

When Dark Radiation Pretends to be Neutrinos

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Questions about Neutrinos

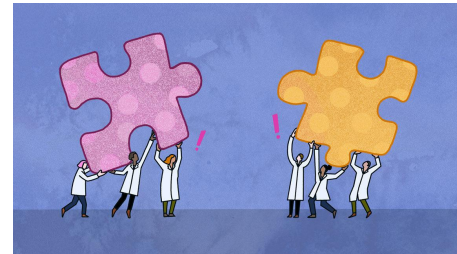
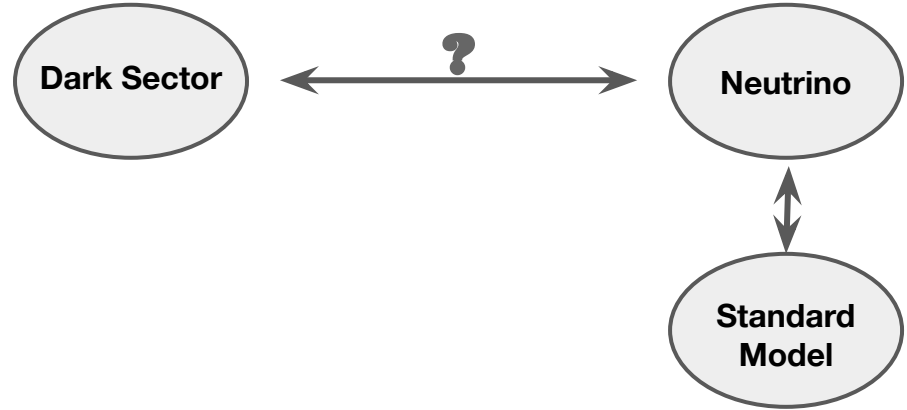
How do they get mass?

Why are they so light?

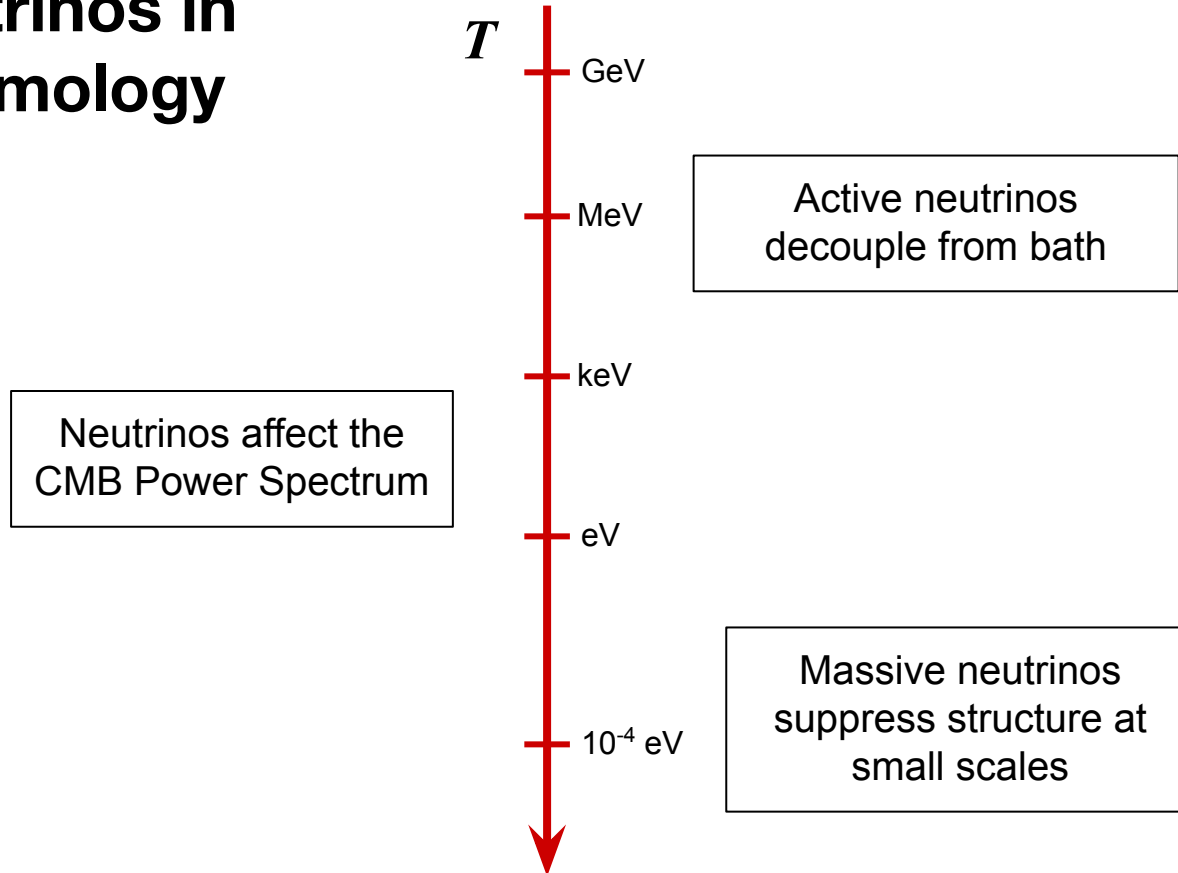
Do they have new interactions?

New particle(s)? Dark sector?

More than three neutrinos?



Neutrinos in Cosmology



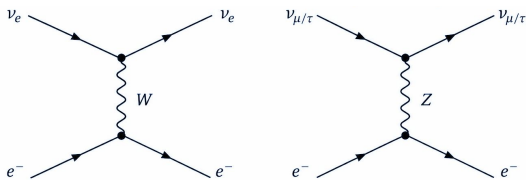
Neutrino Free-streaming After BBN

From a tightly-coupled plasma to collisionless radiation

Before decoupling

$$\Gamma_\nu > H$$

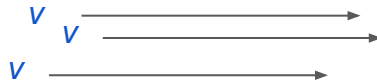
$$T > \text{MeV}$$



After decoupling

$$\Gamma_\nu \lesssim H$$

$$T \lesssim \text{MeV}$$

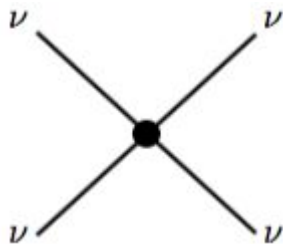


Neutrino (or any radiation) free-streaming generates **anisotropic stress** which modifies the gravitational potentials

$$\sigma_\nu \neq 0 \Rightarrow \phi \neq \psi$$

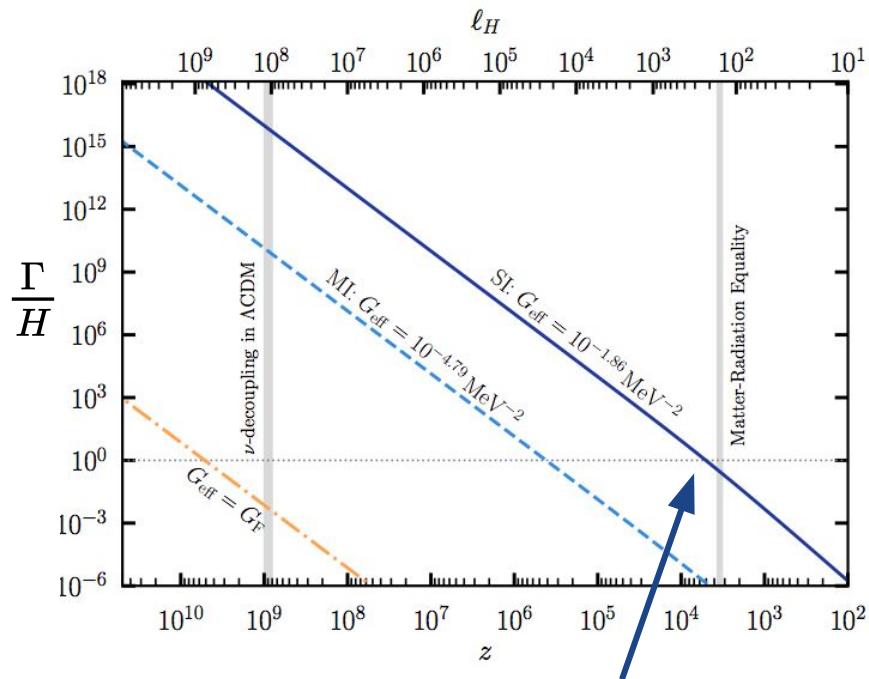
Cosmology w/ Self-interacting Neutrinos

$$\mathcal{L} \supset G_{\text{eff}} \bar{\nu} \nu \bar{\nu} \nu,$$



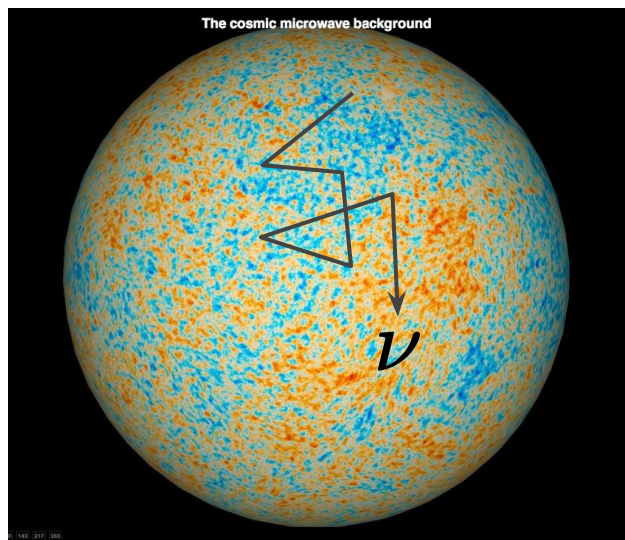
$$\sigma \propto \frac{g_\phi^4}{M_\phi^4} \equiv G_{\text{eff}}^2$$

$$\Gamma \sim G_{\text{eff}}^2 T^5$$

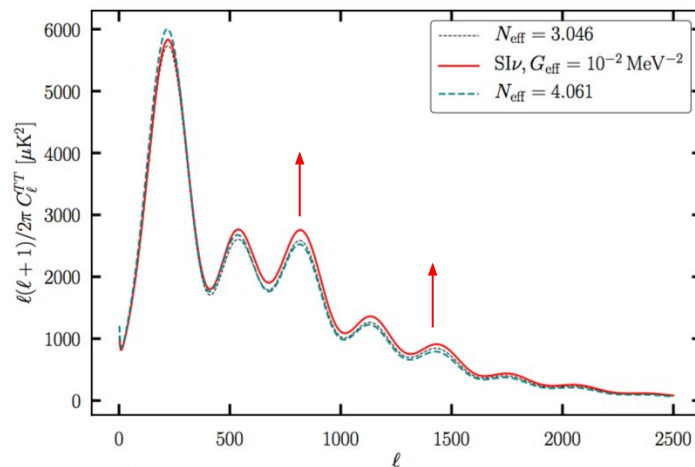


Self-interacting Neutrinos start free streaming much later

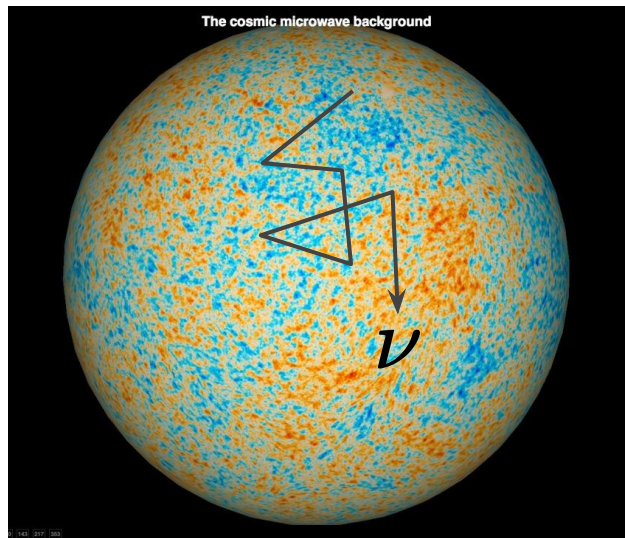
Cosmology w/ Self-interacting Neutrinos



Coupled neutrinos do not free-stream & indirectly help in growth of perturbations



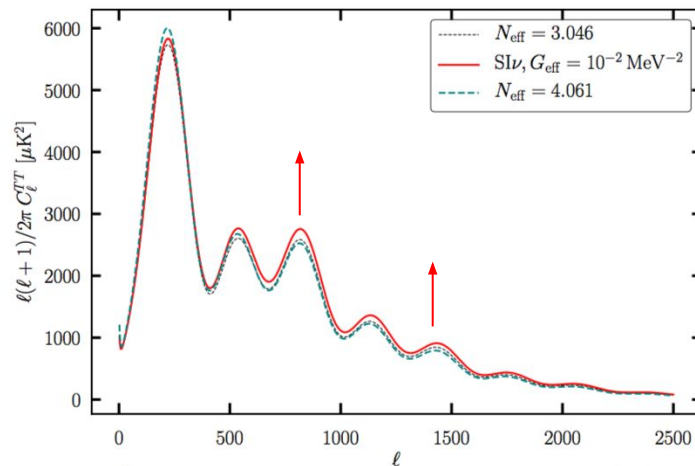
Cosmology w/ Self-interacting Neutrinos



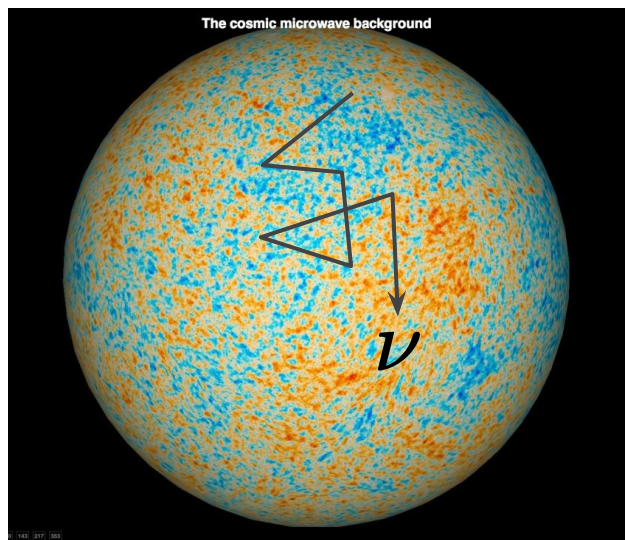
$$\Delta\delta_\gamma \approx -0.27R_\nu$$

Bashinsky & Seljak (PRD 2004)

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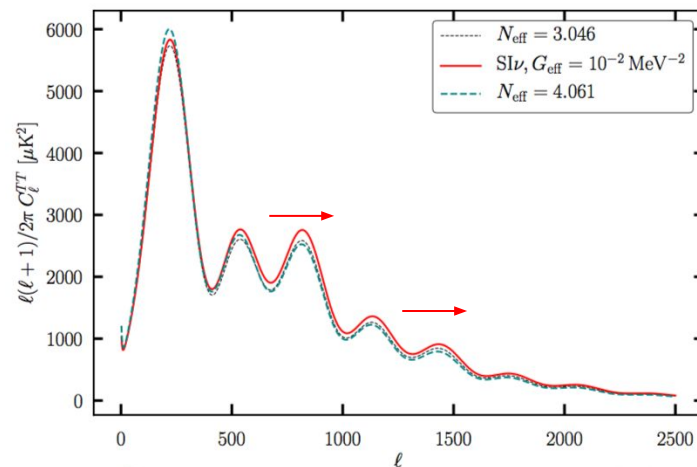
Cosmology w/ Self-interacting Neutrinos



$$\Delta\phi_\gamma \approx 0.19R_\nu$$

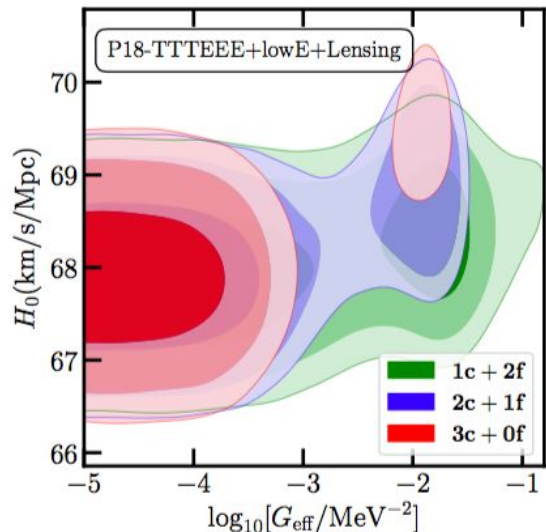
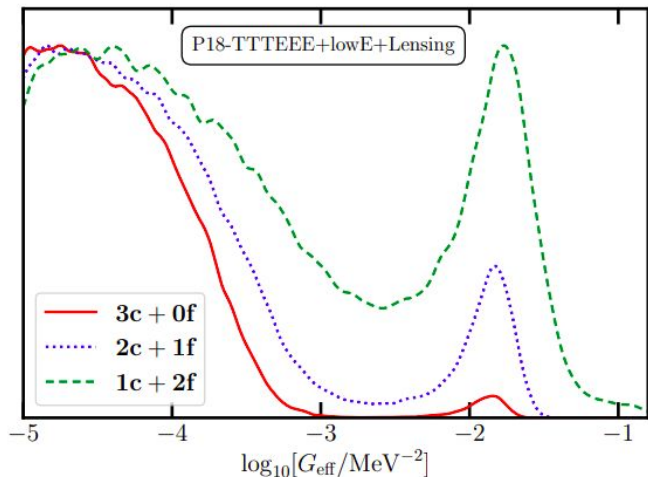
Bashinsky & Seljak (PRD 2004)

They create a **phase shift** in the spectrum
toward smaller scales



Flavor-universal coupling is strongly constrained...

Flavor-dependent coupling/SIDR can still mimic the signal!



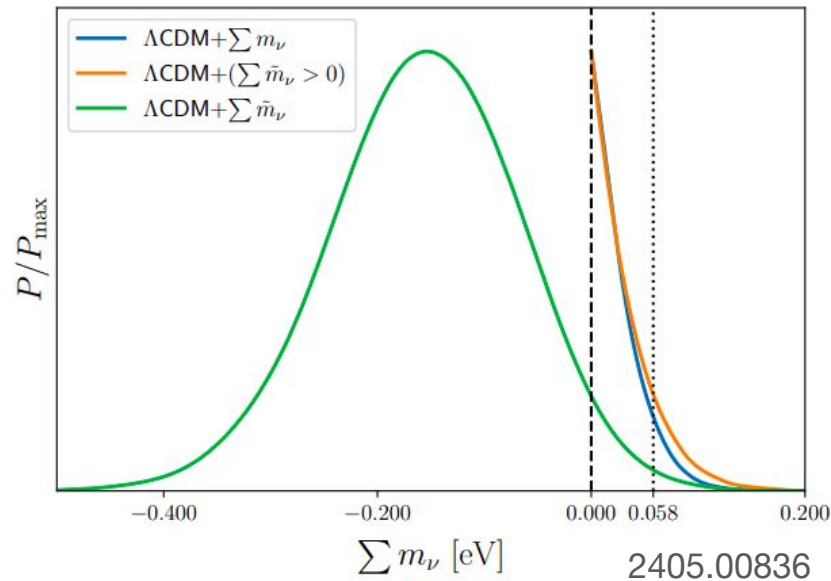
$$\Delta\delta_\gamma \approx -0.27R_\nu$$

$$\phi_\nu \approx 0.19\pi R_\nu$$

$$R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu}$$

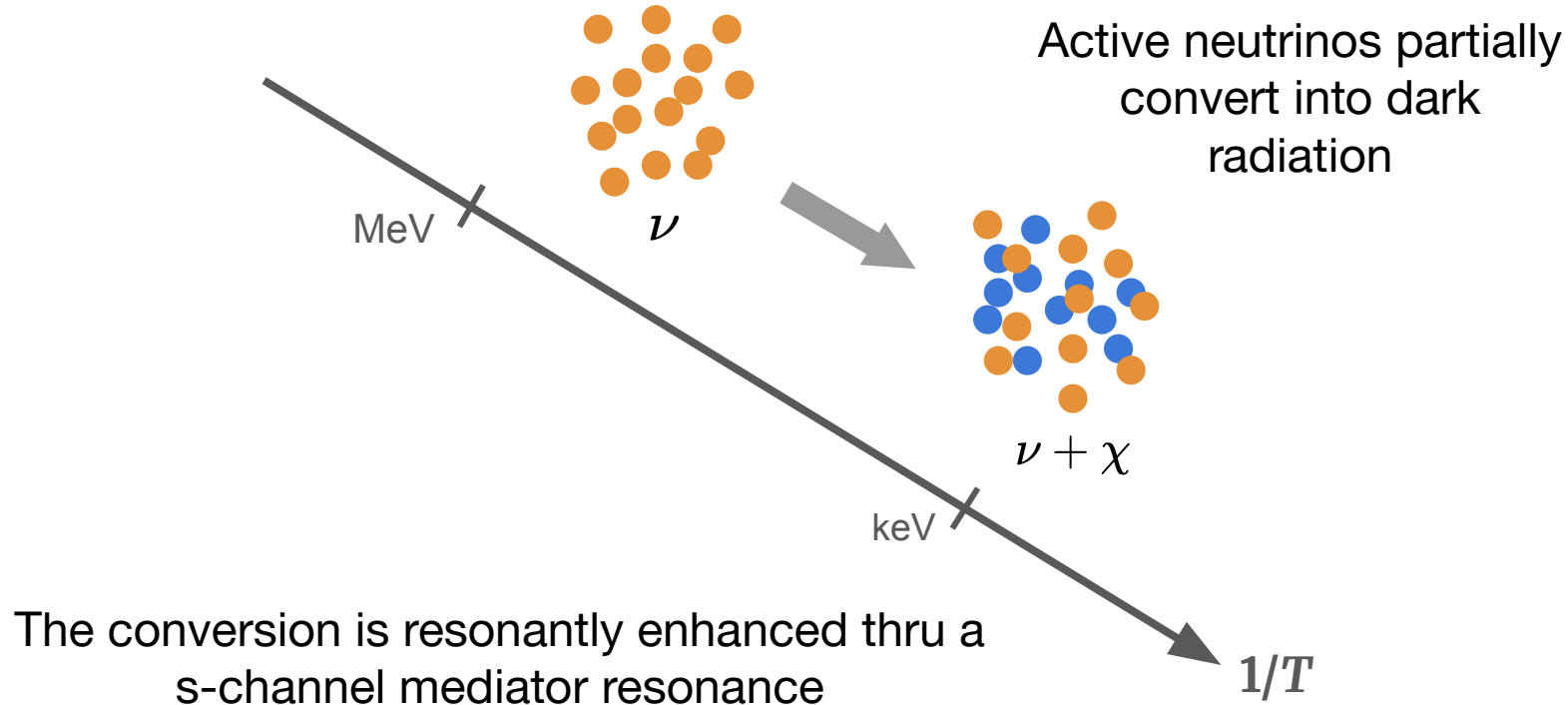
Hint of ‘Negative’ Neutrino Mass?

CMB + BAO data prefer ‘negative’ neutrino mass
⇒ Enhanced matter clustering



See 2405.00836, 2405.03368, 2407.07878, 2503.14744 ...

Self-Interacting DR mimicking SINU

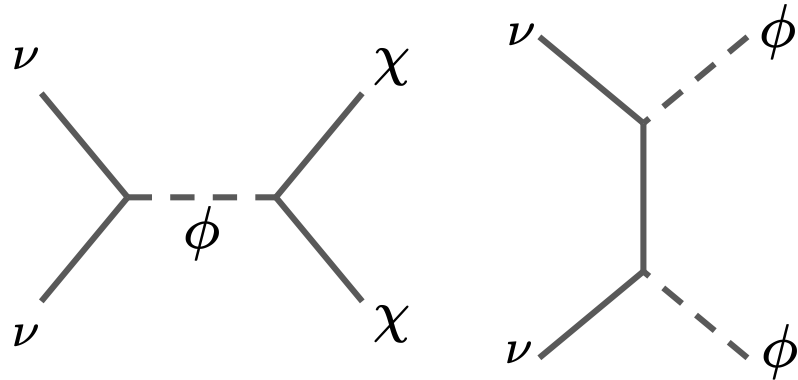


A New Framework using Type I Seesaw

Neutrino sector: $\mathcal{L} \supset \left(y^{\alpha i} L_{\alpha} N_i^c H - \frac{1}{2} M_N^{ii} N_i^c N_i^c + \text{h.c.} \right)$

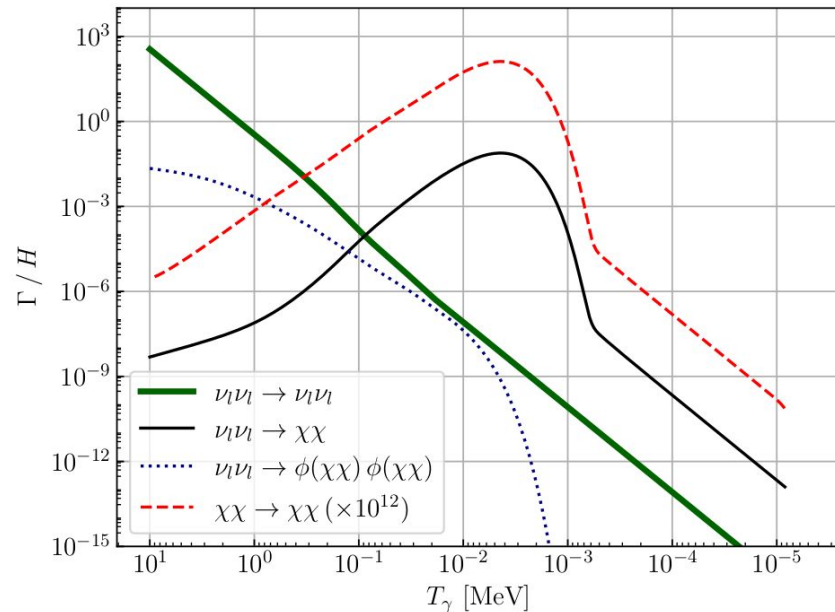
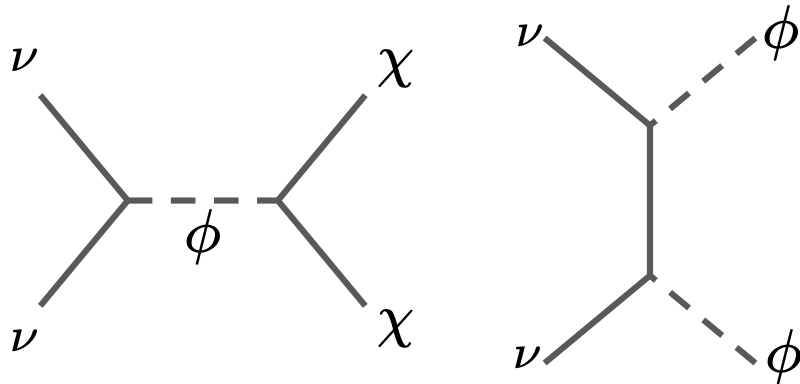
Dark sector: $\mathcal{L}_{\text{dark}} \supset -\frac{1}{2} \lambda_{\phi N} \phi N_i^c N_i^c - \frac{1}{2} \lambda_{\phi \chi} \phi \chi^2 + \text{h.c.}$

Conversion processes



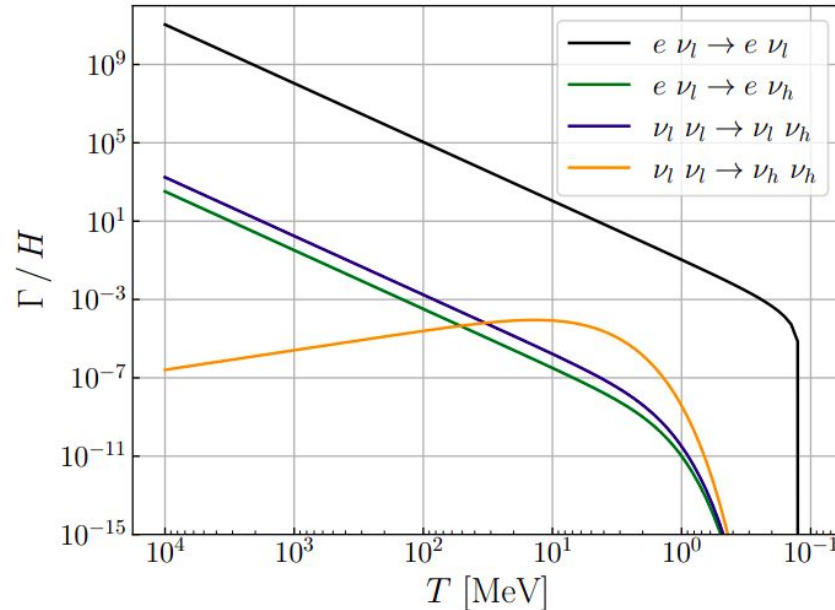
A New Framework using Type I Seesaw

The t-channel process dominates early-on, but the resonant s-channel takes over later when $T \simeq m_\phi$

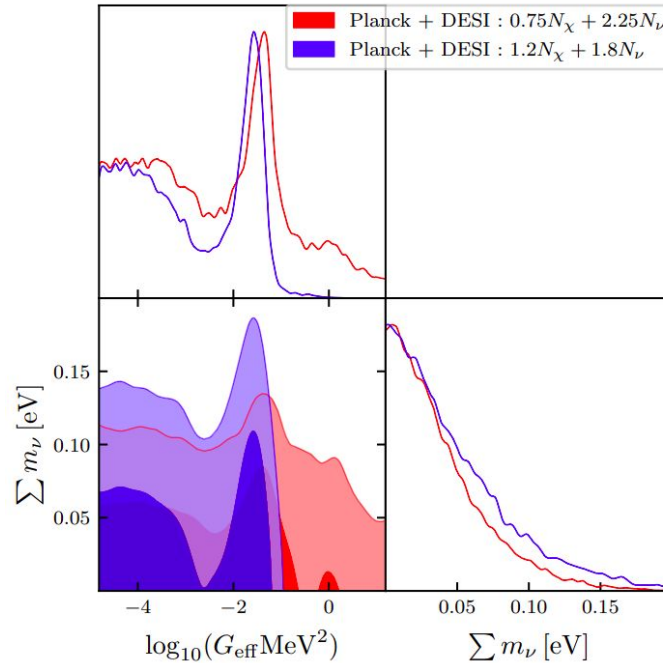


Low reheat to avoid HNL thermalization

Low $T_{\text{rh}} < 100$ MeV does not allow N to get thermal population and decay into DR and increase N_{eff}

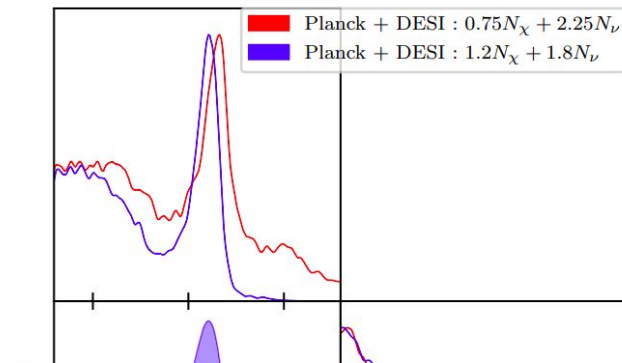


Neutrino mass & coupling strength



Small preference for the SI mode with partial conversion of neutrinos into DR (P18TTTEEE+lensing+DESI yr I)

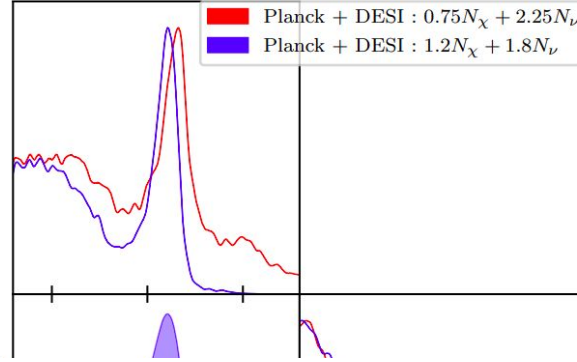
Neutrino self-coupling strength



N_{eff}	Mode	Planck			Planck+DESI		
		$\sum m_\nu$ [eV]	$\log_{10}(G_{\text{eff}} \text{ MeV}^2)$	$\Delta\chi^2$	$\sum m_\nu$ [eV]	$\log_{10}(G_{\text{eff}} \text{ MeV}^2)$	$\Delta\chi^2$
$0.75N_\chi + 2.25N_\nu$	MI	< 0.302	< -3.34	-3.36	< 0.104	< -3.28	-0.74
	SI	< 0.290	< -1.23	-0.26	< 0.114	$-1.27^{+0.28}_{-0.92}$	-1.34
$1.20N_\chi + 1.80N_\nu$	MI	< 0.392	< -3.48	-0.78	< 0.129	< -3.44	-0.34
	SI	< 0.385	$-1.66^{+0.34}_{-0.24}$	-0.38	< 0.149	$-1.65^{+0.30}_{-0.24}$	-1.66

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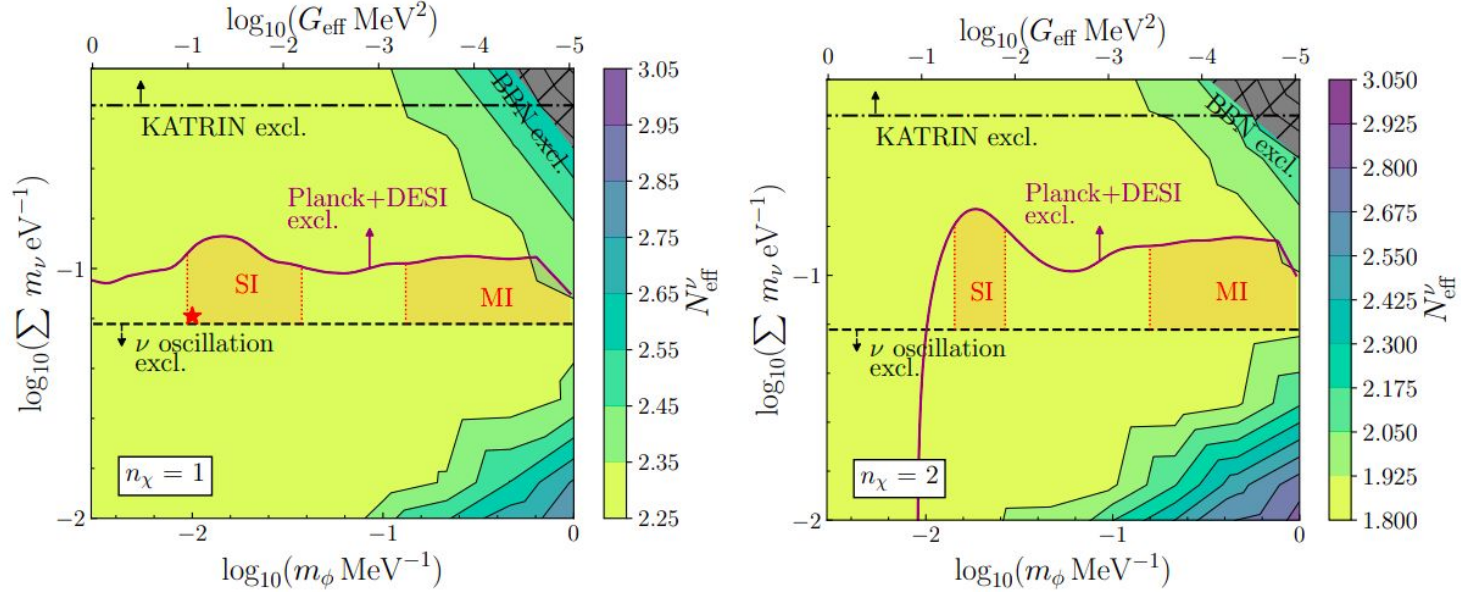
Neutrino mass relaxation



N_{eff}	Mode	Planck			Planck+DESI		
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$$\sum m_\nu^{(N_\chi, N_\nu)} < \sum m_\nu^{(\Lambda\text{CDM})} \left(1 + \frac{N_\chi}{3}\right)$$

Neutrino mass & coupling



Neutrino conversion into DR leaves viable space for the SI & MI modes (P18TTTEEE+lensing+DESI yr I)

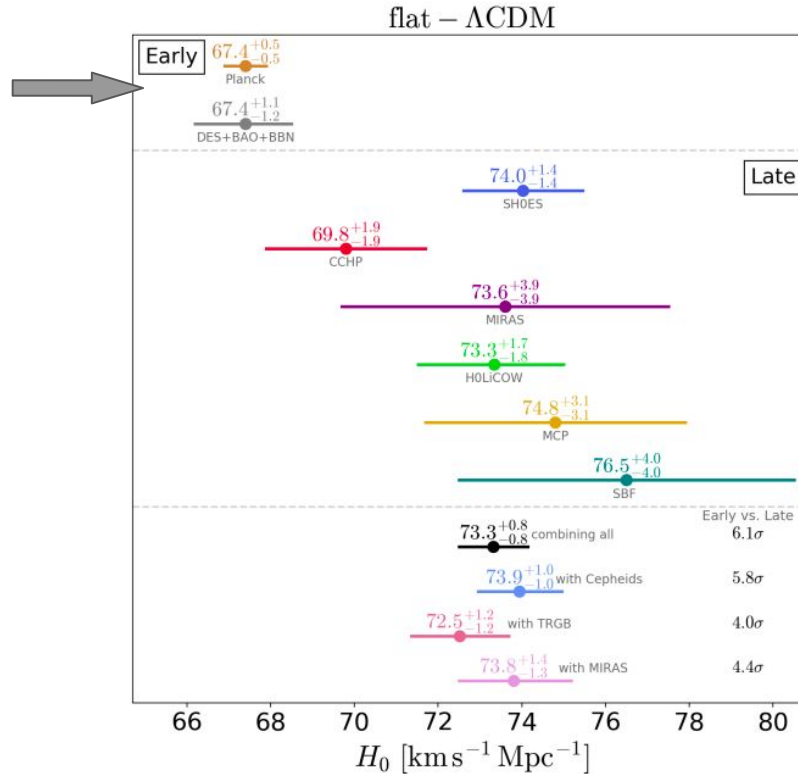
Summary

- BSM self-interaction of neutrinos is a question of natural curiosity
- Hints of it in multiple cosmology observations
- Strongly constrained by laboratory experiments
- We showed a simple realization using self-interacting DR in a Type I seesaw framework
- Neutrino conversion helps relax ν mass constraint

Back ups

The Hubble 'Tension'

Early Universe data
gives smaller value



Late Universe data
gives larger value

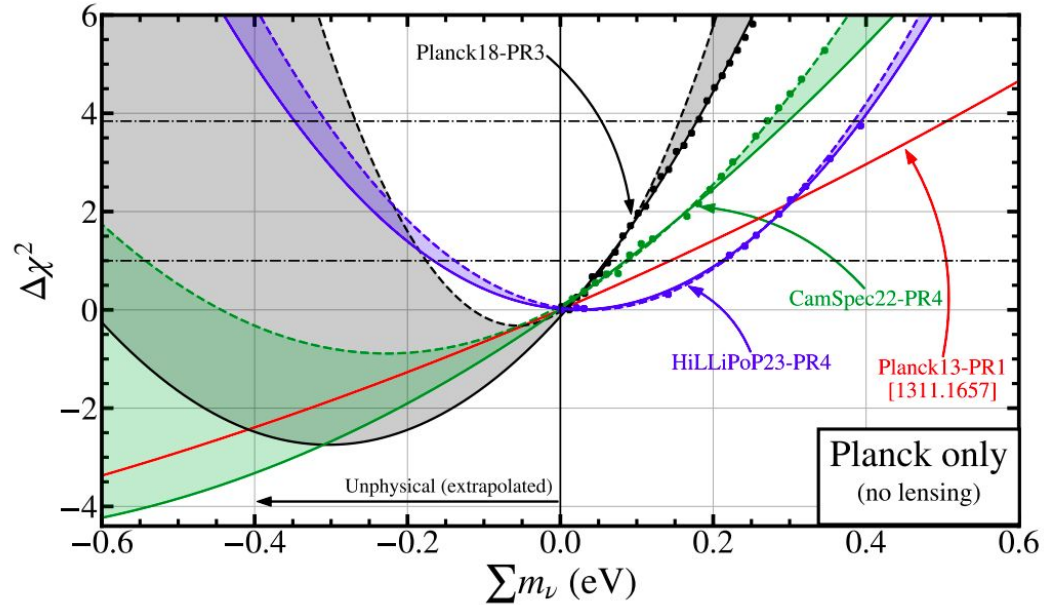
Benchmarks

Effective nos of degrees of freedom

$$(N_\chi, N_\nu) = \begin{cases} (0.75, 2.25) & \text{for } n_\chi = 1 \\ (1.20, 1.80) & \text{for } n_\chi = 2 \end{cases}$$

$$N_{\text{eff}}^\nu \simeq N_{\text{eff}}^{\text{tot}} \frac{g_\nu}{g_\nu + g_\chi}$$

Negative Neutrino Mass from Cosmology?



SN cooling by phi emission

SN1987A observation data excludes the coupling in this region

$$g_{\phi}^{\text{excl}} \simeq (5 \times 10^{-6} - 6 \times 10^{-5}) \times \frac{1}{1 + m_{\phi}/\text{keV}}$$