Constraints on neutrino self-interactions by Multi-Messengers

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NEUTRINO SELF INTERACTIONS - MOTIVATION

Theoretical motivation

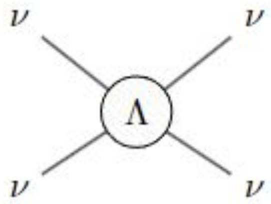
- Neutrino mass generation
- Production of dark matter in the early Universe
- CMB and LSS leave a room to the impact of NSI
  - BSM NSI can lead to significantly larger scattering rates amongst neutrinos and different time/temperature dependence
  - The presence of NSI at early times delay the epoch at which neutrinos begin to free-stream. Compared to the standard CDM model, neutrino self-interactions thus shift the CMB power spectra peaks towards smaller scales.
- Light element abundances
  - Abundance of early elements indicates that neutrinos significantly influenced the era of BBN
- Disagreement between late- and early-time measurements of today's Hubble rate H_0 and the matter power spectrum σ_8

CMB - Cosmic microwave background
LSS - large-scale structures
BBN - Big Bang nucleosynthesis

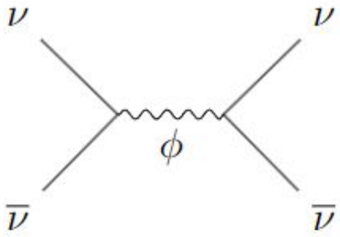
NEUTRINO SELF INTERACTIONS

$$\mathscr{L} = g_{ij}\overline{\nu}_i\gamma_\mu\nu_j\phi^\mu, \quad (i,j=e,\mu,\tau)$$

In the scenario of minimal coupling, neutrinos may couple to a massive scalar, pseudoscalar, **vector**, or axial-vector field

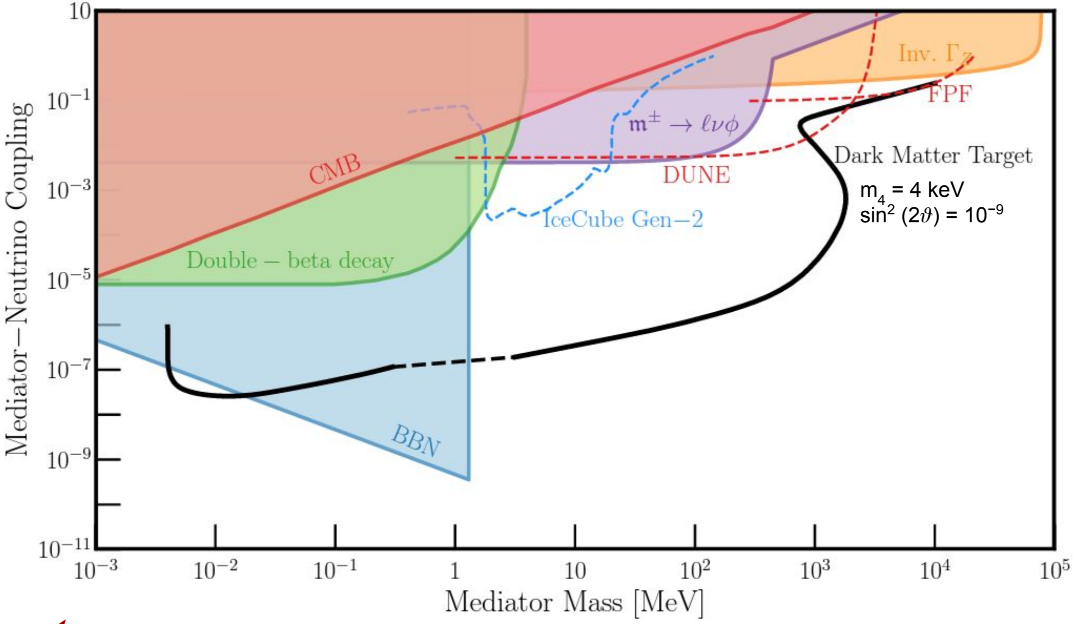


Framework: Dirac neutrinos interacting with a massive spin-one boson φ^μ through a vector coupling .
Vector boson coupling to other particles is effectively negligible.
The mediator mass M and coupling strength g, are free parameters.



How nSI can be measured?

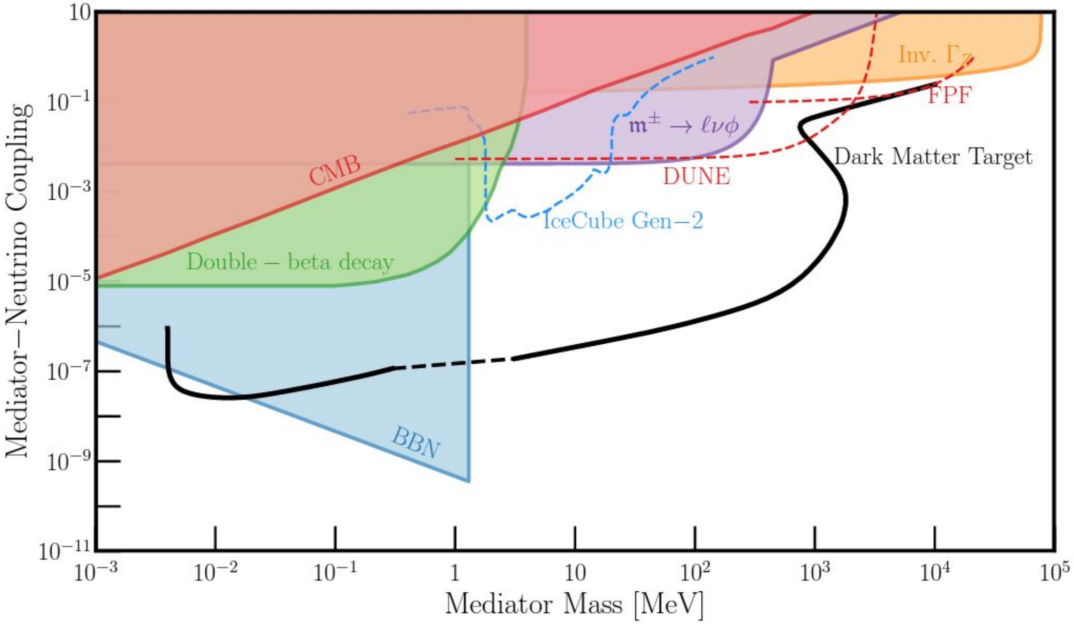
Measurements



Neutrino Self-Interactions: A White Paper - J. M. Berryman et all, 2022

- **Cosmological constraints** (eV-MeV)
  - Light elements abundance
  - Big Bang Nucleosynthesis (BBN)
  - Cosmic Microwave Background (CMB)
  - Matter distribution in the Universe
- **Laboratory bounds** come from searches for
  - neutrinoless double beta decay
  - rare meson, τ decays
  - invisible Z decays
    - $e^+e^- \longrightarrow \gamma\nu\bar{\nu}$
    - $Z \longrightarrow \nu\nu\bar{\nu}\bar{\nu}$
  - invisible Higgs decay

Measurements



★ Astrophysics

- ○ Supernovae signal: duration, composition, spectrum
- ○ Blazars, AGN

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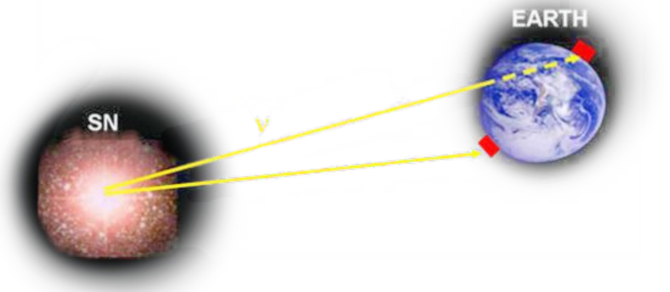
HIGH ENERGY EXTRATERRESTRIAL NEUTRINOS Scattering on Cosmic Neutrino Background (CNB)



- *Interactions of the astrophysical neutrinos with the cosmic neutrino background*

HEν must travel tremendous distances from the source to the detector on Earth. And if we assume NSI, instead of free-streaming, these HEν may scatter on the abundant CNB, which consists of relic neutrinos with very low effective temperature. Thus such a scattering will ensure a ***visible energy loss****, and* ***will remove the HE neutrino from the initial flux****. This is the way how the observation of astrophysical neutrinos can be used to constrain NSI.*

- *Average CNB density*

$n_\nu = 112\ \text{cm}^{-3}$ *per flavour*
$n_\nu \sim 340\ \text{cm}^{-3}$ *total*

$T^{eff}_{CnB} \simeq 1.7\ 10^{-4}$ eV

- *Incoming neutrino energy of electron antineutrino flux*

Blazar: $E_B \in (TeV - PeV)$
$D = 1, 3$ *Gpc*

Supernova: $E_S \sim 10\ MeV$.
$D = 55+15$ *kpc*

SOURCES

Supernova 1987

$E_S \sim 10\ MeV.$

$D = 55+15\ kpc$

NGC 1068:

$E \in (1\text{-}10)\ TeV$

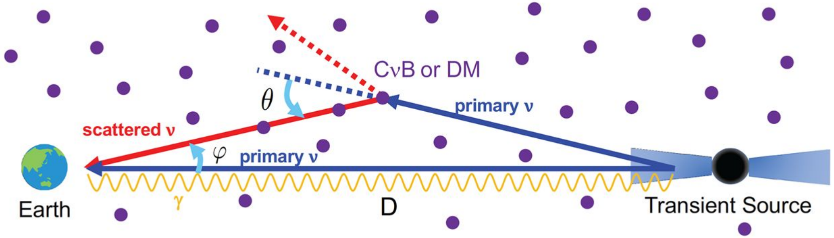
$D = 13\ Mpc$

TXS 0506+056.

$E \sim 290\ TeV$

$D > 1{,}3\ Gpc$

Detected by IceCube and Baikal-GVD



PKS 0735+178

Neutrino events were recorded by IceCube, Baikal-GVD, BUST, and KM3NeT.

$E = 171\ TeV$

The origin of high-energy astrophysical neutrinos: new results and prospects - Sergey Troitsky
Neutrino Echoes from Multimessenger Transient Sources - K. Murase Ian M. Shoemaker

MEAN FREE PATH

$$v_{Moller} = \frac{|\mathbf{v}_X - \mathbf{v}_\nu|}{|\mathbf{v}_X|}$$

In order to establish limits on the νSI coupling constant, it's enough to observe a single neutrino from the flux.
Our next step is to calculate the mean free path, which is the inverse of the interaction rate:

$$\lambda^{-1} = \int \frac{d\mathbf{p}_X}{(2\pi)^3} f(\mathbf{p}_X)\, v_{Moller}\, \sigma(s)$$

- inverse interaction rate

The detection of neutrinos from a HEν source requires that **the mean free path of neutrinos through the CνB is comparable to or greater than the distance to the source.**
So we set this condition to the mean free path to experience at least one interaction

$$D\lambda^{-1} \leq 1$$

where D is the distance to the source.

This results in limits to the coupling of neutrinos with themselves and with other particles.

$$g \leq \left(\frac{\lambda|_{g \to 1}}{D} \right)^{1/4}$$

TWO BACKGROUND REGIMES

Non-relativistic:

$$\lambda_{NR}^{-1} = n_X\,\sigma(s) \qquad n_X = \frac{1}{4\pi^2}\int_0^\infty dE_X E_X^2 f(E_X)$$

$$\frac{|p_X|}{E_X} \to 0, \quad s \to m_X^2 + 2Em_X$$

Ultra relativistic: ★

$$\lambda_{UR}^{-1} = \frac{\sqrt{2}}{4\pi^2}\int_0^\infty dE_X E_X^2\, f(E_X) \int dz \sqrt{1-z}\,\sigma(z, E_X)$$

$$\frac{|p_X|}{E_X} \to 1, \quad s \to 2EE_X(1-z),$$

MASS REGIMES

Heavy massive mediator limit

$$\sigma(s) = g^4\,\frac{as}{M^4}$$

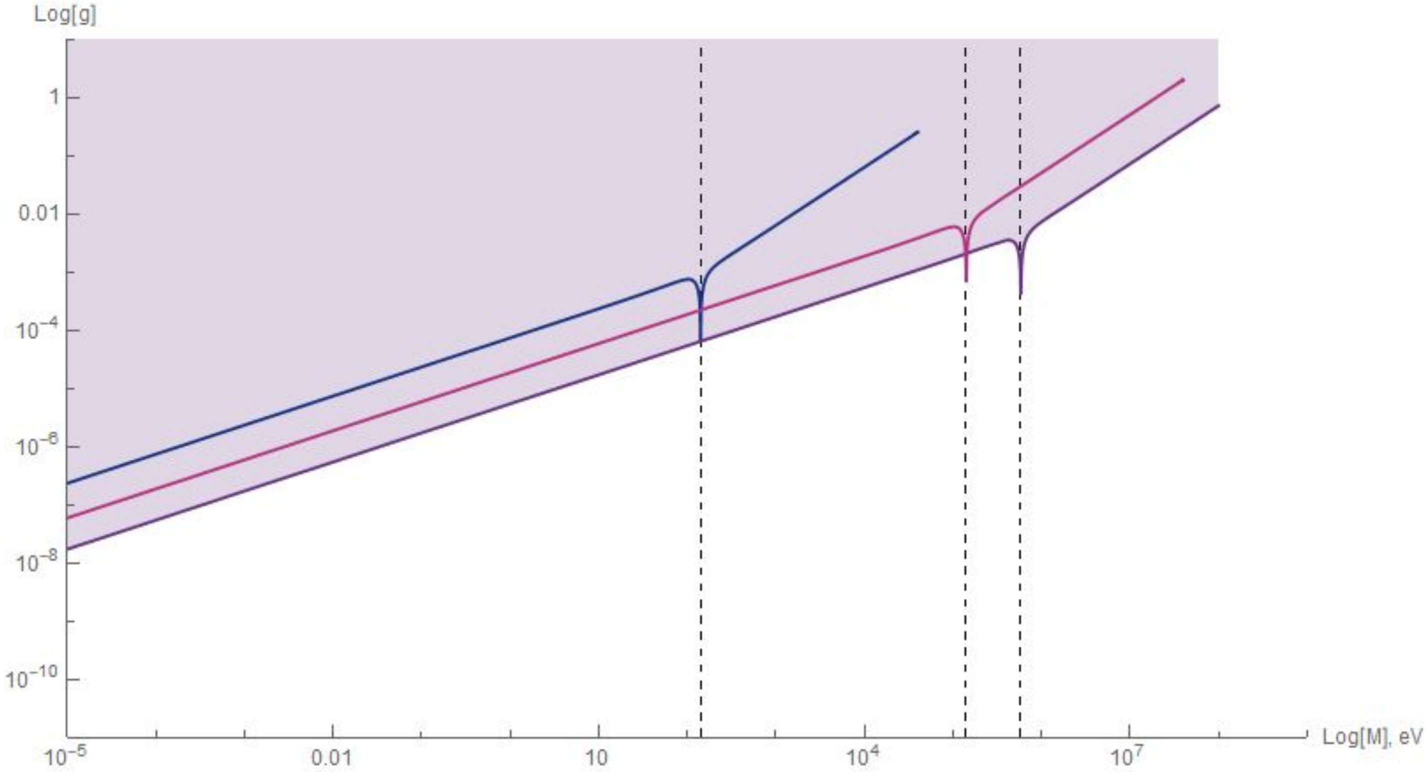
Full mass dependence ★

Massless mediator limit

$$\sigma(s) = g^4\,\frac{a}{s}$$

NON-RELATIVISTIC CONSTRAINTS ON COUPLING CONSTANT FROM SN & B & AGN

$$g \leq \left(\frac{\lambda|_{g\to 1}}{D} \right)^{1/4}$$



No angle cut-off for scattering to 0 and π

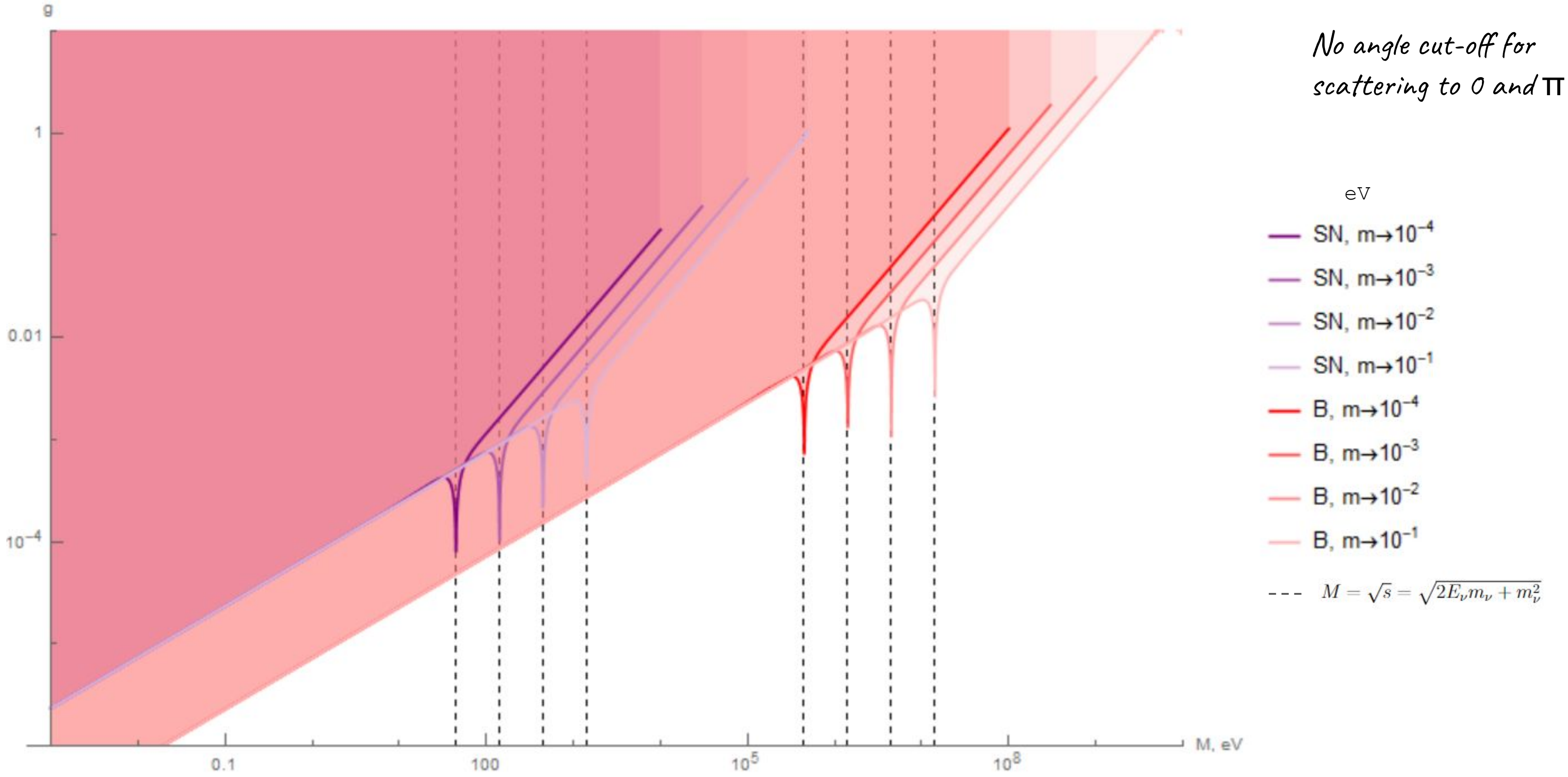
m -> 10^{-3}

--- $M = \sqrt{s} = \sqrt{2E_\nu m_\nu + m_\nu^2}$

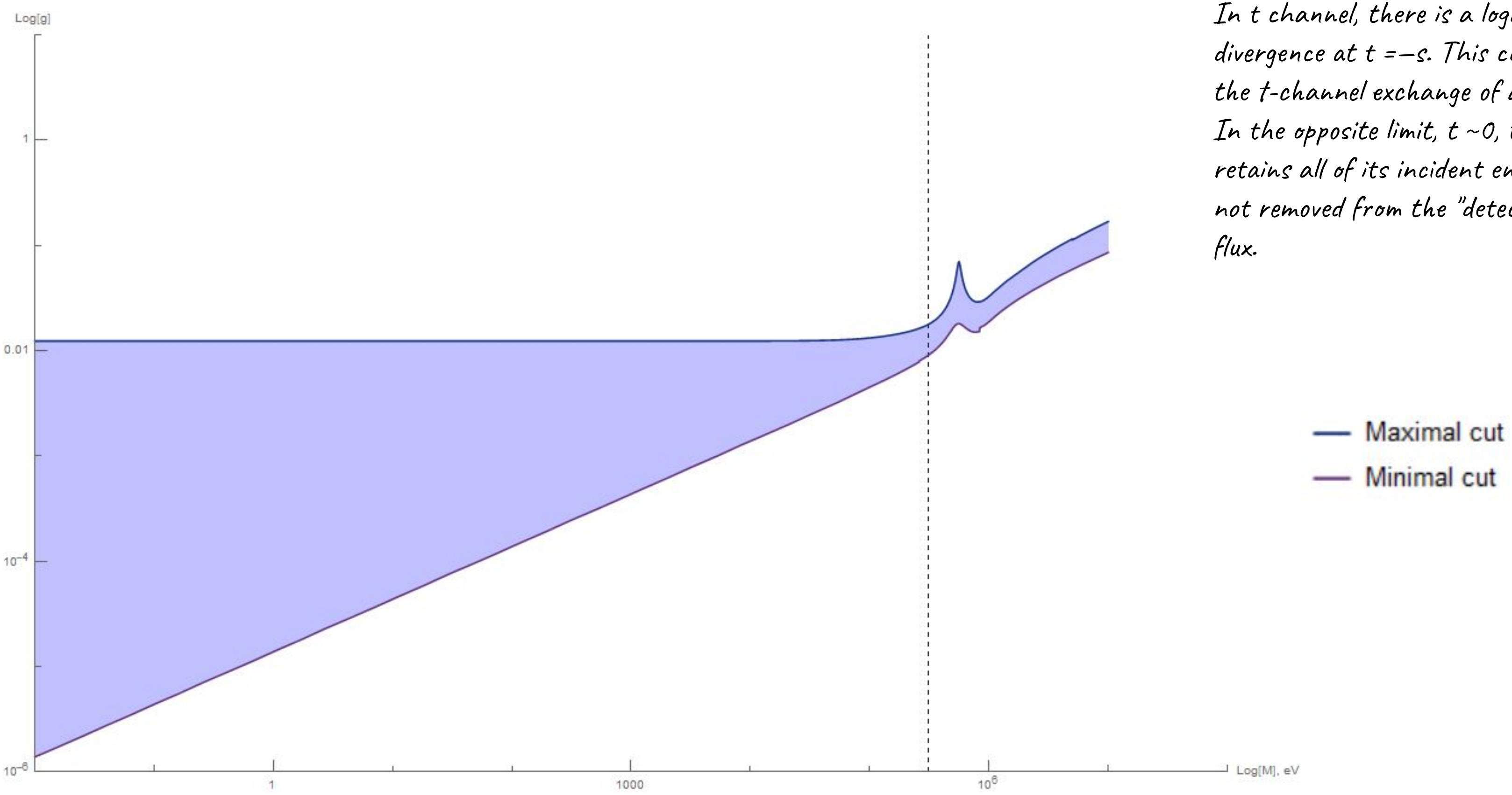
NON-RELATIVISTIC CONSTRAINTS ON COUPLING CONSTANT FROM SN & B: NEUTRINO MASS DEPENDENCE

$$g = \left(\frac{\lambda_{MFP}}{\lambda_{SN}}\right)^{1/4}$$

No angle cut-off for scattering to 0 and π

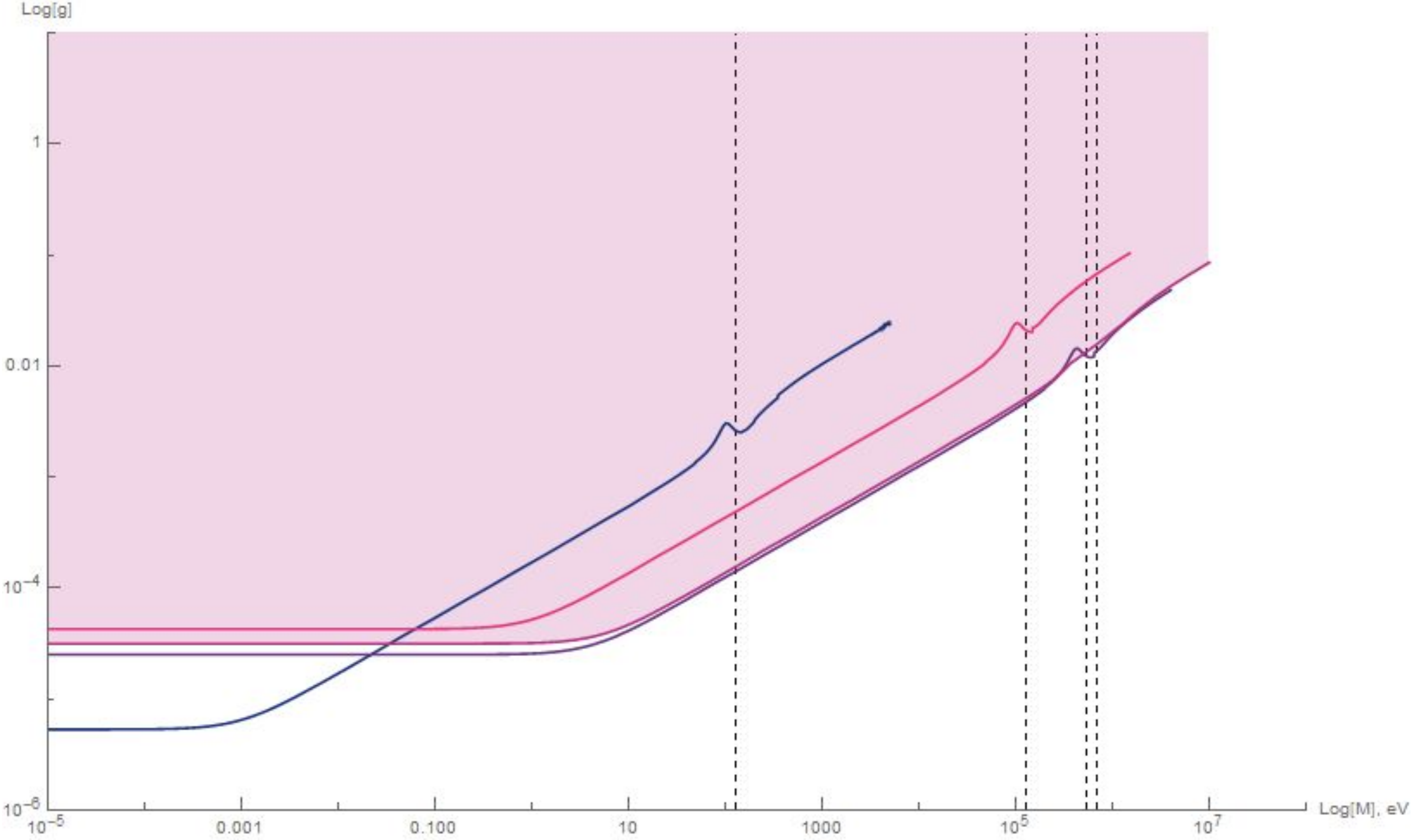


t-channel cut parameter region, Blazar



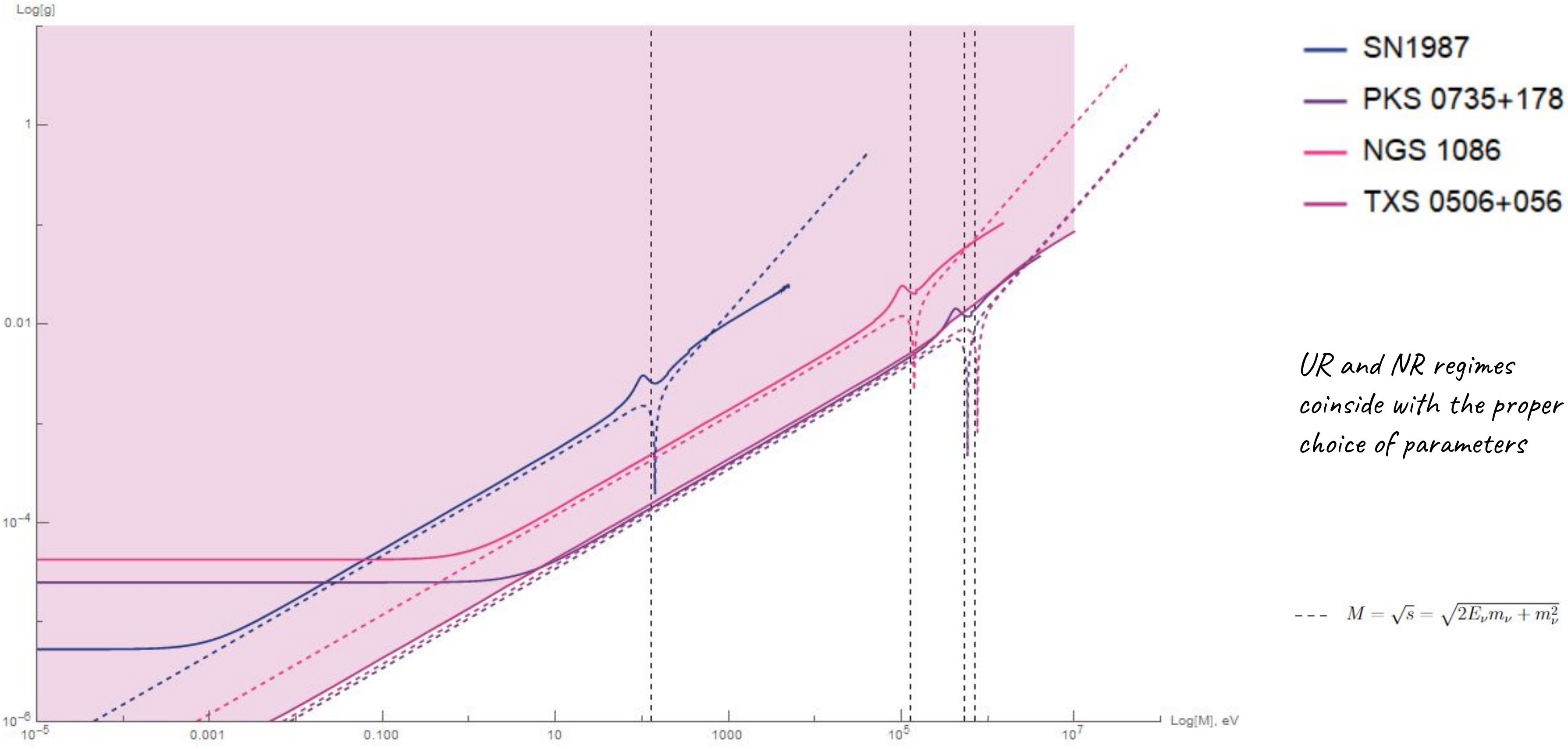
In t channel, there is a logarithmic divergence at t =−s. This corresponds to the t-channel exchange of a massless ν. In the opposite limit, t ~0, the neutrino retains all of its incident energy, and is not removed from the "detectable" flux.

ULTRA-RELATIVISTIC CONSTRAINTS ON COUPLING CONSTANT FROM SN & B & AGN



- Physical cut-off $\varepsilon \to 10^{-10}$
- $m \longrightarrow 0$
- Averaged angle between incident neutrino and background neutrino
- CnuB distribution is reduced to Maxwell-Botzmann

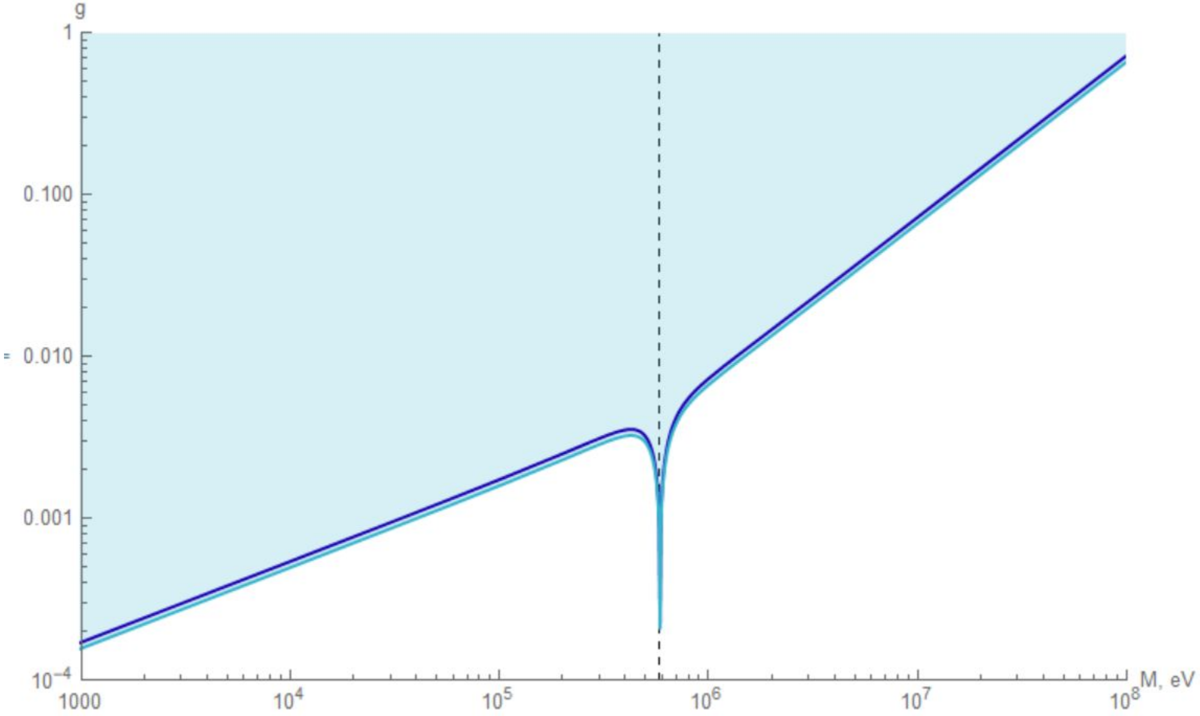
UR+NR CONSTRAINTS ON COUPLING CONSTANT



UR and NR regimes coinside with the proper choice of parameters

$$--- \quad M = \sqrt{s} = \sqrt{2E_\nu m_\nu + m_\nu^2}$$

BLAZAR WITH UNCERTAIN DISTANCE



PKS 0735+178

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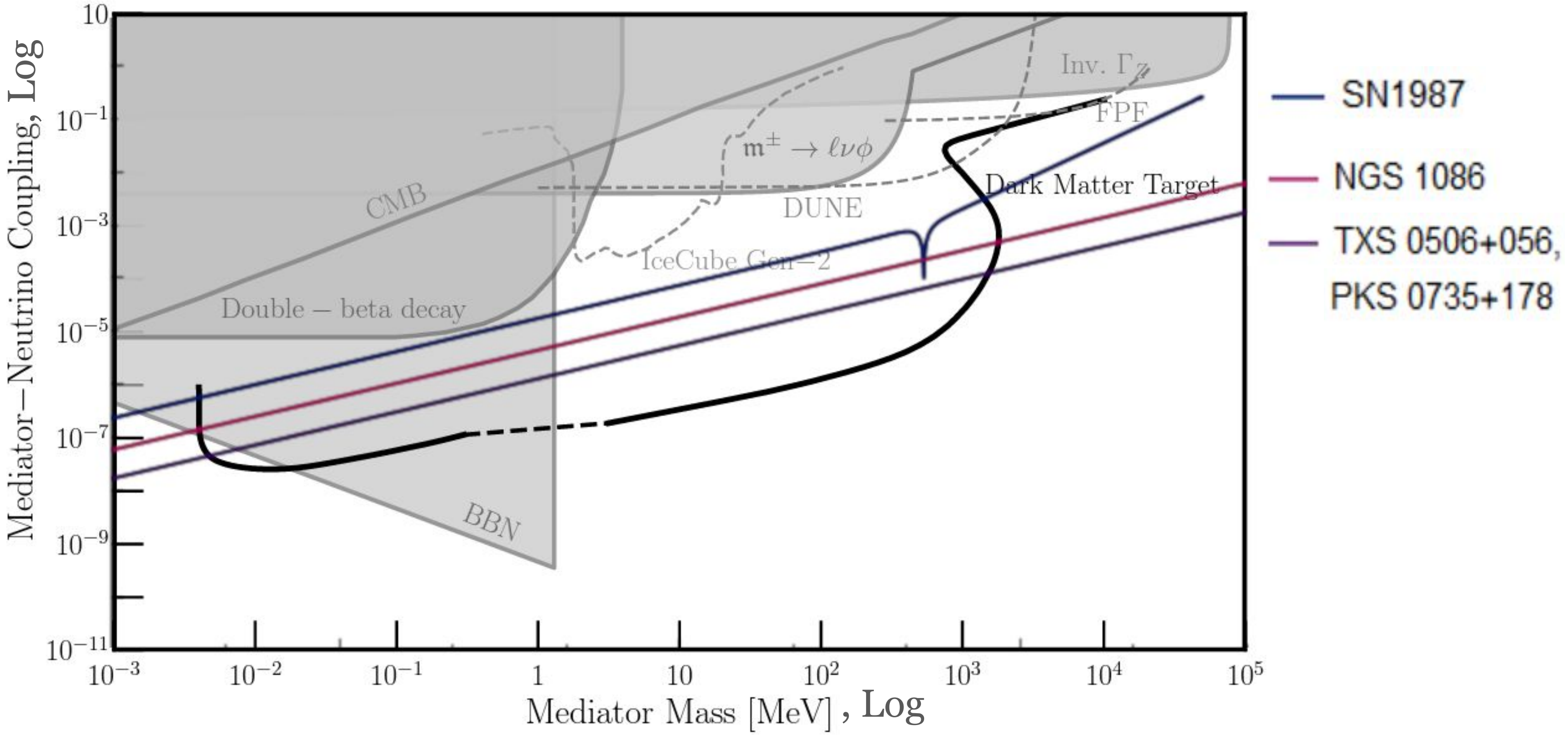
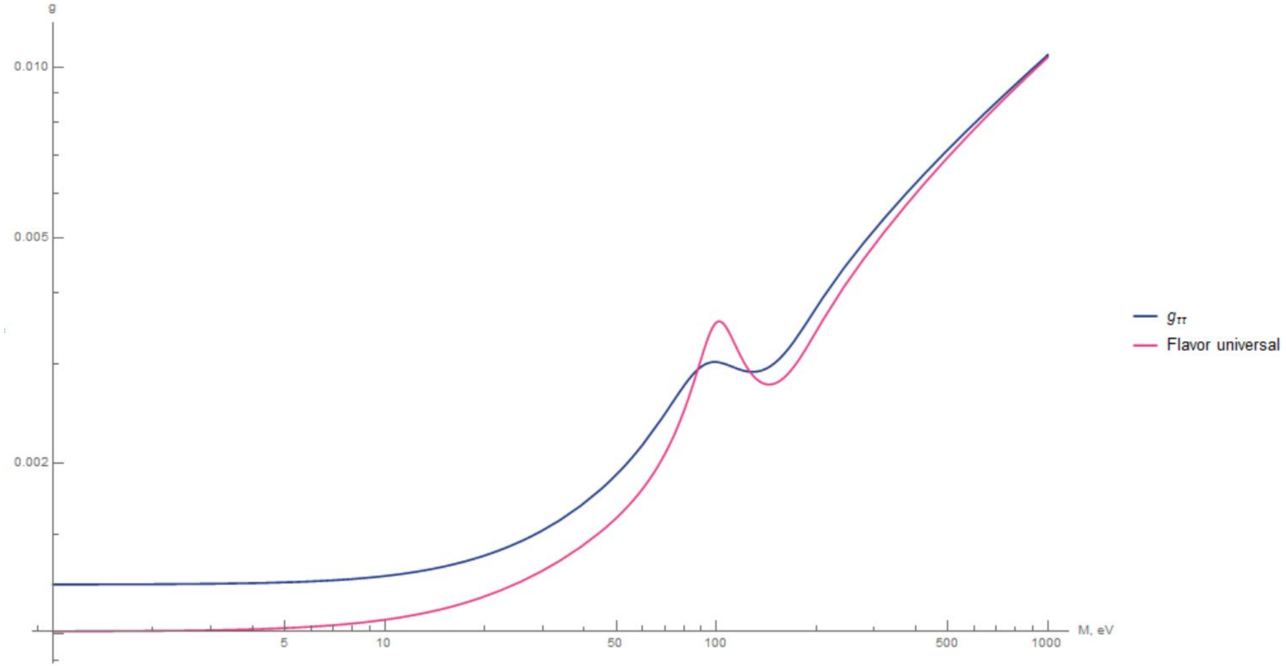
E = 171 TeV

Constraints on NSI coupling constant from SN and B, AGN



flavor Non universal interactions: UR coupling constant for Supernova



RESULTS

In this, work we investigated a particular model of NSI with **Dirac neutrinos** and massive vector boson as NSI mediator

We obtained

- ★ Analytical formula for UR (and NR) CnB with full mass dependence
- ★ Constraints on NSI coupling constant by HE neutrinos propagating through the CnB, from SN, Blazars and AGN neutrinos scattering on NR and UR CnB
- ★ Constraints on flavour-non universal NSI

The results are in consistency with the literature, and offer

- ❖ **more precise analysis on the angle cut-off parameter** for the given model,

and include

- ❖ **intermediate mass region of the NSI mediator** to the constraints on coupling constant.

Literature

[1] Results on Neutrino Non-Standard Interactions with KM3NeT/ORCA6 and ANTARES - *Alfonso Lazo Pedrajas on behalf of the KM3NeT and ANTARES collaborations*
[2] Neutrino Self-Interactions: A White Paper - *Jerey M. Berryman et all*
[3] Gauged Lμ –Lτ Symmetry at the Electroweak Scale - *Julian Heeck, Werner Rodejohann*
[4] Sterile Neutrinos -*Basudeb Dasgupta, Joachim Kopp*
[5] Testing exotic neutrino-neutrino interactions with AGN neutrinos - *Petteri Kera¨nen*
[6] Shedding light on neutrino self-interactions with solar antineutrino searches - *Quan-feng Wu and Xun-Jie Xu*
[7] Diffuse supernova neutrino background *Anna M. Suliga*
[10] Constraining the Self-Interacting Neutrino Interpretation of the Hubble Tension - *Nikita Blinov,∗ Kevin J. Kelly, Gordan Krnjaic, and Samuel D. McDermott 2019*
[11] Toward Powerful Probes of Neutrino Self-Interactions in Supernovae *Po-Wen Chang, Ivan Esteban, John F. Beacom, Todd A. Thompson, and Christopher M. Hirata 2022*
[12] A multi-messenger study of the blazar PKS 0735+178: a new major neutrino source candidate
N. Sahakyan, P. Giommi, P. Padovani, M. Petropoulou, D. Bégué, B. Boccardi, S. Gasparyan
[13] Looking for cosmic neutrino background - C. Yanagisawa
[14] Massive Fermi Gas in the Expanding Universe - A. Trautner
[15] Multimessenger Astronomy and New Neutrino Physics - K. J. Kelly, P. A. N. Machado,
[16] The origin of high-energy astrophysical neutrinos: new results and prospects - Sergey Troitsky
[17] Neutrino Echoes from Multimessenger Transient Sources - K. Murase Ian M. Shoemaker

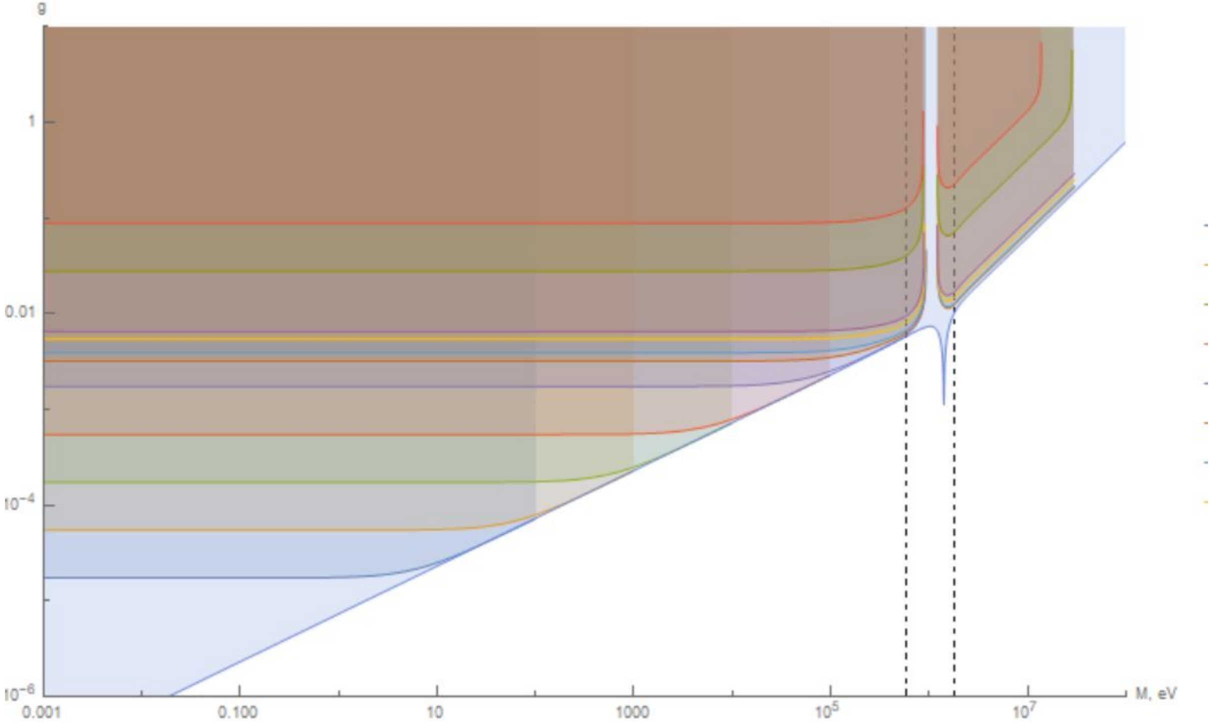
Thank you for attention!

ASSUMPTIONS

- **Mediator mass:** Full dependence over the relevant interval without splitting into the limits
- **Background regime:** both NR and UR
- We average over angle between incident neutrino and background neutrino
- We adopt CVB-spectrum with temperature 10^{-4} eV, however for calculations, we reduce it to the Maxwell-Boltzmann distribution.
- **Angle cut-off** : $s\,(1-e) < t < -es$
- We assume $e - \mu - T$ universality in the non-standard V − V interaction

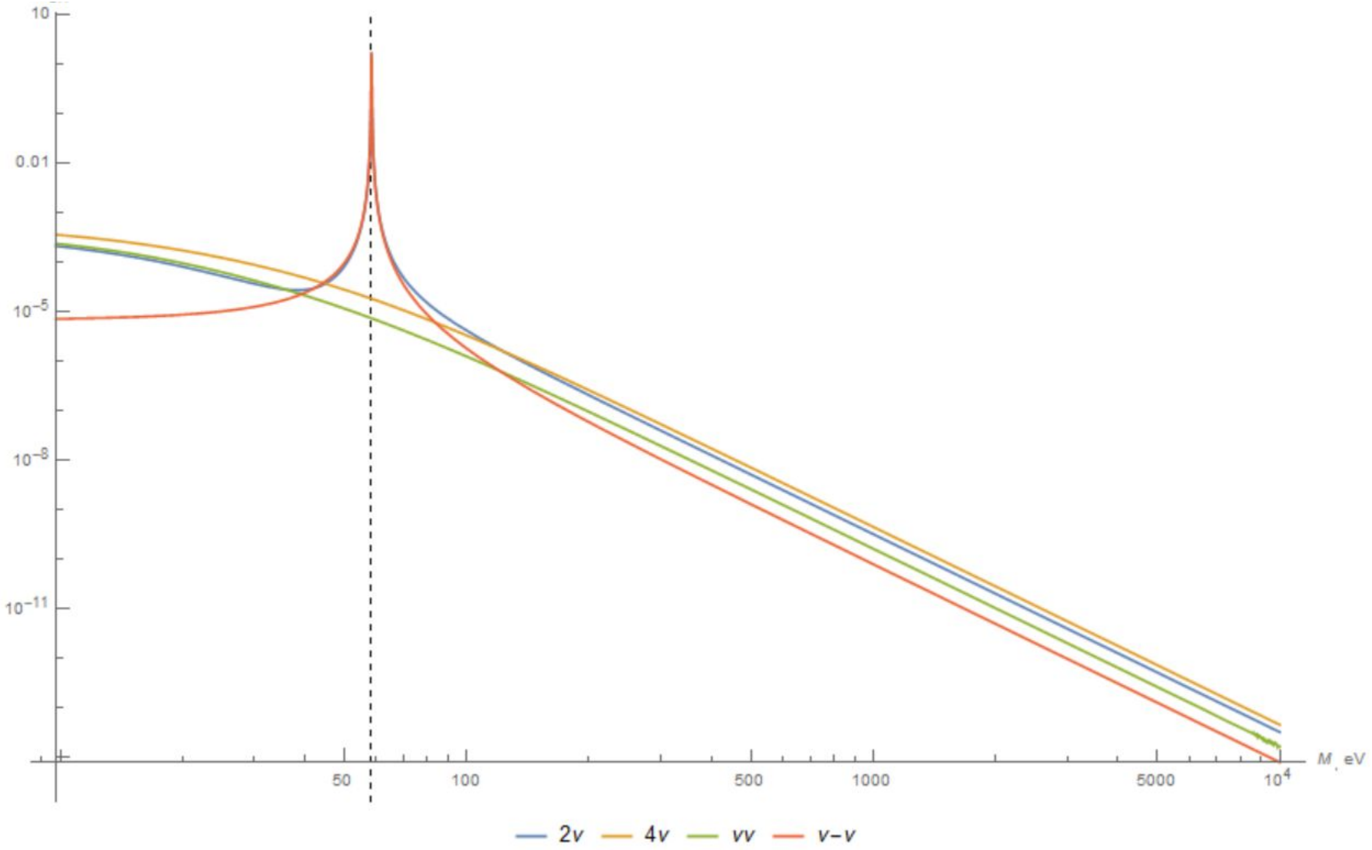
Backup Slides

NR + UR COUPLING CONSTANT FOR BLAZAR



In the region of the small mediator mass, the topic of angle cut-off in the literature is ignored and usually excluded, though the parameter is arbitrary. More accurate approach excludes this region.

Cross-section vs. mediator mass, Log

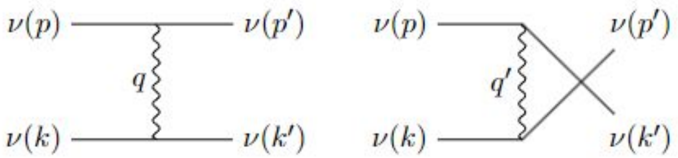


ANGLE CUT-OFF

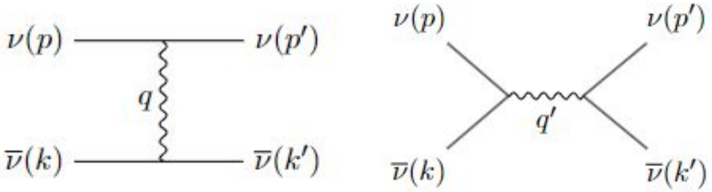
Angle cut-off for scattering to 0 and π. This corresponds to the t-channel exchange of a massless ν. It occurs whenever the final X carries off all of the initial neutrino energy. In the opposite limit, $t \sim 0$, the neutrino retains all of its incident energy, and is not removed from the "detectable" flux. The relevant factor is not the total cross section, but the cross section which describes the transport of energy of the incident neutrino by scattering with low-energy particles. This requires a significant energy loss by the initial neutrino, some substantial fraction of s. We can calculate the relevant fraction of the total cross section by taking the limits of integration to be $-s(1-e)<t< -es$

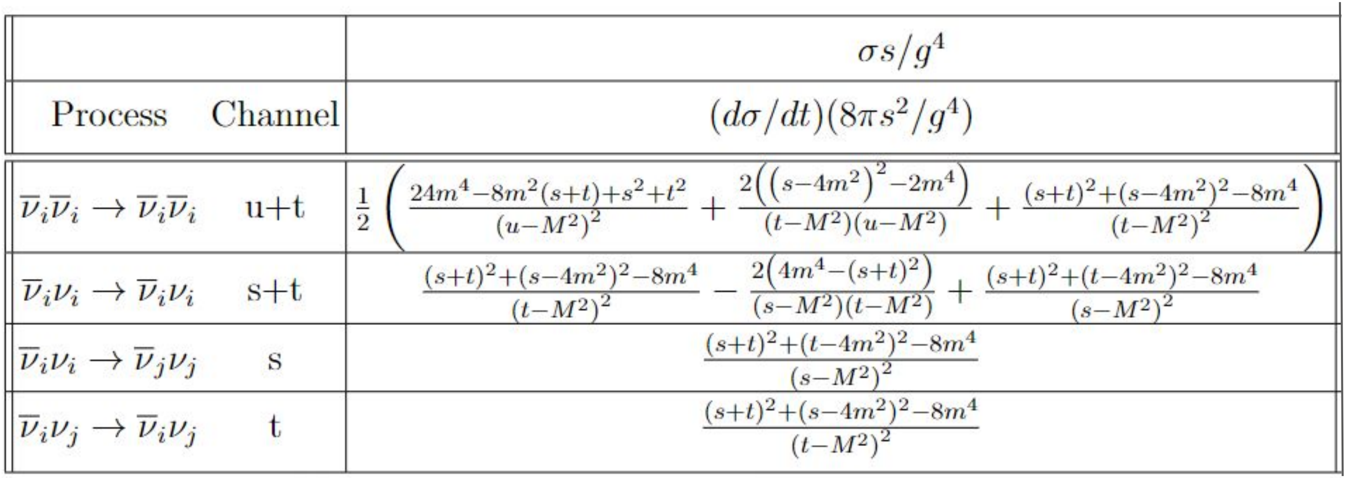
PROCESSES CONTRIBUTING TO THE HEν SCATTERING ON CνB

t+u channel:



t+s channel:

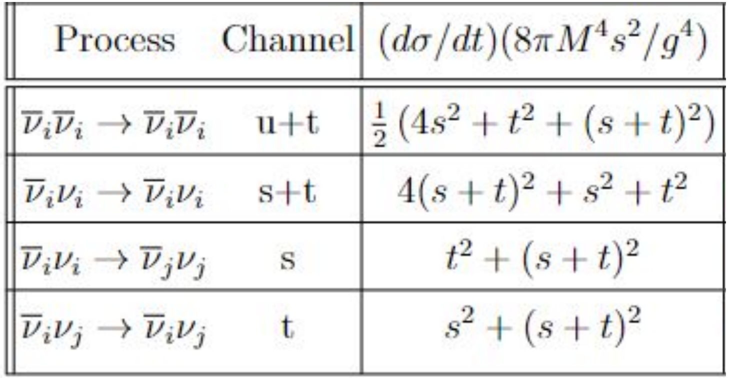




		$\sigma s/g^4$
Process	Channel	$(d\sigma/dt)(8\pi s^2/g^4)$
$\overline{\nu}_i\overline{\nu}_i \to \overline{\nu}_i\overline{\nu}_i$	u+t	$\frac{1}{2}\left(\frac{24m^4-8m^2(s+t)+s^2+t^2}{(u-M^2)^2}+\frac{2\left(\left(s-4m^2\right)^2-2m^4\right)}{(t-M^2)(u-M^2)}+\frac{(s+t)^2+(s-4m^2)^2-8m^4}{(t-M^2)^2}\right)$
$\overline{\nu}_i\nu_i \to \overline{\nu}_i\nu_i$	s+t	$\frac{(s+t)^2+(s-4m^2)^2-8m^4}{(t-M^2)^2}-\frac{2\left(4m^4-(s+t)^2\right)}{(s-M^2)(t-M^2)}+\frac{(s+t)^2+(t-4m^2)^2-8m^4}{(s-M^2)^2}$
$\overline{\nu}_i\nu_i \to \overline{\nu}_j\nu_j$	s	$\frac{(s+t)^2+(t-4m^2)^2-8m^4}{(s-M^2)^2}$
$\overline{\nu}_i\nu_j \to \overline{\nu}_i\nu_j$	t	$\frac{(s+t)^2+(s-4m^2)^2-8m^4}{(t-M^2)^2}$

ASYMPTOTIC LIMITS

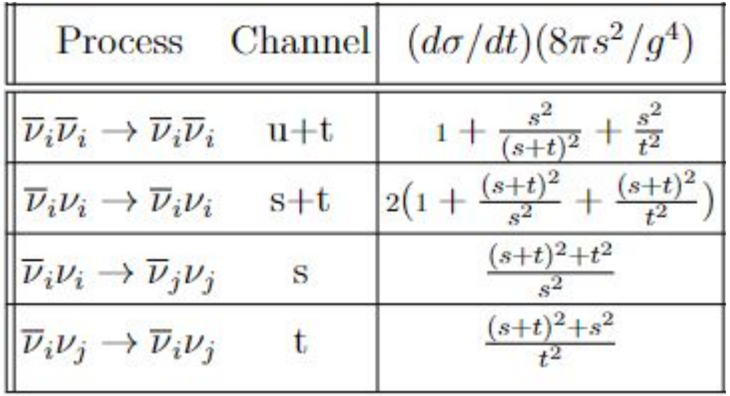
Heavy massive mediator limit



Process	Channel	$(d\sigma/dt)(8\pi M^4 s^2/g^4)$
$\overline{\nu}_i\overline{\nu}_i \to \overline{\nu}_i\overline{\nu}_i$	u+t	$\frac{1}{2}(4s^2+t^2+(s+t)^2)$
$\overline{\nu}_i\nu_i \to \overline{\nu}_i\nu_i$	s+t	$4(s+t)^2+s^2+t^2$
$\overline{\nu}_i\nu_i \to \overline{\nu}_j\nu_j$	s	$t^2+(s+t)^2$
$\overline{\nu}_i\nu_j \to \overline{\nu}_i\nu_j$	t	$s^2+(s+t)^2$

$$\sigma(s) = g^4\,\frac{as}{M^4}$$

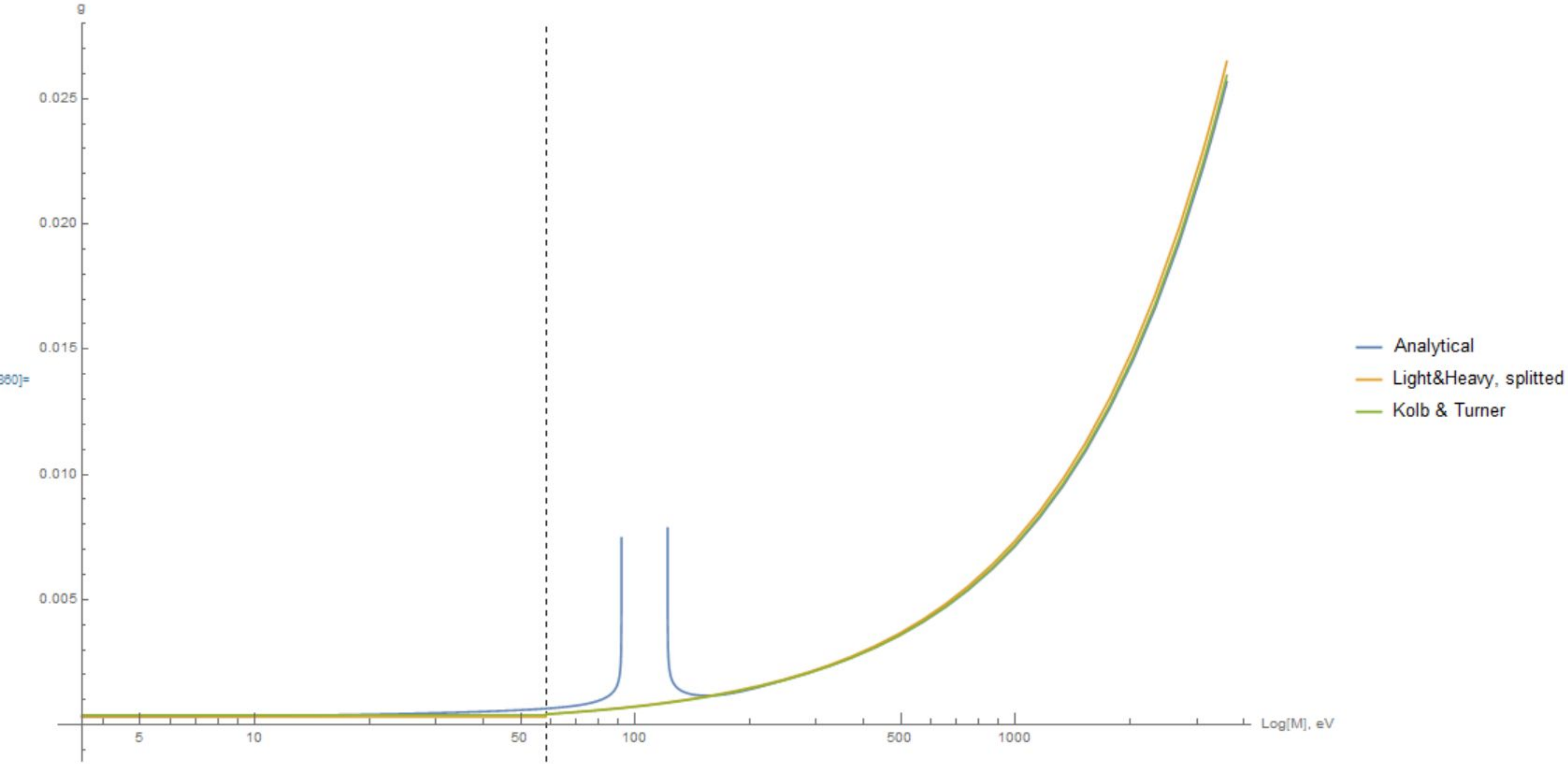
Massless mediator limit



Process	Channel	$(d\sigma/dt)(8\pi s^2/g^4)$
$\overline{\nu}_i\overline{\nu}_i \to \overline{\nu}_i\overline{\nu}_i$	u+t	$1+\frac{s^2}{(s+t)^2}+\frac{s^2}{t^2}$
$\overline{\nu}_i\nu_i \to \overline{\nu}_i\nu_i$	s+t	$2(1+\frac{(s+t)^2}{s^2}+\frac{(s+t)^2}{t^2})$
$\overline{\nu}_i\nu_i \to \overline{\nu}_j\nu_j$	s	$\frac{(s+t)^2+t^2}{s^2}$
$\overline{\nu}_i\nu_j \to \overline{\nu}_i\nu_j$	t	$\frac{(s+t)^2+s^2}{t^2}$

$$\sigma(s) = g^4\,\frac{a}{s}$$

$$d\sigma = d\sigma_{4\nu} + d\sigma_{2\nu} + 2d\sigma_{\overline{\nu}\nu} + 4d\sigma_{\overline{\nu}_i\nu_j}$$



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5
10
50
100
500
1000
Log[M], eV
Analytical
Light&Heavy, splitted
Kolb & Turner