Heavy neutrino searches with Icecube

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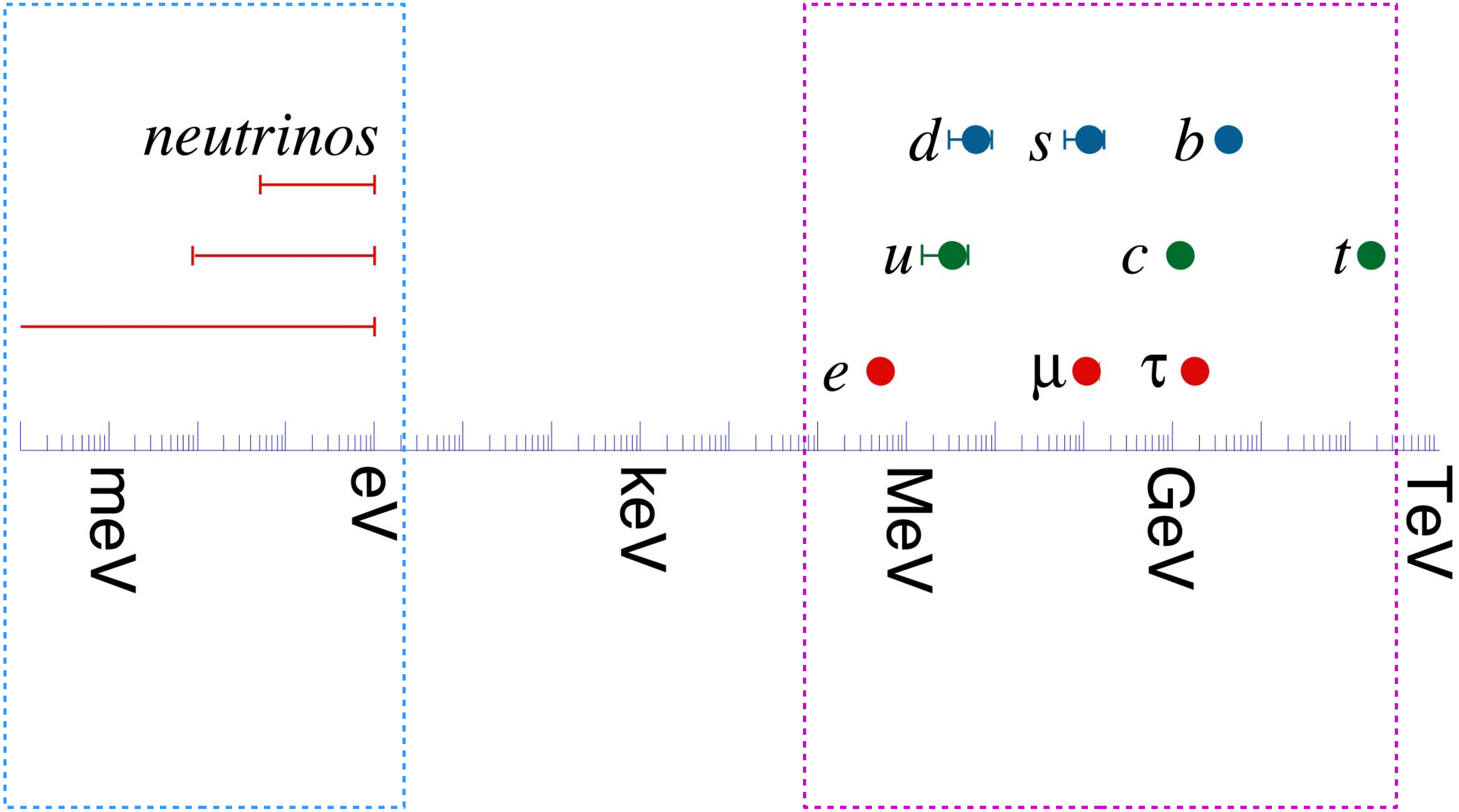
Neutrino masses



Majorana or Dirac?

New fields are required to give neutrinos a mass. Two main ways:

1) Dirac mass: as for the rest of fermions in the SM

$$Y_\nu \overline{L}_L \widetilde{\phi} \nu_R \to m_\nu \bar{\nu}_L \nu_R$$

$$\boxed{Y_\nu \lesssim 10^{-12}}$$

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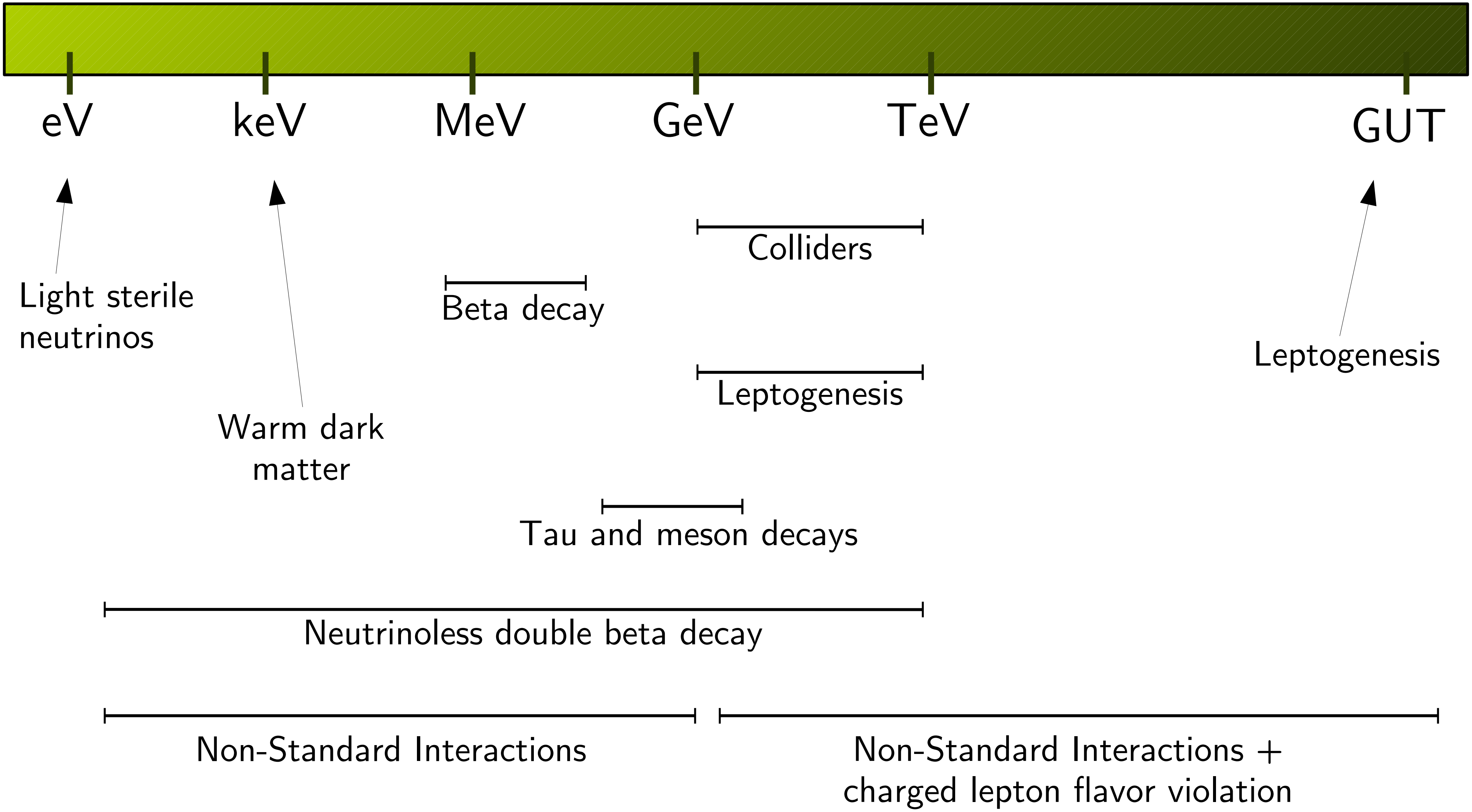
$$\boxed{(\not{L})}$$

$M \gg Y_\nu v$

$$\to m_\nu = Y_\nu^\dagger M^{-1} Y_\nu v^2$$

Type I Seesaw:
Minkowski '77, Gell-Mann, Ramond, Slansky '79, Yanagida '79, Mohapatra, Senjanovic '80

Scale of new physics



eV

keV

MeV

GeV

TeV

GUT

Light sterile neutrinos

Warm dark matter

Beta decay

Colliders

Leptogenesis

Tau and meson decays

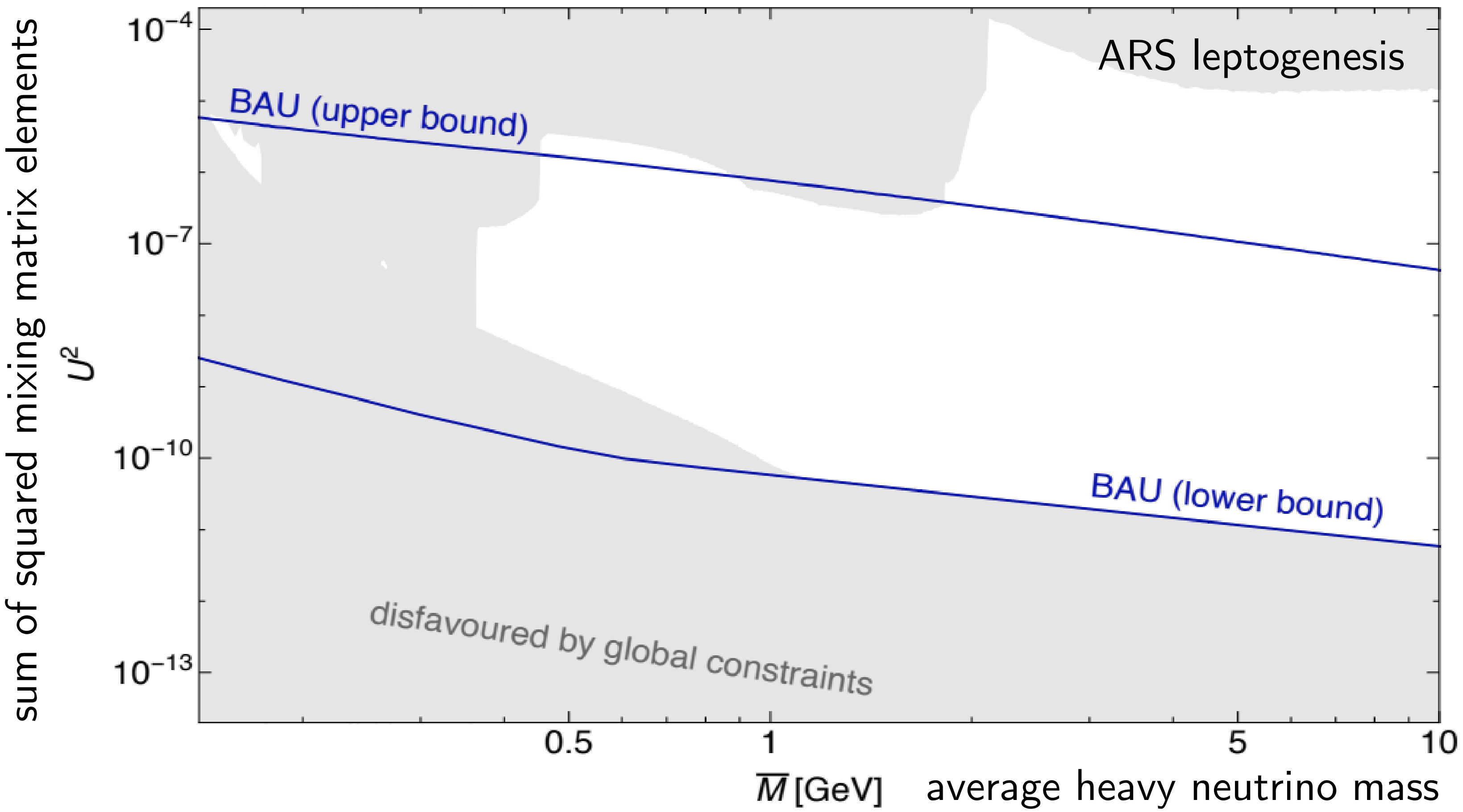
Neutrinoless double beta decay

Leptogenesis

Non-Standard Interactions

Non-Standard Interactions + charged lepton flavor violation

Why the GeV scale?

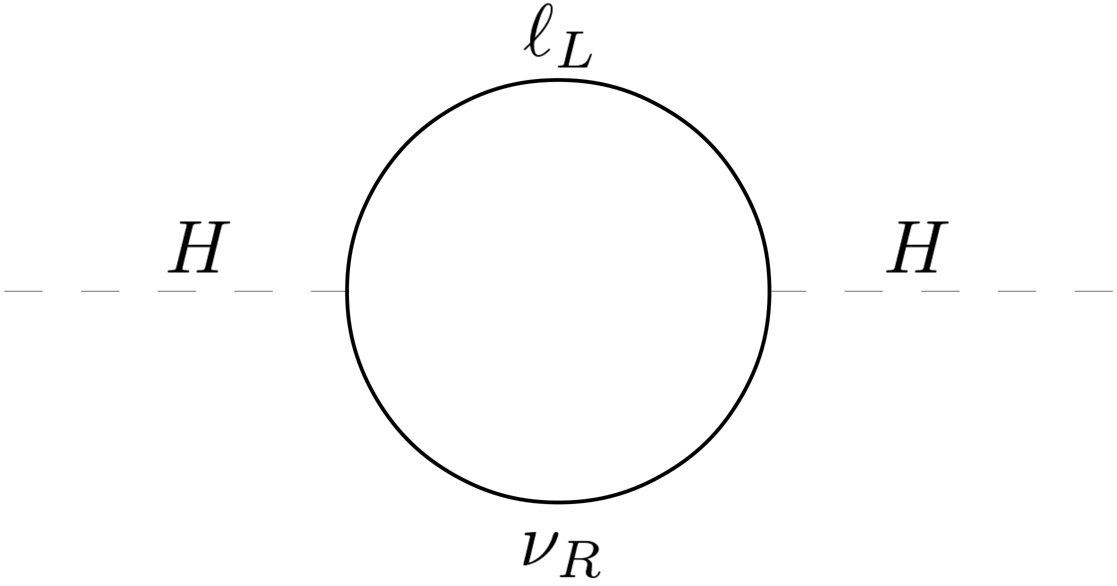


sum of squared mixing matrix elements

average heavy neutrino mass
(two neutrinos)

Figure from the review: Drewes, Garbretch, Hernandez, Kekic, Lopez-Pavon, Racker, Rius, Salvado, Teresi, 1711.02862
(see also, e.g., Eijima, Shaposhnikov and Timiryasov, 1808.10833)

Why a low-scale seesaw?

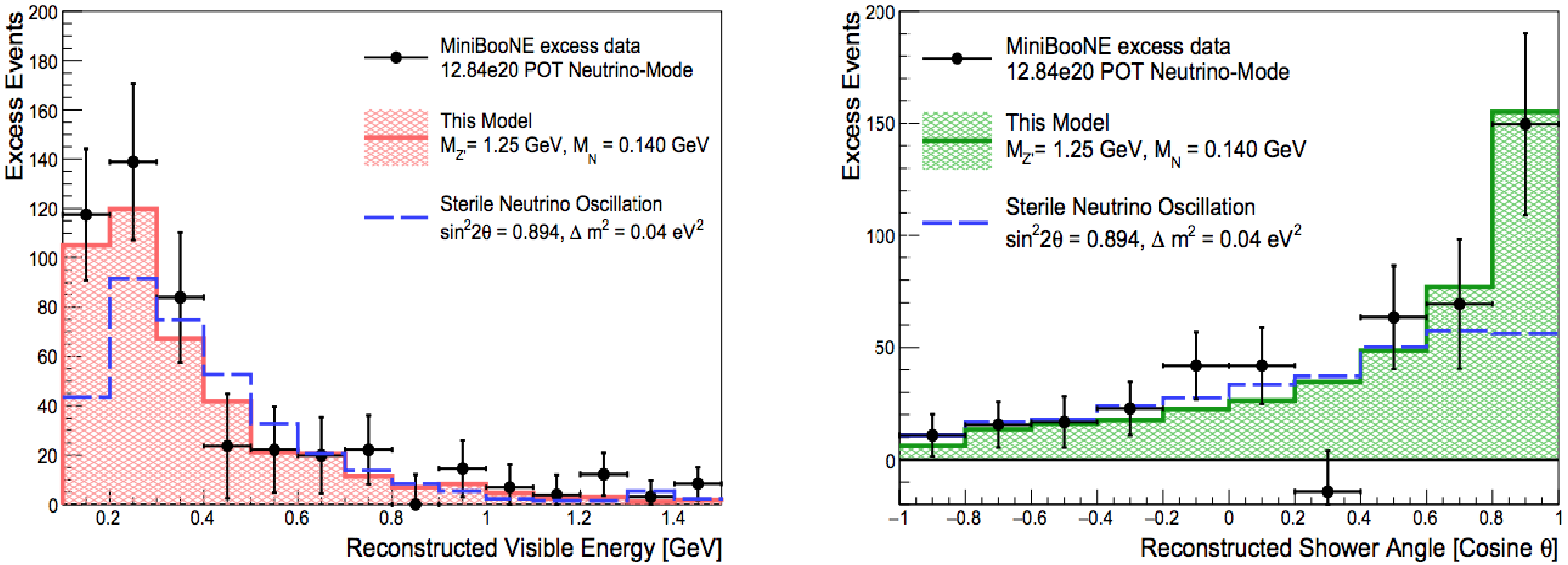


$$\delta\mu^2 \approx \frac{Y_\nu^2}{4\pi^2} M_R^2 \log\left(\frac{q}{M_R}\right)$$

Vissani, hep-ph/9709409

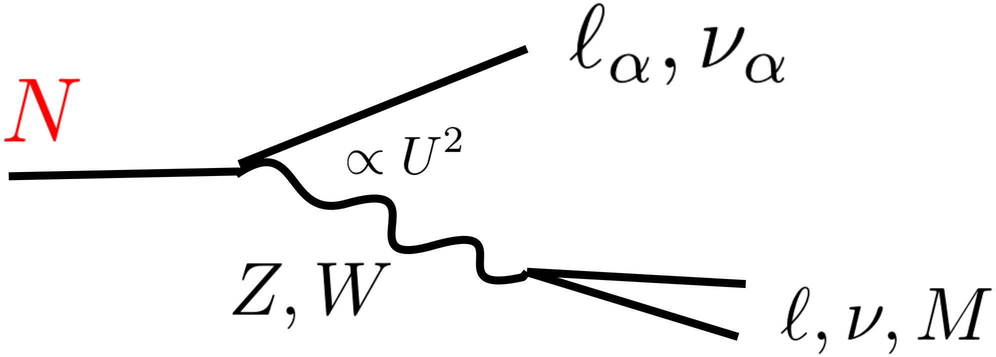
Further motivation...?

Figure from Ballett, Pascoli, Ross-Lonergan, 1808.02915



See also:
Bertuzzo, Jana, Machado, Zukanovich Funchal, 1807.09877
Fischer, Hernandez-Cabezudo, Schwetz, 1909.09561
Gninenko, 1009.5536 and 0902.3802
Palomares-Ruiz, Pascoli, Schwetz, hep-ph0505216
...

Direct searches for GeV neutrinos



$M = \pi, K, \eta, \omega, \ldots$

- Direct searches can be divided into two main categories:
    - Peak searches
    - Displaced decays: fixed target experiments, colliders, ...

$$c\tau \sim \mathrm{few}\left(\frac{\mathrm{GeV}}{m_N}\right)^5\left(\frac{10^{-4}}{U^2}\right)\ \mathrm{m}$$

For detailed calculations of heavy neutrino decay channels see, e.g.:
Ballett, Boschi, Pascoli, 1905.00284; Bondarenko et al, 1805.08567

Direct searches for GeV neutrinos

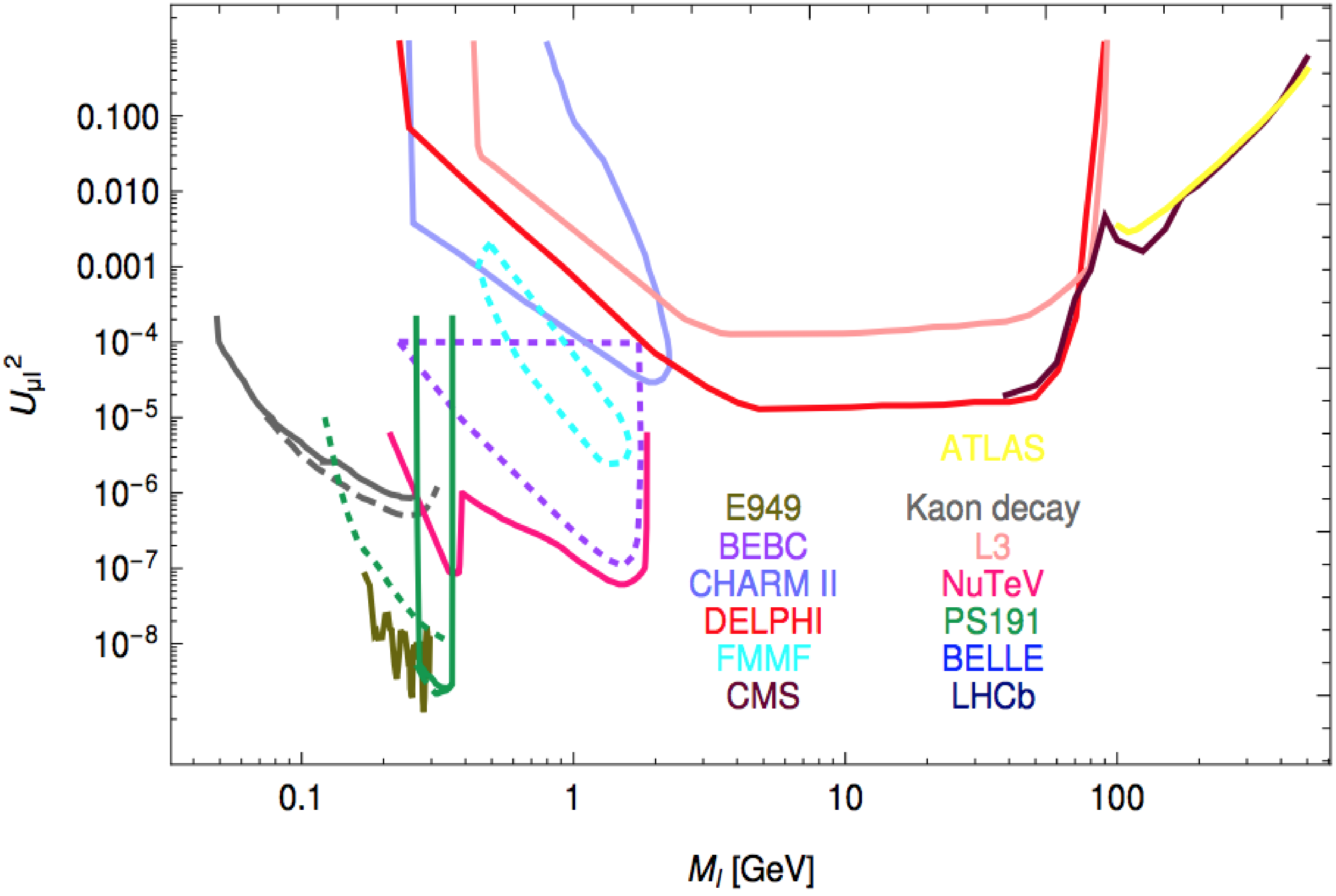


Figure from Drewes and Garbrecht, 1502.00477
(See also Ruchayskiy and Ivashko, 1112.3319, Atre et al, 0901.3589)

Direct searches for GeV neutrinos

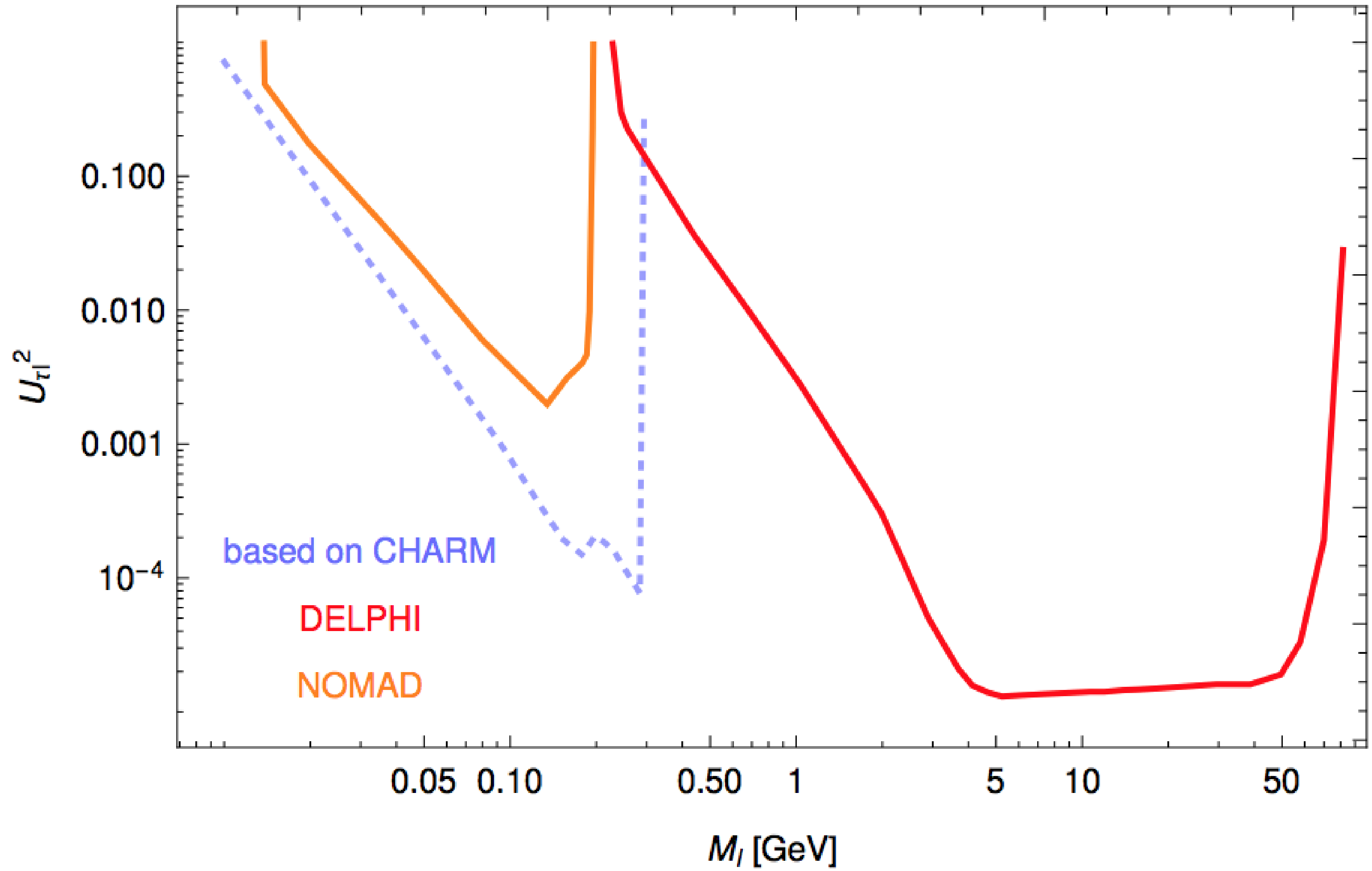
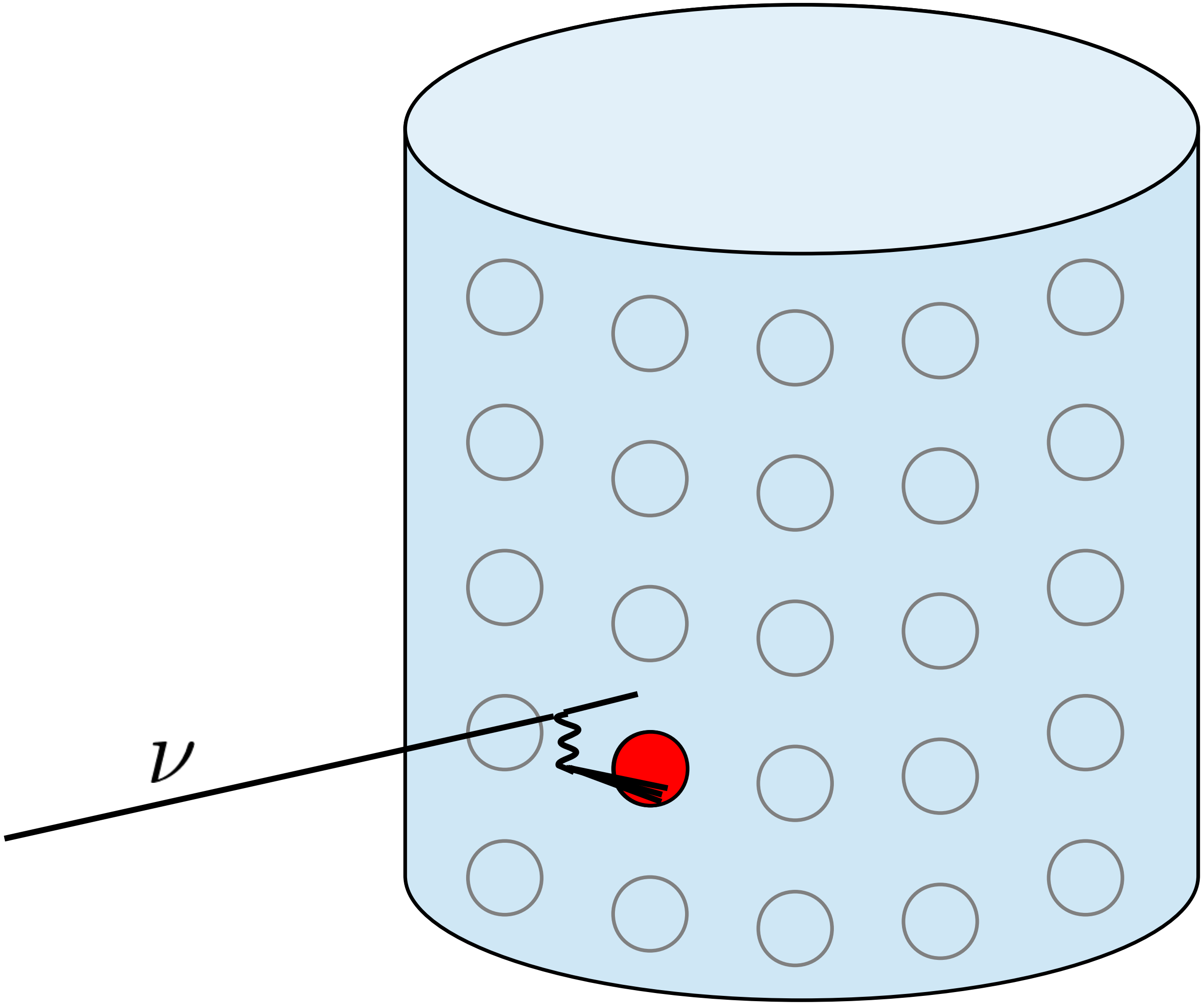
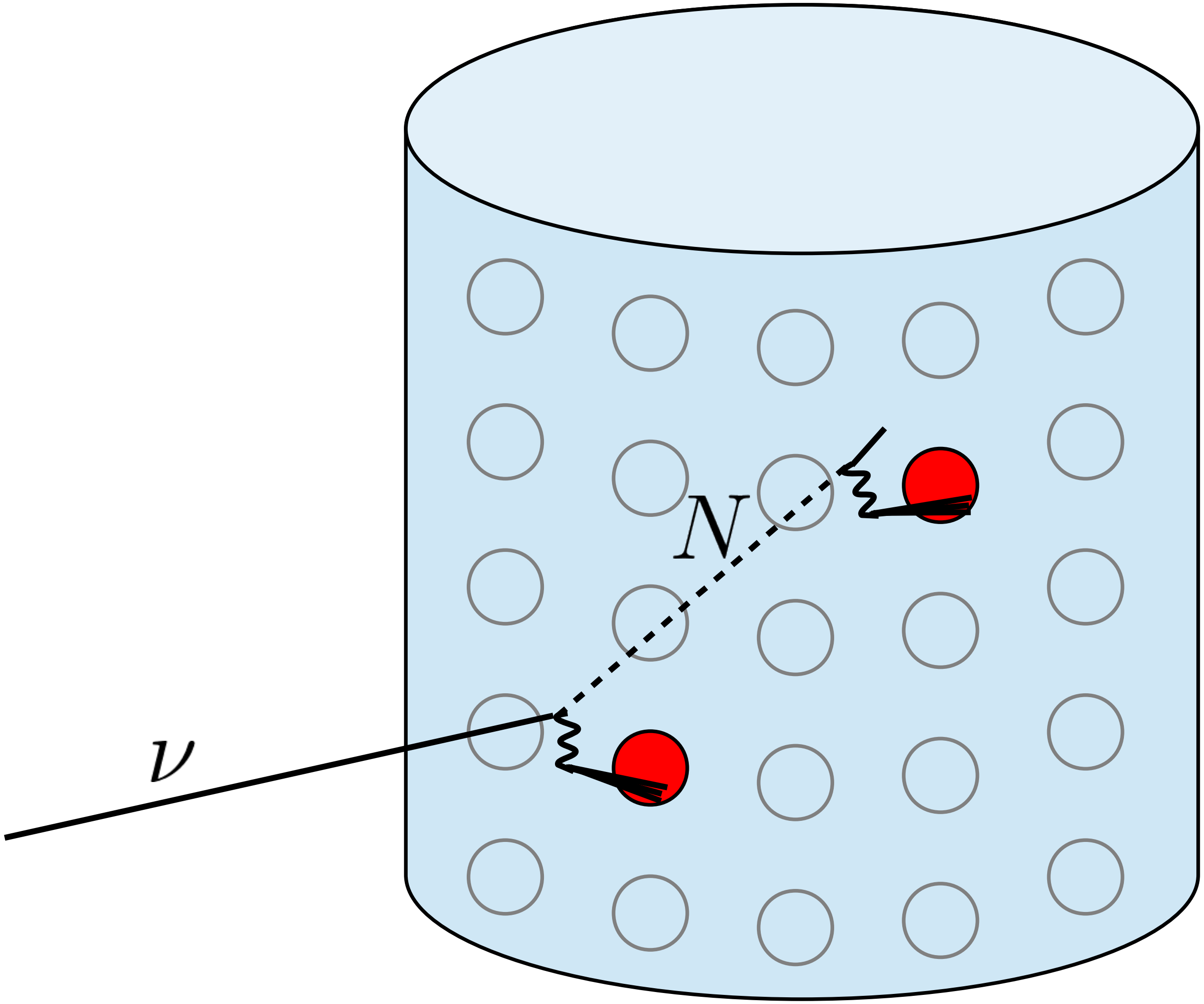


Figure from Drewes and Garbrecht, 1502.00477
(See also Ruchayskiy and Ivashko, 1112.3319, Atre et al, 0901.3589)

Heavy neutrinos produced inside the detector

Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573
Coloma, 1906.02106


ν


N
ν

Double-bangs are expected at UHE

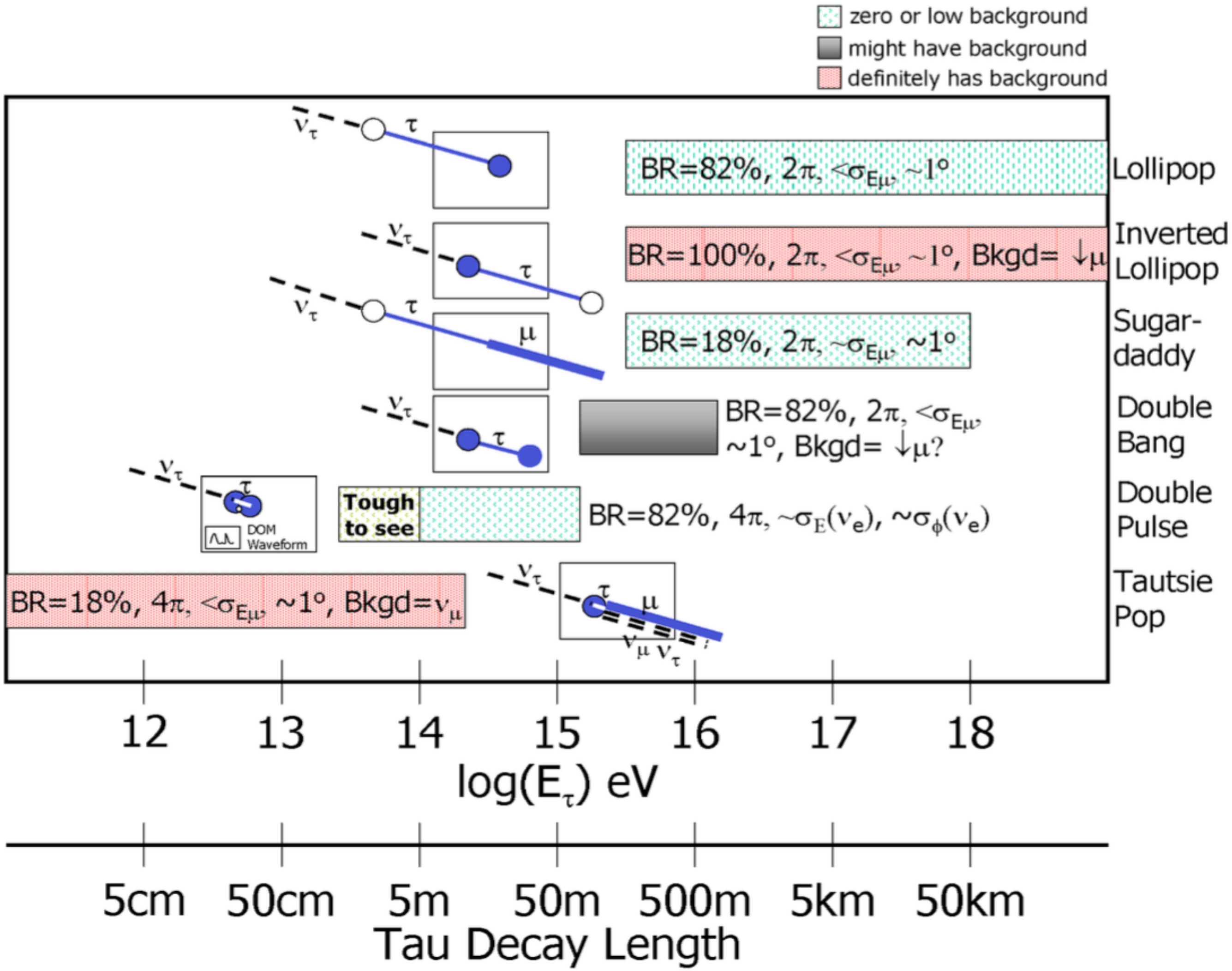
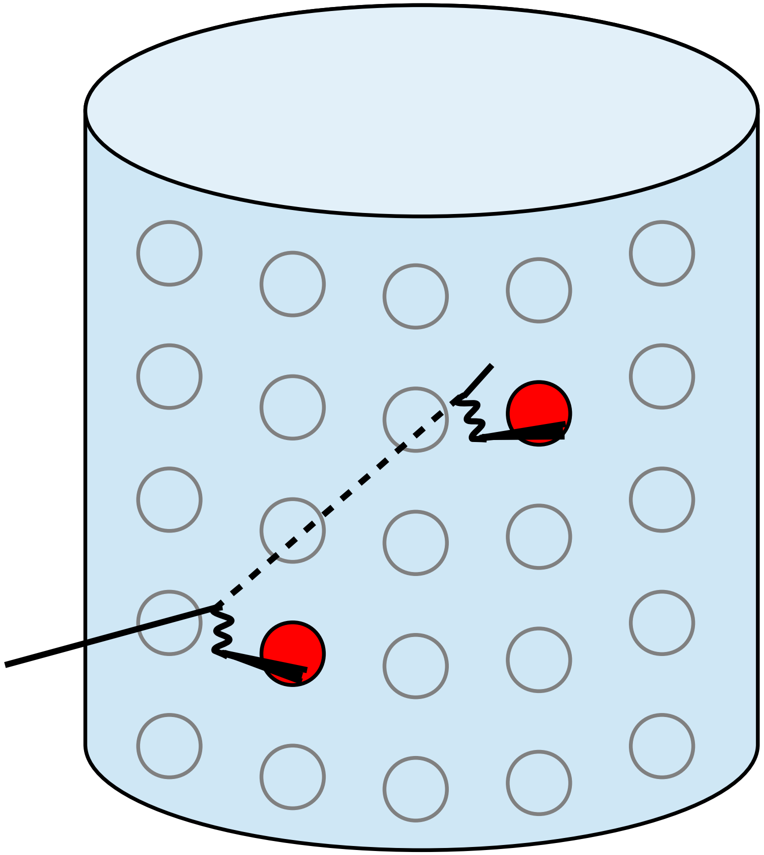


Figure from: Tau Neutrinos in IceCube, D. F. Cowen, TeVPA'06 proceedings
See also Icecube coll., 1509.06212

Low-energy double bangs?

- Key requirements:
  - Trigger has to go off during first shower: 3-4 DOMs hit
  - Minimum energy/distance to reach a DOM (limited by ice absorption): 36 m
  - Minimum separation between the two showers (limited by time resolution, 20 m)



Signal vs background

$$\frac{dN_{ev}}{dt} \simeq \rho_{ice} BR_{vis} \int dE_\nu dE_N d\cos\theta \frac{d\phi_{\nu_\mu}}{dE_\nu d\cos\theta} P_{\nu_\mu \to \nu_\tau} \frac{d\sigma_{\nu_\tau N}}{dE_N} \boxed{V_{det}(L_{lab}, \cos\theta)}$$

Effective volume (depends on the neutrino decay length and detector geometry)

Order-of-magnitude estimates for the signal, for 1 GeV heavy neutrino:

$$N_{sig} \sim \mathcal{O}\left(\frac{|U|^2}{10^{-4}}\right) \text{ events/yr}$$

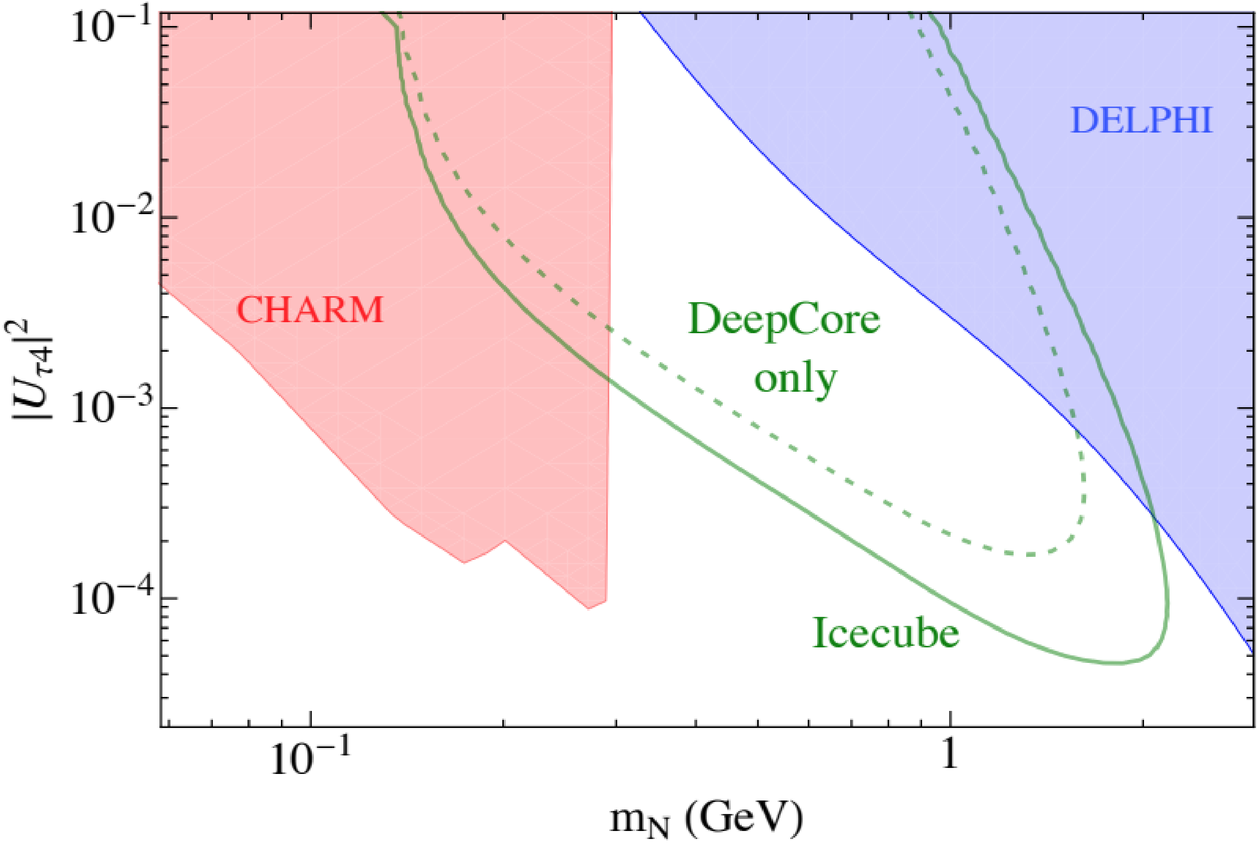
Order-of-magnitude estimates for the background:

$$N_{bg} \sim \mathcal{O}\left(0.05\right) \text{ events/yr}$$

Vanilla scenario: only mixing

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M \overline{\nu}^c_R \nu_R$$

6 years considered

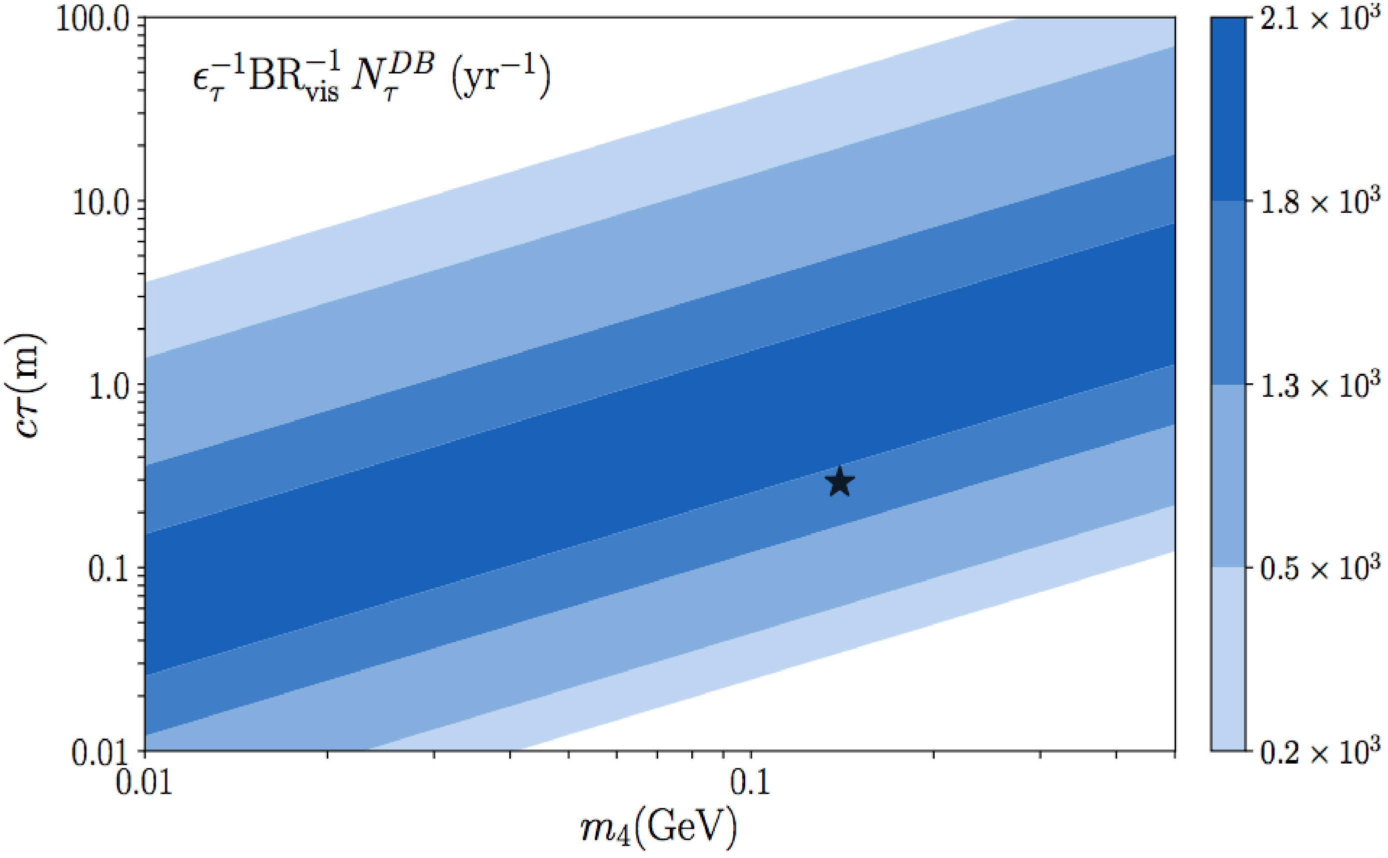


Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573

Light Z' boson + mixing

$$\ldots + U_{\alpha 4} g' \bar{\nu}_\alpha \gamma^\mu P_L \nu_4 Z'_\mu$$

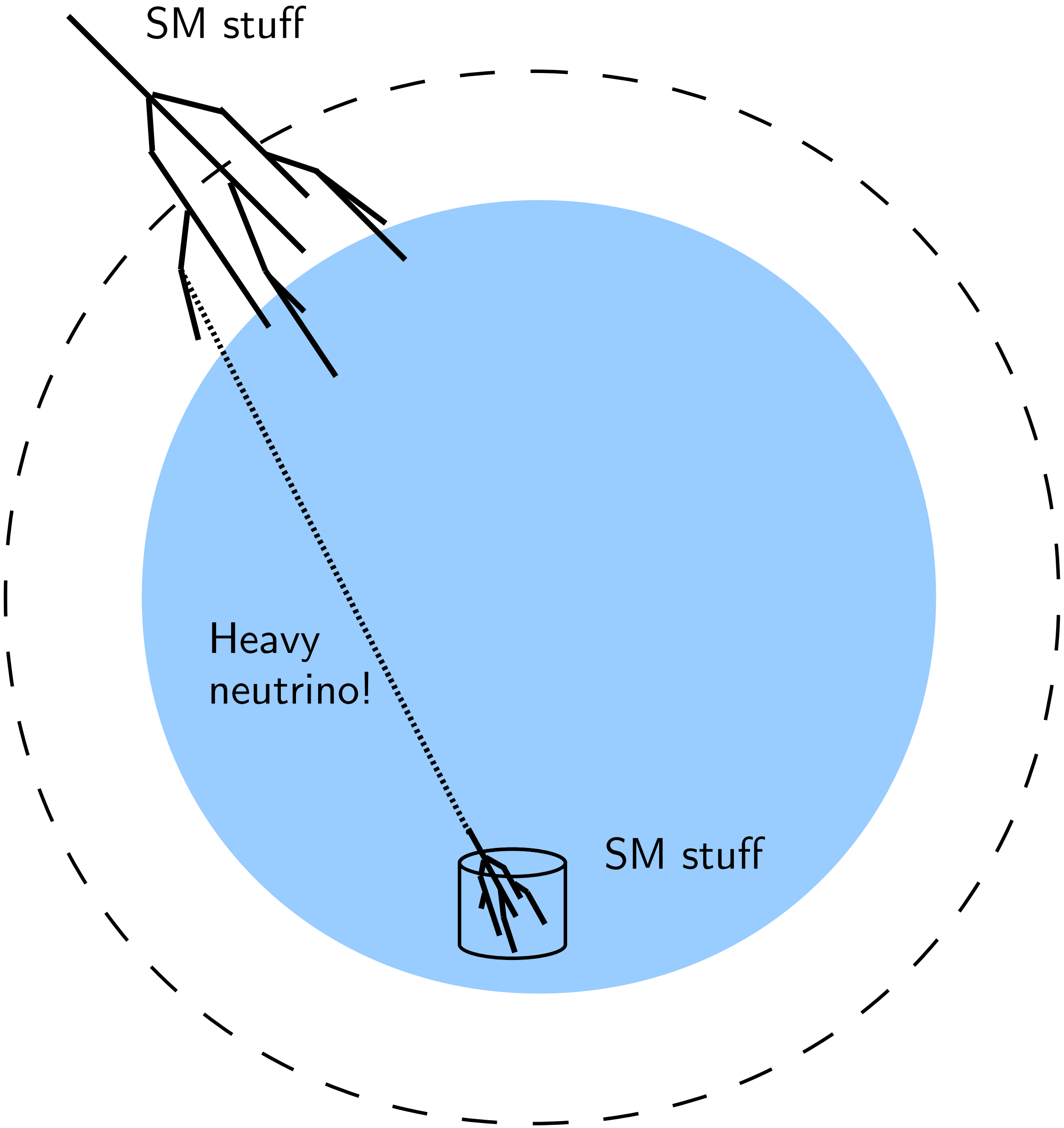
$$N_{\alpha,Z'} = N_{\alpha,Z} \epsilon_\alpha$$



Coloma, 1906.02106

Heavy neutrinos produced in the atmosphere

Arguelles, Coloma, Hernandez, Muñoz, 1910.XXXXX


SM stuff
Heavy neutrino!
SM stuff

Signal computation

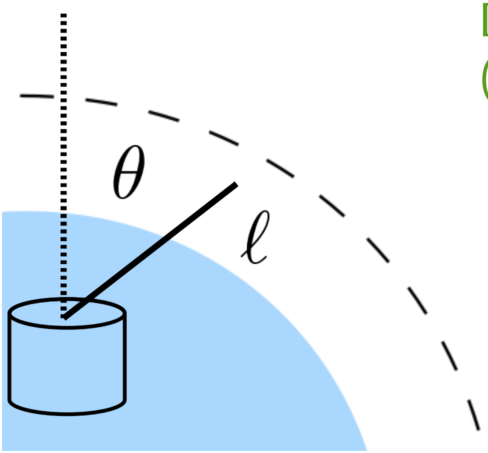
$$\frac{d\Phi_N}{dE_N\,d\cos\theta} = \int_0^{\ell_{\max}} d\ell\,\boxed{\frac{d\Pi_N}{dE_N\,d\cos\theta\,d\ell}}\; e^{-\frac{\ell}{\ell_{\mathrm{decay}}}}$$

Computed as in the SM, but
considering GeV-scale neutrinos

$$N_i^\alpha = \mathrm{Br}(e\text{–like}) \int_{E_N} \boxed{\epsilon^{\alpha\beta}(E_i, E_N)} \int_\theta \boxed{A^{\mathrm{eff}}_{\mathrm{decay}}(E_N, \cos\theta)}\, \frac{d\Phi_N}{dE_N\,d\cos\theta}$$

Detector efficiencies
(estimated)

Geometric acceptance
(geometry)

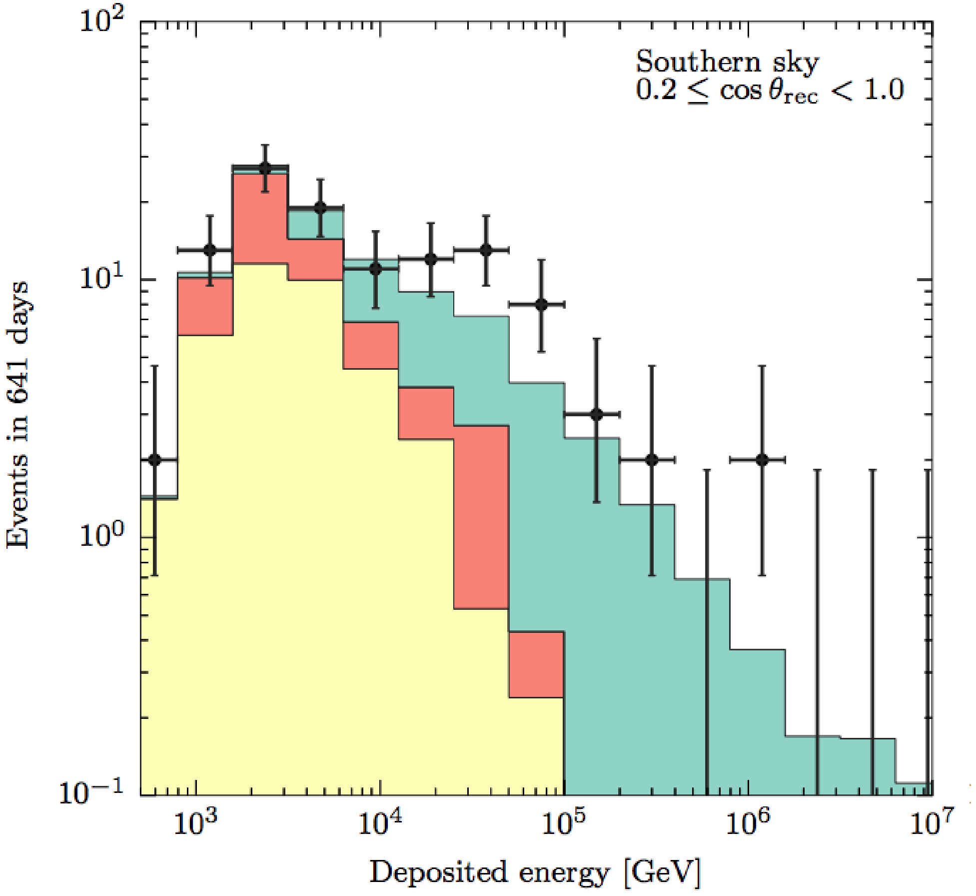


Arguelles, Coloma, Hernandez, Muñoz, 1910.XXXXX

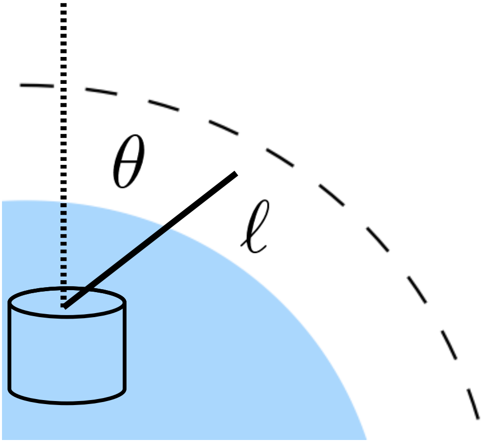
Backgrounds and data

Data release from 1410.1749 used (MESE data, 641 days)

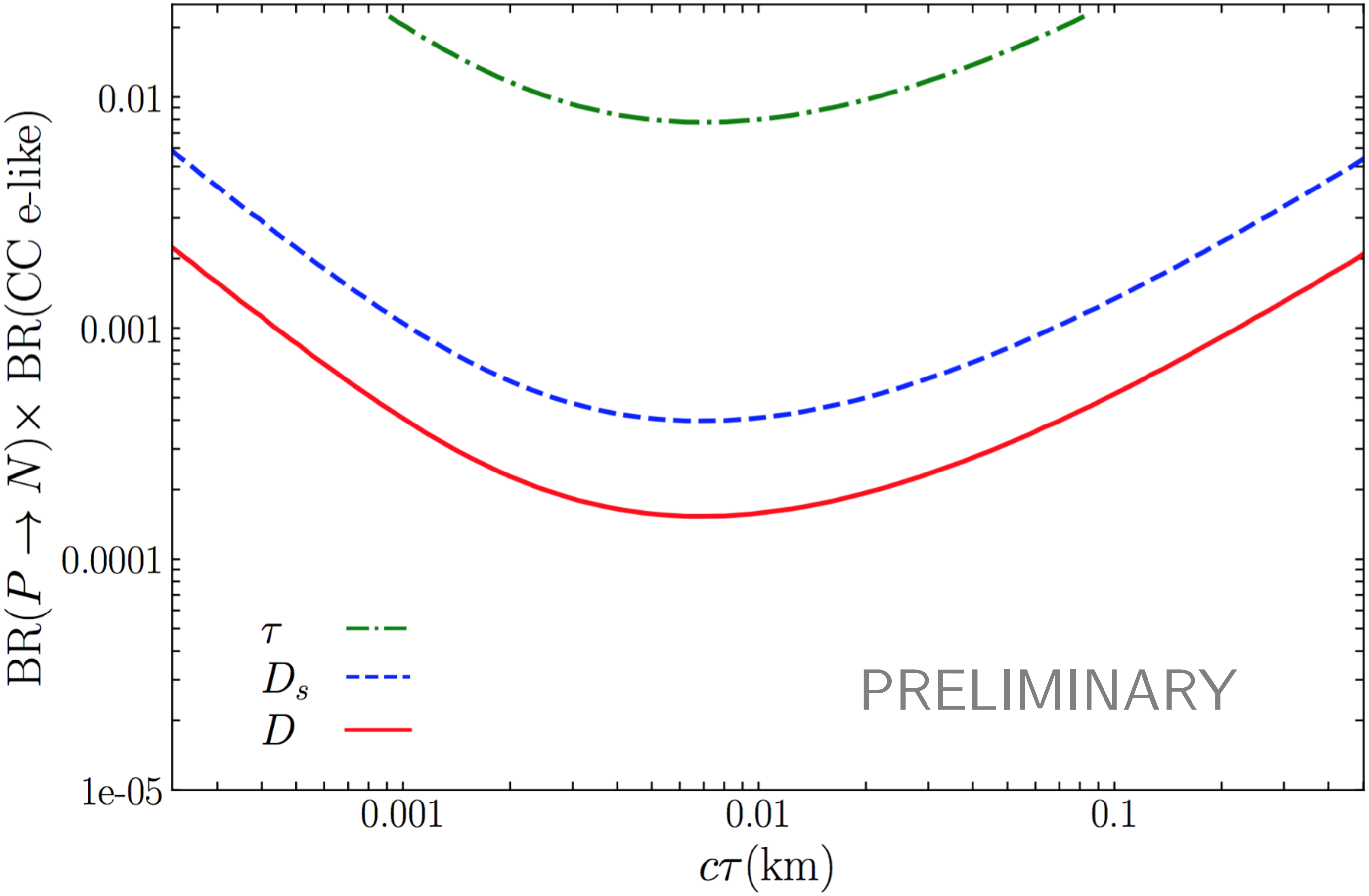
Only down-going events considered (signal region)



Icecube collaboration, 1410.1749



Exclusion regions



Arguelles, Coloma, Hernandez, Muñoz, 1910.XXXXX

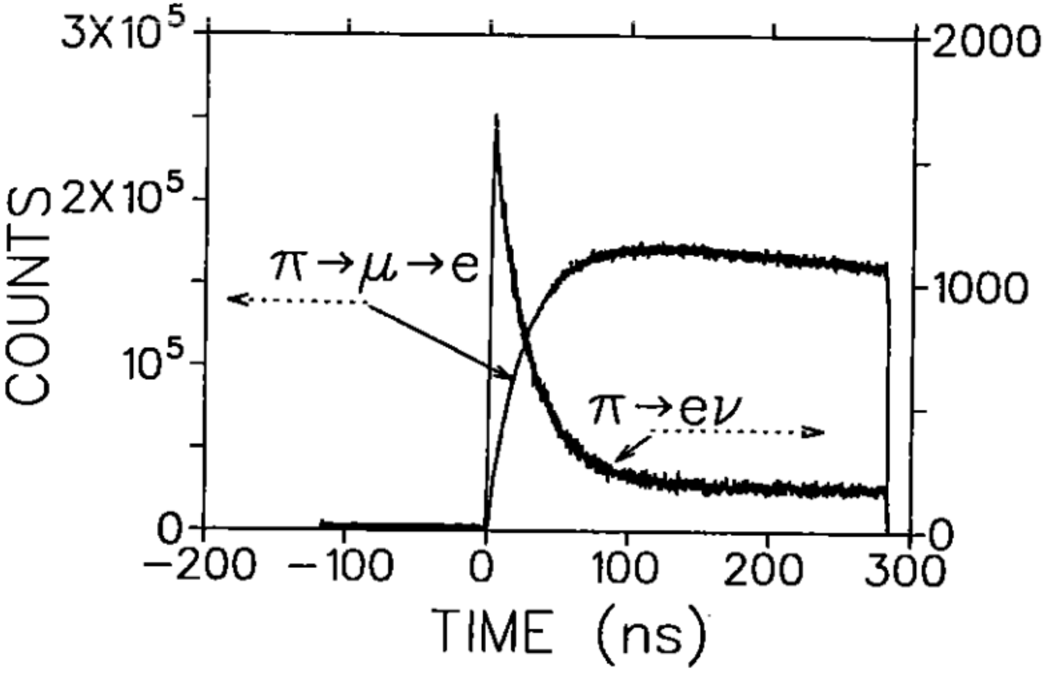
Summary

- GeV neutral leptons are a well-motivated extension of the SM, with a rich phenomenology.
- Neutrino telescopes are sensitive to heavy neutrinos produced in several ways:
    - produced and decayed inside the detector (double-bangs at low energies)
    - produced in the atmosphere, decayed in the detector

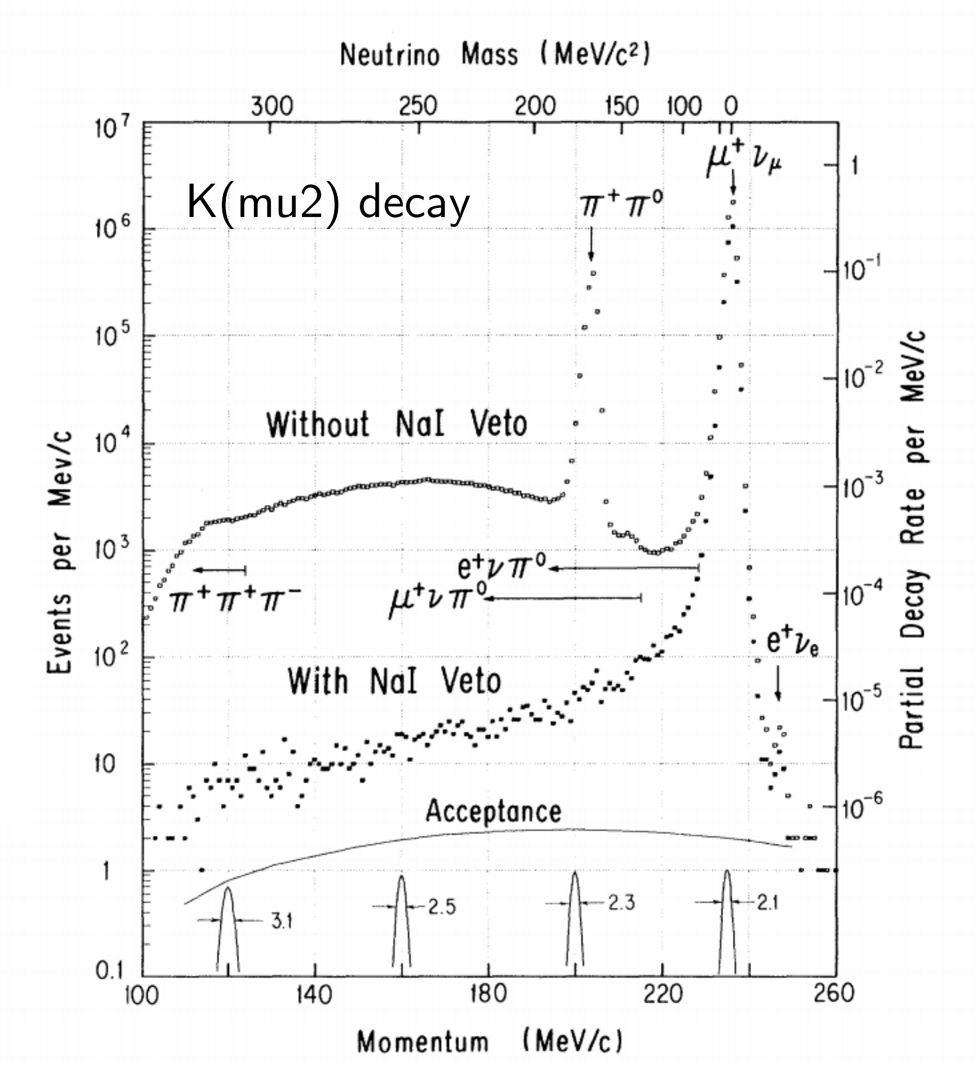
Thank you!!

Backup slides

Peak searches



Britton et al (TRIUMF),
Phys.Rev.Lett. 68 (1992) 3000-3003



Hayano et al, Phys.Rev.Lett. 49 (1982) 1305

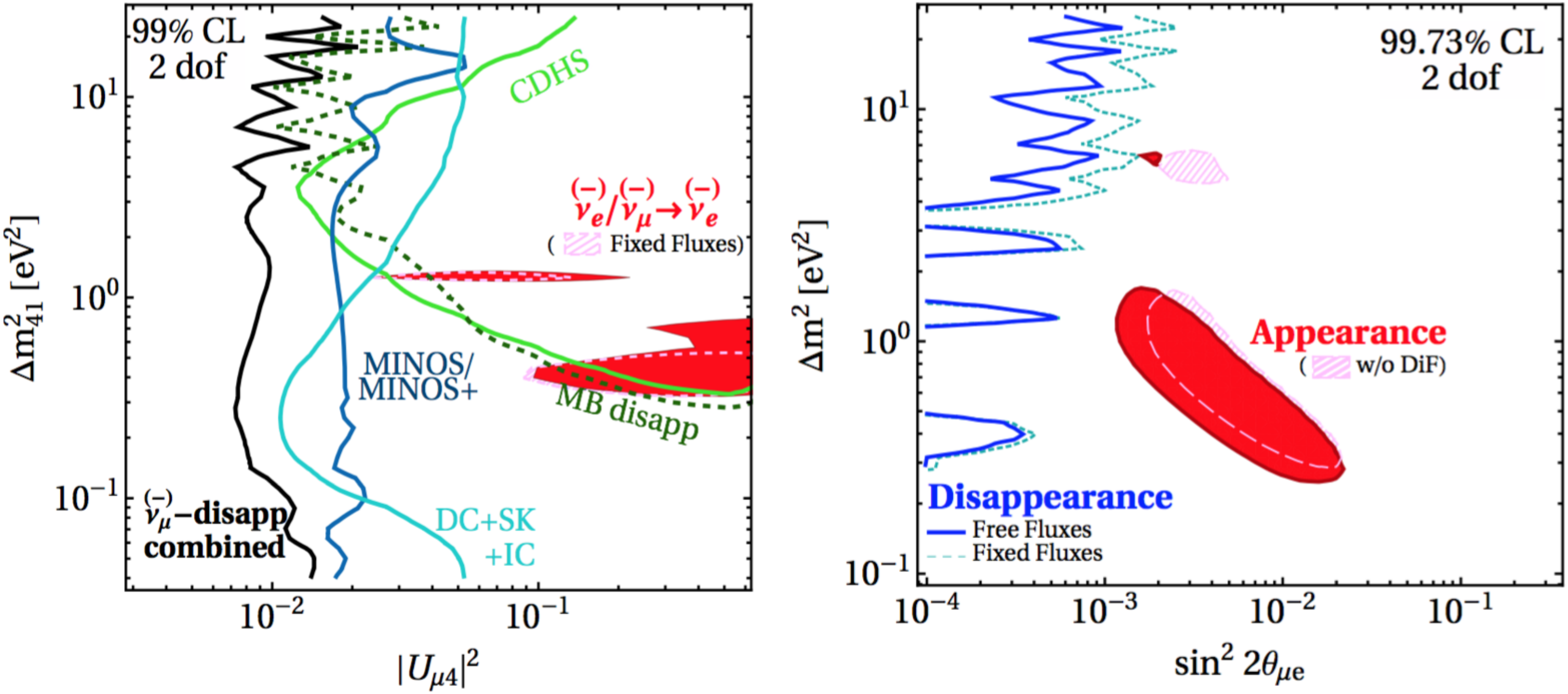
How to search for GeV neutral leptons

- At low energies, we can describe the interactions with mesons through the effective Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{chiral+N} \quad = \quad & \sum_{P^0} G_F V_{\alpha 4}^{*} \mathcal{F}_{P^0} \bar{N}_R^c \, p_\mu P_L \nu_\alpha \\
+ \quad & \sum_{V^0} G_F V_{\alpha 4}^{*} \mathcal{F}_{V^0} \bar{N}_R^c \, \epsilon_\mu P_L \nu_\alpha \\
+ \quad & \sum_{P^\pm} \sqrt{2} G_F V_{\alpha 4}^{*} \mathcal{F}_{P^\pm} \bar{N}_R^c \, p_\mu P_L \ell_\alpha \\
+ \quad & \sum_{V^\pm} \sqrt{2} G_F V_{\alpha 4}^{*} \mathcal{F}_{V^\pm} \bar{N}_R^c \, \epsilon_\mu P_L \ell_\alpha + \text{h.c.}
\end{aligned}
$$

$$P = \pi, K, \ldots \quad V = \eta, \omega, \ldots$$

Tensions in a 3+1 scenario



Dentler et al, 1803.10661
(see also Giunti and Lasserre, 1901.08330)