CONSTRAINTS ON THE PROPERTIES OF LIGHT RELICS FROM COSMOLOGICAL OBSERVATIONS

MASSIMILIANO LATTANZI

INFN, sezione di Ferrara

OKC, Stockholm, Oct 31st 2023

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LIGHT RELICS

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

Present density parameter: $\Omega_{\rm hdm}h^2 = \dfrac{\rho_{\rm hdm}h^2}{\rho_{\rm c}}$

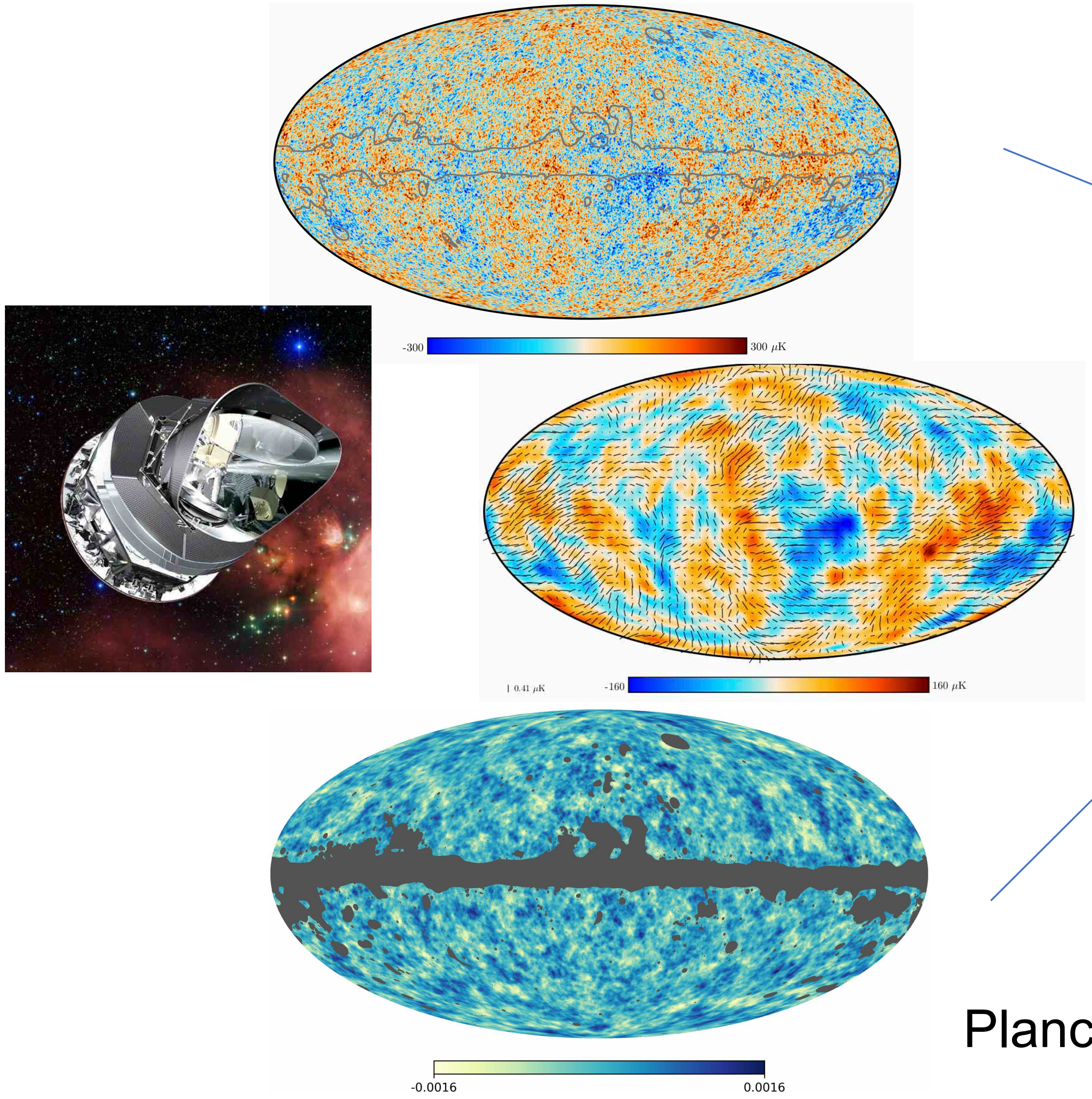
($\propto \sum m_\nu = \sum_{i=1,2,3} m_i$ in LCDM)

Effective number of relativistic species $N_{\rm eff}$

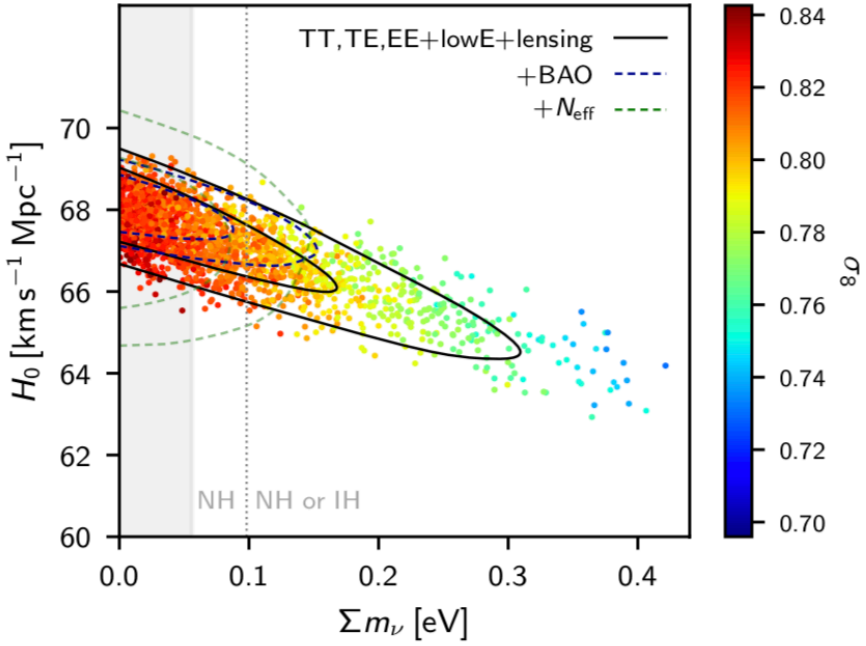
$$\rho_r \equiv \left[1 + N_{\rm eff} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma$$

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

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)

COSMIC NEUTRINO BACKGROUND (CνB)

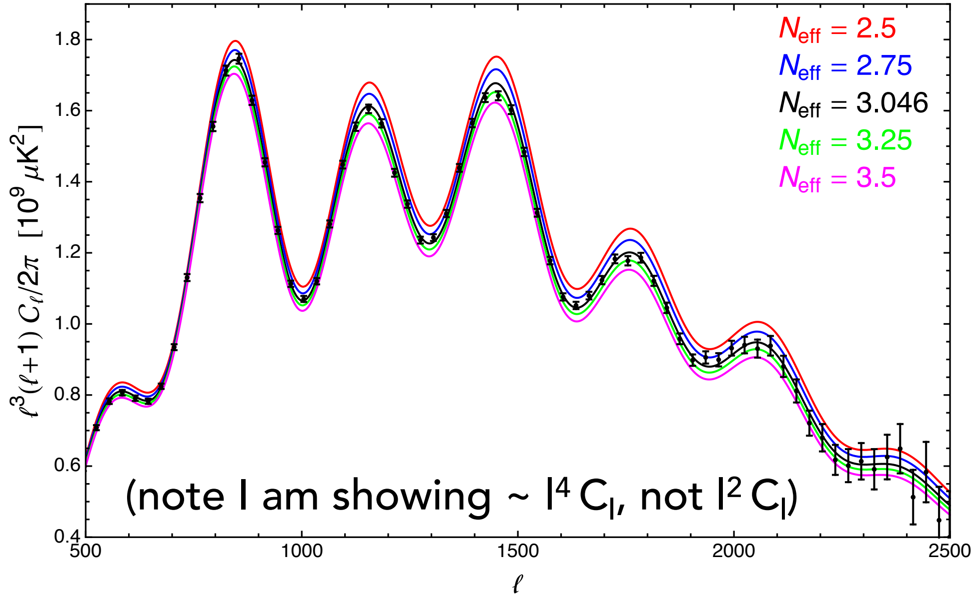
- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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

Theoretical expectation for the three SM neutrinos* :

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

Seen in the CMB small-scale anisotropies



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

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

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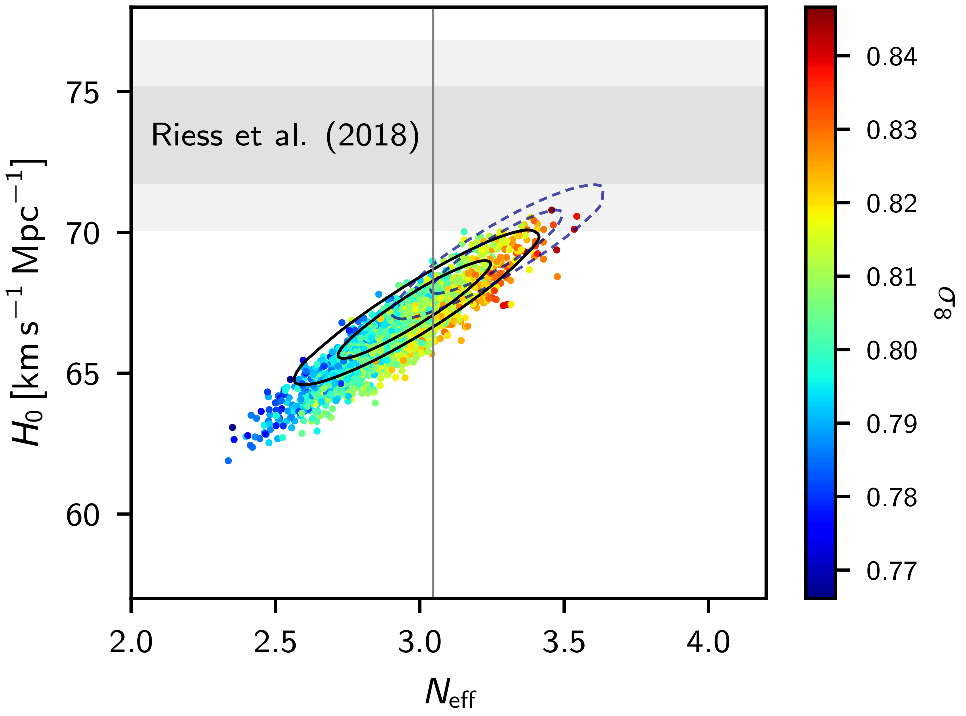

Theoretical expectation for the three SM neutrinos:

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

$N_{\rm eff}$ 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

COSMIC NEUTRINO BACKGROUND (CνB)

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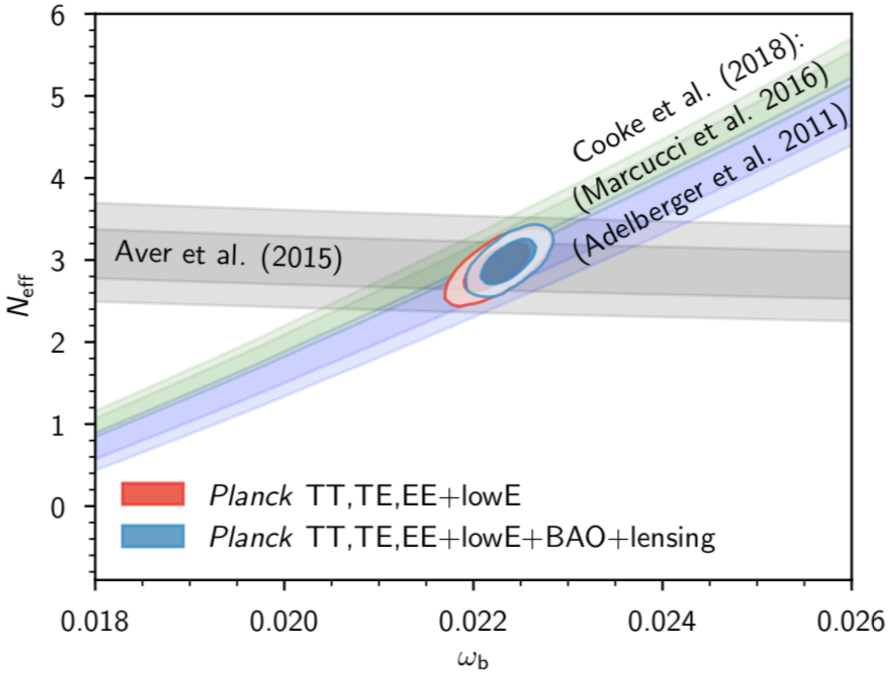


Planck collaboration, VI 2018

Theoretical expectation for the three SM neutrinos:

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

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

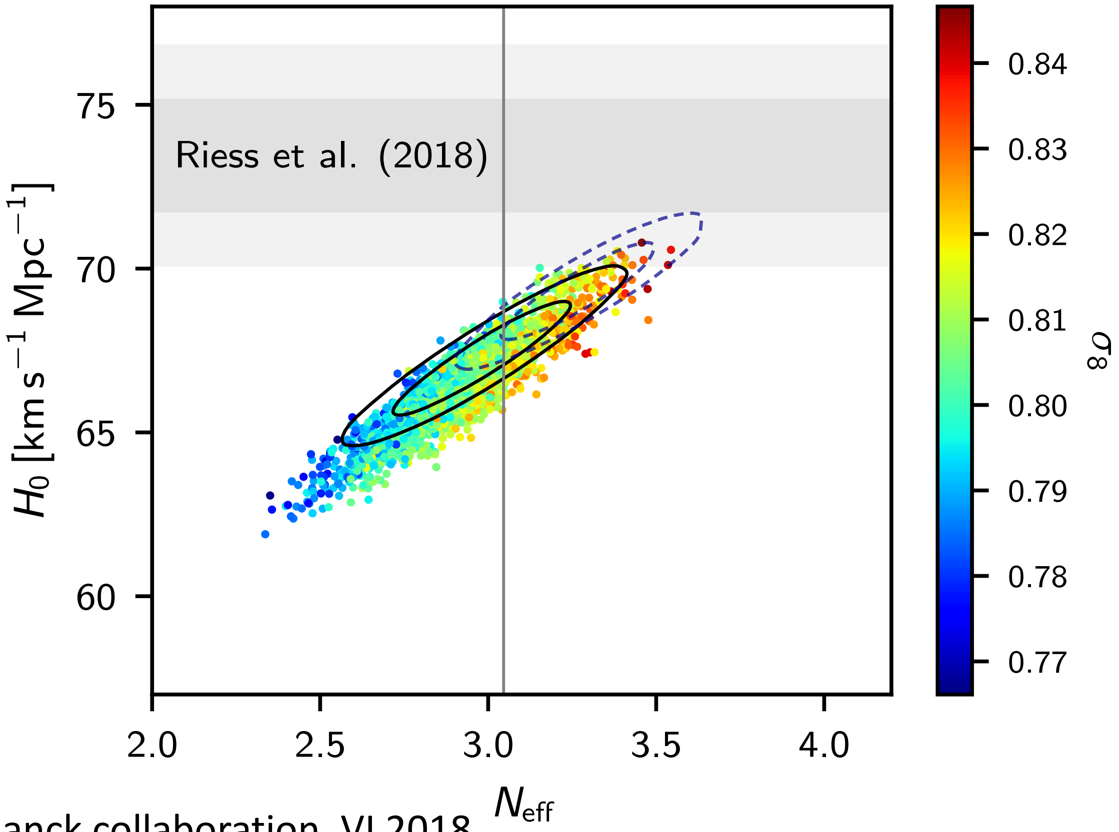
N$_{\rm eff}$ = 2.86 +/- 0.28 [Yp + D/H]

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

Pisanti et al, JCAP 2021
Yeh et al., JCAP 2021

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

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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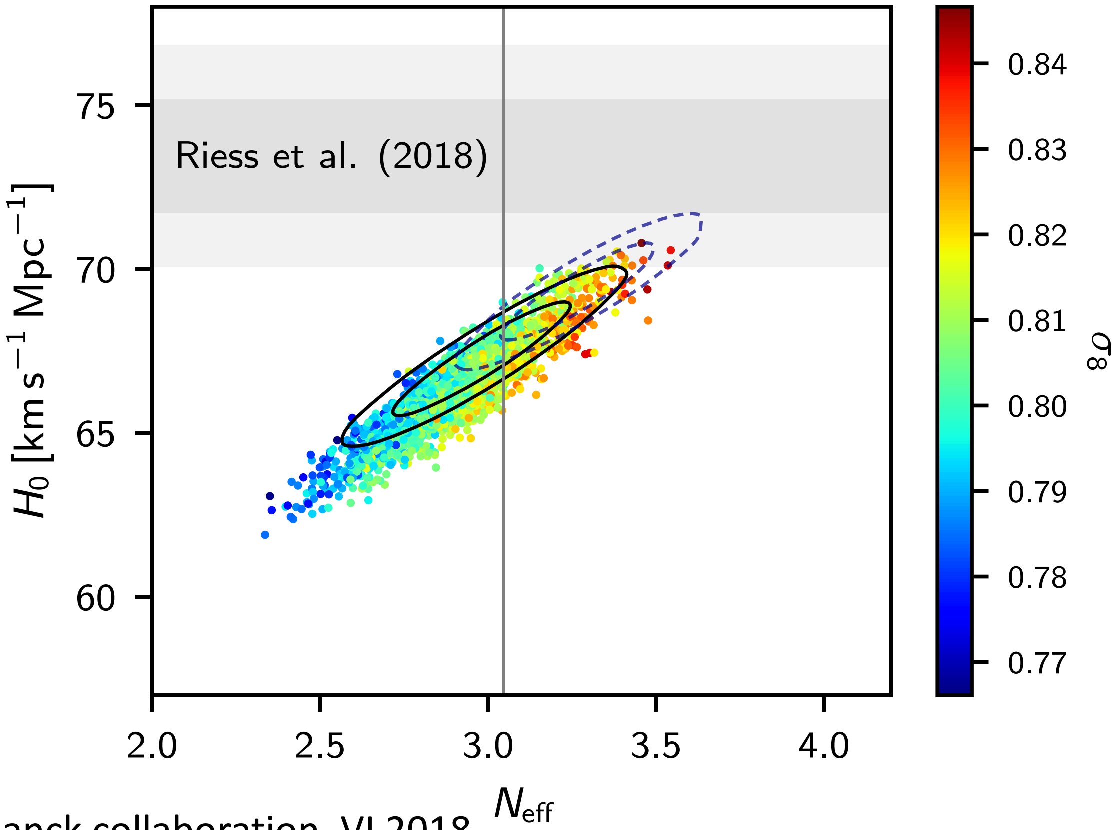


Planck collaboration, VI 2018

Both a blessing and a curse!

We can use $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.044$ 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

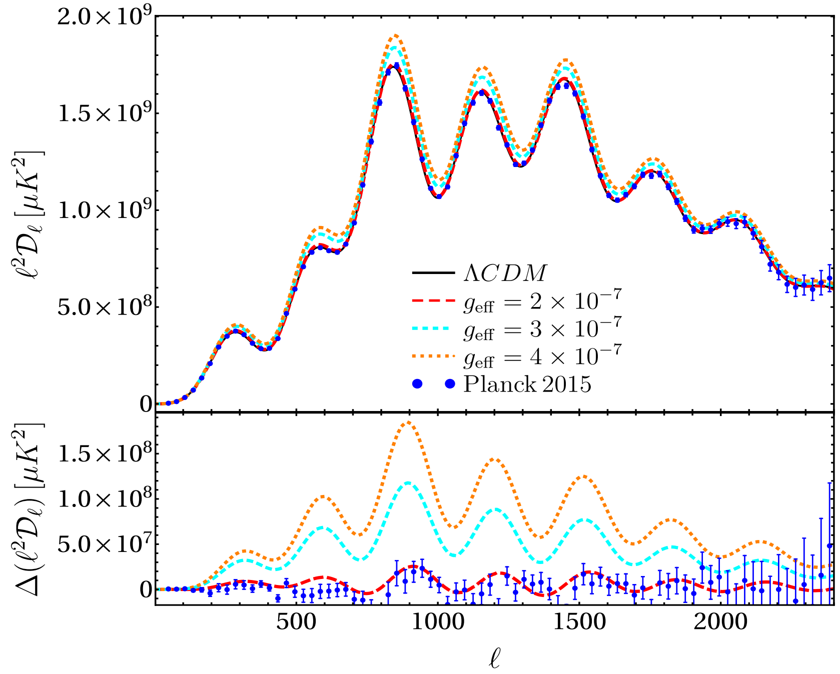
(not really much different from the present situation with dark matter and dark energy, if you think of it!)

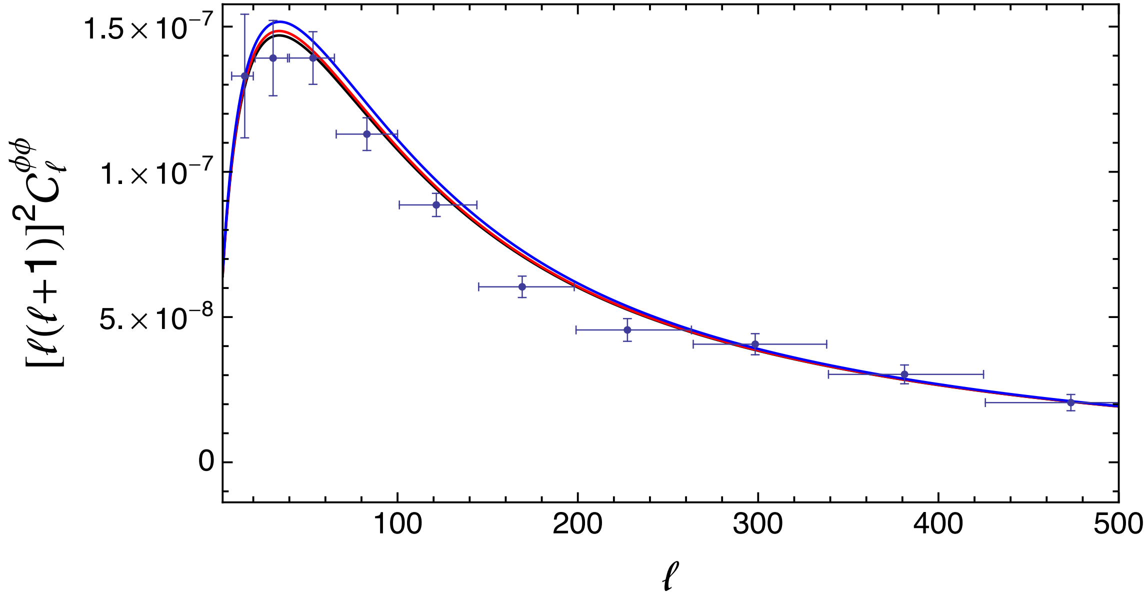
ν NSI IN COSMOLOGY

CMB is also sensitive to the **collisional properties** of light relics (Bashinsky & Seljak 2004)
Neutrino free streaming can be tested!

E.g. a probe of **nonstandard interactions** ⟶

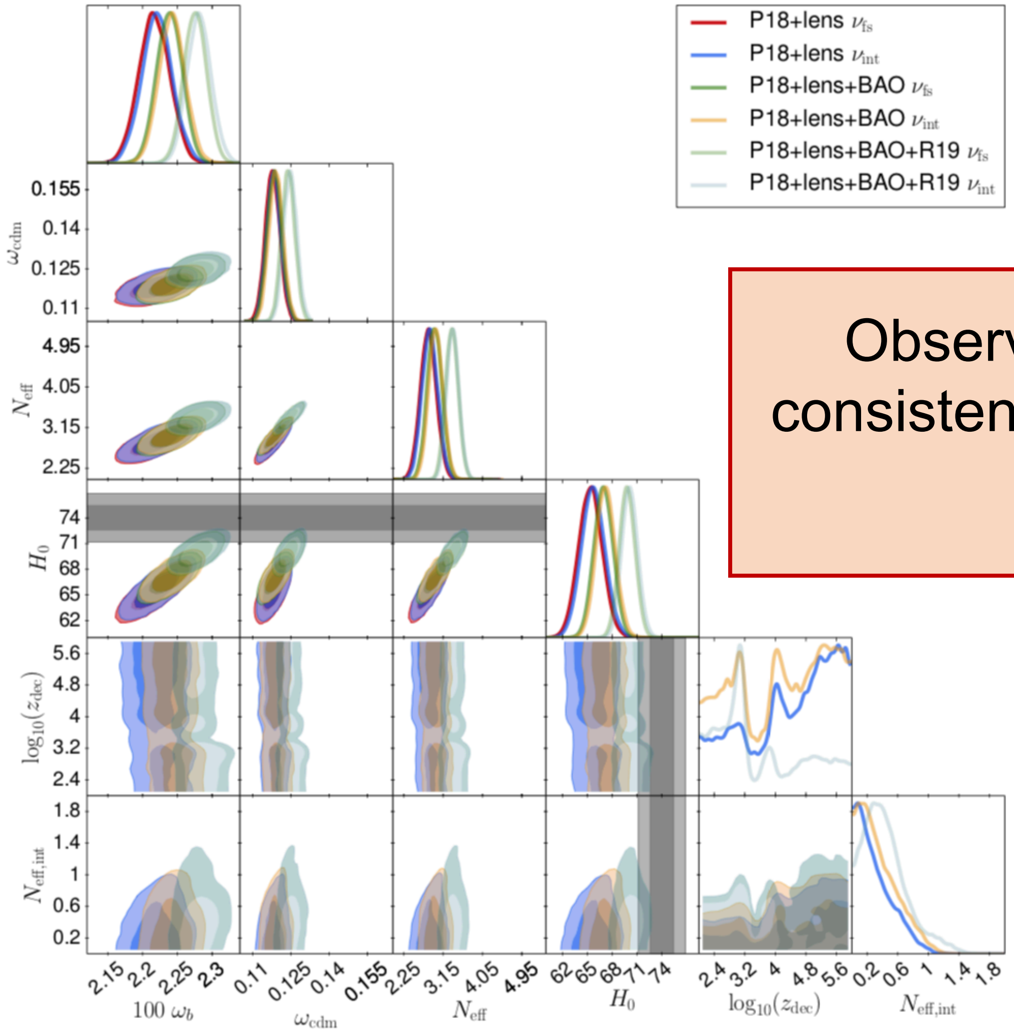
$$\boxed{\mathcal{L}_{\rm int} = \frac{i}{2} g\phi\bar{\nu}_i\gamma^5\nu_i}$$





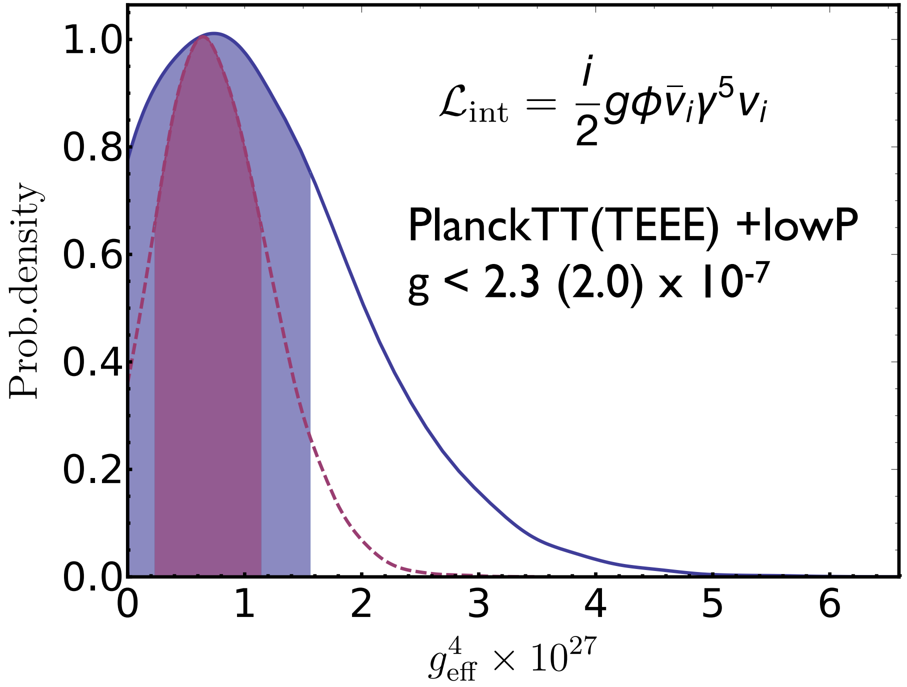
Self-interactions suppress neutrino free-streaming ⟶ larger fluctuations in the gravitational potentials

ν NSI IN COSMOLOGY



Brinckmann, Chang, LoVerde, 2021

Observations are mostly consistent with free-streaming neutrinos



$$\mathcal{L}_{\rm int} = \frac{i}{2} g \phi \bar{\nu}_i \gamma^5 \nu_i$$

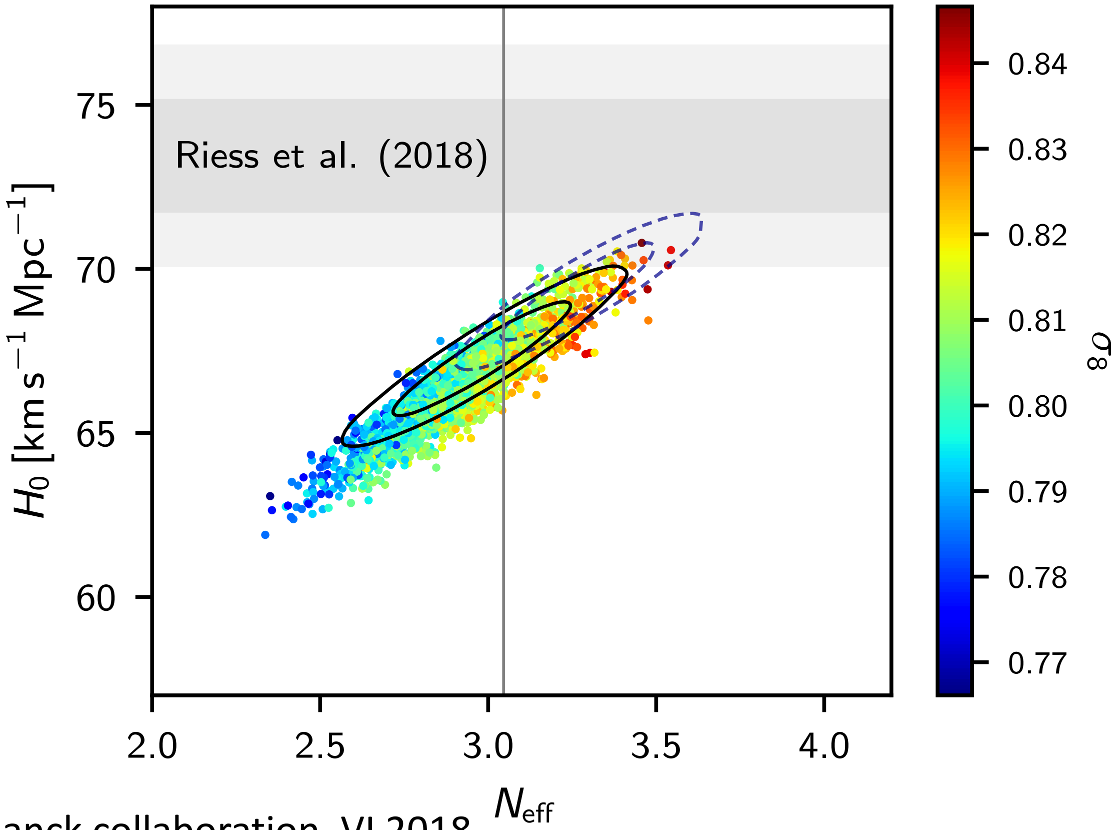
PlanckTT(TEEE) +lowP
$g < 2.3\ (2.0) \times 10^{-7}$

Forastieri, ML, Natoli,, 2019

See also Cyr-Racine & Sigurdson 2013, Archidiacono & Hannestad 2013, Forastieri, ML, Natoli 2015, Oldengott et al 2017, Kreisch et al. 2207.03164, Choudhury, Hannestad, Tram 2207.07142

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

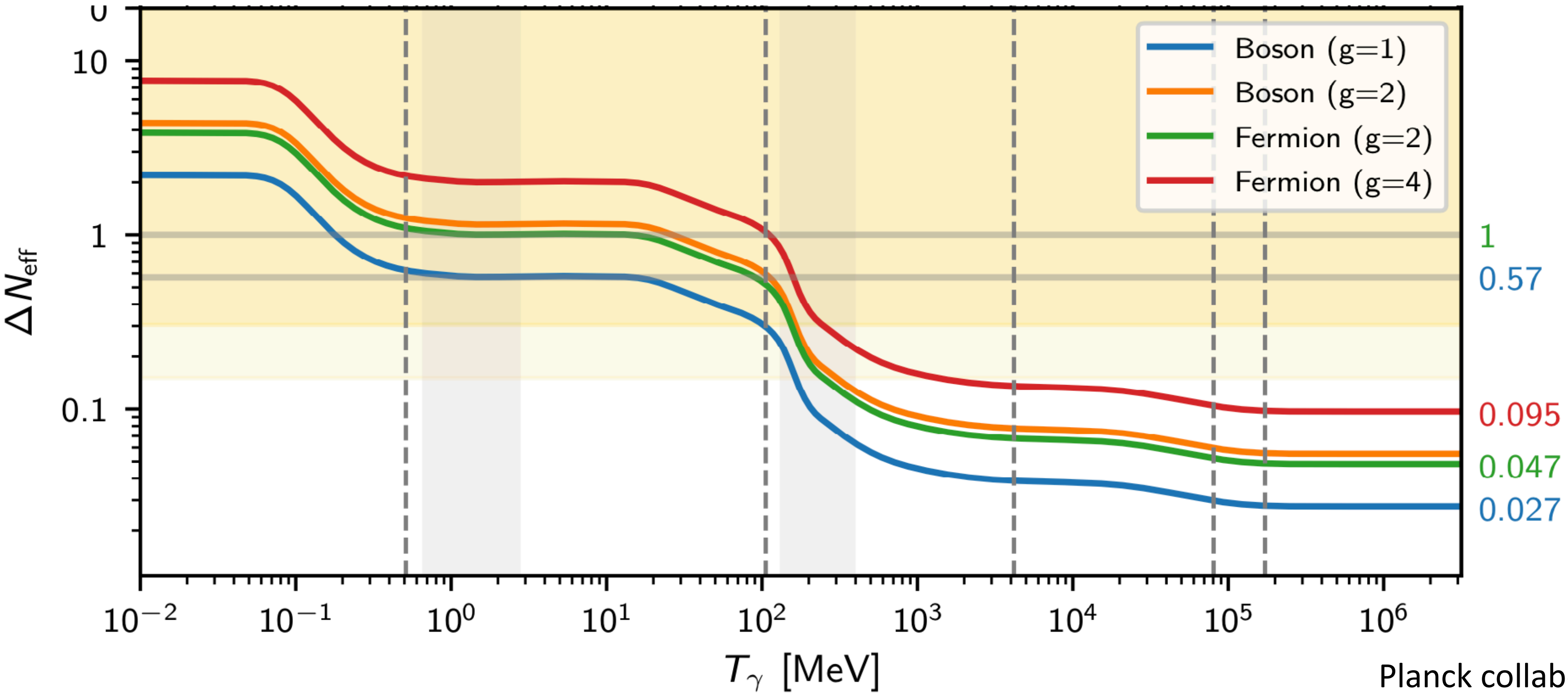
A deviation from the standard value of $N_{\rm eff}$ might be due to:

- **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

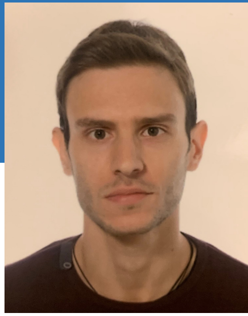
N_{EFF} AND THE DECOUPLING OF SPECIES

For a species that was in thermal equilibrium in the early Universe, ΔN_{eff} is directly related to the decoupling temperature:



Planck collaboration, VI 2018
(after Baumann, Green, Wallisch 2016)

N_{EFF} AND THERMAL AXIONS

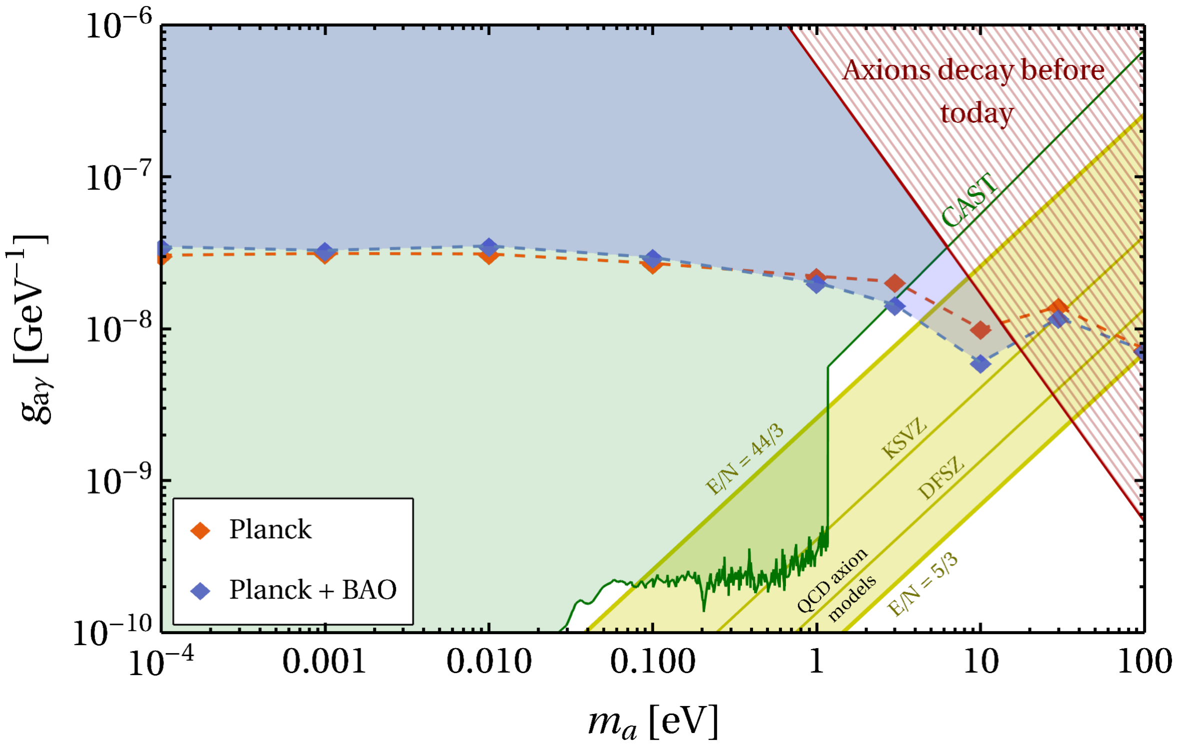


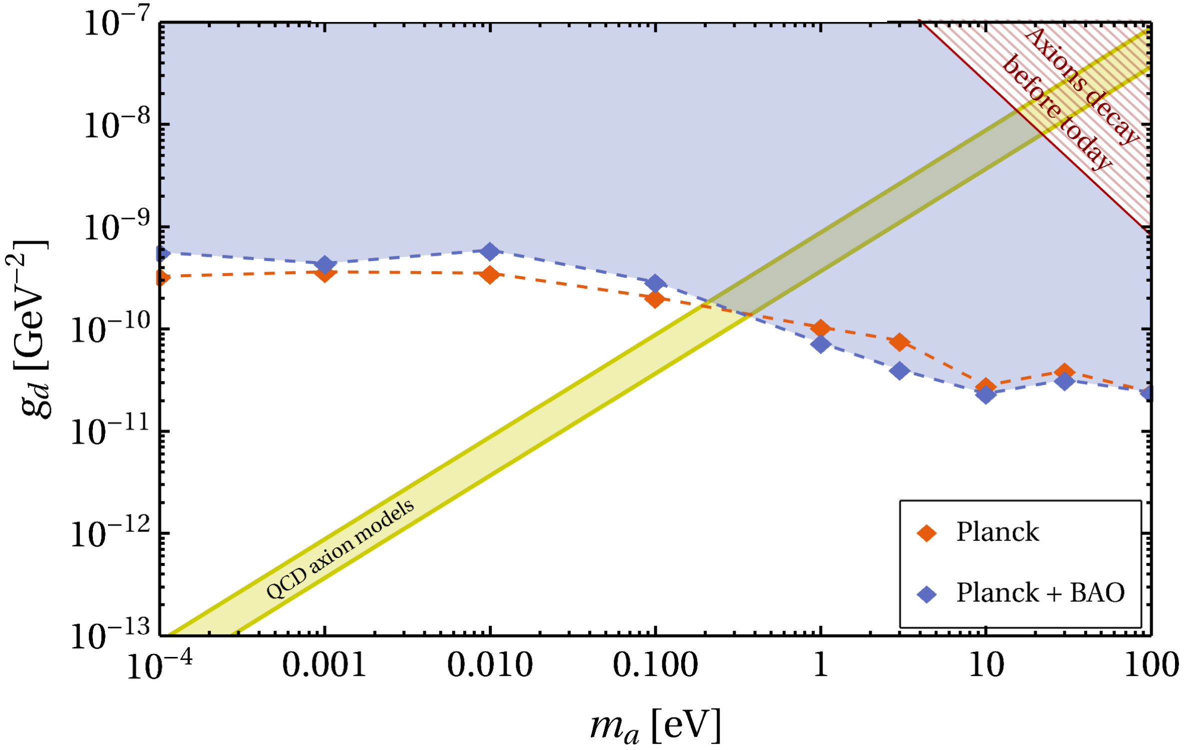
L. Caloni

Axions can be produced thermally in the early Universe
through their coupling to **photons** or **gluons**

$$\mathcal{L}_{a\gamma} = \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

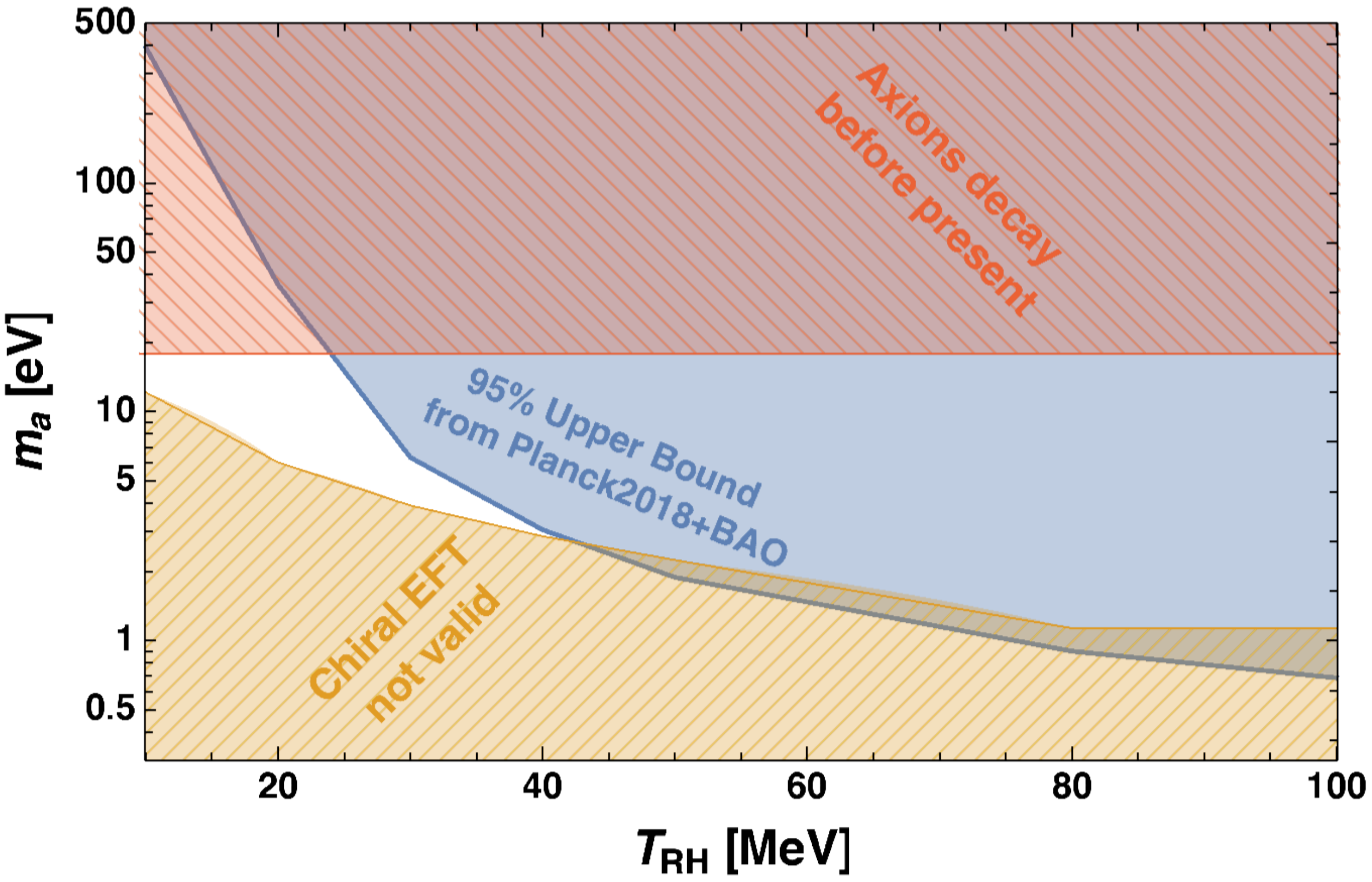
$$\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i}$$





Caloni, ML, Gerbino, Visinelli, 2022

QCD AXIONS IN LOW-REHEATING SCENARIOS



Constraints on light relics properties might depend on the thermal history

E.g. limits on QCD axion masses change in low reheating temperature scenarios

Carenza et al. 2021

LIGHT RELICS FROM NEXT-GEN EXPERIMENTS

Next-generation CMB experiments are expected to provide (see backup slides)

- A ~1-2% measurement of N_{eff} : **$\sigma(N_{eff})$ = 0.07 from SO, 0.03 from CMB-S4**, probing e.g.
  - the existence of additional thermal light species and their interactions
  - the physics of neutrino decoupling
  - expansion history
  - + …..
- Sensitivity for Σm_ν in the 15 – 50 meV range (possibly in combination with LSS: **$\sigma(M_\nu)$ = 12 meV from LiteBIRD+CMB-S4+Euclid**), giving
  - a up to 4σ measurement of the minimum mass in NO allowed by oscillation experiments (~60 meV).
  - The mass ordering if the sum of the masses is close enough to 60 meV.
  - Information on additional species?

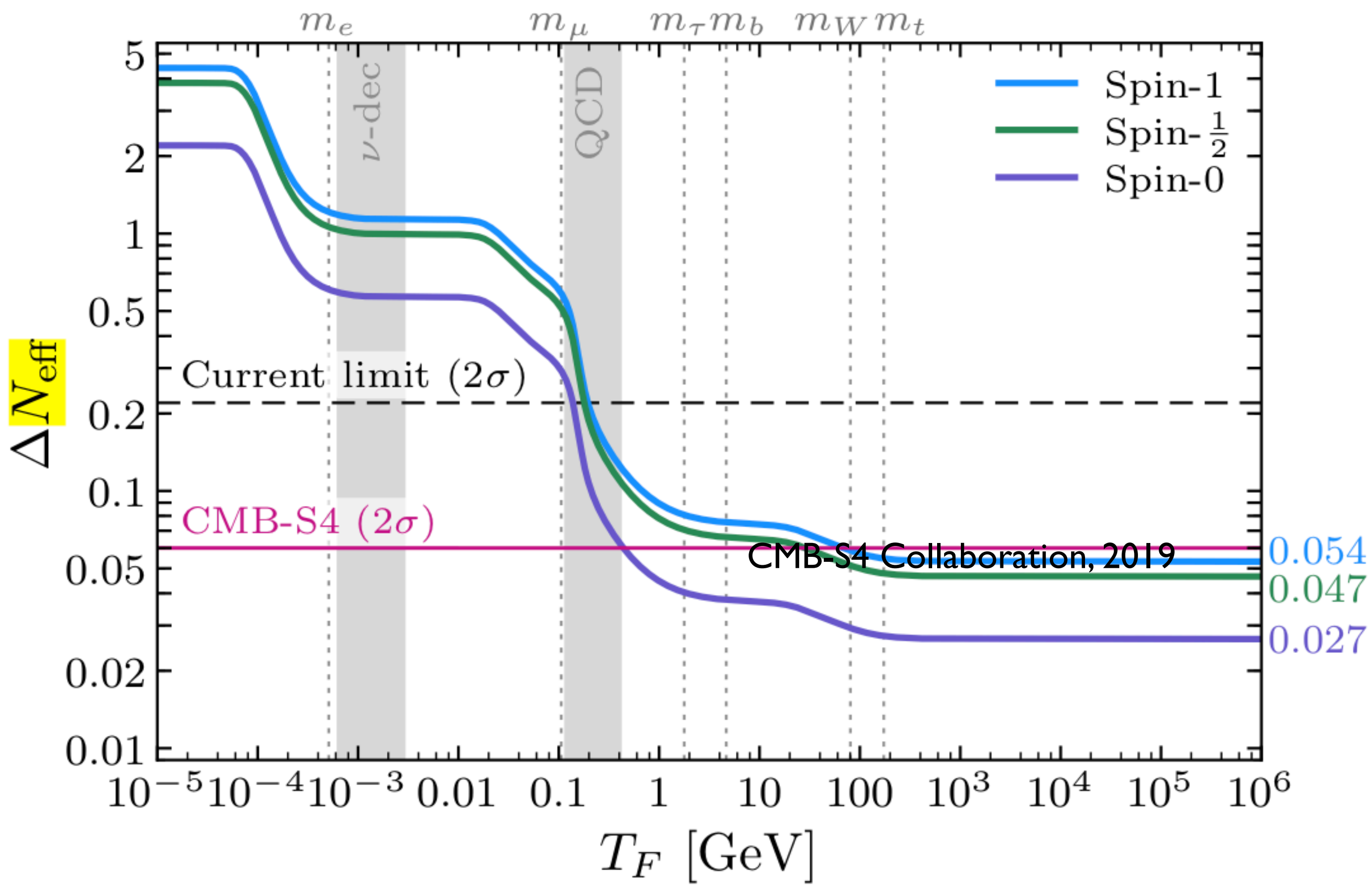
LIGHT RELICS FROM NEXT-GEN EXPERIMENTS

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

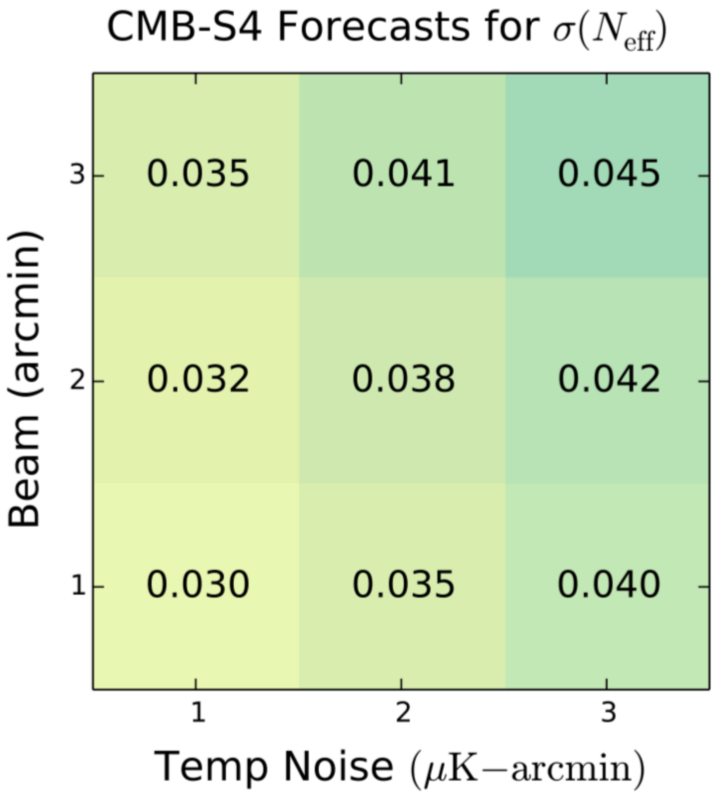
- **Small scales:**
  - Most of the N_{eff} signal is in the damping tail
  - Lensing reconstruction is needed to get the masses
  - Also useful to probe the collisional properties
  - Foreground residuals and beam systematics to be kept under control
  - Theoretical "systematics": impact of nonlinearities 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

N_{EFF} FROM CMB-S4

CMB-S4 will probe the minimum contribution from species in thermal equilibrium (in minimal SM extensions)



CMB-S4 Collaboration, 2019


CMB-S4 Forecasts for $\sigma(N_{\rm eff})$

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

NEUTRINO MAGNETIC MOMENT

If neutrinos have a magnetic moment, e.m. interactions in the plasma can flip the ν helicity → A population of right-handed neutrinos is created from a purely left-handed initial ensemble

Constraints from cosmology and SN

- J. A. Morgan, MNRAS 1981
- J. A. Morgan, PLB 1981
- Fukugita & Yazaki, PRD 1987
- Barbieri & Mohapatra PRL 1988
- Barbieri, Mohapatra & Yanagida PLB 1988
- Notzold, PRD 1988
- Loeb & Stodolsky, PRD 1989
- Elmfors, Enqvist, Raffelt & Sigl, NPB 1997 (EERS87)

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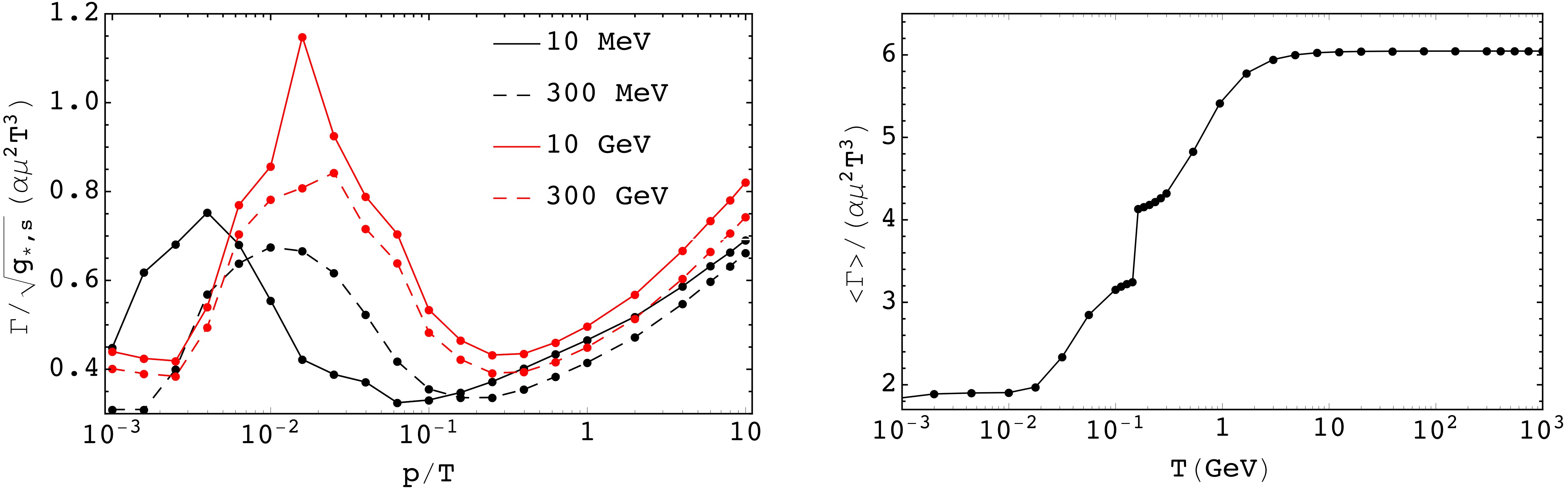
Spin-flip rate



Carenza et al. 2022

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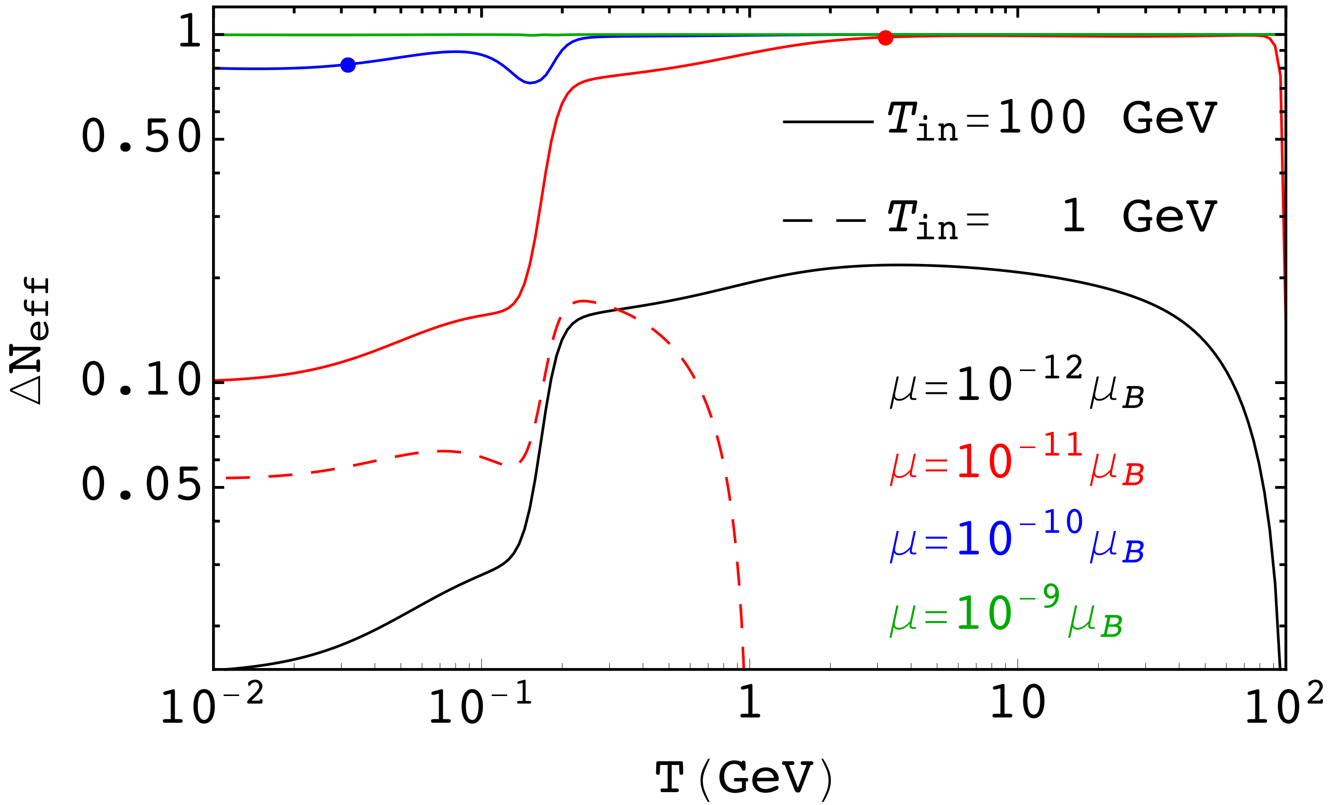

← **TIME**

Carenza+ (incl ML, arXiv:2211.0432)

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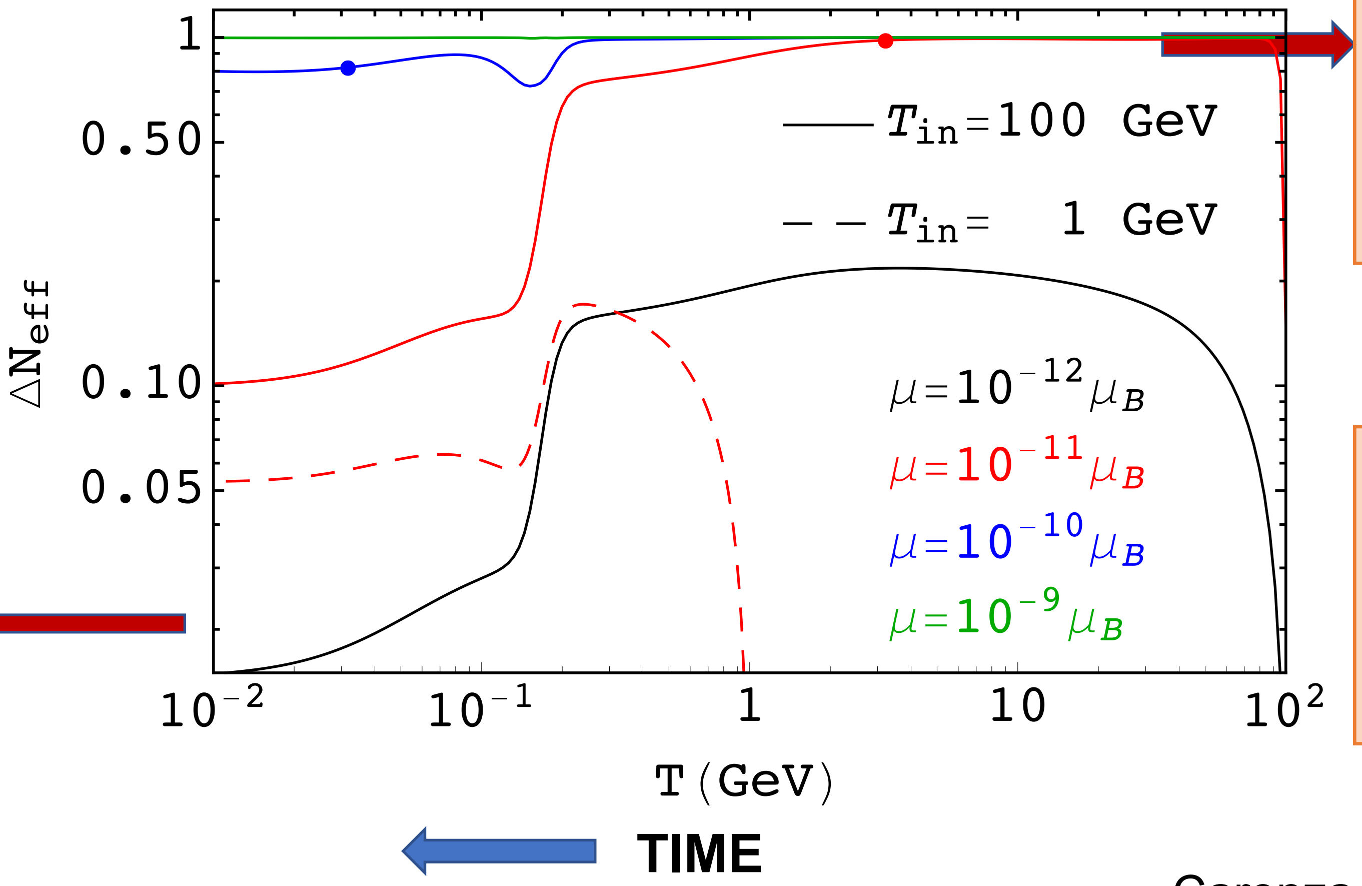


"Large" magnetic moment: thermal equilibrium is established at early times.

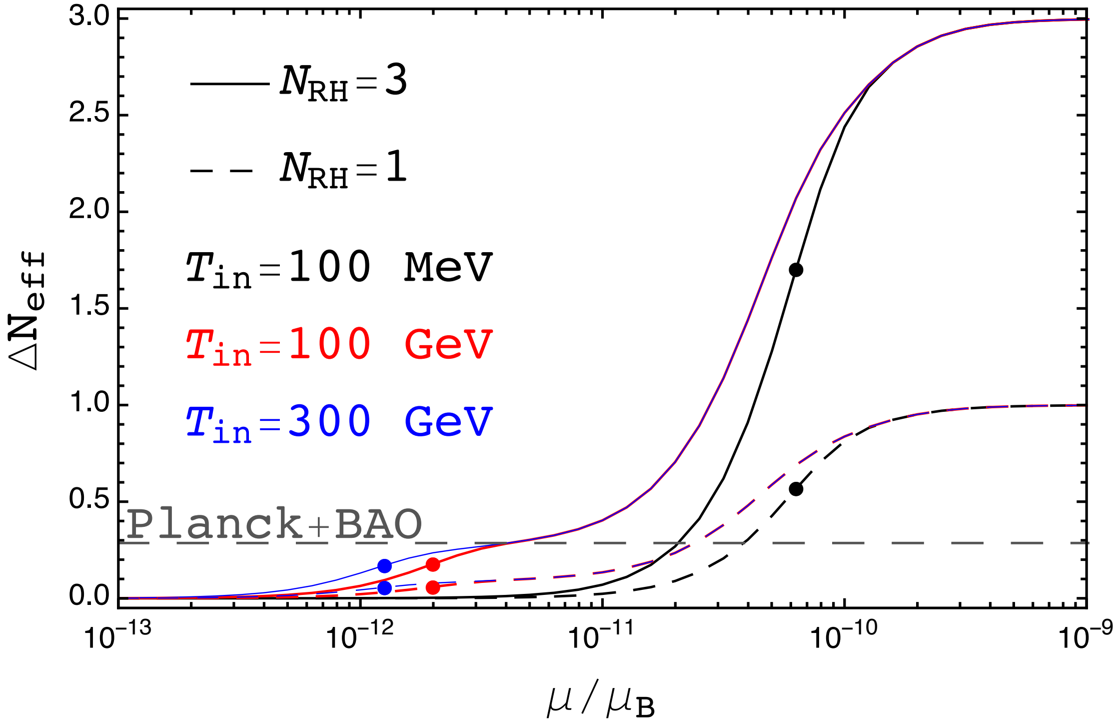
"Small" magnetic moment: thermal equilibrium never established. Freeze-in production. Abundance depends on initial temperature.

In both cases, abundance is diluted by entropy production after decoupling

Carenza+ (incl ML, arXiv:2211.0432)

NEUTRINO MAGNETIC MOMENT

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



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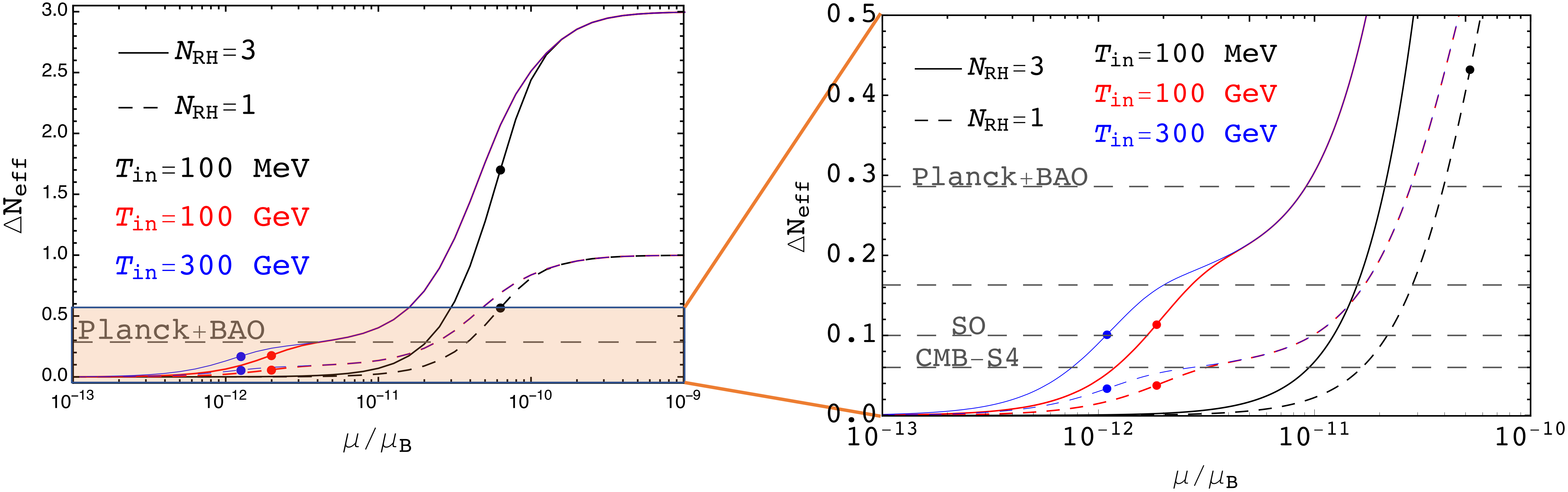


(95% CL bounds)

Carenza+ (incl ML, arXiv:2211.0432)

NEUTRINO MAGNETIC MOMENT

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

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

Carenza+ (incl ML, arXiv:2211.0432)

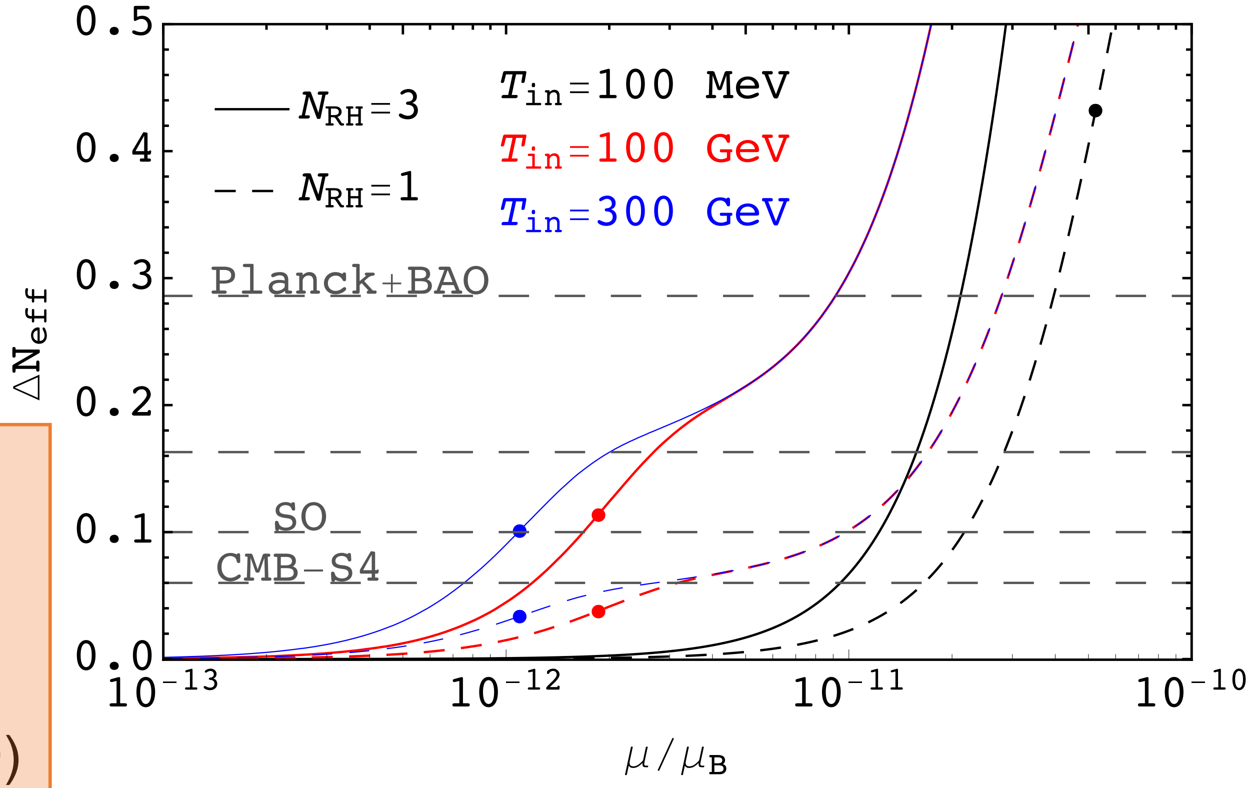
Compare with

$\mu < 6 \times 10^{-11}\ \mu_b$ (cosmo, EERS87, assumes th. eq)

$\mu < 2.7 \times 10^{-12}\ \mu_b$ (cosmo, Li&Xu arXiv:2211.04669) (assumes th. eq)

$\mu < 6.4 \times 10^{-11}\ \mu_b$ (lab, XENONnT arXiv:2207:11330)

$\mu < 1.2 \times 10^{-12}\ \mu_b$ (astro, Capozzi&Raffelt PRD2020)



(95% CL bounds)

NEUTRINO MAGNETIC MOMENT

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

In case of no detection:

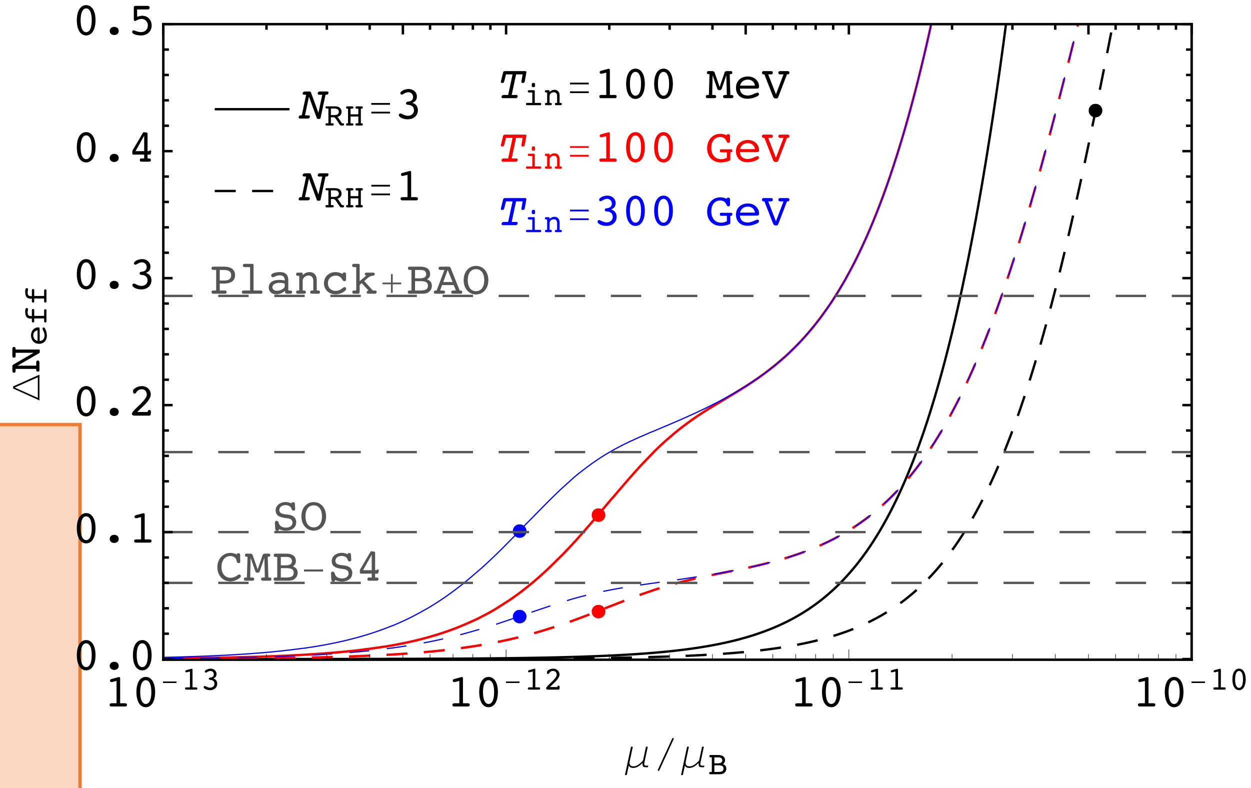
$\mu < 1.7 \text{ x } 10^{-12}\ \mu_{b}$ (SO)

$\mu < 1.2 \text{ x} 10^{-12}\ \mu_{b}$ (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/sqrt(T_{in})
- Nice interplay with r measurements (es. LiteBIRD) since these constrain the energy scale of inflation

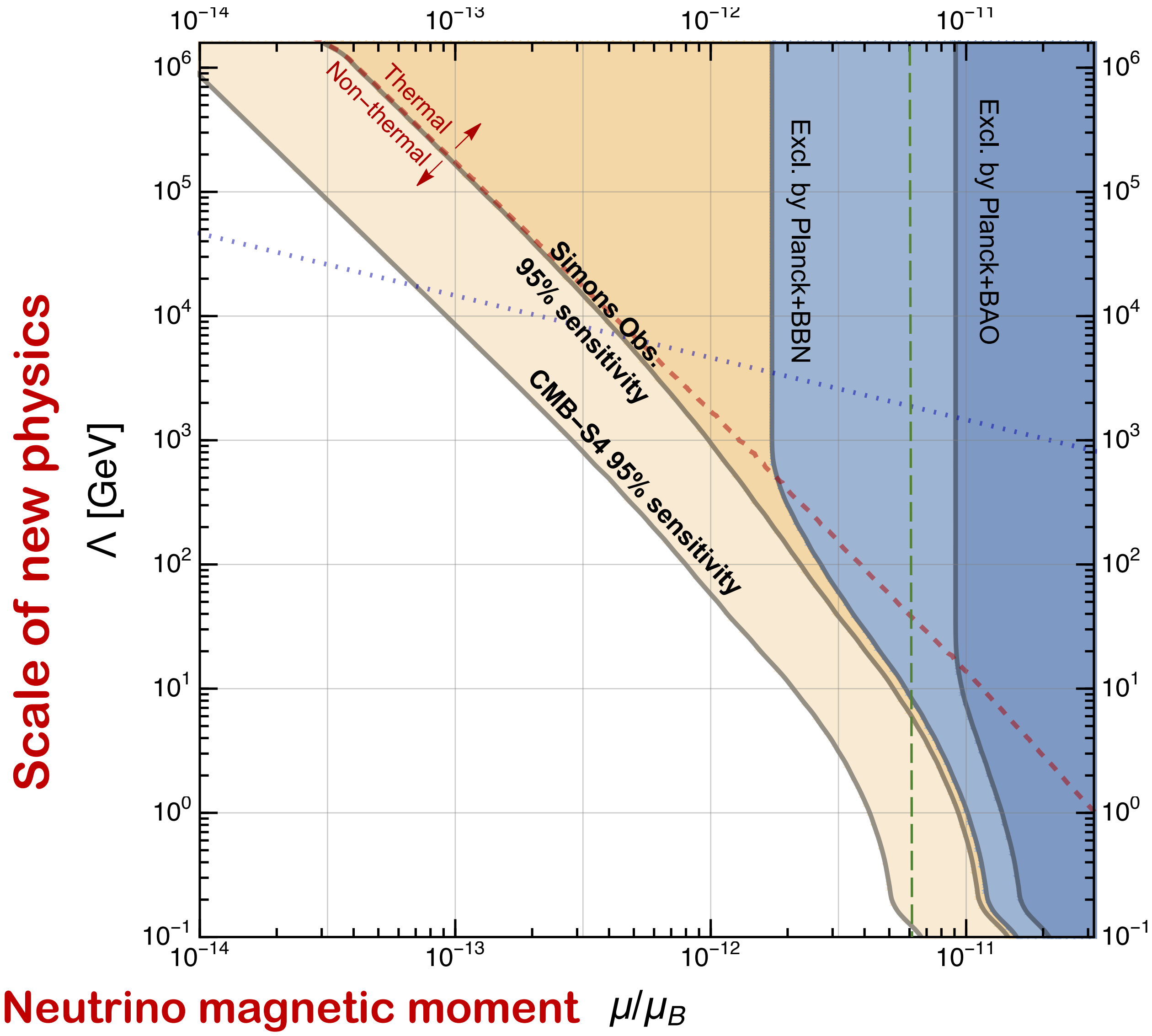


(95% CL bounds)

N_{EFF} FROM FREEZE-IN OF LIGHT SPECIES

Next generation CMB experiments will also allow to probe a completely different scenario, in which light relics have a subthermal abundance (“freeze-in” production)

Specific example: if neutrinos have magnetic moment, right-handed states can be populated from helicity flips in the plasma



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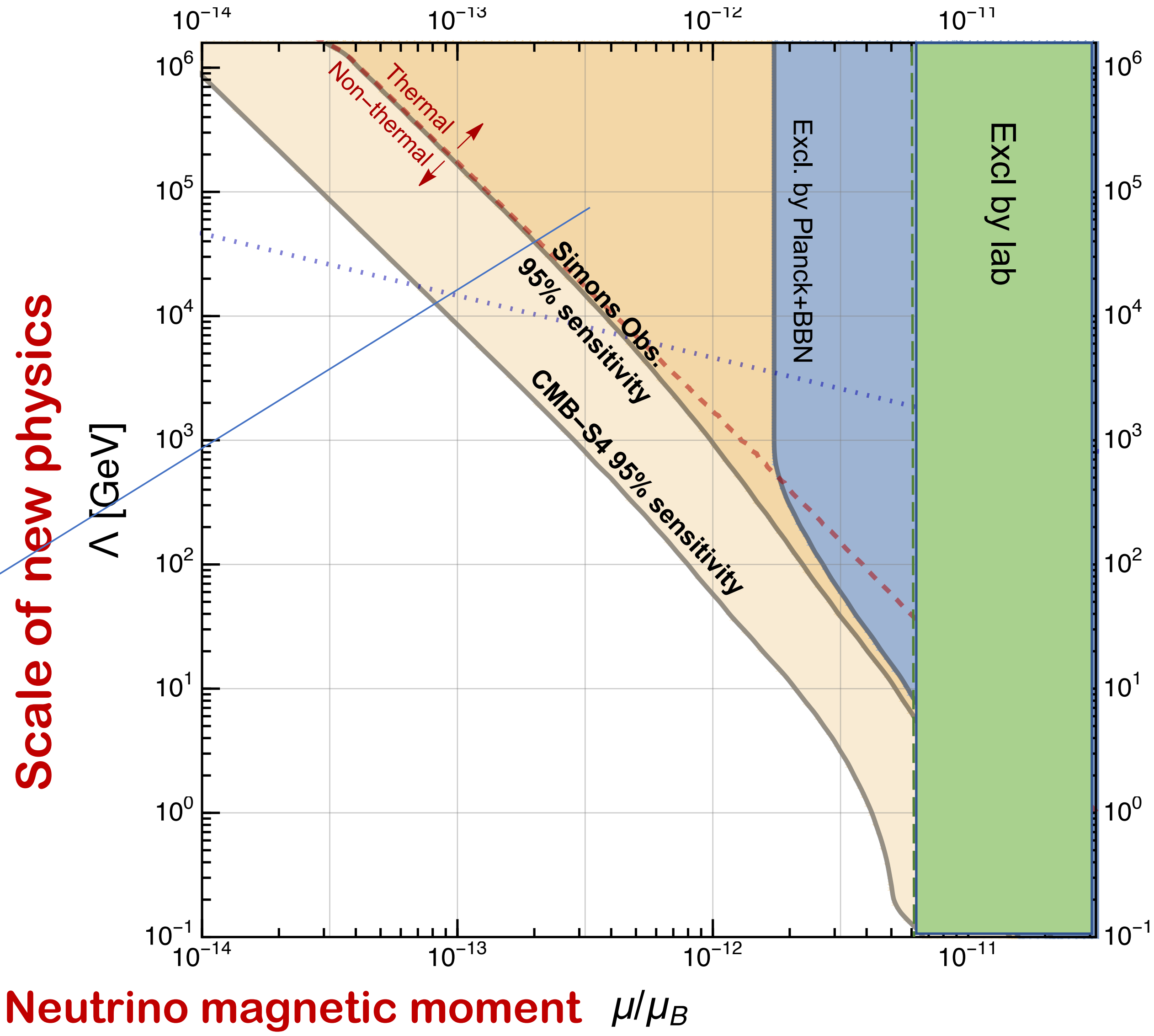


Discovery potential!

SUMMARY

- Coming years will bring a wealth of new, high-precision cosmological data.
- Next-generation cosmic microwave background (CMB) experiments like Simons Observatory, LiteBIRD, CMB-S4, will precisely characterize the CMB polarization anisotropies.
- This will allow to probe the physics of neutrinos and light relics, including
  - Neutrino masses and ordering
  - Neutrinos BSM interactions (self interactions, EM properties…)
  - Physics of neutrino decoupling
  - Thermal history
  - Presence of additional light species (axions, and axion-like particles, sterile neutrinos, …) possibly with sub-thermal abundances

THANKS!

BACKUP SLIDES

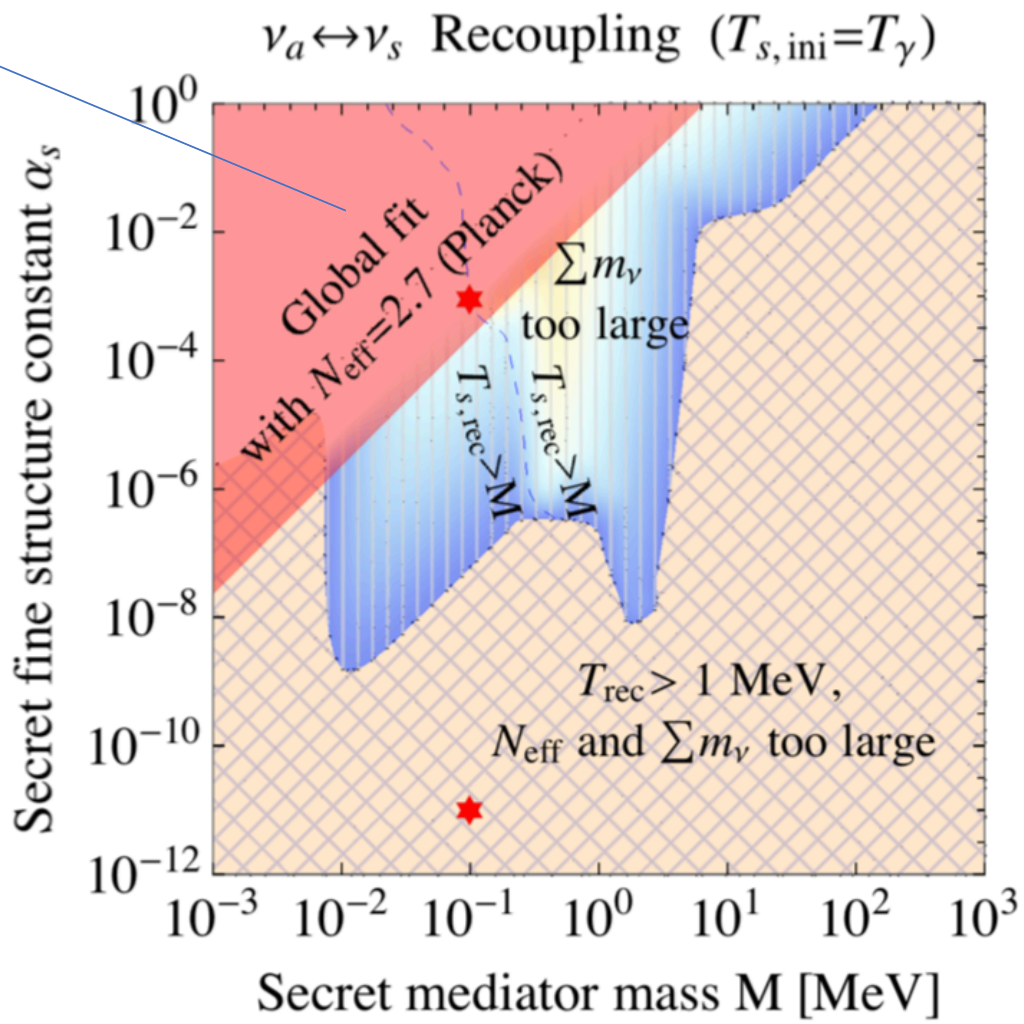
νNSI AND SBL ANOMALIES

Excluded region from Forastieri+ (incl ML) 2017

Catch-22 situation:

If nonstandard interactions are strong enough to prevent sterile neutrino free-streaming (and erase the neutrino mass bound) then they should leave an observable imprint on CMB anisotropies

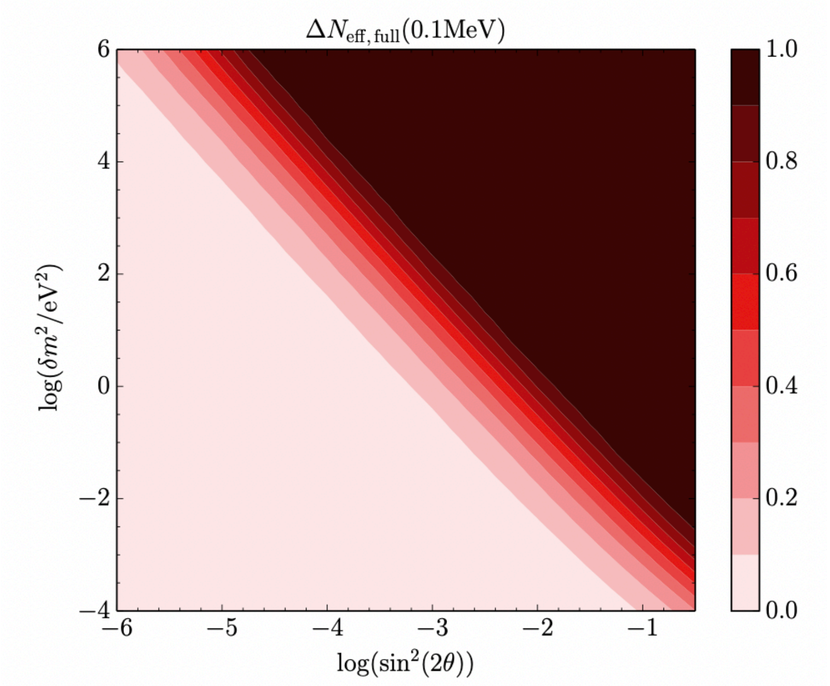
In the end, **you violate either the mass or the interaction strength bound.**



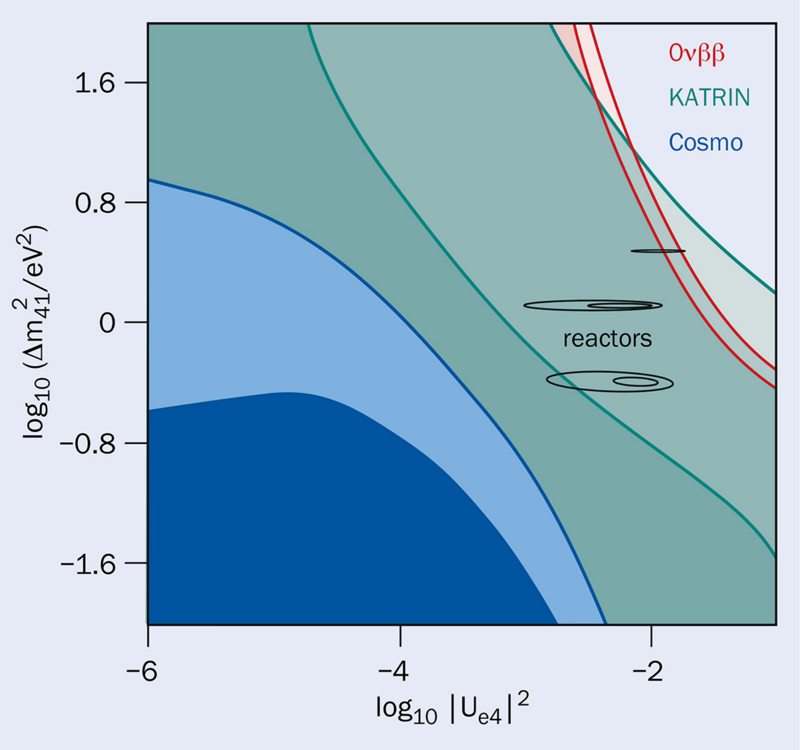
Plot from Chu et al. 2018

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



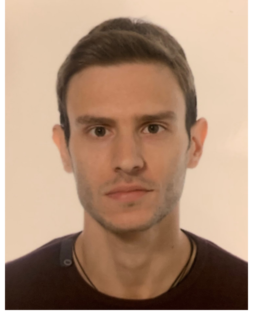
S. Hagstotz

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! (NSI? Large lepton asymmetries?)

See Hagstotz+ (incl ML) 2021

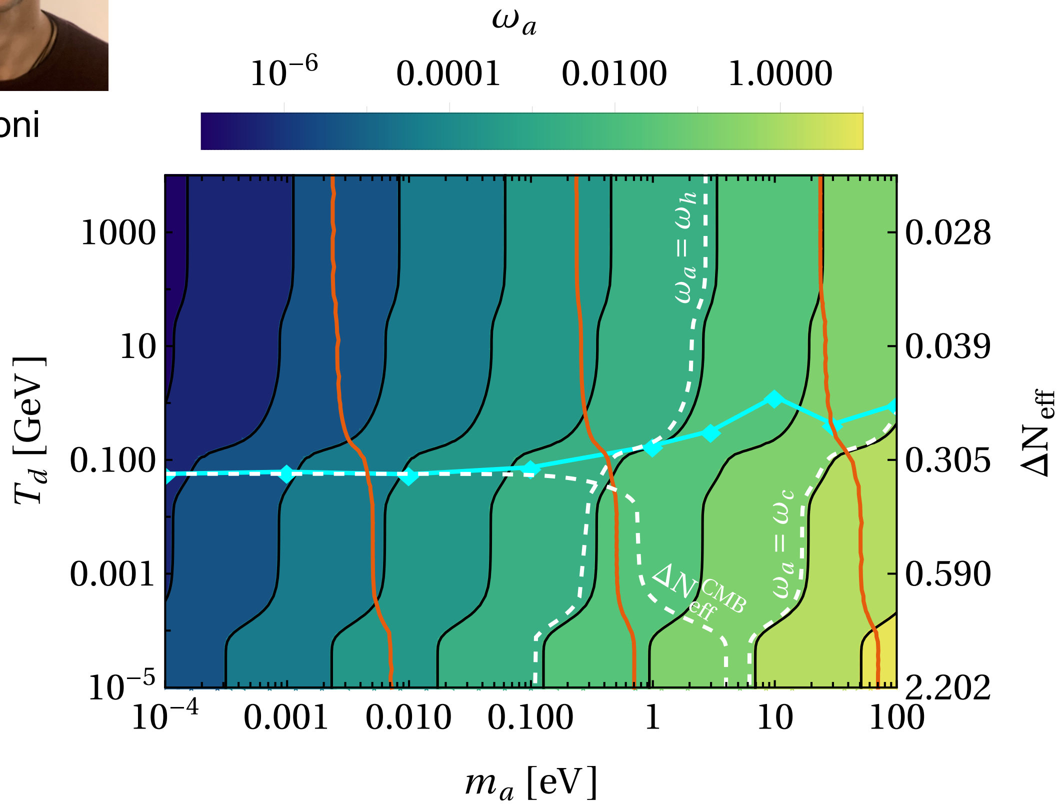
N$_{\text{EFF}}$ AND THERMAL AXIONS

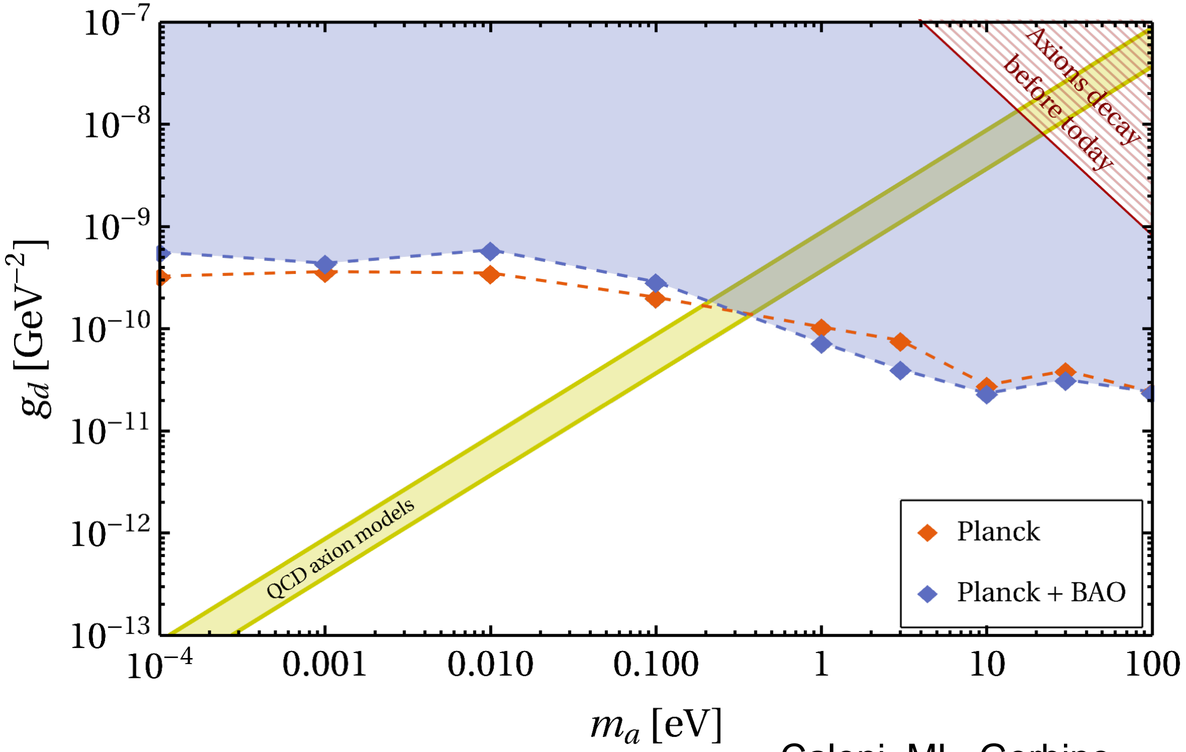


L. Caloni

Axions can be produced thermally in the early Universe through their coupling to photons or **gluons**

$$\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^{i}_{\mu\nu}\tilde{G}^{\mu\nu,i}$$

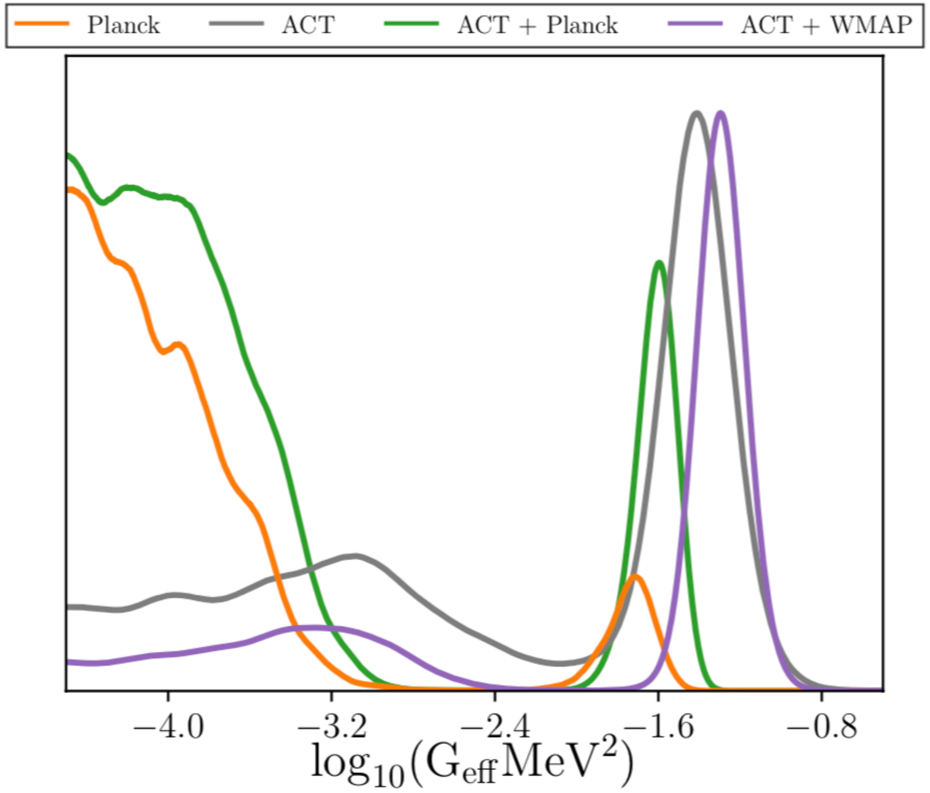




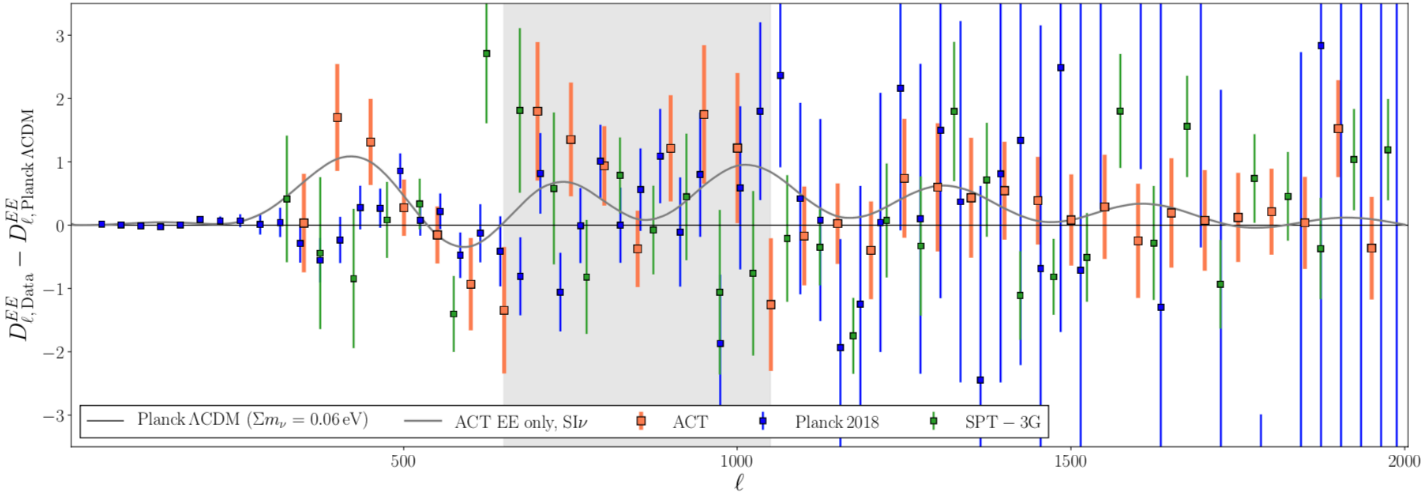
Caloni, ML, Gerbino, Visinelli, 2022

ν NSI IN COSMOLOGY

Preference for delayed onset of neutrino free streaming in the ACT data?

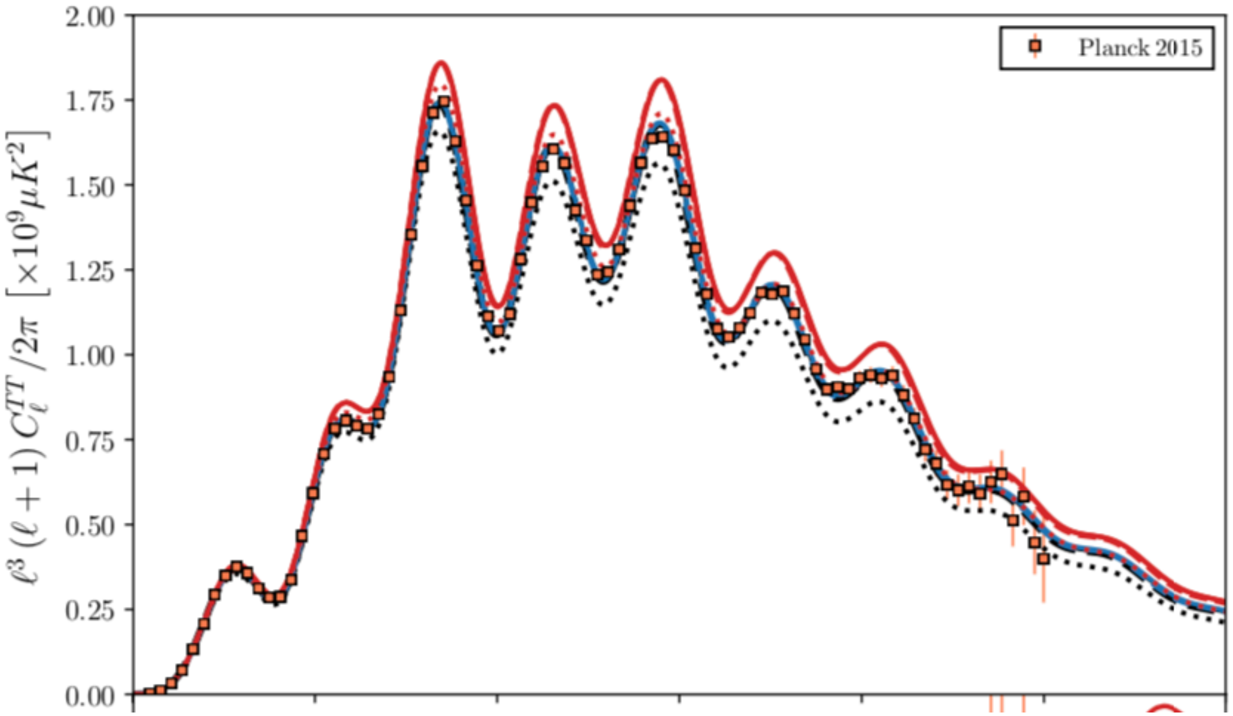


Driven by the ell range 700-1000 in the EE data

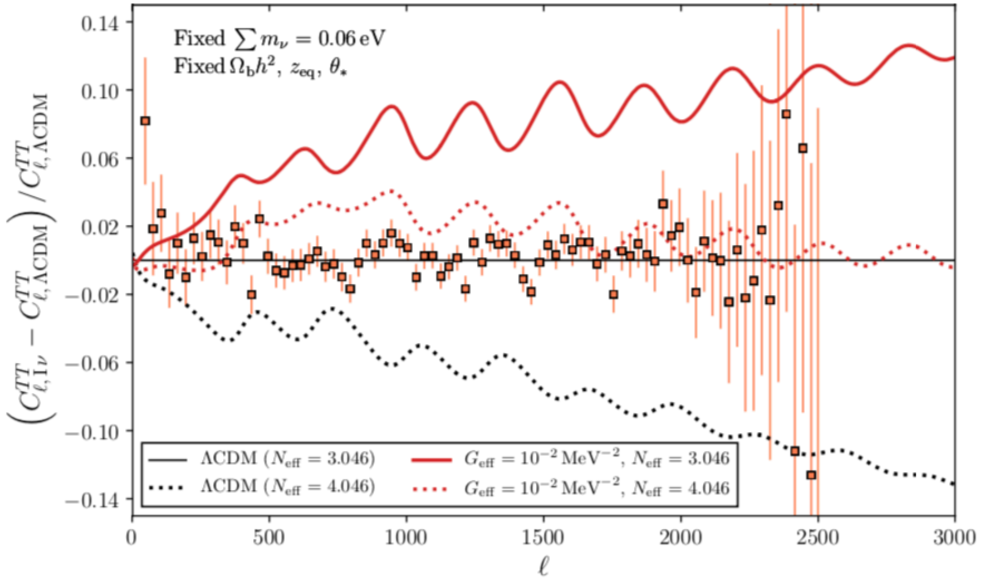


Kreisch et al. 2207.03164

νNSI AND CMB ANISOTROPIES: HEAVY MEDIATOR

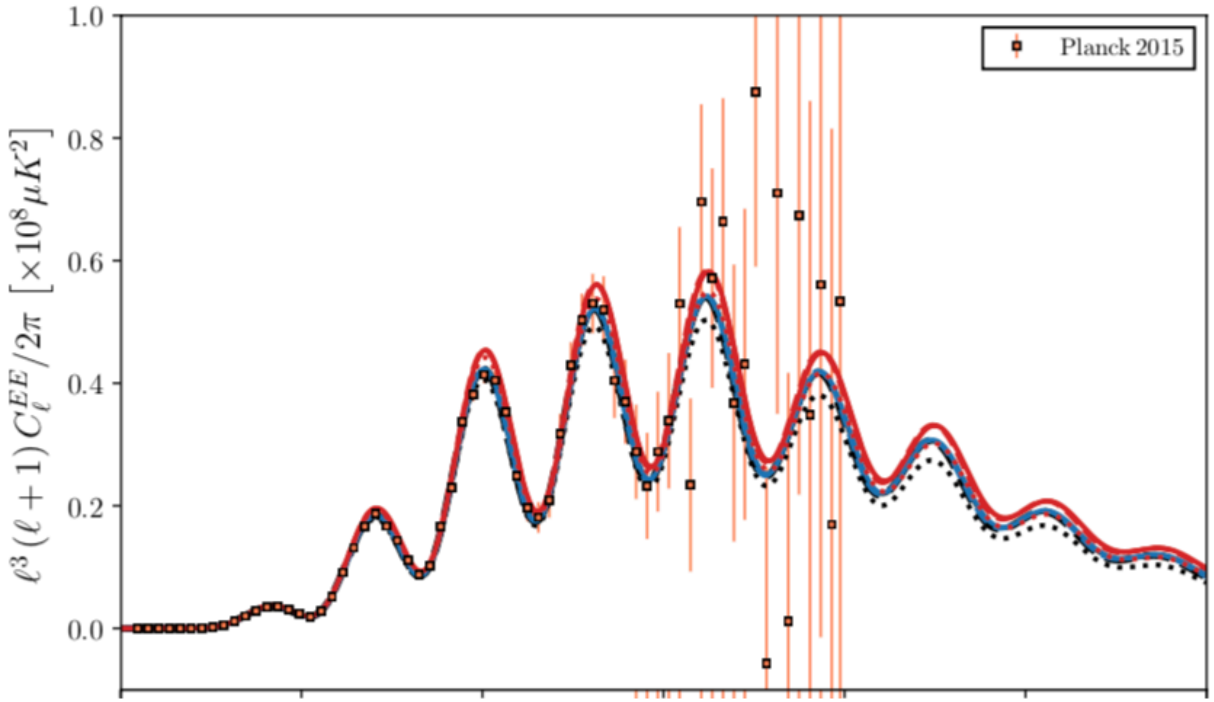


Scales entering the horizon before decoupling are affected
i.e. smaller scales are more affected



Kreisch, Cyr Racine & Dore 2019
See also Cyr-Racine & Sigurdson 2014; Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Wong 2017

νNSI AND CMB ANISOTROPIES: HEAVY MEDIATOR



Kreisch, Cyr Racine & Dore 2019
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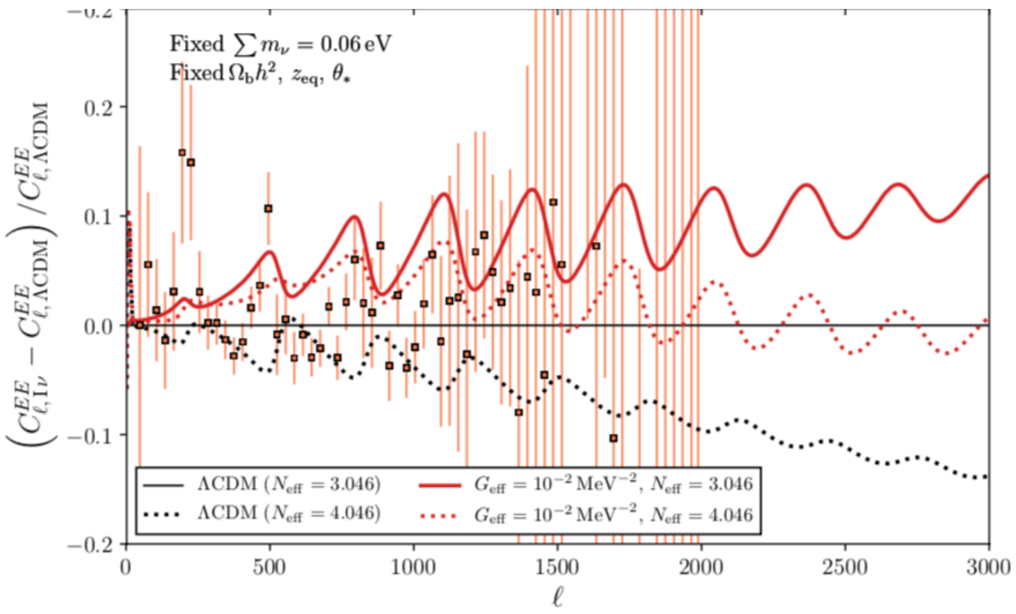
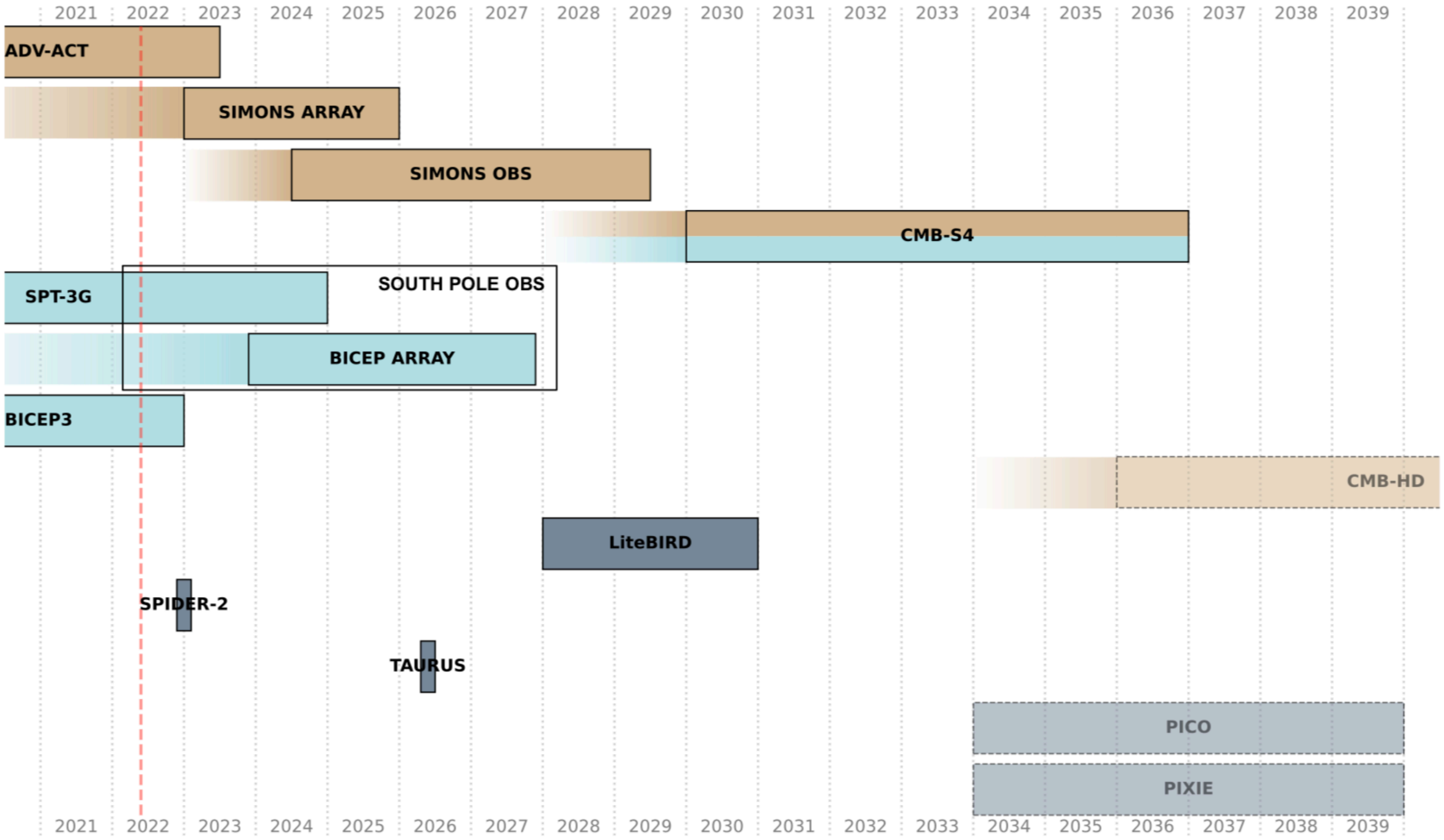
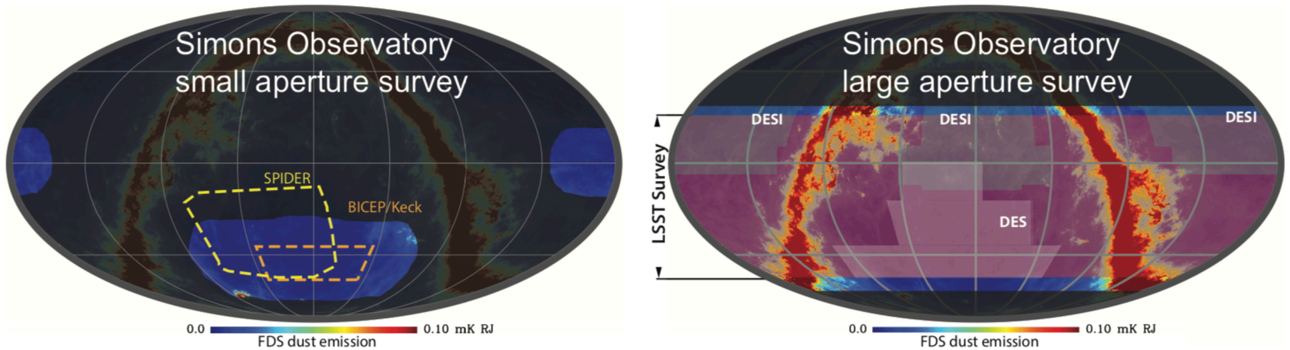


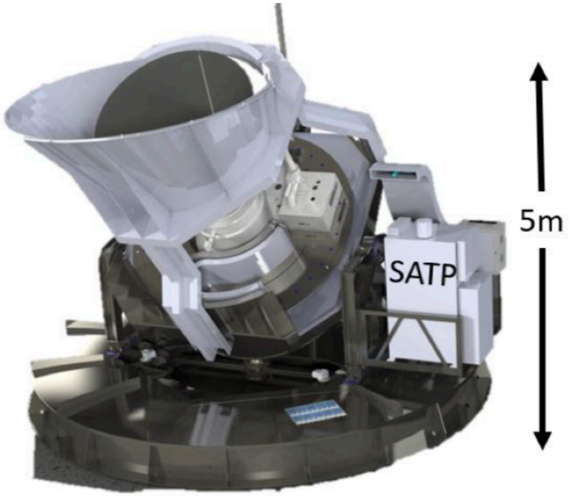
TIMELINE OF CMB EXPERIMENTS



Snowmass2021 Cosmic Frontier: CMB Measurements White Paper
arXiV: 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

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

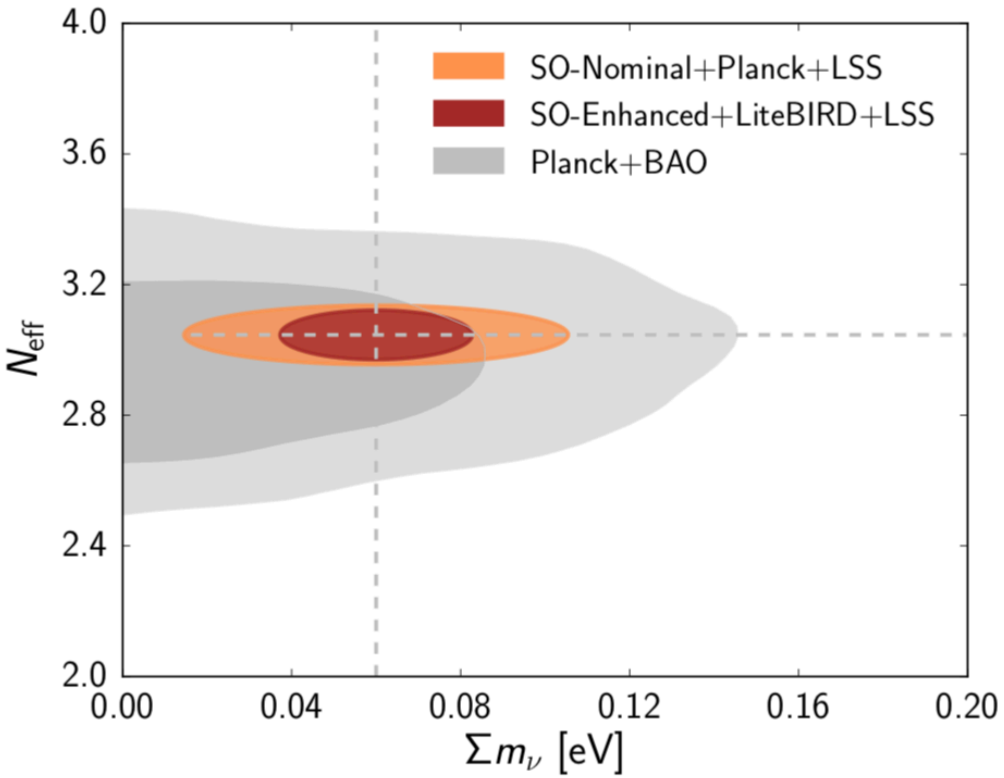
$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

•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

SIMONS OBSERVATORY



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

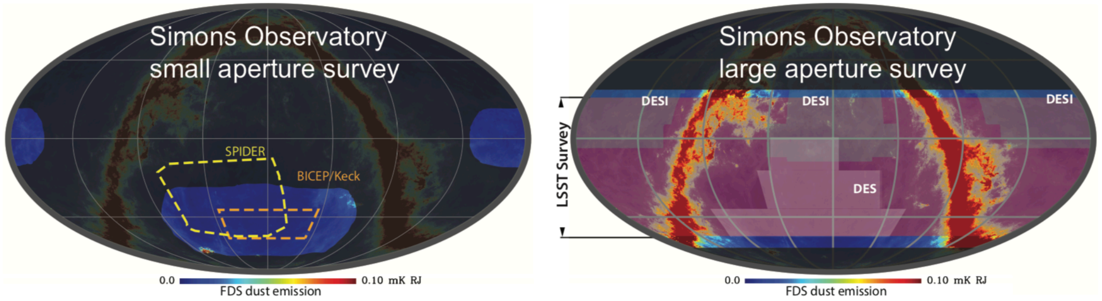
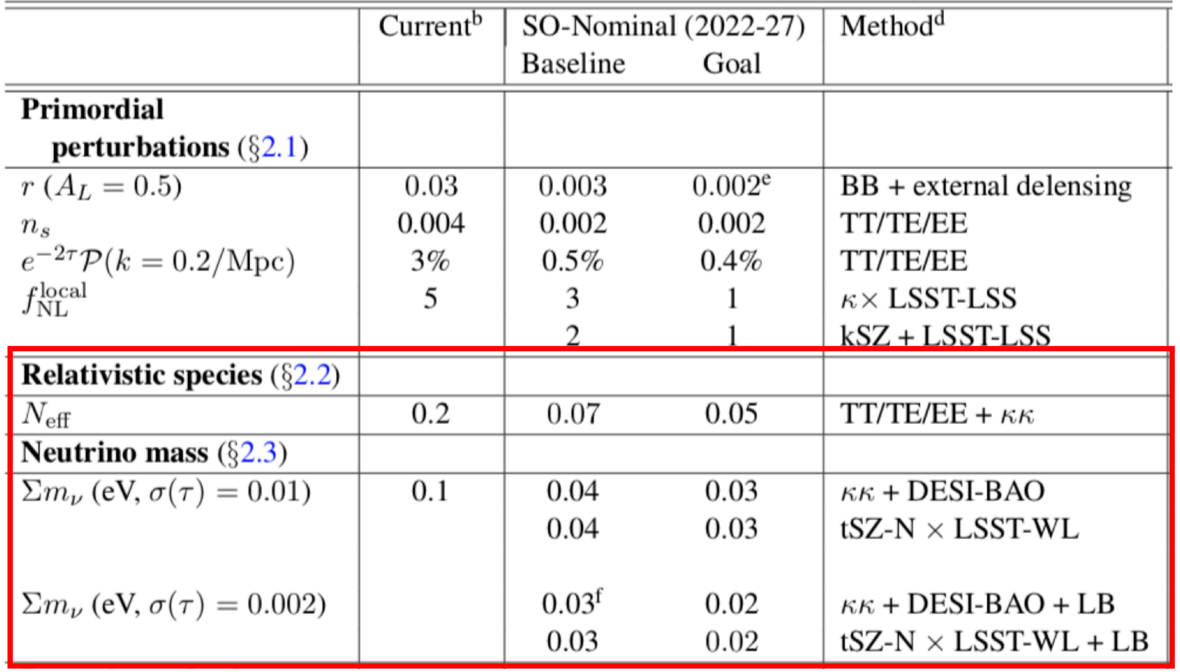
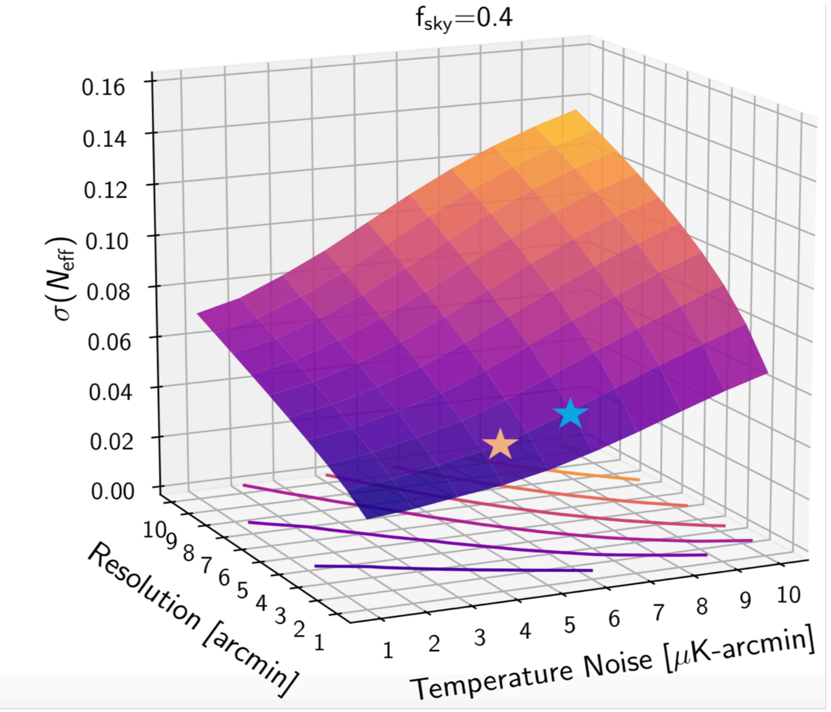


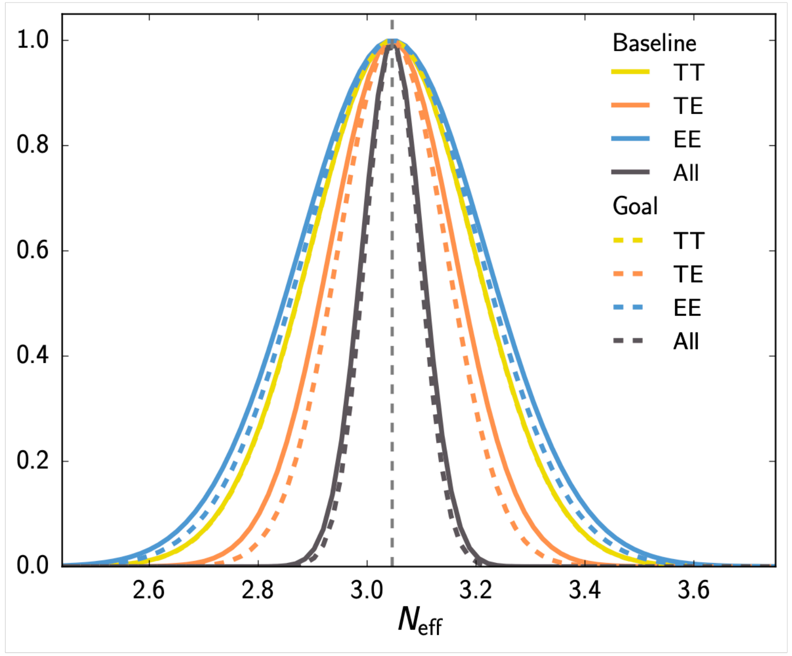
Table 1: Summary of SO-Nominal key science goals[a]

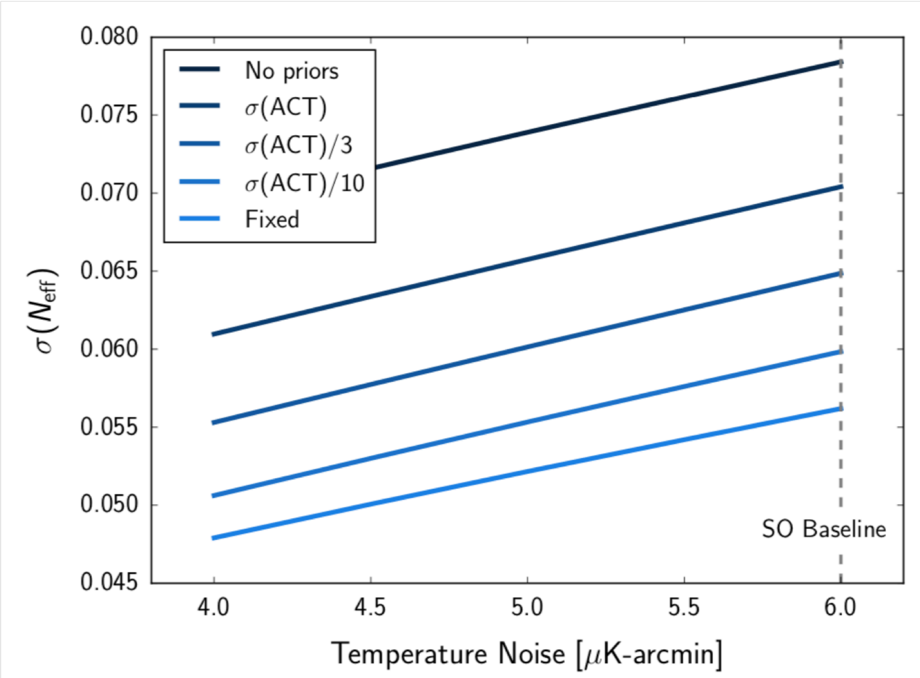


	Current[b]	SO-Nominal (2022-27)		Method[d]
		Baseline	Goal	
Primordial perturbations (§2.1)				
r $(A_L = 0.5)$	0.03	0.003	0.002[e]	BB + external delensing
n_s	0.004	0.002	0.002	TT/TE/EE
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	3%	0.5%	0.4%	TT/TE/EE
$f_{\rm NL}^{\rm local}$	5	3	1	$\kappa\times$ 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 $\times$ 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 $\times$ LSST-WL + LB

N_{EFF} FROM SO







SO collaboration, 2018

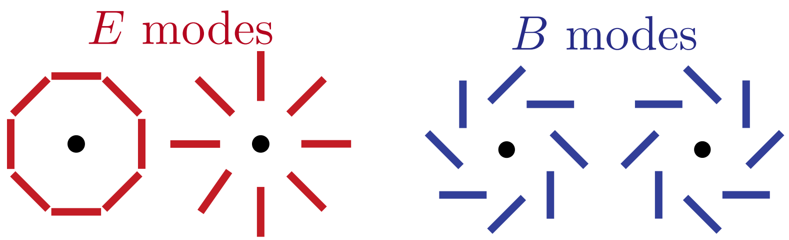
$$\boxed{\sigma(N_{\rm eff}) = 0.07\ [0.05]}$$

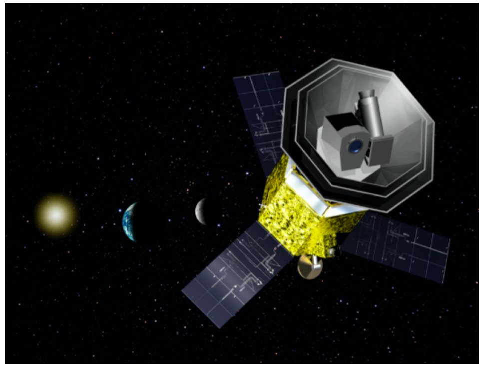
LiteBIRD

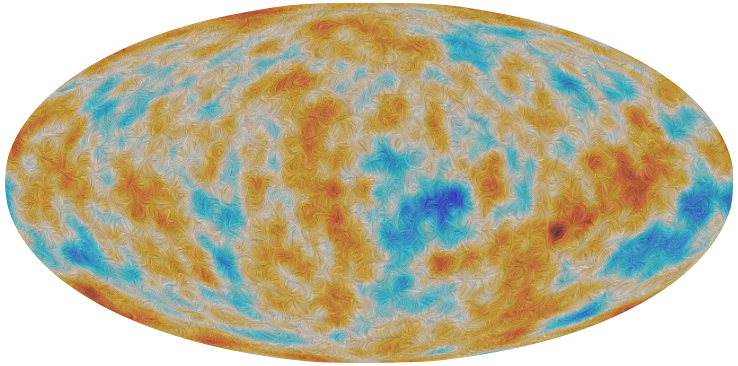
A JAXA-led post-Planck space mission for CMB polarization, with participation from US and Europe

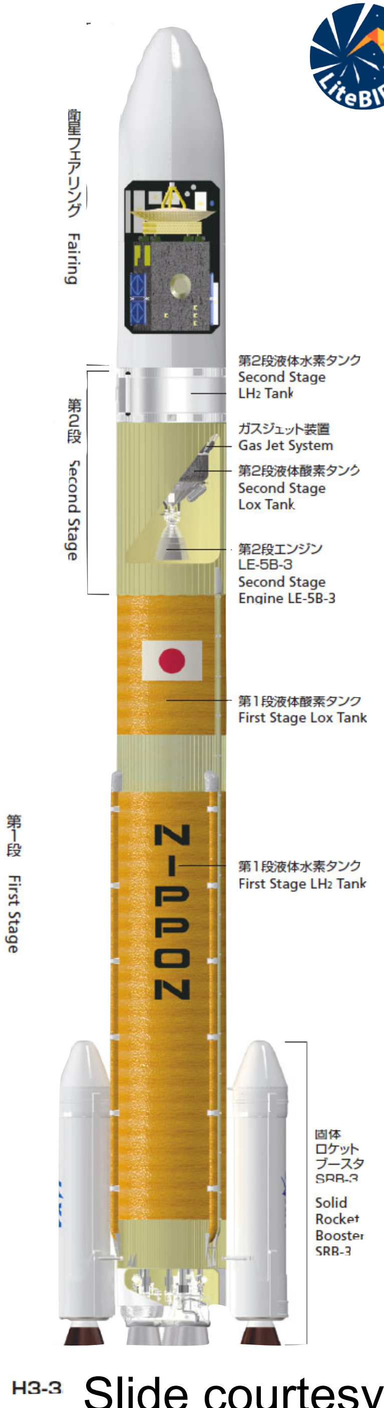
LiteBIRD Overview

- 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 μK arcmin, after component separation





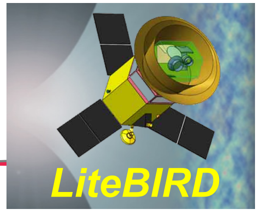




Slide courtesy: G. Signorelli

CMB-S4 - LITEBIRD

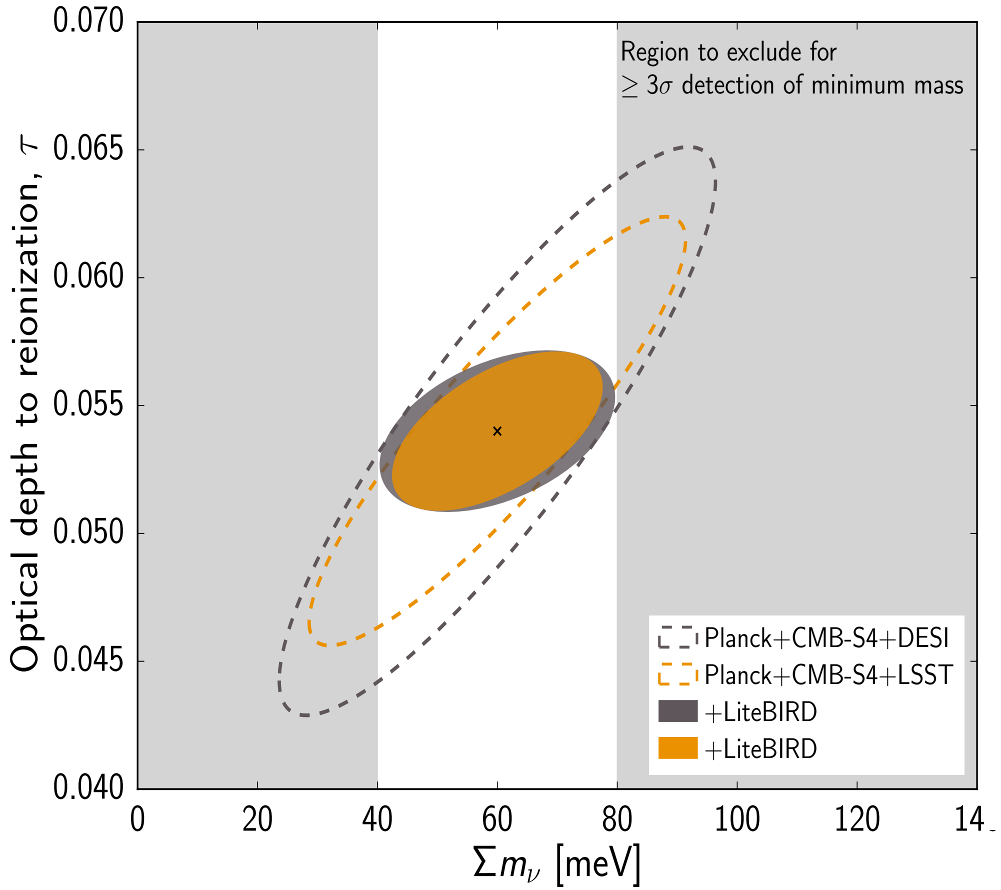
Σm_ν w/ improved τ

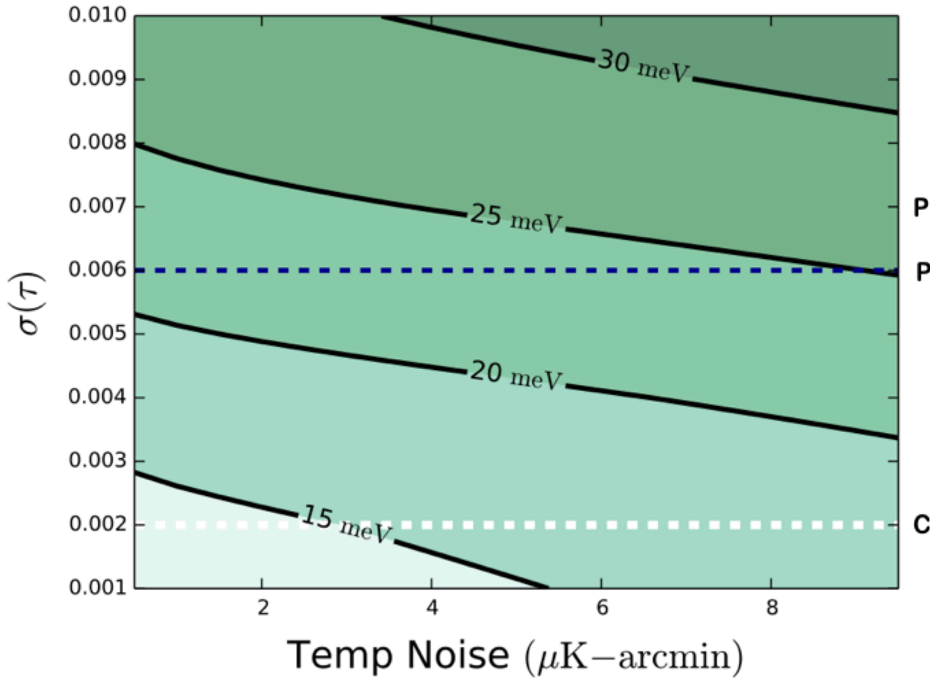


LiteBird Collaboration, arXiv:2202.02773

- $\sigma(\Sigma m_\nu) = 15$ 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.





CMB-S4 Collaboration, 2019

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)

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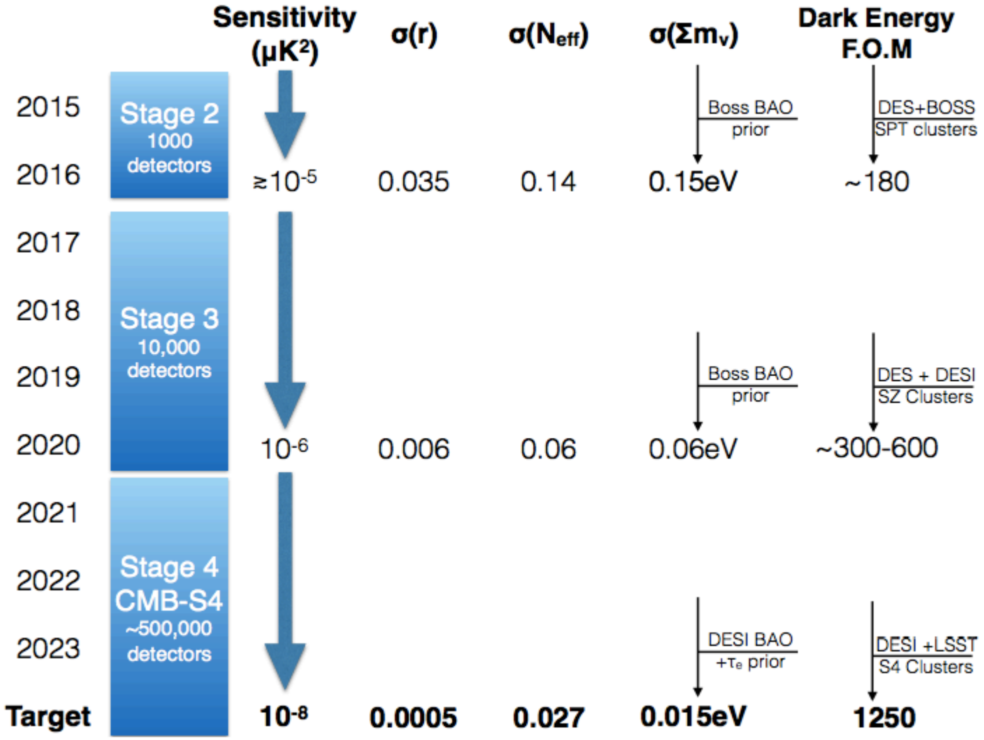


		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		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**

$\sigma(N_{eff}) = 0.027$

See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

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

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, …**

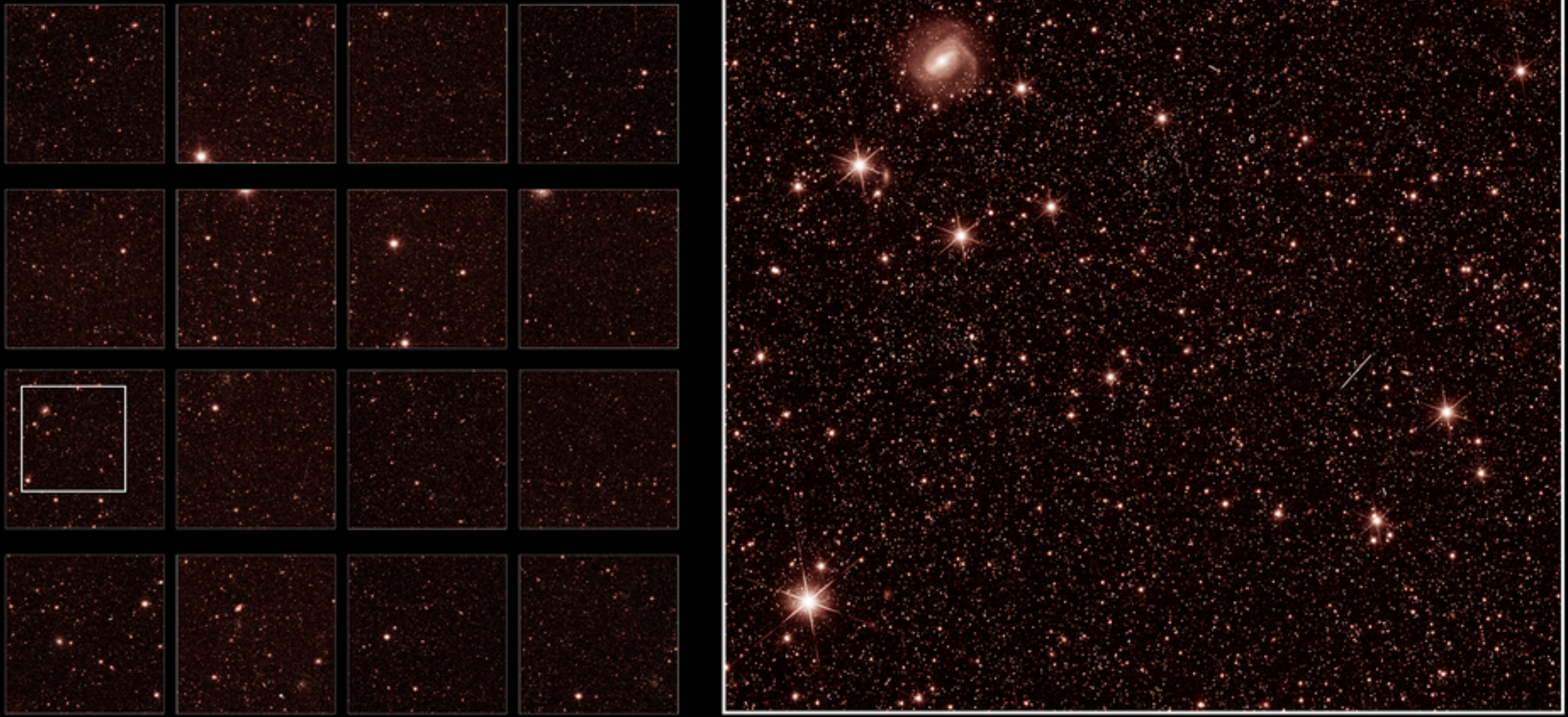
Euclid will measure **weak lensing** and **galaxy clustering** observing 15.000 deg^2 (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg^2)

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

Euclid lift-off on July 1st, 2023!

Currently in performance verification phase

EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT



FORECASTS FOR FUTURE CMB+LSS

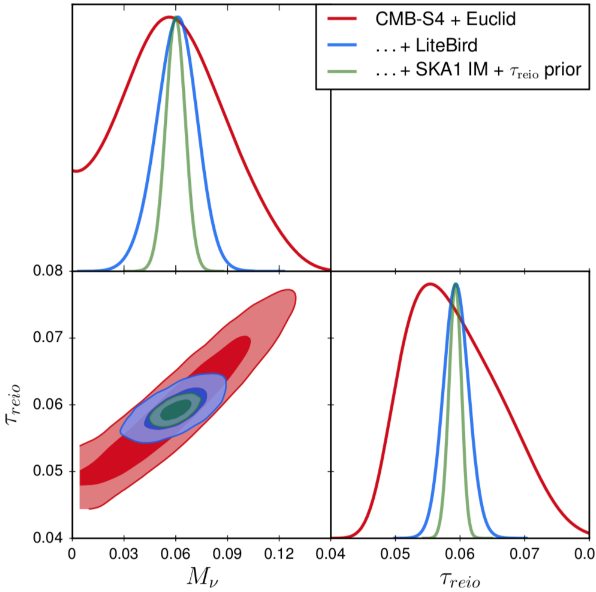
$\sigma(\Sigma m_\nu) = 0.04$ eV from SO (primary+lensing)
+ DESI BAO
(SO Collaboration 2018)

$\sigma(\Sigma m_\nu) = 0.042$ 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