COSMOLOGICAL CONSTRAINS ON NEUTRINOS AND OTHER LIGHT RELICS

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International Conference on the Physics of the Two Infinities

Kyoto, Mar 30th, 2023

Cosmic Neutrino Background (CνB)

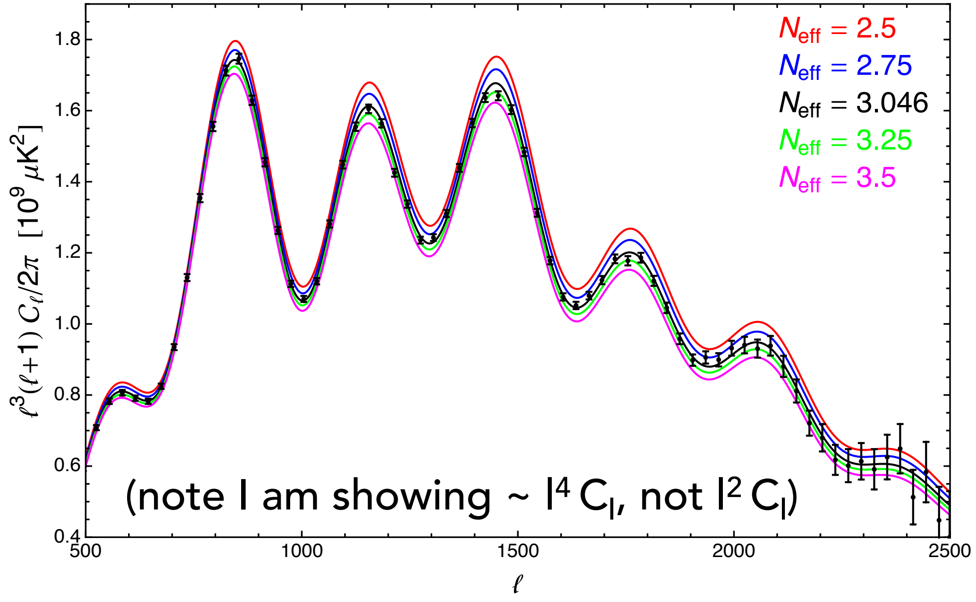
- Neutrinos are the most abundant (number wise) particles in the Universe today, after photons
  ~ 100 particles/cm^3 per family…
- …and were contributing a significant fraction of the energy density during the radiation-dominated era

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

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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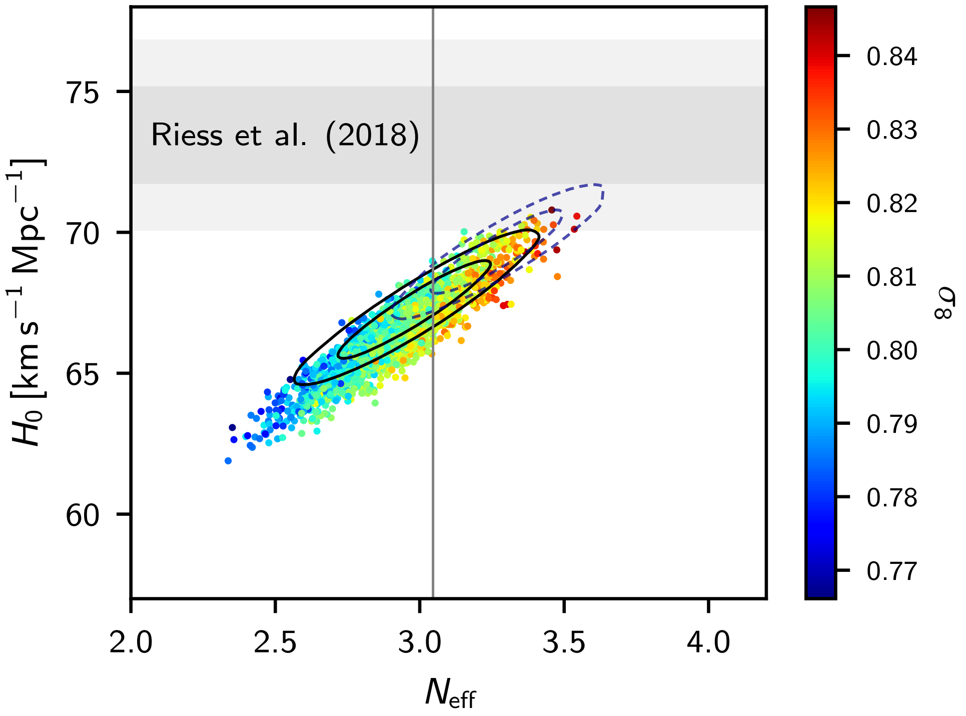

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$$N_{eff} = 3.0440 \pm 0.0002$$

$N_{\rm eff}$ 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

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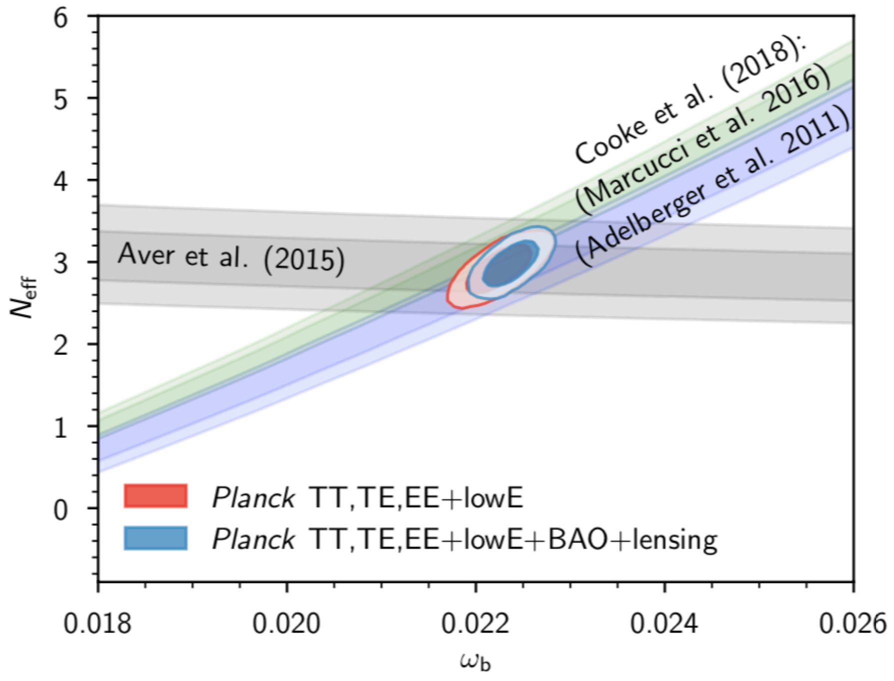


Planck collaboration, VI 2018

Theoretical expectation for the three SM neutrinos:

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

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

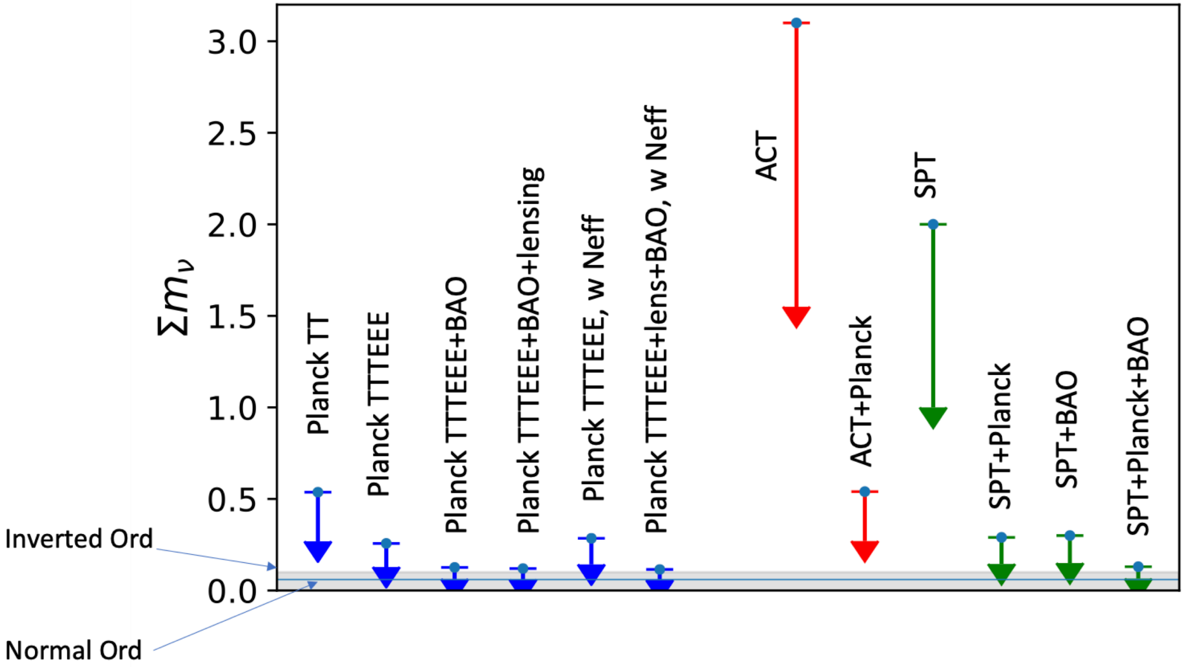
$N_{\rm eff}$ = 2.86 +/- 0.28 [Yp + D/H]

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

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

NEUTRINO MASSES AND COSMOLOGY

- The neutrino abundance and N_{eff} are essentially fixed by the freeze-out of weak interaction, i.e. by the competition between expansion (GR+cosmological principle) and the weak interaction rate (SM).
- Only free parameter in the ν sector is the sum of the masses
- We should really start thinking of LCDM as a 7-parameter model….



See M. Gerbino's talk on Monday!

NEFF AS A PROBE OF NEW PHYSICS

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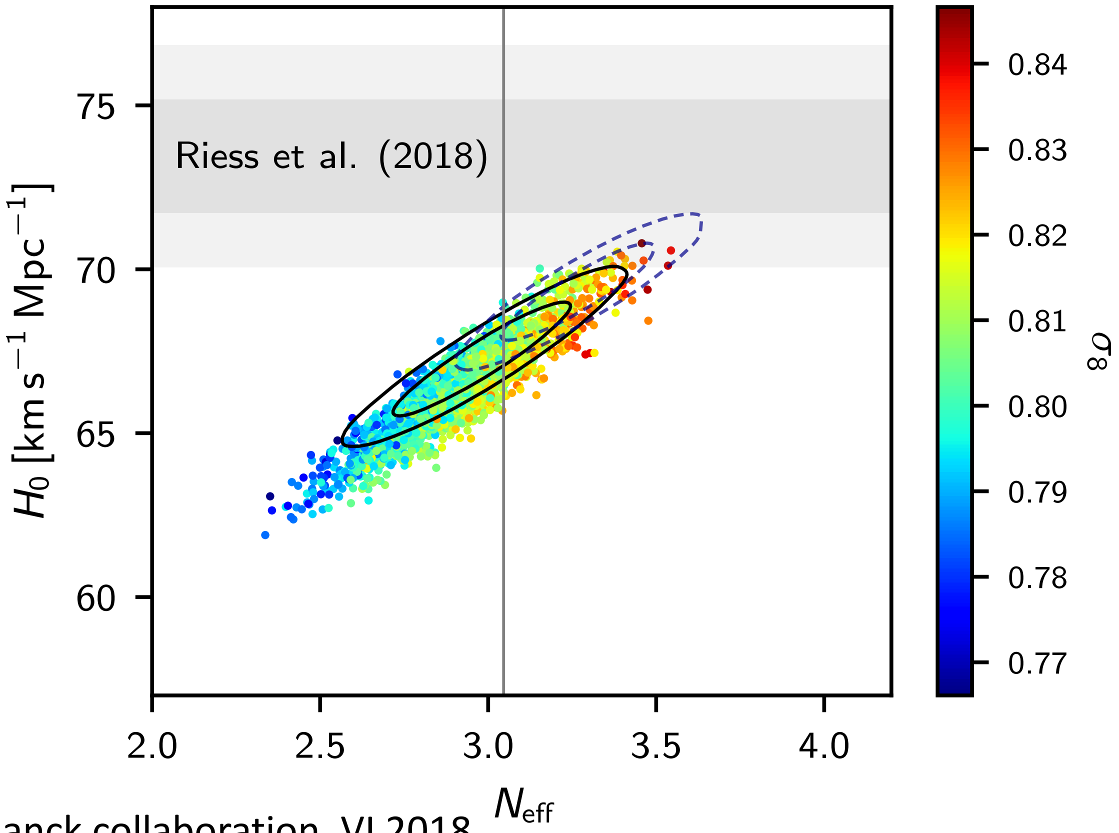

Planck collaboration, VI 2018

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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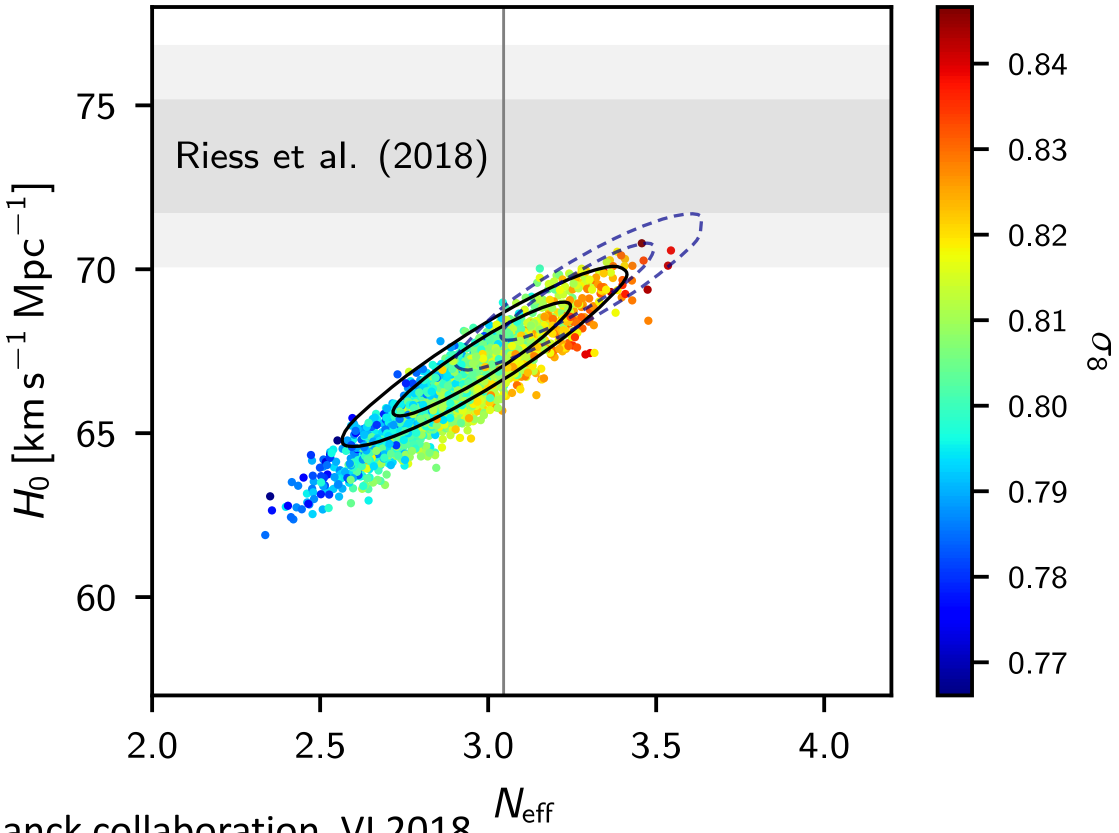


Planck collaboration, VI 2018

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

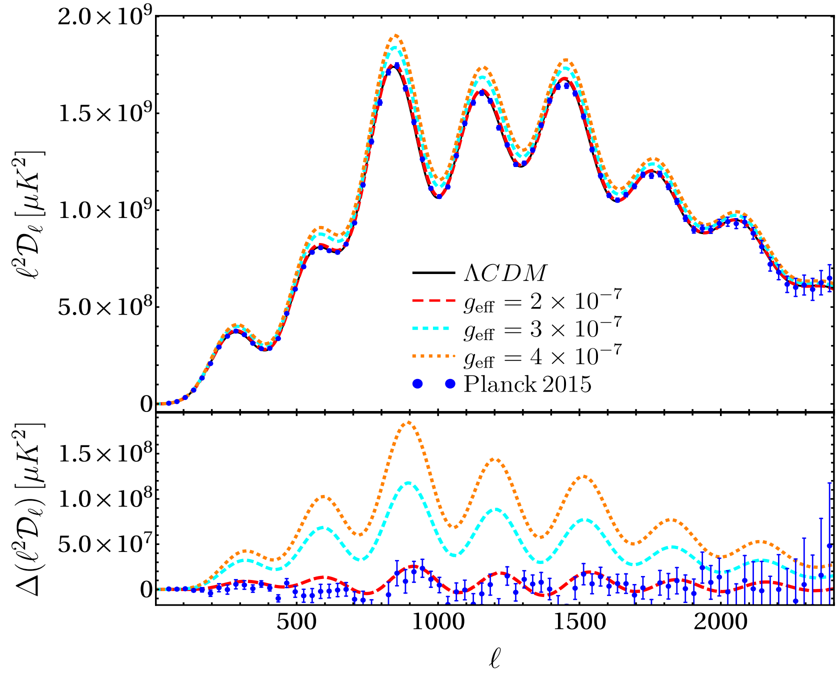
(not really much different from the present situation with dark matter and dark energy, if you think of it!)

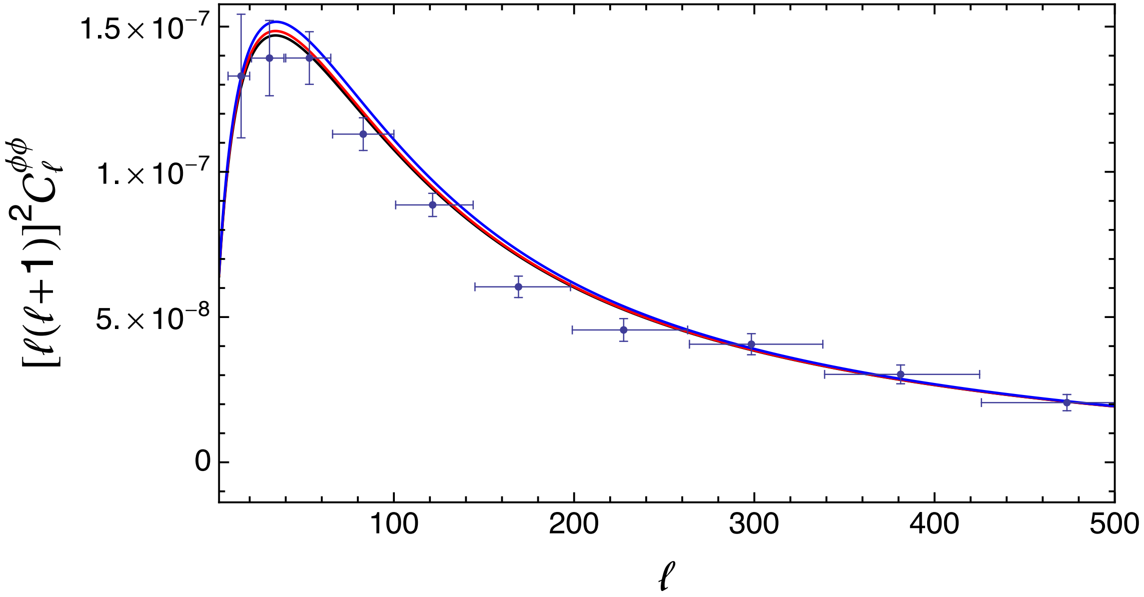
ν NSI IN COSMOLOGY

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** →

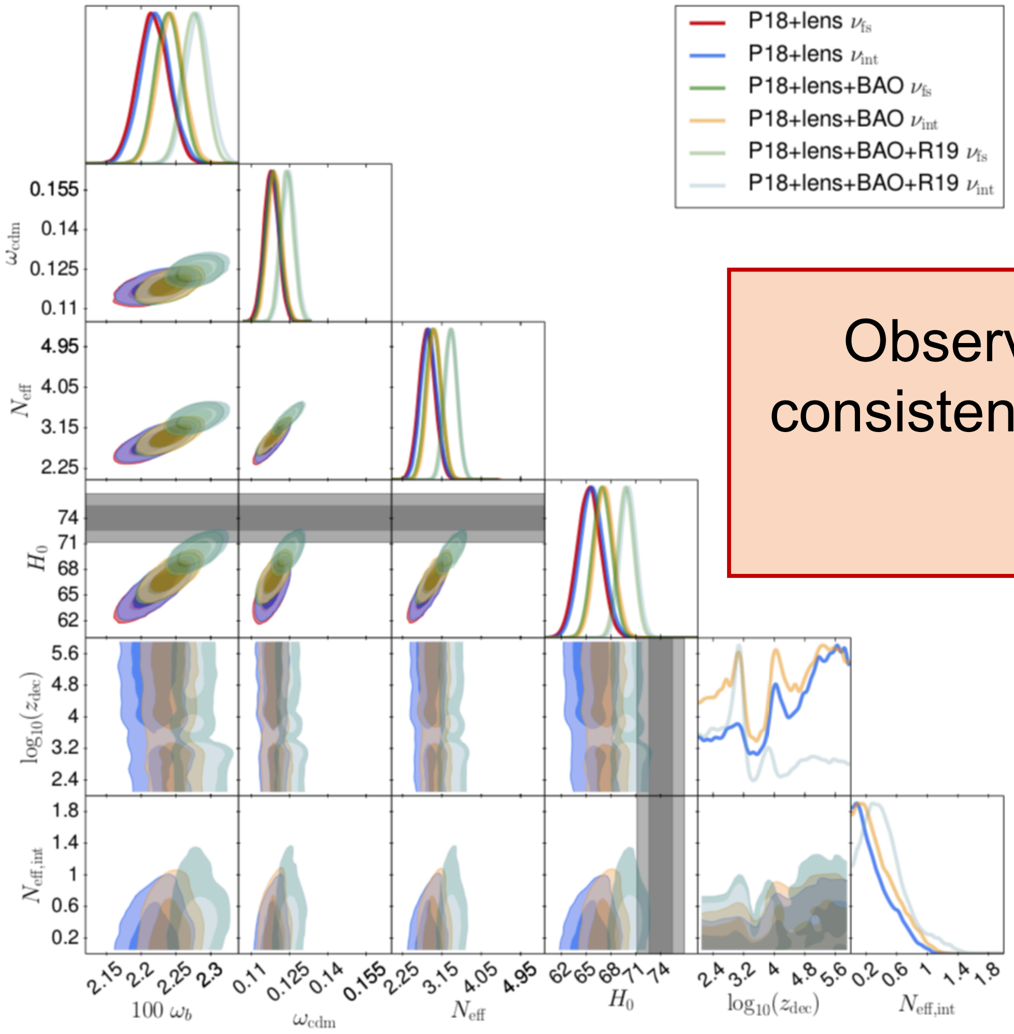
$$\mathcal{L}_{\rm int} = \frac{i}{2} g \phi \bar{\nu}_i \gamma^5 \nu_i$$





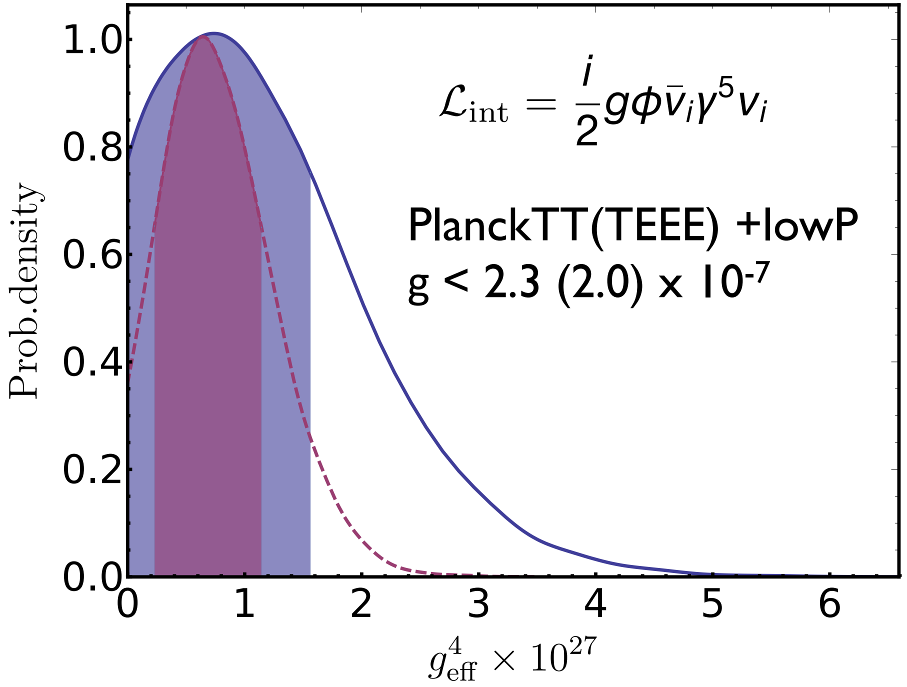
Self-interactions suppress neutrino free-streaming ➡ larger fluctuations in the gravitational potentials

ν NSI IN COSMOLOGY



Brinckmann, Chang, LoVerde, 2021

Observations are mostly consistent with free-streaming neutrinos



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

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

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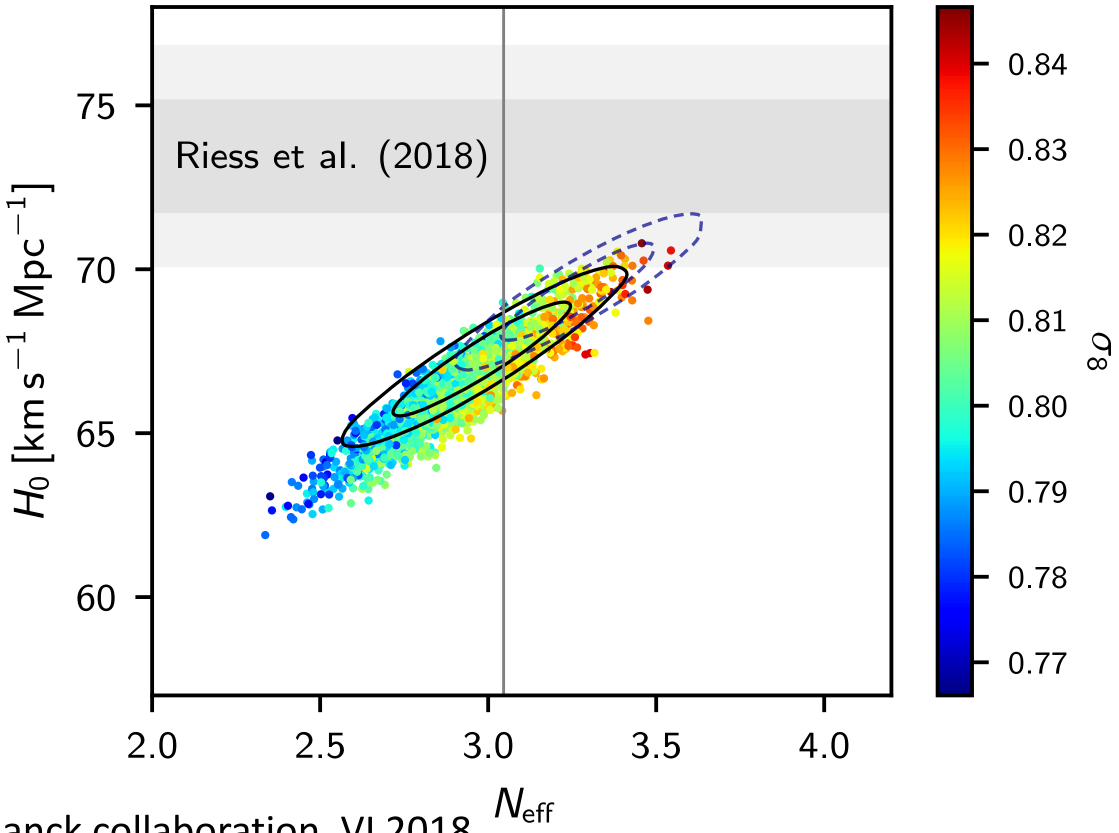

Planck collaboration, VI 2018

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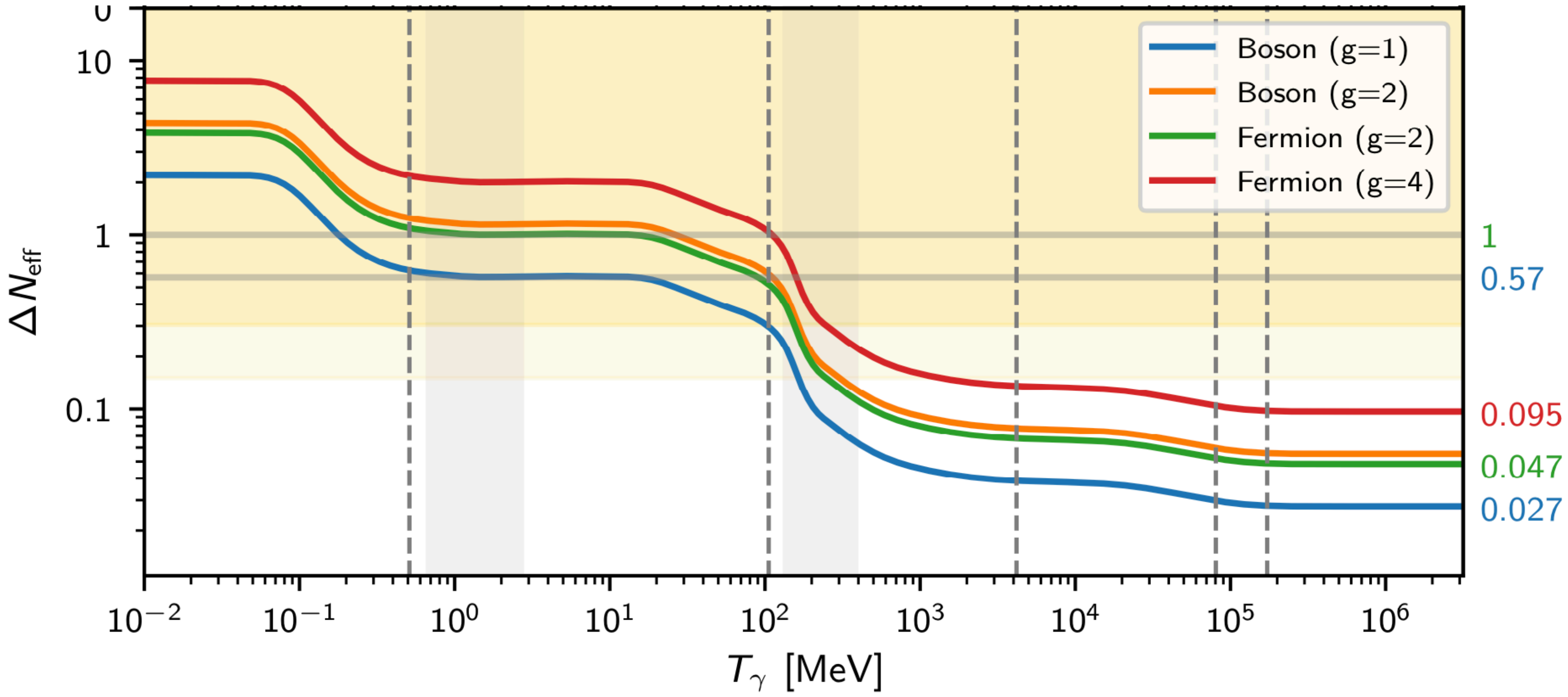
- …..

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

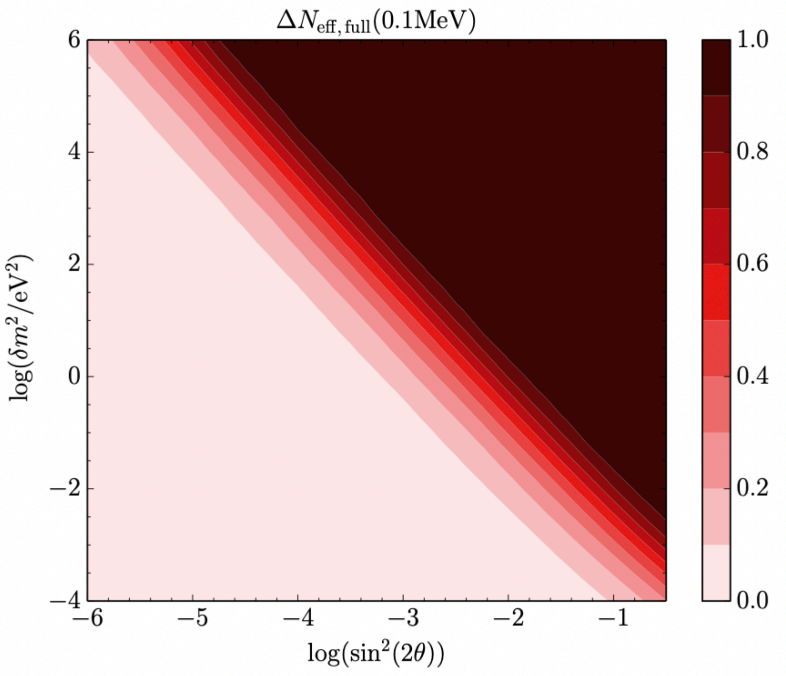
For a species that was in thermal equilibrium in the early Universe, ΔN_{eff} is directly related to the decoupling temperature:



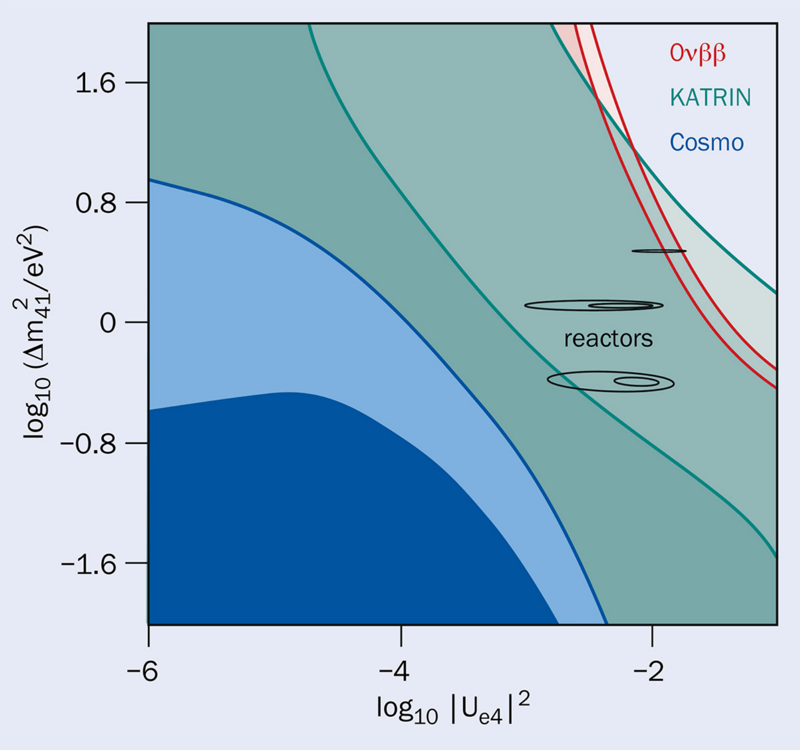
Planck collaboration, VI 2018

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



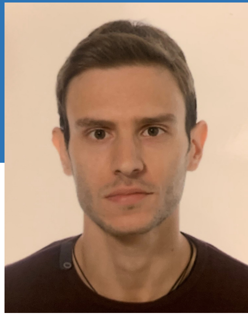
S. Hagstotz

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_{EFF} AND THERMAL AXIONS

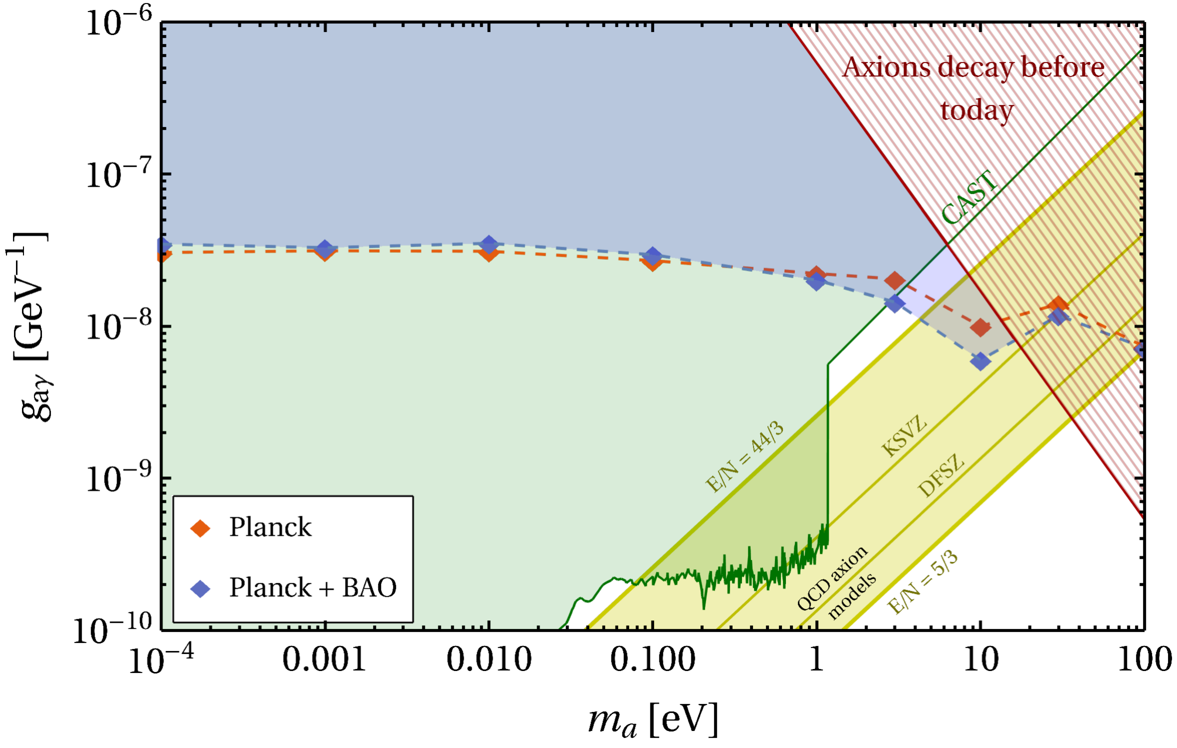


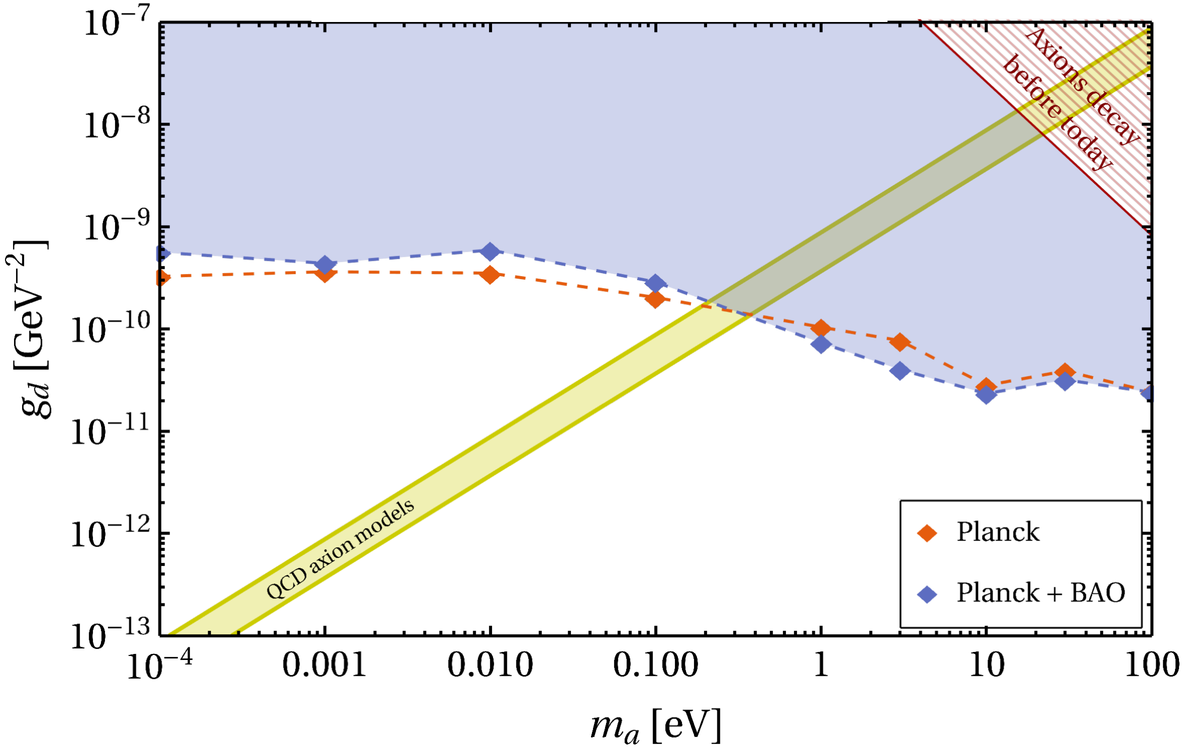
L. Caloni

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

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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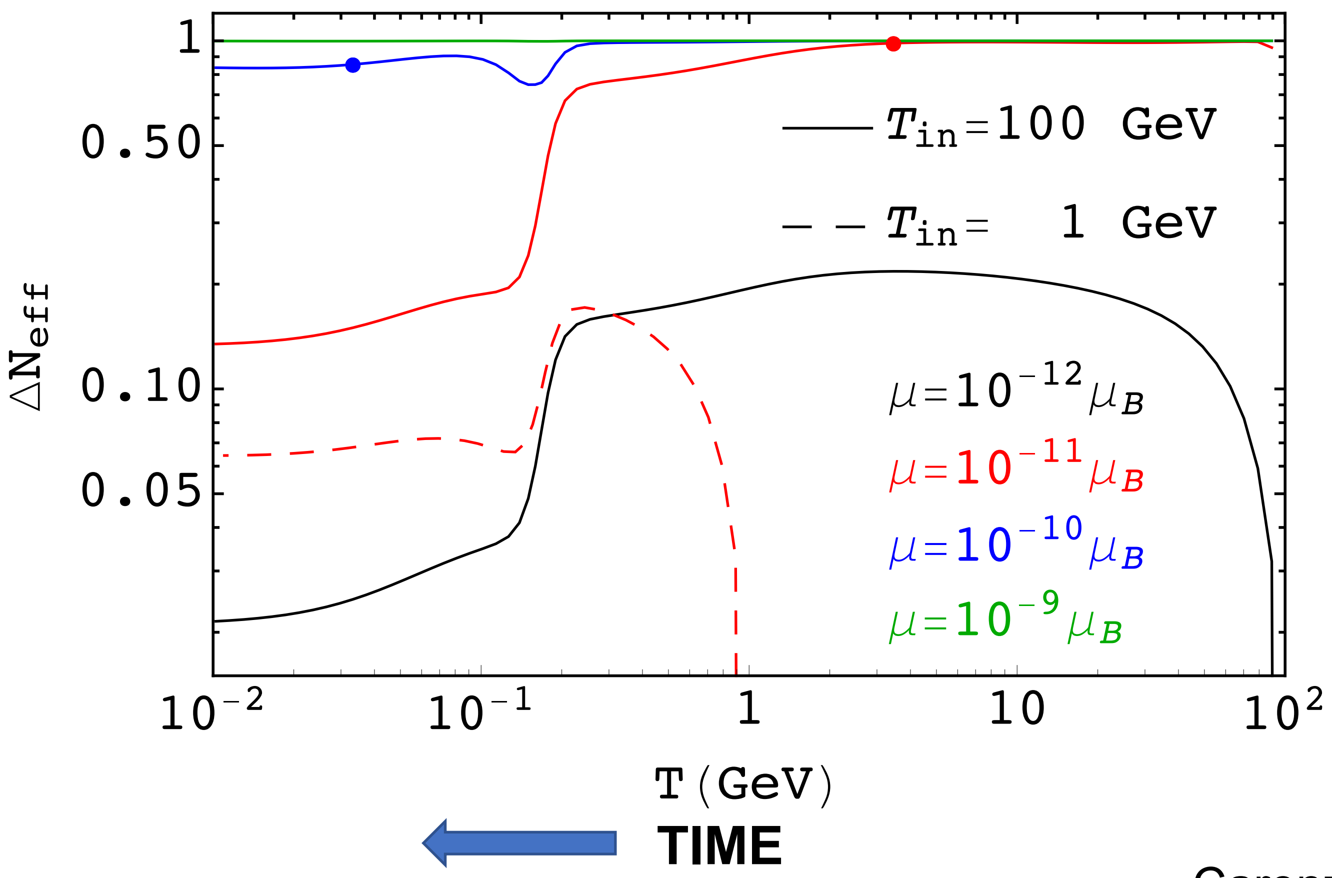

Carenza+ (incl ML, arXiv:2211.0432)

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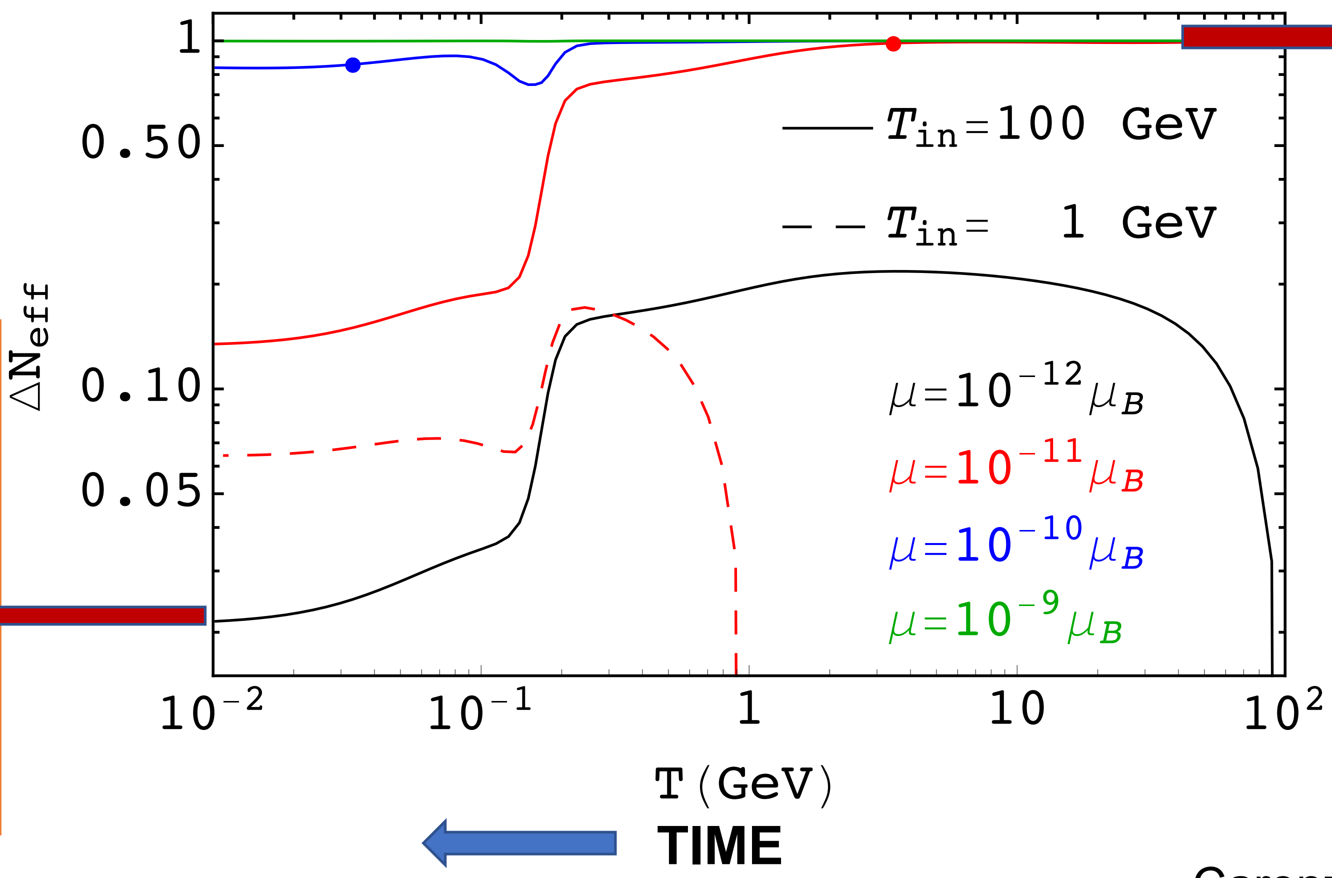


"Large" magnetic moment: thermal equilibrium is established at early times.

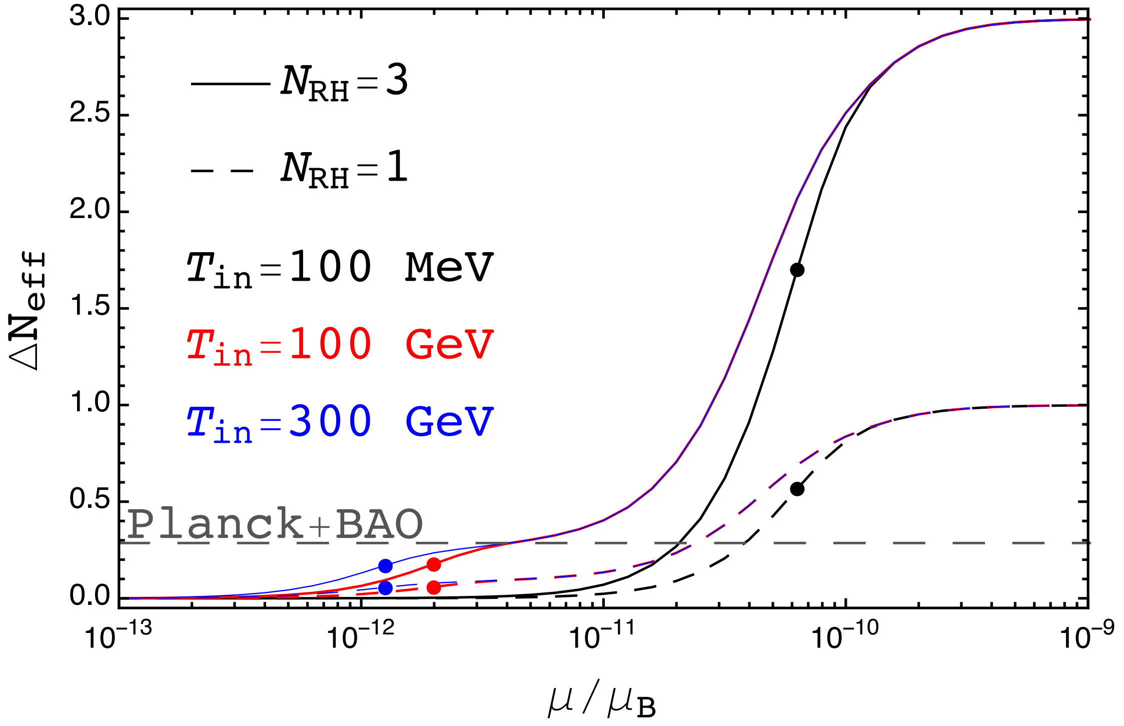
"Small" magnetic moment: thermal equilibrium never established. Freeze-in production. Abundance depends on initial temperature.

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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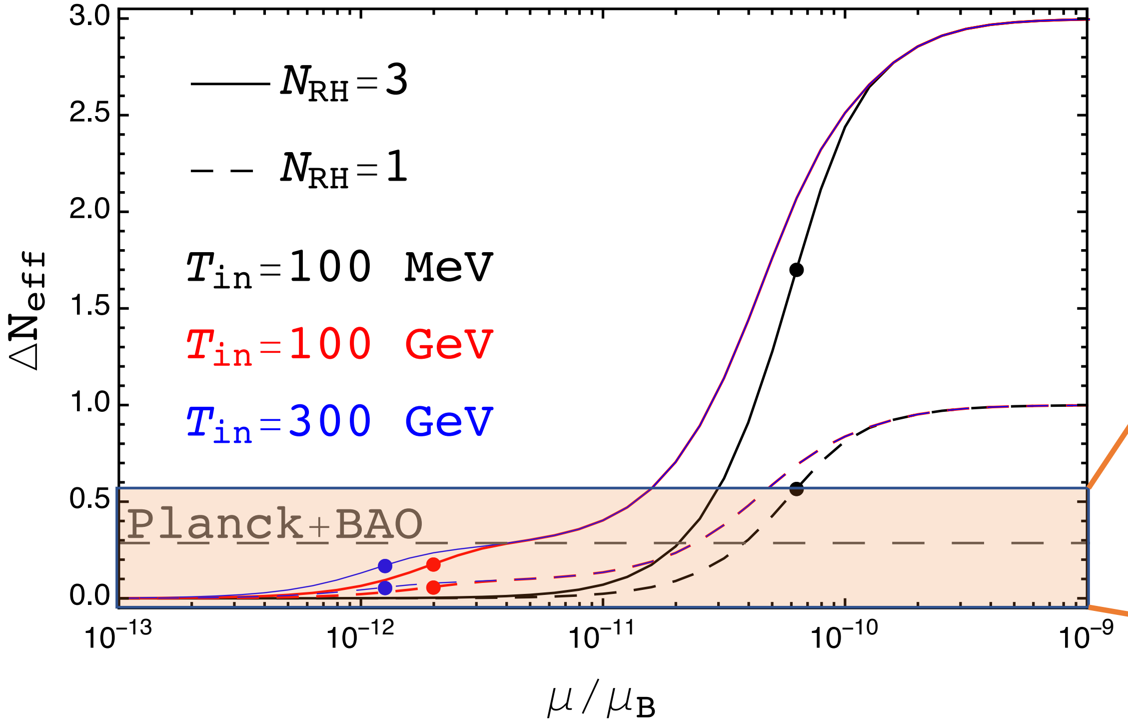

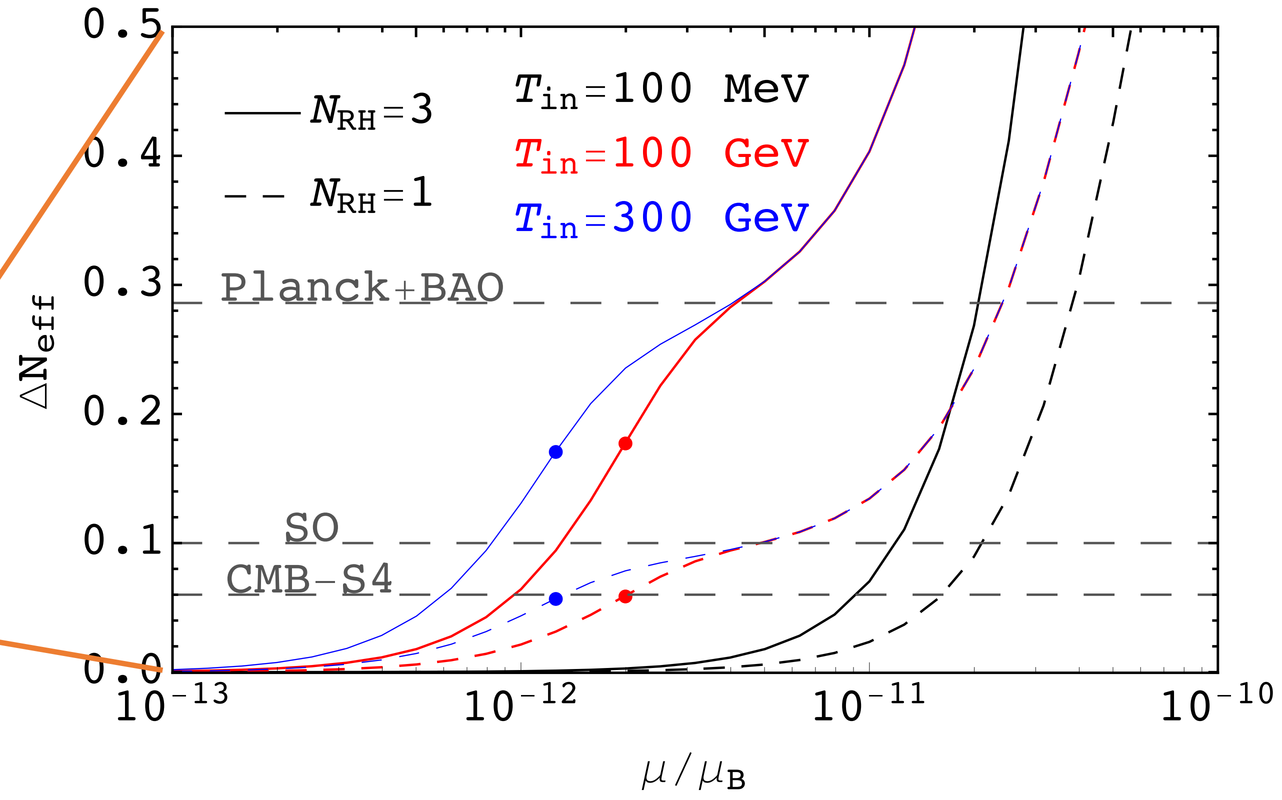

(95% CL bounds)

Carenza+ (incl ML, arXiv:2211.0432)

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

$\mu < 4.6 \times 10^{-12}\ \mu_b$ (Planck+BAO)
$\mu < 1.7 \times 10^{-12}\ \mu_b$ (Planck+BBN)
($T_{max} \geq 100$ GeV)

Carenza+ (incl ML, arXiv:2211.0432)

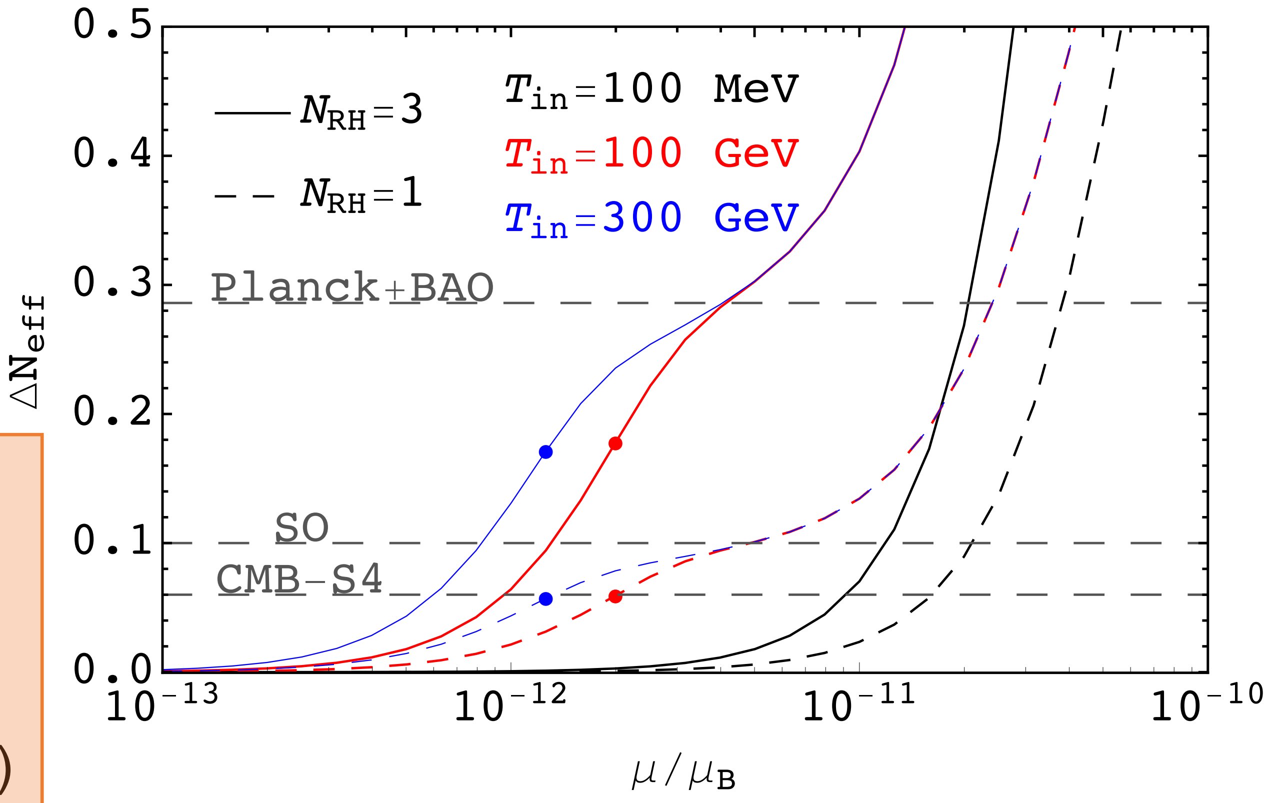
Compare with

$\mu < 6 \times 10^{-11}\ \mu_b$ (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)



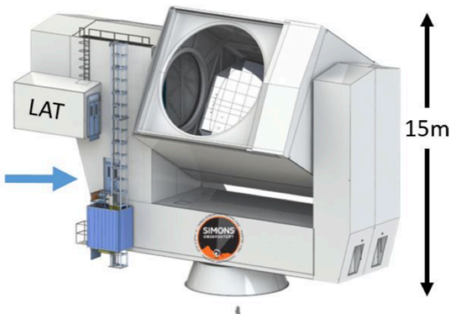
(95% CL bounds)

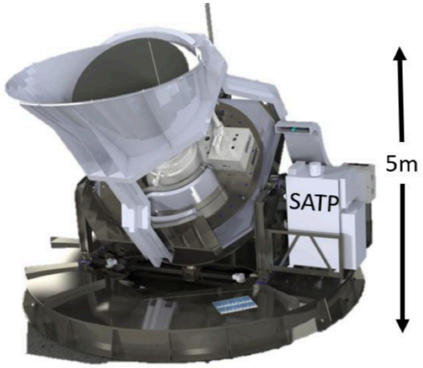
FUTURE PROSPECTS

Euclid

Galaxy survey
Launch in 94 days!

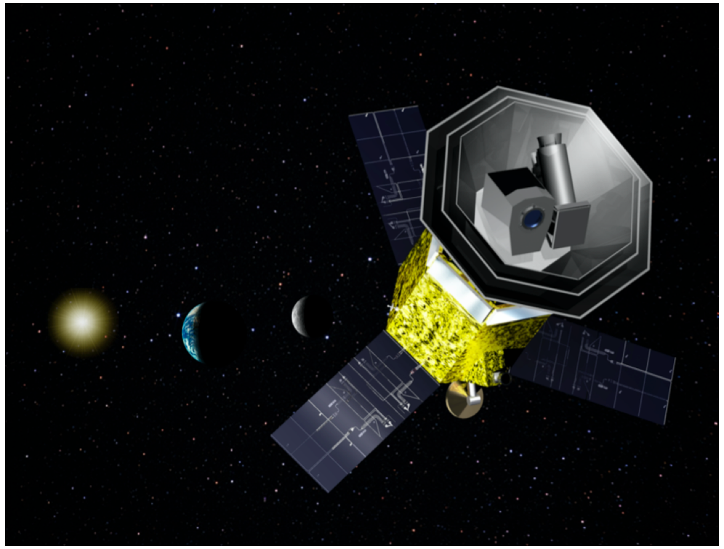
Simons Observatory





CMB pol. anisotropies
(intermediate/small scales)
First light in late 2023

LiteBIRD



CMB pol. anisotropies
(large/intermediate scales)
Launch in 2029

+ many other players!

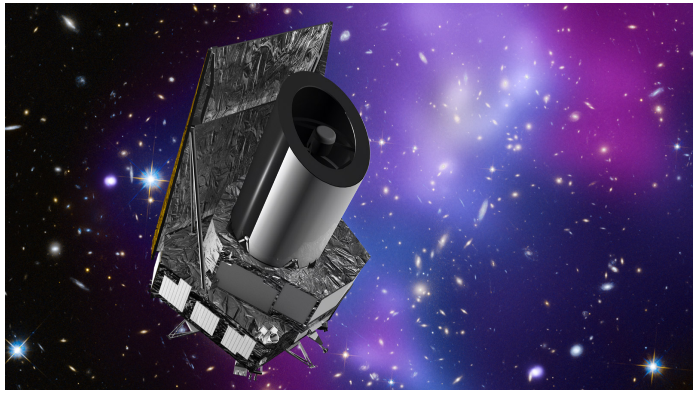
The Euclid Mission

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

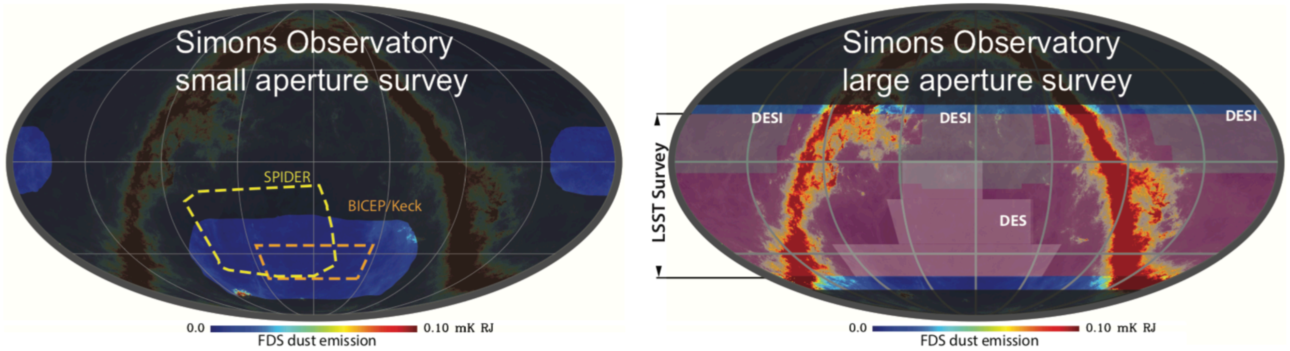
- the origin of the **accelerated expansion** of the Universe
- **Dark energy**, **dark matter** and the behaviour of **gravity at large scales**
- + **neutrino masses, the initial conditions of cosmological evolution, …**

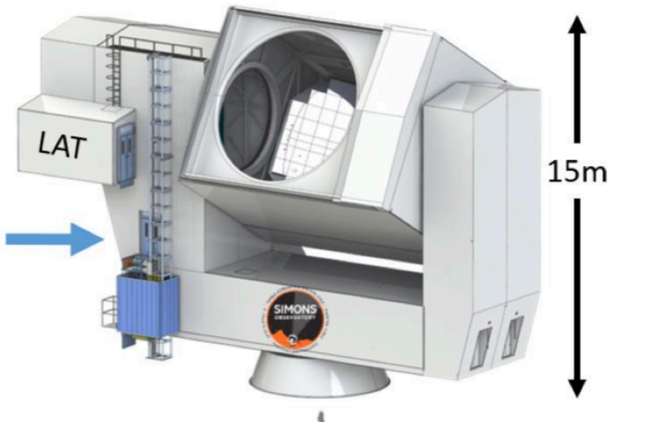
Euclid will measure **weak lensing** and **galaxy clustering** observing 15.000 deg^2 (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg^2)

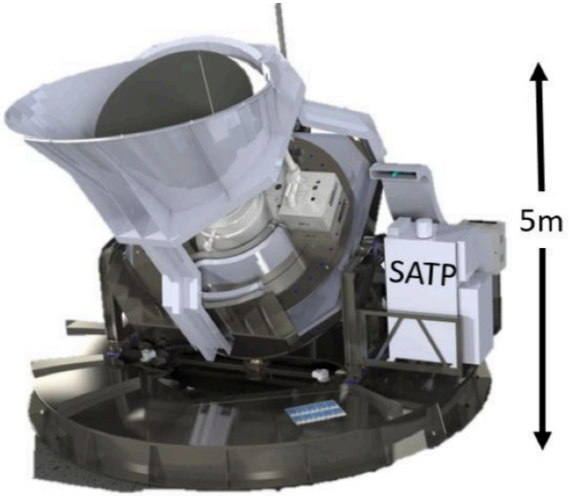
This will allow to reconstruct the **expansion history** and the **growth of cosmological structuree**



SIMONS OBSERVATORY







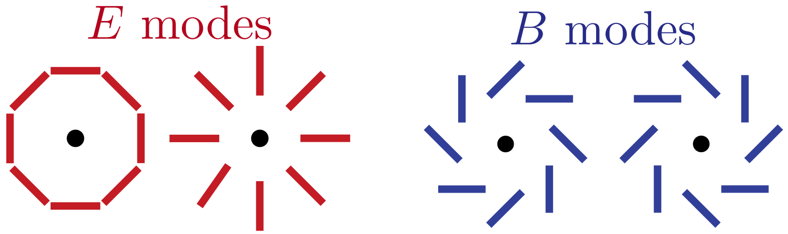
- Ground-based CMB experiment sited in Cerro Toco in the Atacama Desert in Chile
- 5-yr obs campaing starting in 2023
- 3 Small Aperture (0.4m) Telescopes (SATs) for ‘r science’
- 1 Large Aperture (6m) Telescope (LAT) for small-scale (arcmin) science
- > 60k TES detectors
- 10x sensitivity and 5x resolution wrt Planck
- 6 freq. bands from 27 to 280 GHz

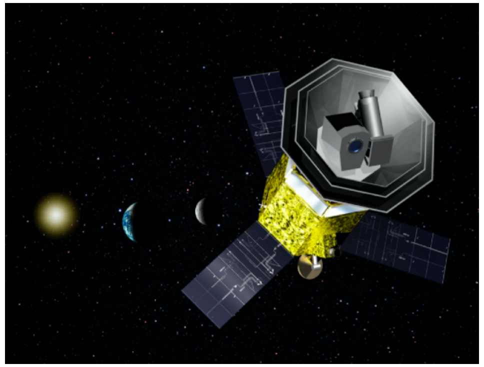
LiteBIRD

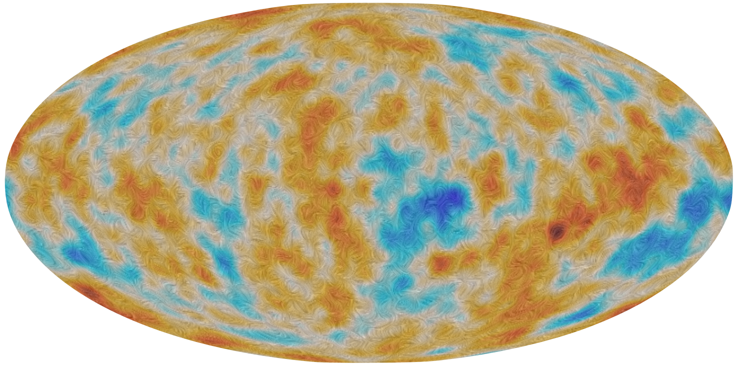
A JAXA-led post-Planck space mission for CMB polarization, with participation from US and Europe

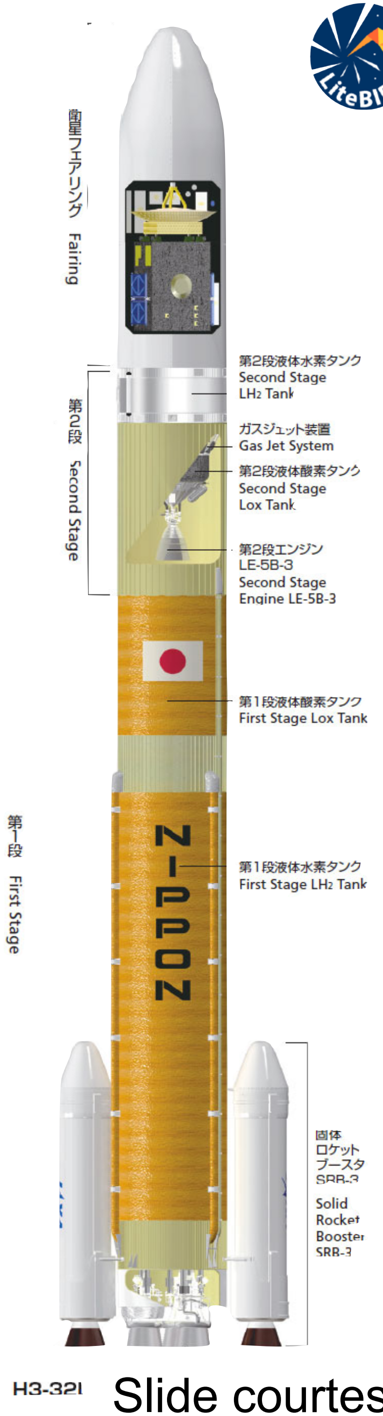
LiteBIRD Overview

- Light satellite for B-modes from Inflation CMB Radiation Observation
- Selected (May 2019) as the next JAXA's L-class mission
- Expected launch in 2029 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



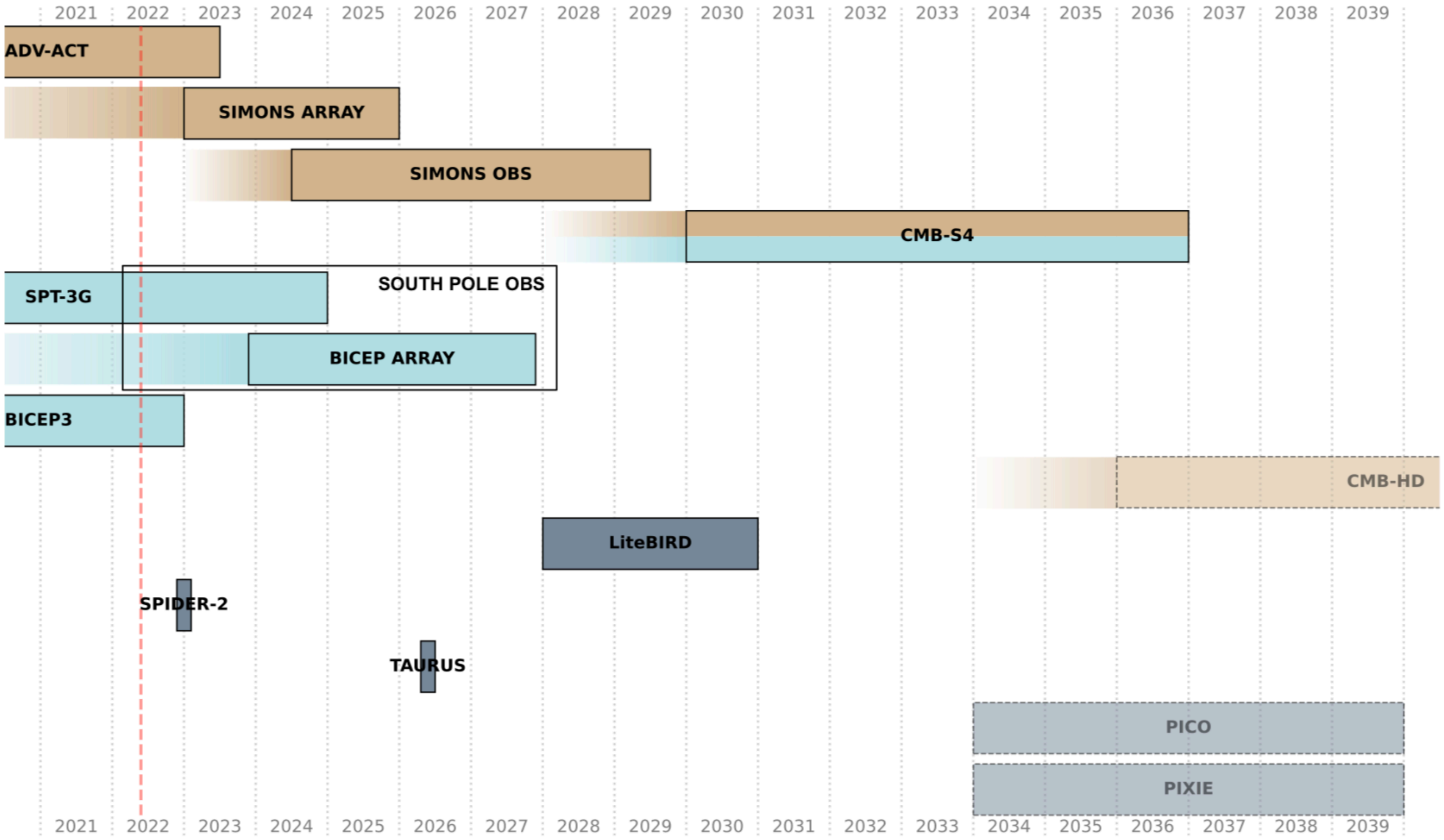






Slide courtesy: G. Signorelli

Timeline of CMB experiments



Snowmass2021 Cosmic Frontier: CMB Measurements White Paper
arXiV: [2203.07638]

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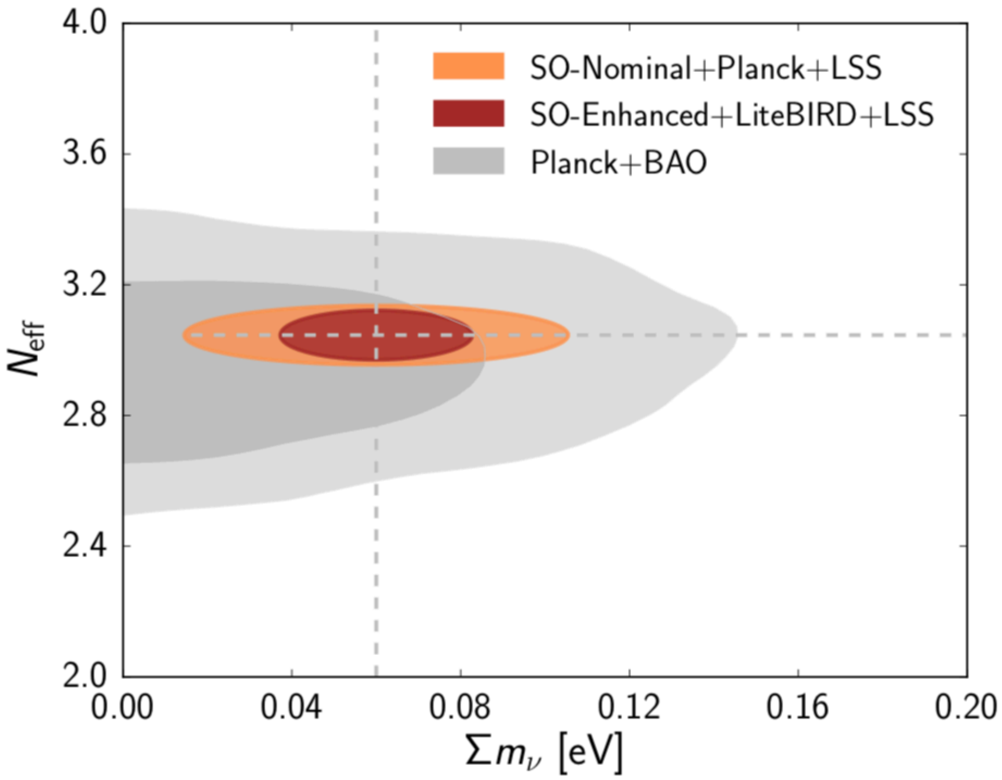


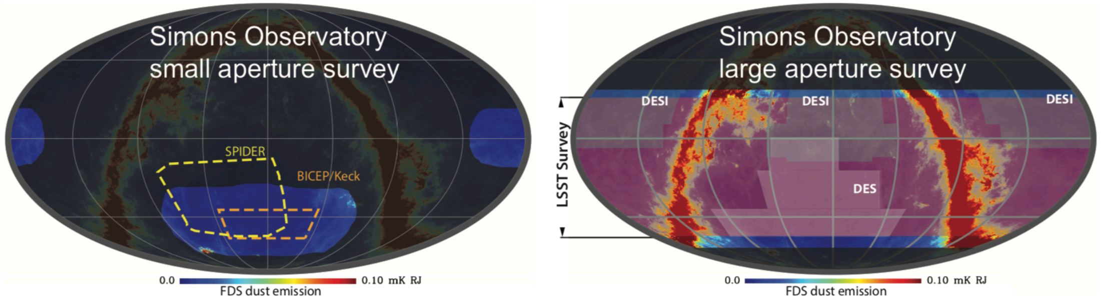


Table 1: Summary of SO-Nominal key science goals[a]

	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 $\times$ 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

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

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

		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 $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

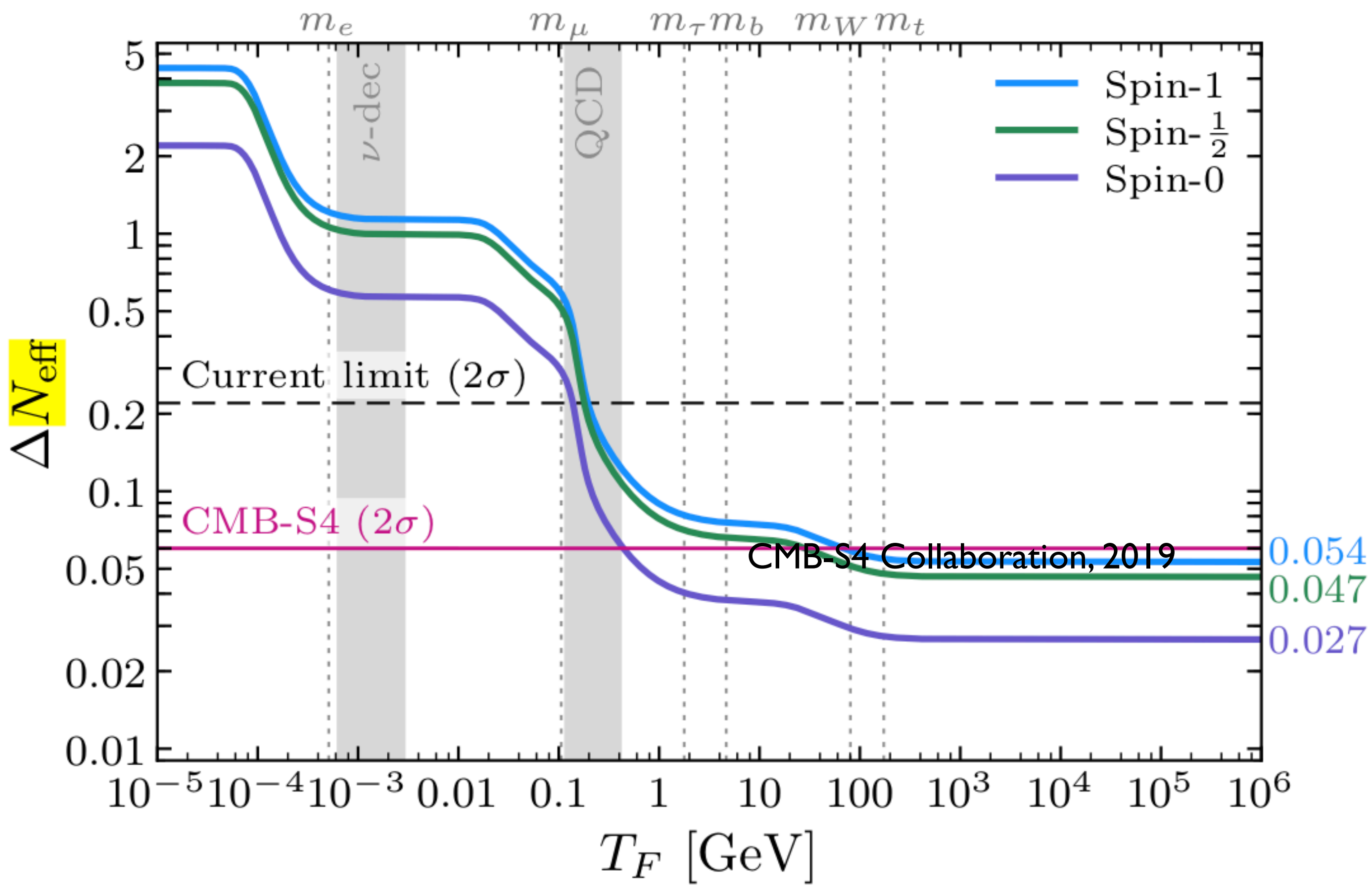
$\sigma(N_{eff}) = 0.027$

See Snowmass 2021 CMB-S4 White Paper
arXiv:2203.08024

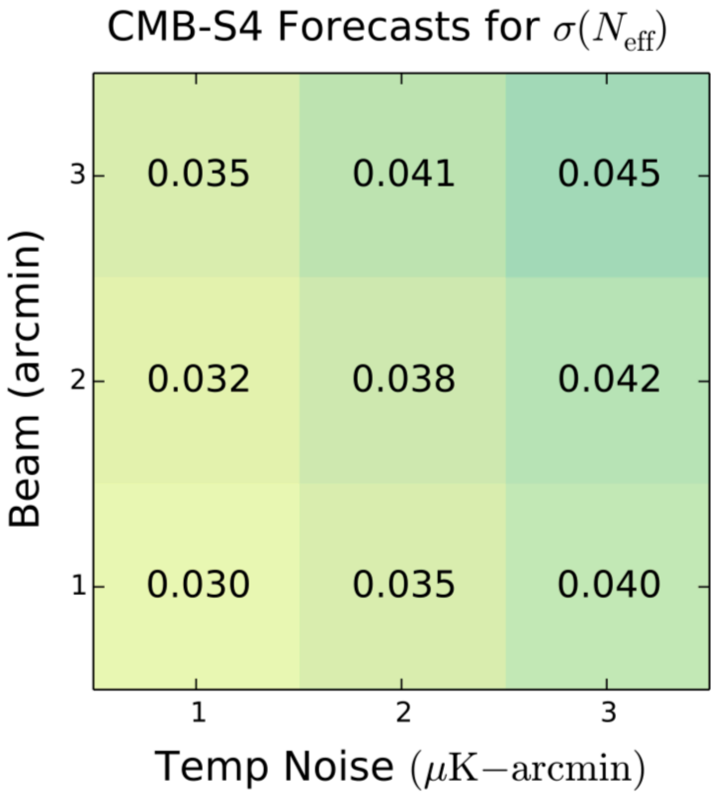
CMB-S4 Science Book (arXiv: 1610:02743)

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 Science Book

NEUTRINO MAGNETIC MOMENT

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

In case of no detection:

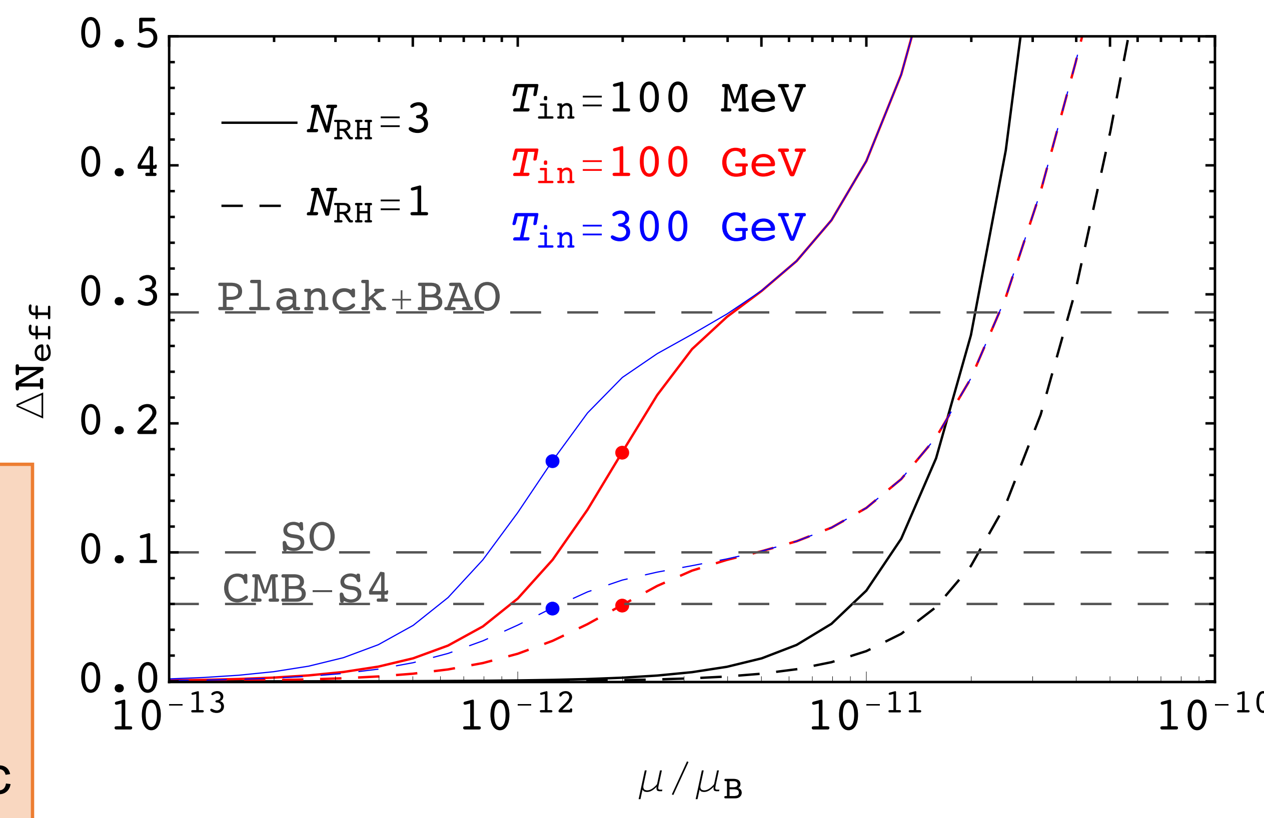
$\mu < 1.3 \times 10^{-12}\ \mu_b$ (SO)

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



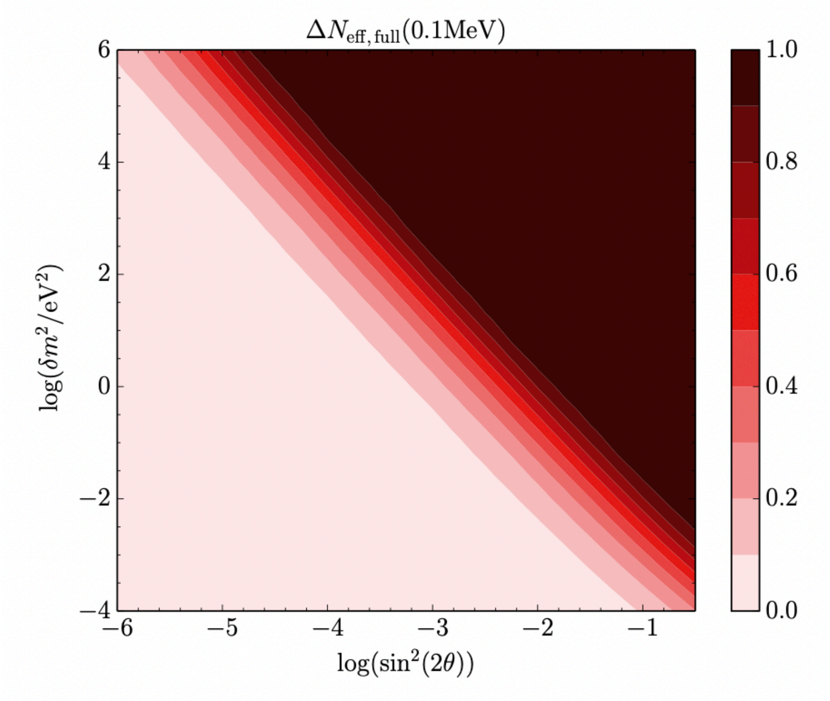
(95% CL bounds)

THANKS!

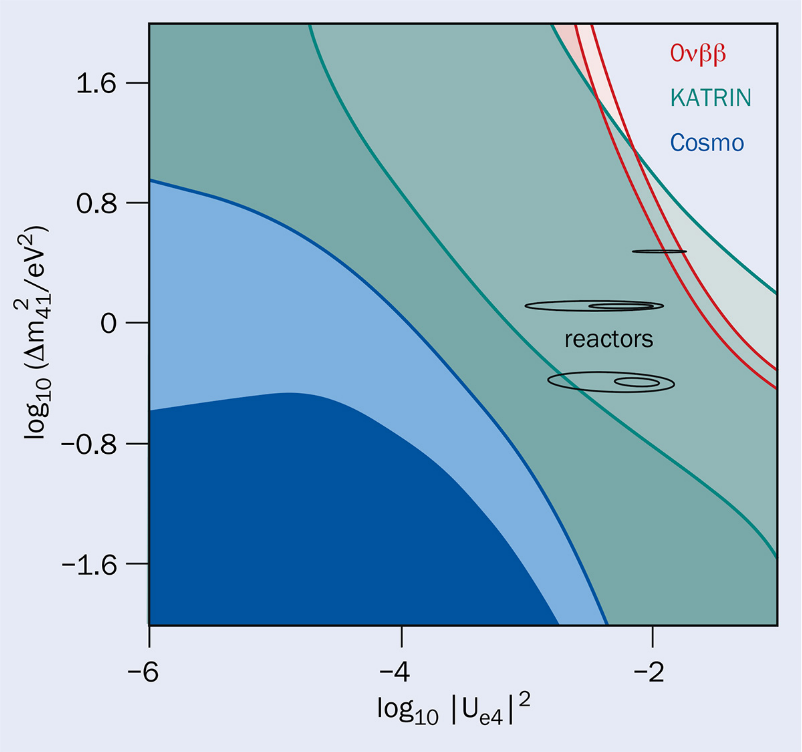
BACKUP SLIDES

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



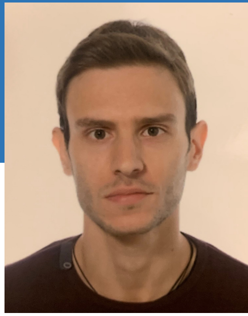
S. Hagstotz

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_{EFF} AND THERMAL AXIONS

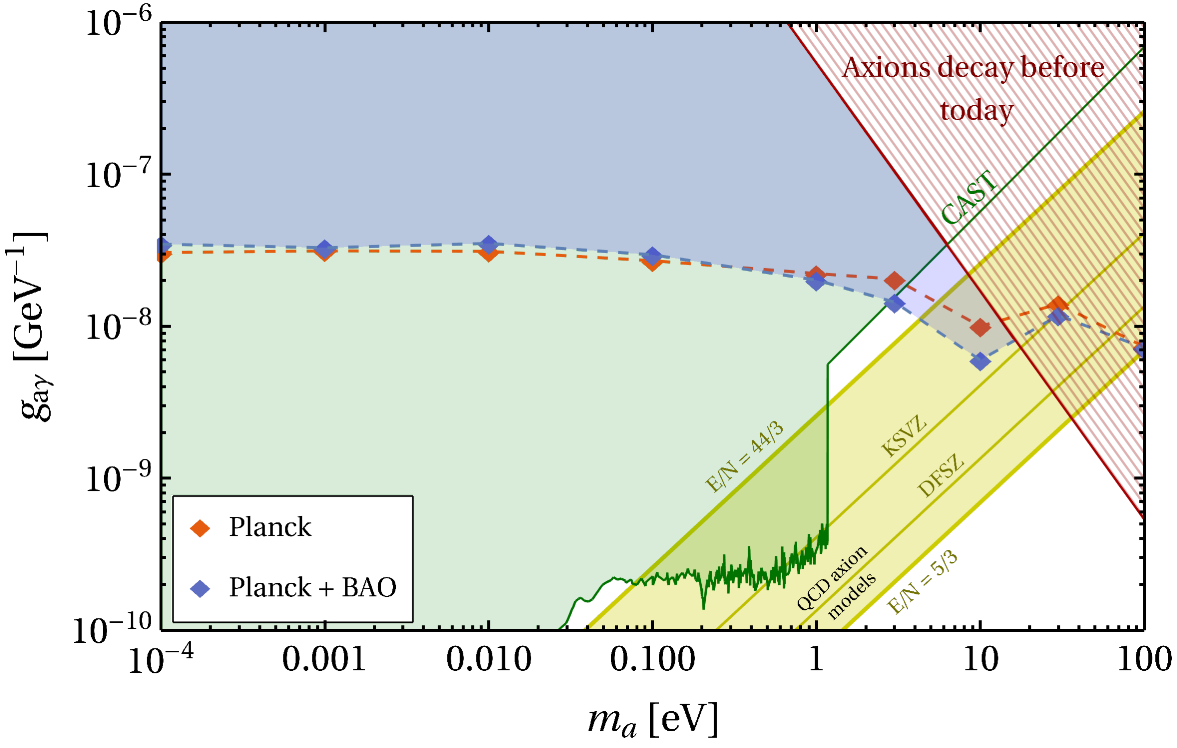


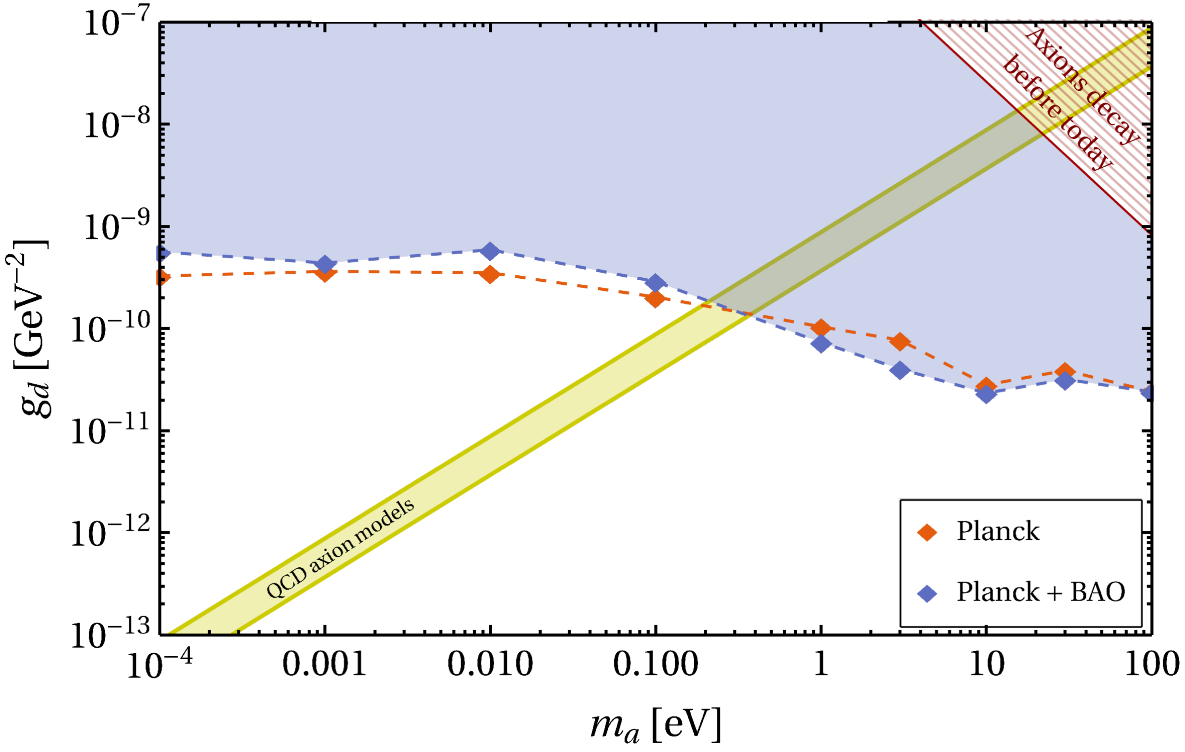
L. Caloni

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

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

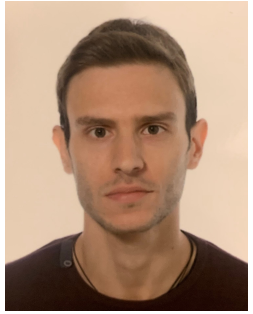
$$\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi} \frac{C_g}{f_a} a G^i_{\mu\nu} \tilde{G}^{\mu\nu,i}$$





Caloni, ML, Gerbino, Visinelli, 2022

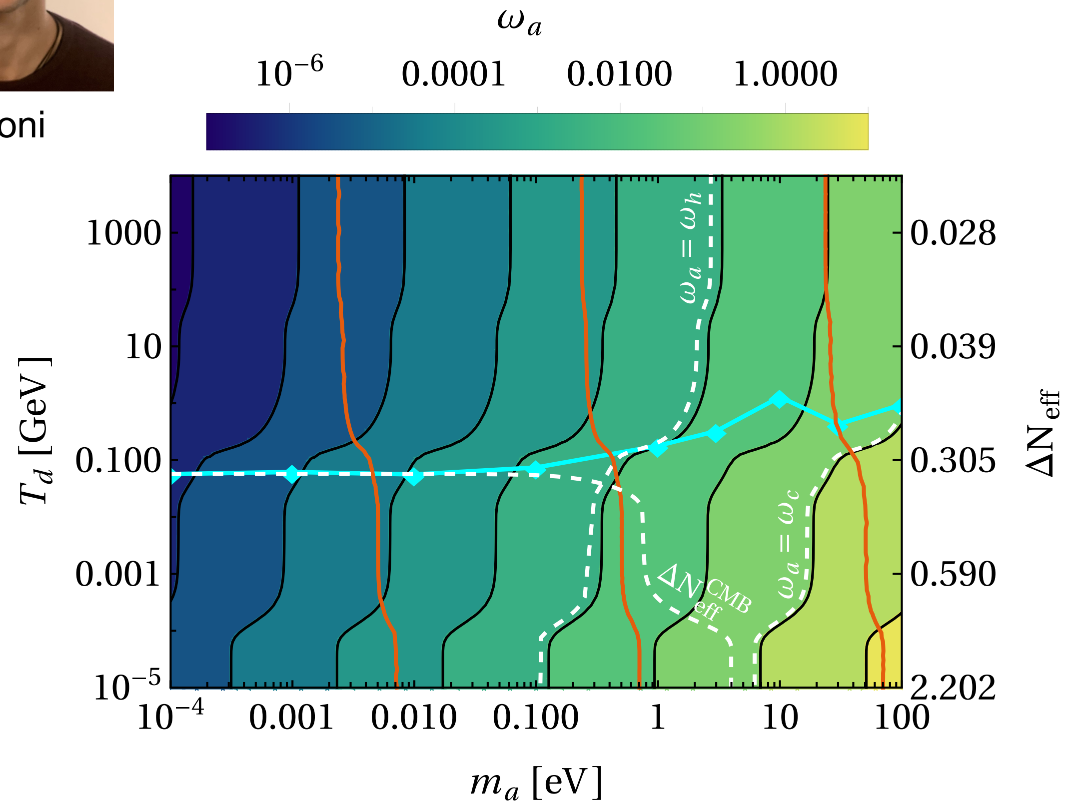
N_{EFF} AND THERMAL AXIONS

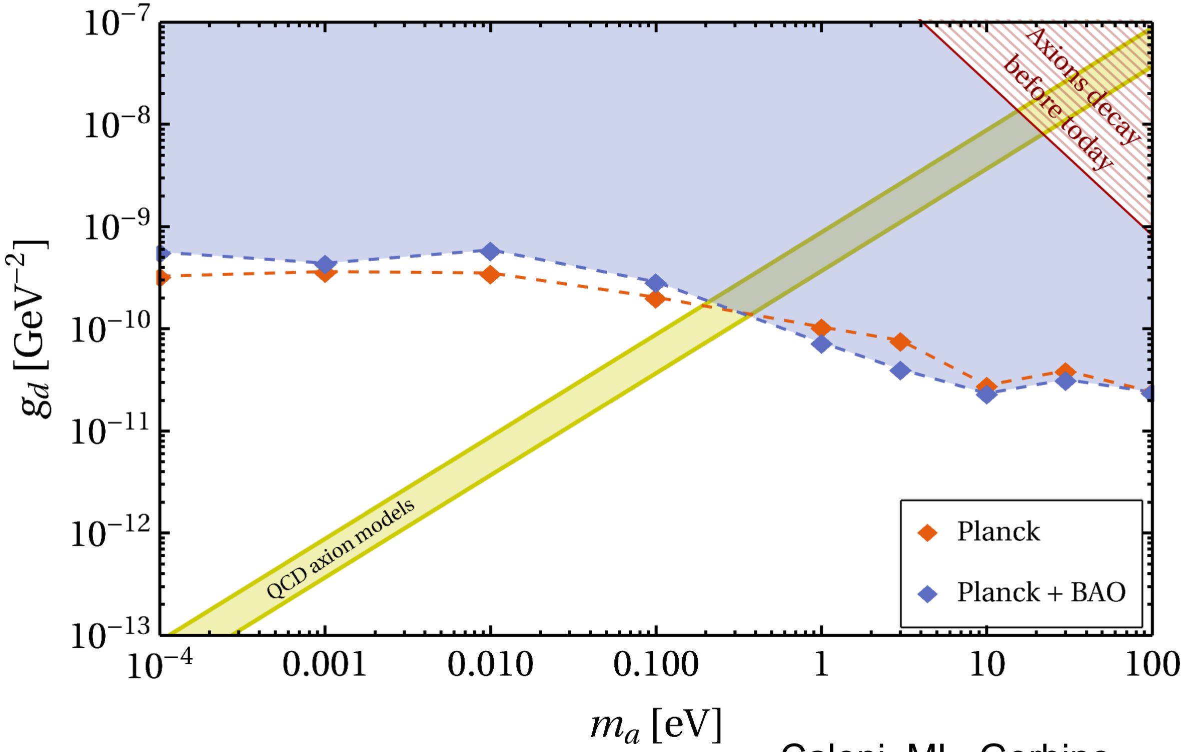


L. Caloni

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

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





Caloni, ML, Gerbino, Visinelli, 2022

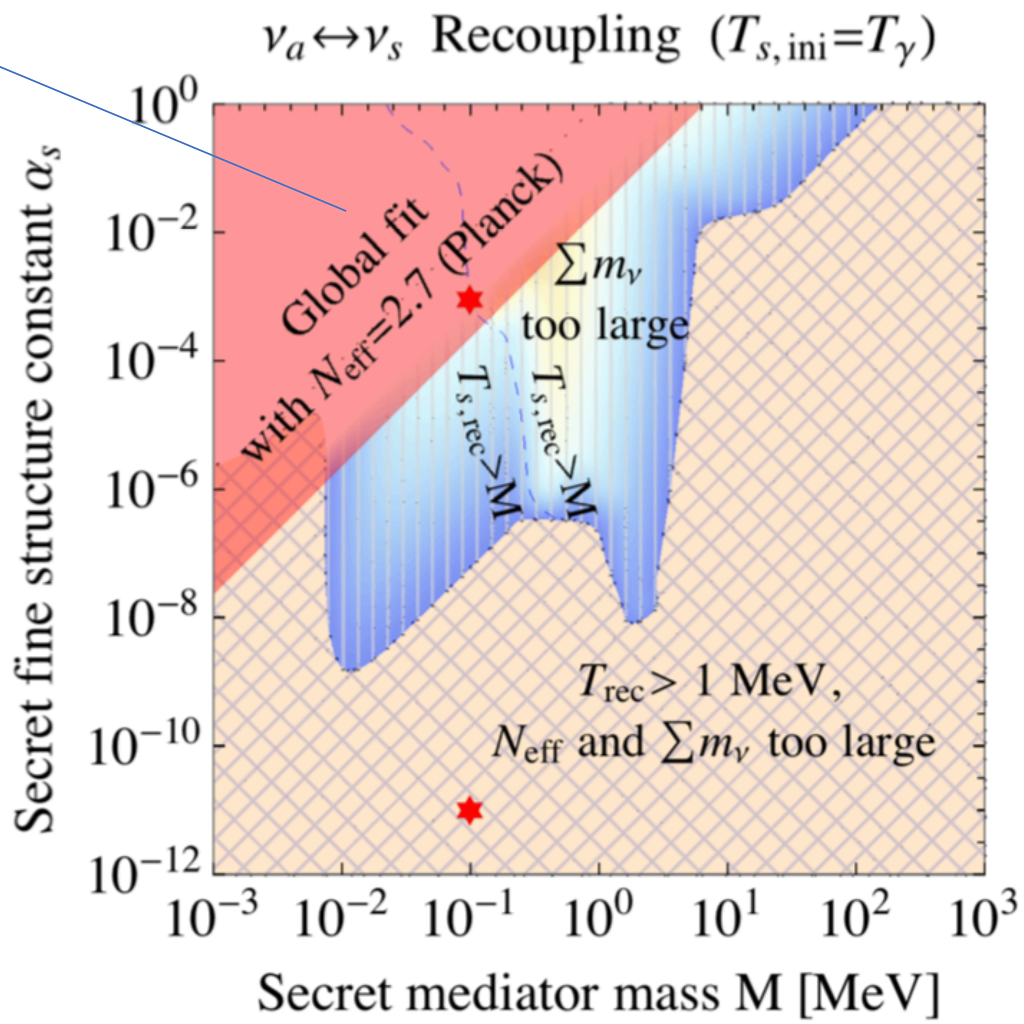
νNSI and SBL anomalies

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

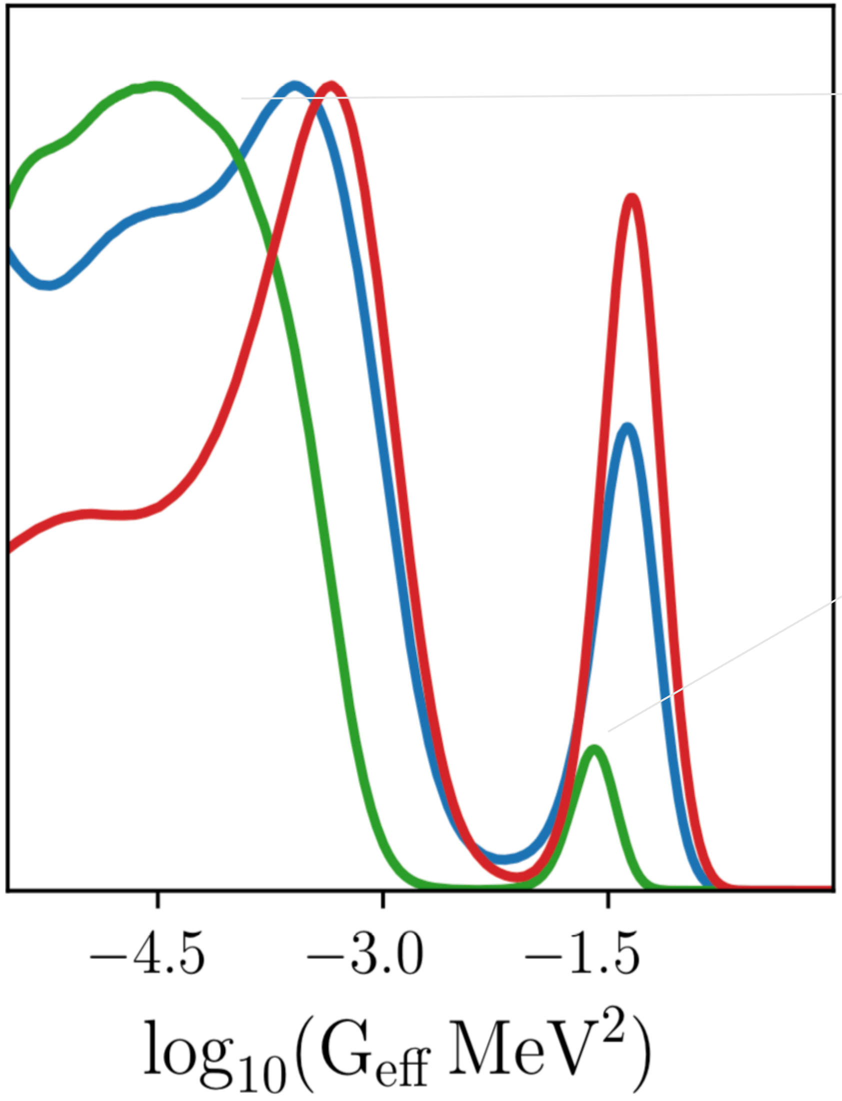
In the end, **you violate either the mass or the interaction strength bound.**



Plot from Chu et al. 2018

Constraints on NSI from Planck 2015

Heavy mediator case



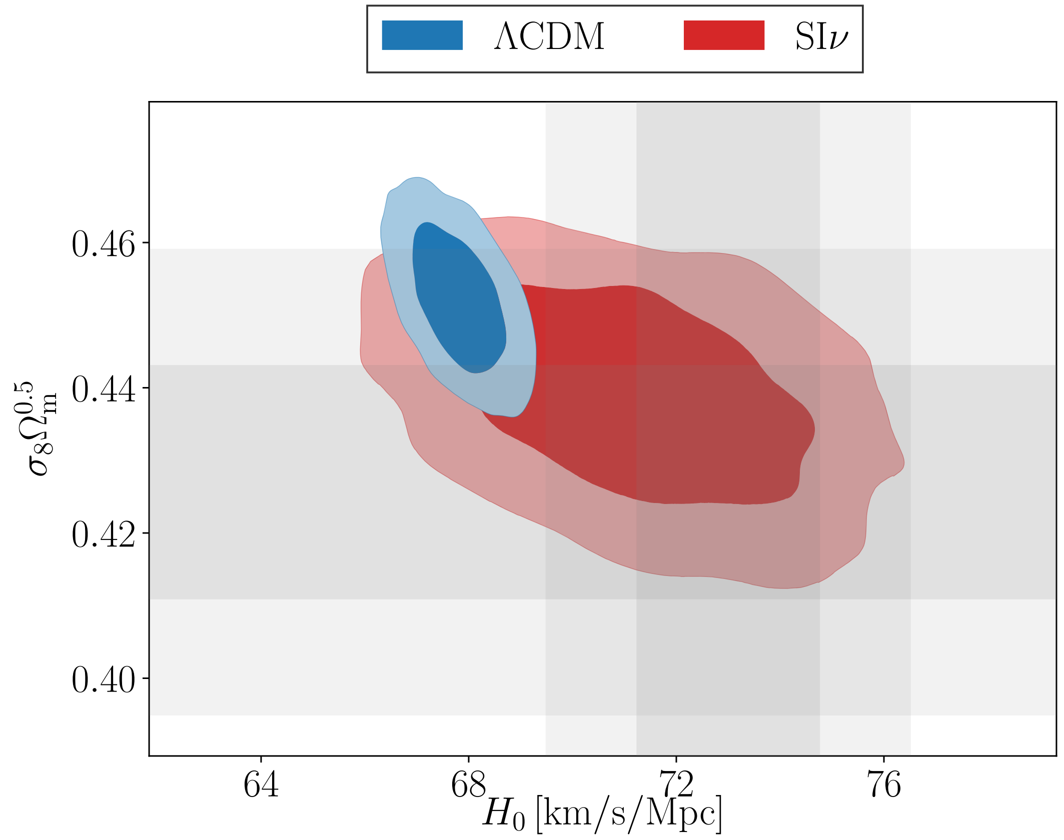
$G_{\rm eff} < 1.4 \times 10^2\,{\rm GeV}^{-2}$

$G_{\rm eff} = (2.5^{+0.8}_{-0.5}) \times 10^4\,{\rm GeV}^{-2}$

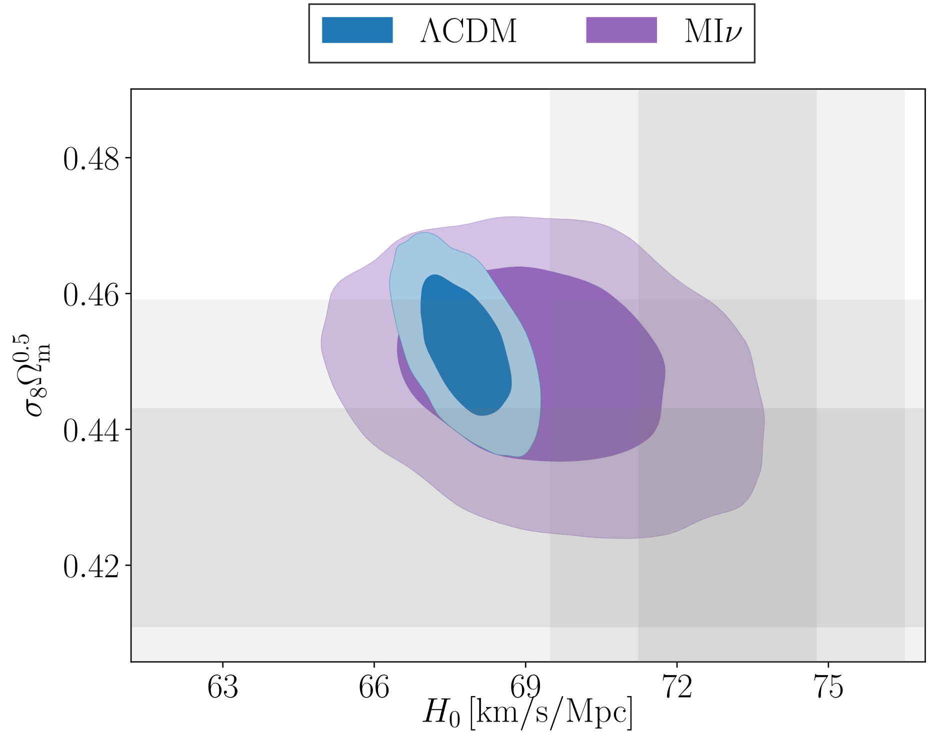
PlanckTTTEEE
PlanckTT+lens+BAO
PlanckTT+lens+BAO+H0

Kreisch et al. 2019

PlanckTT+lens+BAO

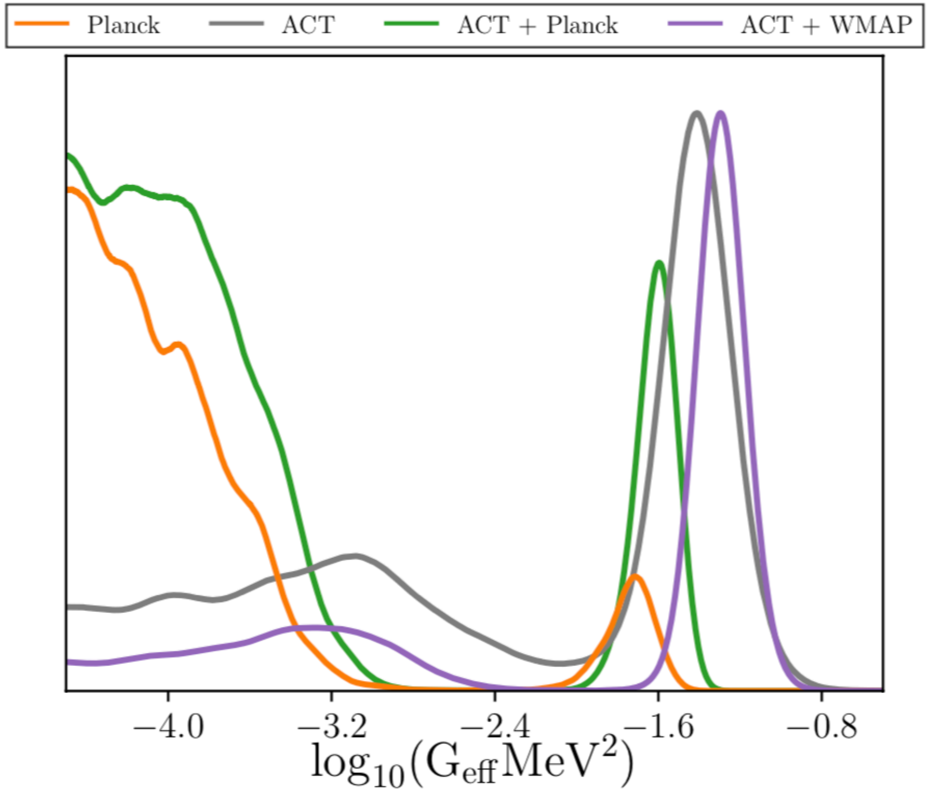


Kreisch et al. 2019

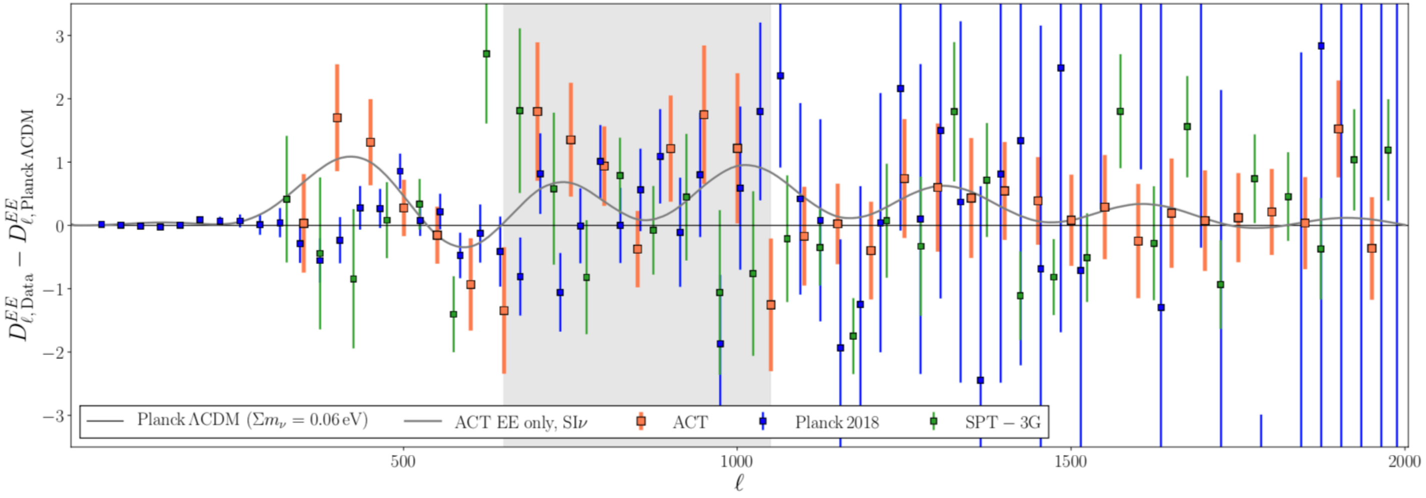


ν NSI IN COSMOLOGY

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

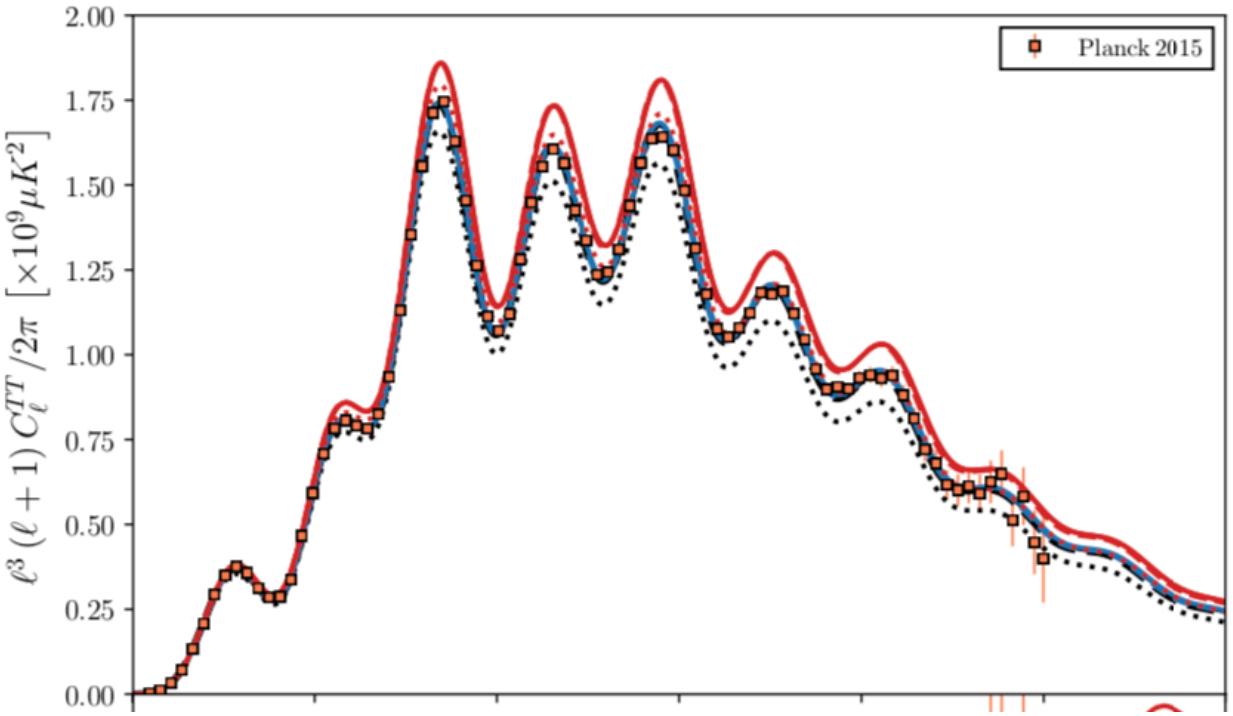


Driven by the ell range 700-1000 in the EE data

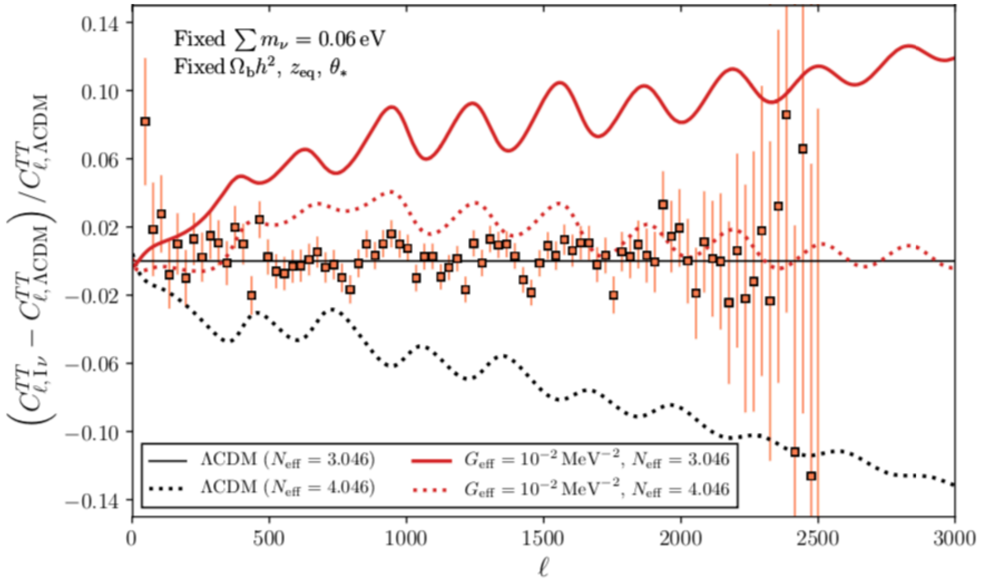


Kreisch et al. 2207.03164

νNSI and CMB anisotropies: Heavy Mediator

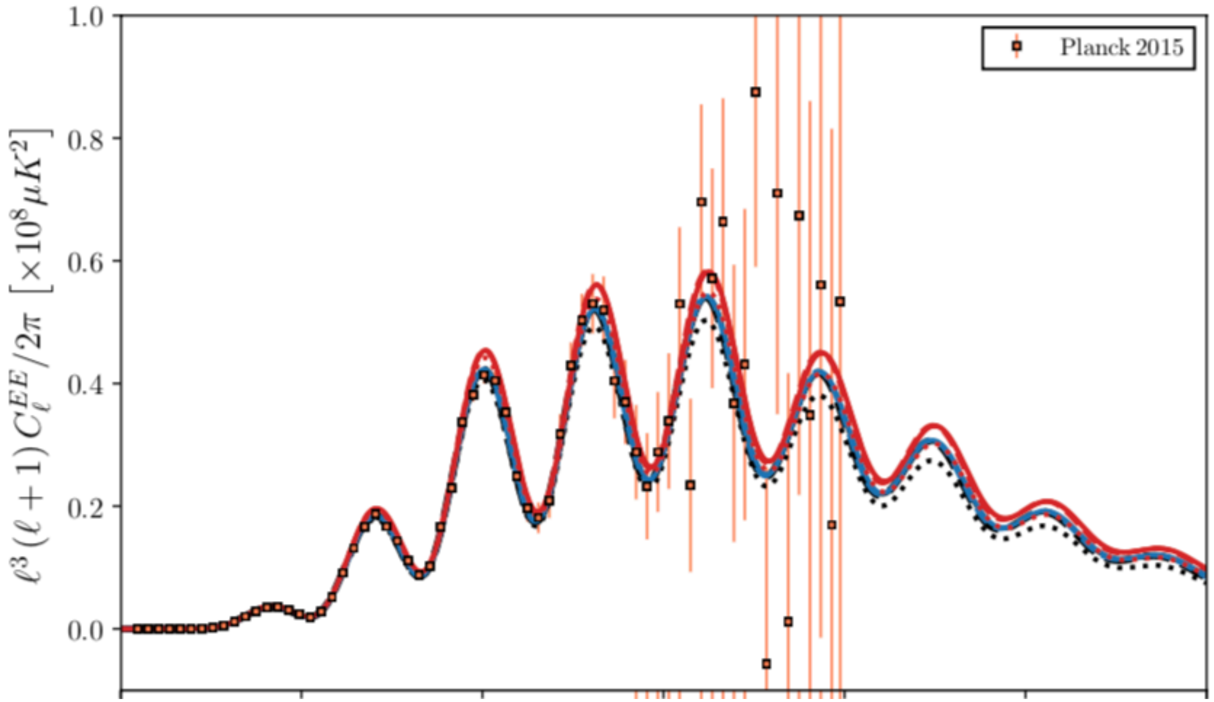


Scales entering the horizon before decoupling are affected
i.e. smaller scales are more affected



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



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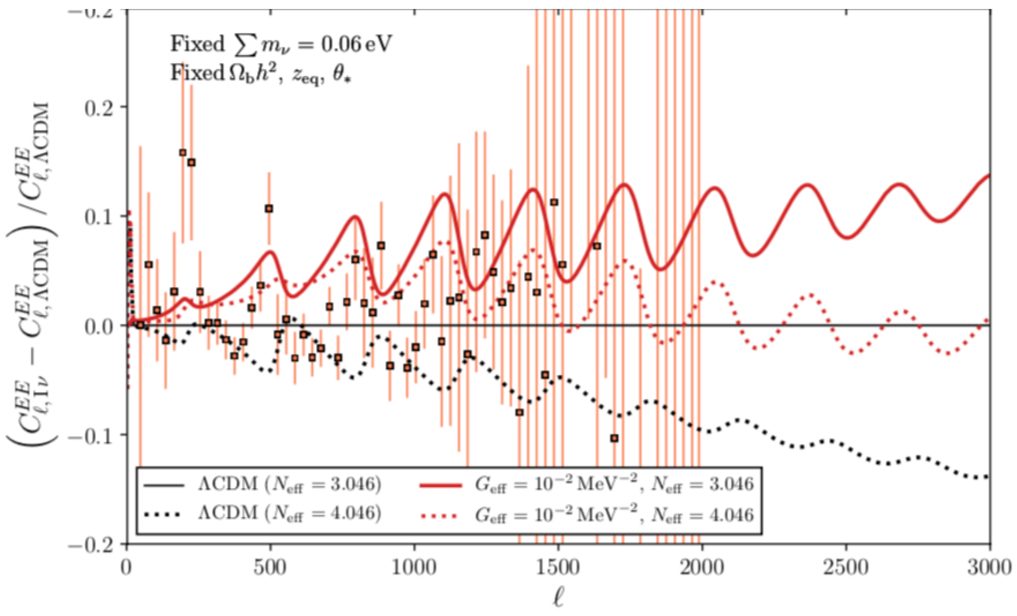
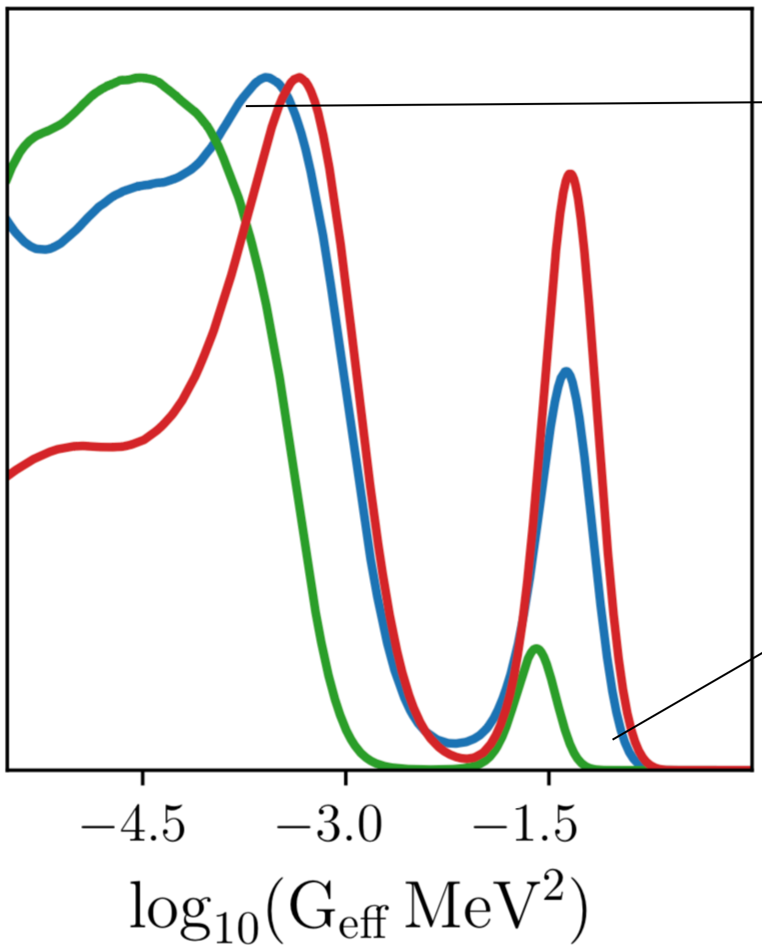


Kreisch, Cyr Racine & Dore 2019
See also Cyr-Racine & Sigurdson 2014; Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Wong 2017

νNSI Constraints: Heavy Mediator



$G_{\rm eff} < 1.4 \times 10^2\,\mathrm{GeV}^{-2}$

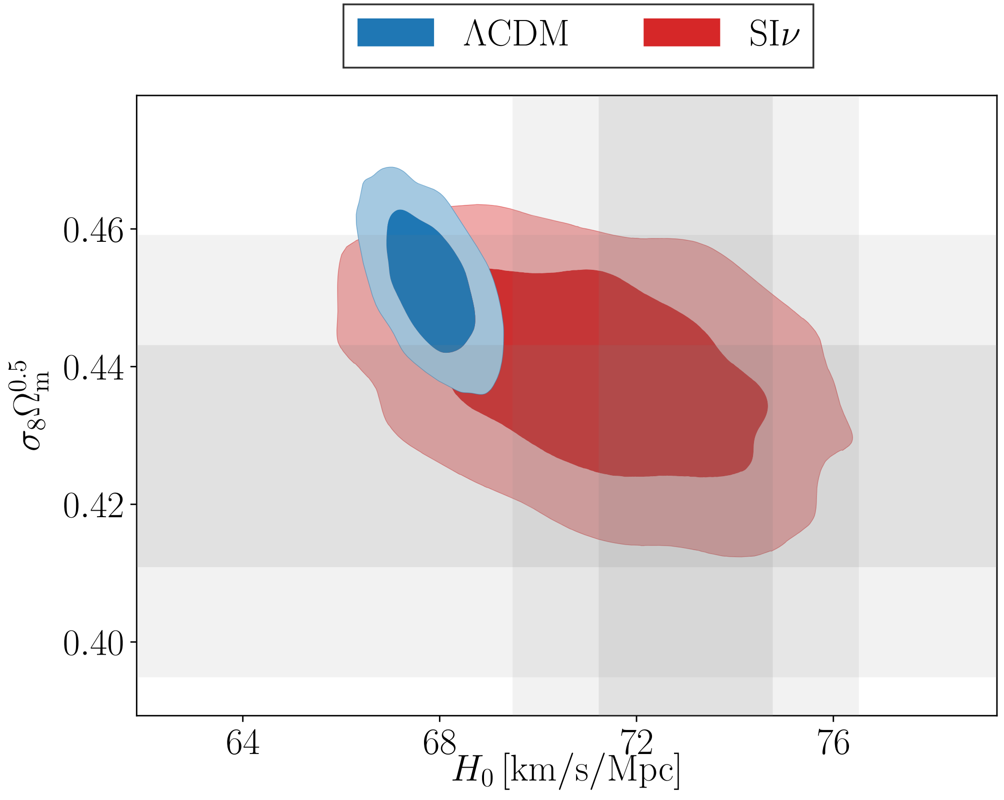
$G_{\rm eff} = (2.5^{+0.8}_{-0.5}) \times 10^4\,\mathrm{GeV}^{-2}$

PlanckTTTEEE
PlanckTT+lens+BAO
PlanckTT+lens+BAO+H0

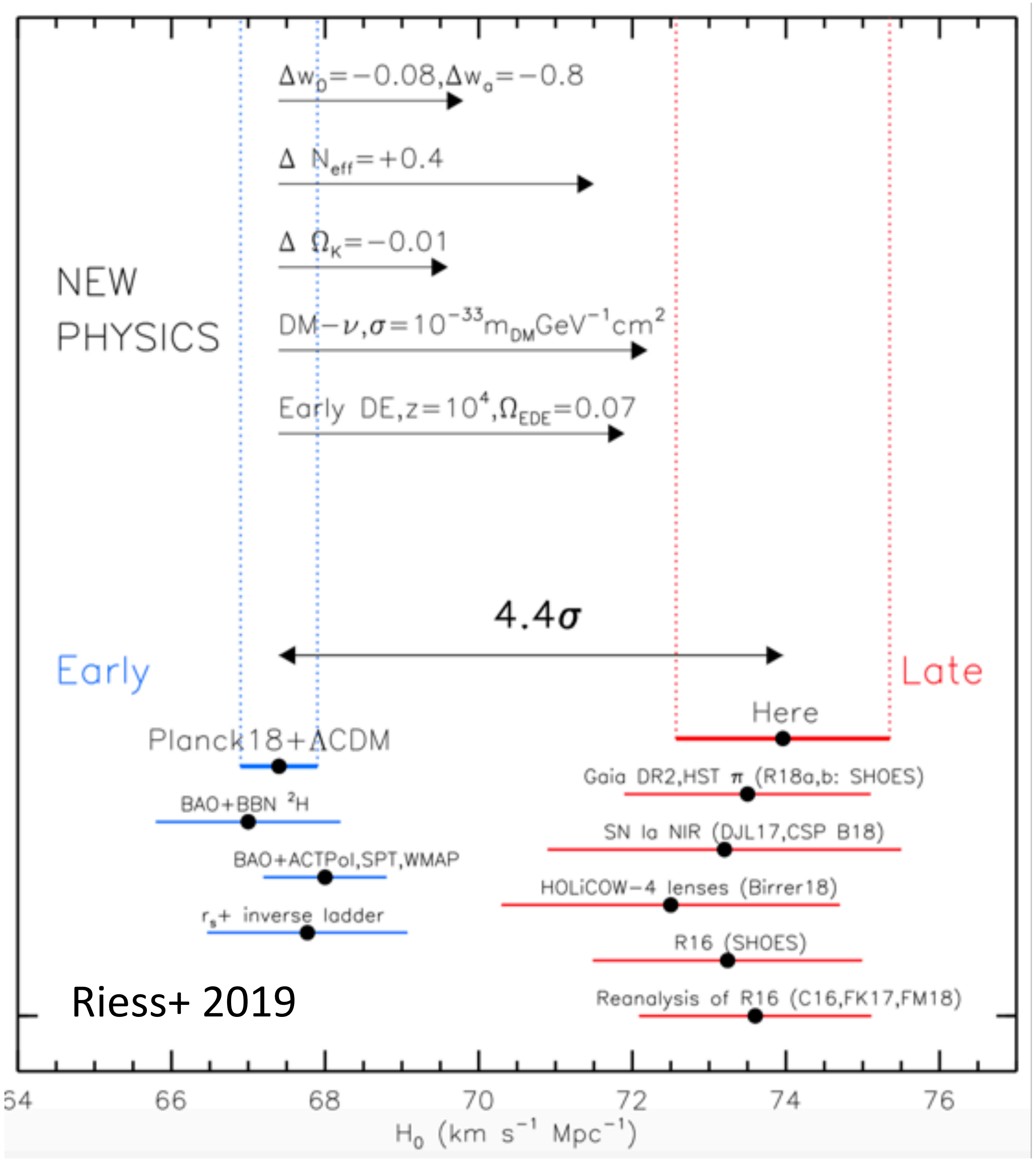
Preference for a "strong-interacting" mode emerges from some data combinations

Kreisch, Cyr Racine & Dore 2019

νNSI: A way to alleviate the Hubble Tension?



Kreisch, Cyr Racine & Dore 2019



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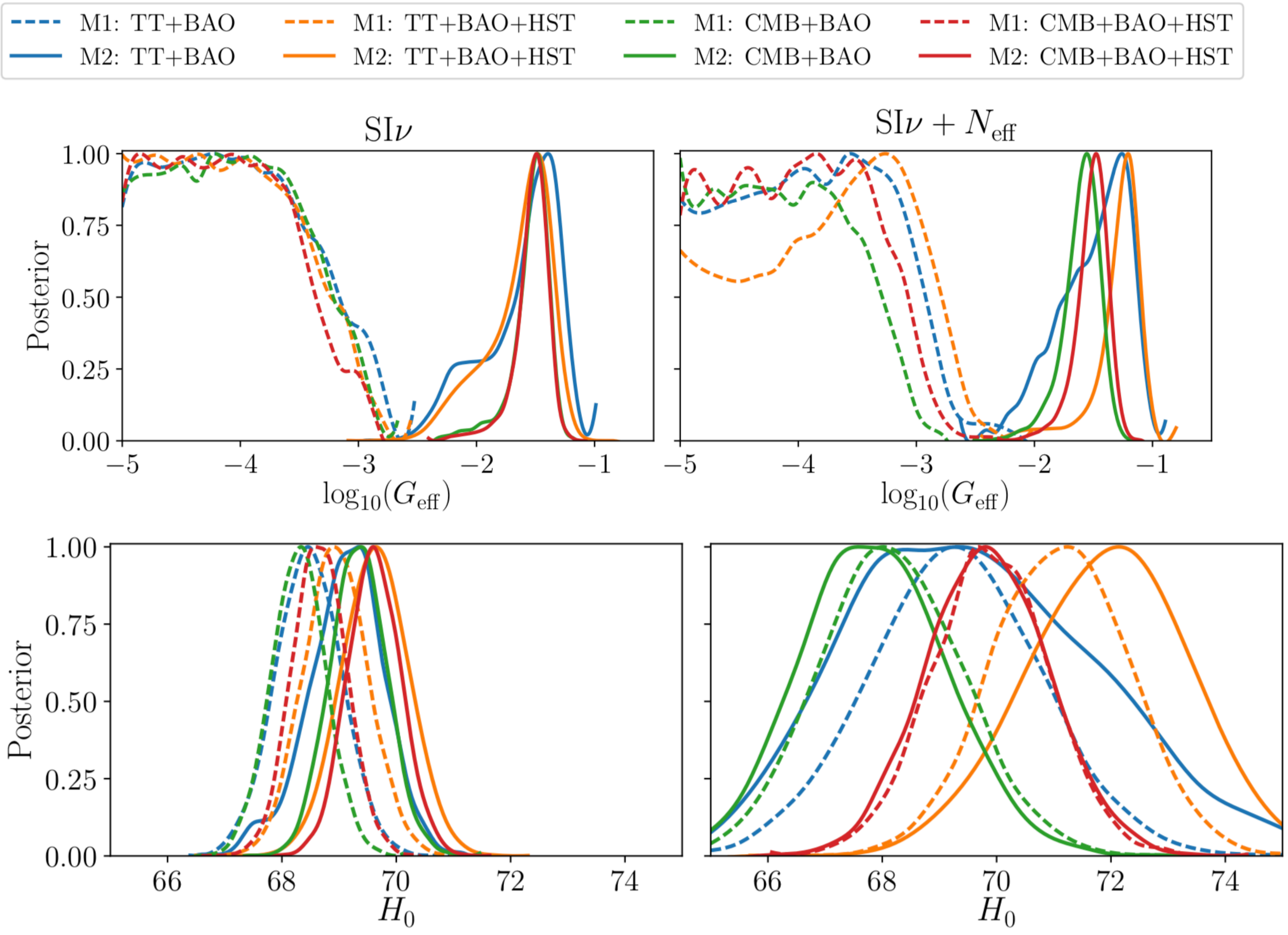
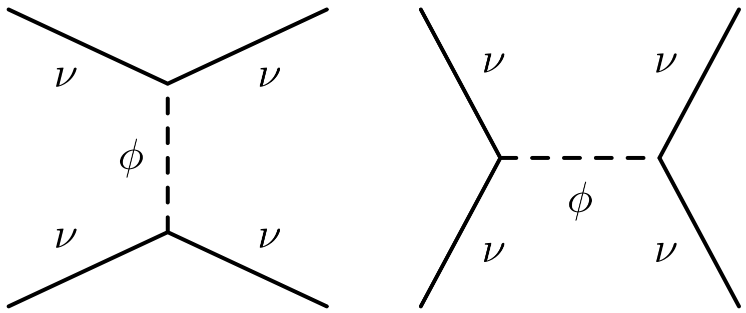


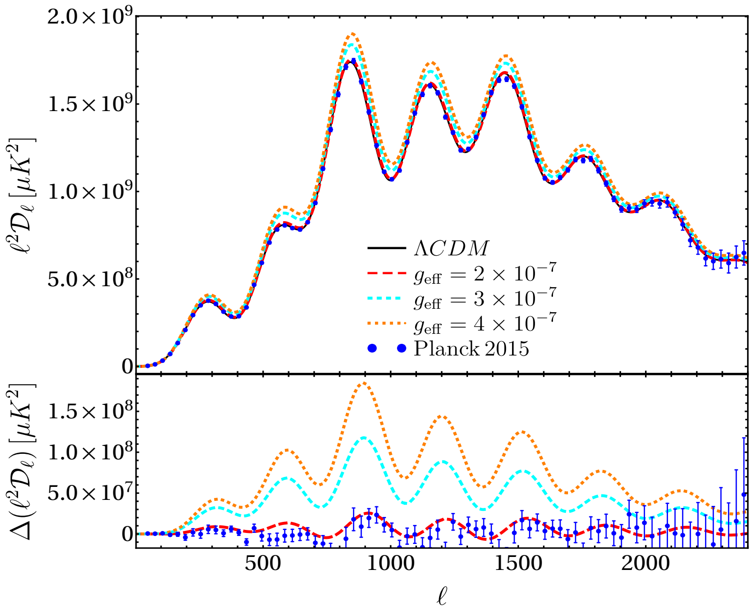
Oldengott et al. 2017

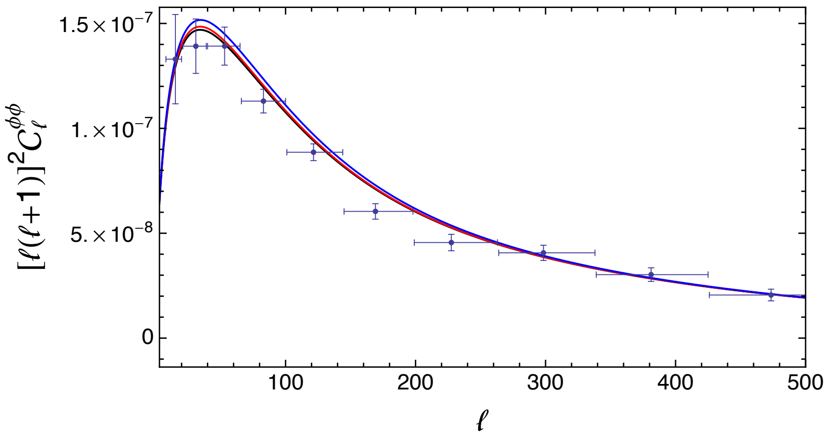
ν NONSTANDARD INTERACTIONS

CMB is also sensitive to the collisional properties of light relics (Bashinsky & Seljak 2004)
E.g. in models of neutrino nonstandard interactions:

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



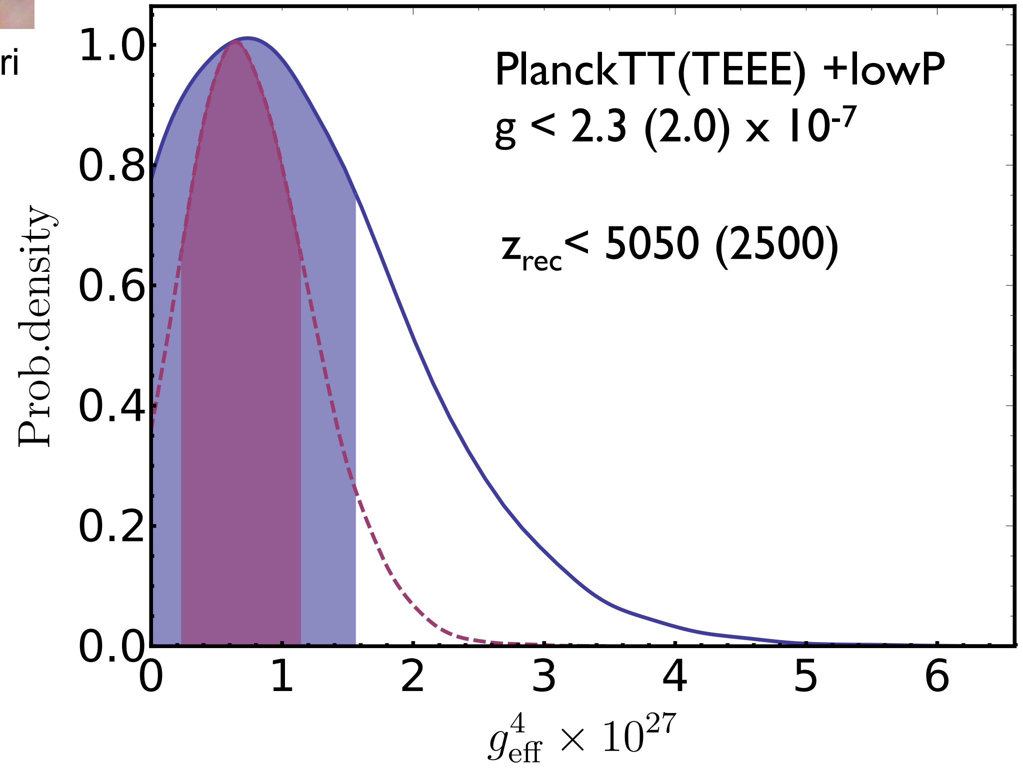


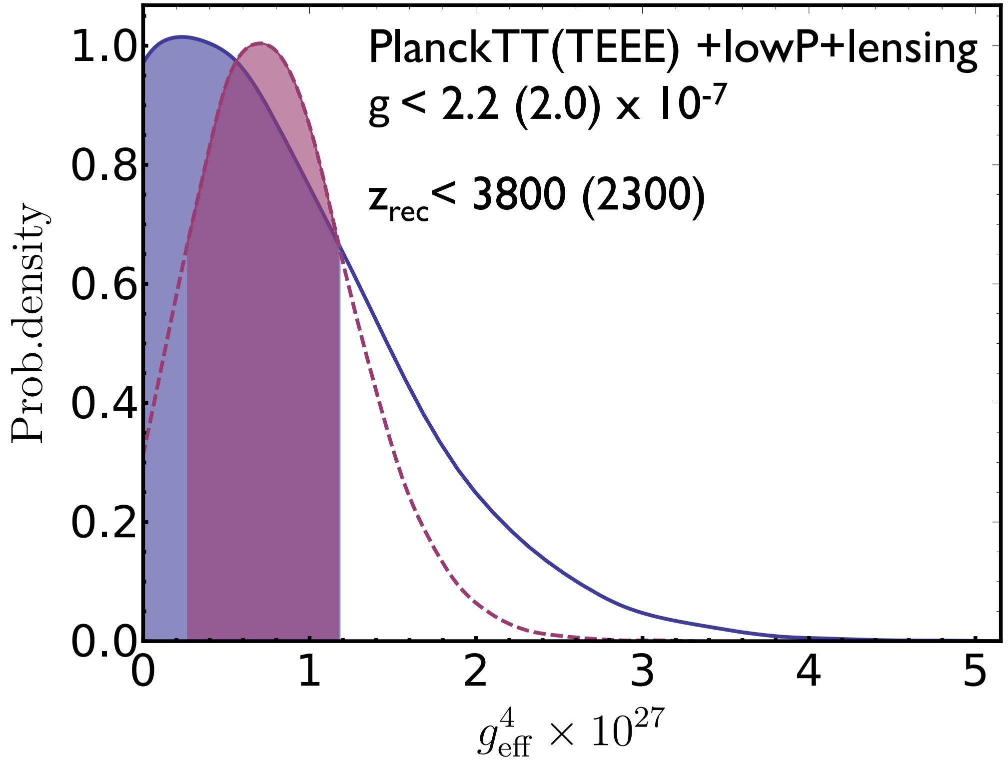


ν NONSTANDARD INTERACTIONS

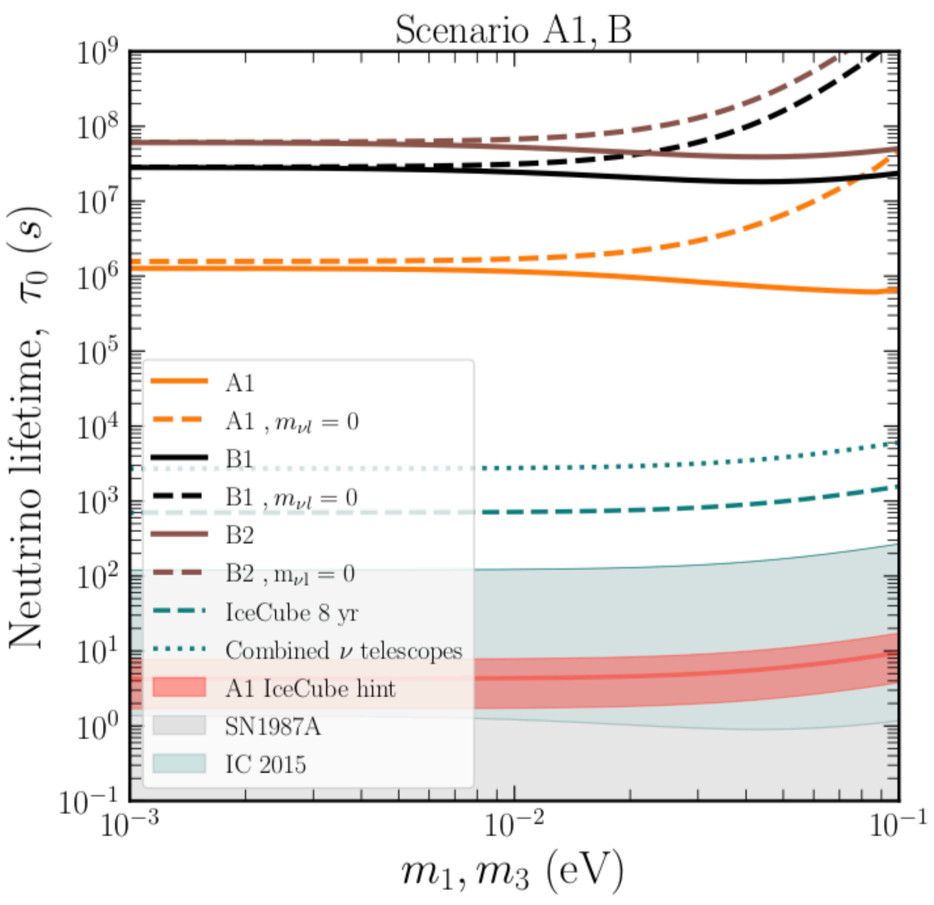
F. Forastieri

Forastieri, ML, Natoli, PRD 2019

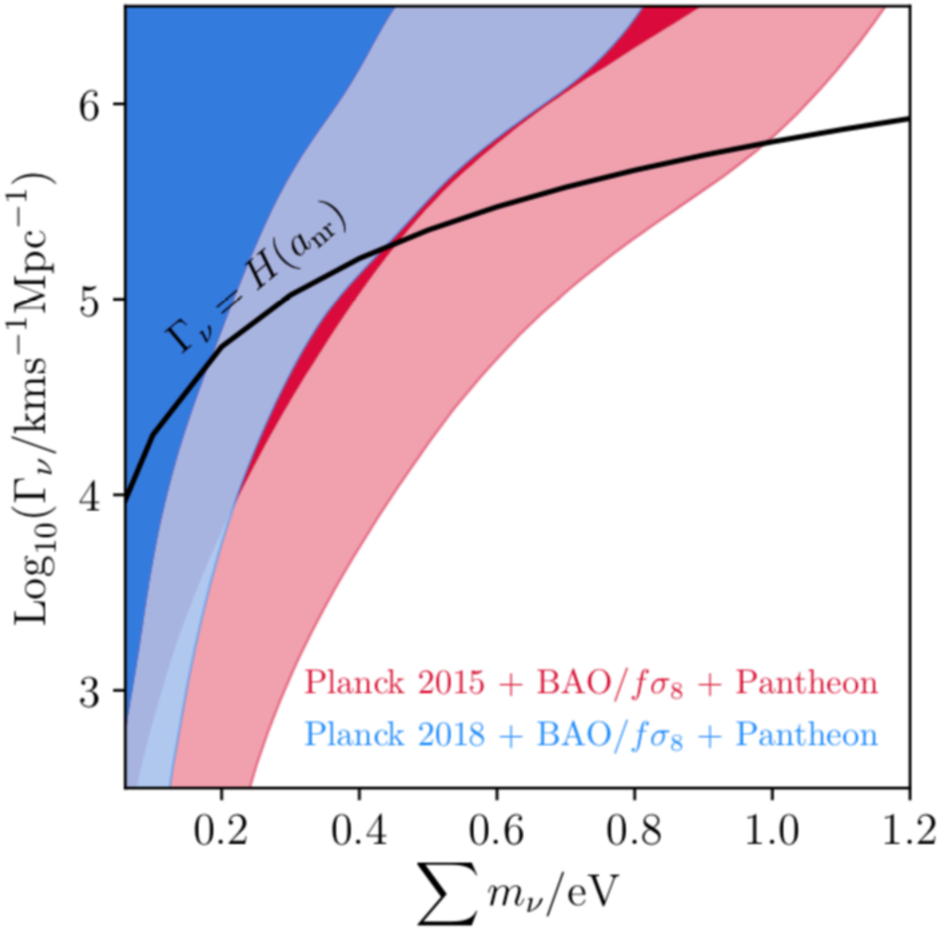




NEUTRINO DECAY



Chen et al. 2016



Abellan et al. 2021