MISURE COSMOLOGICHE

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In cosmology, we tipically observe
realizations of random fields on the sphere.
Let's start from the 3D field in configuration and Fourier space

$$\Phi(\vec{x},\, t) \to \widetilde{\Phi}(\vec{k},\, t) = \mathcal{I}(\vec{k},\, t_{\rm early})\mathcal{T}(\vec{k},\, t)$$

Some random field (e.g. CMB temperature fluctuations) in real and Fourier space

Stochastic initial conditions, set by inflation

Deterministic transfer function

We observe the field projected on the sphere and on the light cone

$$\Phi^{2\mathrm{D}}(\hat{n},\, t_0) = \int_0^\infty W(r)\Phi\Big(\vec{x} = \hat{n}r,\, t = t(r)\Big)dr$$

Projection on the sphere of our random field

Window function

Original 3D field, evaluated on our past light cone

We observe the field projected on the sphere and on the light cone. Schematically:

$$\Phi^{2D}(\hat{n}) \sim \int \Big(\text{initial conditions}\Big) \times \Big(\text{evolution}\Big) \times \Big(\text{projection}\Big)$$

Inflation; very early Universe physics

Expansion and thermal history; matter-energy budget; microphysics

Geometry; expansion history

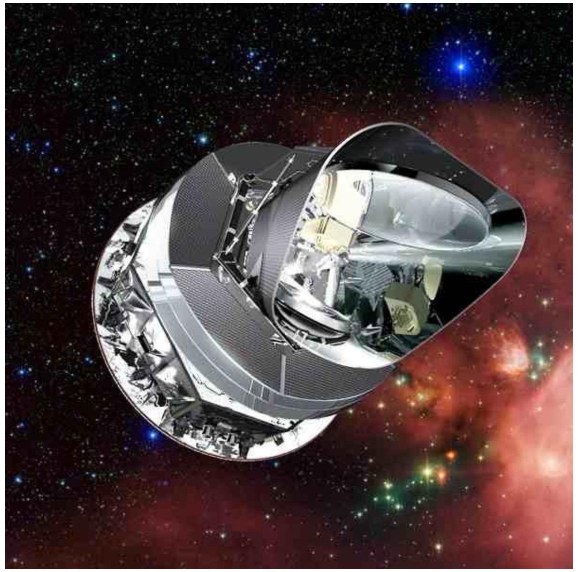
Since the observed fields are stochastic, we can only predict their statistical properties - e.g. the 2-point correlation function, or its harmonic counterpart, the power spectrum

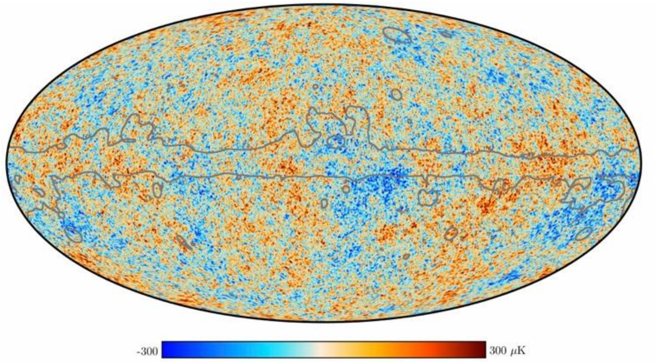
$$\langle \Phi^A(\hat{n})\Phi^B(\hat{n}')\rangle = C^{AB}(\hat{n}\cdot\hat{n}') \longleftrightarrow \langle a^A_{\ell m} a^{B*}_{\ell' m'}\rangle = C^{AB}_\ell \delta_{\ell\ell'}\delta_{mm'}$$

Spherical harmonics expansion:

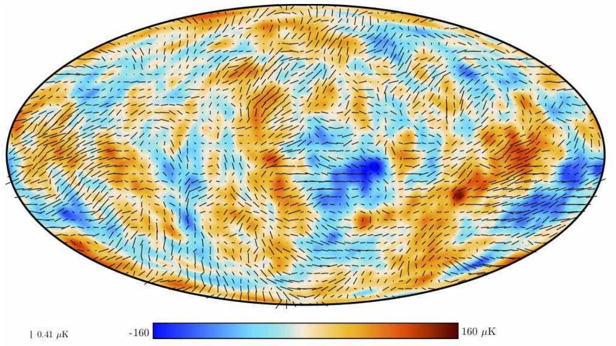
$$\Phi(\hat{n}) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{m=+\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

CMB OBSERVATIONS

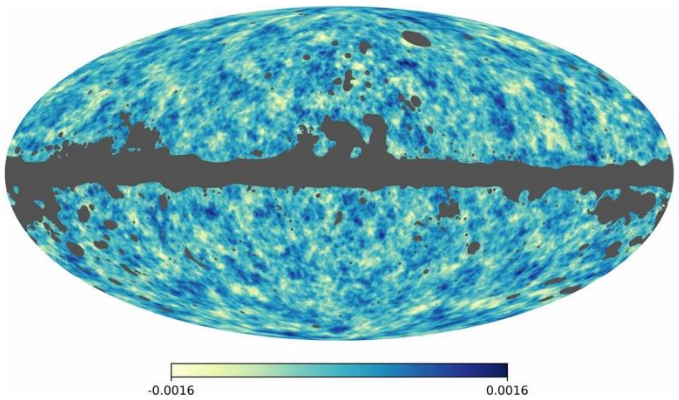




Temperature anisotropies



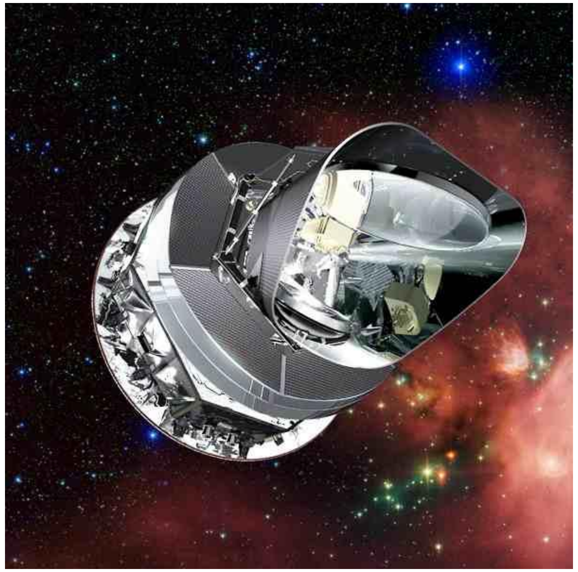
Polarization anisotropies
(two modes: E and B)

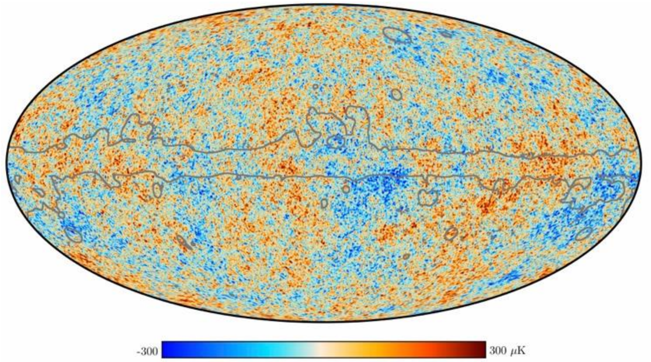


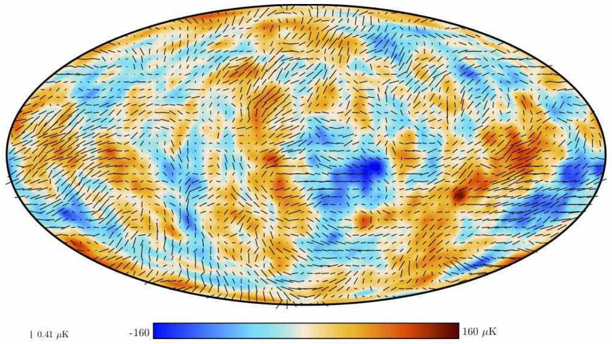
Lensing anisotropies

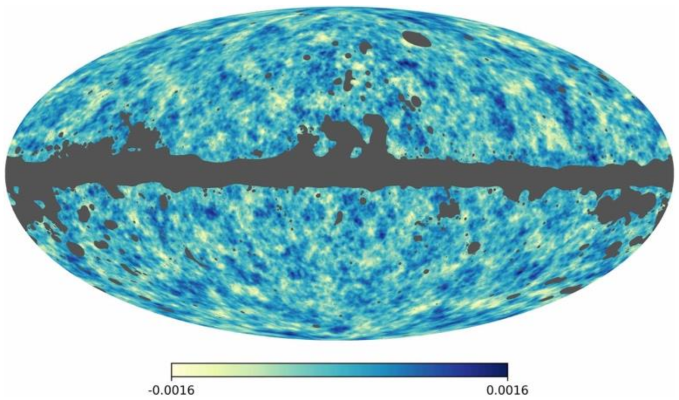
Planck 2018

CMB OBSERVATIONS









Planck 2018

Temperature anisotropies

Measured by Planck down to the cosmic variance limit

Polarization anisotropies (two modes: E and B)

Complete characterization is the main target of next-gen experiments

Primordial B-modes are a smoking gun for inflation

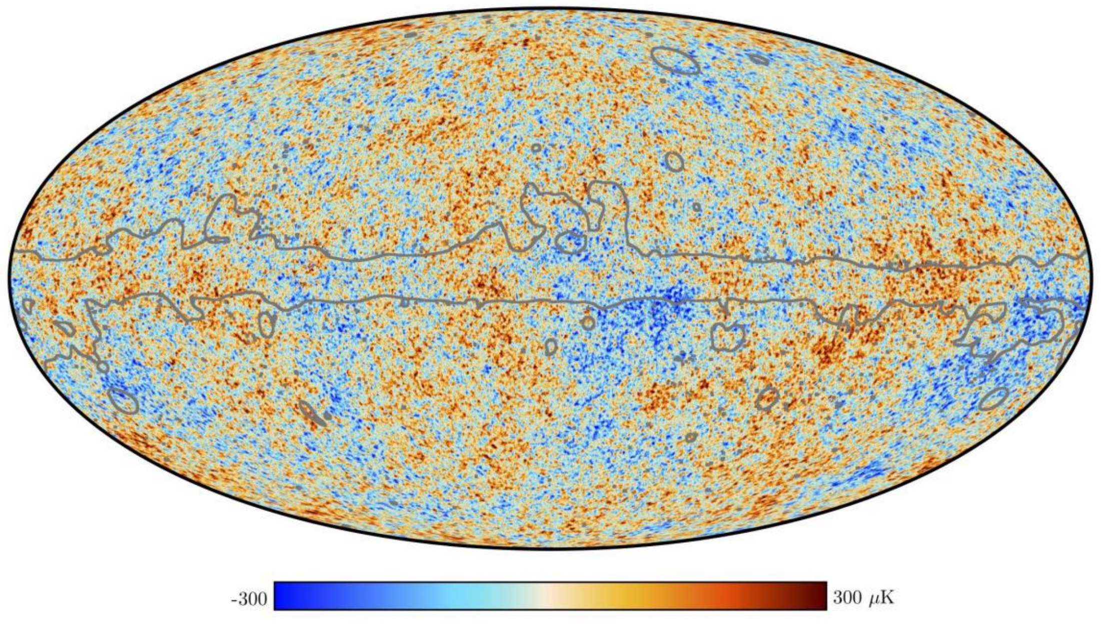
Lensing anisotropies

CMB window to structure formation and the late Universe

Also a target for next-gen experiments

Relevant for e.g. neutrino masses

THE COSMIC MICROWAVE BACKGROUND

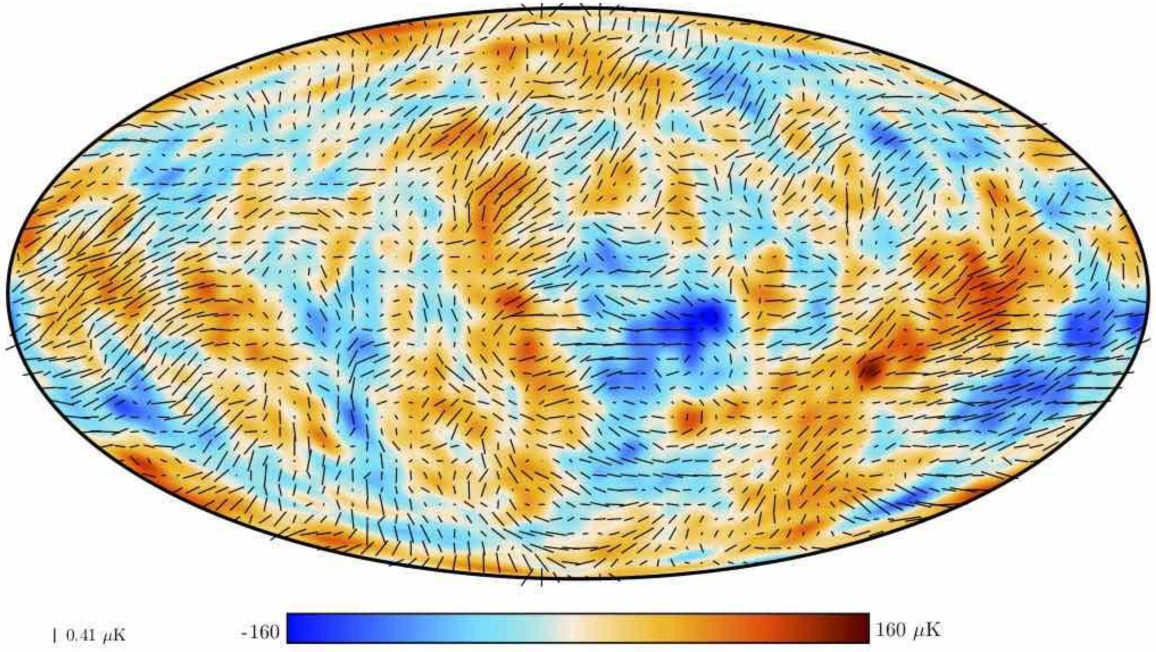


Spherical harmonic expansion:

$$T(\vec{n}) = \sum_{\ell,m} a^T_{\ell m} Y_{\ell m}(\vec{n})$$

$$\langle a^T_{\ell m} a^{T*}_{\ell' m'} \rangle = C^{TT}_\ell \delta_{\ell\ell'} \delta_{mm'}$$

(similarly for E and B pol.)

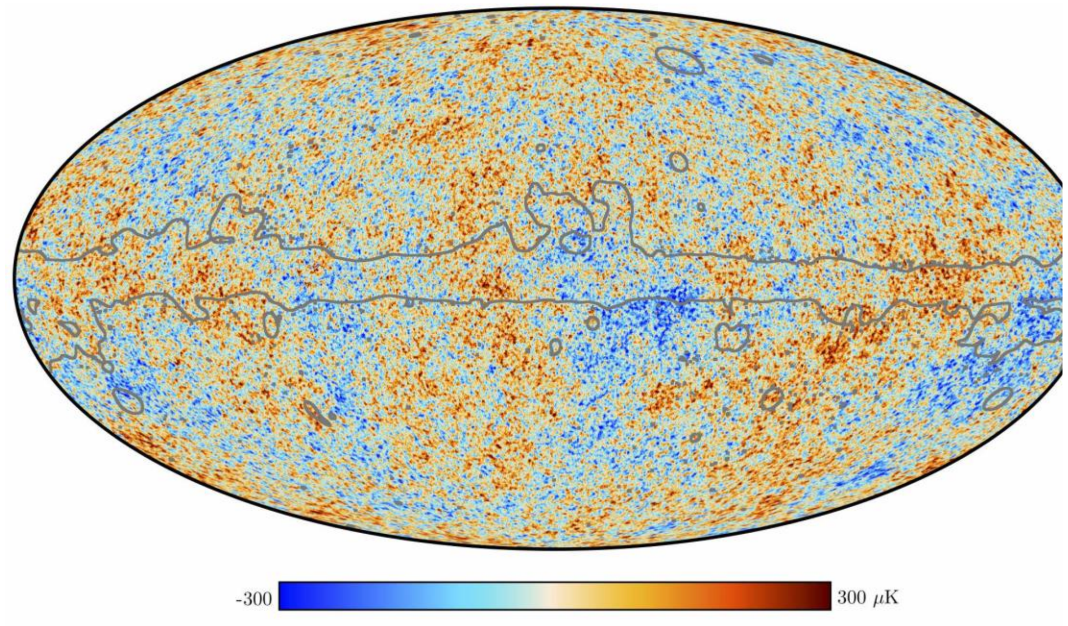


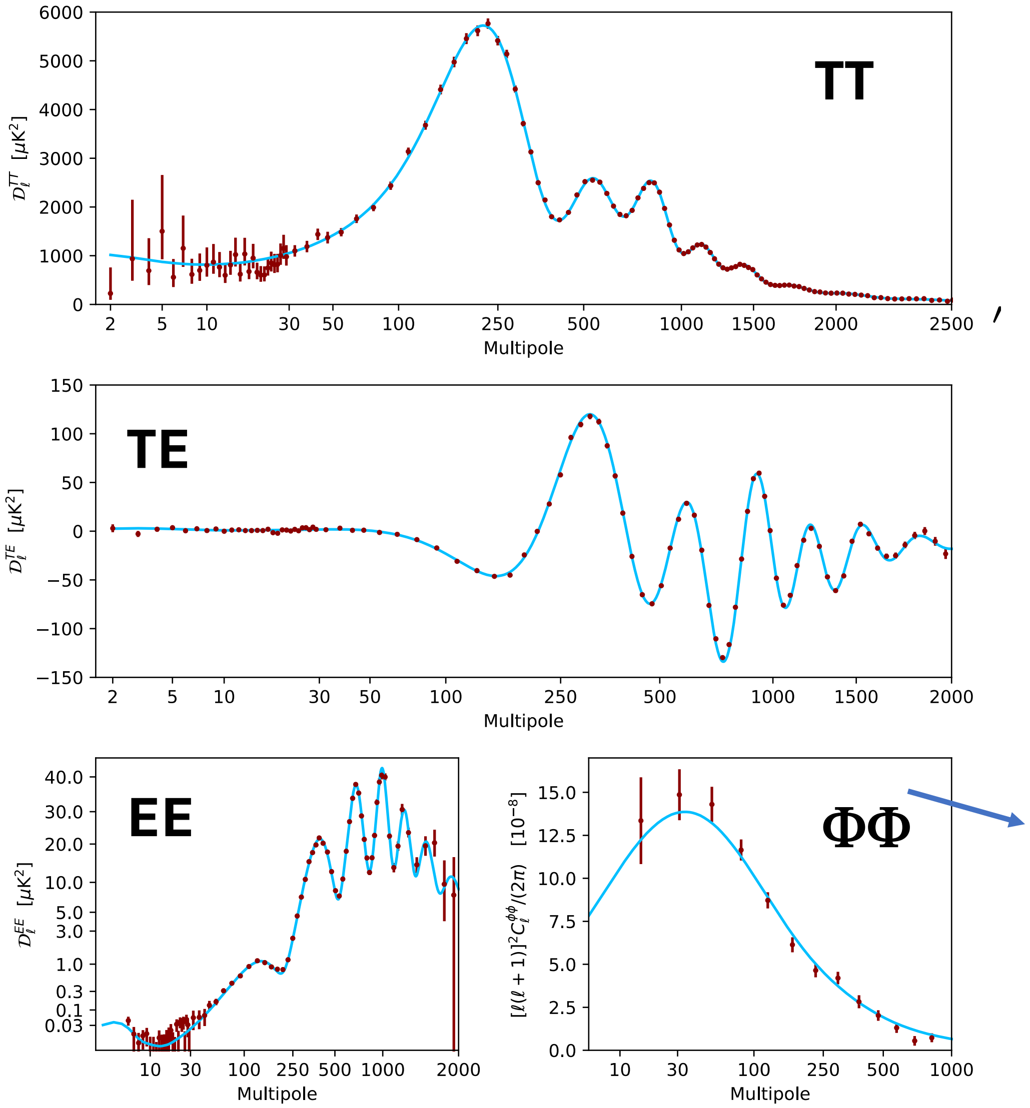
3 maps, 6 correlations: TT, EE, BB, TE, TB, EB

But TB,EB=0 (parity conservation)

Temperature and polarization maps from Planck (2018)

The Cosmic Microwave Background





Lensing power spectrum

3 maps, 6 correlations: TT, EE, BB, TE, TB, EB

But TB,EB=0 (parity conservation)

Temperature and polarization maps from Planck (2018)

Weak Lensing of the CMB

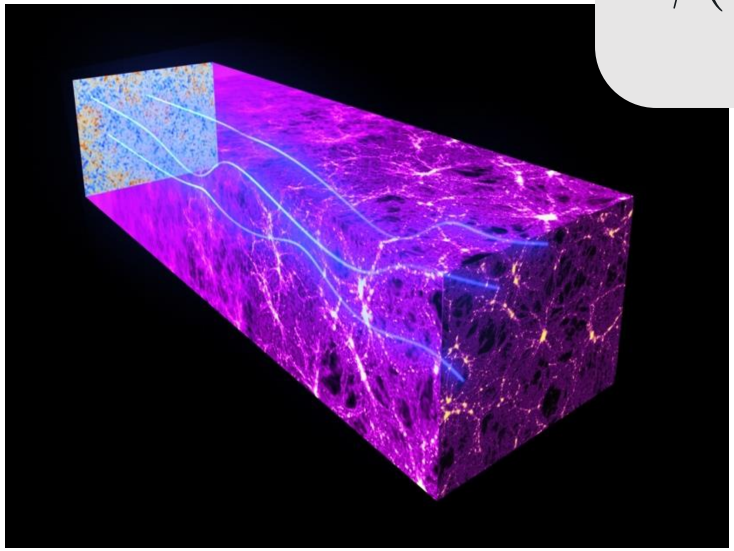
The observed CMB field T^{obs} is displaced wrt to the "unlensed" field T^{unl}, i.e. the one that would be seen in a perfectly homogeneous Universe, due to the lensing effect of intervening structures between us and the LSS:

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

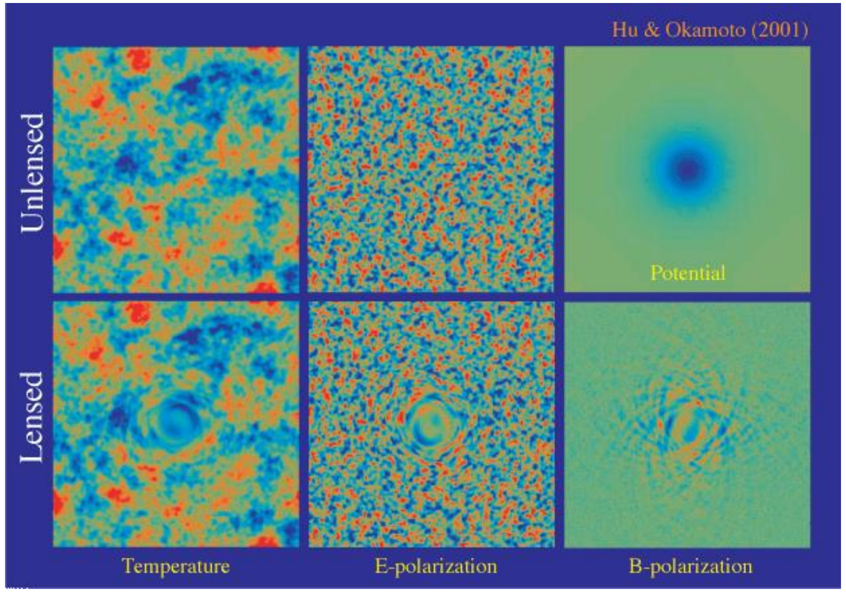
$\vec{d} = \vec{\nabla}\phi$ is the deflection field

Line-of-sight integral of the gravitational potentials

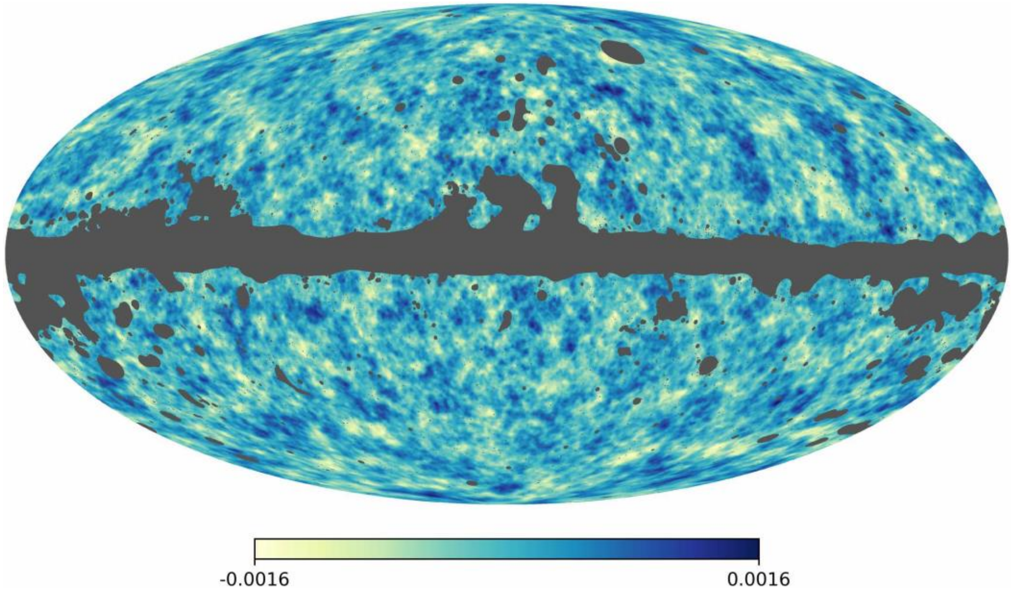
$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$



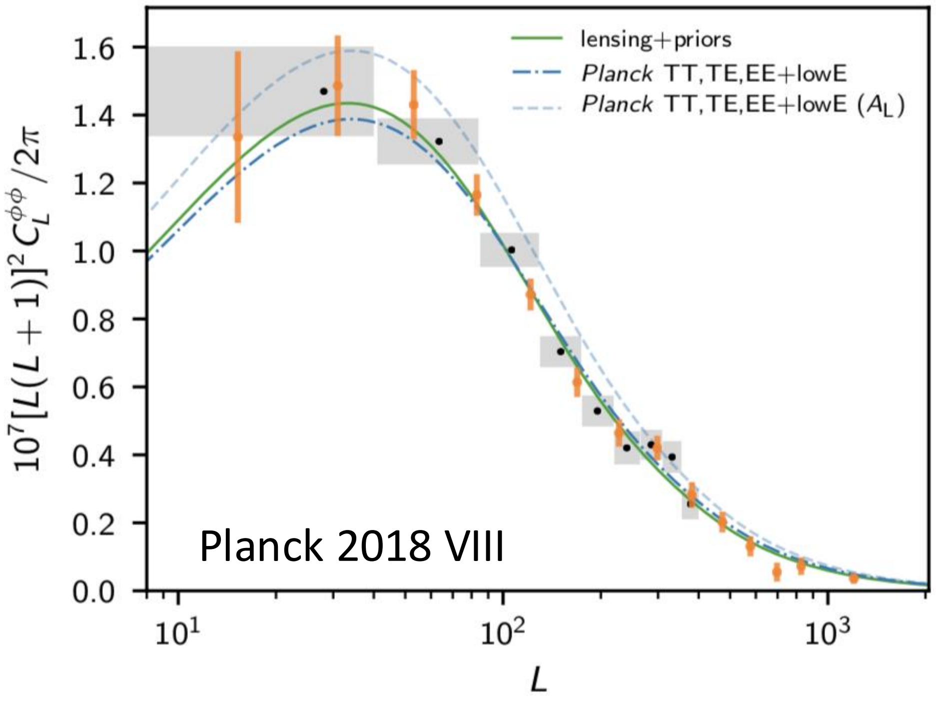
Makes CMB sensitive to the late-time density field, too....



WEAK LENSING OF THE CMB



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

GALAXY SURVEYS

Galaxy number counts

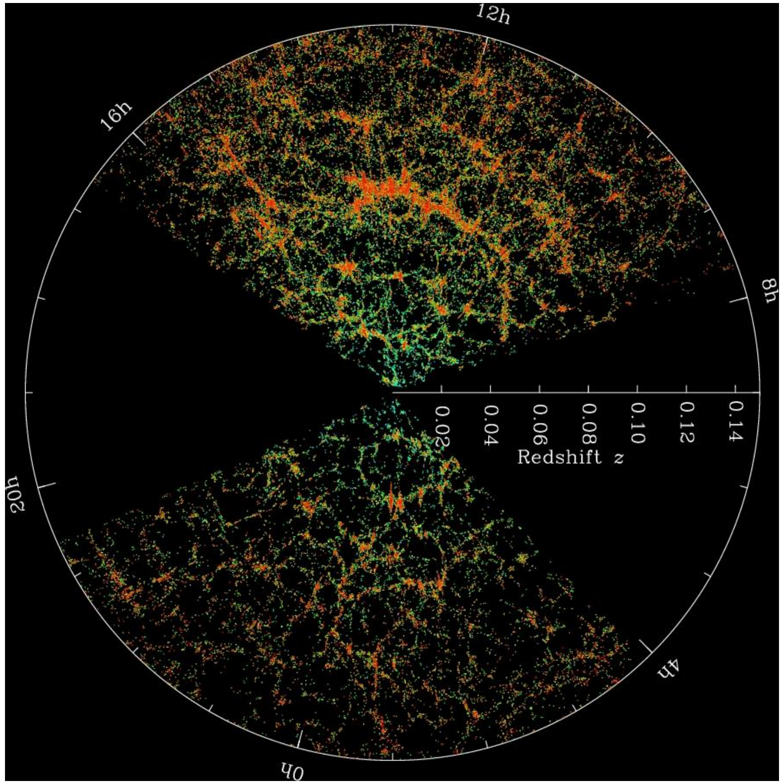
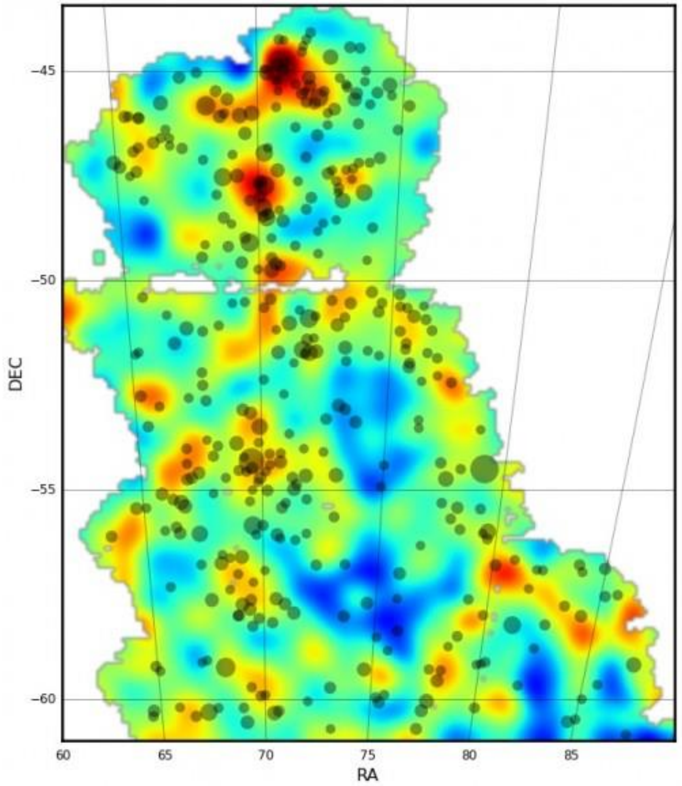


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Cosmic shear

i.e. distortions in galaxy shapes induced by weak gravitational lensing



Weak lensing convergence map from the Dark Energy Survey (DES)

Observations of Large-Scale Structures

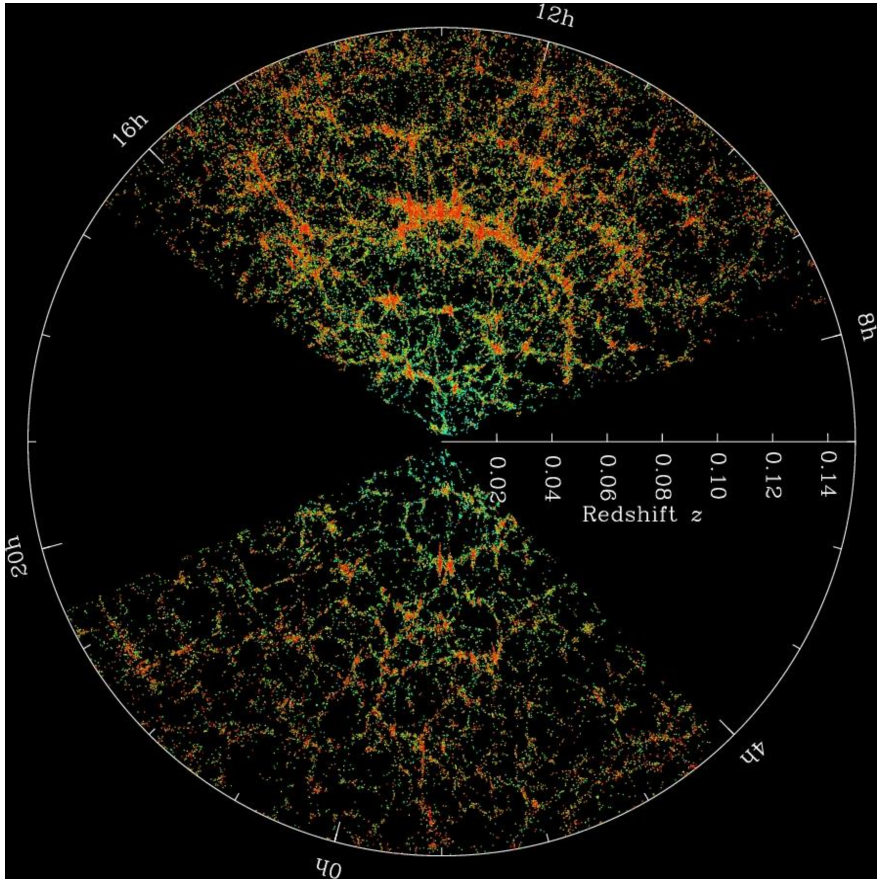


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Fractional density fluctuation:

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

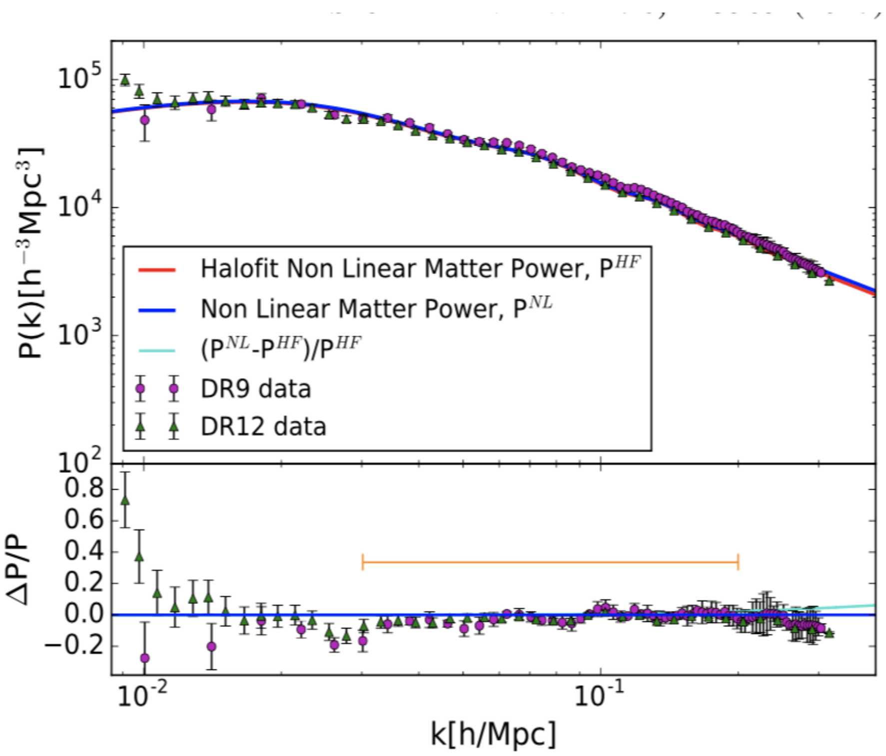
Power spectrum:

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

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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Power spectrum:

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

The power spectrum is the Fourier transform of the 2-point correlation function:

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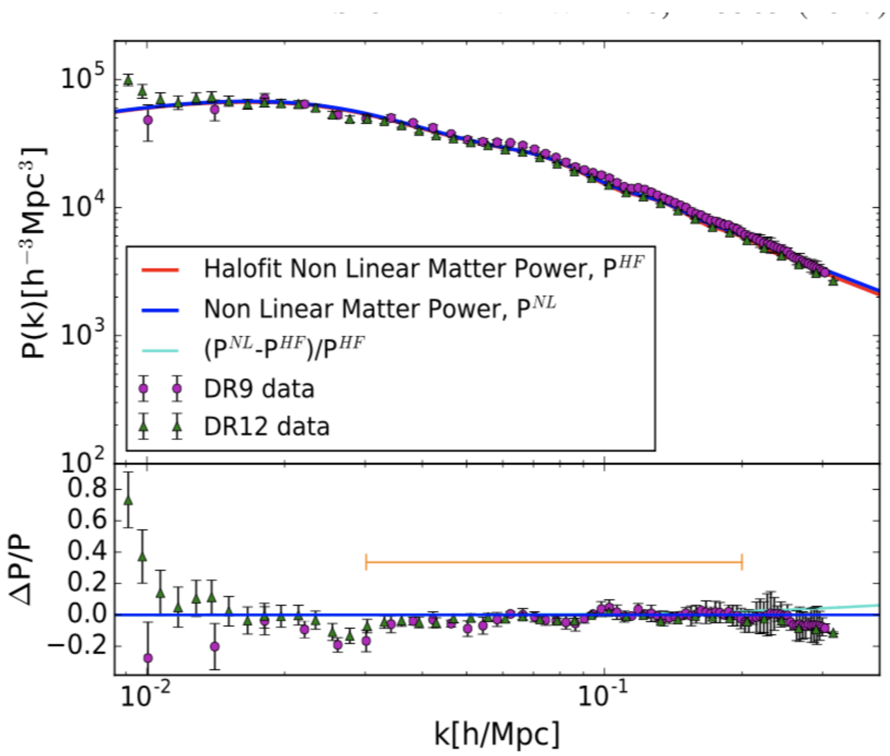
Observations of Large-Scale Structures



data points from BOSS

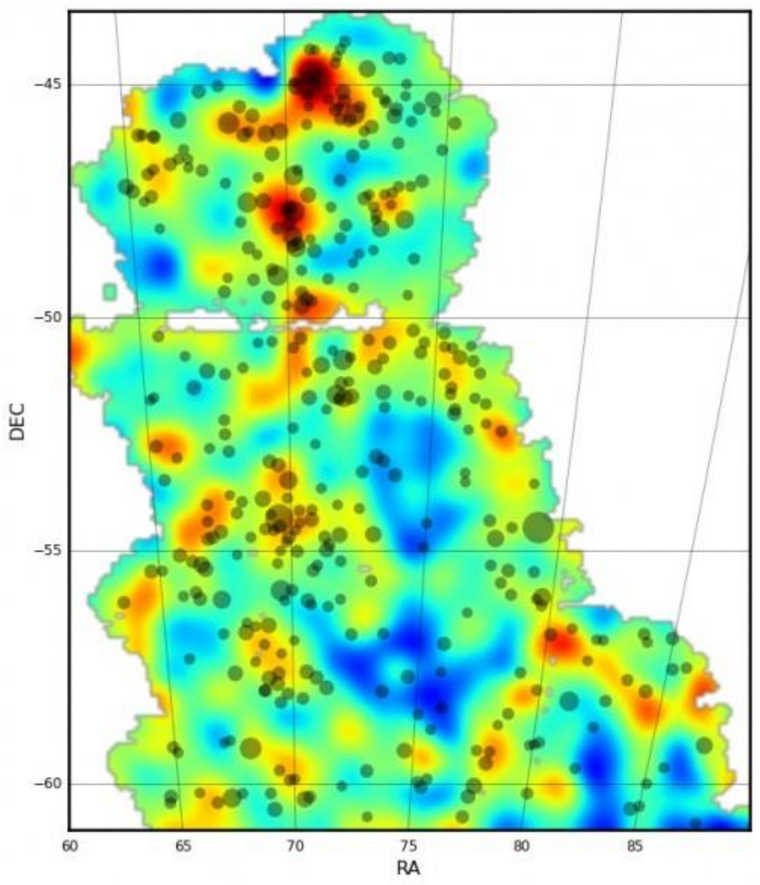
Galaxy surveys measure fluctuations in the galaxy number, $\delta n_g/n_g$.

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.

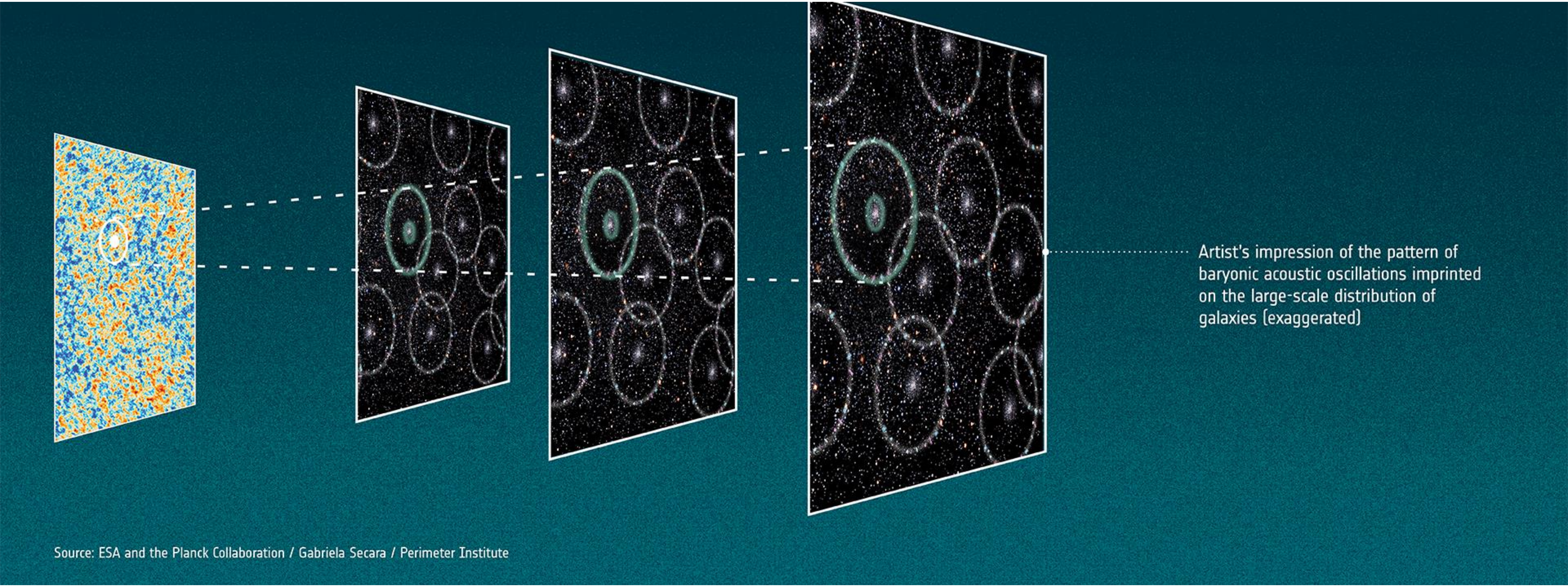
$$\kappa = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_m \int_0^{r_s} dr\, \frac{\delta(r)}{a(r)} \frac{r(r_s - r)}{r_s},$$

Convergence field

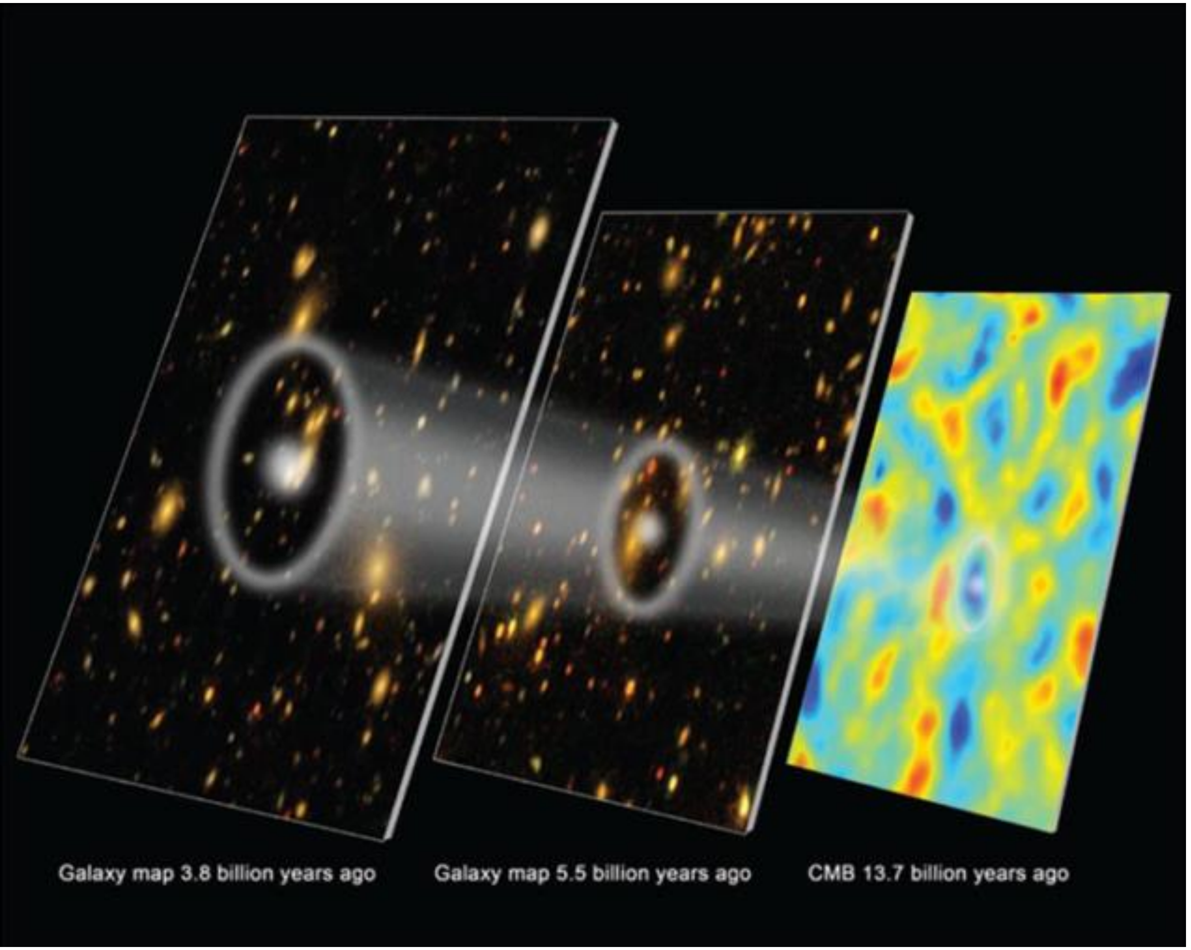
This is a more direct probe of matter fluctuations than galaxy number counts, since the lensing potential is produced by all matter components, including dark matter.

However, issues with nonlinearities remain.

Baryon Acoustic Oscillations

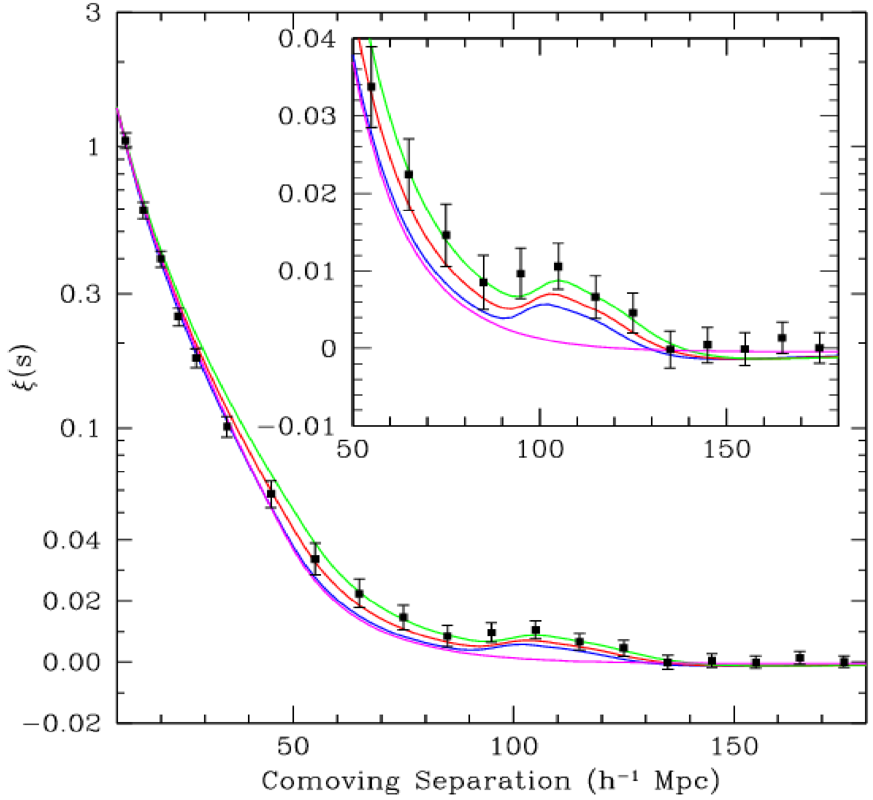


Baryon acoustic oscillations (BAOs)

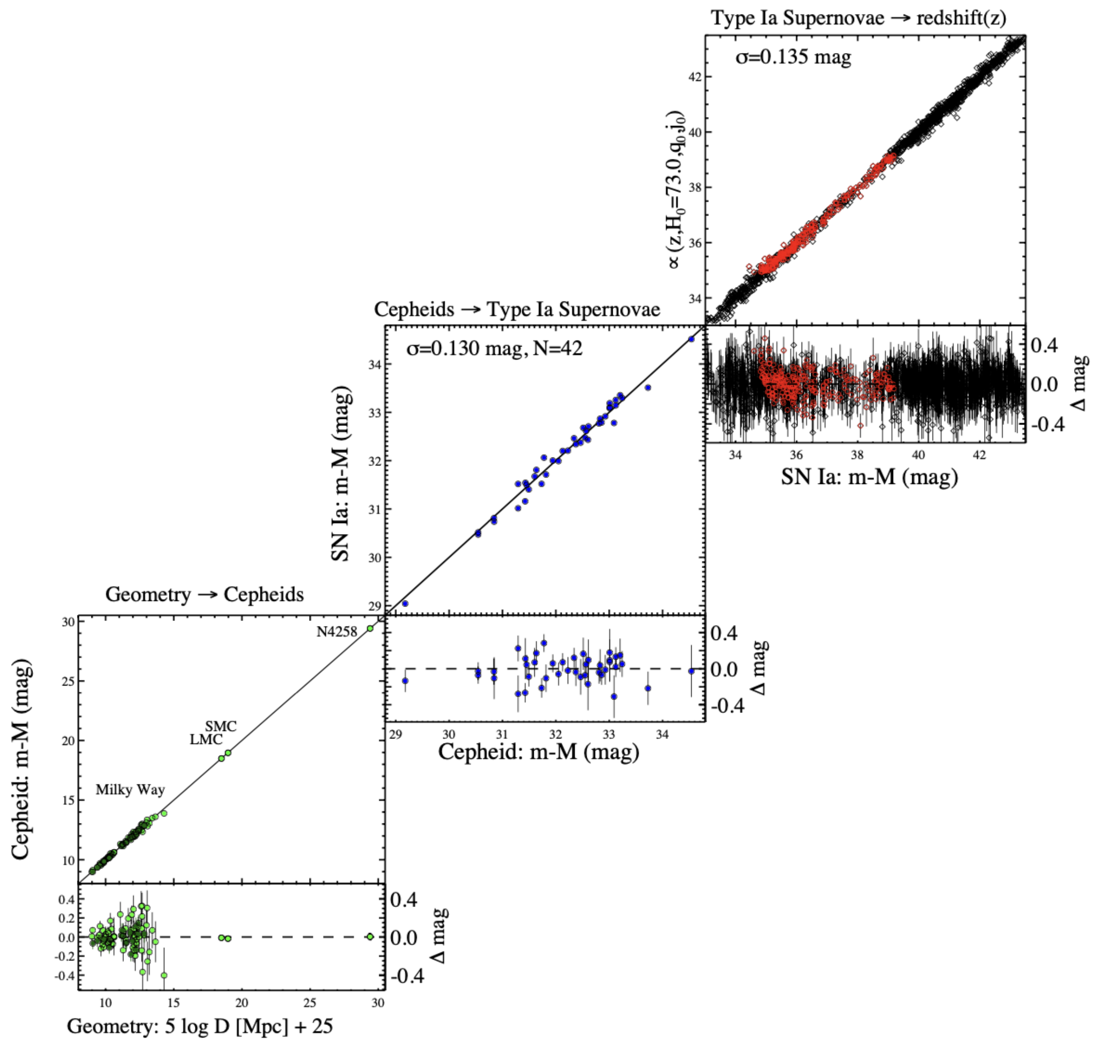


BAOs are the imprint left by the finite sound speed of the baryon-photon fluid in the distribution of galaxies.

BAOs constrain the expansion history



PROBES OF THE EXPANSION HISTORY

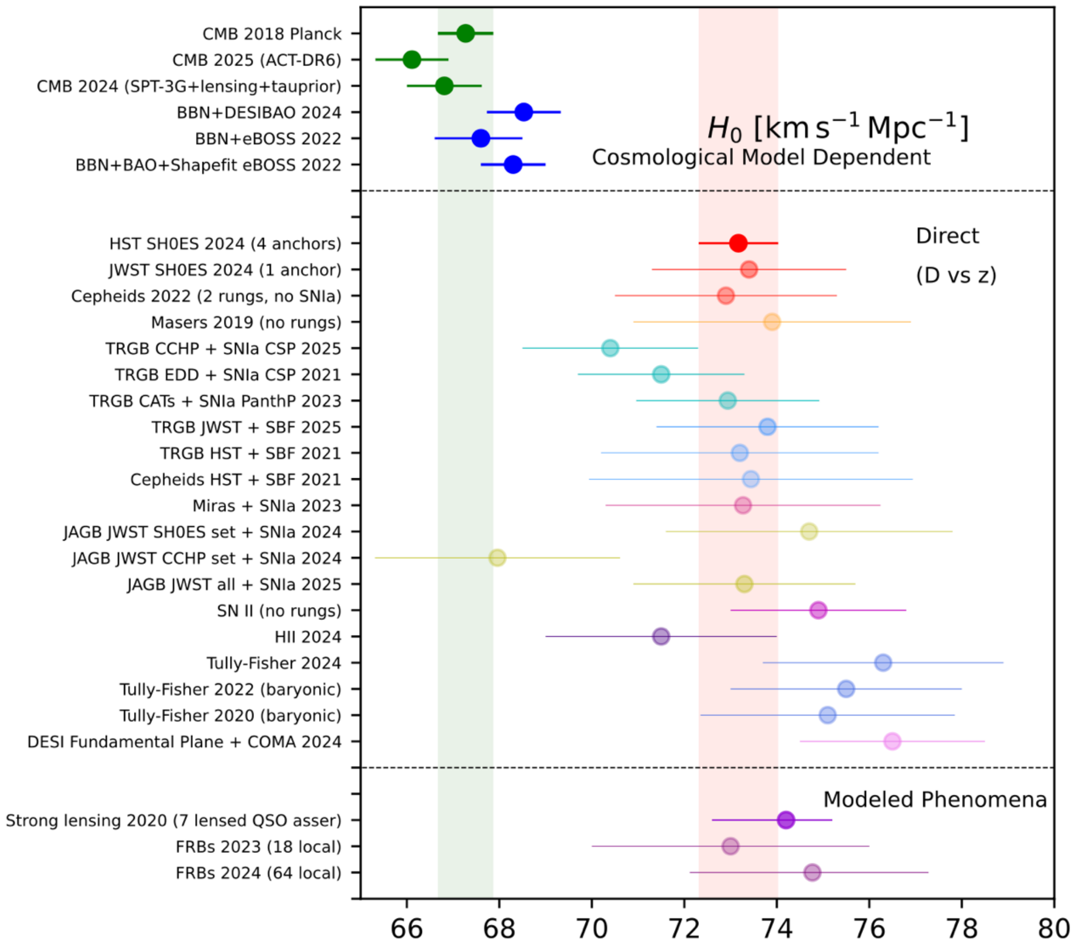


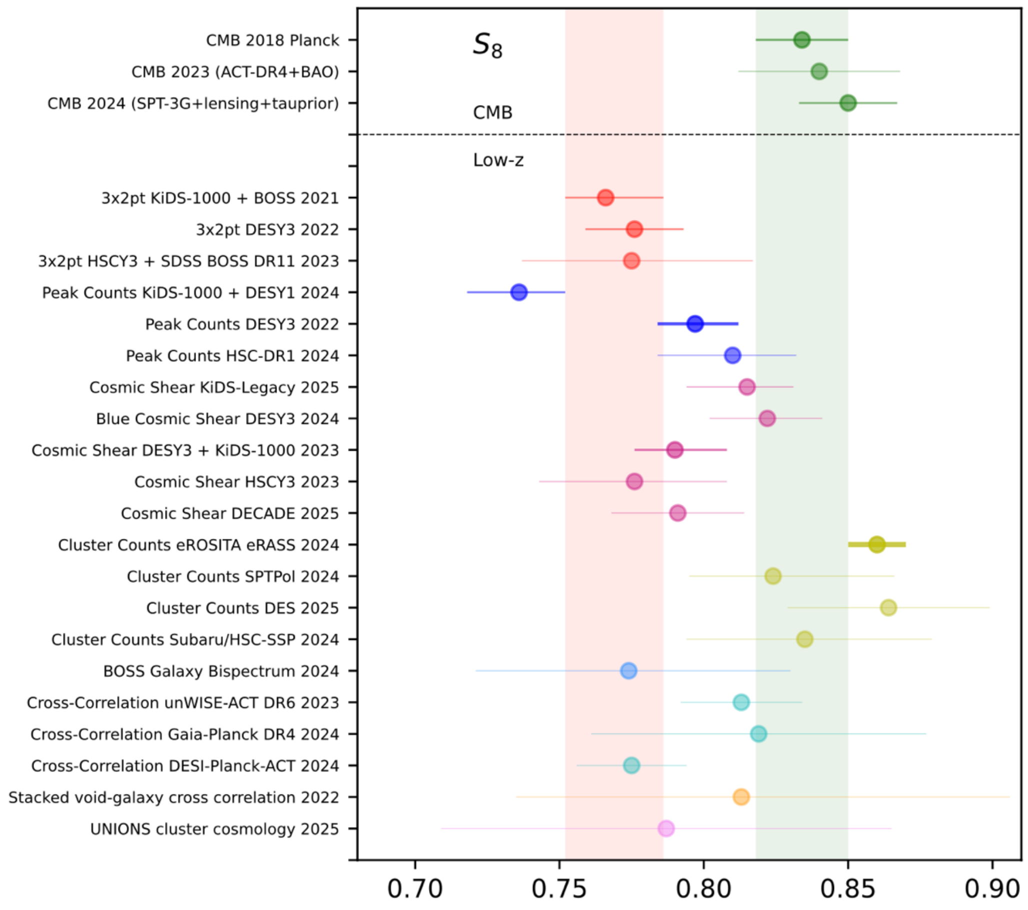
Cepheid-SNIa distance ladder

Direct measurement of the present expansion rate H_0

Riess et al 2024

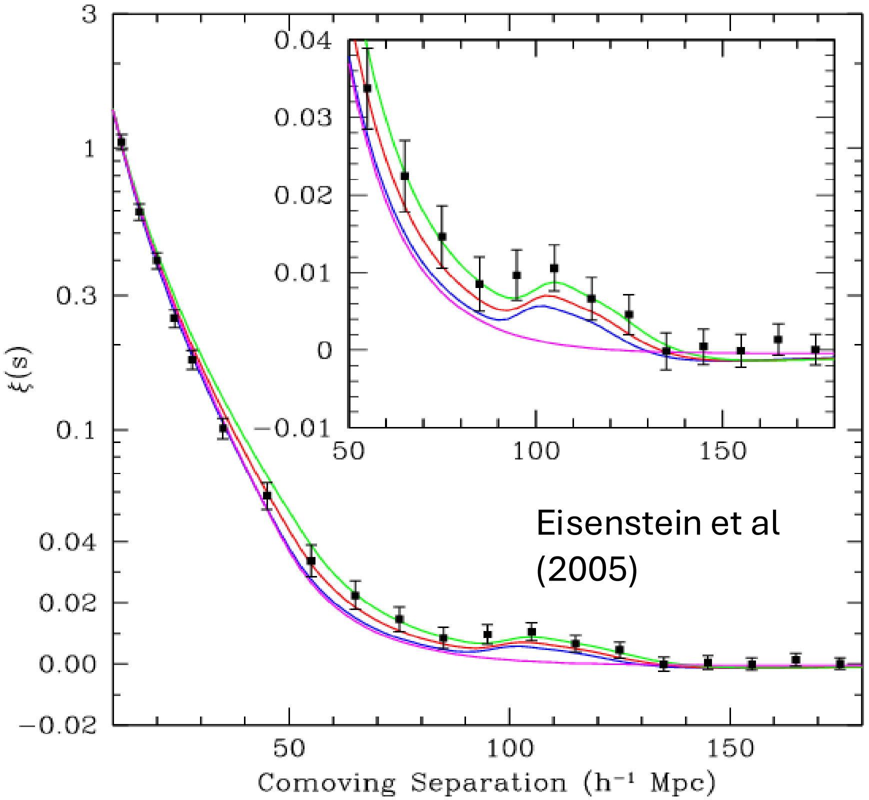
COSMOLOGICAL TENSIONS





Di Valentino, Said + (CosmoVerse network), arXiv:2504.01669

Observations of Large-Scale Structures



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).

The Cosmic Neutrino Background

The presence of a background of relic neutrinos (**CνB**) is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});
- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species
- Free parameters: the three masses (but cosmological evolution mostly depends on their sum)

The Cosmic Neutrino Background

Weak cross section: $\sigma \simeq G_F^2 T^2$

Weak interaction rate $\Gamma = n\langle \sigma v \rangle \sim G_F^2 T^5$

Expansion rate $H \simeq \frac{T^2}{m_{\rm p}}$

Interactions become ineffective when $T=T_d$ such that

$$1 \simeq \frac{\Gamma}{H} \sim G_F^2 T^3 m_{\rm p} \sim \left(\frac{T}{\rm MeV}\right)^3$$

Given this, we can use conservation laws to compute the temperature, density, etc… of neutrinos at a given time.

Relic Neutrinos – Present Energy Density

Neutrinos with a mass > 10^{-4} eV would be nonrelativistic today, with density

$$\Omega_\nu h^2 \equiv \frac{\rho_{\nu,0}}{\rho_{\text{crit},0}} = \frac{\sum_{i=1}^{3} m_i n_{\nu,0}}{\rho_{\text{crit},0}} = \frac{\sum_{i=1}^{3} m_i}{93.14\,\text{eV}}$$

We know from flavour oscillation experiments that at least two of the three active neutrino eigenstates should be non relativistic today, and that the sum of neutrino masses

$$\sum m_i \geq 0.06\,\text{eV} \text{ (Normal ordering), or } \geq 0.10\,\text{eV} \text{ (Inverted ordering)}$$

which implies $$\Omega_\nu h^2 \geq 6 \times 10^{-4} \text{ (NO), or } \geq 10^{-3} \text{ (IO)}$$

THE COSMIC NEUTRINO BACKGROUND

This picture relies on the following:

- Universe was at T>>1MeV at some point
- only weak and gravitational interactions for ν's;
- no sterile neutrinos or other light relics;
- perfect lepton symmetry (zero chemical potential);
- no entropy generation after neutrino decoupling beyond e^+e^- annihilation;
- neutrinos are stable;
- in general, there are no interactions that could lead to neutrino scattering/annihilation/decay

Massive Neutrinos and Cosmological Observables

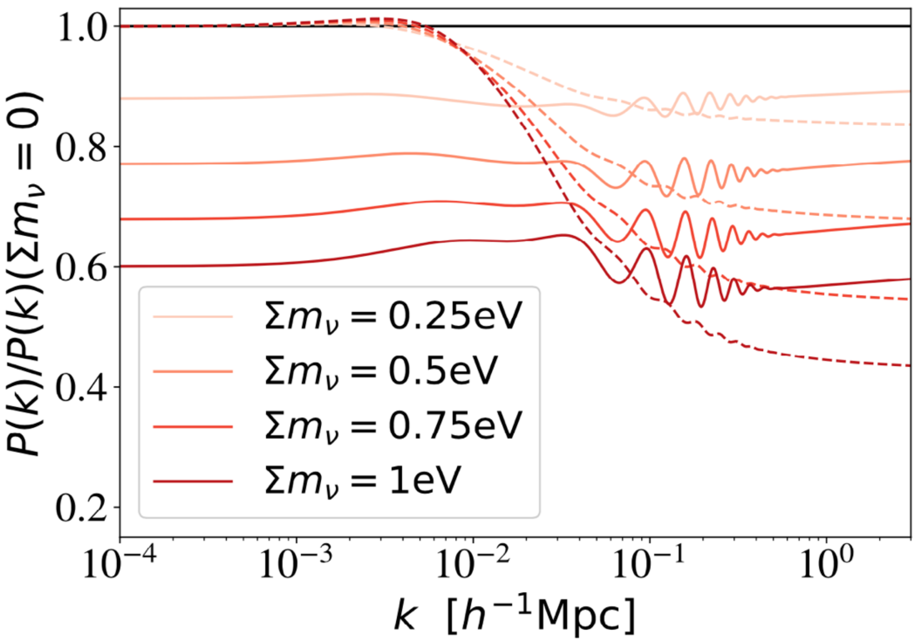
Background expansion:
Assuming *flatness* and a *cosmological constant* (i.e. no dynamical DE), the Friedmann eq. reads:

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

Changing the neutrino mass will change the expansion history at late times

NEUTRINOS IN COSMOLOGY

Change in background expansion + structure formation below the (effective) Jeans scale is **suppressed** in a Universe with massive neutrinos



Lesgourgues & Verde, RPP 2019

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)

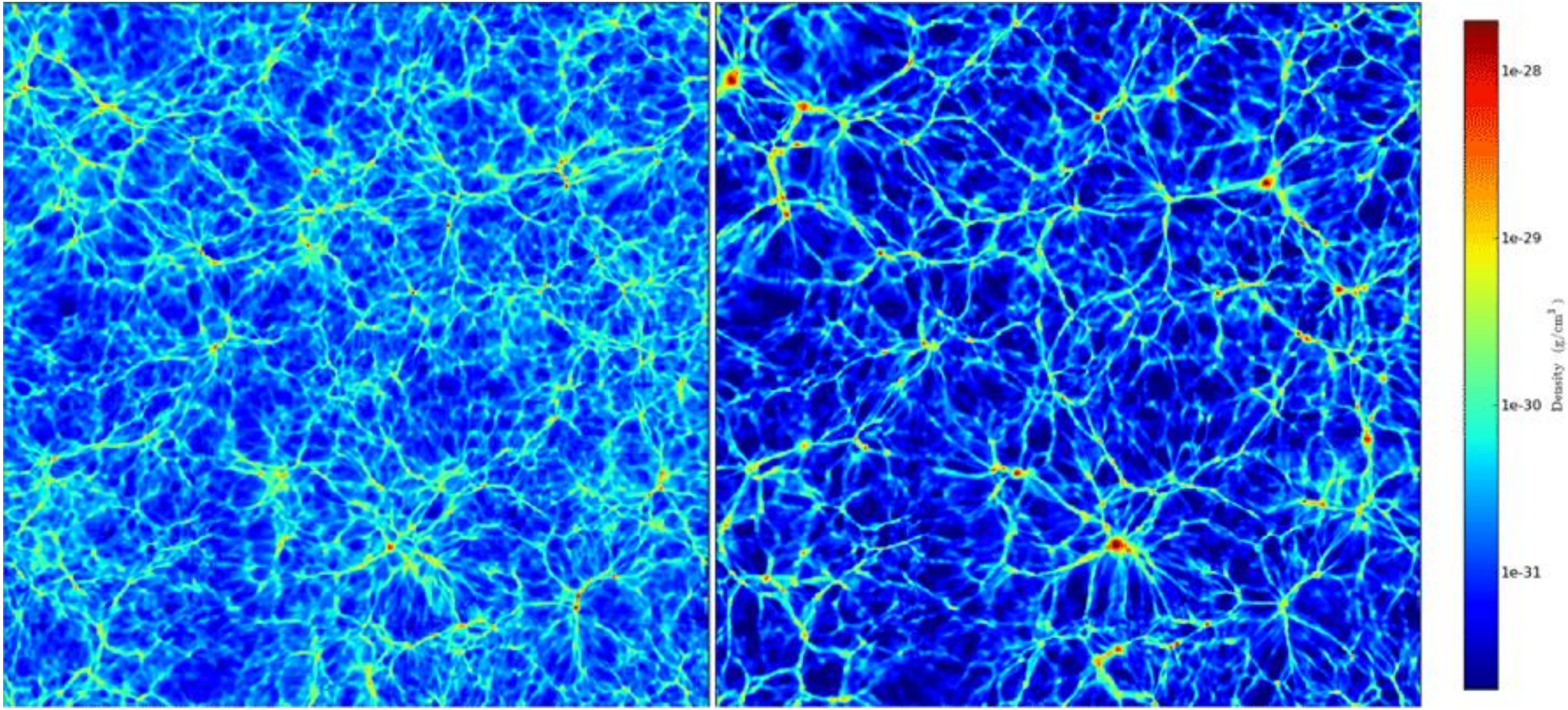
can be used to measure neutrino masses from cosmology.

The effect is proportional to the total energy density in neutrinos

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

$\sum m_\nu = 1.9\,\mathrm{eV}$ No neutrinos

Credit: Agarwal & Feldman



1.5 million lightyears

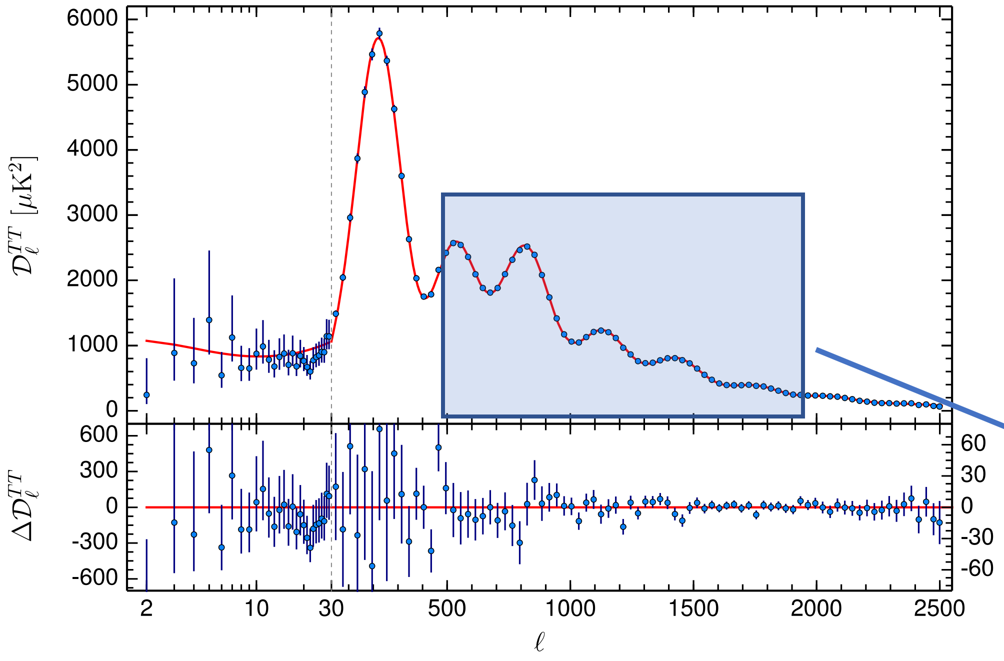
Neutrino masses from cosmology

Cosmological inferences on neutrino masses are based on a comparison between the amplitude of small scale fluctuations at early times (as inferred from the primary CMB) and at late times (as inferred from probes of structure formation, e.g. CMB lensing, galaxy clustering…).

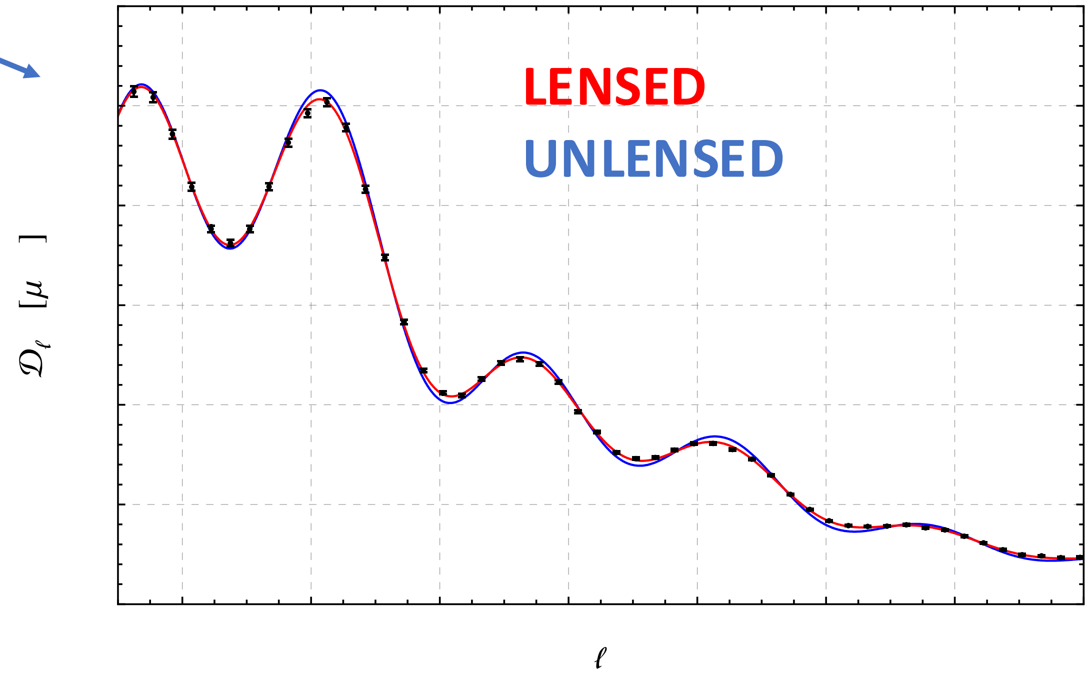
CMB inferences are thus affected by

- Uncertainties in the determination of the initial amplitude (e.g. reionization optical depth)
- Changes in expansion history (changes the time over which structures grow)

WEAK LENSING OF THE CMB



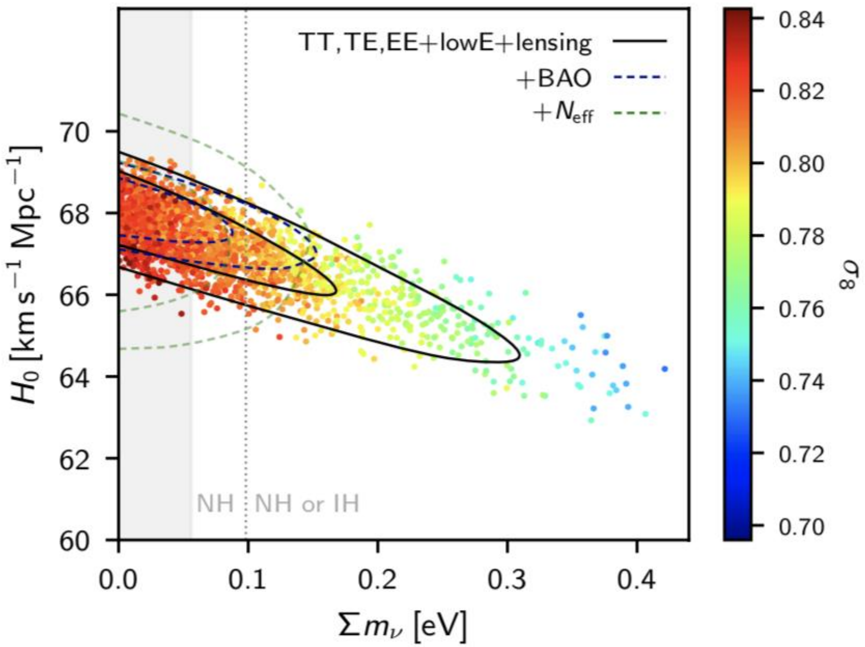
In the power spectrum, lensing causes a smoothing effect at small scales

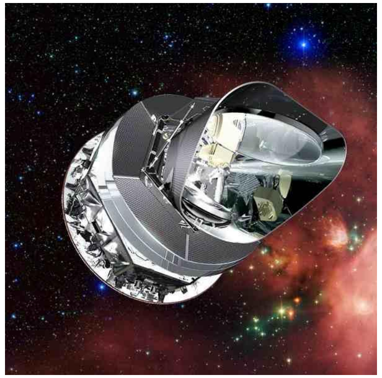


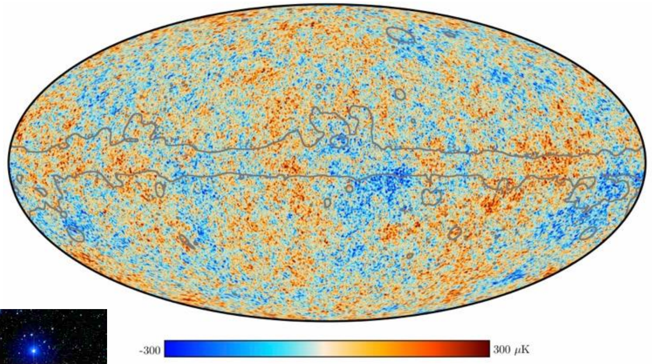
Neutrino free streaming damps matter perturbations and *reduces* lensing

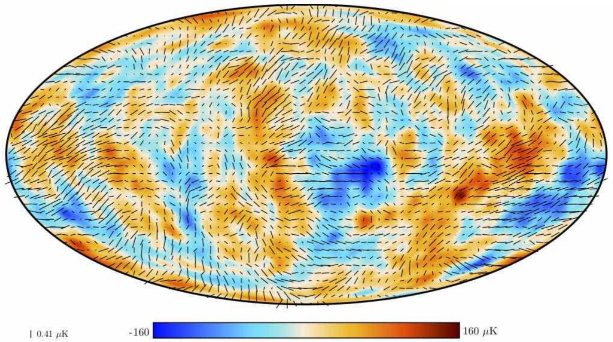
The effect is proportional to the energy density of neutrinos

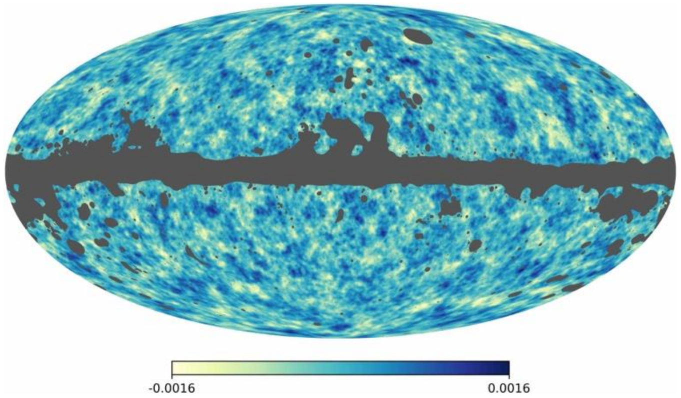
NEUTRINO MASSES AFTER PLANCK











Planck 2018

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

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

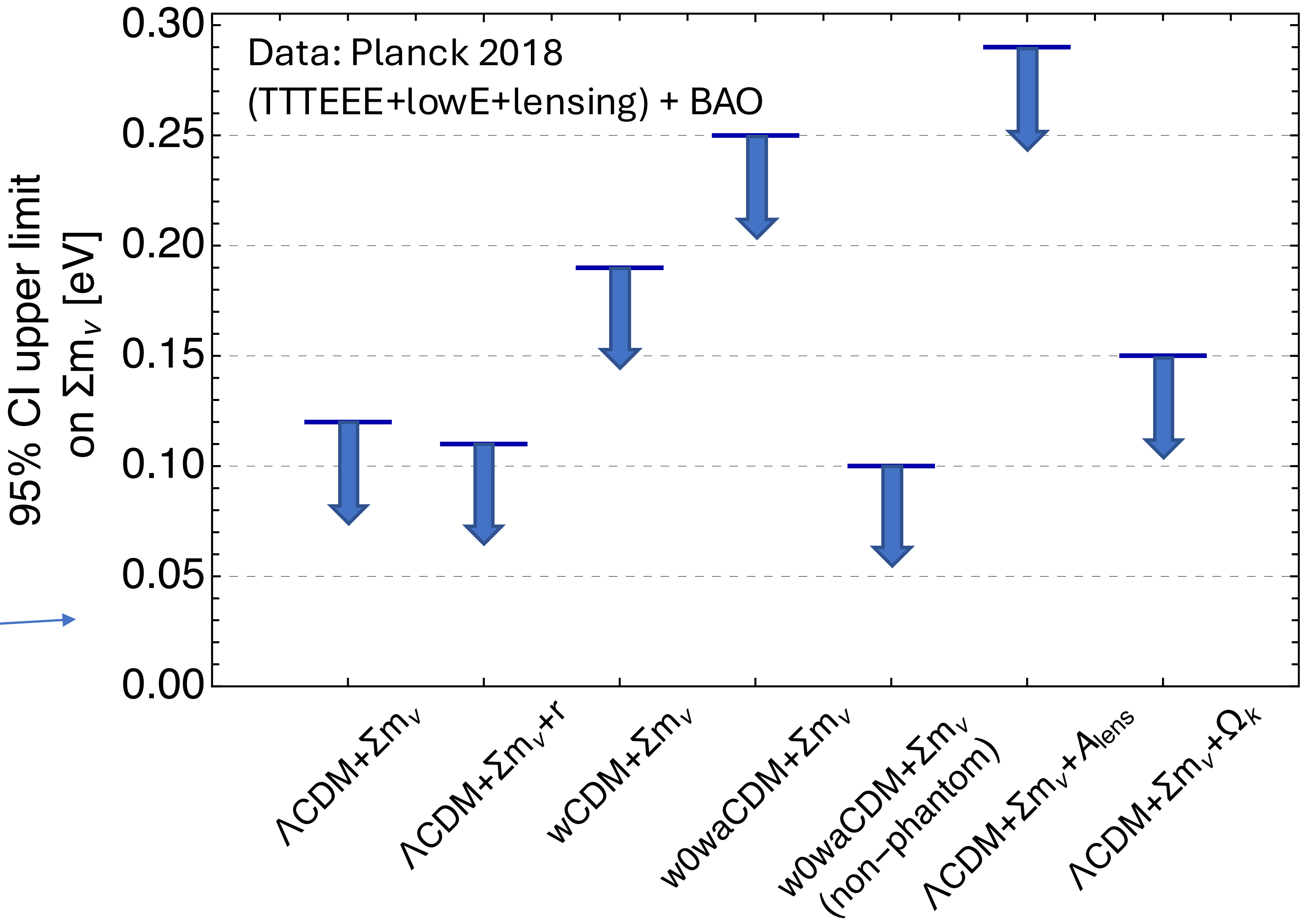
(95% CL)

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)

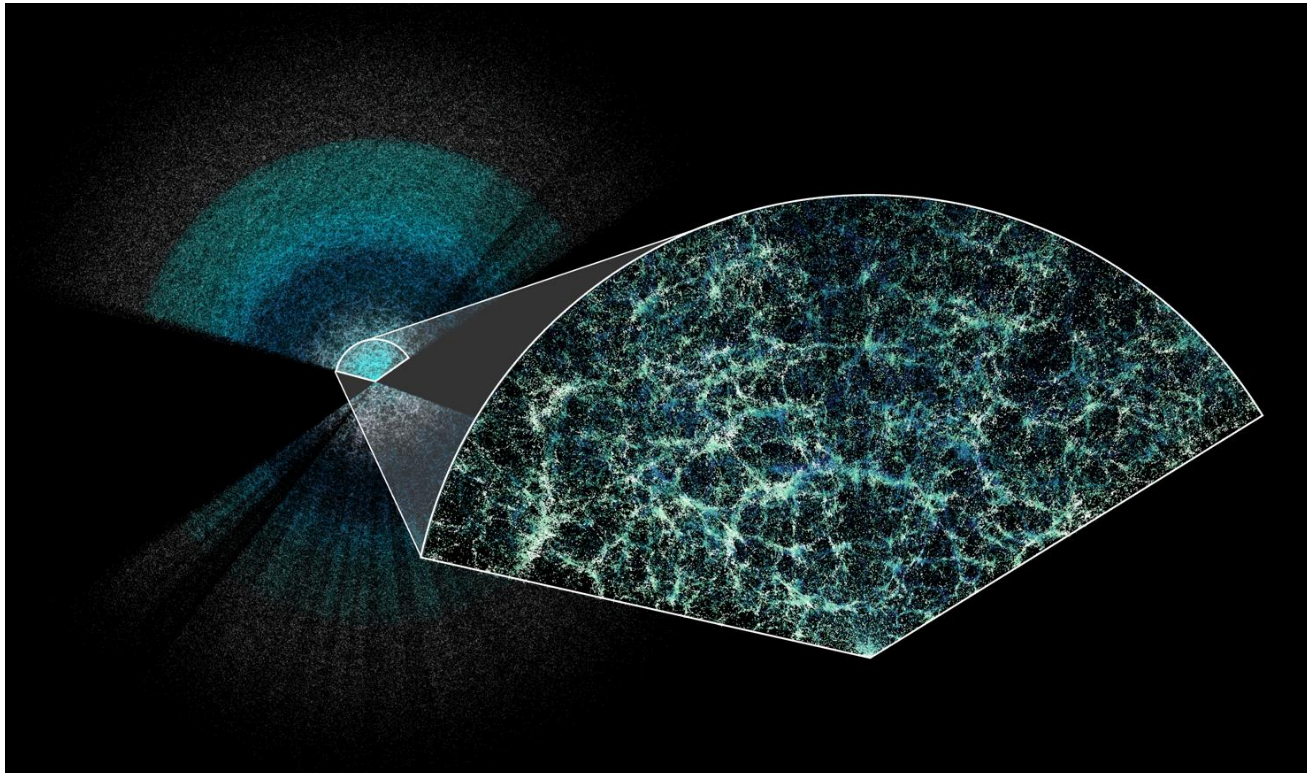
based on S. Roy Choudhury & S. Hannestad (2020) arXiv 1907.12598



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

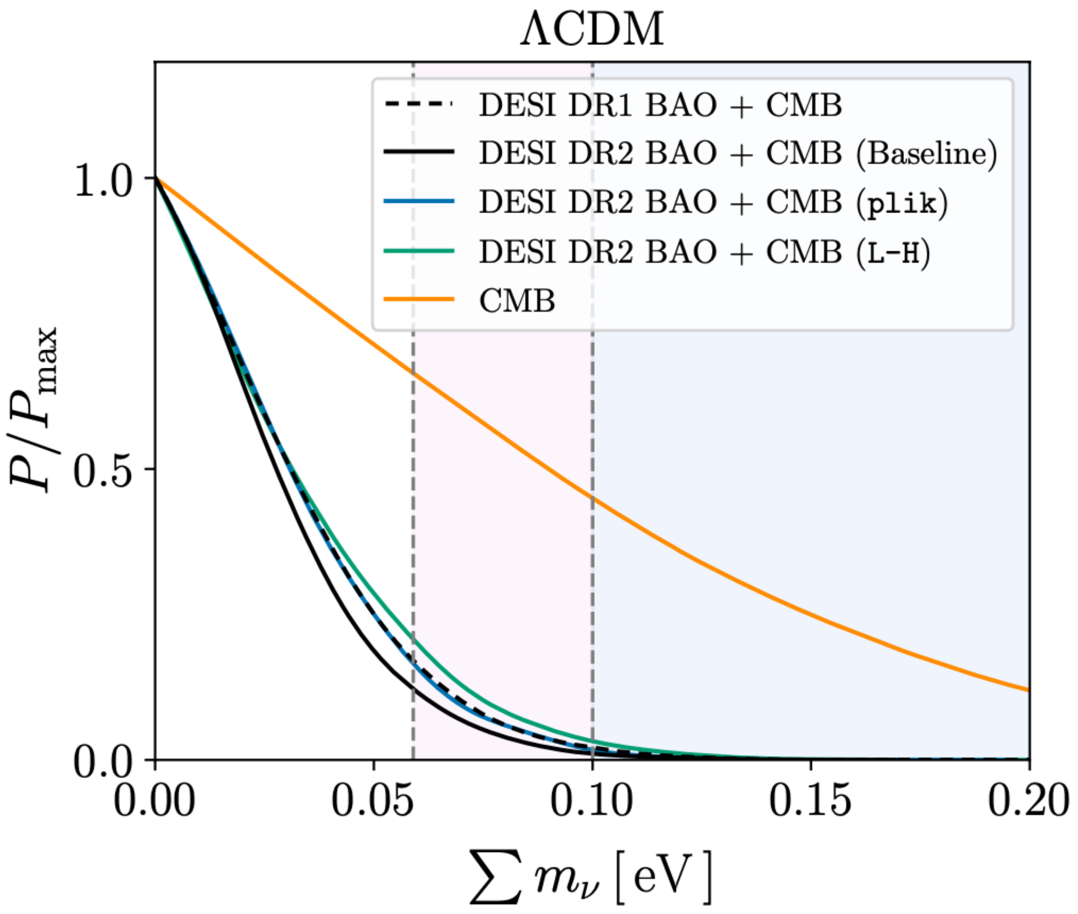
Dark Energy Spectroscopic Instrument

- Largest 3D map of the Universe currently available
- Lookback time 11 Gyrs



First cosmology results presented in April 2024
Second data release (3yrs of data) in March 2025

DESI CONSTRAINTS ON NEUTRINO MASSES

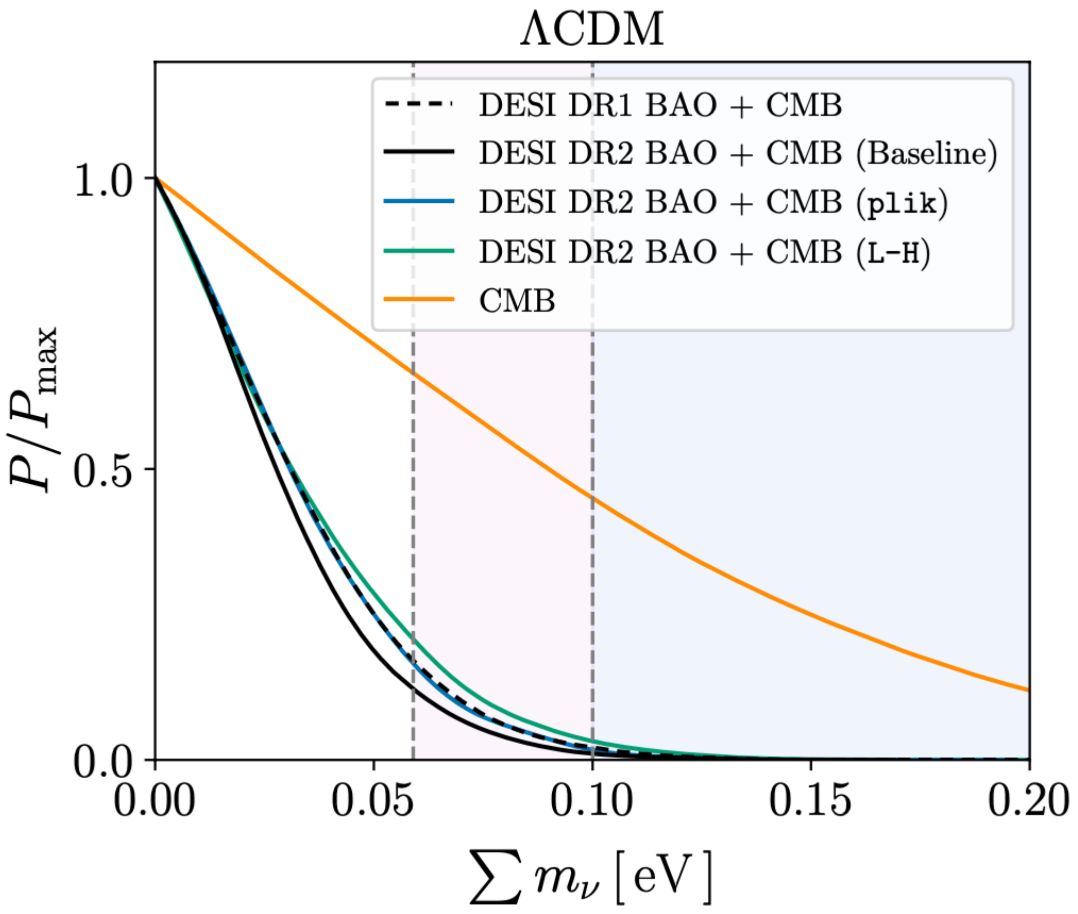


Planck+ACT+DESI BAO
Preference for vanishing neutrino masses

$\Sigma m_\nu < 0.064$ eV @95% CL

DESI Collaboration, arXiv:2503.14744

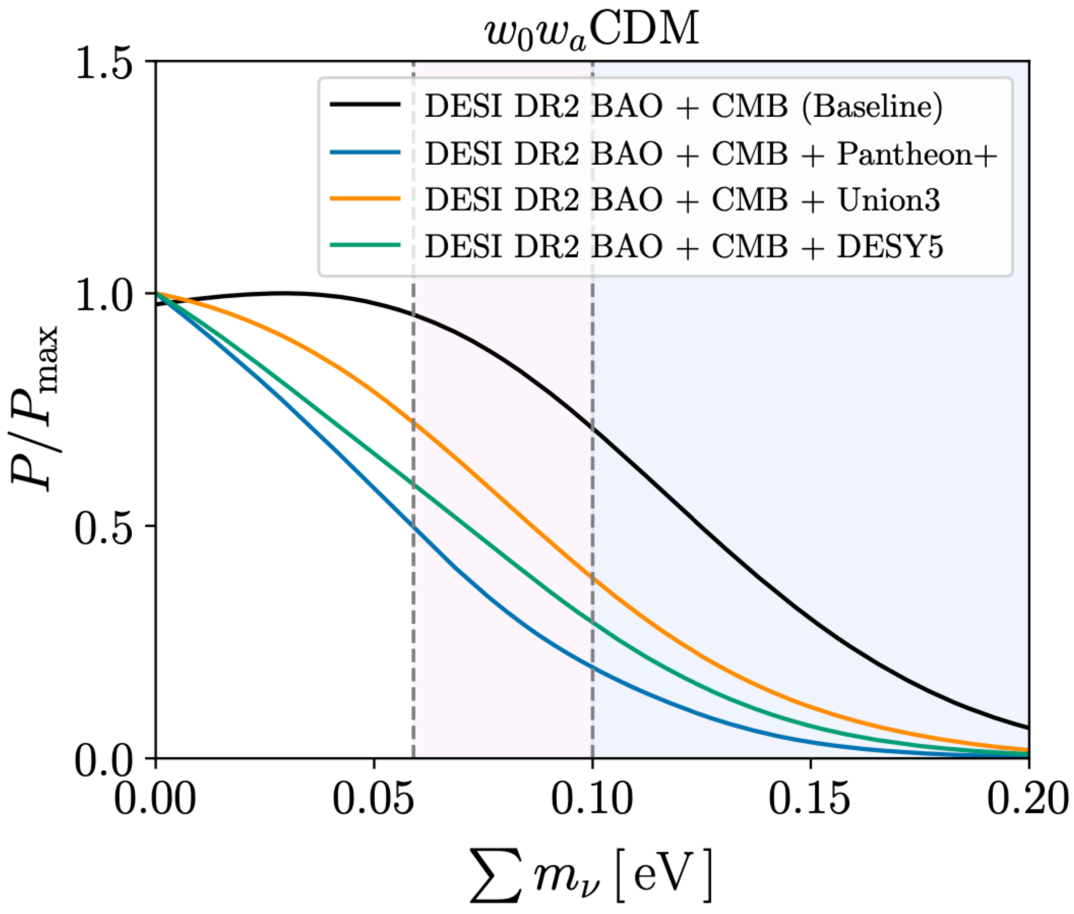
DESI CONSTRAINTS ON NEUTRINO MASSES



- Affected by higher-than-expected CMB lensing and DESI preference for low Ω_m and high $H_0 r_d$
- Hinting at new physics in the neutrino sector (decay, annihilation…) or elsewhere?
- Bound weakens including dynamical DE
- Depends only weakly on the Planck likelihood
- “Negative” neutrino masses?

See Green&Meyers (2407.07878), Craig+. (2405.00836), Naredo-Tuero+ (2407.13831), DESI 2024 VII (2411.12022), Allali&Notari (2406.14554), Elbers+ (2407.10965), Ge+ (SPT-3G coll., 2411.06000)

DESI constraints on neutrino masses



Planck+ACT+DESI BAO
Masses

$\boldsymbol{\Sigma m_\nu < 0.177}$ **eV** @95% CL

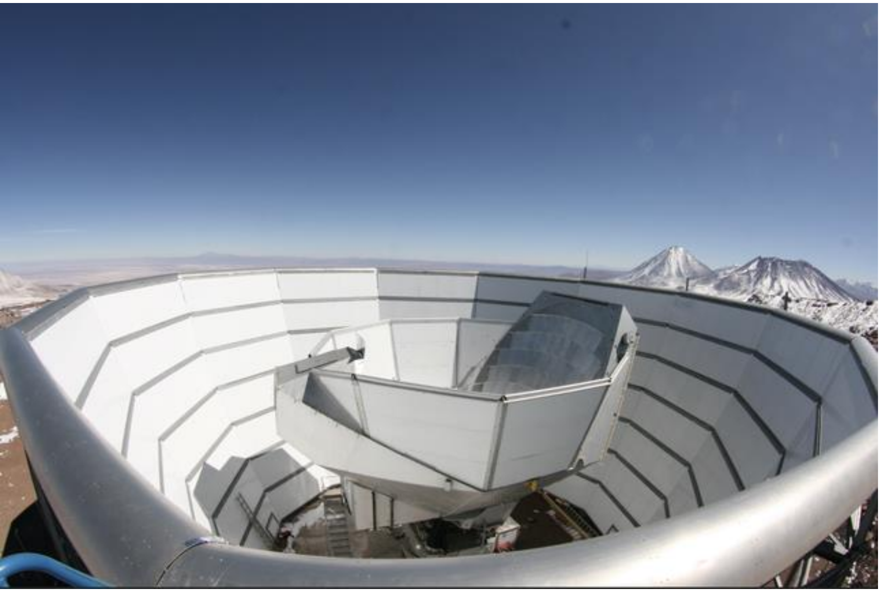
DESI Collaboration, arXiv:2503.14744

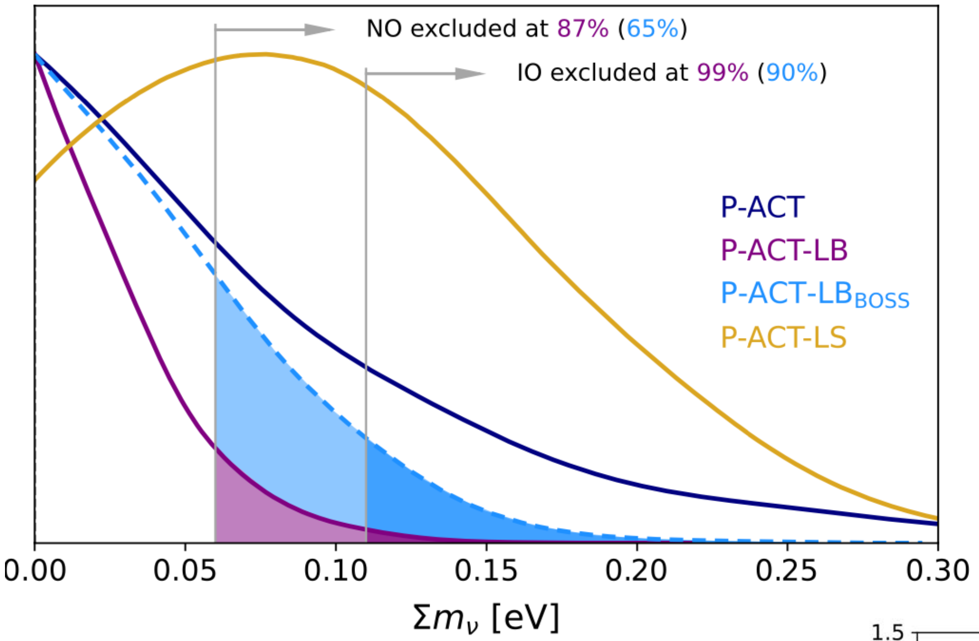
TABLE IV: Results of the cosmological data analysis under three model assumptions: standard cosmology with neutrino masses (ΛCDM+Σ), an extended model accounting for lensing systematics (ΛCDM+Σ+$A_{\rm lens}$), and a nonstandard cosmology with dynamical dark energy and neutrino masses ($w_0 w_a$CDM+Σ). The datasets used are listed in Section III C. For Planck, we consider both Plik and CamSpec likelihoods, which yield very similar results in all cases (shown explicitly only for ΛCDM+Σ). Upper bounds on Σ are reported at the 2σ level.

#	Model	Data set	Σ (2σ)
1	$\Lambda\text{CDM} + \Sigma$	Plik	< 0.175 eV
2		Plik+DESI	< 0.065 eV
3		Plik+DESI+PP	< 0.073 eV
4		Plik+DESI+DESy5	< 0.091 eV
5		camspec	< 0.193 eV
6		camspec+DESI	< 0.064 eV
7		camspec+DESI+PP	< 0.074 eV
8		camspec+DESI+DESy5	< 0.088 eV
9	ΛCDM+Σ+$A_{\rm lens}$	Plik	< 0.616 eV
10		Plik+DESI	< 0.204 eV
11		Plik+DESI+PP	< 0.255 eV
12		Plik+DESI+DESy5	< 0.287 eV
13	$w_0 w_a$CDM+Σ	Plik	< 0.279 eV
14		Plik+DESI	< 0.211 eV
15		Plik+DESI+PP	< 0.155 eV
16		Plik+DESI+DESy5	< 0.183 eV

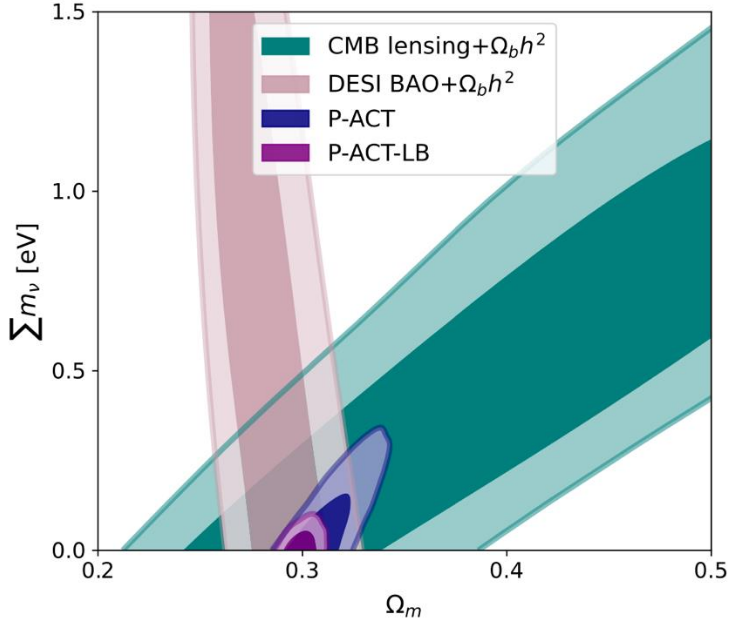
Capozzi et al. 2503.07752

March 18th, 2025: Legacy data release from the Atacama Cosmology Telescope

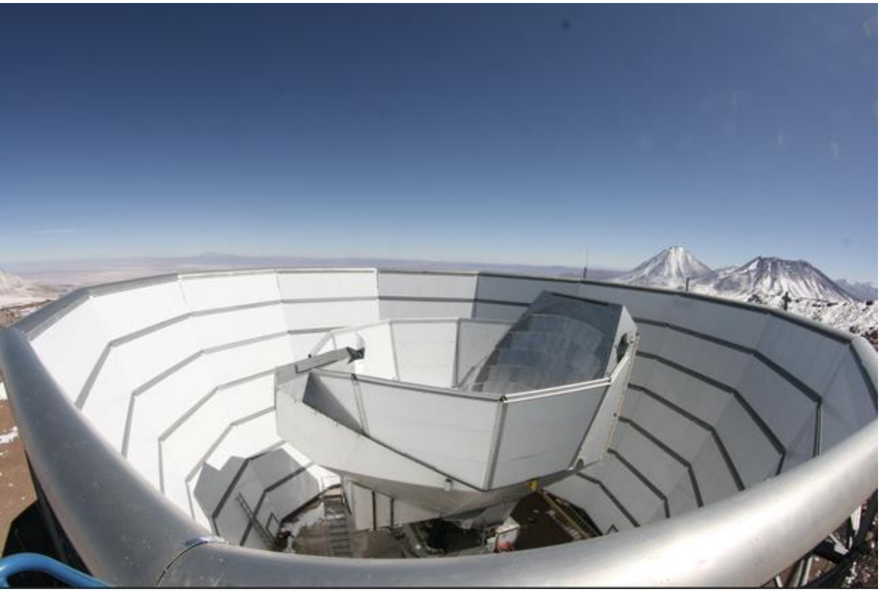


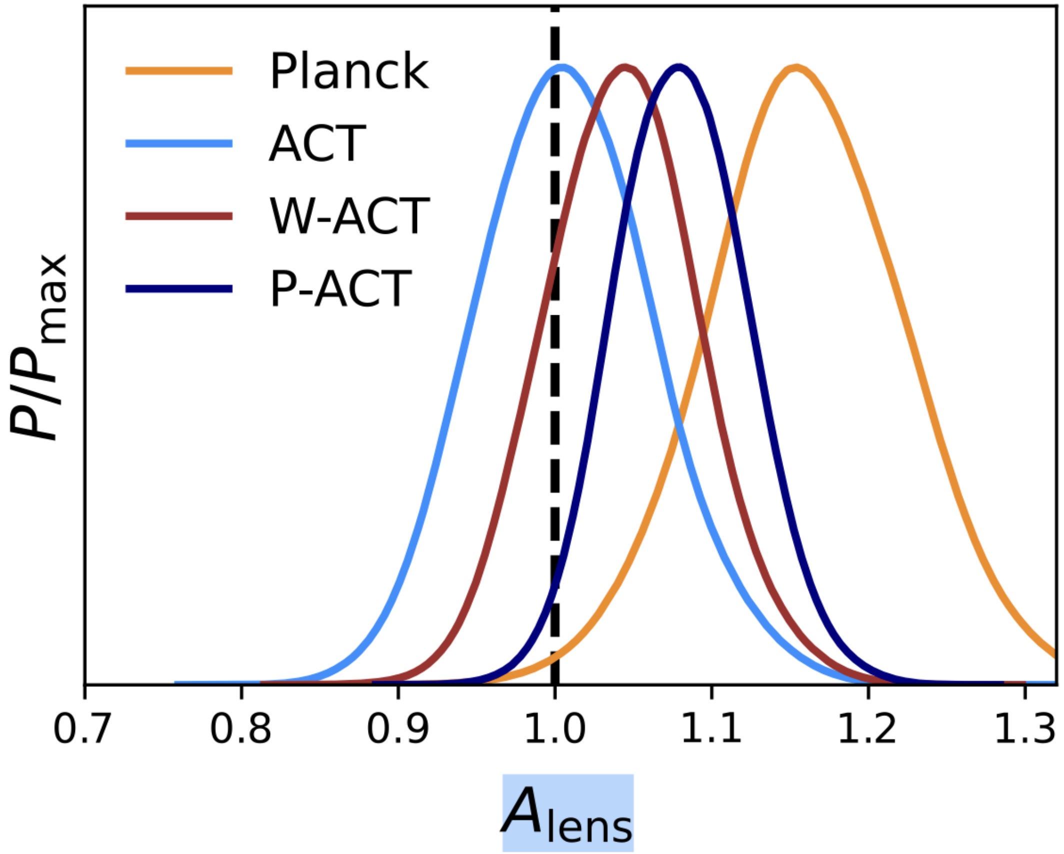


$$\sum m_\nu < 0.082\ \mathrm{eV} \quad (95\%, \text{P-ACT-LB}),$$
$$< 0.083\ \mathrm{eV} \quad (95\%, \text{W-ACT-LB}).$$

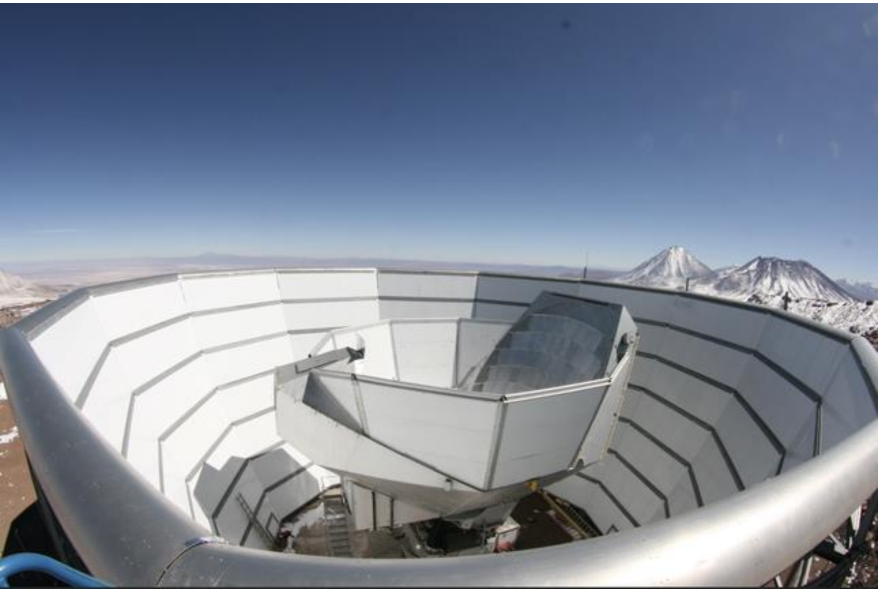


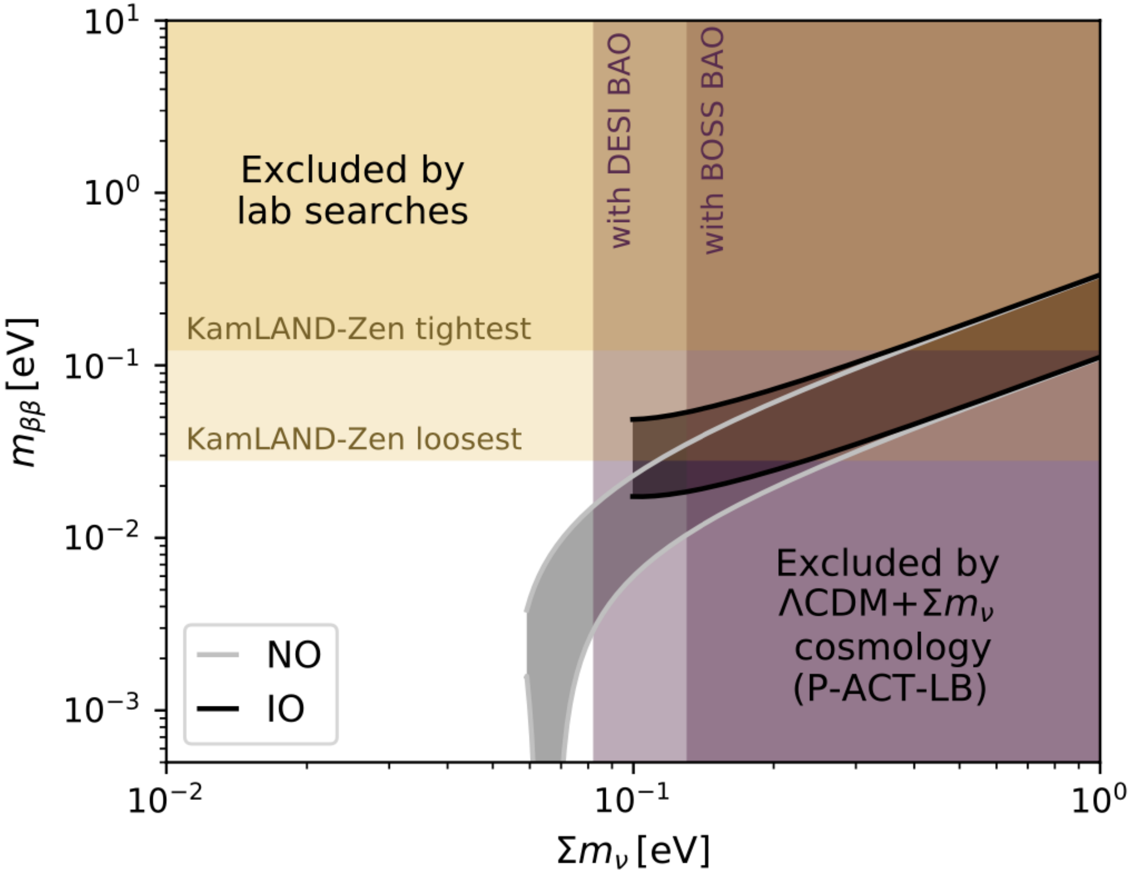
March 18th, 2025: Legacy data release from the Atacama Cosmology Telescope





March 18th, 2025: Legacy data release from the Atacama Cosmology Telescope



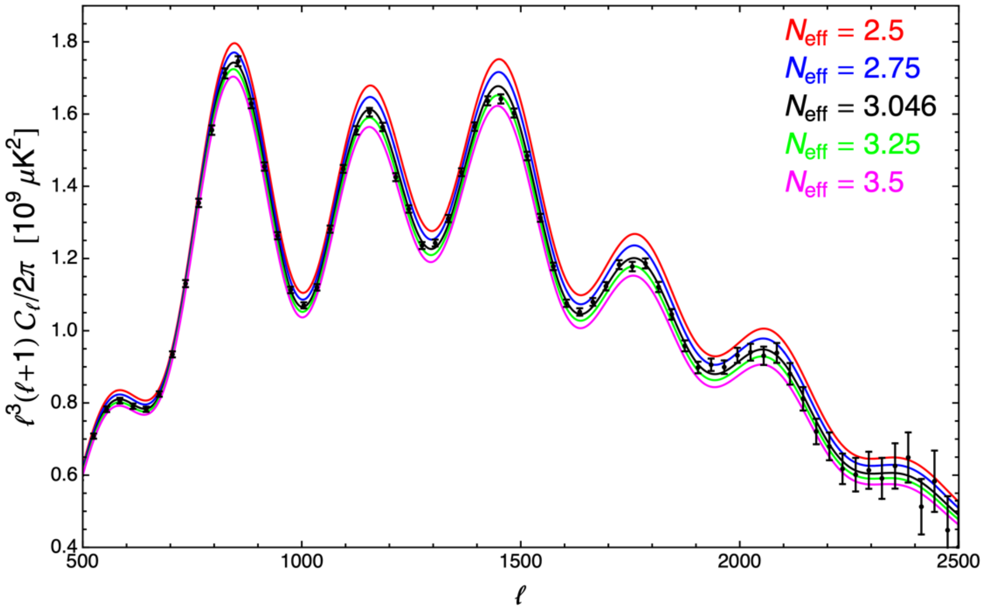


MEASURING N_{EFF}

- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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

Seen in the CMB small-scale anisotropies



(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)

Theoretical expectation for the three SM neutrinos* :

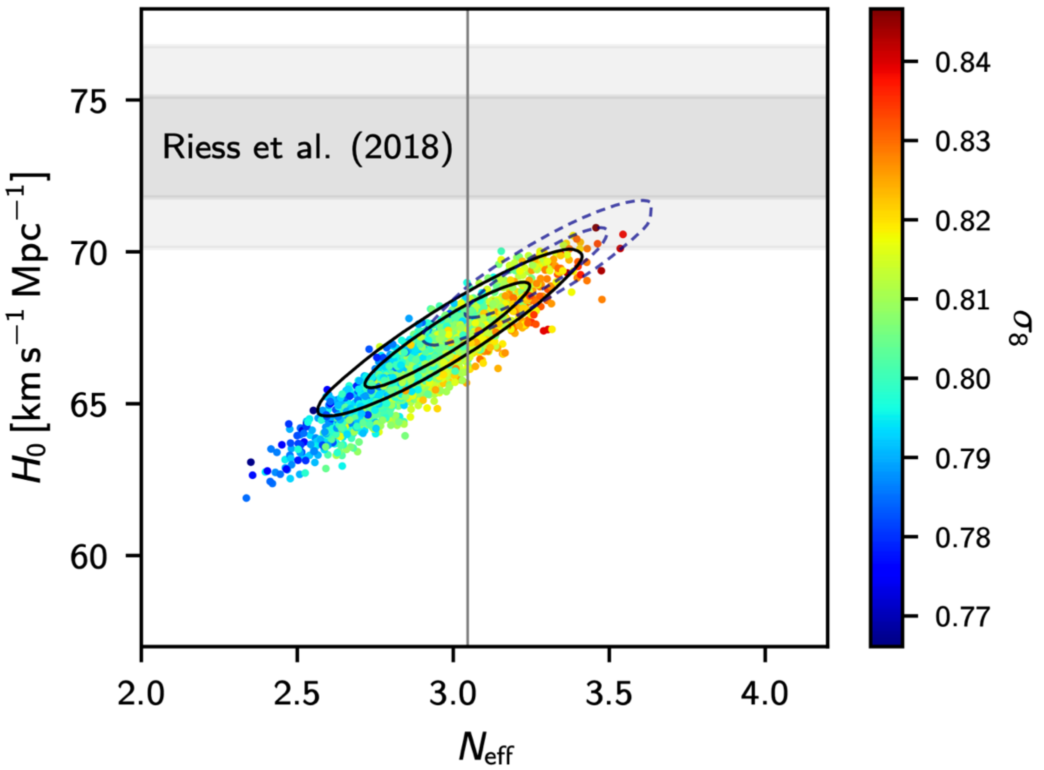
$$N_{eff} = 3.0440 \pm 0.0002$$

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

Constraints on N_{EFF}

- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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



Theoretical expectation for the three SM neutrinos:

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

$N_{\rm eff}$ measured with ~5% precision:

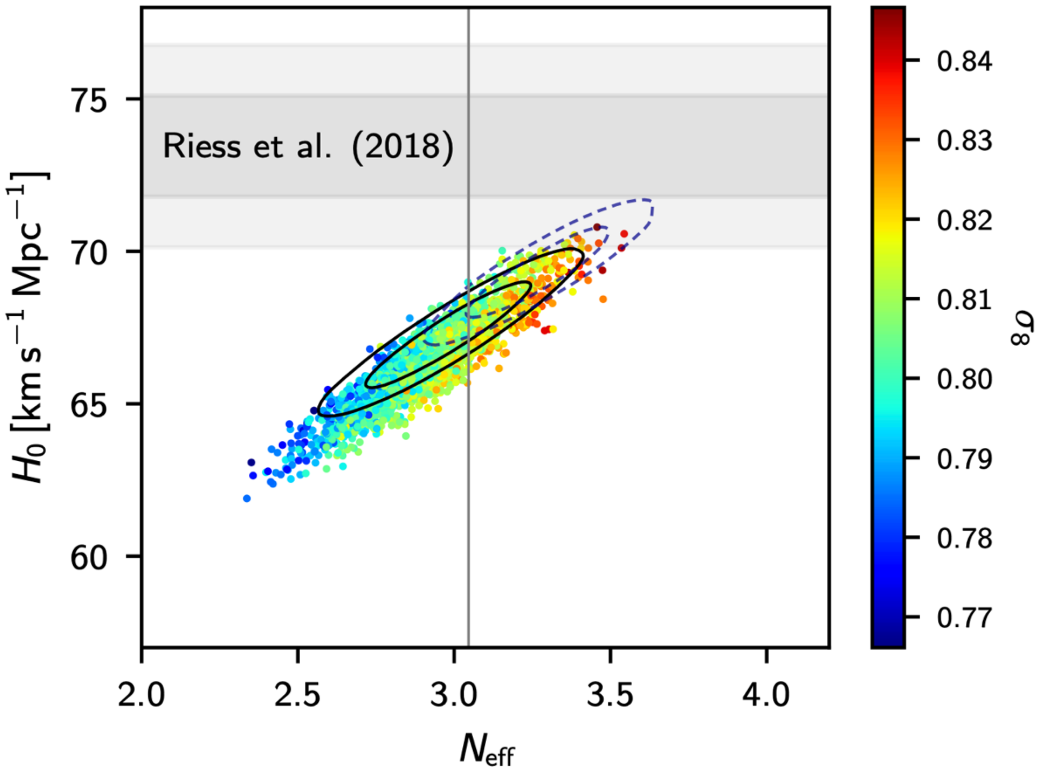
Planck 2018: $N_{\rm eff}$ = 2.89+/- 0.19

In agreement with the theoretical expectation
Excludes a fourth, very light, ***thermalized*** neutrino at more than 5σ

Planck collaboration, VI 2018

N_{EFF} AS A PROBE OF NEW PHYSICS

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



Planck collaboration, VI 2018

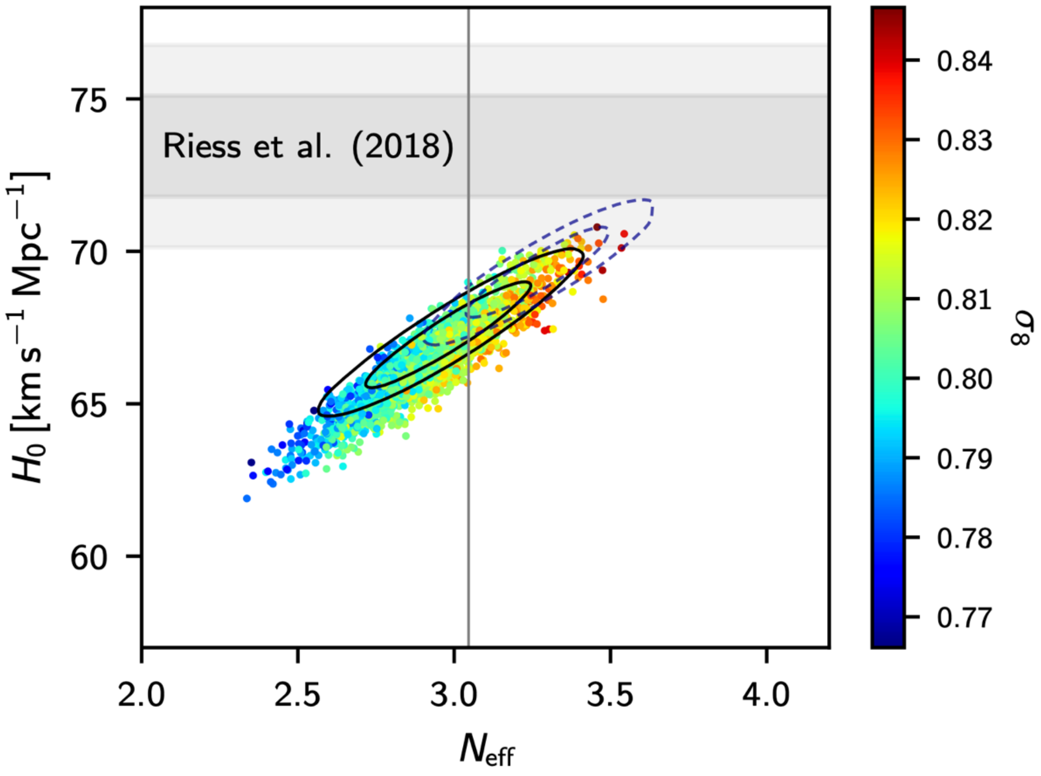
A deviation from the standard value of N_{eff} might be due to:

- 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_{eff} puts tight constraints on theories beyond the SM and beyond ΛCDM

NEFF AS A PROBE OF NEW PHYSICS

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



Planck collaboration, VI 2018

Both a blessing and a curse!

We can use $\Delta N_{\rm eff} = N_{\rm eff} - 3.044$ to probe a wide range of models of new physics…

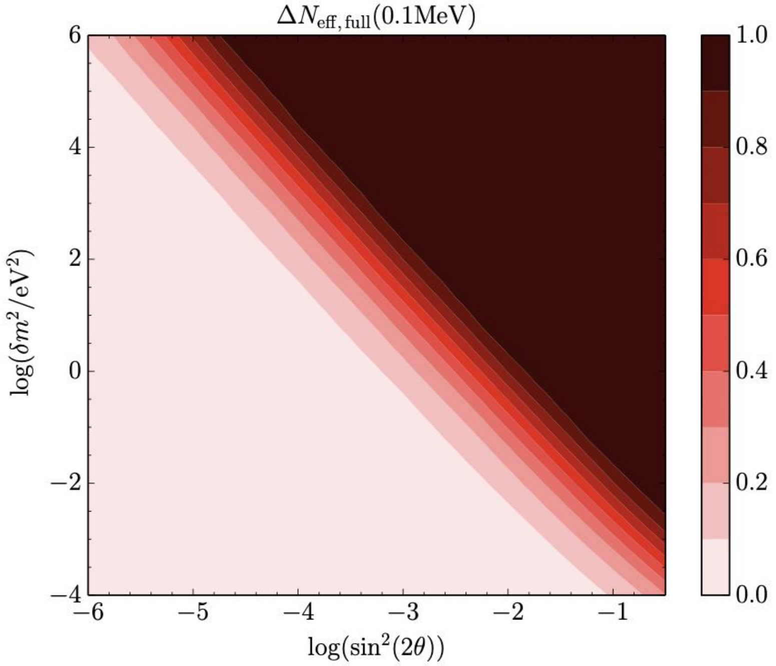
….however, if $\Delta N_{\rm eff} \neq 0$ is measured, how should we interpret it?

- Look for other cosmological signatures (concurring signal in the sum of the masses, effects on cosmological perturbations….)
- Search for confirmation in the lab

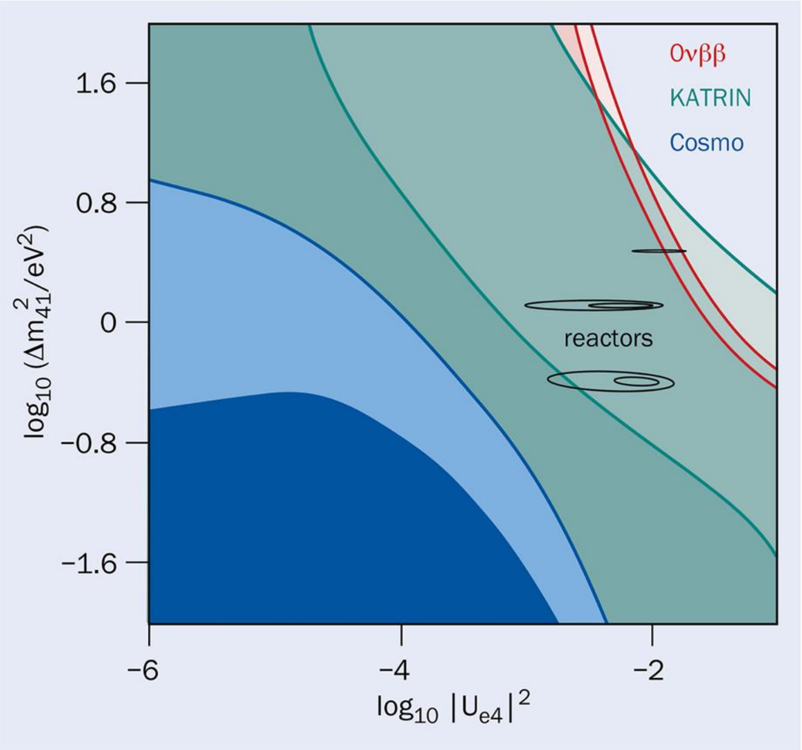
(not really much different from the present situation with dark matter and dark energy, if you think of it!)

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

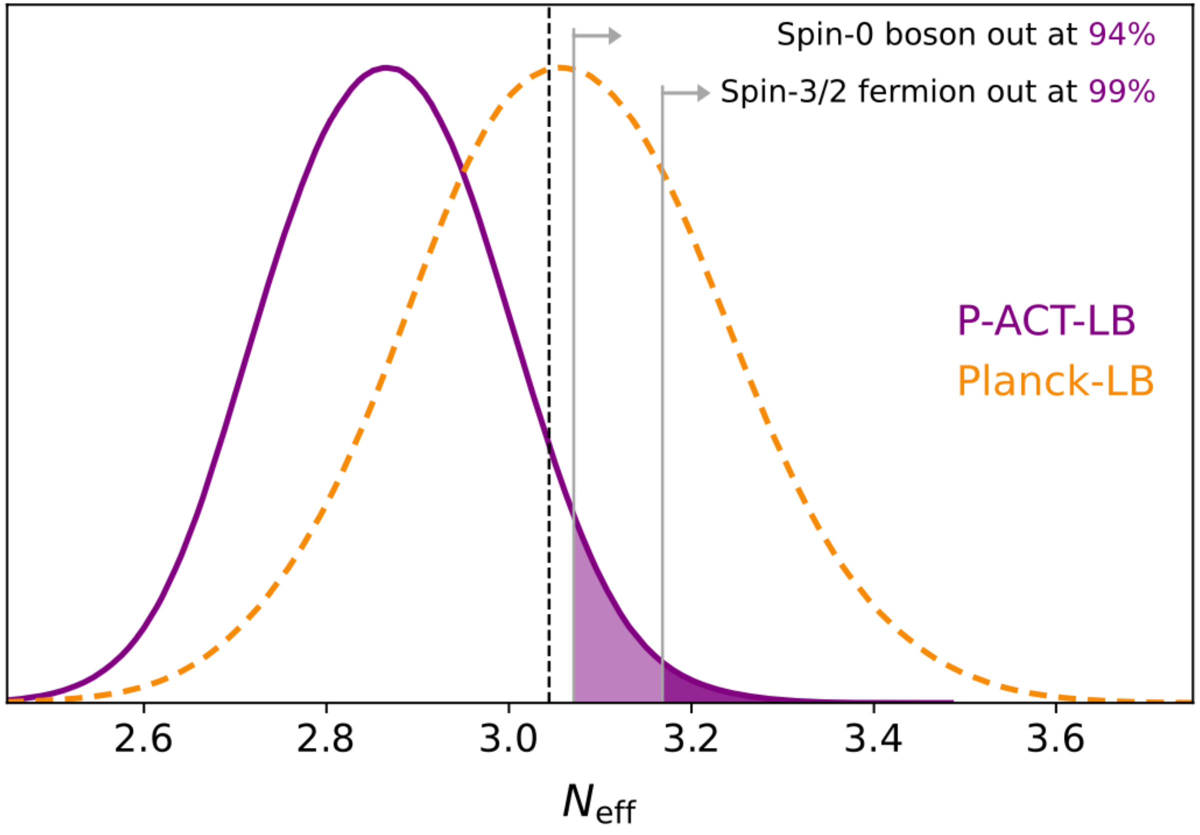


Cosmology robustly exclude region of large sterile mass and mixing params larger than 10^-3 in LCDM extensions

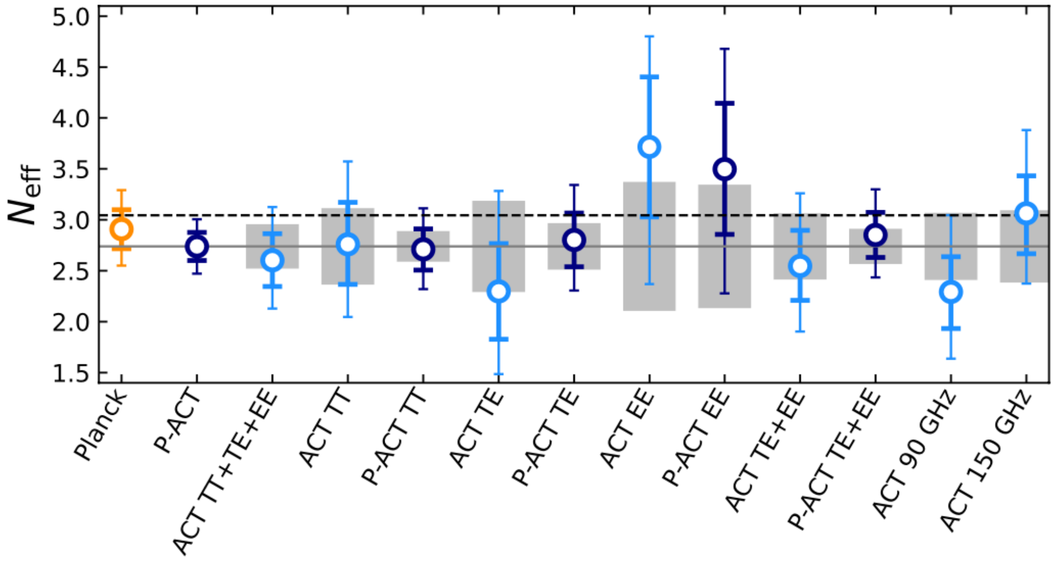
Light sterile solution to short-baseline oscillation anomalies hard to accommodate!

See Hagstotz+ (incl ML) 2021

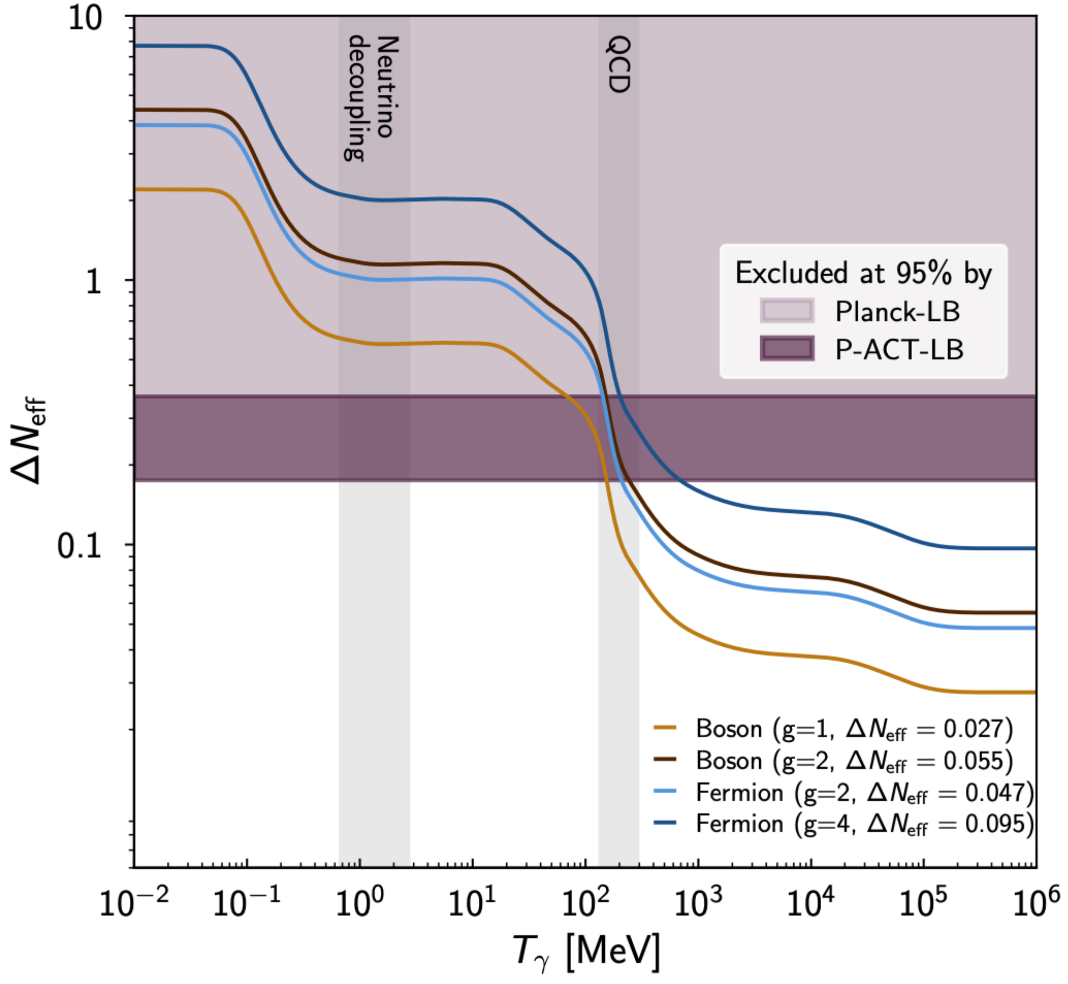
N_{EFF} FROM ACT



N_{eff} = 2.86 +/-0.13



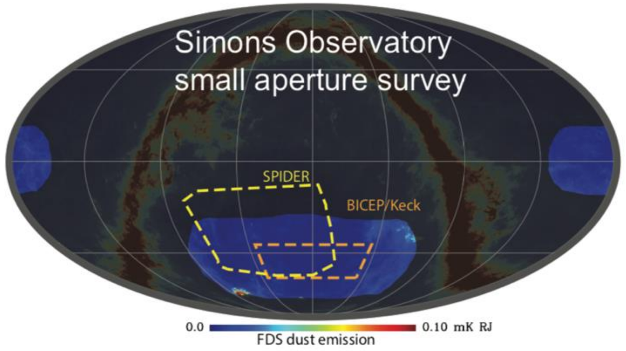
$\Delta N_{eff} = N_{eff} - 3.044$ can be related to the decoupling temperature of additional light species (e.g. axions, sterile neutrinos...)

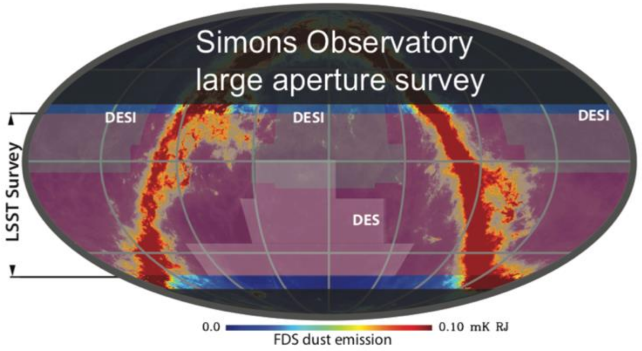


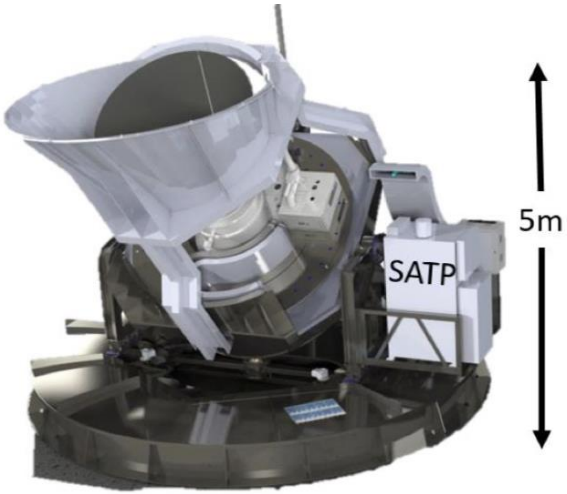
Particles in thermal equilibrium decoupling after the QCD phase transition at T~100 MeV are excluded by present cosmological data

ONGOING AND FUTURE OBSERVATIONAL EFFORTS

Simons Observatory





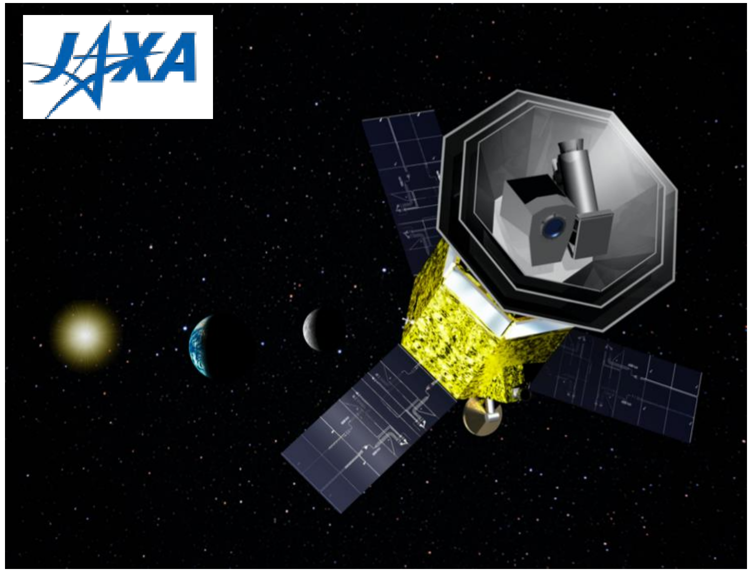


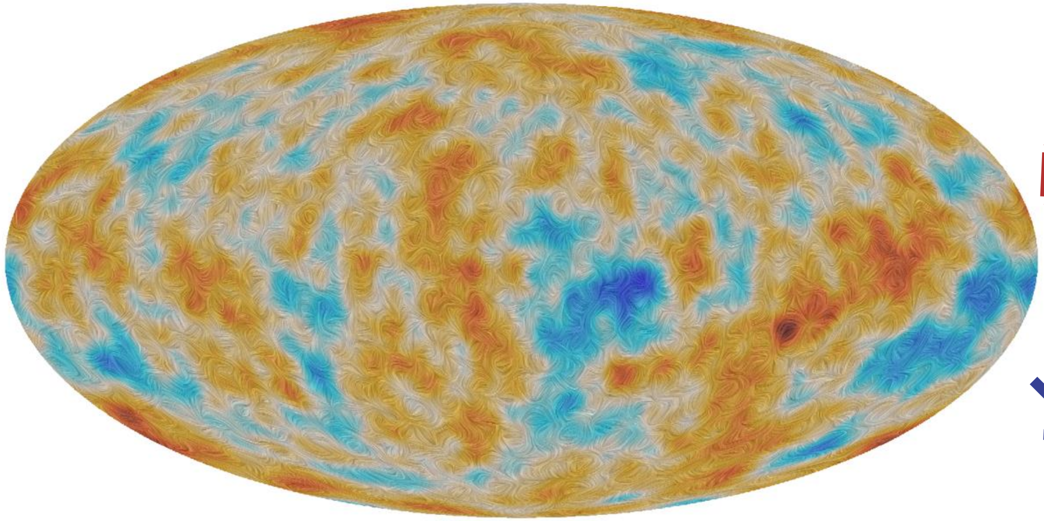
- Ground-based CMB experiment sited in Cerro Toco in the Atacama Desert in Chile
- 5-yr obs campaign
- 3 Small Aperture (0.4m) Telescopes (SATs) for ‘r science’
- 1 Large Aperture (6m) Telescope (LAT) for small-scale (arcmin) science
- > 60k TES detectors
- 10x sensitivity and 5x resolution wrt Planck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

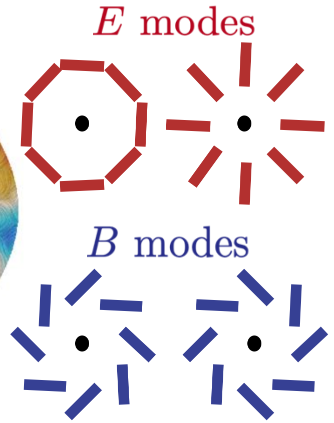
LiteBIRD Overview

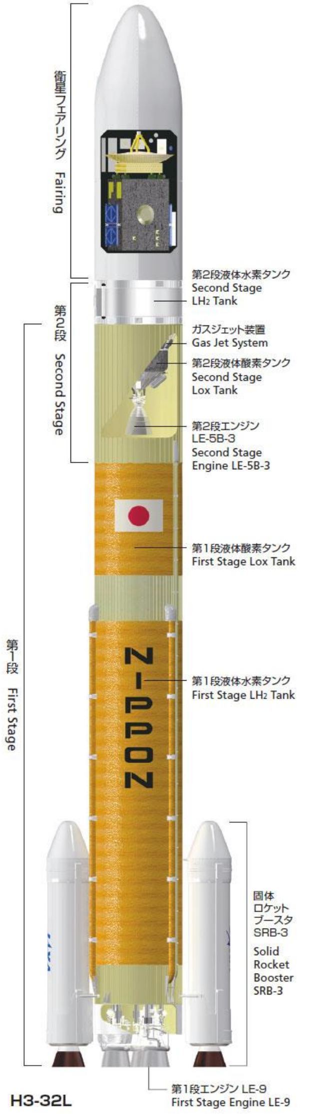
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in the Japanese Fiscal Year 2032 with JAXA's H3 rocket
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

☐ Litebird Collaboration PTEP 2023









CMB STAGE-4

- Definitive ground-based 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
- Currently undergoing reformation

See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

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

New science book currently under development

Galaxy Surveys

Vera Rubin Observatory
Ground-based
Under construction, expected completion in 2024

Euclid Satellite
Launched July 1st 2023

Nancy Roman Space Telescope
Launch in 2027

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**

Euclid lift-off on July 1st, 2023!

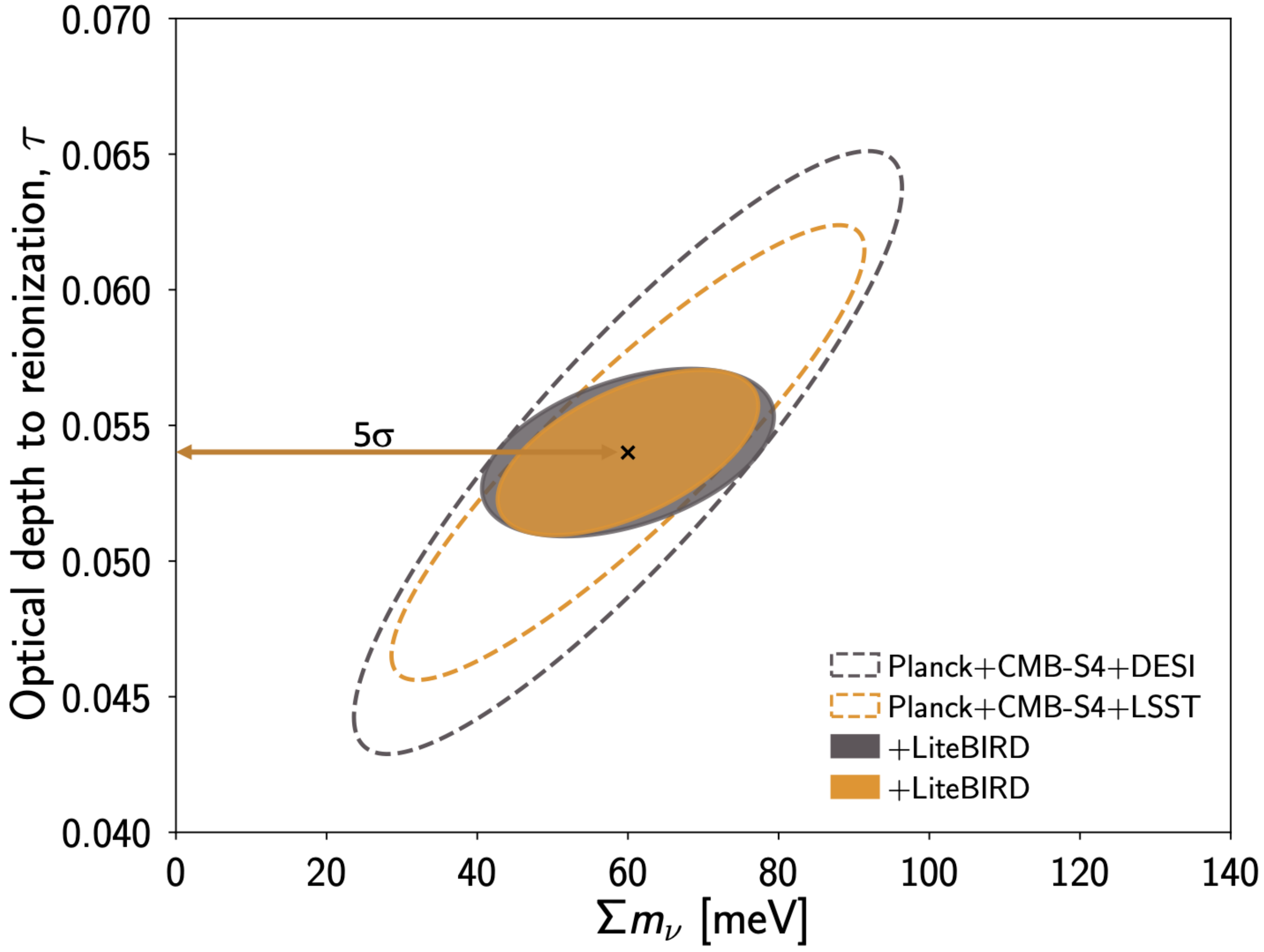
EUCLID AND NEUTRINO MASSES

ΛCDM + $\sum m_\nu$	$\Omega_{m,0}$	$100\,\Omega_{b,0}$	h	n_s	σ_8	$\sum m_\nu$[meV]
Euclid-only						
GC_{sp}	0.0068	0.37	0.033	0.029	0.0077	< 320
WL+GC_{ph}+XC_{ph}	0.0032	0.36	0.035	0.017	0.0047	< 260
WL+GC_{ph}+XC_{ph}+GC_{sp}	0.0026	0.24	0.022	0.013	0.0039	56
WL+GC_{ph}+XC_{ph}+GC_{sp}+CC	0.0025	0.24	0.022	0.012	0.0037	53
Euclid+CMB						
Euclid+*Planck*	0.0023	0.033	0.0021	0.0022	0.0033	23
Euclid+CMB-S4+LiteBIRD	0.0021	0.024	0.0016	0.0014	0.0028	16

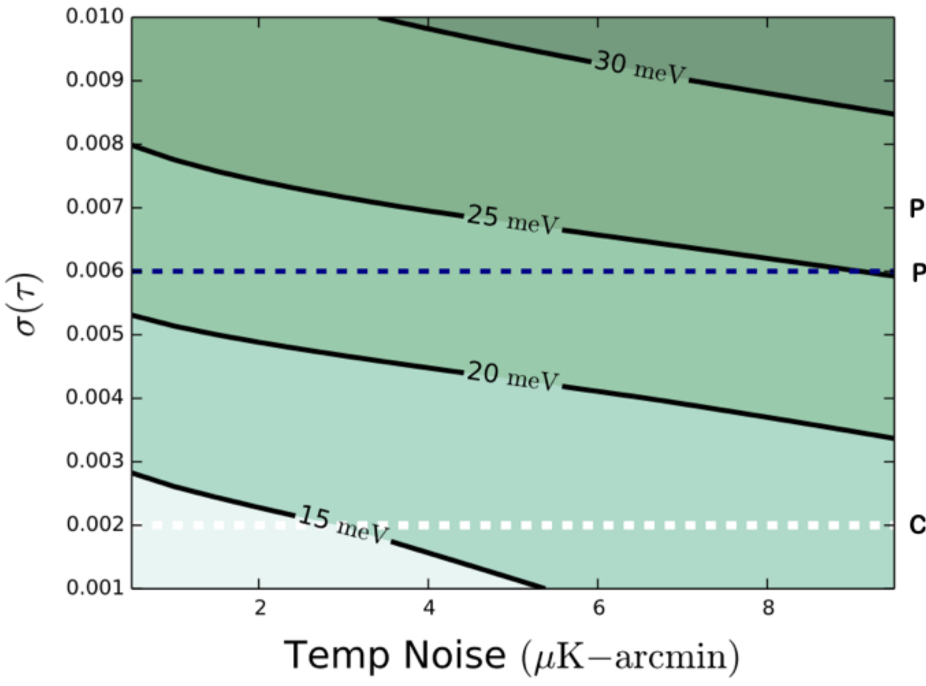
$w_0 w_a$CDM + $\sum m_\nu$	$\Omega_{m,0}$	$100\,\Omega_{b,0}$	h	n_s	σ_8	$\sum m_\nu$[meV]	w_0	w_a
Euclid-only								
WL+GC_{ph}+XC_{ph}+GC_{sp}	0.0043	0.21	0.019	0.010	0.0055	< 220	0.04	0.13
Euclid+CMB								
Euclid+*Planck*	0.0038	0.053	0.0036	0.0022	0.0048	38	0.04	0.12
Euclid+CMB-S4+LiteBIRD	0.0038	0.051	0.0035	0.0015	0.0043	28	0.04	0.11

Archidiacono et al, Euclid preparation LIV

LiteBIRD+CMB-S4+DESI/LSST



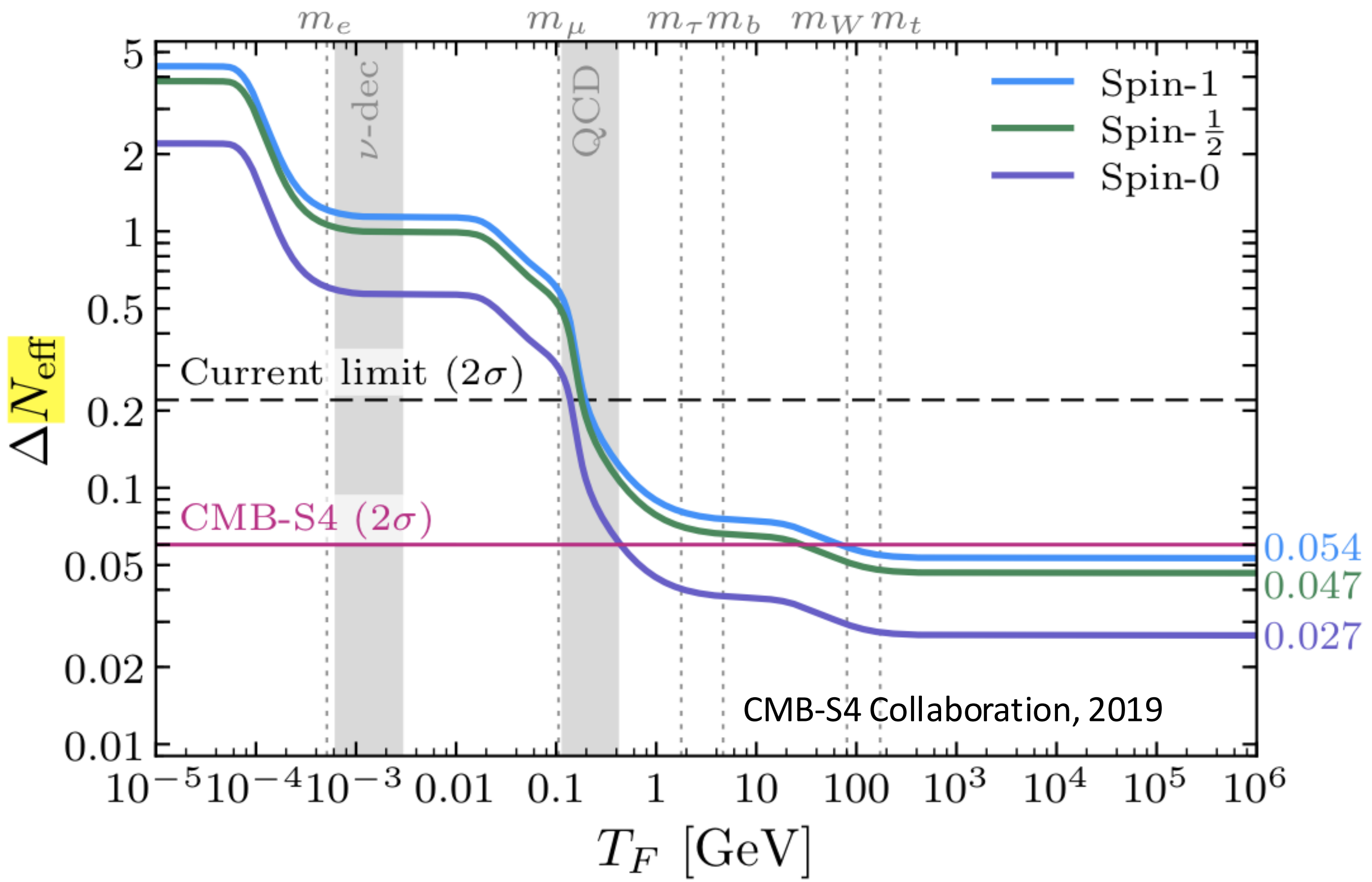
LiteBird Collaboration, arXiv:2202.02773

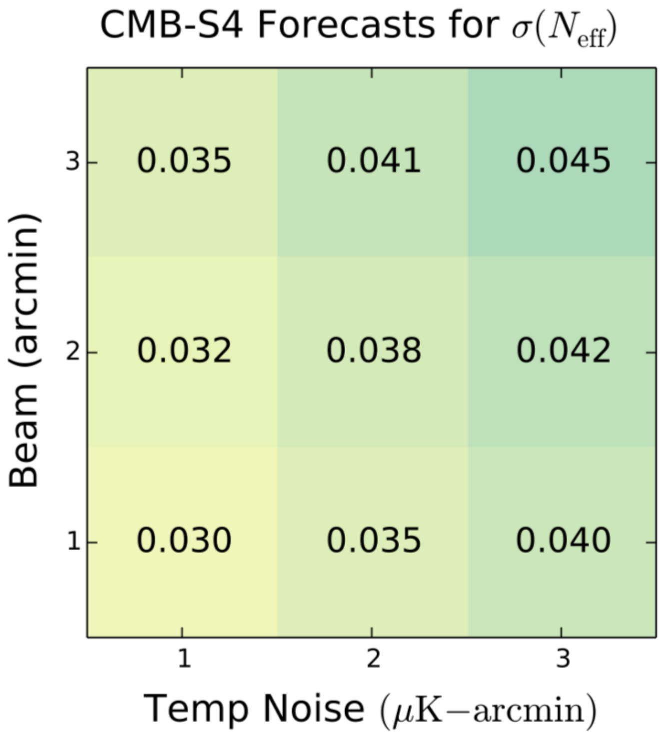


CMB-S4 Collaboration, 2019

N_{EFF} FROM CMB-S4

Contribution of extra species in thermal equlibrium





Beam (arcmin) \ Temp Noise	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

LIGHT RELICS FROM NEXT-GEN EXPERIMENTS

Reaching this 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 is needed to get the masses
  - Also 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 HWP systematics to be kept under control

Summary

- The current data tightly constraint the parameters of the LCDM model…
- … however, tension between datasets have emerged
- No convincing explanation (neither in terms of instrumental systematics nor new physics) has been found
- Neutrino masses can be tightly constrained through cosmological observations
- Model dependency should be accounted for but it’s not a show stopper
- Cosmology-laboratory tension from DESI BAO data?
- Future experiments will increase the sensitivity (in both LCDM and extensions, most notably w0waLCDM)
- Future measurements of Neff can provide hints for BSM physics

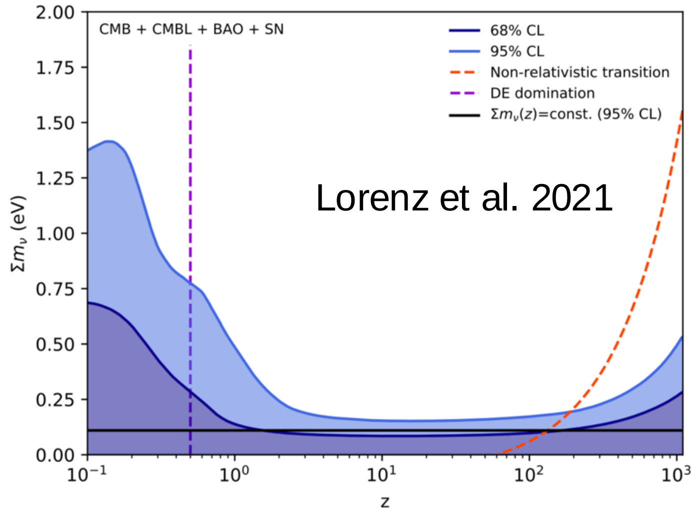
Grazie!

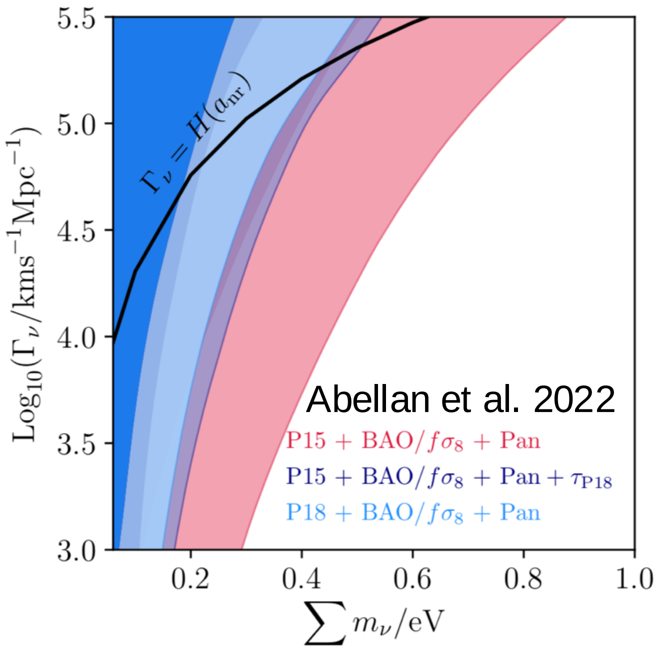
ν masses in ΛCDM Extensions

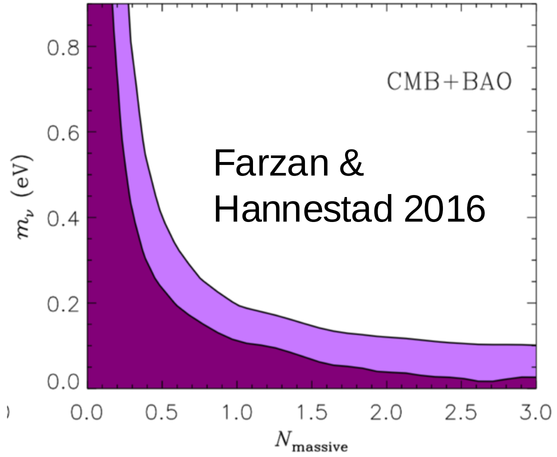
Constraints can be further loosened in alternative models, e.g.

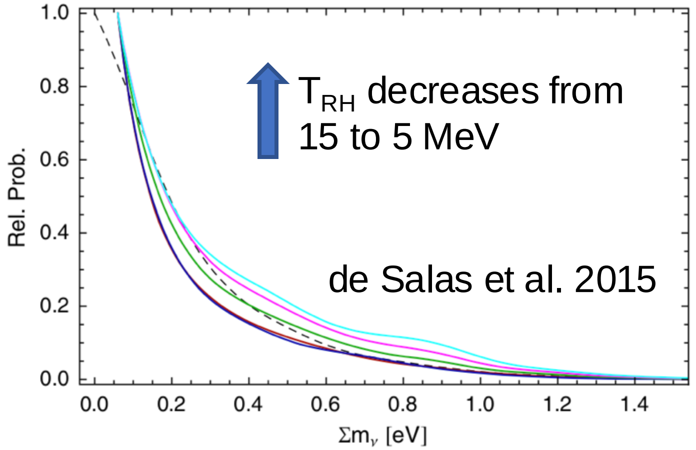
- Neutrino decays
- Late-time phase transitions (mass-varying neutrinos)
- Low-reheating scenarios
- Long-range ν interactions
- Conversion to lighter states

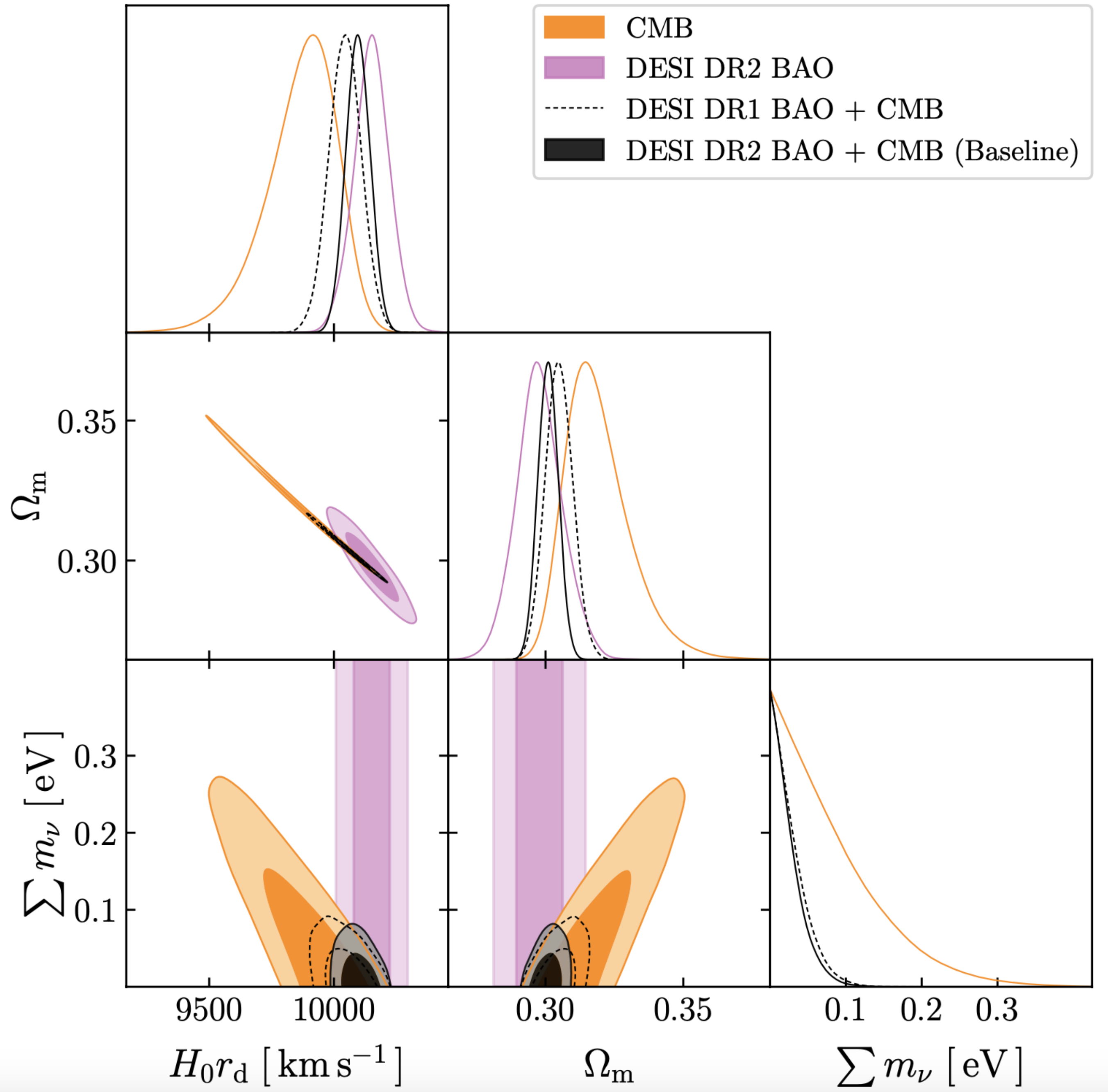
In some cases, this would reopen the window for a detection in KATRIN (see e.g. Alvey et al, 2021)

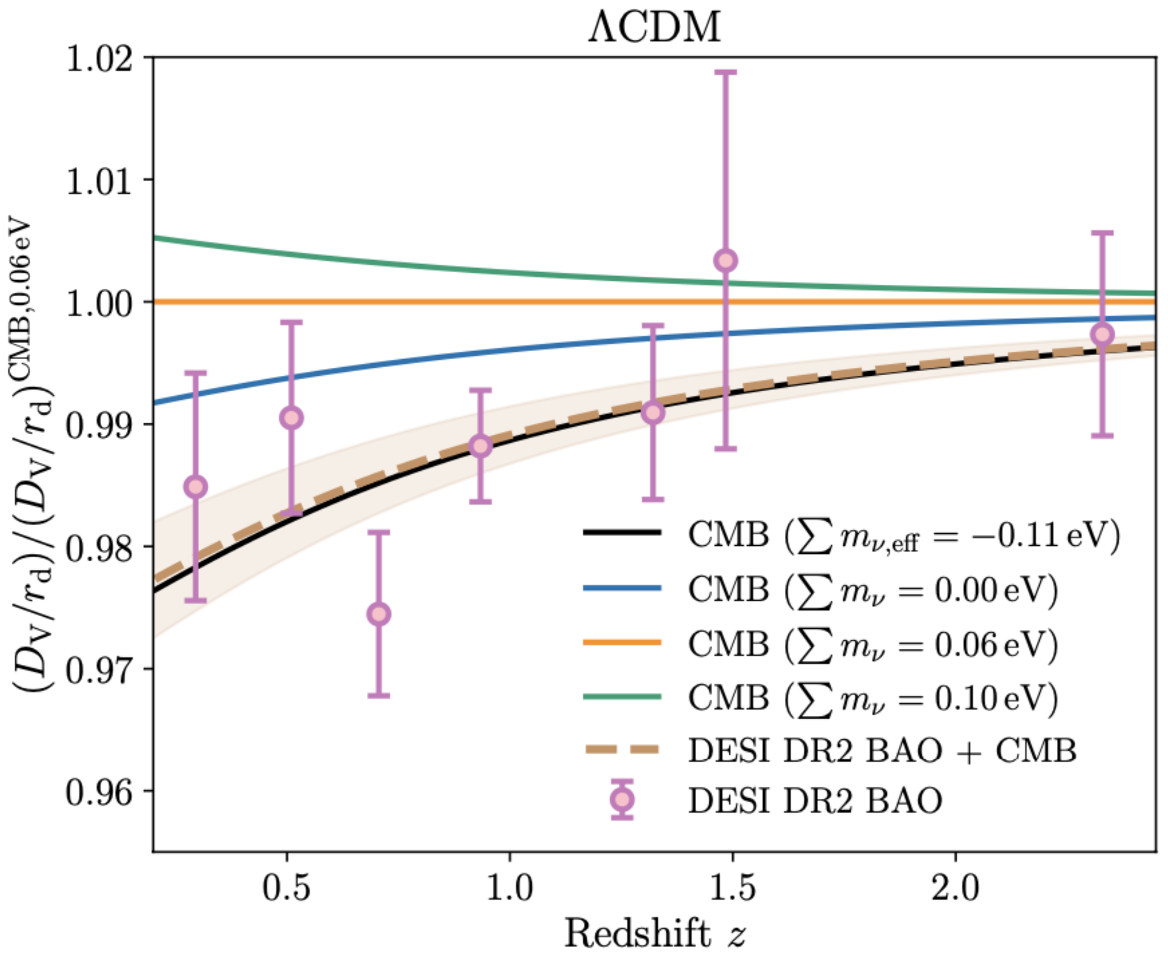


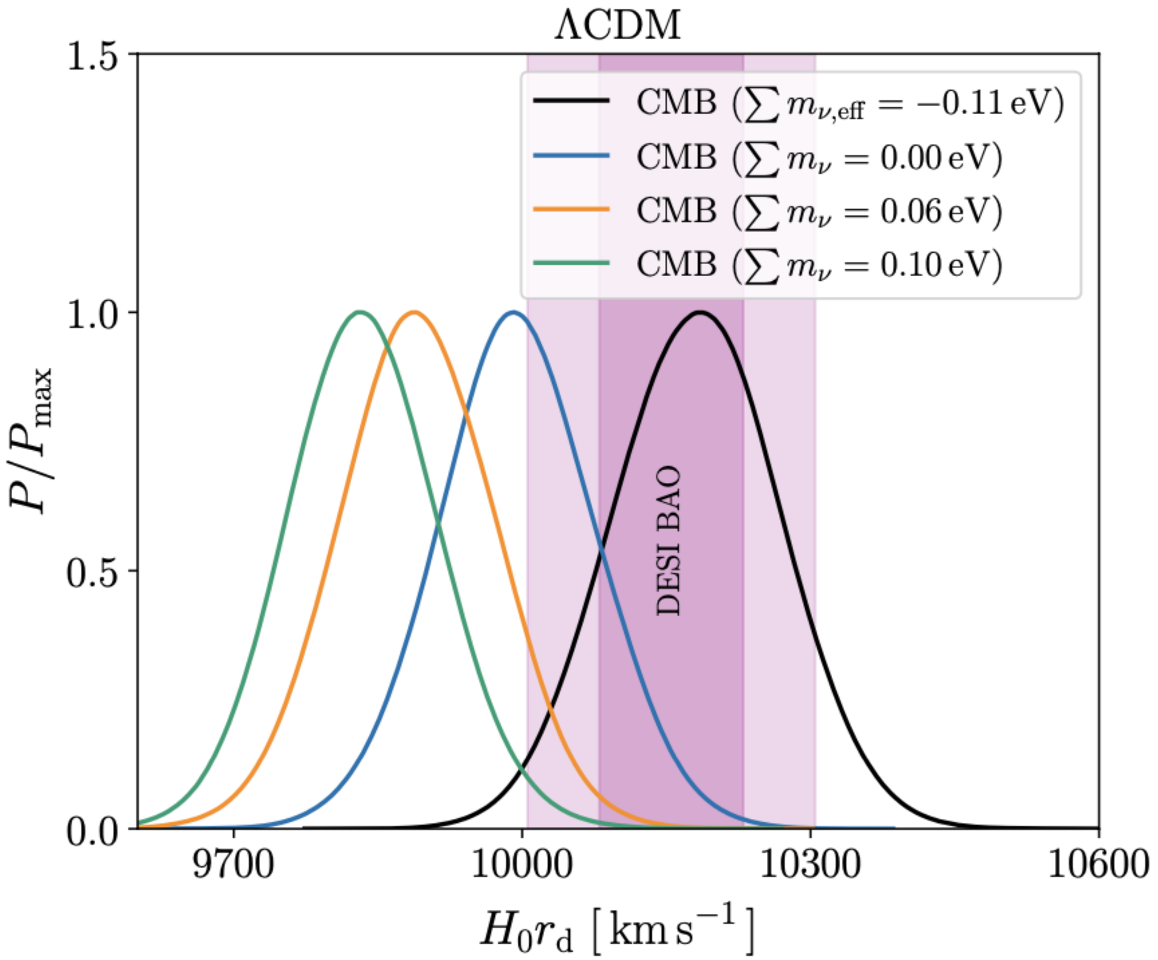







CMB
DESI DR2 BAO
DESI DR1 BAO + CMB
DESI DR2 BAO + CMB (Baseline)
0.35
0.30
Ω_m
0.3
0.2
0.1
$\sum m_\nu$ [eV]
9500
10000
$H_0 r_d$ [km s^{-1}]
0.30
0.35
Ω_m
0.1
0.2
0.3
$\sum m_\nu$ [eV]

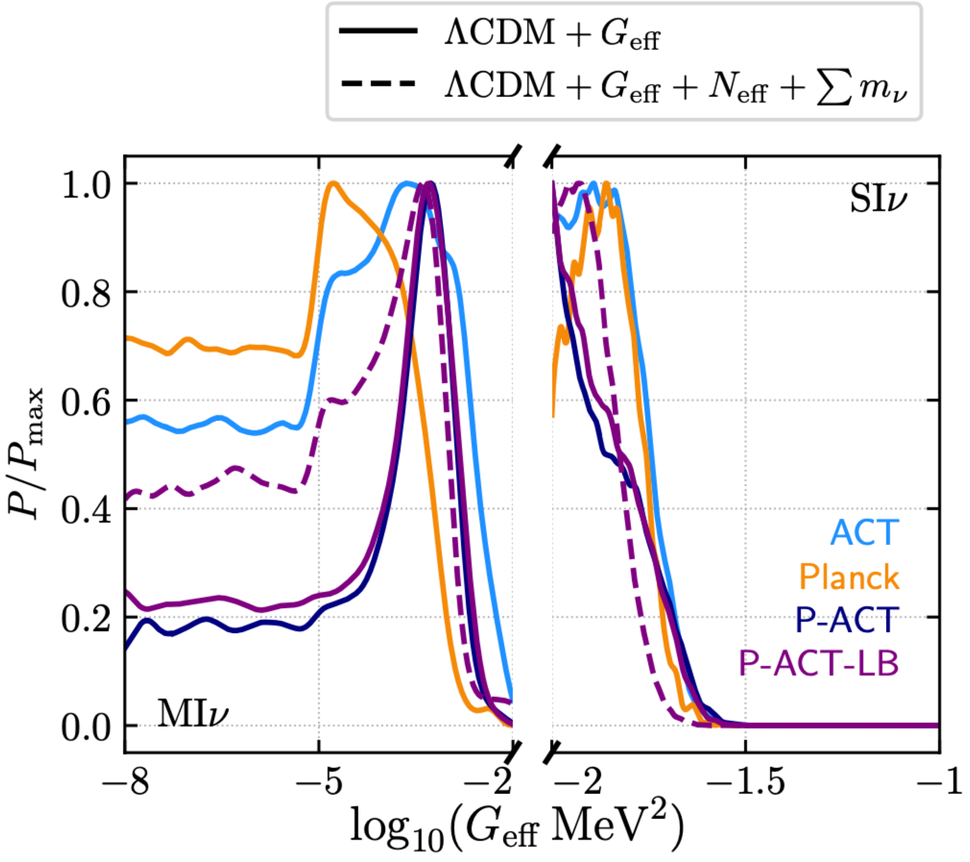

ΛCDM
$(D_V/r_d)/(D_V/r_d)^{CMB,0.06\,eV}$
Redshift z
CMB ($\sum m_{\nu,\rm eff} = -0.11$ eV)
CMB ($\sum m_\nu = 0.00$ eV)
CMB ($\sum m_\nu = 0.06$ eV)
CMB ($\sum m_\nu = 0.10$ eV)
DESI DR2 BAO + CMB
DESI DR2 BAO

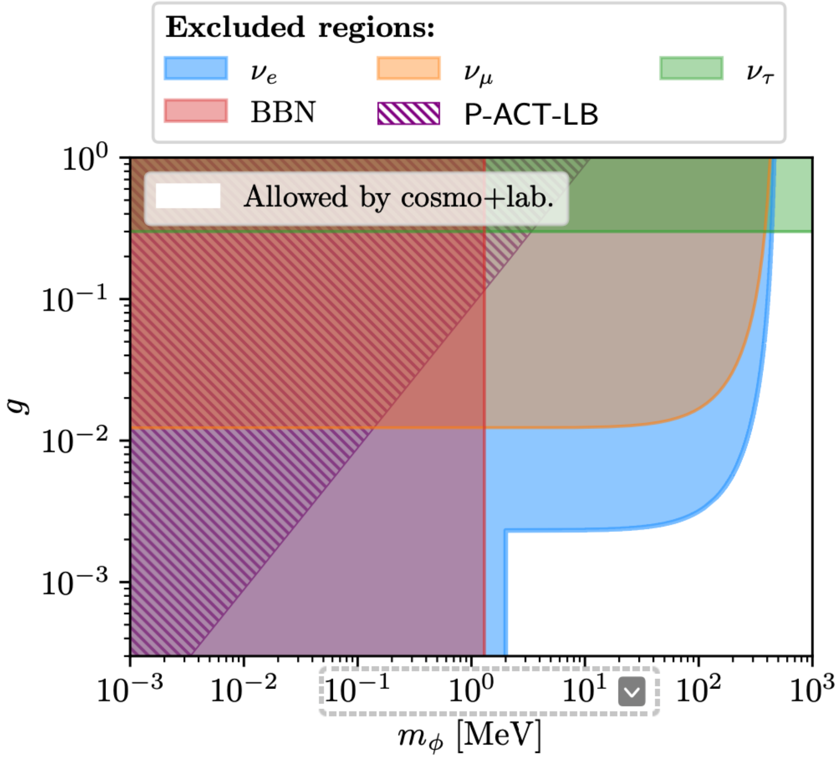

ΛCDM
P/P_{max}
$H_0 r_d$ [km s^{-1}]
CMB ($\sum m_{\nu,\rm eff} = -0.11$ eV)
CMB ($\sum m_\nu = 0.00$ eV)
CMB ($\sum m_\nu = 0.06$ eV)
CMB ($\sum m_\nu = 0.10$ eV)
DESI BAO

NEUTRINO NONSTANDARD INTERACTIONS

$$\mathcal{L} = G_{\text{eff}} \nu\bar{\nu}\nu\bar{\nu}$$

$$G_{\text{eff}} = \frac{g^2}{m_\phi^2}$$





Observations of Large-Scale Structures

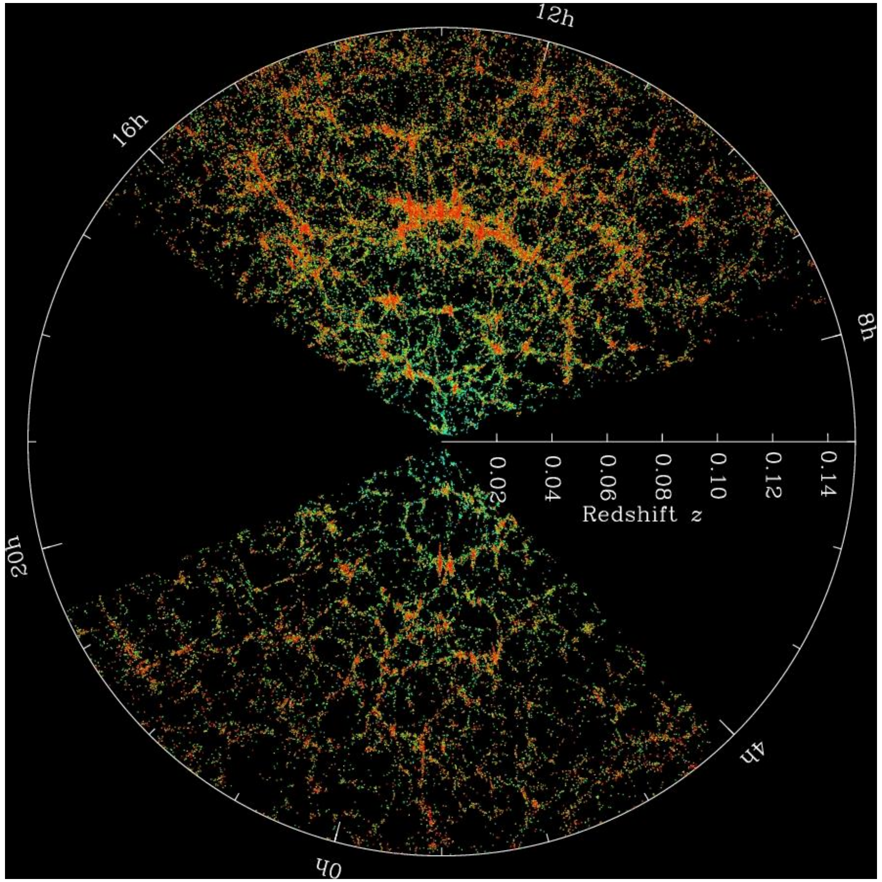


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

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:

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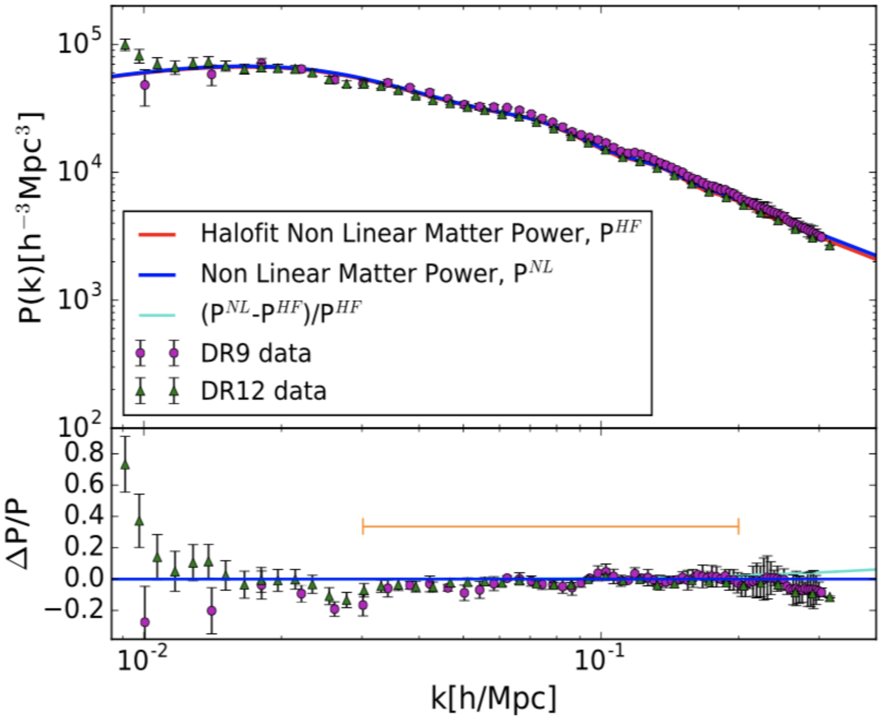
$$P_m(k) \longleftrightarrow \xi_m(r) \equiv \langle \delta_m(x)\delta_m(x+r) \rangle$$

Observations of Large-Scale Structures



data points from BOSS

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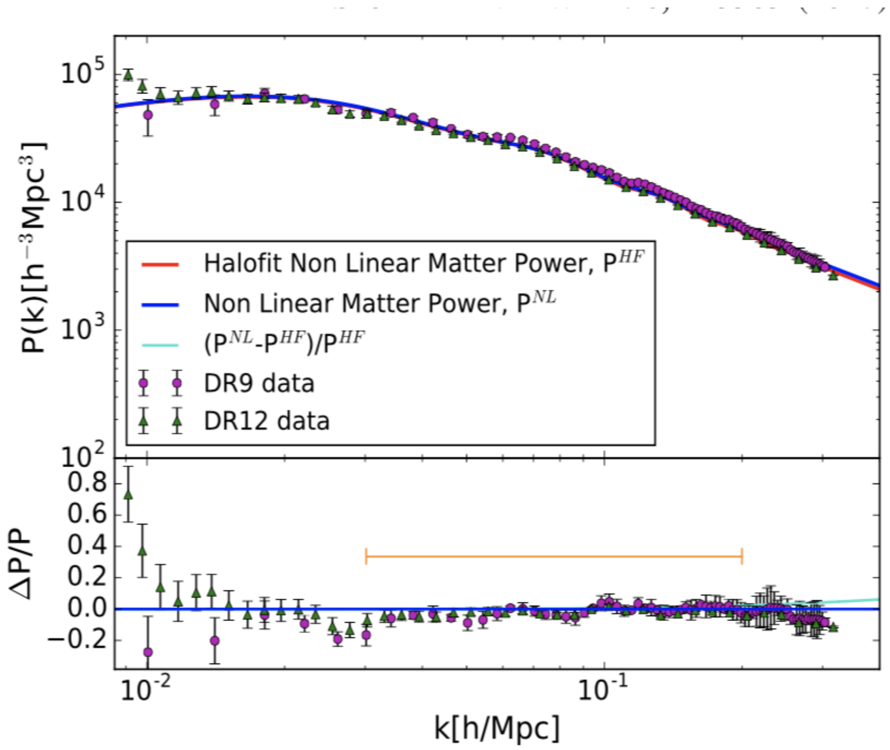

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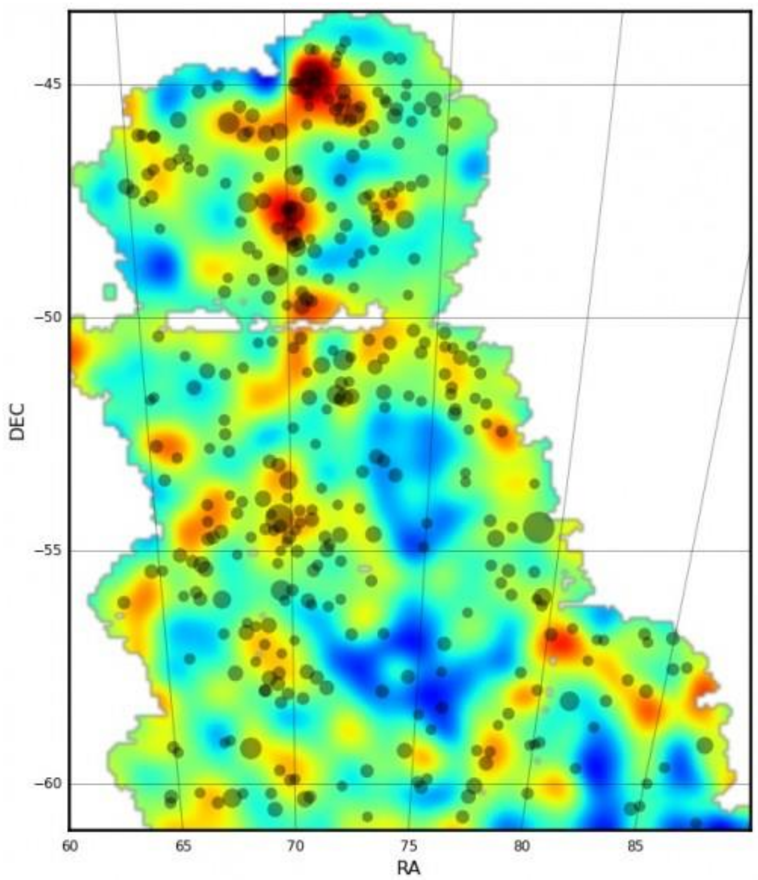

Weak lensing convergence map from the Dark Energy Survey (DES)

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.

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LIGHT RELICS

In the talk, I will focus on neutrinos and light relics (e.g. sterile neutrinos, axions and ALPs, majorons…). This sector is described by (at least) two parameters:

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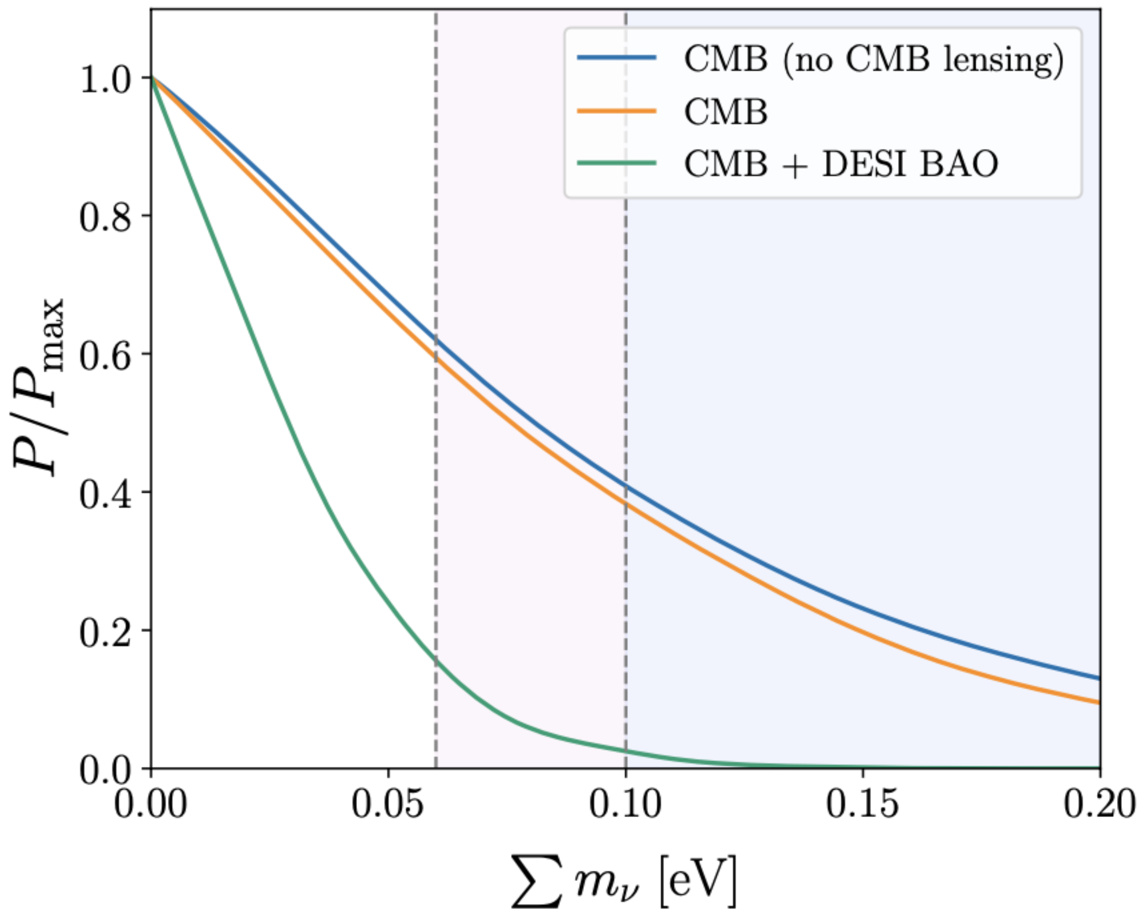
Both parameters measure the density of light species (at different times).

NEUTRINO MASSES AFTER PLANCK

Planck PR4:	$\Sigma m_\nu < 0.26$ eV	TTTEEE+lensing
	$\Sigma m_\nu < 0.11$ eV	+BAO
ACT-DR6	$\Sigma m_\nu < 0.083$ eV	+WMAP+lensing+BAO
	$\Sigma m_\nu < 0.082$ eV	+Planck+lensing+BAO
SPT-3G:	$\Sigma m_\nu < 0.38$ eV	+WMAP
	$\Sigma m_\nu < 0.17$ eV	+Planck
	$\Sigma m_\nu < 0.075$ eV	+Planck+ACT+BAO

Tristram et al 2309.10034; ACT Coll 2503.14454; SPT-3G coll. 2411.06000

DESI CONSTRAINTS ON NEUTRINO MASSES



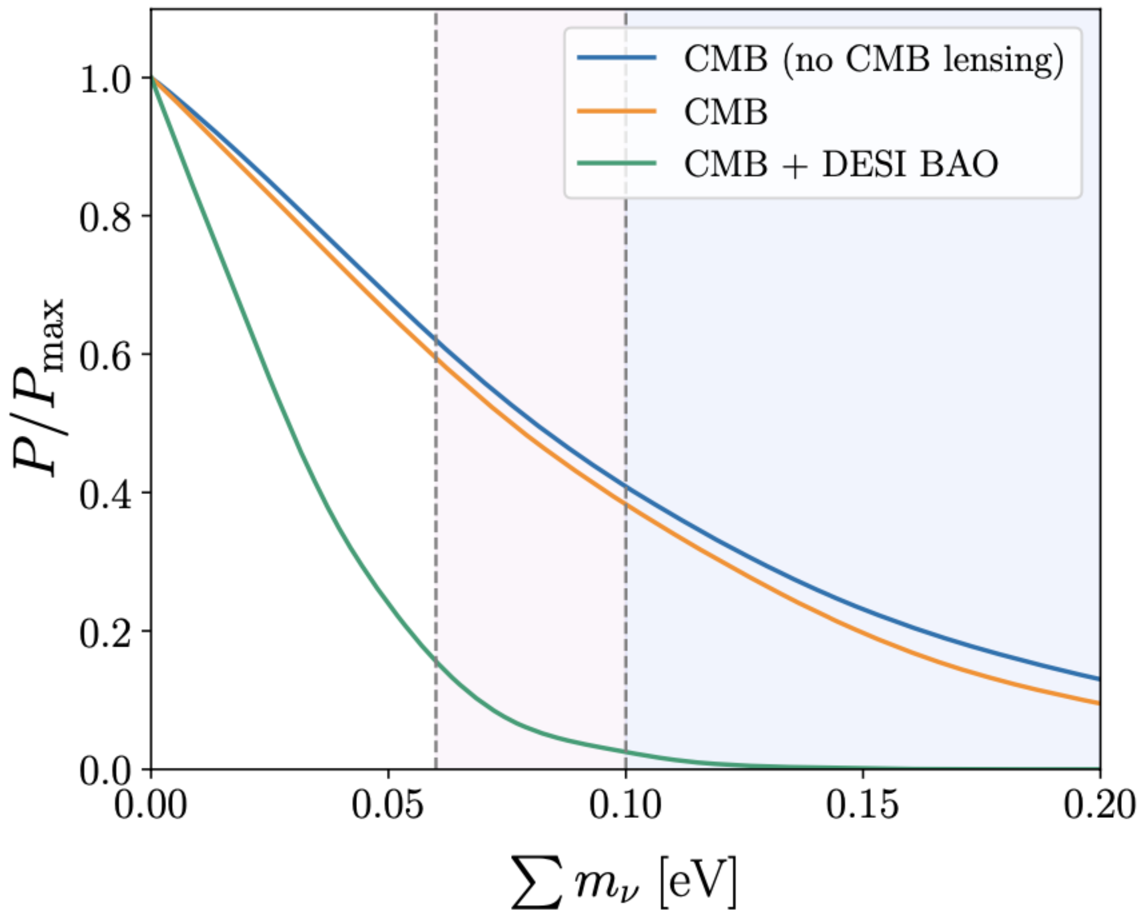
First cosmological results from DESI have appeared in April 2024

Planck+ACT+DESI BAO
Preference for vanishing neutrino masses

Σm_ν < 0.072 eV
(0.081 eV after updating the ACT lensing likelihood)

DESI Collaboration, DESI 2024 VI, arXiv:2404.03002

DESI CONSTRAINTS ON NEUTRINO MASSES



- Affected by higher-than-expected CMB lensing
- Hinting at new physics in the neutrino sector (decay, annihilation…) or elsewhere?
- Bound weakens including dynamical DE
- Depends only weakly on the Planck likelihood
- Driven by a single redshift bin in the DESI BAO data
- “Negative” neutrino masses?

See Green&Meyers (2407.07878), Craig+. (2405.00836), Naredo-Tuero+ (2407.13831), DESI 2024 VII (2411.12022), Allali&Notari (2406.14554), Elbers+ (2407.10965), Ge+ (SPT-3G coll., 2411.06000)

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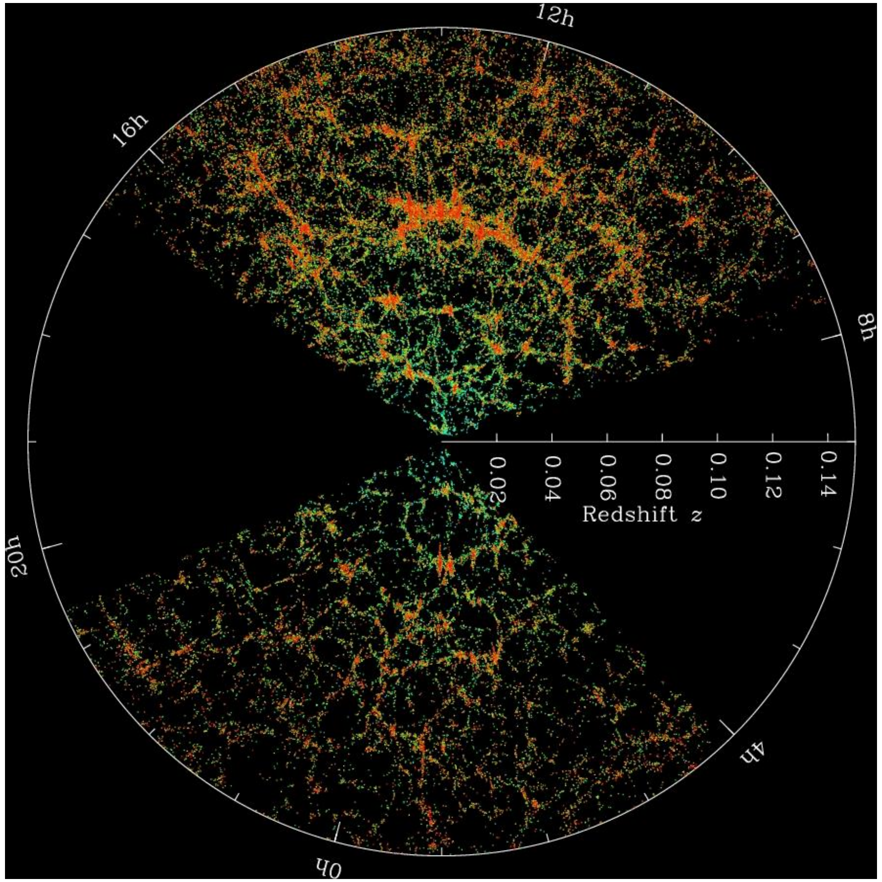

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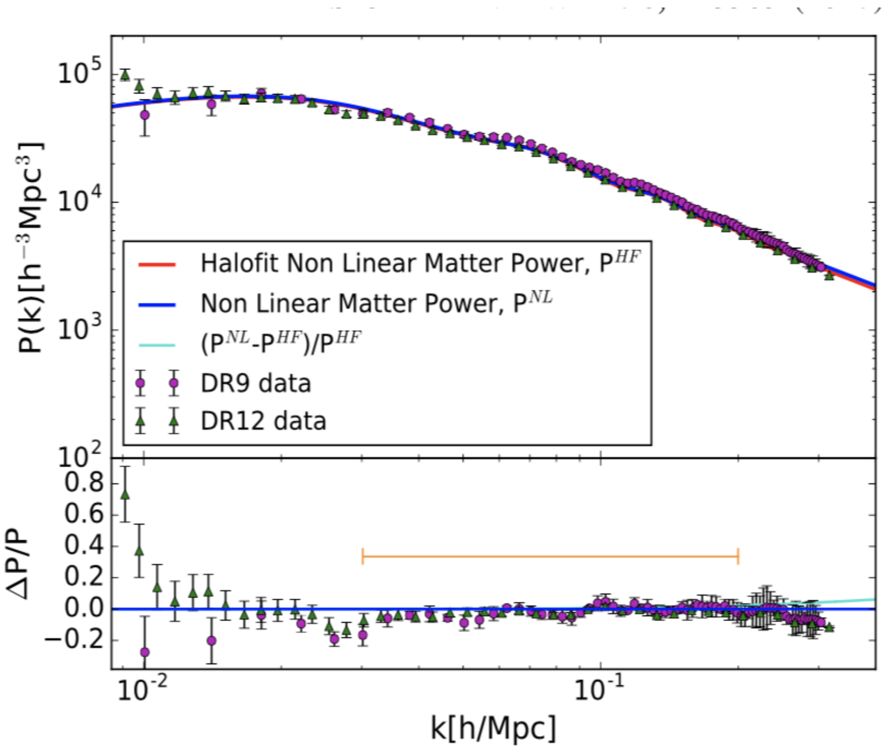

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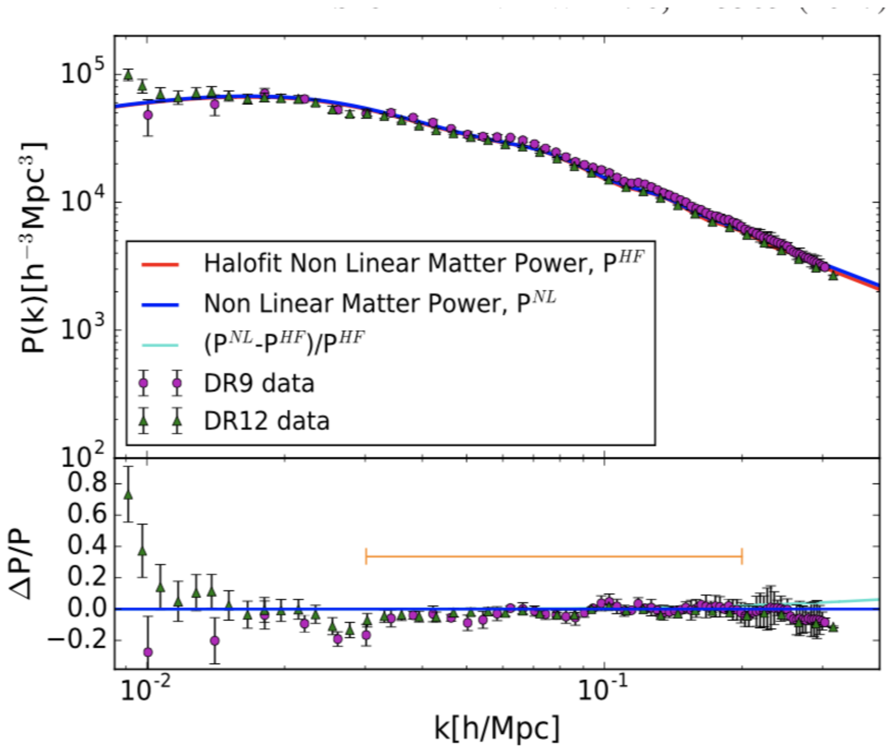

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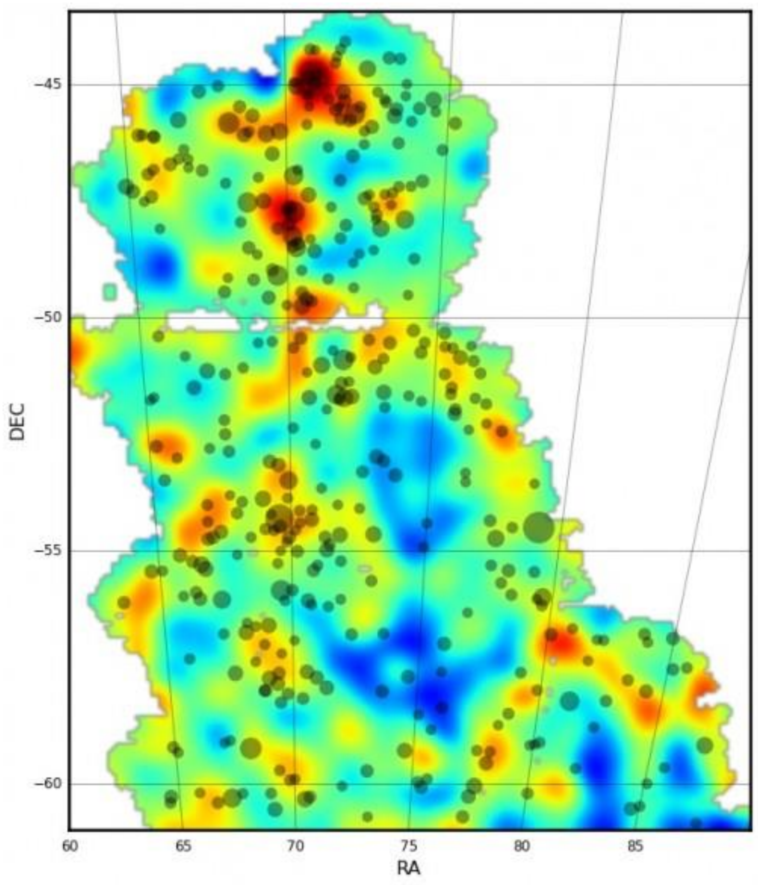

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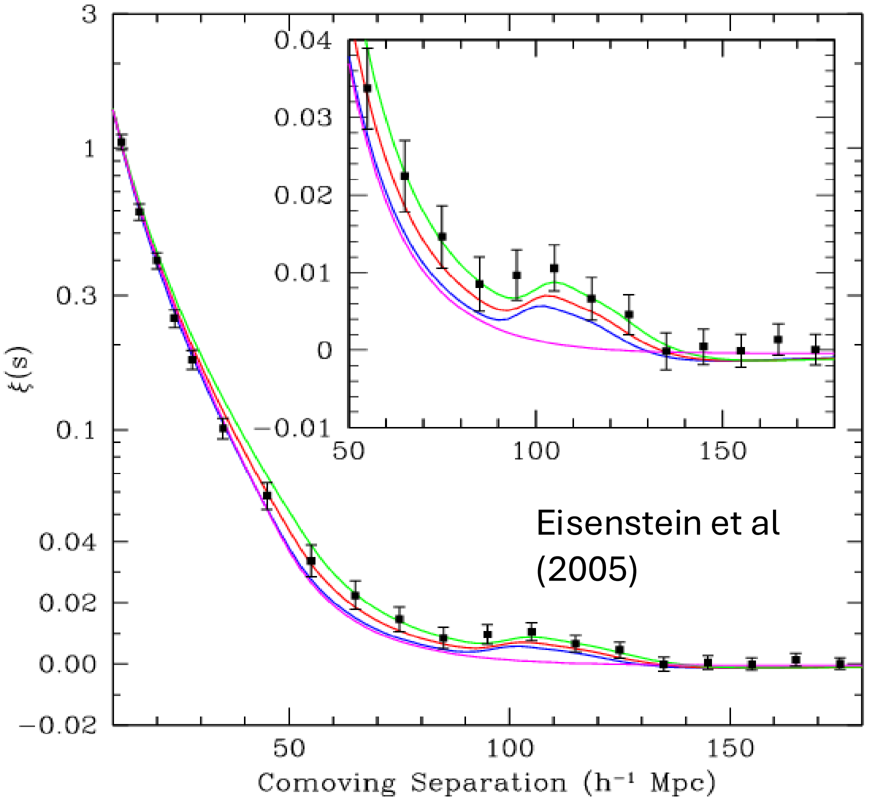


Eisenstein et al (2005)

BAO in coordinate space: peak in the 2-point correlation function

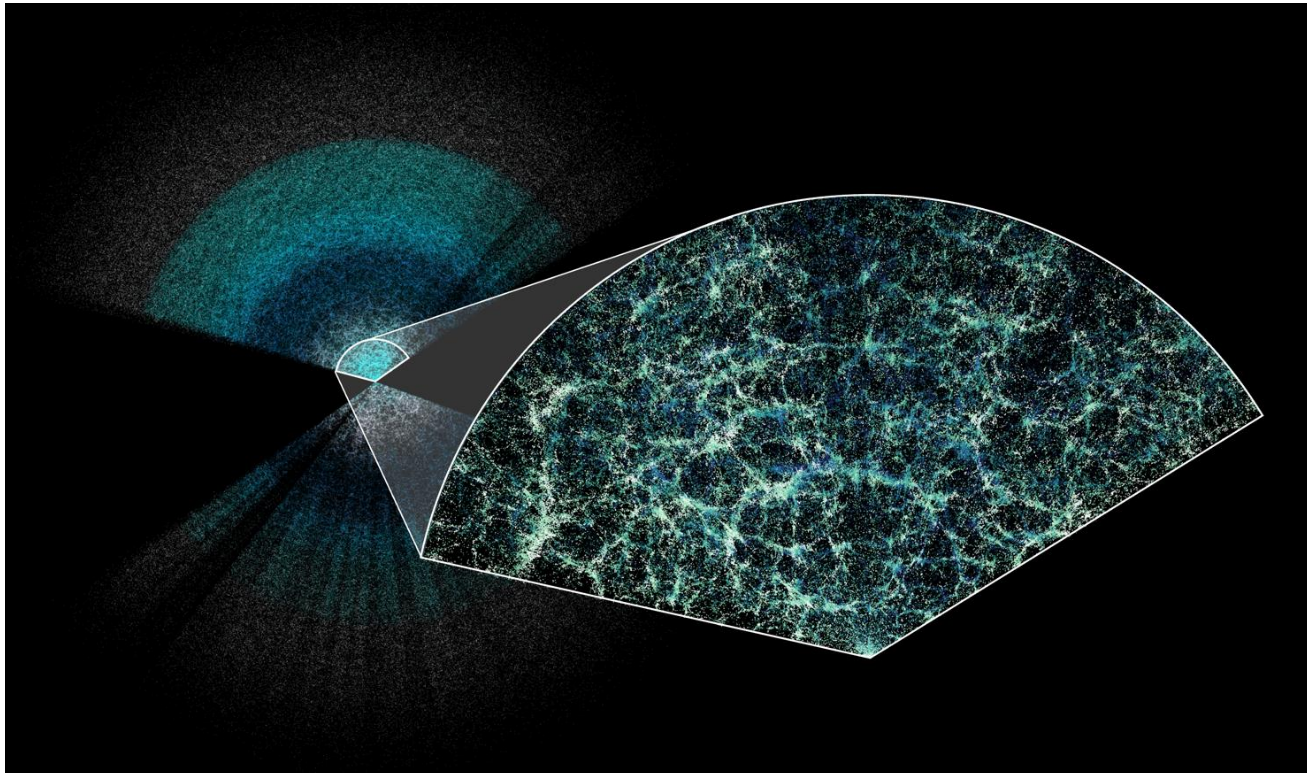
Oscillations in the baryon-photon fluid leave their imprint in the matter power spectrum, other than in the CMB power spectrum.
This is visible as a peak in the 2point correlation function, or small wiggles in the power spectrum.

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).

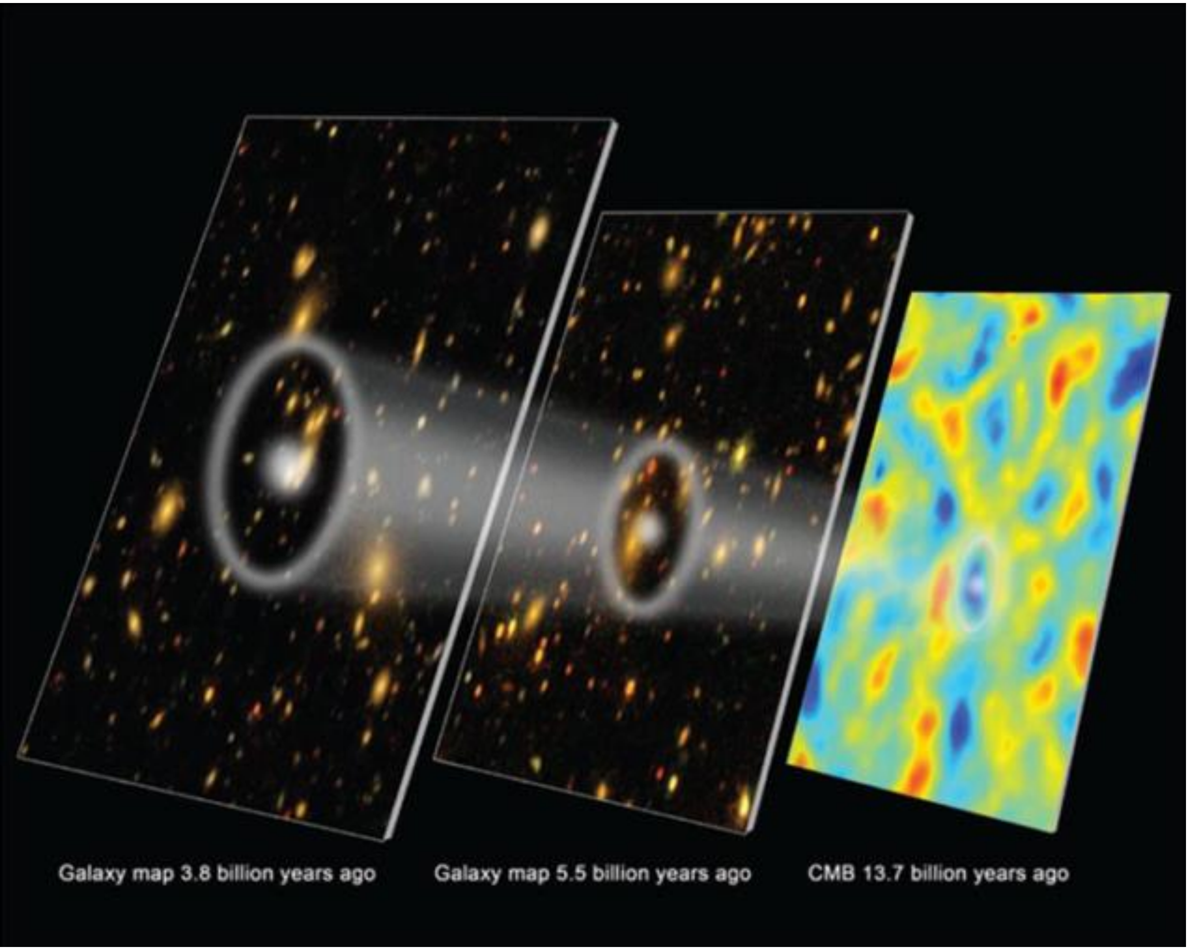
Dark Energy Spectroscopic Instrument

- Largest 3D map of the Universe currently available
- Lookback time 11 Gyrs

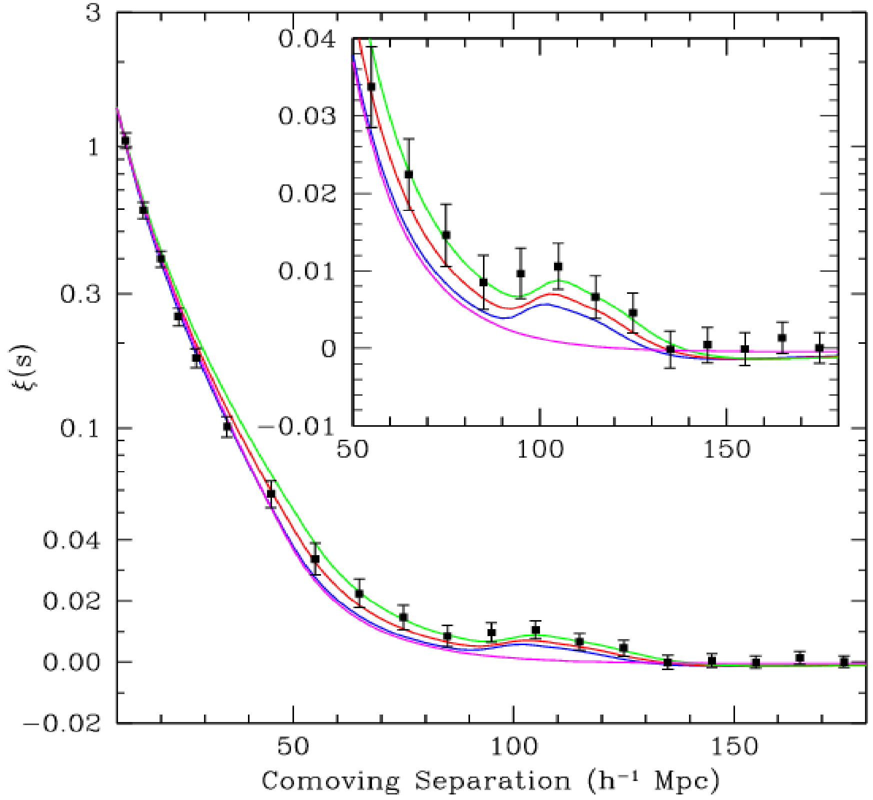


First cosmology results presented in April 2024

Baryon acoustic oscillations (BAOs)



BAOs are the imprint left by the finite sound speed of the baryon-photon fluid in the distribution of galaxies.
BAOs constrain the expansion history



Vera Rubin Observatory
Ground-based
Under construction, expected completion in 2024

Euclid Satellite
Launched July 1st 2023

Nancy Roman Space Telescope
Launch in 2027

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**

Euclid lift-off on July 1st, 2023!

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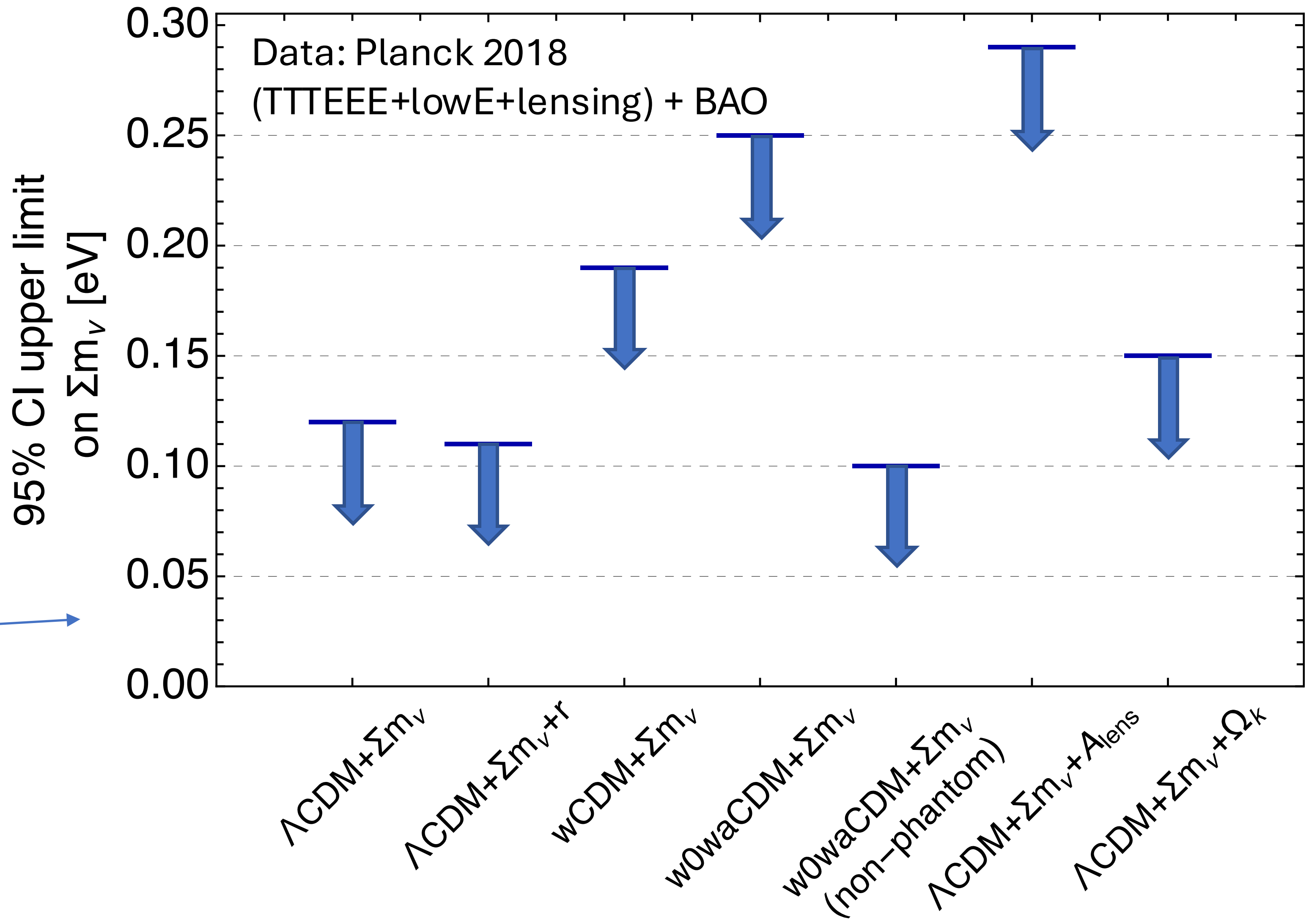
based on S. Roy Choudhury & S. Hannestad (2020) arXiv 1907.12598



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Cosmic Neutrino Background (CνB)

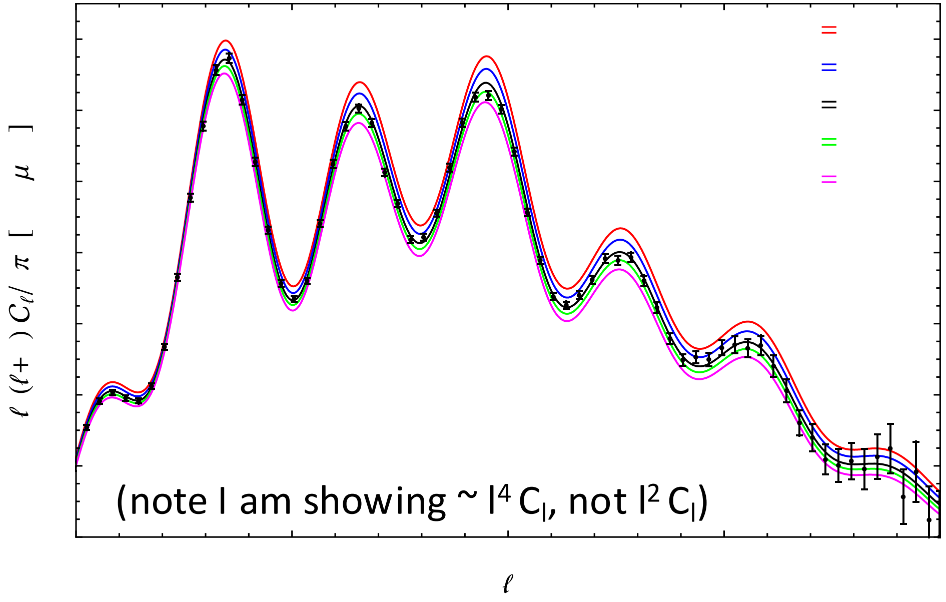
- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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

Theoretical expectation for the three SM neutrinos* :

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

Seen in the CMB small-scale anisotropies



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

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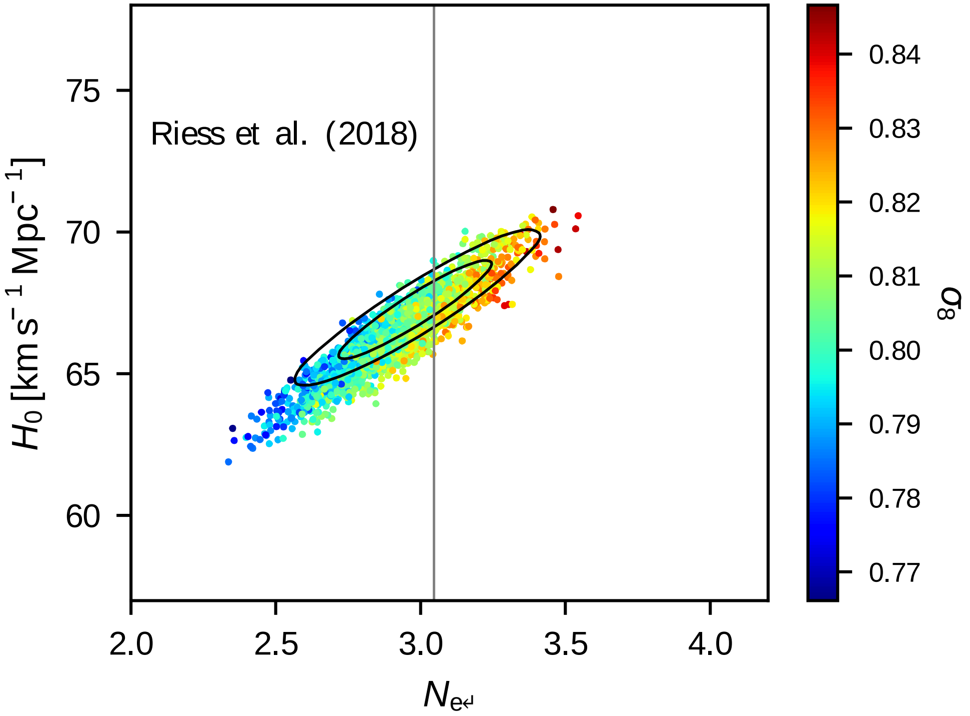

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$N_{\rm eff}$ measured with ~5% precision:

Planck 2018: $N_{\rm eff}$ = 2.89+/- 0.19

In agreement with the theoretical expectation
Excludes a fourth, very light, ***thermalized*** neutrino at more than 5σ

Planck collaboration, VI 2018

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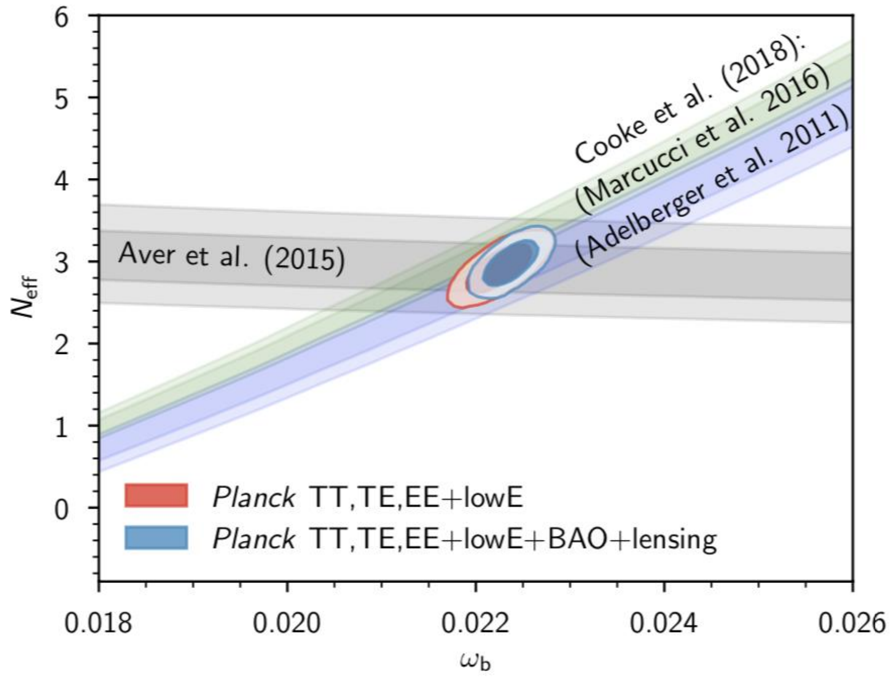

Planck collaboration, VI 2018

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Light element abundances are also sensitive to $N_{\rm eff}$:

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

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

Pisanti et al, JCAP 2021

Yeh et al., JCAP 2021

NEFF AS A PROBE OF NEW PHYSICS

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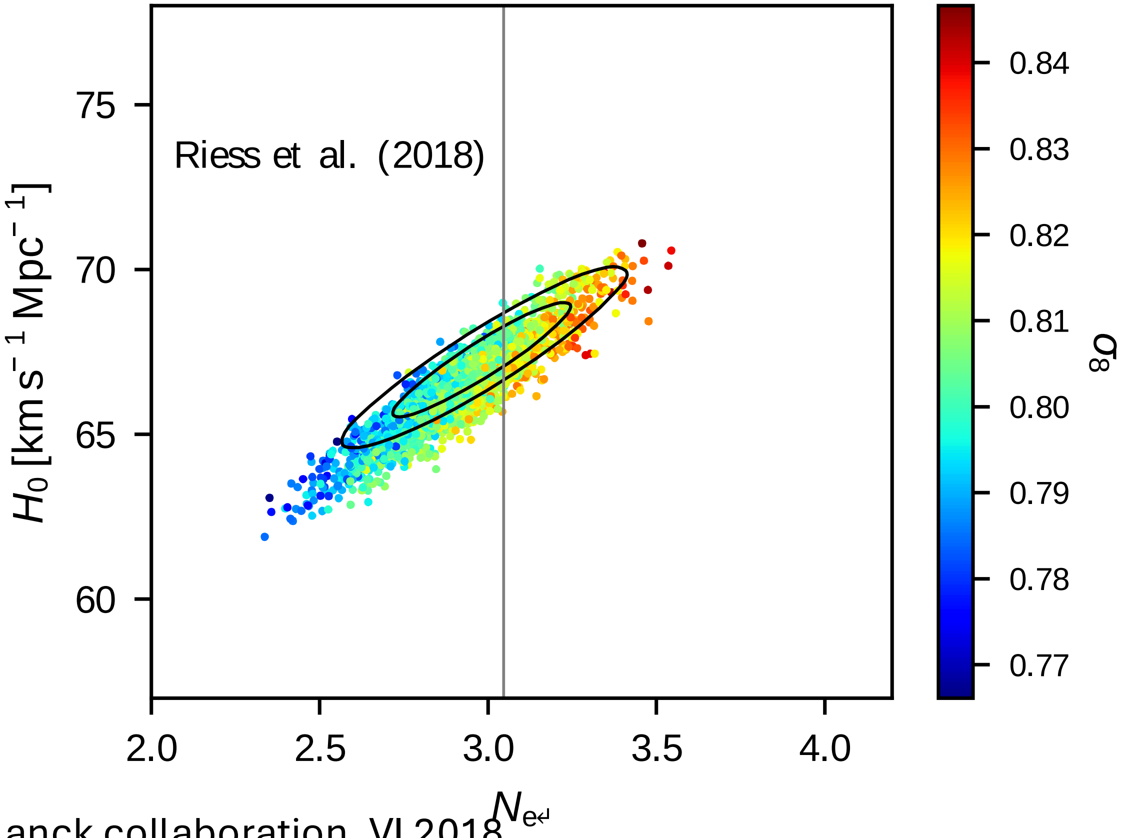

Planck collaboration, VI 2018

A deviation from the standard value of $N_{\rm eff}$ 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 and beyond ΛCDM

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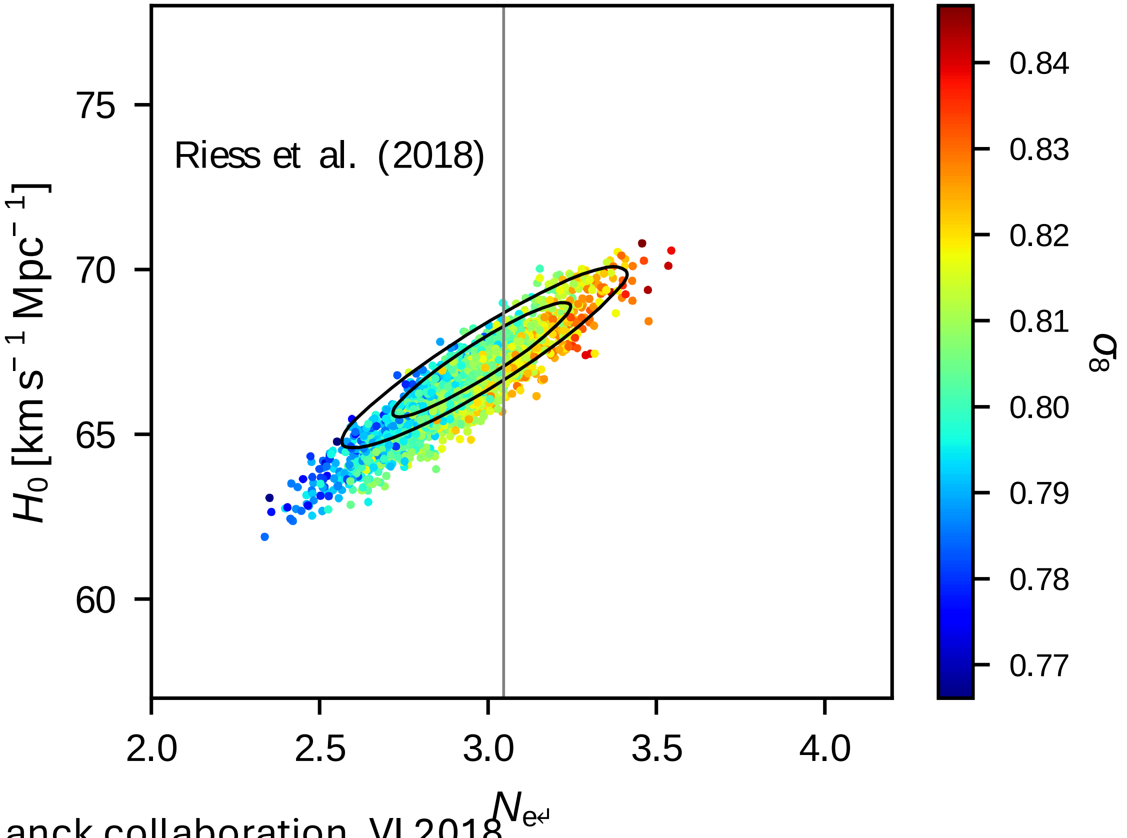


Planck collaboration, VI 2018

Both a blessing and a curse!

We can use $\Delta N_{\rm eff} = N_{\rm eff} - 3.044$ to probe a wide range of models of new physics…

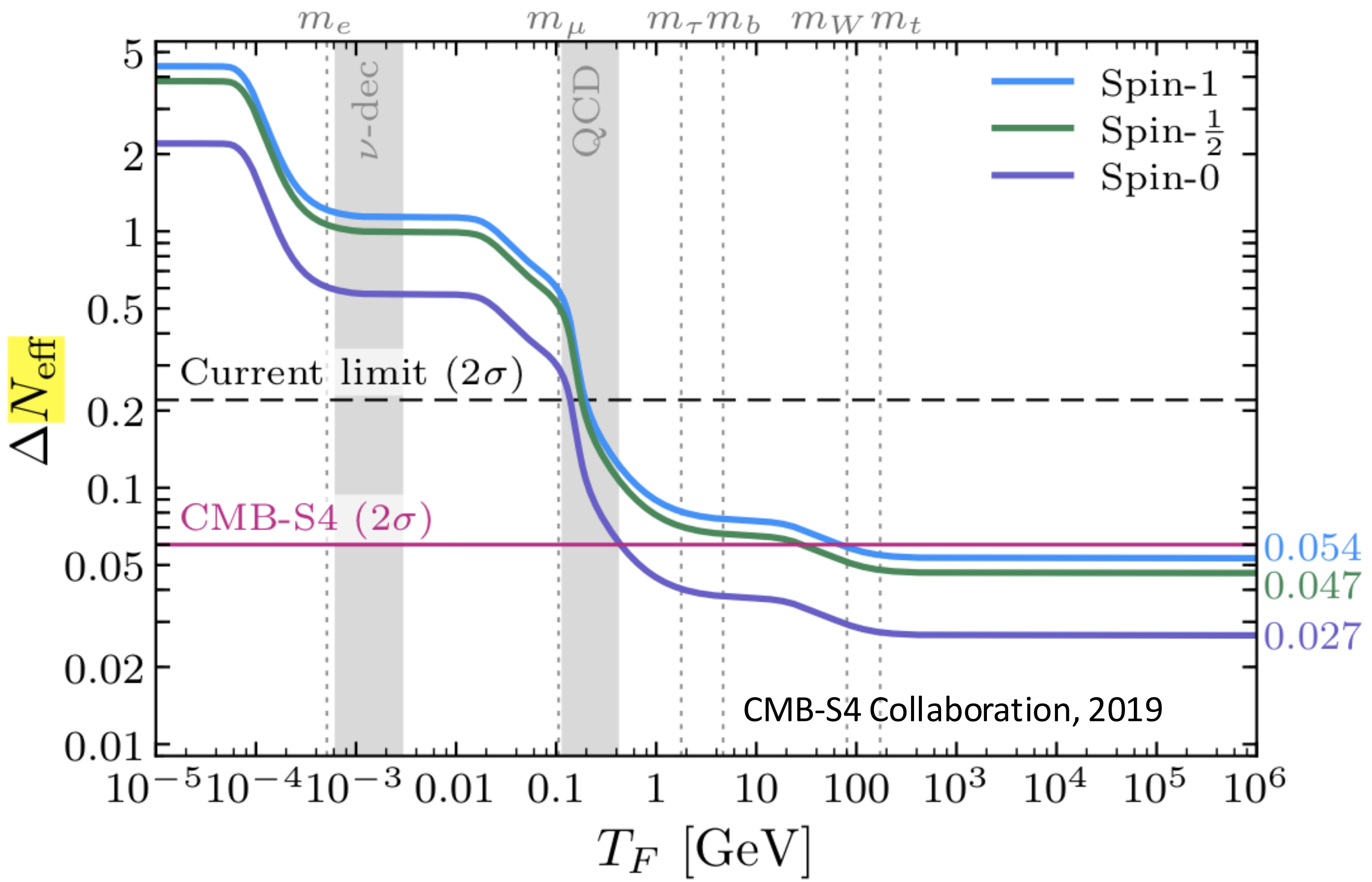
….however, if $\Delta N_{\rm eff} \neq 0$ is measured, how should we interpret it?

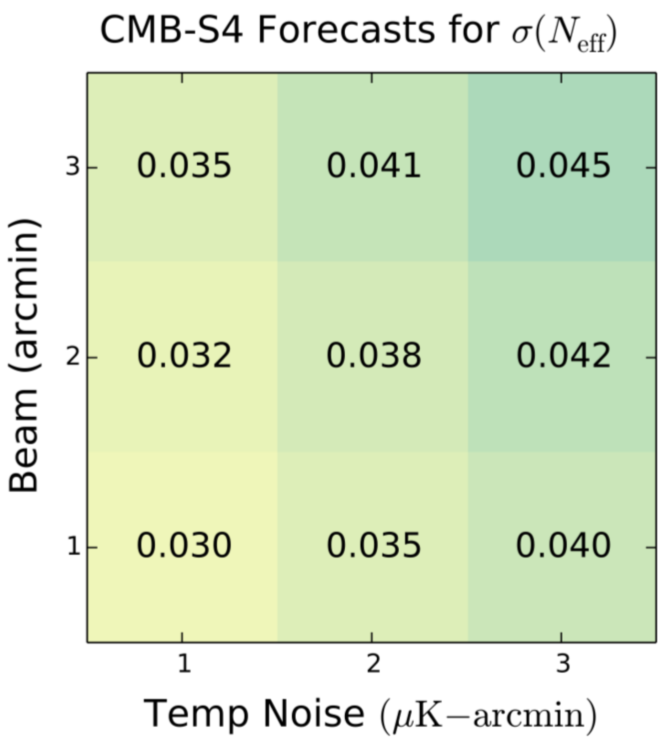
- Look for other cosmological signatures (concurring signal in the sum of the masses, effects on cosmological perturbations….)
- Search for confirmation in the lab

(not really much different from the present situation with dark matter and dark energy, if you think of it!)

N_{EFF} FROM CMB-S4

Contribution of extra species in thermal equlibrium





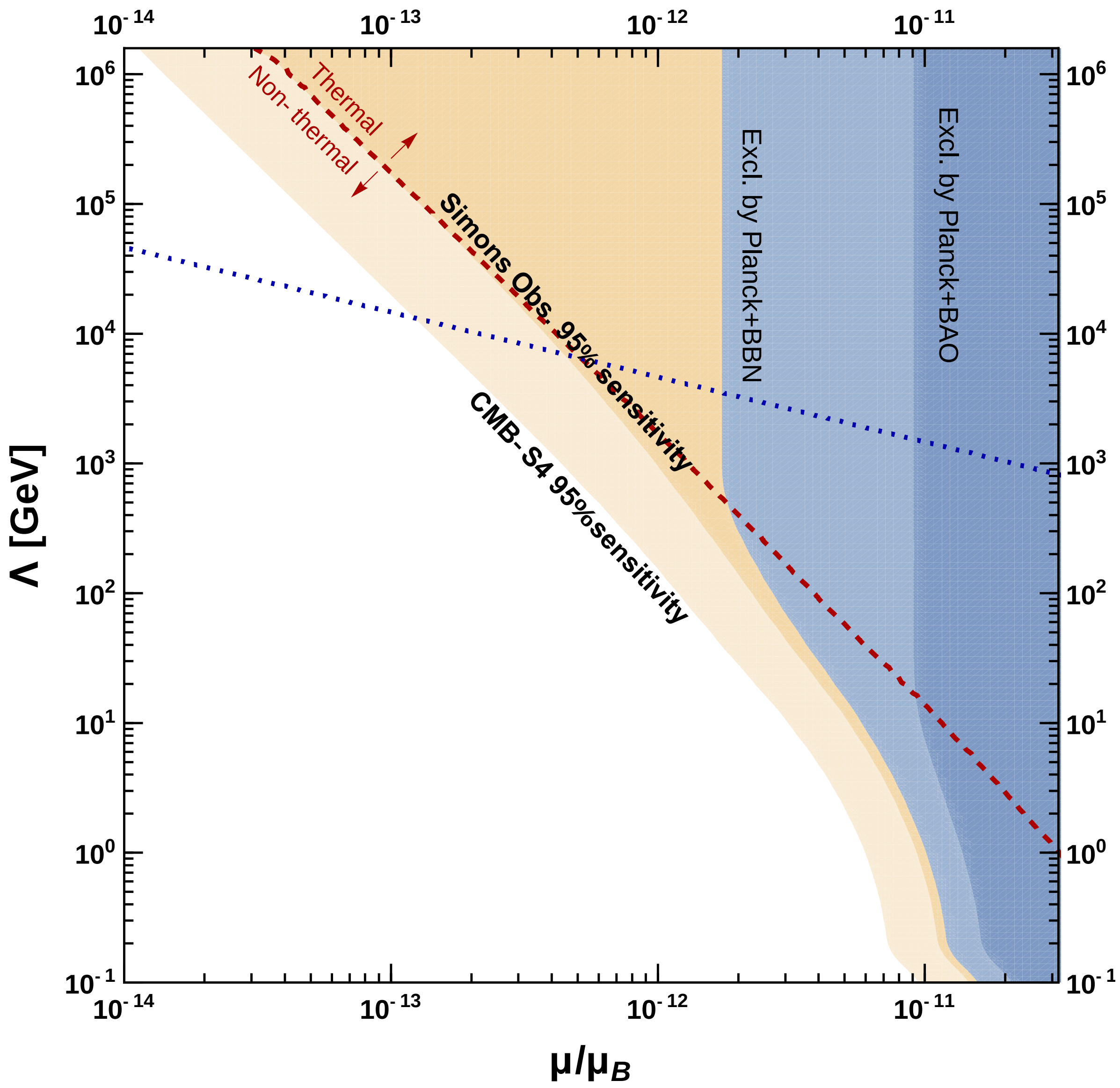
Beam (arcmin) \ Temp Noise (μK$-$arcmin)	1	2	3
3	0.035	0.041	0.045
2	0.032	0.038	0.042
1	0.030	0.035	0.040

CMB-S4 Science Book

Light relics from 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)



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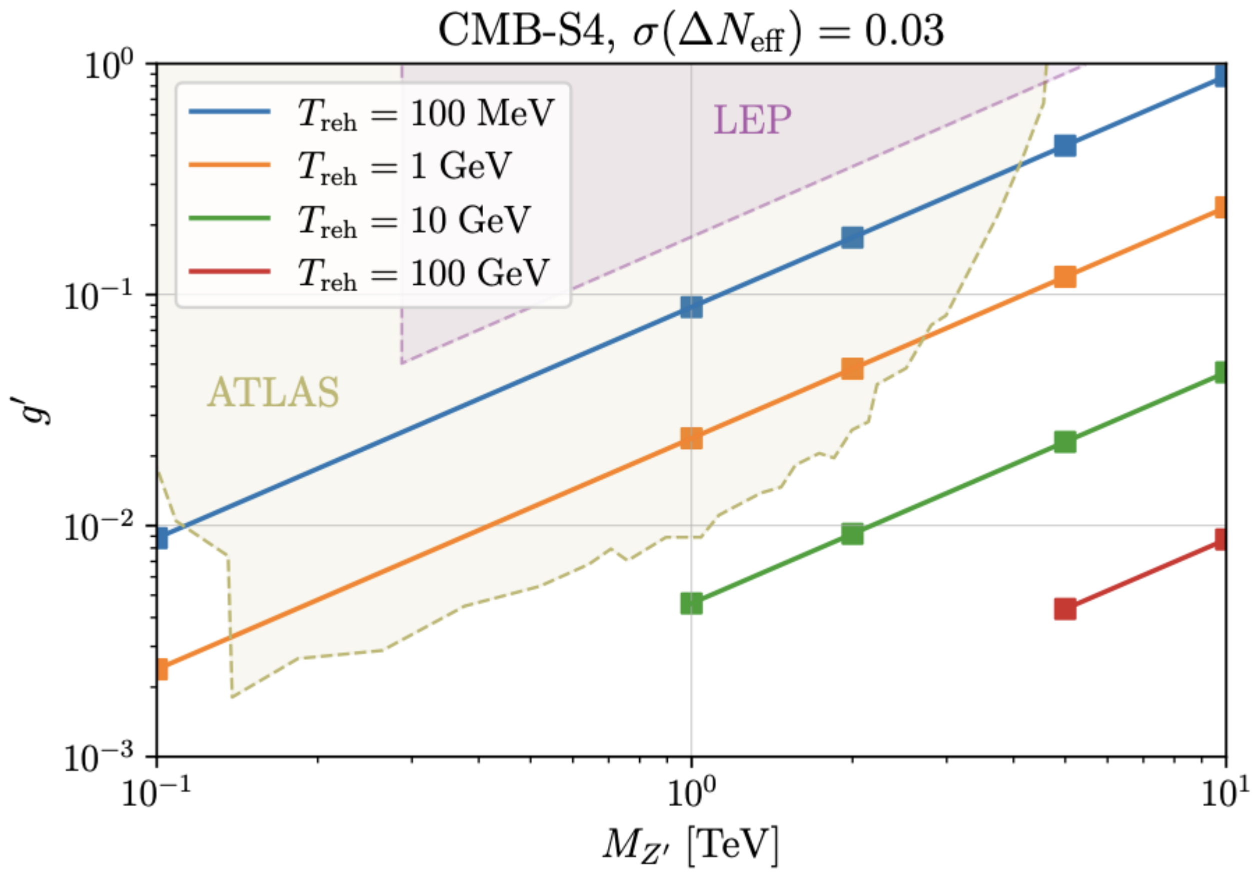
… or for B-L models

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



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

The Cosmic Neutrino Background

Equilibrium between neutrinos and other SM species depends on a competition between

Weak processes

(e.g. ν-e scatterings)

VS.

Cosmic expansion

$$\Gamma \sim G_F^2 T^5$$

$$H \simeq \frac{T^2}{m_\mathrm{p}}$$

$$\Gamma = n\langle\sigma v\rangle \sim G_F^2 T^5$$

$$1 \simeq \frac{\Gamma}{H} \sim G_F^2 T^3 m_\mathrm{p} \sim \left(\frac{T}{\mathrm{MeV}}\right)^3$$

$$\Gamma = n\langle \sigma v \rangle \sim G_F^2 T^5$$

Since the observed fields are stochastic, we can only predict their statistical properties (e.g. the 2-point correlation function)

$$\langle \Phi^A(\hat{n})\Phi^B(\hat{n}')\rangle \sim \int \Big(\text{initial conditions}\Big) \times \Big(\text{evolution}\Big) \times \Big(\text{projection}\Big)$$

Projection on the sphere of our random field

Window function

Original 3D field, evaluated on our past light cone

Relic Neutrinos in the RD era

Let us focus for the moment on early times, when neutrinos are relativistic. After the e+e- annihilation we have

$$\rho_\nu = 3 \times 2 \times \frac{7}{8} \times \frac{\pi^2}{30} T_\nu^4 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

and the total radiation density is

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

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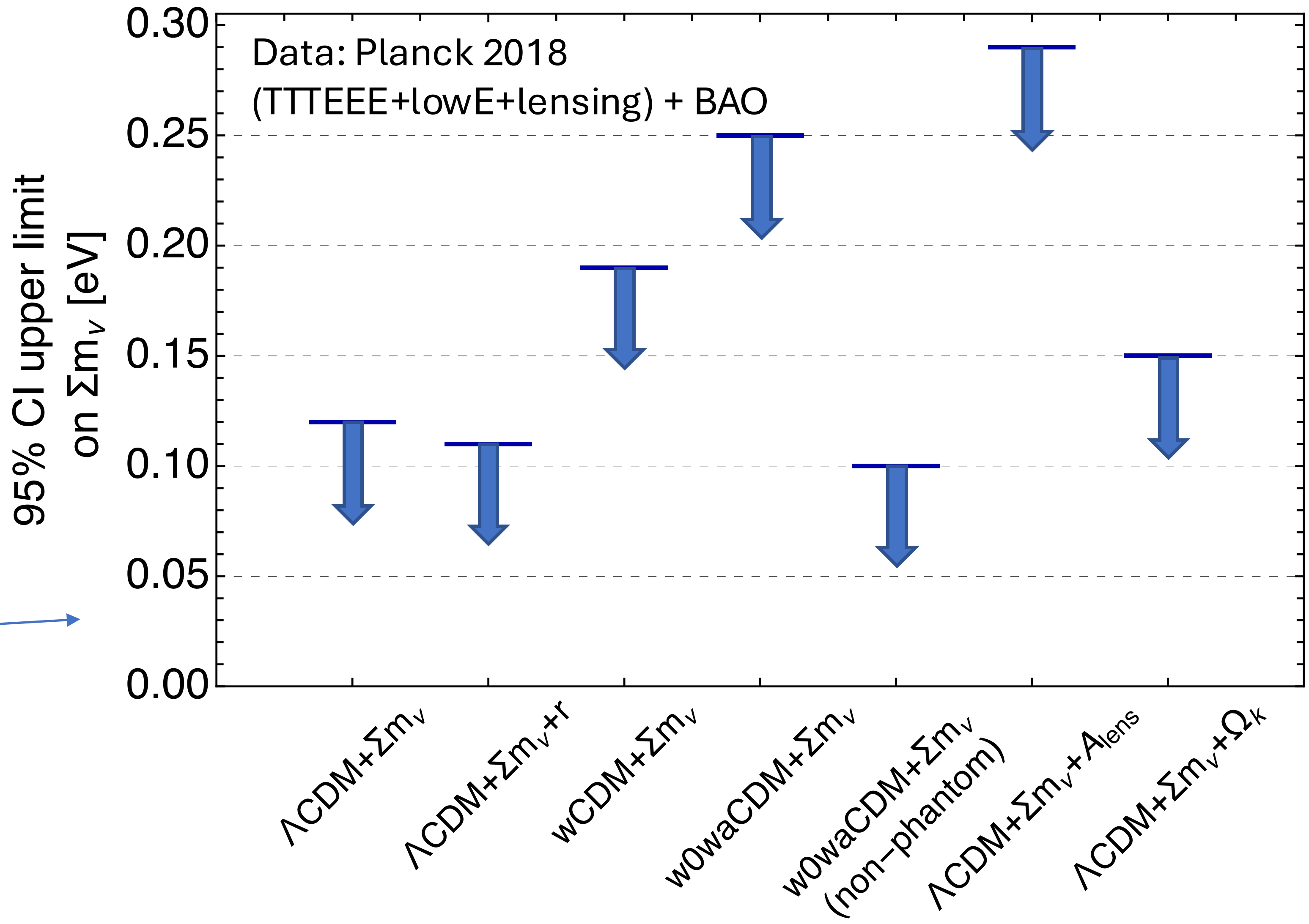

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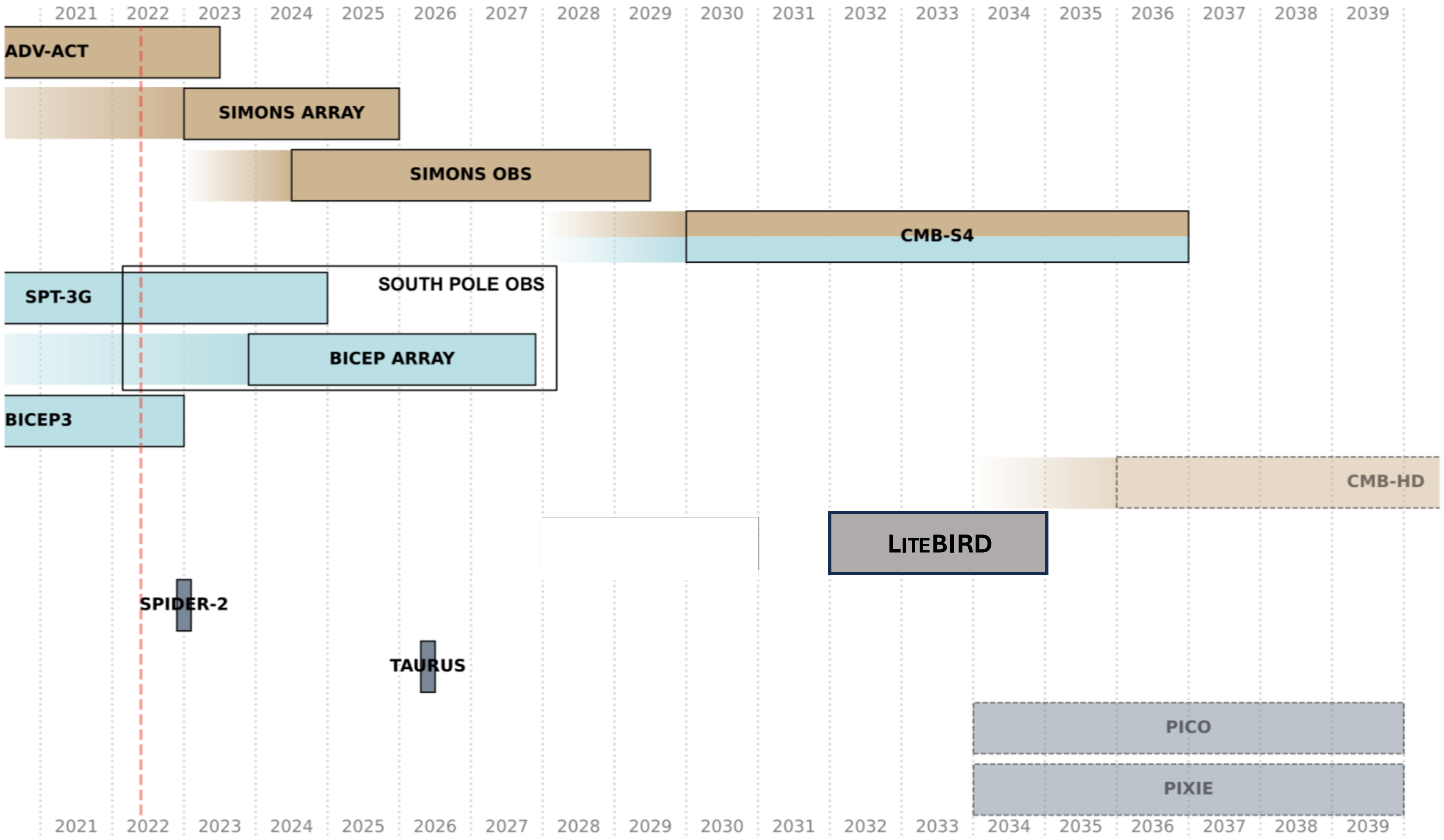
Timeline of CMB experiments



Snowmass2021 Cosmic Frontier: CMB Measurements White Paper, arXiV: [2203.07638](https://arxiv.org/abs/2203.07638)
(with some modifications to account for changes in schedule)

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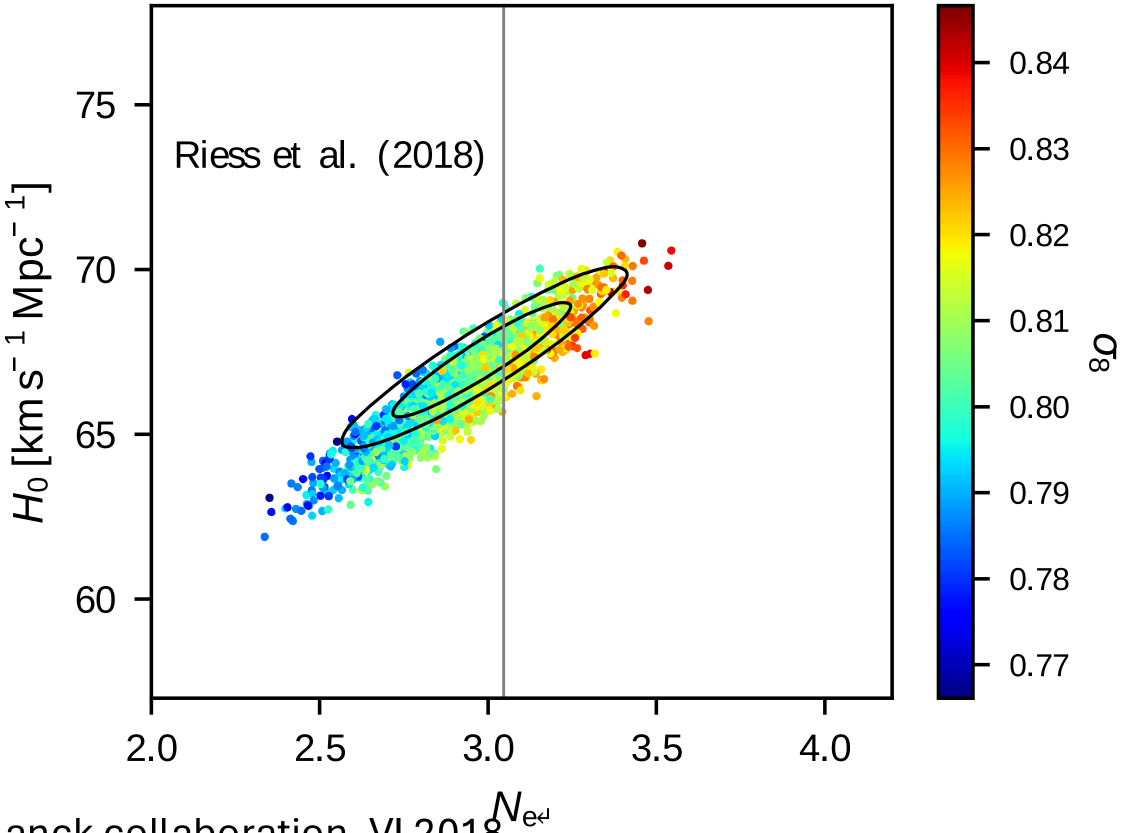

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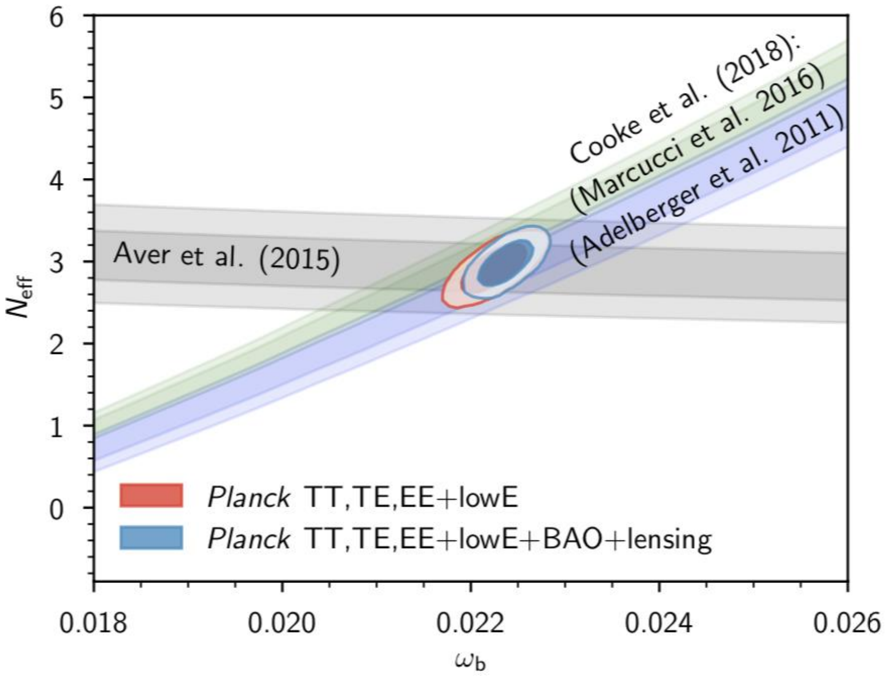
- Look for other cosmological signatures (concurring signal in the sum of the masses, effects on cosmological perturbations….)
- Search for confirmation in the lab

(not really much different from the present situation with dark matter and dark energy, if you think of it!)

Cosmic Neutrino Background (CνB)

- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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



Planck collaboration, VI 2018

Theoretical expectation for the three SM neutrinos:

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

Light element abundances are also sensitive to $N_{\rm eff}$:

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

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

Pisanti et al, JCAP 2021

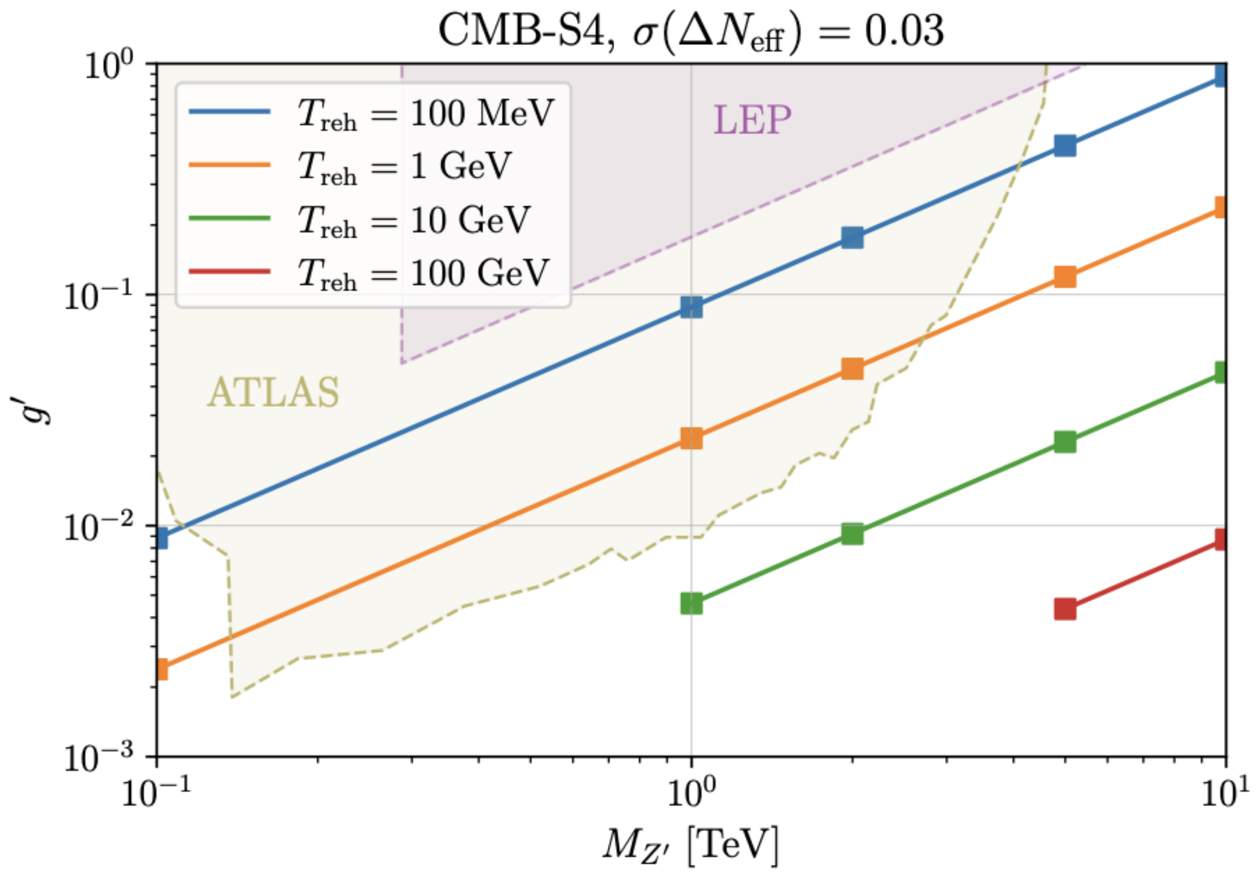
Yeh et al., JCAP 2021

Light relics from freeze-in

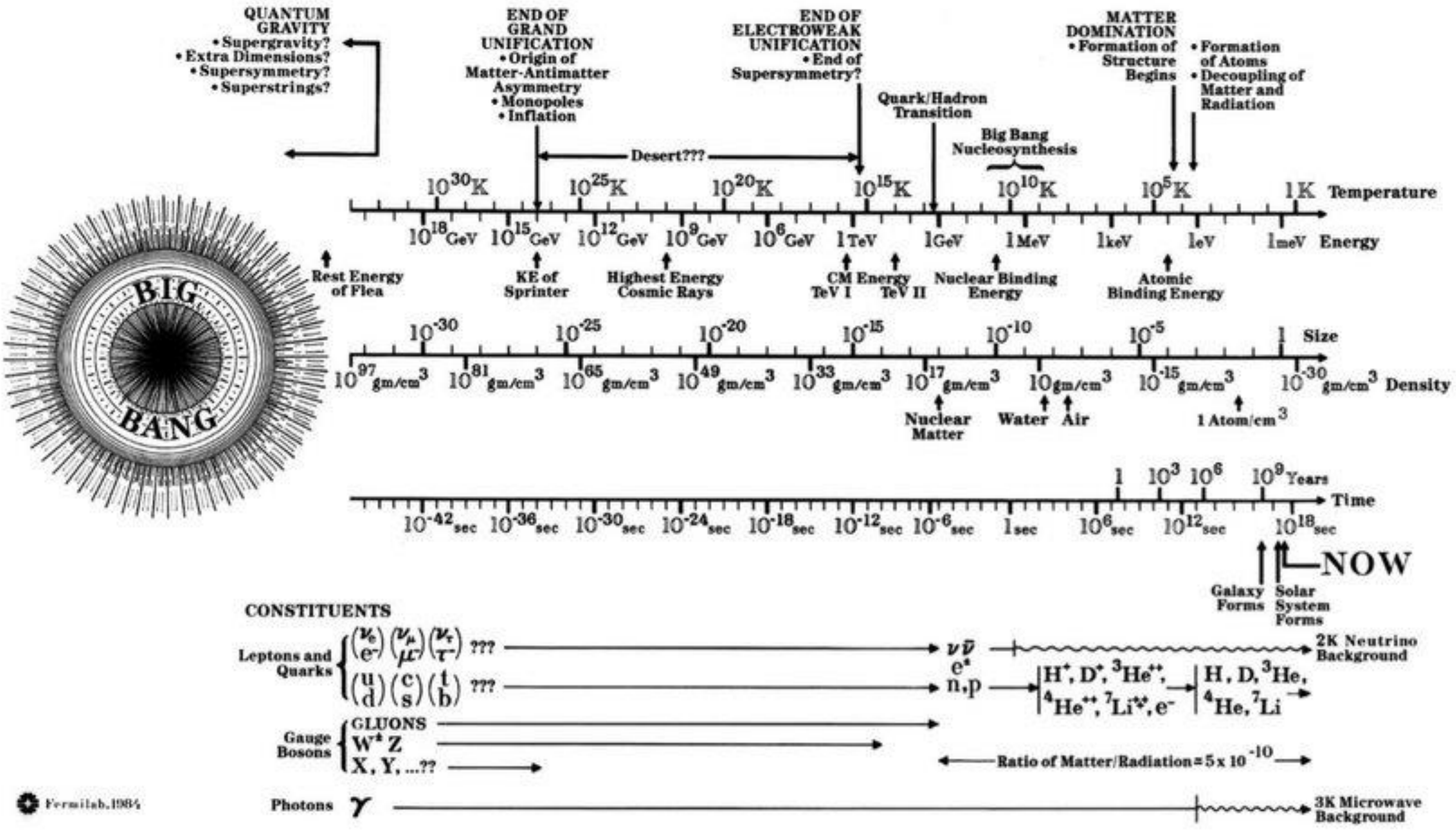
Next-gen experiments will allow to probe the nonthermal (freeze-in) regime of light relics production

… or for B-L models

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



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


QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
Temperature
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
Size
Density
Nuclear Matter
Water
Air
1 Atom/cm3
Years
Time
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
2K Neutrino Background
Gauge Bosons
GLUONS
Ratio of Matter/Radiation ≈ 5 x 10-10
Photons
3K Microwave Background
Fermilab, 1984

The Cosmic Neutrino Background

Equilibrium between neutrinos and other SM species depends on a competition between

Weak processes
(e.g. ν-e scatterings)

VS.

Cosmic expansion

$$\boldsymbol{\Gamma \sim G_F^2 T^5}$$

interaction rate

Fermi constant

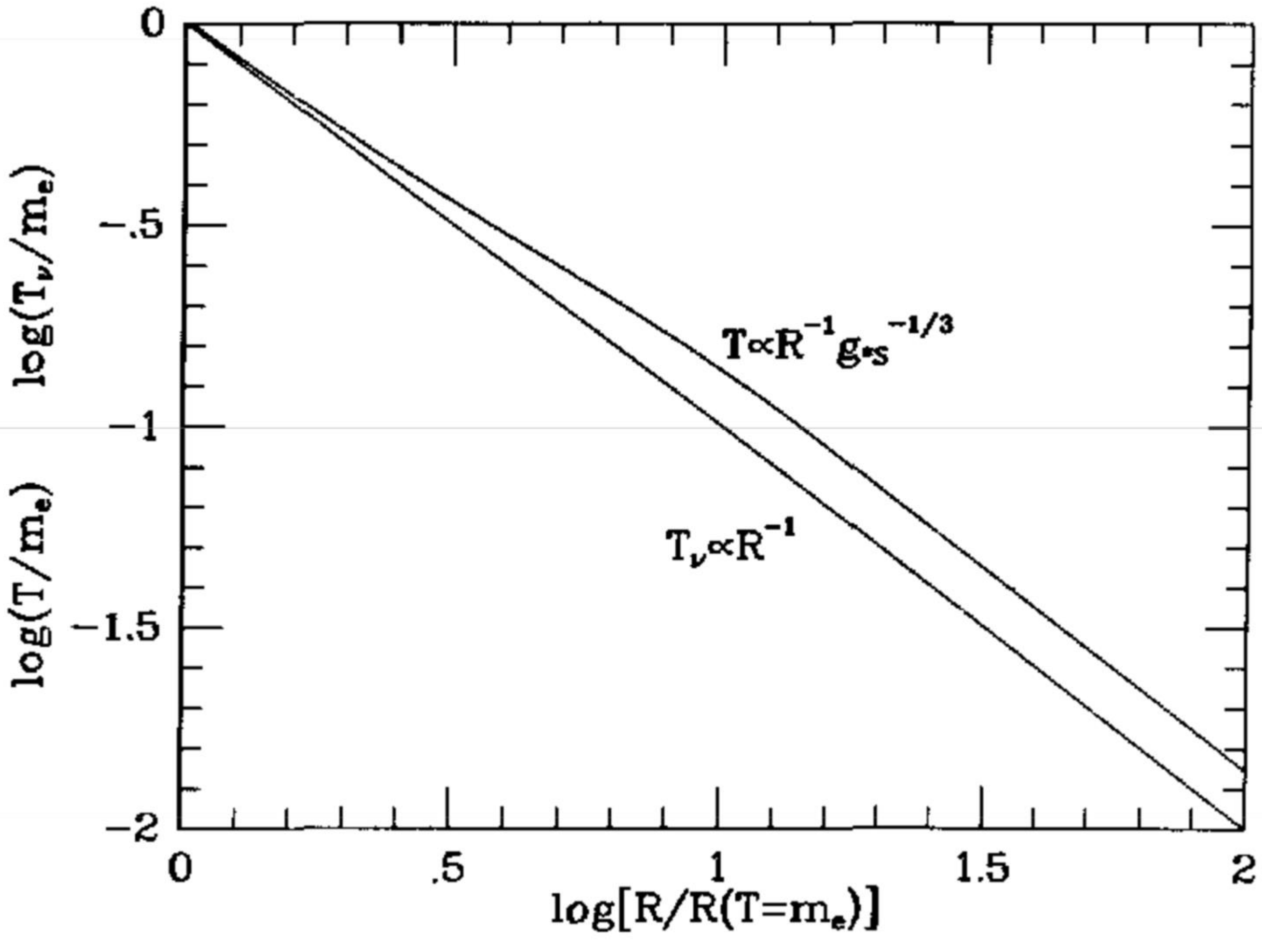
$$\boldsymbol{H \sim \sqrt{G}\, T^2}$$

Hubble parameter (expansion rate)

Gravitational constant

$$\frac{\Gamma}{H} \sim \left(\frac{T}{\mathrm{MeV}}\right)^3$$

NEUTRINO THERMAL HISTORY



From Kolb&Turner

Fig. 3.8: The evolution of T and T_ν through the epoch of $e^\pm$ annihilation.

THE COSMIC NEUTRINO BACKGROUND

- The Universe at 1 MeV < T < 100 MeV is filled by photons, electrons/positrons and neutrinos
- Neutrinos have a common temperature with other SM species for T > 1 MeV
- After decoupling, the expansion cools down both species at the same rate....
- ....however, e^+e^- annihilation heats up the photons
- Simple argument involving entropy conservation gives $T_\nu = (4/11)^{1/3}\, T_\gamma$

The Cosmic Neutrino Background

The present photon temperature is well measured: $T_{\gamma,0} = 2.725$ K. Then:

$$T_{\nu,0} \simeq 1.9\mathrm{K} \simeq 1.6 \times 10^{-4}\mathrm{eV}$$

Remember:
1K = 0.86 x 10^{-4} eV

that corresponds to a present day density per neutrino species

$$n_{\nu,0} = \frac{3}{2}\frac{\zeta(3)}{\pi^2}T^3_{\nu,0} \simeq 113\mathrm{cm}^{-3}$$

(for comparison $n_{\gamma 0} \simeq 400$ cm^{-3})

Thus we expect that the Universe is filled by a background of relic thermal neutrinos, the ***Cosmic Neutrino Background** (**CNuB**)* with temperature and density of the same order of magnitude as CMB photons.
Clearly, the former are much harder to detect than the latter!

The Cosmic Neutrino Background

The presence of a background of relic neutrinos (***CνB***) is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until $T \sim 1$ MeV ($z \sim 10^{10}$);
- Below $T \sim 1$ MeV, neutrino free stream keeping an equilibrium spectrum
- Today $T_\nu = 1.9$ K and $n_n = 113$ part/cm^3 per species
- Free parameters: the three masses (but cosmological evolution mostly depends on their sum)

RELIC NEUTRINOS IN THE RD ERA

Total density in light species at early times

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

# of neutrino families

Fermi-Dirac statistic

Neutrino-to-photon temperature ratio

Relic Neutrinos in the RD era

This is turned into a definition

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

"Effective number of relativistic degrees of freedom"

=

A measure of the energy density of relativistic particles, normalized to the energy density of a "standard" neutrino

Relic Neutrinos in the RD era

Nnu=3 is true in the instantaneous neutrino decoupling approximation. However:

- Decoupling is not instantaneous -> high-momentum neutrinos still coupled to the photon bath -> distortions in the neutrino distribution function + photon/neutrino temperature < (11/4)^1/3
  One should solve the Boltzmann evolution equation (~ % correction to Nnu=3)
  $$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_\alpha}(t,p) = C[f_{\nu_\alpha}; f_{\nu_\beta}; f_{e_\pm}]$$
- QED radiative corrections must be taken into account (finite-temperature corrections to the plasma equation of state)
  sub-percent correction to Nnu=3
- Flavour oscillations are active around neutrino decoupling and must be accounted for
  One should switch to the density matrix approach when solving the Boltzmann equation
  sub-dominant effects
  $$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) \rho_p(t) = -i\left[\left(\frac{1}{2p}M_F - \frac{8\sqrt{2}G_F p}{3m_w^2}E\right), \rho_p(t)\right] + I(\rho_p(t))$$

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

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

Relic Neutrinos – Present Energy Density

Neutrinos with a mass > 10^{-4} eV would be nonrelativistic today, with density

$$\Omega_\nu h^2 \equiv \frac{\rho_{\nu,0}}{\rho_{\mathrm{crit},0}} = \frac{\sum_{i=1}^{3} m_i n_{\nu,0}}{\rho_{\mathrm{crit},0}} = \frac{\sum_{i=1}^{3} m_i}{93.14\,\mathrm{eV}}$$

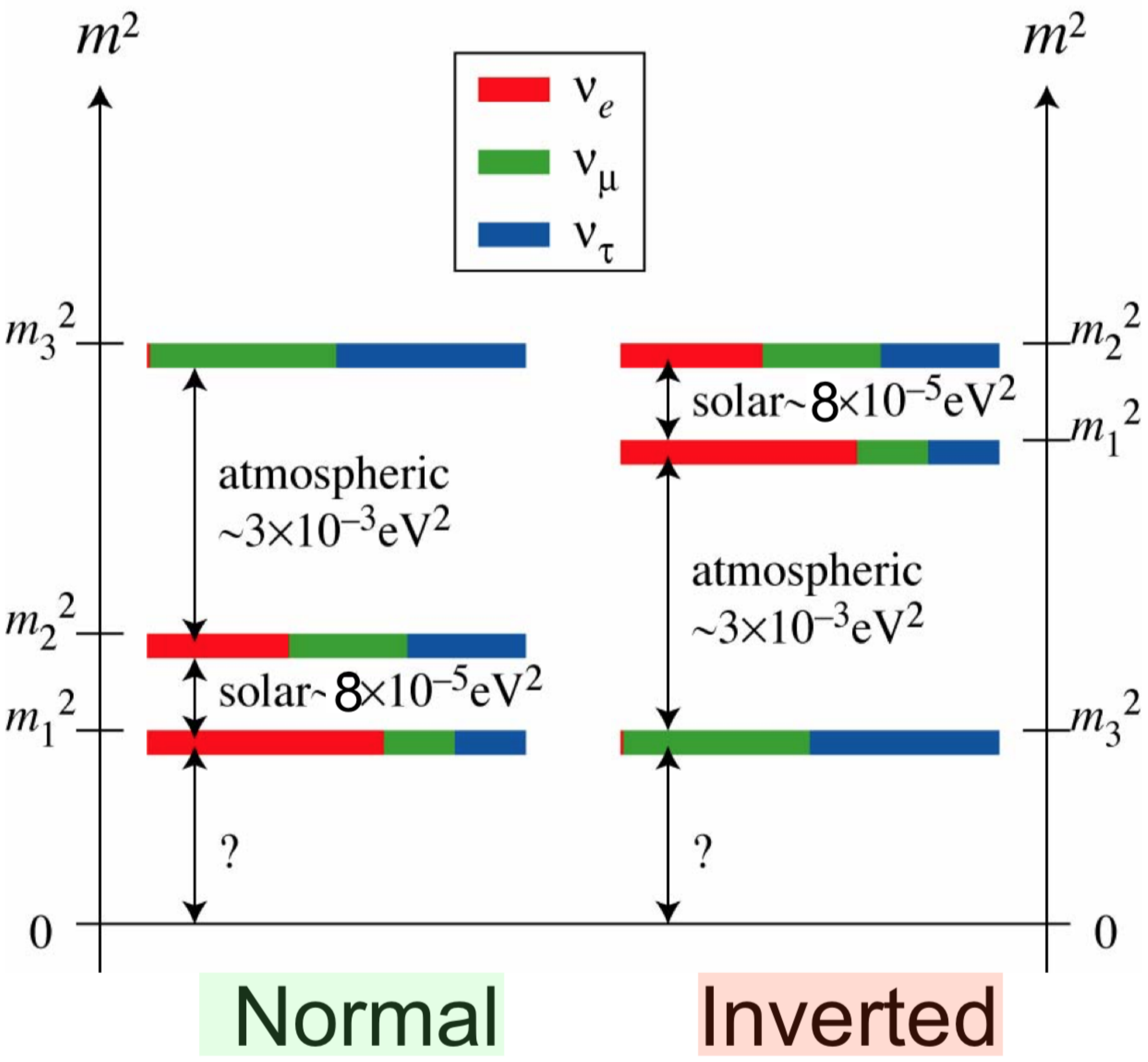
We know from flavour oscillation experiments that at least two of the three active neutrino eigenstates should be non relativistic today, and that the sum of neutrino masses

$$\sum m_i \geq 0.06\,\mathrm{eV}\ \text{(Normal ordering), or}\ \geq 0.10\,\mathrm{eV}\ \text{(Inverted ordering)}$$

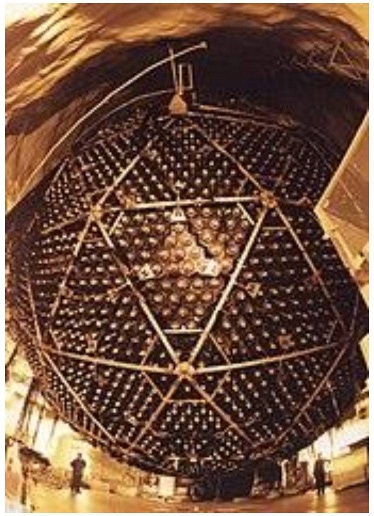
which implies

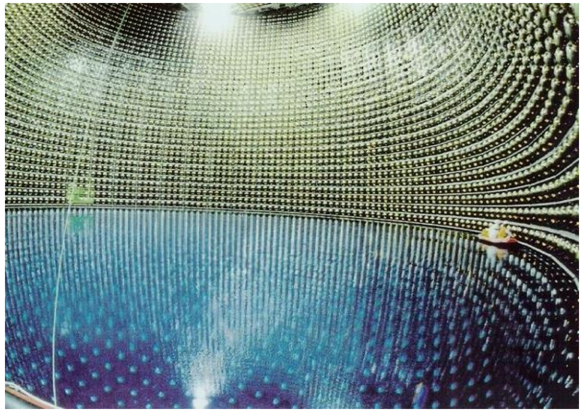
$$\Omega_\nu h^2 \geq 6 \times 10^{-4}\ \text{(NO), or}\ \geq 10^{-3}\ \text{(IO)}$$

RELIC NEUTRINOS – PRESENT ENERGY DENSITY



NEUTRINOS FROM THE LAB





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

Neutrinos have a mass!

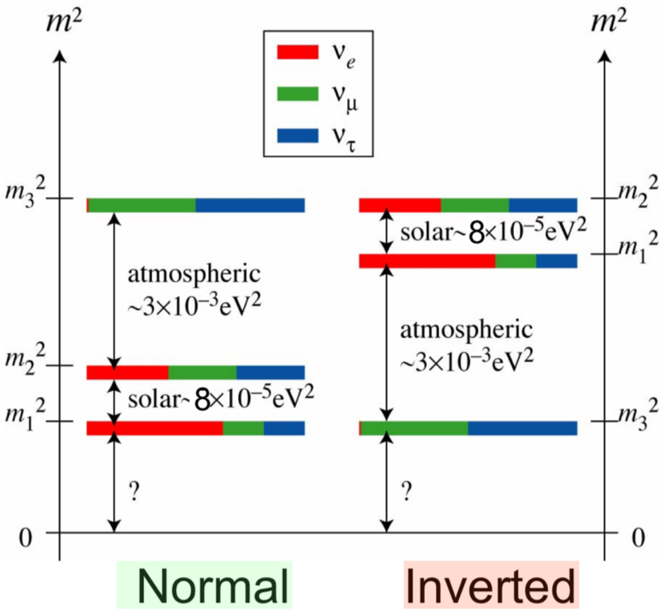
Nobel prize to Kajita & McDonald in 2015

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

We still don't know:

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

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

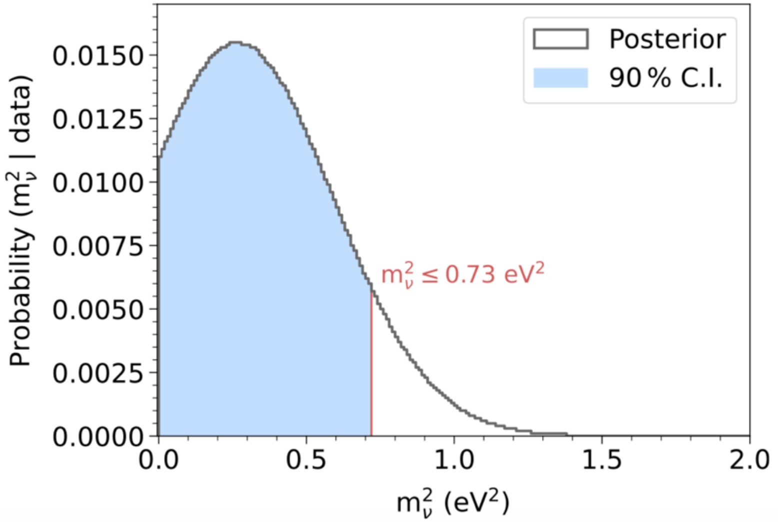


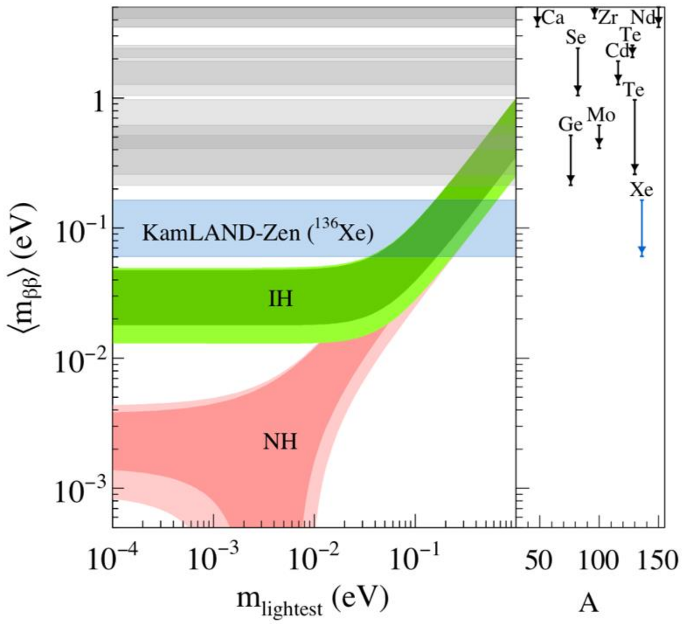
NEUTRINO MASSES FROM THE LAB

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

m_β < 0.35 eV (90%CL) (KATRIN coll., 2024)

Target 90% sensitivity: 0.2 eV

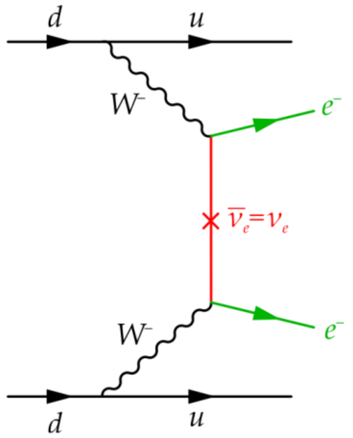




Neutrinoless double β decay (only applies to Majorana ν□s)

$m_{\beta\beta}$ < 0.028 - 0.122 eV (90%CL)

(KamLAND-Zen 800, 2024)

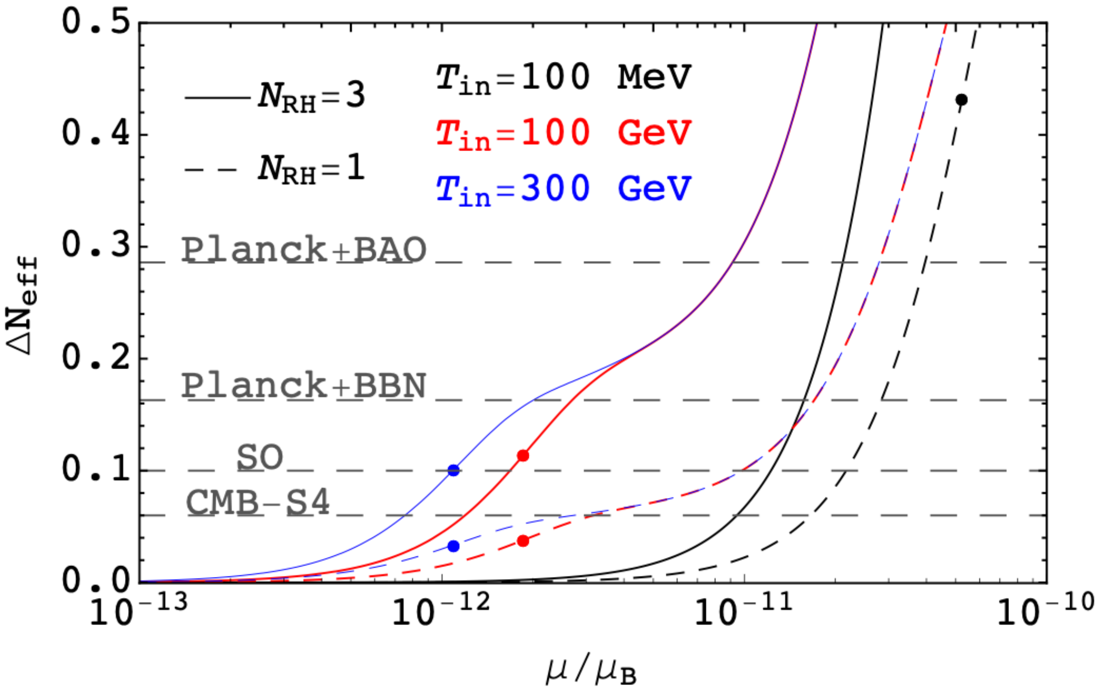


LIGHT RELICS FROM FREEZE-IN

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)

$\mu < 9.1 \times 10^{-12}\ \mu_b$ (Planck+BAO)
$\mu < 1.9 \times 10^{-12}\ \mu_b$ (Planck+BBN)
($T_{max} \geq 100$ GeV)



Light relics from freeze-in

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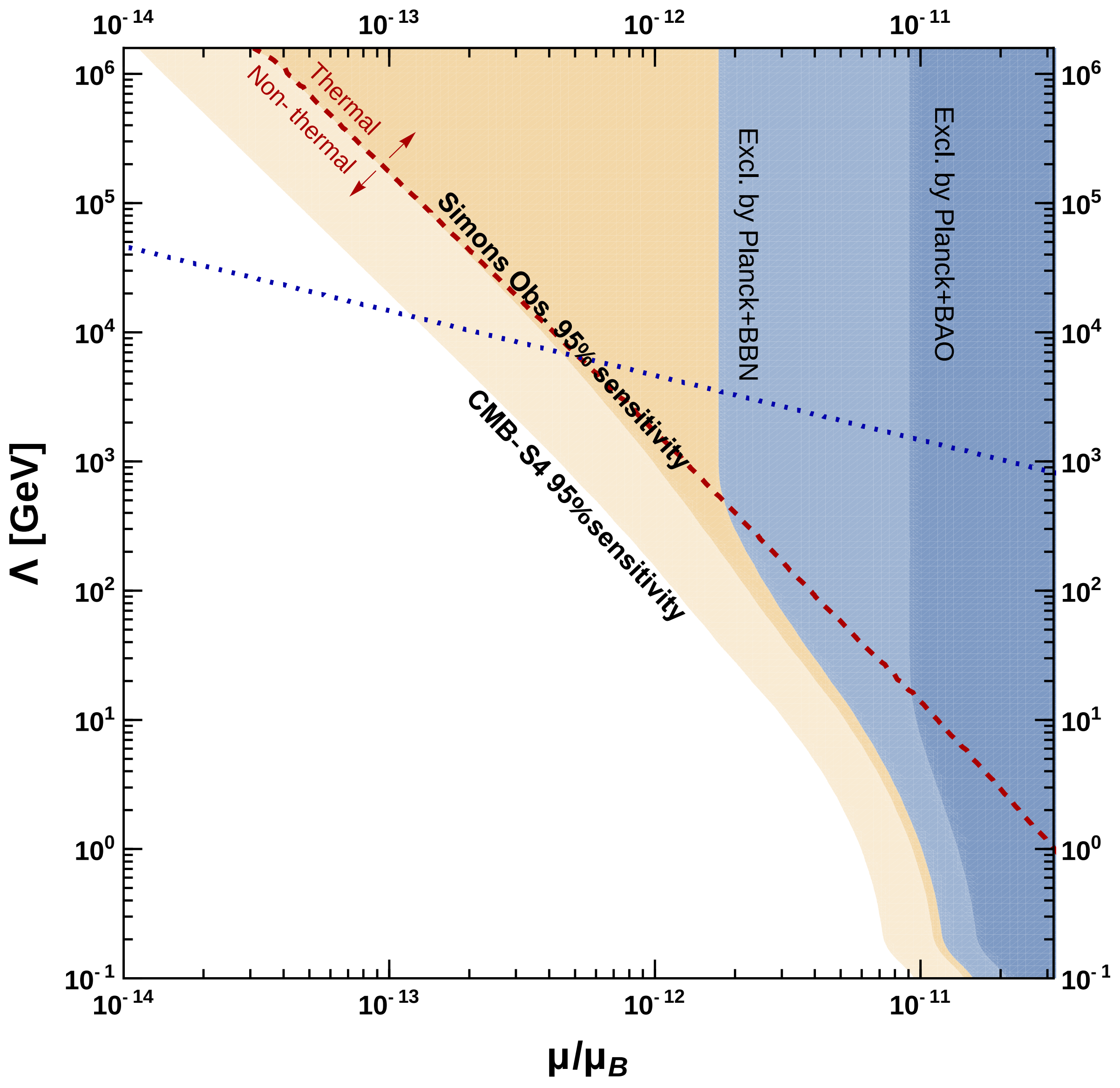
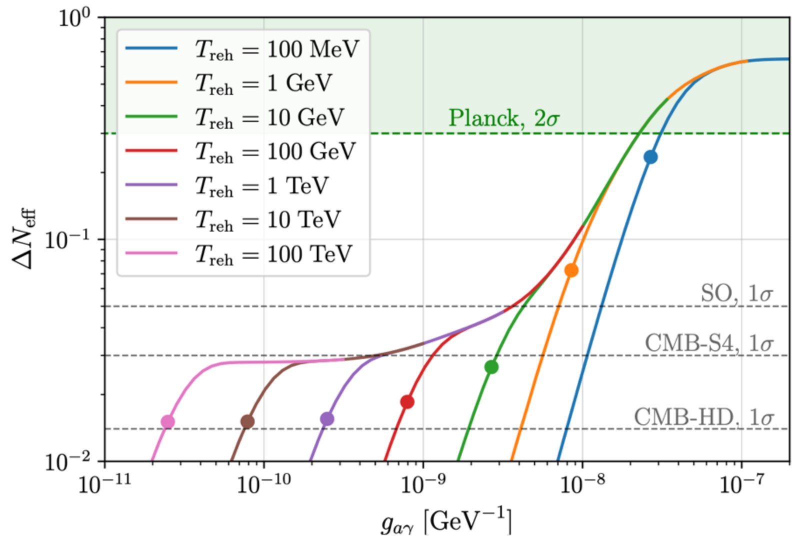


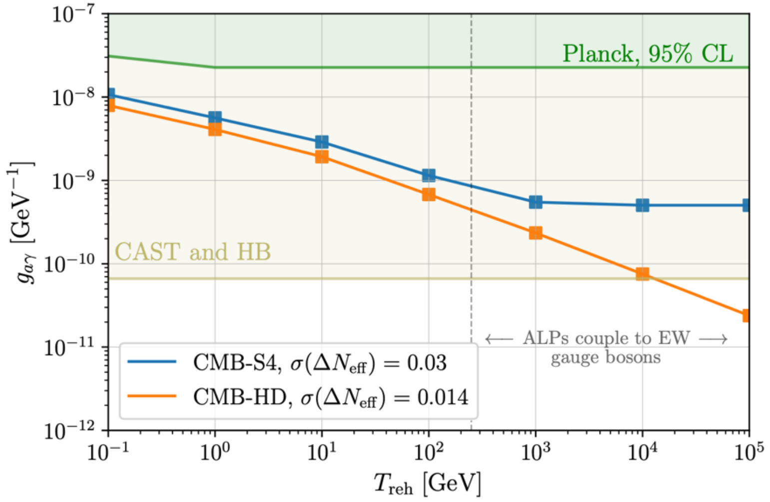
LIGHT RELICS FROM FREEZE-IN

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

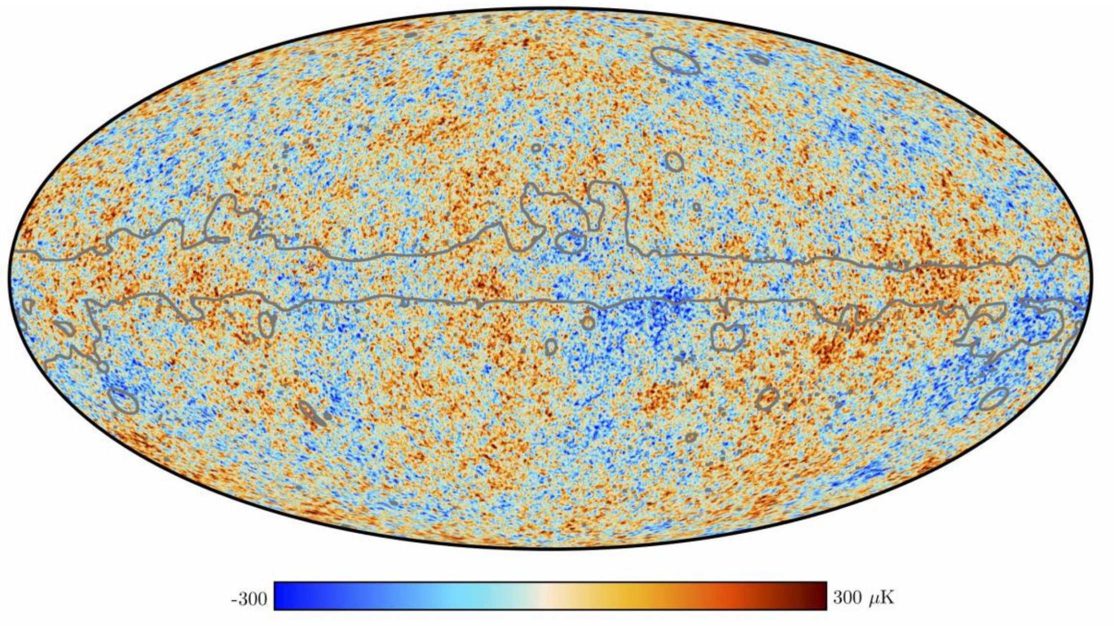
e.g. axions

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





THE COSMIC MICROWAVE BACKGROUND



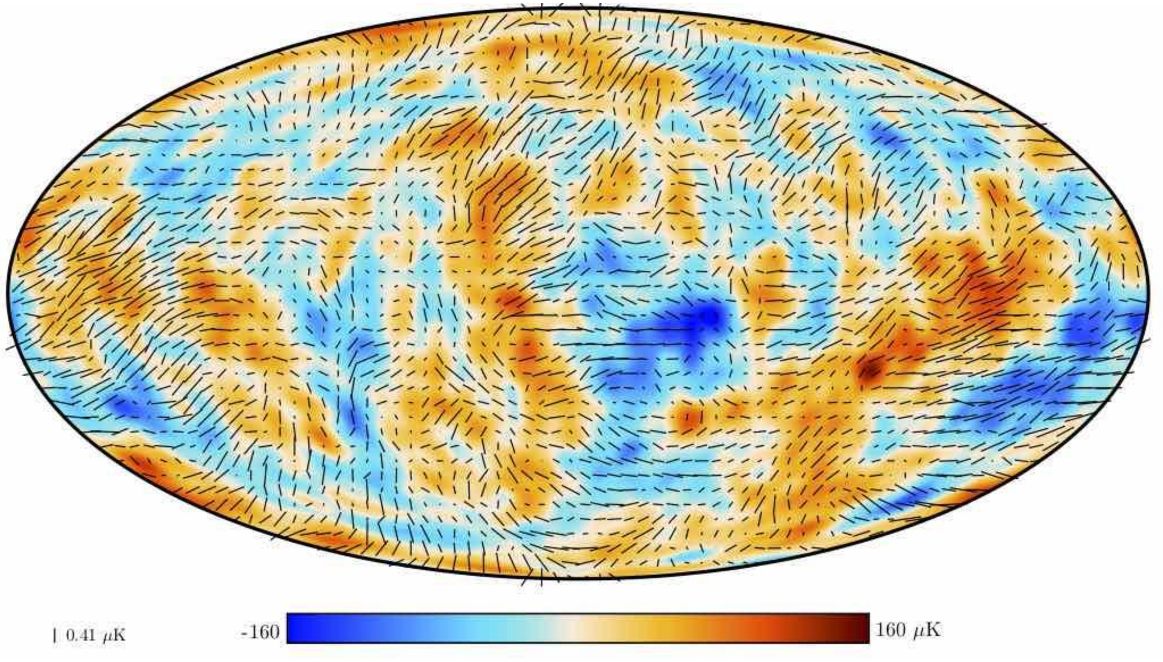
Spherical harmonic expansion:

$$T(\vec{n}) = \sum_{\ell,m} a^T_{\ell m} Y_{\ell m}(\vec{n})$$

$$\langle a^T_{\ell m} a^{T*}_{\ell' m'} \rangle = C^{TT}_\ell \delta_{\ell\ell'} \delta_{mm'}$$

(similarly for E and B pol.)

Fluctuations are gaussian, so all information about the stochastic properties of the maps is contained in their (auto and cross) power spectra C_ℓ



Temperature and polarization maps from Planck (2018)