HNLs at neutrino telescopes

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HIDDeν

MINISTERIO DE CIENCIA E INNOVACIÓN

European Union European Social Fund

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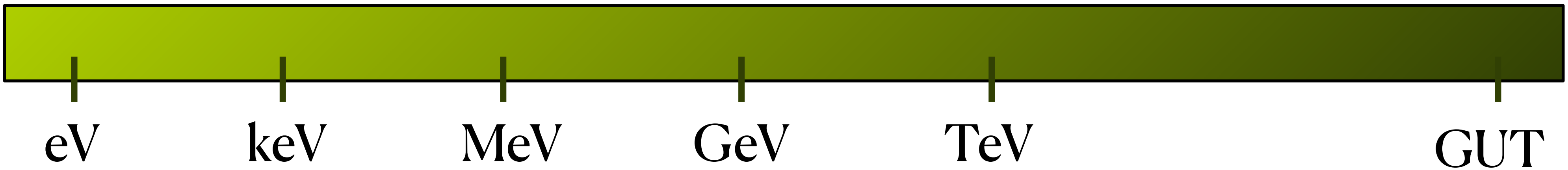
EXCELENCIA SEVERO OCHOA

Outline

- Production of HNL inside neutrino detectors
- Production of HNL inside the Earth mantle
- Production of HNL in the atmosphere

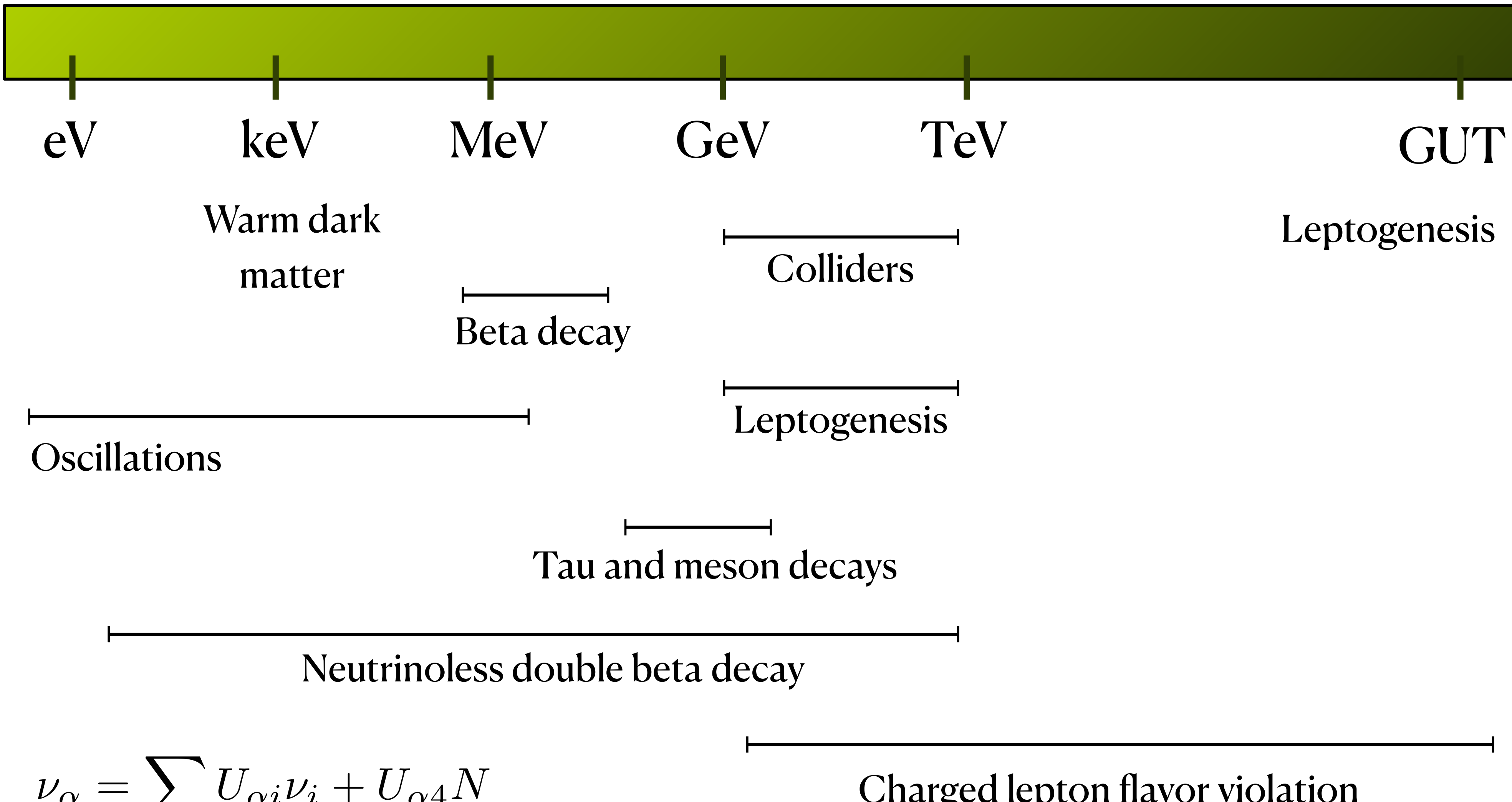
→ I will focus on cases where the HNL decays visibly inside the detector

Heavy neutrinos



$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

Heavy neutrinos

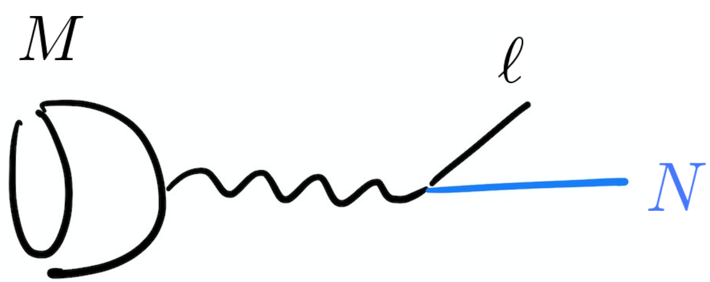


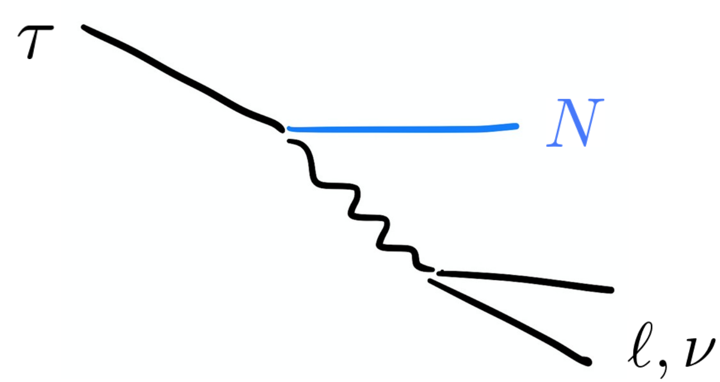
$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i + U_{\alpha 4} N$$

Interactions through mixing

For HNLs around the GeV scale:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i + U_{\alpha 4} N$$

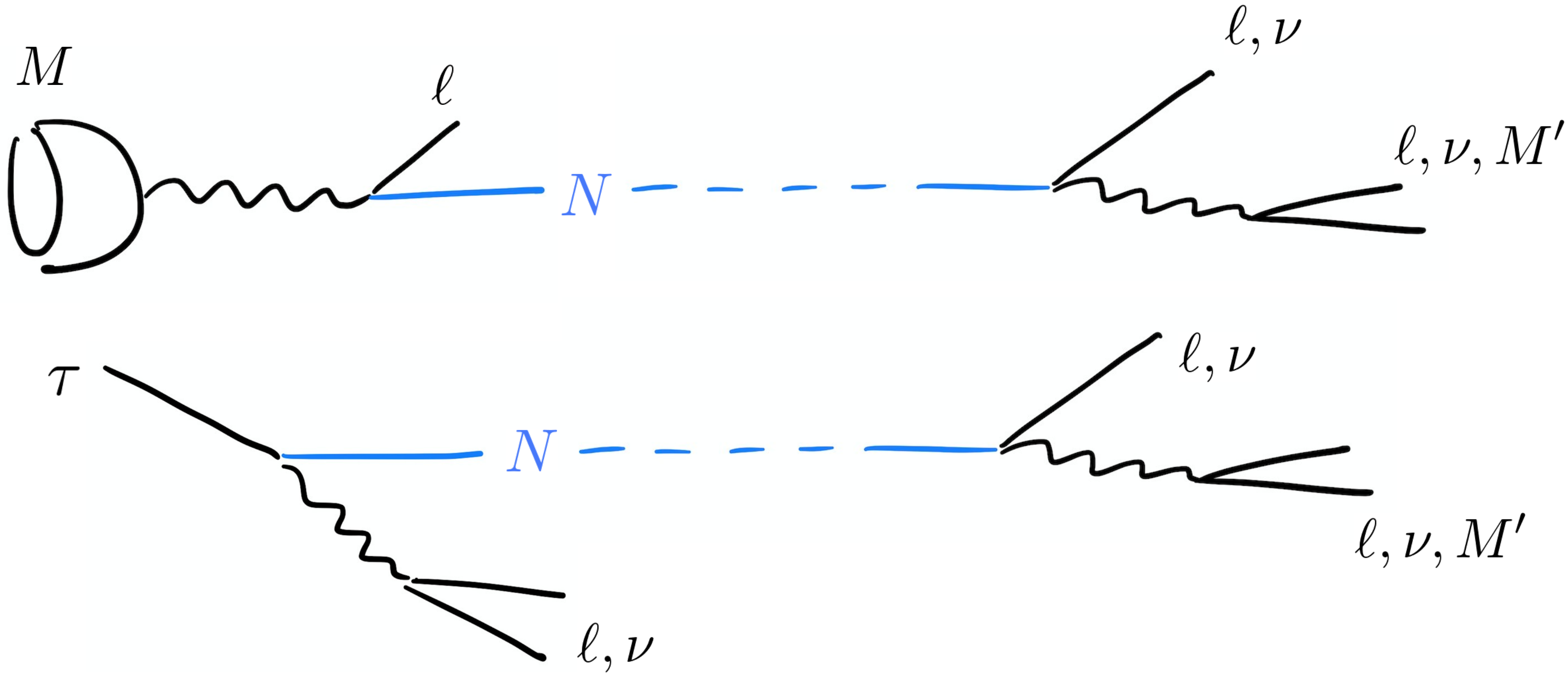




Interactions through mixing

For HNLs around the GeV scale:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i + U_{\alpha 4} N$$



Interactions through mixing

For HNLs around the GeV scale:

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

$$L_{lab,N} \simeq 30 \left(\frac{10^{-3}}{|U_{\tau 4}|^2}\right)\left(\frac{E_N}{10\ \mathrm{GeV}}\right)\ \mathrm{m}$$

For $\begin{cases} m_N \sim 1\ \mathrm{GeV} \\ |U_{e4}| = |U_{\mu 4}| = 0 \end{cases}$

See e.g., Bondarenko, Boyarsky, Gorbunov, Ruchaisky, 1805.08567;
Ballett, Boschi, Pascoli, 1905.00284;
Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic, 2007.03701

Interactions through mixing

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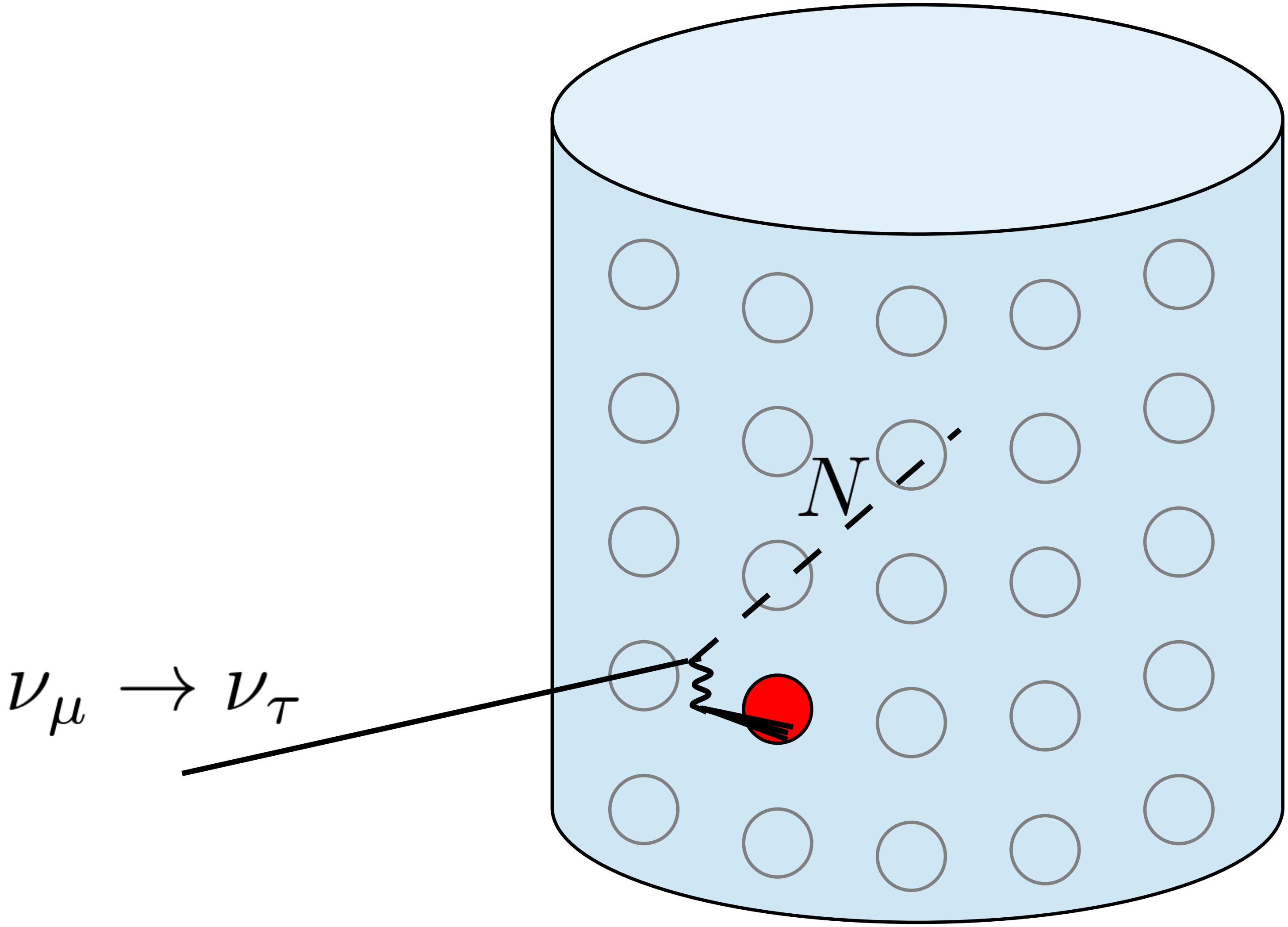
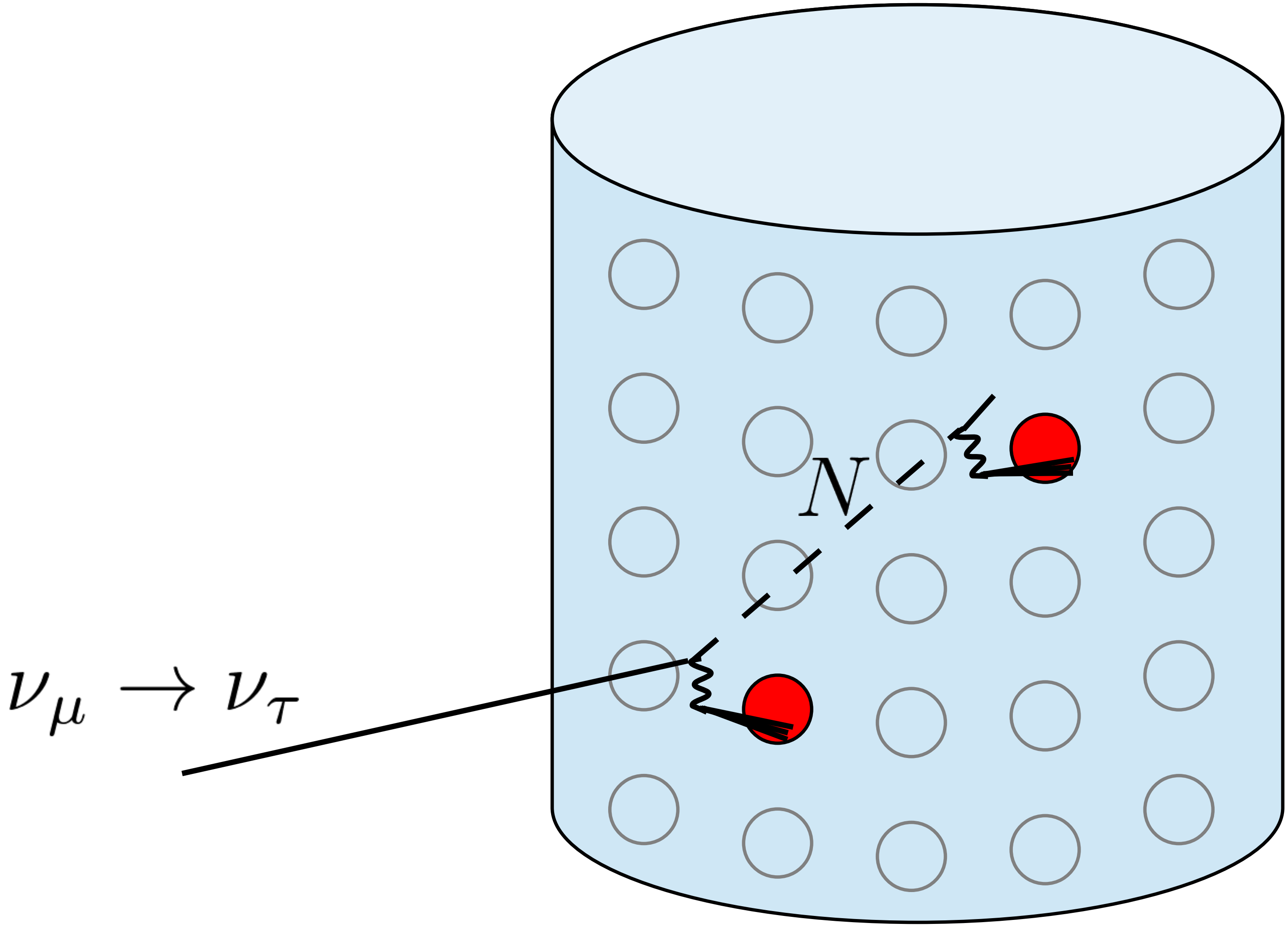
→ $U_{\tau 4}$ is particularly hard to probe using fixed target experiments, though…

(1) Production inside the detector


$\nu_\mu \to \nu_\tau$
N


$\nu_\mu \to \nu_\tau$
N

Double-bangs are expected at UHE

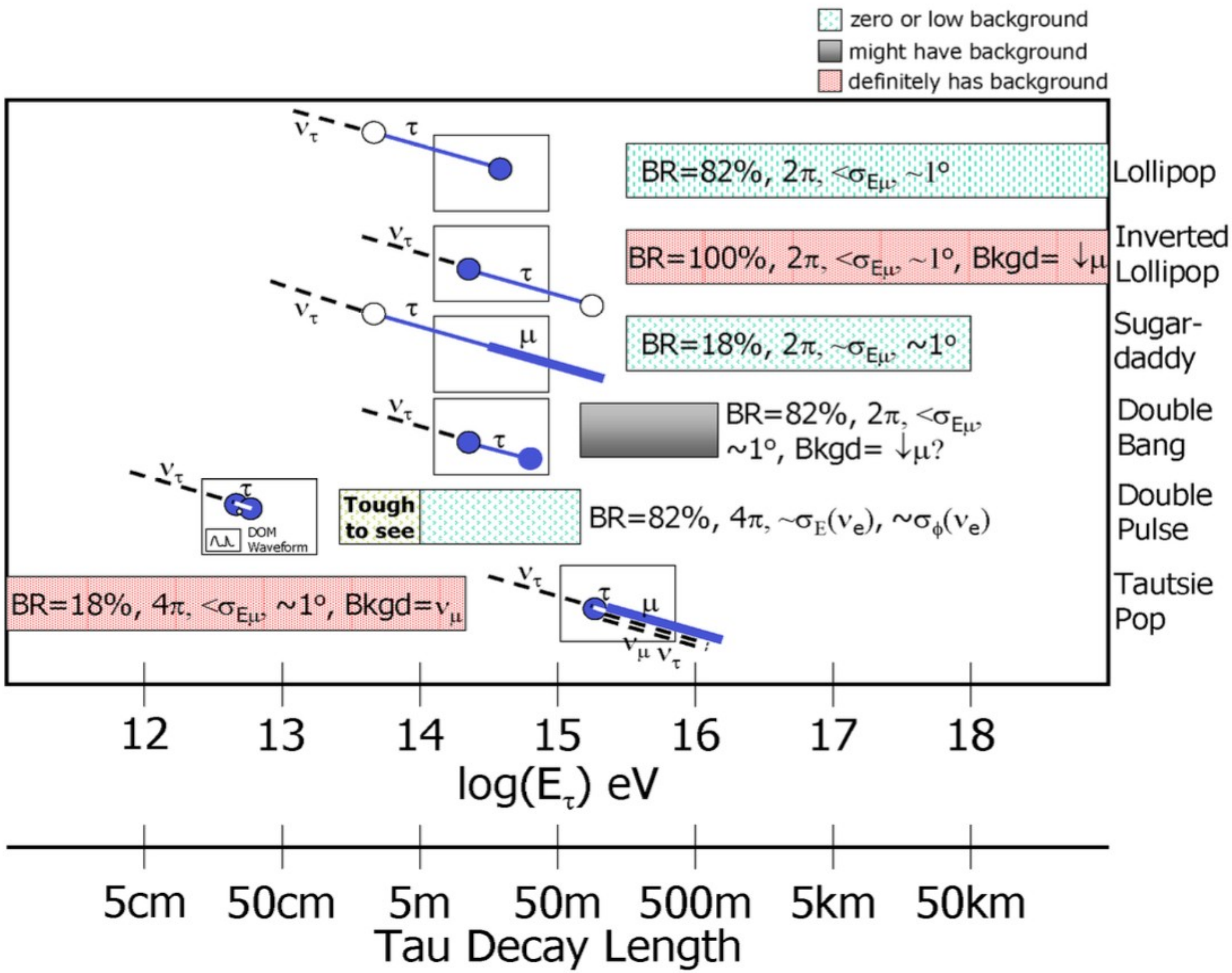


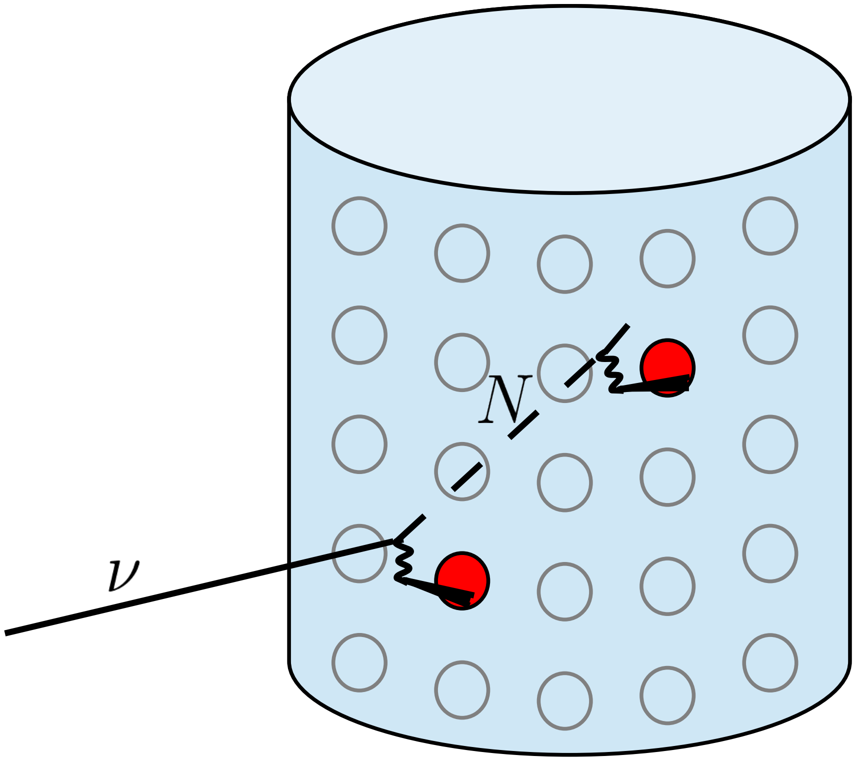
Figure from: Tau Neutrinos in IceCube, D. F. Cowen, TeVPA'06 proceedings

See also Icecube coll., 1509.06212

Low-energy Double-Bangs?

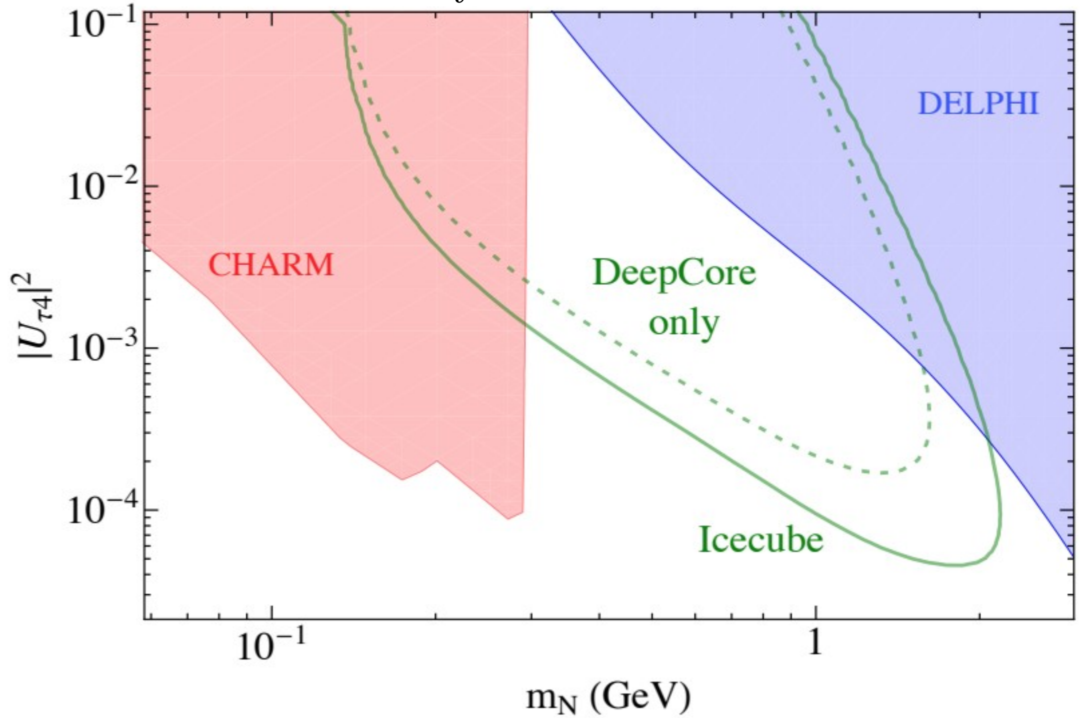
Key requirements for Icecube

- 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)



Vanilla scenario: only mixing

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4}N$$



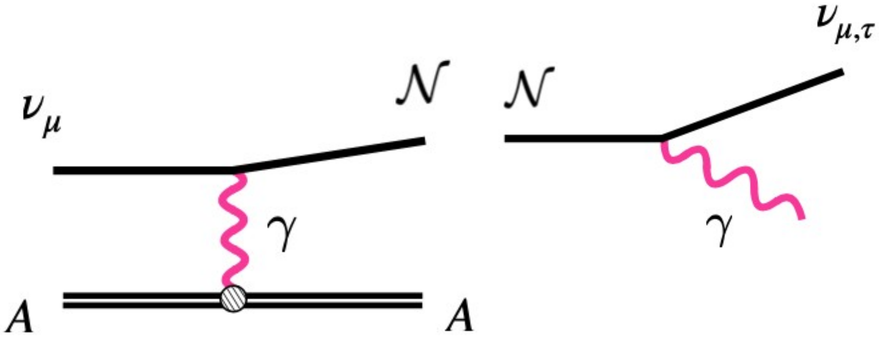
→ 6 yr sensitivity, **assuming zero background**

Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573

→ Newer bounds obtained in: Boiarska et al, 2107.14685 (CHARM recast); ArgoNeut coll., 2106.13684; and Barouki, Marocco, Sarkar, 2208.00416 (BEBC recast)

Non-minimal scenarios

For example:



Dipole portal: $\mu\left(\bar{\nu}_L \sigma_{\mu\nu} N\right) F^{\mu\nu}$

Light Z':

$$-eq_f \chi \bar{f} \gamma^\mu f Z'_\mu + U^*_{\alpha 4} g' \bar{\nu}_\alpha \gamma^\mu P_L N Z'_\mu + \ldots$$

→ These attracted lots of attention, in the context of MiniBooNE/LSND:

Gninenko, 0902.3802 & 1009.5536; Ballett et al, 1808.02915; Bertuzzo et al, 1807.09877; Fischer, Hernandez-Cabezudo, Schwetz, 1909.09561; Arguelles, Hostert, Tsai, 1812.08768; Magill et al, 1803.03262; Abdullahi, Hostert, Pascoli, 2007.11813; Kamp et al, 2206.07100, ...

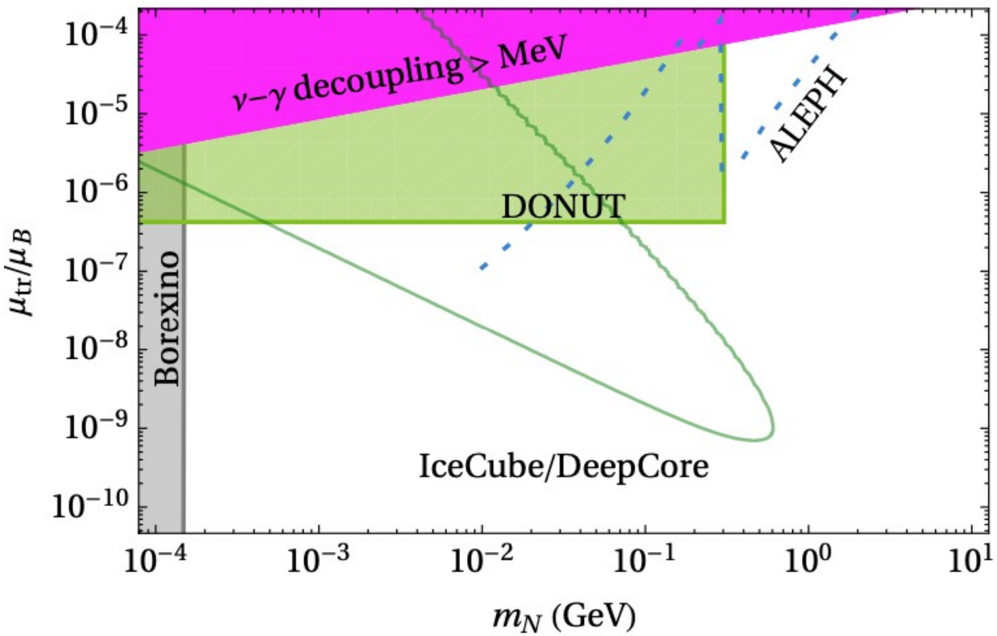
→ see Hostert's talk this morning

Non-minimal scenarios

Dipole

$$L_{lab,N} \simeq 100 \left(\frac{10^{-8}\mu_B}{\mu_\nu}\right)\left(\frac{E_N}{10\ \text{GeV}}\right)\ \text{m}$$

$\nu_\tau - N$



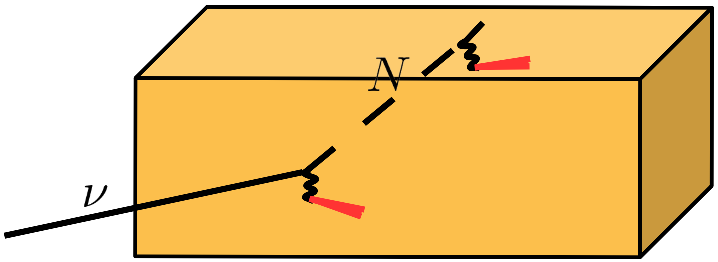
For $m_N \sim 100$ MeV

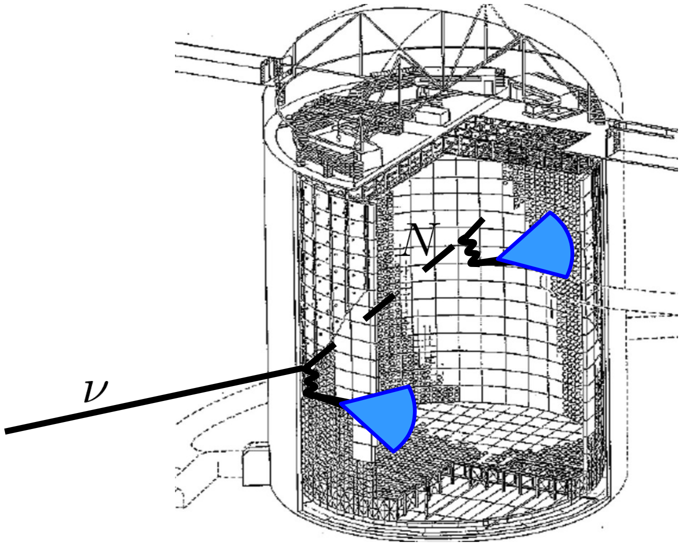
Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573
(see also Coloma, 1906.02106)

DUNE, SK, and HK

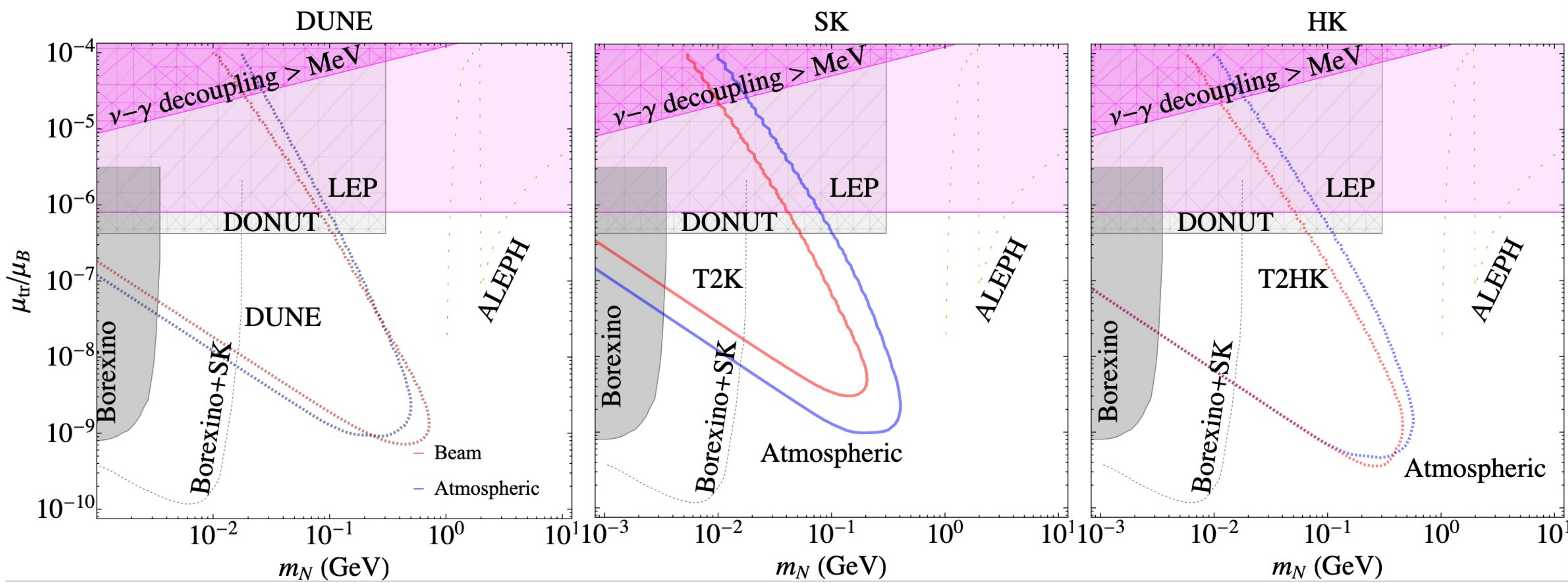
Much smaller volume, but…

- Much better spatial resolution
- Lower energy sensitivity, where the incident flux is highest
- Availability of an intense neutrino beam, besides atmospheric neutrinos
- Near detectors also available





DUNE, SK, and HK

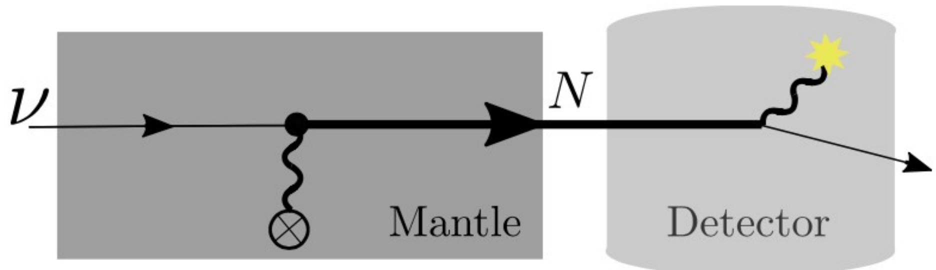


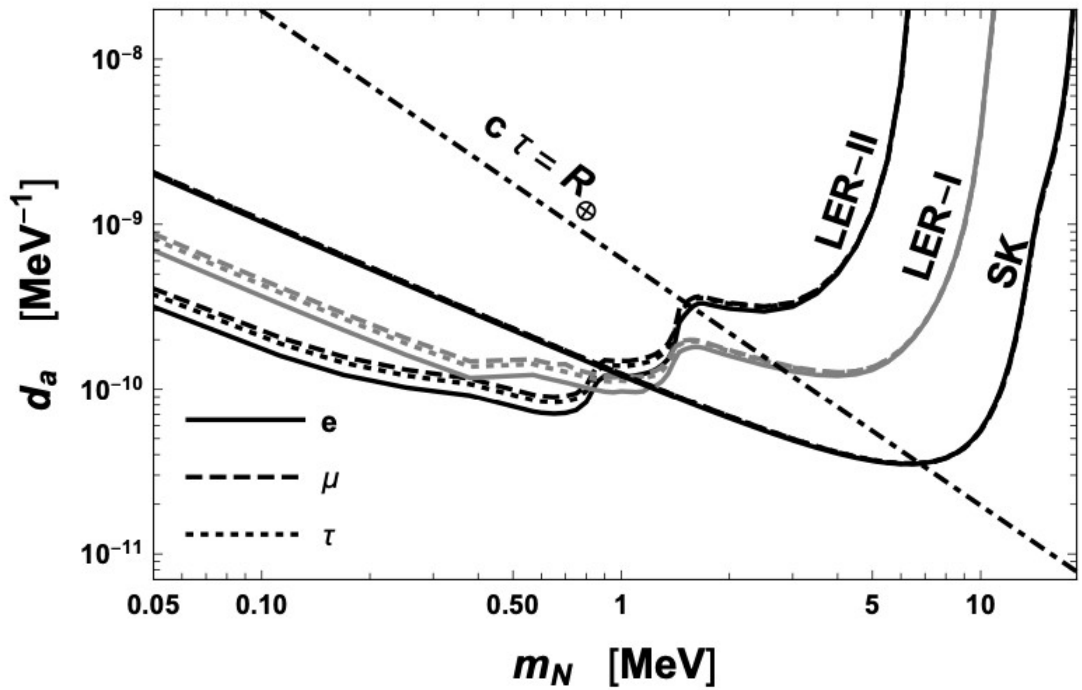
$\nu_\tau - N$

Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker, 2105.09357
(see also Schwetz, Zhou, Zhu, 2105.09699)

(2) HNL production inside the Earth

From solar neutrino up-scattering



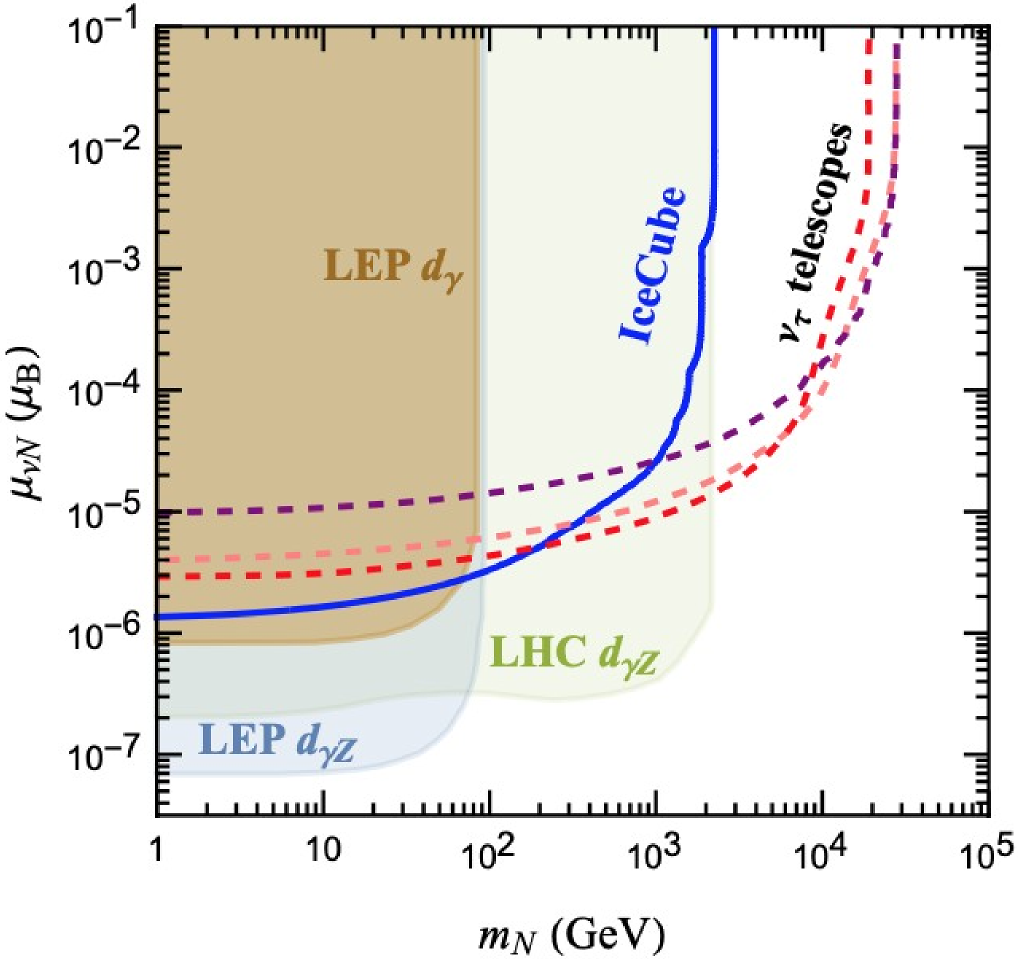


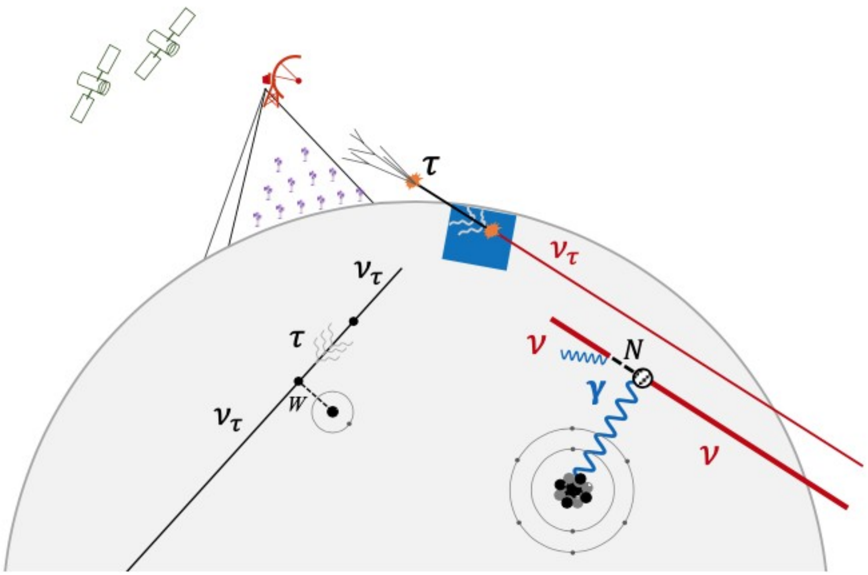
→ Curves indicate where the signal exceeds considerably the SM expectation for solar nus + bg

Plestid, 2010.04193

(for bounds from upscattering inside Borexino, see Brdar et al, 2007.15563)

From UHE neutrino up-scattering





Huang, Jana, Lindner, Rodejohann, 2204.10347

(3) HNL production in the atmosphere

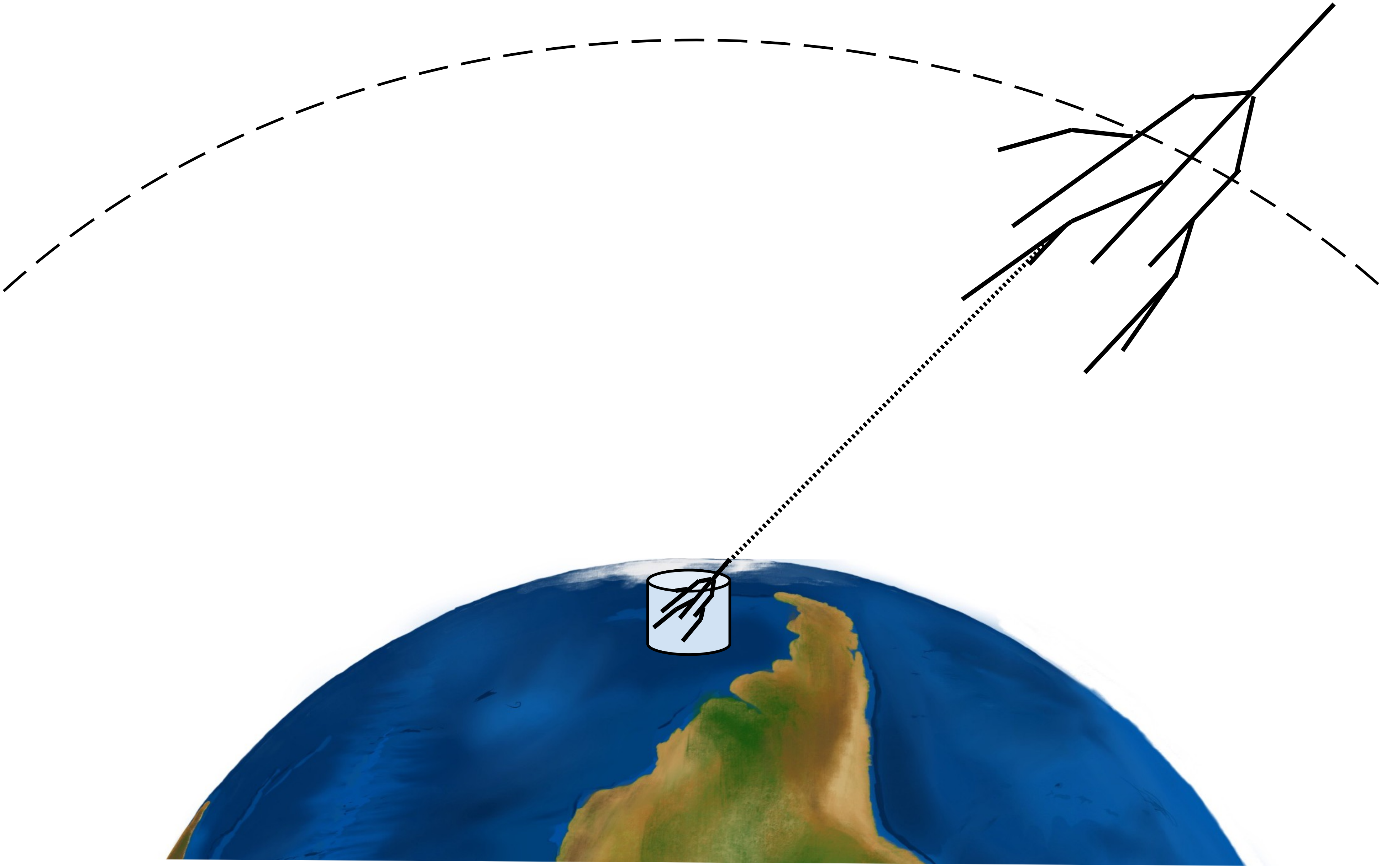


Image credit: https://mingtang.me/

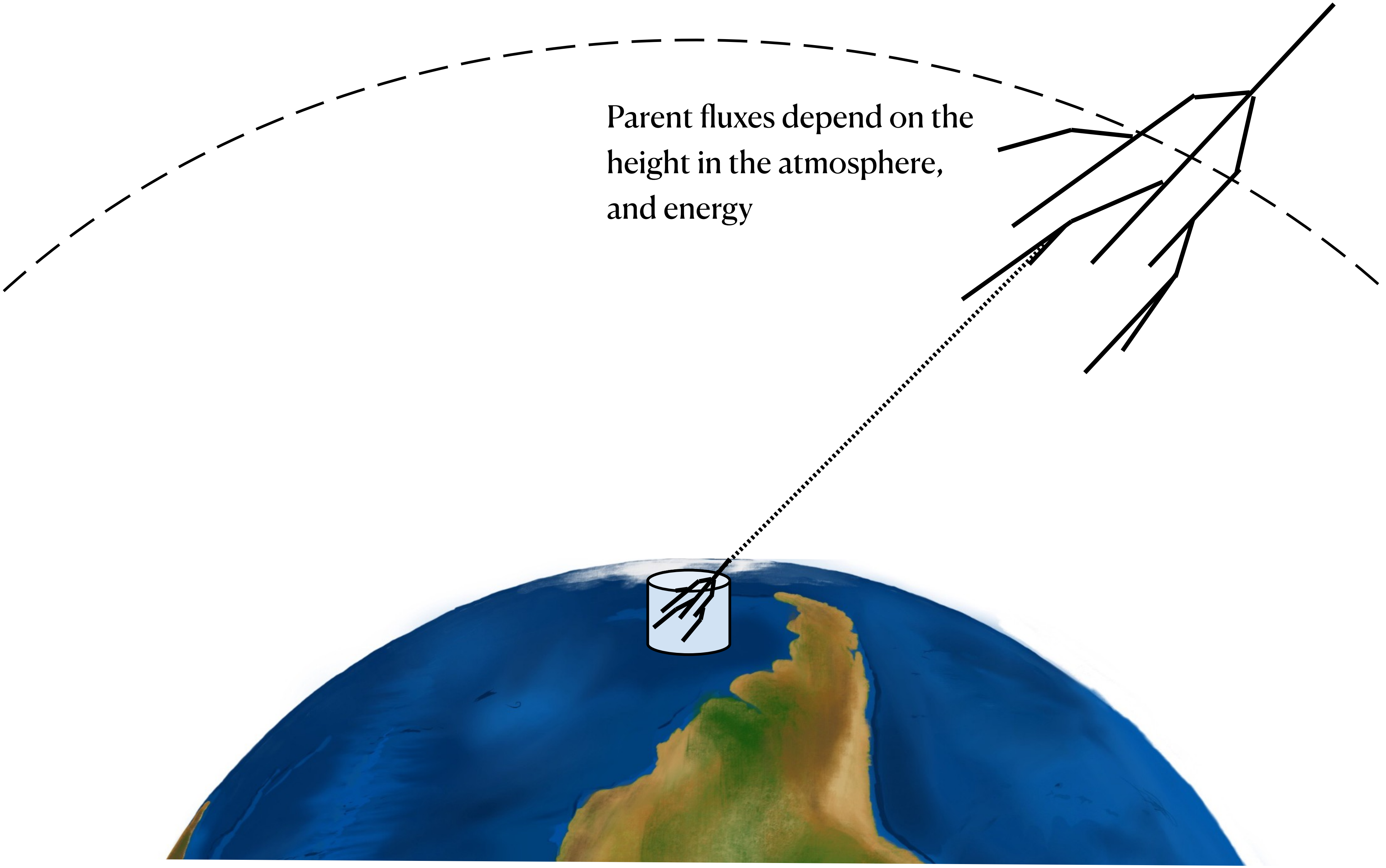
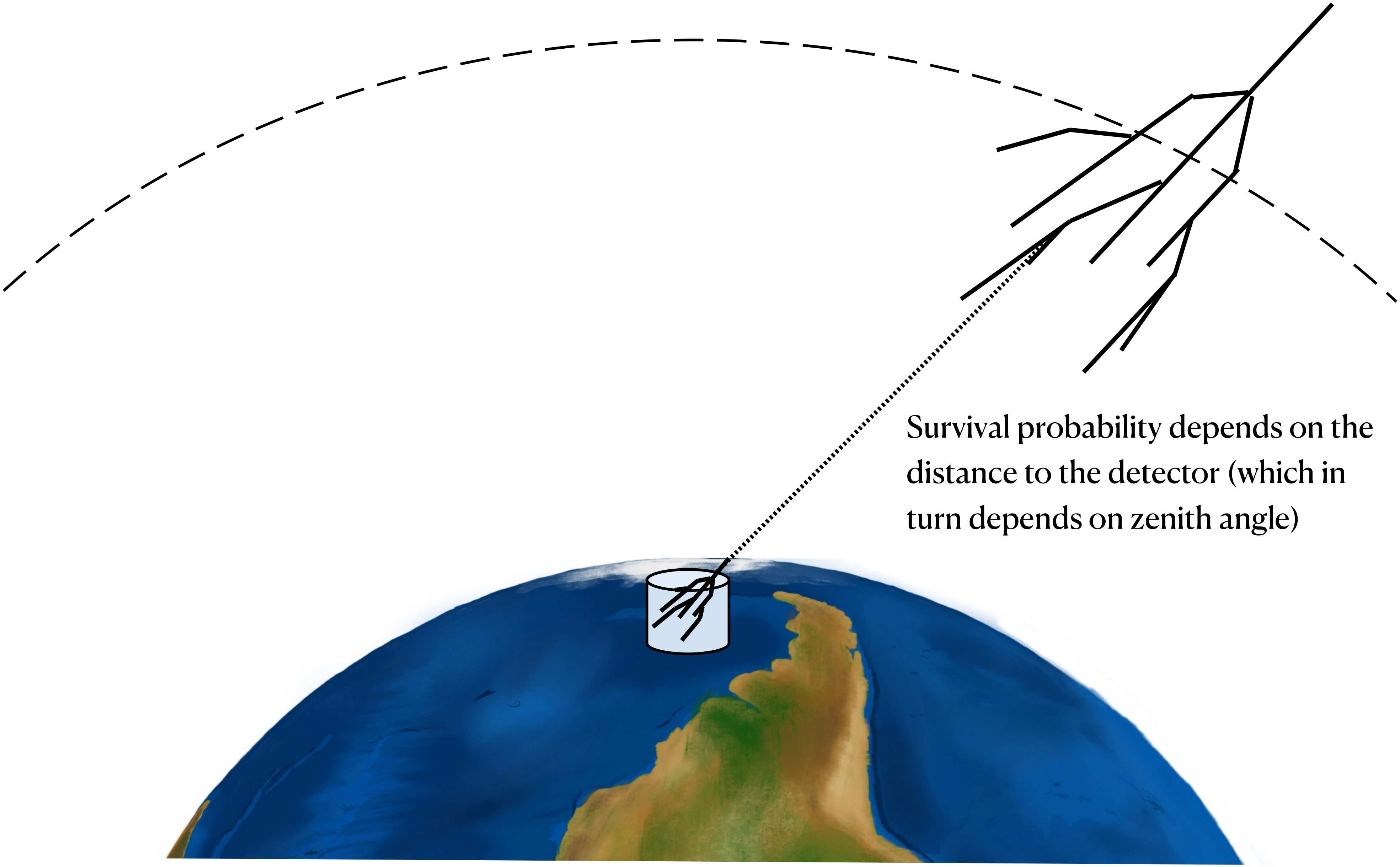
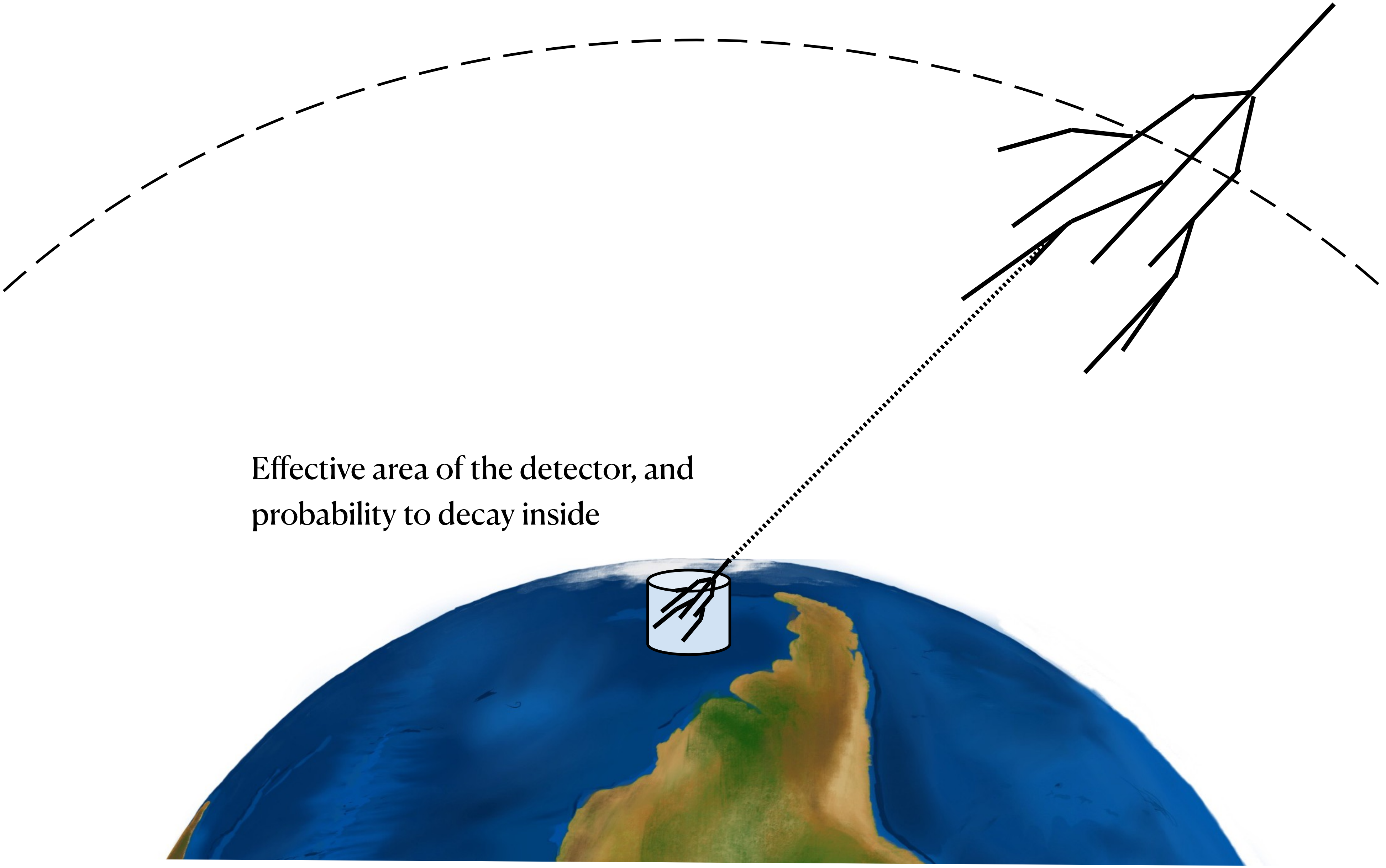


Image credit: https://mingtang.me/



Survival probability depends on the distance to the detector (which in turn depends on zenith angle)

Image credit: https://mingtang.me/



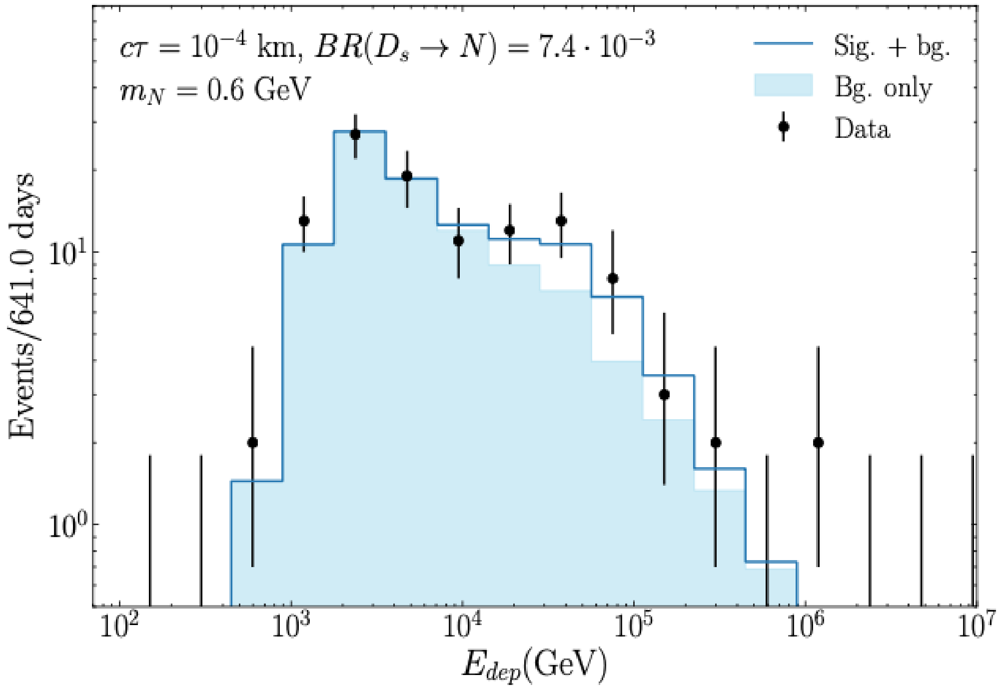
Effective area of the detector, and probability to decay inside

Image credit: https://mingtang.me/

Event rates

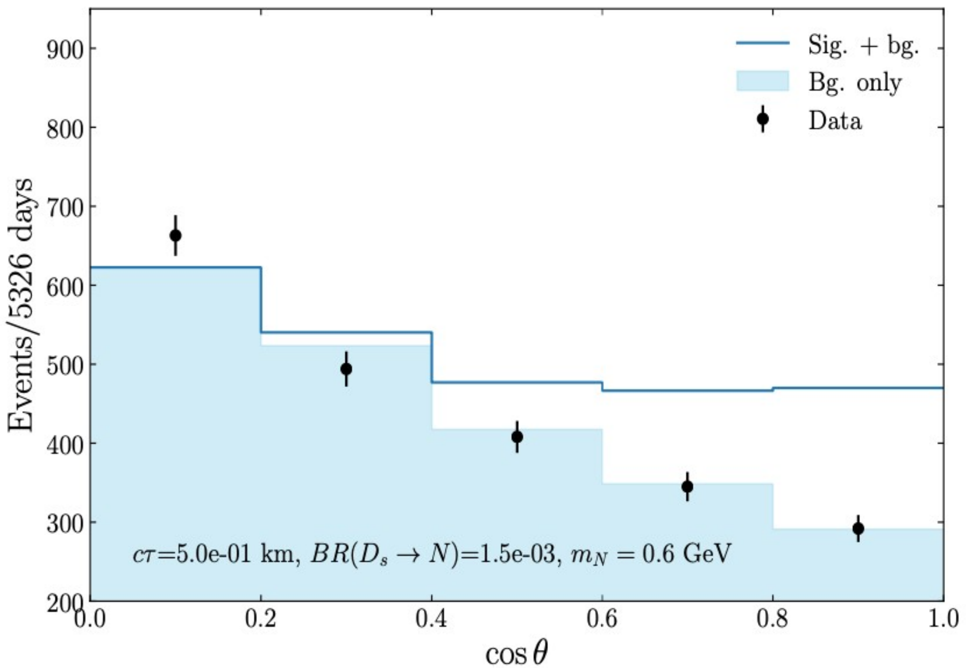
MESE sample at Icecube

Icecube collaboration, 1410.1749



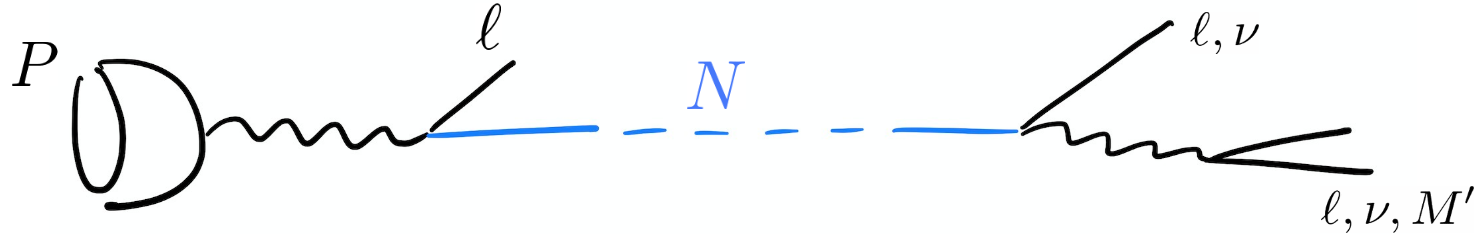
SK I-IV (multi-GeV, FC, e-like)

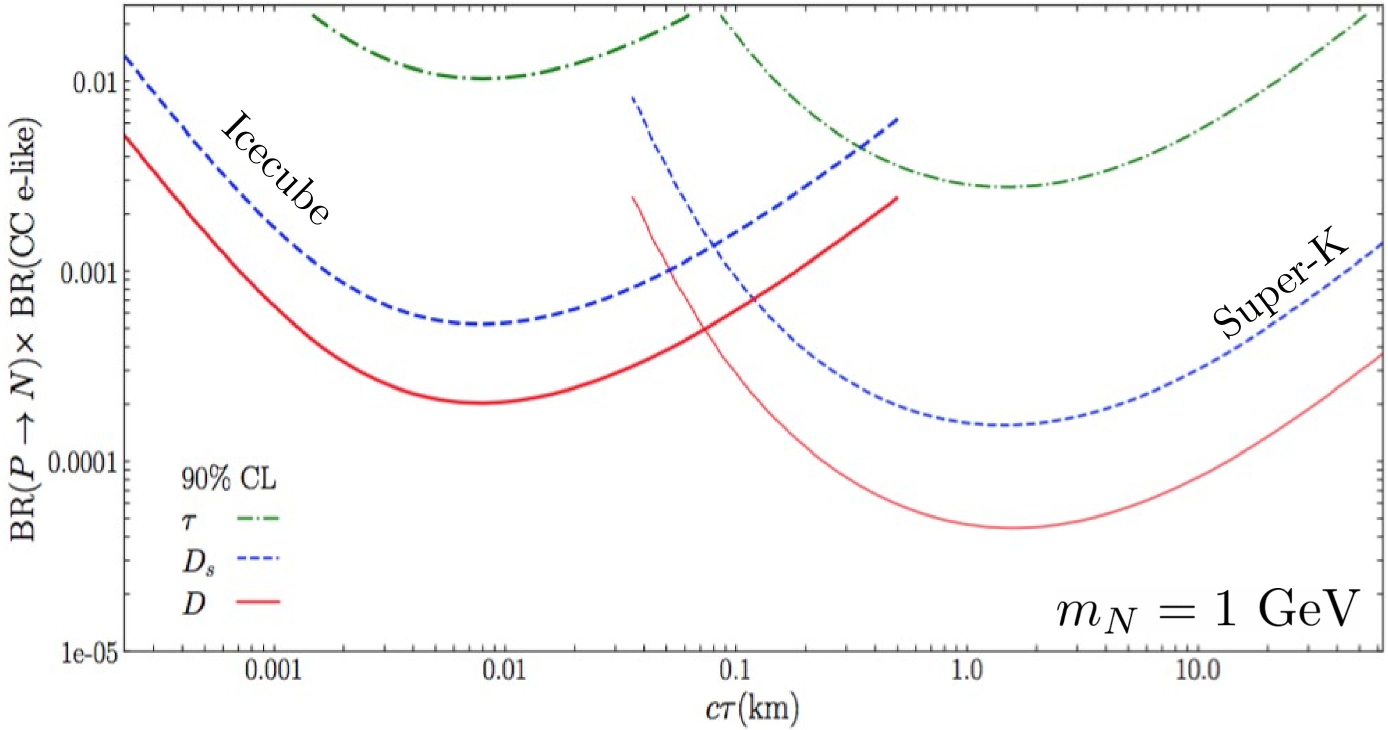
Super-Kamiokande coll. 1710.09126



Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

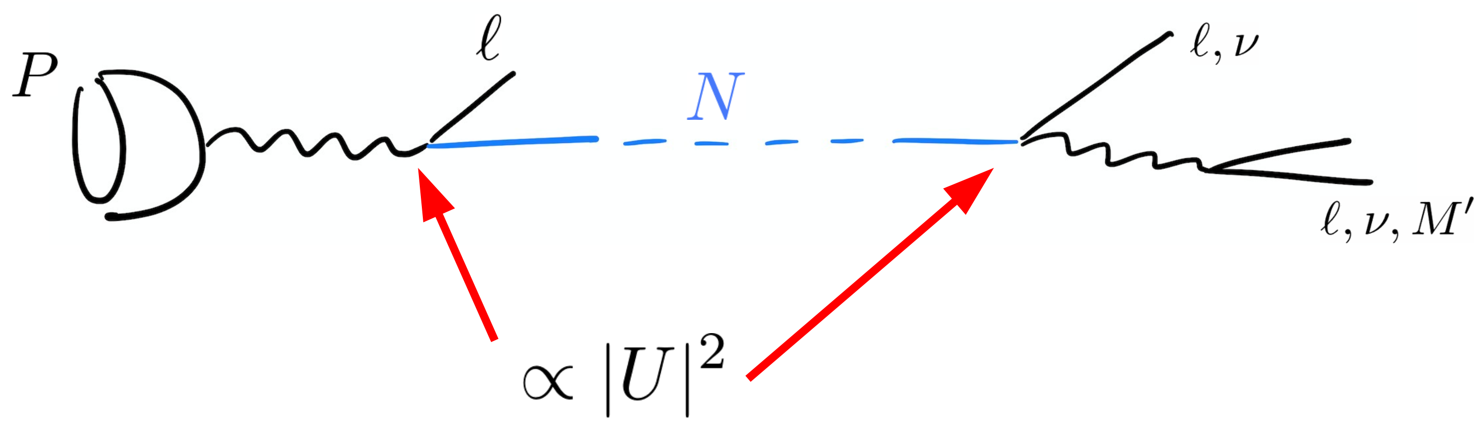
Model-independent results





Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

Vanilla scenario – $U_{\tau 4}$



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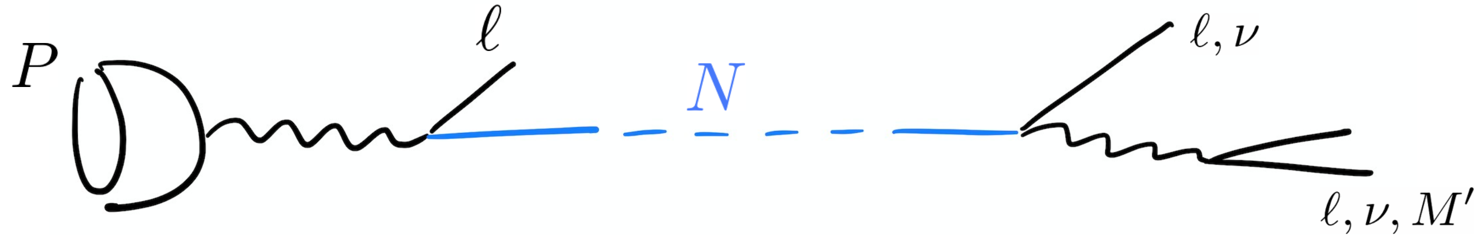
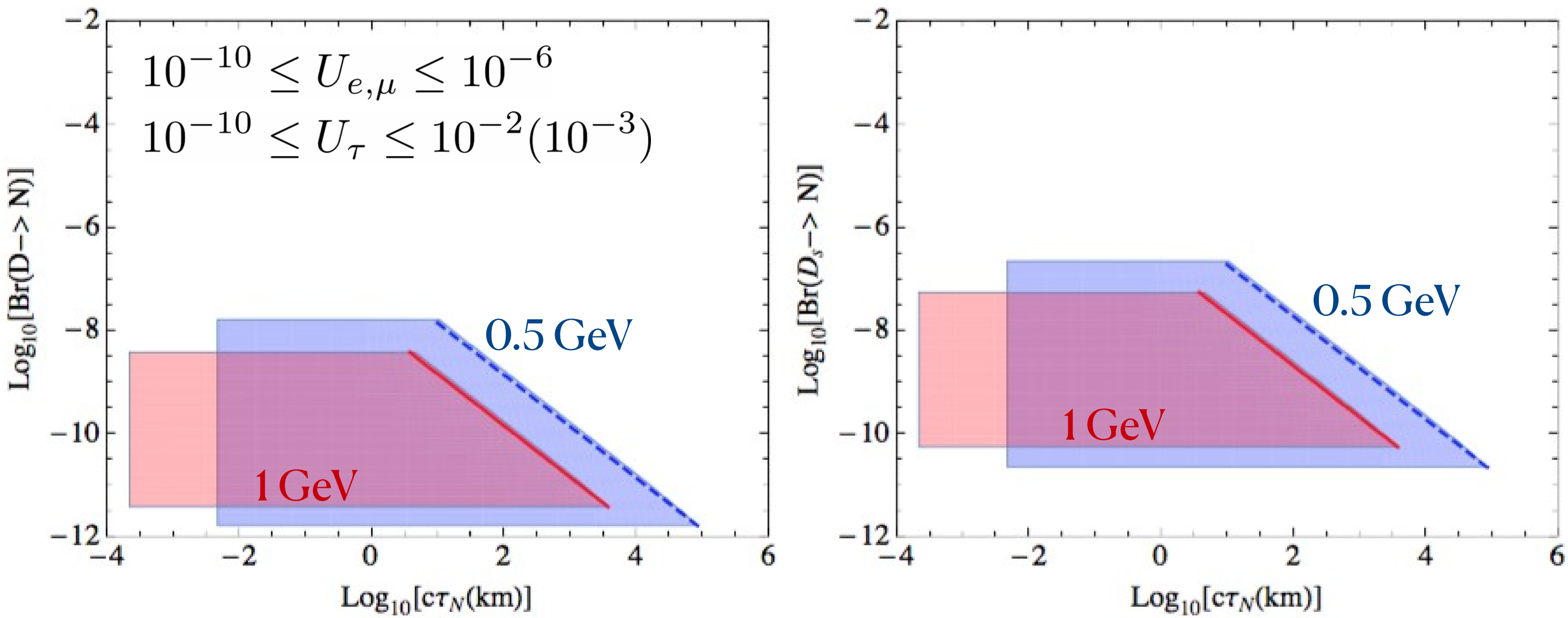
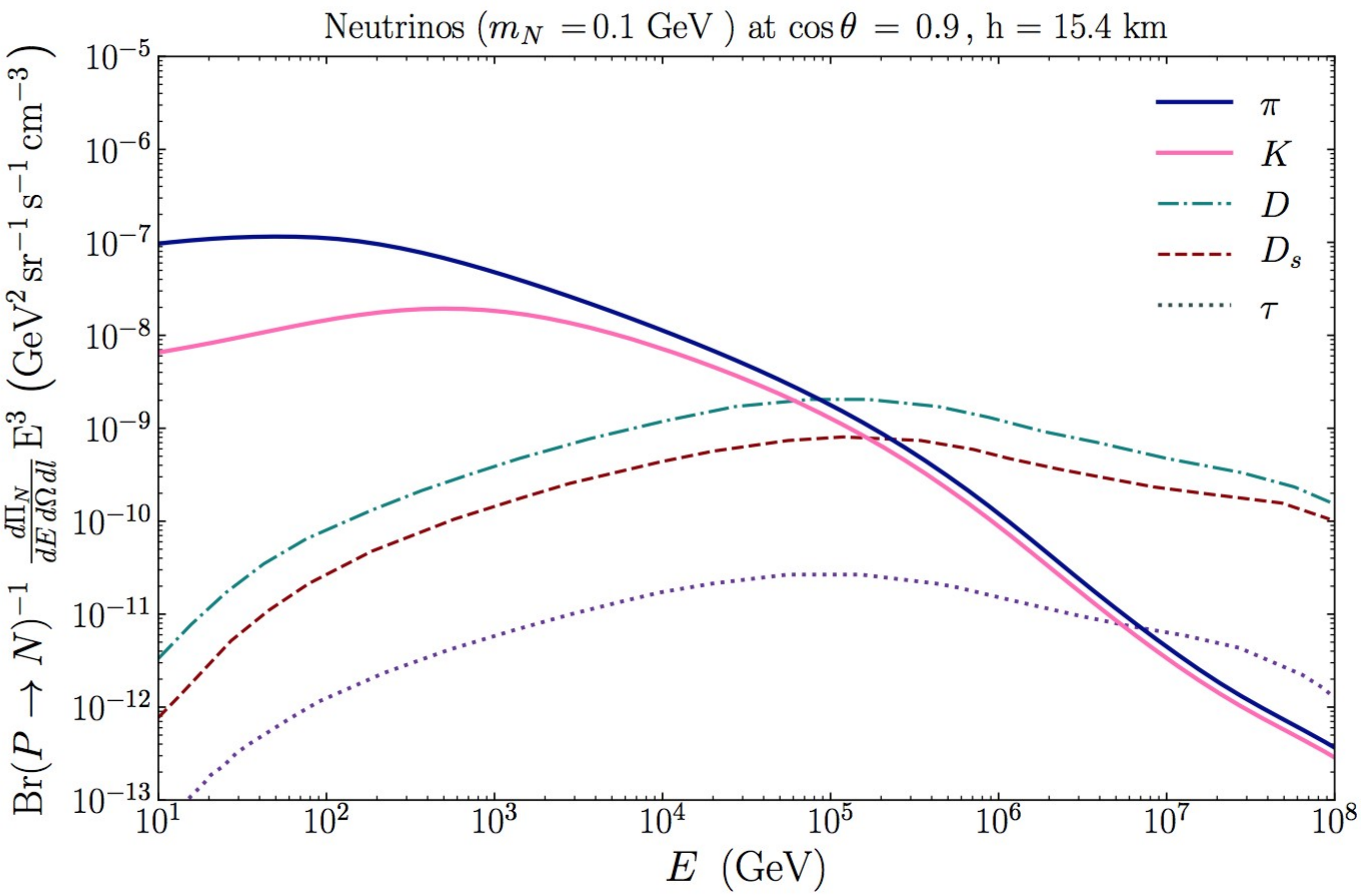




Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

HNLs below the kaon mass



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

HNLs below the kaon mass

An excess would be expected at Icecube in the context of dipole interactions and MiniBooNE

Masip, 1402.0665

Interesting possibilities at SK, sensitive to lower energies

Asaka, Watanabe, 1202.0725
Kusenko, Pascoli, Semikoz, hep-ph/0405198

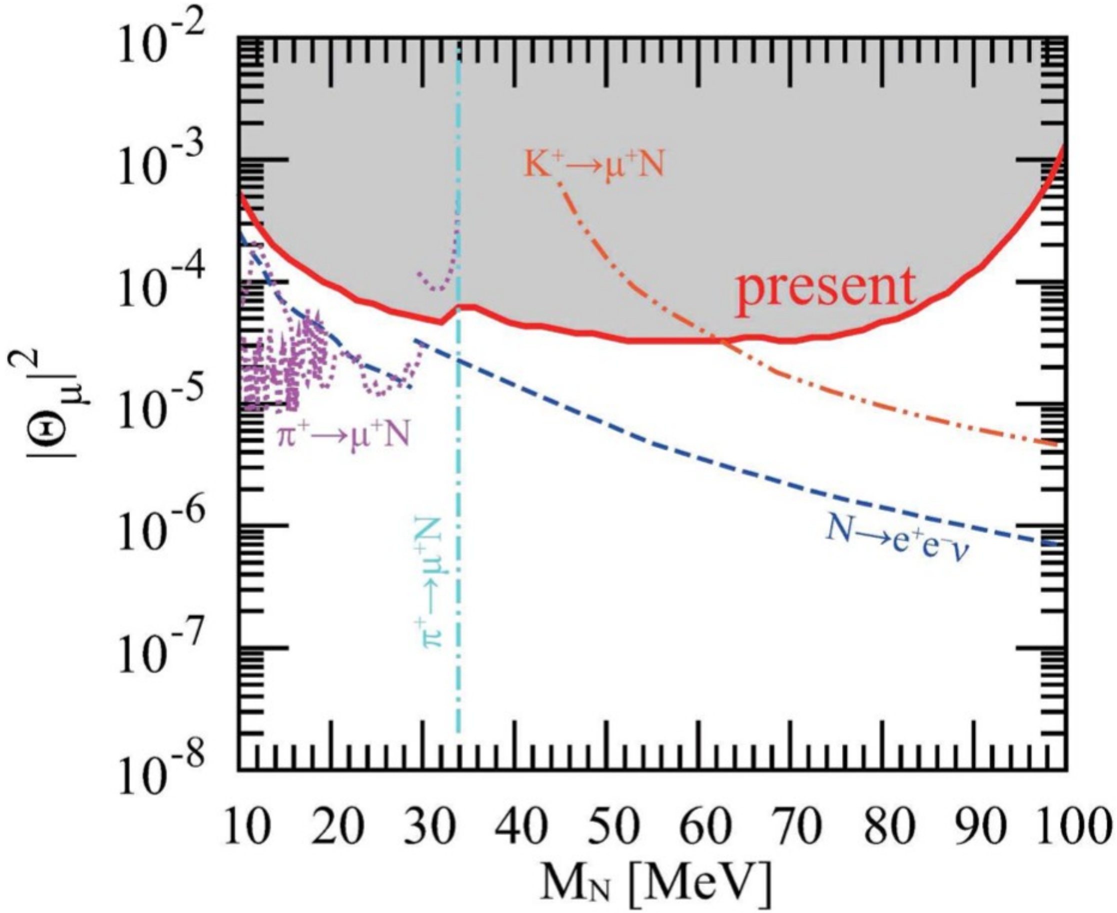
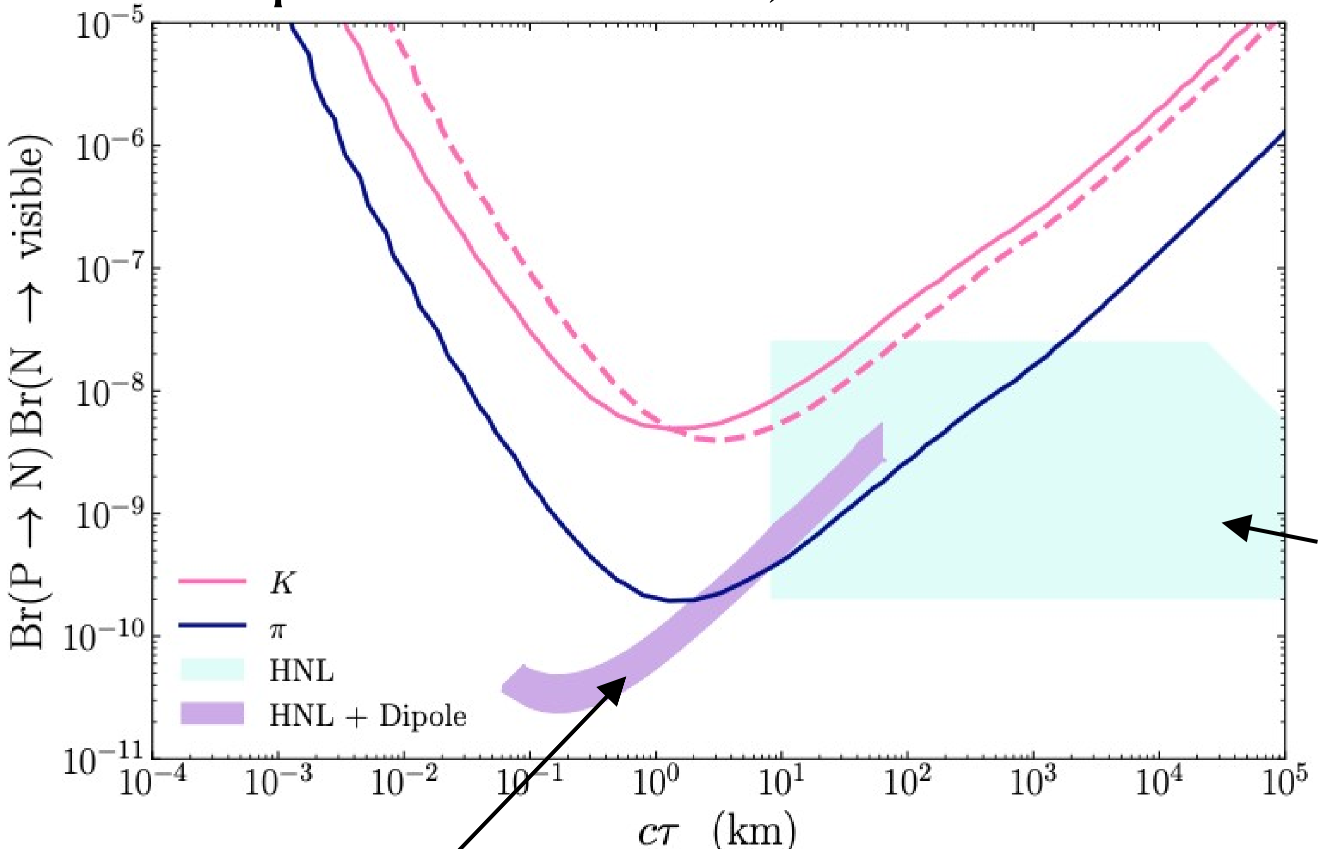


Figure from Asaka, Watanabe, 1202.0725

HNLs below the kaon mass

Super-K exclusion limits, m_N ~ 100 - 250 MeV

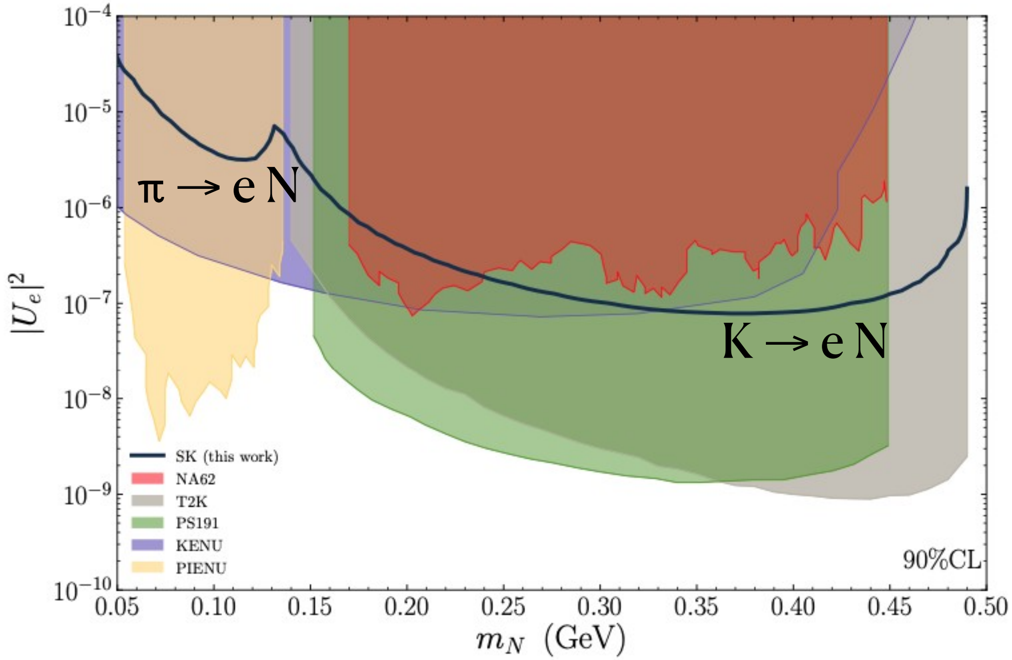


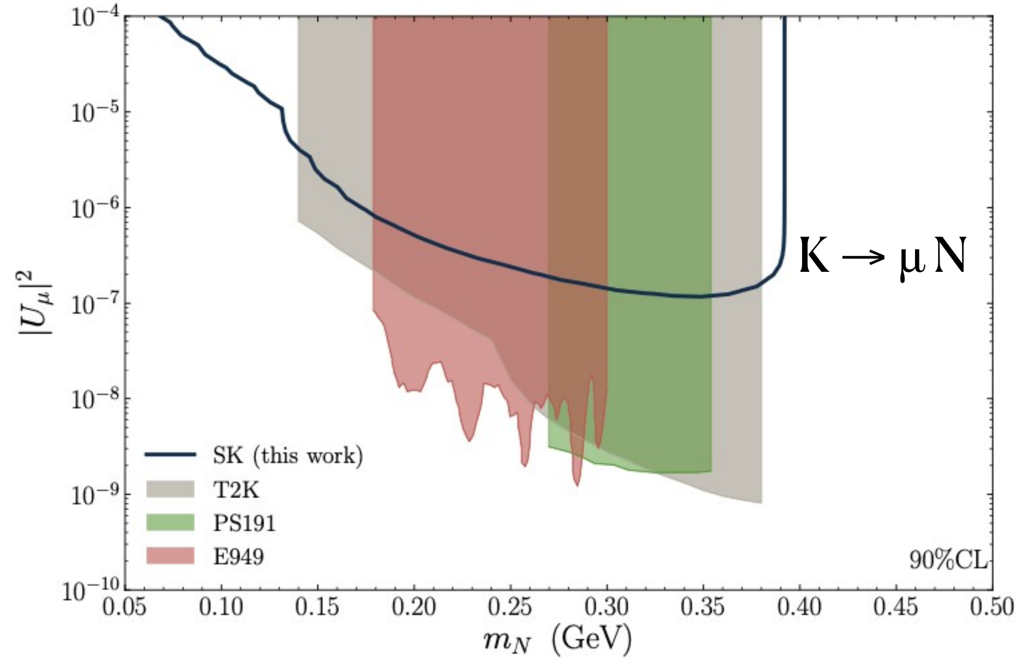
Coloma, Hernandez, Munoz, Shoemaker, 1911.09129

Region currently allowed in the minimal model, for mN=250 MeV

Region favored to explain MiniBooNE in Fischer et al, 1909.09561 [hep-ph]

HNLs below the kaon mass





Coloma, Hernandez, Munoz, Shoemaker, 1911.09129
(see also Kusenko, Pascoli, Semikoz, hep-ph/0405198; Asaka, Watanabe, 1202.0725)

Summary

- I have given an overview of several possibilities to search for the decay of HNL using neutrino telescopes & atmospheric neutrino detectors:
  - Production inside the detector: low-energy double-bang signals
  - Production from up-scattering in the Earth
  - Production in the atmosphere and decay inside neutrino detectors

→ Plenty of room to improve! 2D binning, smaller bins, systematics, bgs, …

- Other experiments? KM3NeT, ORCA?
- The same approach may be applicable to other long-lived particles

Thanks!

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PID2019-108892RB-I00, CEX2020-001007-S

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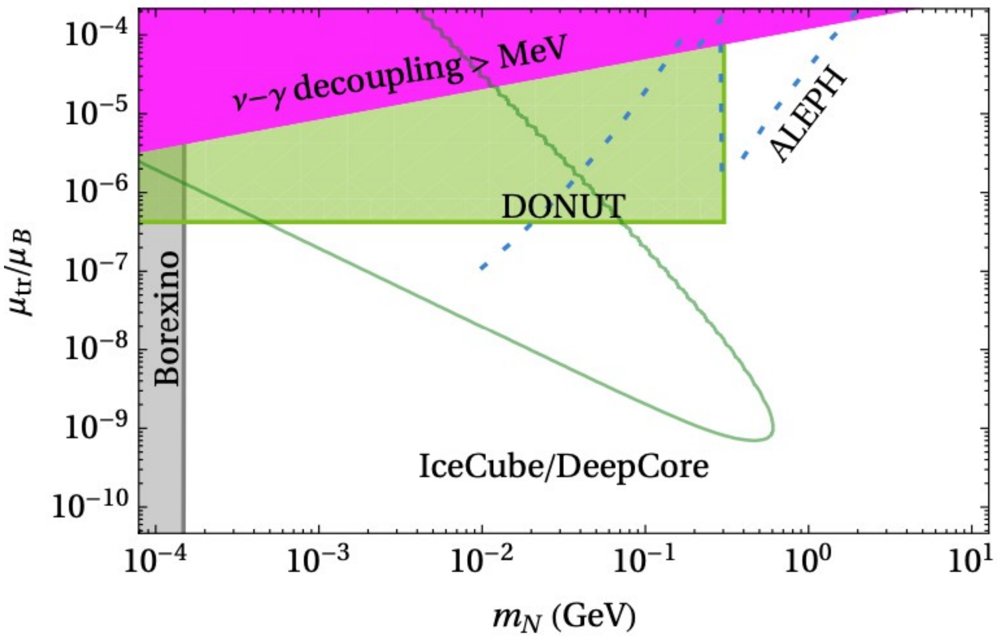
Backup

Non-minimal scenarios

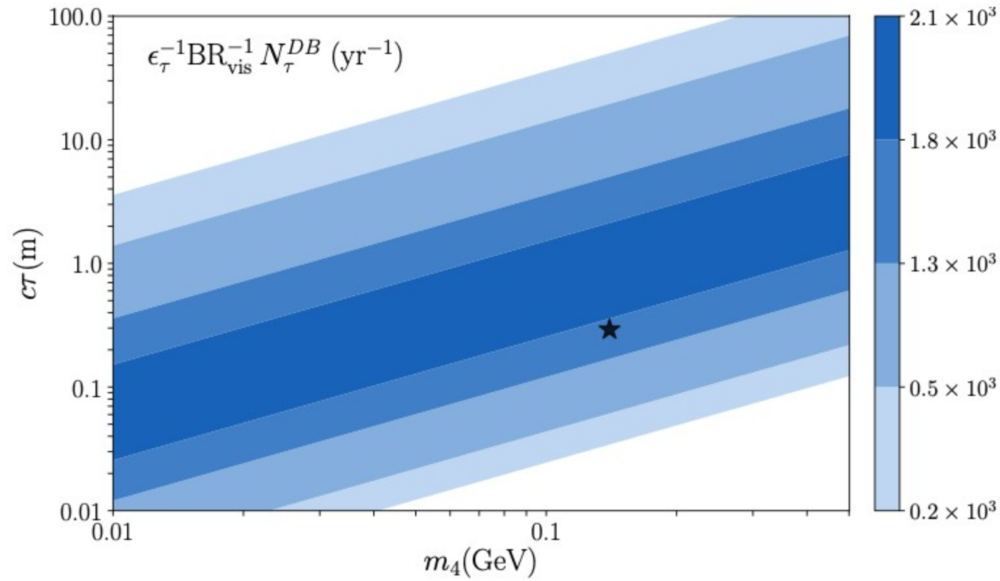
Dipole

Light Z'

$\nu_\tau - N$



$N_\alpha^{Z'} \simeq \epsilon_\alpha N_\alpha$



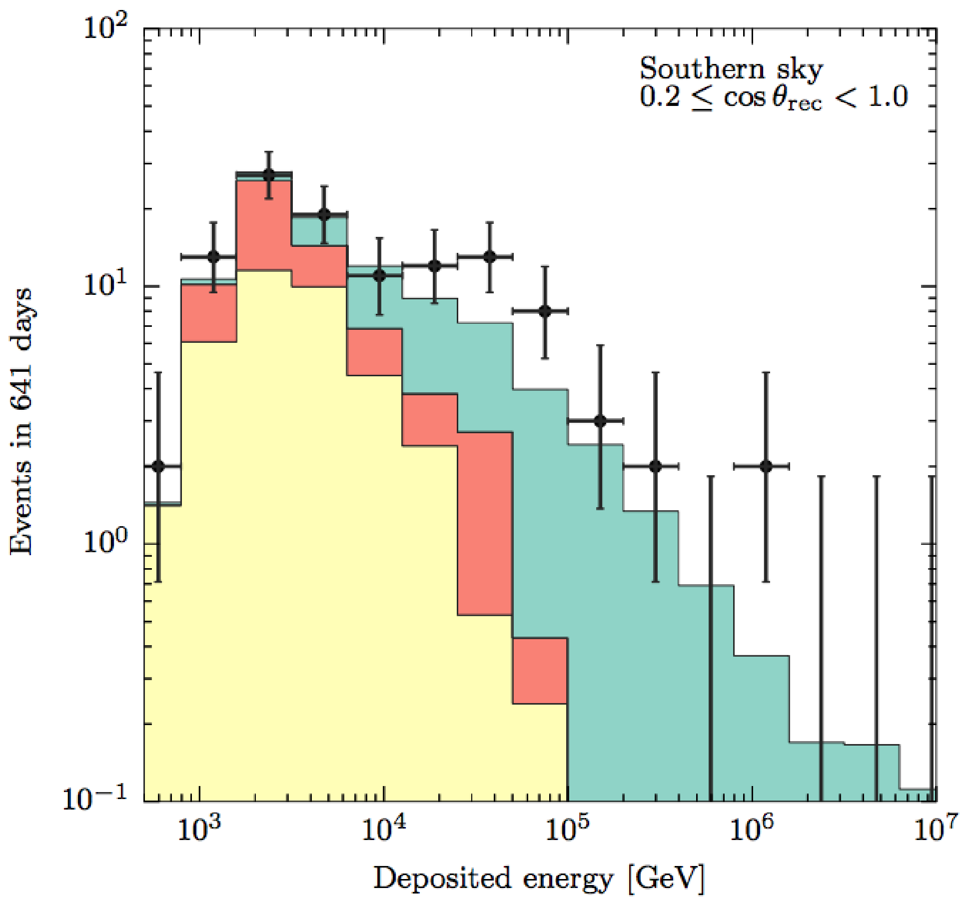
Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573

Coloma, 1906.02106

Data sets

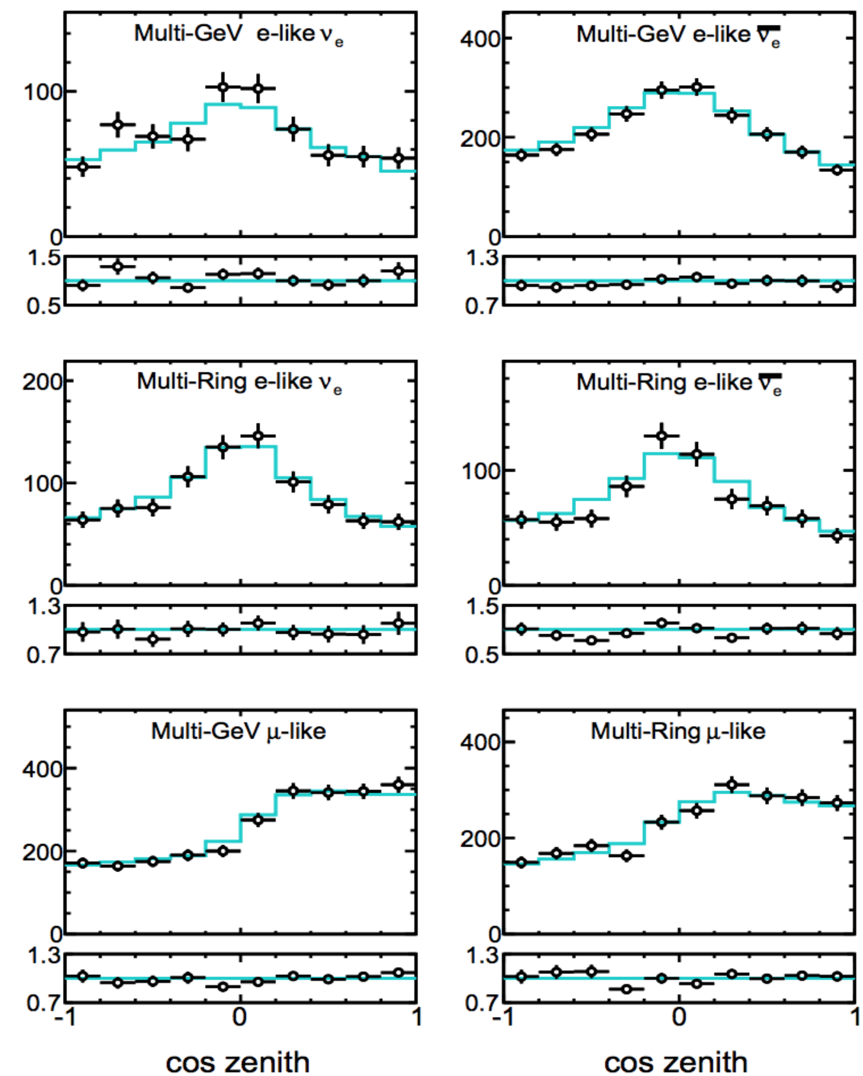
MESE sample at Icecube (641 days)

Icecube collaboration, 1410.1749

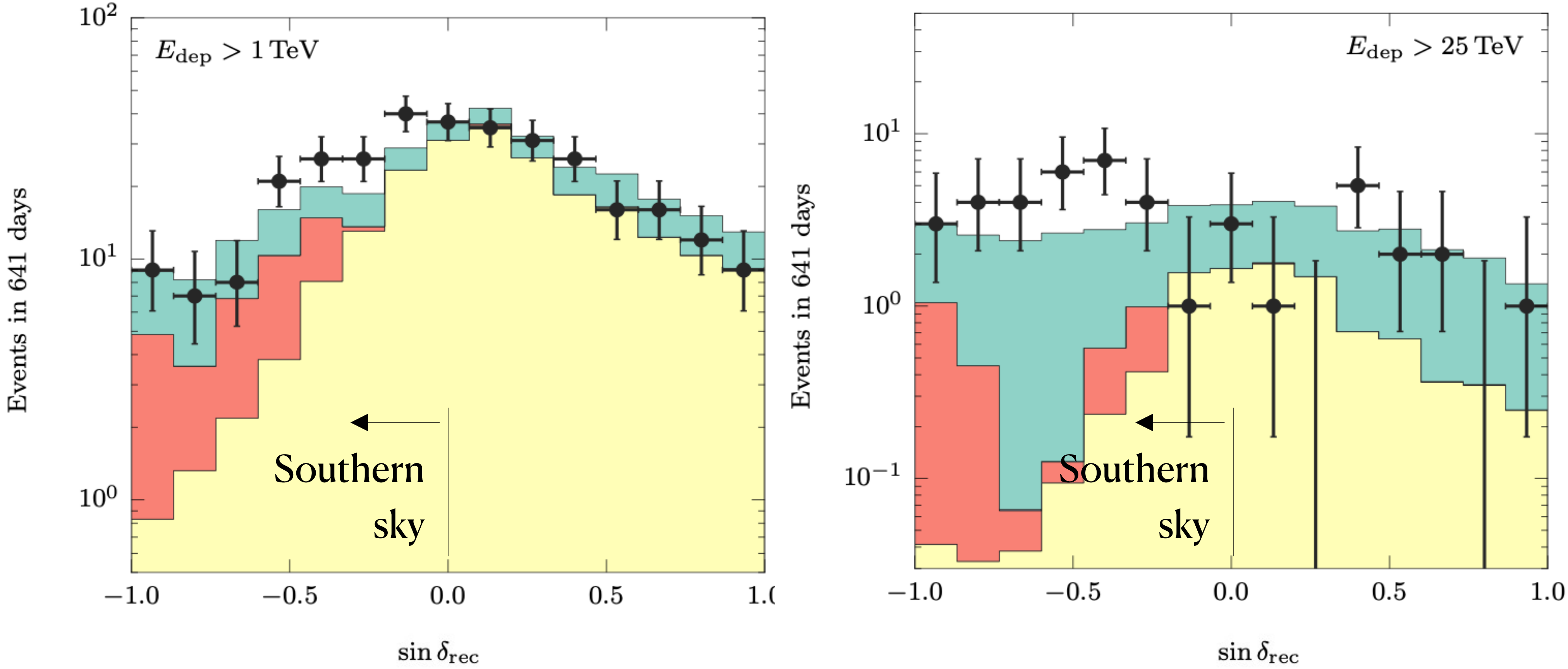


Data from SK I-IV (5,326 days)

Super-Kamiokande coll. 1710.09126

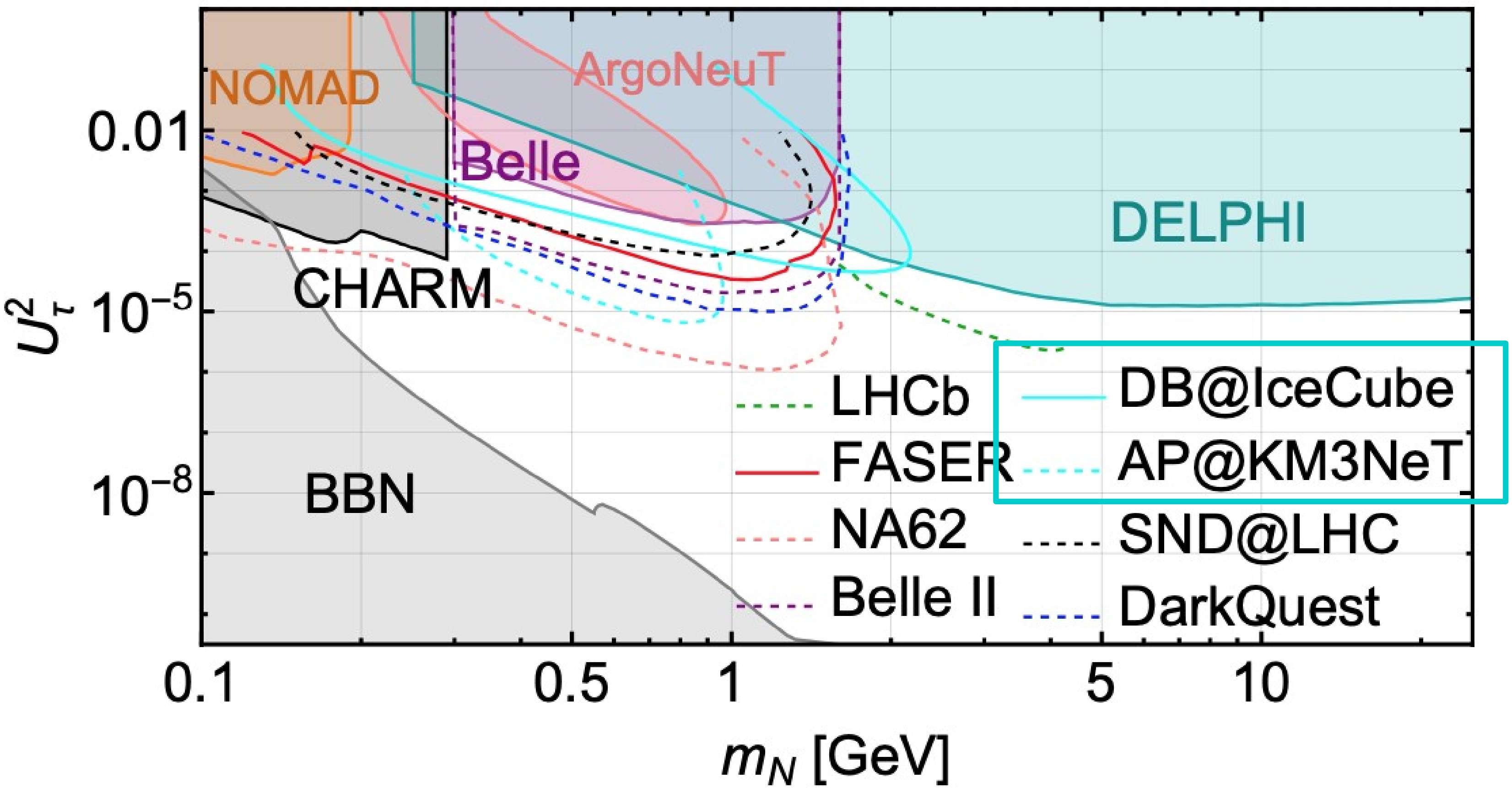


Data sets



$E_{\rm dep} > 1$ TeV
Events in 641 days
Southern sky
$\sin\delta_{\rm rec}$
$E_{\rm dep} > 25$ TeV
Events in 641 days
Southern sky
$\sin\delta_{\rm rec}$

Vanilla scenario – $U_{\tau 4}$



Boiarska, Boyarsky, Mikulenko, Ovchynnikov, 2107.14685