School and Workshop on Dark Matter and Neutrino Detection

Dark Matter — Direct Detection

Lecture 3

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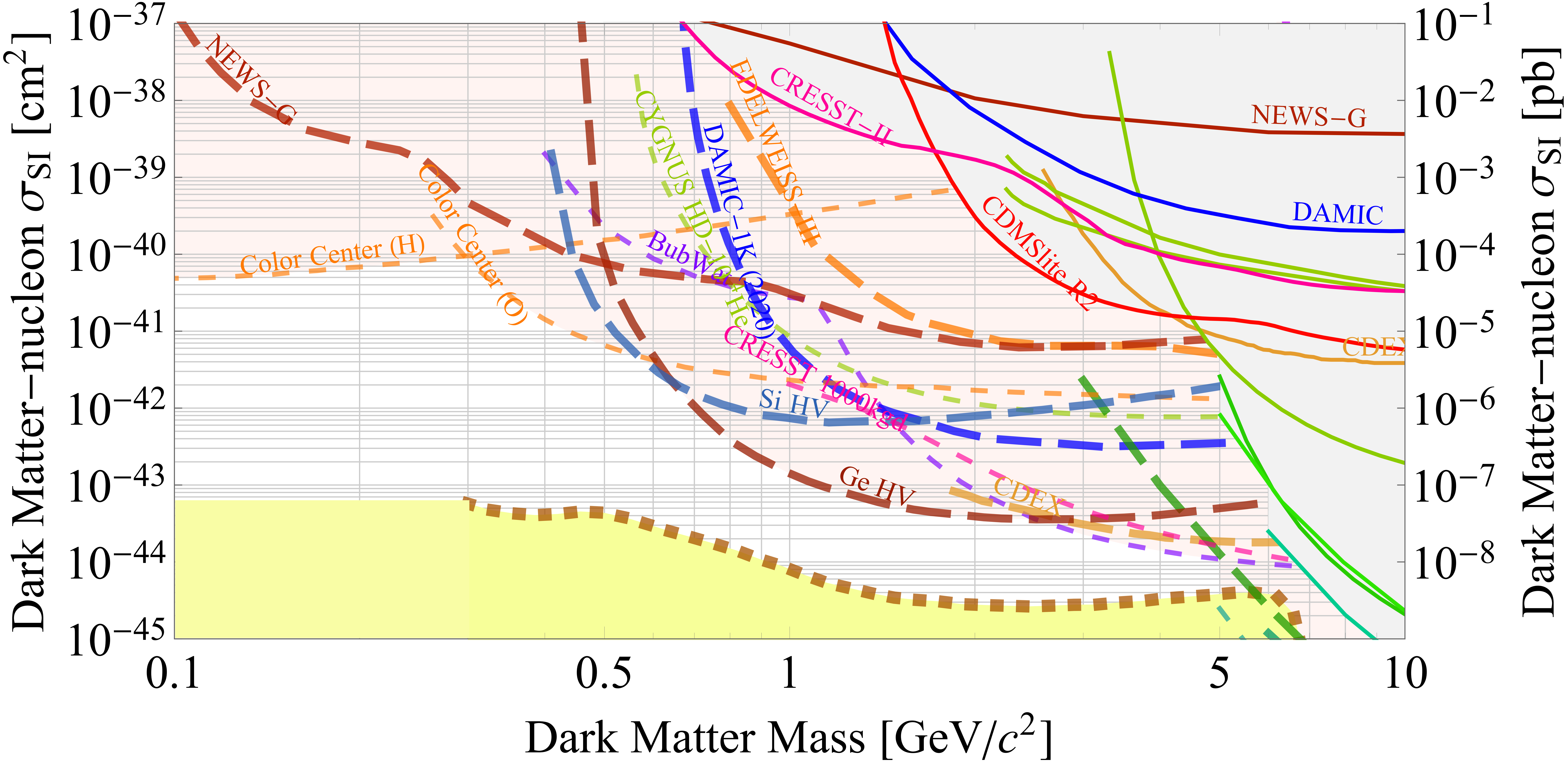
COLEGIO DE FISICA FUNDAMENTAL E
INTERDISCIPLINARIA DE LAS AMERICAS

Outline

- Lecture 1:
  - The dark matter problem
  - WIMP and WIMP-like DM detection
- Lecture 2:
  - WIMP detection technologies
  - Current and future limits
- Lecture 3:
  - More DM detection technologies
  - To the Neutrino Floor, and beyond!
- Lecture 4:
  - The SuperCDMS Experiment
  - meV - 1GeV direct detection
- Lecture 5:
  - Indirect sterile neutrino detection

Last Time: Low Mass Region



PICO Bubble Chamber: Superheated Liquids!

See next talk by Andrew Sonnenschein

-2012

COUPP

PICASSO

2013-17

PICO-2L

PICO-60

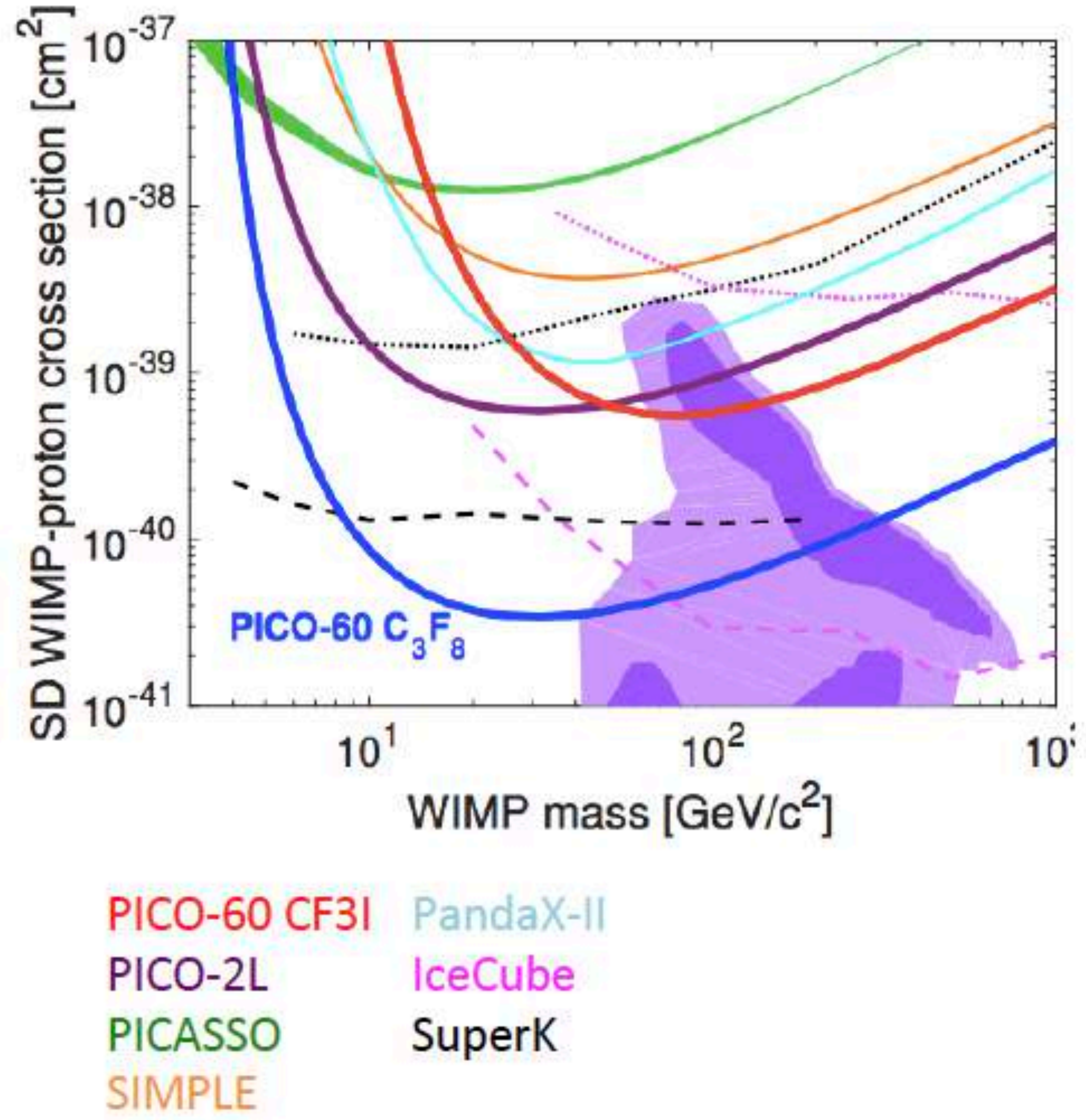
2018-

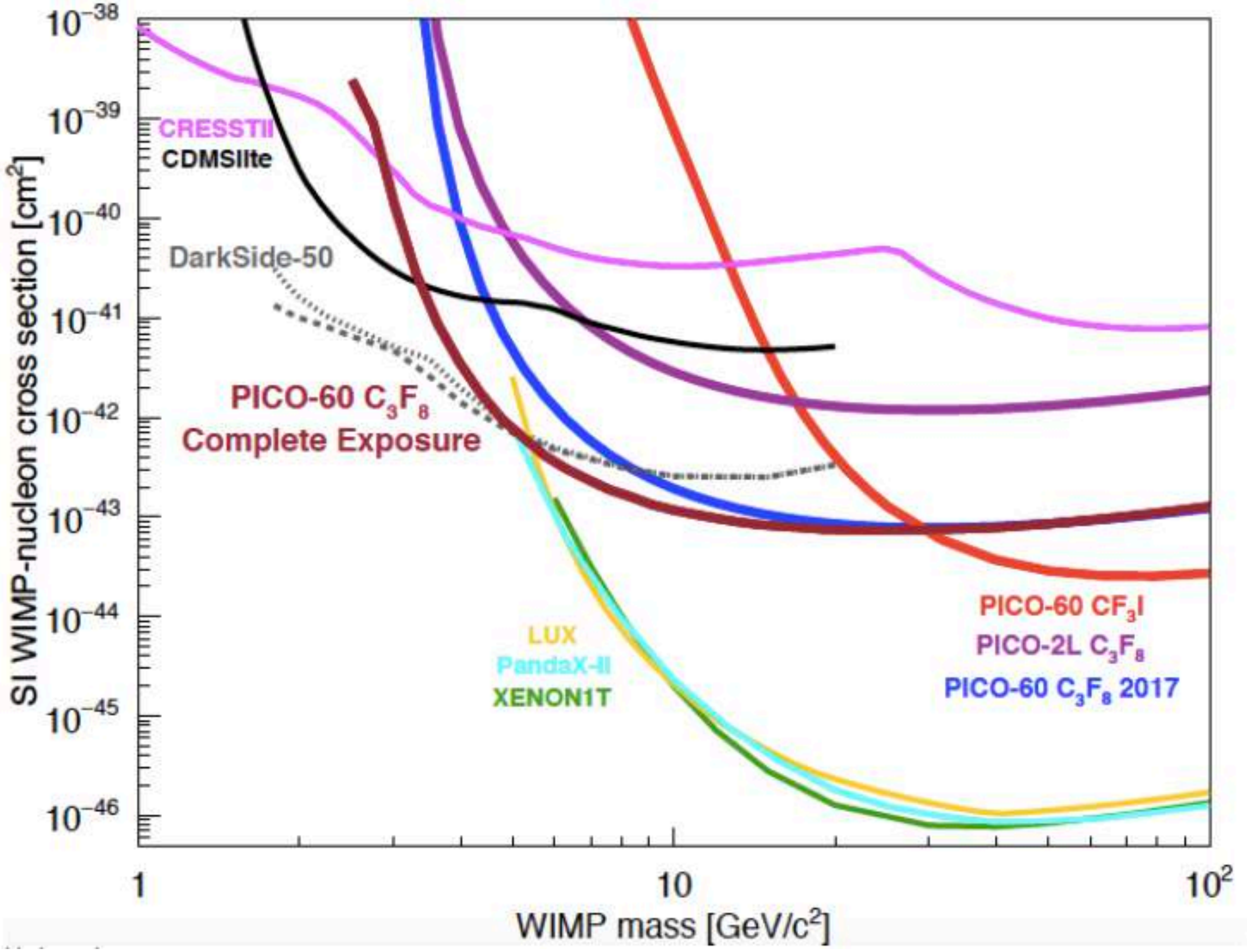
PICO-40L

PICO-500

PICO Bubble Chamber: SD and SI limits!

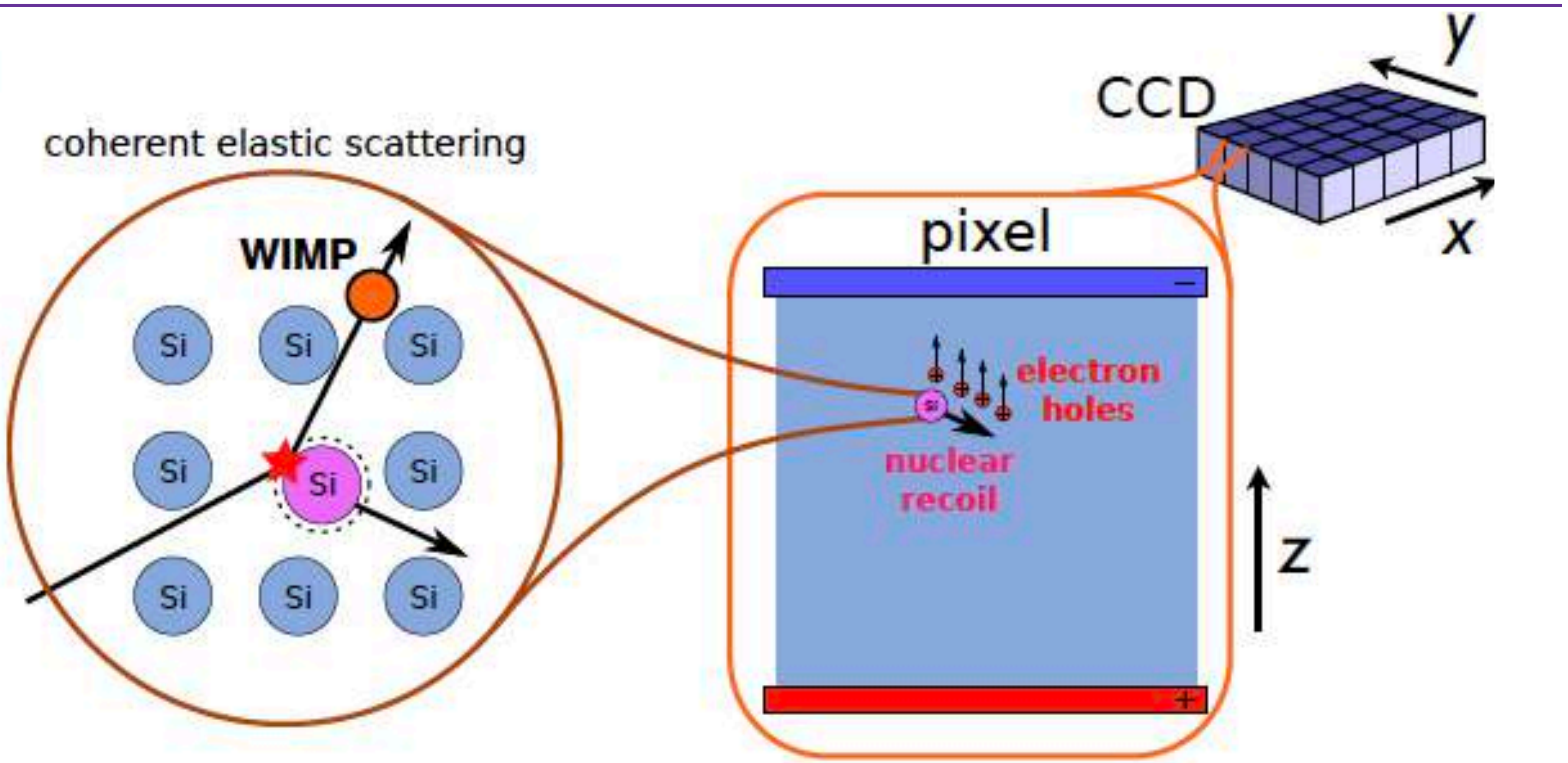
See next talk by Andrew Sonnenschein



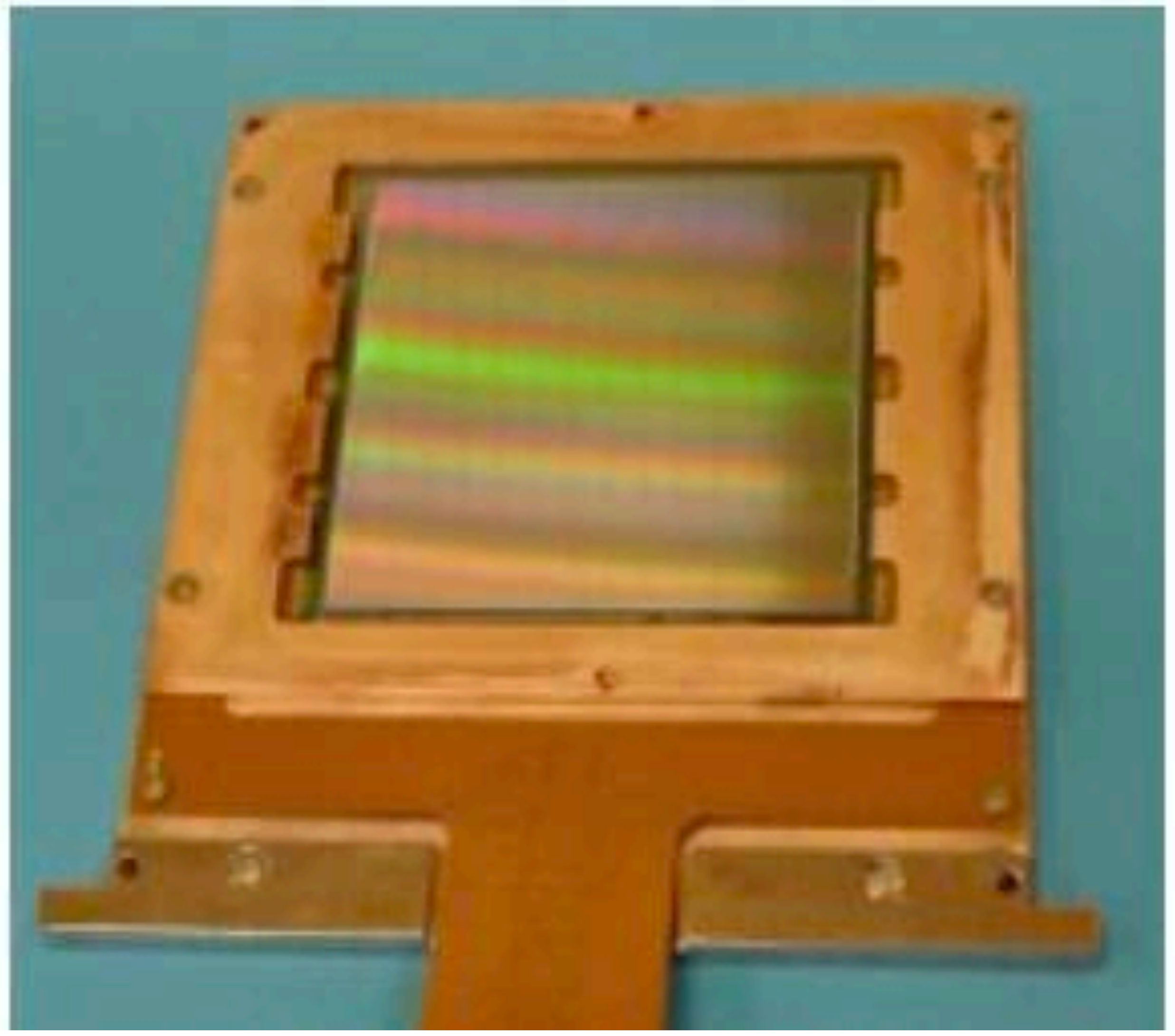


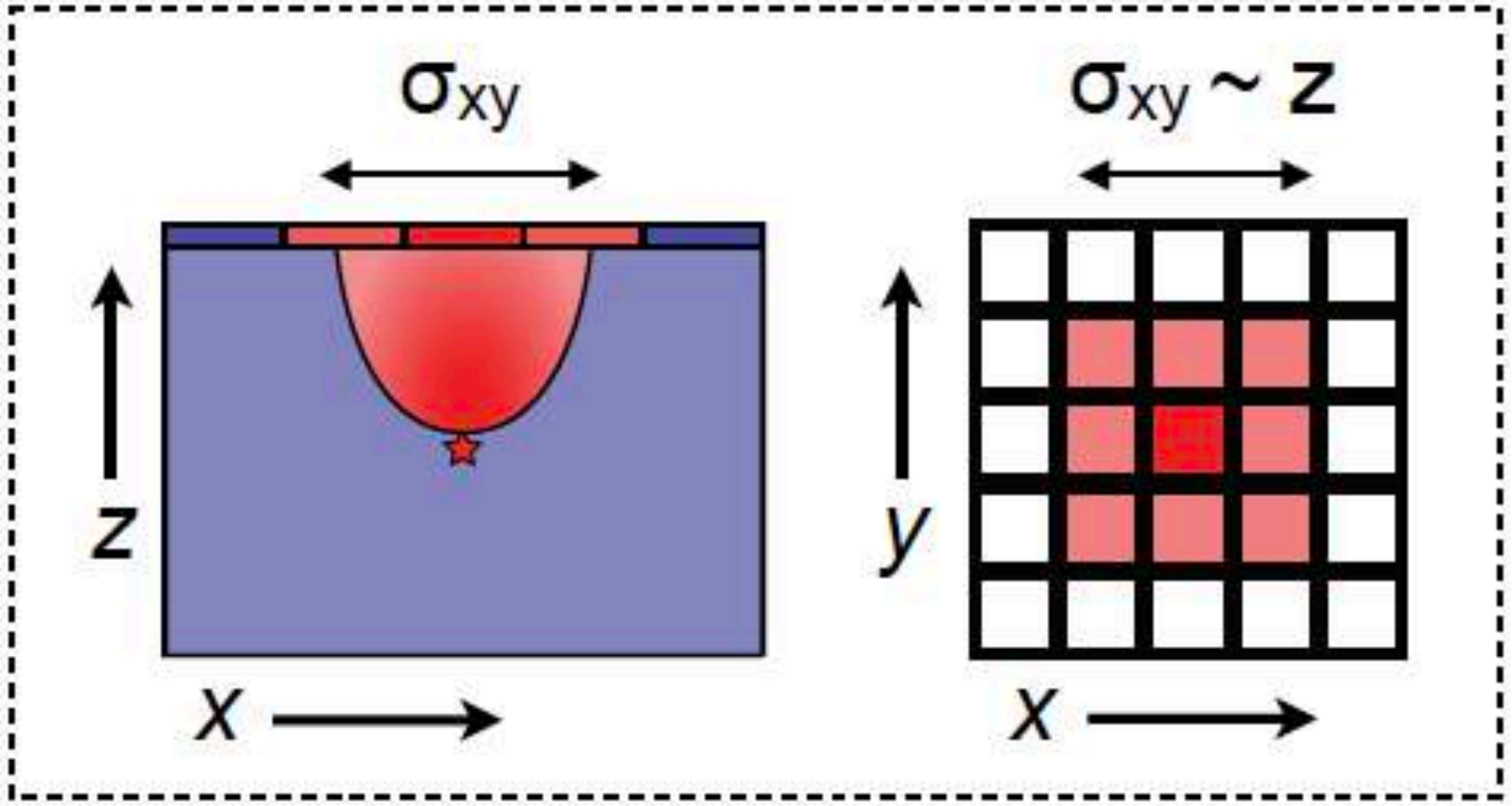
CCD-based DM Search

- Silicon CCD technology highly advanced thanks to utility in astronomical and satellite-based imaging
- WIMPs scatter coherently off of Si nuclei, which recoil and yield detectable ionization signals
- CCDs are "exposed", i.e. collect charge, for $\mathcal{O}$(1 day) and images are then read out for analysis



16 Mpix CCD
LBNL designed
6 cm x 6 cm
15-μm pixel pitch
675-μm thick

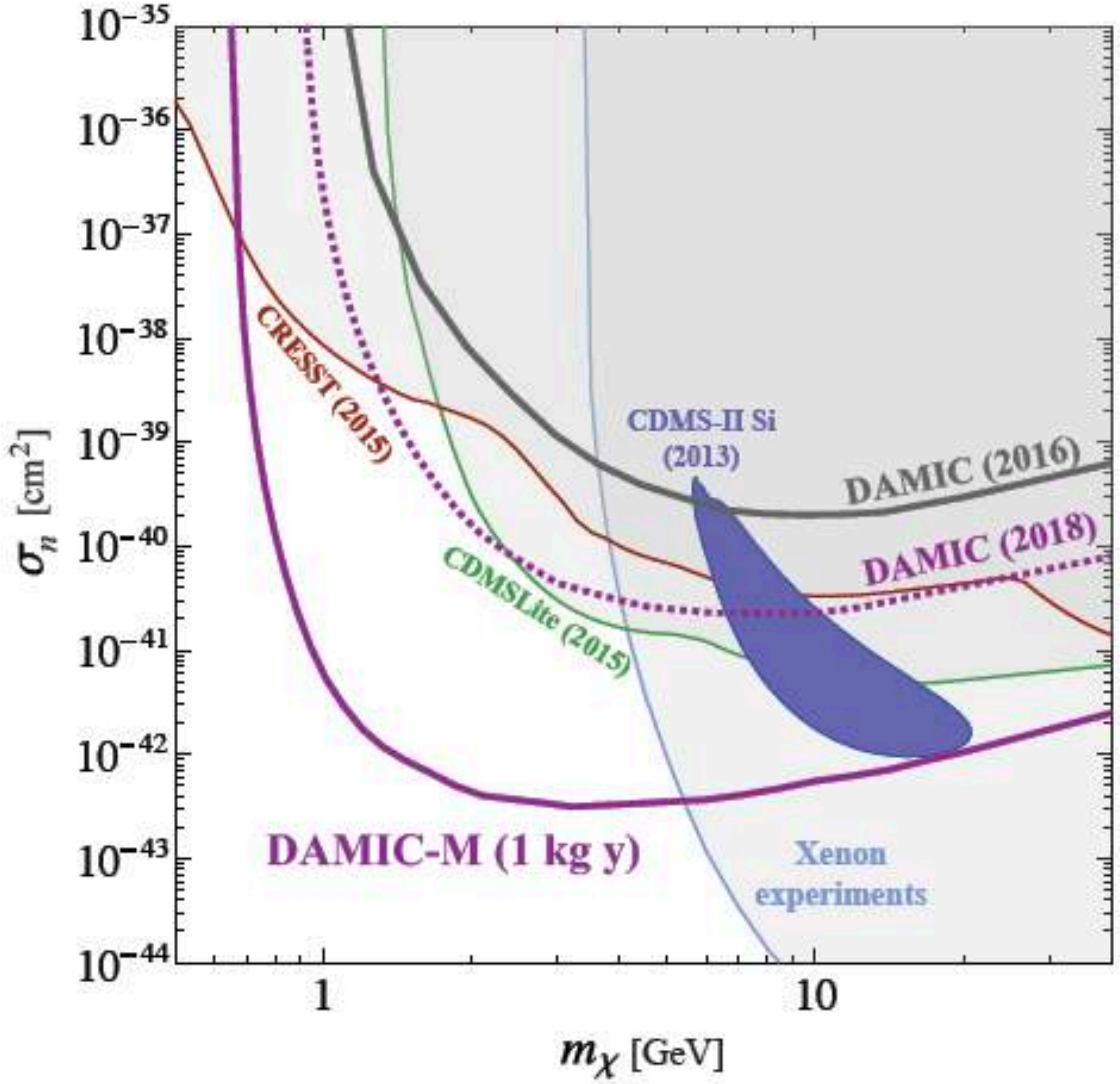




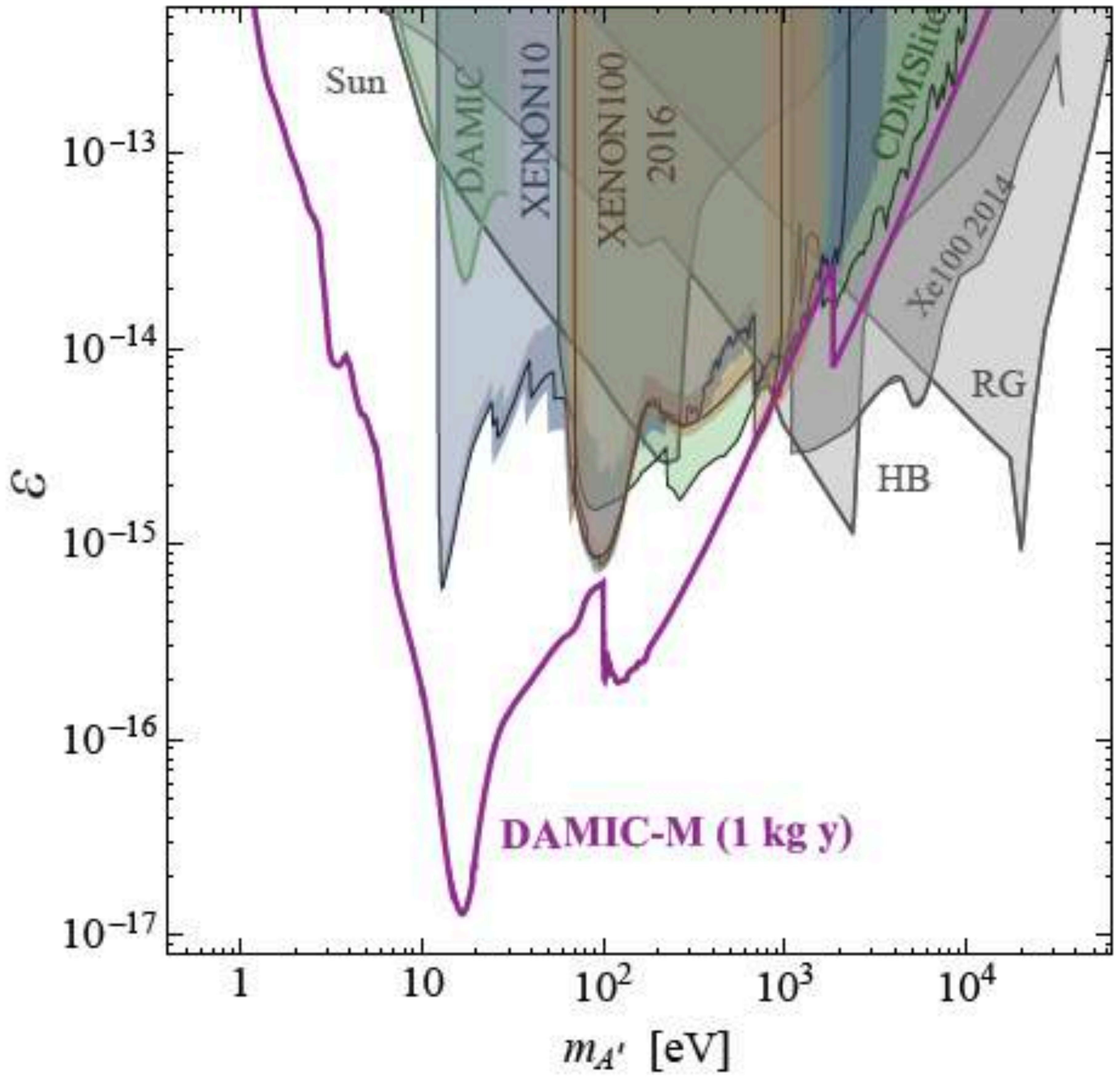
CCD-based DM Search

See talks by Juan Estrada

WIMP nuclear-recoil search

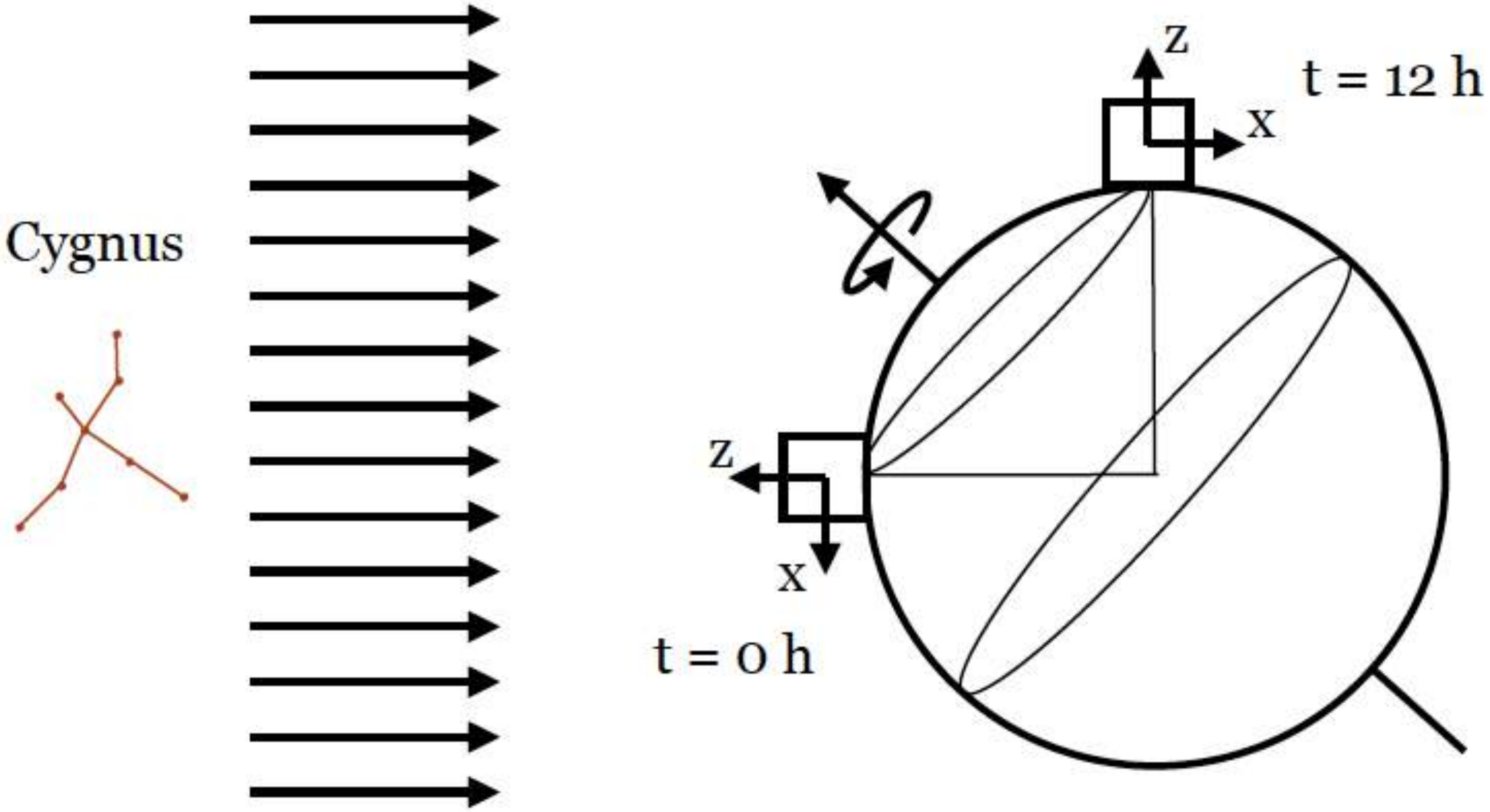


Hidden-photon search



Directional Detection

- Measure WIMP-induced recoil directions with efficient electron-recoil discrimination even at low energy (<20 keV).
- Discriminate and measure Solar neutrino coherent scattering with directionality (^{8}B)
- Probe for WIMPs below neutrino floor.



Directional Detection

- Measure WIMP-induced recoil directions with efficient electron-recoil discrimination even at low energy (<20 keV).
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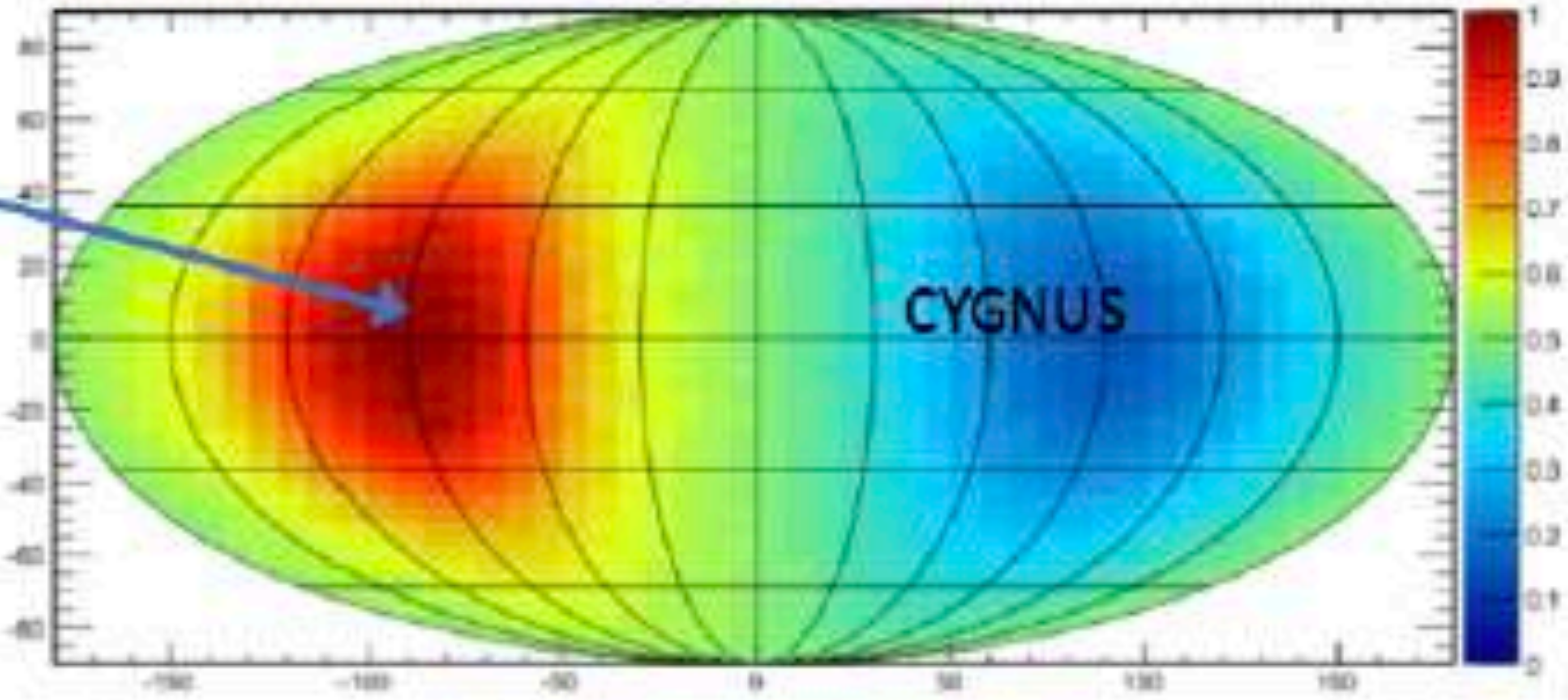
- Probe for WIMPs below neutrino floor.

A review of the discovery reach of directional Dark Matter detection
Physics Reports 627 (2016)

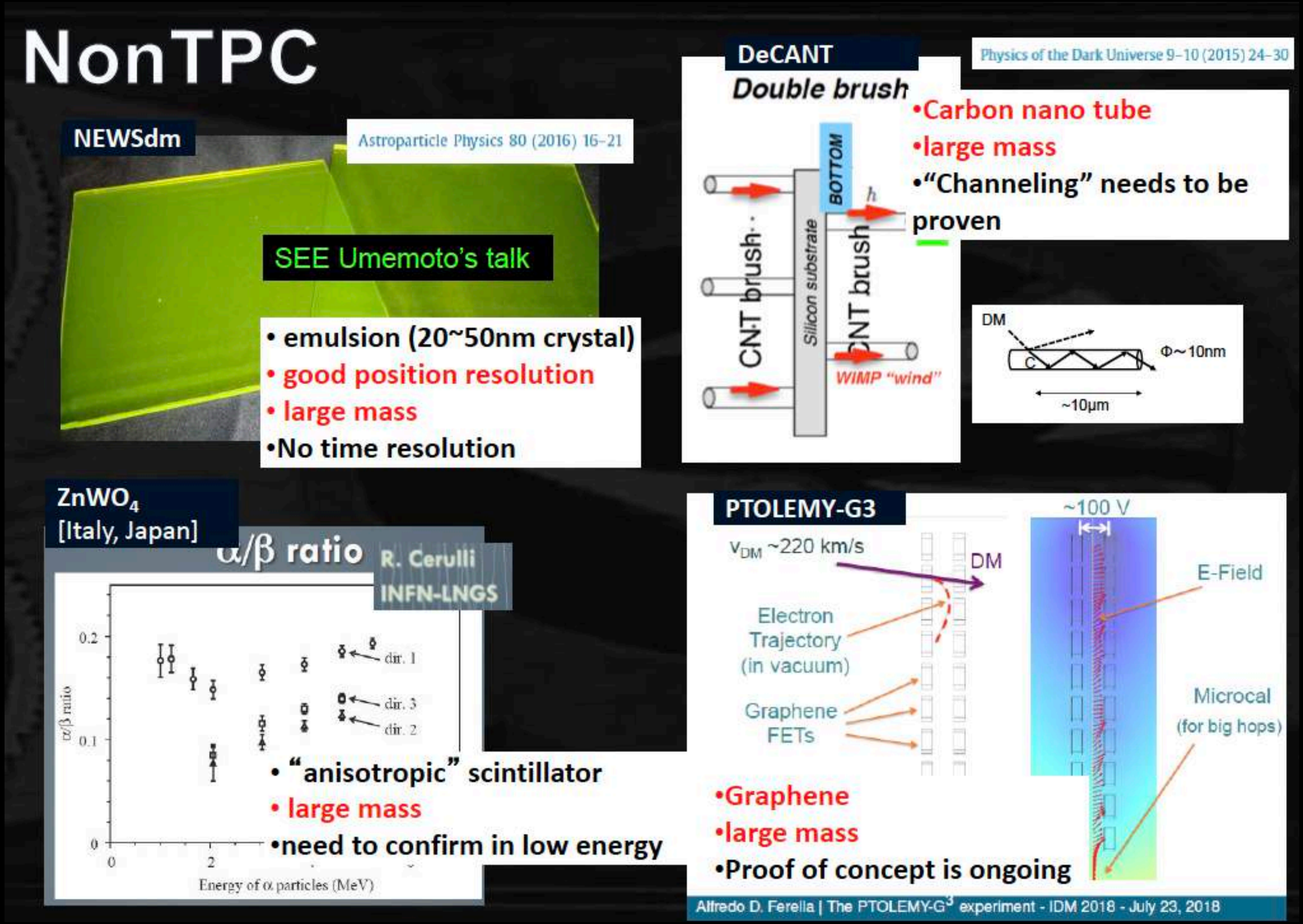


Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV

Galactic dipole: - strongest predicted direct detection signature
- unambiguous proof of cosmological origin

Directional Detection: Non-TPC

From Kentaro Miuchi's talk at IDM



NonTPC

NEWSdm

Astroparticle Physics 80 (2016) 16–21

SEE Umemoto's talk

- emulsion (20~50nm crystal)
- good position resolution
- large mass
- No time resolution

DeCANT

Double brush

Physics of the Dark Universe 9–10 (2015) 24–30

- Carbon nano tube
- large mass
- "Channeling" needs to be proven

$ZnWO_4$

[Italy, Japan]

α/β ratio R. Cerulli INFN-LNGS

- "anisotropic" scintillator
- large mass
- need to confirm in low energy

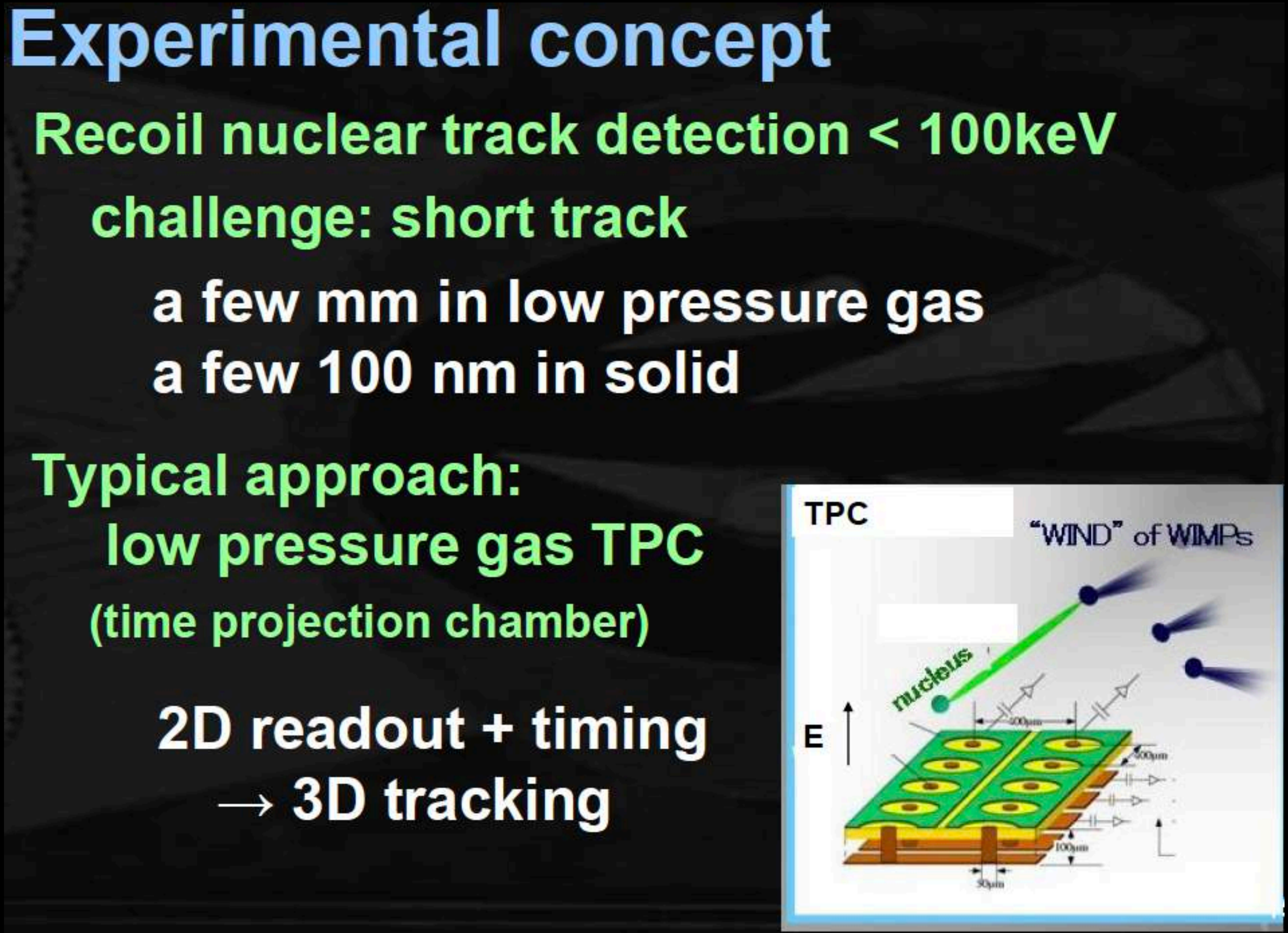
PTOLEMY-G3

- Graphene
- large mass
- Proof of concept is ongoing

Alfredo D. Ferella | The PTOLEMY-G^3 experiment - IDM 2018 - July 23, 2018

Directional Detection: TPC

From Kentaro Miuchi's talk at IDM



Experimental concept

Recoil nuclear track detection < 100keV

challenge: short track

a few mm in low pressure gas

a few 100 nm in solid

Typical approach:

low pressure gas TPC

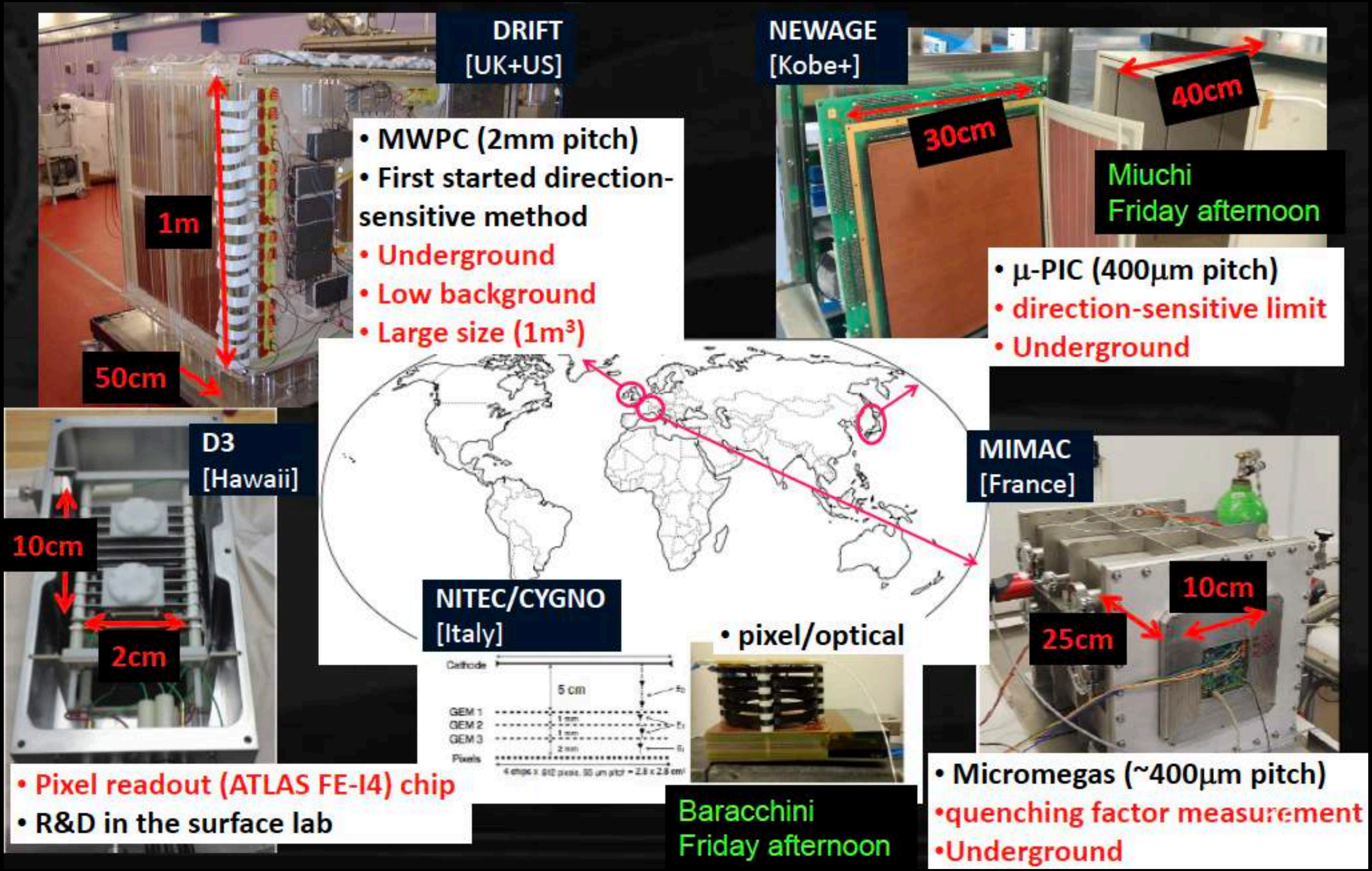
(time projection chamber)

2D readout + timing

→ 3D tracking

Directional Detection: TPC

From Kentaro Miuchi's talk at IDM



DRIFT
[UK+US]

- MWPC (2mm pitch)
- First started direction-sensitive method
- Underground
- Low background
- Large size (1m³)

NEWAGE
[Kobe+]

Miuchi
Friday afternoon

- μ-PIC (400μm pitch)
- direction-sensitive limit
- Underground

D3
[Hawaii]

- Pixel readout (ATLAS FE-I4) chip
- R&D in the surface lab

NITEC/CYGNO
[Italy]

- pixel/optical

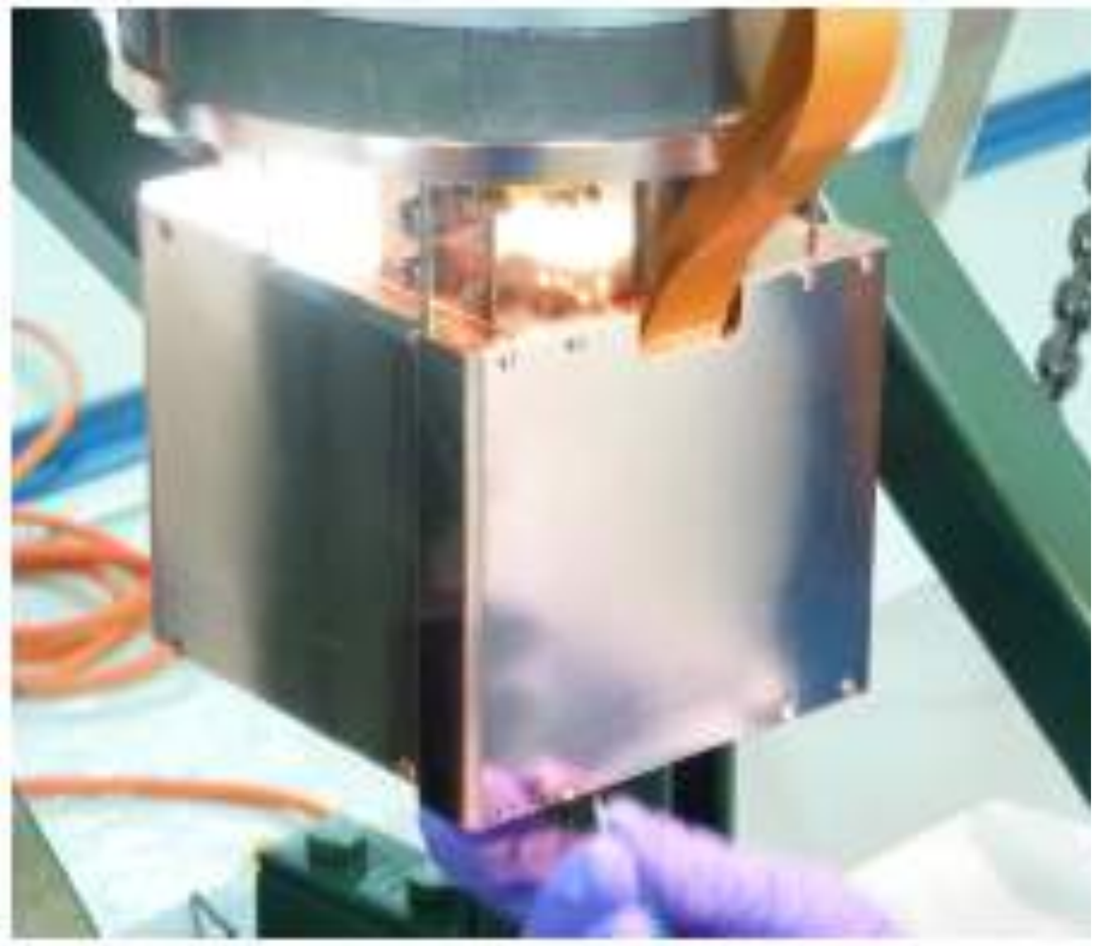
Baracchini
Friday afternoon

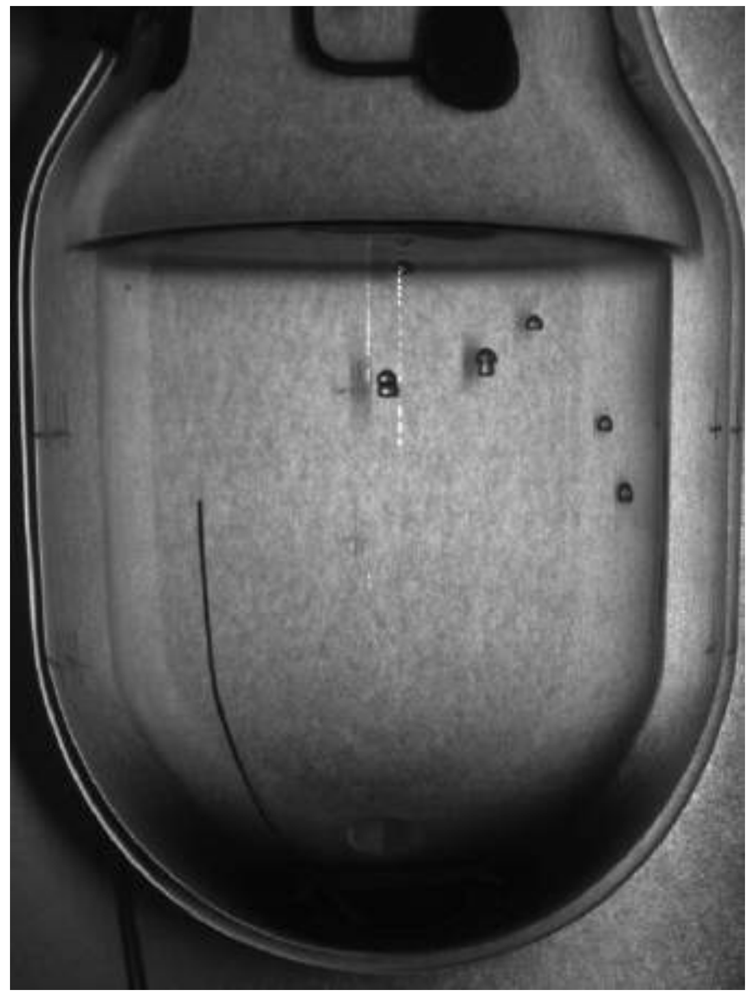
MIMAC
[France]

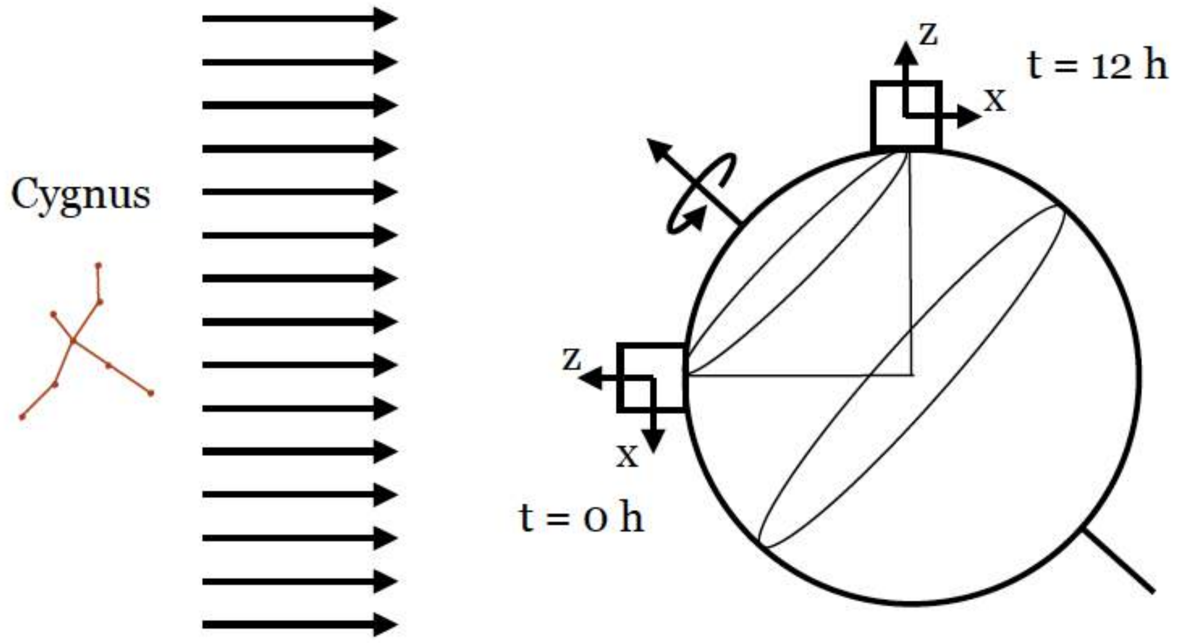
- Micromegas (~400μm pitch)
- quenching factor measurement
- Underground

Review of other Nuclear Detection Technologies

- Silicon CCDs: DAMIC & Sensei
- Bubble Chamber Experiments
  - PICO and COUPP
    - Excellent SD Sensitivity
    - (currently running at SNOLAB)
  - Xenon Bubble Chamber
- Directional Detection Experiments
  - DRIFT, DMTPC, NEWAGE, MIMAC
- New Ideas
  - DNA and/or organic detectors?
  - Molecular dissociation / inelastic collisions?

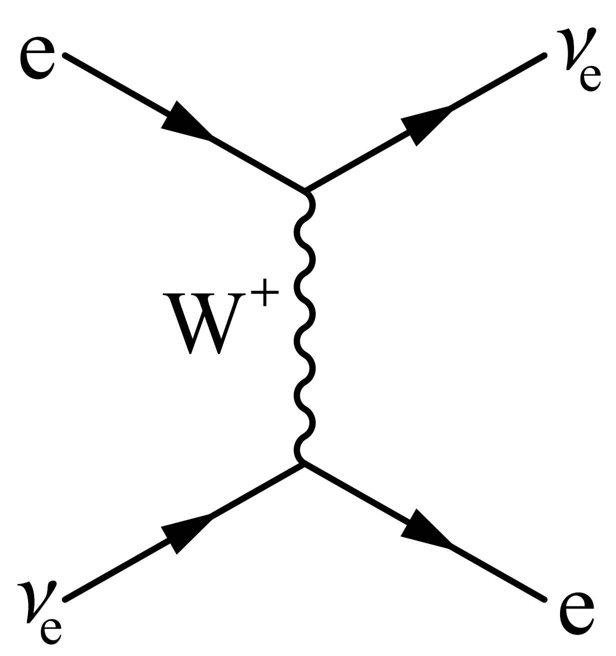
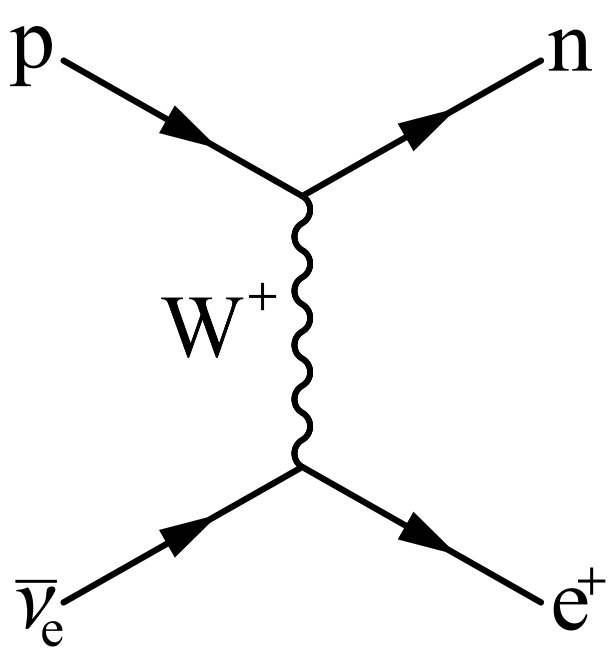
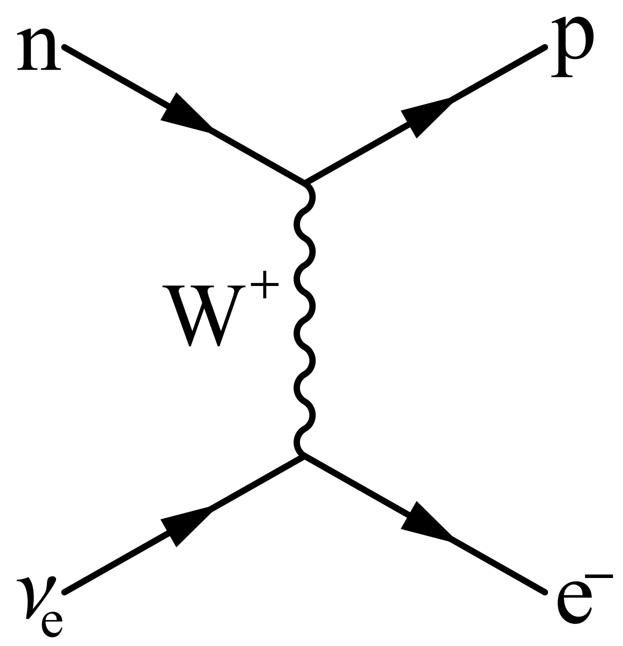
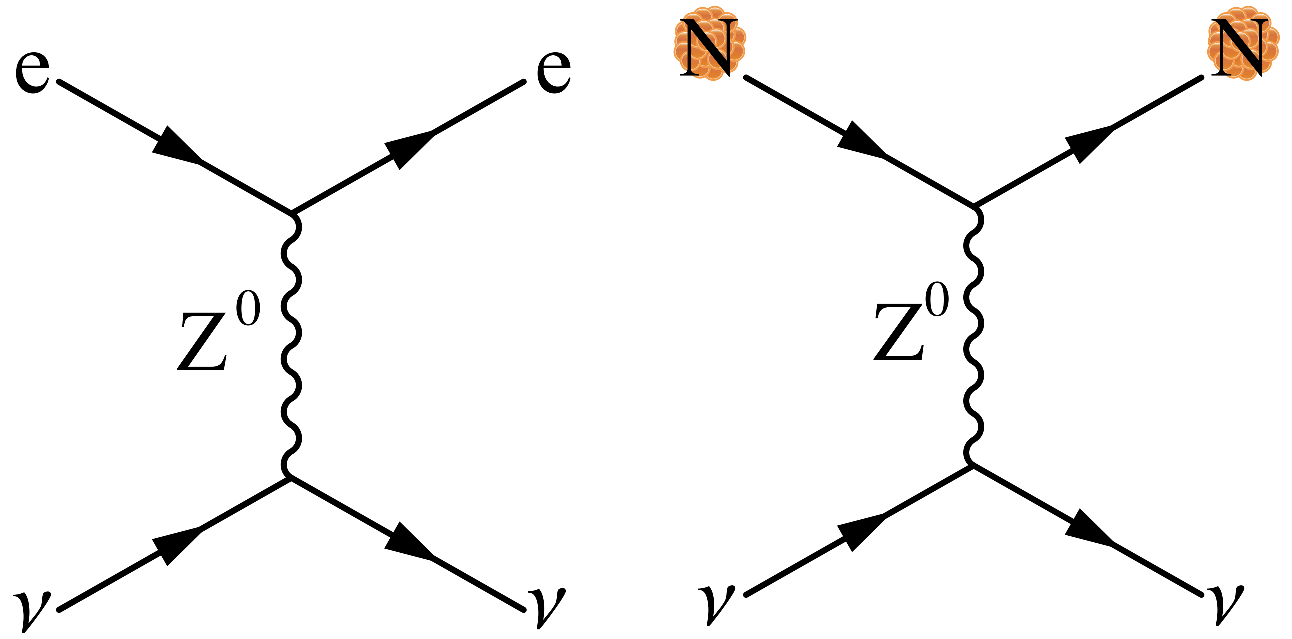




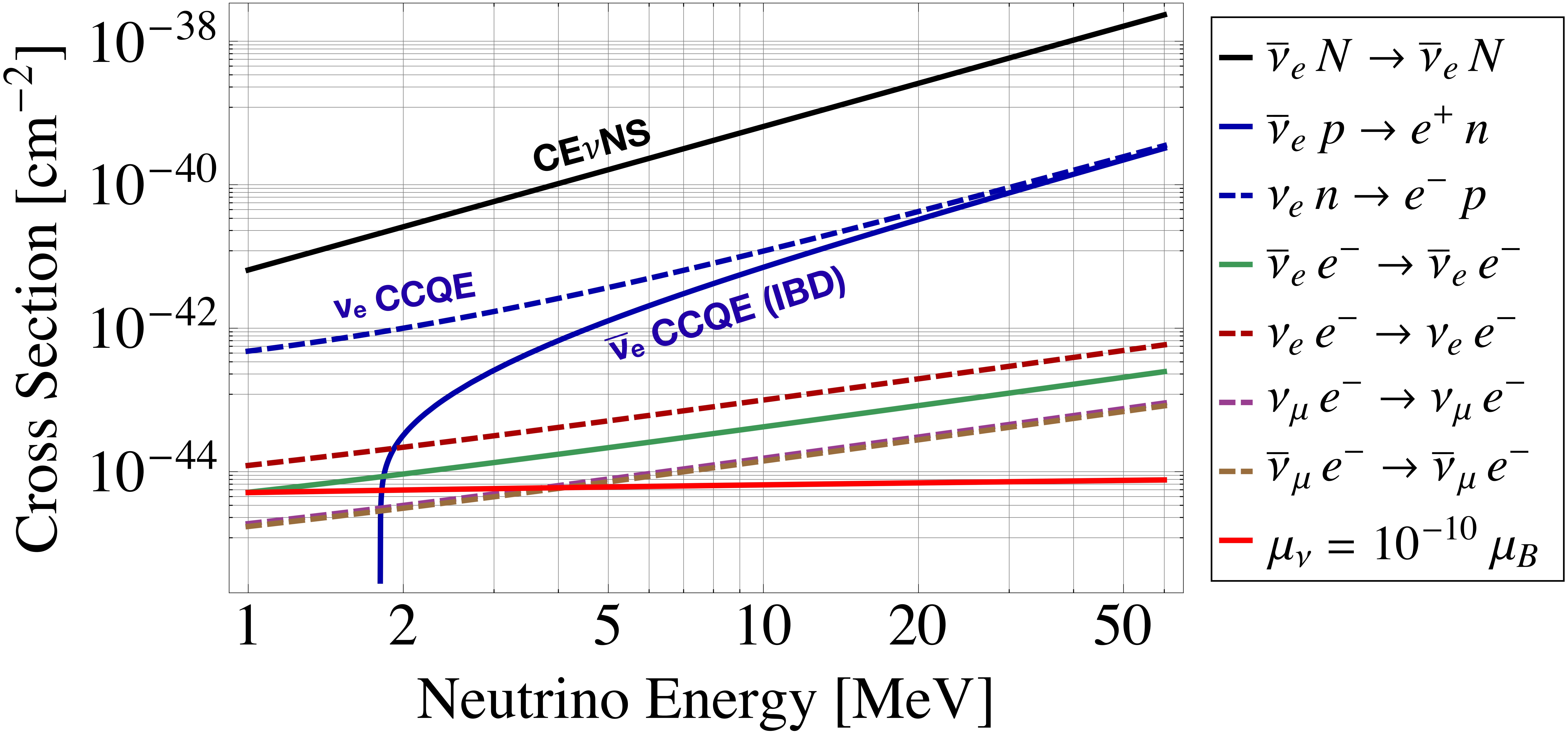


Neutrino Backgrounds

Low-energy ν Interactions

	Elastic	**Quasi-Elastic**
Charged Current	 **For ν_e and $\bar{\nu}_e$**	 **IBD**  **ν_μ, ν_τ not low-E**
Neutral Current	 **For all ν flavors**	

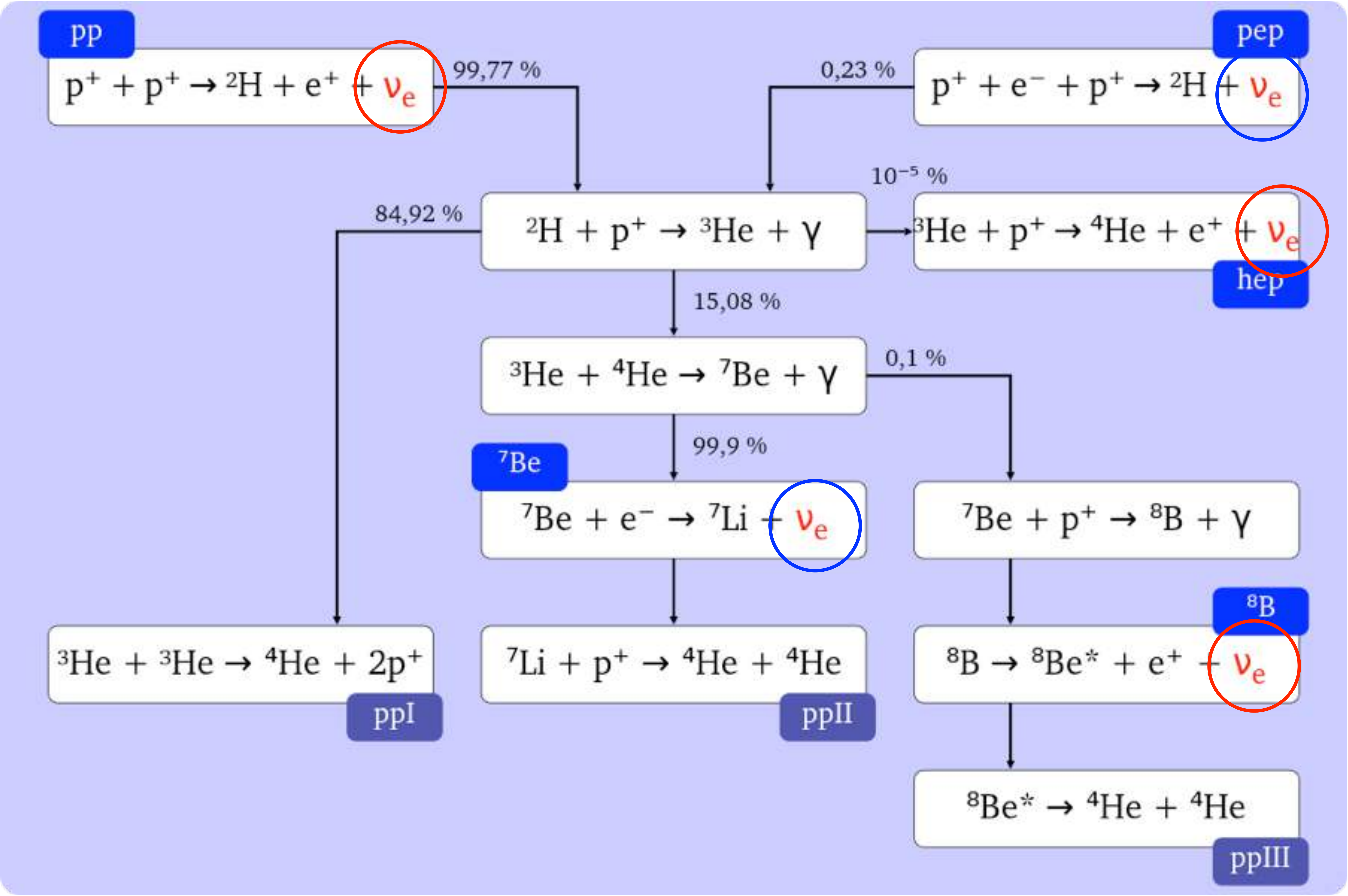
Low-Energy Neutrino Cross Sections



Neutrino Sources for Dark Matter Detectors

- Solar (ν_e)
- Diffuse Supernova Neutrino Background (all flavors)
- Atmospheric (all flavors)
- Geothermal ($\bar{\nu}_e$)
- Reactor ($\bar{\nu}_e$)
- Internal (ββ decays, $\bar{\nu}_e$)
- Supernova (burst, so not really a background, all flavors)

Solar Neutrino pp Chain



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

84,92 %

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

0,1 %

99,9 %

^{7}Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

^{8}B

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

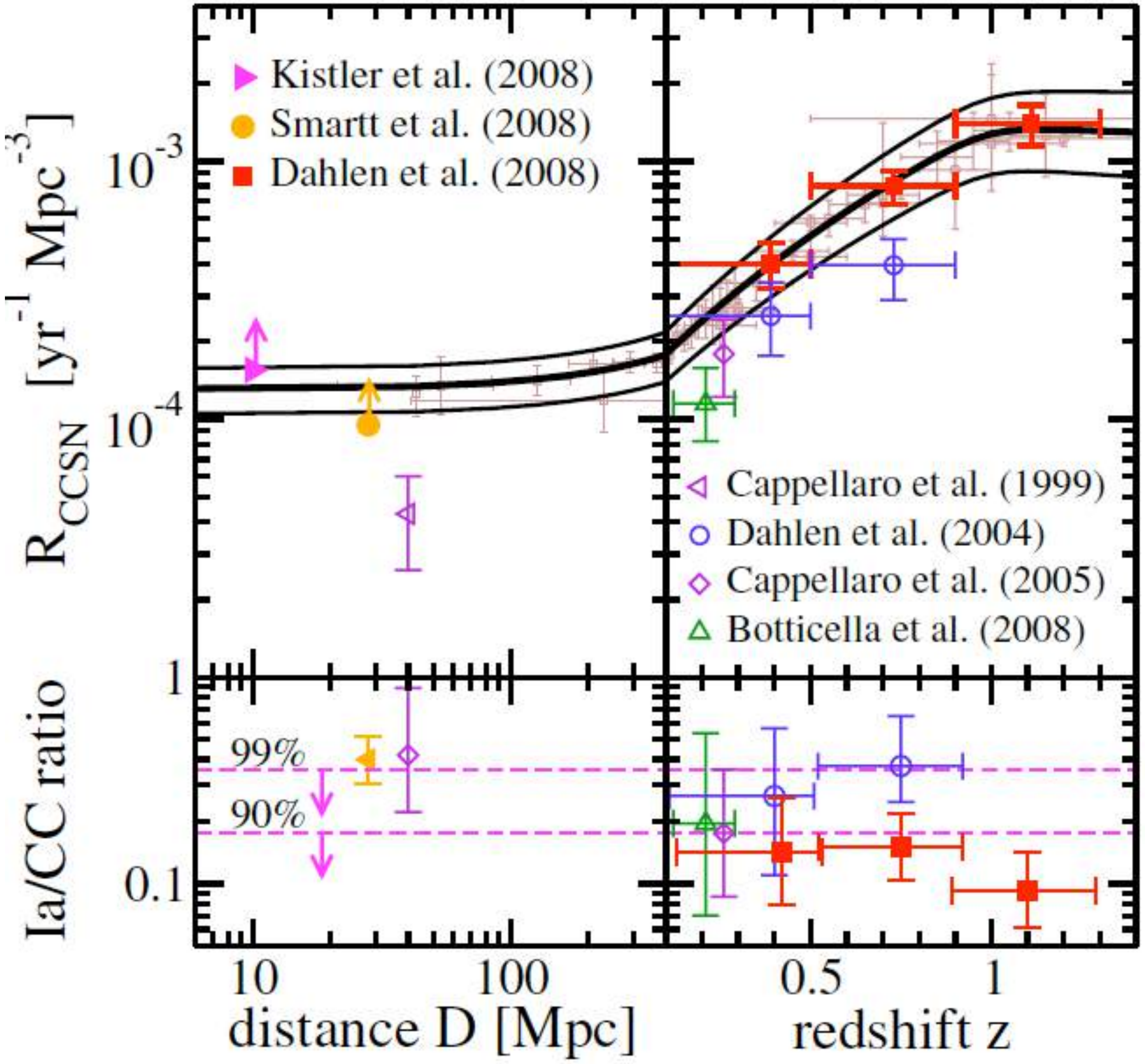
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

ppIII

Diffuse Supernova Background

- Mostly from Core Collapse Supernovae



Horiuchi 2009

Atmospheric Neutrinos

- From Cosmic Ray interaction in atmosphere.

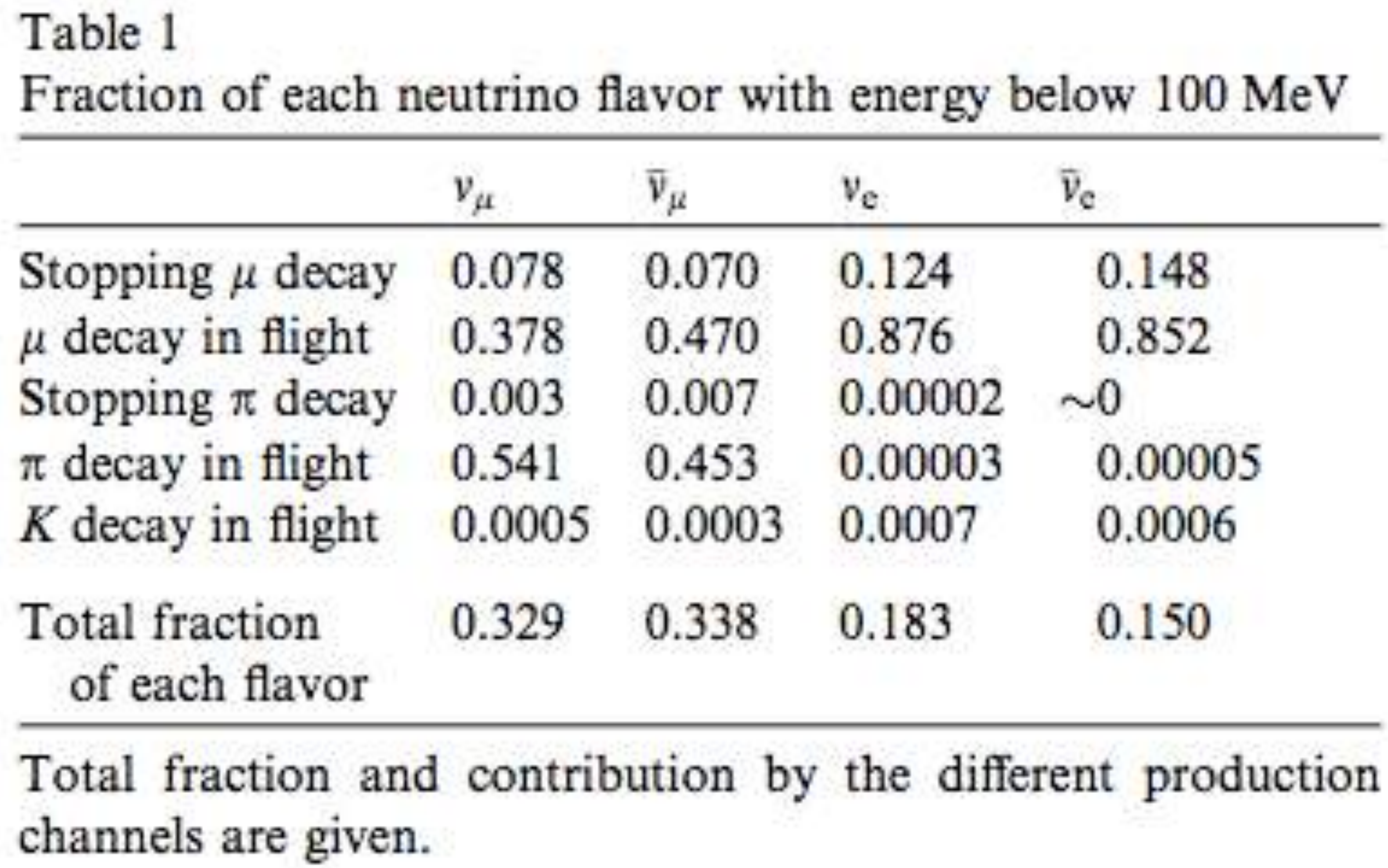


Table 1

Fraction of each neutrino flavor with energy below 100 MeV

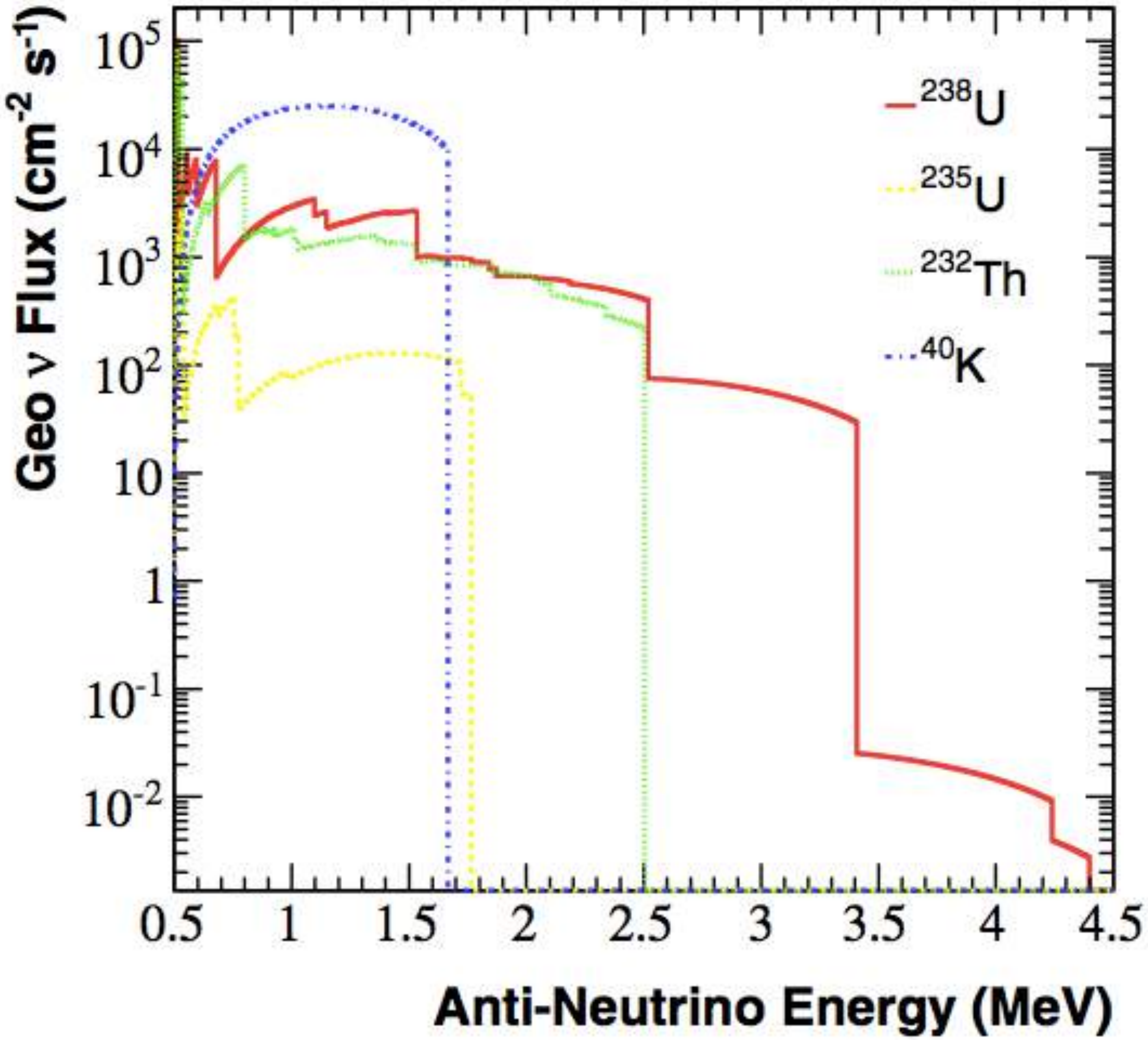
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Stopping μ decay	0.078	0.070	0.124	0.148
μ decay in flight	0.378	0.470	0.876	0.852
Stopping π decay	0.003	0.007	0.00002	~0
π decay in flight	0.541	0.453	0.00003	0.00005
K decay in flight	0.0005	0.0003	0.0007	0.0006
Total fraction of each flavor	0.329	0.338	0.183	0.150

Total fraction and contribution by the different production channels are given.

Battistoni 2009

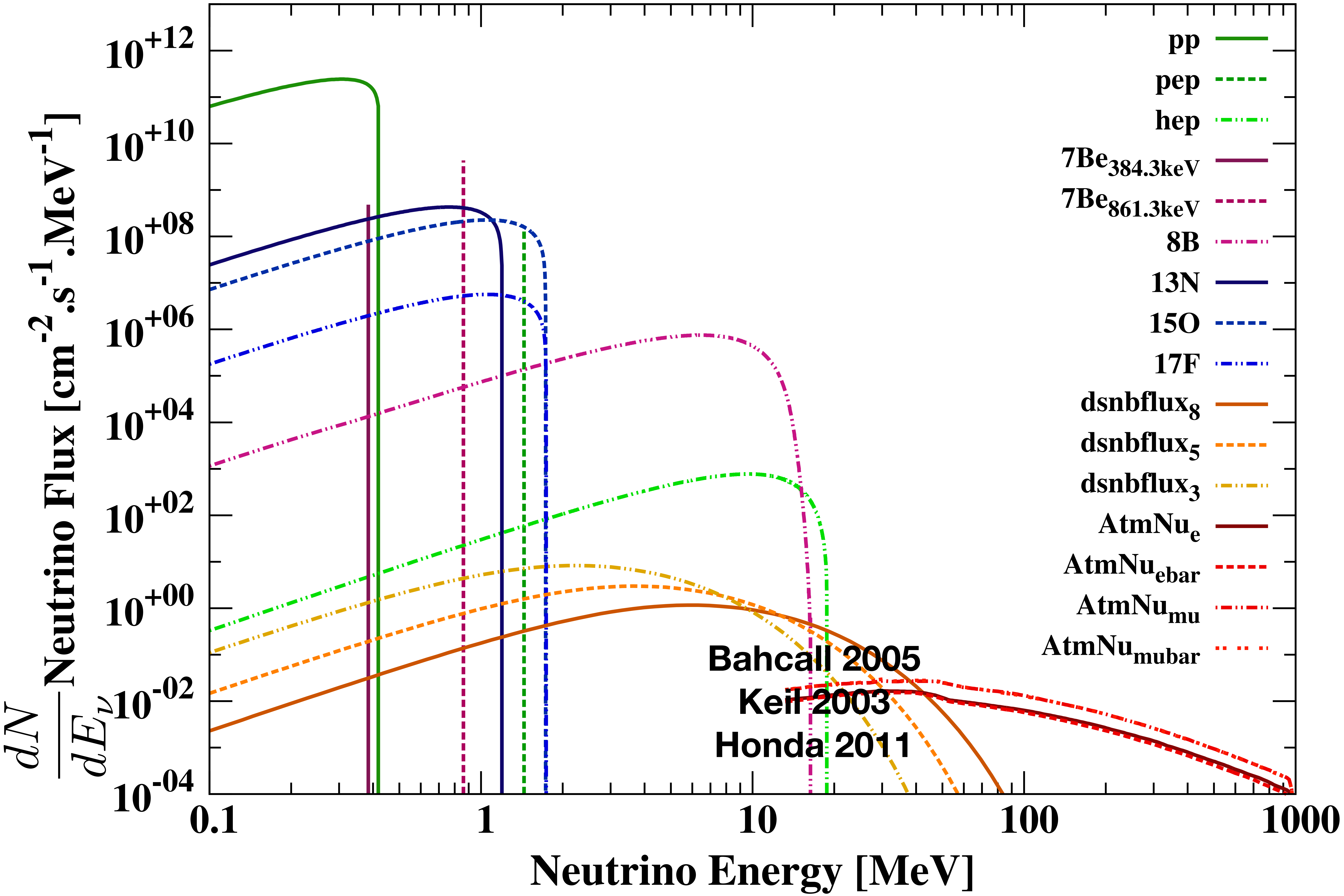
Geoneutrinos and Reactor Neutrinos

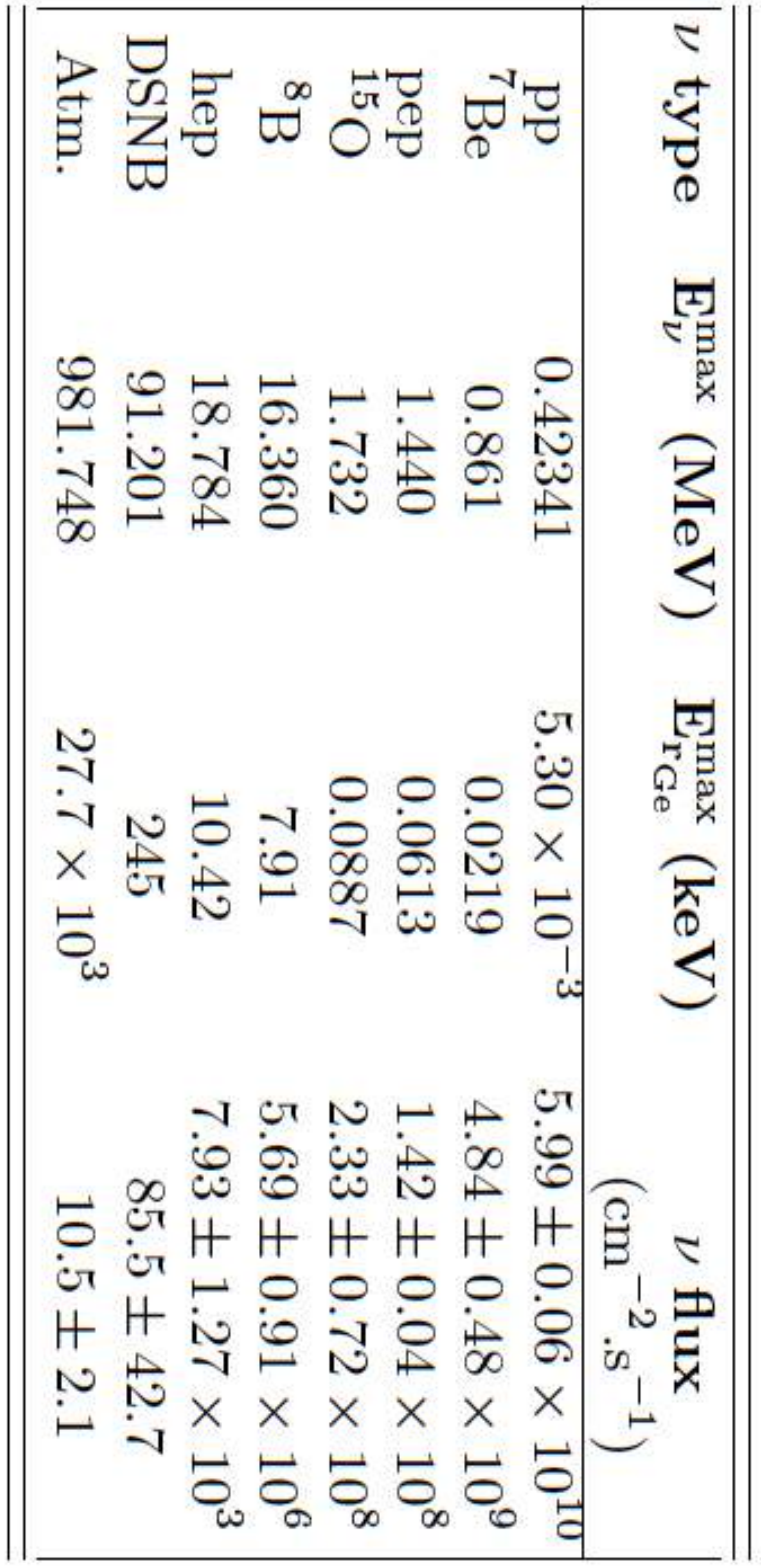
- Geoneutrinos are plentiful, but too low energy and are thus subdominant to the Solar ν flux.
- Reactors νs can are only important if physically close to a reactor, so we can safely ignore them.



Enomoto 2005
Monroe 2007

Neutrino Sources: Solar, Atm, DSNB





ν type	$E_\nu^{\max}$ (MeV)	$E_{r_{Ge}}^{\max}$ (keV)	ν flux ($cm^{-2}.s^{-1}$)
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
^{7}Be	0.861	0.0219	$4.84 \pm 0.48 \times 10^{9}$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^{8}$
^{15}O	1.732	0.0887	$2.33 \pm 0.72 \times 10^{8}$
^{8}B	16.360	7.91	$5.69 \pm 0.91 \times 10^{6}$
hep	18.784	10.42	$7.93 \pm 1.27 \times 10^{3}$
DSNB	91.201	245	85.5 ± 42.7
Atm.	981.748	27.7×10^{3}	10.5 ± 2.1

Coherent Elastic ν-Nucleus Scattering (CEνNS)

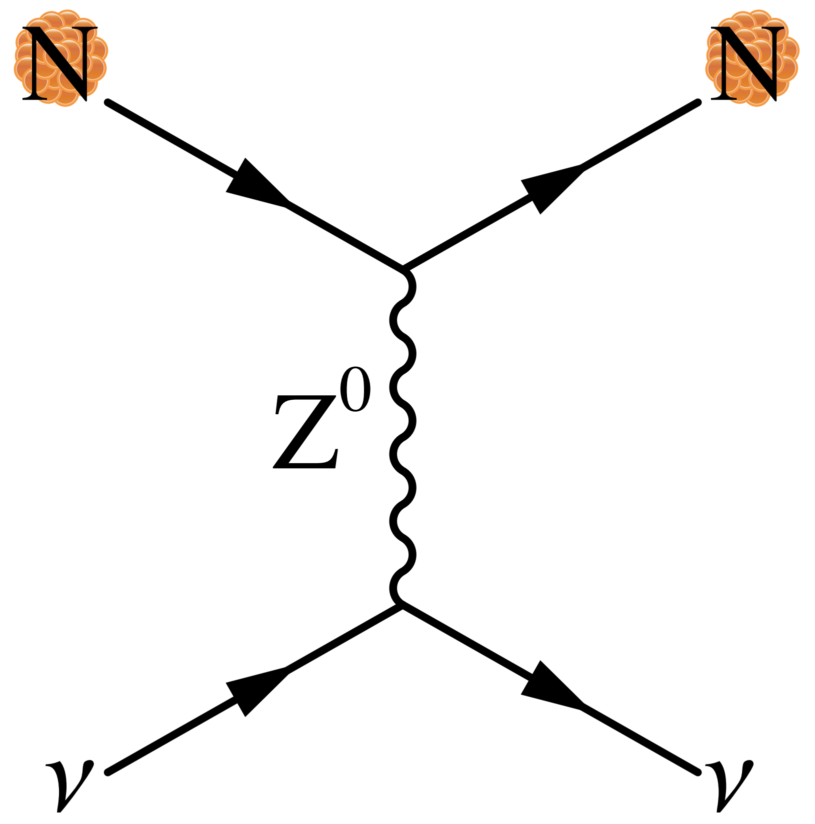
$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

atomic mass

coupling constant

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

= “reduced mass”

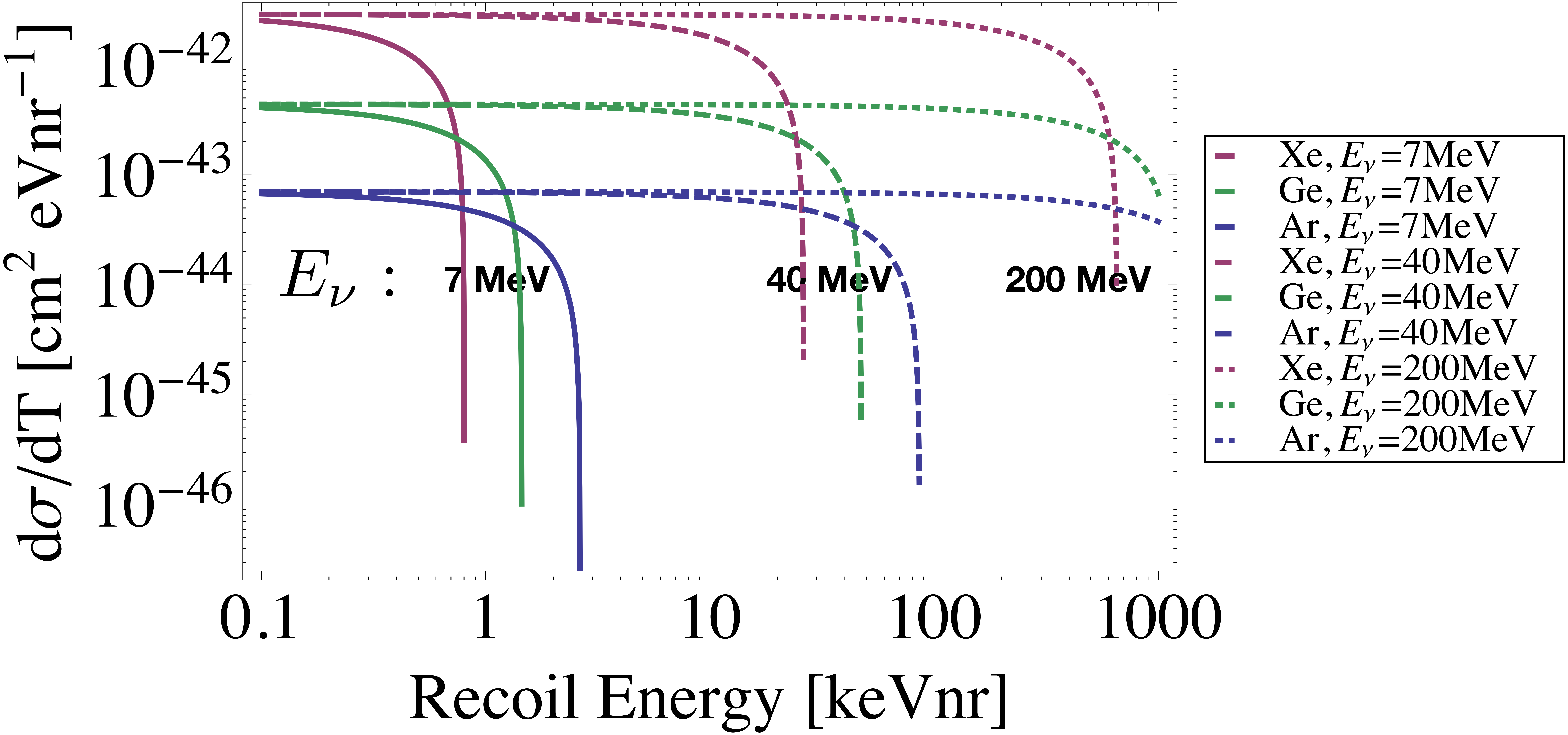


- Same type of process occurs with neutrinos:

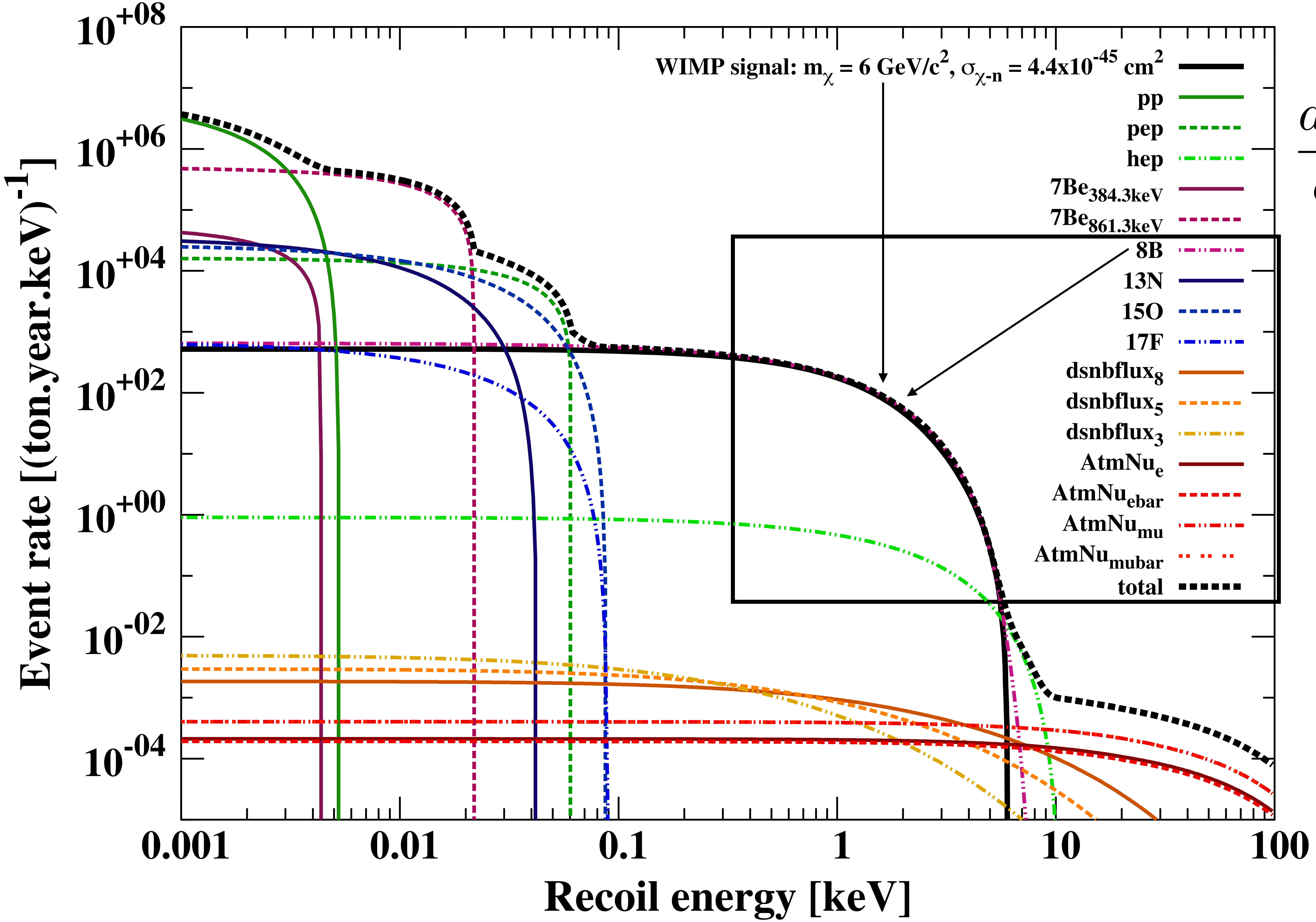
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\left[N - Z(1 - 4\sin^2\theta_W)\right]^2 \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(Q^2)^2$$

Dark Matter detectors are getting good enough to be sensitive to this signal!

CEνNS Cross Sections



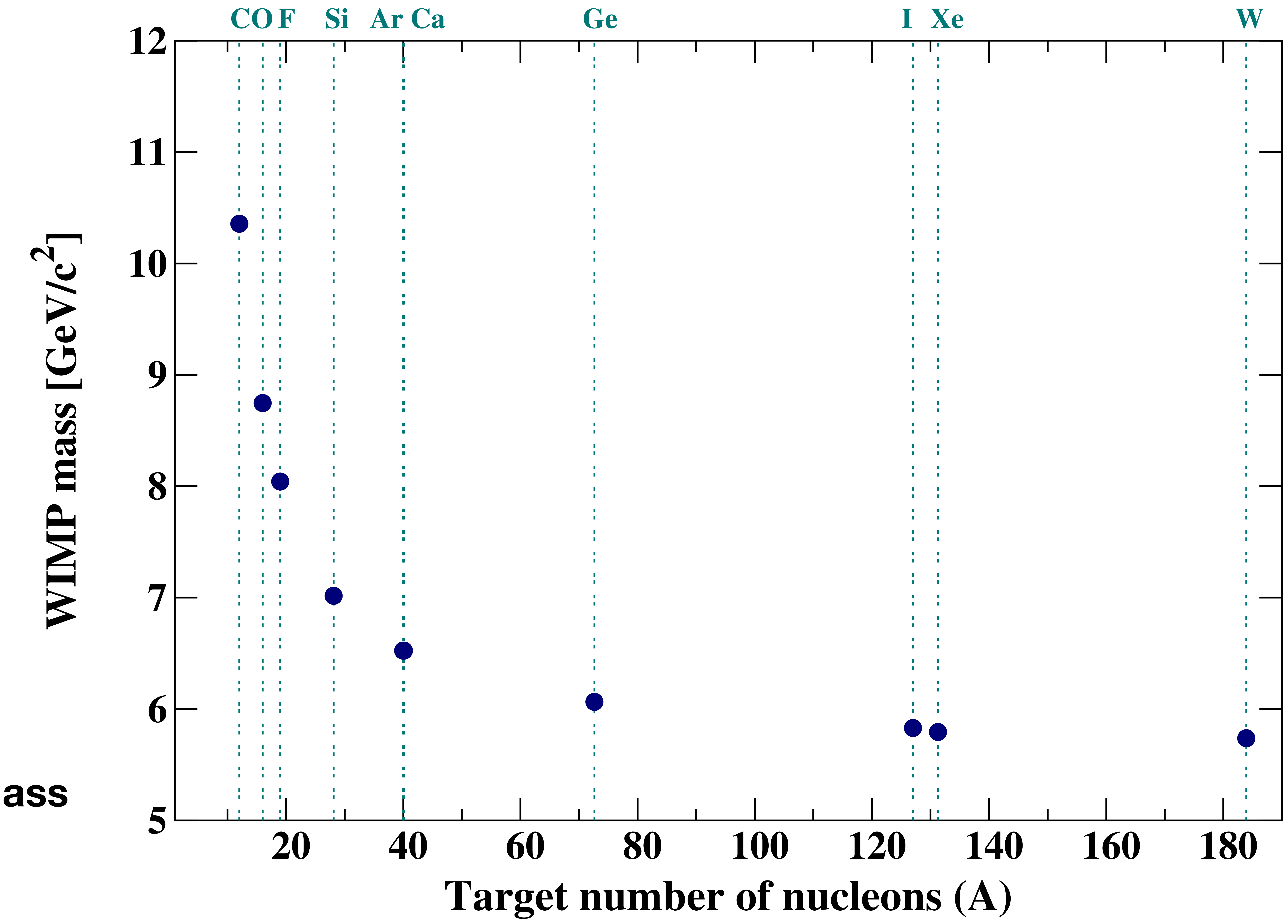
Neutrino CEνNS Recoil Spectrum



$$\frac{dR_\nu}{dT} = \int_{E_\nu^{\min}} \frac{dN}{dE_\nu}\frac{d\sigma}{dT}dE_\nu$$

Fitting the 8B CEνNS Signal As Dark Matter

- The reconstructed parameters are target dependent

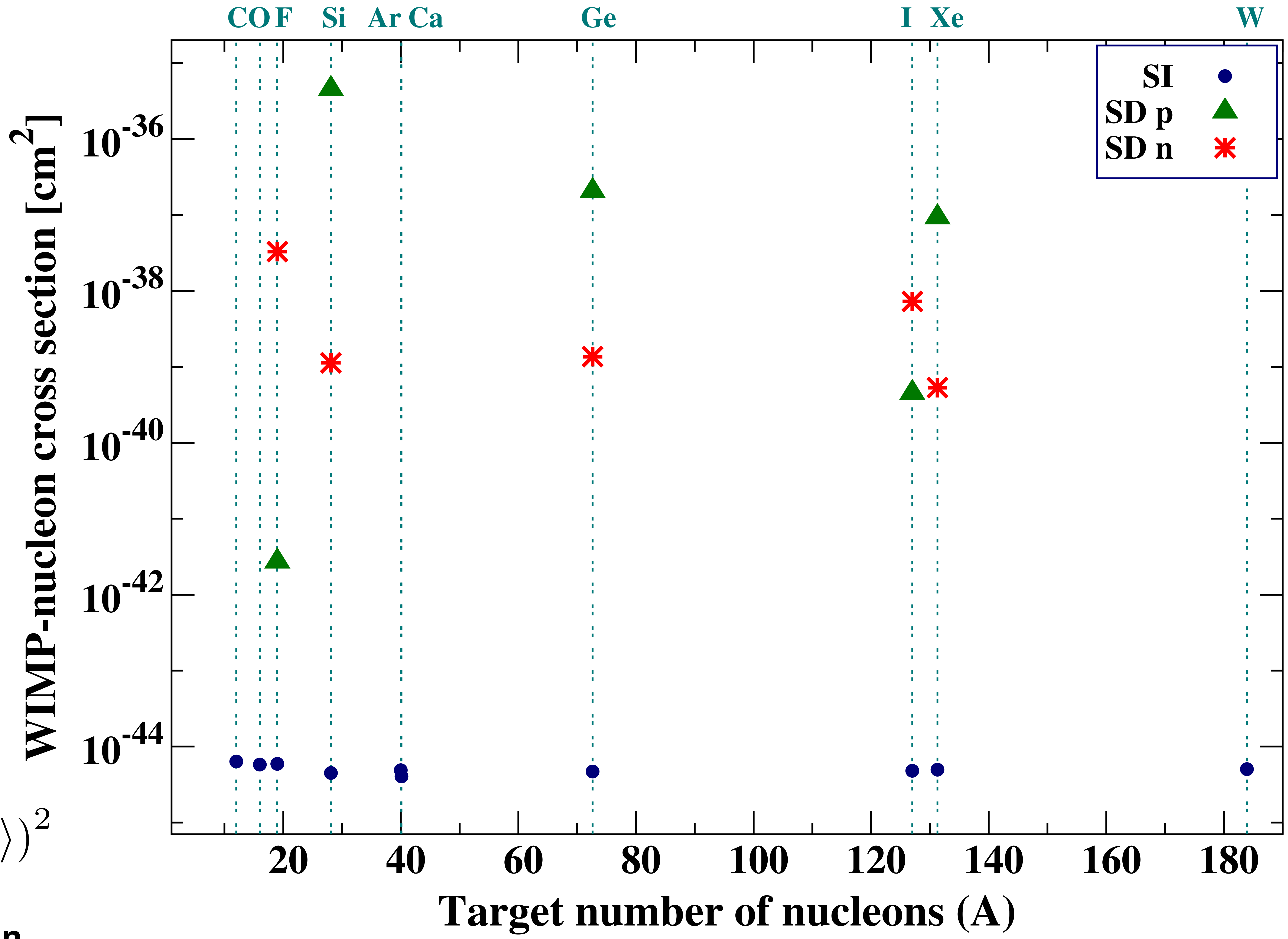


SI: $\sigma_o \simeq \dfrac{4m_r^2}{\pi}\underset{\uparrow}{f}A^2 \longleftarrow$ **atomic mass**

coupling constant

Fitting the 8B CEνNS Signal As Dark Matter

- The reconstructed parameters are target dependent
- They also depend on the assumed interaction mechanism



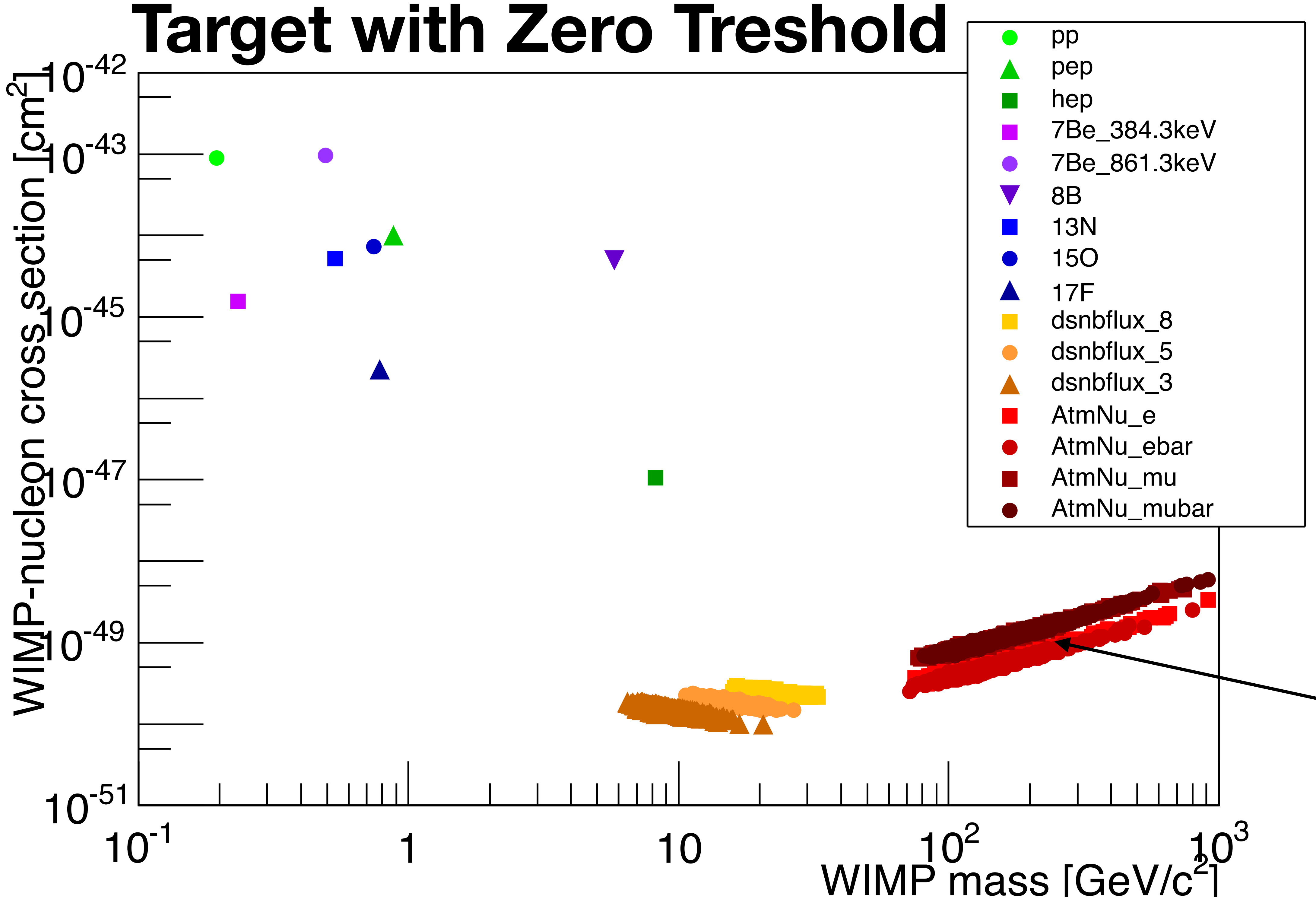
SD: $\sigma_o = \dfrac{32(J+1)}{\pi J} G_F^2\, m_r^2\, (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$

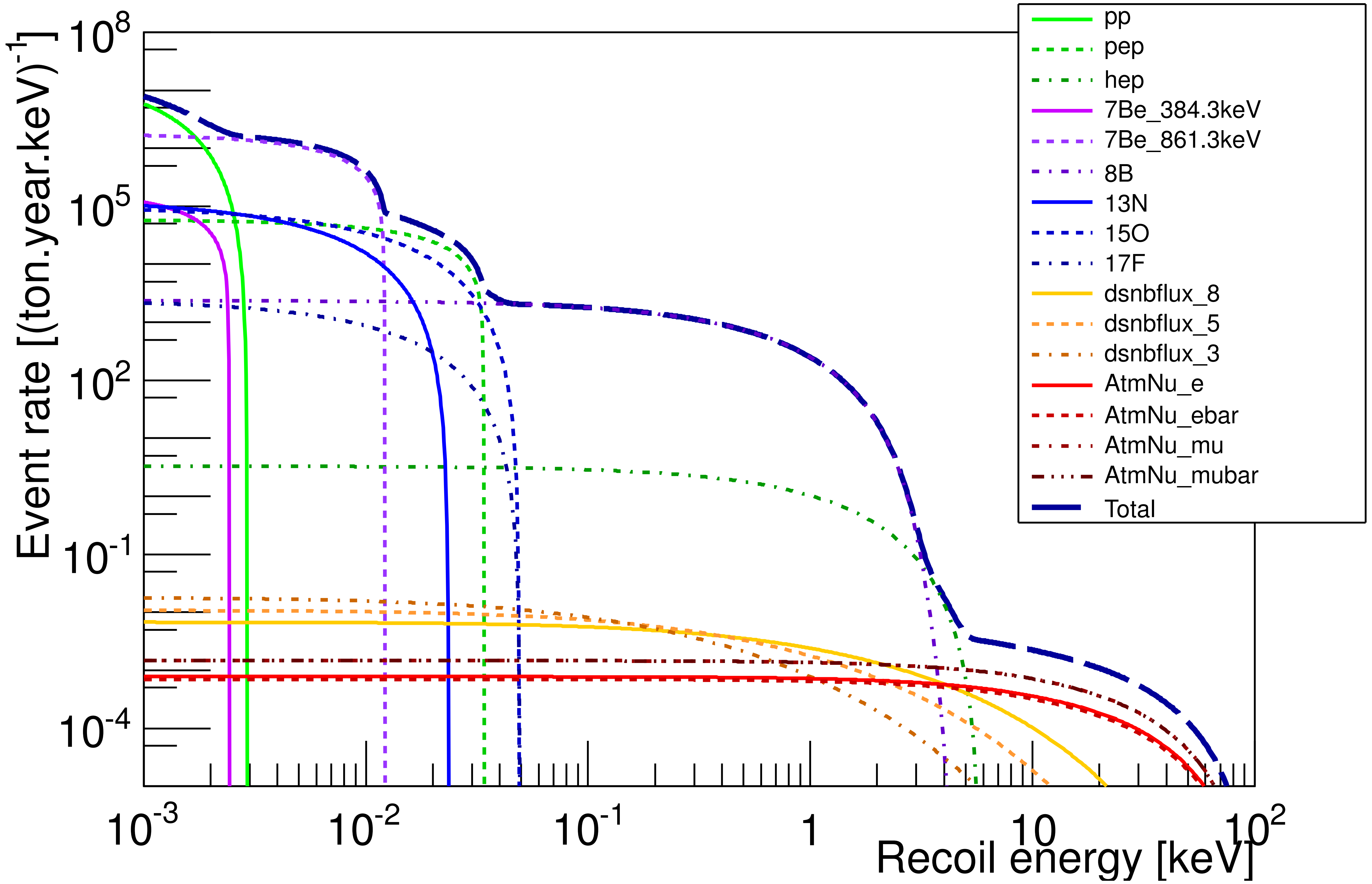
Nuclear Angular Momentum ↑ **Fermi constant** ↑ **Coupling constant** ↑ **Spin** ↑

Fitting the Individual CEνNS Signals As Dark Matter

We can map where each neutrino component would land on the WIMP SI cross section - mass plane

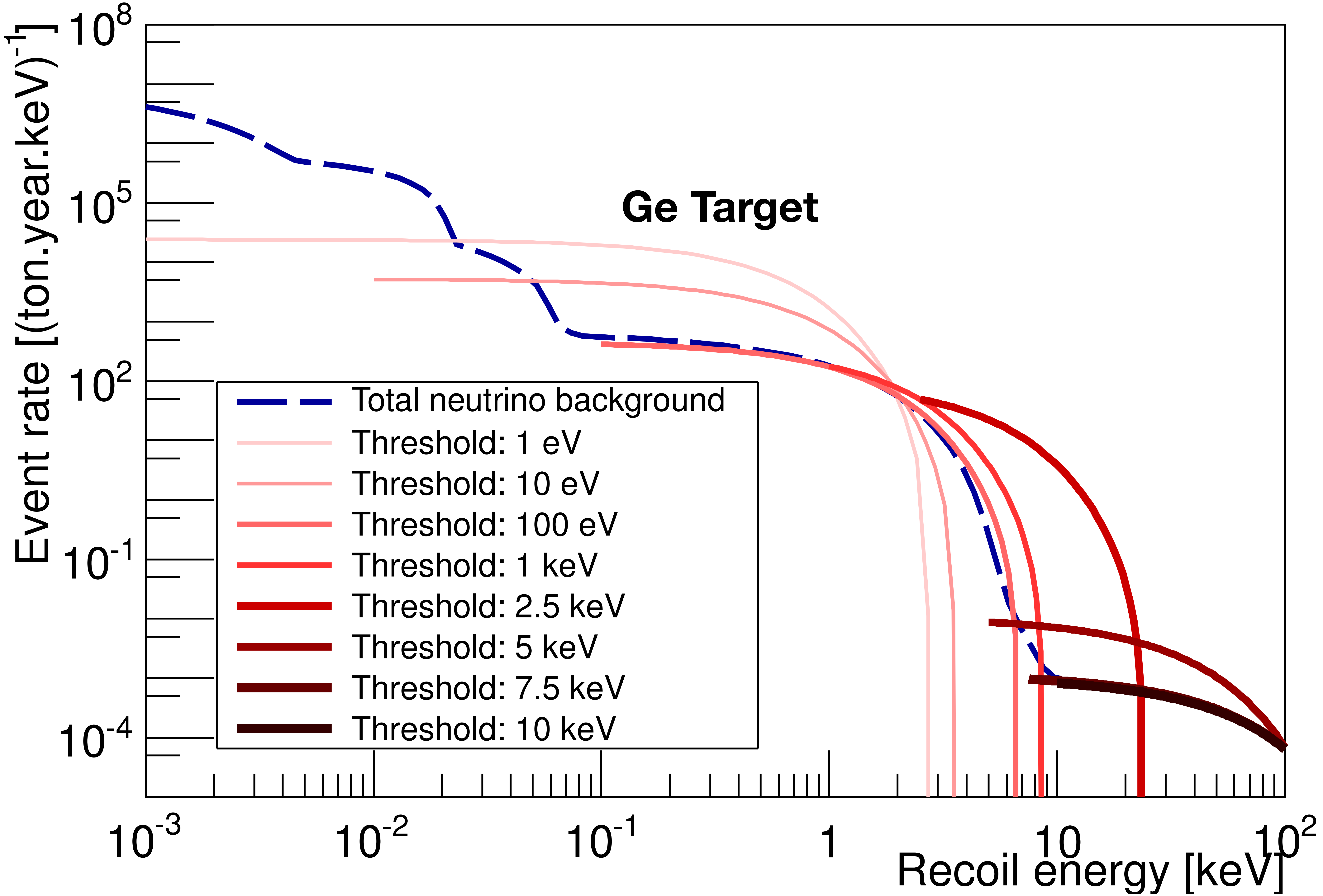
Individual Fits for a Xe Target with Zero Treshold



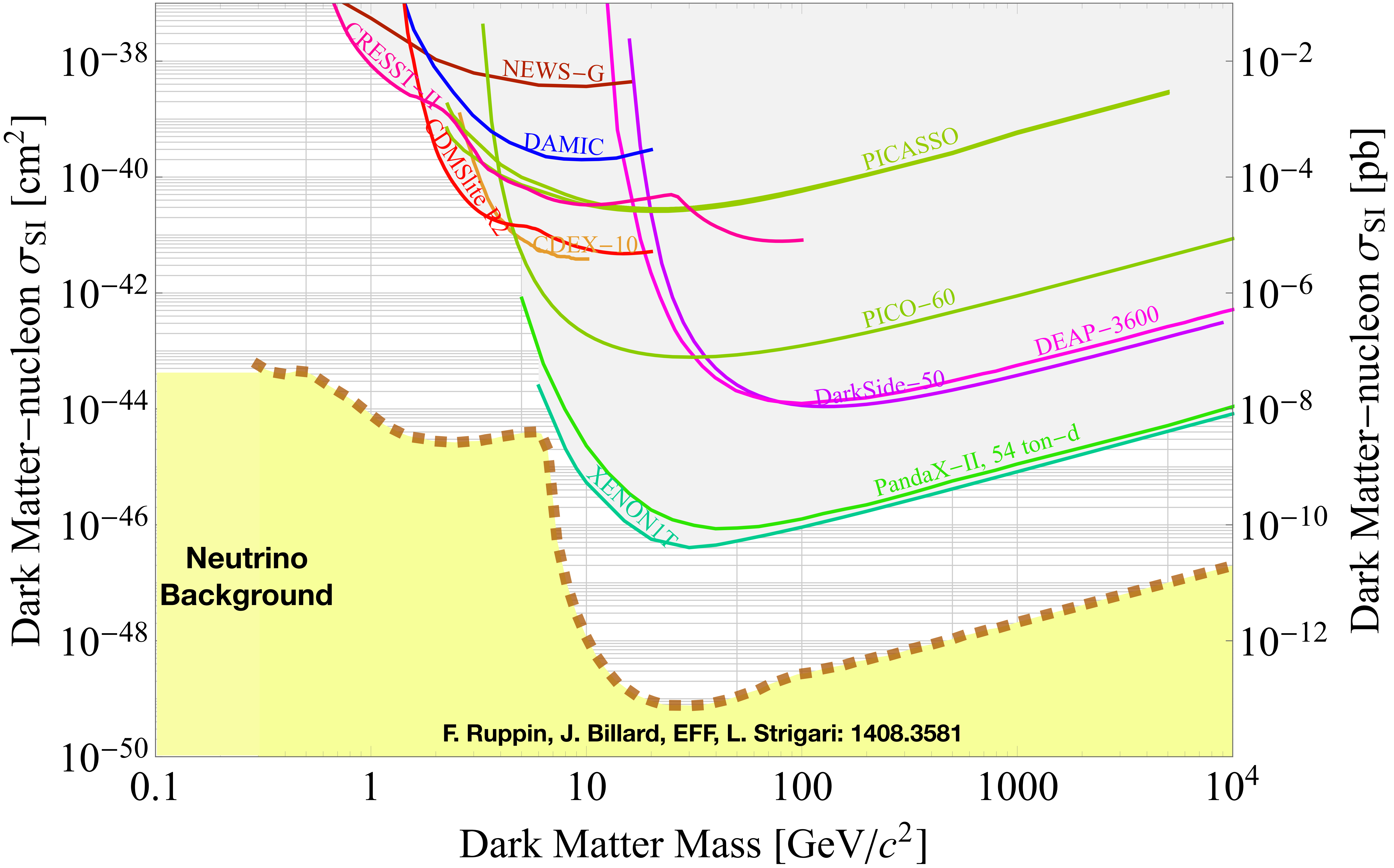


Nuclear form factor prevents WIMP mass determination for at high masses

Fits to the Entire Neutrino Background as WIMPs



The “Neutrino Floor”



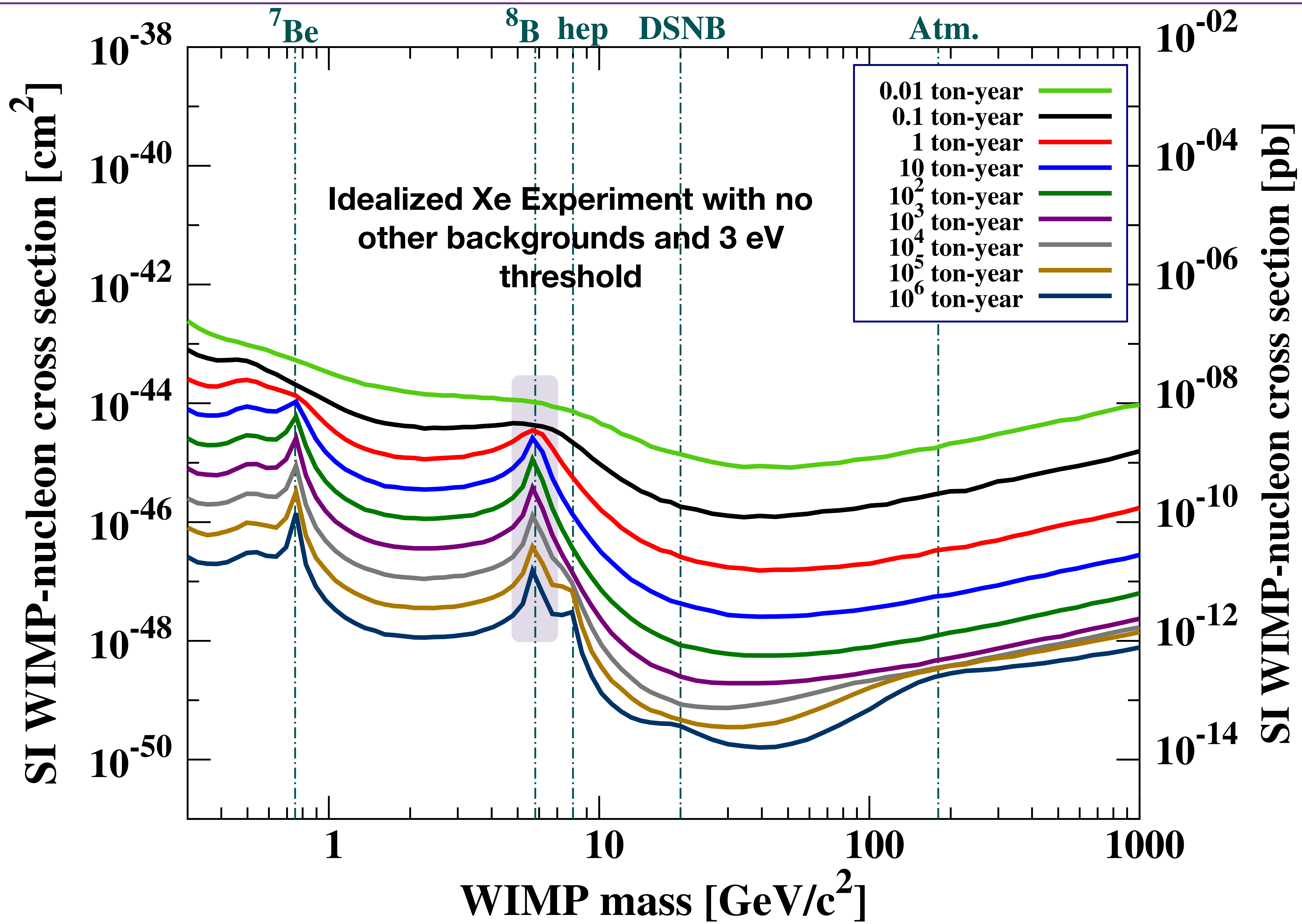
WIMP Discovery Limit

- To asses the discovery potential of WIMP searches, we define the WIMP Discovery Limit
- Definition of WIMP Discovery Limit: If the true WIMP model lies above this limit, then a given experiment has a 90% probability to obtain at least a 3σ detection of the signal.
- We want to gauge the significance of an excess in our data from the expected neutrino background, so we define a likelihood function:

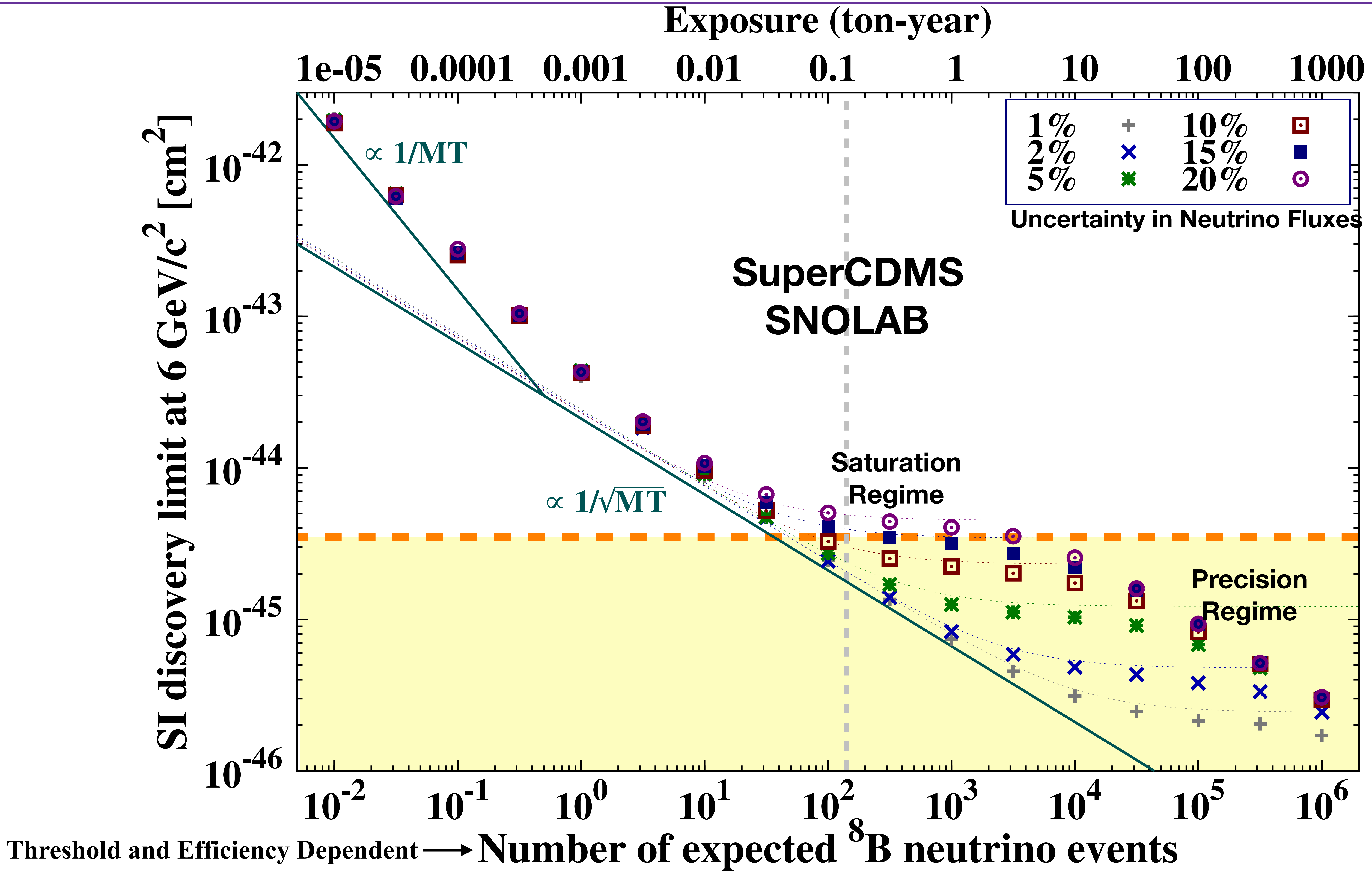
$$\mathscr{L}(\underset{\text{WIMP cross section}}{\sigma_{\chi-n}}, \overset{\nu\text{ Flux}}{\vec{\phi}}) = \frac{e^{-(\overset{\text{Number of WIMP events}}{\mu_\chi} + \sum_{j=1}^{n_\nu} \overset{\text{Number of }\nu\text{ events}}{\mu_\nu^j})}}{\mathrm{N}!} \times \prod_{i=1}^{\mathrm{N}} \left[\mu_\chi \overset{\text{WIMP nuclear recoil energy distribution}}{f_\chi(E_{r_i})} + \sum_{j=1}^{n_\nu} \mu_\nu^j \overset{\nu\text{ nuclear recoil energy distribution}}{f_\nu^j(E_{r_i})} \right] \times \prod_{i=1}^{n_\nu} \overset{\nu\text{ flux uncertainty distribution}}{\mathscr{L}_i(\phi_i)}$$

- Using a likelihood ratio test, we determine what cross section of WIMPs would be detected at 3σ or better 90% of the time

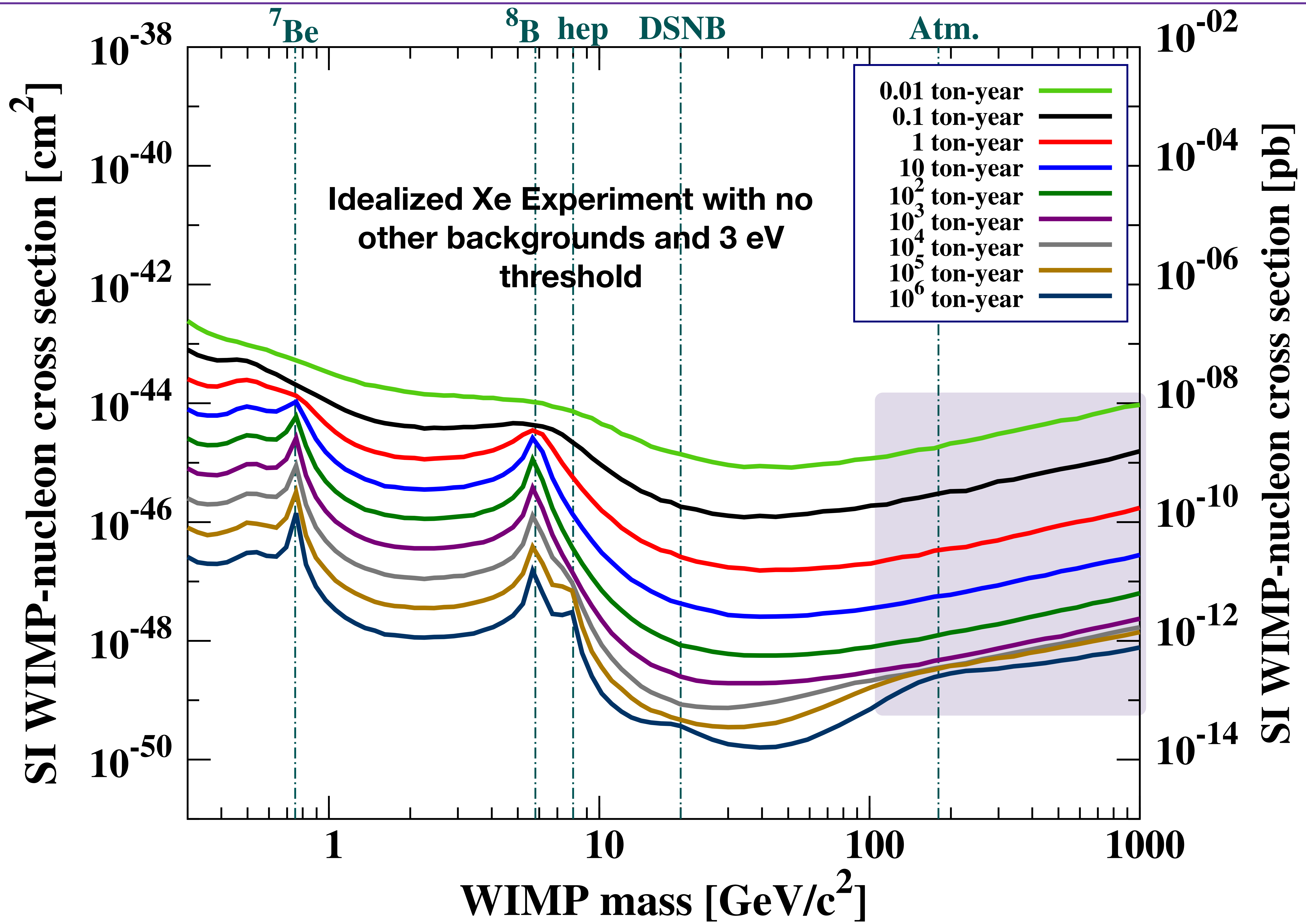
Formally, there is no Neutrino Floor



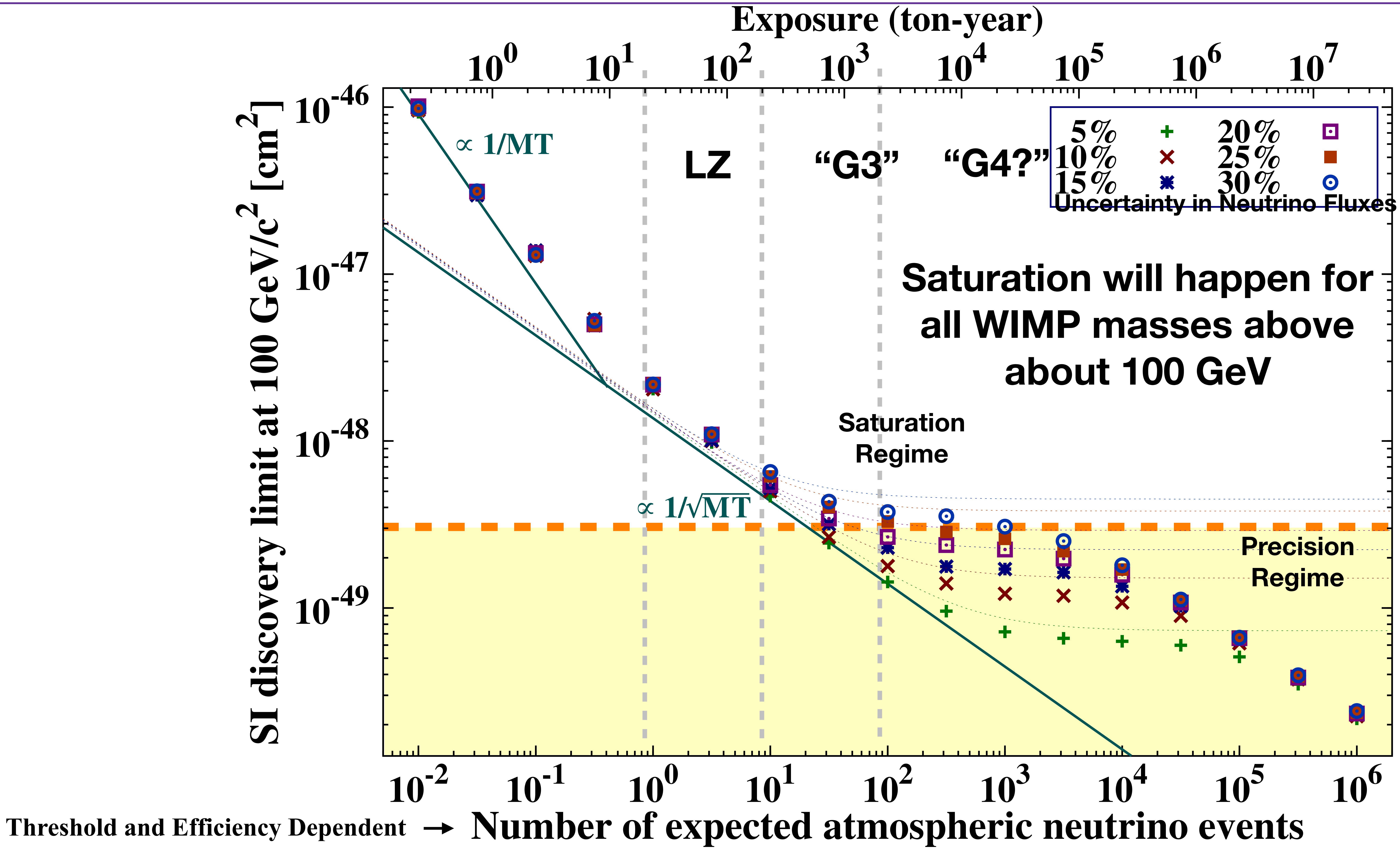
Saturation around 6 GeV WIMP Mass from ^{8}B ν



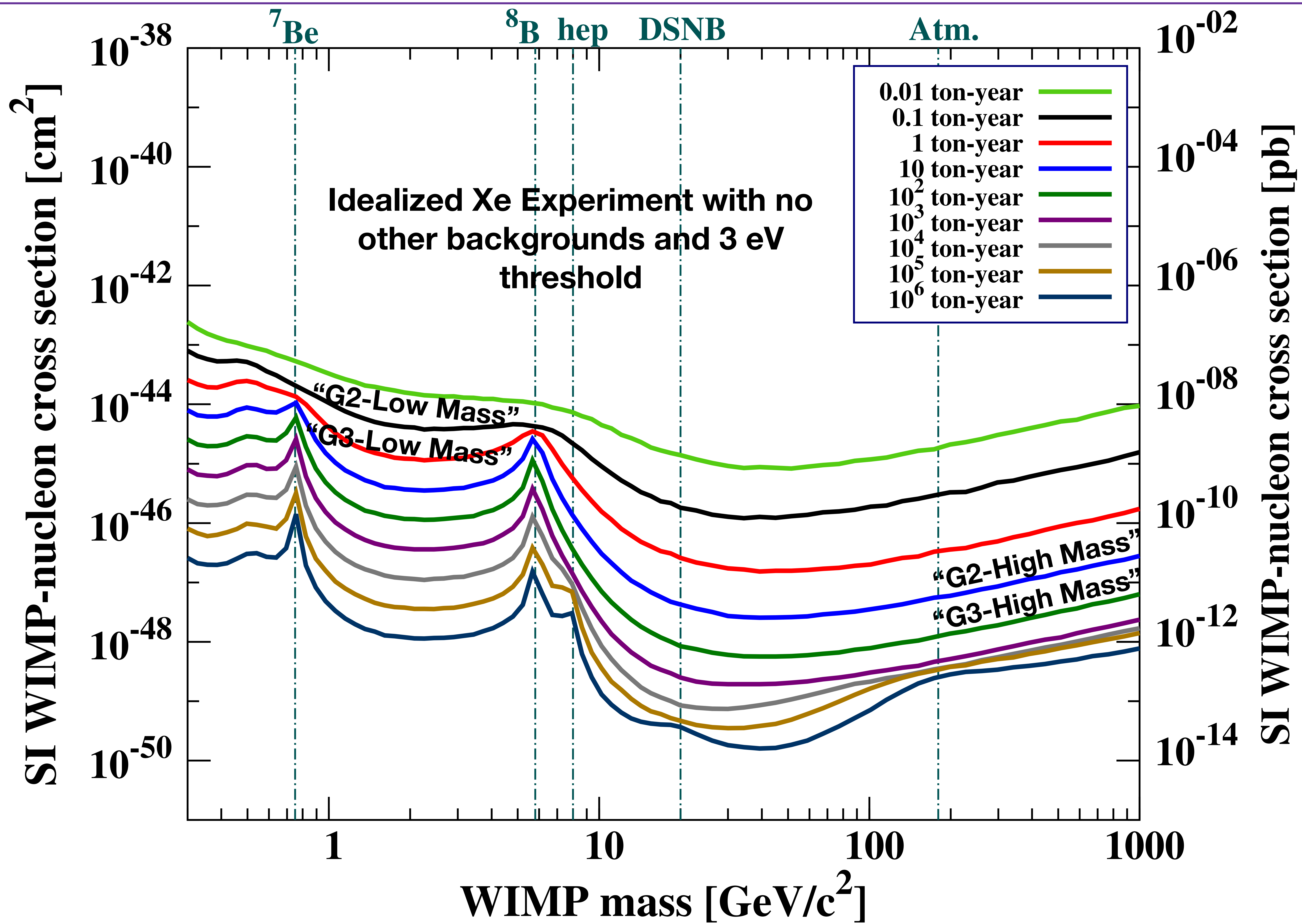
Formally, there is no Neutrino Floor



Saturation above 100 GeV WIMP Masses from Atm ν

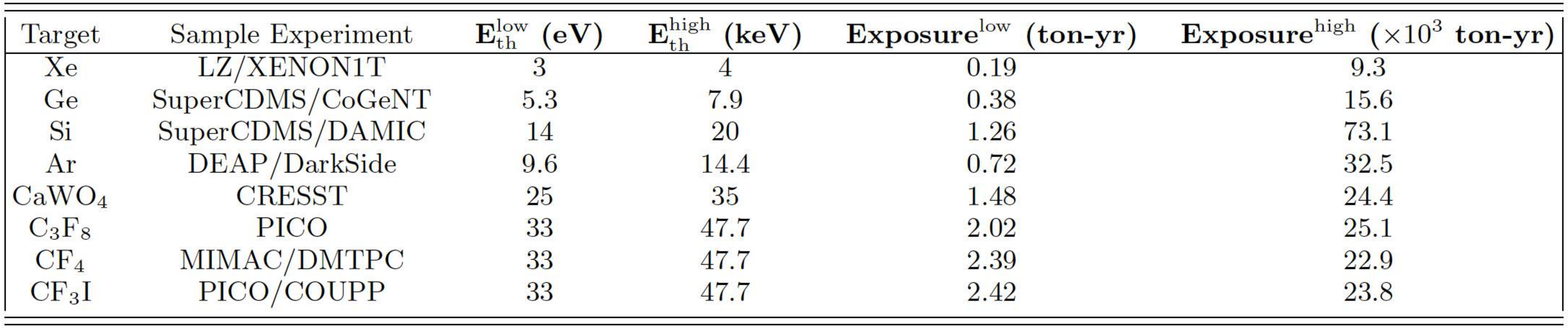


Formally, there is no Neutrino Floor



The WIMP Discovery Limit

- The curve we publish in our papers is constructed from two separate calculations, one at low mass and one at high mass.
- The low mass threshold is set to get no pp neutrino events
- The high mass threshold is set to get no ^{8}B events
- The curve is not a sensitivity curve! Reiterating the definition:
  - If the true WIMP model lies above this limit, then a given experiment has a 90% probability to obtain at least a 3σ detection of the signal.

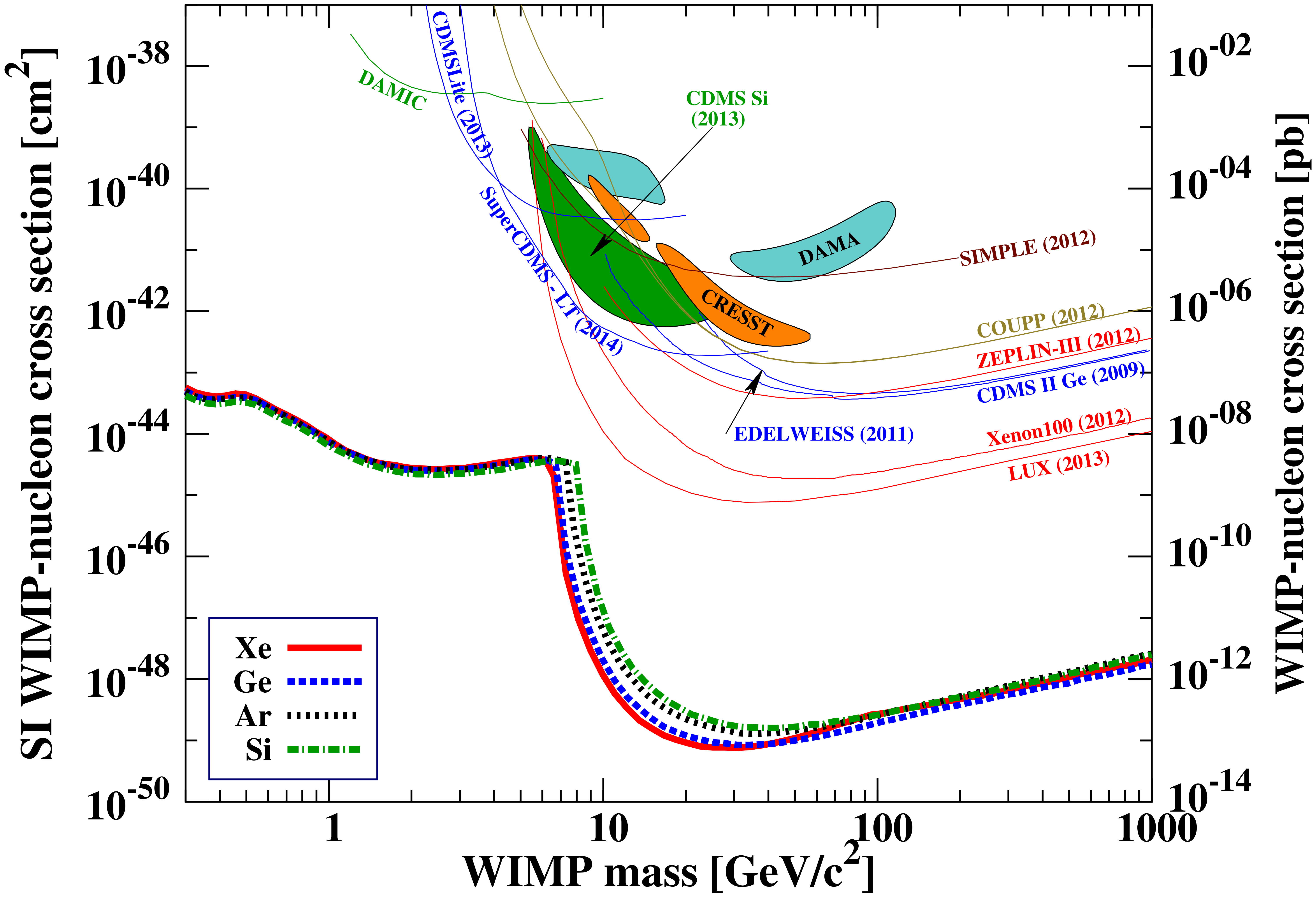


Target	Sample Experiment	E_{th}^{low} (eV)	E_{th}^{high} (keV)	Exposure^{low} (ton-yr)	Exposure^{high} ($\times 10^3$ ton-yr)
Xe	LZ/XENON1T	3	4	0.19	9.3
Ge	SuperCDMS/CoGeNT	5.3	7.9	0.38	15.6
Si	SuperCDMS/DAMIC	14	20	1.26	73.1
Ar	DEAP/DarkSide	9.6	14.4	0.72	32.5
$CaWO_4$	CRESST	25	35	1.48	24.4
C_3F_8	PICO	33	47.7	2.02	25.1
CF_4	MIMAC/DMTPC	33	47.7	2.39	22.9
CF_3I	PICO/COUPP	33	47.7	2.42	23.8

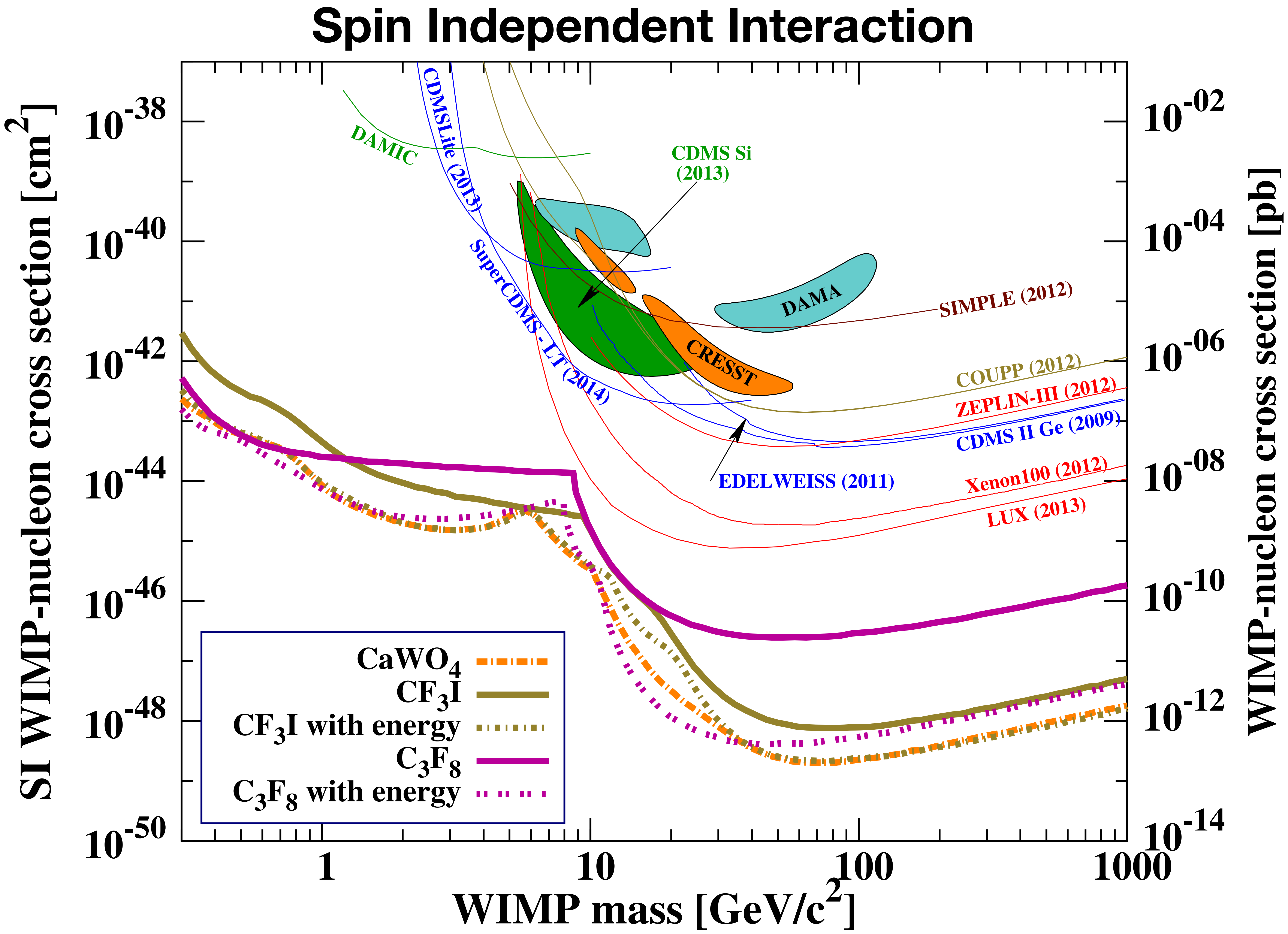
F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

WIMP Discovery Limit for Different Targets

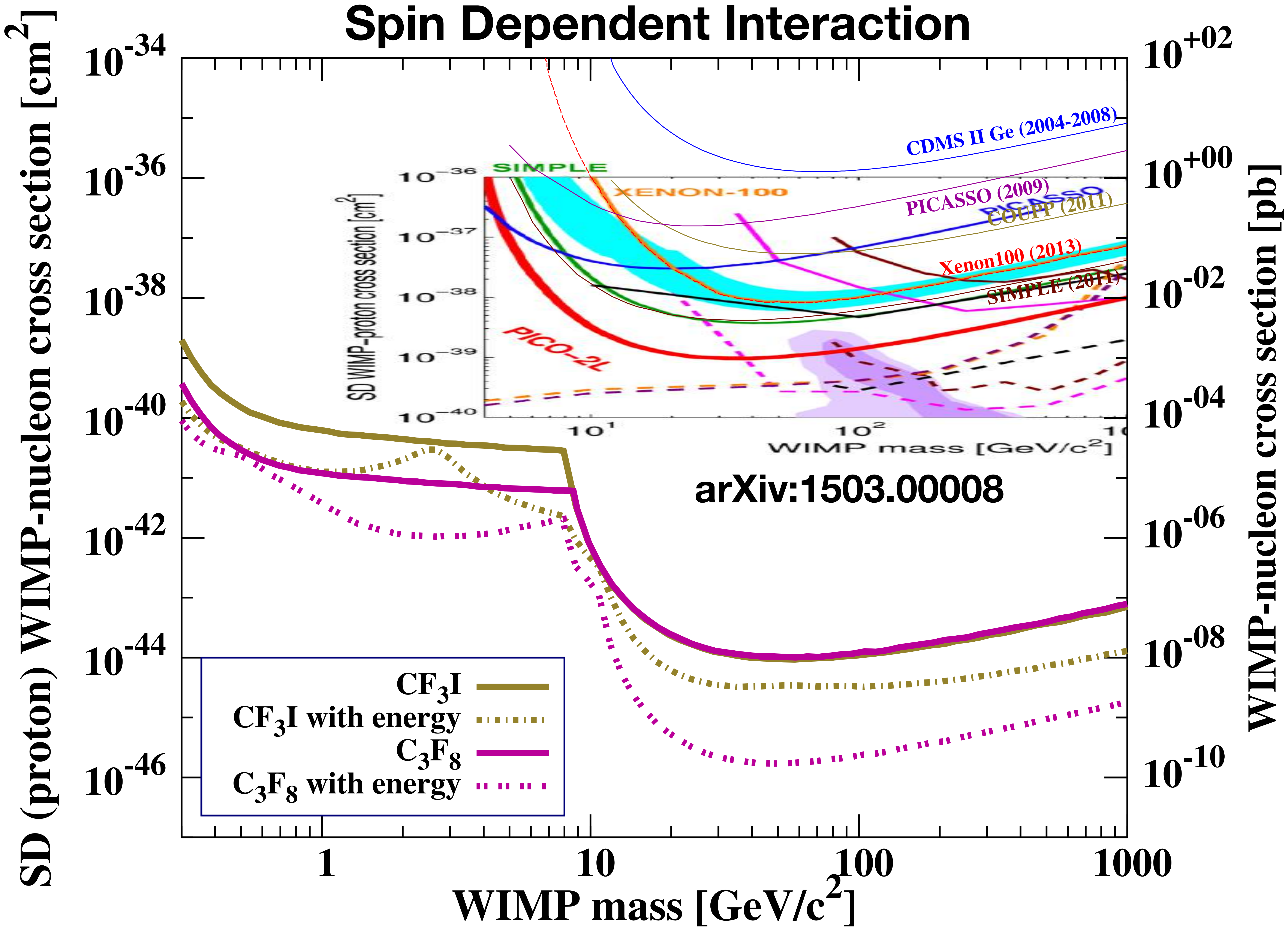
Spin Independent Interaction



WIMP Discovery Limit for Different Targets



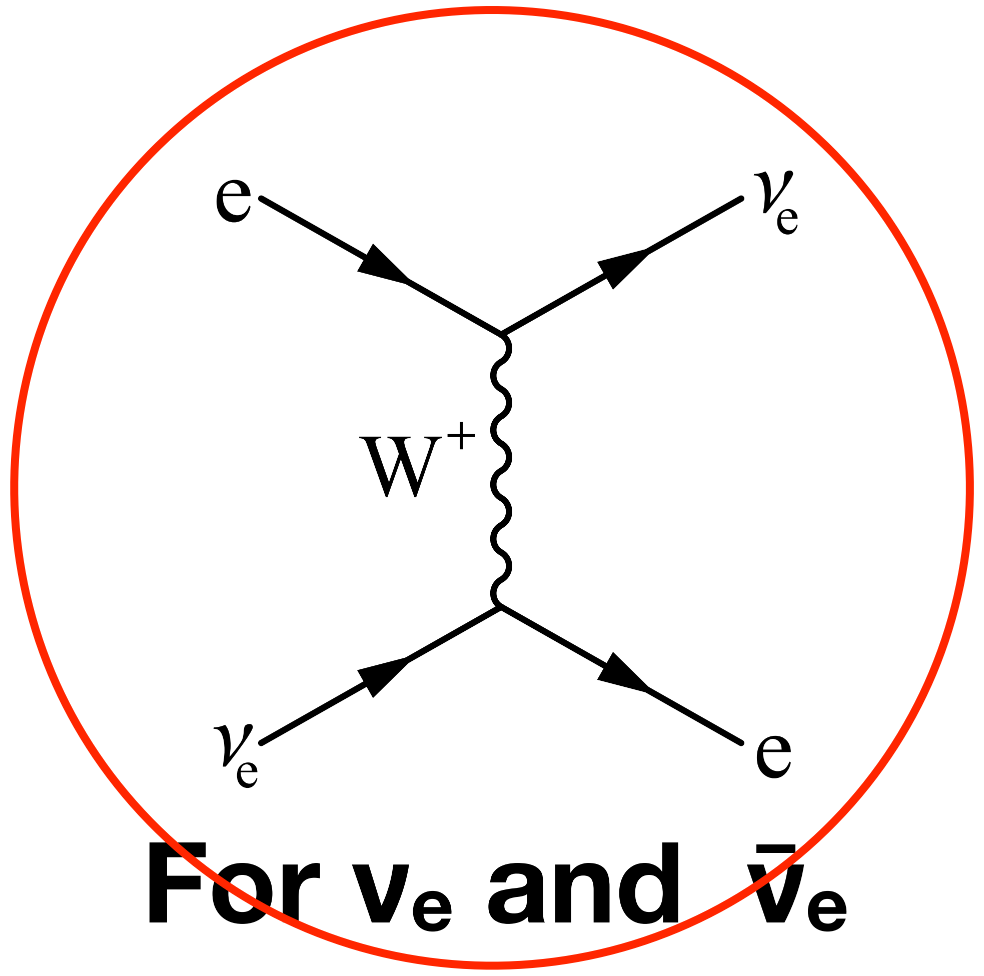
WIMP Discovery Limit for Different Targets

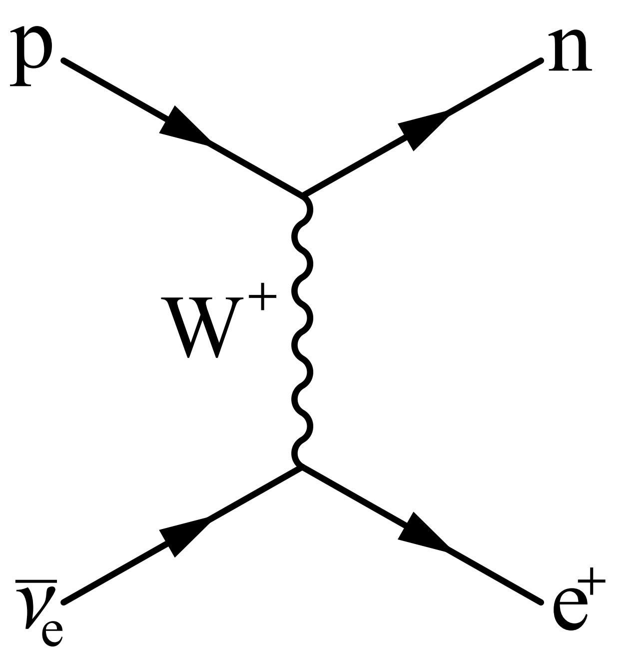


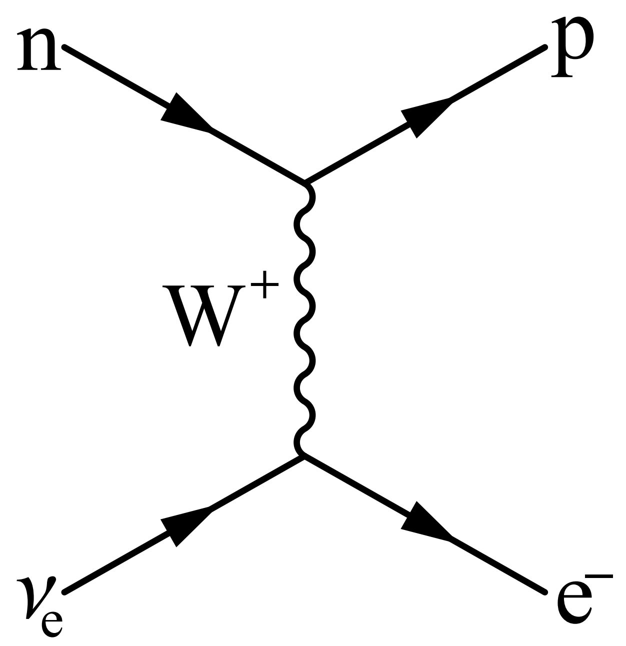
Electron Recoil Backgrounds from Neutrinos

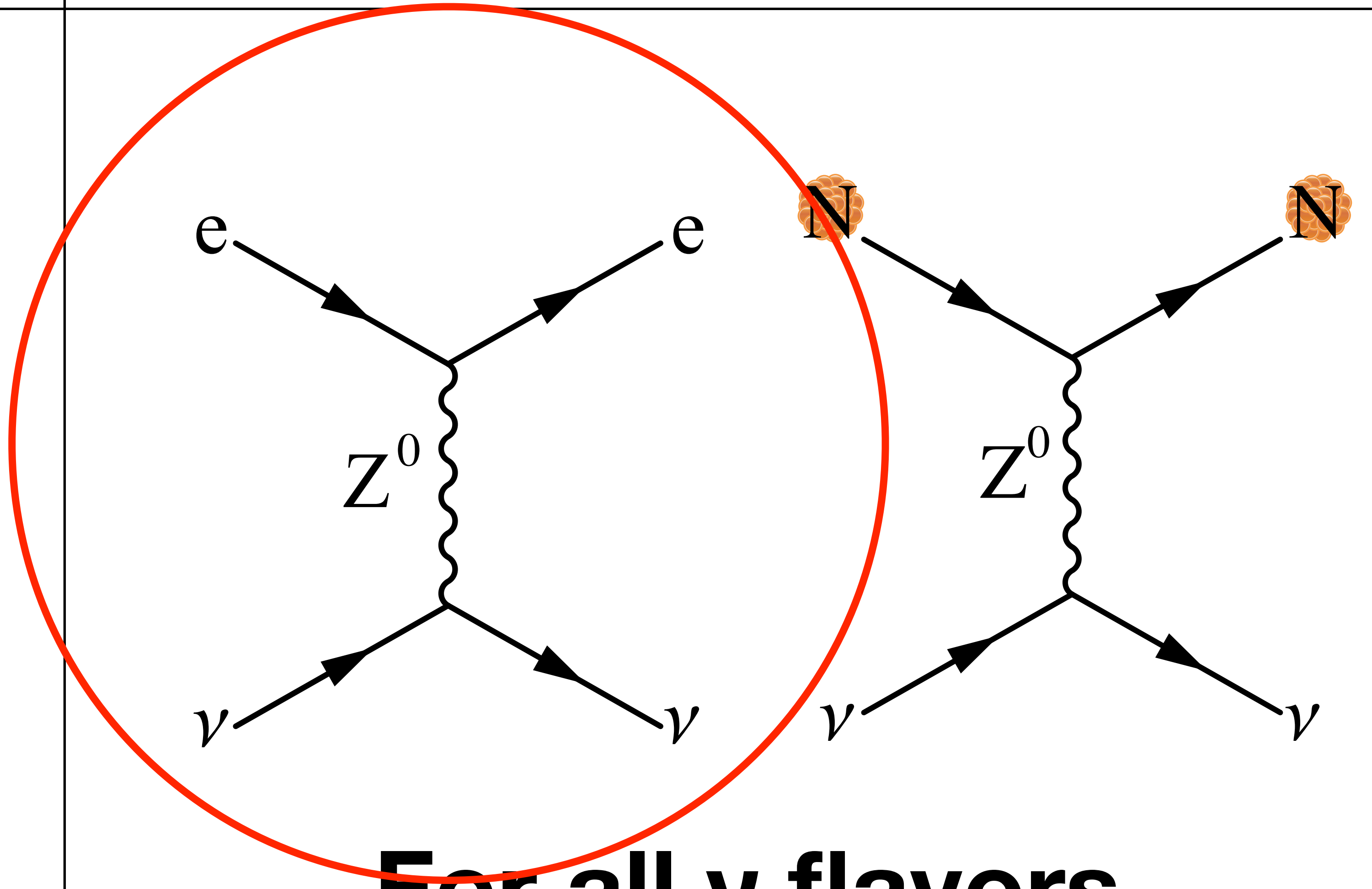
Baudis 2012, Schumann 2015

Low-energy ν Interactions

<table>
<tr><th></th><th>Elastic</th><th>Quasi-Elastic</th></tr>
<tr><td>Charged Current</td><td>

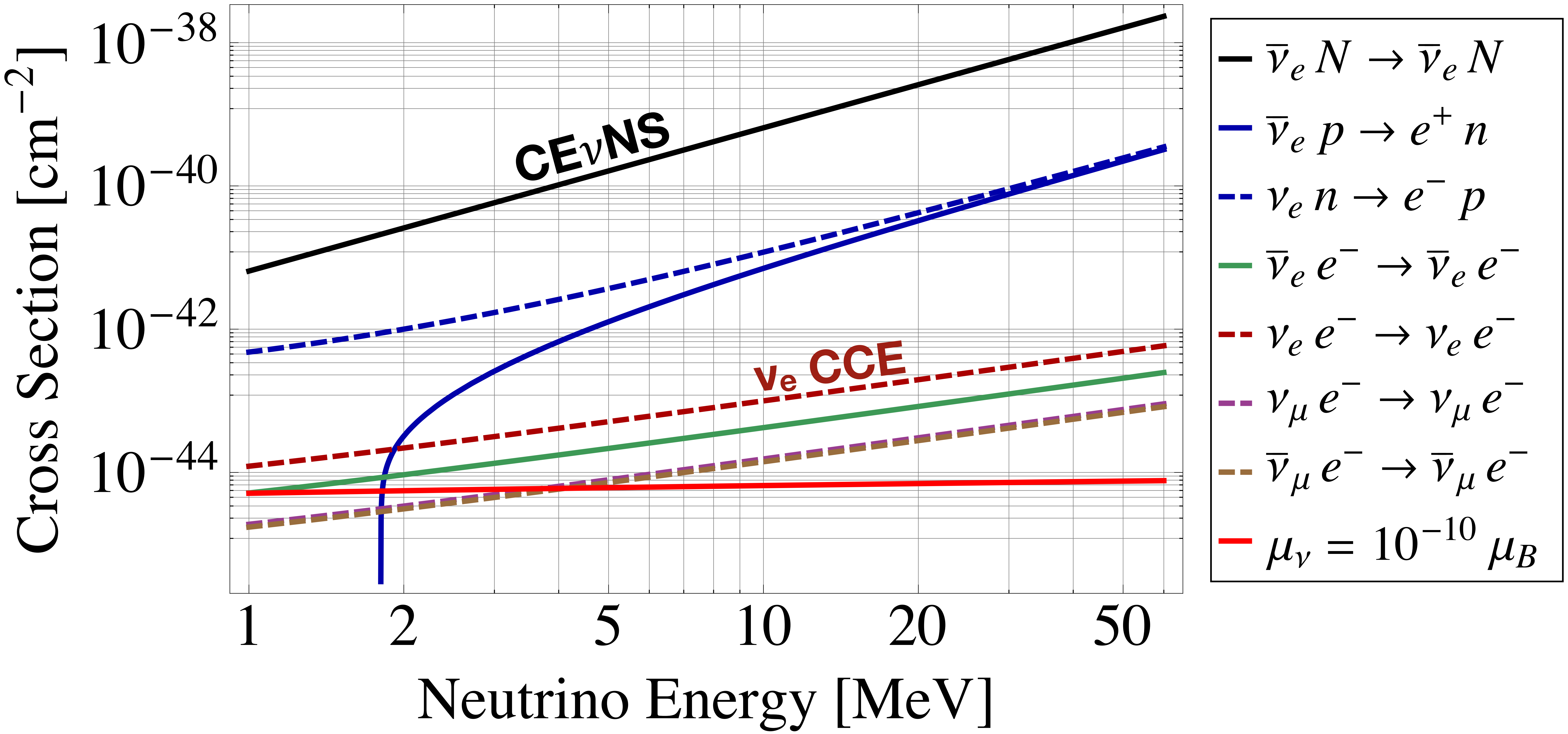
For ν_e and $\bar{\nu}_e$</td><td>

IBD


ν_μ, ν_τ not low-E</td></tr>
<tr><td>Neutral Current</td><td>

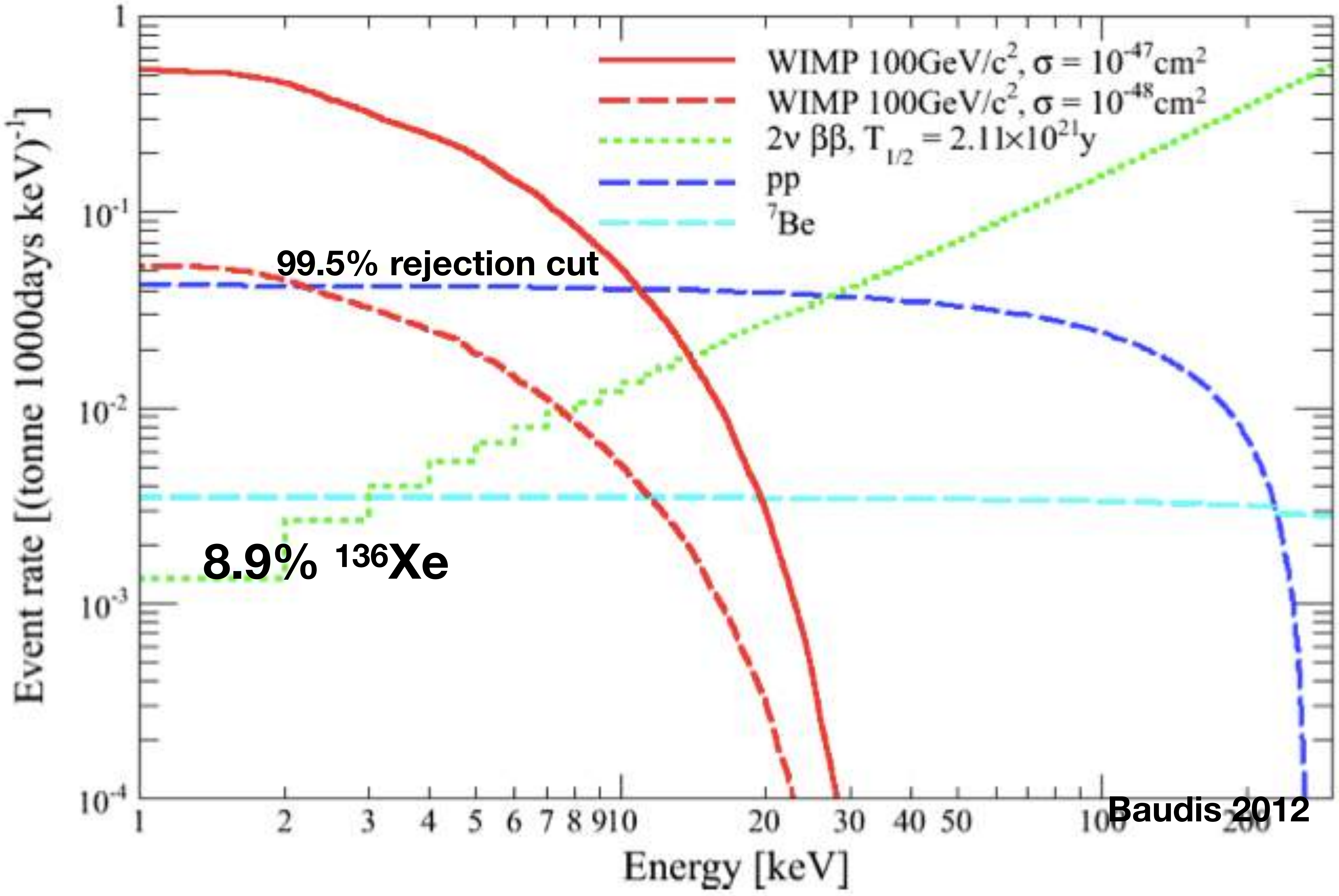
For all ν flavors</td><td></td></tr>
</table>

Low-Energy Neutrino Cross Sections



- Cross Section is 10,000 times smaller than CNS…
- But you get a much higher recoil due to the small mass of the electron.
- Thus pp and ^{7}Be will dominate at 10 keVee recoil

Electron Recoil Backgrounds

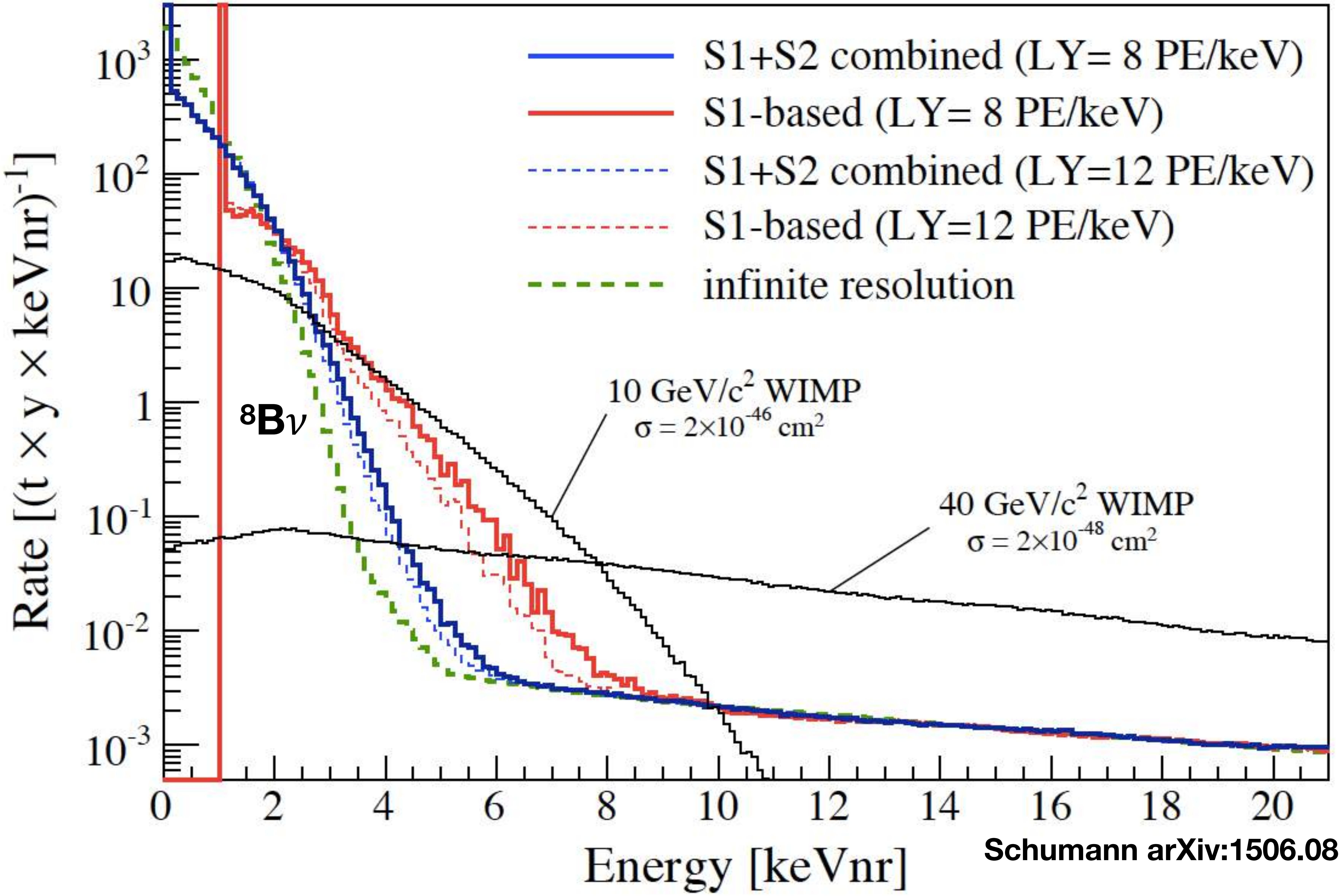


99.5% rejection cut

8.9% ^{136}Xe

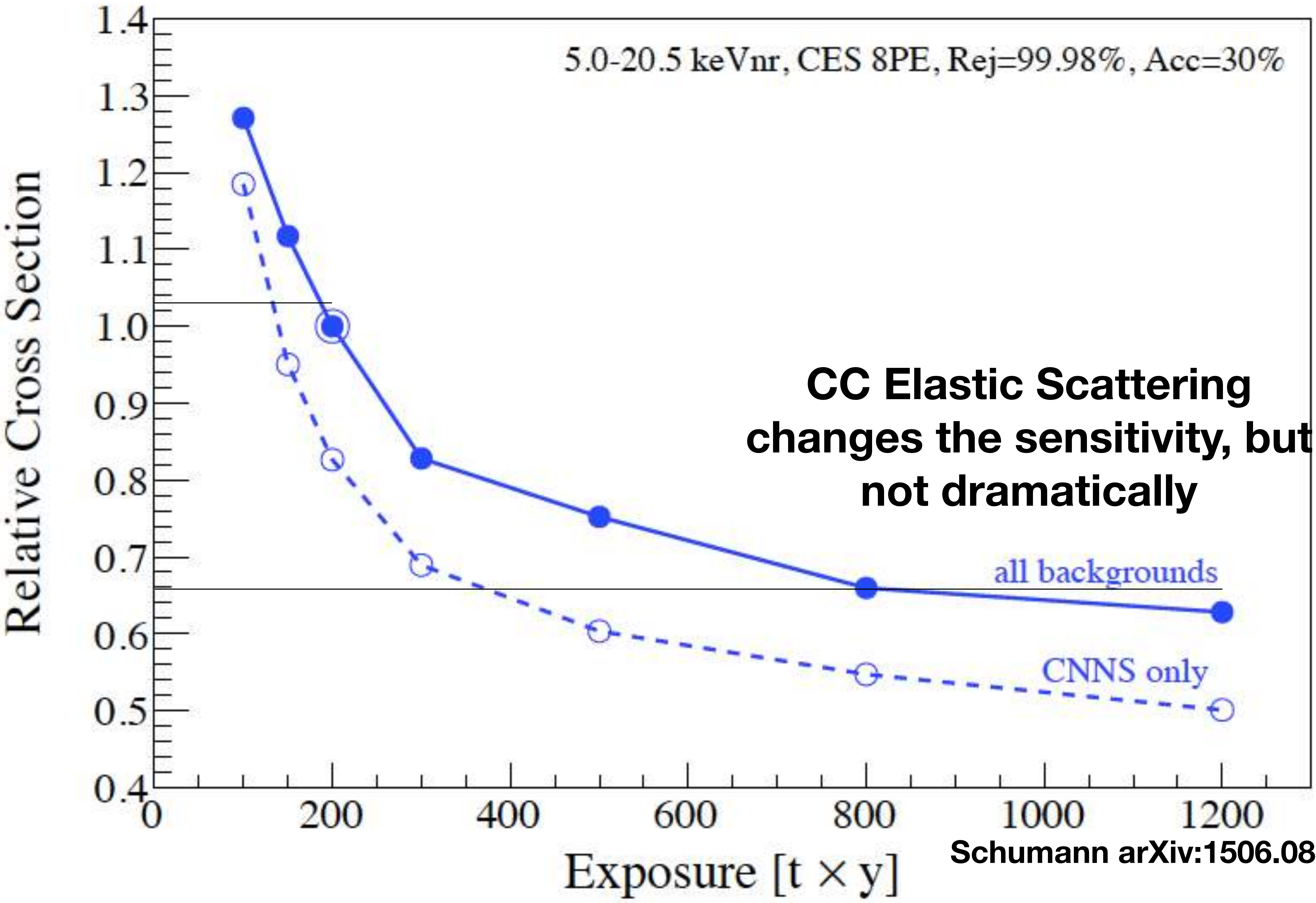
Baudis 2012

Adding both NC and CC interactions



Schumann arXiv:1506.08309

Comparison between Exposure and Sensitivity



CC Elastic Scattering changes the sensitivity, but not dramatically

Schumann arXiv:1506.08309

Strategies to Push Beyond the Neutrino “Floor”

Target Complementarity

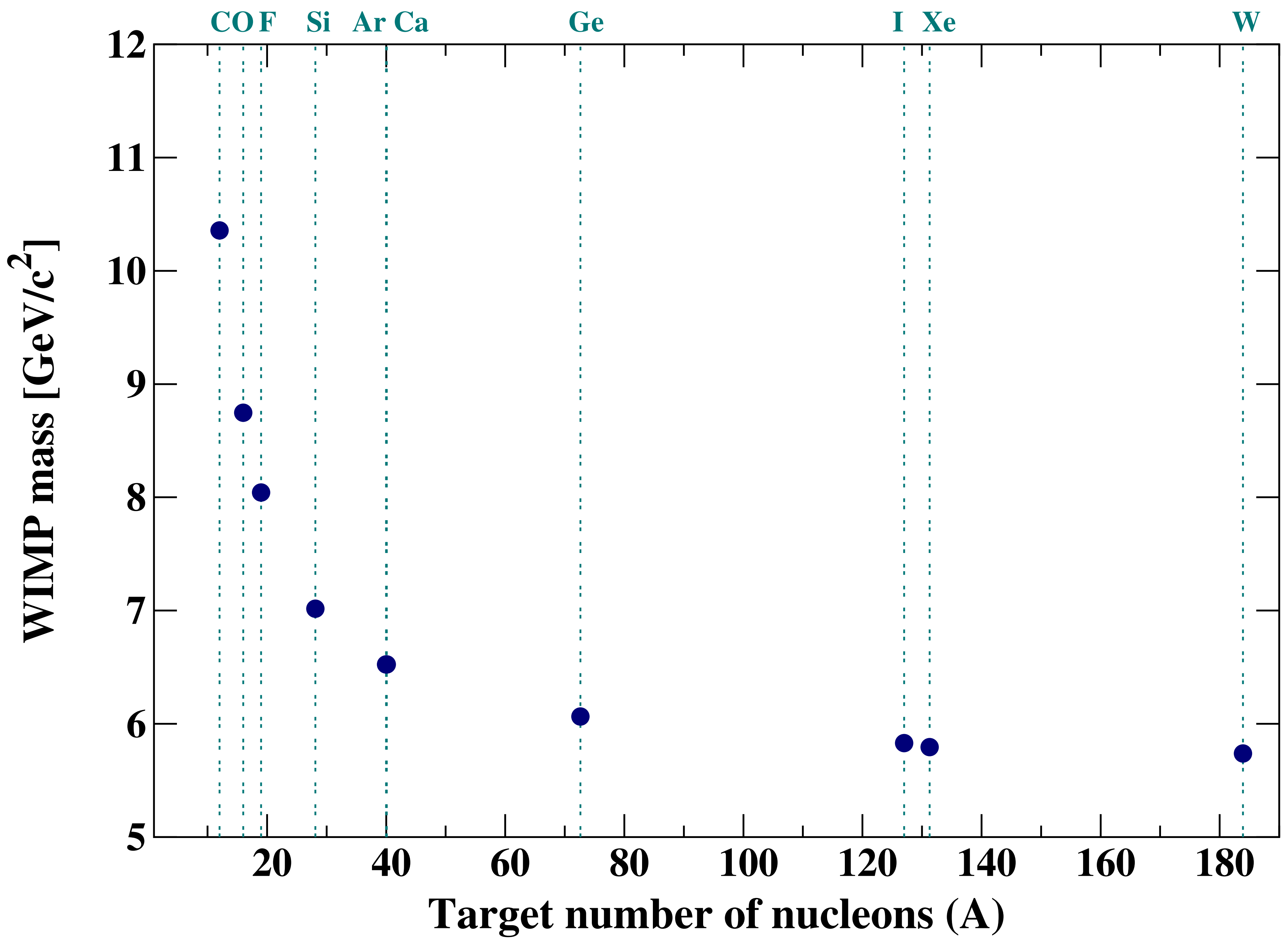
- The reconstructed parameters are target dependent
- Maybe we can eliminate the saturation regime using data from various targets?

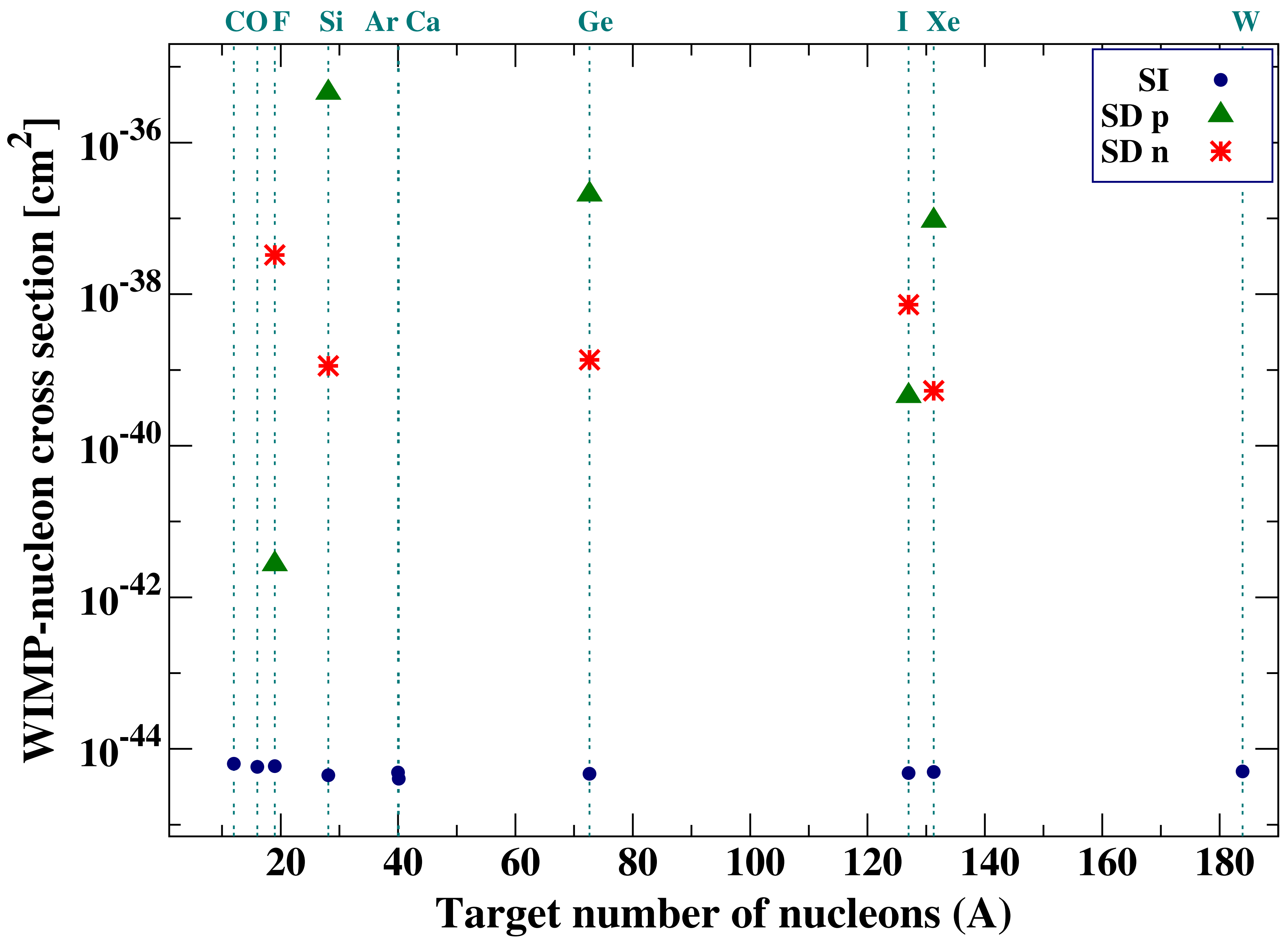
SI: $\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2 \longleftarrow$ **atomic mass**

coupling constant

SD: $\sigma_o = \frac{32(J+1)}{\pi J} G_F^2\, m_r^2\, (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$

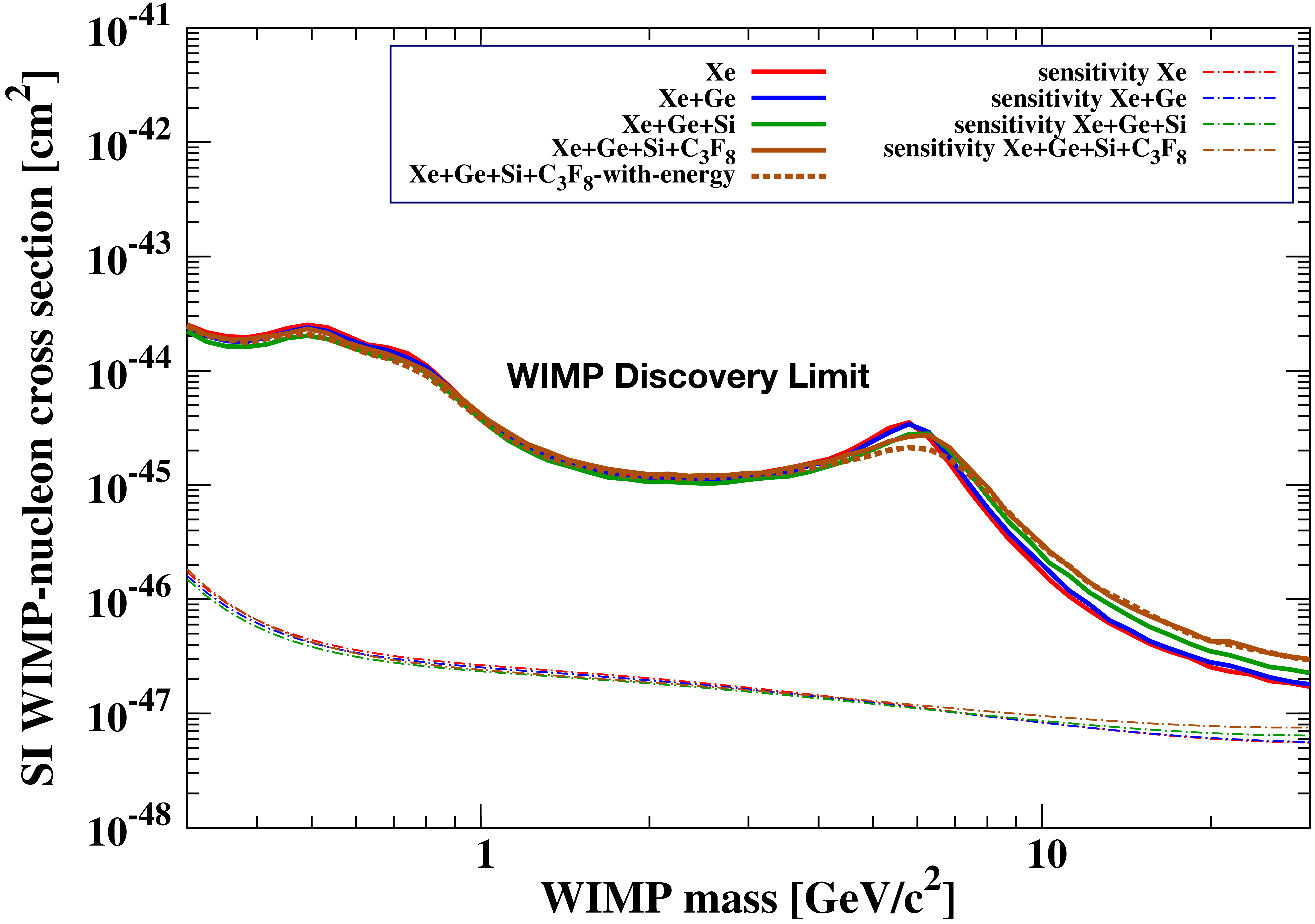
Nuclear Angular Momentum **Fermi constant** **Coupling constant** **Spin**





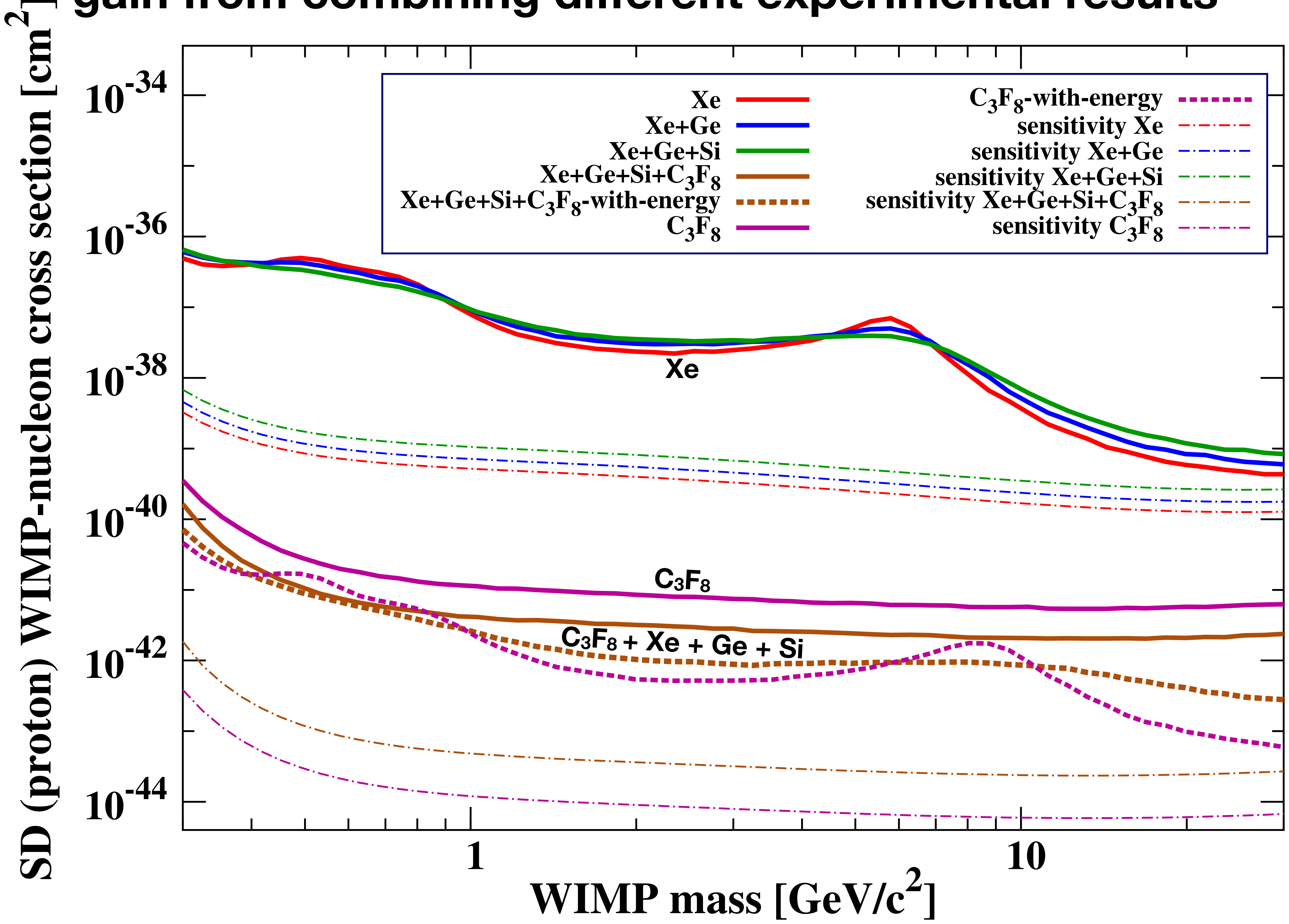
Target Complementarity: Spin Independent

For Spin Independent Interactions, there is little gain from combining different experimental results



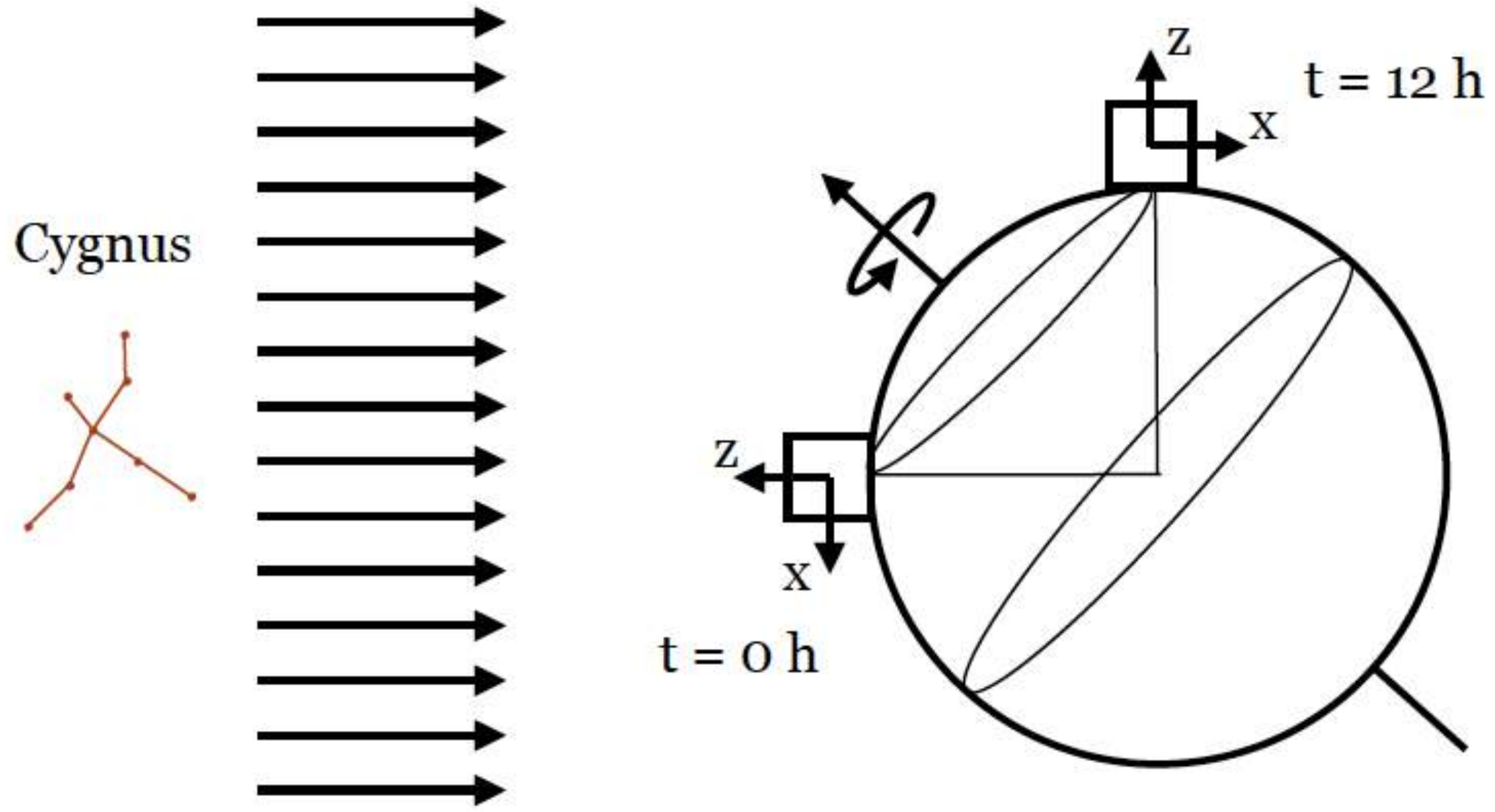
Target Complementarity: Spin Dependent

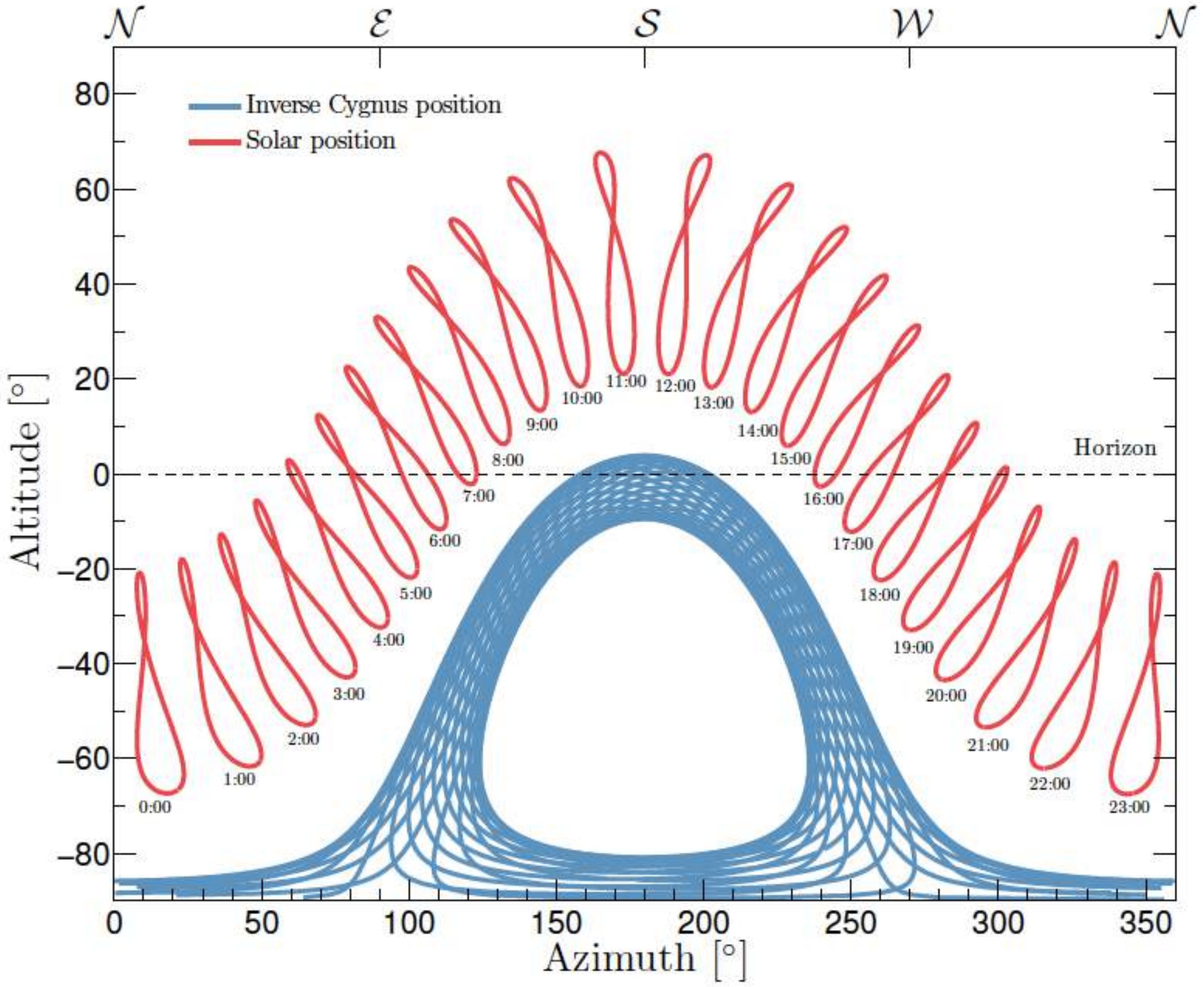
For Spin Dependent Interactions, there is some gain from combining different experimental results



Directional Detectors and the Neutrino Background

- We see a “dark matter wind” in the laboratory due to the motion of the solar system in the Galaxy.
- This wind changes apparent direction in the lab frame due to the diurnal rotation of the Earth
- The direction of the dark matter wind does not overlap with the position of the Sun in the sky, and thus the direction of solar neutrinos is always different than the dark matter wind.
- We can use this to differentiate dark matter signals from neutrino backgrounds!



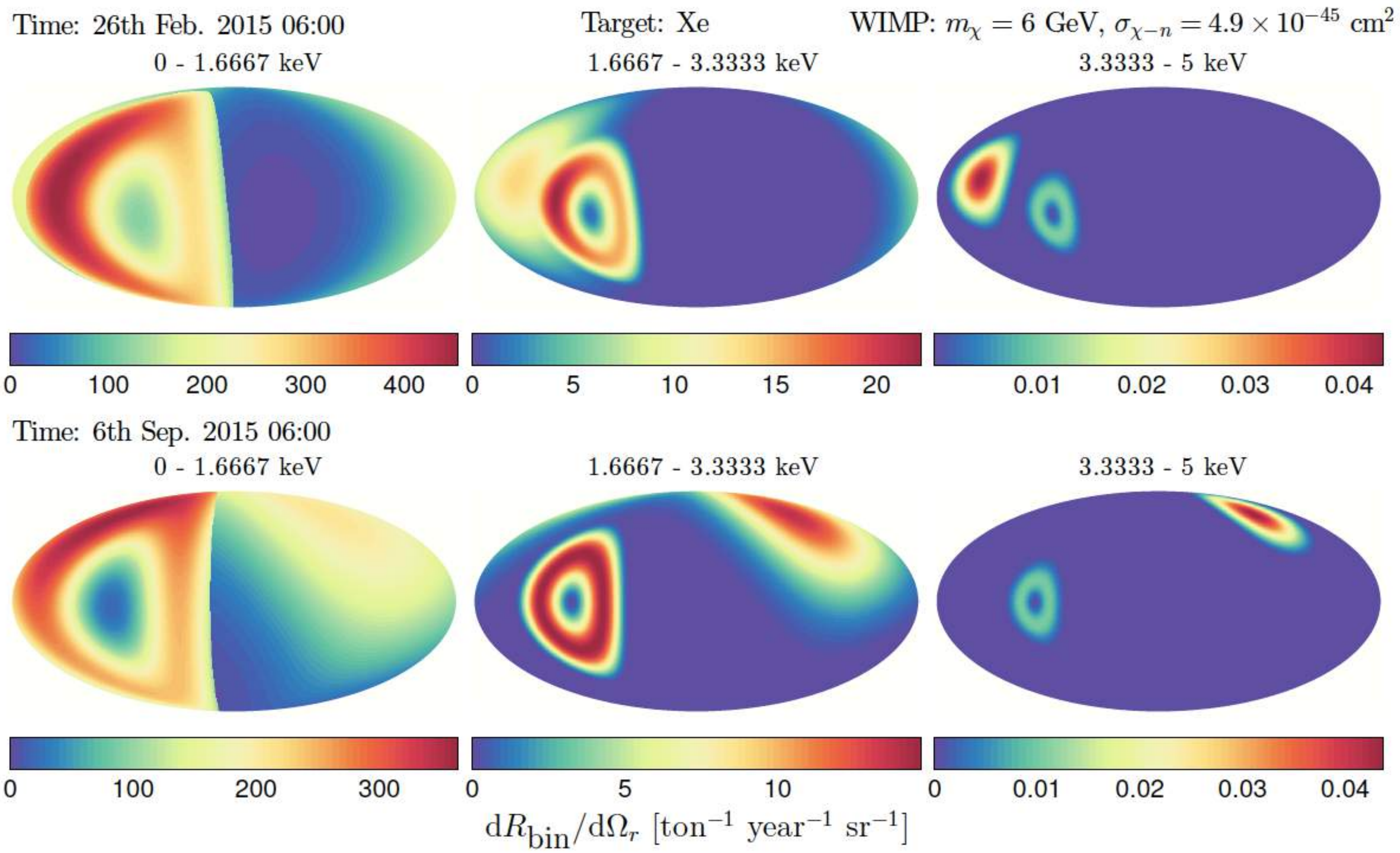


C.A.J. O'Hare, A.M. Green, J. Billard, EFF, L.E. Strigari, arXiv:1505.08061

Directional Detectors and the Neutrino Background

Minimum DM-Sun Separation (60º)

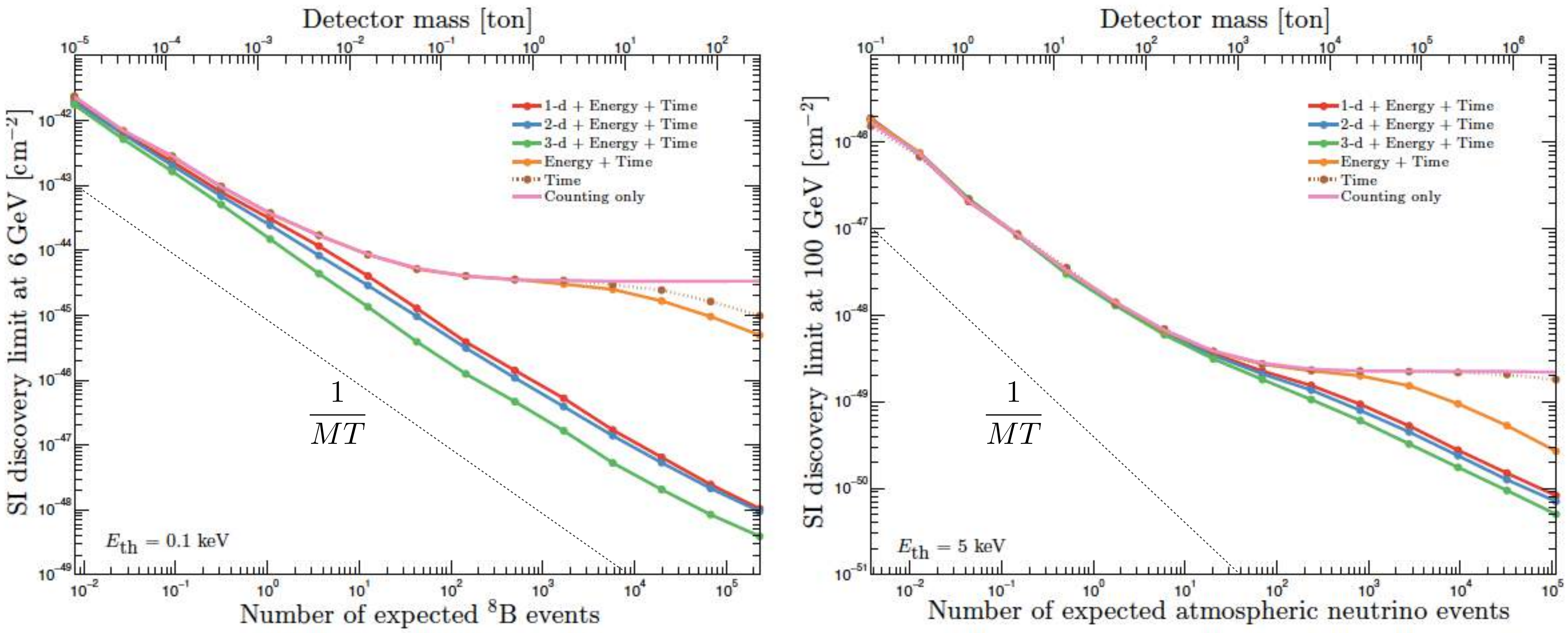
Maximum DM-Sun Separation (120º)



C.A.J. O'Hare, A.M. Green, J. Billard, EFF, L.E. Strigari, arXiv:1505.08061

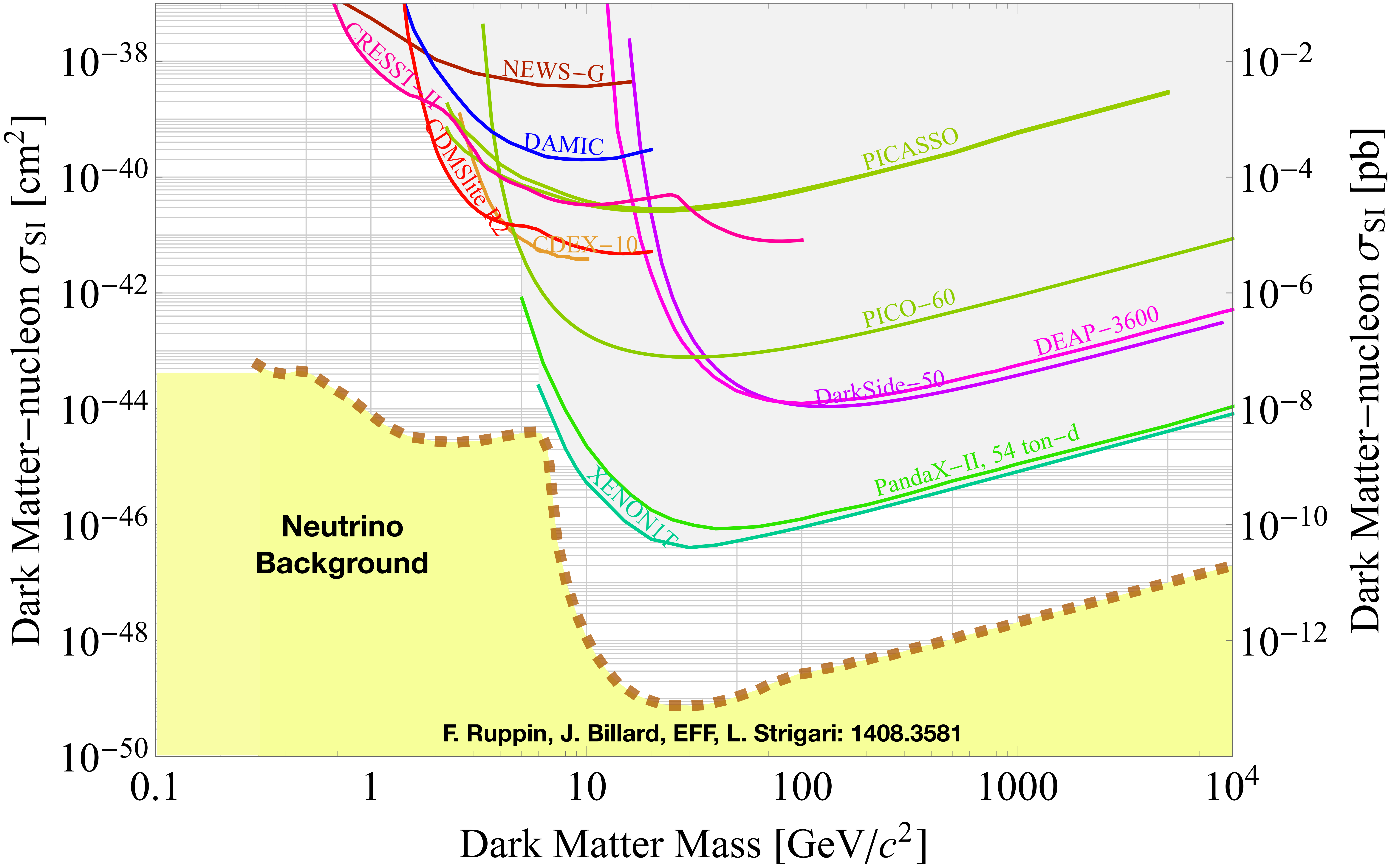
Directional Detectors and the Neutrino Background

- Directional Detectors can keep dark matter searches “background free” from solar neutrinos (note in this study we ignored other backgrounds!)
- Atmospheric Neutrinos look isotropic to directional detectors, and thus still form an irreducible background
- The technology to perform directional detector searches at these exposures is not yet at hand, but this study motivates their continued development



C.A.J. O'Hare, A.M. Green, J. Billard, EFF, L.E. Strigari, arXiv:1505.08061

The "Neutrino Floor" will be a hard wall for a while…



F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

End of Lecture 3