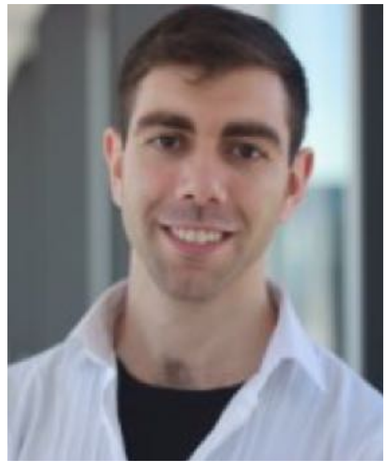
Heavy Neutral Leptons: A MiniBoonE Candidate

POND² - Fermilab - December 7th 2018

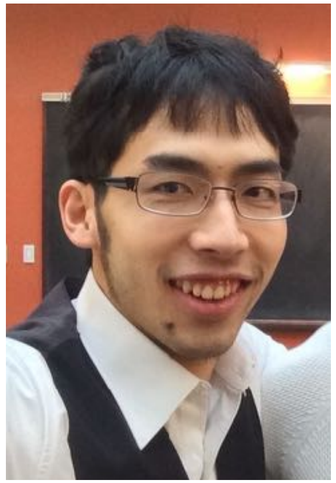
In collaboration with

Maxim Pospelov

Gabriel Magill



Yu-Dai Tsai



Now at **Fermilab**

Ryan Plestid

McMaster University (Hamilton, Ontario)

Perimeter Institute for Theoretical Physics (Waterloo, Ontario)

2018/12/07

plestird@*mcmaster.ca*

Thank You For the Invitation

arXiv:1803.03262

#1 Dipole Portal to HNLs (single photons)
arXiv:1803.03262 (this talk)

#2 Millicharged Particles (soft electron recoil)
arXiv:1806.03310 (see Yu-Dai and Roni's Talks)

#3 Neutrino Trident Production (lepton pairs)
arXiv:1612.05642 , arXiv:1710.08431
Also Matheus' and Yuber's talks and arXiv:1807.10973

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Outline of the Talk

arXiv:1803.03262

Introduction to Dipole Portals

Overview of Existing Constraints

Prospects at the DUNE Near Detector
(and other speculations)

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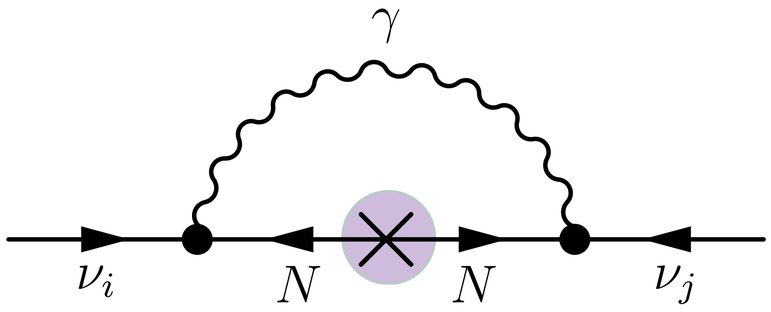
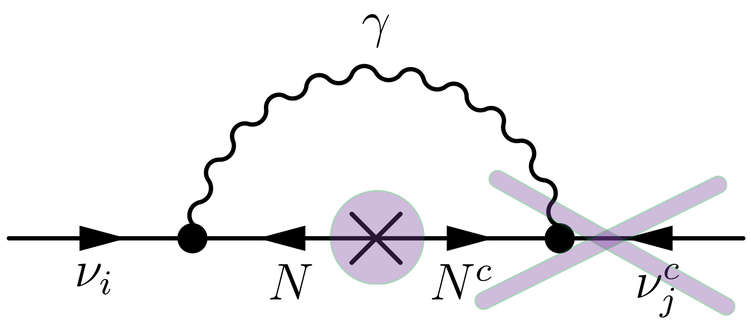
Neutrino Dipole Portal

arXiv:1803.03262

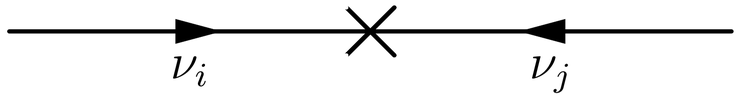
$$\mathcal{L}_{dim\ 5} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N - m\bar{N}N$$



Majorana mass



Dirac mass with hypothetical interactions



Neutrino masses

$$N_D = \begin{pmatrix} N \\ N^{c\dagger} \end{pmatrix}$$

HNL Dirac masses don't allow dipole contribution to neutrino masses!

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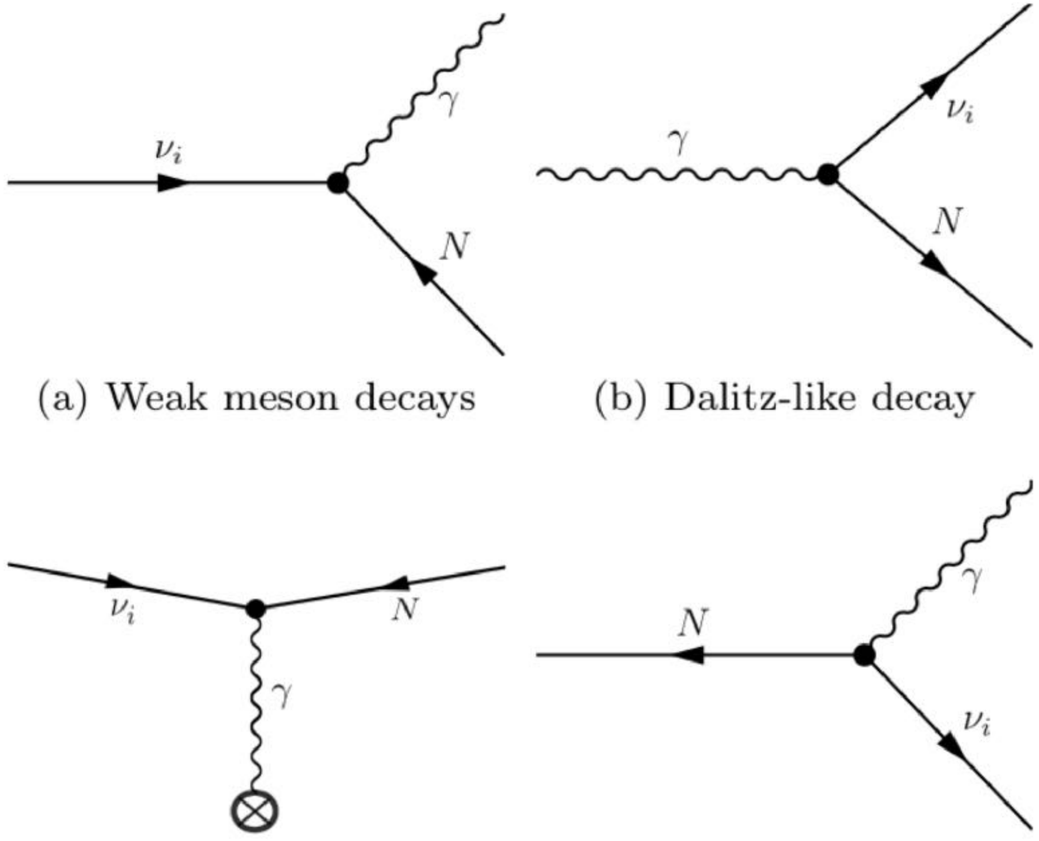

(a) Weak meson decays (b) Dalitz-like decay

(c) Primakoff upscattering (d) $N \to \gamma\nu$ (signal)

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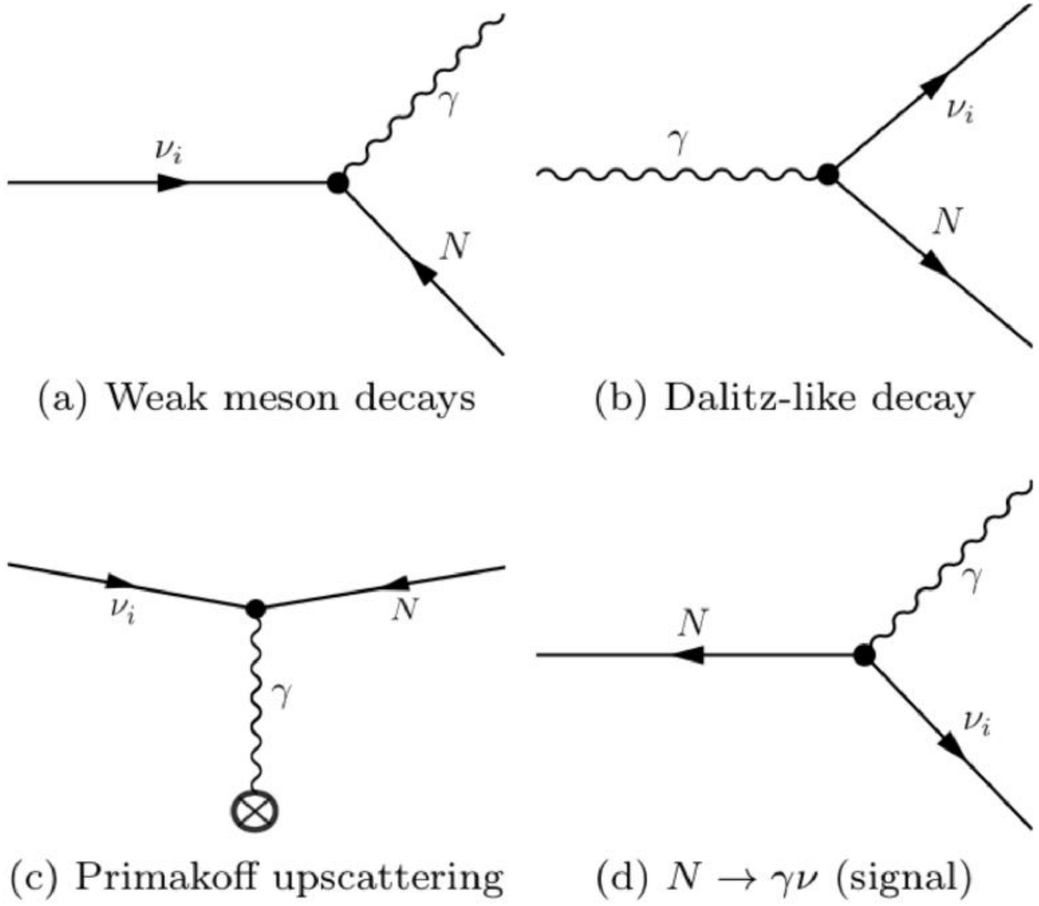

(a) Weak meson decays (b) Dalitz-like decay

(c) Primakoff upscattering (d) $N \to \gamma\nu$ (signal)

Dipole Coupling Features

- Flavor dependent interaction
- Allows off-shell photons and neutrinos to produce HNLs
- Incident neutrinos can "upscatter'" into HNLs
- HNLs decay into a visible photon and a neutrino

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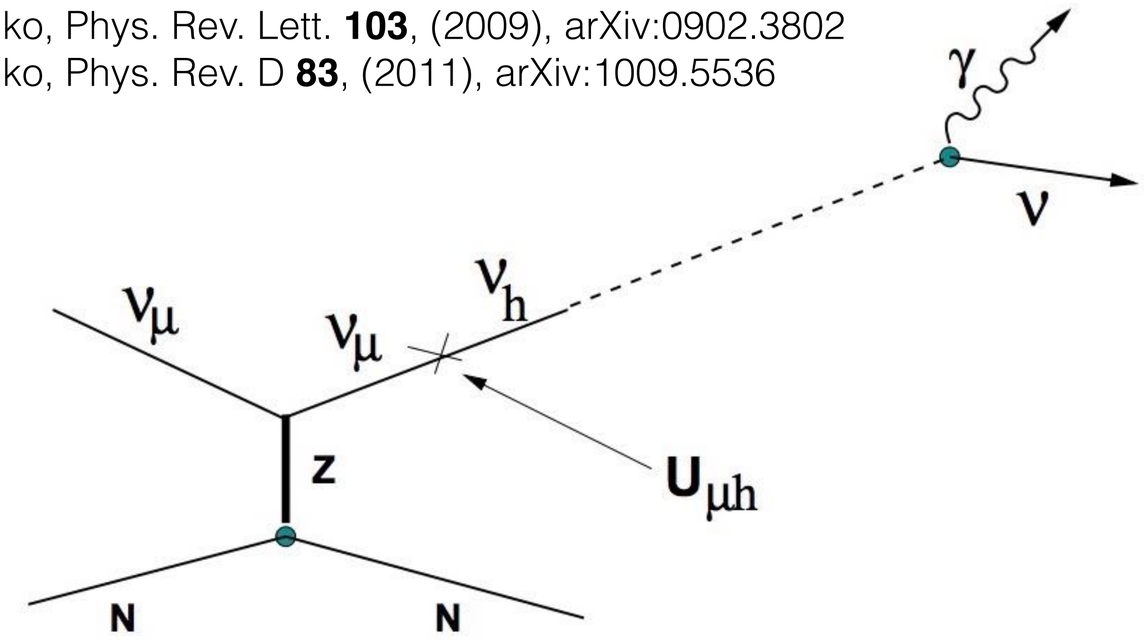
MiniBooNE Anomaly from HNL

arXiv:1803.03262

Gninenko, Phys. Rev. Lett. **103**, (2009), arXiv:0902.3802
Gninenko, Phys. Rev. D **83**, (2011), arXiv:1009.5536



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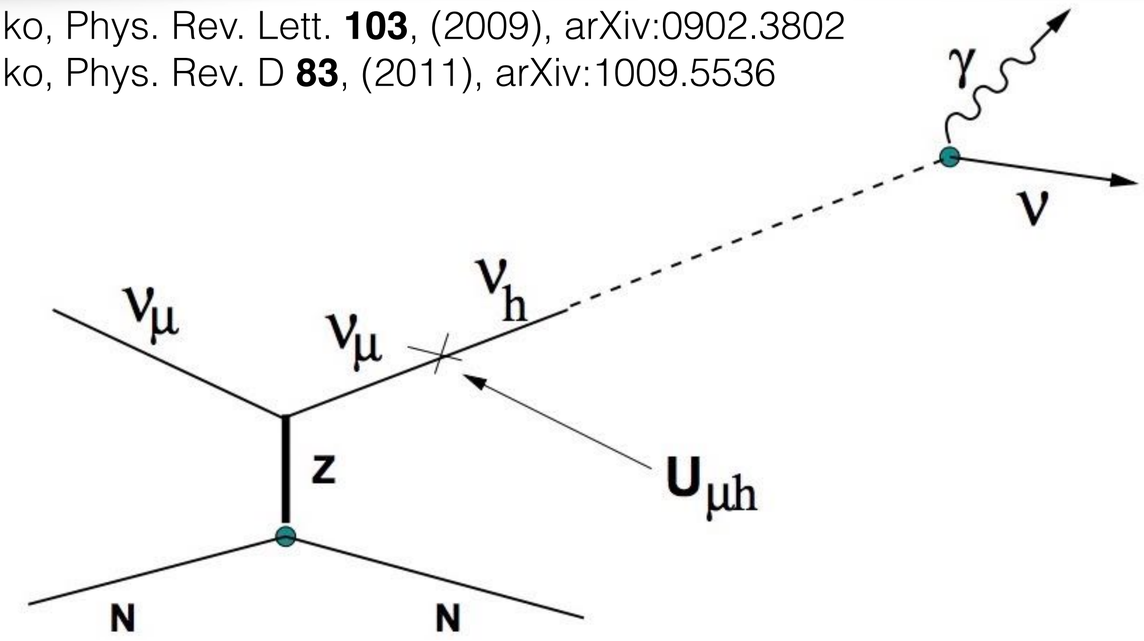
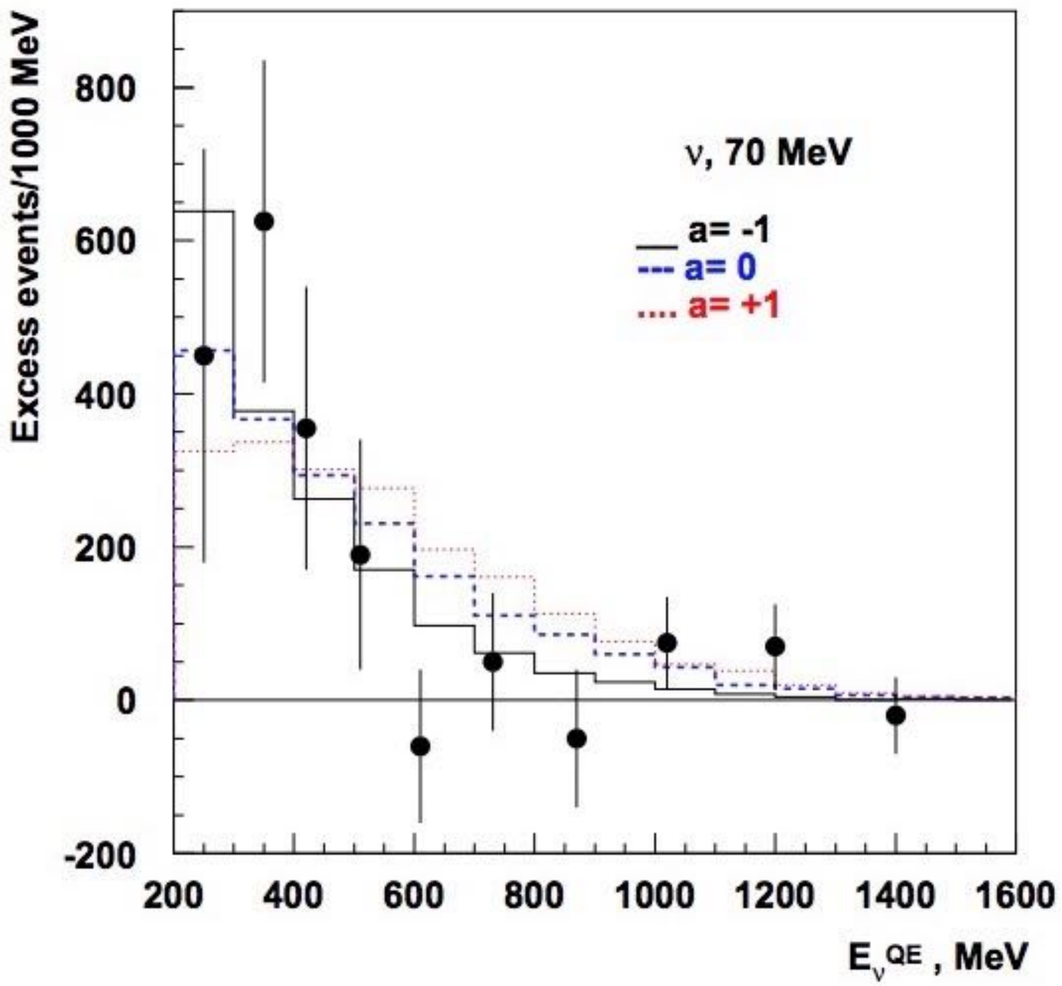


MiniBooNE Anomaly



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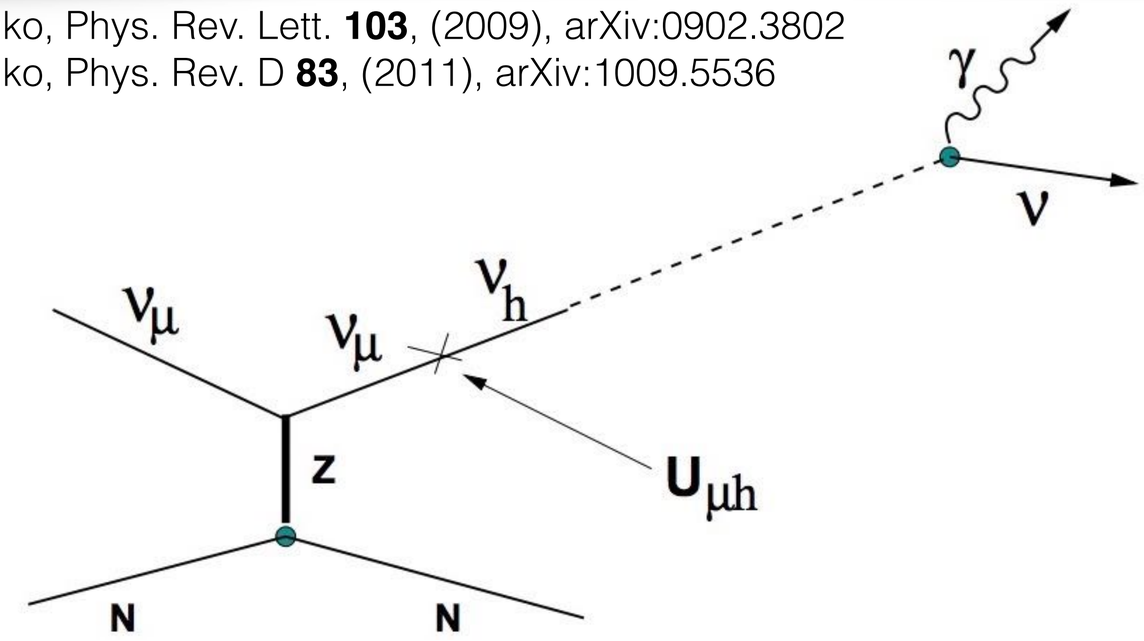


Anomaly Favored Region

LSND+MiniBooNE :

5

$m_N = 40 - 80$ MeV, $d = (3-6) \times 10^{-6}$ GeV^{-1}

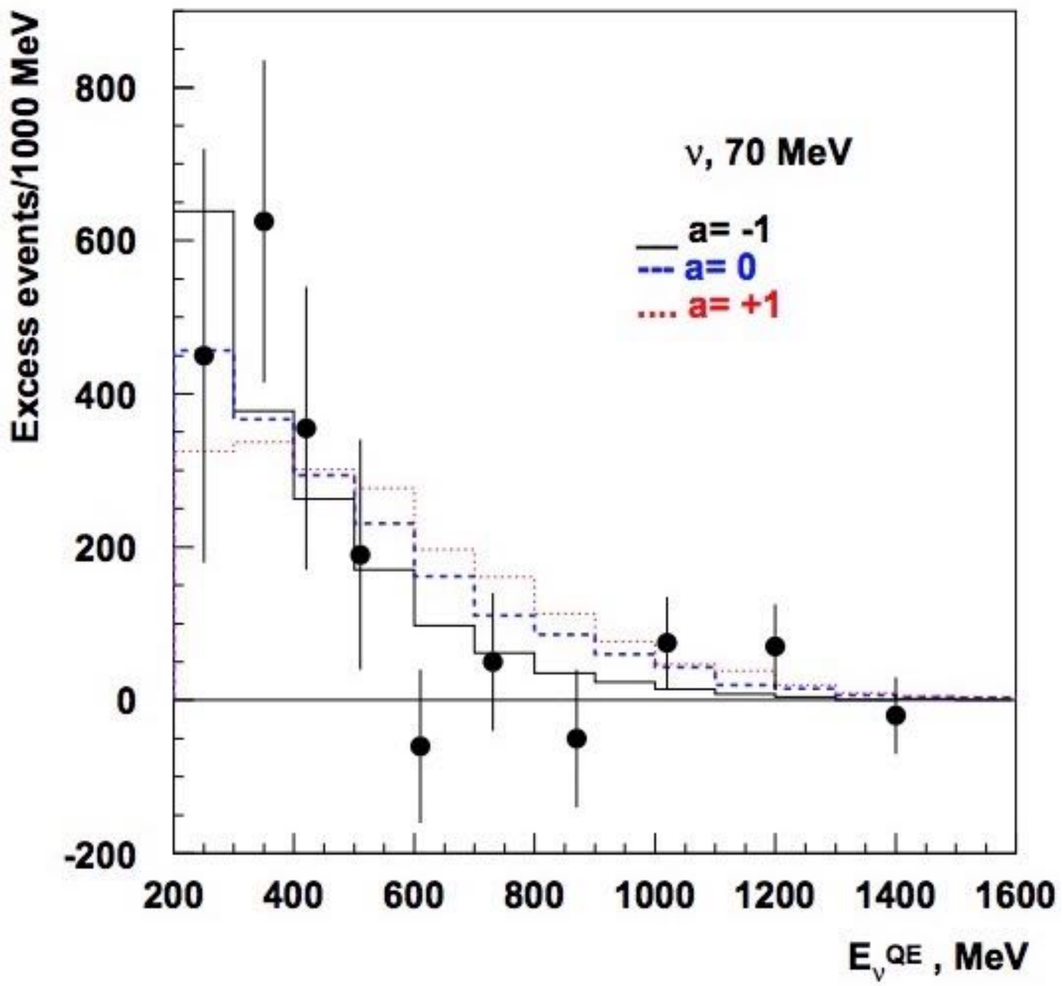
$|U_{\mu h}|^2 \simeq 10^{-3} - 10^{-2}$, $\tau \lesssim 10^{-9}$ s

MiniBooNE :

$m_N = 500$ MeV, $d = (1-9) \times 10^{-7}$ GeV^{-1}

$|U_{\mu h}|^2 \simeq (1-4) \times 10^{-3}$, $\tau \lesssim 10^{-9}$ s

MiniBooNE Anomaly



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In a Broader Context

arXiv:1803.03262

MeV-scale sterile neutrino decays at the Fermilab Short-Baseline Neutrino program

Peter Ballett, Silvia Pascoli and Mark Ross-Lonergan

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E-mail: peter.ballett@durham.ac.uk, silvia.pascoli@durham mark.ross-lonergan@durham.ac.uk

Direct Detection Experiments at the Neutrino Dipole Portal Frontier

Ian M. Shoemaker and Jason Wyenberg

Department of Physics, University of South Dakota, Vermillion, SD 57069, USA

(Dated: December 3, 2018)

Double Bangs from New Physics in IceCube

Pilar Coloma,[1,*] Pedro A. N. Machado,[1,†] Ivan Martinez-Soler,[2,‡] and Ian M. Shoemaker[3,§]

[1]*Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*

[2]*Instituto de Fisica Teorica UAM-CSIC, Calle Nicolas Cabrera 13-15, Universidad Autonoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*

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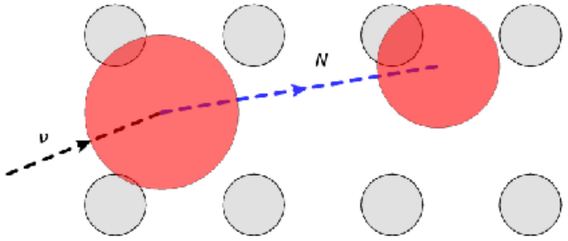

FIG. 1: Schematic illustration of a DB event in IceCube. An incoming active neutrino ν up-scatters into a heavy neutrino N, which then propagates and decays into SM particles. The small circles represent the DOMs while the large circles indicate the positions where energy was deposited.

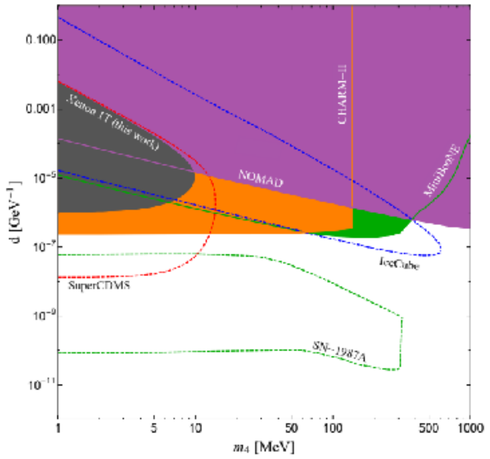

FIG. 4: Expected sensitivity to muon-flavored NDP at XENON1T and a future SuperCDMS exposure. Included are bounds from NOMAD [8, 41], CHARM [8, 42], MiniBooNE [9, 43], IceCube [8], and SN1987A [9].

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In a Broader Context

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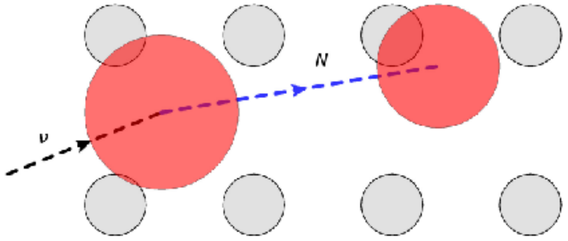

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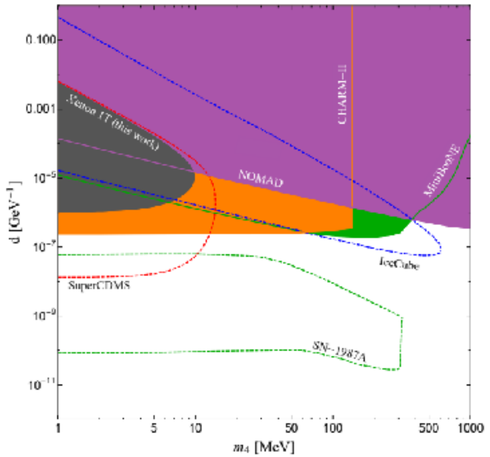

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In a Broader Context

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Generic Effective Operator

- Sterile neutrinos are well motivated over a wide range of mass ranges
- Above an MeV scale cosmology can tell you relatively little
- A dimension five operator between SM and non-SM fields is relatively generic.
- Useful to have **stringent** and **model independent** bounds of such an operator.

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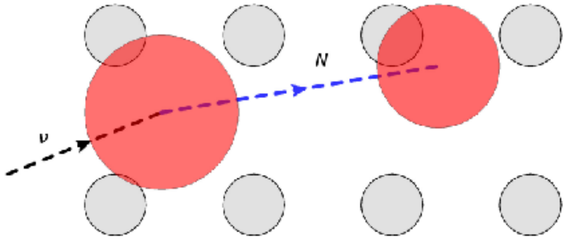

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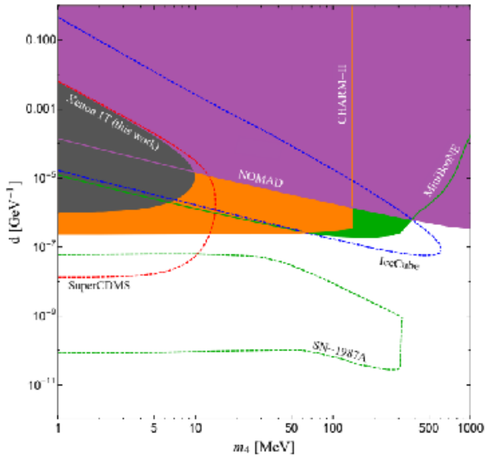

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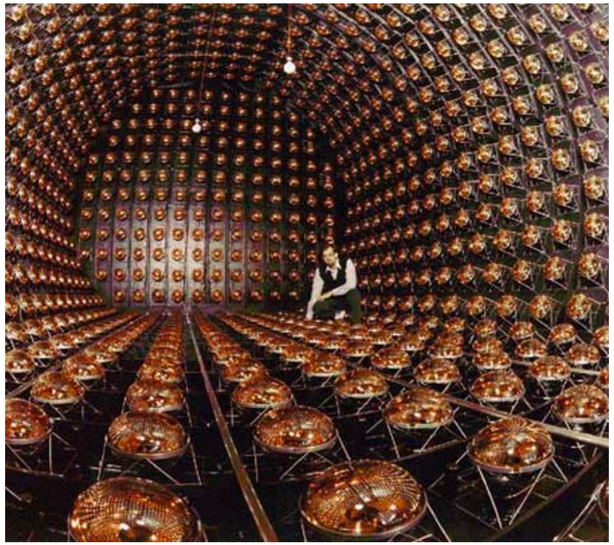
Existing Constraints

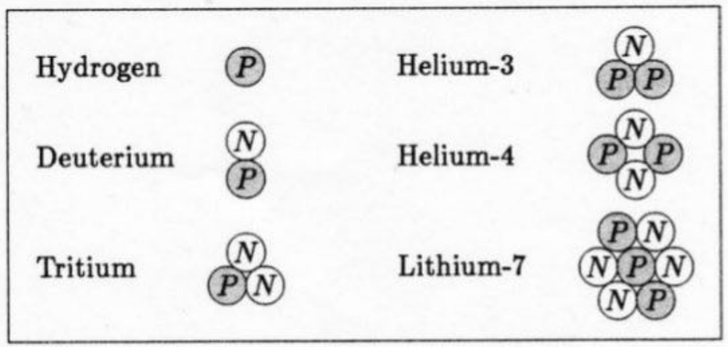
SN1987A



LSND

Big Bang Nucleosynthesis

BBN



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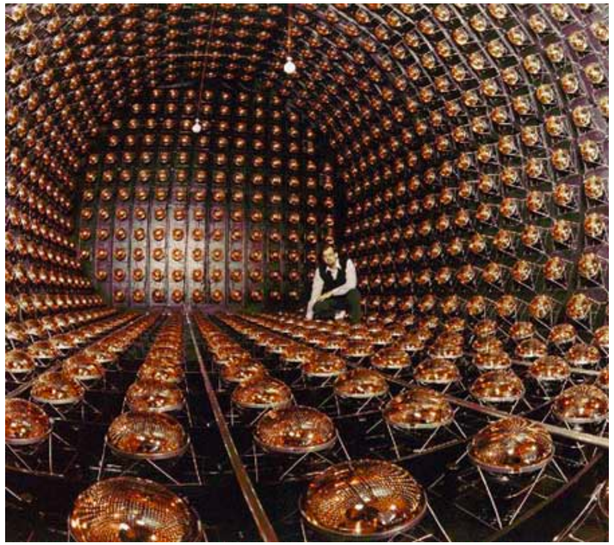
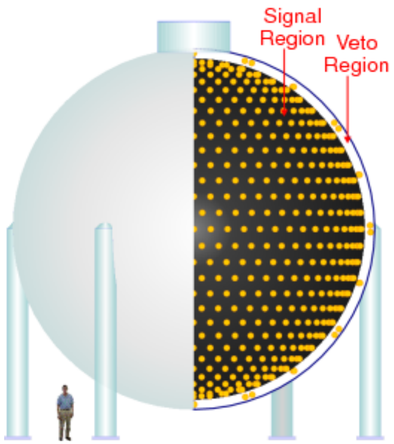


LSND

MiniBooNE



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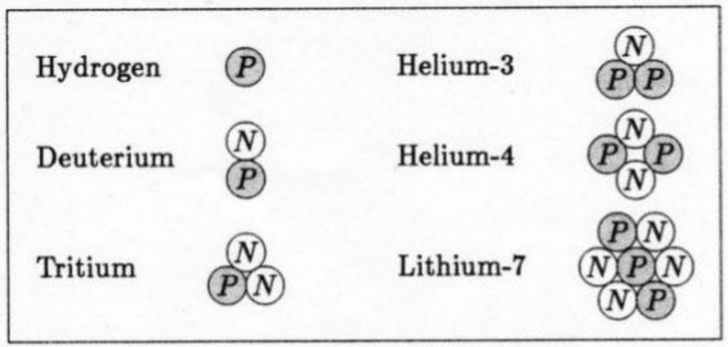

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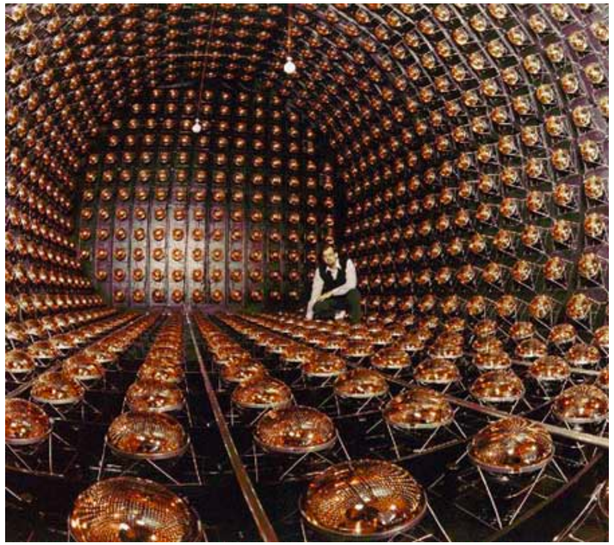
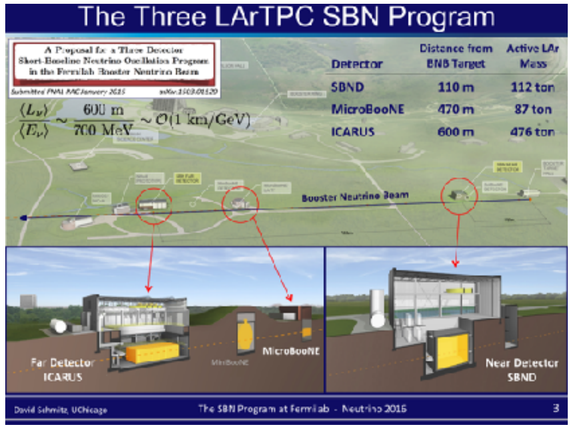


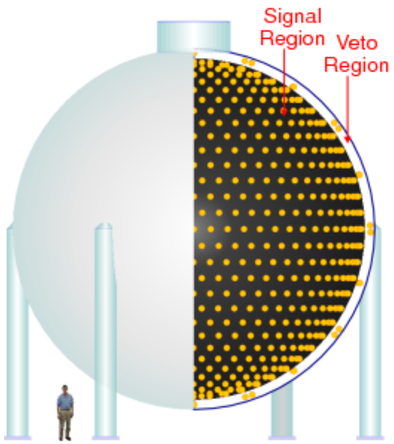
LSND

SBN



(coming soon)

MiniBooNE



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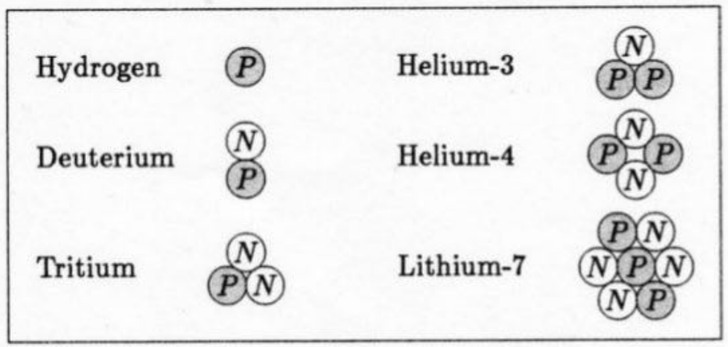
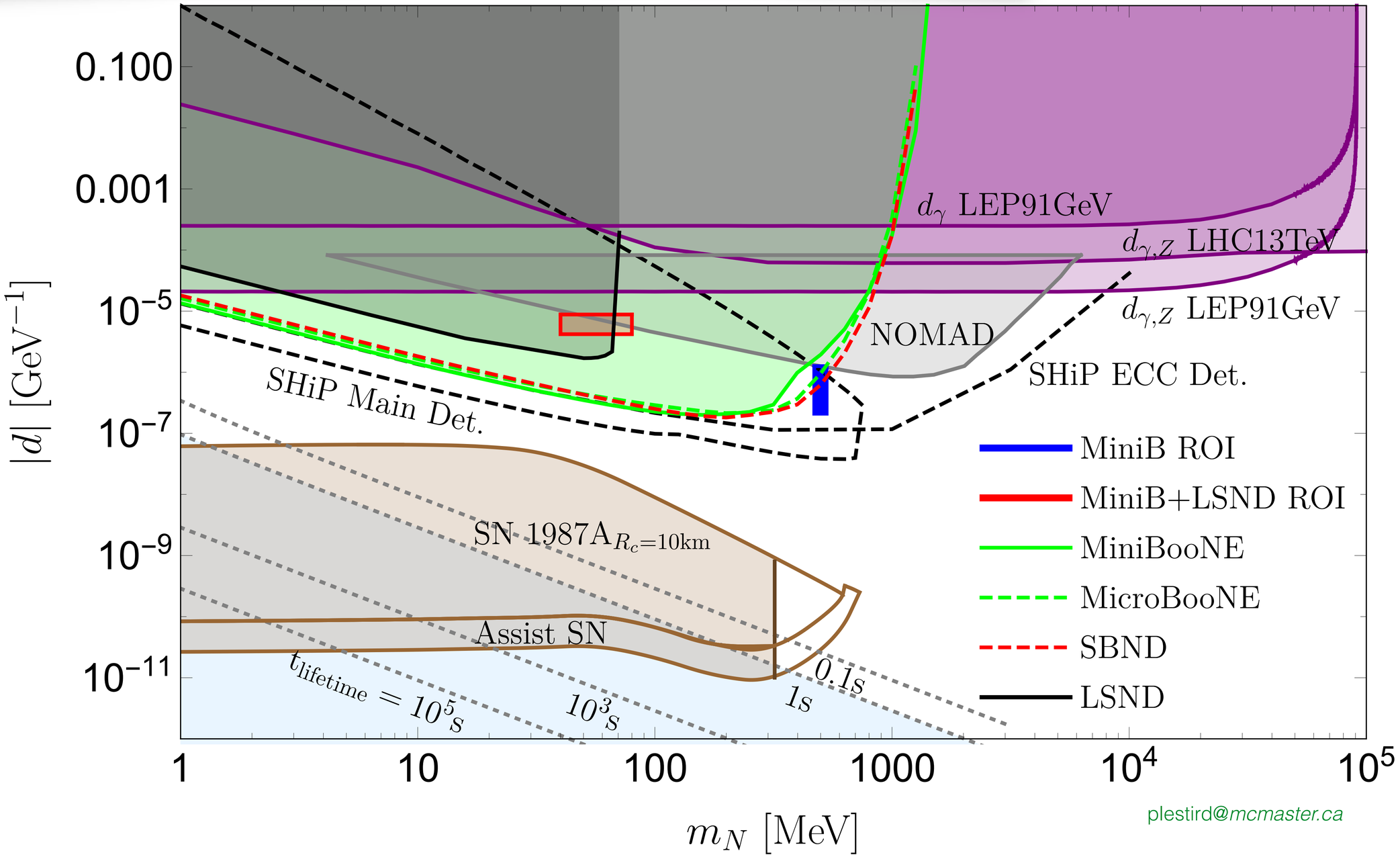


Signatures of a Dipole Portal

arXiv:1803.03262



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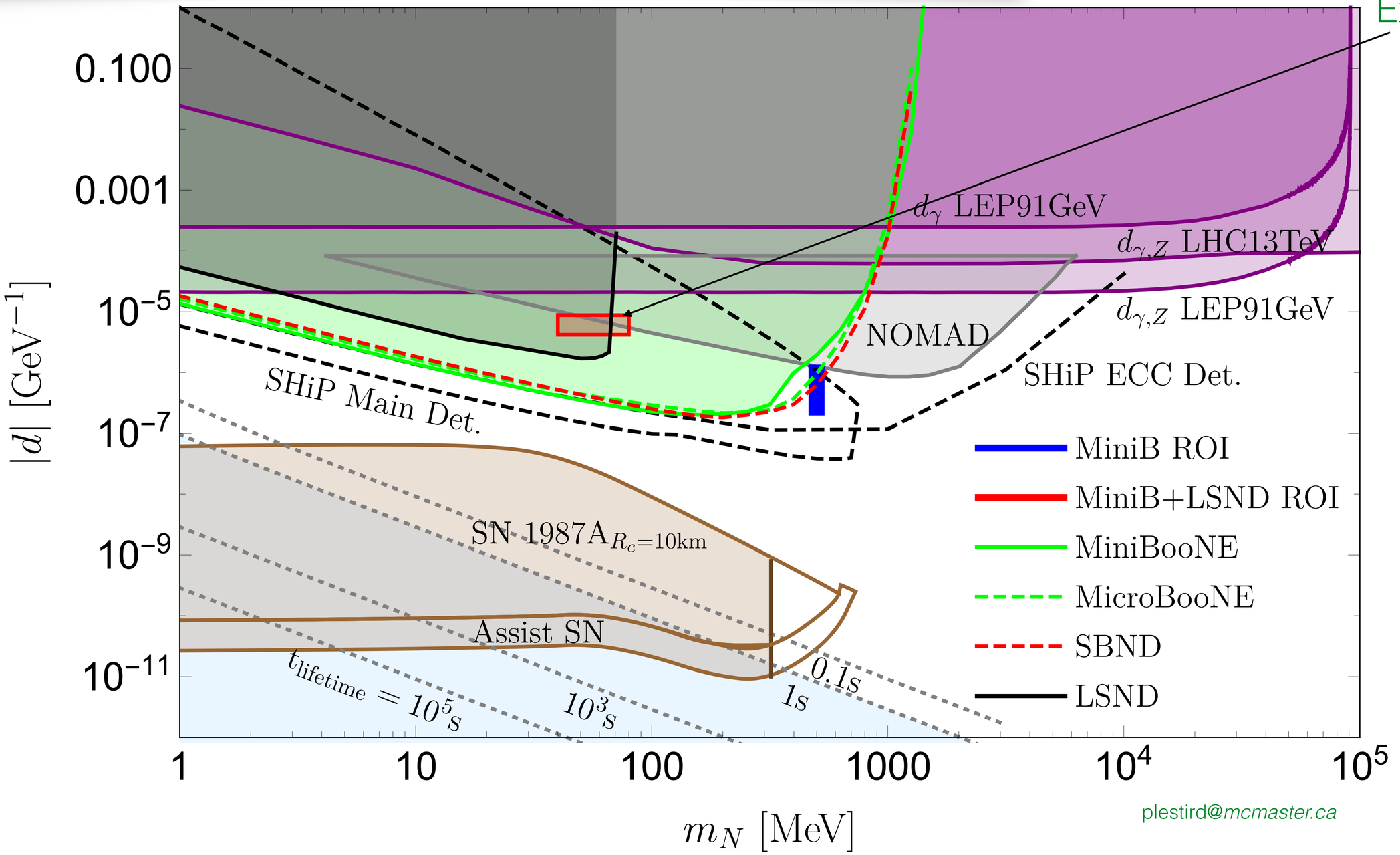
Claim:
Explains LSND



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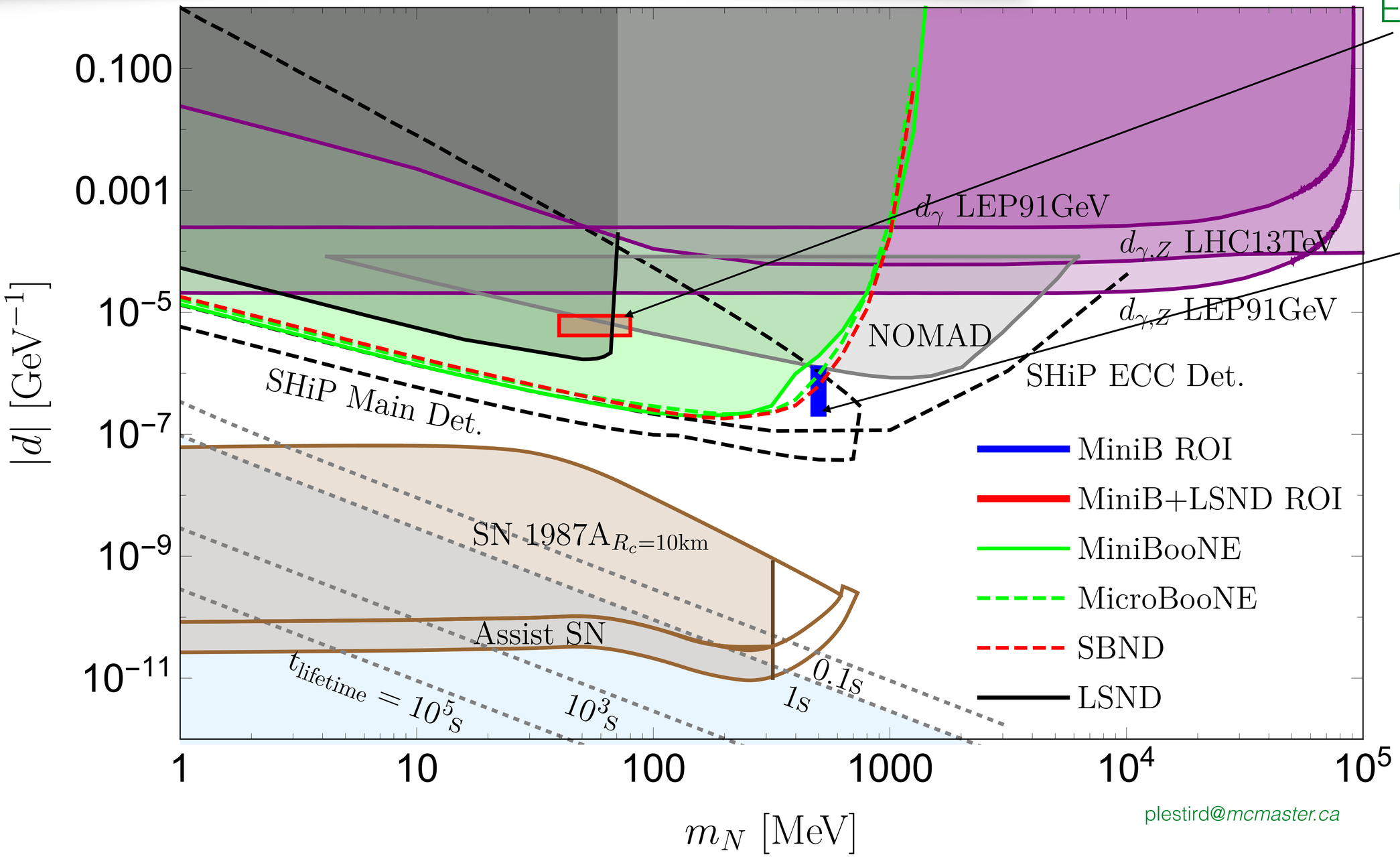
Claim:
Explains MB



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Neutrino Detectors (single photons)

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Signatures of a Dipole Portal

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Neutrino Detectors (single photons)

Collider Searches (single photons)

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Neutrino Detectors (single photons)

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Supernovae Cooling (HNL emission)

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Neutrino Detectors (single photons)

Collider Searches (single photons)

Supernovae Cooling (HNL emission)

Big Bang Nucleosynthesis (modified N_{eff})

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Dipole Portal At Beam Dumps

arXiv:1803.03262

Beam Dump	E_{POT}	L_{Target}	# POT	Technology	E_γ^{min}[GeV]	Bkgs
LSND	1.74 GeV	26m*	1.69×10^{23}	CH_2 Chkov/Scint	0.04	30
mBooNE	9 GeV	540m	5.58×10^{20}	CH_2 Cherenkov	0.3	700
μBooNE	9 GeV	110m	1.3×10^{21}	LAr-TPC	0.2	750
SBND	9 GeV	110m	6.6×10^{20}	LAr-TPC	0.2	13K
SHiP ν_τ	400 GeV	50m	2×10^{20}	Pb/Emulsion	0.1	1K
SHiP Far	400 GeV	100m	2×10^{20}	LAr-TPC	0.1	1K

$$\mu^+ \to \gamma N \nu \ell$$

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μBooNE	9 GeV	110m	1.3×10^{21}	LAr-TPC	0.2	750
SBND	9 GeV	110m	6.6×10^{20}	LAr-TPC	0.2	13K
SHiP ν_τ	400 GeV	50m	2×10^{20}	Pb/Emulsion	0.1	1K
SHiP Far	400 GeV	100m	2×10^{20}	LAr-TPC	0.1	1K

Meson Production

$$\pi^0 \to \gamma \nu N$$
$$\eta \to \gamma \nu N$$
$$K^\pm \to \gamma \ell^\pm N$$
$$\pi^\pm \to \gamma \ell^\pm N$$
$$\mu^+ \to \gamma N \nu \ell$$

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arXiv:1803.03262

Beam Dump	E_{POT}	L_{Target}	# POT	Technology	E_γ^{min}[GeV]	Bkgs
LSND	1.74 GeV	26m*	1.69×10^{23}	CH_2 Chkov/Scint	0.04	30
mBooNE	9 GeV	540m	5.58×10^{20}	CH_2 Cherenkov	0.3	700
μBooNE	9 GeV	110m	1.3×10^{21}	LAr-TPC	0.2	750
SBND	9 GeV	110m	6.6×10^{20}	LAr-TPC	0.2	13K
SHiP ν_τ	400 GeV	50m	2×10^{20}	Pb/Emulsion	0.1	1K
SHiP Far	400 GeV	100m	2×10^{20}	LAr-TPC	0.1	1K

Meson Production

$$\pi^0 \to \gamma \nu N$$
$$\eta \to \gamma \nu N$$
$$K^\pm \to \gamma \ell^\pm N$$
$$\pi^\pm \to \gamma \ell^\pm N$$
$$\mu^+ \to \gamma N \nu \ell$$

Upscattering Production

$$\nu + A \to N + A$$

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Dipole Portal At Beam Dumps

arXiv:1803.03262

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Meson Production

$$\pi^0 \to \gamma \nu N$$
$$\eta \to \gamma \nu N$$

Prompt

$$K^\pm \to \gamma \ell^\pm N$$
$$\pi^\pm \to \gamma \ell^\pm N$$
$$\mu^+ \to \gamma N \nu \ell$$

Upscattering Production

$$\nu + A \to N + A$$

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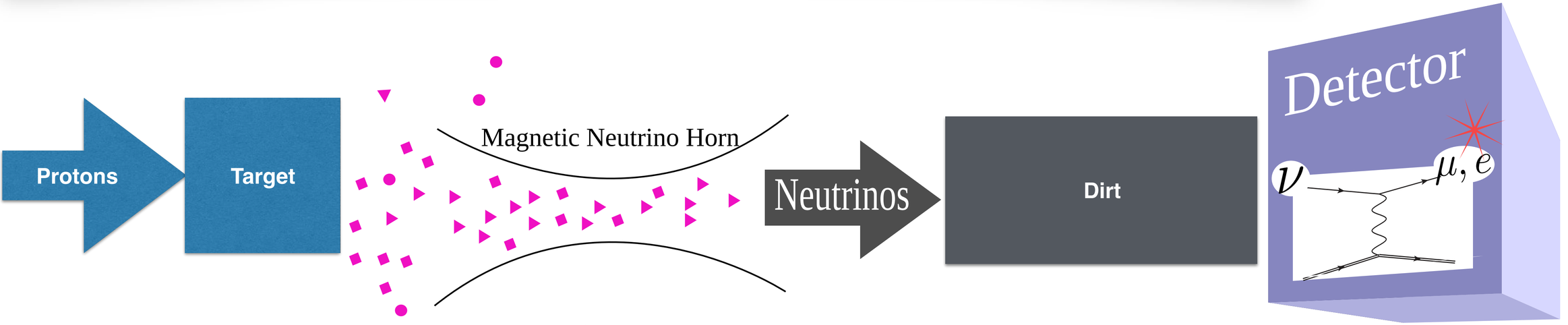
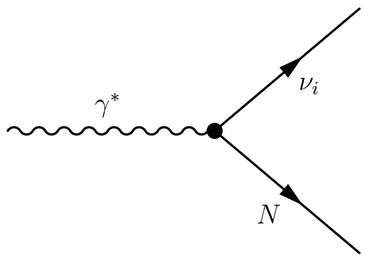
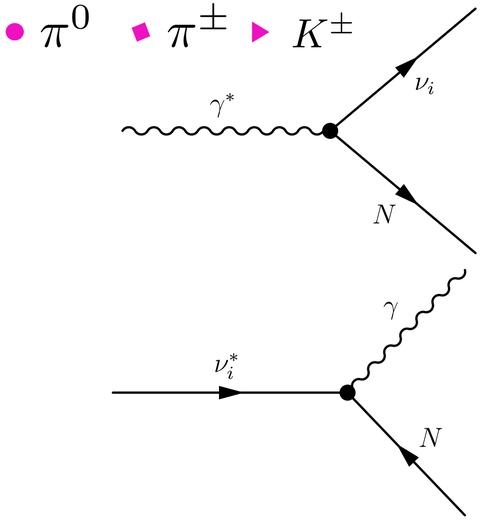
Sources of HNLs At Beam Dumps

arXiv:1803.03262

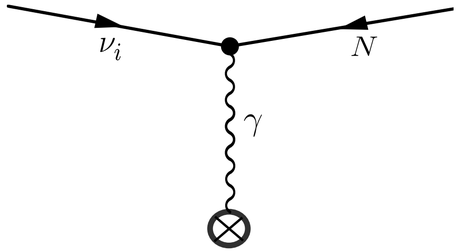




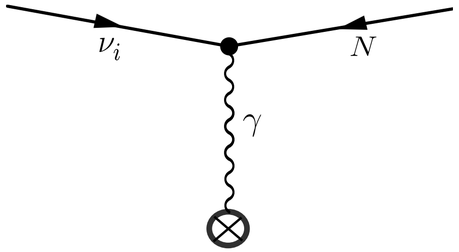
Drell-Yan-like production



Dalitz-like & weak meson decays



Coherent/diffractive upscattering in LOS



Coherent upscattering in detector

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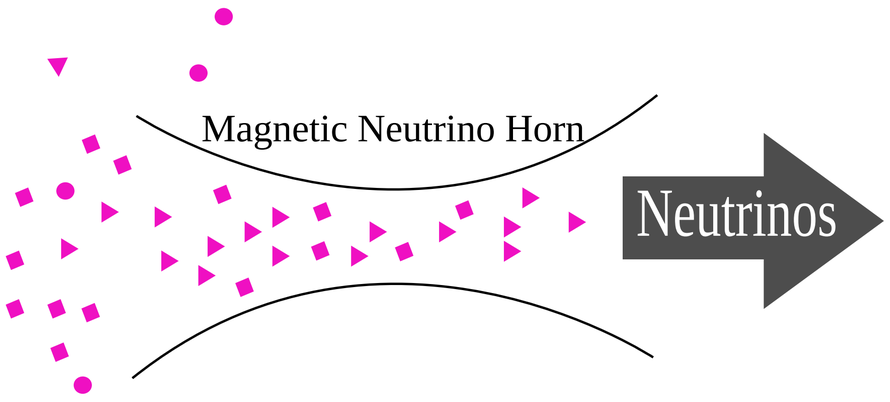
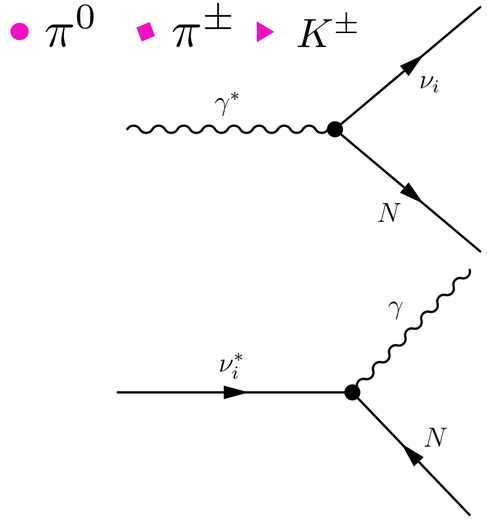
Meson Decays At Beam Dumps

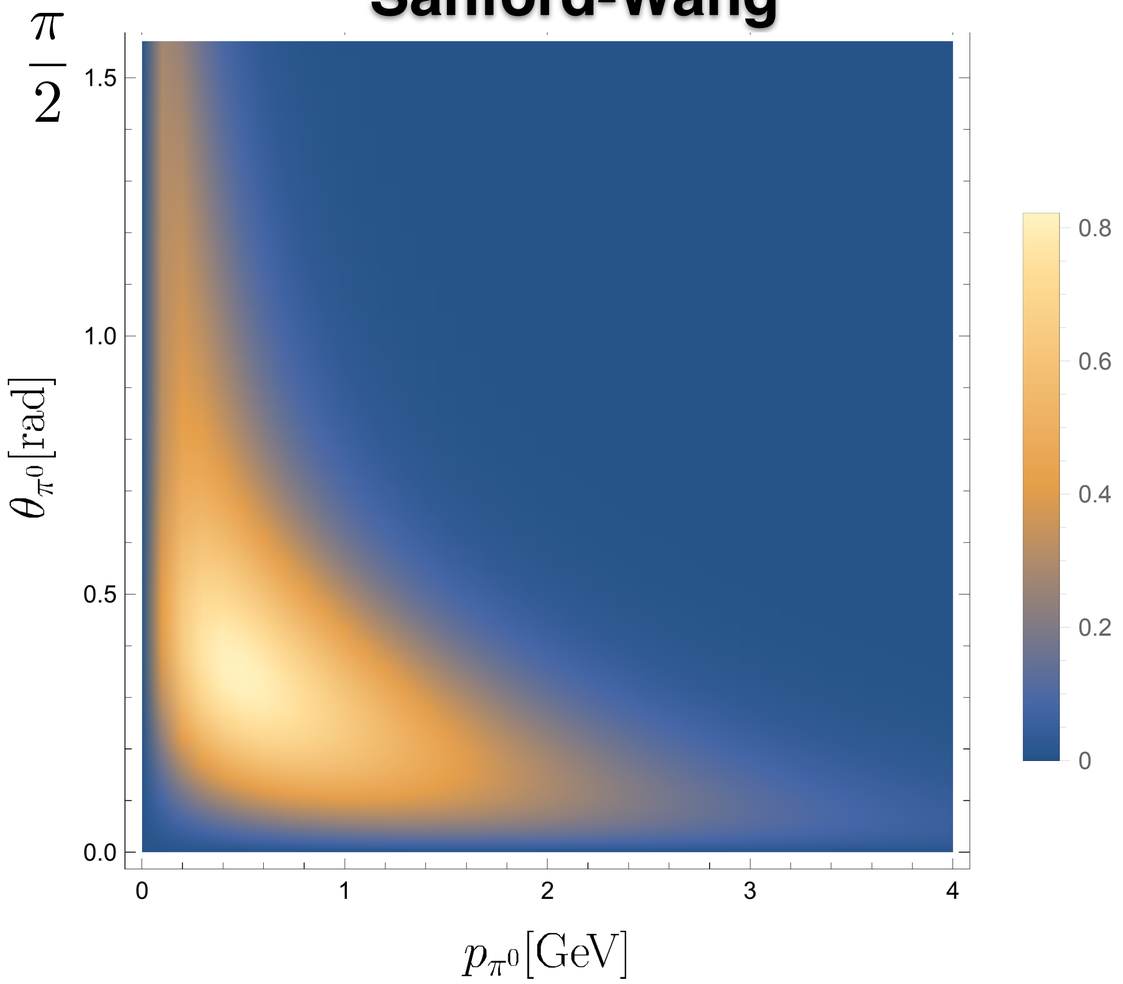
arXiv:1803.03262





Dalitz-like & weak meson decays

Booster Experiments: Sanford-Wang



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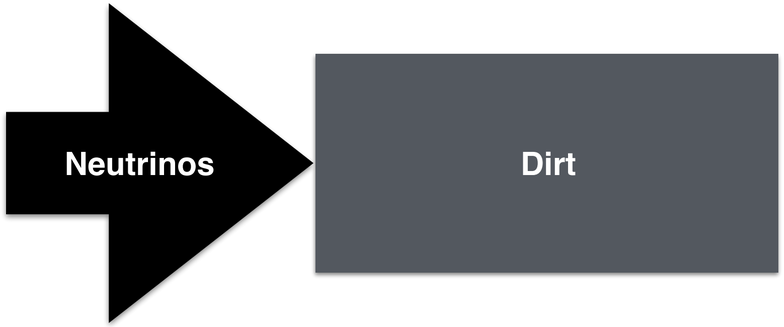
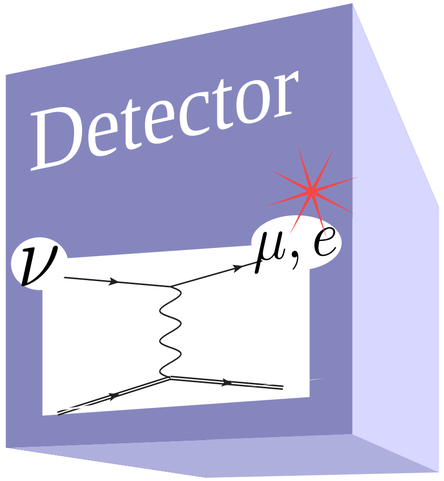
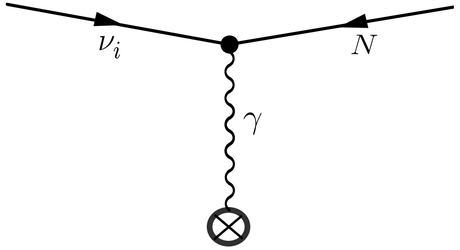
Upscattering Along the Line of Sight

arXiv:1803.03262







Coherent/diffractive upscattering in LOS

$$\sigma_{\rm coh} \sim Z^2 d^2 \log(E_\nu / Q_{\rm min})$$

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Upscattering Along the Line of Sight

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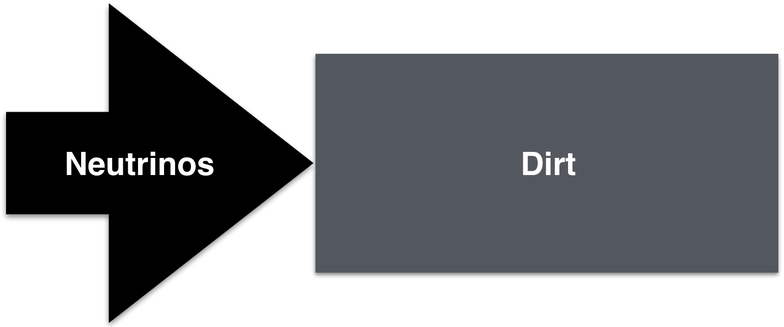

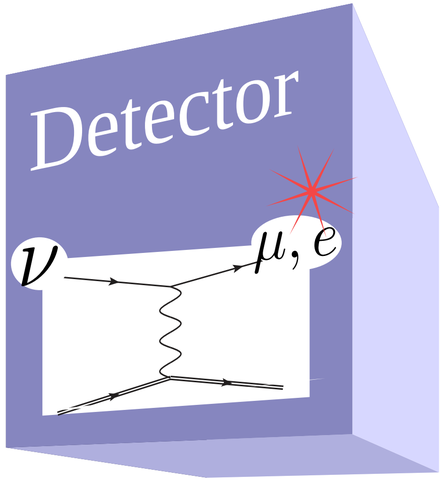

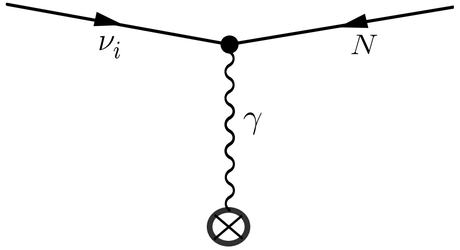

Coherent/diffractive upscattering in LOS

$$\sigma_{\rm coh} \sim Z^2 d^2 \log(E_\nu / Q_{\rm min})$$

Features

- Upscattering along line of sight
- Distribution of `"detector distances"
- Big increase in upscattered flux for long LOS or small detector
- Less important for bigger detectors (see next slide)

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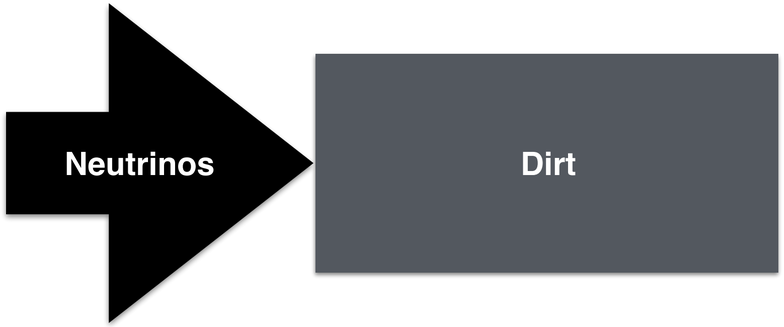
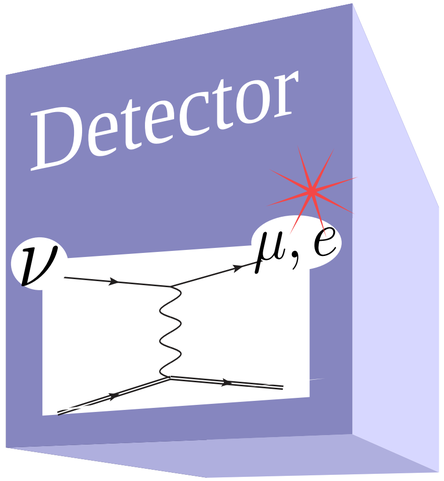
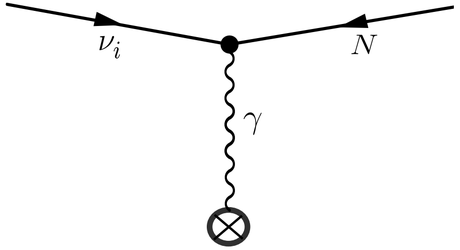
Upscattering Along the Line of Sight

arXiv:1803.03262







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Features

- Upscattering along line of sight
- Distribution of `"detector distances"
- Big increase in upscattered flux for long LOS or small detector
- Less important for bigger detectors (see next slide)

Calculation

- Use collaboration's neutrino fluxes
- Sample 20 points along LOS
- Calculate flux from a given "bin" of dirt
- Compute probability that HNL decays inside detector

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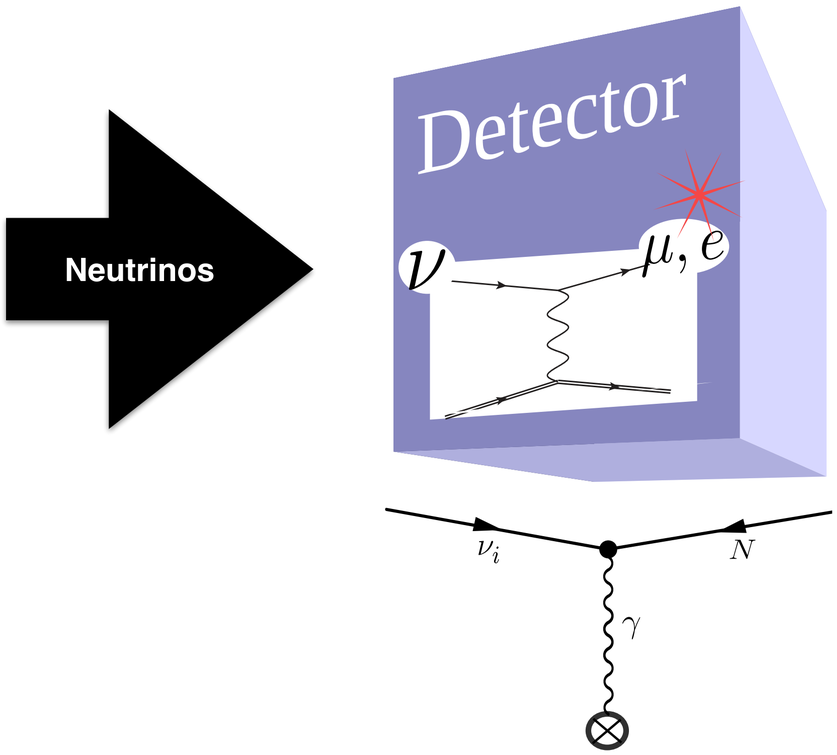
Upscattering Inside the Detector

arXiv:1803.03262



Coherent upscattering in detector

$$\sigma_{\rm coh} \sim Z^2 d^2 \log(E_\nu / Q_{\rm min})$$

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Upscattering Inside the Detector

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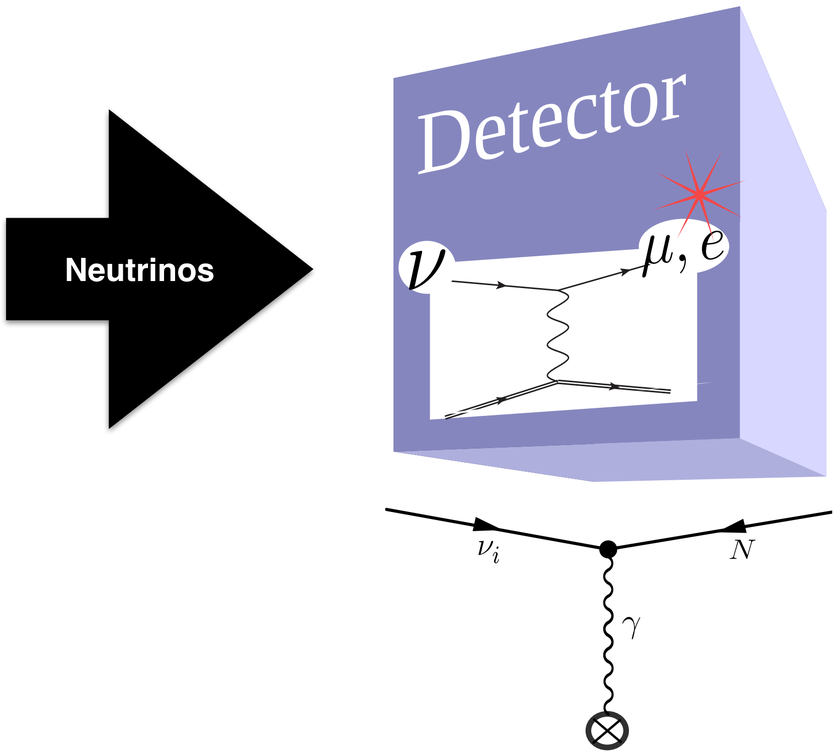

Coherent upscattering in detector

$$\sigma_{\rm coh} \sim Z^2 d^2 \log(E_\nu / Q_{\rm min})$$

Features

- Upscattering occurs within the detector
- All prodcued HNLs should decay inside the detector
- Short distance limit set by detector resolution
- Can be dominant production mode for large detectors made of a high Z material.

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Upscattering Inside the Detector

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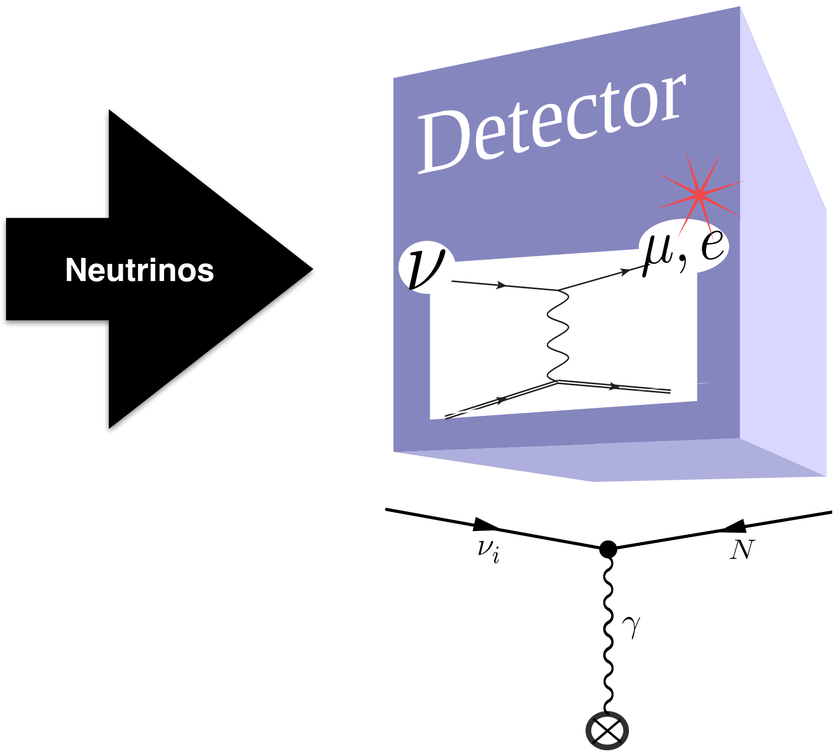

Coherent upscattering in detector

$$\sigma_{\rm coh} \sim Z^2 d^2 \log(E_\nu / Q_{\rm min})$$

Features

- Upscattering occurs within the detector
- All prodcued HNLs should decay inside the detector
- Short distance limit set by detector resolution
- Can be dominant production mode for large detectors made of a high Z material.

Calculation

- Use collaboration's neutrino fluxes
- Calculate number of upscattering events.
- Compute probability that HNL decays inside detector (almost always 100%)

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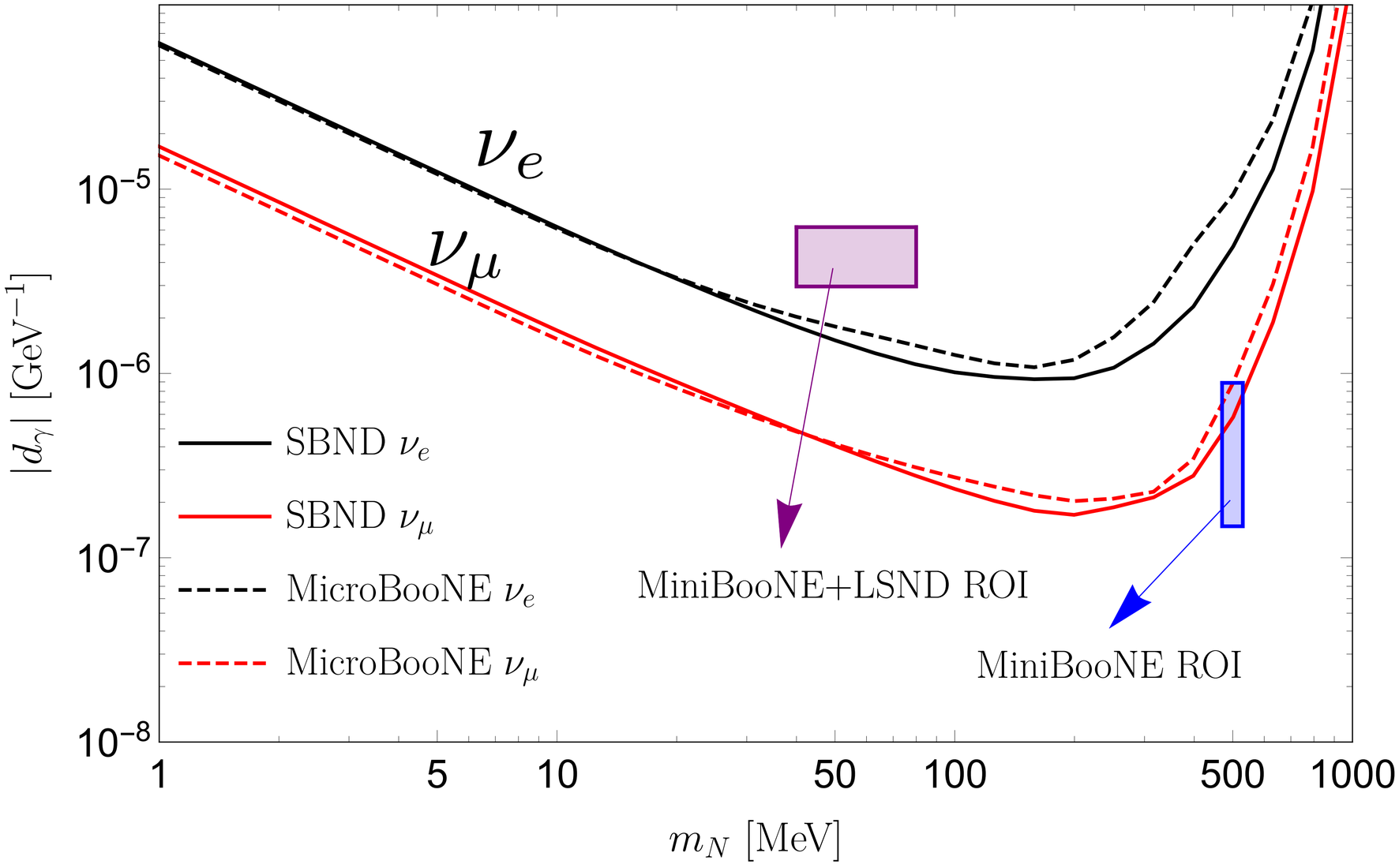
Dipole Portal At Beam Dumps

arXiv:1803.03262



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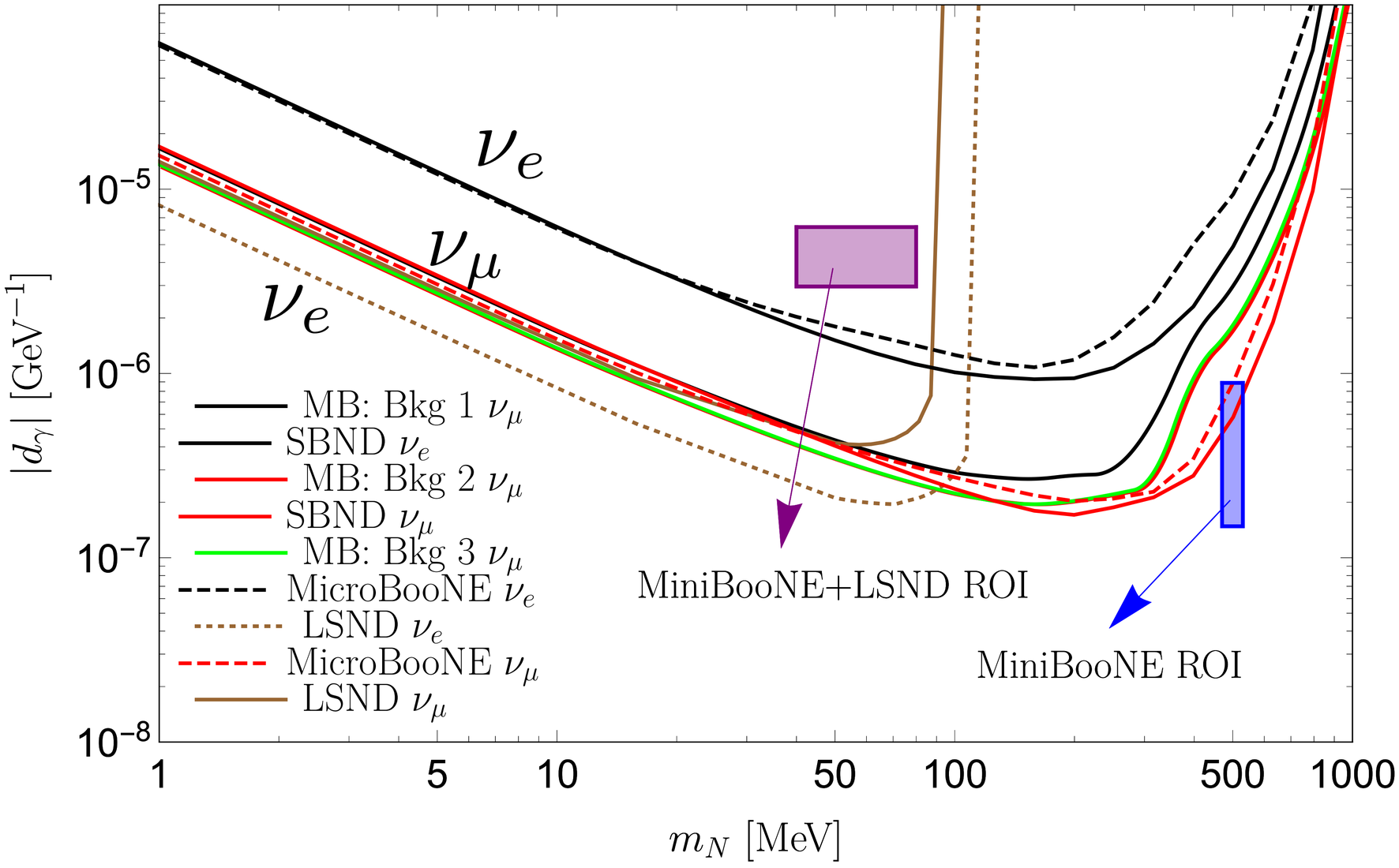

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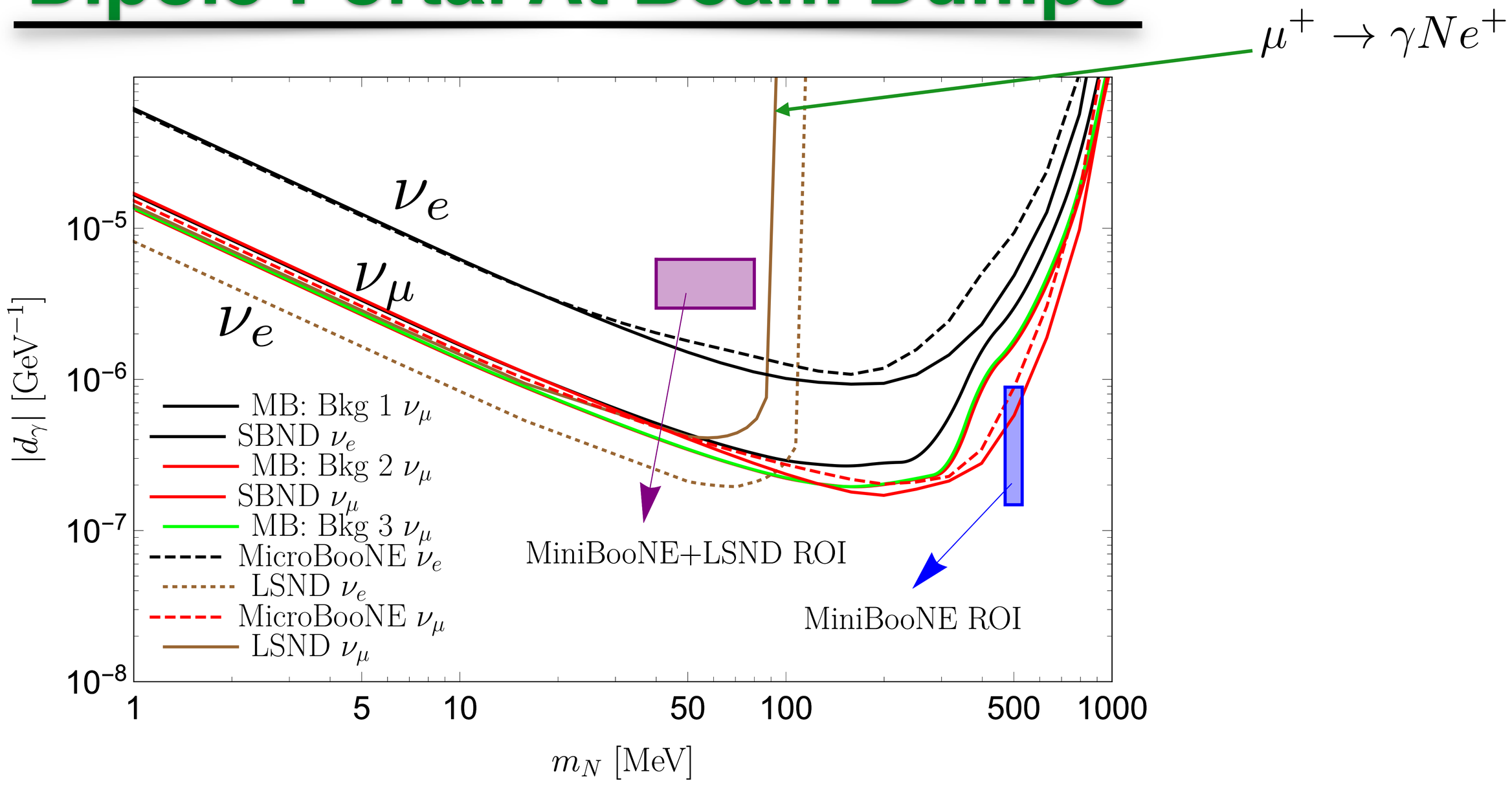

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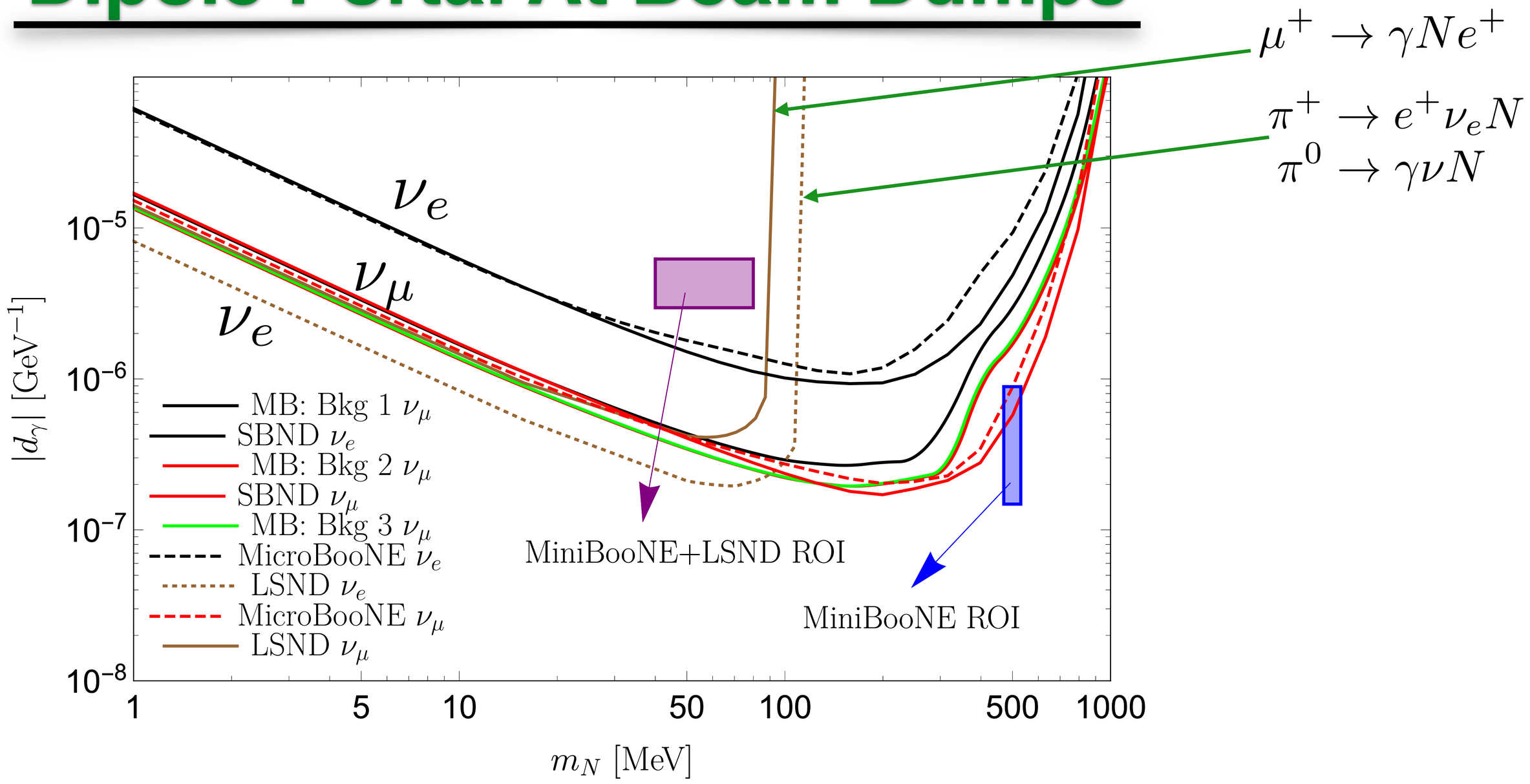

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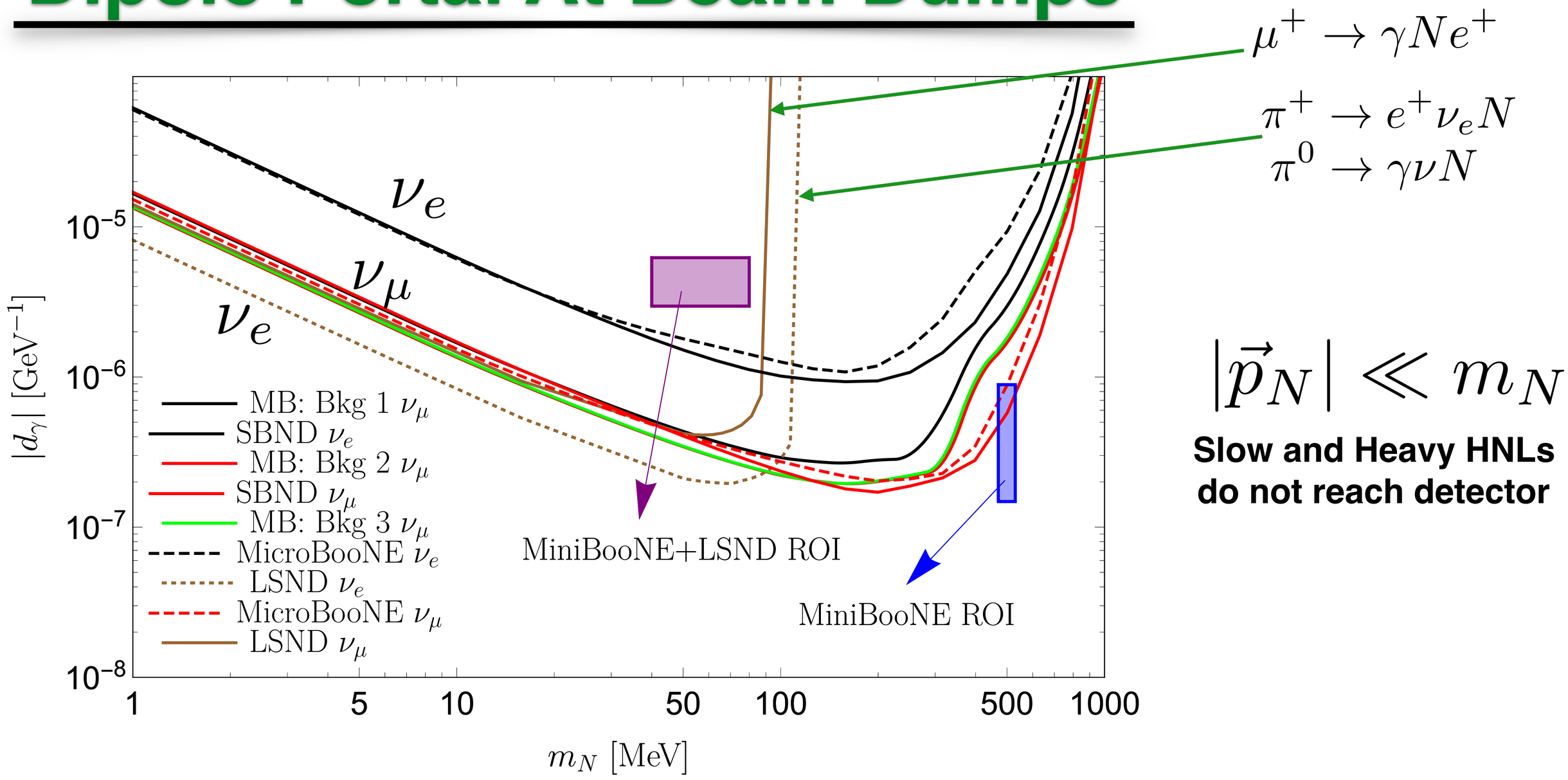

$$|\vec{p}_N| \ll m_N$$

Slow and Heavy HNLs do not reach detector

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Dipole Portal At Beam Dumps

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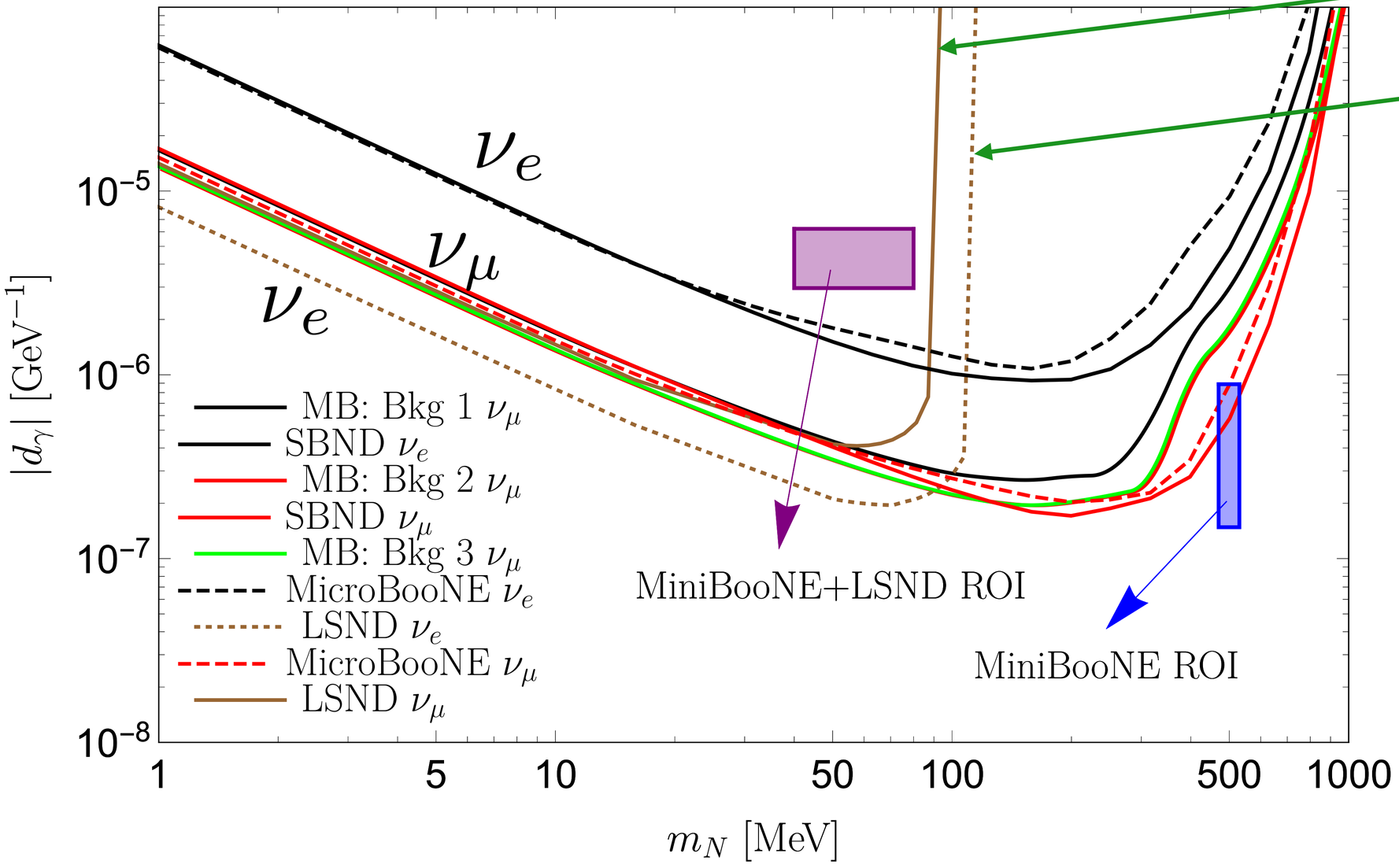

$$\mu^+ \to \gamma N e^+$$

$$\pi^+ \to e^+ \nu_e N$$

$$\pi^0 \to \gamma \nu N$$

$$|\vec{p}_N| \ll m_N$$

Slow and Heavy HNLs do not reach detector

SBN assumes 6 x 10^{20} POT
MicroBooNE 1.3 x 10^{21} POT

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Signatures of a Dipole Portal

arXiv:1803.03262

Neutrino Detectors (single photons)

Collider Searches (single photons)

Supernovae Cooling (HNL emission)

Big Bang Nucleosynthesis (modified N_{eff})

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Dipole Portal At Colliders

arXiv:1803.03262

Colliders	$\sqrt{s}$	$\mathbf{L_{IP}}$	$\mathcal{L}$ [fb^{-1}]	**Technology**	$E_\gamma^{\min}$[GeV]	**Bkgs**
LHC $\gamma + \ell$	8 TeV	1.3 m	19.7	CMS	40	60
LHC γ	13 TeV	1.5 m	36.1	ATLAS	150	1.7K
LEP	91.2GeV	1 m	0.1	e^+e^- Collider	0.7	NA

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$$\bar{L}\left(\bar{d}_{\mathcal{W}}\mathcal{W}^a_{\mu\nu}\tau^a + d_{\mathcal{B}}\mathcal{B}_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D$$

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$$\bar{L}\left(\bar{d}_{\mathcal{W}}\mathcal{W}^a_{\mu\nu}\tau^a + d_{\mathcal{B}}\mathcal{B}_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D \xrightarrow{EW-SB}$$

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Dipole Portal At Colliders

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$$d_W\bar{\ell}W^-_{\mu\nu}\sigma^{\mu\nu}N_D$$

$$\bar{\nu}\left(d_\gamma F_{\mu\nu} - d_Z Z_{\mu\nu}\right)\sigma^{\mu\nu}N_D$$

$$d_\gamma = \frac{\mathrm{v}}{\sqrt{2}}\left(d_B\cos\theta_w + \frac{d_{\mathcal{W}}}{2}\sin\theta_w\right)$$

$$d_W = \frac{\mathrm{v}}{\sqrt{2}}\frac{d_{\mathcal{W}}}{2}\times\sqrt{2}$$

$$d_Z = \frac{\mathrm{v}}{\sqrt{2}}\left(\frac{d_{\mathcal{W}}}{2}\cos\theta_w - d_B\sin\theta_w\right)$$

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Exp.	Plot Label	Assumptions	Probed d
LEP	d_γ	$\overline{d_{\mathcal{W}}} = 0,\ d_Z = 0$	$\overline{d_B}$
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LHC	$d_{\gamma,Z}$	$\overline{d_{\mathcal{W}}} = 0$	$\overline{d_B}$
	$d^a_{\gamma,W}$	$d_\gamma = a \times \overline{d_{\mathcal{W}}}$	$\overline{d_{\mathcal{W}}}$

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Dipole Portal At Colliders

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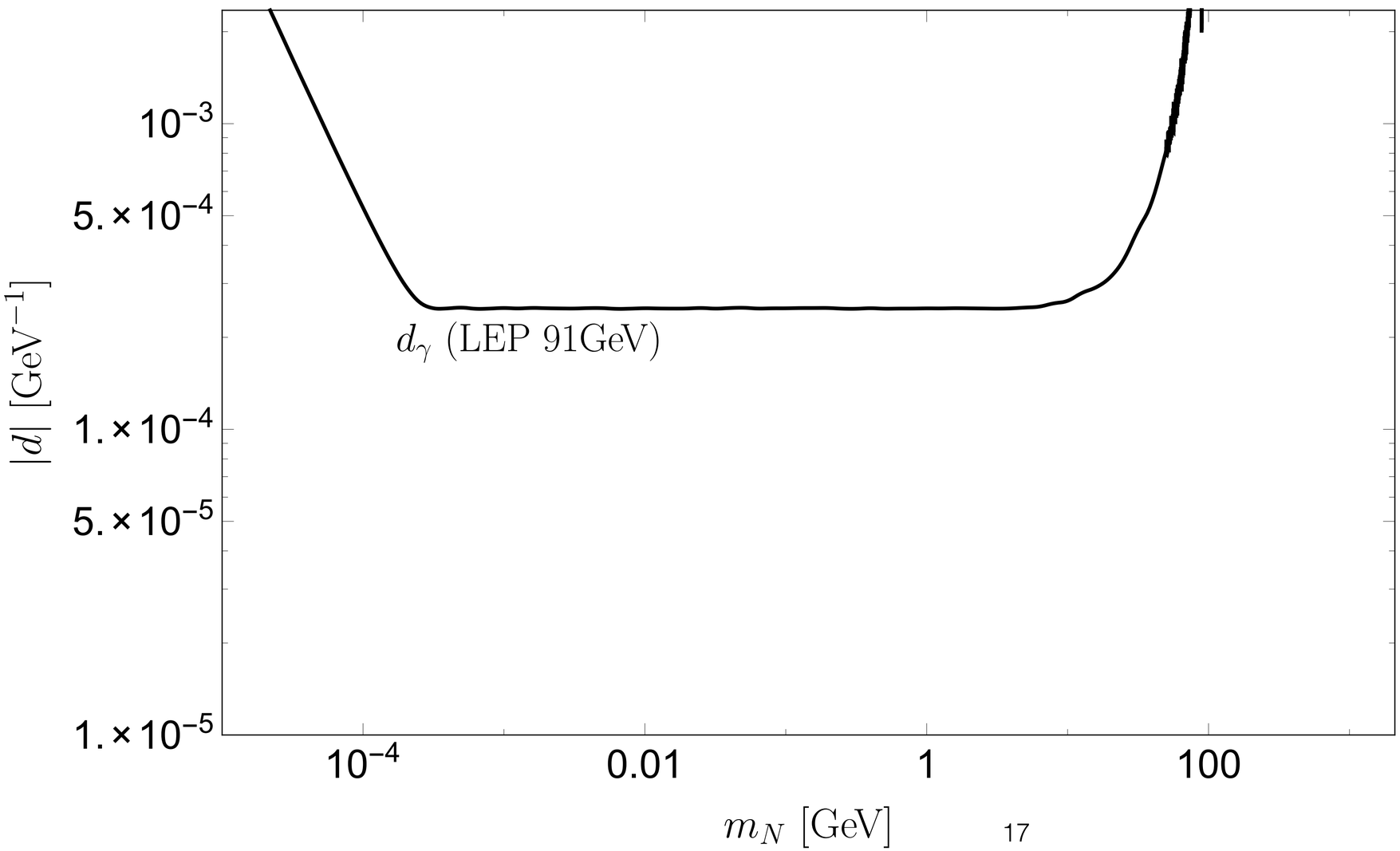

Single Photon Searches

@LEP91GeV (Monophoton):
arXiv:hep-ph/9611437, Phys.Rev.D55 (1997)

Exp.	Plot Label	Assumptions	Probed d
LEP	d_γ	$\overline{d_\mathcal{W}} = 0,\ d_Z = 0$	$\overline{d_B}$
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LHC	$d_{\gamma,Z}$	$\overline{d_\mathcal{W}} = 0$	$\overline{d_B}$
	$d^a_{\gamma,W}$	$d_\gamma = a \times \overline{d_\mathcal{W}}$	$\overline{d_\mathcal{W}}$

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Dipole Portal At Colliders

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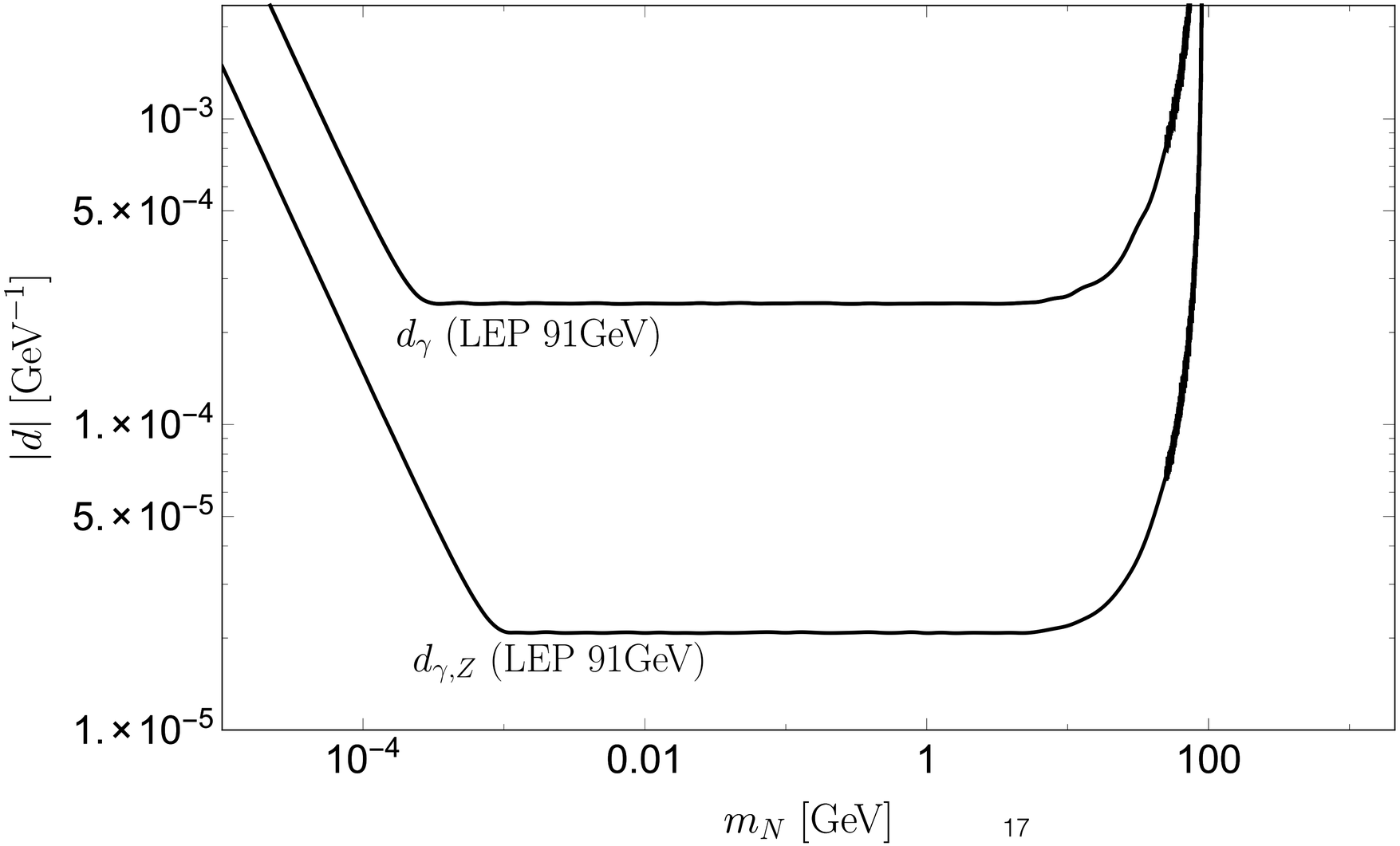

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	$d^a_{\gamma,W}$	$d_\gamma = a \times \overline{d_\mathcal{W}}$	$\overline{d_\mathcal{W}}$

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Dipole Portal At Colliders

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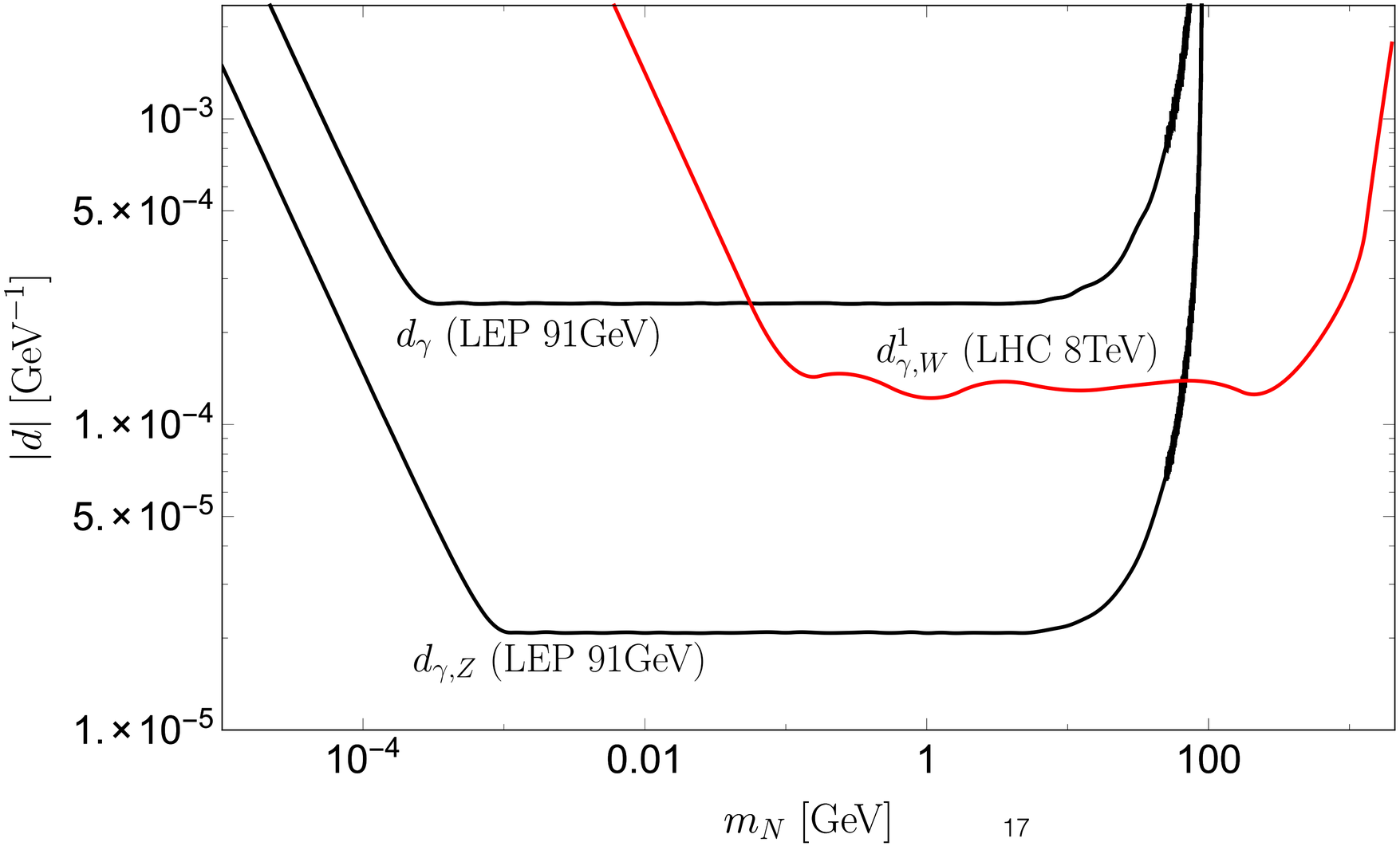

Single Photon Searches

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CMS8TeV (Photon+Lepton):
arXiv:1508.01218, Phys. Lett. B 757 (2016)

Exp.	Plot Label	Assumptions	Probed d
LEP	d_γ	$\overline{d_\mathcal{W}} = 0,\ d_Z = 0$	$\overline{d_B}$
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	$d^a_{\gamma,W}$	$d_\gamma = a \times \overline{d_\mathcal{W}}$	$\overline{d_\mathcal{W}}$

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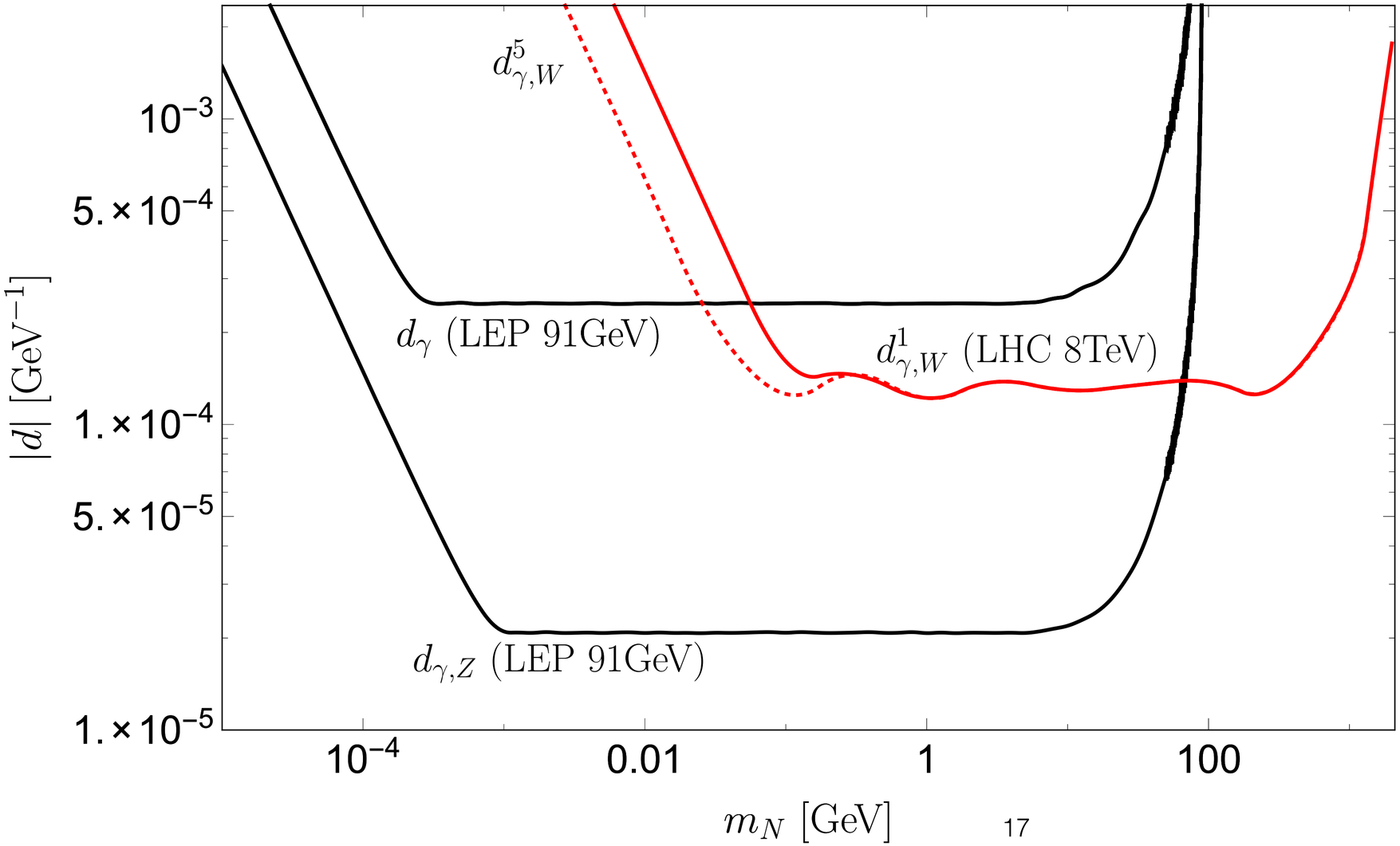
Dipole Portal At Colliders

arXiv:1803.03262



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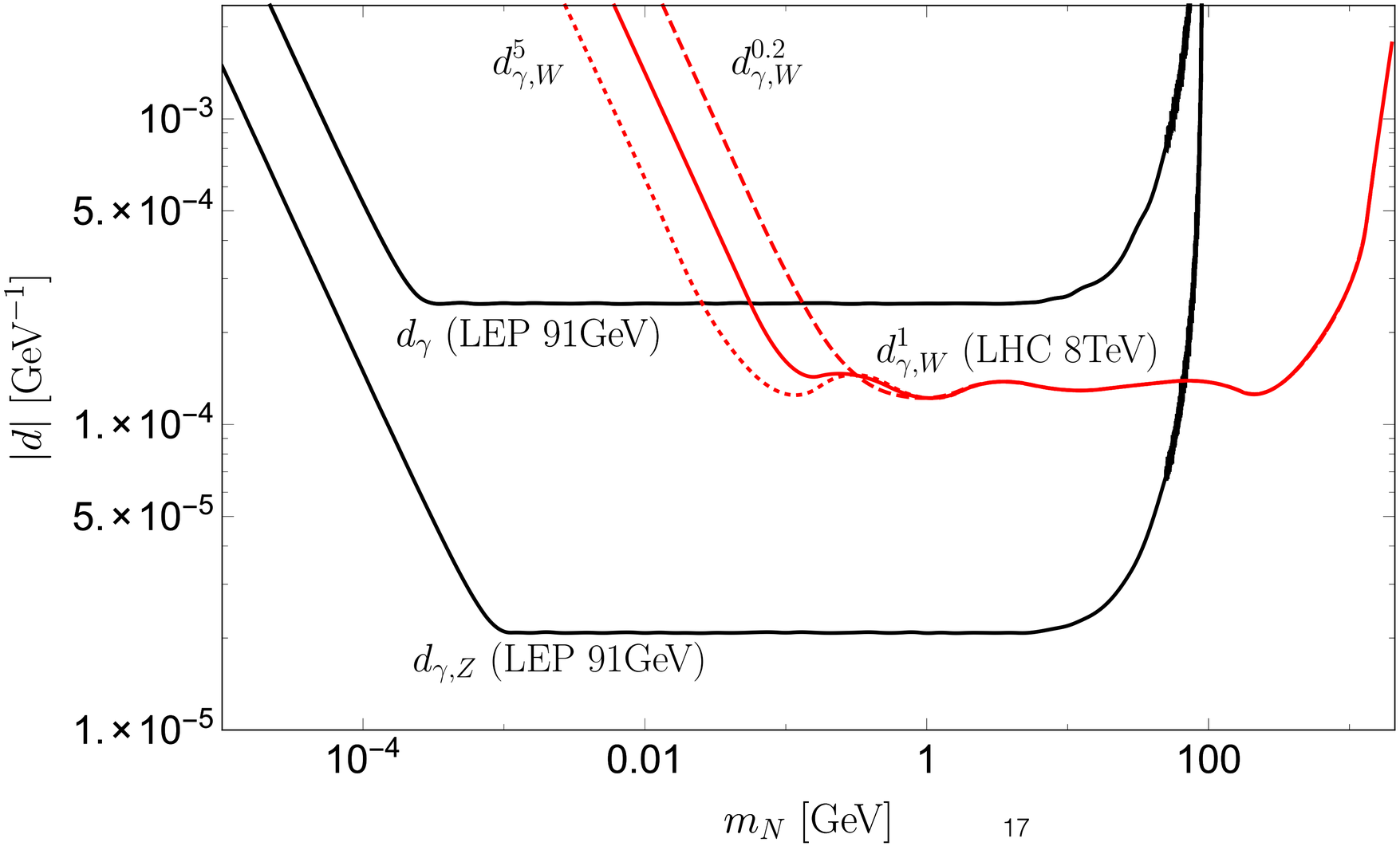

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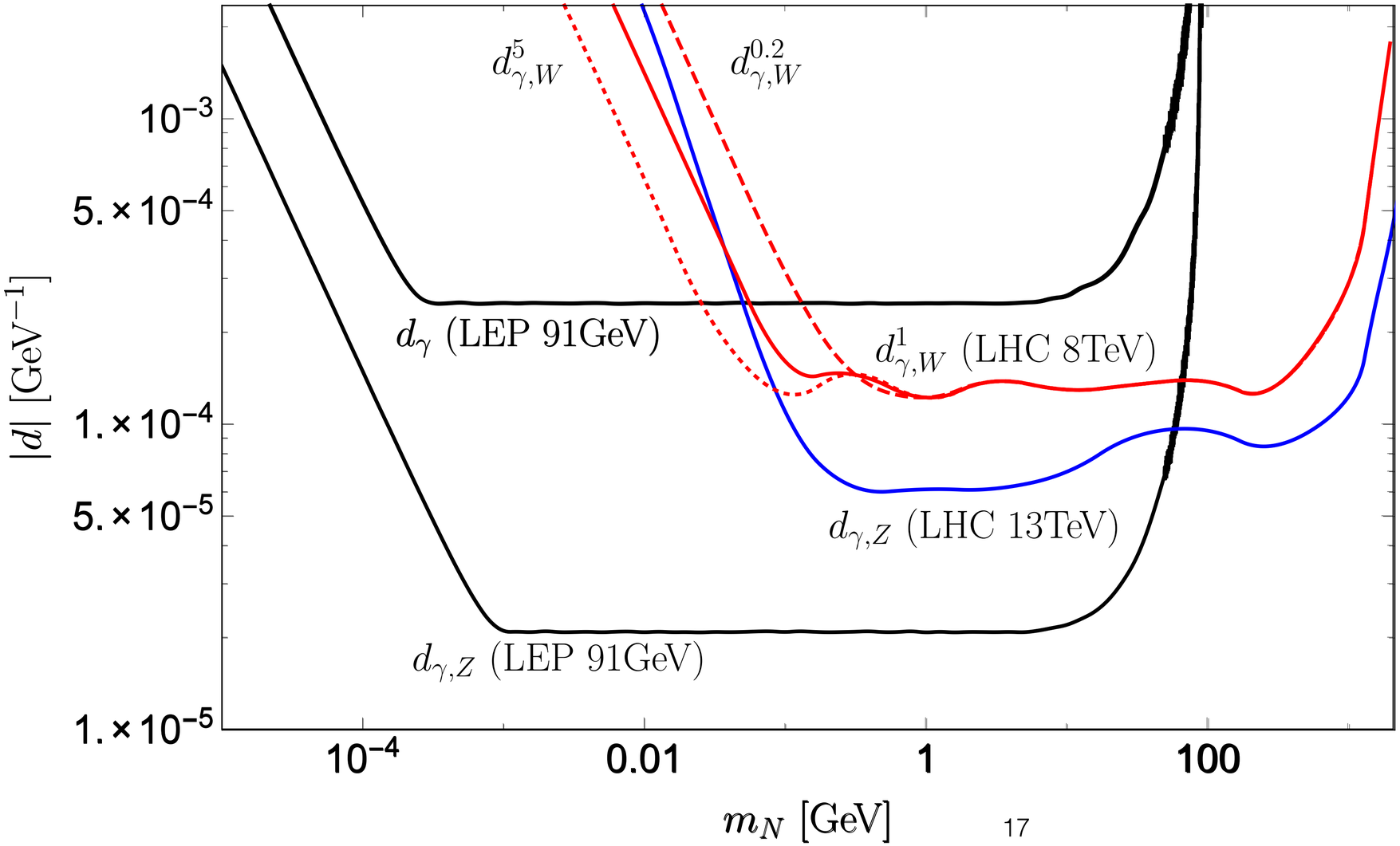

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Dipole Portal At Colliders

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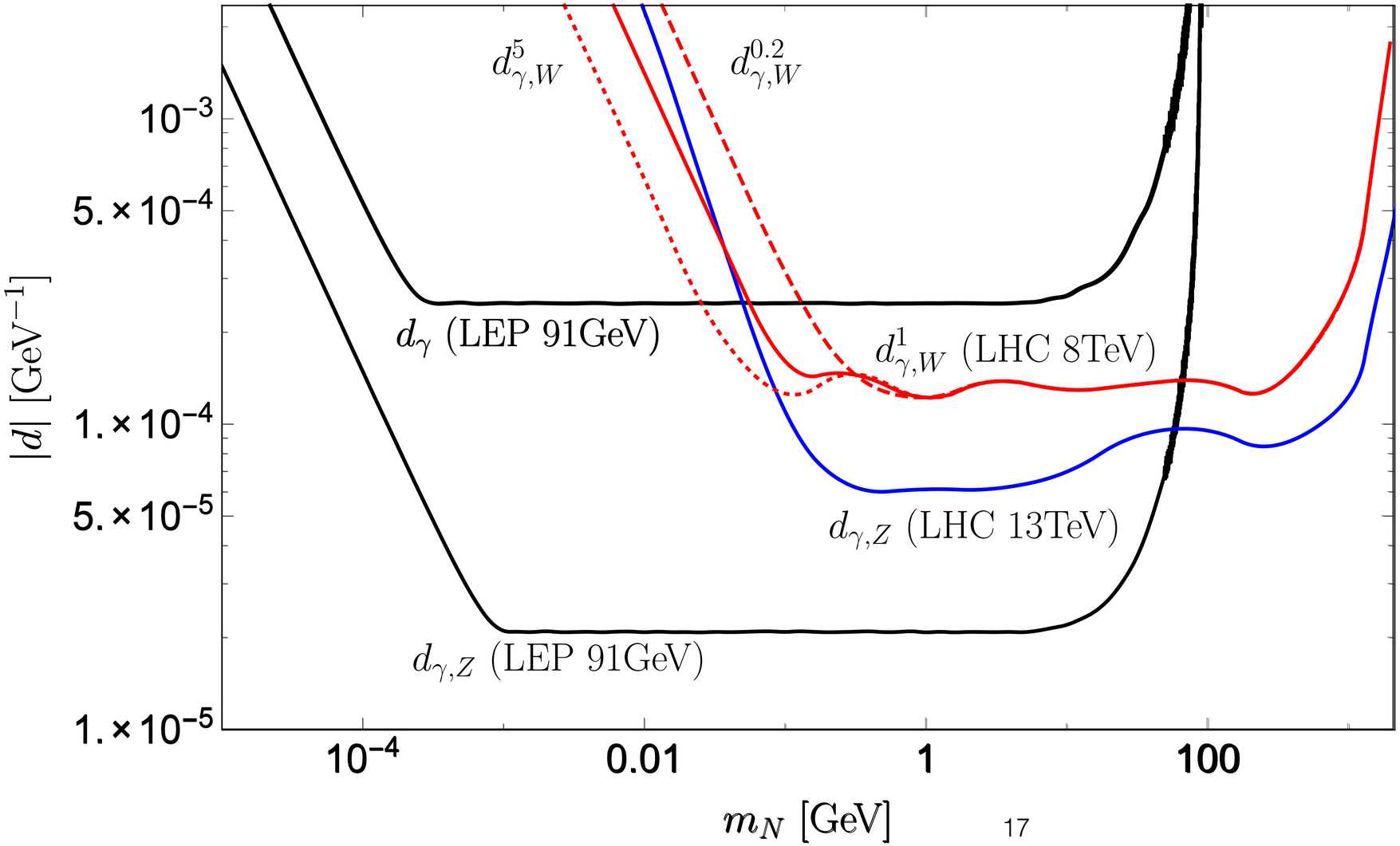
At colliders, inclusive sum over final state neutrinos gives sensitivity to all dipole coupling flavours!



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Signatures of a Dipole Portal

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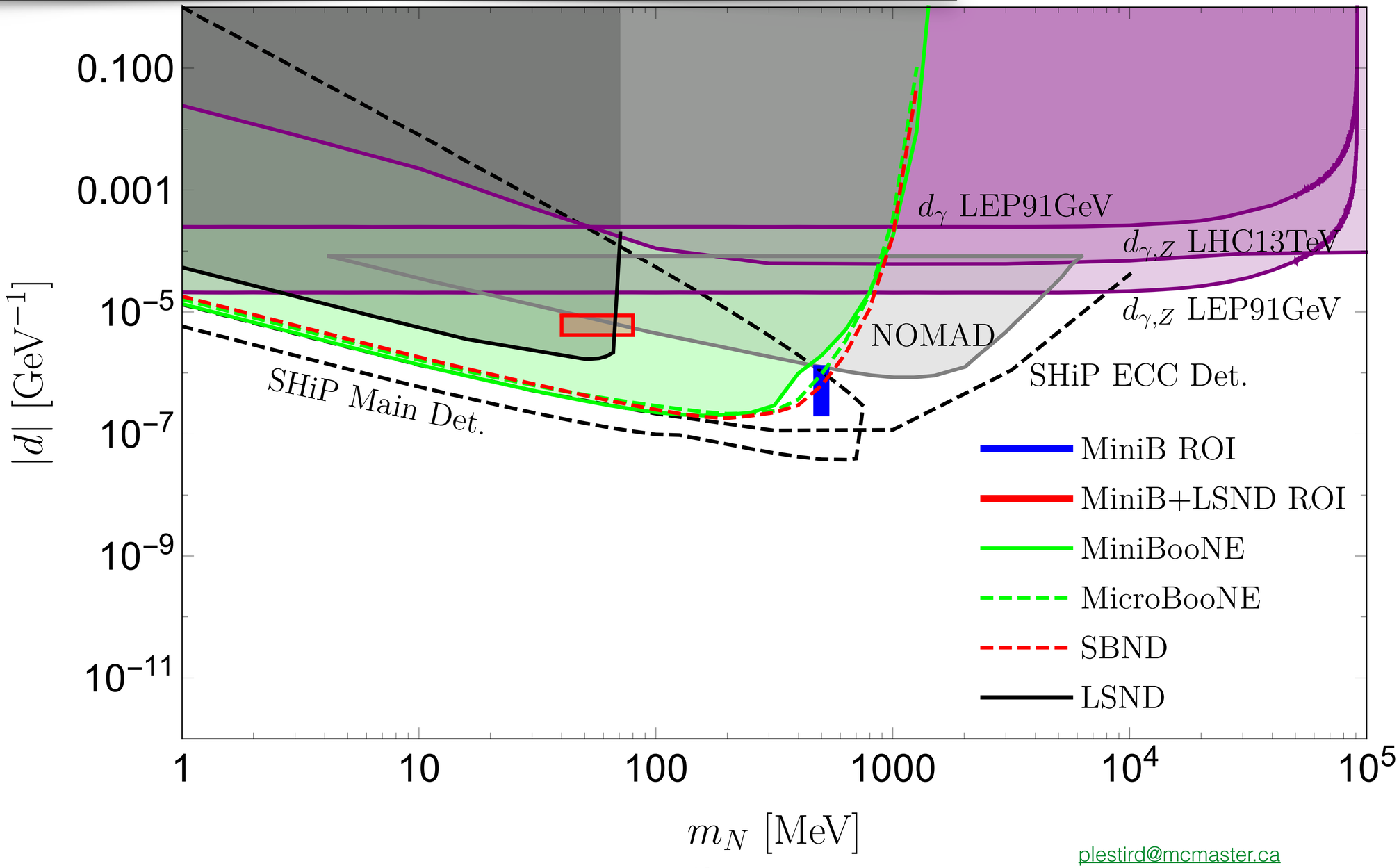

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Neutrino Detectors (single photons)

Collider Searches (single photons)

Supernovae Cooling & BBN

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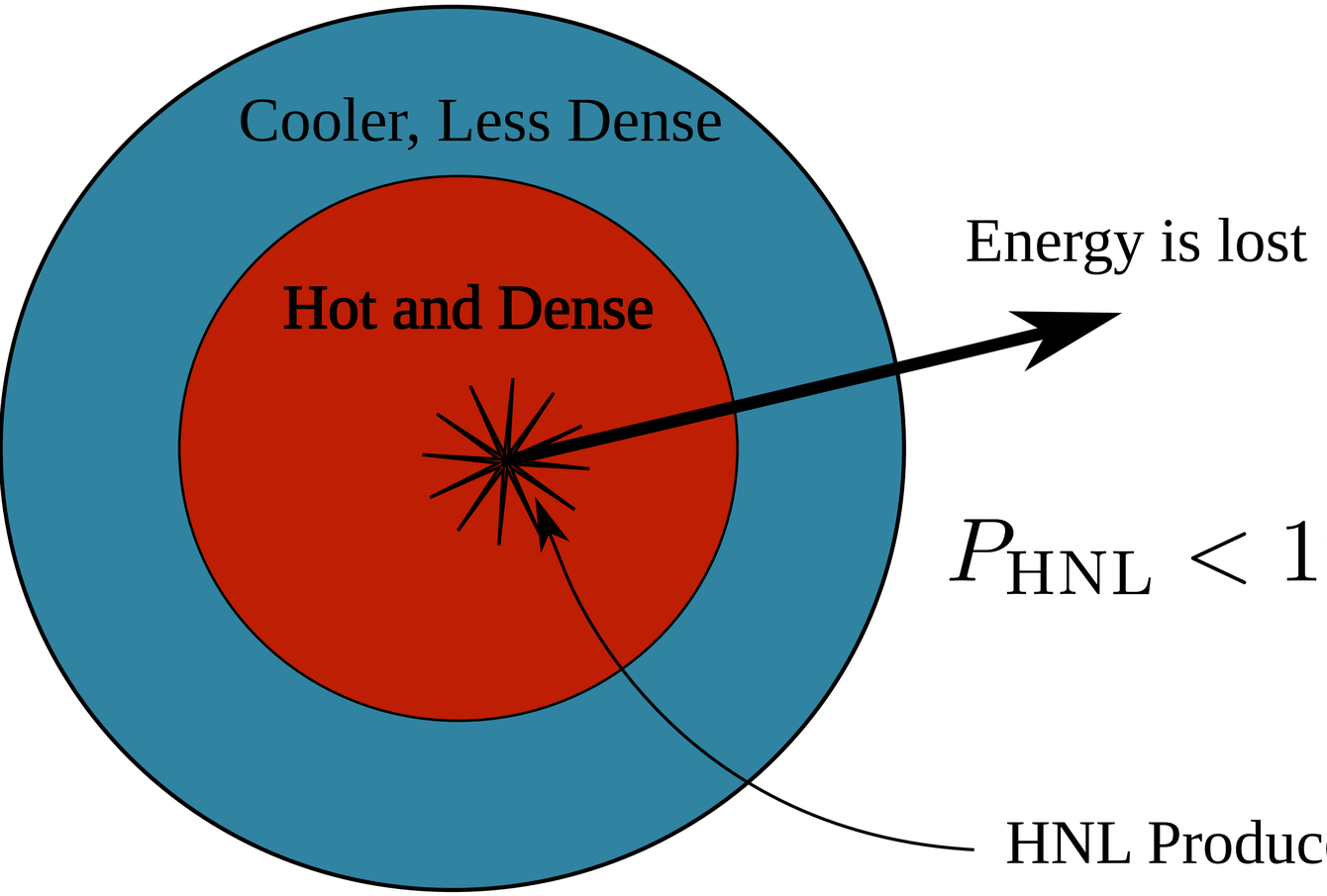

$$P_{\mathrm{HNL}} < 10\% P_{\nu}$$

Need to produce HNL to affect cooling

If the dipole coupling is too small then not enough HNLs will be produced to affect cooling.

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Supernova Cooling

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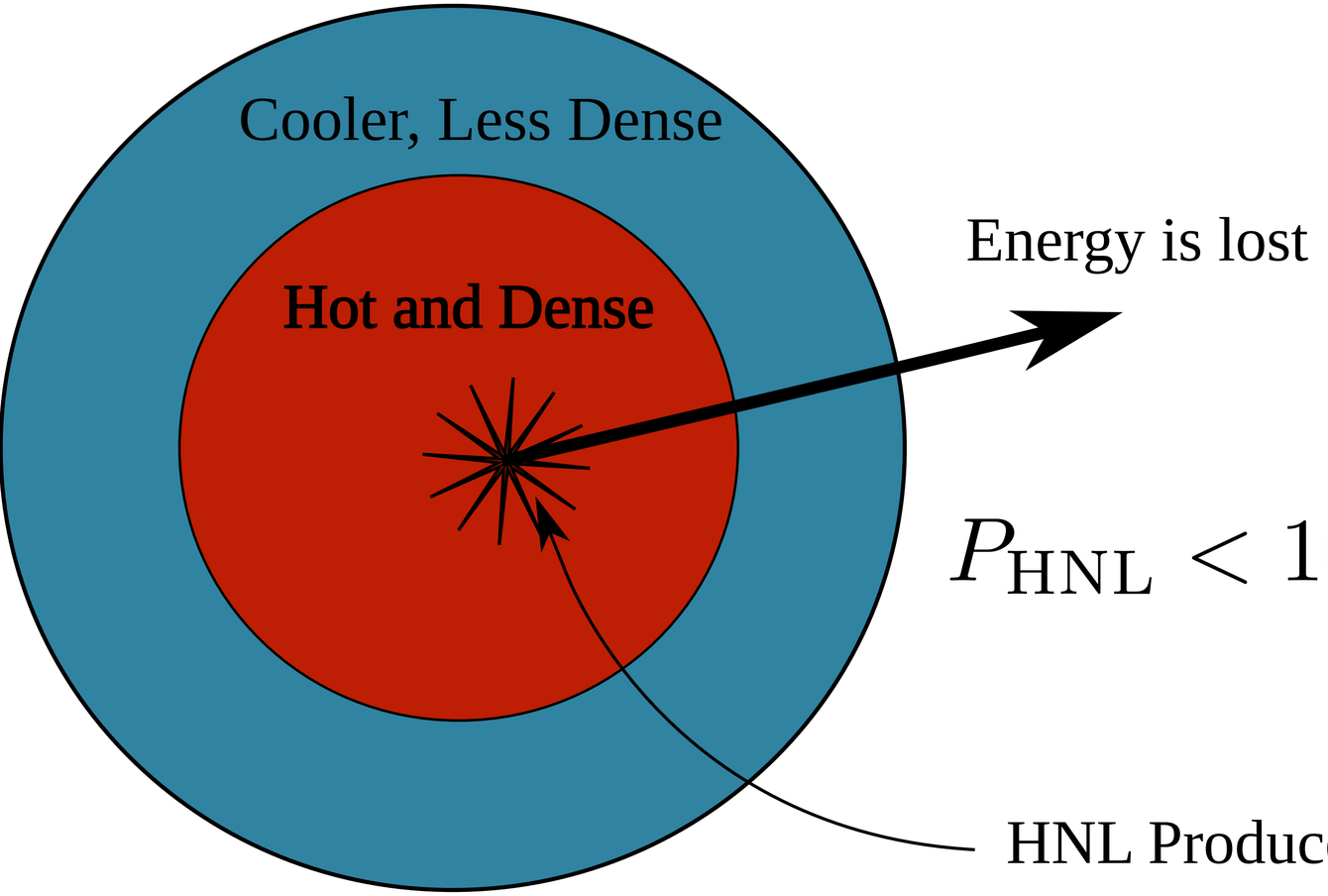

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Need to produce HNL to affect cooling

If the dipole coupling is too small then not enough HNLs will be produced to affect cooling.

Production Channels

$$\nu + e^{\pm} \to N + e^{\pm}$$

$$\nu + p \to N + p$$

$$e^{+} + e^{-} \to \overline{\nu} + N$$

$$\gamma + \nu \to N$$

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Supernova Cooling

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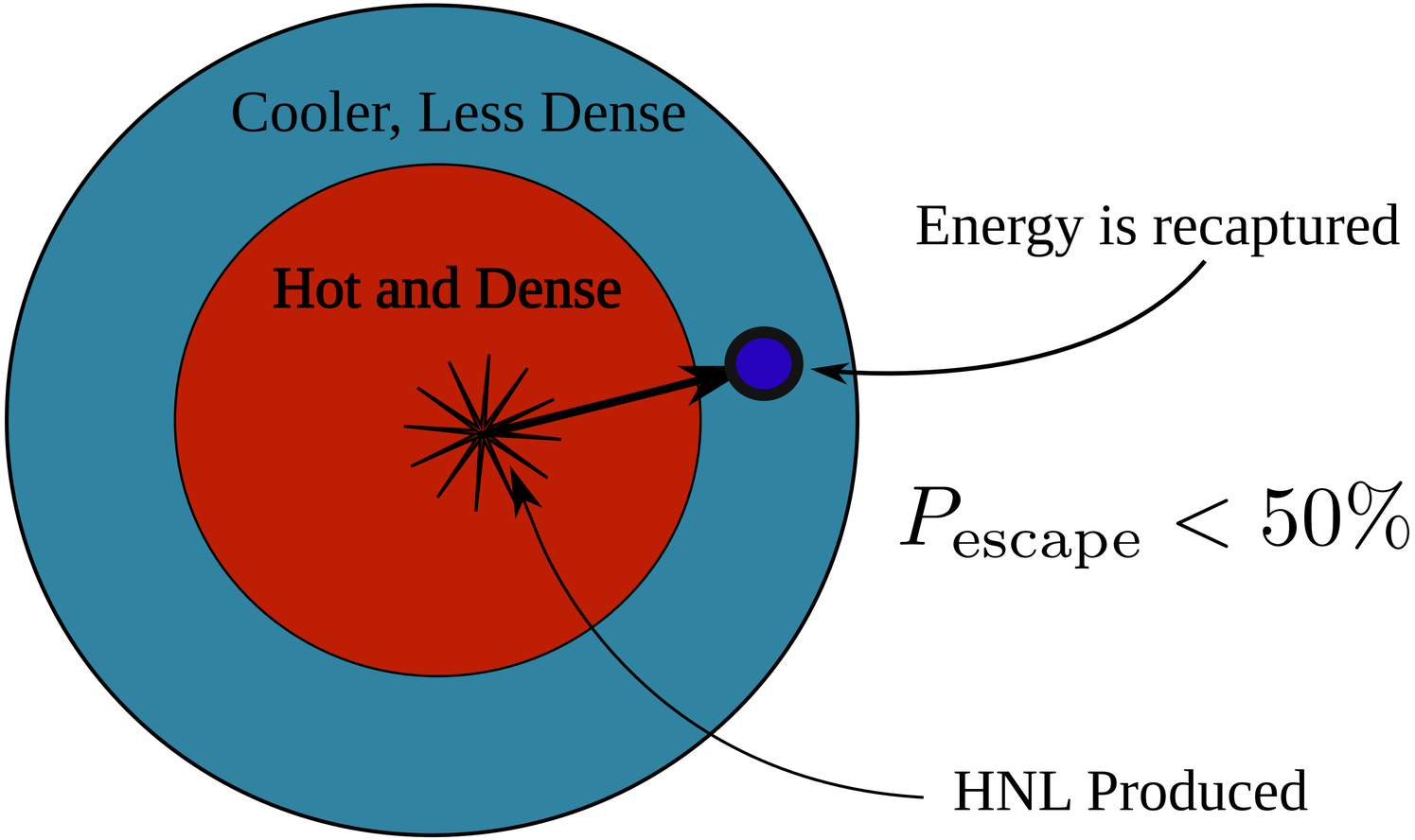

No cooling if HNL cannot escape

If the dipole coupling is too big then all of the HNLs will be reabsorbed without cooling the core

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Supernova Cooling

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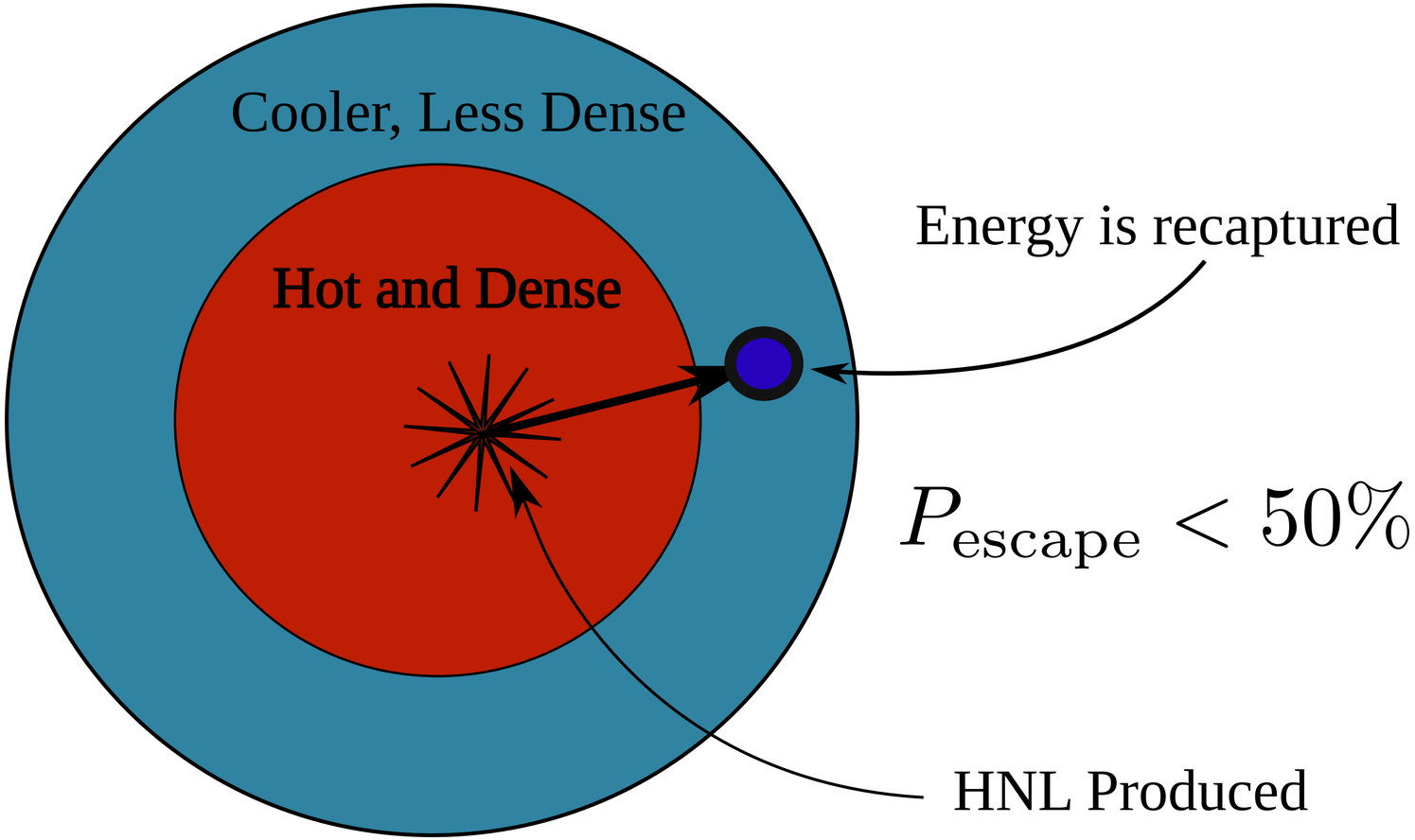

$$P_{\text{escape}} < 50\%$$

No cooling if HNL cannot escape

If the dipole coupling is too big then all of the HNLs will be reabsorbed without cooling the core

"Absorption" Channels

$$N + e^{\pm} \to \nu + e^{\pm}$$

$$N + p \to \nu + p$$

$$\overline{\nu} + N \to e^{+} + e^{-}$$

$$N \to \gamma + \nu$$

$$N + \text{SN} \to N + \text{SN}$$

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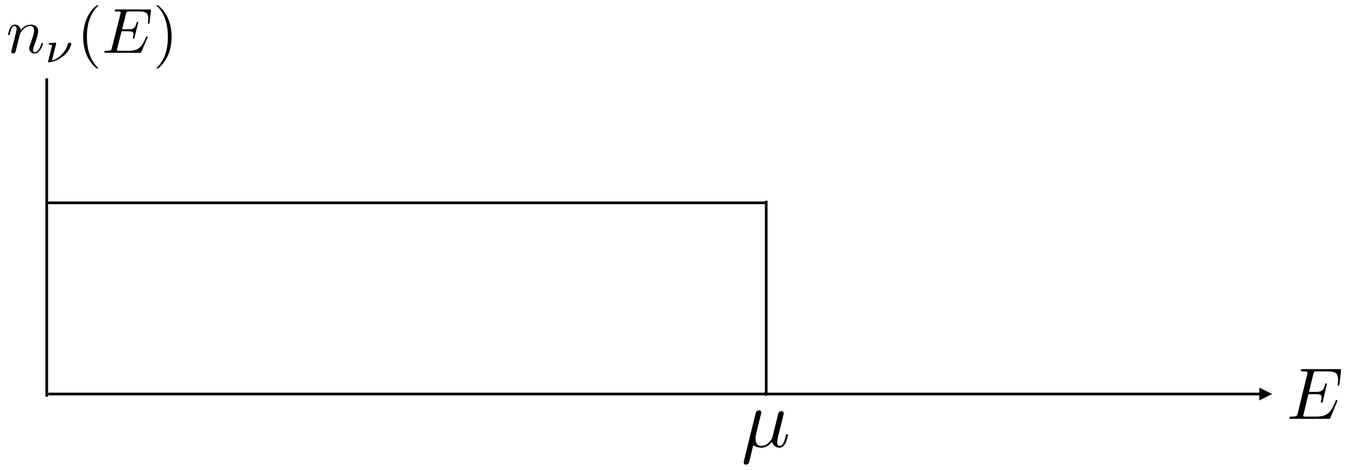
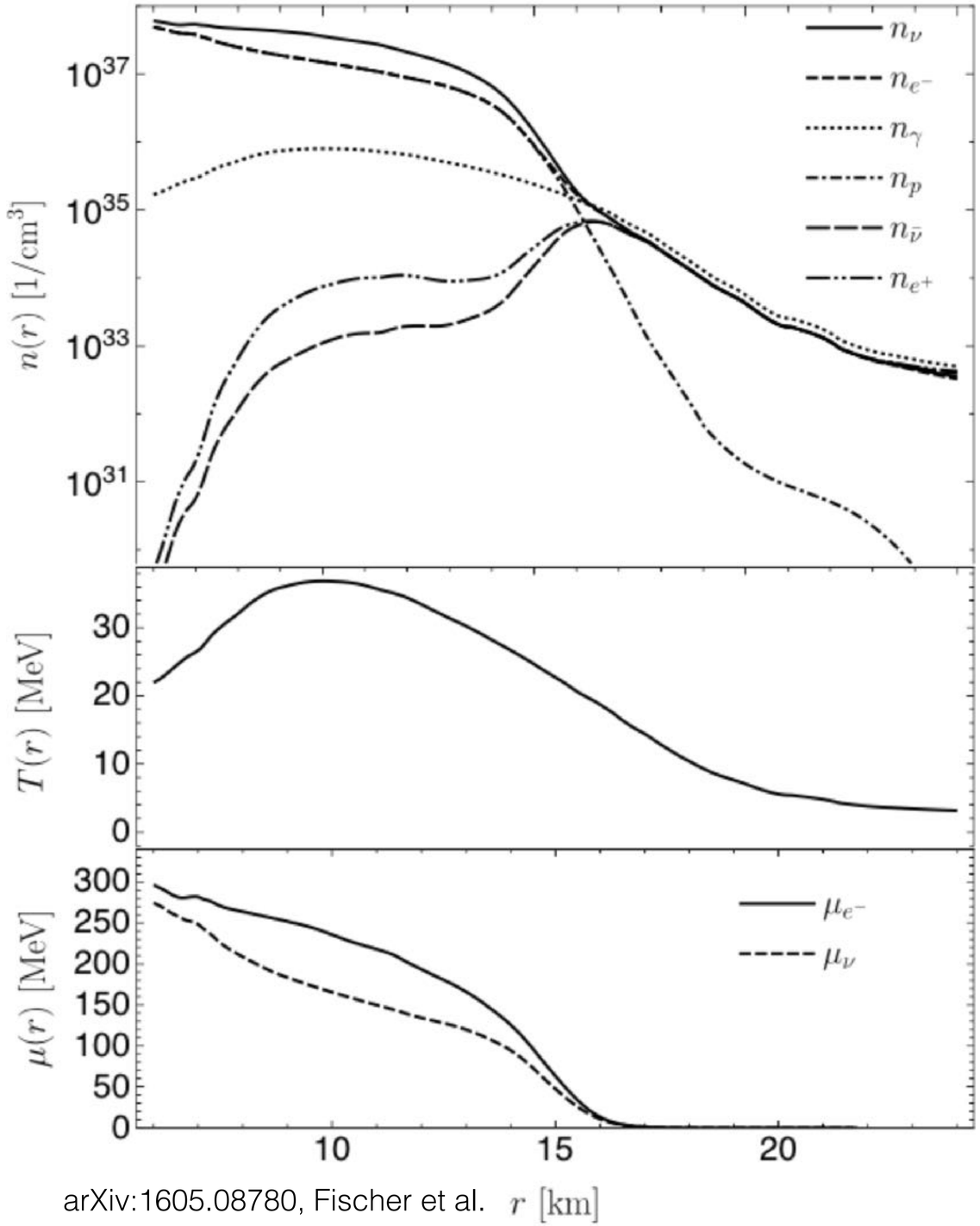
Supernova Cooling

Features of SN Core

- High chemical potentials.
- Pauli blocking is very important.
- High energy (250 MeV) Fermi sea.
- Can probe high masses of HNLs.



$$N + e^- \to \nu + e^-$$



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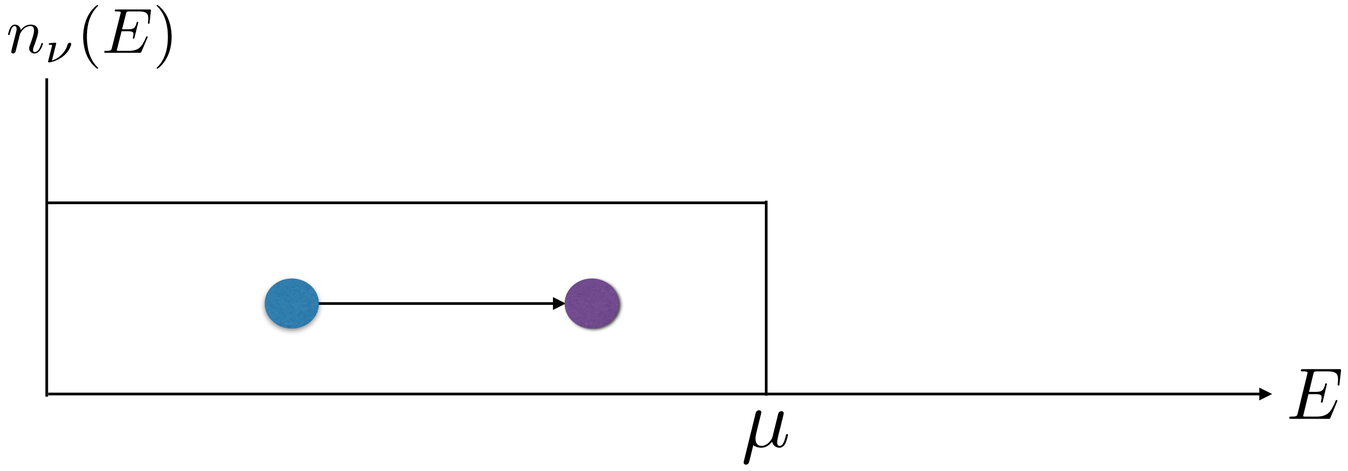

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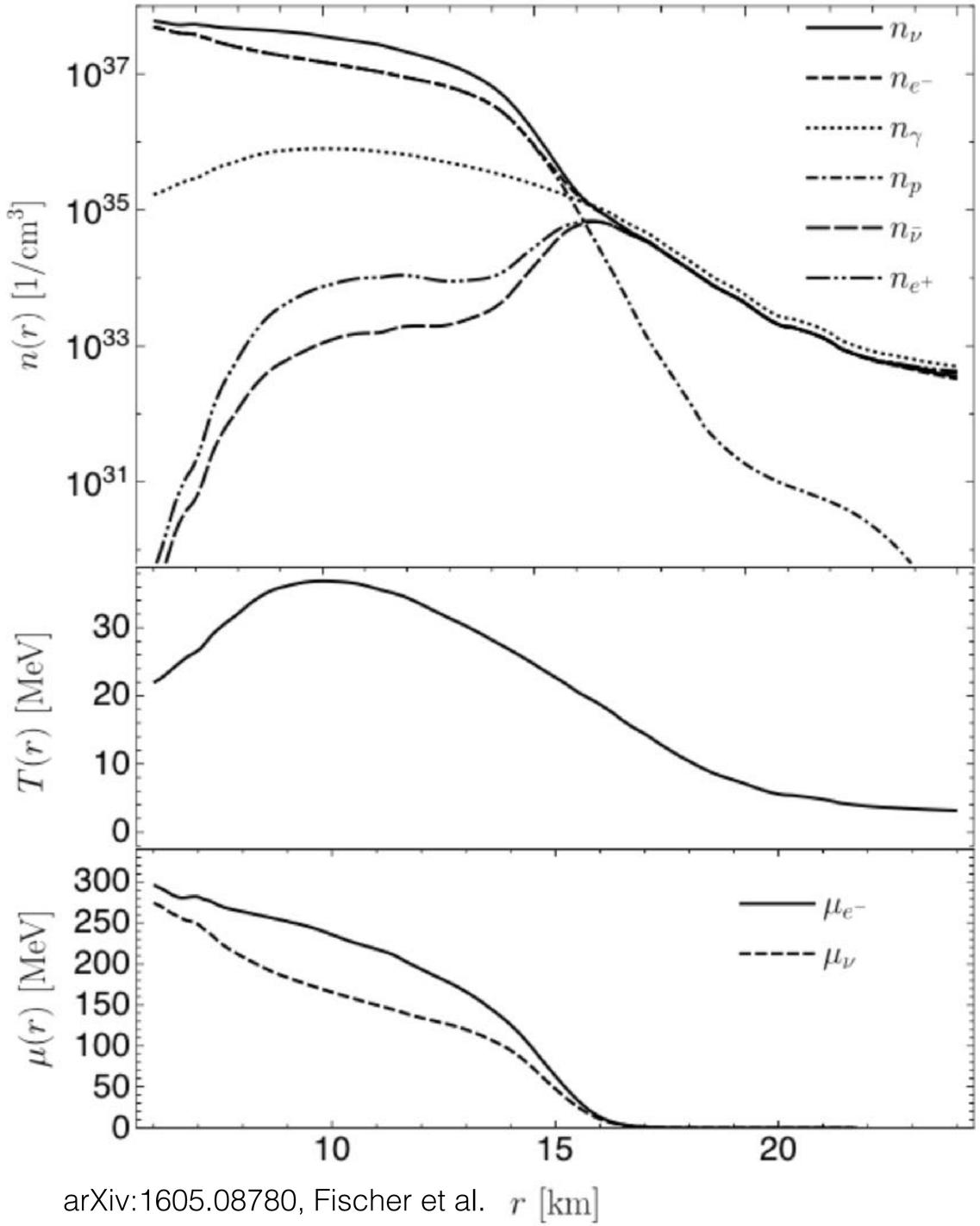

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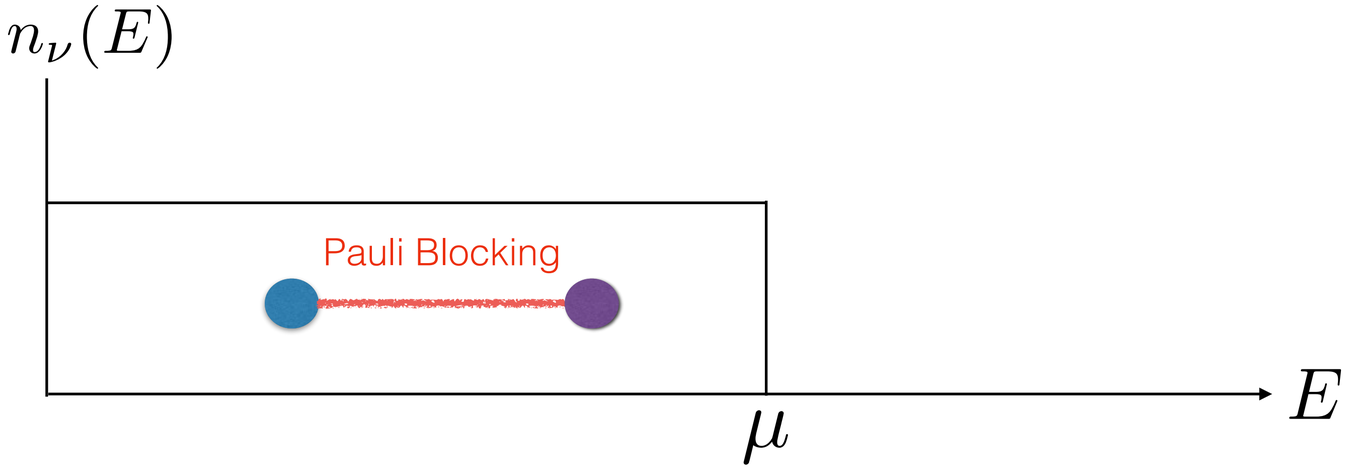

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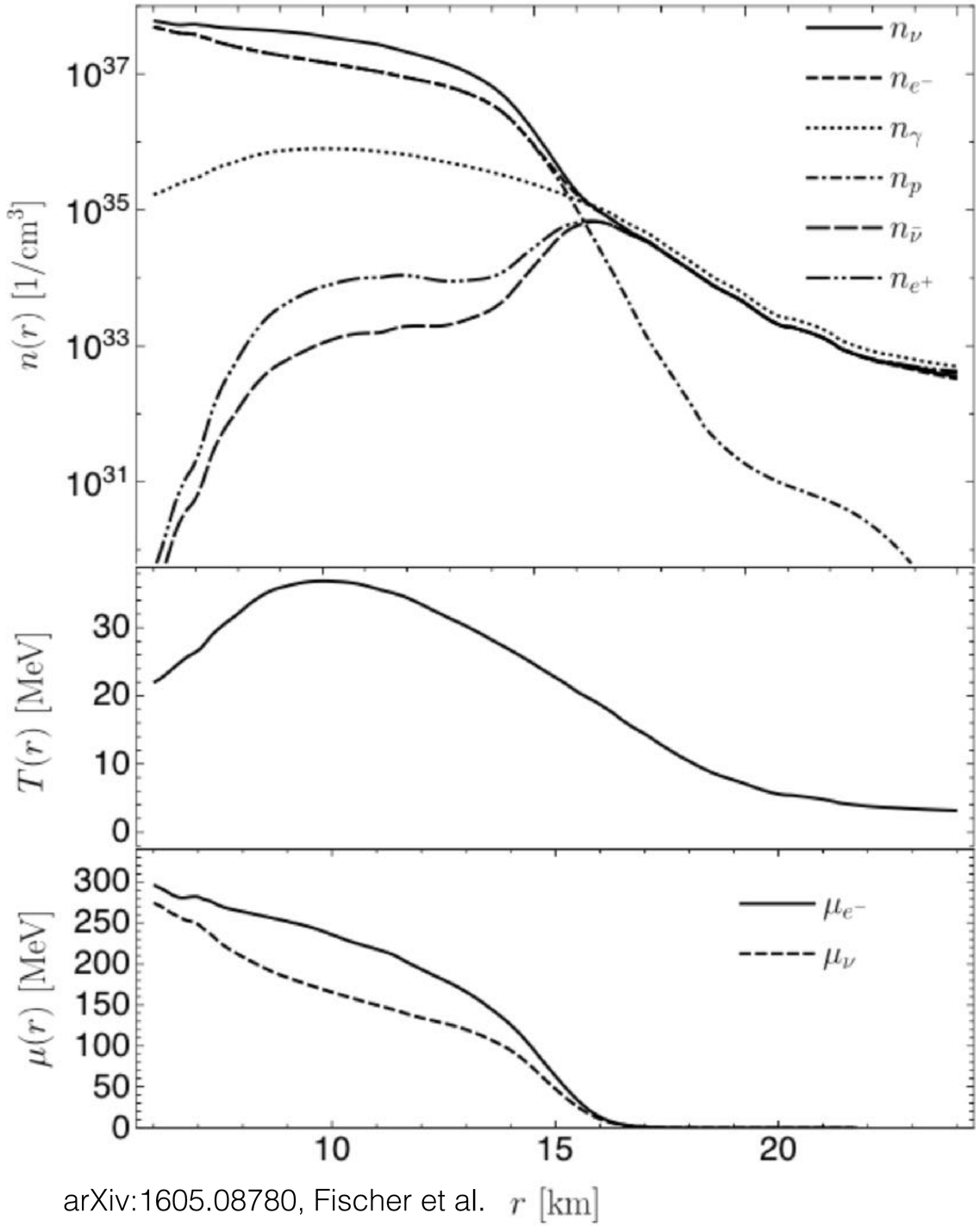

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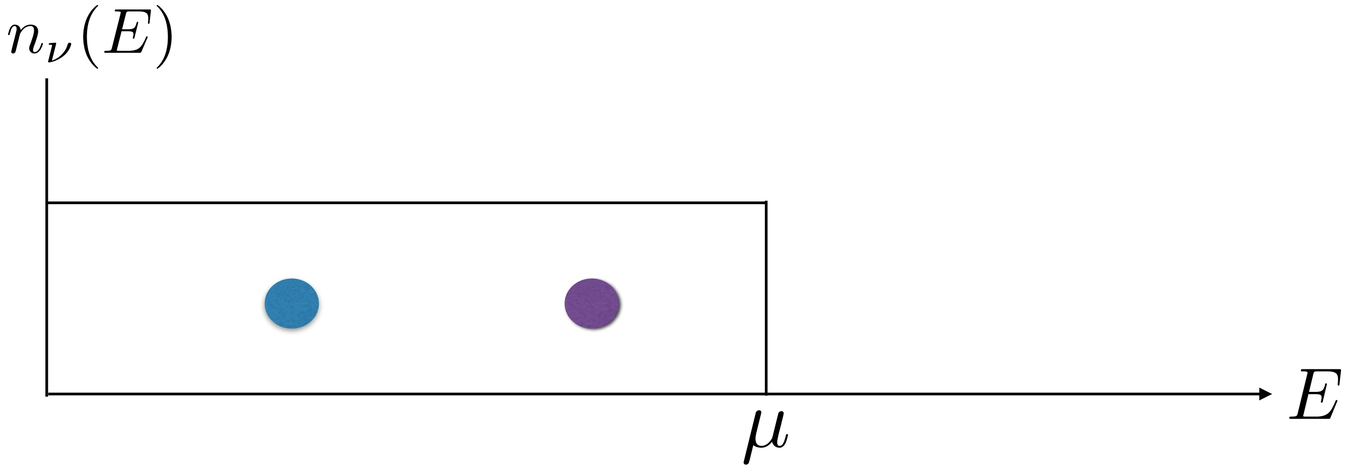

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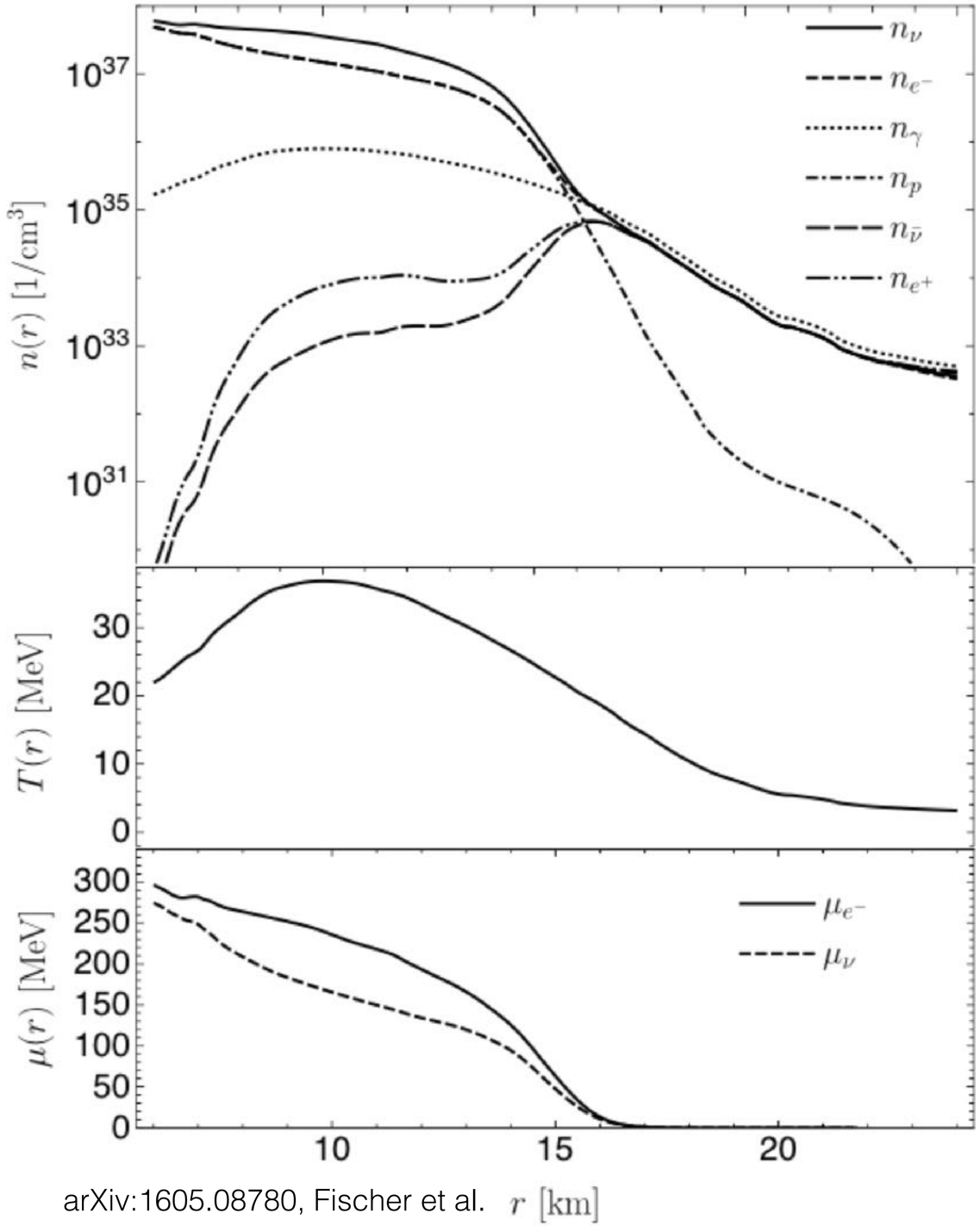

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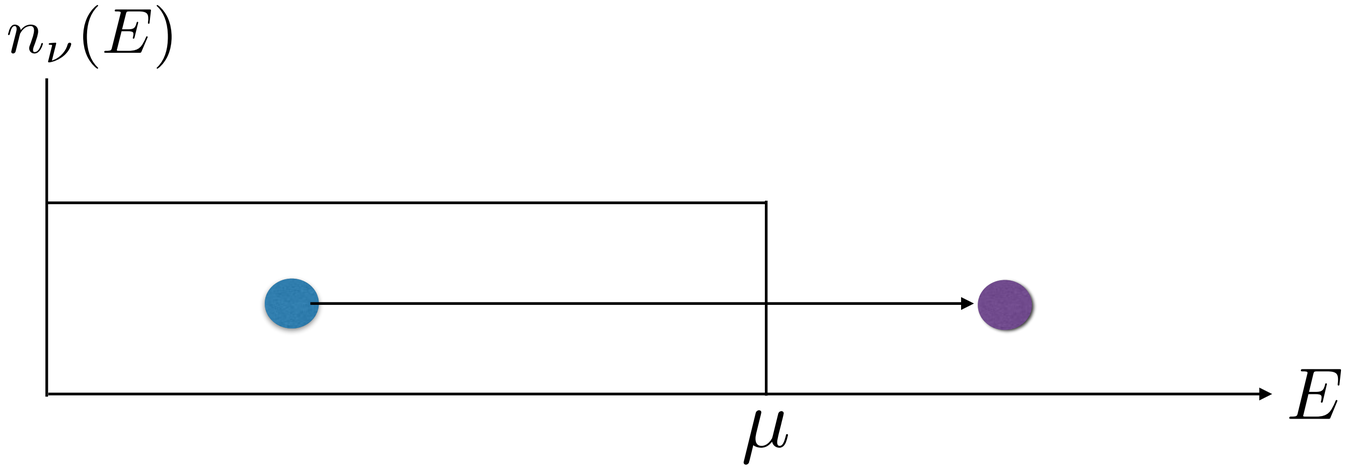

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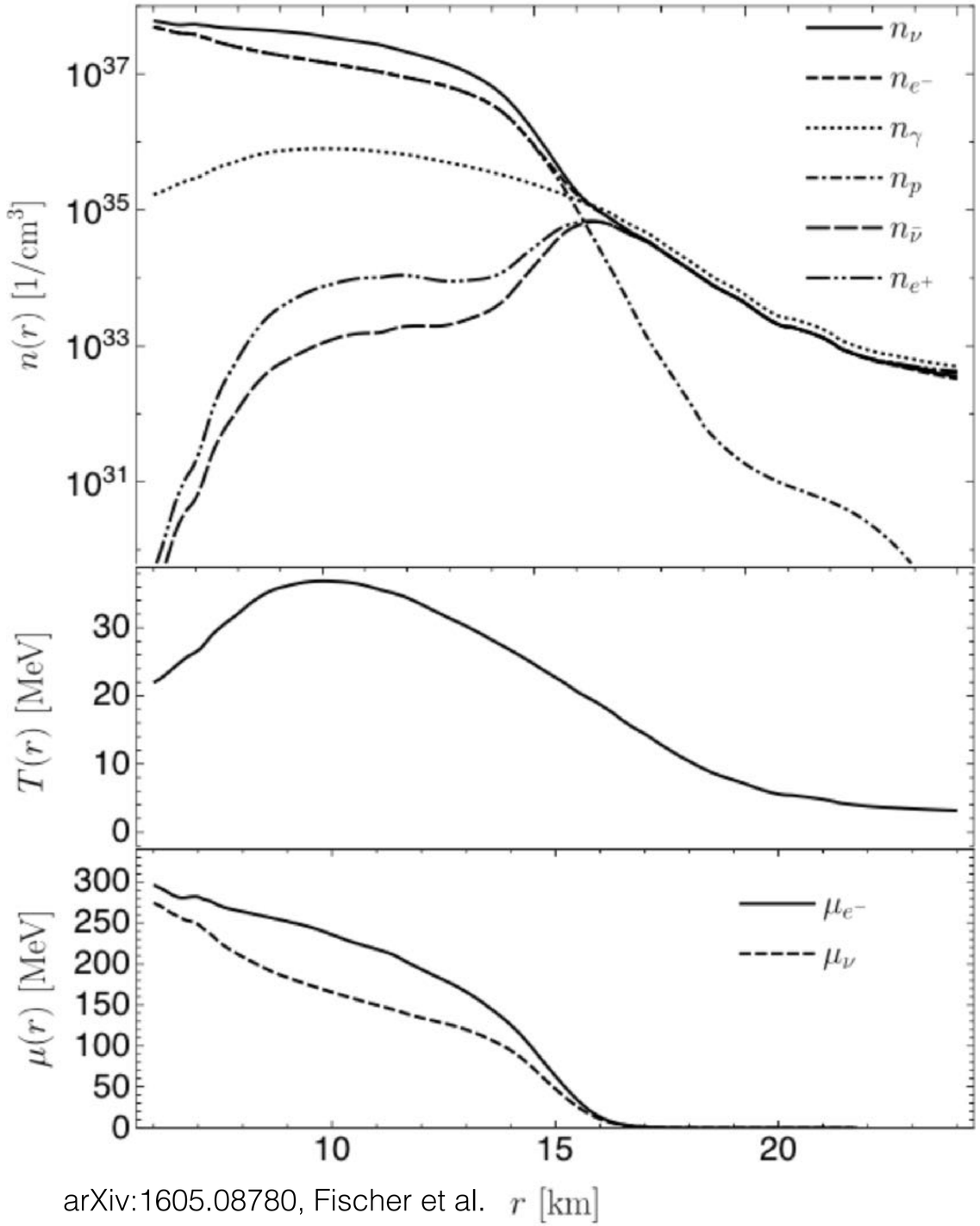

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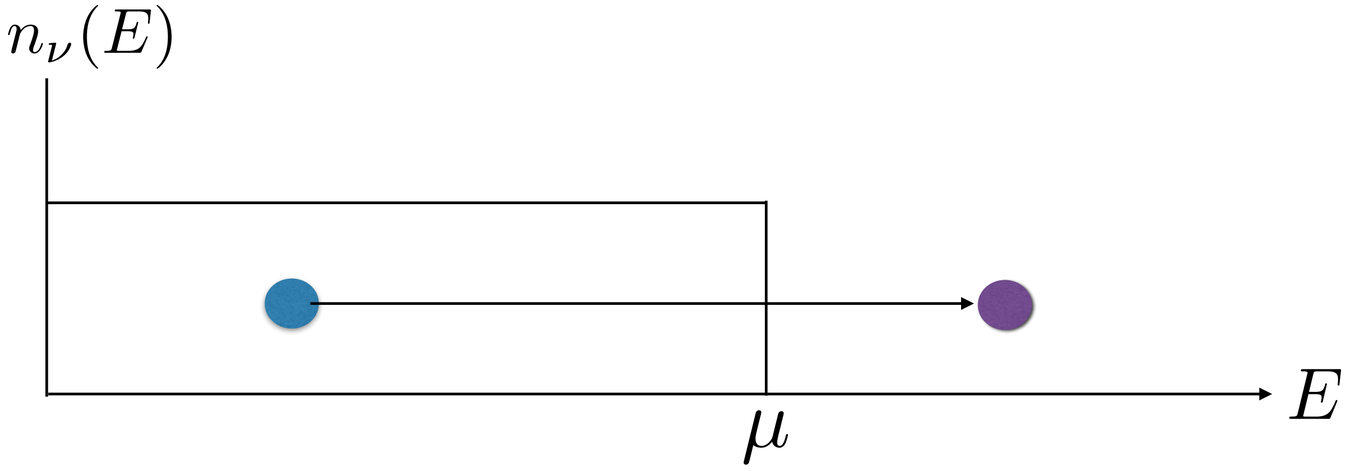

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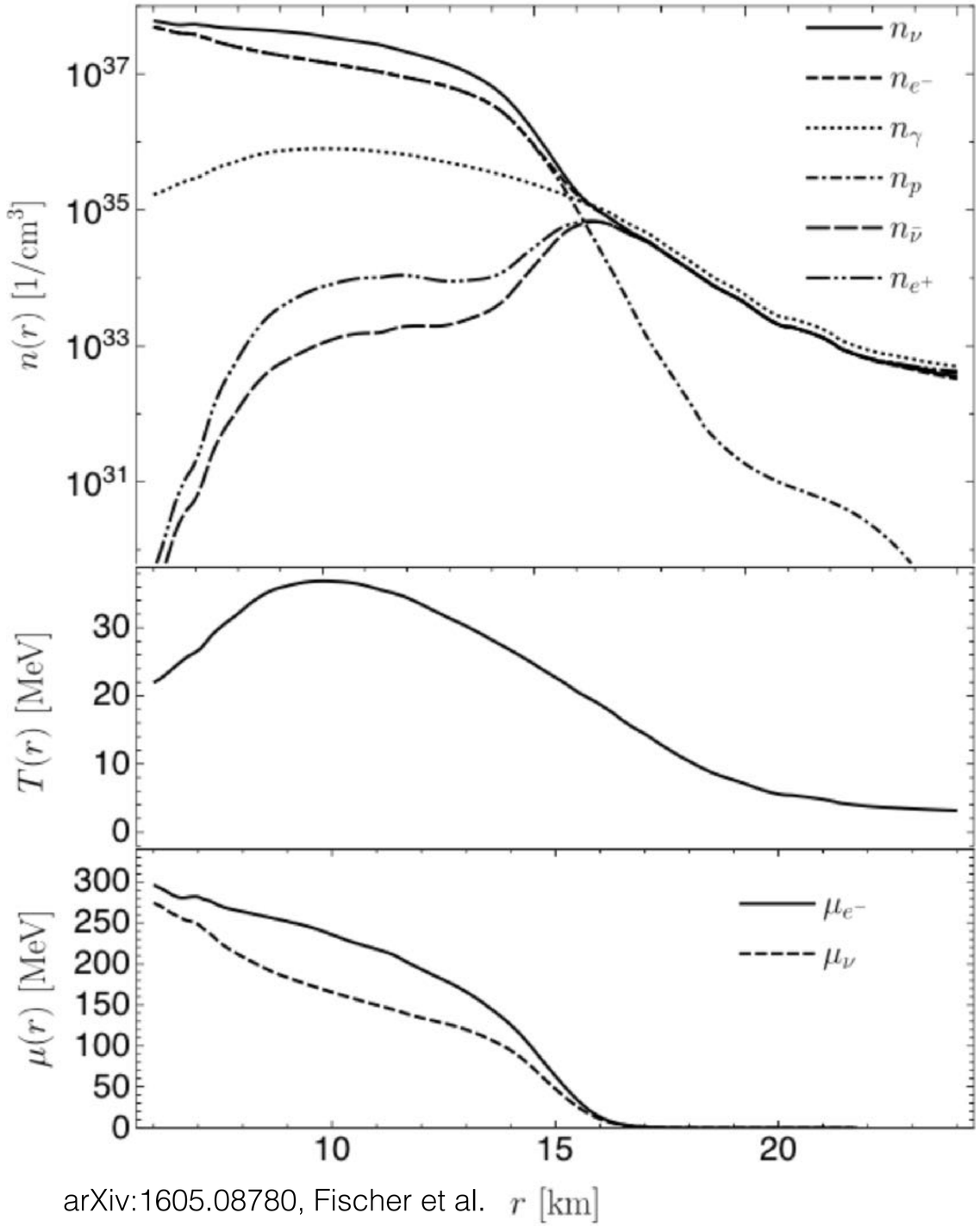

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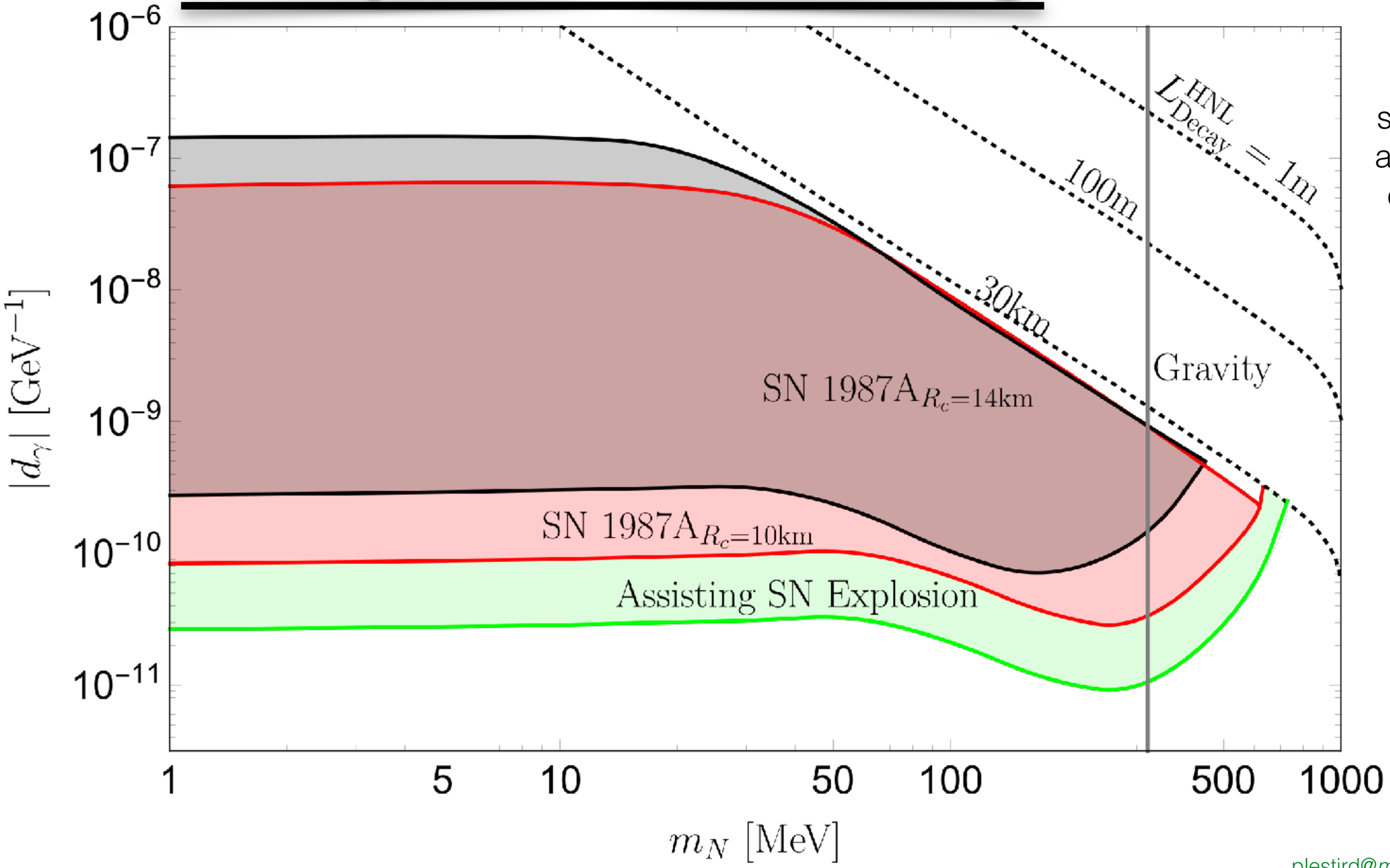
Supernova Cooling

arXiv:1803.03262



Large reach in mass is set by Fermi degeneracy and chemical potential of electrons and neutrinos

$\mu \gtrsim 200$ MeV

$T \sim 37$ MeV

Gravitational trapping bound determined by solving at the location in which most of the produced HNLs escape

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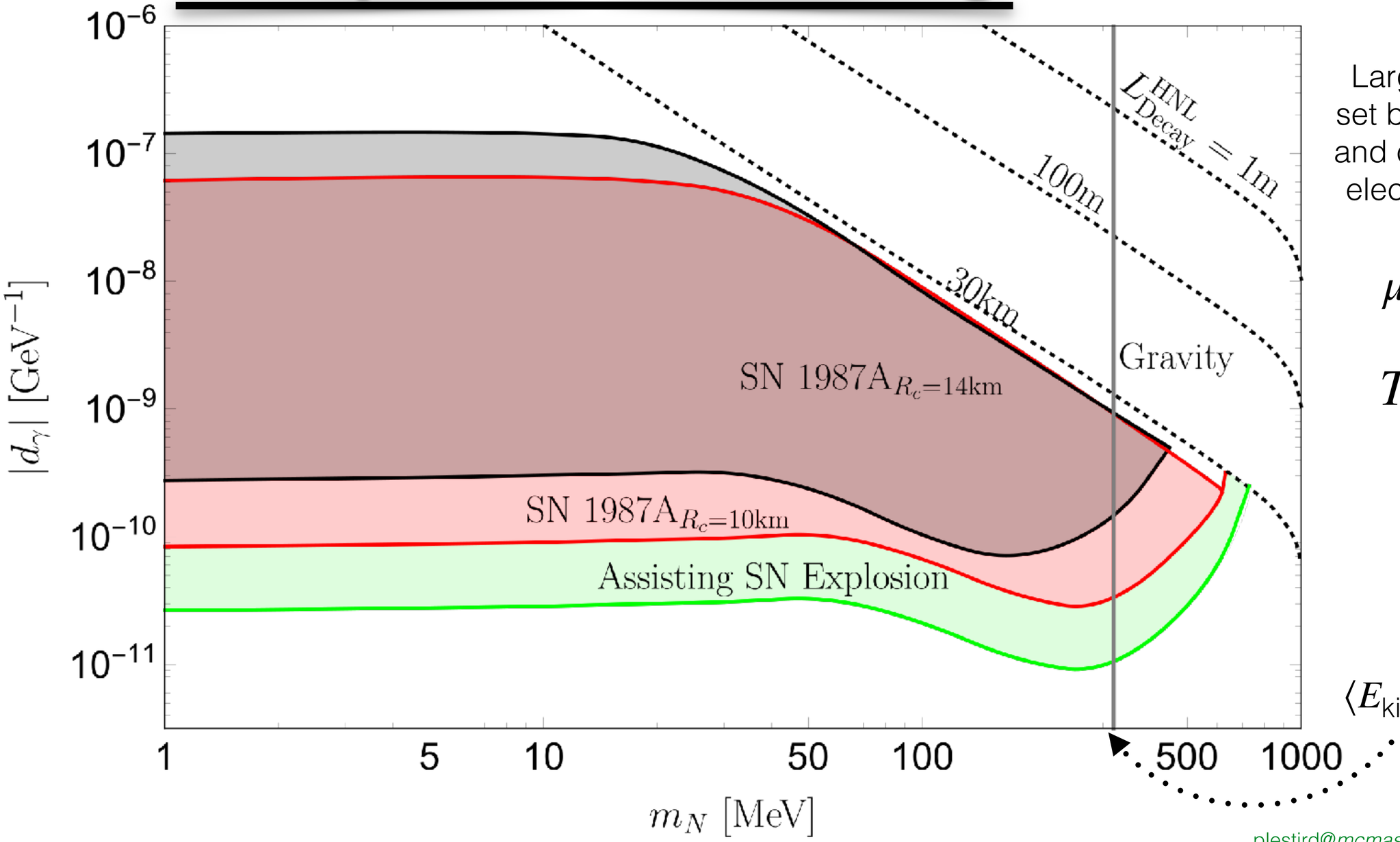

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$$\langle E_{\rm kin}\rangle_{\rm HNL} \leq \frac{G M_{\rm SN}\, m_{\rm HNL}}{R_{\rm SN}}$$

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Signatures of a Dipole Portal

arXiv:1803.03262

Neutrino Detectors (single photons)

Collider Searches (single photons)

Supernovae Cooling (HNL emission)

Big Bang Nucleosynthesis (modified N_{eff})

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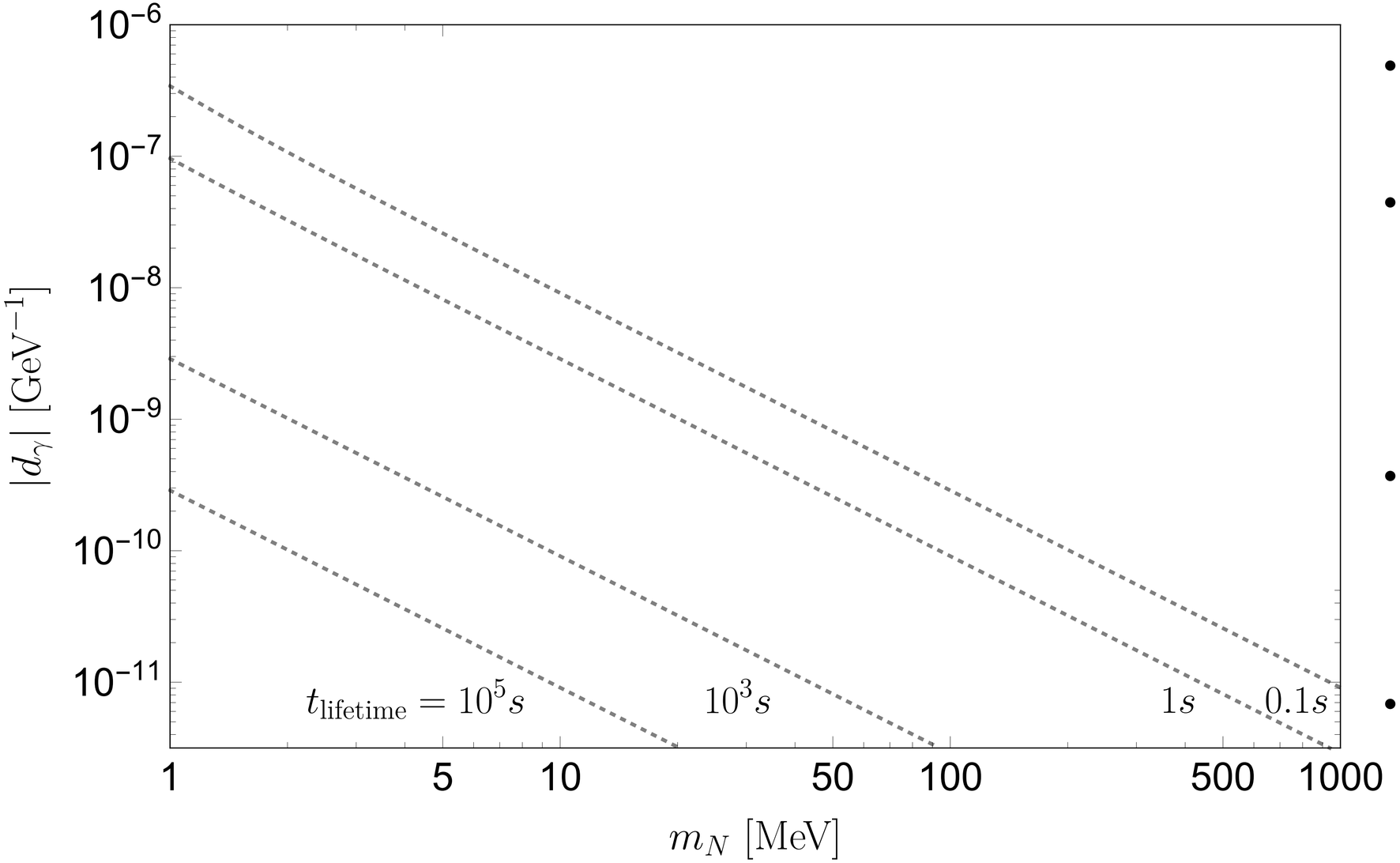
Consequences for BBN

arXiv:1803.03262



Considerations:

- For T > 1MeV, neutrons/protons in chemical equilibrium
- At T = 1MeV, neutron/proton ratio determines He4 and Deuterium abundance

$$T \sim 1 \text{ MeV} \leftrightarrow t \sim 0.1 \text{ s}$$

- If HNLs thermally populated in very early universe with lifetimes they will inject additional EM energy.
- This can distort n/p balance, affecting light element abundances

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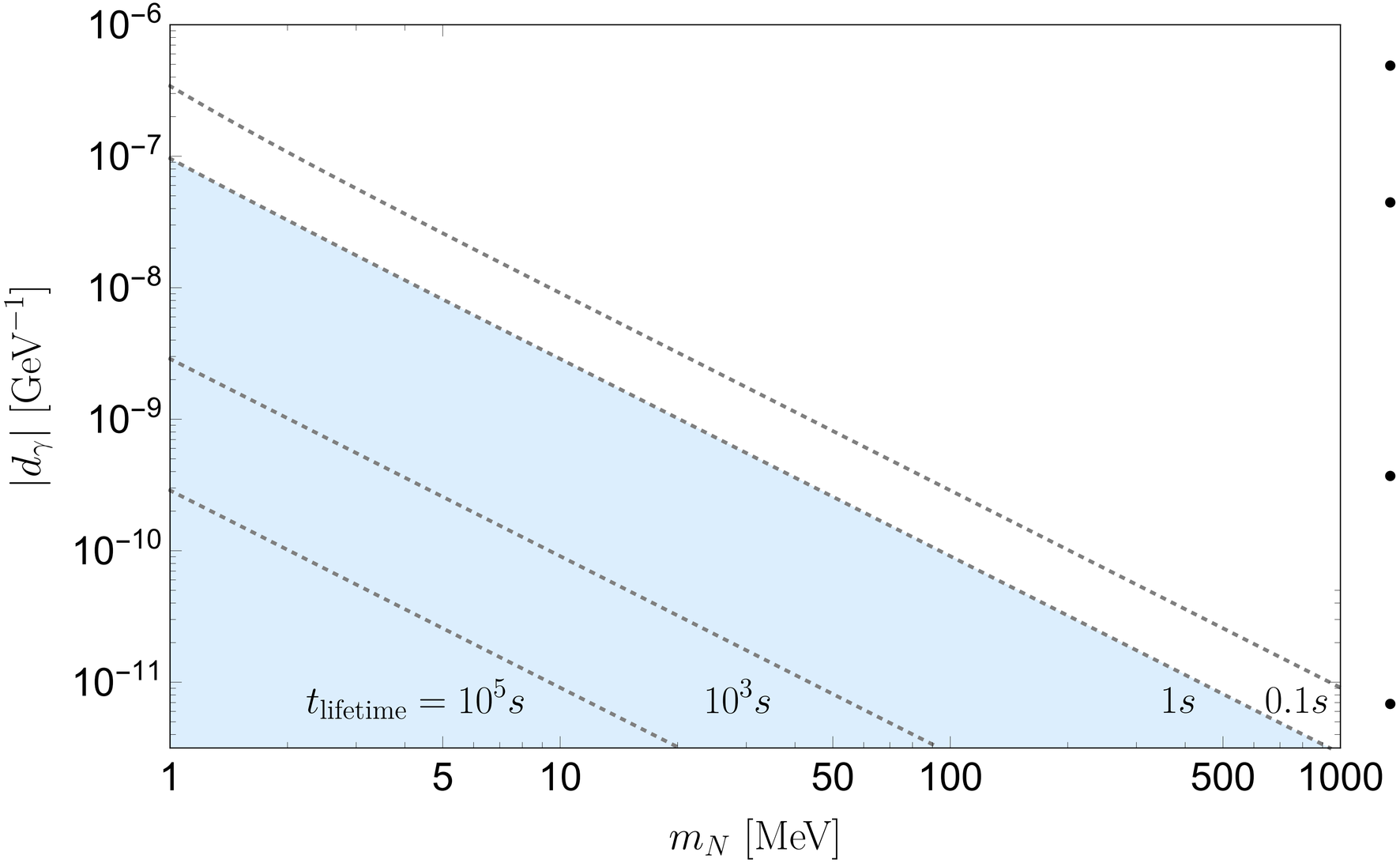

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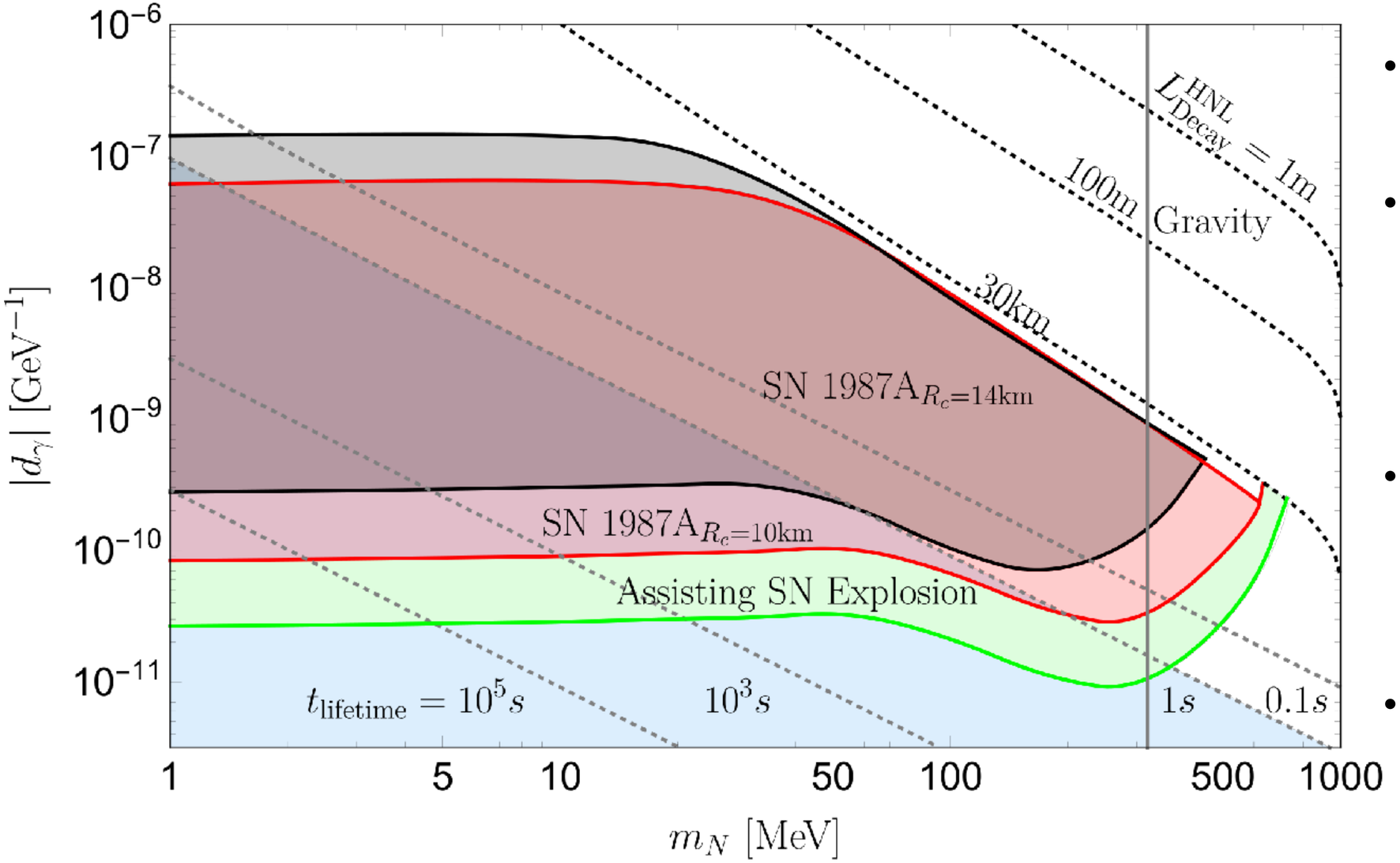

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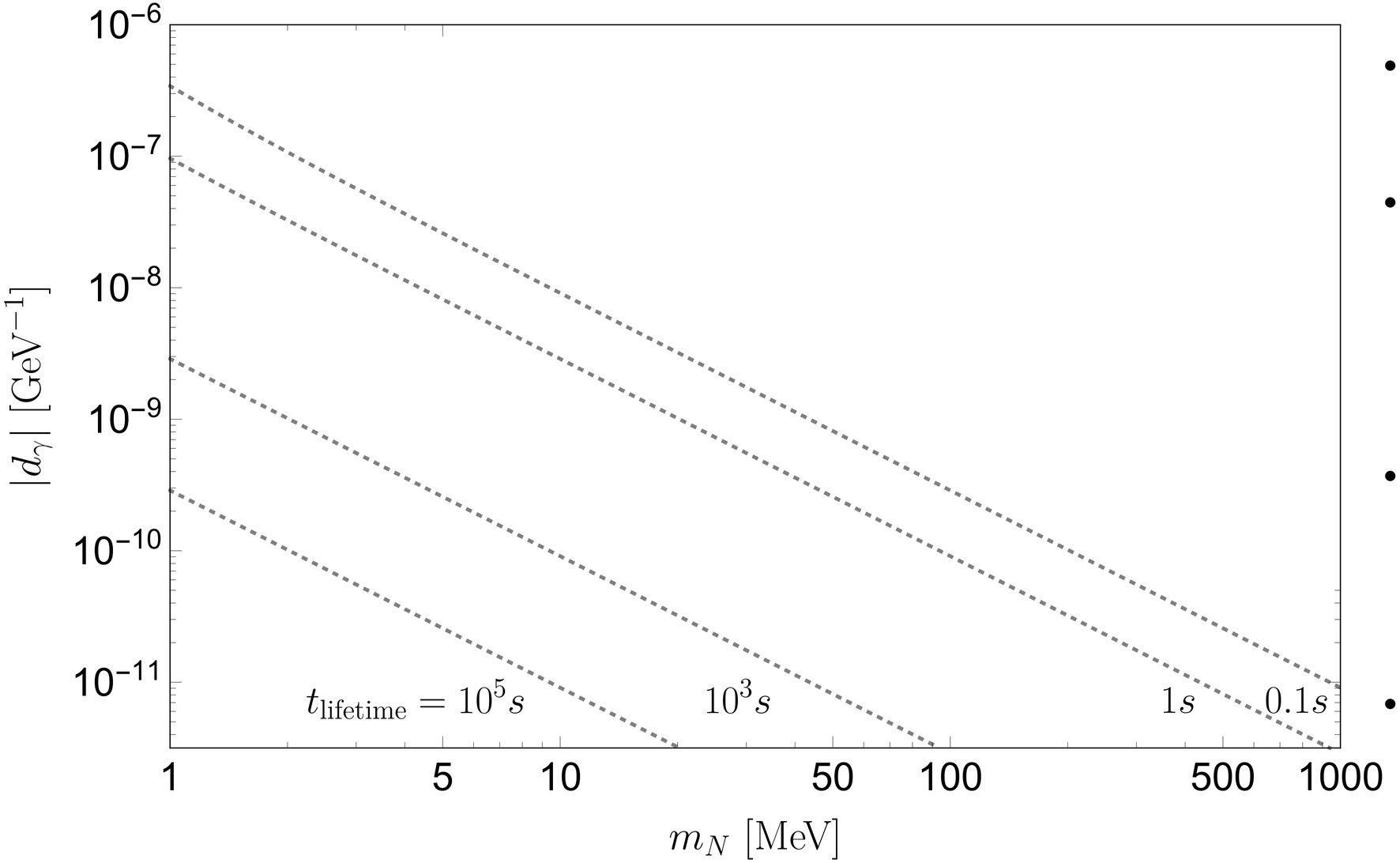

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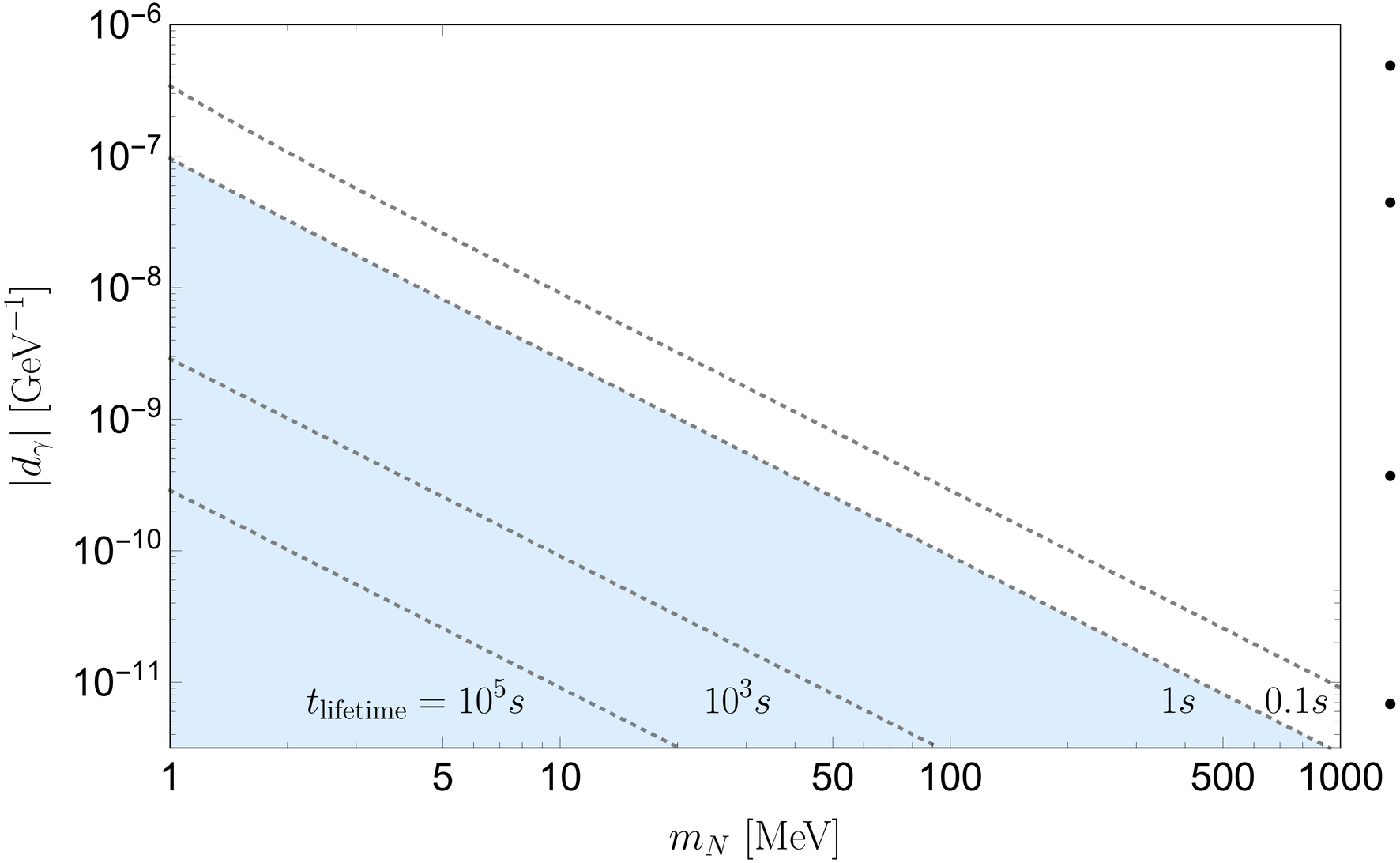

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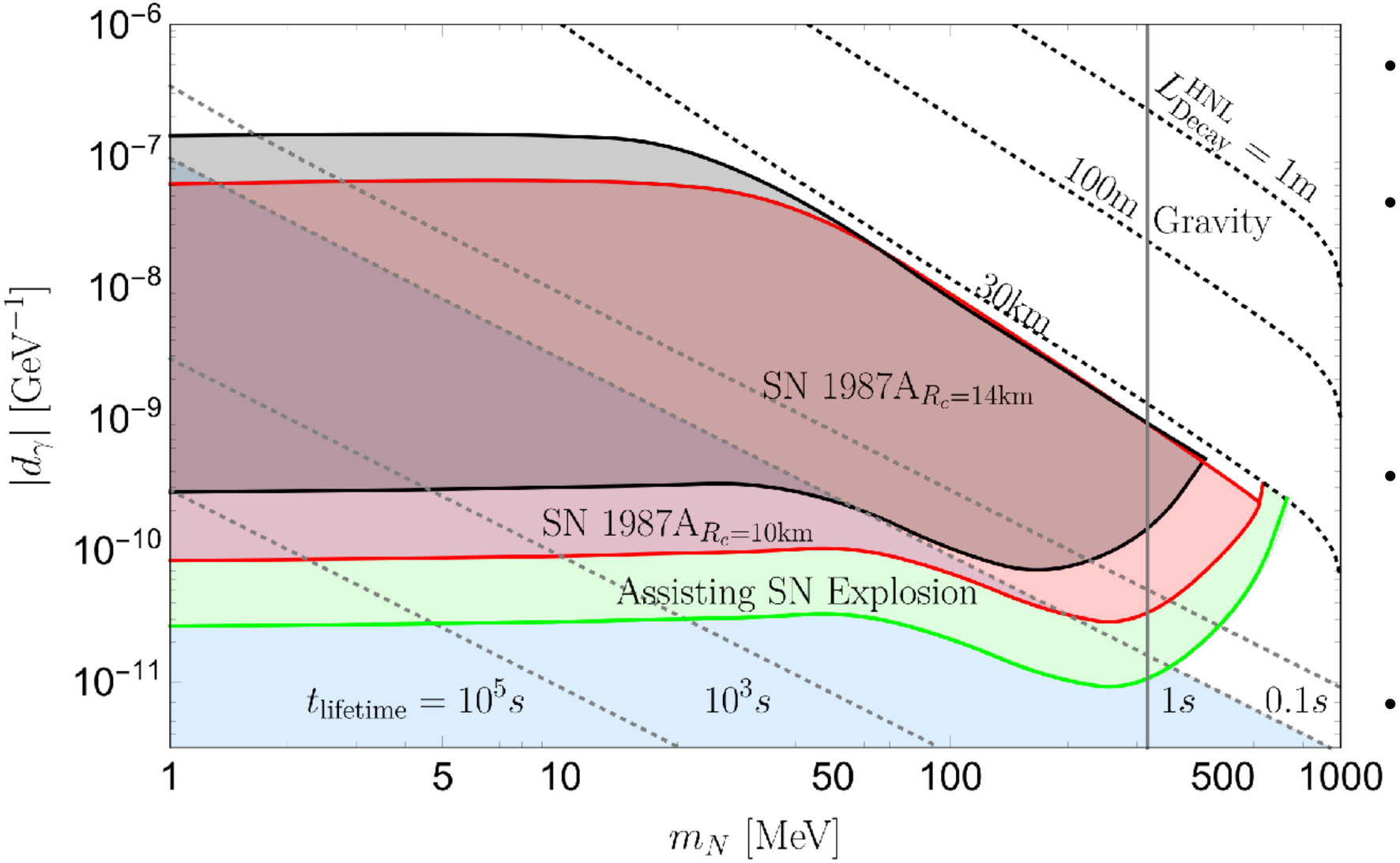

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What About DUNE?

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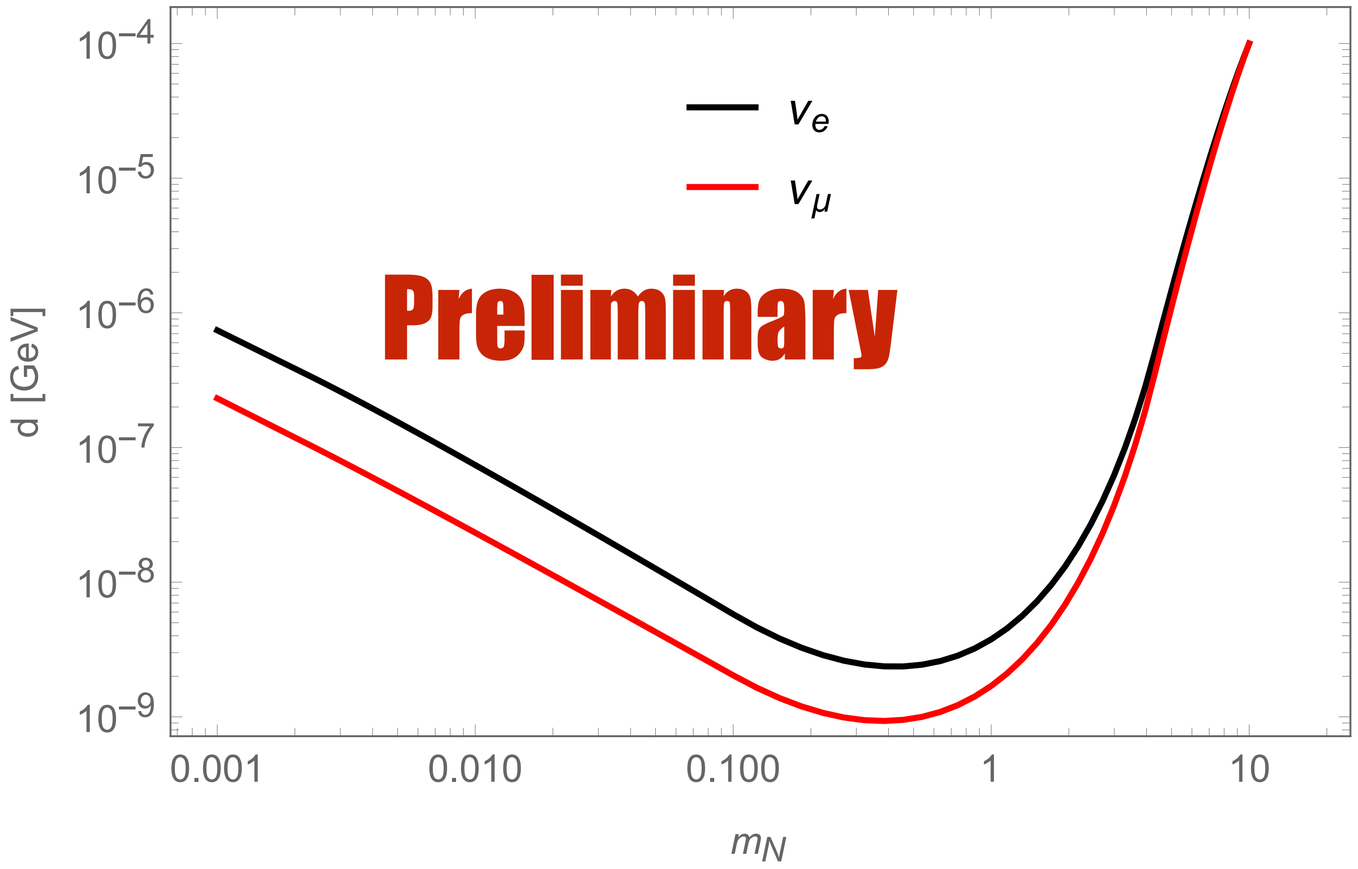
DUNE Near Detector

arXiv:1803.03262



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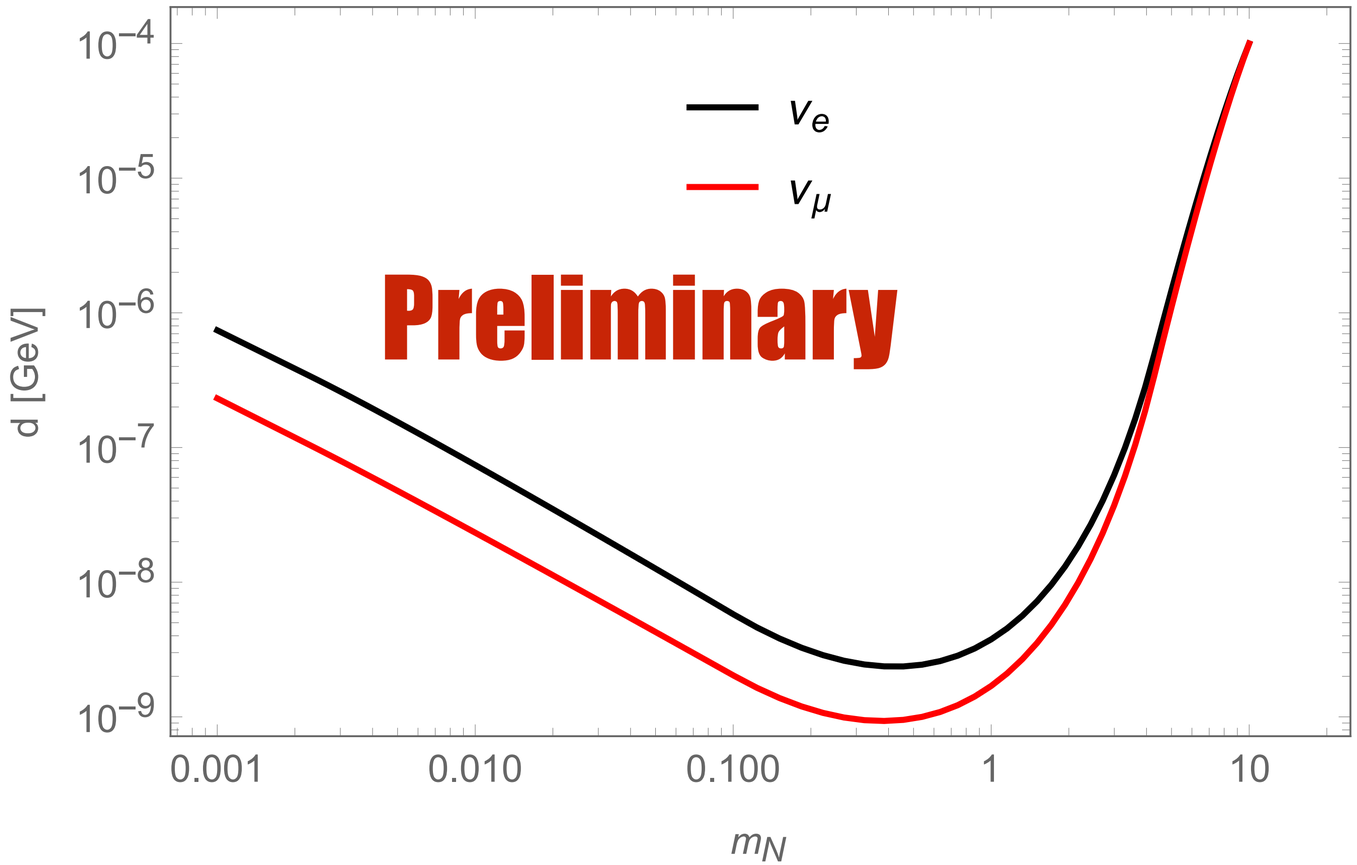

Assumptions

- 2 x 10^{21} POT
- 3 m x 7 m x 5 m detector volume
- 304 m of SiO2 (sand) along line of sight.
- 10 m decay length (5 m LAr+5 m HPgTPC).
- Used 2017 collaboration fluxes from

http://home.fnal.gov/~ljf26/2017DUNEFluxes/OptimizedEngineeredNov2017/

- Only up-scattering included (this is conservative)
- 500 MeV cut on photon energy

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DUNE Near Detector

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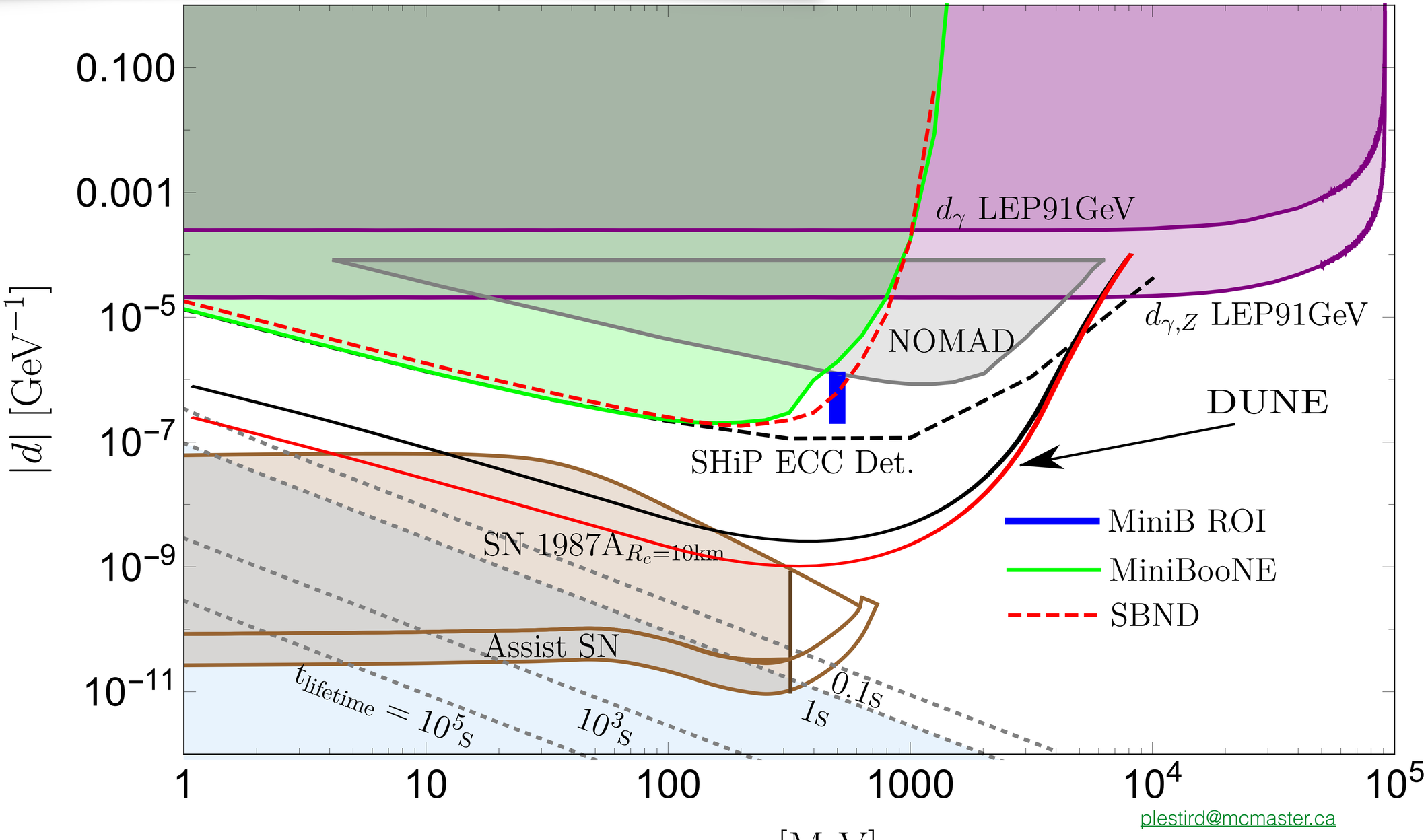

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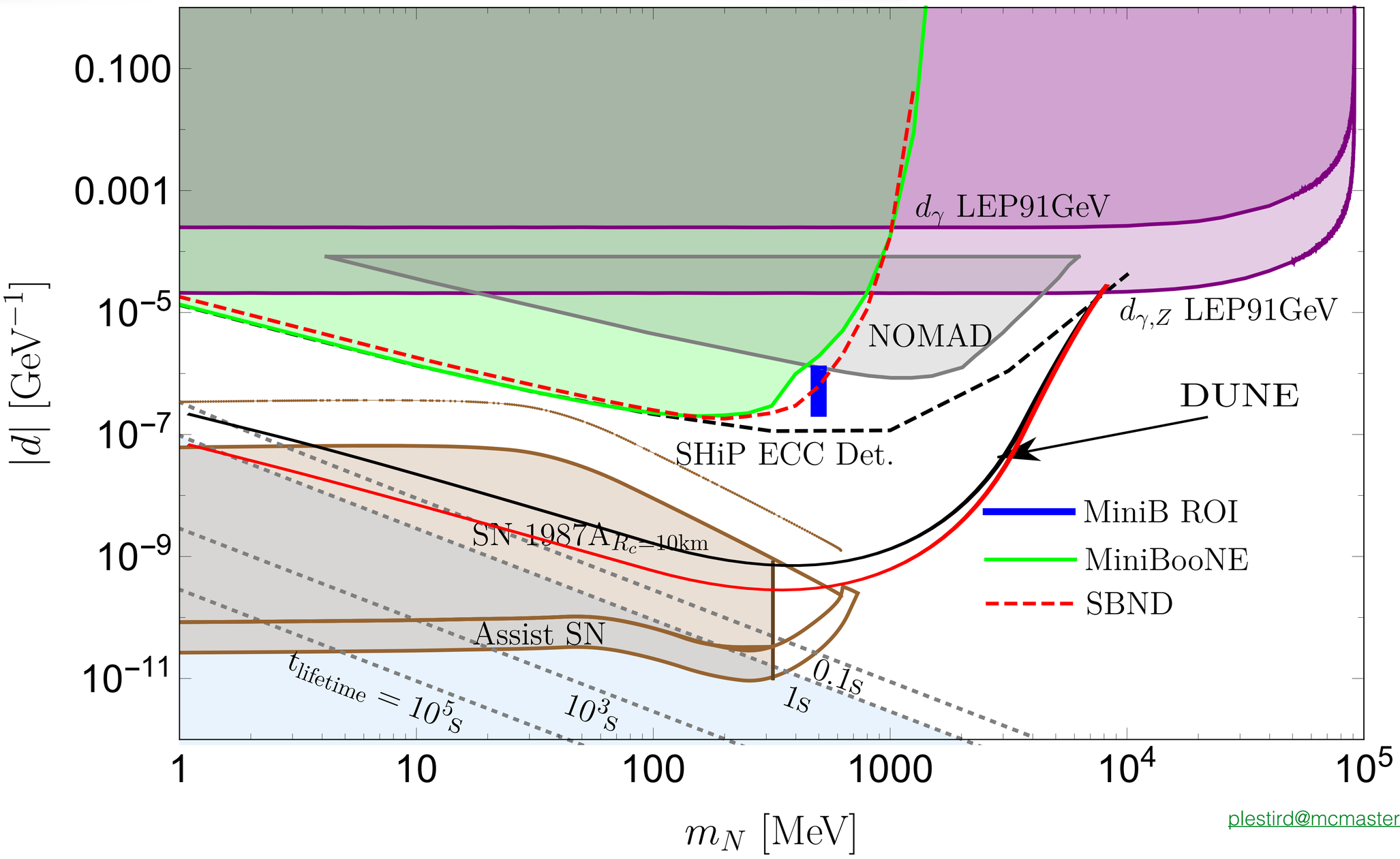

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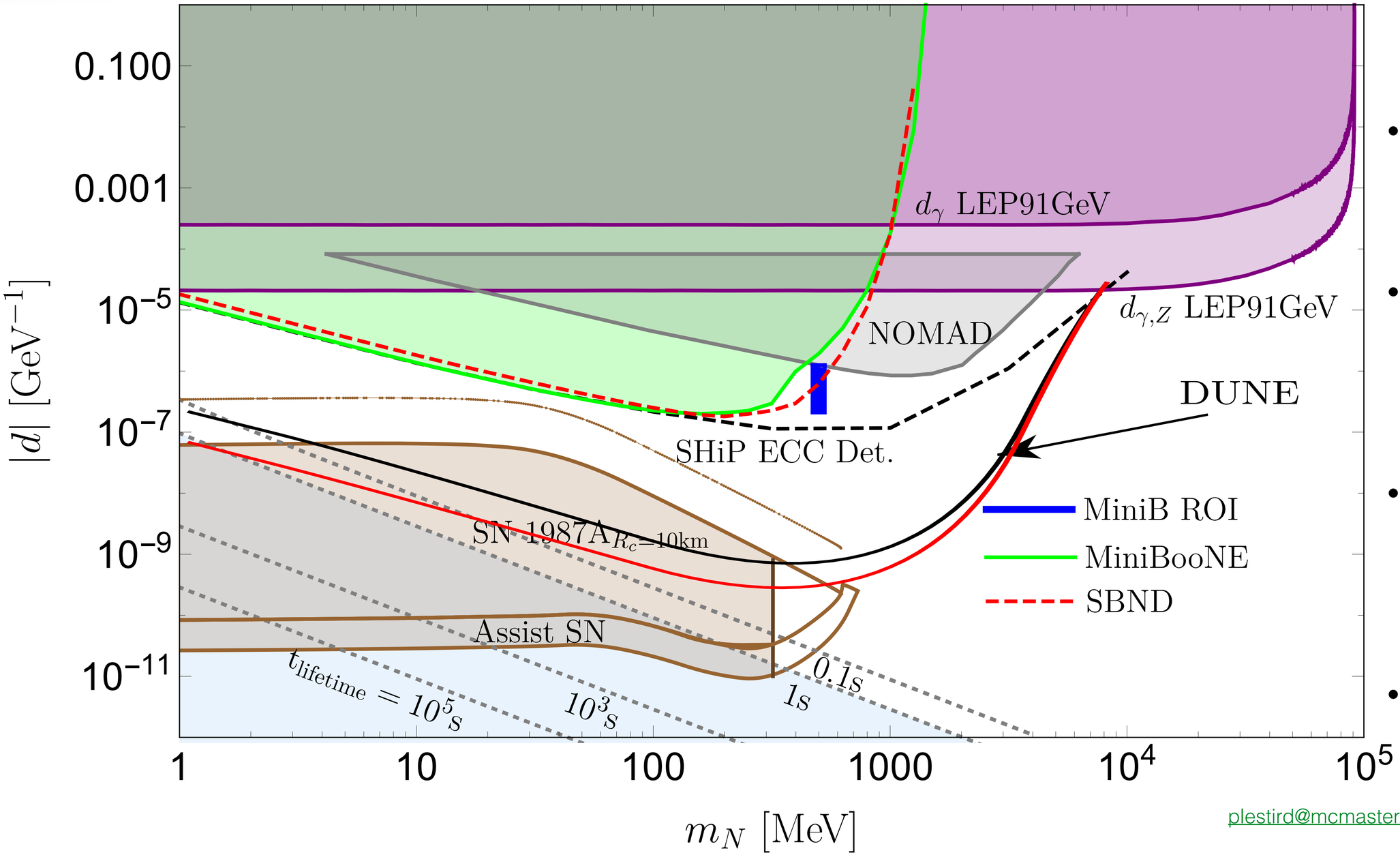
DUNE Near Detector

arXiv:1803.03262



SN Conservative

- Upper curve only demands a 50% escape probability
- Roughly 10^6 more HNLs being produced than at low curve
- Likely underestimates constraint by a factor of 5
- SN floor could be higher

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What About the MiniBooNE Anomaly?

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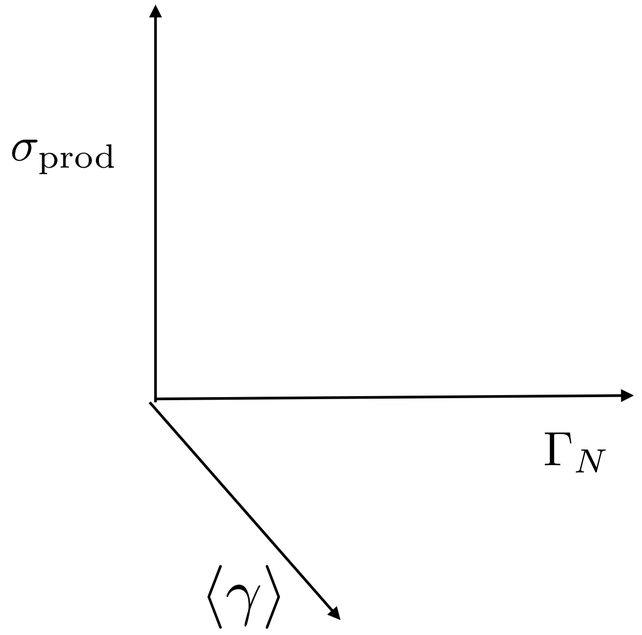
Basic Phenomenology

arXiv:1803.03262

$$E_N \sim E_\nu + \frac{t}{2m_{\mathrm{Ar}}}$$

$$\langle\gamma\rangle \sim \frac{\langle E_\nu\rangle}{m_N}$$

Relevant Parameter Space



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Basic Phenomenology

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Considerations

1. Production cross section
2. Lifetime of HNL
3. Boost of HNL

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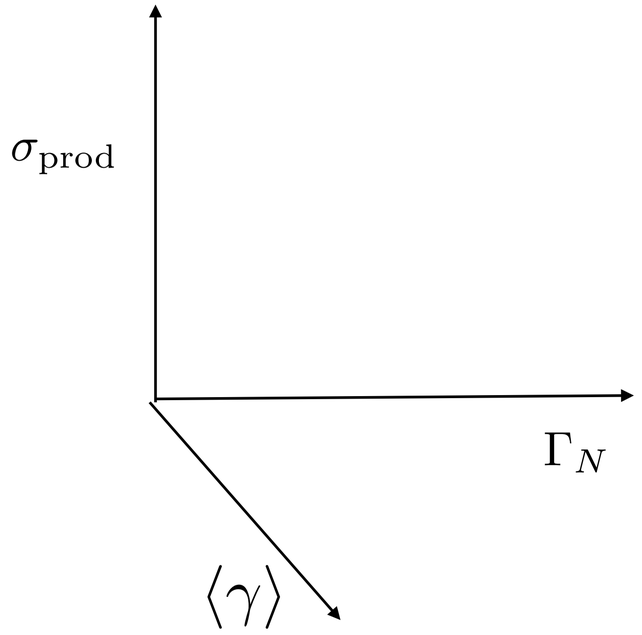

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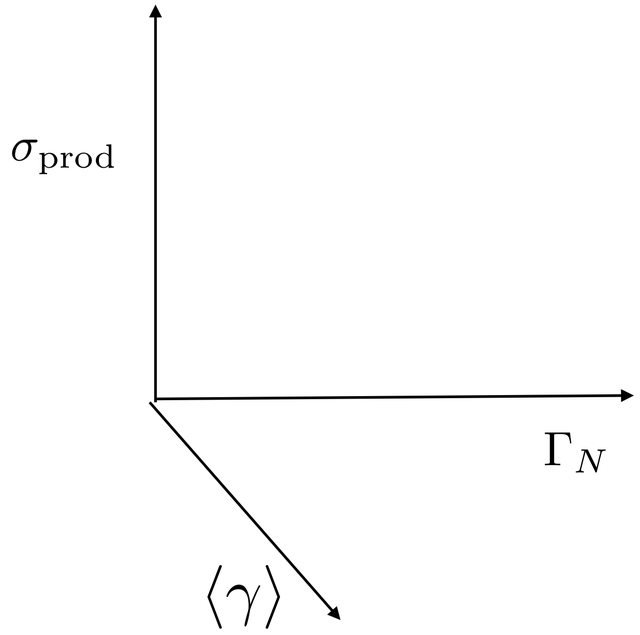

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Ingredients

1. Mass mixing (gives you NC production as an extra knob)
2. Flavour dependent couplings (can tune decay length relative to production cross section)
3. Mass of HNL. This (+production kinematics) determines the boost factor

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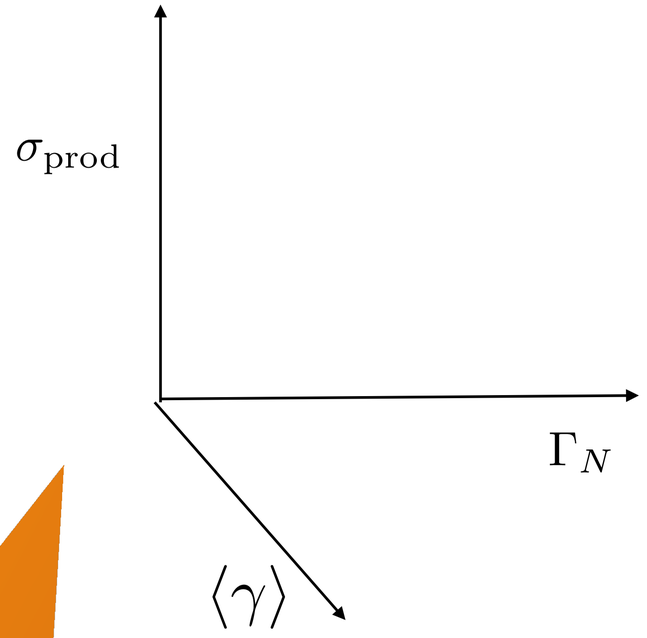

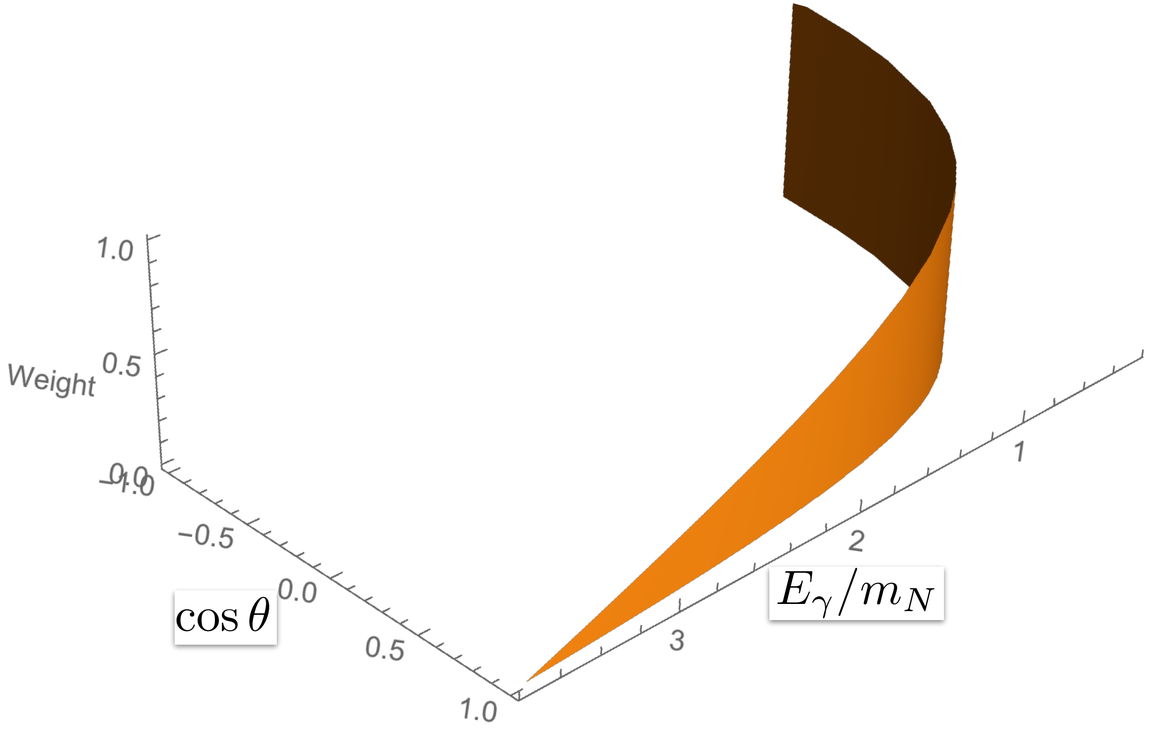

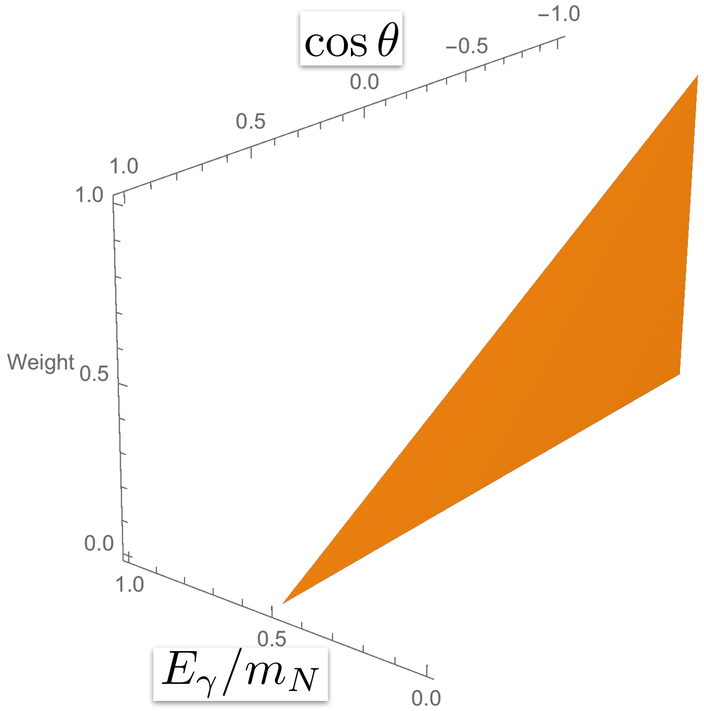

$$\langle\gamma\rangle = 2$$

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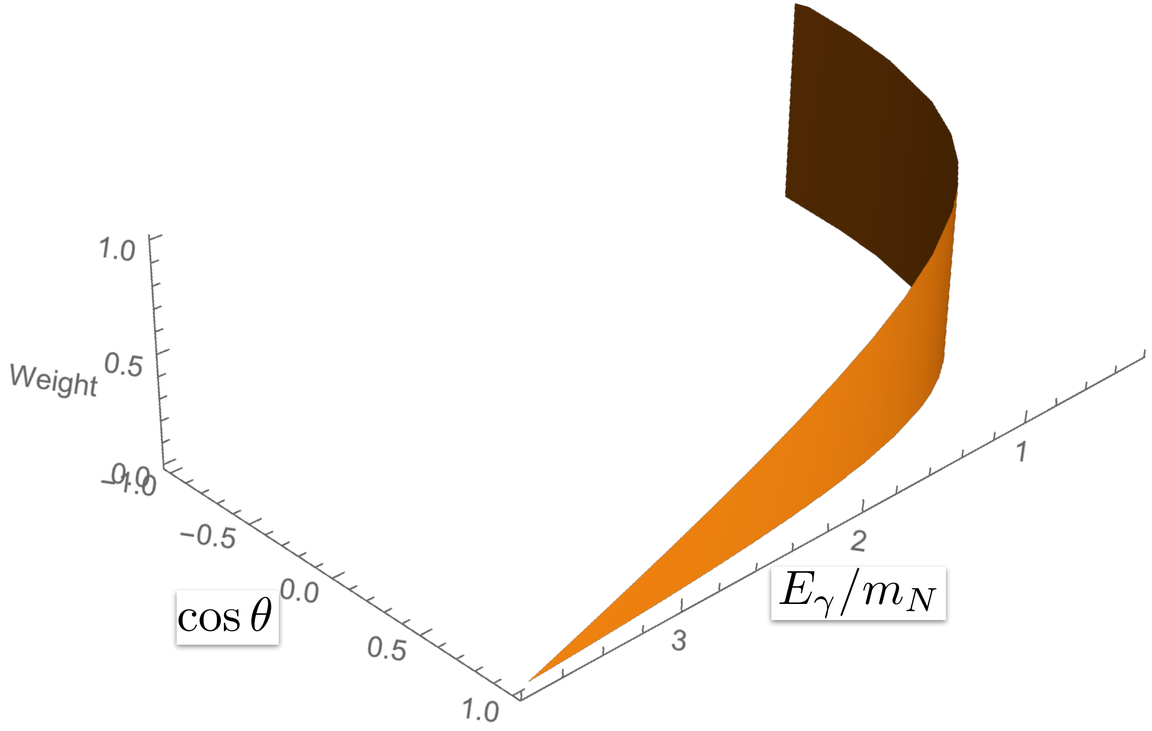
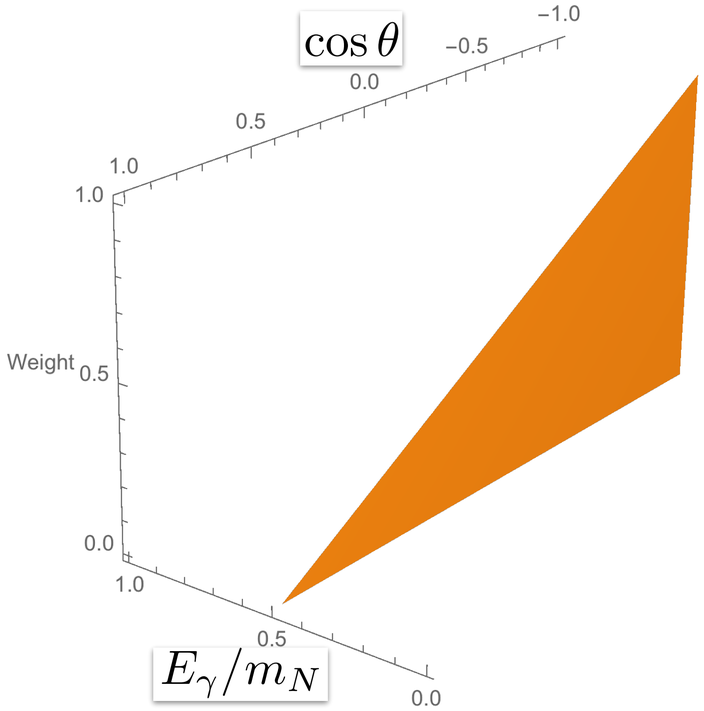
Lab Frame Distribution





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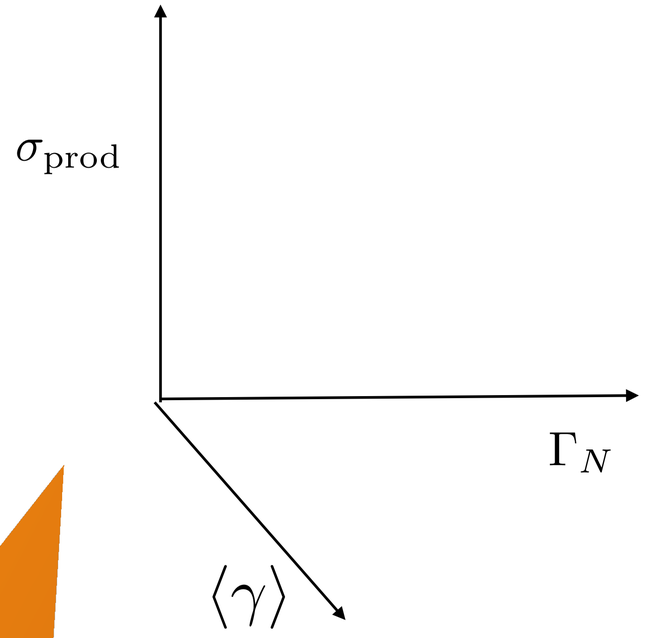

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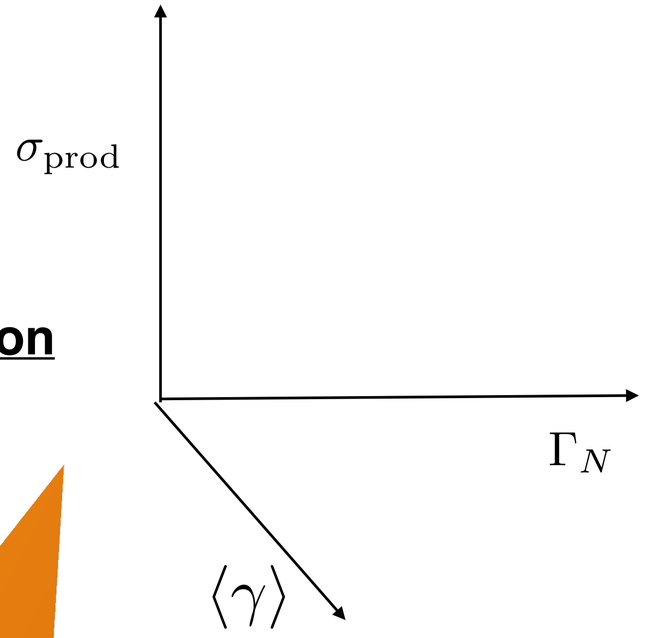
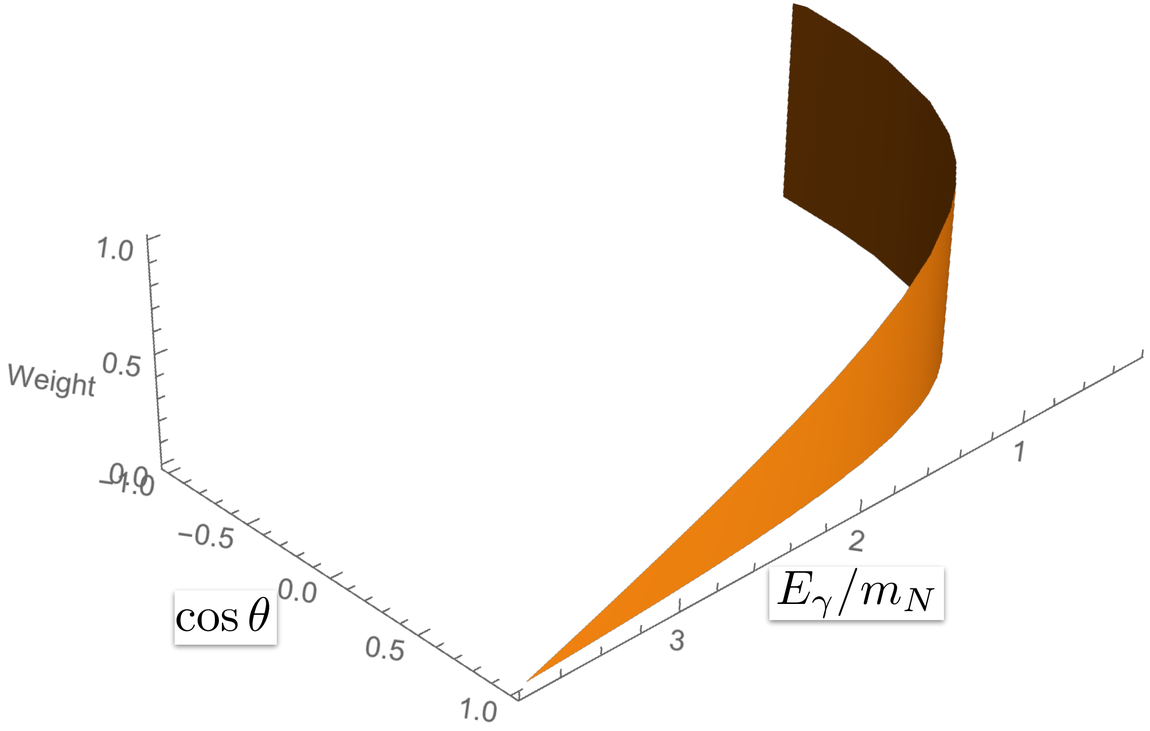
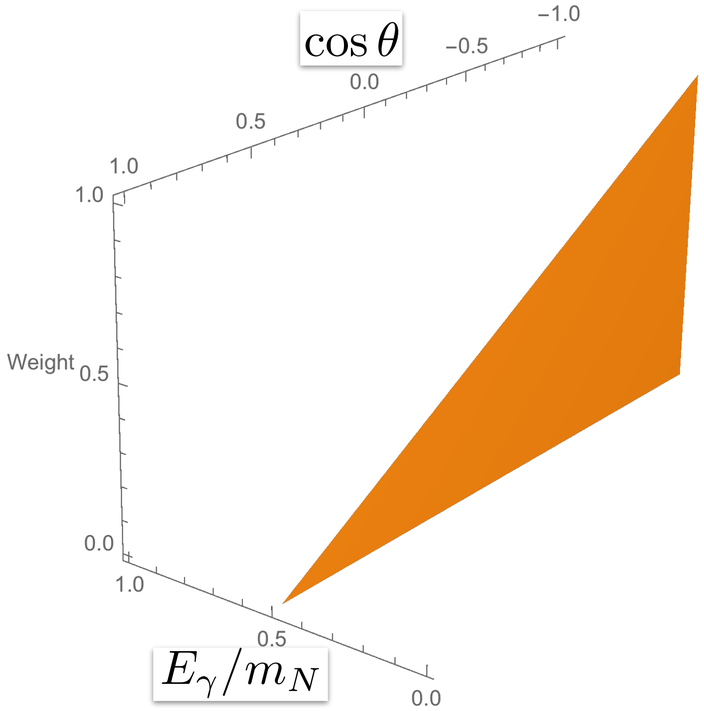


Lab Frame Distribution



$$\langle\gamma\rangle = 2$$

Rest Frame Distribution



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Okay so what about MiniBooNE?

arXiv:1803.03262

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Short Answer

I dont know!

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Okay so what about MiniBooNE?

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Short Answer

I dont know!

So what is the long answer?

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Okay so what about MiniBooNE?

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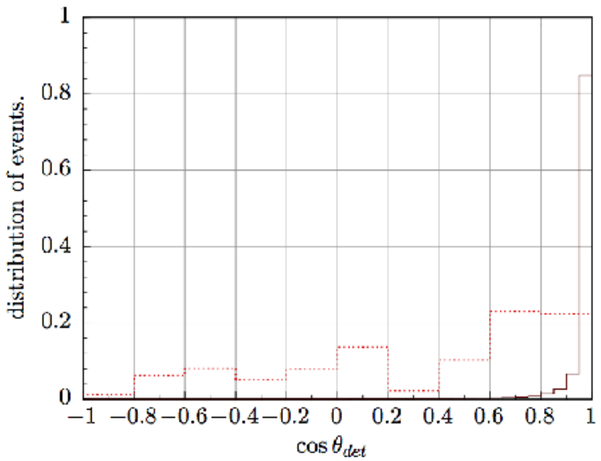

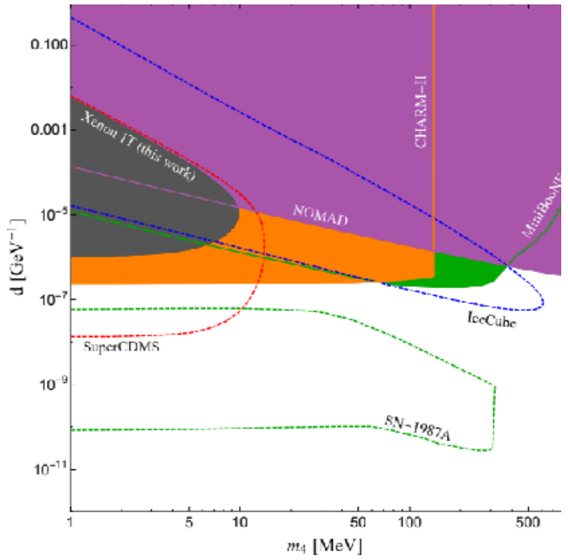

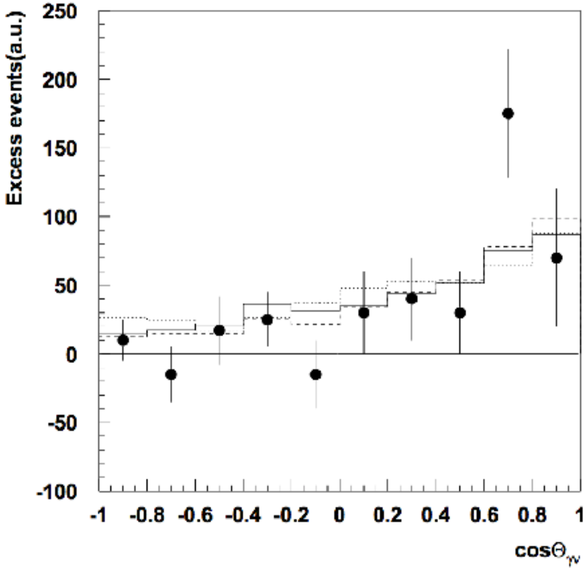

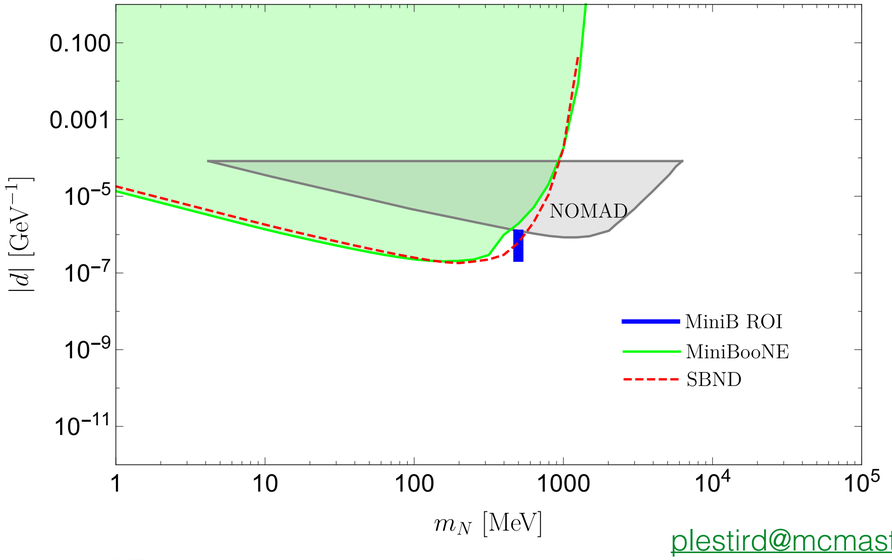

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Okay so what about MiniBooNE?

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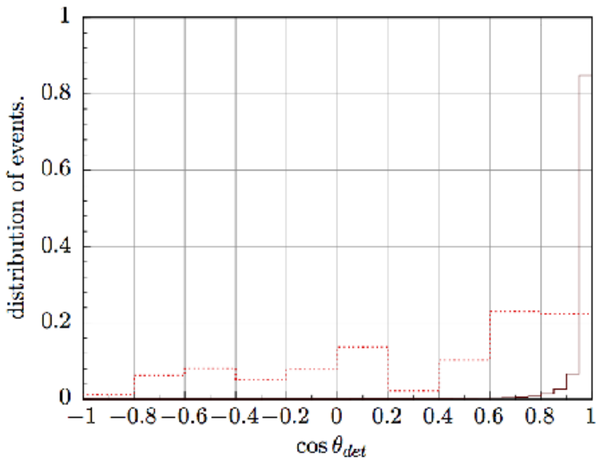
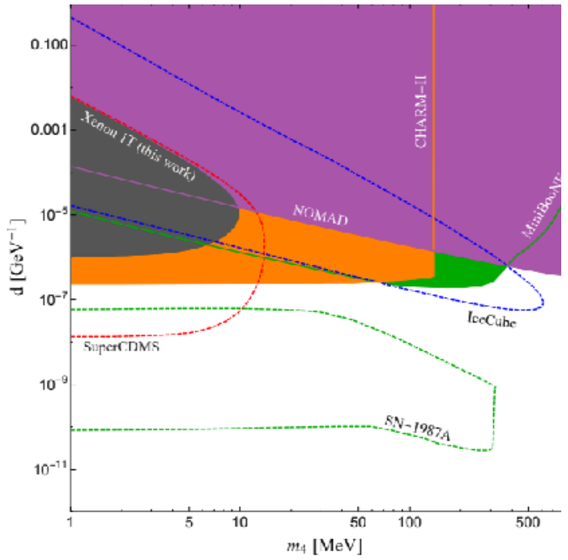
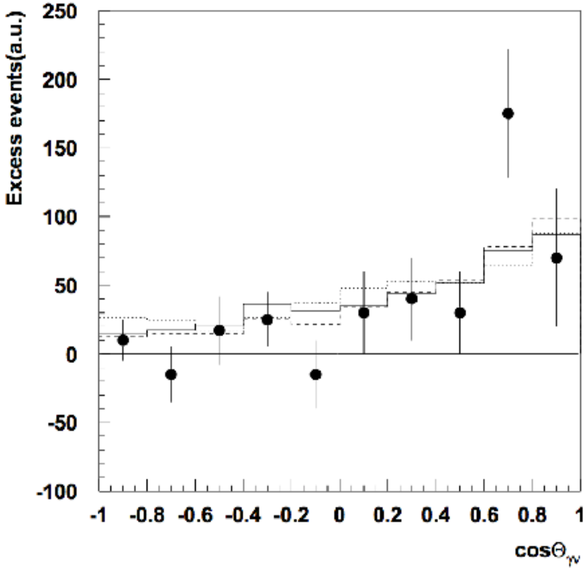
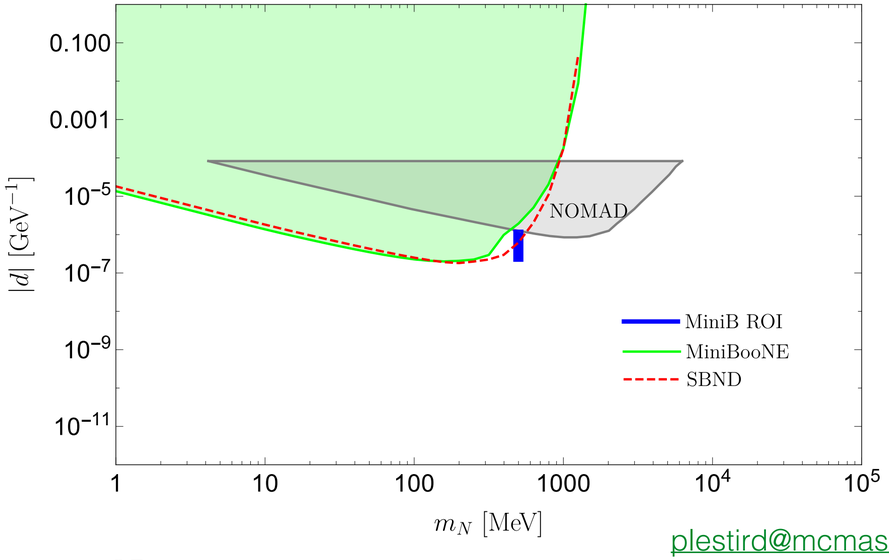
Angular distribution depends sensitively on mass









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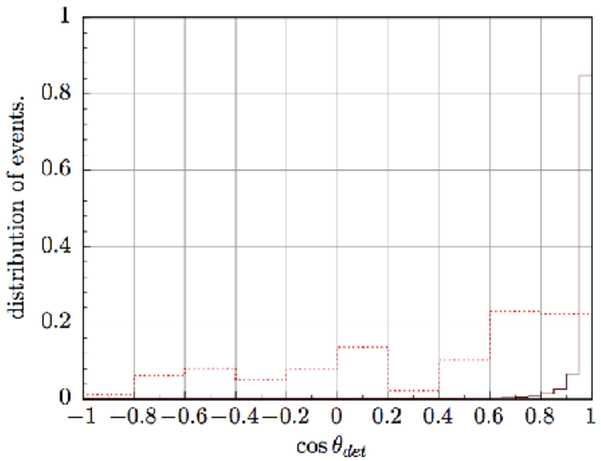
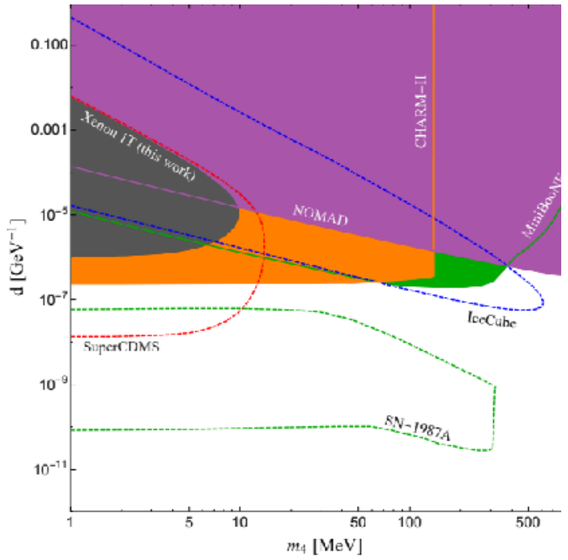
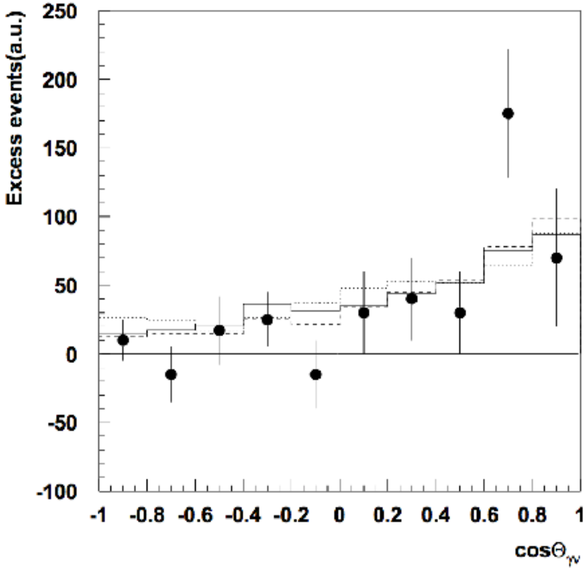


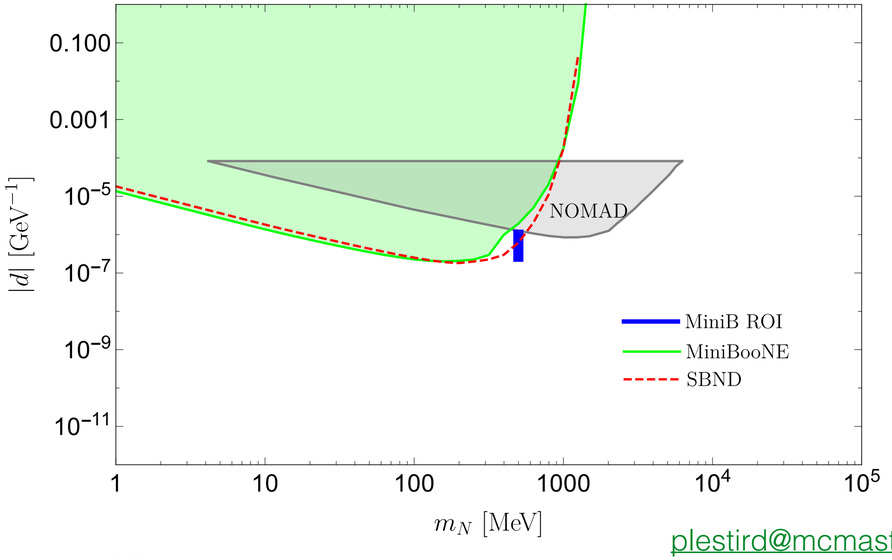
Radionov arXiv:1303.4587

Claim: Angular distribution rules out dipole portal for excess

$m_N \sim 50$ MeV







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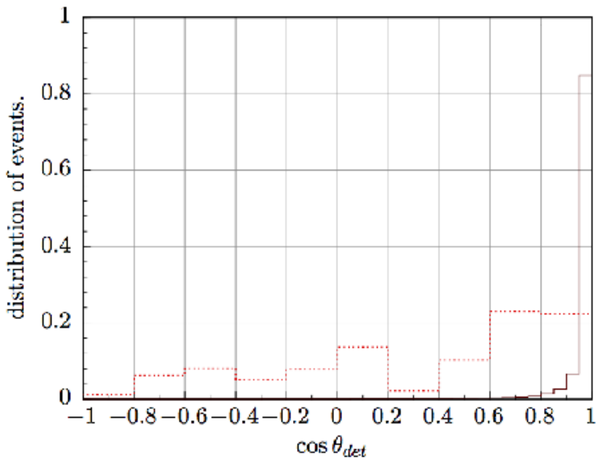

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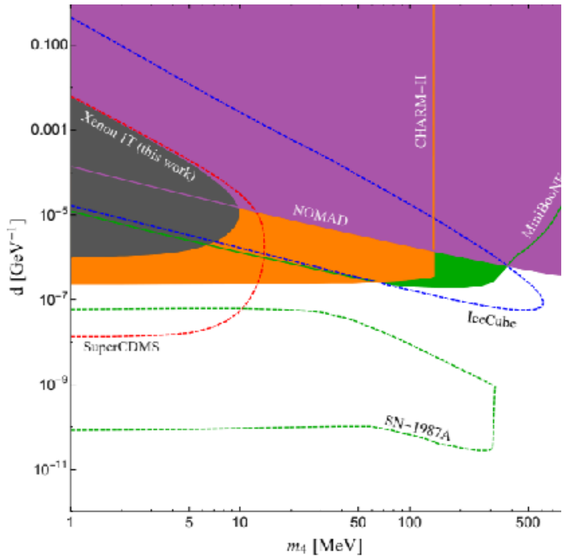
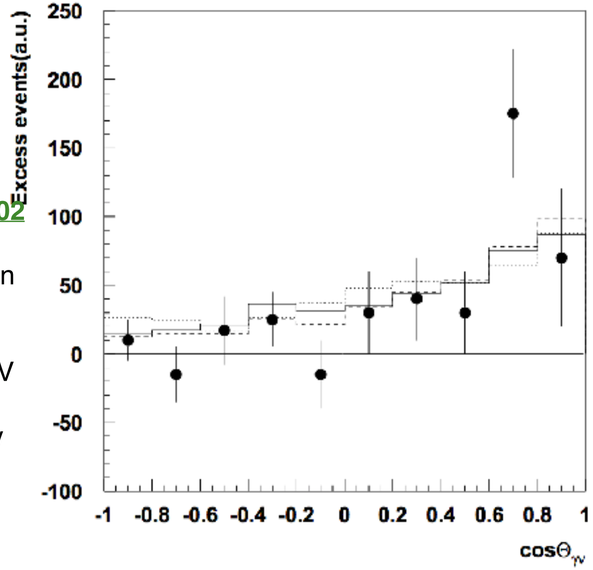


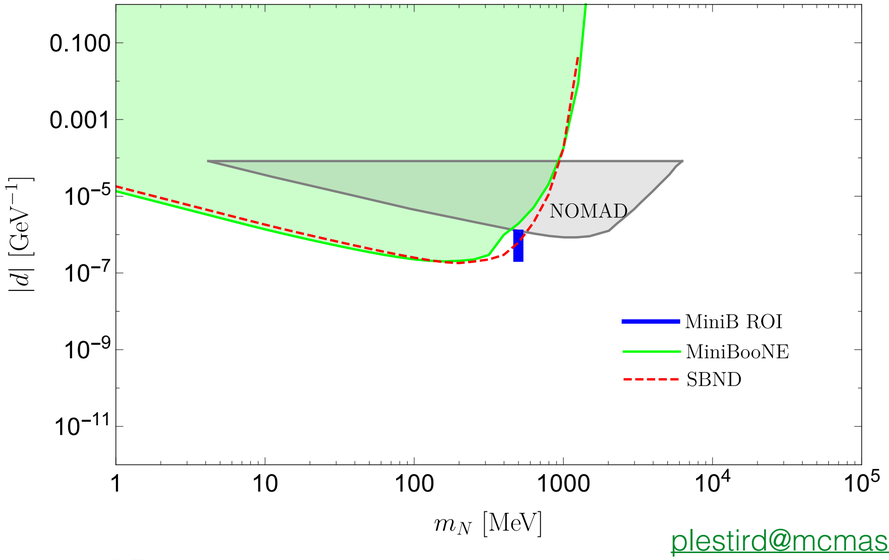
Gninenko arXiv:0902.3802

Claim: Angular distribution consistent with excess

$m_N \sim 400$ MeV & 600 MeV

Including cuts on energy





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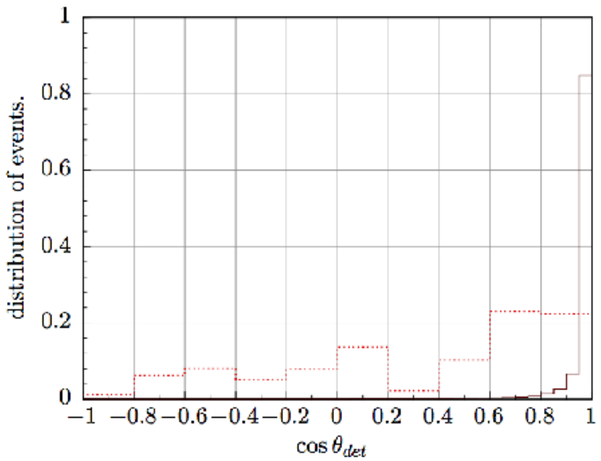

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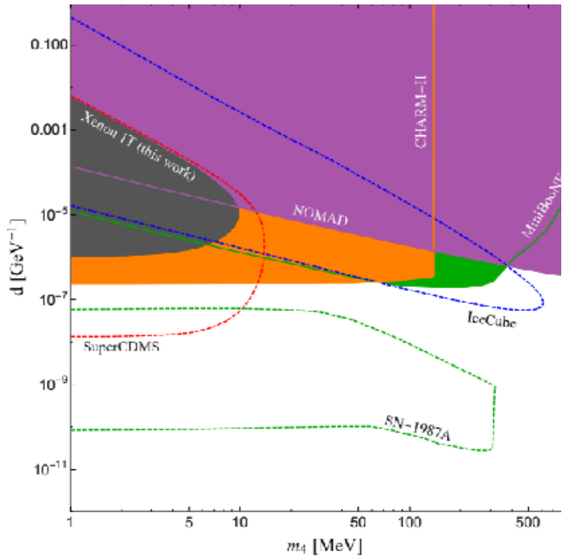

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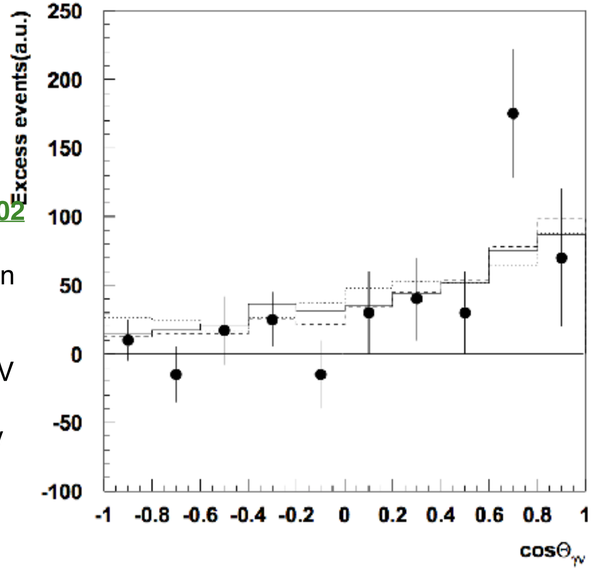

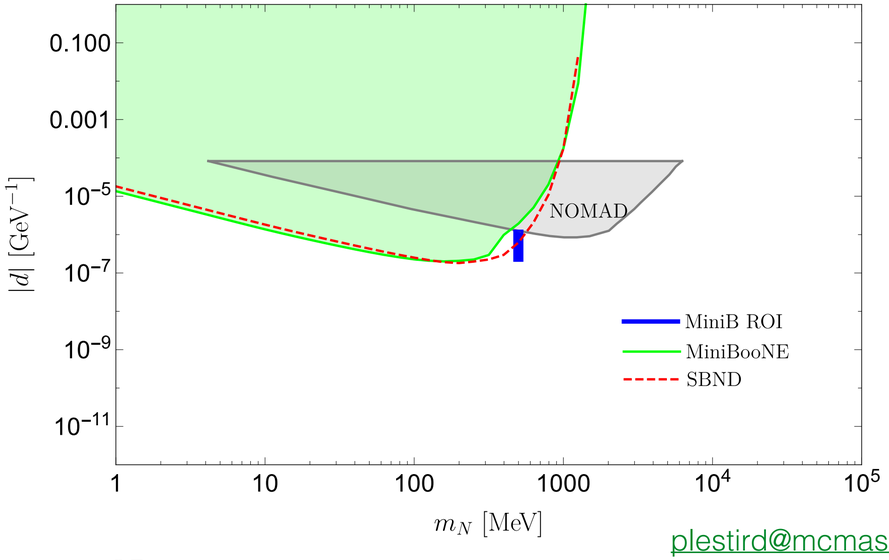

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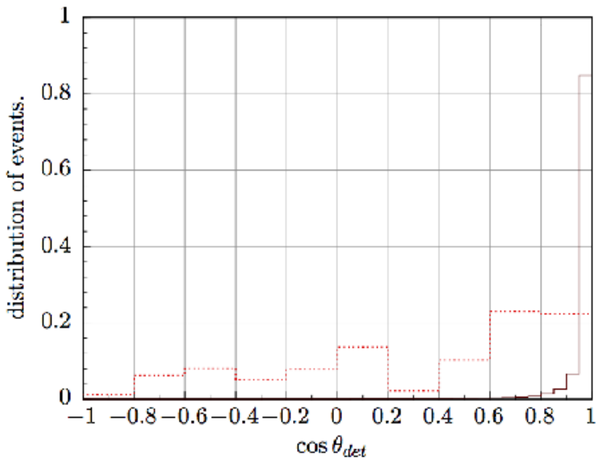

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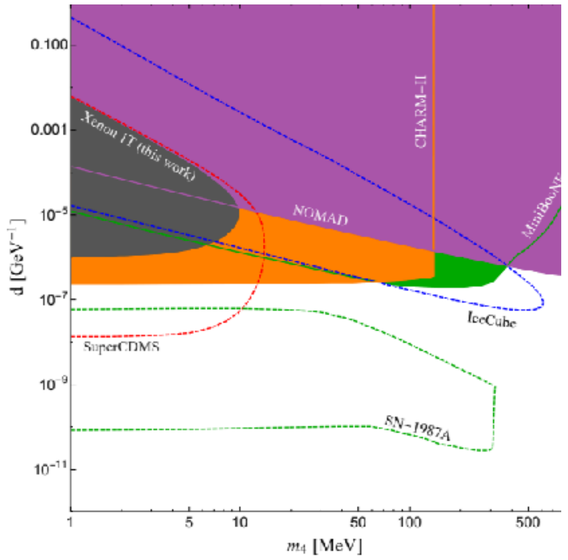

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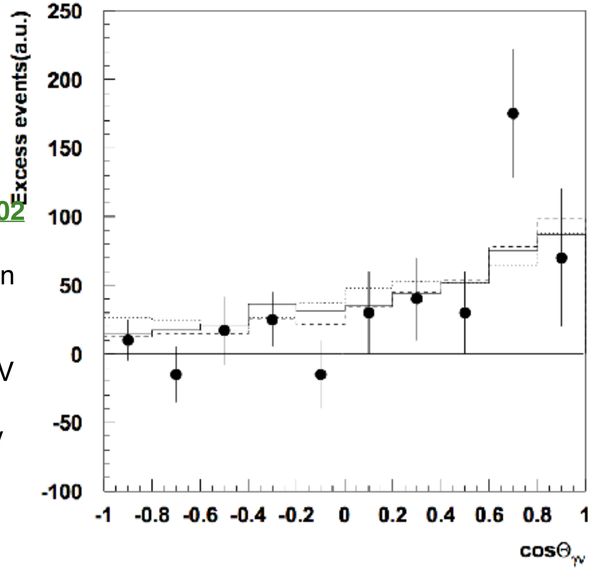

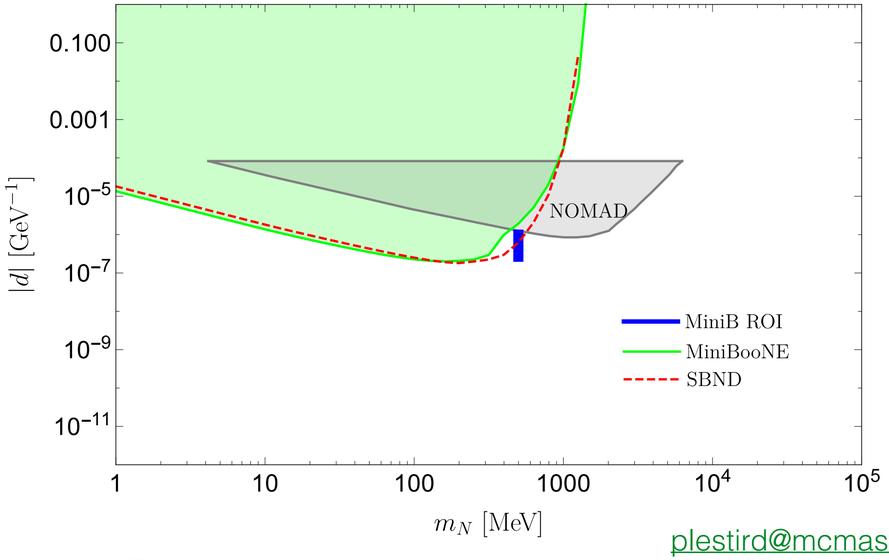

Our Work

Claim: SBND and MicroBooNE can probe anomalous region in the near future

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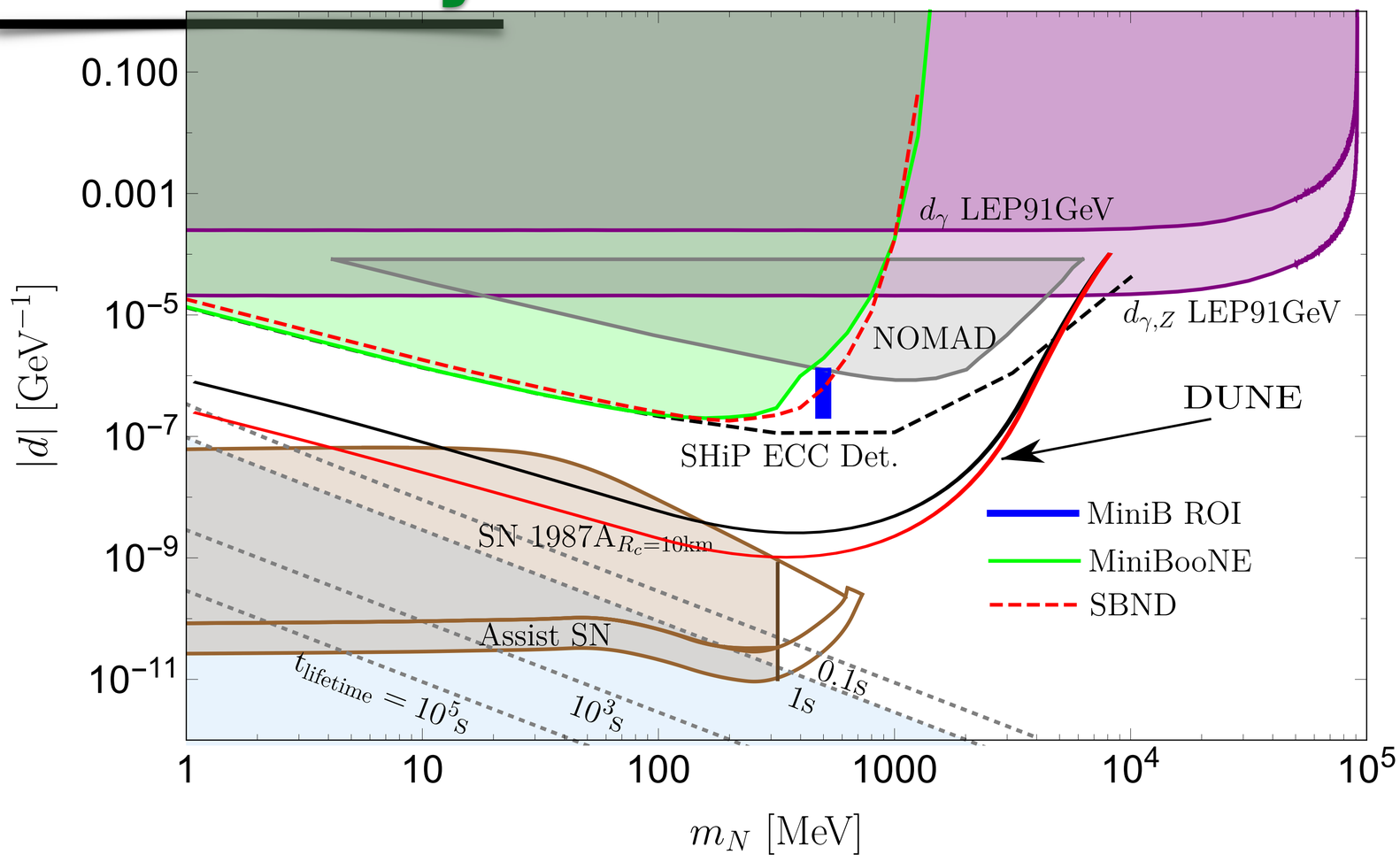
Summary

arXiv:1803.03262



Work supported by

NSERC CRSNG

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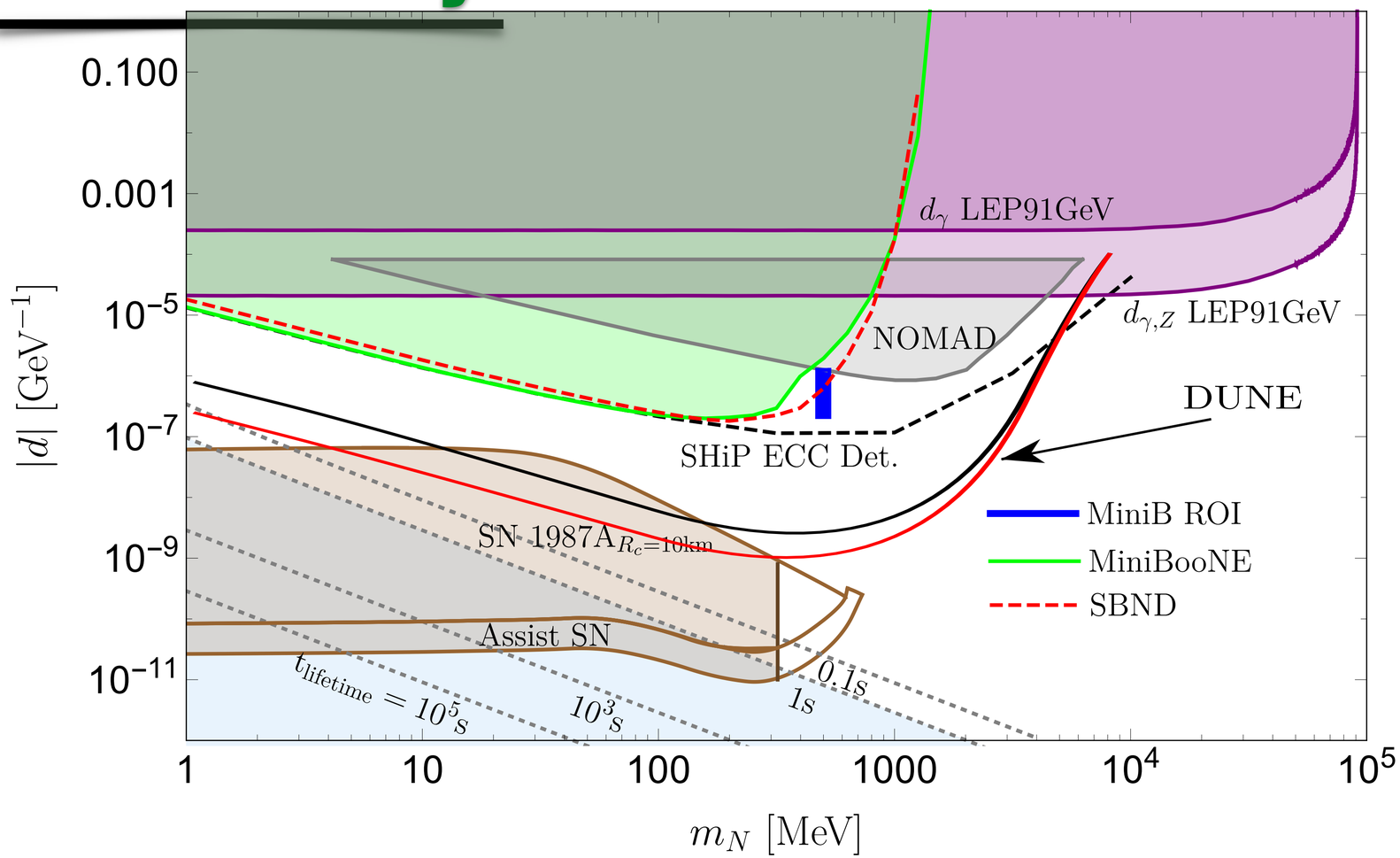

Conclusions

- **HNLs produce rich signatures in neutrino experiments, colliders, supernovae and BBN**
- **We have provided model independent constraints on a dipole portal**
- **SBND (and ICECUBE) can probably give a definitive verdict on MiniBooNE ROI.**
- **DUNE can potentially push down to the “SN1987 -floor"**

Work supported by

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Thank You!

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Questions?

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Backup Slides

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Details of SBN Analysis

arXiv:1803.03262

Details of SBN Analysis

arXiv:1803.03262

SBND

- 6 x 10^{20} POT exposure
- Used collaboration estimates for single photon misID rate to backout single photon backgrounds
- Imposed the following cuts

$$E_{\gamma\ \mathrm{lab}} > 200\ \mathrm{MeV} \quad \theta_{\gamma\ \mathrm{lab}} > \pi/2$$

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Details of SBN Analysis

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MicroBooNE

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- 6 x 10^{20} POT exposure
- Used collaboration estimates for single photon misID rate to backout single photon backgrounds
- Imposed the following cuts

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Details of SBN Analysis

arXiv:1803.03262

MicroBooNE

- 1.3 x 10^{20} POT exposure
- Used collaboration estimates for single photon misID rate to backout single photon backgrounds
- Imposed the following cuts

$$E_{\gamma\ \mathrm{lab}} > 200\ \mathrm{MeV} \quad \theta_{\gamma\ \mathrm{lab}} > \pi/2$$

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