Neutrino Background in Dark Matter Direct Detection Experiments: Standard Model and beyond

Yuber F. Perez-Gonzalez
Instituto de Física Teórica, Universidade Estadual Paulista &
ICTP – South American Institute for Fundamental Research &
Instituto de Física, Universidade de São Paulo

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IFT - UNESP
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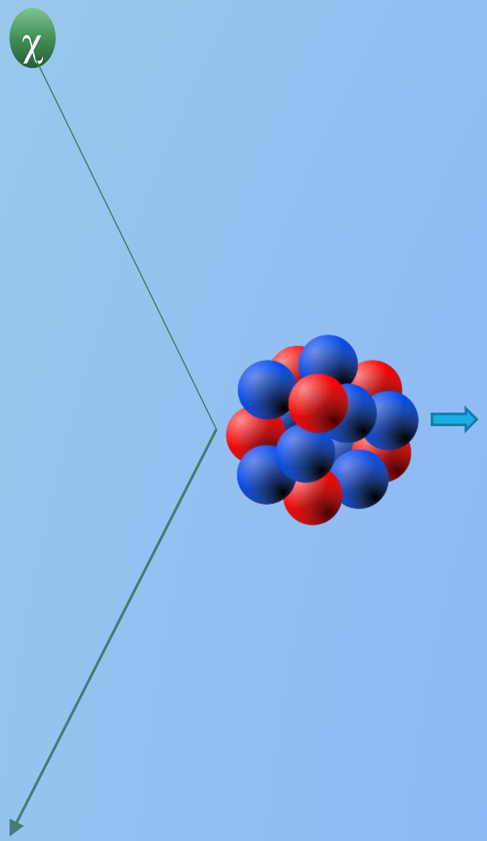
DO ESTADO DE SÃO PAULO

Overview

- DM Direct detection principle
- Coherent neutrino-nucleus scattering (CνNS)
- CνNS as irreducible background
- SM Neutrino Discovery Limit
- Flavour-independent BSM
- Flavour-dependent BSM

Principle of WIMP Direct Detection

Elastic scattering



A possible interaction between WIMP and nuclei

DM density

DM-nucleon total cross section

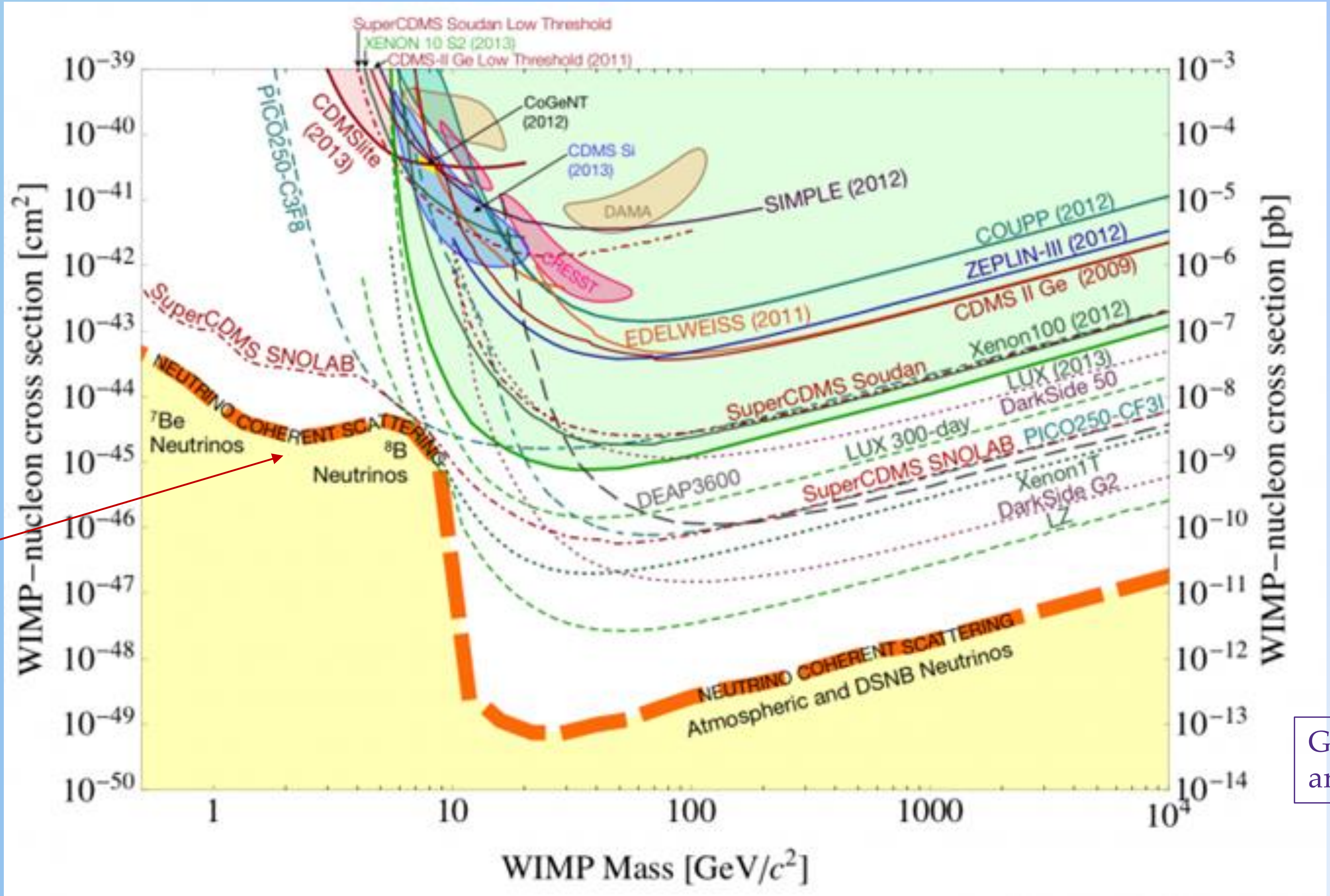
Nuclear Form Factor

$$\left.\frac{dR}{dE_R}\right|_\chi = \mathcal{N} \frac{\rho_0 \sigma_0^n}{\sqrt{\pi}\mu_n^2 m_\chi v_0^2} A^2 \boxed{\mathcal{F}(E_R)^2} \boxed{T(E_R, m_\chi)}$$

WIMP mass

DM distribution

Current and Future Limits



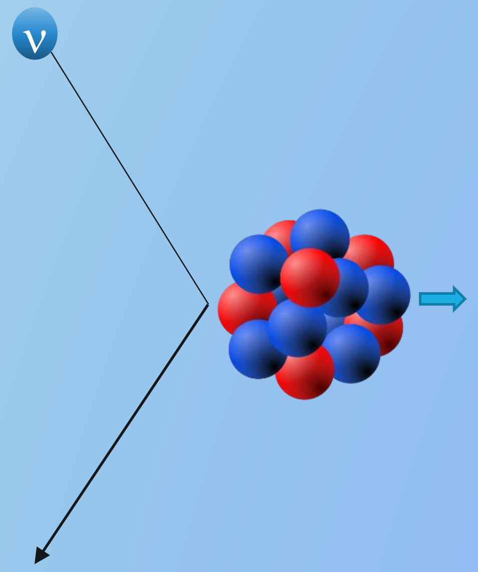
What does this *neutrino floor* mean?

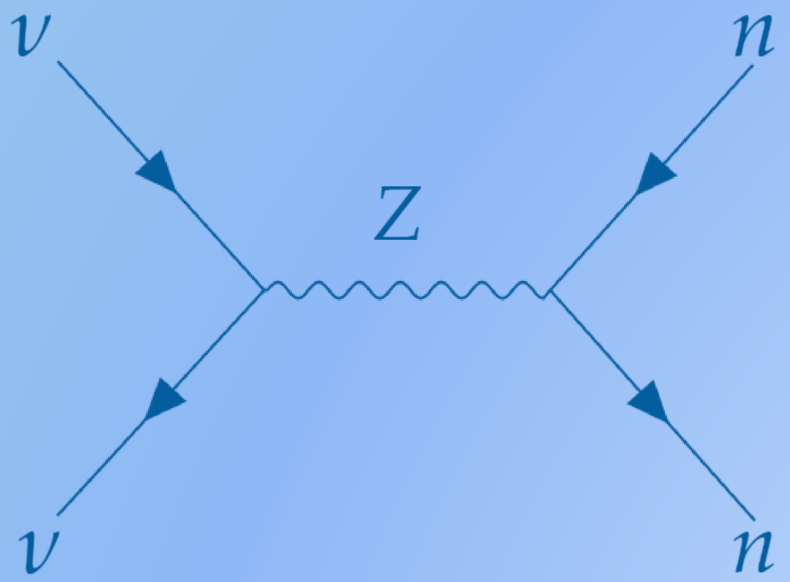
J. Billard *et. al.* *PRD* 89 (2014) 023524

Gelmini arXiv:1502.01320

Coherent Neutrino-Nucleus Scattering (CνNS)

D. Freedman
PRD 9 (1974) 1389





Neutral current process

First Measured in 2017!

Science 357 (2017) 1123
arXiv:1708.01294

Recoil energy

$$\left.\frac{d\sigma^{\nu}}{dE_R}\right|_{SM} = \frac{G_F^2 m_N}{4\pi}\mathcal{F}(E_R)^2\left[N + (4s_W^2 - 1)Z\right]^2\left(1 - \frac{m_N E_R}{2E_\nu^2}\right)$$

Nuclear properties

Recoil rates

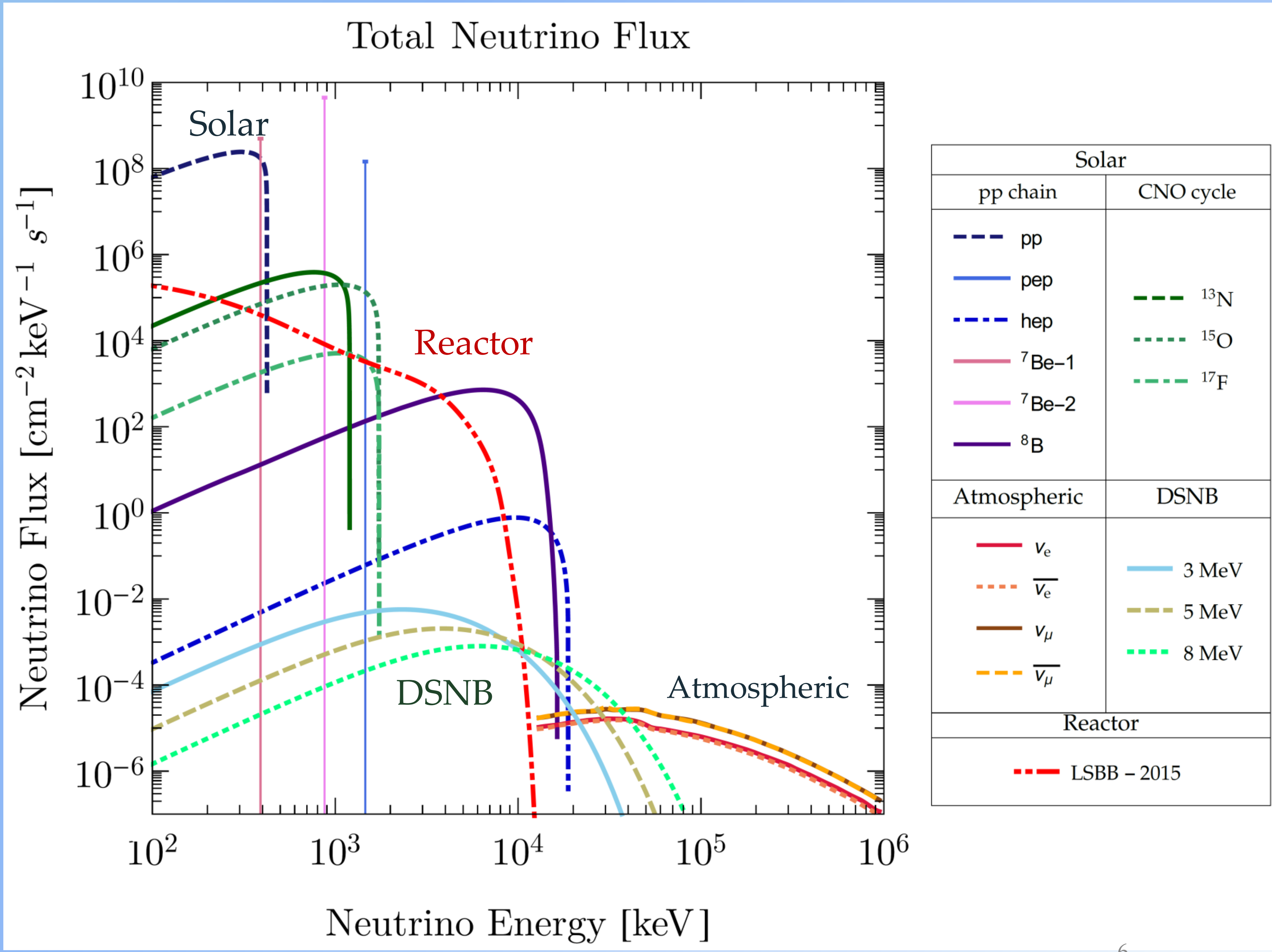
Neutrino Fluxes

$$\left.\frac{dR}{dE_R}\right|_\nu = \boxed{\mathcal{N}} \int_{\boxed{E^\nu_{\mathrm{min}}}} \boxed{\frac{d\Phi}{dE_\nu}} \frac{d\sigma^\nu}{dE_R} dE_\nu$$

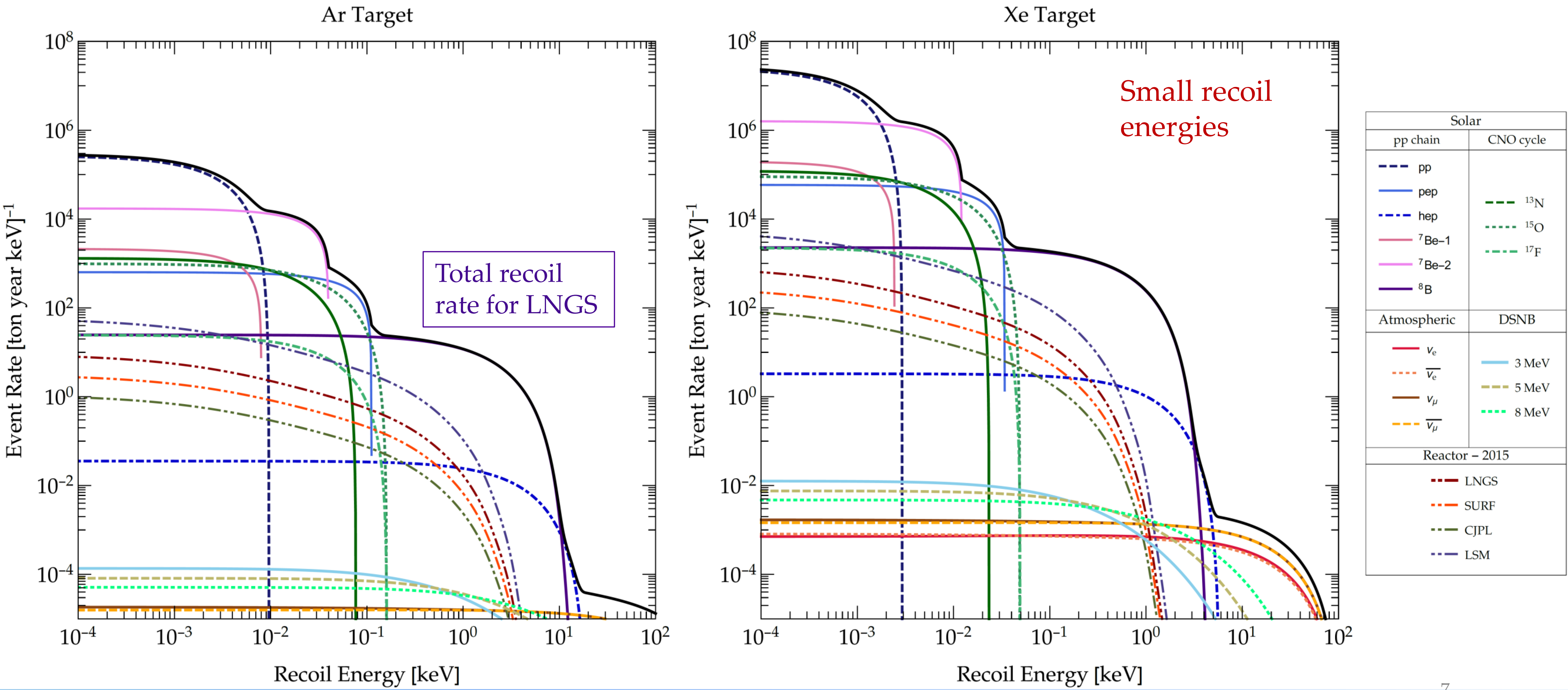
Number of targets

Minimal neutrino energy

$$E^\nu_{\mathrm{min}} = \sqrt{\frac{m_N E_R}{2}}$$

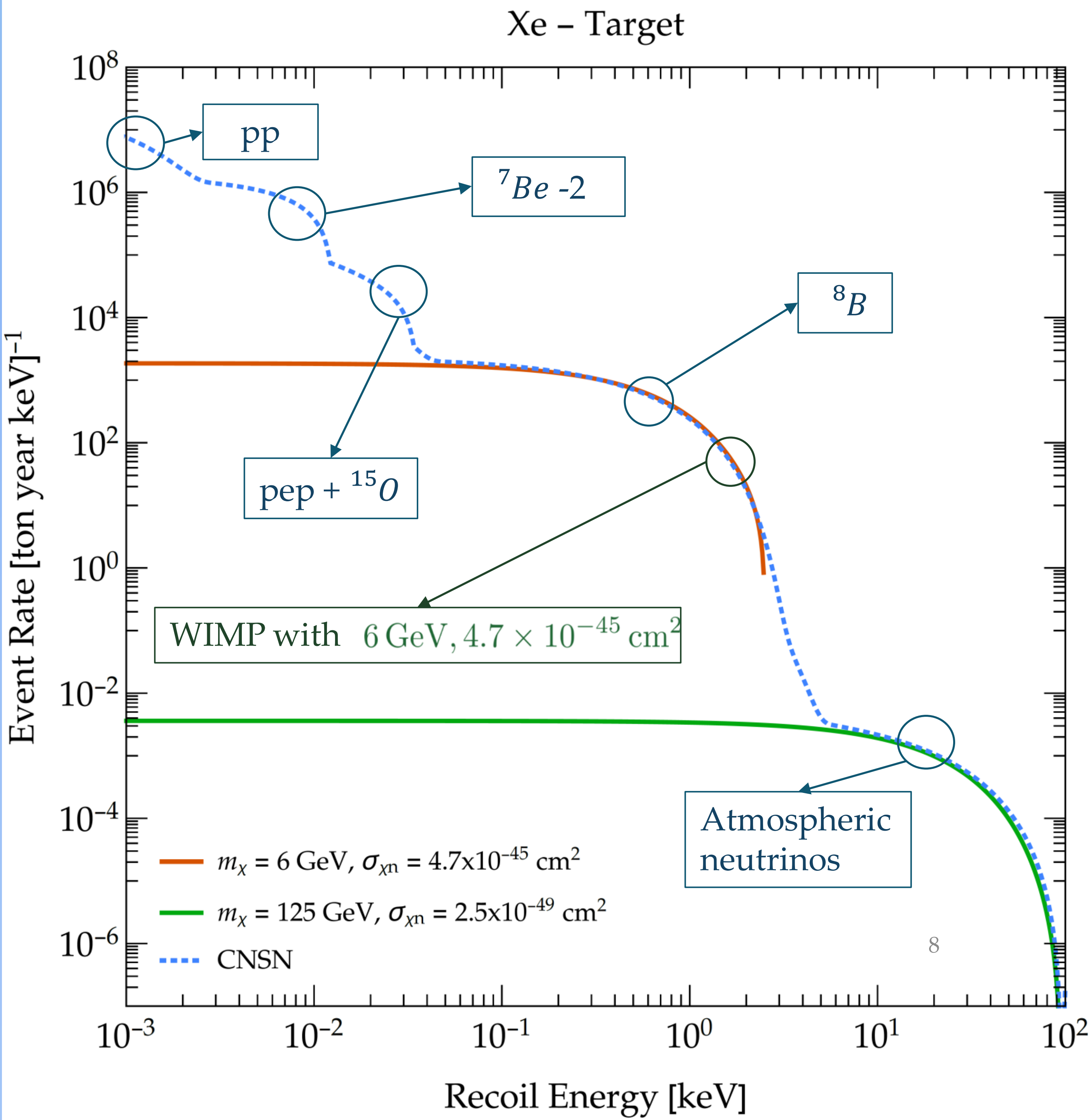


Recoil rates



CνNS as an irreducible background

A WIMP signal can perfectly be mimicked by neutrino scatterings.



Neutrino Discovery Limit - 1

Cowan et al. - Eur. Phys. J. C (2011) 71: 1554
Billard et. al. - Phys. Lett. B 691, 156 (2010).
Phys. Rev. D 83,075002 (2011)

How to describe consistently when do neutrinos become relevant?

Real experiment compares two hypothesis

Signal + Background

WIMP + neutrinos

Background Only

Neutrinos

Simulation of the real analysis for some fixed experimental parameters

Profile Likelihood

$$\mathcal{L}(\boxed{\sigma_{\chi n}, m_\chi}, \phi_\nu)$$

Unknown parameters

Nuisance Parameters

Uncertainities on the neutrino fluxes.

A neutrino spectrum can hinder the WIMP spectrum

Neutrino Discovery Limit

Due to our lack of knowledge on neutrino fluxes

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Neutrino Discovery Limit - 2

How to describe consistently when do neutrinos become relevant?

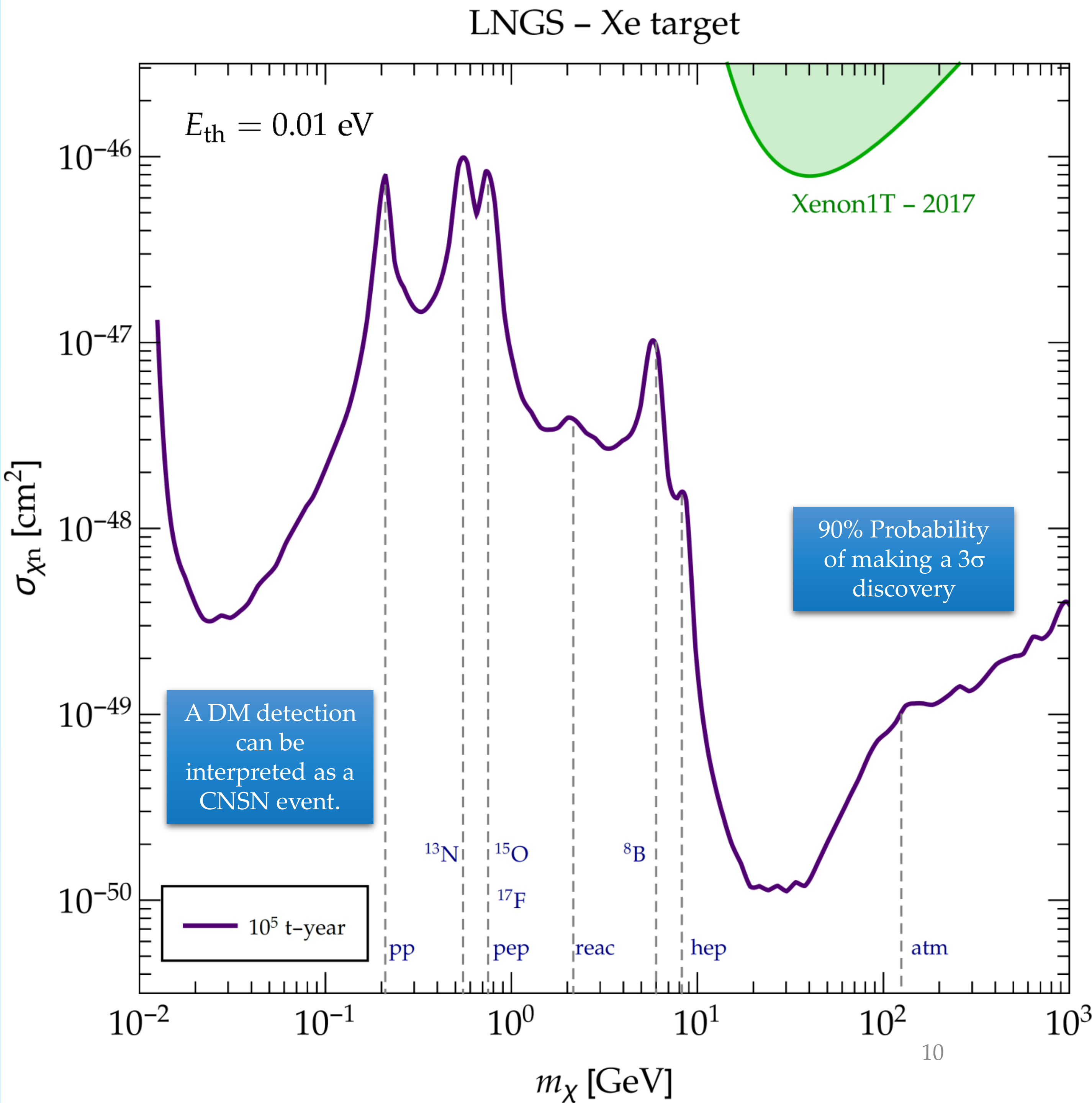
Profile Likelihood

$$\mathcal{L}(\sigma_{\chi n}, m_\chi, \phi_\nu)$$

Neutrino Discovery Limit

Due to our lack of knowledge on neutrino fluxes

Uncertainities on the neutrino fluxes.



Neutrino Discovery Limit - 3

How to describe consistently when do neutrinos become relevant?

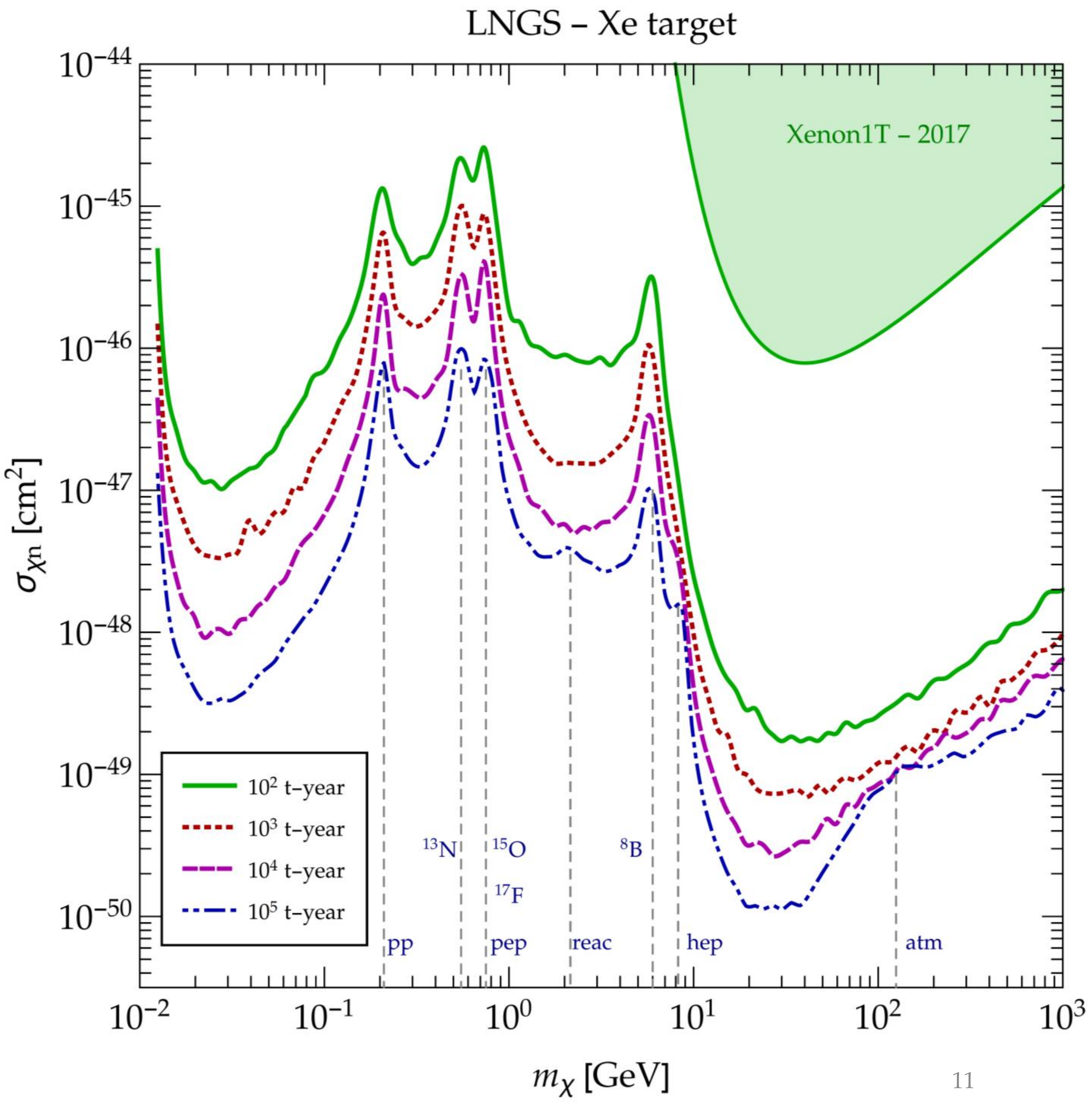
Profile Likelihood

$$\mathcal{L}(\sigma_{\chi n}, m_\chi, \phi_\nu)$$

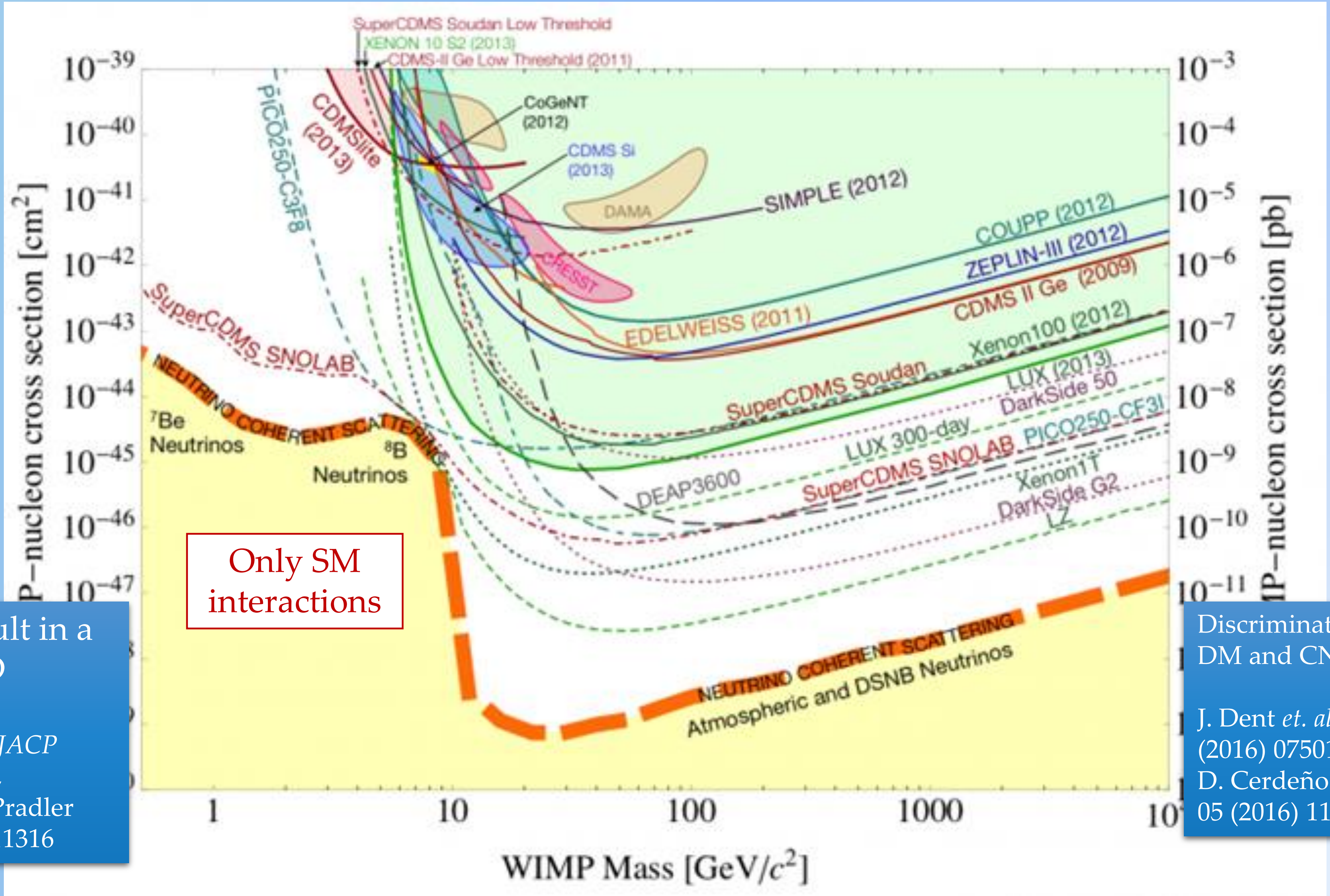
Neutrino Discovery Limit

Due to our lack of knowledge on neutrino fluxes

Uncertainities on the neutrino fluxes.



Neutrino Discovery Limit - 4



Only SM interactions

NSI can result in a signal at DD

R Harnik *et. al. JACP* (2012) 1207-026,
M Pospelov, J. Pradler *PRD* 85 (2012) 11316

Discrimination between DM and CNSN

J. Dent *et. al. PRD* 93 (2016) 075018,
D. Cerdeño *et. al. JHEP* 05 (2016) 118

What if there's Beyond the SM physics?

- Flavour independent

  Simplified models (scalar and vector) coupling with both DM and neutrinos

  R Harnik et. al. - JACP (2012) 1207-026

  E. Bertuzzo, F. Deppisch, S. Kulkarni, YFPG and R. Zukanovich Funchal
  JHEP 1704 (2017) 073,
  arXiv:1701.07443 [hep-ph]

- Flavour dependent

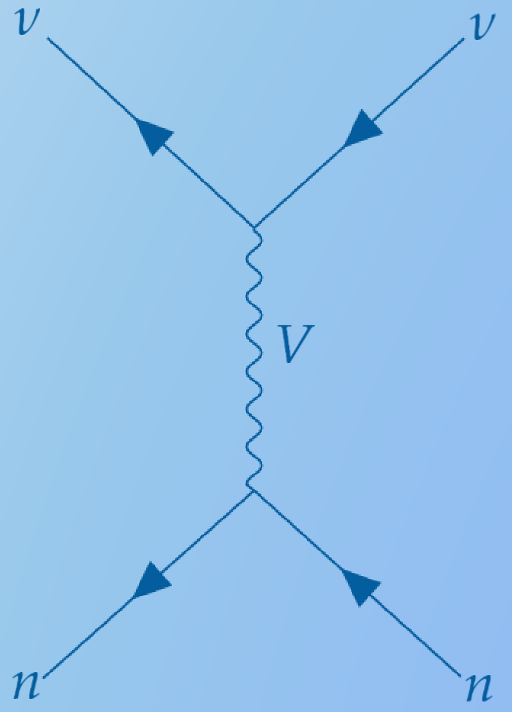
  Neutral Current Non-Standard Interactions (NC-NSI)

  B. Dutta et. al. - Phys. Lett. B773 (2017) 242

  D. Aristizabal Sierra - arXiv:1712.09667

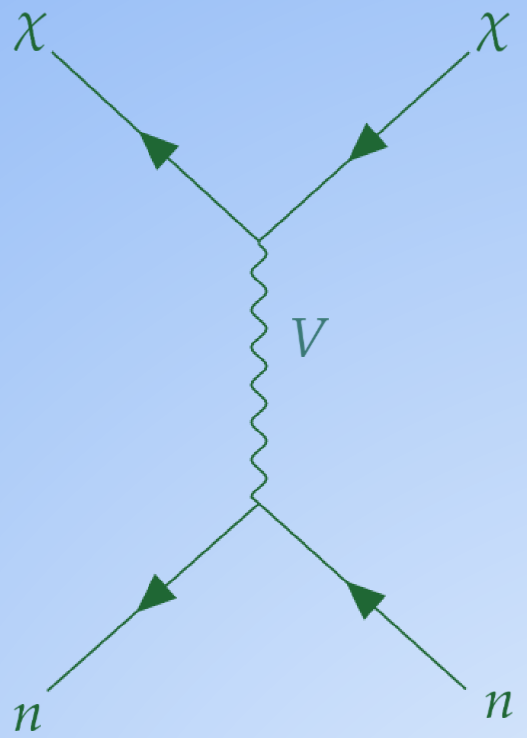
  M. C. Gonzalez-Garcia, M. Maltoni, YFPG and R. Zukanovich Funchal
  JHEP 1807 (2018) 019,
  arXiv:1803.03650 [hep-ph]

Flavour Independent - Vector Mediator



$$\mathscr{L}_{\mathrm{V}} = V_\mu (J_f^\mu + J_\chi^\mu) + \frac{m_V^2}{2} V_\mu V^\mu$$

$$J_f^\mu = \sum_{f=\chi,\nu,q} \bar{f} \gamma^\mu (g_V^f + g_A^f \gamma_5) f$$



$$\left.\frac{d\sigma^\nu}{dE_R}\right|_{\mathrm{V}} = \mathcal{G}_V \left.\frac{d\sigma^\nu}{dE_R}\right|_{\mathrm{SM}}$$

All dependence in the parameters → Posible destructive interference

$\mathcal{G}_V = 1$ → SM

$$\left.\frac{d\sigma_{\mathrm{SI}}^\chi}{dE_R}\right|_{\mathrm{V}} = \mathcal{F}^2(E_R) \frac{(g_V^\chi)^2 Q_V^2}{4\pi} \frac{m_\chi m_N}{E_\chi (q^2 - m_V^2)^2}$$

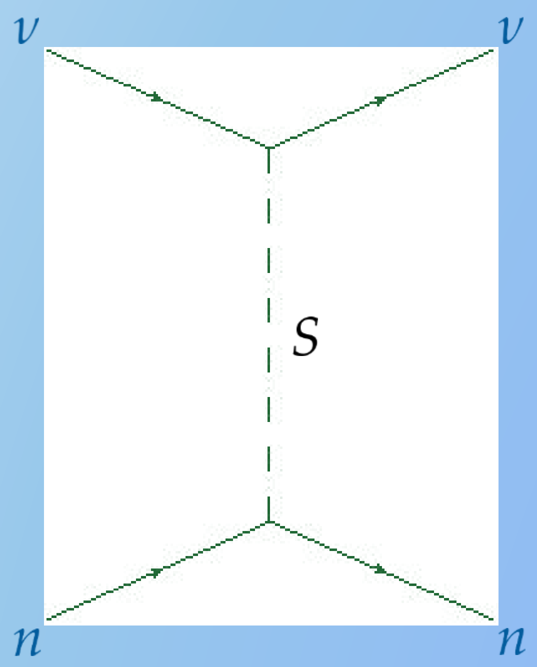
Spin-independent interaction

$g_A^\chi = 0$

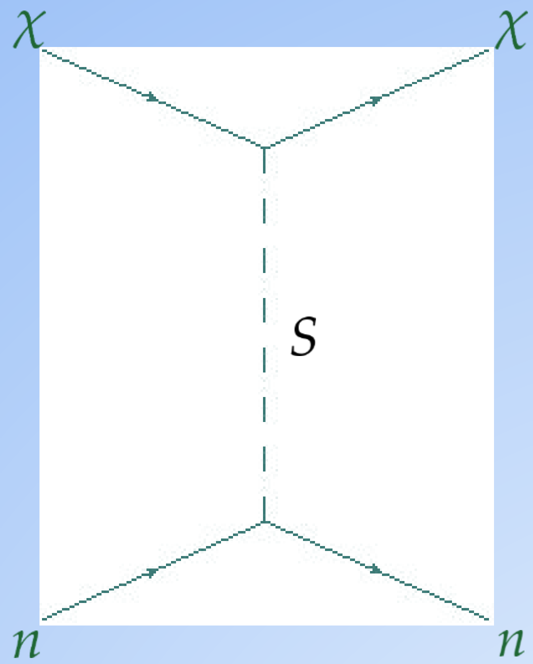
Momentum transfer

Flavour Independent - Scalar Mediator

Different Lorentz Structure → Modfication of the shape of the recoil rate



$$\mathscr{L}_s = S\left(\sum_f g_S^f \bar{f} f + g_S^\chi \bar{\chi}\chi\right) - \frac{1}{2} m_S^2 S^2$$



$$\left.\frac{d\sigma^\nu}{dE_R}\right|_S = \left.\frac{d\sigma^\nu}{dE_R}\right|_{SM} + \mathcal{F}^2(E_R)\frac{\mathcal{G}_S^2 G_F^2}{4\pi}\frac{m_S^4 E_R m_N^2}{E_\nu^2(q^2-m_S^2)^2}$$

Dependence on the scalar couplings

$\mathcal{G}_S = 0 \rightarrow$ SM

$$\left.\frac{d\sigma^\chi_{SI}}{dE_R}\right|_S = \mathcal{F}^2(E_R)\frac{(g_S^\chi)^2 \mathcal{Q}_S^2}{4\pi}\frac{m_\chi m_N}{E_\chi(q^2-m_S^2)^2}$$

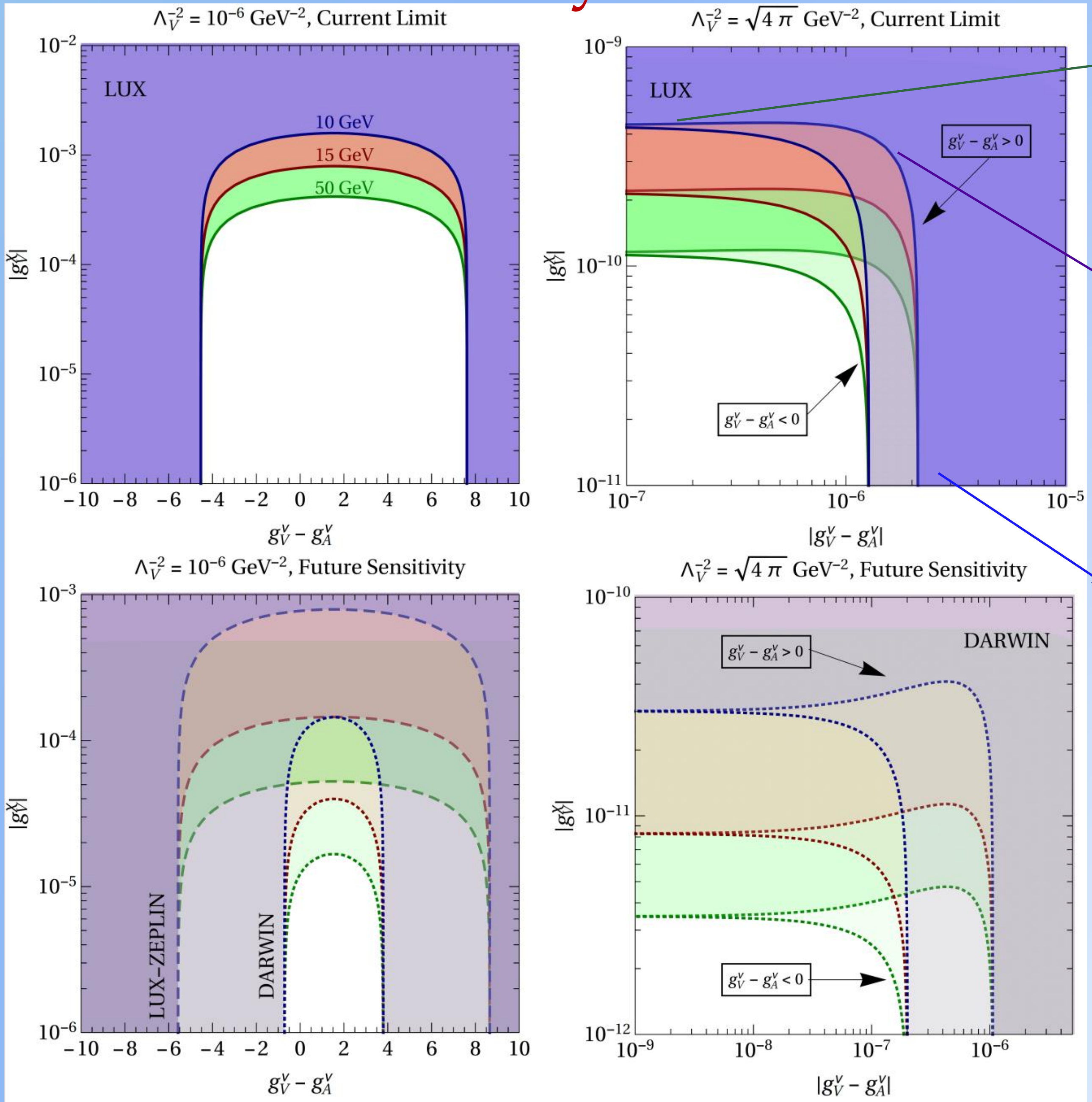
Scalar Form Factors

Current Limits and Future Sensitivity –Vector

$$\mathrm{Ev}^{\nu} = \int_{E_{\rm th}} \frac{dR}{dE_R}\bigg|_{\nu} \varepsilon(E_R)\, dE_R\,,$$

$$\mathrm{Ev}^{\chi} = \int_{E_{\rm th}} \frac{dR}{dE_R}\bigg|_{\chi} \boxed{\varepsilon(E_R)}\, dE_R\,.$$

Experimental efficiency



DM dominates

DM + ν

ν dominates

LUX Current Limit

$$\mathcal{G}_V \lesssim 3.6$$

$$\Lambda_V^{-2} \equiv \frac{g_V^q}{m_V^2}$$

Current Limits and Future Sensitivity – Scalar

$$\mathrm{Ev}^{\nu} = \int_{E_{\rm th}} \left.\frac{dR}{dE_R}\right|_{\nu} \varepsilon(E_R)\, dE_R\,,$$

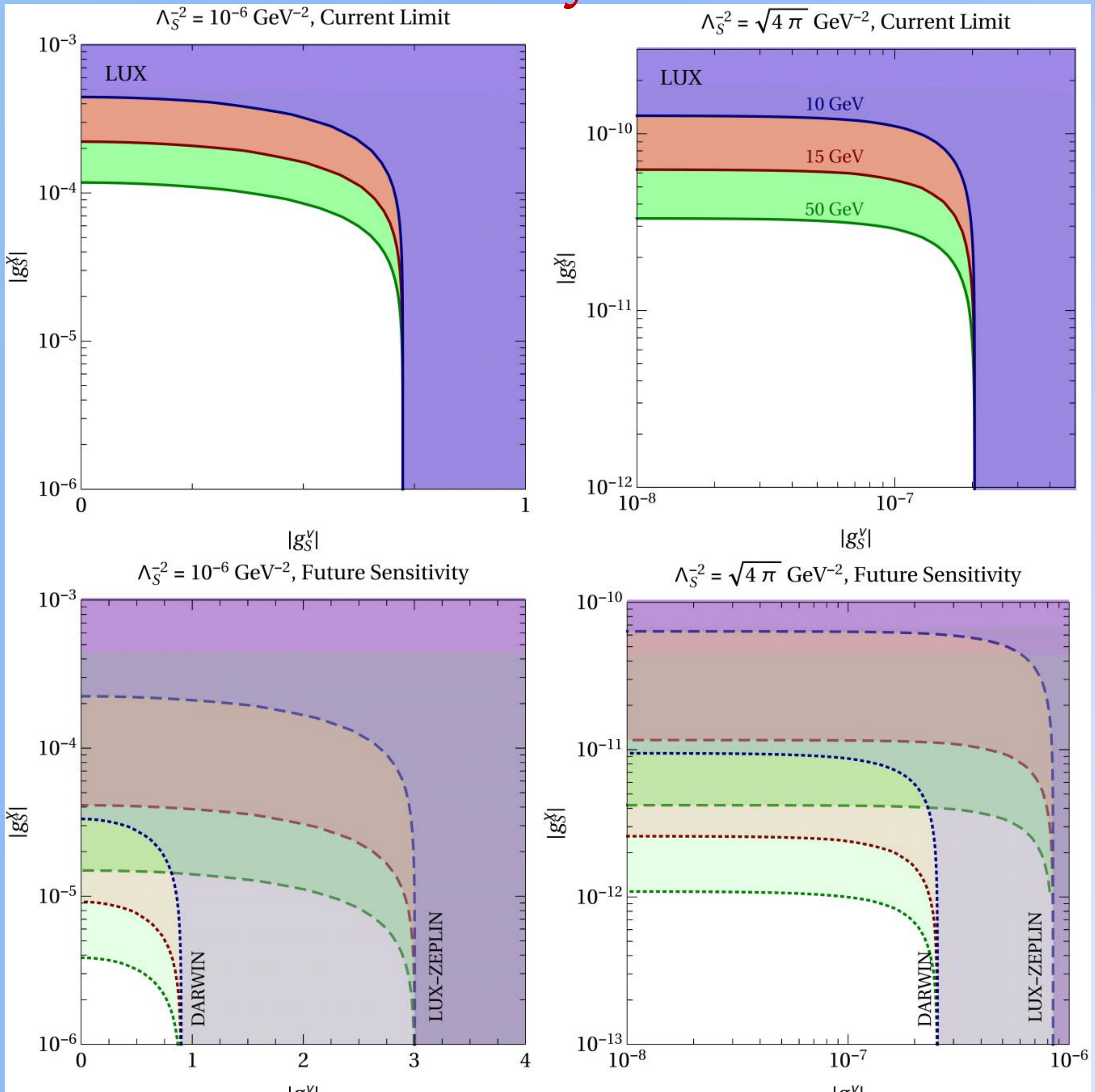
$$\mathrm{Ev}^{\chi} = \int_{E_{\rm th}} \left.\frac{dR}{dE_R}\right|_{\chi} \boxed{\varepsilon(E_R)}\, dE_R\,.$$

Experimental efficiency

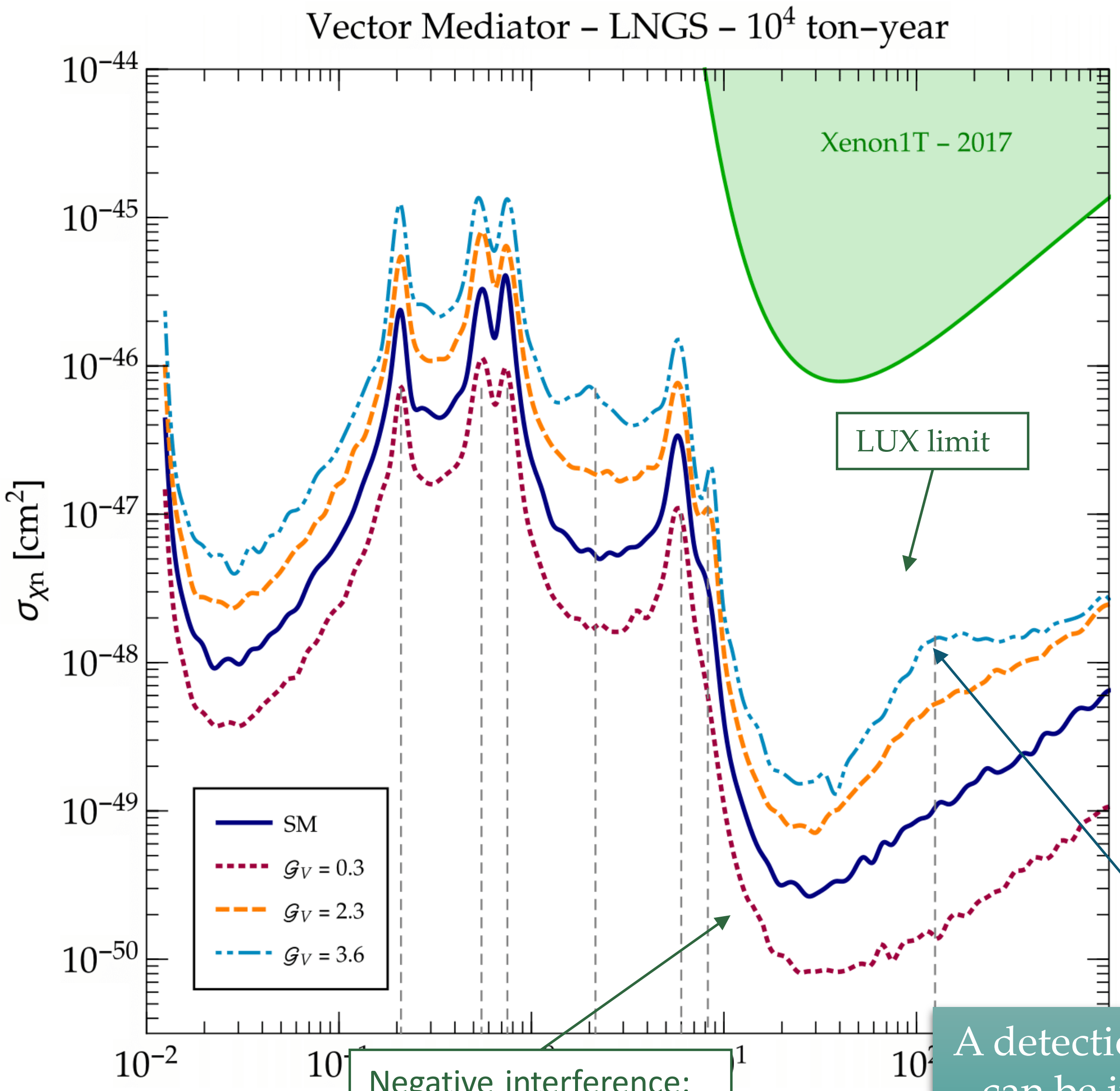
LUX Current Limit

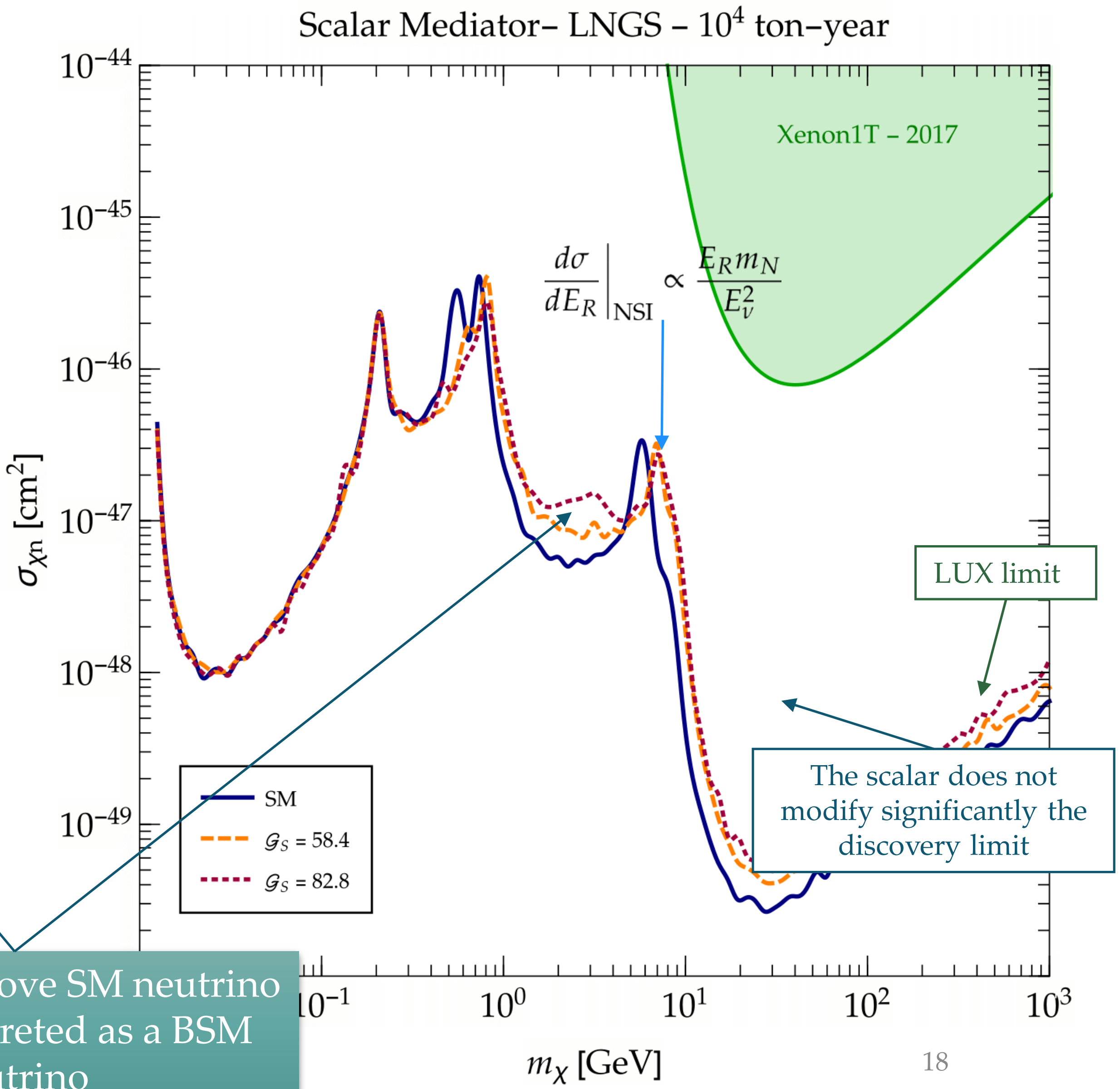
$\mathcal{G}_S \lesssim 82.8$

$$\Lambda_S^{-2} \equiv \frac{g_S^q}{m_S^2}$$



Sensitivity to DM-nucleon scattering -6





Negative interference:
Lower neutrino floor

A detection above SM neutrino can be interpreted as a BSM neutrino

The scalar does not modify significantly the discovery limit

Flavour dependent scenario – NC-NSI

Chiral Projector

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \boxed{\epsilon_{\alpha\beta}^{f,P}} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\boxed{\bar{f}}\gamma_\mu \boxed{P} f)$$

General parametrization

Parametrization of BSM physics

f = u,d

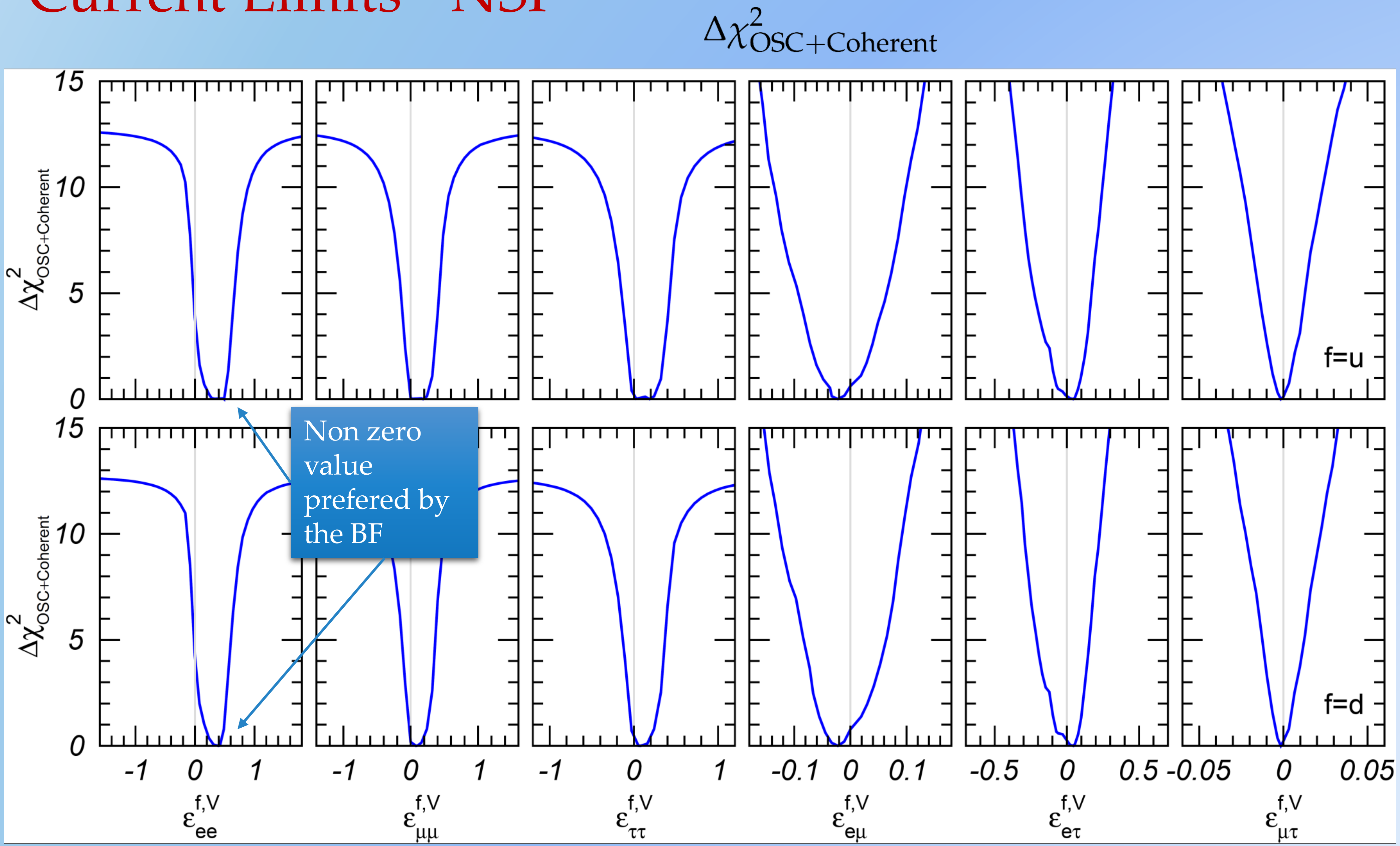
CNNS cross section

$$\left.\frac{d\sigma^\nu(\nu_\alpha)}{dE_R}\right|_{\text{NSI}} = \boxed{[\mathcal{Q}_{\text{NSI}}^{\alpha}]^2} \mathcal{F}^2(E_R) \frac{G_F^2 m_N}{4\pi}\left(1 - \frac{m_N E_R}{2E_\nu^2}\right)$$

Flavour dependent coefficient

We have to include neutrino oscillations effects

Current Limits - NSI



Global fit of neutrino oscillation data + COHERENT results

Marginalized chi-square

Recoil rate with NSI

We must include neutrino oscillations

Neutrino at the source

Neutrino at the detector

$$\left.\frac{dR}{dE_R}\right|_{\nu} = \mathcal{N} \sum_{\nu_\alpha,\nu_\beta} \int_{E^{\nu}_{\rm min}} \boxed{\left.\frac{d\Phi}{dE_\nu}\right|_{\nu_\alpha}} \boxed{P(\nu_\alpha \to \nu_\beta, E_\nu)} \boxed{\left.\frac{d\sigma^{\nu}(\nu_\beta)}{dE_R}\right|_{\rm NSI}} dE_\nu$$

Oscillation probability

Solar Neutrinos

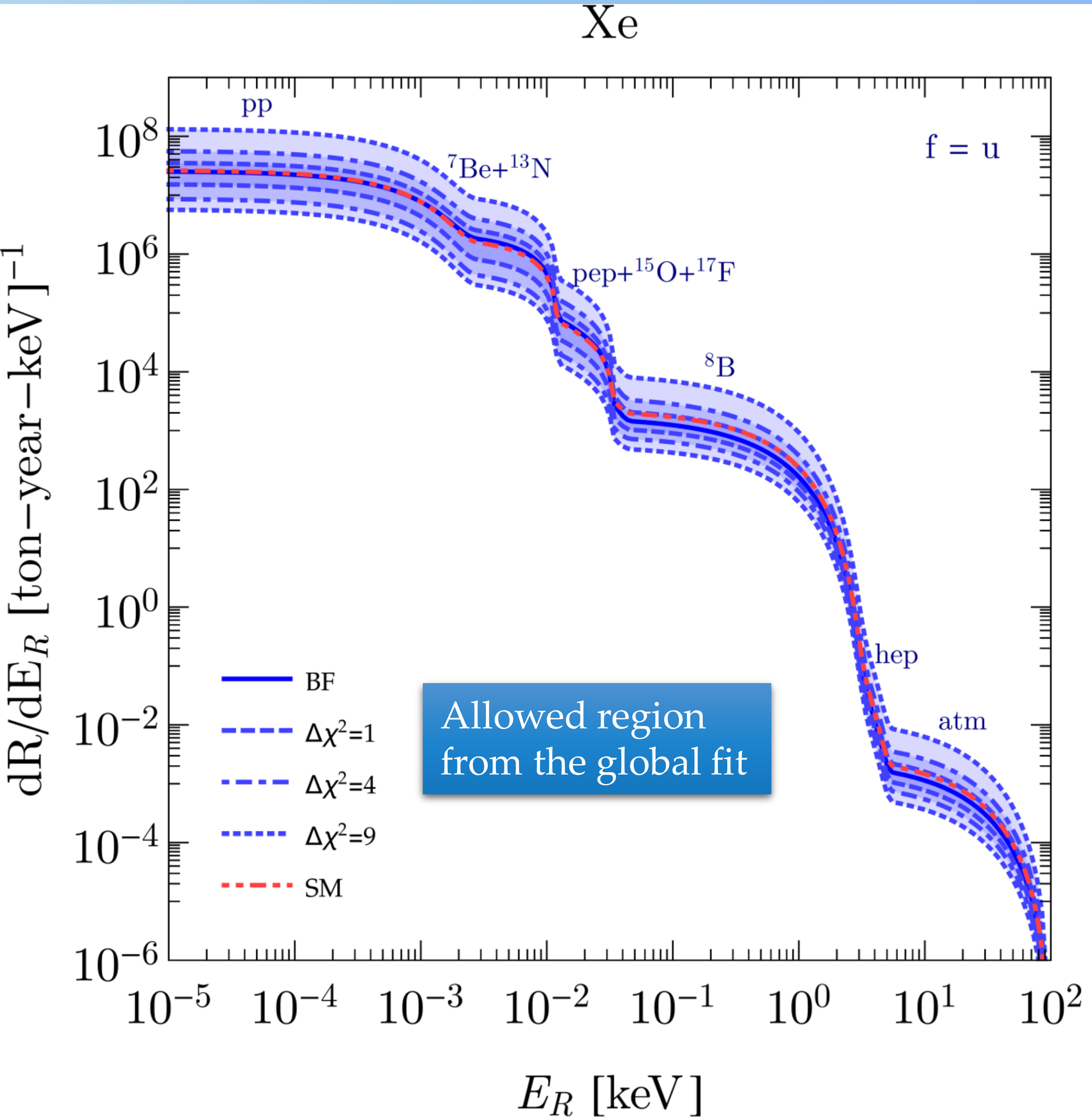
MSW effect at play

Atmospheric neutrinos

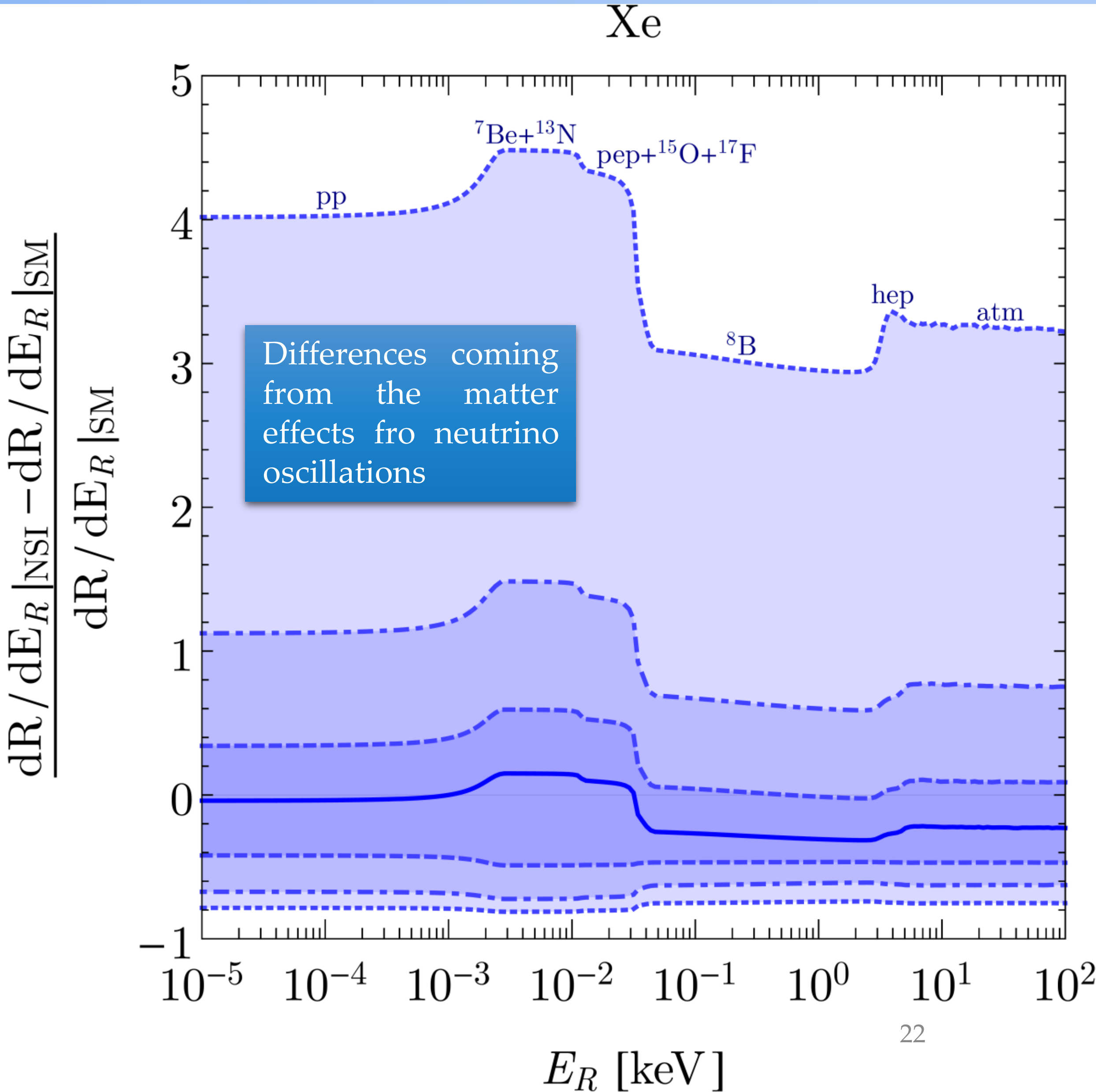
Average at zenit angle

Effects only included because of BSM physics

Recoil rate with NSI - 2

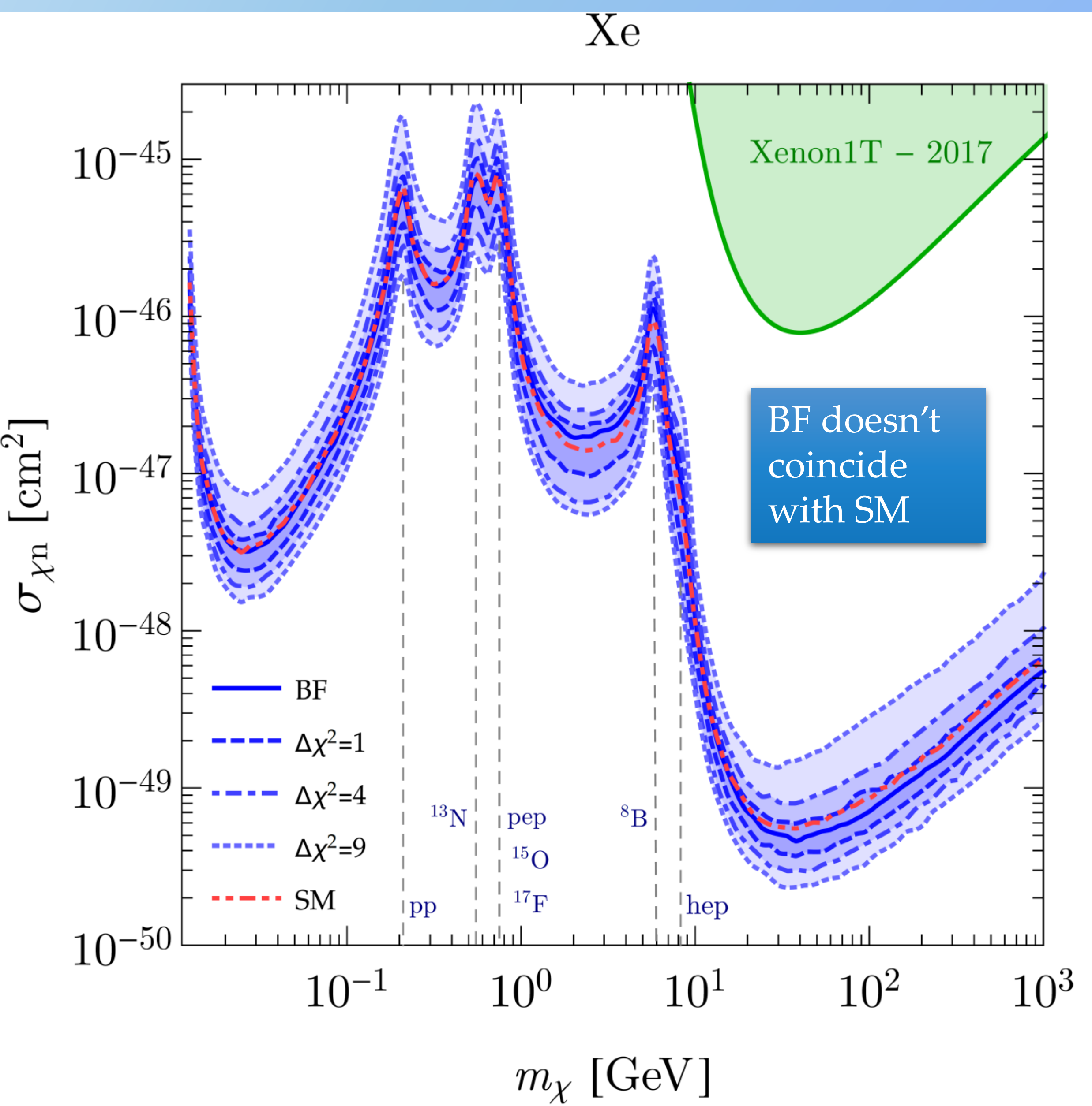


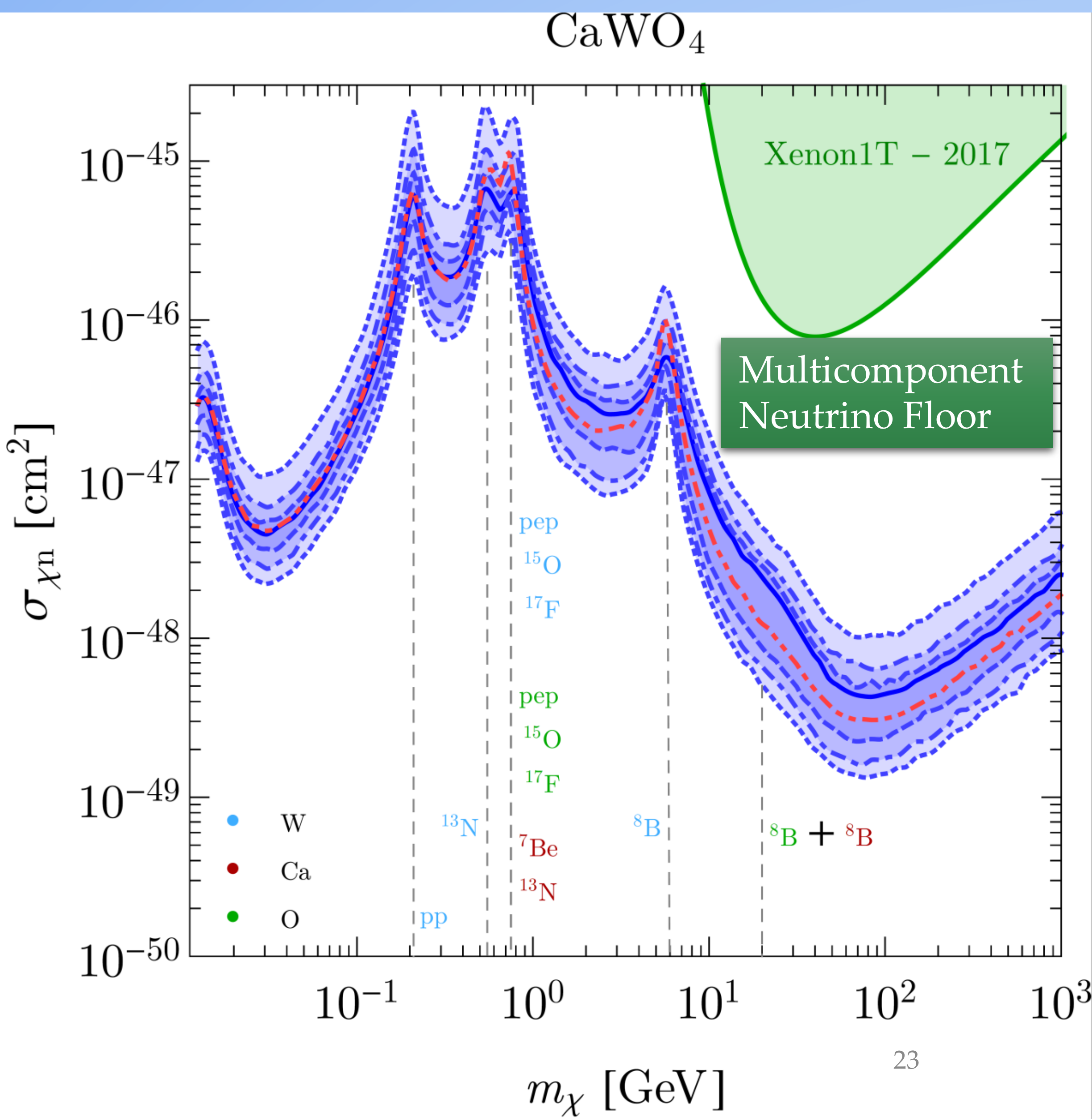
Allowed region from the global fit



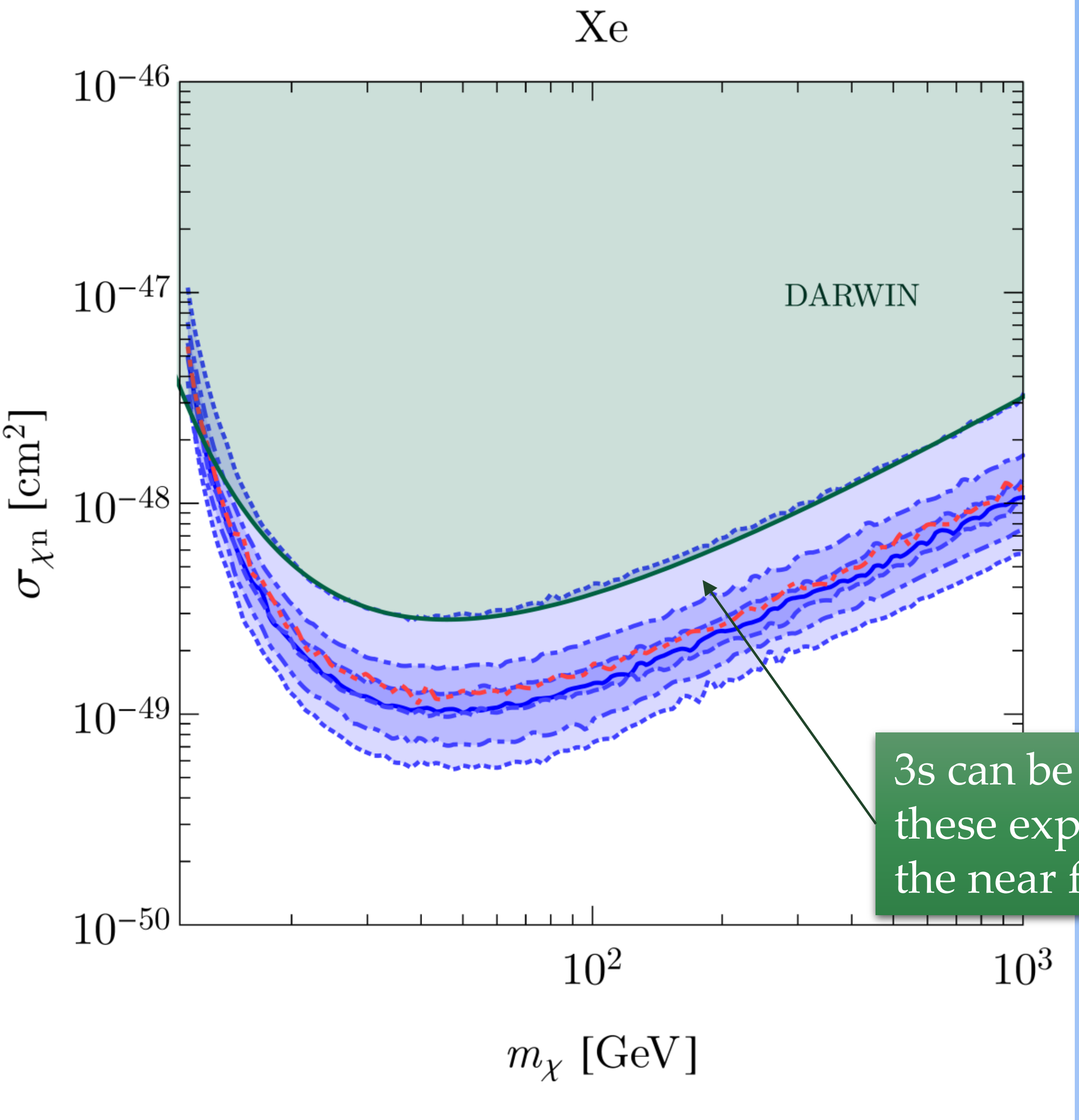
Differences coming from the matter effects fro neutrino oscillations

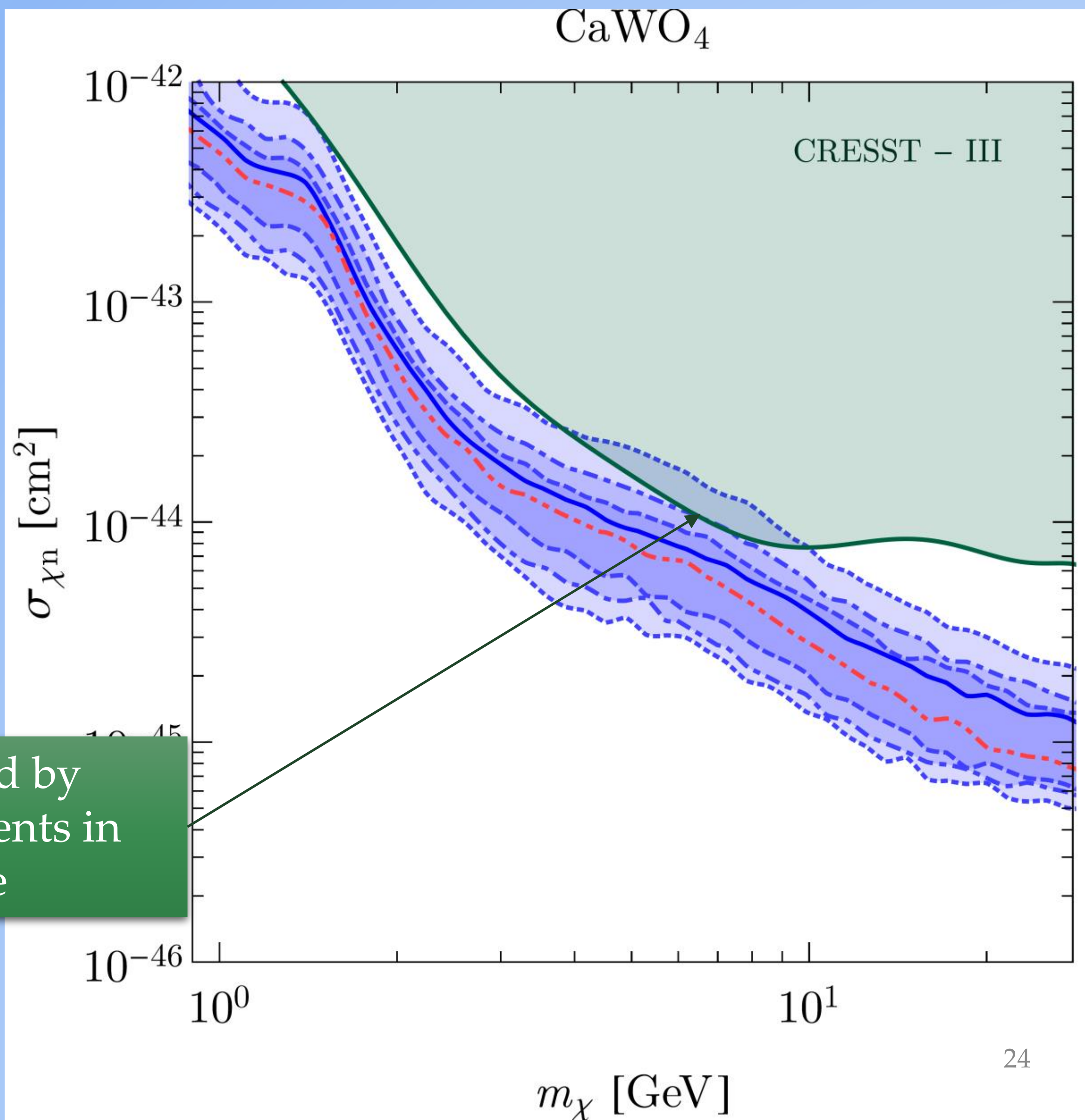
Neutrino Discovery Limit including NSI





Neutrino Discovery Limit including NSI - 2





3s can be tested by these experiments in the near future

Summary

- Future Direct Detection experiments will be sensitive to CNSN, opening another window to study neutrino physics.
- An absence of a WIMP signal put limits in a interaction that affects both DM and νs.
- Improvements on the measurements of neutrino fluxes and/or a detection of the CNSN.
- Flavour independent scenarios can be constrained by current limits, but they can be sensitive to other experimental data
- Flavour dependent BSM interactions are more constrained due to neutrino oscillation physics
- Neutrino physics and DM physics might be interconected.
- Important to study the interplay between these two invisible particles.

¡Gracias!

Backup Slides

Quantum Mechanical Coherence

Suppose a elastic scattering of an elementary projectile into a composite system

Positions of the individual components

Number of constituents

Amplitude of the scattering

$$F(\vec{p}\,',\vec{p}) = \sum_{j=1}^{A} f_j(\vec{p}\,',\vec{p})e^{i\,\vec{q}\cdot\vec{x}_j}$$

$$\vec{q} \equiv \vec{p}\,' - \vec{p}$$

Differential cross section

$$\frac{d\sigma}{d\Omega} = |F(\vec{p}\,',\vec{p})|^2 = \sum_{j=1}^{A} |f_j(\vec{p}\,',\vec{p})|^2 + \sum_{j,k}^{j\neq k} f_j(\vec{p}\,',\vec{p}) f_j(\vec{p}\,',\vec{p})^\dagger e^{i\vec{q}\cdot(\vec{x}_j-\vec{x}_k)}$$

When momentum transfer is small compared to relative size of the system

$$qR \ll 1$$

$$R = \max_{ij} |\vec{x}_i - \vec{x}_j|$$

$$\frac{d\sigma}{d\Omega} = A^2 |f_j(\vec{p}\,',\vec{p})|^2$$

Contributions add coherently

When do neutrinos become relevant?

One neutrino event contour line → Representation of CNSN in the (σ_0^n, m_χ) plane.

J. Billard *et. al.*
PRD89 (2014) 023524

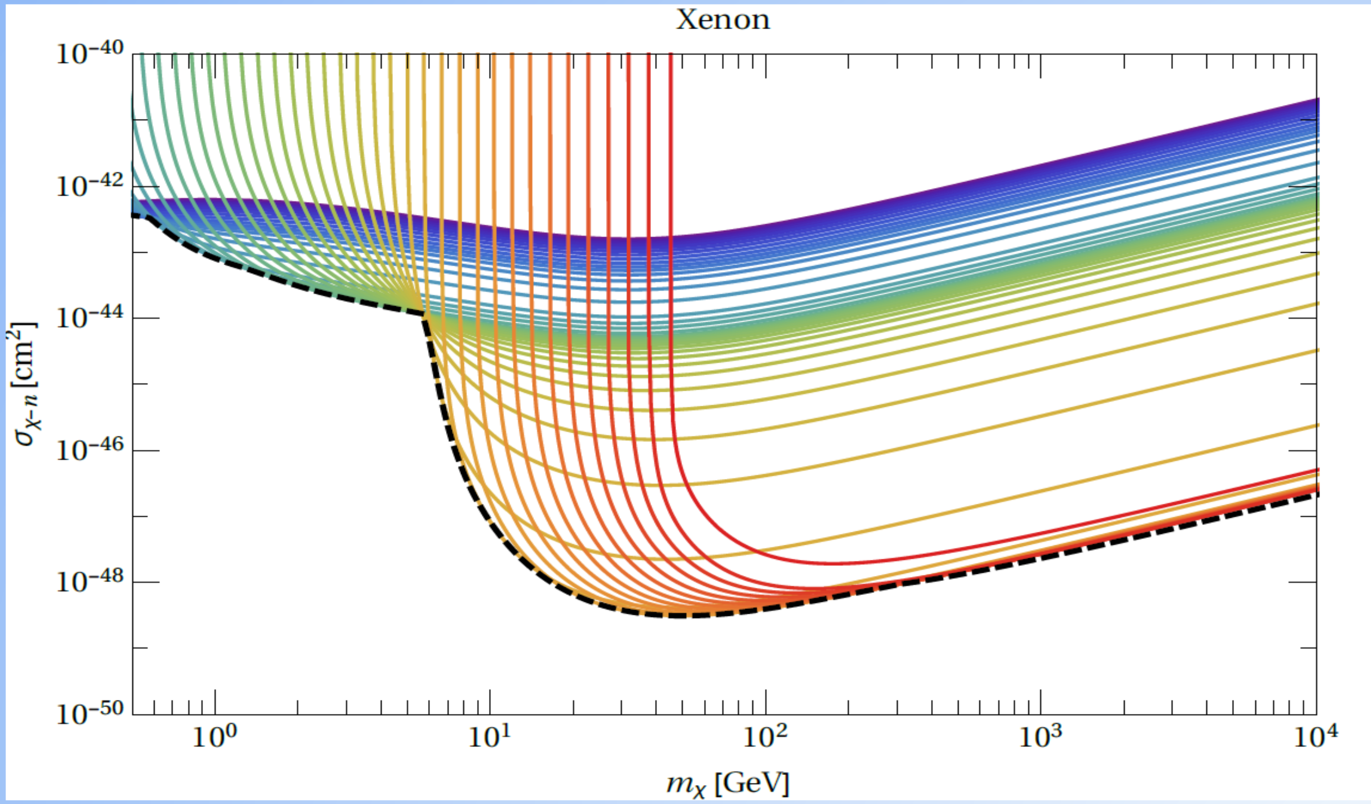
- Determine the exposure needed to obtain one neutrino event,

$$\mathcal{E}_\nu(E_{\rm th}) = \frac{Ev^\nu = 1}{\int_{E_{\rm th}} dE_R \left.\frac{dR}{dE_R}\right|_\nu}$$

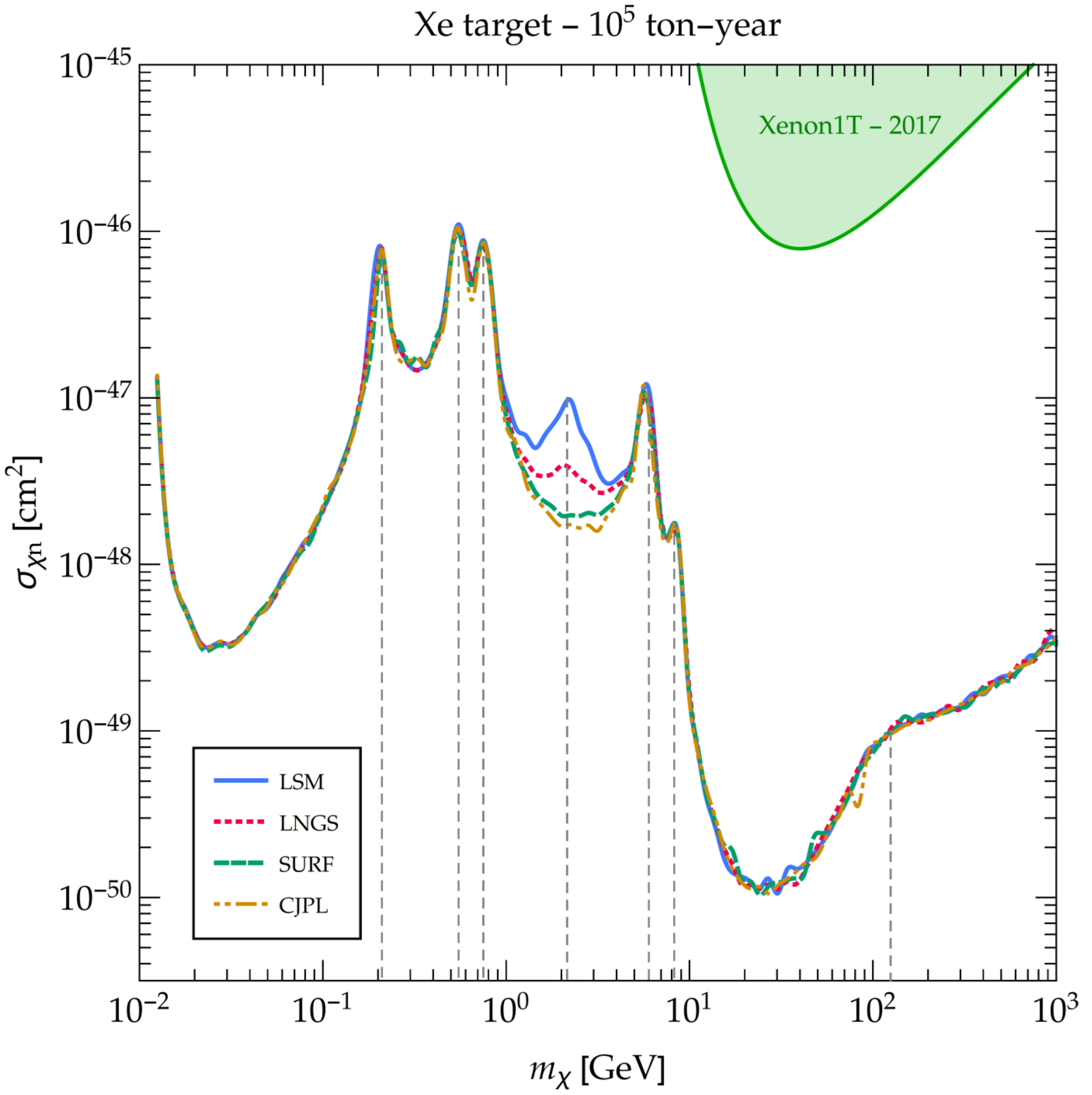
- Compute the background-free exclusion limits at 90% of C.L.

$$\sigma_{0,\rm exc}\big|_{90\%} = \frac{-\log[1-0.9]}{\mathcal{E}_\nu(E_{\rm th}) \int_{E_{\rm th}} dE_R \left.\frac{dR}{dE_R}\right|_{\chi,\sigma_0^n=1}}$$

- Take the lowest cross section in each WIMP mass.



Reactor contributions



Profile Likelihood – Neutrino Floor

Binned likelihood function

Relevant parameters

$$\mathcal{L}(\sigma_{\chi n}, m_\chi, \phi_\nu, \mathbf{\Theta}) = \prod_{i=1}^{n_b} \mathcal{P}\left(\mathrm{Ev}_i^{\mathrm{obs}} \middle| \mathrm{Ev}_i^{\chi} + \sum_{j=1}^{n_\nu} \mathrm{Ev}_i^{\nu}(\phi_\nu^j); \mathbf{\Theta}\right) \times \prod_{j=1}^{n_\nu} \mathcal{L}(\phi_\nu^j)$$

Poisson distribution

Likelihood functions for the neutrino fluxes

Nuisance parameters

Comparison between neutrino-only and neutrino+DM hypotheses

$$\lambda(0) = \frac{\mathcal{L}(\sigma_{\chi n} = 0, \hat{\hat{\phi}}_\nu, \mathbf{\Theta})}{\mathcal{L}(\hat{\sigma}_{\chi n}, \hat{\phi}_\nu, \mathbf{\Theta})}$$

Ensemble of 2000 experiments

Significance

$$Z = \sqrt{-2 \ln \lambda(0)}$$

Significance achieved 90% of the times

$$\int_0^{Z_{90}} p(Z|H_0)\, dZ = 0.90$$

$$\boxed{Z_{90} = 3}$$

Significance achieved 90% of the times for a 3σ discovery

Neutrino Discovery Limit - 3

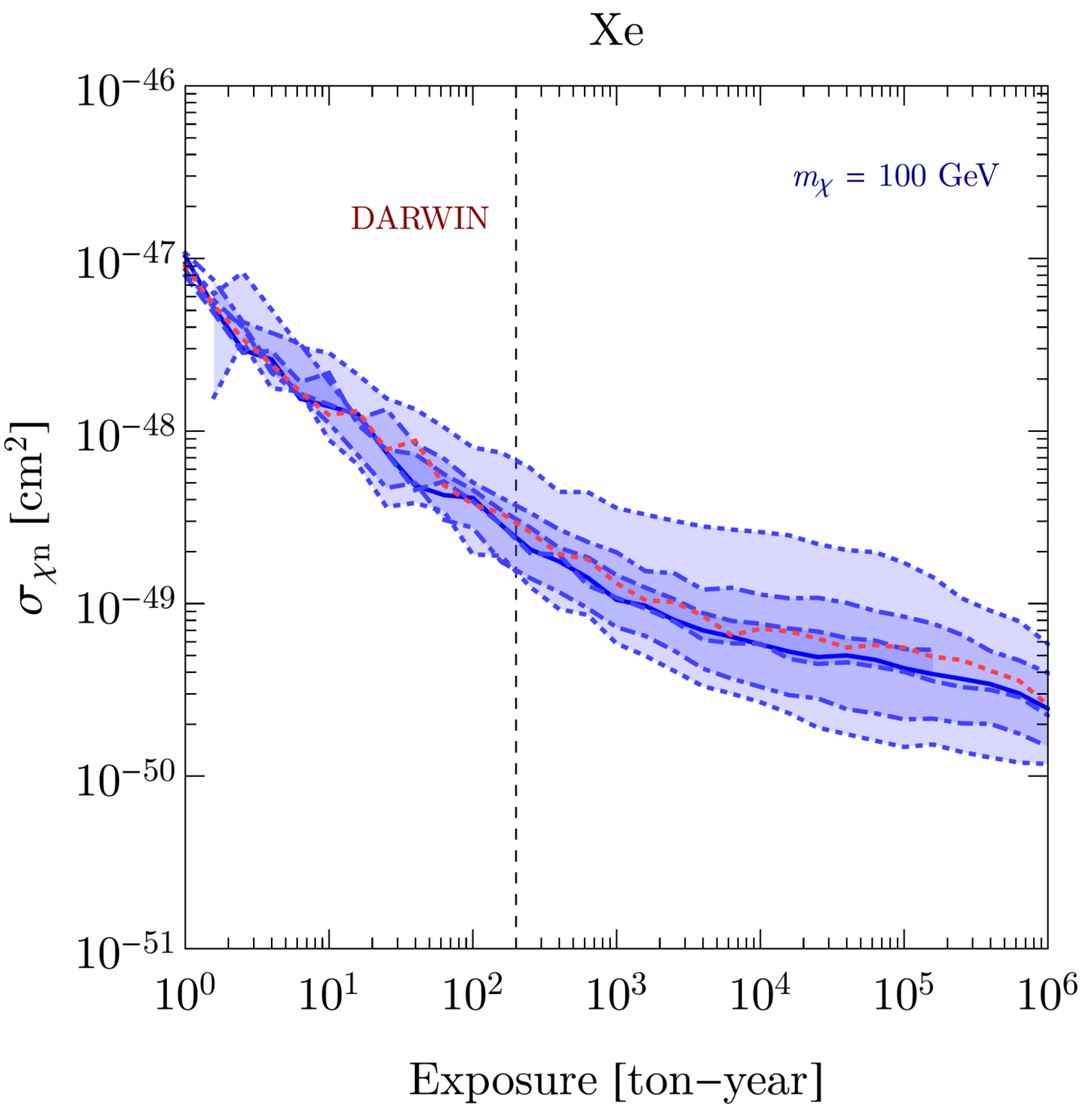
How to describe consistently when do neutrinos become relevant?

Profile Likelihood

$$\mathcal{L}(\sigma_{\chi n}, m_\chi, \phi_\nu)$$

Neutrino Discovery Limit

Due to our lack of knowledge on neutrino fluxes



Uncertainities on the neutrino fluxes.

Maximum Likelihood

$$\mathcal{L}(\hat{\theta}|N) = P(\hat{\theta}|N) = \frac{(b+\mu(\hat{\theta}))^N e^{-(b+\boxed{\mu(\hat{\theta})})}}{N!}$$

Number of DM+ν events

Ranges considered

$$0 \leq |g_V^{\nu}| \leq 5, \quad 0 \leq |g_A^{\nu}| \leq 5, \quad 0 \leq |g_V^{\chi}| \leq 1$$

LUX

- Target: Xenon
- We considered efficiency of LUX-2016
- Exposure: 3.35*10^4 kg-day
- N=2, b=1.9, per ton-year

LZ

- Target: Xenon
- NR efficiency of 50%
- Exposure: 15 ton-year
- N=1, b=0.64, per ton-year

DARWIN

- Target: Xenon
- NR efficiency of 30%
- Exposure: 200 ton-year
- N=1, b=0.64, per ton-year

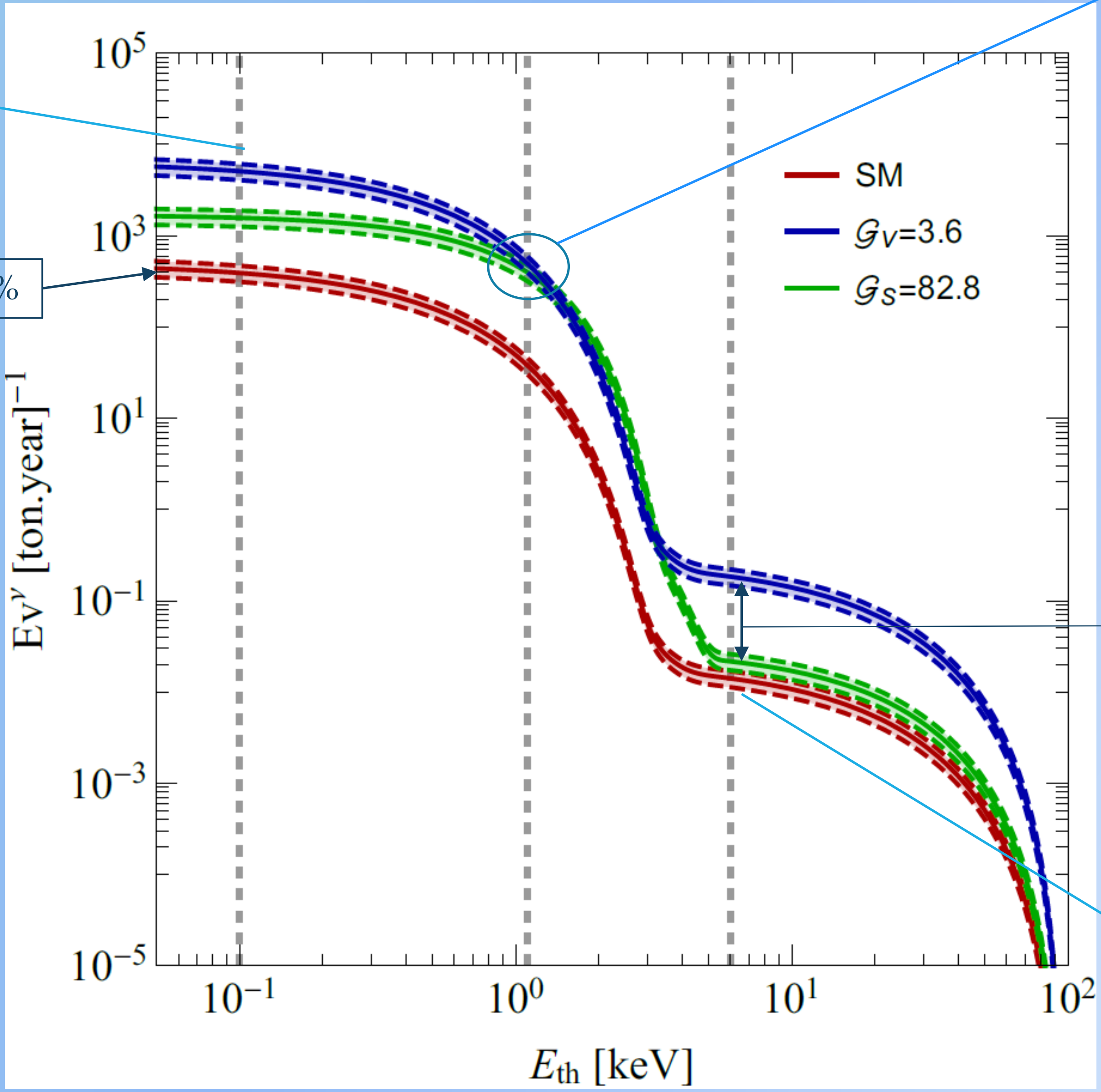
Sensitivity to DM-nucleon scattering - 4

Eth = 0.1 keV

Variation of the efficiency of 10%

Different structures

Non-trivial behaviour



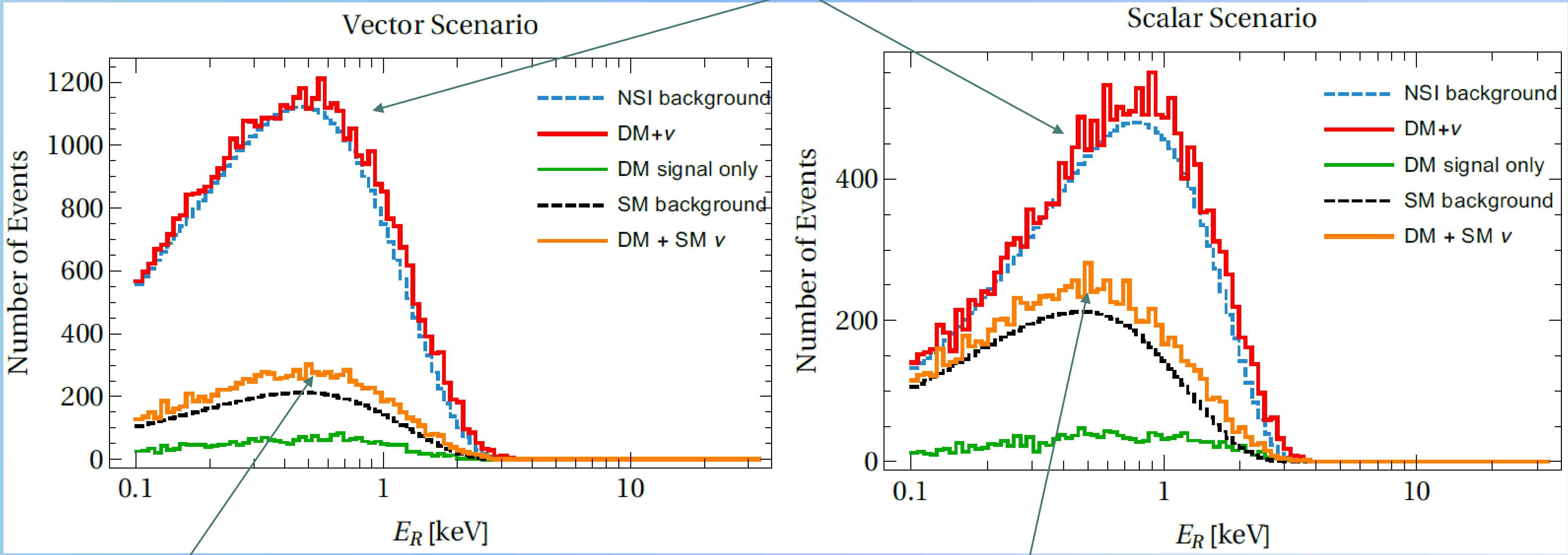
LUX: Eth = 1.1 keV

~ 4 times

LZ, DARWIN: Eth = 6 keV

Sensitivity to DM-nucleon scattering - 5

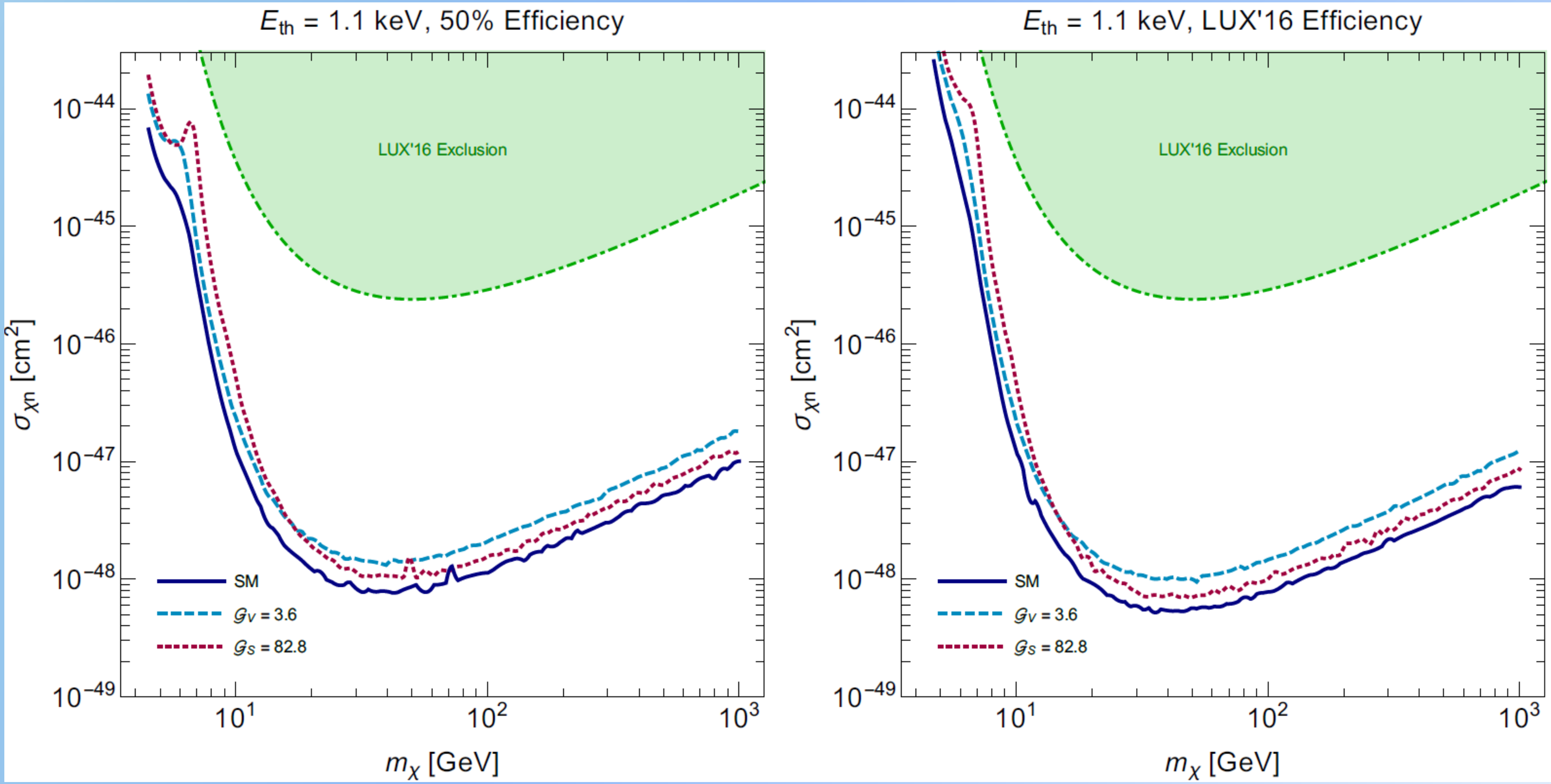
DM interpreted as a variation of the ν flux



DM distinguishable from νs

DM distinguishable from νs

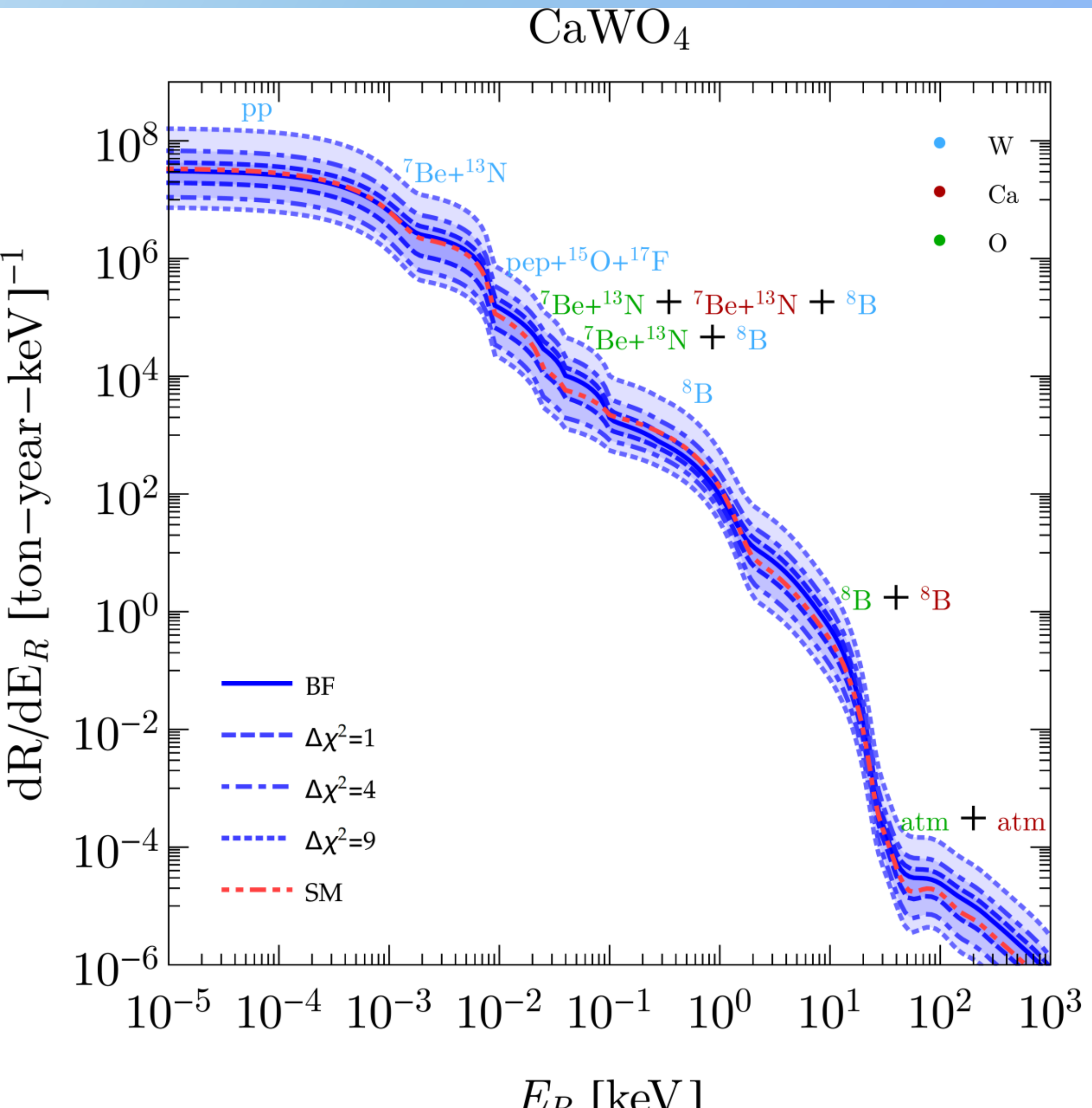
Neutrino Floor – Eth LUX

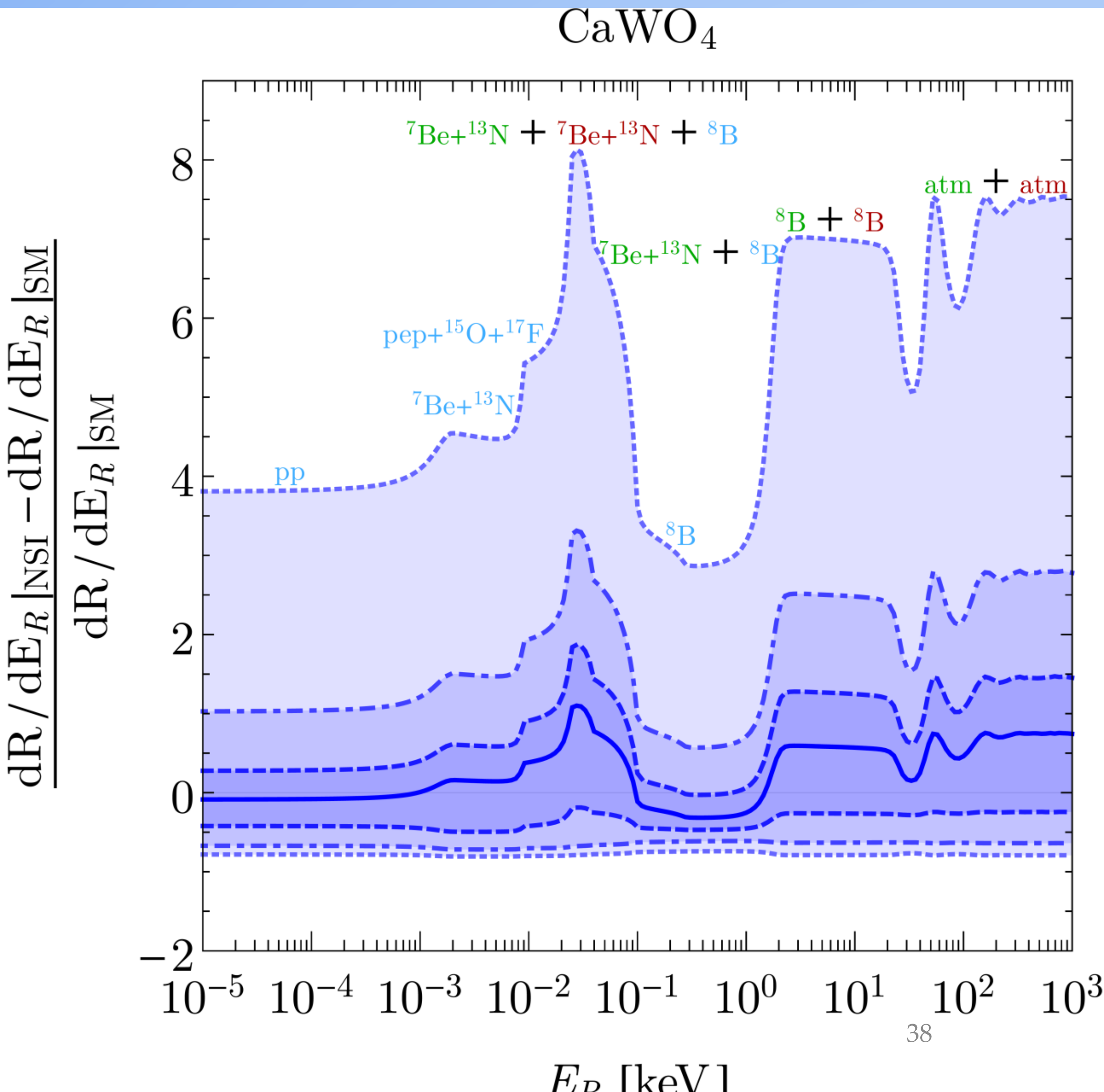


NSI - Flavour dependent coefficient

$$[\mathcal{Q}^{\alpha}_{\mathrm{NSI}}]^2 = 4\Bigg\{ \left[N\left(-\frac{1}{2} + \epsilon^{u,V}_{\alpha\alpha} + 2\epsilon^{d,V}_{\alpha\alpha}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon^{u,V}_{\alpha\alpha} + \epsilon^{d,V}_{\alpha\alpha}\right)\right]^2 + \sum_{\beta\neq\alpha}\left[N\left(\epsilon^{u,V}_{\alpha\beta} + 2\epsilon^{d,V}_{\alpha\beta}\right) + Z\left(2\epsilon^{u,V}_{\alpha\beta} + \epsilon^{d,V}_{\alpha\beta}\right)\right]^2 \Bigg\}$$

$CaWO_4$


CaWO4
pp
7Be+13N
pep+15O+17F
7Be+13N + 7Be+13N + 8B
7Be+13N + 8B
8B
8B + 8B
atm + atm
W
Ca
O
BF
Δχ2=1
Δχ2=4
Δχ2=9
SM
dR/dER [ton−year−keV]−1
ER [keV]


CaWO4
7Be+13N + 7Be+13N + 8B
atm + atm
8B + 8B
7Be+13N + 8B
pep+15O+17F
7Be+13N
pp
8B
(dR/dER|NSI − dR/dER|SM) / dR/dER|SM
ER [keV]