Testing non-standard neutrino interactions with cosmology

Future cosmology 2023, IESC Cargese

Petter Taule

petter.taule@ipht.fr

Based on 2207.04062, PRD ‘22 with Miguel Escudero and Mathias Garny

Neutrinos in cosmology

- Early universe: neutrinos represent **40%** of the energy density
- In the Standard Model, neutrinos decouple from the plasma at $T \sim 0.2\ \mathrm{eV}\ (t \sim 0.1\ \mathrm{s})$

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- Leave impacts on the CMB and matter clustering via the background evolution as well as on the perturbation level via Einstein's equations
- Hence, cosmological observations can be used as a laboratory to test neutrino properties!

Damping neutrino freestreaming

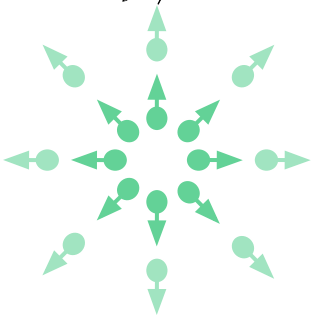
- Neutrino freestreaming leaves unique imprints in the CMB [1,2]

$$\delta_\nu,\ \sigma_\nu \quad \longrightarrow \quad \delta g_{\mu\nu} \quad \longrightarrow \quad \delta T_{\rm CMB}$$

➔ C_l suppression and *phase shift*

Freestreaming neutrinos

$\sigma_\nu \neq 0$



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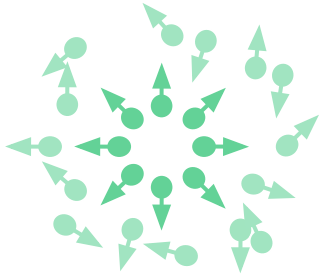
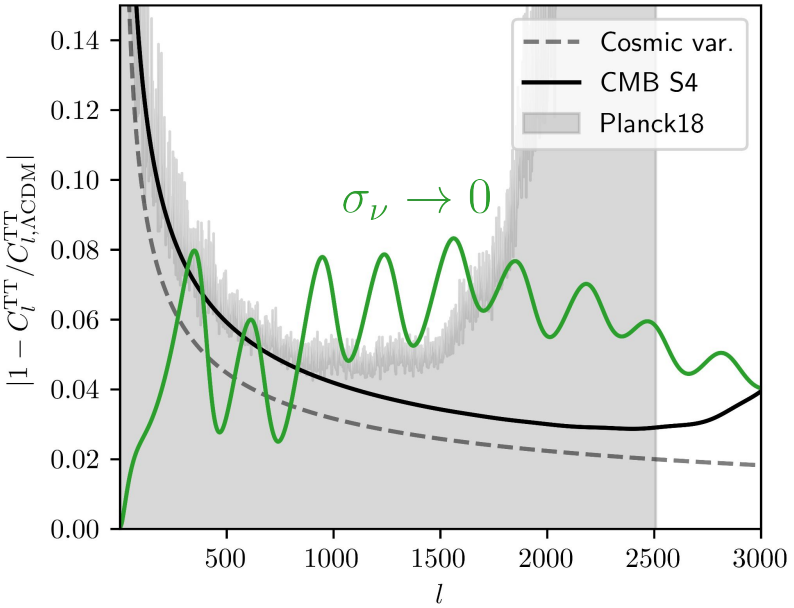


Image: M. Escudero

Effect on angular power spectrum: interaction driving neutrino anisotropic stress to zero



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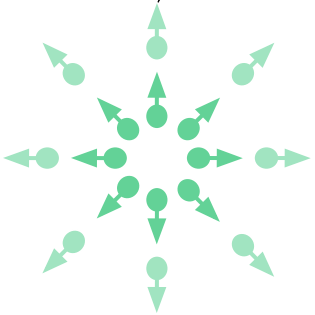

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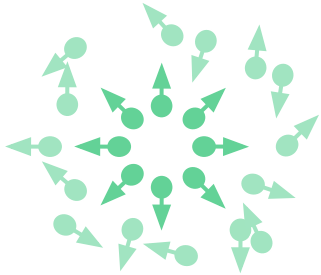

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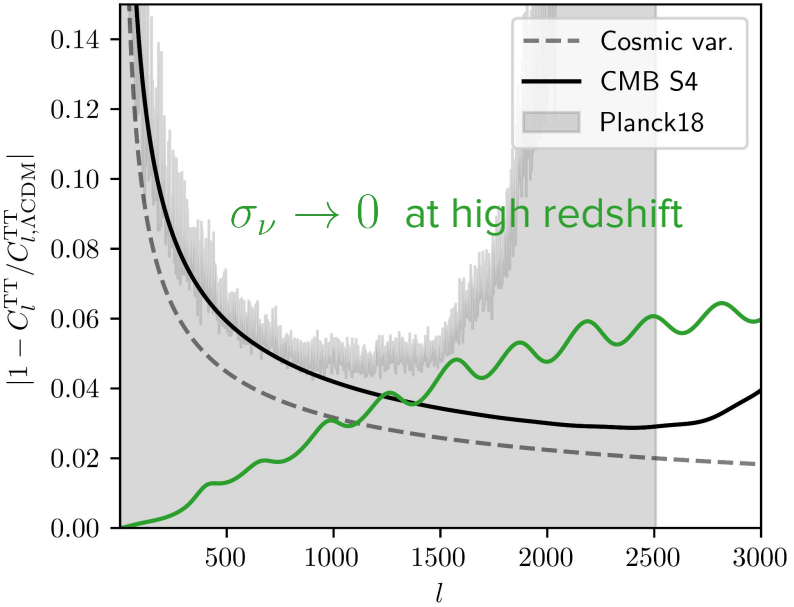

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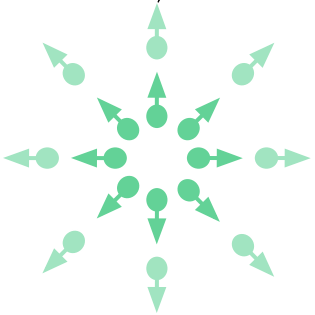

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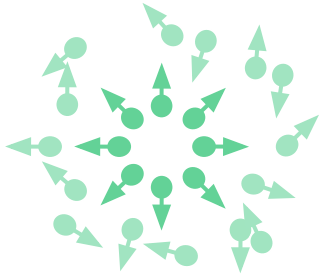

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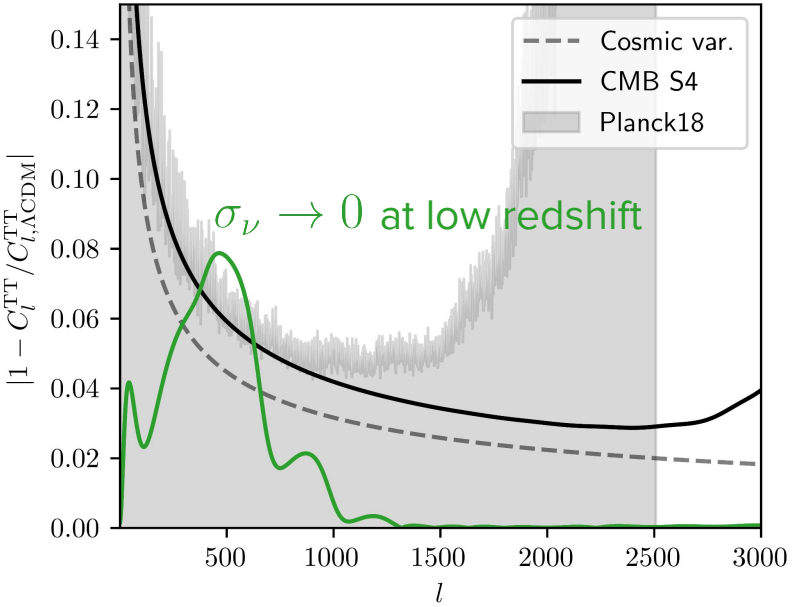

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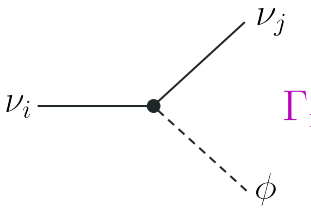
Interaction models

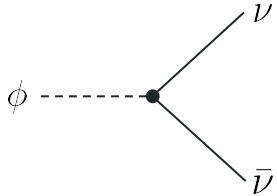
Neutrino decays



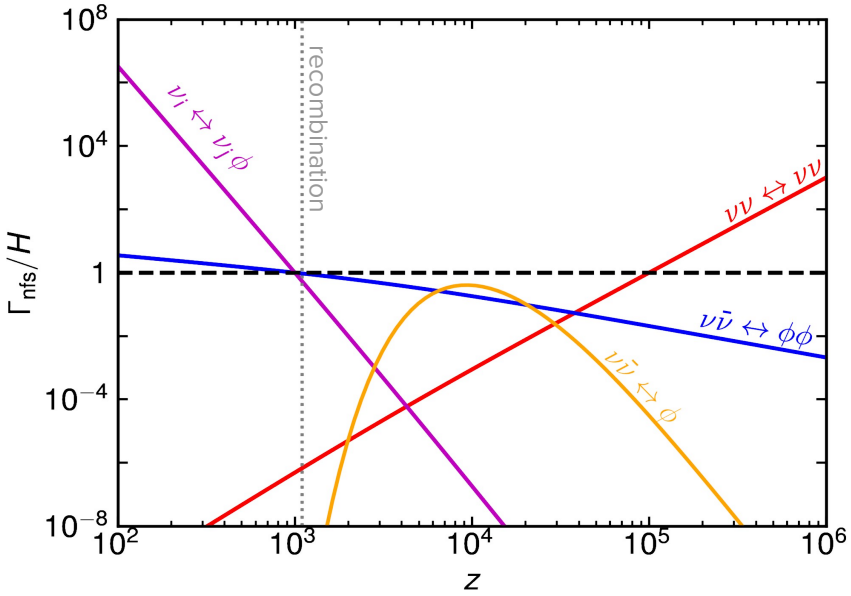
$\Gamma_{\rm nfs} \propto T^{-5}$

Hannestad and Raffelt [hep-ph/0509278]
Basboll, Bjaelde, Hannestad and Raffelt [0806.1735]
Escudero and Fairbairn [1907.05425]
Chacko, Dev, Du, Poulin and Tsai [1909.05275]
Chacko, Dev, Du, Poulin and Tsai [2002.08401]
Barenboim et. al. [2011.01502]
Chen, Oldengott, Pierobon and Wong [2203.09075]
bellán, Chacko, Dev, Du, Poulin, and Tsai [2112.13862]
...

eV-scale boson mediator



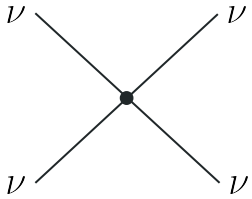
Chacko, Hall, Okui and Oliver [hep-ph/0312267]
Escudero and Witte [1909.04044]
Escudero and Witte [2004.01470]
Escudero and Witte [2103.03249]
...



$\Gamma_{\rm nfs} \propto {\rm e}^{-m_\phi/T}$ $T < m_\phi$

$\Gamma_{\rm nfs} \propto T^{-5}$ $T > m_\phi$

Neutrino scatterings



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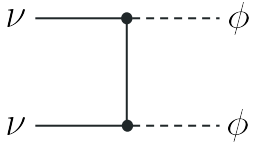
Cyr-Racine, and Sigurdson [1306.1536]
Oldengott, Rampf and Wong [1409.1577]
Lancaster, Cyr-Racine, Knox and Pan [1704.06657]
Oldengott, Tram, Rampf and Wong [1706.02123]
Kreisch, Cyr-Racine and Doré [1902.00534]
Park et.al [1904.02625]
Das and Ghosh [2011.12315]
Choudhury, Hannestad and Tram [2012.07519]
Brinckmann, Chang, and LoVerde [2012.11830]
Kreisch et.al. [2207.03164]
...

Neutrino annihilations



$\Gamma_{\rm nfs} \propto T$

Beacom, Bell and Dodelson [astro-ph/0404585]
Hannestad [astro-ph/0411475]
Bell, Pierpaoli and Sigurdson [astro-ph/0511410]
Archidiacono and Hannestad [1311.3873]
Forastieri and Lattanzi and Natoli [1504.04999]
Forastieri and Lattanzi and Natoli [1904.07810]
Venzor, Garcia-Arroyo Pérez-Lorenzana and De-Santiago [2202.09310]
...

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  What is the window of redshifts in which Planck CMB measurements are sensitive to neutrino interactions?

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$$\Gamma_{\rm nfs} \propto T^{n_{\rm int}}$$
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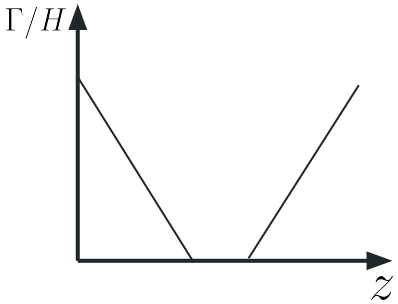

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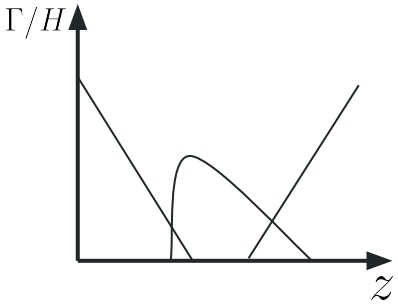

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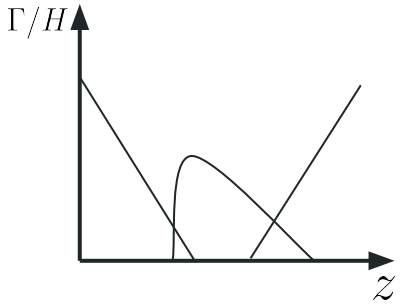

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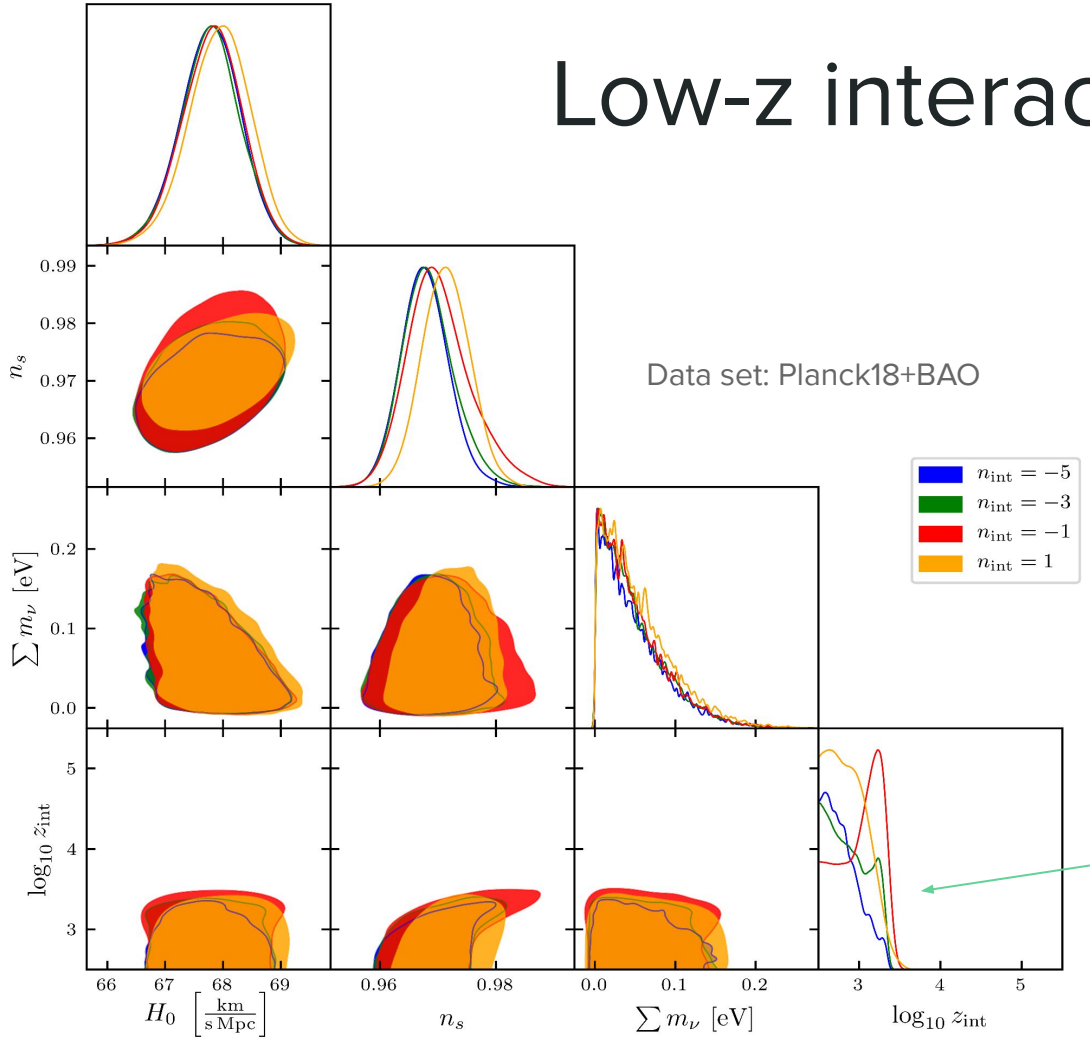
- Approximations:
  - ➔ Treat neutrinos as an ultrarelativistic species with the energy density of ΛCDM
  - ➔ Relaxation approximation: k- and q-independent collision term in Boltzmann hierarchy

Low-z interactions



- MCMC with MontePython
- Interaction rate:

$$\Gamma_{\rm nfs} = H(z_{\rm int}) \left(\frac{1+z_{\rm int}}{1+z}\right)^{n_{\rm int}}$$

- No model exhibit significant preference for interaction
- Approximate model-independent upper limit:

$$z_{\rm int} \lesssim 2000$$

High-z interactions

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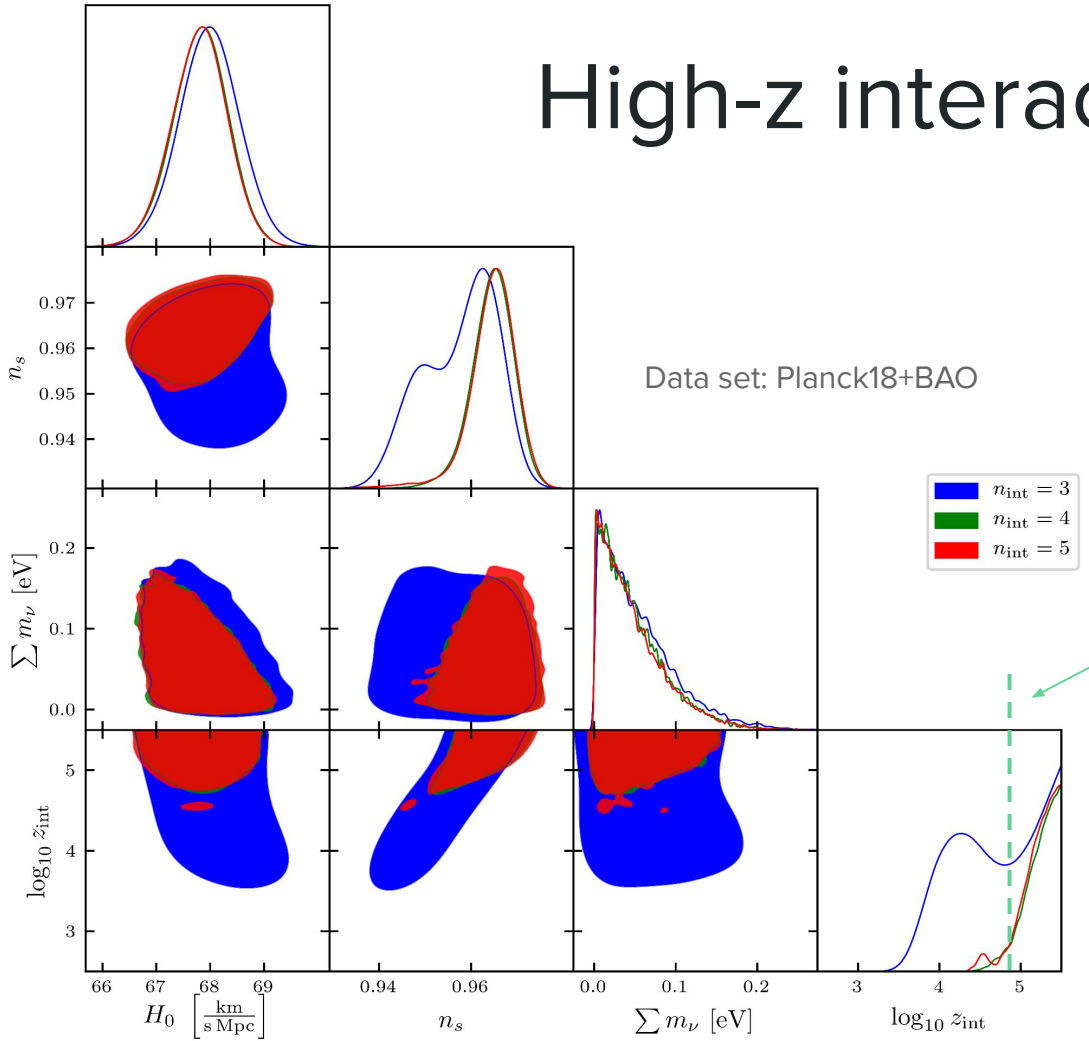
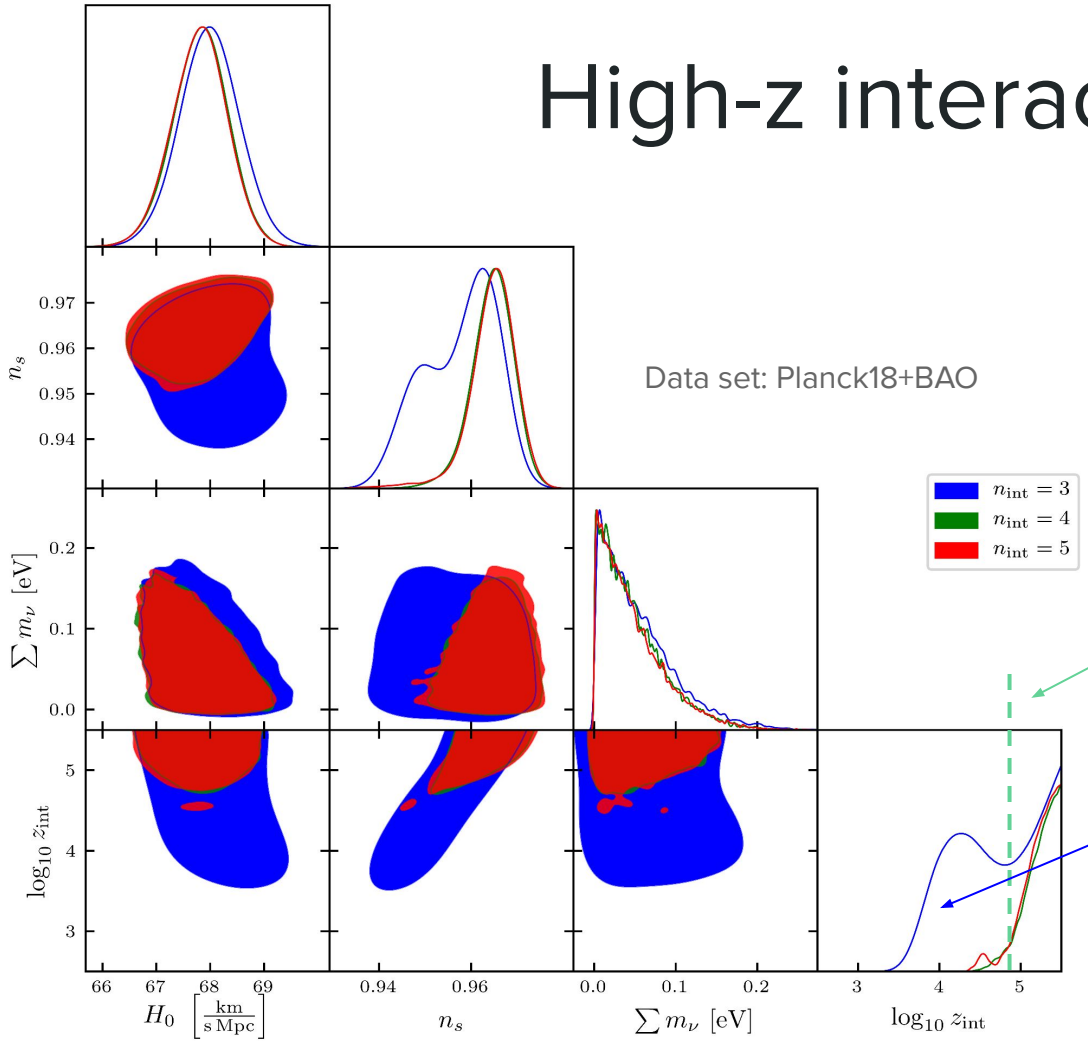


- No significant preference for interaction
- Approximate lower limit:

$$z_{\rm int} \gtrsim 9 \times 10^4$$

High-z interactions



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- Particular case $n_{\rm int} = 3$

$$\Gamma_{\rm nfs} \propto T^3$$
$$H \propto T^2$$

➔ Degeneracy with n_s

➔ Does not correspond to a known model

Transient interaction rate

- Next: constrain *depth* of redshift window
- “Bump”-like interaction which enters/exits
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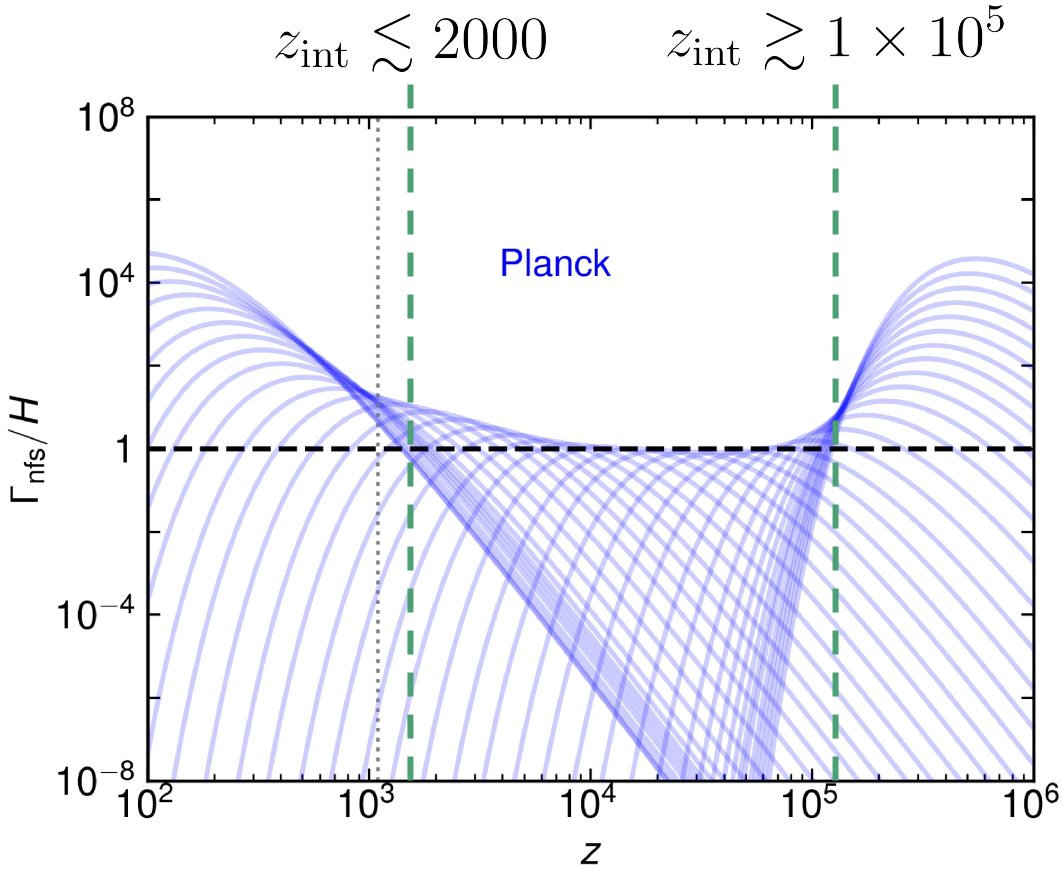
- 2 sigma bounds →



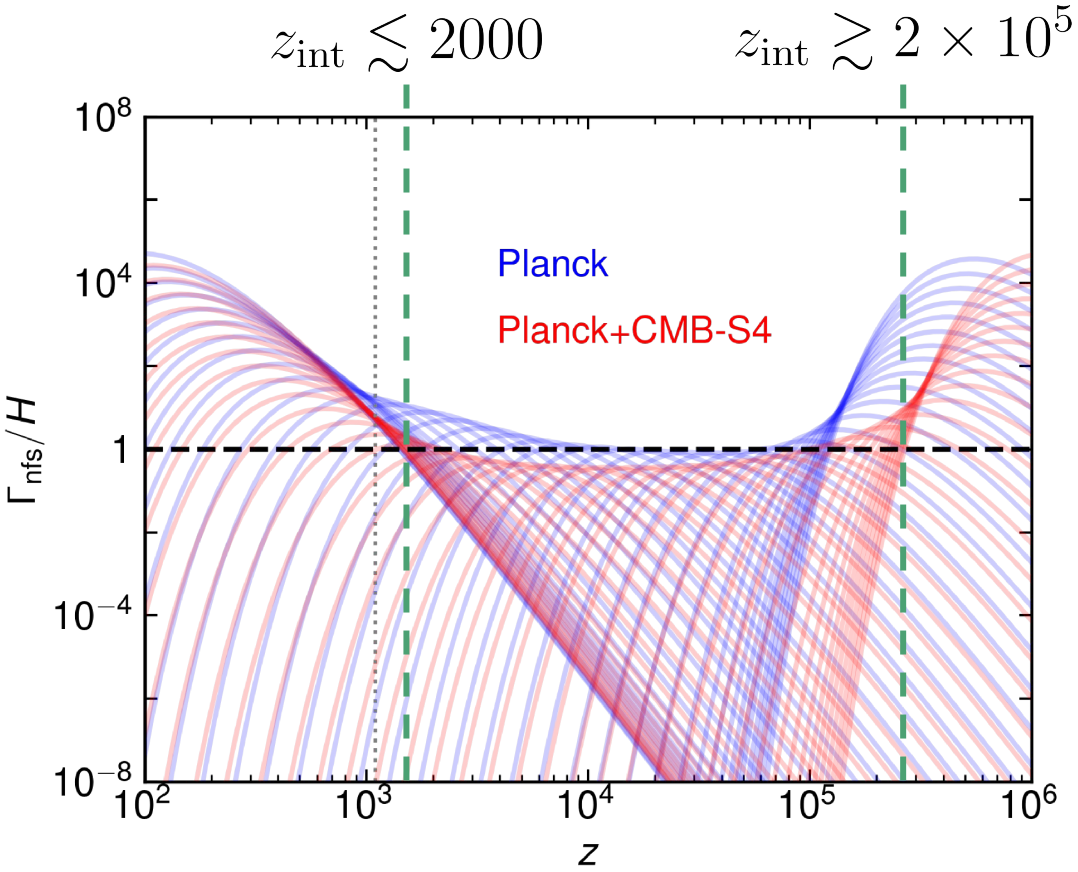
Data set: Planck18+BAO

Transient interaction rate

- CMB-S4 forecast assuming fiducial ΛCDM
- Improved high-l constraints

➔ Factor 2 improvement of upper bound

- Overall increase in redshift window *depth*



Matter clustering

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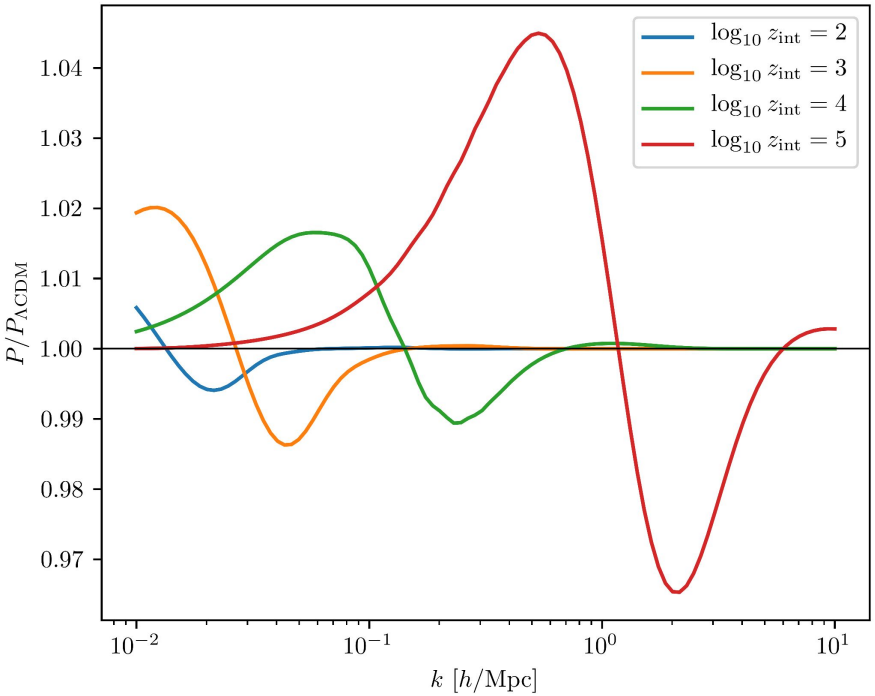
- Neutrino interactions affect metric potentials and hence in turn the matter power spectrum
- *Given CMB constraints, what can galaxy clustering further tell us about non-standard neutrino interactions?*
- Consider transient interactions:
  - ➔ $\log_{10} z_{\rm int} = [2, 3, 4, 5]$
  - ➔ Amplitude = CMB 2σ bound

Relative matter power spectrum vs ΛCDM at $z = 0$



Summary

- Neutrino freestreaming leaves unique imprints in the CMB
  ➔ Non-standard neutrino properties can be tested by the CMB
- We take a model-independent approach and find a **freestreaming window**

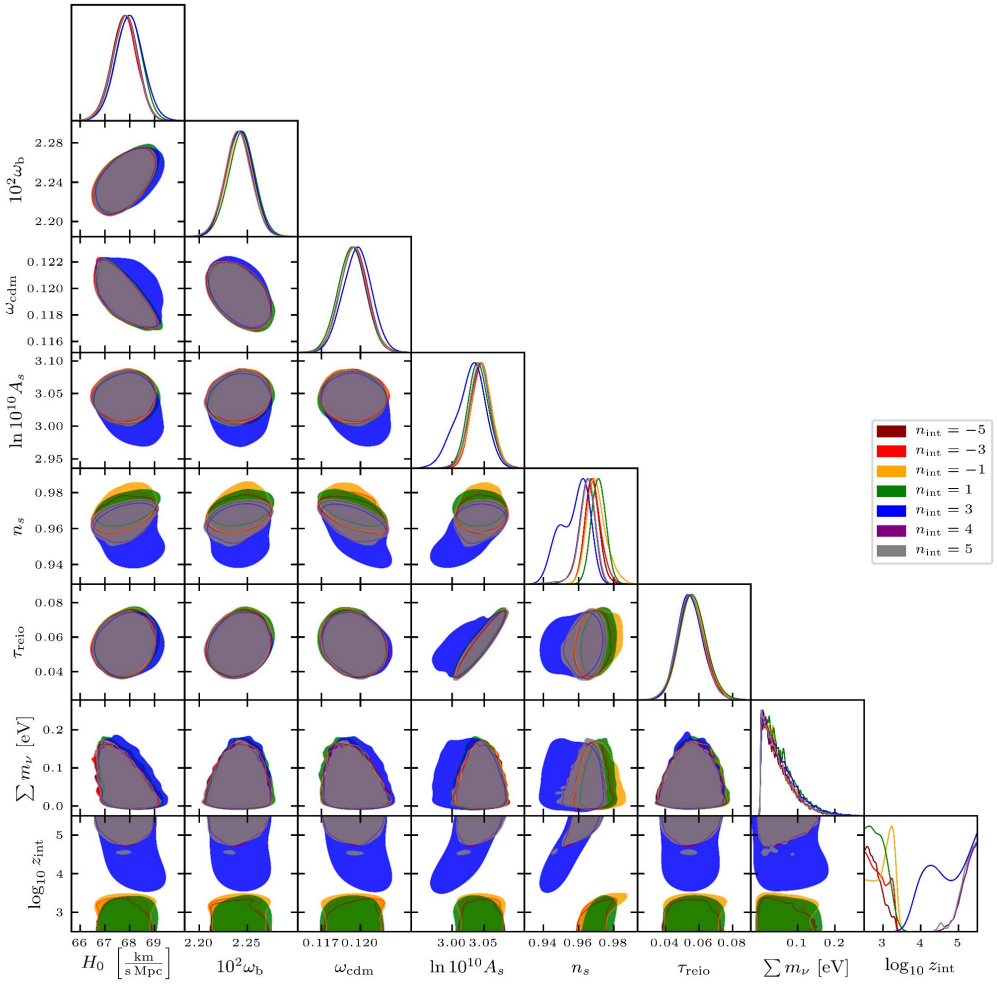
$$2000 \lesssim z_{\rm int} \lesssim 10^5 \qquad 0.34\ {\rm eV} \lesssim T_\nu \lesssim 15\ {\rm eV}$$

  in which neutrinos cannot have significant interactions
- The exception is $\Gamma_{\rm nfs} \propto T^3$ which represents no known particle physics model
- CMB-S4 extends the window to

$$2000 \lesssim z_{\rm int} \lesssim 2 \times 10^5 \qquad 0.34\ {\rm eV} \lesssim T_\nu \lesssim 30\ {\rm eV}$$

- Galaxy clustering can further constrain models with high $z_{\rm int}$

Extra slides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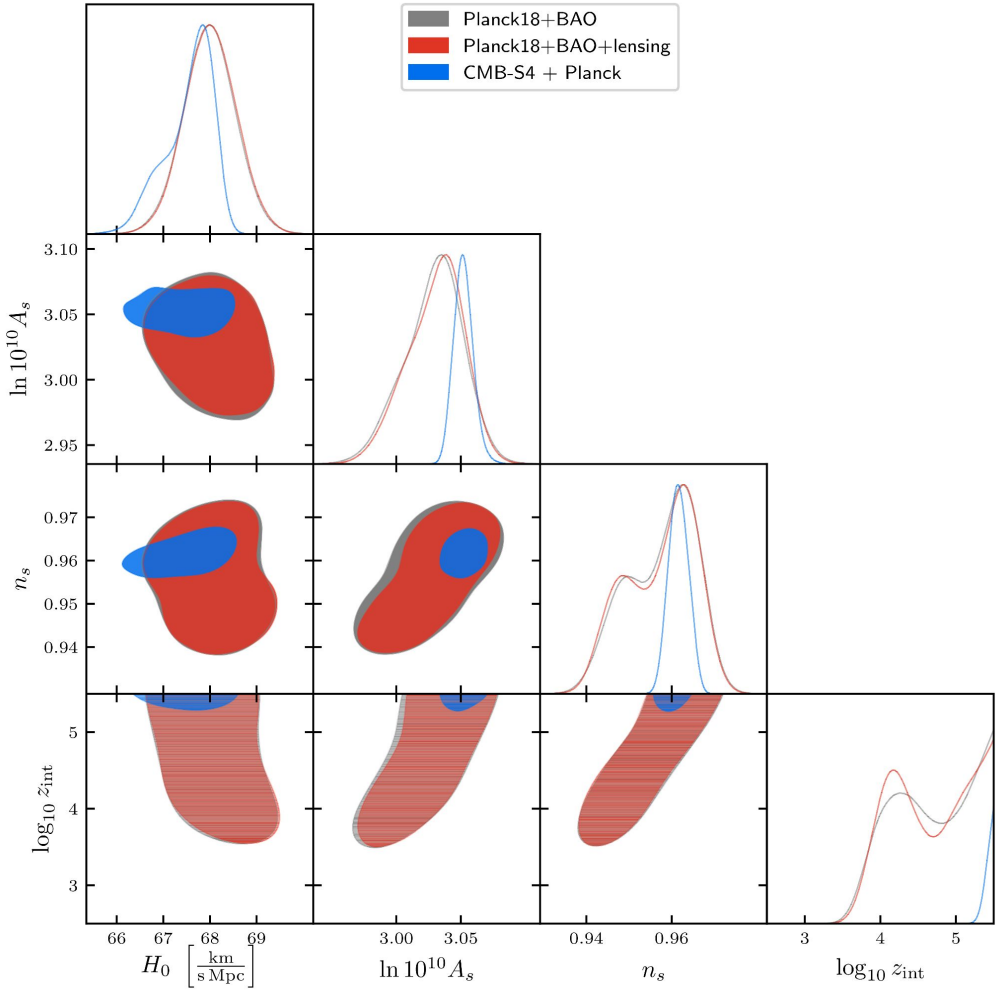
H_0 $\left[\frac{\rm km}{\rm s\,Mpc}\right]$
$10^2\omega_{\rm b}$
$\omega_{\rm cdm}$
$\ln 10^{10} A_s$
n_s
$\tau_{\rm reio}$
$\sum m_\nu$ [eV]
$\log_{10} z_{\rm int}$


Planck18+BAO
Planck18+BAO+lensing
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