Neutrino absorption below PeV scale at IceCube

Kunio Kaneta (ICRR)

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In collaboration with Masahiro Ibe (ICRR & IPMU)

Reference: arXiv:1407.2848

PPP2014, 29-Jul. 2014

CνB absorption line in the neutrino spectrum at IceCube

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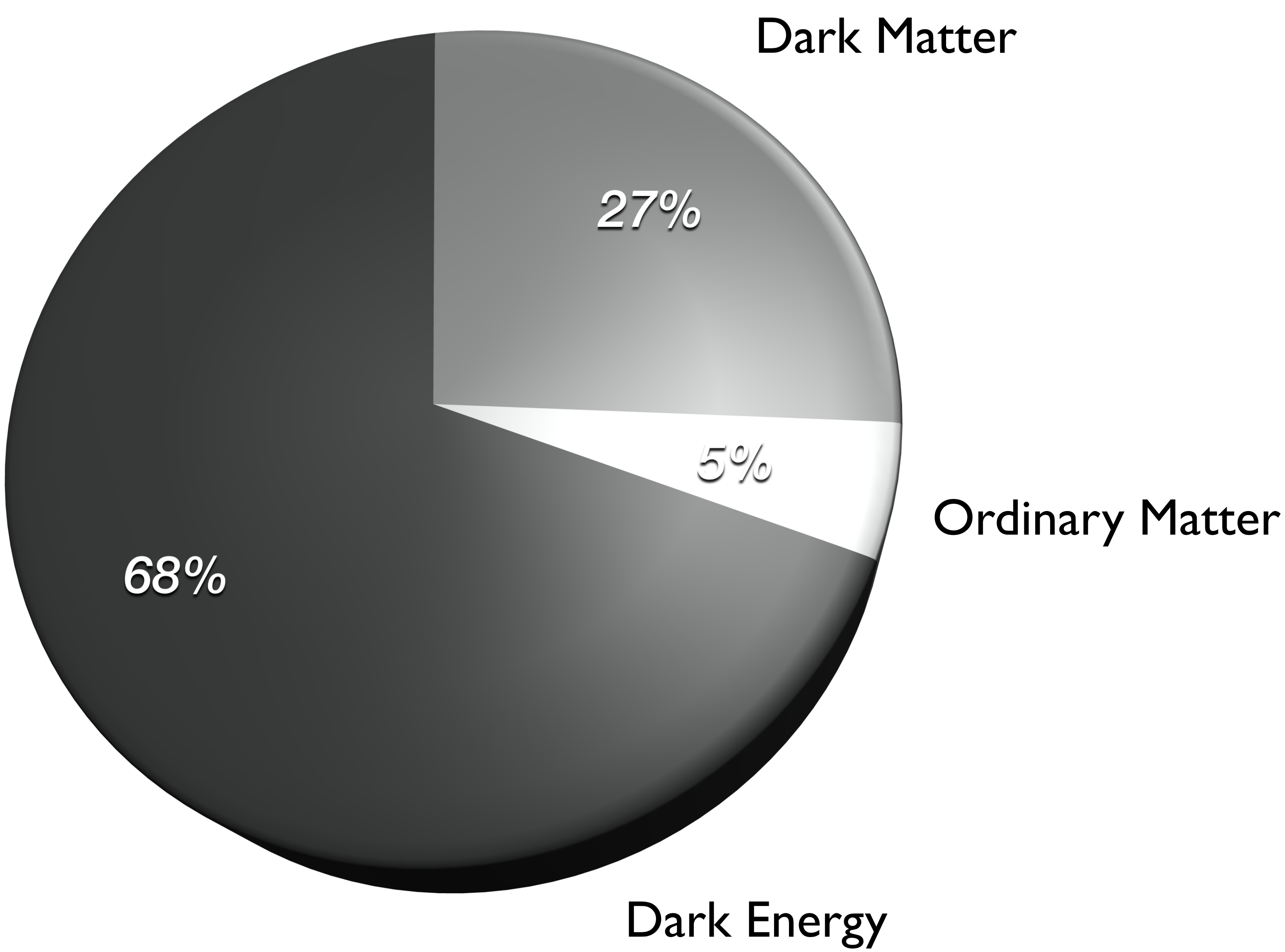
Outline

1. Introduction
2. Neutrino absorption at sub-PeV scale
3. Viable models
4. Summary

Energy budget of the Universe



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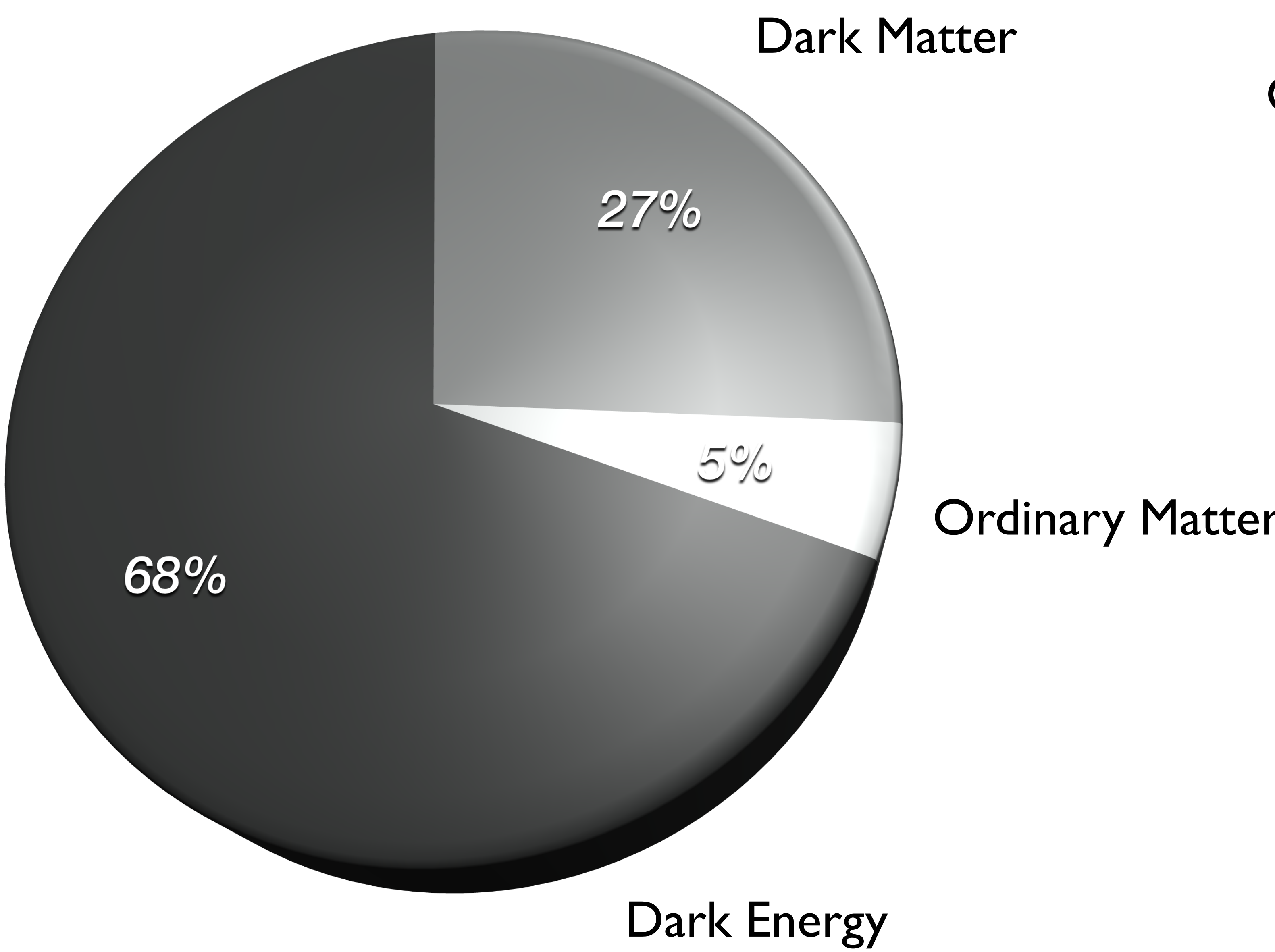

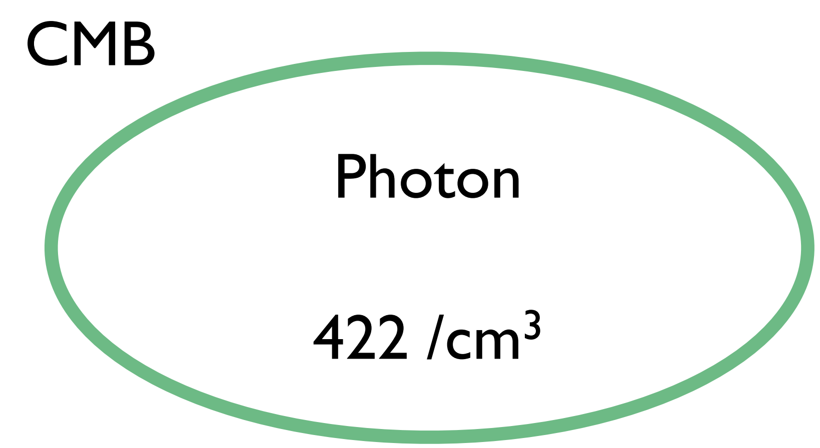

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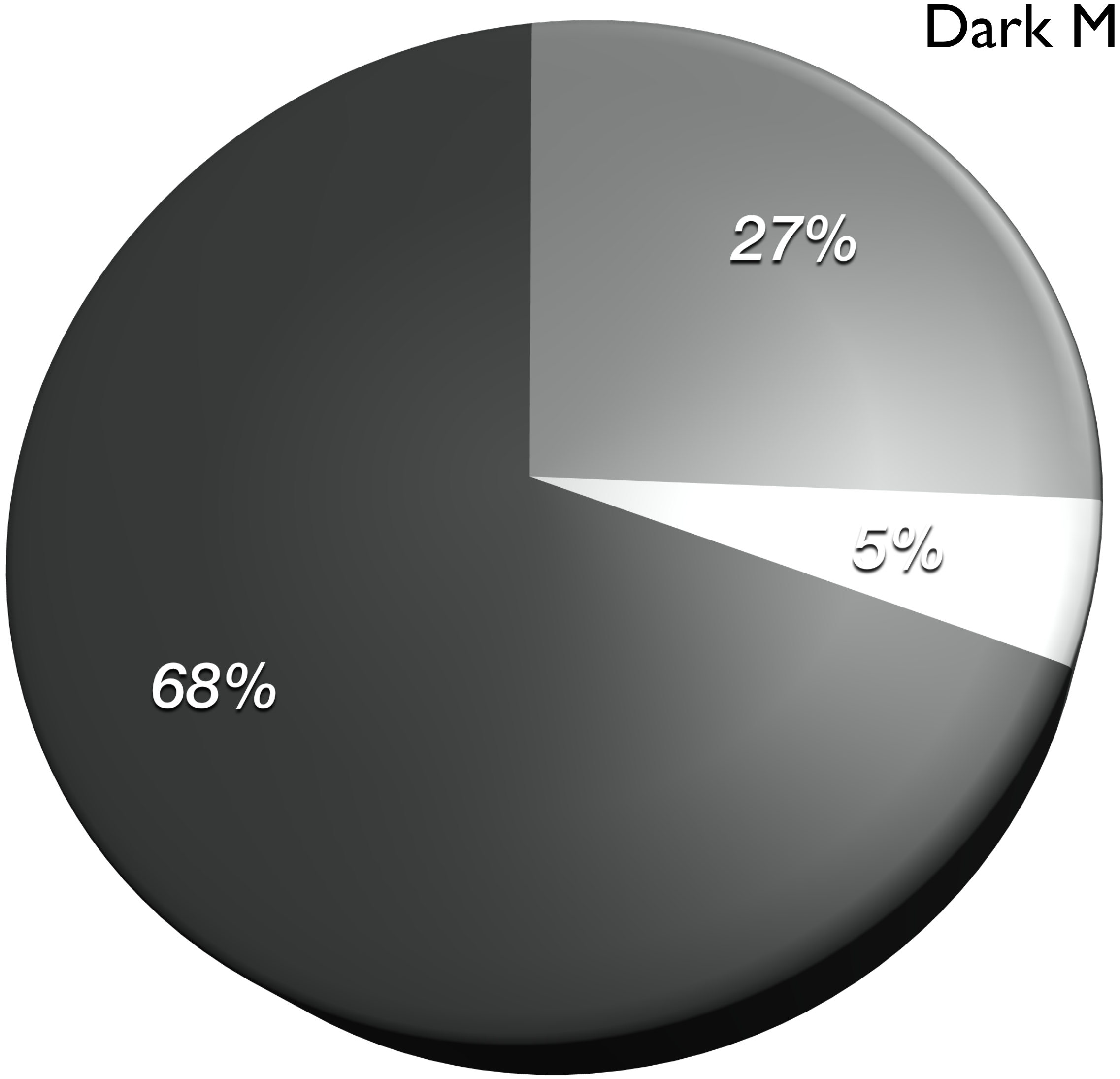


CMB

Photon

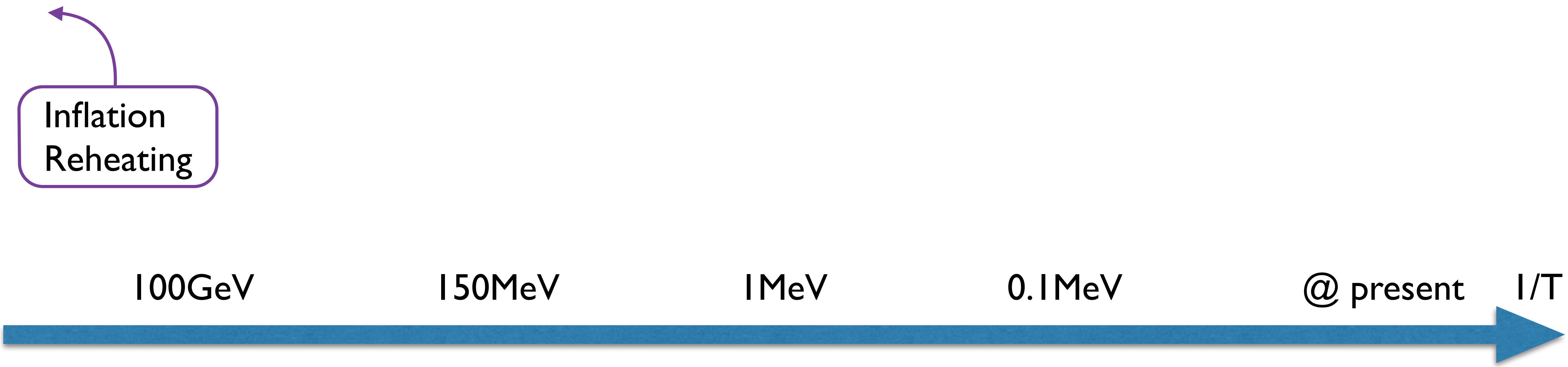
422 /cm^3

Neutrino

56 /cm^3 × 3 flavors

CνB

* Cosmic neutrino background (CνB)



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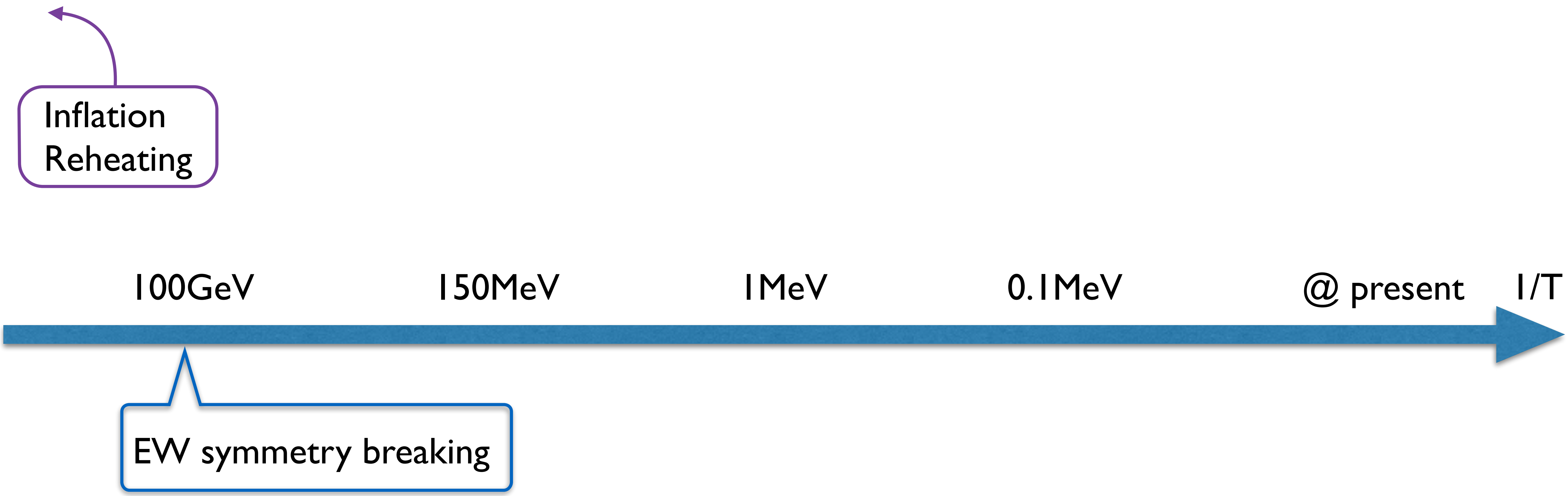

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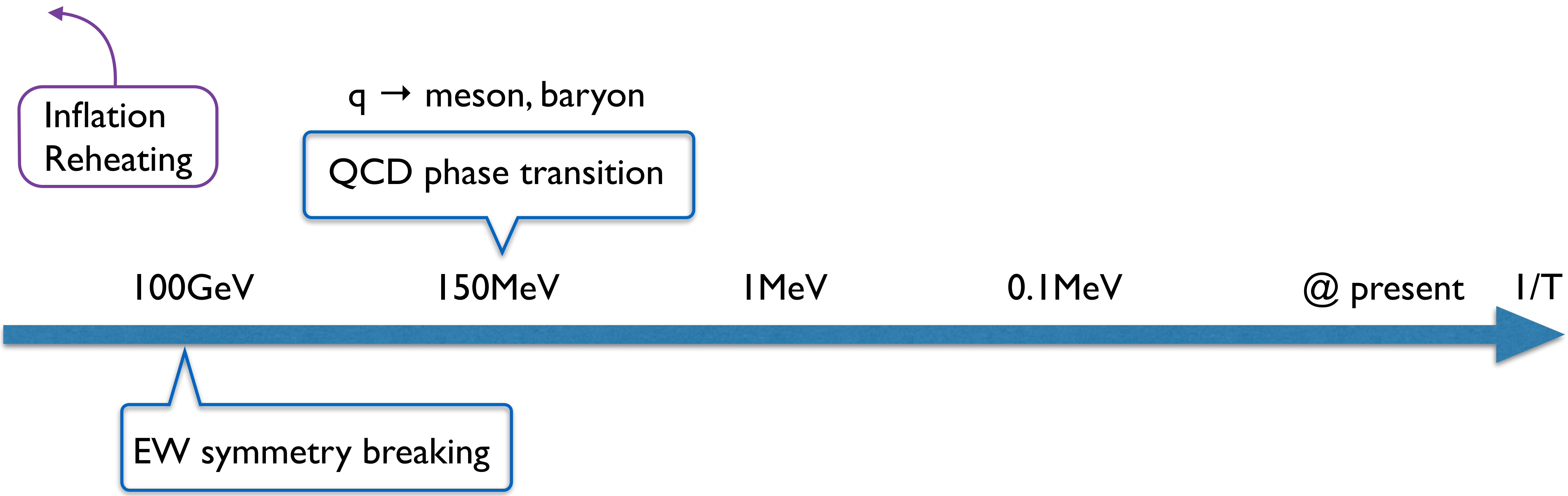

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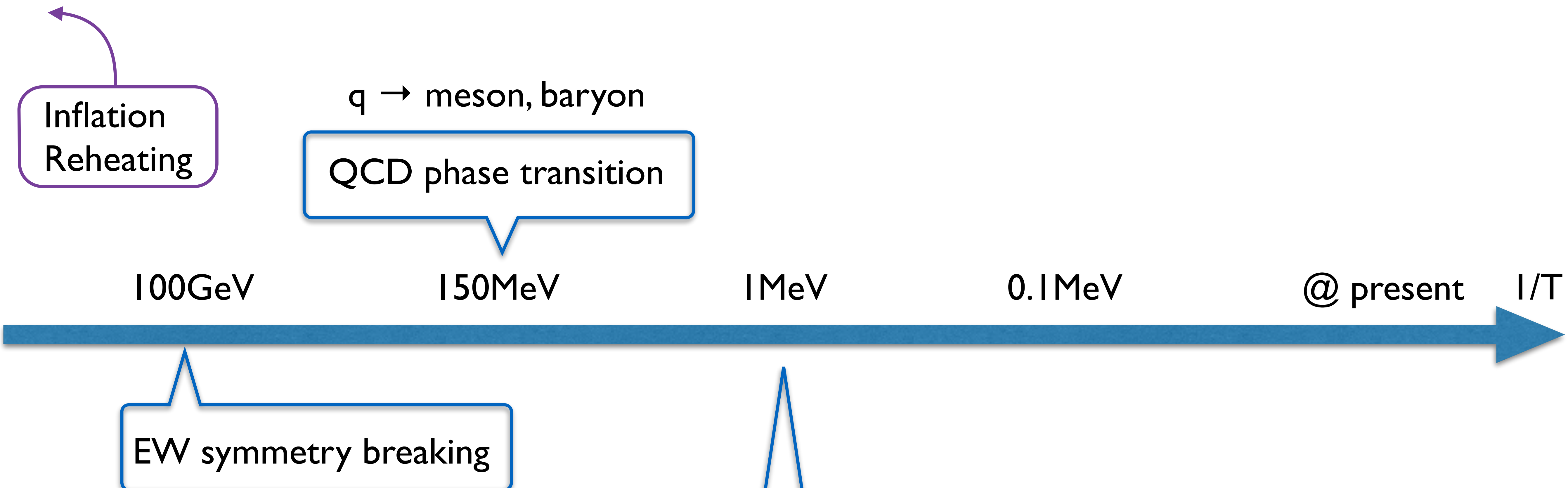
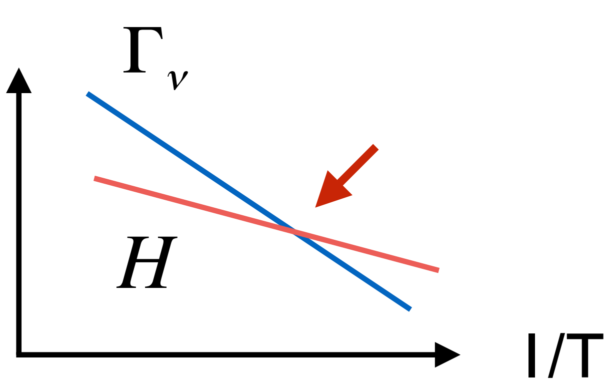


* Neutrino decoupling



cross section → annihilation rate

$$\sigma \simeq G_F^2 T^2 \;\longrightarrow\; \Gamma_\nu = n\langle \sigma v \rangle \simeq G_F^2 T^5$$

decoupling: $$\frac{\Gamma_\nu}{H} \simeq \frac{G_F^2 T^5}{T^2 / M_{pl}} \sim \left(\frac{T}{1MeV}\right)^3 \;\longrightarrow\; \textbf{C}\boldsymbol{\nu}\textbf{B}$$

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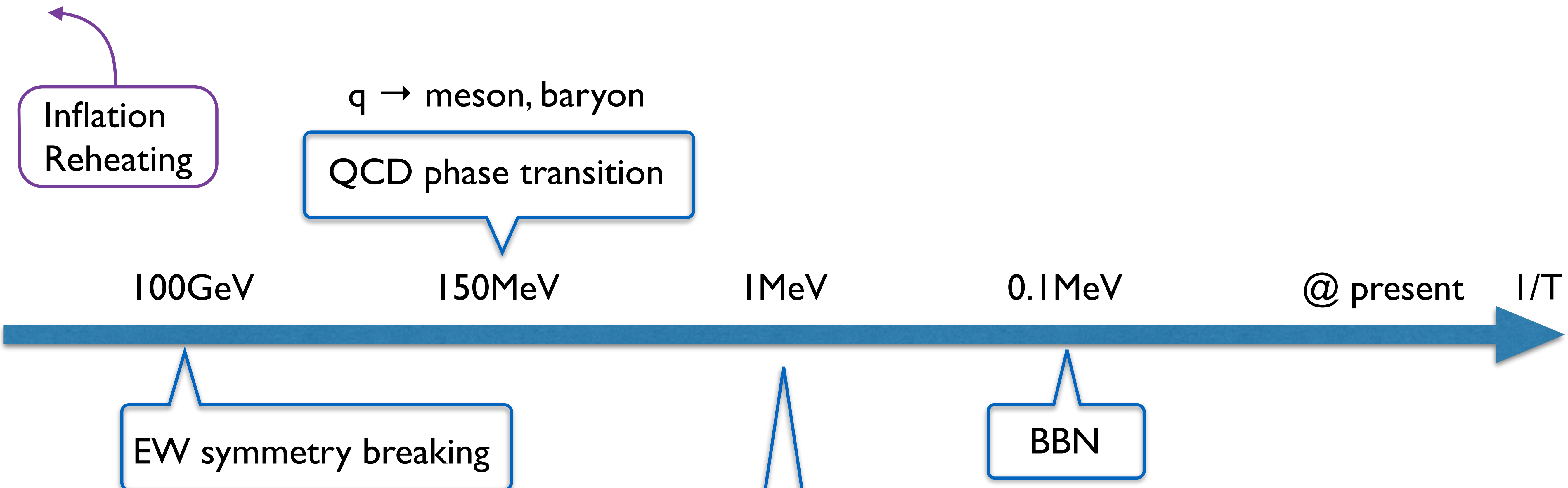

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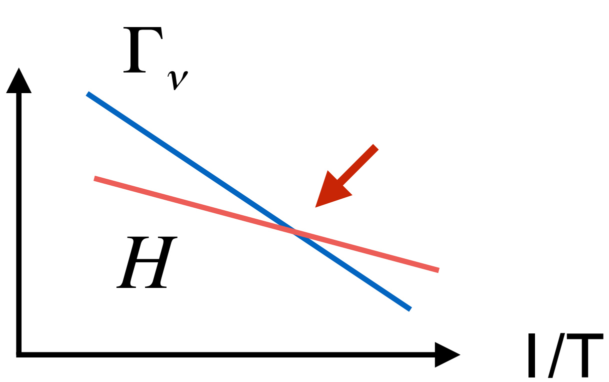

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* Cosmic neutrino background (CνB)

(1eV=1.16 × 10^4K)

*** Present Universe**

CMB: $T_\gamma \sim 2.7K$

CνB: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.9K$

Inflation
Reheating

q → meson, baryon

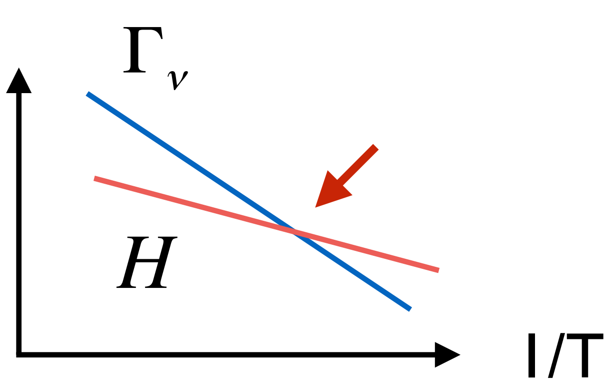
QCD phase transition

100GeV | 150MeV | 1MeV | 0.1MeV | @ present | 1/T

EW symmetry breaking

BBN

* Neutrino decoupling



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(1eV=1.16 × 10^4K)

Inflation
Reheating

q → meson, baryon

QCD phase transition

plays a central role

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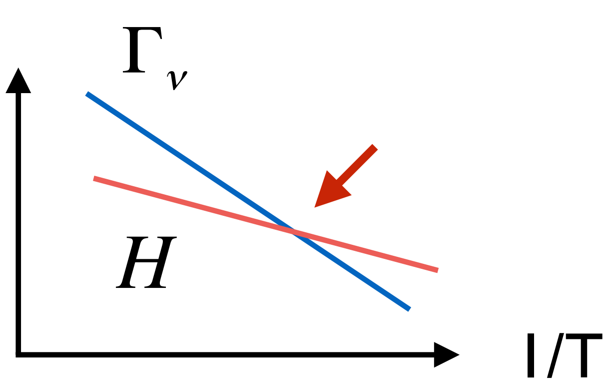

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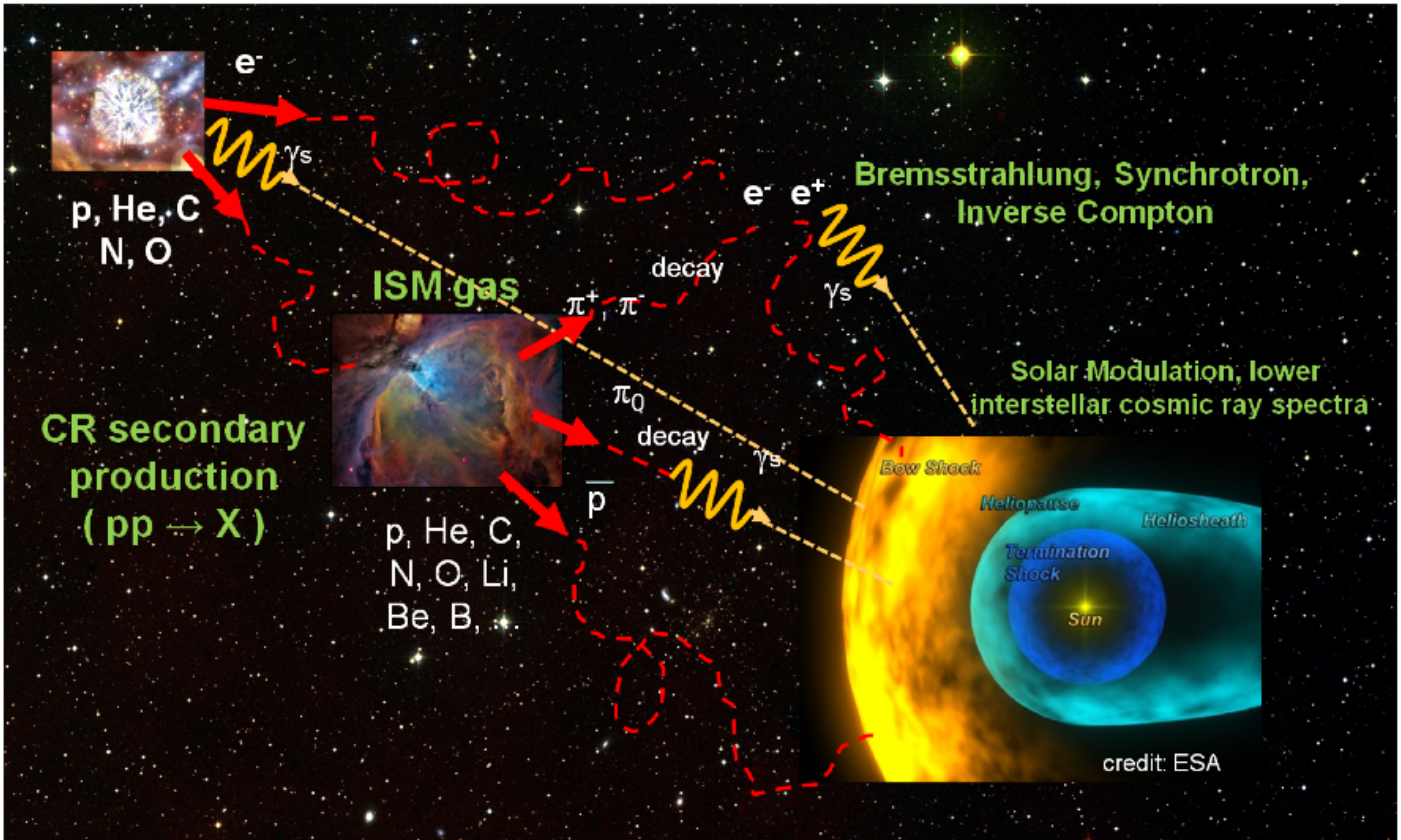
* Cosmic rays

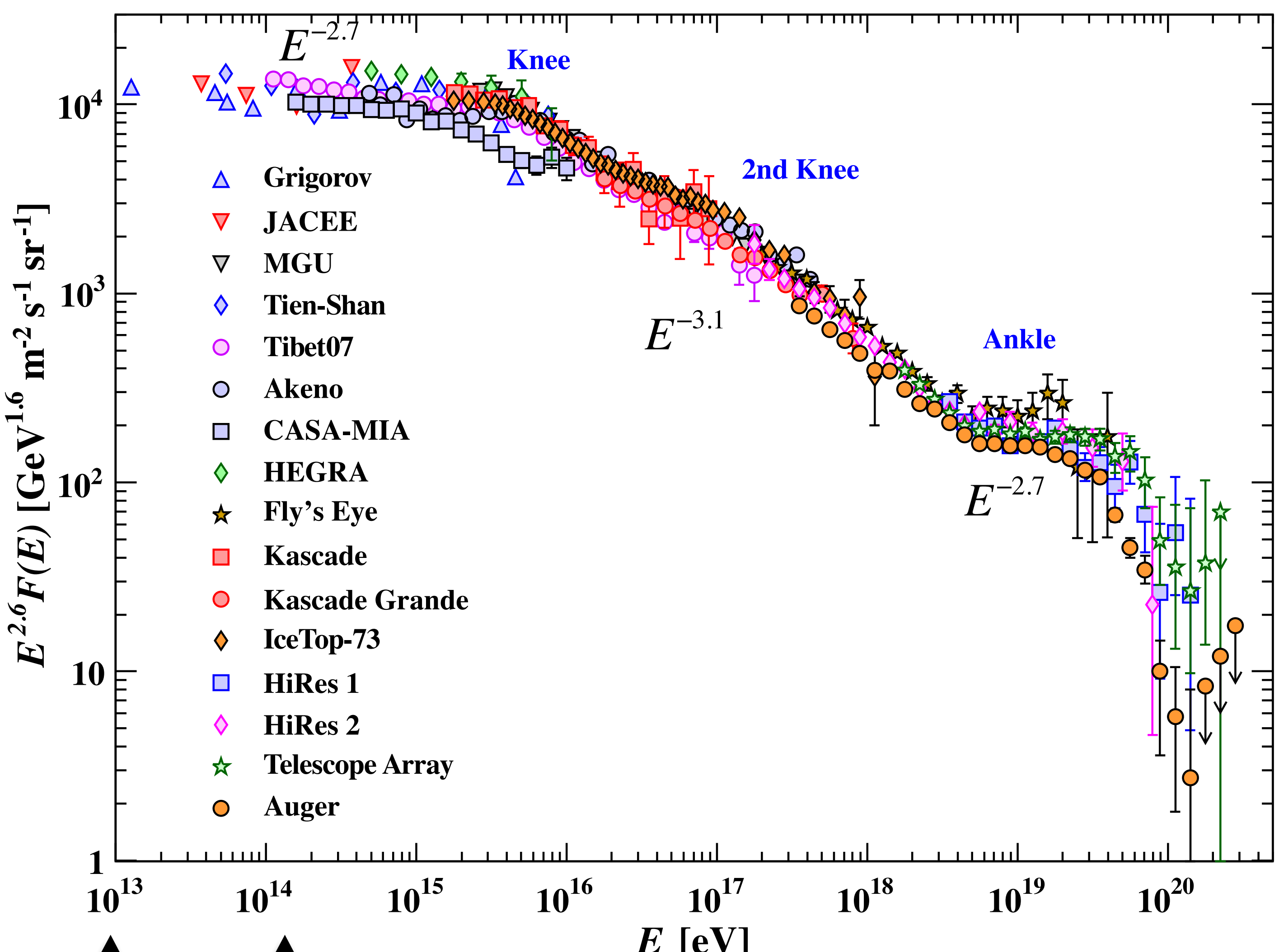
composition: p, He, C, O, …



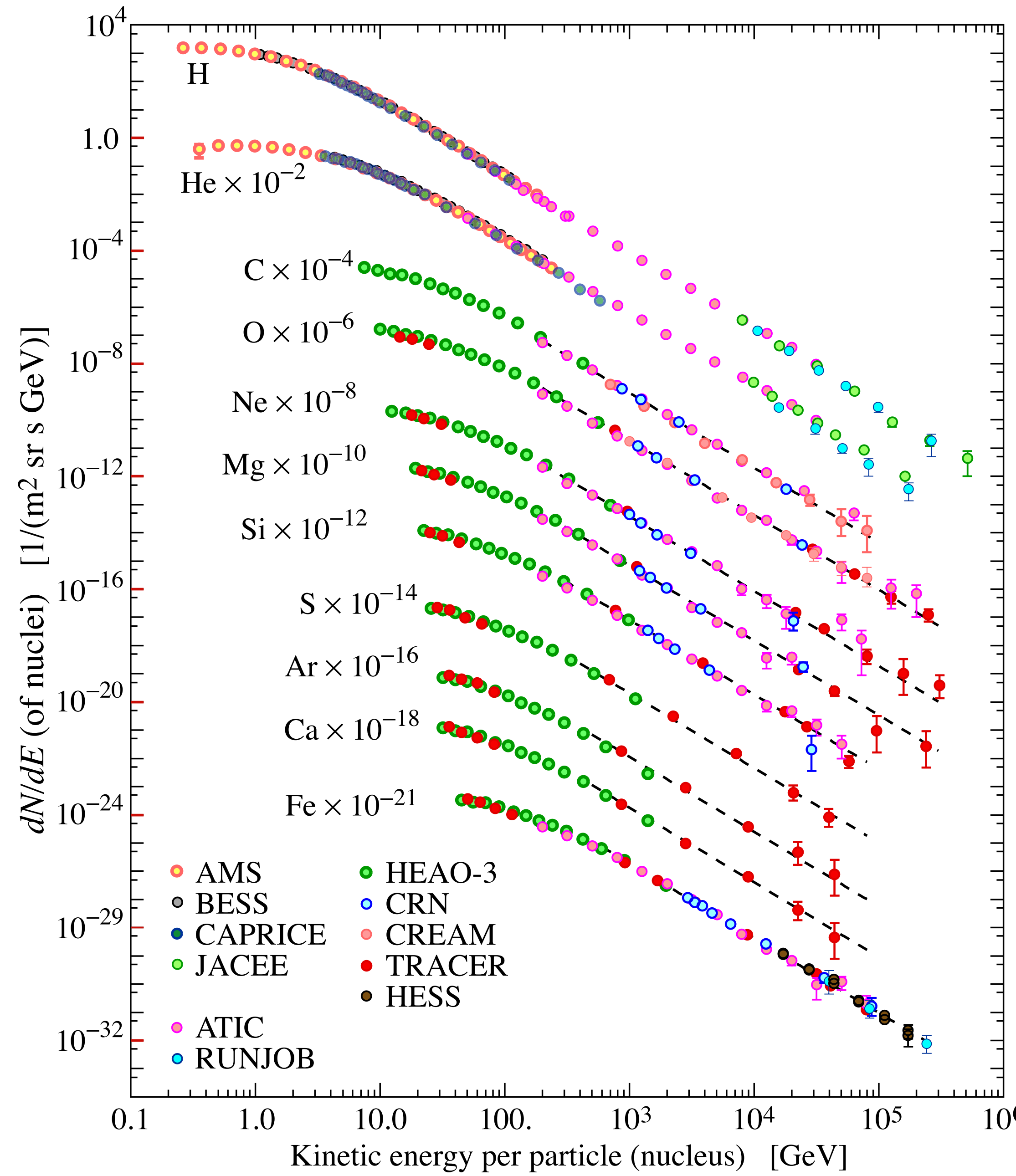
1407.1143

PDG

Energy spectrum: $N(E) = N_0 E^{-\alpha}$



1 TeV
14LHC



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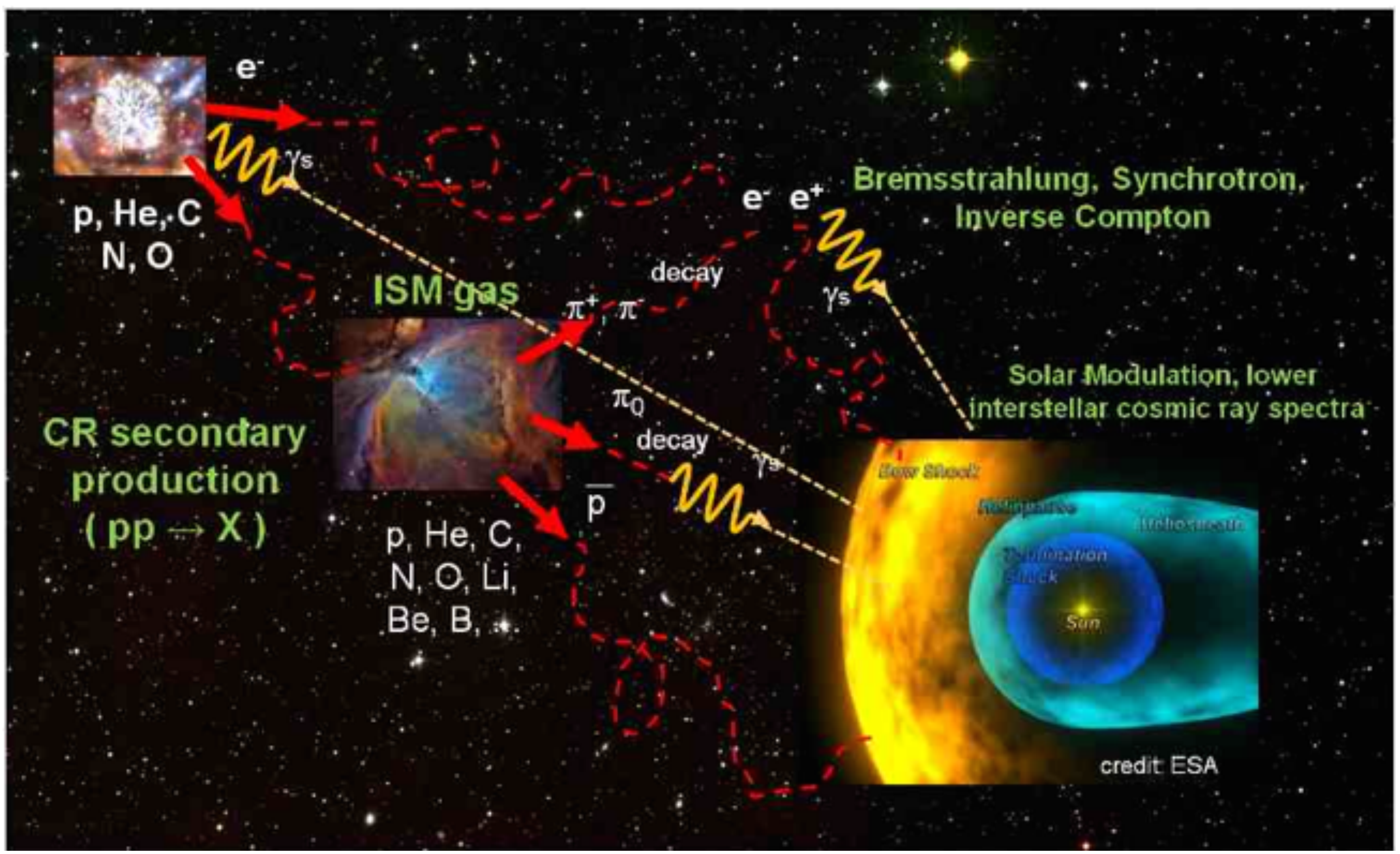
* Cosmic-ray neutrinos and IceCube

$$p + \underset{\text{CMB}}{\gamma} \rightarrow \Delta^+ \rightarrow n\ (p) + \pi^+\ (\pi^0)$$

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \rightarrow \gamma + \gamma$$



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γ

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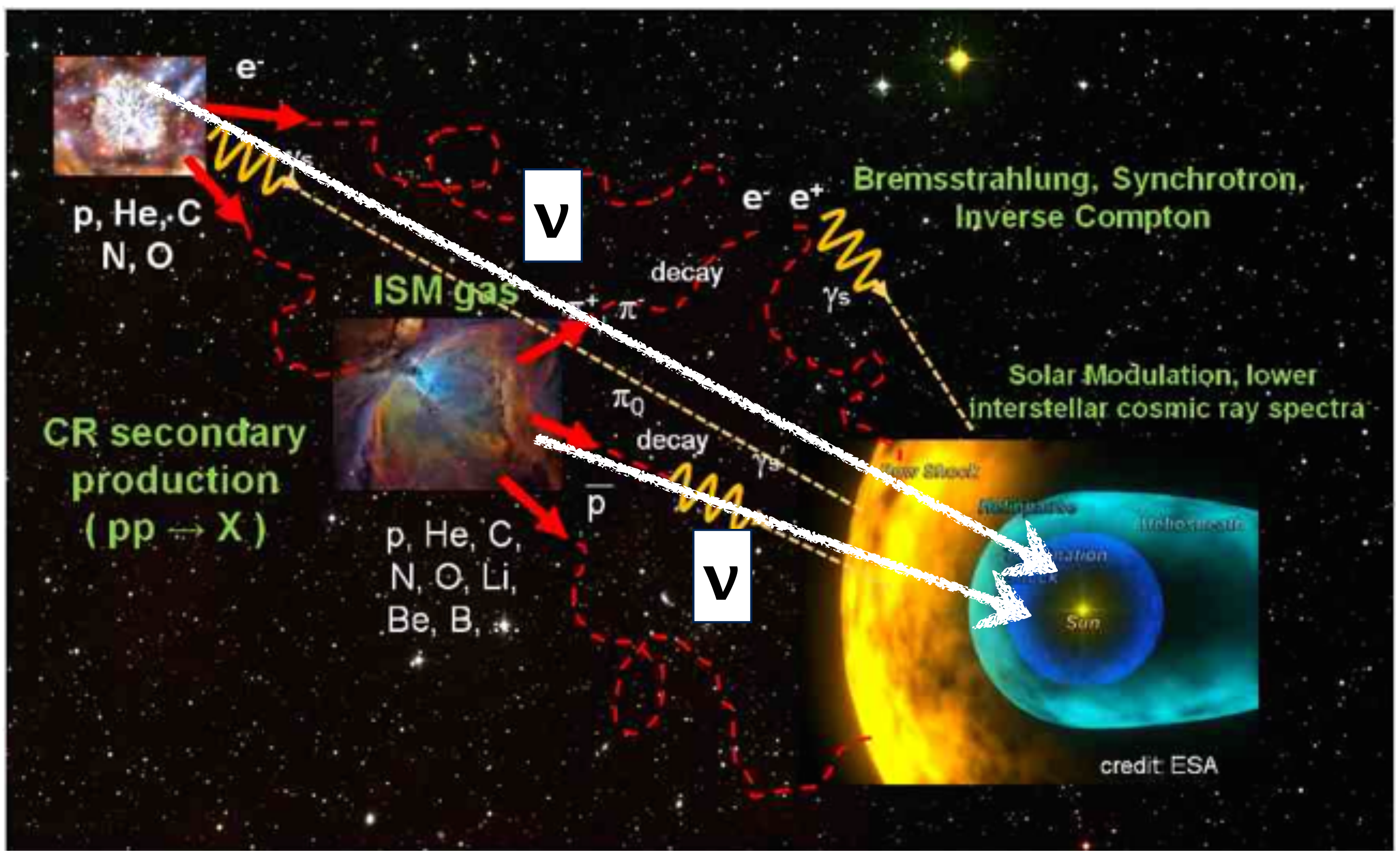

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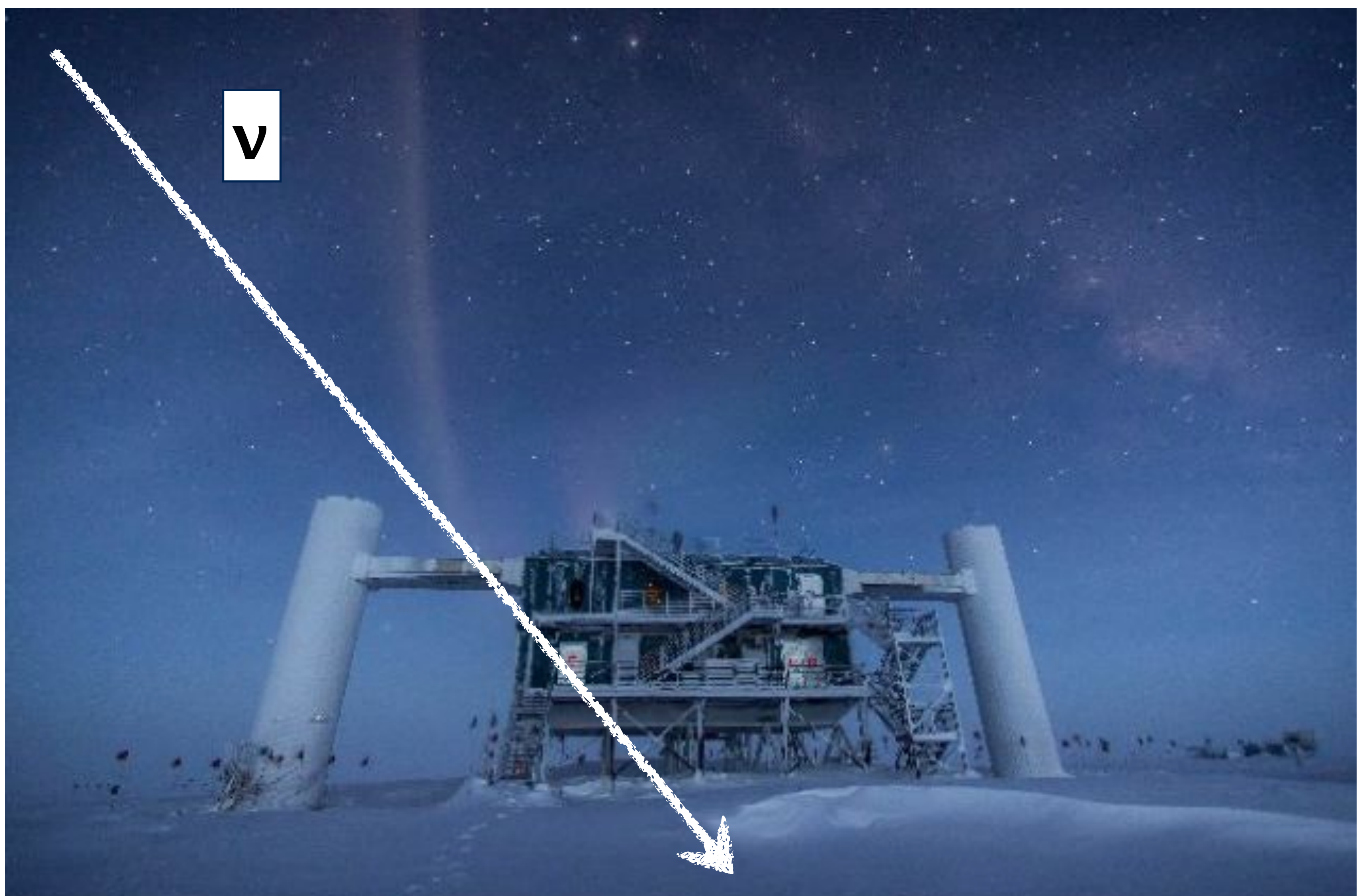

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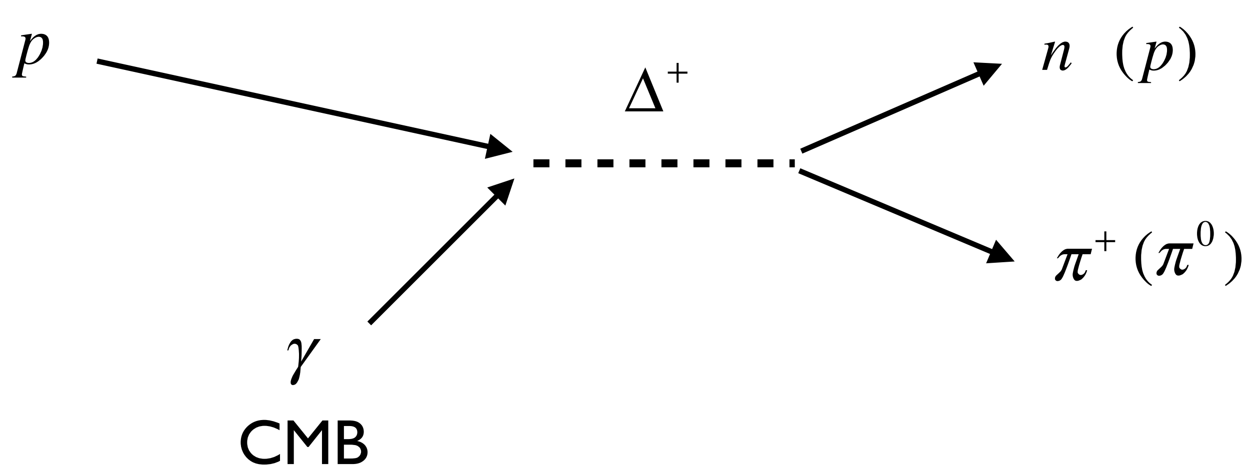

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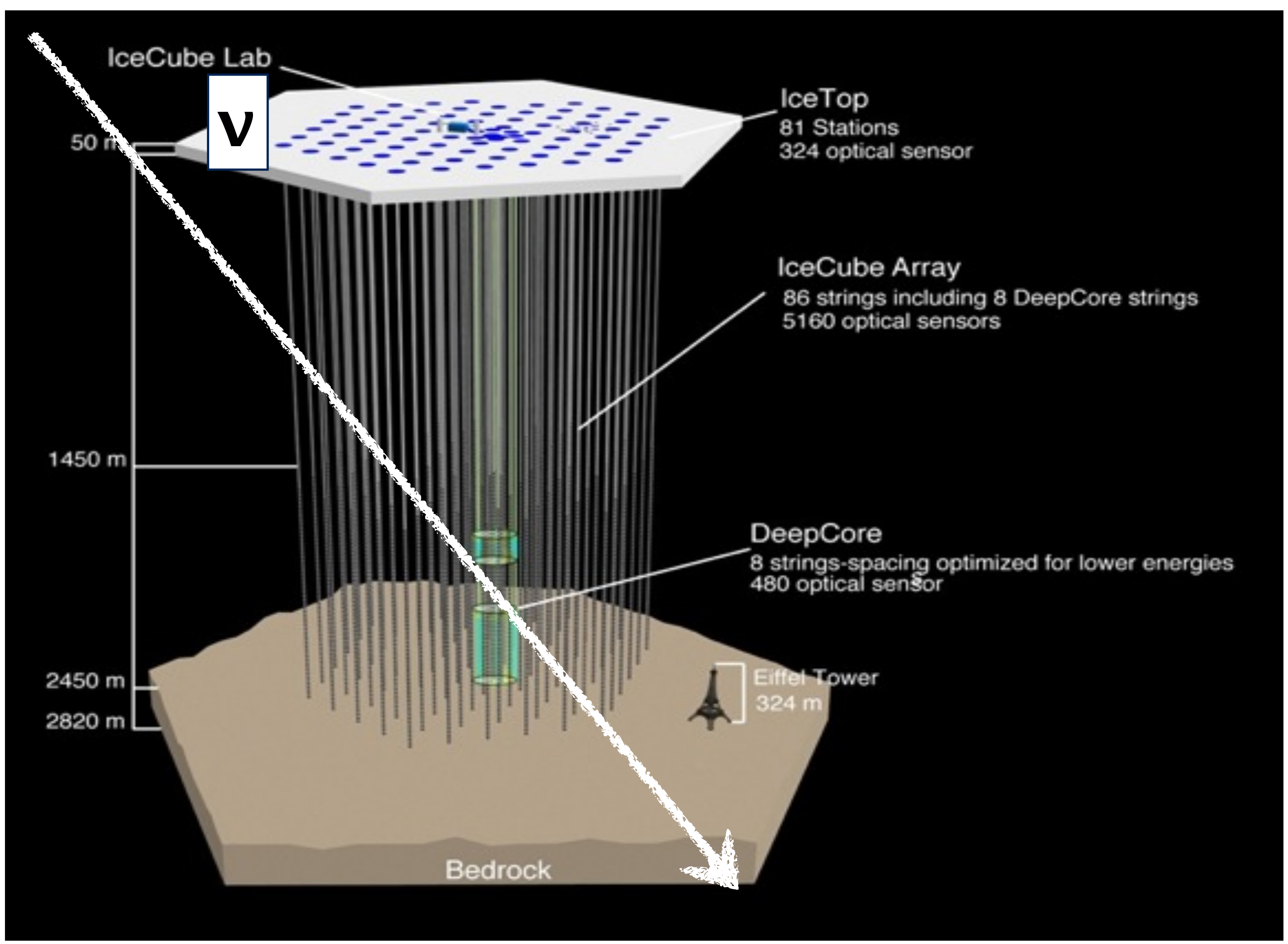

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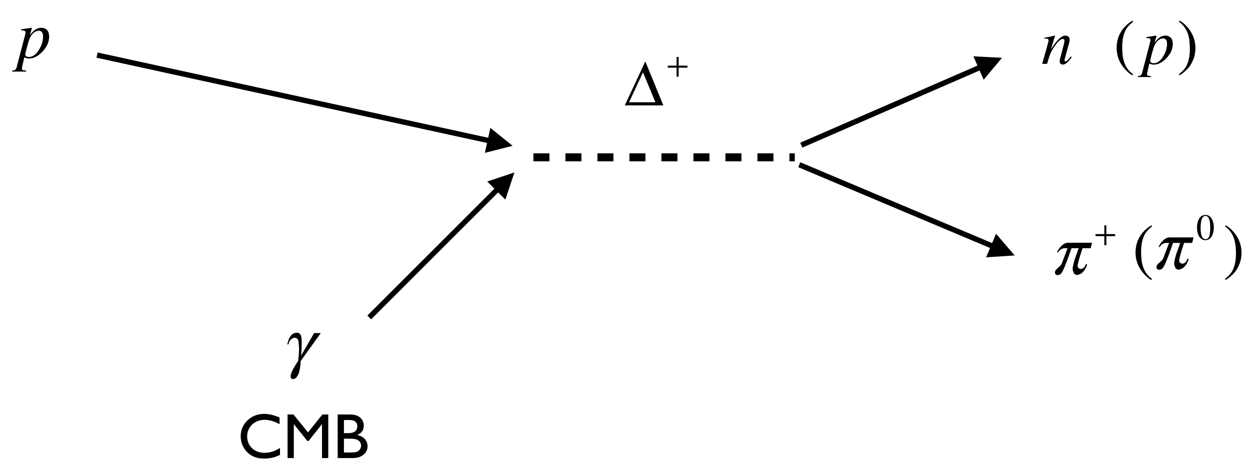

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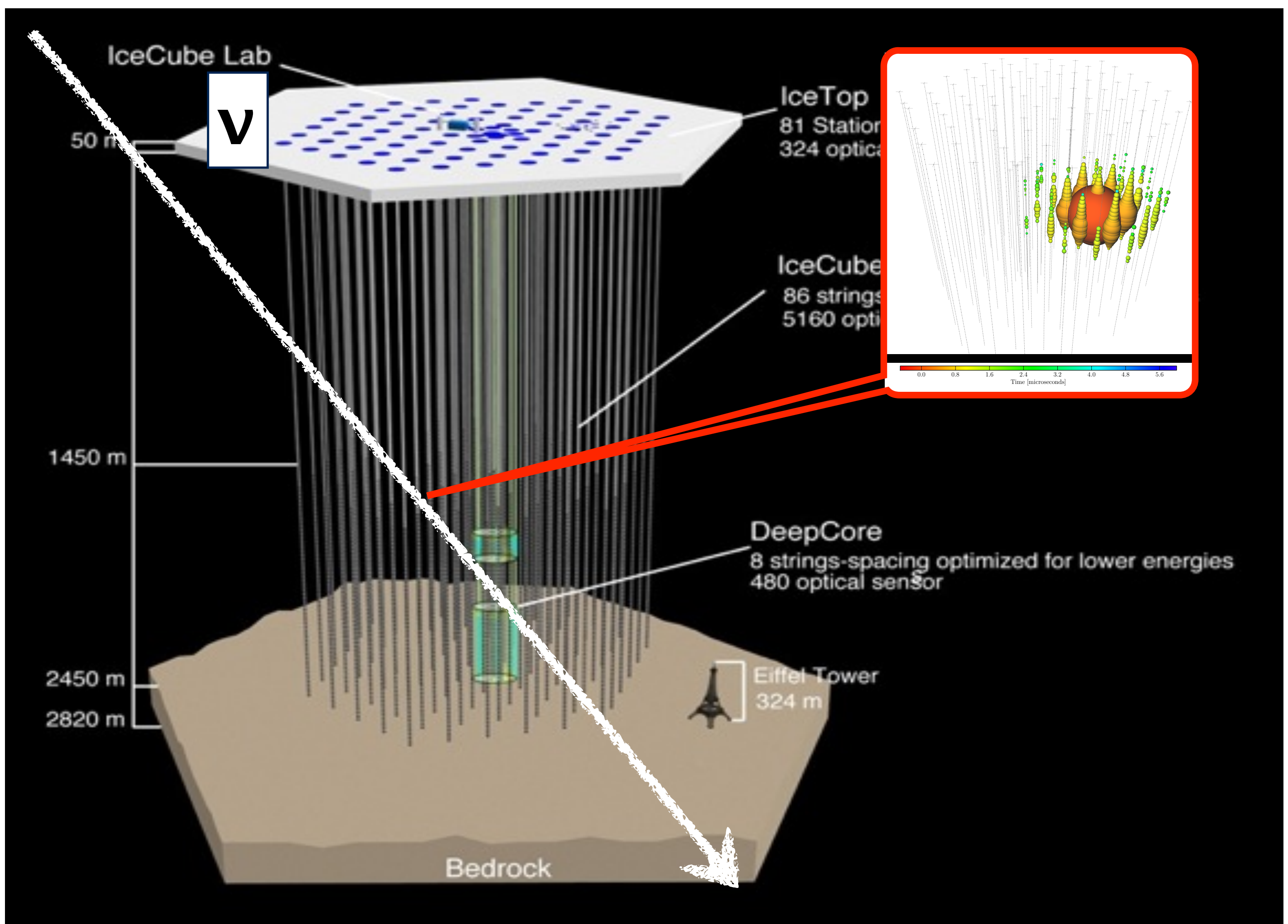
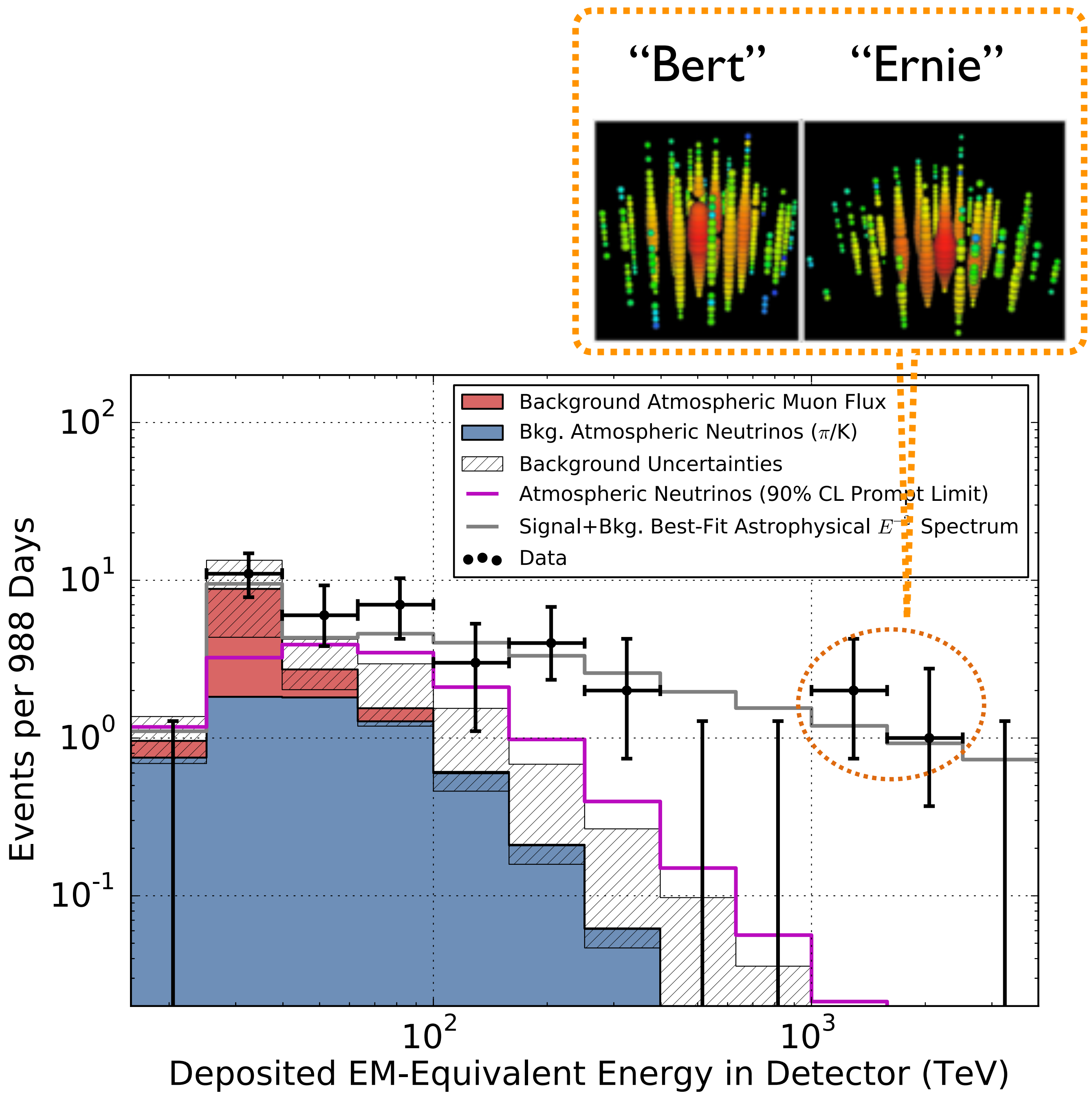
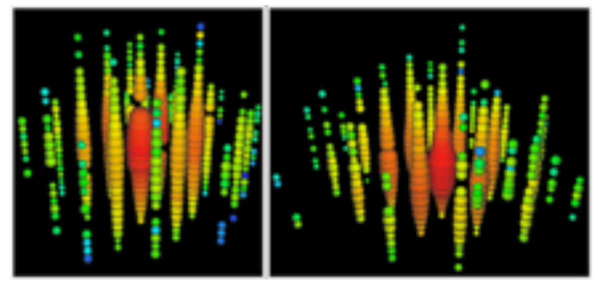


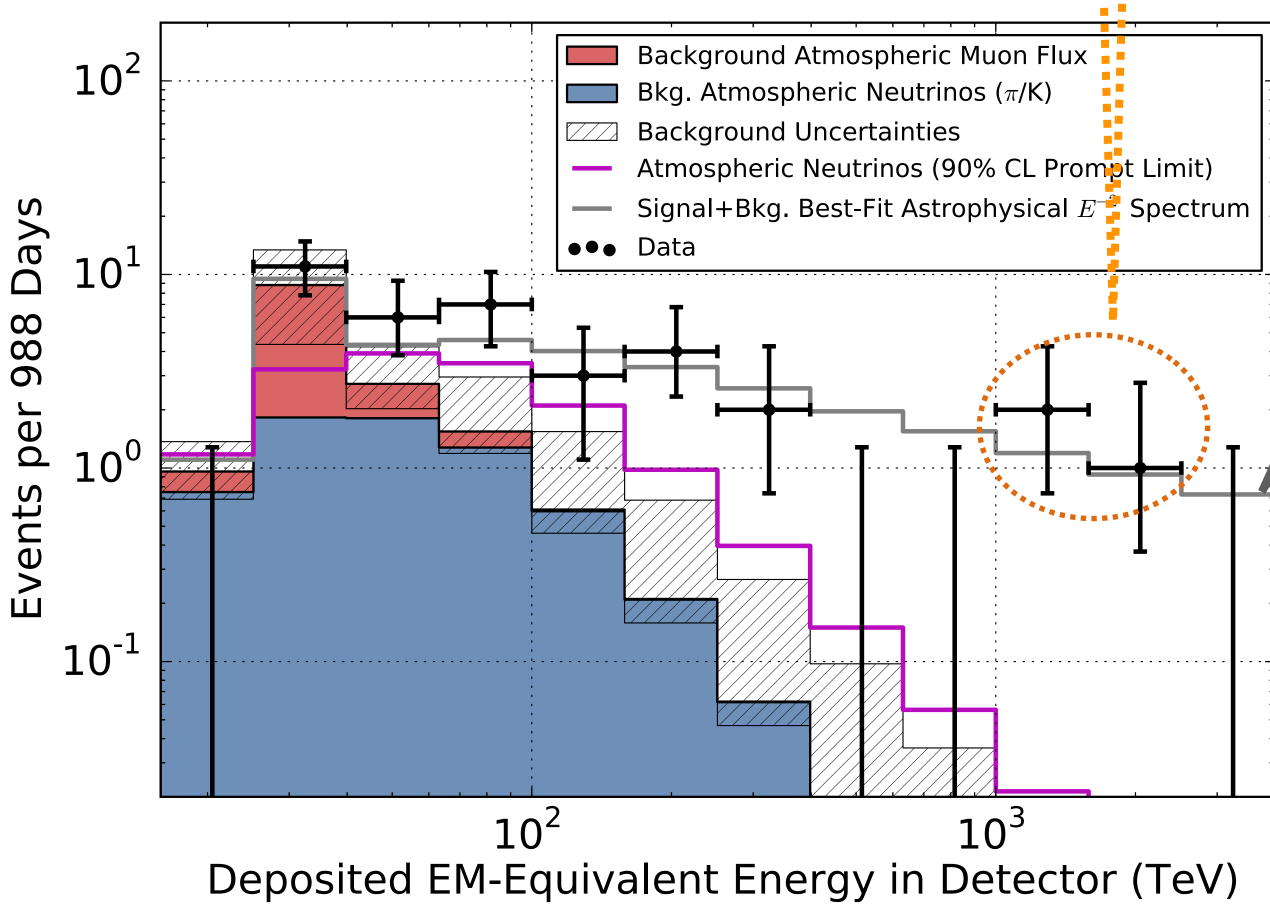
* IceCube result



* IceCube result

“Bert” “Ernie”





BEST-FIT (gray line)

$$N(E_\nu) \propto E_\nu^{-2}$$

“1st order Fermi acceleration mechanism”

(SNRs, GRBs, AGNs, star forming galaxies)

* IceCube result

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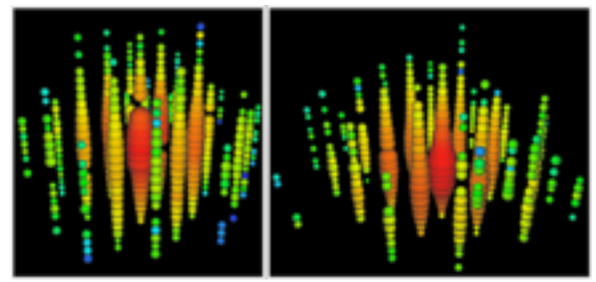

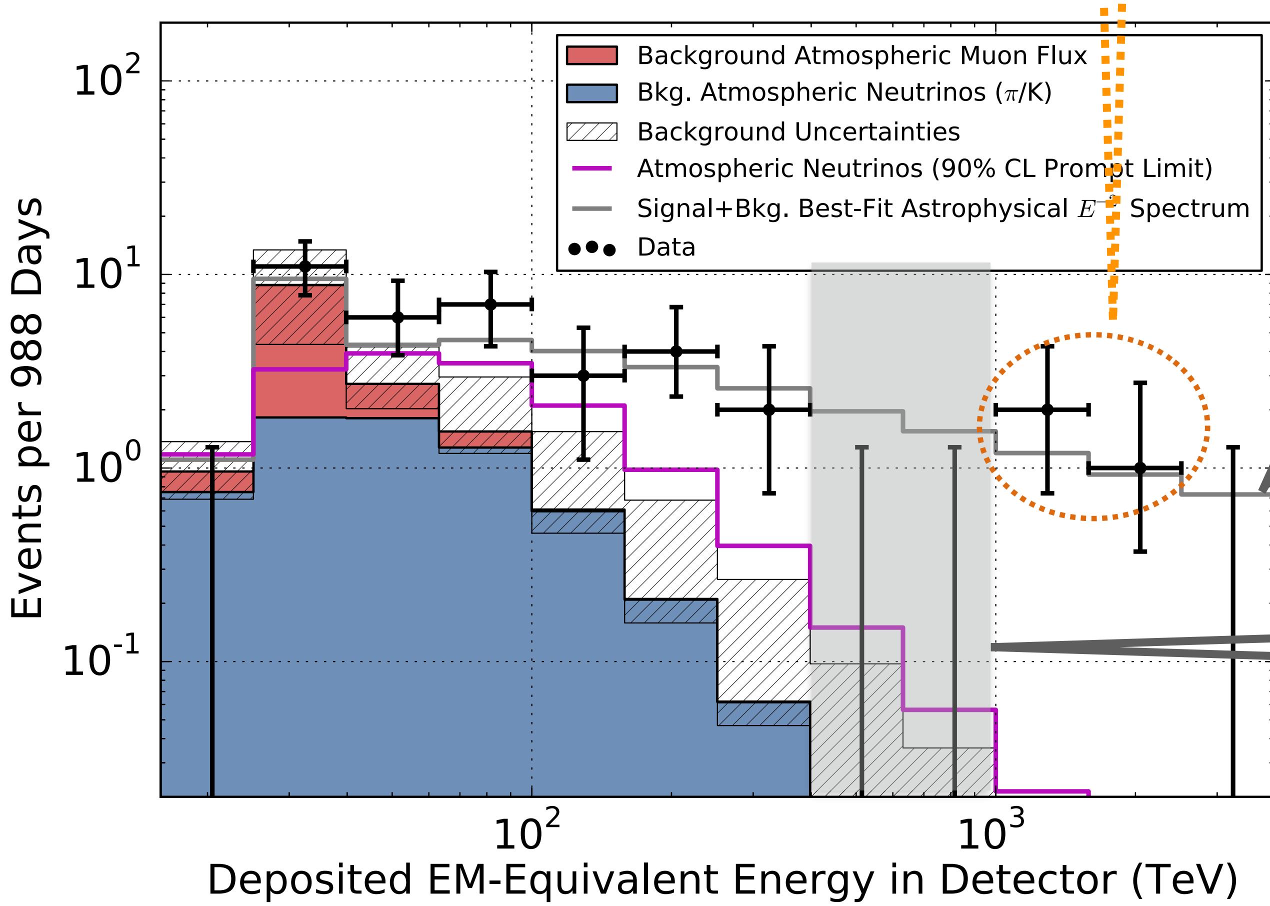

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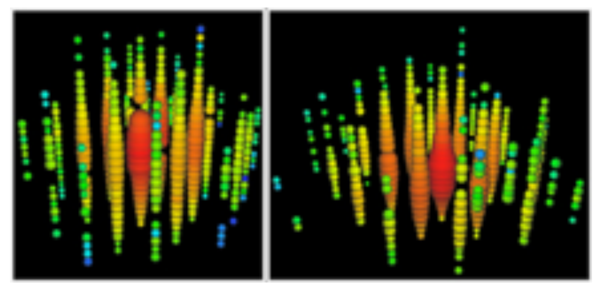

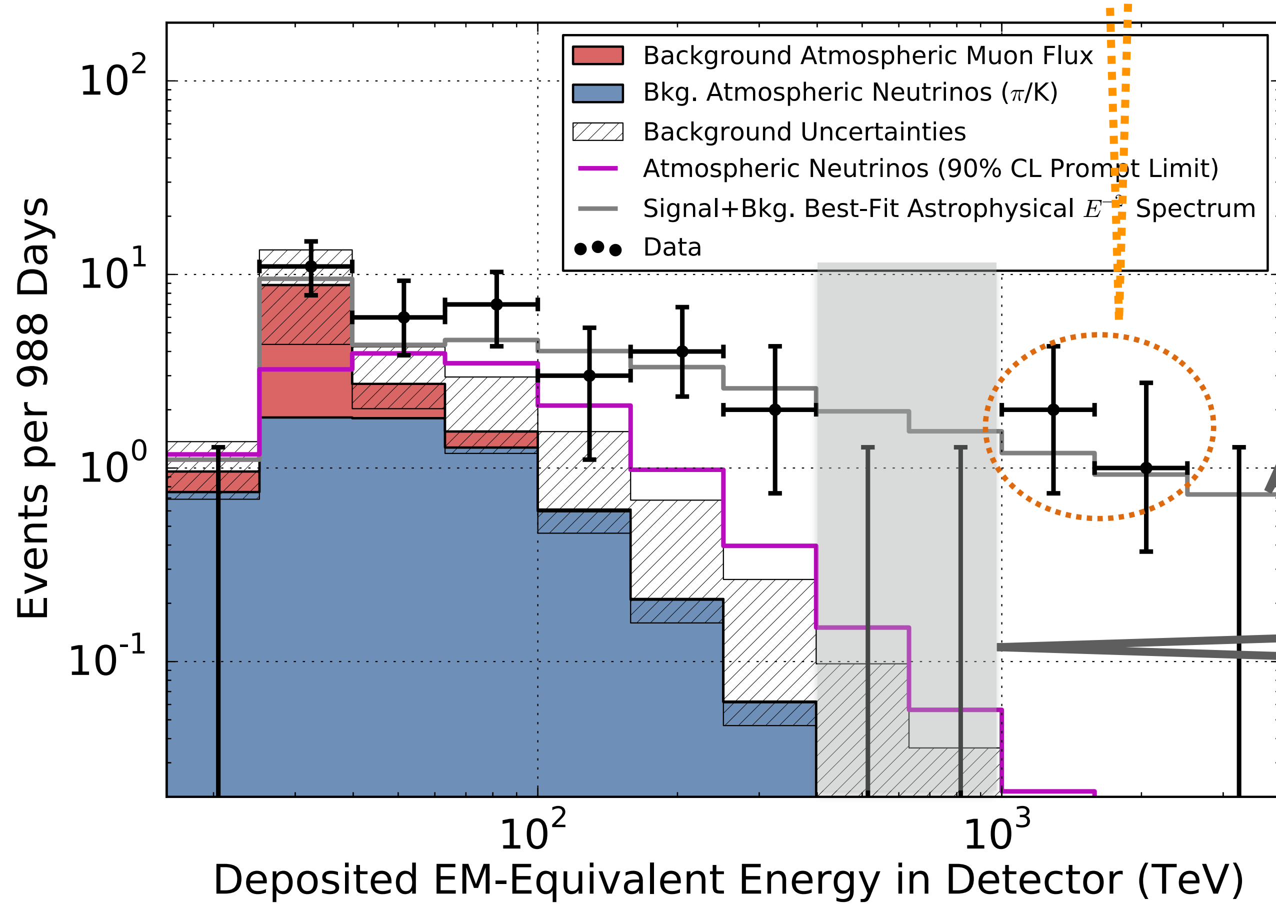

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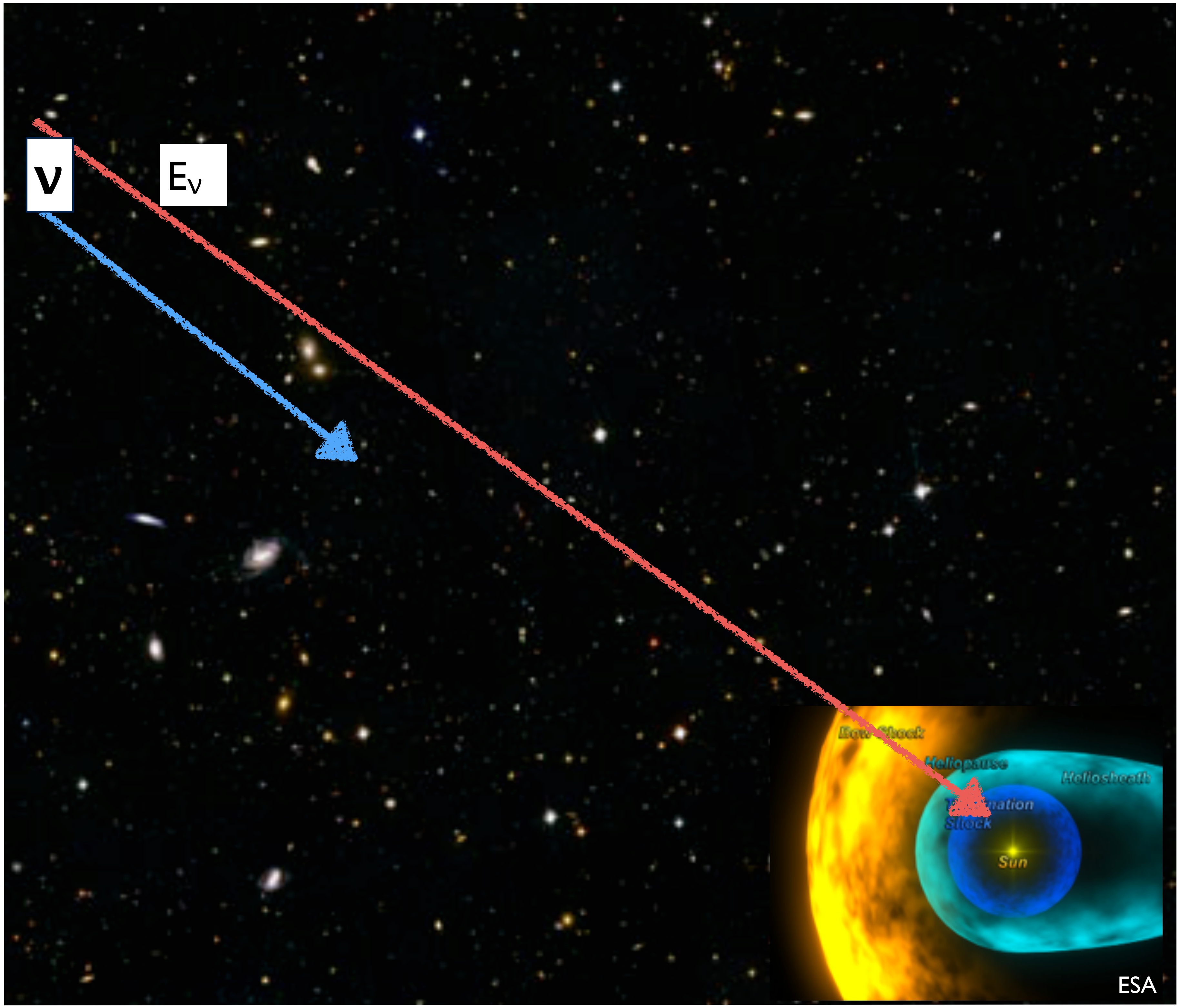
It looks like *"absorption line"!*

2, Neutrino absorption at sub-PeV scale

* Neutrino absorption scenario; essence



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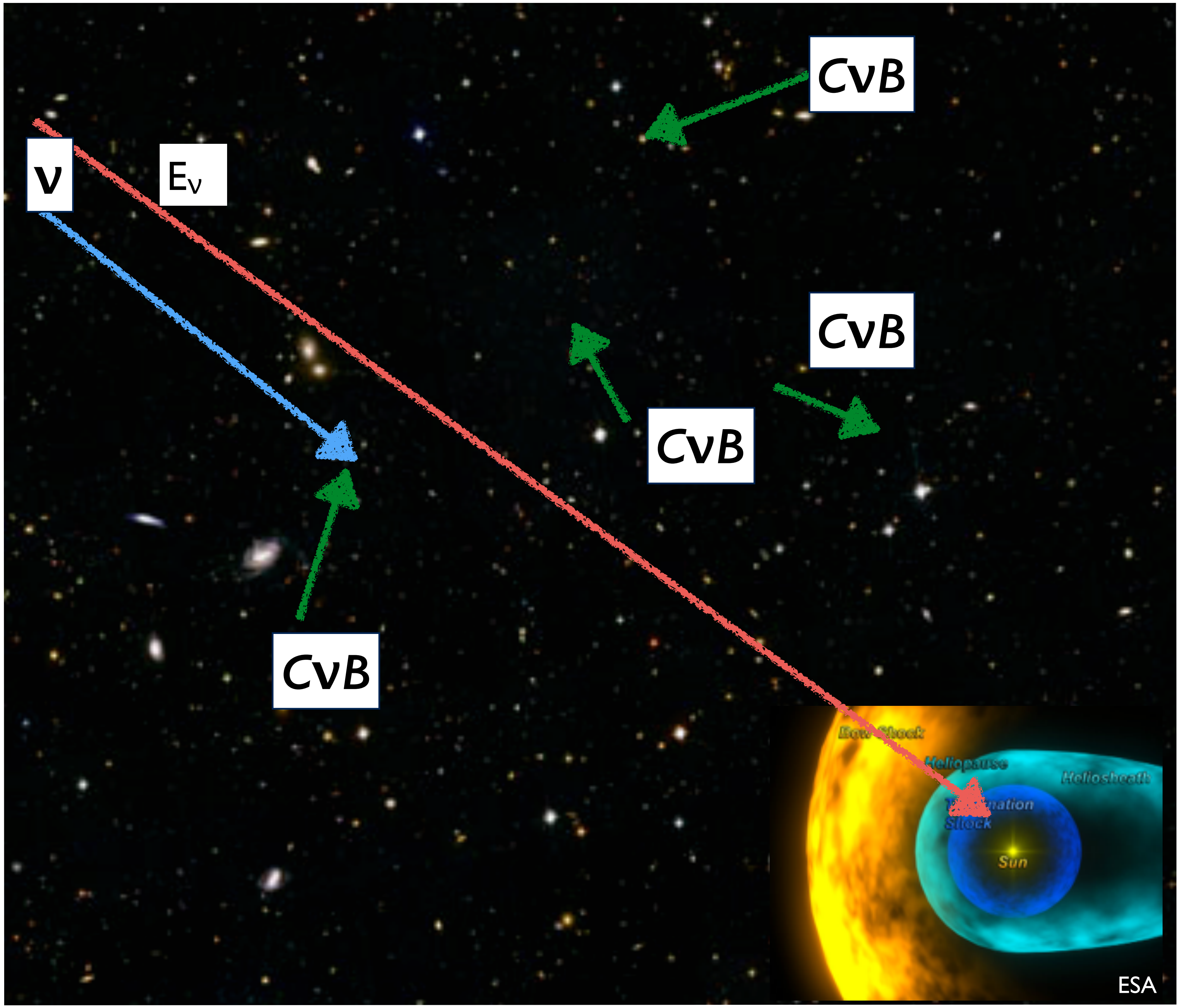

relevant process:

$$\nu\nu_{C\nu B} \to \nu\nu$$

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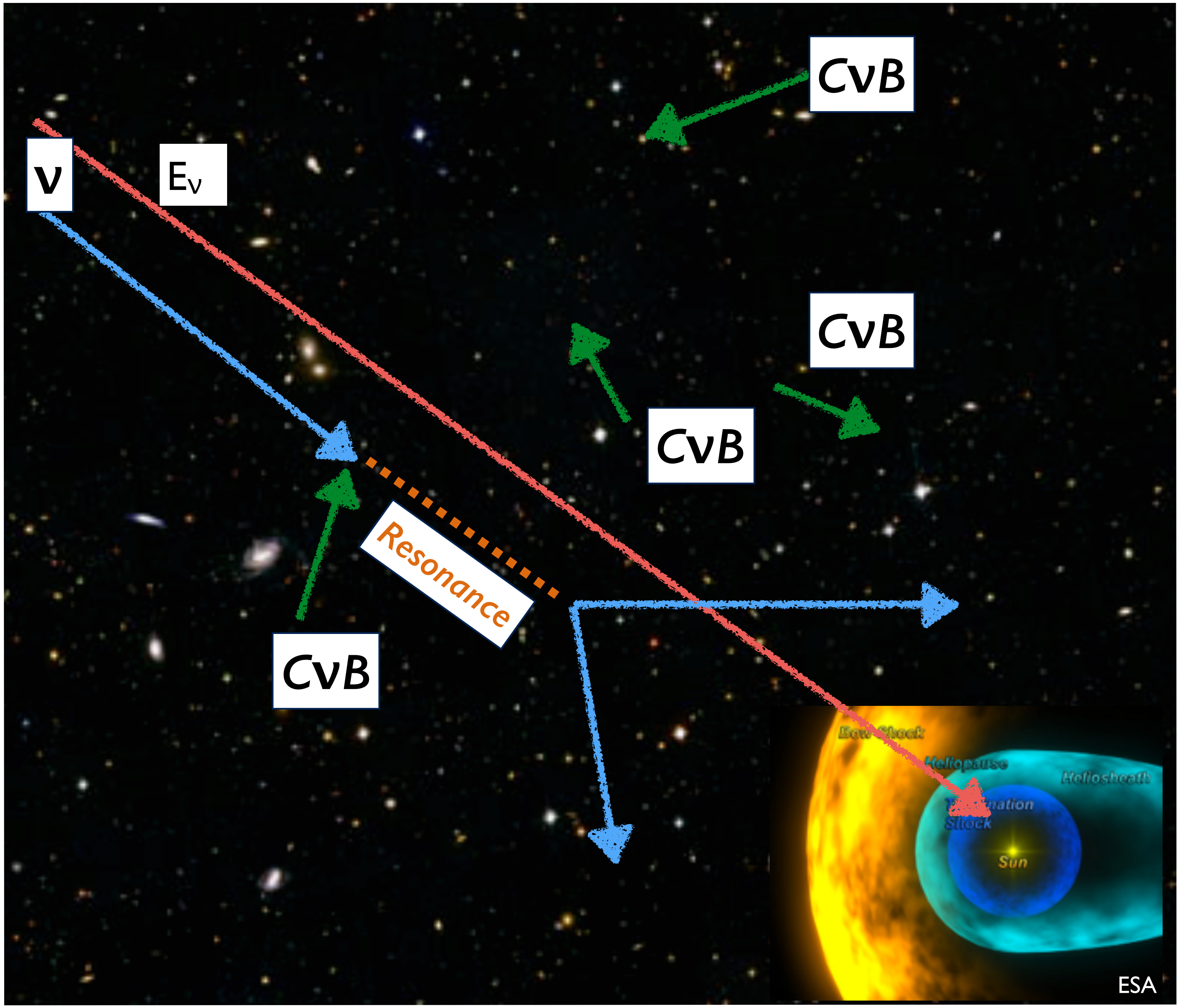

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new resonance:

$$\nu \nu_{C\nu B} \longrightarrow s \longrightarrow \nu \nu$$

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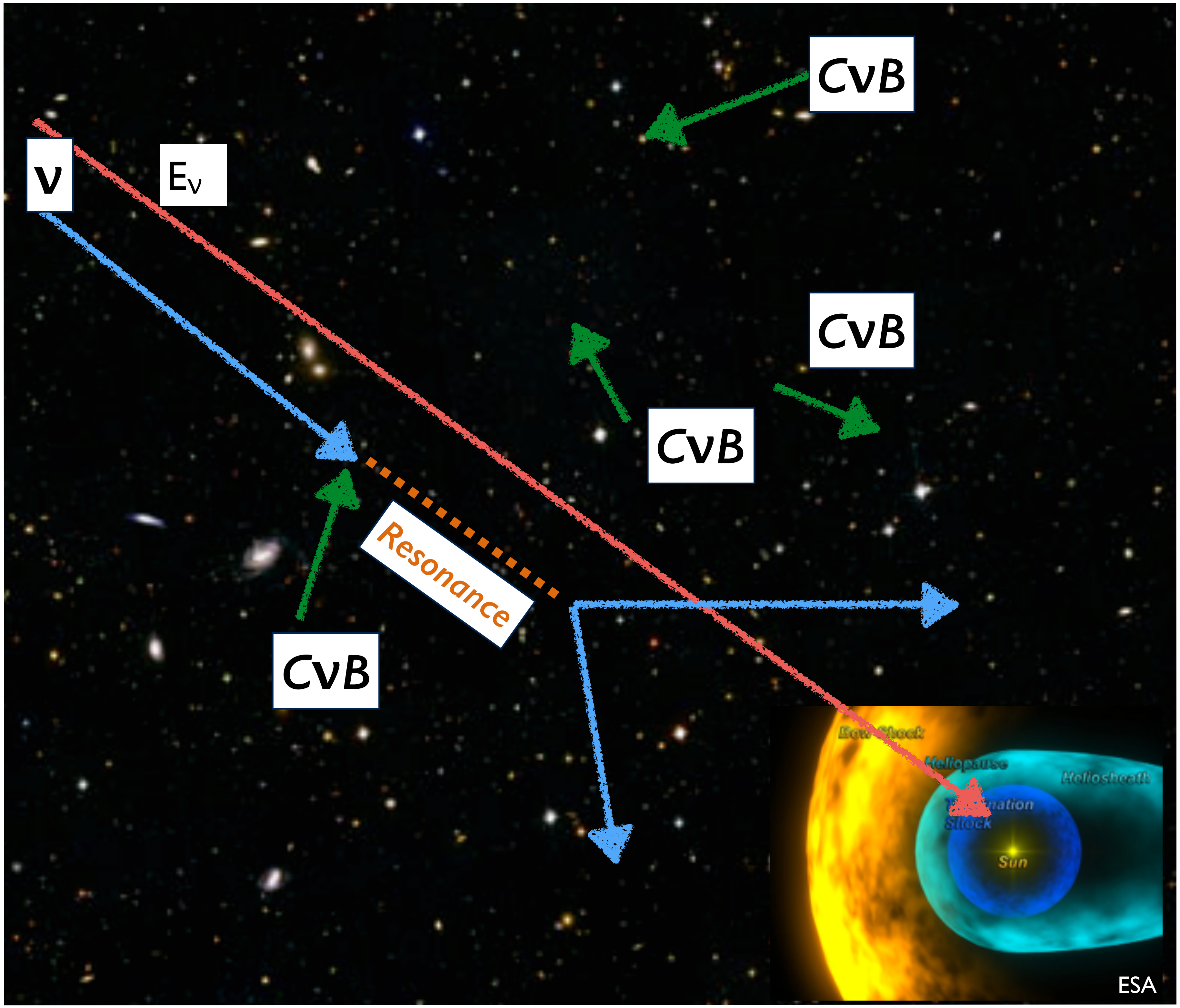

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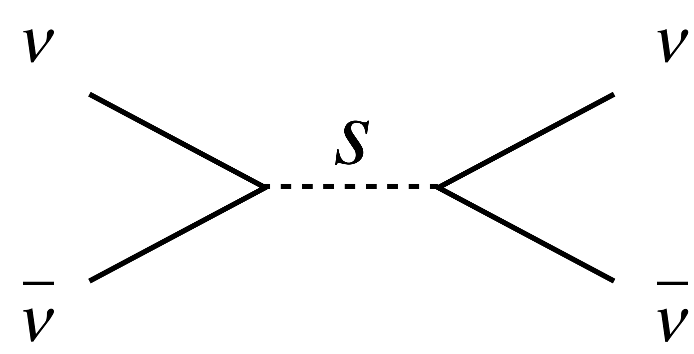
Where is the new resonance if 1PeV neutrino is absorbed?

$$E \simeq \sqrt{2m_\nu E_\nu} \sim \sqrt{10^{-10}10^{6}}GeV$$
$$= 10\,MeV$$

* Neutrino absorption scenario; demonstration

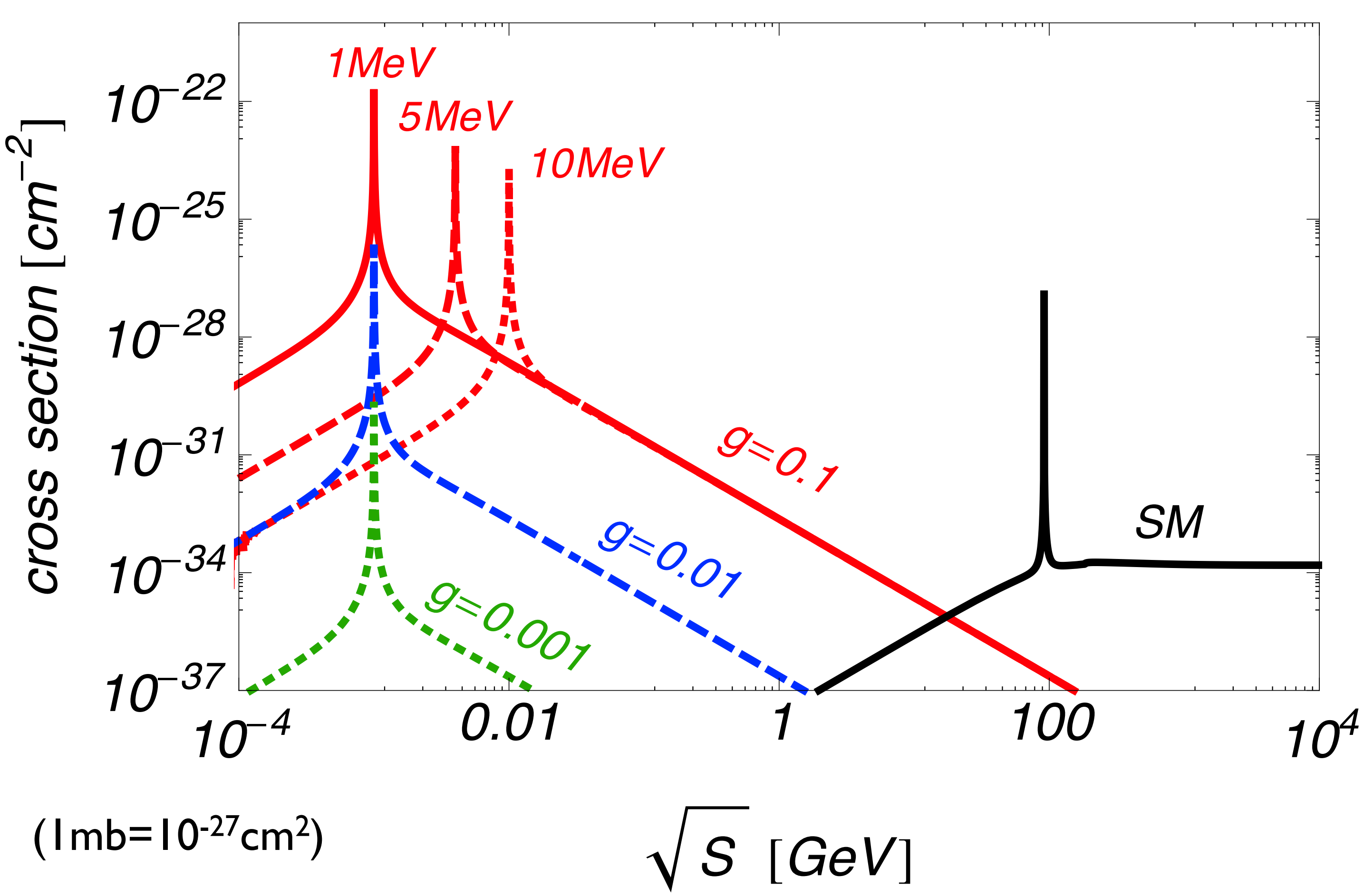
We need MeV scale particle interacting with neutrinos.

$$\mathcal{L}_{s-\nu} = g s \bar{\nu}_i \nu_j$$



(1 flavor)

neutrino−neutrino scattering cross section



(1mb=10^{-27}cm^2)

$$\sigma \simeq \frac{g^4}{16\pi} \frac{S}{\left(S - M_s^2\right)^2 + M_s^2 \Gamma_S^2}$$

$$\Gamma_s \simeq \frac{g^2}{16\pi} M_s$$

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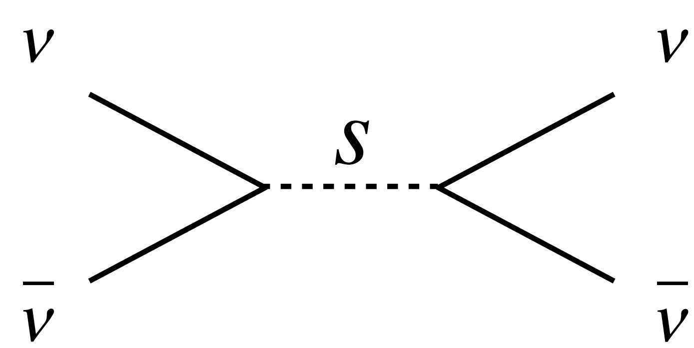

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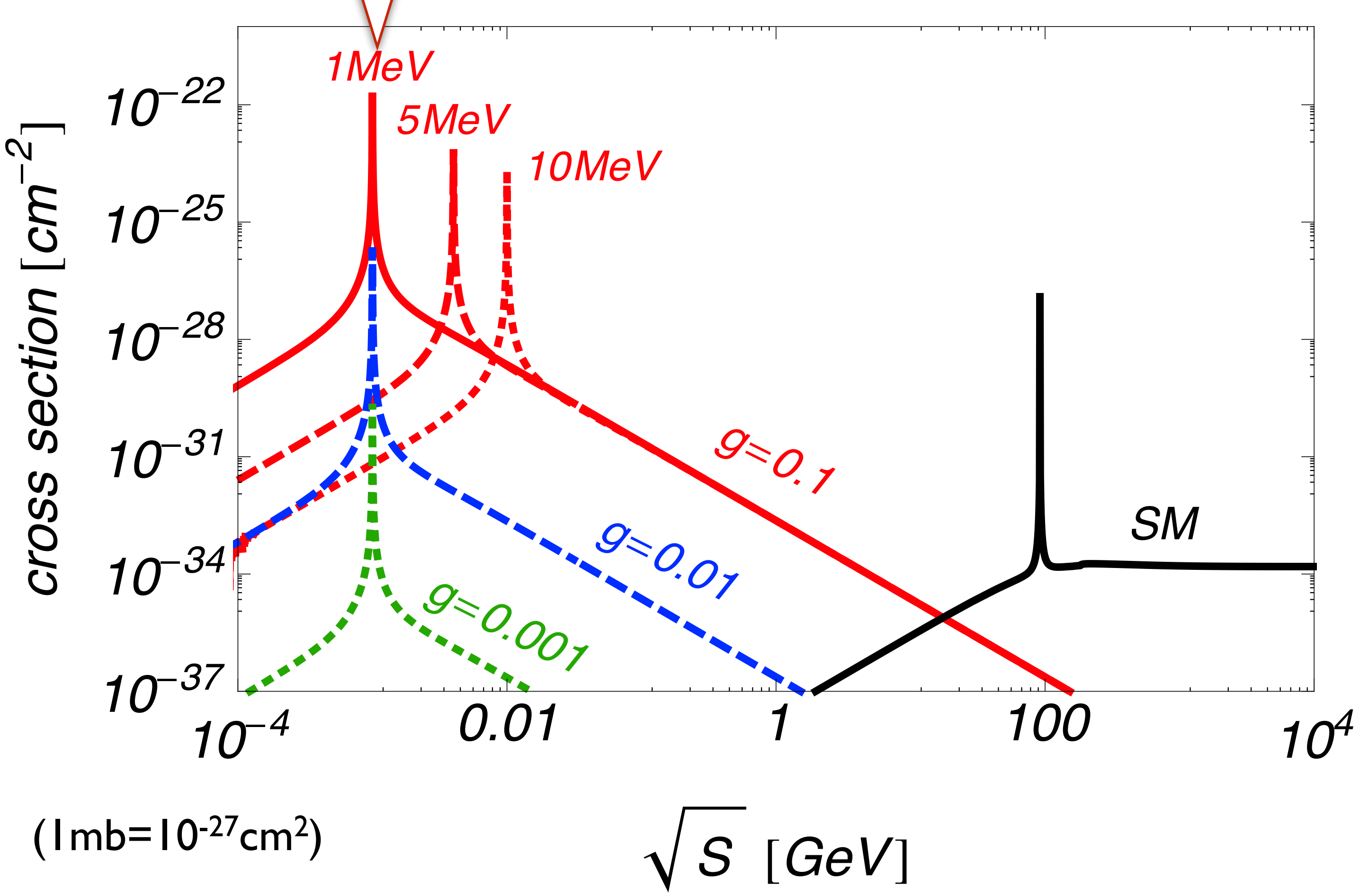
The absorption line may appear around the resonance region



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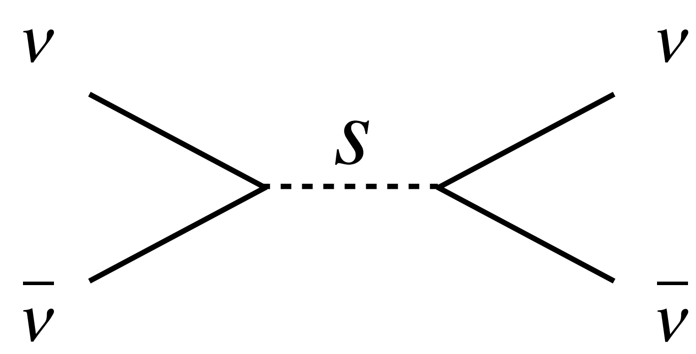

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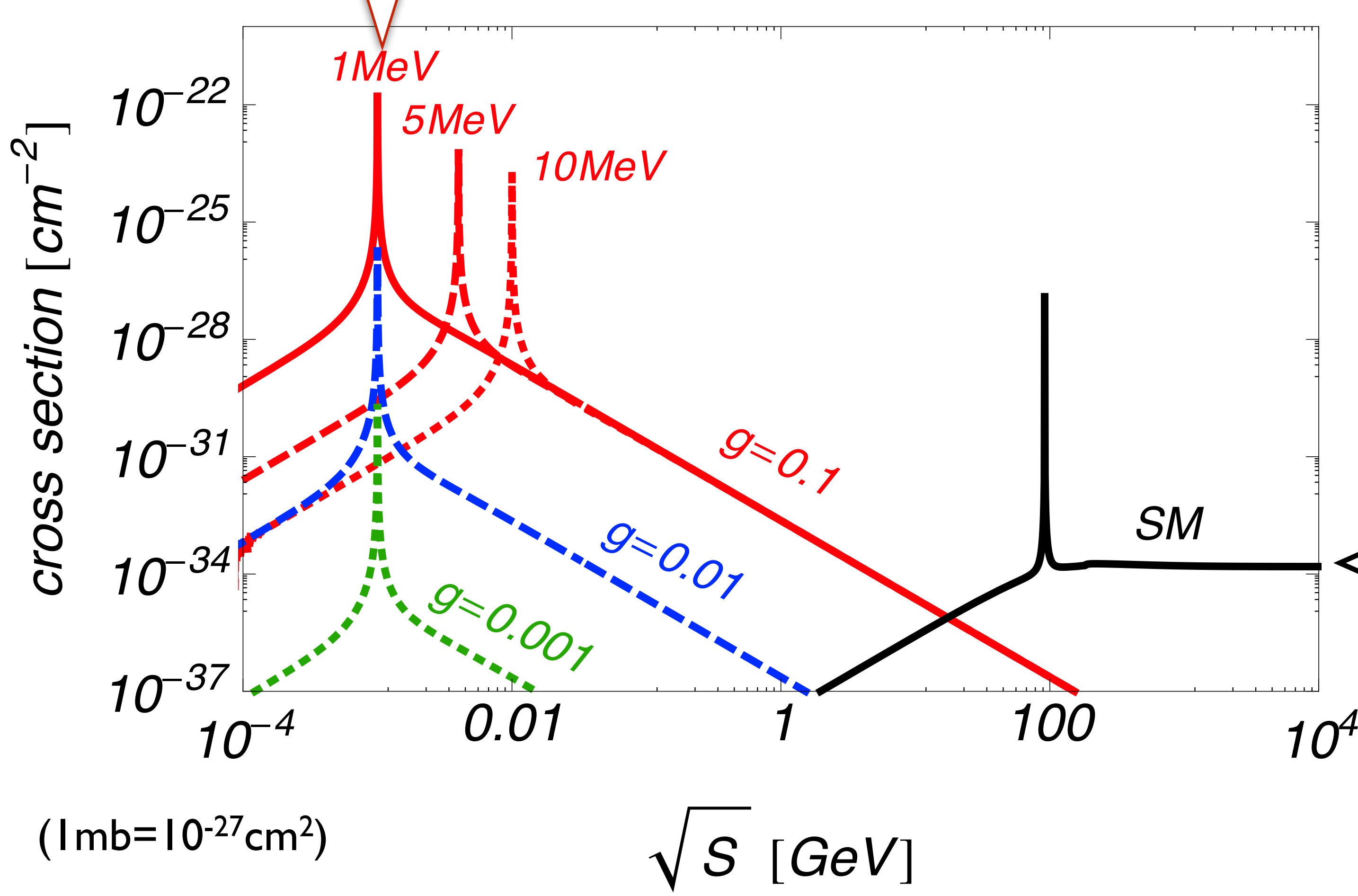

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SM processes

$$\nu_l \bar{\nu}_{l,\mathrm{C}\nu\mathrm{B}} \to f \bar{f} \;\; (f = \nu_l, l, q, \cdots)$$

$$\nu_l \bar{\nu}_{l',\mathrm{C}\nu\mathrm{B}} \to \nu_l \bar{\nu}_{l'}, l \bar{l}' \;\; (l \neq l'),$$

$$\nu_l \nu_{l',\mathrm{C}\nu\mathrm{B}} \to \nu_l \nu_{l'}.$$

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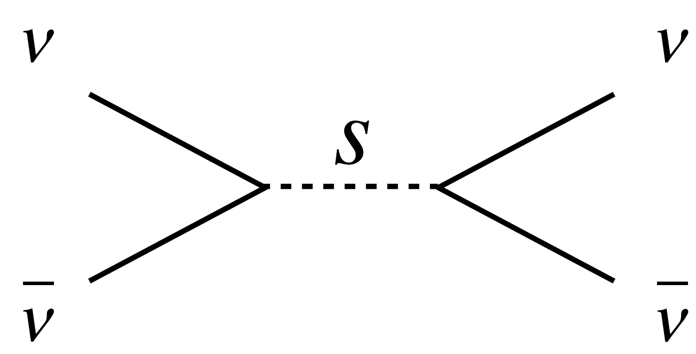

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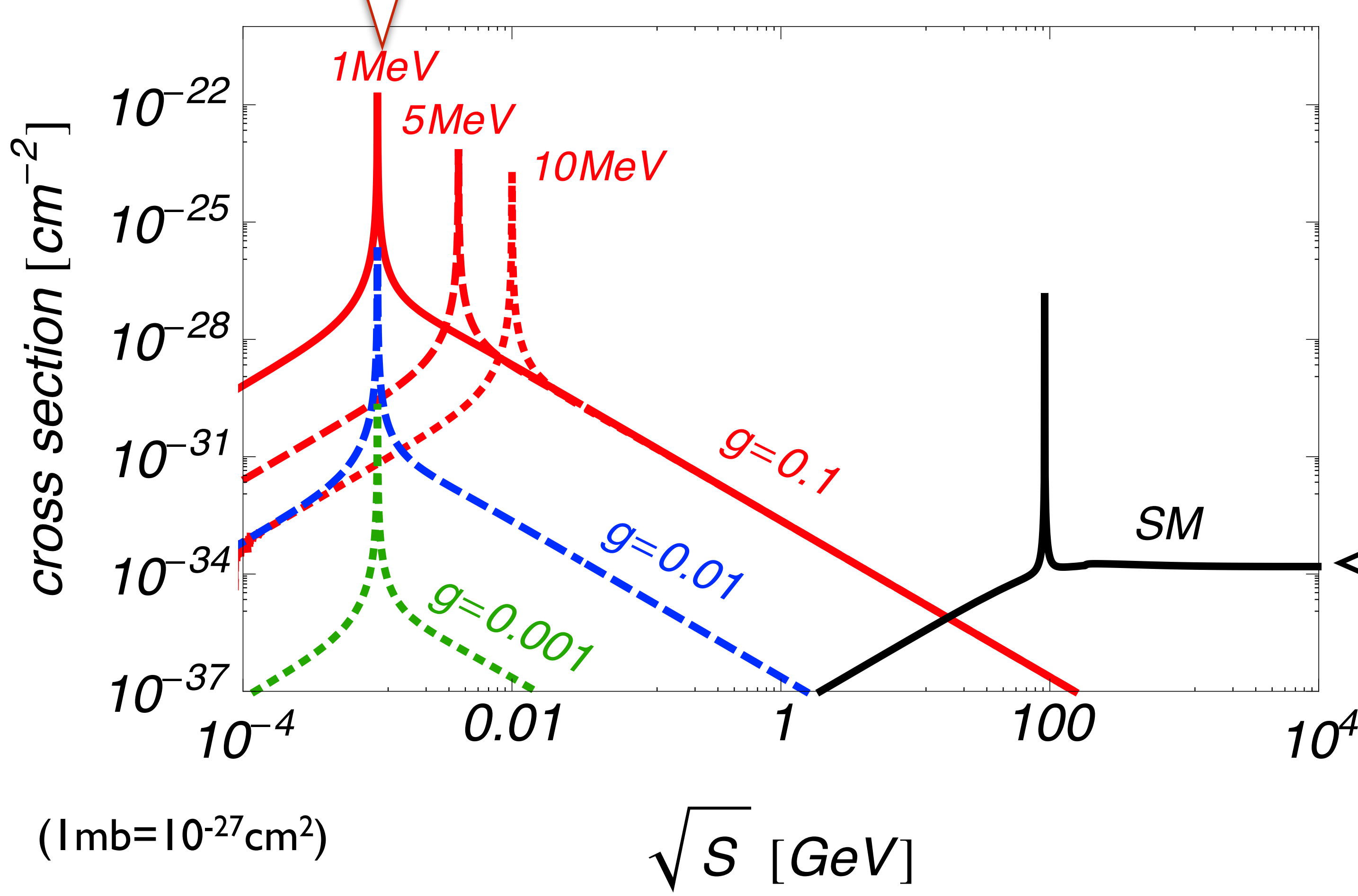

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SM processes

$$E_\nu = M_Z^2/(2m_\nu) \sim 10^{13} \text{ GeV}$$

* Neutrino absorption scenario; demonstration

Where did the cosmic neutrinos come from?

* Neutrino absorption scenario; demonstration

Where did the cosmic neutrinos come from?

current knowledge; high energy neutrino source is unknown

SNRs, GRBs, AGNs, star forming galaxies, …

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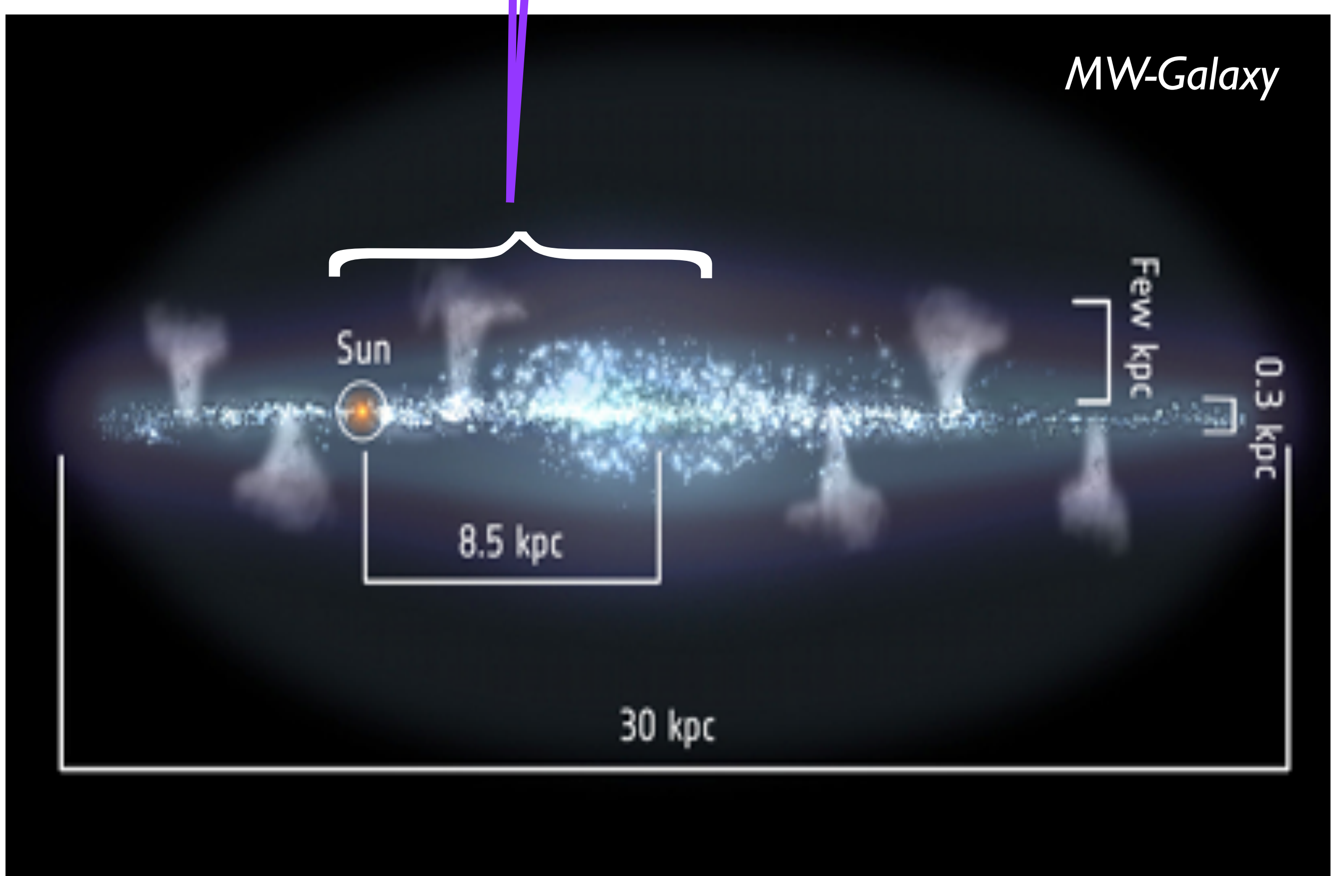
O(10) kpc



ESA

http://sci.esa.int/xmm-newton/47990-new-evidence-for-galactic-fountains-in-the-milky-way/

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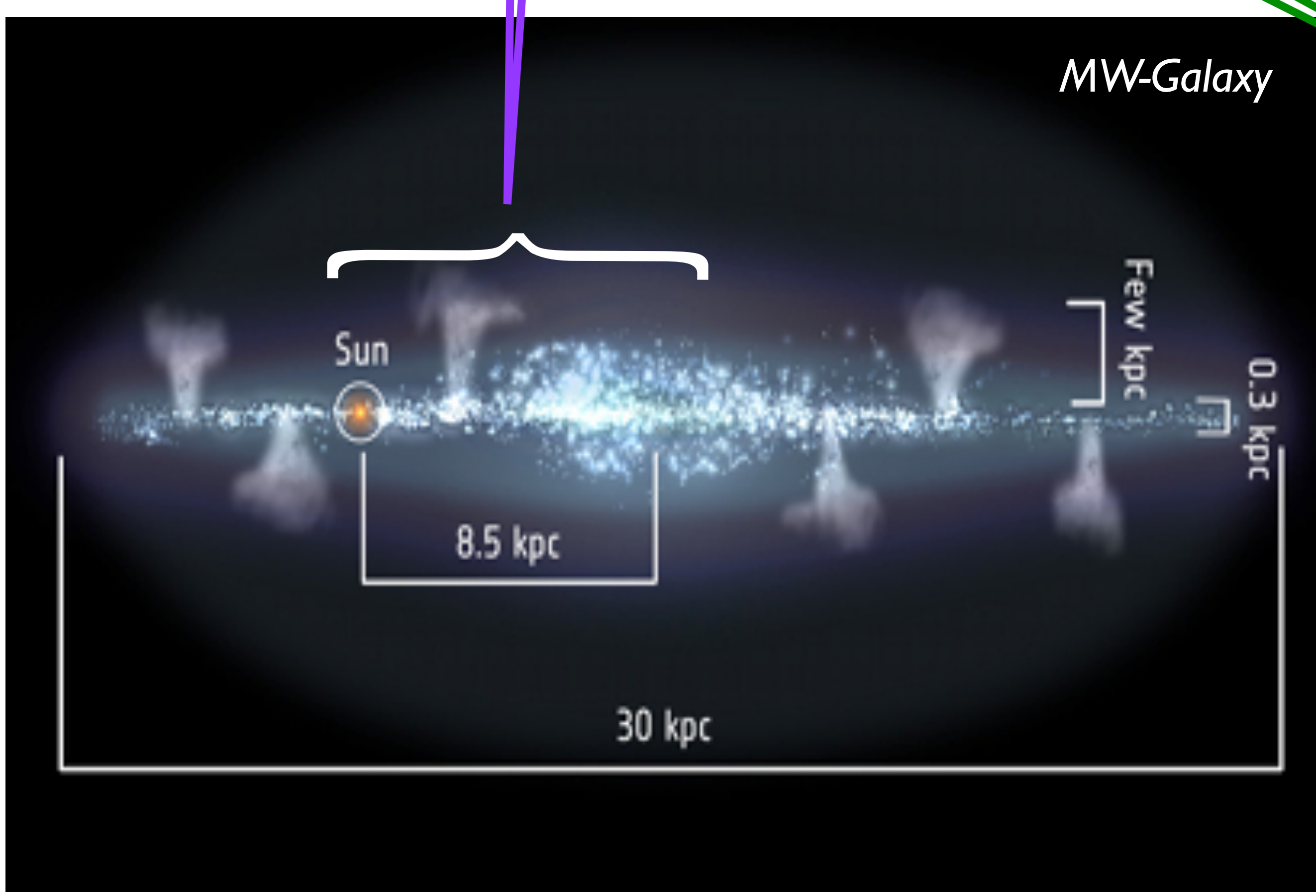
O(10) kpc

O(1) Gpc



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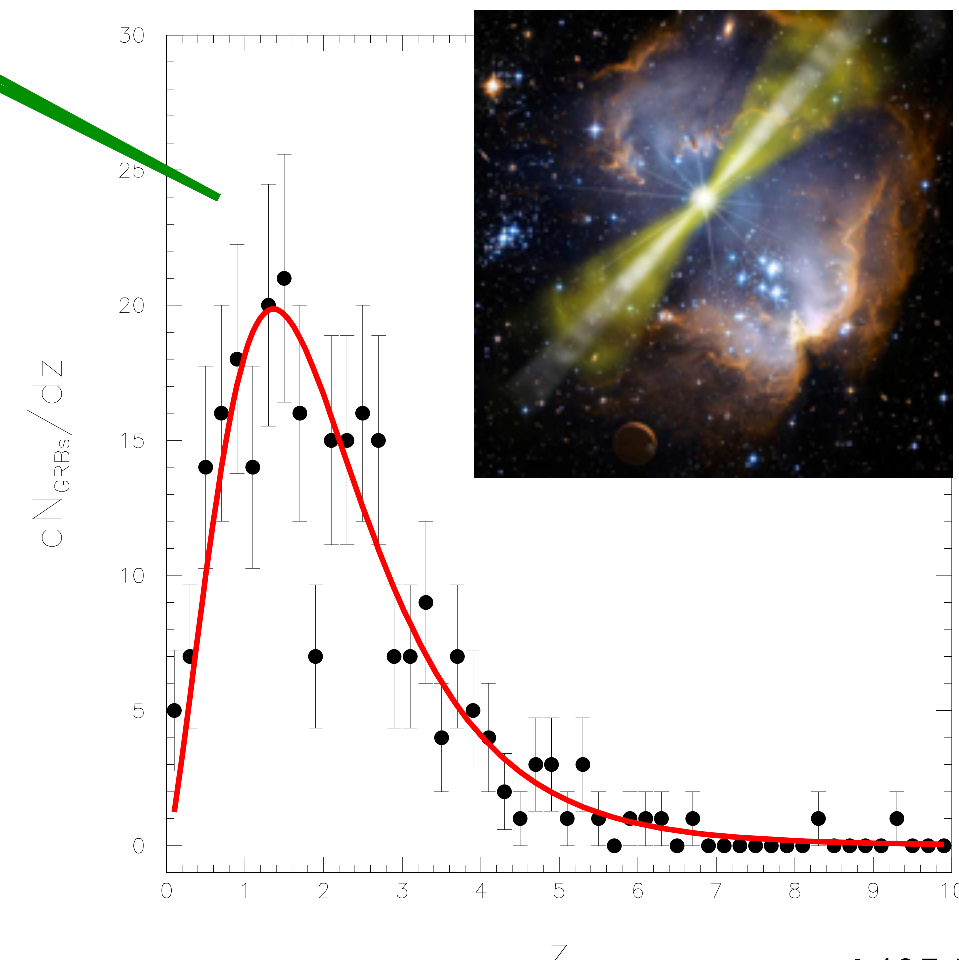

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* Neutrino absorption scenario; demonstration

How far can neutrinos go through in space?

* Neutrino absorption scenario; demonstration

How far can neutrinos go through in space?

mean free path:

$$\lambda(E_\nu) = \left[\int \frac{d^3p}{(2\pi)^3} \sigma(E_\nu, p) f_{C\nu B}(p) \right]^{-1}$$

Fermi-Dirac distribution:

$$f_{C\nu B}(p) = \left[Exp\left(\left| \vec{p} \right| / T_{C\nu B} \right) + 1 \right]^{-1}$$

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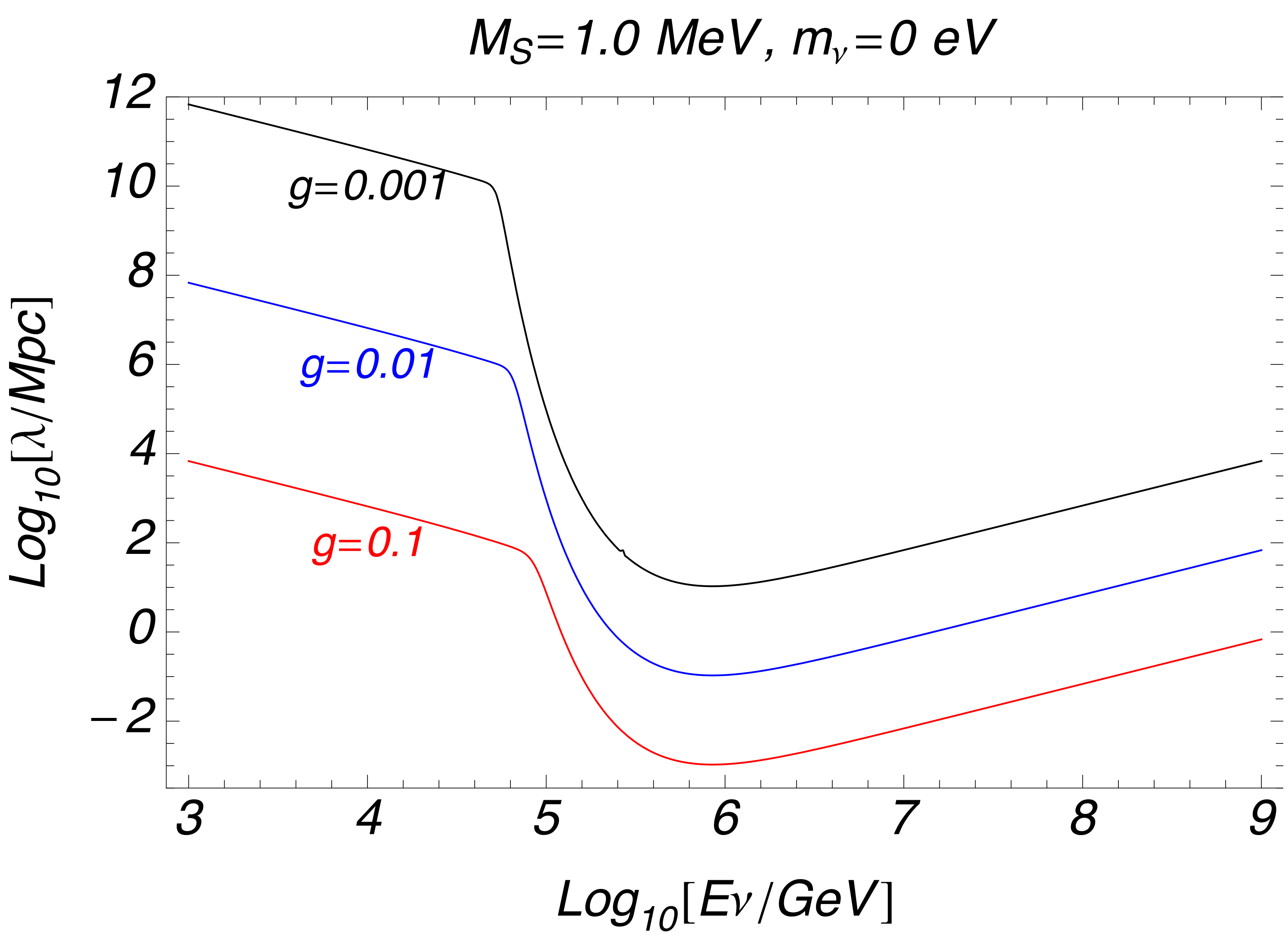

(1 Mpc = 1.56 x 10^{38} GeV^{-1})

* Neutrino absorption scenario; demonstration

How far can neutrinos go through in space?

mean free path:

$$\lambda(E_\nu) = \left[\int \frac{d^3 p}{(2\pi)^3} \sigma(E_\nu, p) f_{C\nu B}(p) \right]^{-1}$$

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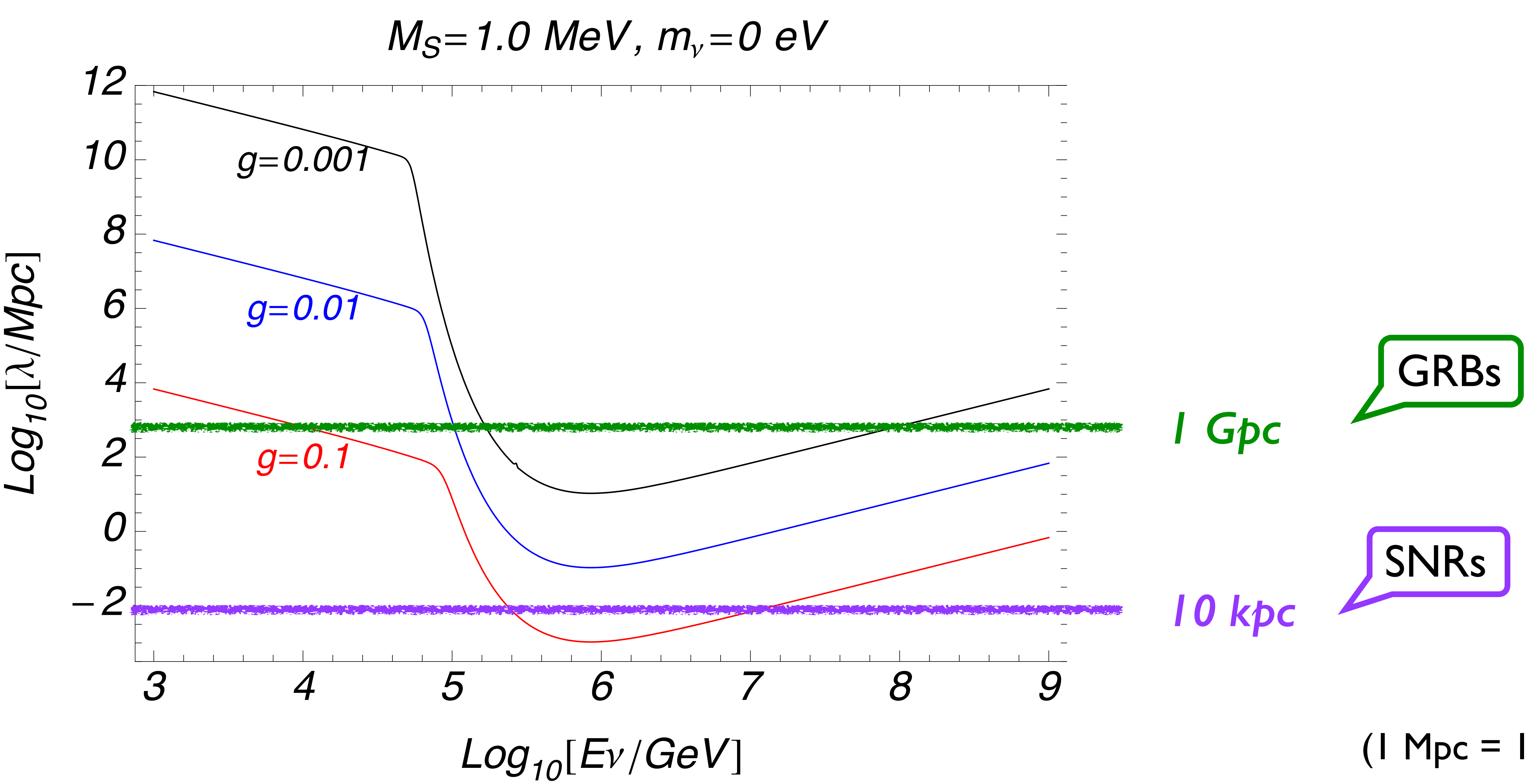

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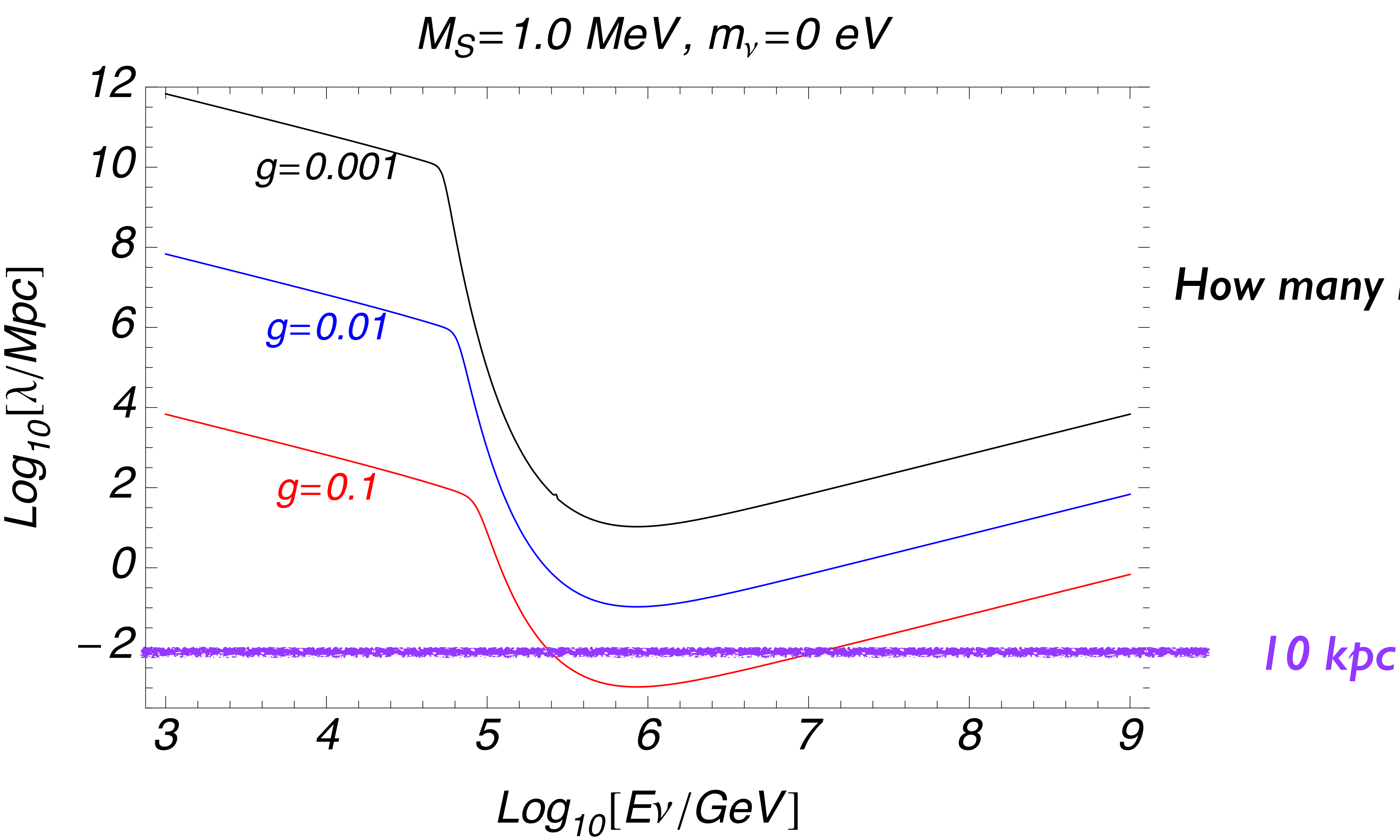

How many neutrinos can reach to the Earth?

sample case

SNRs

(1 Mpc = 1.56×10^{38} GeV^{-1})

* Neutrino absorption scenario; demonstration

How far can neutrinos go through in space?

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Fermi-Dirac distribution:

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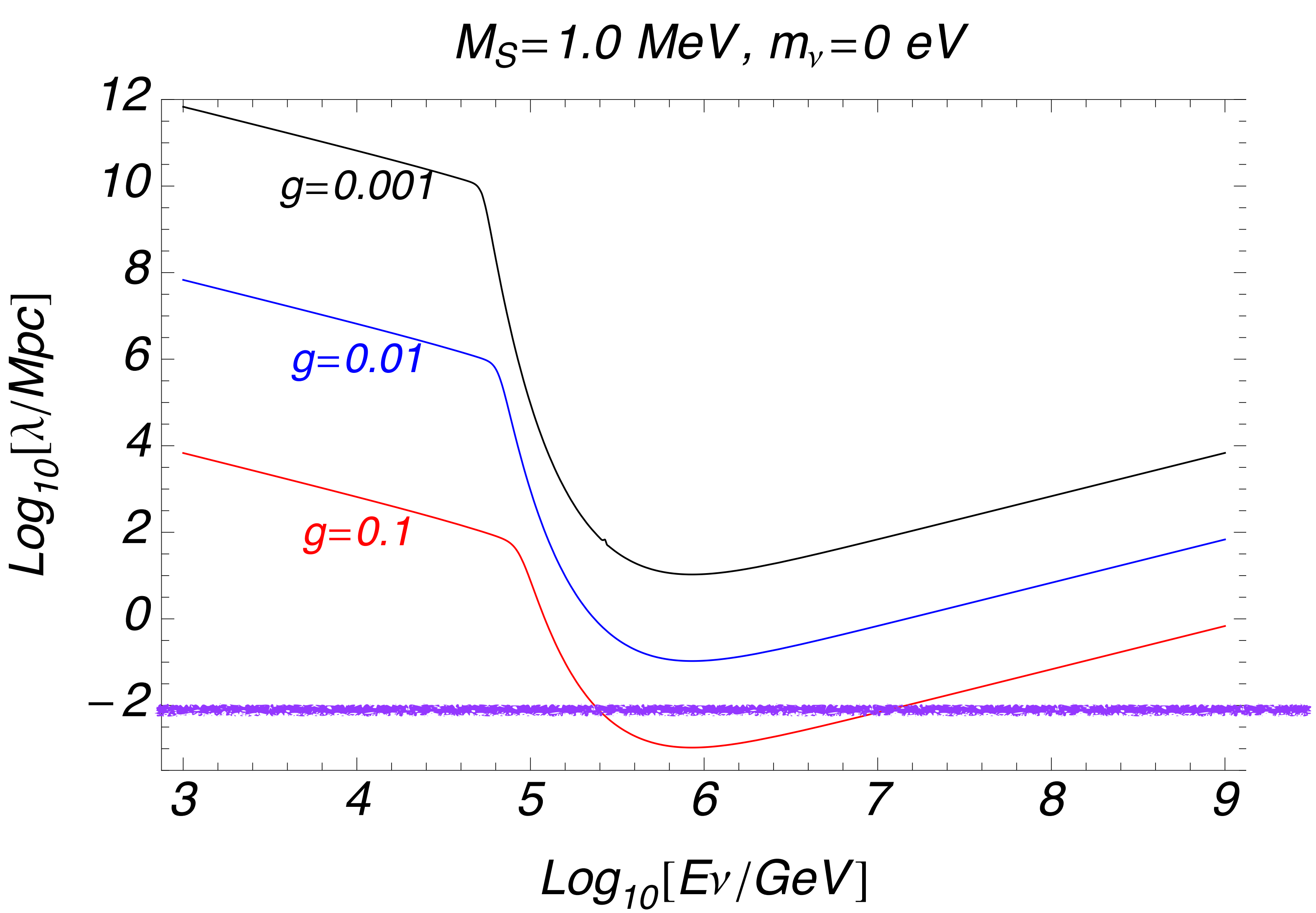

10 kpc

SNRs

number of neutrinos:

$$\frac{dN_\nu}{dL}(E_\nu,z)\simeq-\frac{N_\nu(E_\nu,z)}{\lambda(E_\nu)}$$

traveling distance

$$L=(c/H_0)\int dz\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{-1/2}$$

(1 Mpc = 1.56 x 10^{38} GeV^{-1})

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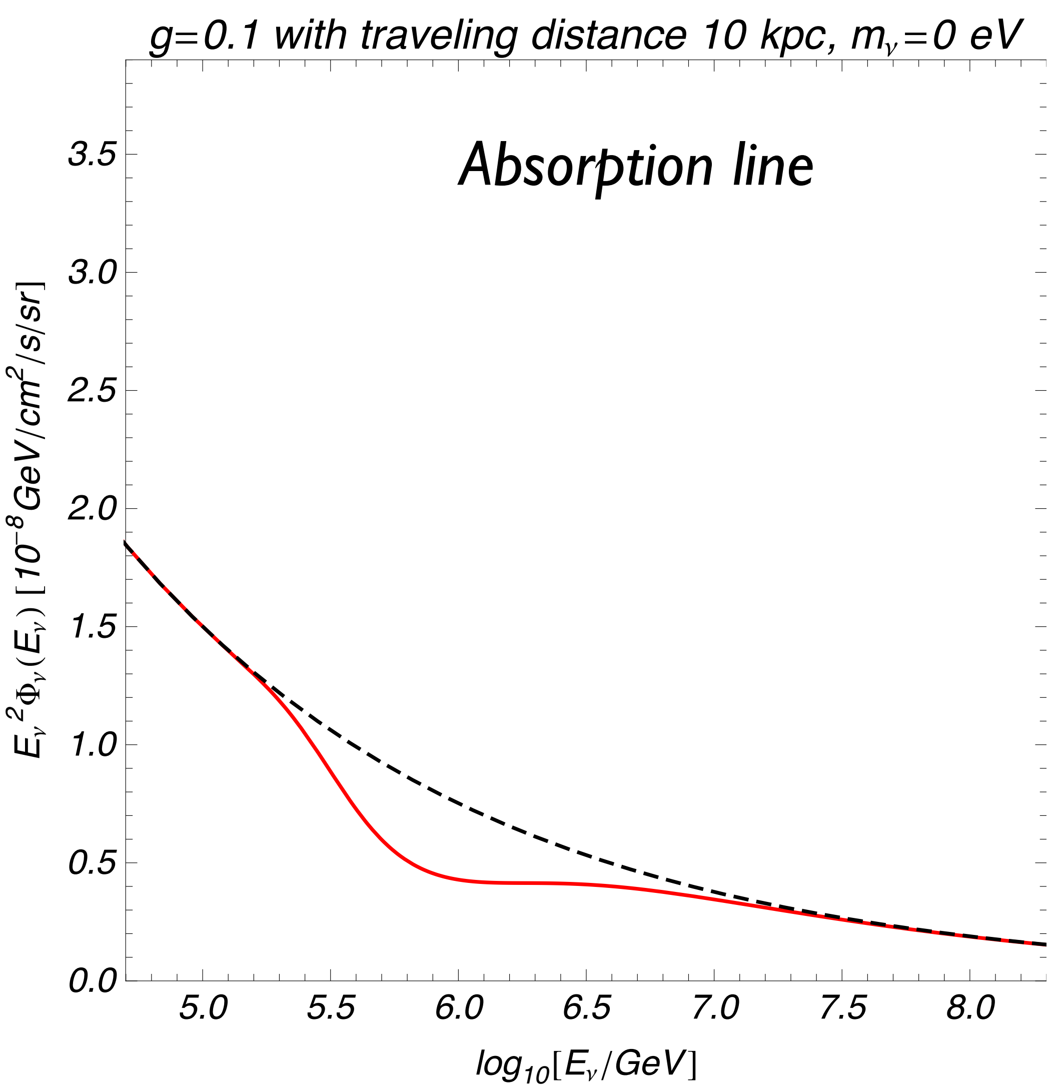

number of neutrinos:

$$\frac{dN_\nu}{dL}(E_\nu, z) \simeq -\frac{N_\nu(E_\nu, z)}{\lambda(E_\nu)}$$

traveling distance

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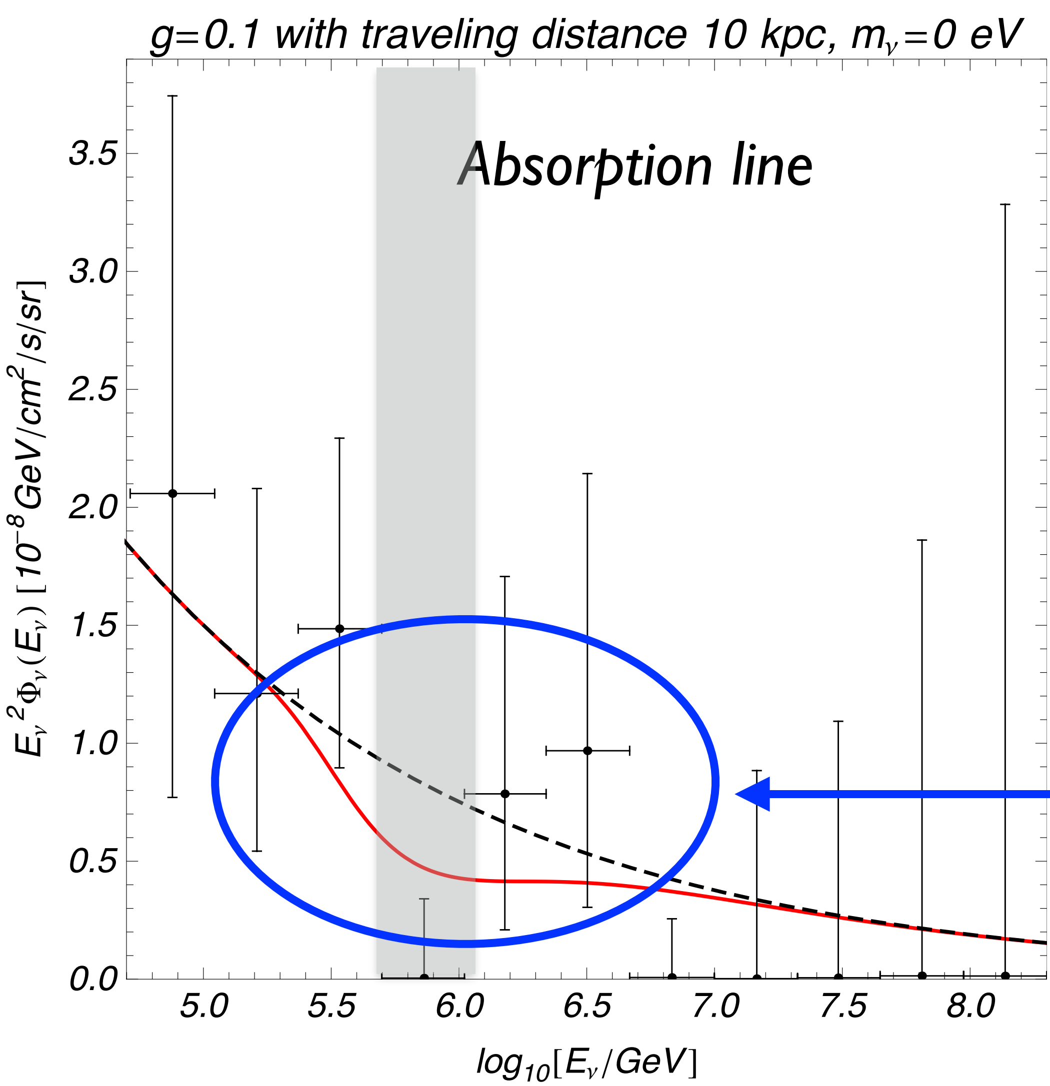

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The absorbed region seems too broad to explain the null-event region …

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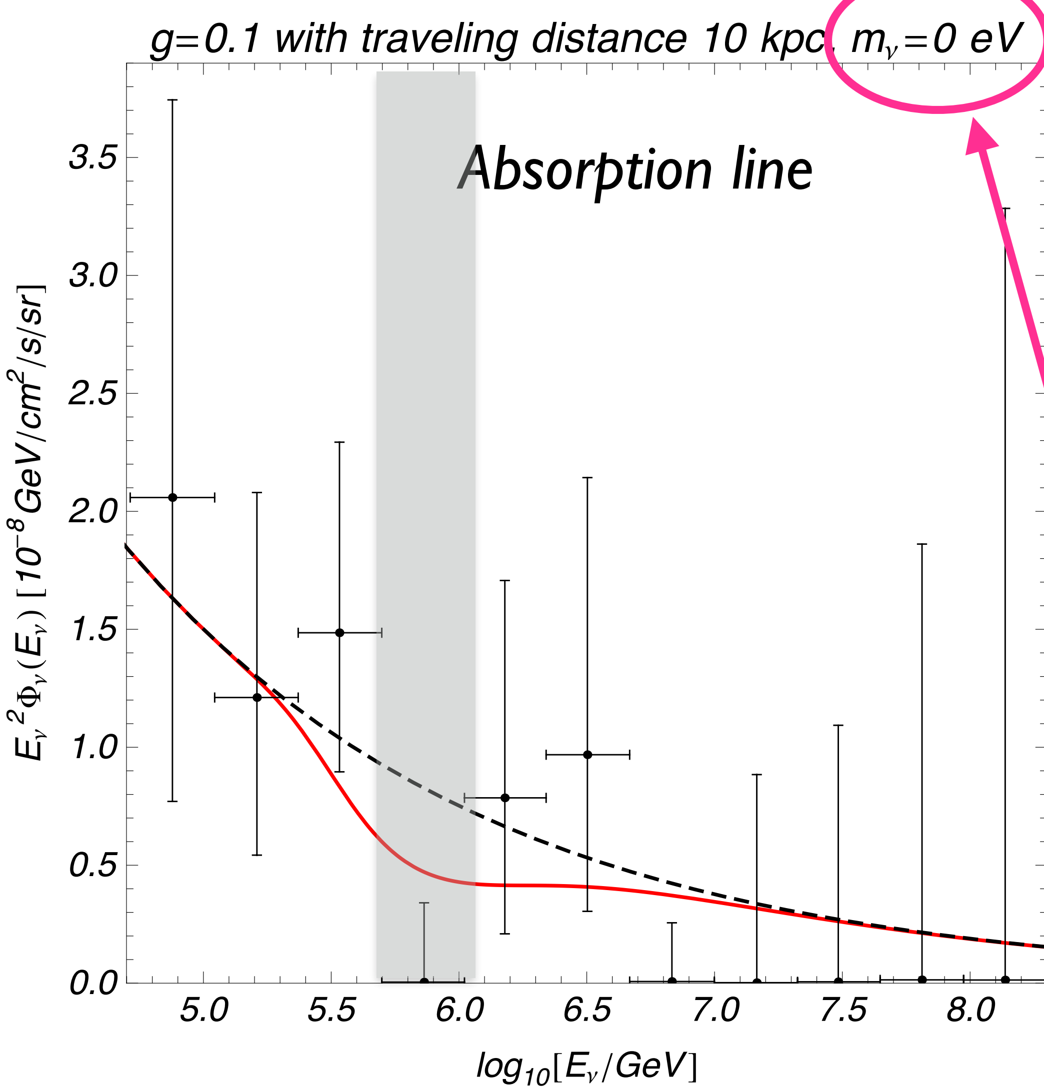

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traveling distance

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The absorbed region seems too broad to explain the null-event region …

Let us consider m_ν dependence.

* Neutrino absorption scenario; neutrino mass dependence

simple kinematics

head-on collision $\nu \longrightarrow \quad \longleftarrow \nu_{C\nu B}$

$$\left(E_\nu, \sqrt{E_\nu^2 - m_\nu^2}\right) \qquad \left(\sqrt{m_\nu^2 + |\vec{p}_{C\nu B}|}, -|\vec{p}_{C\nu B}|\right)$$

How large E_ν can contribute to the resonance region?

On pole condition: $M_s^2 = S$ (back-to-back case)

$$= 2\left[m_\nu^2 + E_\nu \sqrt{m_\nu^2 + |\vec{p}_{C\nu B}|^2} - \sqrt{E_\nu^2 - m_\nu^2}\, |\vec{p}_{C\nu B}| \right]$$

→ constraint on (E_ν, $p_{C\nu B}$) to realize this condition for each m_ν

Fermi-Dirac distribution: $f_{C\nu B}(p_{C\nu B}) = \left[Exp(|\vec{p}_{C\nu B}| / T_{C\nu B}) + 1 \right]^{-1}$

→ gives the information; how large probability the relevant $p_{C\nu B}$ has.

* Neutrino absorption scenario; neutrino mass dependence

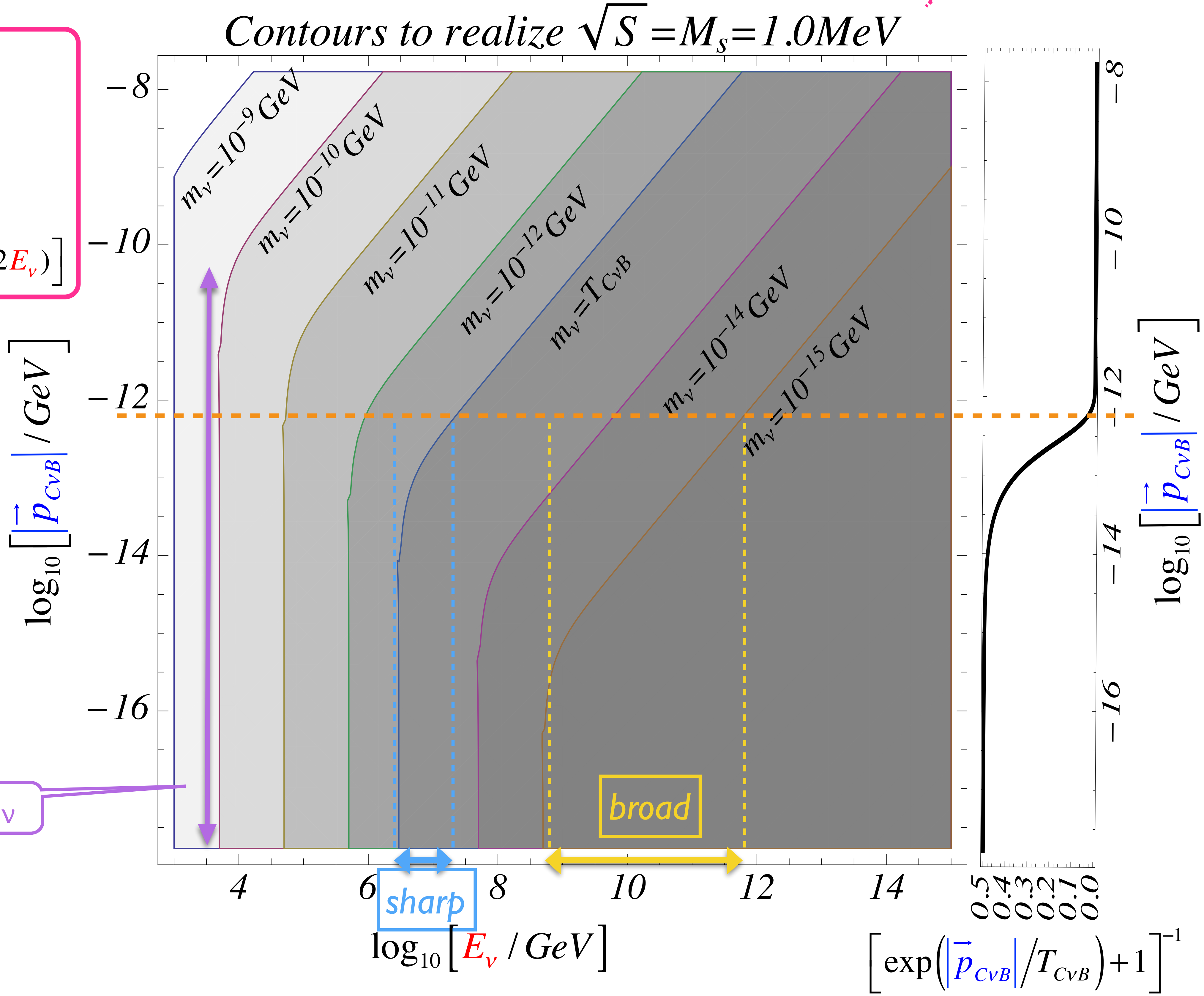
$$\sqrt{S} = f(E_\nu, |\vec{p}_{C\nu B}|, m_\nu)$$

$(|\vec{p}_{C\nu B}| \ll m_\nu)$

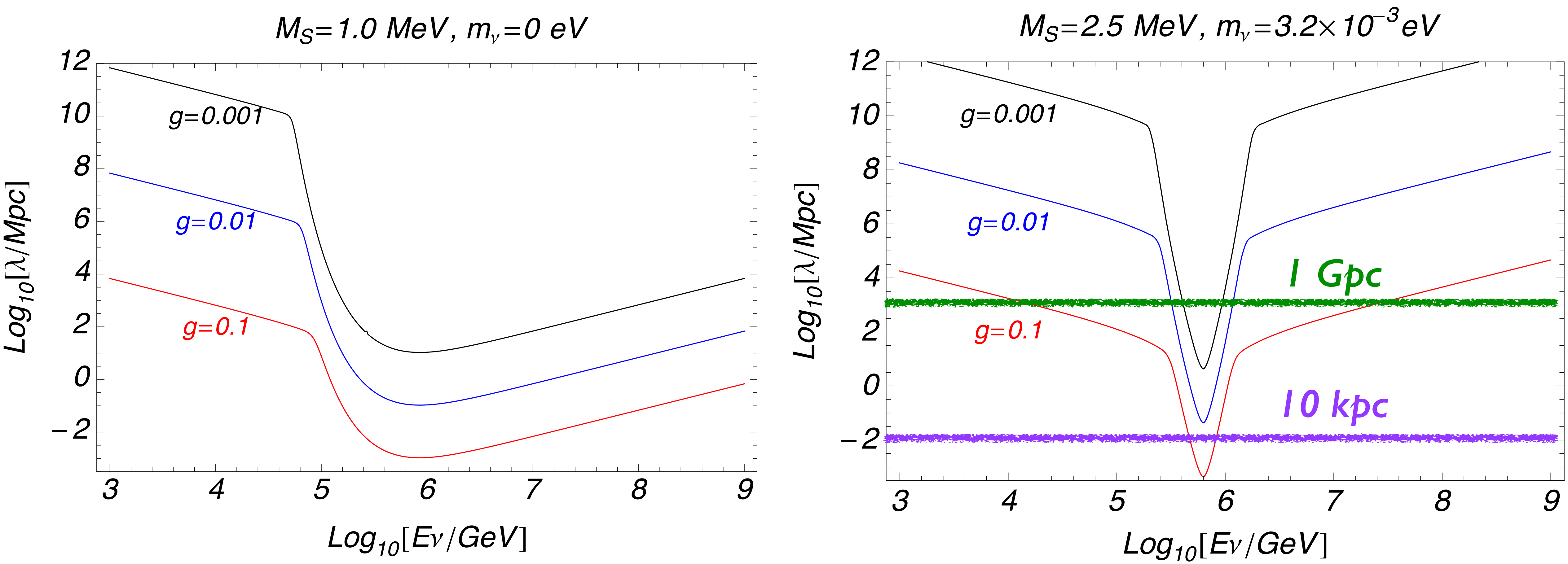
$$S \sim 2m_\nu [m_\nu + E_\nu]$$

$(|\vec{p}_{C\nu B}| \gg m_\nu)$

$$S \sim 2m_\nu^2 [1 + |\vec{p}_{C\nu B}|/(2E_\nu)]$$



* Neutrino absorption scenario; massless vs. massive



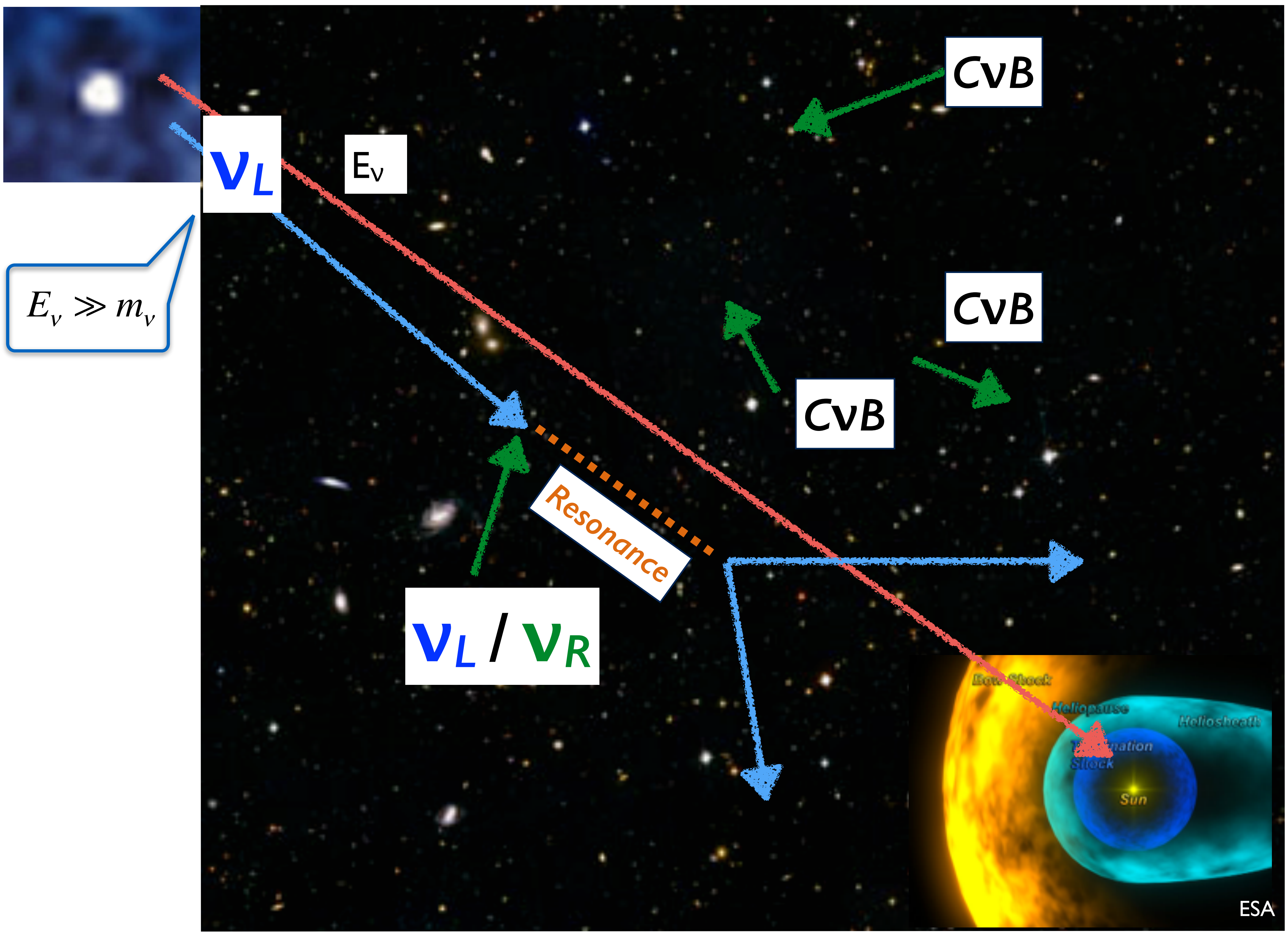
Absorption line also has a sensitivity to neutrino masses!

Next, let us consider more realistic models.

3, Viable models

* We need MeV scale scalar particle interacting with neutrinos.

* New interaction should involve left-handed neutrino.



Attempt 1. Inverse seesaw model with a neutrinophilic scalar doublet

	l	N_N	$\bar{N}_R$	h	h_N
L	$+1$	$+1$	-1	0	-2
Z_2	$+$	$+$	$-$	$+$	$-$

$$\mathcal{L} \supset g h_N l N_N + y h l \bar{N}_R + M \bar{N}_R N_N + m N_N N_N.$$

potential

$$V = -\mu_h^2 |h|^2 + \lambda (h^\dagger h)^2 + \mu_N^2 |h_N|^2 + \lambda_1 (h_N^\dagger h_N)^2 + \lambda_2 |h|^2 |h_N|^2 - \lambda_3 |h^\dagger h_N + h.c.|^2$$

$$\Rightarrow \langle h_N \rangle = 0$$

(different from νHDM)

neutrino mass matrix:

$$M_\nu = \begin{array}{c} \begin{array}{ccc} l & \bar{N}_R & N_N \end{array} \\ \begin{bmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & m \end{bmatrix} \end{array} \xrightarrow{(m \ll m_D \ll M)} \simeq \begin{bmatrix} m_D^2 \frac{m}{M^2} & 0 & 0 \\ 0 & M - \frac{m_D^2}{2M} + \cdots & 0 \\ 0 & 0 & M + \frac{m_D^2}{2M} + \cdots \end{bmatrix}$$

"Inverse See-Saw"

$$m_\nu = 0.1 eV \left(\frac{yv}{100 GeV}\right)^2 \left(\frac{m}{10 eV}\right) \left(\frac{M}{1 TeV}\right)^{-2}$$

effective theory:

$$L_{eff} \simeq \boxed{\frac{gyv}{M}} h_N^0 \nu_L \nu_L \equiv g^{eff} h_N^0 \nu_L \nu_L$$

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$$V = -\mu_h^2 |h|^2 + \lambda (h^\dagger h)^2 + \mu_N^2 |h_N|^2 + \lambda_1 (h_N^\dagger h_N)^2 + \lambda_2 |h|^2 |h_N|^2 - \lambda_3 \underline{|h^\dagger h_N + h.c.|^2}$$

$$\Rightarrow \langle h_N \rangle = 0$$

(different from νHDM)

custodial symmetric terms

$$\varepsilon_{ab}\varepsilon_{ij}\Psi_{ia}\Psi^N_{jb} \qquad \Psi_{ia} = \begin{pmatrix} h^0 & h^+ \\ h^- & h^0 \end{pmatrix}_{ia} \qquad \Psi^N_{jb} = \begin{pmatrix} h_N^0 & h_N^+ \\ h_N^- & h_N^0 \end{pmatrix}_{jb}$$

$$\lambda_2 - \lambda_3 \sim O(10^{-6})$$

mass spectrum

$$h_N = \begin{pmatrix} h_N^0 + iA^0 \\ h_N^- \end{pmatrix} \qquad \left\{ \begin{array}{l} m_{h_N^0}^2 \sim \mu_N^2 + (\lambda_2 - \lambda_3) v^2 \\ m_{A^0, h_N^-}^2 \sim \mu_N^2 + \lambda_2 v^2 \end{array} \right. \xrightarrow{\mu_N^2 \ll v^2} \begin{array}{l} m_{h_N^0} \sim O(1) MeV \\ m_{A^0, h_N^-} \sim O(100) GeV \end{array}$$

experimental limits?

Attempt 1. Inverse seesaw model with a neutrinophilic scalar doublet

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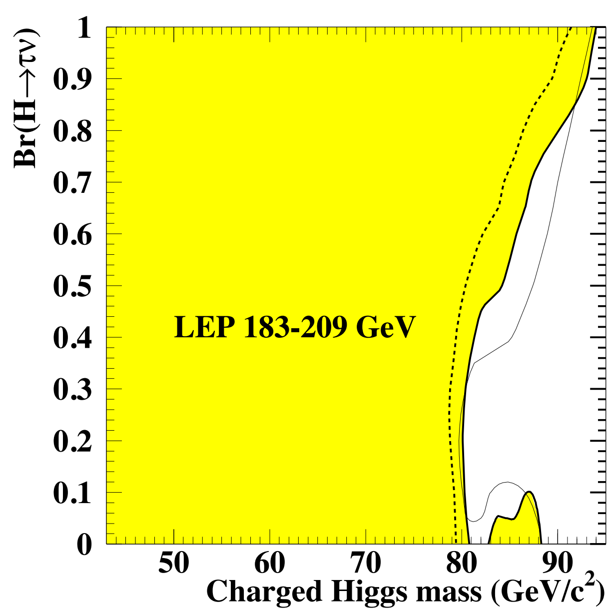
experimental limits

1303.4097

* LEP

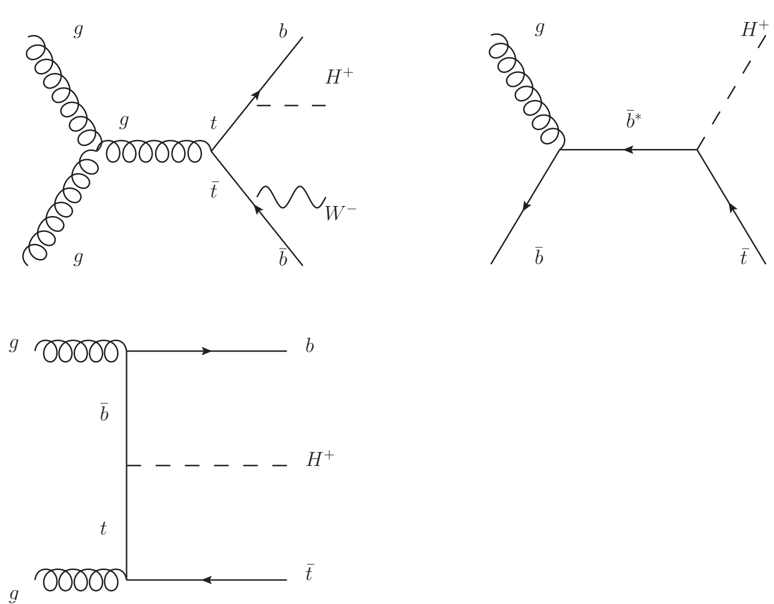
$H^+H^- \to \tau\nu\tau\nu$



$m_{h_N^-} > 100 GeV$

1301.6065

* LHC

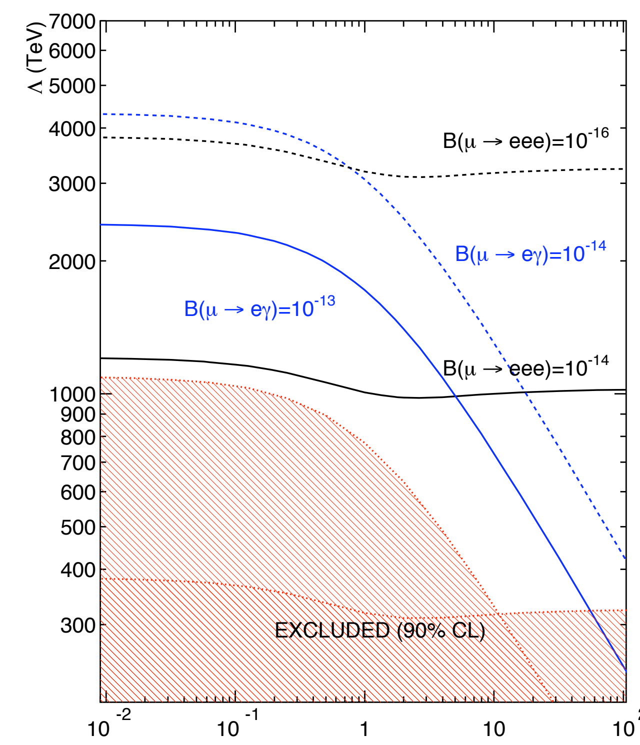


h_N does not couple to quarks!

ATLAS-CONF-2013-090

* LFV $\mu \to e\gamma$

$$\frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu}$$



$\Lambda > 1000 GeV$

$\longrightarrow$ $m_{h_N^-} > 100 GeV$

including loop factor
(and coupling)

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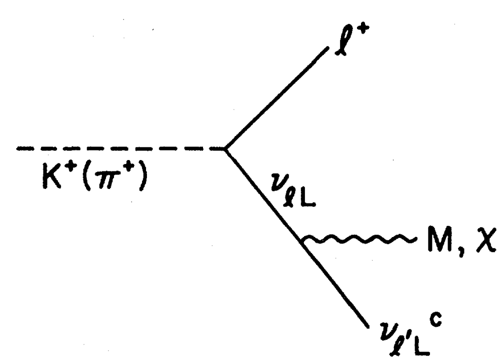
$$\mathcal{L} \supset g h_N l N_N + y h l \bar{N}_R + M \bar{N}_R N_N + m N_N N_N .$$

experimental limits

* Meson decay ($\pi/K \to l \nu_{l'} h_N^0$)



flavor basis: $g_{ab}^{\rm eff} h_N^0 \bar{\nu}_a \nu_b \ (a, b = e, \mu, \tau)$

$\downarrow$

mass basis: $g_{ij} = (U_{\rm PMNS}^\dagger)_{ia} g_{ab}^{\rm eff} (U_{\rm PMNS})_{bj} \ (i, j = 1, 2, 3)$

$$U_{\rm PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\delta = \alpha_1 = \alpha_2 = 0, \ s_{12}^2 = 0.31, \ s_{23}^2 = 0.51 \text{ and } s_{13}^2 = 0.023$

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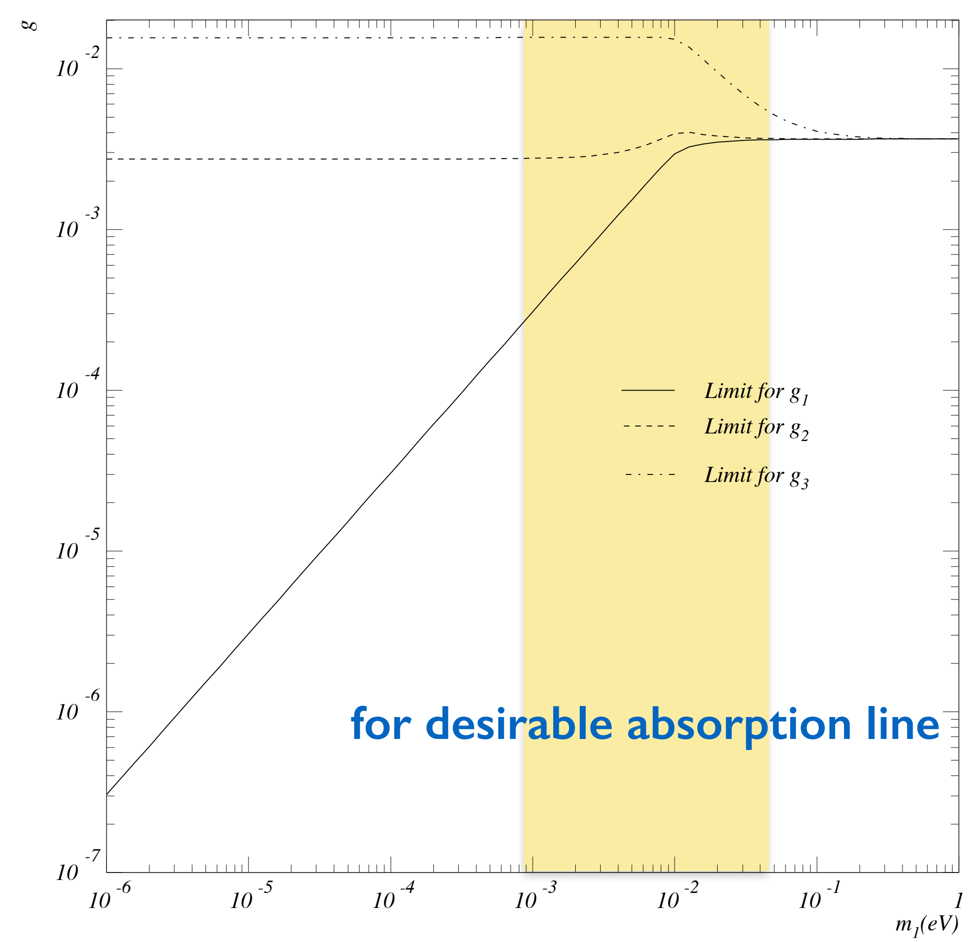
mass basis

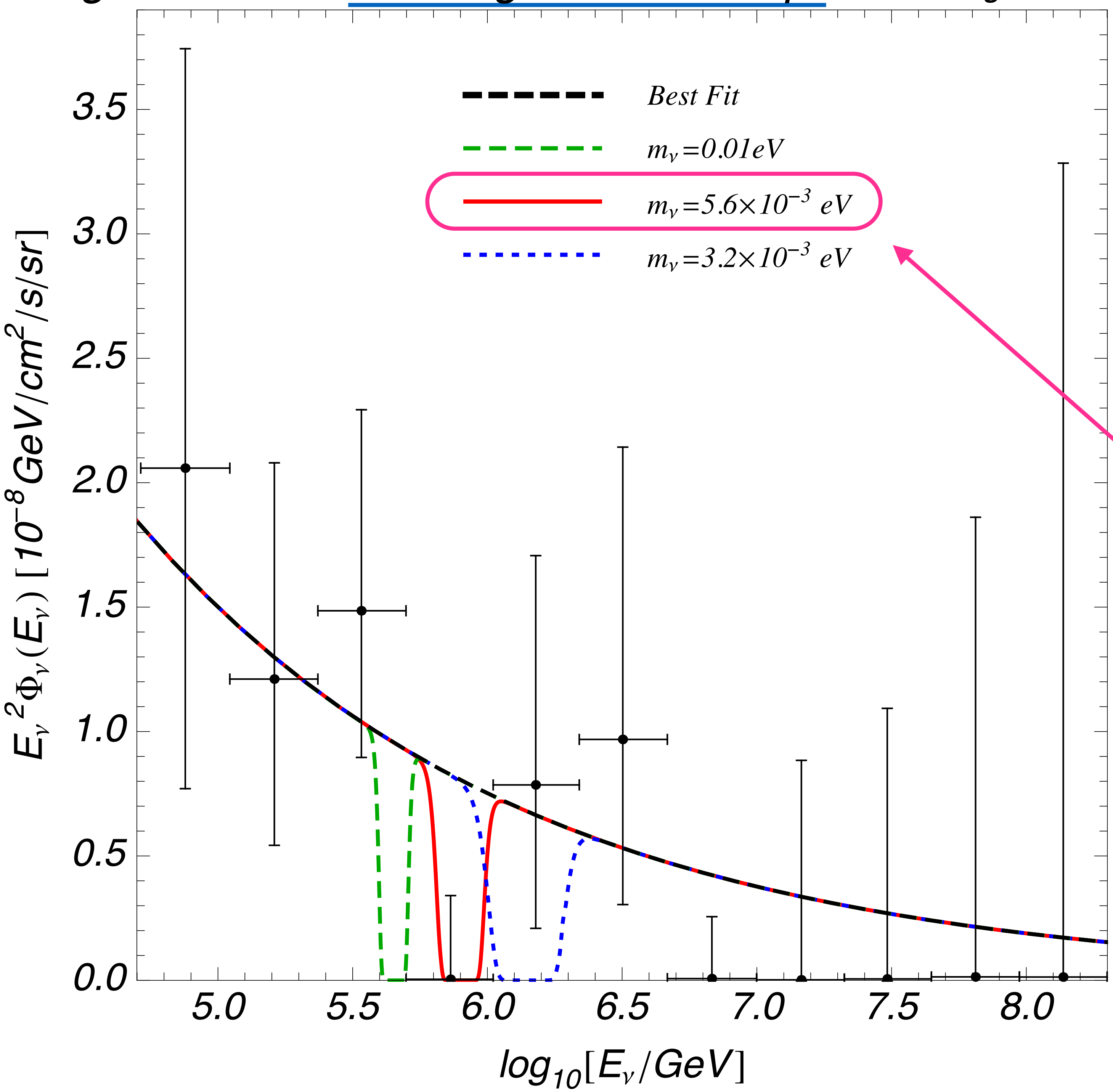


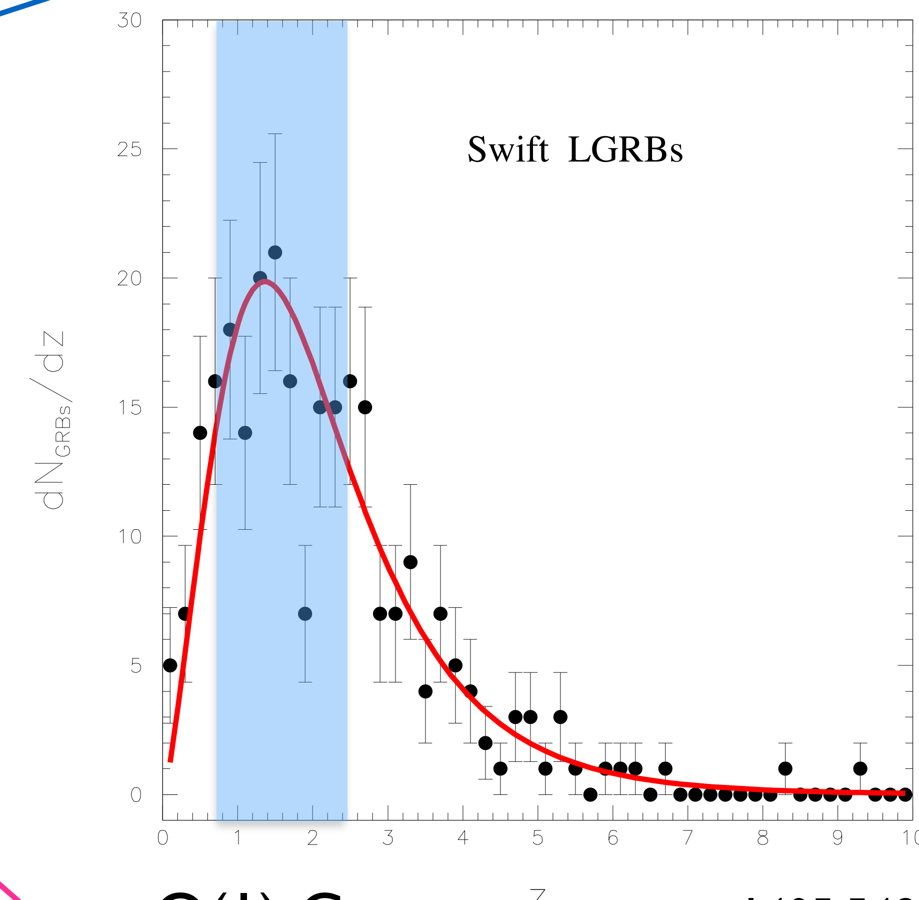
We take $g_{11}=10^{-3}$ in mass basis for conservative case.

* absorption line in a sample parameter set

suppose E^{-2} from GRBs

$g=10^{-3}$ with traveling distance 1Gpc and $M_s=3MeV$





O(1) Gpc

1405.5487

$$m_\nu \sim \sqrt{\Delta m_{12}}$$

$$(\Delta m_{12} = 7.6\times10^{-5}\,eV^2)$$

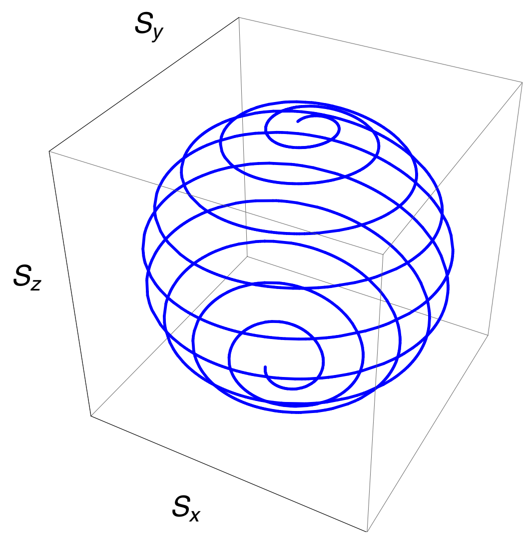
Degenerated spectrum for ν_1 and ν_2 is rather favored.

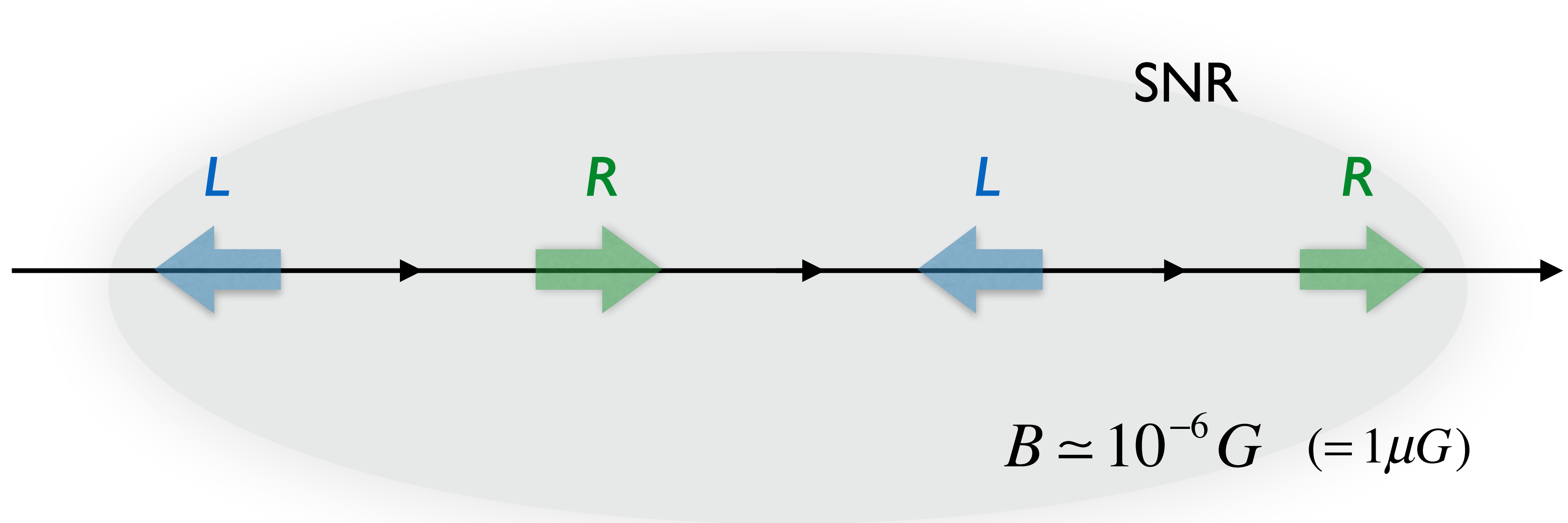
(normal hierarchy is assumed)

Attempt 2. Large neutrino magnetic moment scenario

If neutrino has the large magnetic moment, chirality flip of cosmic-ray neutrino takes place.

Larmor precession





galactic magnetic field

Larmor frequency: $\omega = \mu_\nu B$

neutrino magnetic moment

Chirality flip takes place at $\omega t = \pi$ $\Longleftrightarrow$ $L_{\mathrm{cf}} = \pi / \mu_\nu B$

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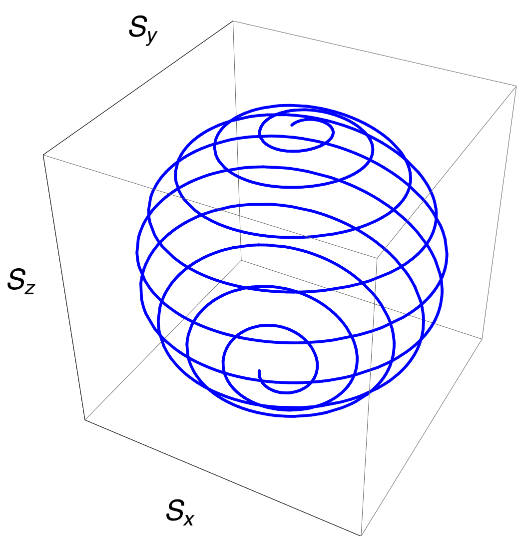
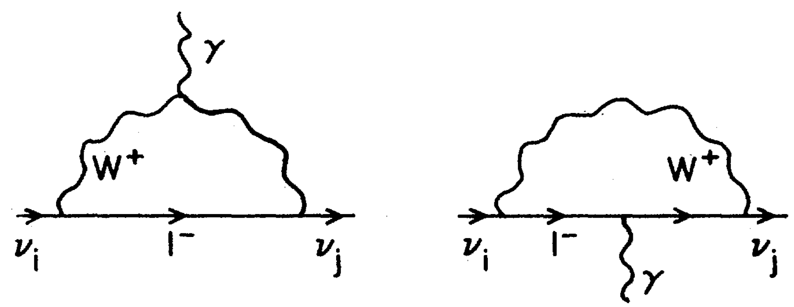


* SM



$$\mu_\nu \simeq \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} \sim 3\times10^{-19}\left(\frac{m_\nu}{eV}\right)\mu_B$$

$$\mu_B = 5.79\times10^{-11}\,MeV/T \qquad \text{(PDG)}$$

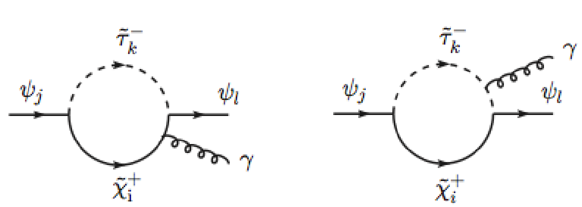
$(1G = 10^{-4}T)$

$$L_{\rm cf} = \pi/\mu_\nu B \simeq 10\left(\frac{0.1\,{\rm eV}}{m_\nu}\right)\left(\frac{\mu G}{B}\right)\,{\rm Gpc}$$

If new physics can enhance μ_ν, it is possible to flip the chirality during the flight.

* example: MSSM + vector-like lepton

1312.2505



	Neutrino Mass Eigenvalues (GeV)	$m_{\nu_3} = 5.2\times10^{-11}$ $m_{\nu_2} = 9.2\times10^{-12}$ $m_{\nu_1} = 9.7\times10^{-13}$
(i) $m_{\chi^\pm} = 256$ GeV	μ_2	1.2×10^{-10}
$m_{\tilde{\tau}} = 162$ GeV	μ_1	2.5×10^{-13}
	ν_3 lifetime	3.9×10^{14} yrs
(ii) $m_{\chi^\pm} = 267$ GeV	μ_2	4.6×10^{-10}
$m_{\tilde{\tau}} = 202$ GeV	μ_1	1.3×10^{-12}
	ν_3 lifetime	2.5×10^{14} yrs
(iii) $m_{\chi^\pm} = 268$ GeV	μ_2	2.2×10^{-10}
$m_{\tilde{\tau}} = 158$ GeV	μ_1	1.1×10^{-13}
	ν_3 lifetime	1.8×10^{14} yrs
(iv) $m_{\chi^\pm} = 272$ GeV	μ_2	-7.6×10^{-10}
$m_{\tilde{\tau}} = 195$ GeV	μ_1	-1.3×10^{-13}
	ν_3 lifetime	8.8×10^{13} yrs

* experimental bound $\quad \mu_\nu \leq 5.4\times10^{-11}\mu_B$

(Borexino, Phys.Rev.Lett.101:091302)

$$\Rightarrow \quad L_{cf} \sim O(1)kpc$$

Attempt 2. Large neutrino magnetic moment scenario

If neutrino has the large magnetic moment, chirality flip of cosmic-ray neutrino takes place.

In this case, it is not necessary that new interaction has to involve left-handed neutrinos.

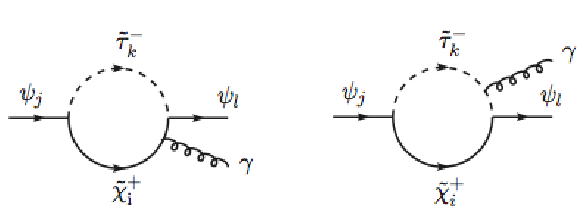
$$\mathcal{L} \supset gs\bar{N}_R\bar{N}_R,$$

Other situations are the same as the previous model.
(meson decay, etc.)

If new physics can enhance μ_ν, it is possible to flip the chirality during the flight.

* example: MSSM + vector-like lepton

1312.2505



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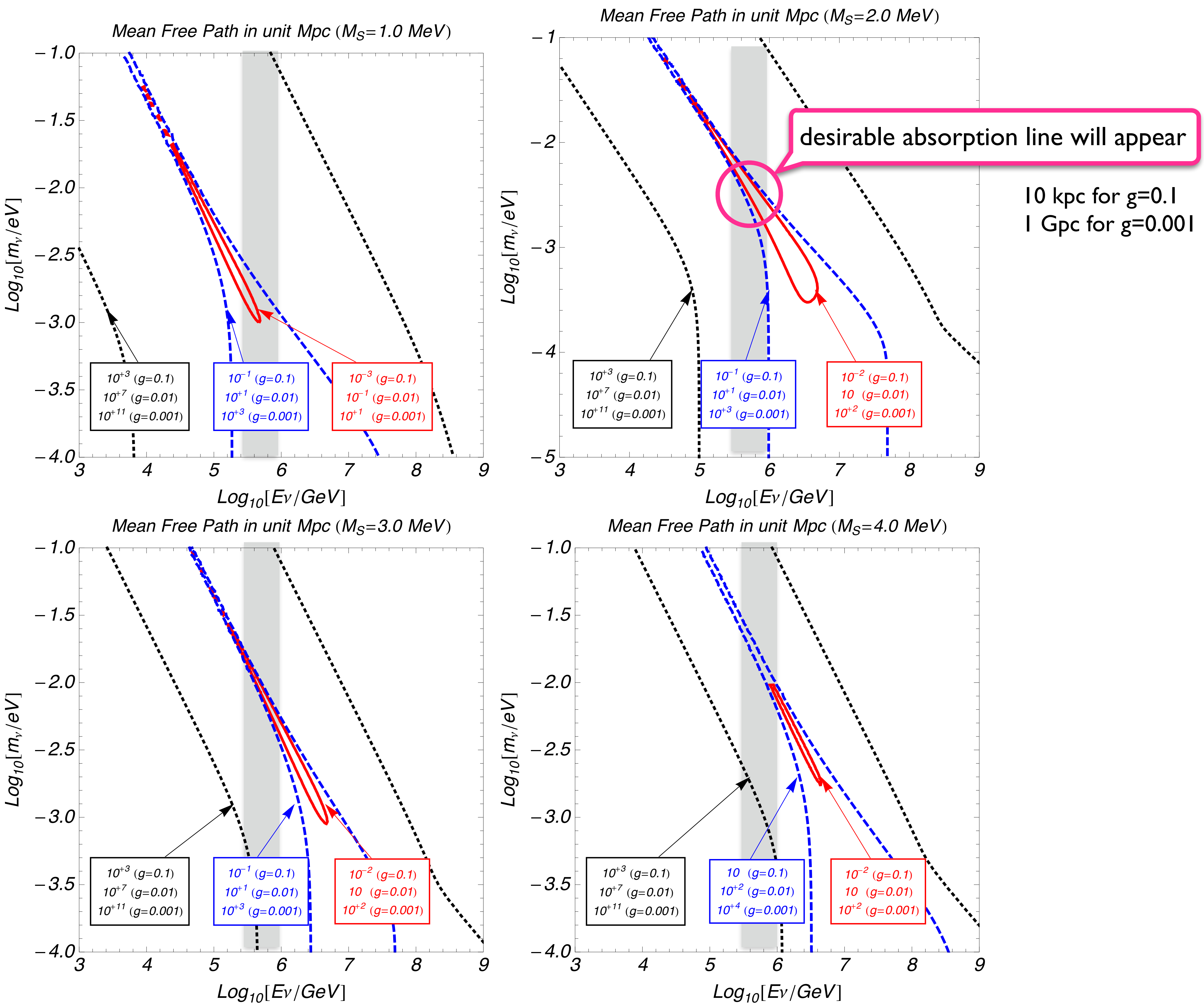
(Borexino, Phys.Rev.Lett.101:091302)

$$L_{cf} \sim O(1)kpc$$

Summary

* CνB absorption around sub-PeV scale is discussed.
* **Such absorption line may indicate MeV scale particle interacting with neutrinos.**
* **The line shape is also sensitive to neutrino masses.**
* As viable models, "neutrinophilic doublet scalar" and "large neutrino magnetic moment scenario" are discussed.
* Those models are testable in future collider experiments.

2. Neutrino absorption at sub-PeV scale



10 kpc for g=0.1
1 Gpc for g=0.001

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Z_2	$+$	$+$	$-$	$+$	$-$

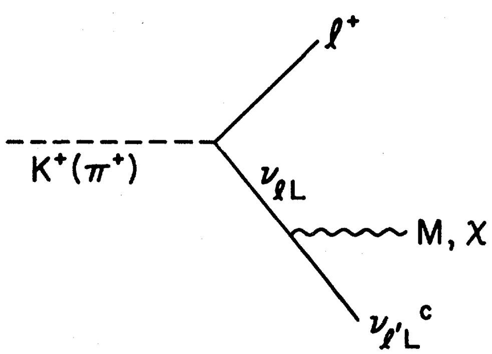
$$\mathcal{L} \supset g h_N l N_N + y h l \bar{N}_R + M \bar{N}_R N_N + m N_N N_N .$$

experimental limits

Phys.Rev. D75 (2007) 094001

mass basis

* Meson decay ($\pi/K \to l \nu_{l'} h_N^0$)



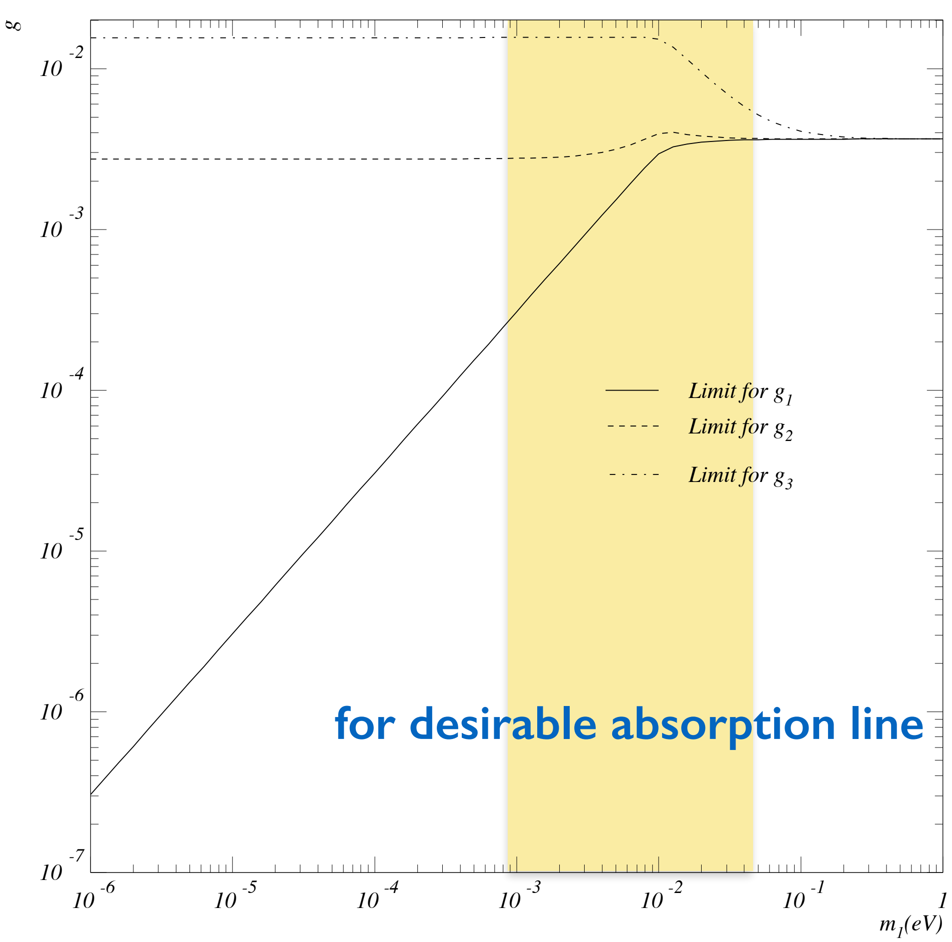
flavor basis: $g_{ab}^{\rm eff} h_N^0 \bar{\nu}_a \nu_b \ (a, b = e, \mu, \tau)$

$\downarrow$

mass basis: $g_{ij} = (U_{\rm PMNS}^\dagger)_{ia} g_{ab}^{\rm eff} (U_{\rm PMNS})_{bj} \ (i, j = 1, 2, 3)$

$$U_{\rm PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\delta = \alpha_1 = \alpha_2 = 0, \ s_{12}^2 = 0.31, \ s_{23}^2 = 0.51 \text{ and } s_{13}^2 = 0.023$



Attempt 1. Inverse seesaw model with a neutrinophilic scalar doublet

	l	N_N	$\bar{N}_R$	h	h_N
L	$+1$	$+1$	-1	0	-2
Z_2	$+$	$+$	$-$	$+$	$-$

$$\mathcal{L} \supset g h_N l N_N + y h l \bar{N}_R + M \bar{N}_R N_N + m N_N N_N.$$

experimental limits

* Meson decay ($\pi/K \to l \nu_{l'} h_N^0$)

Other case (limit for flavor basis couplings)

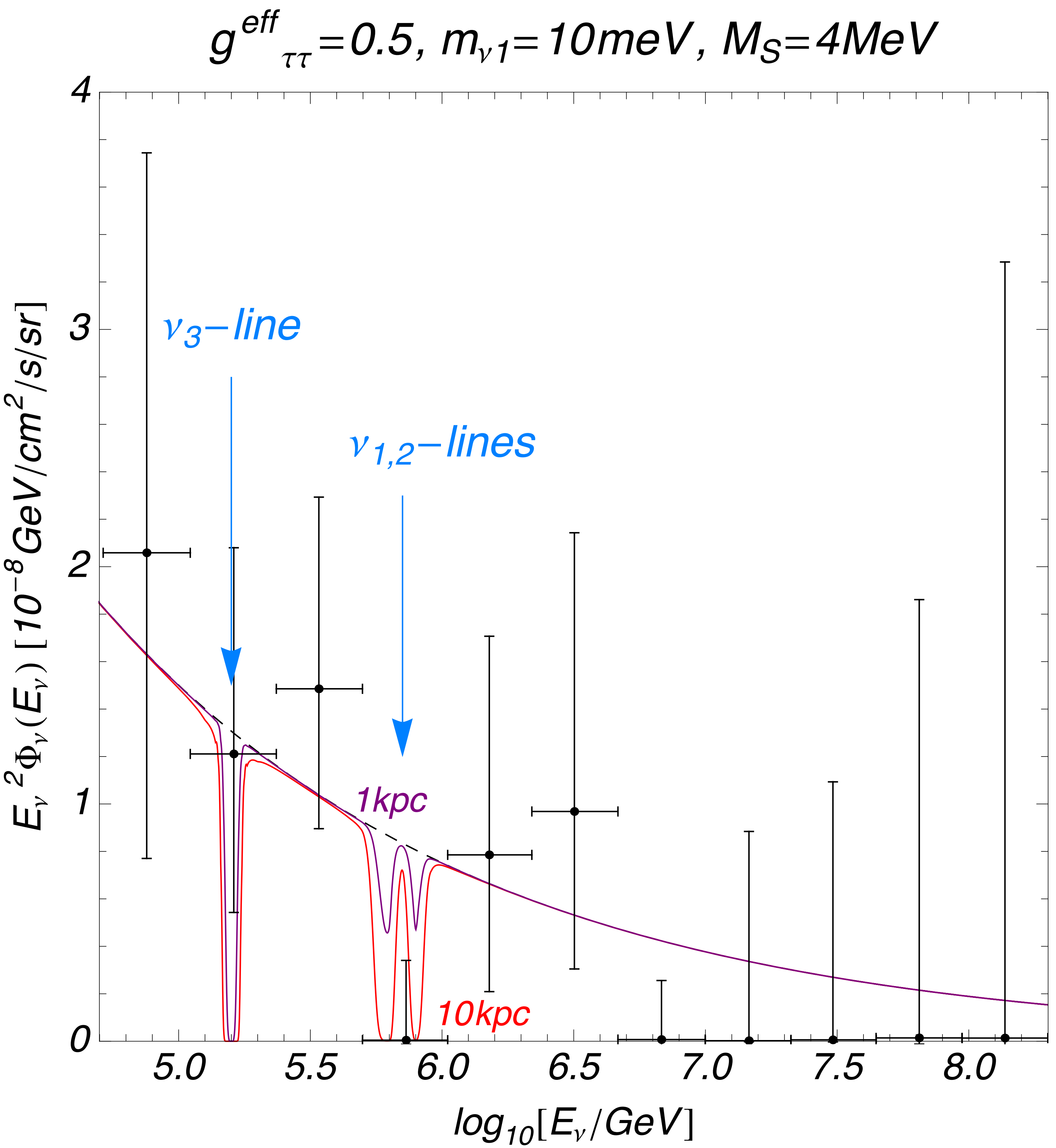
$$\sum_{l=e,\mu,\tau} |g_{el}^{\rm eff}|^2 < 5.5 \times 10^{-6}, \quad \sum_{l=e,\mu,\tau} |g_{\mu l}^{\rm eff}|^2 < 4.5 \times 10^{-5} \text{ and } \sum_{l=e,\mu,\tau} |g_{\tau l}^{\rm eff}|^2 < 3.2.$$

→ only $g_{\tau\tau}^{eff} = 0.5$ is assumed

flavor basis: $g_{ab}^{\rm eff} h_N^0 \bar{\nu}_a \nu_b \ (a, b = e, \mu, \tau)$

$$g_{ij} = \begin{pmatrix} 0.0966234\, g^{\rm eff}_{\tau\tau} & -0.202561\, g^{\rm eff}_{\tau\tau} & 0.215073\, g^{\rm eff}_{\tau\tau} \\ -0.202561\, g^{\rm eff}_{\tau\tau} & 0.424647\, g^{\rm eff}_{\tau\tau} & -0.450878\, g^{\rm eff}_{\tau\tau} \\ 0.215073\, g^{\rm eff}_{\tau\tau} & -0.450878\, g^{\rm eff}_{\tau\tau} & 0.47873\, g^{\rm eff}_{\tau\tau} \end{pmatrix}$$

mass basis: $g_{ij} = (U^\dagger_{\rm PMNS})_{ia} g_{ab}^{\rm eff} (U_{\rm PMNS})_{bj} \ (i, j = 1, 2, 3)$



$g^{eff}_{\tau\tau}=0.5,\ m_{\nu 1}=10meV,\ M_S=4MeV$
ν_3-line
$\nu_{1,2}-lines$
1kpc
10kpc
$E_\nu^{\ 2}\Phi_\nu(E_\nu)\ [10^{-8}GeV/cm^2/s/sr]$
$log_{10}[E_\nu/GeV]$