

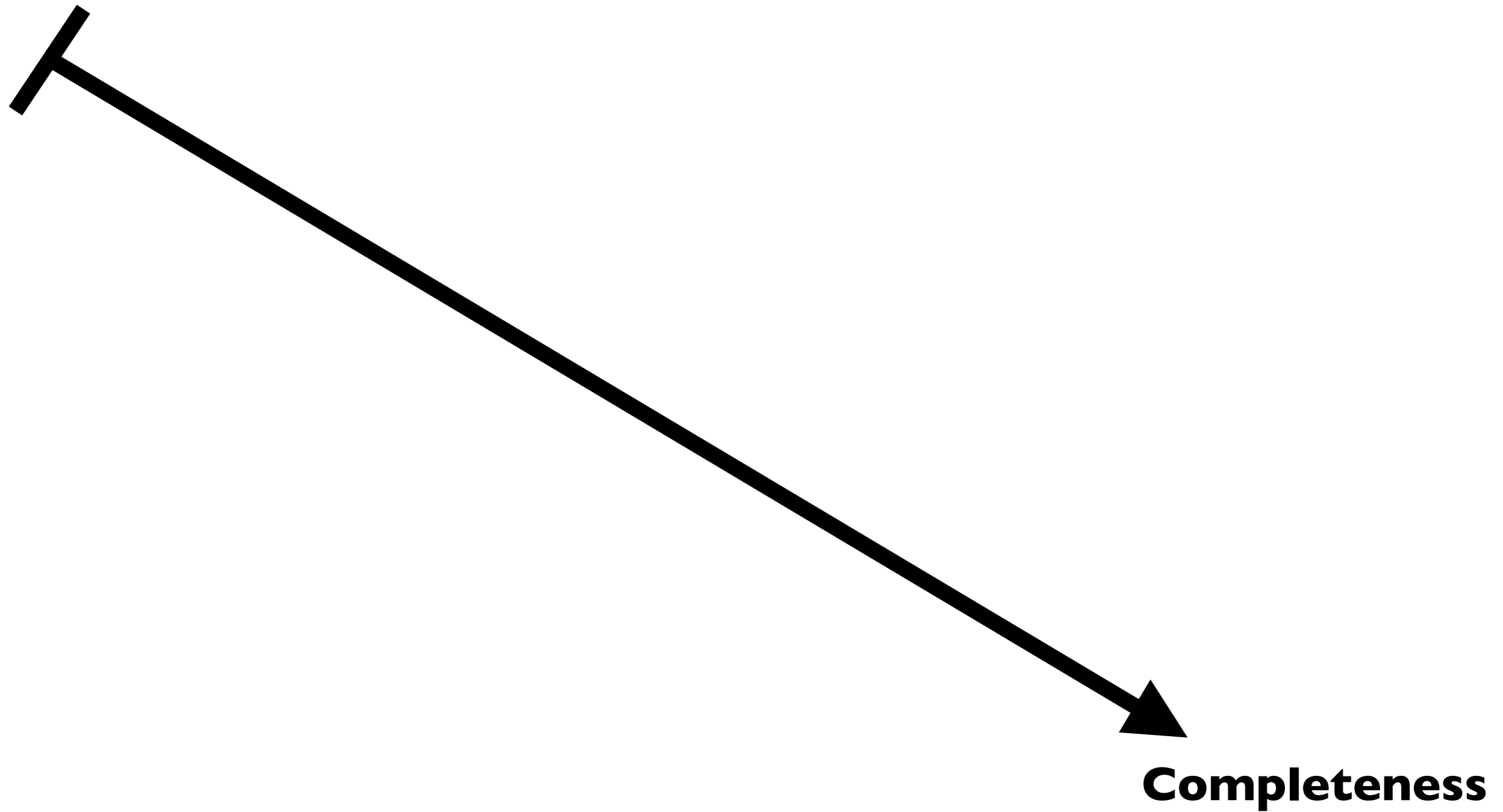
# Theoretical Landscape of Neutrino BSM

Ian M. Shoemaker

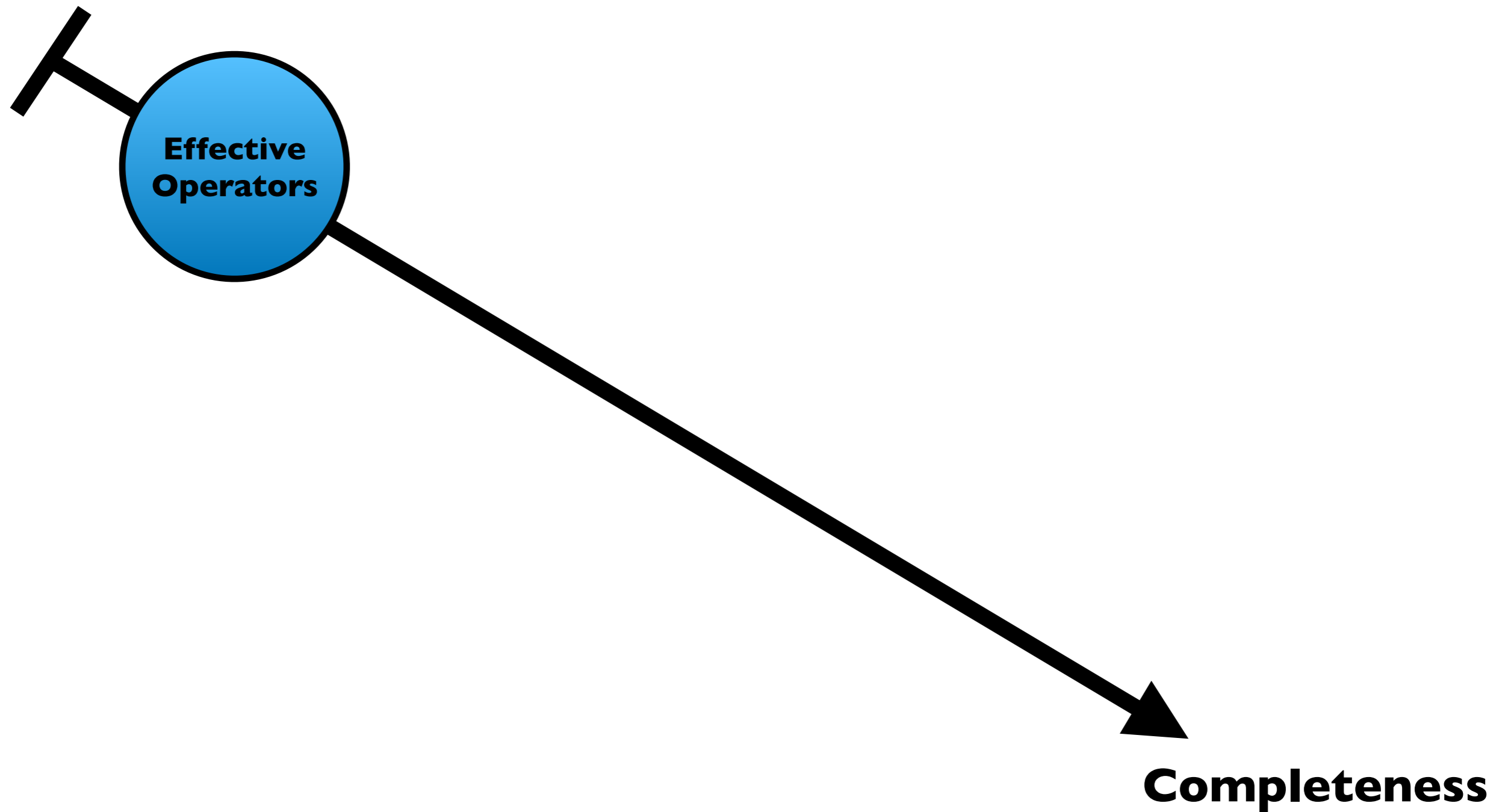


*New Opportunities at the Next  
Generation Neutrino Experiments  
April 12th, 2019*

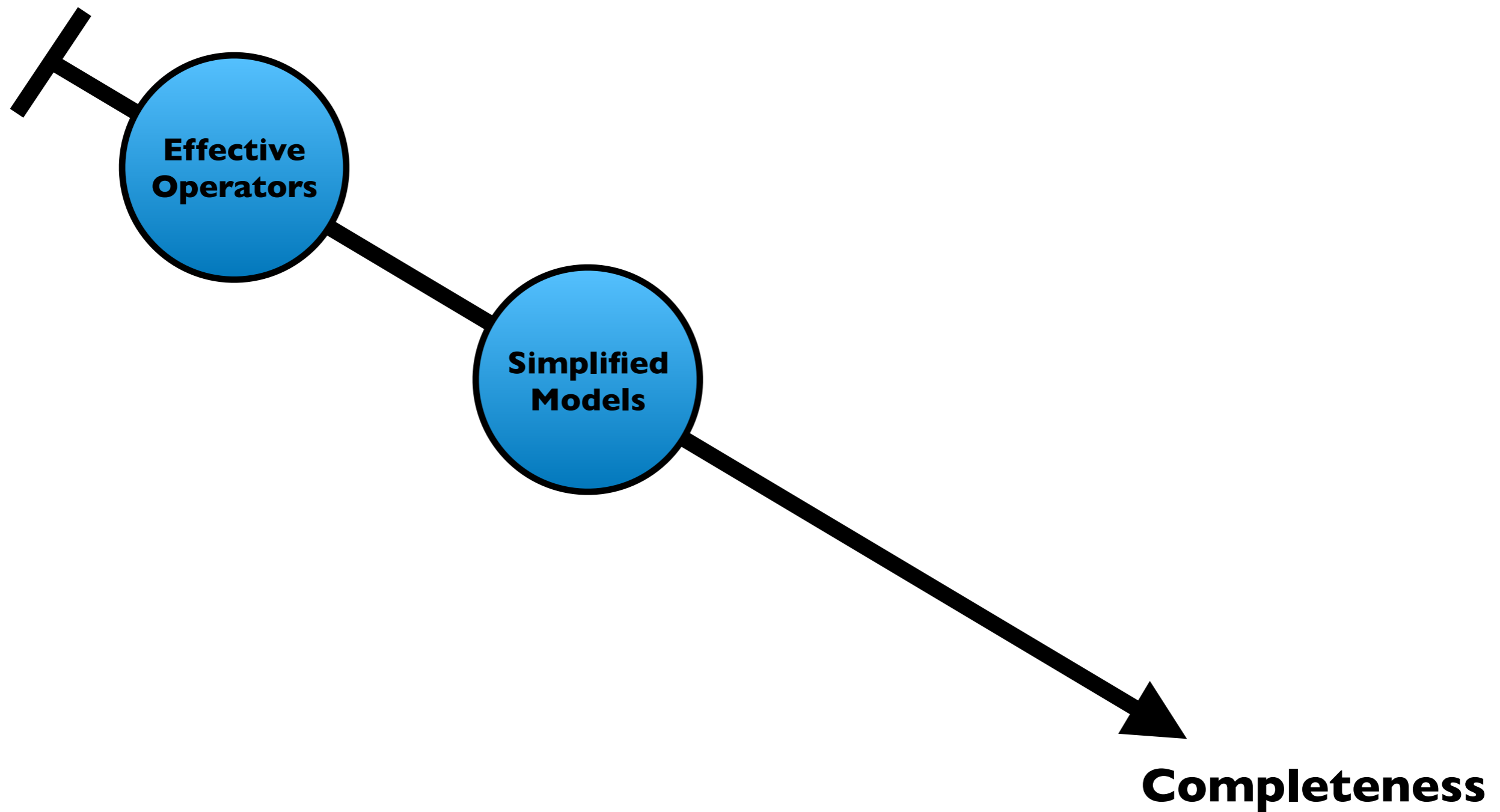
# Neutrino BSM Spectrum



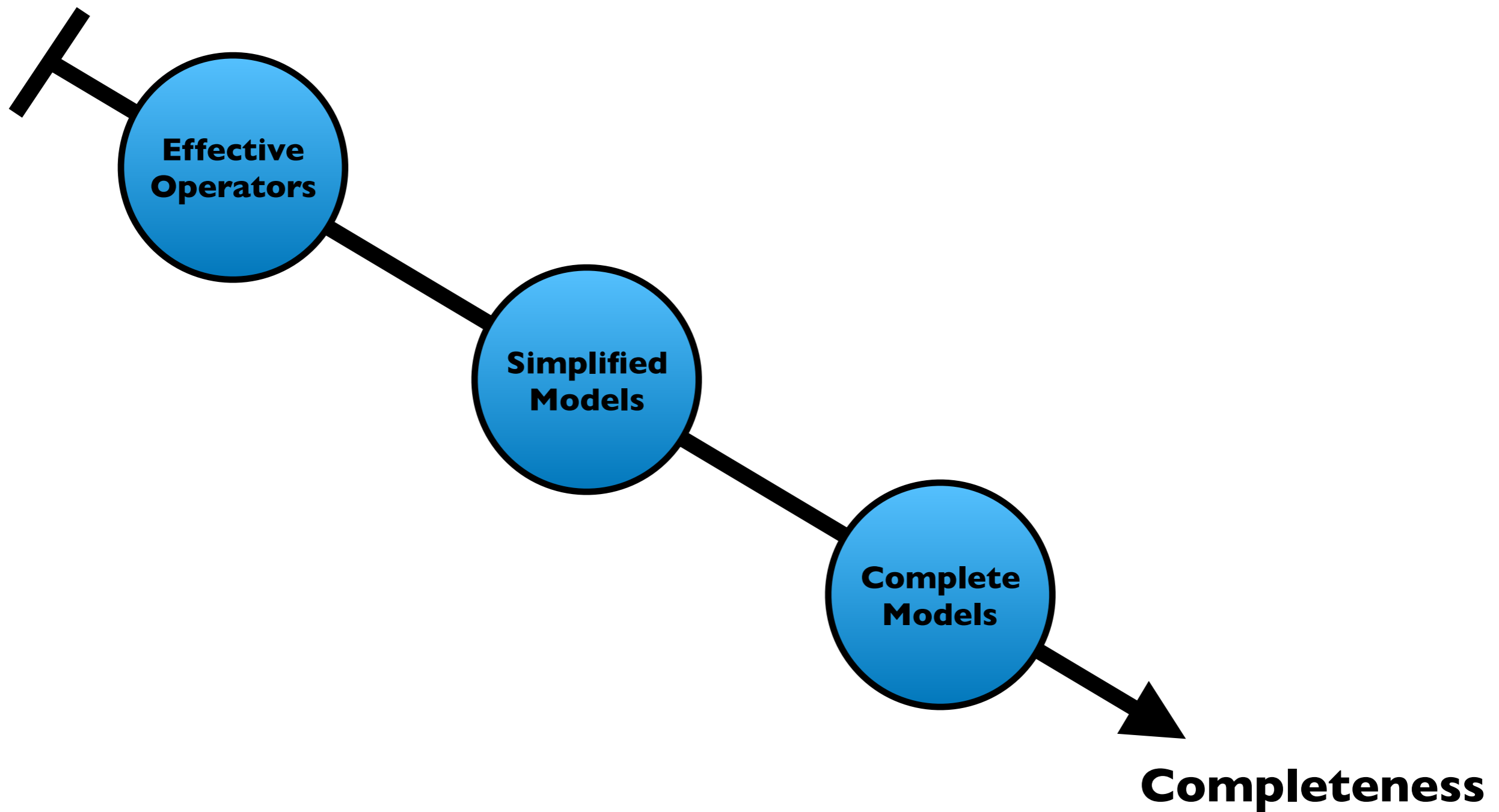
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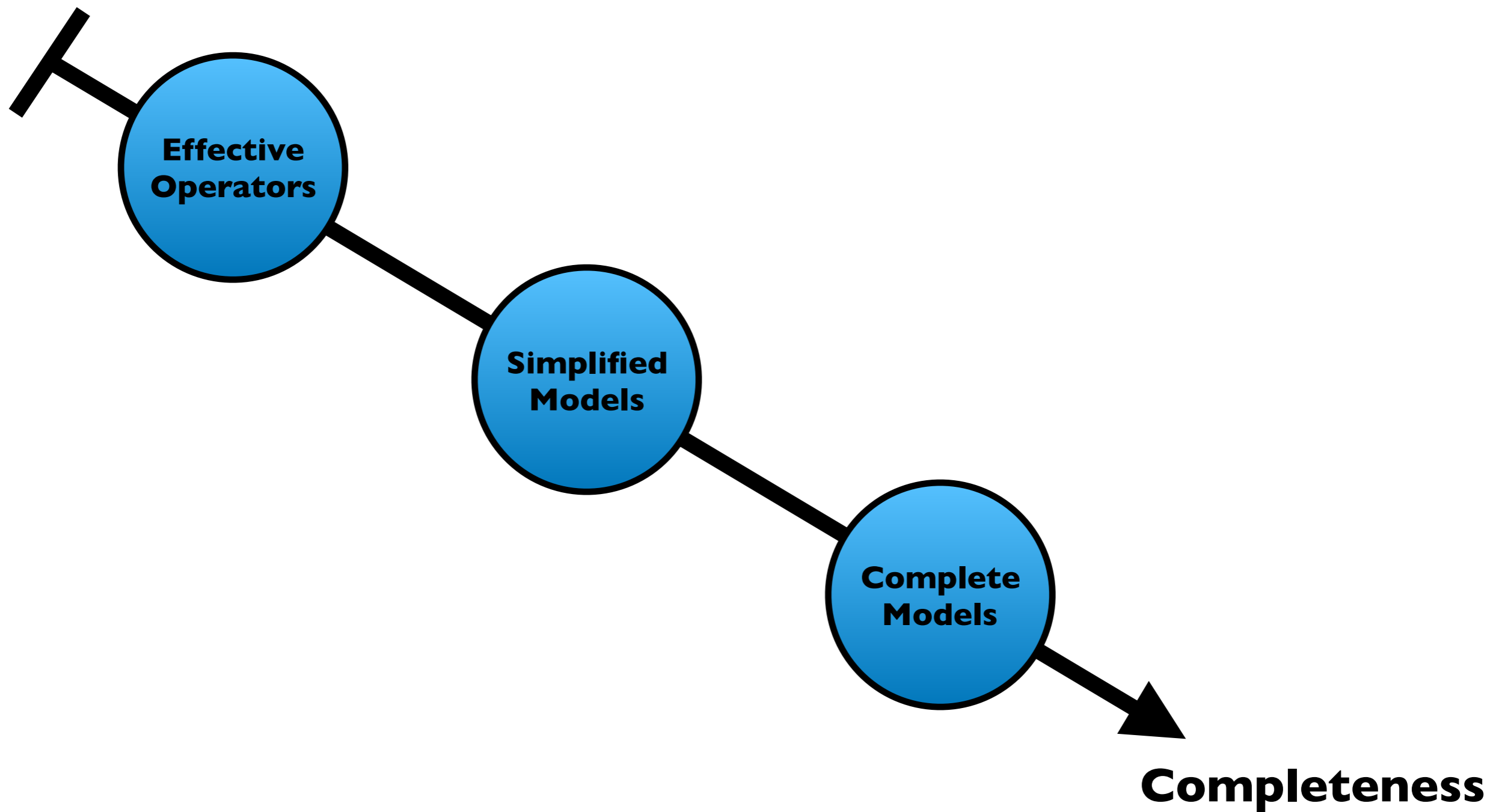
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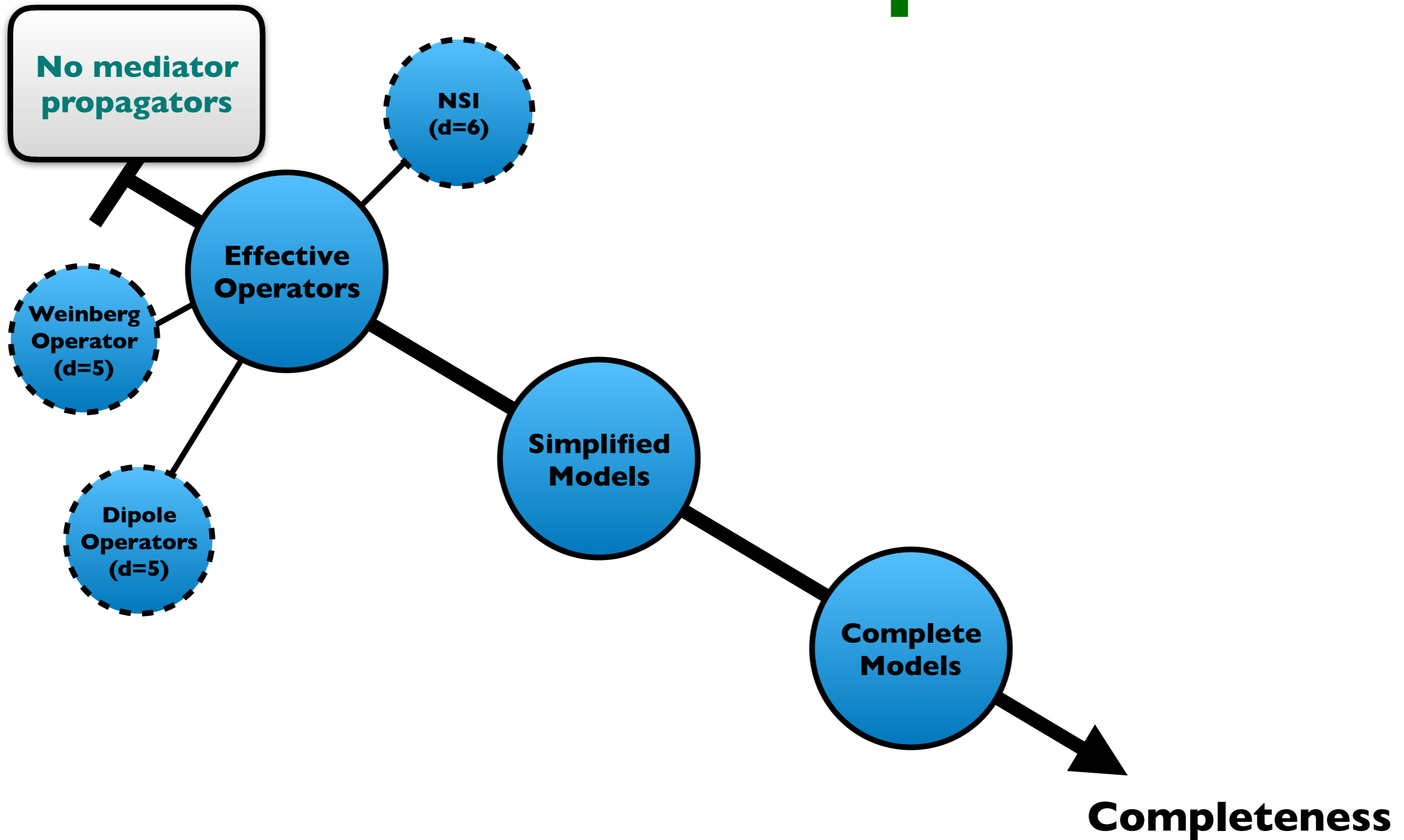
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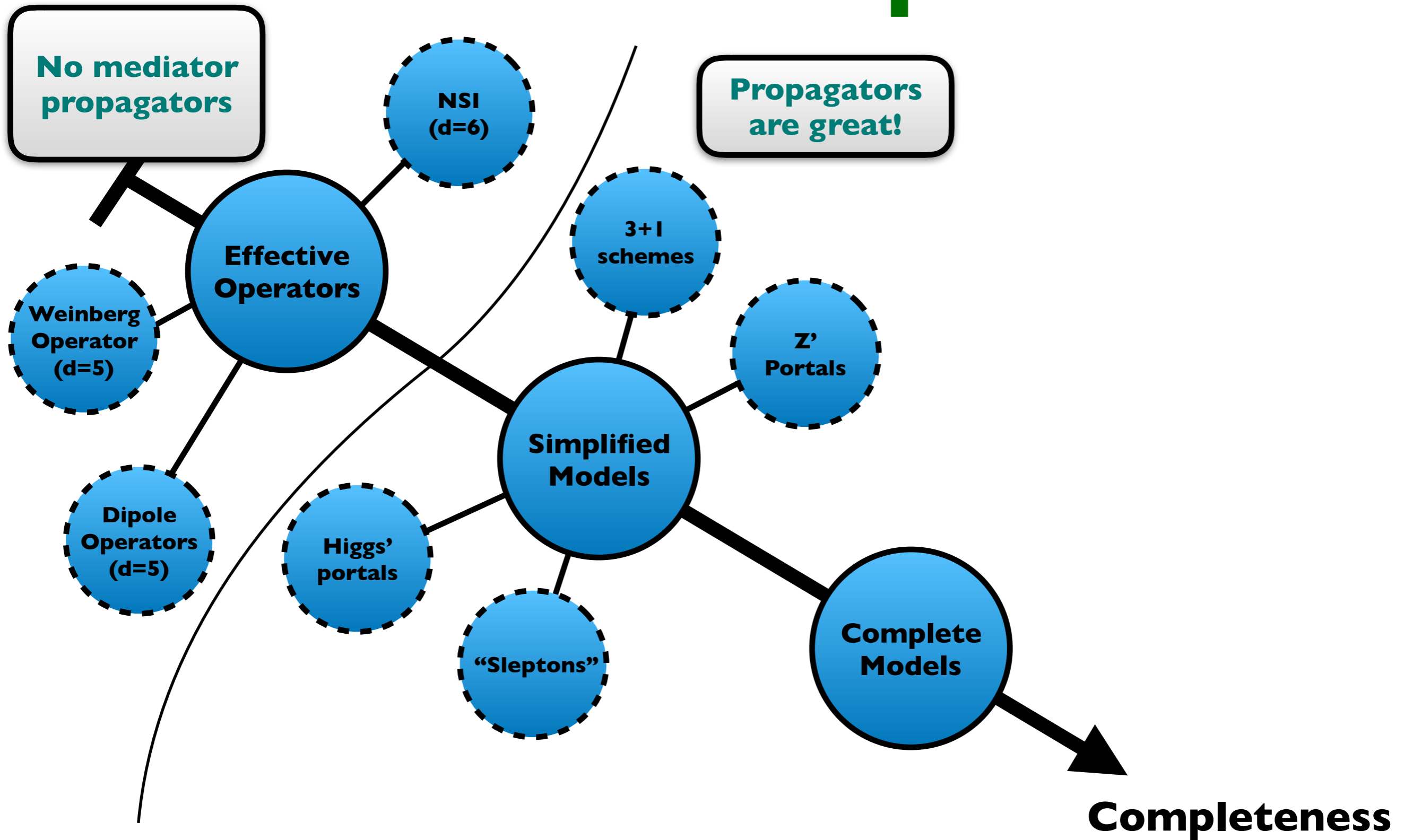
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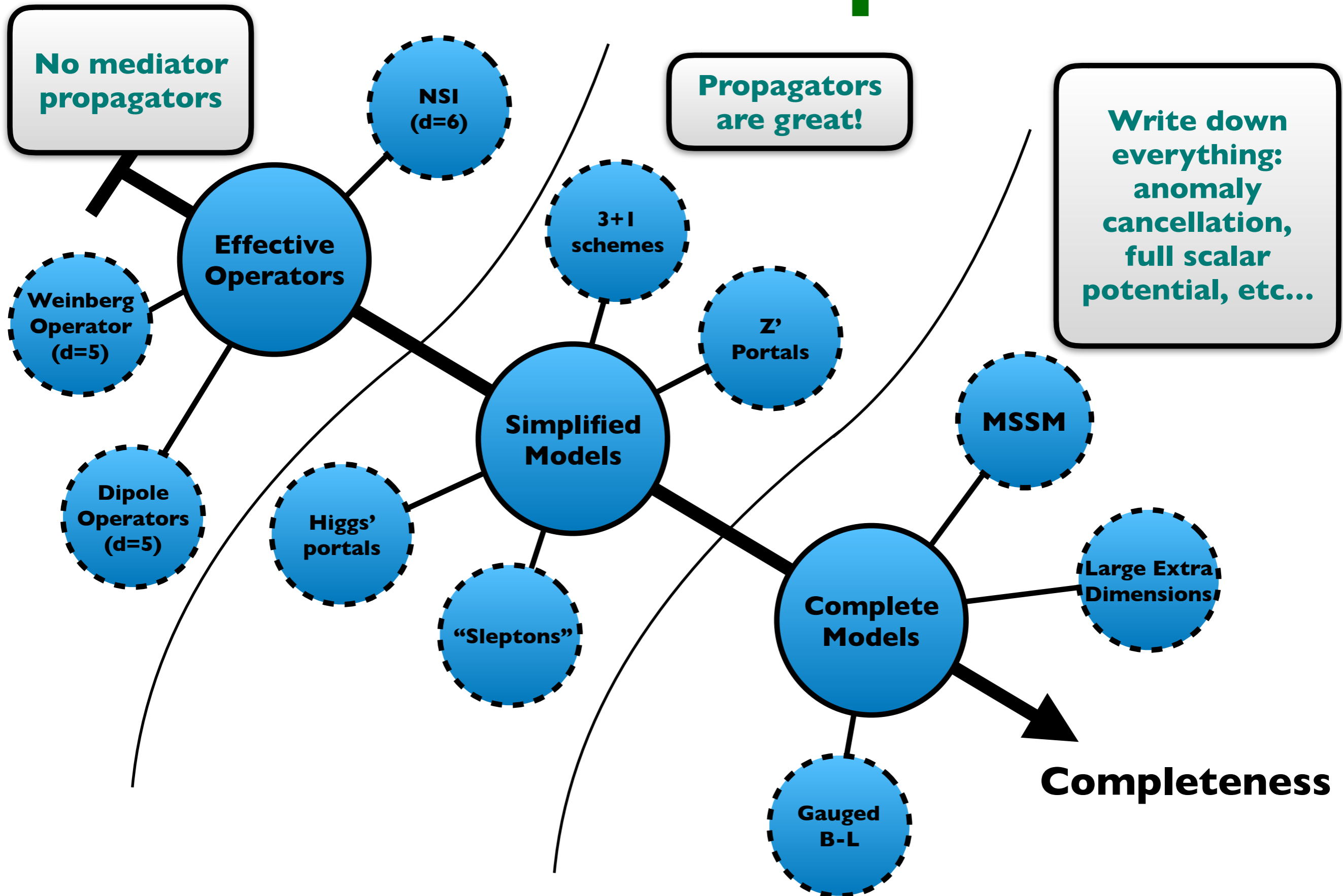
# Neutrino BSM Spectrum



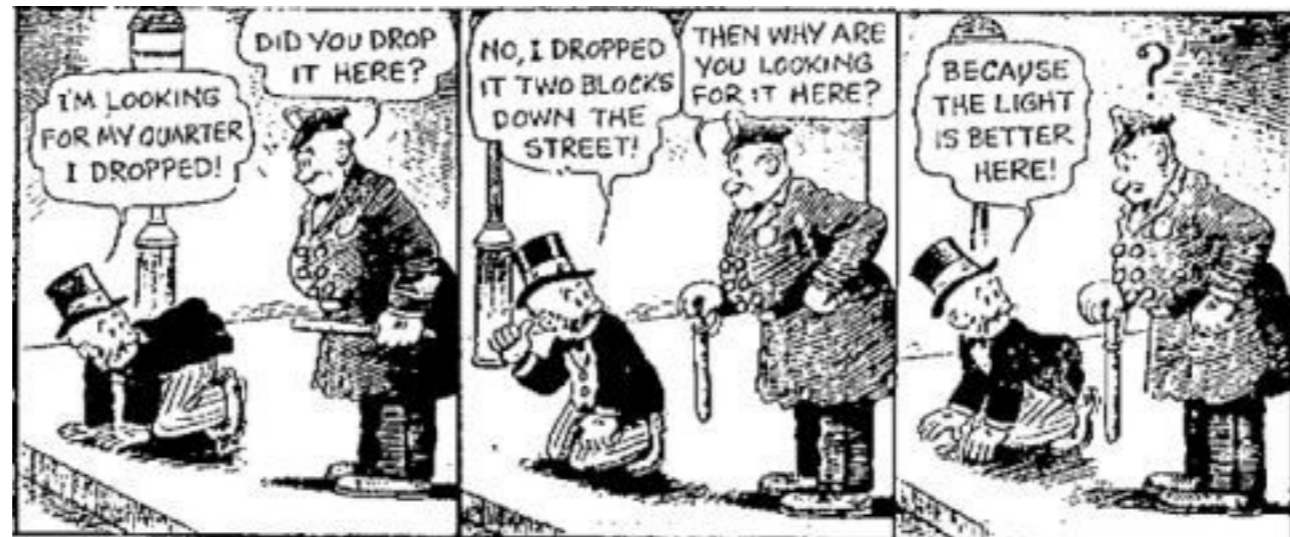
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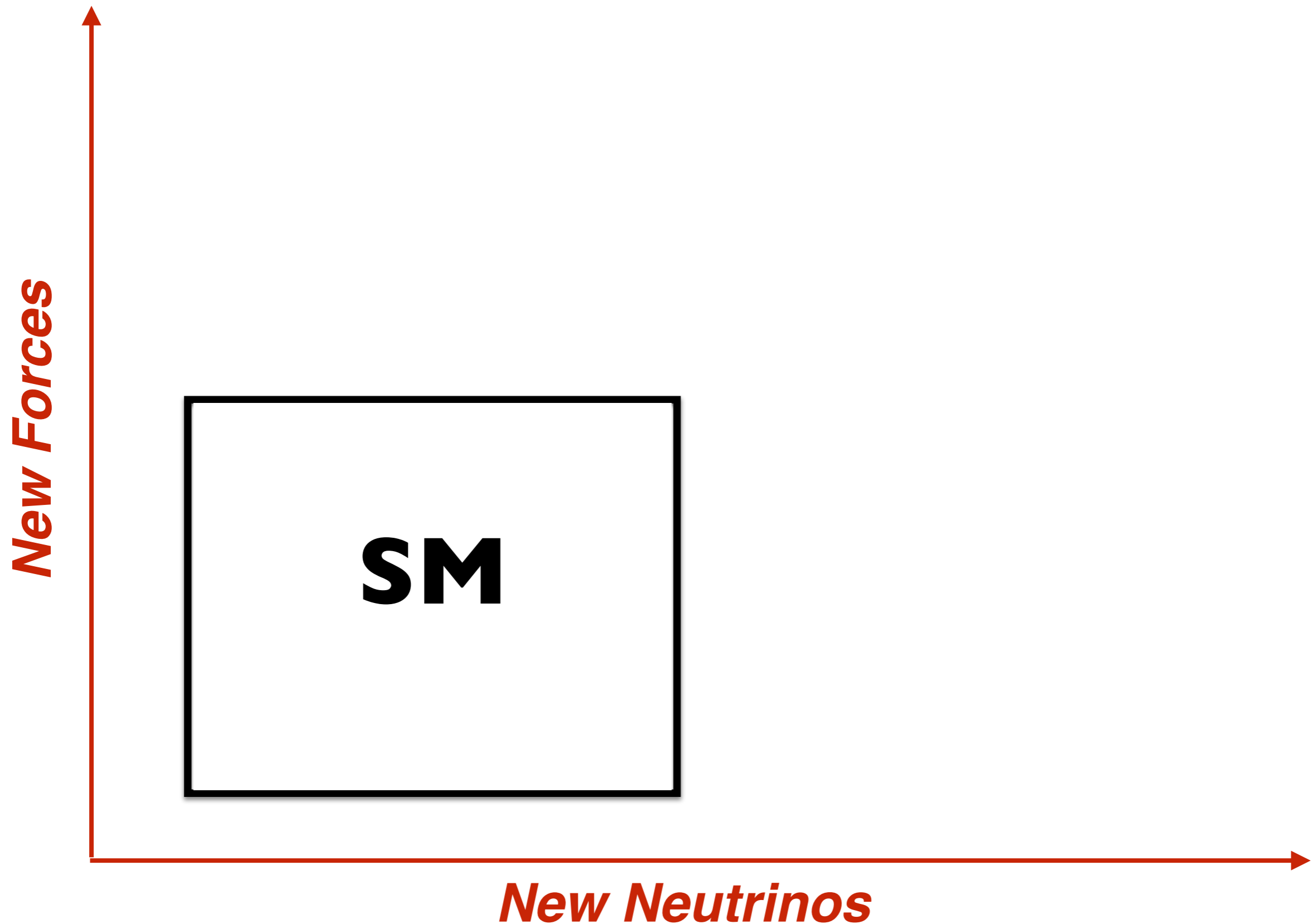
# Lampposts and BSM



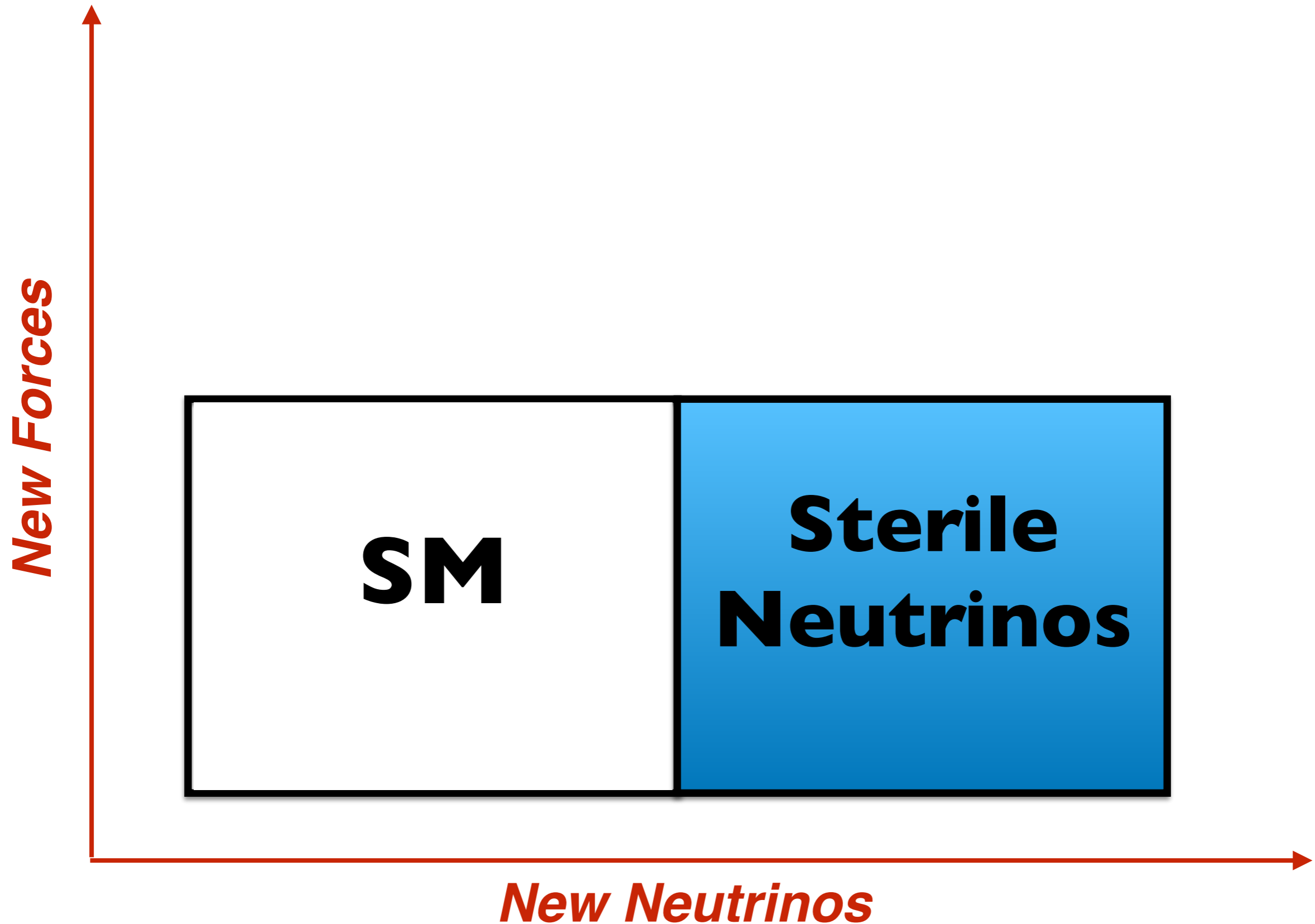
## Implications of the lamppost :

- 1) **We have a lot of lampposts nowadays. Exploit synergies, complementarities.**
- 2) **Well-motivated and cheap new lampposts?**
- 3) **Might find interesting new physics beyond original intent.**

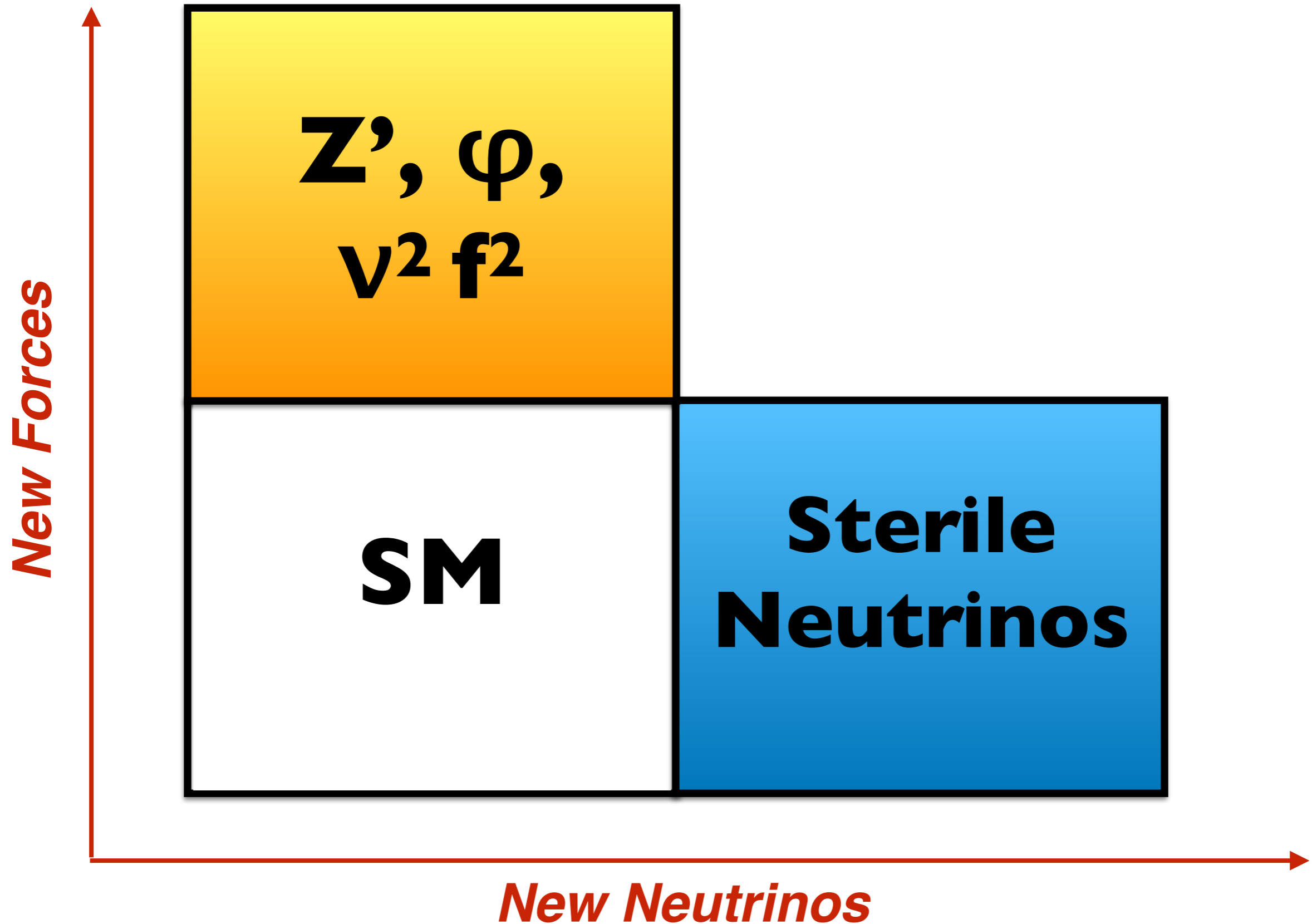
# BSM Space Schema



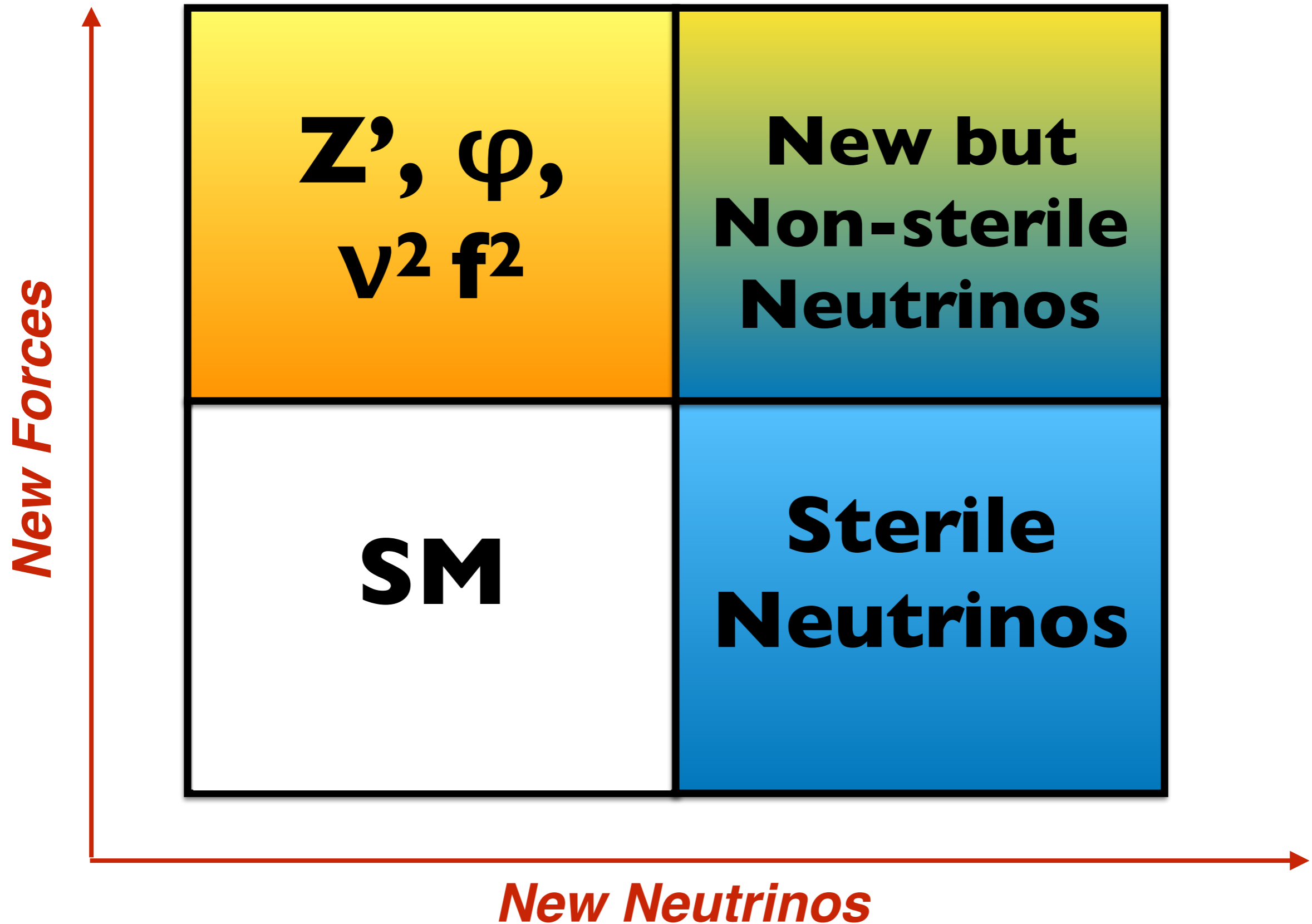
# BSM Space Schema



# BSM Space Schema



# BSM Space Schema



# Sterile Neutrinos

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

**SM gauge singlets**

# Sterile Neutrinos

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

**Mass Matrix:**

$$M = \begin{pmatrix} 0 & D_{3 \times N} \\ D_{N \times 3}^T & M_{N \times N} \end{pmatrix}$$

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- **Need at least two of them for atm/sol mass splittings  $N = 2$ .**
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How can we find them?  
1) Modified oscillations  
2) Up-scattering production  
3) Meson decay production

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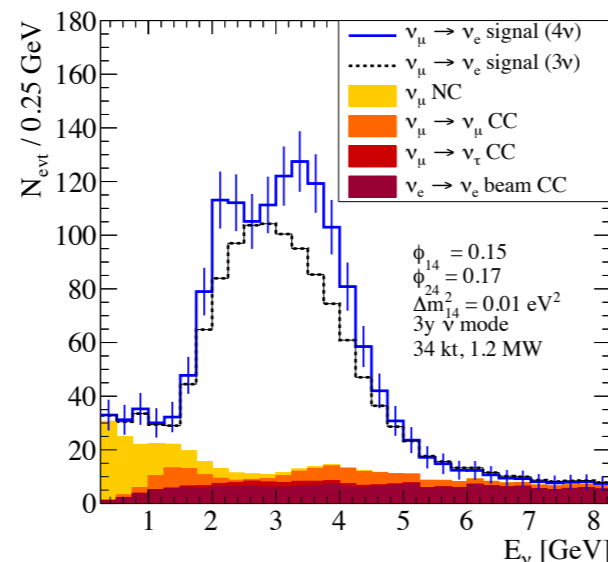
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# Sterile Neutrinos at DUNE

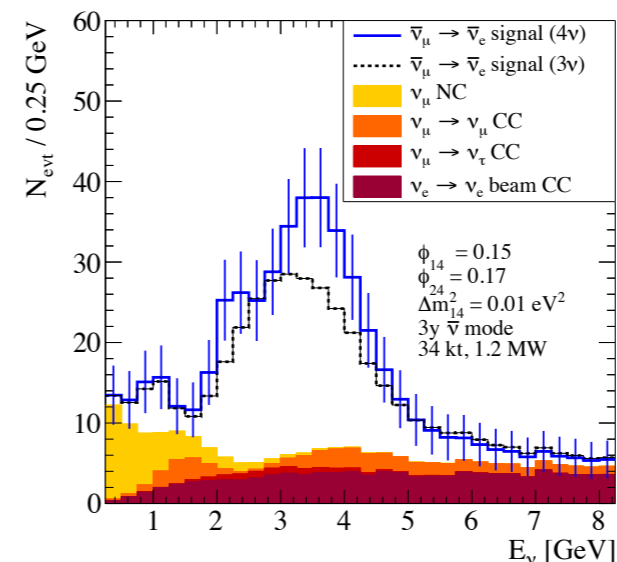
Berryman, de Gouvea, Kelly, and Kobach [1507.03986]

**Appearance**

$$\nu_\mu \rightarrow \nu_e$$



(a)



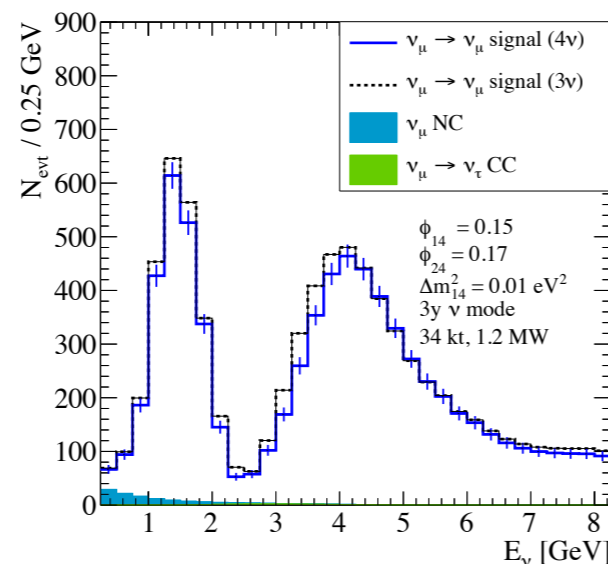
(b)

**Appearance**

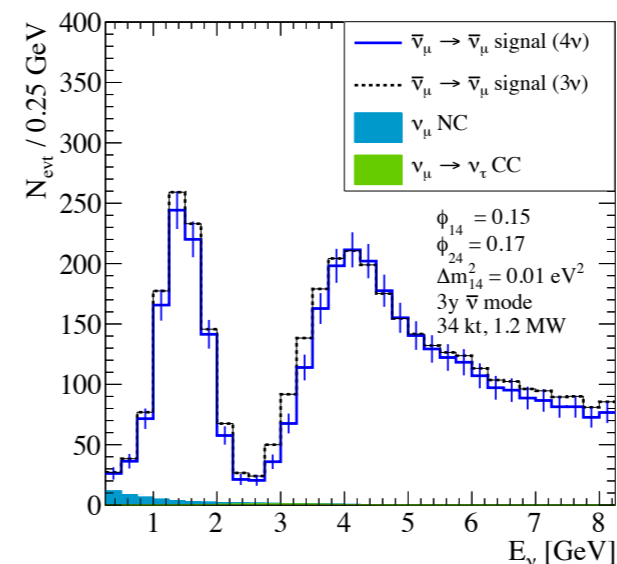
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

**Disappearance**

$$\nu_\mu \rightarrow \nu_\mu$$



(c)



(d)

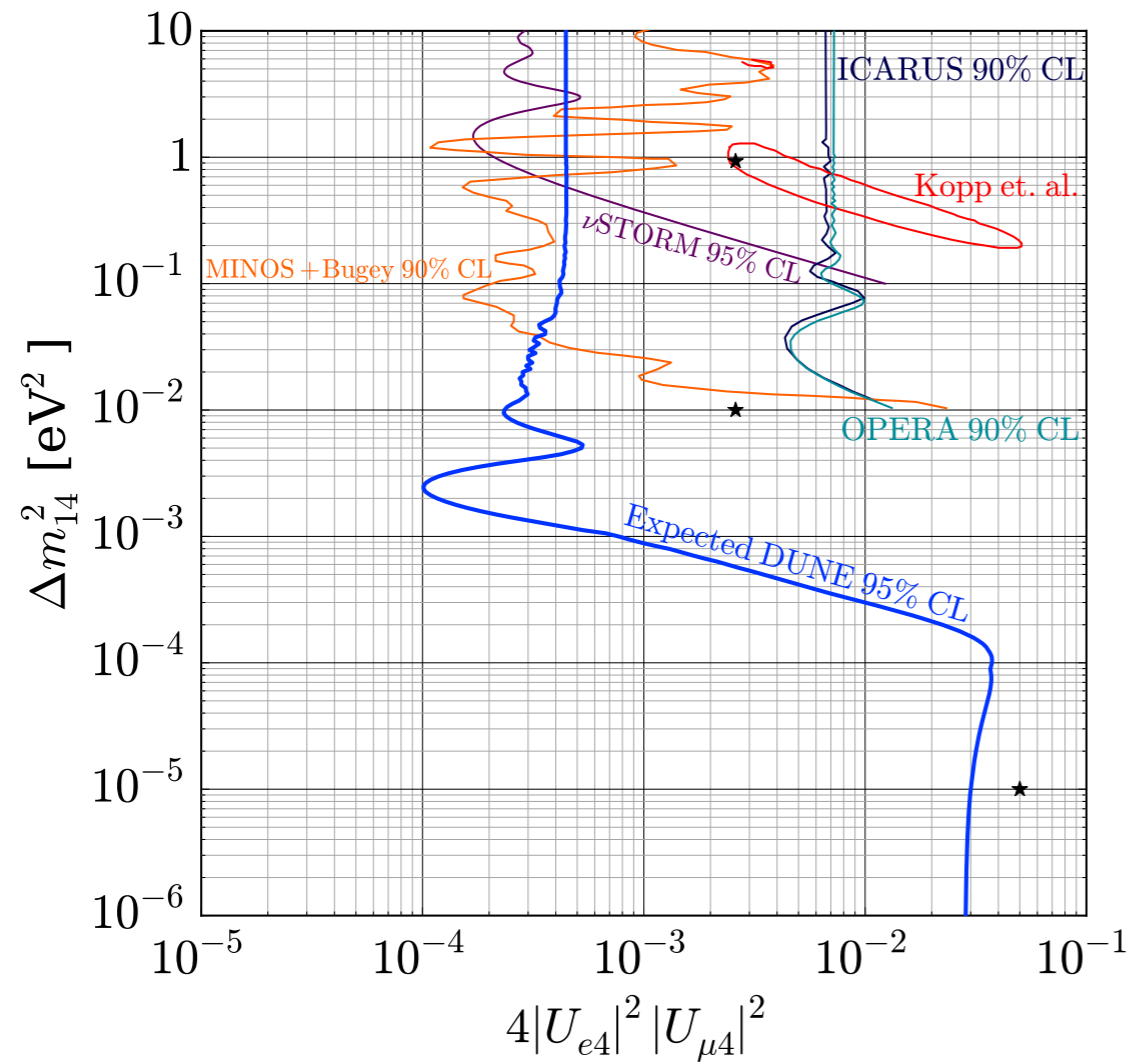
**Disappearance**

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

FIG. 1: Expected signal and background yields for six years (3y  $\nu$  + 3y  $\bar{\nu}$ ) of data collection at DUNE, using fluxes projected by Ref. [1], for a 34 kiloton detector, and a 1.2 MW beam. (a) and (b) show appearance channel yields for neutrino and antineutrino beams, respectively, while (c) and (d) show disappearance channel yields. The 3 $\nu$  signal corresponds to the standard three-neutrino hypothesis, where  $\sin^2 \theta_{12} = 0.308$ ,  $\sin^2 \theta_{13} = 0.0235$ ,  $\sin^2 \theta_{23} = 0.437$ ,  $\Delta m_{12}^2 = 7.54 \times 10^{-5} \text{ eV}^2$ ,  $\Delta m_{13}^2 = 2.43 \times 10^{-3} \text{ eV}^2$ ,  $\delta_{CP} = 0$ , while the 4 $\nu$  signal corresponds to  $\sin^2 \phi_{12} = 0.315$ ,  $\sin^2 \phi_{13} = 0.024$ ,  $\sin^2 \phi_{23} = 0.456$ ,  $\sin^2 \phi_{14} = 0.023$ ,  $\sin^2 \phi_{24} = 0.030$ ,  $\Delta m_{14}^2 = 10^{-2} \text{ eV}^2$ ,  $\eta_1 = 0$ , and  $\eta_s = 0$ . Statistical uncertainties are shown as vertical bars in each bin. Backgrounds are defined in the text and are assumed to be identical for the three- and four-neutrino scenarios: any discrepancy is negligible after accounting for a 5% normalization uncertainty.

# Sterile Neutrinos at DUNE

Berryman, de Gouvea, Kelly, and Kobach [1507.03986]

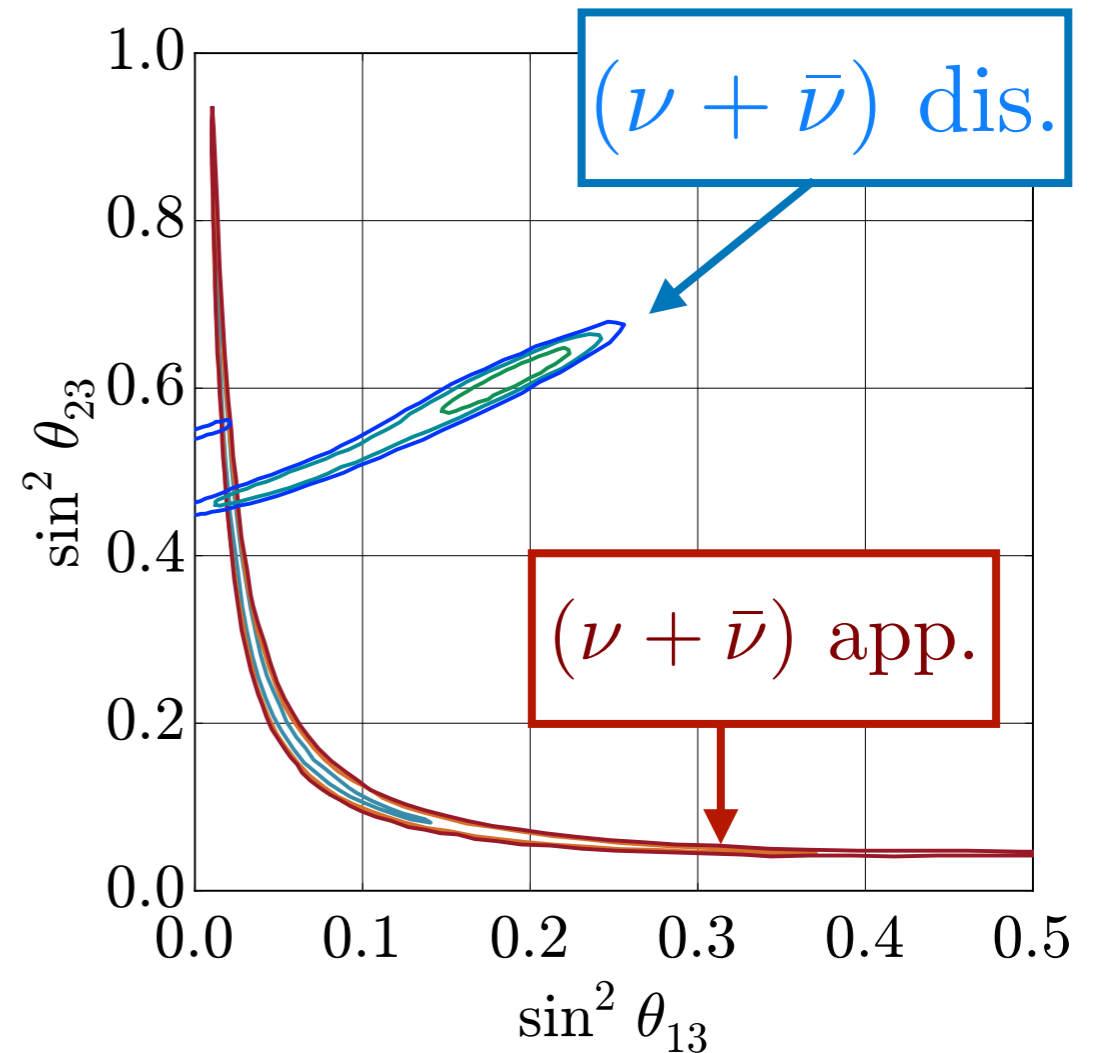
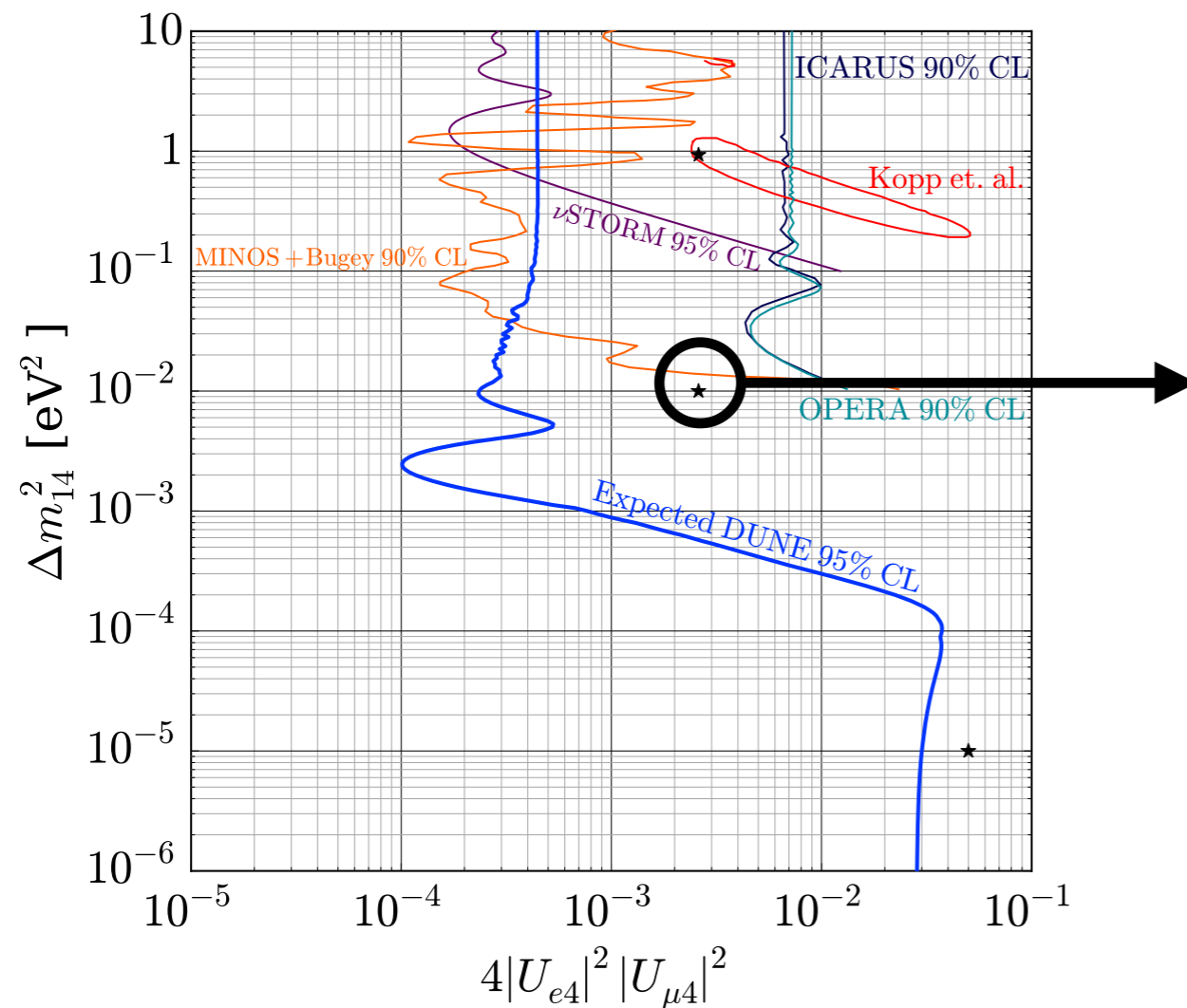


	$\sin^2 \phi_{14}$	$\sin^2 \phi_{24}$	$\Delta m_{14}^2$ (eV <sup>2</sup> )	$\eta_s$	$\sin^2 \phi_{12}$	$\sin^2 \phi_{13}$	$\sin^2 \phi_{23}$	$\Delta m_{12}^2$ (eV <sup>2</sup> )	$\Delta m_{13}^2$ (eV <sup>2</sup> )	$\eta_1$
<b>Case 1</b>	0.023	0.030	0.93	$-\pi/4$	0.315	0.0238	0.456	$7.54 \times 10^{-5}$	$2.43 \times 10^{-3}$	$\pi/3$
<b>Case 2</b>	0.023	0.030	$1.0 \times 10^{-2}$	$-\pi/4$	0.315	0.0238	0.456	$7.54 \times 10^{-5}$	$2.43 \times 10^{-3}$	$\pi/3$
<b>Case 3</b>	0.040	0.320	$1.0 \times 10^{-5}$	$-\pi/4$	0.321	0.0244	0.639	$7.54 \times 10^{-5}$	$2.43 \times 10^{-3}$	$\pi/3$

# Sterile Neutrinos at DUNE

Berryman, de Gouvea, Kelly, and Kobach [1507.03986]

Test 3nu paradigm!



	$\sin^2 \phi_{14}$	$\sin^2 \phi_{24}$	$\Delta m_{14}^2$ (eV <sup>2</sup> )	$\eta_s$	$\sin^2 \phi_{12}$	$\sin^2 \phi_{13}$	$\sin^2 \phi_{23}$	$\Delta m_{12}^2$ (eV <sup>2</sup> )	$\Delta m_{13}^2$ (eV <sup>2</sup> )	$\eta_1$
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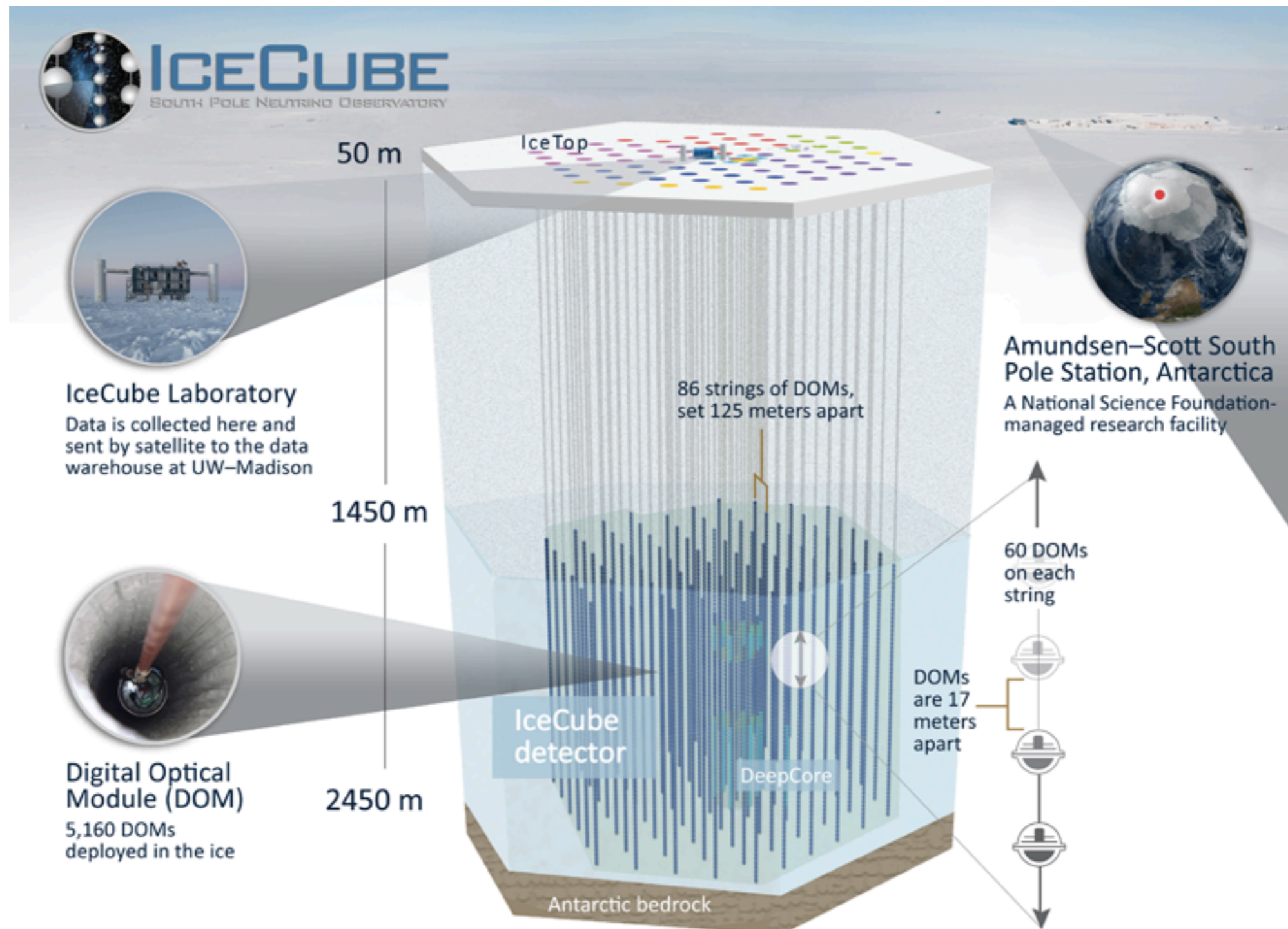
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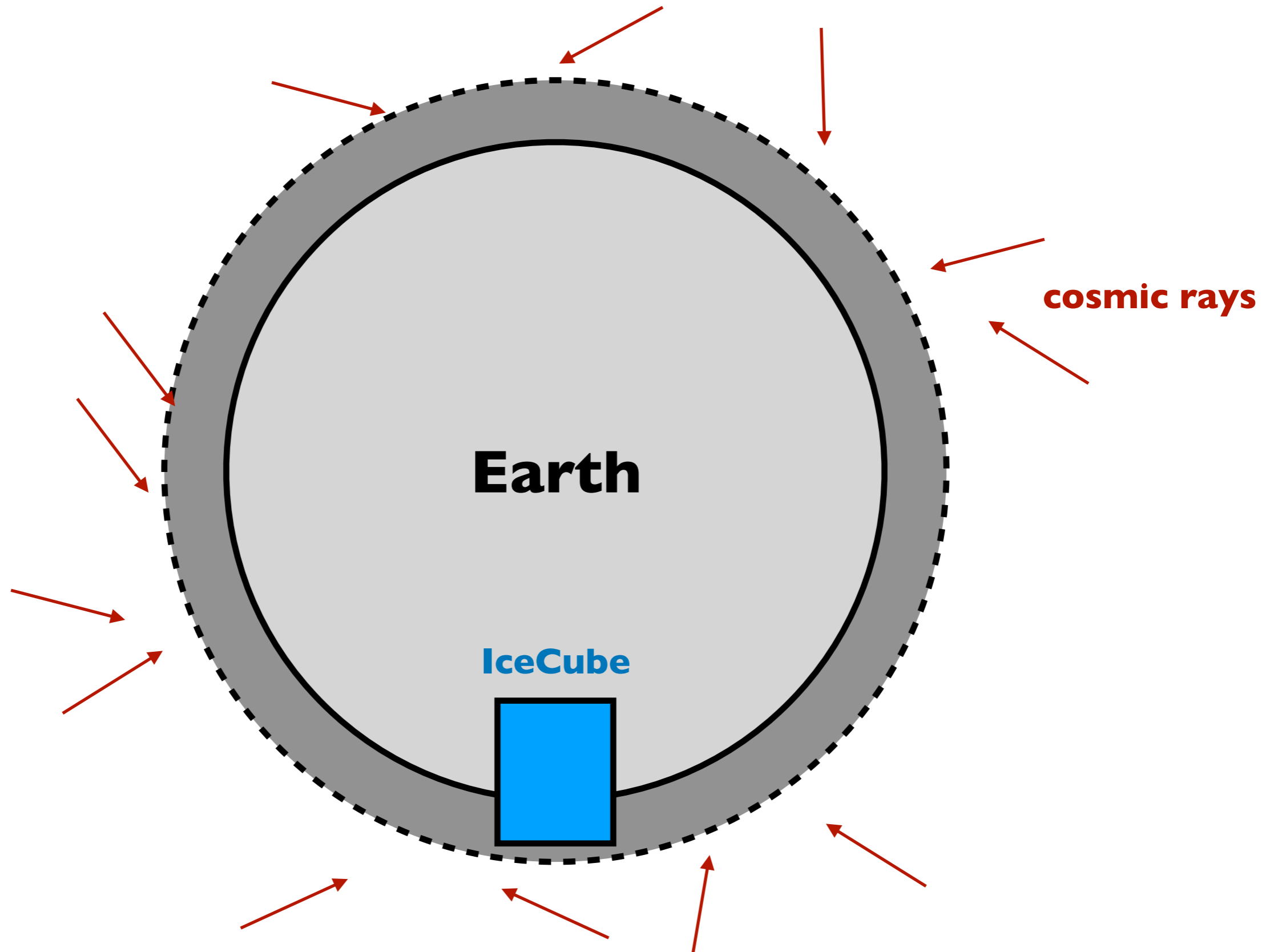
3) Meson decay production

# New Physics Signatures at IceCube



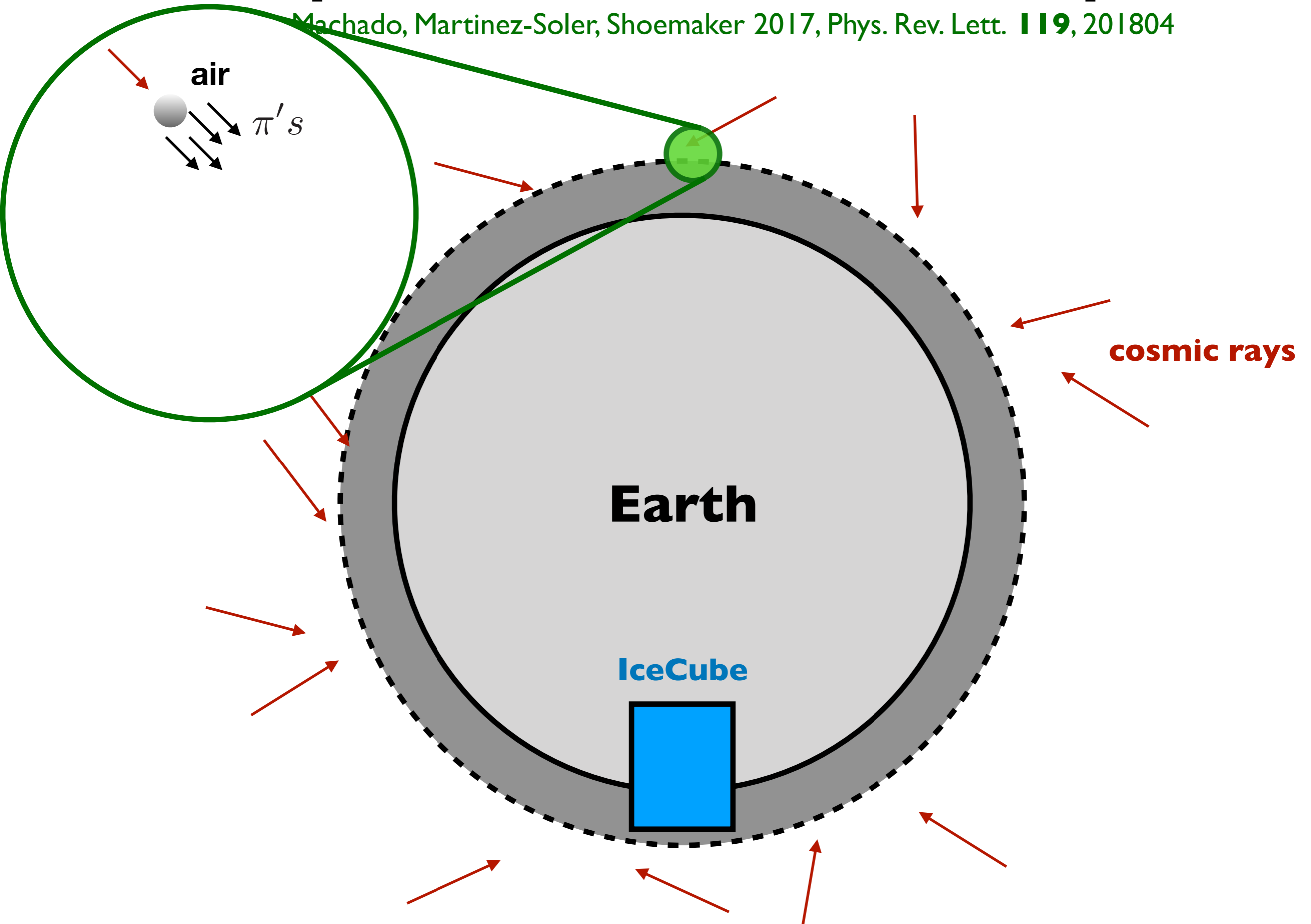
# Atmospheric Neutrinos as a BSM probe

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



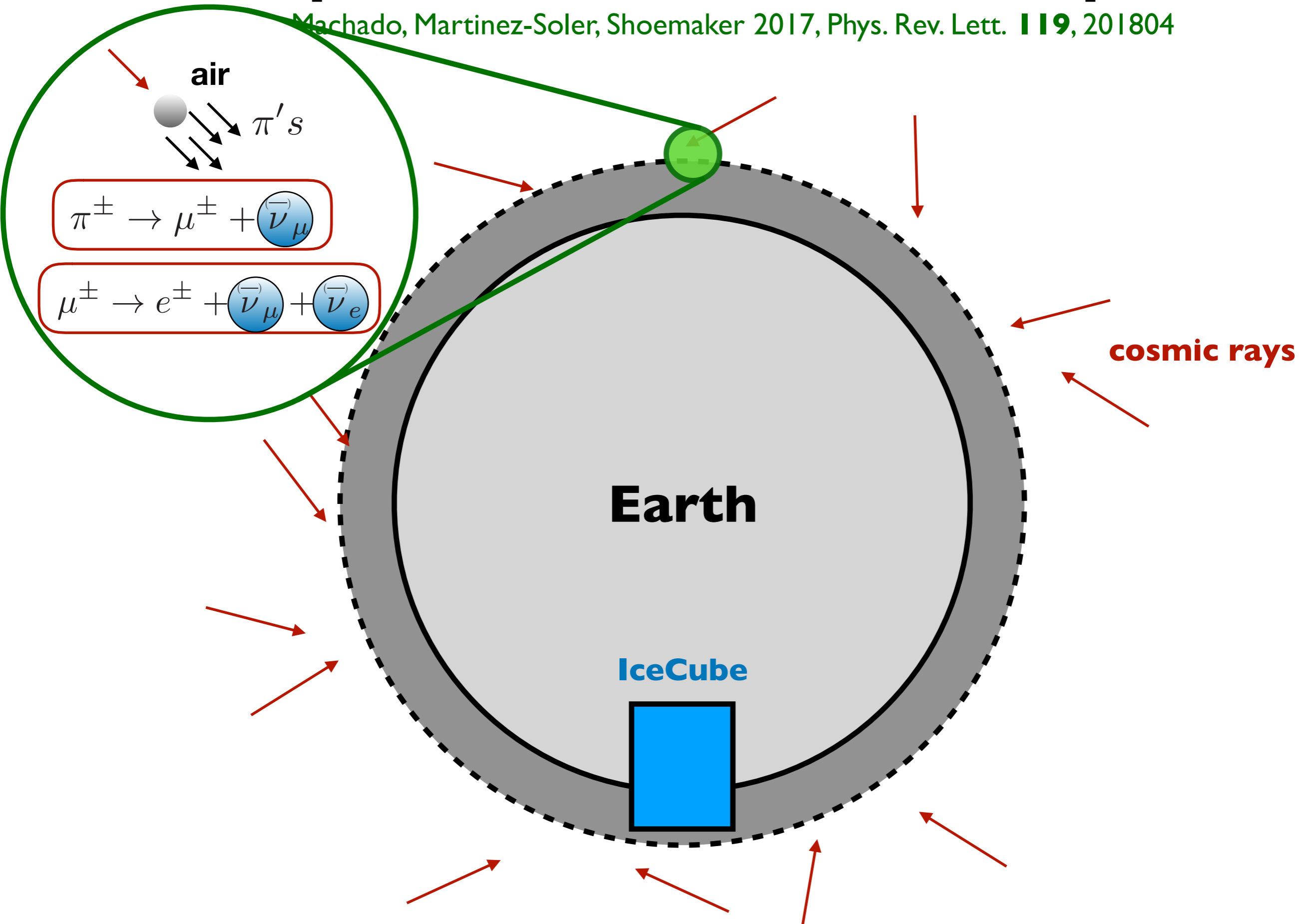
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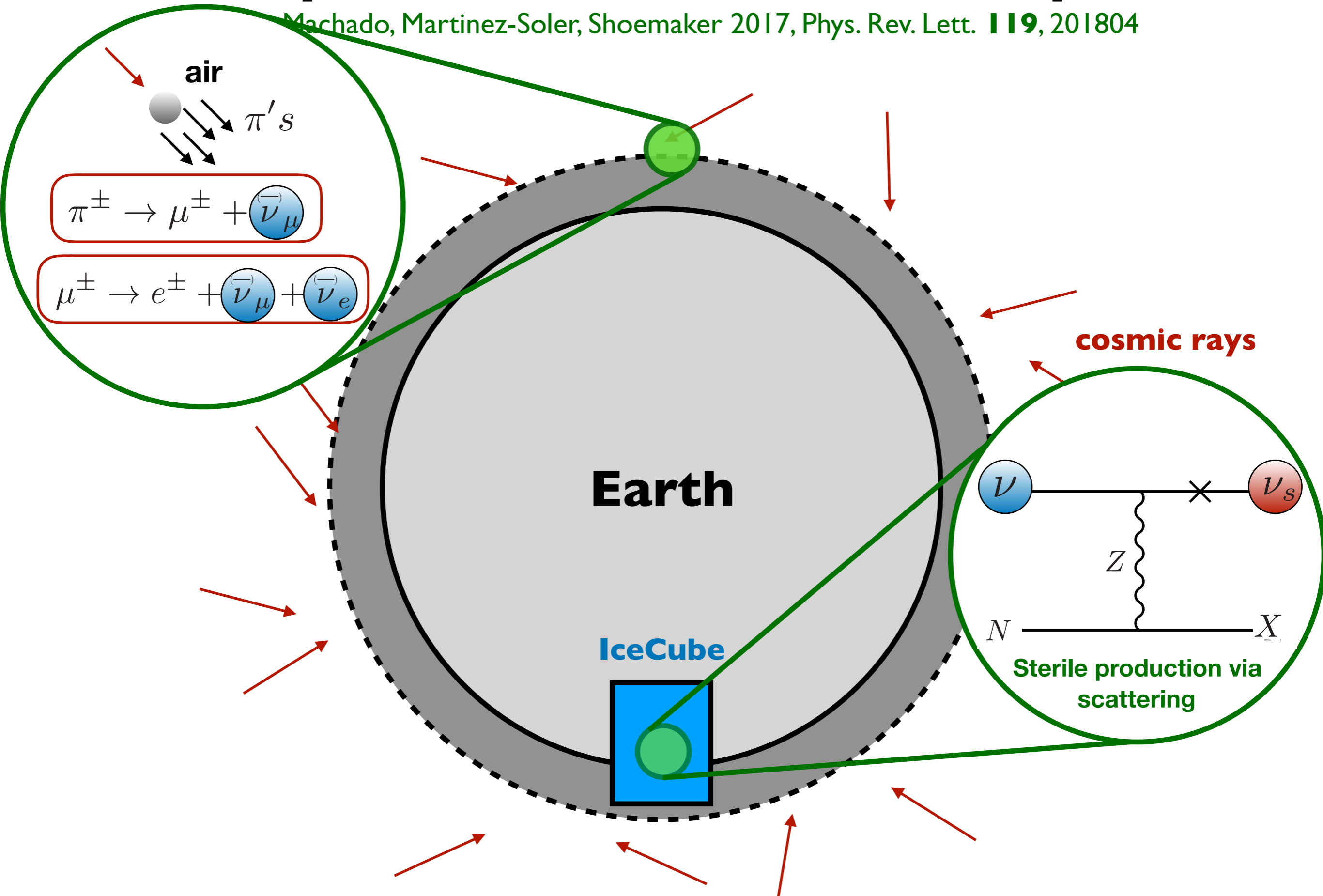
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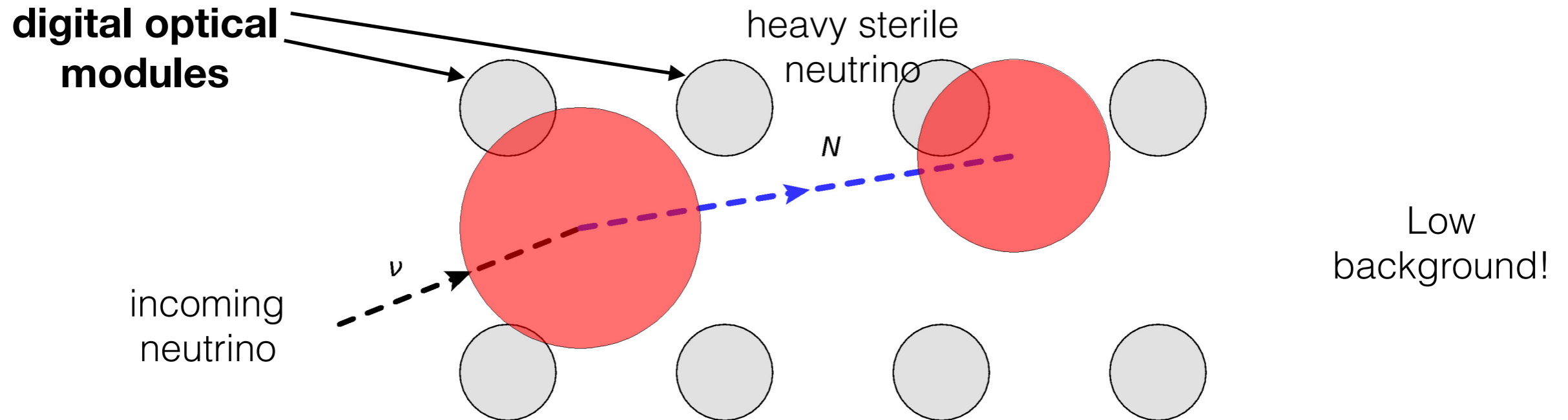
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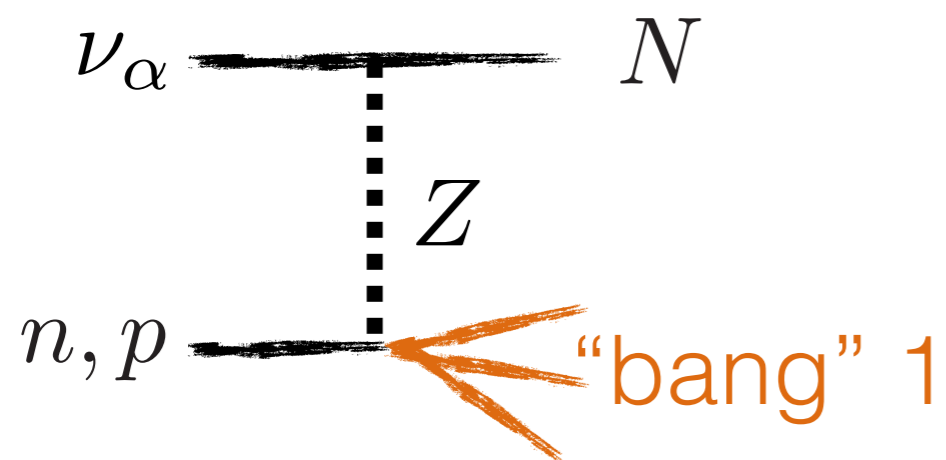


# “Double-bangs” from Sterile Neutrinos

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



Step 1: produce  $N$



Step 2:  $N$  decays

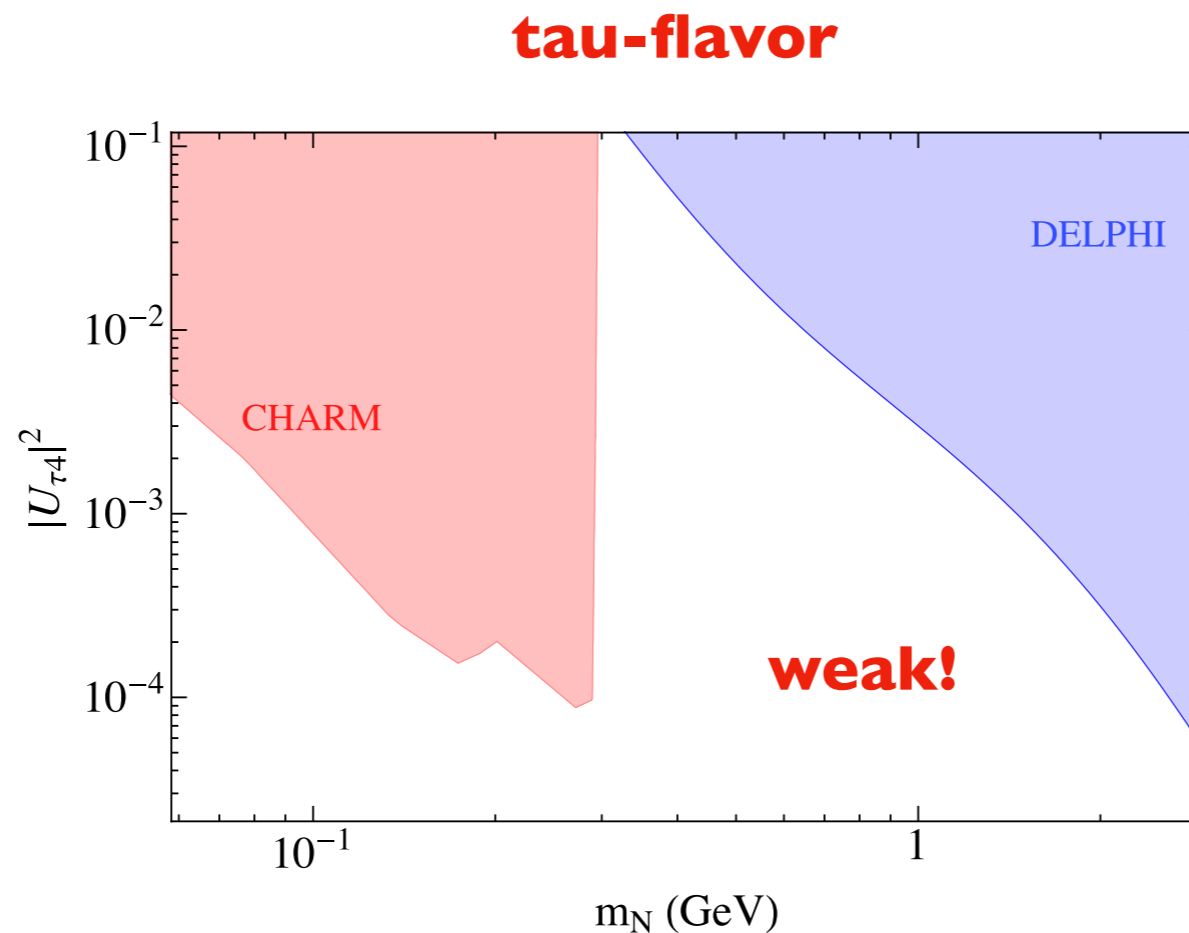


No extra radiation between steps 1 and 2.

# Existing Constraints

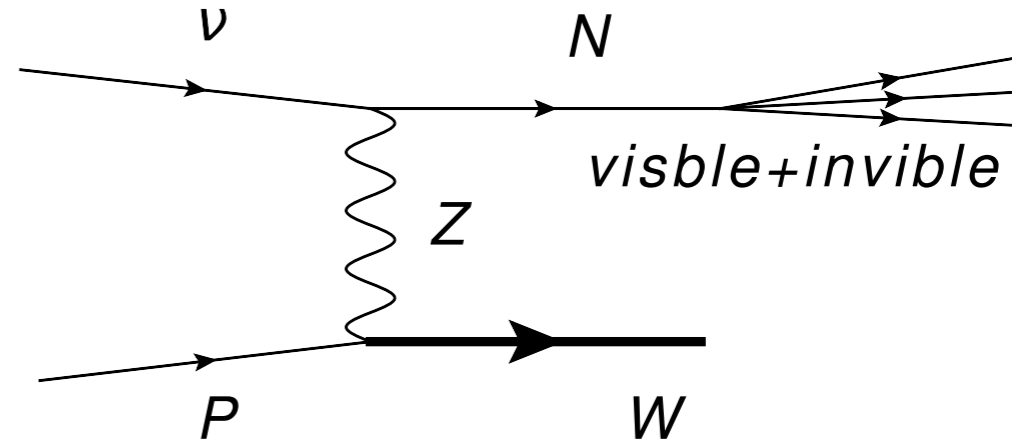
- Assume sizable mixing with only one heavy neutrino

$$\nu_{\alpha L} = \sum_{i=1}^3 U_{\alpha i} \nu_{iL} + U_{\alpha 4} N_{4R}^c$$



# Boosted decay length

$$N_4 \rightarrow \text{visible} + \text{invisible}$$



$$N_4 \rightarrow \nu_l P^0 \text{ (Pseudoscalar mesons)}$$

$$N_4 \rightarrow \nu_l V^0 \text{ (Neutral vector mesons)}$$

$$N_4 \rightarrow l^- P^+ \text{ (Charged pseudoscalar mesons)}$$

$$N_4 \rightarrow l^- V^+ \text{ (Charged vector mesons)}$$

$$N_4 \rightarrow \tau \nu_l l^+ \tau$$

$$N_4 \rightarrow \nu_{l_1} l_2^+ l_2^-$$

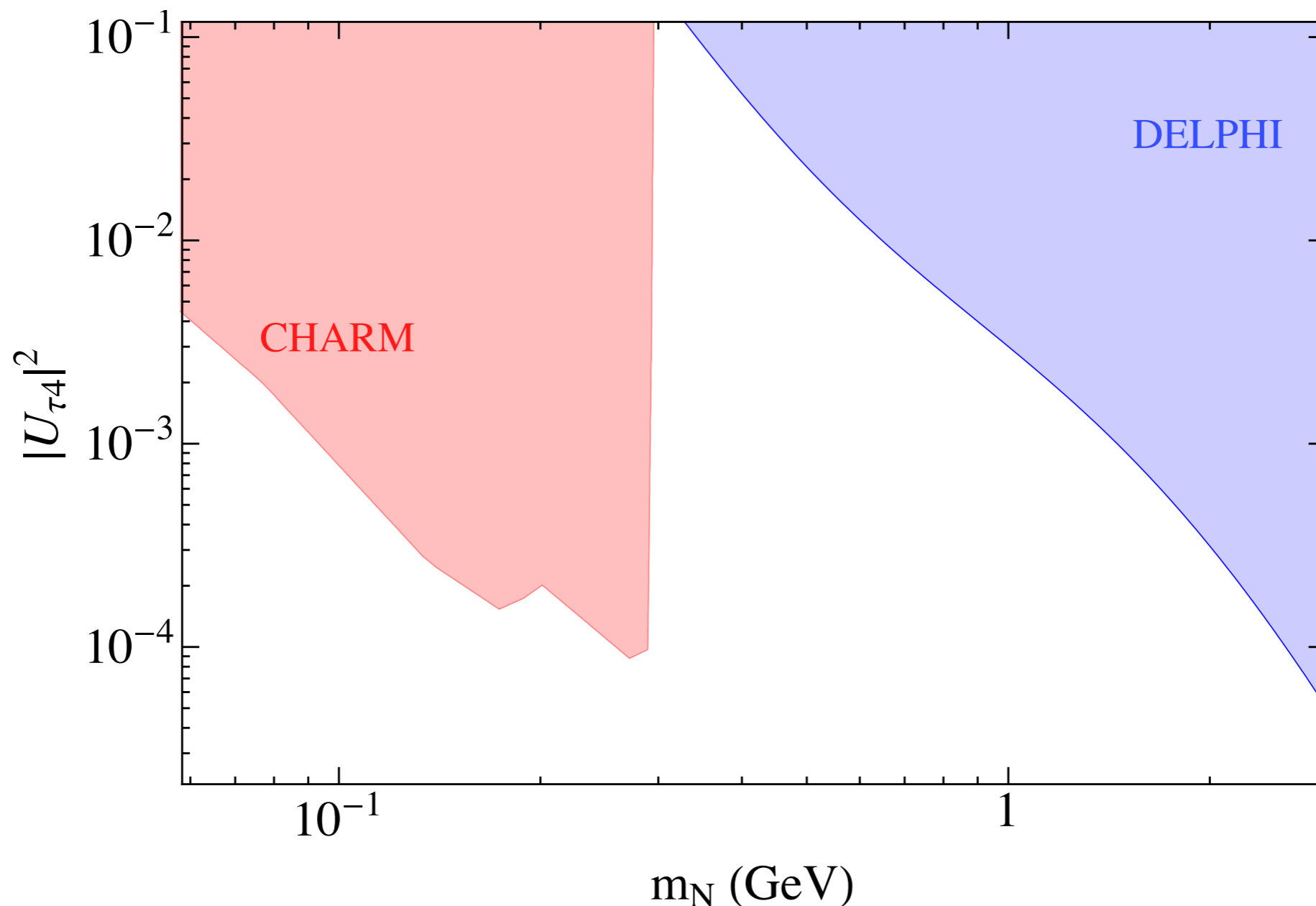
$$N_4 \rightarrow \nu \nu \bar{\nu}$$

## Example

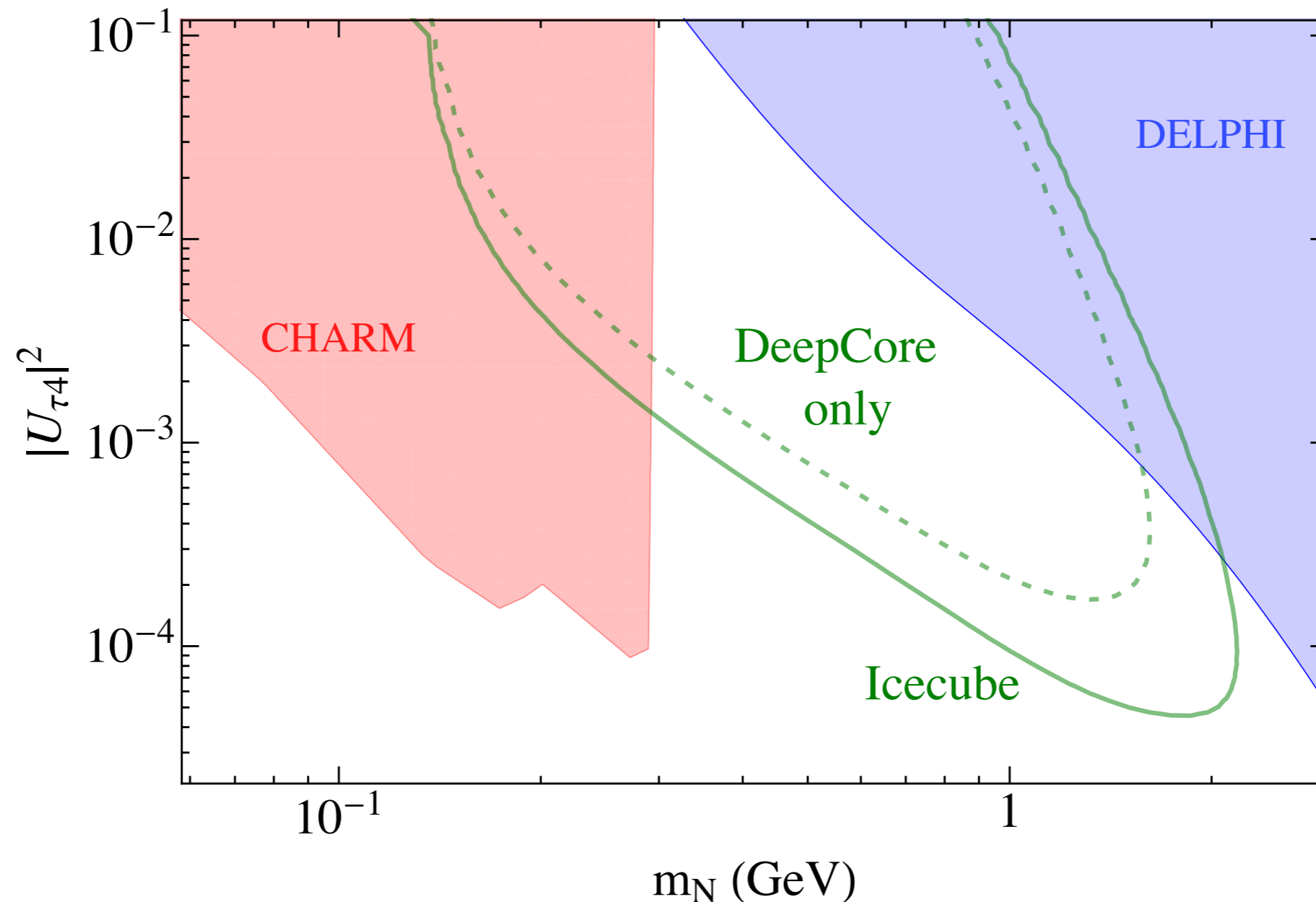
$$m_N = 1 \text{ GeV and } |U_{\tau 4}|^2 = 10^{-3}$$

$$\text{and } 10 \text{ GeV boost} \Rightarrow L_{\text{lab}} \sim 20 \text{ m}$$

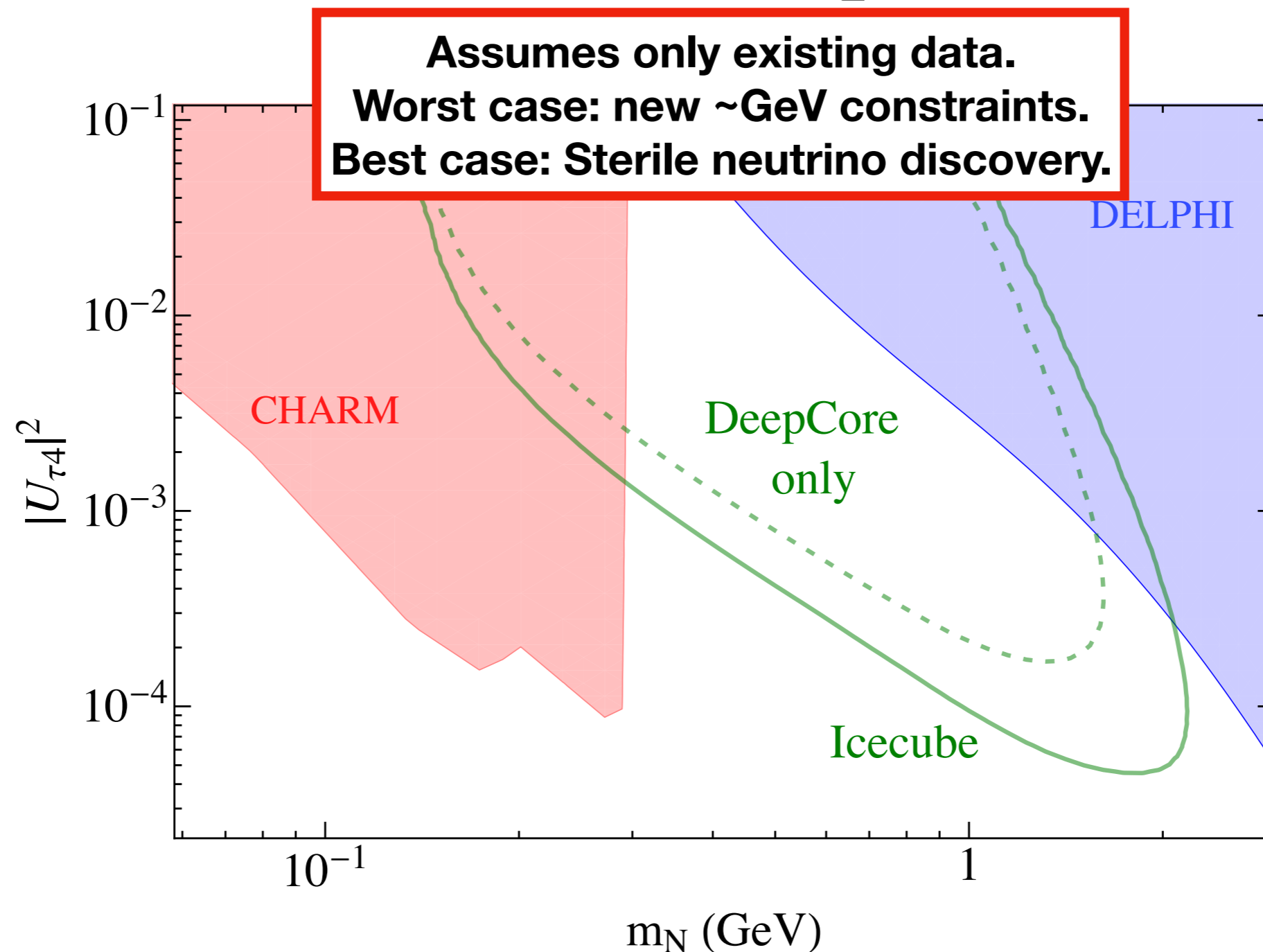
# Heavy Neutrinos from the Atmosphere



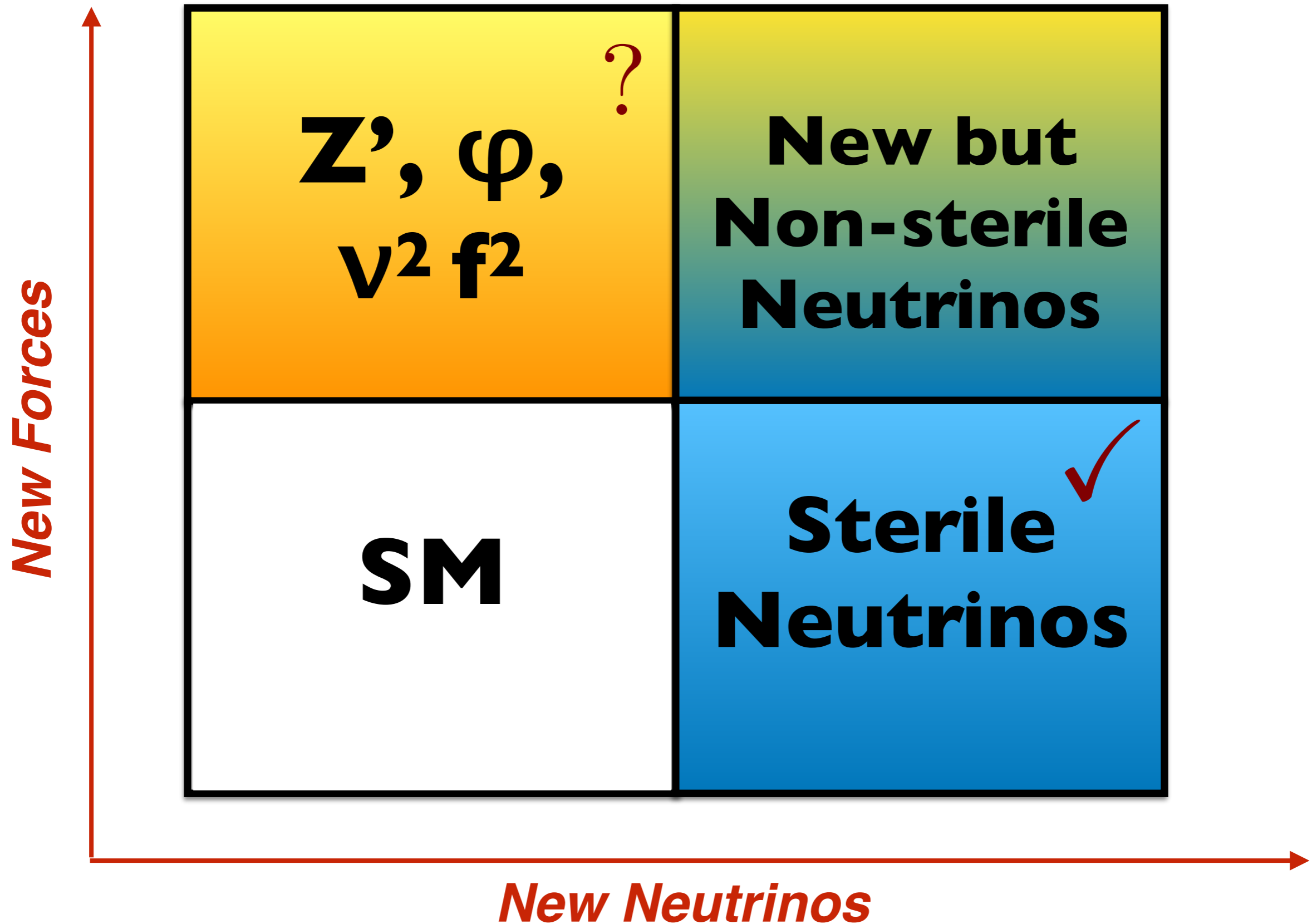
# Heavy Neutrinos from the Atmosphere



# Heavy Neutrinos from the Atmosphere



# BSM Space Schema



# What can $\nu$ -forces do?

- **Modify scattering rates:** exchange of new force carrier, contact interactions.
- **Modify oscillations:** additional matter effect from forward scattering on electrons, quarks, or DM.
- **Introduce decay channel:** Majoron(-like) models can allow for neutrino decay [Denton, Tamborra 2017]
- **Shorten mean free path:**  $\nu$ - $\nu$  or  $\nu$ -DM scatterings on cosmological distances [Kolb, Turner 1987], [Ng, Beacom 2014], [Ioka, Murase 2014], ...
- **Altered cosmology:** new scattering rates/matter potential change thermal history. [Babu, Rothstein 1992], [Dasgupta, Kopp 2013], [Cherry, Friedland, IMS 2016], ...

# Searching for BSM physics Effectively

- **Regard the Standard Model as a low-energy effective theory. Can incorporate neutrino masses via Weinberg operator**

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$$c^{d=5} \frac{(LH)^2}{\Lambda} \quad \text{valid up to } E \lesssim \Lambda$$

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$$c^{d=5} \frac{(LH)^2}{\Lambda} \quad \text{valid up to } E \lesssim \Lambda$$

- **Rinse and repeat:**

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{d=5}{\Lambda} \mathcal{O}^{d=5} + \frac{d=6}{\Lambda} \mathcal{O}^{d=6} + \dots$$

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$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{d=5}{\Lambda} \mathcal{O}^{d=5} + \frac{d=6}{\Lambda} \mathcal{O}^{d=6} + \dots$$

**CC NSI**

$$(\bar{l}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{q} \gamma^\mu P q')$$

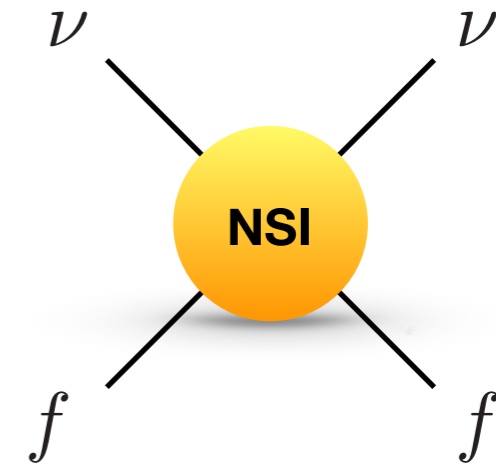
**Source, detector effects**

**NC NSI**

$$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f)$$

**propagation effects**

# Matter Matters!



## Neutrino oscillations in matter

L. Wolfenstein

*Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*

(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta) (\bar{f} \gamma_\rho P f)$$

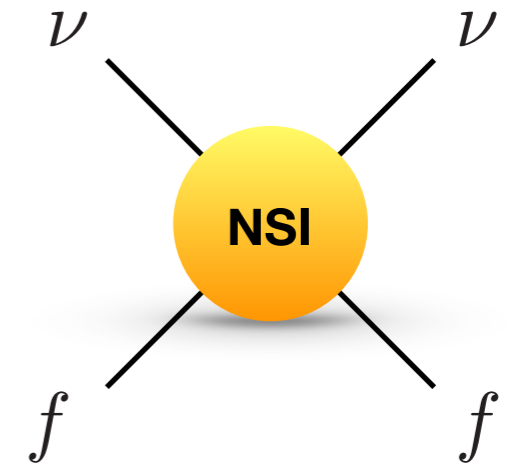
Neutrino Flavor

f = SM fermion  
P=L,R

- **Coherent forward scattering** crucial for neutrino oscillations.
- Oscillation physics constrain **neutrino-medium interactions**.

# 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, Razaque (2007)], [Friedland, IMS (2012)], [Mocioiu, Wright (2014)], [Coloma (2015)]...

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

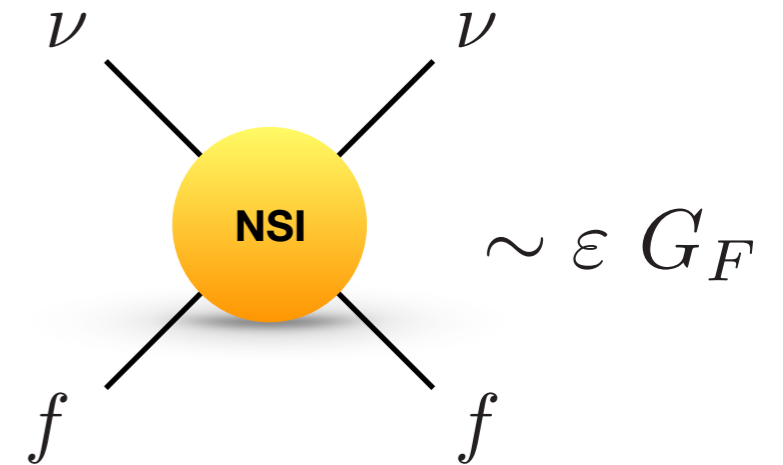
[Davidson et al. (2003)], [Coloma et al. (2017)], [Liao, Marfatia (2017)], [Dutta, Liao, Strigari, Walker (2017)], [Dent, Dutta, Liao, Newstead, Stirgari, Walker (2017)], [Denton, Farzan, IMS (2018)].

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

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

(very incomplete list)

# Oscillation Degeneracies



- Oscillation data allow large NSI in the “LMA-dark” window.

**standard LMA**

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

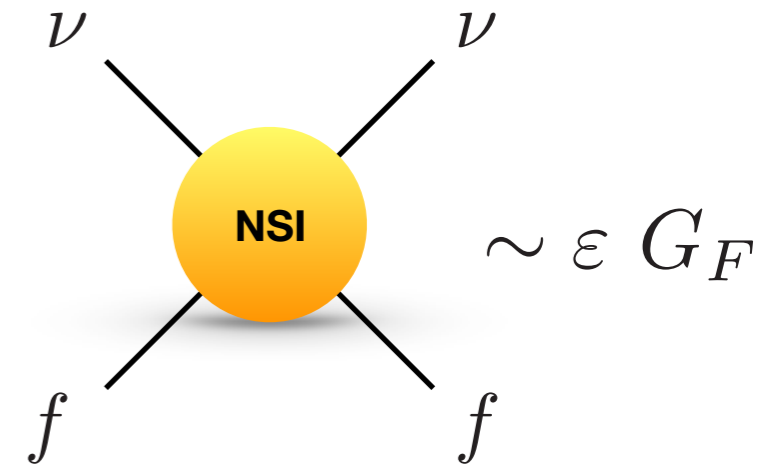
osc.  
degenerate  
↔

**LMA-dark**

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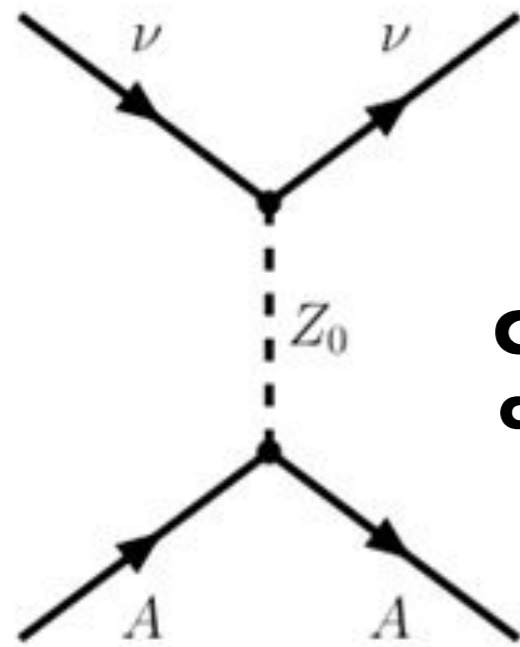
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$$45^\circ < \theta_{12} < 90^\circ$$

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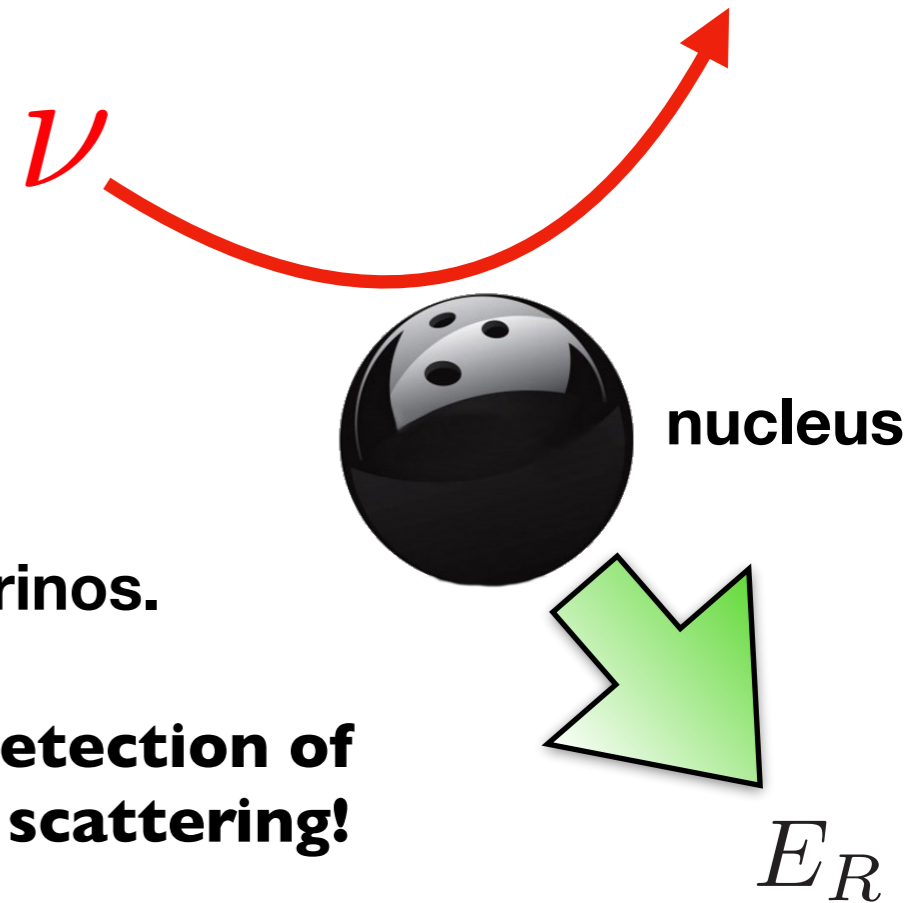
**Scattering data can break this degeneracy.**

# COHERENT Strategies for New Physics



Stopped pion source = low-E neutrinos.

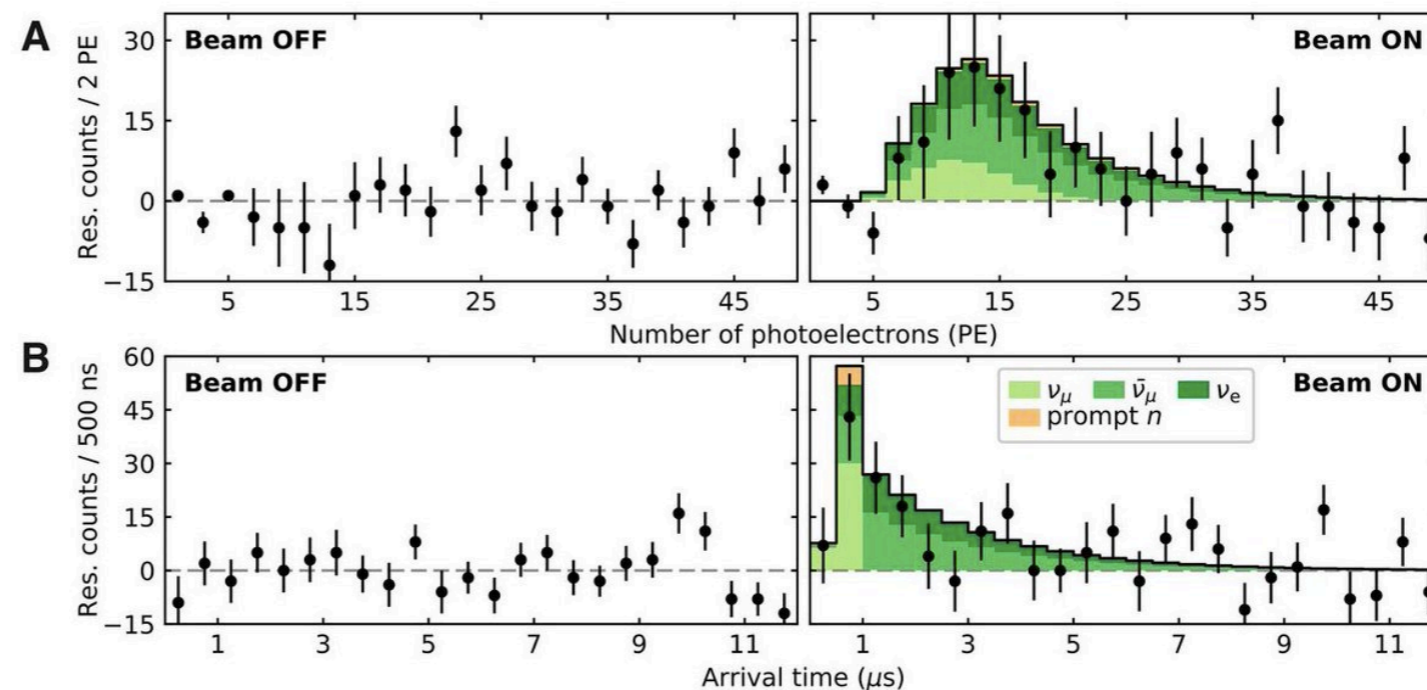
**COHERENT Collaboration: First detection of coherent elastic neutrino-nucleus scattering!**



See Gleb  
Sinev's talk

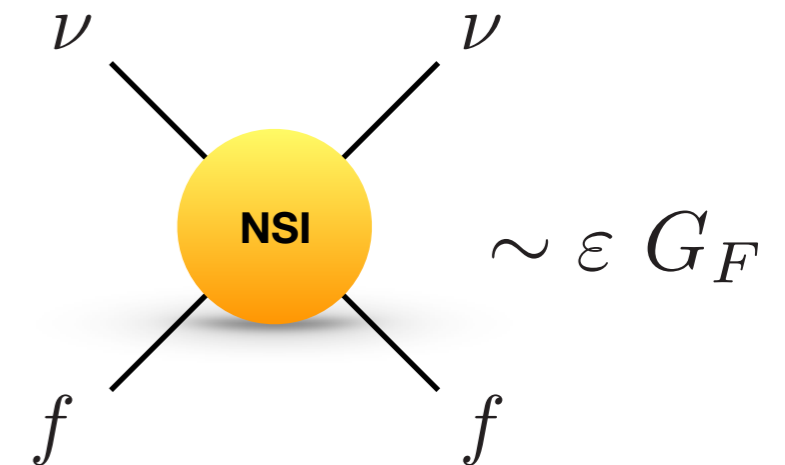
See Andrew  
Kubik's talk

**COHERENT Collaboration, 2017 [1708.01294].**



Can test BSM contributions to neutrino scattering.

# Oscillation Degeneracies



- Oscillation data still allow large NSI in the “LMA-dark” window.

standard LMA

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

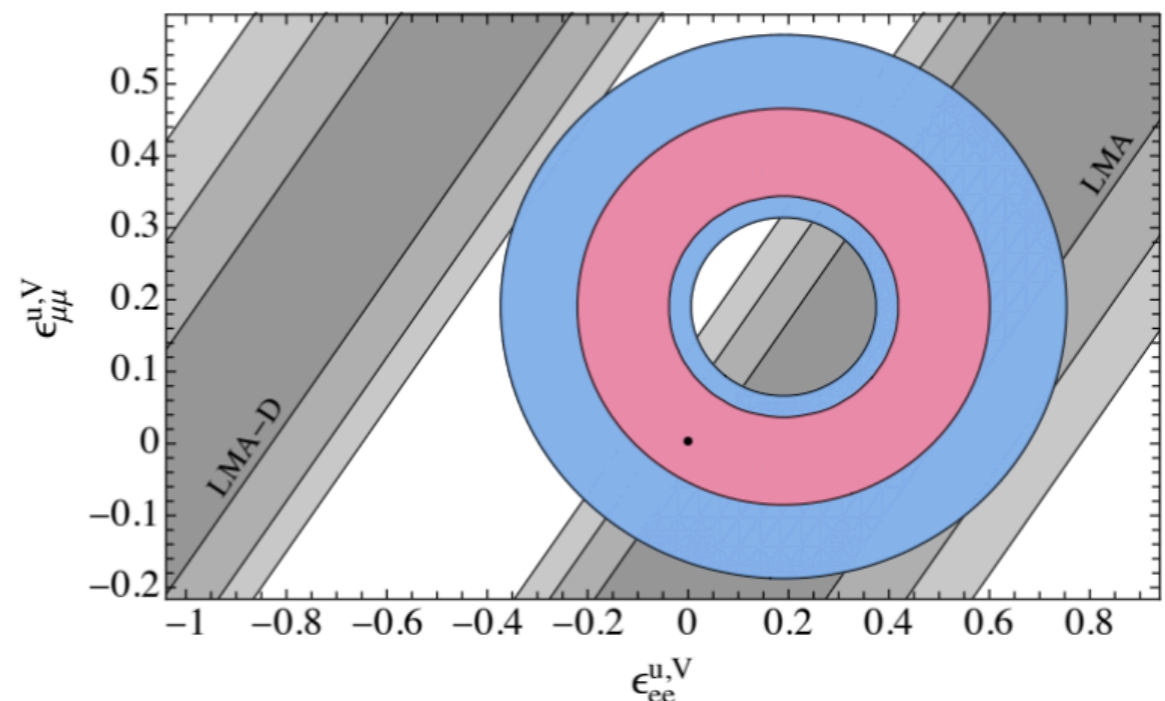
LMA-dark

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

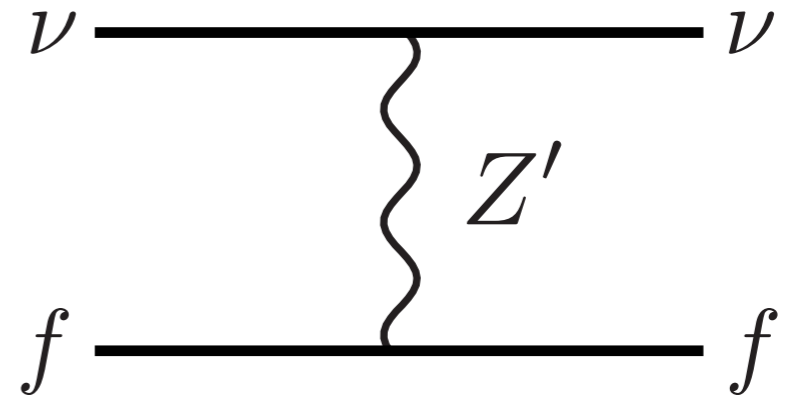
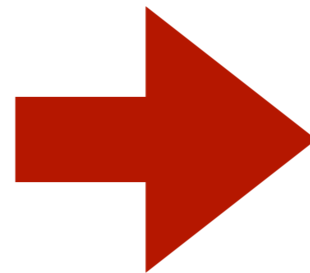
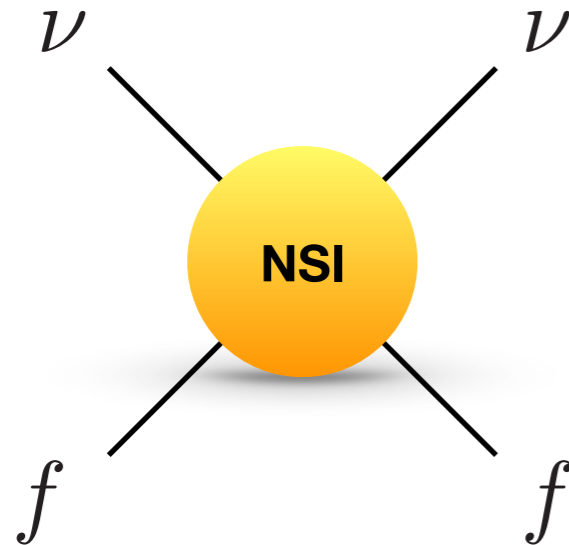
$$+ \epsilon \sim \mathcal{O}(1)$$

**COHERENT** breaks  
degeneracy, rules out  
LMA-D.

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



# NSI at low masses

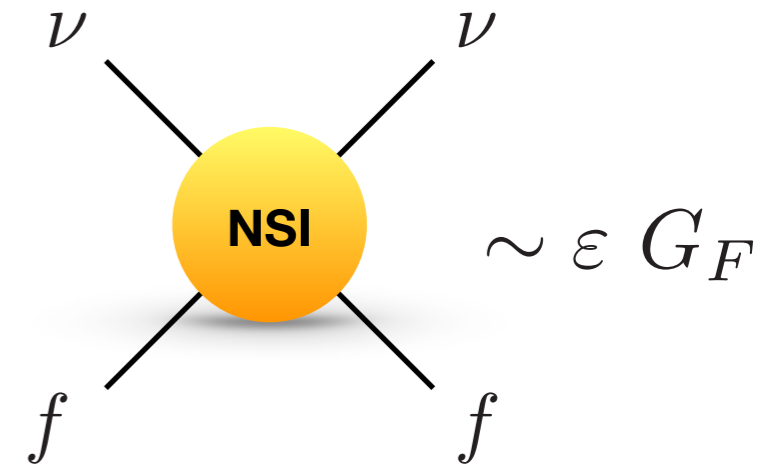


$$\varepsilon G_F \sim \frac{g^2}{m_{Z'}^2}$$

- Various models on the market involving gauge B & L combinations and/or introducing heavy sterile neutrinos.

[Pospelov (2011)], [Farzan (2015)], [IMS, Farzan (2015)], [Farzan, Heeck (2016)], [Babu, Friedland, Machado, Mocioiu (2017), Denton, Farzan, IMS (2018)].

# COHERENT Strategies for “LMA-Dark”

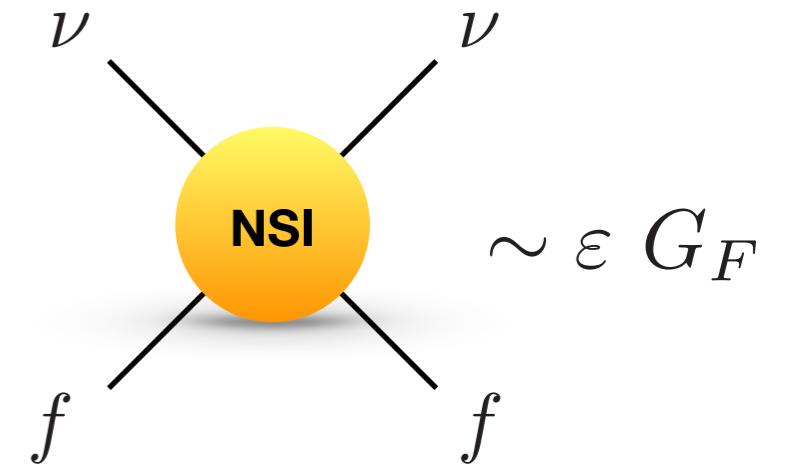


- Closer look at COHERENT’s sensitivity to NSI, by peering inside the operator:

$$\frac{d\sigma^{\text{NSI}}}{dE_R} \propto \begin{cases} \frac{g_\nu^2 g_q^2 m_N}{m_{Z'}^4} & \text{if } m_{Z'} \gg q, \\ \frac{g_\nu^2 g_q^2 m_N}{q^4} & \text{if } m_{Z'} \ll q. \end{cases}$$

$\longrightarrow \epsilon \text{ limits}$   
 $\longrightarrow g \text{ limits}$

# COHERENT Strategies for “LMA-Dark”



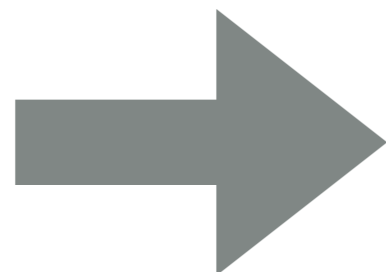
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$\longrightarrow \epsilon \text{ limits}$   
 $\longrightarrow g \text{ limits}$

- Whereas for oscillation propagation the matter potential comes from forward coherent scattering (i.e.  $t=0$ ):

$$V_{\text{matt}} = \frac{g_\nu g_q}{m_{Z'}^2} n_f.$$

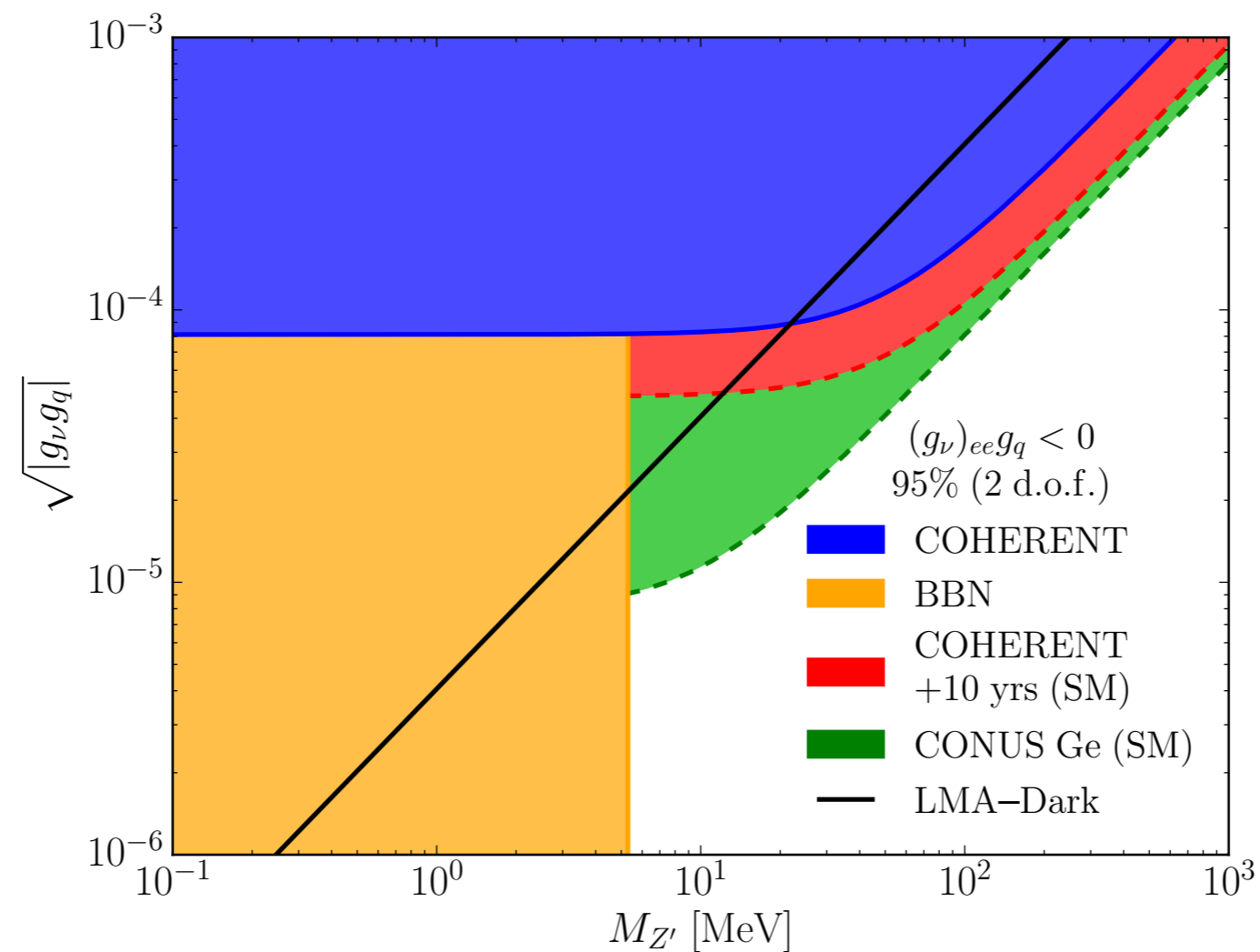


Low masses!

# NSI @ low-masses

Denton, Farzan, IMS [1804.03660]

## e-flavor NSI



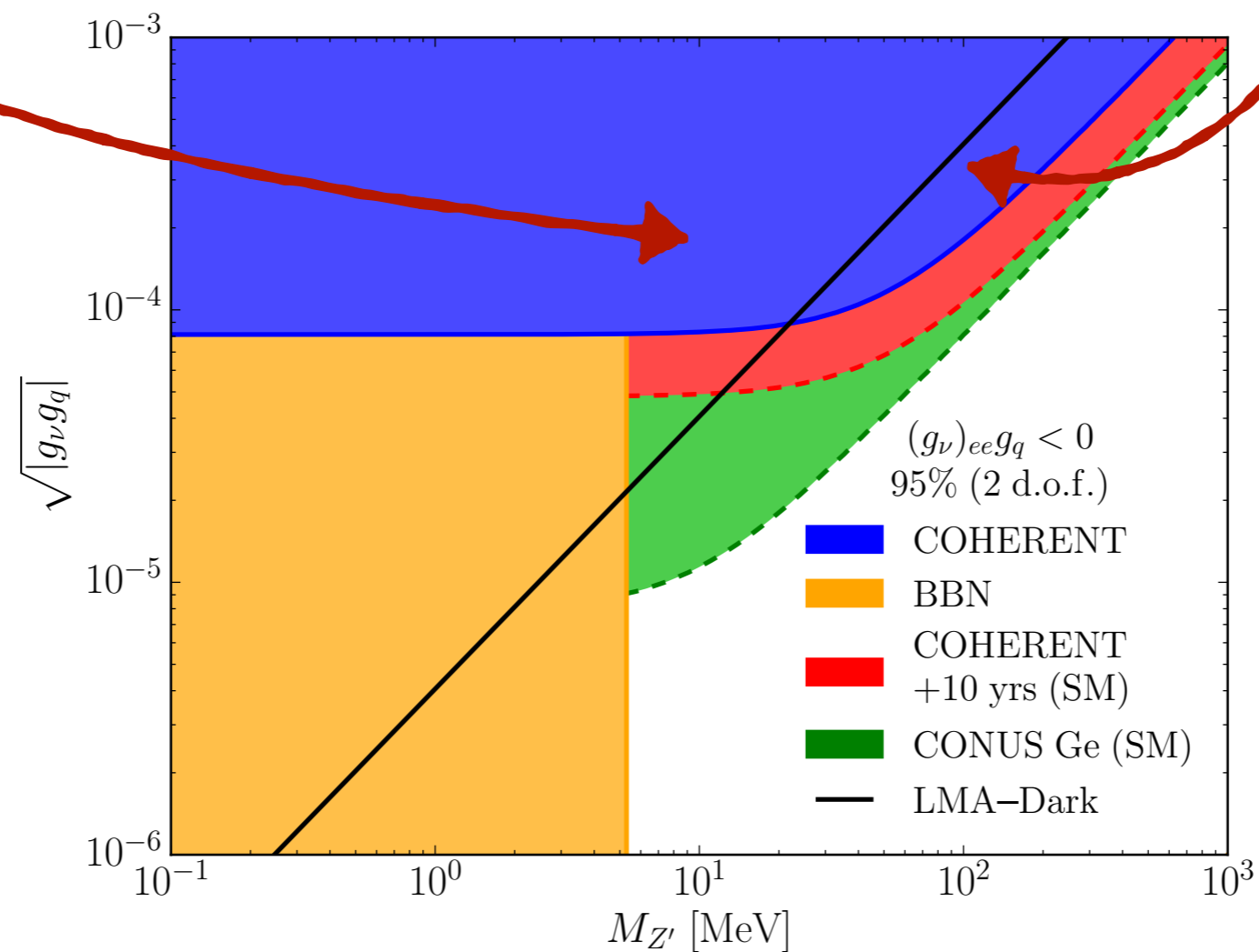
# NSI @ low-masses

Denton, Farzan, IMS [1804.03660]

Current COHERENT

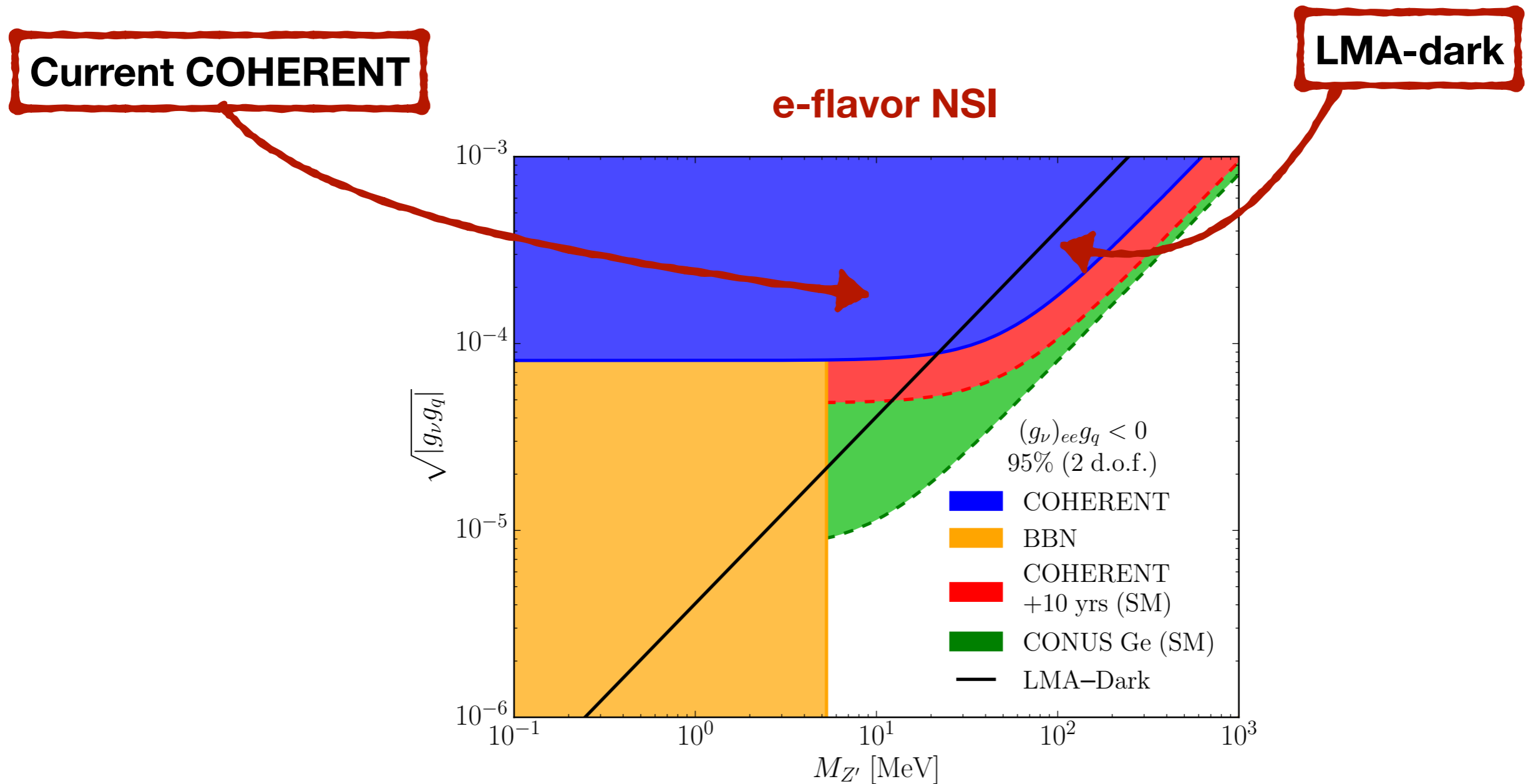
LMA-dark

e-flavor NSI



# NSI @ low-masses

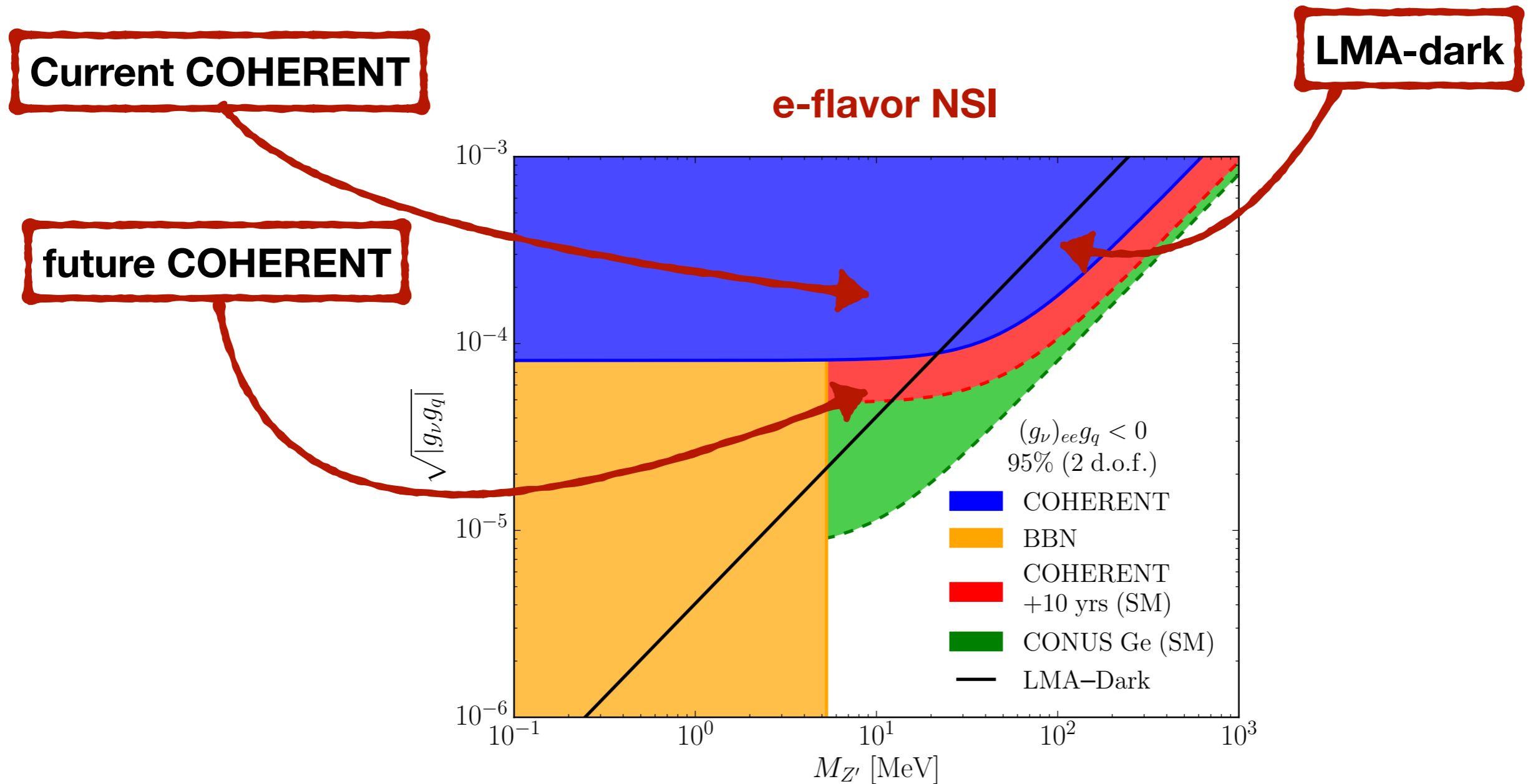
Denton, Farzan, IMS [1804.03660]



- **COHERENT + CMB data allow for a small window of masses with **large NSI**.**

# NSI @ low-masses

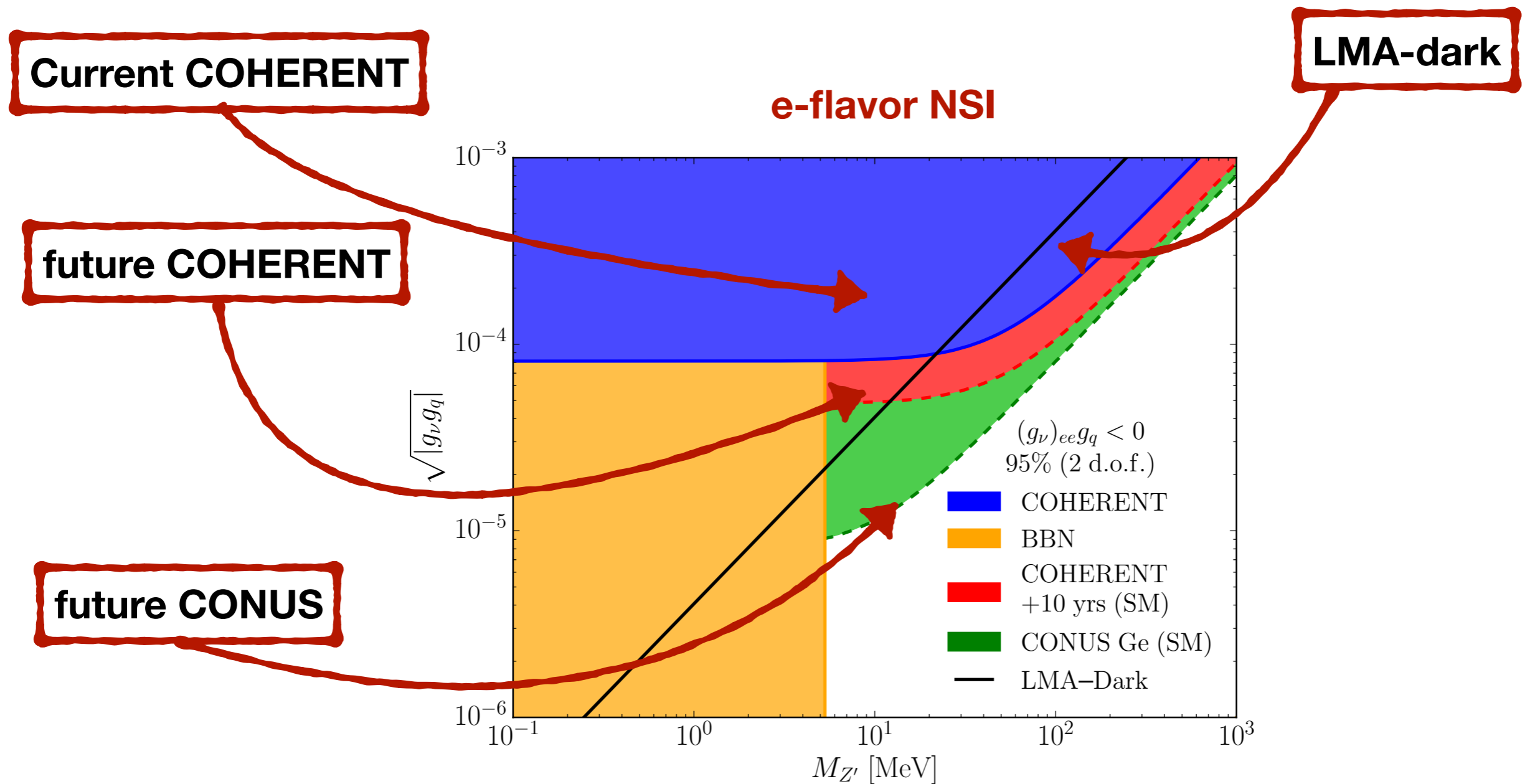
Denton, Farzan, IMS [1804.03660]



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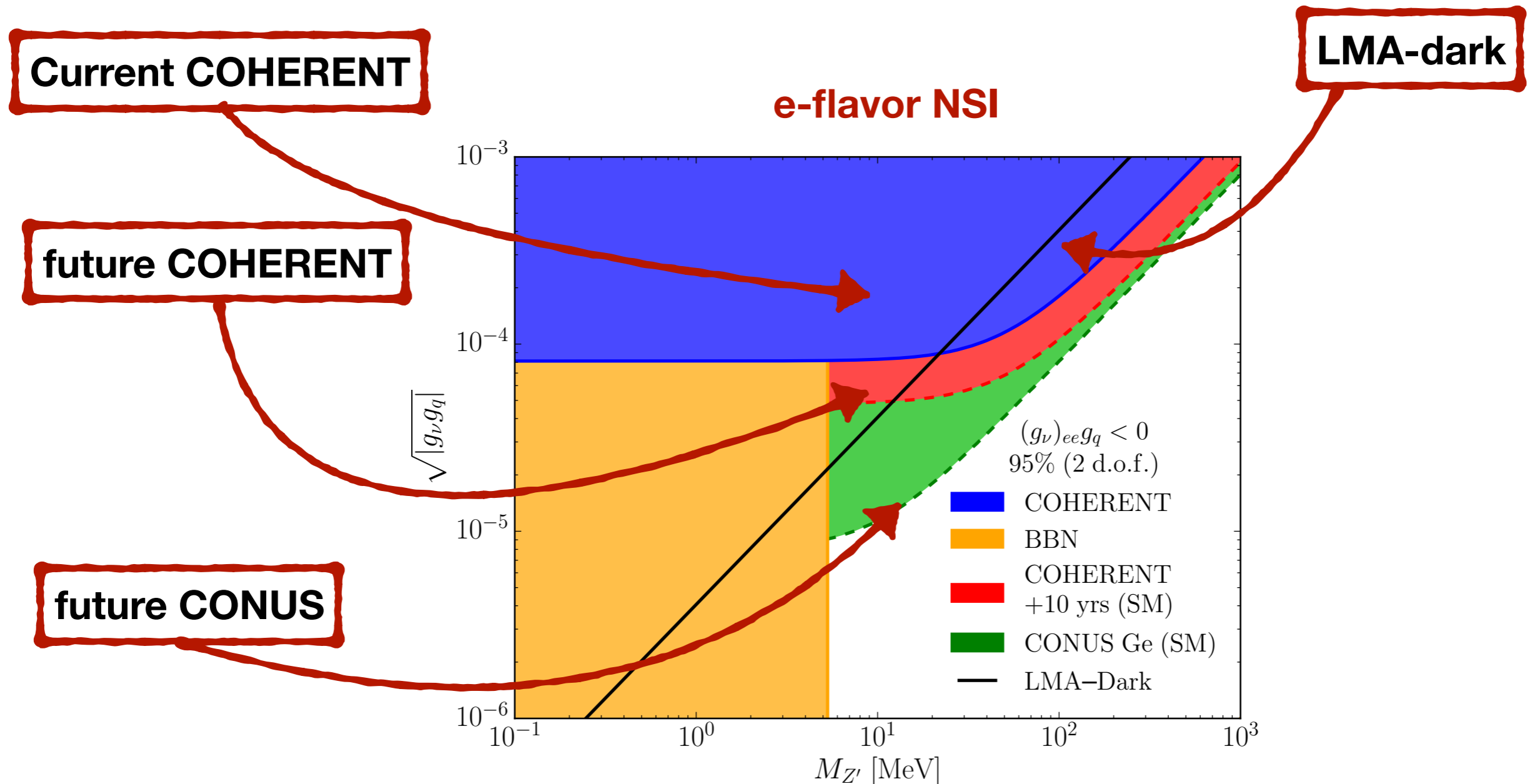
Denton, Farzan, IMS [1804.03660]



- **COHERENT + CMB data allow for a small window of masses with large NSI.**

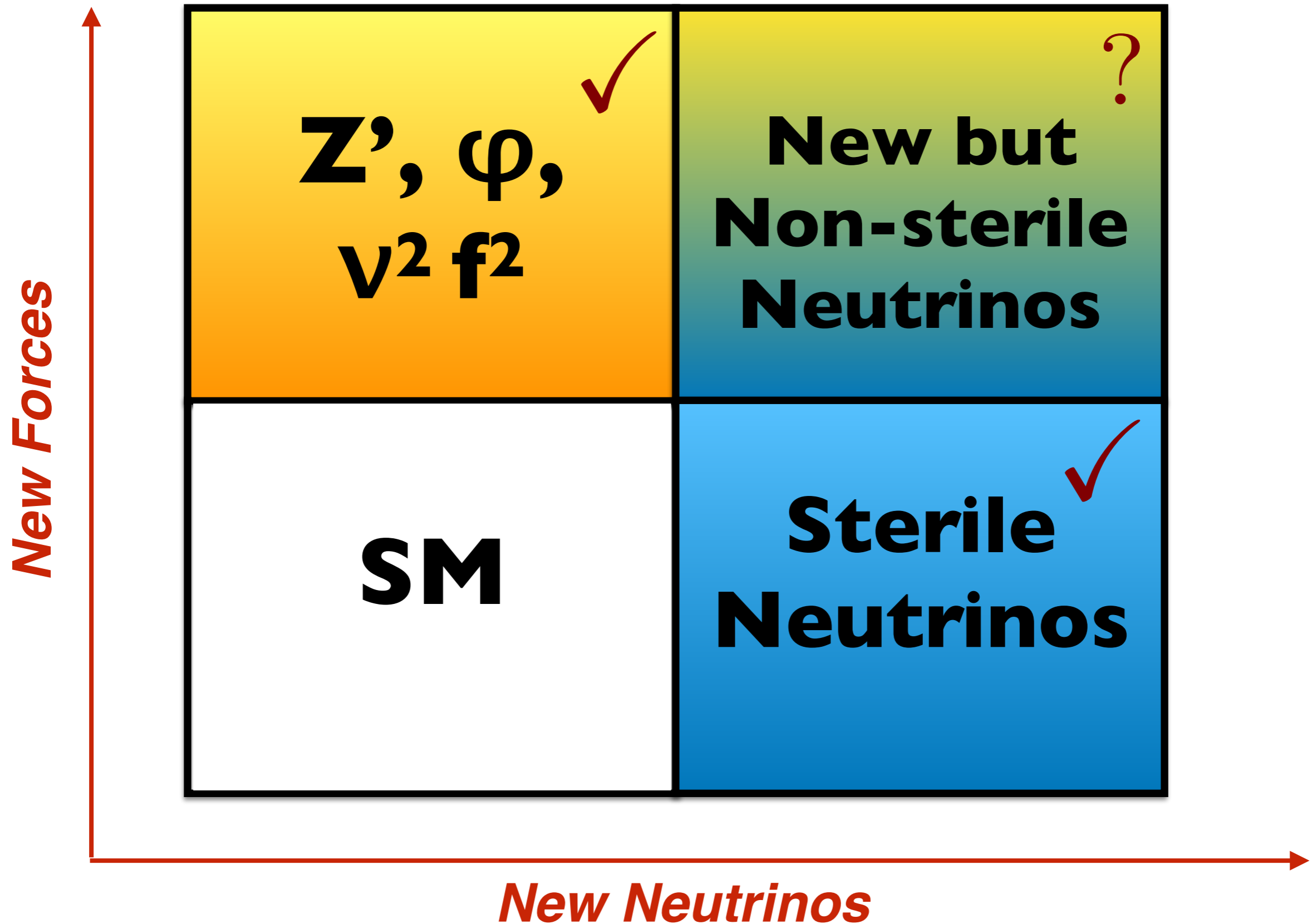
# NSI @ low-masses

Denton, Farzan, IMS [1804.03660]



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

# BSM Space Schema



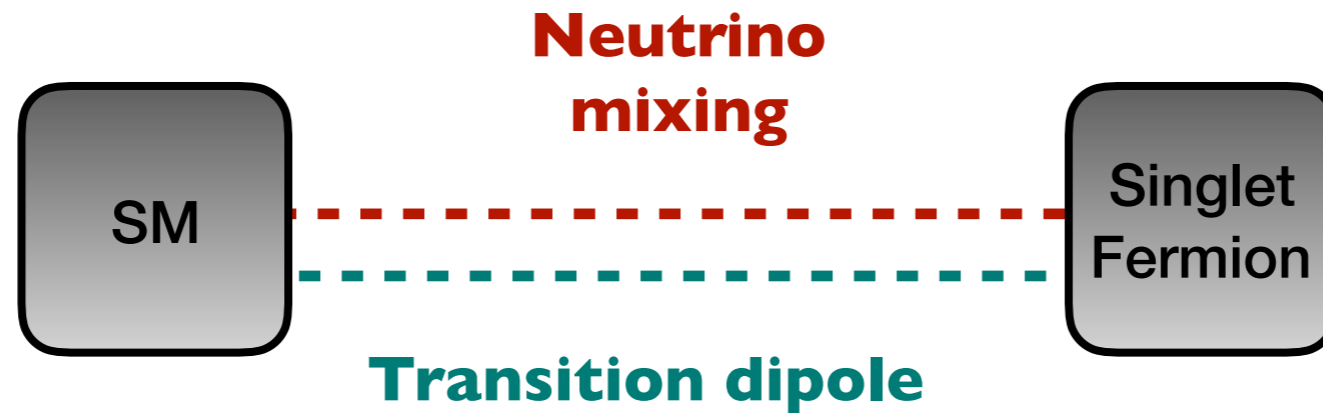
# Potential EM Properties of Sterile Neutrinos

- Don't know dominant Sterile Neutrino -SM “portal”
- Could be higher-dim. operator.

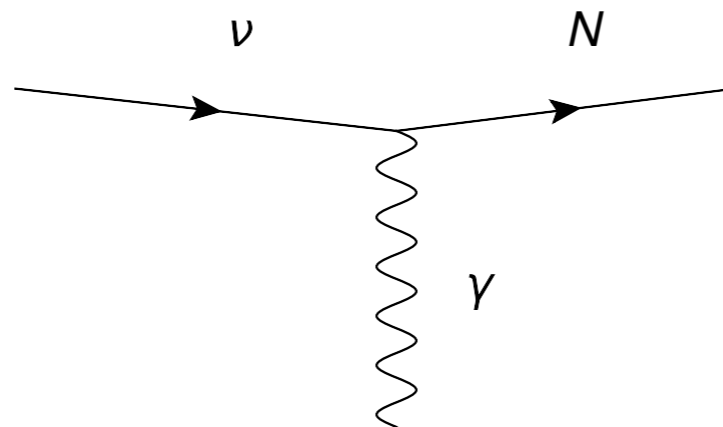


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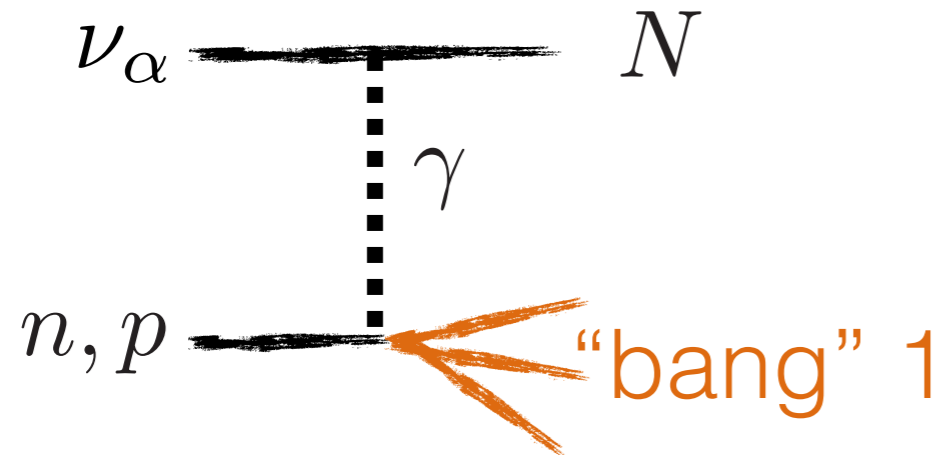


$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$



# Potential EM Properties of Sterile Neutrinos

Step 1: produce N



Step 2: N decays

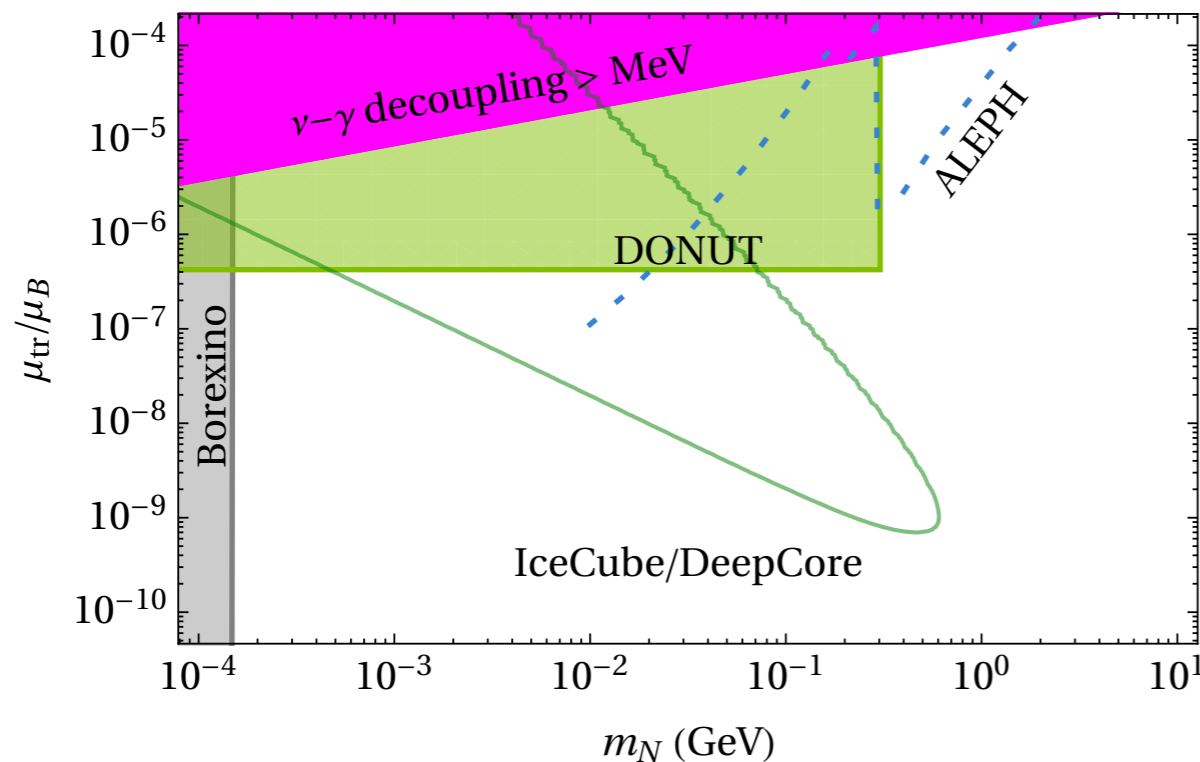


# Potential EM Properties of Sterile Neutrinos

Step 1: produce N



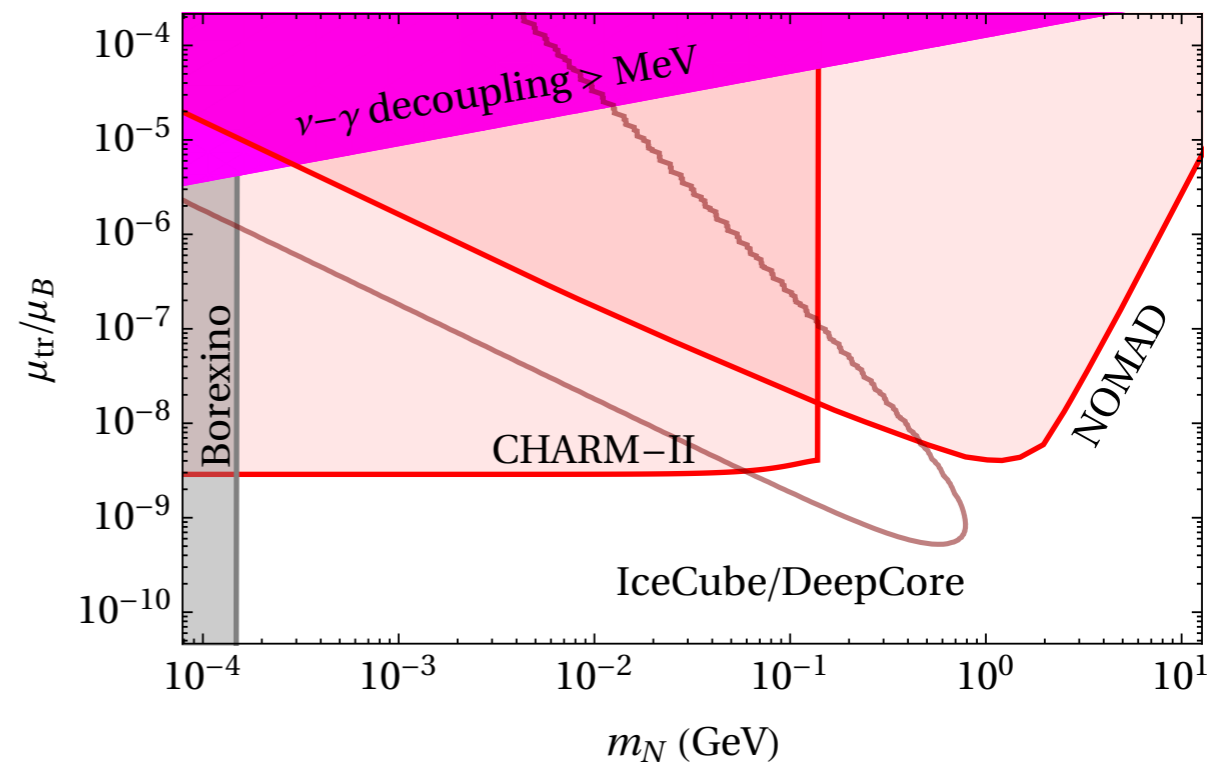
$\nu_\tau - N$  transition



Step 2: N decays



$\nu_\mu - N$  transition

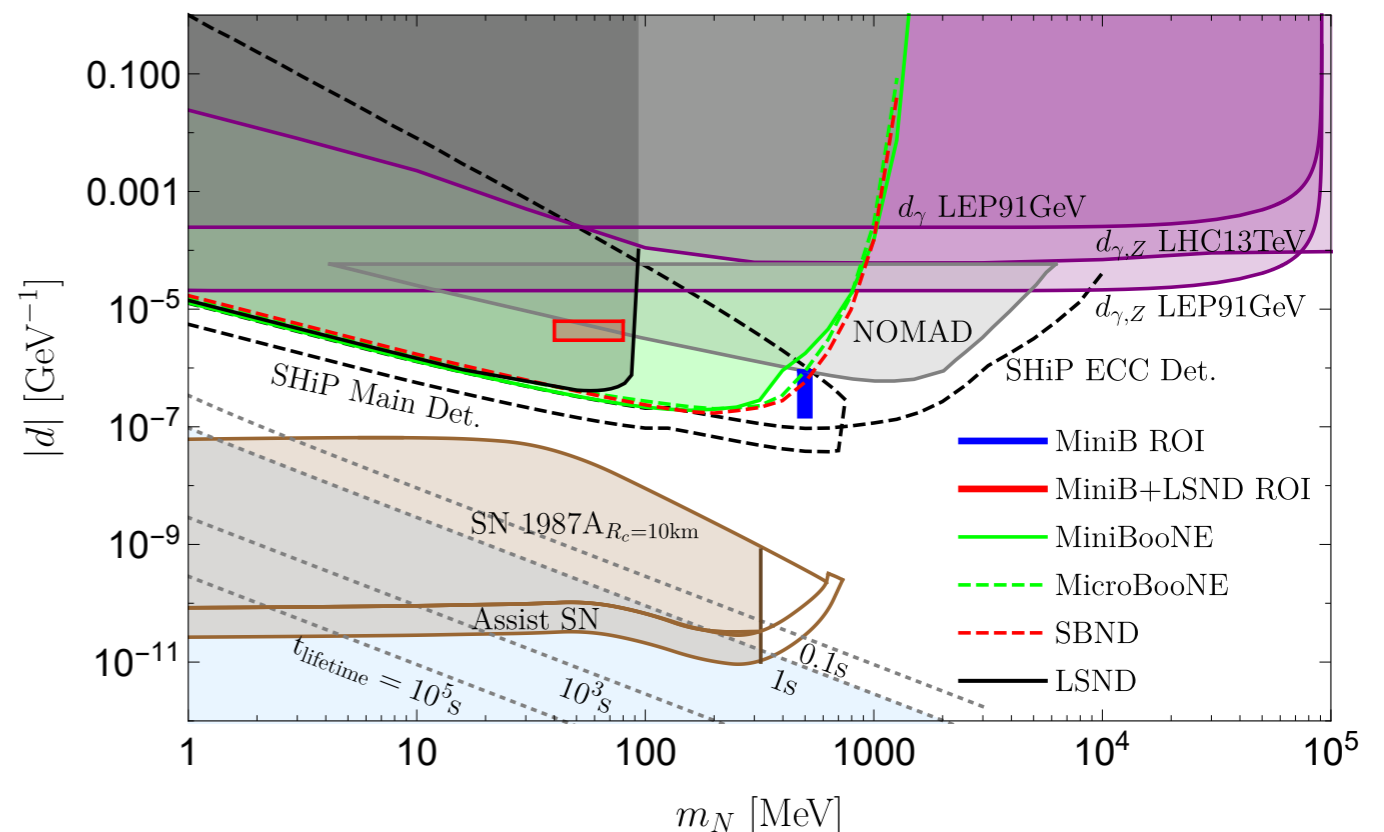
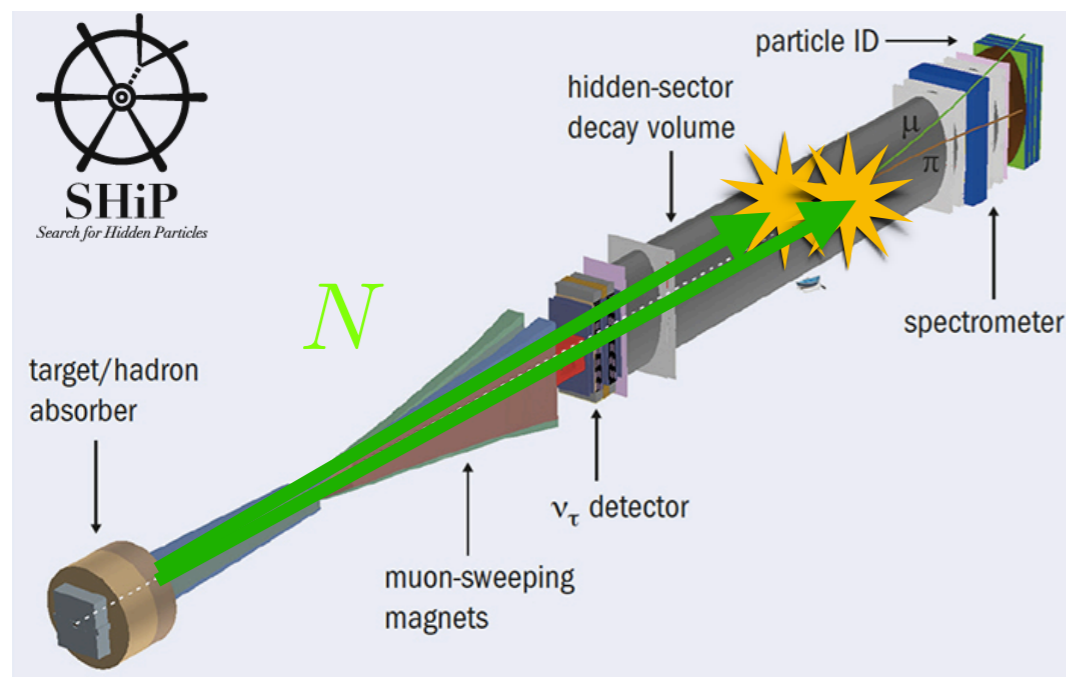


# Dipole portal to heavy neutral leptons

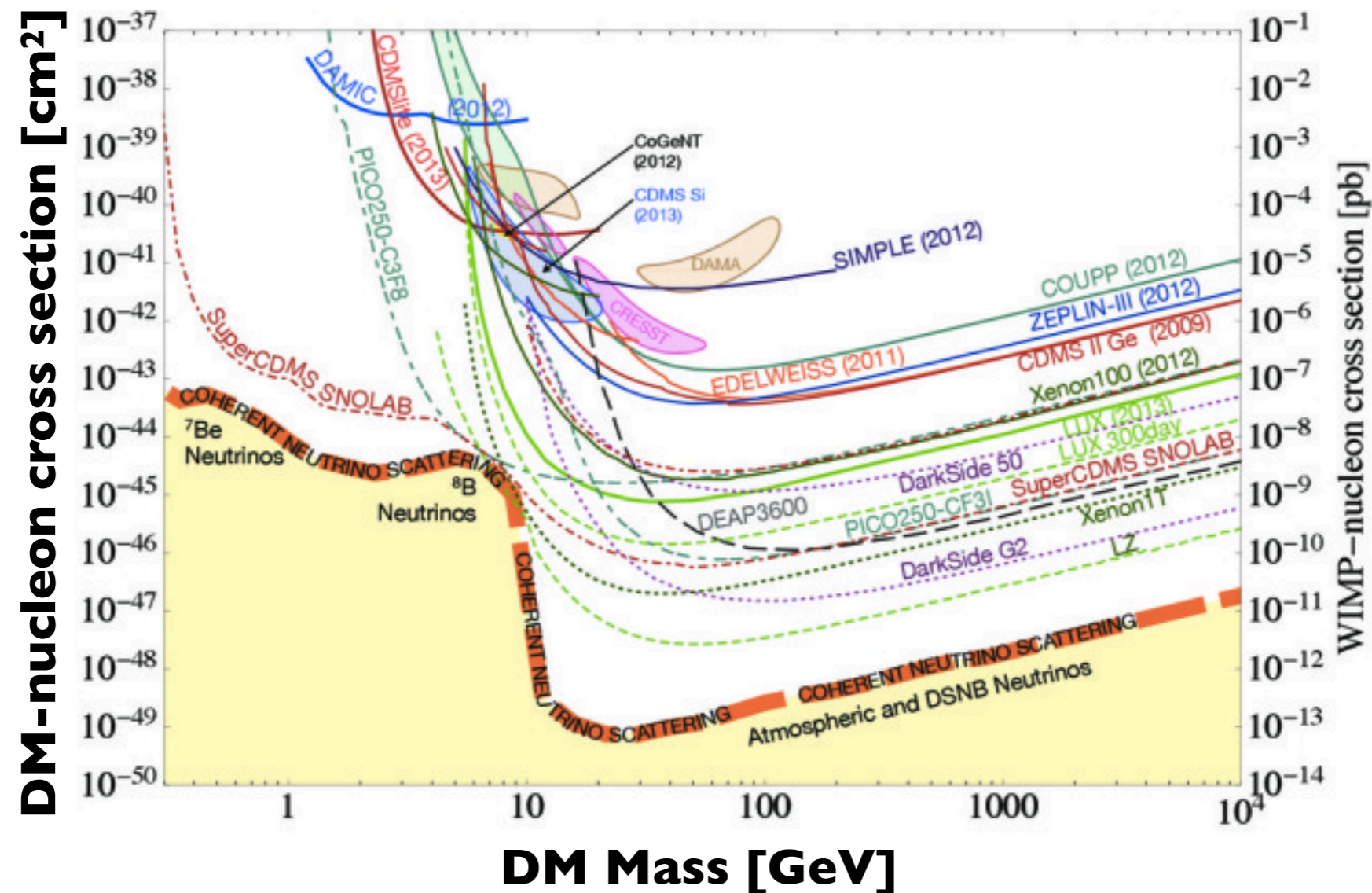
Magill, Plestid, Pospelov, Tsai [1803.03262]

$$\mathcal{L} \supset \bar{N}(i\not{\partial} - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c.).$$

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

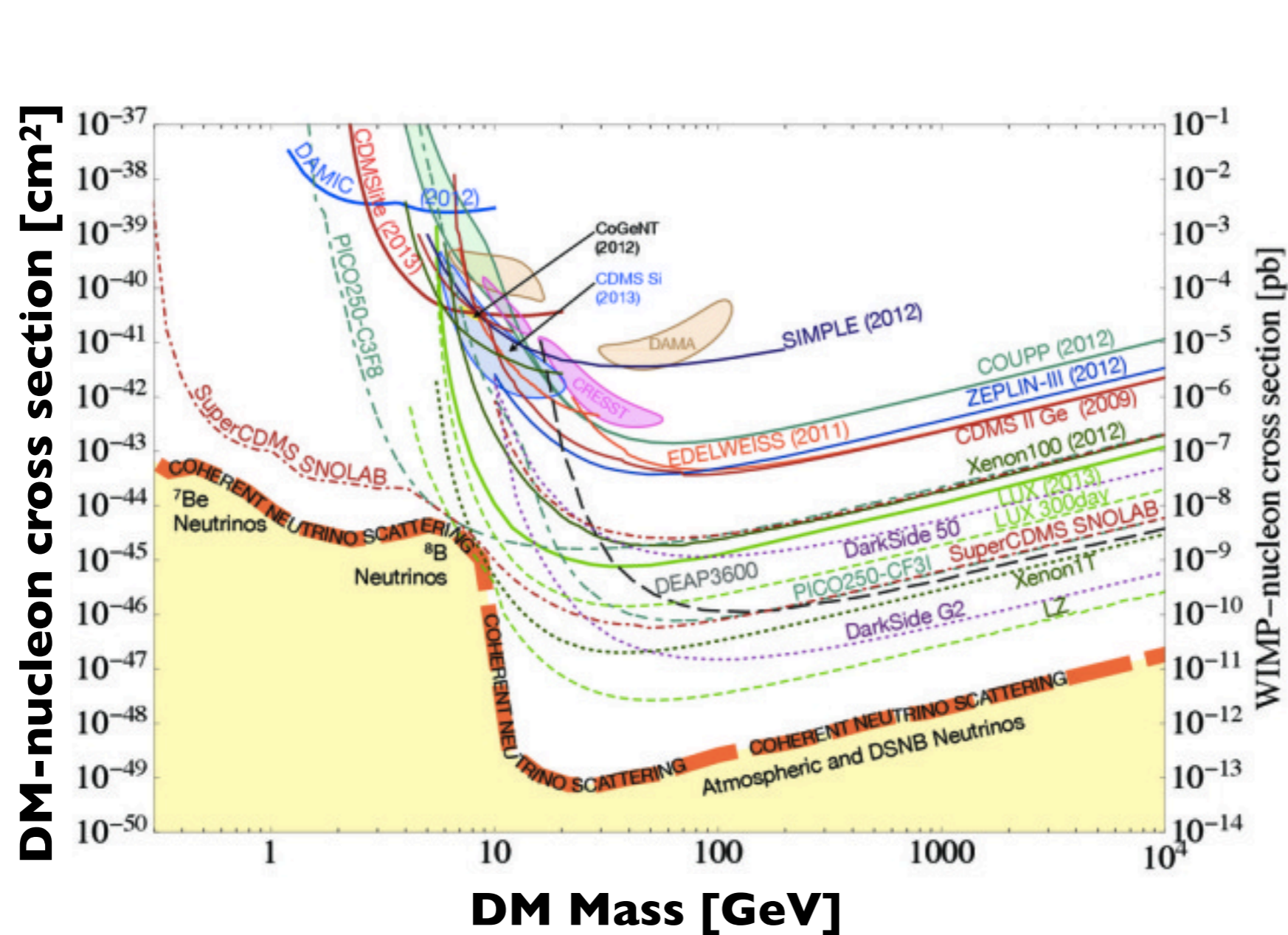


# Future of DM Direct Detection



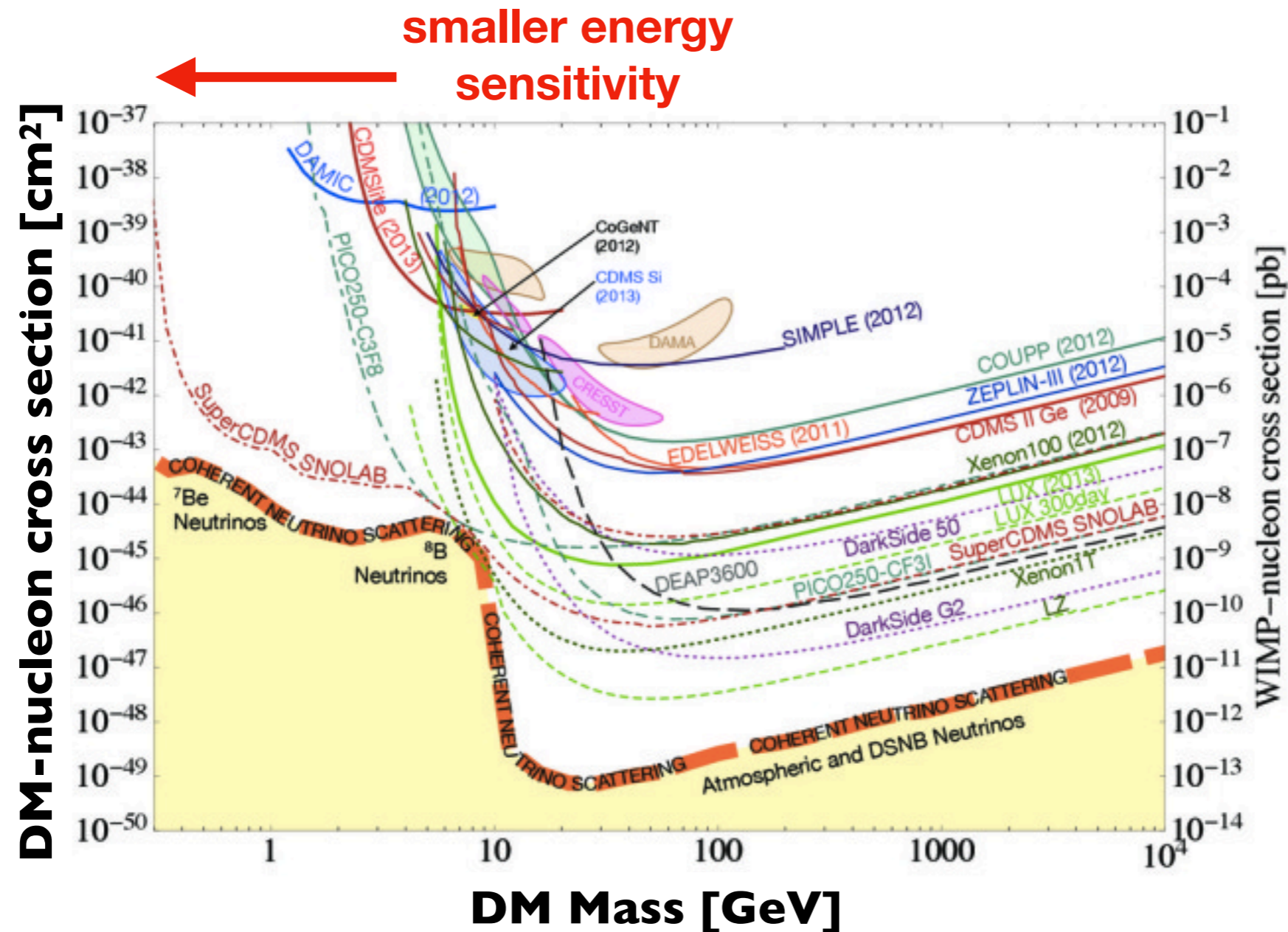
Eventually run into a “neutrino floor.” Bad for DM, but good for neutrinos!

# Future of DM Direct Detection



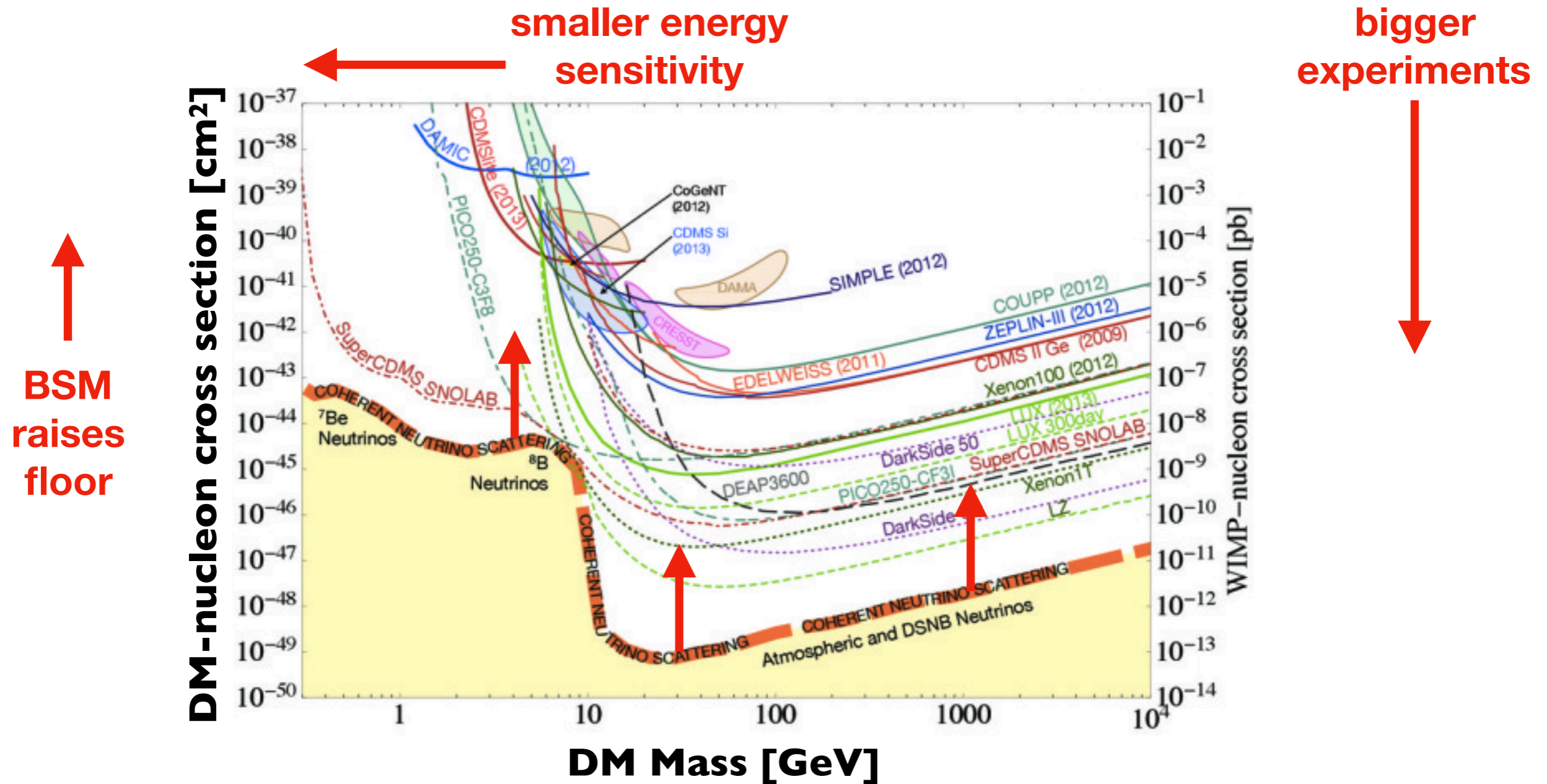
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Eventually run into a “neutrino floor.” Bad for DM, but good for neutrinos!

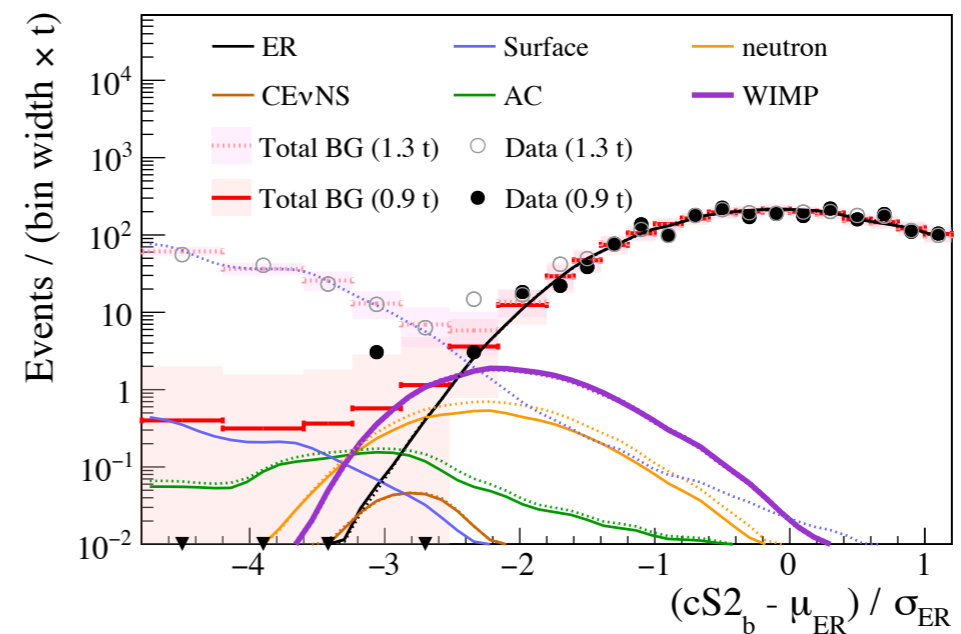
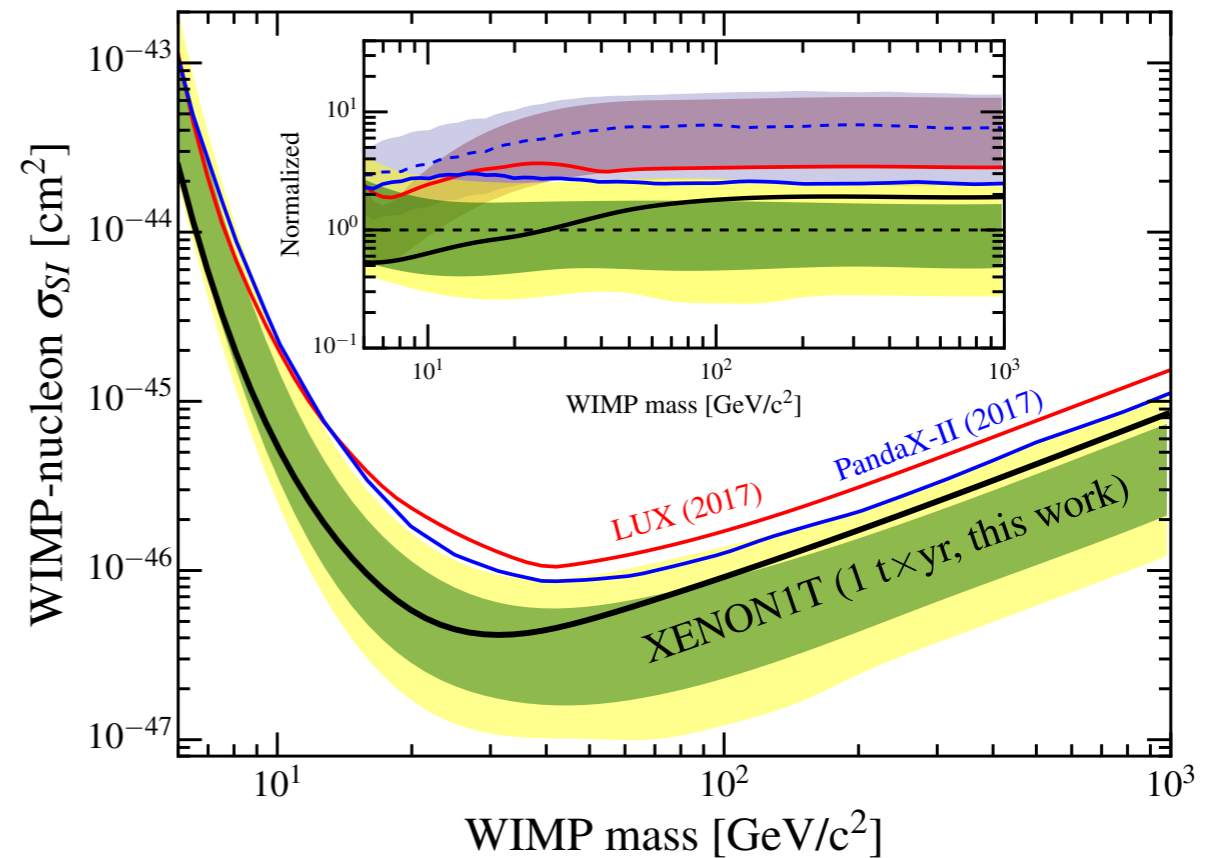
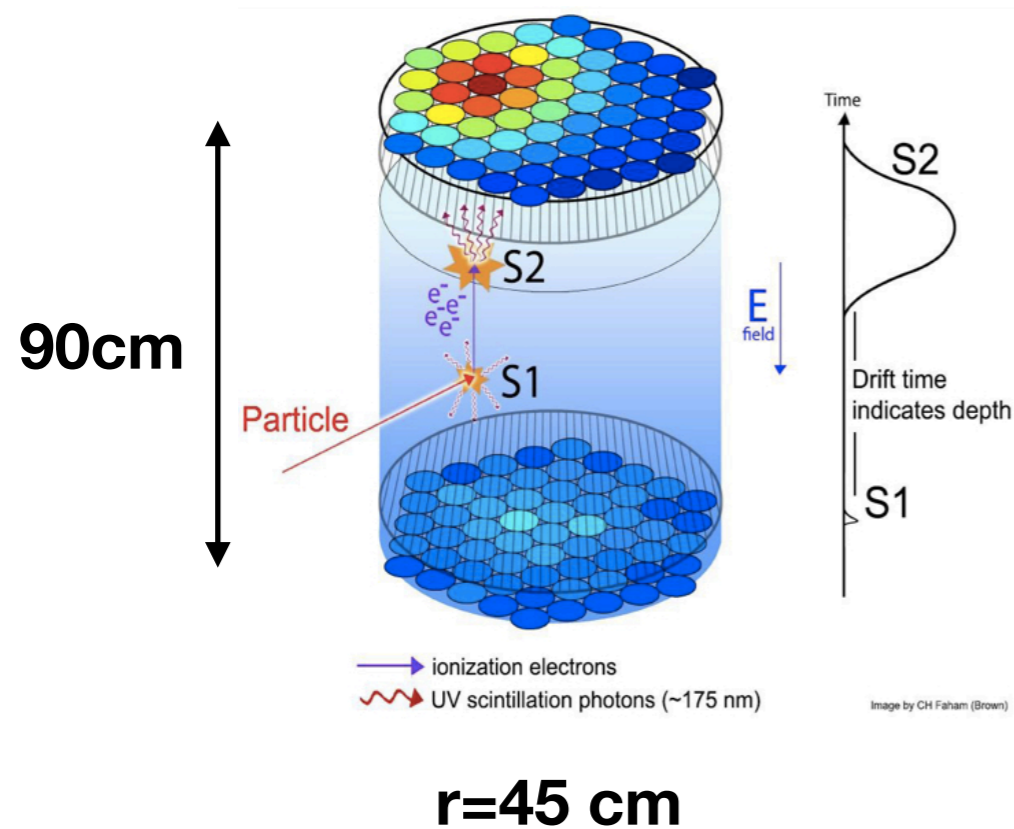
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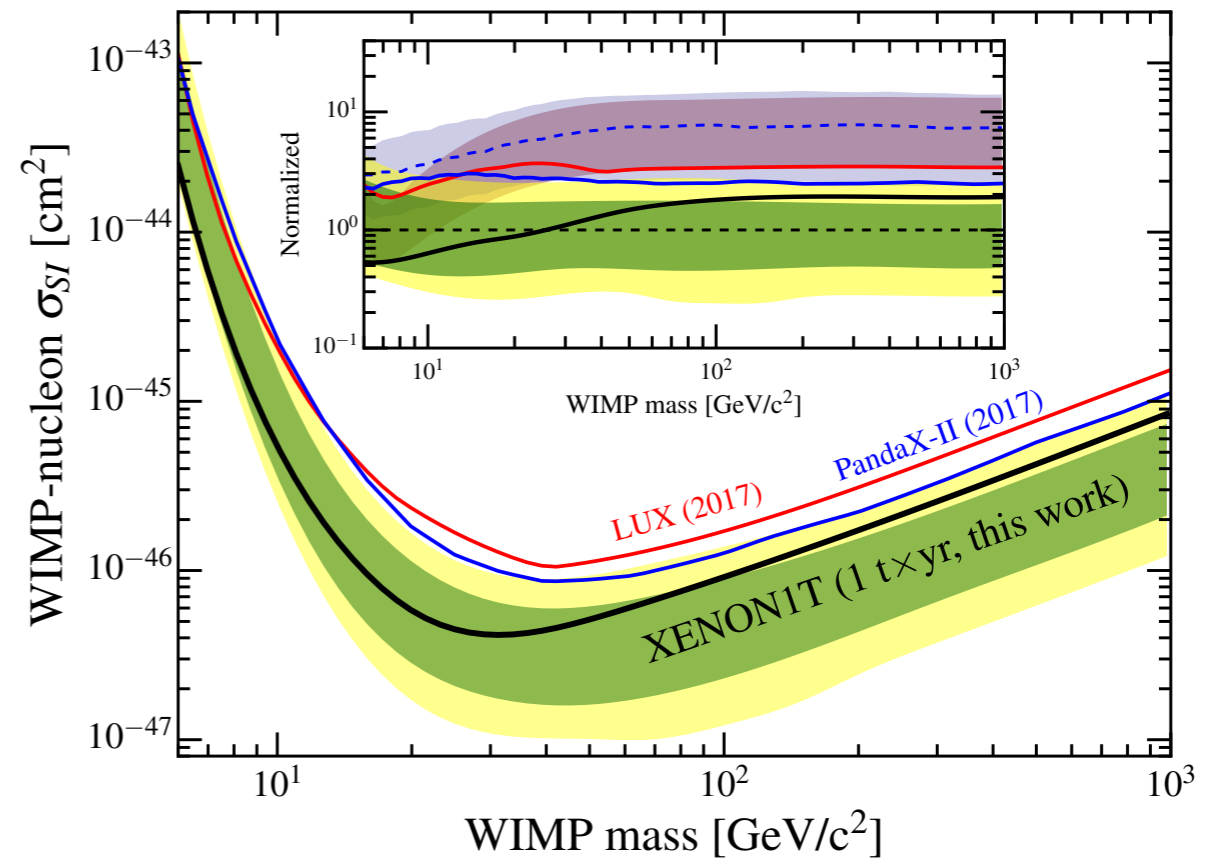
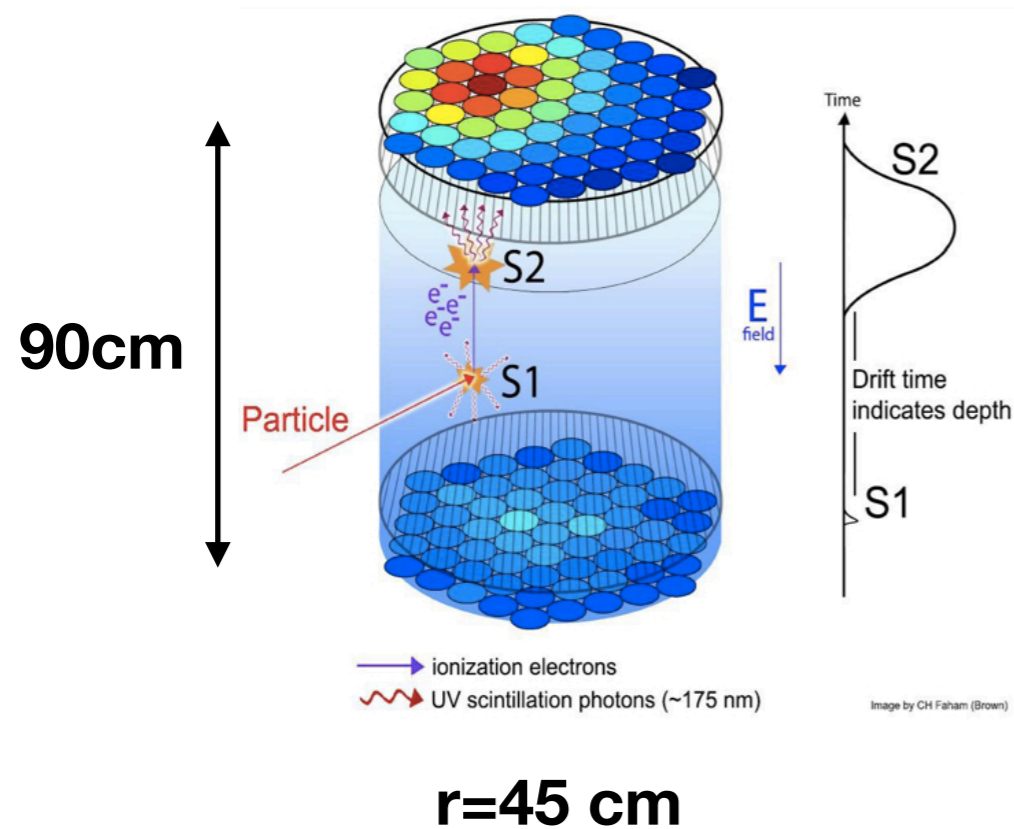
# XENON1T comes close to the floor

1805.12562

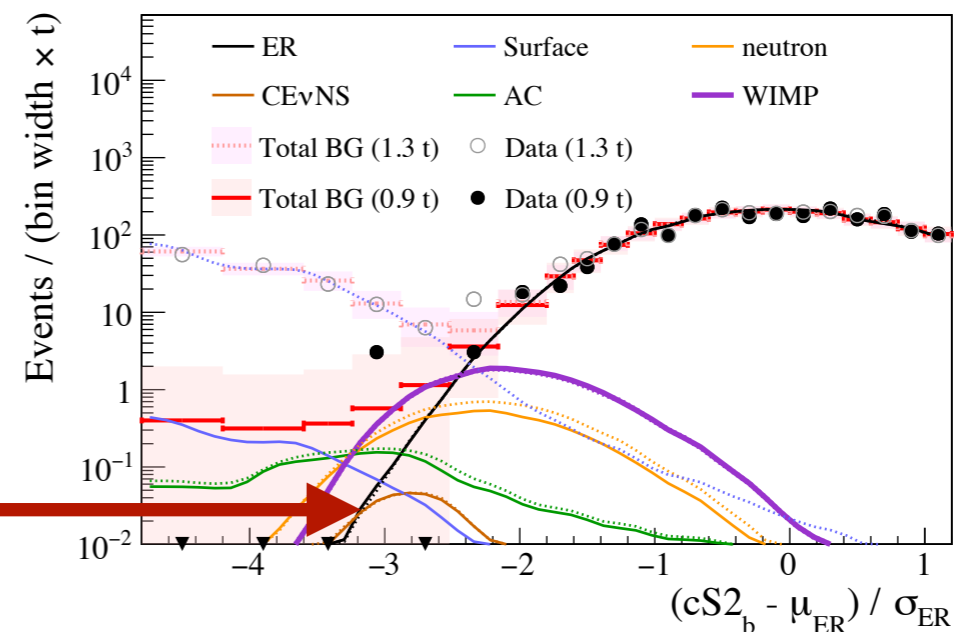


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1805.12562



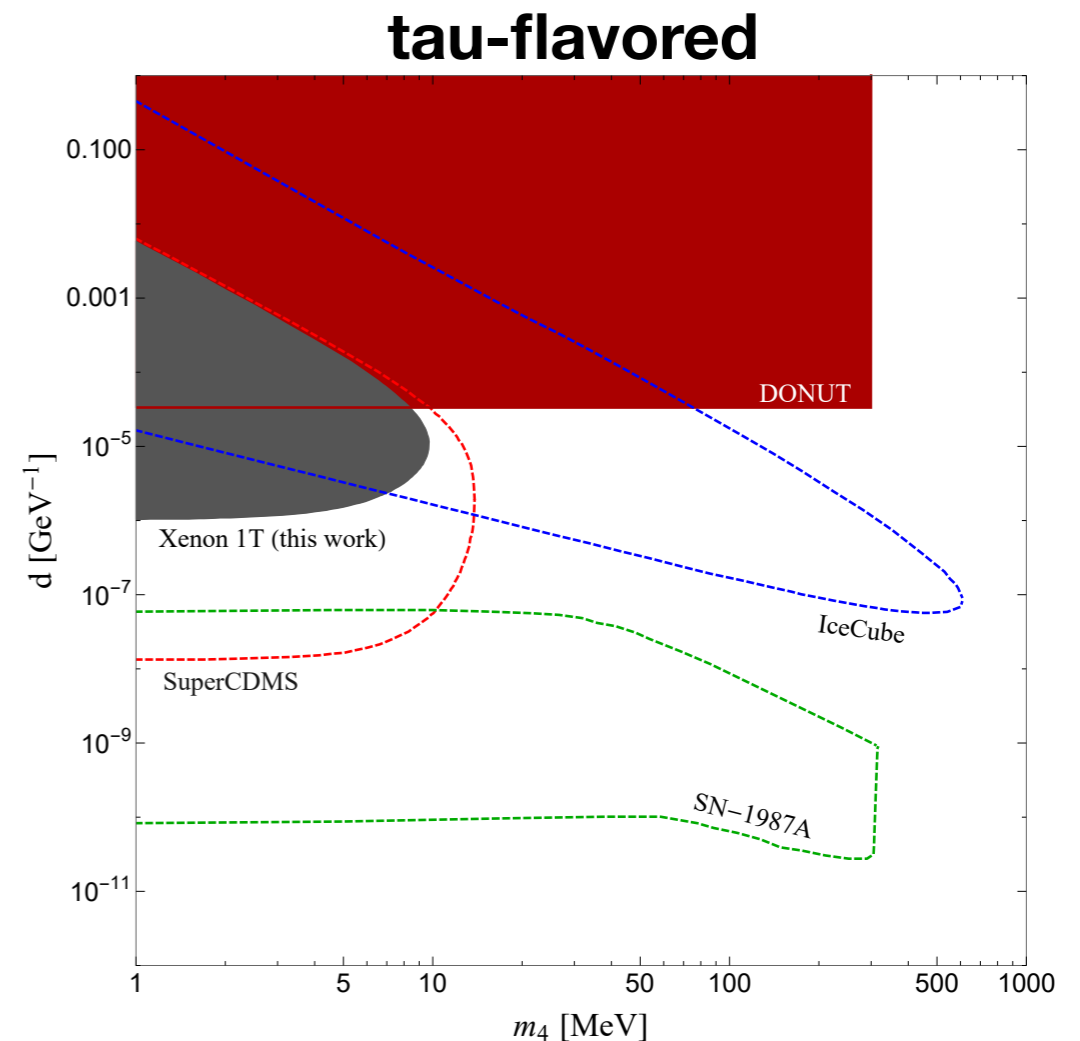
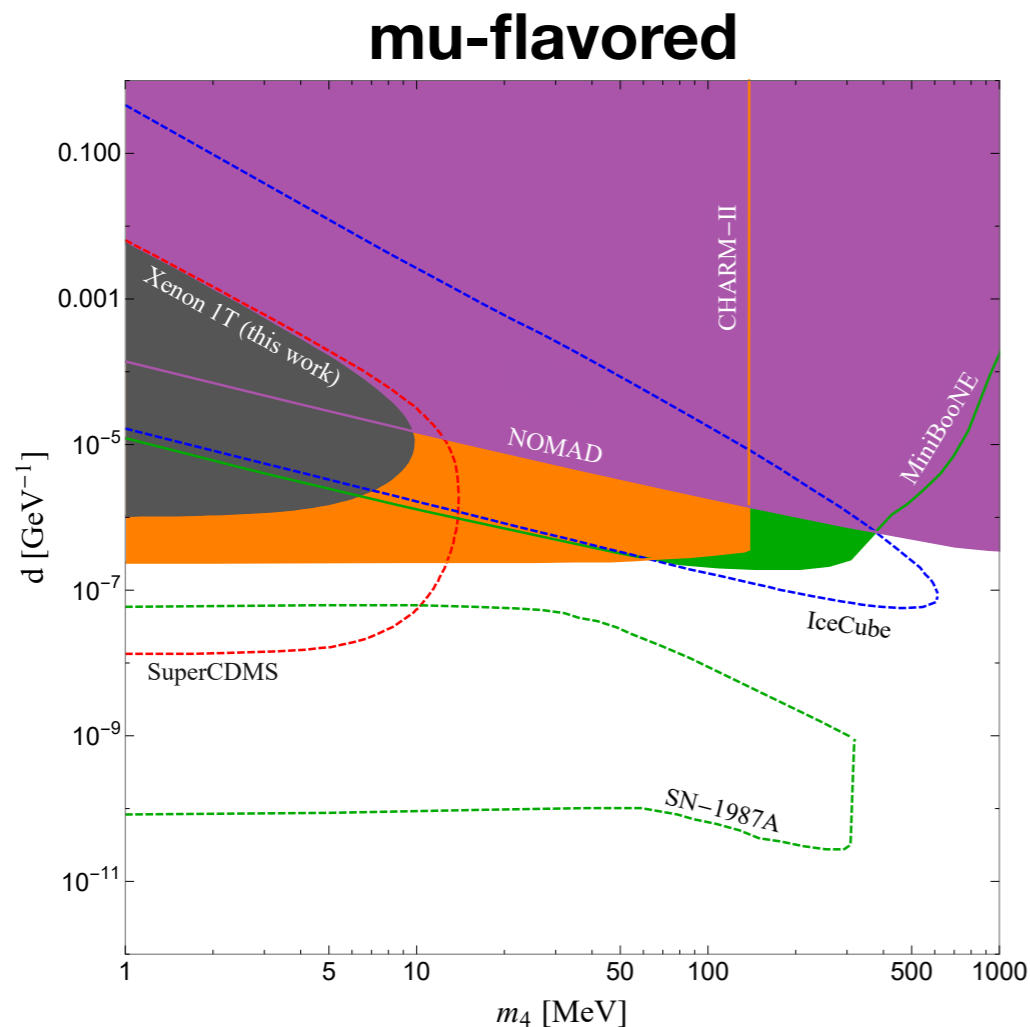
**Coherent Elastic  
Neutrino-Nucleus  
Scattering  
 $\sim 0.02$  events**



# Direct Detection Experiments at the Neutrino Dipole Portal Frontier

IMS, Wyenberg (PRD in press 2019)

$$\mathcal{L}_{\text{NDP}} \supset d (\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N)$$



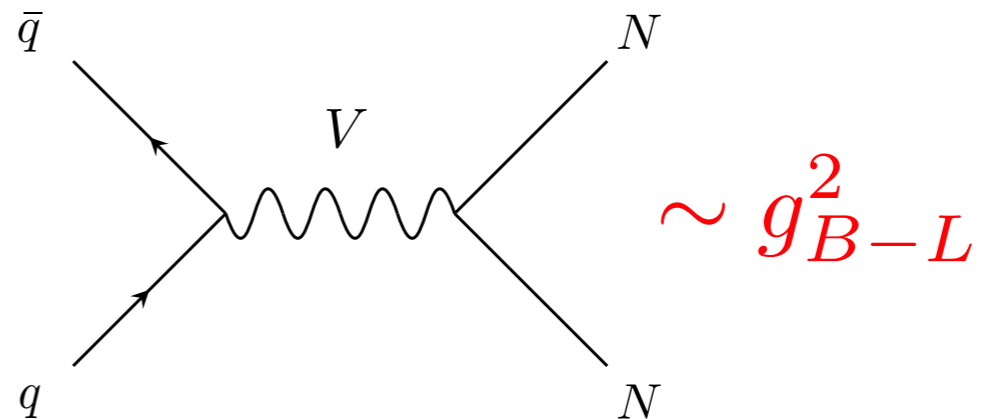
- **Current XENON1T data improves bounds more than order of magnitude at low masses in **tau** case.**
- **Future data can close gap down to the SN1987A limit (Magill, Plestid, Pospelov, Tsai, [1803.03262]) for both **muon/tau**.**

# Shedding Light on Neutrino Masses with Dark Forces

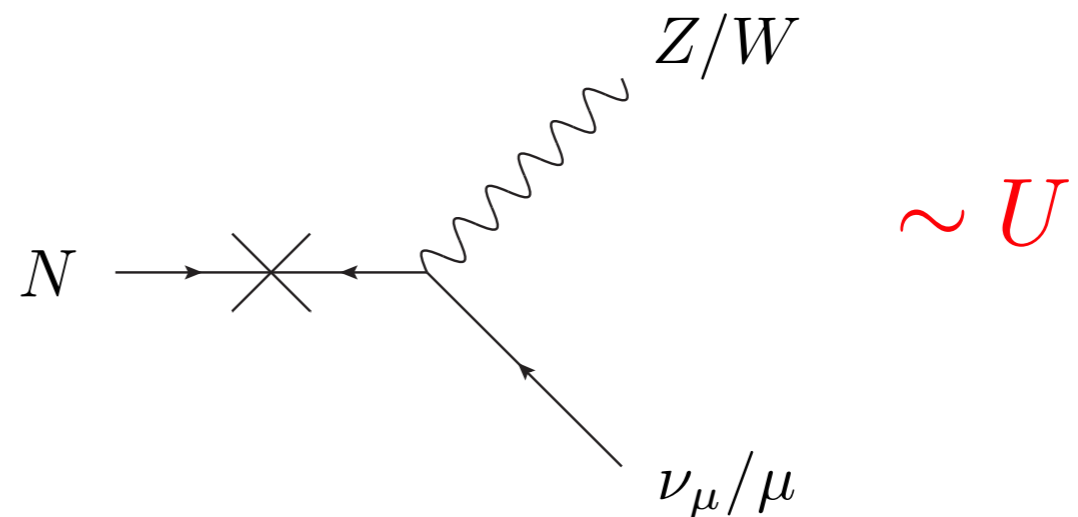
Batell, Pospelov, Shuve [1604.06099]

Think globally/act locally:  $U(1)_{B-L}$

Make it from new  
gauge force



break it from  
EW force



Scenarios with non-EW decay rates too?

# Seesaw Tests at SHiP

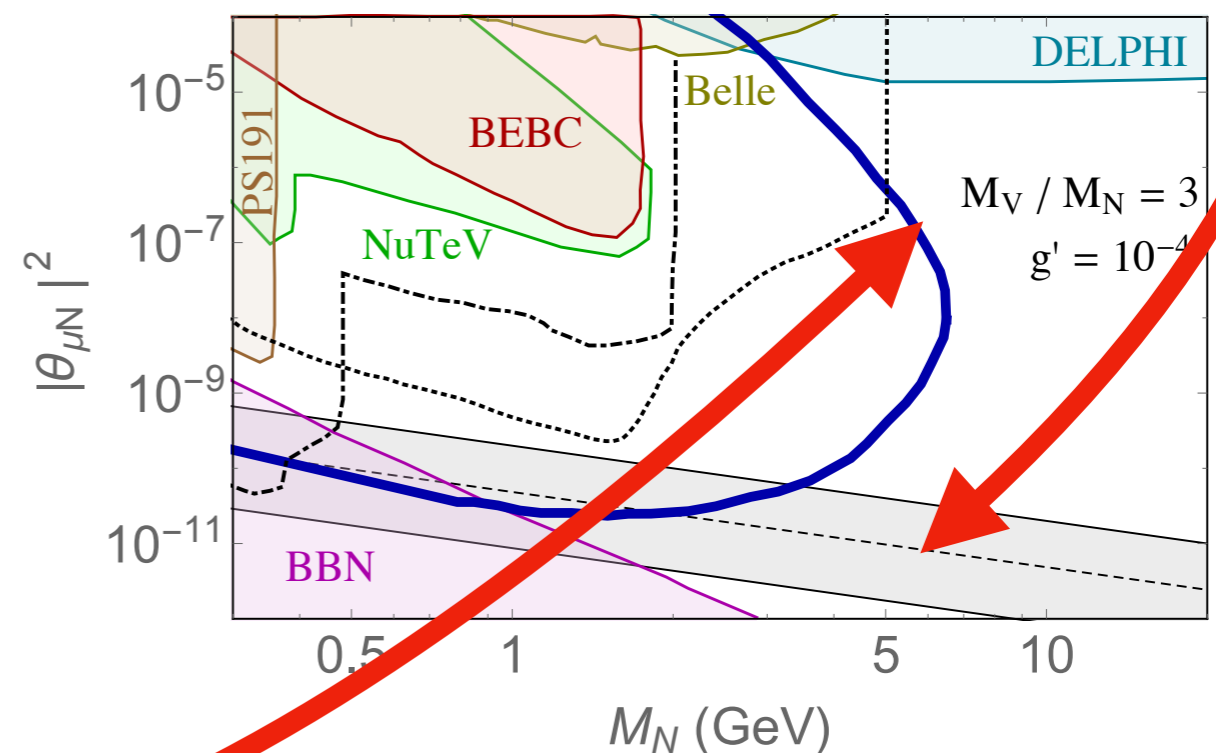
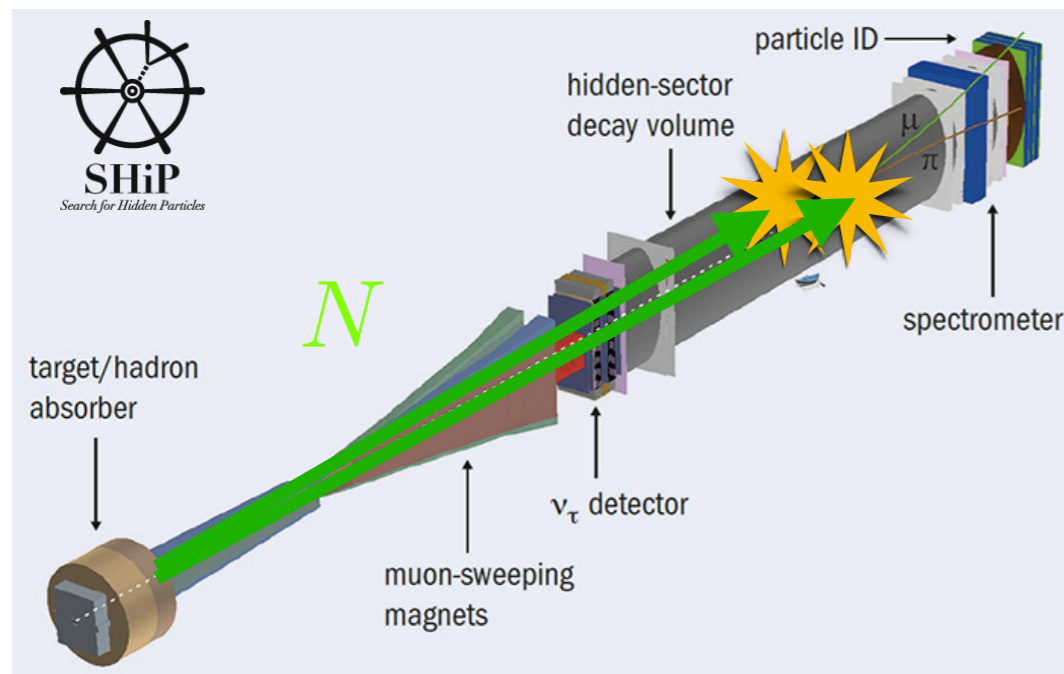
**Seesaw relations:**

$$m_\nu \approx \frac{M_D^2}{M_N}, \quad \theta^2 \approx \frac{m_\nu}{M_N}$$

$$M \approx M_N,$$

**→**  $\theta_{s-s}^2 \sim 5 \times 10^{-11} \times \left( \frac{1 \text{ GeV}}{M_N} \right)$

**Fix gauge boson coupling/mass**



**SHiP**

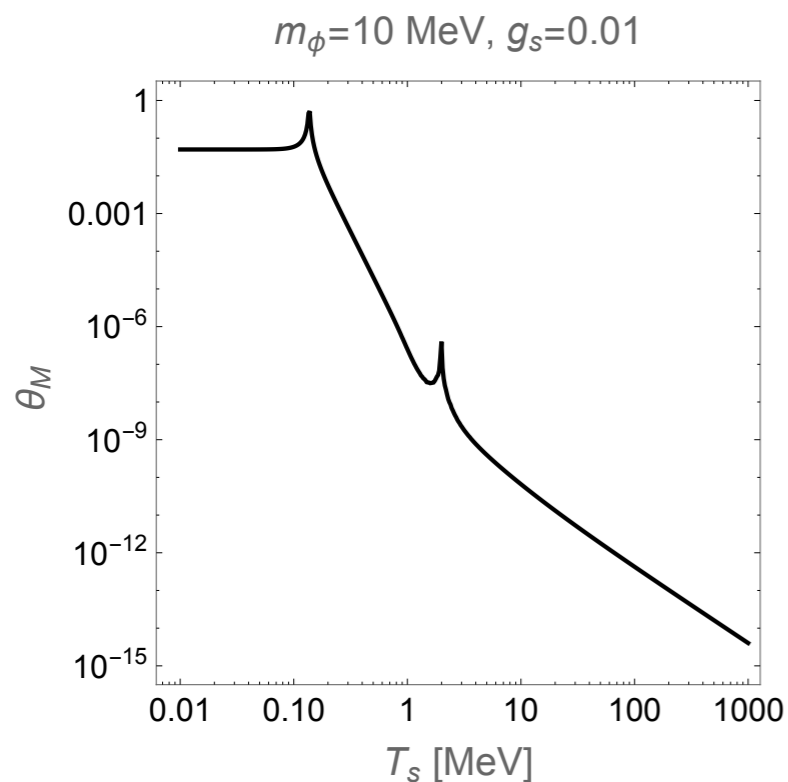
# Conclusions

- BSM landscape is vast, likely still new continents to discover.
- BSM modifications can come in at source, propagation, or detector.
- Always beneficial to repurpose existing experiments when possible.
  - 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.

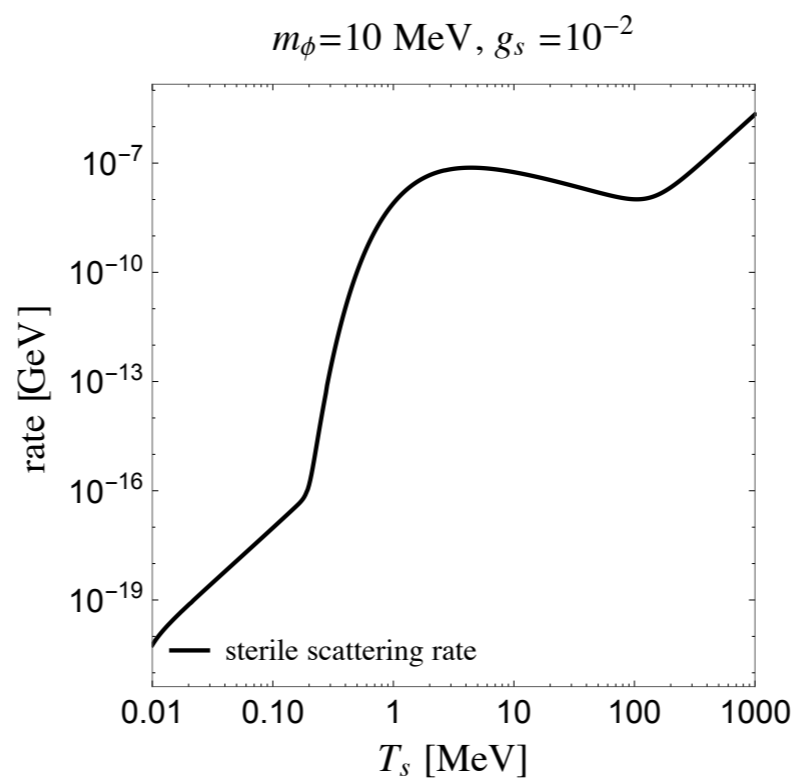
# Early Universe Oscillations/Scattering

- The new interaction can **recouple** the two populations:
- Dangerous if this happens before active decoupling ( $\sim$ few MeV).

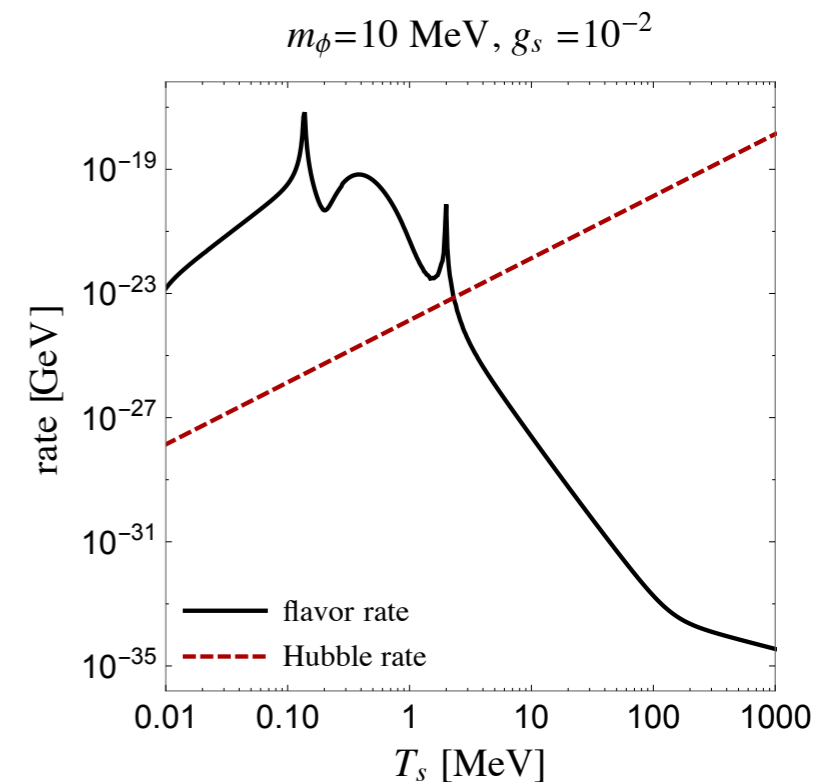
mixing angle



scattering rate



recoupling rate



Sharp features  $\Rightarrow$  precise recoupling temperature depend sensitively on the mass/coupling.