Constraints on neutrino self-interactions by supernovae and blazars

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Multimessengers: Supernova, Blazar
- high energy extraterrestrial neutrinos

Supernova emits an enormous flux of electron antineutrino

$N = 10^{58}$ with energy around

$\langle E_S \rangle \sim 10\ MeV$.

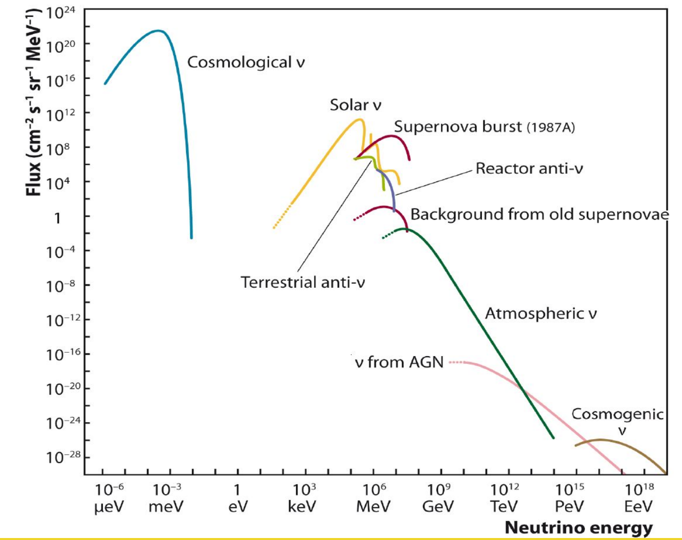
$D = 55 + 15$ kpc

The great distance to the supernova, affords a unique opportunity to place limits that in cannot be matched by terrestrial experiments.

Meanwhile we assume that supernovae produce neutrinos only in MeV range, blazars produce also astrophysical neutrinos in

$E_B \in (TeV - PeV)$ energy range.

Blazar TXS 0506+056 - 13+5 TeV-PeV neutrinos



Cosmic Neutrino Background (CNB)

- *One the most abundant particles in the Universe*

$$n_\nu = 112\ \text{cm}^{-3}\ \text{per flavour}$$

- *CNB decoupled from other particles earlier than CMB*

- *Nowadays "temperature" of CNB*

$$T_{now} \simeq 1.9\ \text{K} \simeq 1.7\ 10^{-4}\ \text{eV}$$

- *CNB-spectra*

$$n_{F.D.} = (1 + e^{|p|/T})^{-1}$$

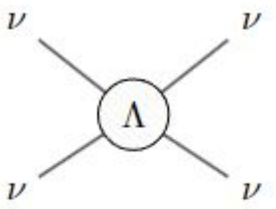
- *Nucleosynthesis*
- *Cosmic Microwave Background*
- *Large-Scale Structure*
- *Neutrino properties*

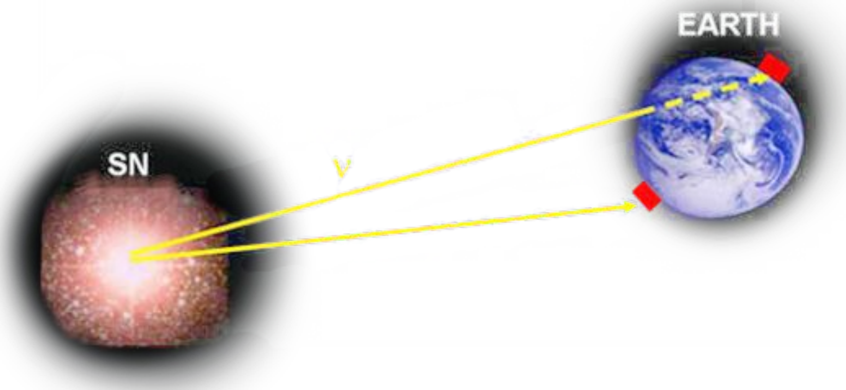
[1] Looking for cosmic neutrino background – C. Yanagisawa
[2] Massive Fermi Gas in the Expanding Universe – A. Trautner

Neutrino Self interactions

- Interactions of the astrophysical neutrinos with the cosmic neutrino background
  - Extraterrestrial neutrinos need to traverse large distances on their way to Earth. Within the SM this is not an issue since the probability of an interaction between neutrinos and matter is very small. However, in the presence of new, beyond the SM interactions, this can change. This can turn the universe opaque to astrophysical neutrinos. Thus the observation of astrophysical neutrinos can be used to constrain secret interactions.
- Energy Transport in Dense Media
  - NSI influence the energy transport and heating mechanisms within the SN core, affecting the dynamics of the explosion, the production of heavy elements, the dynamics of dense medium in NS
- Neutrino Flavor Oscillations
  - neutrinos can experience matter-enhanced flavor transitions due to NSI
- Cosmology
  - NSI can influence the evolution of neutrinos in the early universe, impacting cosmological observations and constraints on neutrino properties.

Effective coupling constant





$$\nu_\alpha \nu_\beta \to \nu_\alpha \nu_\beta, \quad (\nu_{\alpha,\beta} = \nu_{e,\mu,\tau}, \overline{\nu}_{e,\mu,\tau})$$

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

$$\overline{\nu}_e + C\nu B = (\overline{\nu}_e \overline{\nu}_e \to \overline{\nu}_e \overline{\nu}_e) + (\nu_e \overline{\nu}_e \to \nu_e \overline{\nu}_e) + \\ +2(\nu_e \overline{\nu}_e \to \nu_\mu \overline{\nu}_\mu) + 4(\nu_\mu \overline{\nu}_e \to \nu_\mu \overline{\nu}_e)$$

- ϕ^μ is a vector boson

Mean free path

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

$$\lambda^{-1} = \frac{1}{4\pi} \int d|\mathbf{p}_X||\mathbf{p}_X|^2 f(\mathbf{p}_X) \int dz\, v_{Moller}\, \sigma(s)$$

The detection of neutrinos from a HEν source, like SN1987A, requires that the mean free path of neutrinos through the CνB is comparable to or greater than the distance to the supernova. This results in limits to the cross sections of neutrinos with themselves and with other particles.

Two background regimes

Non-relativistic: $\frac{|p_X|}{E_X} \to 0, \quad s \to m_X^2 + 2Em_X, \quad v_{Moller} = 1$

Ultra relativistic: $\frac{|p_X|}{E_X} \to 1, \quad s \to 2EE_X(1-z), \quad v_{Moller} = \sqrt{2(1-z)}$

$$\lambda_{NR}^{-1} = n_X\, \sigma(s)$$

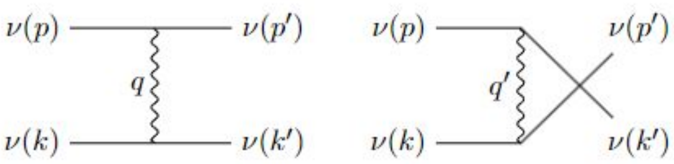
$$\lambda_{UR}^{-1} = \frac{\sqrt{2}}{4\pi^2} \int_0^\infty dE_X E_X^2\, f(E_X) \int dz \sqrt{1-z}\, \sigma(z, E_X)$$

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

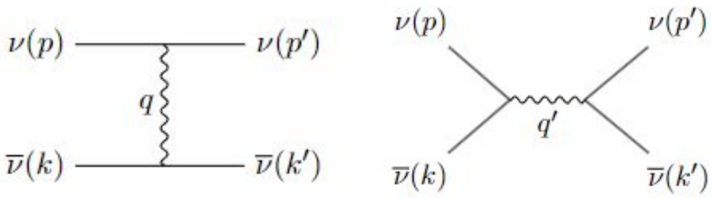
$$n_X = \frac{1}{4\pi^2} \int_0^\infty dE_X E_X^2 f(E_X)$$

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	$\frac{1}{2}\left(\frac{24m^4-8m^2(s+t)+s^2+t^2}{(u-M^2)^2}+\frac{2\left((s-4m^2)^2-2m^4\right)}{(t-M^2)(u-M^2)}+\frac{(s+t)^2+(s-4m^2)^2-8m^4}{(t-M^2)^2}\right)$
$\overline{\nu}_i\nu_i \rightarrow \overline{\nu}_i\nu_i$	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	$s^2+(s+t)^2$

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

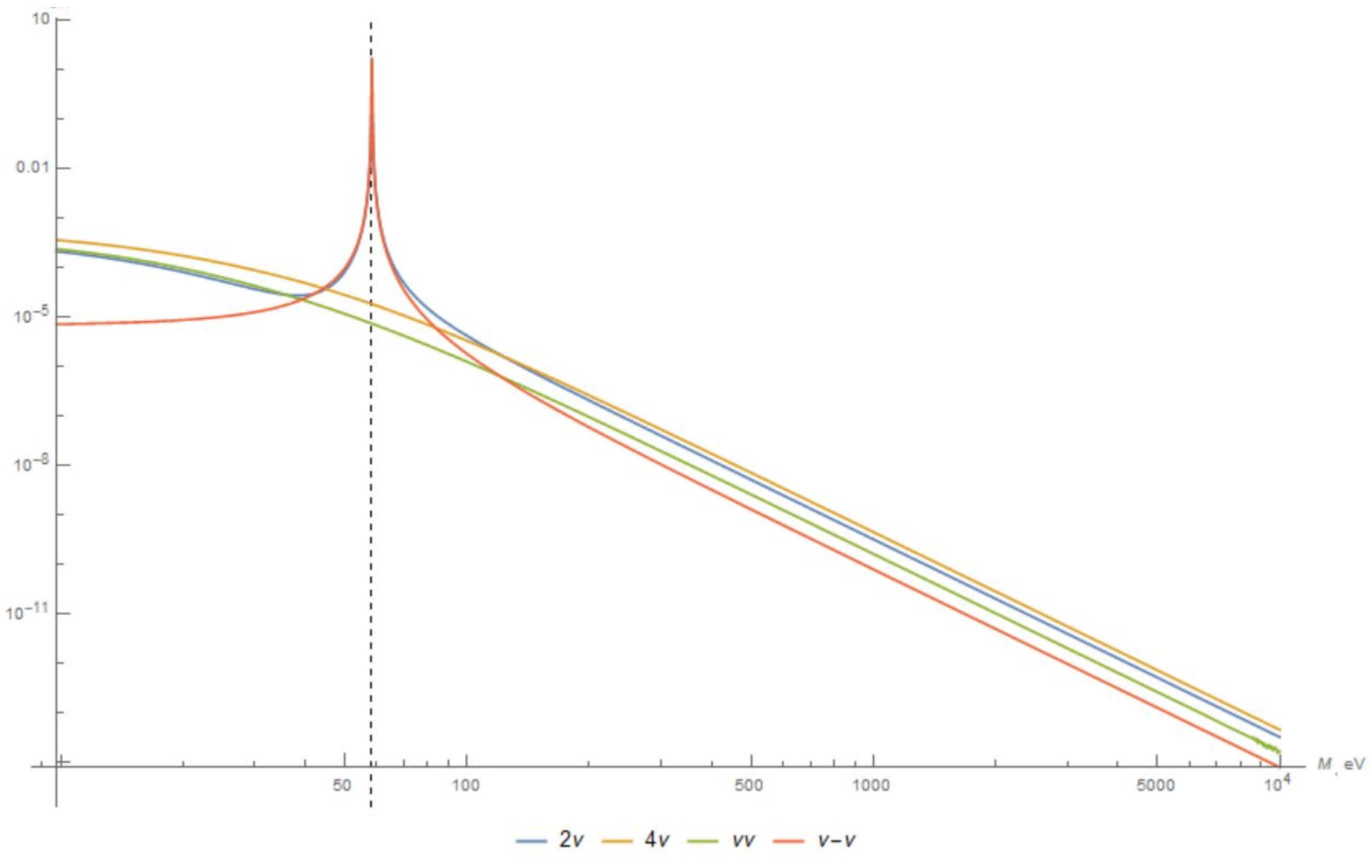
Massless mediator limit

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	$\frac{(s+t)^2+s^2}{t^2}$

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

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

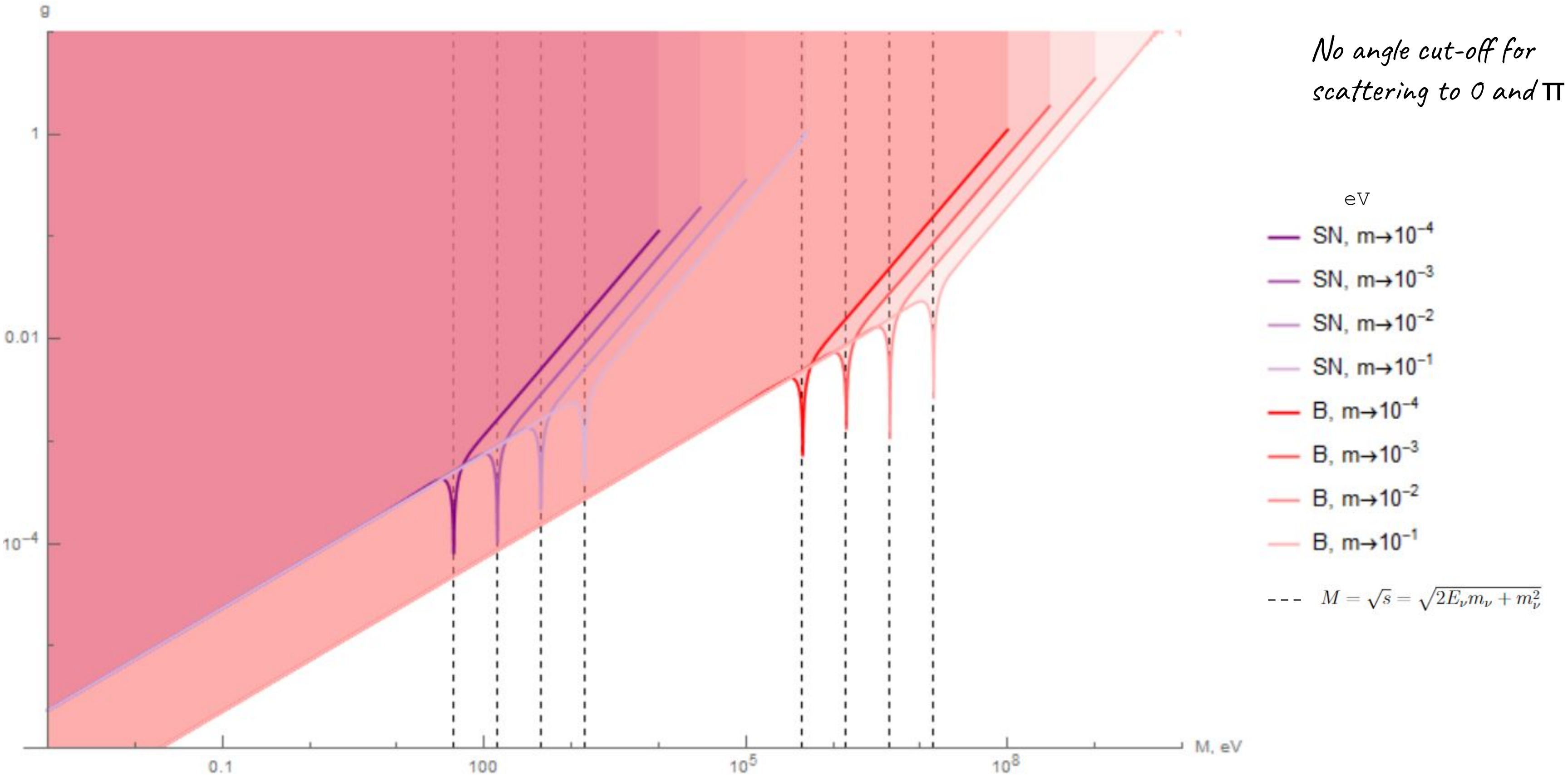
Cross-section vs. mediator mass, Log



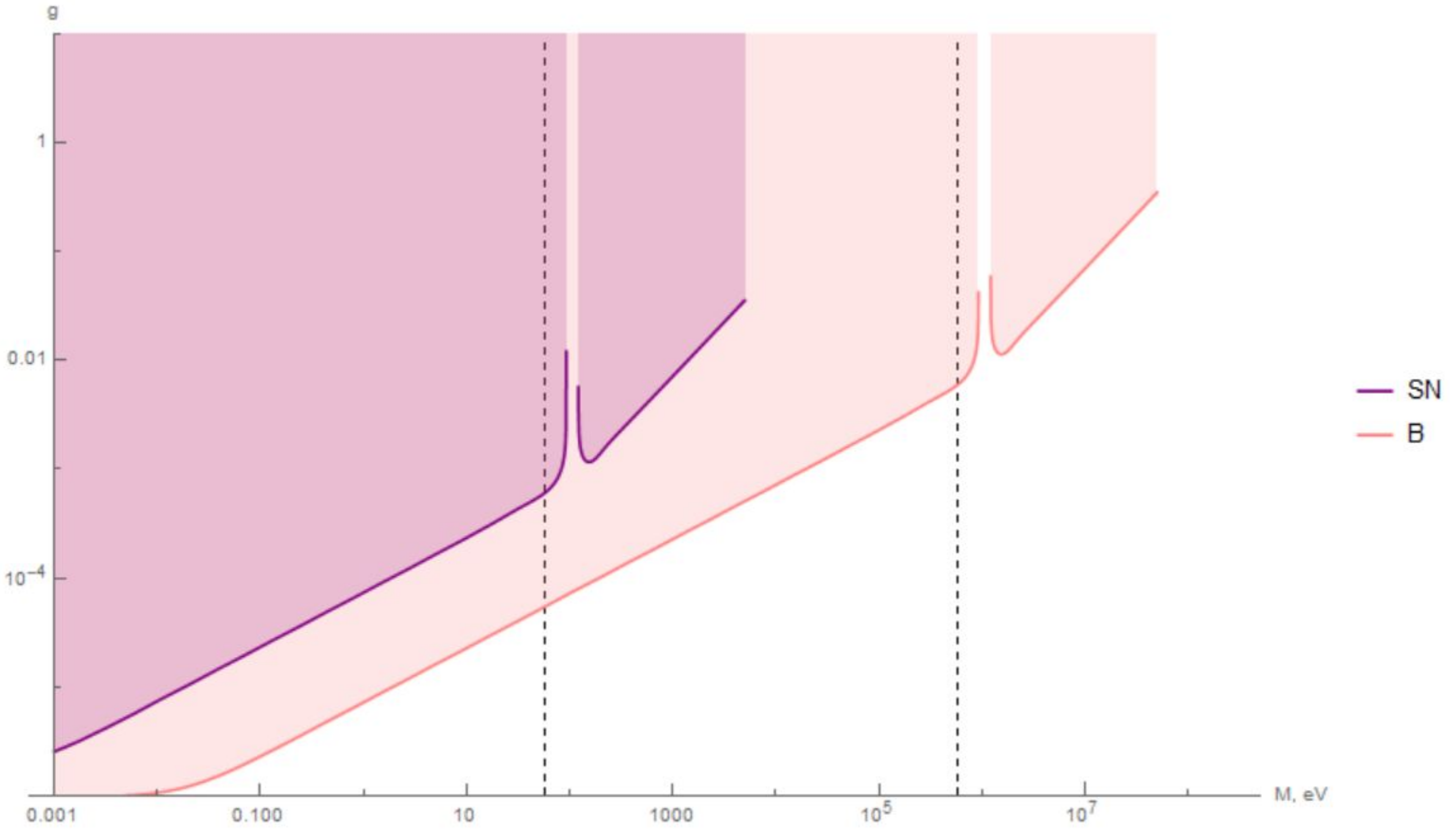
Non-relativistic constraints on coupling constant from SN & B

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

No angle cut-off for scattering to 0 and π

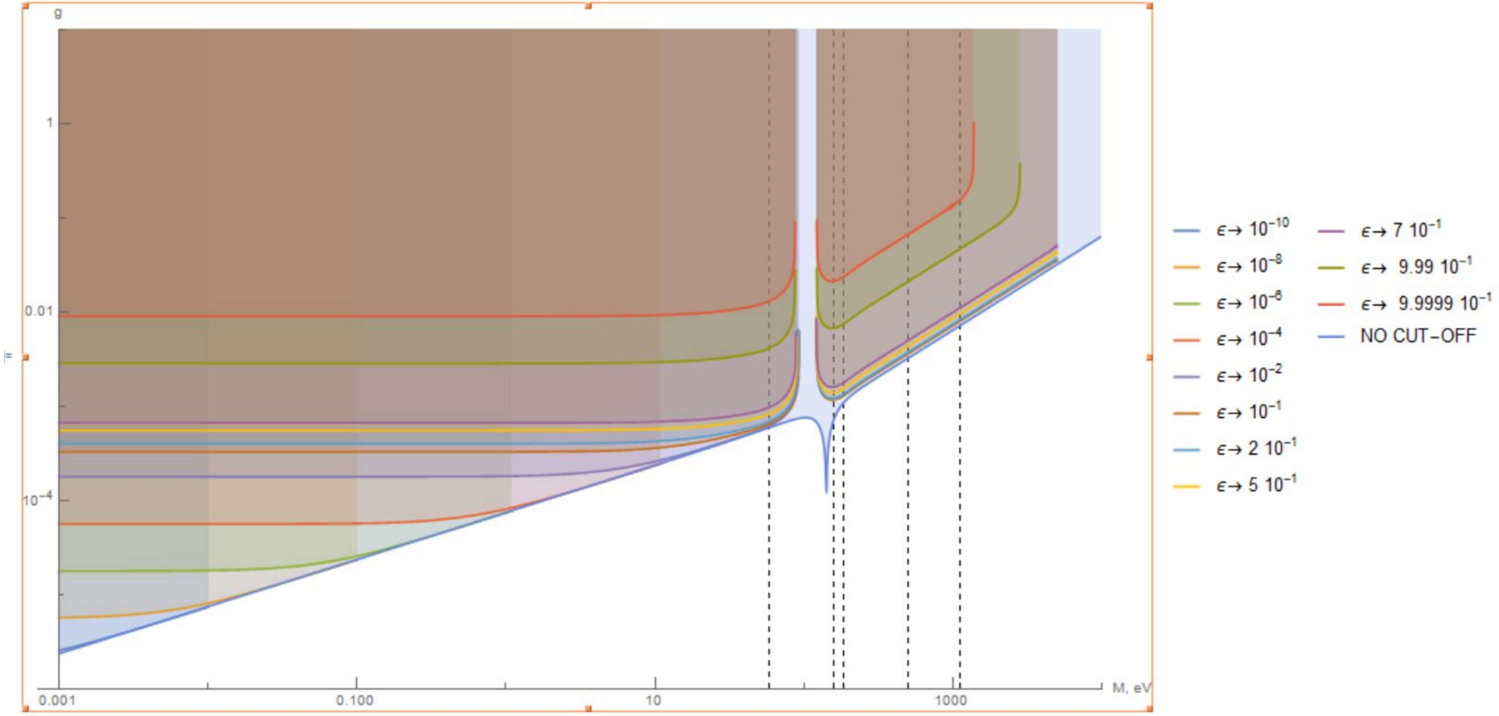


Ultra-relativistic constraints on coupling constant from SN & B

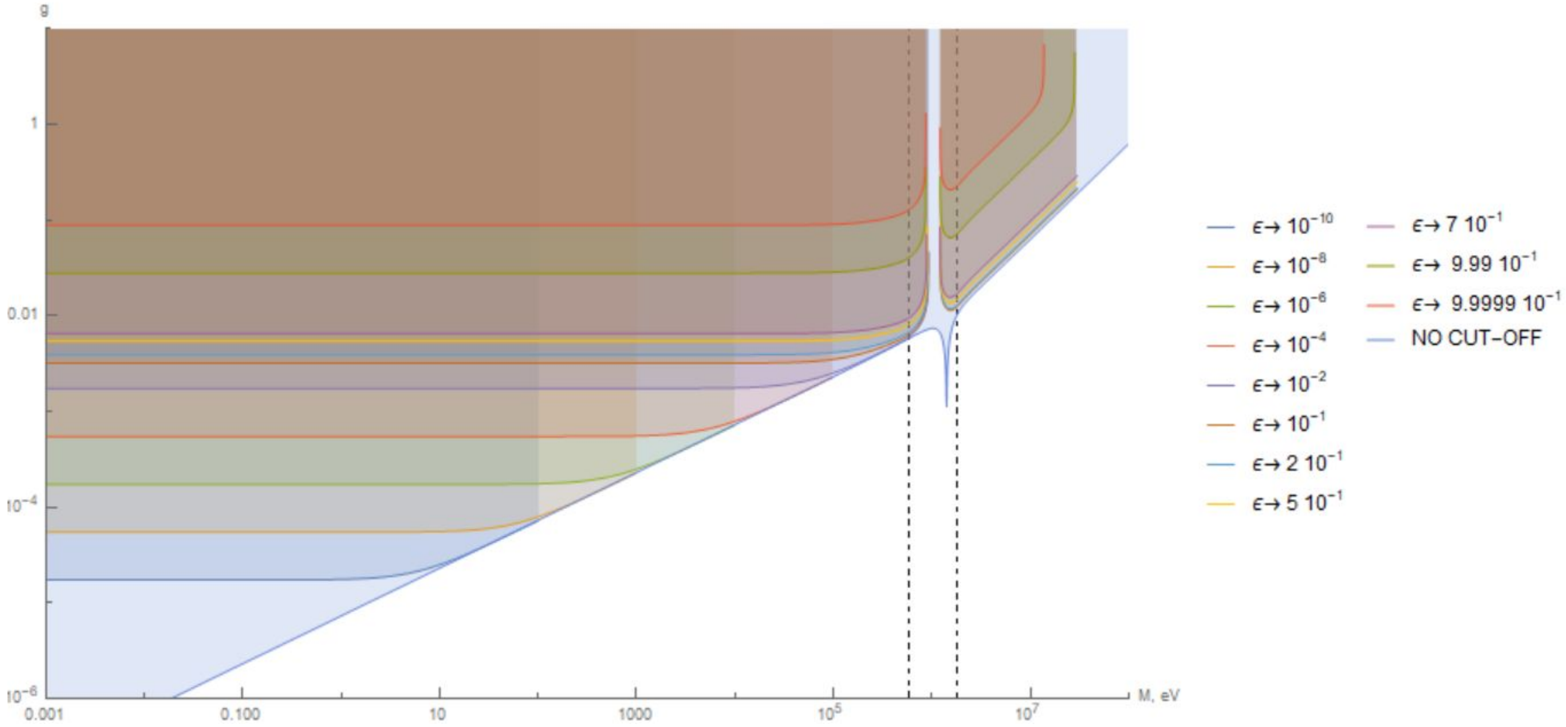


- *Cut-off*
- *m ⟶ 0*
- *Averaged angle between incident neutrino and background neutrino*
- *CnuB distribution is reduced to an exponential function*

NR + UR coupling constant for SN



NR + UR coupling constant for Blazar



Results

In this, work we

- investigated a particular model for secret neutrino interactions with Dirac neutrinos and massive vector boson as NSI mediator
- presented the relevant cross sections and interaction rates
- presented a recipe of constraining NSI coupling constant by HE neutrinos propagating through the CnB
- presented constraints from hypothetical SN and Blazar neutrinos scattering on CnB

Obtained results are in consistency with the literature, and offer more precise analysis on the angle cut-off parameter, and include intermediate mass region of the NSI mediator to the constraints on coupling constant.

Distinctive features worth further investigatigation by implying NO/IO neutrino hierarchy.

Thank you for attention!

Backup Slides

Let's denote Γ as

$$\lambda^{-1} = g^4 \Gamma \tag{41}$$

$$\Gamma_{4\nu} = d_0 + d_2 eEi_2 + d_3 eEi_3 \tag{42}$$

$$\Gamma_{2\nu} = c_0 + c_1 eEi_1 + c_2 eEi_2 + c_3 eEi_3 \tag{43}$$

$$\Gamma_{\overline{\nu}\nu} = b_0 + b_2 eEi_2 + b_3 eEi_3 \tag{44}$$

$$\Gamma_{\overline{\nu}_i \nu_j} = a_0 + a_1 eEi_1 \tag{45}$$

where a, b, c, d - are polynomials of M^2.

$$eEi(x) = e^{-x} Ei(x) \tag{46}$$

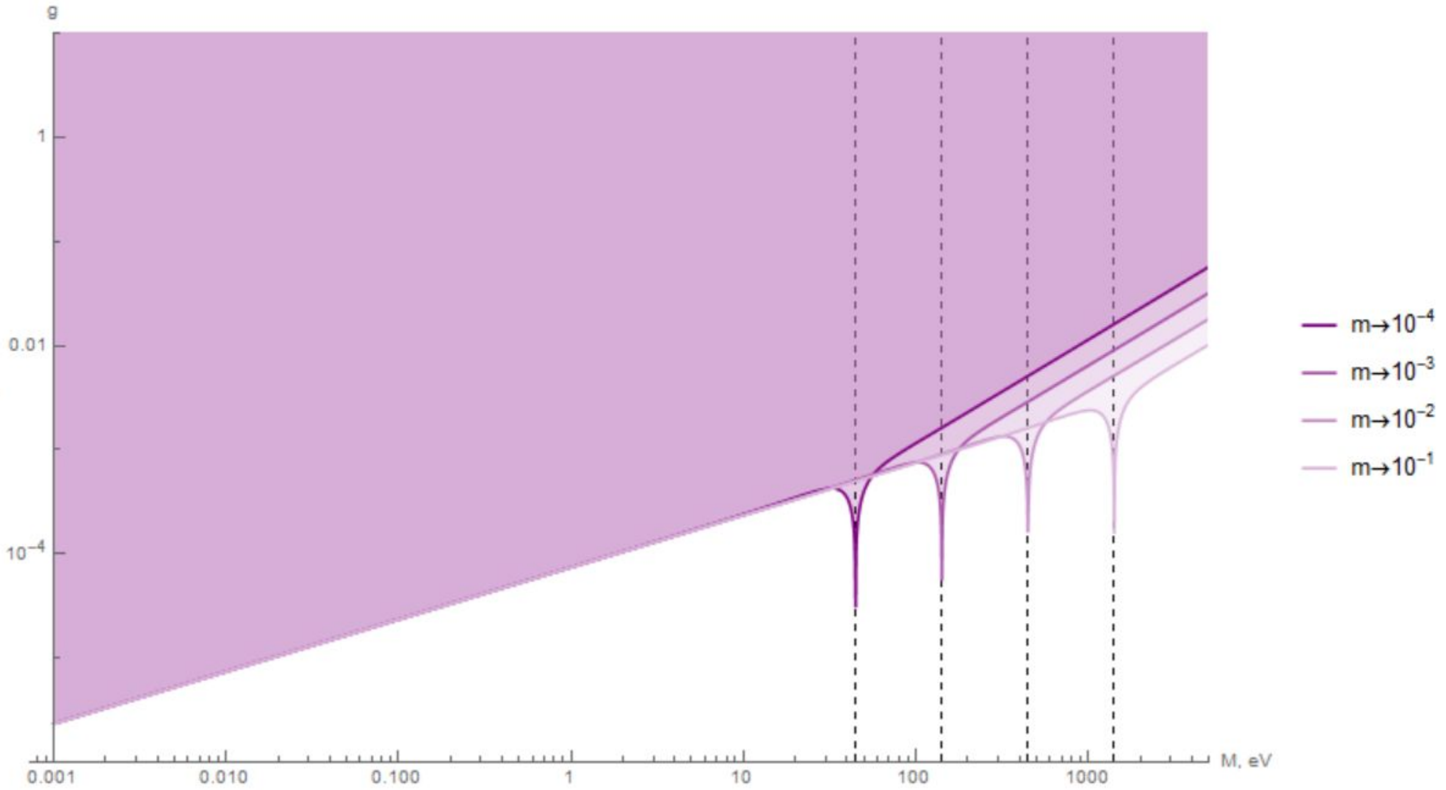
where $Ei(x)$ is the exponential integral.

Assumptions

a) Cross-sections contain the following approximations:
   i) equal neutrino masses
   ii) equal coupling constants for each neutrino flavor.

b) Decay rate and Coupling constant:
   i) zero neutrino masses
   ii) averaged angle between incident neutrino and background neutrino
   iii) CnuB distribution is reduced to an exponential function

Results



Differential cross-section

Process	Channel
$\overline{\nu}_i\overline{\nu}_i \to \overline{\nu}_i\overline{\nu}_i$	u+t
$\overline{\nu}_i\nu_i \to \overline{\nu}_i\nu_i$	s+t
$\overline{\nu}_i\nu_i \to \overline{\nu}_j\nu_j$	s
$\overline{\nu}_i\nu_j \to \overline{\nu}_i\nu_j$	t

$$(\lambda_{SN}\ (1/2\ n\Gamma 12_{4\nu} + n\Gamma 12_{2\nu} + 4\ n\Gamma 12_{\nu\nu} + 2\ n\Gamma 12_{\nu^- \nu}))^{-1/4}$$

$$n\Gamma 12_{\nu^- \nu} = a0 + a1\ eEi1;$$
$$n\Gamma 12_{\nu\nu} = b0 + b2\ eEi2 + b3\ eEi3;$$
$$n\Gamma 12_{2\nu} = c0 + c1\ eEi1 + c2\ eEi2 + c3\ eEi3;$$
$$n\Gamma 12_{4\nu} = d0 + d2\ eEi2 + d3\ eEi3;$$

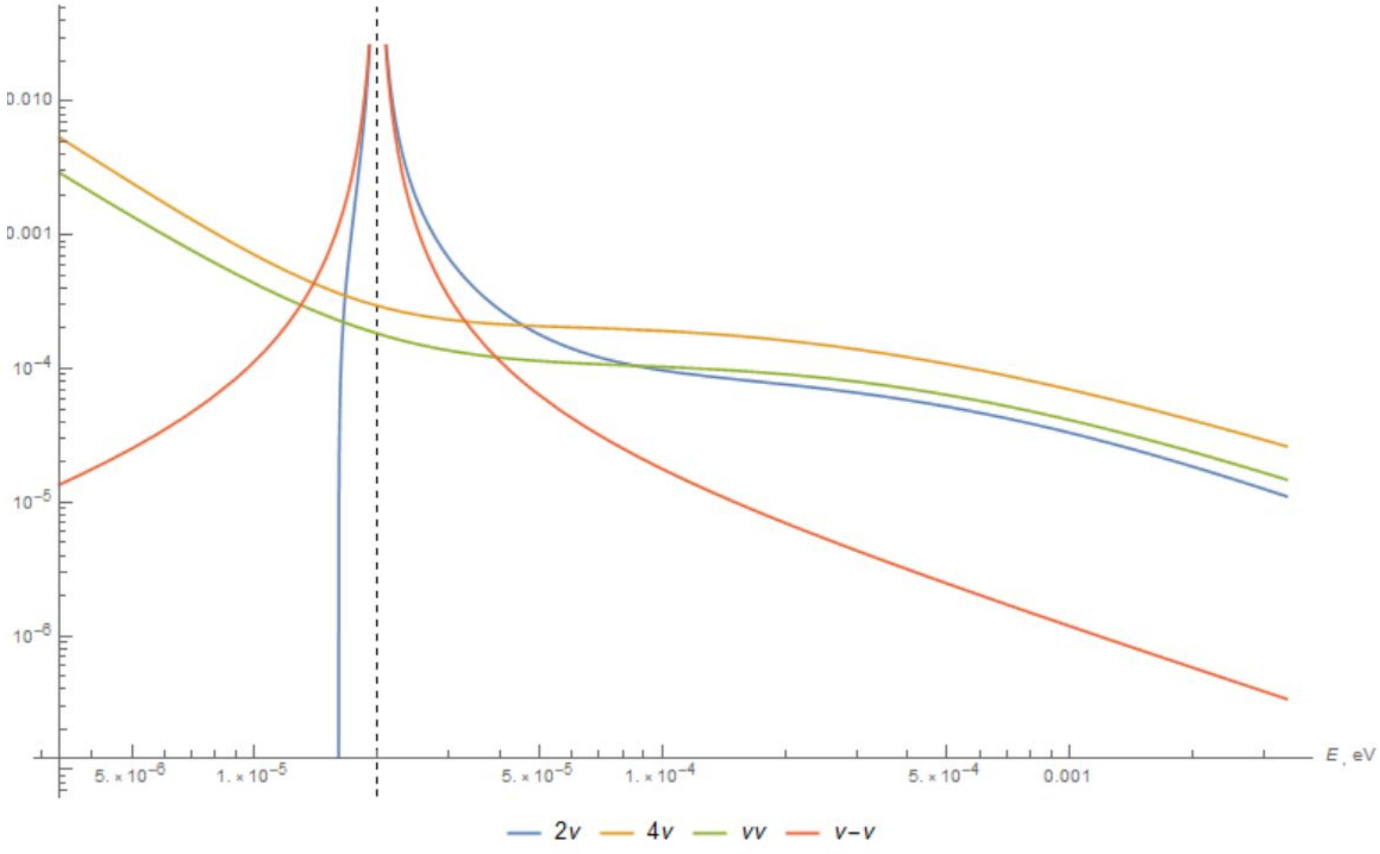
$$eEi1 = e^{-\frac{M^2}{2\ Enu\ T}}\ ExpIntegralEi\left[\frac{M^2}{2\ Enu\ T}\right];$$

$$eEi2 = e^{\frac{M^2}{2\ Enu\ T - Enu\ T\ \epsilon}}\ ExpIntegralEi\left[\frac{M^2}{Enu\ T\ (-2+\epsilon)}\right];$$

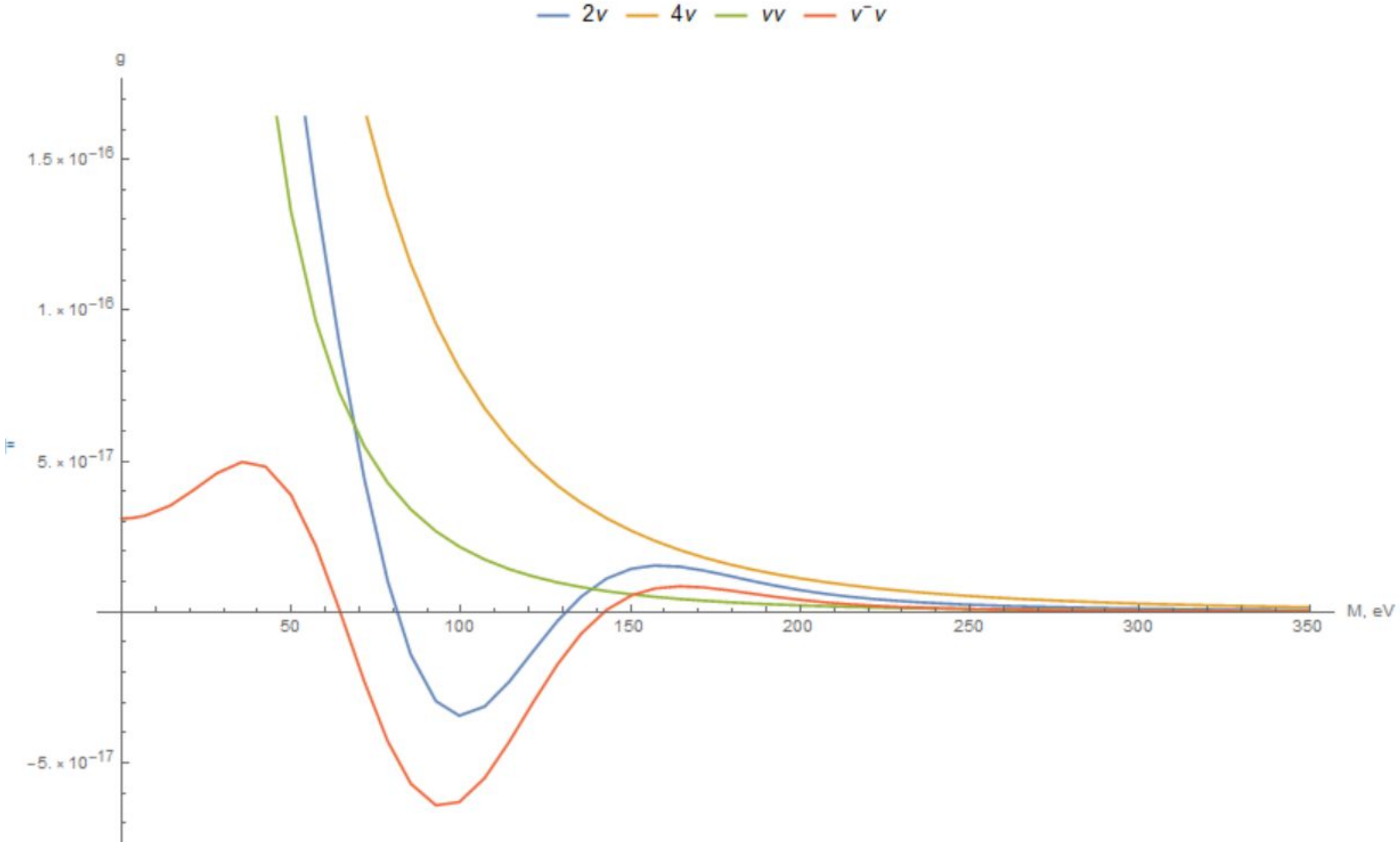
$$eEi3 = e^{\frac{M^2}{Enu\ T\ \epsilon}}\ ExpIntegralEi\left[-\frac{M^2}{Enu\ T\ \epsilon}\right];$$

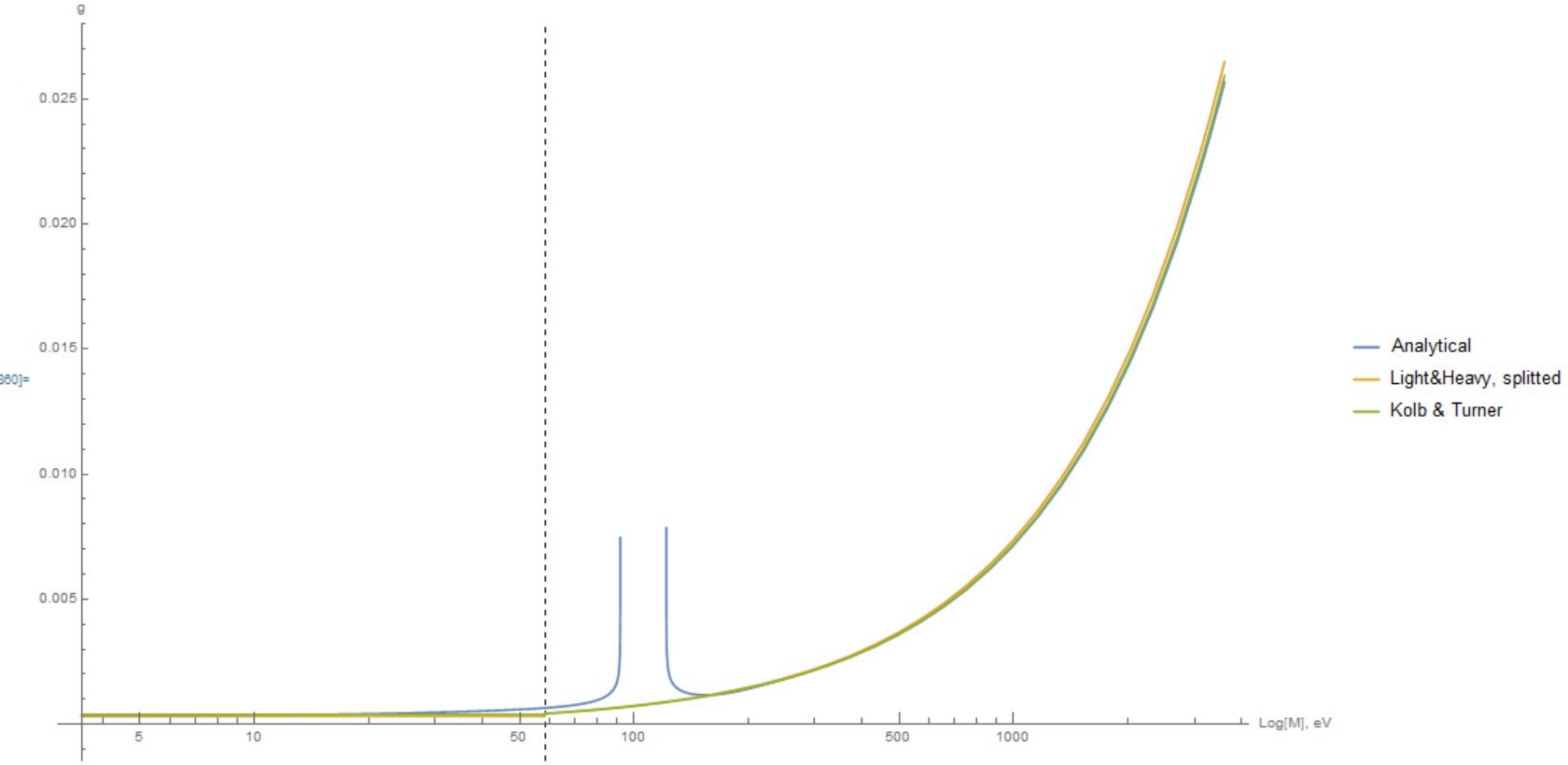
$$eEi4 = e^{\frac{M^2}{Enu\ T}}\ ExpIntegralEi\left[\frac{-M^2}{Enu\ T}\right];$$

Cross-section from CnuB energy, Log

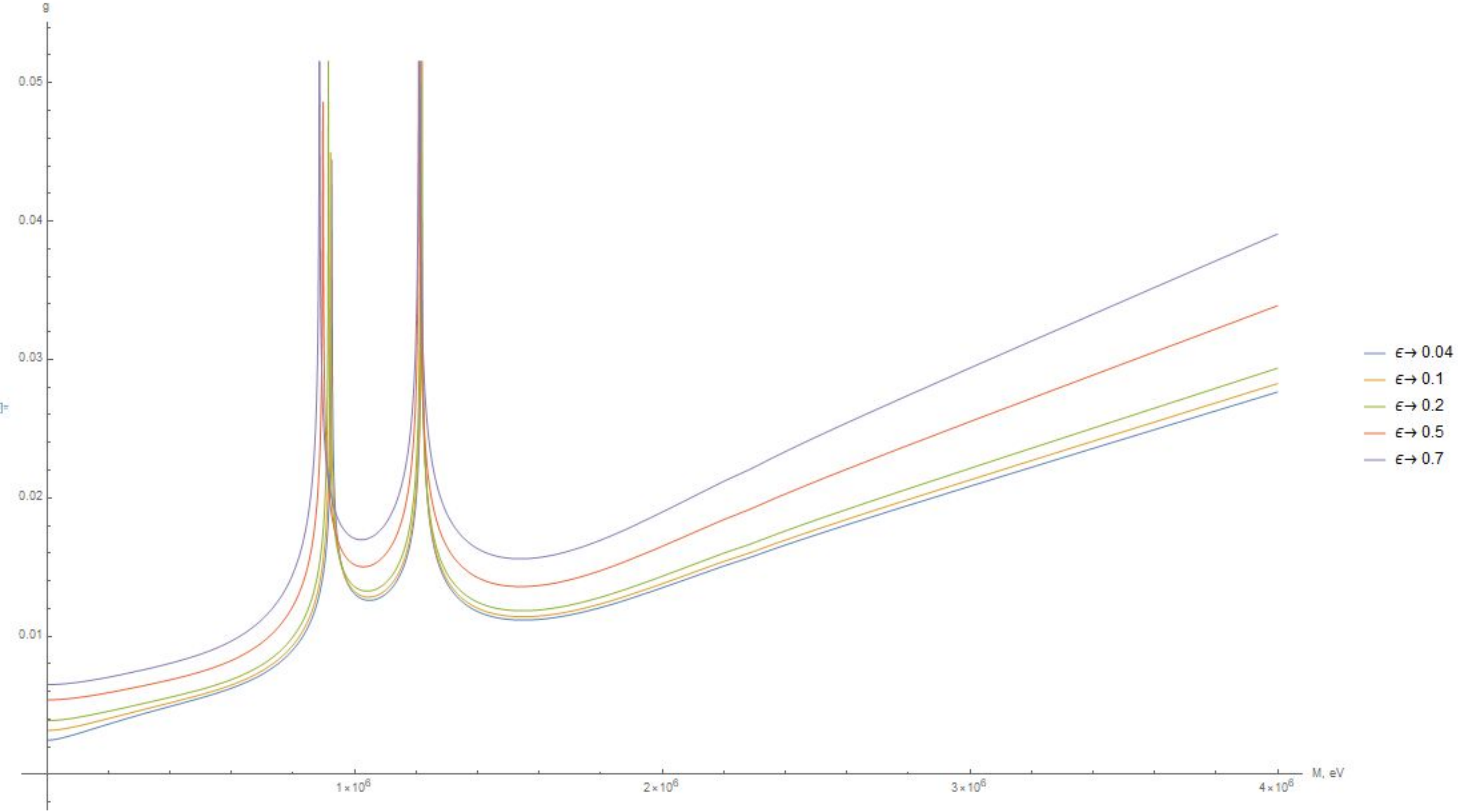


Decay rates from mediator mass

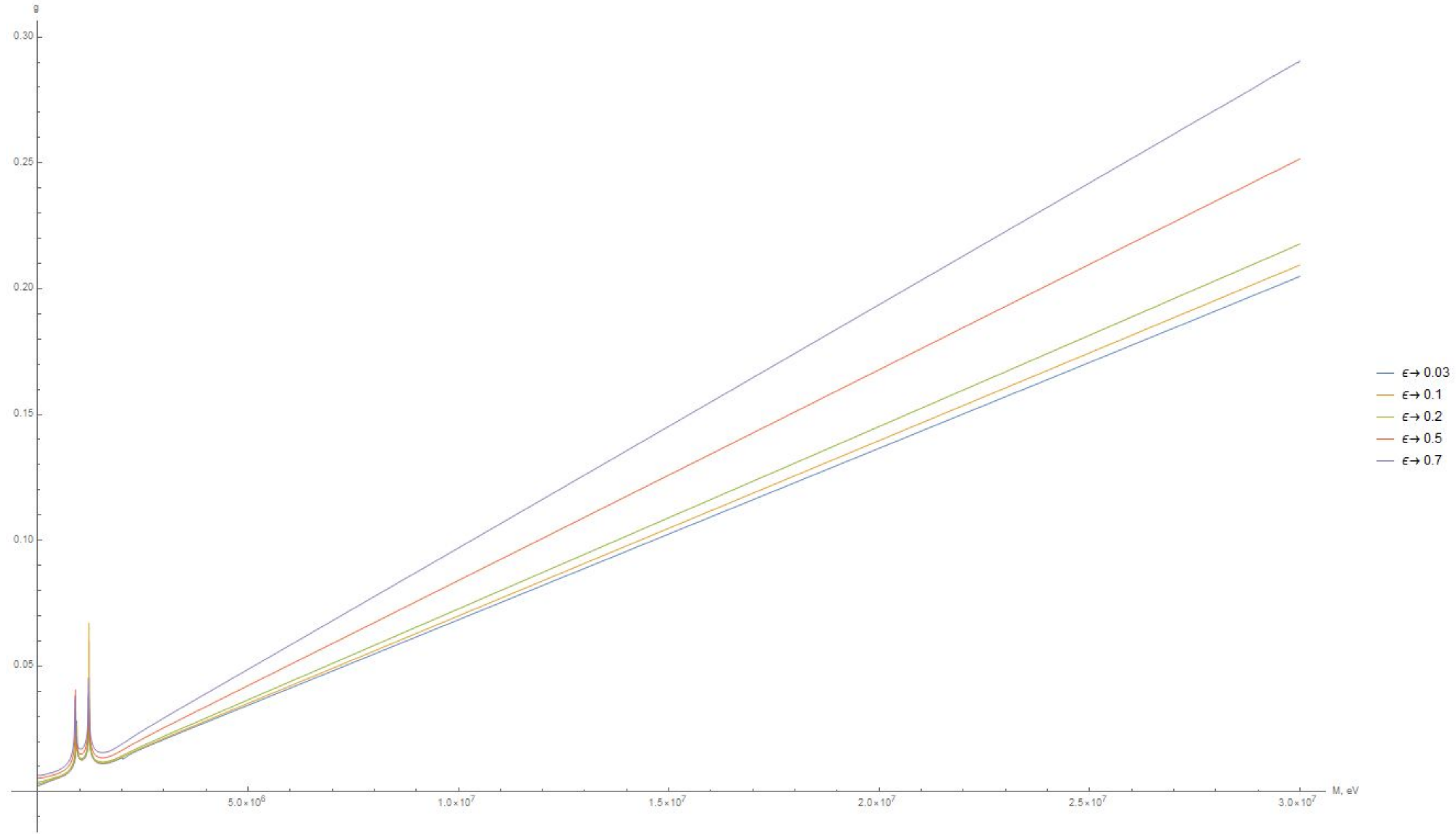


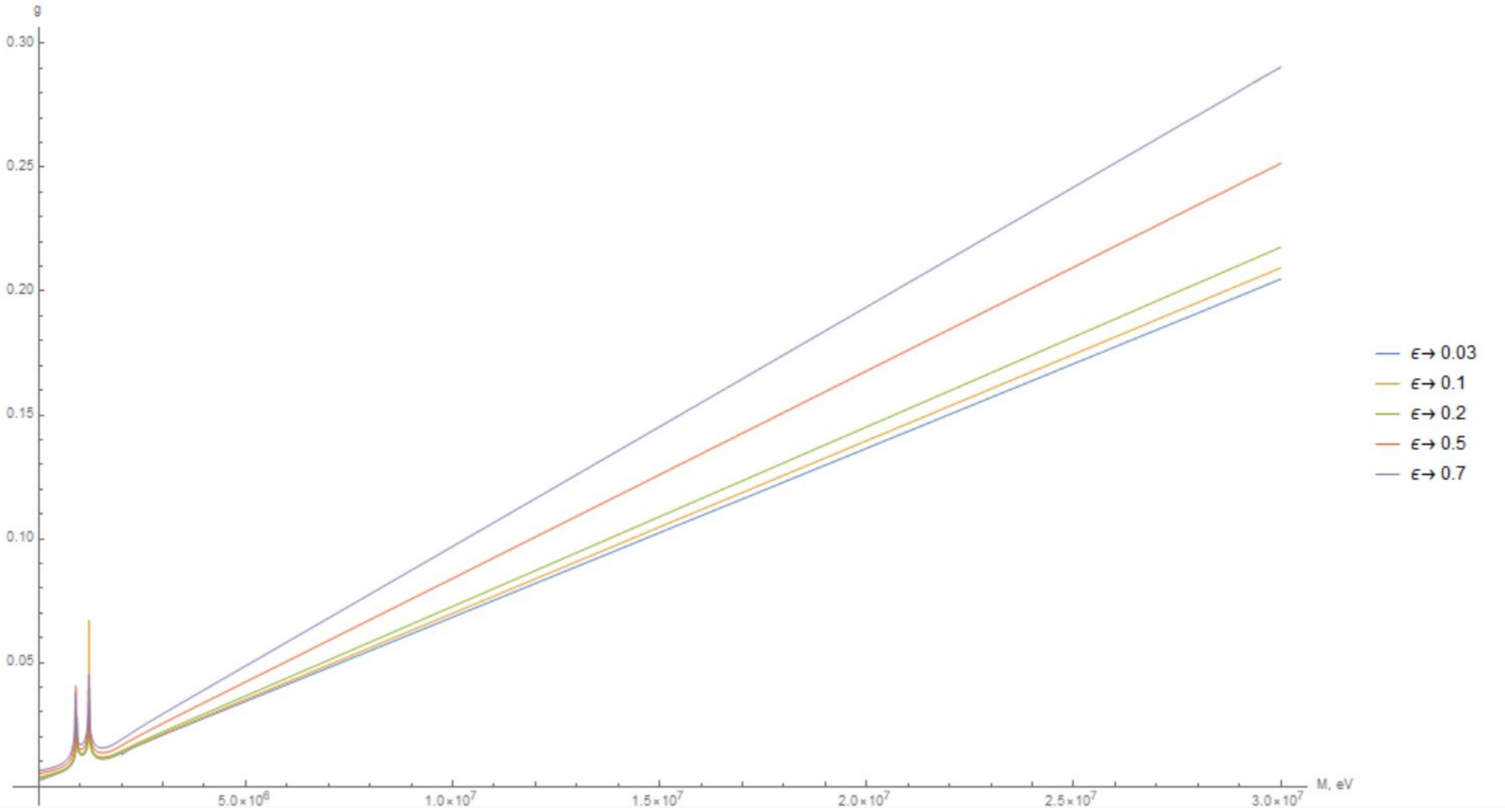

g
0.025
0.020
0.015
0.010
0.005
[360]=
5
10
50
100
500
1000
Log[M], eV
Analytical
Light&Heavy, splitted
Kolb & Turner

Blazar



g
0.05
0.04
0.03
0.02
0.01
1×10^6
2×10^6
3×10^6
4×10^6
M, eV
ϵ→ 0.04
ϵ→ 0.1
ϵ→ 0.2
ϵ→ 0.5
ϵ→ 0.7


g
0.30
0.25
0.20
0.15
0.10
0.05
5.0×10^6
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
M, eV
ε→ 0.03
ε→ 0.1
ε→ 0.2
ε→ 0.5
ε→ 0.7


g
0.30
0.25
0.20
0.15
0.10
0.05
5.0×10^6
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
M, eV
ϵ→ 0.03
ϵ→ 0.1
ϵ→ 0.2
ϵ→ 0.5
ϵ→ 0.7