Constraints on neutrino self-interactions by Multi-Messengers

Maria Petropavlova

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Charles University

Andreas Trautner

Max-Planck-Institut für Kernphysik

Adam Smetana

Institute of Experimental and AppliED Physics
Czech Technical University in Prague

WHAT IS SO INTERESTING ABOUT NSI?

NEUTRINO SELF INTERACTIONS - MOTIVATION

What allows us to consider NSI?

- CMB and LSS leave a room to the impact of NSI
- Abundance of early elements indicates that neutrinos significantly influenced the era of Big Bang nucleosynthesis
- NSI could alter the typical free-streaming behavior of neutrinos during the radiation-dominated period after their weak decoupling

Why we are interested in NSI?

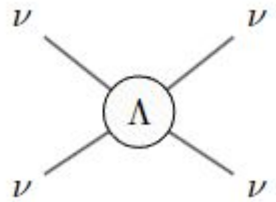
- NSI potentially can resolve modern cosmology tensions in measurements of today's Hubble rate H_0 and the matter power spectrum σ_8,
- potentially can explain anomalies between different neutrino oscillation experiments

CMB - Cosmic microwave background
LSS - large-scale structures

Okay, so how do you introduce NSI?

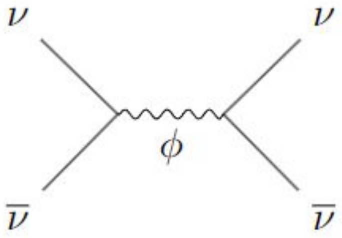
Neutrino Self interactions

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



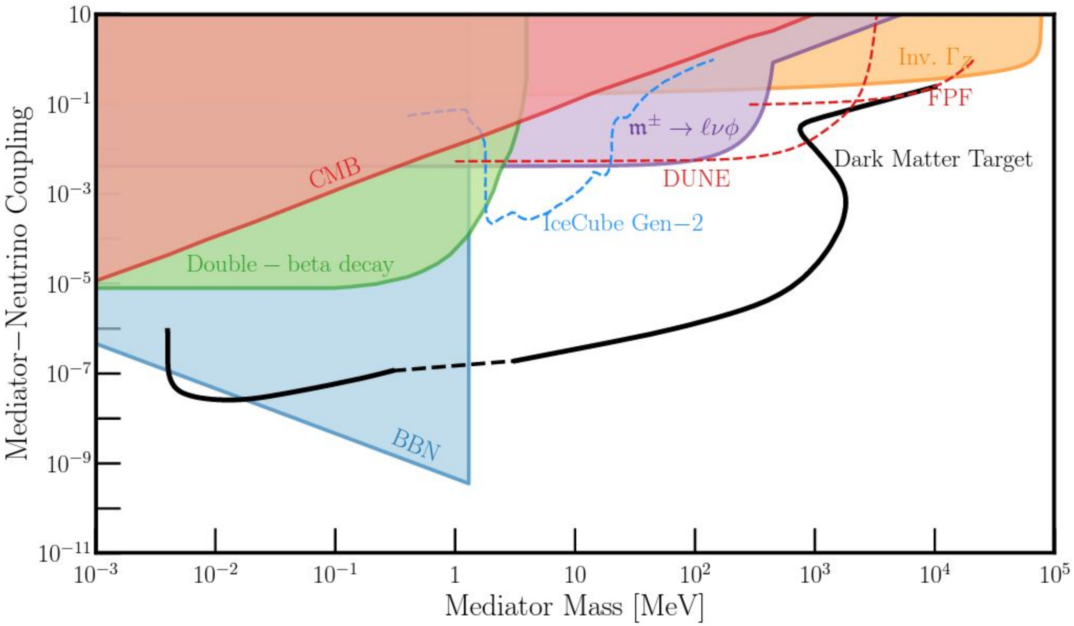
Framework: Dirac neutrinos interacting with a massive spin-one boson φ^μ through a vector coupling .
Vector boson coupling to other particles is effectively negligible.
The mediator mass M and coupling strength g, are free parameters.

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



But how do we measure such interactions?

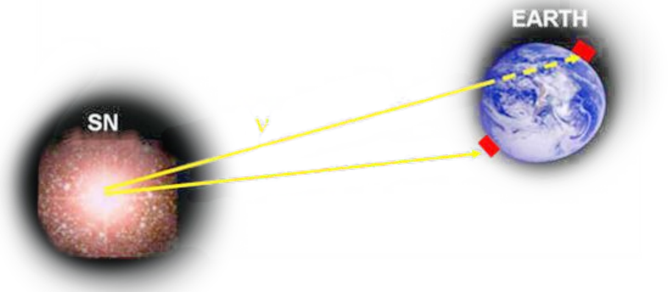
Measurements



- ★ **Cosmological constraints**
  - ○ Big Bang Nucleosynthesis (BBN) and Cosmic Microwave Background (CMB)
- ★ **Laboratory bounds** come from searches for
  - ○ neutrinoless double beta decay
  - ○ rare meson, T and Z→ VVV ¯V ¯ decays;

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

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*

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

- *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

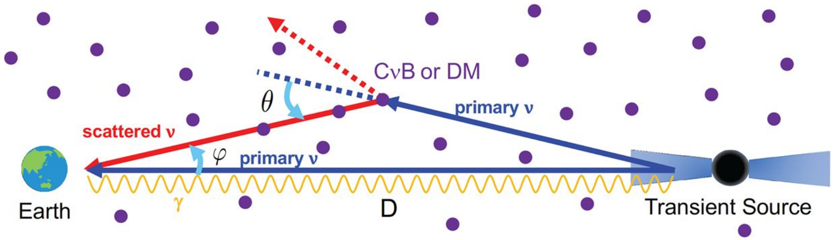
$D > 1{,}3$ Gpc

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

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

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

- 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

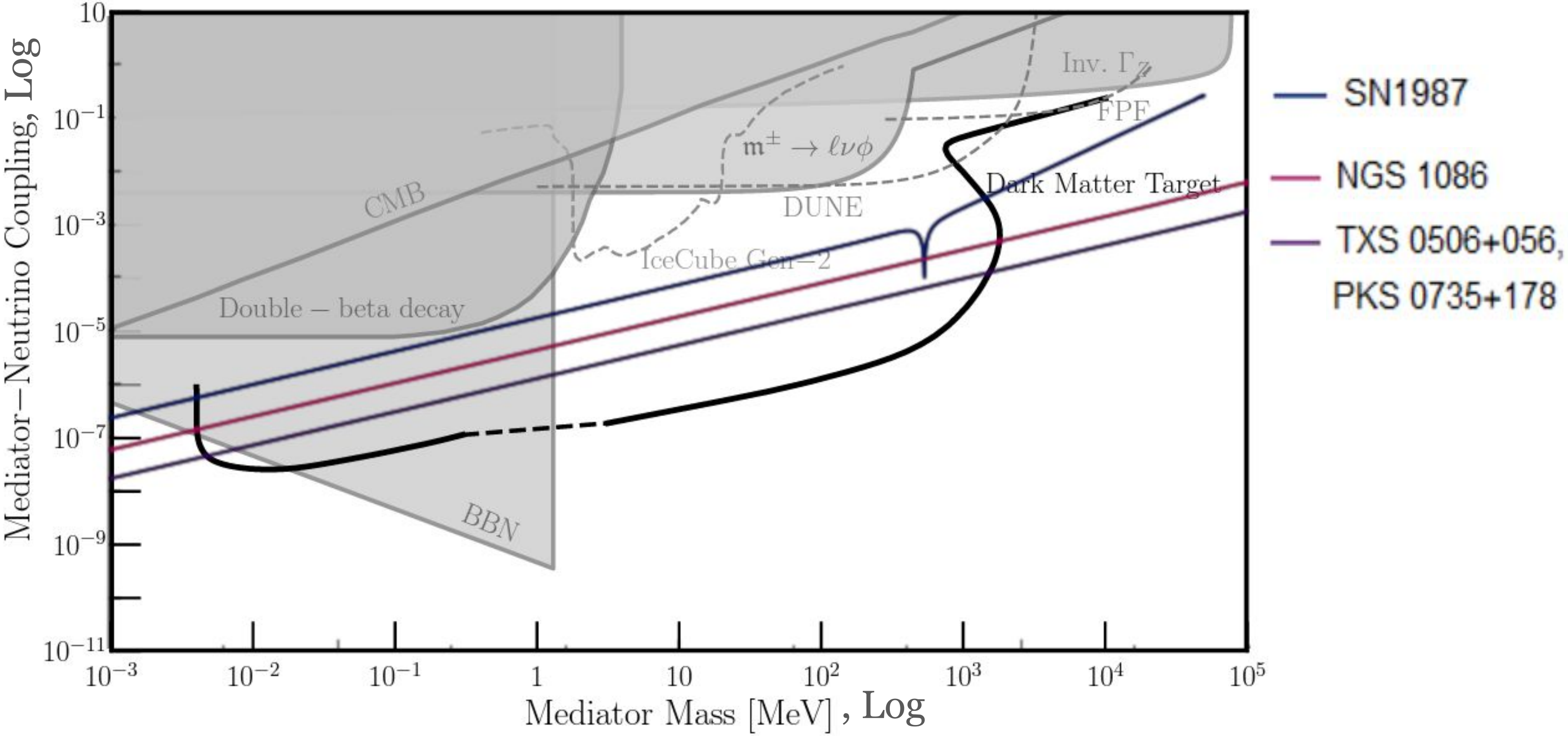
$$\sigma(s) = g^4\, \frac{as}{M^4}$$

Full mass dependence ★

Massless mediator limit

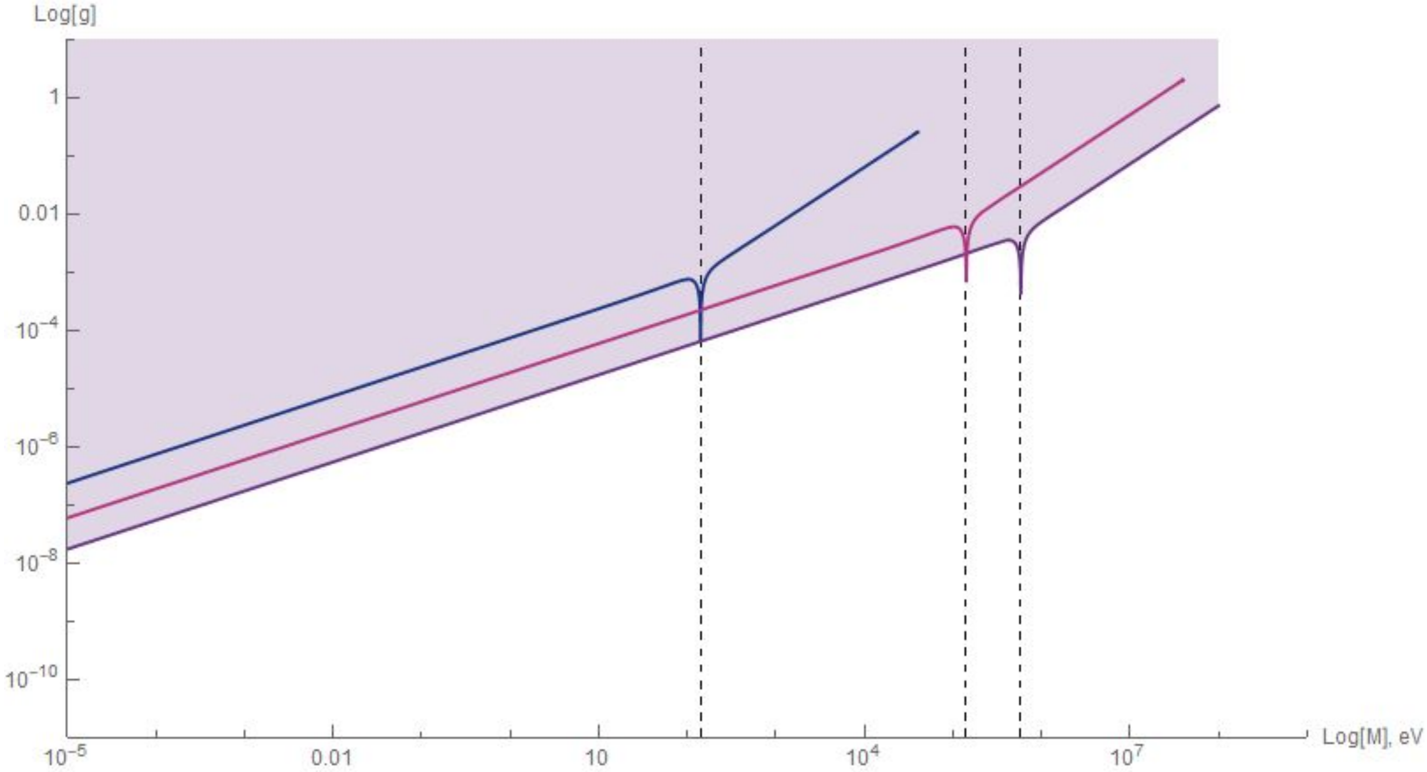
$$\sigma(s) = g^4\, \frac{a}{s}$$

Constraints on NSI coupling constant from SN and B, AGN



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

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



— SN1987

— NGS 1086

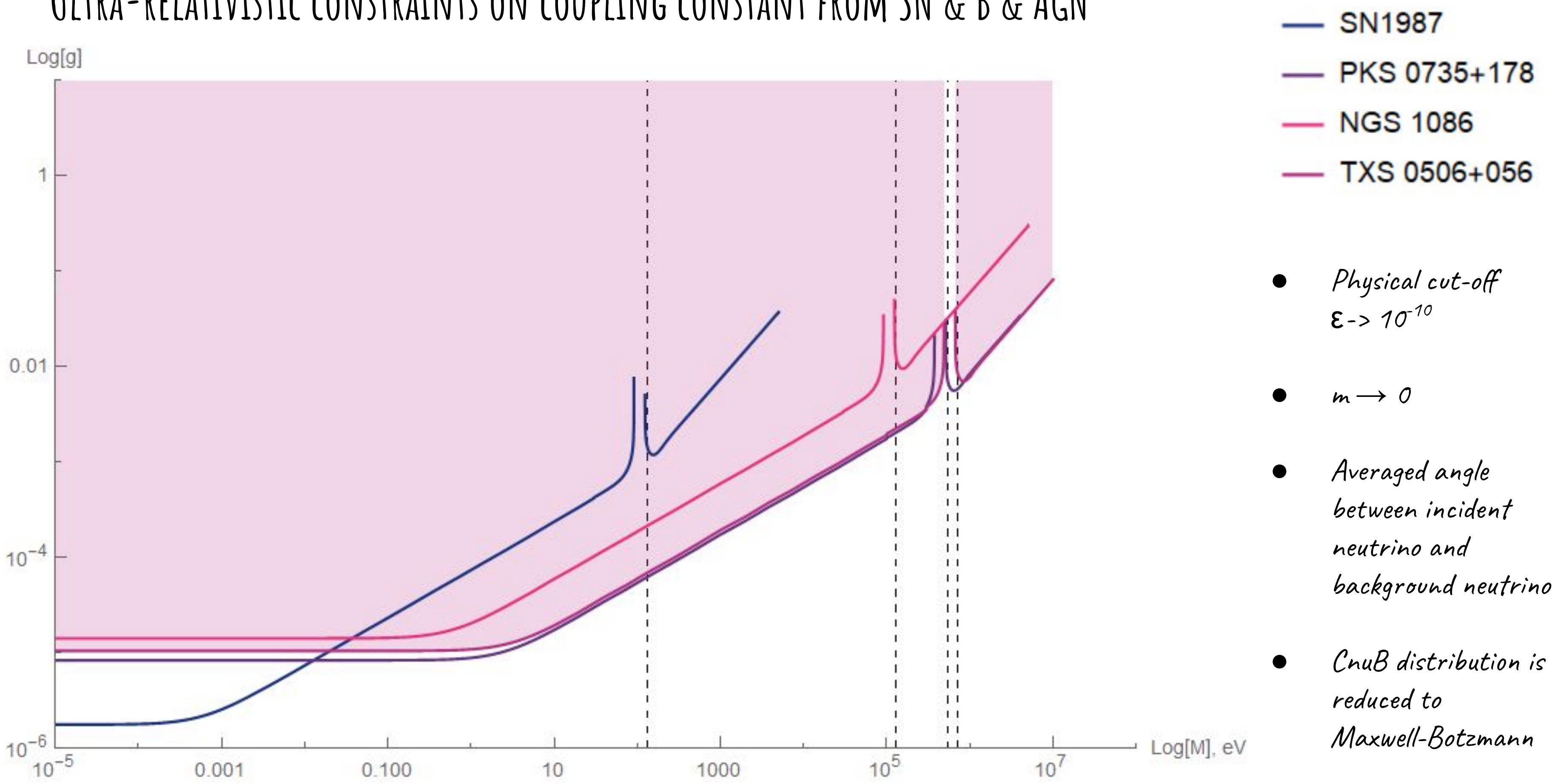
— TXS 0506+056, PKS 0735+178

No angle cut-off for scattering to 0 and π

m -> 10^{-3}

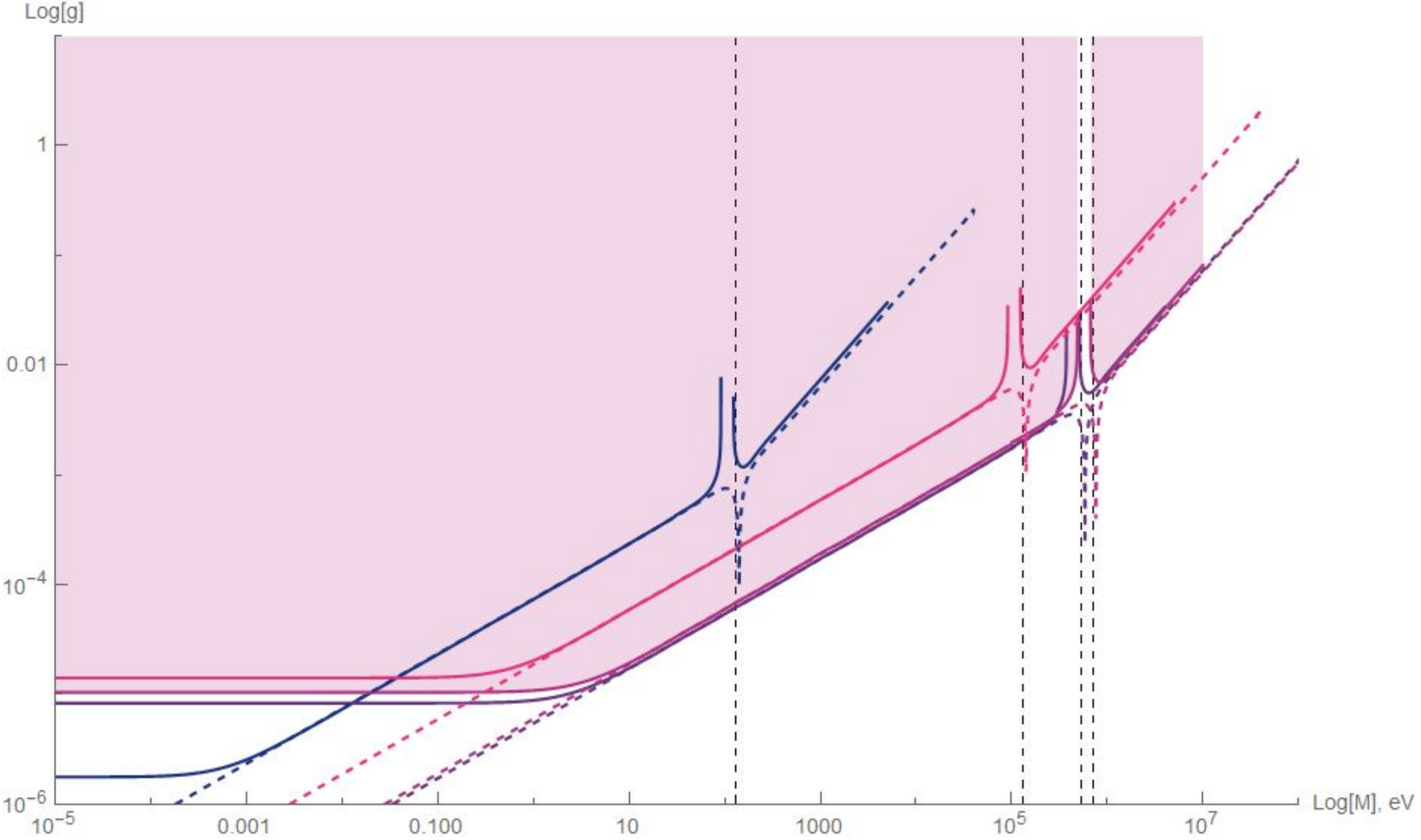
--- $M = \sqrt{s} = \sqrt{2E_\nu m_\nu + m_\nu^2}$

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



- *Physical cut-off* ε-> 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

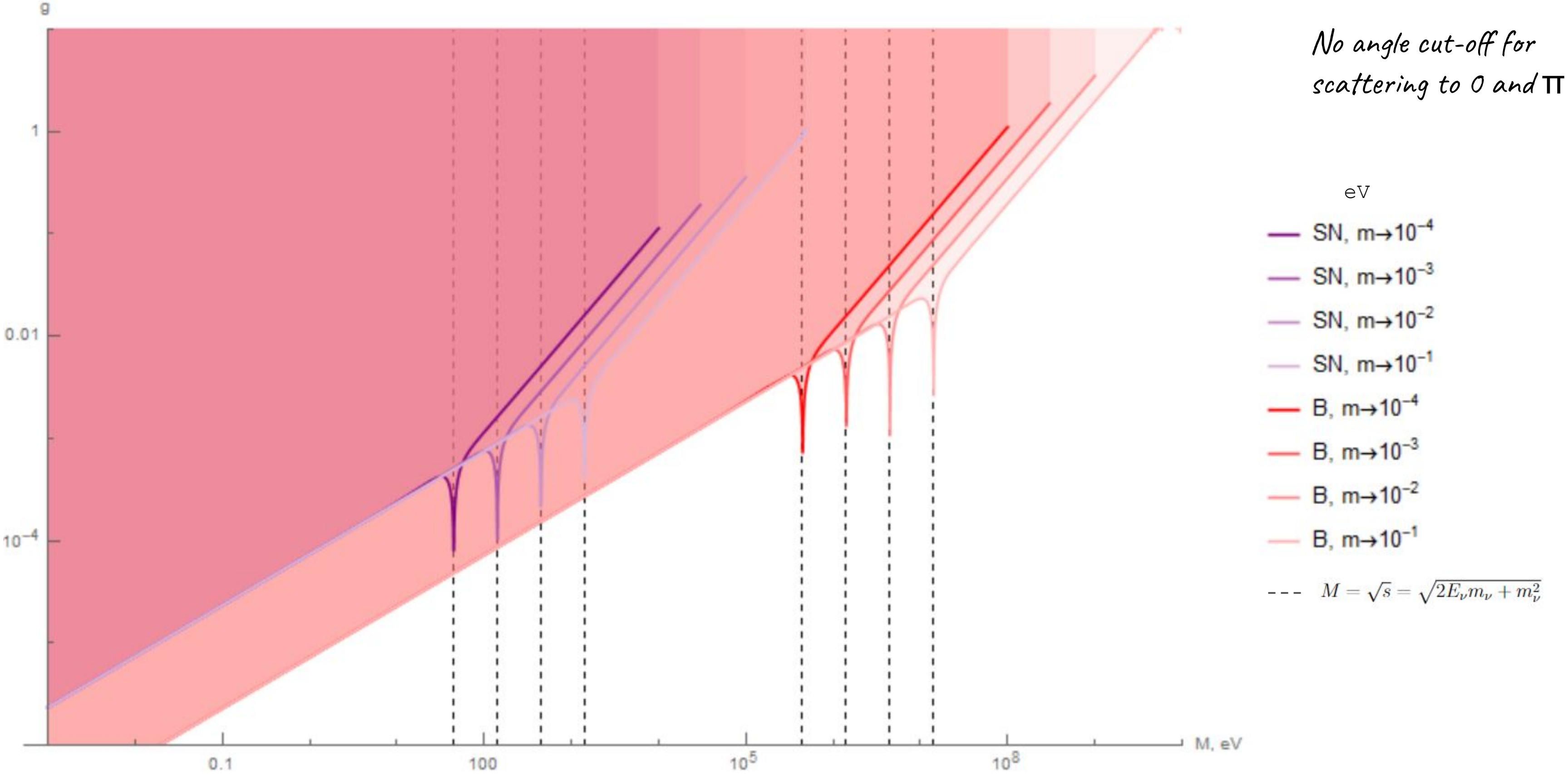


UR and NR regimes coinside with the proper choice of parameters

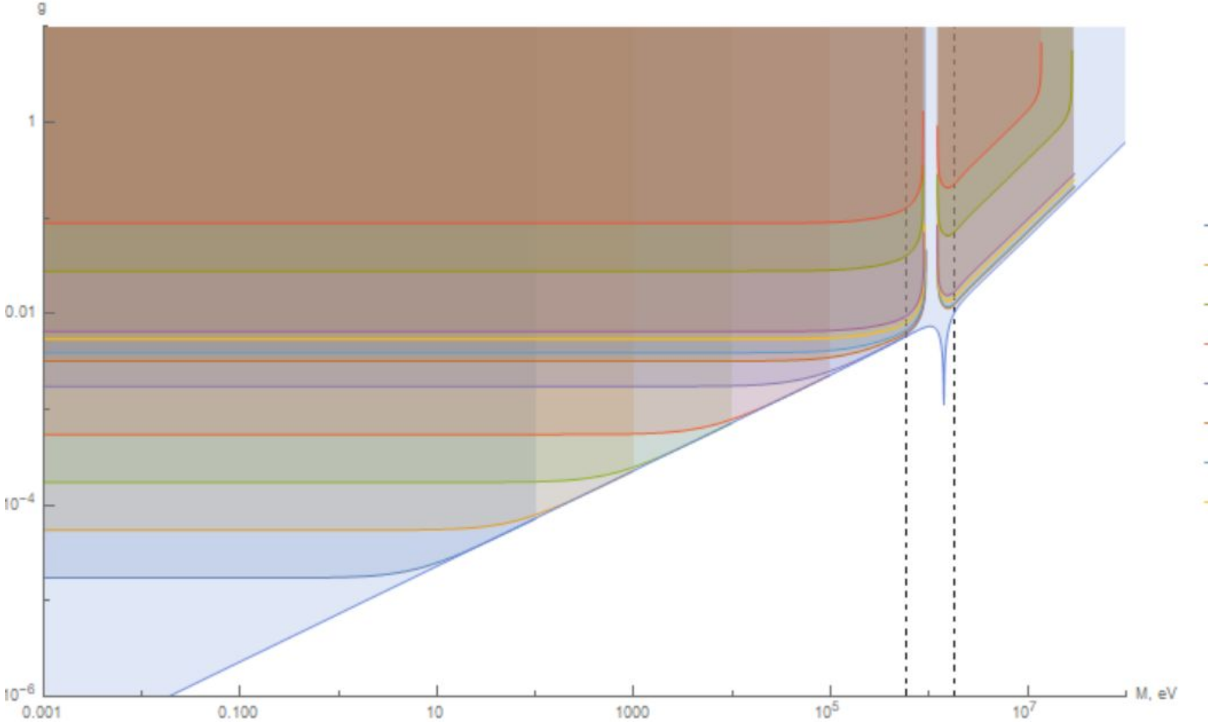
Non-relativistic constraints on coupling constant from SN & B: Neutrino mass dependence

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

No angle cut-off for scattering to 0 and π



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.

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

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.

Thank you for attention!

Sep 16 – 27, 2024
IEAP CTU in Prague

EuCAPT
Astroneutrino Theory Workshop 2024
Prague, Czech Republic

- **New neutrino interactions in laboratory**
  (neutrino self-interactions, model building, coherent scattering, short-baseline anomalies, reactor anomalies)
- **New neutrino interactions in Cosmology**
  (cosmological tensions, leptogenesis, CNB detectability)
- **New neutrino interactions in Astrophysics**
  (supernovae, diffuse supernovae fluxes, (U)HE cosmic rays, refractive effects from NSI, DM self-interactions via neutrino exchange)

LITERATURE

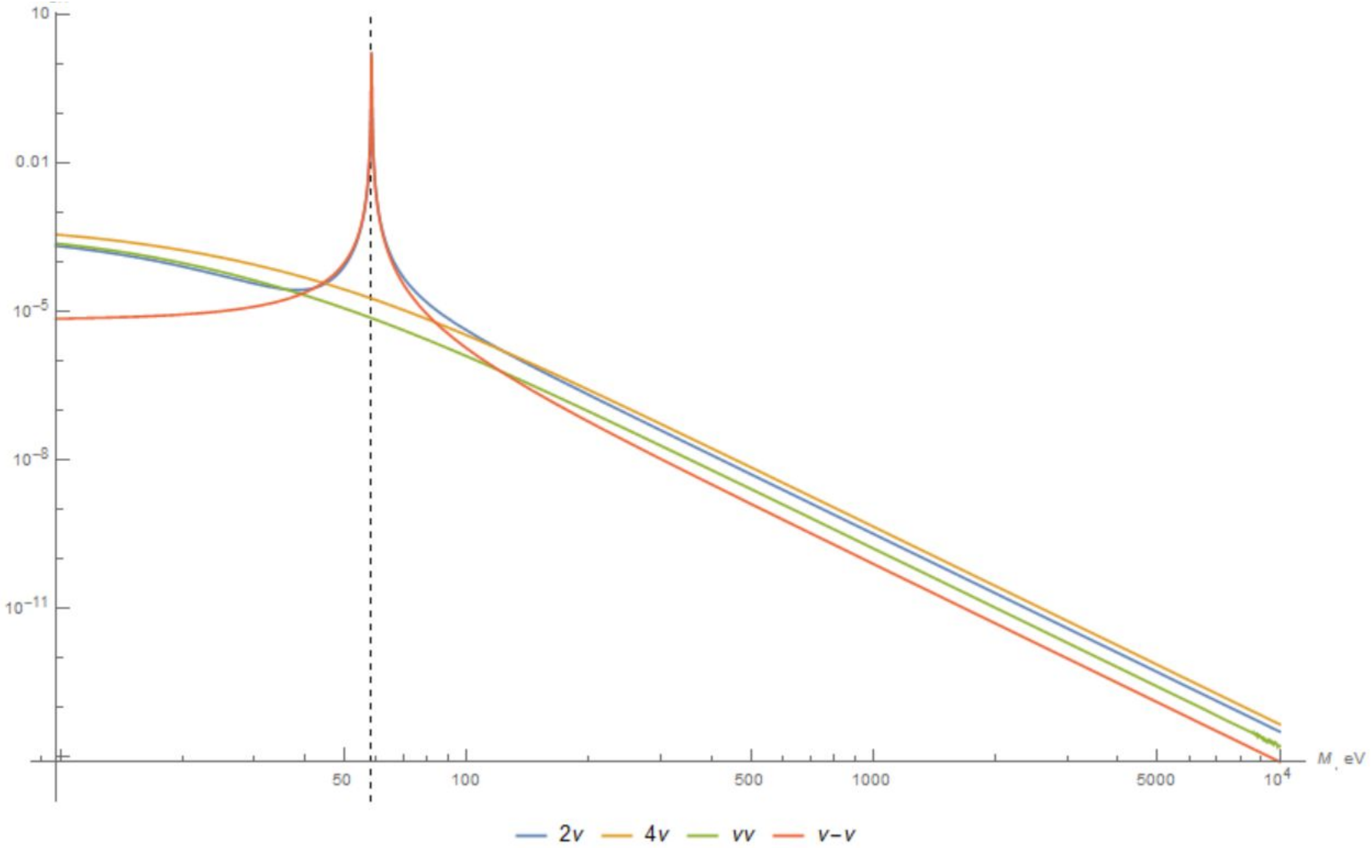
[1] Looking for cosmic neutrino background - C. Yanagisawa
[2] Massive Fermi Gas in the Expanding Universe - A. Trautner
[3] Multimessenger Astronomy and New Neutrino Physics - K. J. Kelly, P. A. N. Machado,
[4] Neutrino Self-Interactions: A White Paper - J. M. Berryman et all, 2022
[5] The origin of high-energy astrophysical neutrinos: new results and prospects - Sergey Troitsky
[6] Neutrino Echoes from Multimessenger Transient Sources - K. Murase Ian M. Shoemaker

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 CνB-spectrum with temperature 10^{-4} eV, however for calculations, we reduce it to the Maxwell-Boltzmann distribution.
- **Angle cut-off** : s (l–e) < t < - es
- We assume e – μ – τ universality in the non-standard ν – ν interaction

Backup Slides

CROSS-SECTION VS. MEDIATOR MASS, LOG

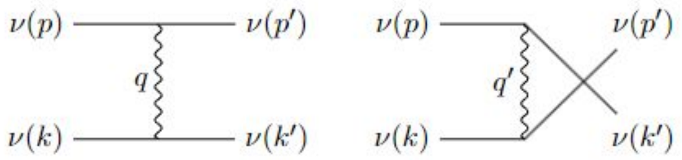


Angle cut-off

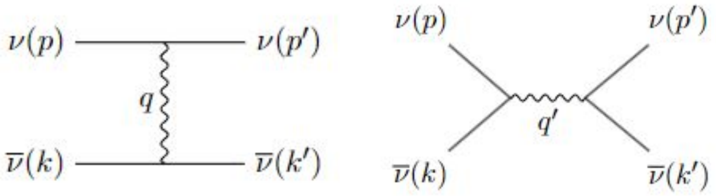
Angle cut-off for scattering to 0 and π. This corresponds to the t-channel exchange of a massless v. It occurs whenever the final X carries off all of the initial neutrino energy. In the opposite limit, $t \sim 0$, the neutrino retains all of its incident energy, and is not removed from the "detectable" 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 $-s(1-e)<t< - es$

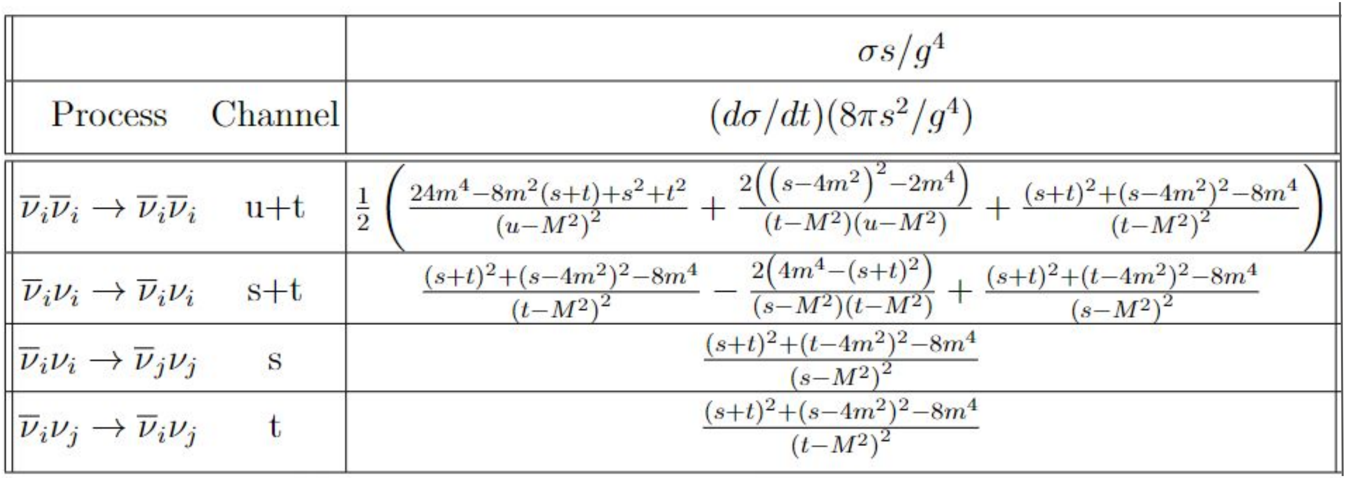
PROCESSES CONTRIBUTING TO THE HEν SCATTERING ON CνB

t+u channel:



t+s channel:

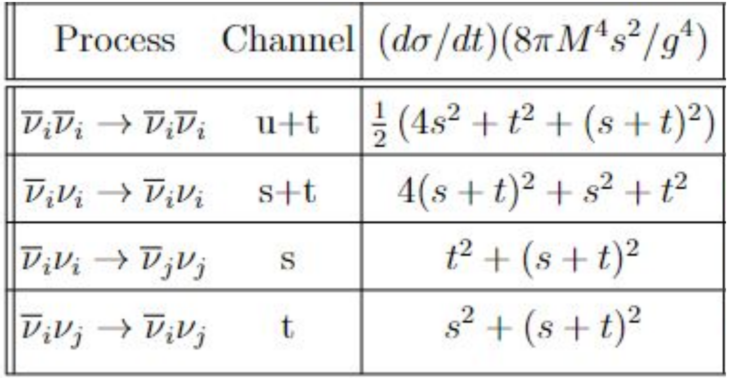




		$\sigma s/g^4$
Process	Channel	$(d\sigma/dt)(8\pi s^2/g^4)$
$\overline{\nu}_i\overline{\nu}_i \rightarrow \overline{\nu}_i\overline{\nu}_i$	u+t	$\frac{1}{2}\left(\frac{24m^4-8m^2(s+t)+s^2+t^2}{(u-M^2)^2}+\frac{2\left(\left(s-4m^2\right)^2-2m^4\right)}{(t-M^2)(u-M^2)}+\frac{(s+t)^2+(s-4m^2)^2-8m^4}{(t-M^2)^2}\right)$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

ASYMPTOTIC LIMITS

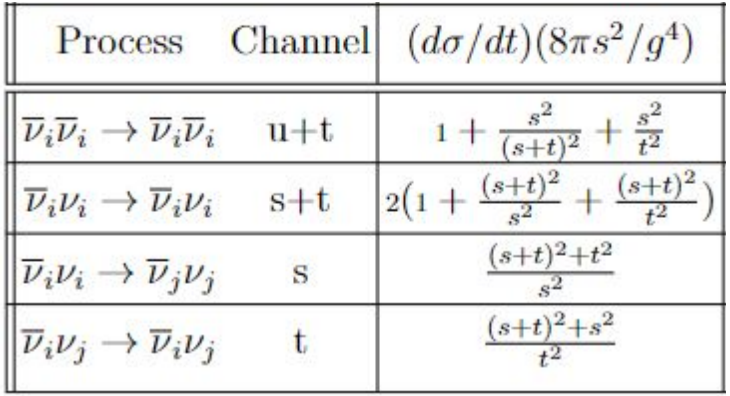
Heavy massive mediator limit



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

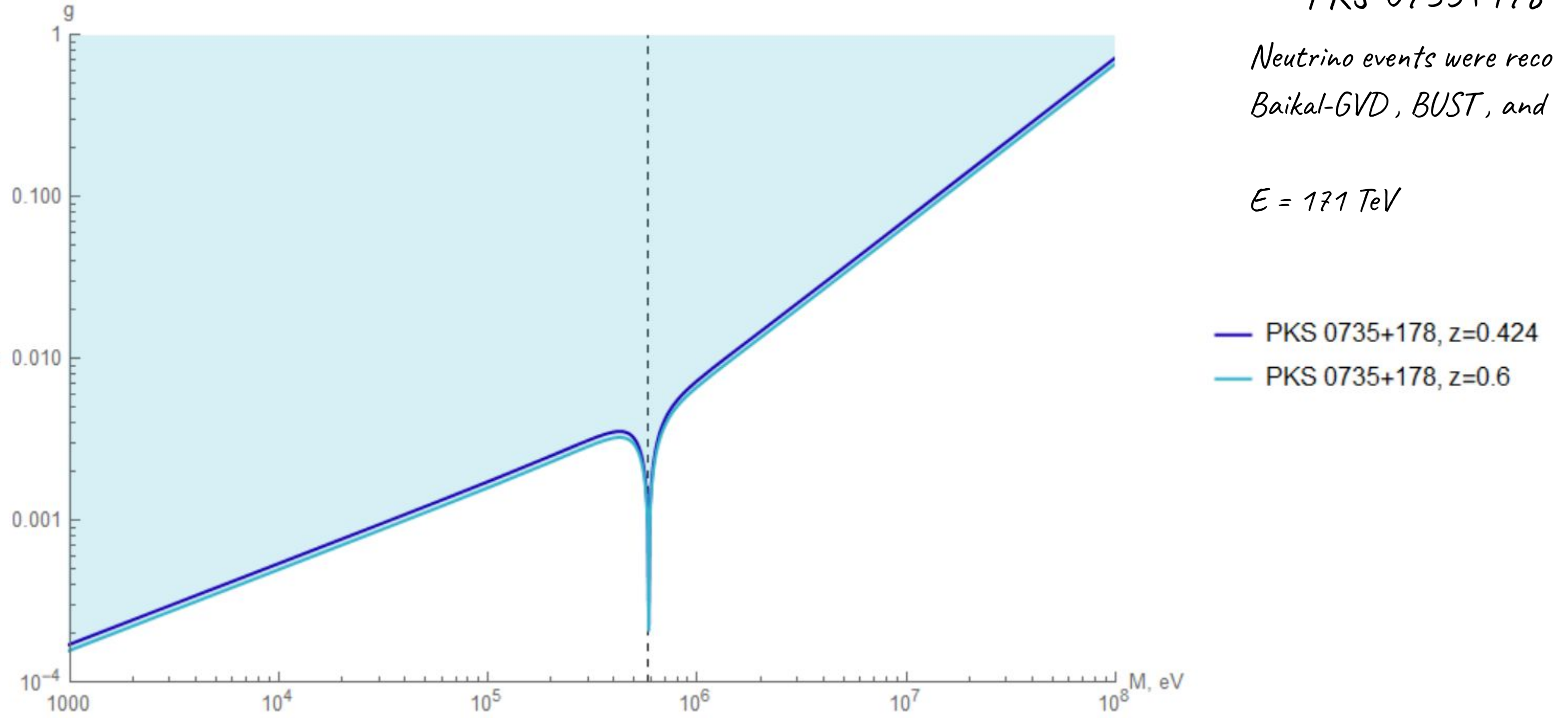


Process	Channel	$(d\sigma/dt)(8\pi s^2/g^4)$
$\overline{\nu}_i\overline{\nu}_i \to \overline{\nu}_i\overline{\nu}_i$	u+t	$1+\frac{s^2}{(s+t)^2}+\frac{s^2}{t^2}$
$\overline{\nu}_i\nu_i \to \overline{\nu}_i\nu_i$	s+t	$2(1+\frac{(s+t)^2}{s^2}+\frac{(s+t)^2}{t^2})$
$\overline{\nu}_i\nu_i \to \overline{\nu}_j\nu_j$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

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

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

BLAZAR WITH UNCERTAIN DISTANCE



PKS 0735+178

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

E = 171 TeV