Fermilab

Northwestern University

New particles from the Sky

Iván Martínez Soler

IceDUNE

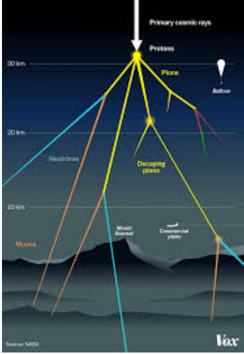
JUNE 16-18, 2021

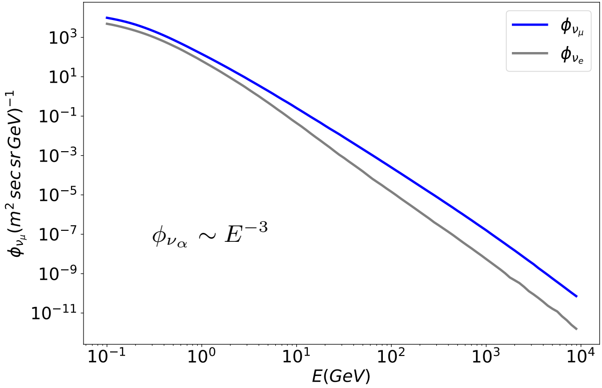
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Atmospheric neutrinos

In the atmosphere, **Cosmic Rays** interact with atmospheric nuclei and generates a **neutrino flux**





$$
\begin{aligned}
\pi^\pm &\to \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \\
K^\pm &\to \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \\
\mu^\pm &\to e^\pm + \nu_e(\overline{\nu_e}) + \nu_\mu(\overline{\nu_\mu})
\end{aligned}
$$

See Prof. Thomas Gaisser Talk's

Atmospheric neutrinos

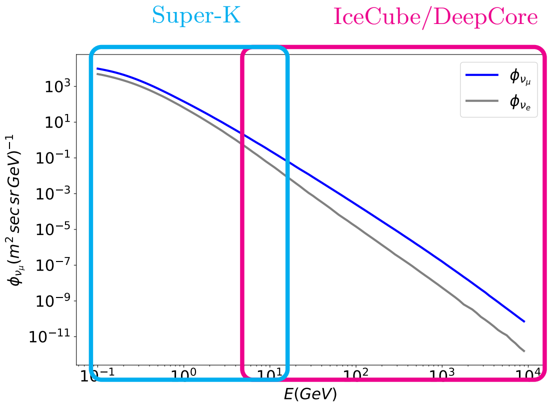
At present, several experiments are measuring the neutrino flux at different energy scales

Super-K

- 22.5 kton water Cherenkov
- Measures the neutrino flux from the **sub-GeV**
- Event sample divided in: FC, PC and Up-μ

IceCube/DeepCore

- $\sim$ 1km^3 ice Cherenkov
- Measures the **high energy** part of the flux $E \geq 5$ GeV
- Events sample divided in: cascades and tracks



See Summer Bolt Talk's

Atmospheric neutrinos

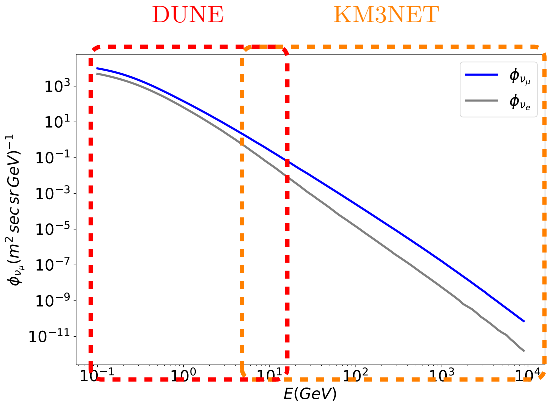
In the **future**, we will constraint the atmospheric neutrino flux with **high precision**

DUNE

- 40 kton LArTPC
- Measures the neutrino flux from the Sub-GeV
- **Good event topology reconstruction** at low energies

KM3NeT

- Two detectors: Orca and Arca
- Water Cherenkov
- Northern hemisphere



See Thomas Junk Talk's

We can use the atmosphere to search for **BSM physics**

Heavy neutral leptons

A robust indication of BSM physics is $m_\nu \neq 0$

- Neutrino masses can be explained by adding to the SM right-handed neutrinos (N_R)

$$\mathcal{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N^c_R} N_R + h.c.$$

- For $M_R \gg v$

$$m_\nu \sim \frac{Y_\nu^\dagger Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

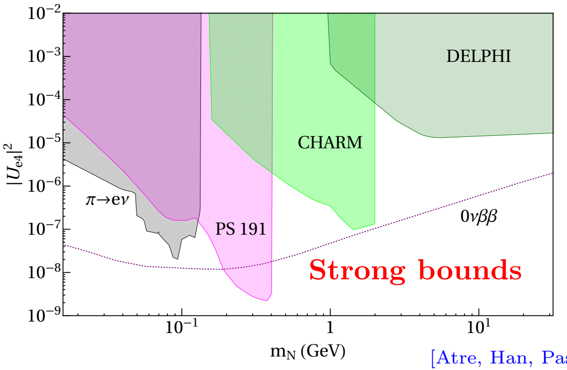
  - The suppression of M_R can explain the small neutrino masses

Heavy neutral leptons

In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4} N^c_{4R}$$

In the presence of $\nu - N - Z$ interaction



[Atre, Han, Pascoli, and Zhang, 0901.3589]

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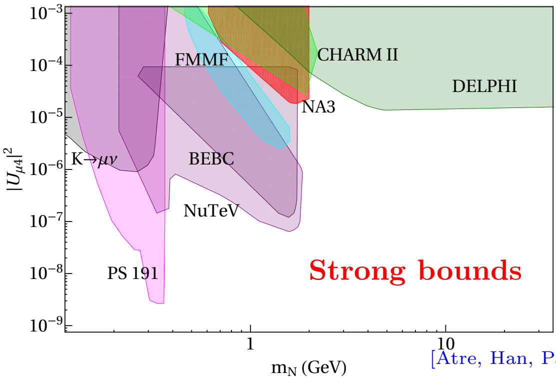

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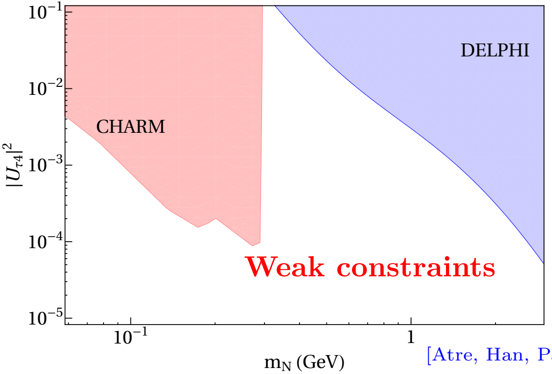
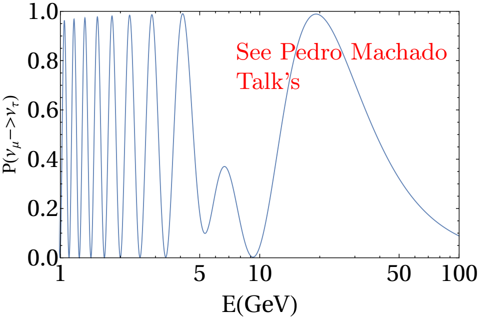


[Atre, Han, Pascoli, and Zhang, 0901.3589]

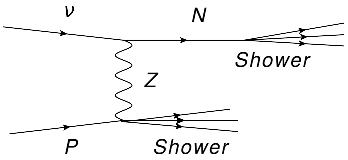
Heavy neutral leptons

The **flavor oscillation** of atmospheric neutrinos creates ν_τ



- Heavy neutrinos can travel long distance with low initial energies.
- We will look for double bang signals:

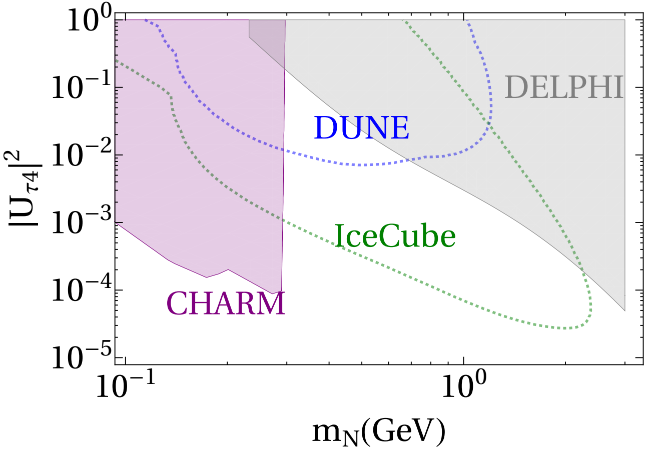
$$\nu_\tau + N \to N_4 + \text{shower}$$
$$N_4 \to \text{shower}$$



- The decay length depends on M_4 and on $|U_{\tau 4}|^2$
- Cross section proportional to mixing parameter $|U_{\tau 4}|^2$

Heavy neutral leptons

Double-Bang signals can be used to search for **HNLs in IceCube and DUNE**

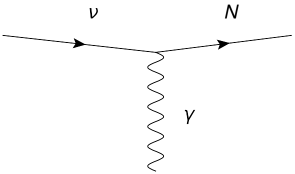


Coloma, Machado, IMS, Shoemaker (1707.08573)
Atkinson, Coloma, IMS, Rocco, Shoemaker (2105.09357)

Heavy neutral lepton: Transition magnetic moment

- We are interested in a transition magnetic moment

$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$

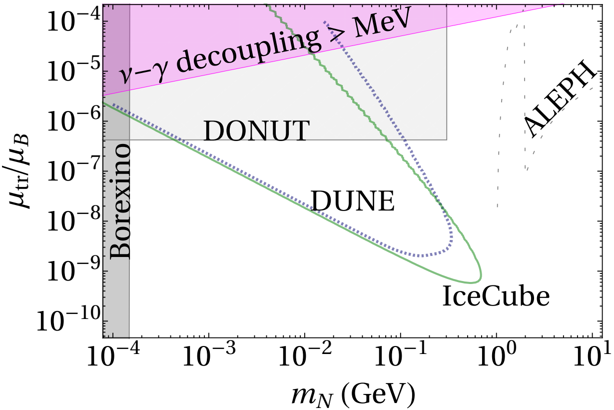


- The decay length $N \to \nu_i \gamma$

$$\Gamma = \frac{\mu_\nu^2 M_4^3}{16}$$

Heavy neutral leptons

Double-Bang signals can be used to search for neutrino **transition magnetic moments**



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Heavy neutral leptons

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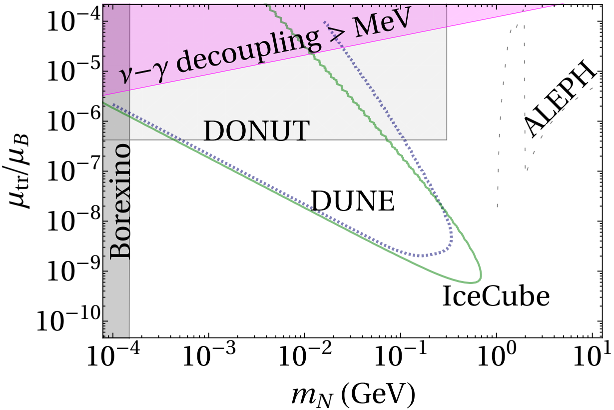


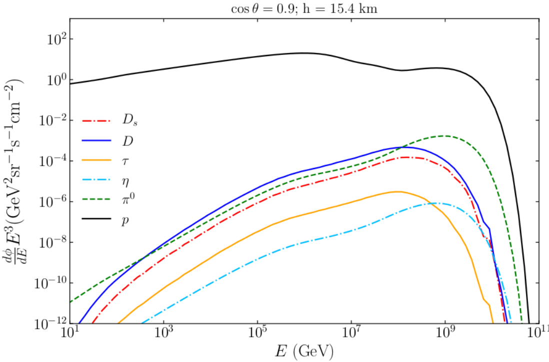
Explain MiniBooNE Excess: Vergani, Kamp, Diaz, Argüelles, Conrad, Shaezitz, Uchida (2105.06470)

Coloma, Machado, IMS, Shoemaker (1707.08573)
Atkinson, Coloma, IMS, Rocco, Shoemaker (2105.09357)

Heavy neutral leptons

HNLs can also be produced in the atmosphere after the Cosmic Ray interaction

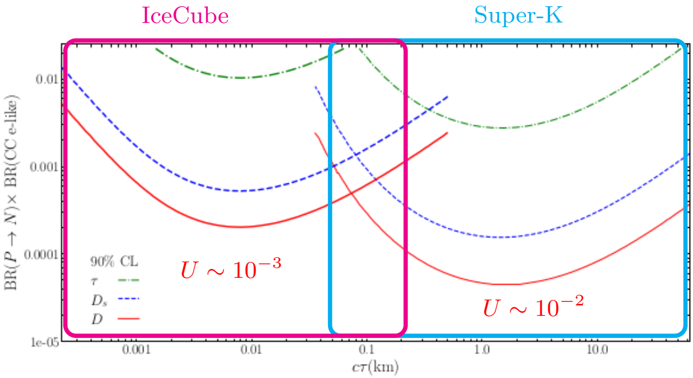
- HNLs can be generated in two three-body decays of mesons
- The main production channels π, K, D and τ



Argüelles, Coloma, Hernández, Muñoz (1910.12839)

Heavy neutral leptons

The detector will search for the decay of HNLs inside the detector.



$m_N = 1\text{GeV}$

Argüelles, Coloma, Hernández, Muñoz (1910.12839)

IceCube

- $E > 100$ GeV
- Cascades contained in IceCube

Super-K

- multi GeV sample
- e-like fully-contained topology

Dark photons

The SM can be extended by an extra U(1) that couples to the visible sector via the kinetic mixing

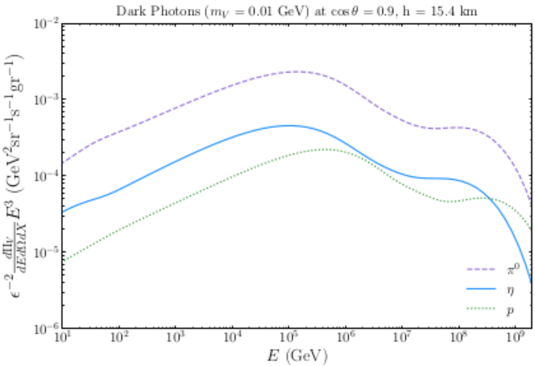
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu} - \frac{1}{2} m_V^2 V_\mu V^\mu$$

- V is called dark photon
- The dark photon couples to all charged particles with a factor ϵ
- m_V is the mass of the dark photon

Dark photons

The Cosmic Ray interaction with the **atmosphere** can also produce **Dark photons**

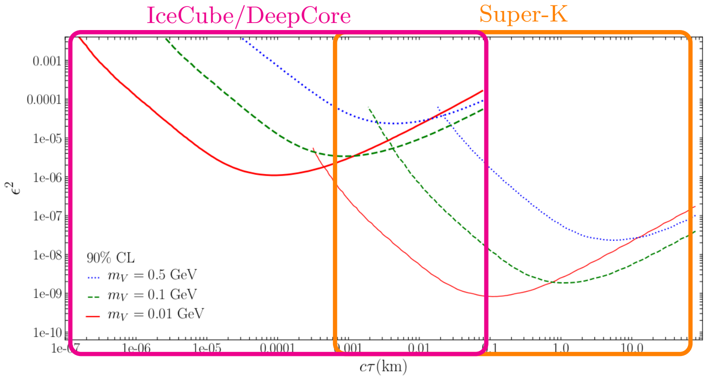
- The production mechanism will depend on the mass of the dark photon
- For $m_V \leq m_\pi$, the main production mechanism is pion decay ($\pi_0 \to \gamma V$)
- For higher masses, other processes can contribute, like bremsstrahlung ($pp \to pp\gamma$)



Argüelles, Coloma, Hernández, Muñoz (1910.12839)

Dark photons

- The steep decrease of the dark photon flux with the energy increase the sensitivity at lower energies
- The main detection mechanism is the decay of V into a electron-pair or hadrons



$\phi_V \sim E^{-3}$

Argüelles, Coloma, Hernández, Muñoz (1910.12839)

Millicharge particles

Together with a U(1) symmetry, SM can also be extended with a dark sector.

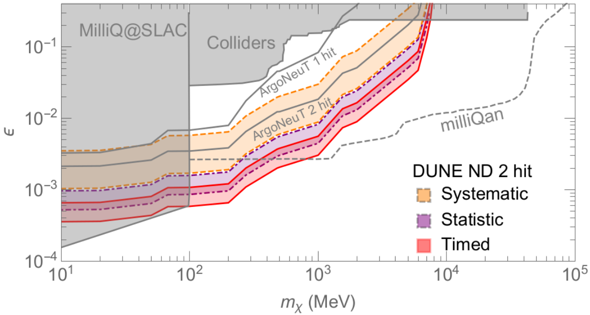
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} + \mathcal{L}_{DS}$$

- In this case, we will consider a massless vector boson
- Any particle in the DS that couples to V_μ will have an electric charge ϵ (mCPs).

Millicharge particles

Several production mechanism can produce mCPs

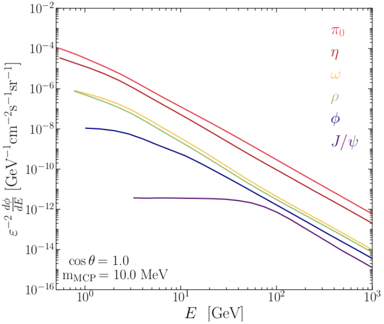
- Meson decays:
  - $\pi^0 \to \gamma\chi\overline{\chi}$
  - $J/\Psi \to \chi\overline{\chi}$
- Drell-Yan
- ...
- Beam dump experiment good experimental candidates.



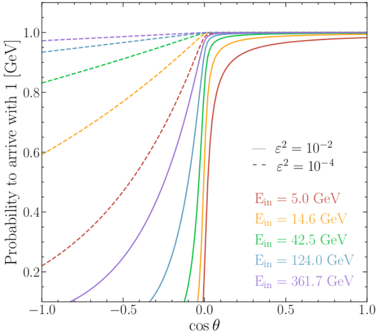
Harnik, Liu and Palamara (1902.03246)

Millicharge particles

mCP can also be produced in the atmosphere in the collision of Cosmic-Rays



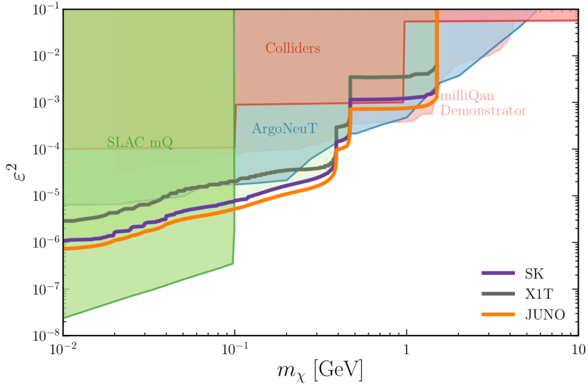
The mCP flux will be absorbed by the interaction with the Earth



Argüelles, kelly and Muñoz (2104.13924)

Millicharge particles

Sensitivity for a single-hit in the detector



Argüelles, kelly and Muñoz (2104.13924)

See also: Plestid, Takhistov, Tsai, Bringmann, Kusenko Pospelo (2002.11732)

Conclusions

- The interaction of Cosmic Rays with the **atmosphere** can be a source of **BSM** physics
- In this talk, we have explored several scenarios: **HNLs, Dark Photons and mCPs**.
- Different signals can be used: **Double-Bangs, Cascades...**
- **Competitive bounds** can be placed by present and future experiments.

Thank you!