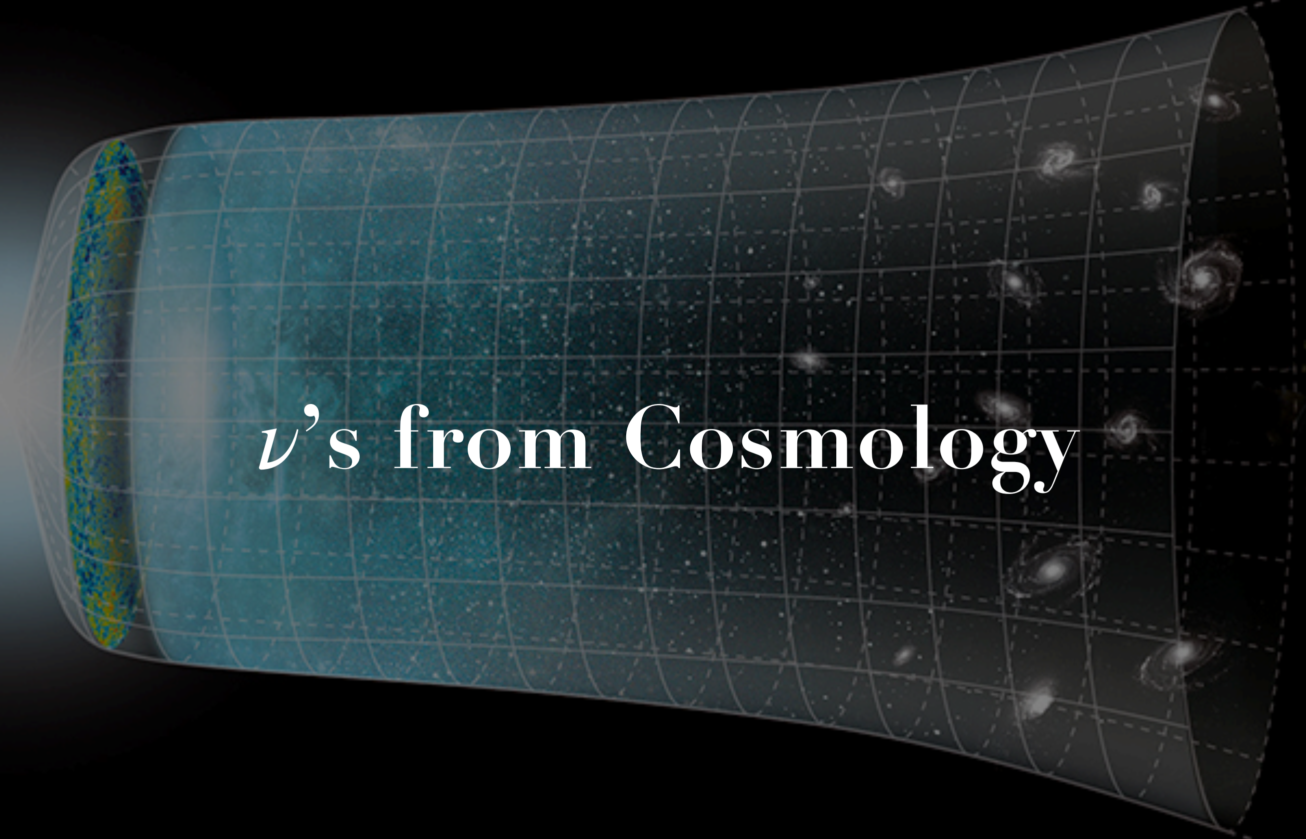
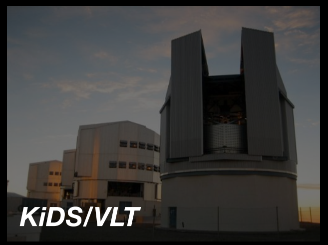
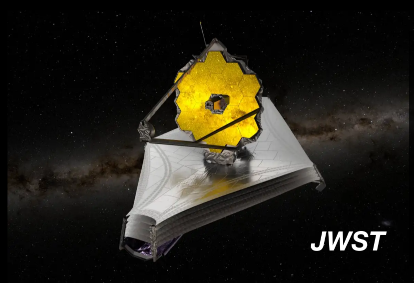
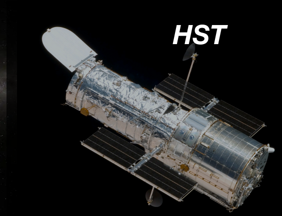
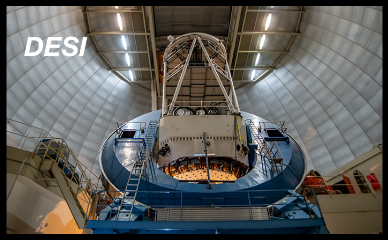


ν's from Cosmology









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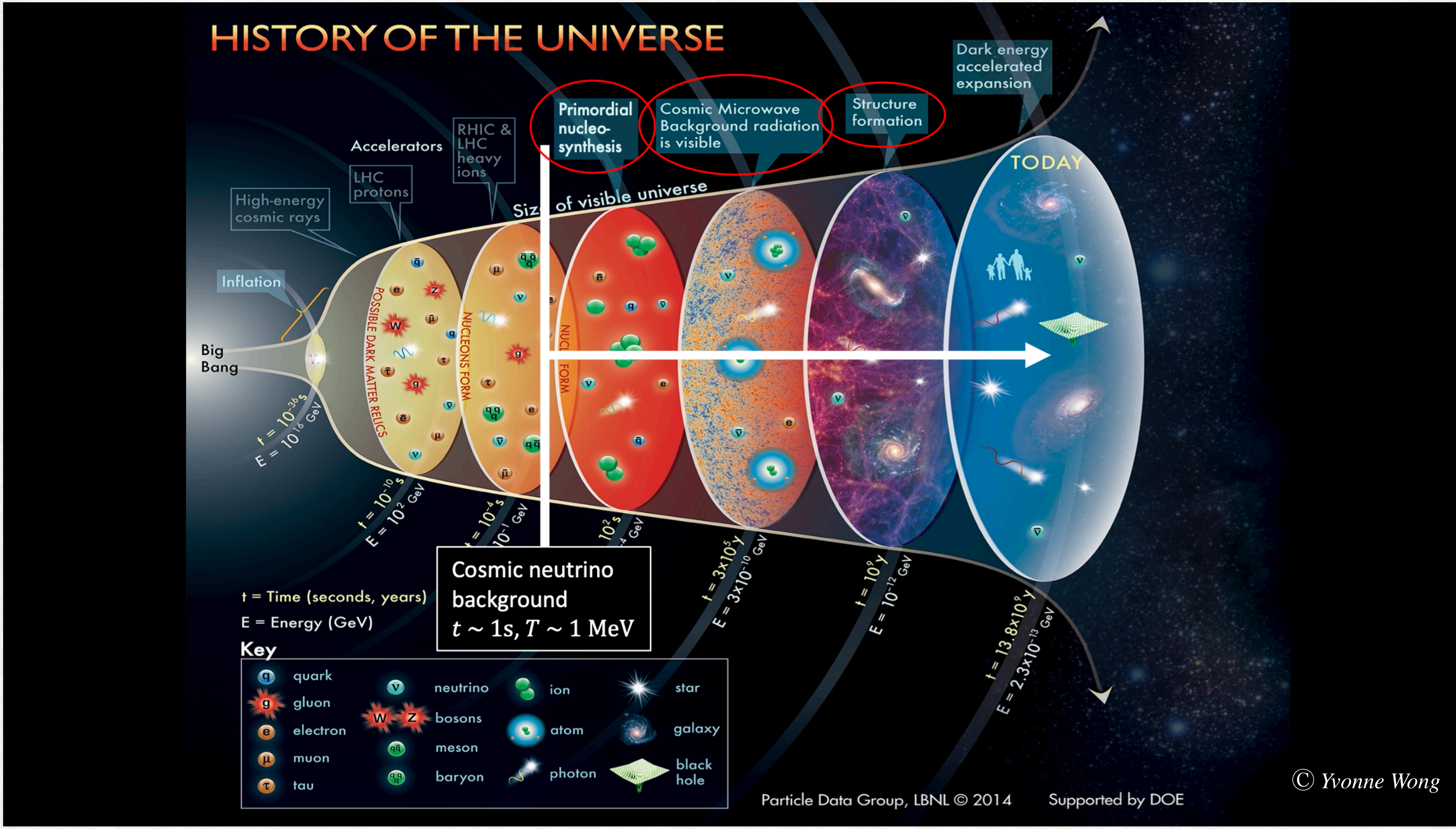
IRN Neutrino
IP2I, Lyon
June 13th, 2025

Schematic view of ν through the universe



- Before 1 MeV: ν interact efficiently through the weak interaction. They form a perfect thermalized fluid.
- After 1 MeV: The weak interaction drops below Hubble. They form a free-streaming "frozen" fluid.

The cosmic ν-background

- ν carry a frozen Fermi-Dirac distribution $f_\nu(E_\nu, t) = \frac{1}{1 + \exp(p/T_\nu)}$ does not depend on m_ν!
- ν are slightly colder than CMB: they decouple before $e^{\pm}$ annihilations $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$

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- $N_{\rm eff}$ parametrizes the number of massless ν-like species $\rho_R = \rho_\gamma \left(1 + \dfrac{7}{8}\left(\dfrac{4}{11}\right)^{4/3} N_{\rm eff}\right)$ $\Omega_i = \dfrac{\rho_i}{\rho_c}$

- $N_{\rm eff} = 3.044$ in the standard model, such that today $n_{\rm C\nu B} \simeq 110\ {\rm cm}^{-3}$ and $\Omega_{C\nu B} \simeq \dfrac{m_\nu}{93h^2\ {\rm eV}}$

- Relativistic ν are free-streaming: specific impact on CMB at early-times; on structures at late-times.

Cosmology provides strong bounds on ν-physics

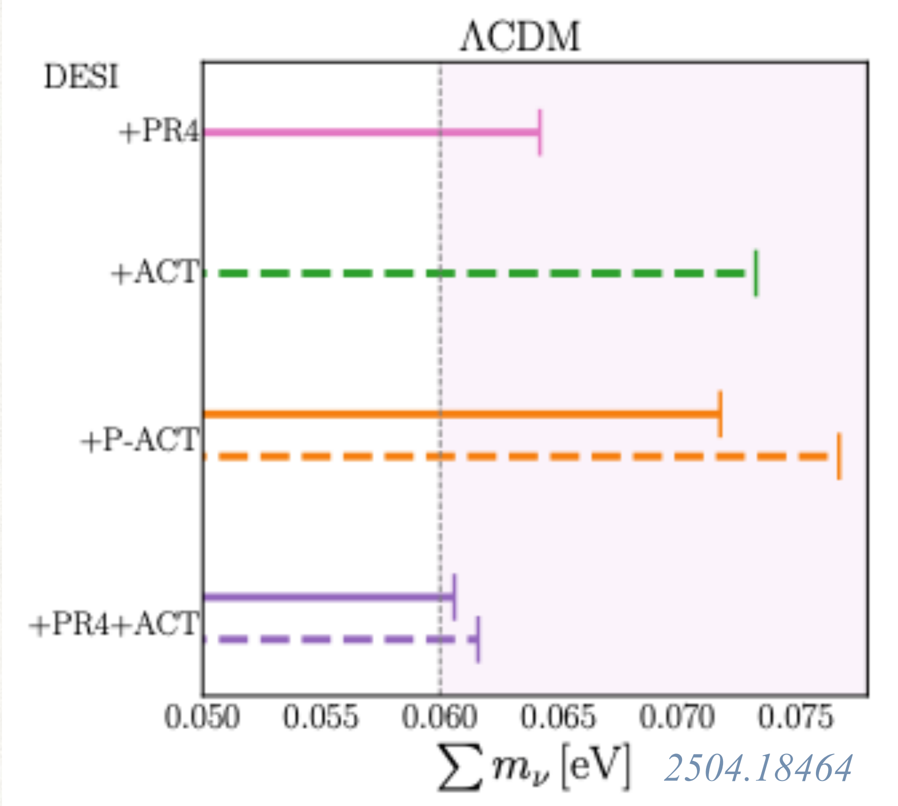
- Strongest bounds to date on $\sum m_\nu$ (at 95% CL)

Katrin: < 1.35 eV *Science 2025*

Planck 2018 + BAO < 0.12eV *Planck 1807.06209*

Planck 2018 + DESI DR2 < 0.0691 eV *DESI 2503.14738*

Planck 2020 + ACT + DESI DR2 < 0.0606 eV *DESI 2504.18464*



2504.18464

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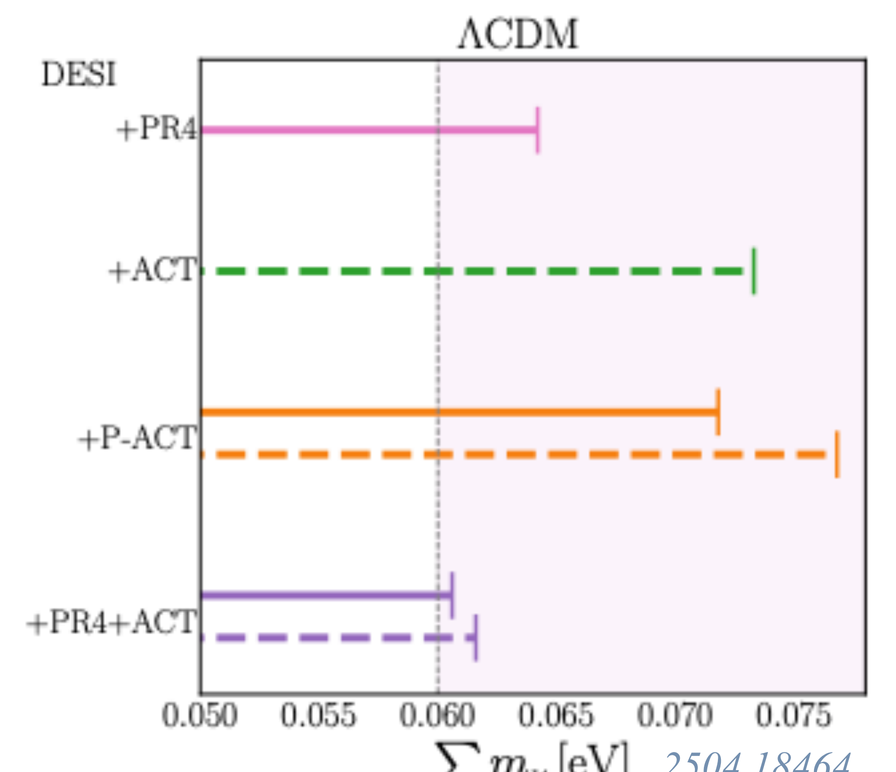


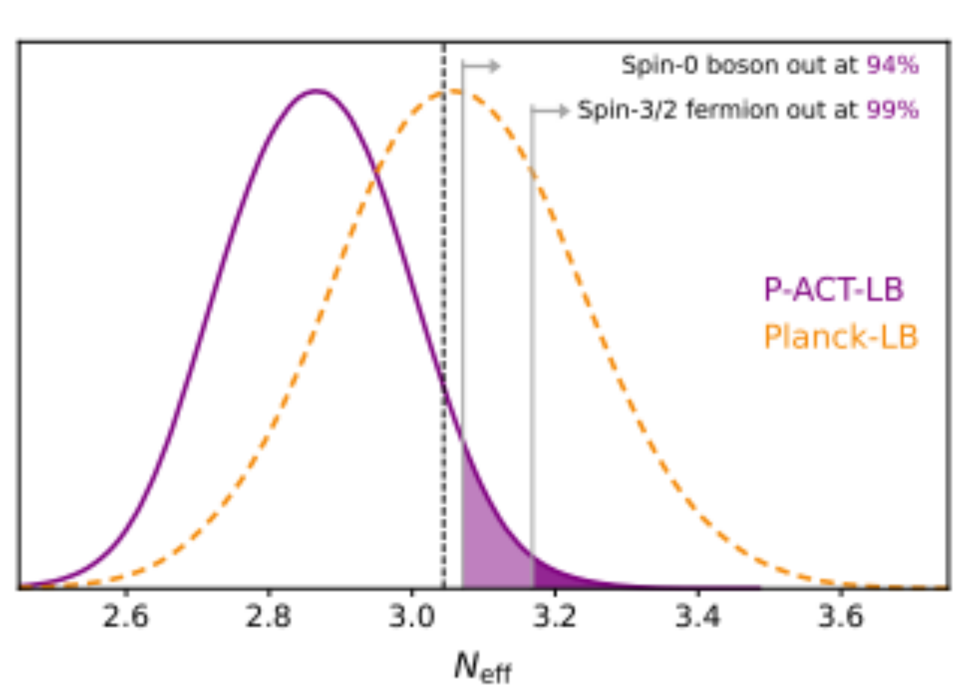
2504.18464

- Strongest bounds on number of ν-like species (at 68% CL)

Planck 2018 + BAO $N_{\rm eff} = 2.99 \pm 0.17$ *Planck 1807.06209*

Planck 2018 + ACT + DESI DR1 $N_{\rm eff} = 2.86 \pm 0.13$

ACT 2503.14454



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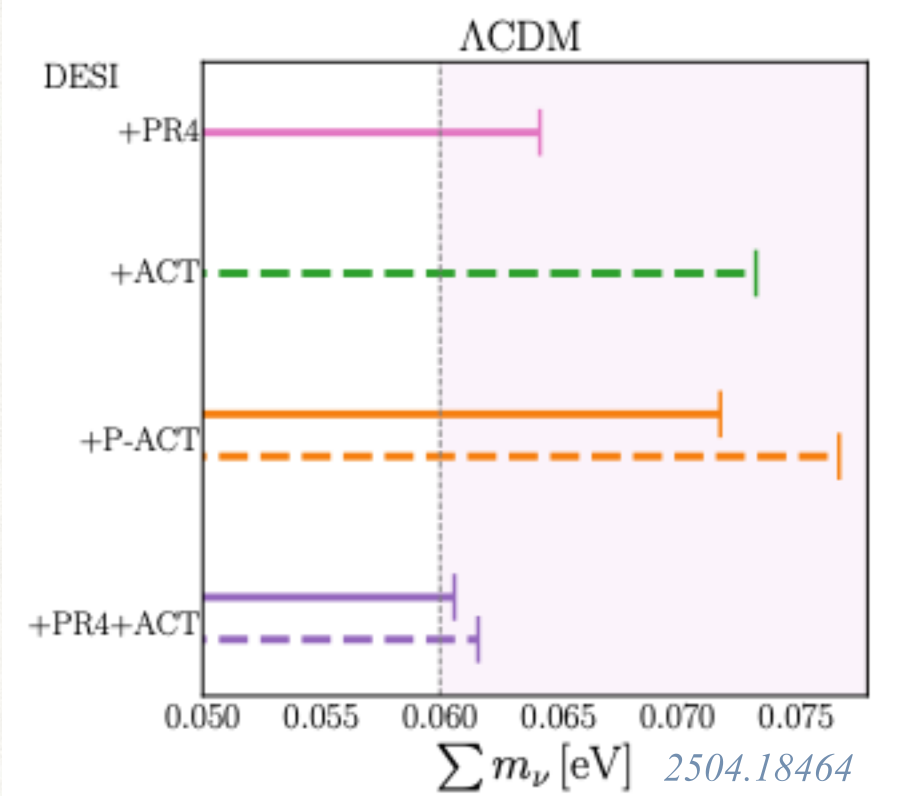

2504.18464

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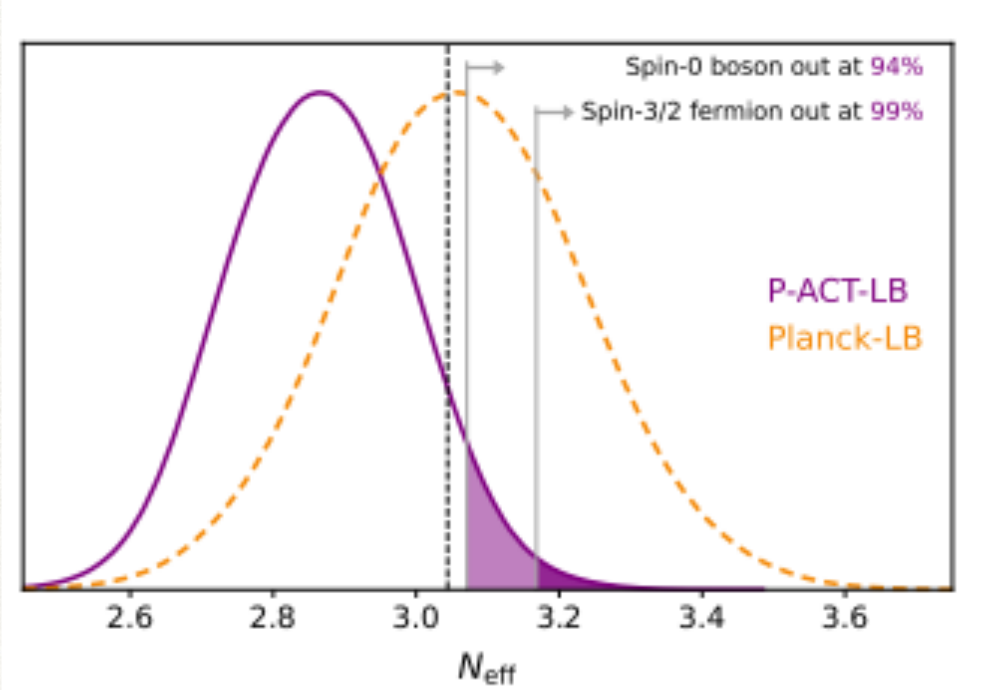


Where are the neutrinos?!

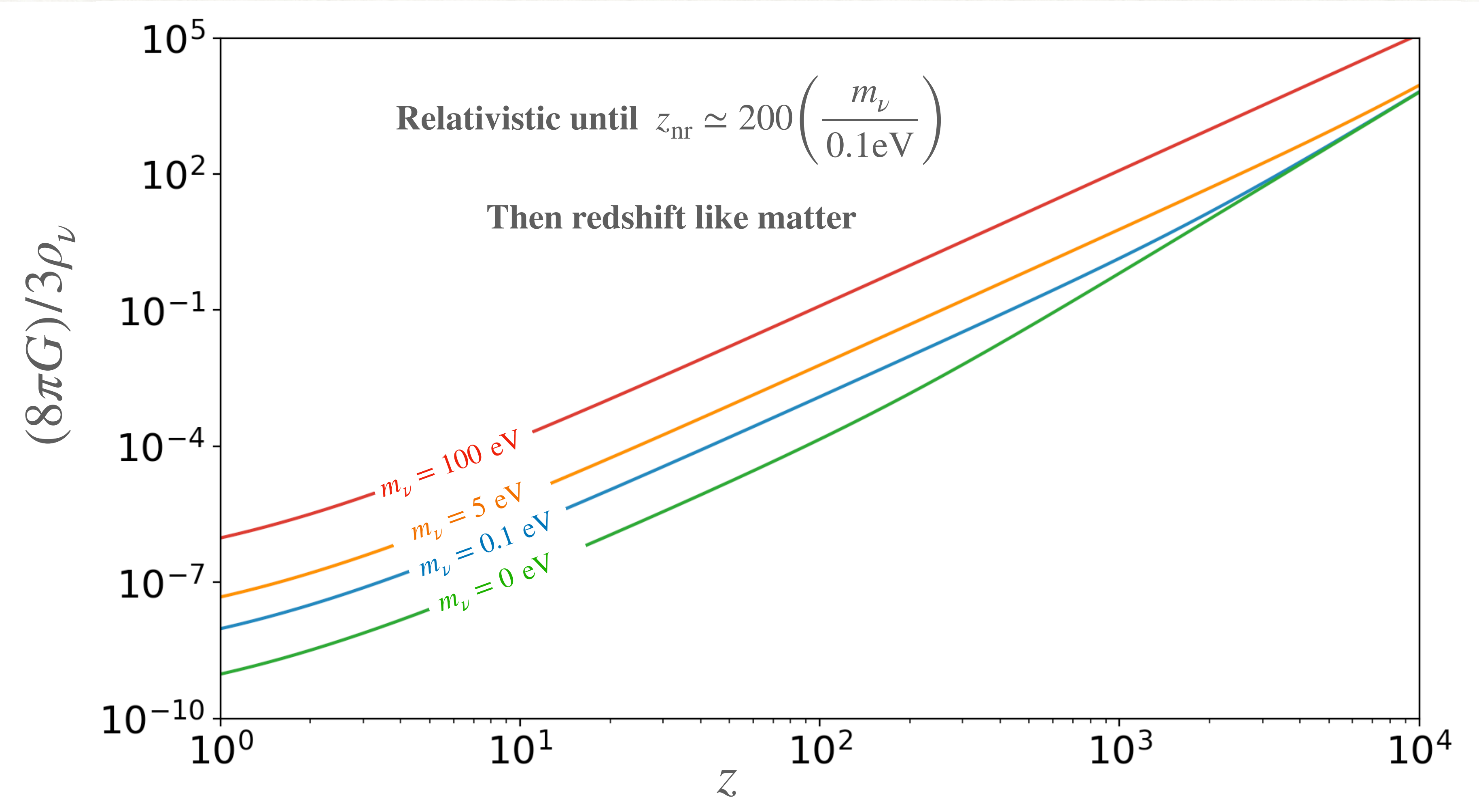
m_ν can affect cosmological distances

- ν can affect the homogeneous expansion

$$H(z) \equiv \frac{\dot{a}}{a} = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda + \ldots}$$

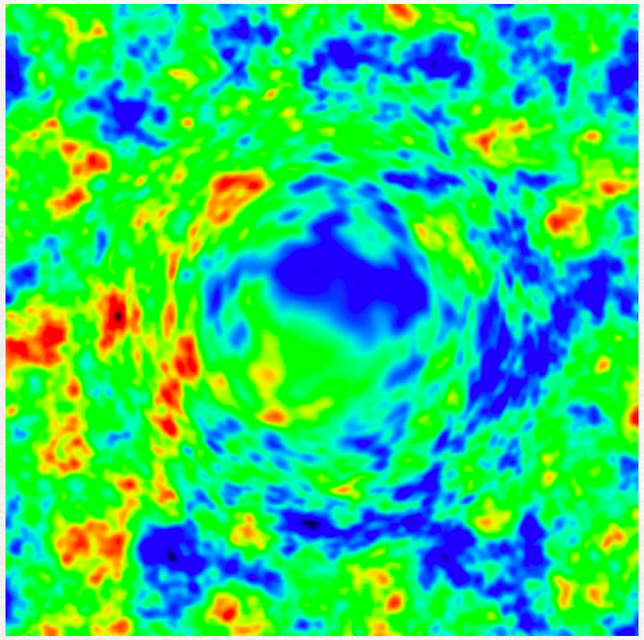
- Affect distance measurements via SN1a and BAO

$$D_M(z) = \int_0^z \frac{cdz}{H(z)}$$

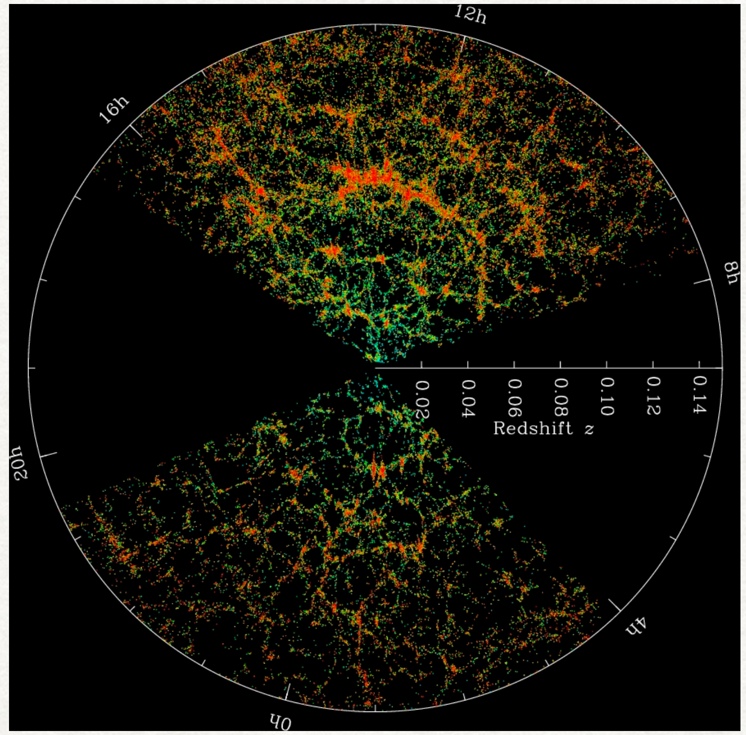


m_ν can affect probes of matter structuring

CMB weak lensing

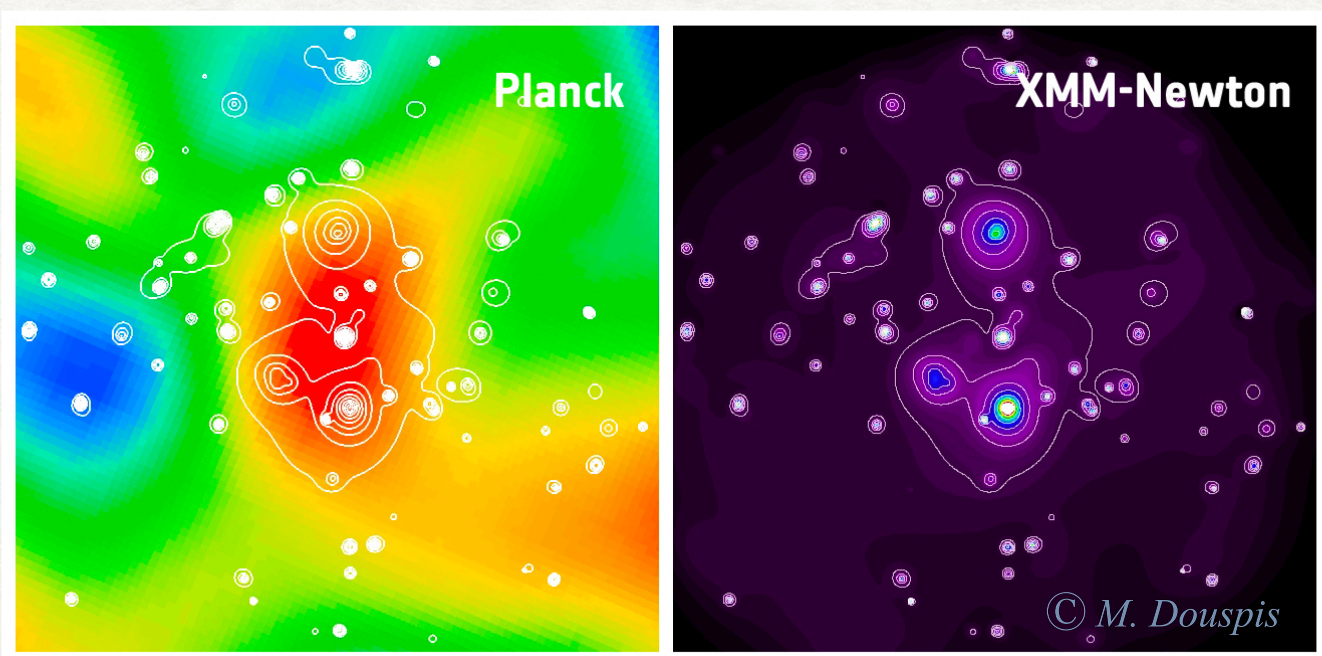


Galaxy correlation function (SDSS/BOSS)

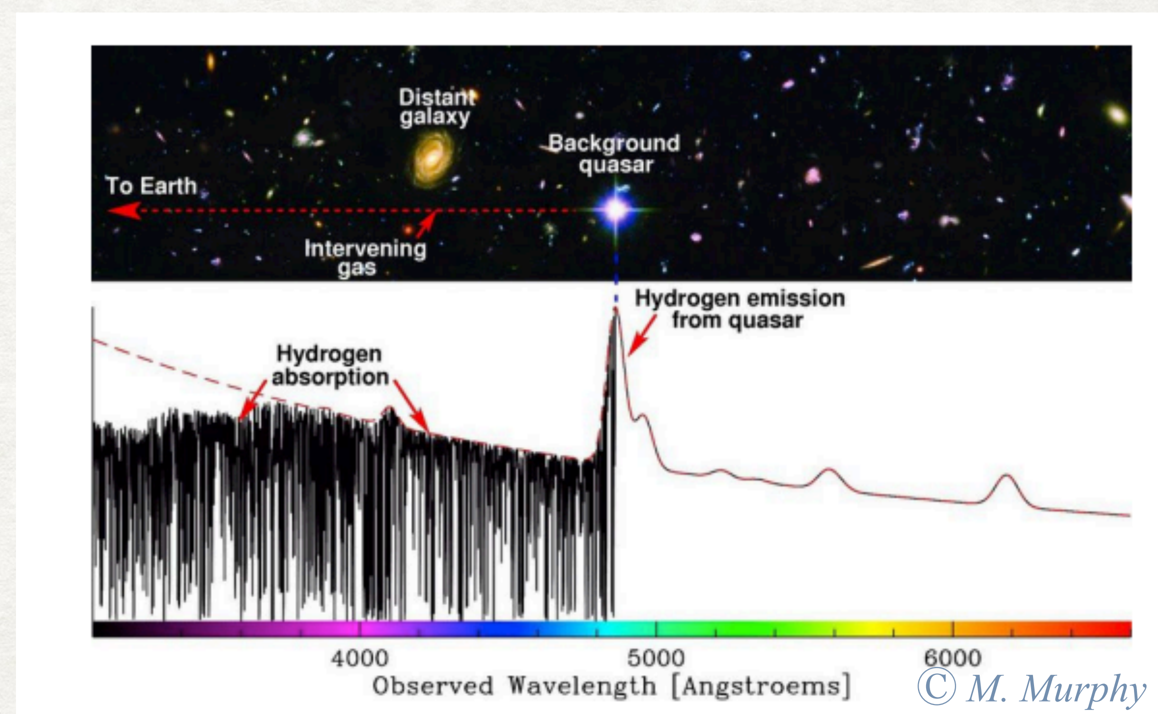


Galaxy weak lensing (KiDS / DES)

Galaxy cluster mass function

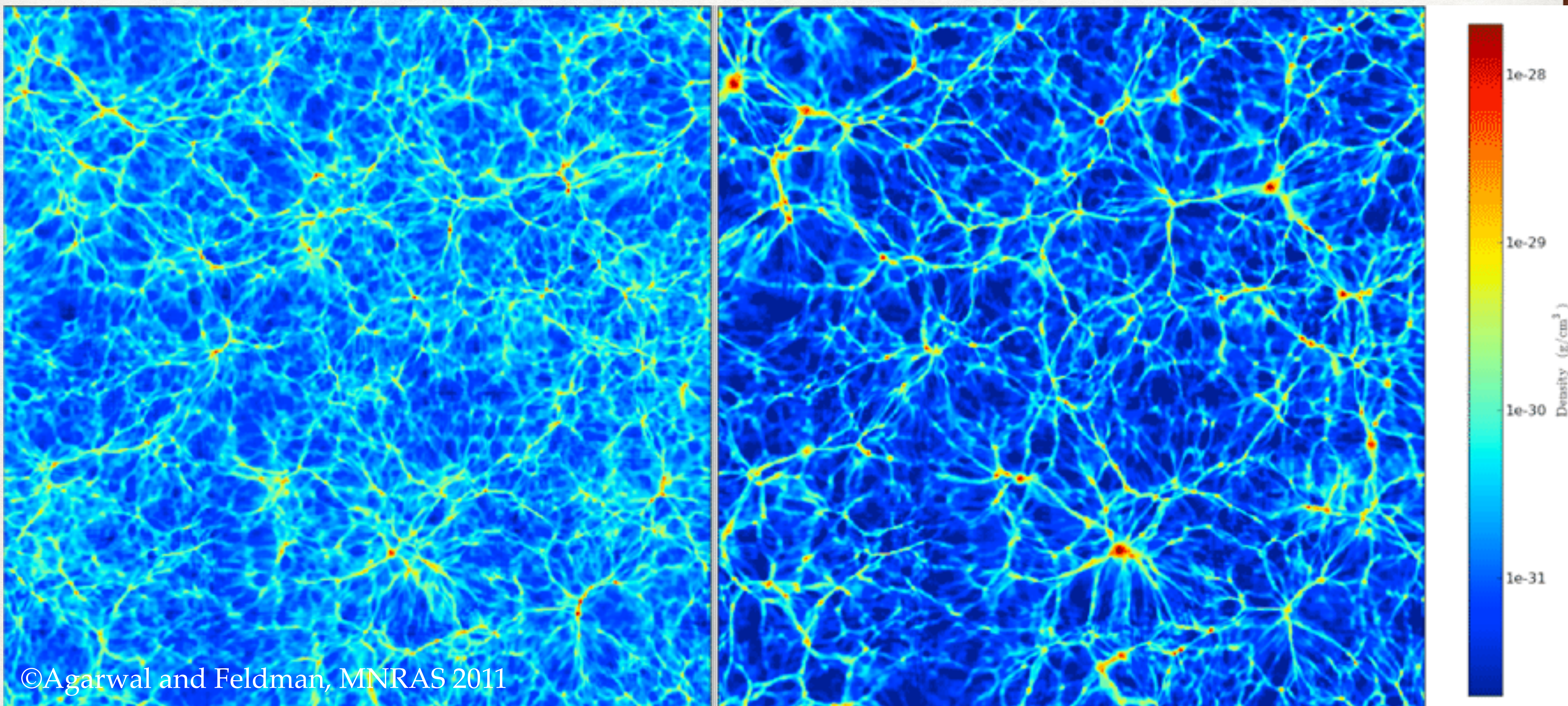


The Lyman-α forest (MIKE/HIRES)



m_ν suppresses the clustering of matter

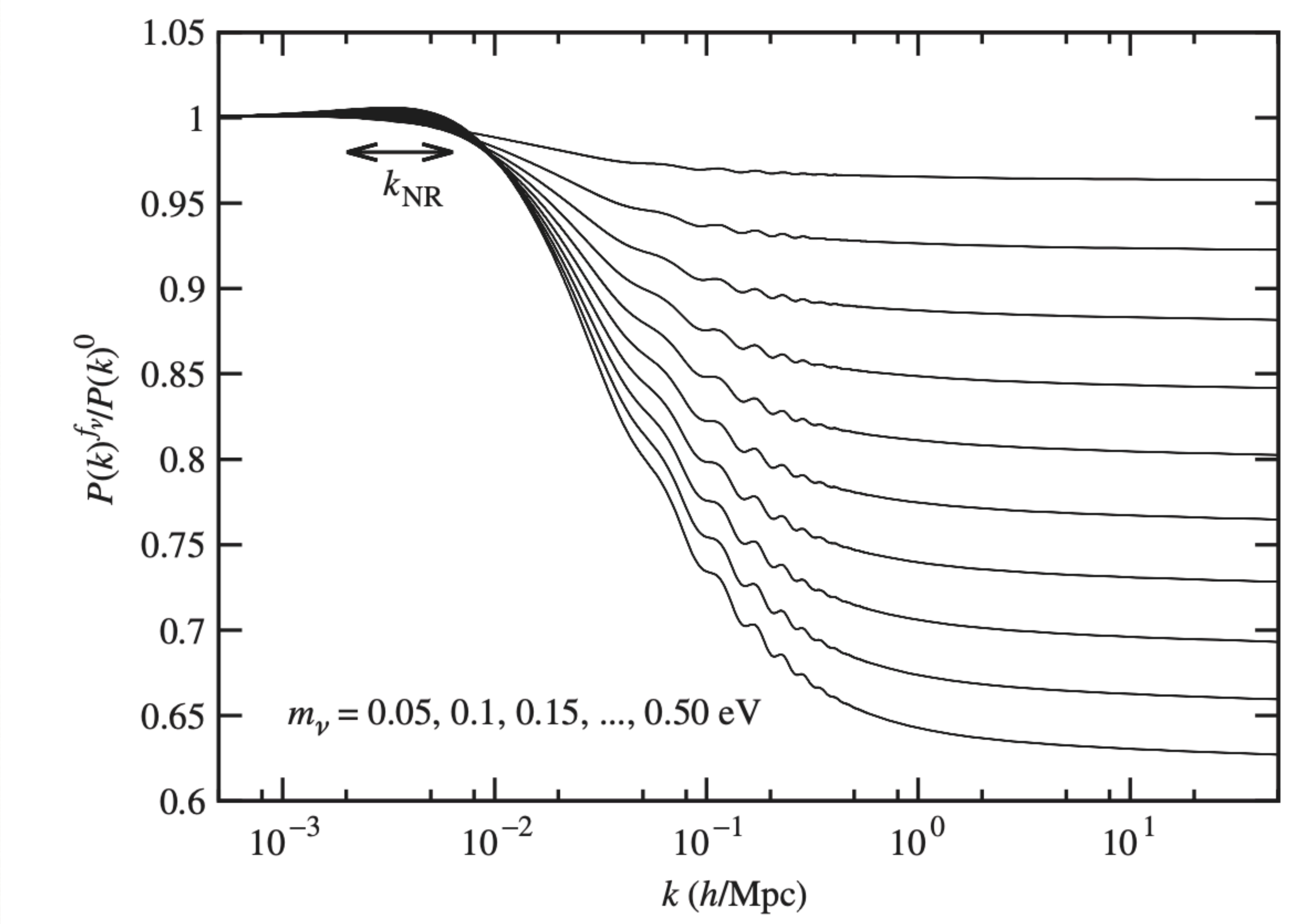
$M_\nu = 1.9$ eV $\qquad\qquad$ $M_\nu = 0$ eV



The density field is "smoother" on small scales

m_ν suppresses the matter power spectrum

For ν's suppression at $k \geq k_{\rm nr} \equiv 0.01 \left(\frac{m_\nu}{1\text{eV}}\right)^{1/2} \left(\frac{\Omega_m}{0.3}\right)^{1/2} h\text{Mpc}^{-1}$ and amplitude $\frac{\Delta P}{P} \simeq -8 \frac{\omega_\nu}{\omega_{\rm m}}$



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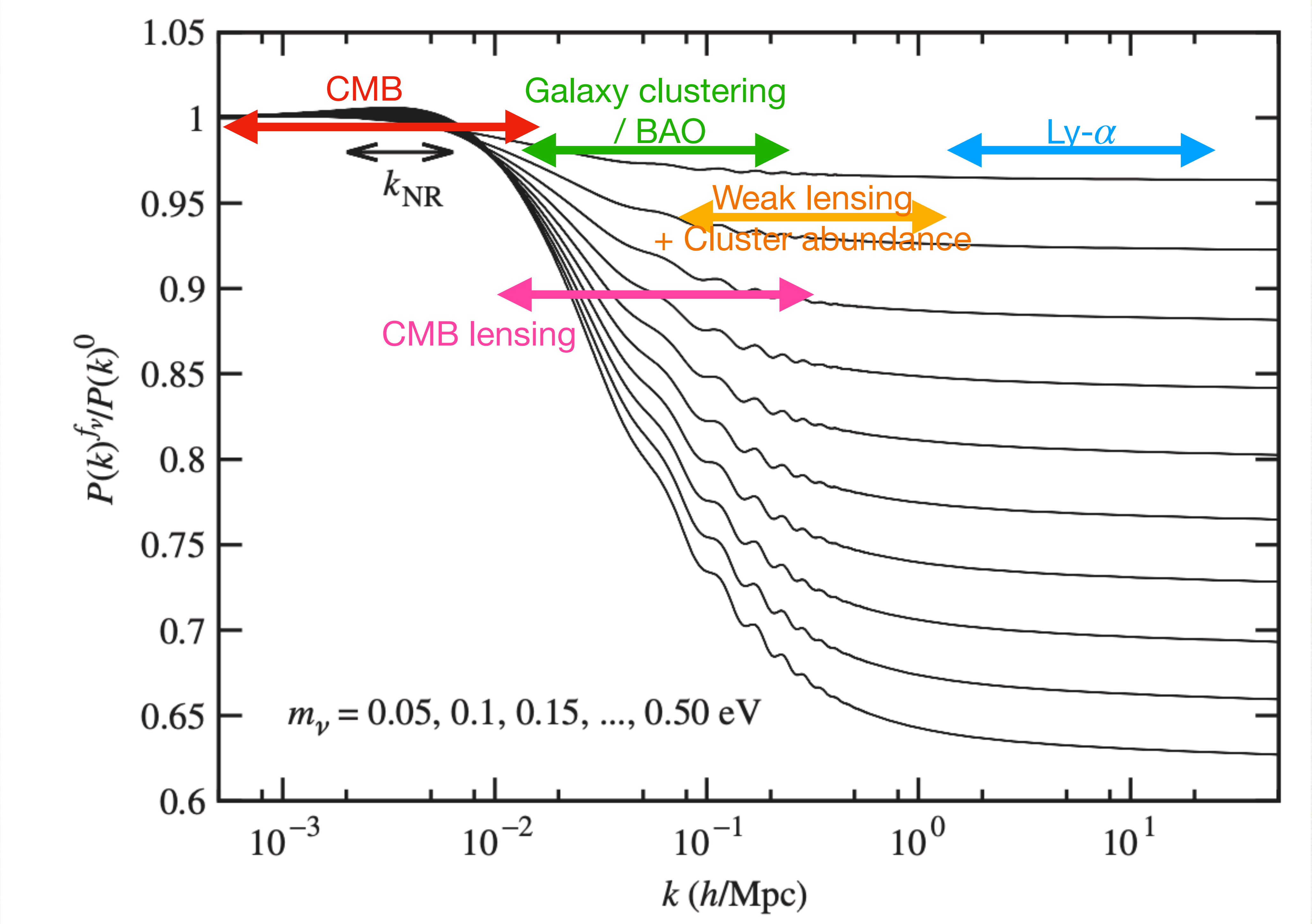
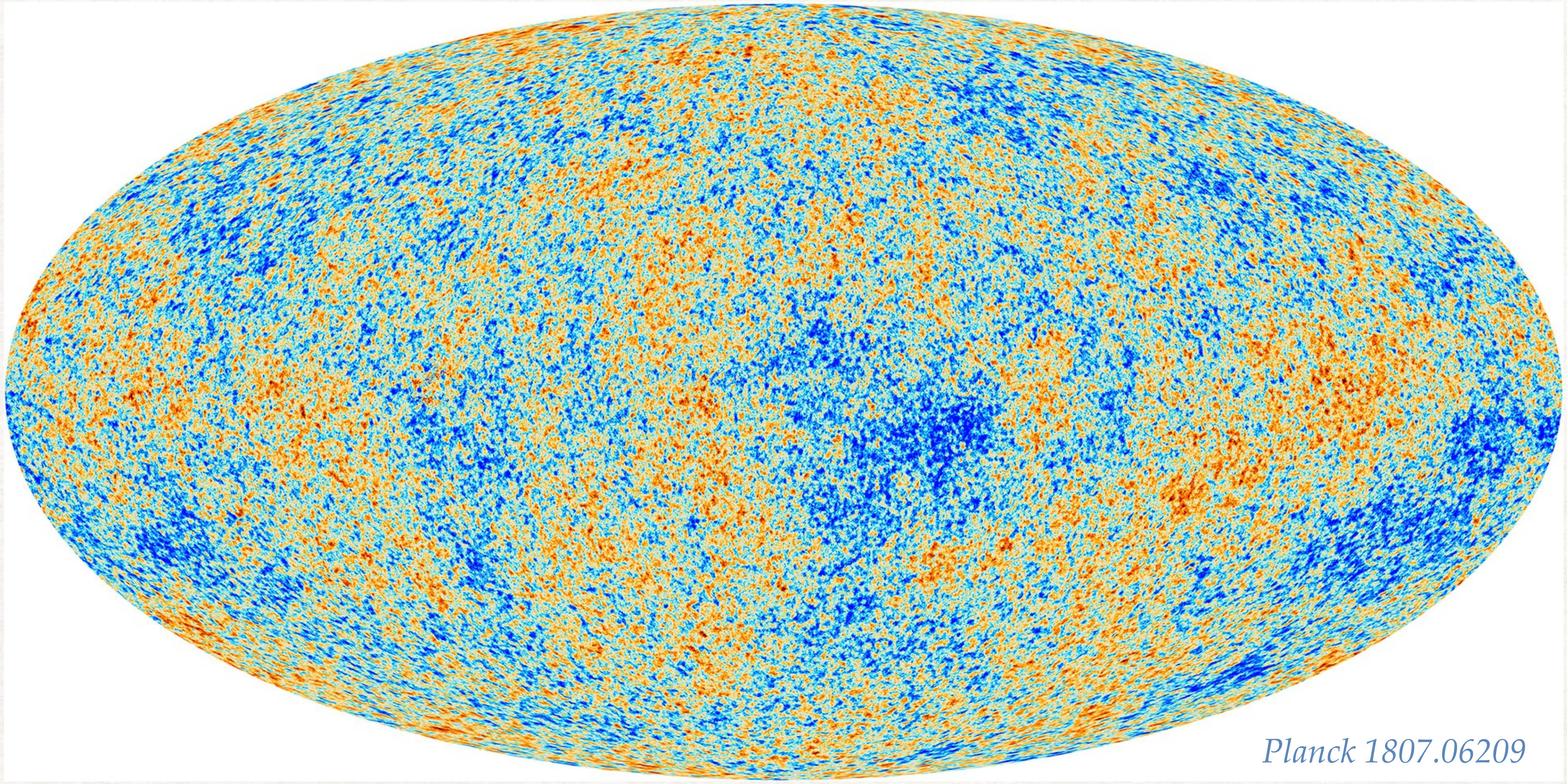


ν can affect the cosmic microwave background

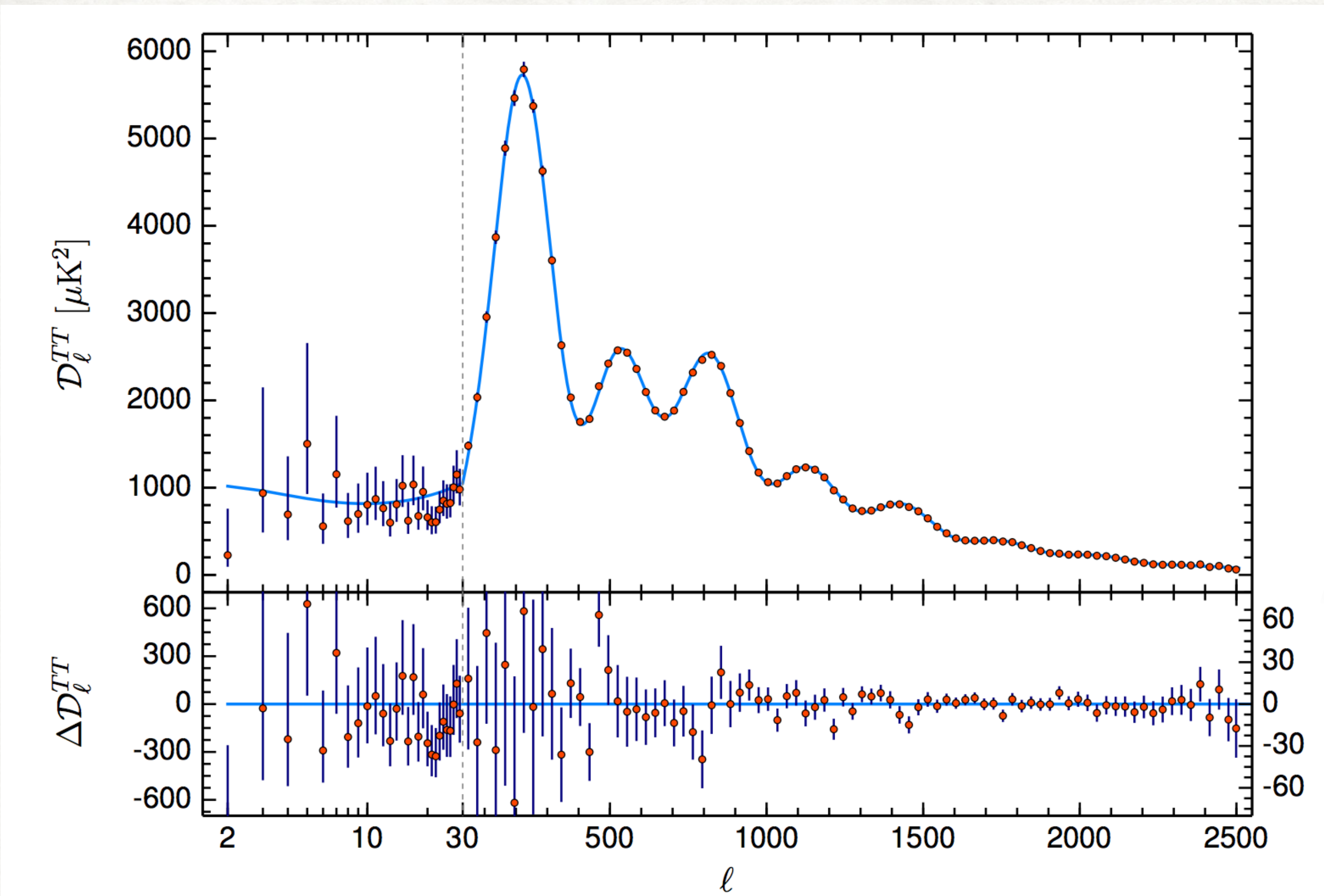
A perfect black-body carrying tiny anisotropies $\Delta T/T \sim 10^{-5}$

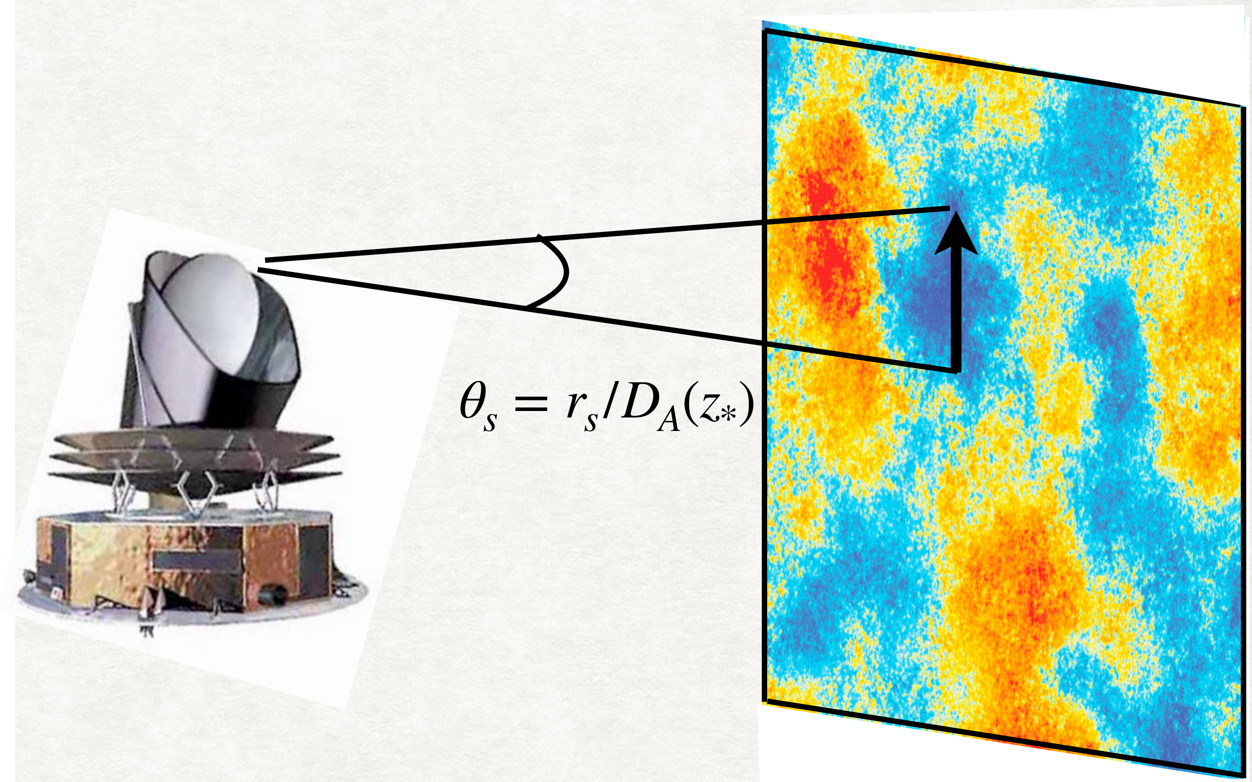


Planck 1807.06209

- Snapshot of inhomogeneities in our universe 380 000 years after the Big Bang
- Very sensitive probe of the early universe, in particular from $z \sim 10^5$ to the era of recombination

Cosmic Microwave Background power spectra

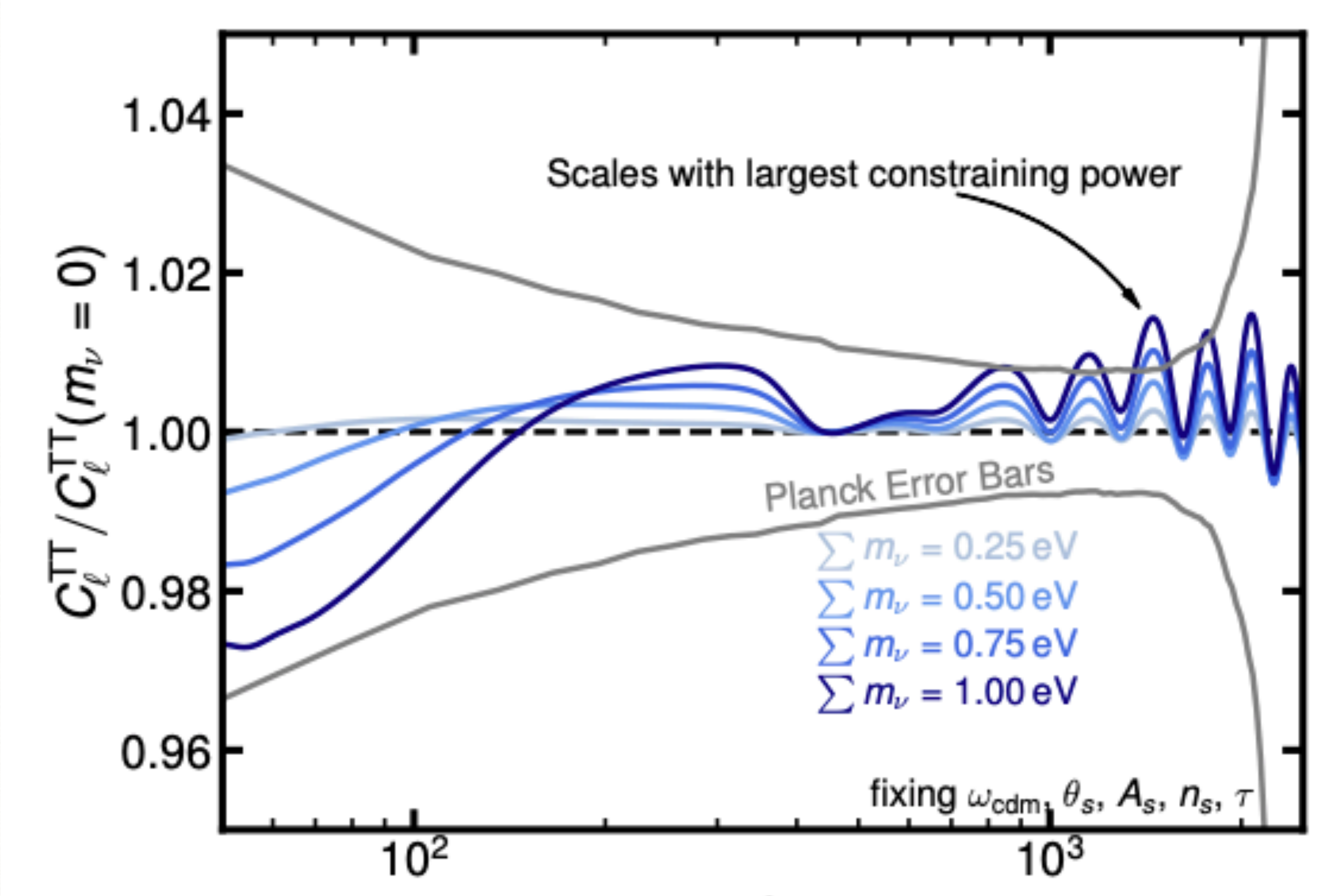




- The anisotropy pattern is due to an acoustic wave propagating in the plasma: baryon acoustic oscillations.
- The CMB power spectra carries information about the plasma in which the wave propagated.
- Characteristic scale: the sound horizon $\theta_s = r_s/D_A(z_*) \equiv \pi/\ell_s \sim 1^\circ$

m_ν affects the CMB power spectrum

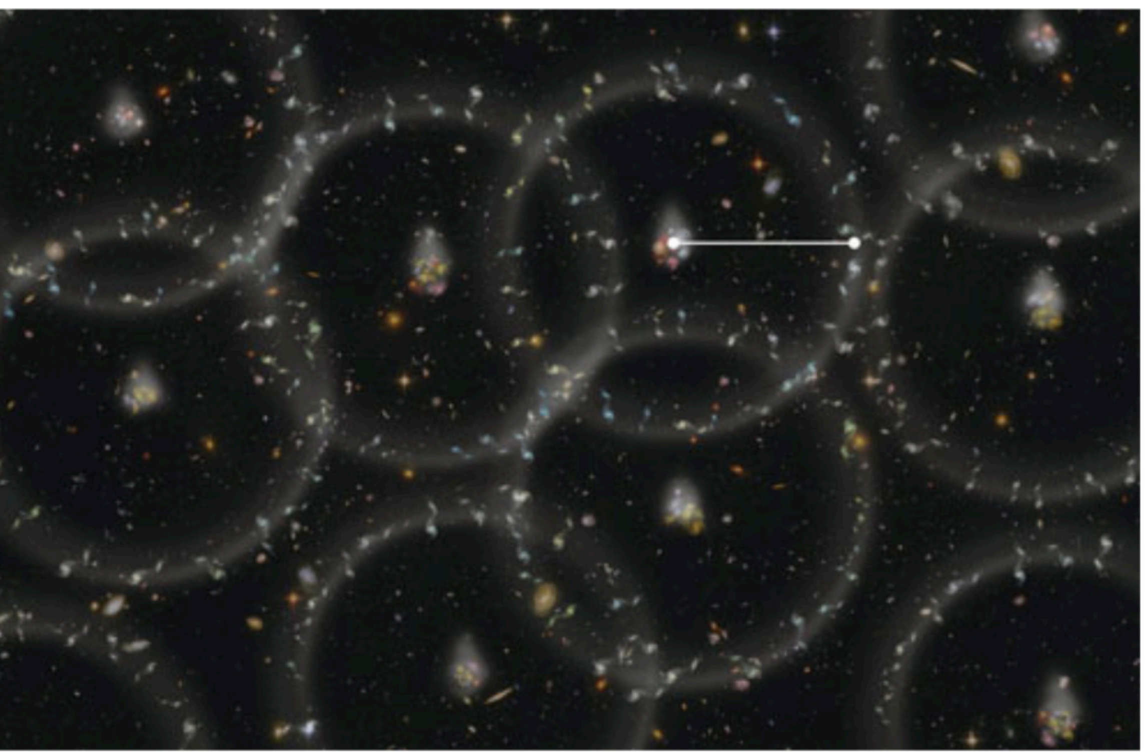
For $\sum m_\nu < 1$ eV, the main effect of neutrinos is to alter the lensing in the CMB



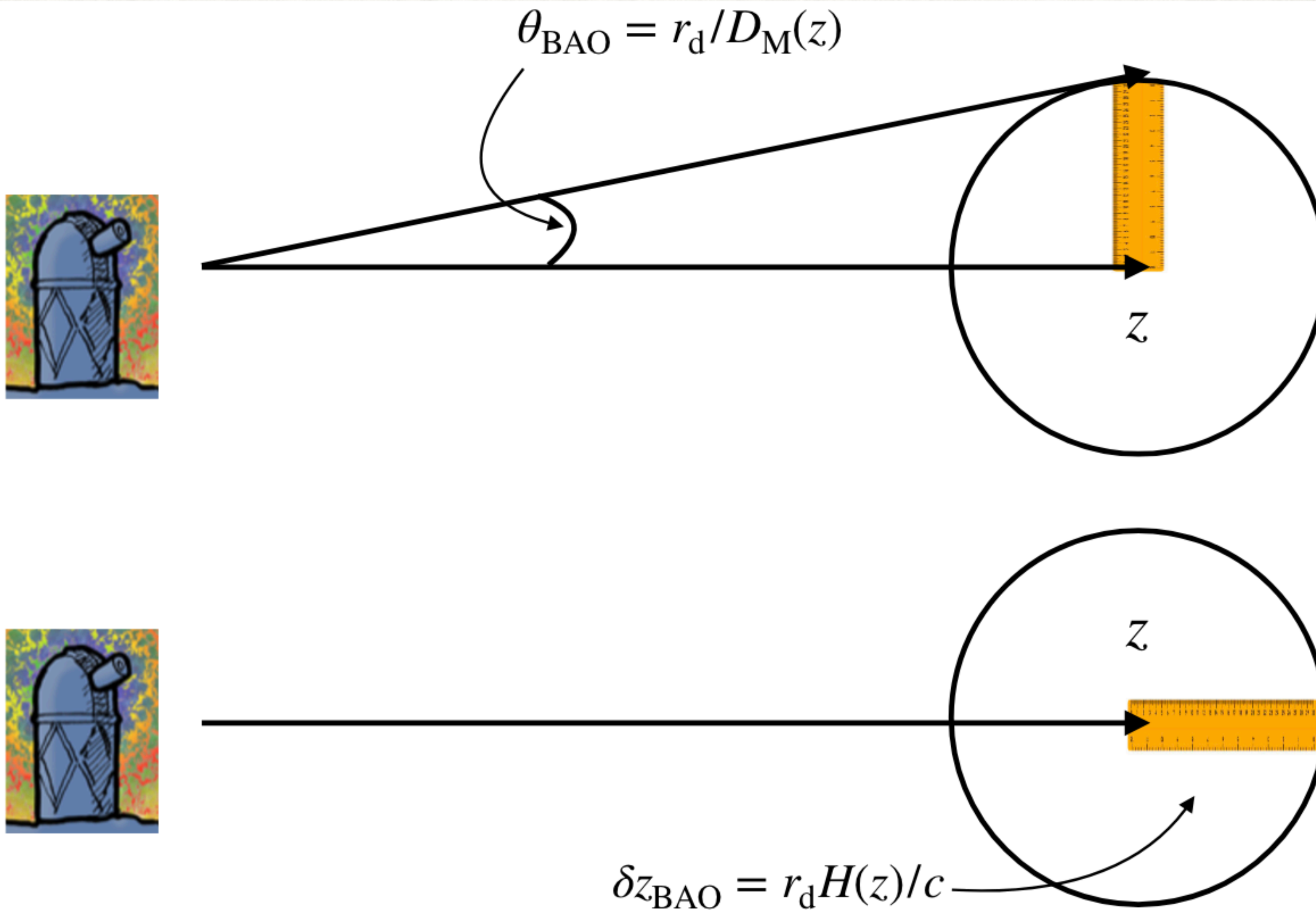
Naredo-Tuero (VP)++ 2407.13831

The Baryonic Acoustic Oscillation with DESI

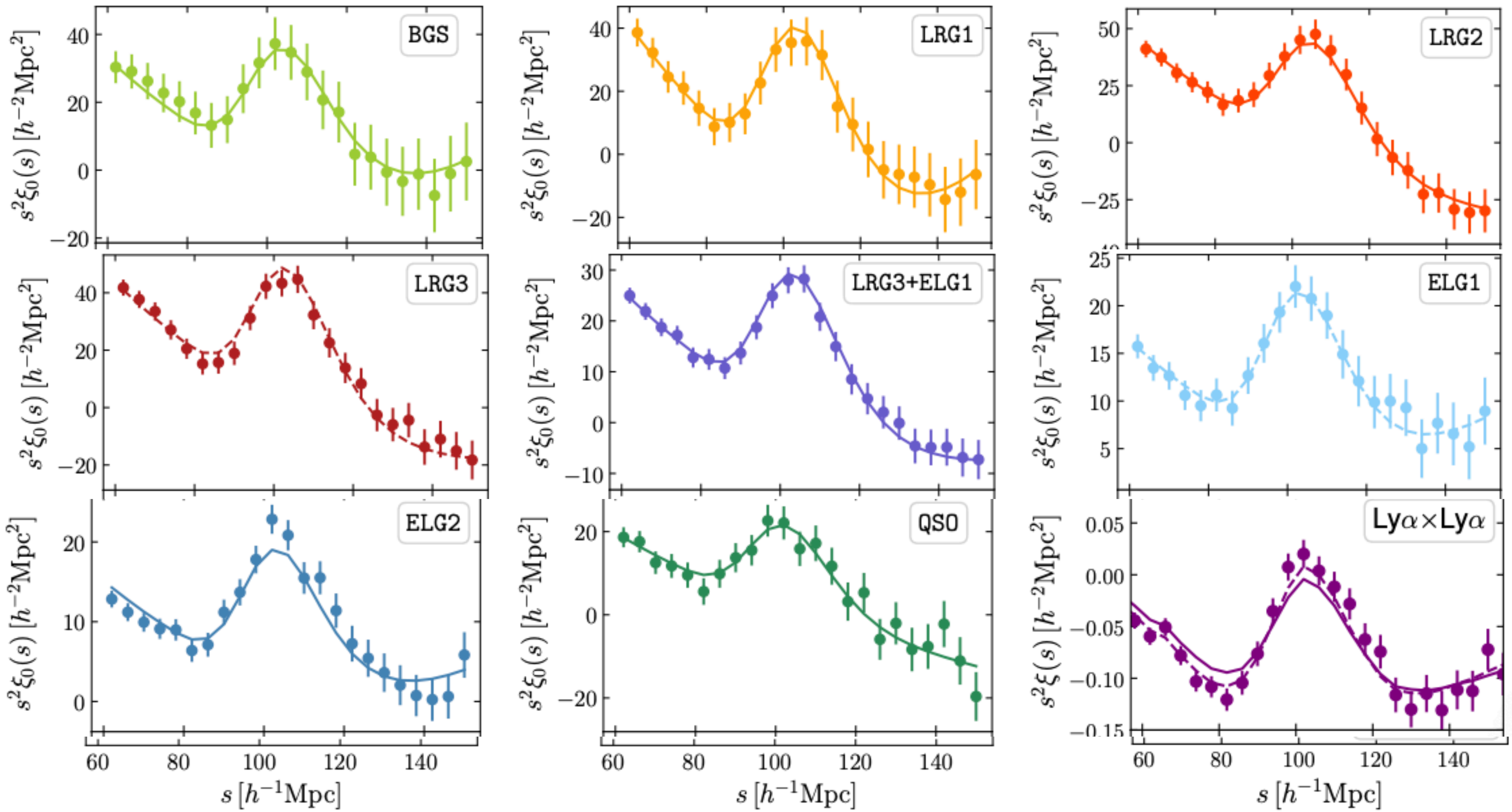
- Galaxy catalogues made of over 5 000 000 objects with $z \sim 0.1 - 2.1$
- Baryonic acoustic oscillation is the counterparts of what is seen in CMB anisotropies



Picture from Etienne Burtin



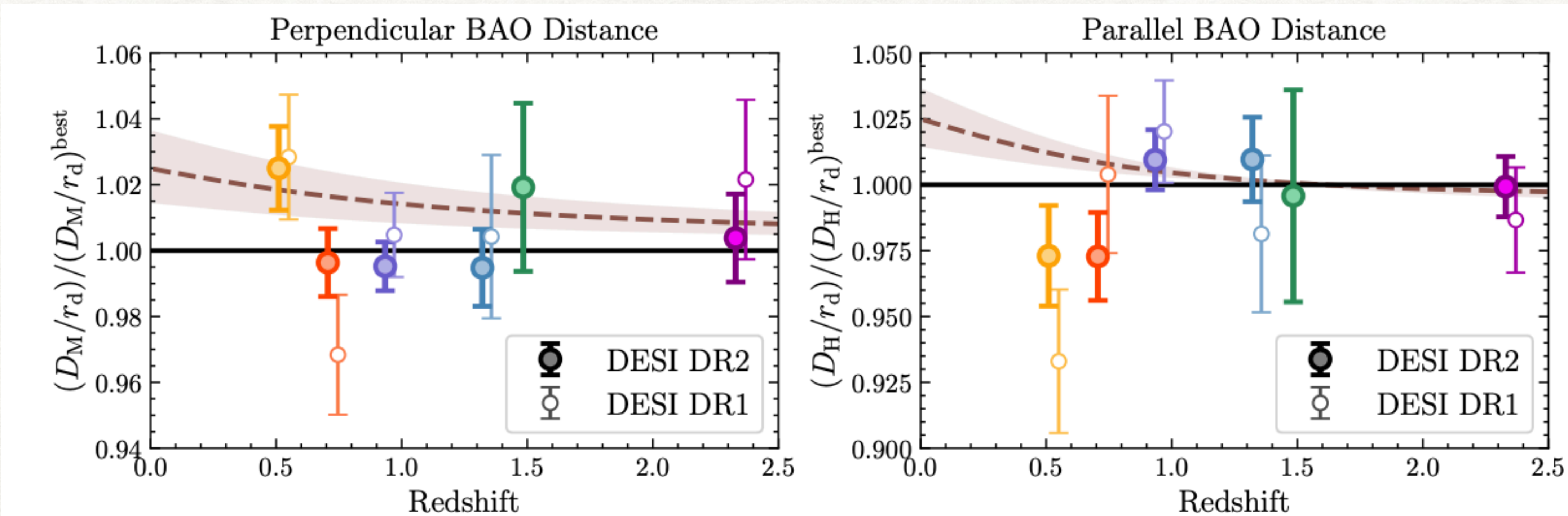
BAO measurements from DESI



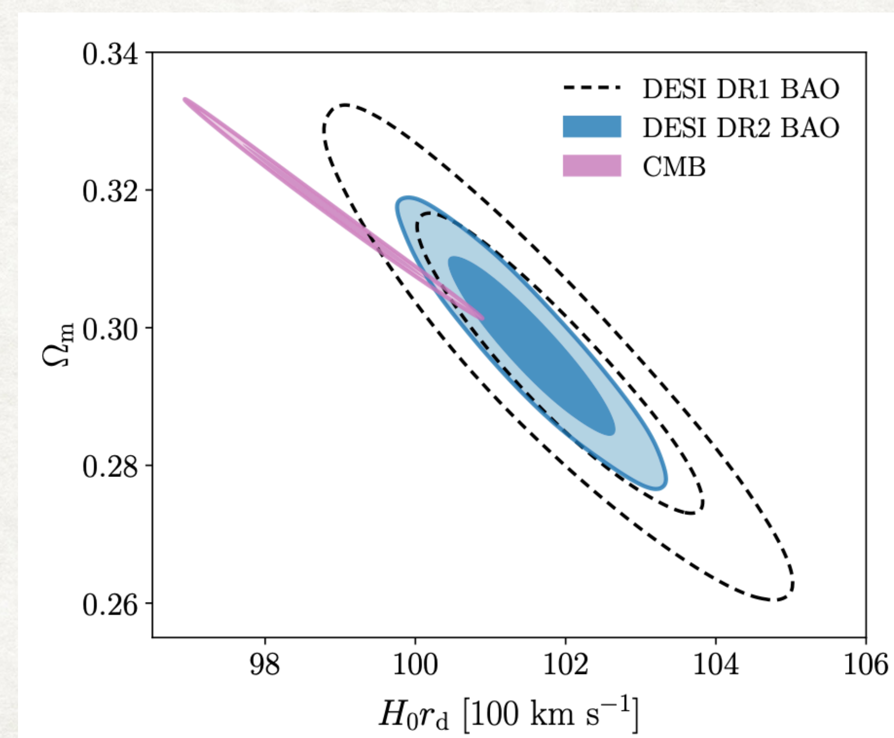
DESI 2503.14738

New Physics in DESI data?

- Under ΛCDM, 2.3σ tension between CMB and BAO data



- Under ΛCDM, the BAO allows to measure Ω_m and $H_0 r_d$.



$$\frac{r_d}{D_M} \equiv \frac{H_0 r_s(z_d)}{\int_0^z dz\left(\Omega_m[(1+z)^3-1]+1\right)^{-1/2}}$$

$$\frac{r_d}{D_H} \equiv H_0 r_s(z_d)\sqrt{\Omega_m[(1+z)^3-1]+1}$$

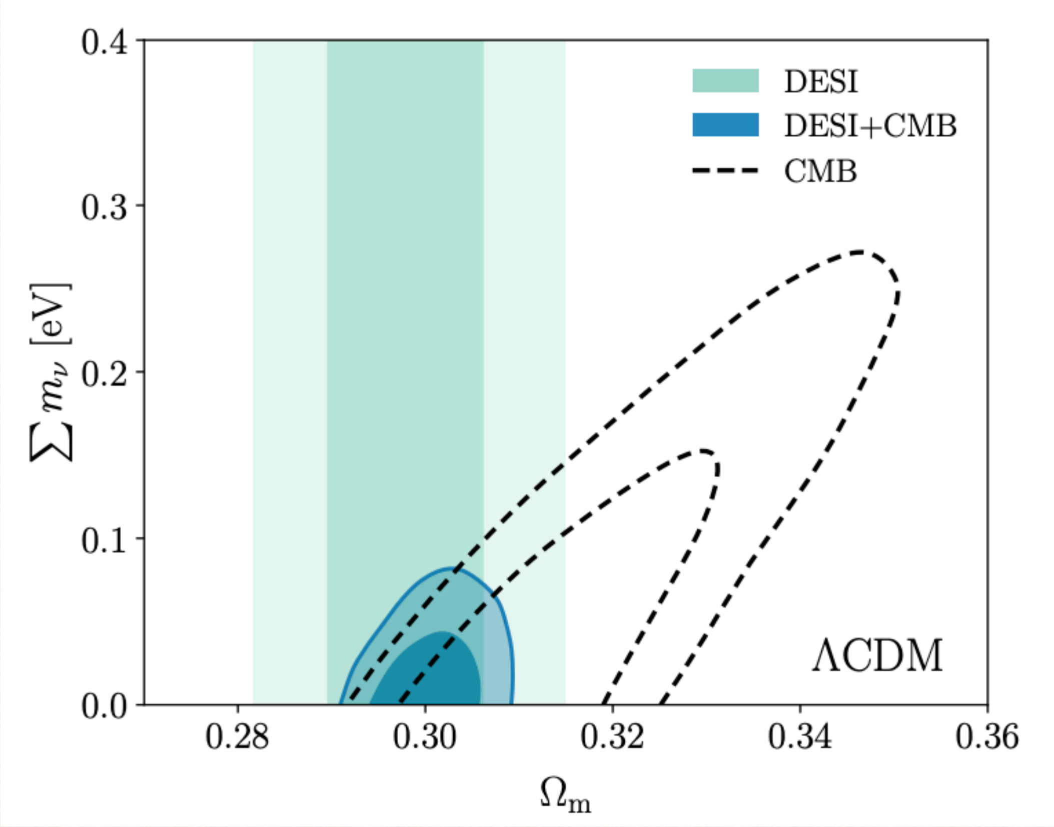
Strong constraints to M_ν from background effect

CMB+DESI $\sum m_\nu < 0.06$ eV

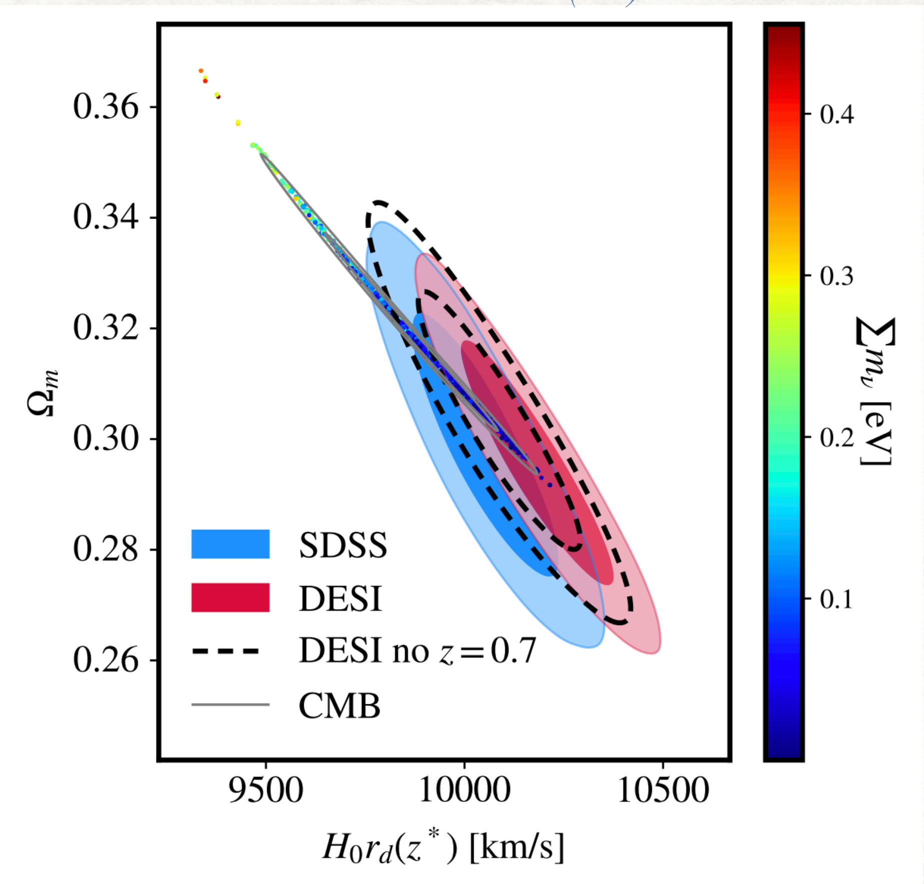
DESI 2504.18464

- ν mass also means larger Ω_m today: affects cosmological distances!
- The combination of *Planck* with BAO and SN1a breaks the degeneracy with Ω_m.
- Strong bound is driven by the mild tension in the $\Omega_m - H_0 r_d$ plane

DESI 2503.14738



Naredo-Tuero (VP)++ 2407.13831

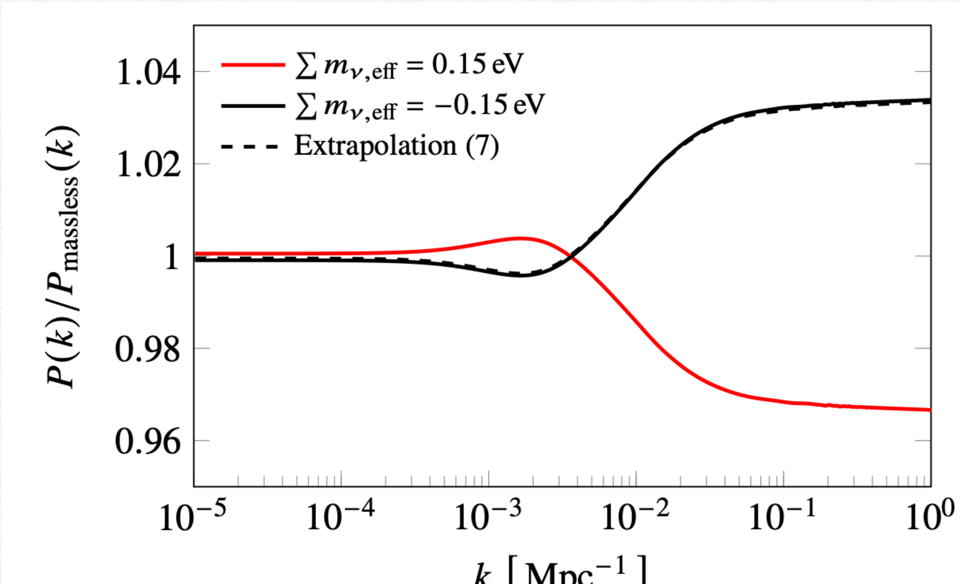


No ν's is good news?

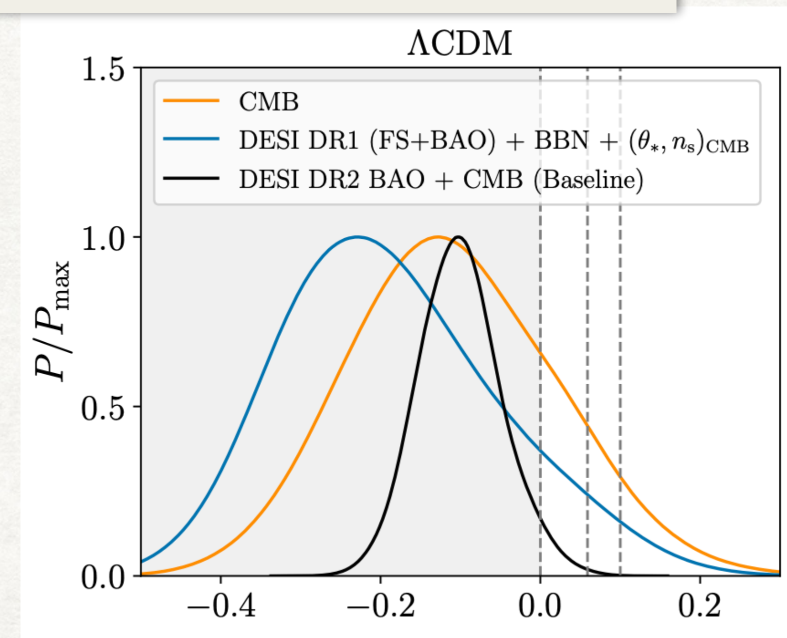
Craig++ 2405.00836

- When allowing for (effective) $m_\nu < 0$ eV

$$\sum m_{\nu,\mathrm{eff}} = -0.101^{+0.047}_{-0.056}\ \mathrm{eV}$$

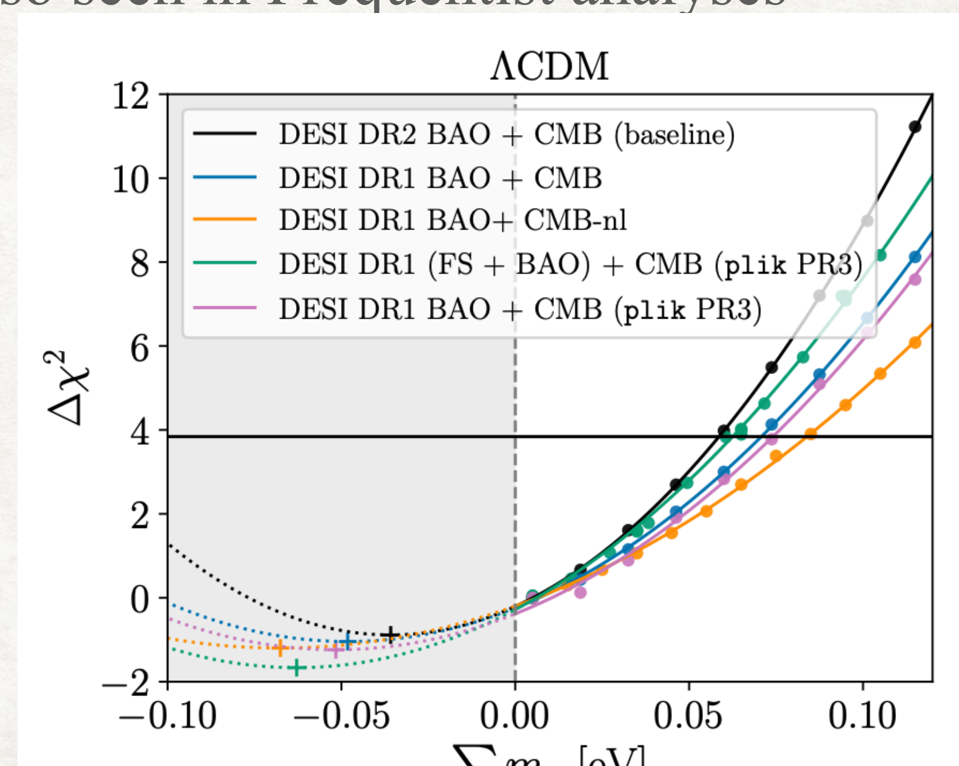


Elbers++ 2407.10965

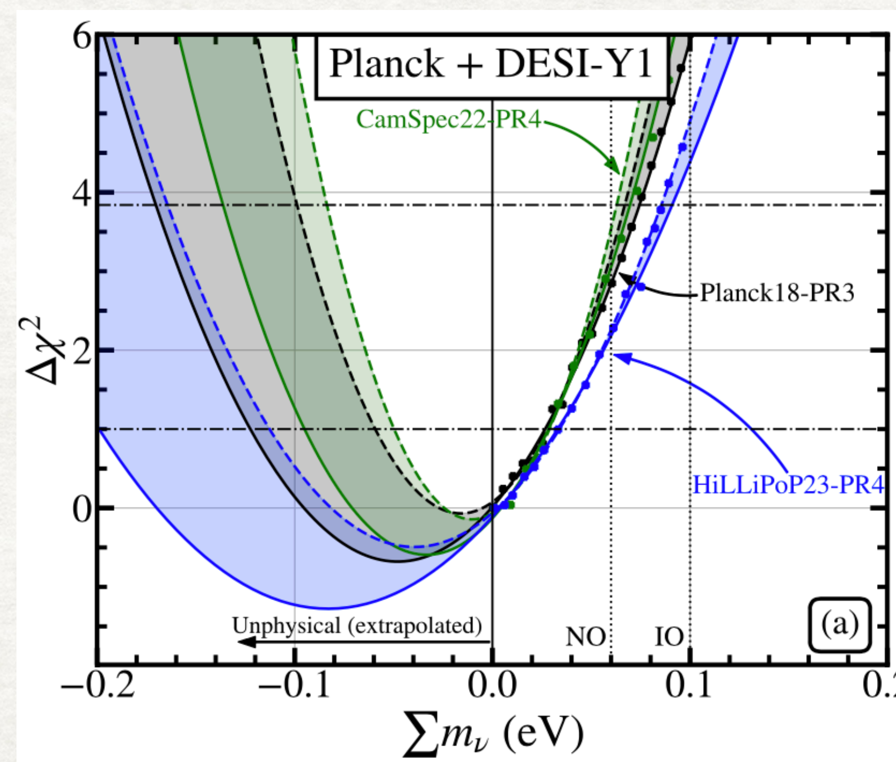


DESI 2503.14744

- Also seen in Frequentist analyses



DESI 2503.14744



Naredo-Tuero (VP)++ 2407.13831

A statistical fluke?

Science | Current Issue | First release papers | Archive | About | Submit manuscript

HOME > SCIENCE > VOL. 388, NO. 6743 > DIRECT NEUTRINO-MASS MEASUREMENT BASED ON 259 DAYS OF KATRIN DATA

RESEARCH ARTICLE | PARTICLE PHYSICS

Direct neutrino-mass measurement based on 259 days of KATRIN data

Abstract

That neutrinos carry a nonvanishing rest mass is evidence of physics beyond the Standard Model of elementary particles. Their absolute mass holds relevance in fields from particle physics to cosmology. We report on the search for the effective electron antineutrino mass with the KATRIN experiment. KATRIN performs precision spectroscopy of the tritium β-decay close to the kinematic endpoint. On the basis of the first five measurement campaigns, we derived a best-fit value of $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$, resulting in an upper limit of $m_\nu < 0.45$ eV at 90% confidence level. Stemming from 36 million electrons collected in 259 measurement days, a substantial reduction of the background level, and improved systematic uncertainties, this result tightens KATRIN's previous bound by a factor of almost two.

- Within Katrin, it is attributed to under fluctuations compatible with statistical fluke
- There are two main reasons driving this preference in CMB data, both still compatible with fluke

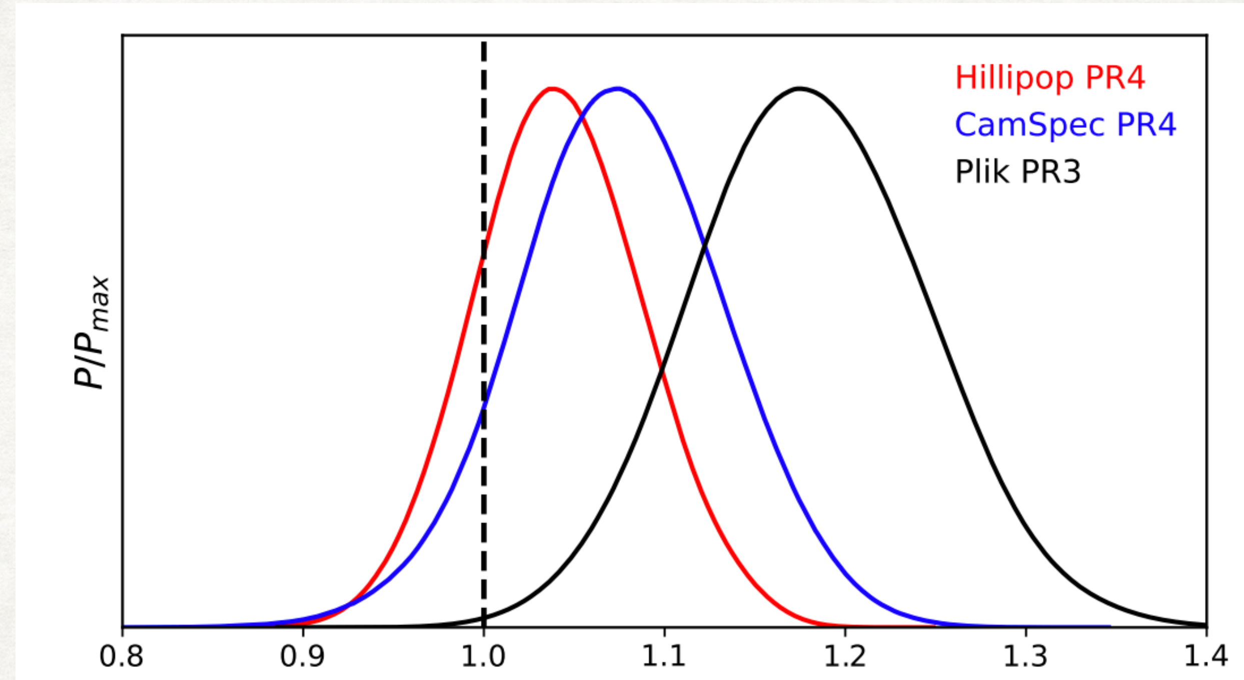
$m_\nu < 0$ is due to a "lensing anomaly" in Planck

- Planck 2018 has an anomalous amount of lensing

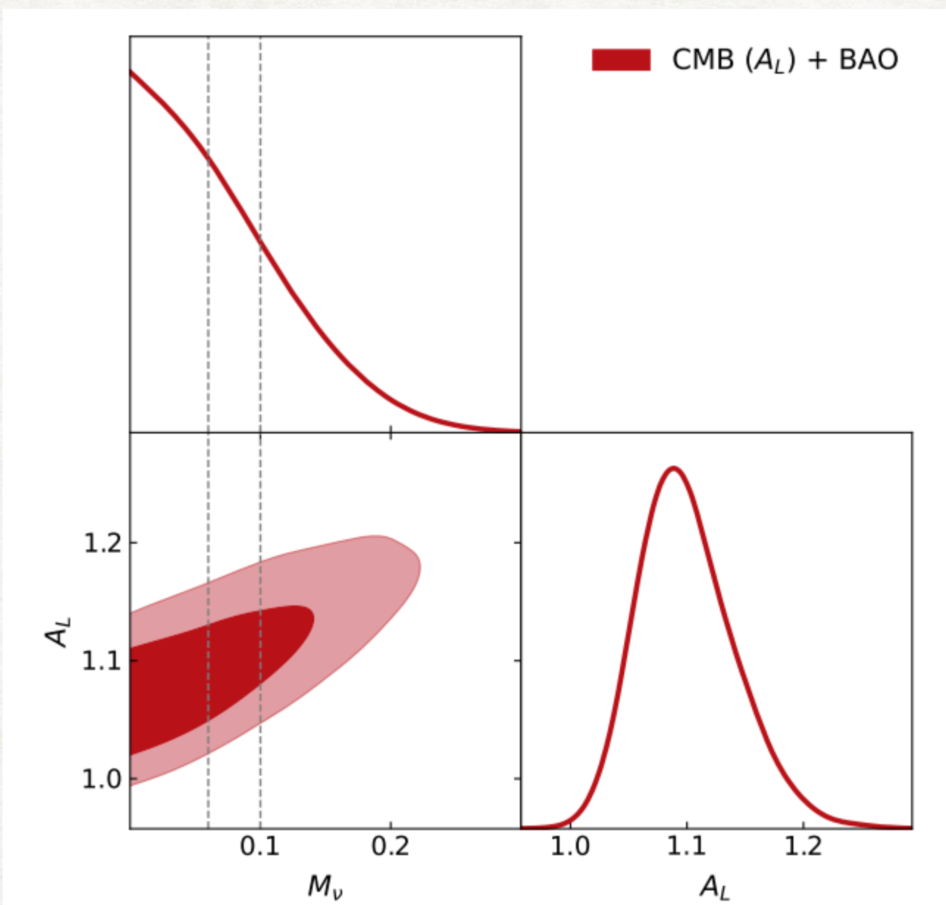
$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}, \quad A_L = 1.180 \pm 0.065$$

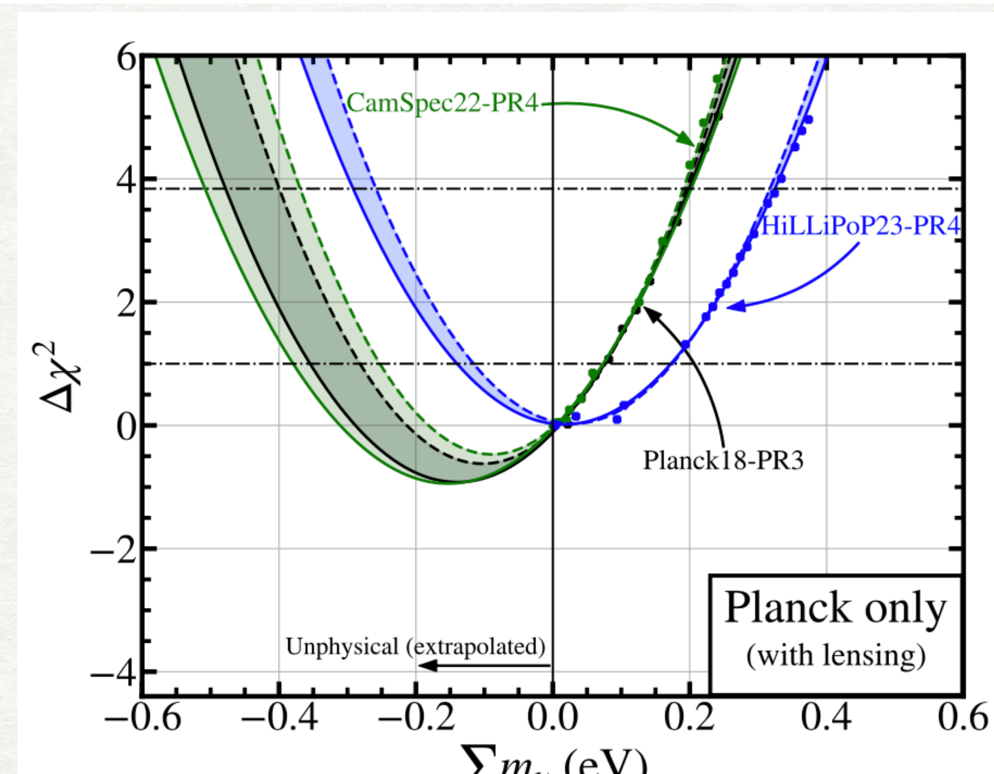
- This anomaly went down with PR4

$$A_L = 1.039 \pm 0.052$$



Tristram++ 2309.10034





Naredo-Tuero (VP)++ 2407.13831

- The preference for $m_\nu < 0$ goes away when using a newer version *Planck* data (NPIPE)

The role of the optical depth τ

- The amplitude is correlated with the optical depth to reionization τ

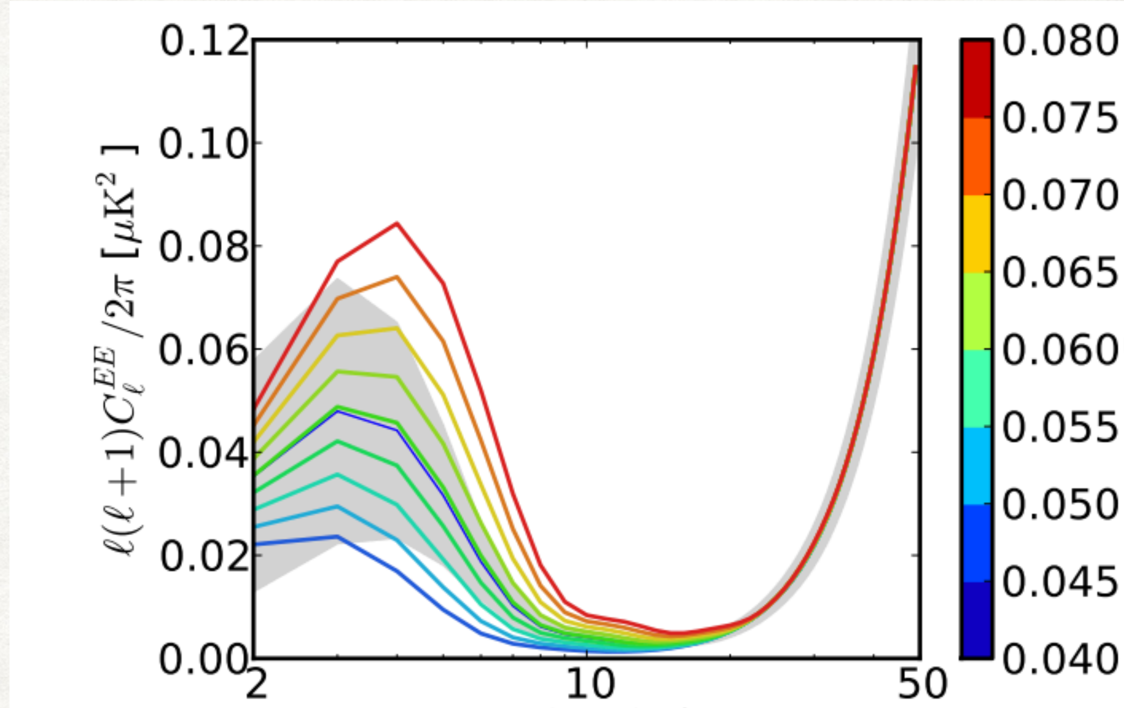
$$C_\ell \propto A_s \exp(-2\tau)$$

- The low-ℓ EE spectrum constrains

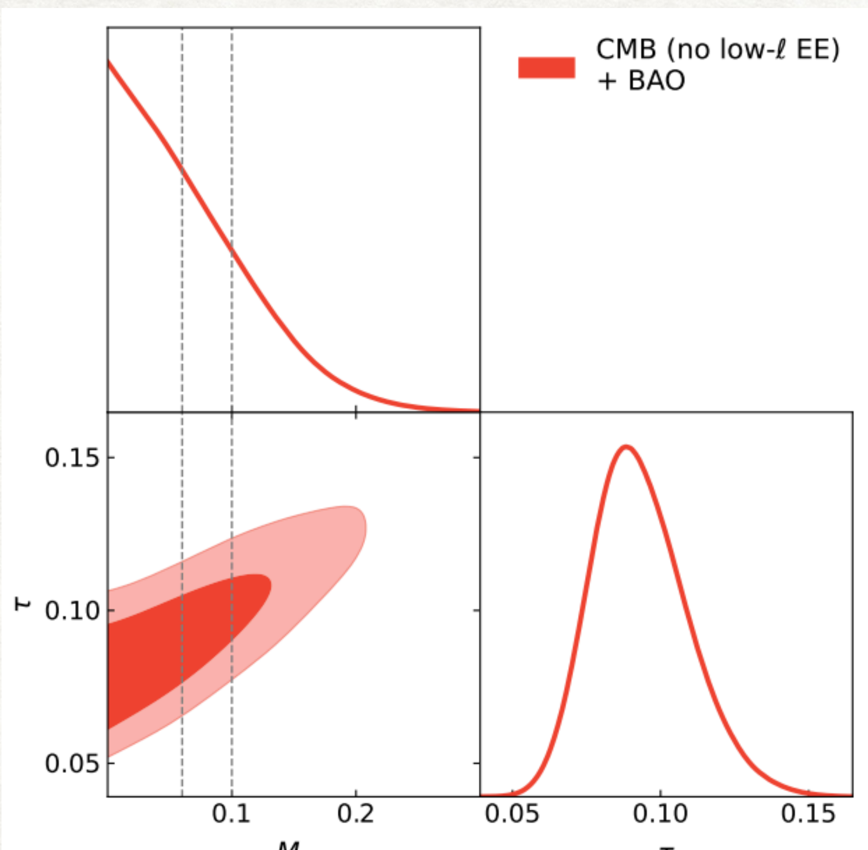
$$\tau = 0.0592 \pm 0.0062$$

- Without low$-\ell$ EE information,

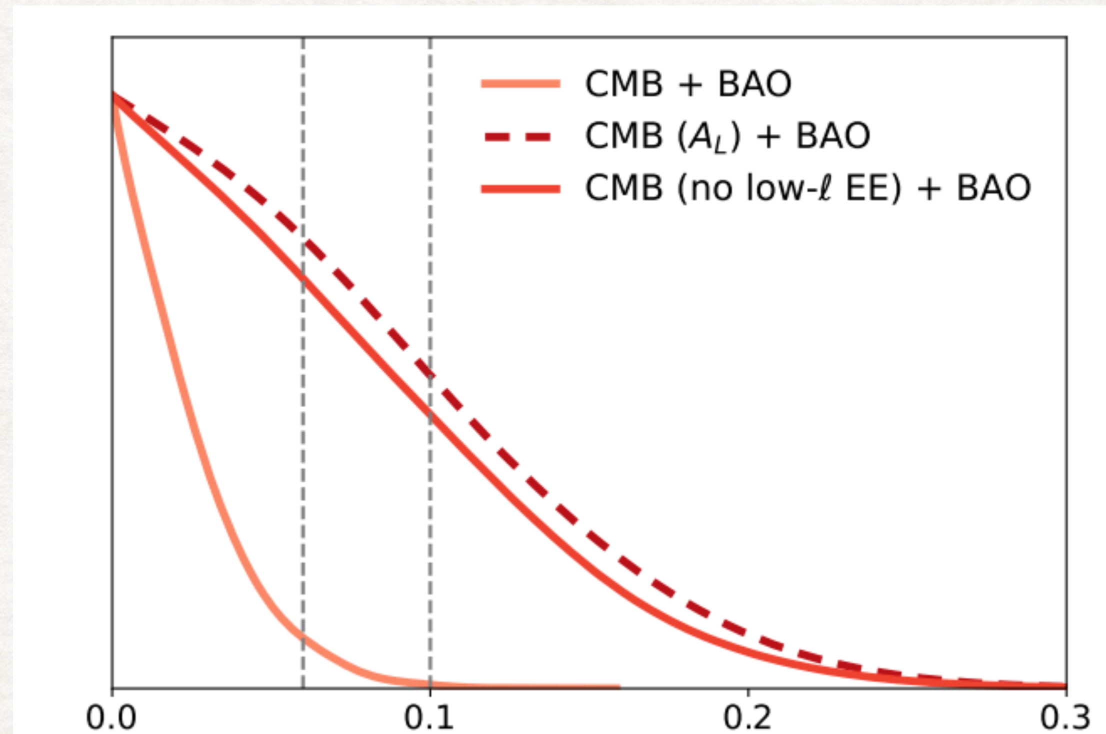
$$\tau = 0.09 \pm 0.012\,, \quad \sum m_\nu < 0.2 \text{ eV}$$



Planck 2016

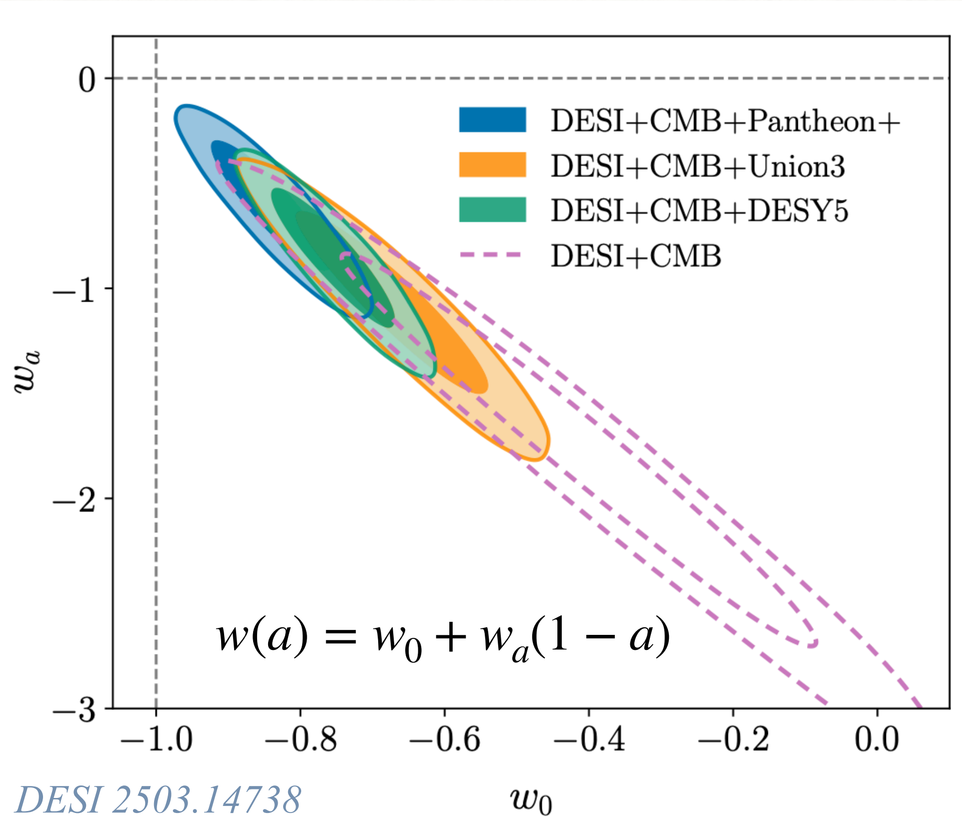


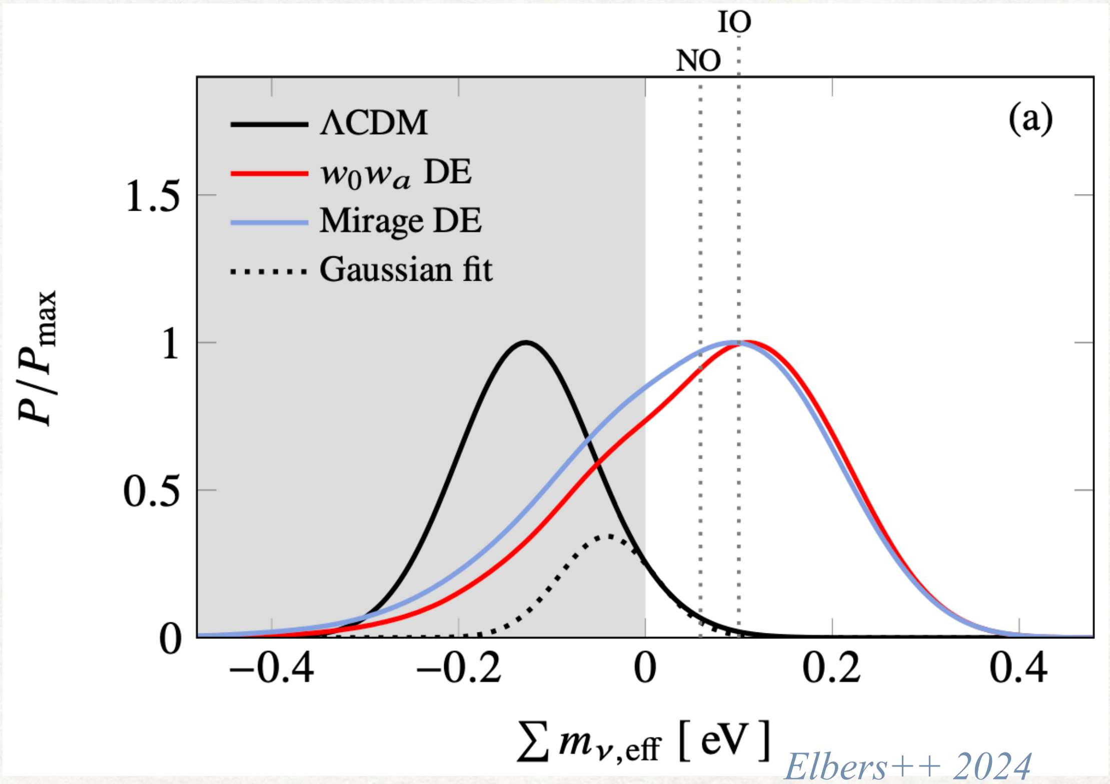
Karwal+ 2504.21813

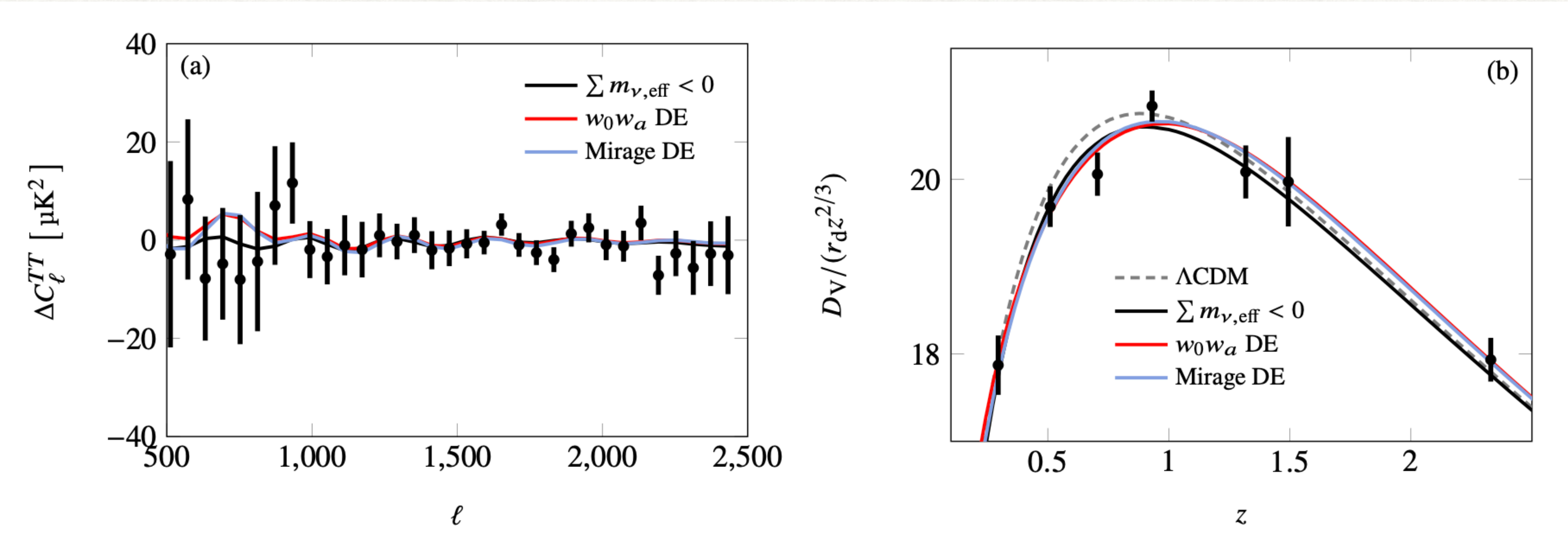


Karwal+ 2504.21813

m_ν is degenerate with the effect of dark energy







Summary of neutrino mass bounds

DESI 2503.14744, 2504.18464

- Despite anomalies, it is hard to get rid of the neutrino mass bound from cosmology

Flat ΛCDM (3 deg ν's)

Planck+DESI $\sum m_\nu < 0.064$ eV

Planck+ ACT +DESI $\sum m_\nu < 0.06$ eV

$w_0 w_a$CDM (3 deg ν's)

Planck+DESI $\sum m_\nu < 0.163$ eV

Planck+ ACT +DESI $\sum m_\nu < 0.152$ eV

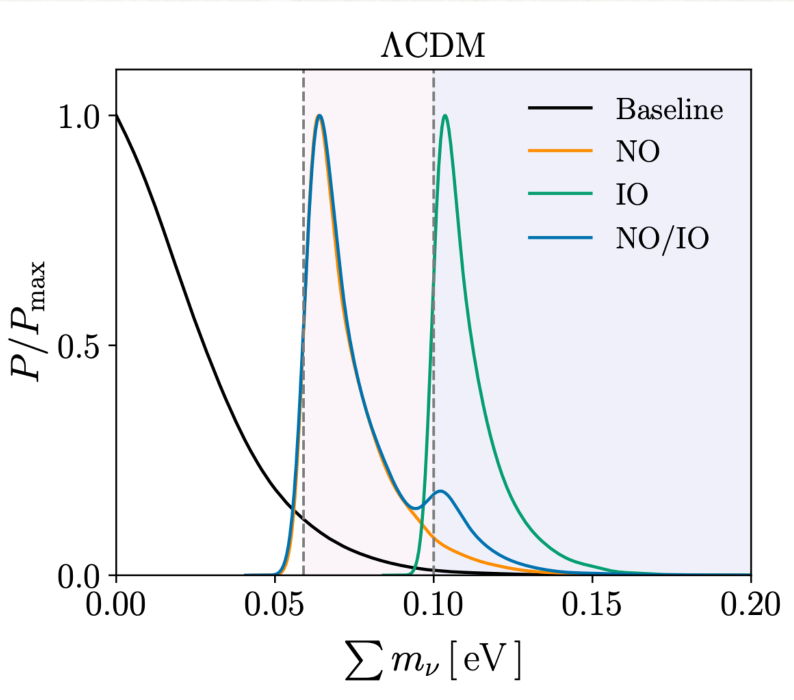
Planck+ ACT + SN1a $\sum m_\nu < 0.117$-0.139 eV

- Enforcing neutrino mass ordering leads to a preference for NO over IO at 10 : 1

Planck + DESI + NuFIT6.0 (ΛCDM)

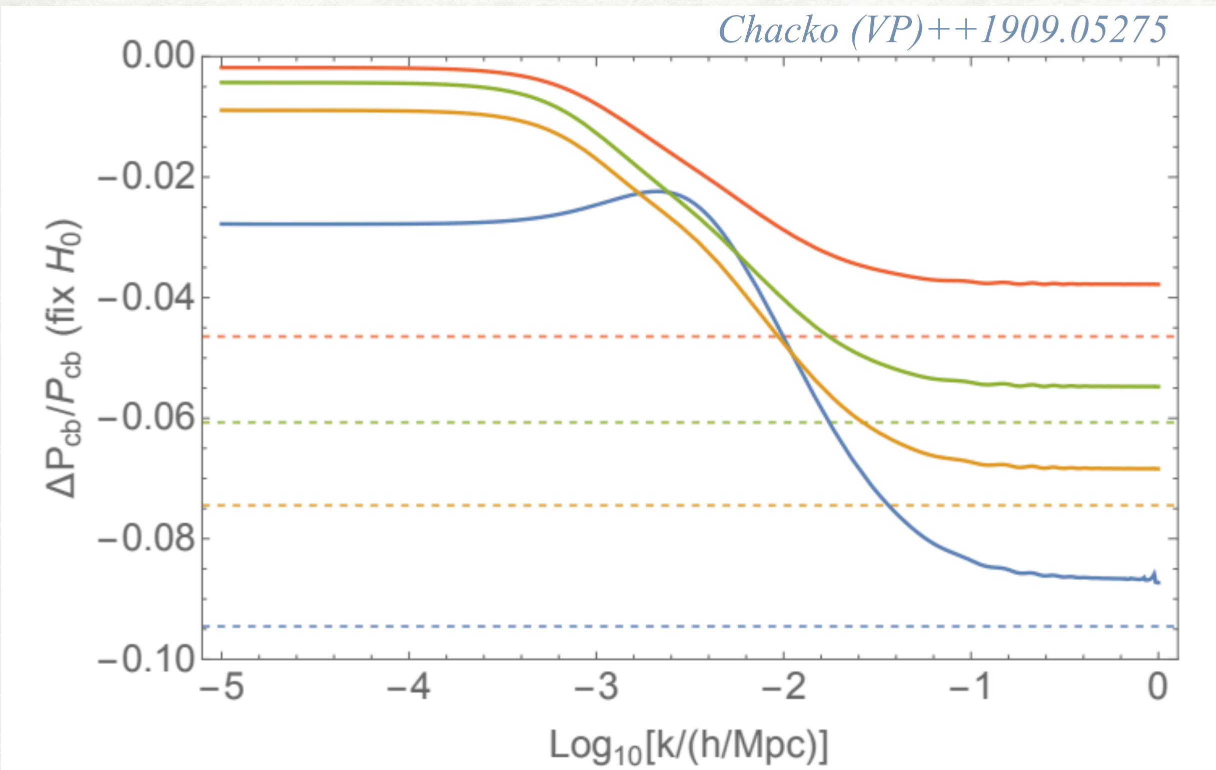
NO $\sum m_\nu < 0.101$ eV $\Rightarrow m_l < 0.023$ eV

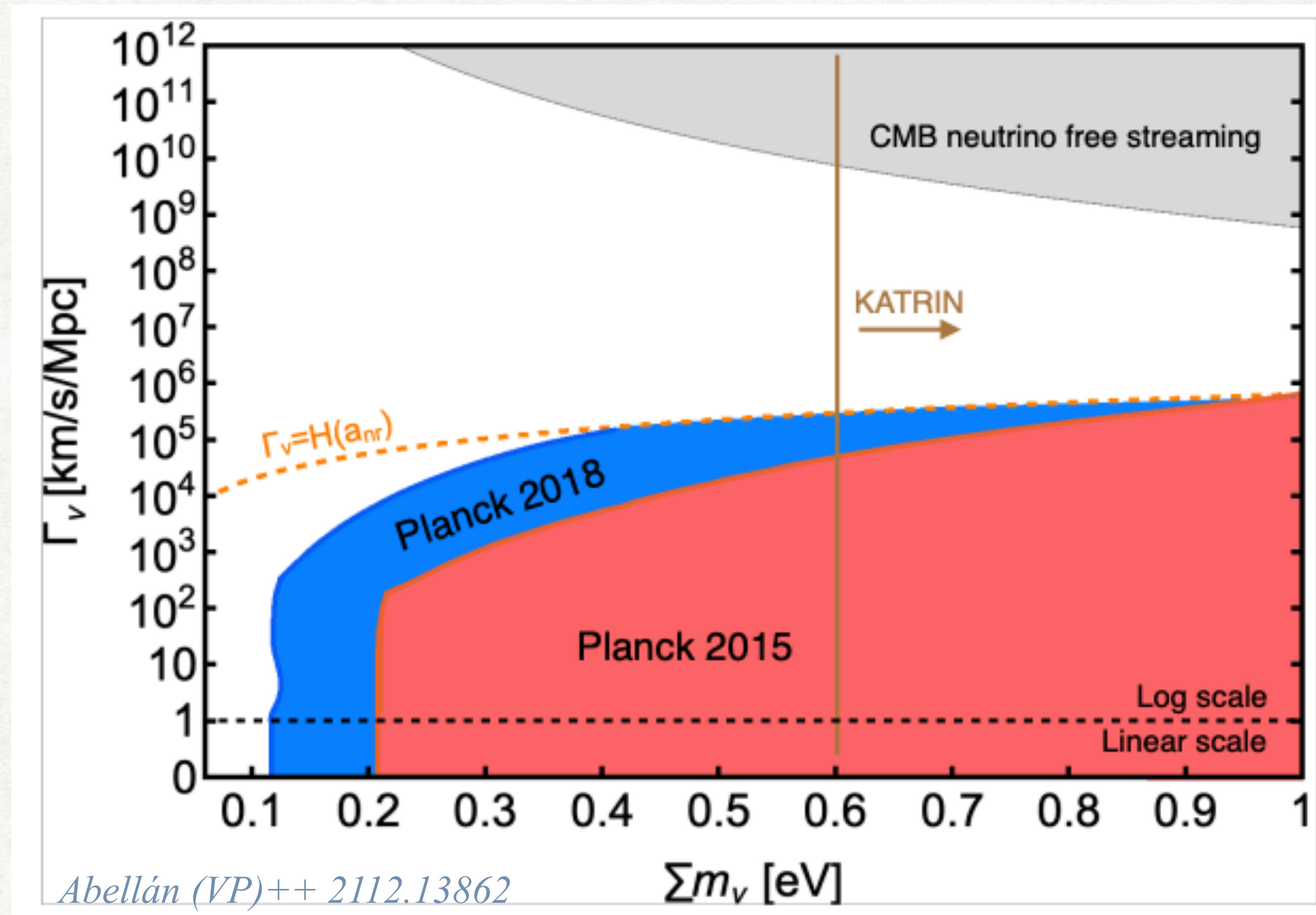
IO $\sum m_\nu < 0.133$ eV $\Rightarrow m_l < 0.024$ eV



ν decays could explain no cosmological detection

- Consider a scenario where ν decay at late-times: $\nu_i \rightarrow \nu_4 \phi$ $$\bar{f}_\nu(q,\tau) = \bar{f}_{\rm ini}(q) e^{-\Gamma_\nu \int_{\tau_{\rm ini}}^{\tau} \frac{a}{\gamma(a)} d\tau'},$$





- Neutrino decays may reconcile a detection at Katrin and cosmology bounds if $\tau_\nu < 8 \times 10^{12}\mathrm{s}\ (\mathrm{eV}/m_\nu)^{3/2}$
- Detection of non-zero M_ν could lead to strong constraints on $\tau_\nu^{\rm inv.} > \tau_u \sim 10^{19} s$.

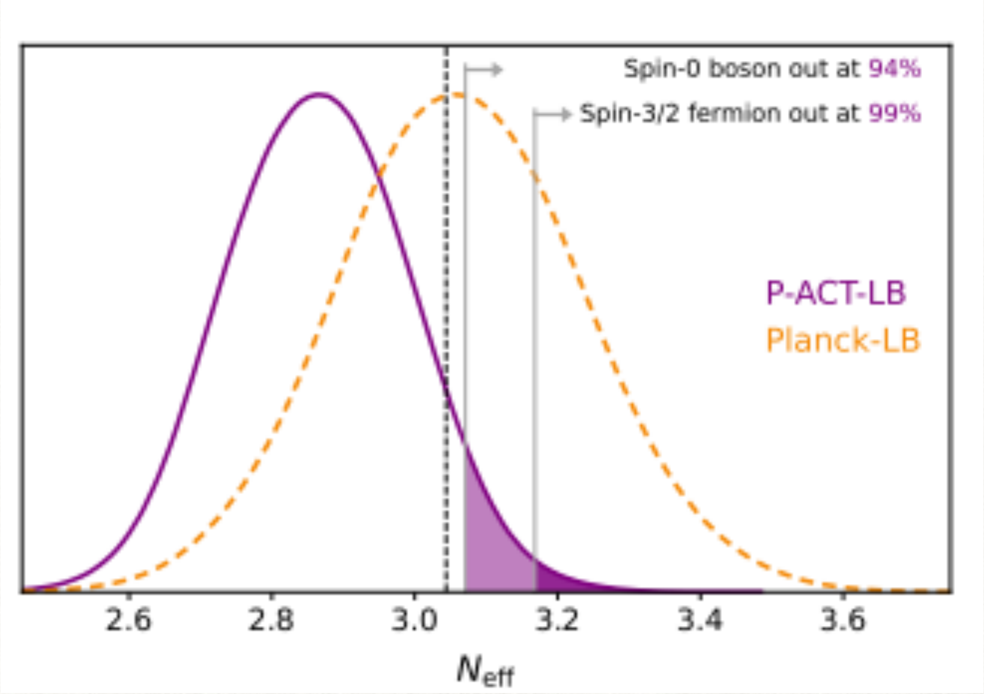
See e.g. Chacko++ hep-ph/0312267, Hannestad&Raffelt hep-ph/0509278, Archidiacono++ 1311.3873, Escudero&Fairbarn 1907.05425, Chen++2203.09075

Current constraints to $N_{\rm eff}$

- Strongest bounds on number of ν-like species (at 68% CL)

Planck 2018 + BAO $N_{\rm eff} = 2.99 \pm 0.17$ *Planck 1807.06209*

Planck 2018 + ACT + DESI DR1 $N_{\rm eff} = 2.86 \pm 0.13$ *ACT 2503.14454*

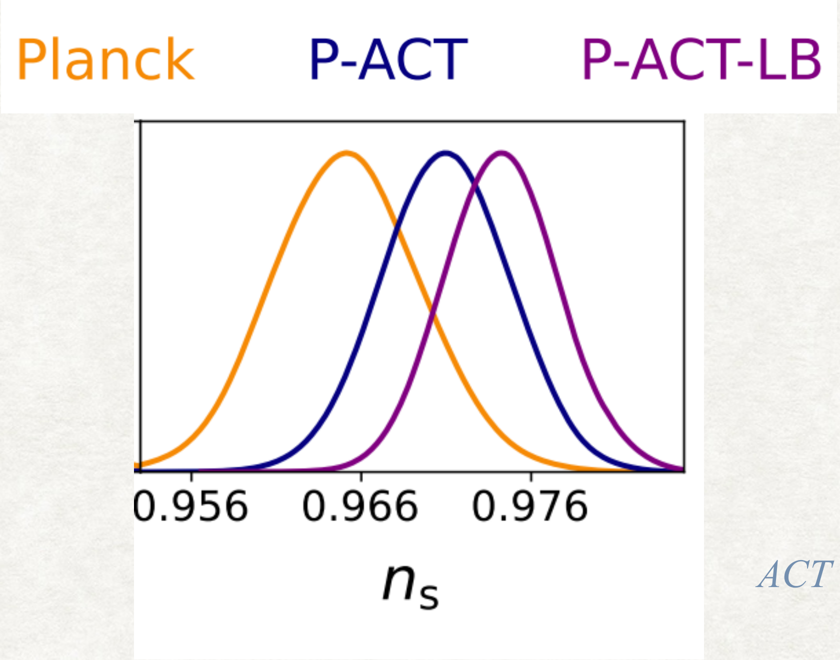


- The bounds have increased mostly because ACT prefers a slightly more scale-invariant spectrum

$$\mathscr{P}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$n_s = 0.9651 \pm 0.0044$ *Planck* 2018

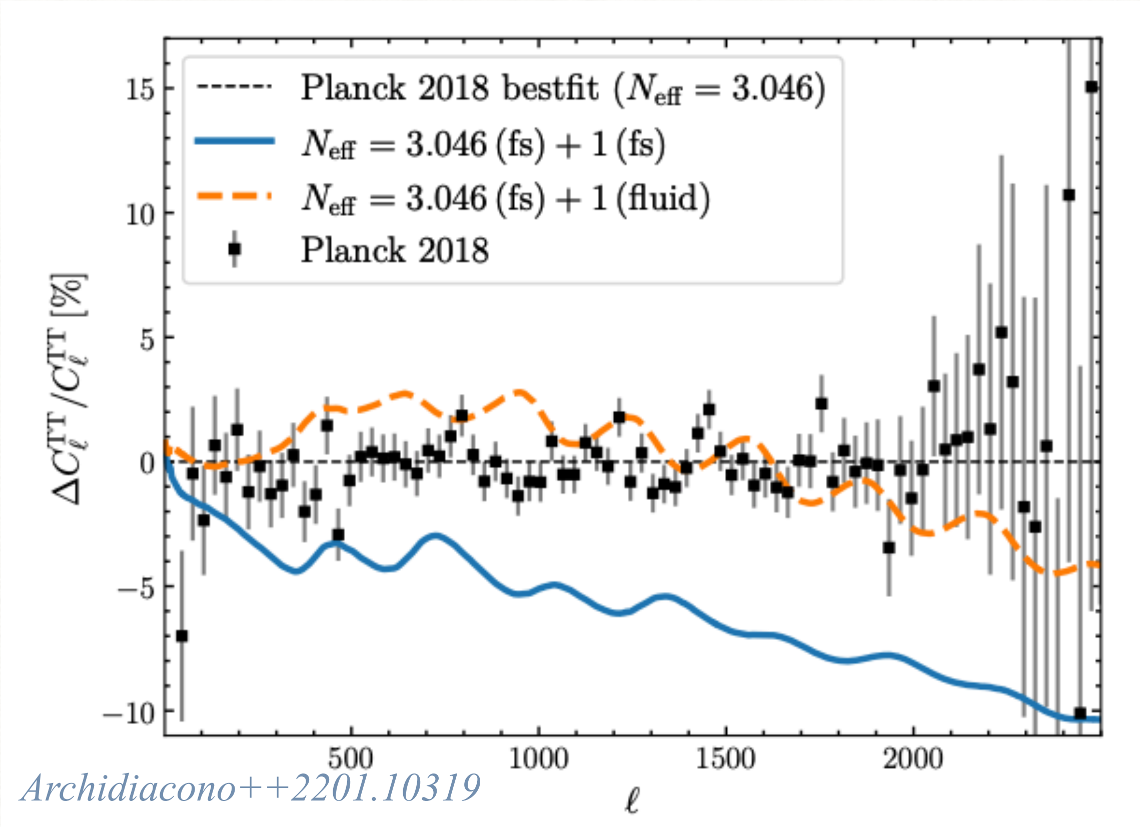
$n_s = 0.9743 \pm 0.0034$ *Planck* + ACT

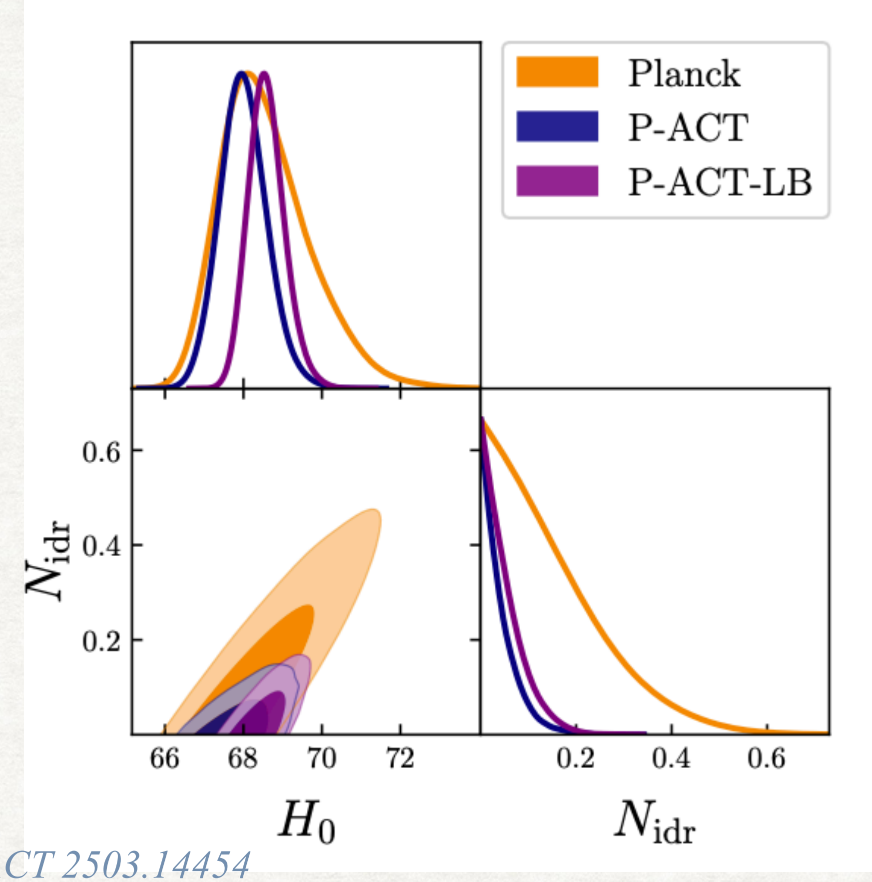


ACT 2503.14454

- BBN allows to constrain $N_{\rm eff} = 2.88 \pm 0.27$ (68% C.L.) *Pitrou++1801.08023*

CMB probes exotic ν interaction





ACT 2503.14454

- Exotic self-interaction can erase free-streaming and make extra radiation behaves as perfect fluid.
- Once interactions are switched on: γ-perturbations are enhanced / phase is washed-out.

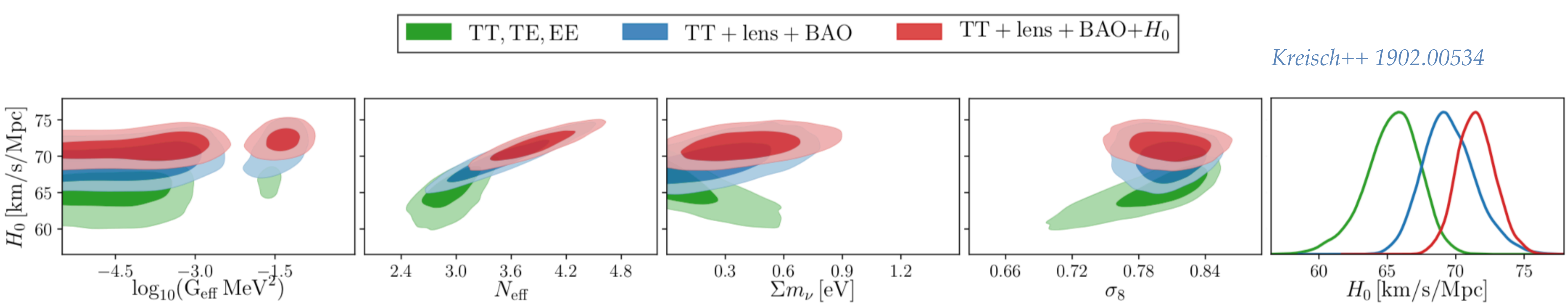
Planck + ACT +DESI

$\Delta N_{\rm eff} < 0.076$

$N_{\rm IDR} < 0.134$

ν self-interaction can alter CMB bounds

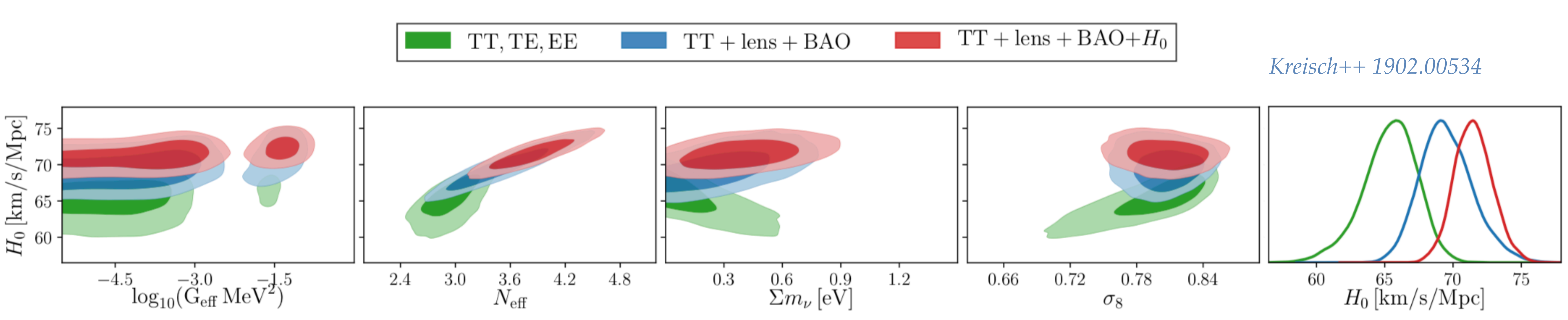
Kreisch++ 1902.00534



- $\mathscr{L} = G_{\rm eff}\bar{\nu}\nu\bar{\nu}\nu$ Neutrino interacting through (pseudo-) scalar heavy mediator, analogous to Fermi interaction

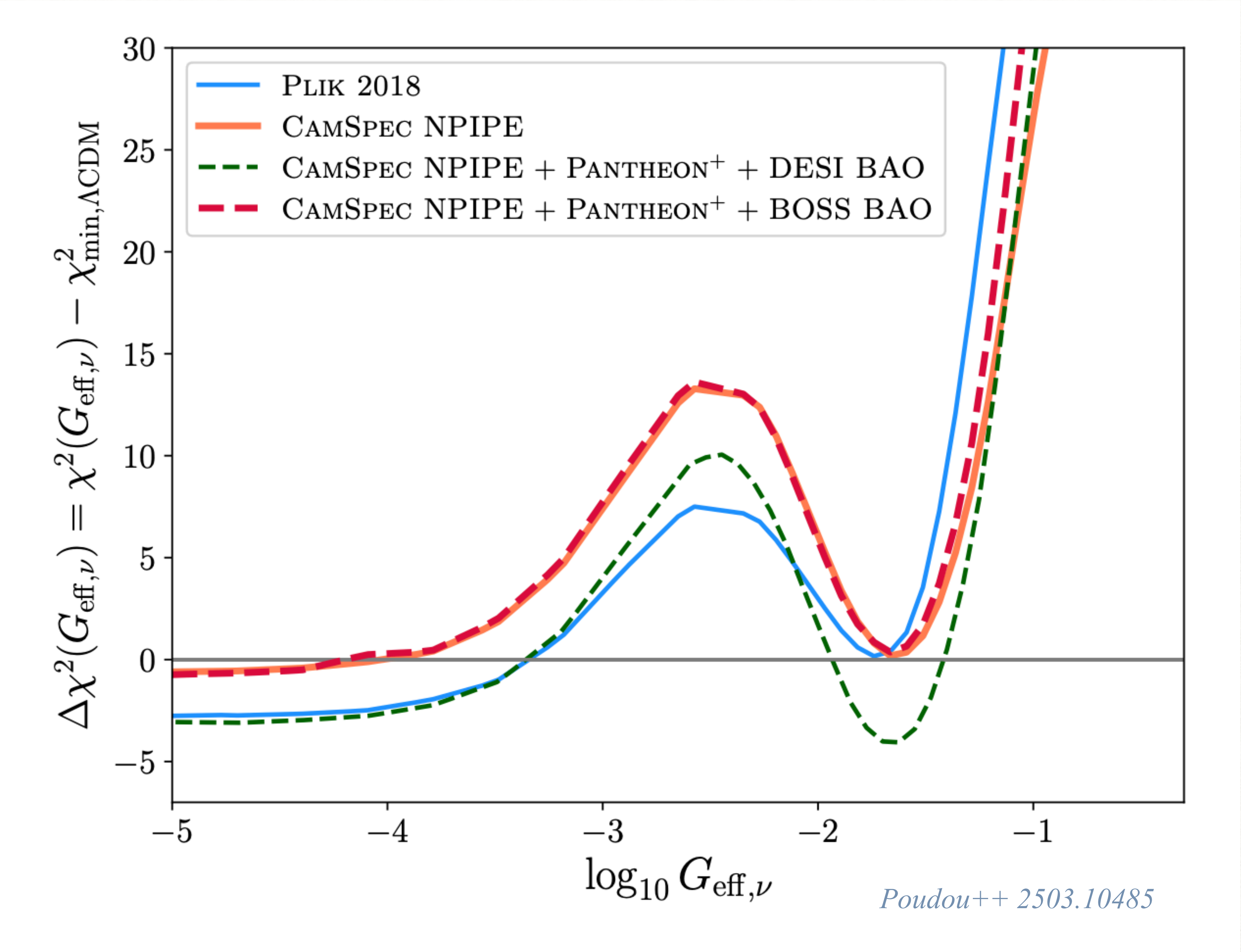
- There exists two "modes" in *Planck* TT data! *Lancaster++ 1704.06657*

ν self-interaction can alter CMB bounds



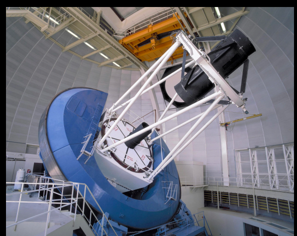
- $\mathscr{L} = G_{\rm eff}\bar{\nu}\nu\bar{\nu}\nu$ Neutrino interacting through (pseudo-) scalar heavy mediator, analogous to Fermi interaction
- There exists two "modes" in *Planck* TT data! *Lancaster++ 1704.06657*
- Standard ν with $G_{\rm eff} = G_{\rm F}$, $N_{\rm eff} = 2.99 \pm 0.34$, $\sum m_\nu < 0.12$, $H_0 \simeq 67$ km/s/Mpc, eV and $\sigma_8 \simeq 0.83$
- Exotic ν with $G_{\rm eff} = 10^{10} G_{\rm F}$ (!!) $N_{\rm eff} = 4 \pm 0.3$, $\sum m_\nu = 0.4 \pm 0.2$, $H_0 \simeq 72$ km/s/Mpc, eV and $\sigma_8 \simeq 0.79 \pm 0.02$
- Can we firmly kill the strongly interacting mode?

It is hard to kill strong self interactions!



- Planck polarization + BAO data disfavor the strongly interacting mode.
- New DESI and Planck NPIPE have equal likelihoods between standard model neutrinos and SI interacting ones
- Even ACT DR6 “likes” having one (out of three) SI neutrinos

Towards measuring ν properties

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to $N_{\rm eff}$
	DESI	2023	0.02-0.03 eV	0.08-0.13
	**ESA Euclid**	**2024**	**0.011 – 0.02 eV**	**0.05**
	**LSST**	**2024**	**0.015 eV**	**0.05**
	**CMB-S4**	**2027**	**0.015 eV**	**0.02 – 0.04**

Also SKA, Hera can help in measurement 21cm power spectrum and reionization.

In the future, cosmological probes are expected to detect the neutrino mass even if $M_\nu = 0.06$ eV

However systematics will have to be under control *Cf Maria's talk*

Cosmology provides strong bounds on ν-physics

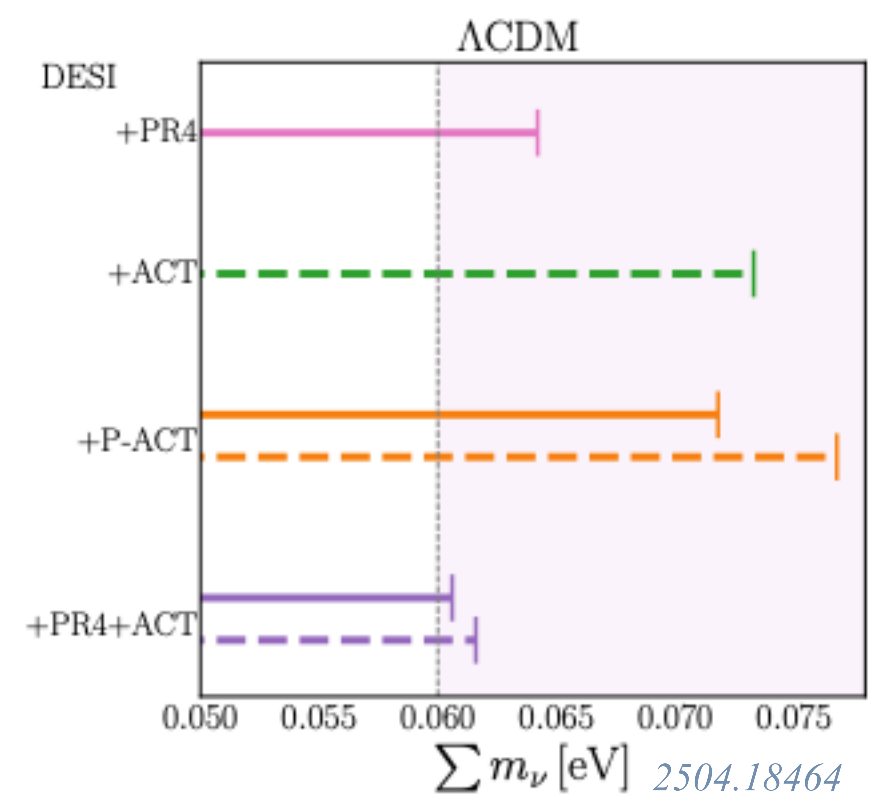
- Strongest bounds to date on $\sum m_\nu$ (at 95% CL)

Katrin: < 1.35 eV *Science 2025*

Planck+ ACT +DESI $\sum m_\nu < 0.06$ eV Flat ΛCDM

Planck+ ACT + SN1a $\sum m_\nu < 0.117\text{-}0.139$ eV $w_0 w_a$CDM

DESI 2504.18464



2504.18464

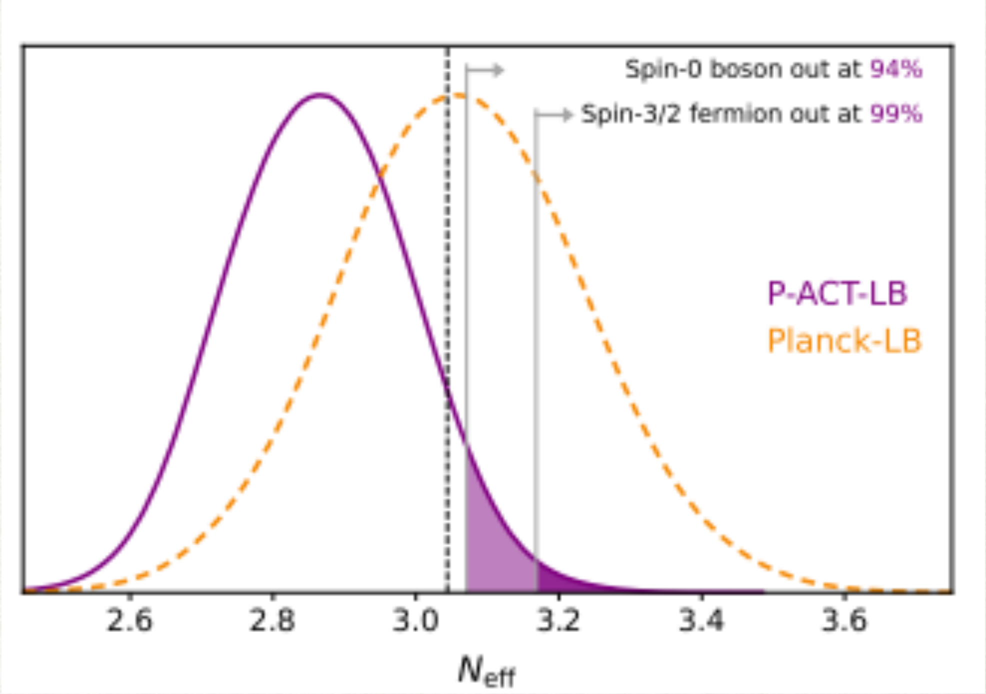
- Hints of negative (!) neutrino masses tied to anomalies and/or model dependent

- Strongest bounds on number of ν-like species (at 68% CL)

Planck 2018 + ACT + DESI DR1

$N_{\rm eff} = 2.86 \pm 0.13$ $N_{\rm IDR} < 0.134$

ACT 2503.14454



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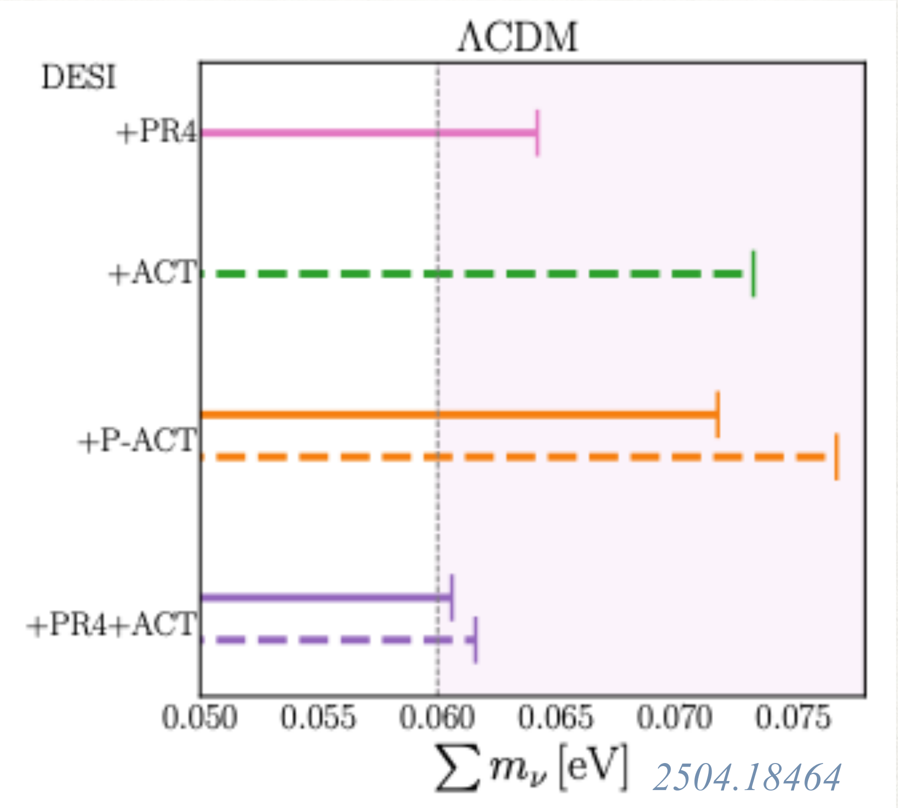

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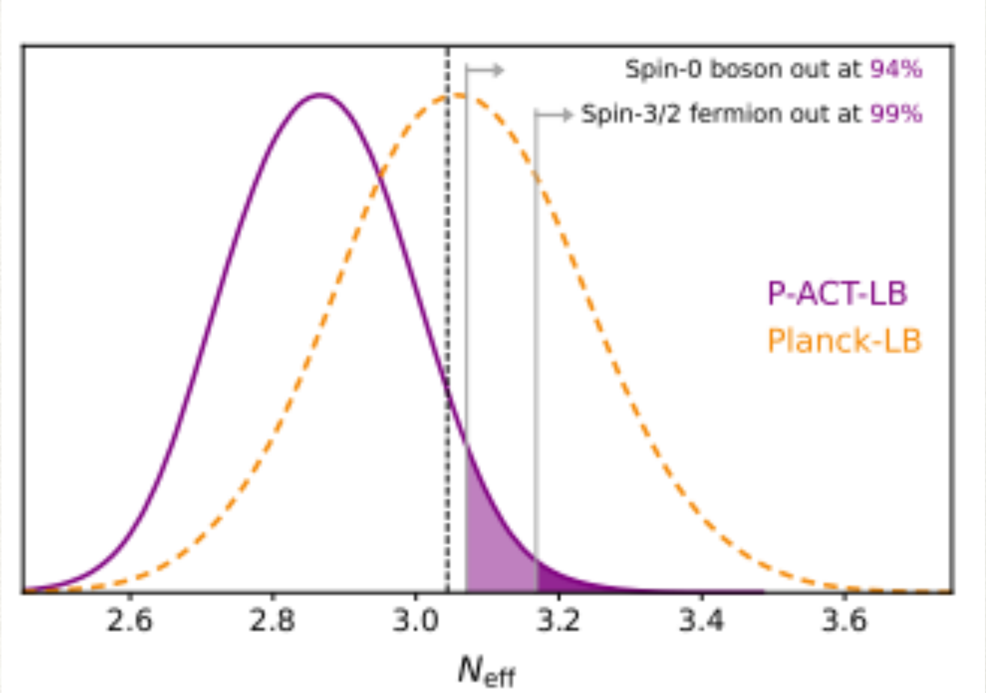

We are on the verge of interesting discoveries about neutrino in cosmology