Centre for Dark Matter Particle Physics

THE UNIVERSITY OF SYDNEY

Breaking through the neutrino floor

11 November 2019

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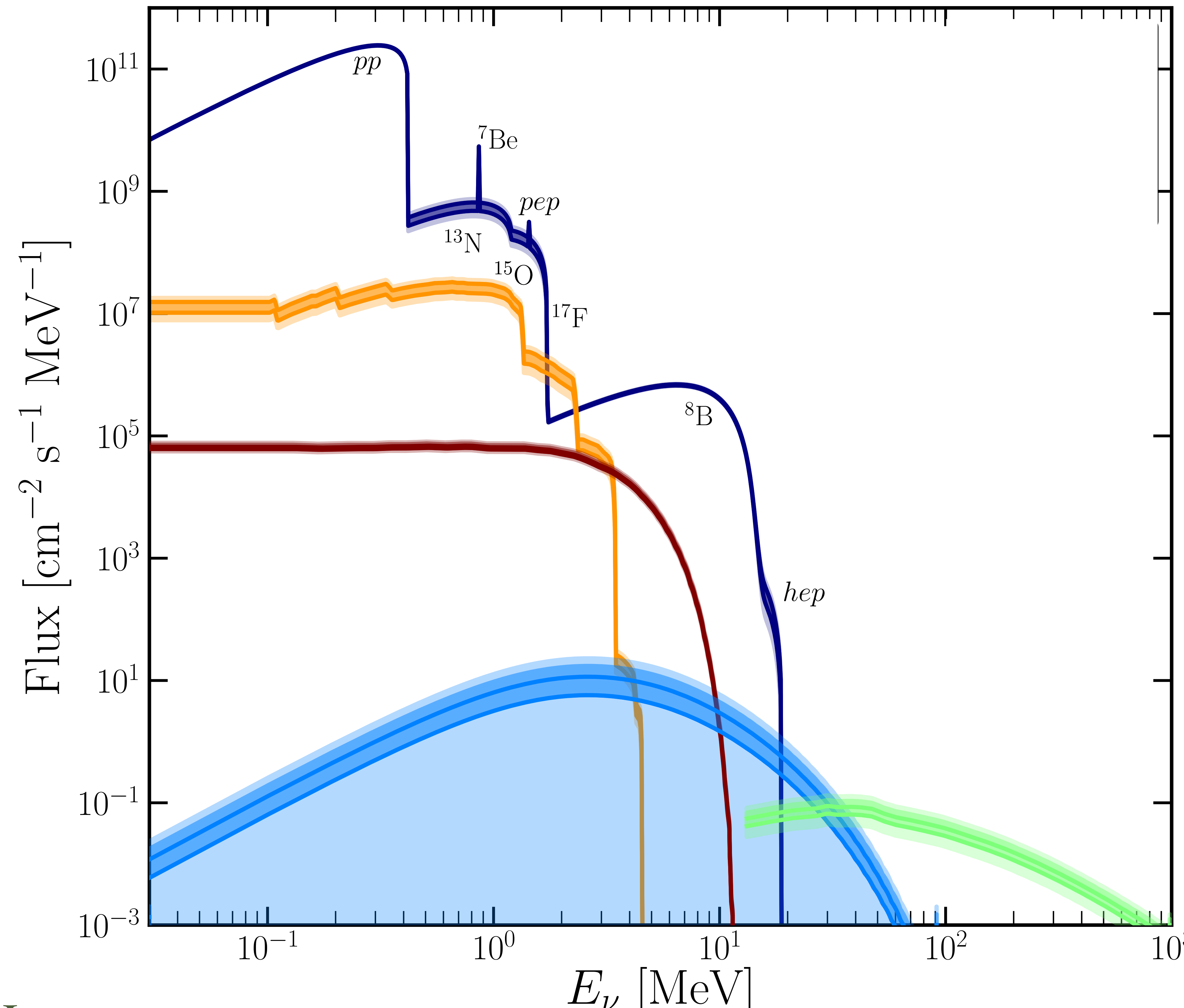
University of Sydney

How to break through the neutrino floor:

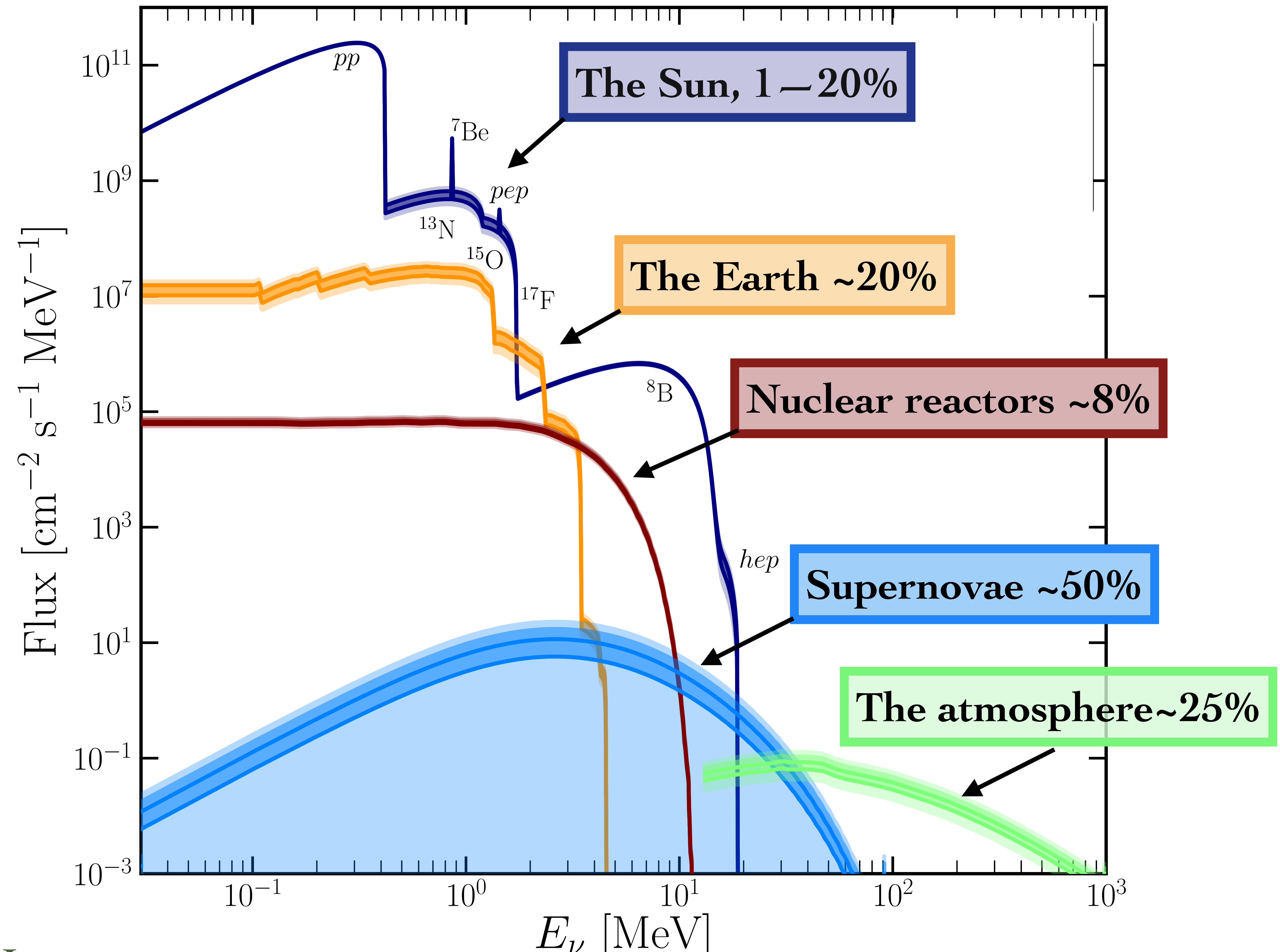
5 methods, ordered in increasing effectiveness

1. Detect *a lot* of events
2. Improve neutrino flux measurements
3. Use annual modulation
4. Have multiple target nuclei
5. Use directional detectors

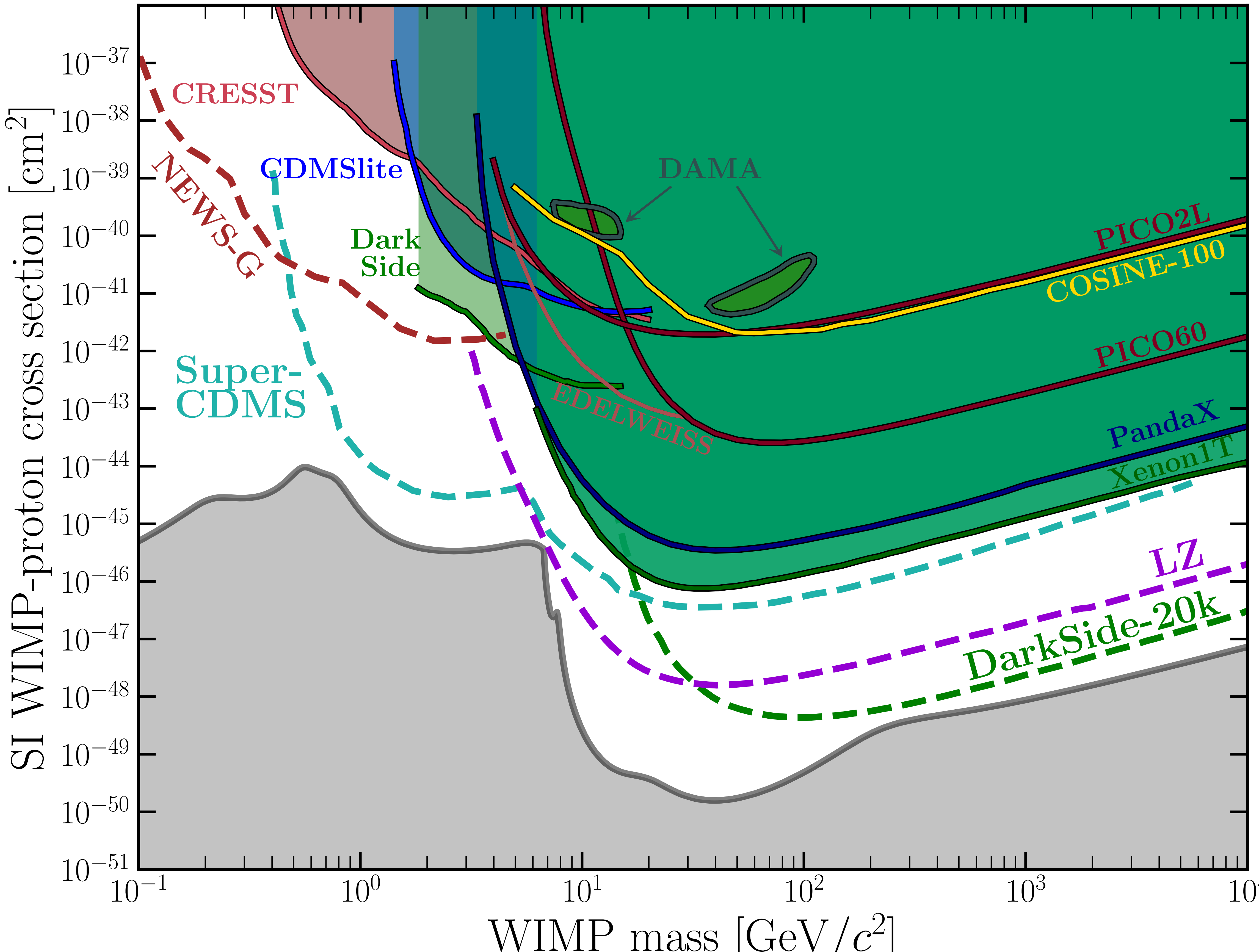
(Recap) Neutrino flux uncertainties



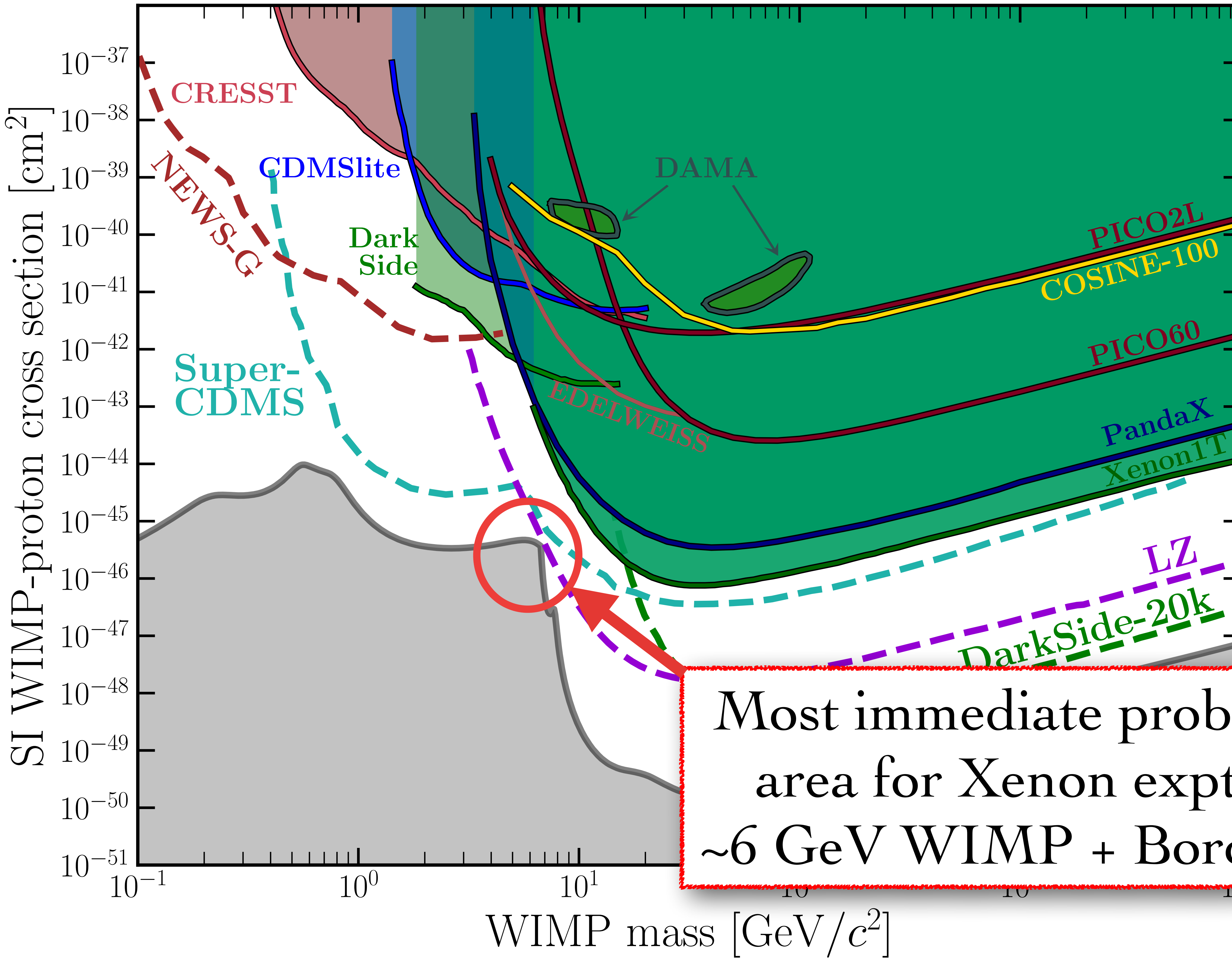
(Recap) Neutrino flux uncertainties



(Recap) The neutrino floor

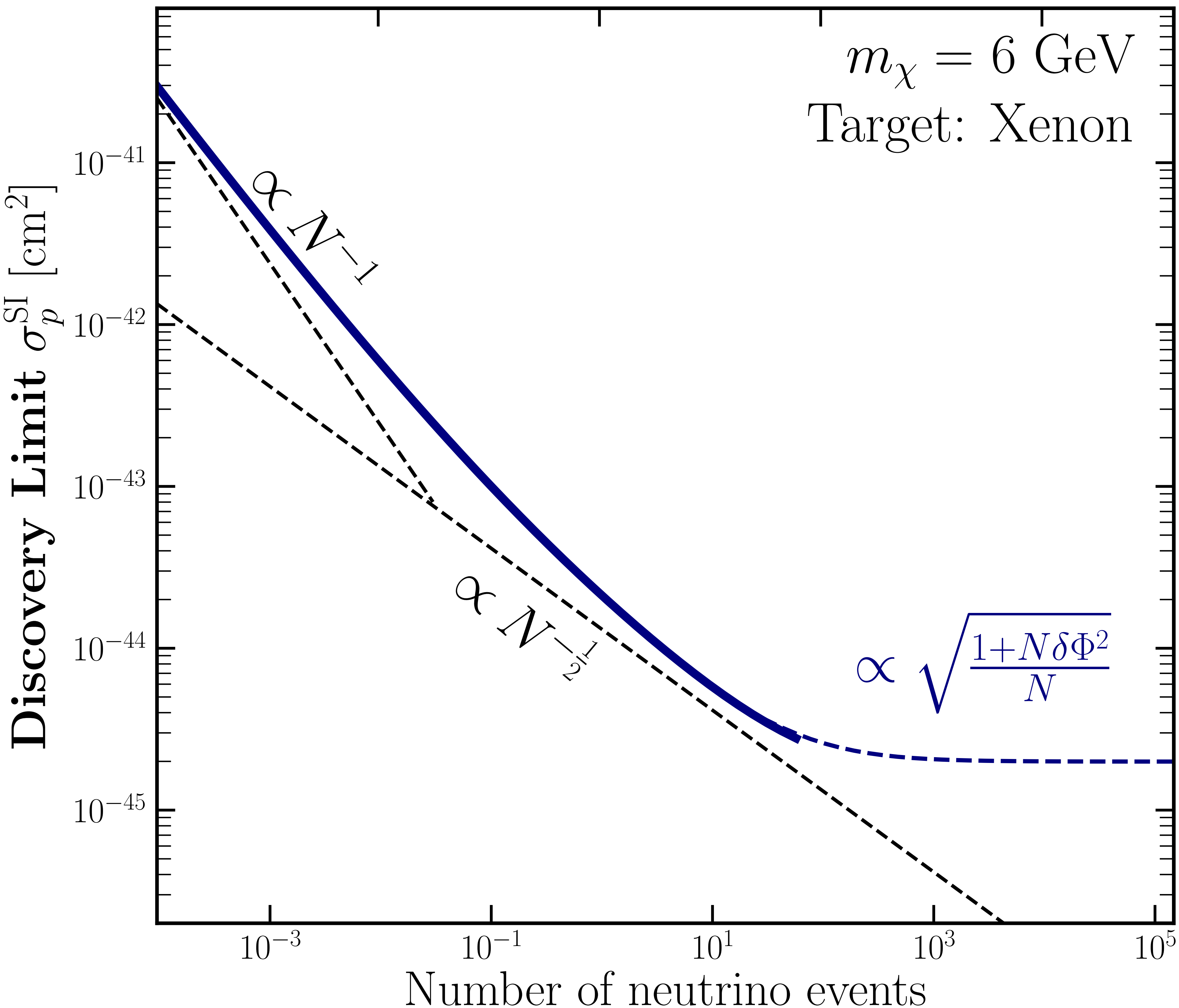


(Recap) The neutrino floor



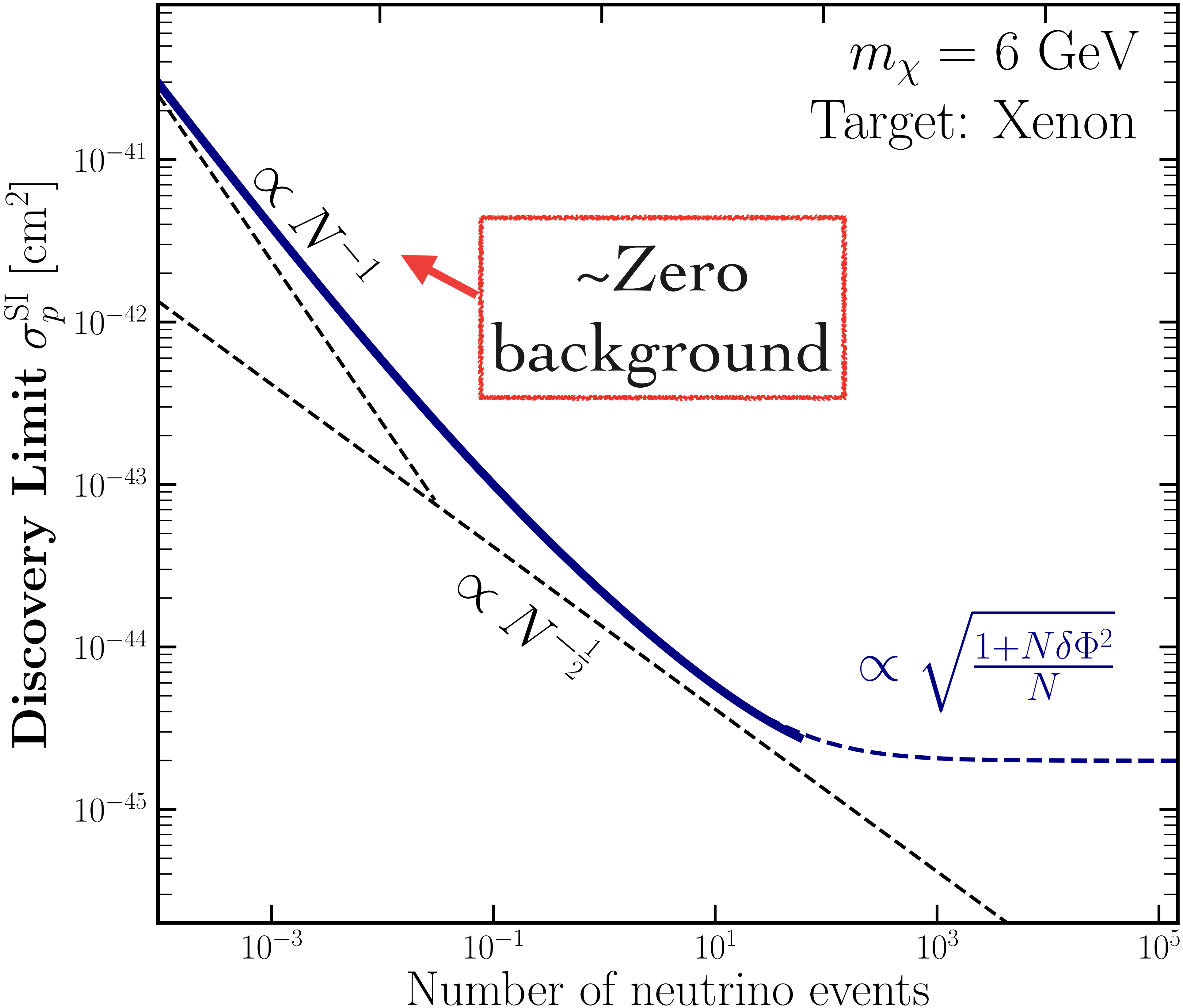
Most immediate problem area for Xenon expts.
~6 GeV WIMP + Boron-8

Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos



$\delta\Phi$ = flux uncertainty

Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos



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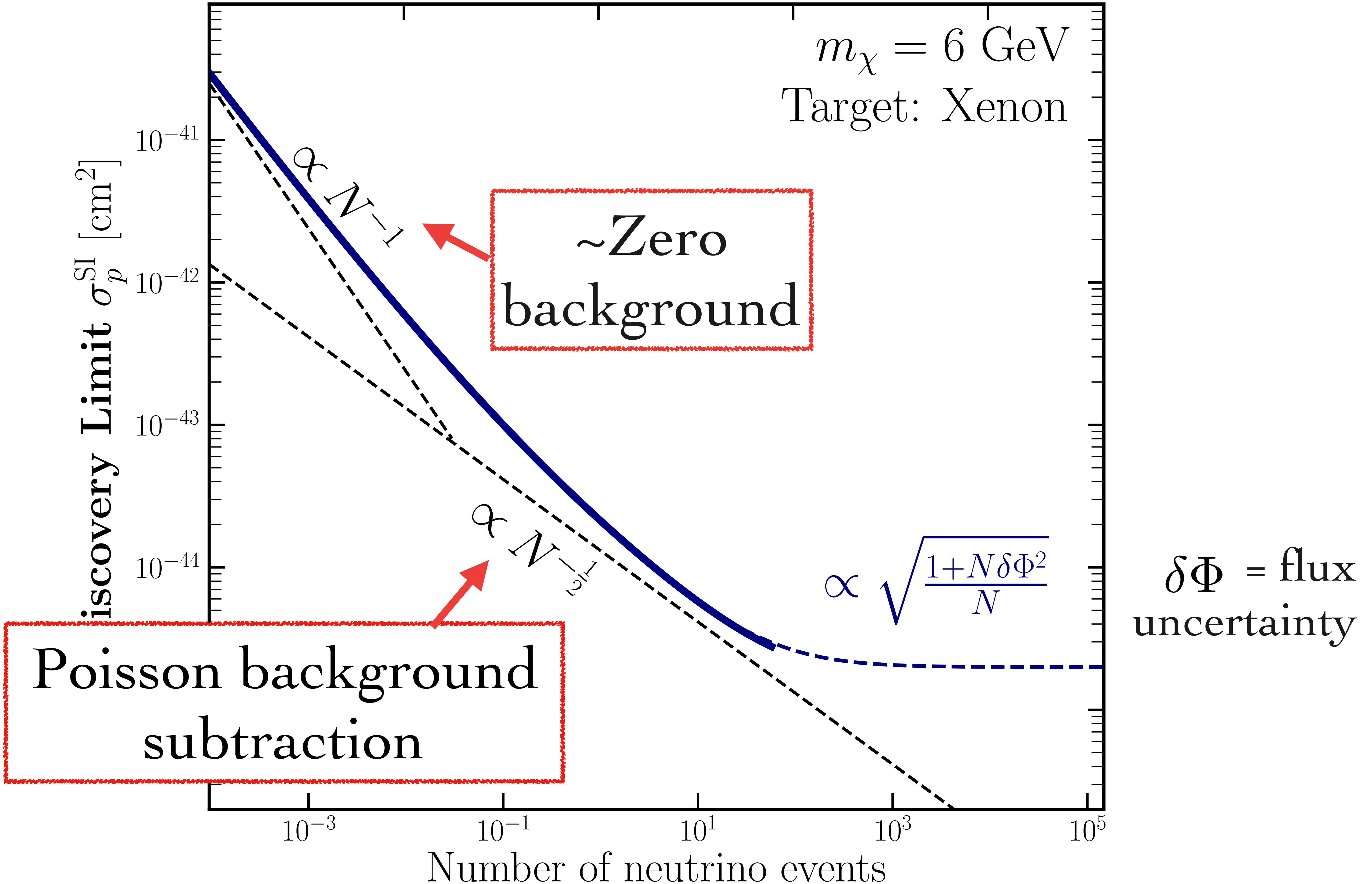
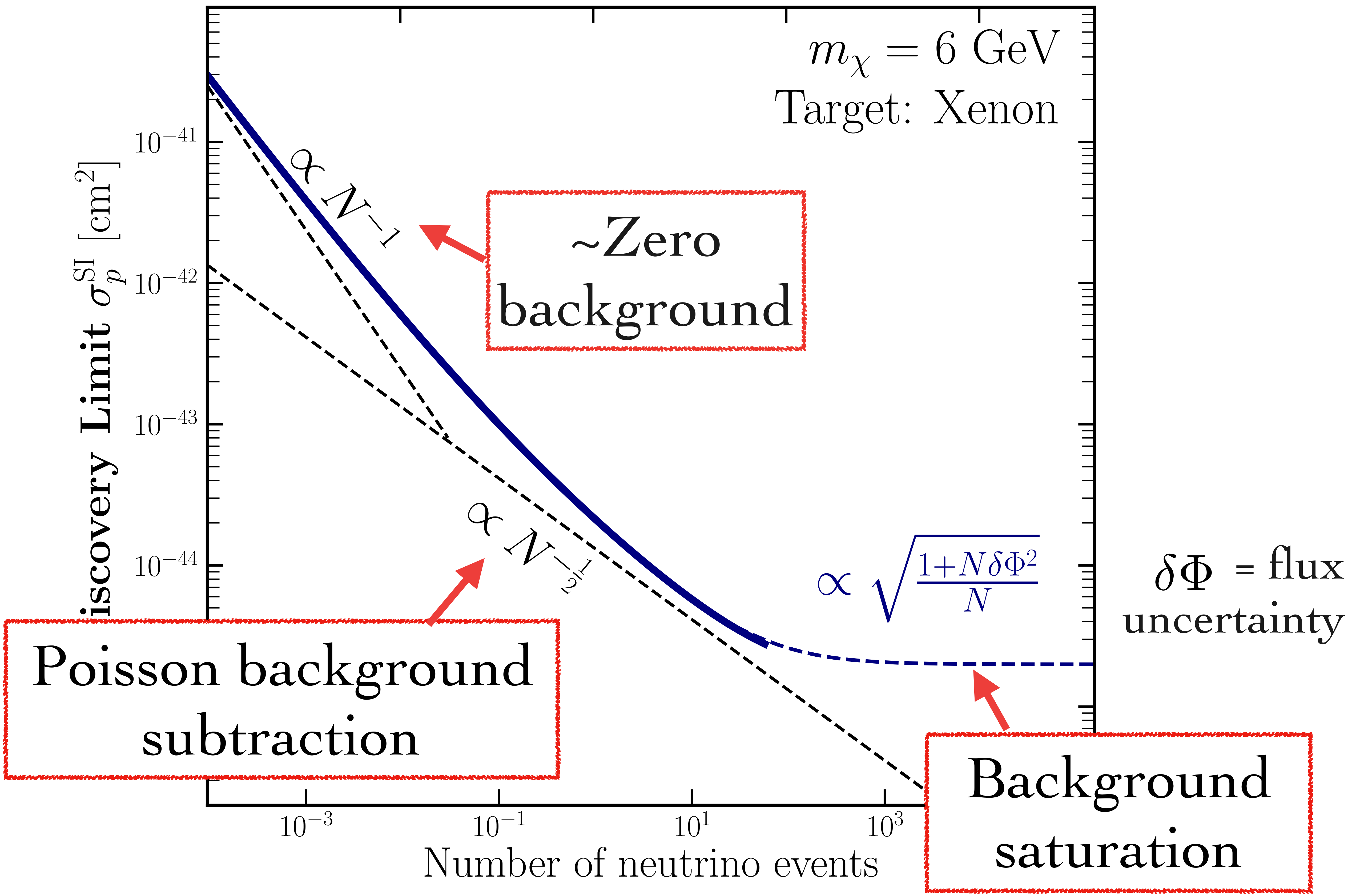
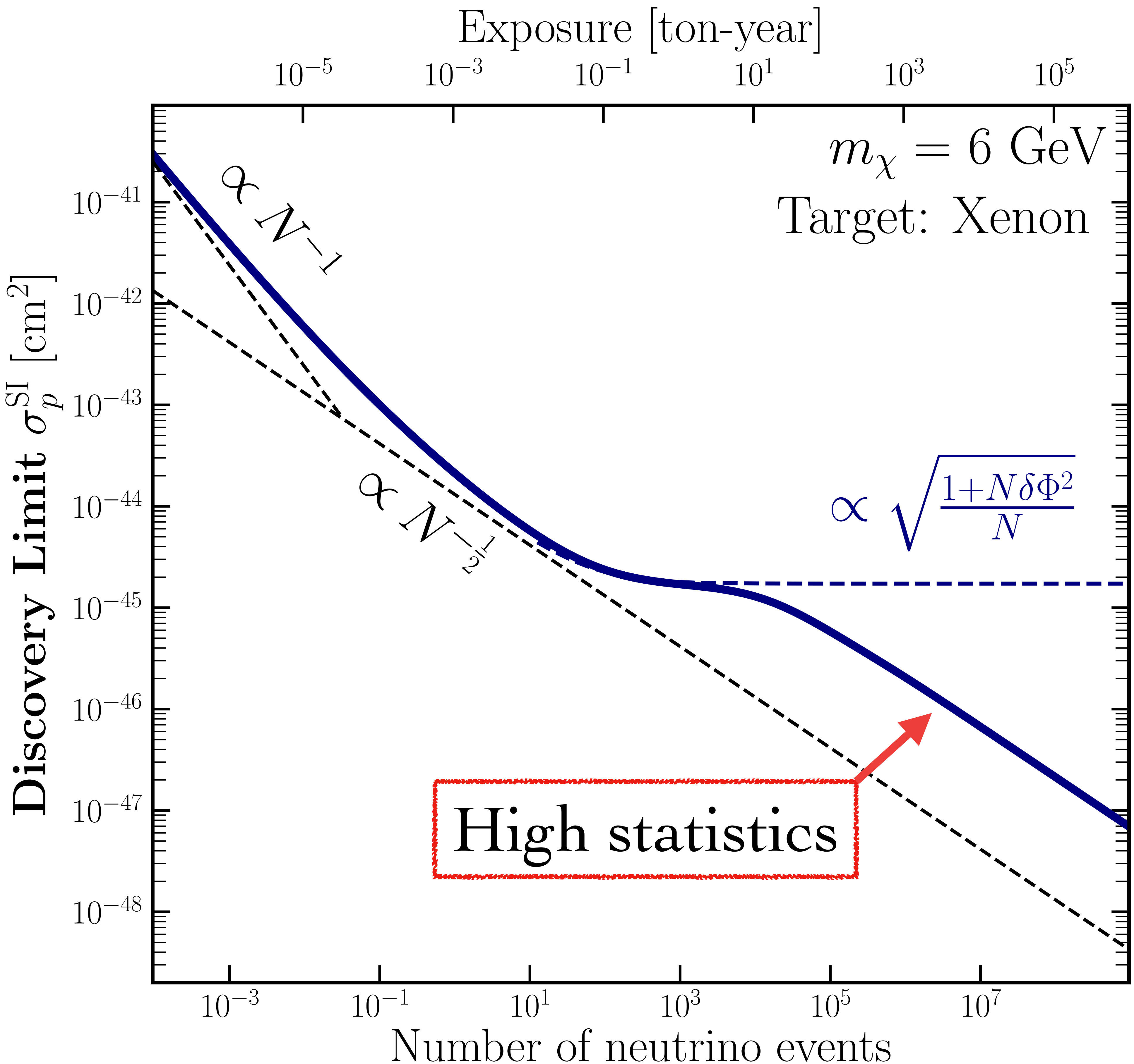
Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos



Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos





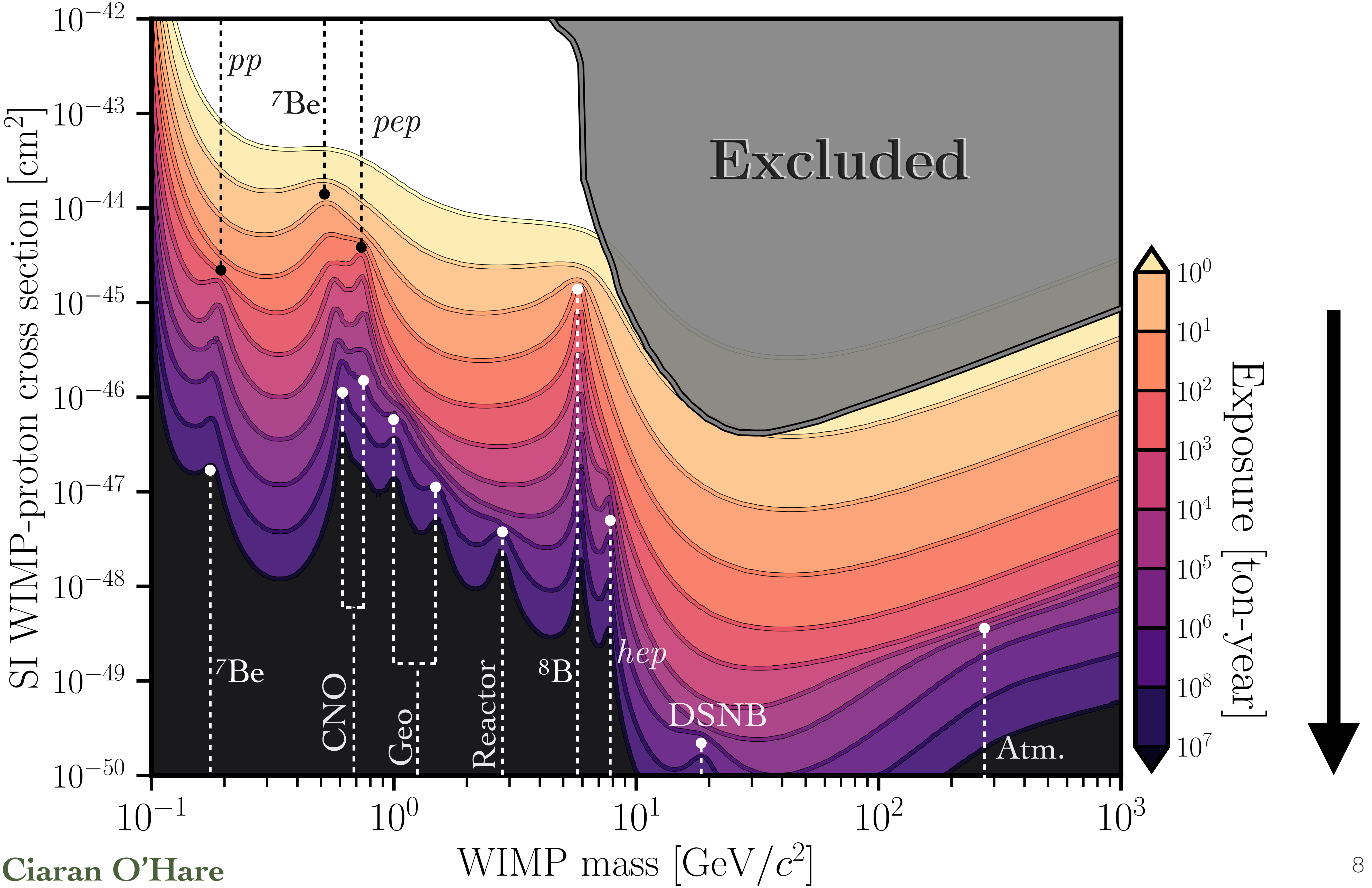
WIMP/ Neutrinos not **identical**

→ at very high statistics, can start to discriminate

Method 1: Use recoil energies

But this requires a lot of events, and very good energy reconstruction

This means you can push through the background
<u>but very slowly</u>



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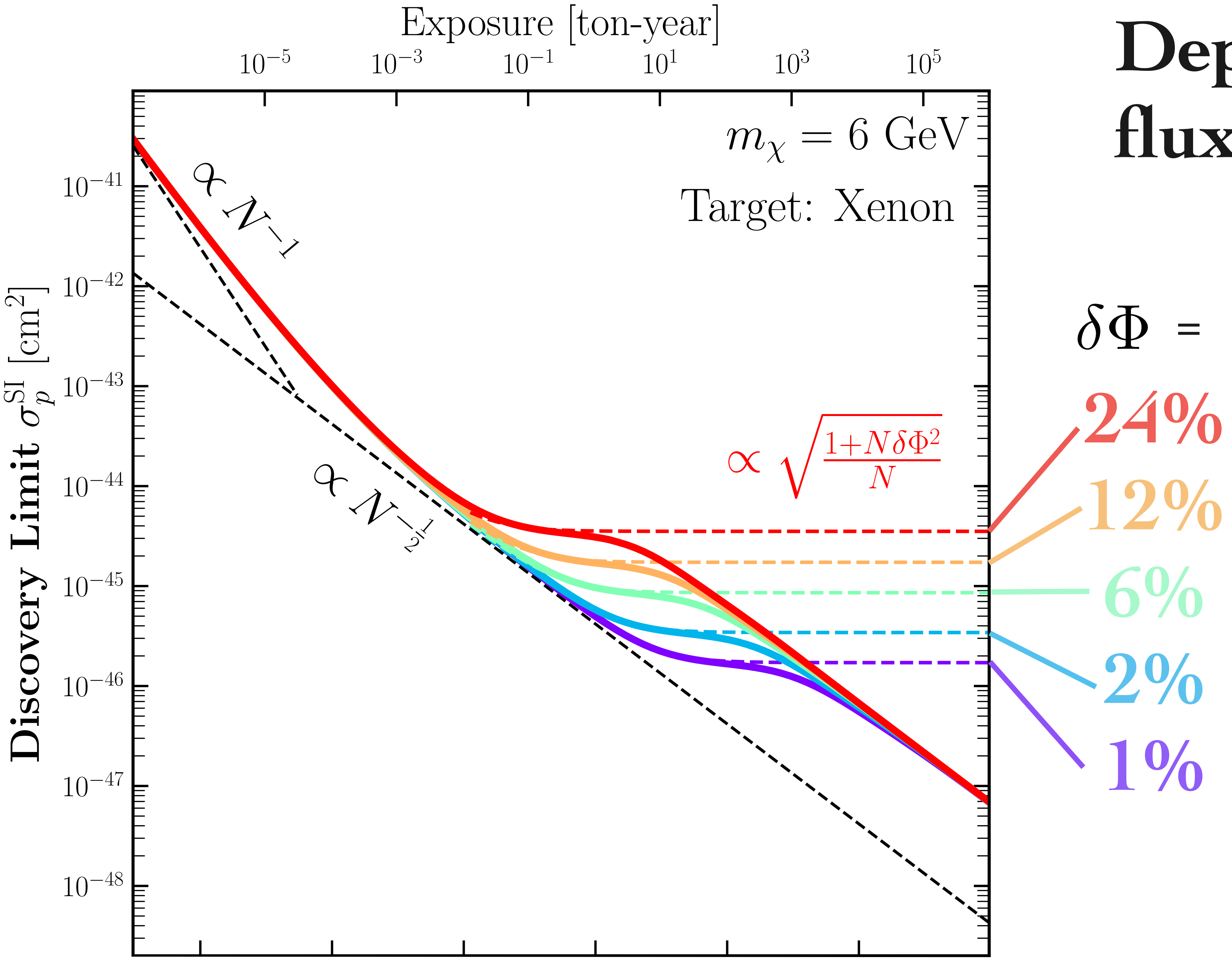
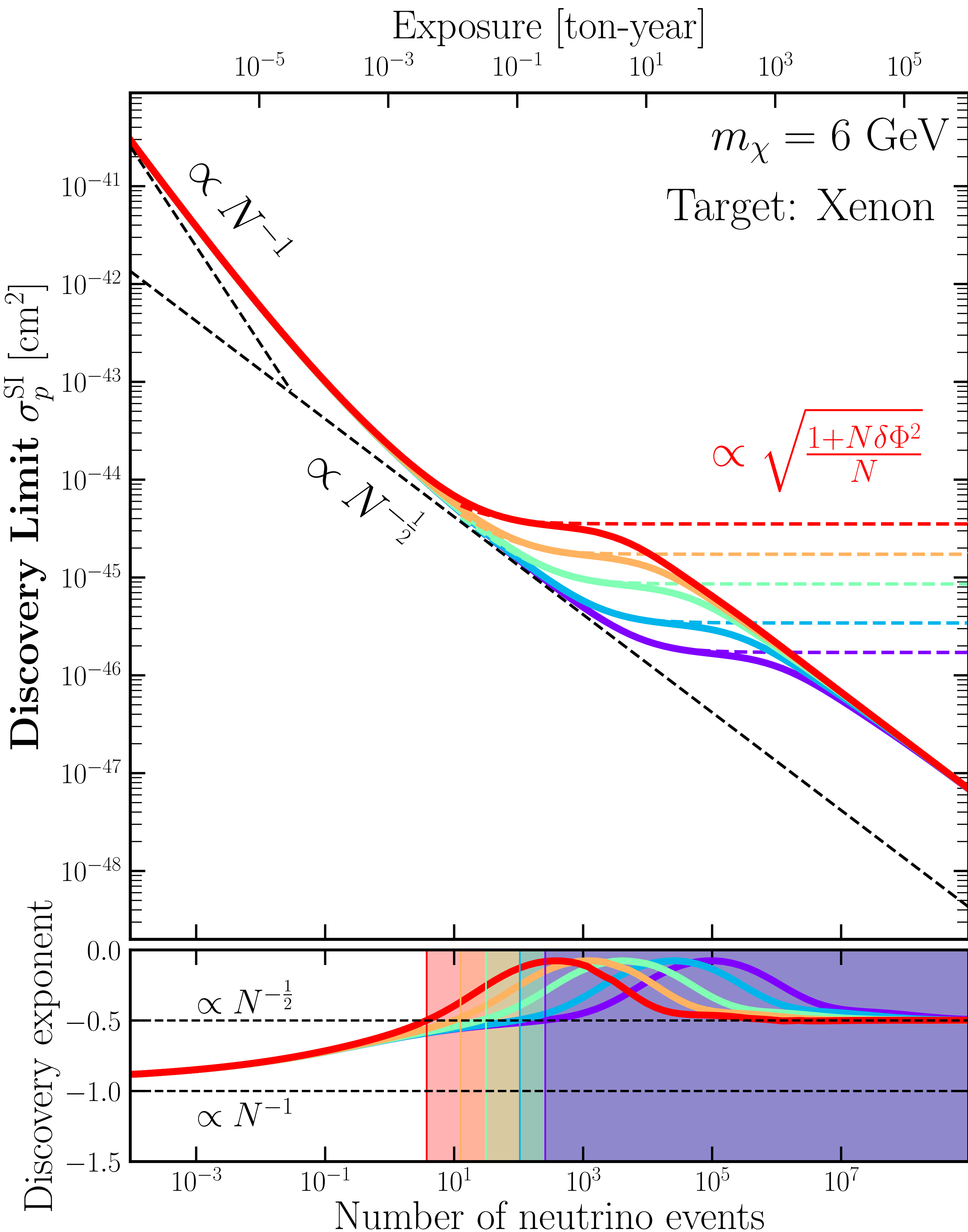
Dependence on flux uncertainty



Better flux measurement → neutrino floor is lower

Dependence on flux uncertainty



$\delta\Phi$ =

24%

12%

6%

2%

1%

Better flux measurement → neutrino floor is lower

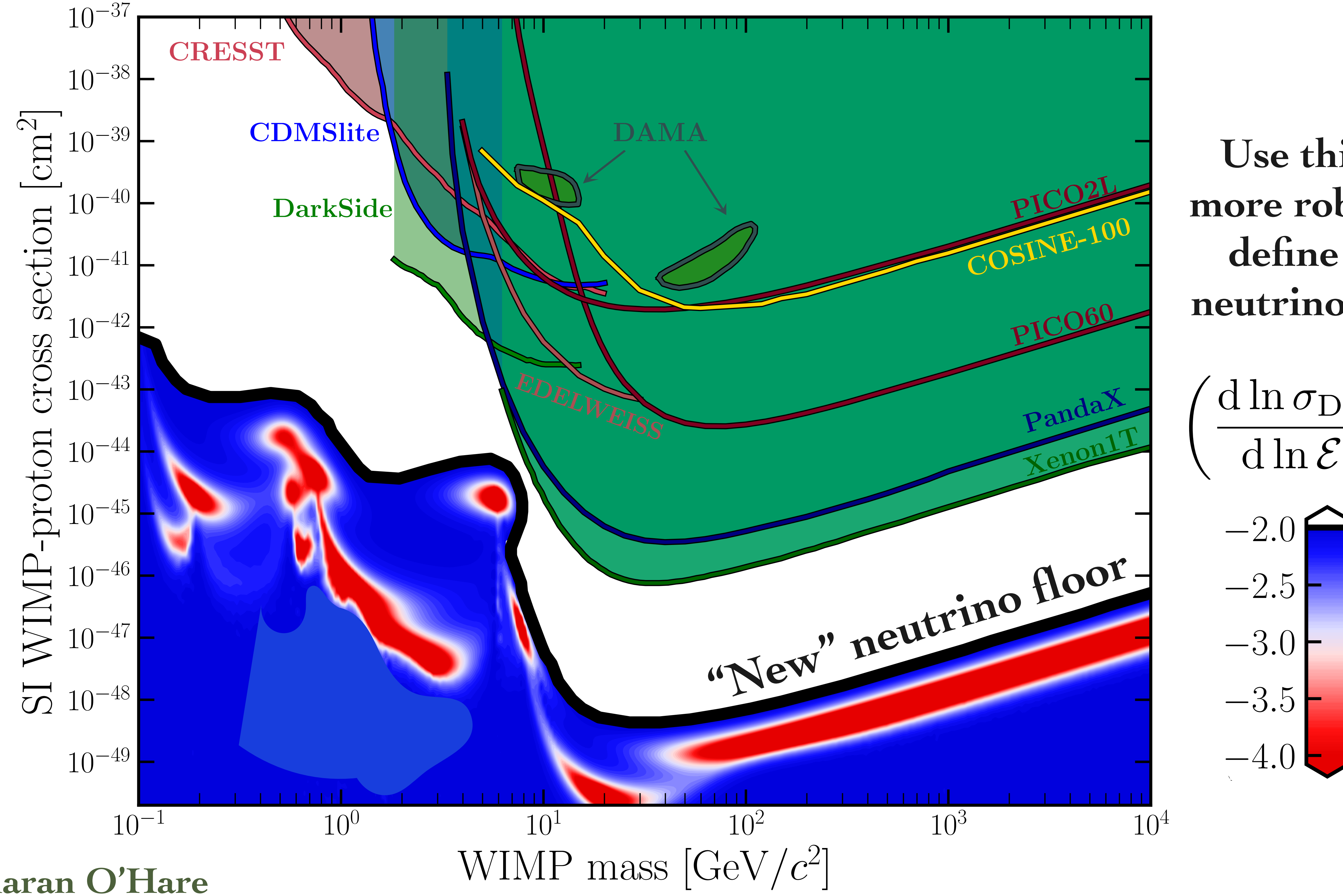
$$\frac{\text{d}\log(\text{discovery limit})}{\text{d}\log(\text{exposure})}$$

~~Method 1: Detect a lot of events~~

Method 2: Improve neutrino flux measurements

But this doesn't break through the neutrino floor,
it merely **delays** it

$$\left(\frac{\mathrm{d(Discovery\ limit)}}{\mathrm{d(Exposure)}}\right)^{-1} = -2$$ for standard Poissonian background subtraction



Use this to more robustly define the neutrino floor

$$\left(\frac{\mathrm{d}\ln\sigma_{\rm DL}}{\mathrm{d}\ln\mathcal{E}}\right)^{-1}$$

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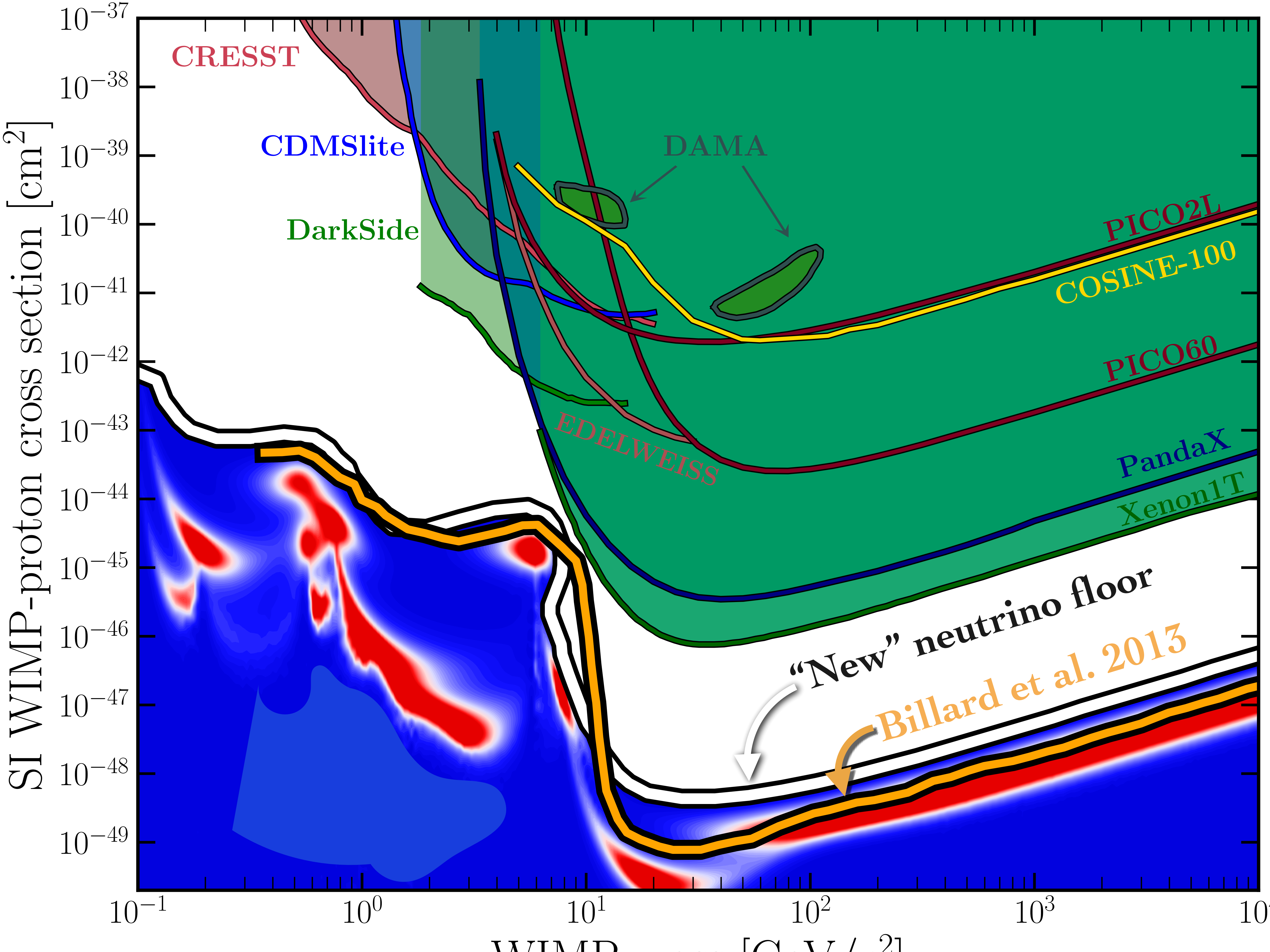

CRESST
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
PandaX
Xenon1T
"New" neutrino floor
Billard et al. 2013
SI WIMP-proton cross section [cm^2]
WIMP mass [GeV/c^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

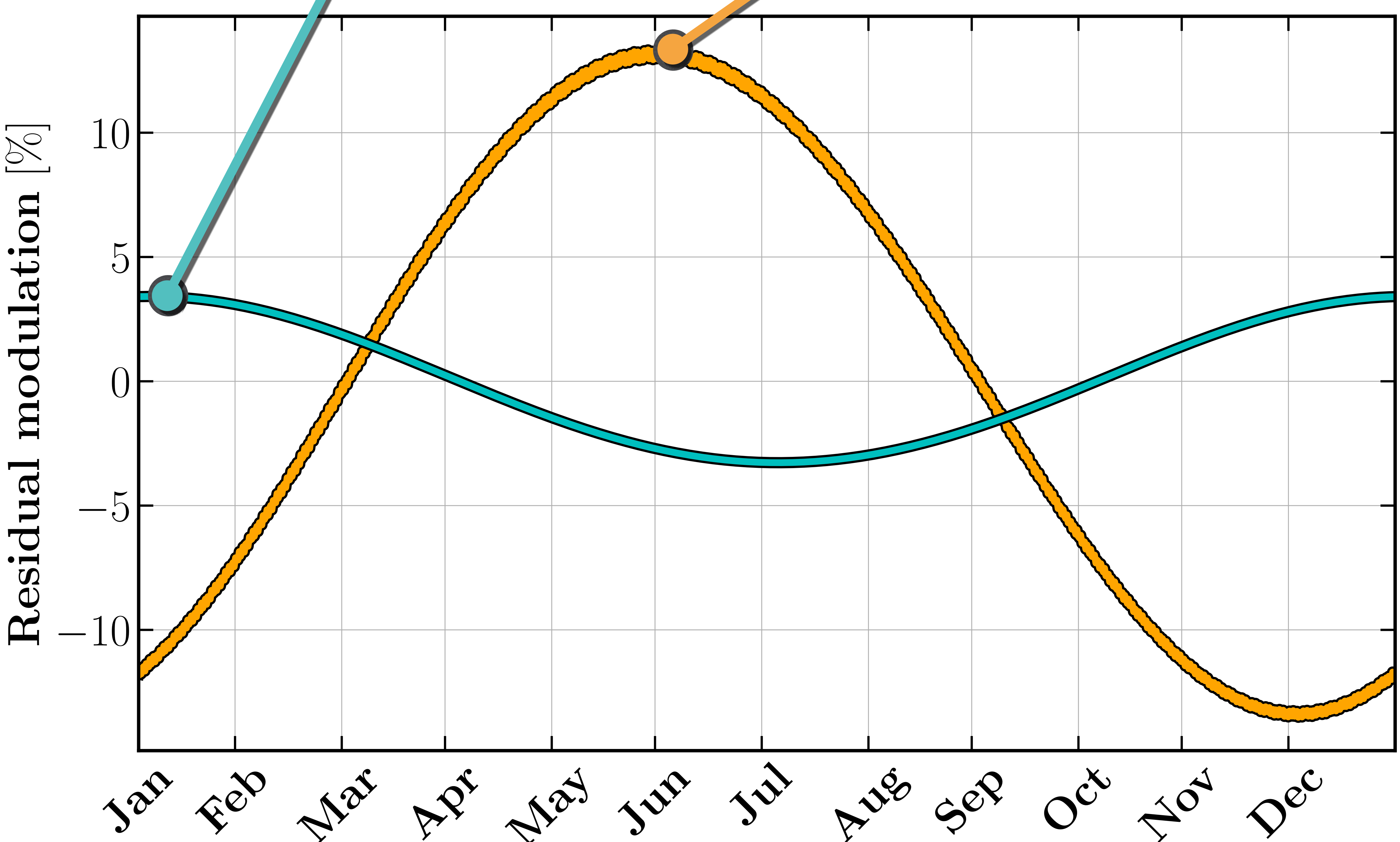
We want to **overcome** the neutrino floor,
Not just move it somewhere else

We need **more information**

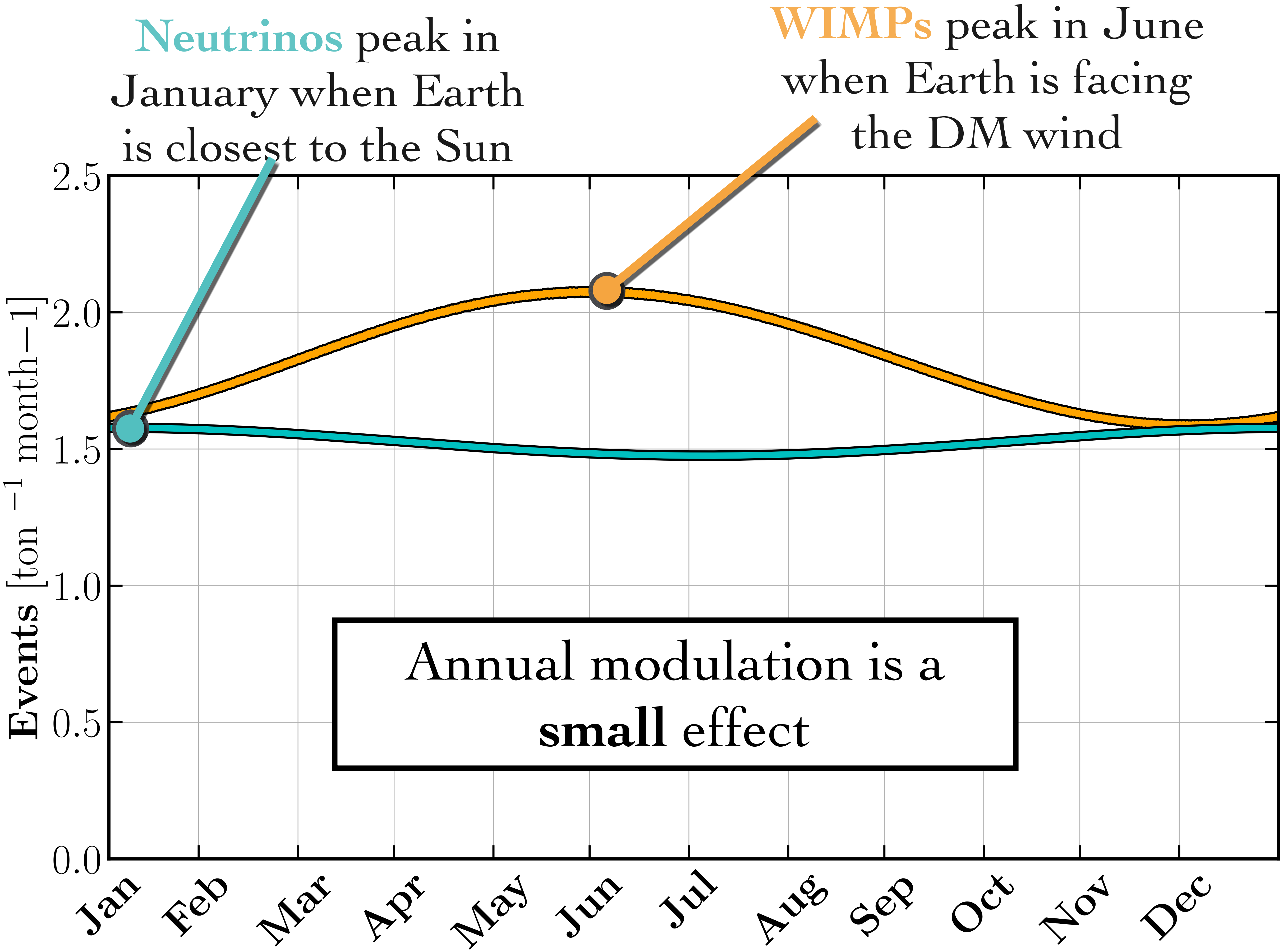
Annual modulation

Neutrinos peak in January when Earth is closest to the Sun

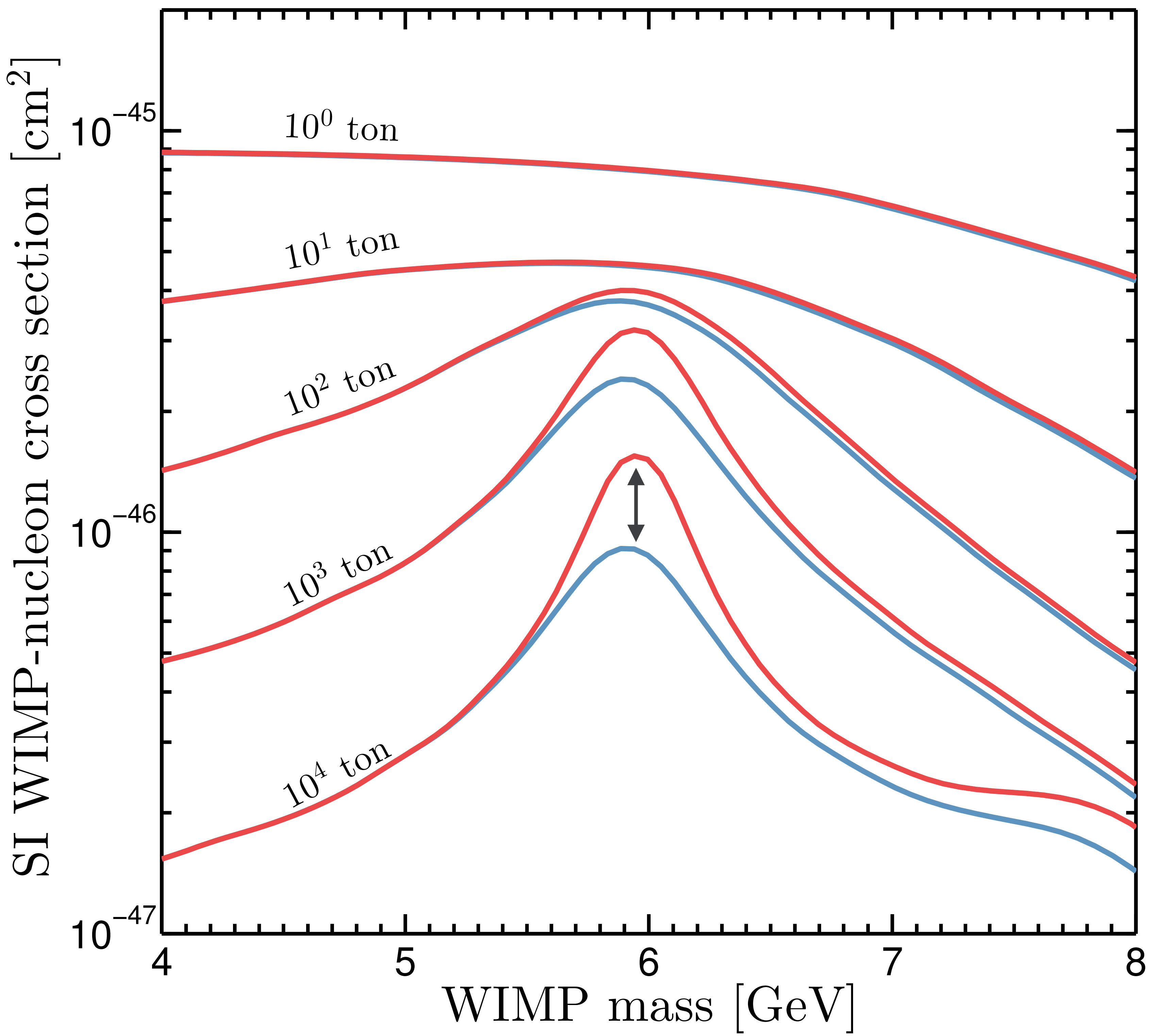
WIMPs peak in June when Earth is facing the DM wind



Annual modulation



Annual modulation: does it help?



Information used:

Energy only

Energy+Time

Increasing exposure

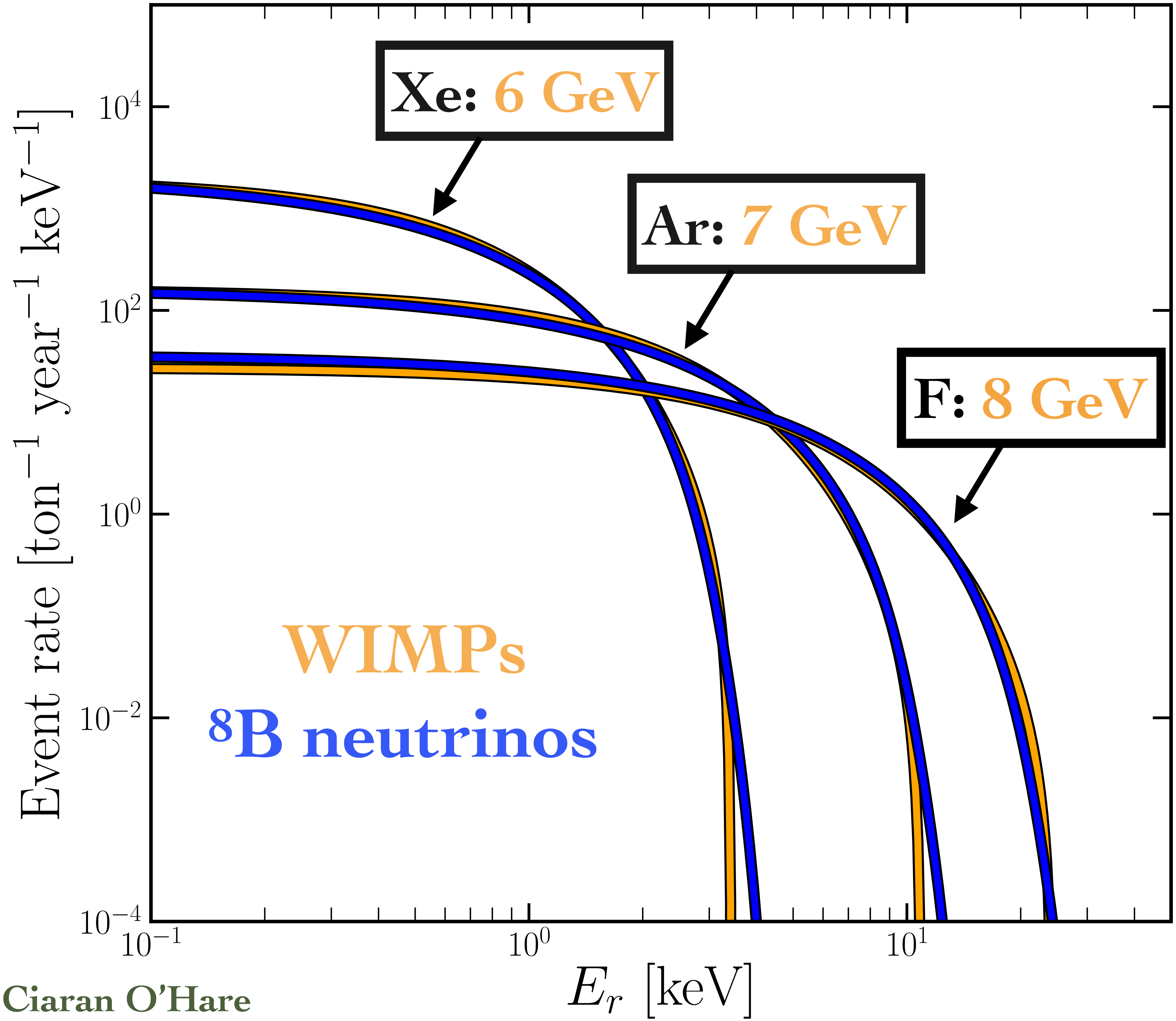
~~Method 1: Detect a lot of events~~

~~Method 2: Improve neutrino flux measurements~~

Method 3: Use annual modulation

This helps, but the signal is **too small**

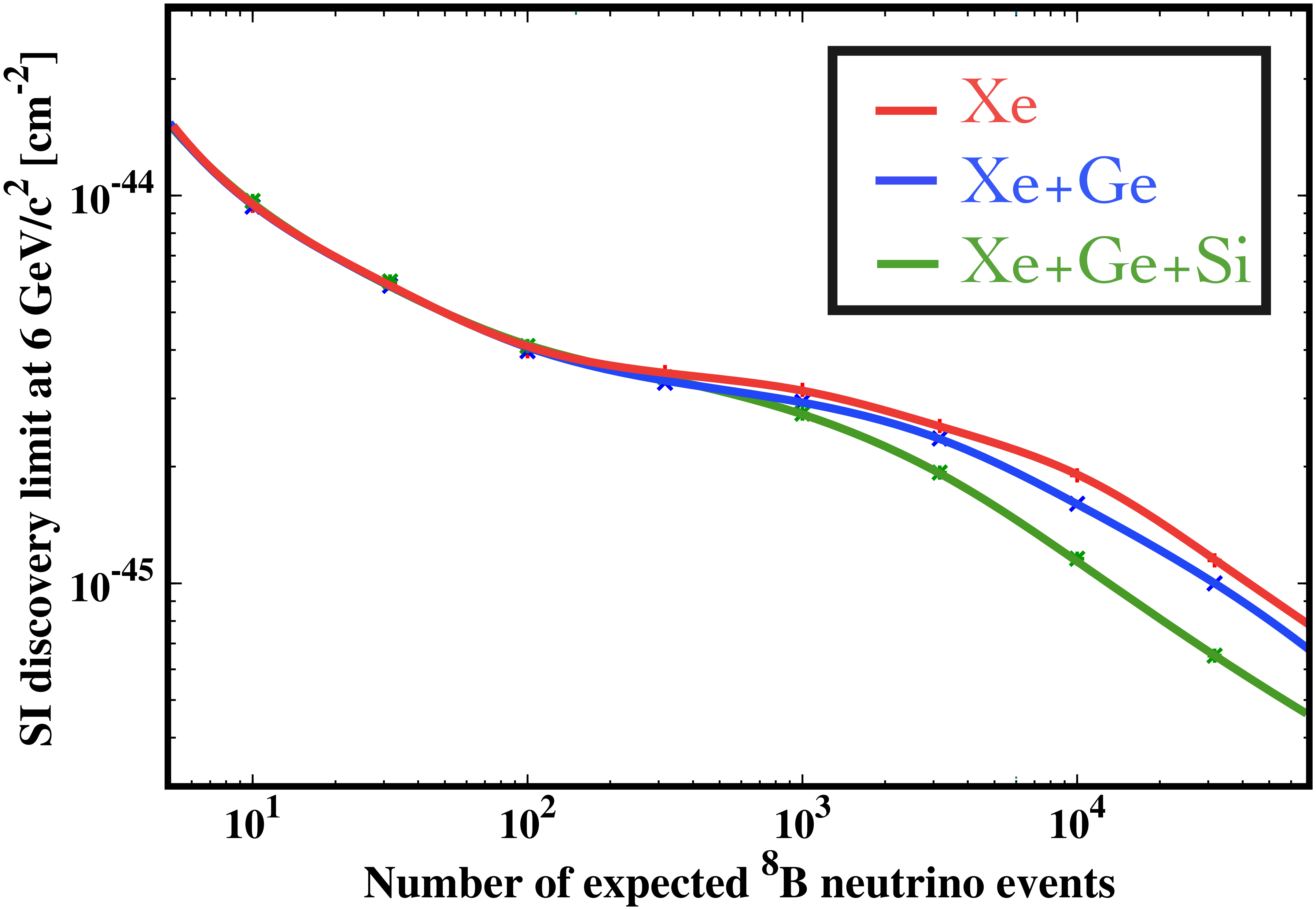
Target complementarity



Neutrinos look like different WIMP masses, for different target nuclei

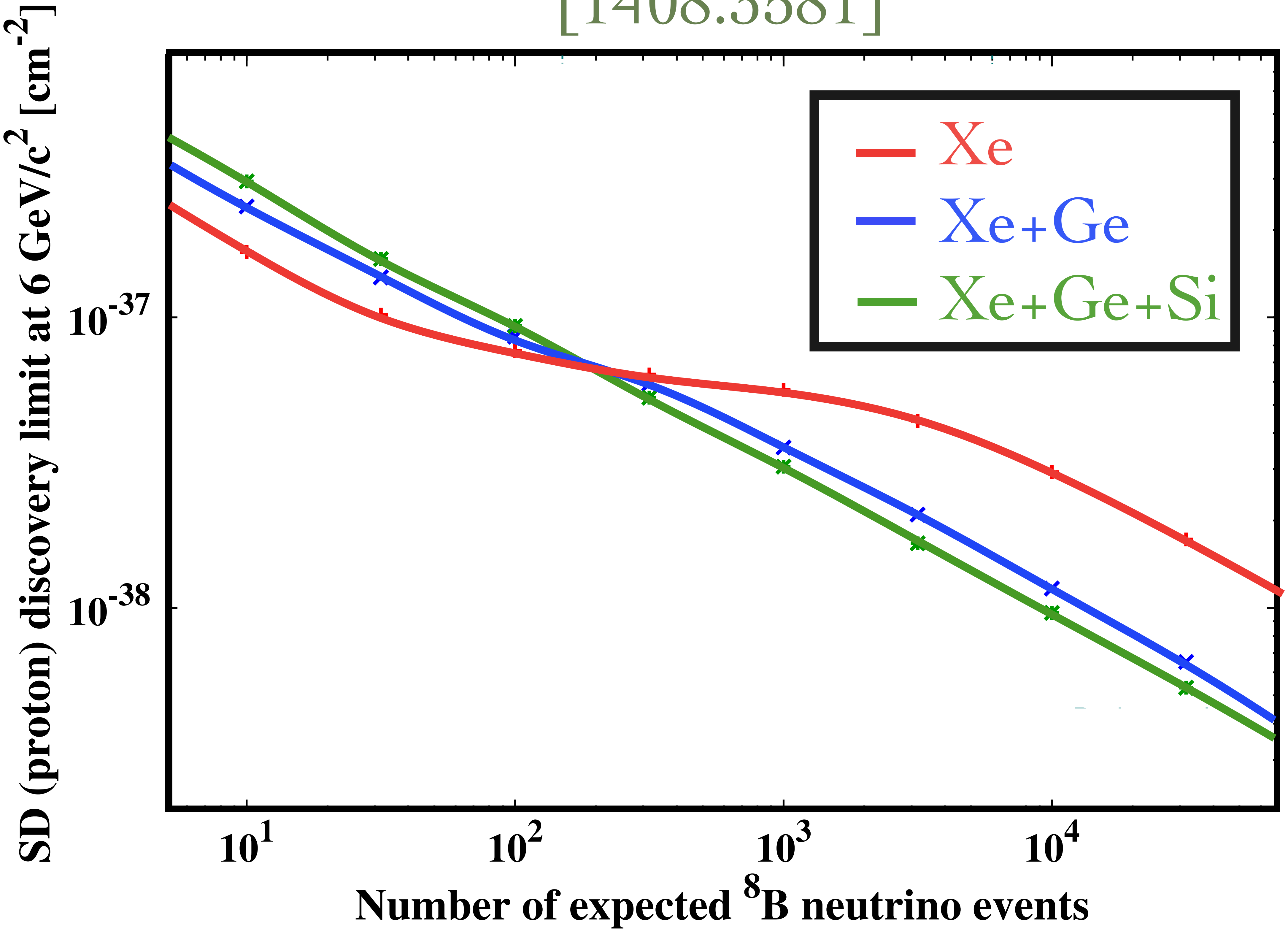
Target complementarity (SI)

[1408.3581]



Target complementarity (SD)

[1408.3581]



~~Method 1: Detect a lot of events~~

~~Method 2: Improve neutrino flux measurements~~

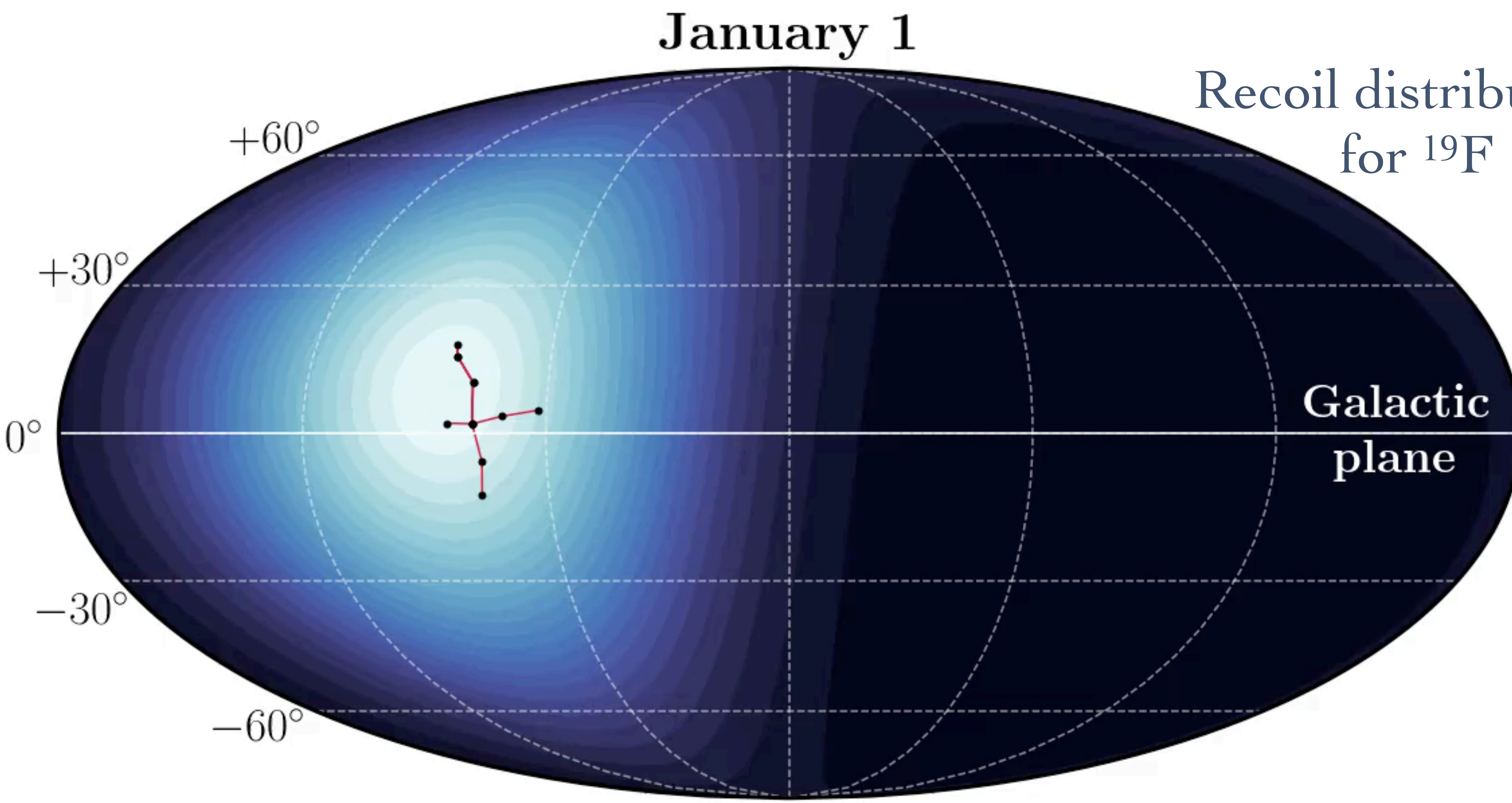
~~Method 3: Use annual modulation~~

Method 4: Use multiple targets

This helps too, but only substantially for SD interactions, and still requires a lot of events

Directional detection

Nothing other than dark matter will give a signal that points back to Cygnus,

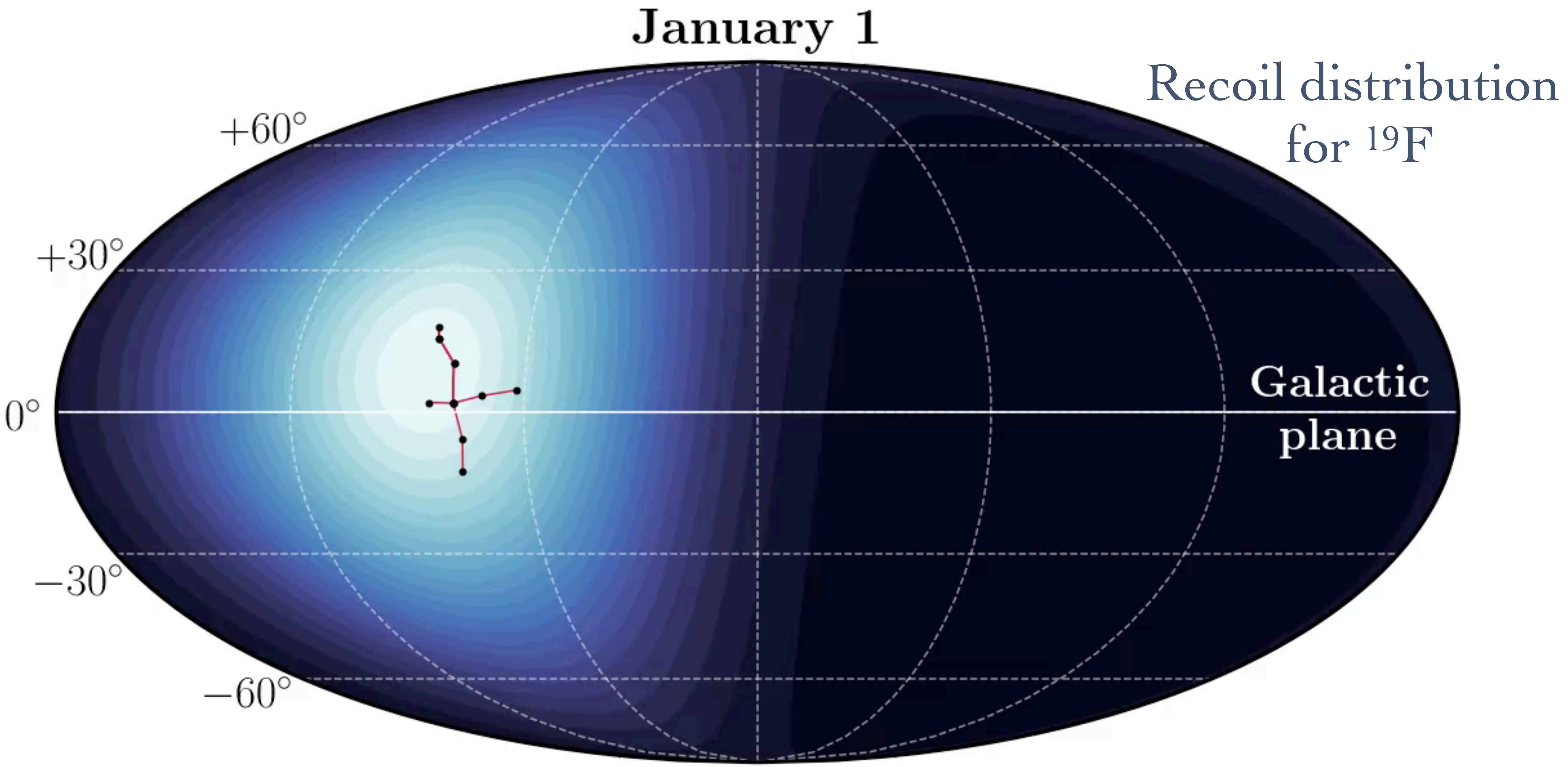


Recoil distribution for ^{19}F

(movie)

Directional detection

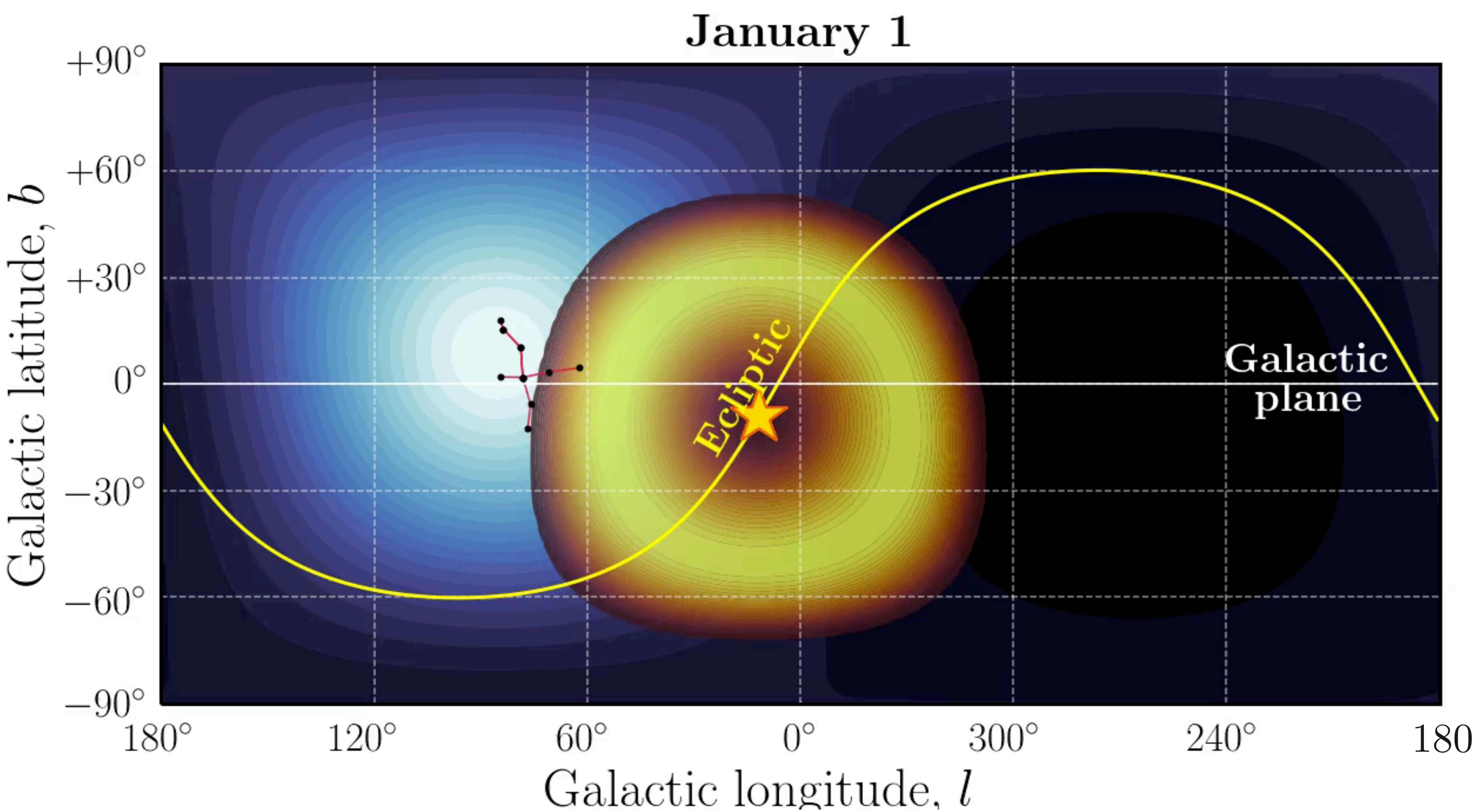
Nothing other than dark matter will give a signal that points back to Cygnus,



(movie)

Galactic coordinates

WIMP recoils   Solar neutrino recoils

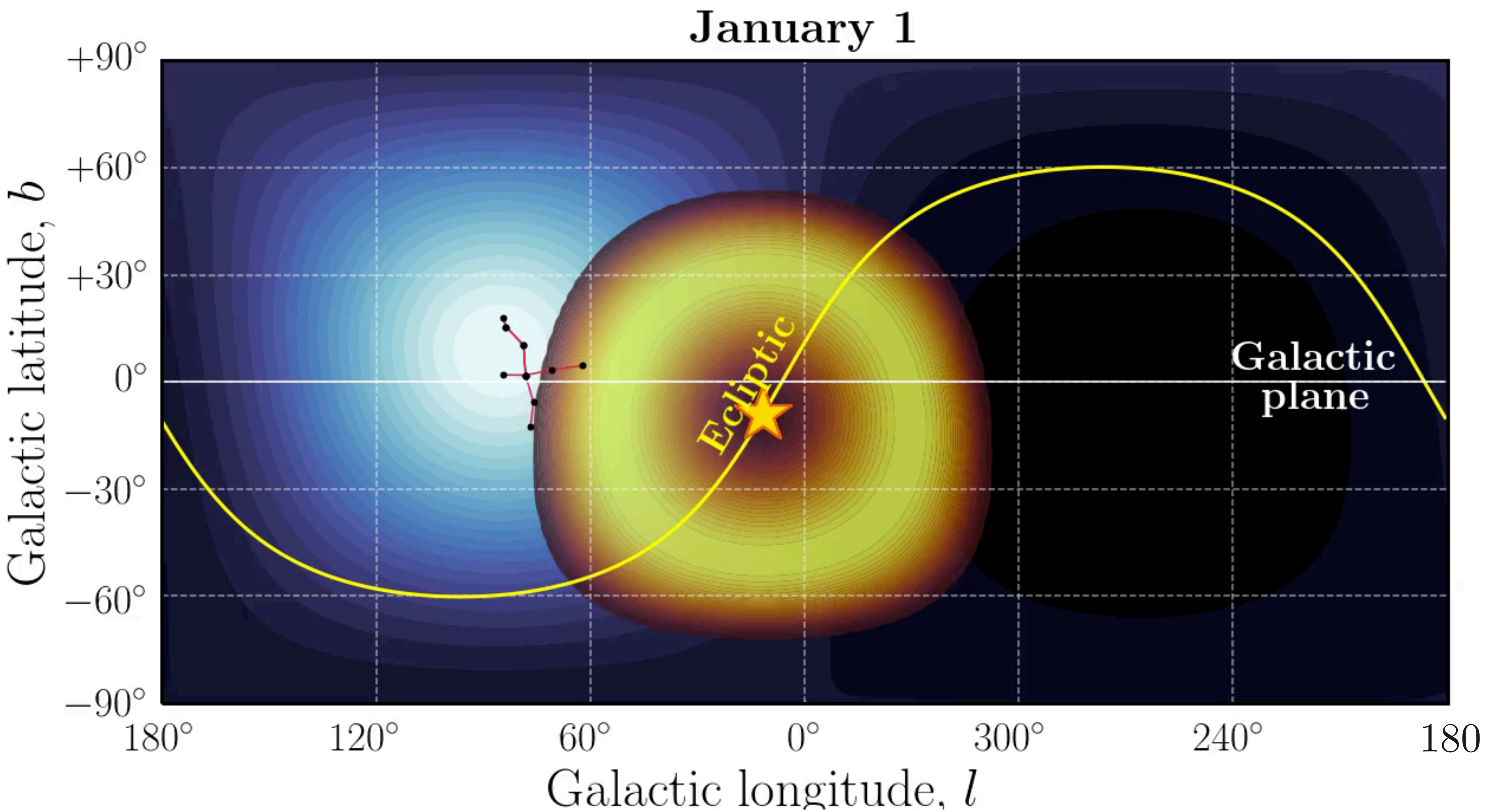


(Fluorine recoils above 3 keVr)

(movie)

Galactic coordinates

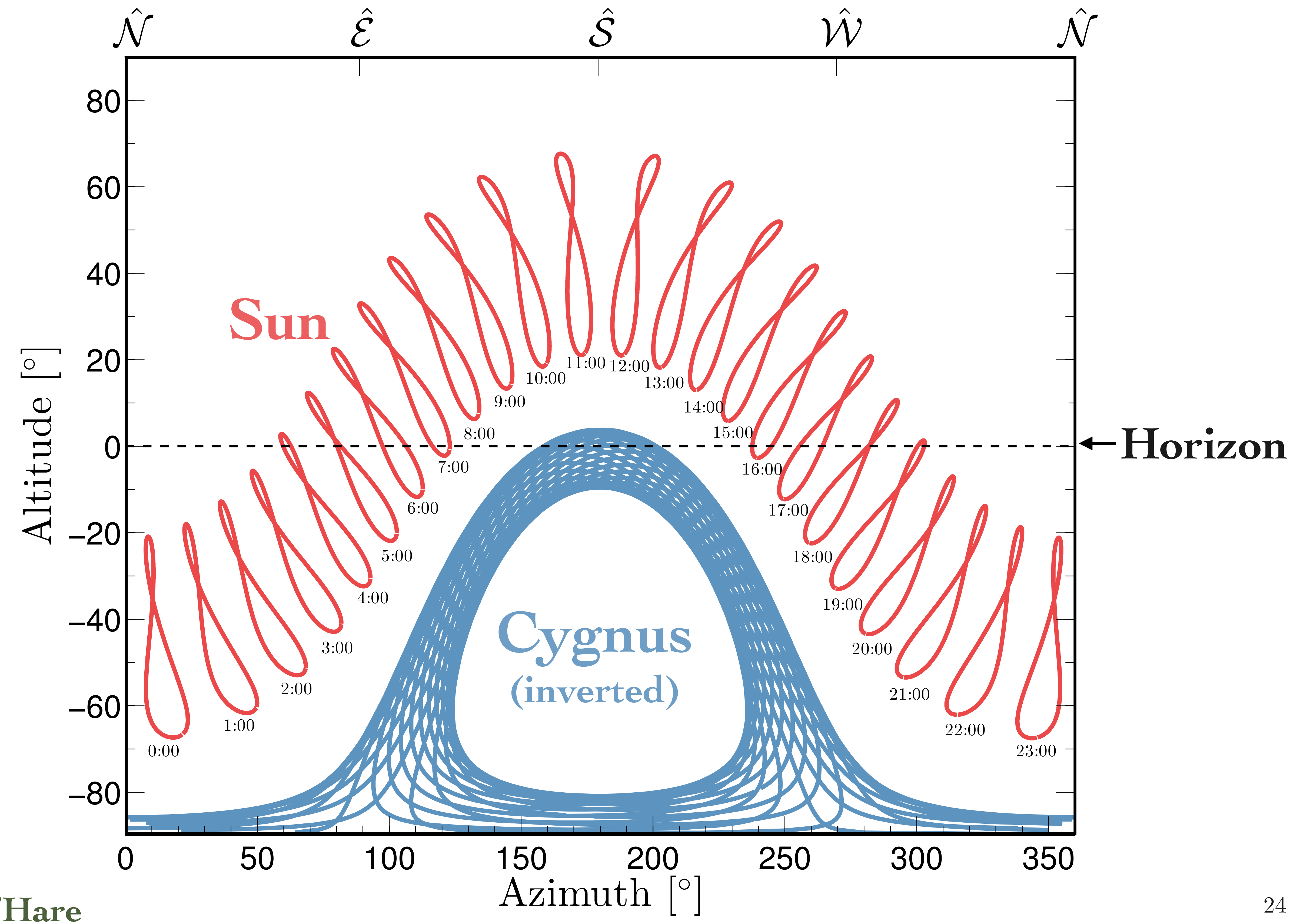
WIMP recoils | Solar neutrino recoils



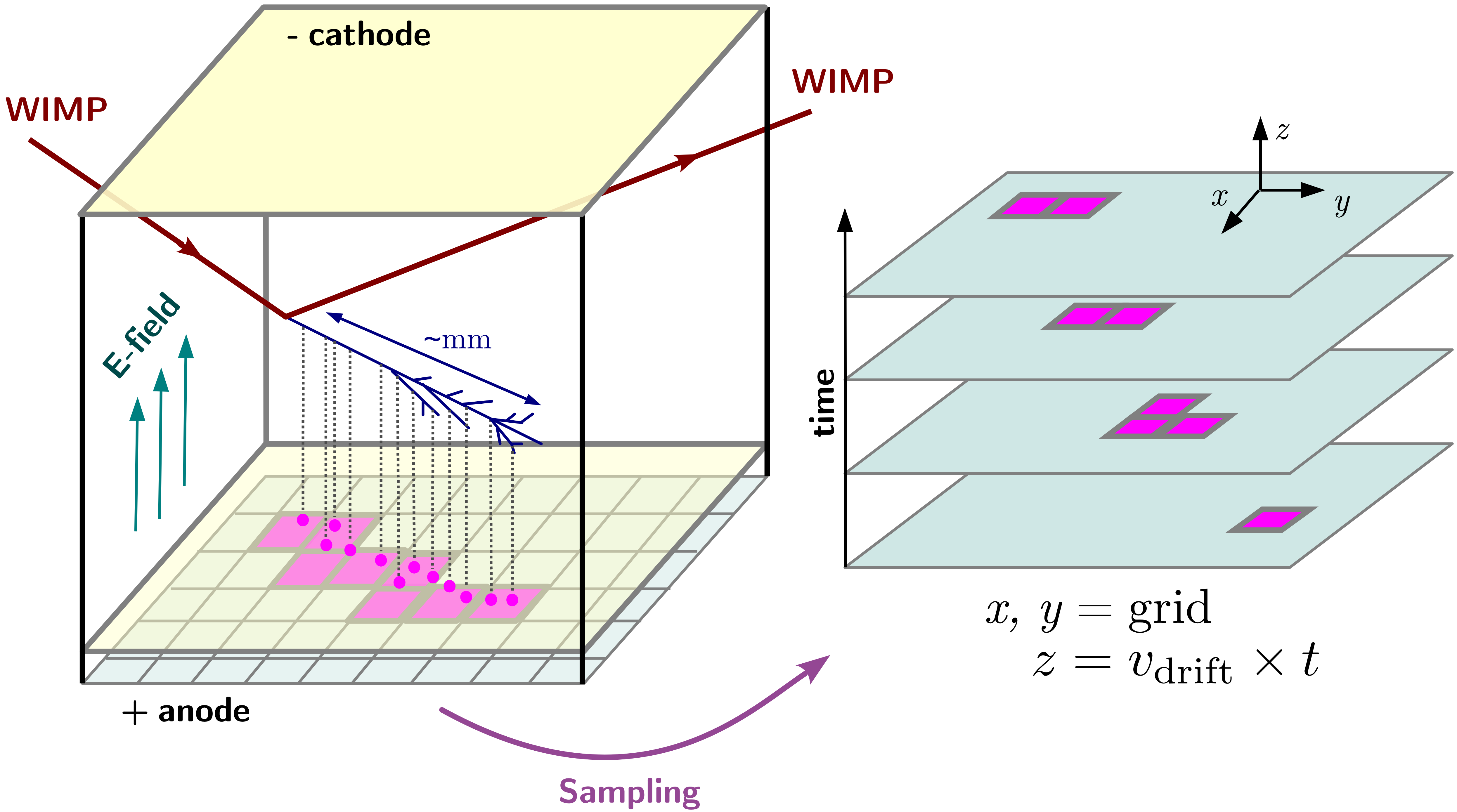
(Fluorine recoils above 3 keVr)

(movie)

Position of Sun/Cygnus at every hour of the day over the full year, in **laboratory** coordinates



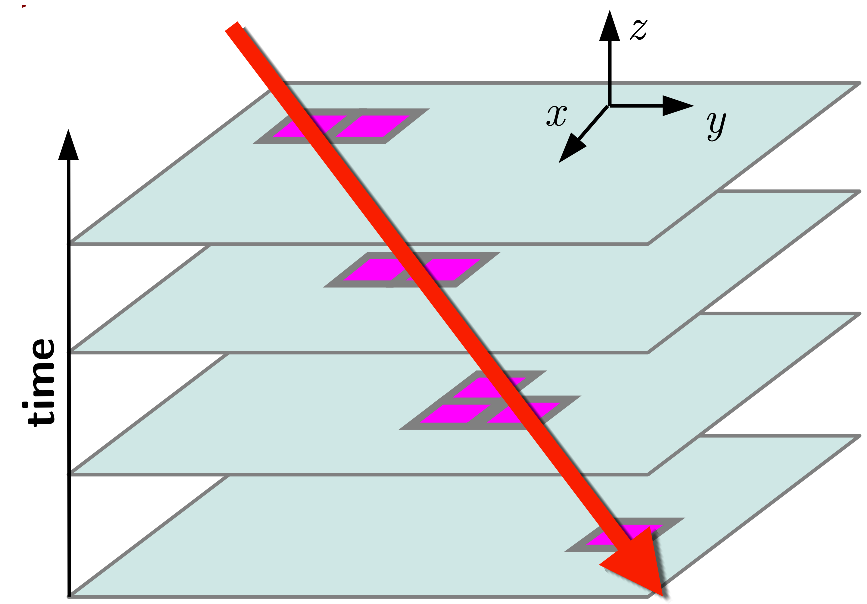
Low-pressure gas TPC

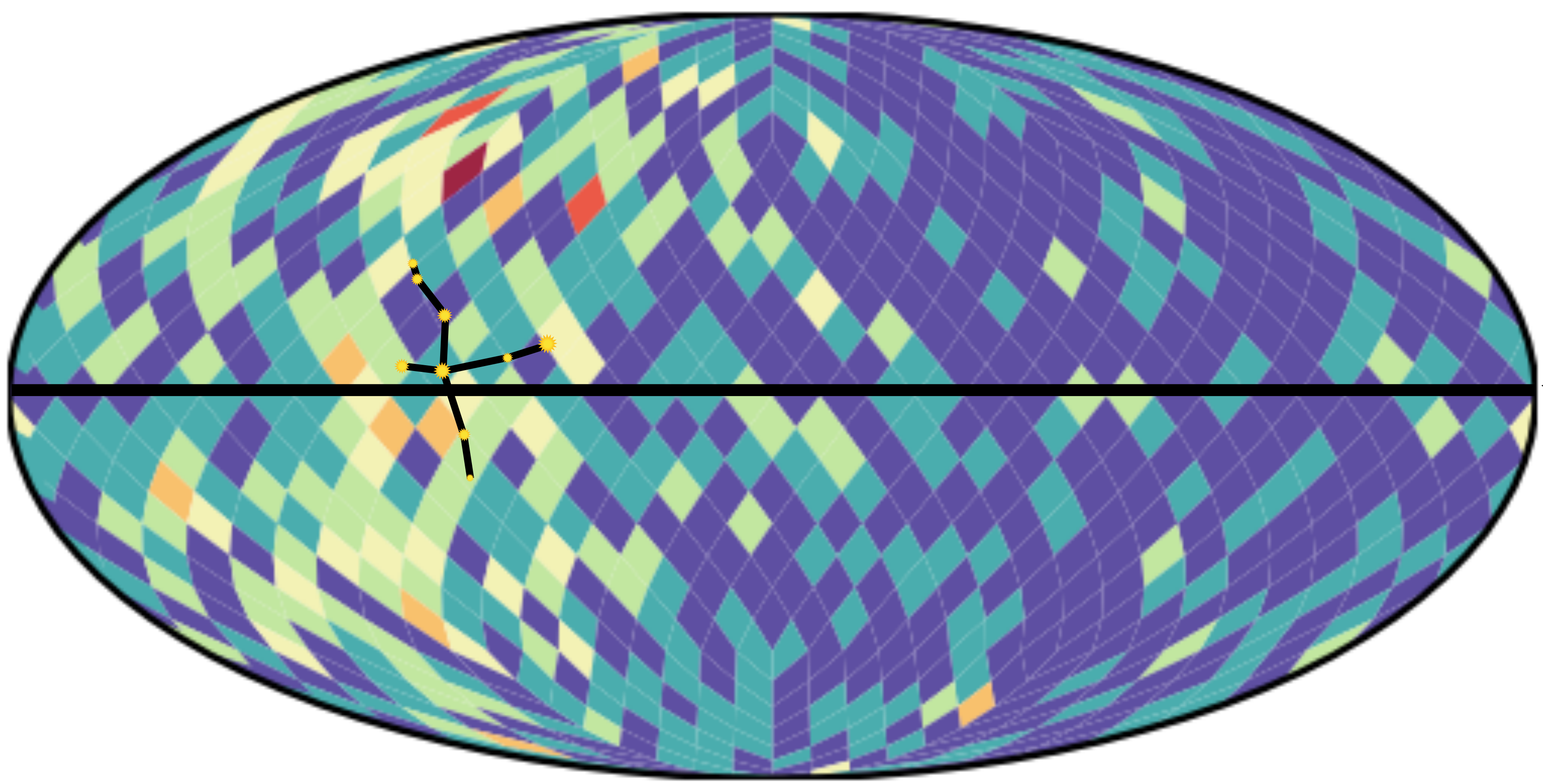


Measuring the full track: 3D readout

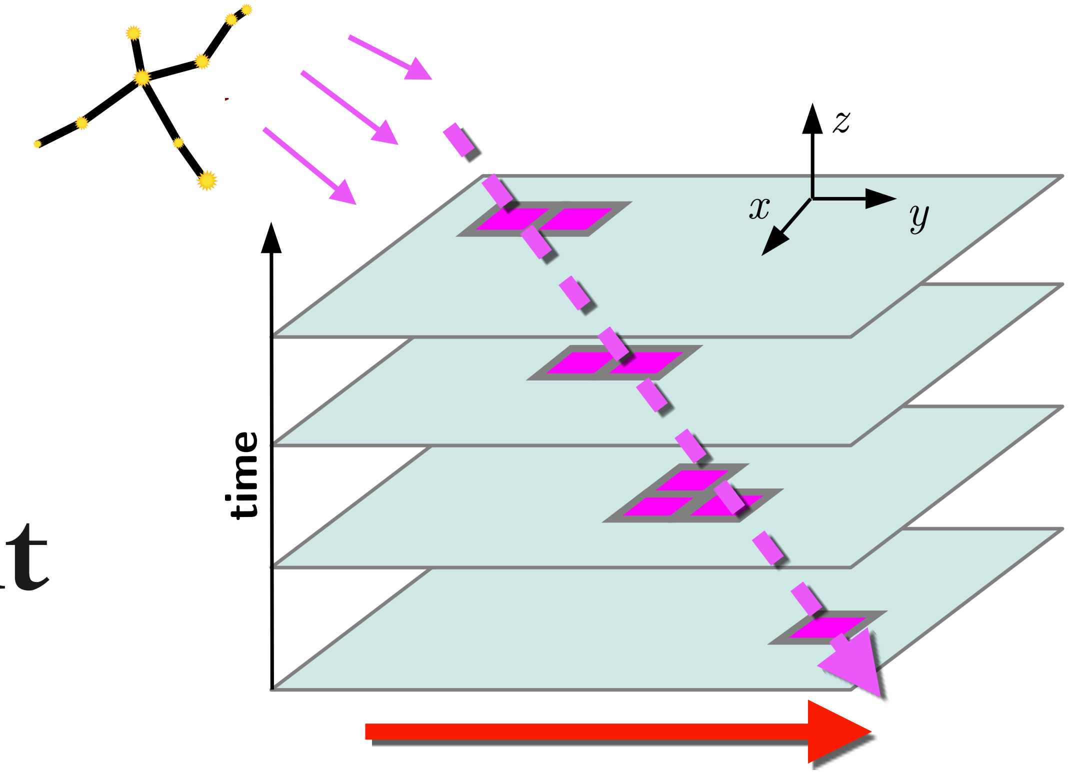
All recoils are 3D **vectors** and are time-tagged so can be reoriented in the Galactic frame:

$$\hat{\mathbf{q}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$$



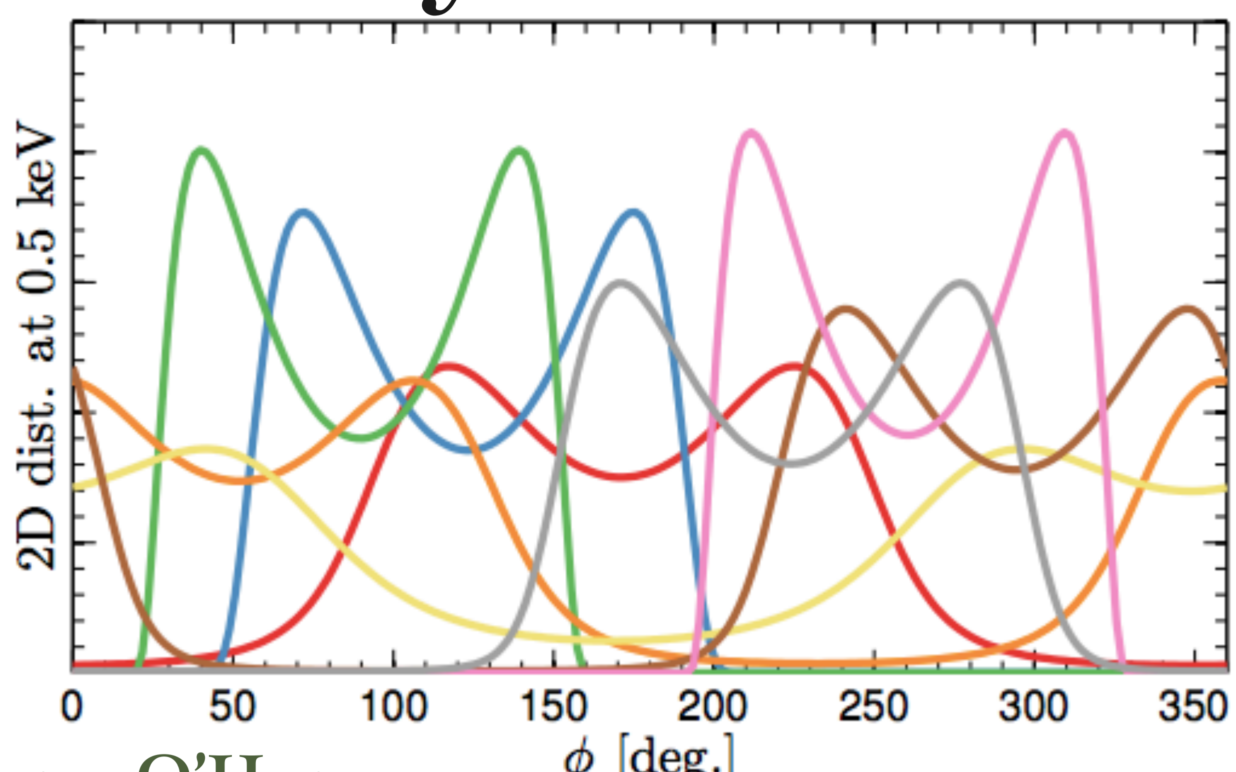


2D Readout

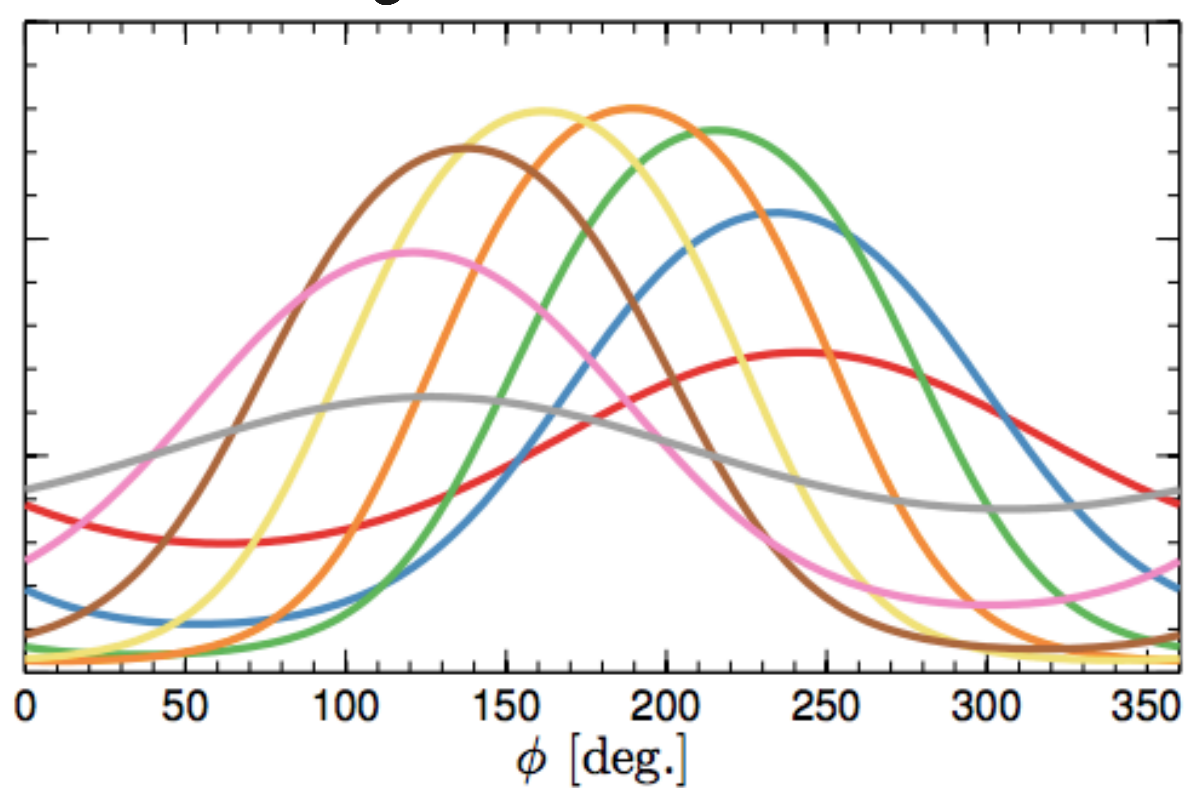


$$\hat{\mathbf{q}} = \sin\theta\cos\phi\,\hat{\mathbf{x}} + \sin\theta\sin\phi\,\hat{\mathbf{y}} + \cos\theta\,\hat{\mathbf{z}}$$

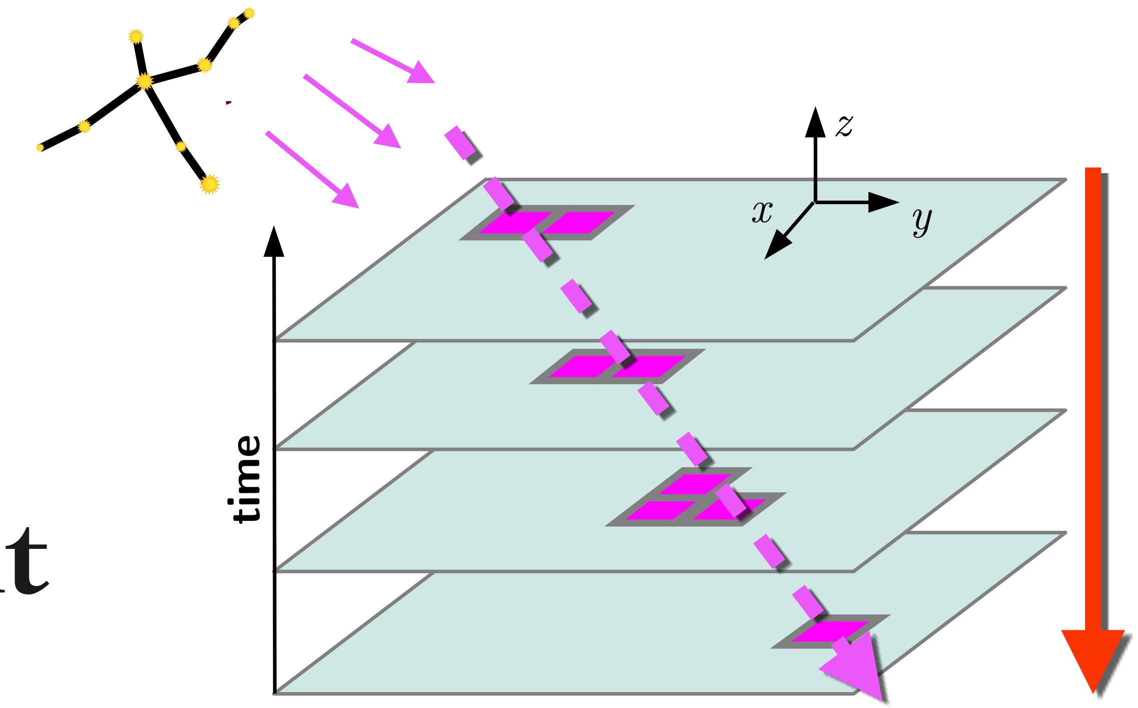
Neutrino Daily modulation



WIMP Daily modulation

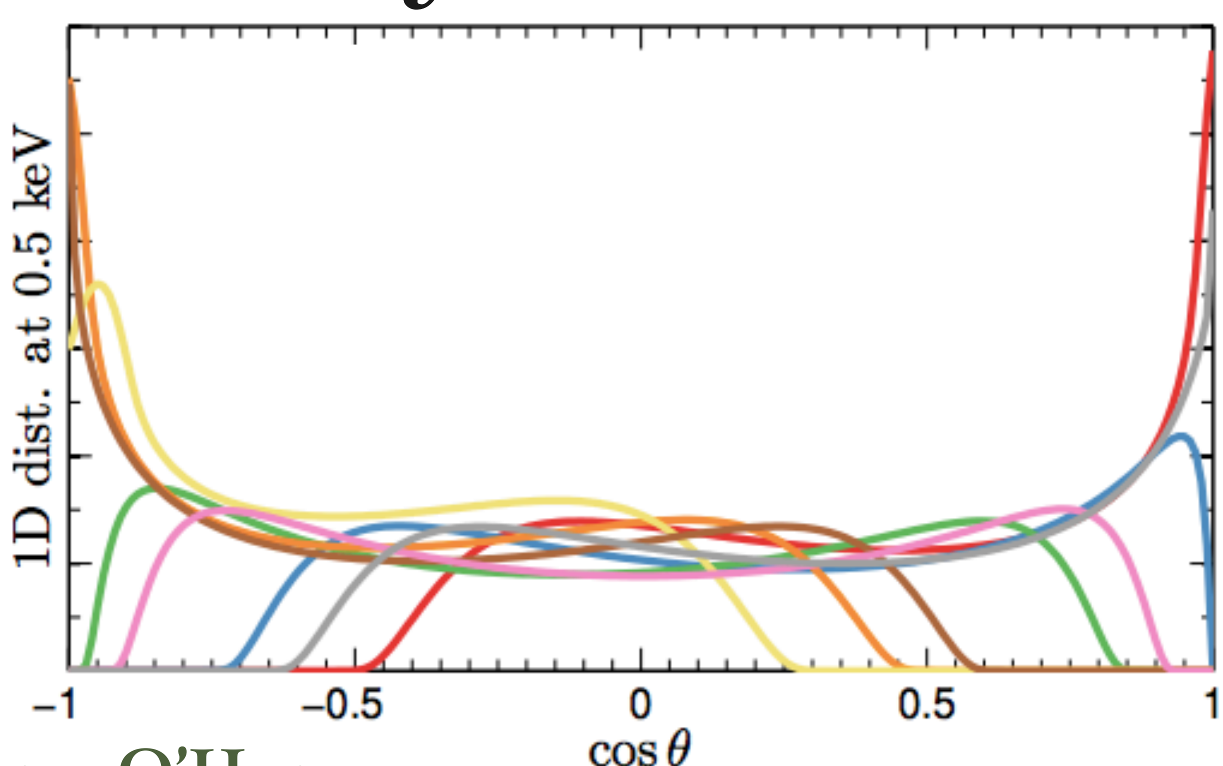


1D Readout

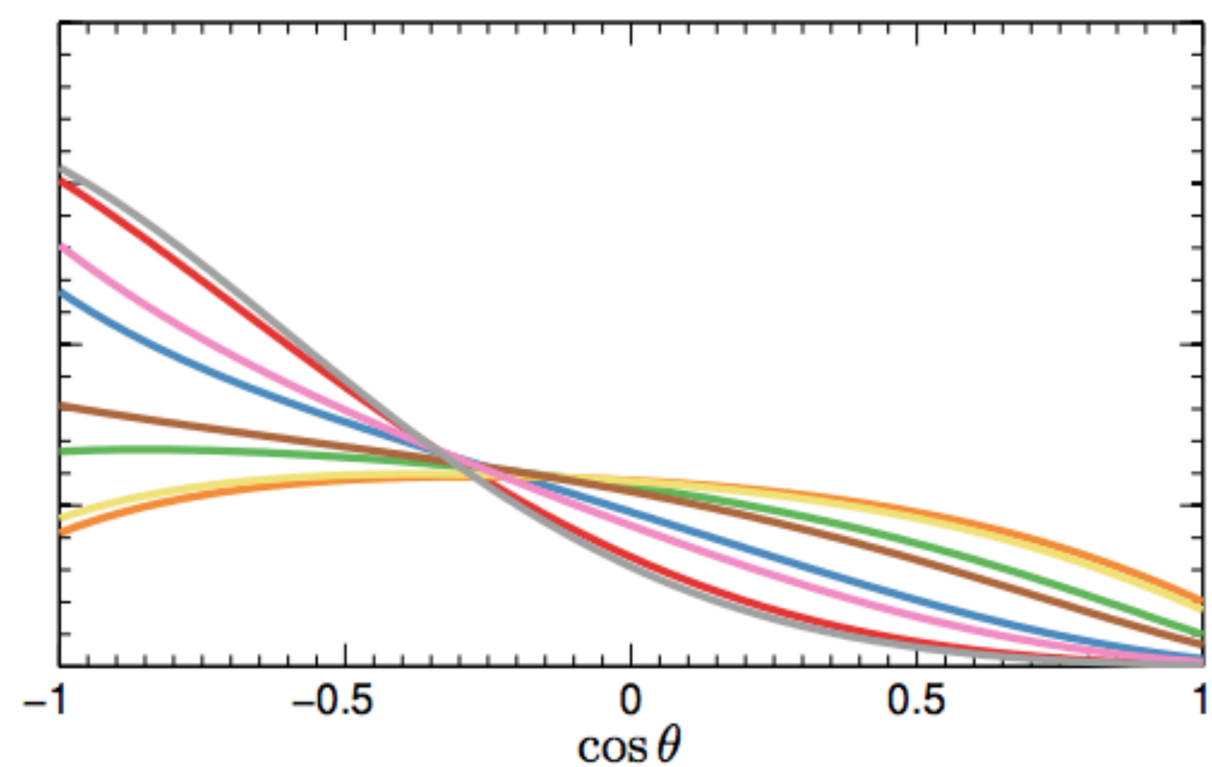


$$\hat{\mathbf{q}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \boxed{\cos\theta\hat{\mathbf{z}}}$$

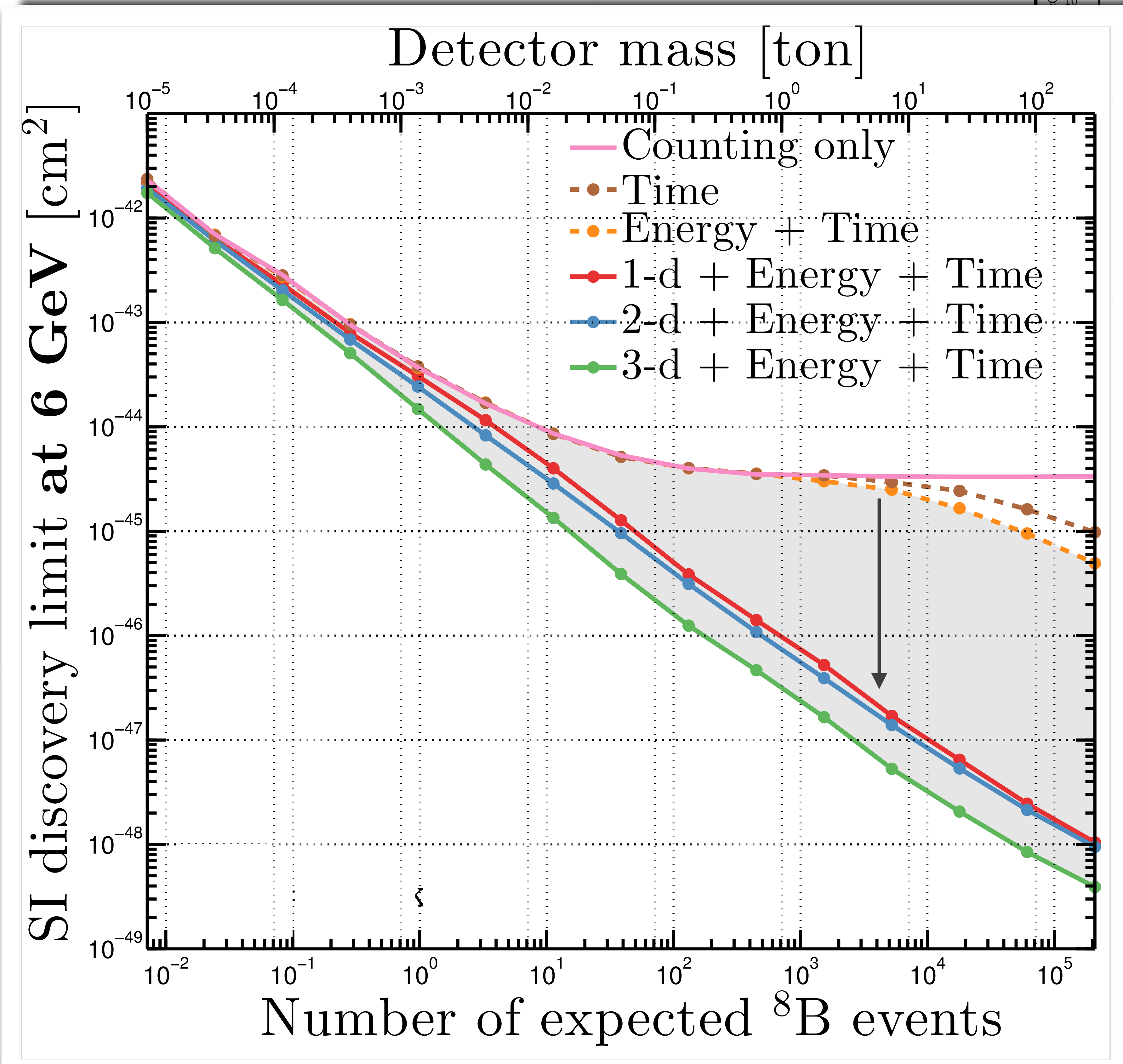
Neutrino Daily modulation

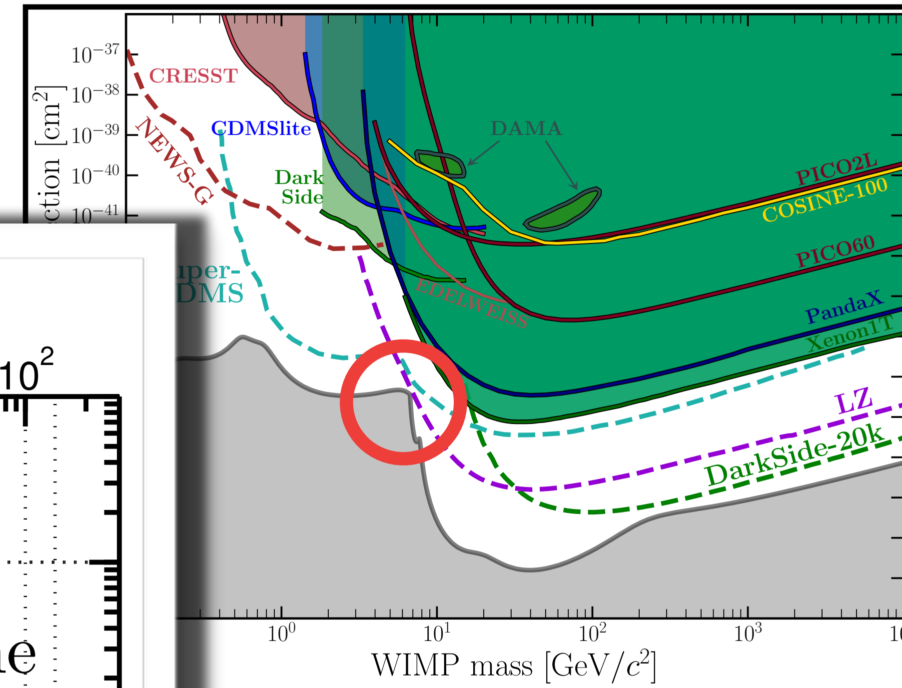


WIMP Daily modulation



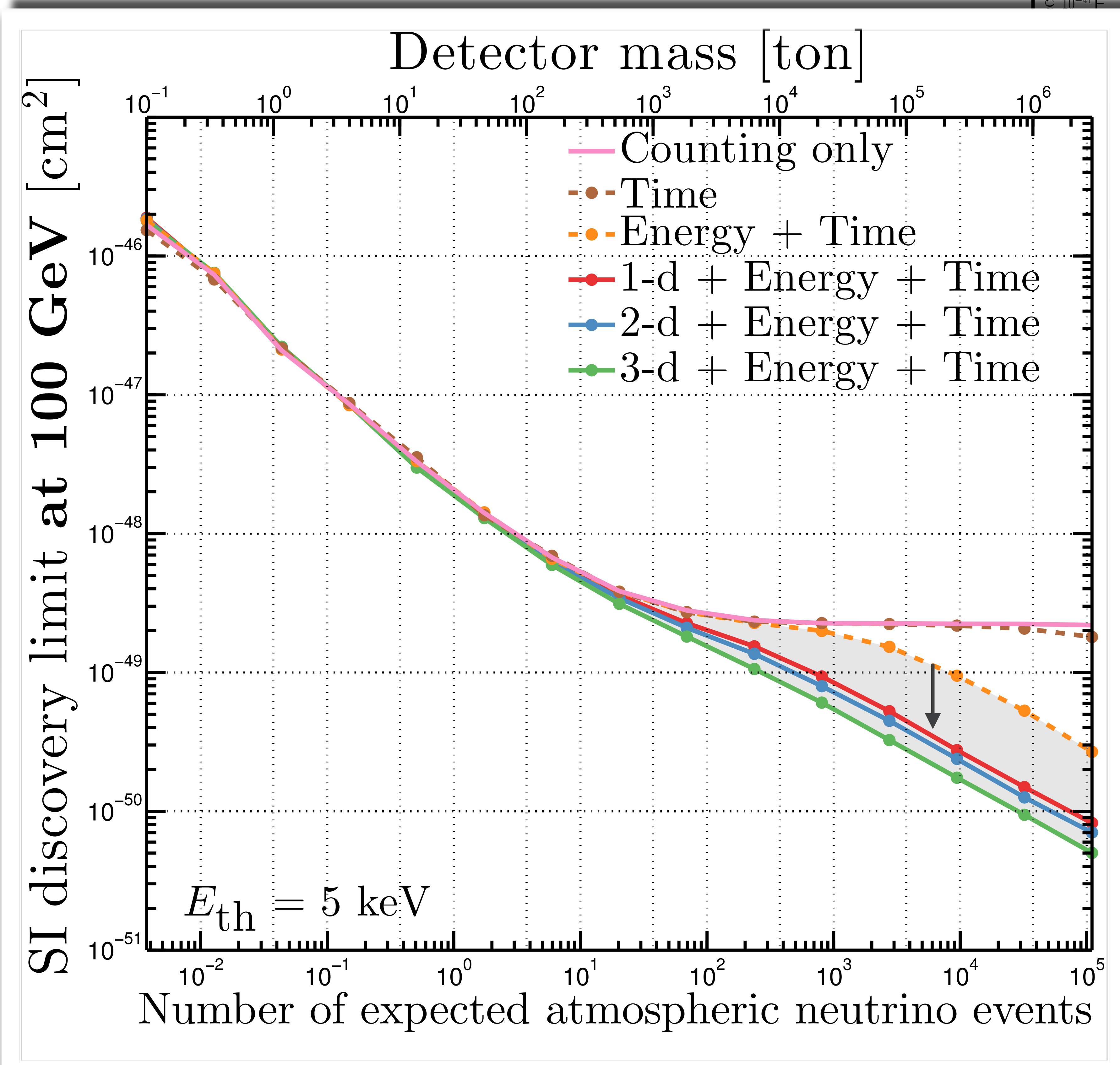
Comparing methods: Solar

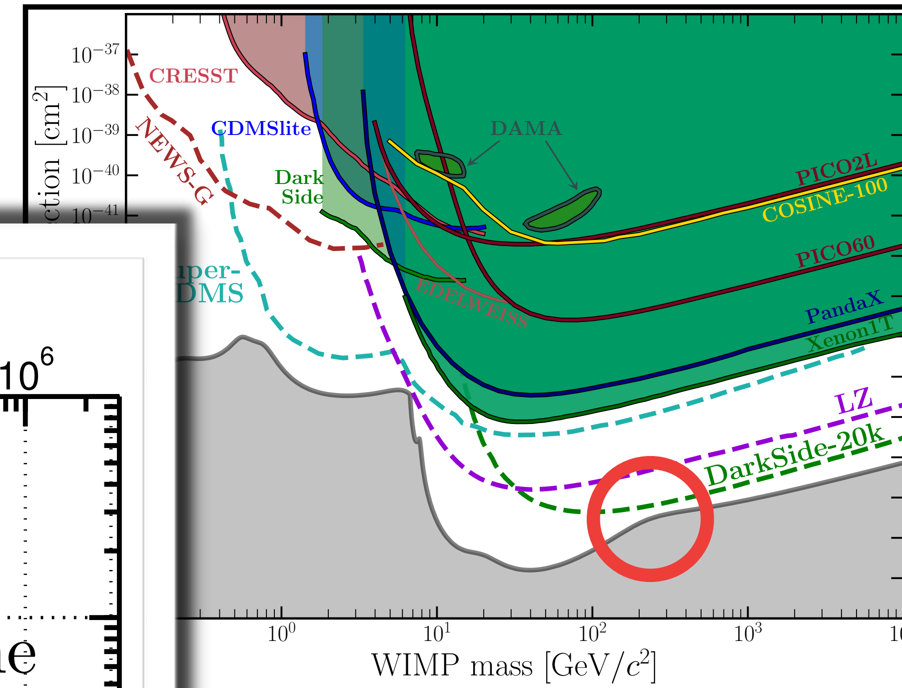




Directionality powerful for subtracting Solar neutrinos

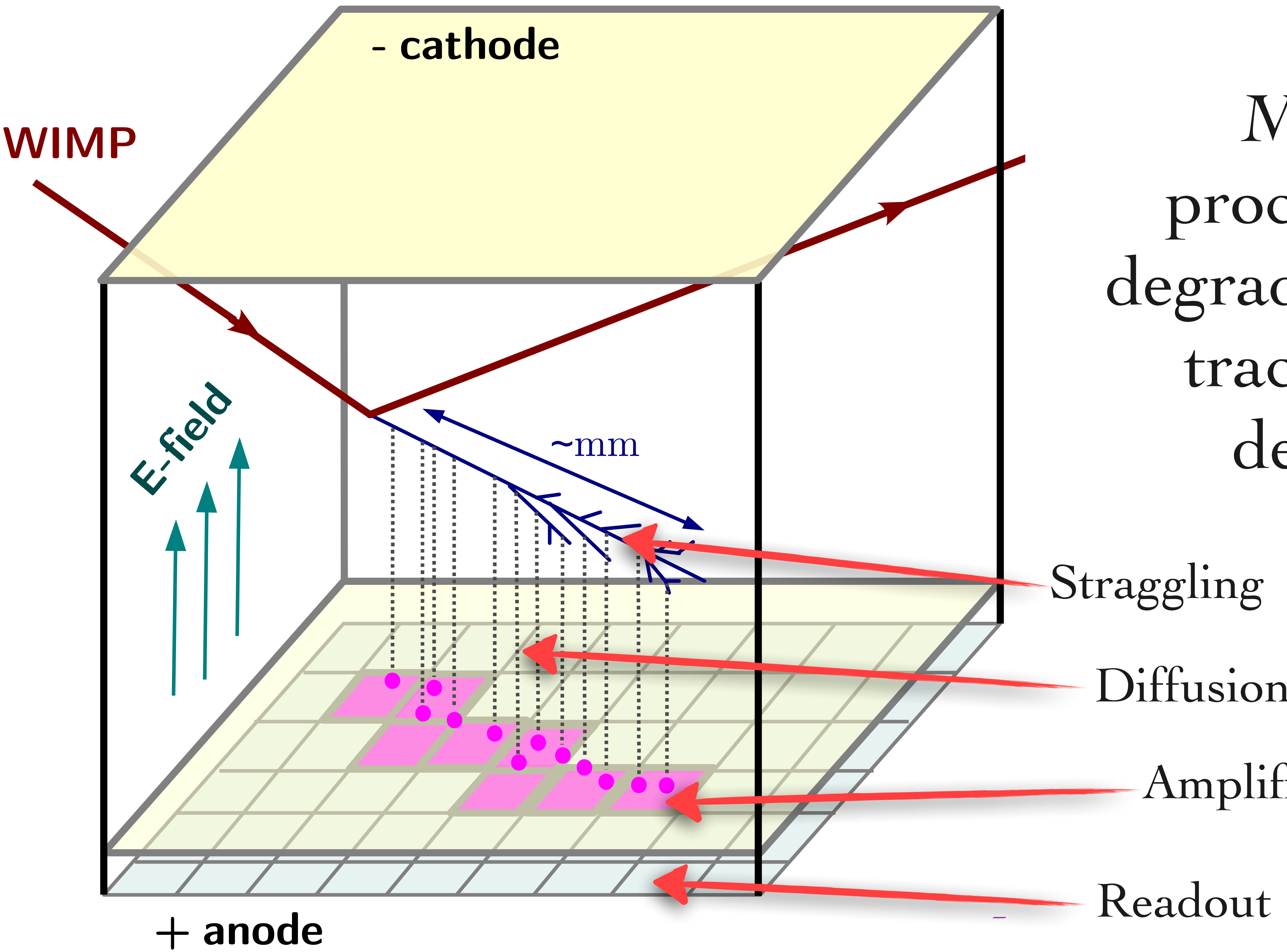
Comparing methods: Atm.





Directionality less powerful for subtracting atmospheric neutrinos

Real tracks are imperfect



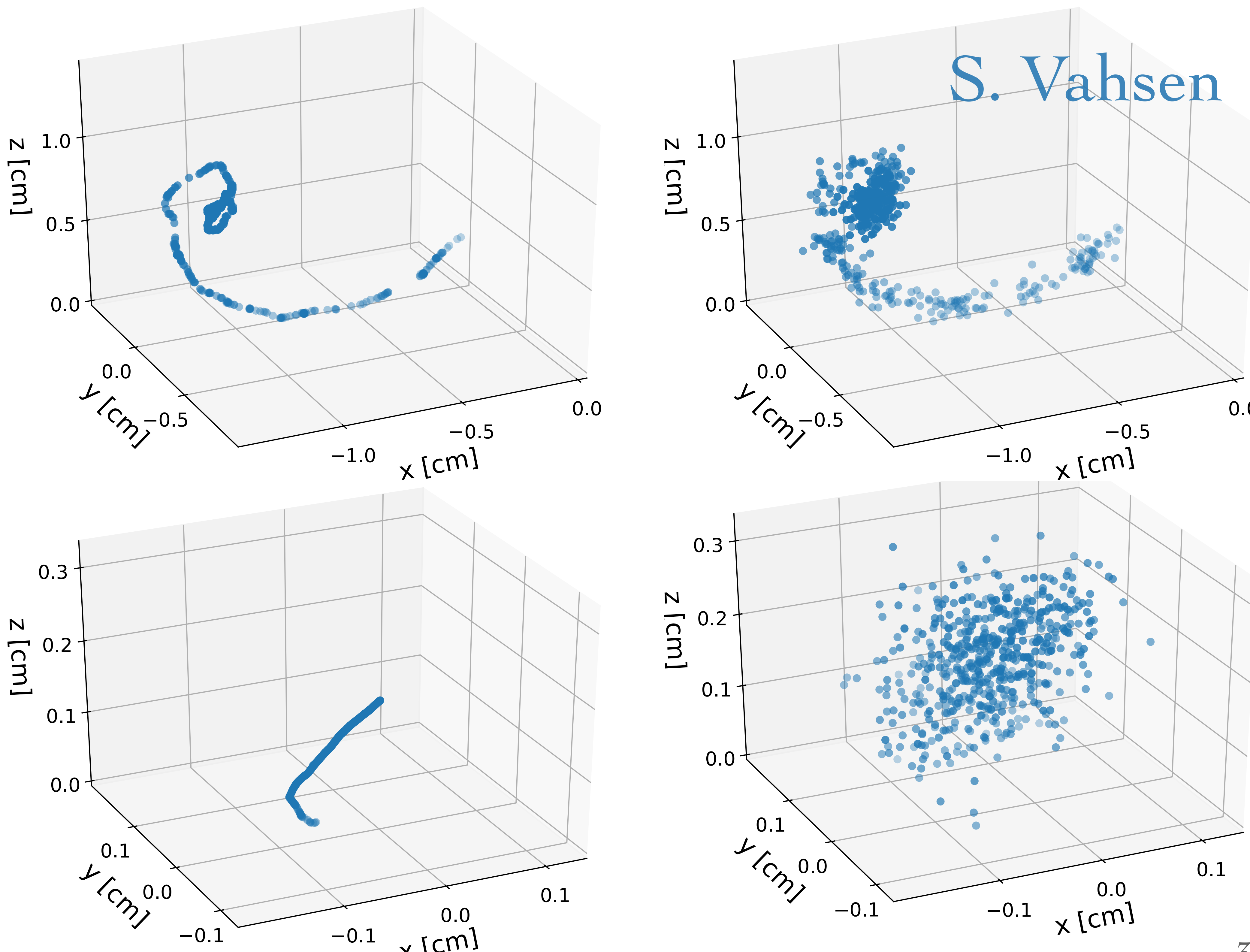
Multiple processes will degrade the recoil track during detection

Recoil tracks (in He+SF_6 at 1 atm)

Before drift | After 25 cm drift

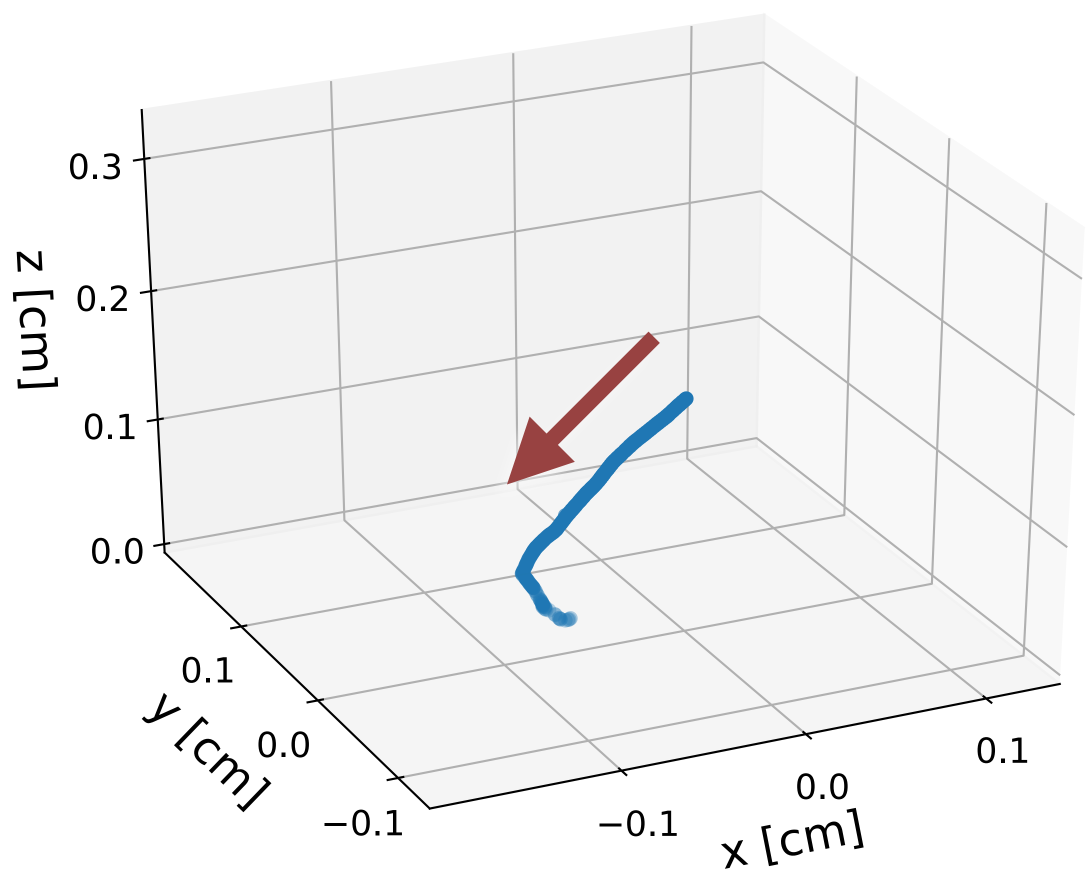
Electron: 20 keV

He Nucleus: (25 keVr)

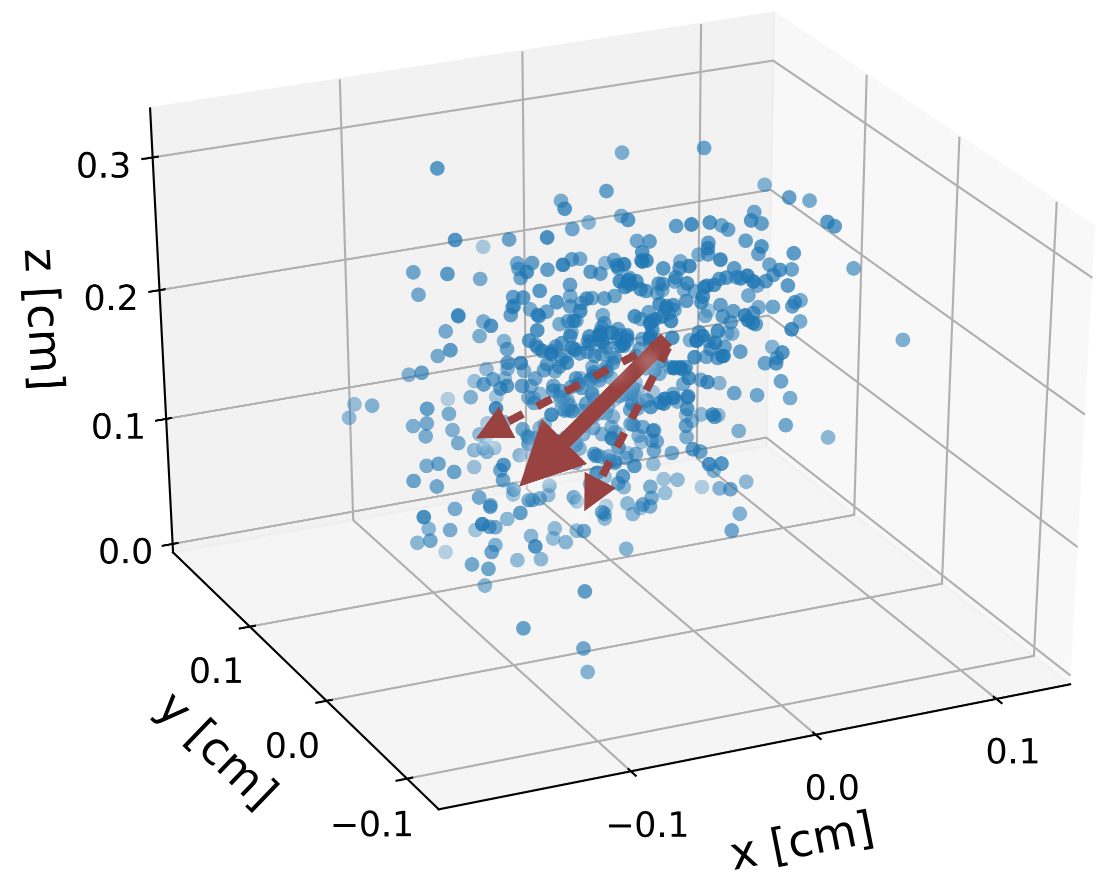


Angular resolution

Original track



Track after 25 cm drift

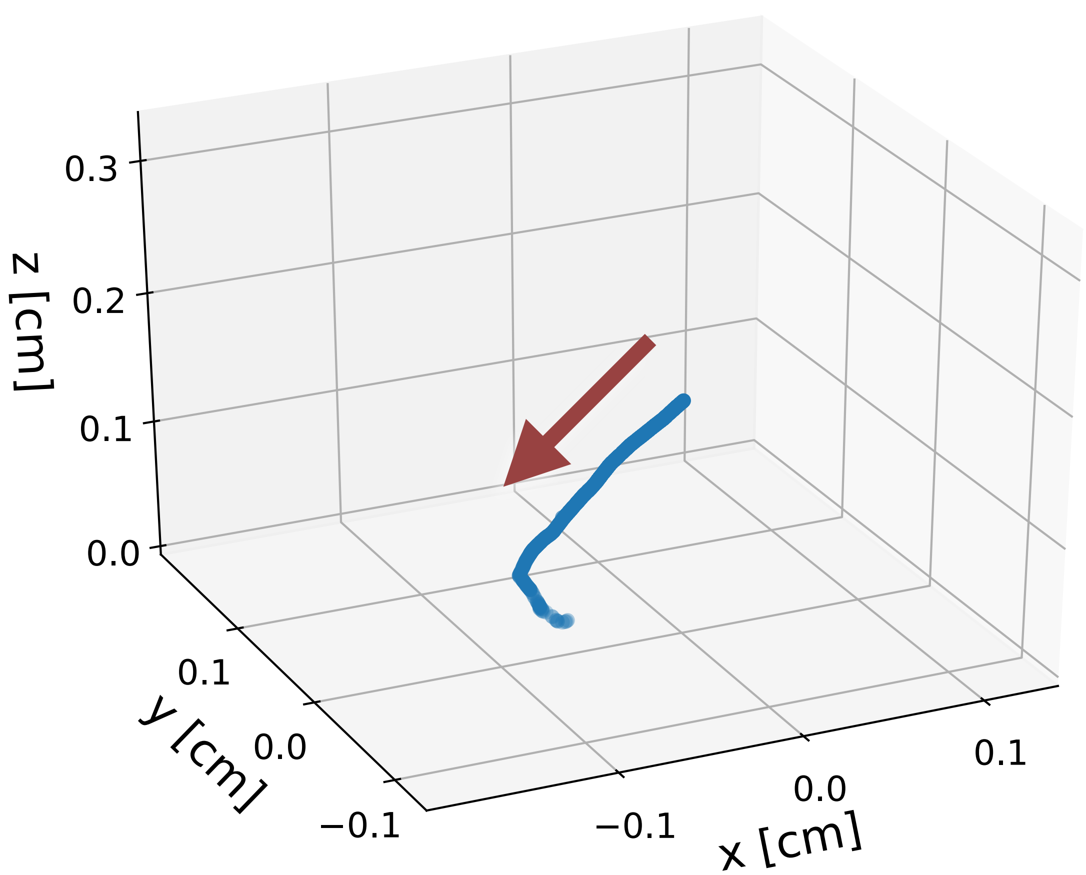


25 keVr Helium recoil in 1 atm of 755:5 He:SF_6

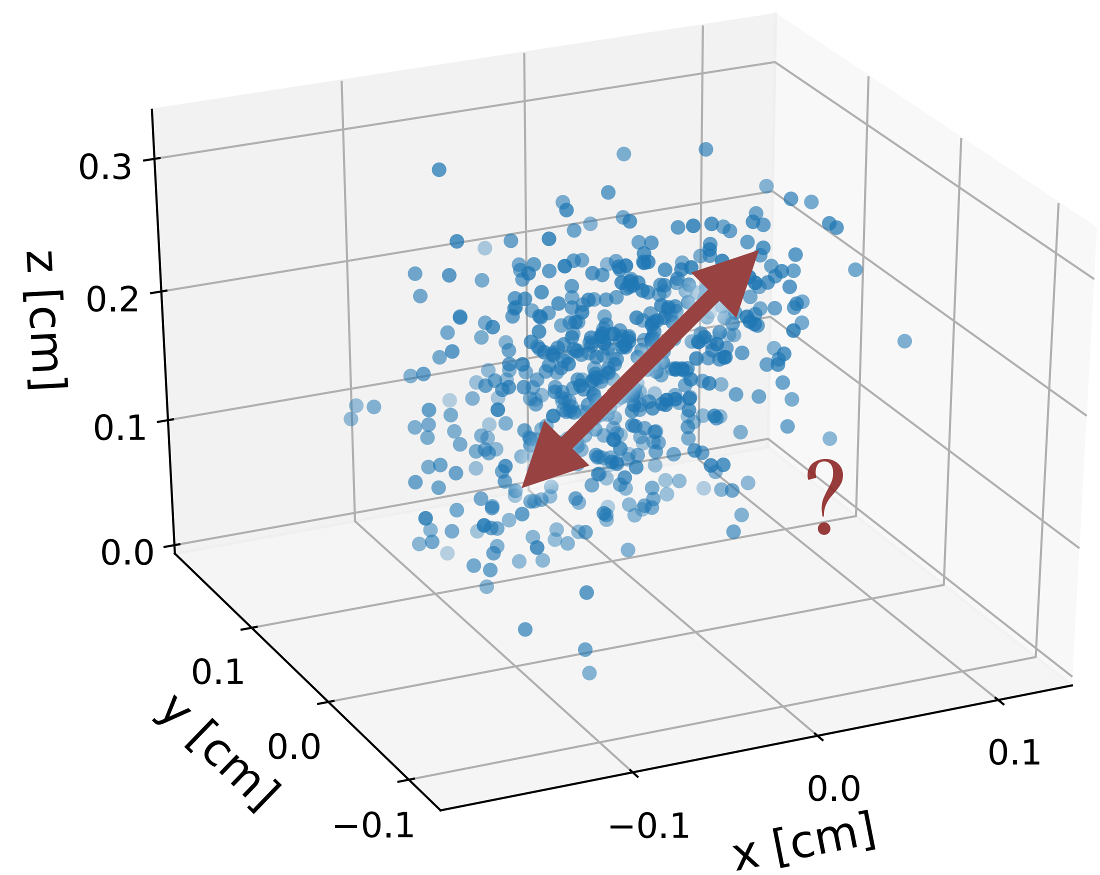
Head-tail recognition

Ability to recognise the forward-backward sense of a recoil

Original track



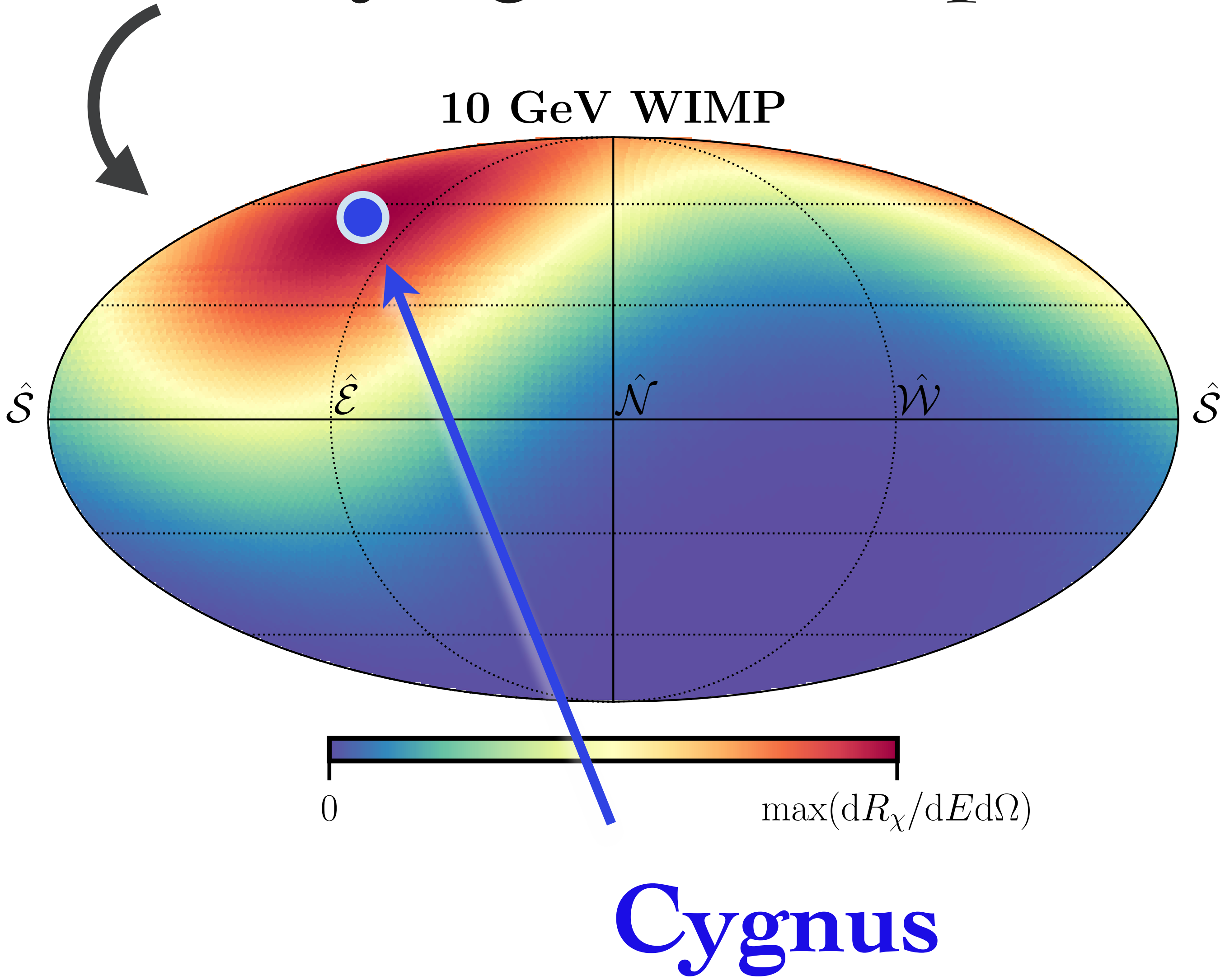
Track after 25 cm drift

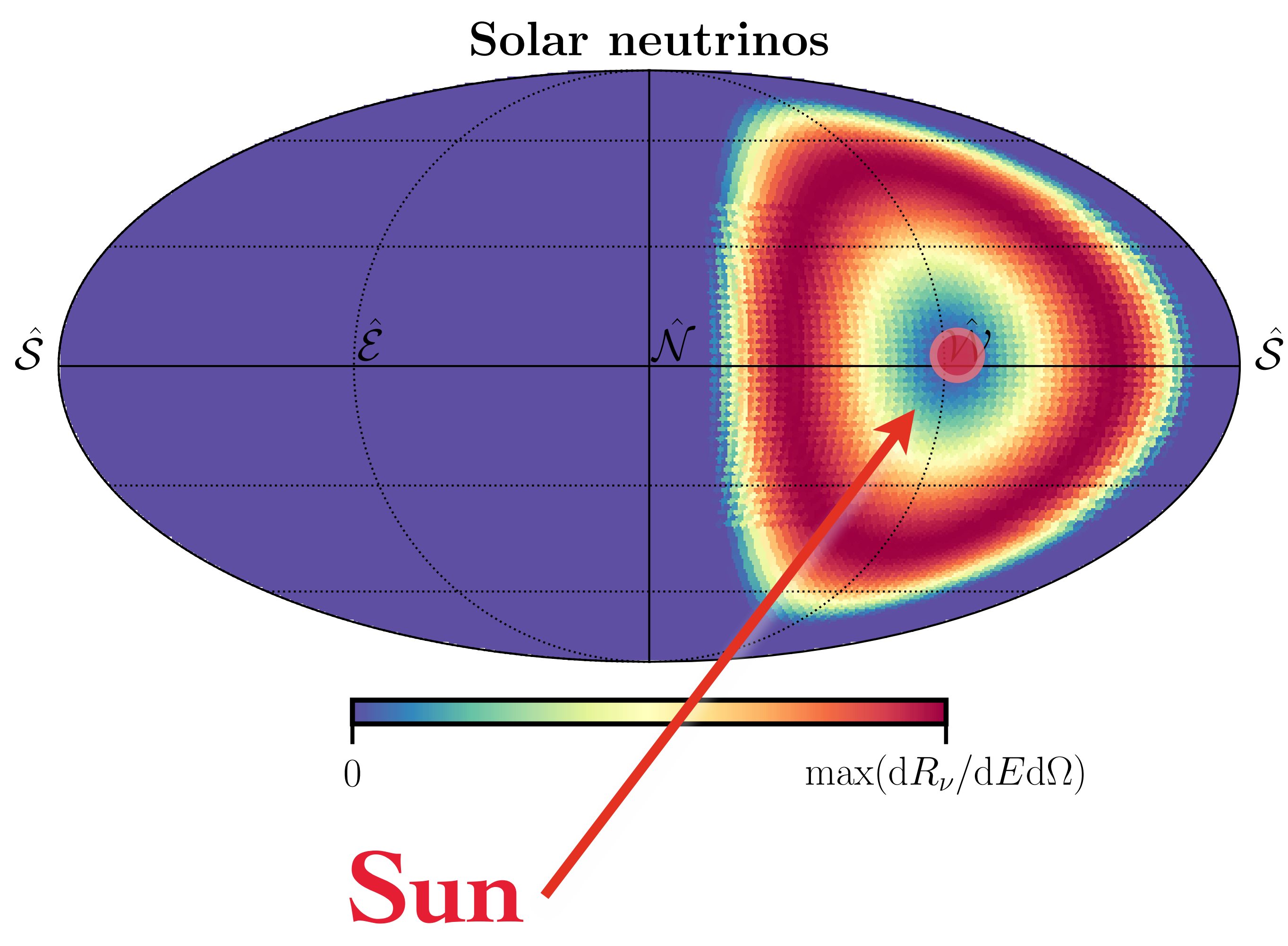


Signal in laboratory coordinates:

Expt: Fluorine recoils above 3 keV_r
Location: Boulby, UK
Time: 12 Sep. 18:00 GMT

Underlying recoil maps (i.e. perfect track reconstruction)

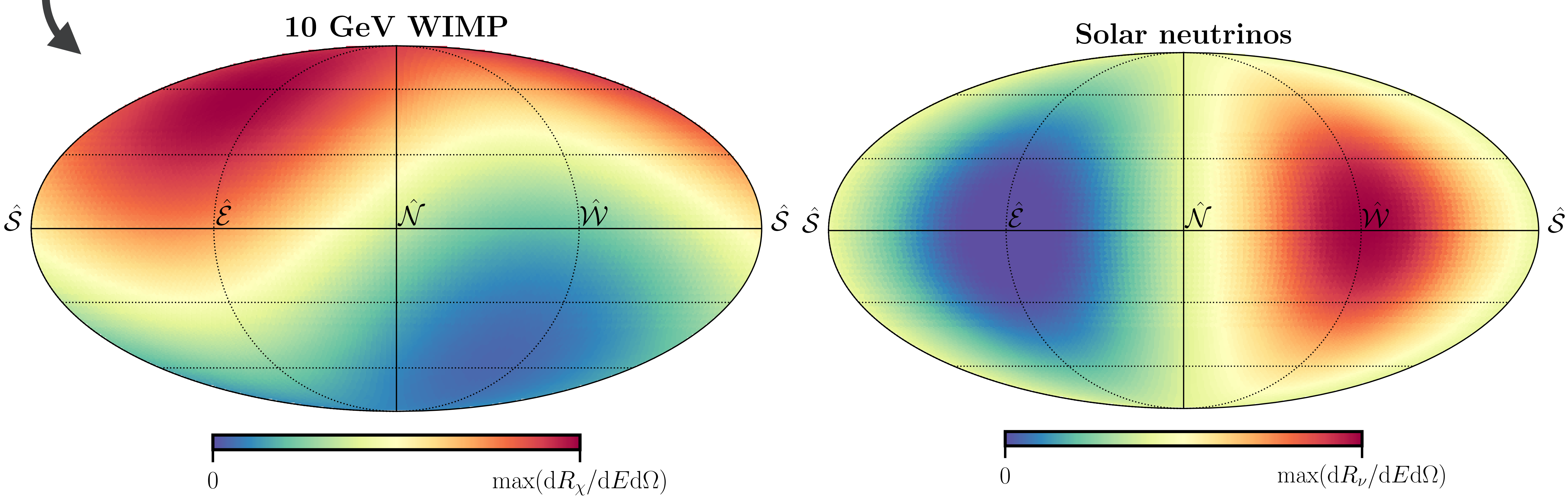




Signal in a "realistic" detector

Angular resolution → smears distributions in angle
No head-tail → folds one half of sky on to the other

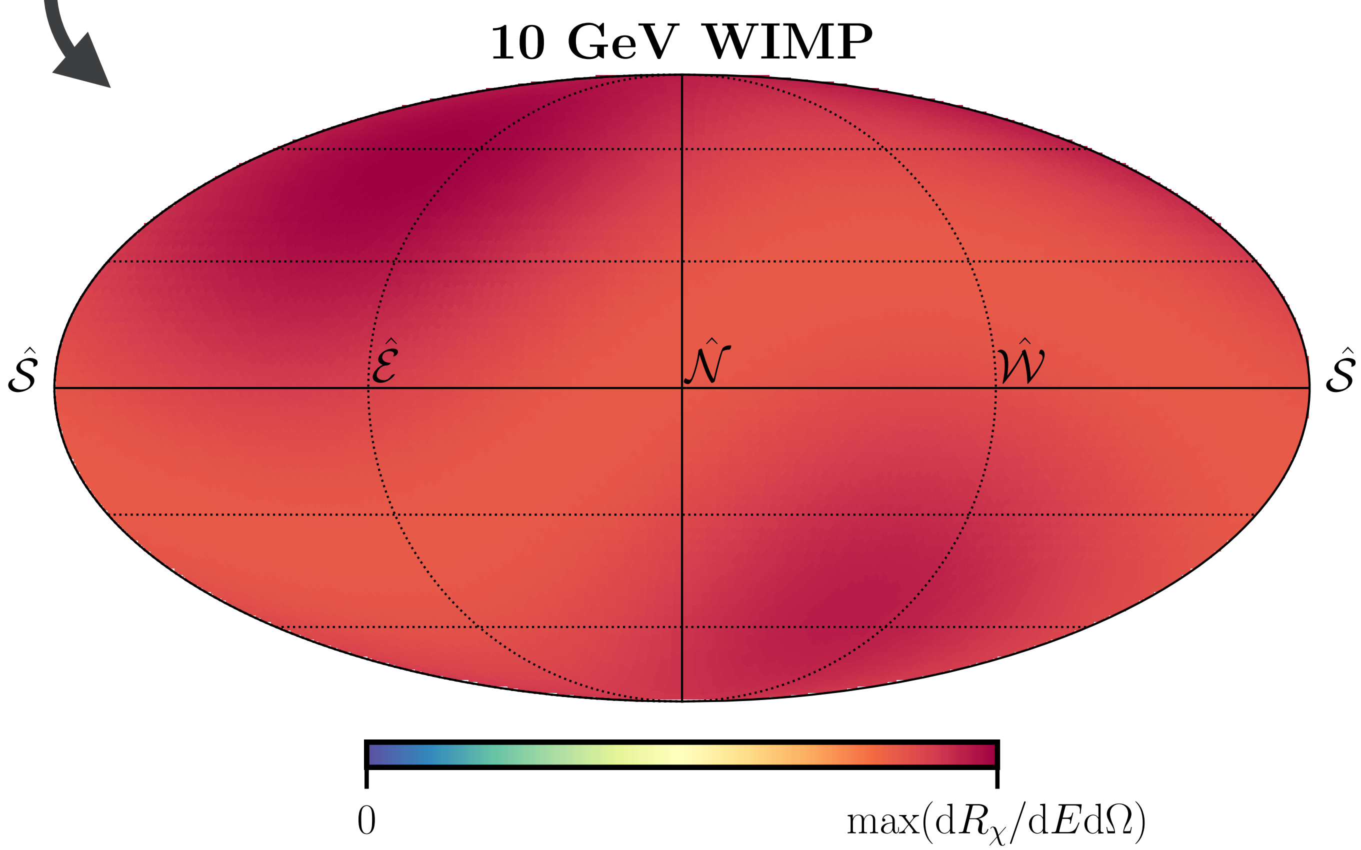
The same maps after 30° **angular resolution** applied

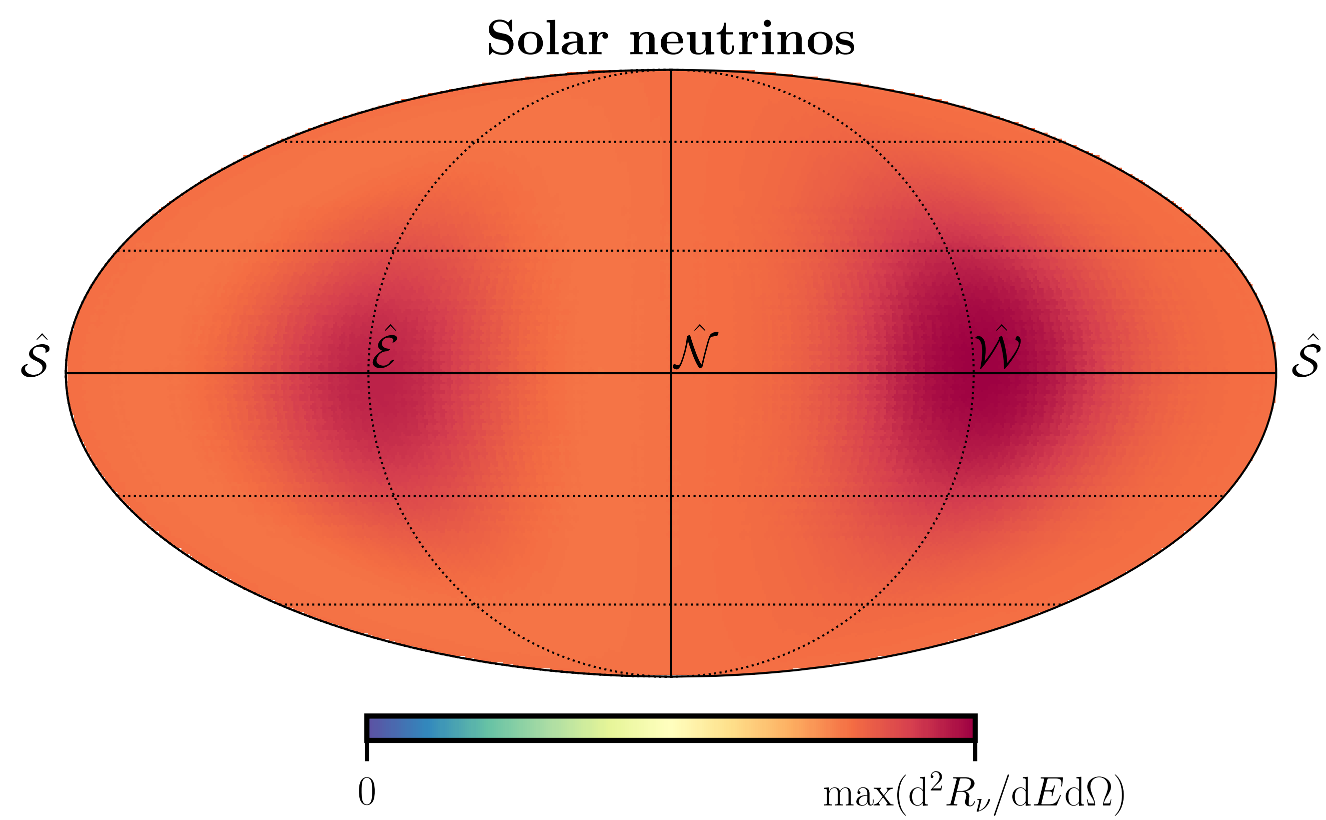


Signal in a "realistic" detector

Angular resolution → smears distributions in angle
No head-tail → folds one half of sky on to the other

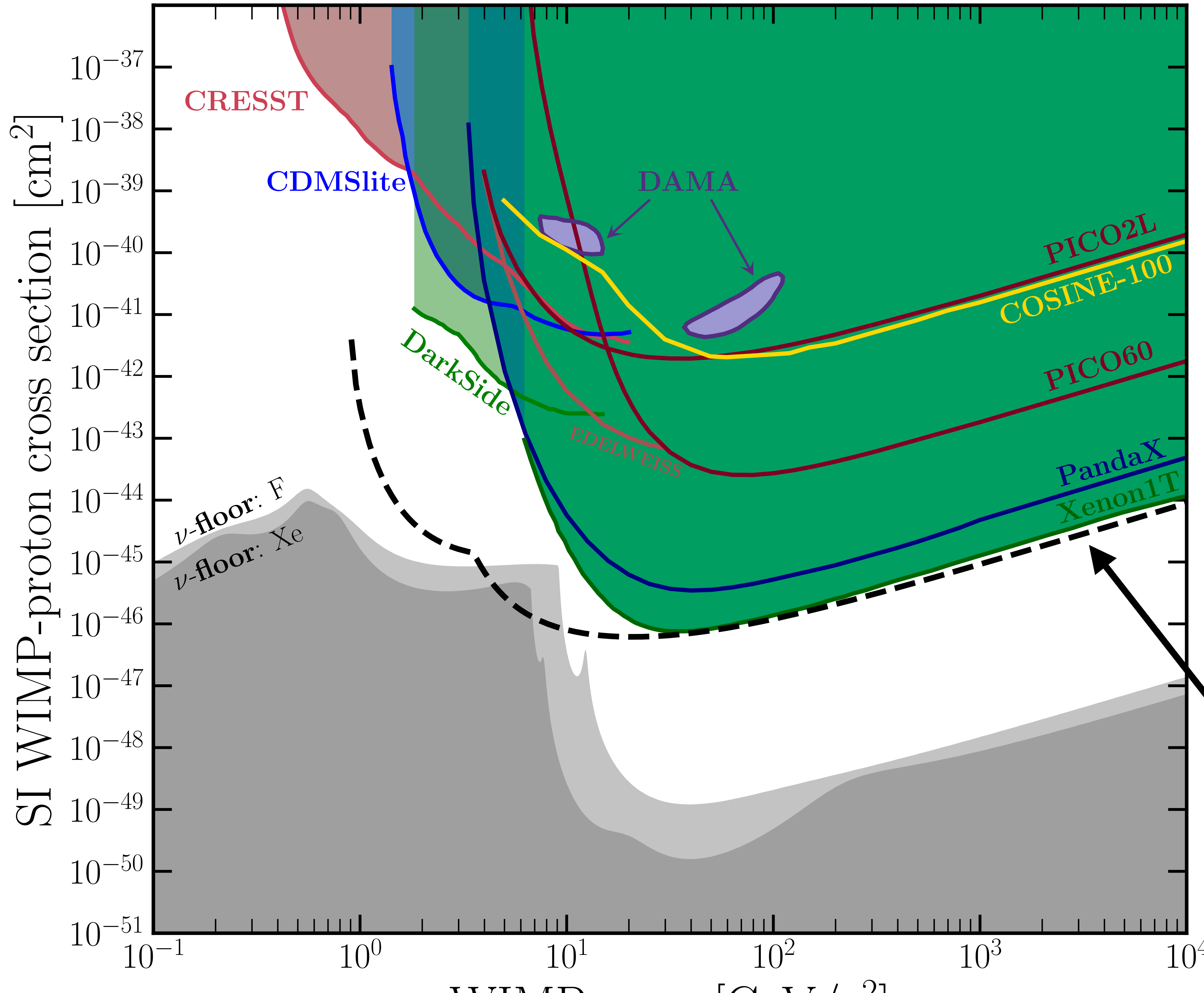
30° **angular resolution** and *75%* correct **head-tail recognition**

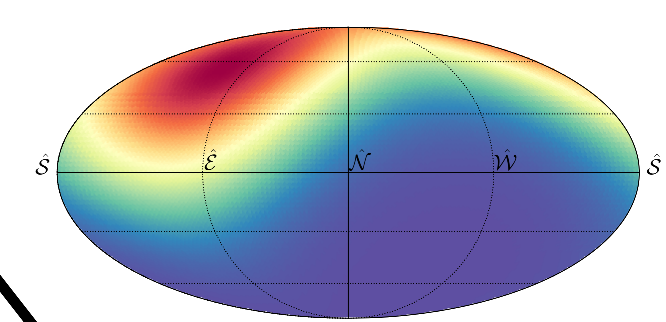




How much does detector performance matter?

(1 atm He+SF_6 TPC, 1000 m^3 x 6 years)

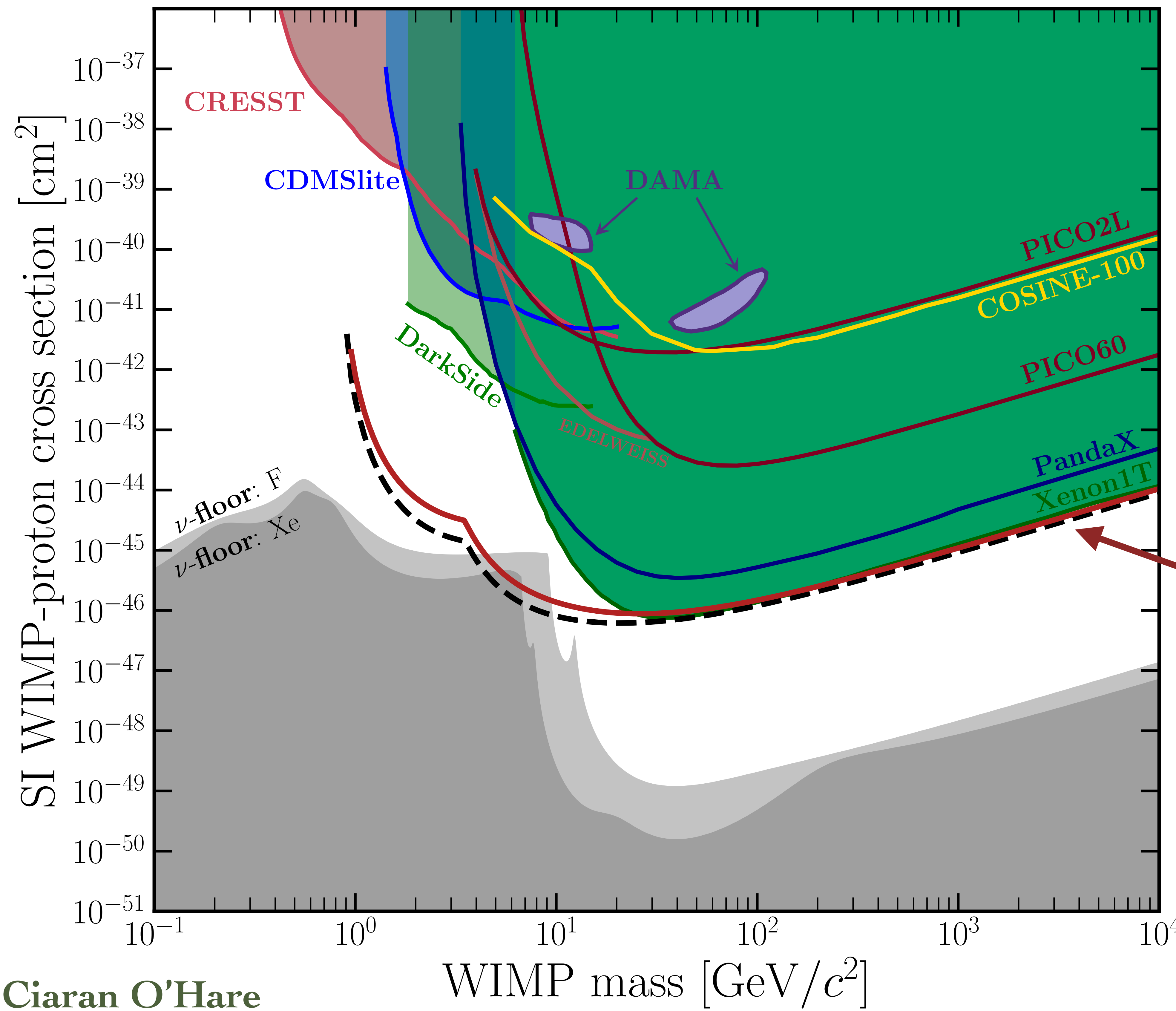


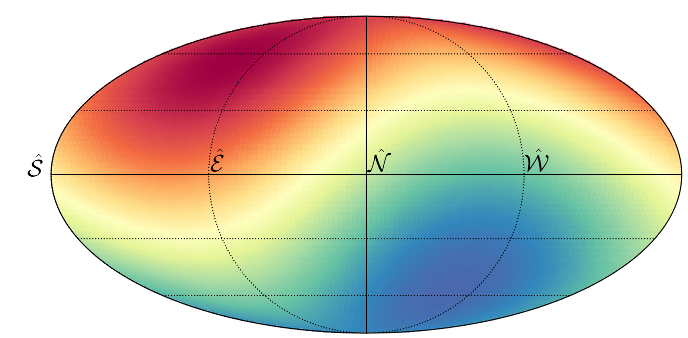


Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(1 atm He+SF_6 TPC, 1000 m^3 x 6 years)



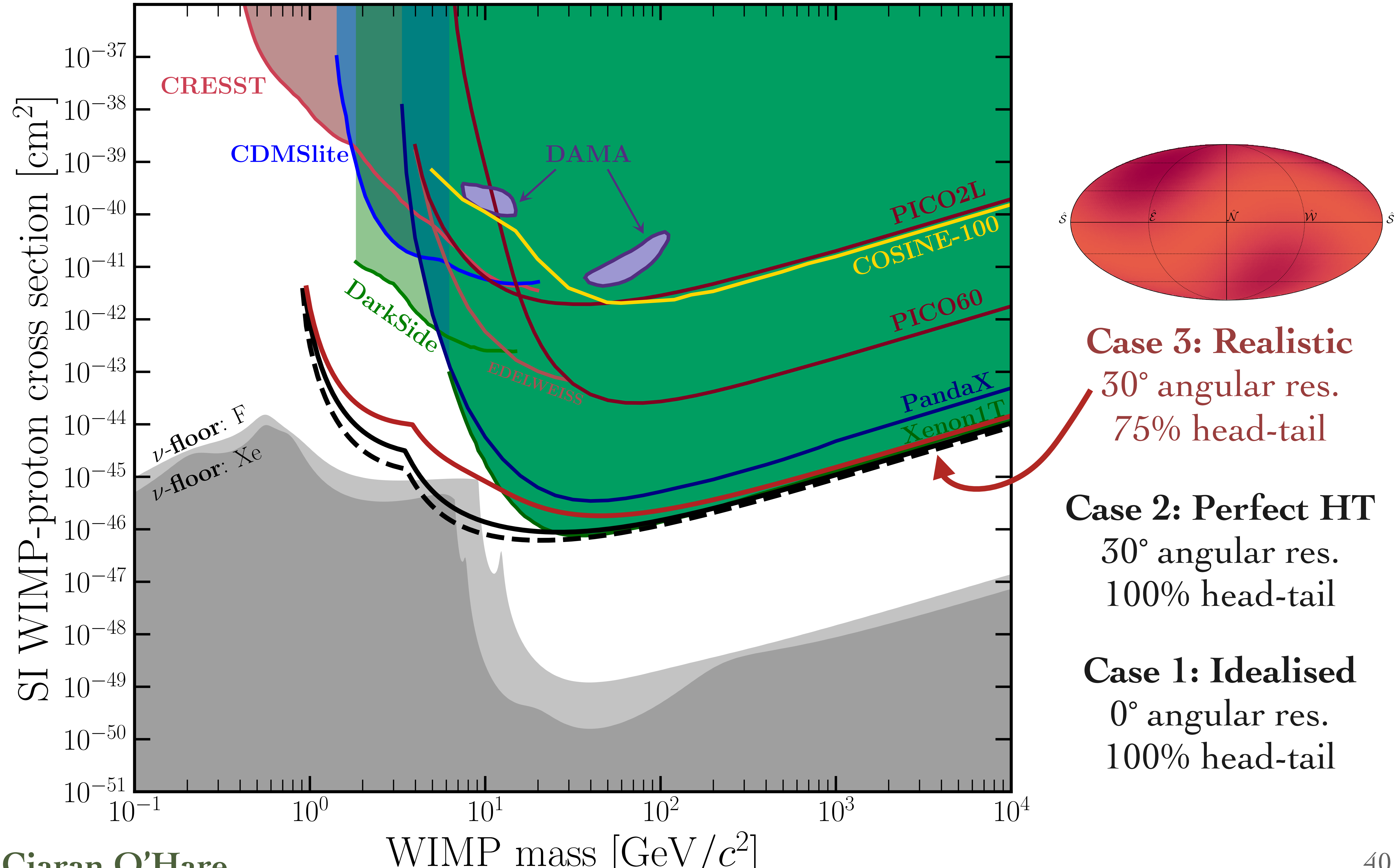


Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(1 atm He+SF_6 TPC, 1000 m^3 x 6 years)



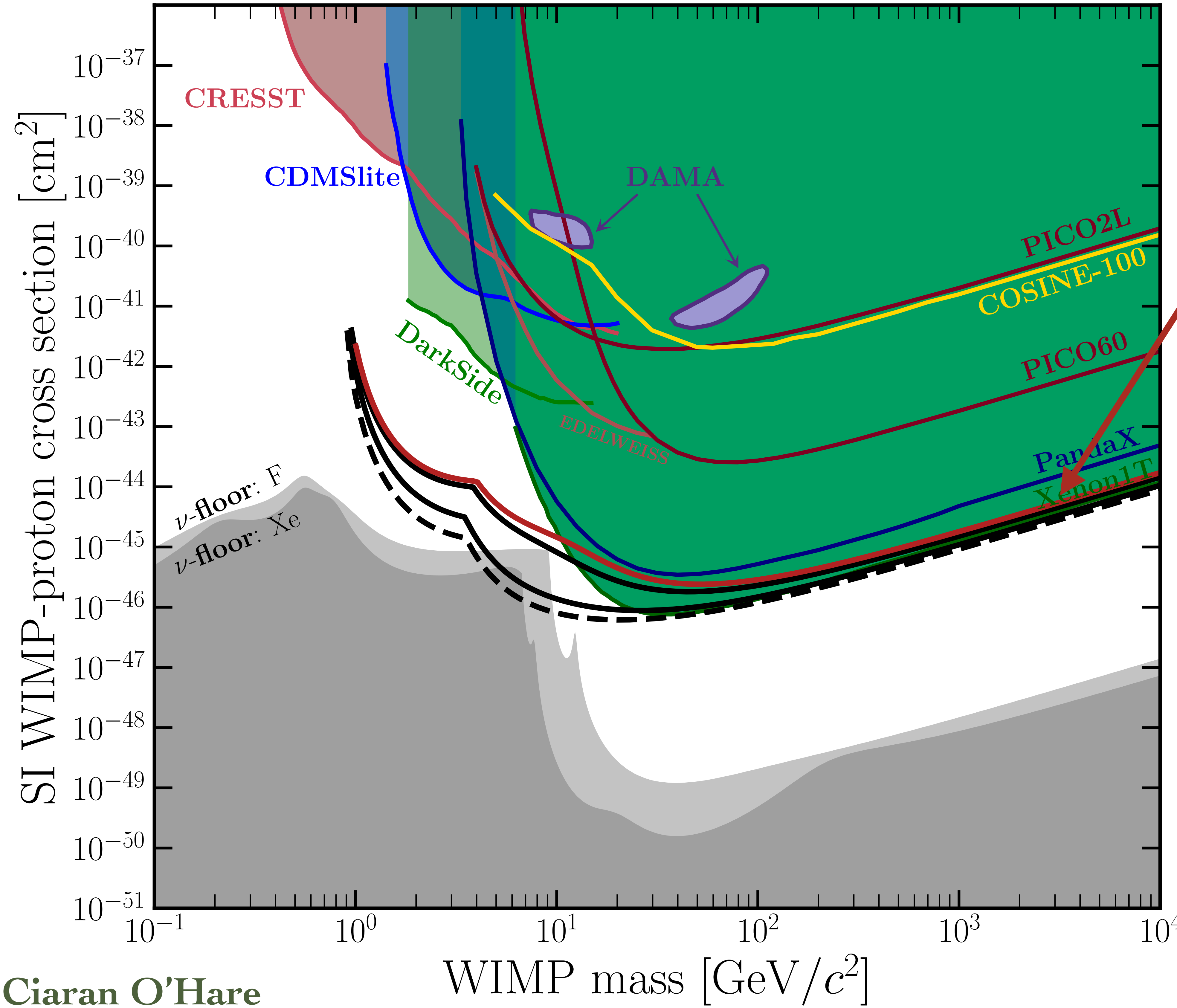
Case 3: Realistic
30° angular res.
75% head-tail

Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(1 atm He+SF_6 TPC, 1000 m^3 x 6 years)



Case 4: No directionality
1 rad angular res.
50% head-tail

Case 3: Realistic
30° angular res.
75% head-tail

Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

~~**Method 1: Detect a lot of events**~~

~~**Method 2: Improve neutrino flux measurements**~~

~~**Method 3: Use annual modulation**~~

~~**Method 4: Use multiple targets**~~

Method 5: Use directional detectors

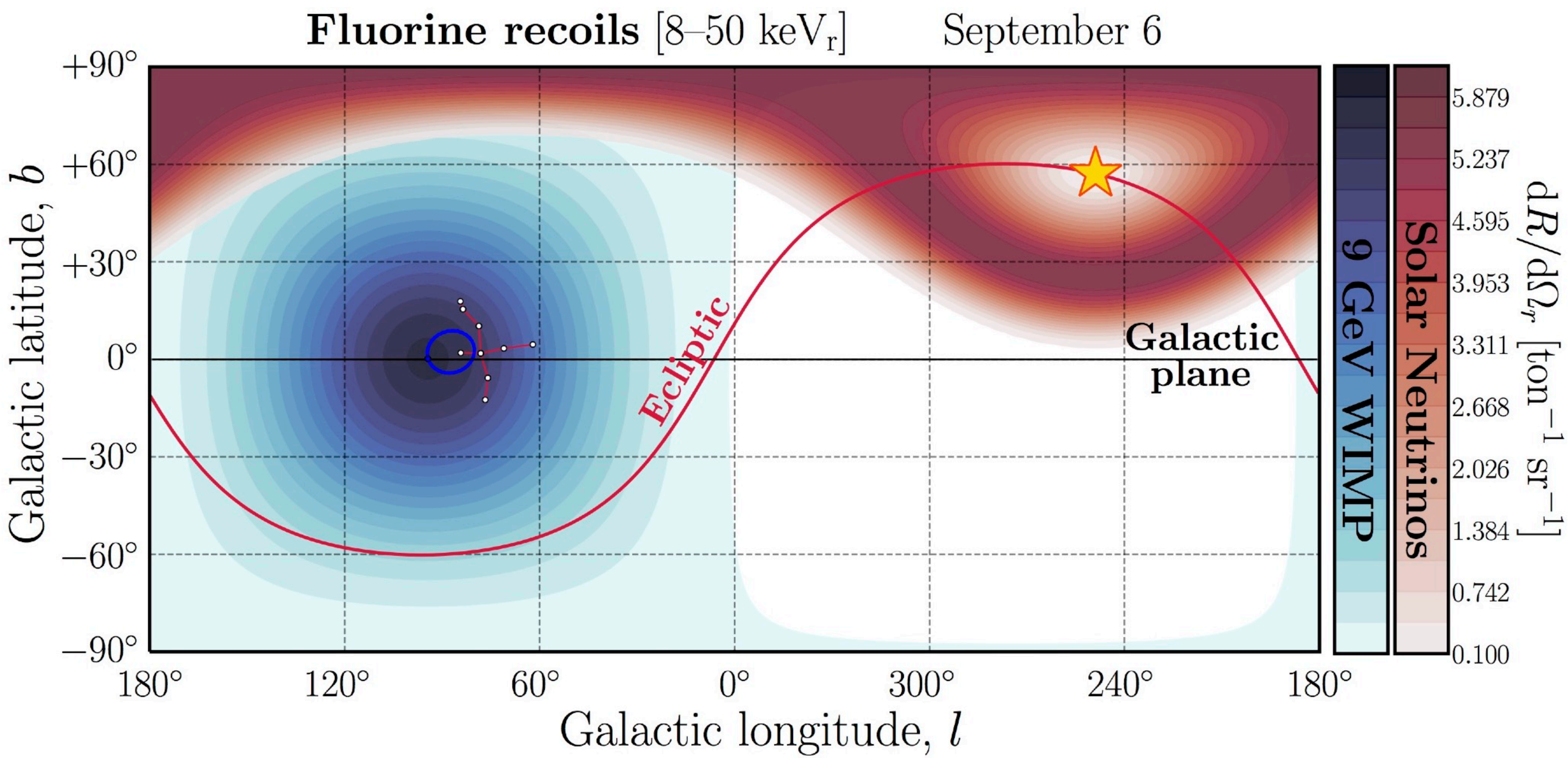
The most powerful way to remove the background

Idealised detector → Neutrino floor completely removed

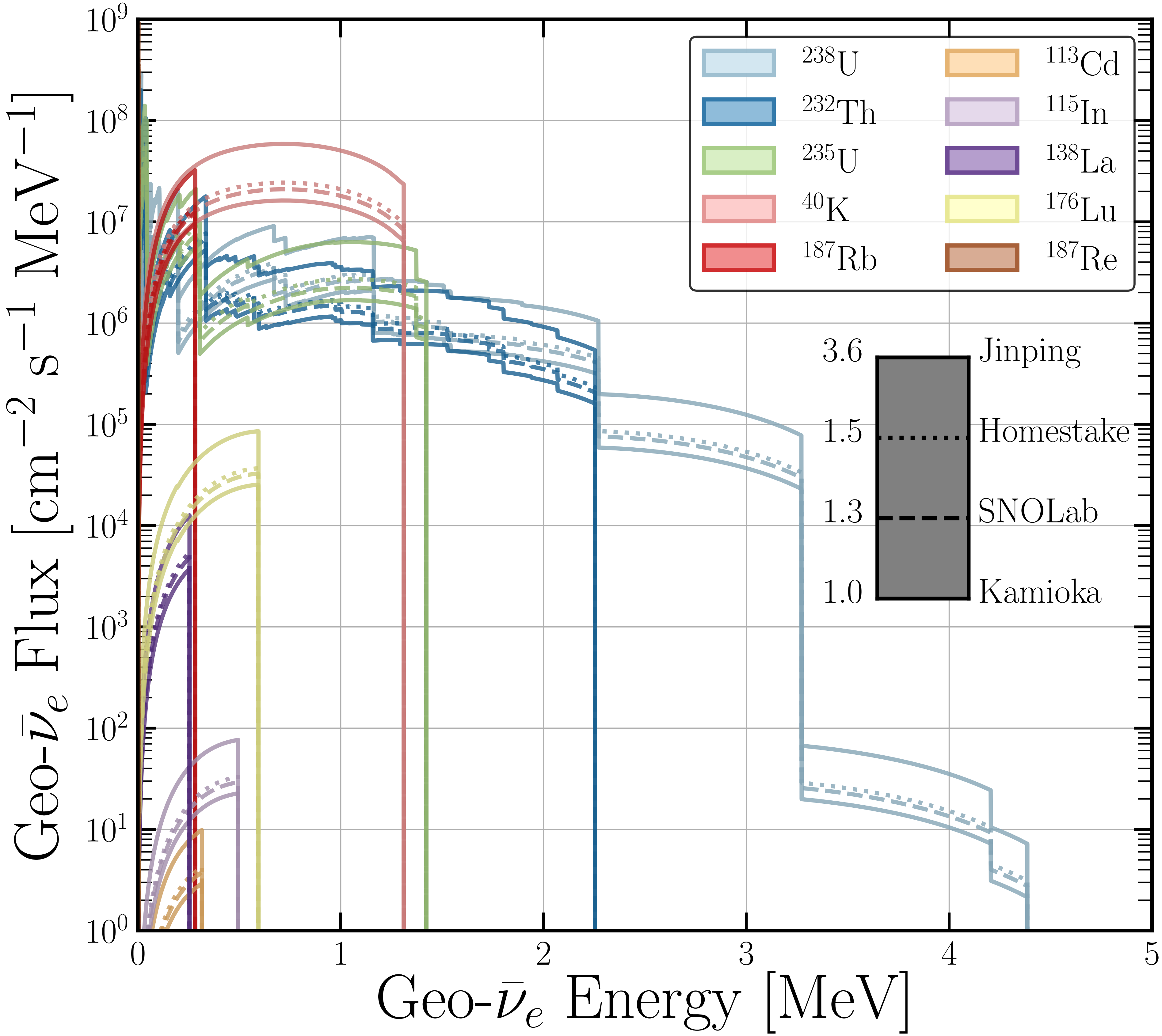
Realistic detector → Need <30° resolution and <75% Head-tail

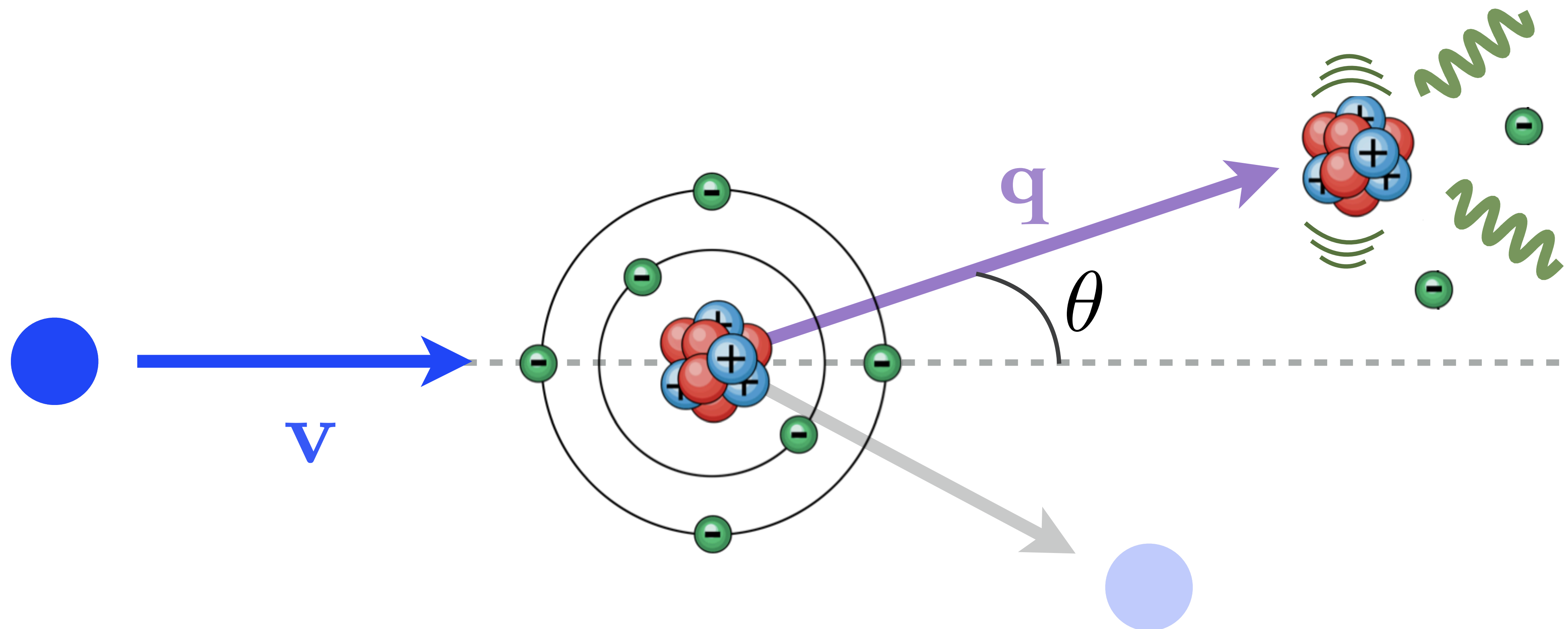
Extra slides

Nothing mimics dark matter, including solar neutrinos



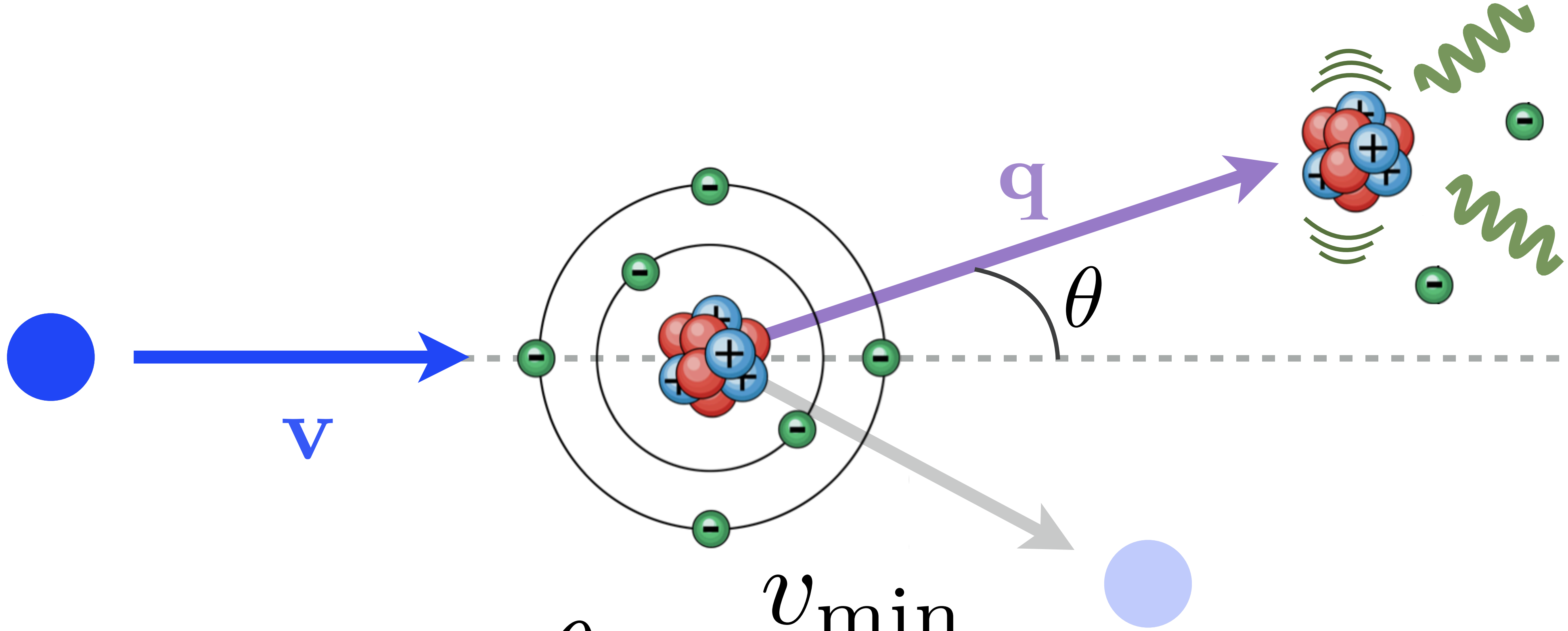
Geoneutrino flux depends on location





Momentum transfer: $$q = 2\mu_N v \cos\theta$$

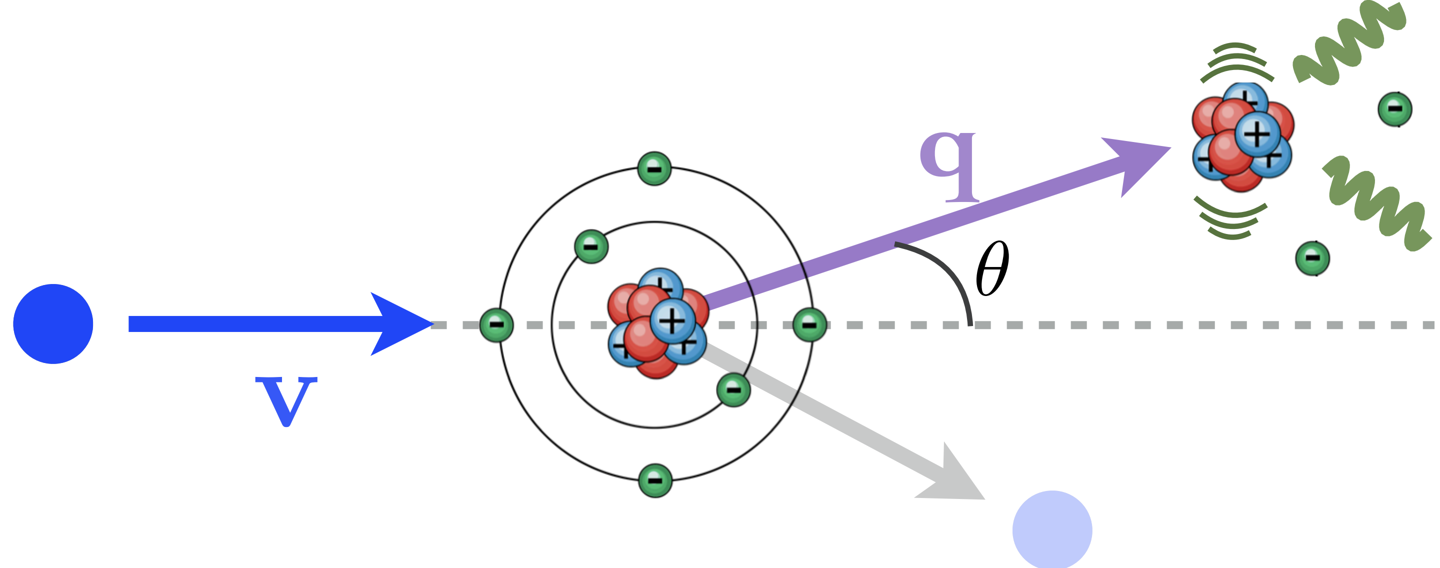
Or equivalently, $$\cos\theta = \frac{v_{\rm min}}{v}$$



$$\cos\theta = \frac{v_{\rm min}}{v}$$

Convert usual scattering cross section vs energy, into a cross section vs energy and angle by imposing the kinematic relation:

$$\frac{{\rm d}\sigma}{{\rm d}E_r{\rm d}\Omega_r} = \frac{{\rm d}\sigma}{{\rm d}E_r}\frac{1}{2\pi}\delta\left(\cos\theta - \frac{v_{\rm min}}{v}\right)$$



To get the full rate integrate the cross section with the DM flux:

$$\frac{\mathrm{d}^2 R}{\mathrm{d}E_r \mathrm{d}\Omega_r} = \frac{\rho_0}{m_N m_\chi} \int_{v>v_{\min}}^{\infty} v f_{\mathrm{lab}}(\mathbf{v}) \frac{\mathrm{d}^2\sigma}{\mathrm{d}E_r \mathrm{d}\Omega_r} \mathrm{d}^3\mathbf{v}$$

Energy dependence of most cross sections will look like:

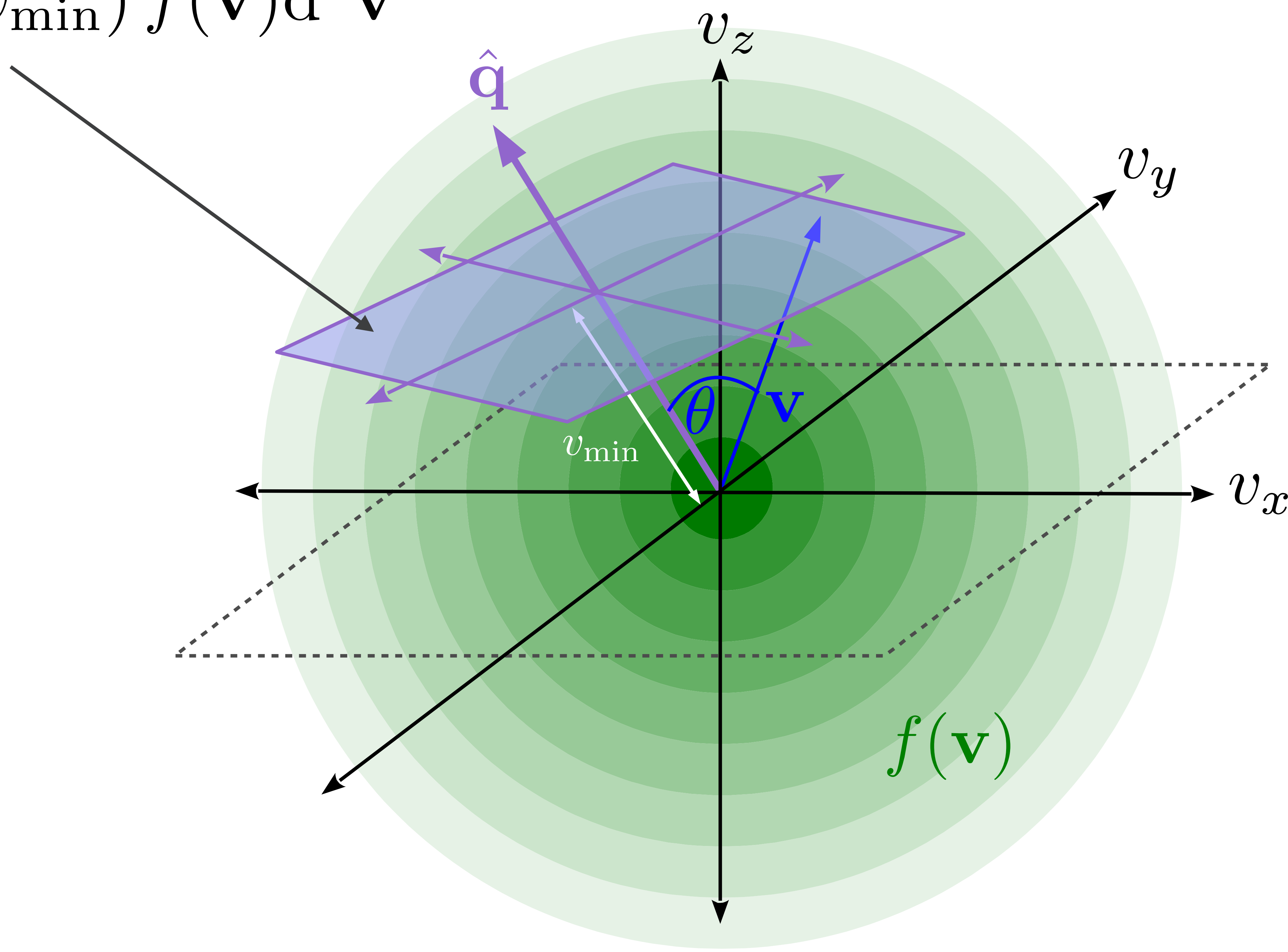
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{m_N \mathcal{C}_N \sigma_p}{2\mu_p^2 v^2} F^2\left(E_r\right)$$

$$\rightarrow \quad \frac{\mathrm{d}^2 R}{\mathrm{d}E_r \mathrm{d}\Omega_r} = \frac{\rho_0 \mathcal{C}_N \sigma_p}{4\pi m_\chi \mu_p^2} F^2\left(E_r\right) \boxed{\int \delta(v\cos\theta - v_{\min}) f(\mathbf{v}) \mathrm{d}^3\mathbf{v}}$$

"Radon transform" encodes all direction sensitivity

Radon transform

$$\int \delta\left(v\cos\theta - v_{\min}\right) f(\mathbf{v}) \mathrm{d}^3\mathbf{v}$$



Readout dimensionality depends on technology

1d - just drift direction (z)

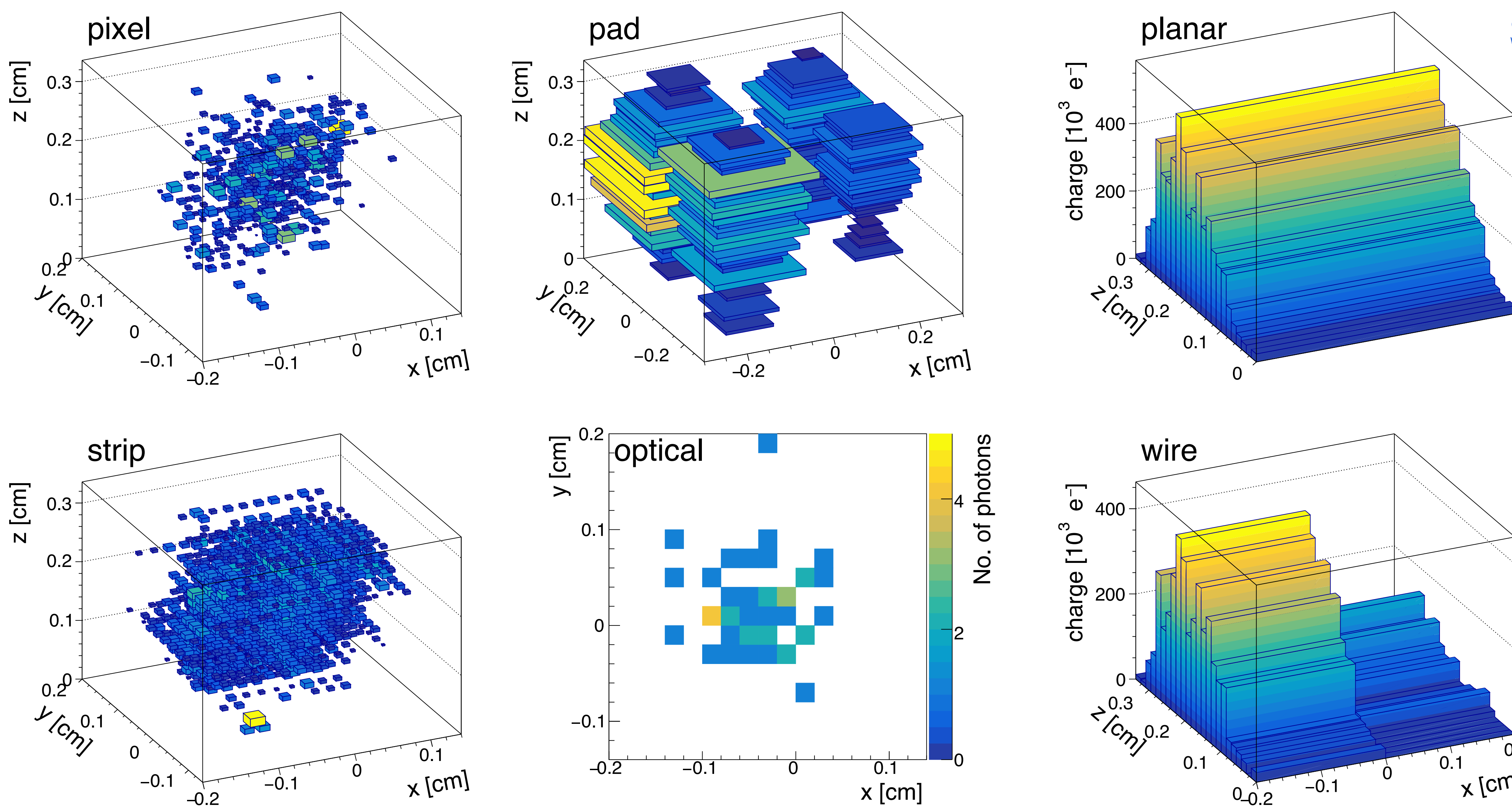
e.g. ***planar*** (just time dependence of charge), ***wire*** (e.g. DRIFT)

2d → just readout plane (x,y)

e.g. ***optical*** (CCDs)

3d → readout plane + drift direction (x,y,z)

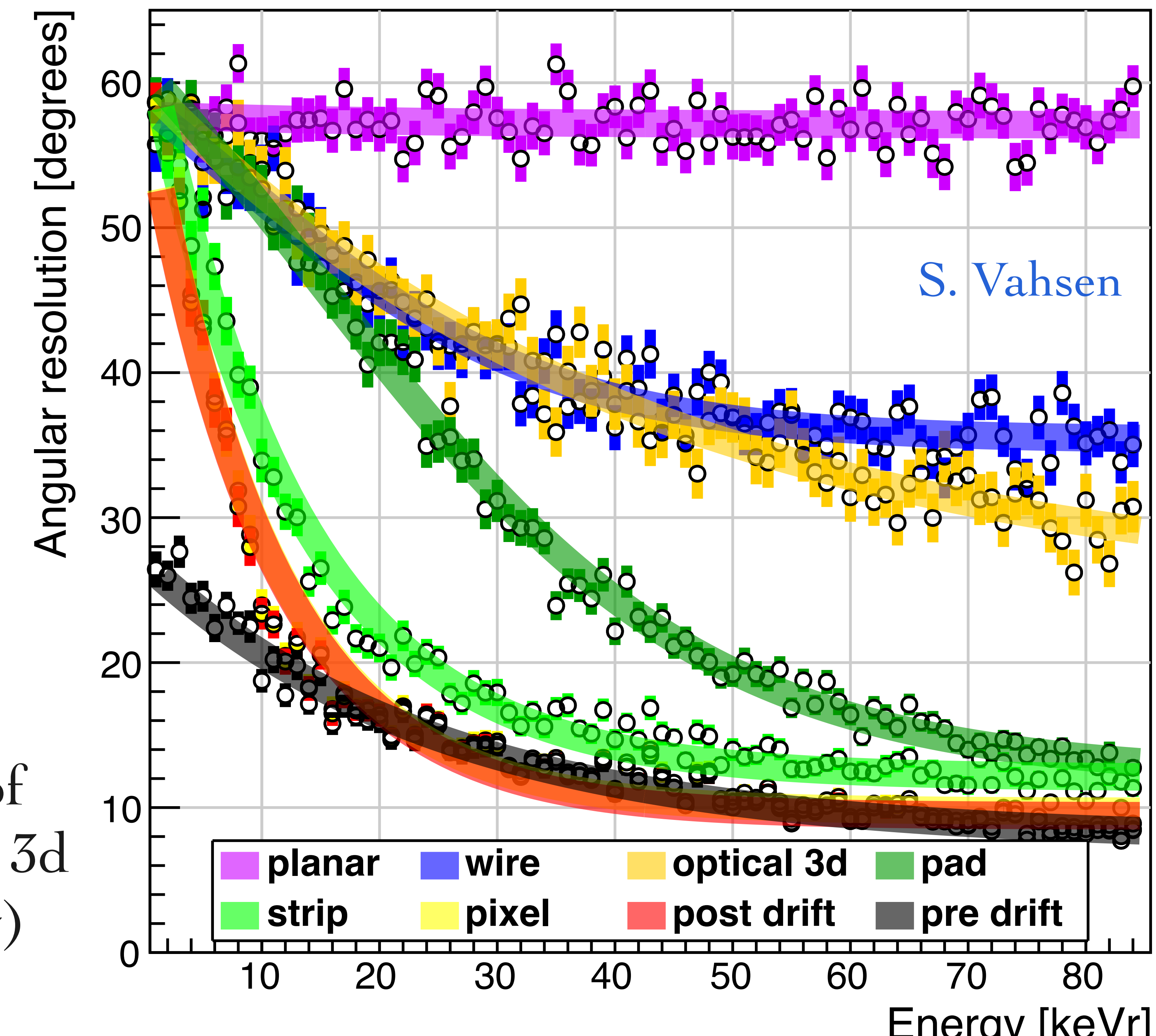
e.g. ***pixel*** chips, muPIC ***strips***, Cameras+PMTs (CYGNO), ***pad***



S. Vahsen

Angular resolution

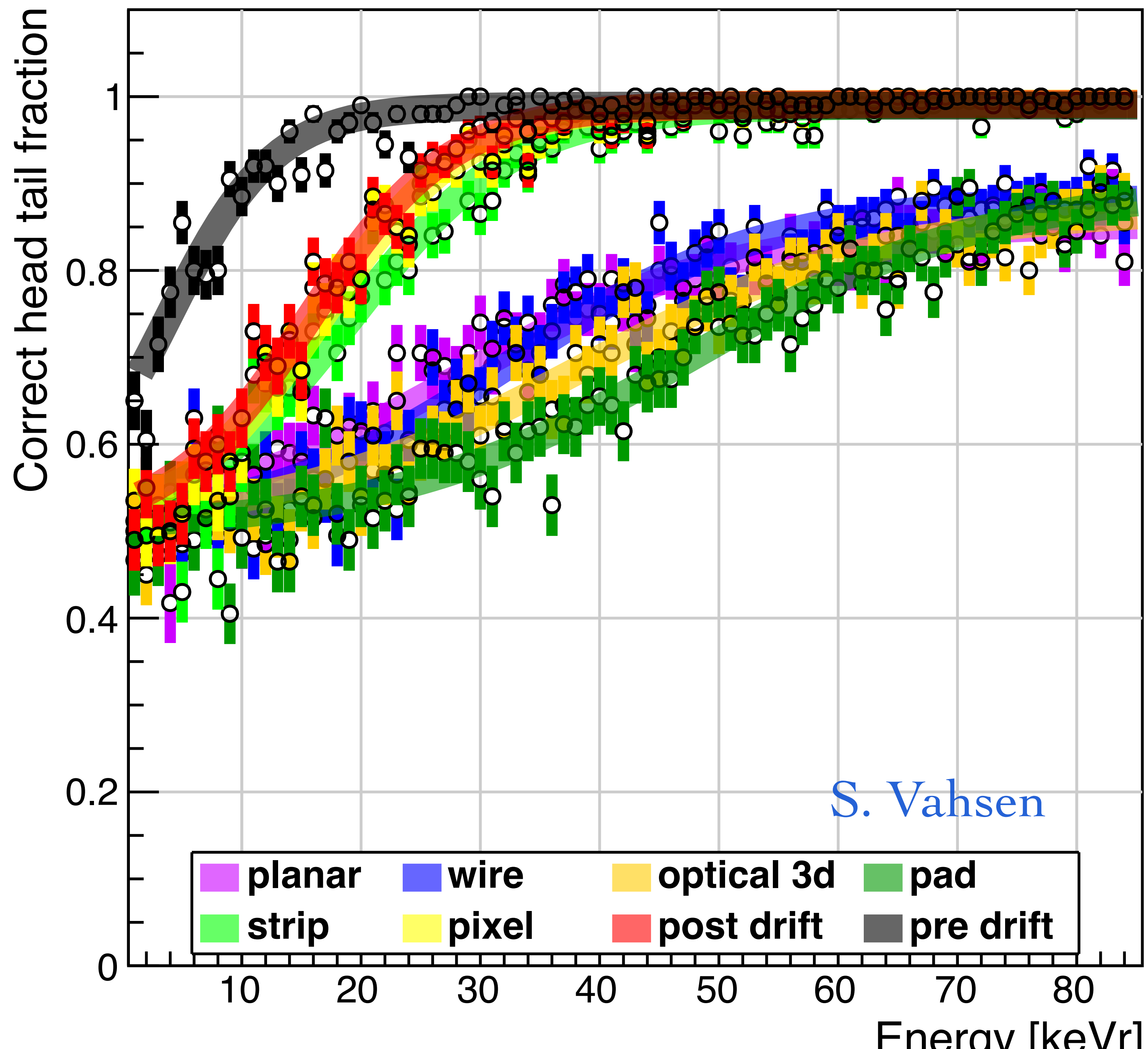
Angular resolution improves with energy because tracks are longer and more charge is generated



He recoils in 755:5 Torr of $He:SF_6$, (except for optical 3d which has 740:20 $He:CF_4$)

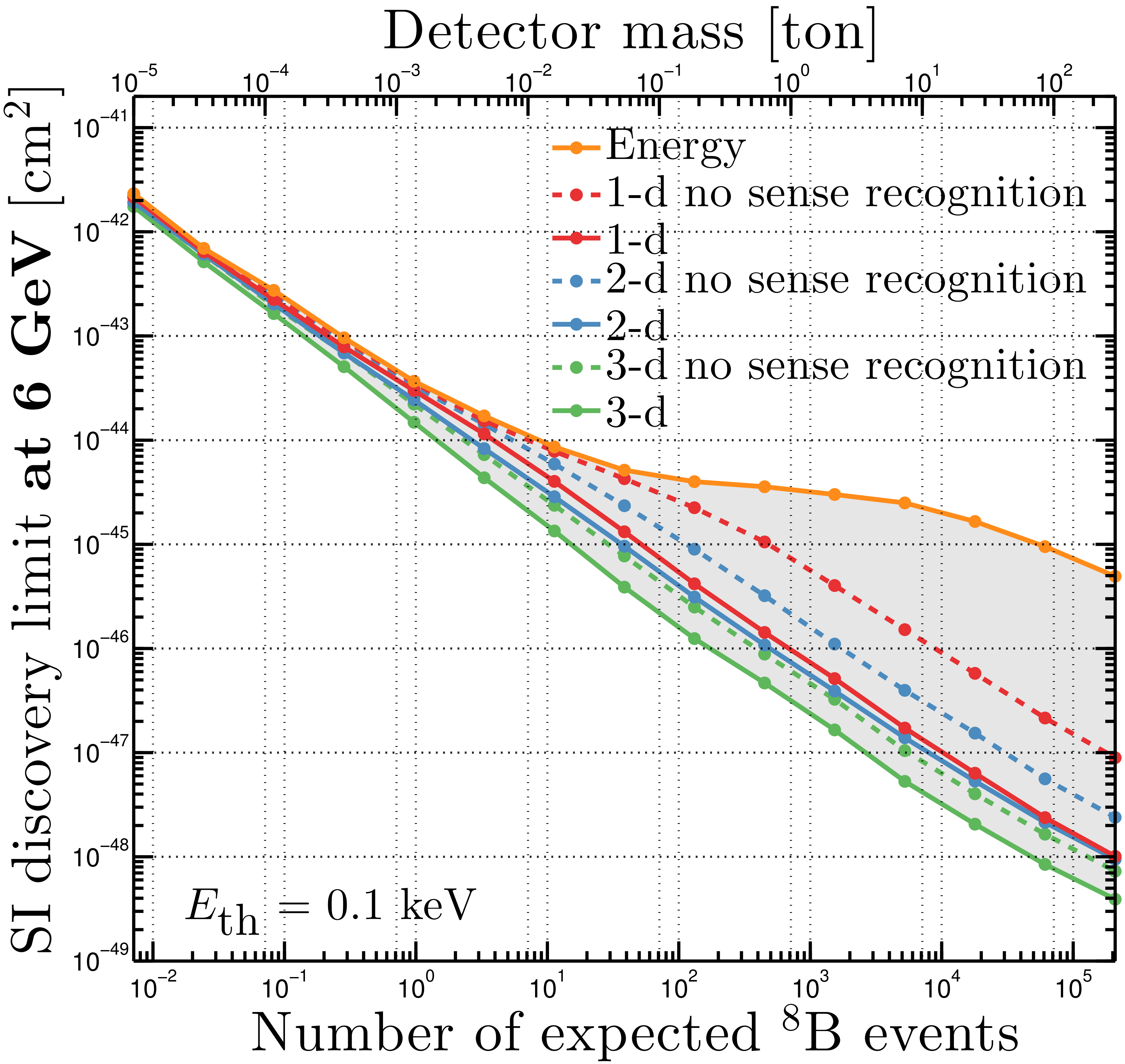
Head-tail recognition

Head-tail recognition also improves with energy because tracks are longer and more charge is generated



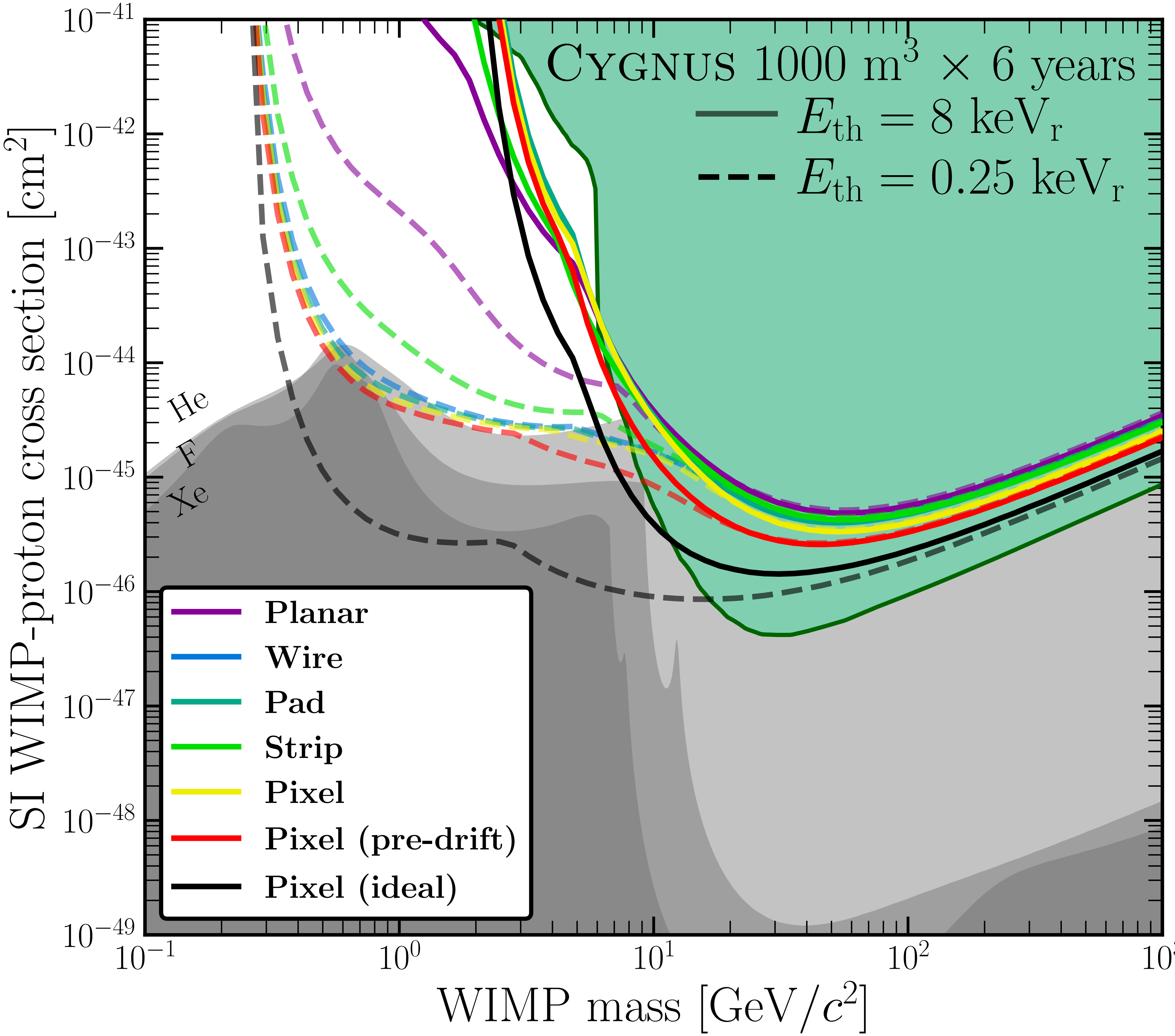
He recoils in 755:5 Torr of $He:SF_6$, (except for optical 3d which has 740:20 $He:CF_4$)

Is Head-tail or track dimensionality more important?

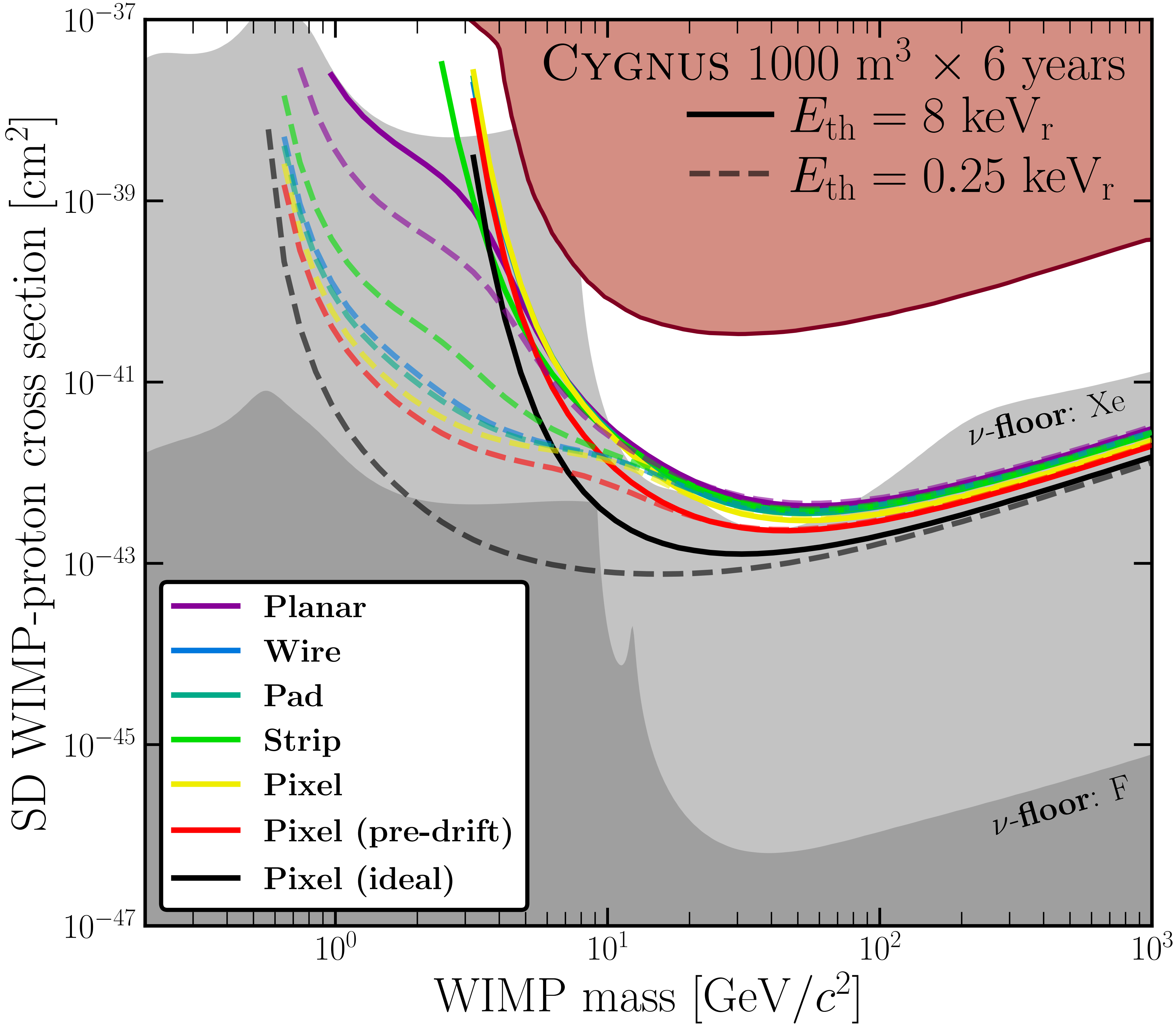


Better to have 3d readout **without** HT than 1d/2d readout **with** HT

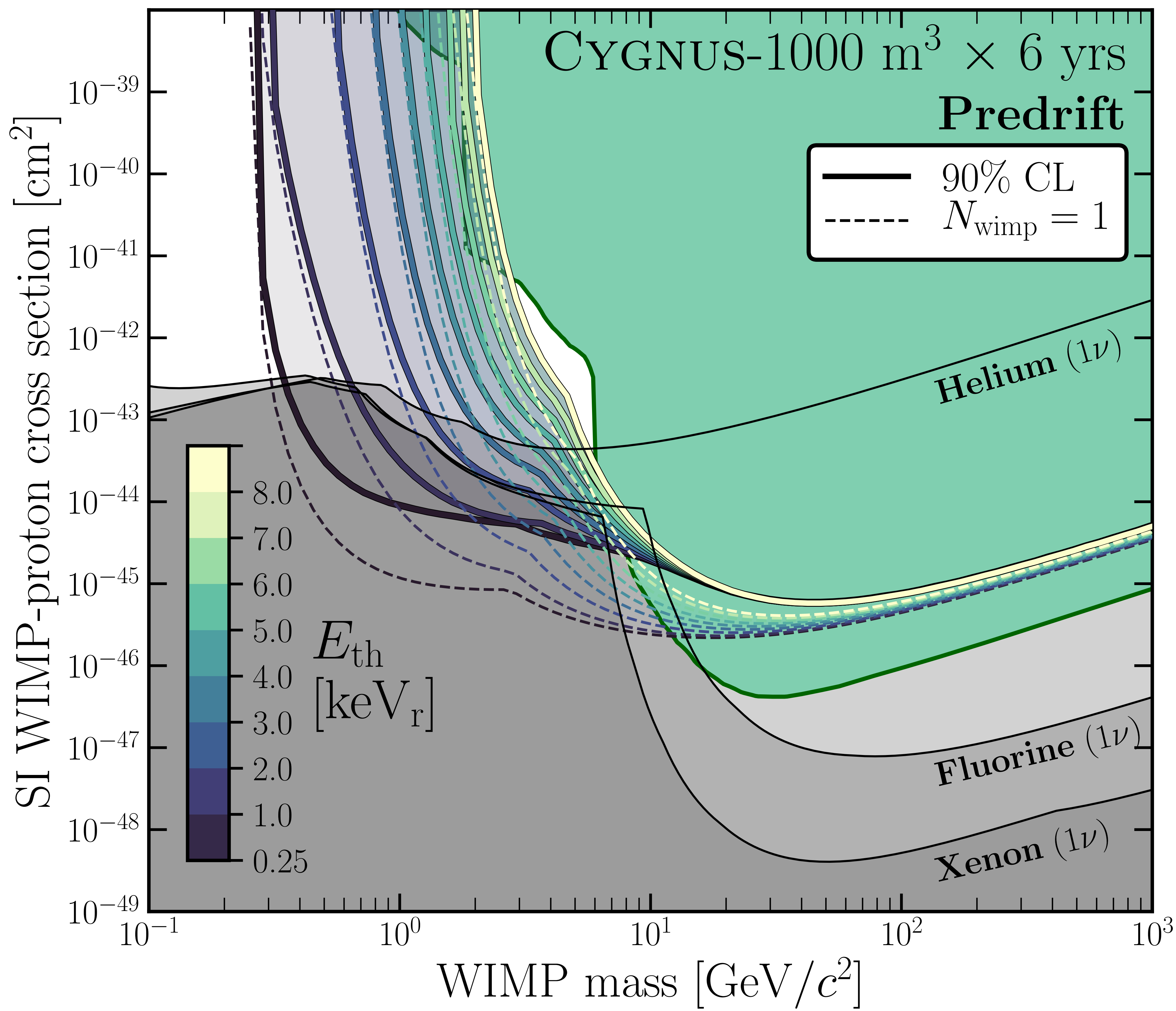
Physics reach
(WIMP nuclear scattering vs neutrino background)



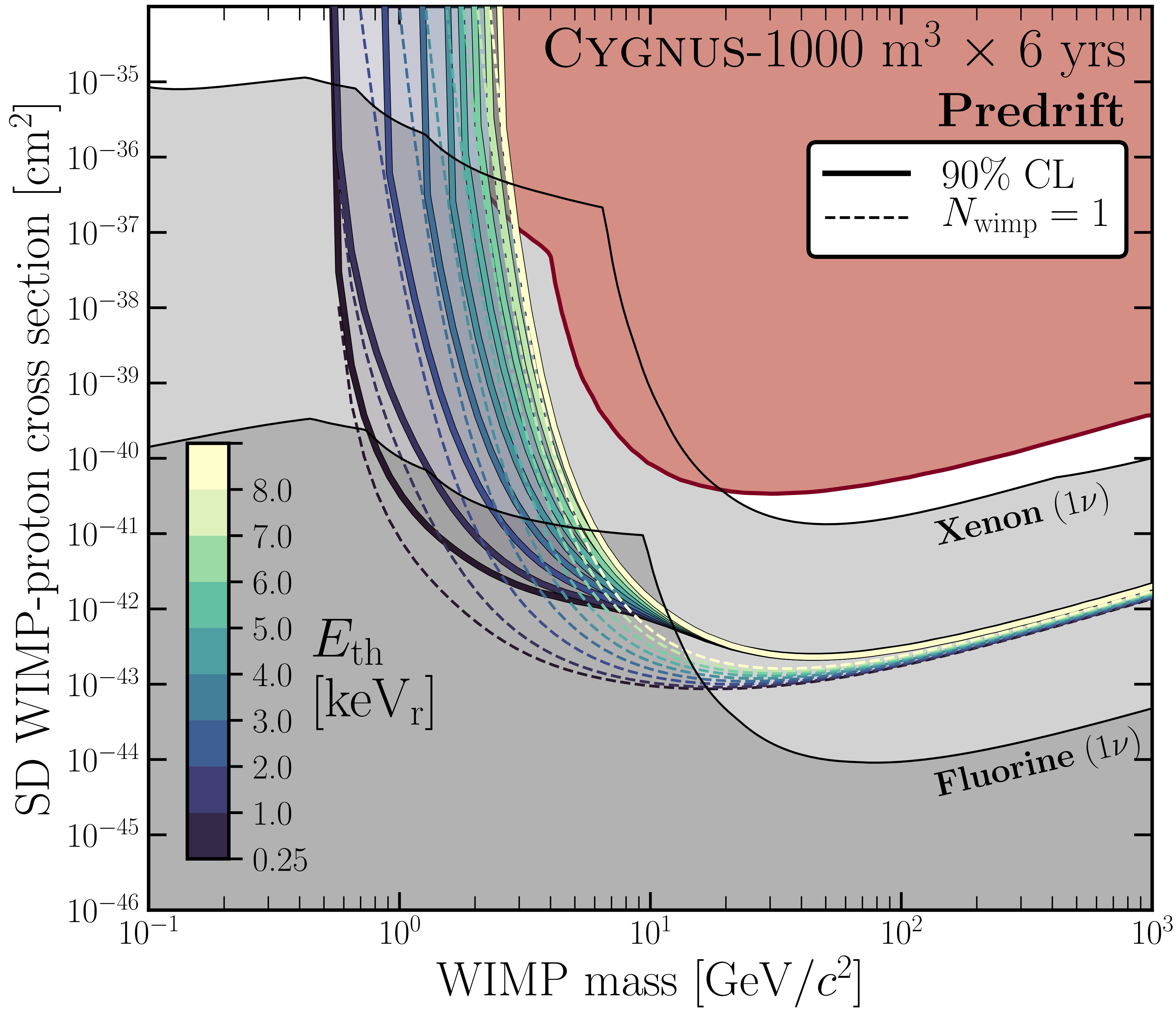
Physics reach
(WIMP nuclear scattering vs neutrino background)

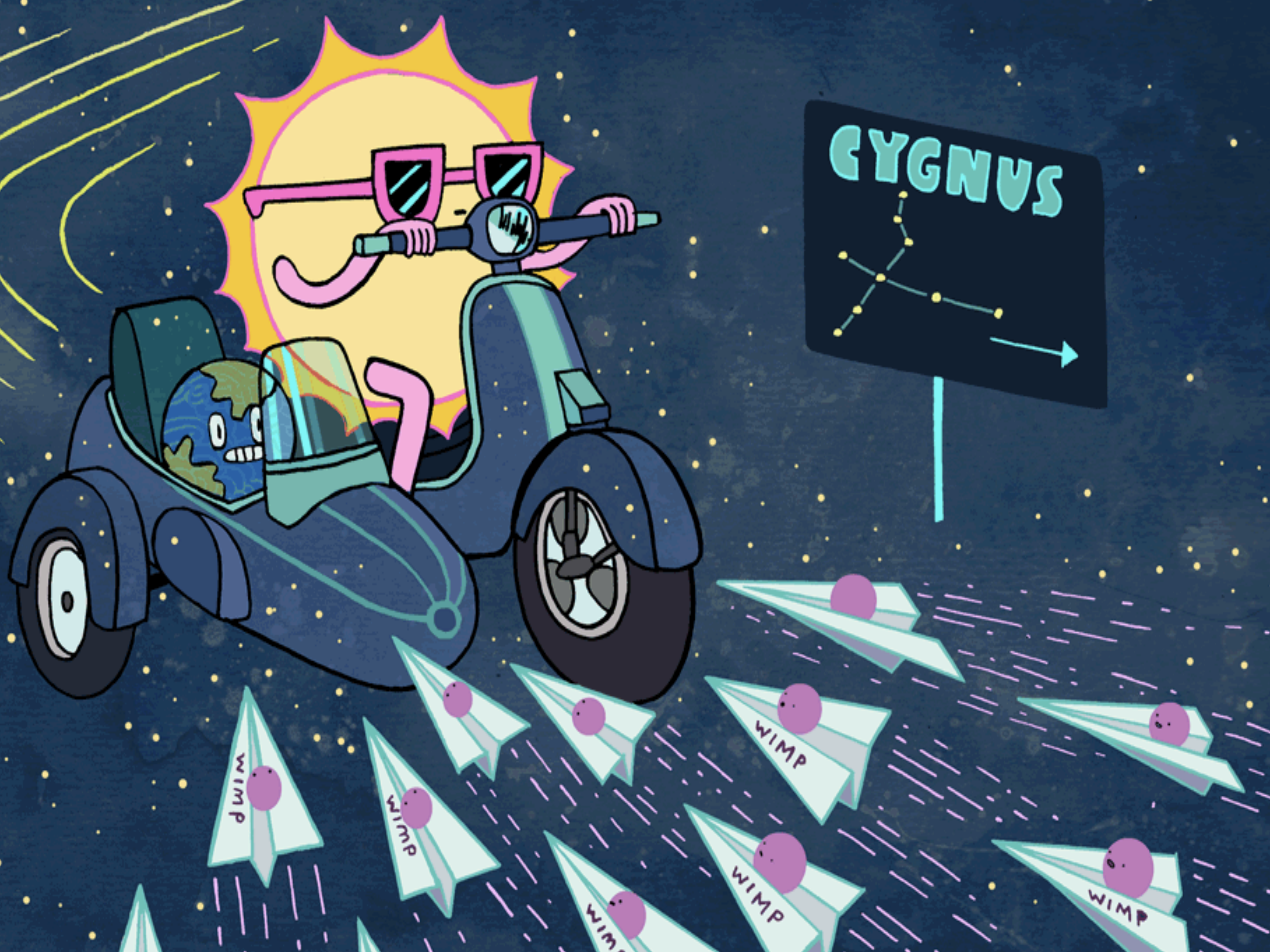


Physics reach vs Threshold: Spin dependent



Physics reach vs Threshold: Spin dependent




CYGNUS
WIMP