NEUTRINO COSMOLOGY AND DARK MATTER

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From Theory to Observations

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LECTURE 2

NEUTRINO FREE STREAMING

Distinctive features of ultrarelativistic neutrinos *on the evolution of cosmological perturbations* stem from the fact that they are collisionless and moving at (nearly) the speed of light. This ``free streaming'' allows neutrinos to escape overdense region and thus suppresses the growth of pertubations

- Neutrino free streaming will suppress metric fluctuations (i.e. gravitational potentials) once these enter the horizon (see Bashinsky and Seljak, 2004). Thus temperature fluctuations are “less boosted” at scales where neutrino do not cluster, especially during the RD era (when the neutrino contribution to the total density is larger)

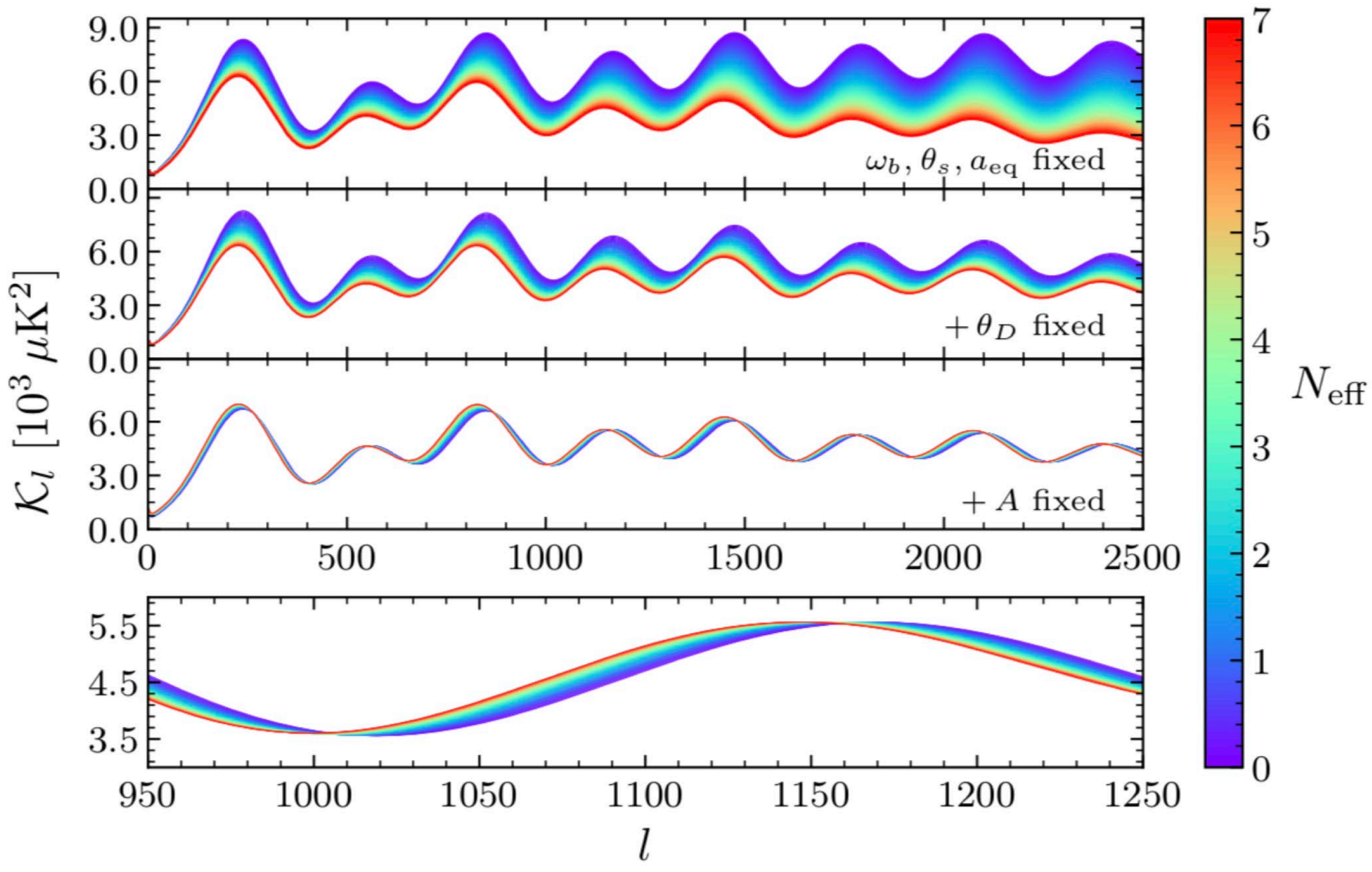
- Neutrino drag: free-streaming neutrinos move at a speed larger than the speed of sound in the photon-baryon fluid. This “pulls” temperature perturbations out of potential wells (Bashinsky and Seljak, 2004). This shifts the phase of baryon–photon oscillations towards larger scales.

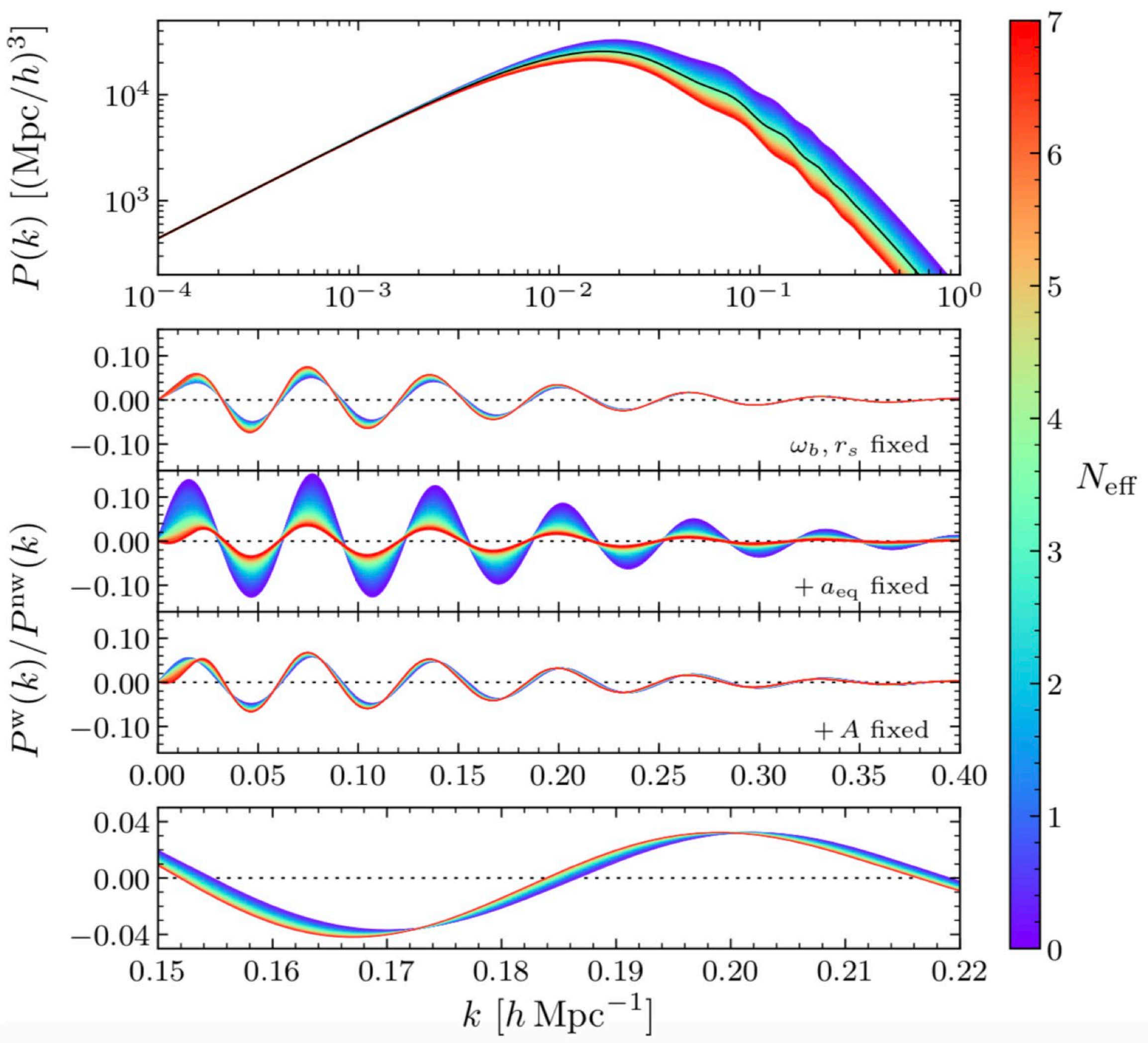
- At later times, matter perturbations below the free-streaming scale are suppressed (Bond, Efstathiou & Silk 1980). This also propagates to the CMB through lensing.

(note that all these effects depend on the free-streaming nature of neutrinos, while the background effects discussed so far are insensitive to that…)

NEFF – PHASE SHIFT

Bashinsky&Seljak, 2004





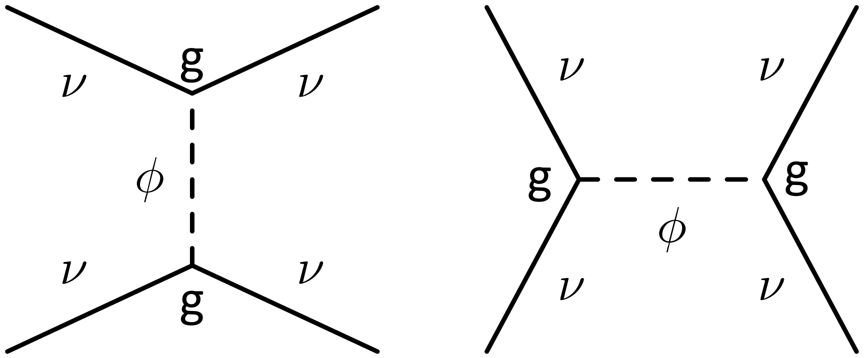
Credts: D. Baumann+, 2018

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….

Cosmological Phenomenology of νNSI

Collisional processes affect the perturbation evolution of relic neutrinos



Two limiting regimes: $\langle \sigma v \rangle \sim \frac{g^4}{E^2} \sim \frac{g^4}{T^2}$

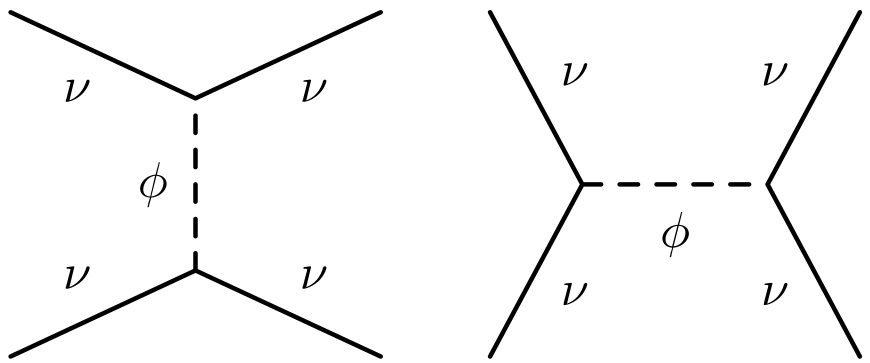
Light mediator ($M_\phi << T$)

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

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

Cosmo Phenomenology of νNSI: Light mediator

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



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

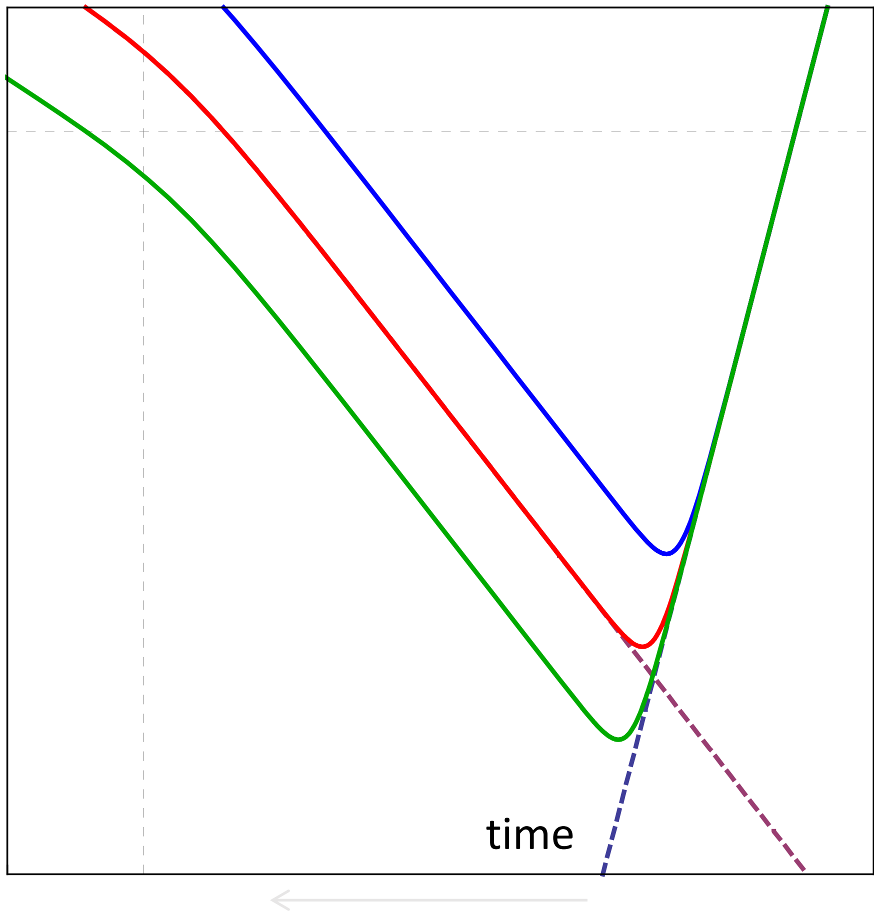
e.g., in simple majoron models: $\sigma \simeq \frac{1}{32\pi}\frac{g^4}{s}$

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

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



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

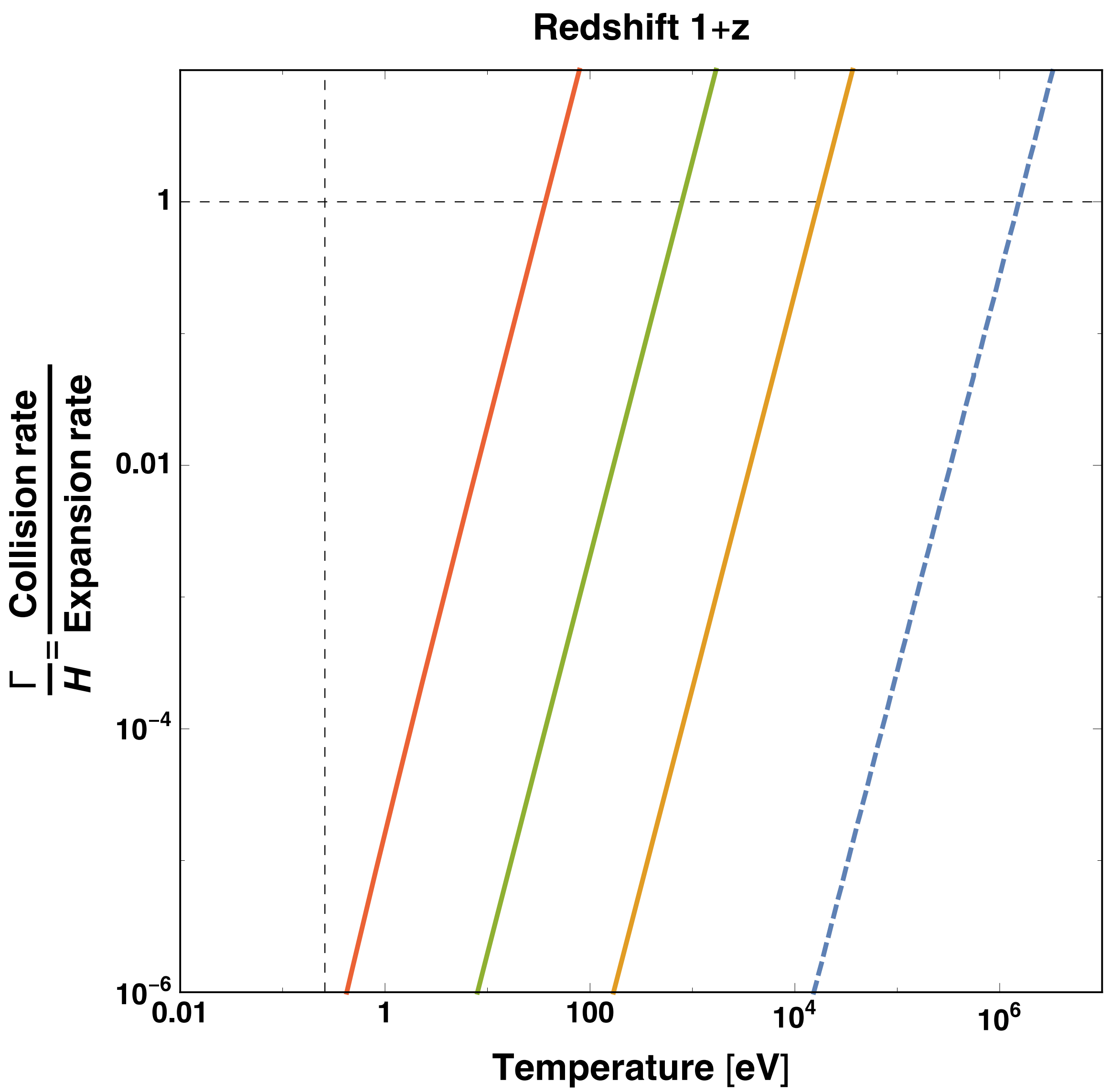
g_{eff} = 1.5 x 10^{-7}

g_{eff} = 2.7 x 10^{-7}

g_{eff} = 5 x 10^{-7}

Recoupling happens earlier for larger cuplings

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

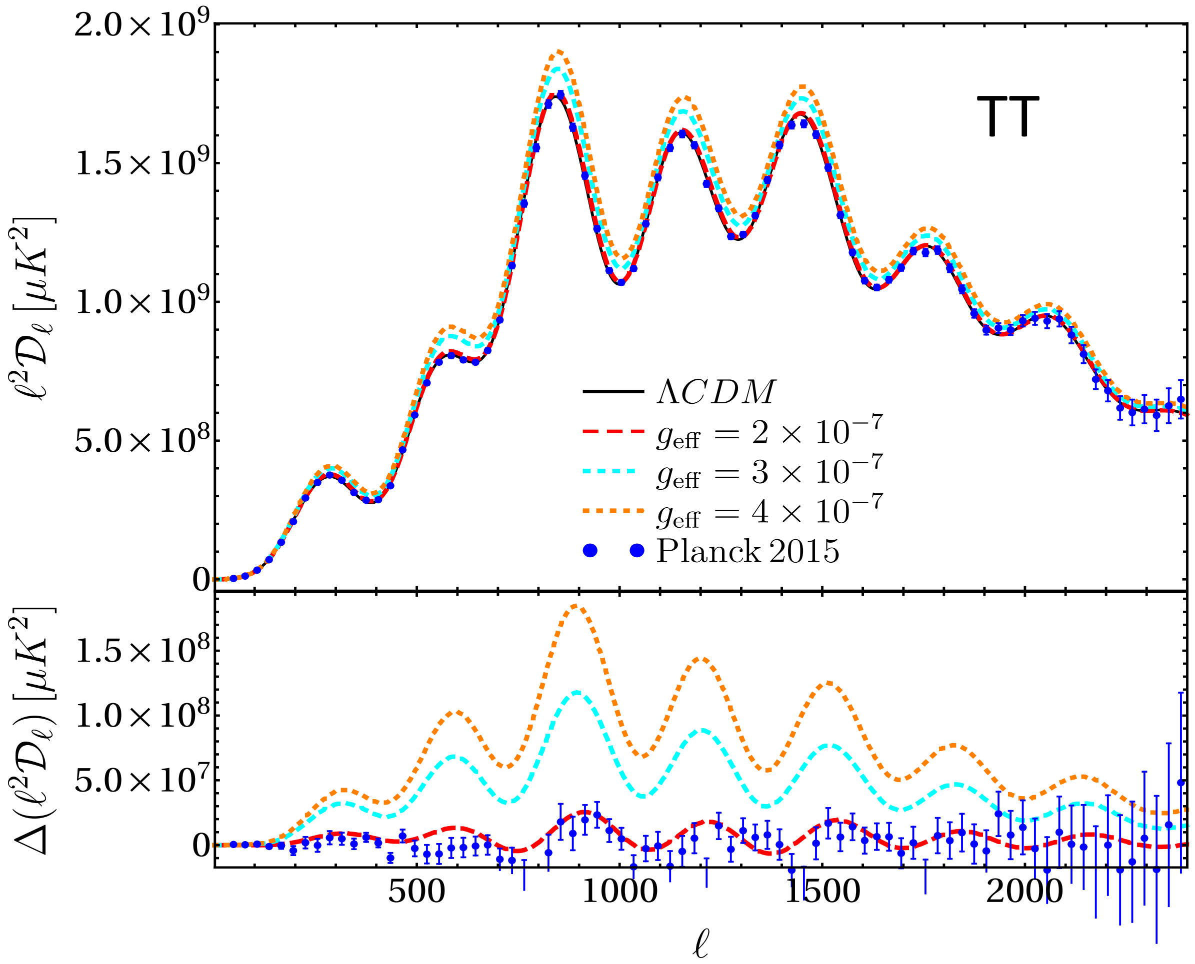
Neutrino free-streaming affects photon perturbations in two ways (Bashinsky & Seljak 2004):

- 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



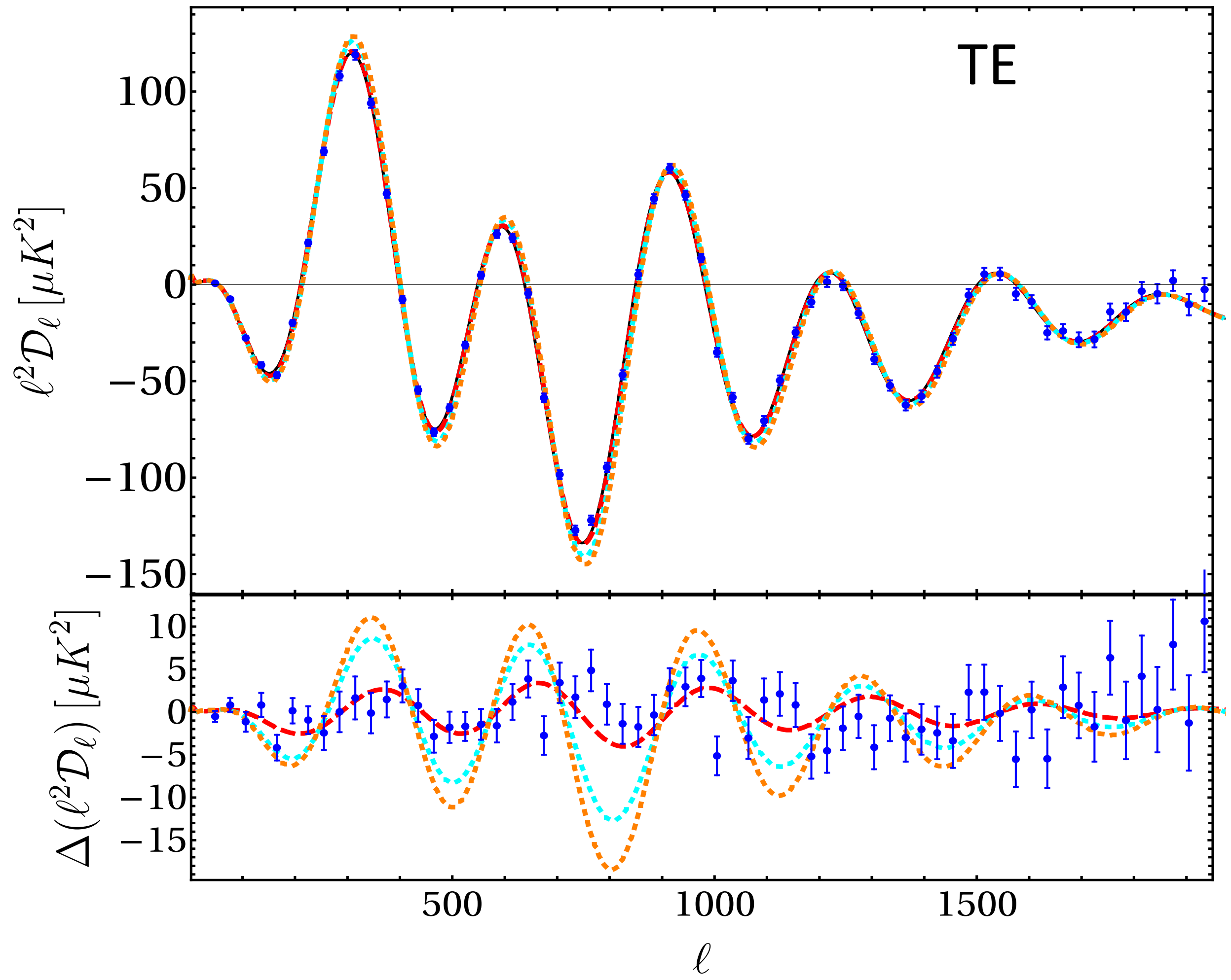
Scales entering the horizon between recoupling and equality are affected i.e. "larger" scales (up to the scale of matter radiation equality)

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



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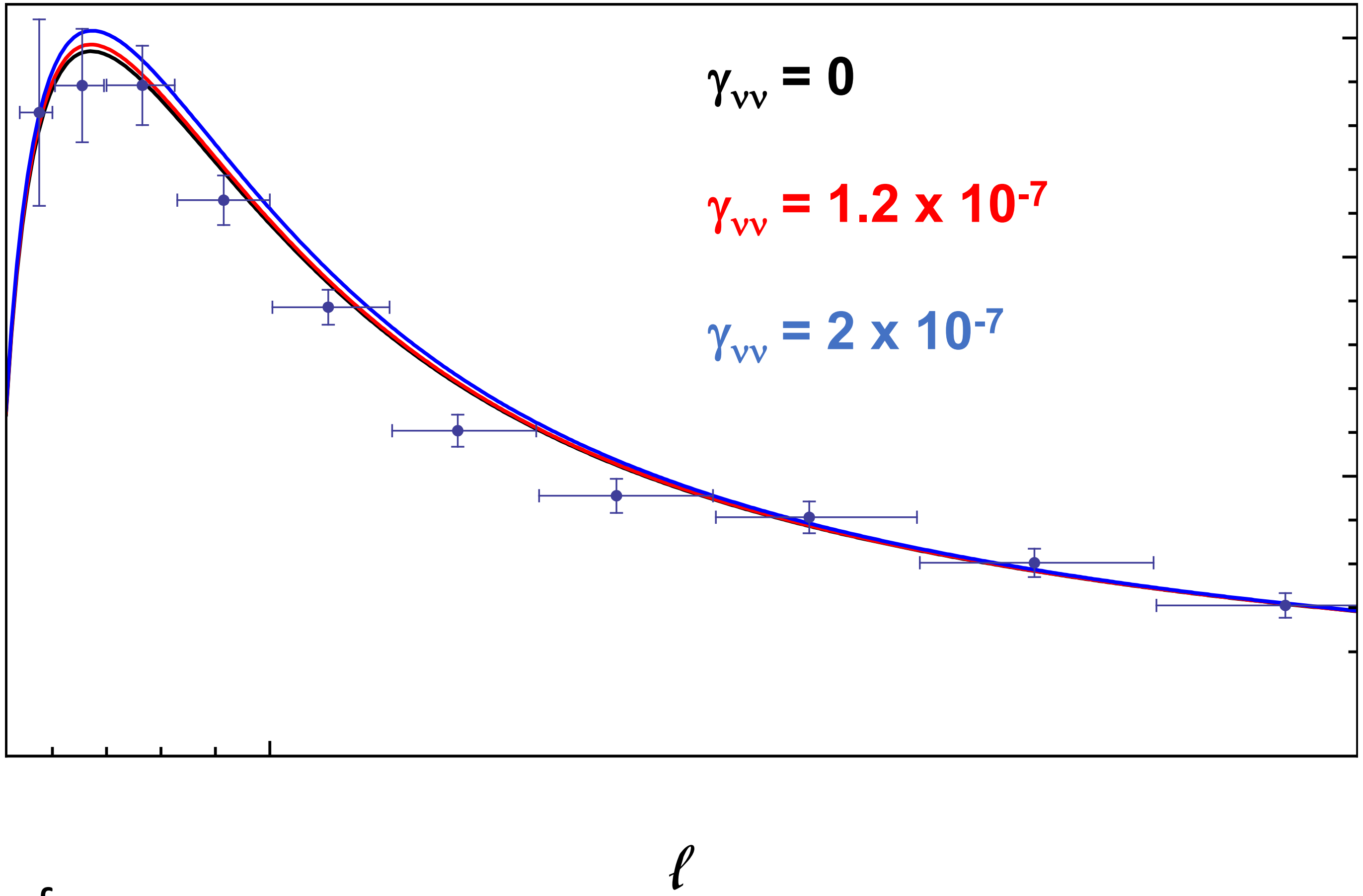
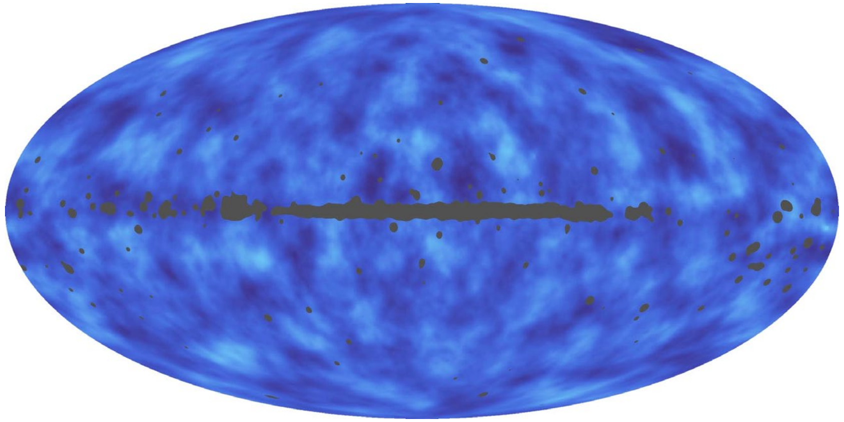
νNSI AND CMB ANISOTROPIES: LIGHT MEDIATOR

POWER SPECTRUM OF THE CMB LENSING POTENTIAL



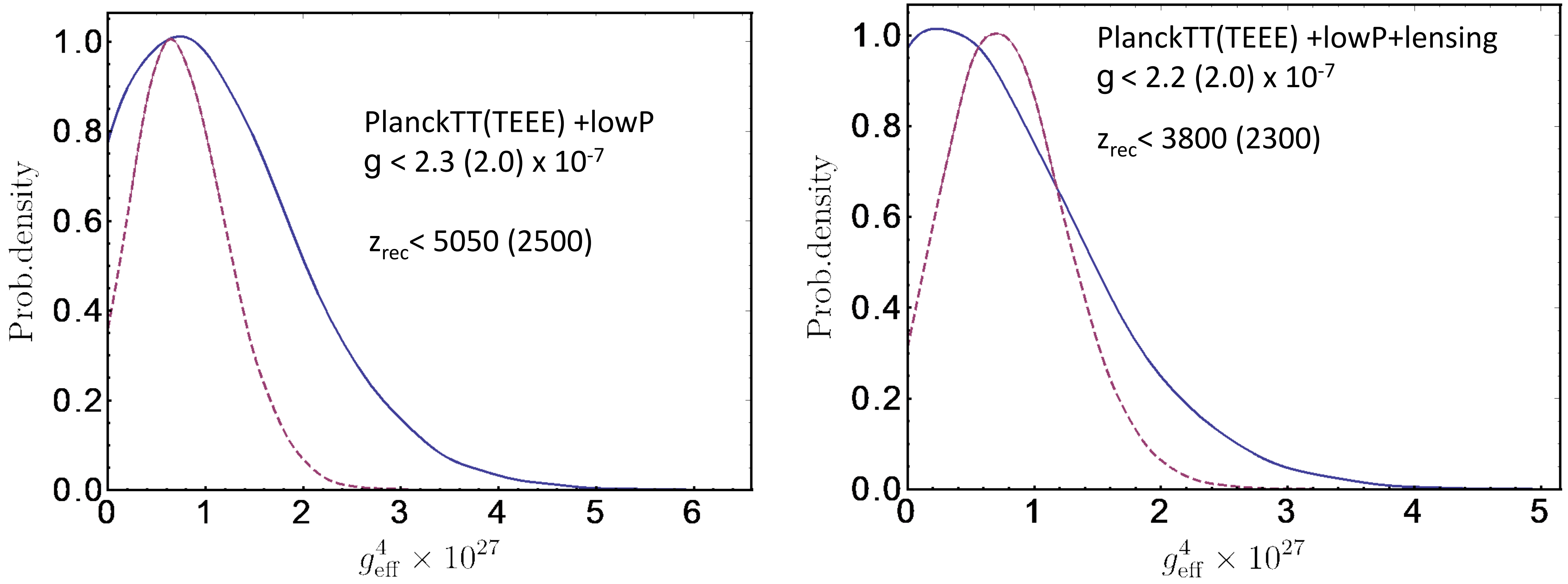


Lensing potential estimated from the four-point correlation function

Larger interactions suppress free-streaming → More lensing

Data points are from Planck 2015

νNSI and Planck: Light Mediator

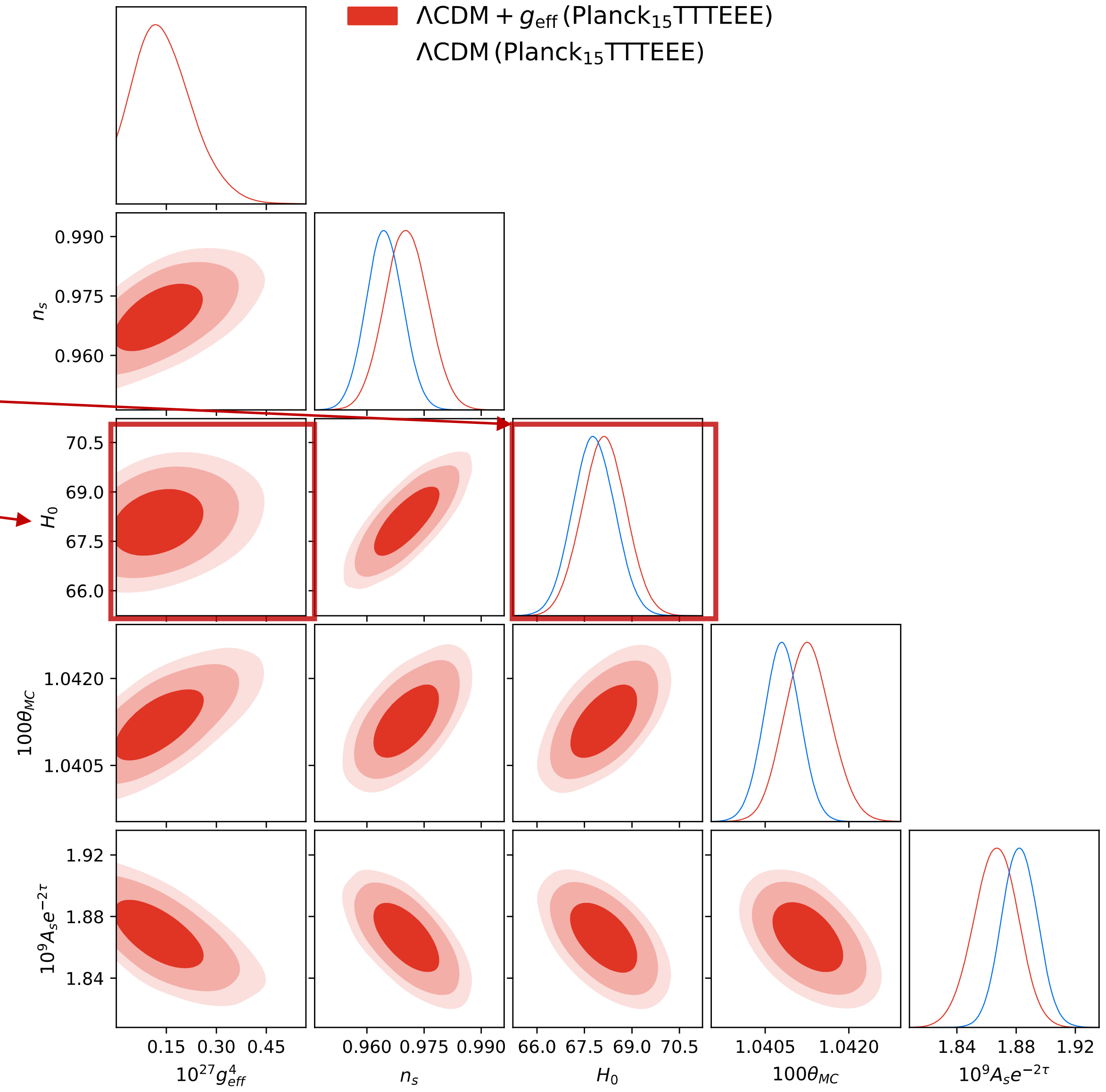


Forastieri, ML, Natoli, PRD 2019

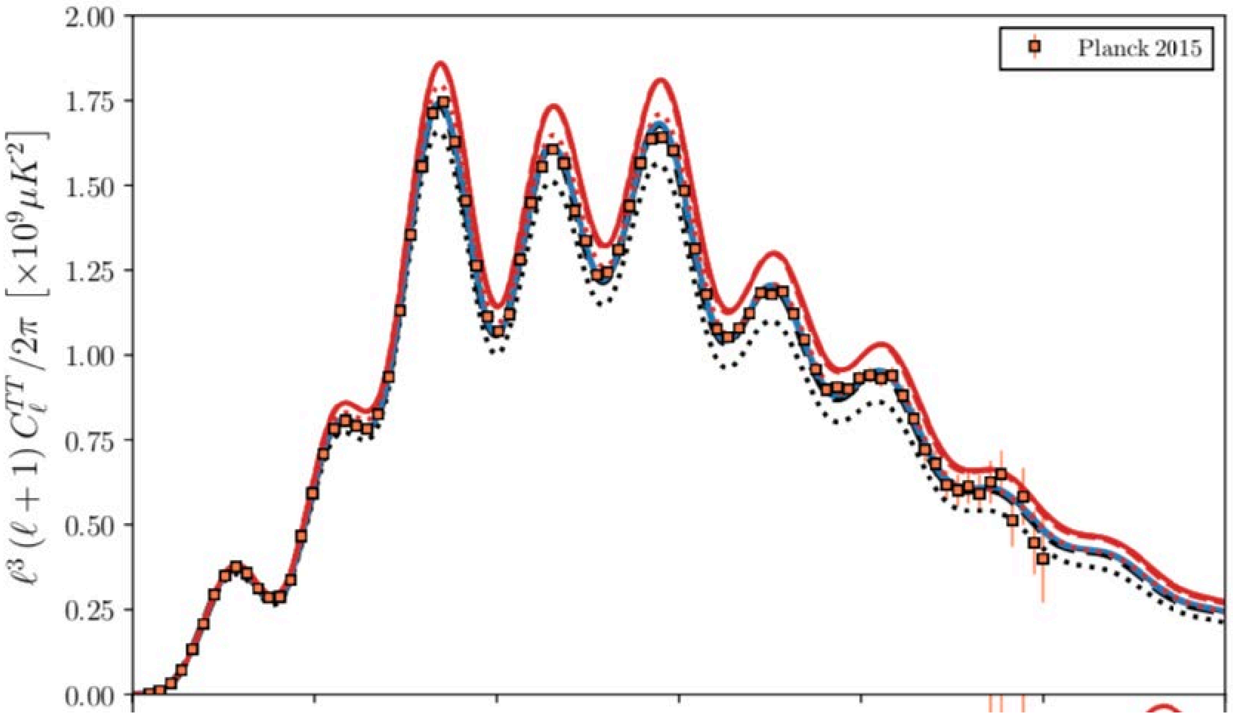
Limits are 95% CL

νNSI and Planck: Light Mediator

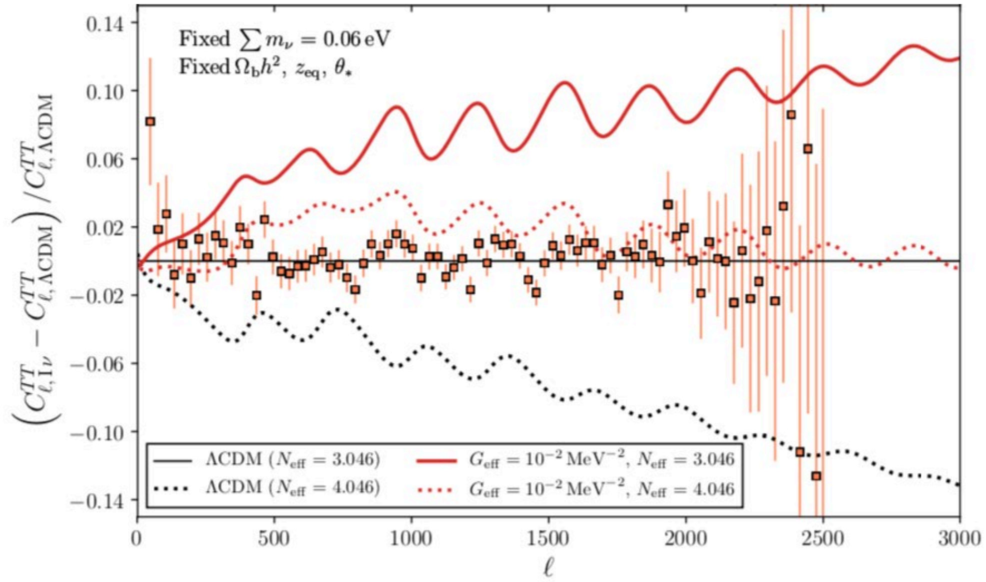
Does not seem to help towards alleviating the Hubble tension!



νNSI AND CMB ANISOTROPIES: HEAVY MEDIATOR

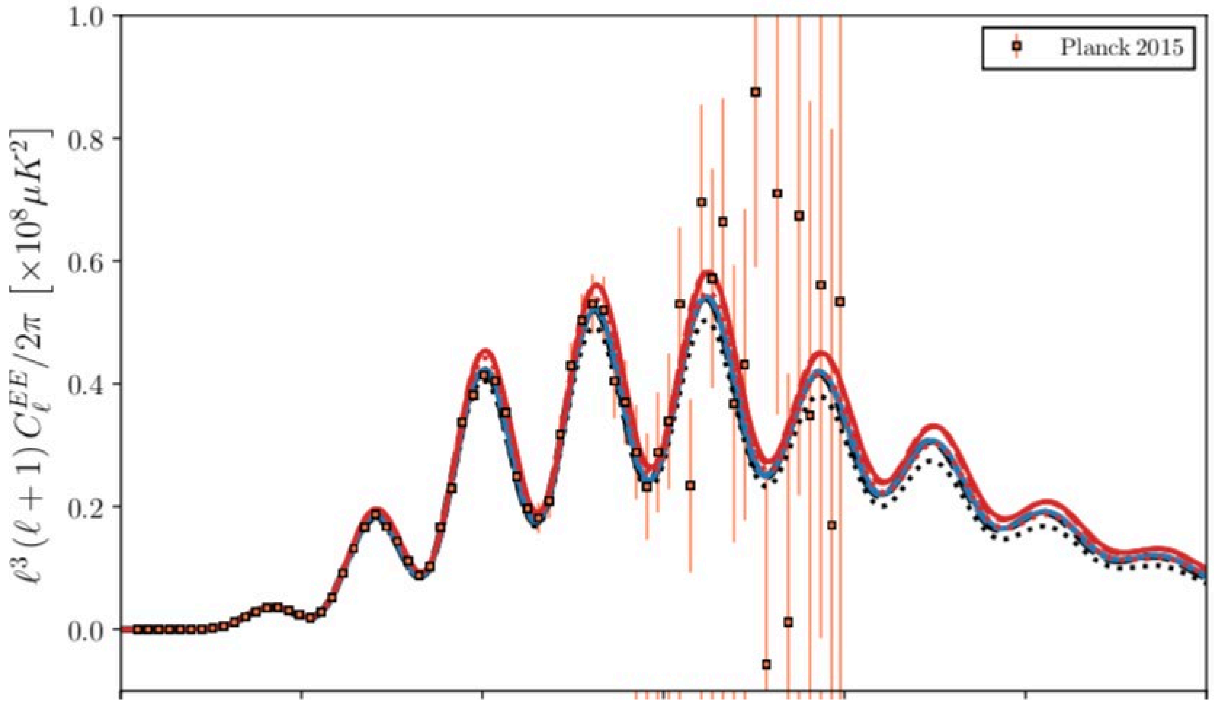


Scales entering the horizon before decoupling are affected
i.e. smaller scales are more affected



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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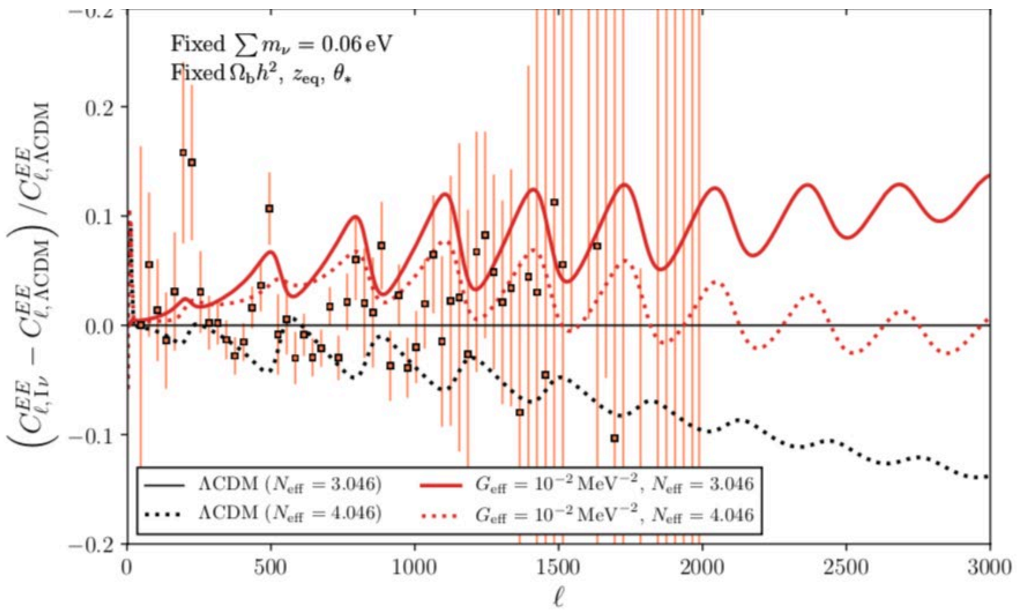

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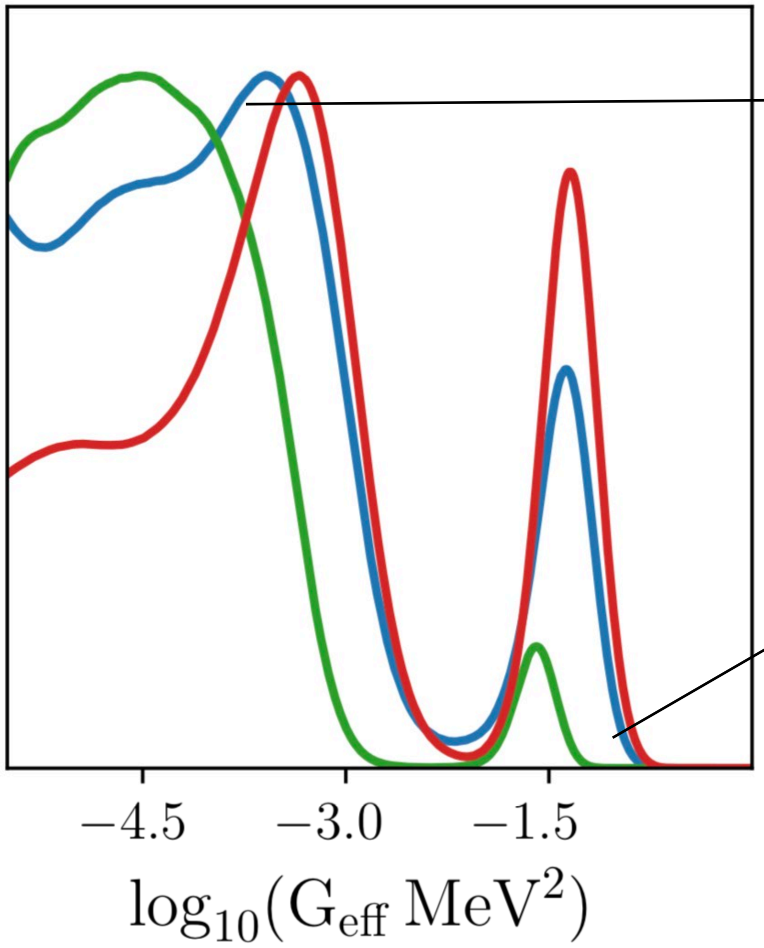
νNSI Constraints: Heavy Mediator



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

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

PlanckTTTEEE
PlanckTT+lens+BAO
PlanckTT+lens+BAO+H0 (handle with care!)

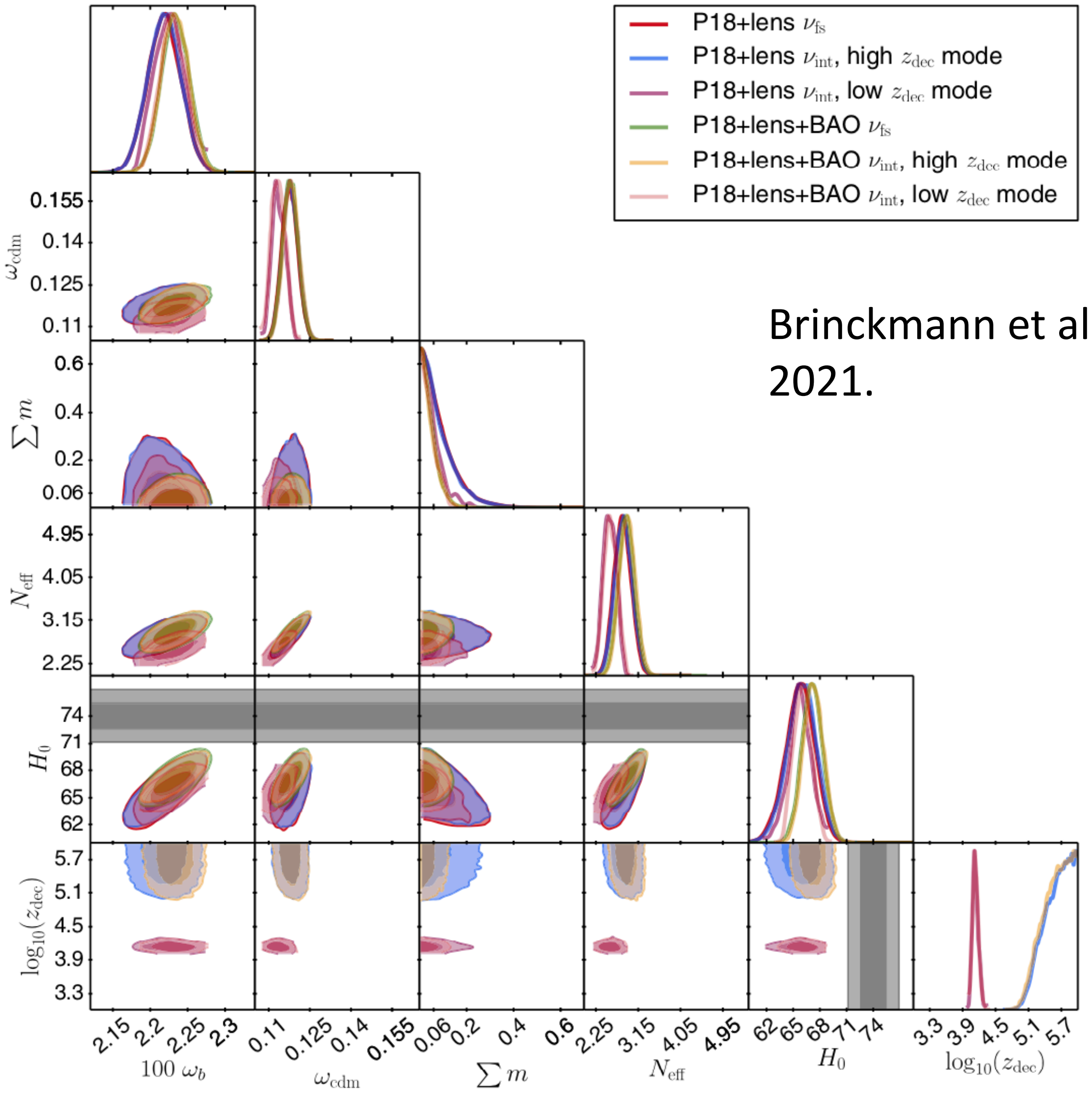
Preference for a "strong-interacting" mode emerges from some data combinations

Kreisch, Cyr Racine & Dore 2019

νNSI Constraints: Heavy Mediator

More recent analysis find that, when the full suite of Planck (including small-scale pol.) + BAO is used, the significance of the strong interacting mode becomes marginal, together with its ability to alleviate the Hubble tension.

This also holds when a more general mixture of free-streaming and collisional species is allowed (see Brinckmann et al. 2021; Das & Ghosh 2021)



Brinckmann et al 2021.

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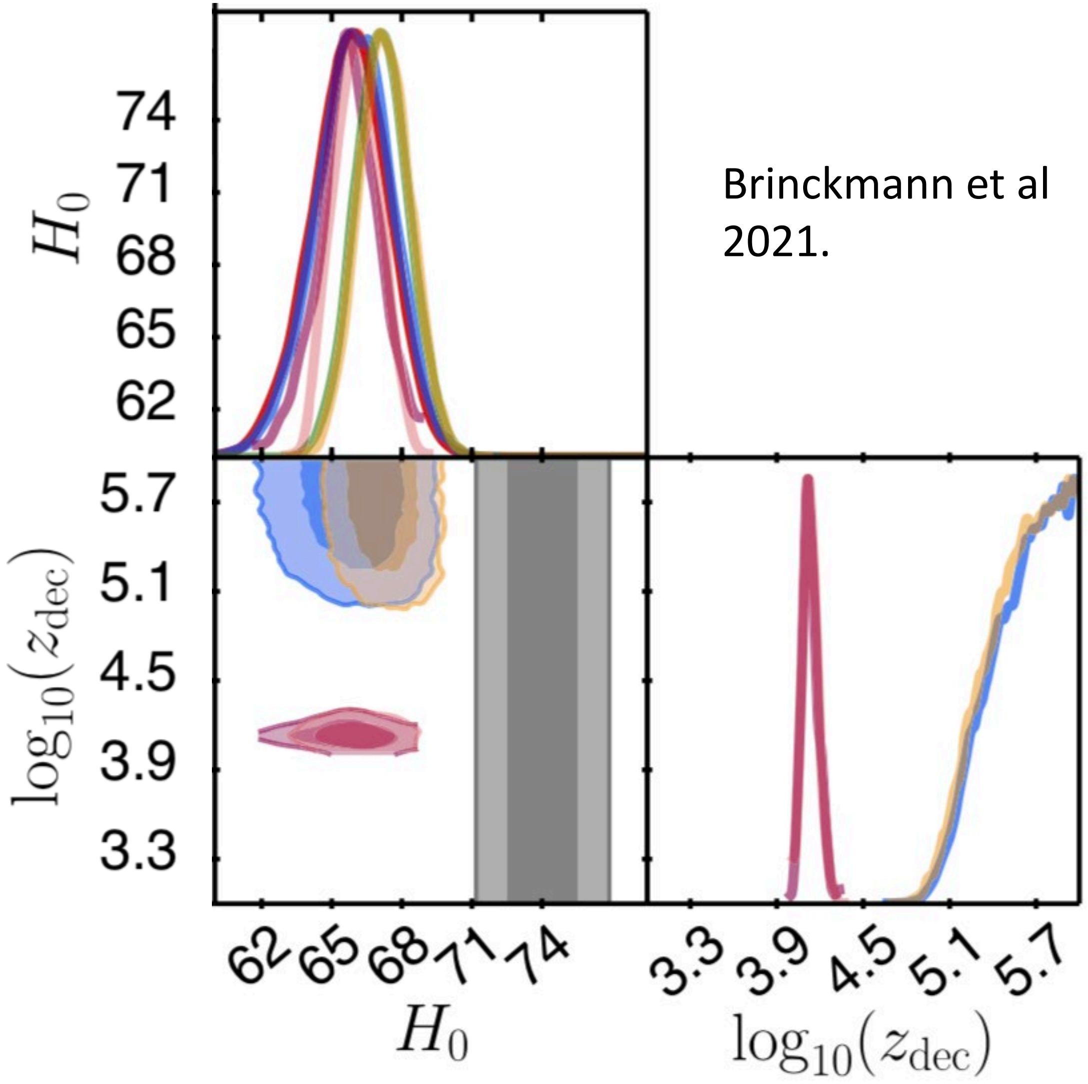

Brinckmann et al 2021.