Istituto Nazionale di Fisica Nucleare

NEUTRINO PROPERTIES FROM COSMOLOGY

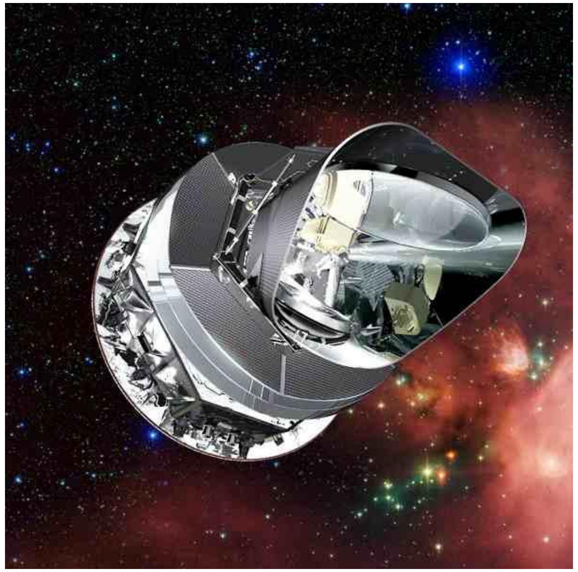
MASSIMILIANO LATTANZI

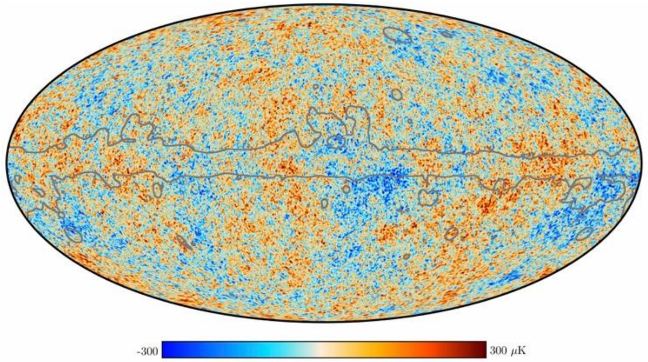
INFN, sezione di Ferrara

NOW 2024

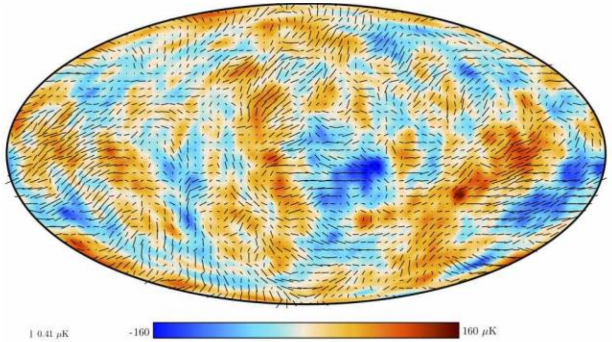
Otranto, Sept. 7th, 2024

CMB OBSERVATIONS

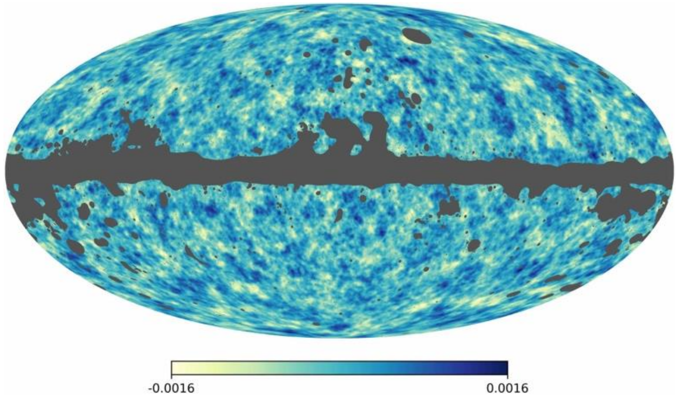




Temperature anisotropies



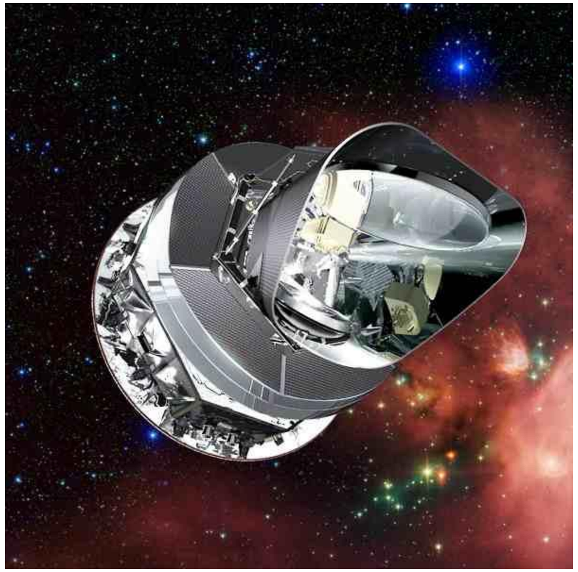
Polarization anisotropies
(two modes: E and B)

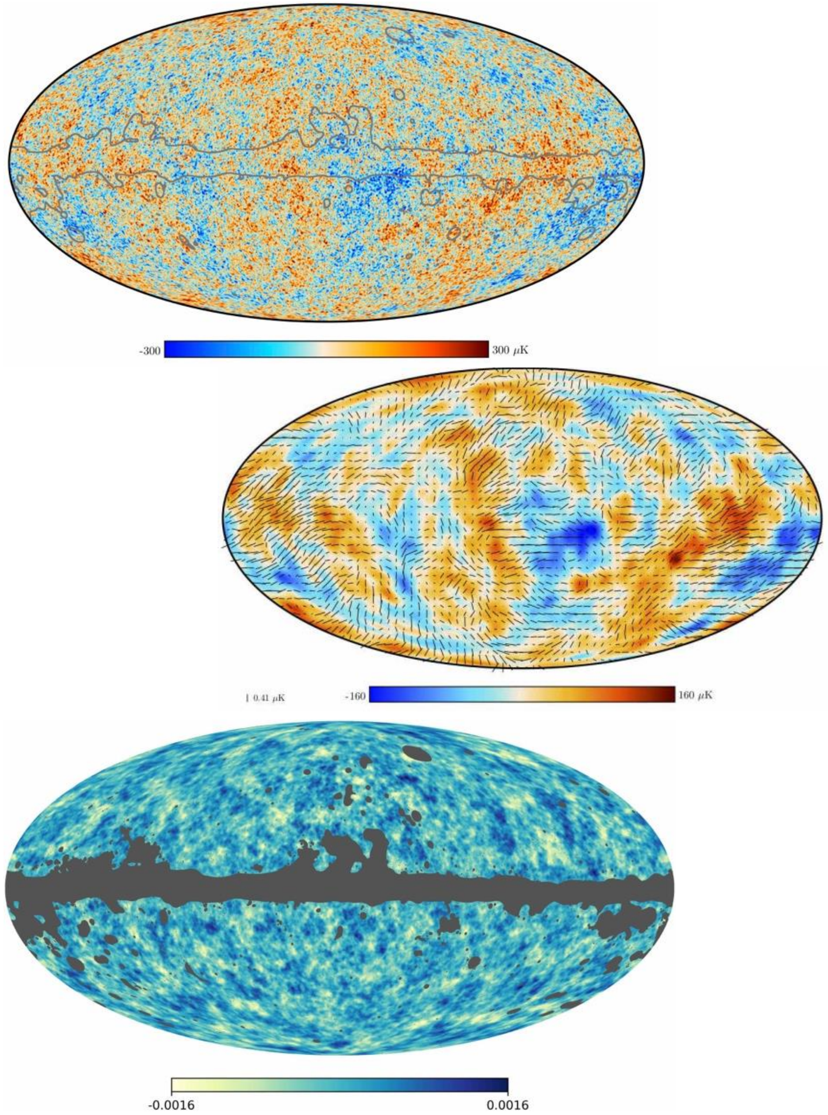


Lensing anisotropies

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

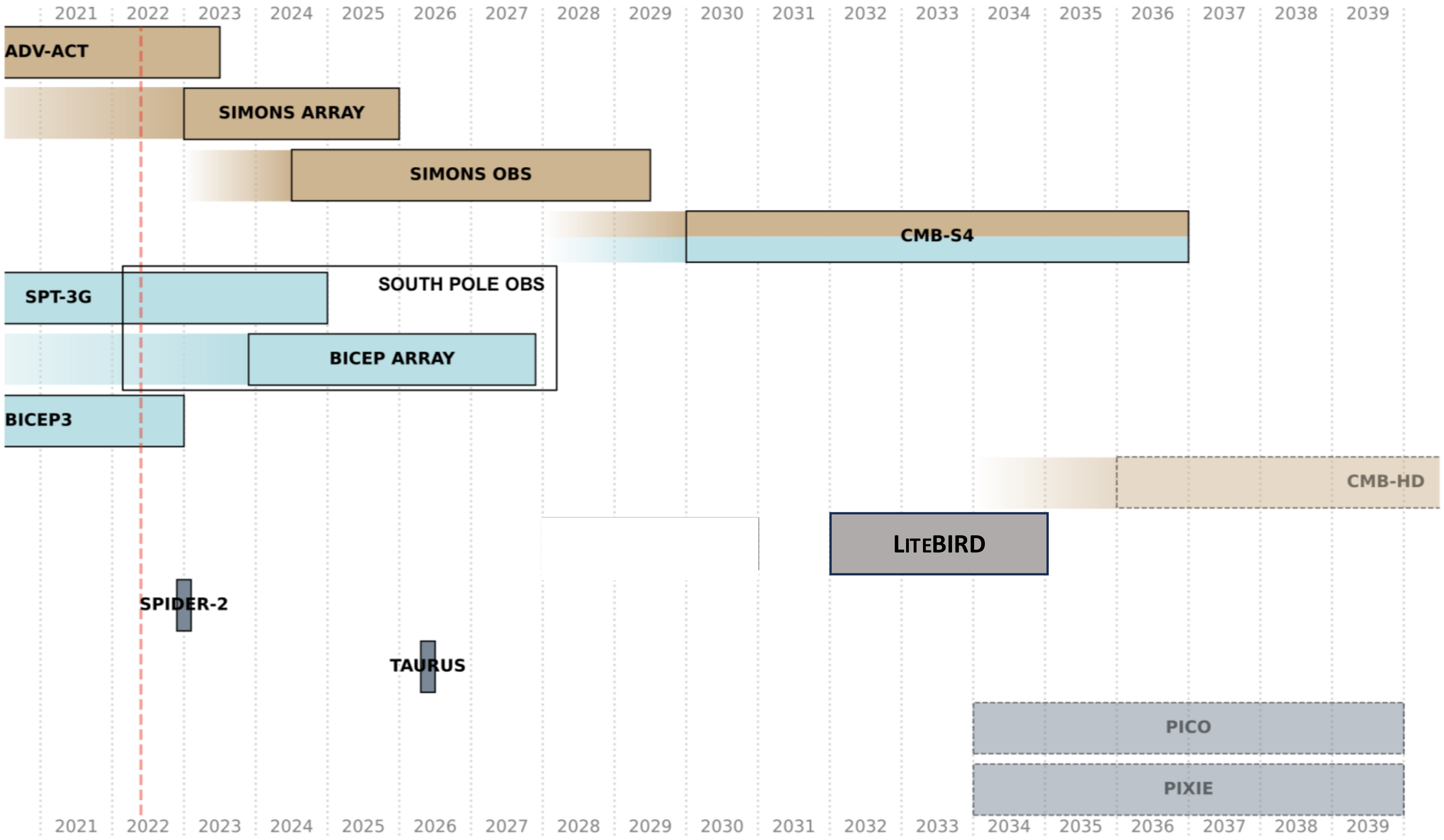
Lensing anisotropies

CMB window to structure formation and the late Universe

Also a target for next-gen experiments

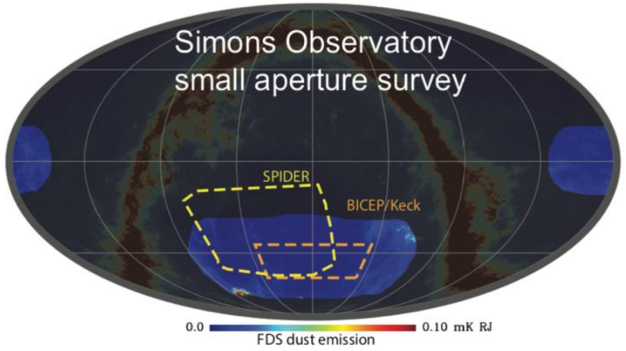
Relevant for e.g. neutrino masses

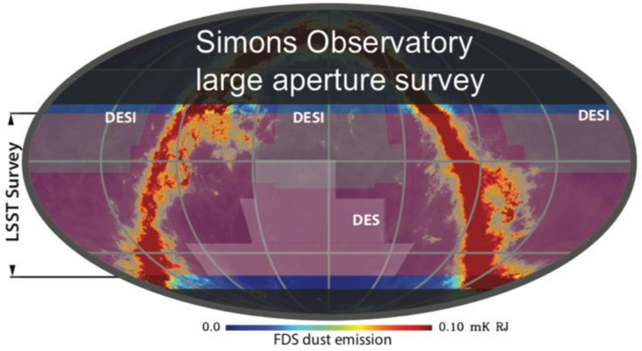
TIMELINE OF CMB EXPERIMENTS

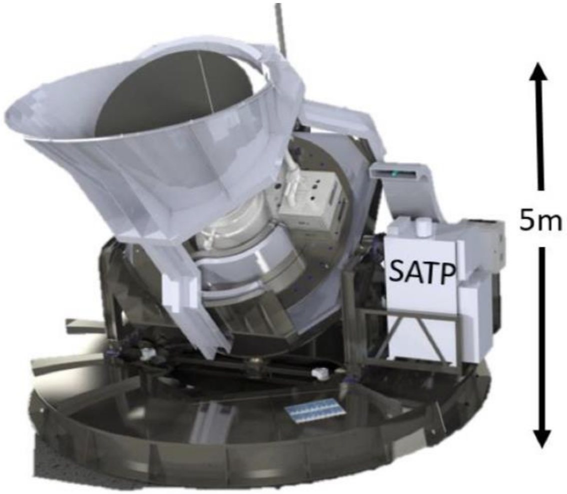


Snowmass2021 Cosmic Frontier: CMB Measurements White Paper, arXiV: [2203.07638](2203.07638)
(with some modifications to account for changes in schedule)

Simons Observatory





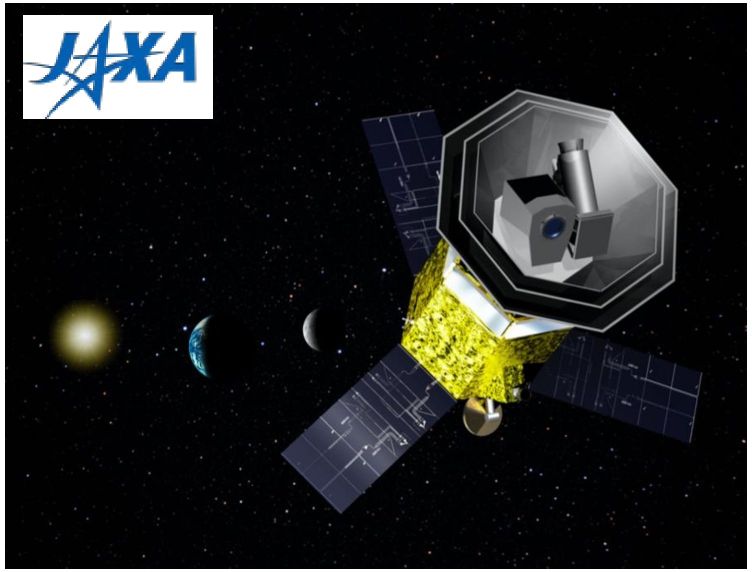


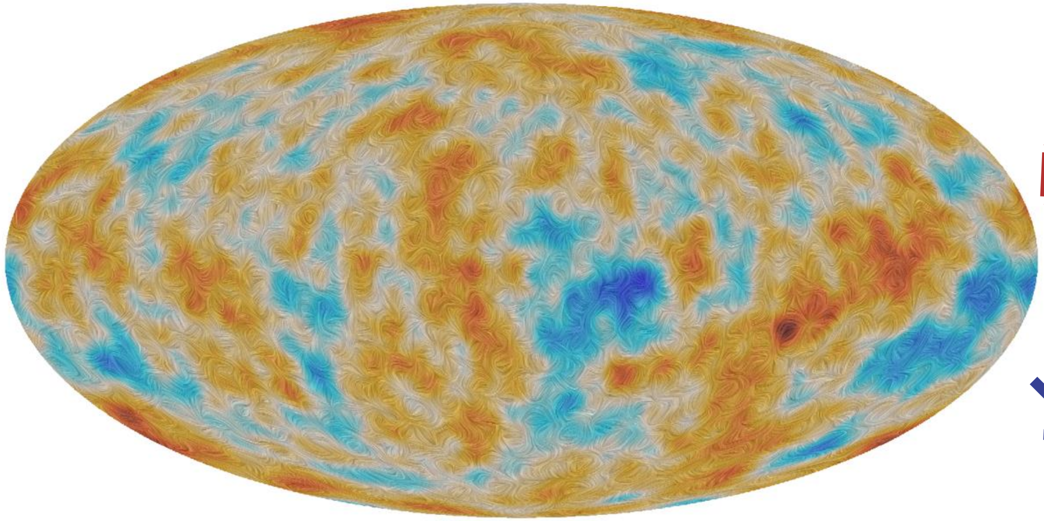
- Ground-based CMB experiment sited in Cerro Toco in the Atacama Desert in Chile
- 5-yr obs campaign
- 3 Small Aperture (0.4m) Telescopes (SATs) for ‘r science’
- 1 Large Aperture (6m) Telescope (LAT) for small-scale (arcmin) science
- > 60k TES detectors
- 10x sensitivity and 5x resolution wrt Planck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

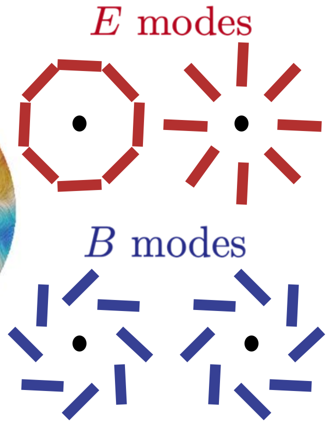
LiteBIRD Overview

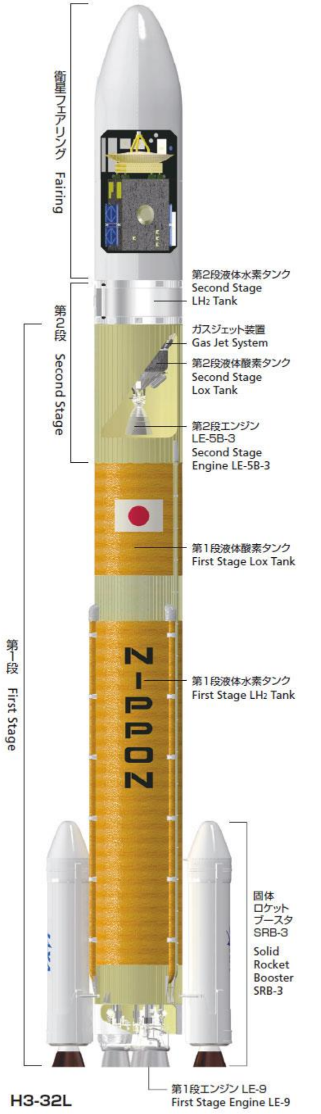
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA’s L-class mission selected in May 2019
- Expected launch in the Japanese Fiscal Year 2032 with JAXA’s H3 rocket
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2
- 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

See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

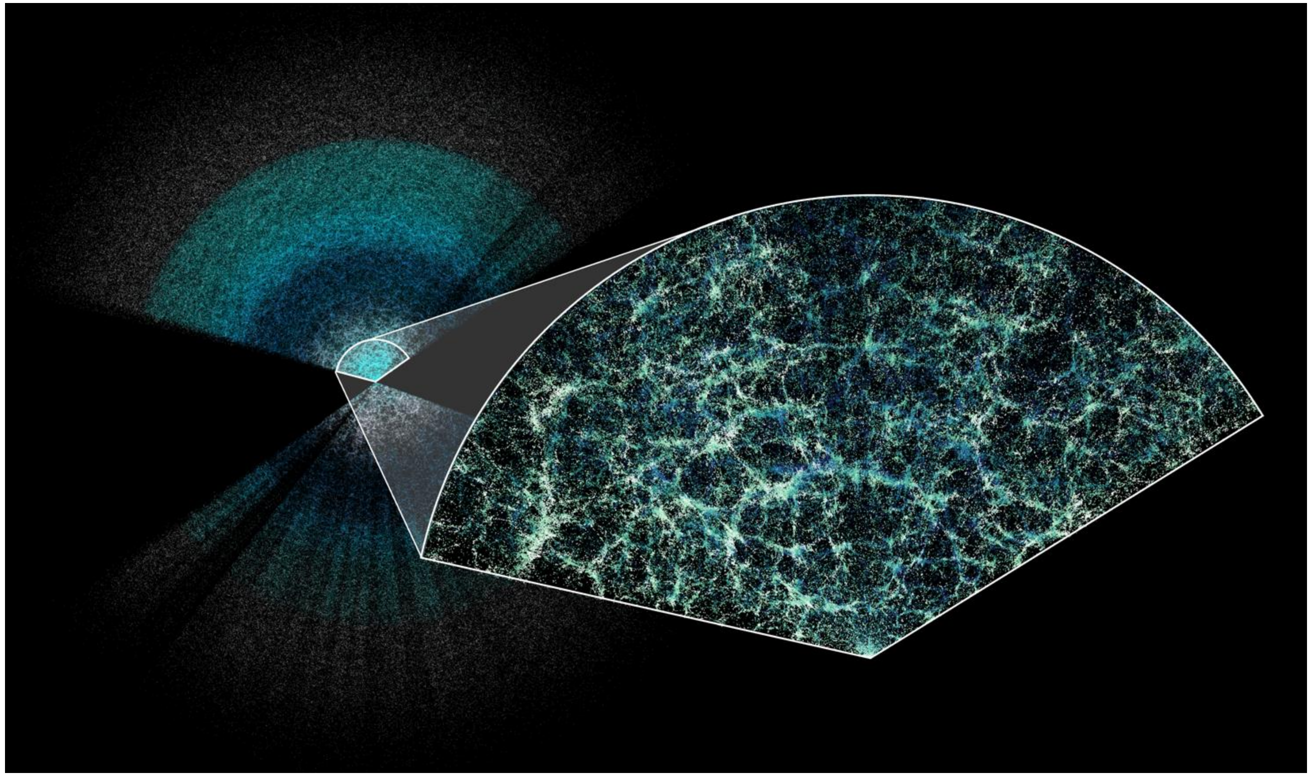
CMB-S4 Science Book (arXiv: 1610:02743)

Next-gen CMB experiments will allow to better characterize the properties of light relics through:

- Better determination of the optical depth from large-scale E-modes
- Constraints on late-time structure formation from lensing
- Better measurement of the small-scale polarization (damping tail)

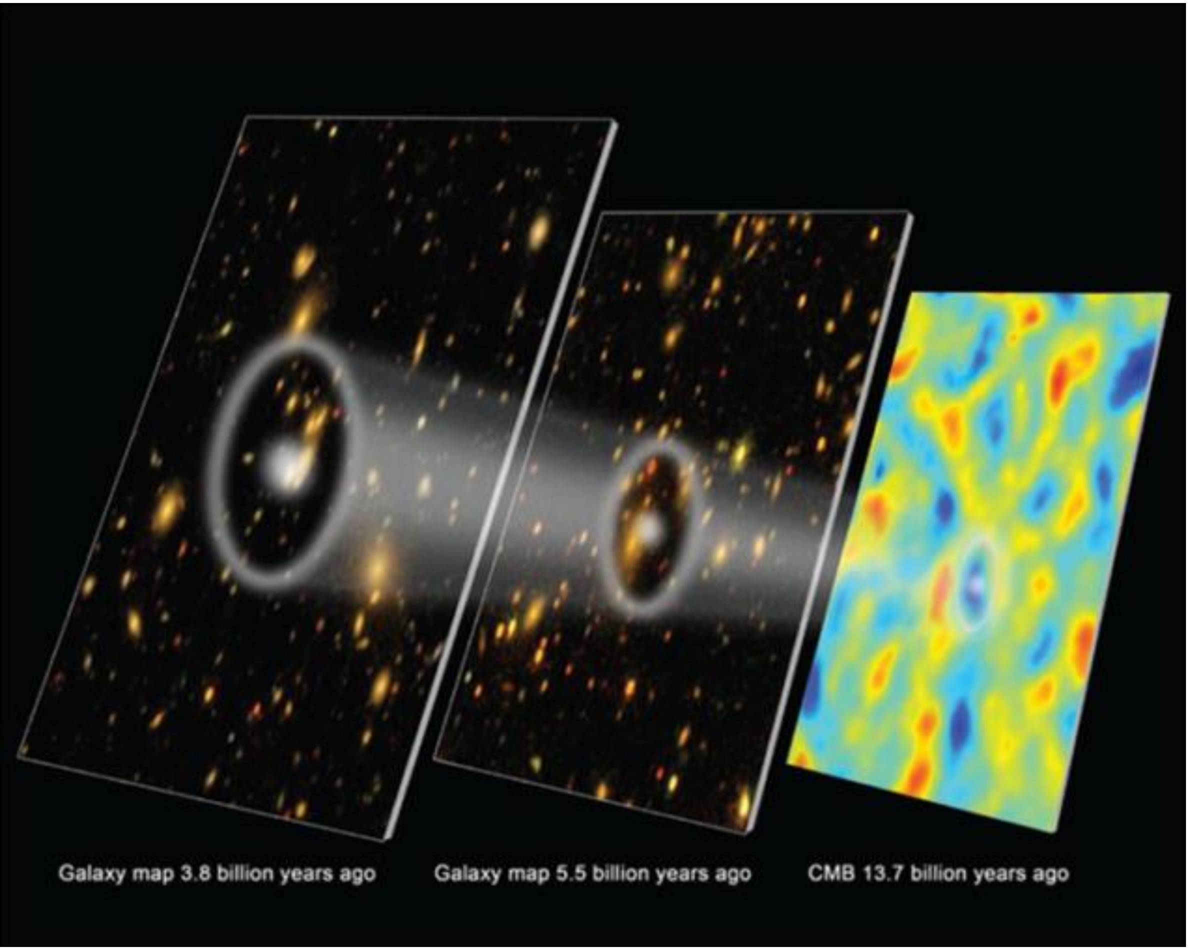
DARK ENERGY SPECTROSCOPIC INSTRUMENT

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

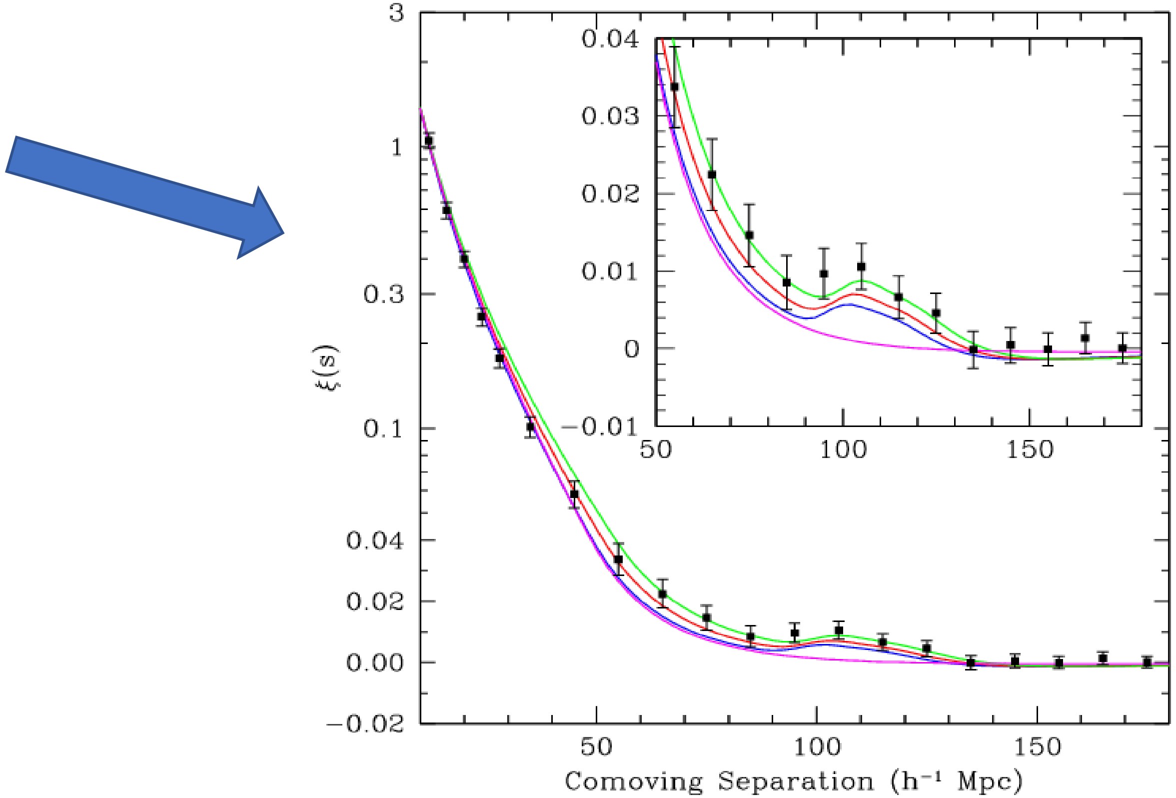


First cosmology results presented in April 2024

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



Euclid Satellite
Launched July 1st 2023

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

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!

$$k_{\rm fs} \simeq 0.018\, \Omega_m^{1/2} \left(\frac{m_\nu}{1\,{\rm eV}}\right)^{1/2} h{\rm Mpc}^{-1}$$

Free streaming scale

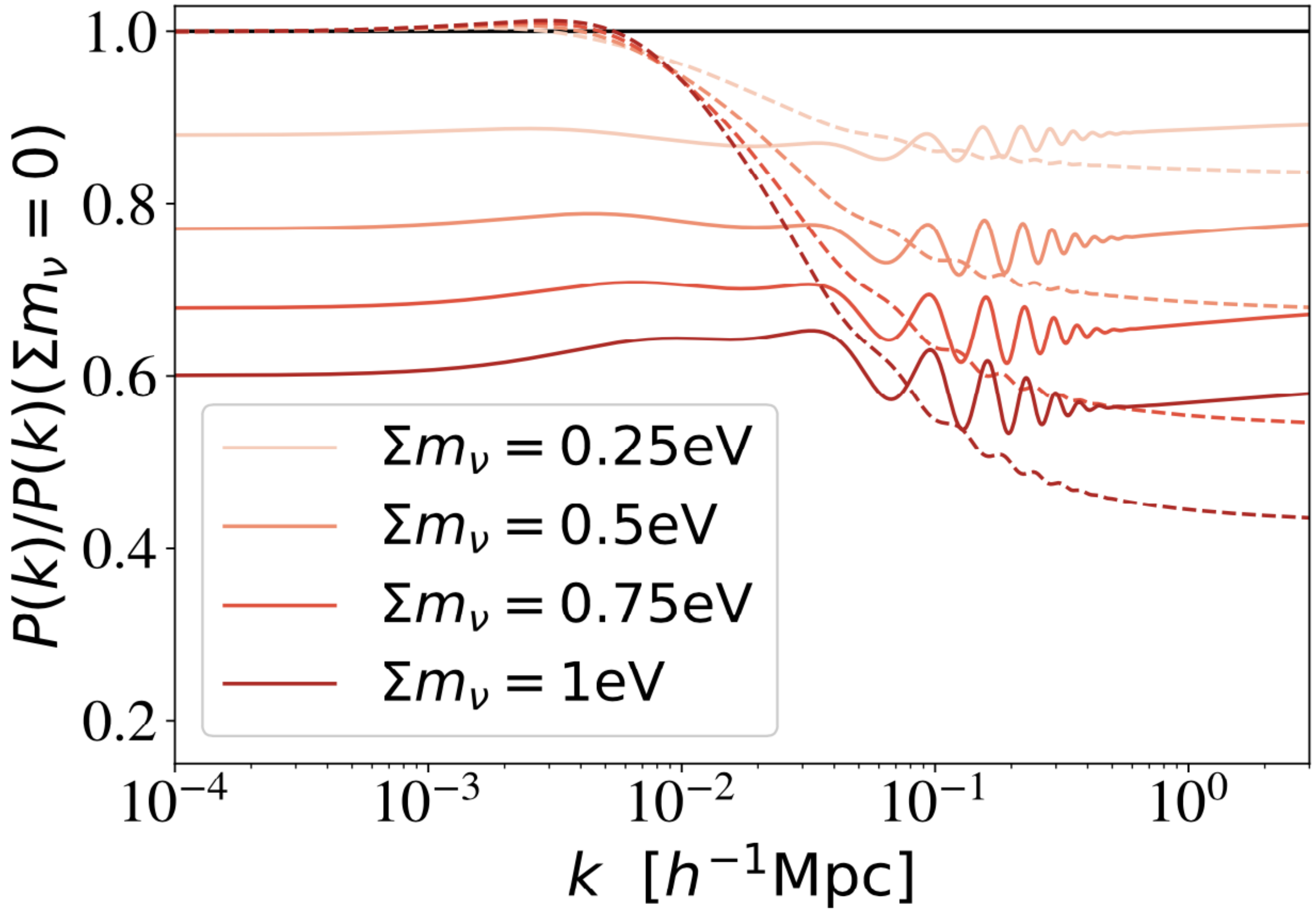
$$\delta_m(k \gg k_{\rm fs}) \propto a^{1-(3/5)\Omega_\nu/\Omega_m}$$

Suppressed growth

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

Acoustic phase shift

NEUTRINOS AND STRUCTURE FORMATION



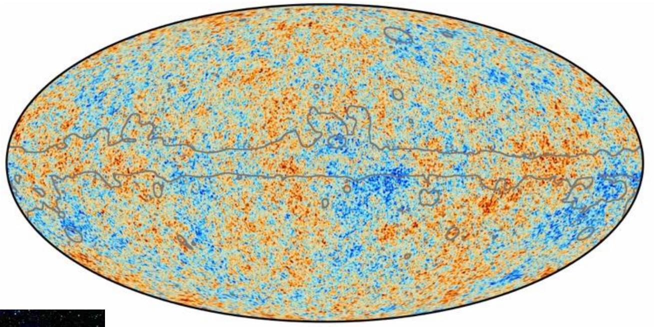
Lesgourgues & Verde, RPP 2019

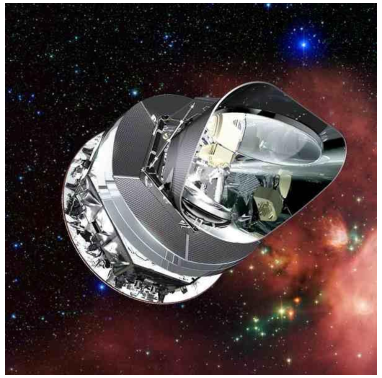
Neutrino free streaming suppresses small-scale density fluctuations

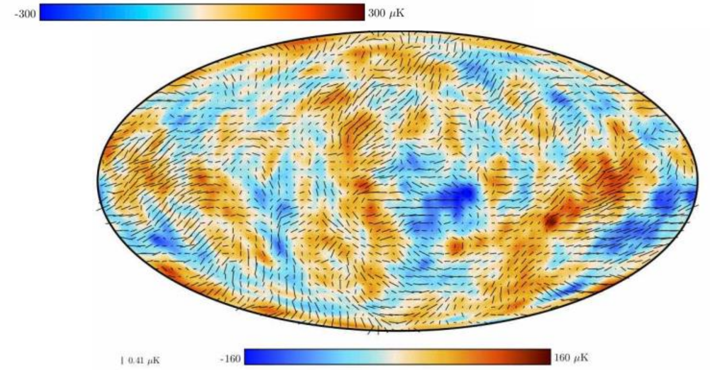
Effect is proportional to the total energy density in neutrinos

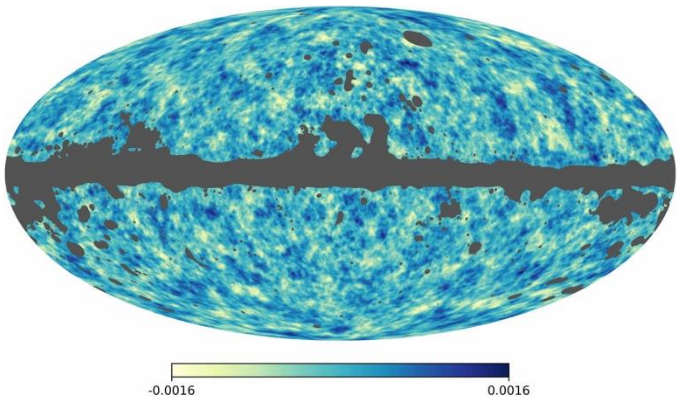
$$\Omega_\nu h^2 = 6.2 \times 10^{-4} \left(\frac{\sum m_\nu}{58\,\mathrm{eV}} \right)$$

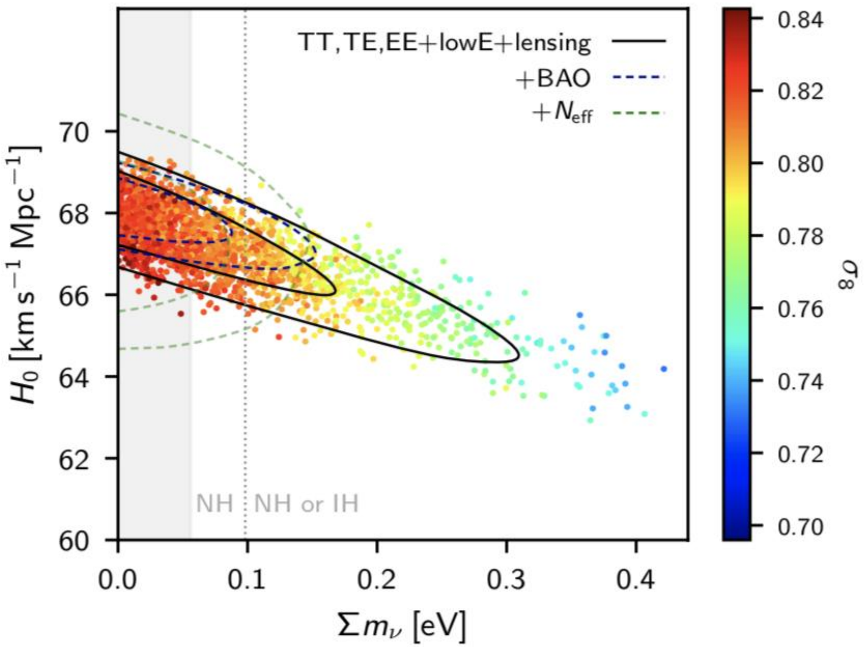
NEUTRINO MASSES AFTER PLANCK











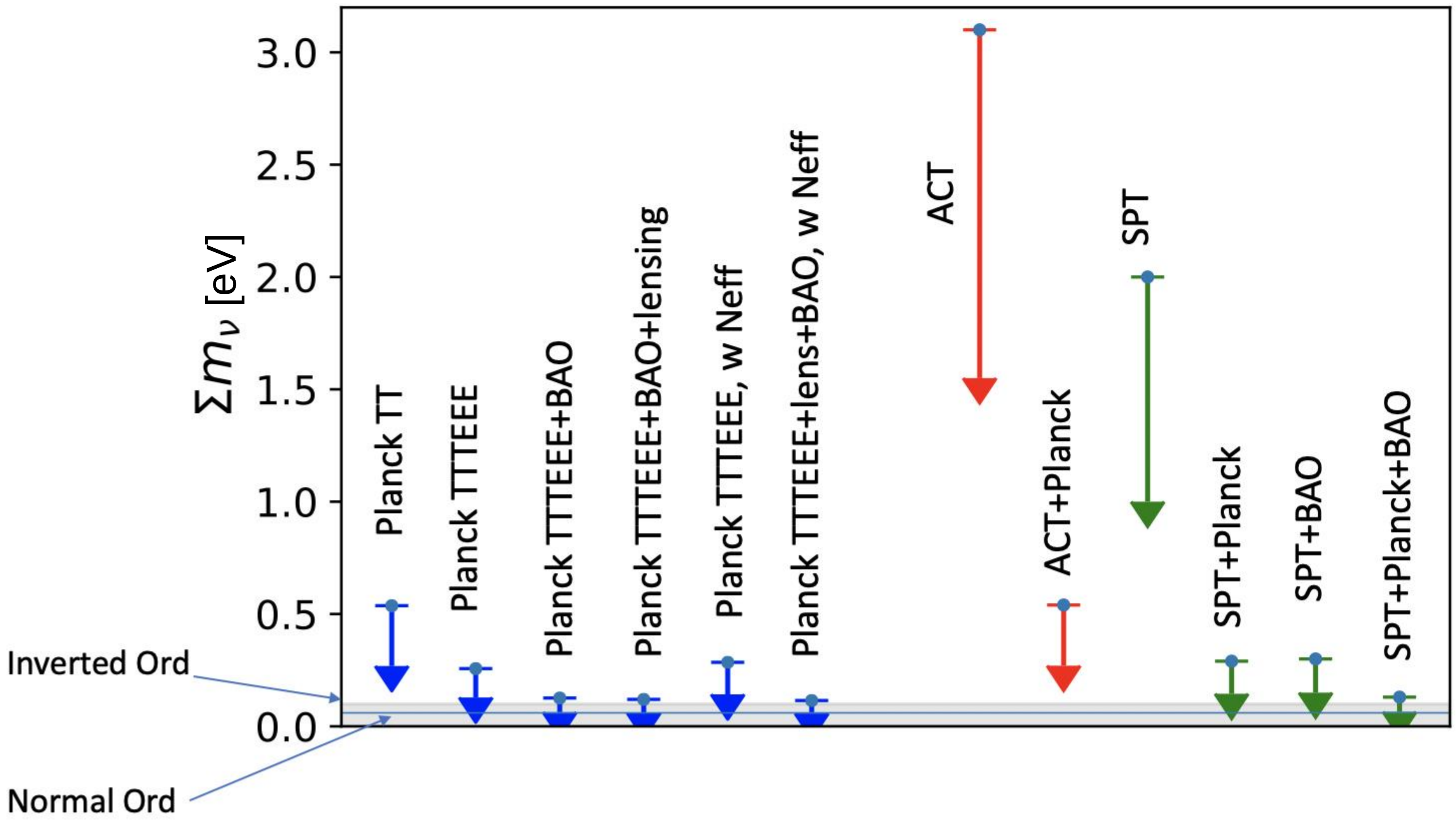
Planck 2018

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

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

(95% CL)

ν MASSES IN ΛCDM: PRESENT STATUS



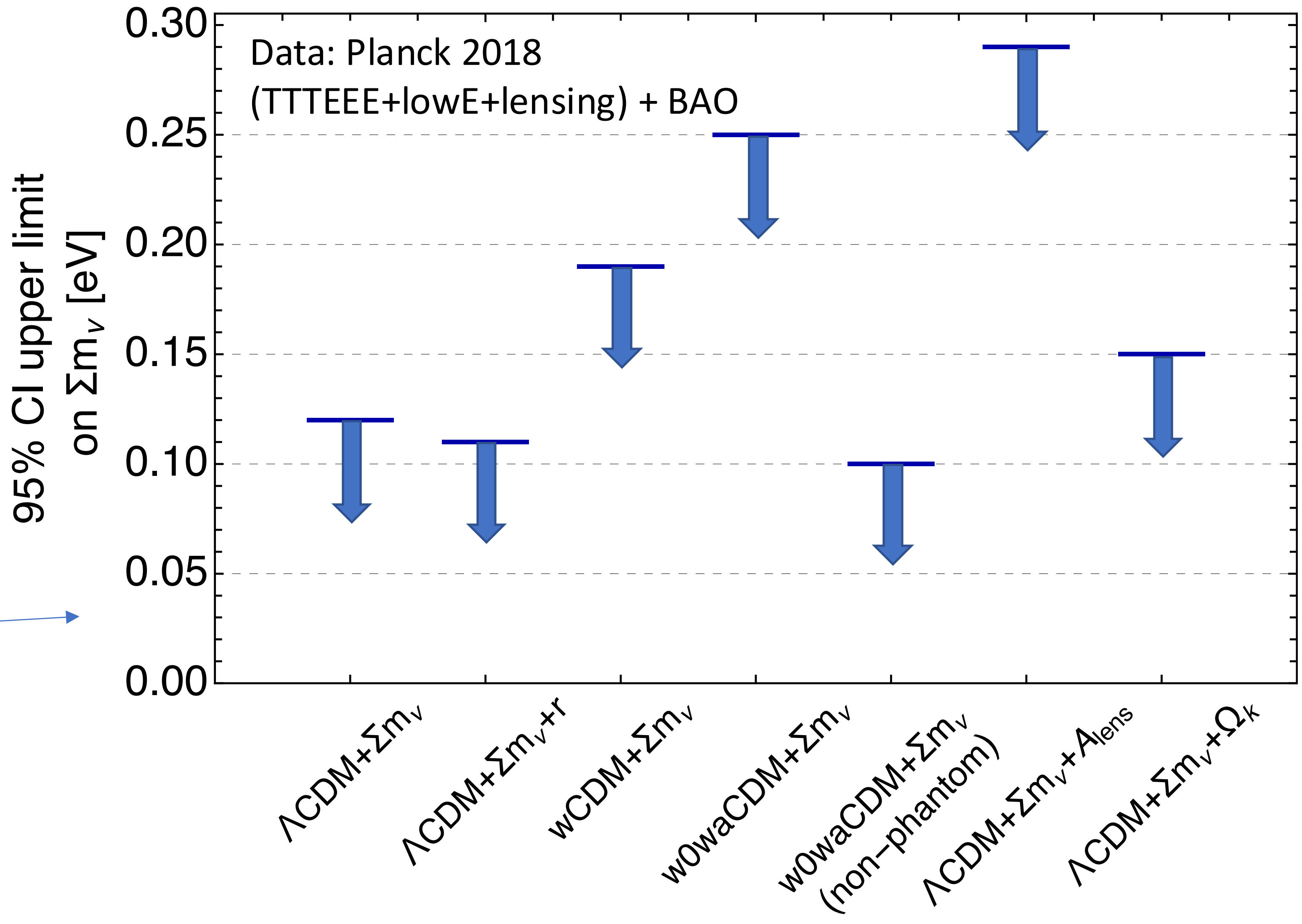
Credit: M. Gerbino

ν MASSES IN ΛCDM EXTENSIONS

It is by now well known that neutrino mass constraints are degraded in:

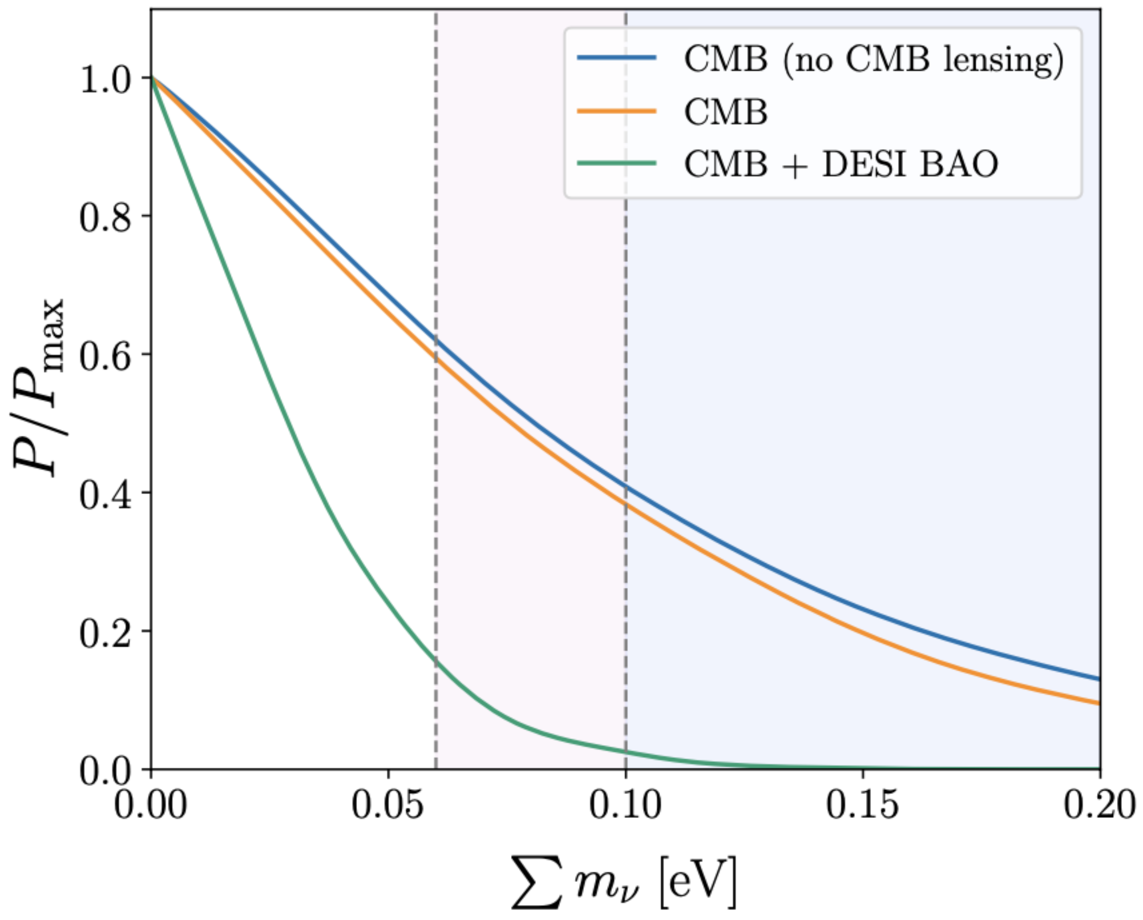
- Dynamical DE models (but only for phantom DE!, see e.g. Vagnozzi et al. 2019)
- Non-flat models
- Models with varying lensing amplitude (which is however not a physical parameter – basically a way to eliminate the information from CMB lensing)

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


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

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

DESI CONSTRAINTS ON NEUTRINO MASSES

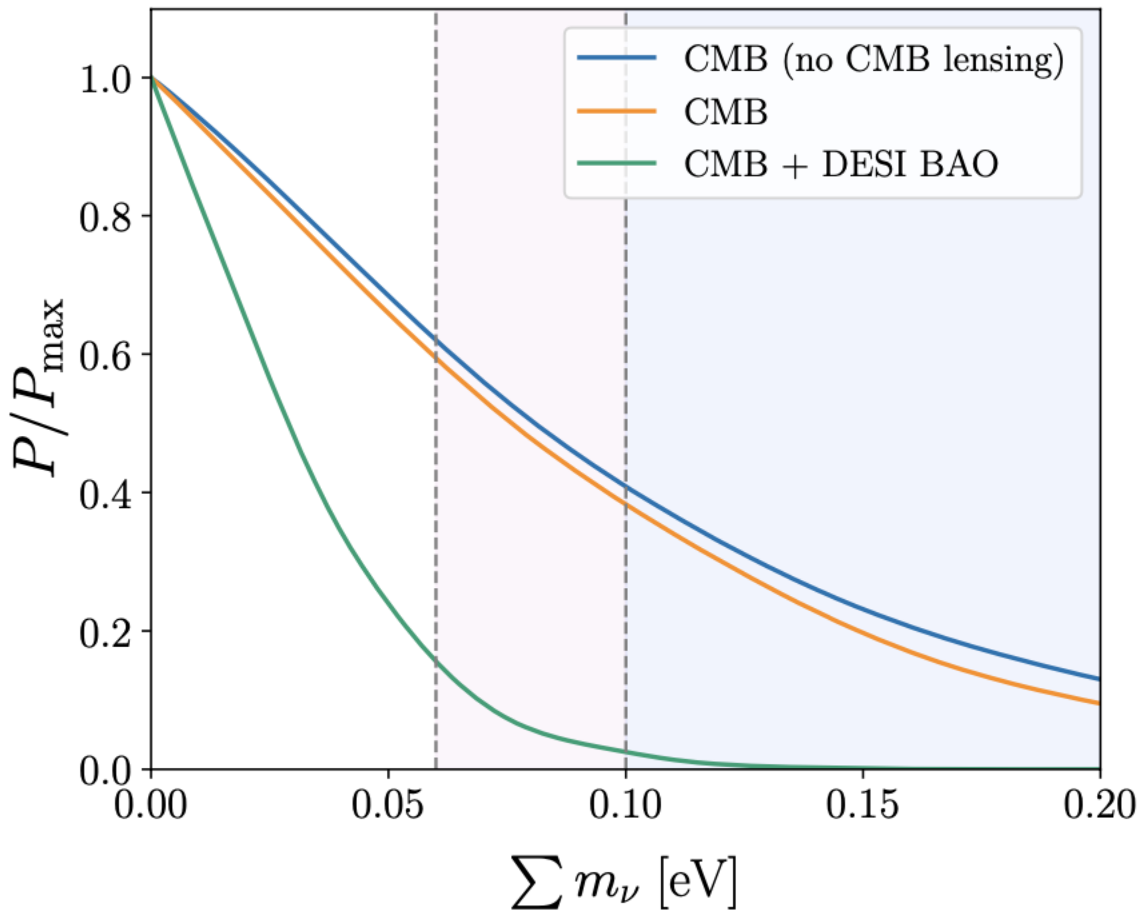


First cosmological results from DESI have appeared last April

Planck+ACT+DESI BAO
Preference for vanishing neutrino masses

$\Sigma m_\nu < 0.072$ eV

DESI CONSTRAINTS ON NEUTRINO MASSES



- Driven by higher-than-expected CMB lensing (Green&Meyers[1])
- Hinting at new physics in the neutrino sector (decay, annihilation…) or elsewhere? (Craig et al.[2])
- Bound weakens including dynamical DE (Green&Meyers[1], Naredo-Tuero et al.[3])
- Also weakens when using Planck PR4 likelihood (Naredo-Tuero et al.[3])
- Driven by a single redshift bin in the DESI data (Naredo-Tuero et al.[3])

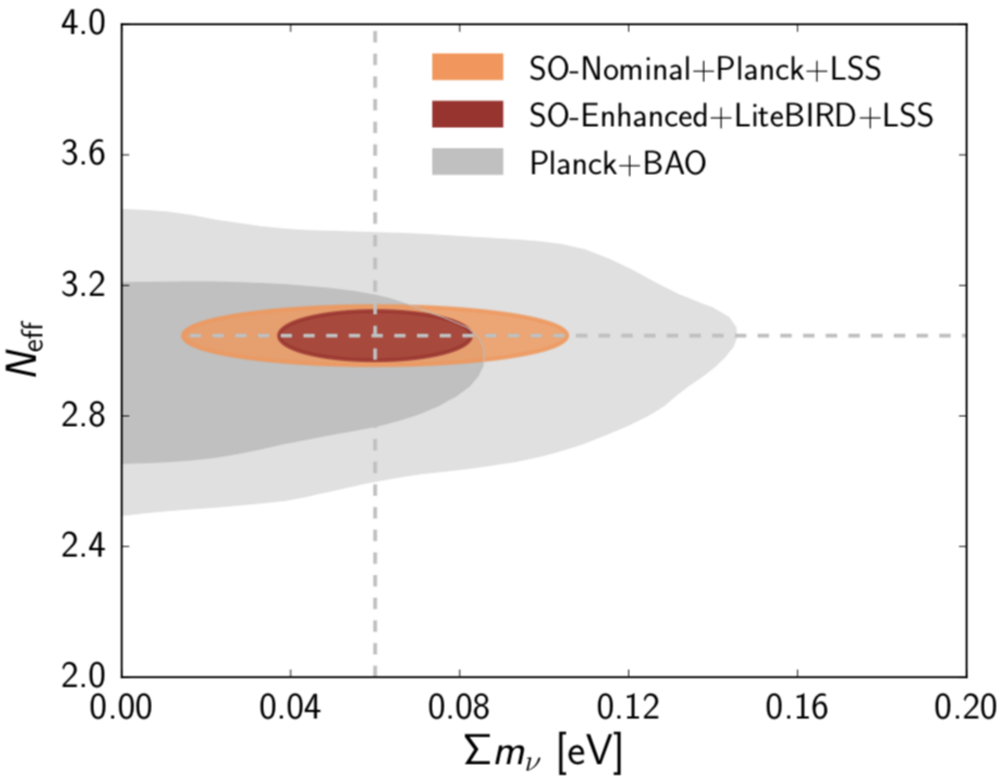
[1] arXiv:2407.07878
[2] arXiv:2405.00836
[3] arXiv:2407.13831

SCIENTIFIC POTENTIAL FOR NEUTRINO PHYSICS

TL;DR (see the next slides for more details!)

- Different combinations of next-generation CMB and LSS measurements will provide a sensitivity for Σm_ν in the 15 – 50 meV range. The lower-end sensitivities rely on a cosmic-variance limited measurement of the reionization optical depth from LiteBIRD.
- This is enough for a up to 4sigma measurement of the minimum mass in NO allowed by oscillation experiments (~60 meV).
- Will also allow to determine the mass ordering if the sum of the masses is close enough to 60 meV.

SIMONS OBSERVATORY



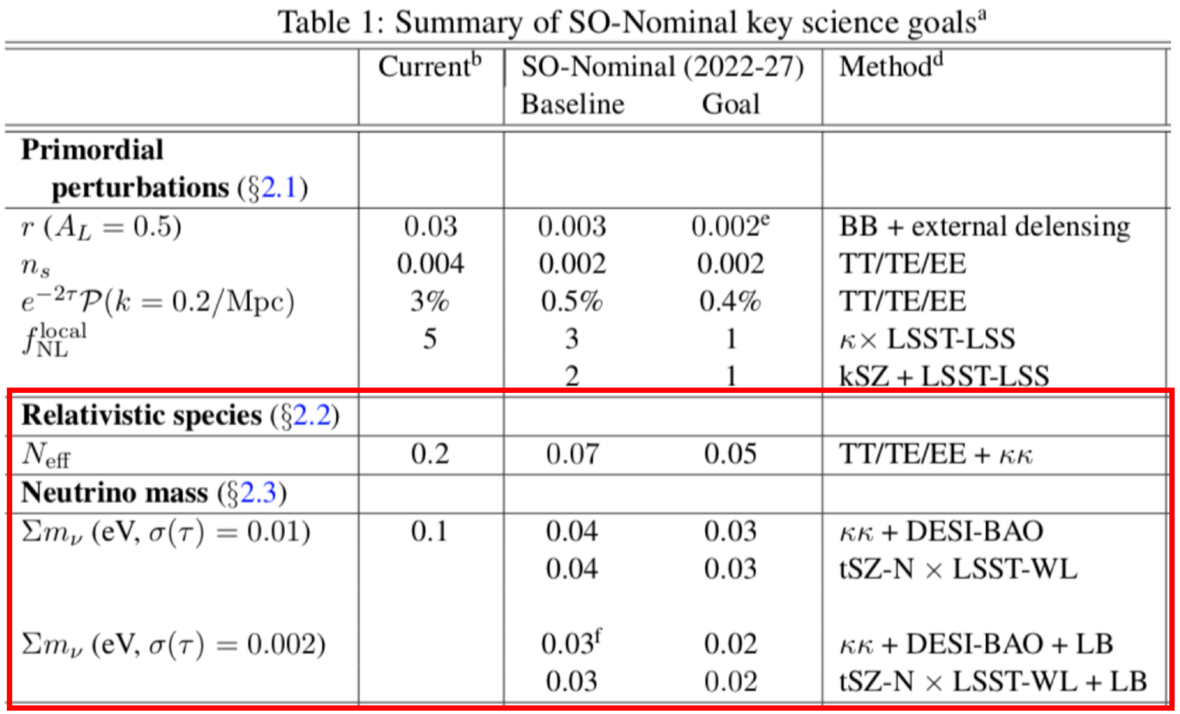
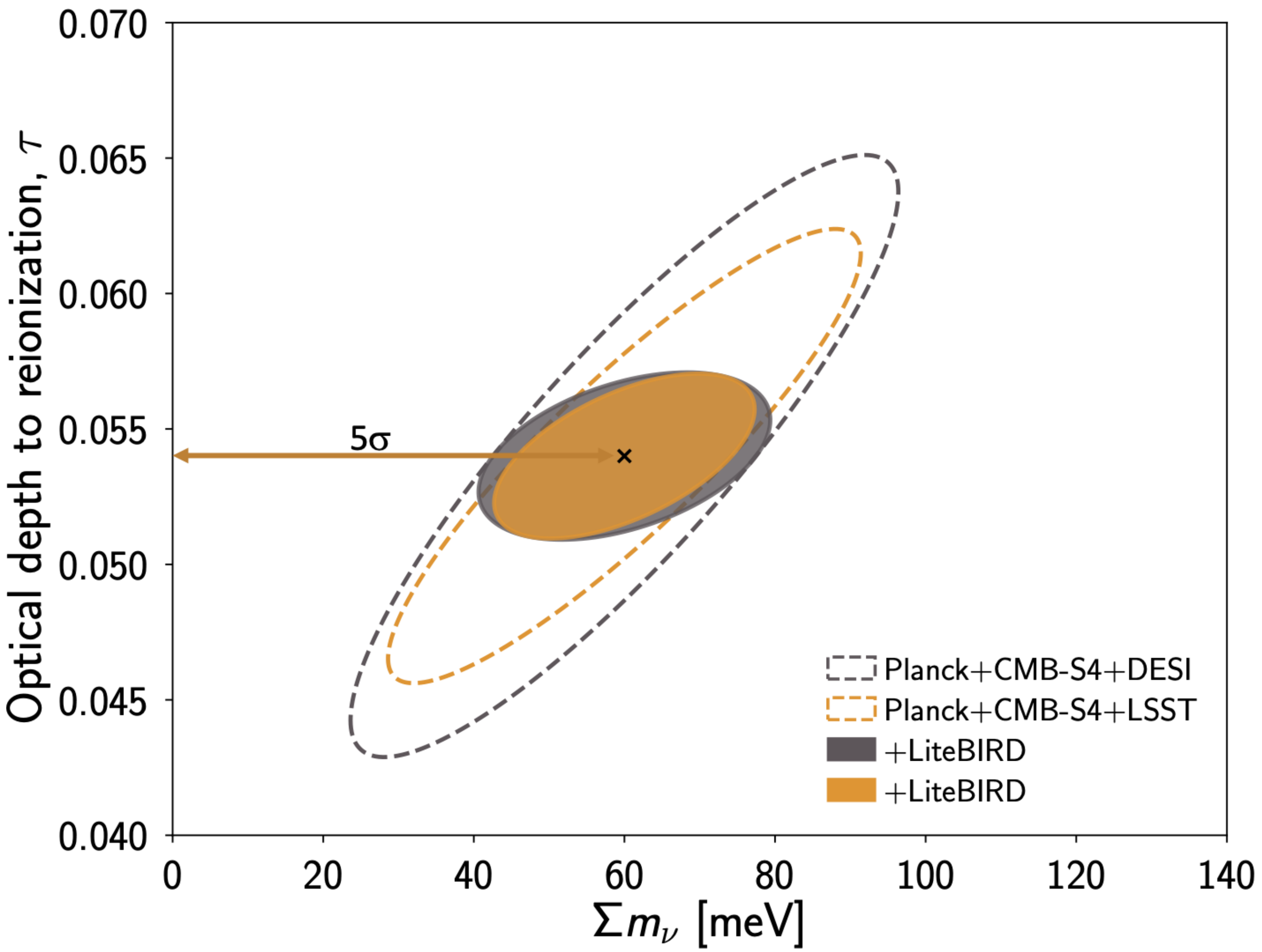


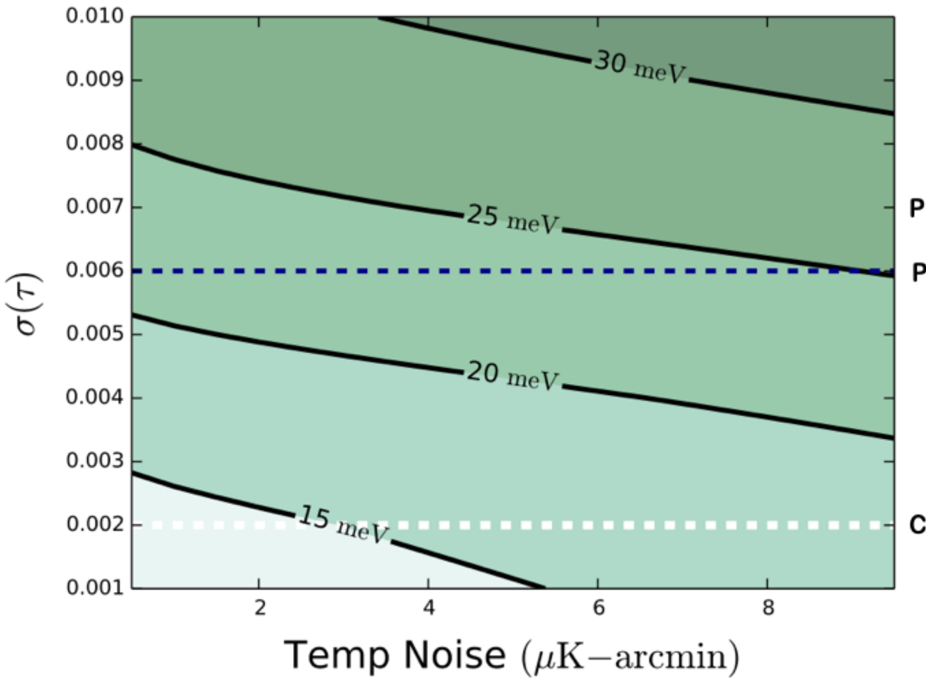
Table 1: Summary of SO-Nominal key science goals[a]

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

LITEBIRD+CMB-S4+DESI/LSST

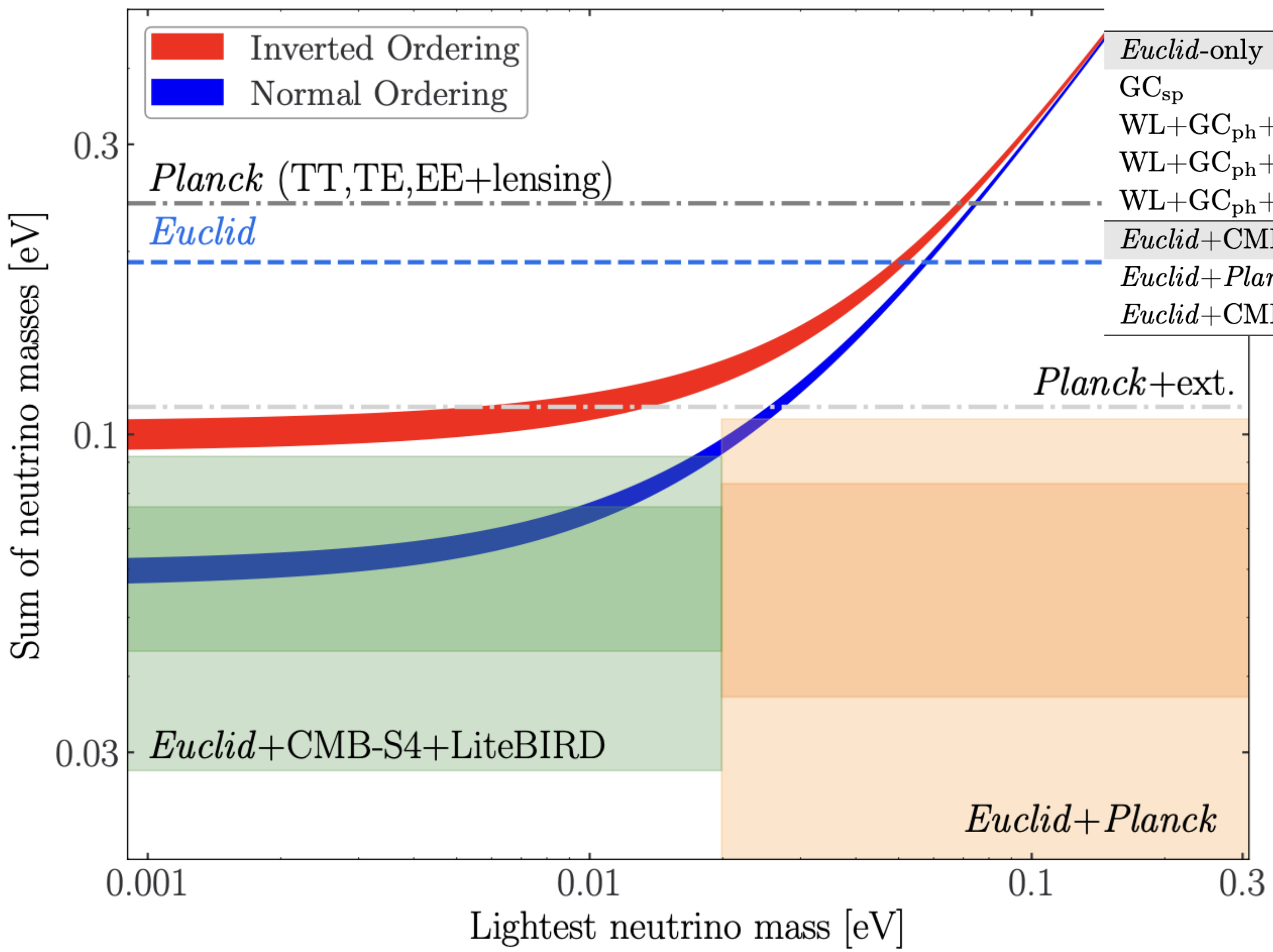


LiteBird Collaboration,
arXiv:2202.02773



CMB-S4 Collaboration, 2019

EUCLID+CMB



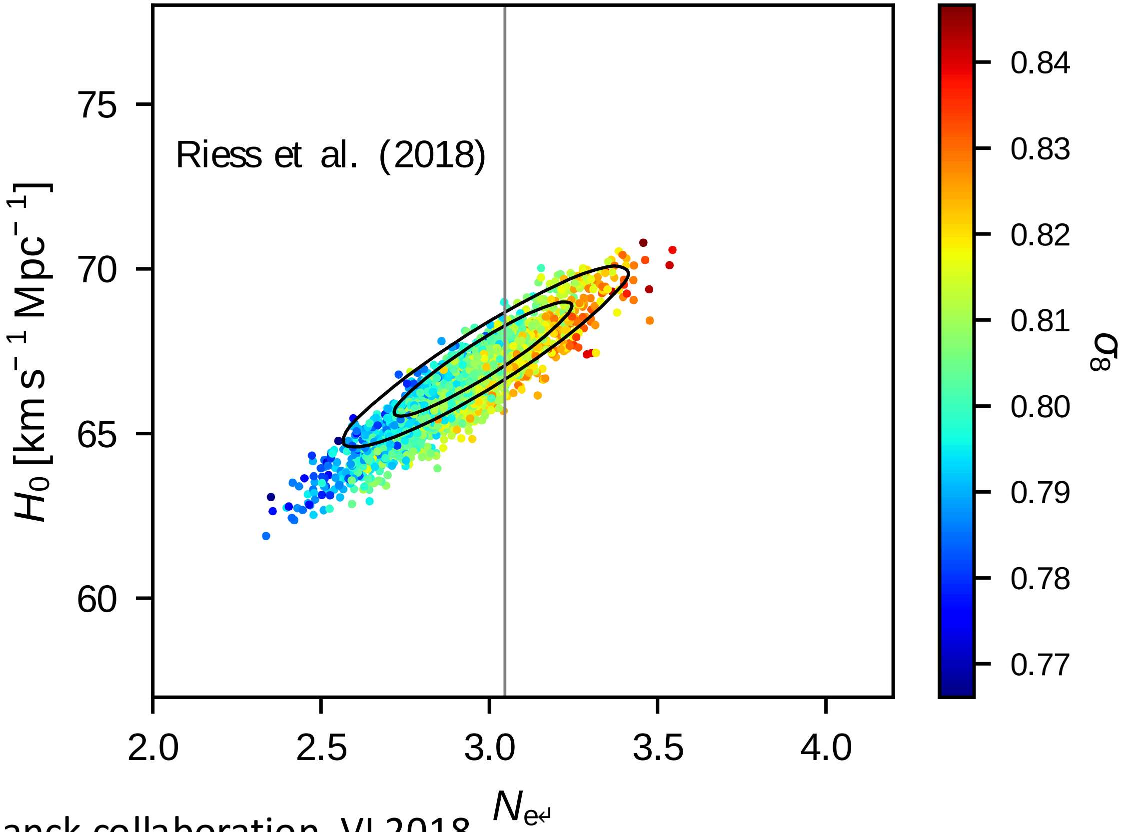
	$\Lambda\mathrm{CDM} + \sum m_\nu$					
	$\Omega_{\mathrm{m},0}$	$100\,\Omega_{\mathrm{b},0}$	h	n_s	σ_8	$\sum m_\nu$[meV]
Euclid-only						
$\mathrm{GC_{sp}}$	0.0068	0.37	0.033	0.029	0.0077	< 320
$\mathrm{WL+GC_{ph}+XC_{ph}}$	0.0032	0.36	0.035	0.017	0.0047	< 260
$\mathrm{WL+GC_{ph}+XC_{ph}+GC_{sp}}$	0.0026	0.24	0.022	0.013	0.0039	56
$\mathrm{WL+GC_{ph}+XC_{ph}+GC_{sp}+CC}$	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

Archidiacono et al., (Euclid collaboration)
arXiv:2405.06047

See also S. Pamuk talk on Sep. 3rd !

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

Theoretical expectation for the three SM neutrinos* :

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

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

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

NEFF AS A PROBE OF NEW PHYSICS

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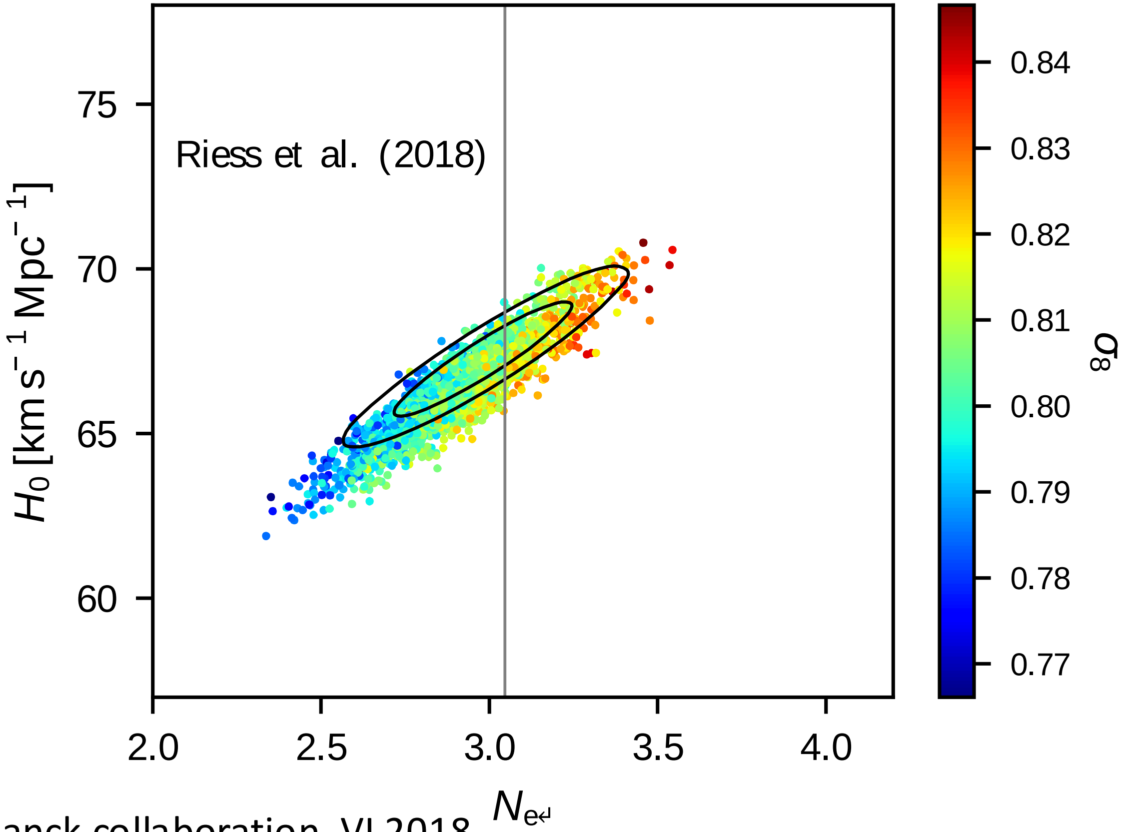


Planck collaboration, VI 2018

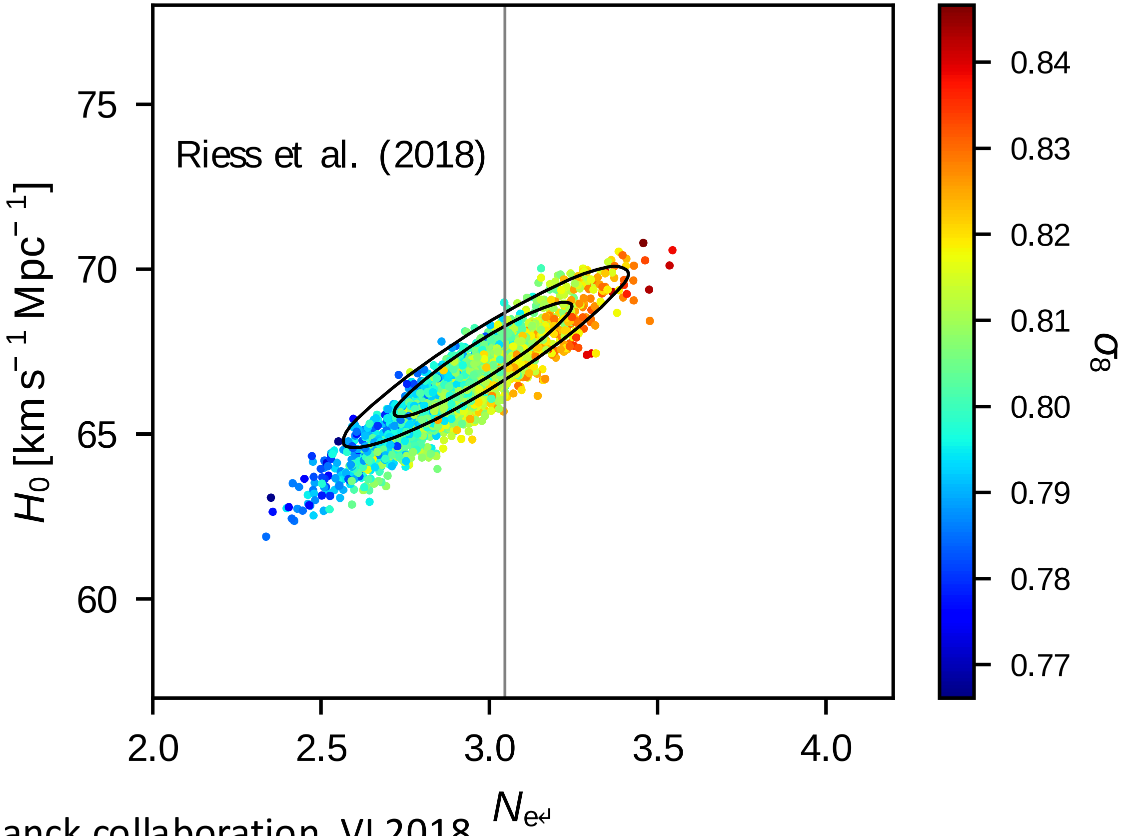
A deviation from the standard value of $N_{\rm eff}$ might be due to:

- 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

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!

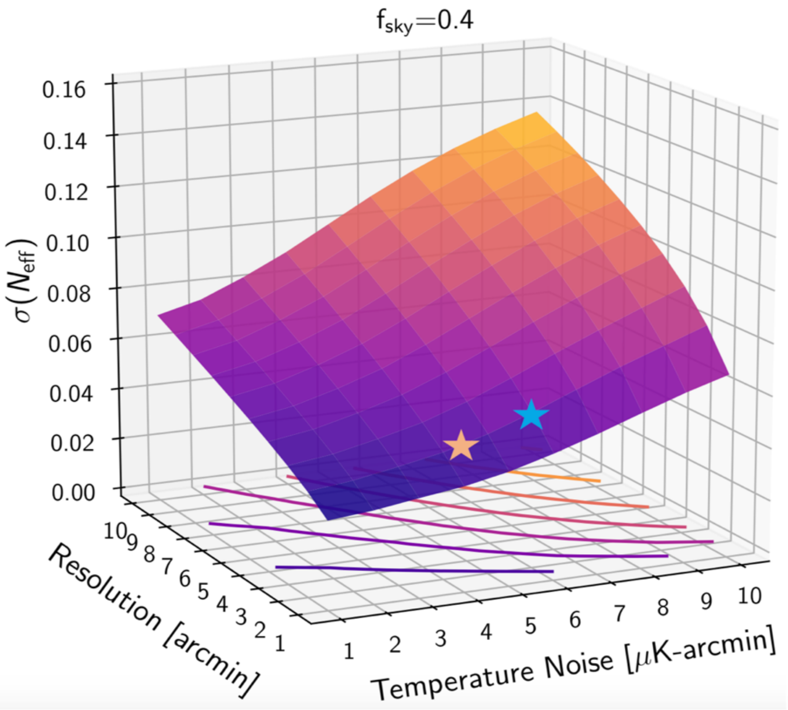
We can use $\Delta N_{\rm eff} = N_{\rm eff} - 3.044$ to probe a wide range of models of new physics…

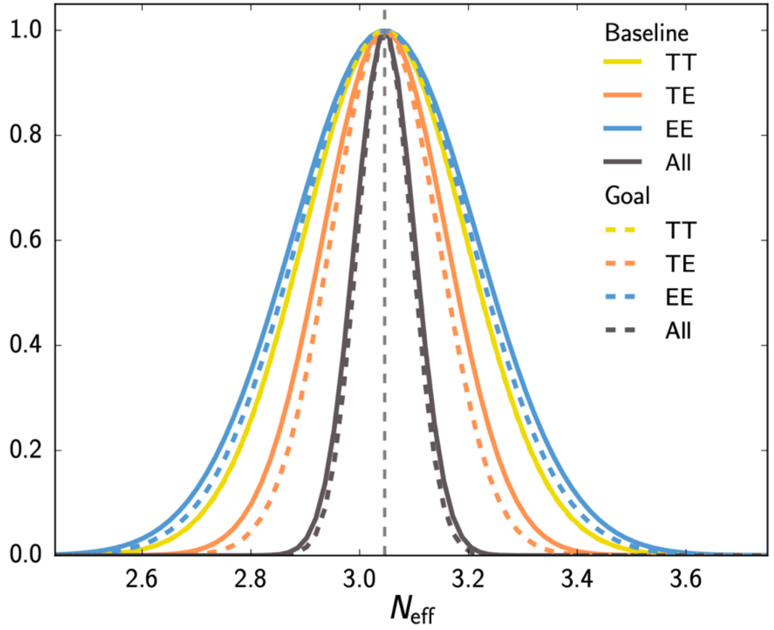
….however, if $\Delta N_{\rm eff} \neq 0$ is measured, how should we interpret it?

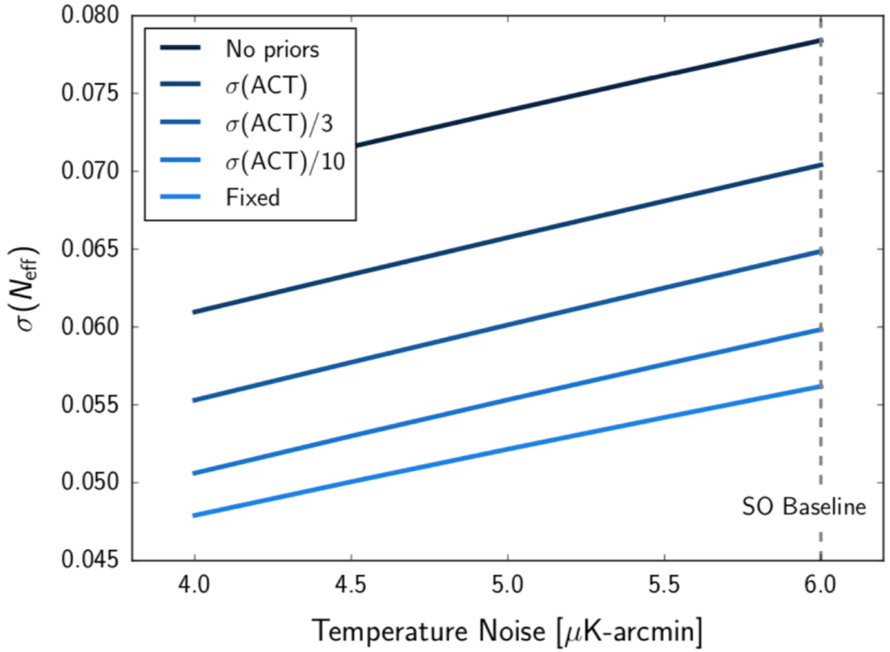
- Look for other cosmological signatures (concurring signal in the sum of the masses, effects on cosmological perturbations….)
- Search for confirmation in the lab

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

N_{EFF} FROM SO





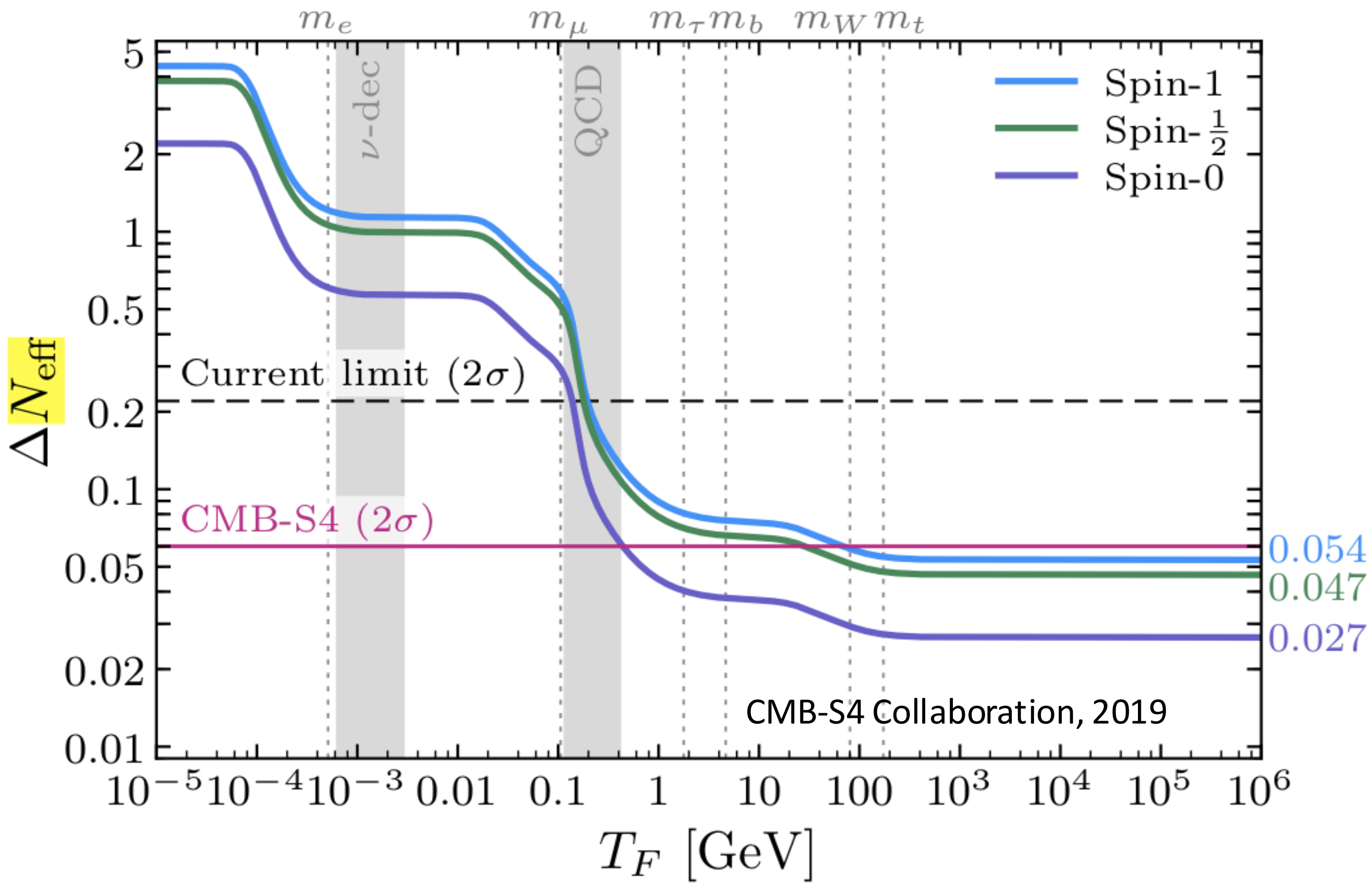


SO collaboration, 2018

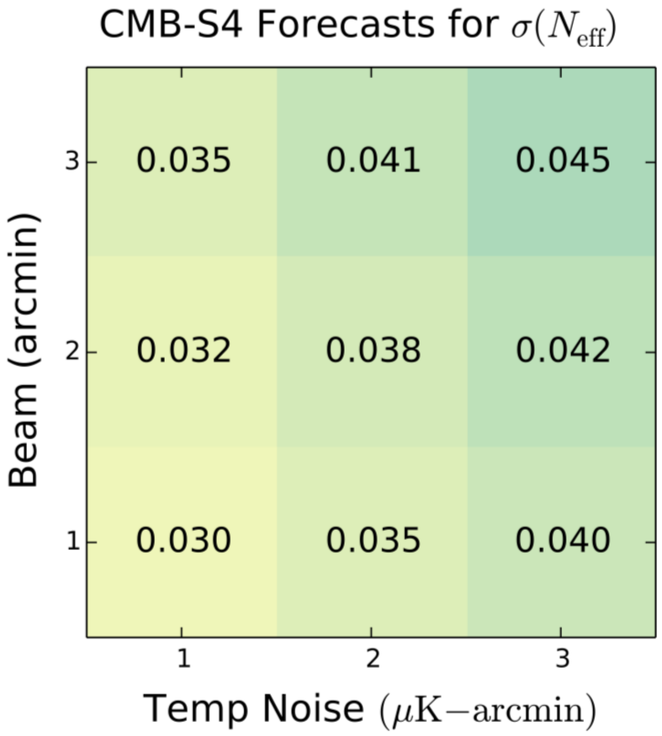
$$\boxed{\sigma(N_{\rm eff}) = 0.07\ [0.05]}$$

N_{EFF} FROM CMB-S4

Contribution of extra species in thermal equlibrium



CMB-S4 Collaboration, 2019



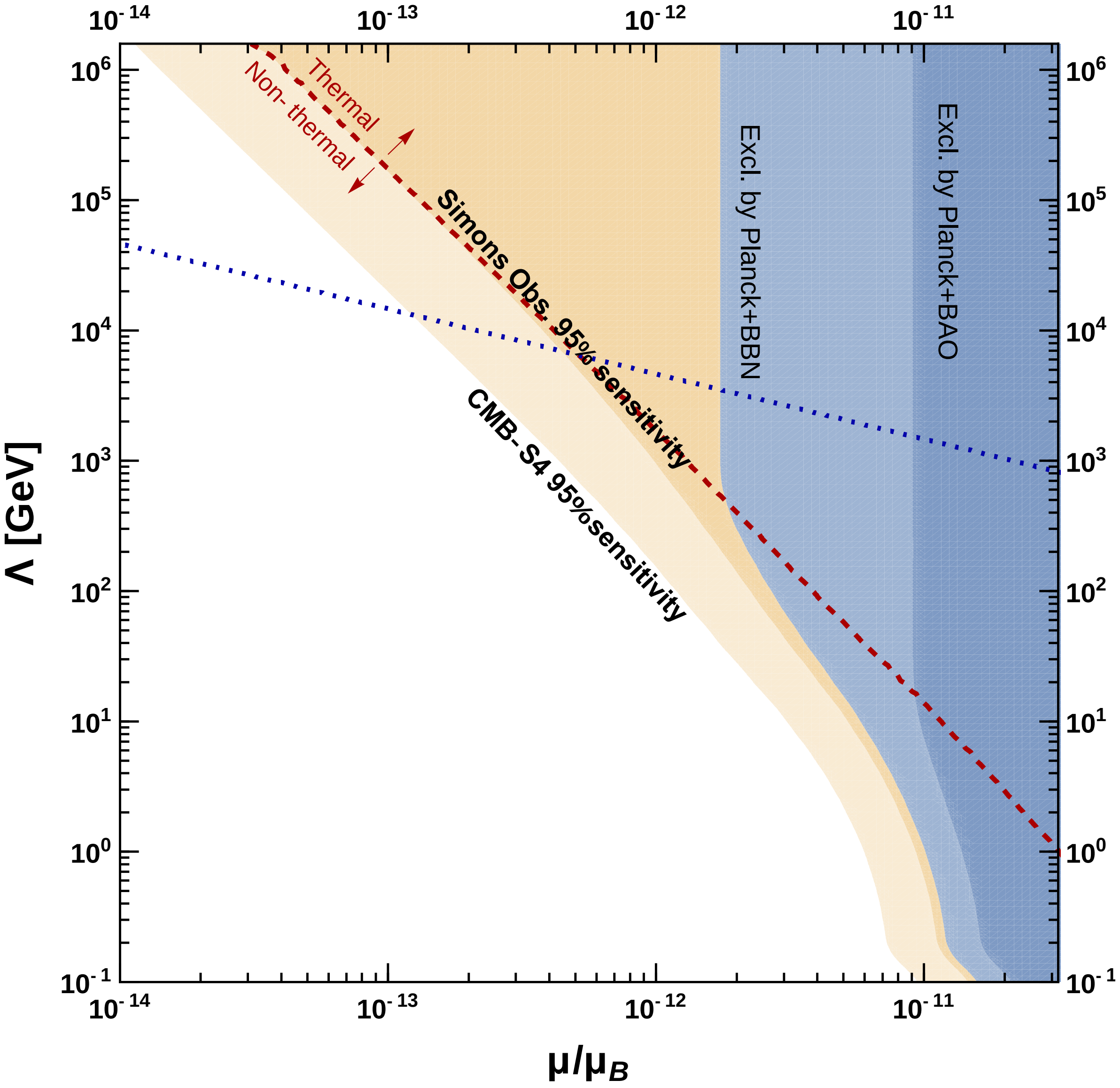
Beam (arcmin) \ Temp Noise (μK$-$arcmin)	1	2	3
3	0.035	0.041	0.045
2	0.032	0.038	0.042
1	0.030	0.035	0.040

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)

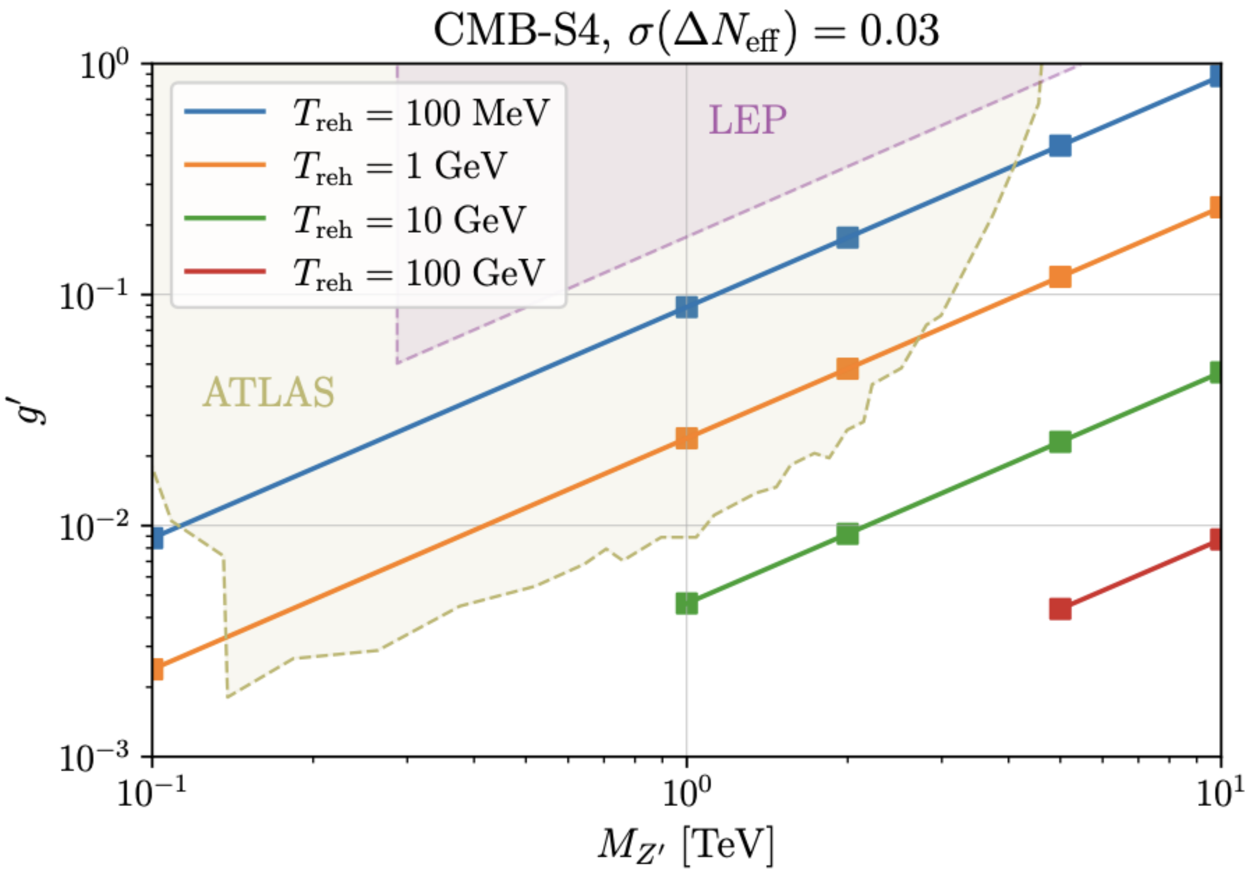


LIGHT RELICS FROM FREEZE-IN

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)



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

SUMMARY

- Cosmology provides tight constraints on the sum of neutrino masses in the framework of the LCDM model
- … in fact, maybe too tight! Hint for new physics or something else?
- A wealth of new data will be available in the next years from next-generation CMB and LSS experiments
- Expect to measure minium neutrino mass in NO (assuming the LCDM model)
- Measurements of N_{eff} will provide information on the light relics sector…
- … allowing to probe the freeze-in production regime (i.e. very weak couplings)

THANKS!

BACKUP SLIDES

FORECASTS FOR FUTURE CMB+LSS

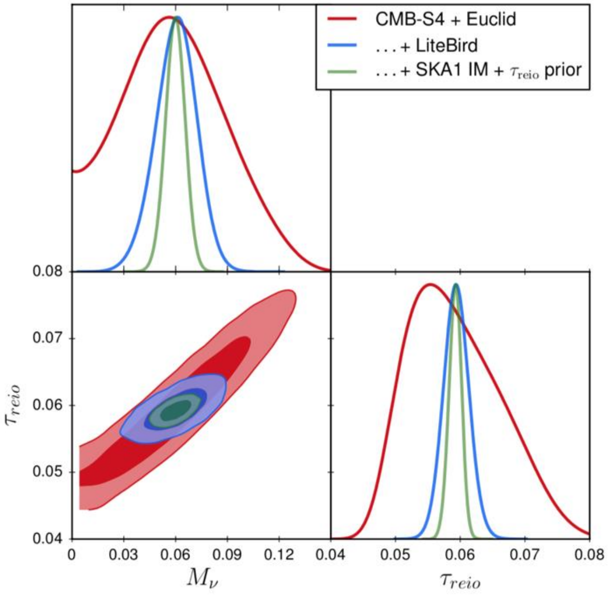
$\sigma(\Sigma m_\nu)$ = 0.04 eV from SO (primary+lensing)
+ DESI BAO
(SO Collaboration 2018)

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

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

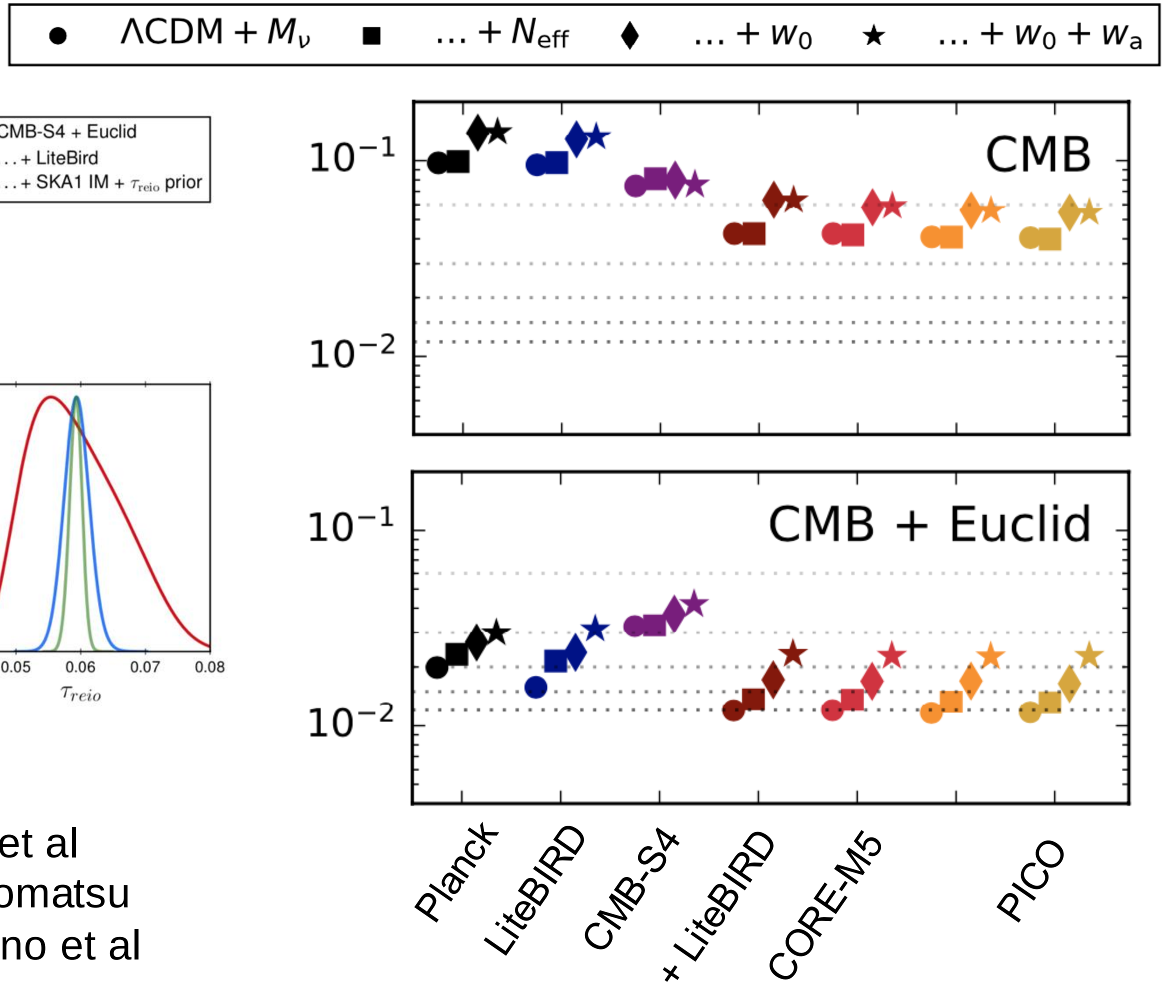
CMB+LSS will provide a statistically significant detection of neutrino masses in ΛCDM (remember $\Sigma m_\nu > 0.06$ eV).

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



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

Brinckmann, Hooper,+, JCAP 2019



SIMONS OBSERVATORY - MNU

- CMB lensing from SO combined with DESI BAO

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

- Sunyaev-Zeldovich cluster counts from SO calibrated with LSST weak lensing

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

- thermal SZ distortion maps from SO combined with DESI BAO

$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

- legacy SO dataset combined with cosmic-variance-limited measurement of reionization optical depth from LiteBIRD

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

SO Collaboration, 2018

THE EUCLID MISSION

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

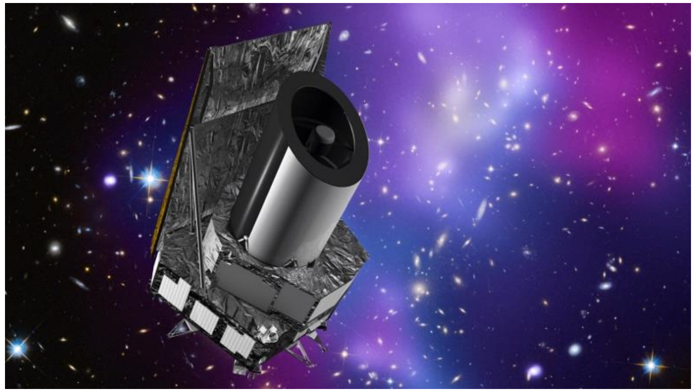
- the origin of the **accelerated expansion** of the Universe
- **Dark energy**, **dark matter** and the behaviour of **gravity at large scales**
- + **neutrino masses, the initial conditions of cosmological evolution, …**

Euclid will measure **weak lensing** and **galaxy clustering** observing 15.000 deg^2 (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg^2)

This will allow to reconstruct the **expansion history** and the **growth of cosmological structuree**

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

(Sprenger et al. 2019)



NEUTRINO MAGNETIC MOMENT

Measurements of Neff can be used to constrain the neutrino magnetic moment

In case of no detection:

$\mu < 1.3 \times 10^{-12}\ \mu_b$ (SO)

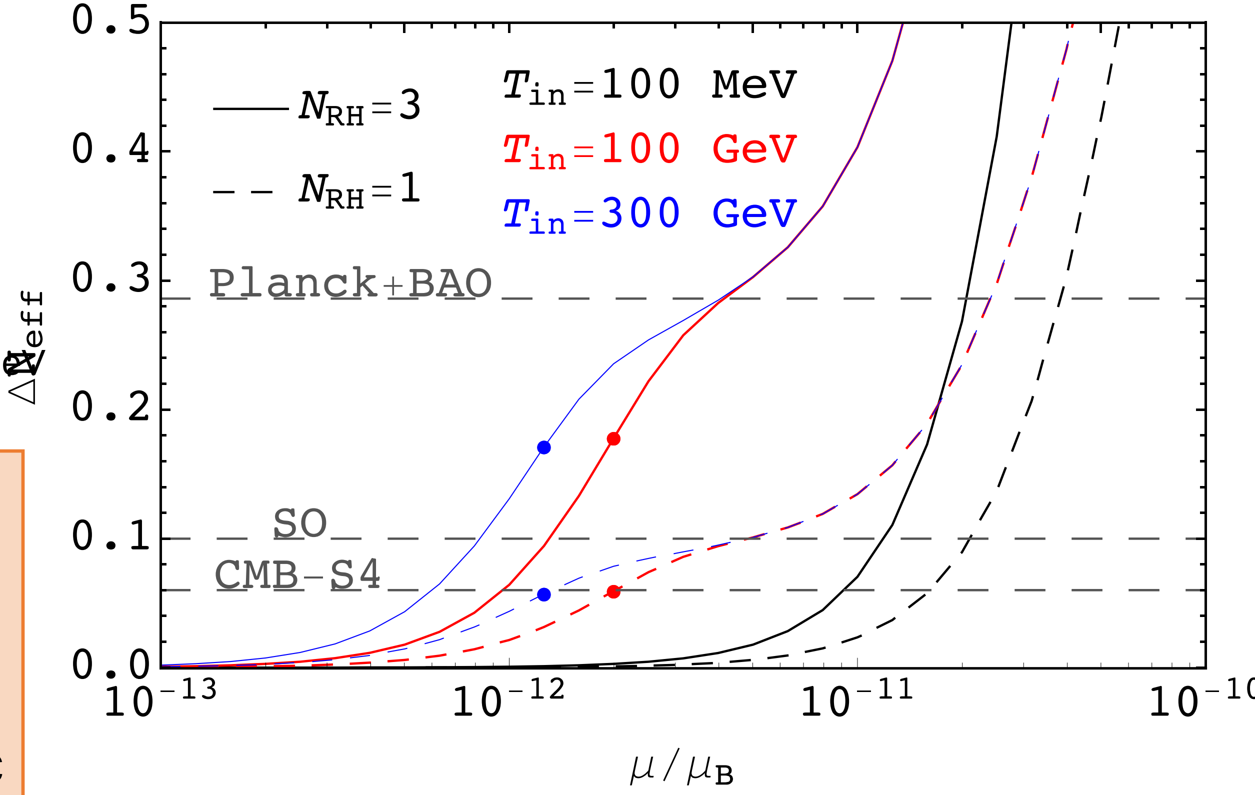
$\mu < 9.6 \times 10^{-11}\ \mu_b$ (S4)

(T_{in} = 100 GeV)

Carenza+ (incl ML, arXiv:2211.0432)

- Probes the freeze-in regime!
- Final abundance will depend on T_{in}
- Constraints scale like $1/\mathrm{sqrt}(T_{in})$
- For $T_{in}=(V_{inf})^{1/4} = 10^{16}$ GeV this might even probe the SM prediction for the magnetic moment of Dirac neutrinos
- Nice interplay with r measurements (es. LiteBIRD) since these constrain the energy scale of inflation

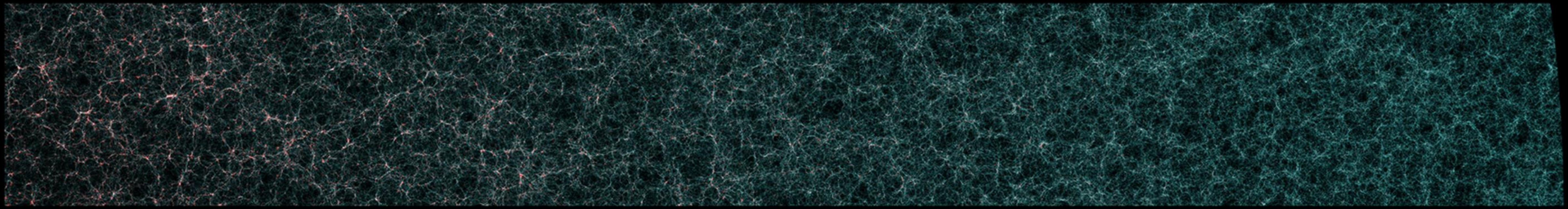
a 15 – 50 meV



(95% CL bounds)

EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT

PROBES OF STRUCTURE FORMATION



Different means of reconstructing a 3D map of the matter distribution:

- Galaxy clustering
- Cosmic shear (aka galaxy weak lensing)
- Galaxy clusters
- Lyman-alpha forest
- 21cm emission

PROBES OF STRUCTURE FORMATION

Galaxy clustering as measured by the Sloan Digital Sky Survey

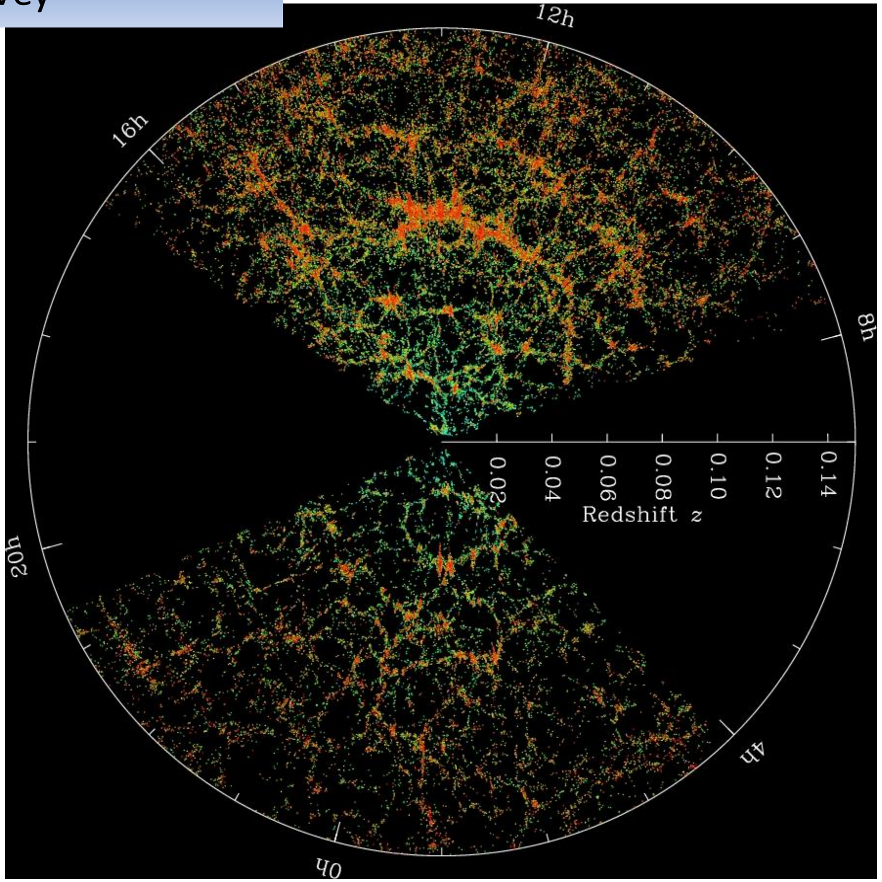
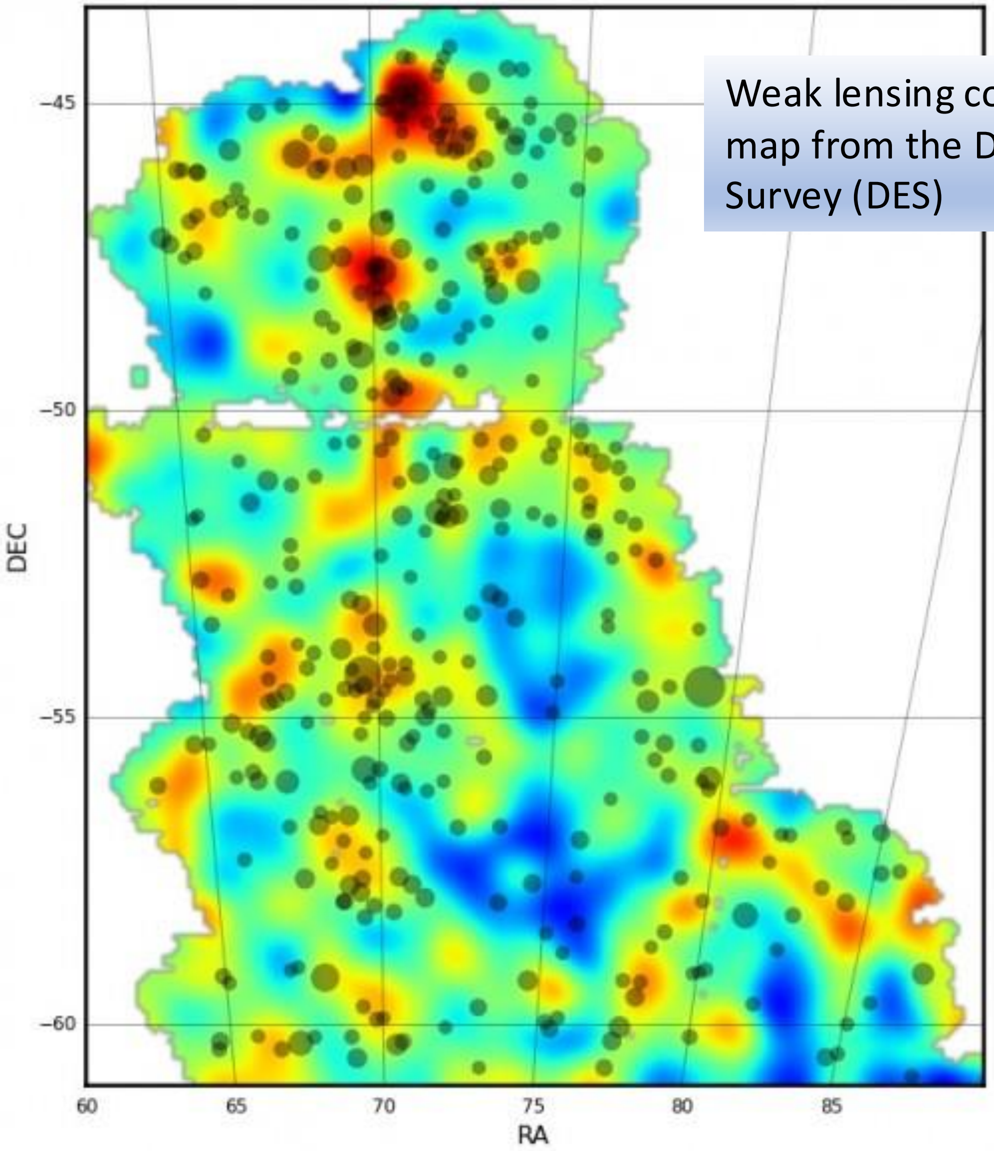


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

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

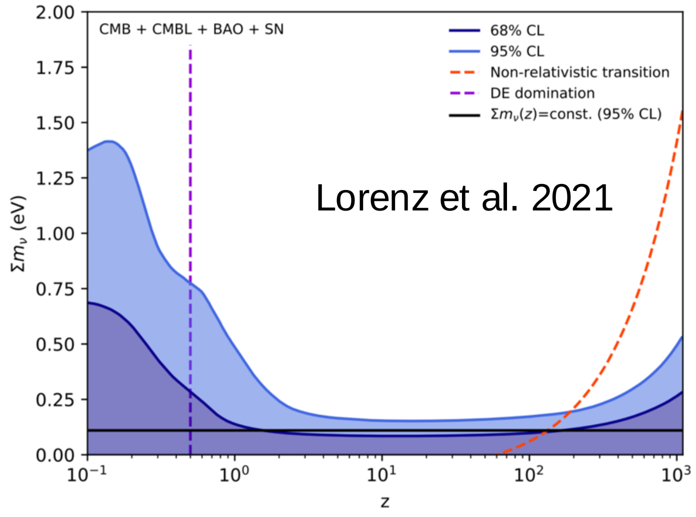


ν MASSES IN ΛCDM EXTENSIONS

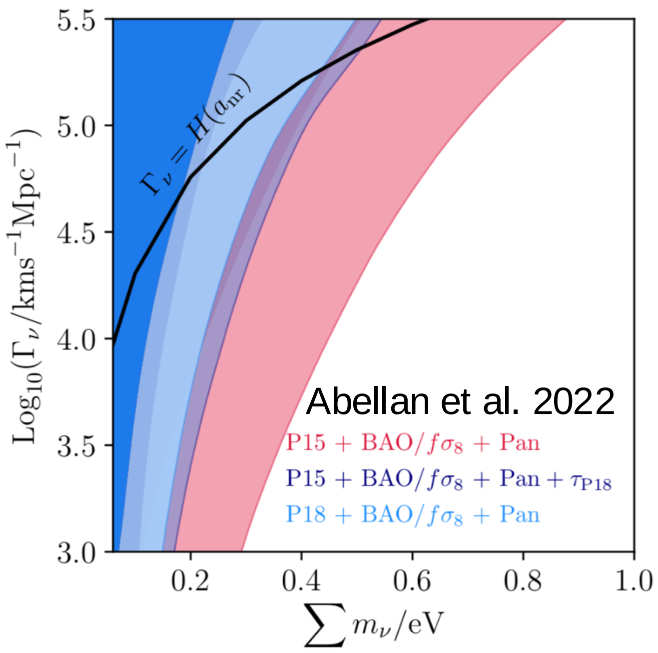
Constraints can be further loosened in alternative models, e.g.

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

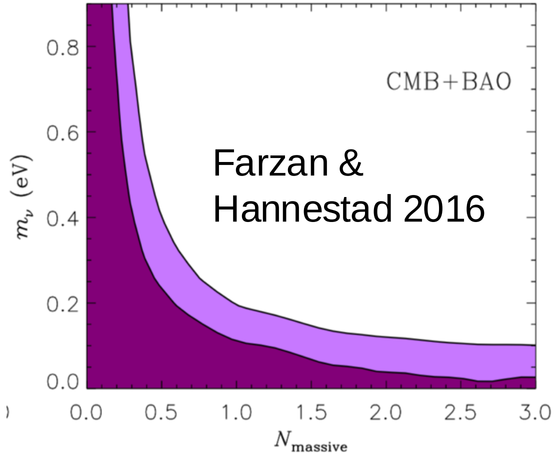
In some cases, this would reopen the window for a detection in KATRIN (see e.g. Alvey et al, 2021)



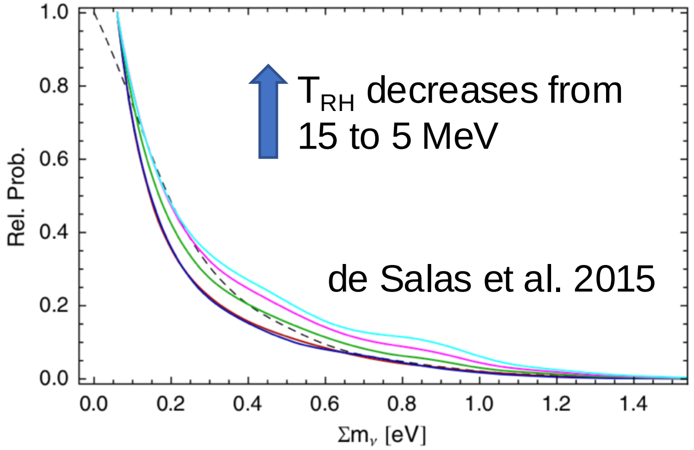
Lorenz et al. 2021



Abellan et al. 2022

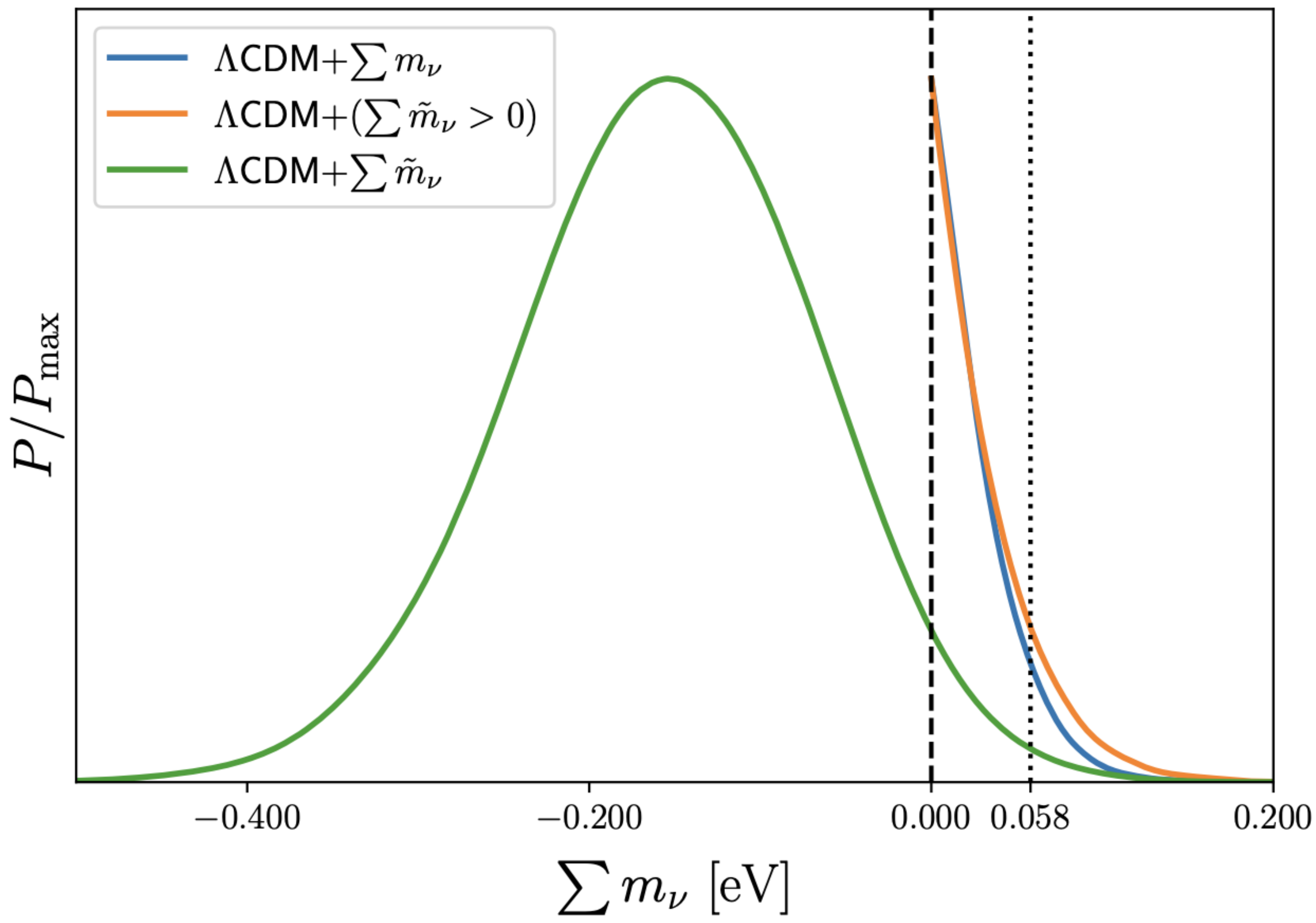


Farzan & Hannestad 2016



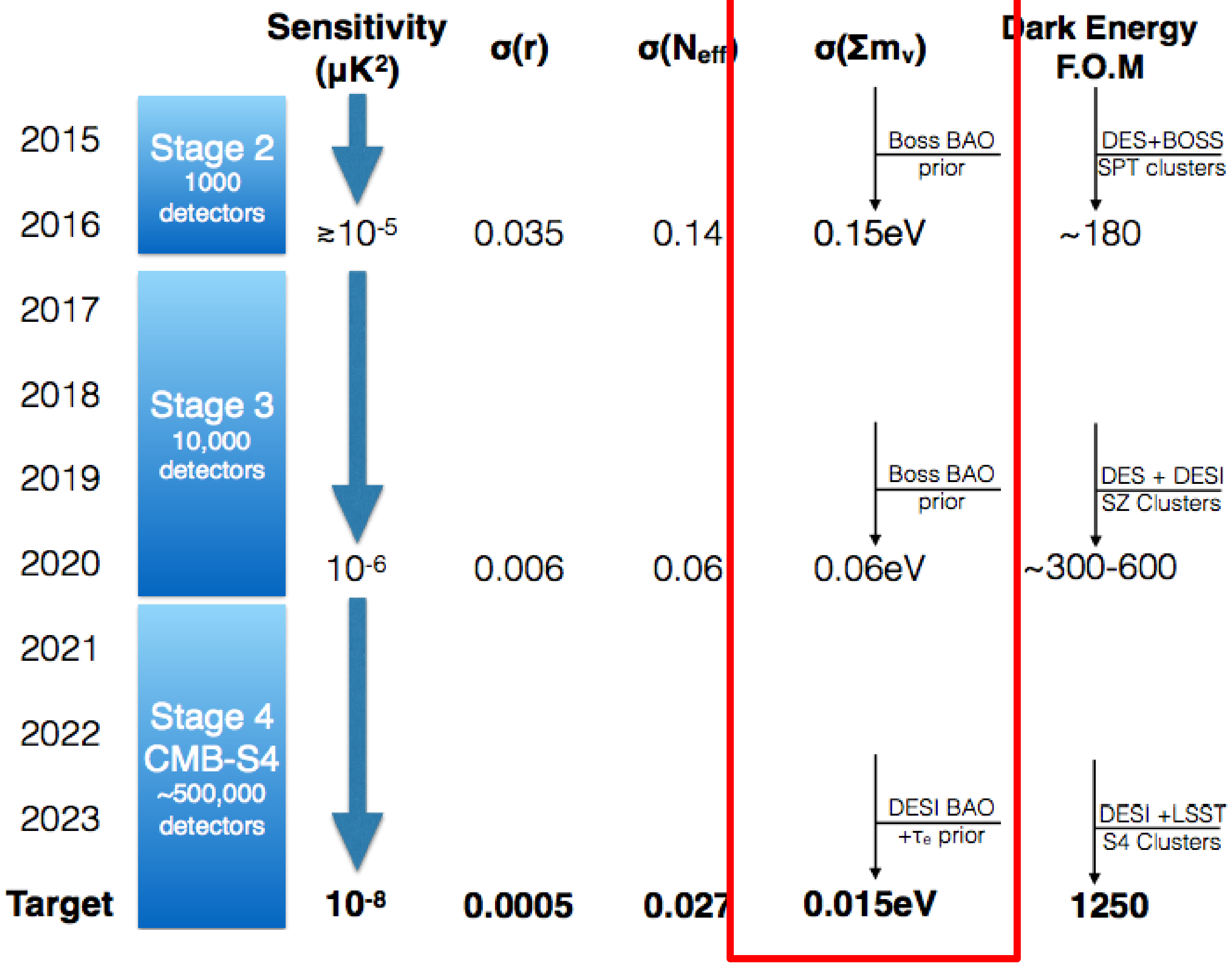
T_{RH} decreases from 15 to 5 MeV

de Salas et al. 2015



Craig et al.
arXiv: 2405.00836

NEUTRINO PARAMETERS FROM CMB-S4

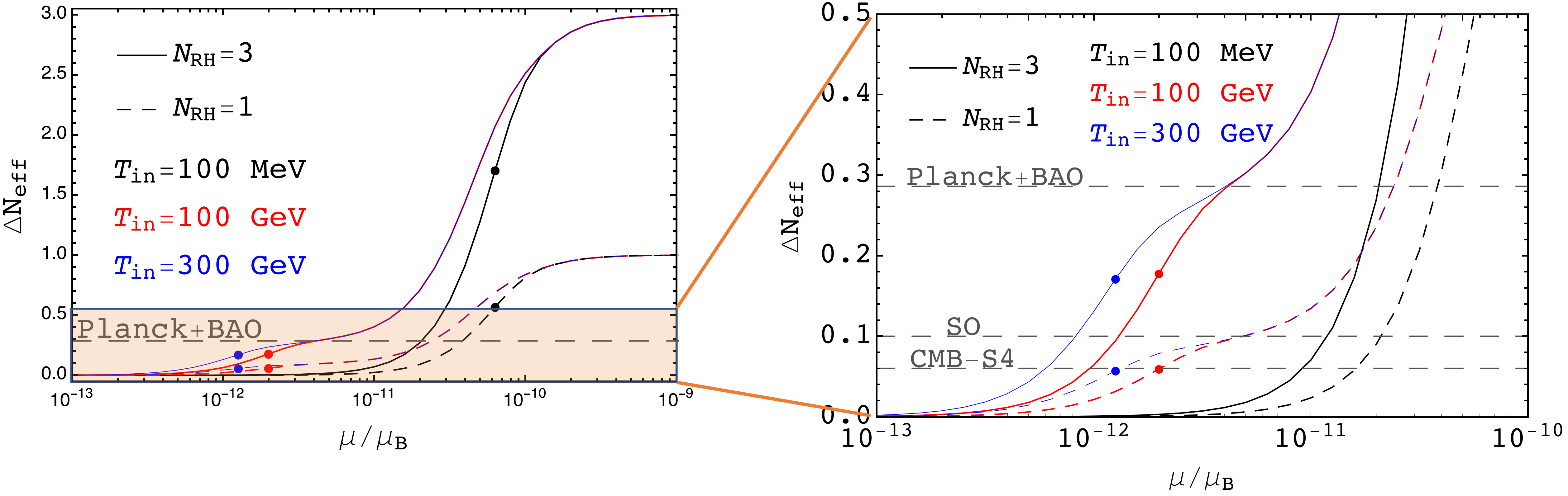


		Sensitivity (μK²)	σ(r)	σ(N_{eff})	σ(Σm_ν)	Dark Energy F.O.M
2015	**Stage 2** 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	**Stage 3** 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	**Stage 4** CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO +τ_e prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

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

NEUTRINO MAGNETIC MOMENT

Measurements of Neff can be used to constrain the neutrino magnetic moment



(95% CL bounds)

Carenza+ (incl ML, arXiv:2211.0432)