PROBING NEUTRINO INTERACTIONS WITH COSMOLOGICAL OBSERVATIONS

MASSIMILIANO LATTANZI

INFN, sezione di Ferrara

HEP Division Seminar

Argonne National Laboratory

July 15th, 2020

Outline of the talk

- Introduction
- Non-standard Interactions in the active neutrino sector
- Non-standard Interactions in the sterile neutrino sector

Outline of the talk

- Introduction
- Non-standard Interactions in the active neutrino sector
- Non-standard Interactions in the sterile neutrino sector

The Cosmic Neutrino Background

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

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

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

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

The Cosmic Neutrino Background

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

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

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

Interactions become ineffective when $T=T_d$ such that

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

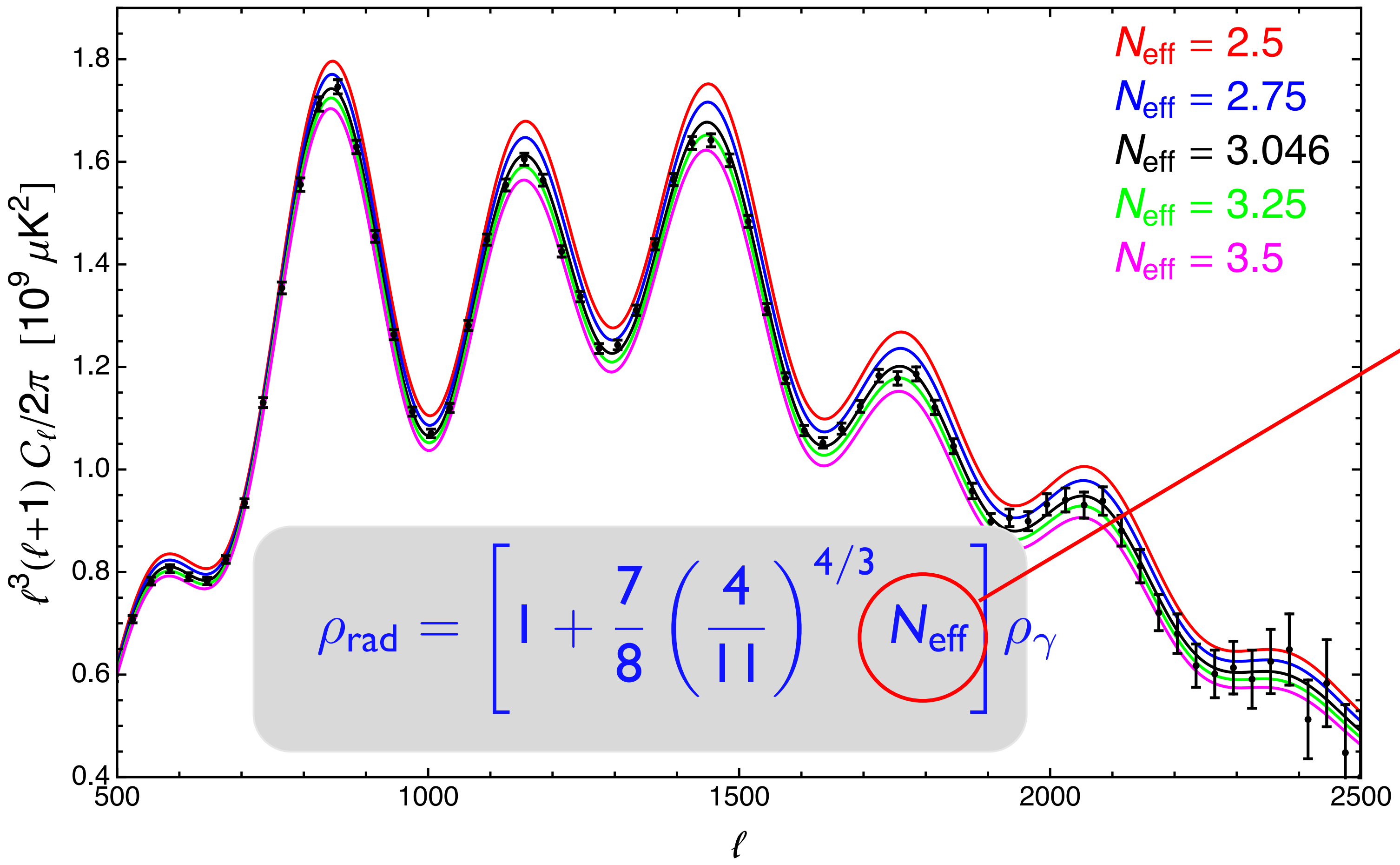
Given this, we can use conservation laws to compute the temperature, density, etc… of neutrinos at a given time.

The Cosmic Neutrino Background

The ΛCDM(+ν) model assumes:

- only weak and gravitational interactions for ν's;
- no sterile neutrinos or other light relics;
- perfect lepton symmetry (zero chemical potential);
- no entropy generation after neutrino decoupling beyond e^+e^- annihilation;
- neutrinos are stable;
- in general, there are no interactions that could lead to neutrino scattering/annihilation/decay

Observing the CNuB



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

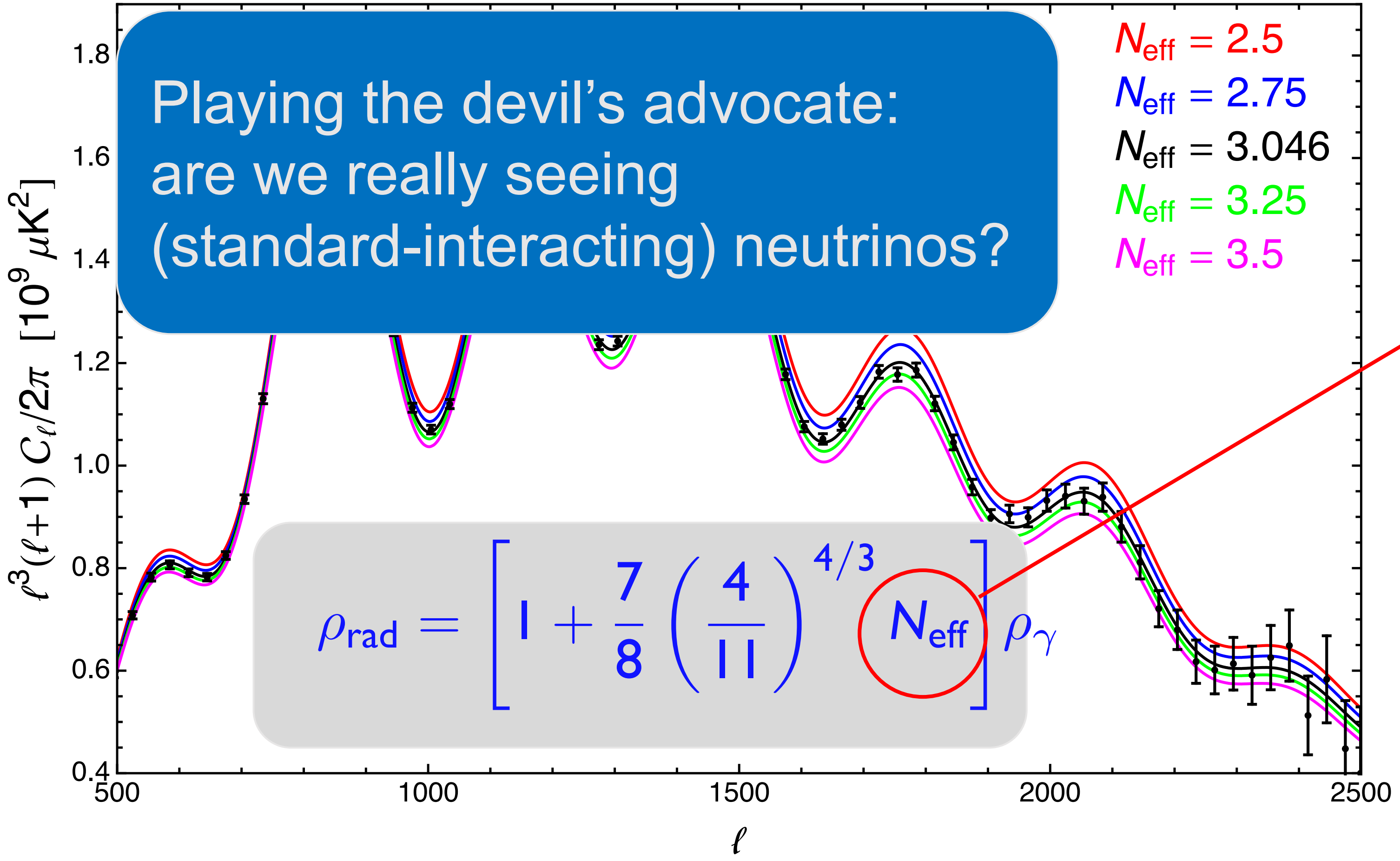
Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Planck 2018 + BAO:
Neff = 2.99+/- 0.17

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

Due to non-instantaneous decoupling, the standard expectation is **N_{eff} = 3.046**
(updated calculation gives N_{eff} = 3.045; see de Salas & Pastor 2016)

OBSERVING THE CNUB



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

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Planck 2018 + BAO:
Neff = 2.99+/- 0.17

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

Due to non-instantaneous decoupling, the standard expectation is **N_{eff} = 3.046**
(updated calculation gives N_{eff} = 3.045; see de Salas & Pastor 2016)

Why ν non-standard interactions?

- Why not? nuNSI are grounded in particle physics models and might be related to neutrino mass generation (e.g. Majoron models)

- Why not (II)? Relic ν's are extremely difficult to detect directly. It is a good idea to test their properties.

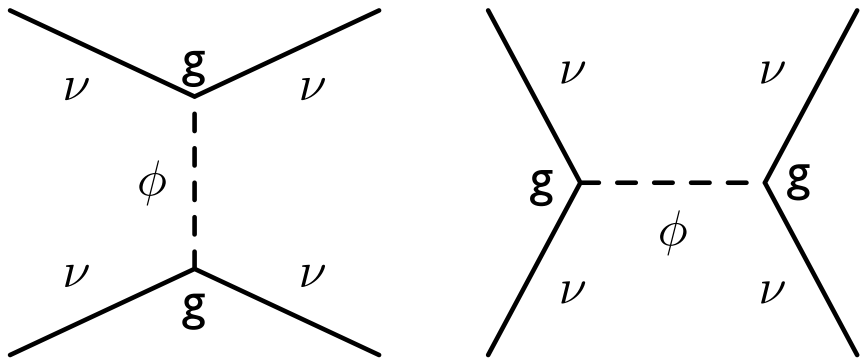
- Might help in explaining observed tensions….

Outline of the talk

- Introduction
- Non-standard Interactions in the active neutrino sector
- Non-standard Interactions in the sterile neutrino sector

Cosmological Phenomenology of νNSI

Collisional processes affect the perturbation evolution of relic neutrinos



Two limiting regimes:

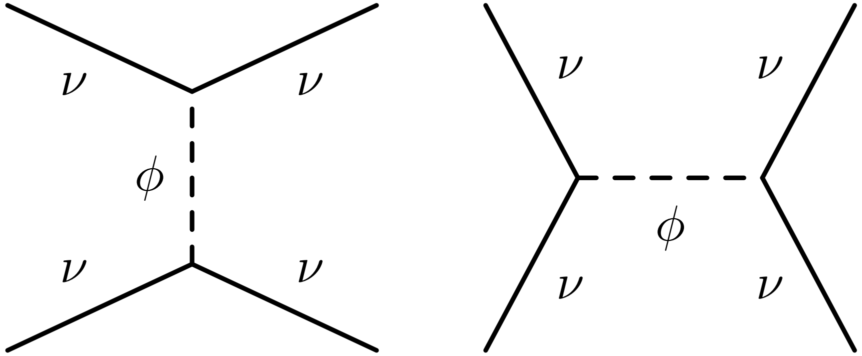
Light mediator (M_ϕ << T) $\langle \sigma v \rangle \sim \frac{g^4}{E^2} \sim \frac{g^4}{T^2}$

Heavy mediator (M_ϕ >> T) $\langle \sigma v \rangle \sim \frac{g^4}{M_\phi^4} E^2 \sim G_\phi^2 T^2$

$$G_\phi \equiv \frac{g^2}{M_\phi^2}$$

Cosmo Phenomenology of νNSI: Light mediator

Collisional processes can suppress stress and affect the perturbation evolution of cosmological neutrinos



In the UR limit: $\sigma \sim \frac{g^4}{s} \sim \frac{g^4}{T^2}$

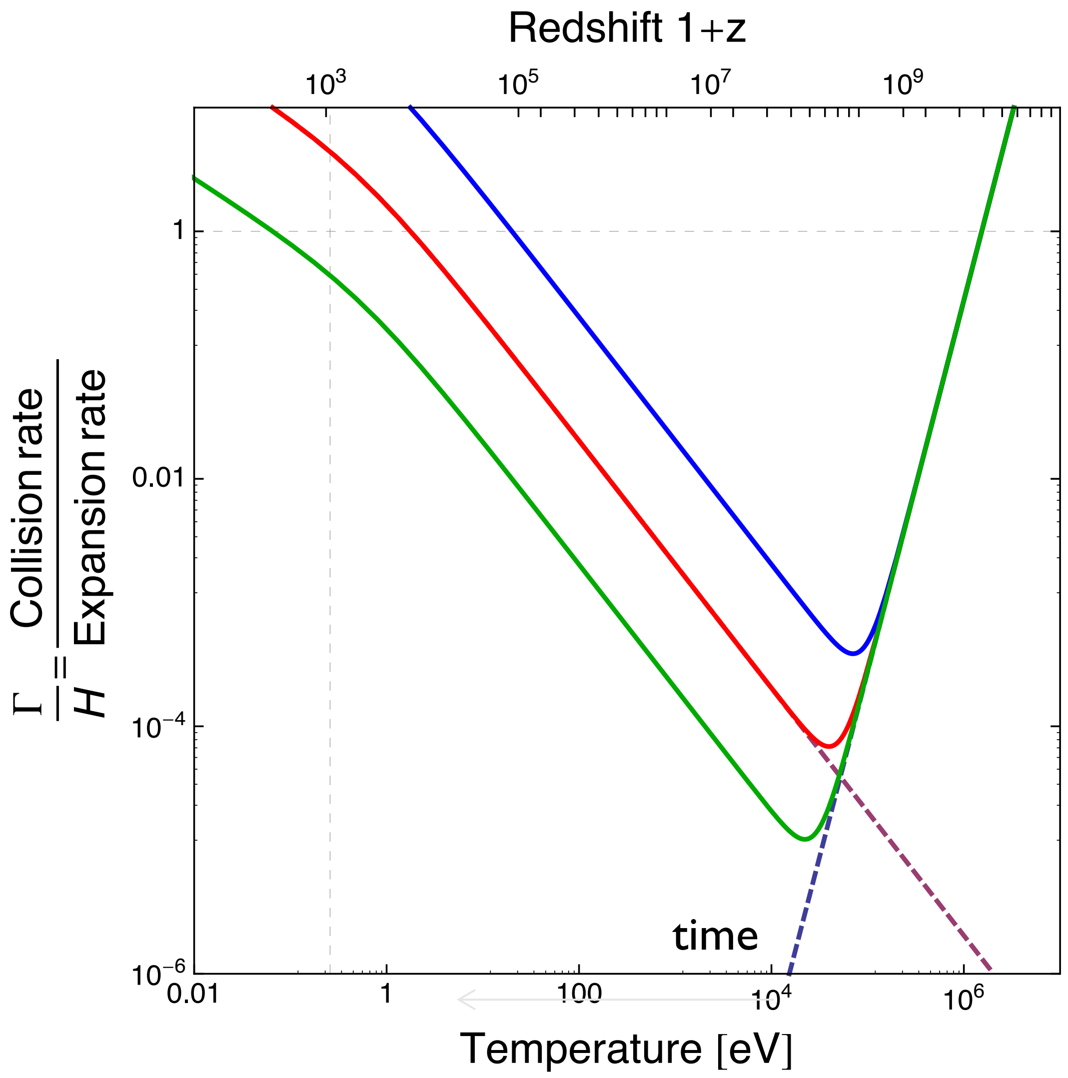
e.g., in simple majoron models: $\sigma \simeq \frac{1}{32\pi}\frac{g^4}{s}$

→ $\Gamma_{\nu\nu} = \langle \sigma_{\rm bin} v \rangle n_{\rm eq} \propto g^4 T \,,$

H grows as T^2 (RD) and $T^{3/2}$ (MD) so the ratio Γ/H *increases* with time. Neutrinos **recouple** at low temperatures! In the following I write generically

$$\Gamma_{\nu\nu} = (\dots) \times \frac{g^4}{T_\nu^2} \times \frac{3\zeta(3)}{2\pi^2} T_\nu^3 = g_{\rm eff}^4 \times \frac{3\zeta(3)}{2\pi^2} T_\nu$$

Cosmo Phenomenology of νNSI: Light mediator



$$\frac{\Gamma}{H} \sim \frac{g^4 M_{\rm Pl}}{T}$$

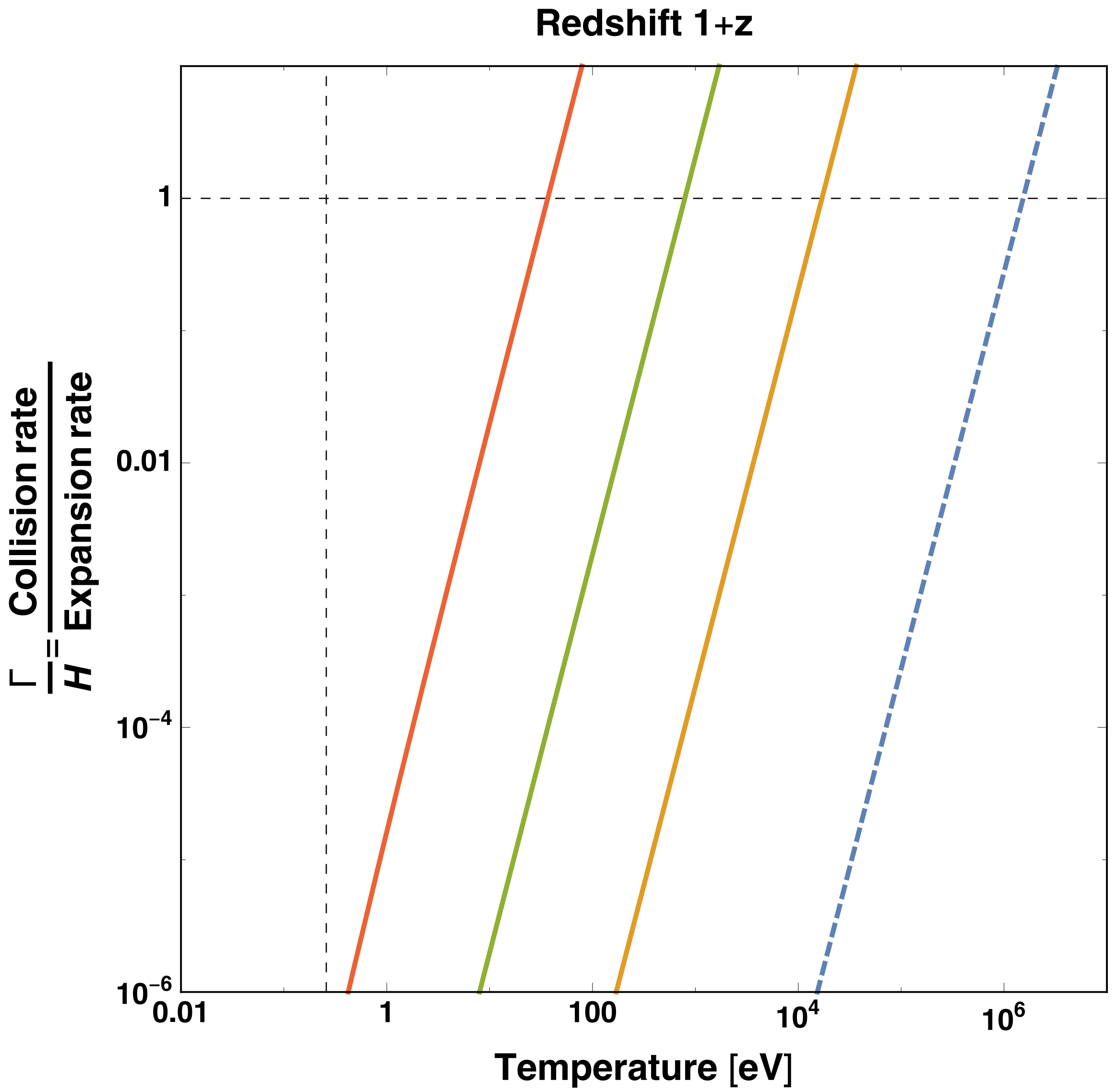
$g_{eff} = 1.5 \times 10^{-7}$

$g_{eff} = 2.7 \times 10^{-7}$

$g_{eff} = 5 \times 10^{-7}$

Recoupling happens earlier for larger ouplings

COSMO PHENOMENOLOGY OF νNSI: HEAVY MEDIATOR



$$\frac{\Gamma}{H} \sim G_\phi^2 T^3 M_{\rm Pl}$$

$G_\phi << G_F$

$G_\phi = (10\ \text{GeV})^{-2}$

$G_\phi = (1\ \text{GeV})^{-2}$

$G_\phi = (0.1\ \text{GeV})^{-2}$

Decoupling happens later for larger ouplings

Cosmological Phenomenology of νNSI

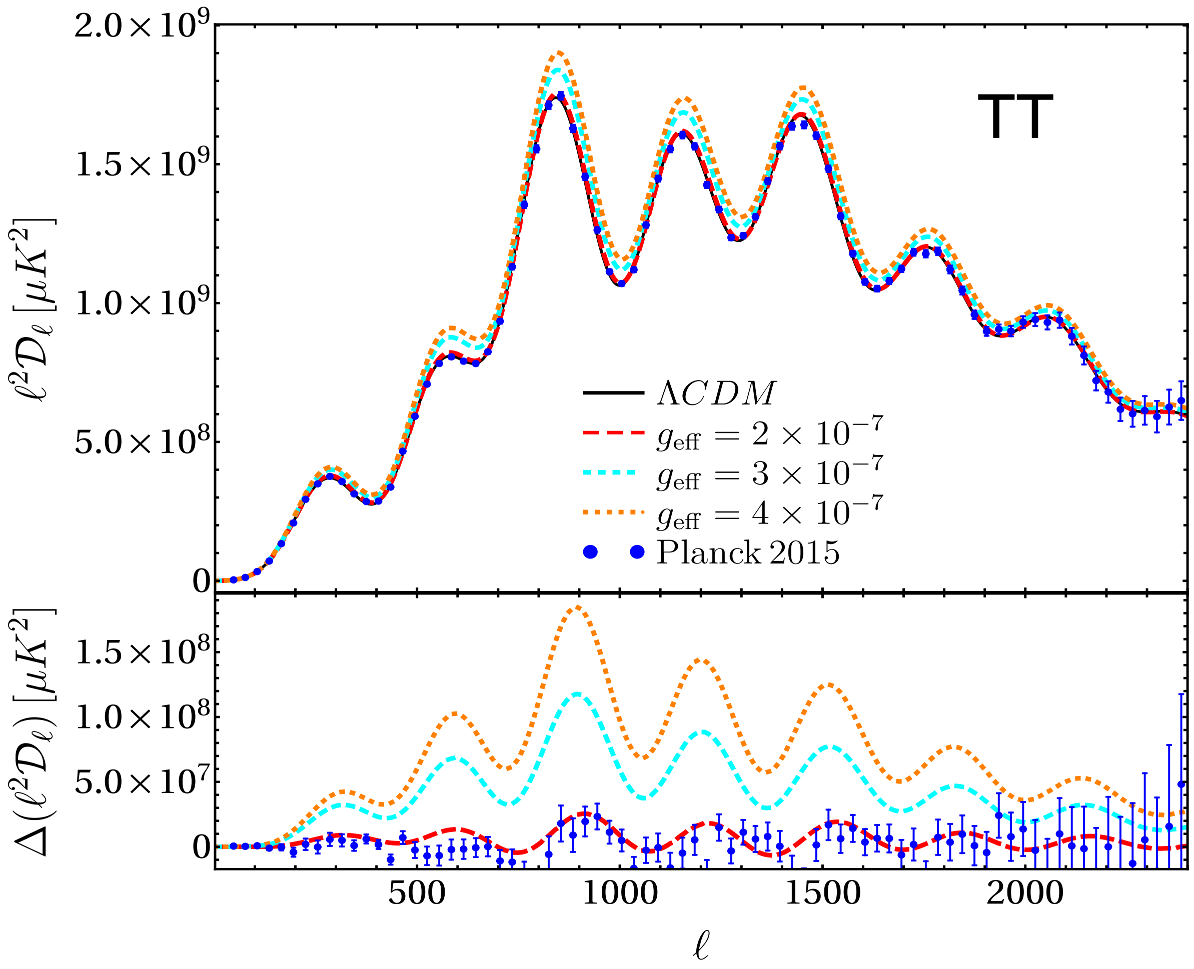
Neutrino free-streaming affects photon perturbations in two ways (Bashinsky & Seljak 2004):

- by "pulling" ahead photon-baryon wavefronts: this imprints a phase shift in the CMB power spectra

- by making gravitational potentials decay away more rapidly: this suppresses the amplitude of the spectrum

Both effects happen at the time the perturbation enters the horizon, and are relevant during the RD era

νNSI and CMB anisotropies: Light Mediator



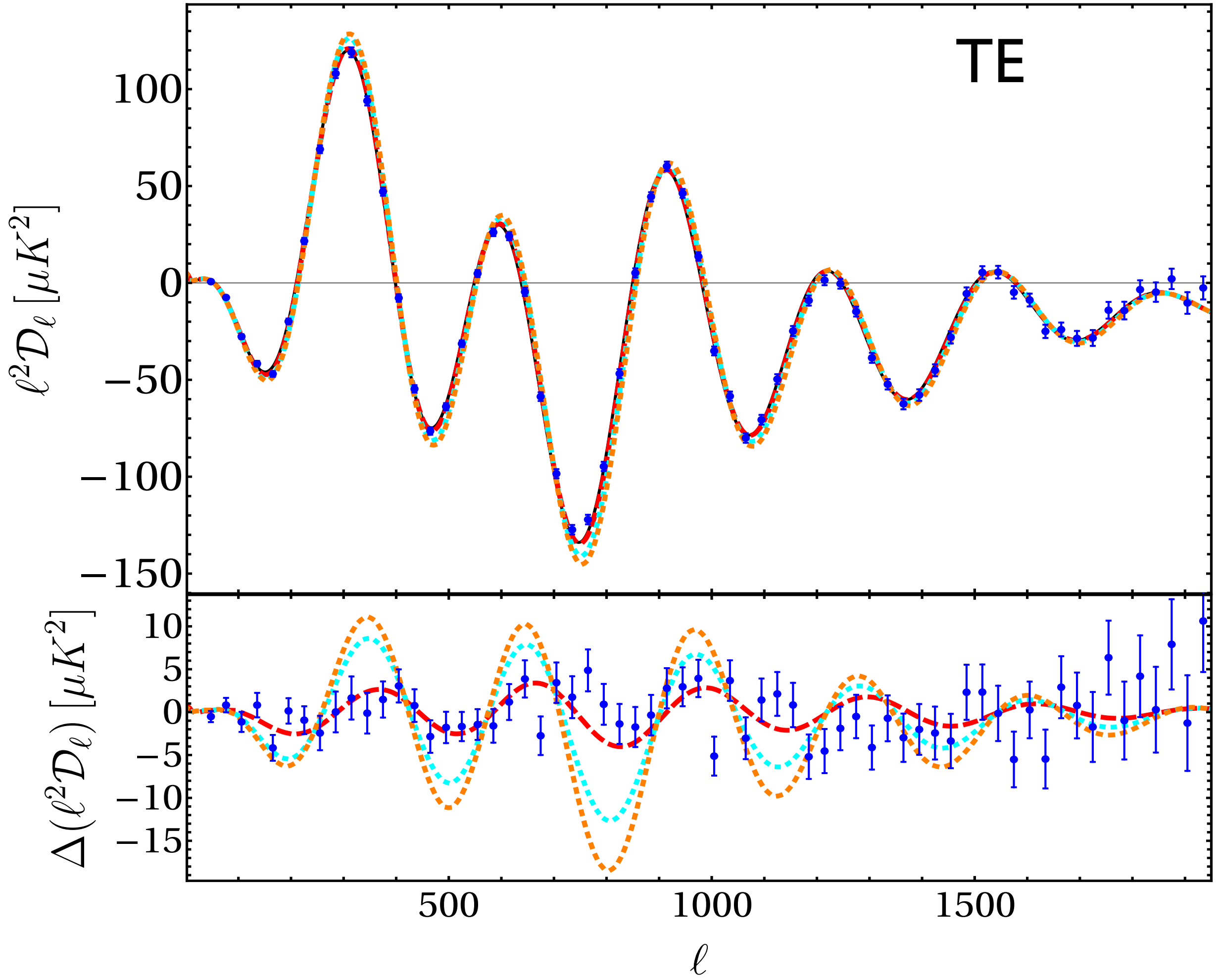
Scales entering the horizon between recoupling and equality are affected i.e. "larger" scales (up to the scale of matter radiation equality)

Overall boost of the spectrum amplitude + phase shift

Data points are from Planck 2015

(Forastieri, ML, Natoli, 2015, 2019; see also Archidiadono, Hannestad 2013; Cyr-Racine, Sigurdson 2013)

νNSI and CMB anisotropies: Light Mediator



Scales entering the horizon between recoupling and equality are affected i.e. "larger" scales (up to the scale of matter radiation equality)

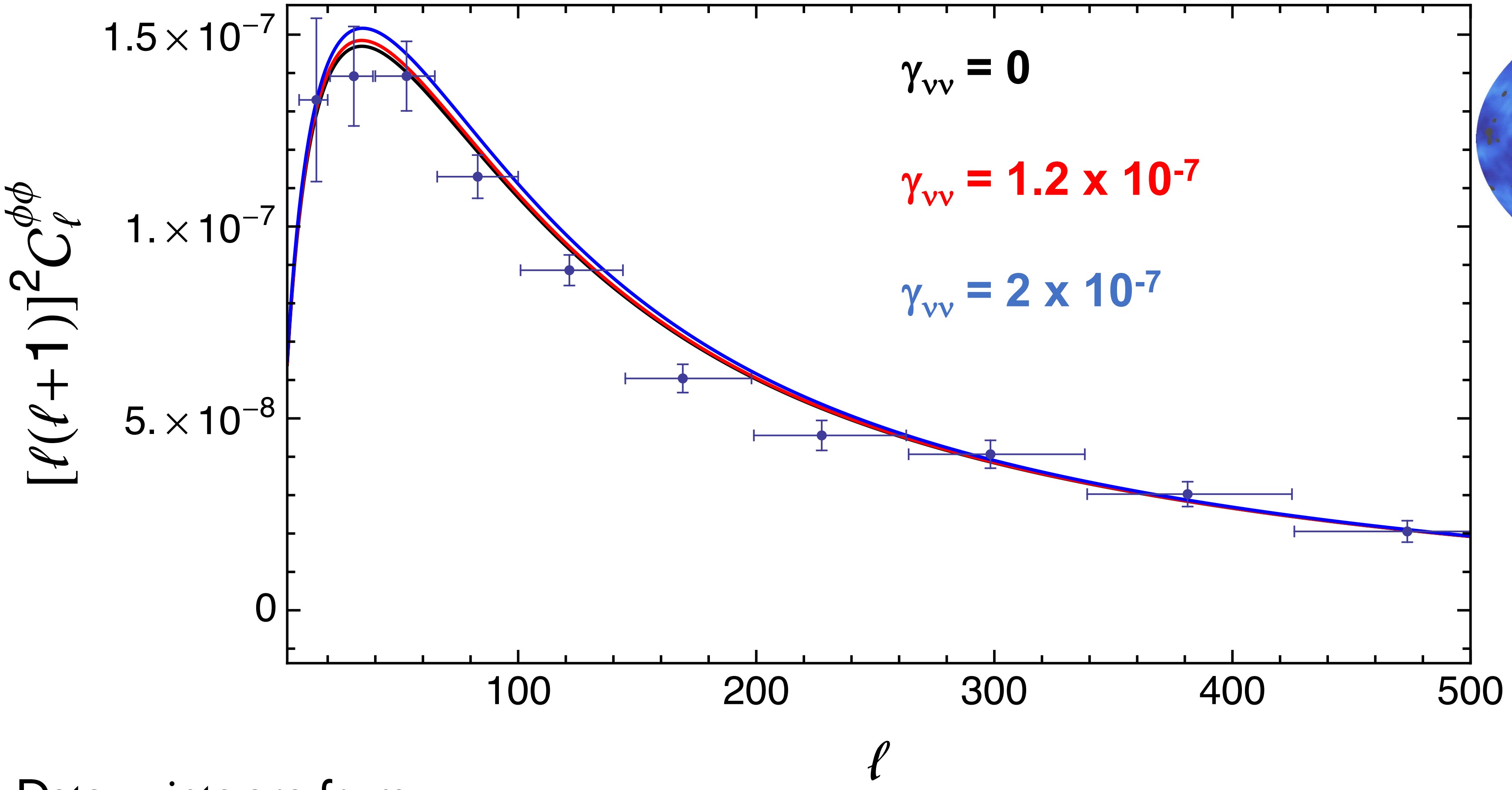
Overall boost of the spectrum amplitude + phase shift

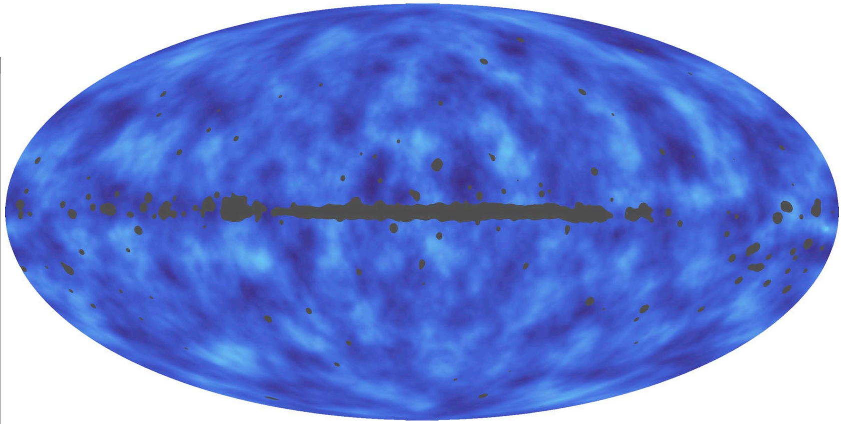
Data points are from Planck 2015

(Forastieri, ML, Natoli, 2015, 2019; see also Archidiadono, Hannestad 2013; Cyr-Racine, Sigurdson 2013)

νNSI and CMB anisotropies: Light Mediator

Power spectrum of the CMB lensing potential



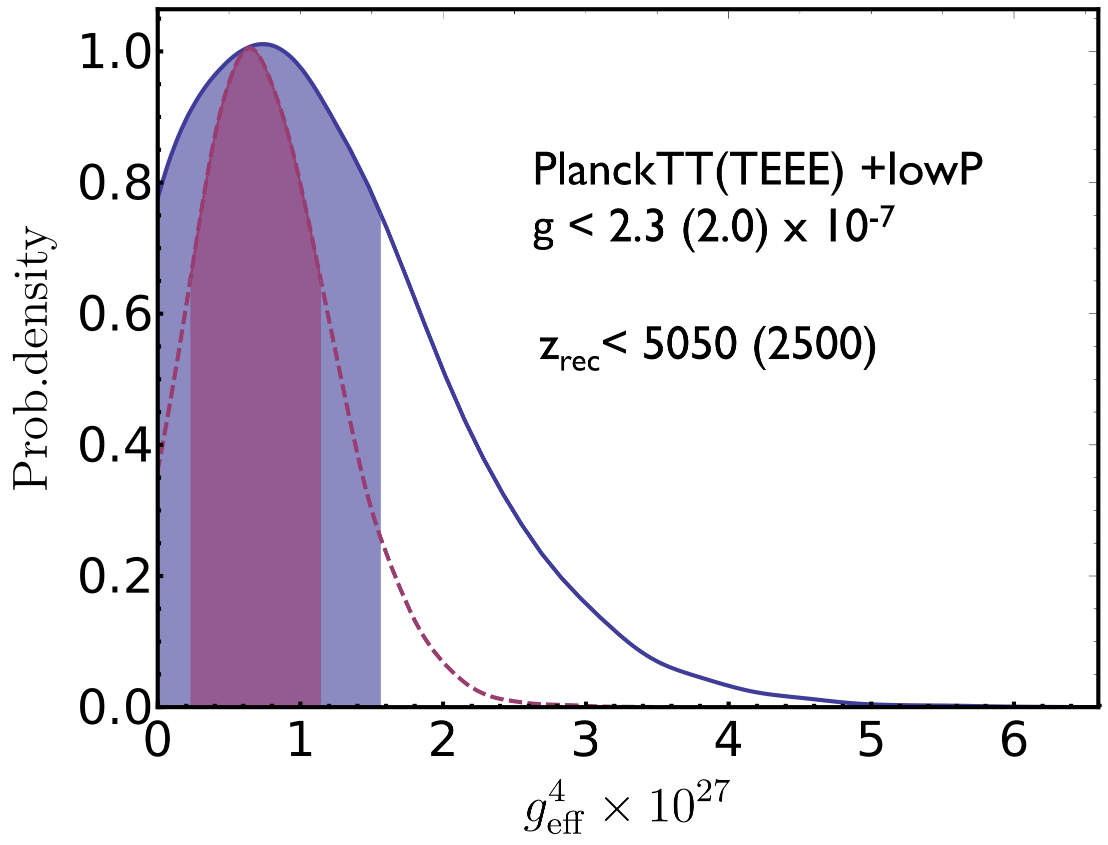


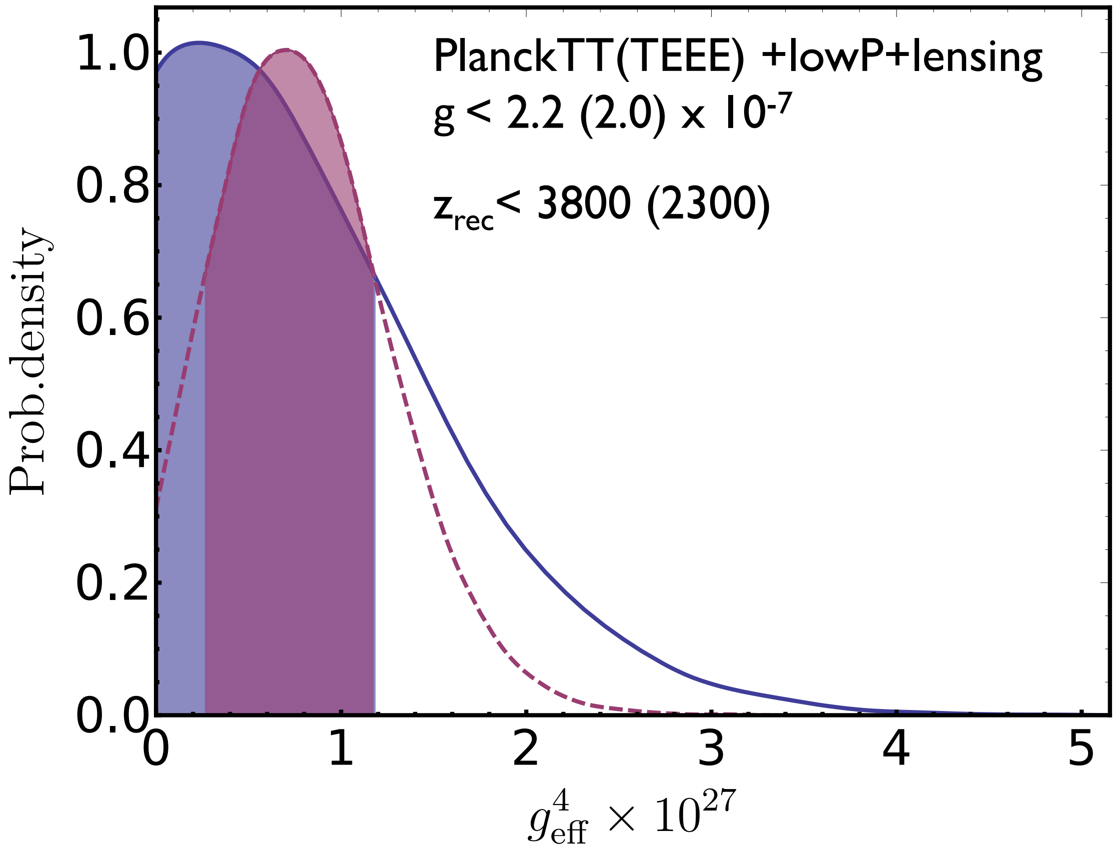
Lensing potential estimated from the four-point correlation function

Larger interactions suppress free-streaming → More lensing

Data points are from Planck 2015

νNSI AND PLANCK 2015: LIGHT MEDIATOR

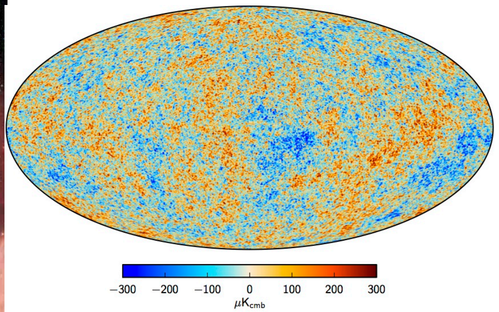




Forastieri, ML, Natoli, PRD 2019

Limits are 95% CL

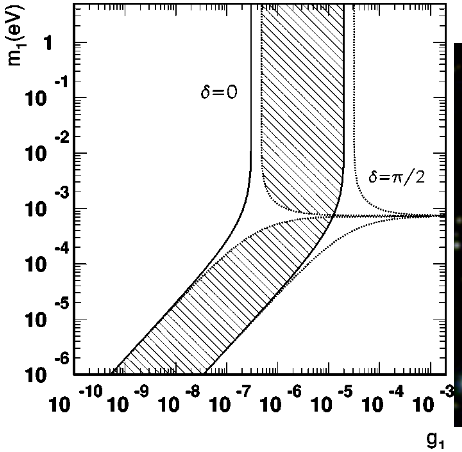
Probes of νNSI



cosmology

$g_{ij} < 2 \times 10^{-7}$

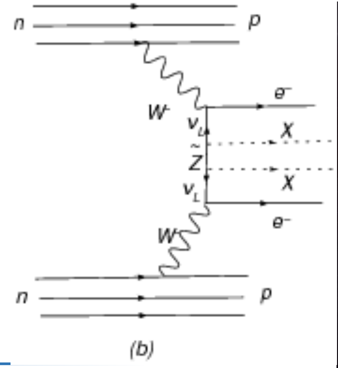
(mass basis)



Supernovae: $g_{i'j'} < 3 \times 10^{-7}$ or $g_{i'j'} > 2 \times 10^{-5}$

(medium basis)

$$\mathcal{L} \supset h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi \,,$$

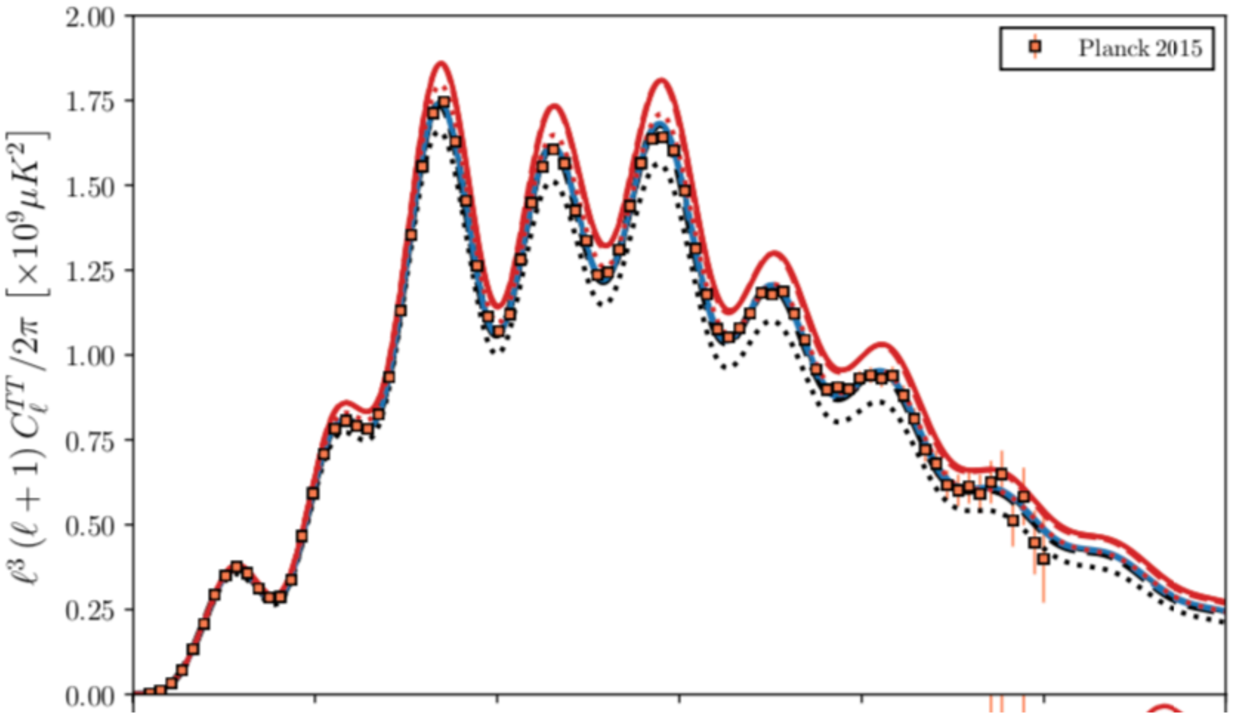


0ν2β decay

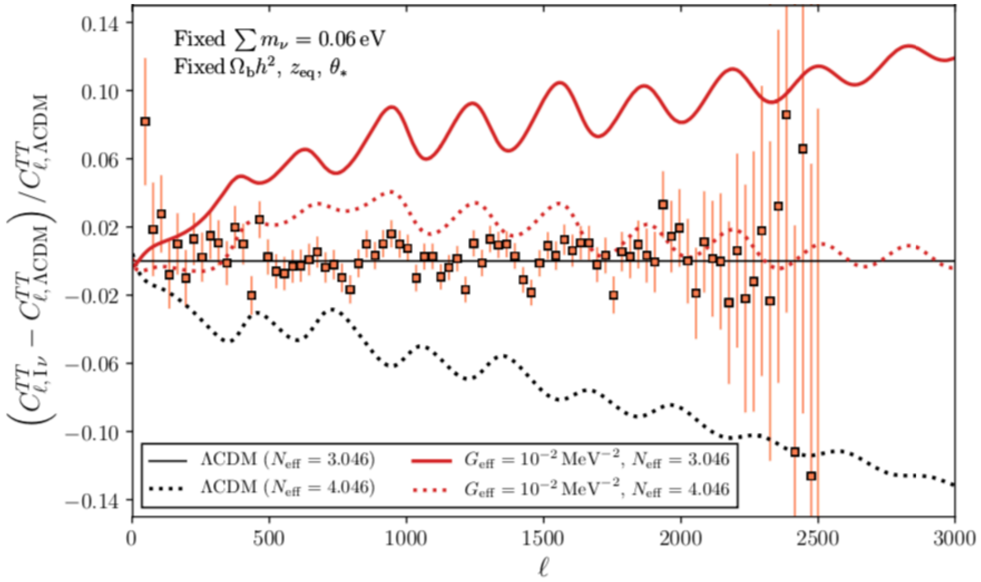
$g_{ee} < (0.8 \div 1.6) \times 10^{-5}$

(flavor basis)

νNSI and CMB anisotropies: Heavy Mediator

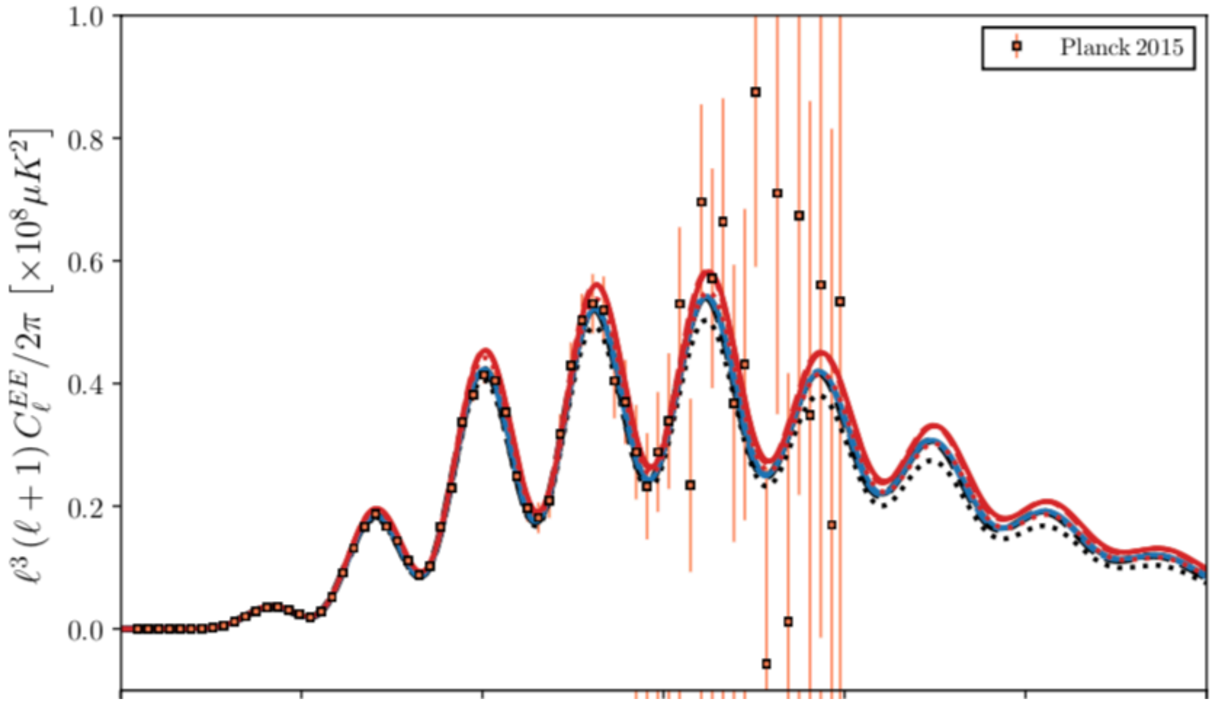


Scales entering the horizon before decoupling are affected
i.e. smaller scales are more affected

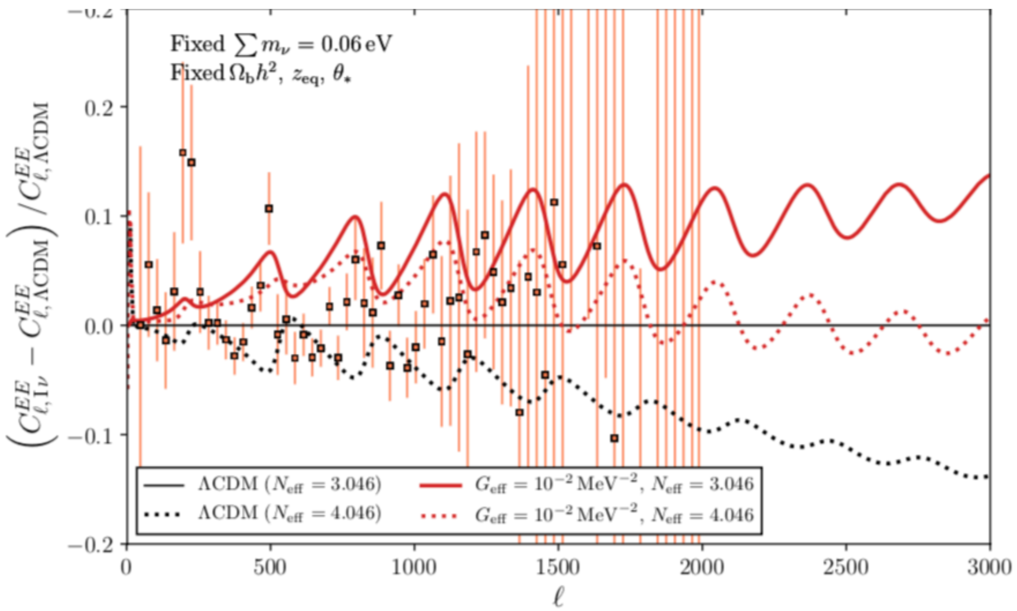


Kreisch, Cyr Racine & Dore 2019
See also Cyr-Racine & Sigurdson 2014; Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Wong 2017

νNSI AND CMB ANISOTROPIES: HEAVY MEDIATOR

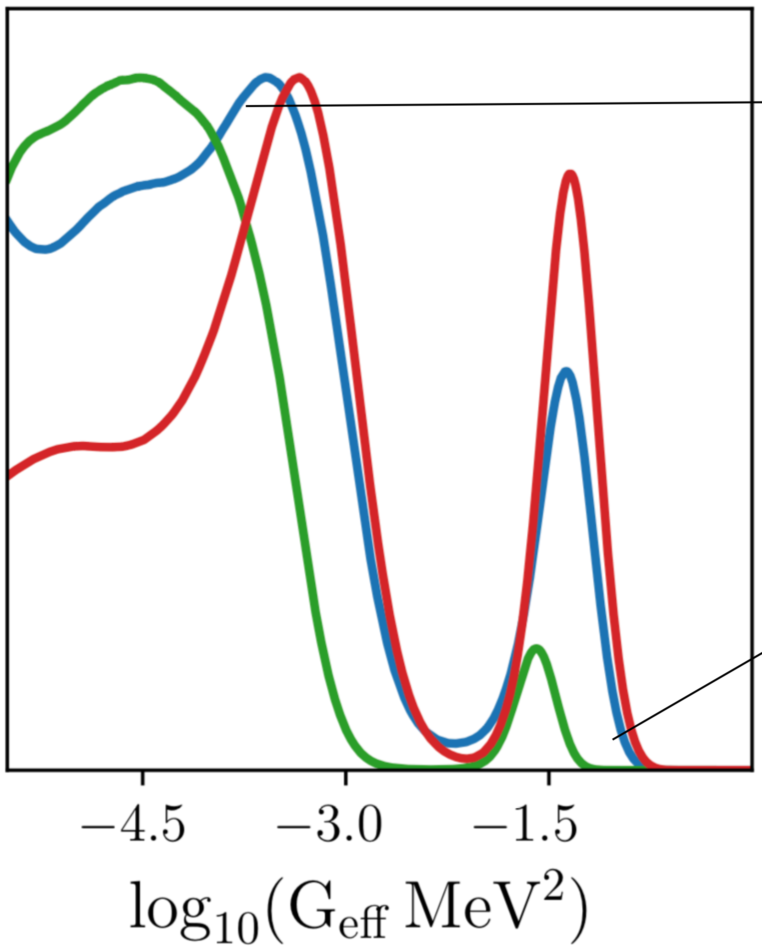


Scales entering the horizon before decoupling are affected
i.e. smaller scales are more affected



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

νNSI Constraints: Heavy Mediator



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

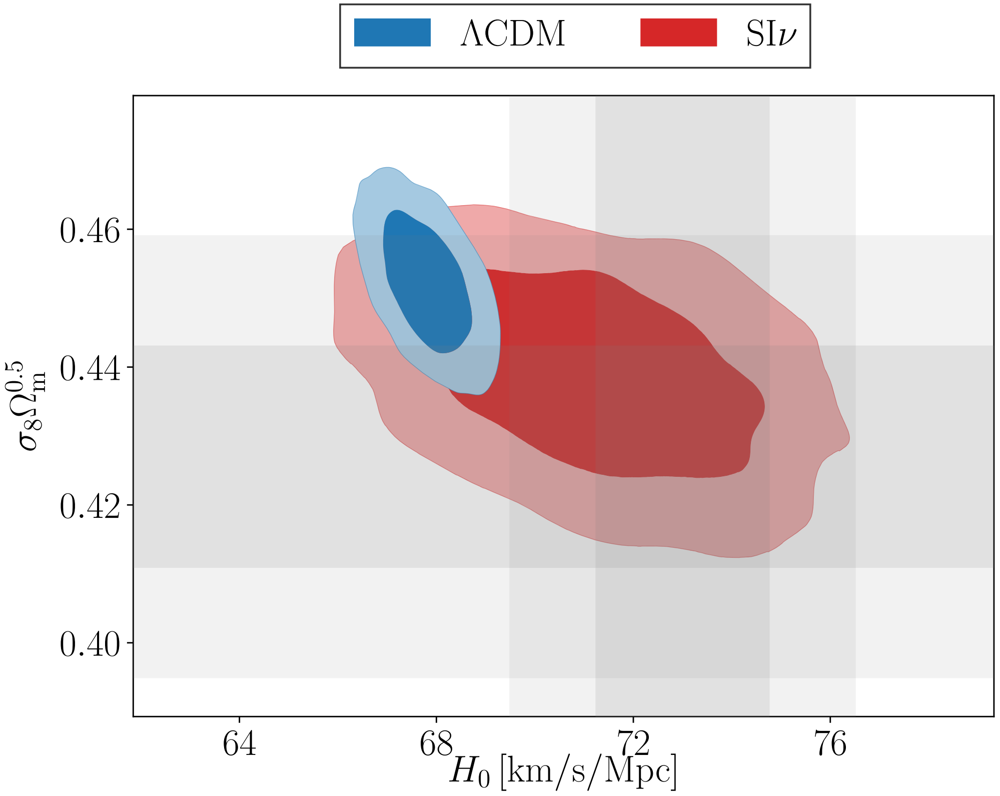
$$G_{\rm eff} = (2.5^{+0.8}_{-0.5}) \times 10^4\,{\rm GeV}^{-2}$$

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

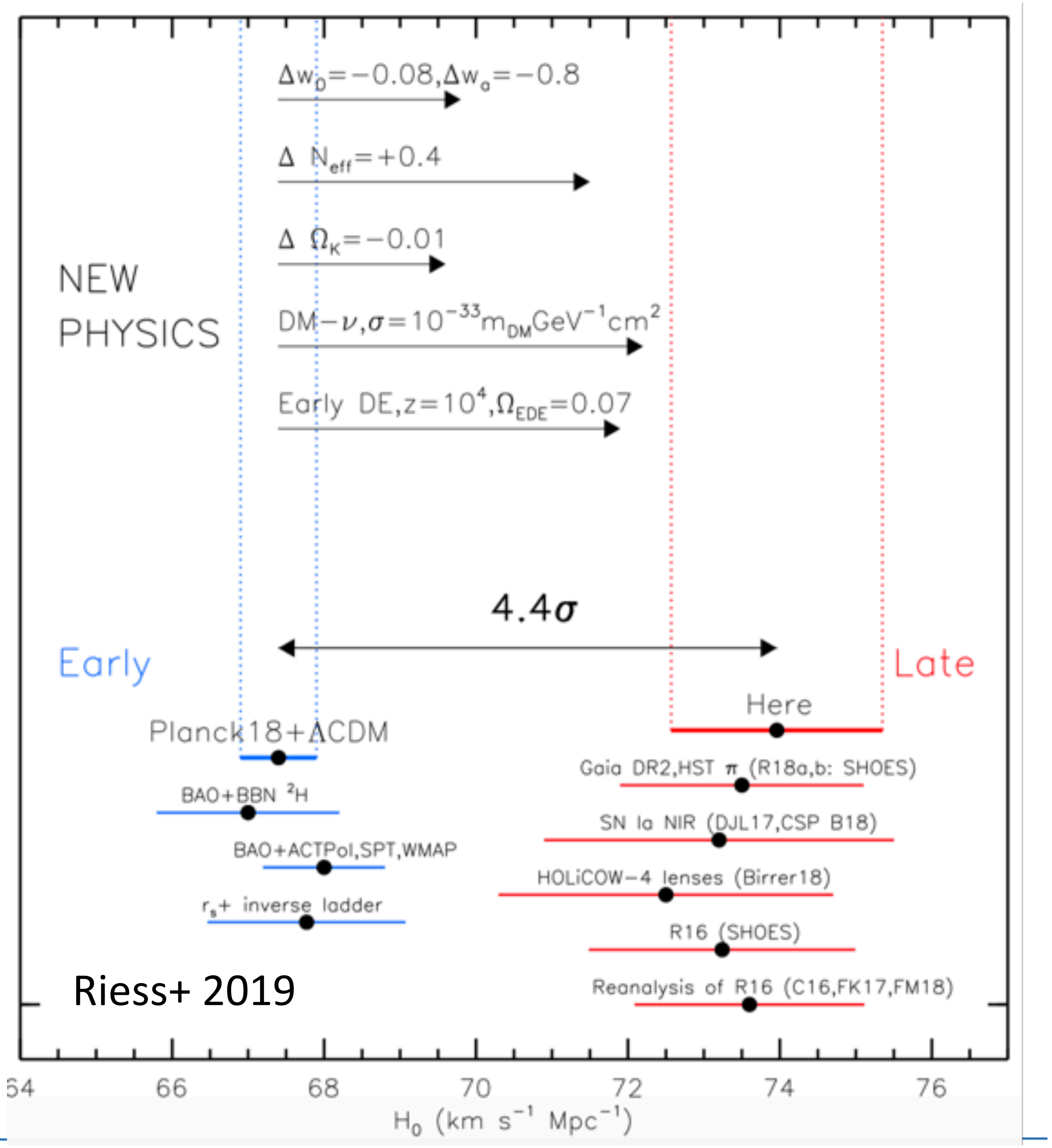
Preference for a "strong-interacting" mode emerges from some data combinations

Kreisch, Cyr Racine & Dore 2019

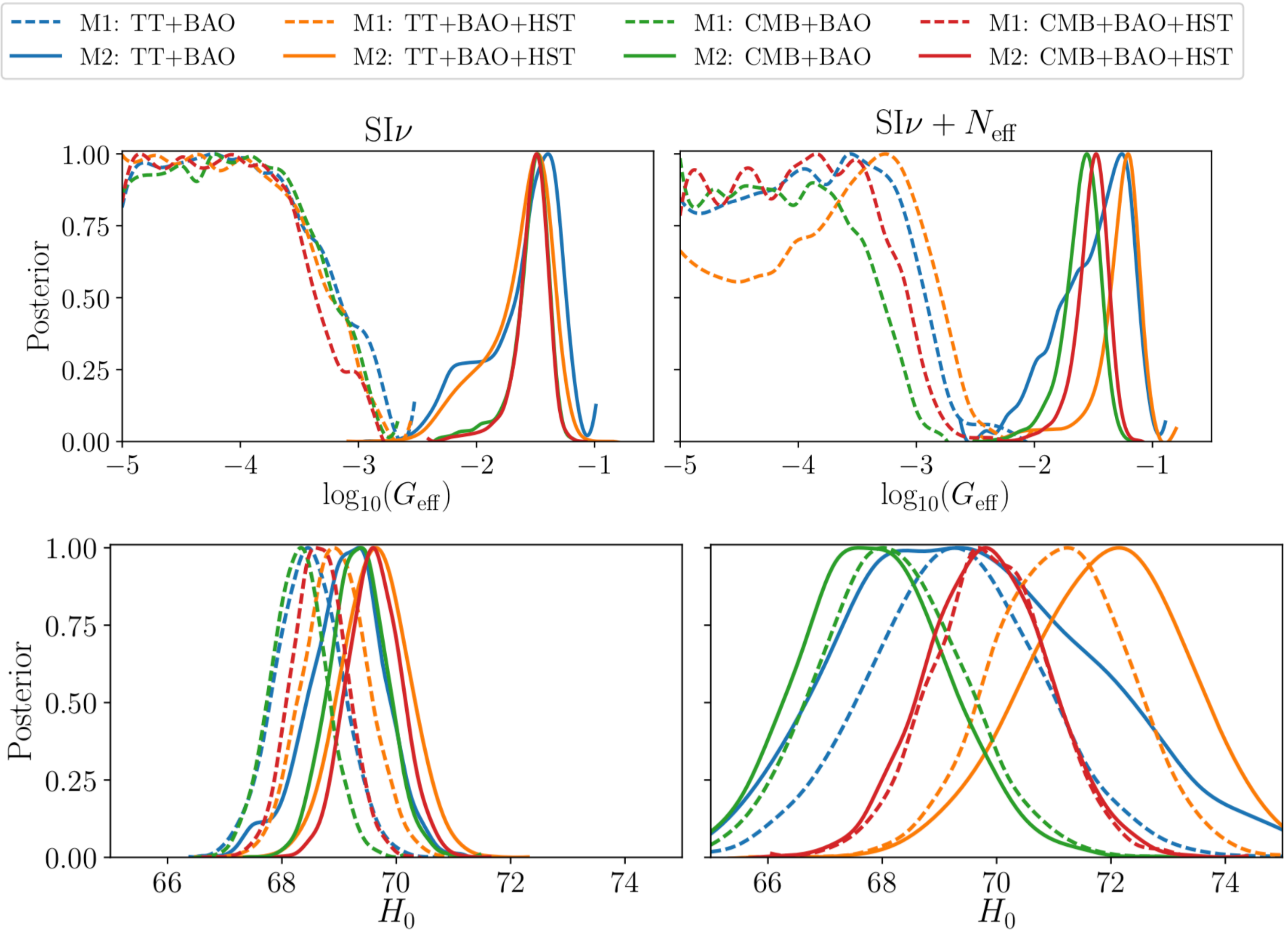
νNSI: A WAY TO ALLEVIATE THE HUBBLE TENSION?



Kreisch, Cyr Racine & Dore 2019



νNSI: A way to alleviate the Hubble Tension?

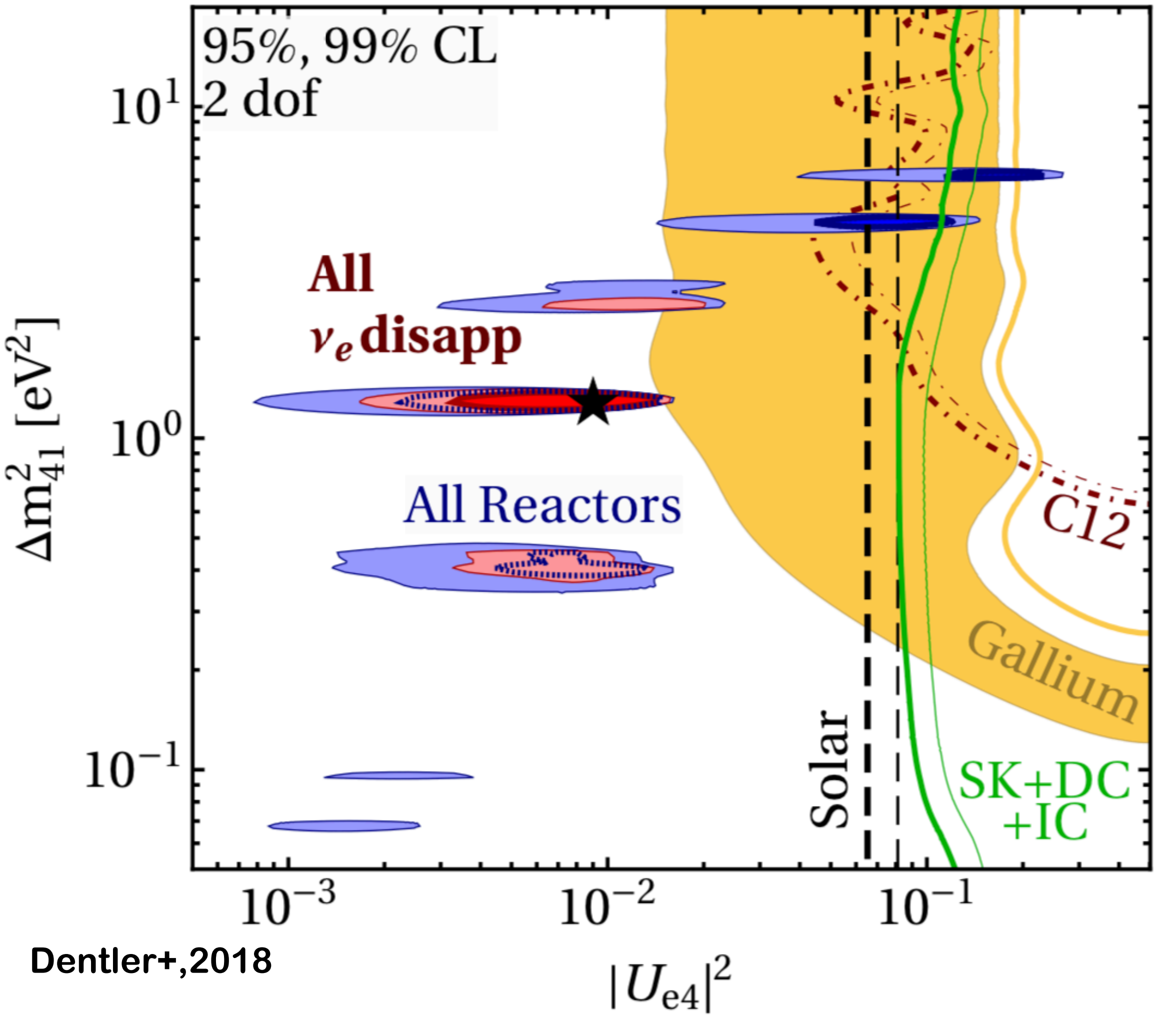


Oldengott et al. 2017

Outline of the talk

- Introduction
- Non-standard Interactions in the active neutrino sector
- Non-standard Interactions in the sterile neutrino sector

CROSS-CHECK SCENARIO: LIGHT STERILE NEUTRINO



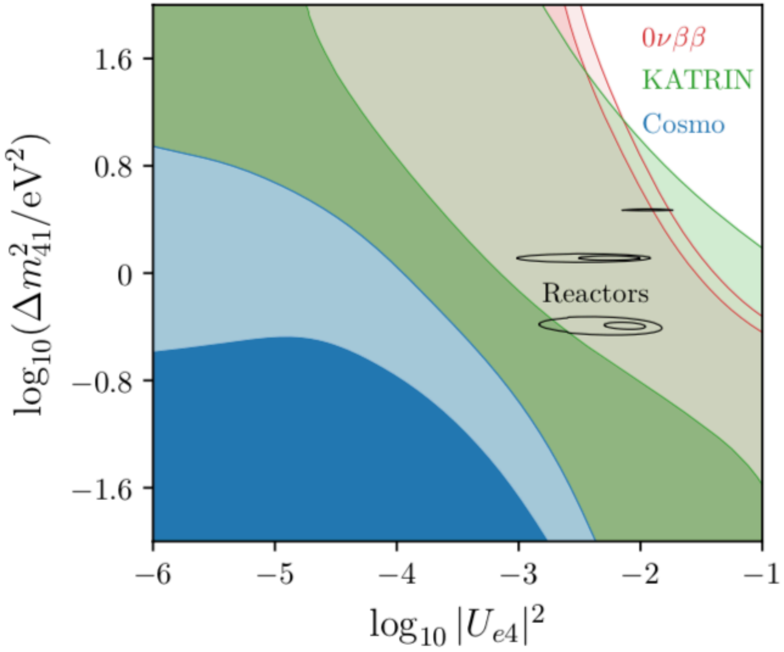
Dentler+,2018

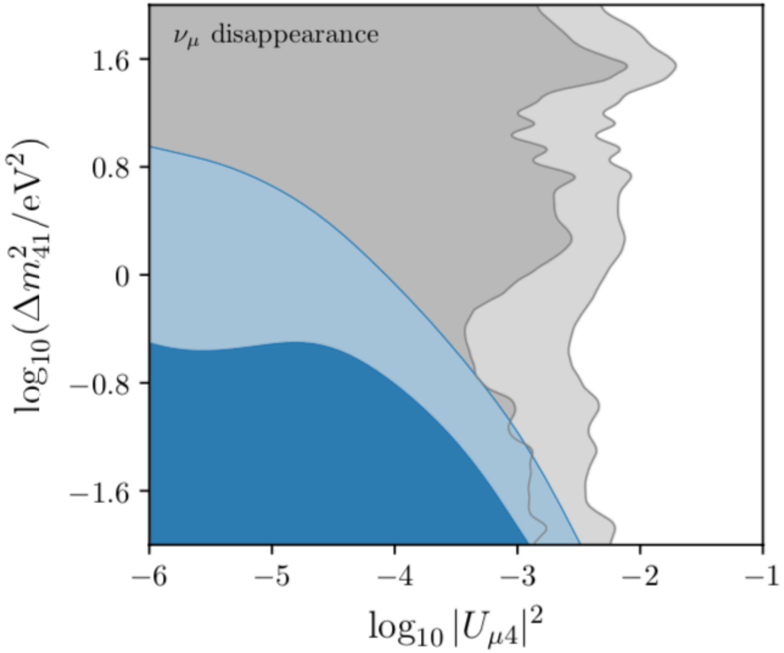
Possible solution(s)
to anomalies:
existence of a light sterile neutrino
with non-negligible mixing
with electronic nu

$$\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau),$$

$$(\nu_{sR})^C = \sum_{k=1}^{N} U_{(3+s)k} \nu_{kL} \quad (s = 1, \ldots, N_s),$$

CROSS-CHECK SCENARIO: LIGHT STERILE NEUTRINO





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

Light sterile solution to anomalies hard to accommodate

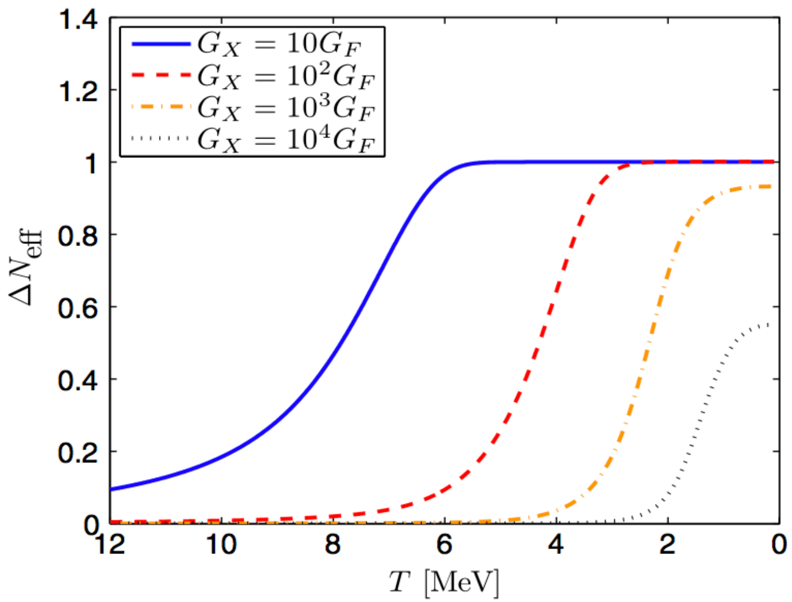
Parameter	experimental upper limit (95%)	cosmological upper limit (95%) $\mathcal{P}(\log\Delta m^2_{14})$	$\mathcal{P}(m_4)$	$\mathcal{P}(\Delta m^2_{14})$
m_4 [eV]	-	1.6	4.4	6.8
$\log_{10}\lvert U_{e4}\rvert^2$	-	−3.04	−3.43	−4.0
$\log_{10}\lvert U_{\mu 4}\rvert^2$	−2.2 (ν_μ)	−3.17	−3.55	−4.16
$\log_{10}\lvert U_{\tau 4}\rvert^2$	−0.8 (ν_μ)	−3.18	−3.55	−4.19

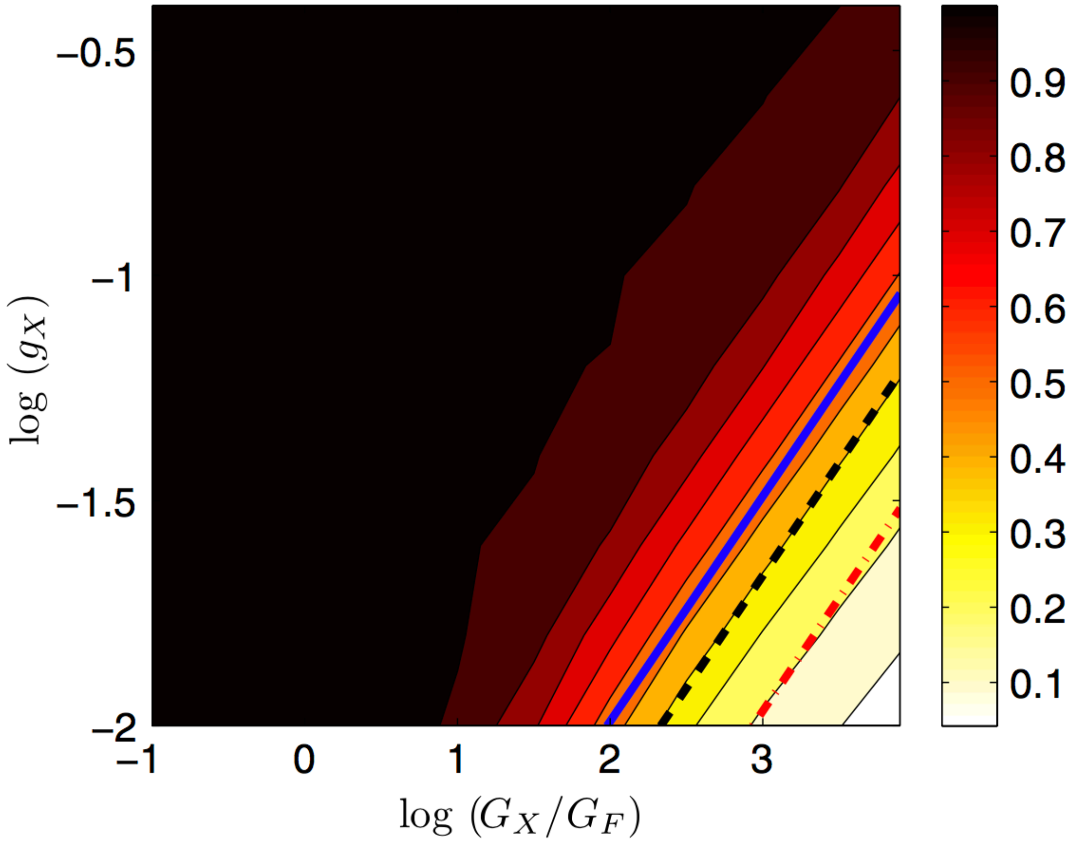
Hagstotz+(incl.MG),2020

νNSI and SBL anomalies

A possible solution:
new ("secret") neutrino interactions in the sterile sector can prevent production in the early Universe

$$\mathcal{L}_s = g_X \bar{\nu}_s \gamma_\mu \frac{1}{2} (1-\gamma_5) \nu_s X^\mu$$





Hannestad et al. 2014; Dasgupta & Kopp 2014; Bringmann et al 2014; Saviano et al 2014; Mirizzi et al 2015; Chu,Dasgupta,Kopp 2015; Chu et al. 2018

νNSI AND SBL ANOMALIES

MSW effect

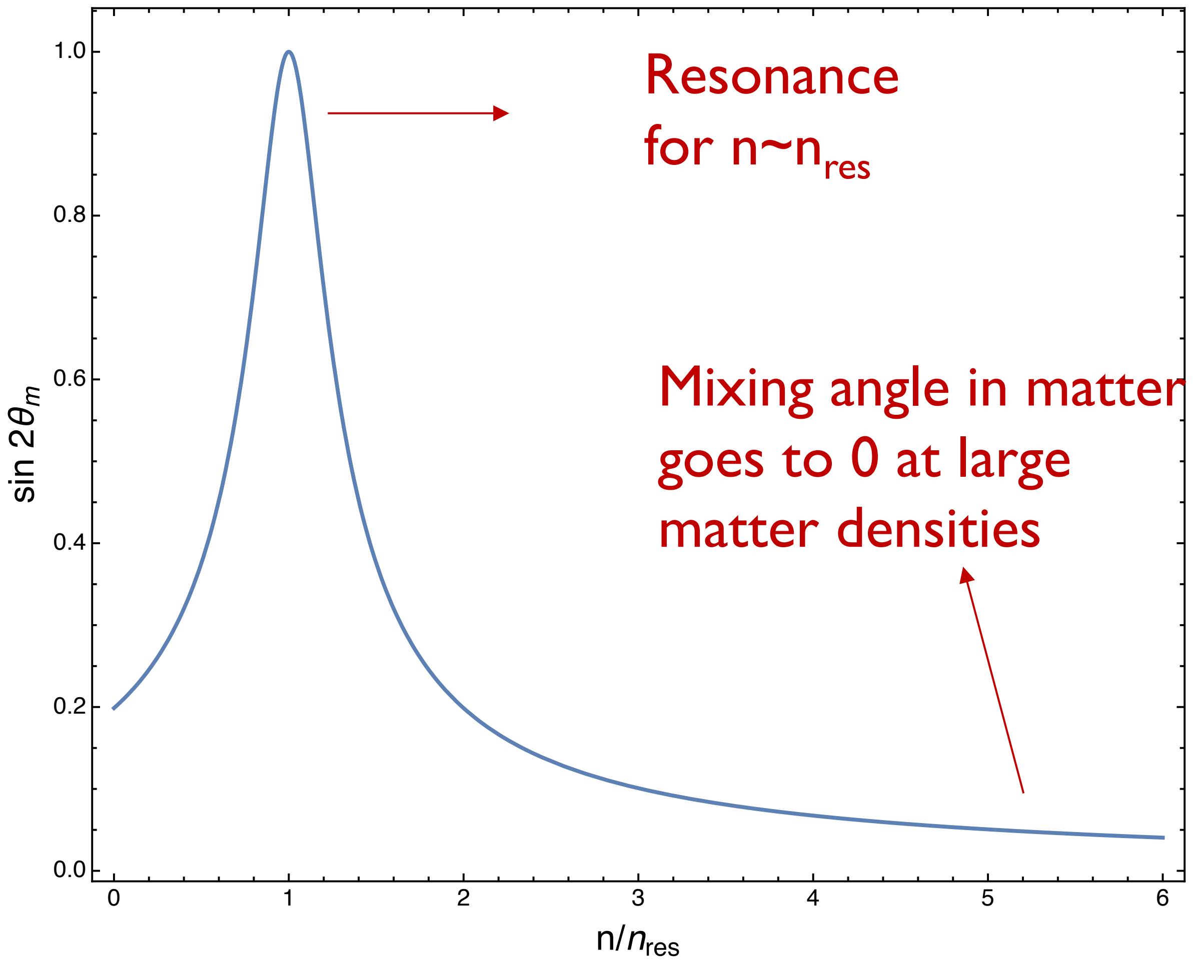
Mixing angle in matter is changed due to the effect of neutrino – matter (usually electrons) scattering

In ordinary matter (i.e., weak interactions)

$$n_{\rm res} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F}$$

For secret vector interactions, $G_F \rightarrow G_X$

Active-sterile oscillations are suppressed by the sterile own matter potential ("quantum zeno effect")

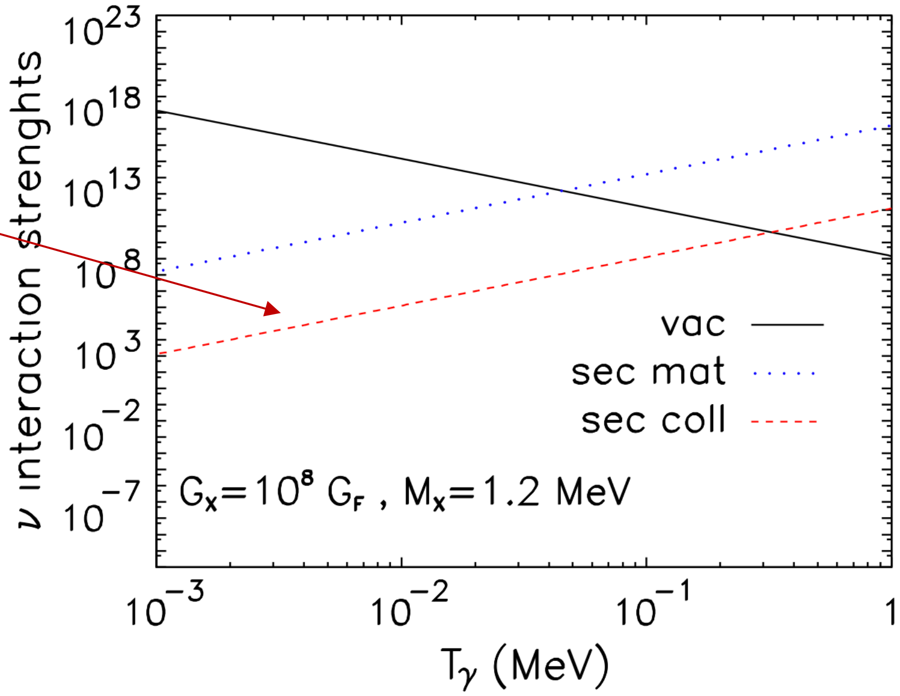


νNSI AND SBL ANOMALIES

For $g_x > 10^{-2}$ and $M_X < 10$ MeV, it is still possible to copiusly produce neutrinos at low (T<1 MeV) temperatures, through an interplay between vacuum oscillations and collisions ("*scattering-induced decoherence*") (Saviano et al 2014; Mirizzi et al 2015;)

Relaxation rate to chemical equilibrium:

$$\Gamma_t \simeq \langle P(\nu_\alpha \to \nu_s) \rangle_{\rm coll} \Gamma_X .$$



Number conservation and flavour equilibration imply

$n_{s,after} = n_{a,after} = 3/4\ n_{a,before}$

Then collisions lead to thermalization and

$$T_\nu = \left(\frac{3}{4}\right)^{1/3} T_\nu^{\rm std} \quad \longrightarrow \quad N_{\rm eff} = 4 \times \left(\frac{3}{4}\right)^{4/3} \simeq 2.7$$

νNSI AND SBL ANOMALIES

ΛCDM (N_{eff}=2.7) + m_s + G_X

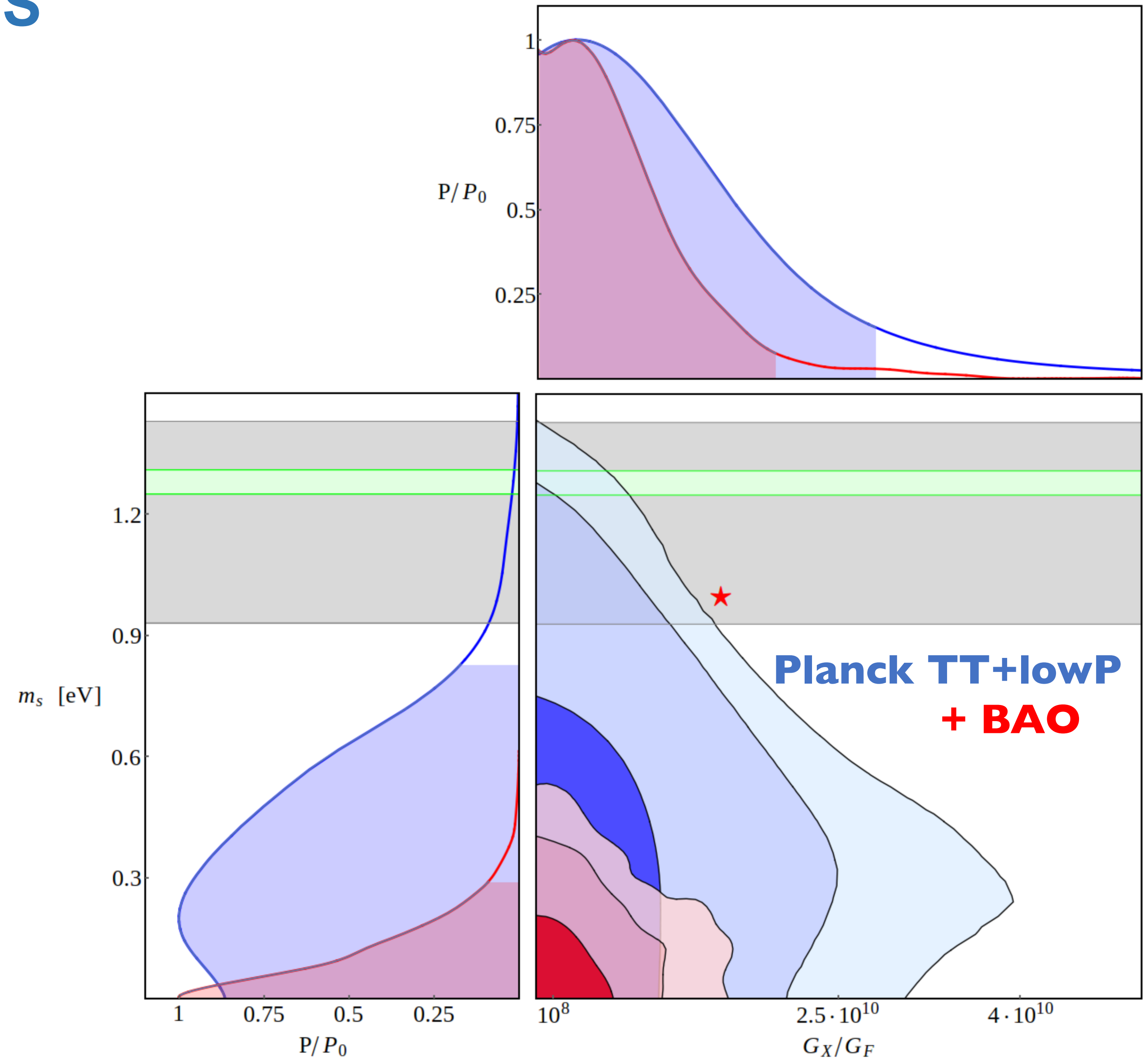
G_X < 2.8 (1.97) x 10^{10} G_F
m_s < 0.82 (0.29) eV

H_0 =62.6 +/- 1.8 km/s/Mpc
(65.3 +/- 0.7)

(G_X > 10^8 is always assumed)

The mass constraint is still there!

Forastieri+ (incl ML) 2017



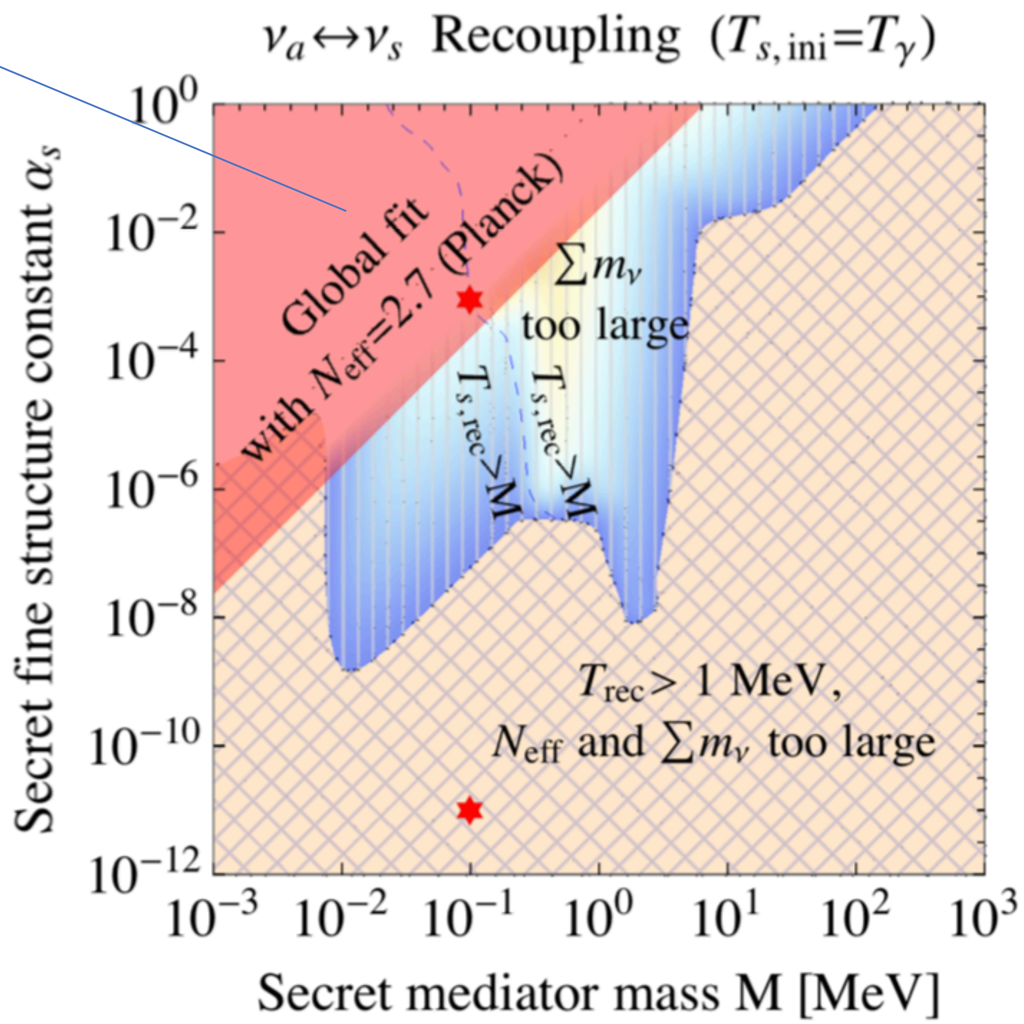
νNSI AND SBL ANOMALIES

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

νNSI and SBL anomalies (and H0 again!)

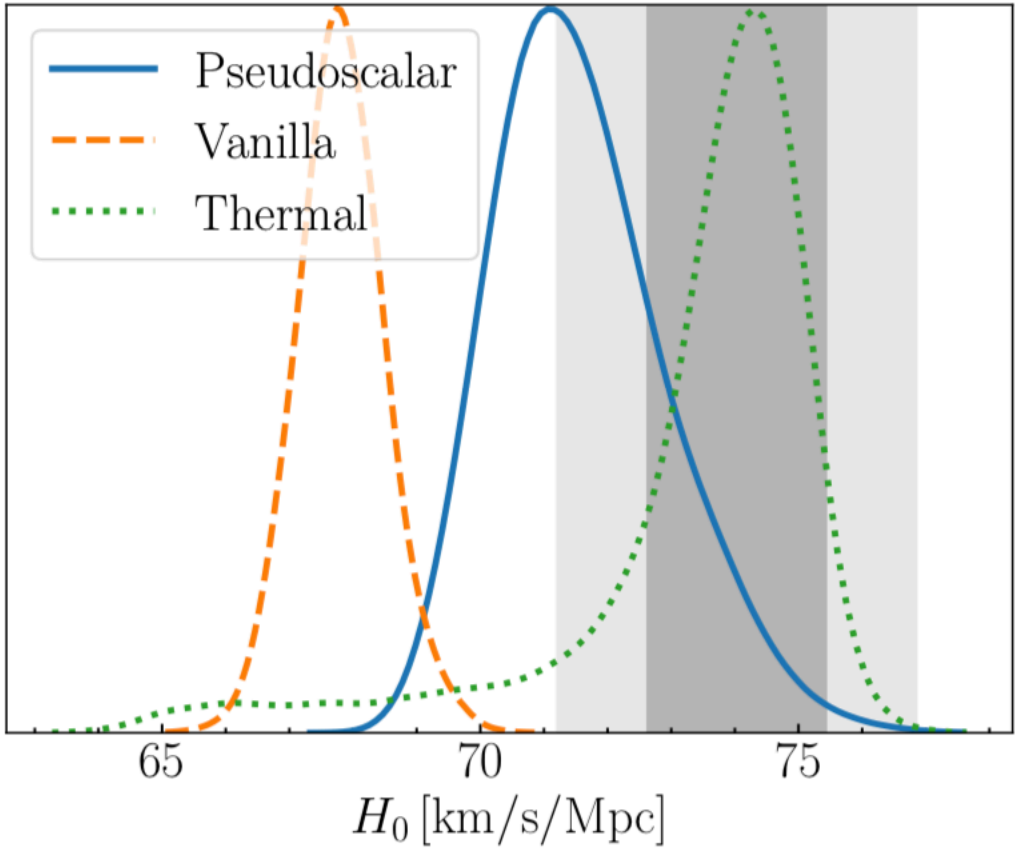
Another possibility: couple the sterile neutrino to a light pseudoscalar (Archidiacono et al. 2015, 2016, 2020)

- Lack of free-streaming in the sterile-pseudoscalar fluid;

- Annihilation of steriles to pseudoscalars when $T<m_s$

This yields a good fit to the combined CMB + HST data, but a poor fit to CMB alone.

Moreover, high-ell polarization excludes most of the parameters space for m_s allowed by SBL anomalies

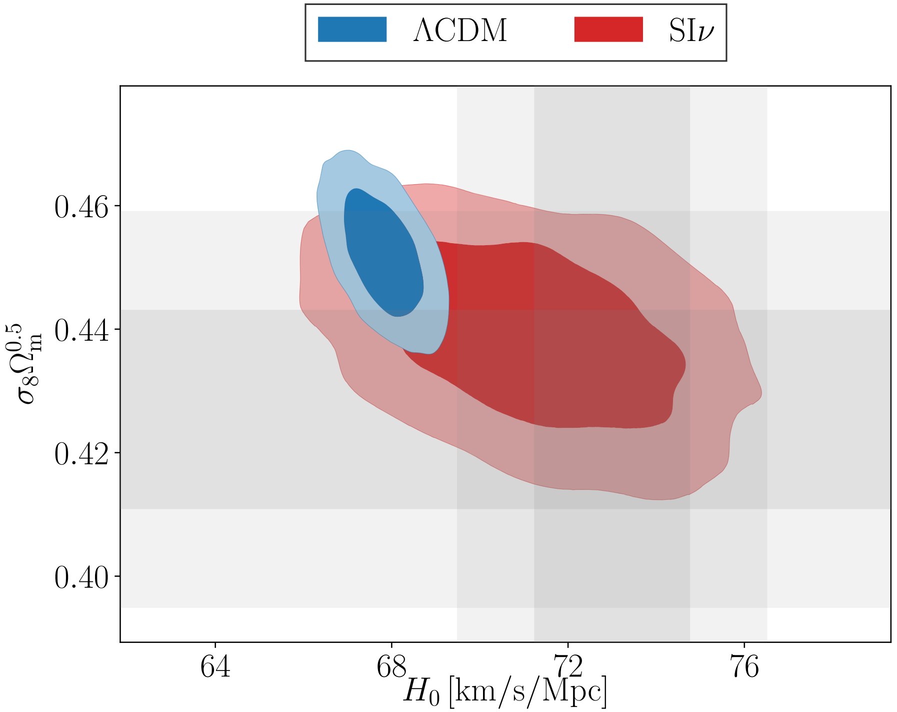


Uses Planck2018 TTTEEE data

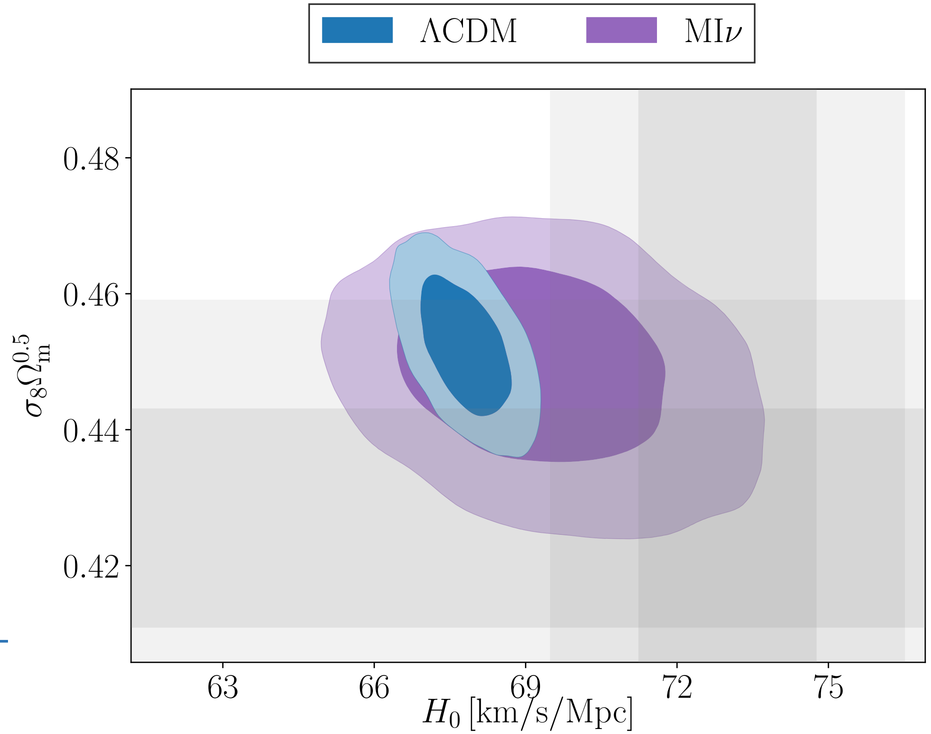
Summary

- Cosmological observations are in good agreement with the standard picture of the evolution of the neutrino background;
- the precision of the available data allows to test non-standard scenarios with high accuracy;
- the strength of neutrino interactions mediated by a light particle is constrained by CMB observations at the 10^{-7} level ($z_{rec} < 4000$ from PlanckTT+lowP+lensing)…
- …while, for a heavy mediator, $G_{eff} < 10^2$ GeV^{-2}.
- Use of non-standard interactions in the active and/or sterile sector to erase or alleviate tensions (e.g. H0, SBL anomalies) seems problematic

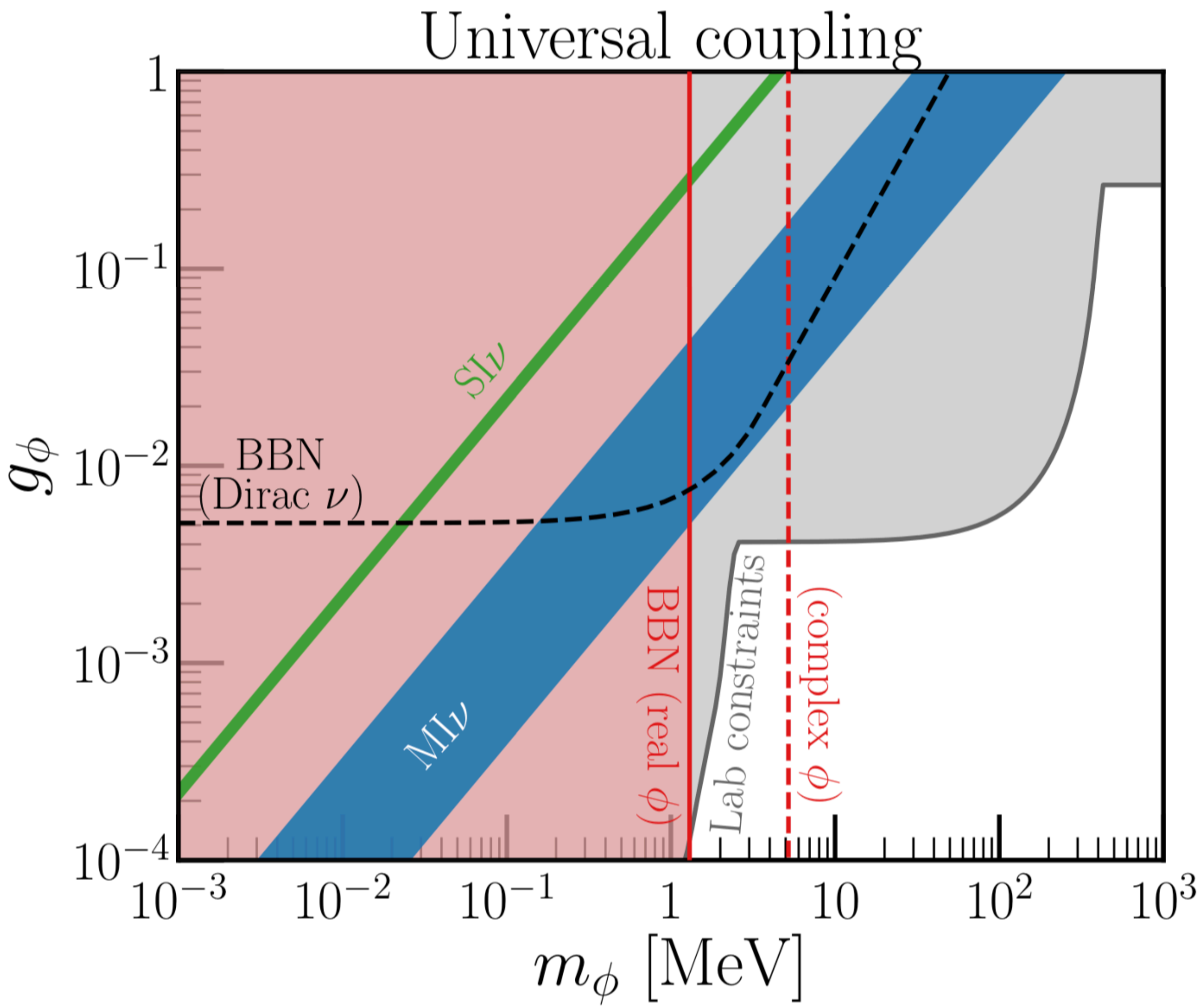
BACKUP SLIDES



PlanckTT+lens+BAO

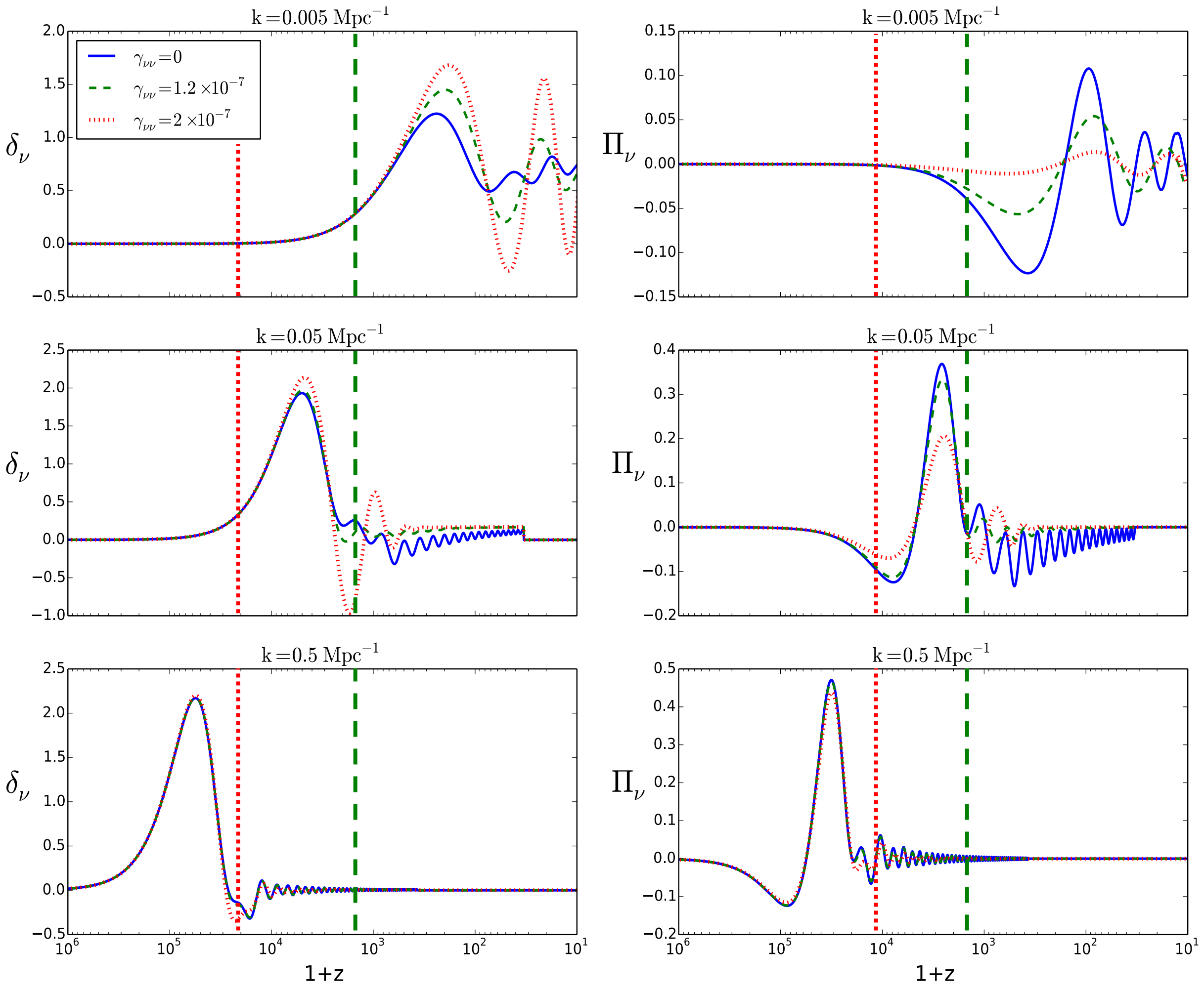


Kreisch et al. 2019

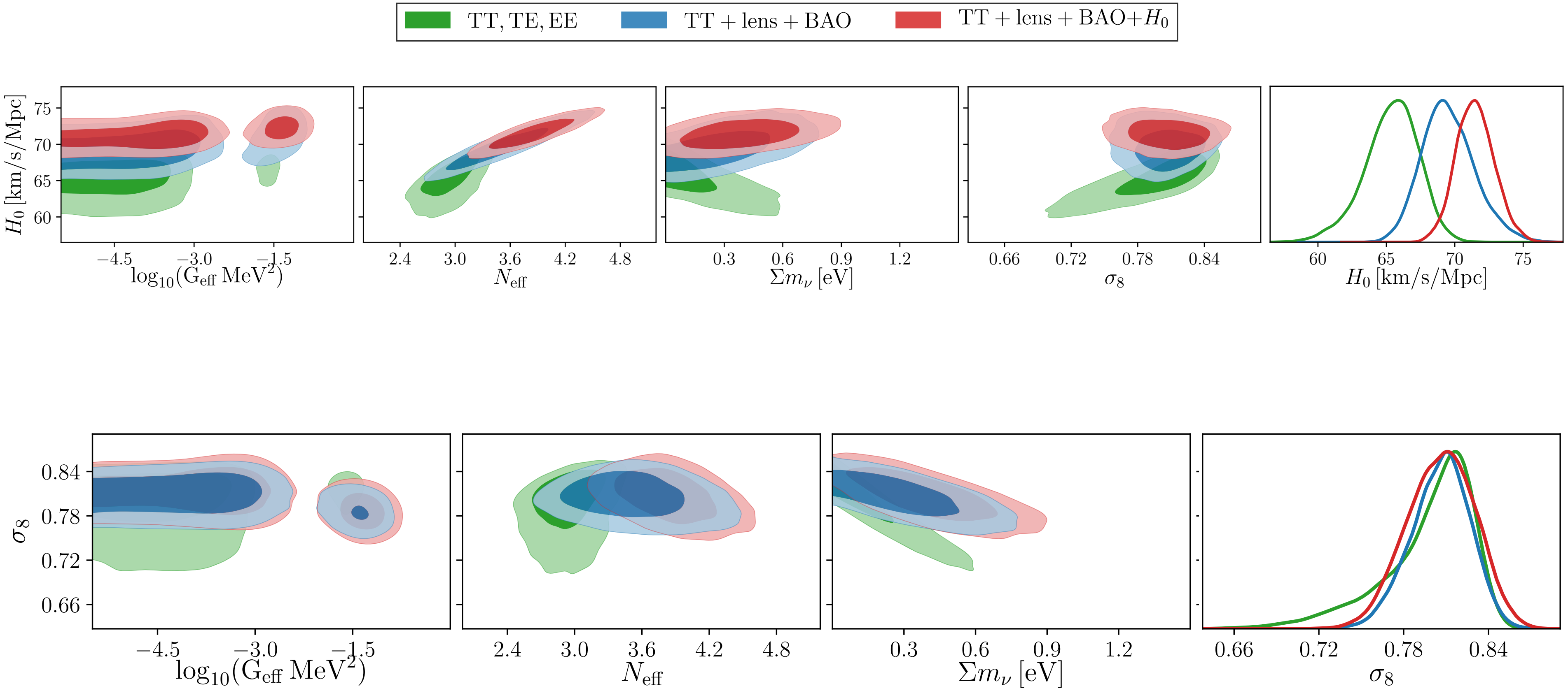


Blinov et al., 2019

Secret Interactions and cosmological perturbations

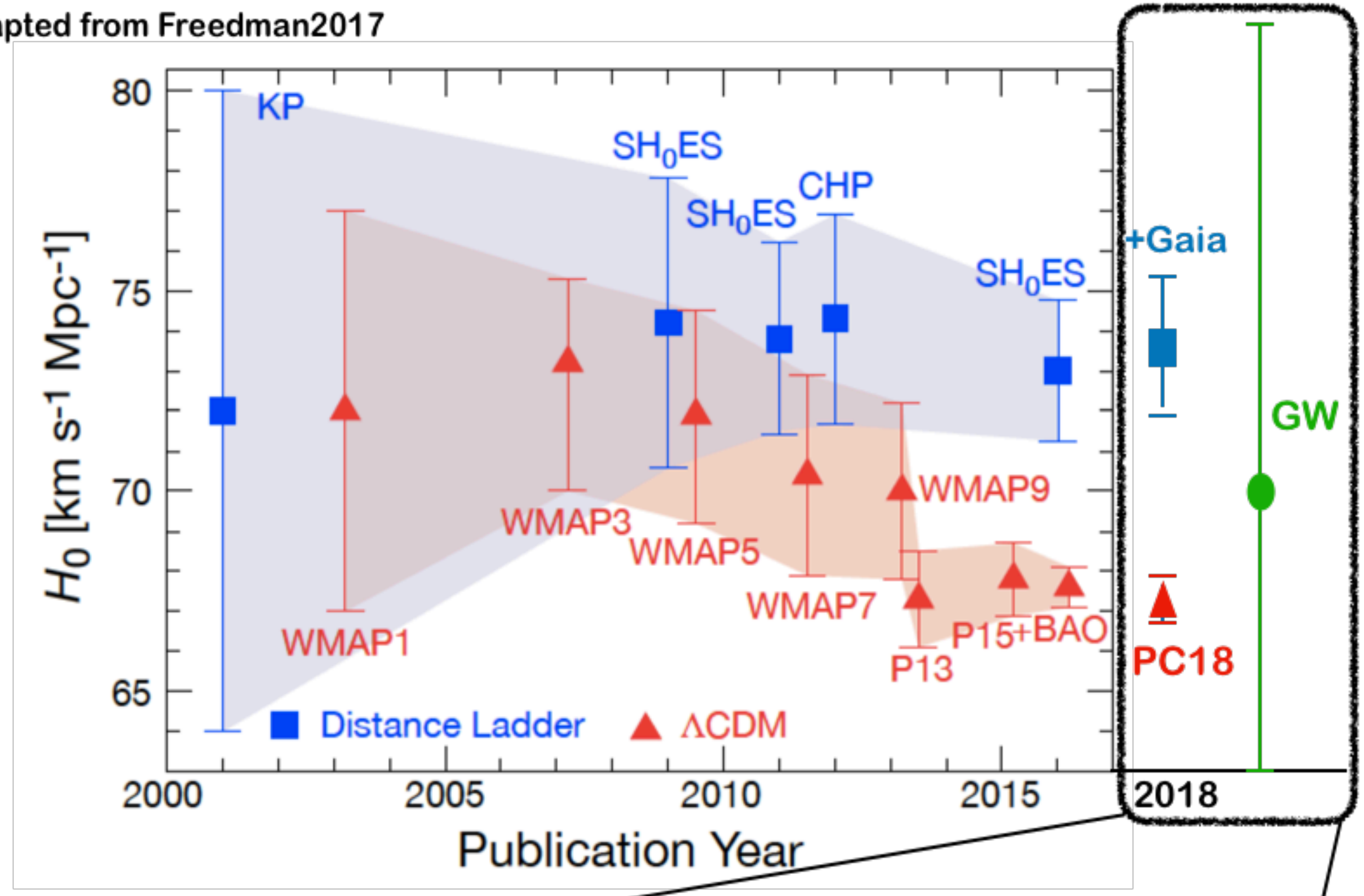


Higher order momenta are driven to zero by the collisions
flucuations are confined to the monopole and dipole



Kreisch et al. 2019

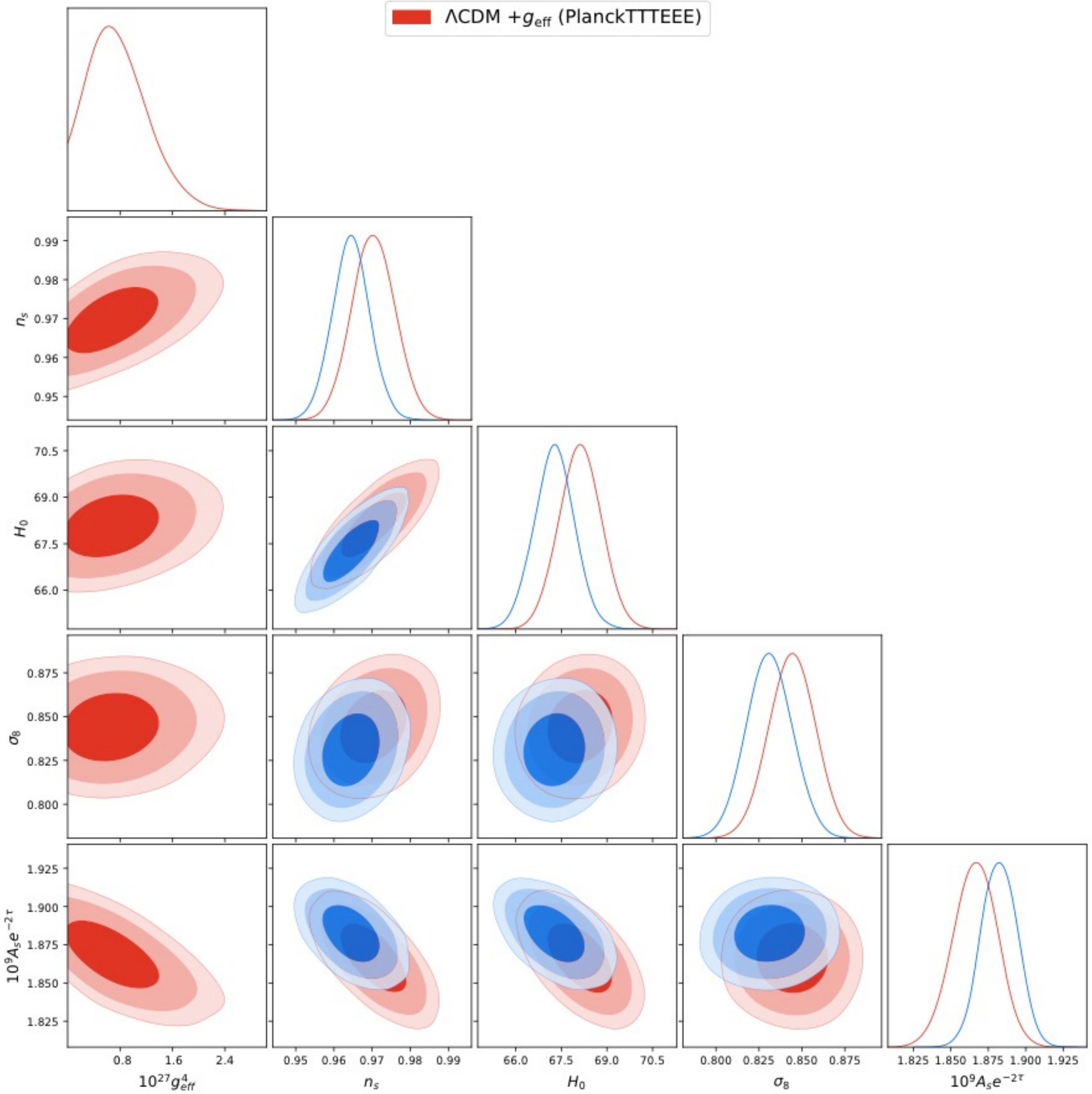
Adapted from Freedman2017



$$H_0 = (73.52 \pm 1.62)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$ Riess+,2018

$$H_0 = (67.27 \pm 0.60)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$ Planck Coll.VI,2018

3.6sigma tension in 2018


ΛCDM +g_{eff} (PlanckTTTEEE)
$10^{27}g^4_{eff}$
n_s
H_0
σ_8
$10^9A_se^{-2\tau}$
0.8 1.6 2.4
0.95 0.96 0.97 0.98 0.99
66.0 67.5 69.0 70.5
0.800 0.825 0.850 0.875
1.825 1.850 1.875 1.900 1.925