Charting New Directions in the BSM Landscape with Neutrino Experiments

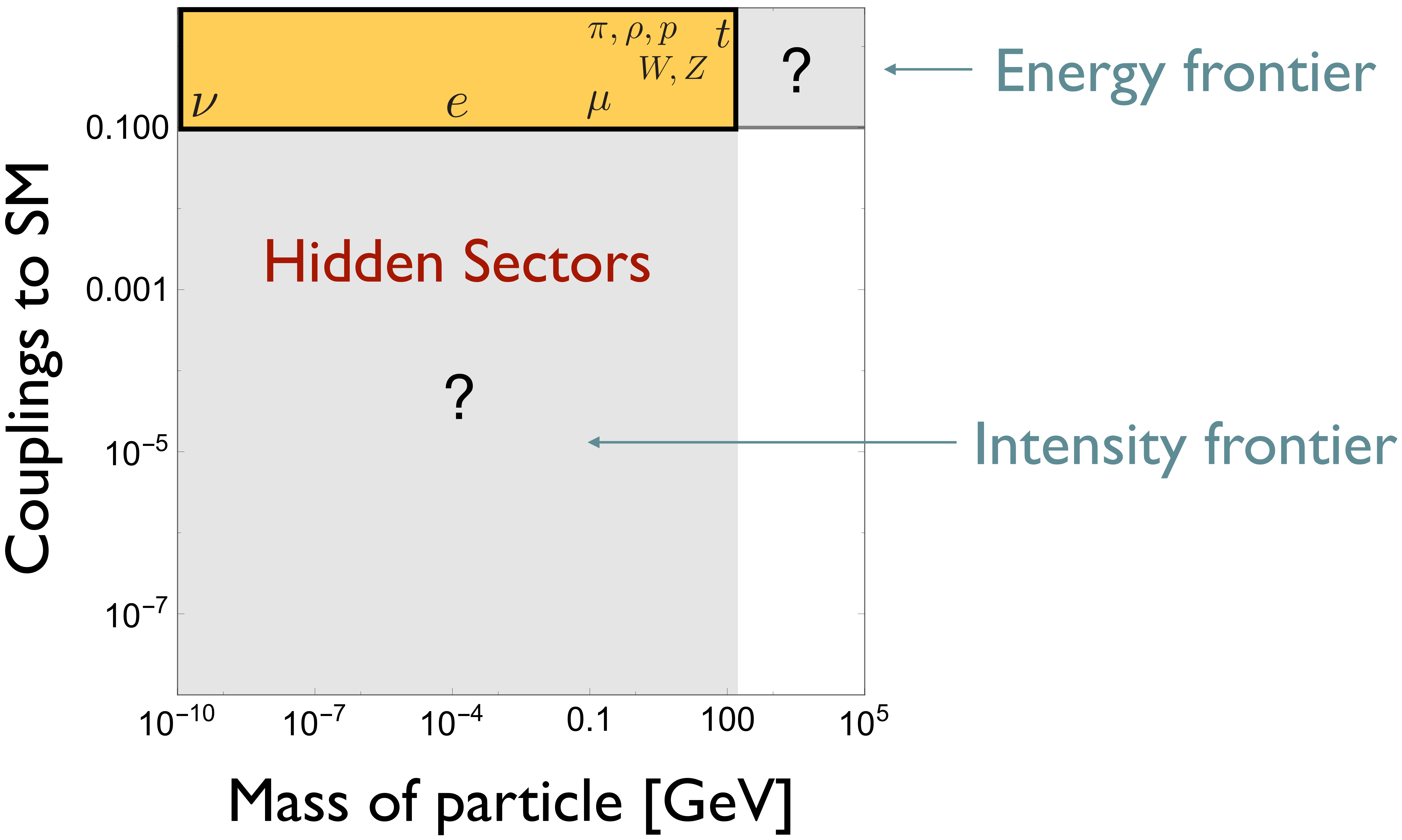
Ian M. Shoemaker

VIRGINIA TECH

NuCo 2021: Neutrinos en Colombia

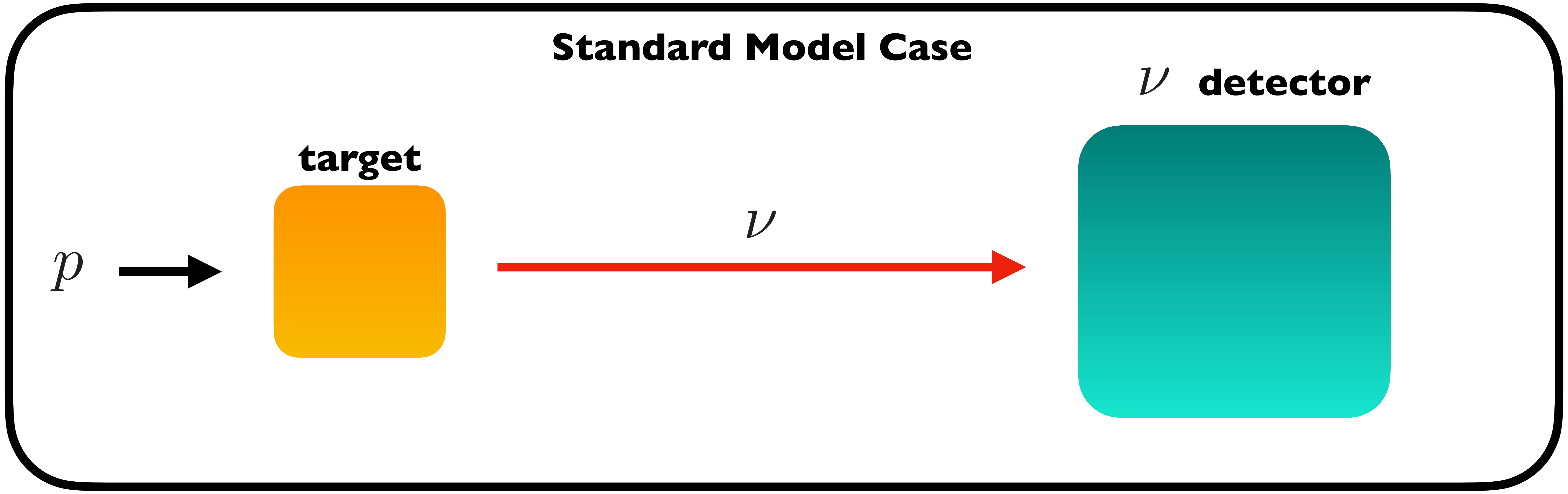
July 28th, 2021

Where is new physics?



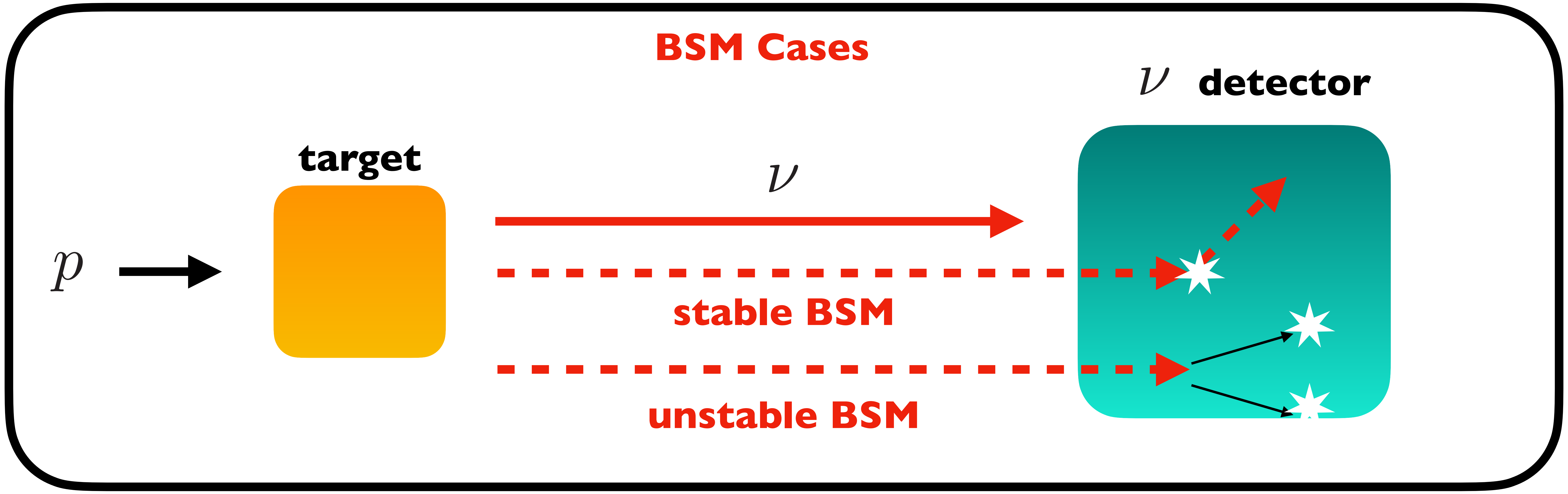
Need a multi-pronged effort to find new physics.

Qualitatively Distinct Classes



1. Proton collisions create unstable mesons.
2. Mesons decay to final states including neutrinos.
3. Neutrinos undergo trivial propagation.
4. Neutrinos interact in detector via “known” SM processes.

Qualitatively Distinct Classes



x 1. Proton collisions create unstable mesons. + new particles
2. Mesons decay to final states including neutrinos.
3. Neutrinos undergo trivial propagation.
4. Neutrinos interact in detector via “known” SM processes.

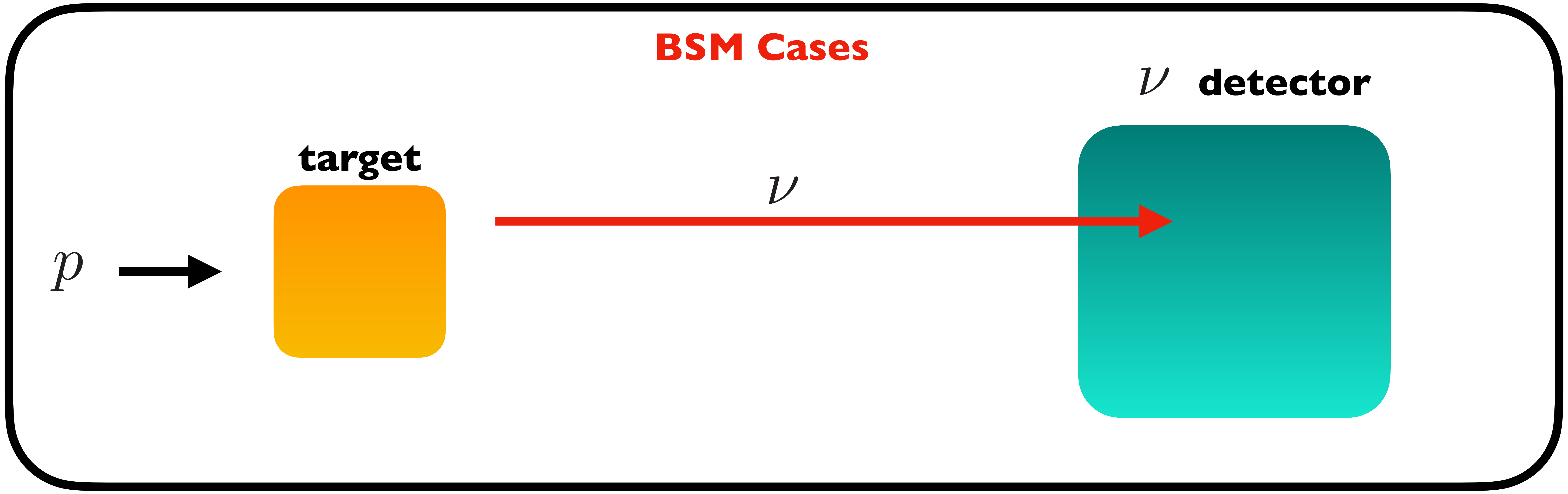
unstable BSM

dark photons,
heavy RH neutrinos, ...

stable BSM

light dark matter,
millicharged particles, ...

Qualitatively Distinct Classes

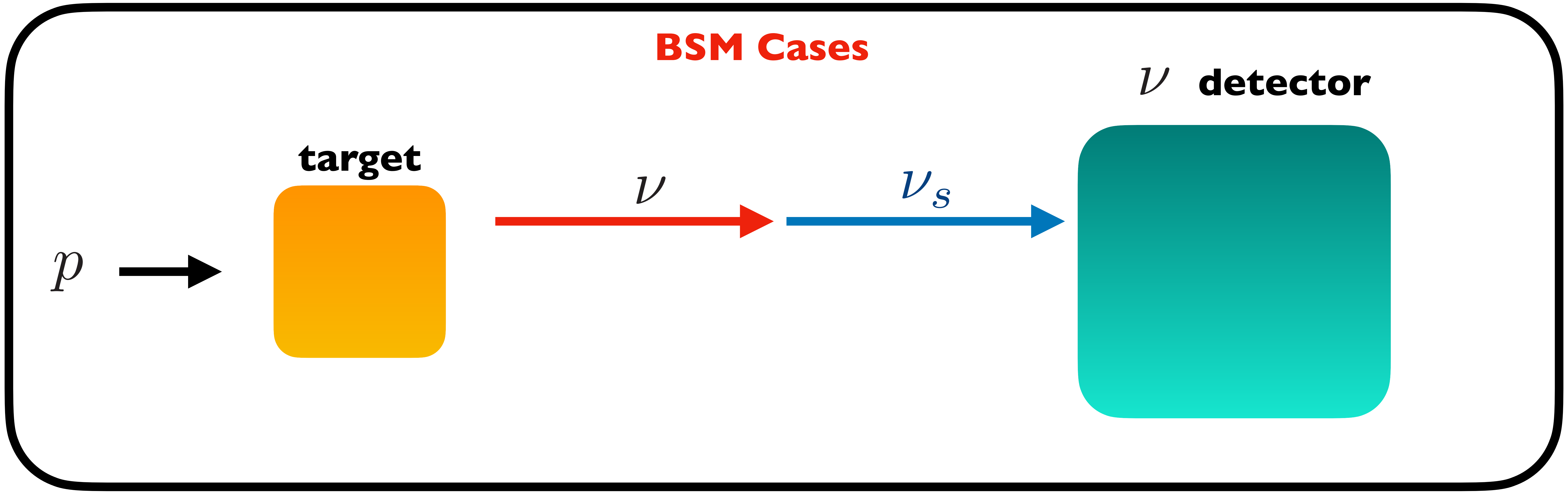


1. Proton collisions create unstable mesons.
2. Mesons decay to final states including neutrinos.
3. Neutrinos undergo trivial propagation.

x 4. Neutrinos interact in detector via “known” SM processes. +BSM scattering

NSI,
dipole portal,
Z′ (tridents) etc..

Qualitatively Distinct Classes



1. Proton collisions create unstable mesons.
2. Mesons decay to final states including neutrinos.
3. x Neutrinos undergo trivial propagation. new states in propagation
4. Neutrinos interact in detector via “known” SM processes.

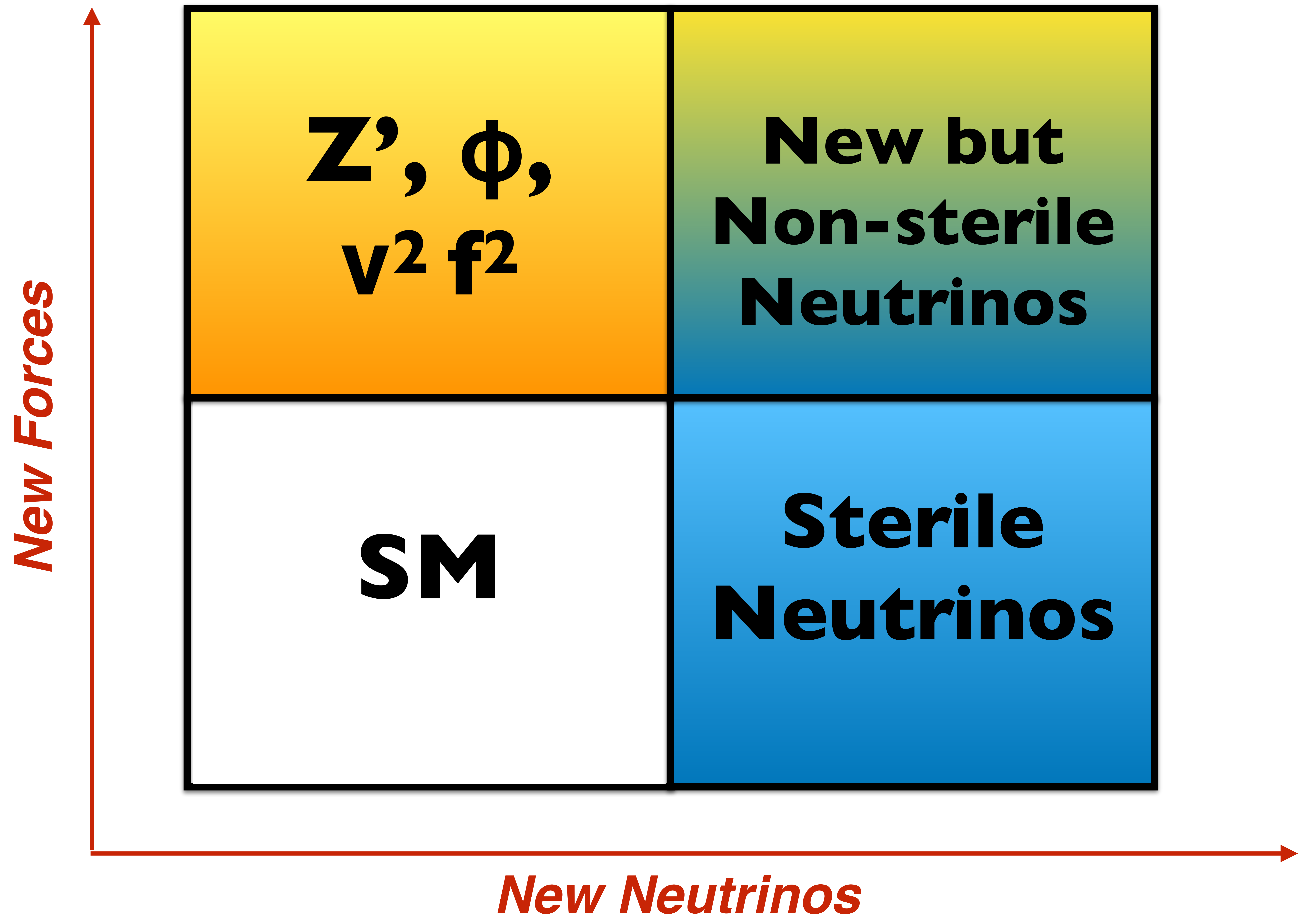
Sterile Neutrinos

Part 1

Neutrino BSM

- -Sterile Neutrinos
- -Heavy Neutral Leptons
- -Non-standard neutrino interactions (NSI)

BSM Space Schema



Sterile Neutrinos

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

SM gauge singlets

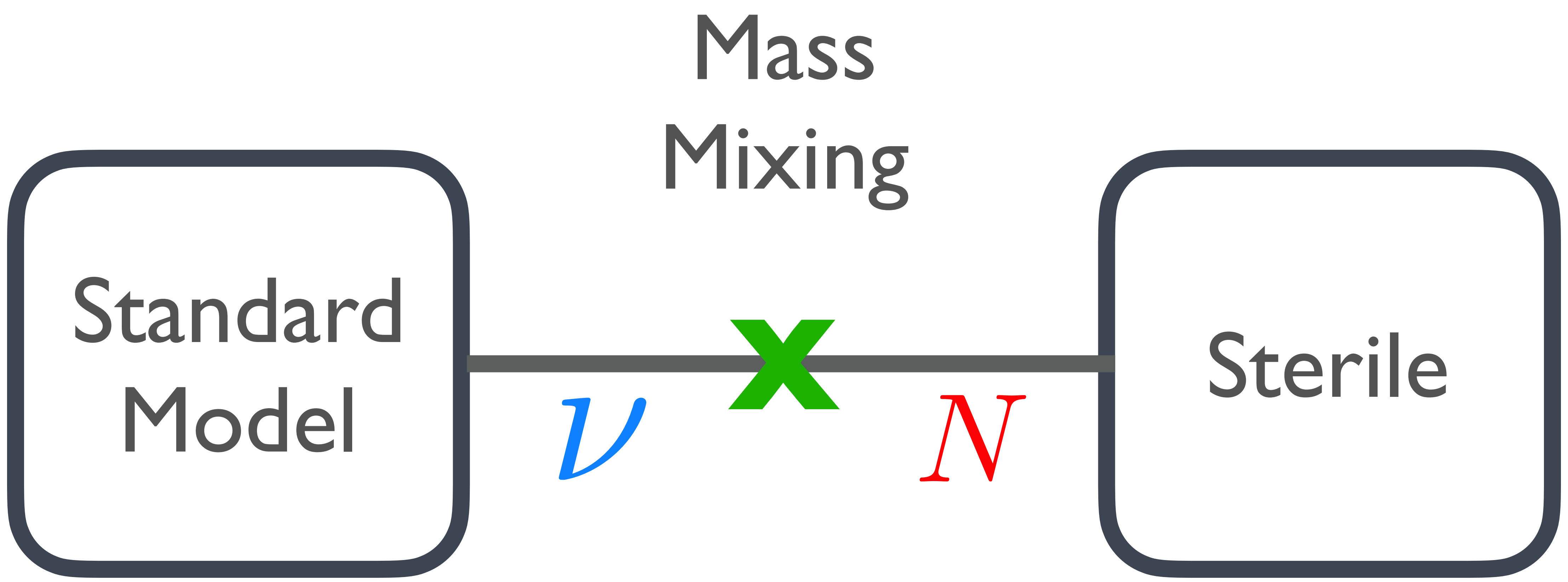
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu\gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

Mass Matrix: $$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

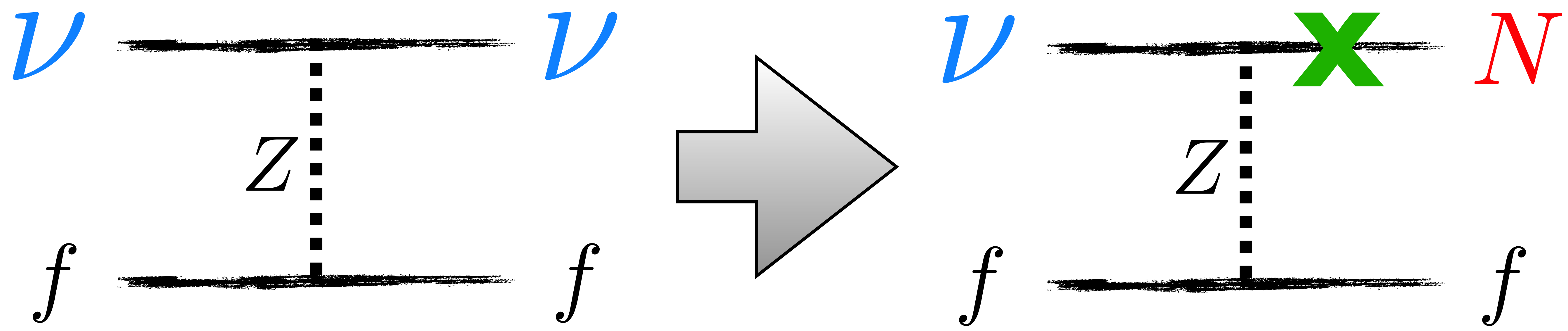
- **Unlike SM fermions, their # is not constrained by anomaly cancellation.**
- **Don't know the number of steriles!**
- **Need at least two of them for atm/sol mass splittings N =2.**
- **If N=3, can accommodate oscillations and DM.**

How can we find them?
1) Modified oscillations
2) Up-scattering production
3) Meson decay production

Inheriting Weak Interaction



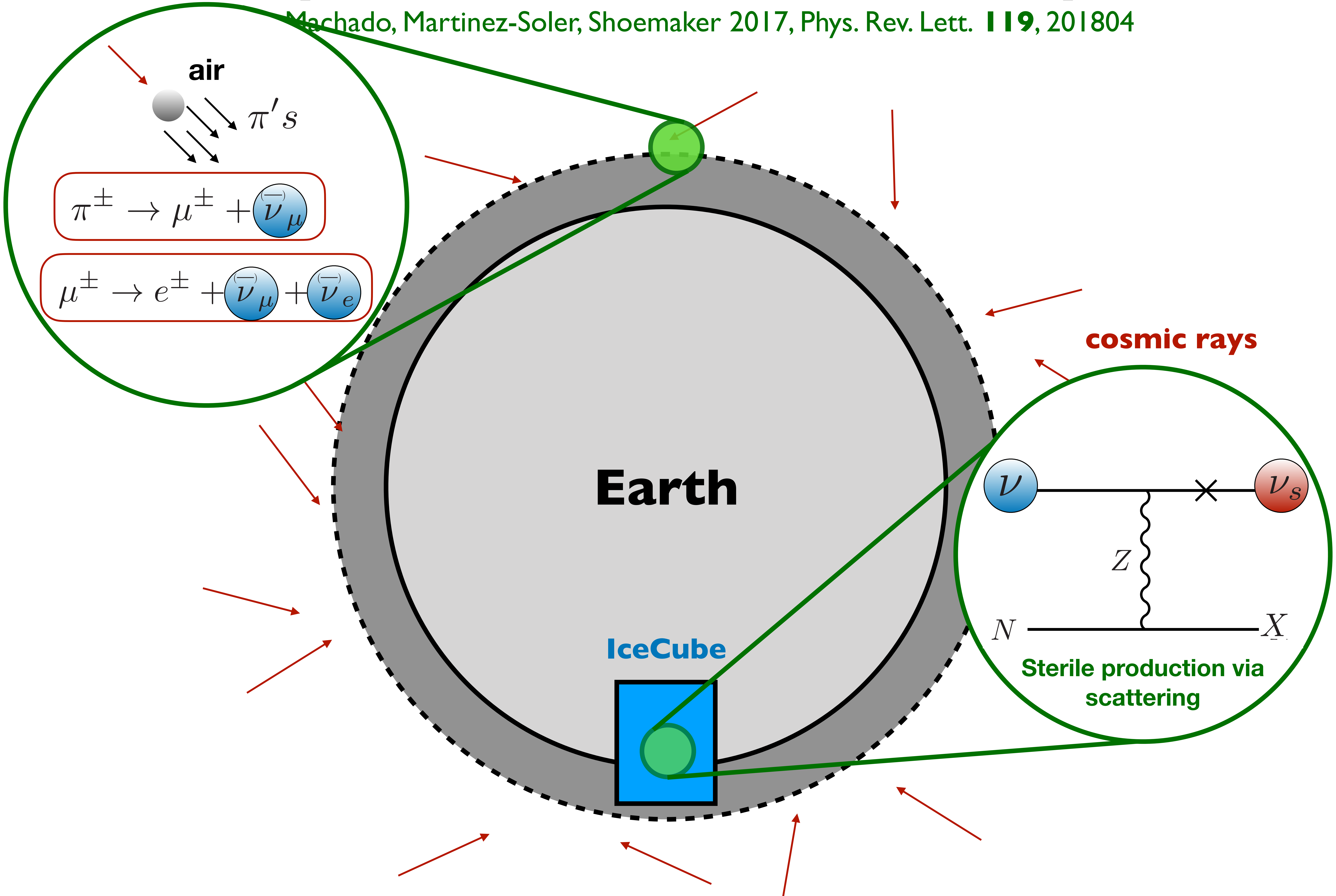
For example:



$$\sigma_{\nu \to N} \sim \theta^2 \sigma_{\mathrm{SM}}$$

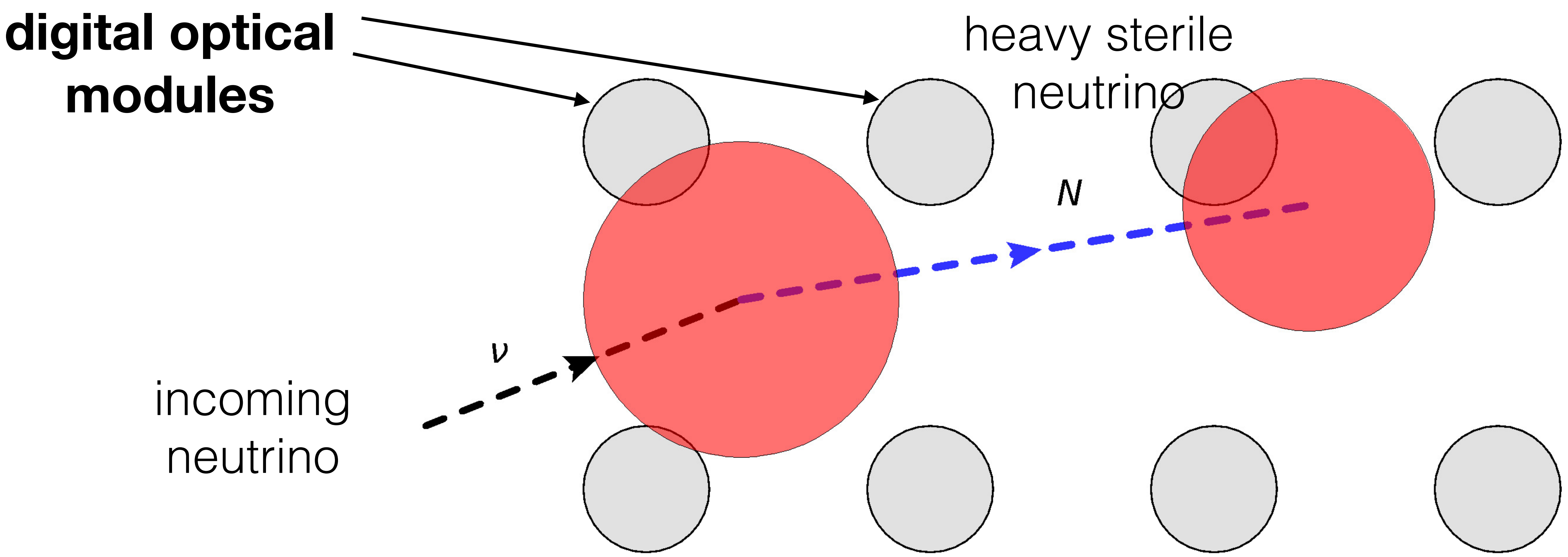
Atmospheric Neutrinos as a BSM probe

Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804



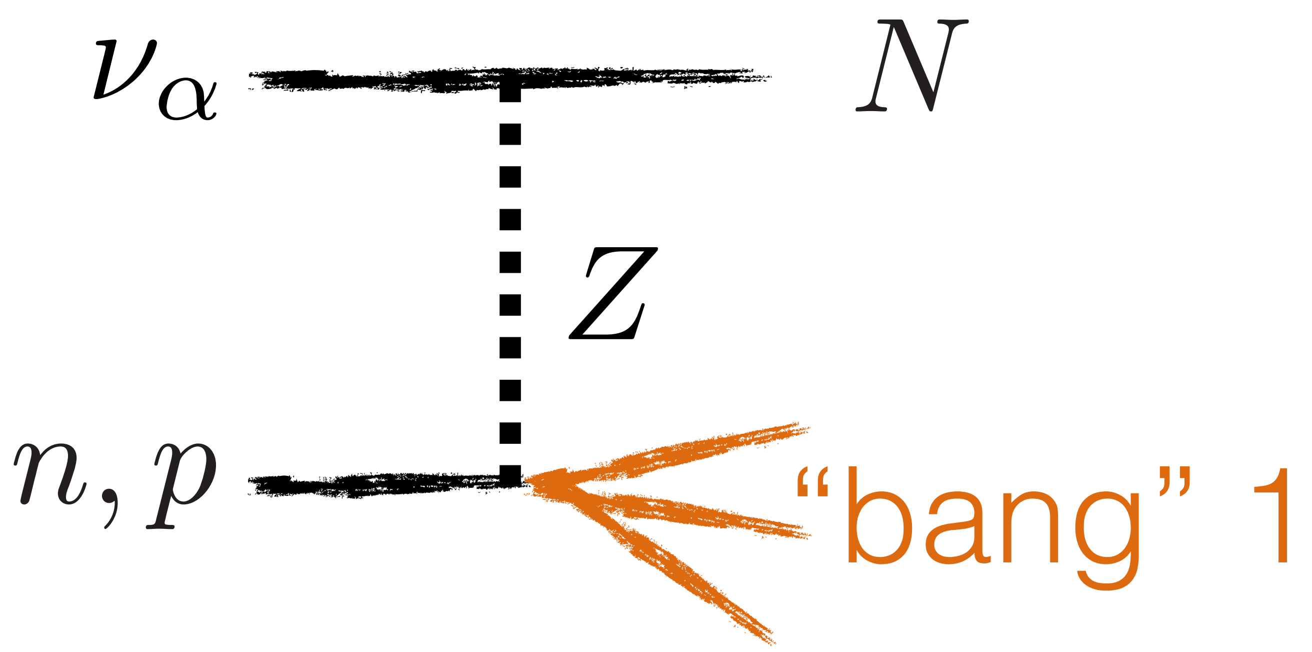
"Double-bangs" from Sterile Neutrinos

Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804



Low background!

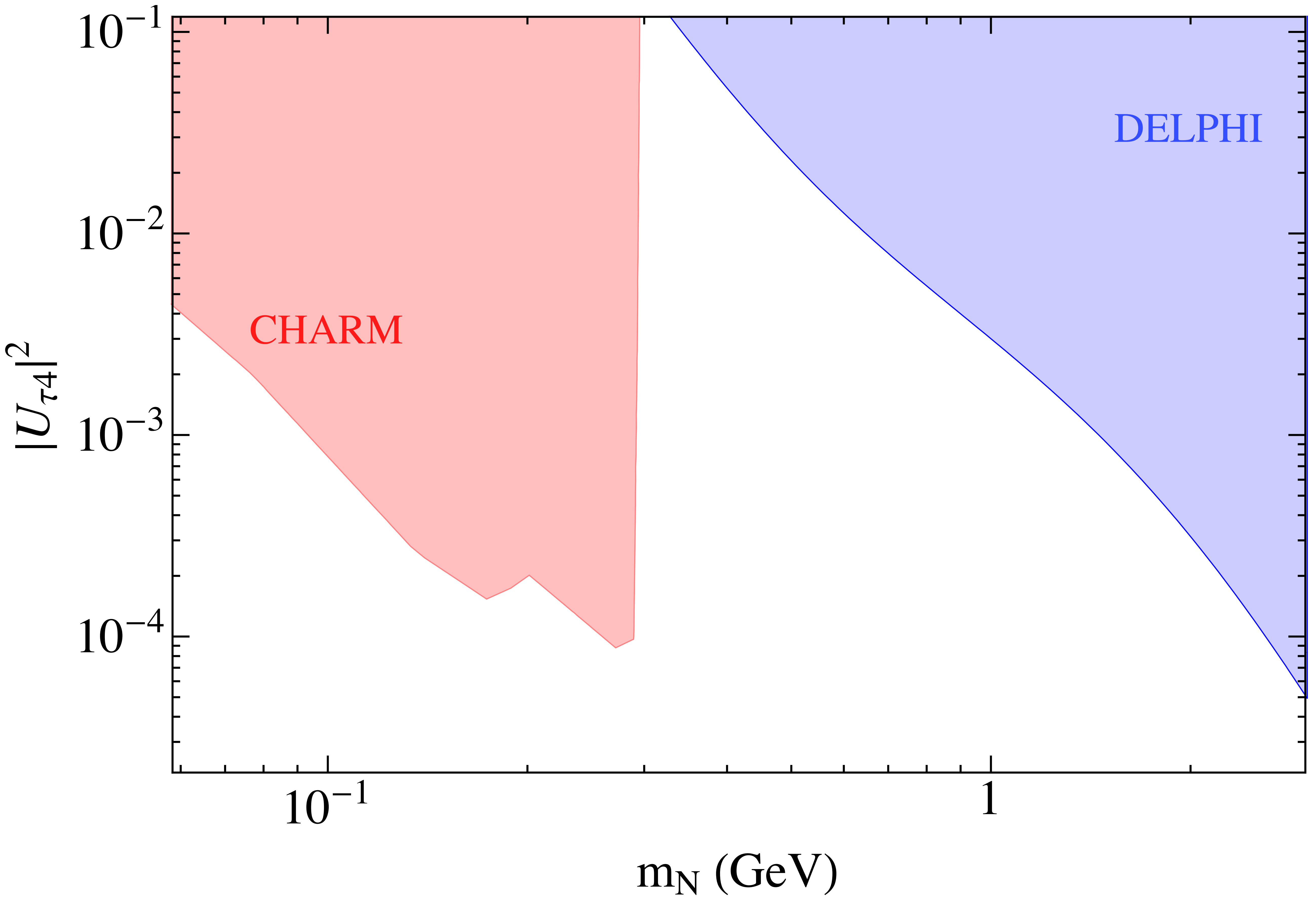
Step 1: produce N



Step 2: N decays

No extra radiation between steps 1 and 2.

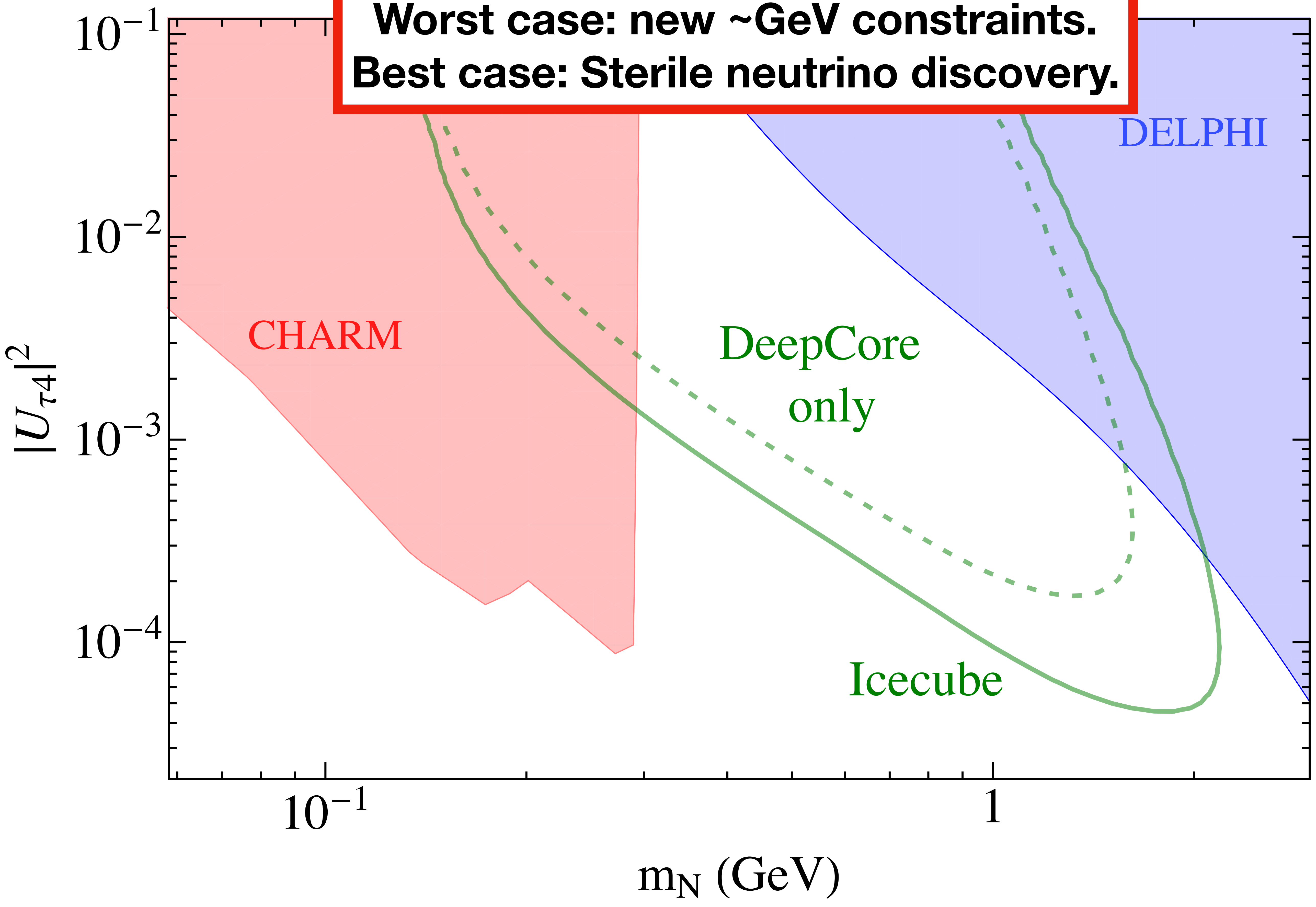
Heavy Neutrinos from the Atmosphere



Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804

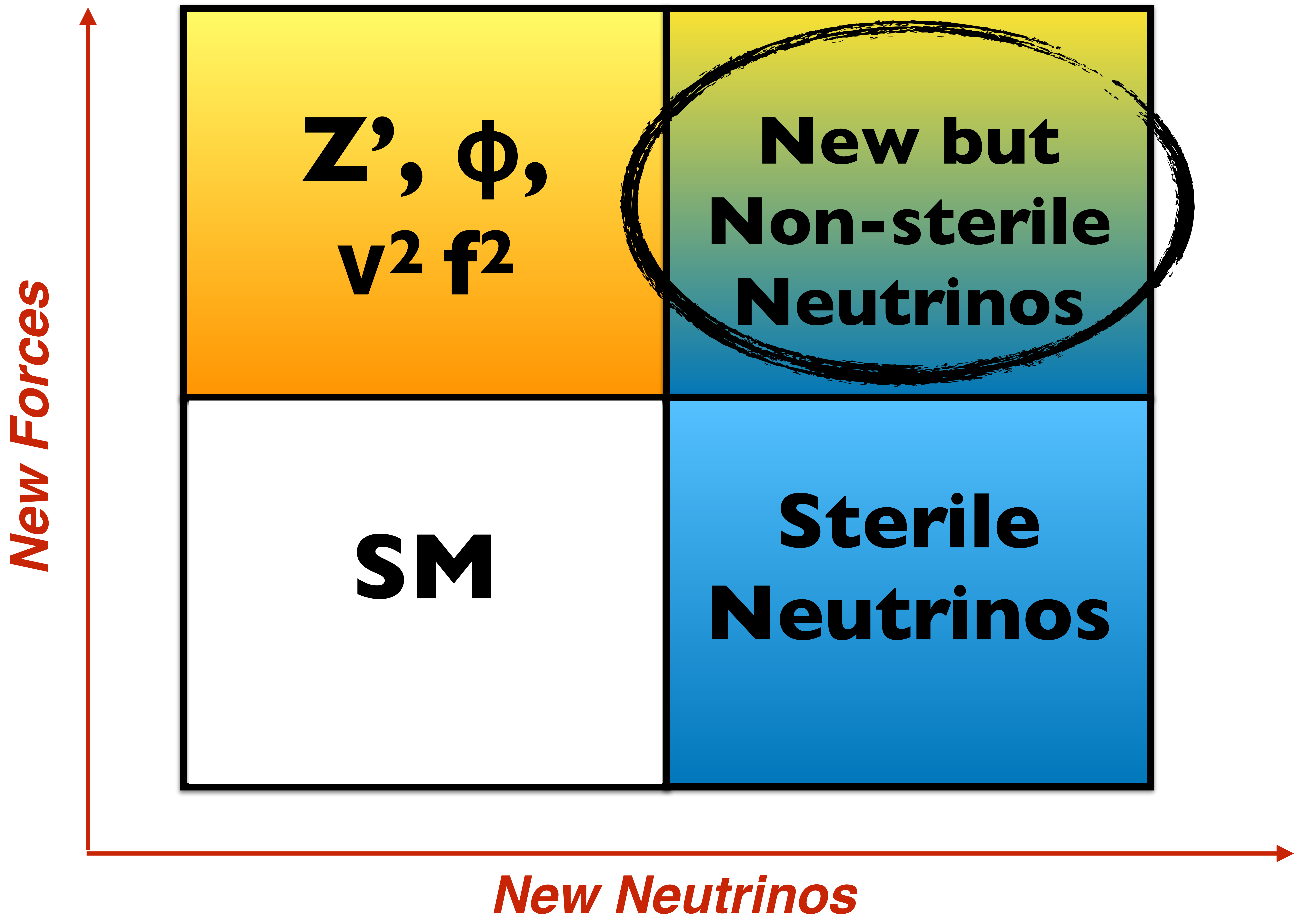
Heavy Neutrinos from the Atmosphere

Assumes only existing data.
Worst case: new ~GeV constraints.
Best case: Sterile neutrino discovery.



Coloma, Machado, Martinez-Soler, Shoemaker 2017, Phys. Rev. Lett. **119**, 201804

BSM Space Schema



Why?

- We like Occam. Nature doesn't always seem to.
- Dark Matter may suggest an entirely new sector of particles/ forces.
- New theory ideas often:
    - Incite new experimental strategies.
    - Interpret existing data in a new way.
    - Novel synergistic complementarity of experiments.

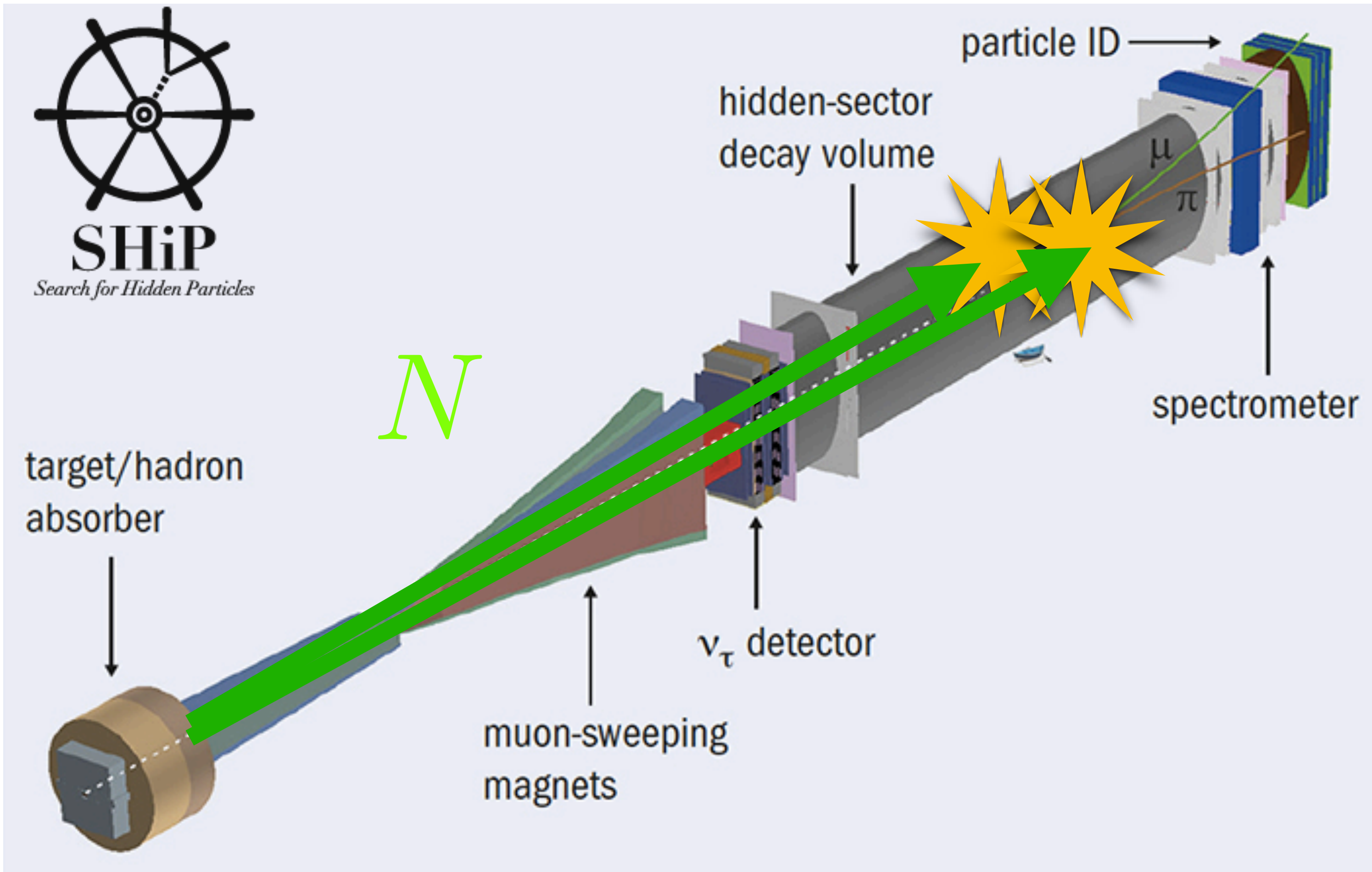
Dipole portal to heavy neutral leptons

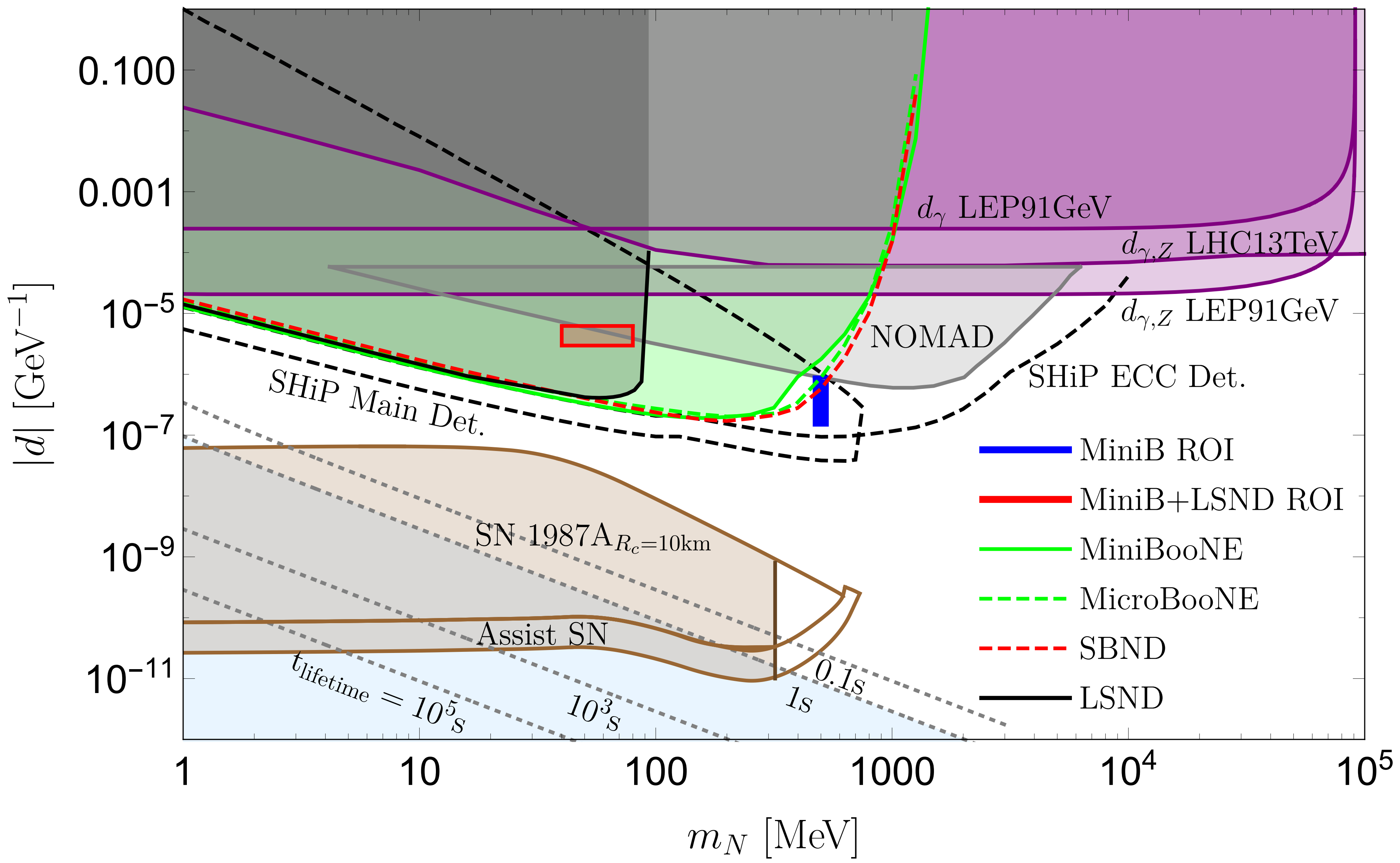
Magill, Plestid, Pospelov, Tsai [1803.03262]

$$\mathcal{L} \supset \bar{N}(i\partial\!\!\!/ - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c).$$

- **Systematically examine production mechanisms: up-scattering, off-shell photon, meson decays.**
- **Astrophysics-terrestrial experiment complementarity.**

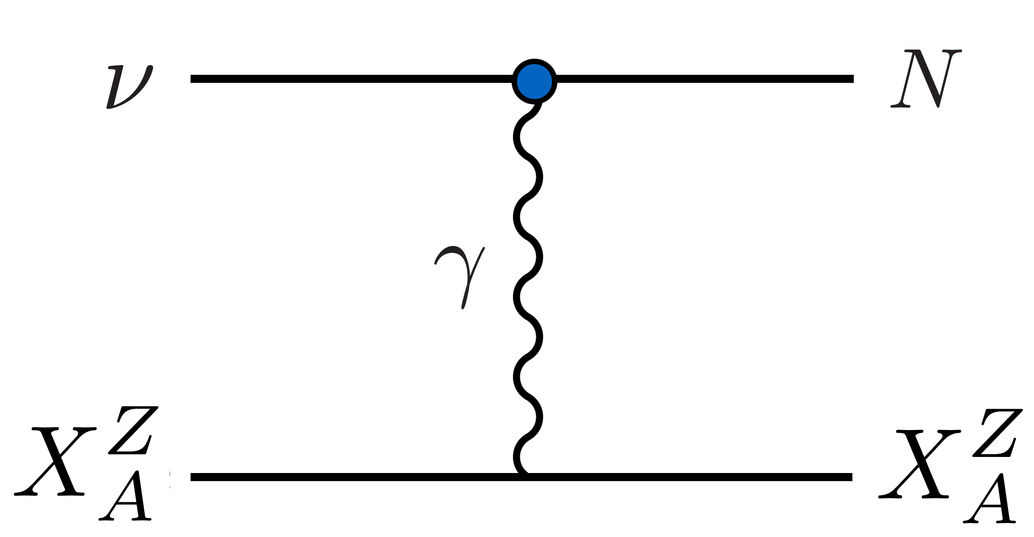
high-intensity SHiP beam dump experiment



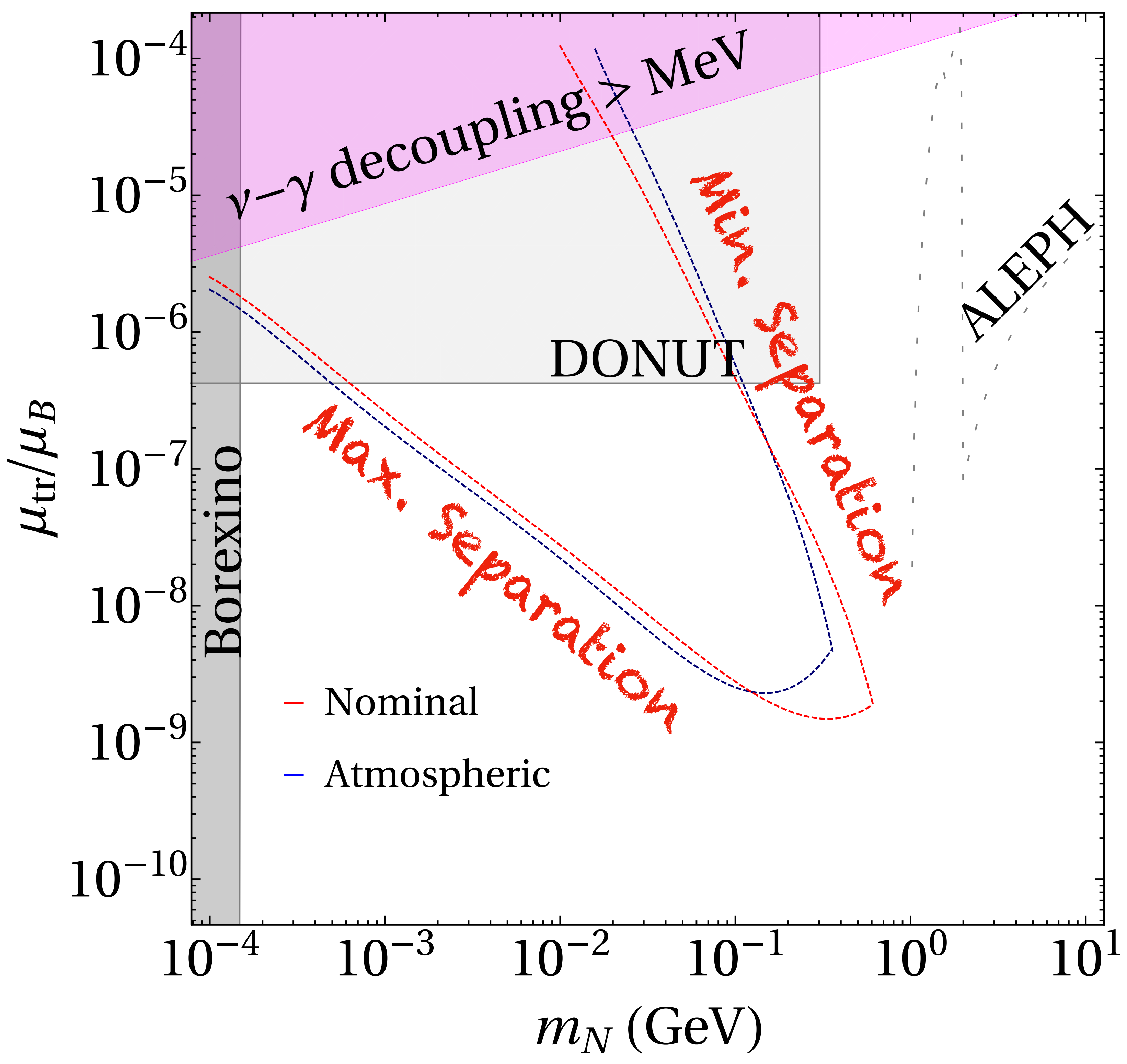


See also: Brdar, Greljo, Kopp, Opferkuch (2020); Plestid (2020), IMS; Tsai, Wyenberg (2020).

DUNE and Transition Dipole Moments

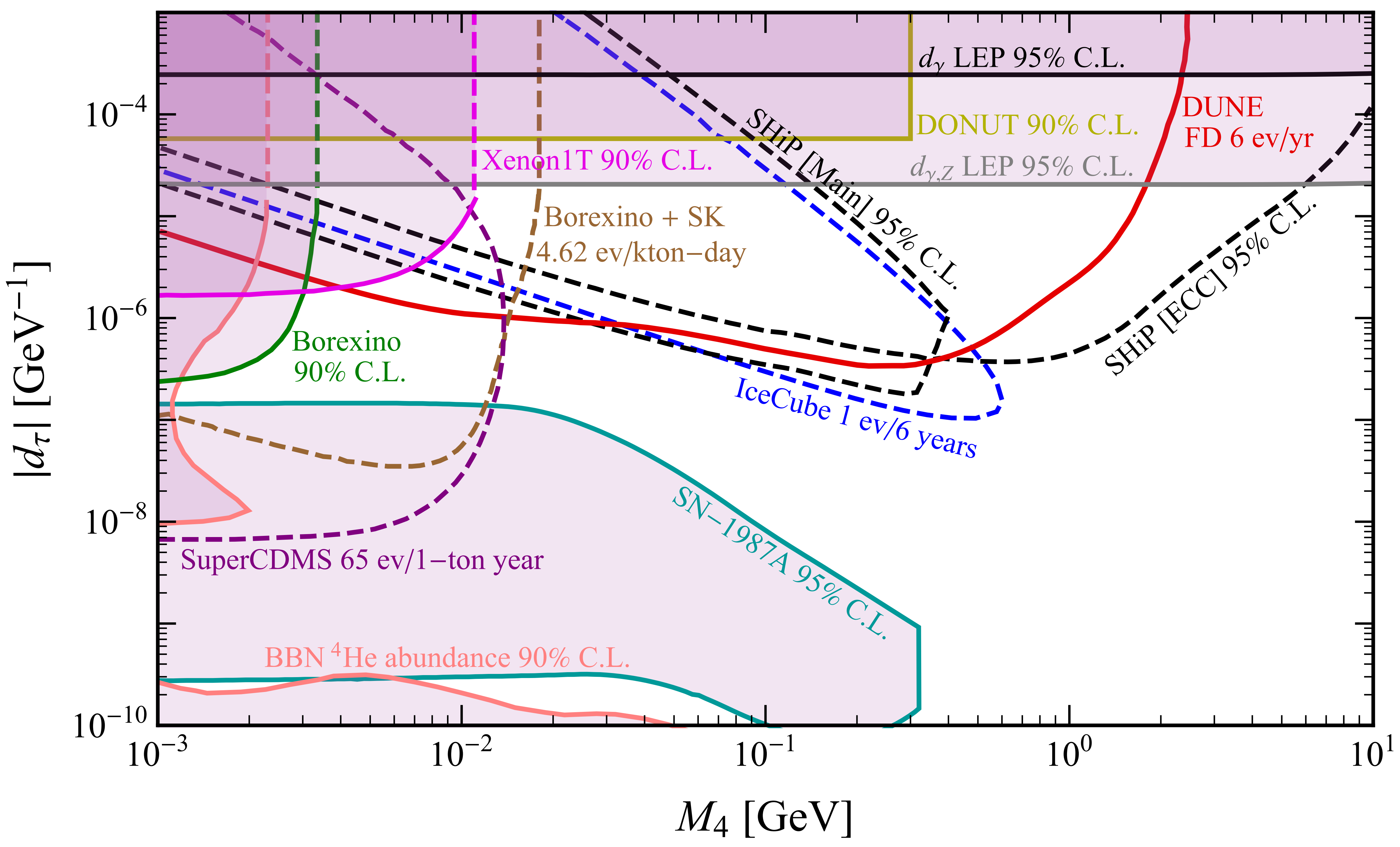


Double-bangs @ DUNE



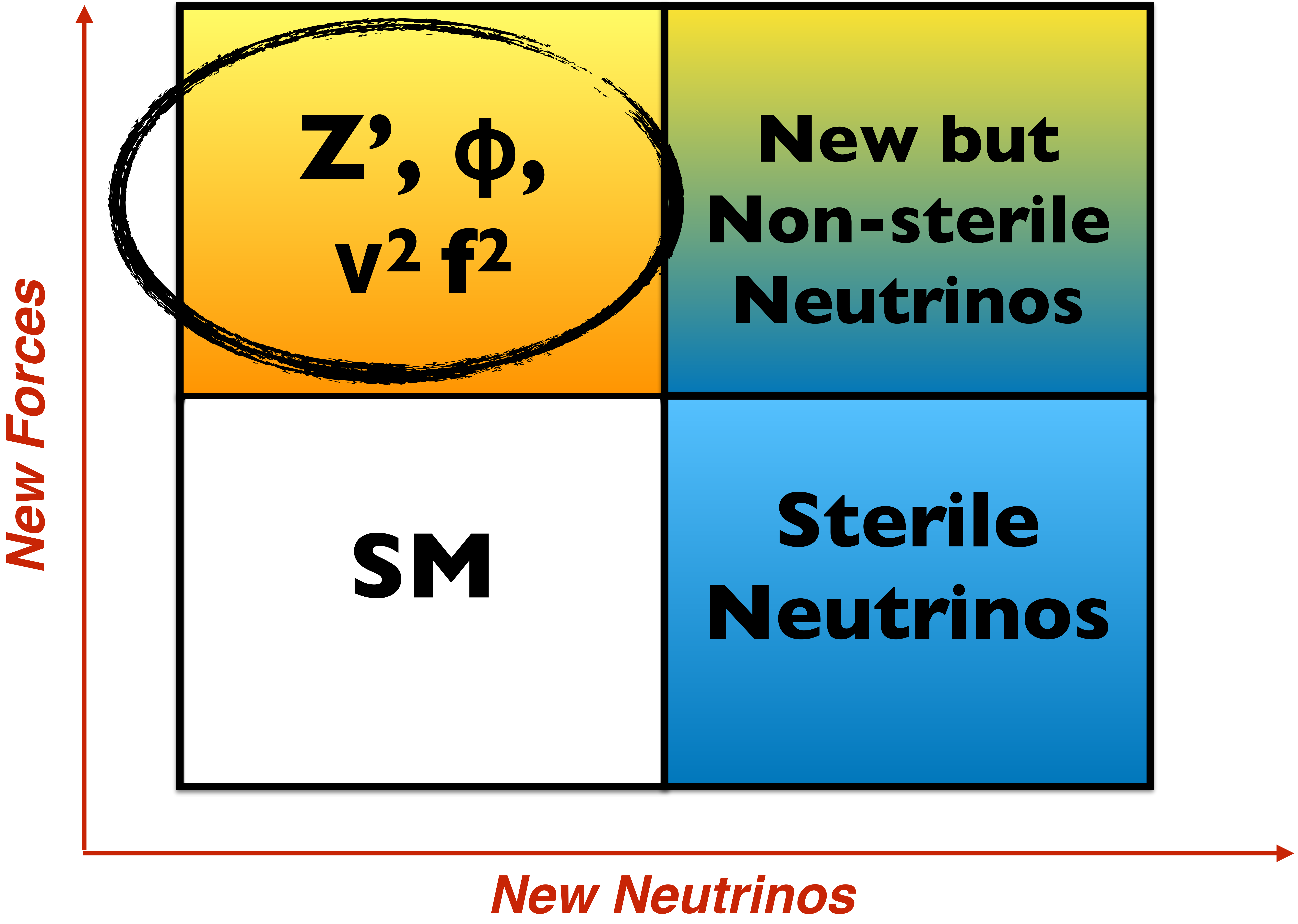
Mack, Coloma, Martinez-Soler, Rocco, IMS [2105.09357]

Mono-photon signals @ DUNE



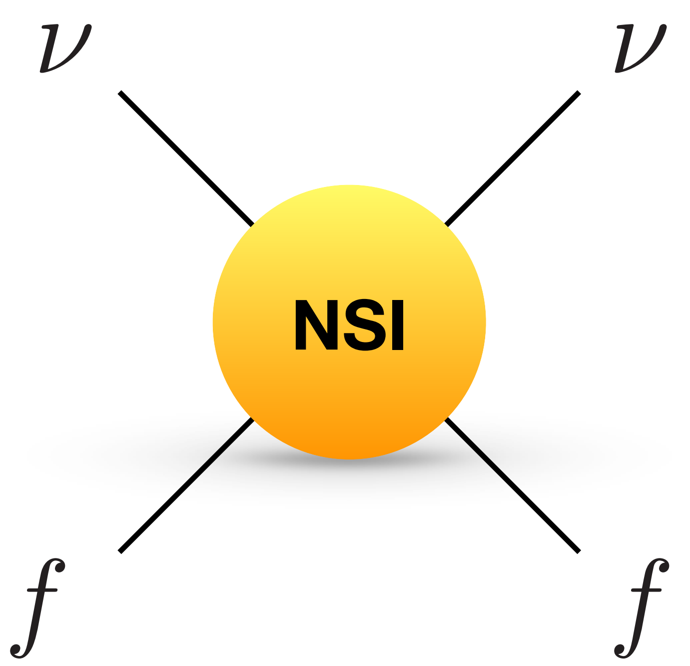
Schwetz, Zhou, Zhu [2105.09699]

BSM Space Schema



NSI Phenomenology

[*Review*: Farzan, Tortola 1710.09360]



- **Oscillation Data**: solar, atmospheric, astrophysical.

  [Guzzo, et al. (2001)], [Fornengo, et al. (2001)], [Friedland, Lunardini, Maltoni (2004)], [Friedland, Lunardini, Pena-Garay (2004)], [Guzzo, de Holanda, Peres (2004)], [Miranda, Tortola, Valle (2004)], [Mena, Mocioiu, Razzaque (2007)], [Friedland, IMS (2012)], [Mocioiu, Wright (2014)], [Coloma (2015)], Coloma, Gonzalez-Garcia, Maltoni (2020)], …

- **Scattering Data**: NuTeV, CHARM, COHERENT.

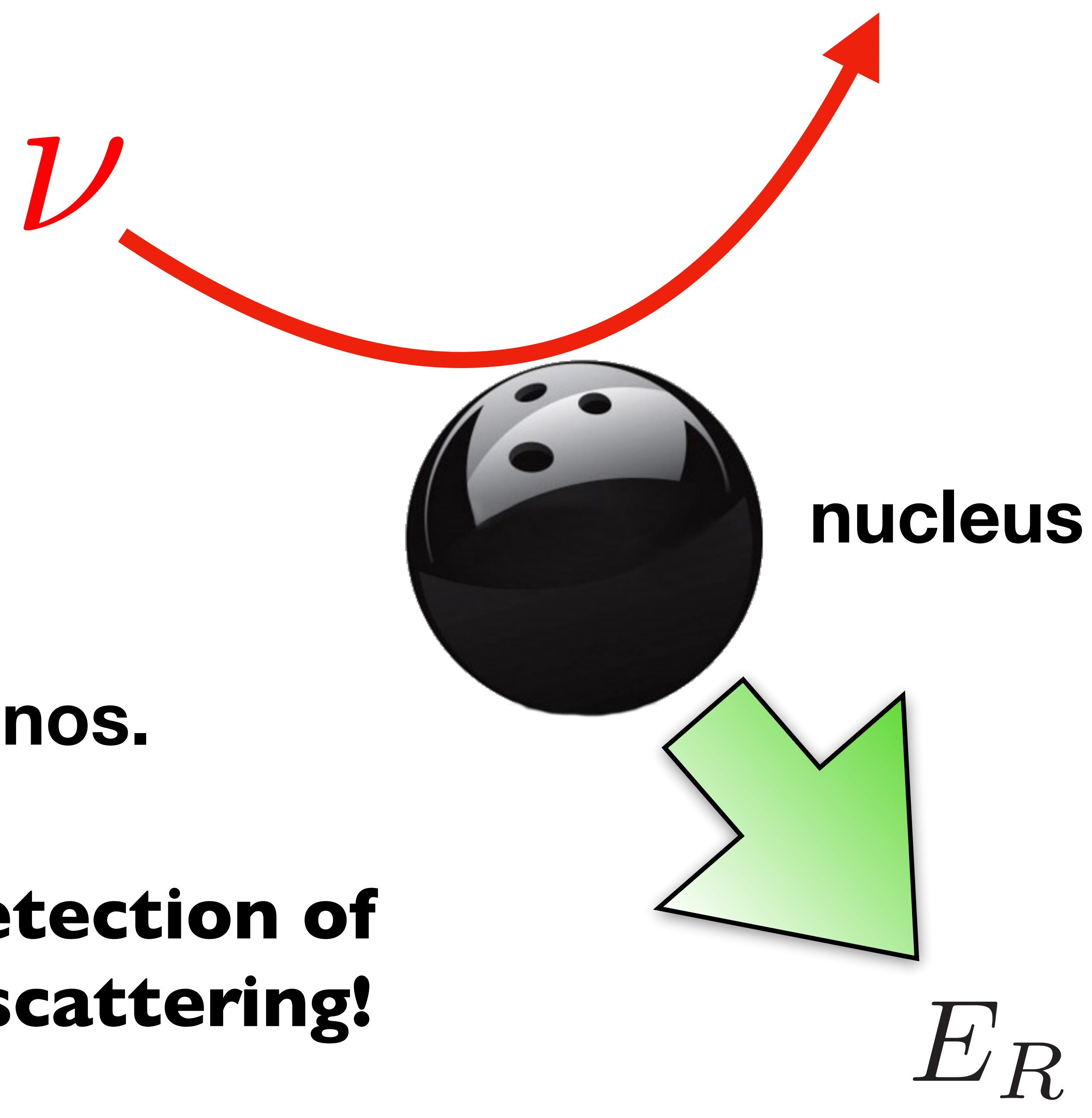
  [Davidson et al. (2003)], [Coloma et al. (2017)], [Liao, Marfatia (2017)], [Dutta, Liao, Strigari, Walker (2017)], [Dent, Dutta, Liao, Newstead, Stirgari, Walker (2017)], [Denton, Farzan, IMS (2018)], Coloma, Esteban, Gonzalez-Garcia, Maltoni (2019)], …

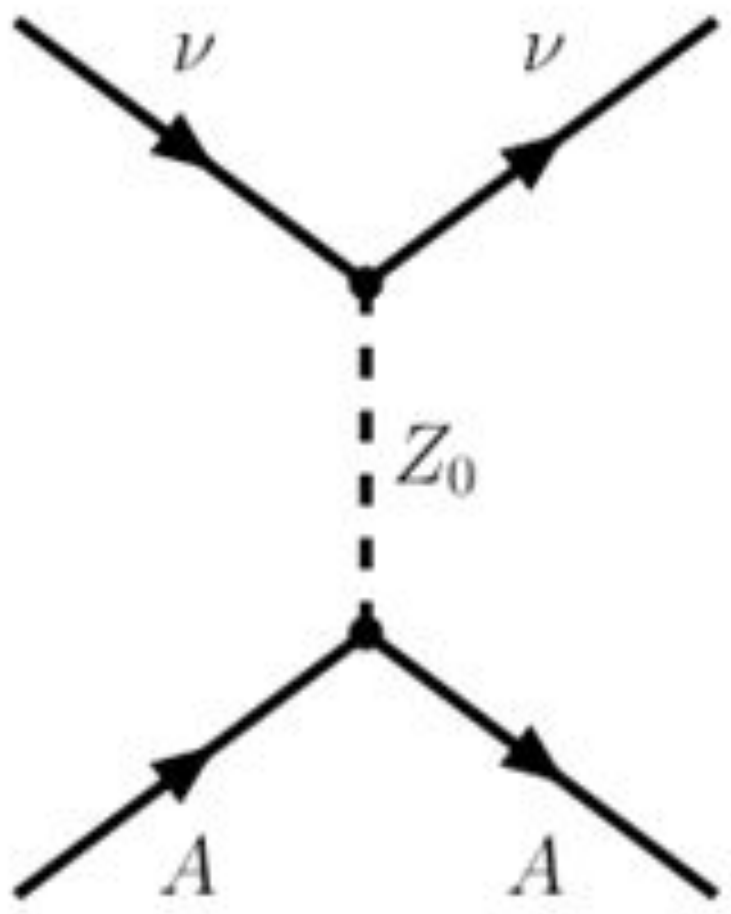
- **Collider Data**: LEP, Tevatron, LHC.

  [Berezhiani, Rossi (2001)], [Friedland, Graesser, IMS, Vecchi (2011)], …

(very incomplete list) → See B. Dev et al. "Neutrino Non-Standard Interactions: A Status Report" 2019

COHERENT Strategies for New Physics

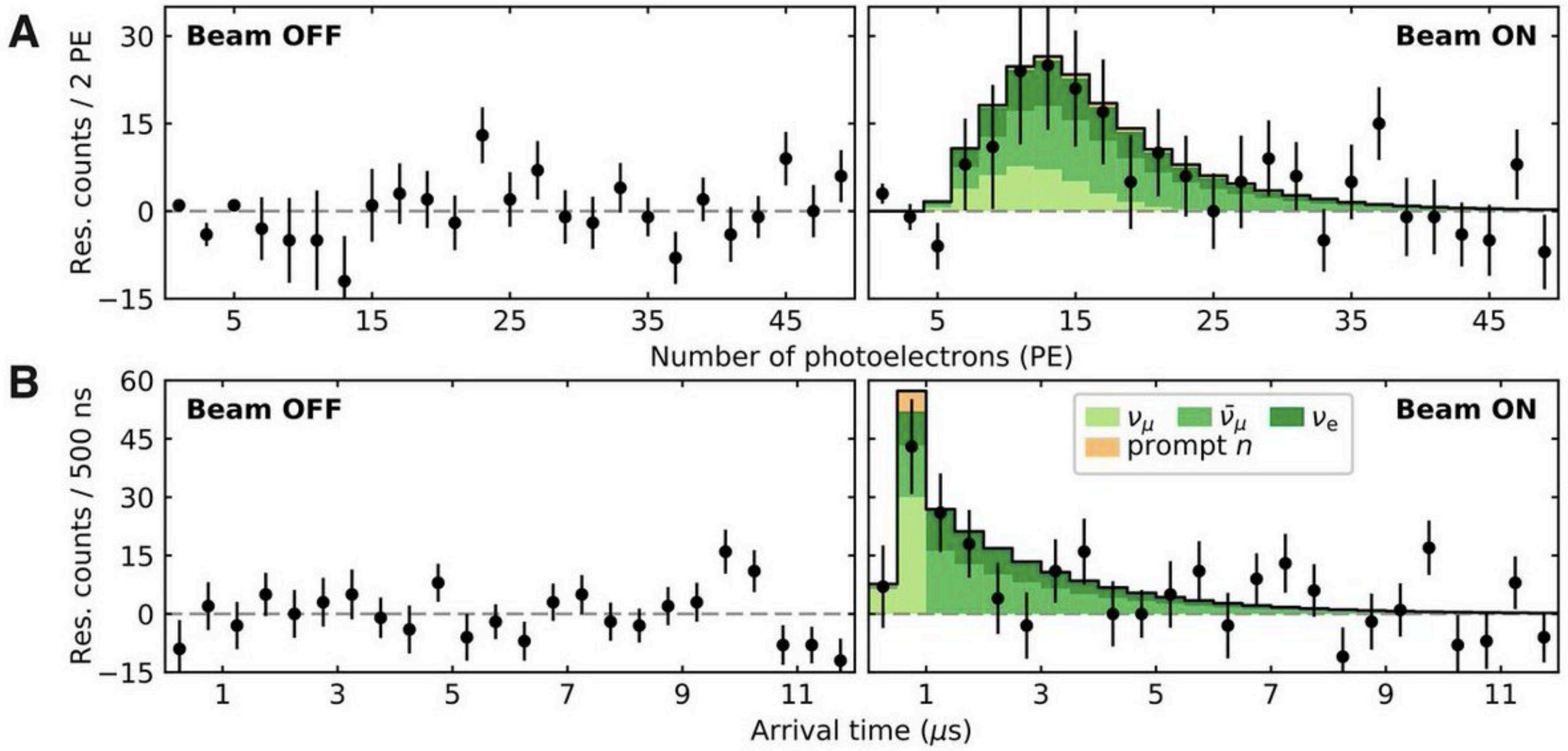




Stopped pion source = low-E neutrinos.

COHERENT Collaboration: First detection of coherent elastic neutrino-nucleus scattering!

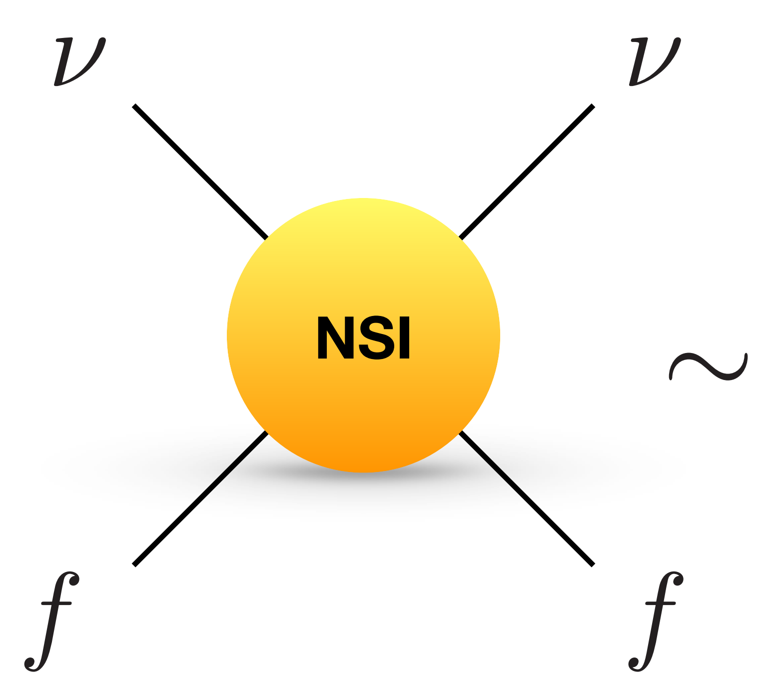
COHERENT Collaboration, 2017 [1708.01294].



See: IMS [1703.05774]

Can test BSM contributions to neutrino scattering.

Oscillation - Scattering Complementarity



$\sim \varepsilon\, G_F$

- Oscillation data allow for large NSI in the "LMA-dark" window.

<u>standard LMA</u>

$$\theta_{12} \simeq 34^\circ$$

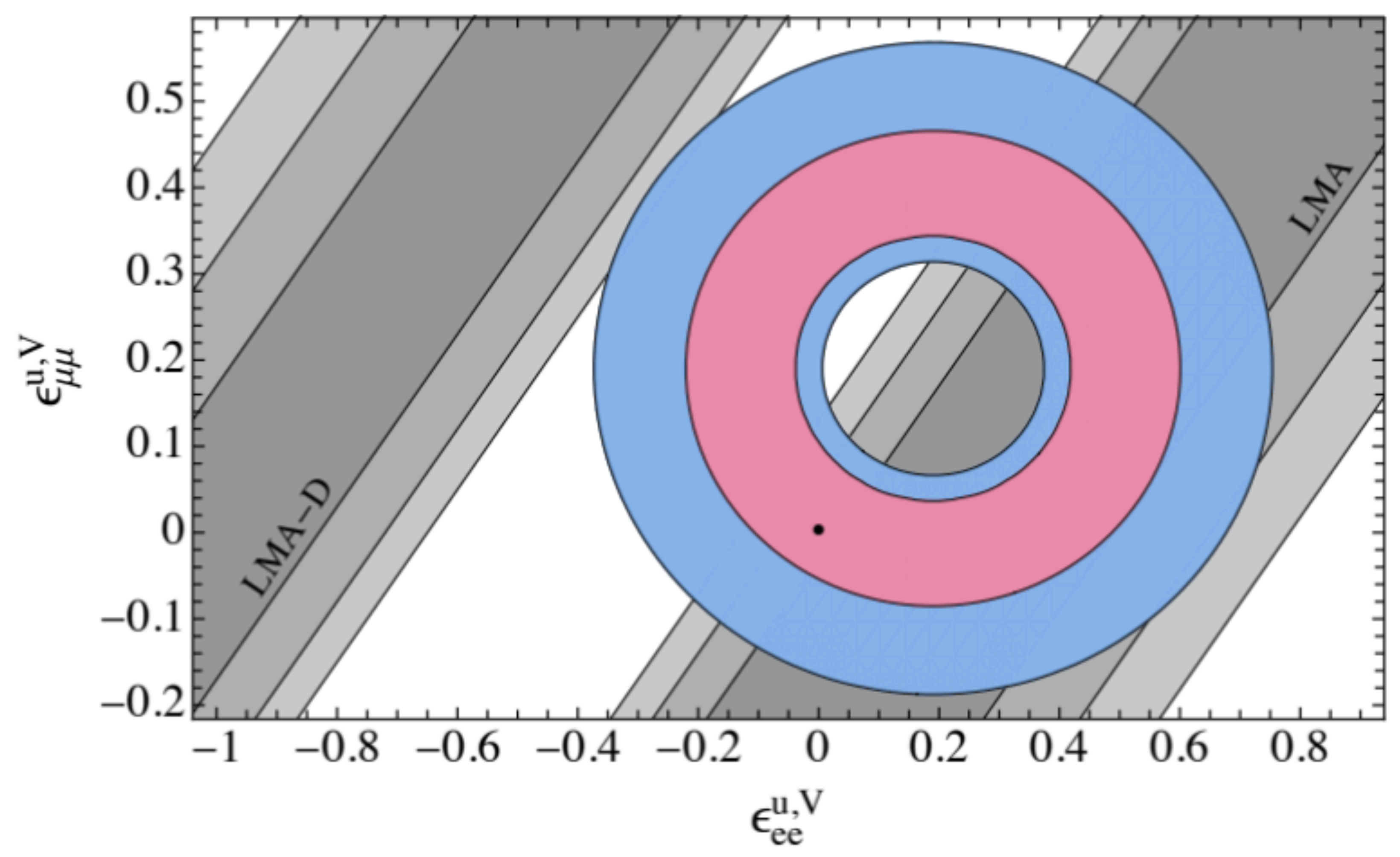
<u>LMA-dark</u>

$$45^\circ < \theta_{12} < 90^\circ$$

$$+ \;\; \varepsilon \sim \mathcal{O}(1)$$

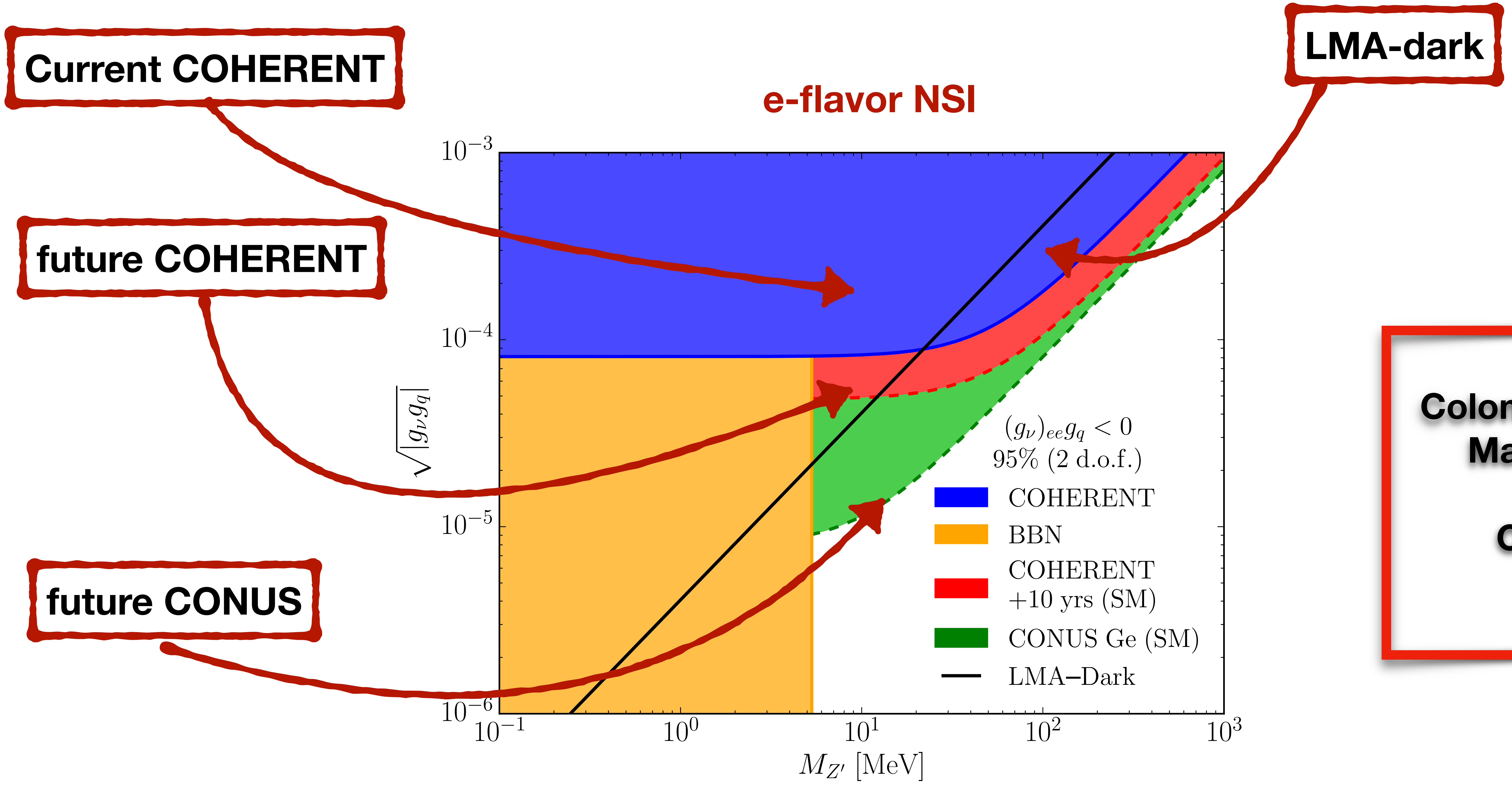
COHERENT breaks degeneracy, rules out LMA-D.

Coloma, Gonzalez-Garcia, Maltoni, Schwetz [1708.02899]



NSI @ low-masses

Denton, Farzan, IMS [1804.03660]



See Also:
Coloma, Gonzalez-Garcia, Maltoni [2009.14220]
&
Chaves, Schwetz [2102.11981]

- **COHERENT + CMB data allow for a small window of masses with large NSI.**
    - **Future COHERENT data and reactor experiments (CONUS) will cover the gap.**

Part 2

Non-Neutrino BSM
@ Neutrino Experiments

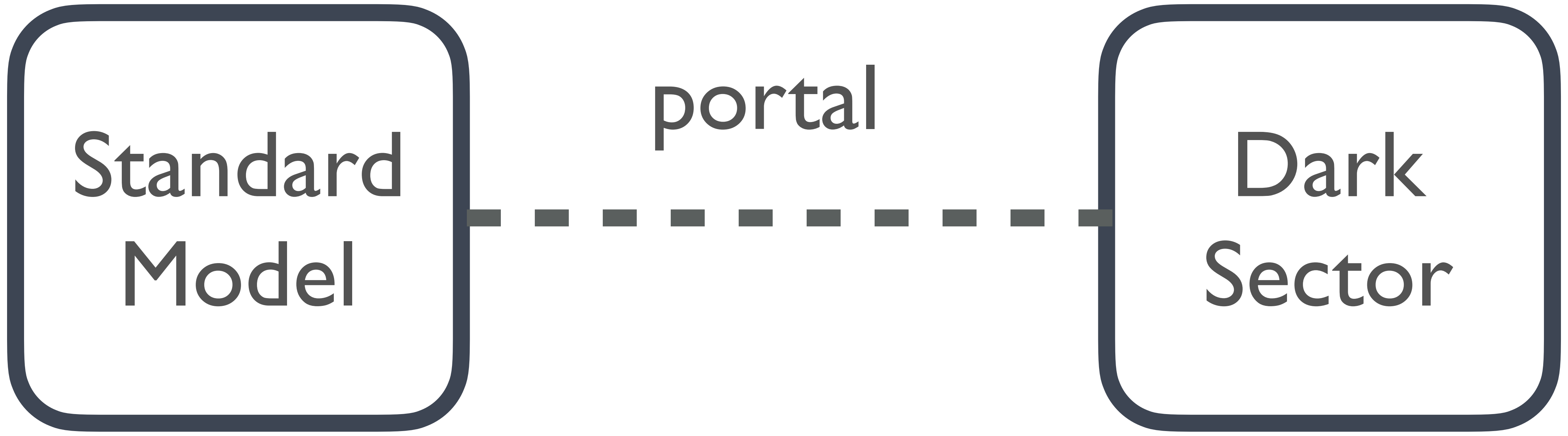
(Happy accidents!)

-Light Dark Matter
-Axion-like particles
-New Force carriers

Secluded DM

Dark (Hidden) ((Secluded)) Sector Models

[Batell, Pospelov, Ritz (2009)]

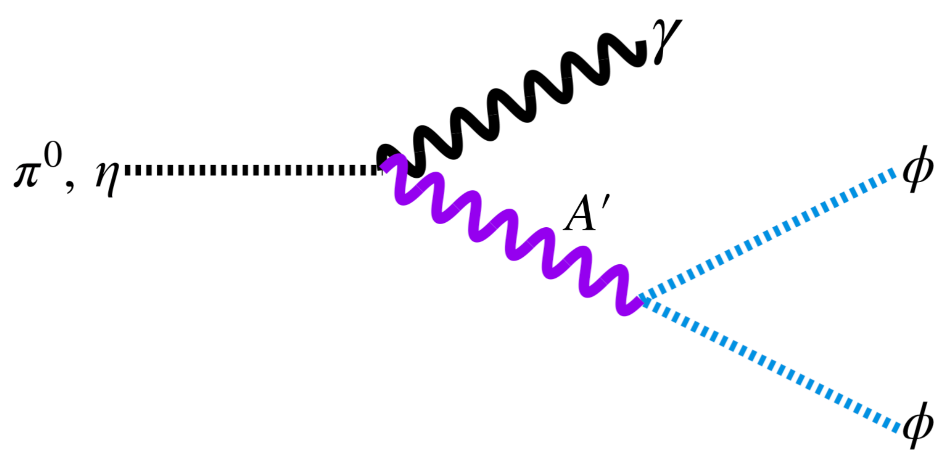


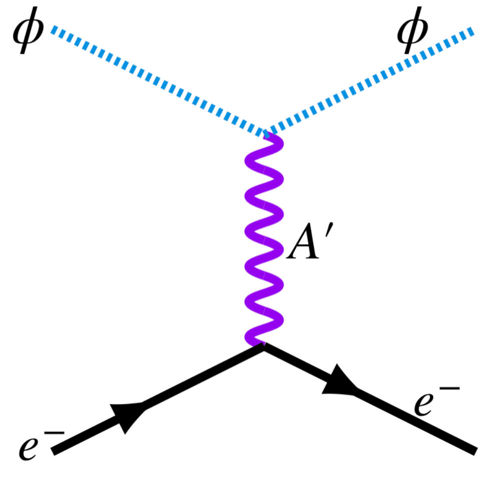
$$\mathscr{L}_{\rm portal} = \begin{cases} \epsilon F_{\mu\nu} F_h'^{\mu\nu} & \text{(photon portal)} \\ h|H^2||H_h^2| & \text{(Higgs portal)} \\ y(LH)N & \text{(neutrino portal),} \end{cases}$$

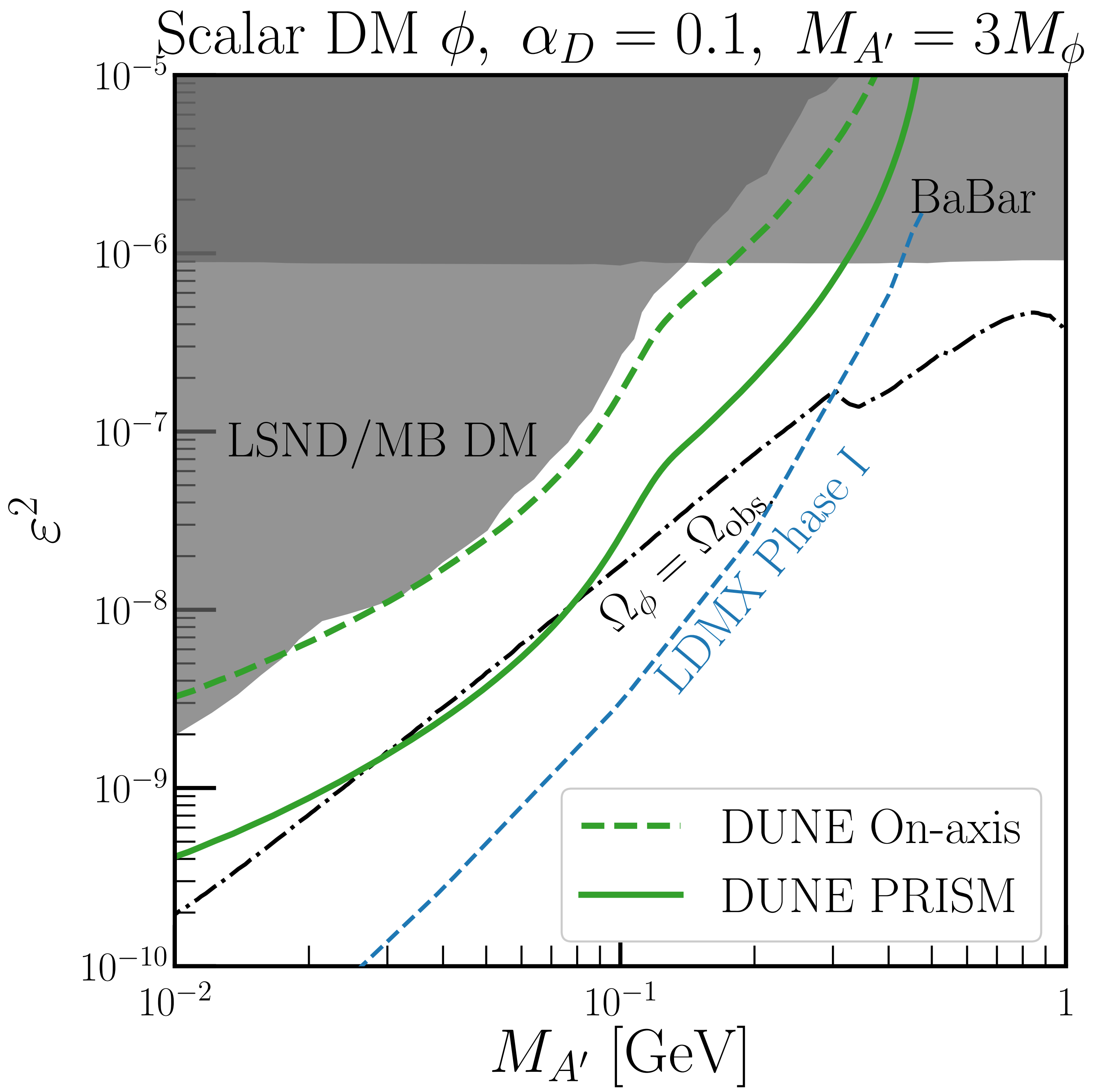
Only 3 renormalizable portals!

Light DM @ DUNE

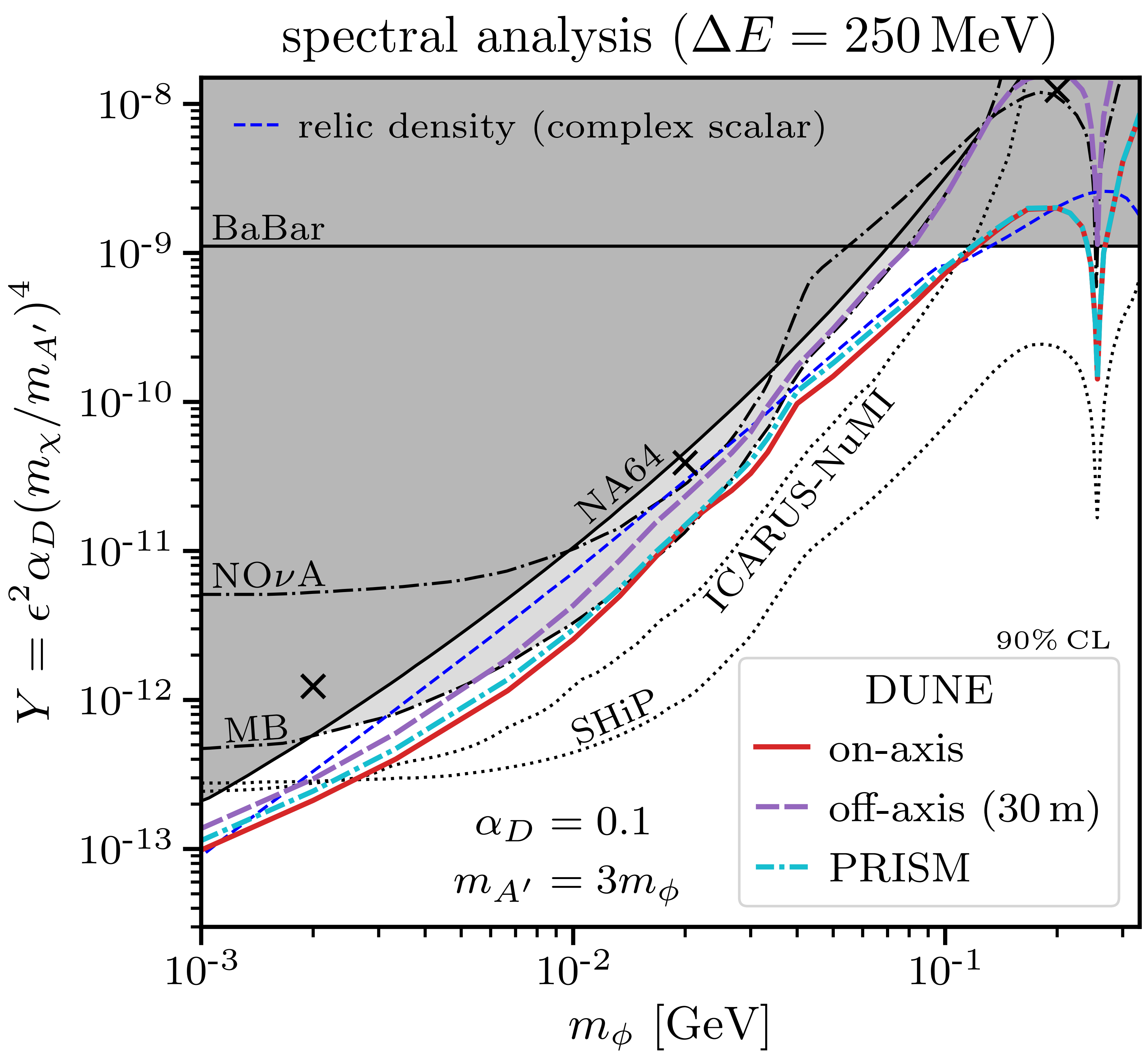
See Also: Coloma, Dobrescu, Frugiuele, Harnik [1512.03852]







De Romeri, Kelly, Machado [1903.10505]



Breitbach, Buonocore, Frugiuele, Kopp, Mittnach [2102.03383]

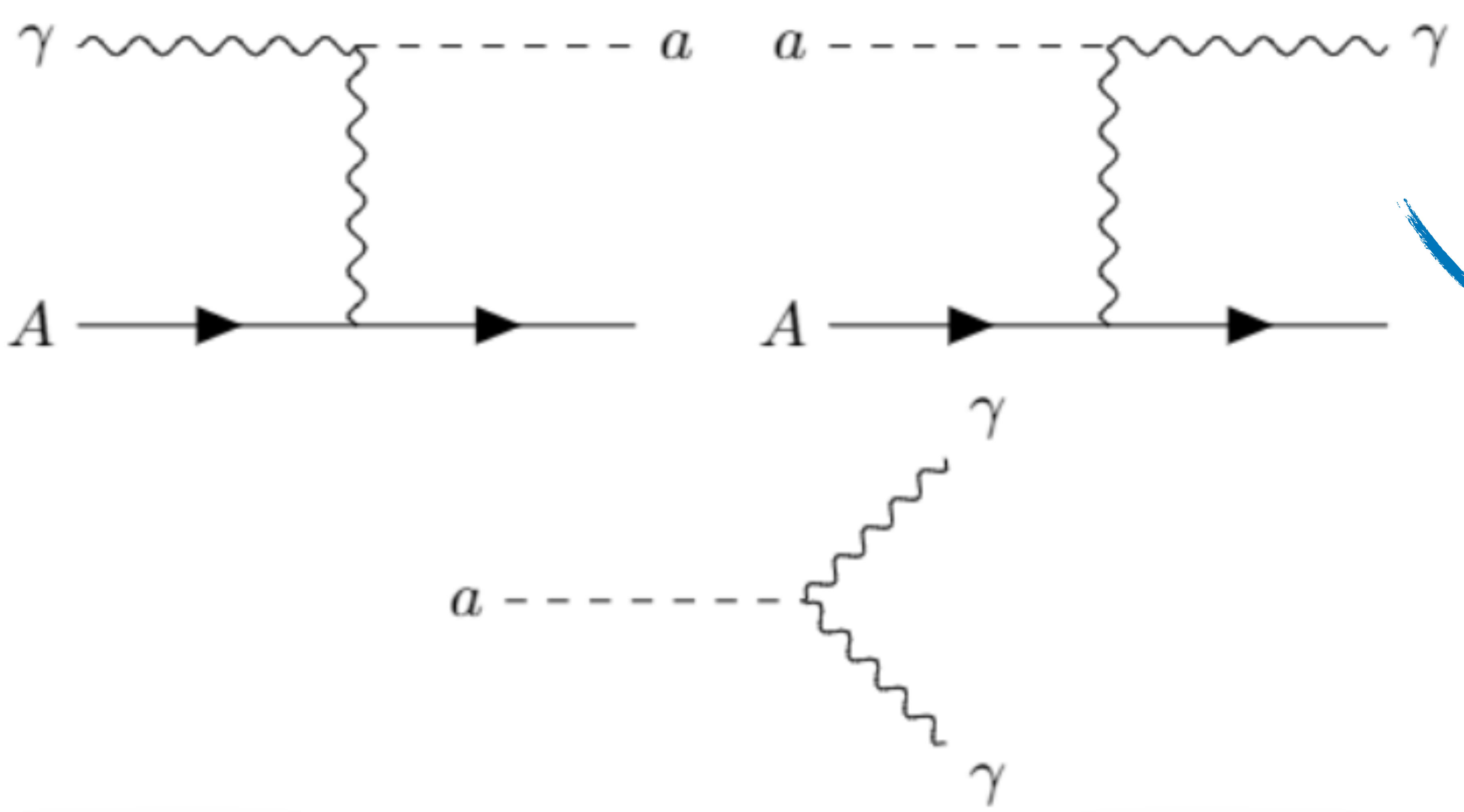
Axions @ DUNE

Axion-like Particles at Future Neutrino Experiments: Closing the "Cosmological Triangle"

Vedran Brdar, Bhaskar Dutta, Wooyoung Jang, Doojin Kim, Ian M. Shoemaker, Zahra Tabrizi, Adrian Thompson, Jaehoon Yu

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

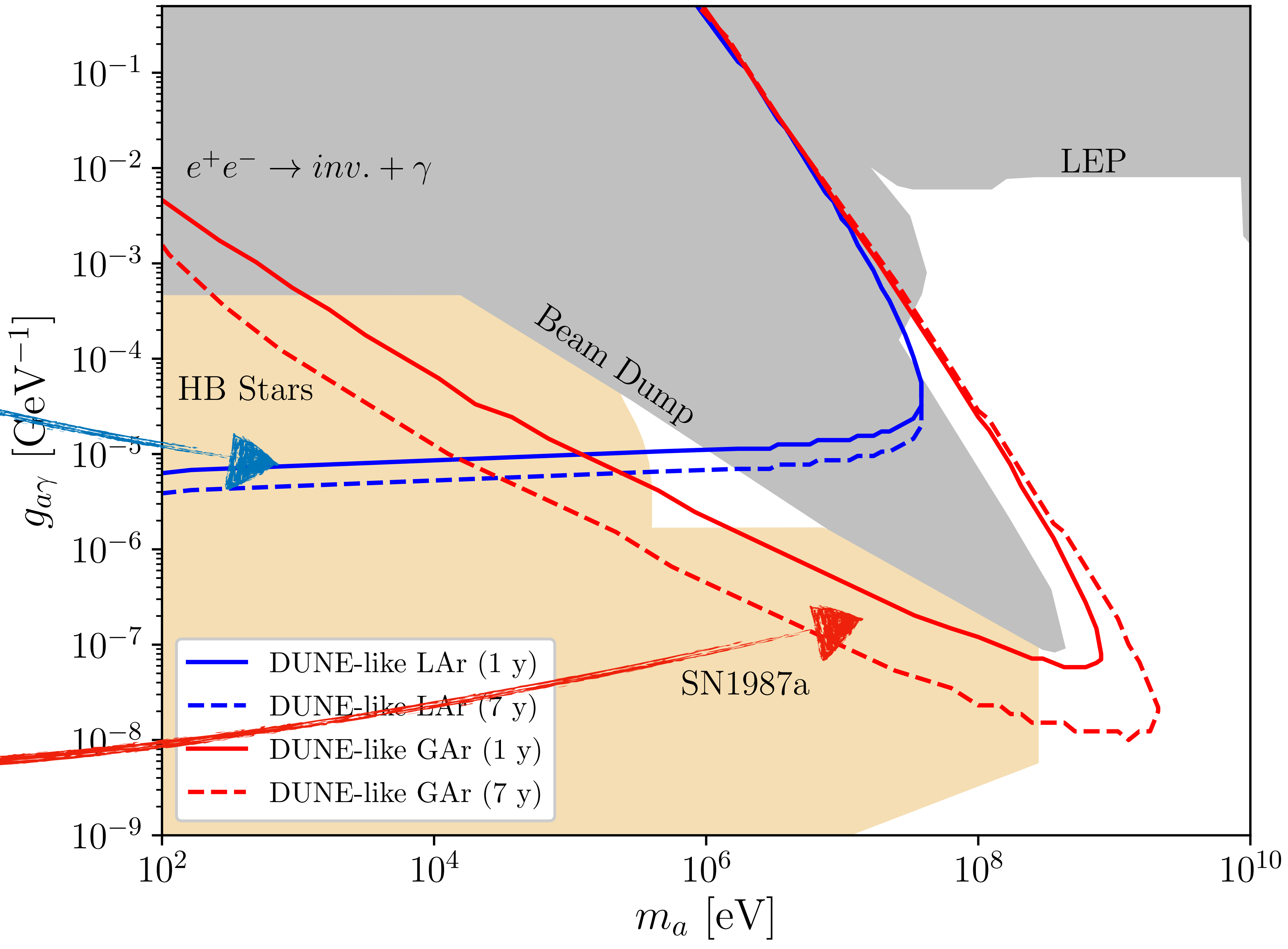
Primakoff production



Scattering

Decay

Phys. Rev. Lett. 126, 201801 (2021)



See also:

Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson, PRL, 2020

Kelly, Kumar, Liu, 2020

Conclusions

- BSM landscape is vast, likely still new continents to discover.
- We should cast a wide net
  - An array of interesting, well-motivated physics to search for in near future.
  - We need to simultaneously expand the theoretical terrain and to widen the experimental search strategies if we are going to uncover the New Standard Model.