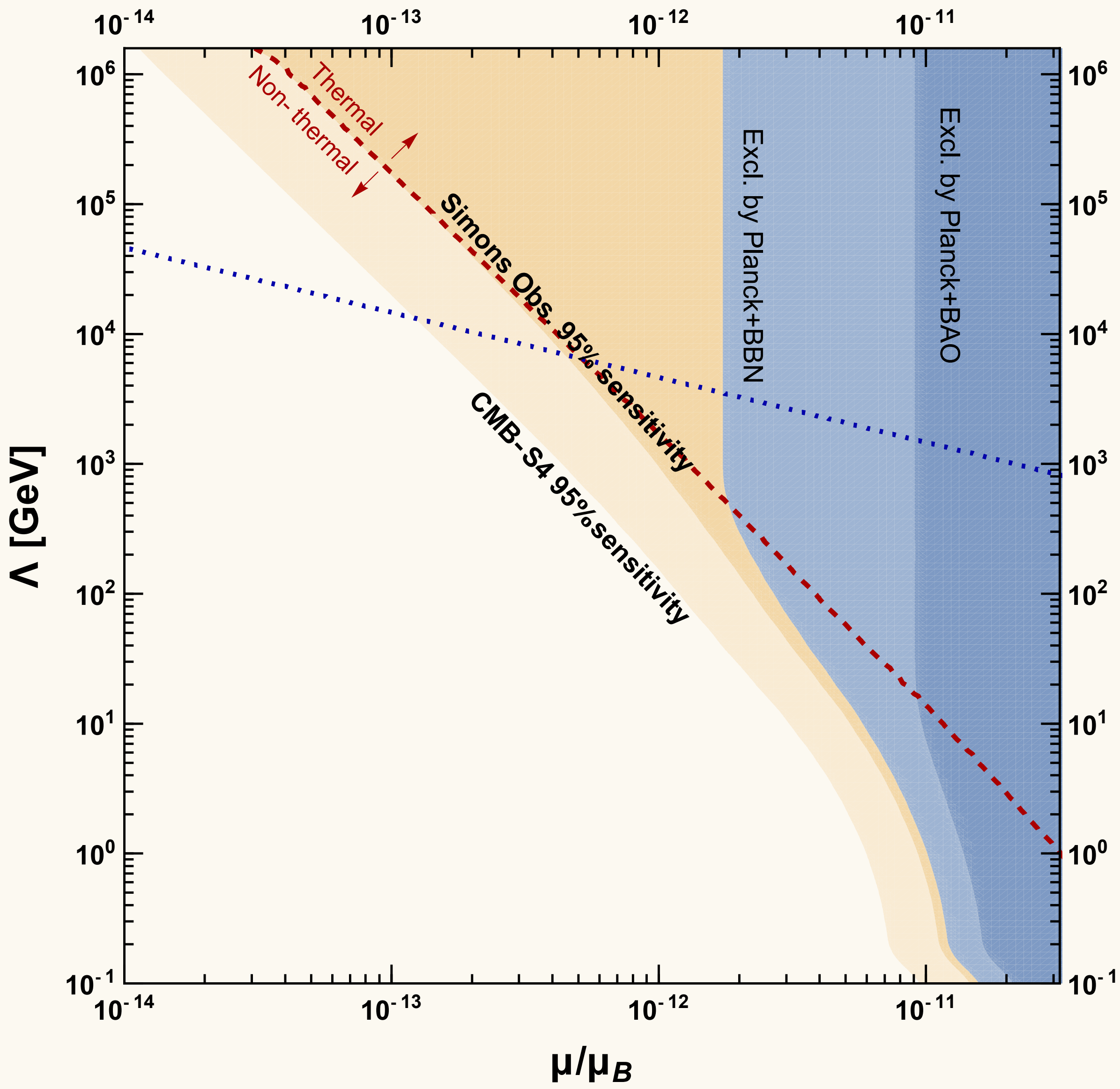


CMB-S4 Science Book

BEYOND THERMAL EQUILIBRIUM: FREEZE-IN

Next-gen experiments will allow to probe the nonthermal (freeze-in) regime of light relics production

Relevant e.g. for the magnetic moment of Dirac neutrinos…
(Lucente, Carenza, Gerbino, Giannotti, ML, PRD 2024)

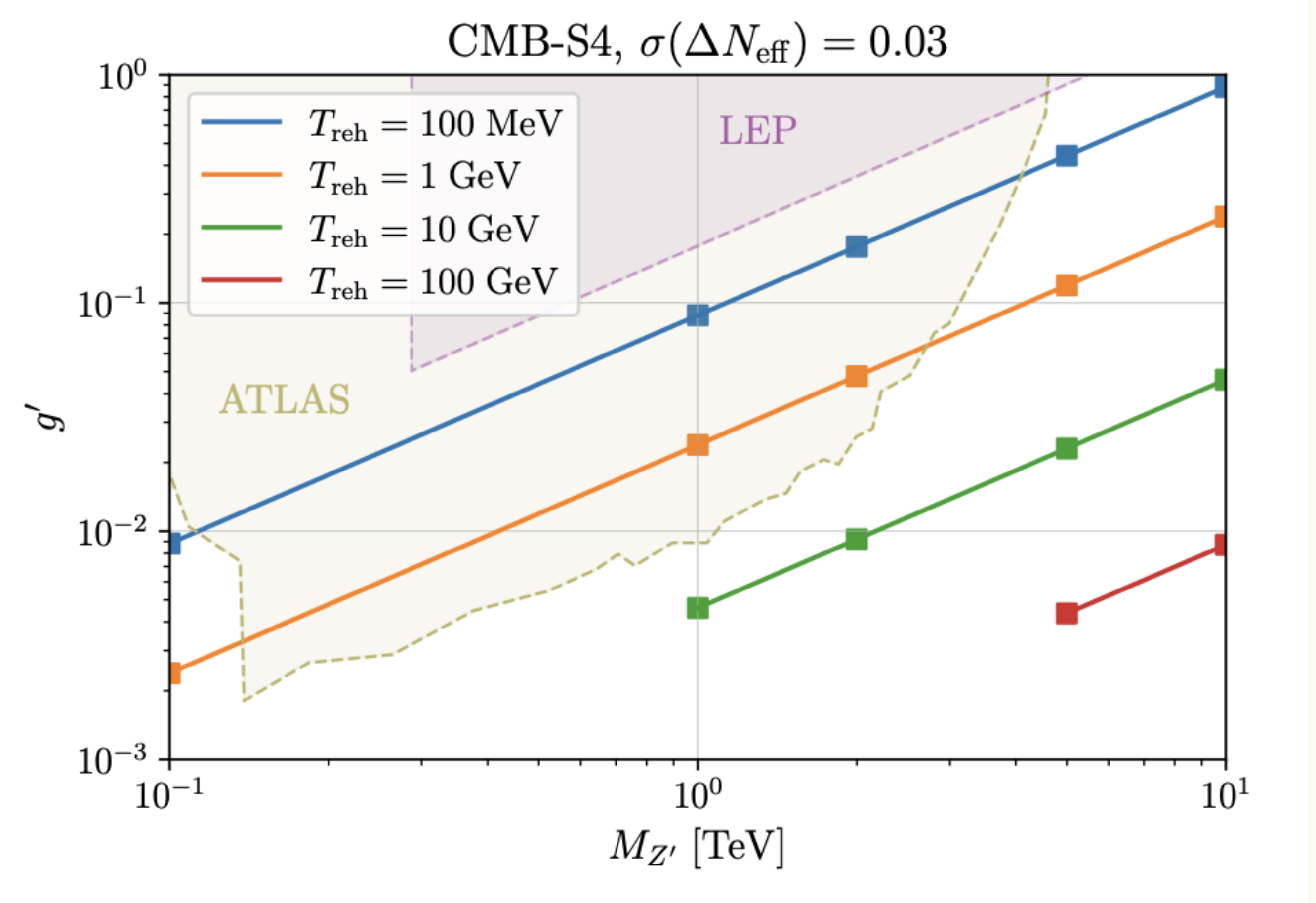


BEYOND THERMAL EQUILIBRIUM: FREEZE-IN

Next-gen experiments will allow to probe the nonthermal (freeze-in) regime of light relics production

… or for B-L models

(Caloni, Stengel Gerbino, ML, arXiv: 2405.09449)



$$\mathcal{L} = g' Z'_\mu \sum_i \left[\frac{1}{3} \left(\bar{u}_i \gamma^\mu u_i + \bar{d}_i \gamma^\mu d_i \right) - \bar{e}_i \gamma^\mu e_i - \bar{\nu}_{L,i} \gamma^\mu \nu_{L,i} - \bar{\nu}_{R,i} \gamma^\mu \nu_{R,i} \right] ,$$

LIGHT RELICS FROM NEXT-GEN EXPERIMENTS

Reaching these goals requires a precise and accurate measurement of both **large** and **small** scale CMB

- **Small scales:**
  - Most of the N_{eff} signal is in the damping tail
  - Lensing reconstruction needed to get the masses
  - useful to probe the collisional properties
  - Foreground residuals and beam systematics to be kept under control
  - Theoretical “systematics”: impact of nonlinearities on CMB lensing
- **Large scales:**
  - A CV-limited measurement of the optical depth is needed to reach the lowest possible sensitivity on M_ν.
  - Large-scale foregrounds and instrumental systematics to be kept under control

Discussion

- What is needed for a reliable measurement of neutrino mass?
- How to deal with model dependency?
- What if tension with lab persists? How to interpret/explain it?
- How to distinguish possible interpretations of a measurement of $\Delta N_{eff} \neq 0$? (e.g., extra species vs nonstandard neutrino decoupling)?
- Can we go beyond N_{eff}? E.g. how sensitive are future experiment to neutrino spectral distortions, or to highly nonthermal light relics?