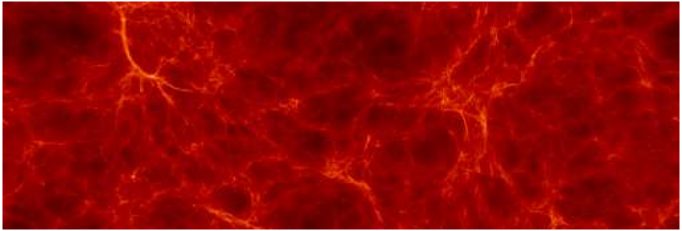
Neutrino interactions from the cosmos

Fermilab Theory Seminar



Structure formation with neutrinos. From arXiv:1003.2422

Ivan Esteban

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The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

14$^{\text{th}}$ October 2021

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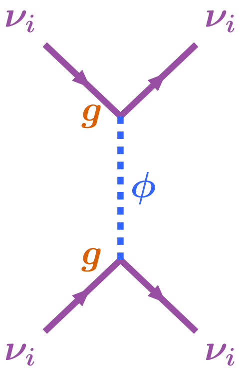
arXiv:2101.05804, arXiv:2107.13568

Neutrino self-interactions

Do neutrinos have sizable self-interactions? (Larger than weak interactions)

$\mathcal{L}_{\text{int}} \sim -g\bar{\nu}\nu\phi$



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Neutrino self-interactions

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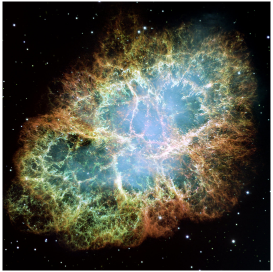
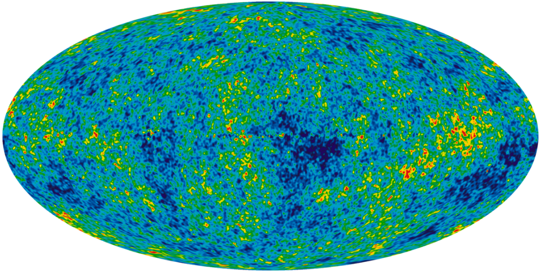
$$\mathcal{L}_{\text{int}} \sim -g\bar{\nu}\nu\phi$$

But, why should we care?

- It is a fundamental question, may shed light into the neutrino mass origin.
- Let's be practical: neutrinos are everywhere!





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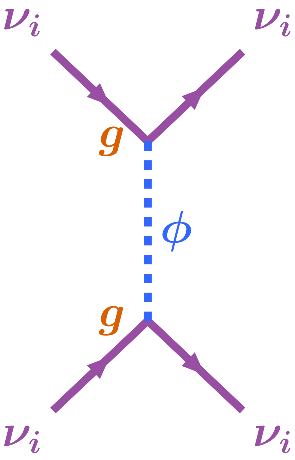

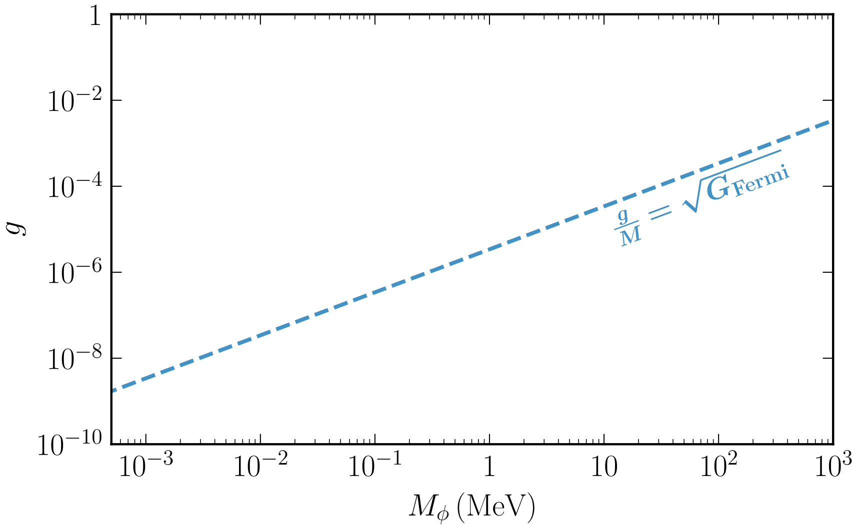

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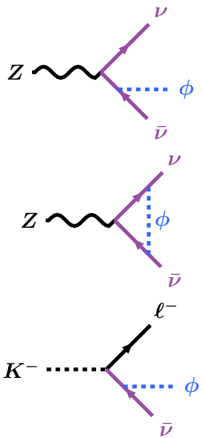
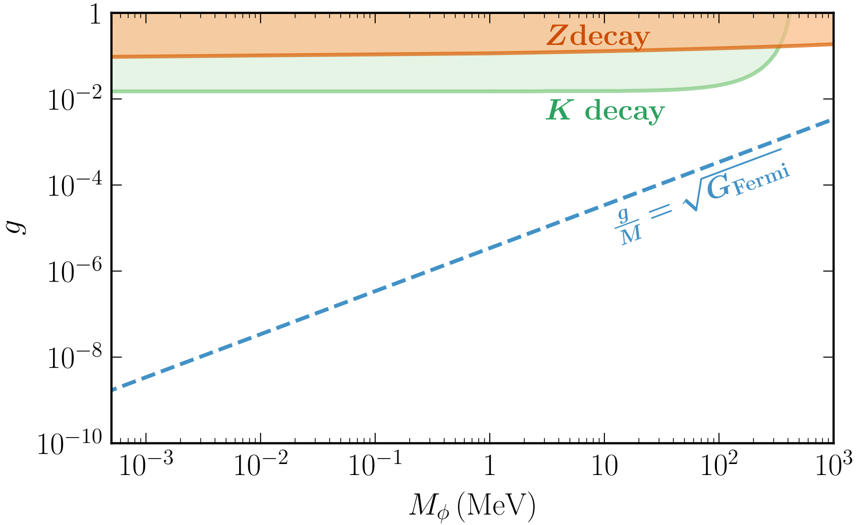
Neutrino self-interactions and where to find them

Blinov, Kelly, Krnjaic, McDermott, 1905.02727; Brdar, Lindner, Vogl, Xu, 2003.05339

Particle physics





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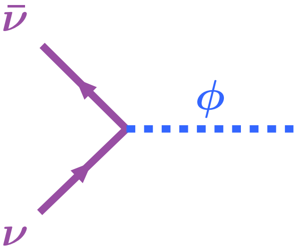
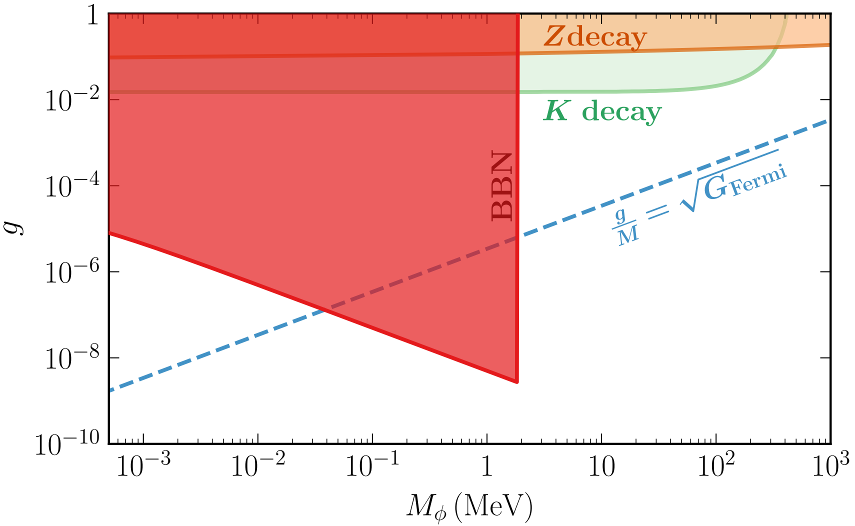
Neutrino self-interactions and where to find them

Escudero, Witte, 1909.04044

Big Bang Nucleosynthesis



Extra radiation by producing the force mediator!



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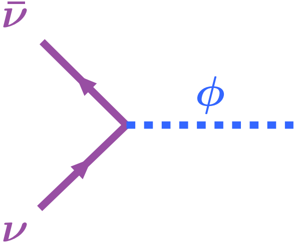
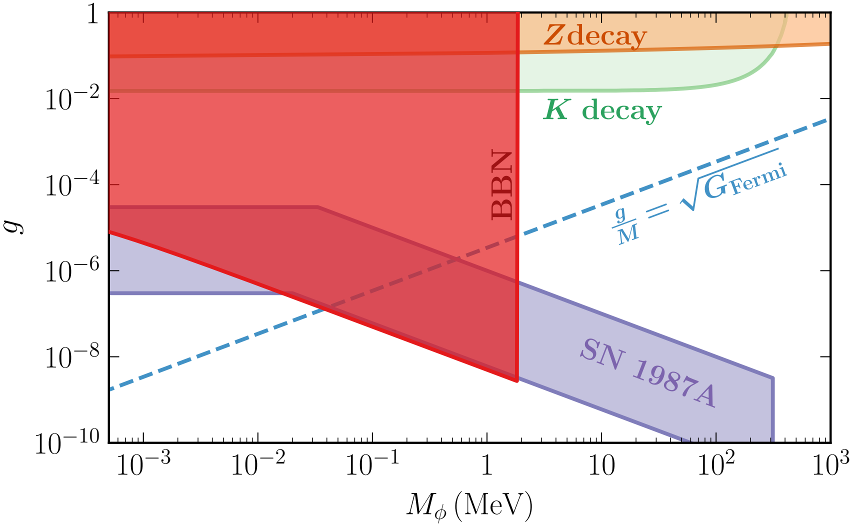
Neutrino self-interactions and where to find them

Heurtier, Zhang, 1609.05882; Kachelriess, Tomas, Valle, hep-ph/0001039; Farzan, hep-ph/0211375. Thanks to Po-Wen Chang!

SN1987A



Extra cooling by producing the force mediator!



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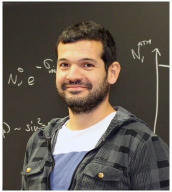
Big picture [Esteban, Salvado, 2101.05804]

ϕ, ν



- Neutrinos will source a scalar field, with
  - Strength $\sim g$
  - Range $\sim 1/M_\phi \sim 10^{-5}\,\mathrm{cm} \times (\mathrm{eV}/M_\phi)$
- The sourced field will *backreact on the neutrinos* as long as
  1. $n_\nu \gtrsim M_\phi^3$
  2. $E_\nu \lesssim m_\nu$ $(\bar{\nu}\nu = \bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
- To probe this, we need *high-density, low energy* neutrinos: **the Early Universe!**

At $z \sim 1000$, when CMB was formed, $n_\nu \sim 10^{14}\,\mathrm{cm}^{-3}$ and $E_\nu \sim 0.1\mathrm{eV}$.

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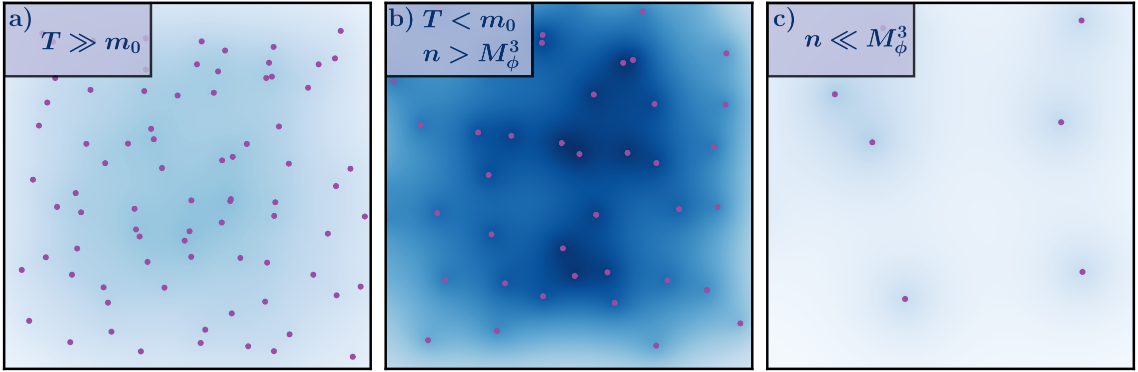
Overall picture



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Signatures in cosmology

- Homogeneous cosmology $\Longrightarrow$ gravity $\Longrightarrow \rho$, p (or $w \equiv p/\rho$).
  Generic assumption = *ideal gas*. But systems with long-range interactions are **not** ideal gases!
  E.g., Van der Walls gas

- Can we *consistently* understand the whole evolution?
  N.B.: though not discussed in the talk, we also study perturbations. Ask about it!

- What are the observational consequences and possible signals/bounds?
  - Cosmic Microwave Background anisotropies
  - Large Scale Structure observations (Baryon Acoustic Oscillations)

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Equations of motion

$$i\not{D}\nu - (m_0 + g\phi)\nu = 0 \Longrightarrow$$

Effective neutrino mass $\tilde{m}(\phi) \equiv m_0 + g\phi$.
Time-dependent as ϕ evolves.

$$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\nu}\nu$$

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$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\nu}\nu \Longrightarrow$ Klein-Gordon equation with *Hubble friction* and **source term**. For $M_\phi \gg H$ and average rhs over neutrino (+antineutrino) distribution $f(p)$,

$$M_\phi^2 \phi = -g \int \mathrm{d}^3 p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)$$

N.B.: $M_\phi \gg H$ means $M_\phi \gtrsim 10^{-25}\,\mathrm{eV}$. I.e., we are exploring interaction ranges $\ll \mathrm{Mpc}$. Otherwise, we recover quintessence.

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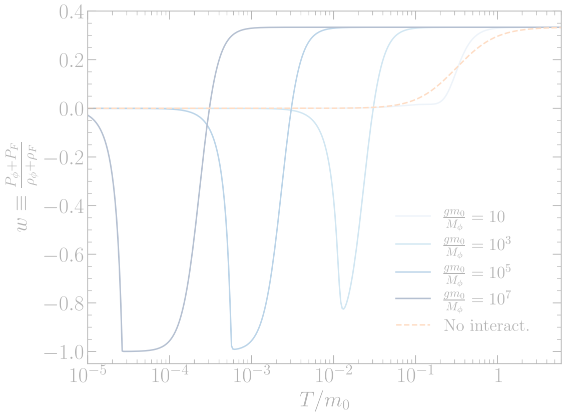
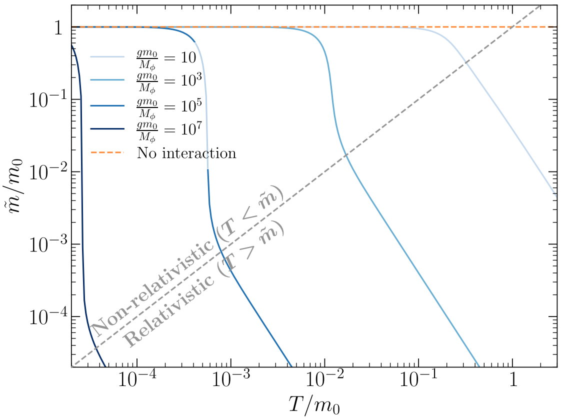
Some results [Esteban, Salvado, 2101.05804]





Neutrinos will stay *relativistic* as long as there are many neutrinos within the interaction range.

Small couplings, long ranges

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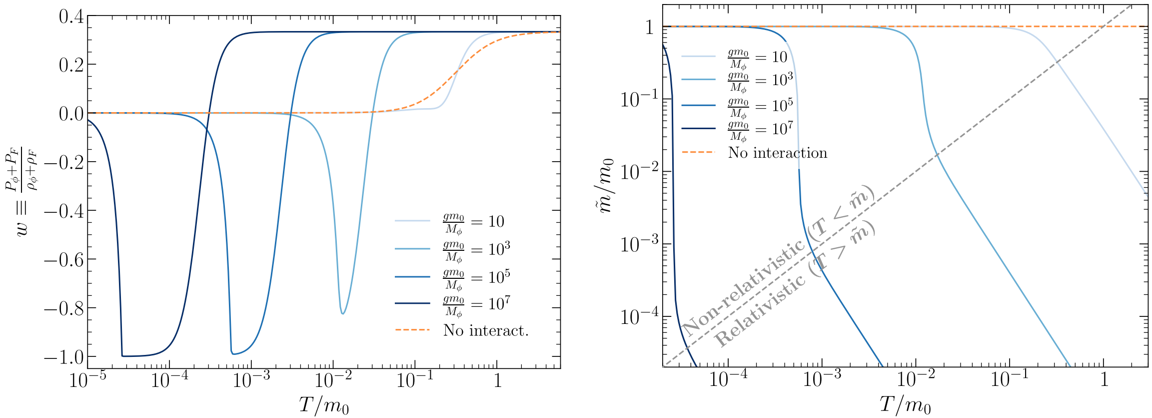
Some results [Esteban, Salvado, 2101.05804]



The equation of state $w \equiv \frac{P}{\rho}$ is relevant as $\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H(1+w)$ (i.e., how fastly ρ changes)

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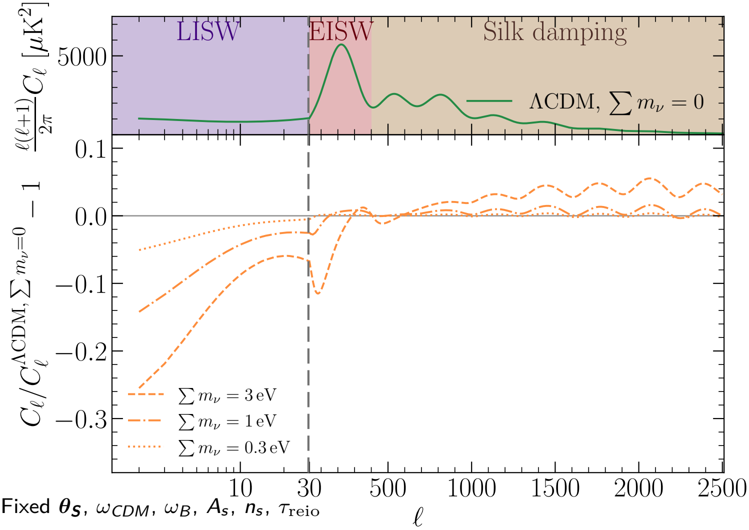
Effects on CMB: Neutrino masses



Fixed $\boldsymbol{\theta_S}$, ω_{CDM}, ω_B, A_s, n_s, $\tau_{\rm reio}$

J. Lesgourgues, G. Mangano, G. Miele, S. Pastor, Neutrino Cosmology (2013)

For fixed $\theta_S = \dfrac{\int_{z_{\rm rec}}^{\infty} c_s \frac{\mathrm{d}z'}{H(z')}}{\int_0^{z_{\rm rec}} \frac{\mathrm{d}z'}{H(z')}}$,

$\sum m_\nu \neq 0$ has 3 main effects:

1. EISW, which directly tests the *equation of state*.
2. To keep θ_S fixed, H_0 decreases $\Rightarrow \Omega_\Lambda$ decreases $\Rightarrow$ less LISW.
3. $\theta_D \sim \dfrac{\sqrt{\int_{z_{\rm rec}}^{\infty} \frac{1}{a n_e \sigma_T} \frac{\mathrm{d}z'}{H(z')}}}{\int_0^{z_{\rm rec}} \frac{\mathrm{d}z'}{H(z')}}$

Small couplings, long ranges

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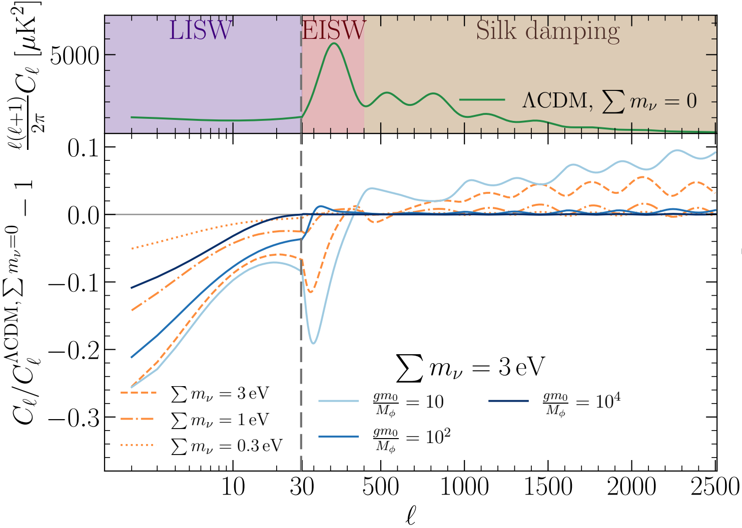
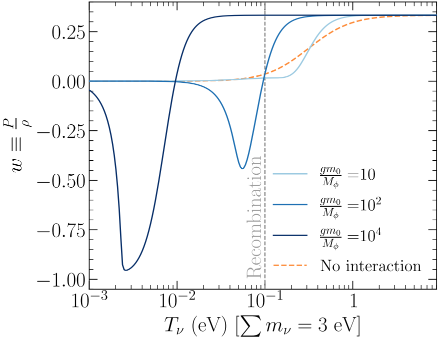
Effects on CMB: Adding the interaction





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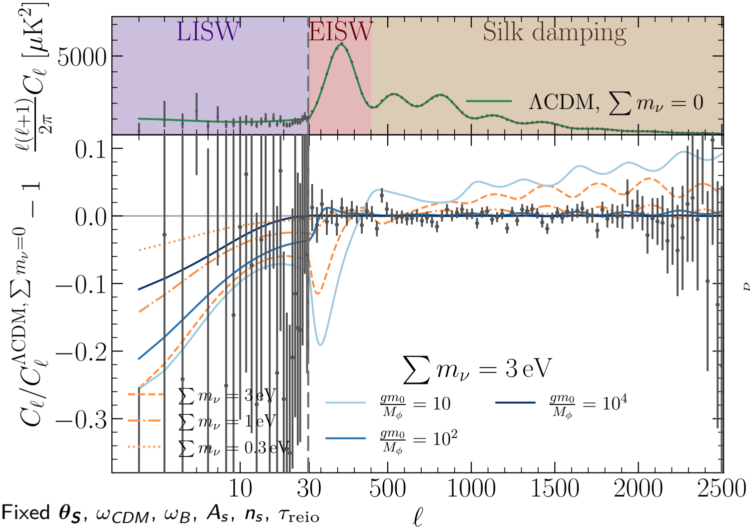
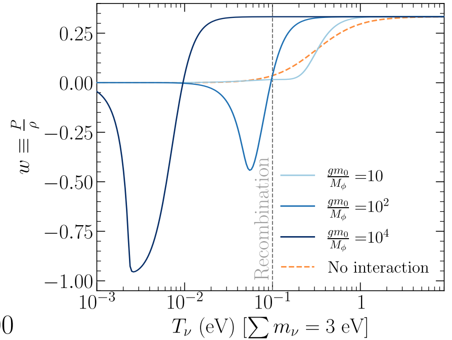
Effects on CMB: Data



Fixed θ_s, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}

The Planck constraint will be essentially *behave like radiation for* $T > T_{rec}$.



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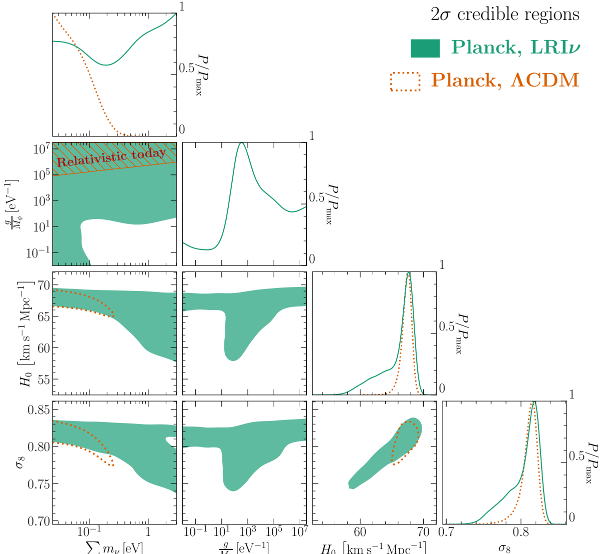
Results: Planck



All the allowed region has essentially the same behavior before recombination: neutrinos with $w = 1/3$.

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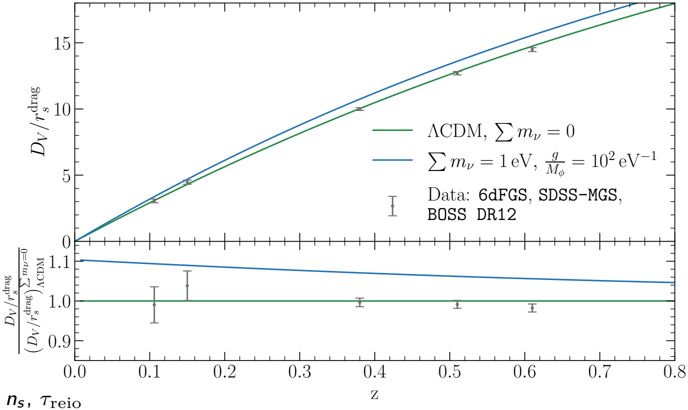
BAO constraints

BAO approximately measure $\dfrac{\int_{z_{\text{drag}}}^{\infty} c_s \frac{\mathrm{d}z'}{H(z')}}{\left[\frac{z}{H(z)}\left(\int_0^z \frac{\mathrm{d}z'}{H(z')}\right)^2\right]^{1/3}}$, sensitive to late-time evolution of H, i.e., to ρ.



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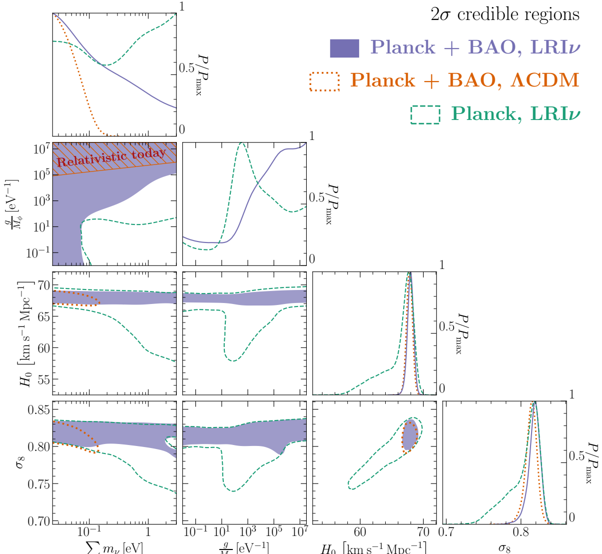

- As neutrinos become non-relativistic late, BAO is quite sensitive.
- Neutrino mass bound still *fully avoided*. **KATRIN could see something!**

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Future: Large Scale Structure

- As we have seen, late-time probes can efficiently explore neutrino long-range interactions.

- This decade, we expect precise LSS probes of the matter power spectrum!

L. Amendola *et al.* [Euclid Theory WG], "Cosmology and fundamental physics with the Euclid satellite," arXiv:1606.00180.

R. Maartens *et al.* [SKA Cosmology SWG], "Overview of Cosmology with the SKA," arXiv:1501.04076.

J. Pritchard *et al.* [Cosmology-SWG and EoR/CD-SWG], "Cosmology from EoR/Cosmic Dawn with the SKA," arXiv:1501.04291.

P. A. Abell *et al.* [LSST Science and LSST Project], "LSST Science Book, Version 2.0," arXiv:0912.0201.

T. Sprenger *et al.*, "Cosmology in the era of Euclid and the Square Kilometre Array," arXiv:1801.08331.

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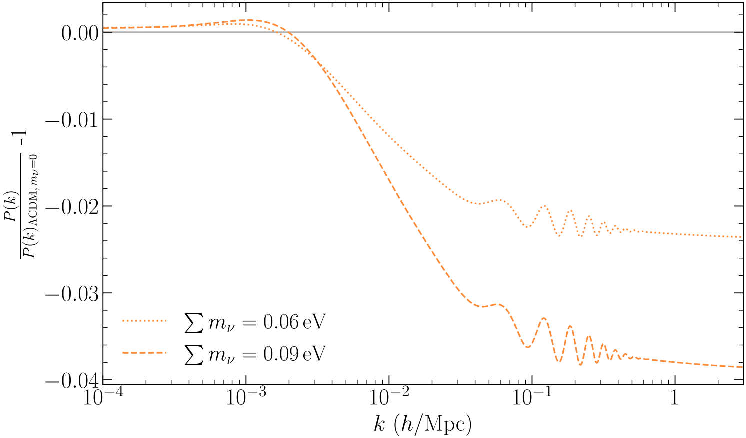
Impact on matter power spectrum



$\sum m_\nu \neq 0$ has two main effects:

1. Small enhancement at $k \sim 10^{-3}\ h/\mathrm{Mpc}$, due to clustering.
2. Suppression at large k, as for $w < 1/3$ neutrinos redshift slower and contribute more to Hubble friction.

Sensitive to energy density in neutrinos and **equation of state**!

Fixed Ω_M, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}. $z = 0$.

Small couplings, long ranges

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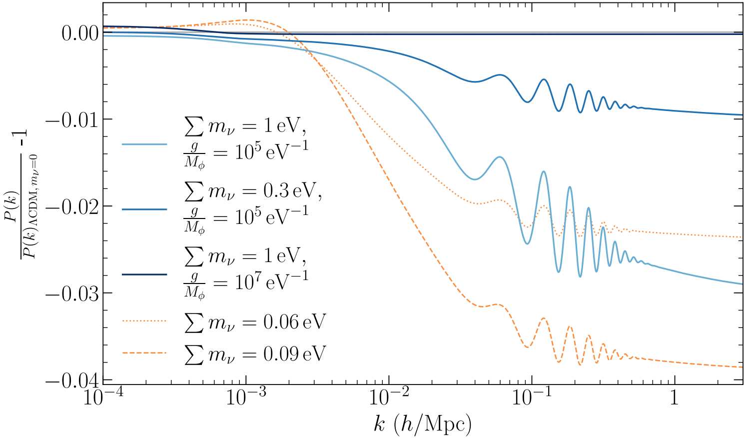

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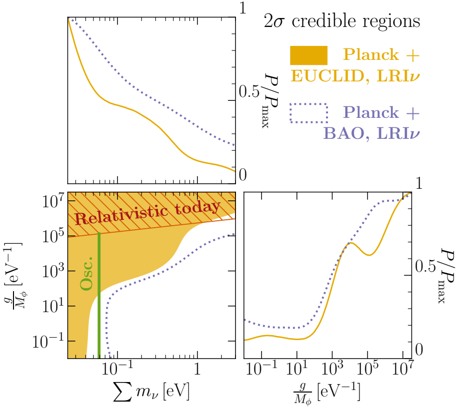
Euclid

T. Sprenger *et al.*, "Cosmology in the era of Euclid and the Square Kilometre Array," arXiv:1801.08331.

Euclid should have $\sim$ 2–3σ sensitivity to $\sum m_\nu = 0.06\,\mathrm{eV}$, the smallest value allowed by oscillations.

Scenario 1: Euclid compatible with $\sum m_\nu = 0$



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Euclid

Interesting complementarity with KATRIN!

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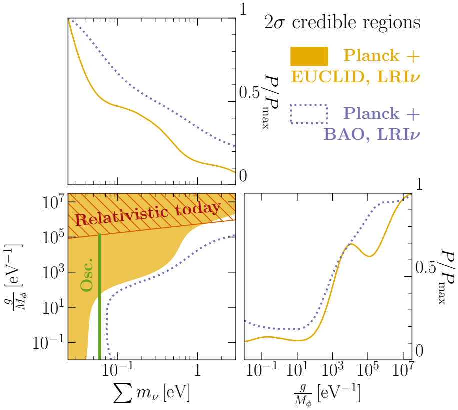
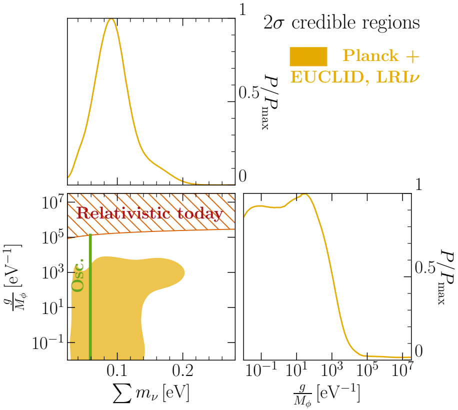


Scenario 2: Euclid measures $\sum m_\nu = 0.08\,\mathrm{eV}$



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Take-home messages

1. Cosmology can probe long-range neutrino self-interactions!

2. These change the *effective neutrino mass* and *equation of state*.

3. Cosmological $\sum m_\nu$ measurements are mostly measurements of the neutrino equation of state: ***degeneracy with self-interactions!***:
   - Long-range interactions *remove the cosmological neutrino mass bound*.
     KATRIN could see $\sum m_\nu \neq 0$! EUCLID could test this!
   - In the future, cosmology could see no neutrino mass, in contradiction with oscillations!

4. A very rich cosmo-lab *interplay*.

Back to the big picture

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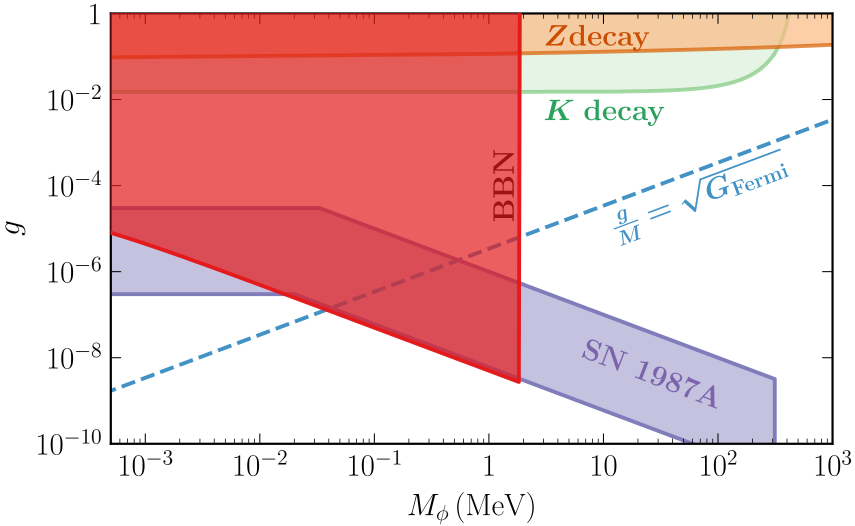

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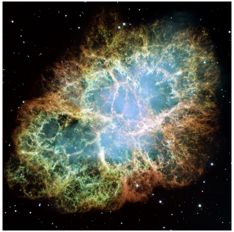
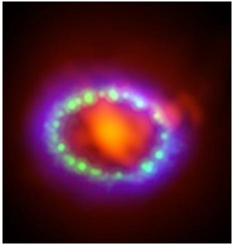
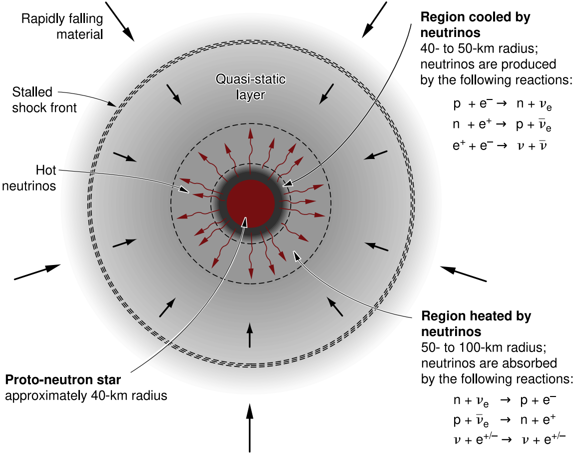
Supernovae

S. Shalgar, I. Tamborra, M. Bustamante, "Core-collapse supernovae stymie secret neutrino interactions" arXiv:1912.09115.







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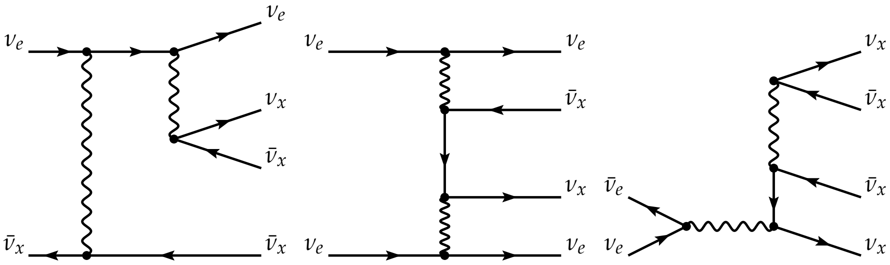

$$2\nu \to 4\nu \Longrightarrow \langle E_\nu \rangle \to \langle E_\nu \rangle / 2$$

And $\sigma_{\nu N} \propto \langle E_\nu \rangle^2$, so neutrino energy deposition on the shock would be more rare!

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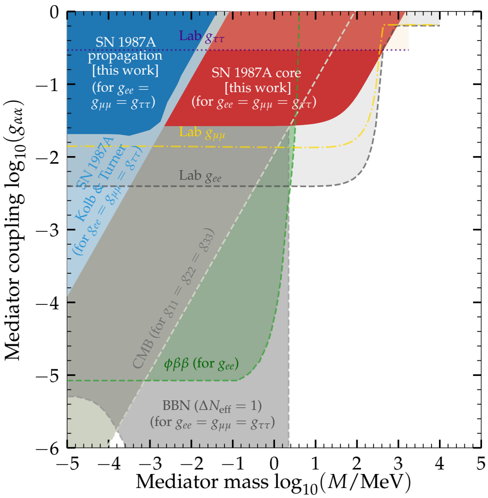

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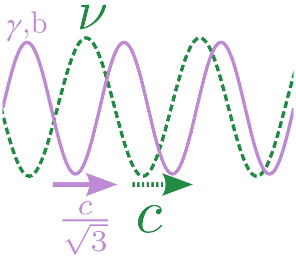
Cosmology

In this context, the interaction turns a system of free particles into a *strongly coupled fluid*. How can this affect, e.g., the Early Universe?

- When the CMB is formed, neutrinos are $\sim 40\%$ of the energy density of the Universe!
- At those times
  - Photons and baryons **oscillate** (tightly-coupled acoustic waves, at $\boldsymbol{c}/\sqrt{\mathbf{3}}$)
  - Neutrinos just **freely propagate** (free-stream, at $\boldsymbol{c}$)

  Neutrinos will gravitationally pull! Bashinsky, Seljak, astro-ph/0310198

  Or, will they? self-interactions can make neutrinos a tightly-coupled fluid too.



Large couplings, short ranges

Ivan Esteban, Ohio State University esteban.6@osu.edu

Cosmology

In this context, the interaction turns a system of free particles into a *strongly coupled fluid*. How can this affect, e.g., the Early Universe?

- When the CMB is formed, neutrinos are $\sim 40\%$ of the energy density of the Universe!
- At those times
  - Photons and baryons **oscillate** (tightly-coupled acoustic waves, at $\boldsymbol{c/\sqrt{3}}$)
  - Neutrinos just **freely propagate** (free-stream, at $\boldsymbol{c}$)

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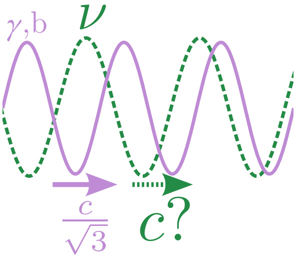

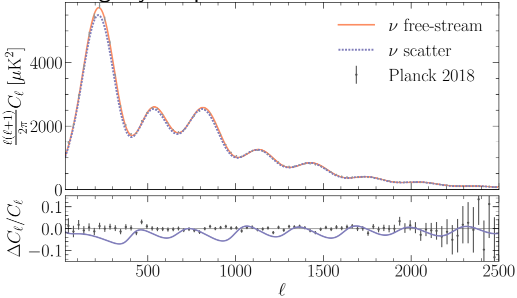

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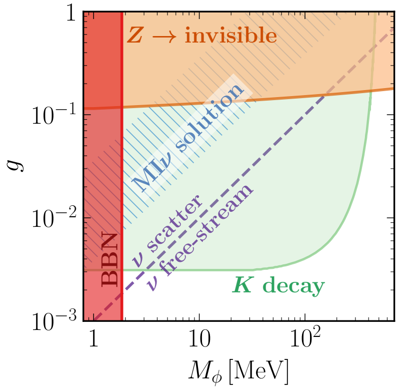
arXiv:2101.05804, arXiv:2107.13568

The Moderately Interacting Neutrino (MIν) solution



Cyr-Racine, Sigurdson, 1306.1536; Lancaster, Cyr-Racine, Knox, Pan, 1704.06657; Oldengott, Tram, Rampf, Wong, 1706.02123; Kreisch, Cir-Racine, Dor, 1902.00534; Barenboim, Denton, Oldengott, 1903.02036; ...

Non-free-streaming neutrinos may affect how we infer cosmological parameters from CMB anisotropies!

Most notably H_0, σ_8, and inflationary parameters N.B.: beware of polarization data, though

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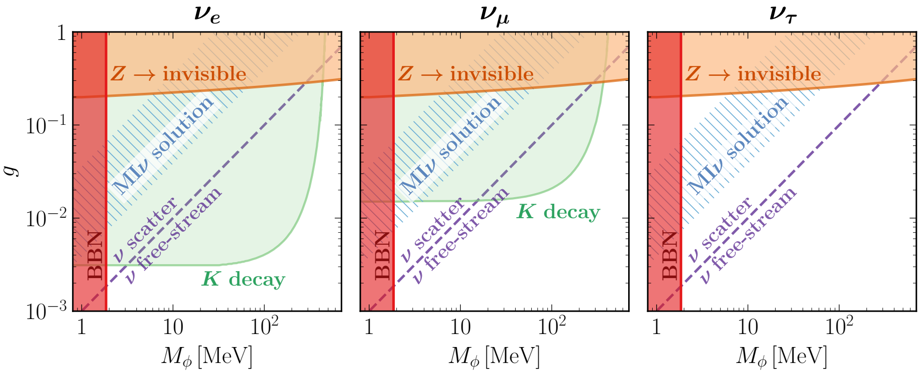

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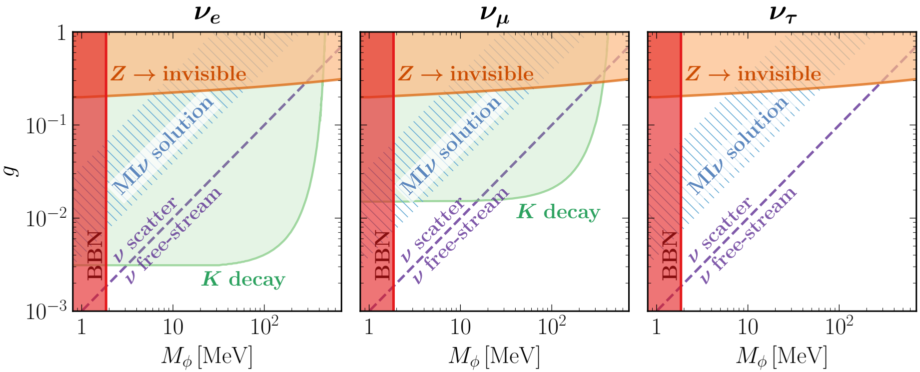
Esteban, Pandey, Brdar and Beacom [2107.13568]



An opportunity opens to explore ν_τ self-interactions. As we show in our paper, we can catch it!
ν_τ are hard to *directly* produce, but oscillations can help us.

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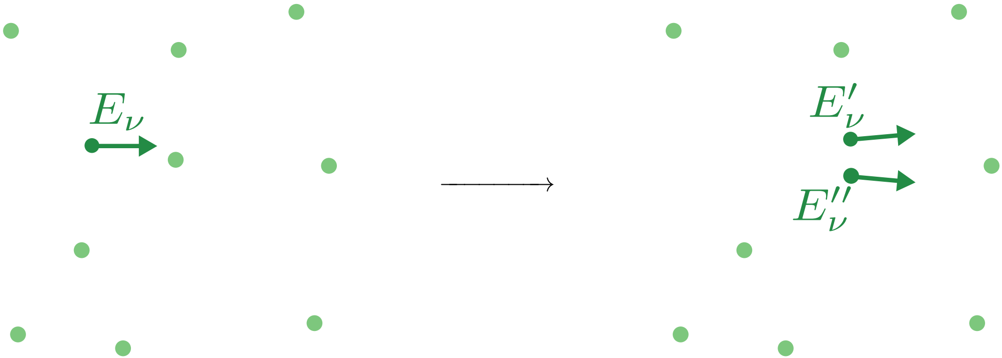
Effect on astrophysical neutrinos: the big picture

Kolb & Turner, 1987



Resonantly enhanced when $E_{\text{center-of-mass}} \equiv \sqrt{s} = \sqrt{2E_\nu m_\nu} = M_\phi$.

For $M_\phi \sim 10\,\mathrm{MeV}$, $E_\nu \sim 10^5\,\mathrm{GeV}$: **astrophysical neutrinos at IceCube!**

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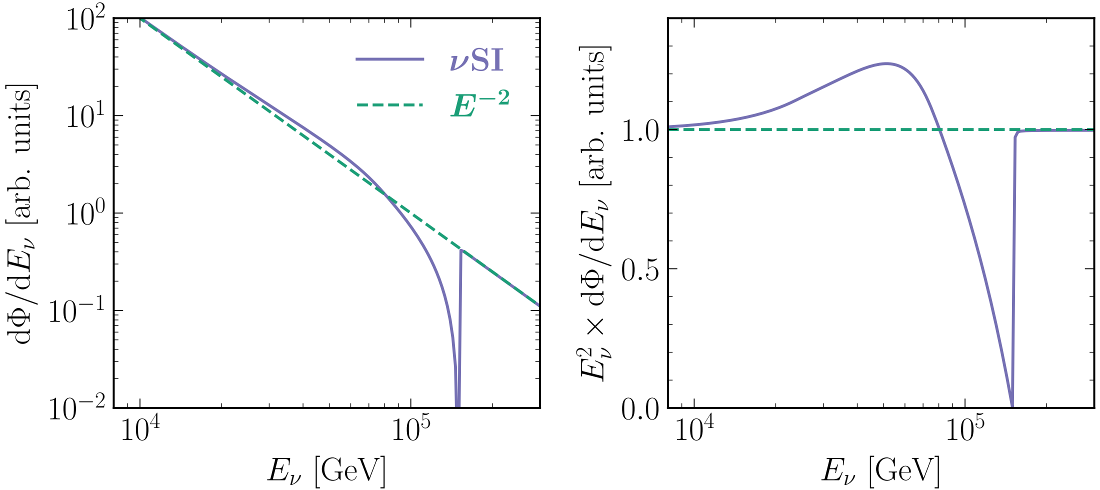
Effect on astrophysical neutrinos: the big picture

Hooper, hep-ph/0701194; Ng, Beacom, 1404.2288; Ioka, Murase, 1404.2279; . . .

$$E_\nu^{\mathrm{res}} = \frac{M_\phi^2}{2m_\nu}$$



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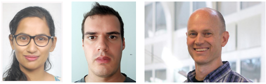
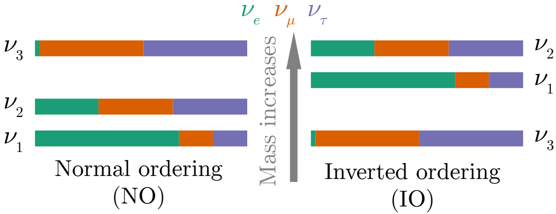
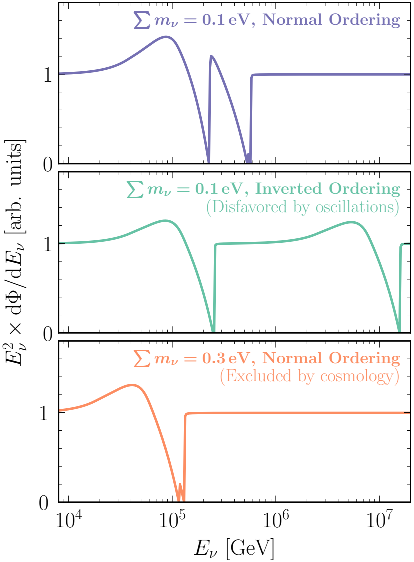
Focusing on ν_τ + 2021 [Esteban et al, 2107.13568]

Esteban, Pandey, Brdar, Beacom, arXiv:2107.13568.



What do we know about the neutrino spectrum?





$\sum m_\nu < 0.12\,\mathrm{eV}$, $\sqrt{\Delta m^2_{32}} \sim \sqrt{\Delta m^2_{31}} \sim 0.05\,\mathrm{eV}$

$E_\nu^{\mathrm{res,i}} = M_\phi^2/2m_i$

- Look for (close) double dips!

  And stay tuned on oscillations + cosmology!

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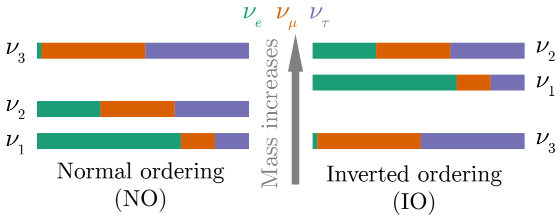

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- Look for (close) double dips!
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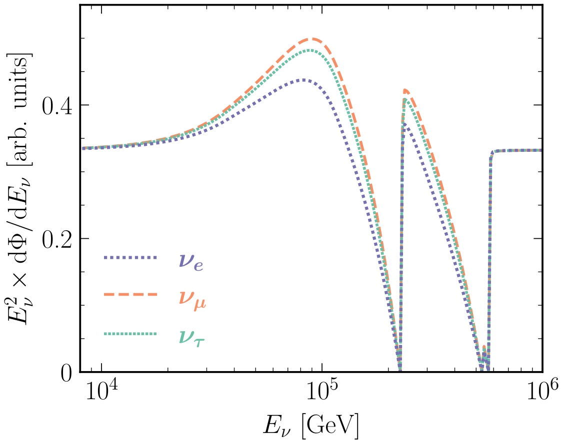
- Look for all flavors!



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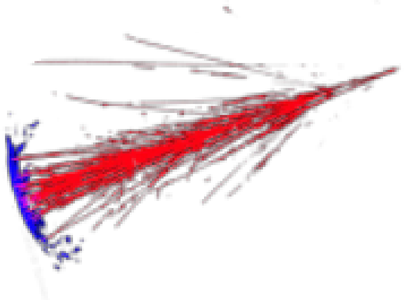

What do we know about the neutrino spectrum?

- Look for (close) double dips!
  And stay tuned on oscillations + cosmology!
- Look for all flavors!

To compare with data, we need a realistic treatment

- Detector effects
- Proper theoretical ν-ν scattering calculation
  (Scattering off the resonance is relevant!)

ivan-esteban-phys/nuSIprop

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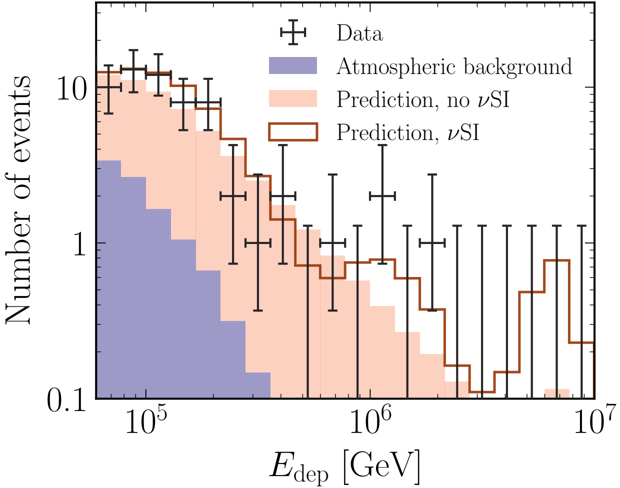
IceCube?

(HESE. Predictions generated with content in Abbasi et al, 2011.03545. We thank C. Arguelles & A. Schneider)



No νSI: $\phi \propto E^{-2.9}$

νSI: $\phi \propto E^{-2}$, $g = 0.1$, $M_\phi = 7$ MeV

Current IceCube data is not good because

- Low statistics $\Rightarrow$ fluctuations
- Small energy range $\Rightarrow$ degeneracy with unknown astrophysical neutrino flux

We need IceCube-Gen2

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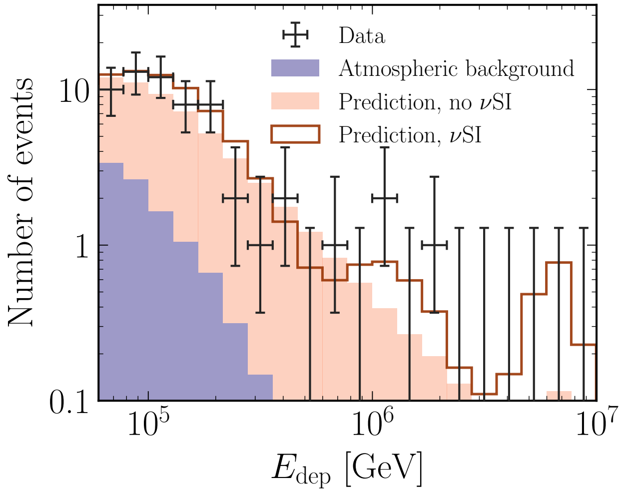

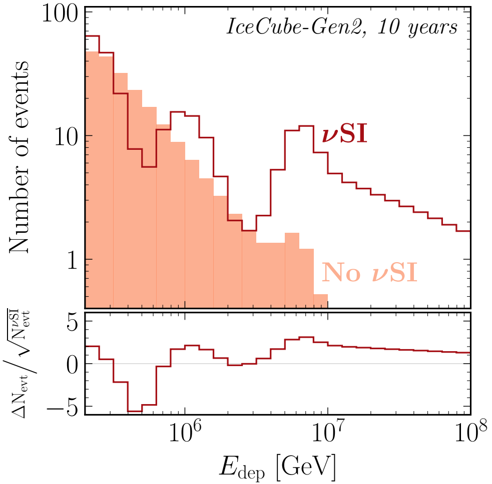

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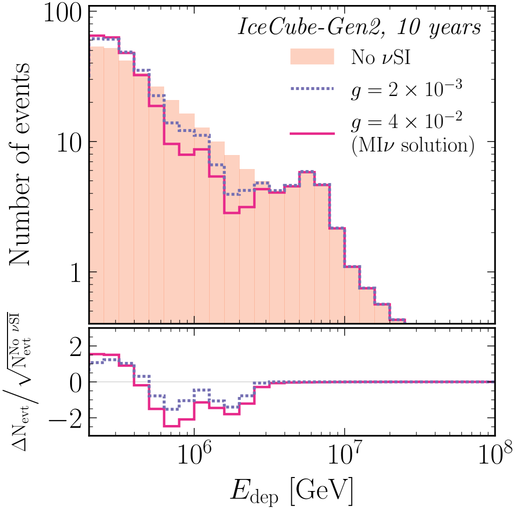
IceCube-Gen2



- For $M_\phi = 10\,\mathrm{MeV}$.
- Dashed line $\Rightarrow \sim 1$ scattering across the entire Universe!
  It will be *very challenging* to improve upon Gen2!

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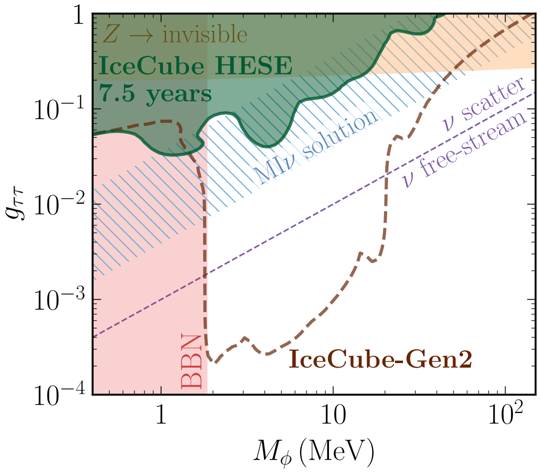
Present constraints and future sensitivity

(HESE analysis generated with content in Abbasi et al, 2011.03545. We thank C. Arguelles & A. Schneider)



$$E_\nu^{\mathrm{res}} = \frac{M_\phi^2}{2m_\nu}$$

- IceCube-Gen2 will be **very powerful**!
  Could even be sensitive to self-interactions among other flavors!
- Gen2 will exploit **the full potential** of neutrino astronomy to probe νSI.

Large couplings, short ranges

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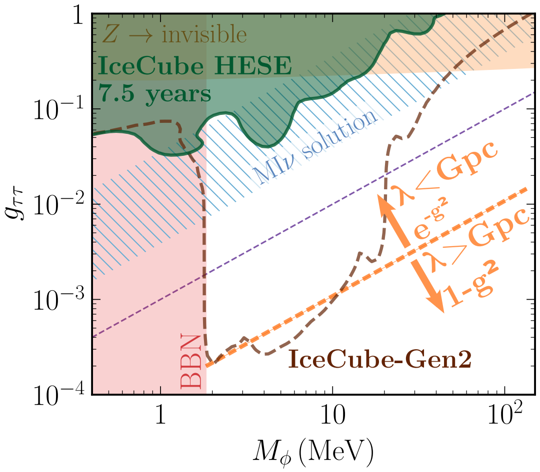

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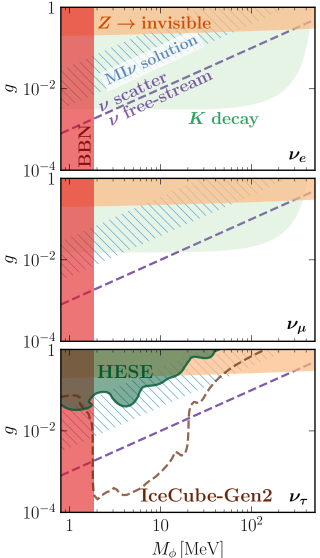
Take-home messages



1. Neutrino self-interactions are not only fundamentally interesting, **they affect our understanding of the Early Universe**. Unexplored ν_τ sector $\Rightarrow$ **opportunity for neutrino telescopes**.
2. We define a roadmap for *making decisive progress*:
   - IceCube-Gen2
   - Improved theoretical treatment
   - Realistic treatment of detection effects

   Gen2 will realize the full potential. It can also probe ν_e, ν_μ!
3. This is just the beginning: hints will be testable. Improvements in
   - Astrophysics, **point sources**, cosmology
   - Flavor
   - Ultra-High Energy neutrinos
   - . . .

   are welcome!

https://github.com/ivan-esteban-phys/nuSIprop

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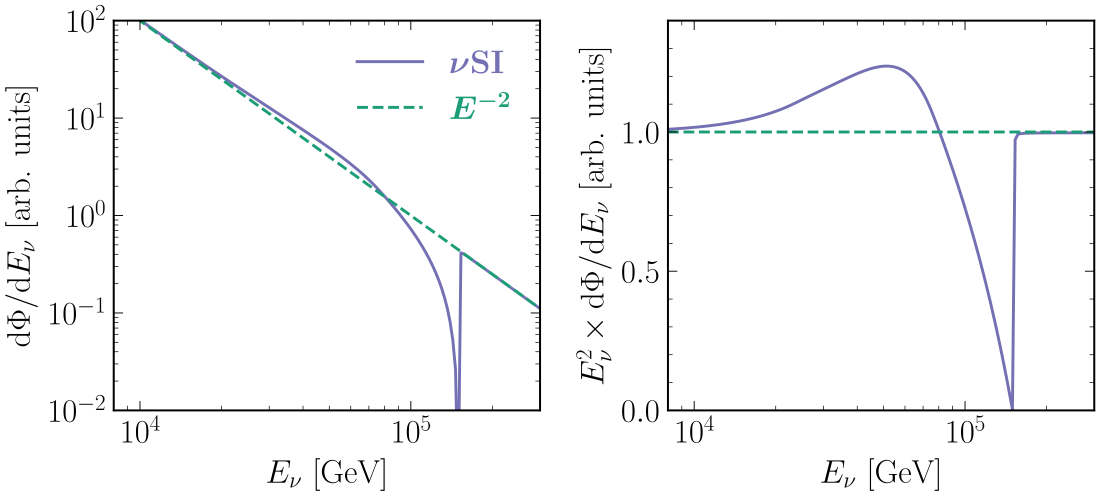
Future: point sources



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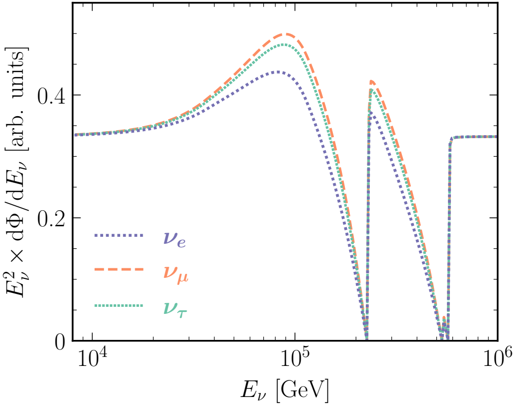
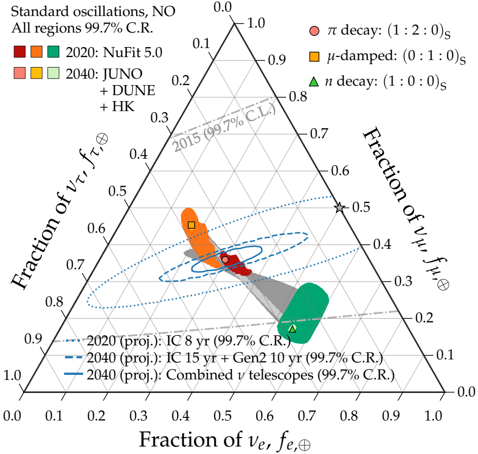
Future: flavor

Song, Li, Argüelles, Bustamante, Vincent, arXiv:2112.12893.





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Future: Ultra-High Energy neutrinos

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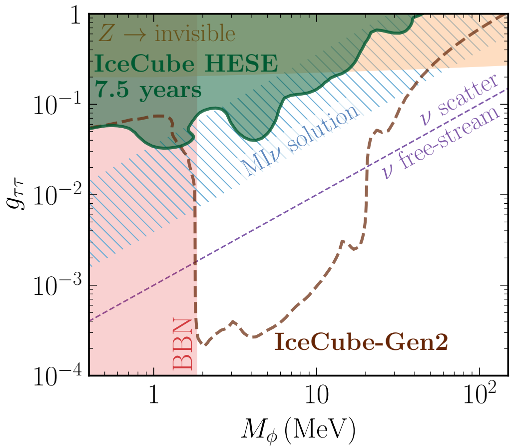

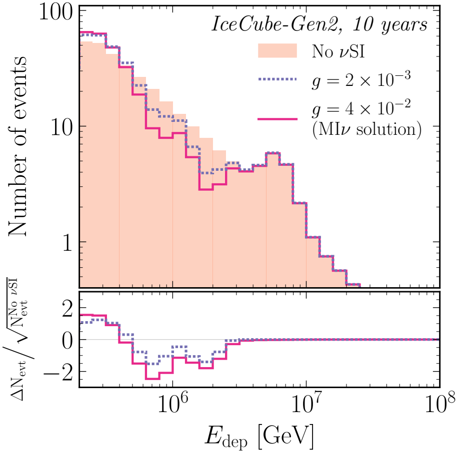

Conclusions

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- Exploring neutrino self-interactions is a good example of particle physics – astrophysics interplay:
  - Particle physics results (theory & experiment) with consequences in astrophysics.
  - Astrophysical observations can explore particle physics!

  In general, very rich physics arises.

- Long-range effects can modify neutrino mass & equation of state.
  They spoil cosmology neutrino mass measurements!

  We need the **interplay with particle physics** to get a global picture.

- Short-range effects can bias our understanding of astrophysical & cosmological environments (supernovae, precision cosmology).
  But, in turn, astrophysical neutrinos offer an independent probe.

  IceCube-Gen2 will inaugurate the era of **precision** high-energy astrophysical exploration of neutrino self-interactions!