Atmospheric Long-Lived Particle Searches

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IFIC, UV/CSIC

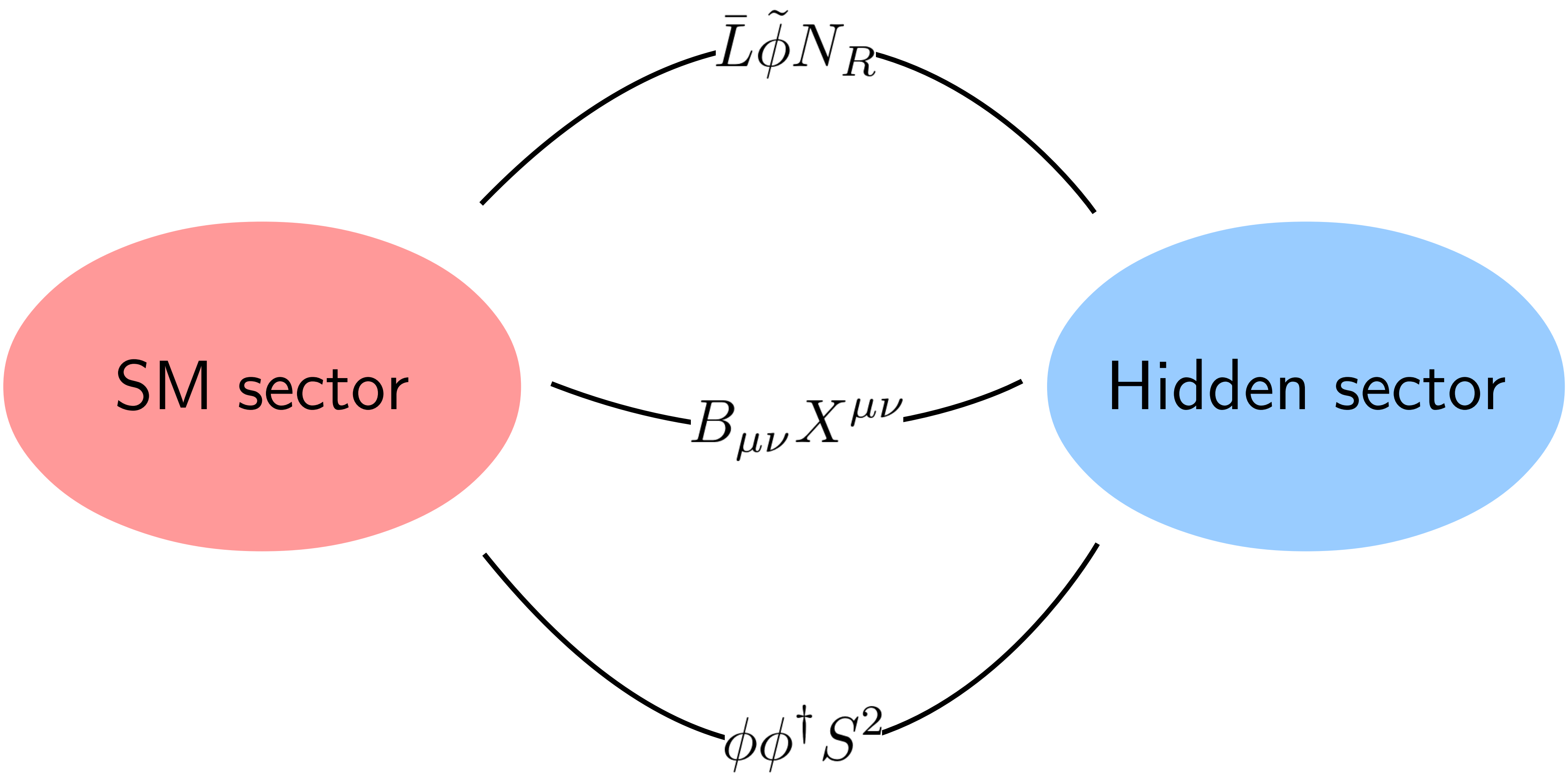
Based on:
Argüelles, Coloma, Hernandez, Muñoz, 1910.12839
Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129

Brookhaven Neutrino Theory Virtual Seminars
April 6th 2019

Outline

1) Introduction/motivation
2) Heavy neutral leptons
    - Sensitivity to general (non-minimal) models
    - Sensitivity to the minimal scenario
3) Dark photons, and a B-L model

Where is the new physics?



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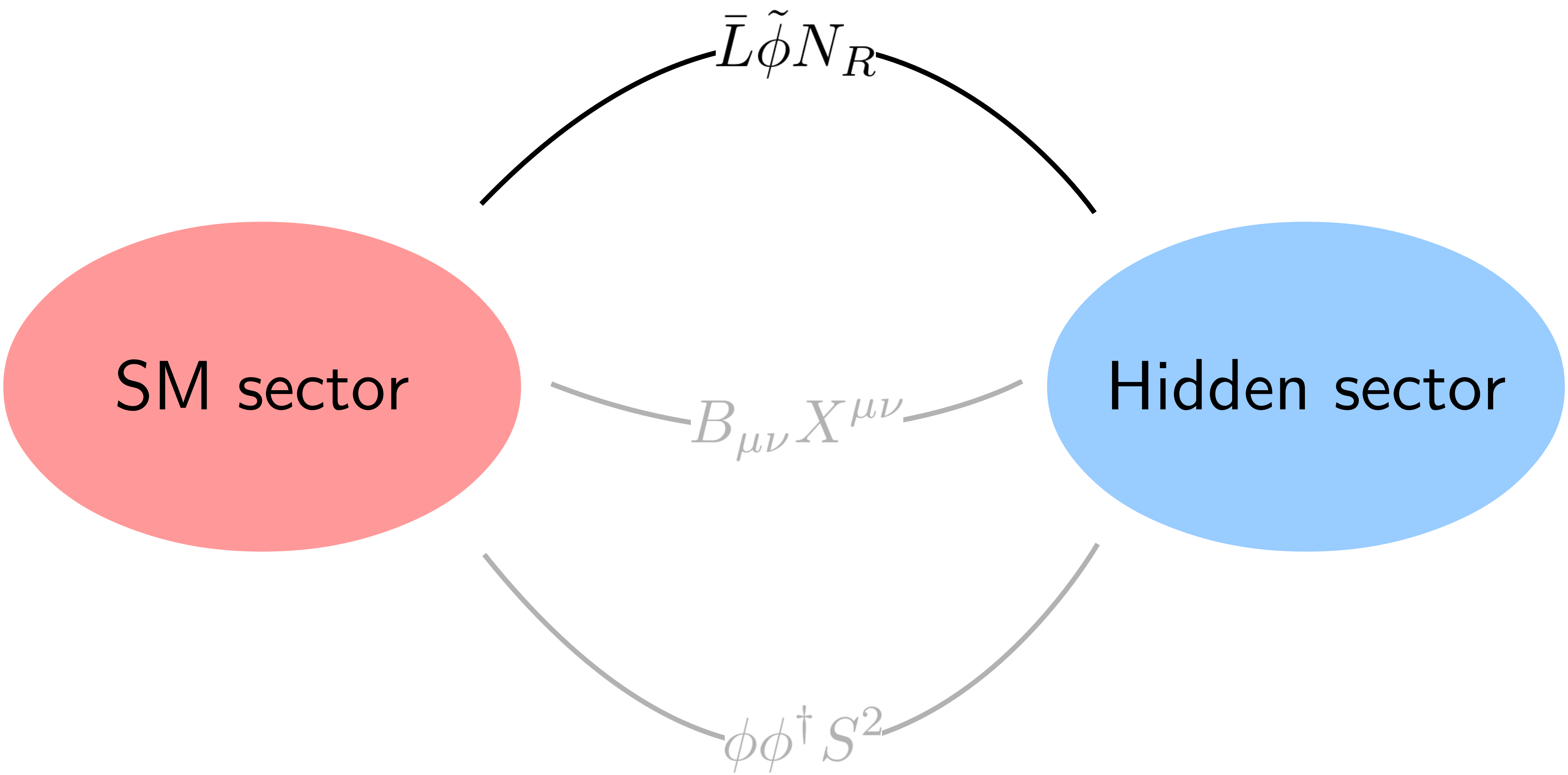
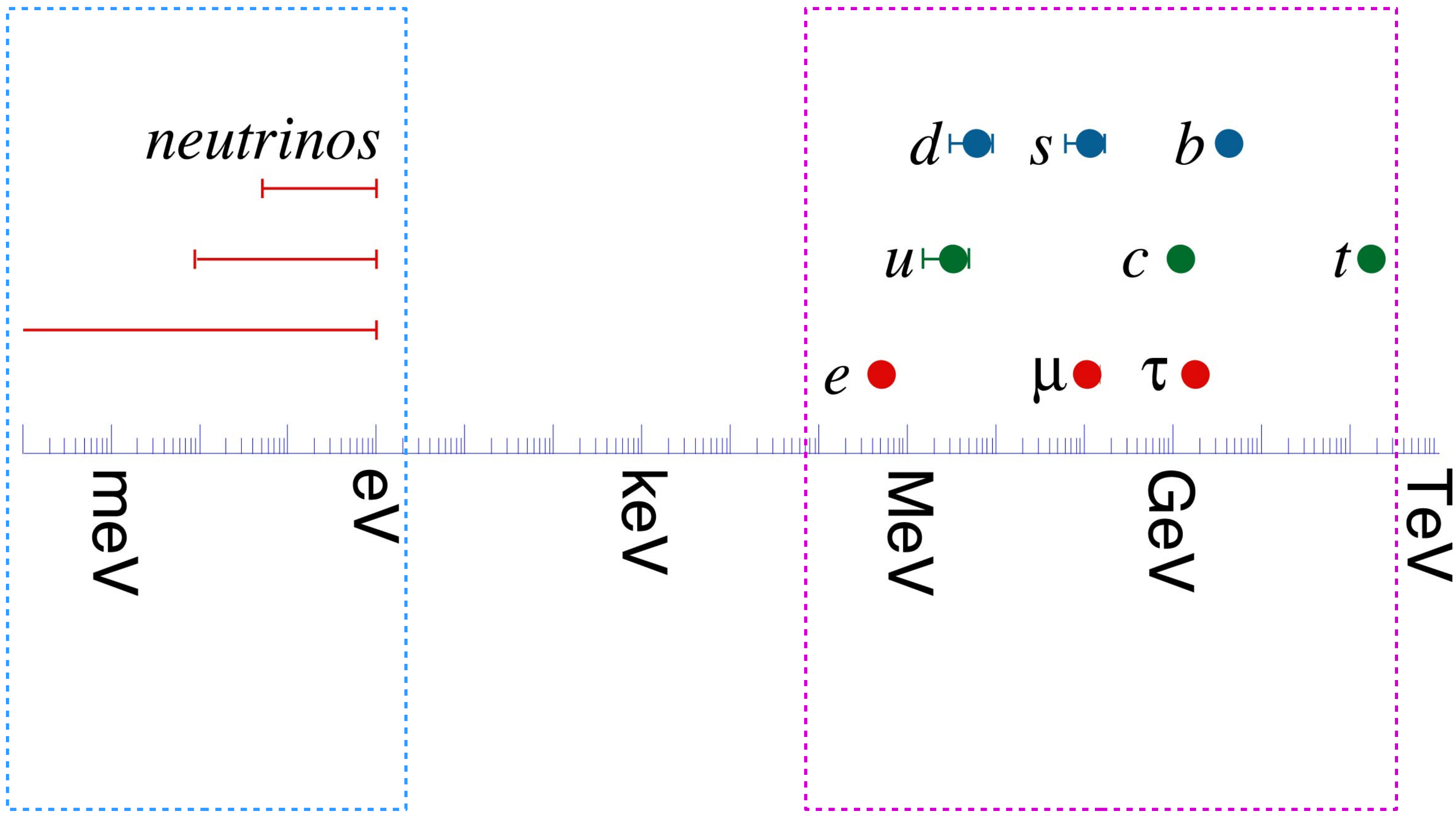


Neutrino masses



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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2) A Majorana mass. For example:

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

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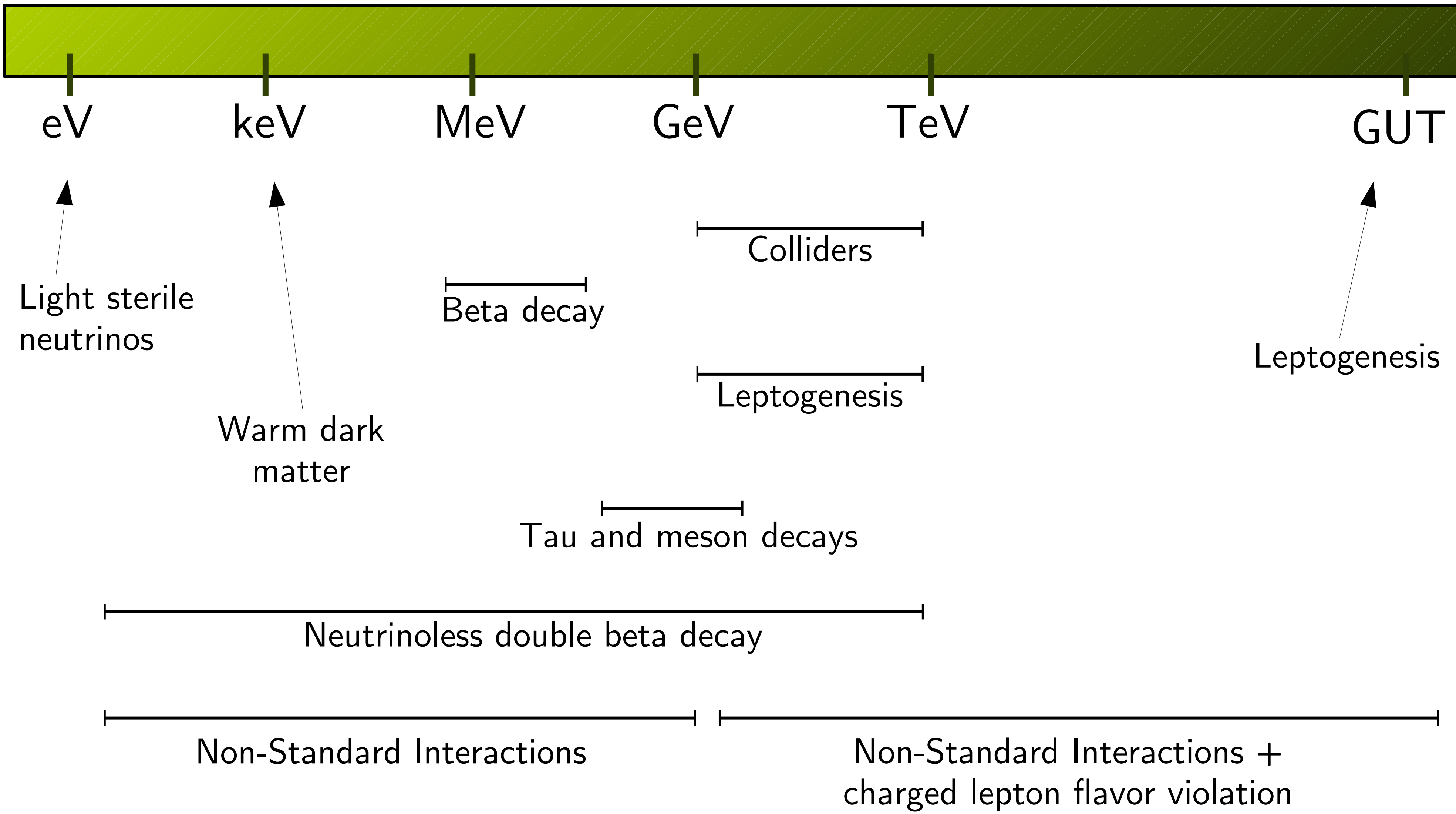
$$\xrightarrow{M \gg Y_\nu v} m_\nu = Y_\nu^\dagger M^{-1} Y_\nu v^2$$

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

Scale of new physics



Why the GeV scale?

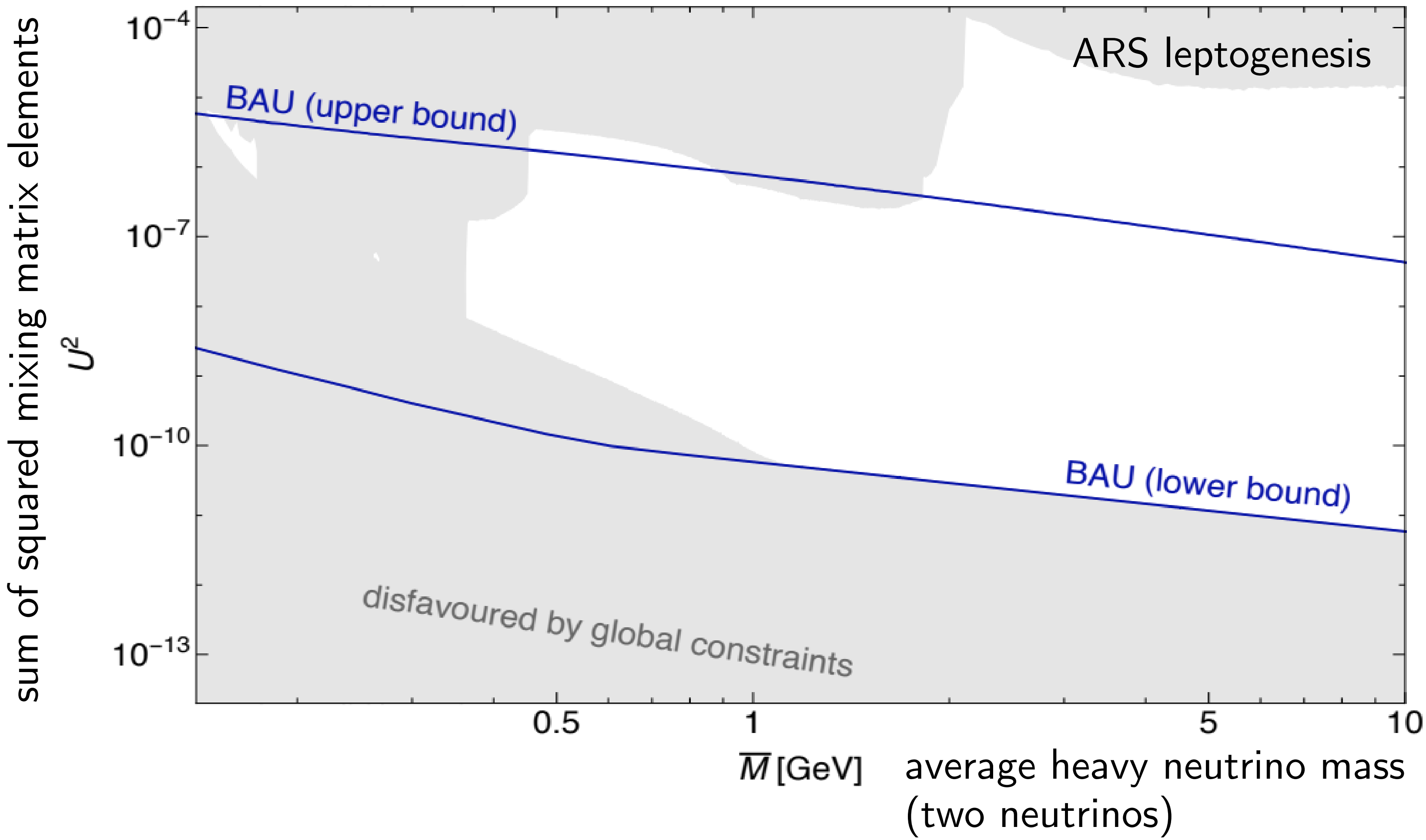
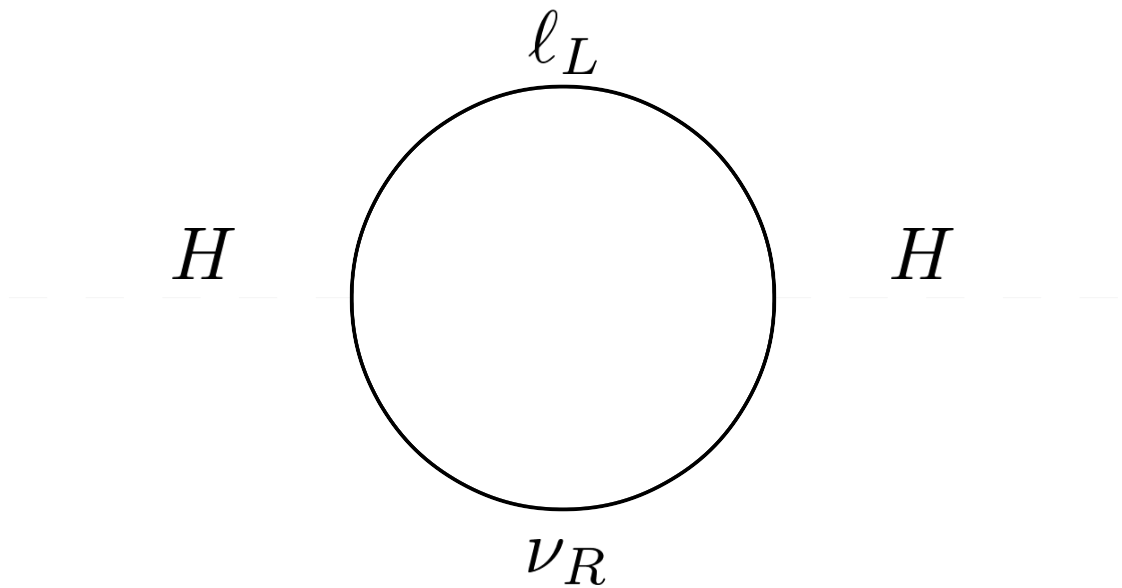


Figure from the review: Drewes, Garbretch, Hernandez, Kekic, Lopez-Pavon, Racker, Rius, Salvado, Teresi, 1711.02862
(see also, e.g., Eijima, Shaposhnikov and Timiryasov, 1808.10833)

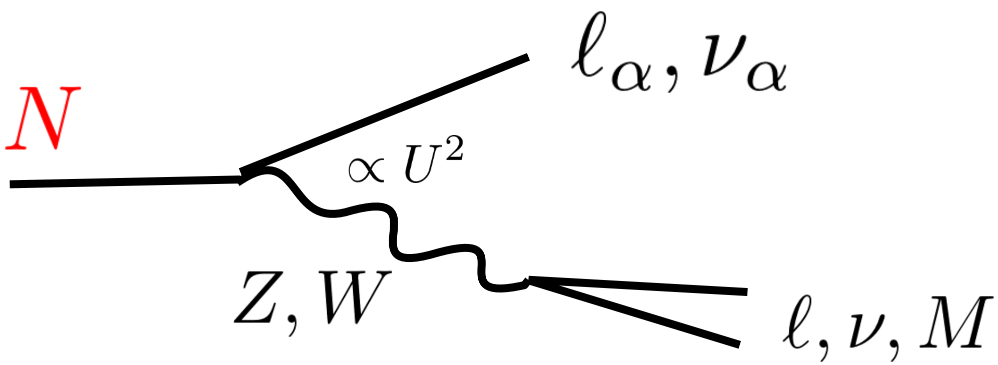
Why a low-scale seesaw?



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

Vissani, hep-ph/9709409
Casas, Espinosa, Hidalgo, hep-ph/0410298

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

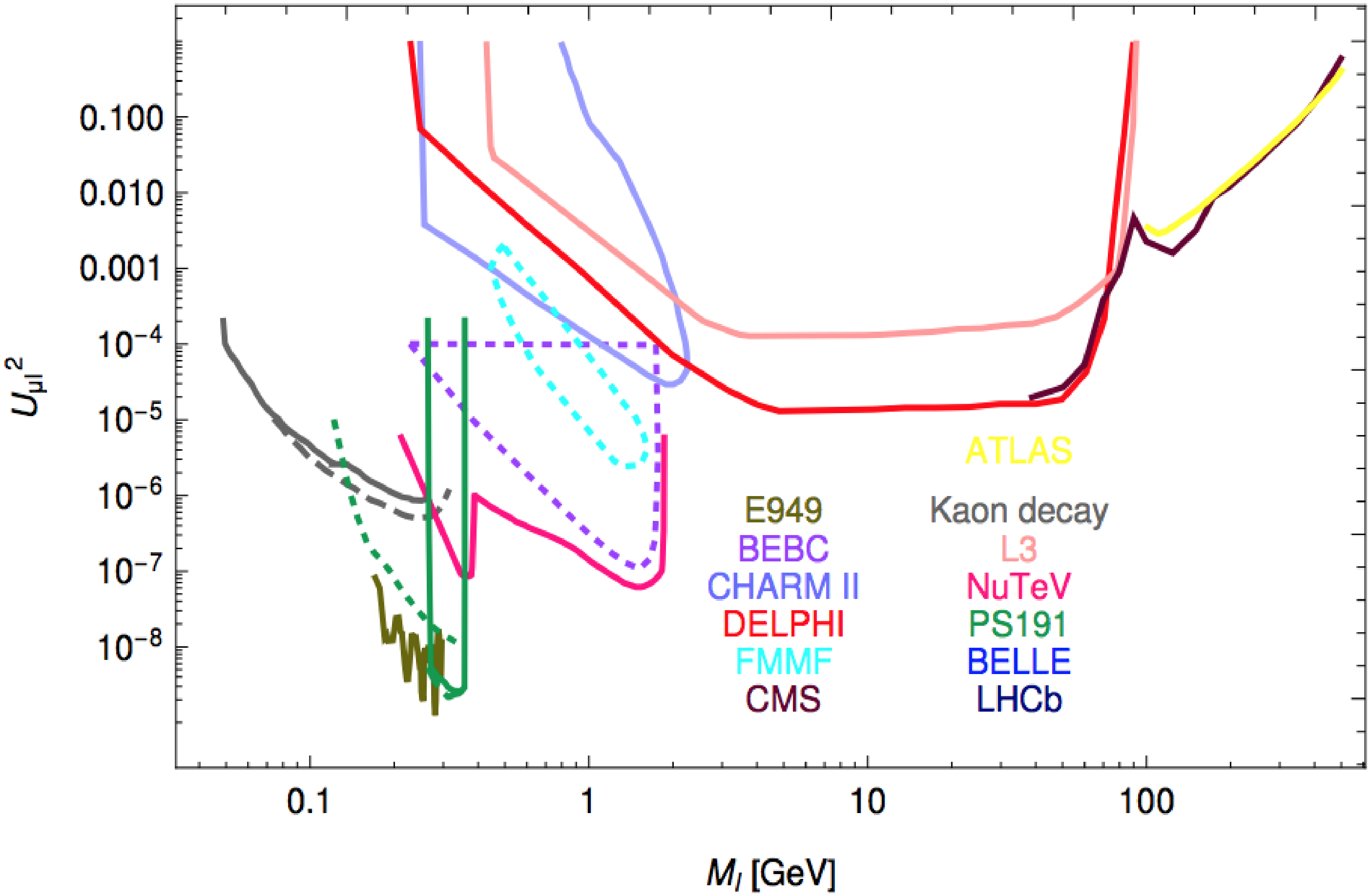
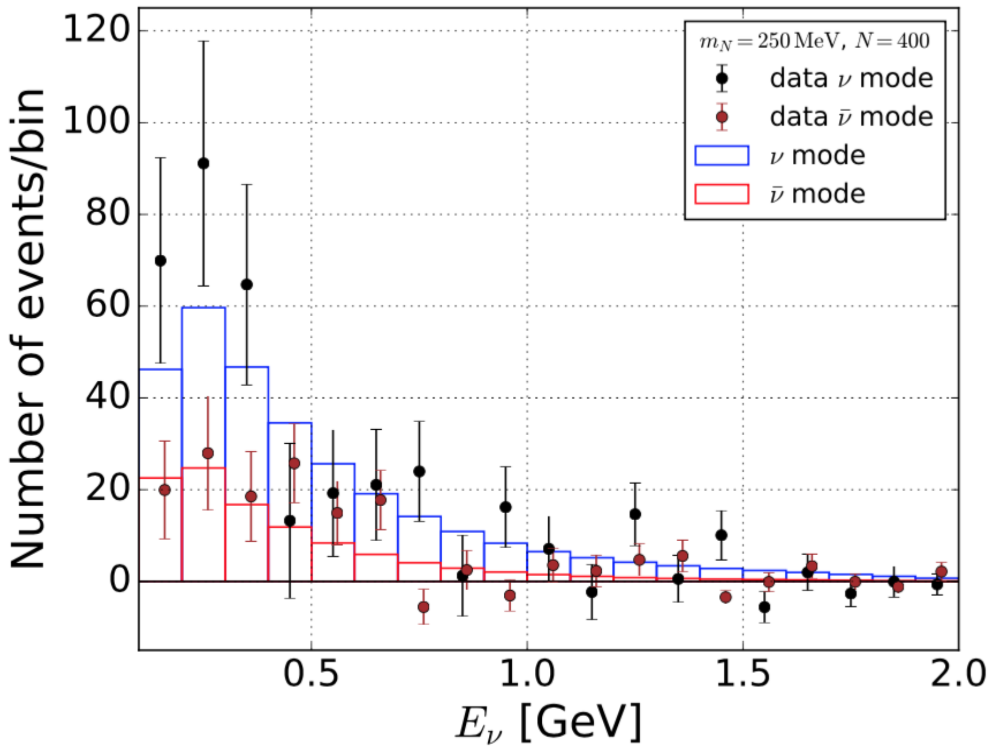
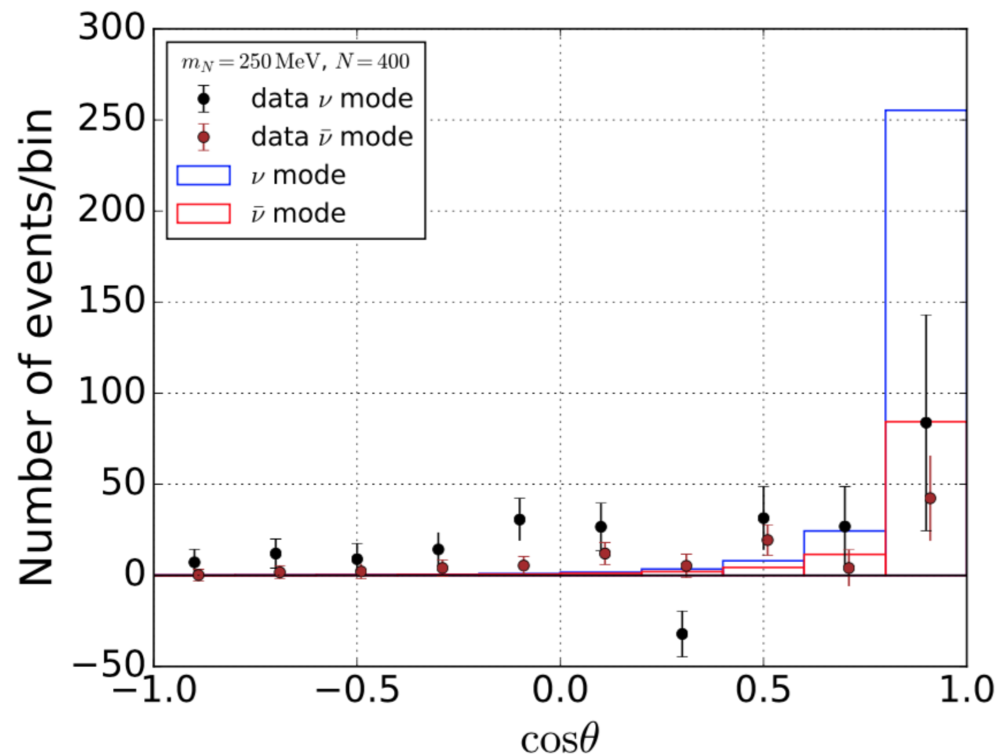


Figure from Drewes and Garbrecht, 1502.00477
(See also Bryman and Shrock, 1904.06787 and 1909.11198,
Ruchayskiy and Ivashko, 1112.3319, Atre et al, 0901.3589)

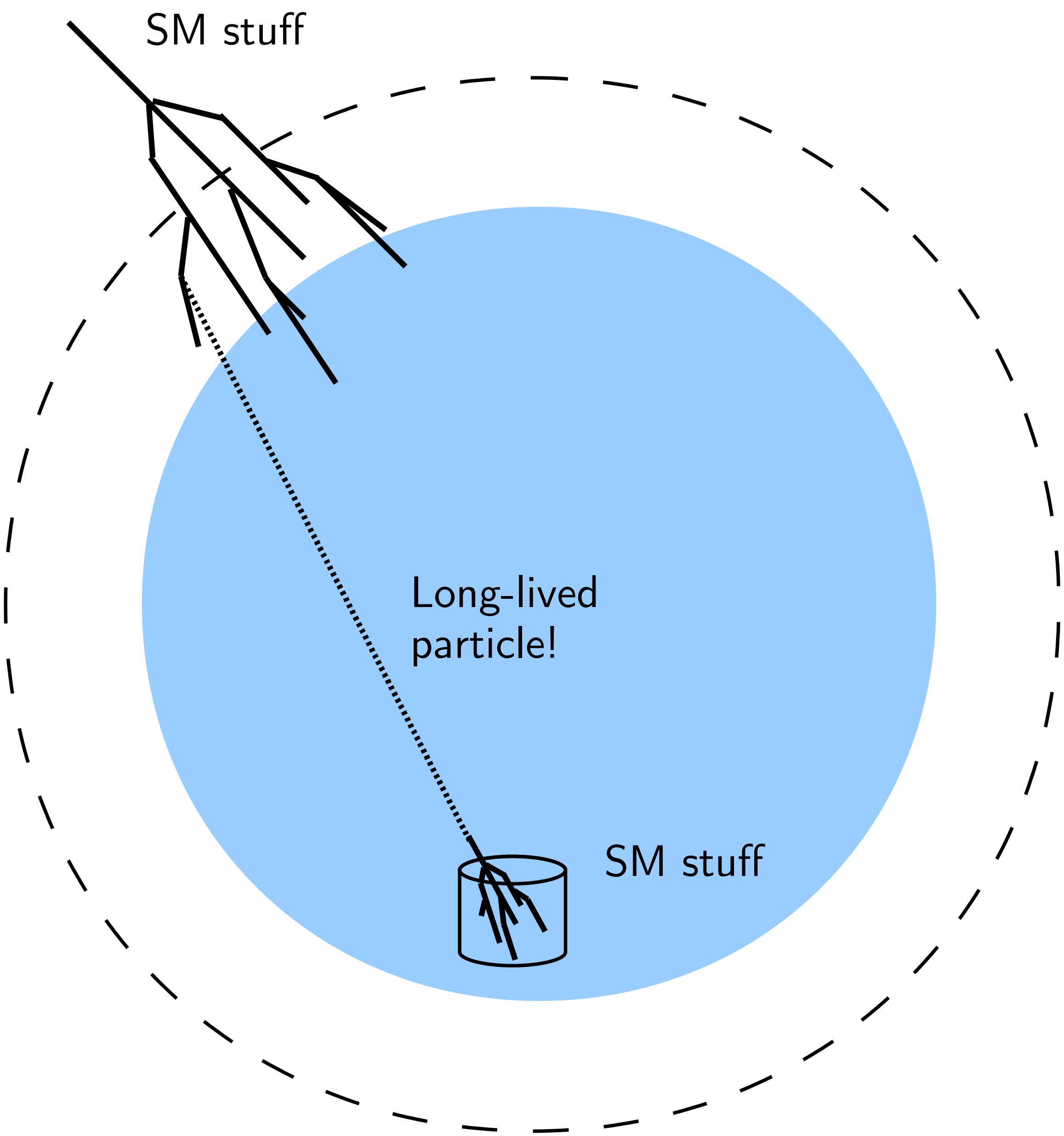
Further motivation...?

Figure from Fischer, Hernandez-Cabezudo, Schwetz, 1909.09561





See also:
Ballett, Pascoli, Ross-Lonergan, 1808.02915
Bertuzzo, Jana, Machado, Zukanovich Funchal, 1807.09877
Dentler, Esteban, Kopp, Machado, 1911.01427
deGouvea, Peres, Prakash, Stenico, 1911.01447
Gninenko, 1009.5536 and 0902.3802
Palomares-Ruiz, Pascoli, Schwetz, hep-ph/0505216


SM stuff
Long-lived
particle!
SM stuff

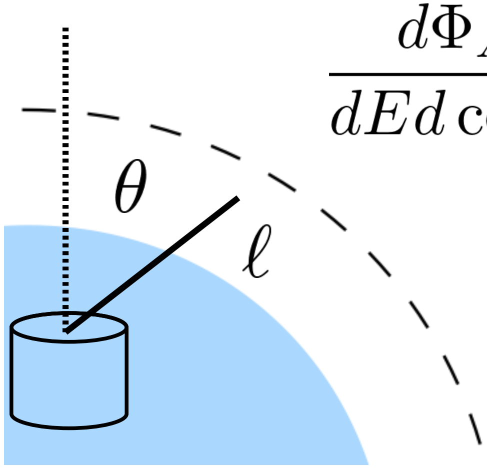
Signal computation

Production profile for the long-lived particle:

$$\frac{d\Pi_A}{dE\,d\cos\theta\,d\ell} = \sum_{ch} \int_{E_P^{\min}}^{E_P^{\max}} dE_P \frac{1}{\gamma_P \beta_P c\tau_P} \frac{d\Phi_P(E_P,\cos\theta)}{dE_P\,d\cos\theta} \frac{dn_{ch}(E_P,E)}{dE}$$

See, e.g., Gondolo, Ingleman and Thunman, hep-ph/9505417

From there, we get the flux as:



$$\frac{d\Phi_A}{dE\,d\cos\theta} = \int_0^{\ell_{\max}} d\ell \frac{d\Pi_A}{dE\,d\cos\theta\,d\ell} e^{-\frac{\ell}{L_{\rm decay}}} \qquad (A \equiv V, N)$$

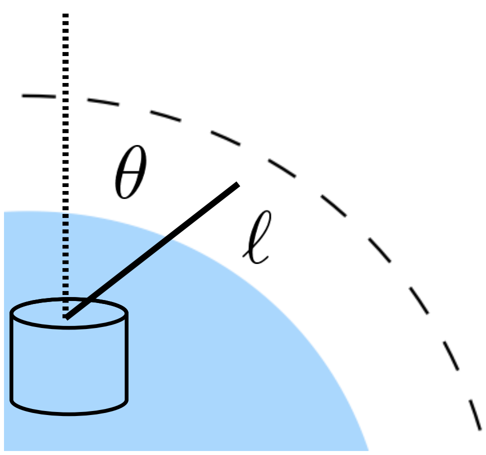
Parent meson fluxes extracted from MCEq: https://github.com/afedynitch/MCEq

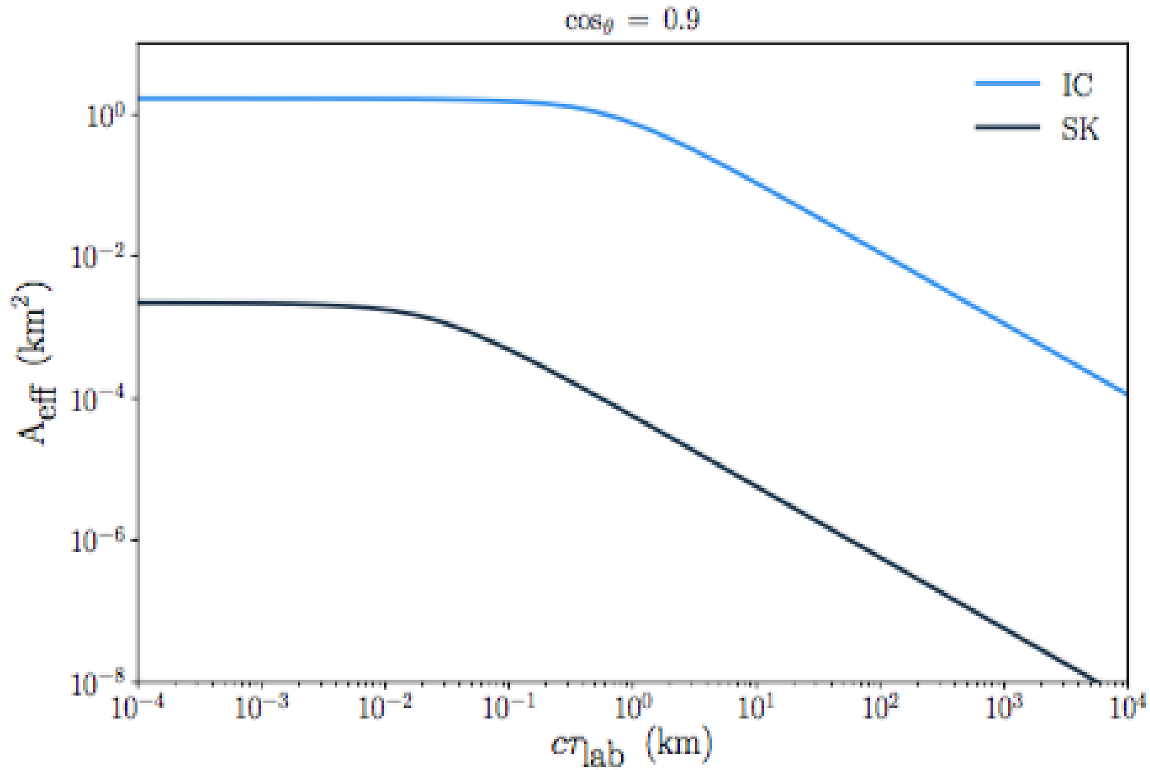
Signal computation

$$\frac{dN_i^\alpha}{dE\,d\cos\theta} \propto \mathrm{Br}(\alpha\!-\!\mathrm{like})\;\epsilon^\alpha\;\Delta T\;A^{\mathrm{eff}}_{\mathrm{decay}}(E,\cos\theta)\;\frac{d\Phi_A}{dE\,d\cos\theta}$$

Detector efficiencies (estimated)

Geometric acceptance

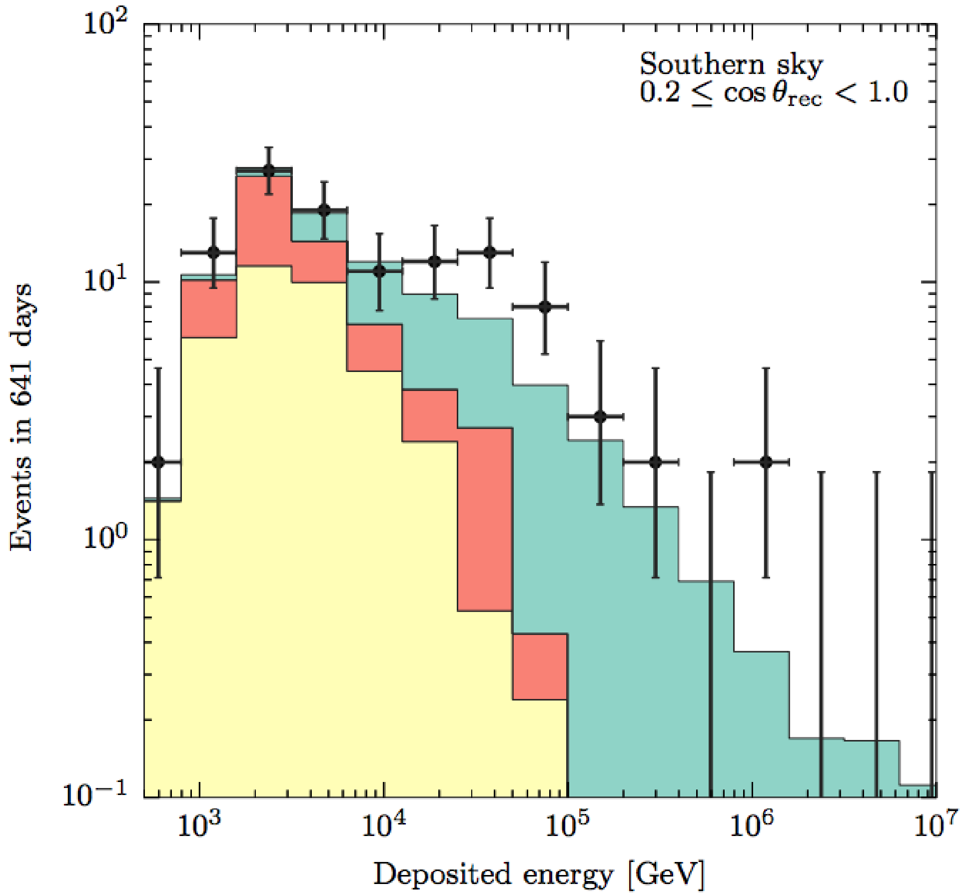




Backgrounds and data

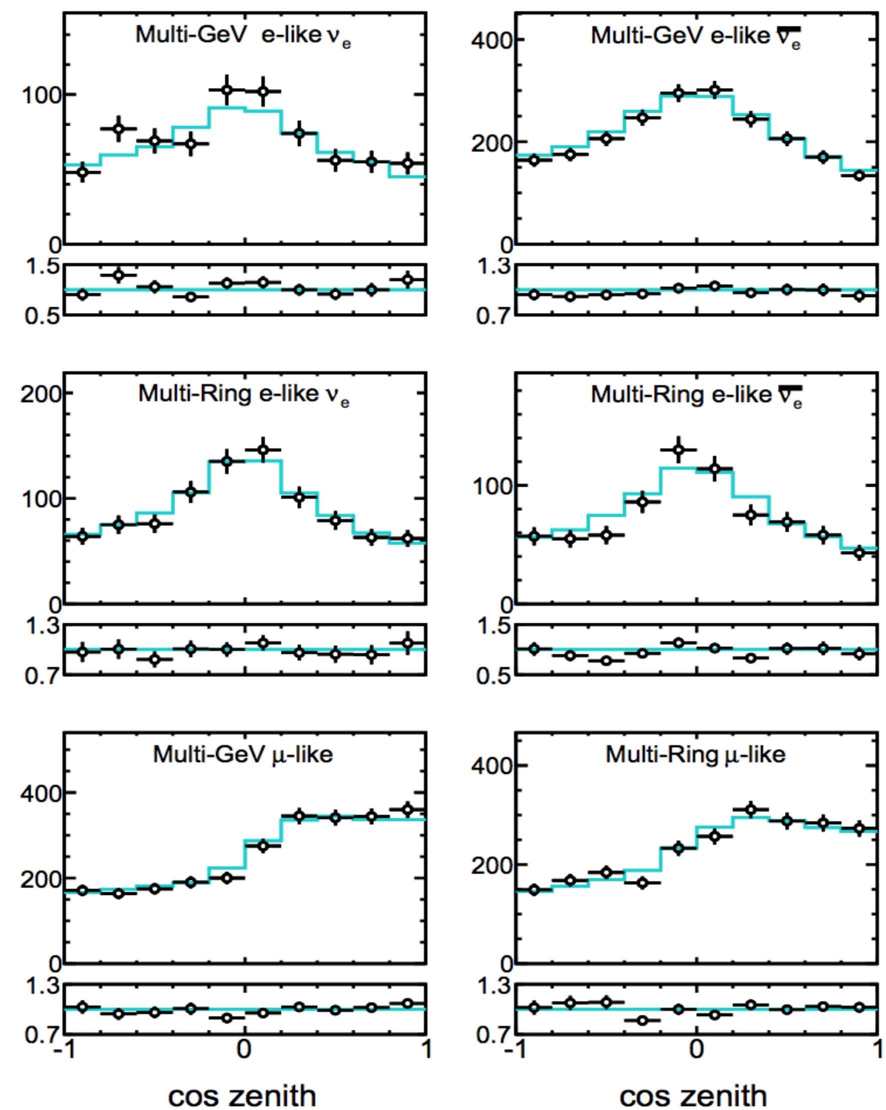
MESE sample at Icecube (641 days)

Icecube collaboration, 1410.1749

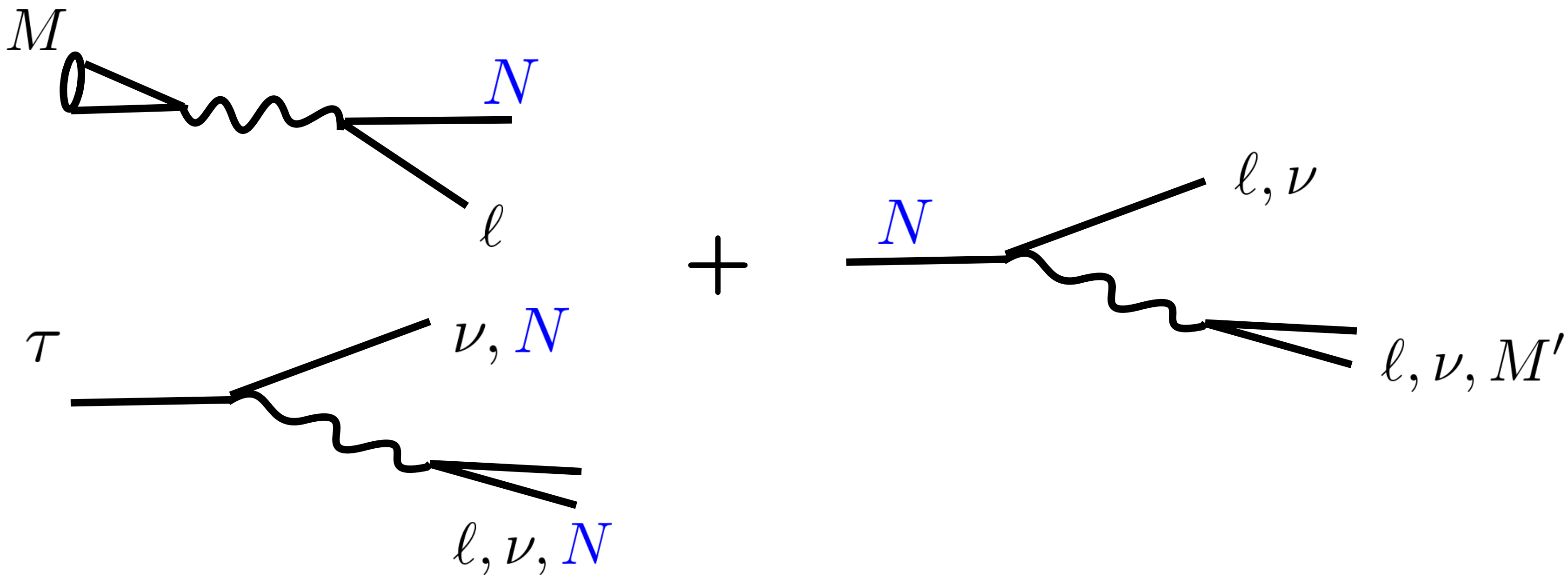


Data from SK I-IV (5,326 days)

Super-Kamiokande coll. 1710.09126



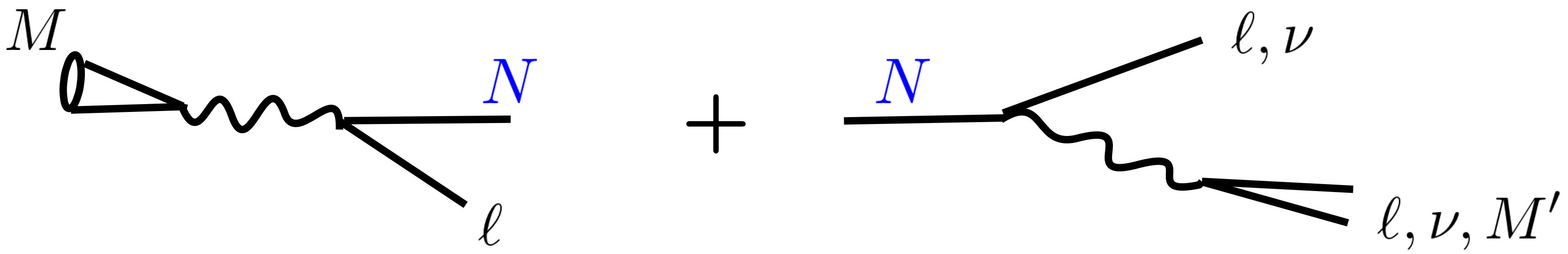
HNL production and decay

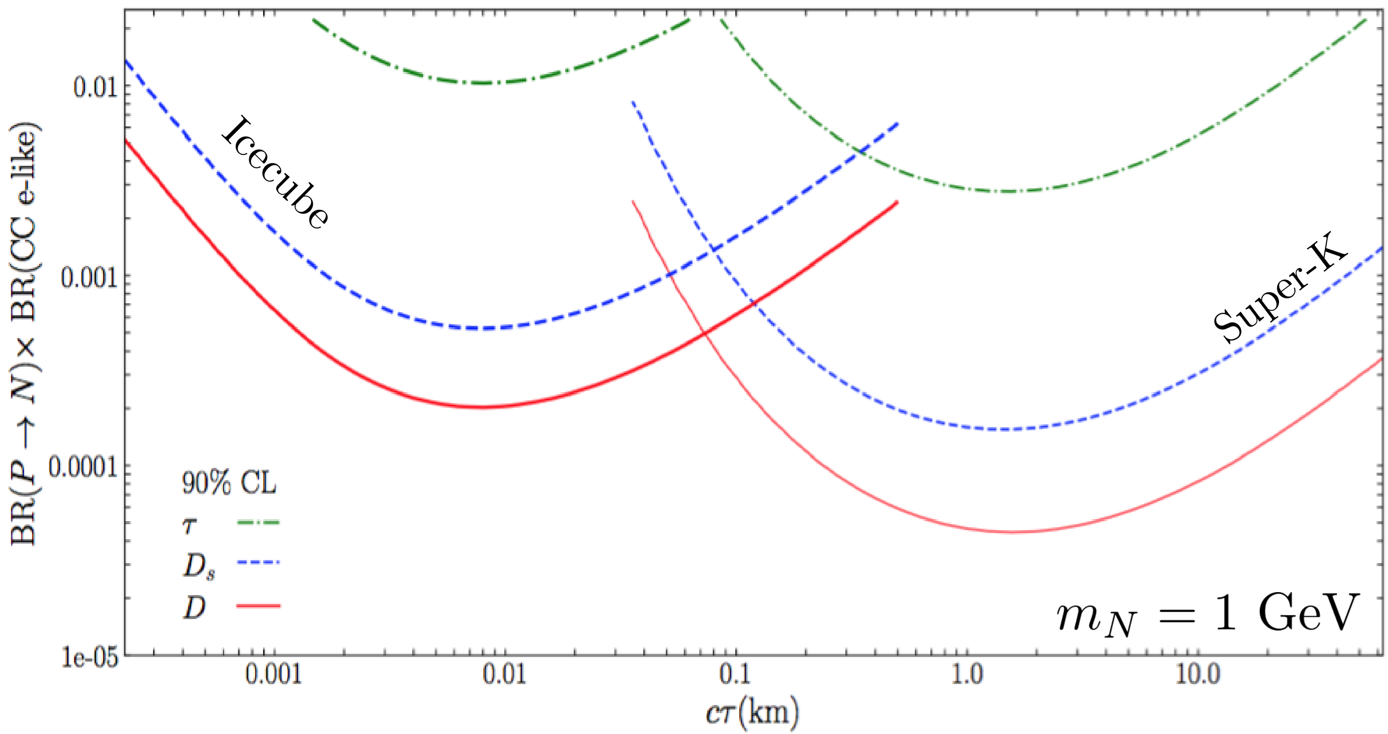


$\rightarrow$ Maximum sensitivity if decay length *in the lab frame* is O(10) km

Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

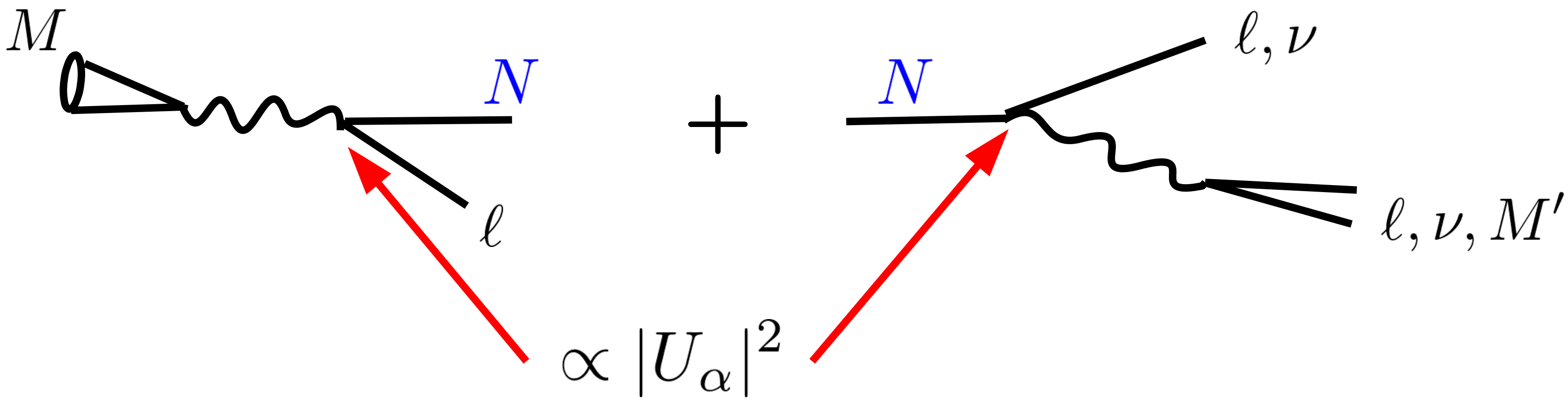
HNL above the kaon mass





Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

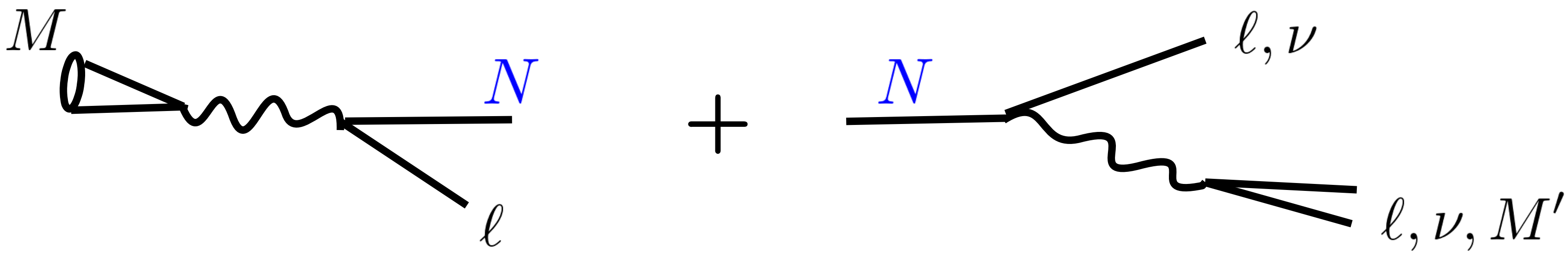
HNL: minimal scenario

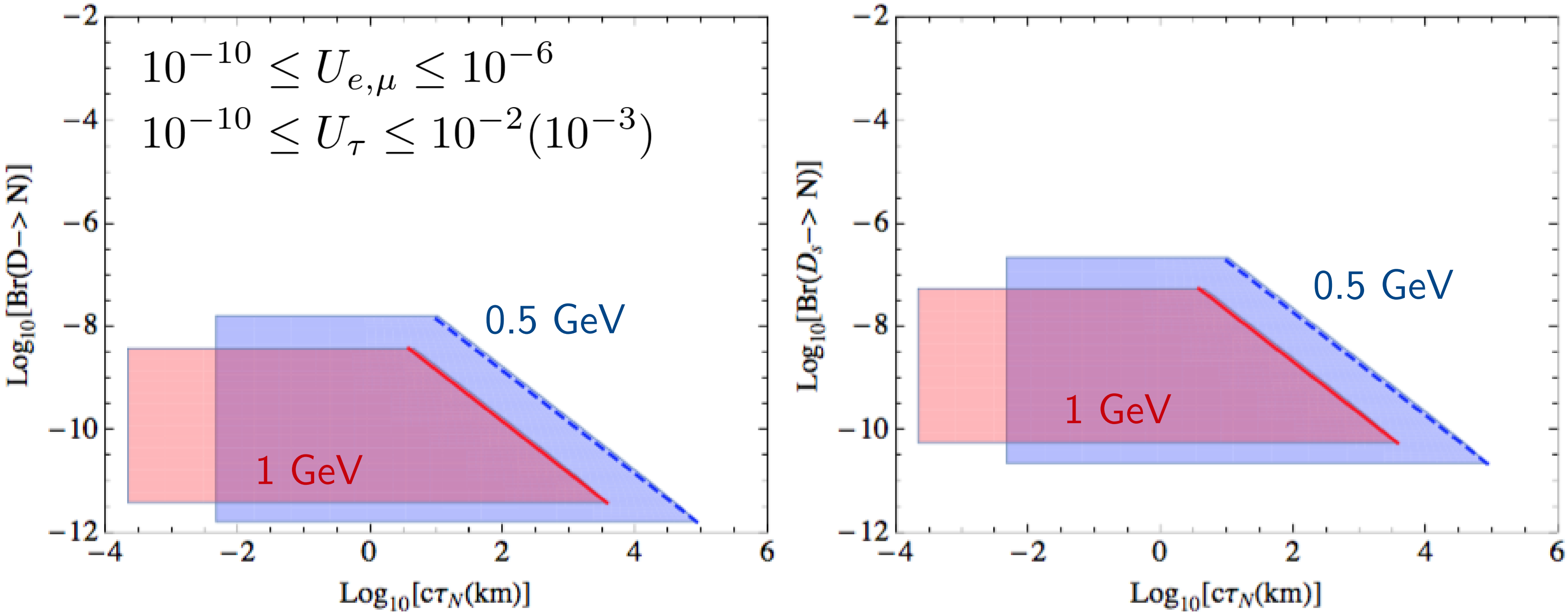


$$\mathcal{L}_N = \mathcal{L}_{SM} + \sum_j i\bar{N}_j \gamma^\mu \partial_\mu N_j - \left(Y_{\alpha j} \bar{L}_\alpha \tilde{\Phi} N_j + \frac{m_{N_j}}{2} \bar{N}_j N_j^c \right)$$

Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

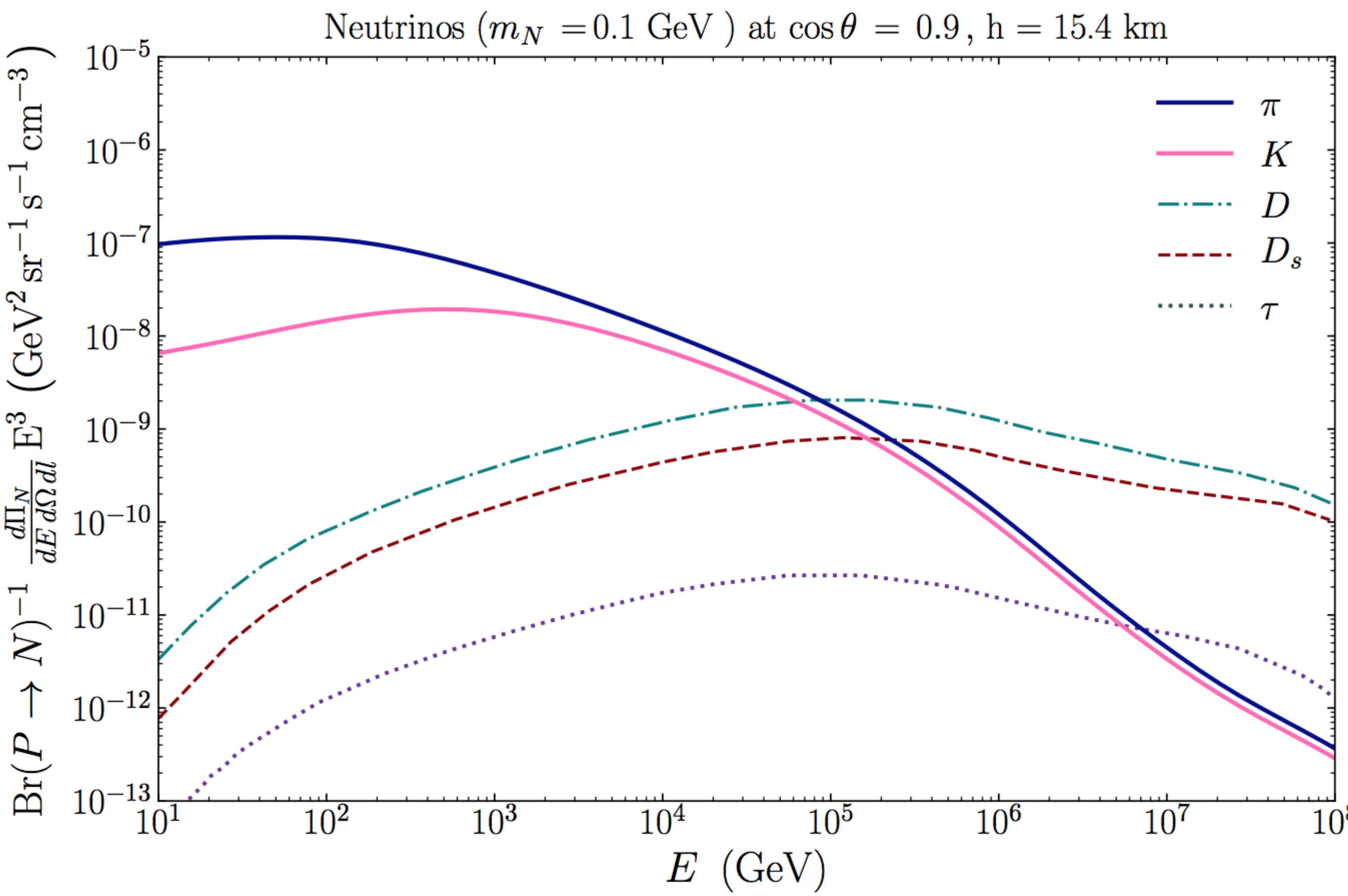
HNL: minimal scenario





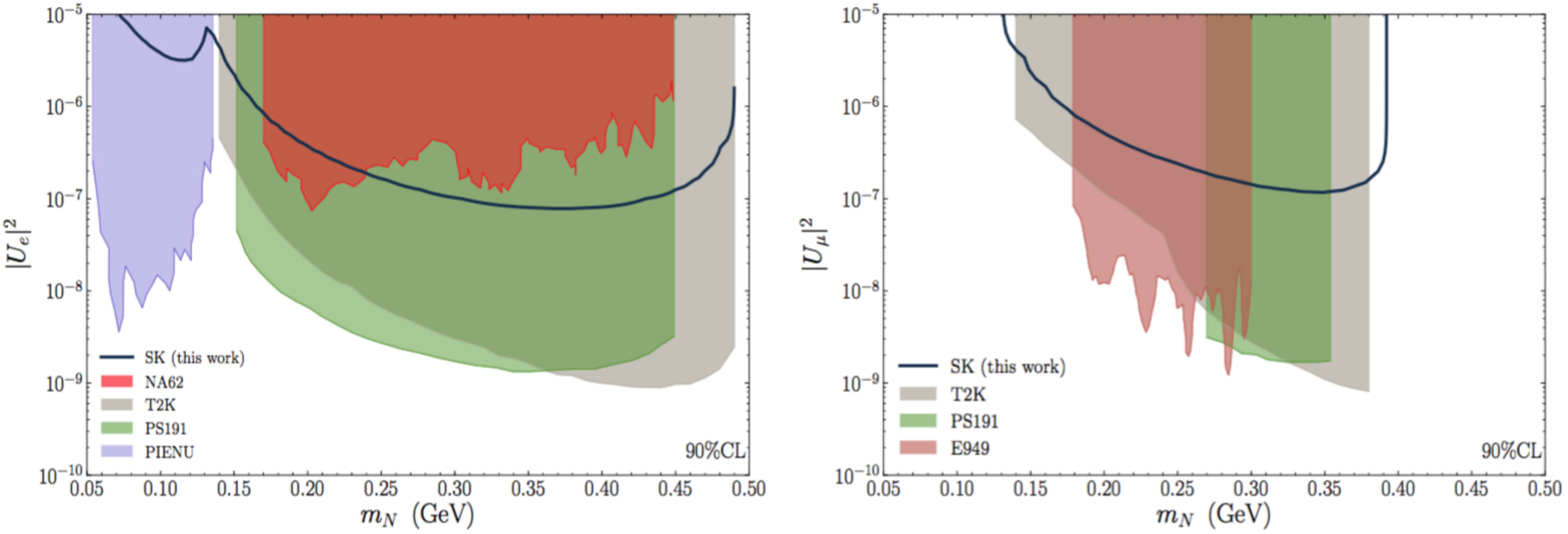
Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

HNL production per parent



Argüelles, Coloma, Hernandez, Muñoz, 1910.12839
Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129

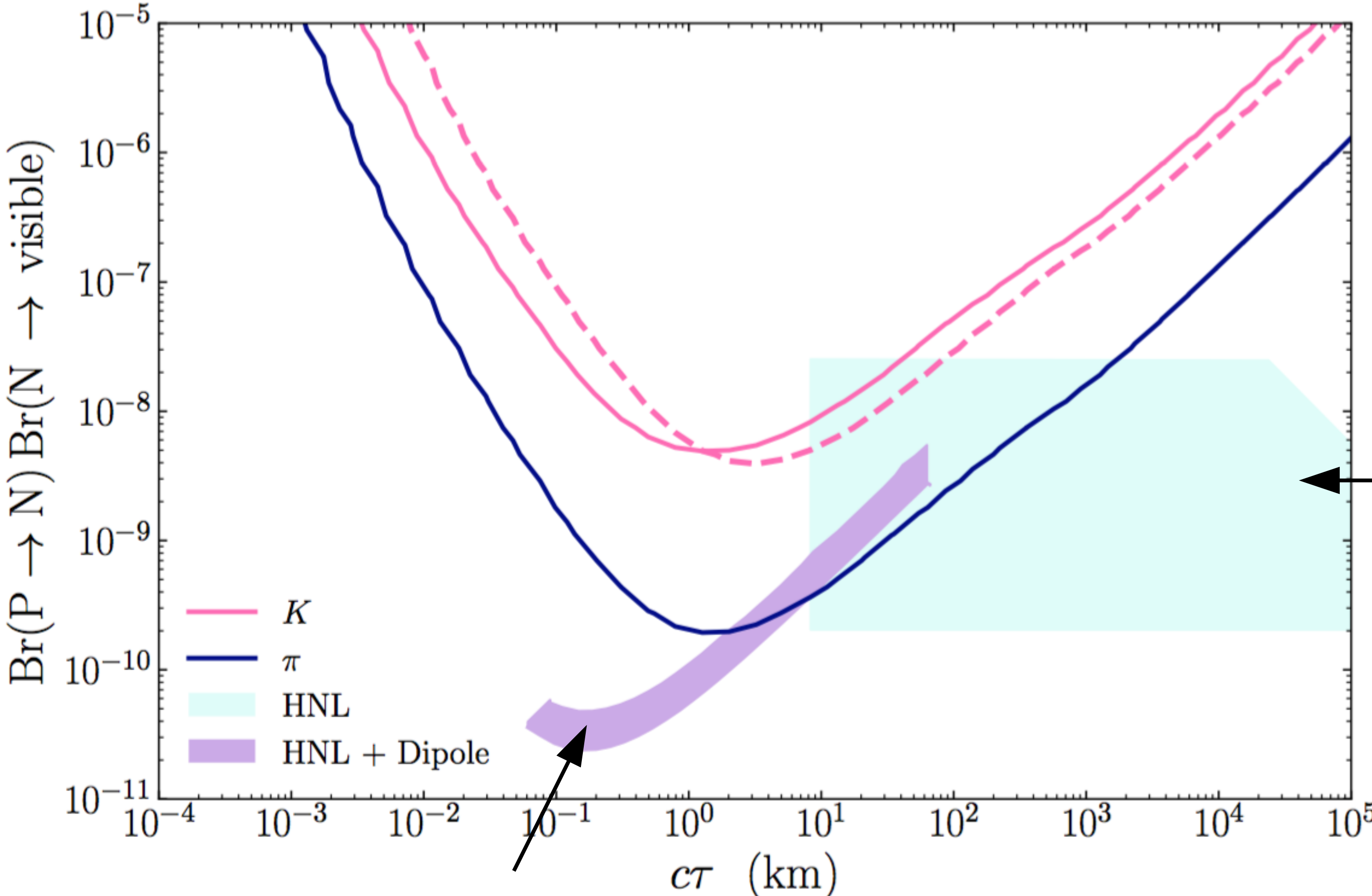
HNL below the kaon mass



Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129
(see also Asaka and Watanabe, 1202.0725, Kusenko, Pascoli and Semikoz, hep-ph/0405198

HNL below the kaon mass

Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129



Minimal HNL

$m_N = 250$ MeV

$|U_{e/\mu}|^2 \in [10^{-8}, 10^{-10}]$

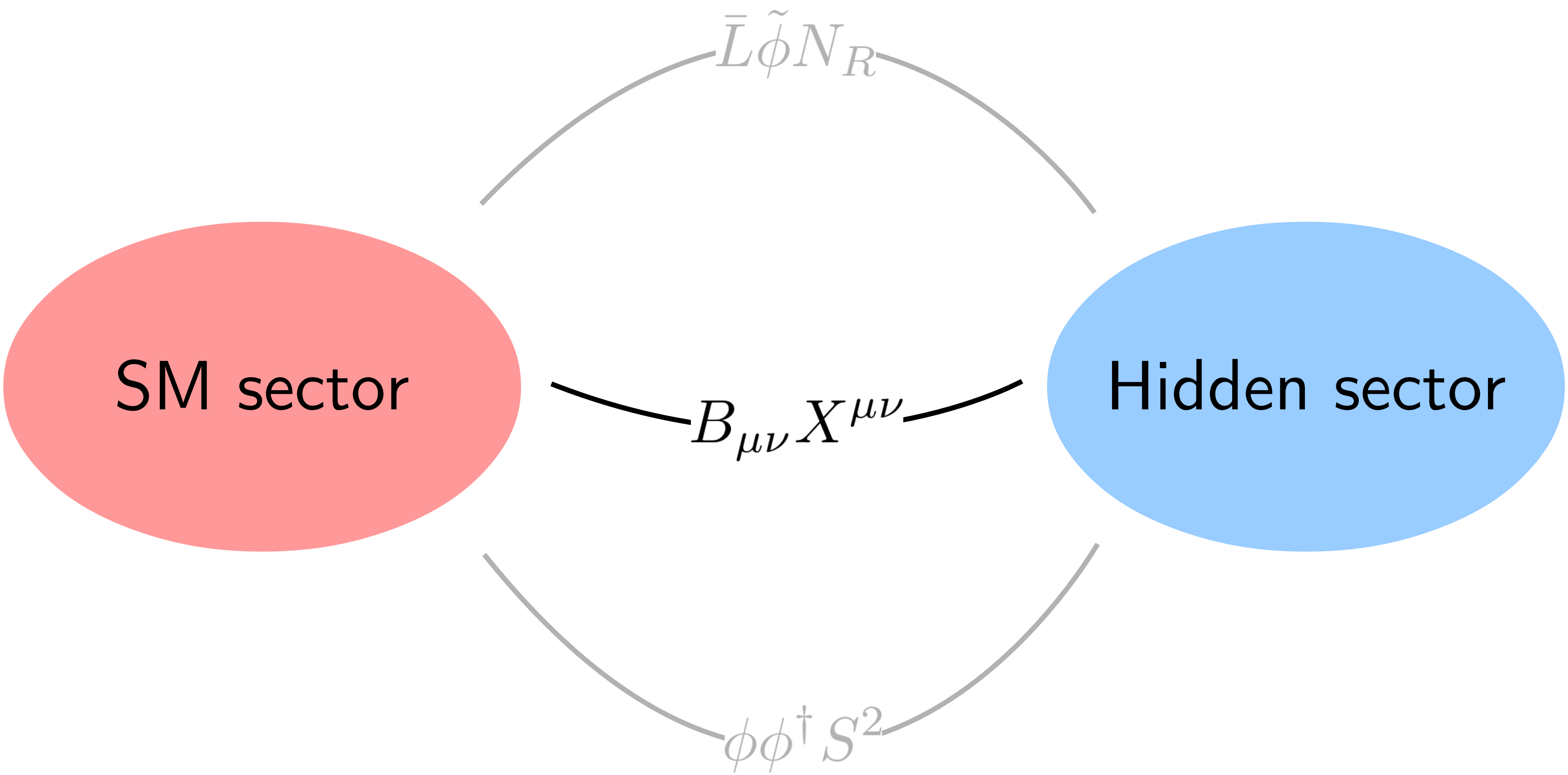
$|U_\tau|^2 \in [10^{-10}, 10^{-4}]$

$m_N = 260$ MeV

Fischer et al, 1909.09561

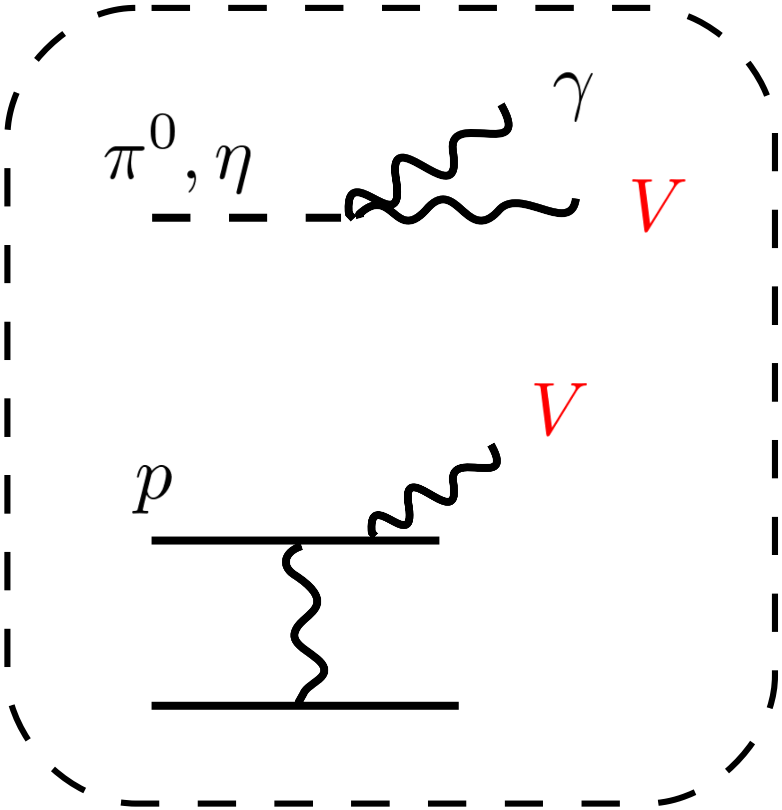
Dark photons

Where is the new physics?



Dark photons: kinetic mixing

$$\mathcal{L}_V = \mathcal{L}_{SM} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu$$



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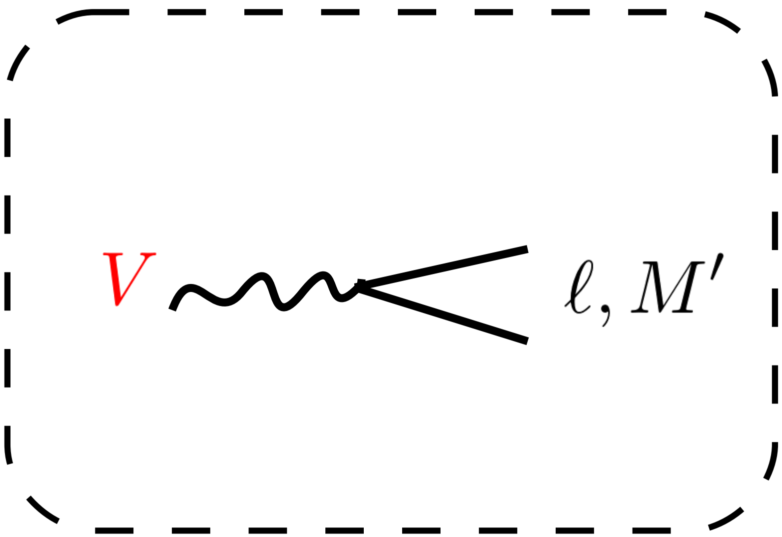

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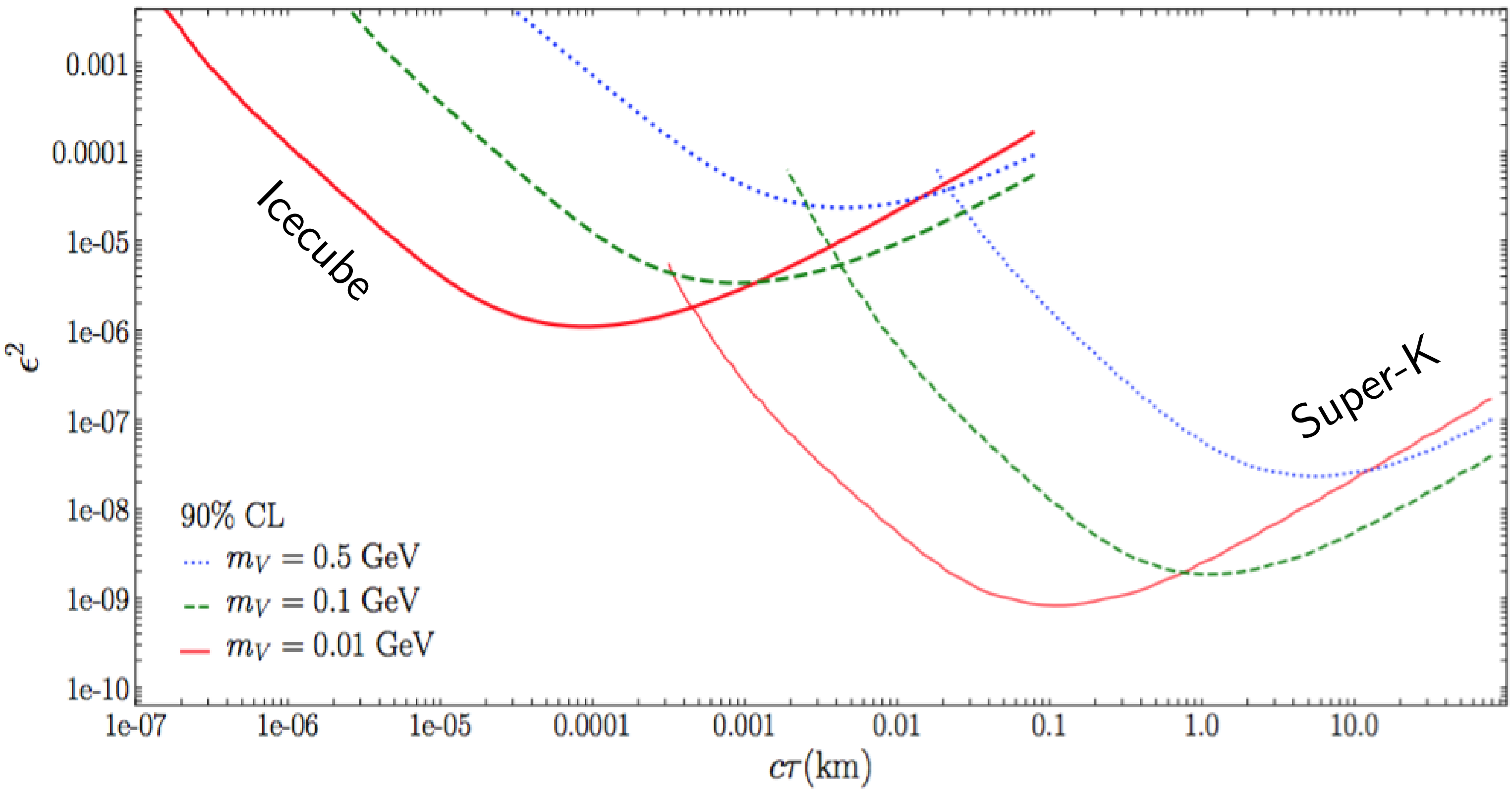

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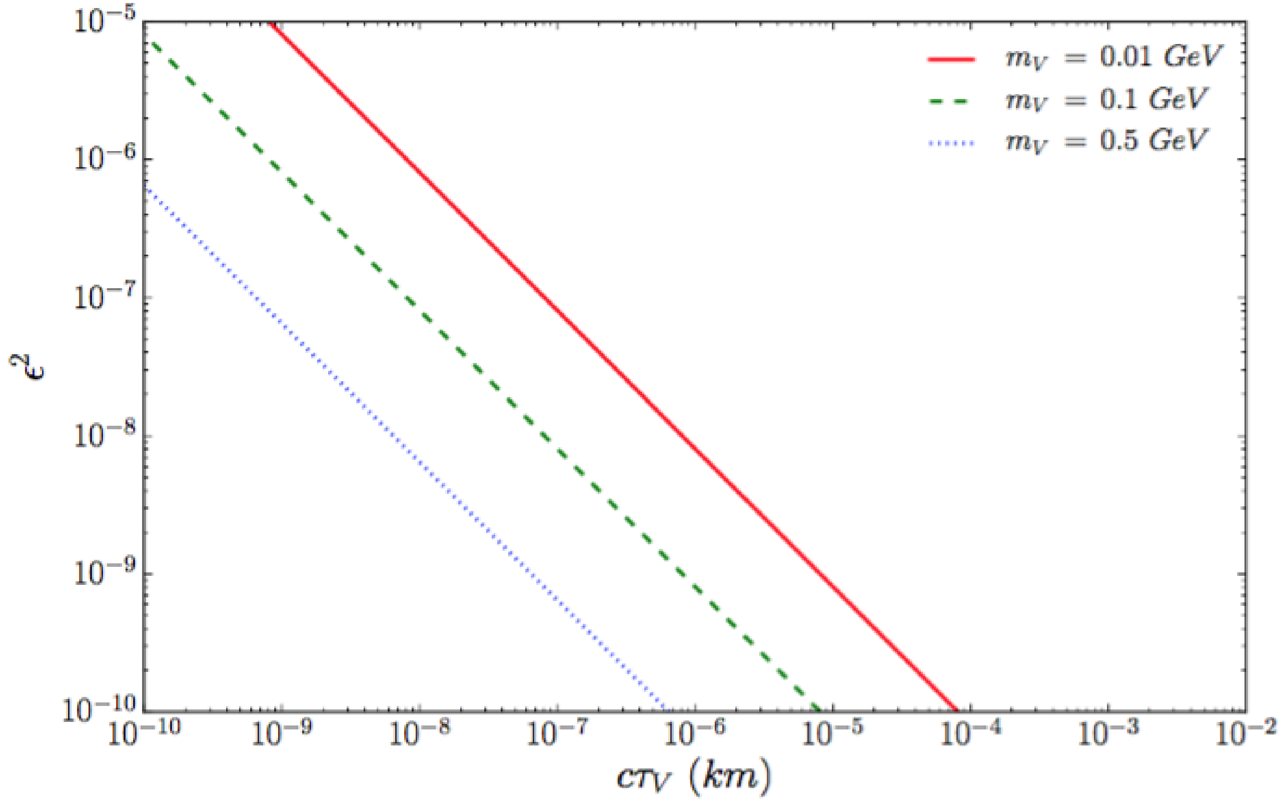
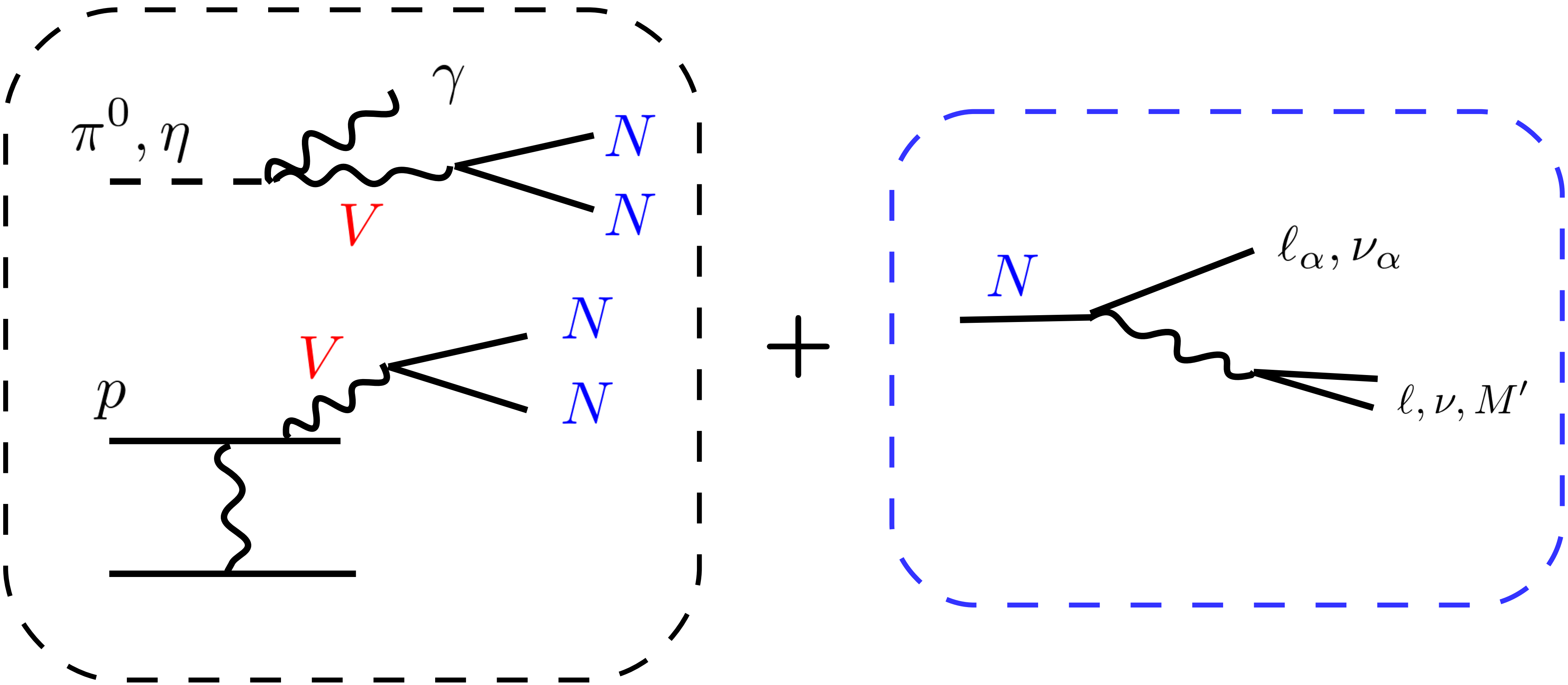


Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

Dark photons: B-L model

$$\mathcal{L} = \mathcal{L}_N - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu + g_{\mathrm{B-L}}\left(\sum_f Q^f_{B-L}\overline{f}\gamma^\mu f V_\mu - \overline{N}\gamma^\mu N V_\mu\right)$$



Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

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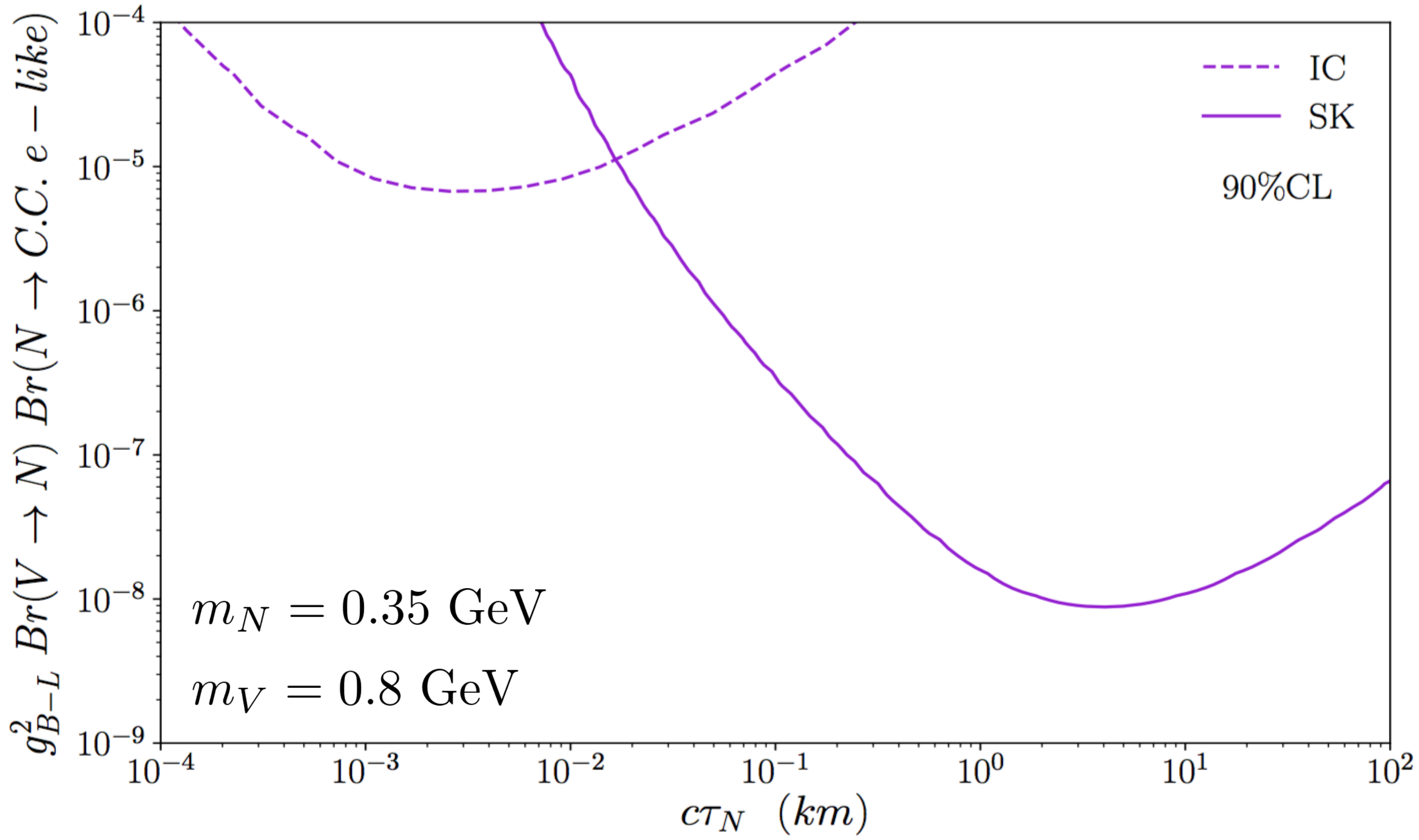

Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

Summary

- Atmospheric neutrino detectors are well-suited to search for the decay products of long-lived particles produced in the atmosphere
    - Optimal sensitivity for decay lengths in the range of tens of kilometers
- We have derived exclusion limits using Icecube and SK data
    - We have studied HNL, dark photons and a B-L model
    - Our limits are shown in the BR – $c\tau$ plane, allowing to be easily interpreted for non-minimal scenarios
    - SK able to constrain the minimal HNL model as well, for m_N below the kaon mass

Thank you!!