

A photograph of the Vienna cityscape at sunset. In the foreground, the colorful, tiled roof of St. Stephen's Cathedral is visible. The background shows the dense urban architecture of Vienna, with numerous buildings, rooftops, and distant hills under a warm, orange sky.

OBSERVATIONAL COSMOLOGY - OVERVIEW

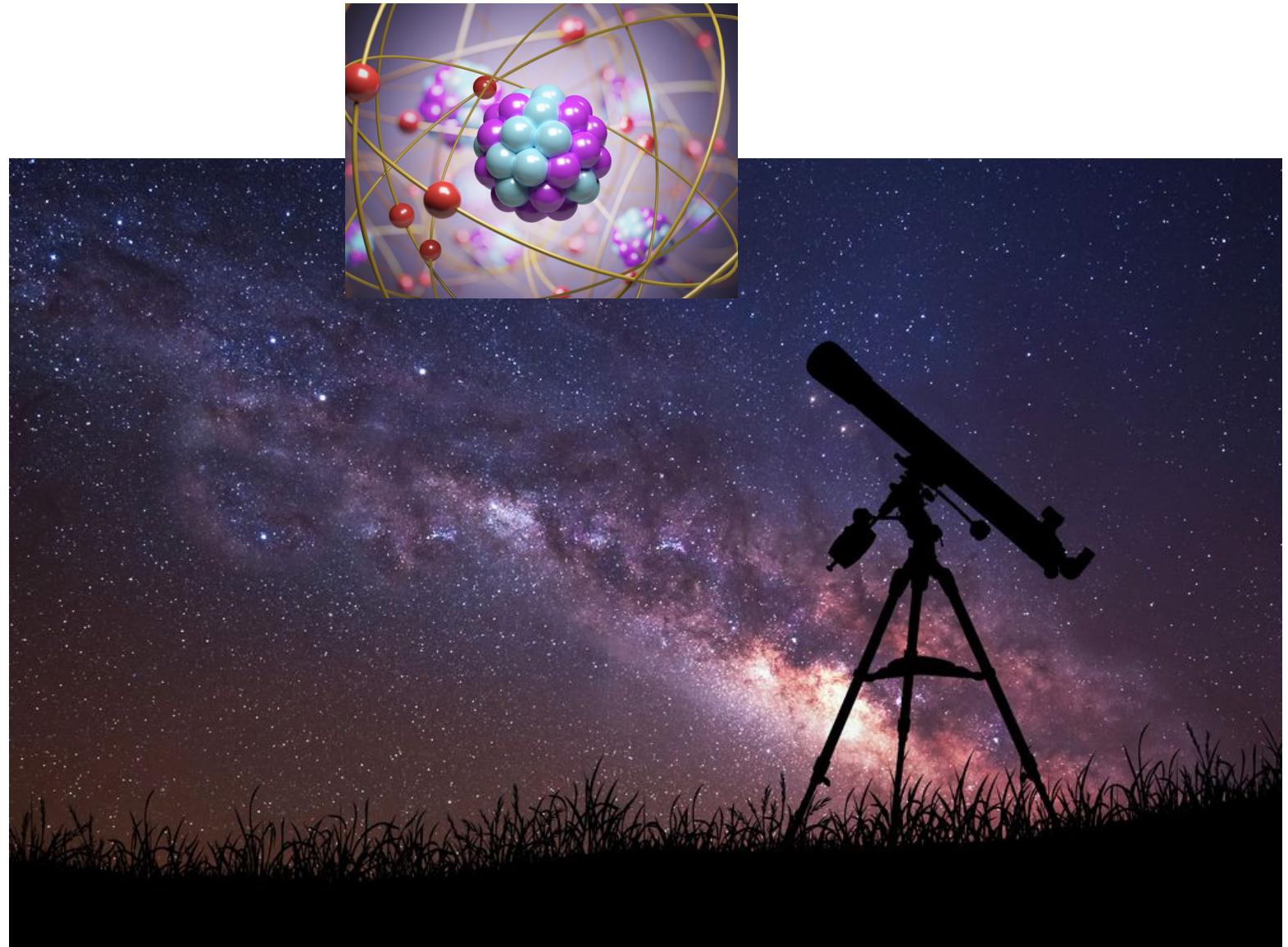
MASSIMILIANO LATTANZI

INFN, sezione di Ferrara

TAUP 2023

Vienna, Aug. 28th, 2023

Long history of fruitful
interplay between
cosmological/astrophysical
observations and particle
physics!



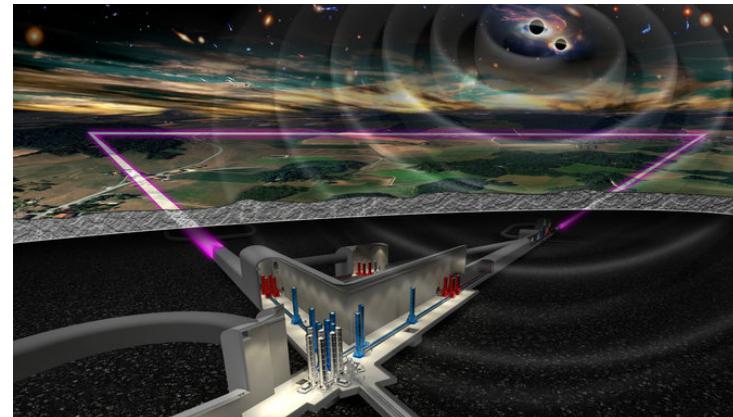
WHERE DO WE STAND?

- Most cosmological observations can be coherently interpreted in terms of the standard (Λ CDM) cosmological model
- Parameters of the model are measured at the ~1% level or better (with one exception)
- Still, tensions have surfaced between early- and late-time observations
- Origin of late accelerated expansion is still unknown (dark energy? modified gravity?)...
- ... as well as the precise nature of dark matter.
- Slow-roll inflation is still the preferred scenario for the early Universe, but the details of the model are still unknown
- No evidence for BSM physics in the light relics sector

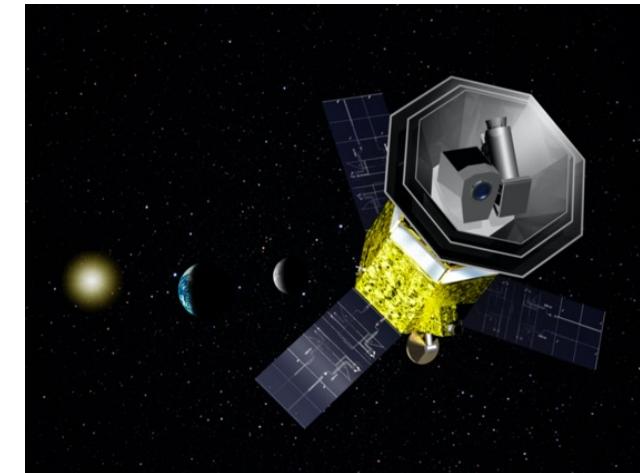
WINDOWS ON THE UNIVERSE



Large-scale
structures from
cosmic surveys



Observations of the cosmic
microwave background

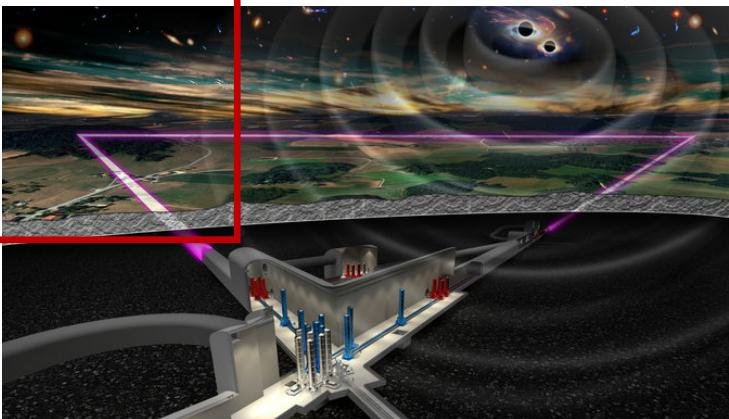


Cosmological gravitational
wave background

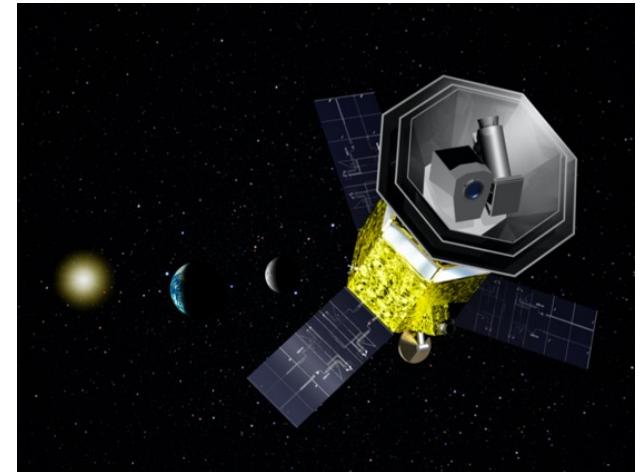
WINDOWS ON THE UNIVERSE



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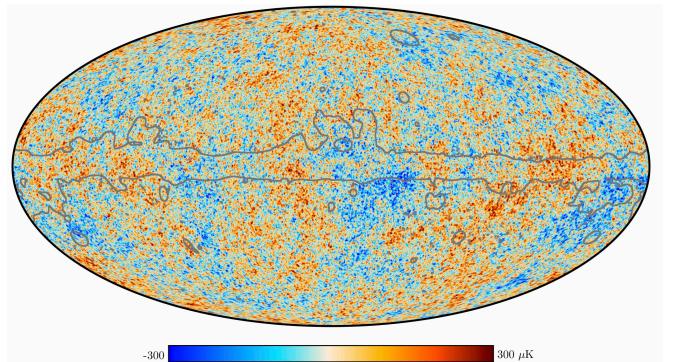
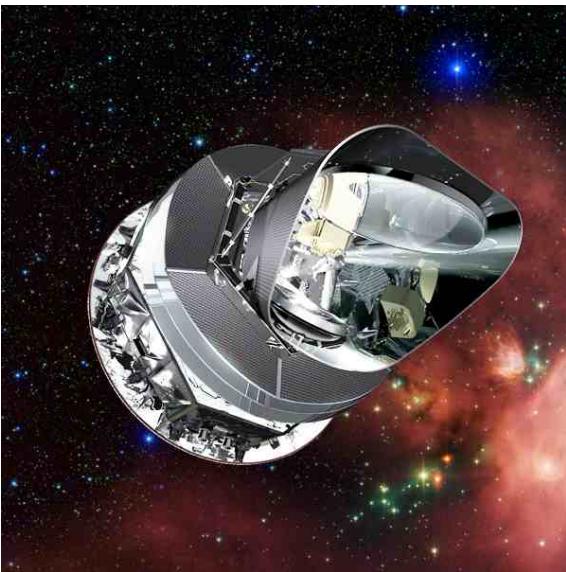


Observations of the cosmic
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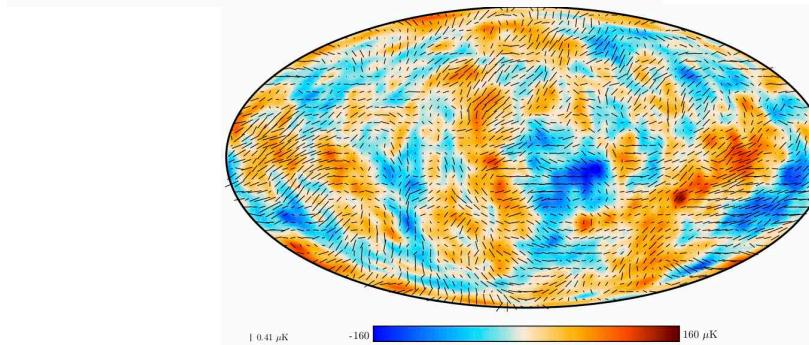


Cosmological gravitational
wave background

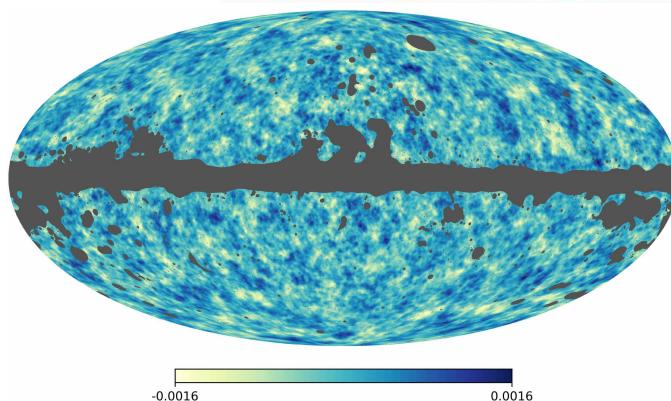
CMB OBSERVATIONS



Temperature anisotropies



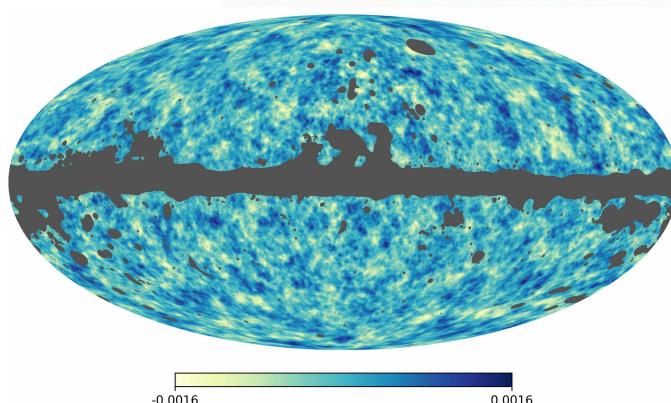
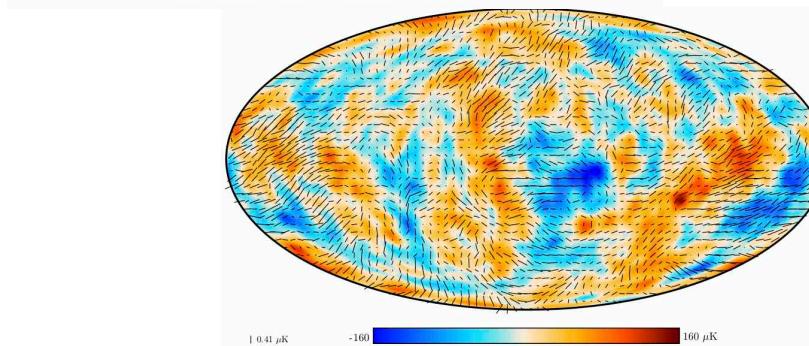
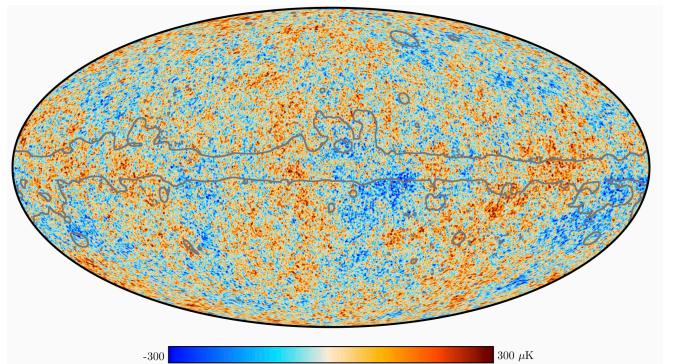
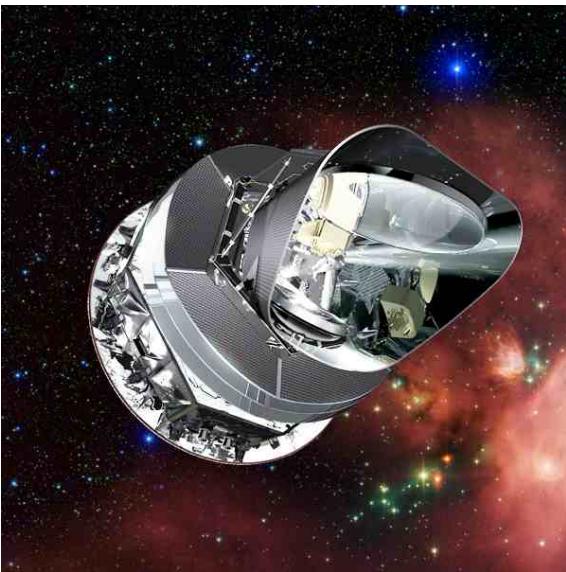
Polarization anisotropies (two modes: E and B)



Lensing anisotropies

Planck 2018

CMB OBSERVATIONS



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

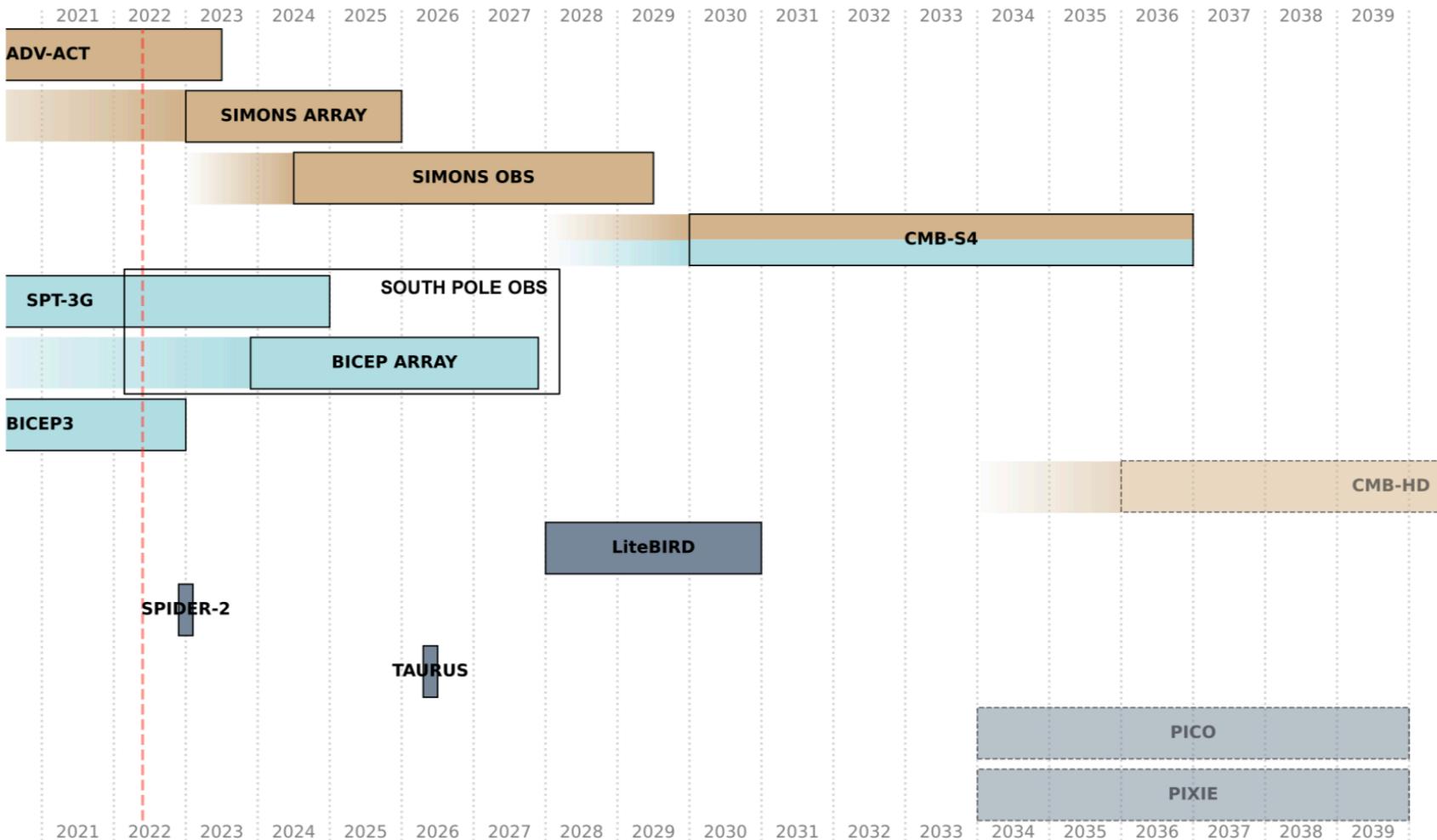
Lensing anisotropies

CMB window to structure formation and the late Universe

Also a target for next-gen experiments

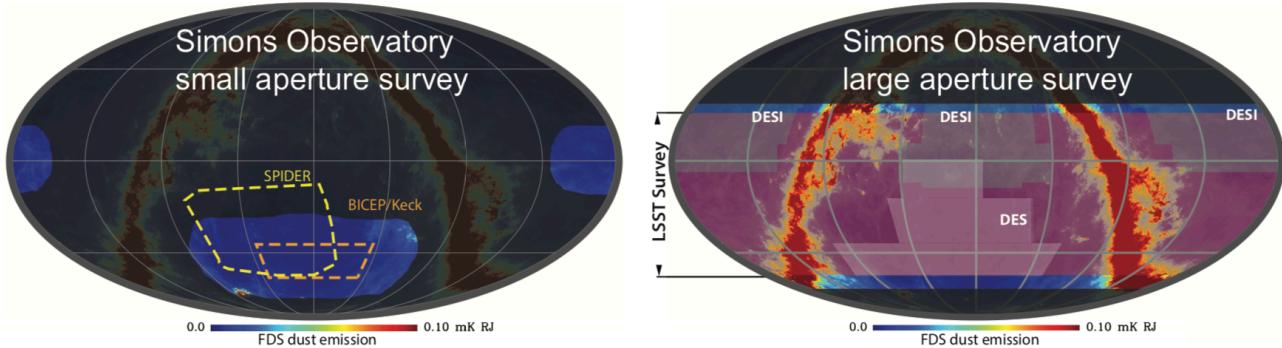
Relevant for e.g. neutrino masses

TIMELINE OF CMB EXPERIMENTS



Snowmass2021 Cosmic Frontier: CMB Measurements White Paper
arXiv: [2203.07638](https://arxiv.org/abs/2203.07638)

SIMONS OBSERVATORY



- Ground-based CMB experiment sited in Cerro Toco in the Atacama Desert in Chile
- 5-yr obs campaing starting in 2023
- 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

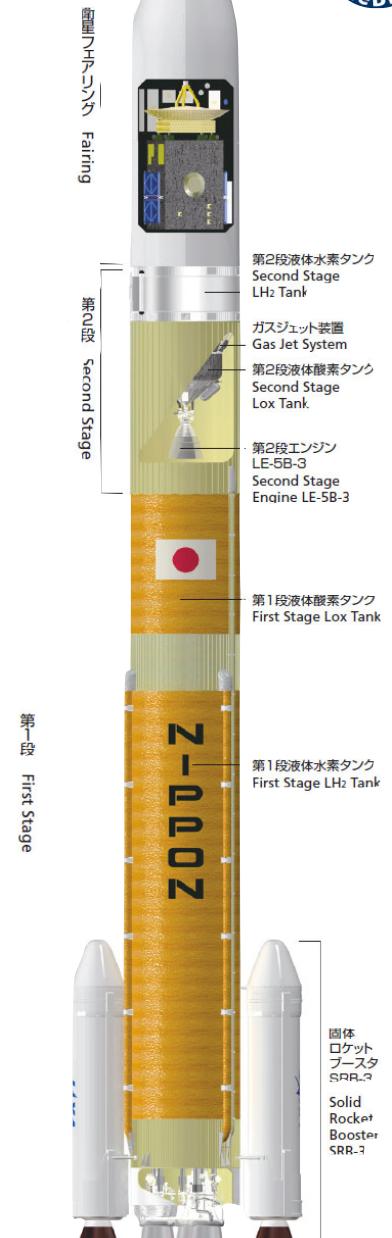
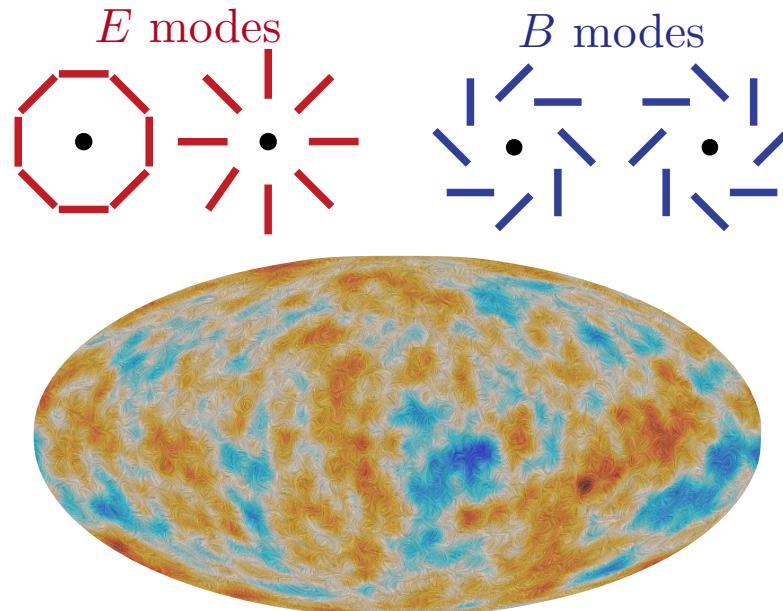
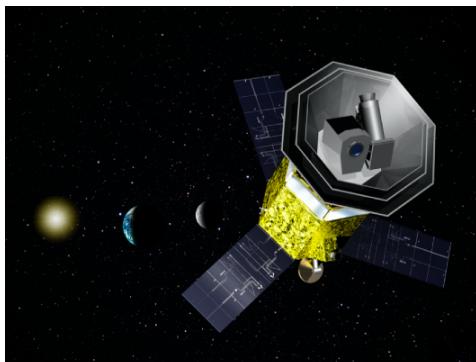
LiteBIRD

A JAXA-led post-Planck
space mission for CMB
polarization, with participation
from US and Europe

LiteBIRD Overview



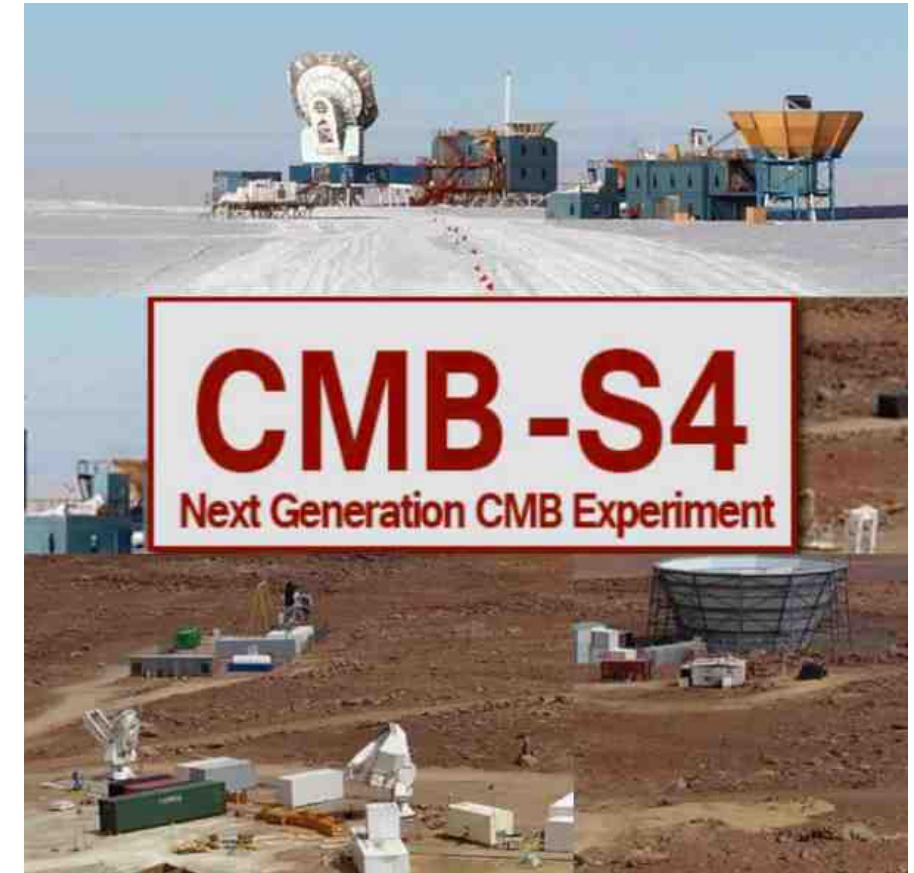
- Light satellite for B-modes from Inflation CMB Radiation Observation
- Selected (May 2019) as the next JAXA's L-class mission
- Expected launch ~2030 with JAXA H3 rocket
 - LiteBIRD is the only CMB space mission that can be realized in 2020s
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (40–402 GHz, 15 bands) at 70–18 arcmin
 - three telescopes: LFT, MFT, HFT.
- 4508 TES detectors cooled down to 100 mK read by SQUIDS
- Final combined sensitivity: $2.2 \mu\text{K arcmin}$, after component separation



H3-3 Slide courtesy: G. Signorelli

CMB STAGE-4

- Definitive ground-bases 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



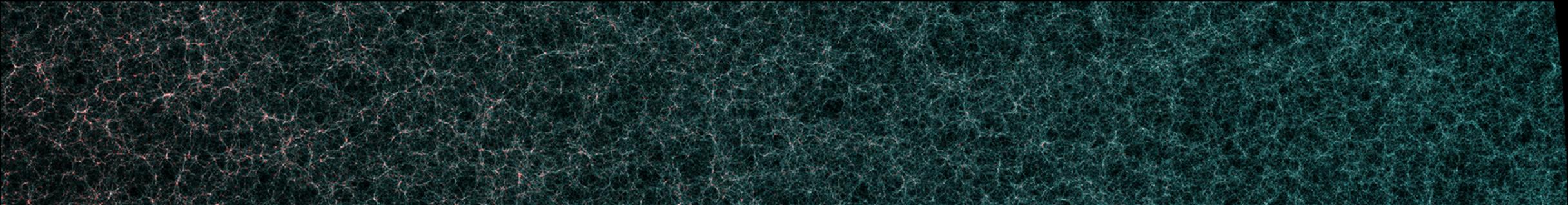
See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

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

Improved polarization measurements and lensing reconstruction will yield

- Inflationary science from B-modes (possibly a detection of tensor modes)
- Inflationary science from nongaussianities (see next talk)
- Better determination of the optical depth from large-scale E-modes (and possibly from the small scale kinetic Sunyaev-Zel'dovich effect)
- Constraints on late-time structure formation from lensing (useful for neutrino masses) (also useful information from SZ clusters)
- Constraints on light relics (neutrinos, both active and sterile, thermal axions, etc) from the small scales (damping tail)

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

Galaxy clustering as measured by the Sloan Digital Sky Survey

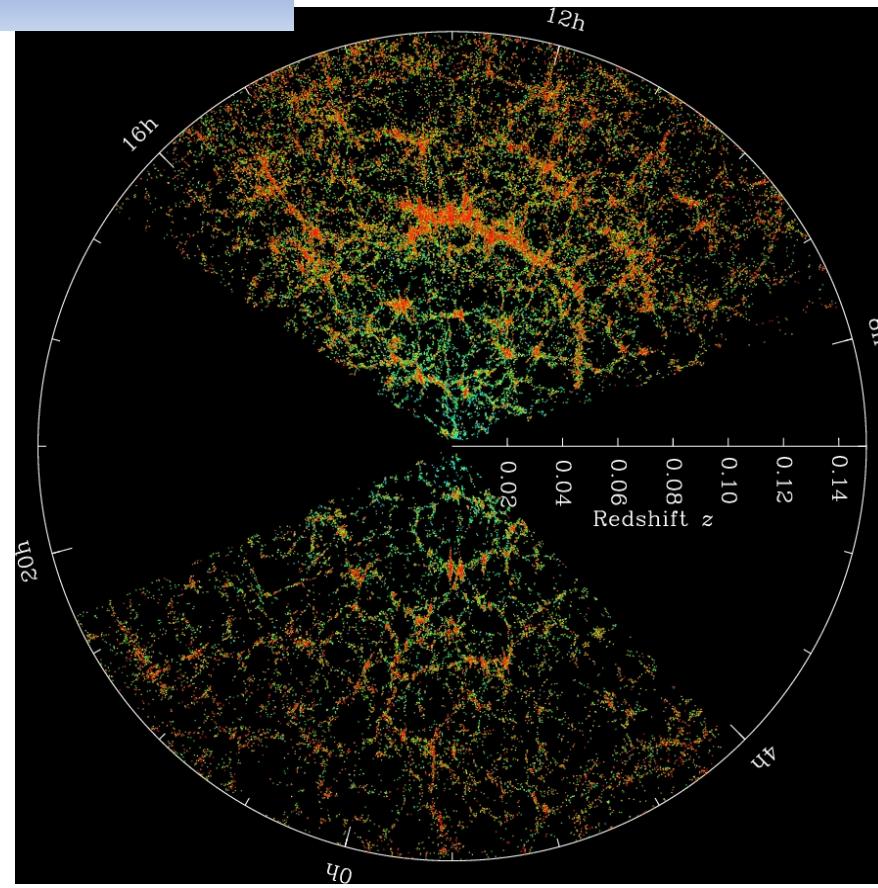
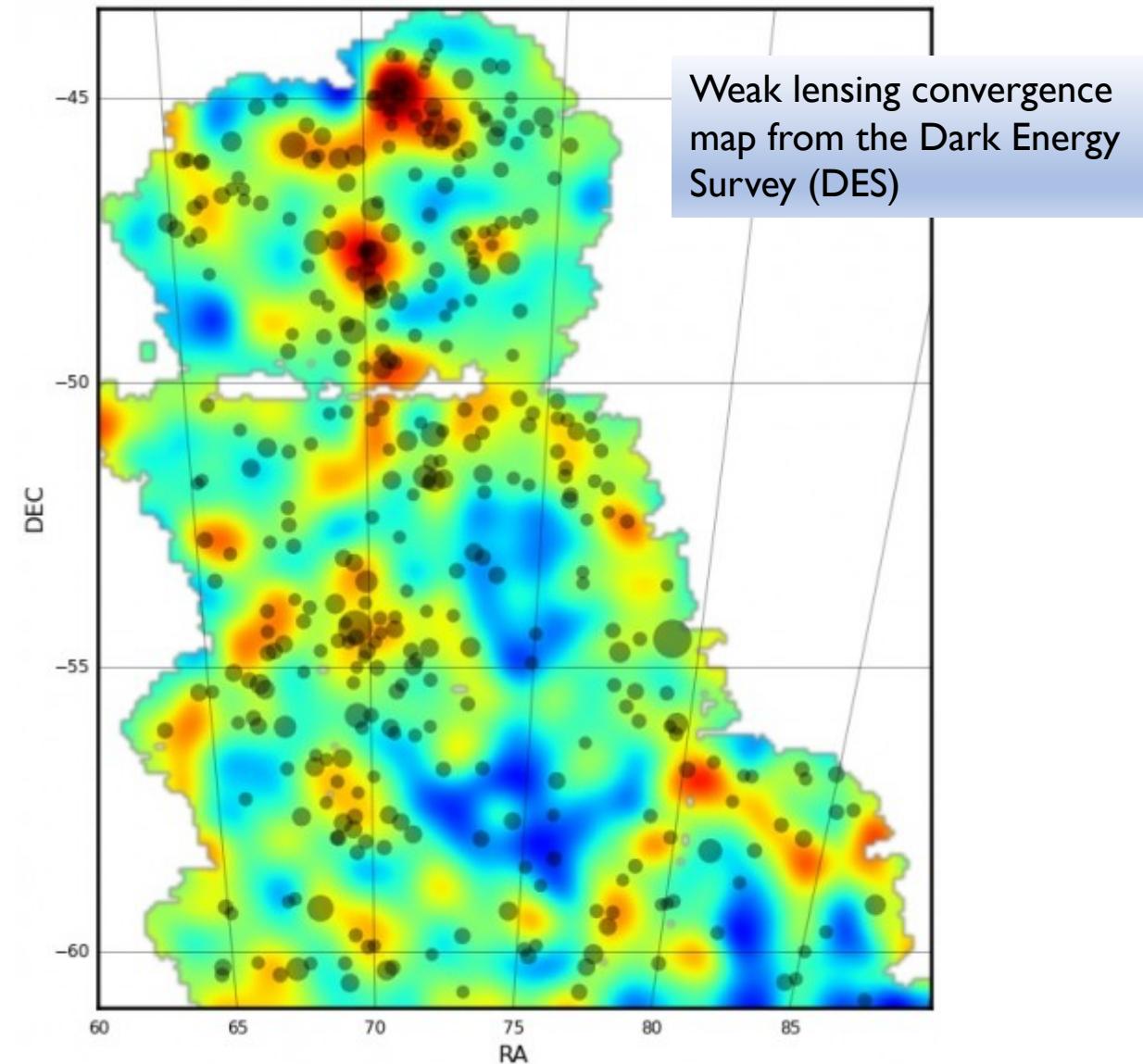
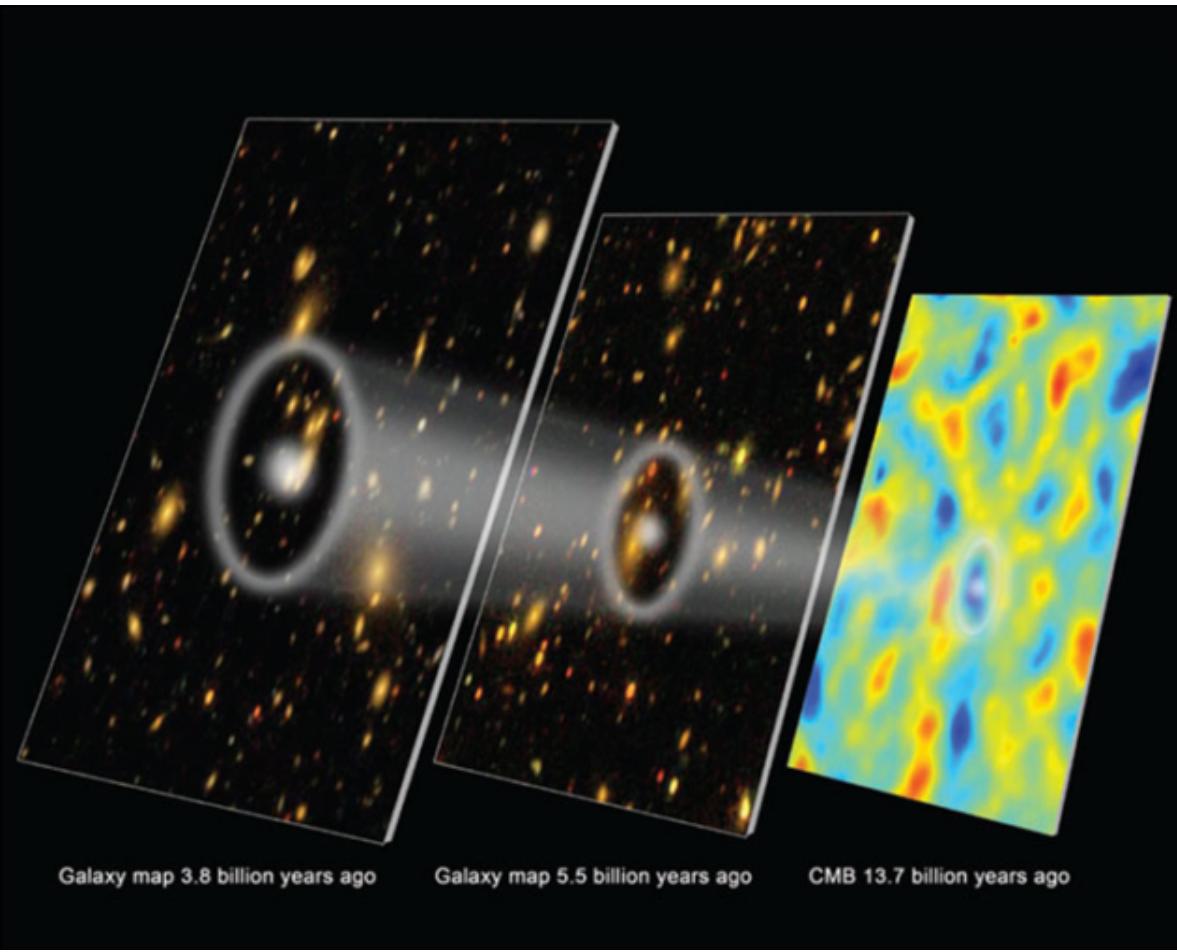


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

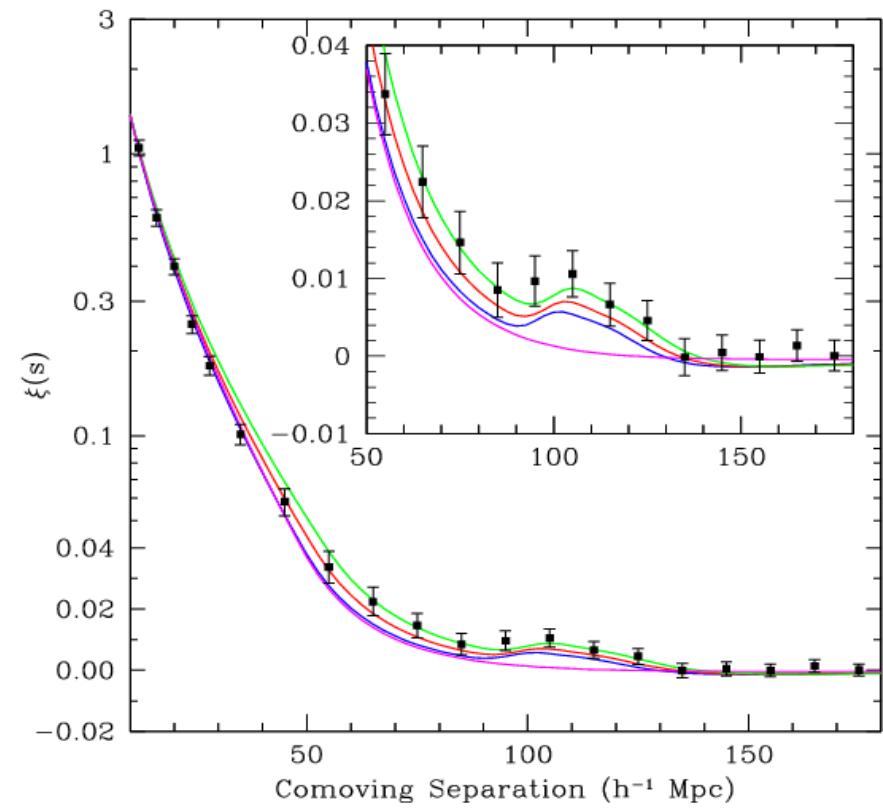
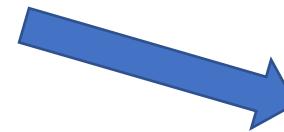


Weak lensing convergence map from the Dark Energy Survey (DES)

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,
currently in performance
verification phase



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

Nancy Roman Space
Telescope
Launch in mid 2020s



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 deg² (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg²)

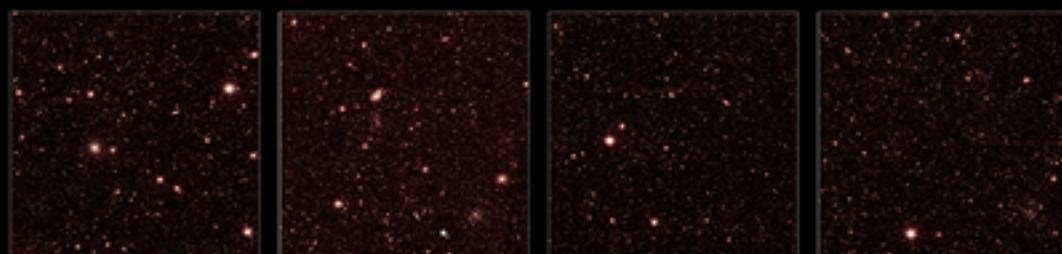
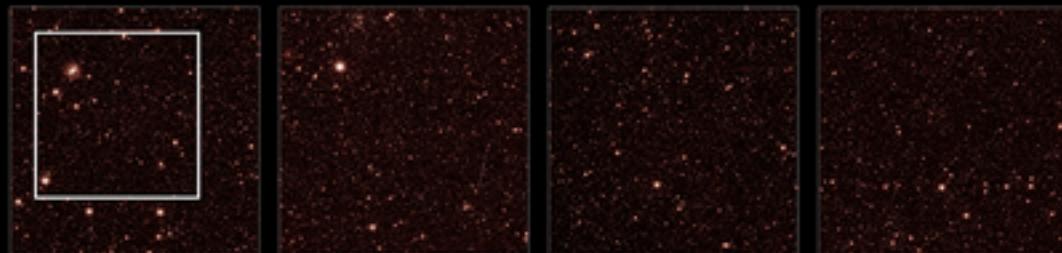
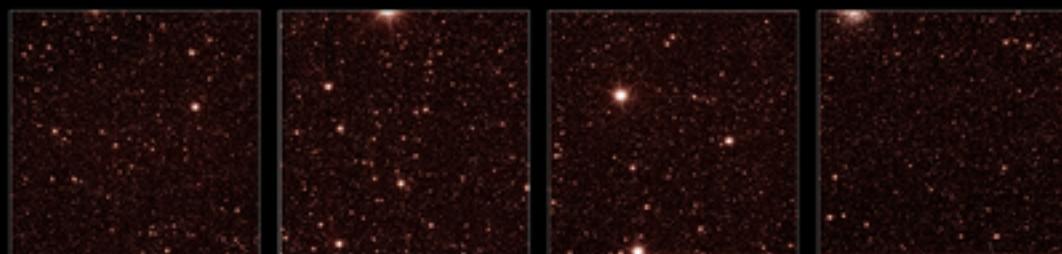
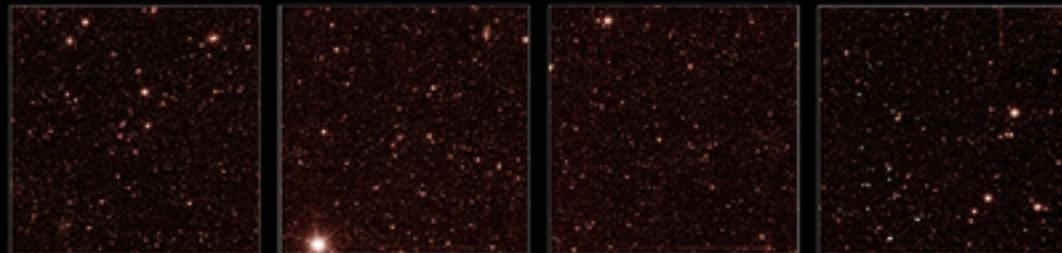
This will allow to reconstruct the **expansion history** and the **growth of cosmological structures**

Euclid lift-off on July 1st, 2023!

Currently in performance verification phase



EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT



By probing structure formation and the late-time expansion history, observations of large scale structure will allow to

- Investigate the origin of the accelerated expansion (dark energy/modified gravity?)
- Constrain dark energy and modified gravity models
- Probe inflation physics through the spectrum of primordial density perturbations
- Constrain the mass of neutrinos and other light relics
- Investigate the properties of dark matter (e.g. is it cold or warm? self-interacting?)

SCIENTIFIC POTENTIAL FOR NEUTRINO PHYSICS

In the last part of the talk, I will summarize the scientific potential of next-generation cosmological observations for the physics of neutrinos and light relics.

Sum of neutrino masses:

$$\sum m_\nu \equiv \sum_i m_i$$

Effective number of relativistic species N_{eff}

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

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.
- N_{eff} can be measured with 0.03 sensitivity
- This can probe the physics of neutrino decoupling (see P. Martinez Miravé's talk), the thermal history of the Universe (see S. Pastor's talk), neutrino interactions, the presence of additional light relics like sterile neutrinos, axions, as well as their decoupling temperature...

SIMONS OBSERVATORY - MNU

- CMB lensing from SO combined with DESI BAO

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

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

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

- thermal SZ distortion maps from SO combined with DESI BAO

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

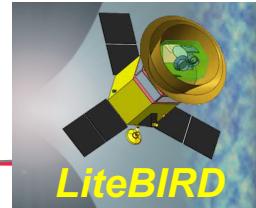
- legacy SO dataset combined with cosmic-variance-limited measurement of reionization optical depth from LiteBIRD

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

SO Collaboration, 2018

CMB-S4 - LiteBIRD

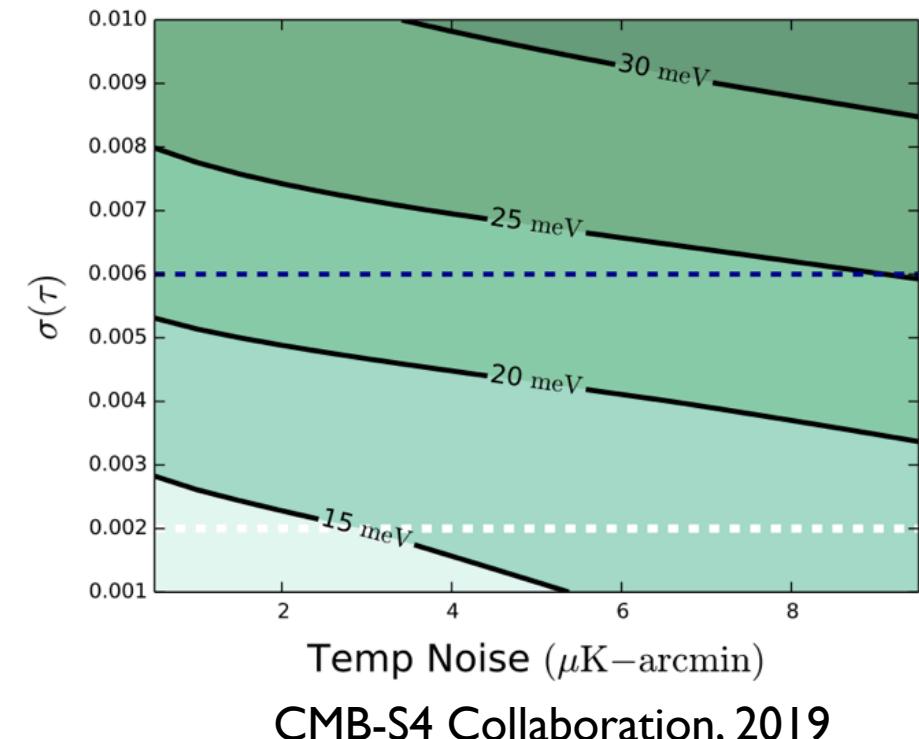
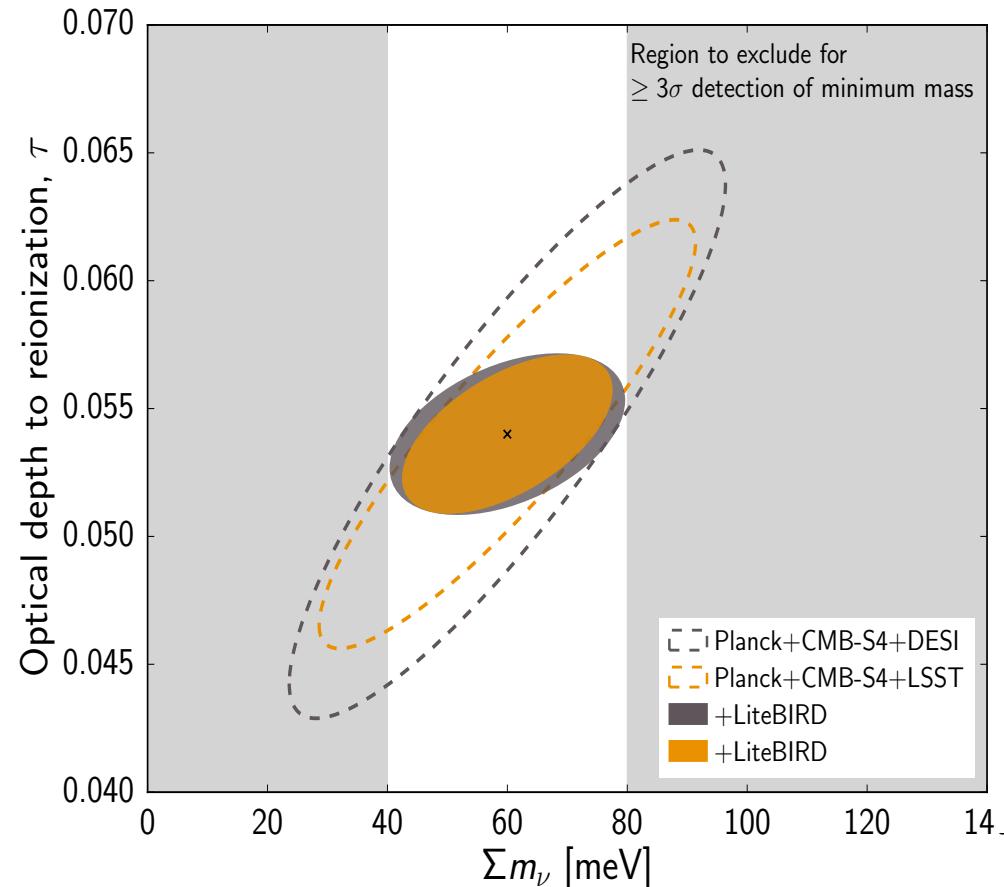
Σm_ν w/ improved τ



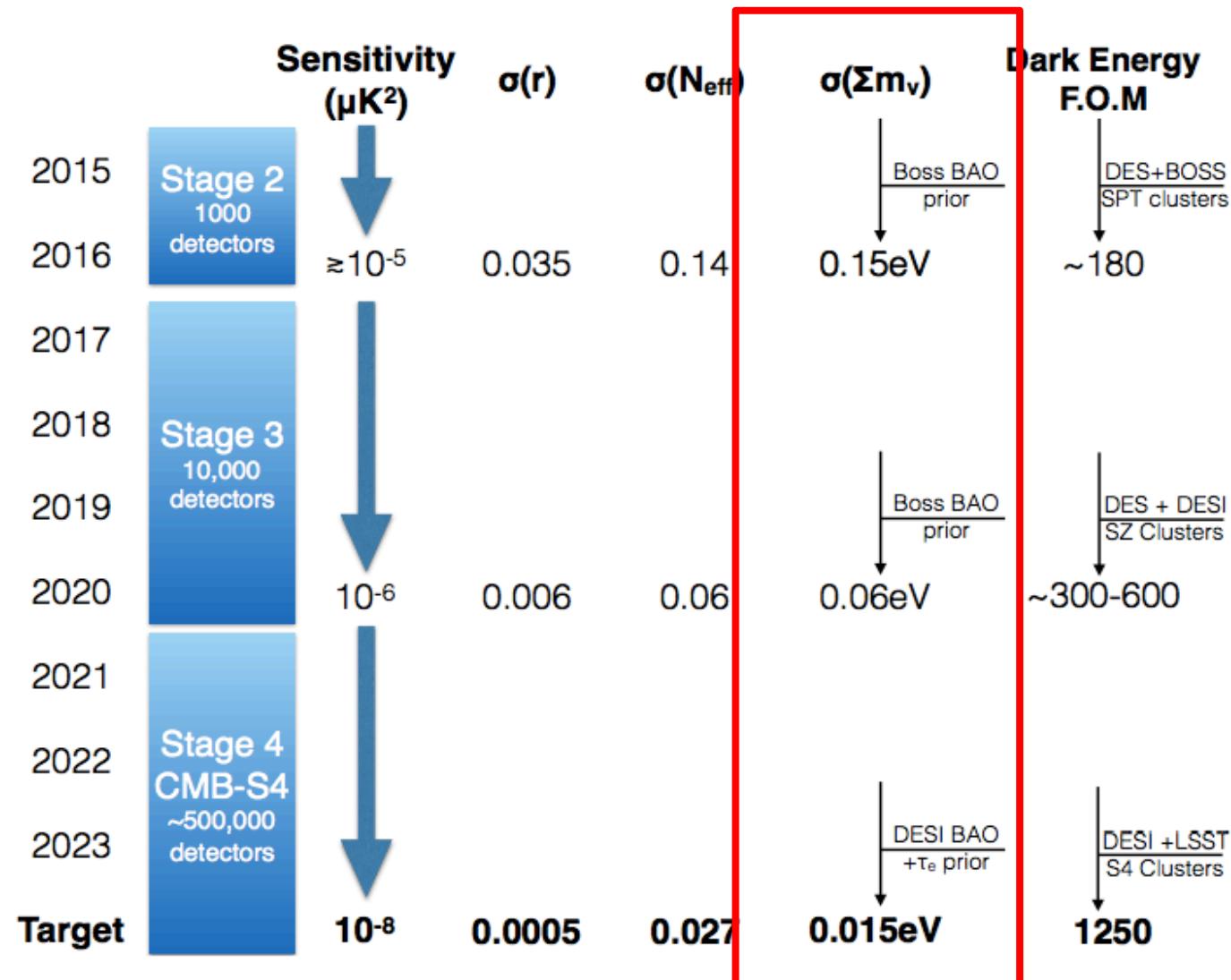
LiteBird Collaboration,
arXiv:2202.02773

- $\sigma(\Sigma m_\nu) = 15 \text{ meV}$
- $\geq 3\sigma$ detection of minimum mass for normal hierarchy
- $\geq 5\sigma$ detection of minimum mass for inverted hierarchy

Caveat:
No systematic error included yet.



NEUTRINO PARAMETERS FROM CMB-S4



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

SIMONS OBSERVATORY

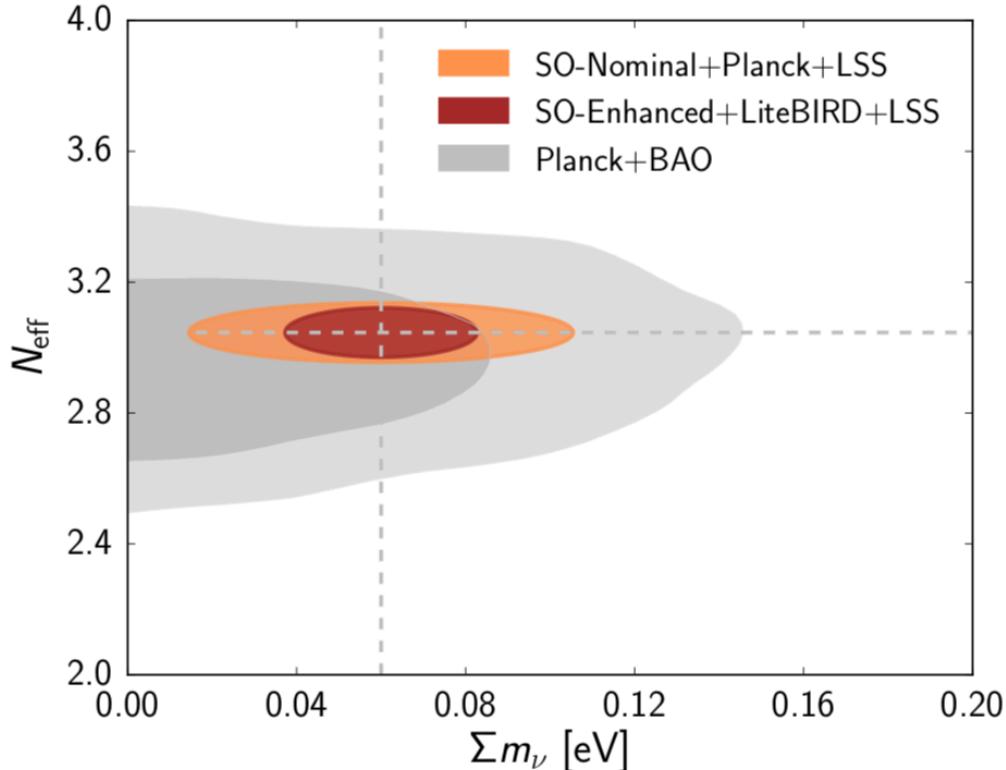


Table 1: Summary of SO-Nominal key science goals^a

	Current ^b Baseline	SO-Nominal (2022-27) Goal	Method ^d
Primordial perturbations (§2.1)			
$r (A_L = 0.5)$	0.03	0.003	0.002 ^e
n_s	0.004	0.002	0.002
$e^{-2\tau}\mathcal{P}(k = 0.2/\text{Mpc})$	3%	0.5%	0.4%
$f_{\text{NL}}^{\text{local}}$	5	3	1
		2	1
Relativistic species (§2.2)			
N_{eff}	0.2	0.07	0.05
Neutrino mass (§2.3)			
Σm_ν (eV, $\sigma(\tau) = 0.01$)	0.1	0.04	0.03
		0.04	0.03
Σm_ν (eV, $\sigma(\tau) = 0.002$)		0.03 ^f	0.02
		0.03	0.02

FORECASTS FOR FUTURE CMB+LSS

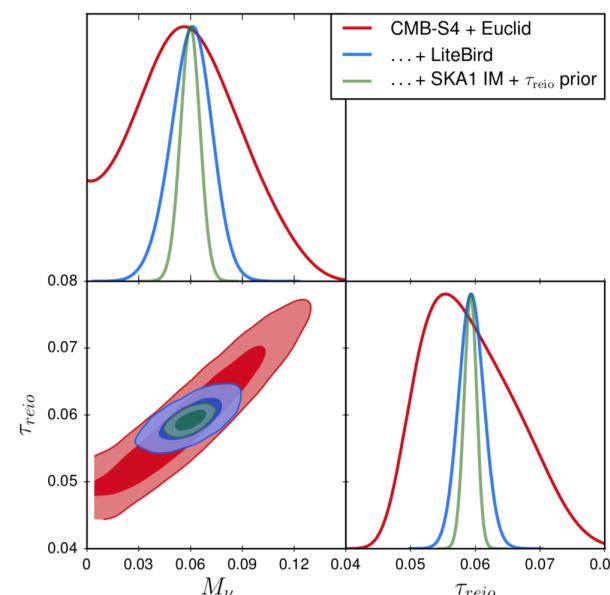
$\sigma(\Sigma m_\nu) = 0.04 \text{ eV}$ from SO (primary+lensing)
+ DESI BAO
(SO Collaboration 2018)

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

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

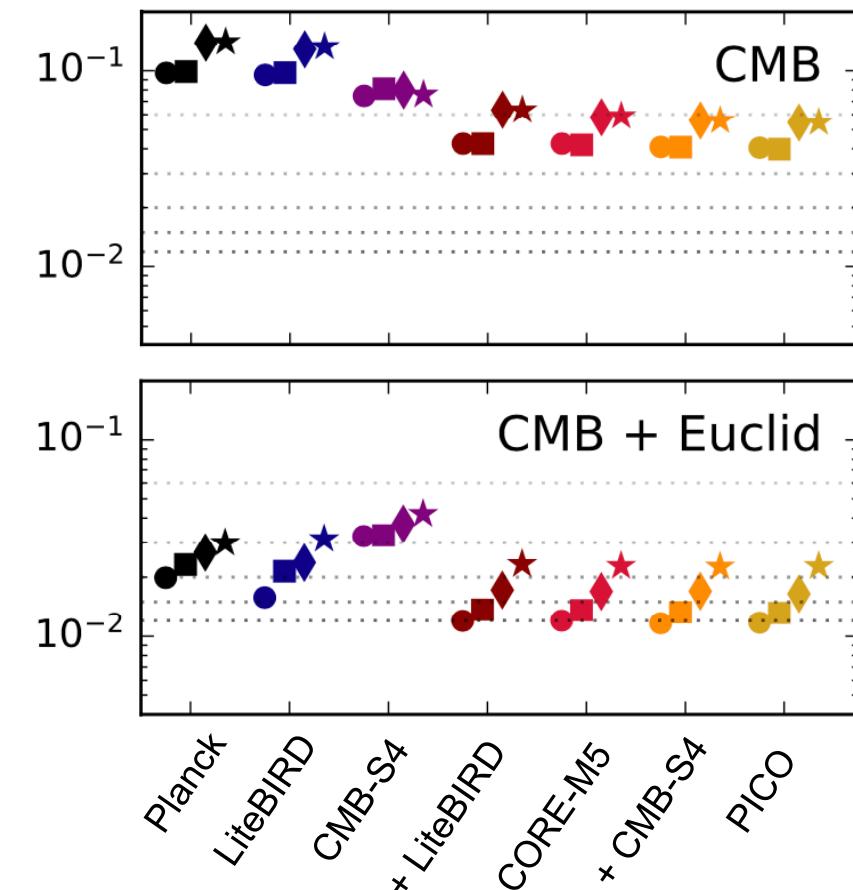
CMB+LSS will provide a statistically significant detection of neutrino masses in Λ CDM (remember $\Sigma m_\nu > 0.06 \text{ eV}$).

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

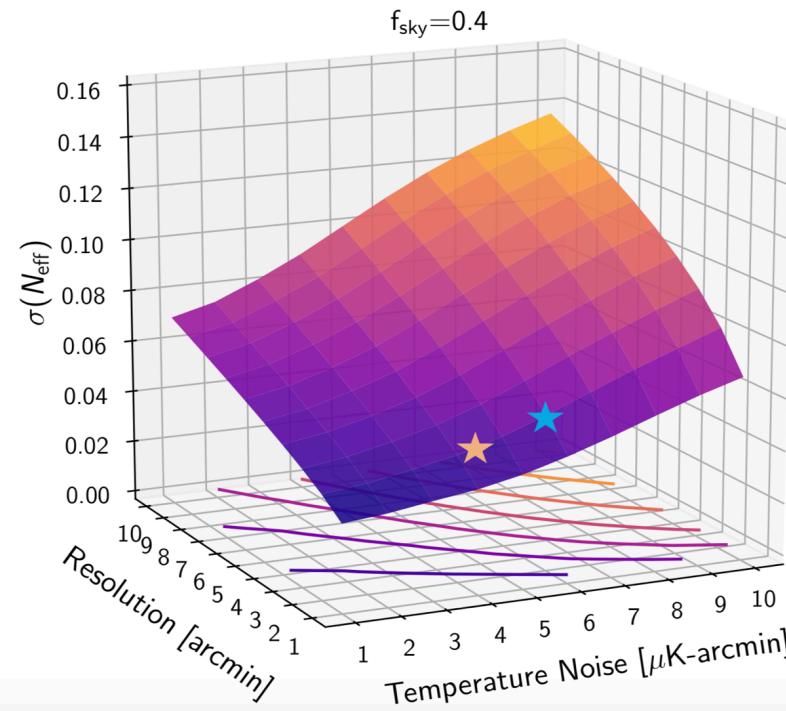


See also Allison et al 2015; Boyle & Komatsu 2018; Archidiacono et al 2017.

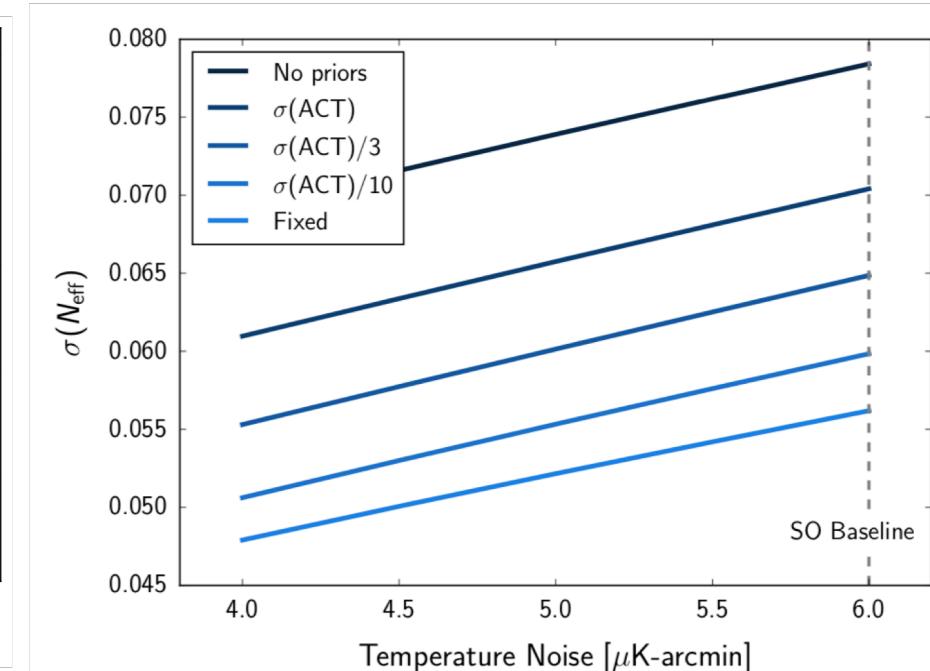
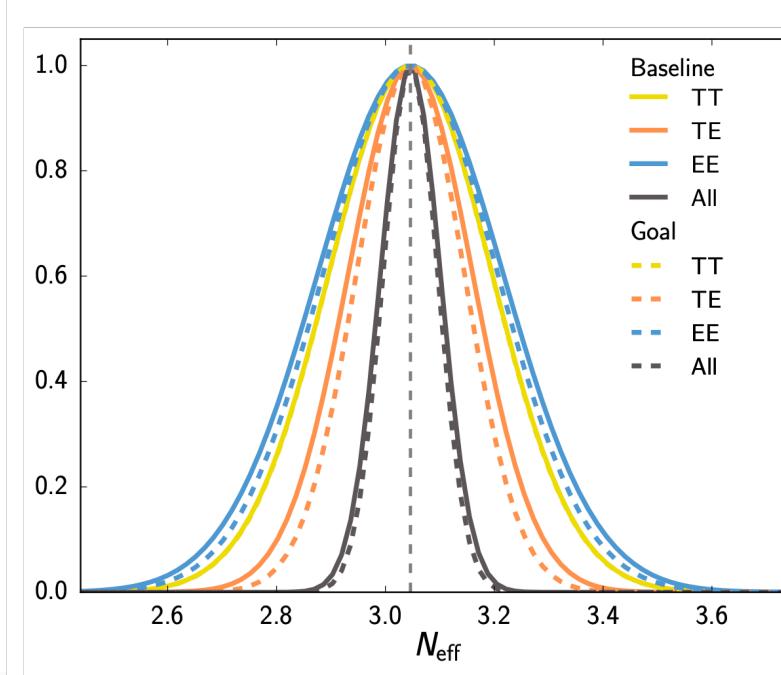
Brinckmann, Hooper,+, JCAP 2019



N_{eff} FROM SO

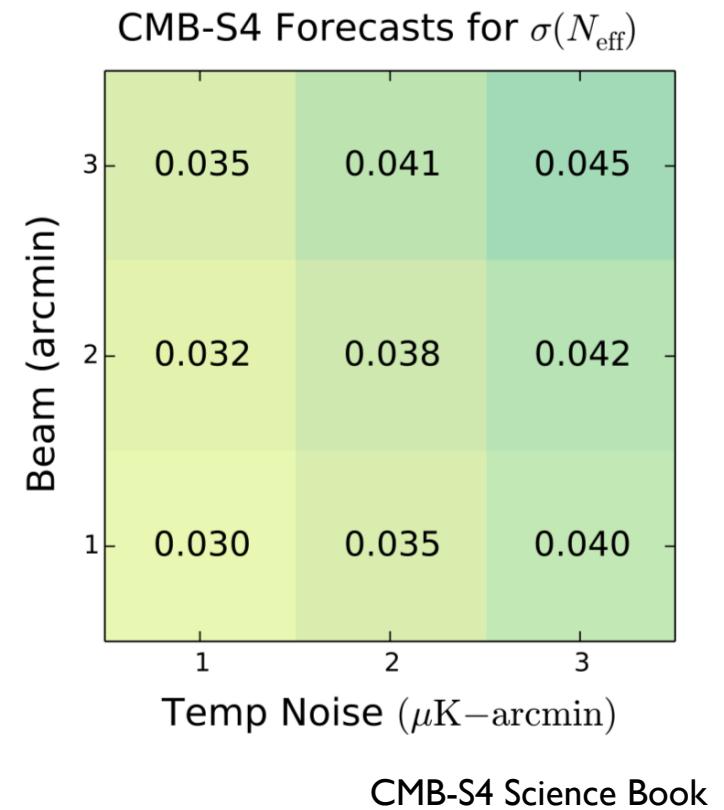
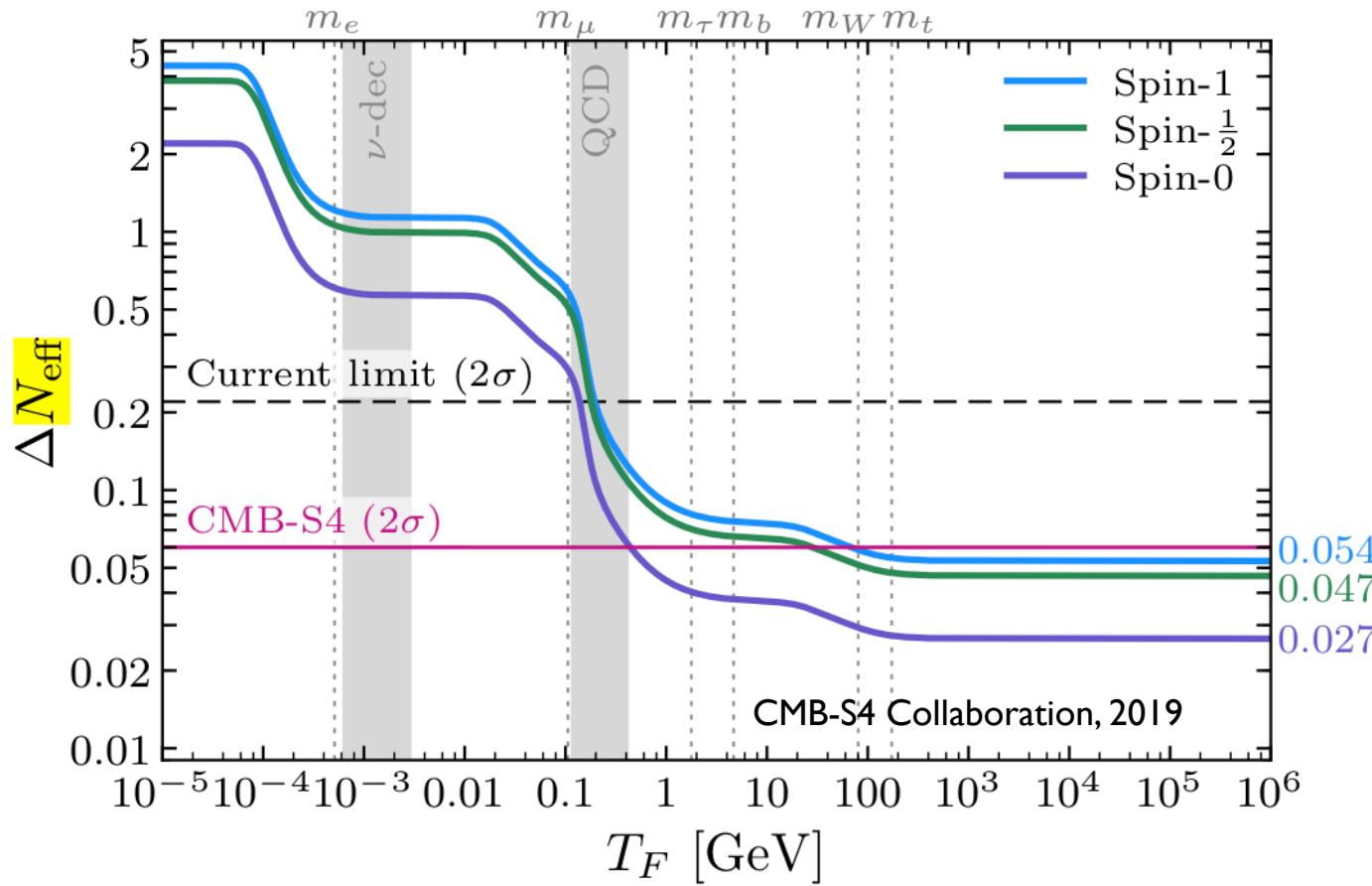


SO collaboration, 2018



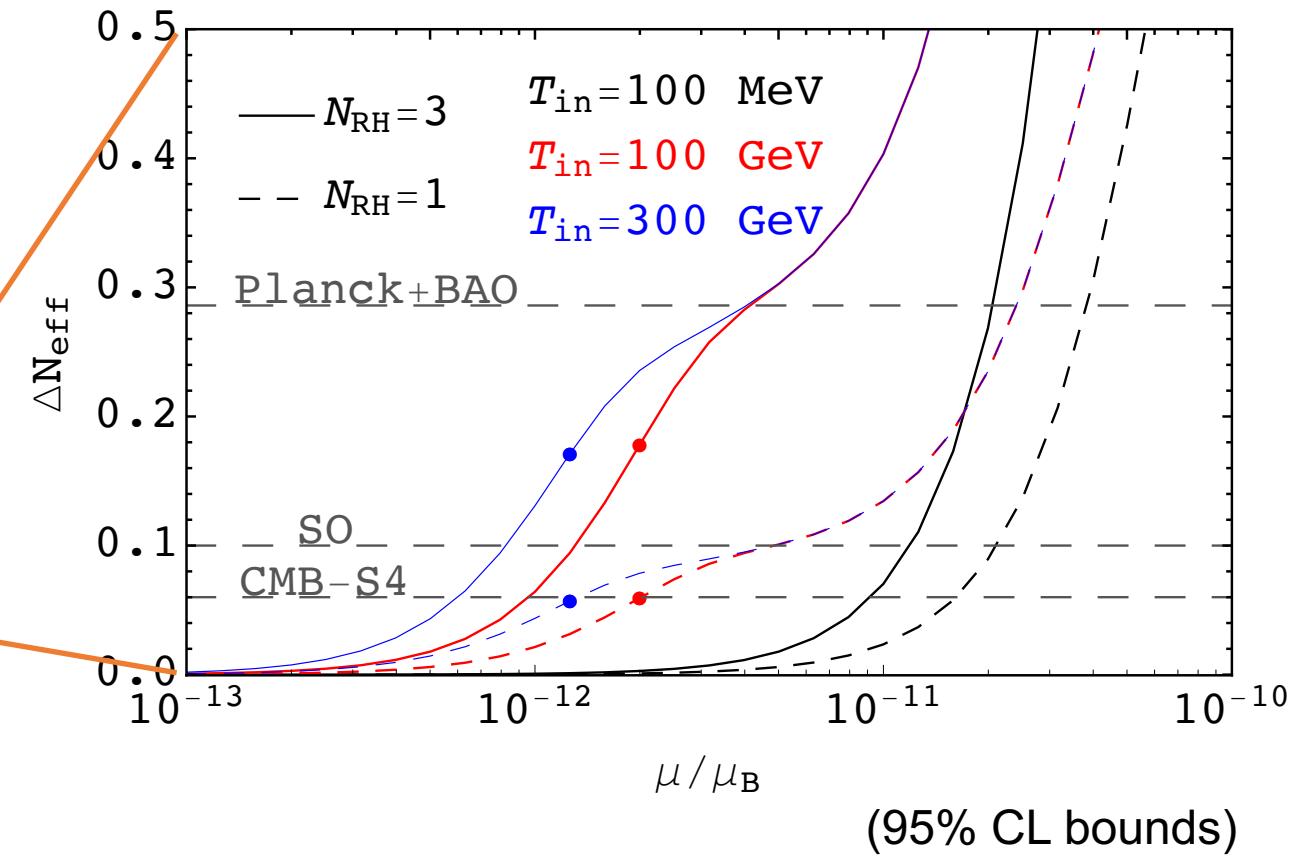
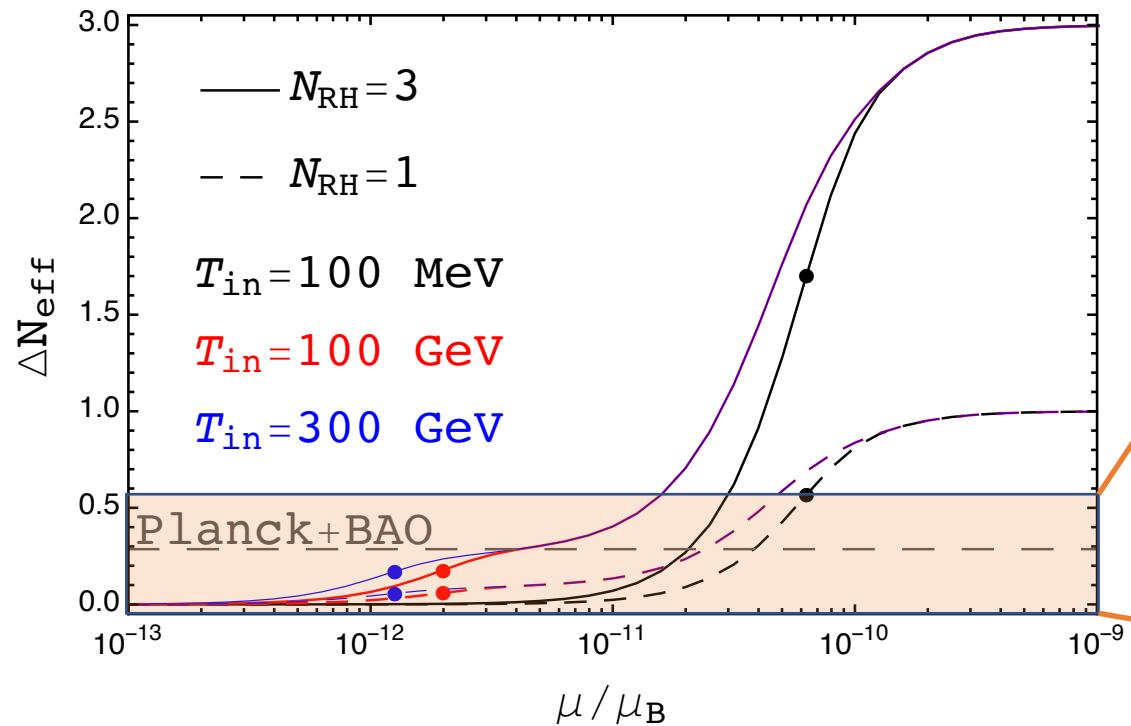
$$\sigma(N_{\text{eff}}) = 0.07 [0.05]$$

N_{EFF} FROM CMB-S4



NEUTRINO MAGNETIC MOMENT

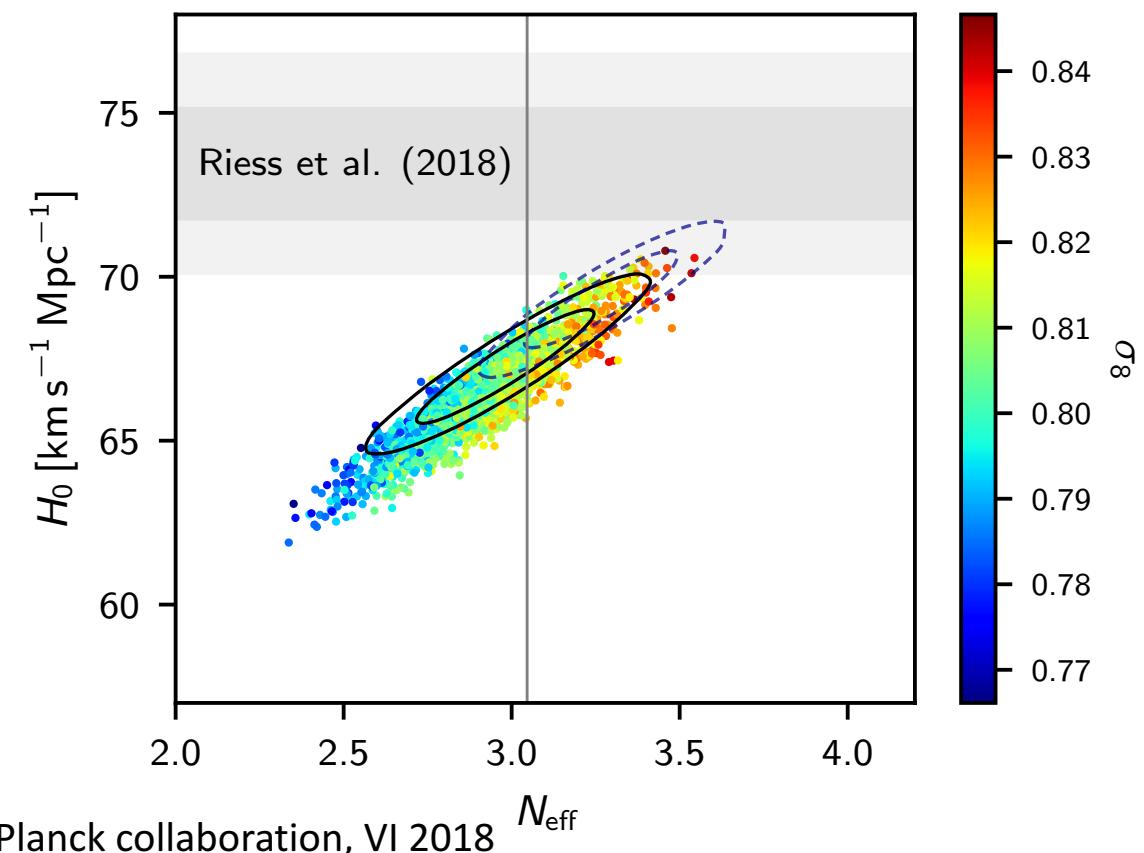
Measurements of N_{eff} can be used to constrain the neutrino magnetic moment



Carenza+ (incl ML, arXiv:2211.0432)

NEFF AS A PROBE OF NEW PHYSICS

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



Theoretical expectation for the three SM neutrinos* :

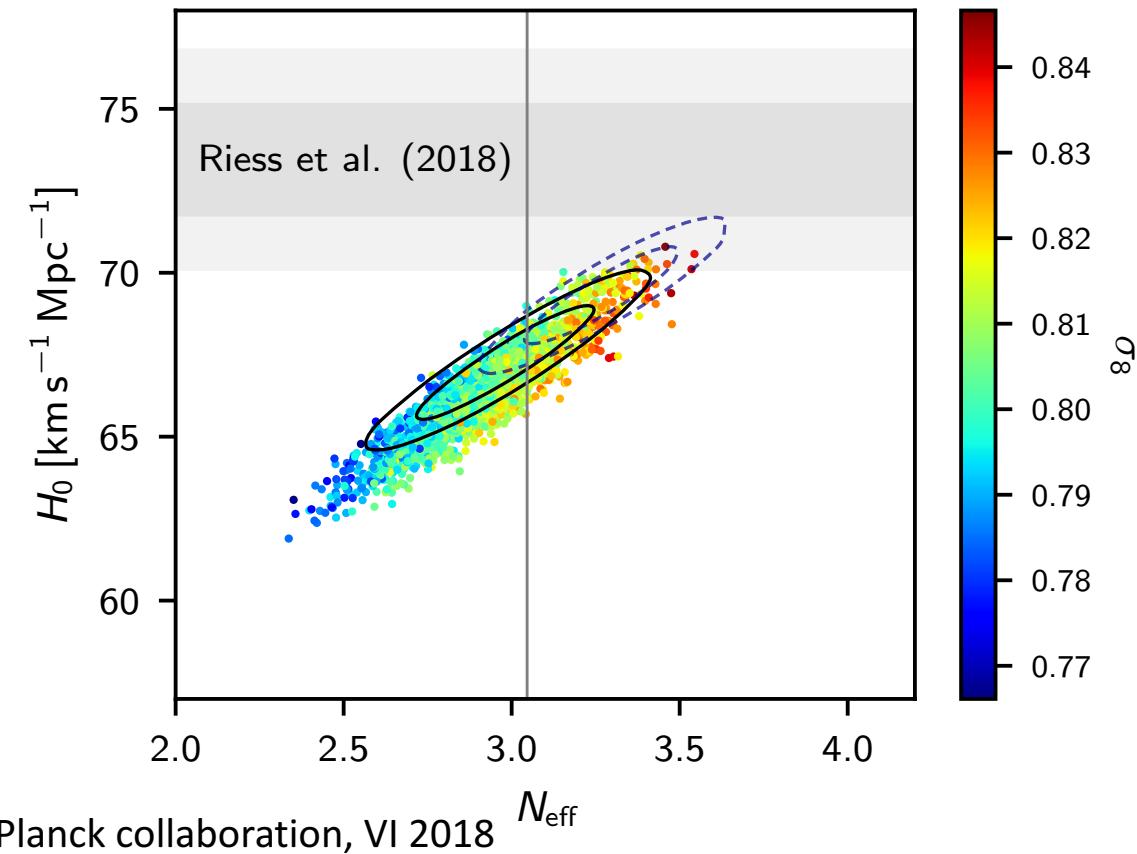
$$N_{\text{eff}} = 3.0440 \pm 0.0002$$

In general, the observed N_{eff} puts tight constraints on theories beyond the SM and beyond Λ CDM

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

NEFF AS A PROBE OF NEW PHYSICS

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



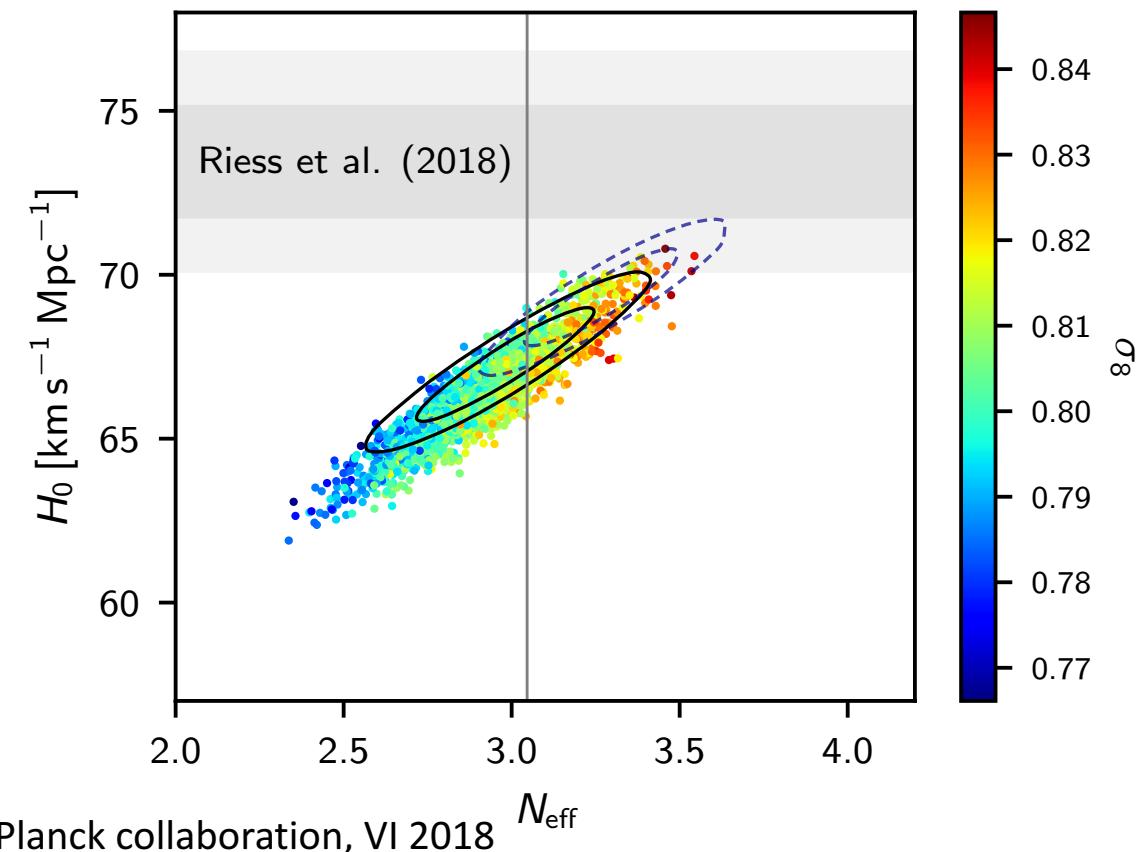
A deviation from the standard value of N_{eff} might be due to:

- 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 Λ CDM

NEFF AS A PROBE OF NEW PHYSICS

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



Both a blessing and a curse!

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

....however, if $\Delta N_{\text{eff}} \neq 0$ 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!)

SUMMARY

- Coming years will bring a wealth of new, high-precision cosmological data.
- Cosmological surveys like Euclid, Vera Rubin Observatory, Nancy Roman Space Telescope and SKA will provide observations of cosmic large-scale structures (LSS).
- Next-generation cosmic microwave background (CMB) experiments like Simons Observatory, LiteBIRD, CMB-S4, will precisely characterize the CMB polarization anisotropies.
- Scientific targets include:
 - Inflationary science (tensor modes, non gaussianities, primordial features...)
 - dark energy and modified gravity
 - neutrino properties (masses, interactions...)
 - light relics

THANKS!