



Centre for Dark Matter
Particle Physics



THE UNIVERSITY OF
SYDNEY

Breaking through the neutrino floor

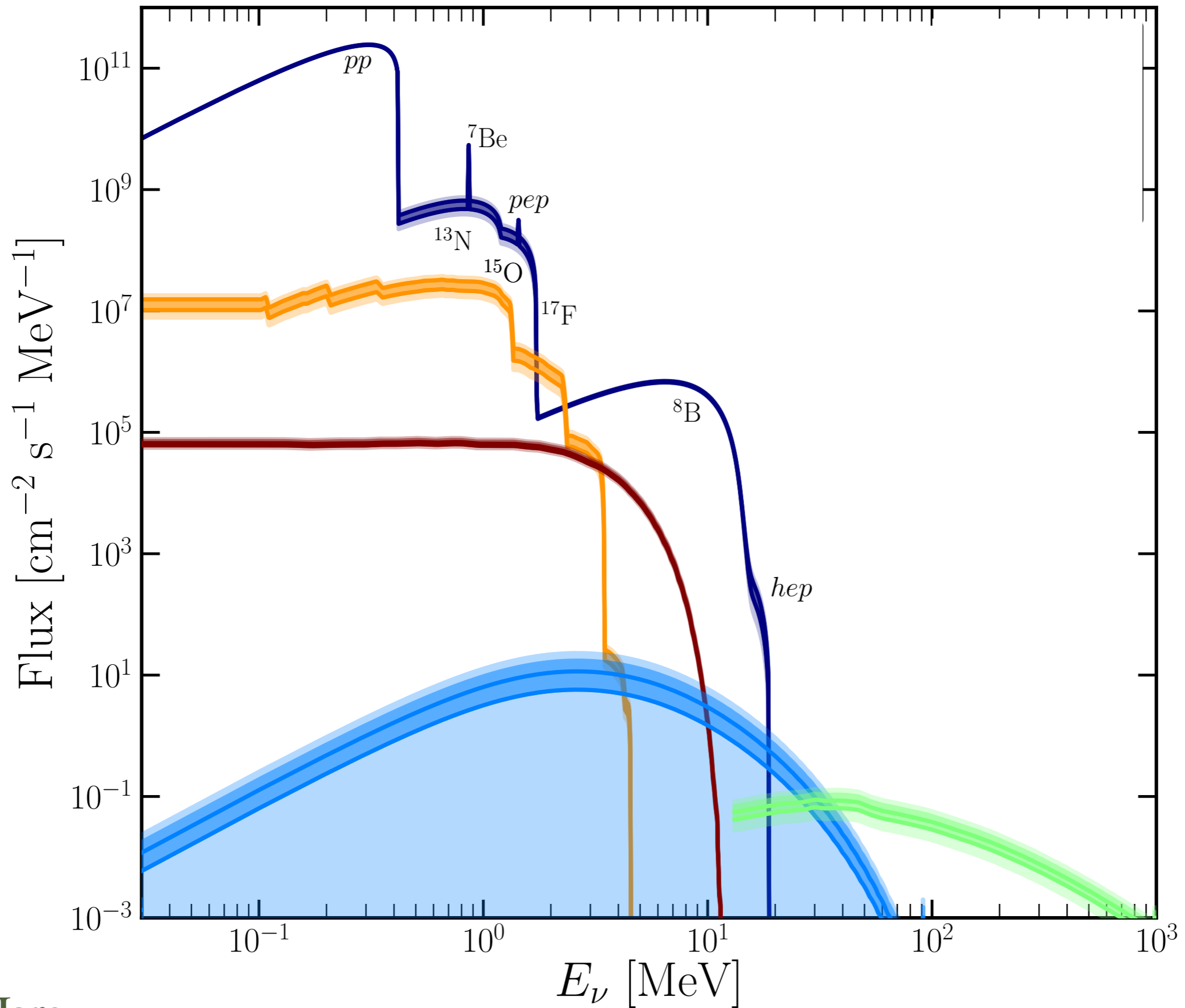
Ciaran O'Hare
University of Sydney

How to break through the neutrino floor

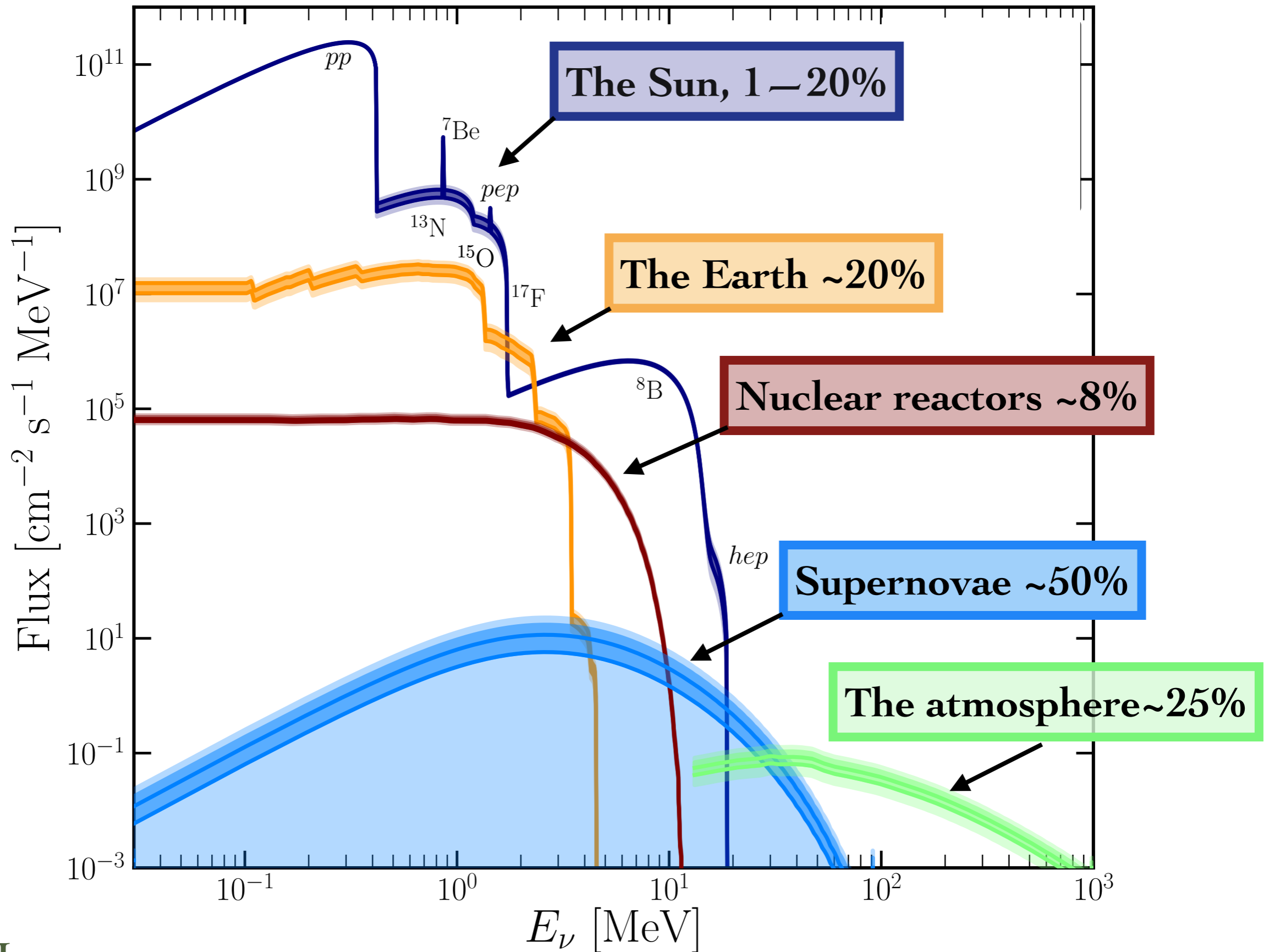
5 methods, increasing effectiveness

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

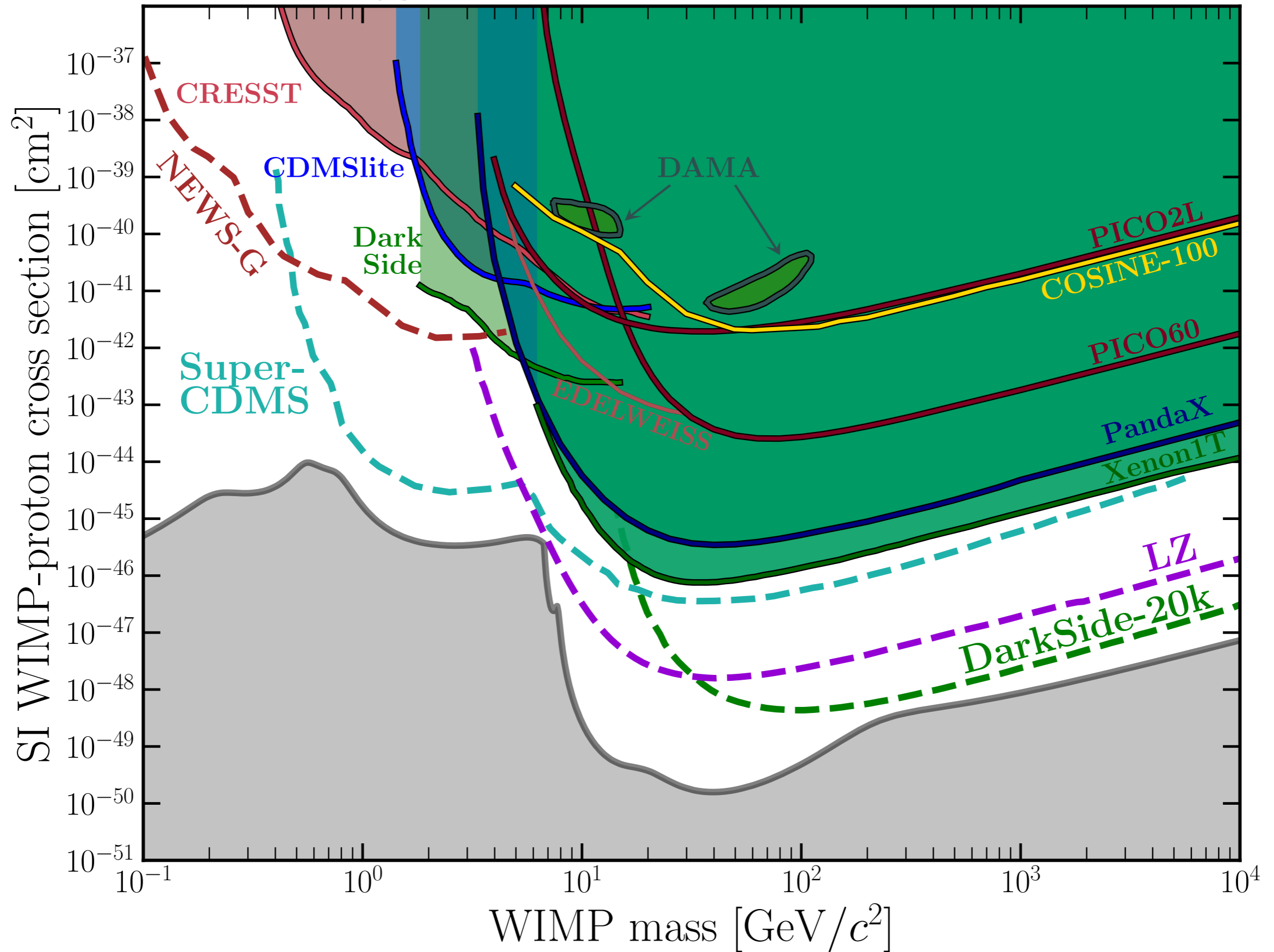
(Recap) Neutrino fluxes + Uncertainties



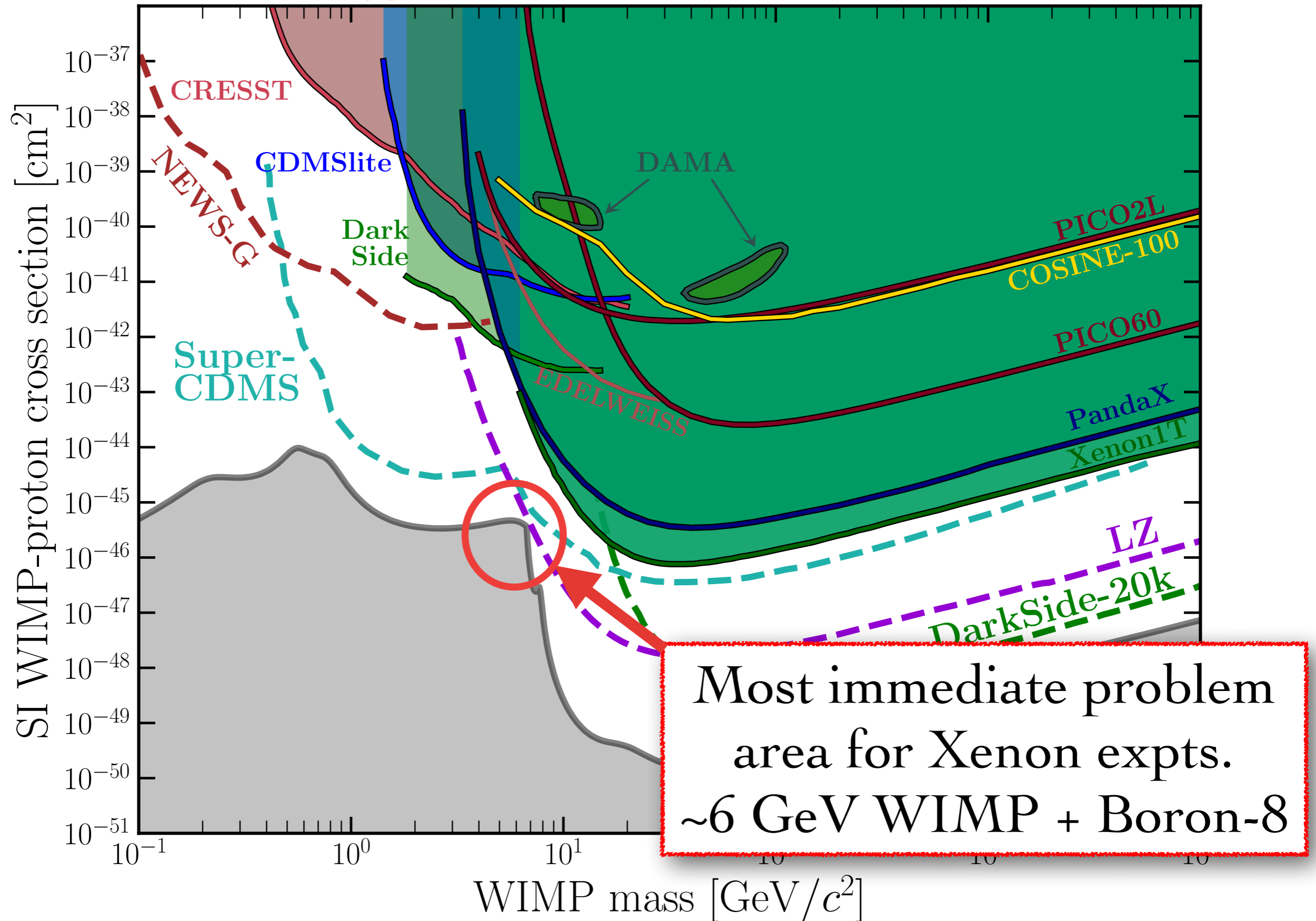
(Recap) Neutrino fluxes + Uncertainties



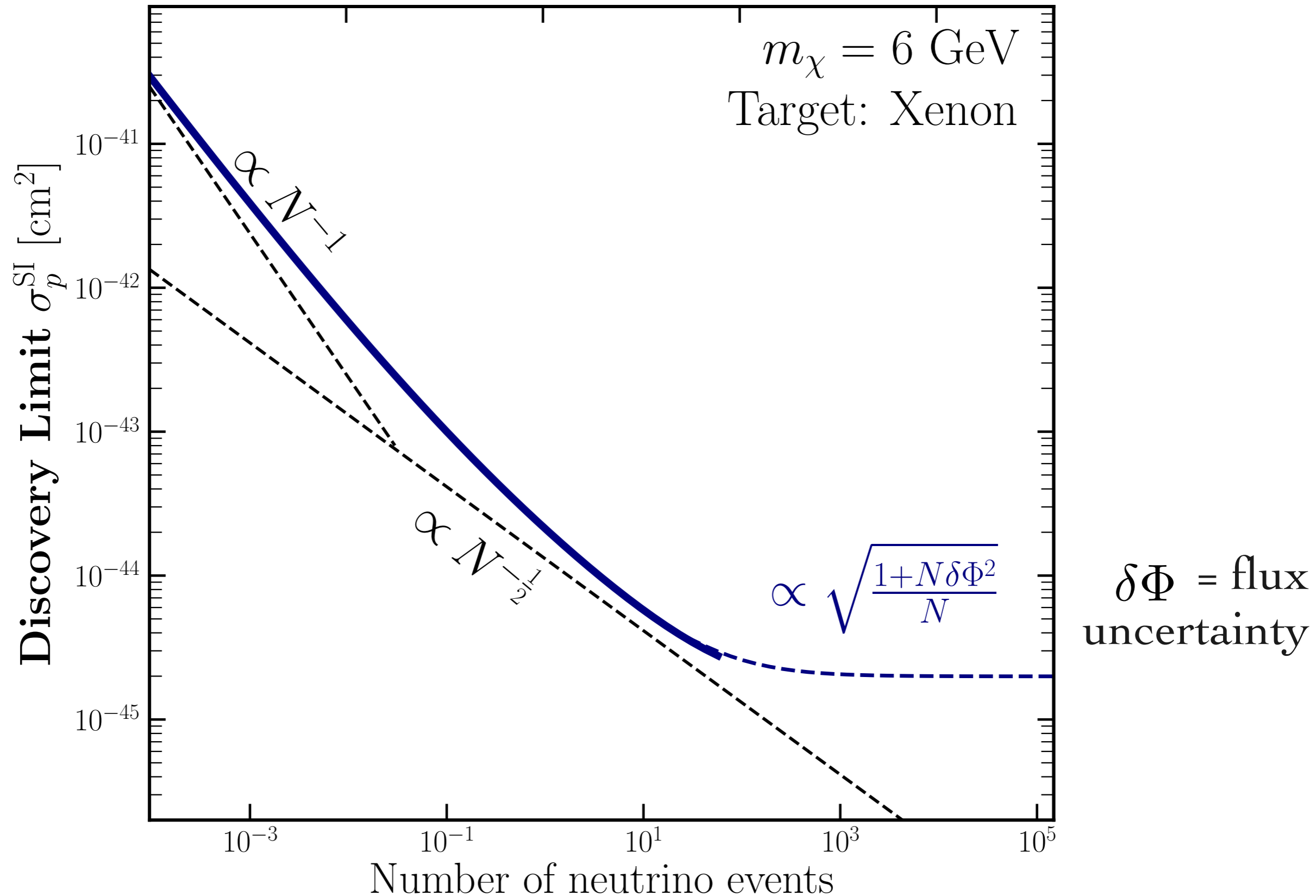
(Recap) The neutrino floor



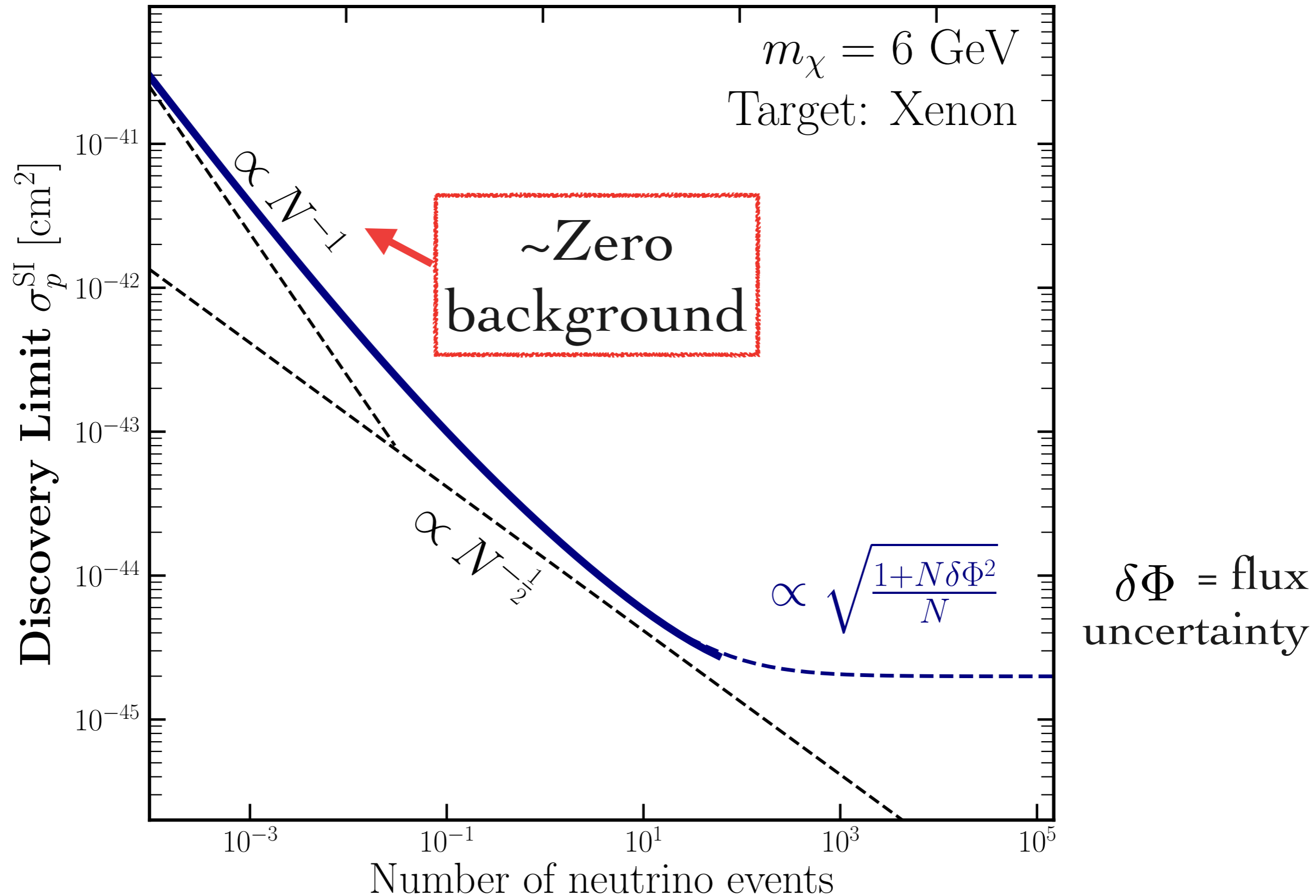
(Recap) The neutrino floor



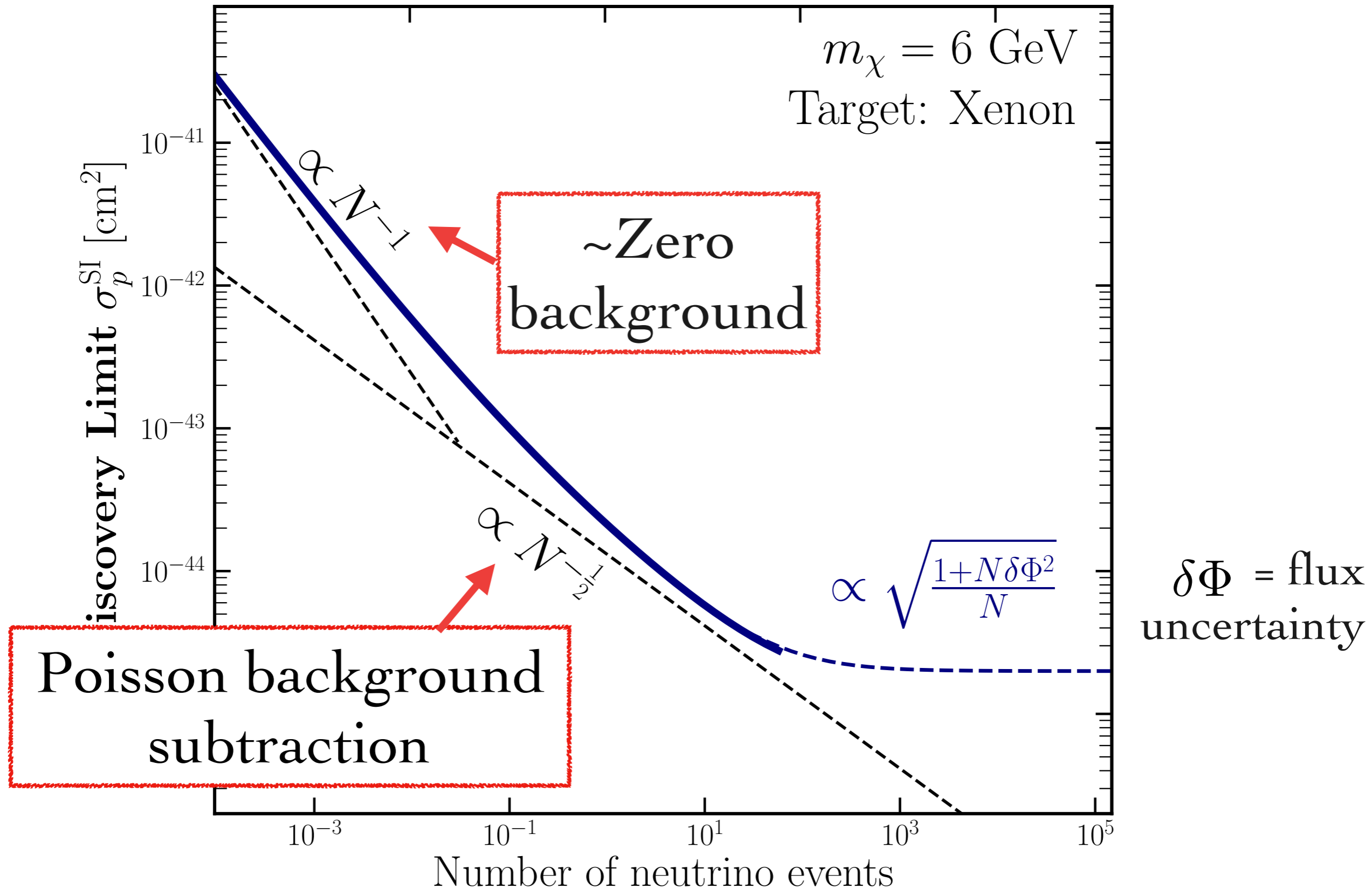
Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos



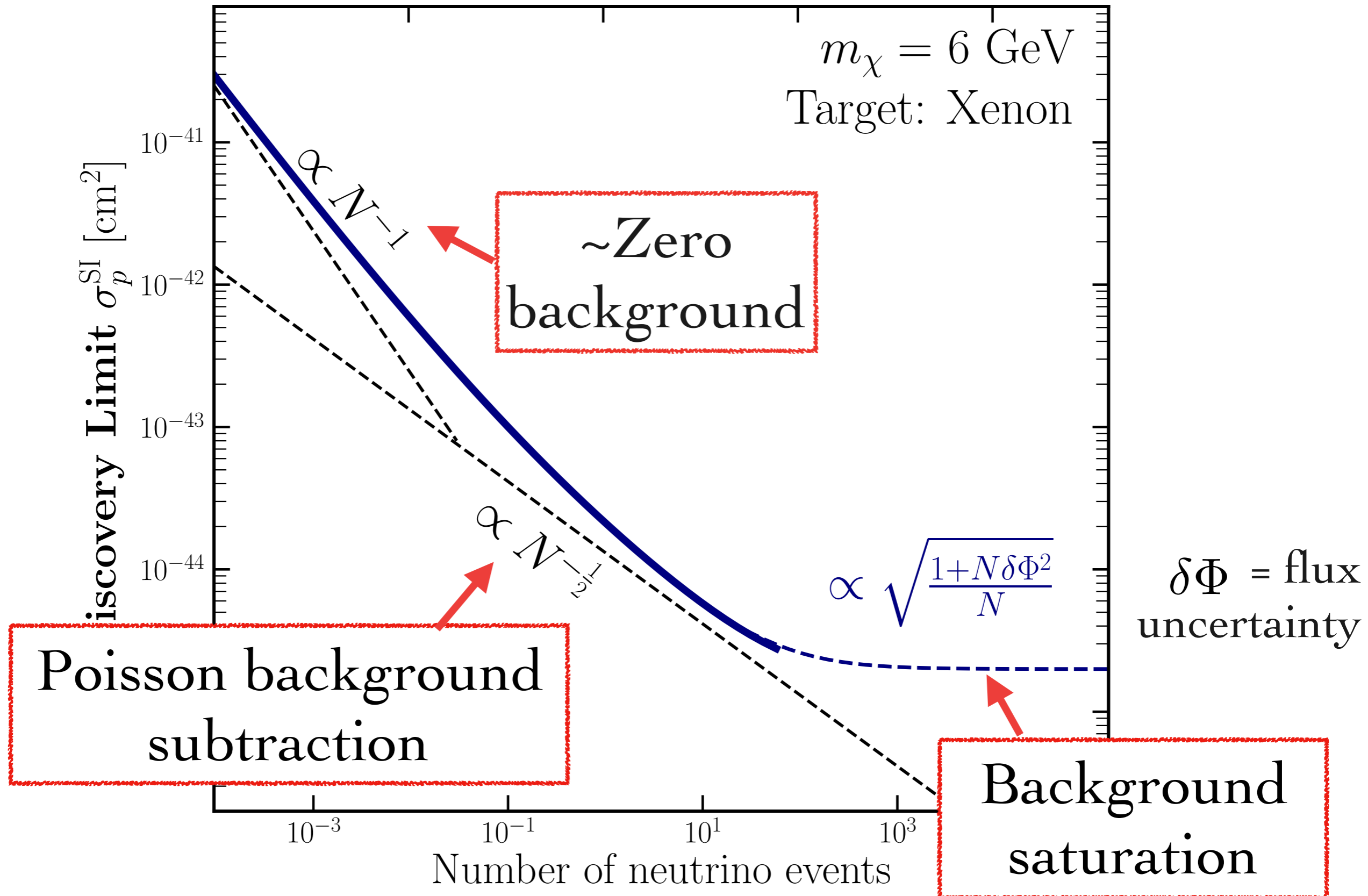
Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos

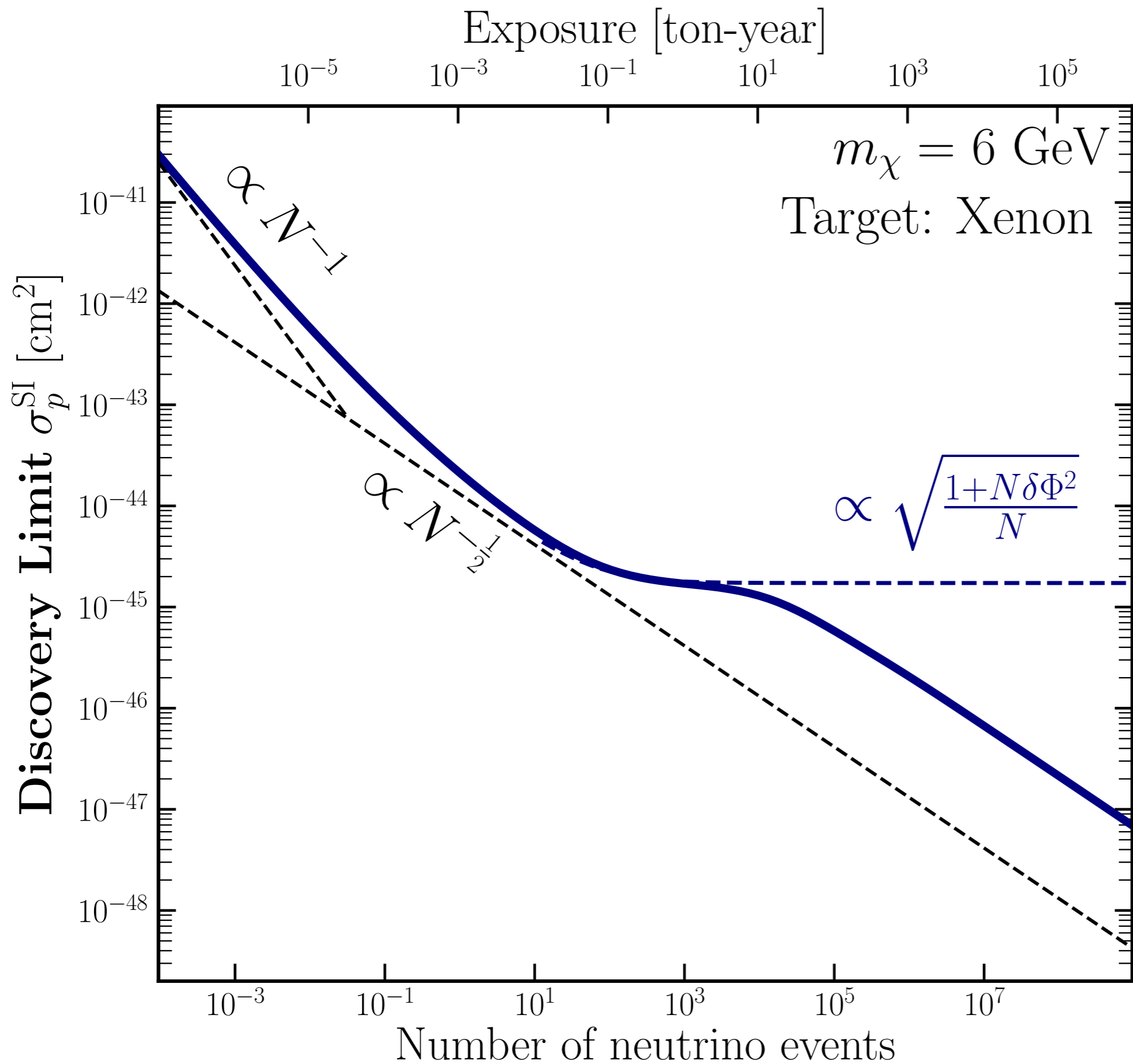


Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos



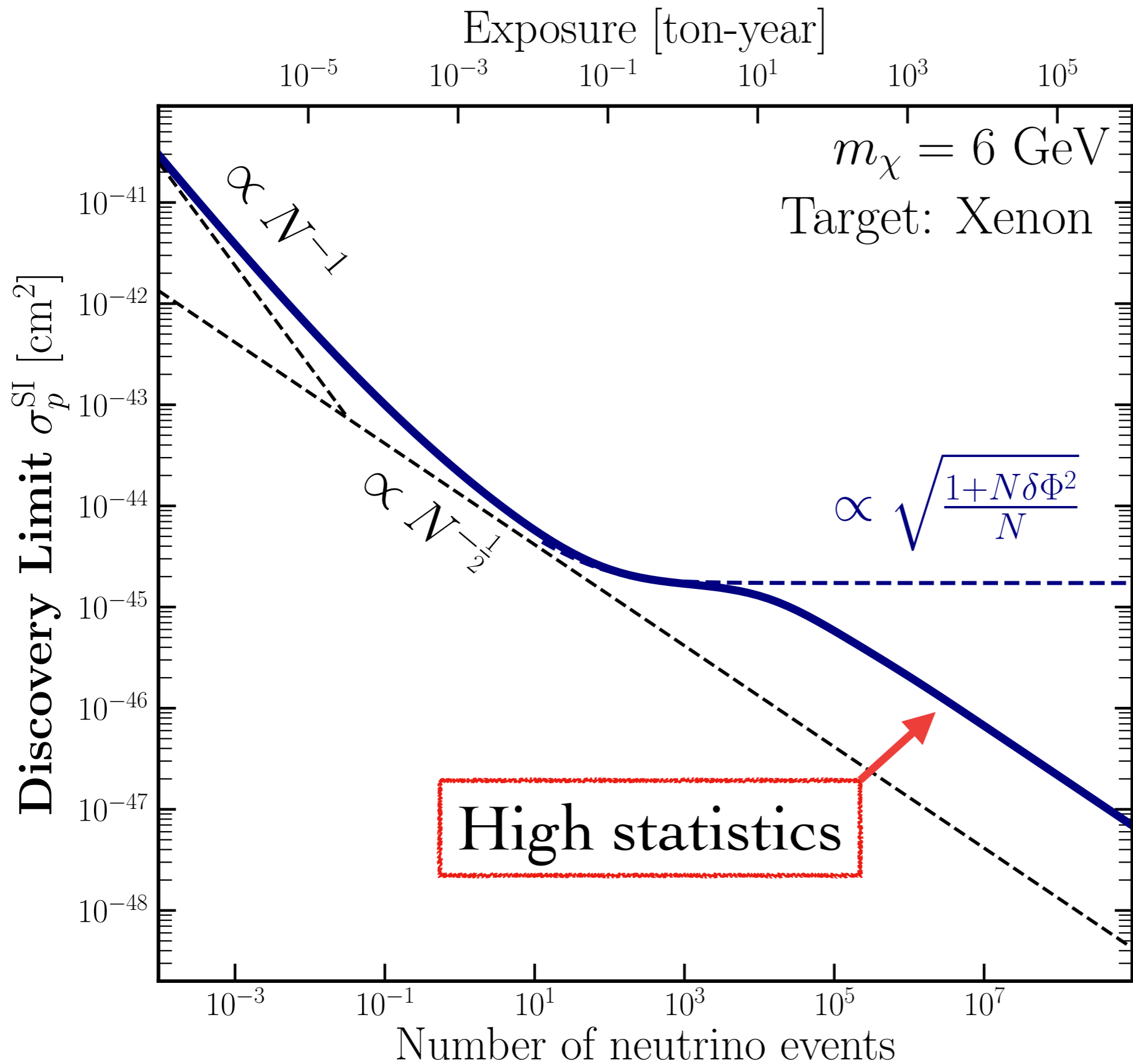
Scaling of discovery limit at 6 GeV for increasing numbers of background neutrinos





WIMP/
Neutrinos not
identical

→ at very
high statistics,
can start to
discriminate



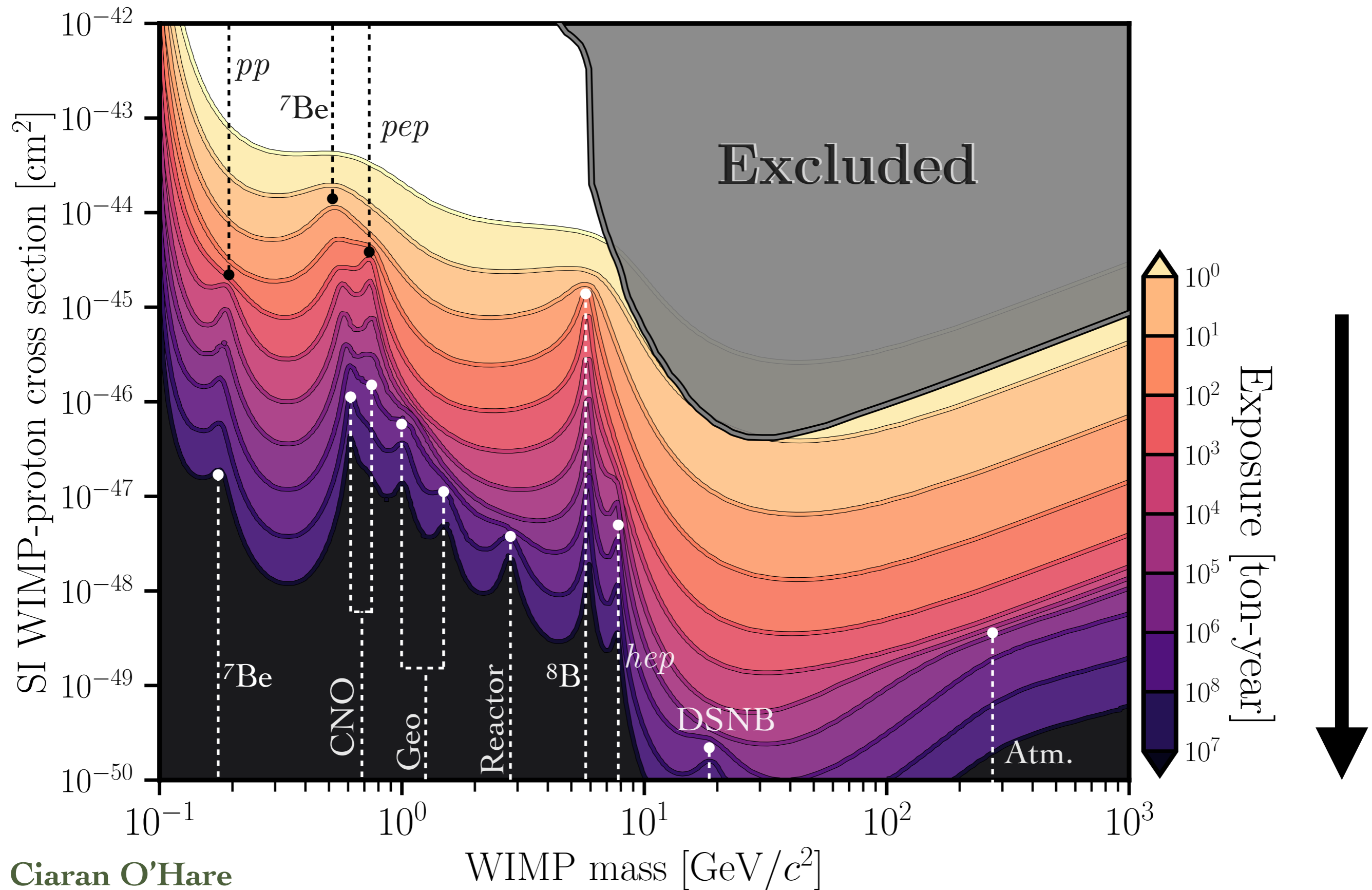
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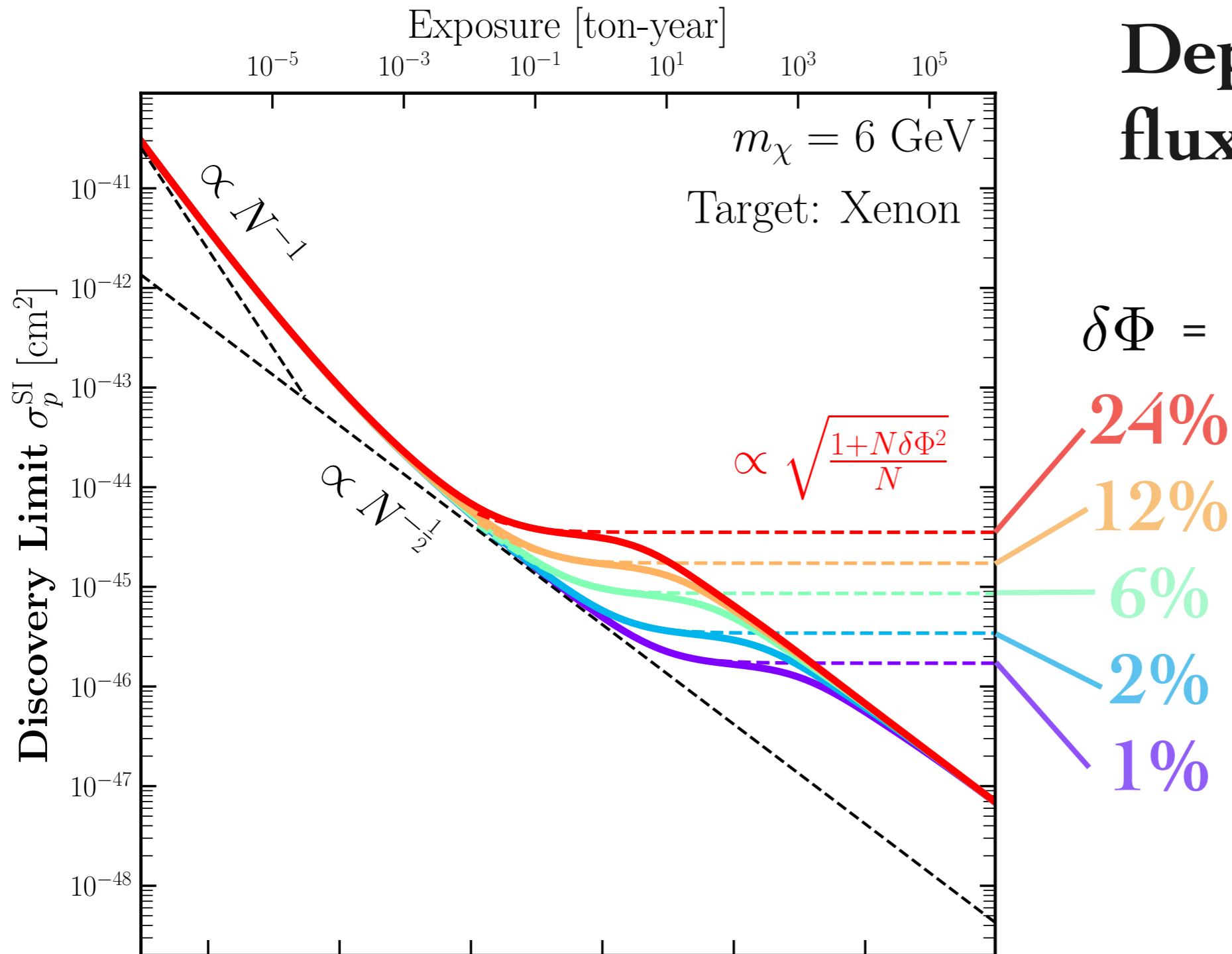
Method 1: Use recoil energies

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

This means you can push through the background
but very slowly

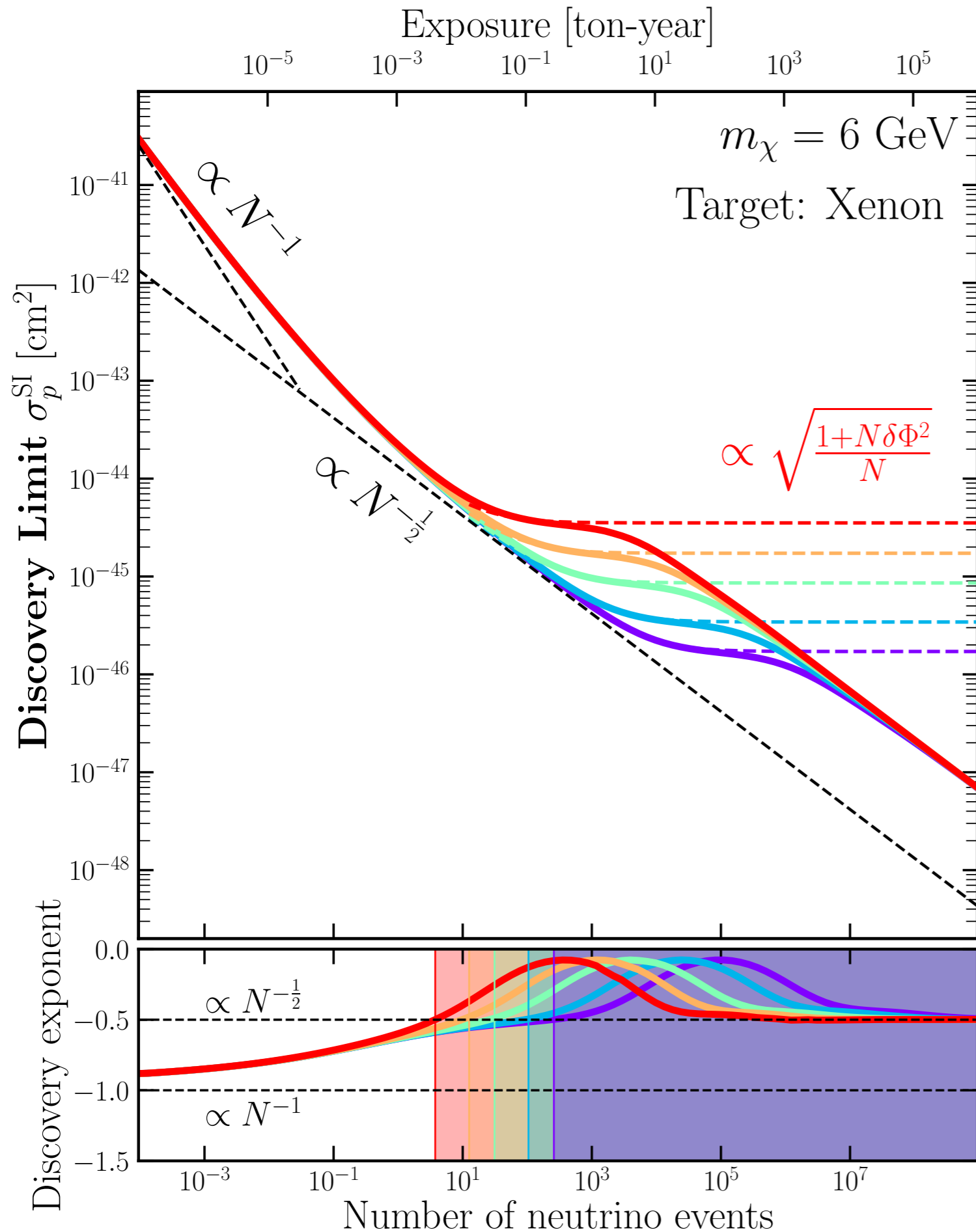


Dependence on flux uncertainty



Better flux measurement
→ neutrino floor is lower

Dependence on flux uncertainty



$\delta\Phi =$

24%

12%

6%

2%

1%

Better flux measurement
 \rightarrow neutrino floor
 is lower

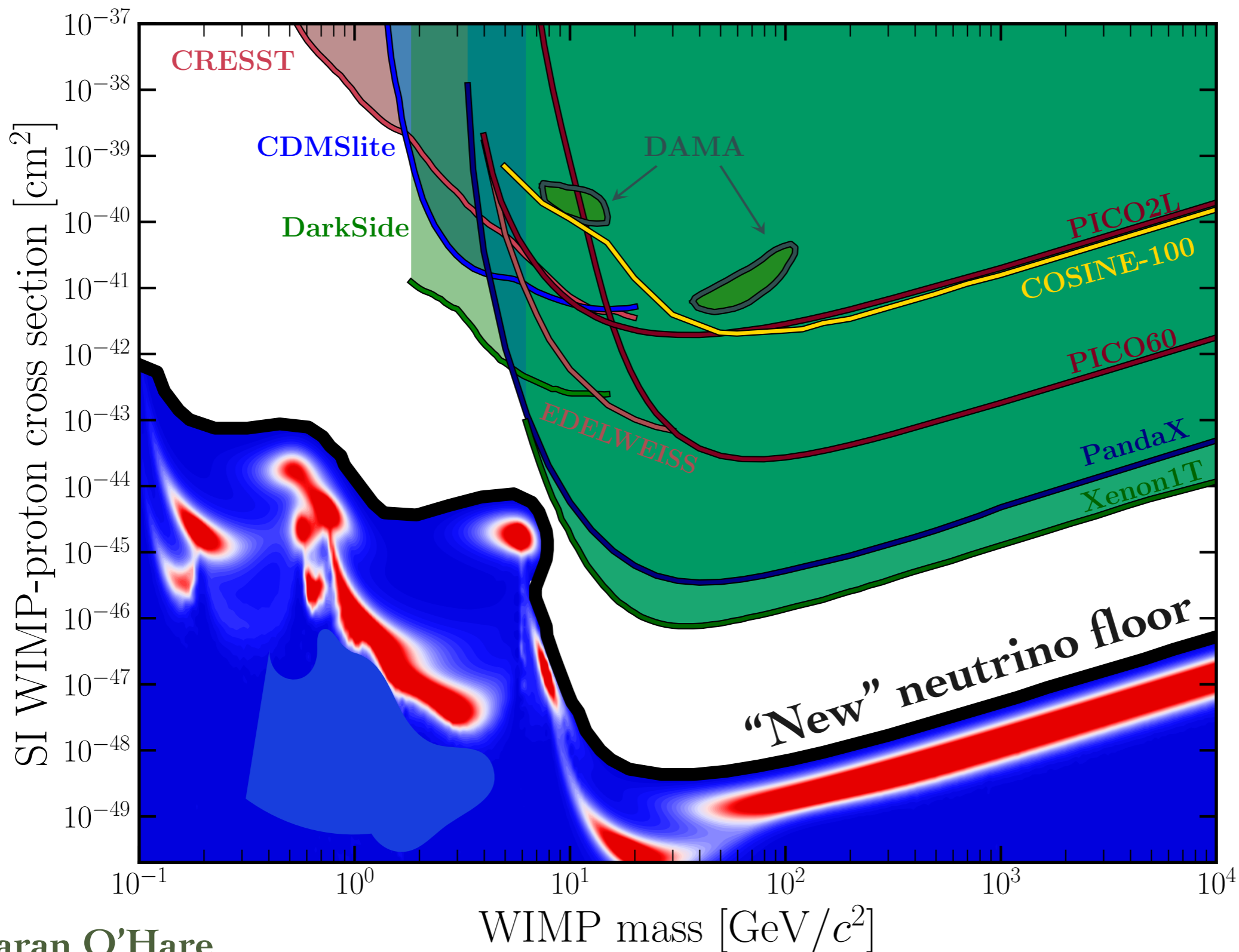
$$\frac{d \log(\text{discovery limit})}{d \log(\text{exposure})}$$

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

Method 2: Improve neutrino flux measurements

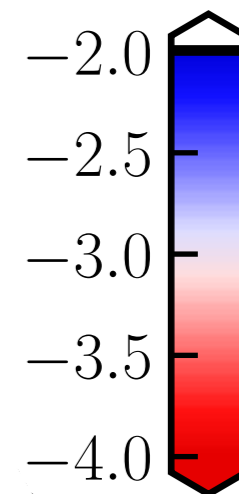
But this doesn't break through the neutrino floor,
it merely **delays** it

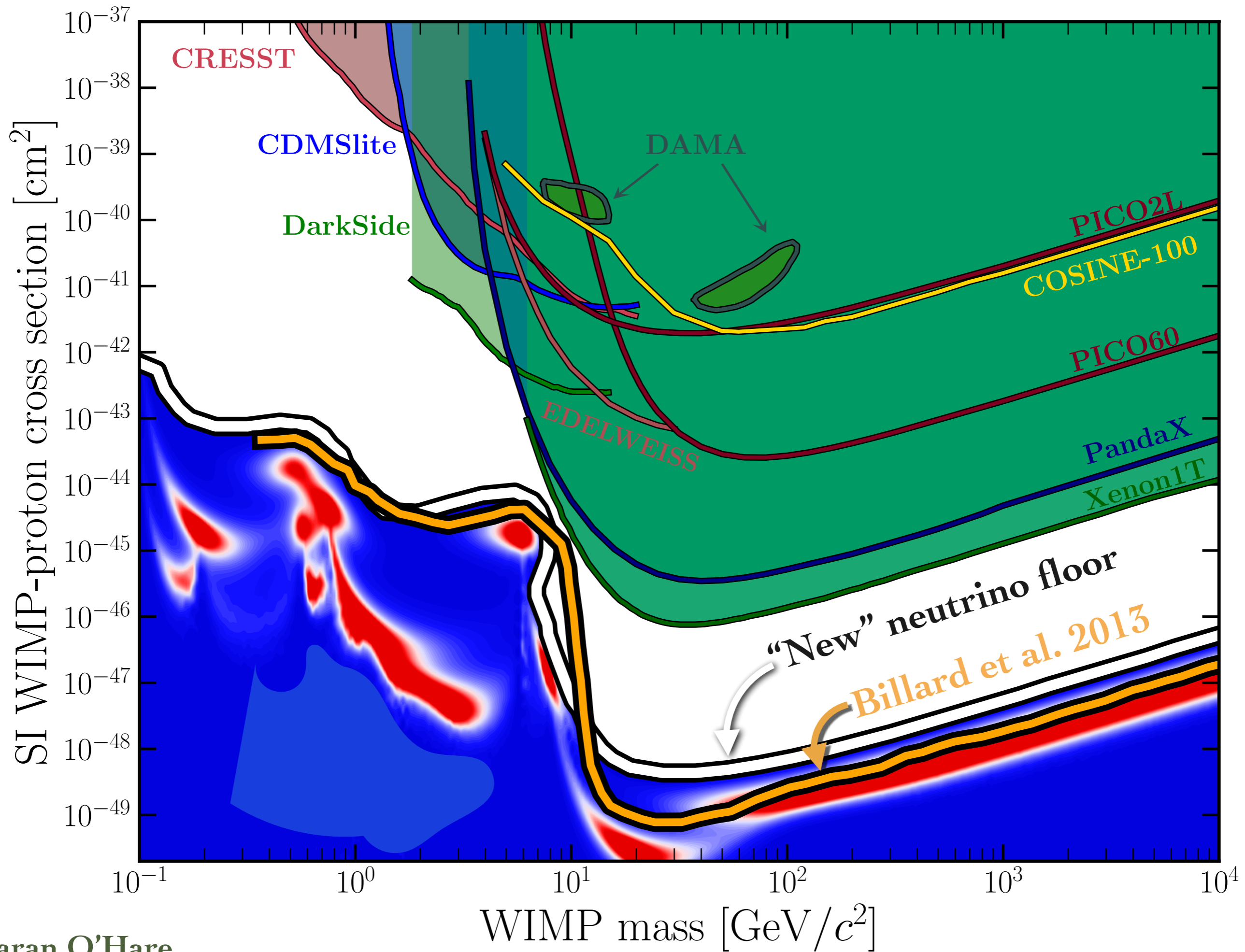
$$\left(\frac{d(\text{Discovery limit})}{d(\text{Exposure})} \right)^{-1} = -2 \quad \text{for standard Poissonian background subtraction}$$



Use this to more robustly define the neutrino floor

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





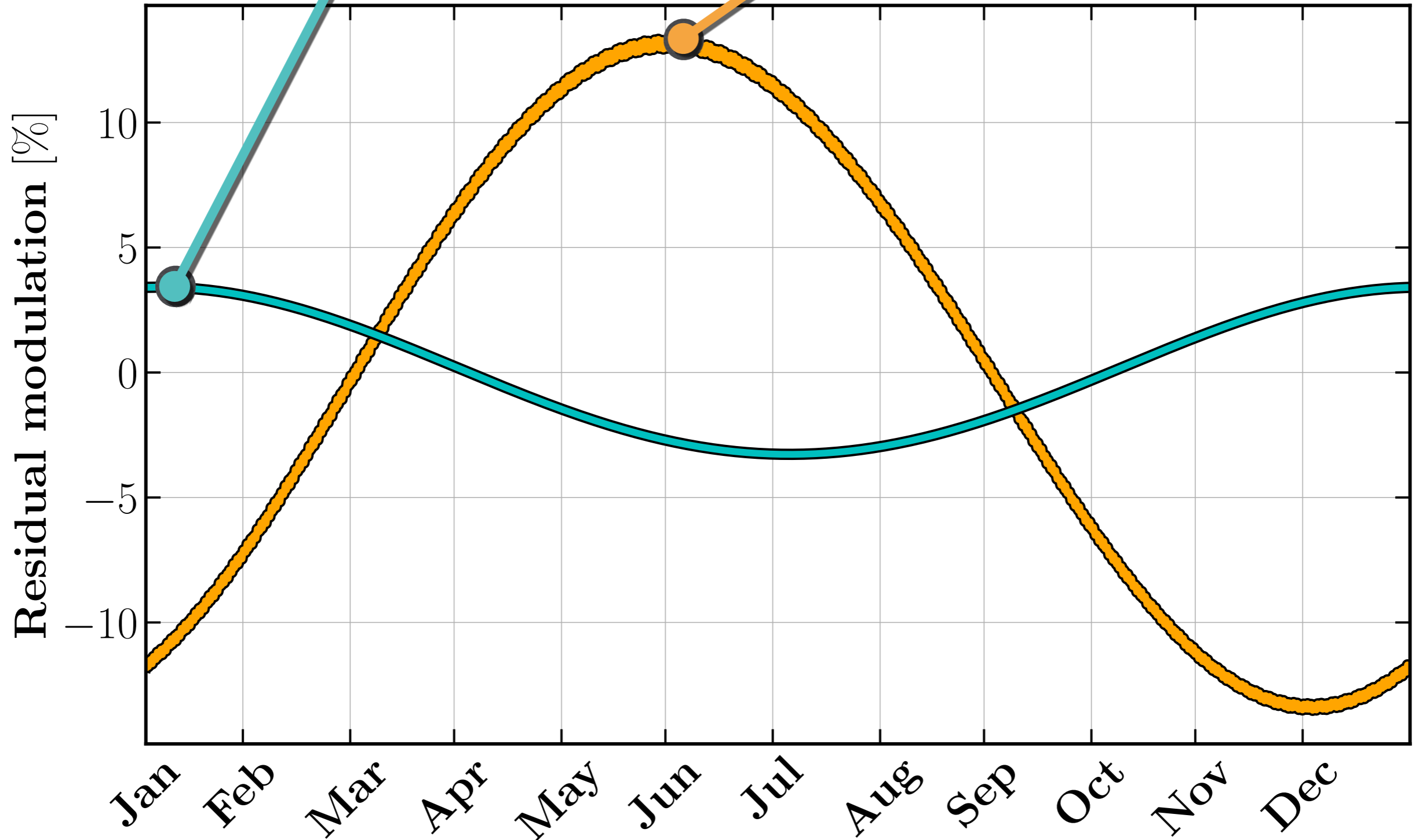
We want to **overcome** the neutrino floor,
Not just move it somewhere else

We need **more information**

Annual modulation

Neutrinos peak in January when Earth is closest to the Sun

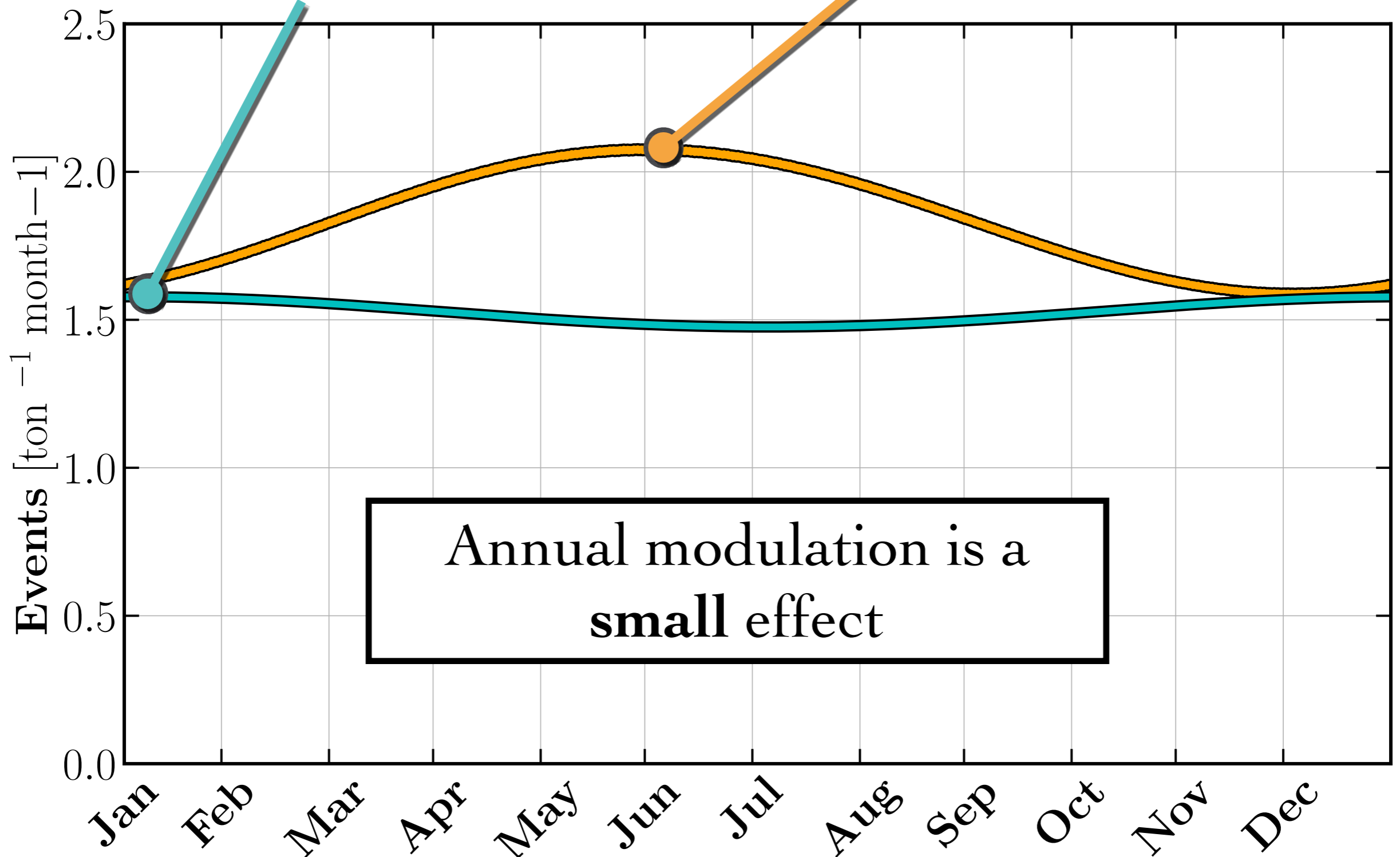
WIMPs peak in June when Earth is facing the DM wind



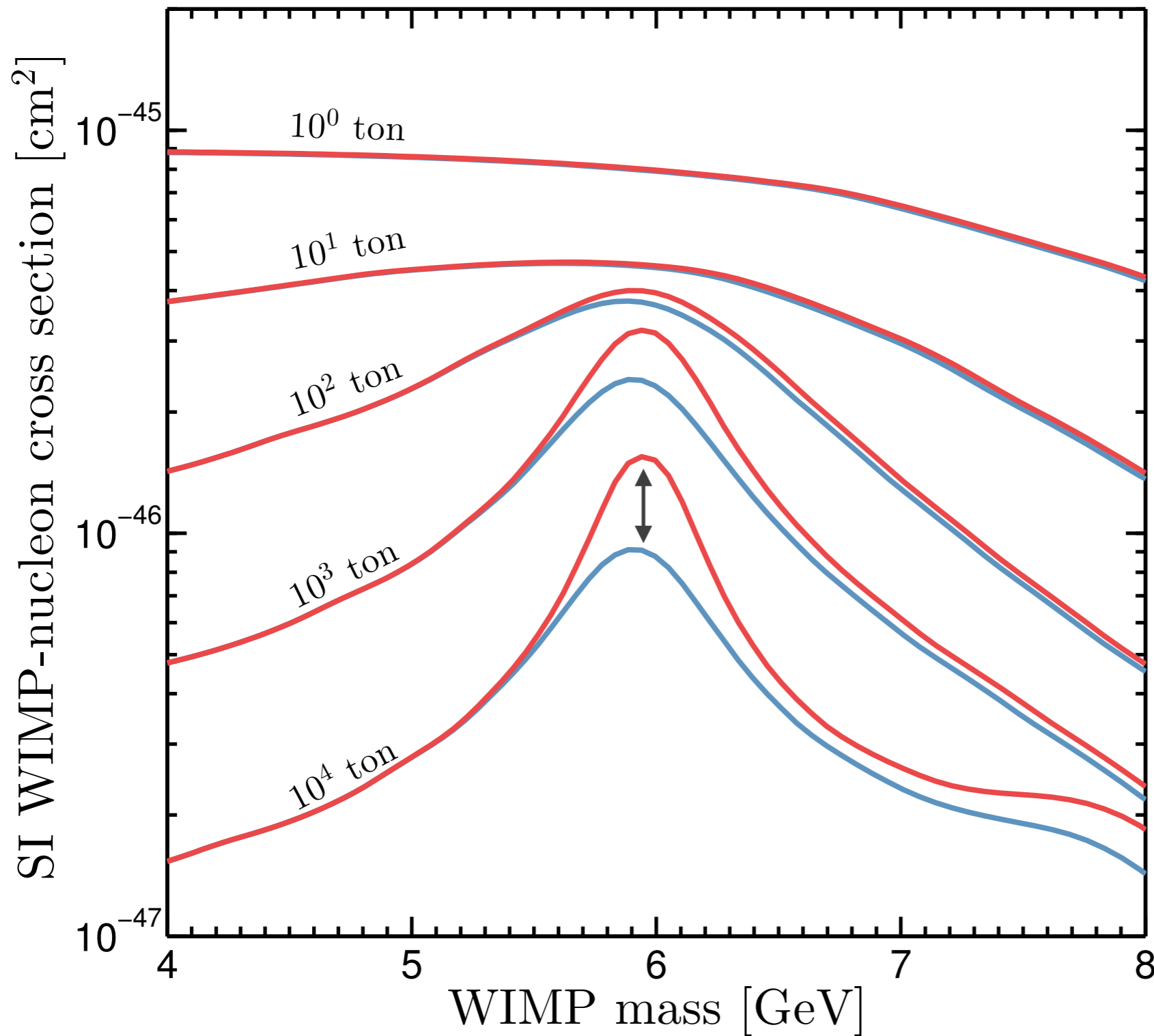
Annual modulation

Neutrinos peak in January when Earth is closest to the Sun

WIMPs peak in June when Earth is facing the DM wind



Annual modulation: does it help?



Information used:

Energy only

Energy + Time



Increasing
exposure

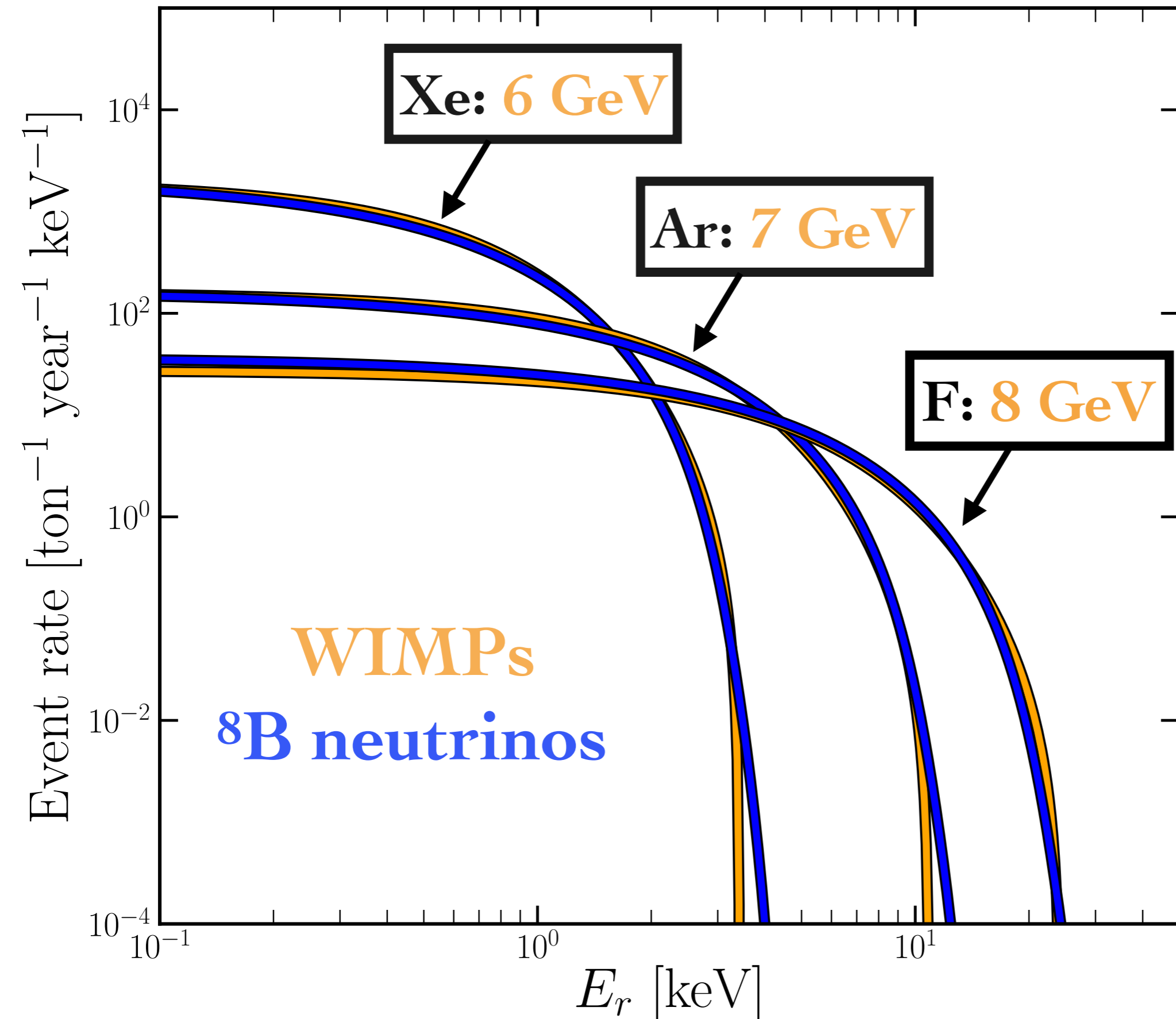
~~Method 1: Detect a lot of events~~

~~Method 2: Improve neutrino flux measurements~~

Method 3: Use annual modulation

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

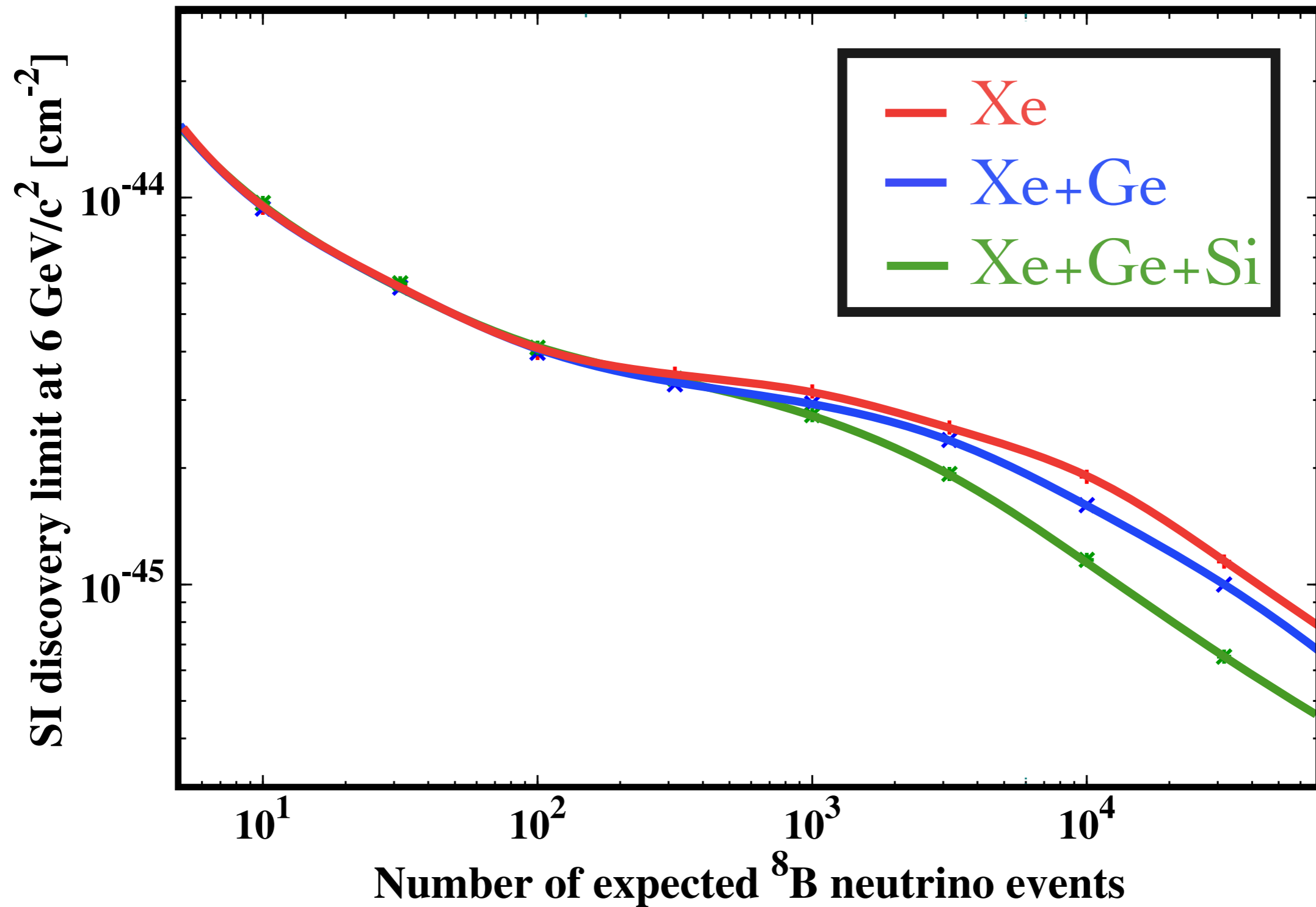
Target complementarity



Neutrinos look like different WIMP masses, for different target nuclei

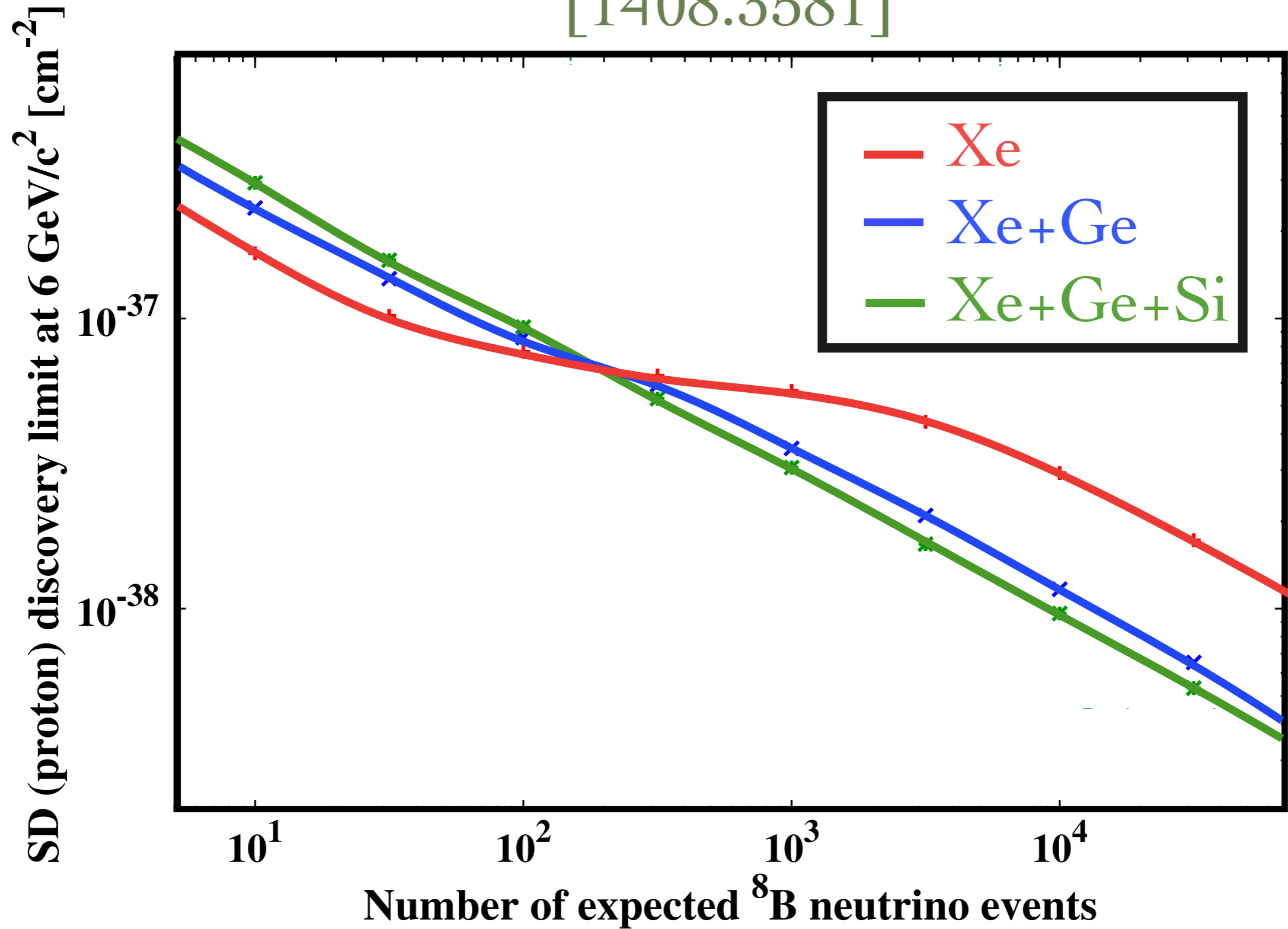
Target complementarity (SI)

[1408.3581]



Target complementarity (SD)

[1408.3581]



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

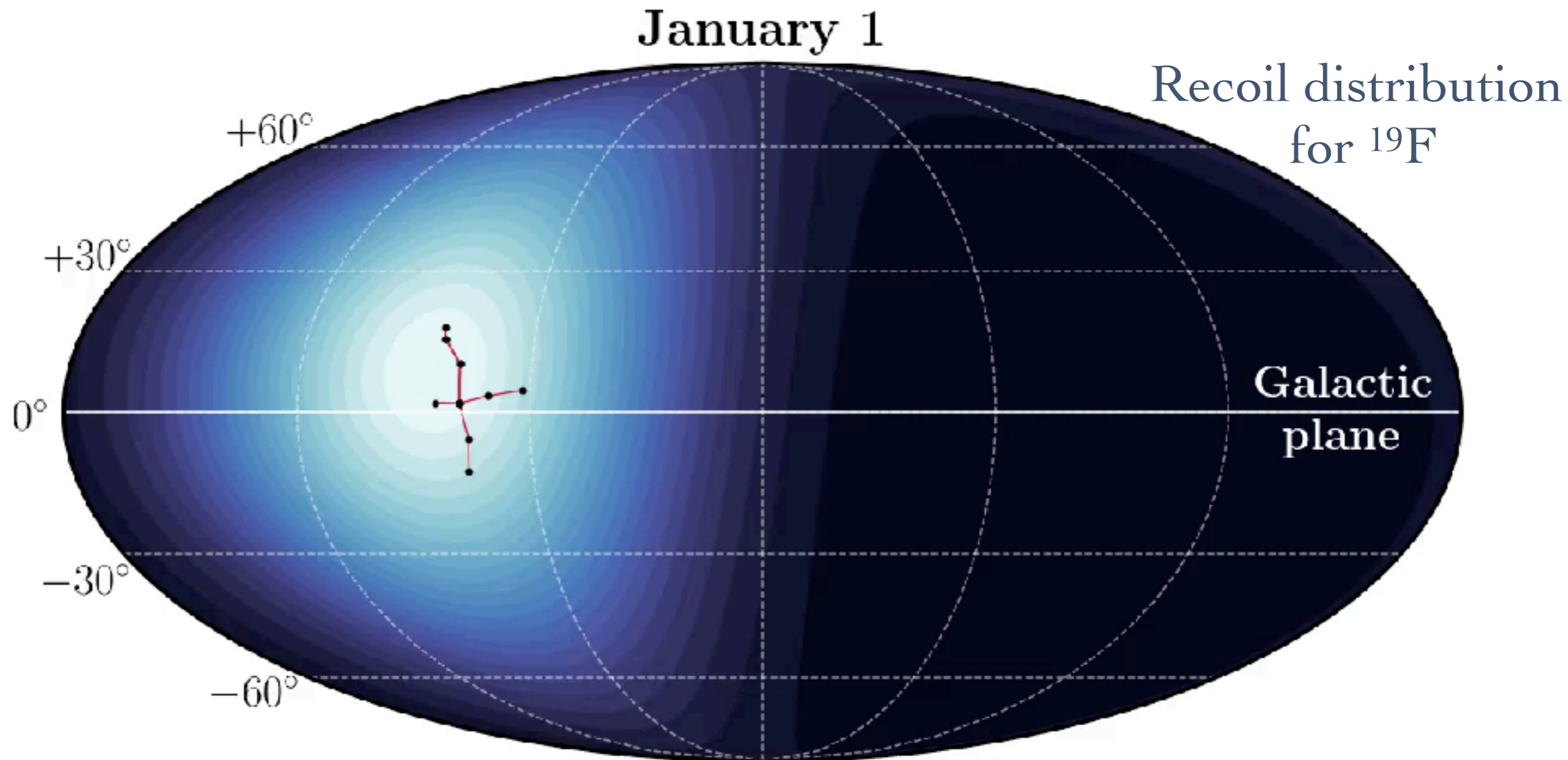
~~Method 2: Improve neutrino flux measurements~~

~~Method 3: Use annual modulation~~

Method 4: Use multiple targets

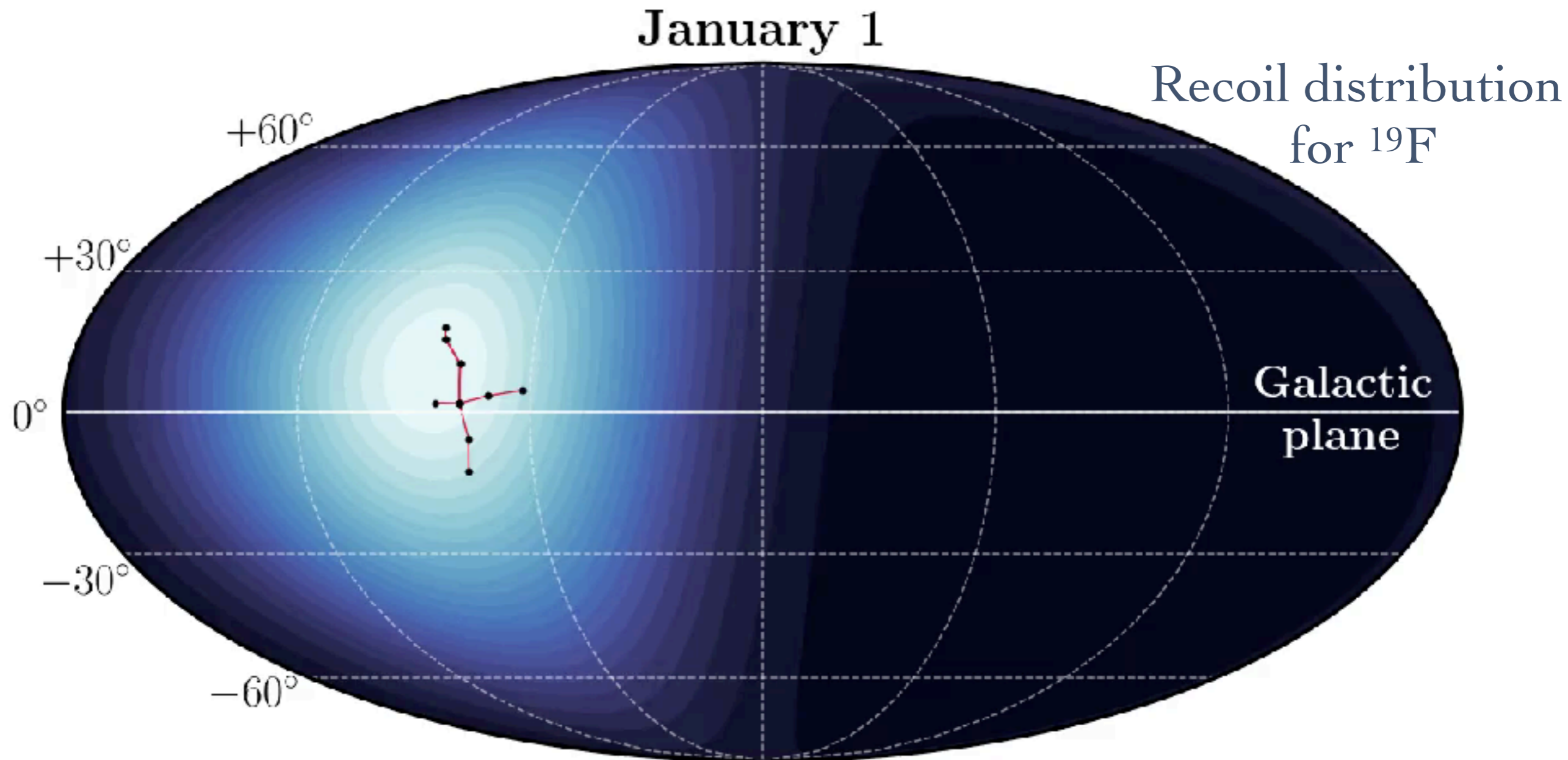
This helps too, but only substantially for SD interactions, and still requires a lot of events

But the case is stronger than that. Nothing other than **DM** will give a signal that points back to Cygnus,
→ A directional detector discovers DM
→ ~30 events needed to confirm signal aligned with Cygnus



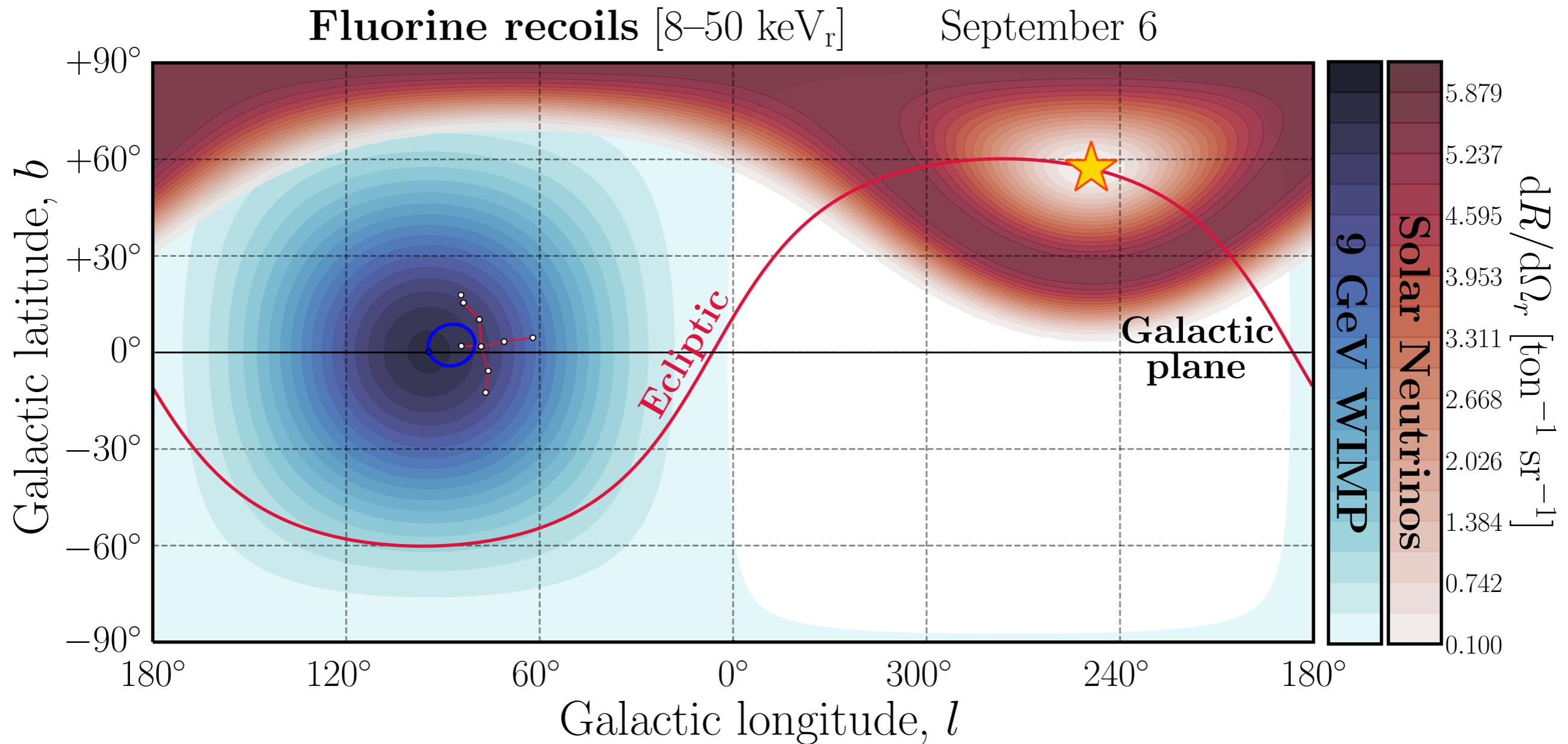
(movie)

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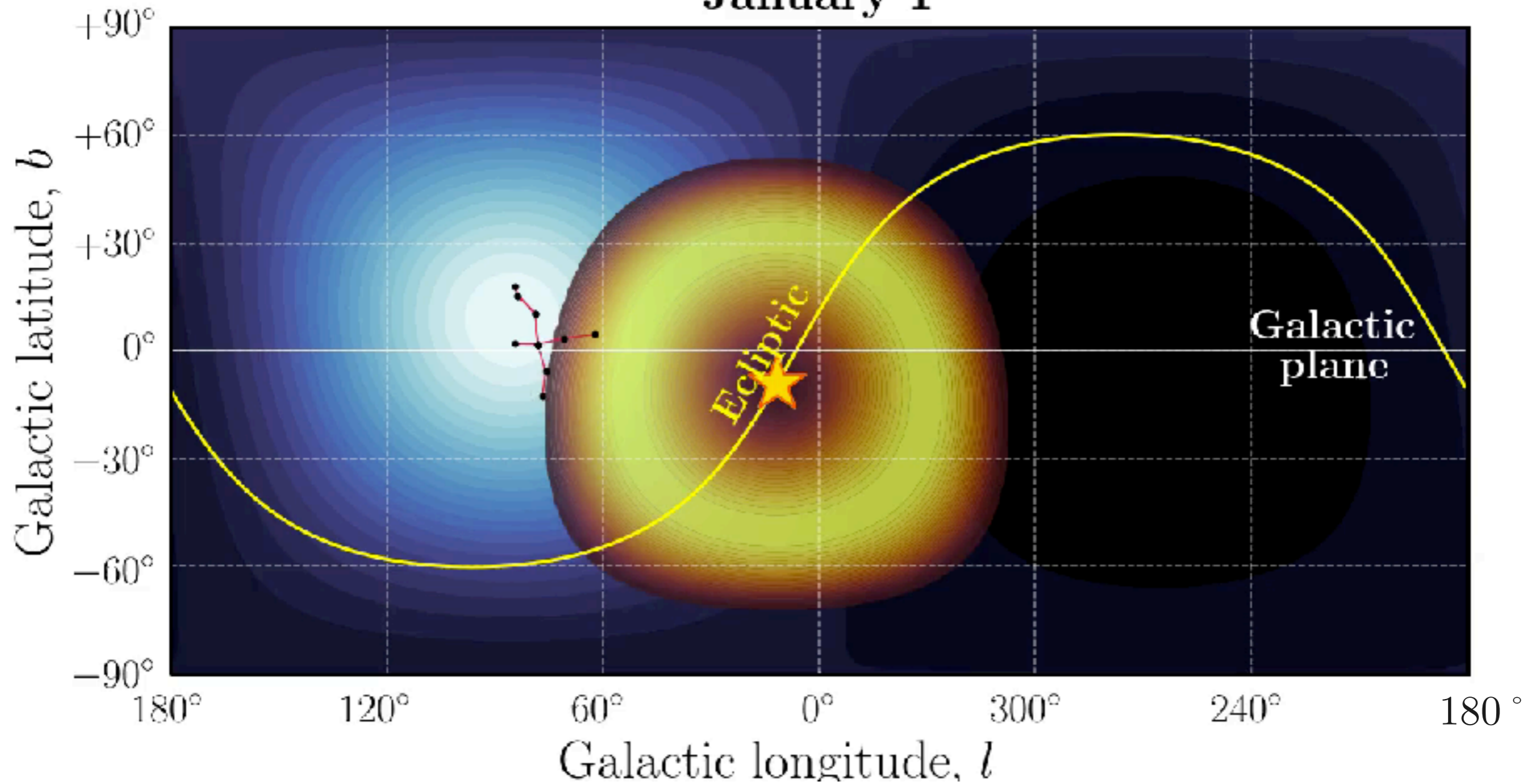
(movie)

Nothing mimics dark matter, including solar neutrinos



Nothing mimics dark matter, including **solar neutrinos**

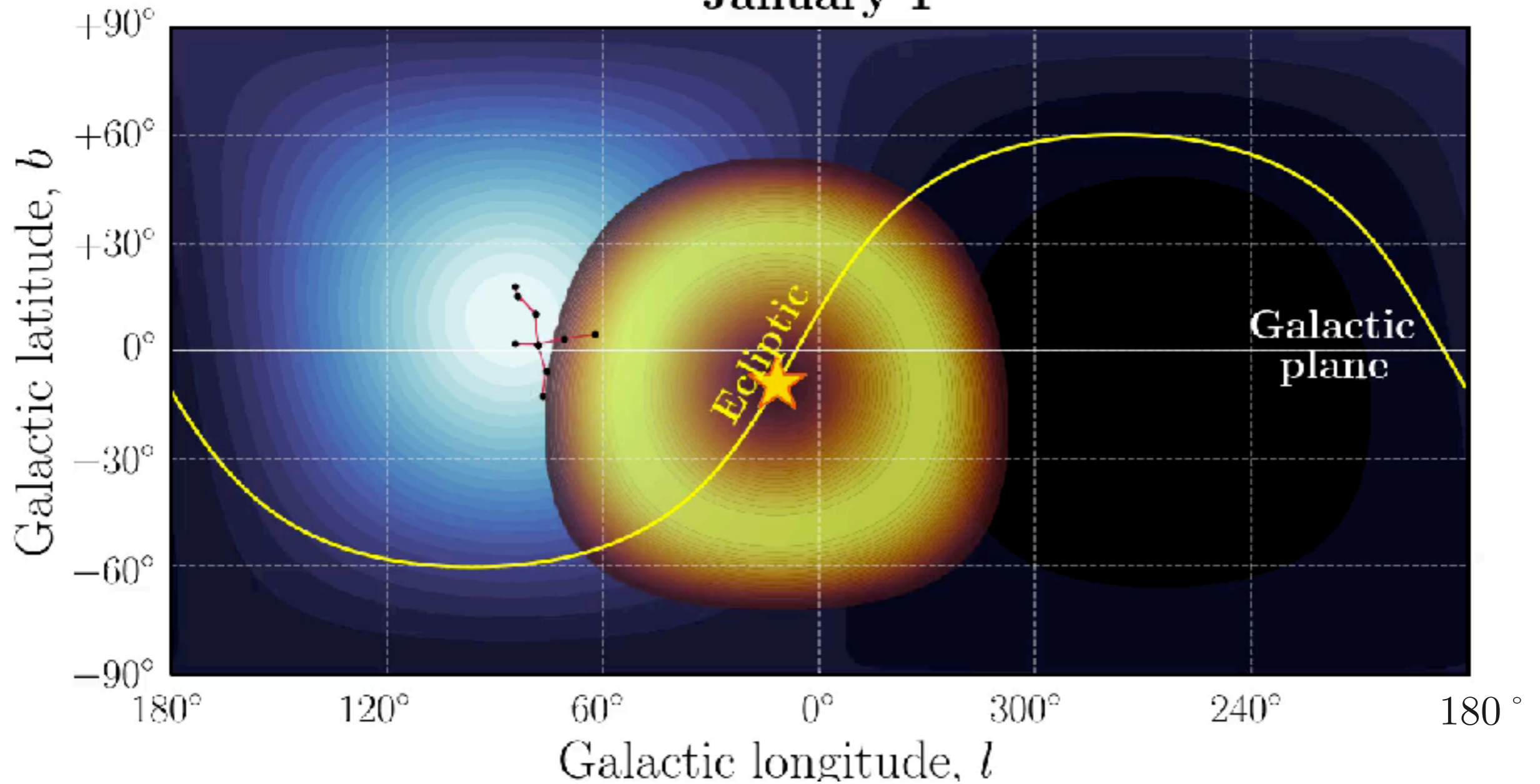
January 1



(movie)

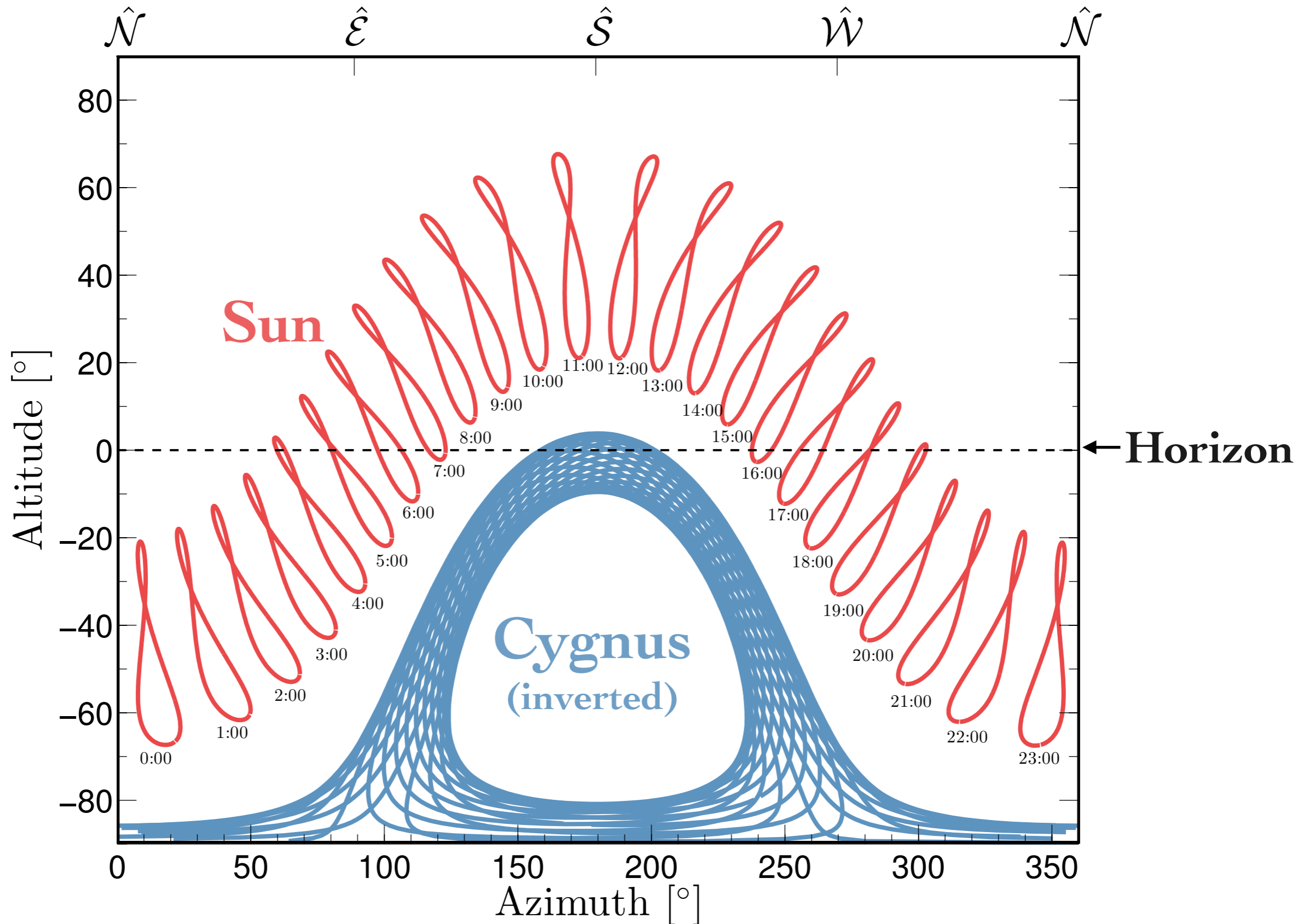
Nothing mimics dark matter, including **solar neutrinos**

January 1

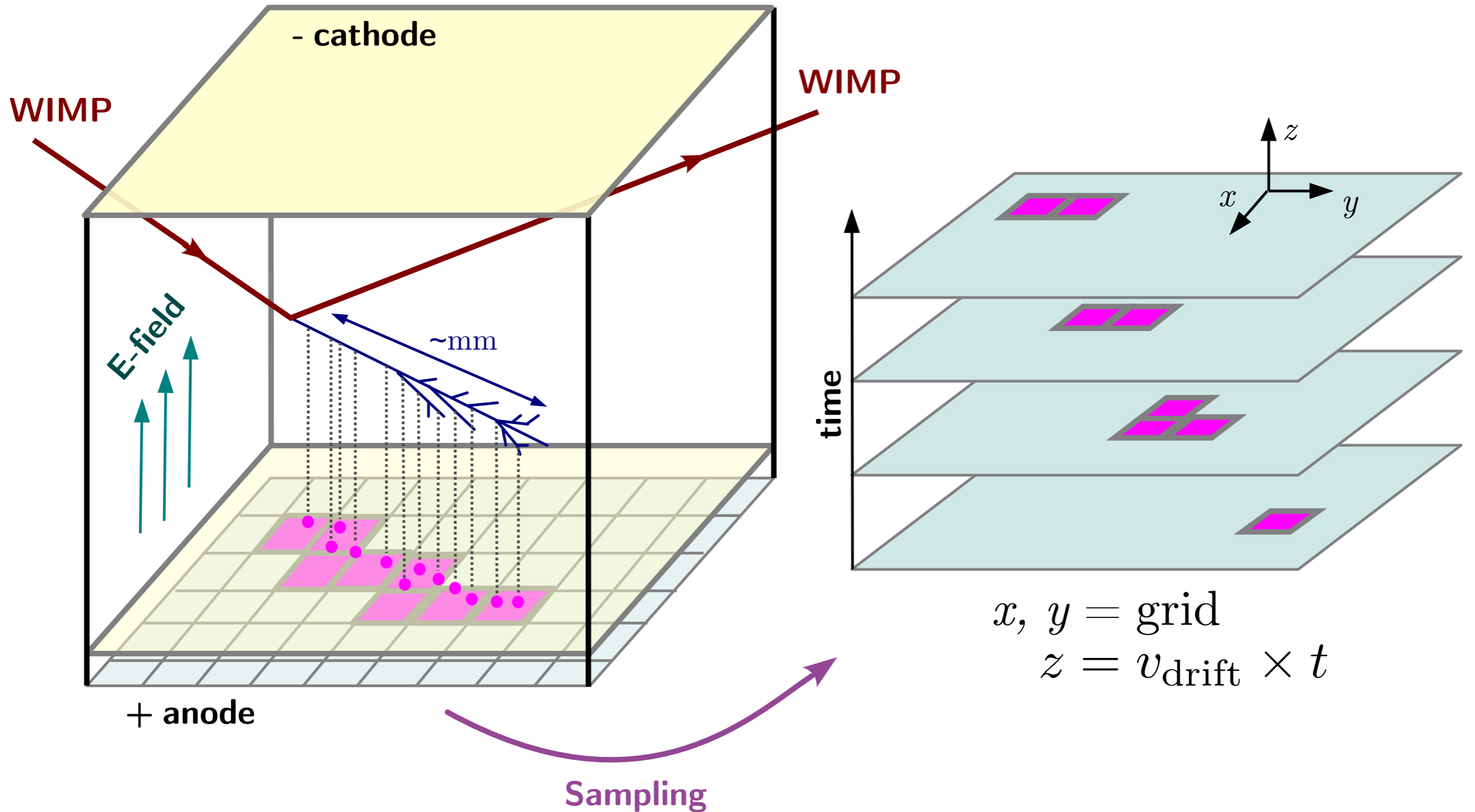


(movie)

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



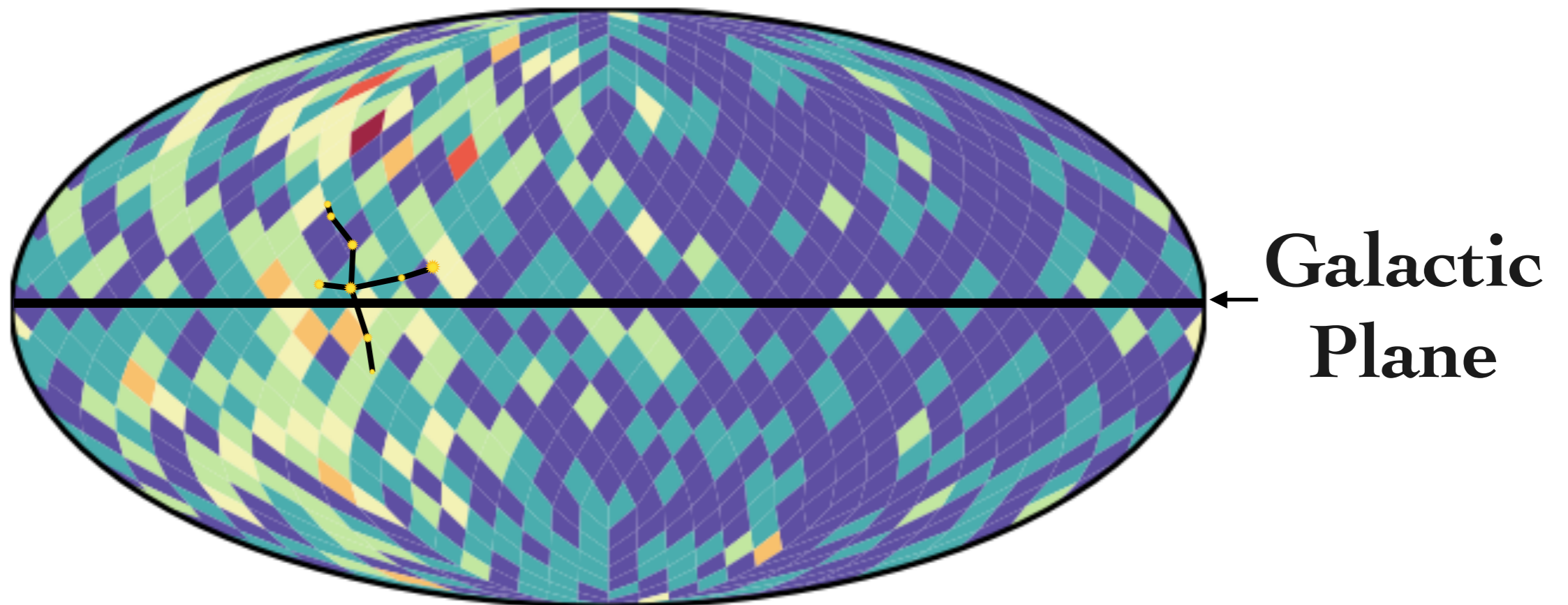
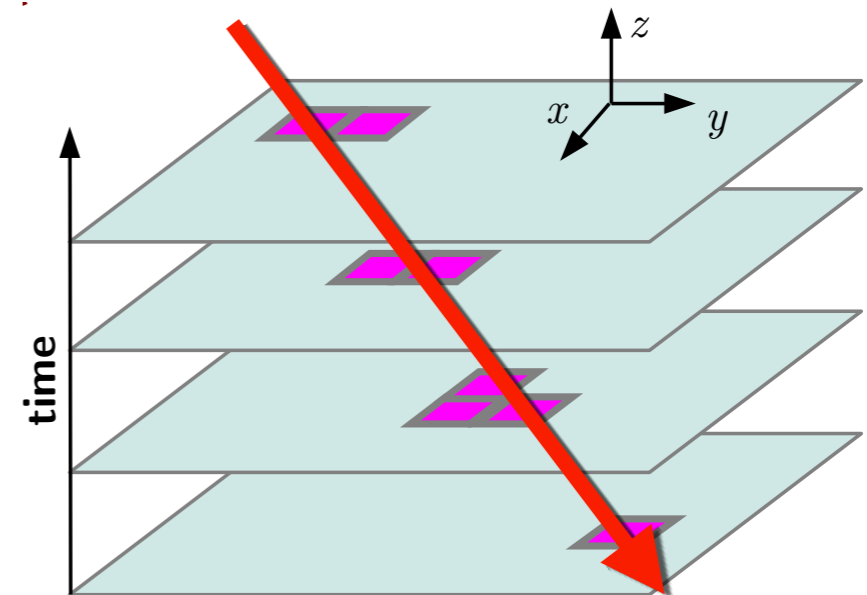
Low-pressure gas TPC



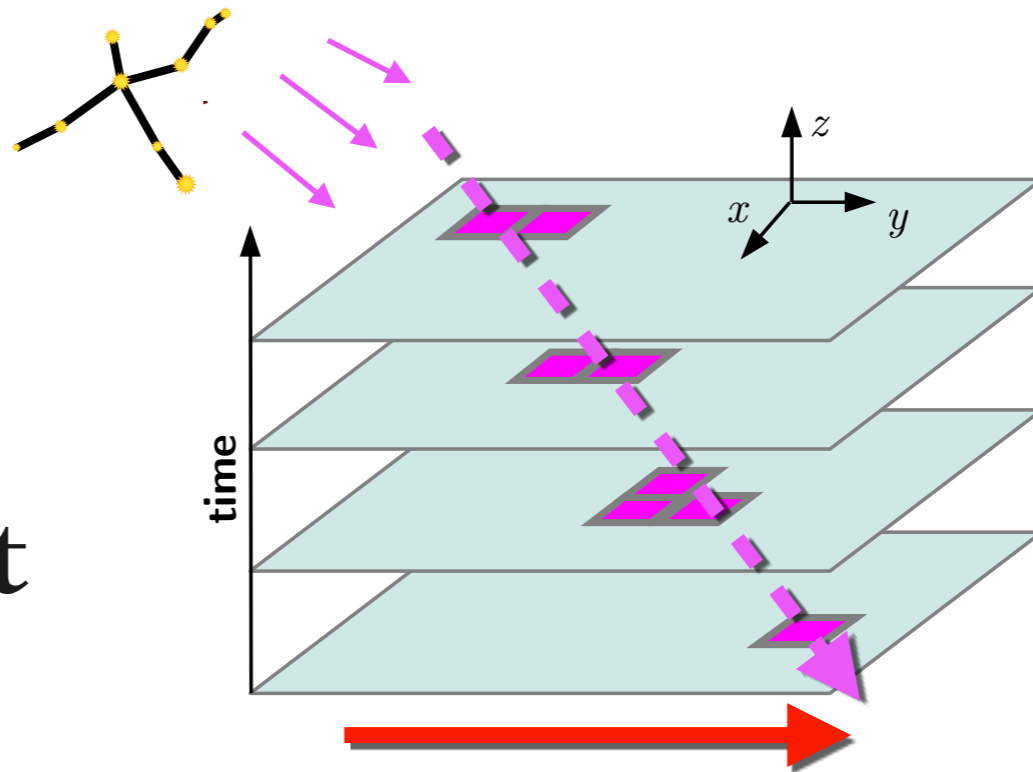
Measuring the full track: 3D readout

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

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

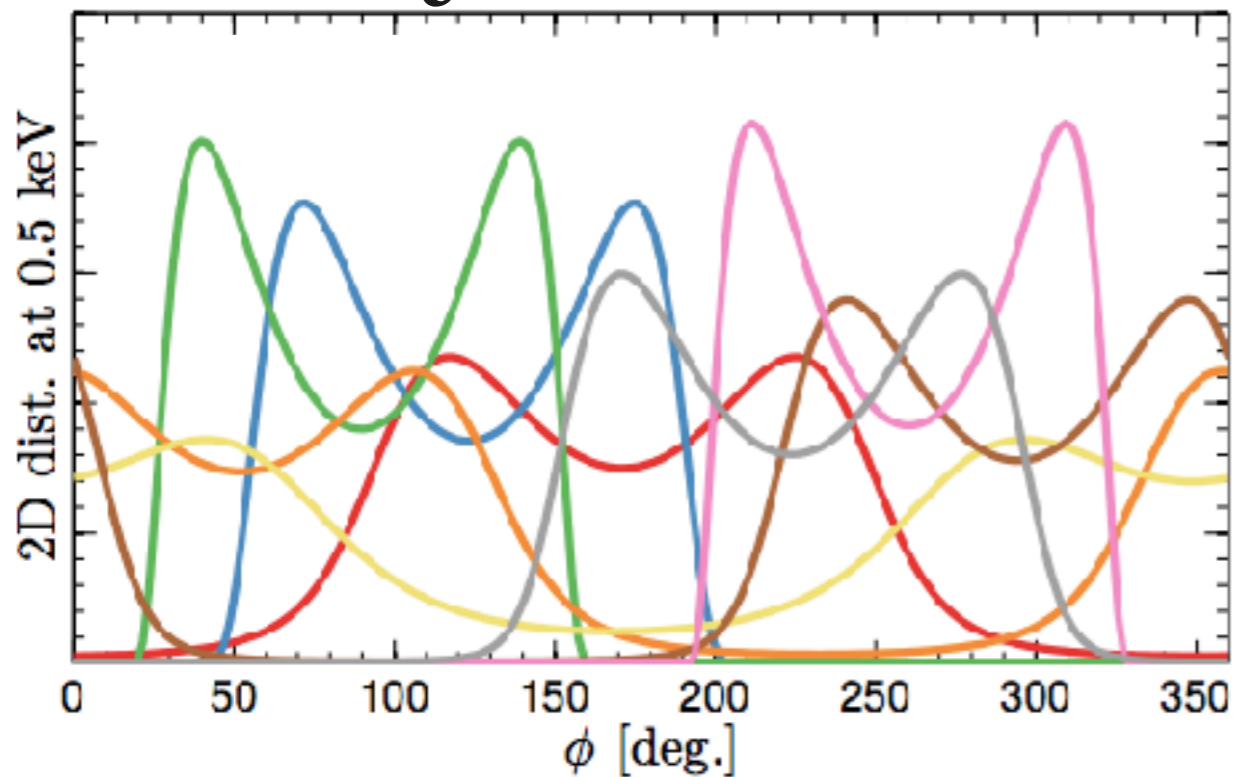


2D Readout

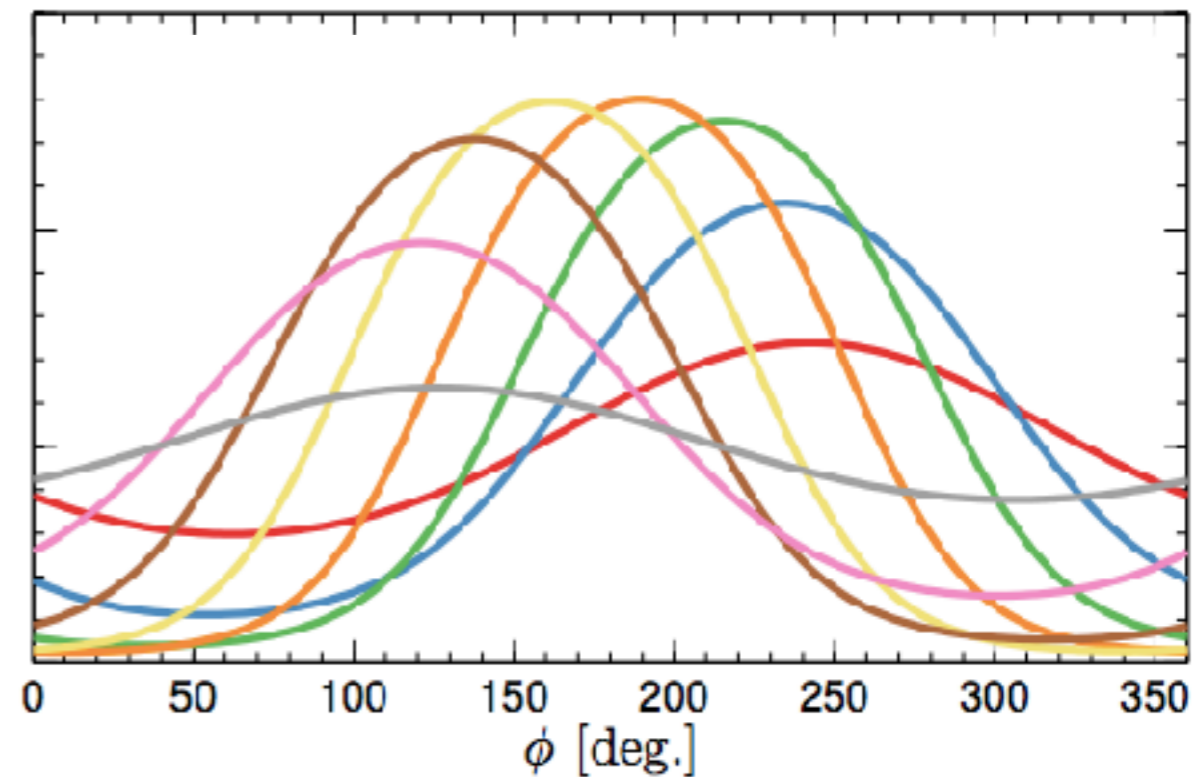


$$\hat{q} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}$$

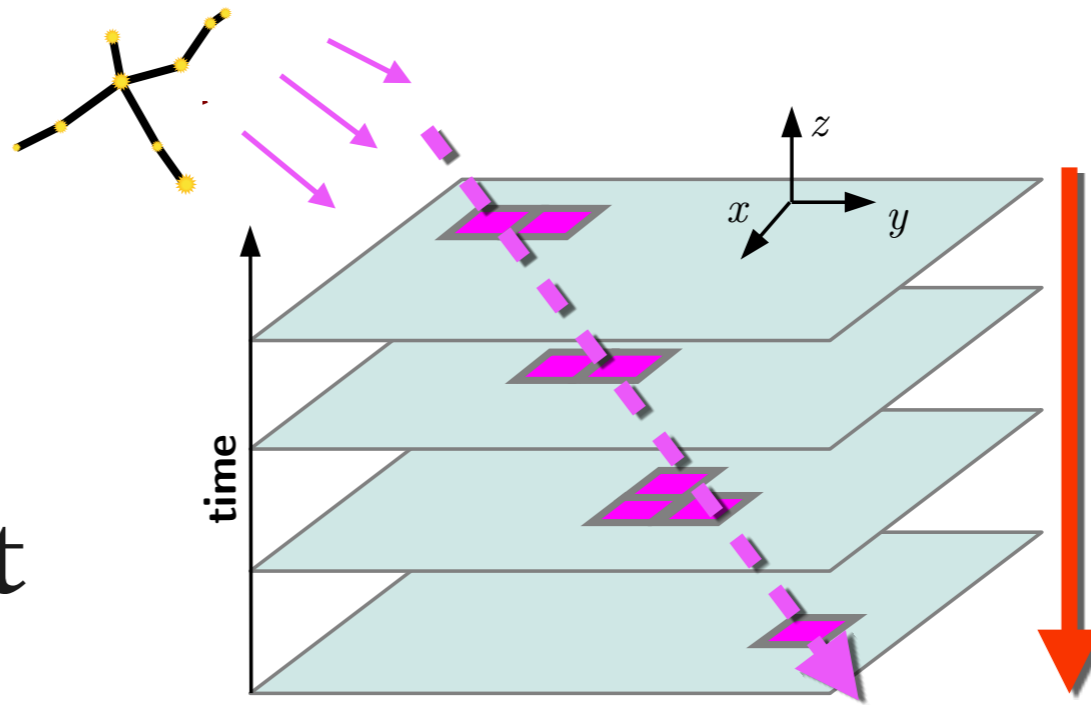
Neutrino Daily modulation



WIMP Daily modulation



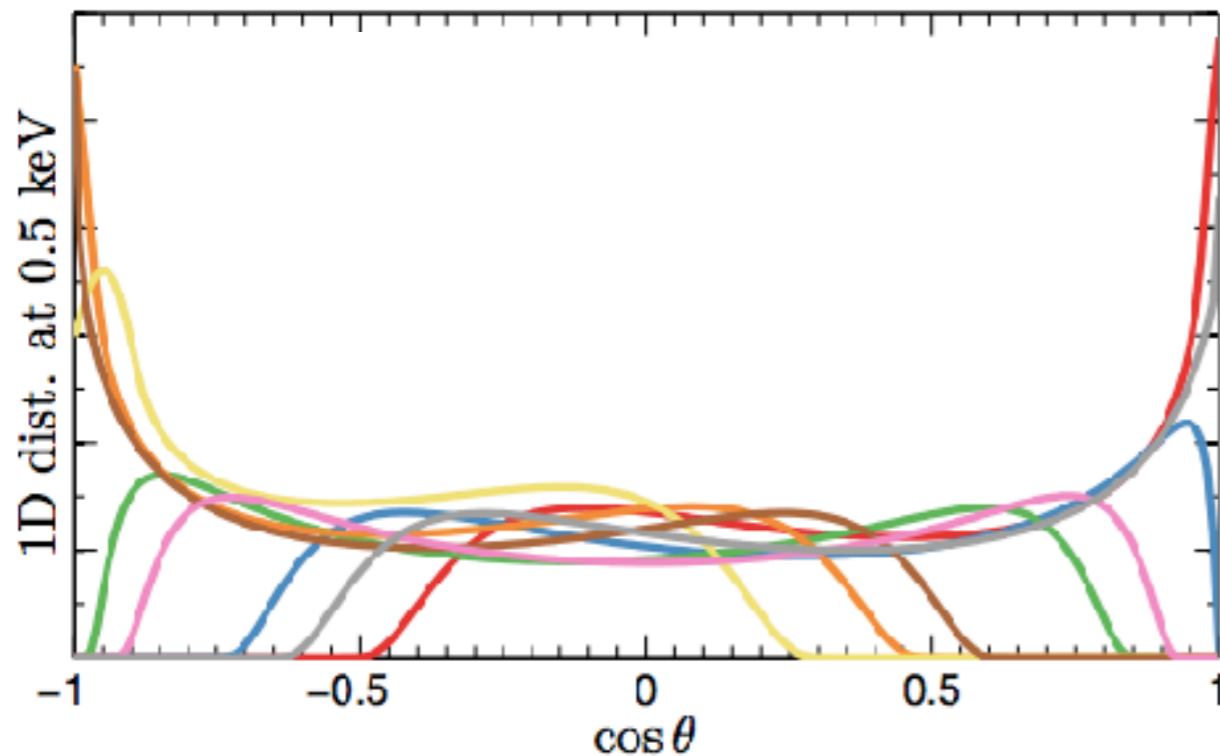
1D Readout



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

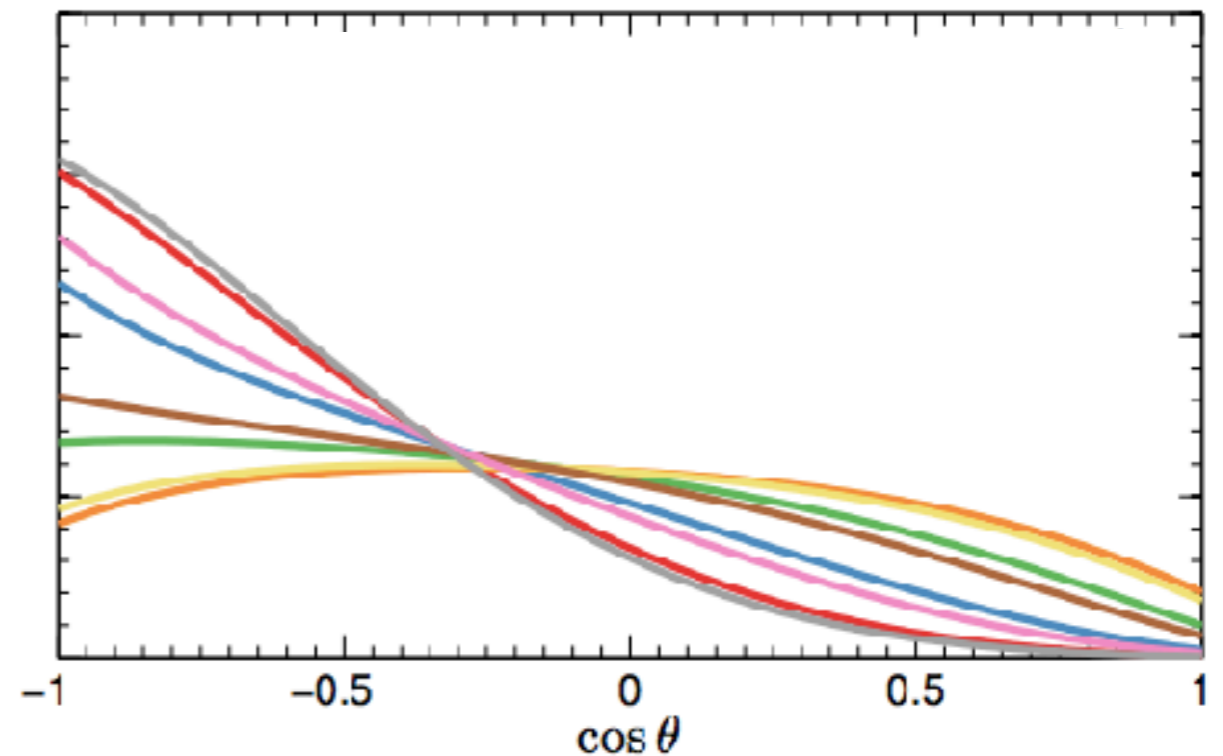
Neutrino

Daily modulation

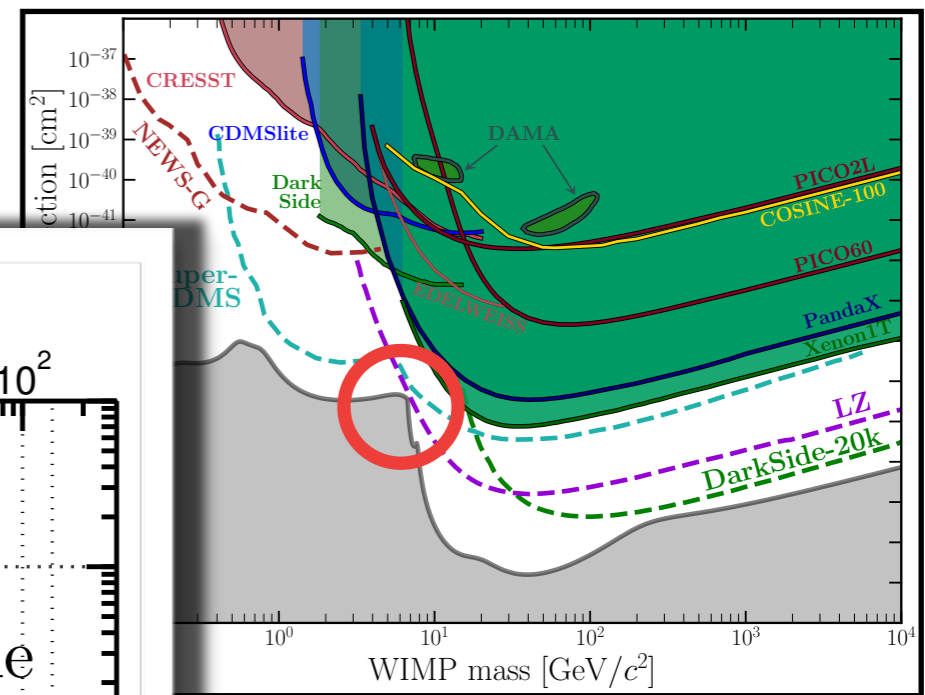
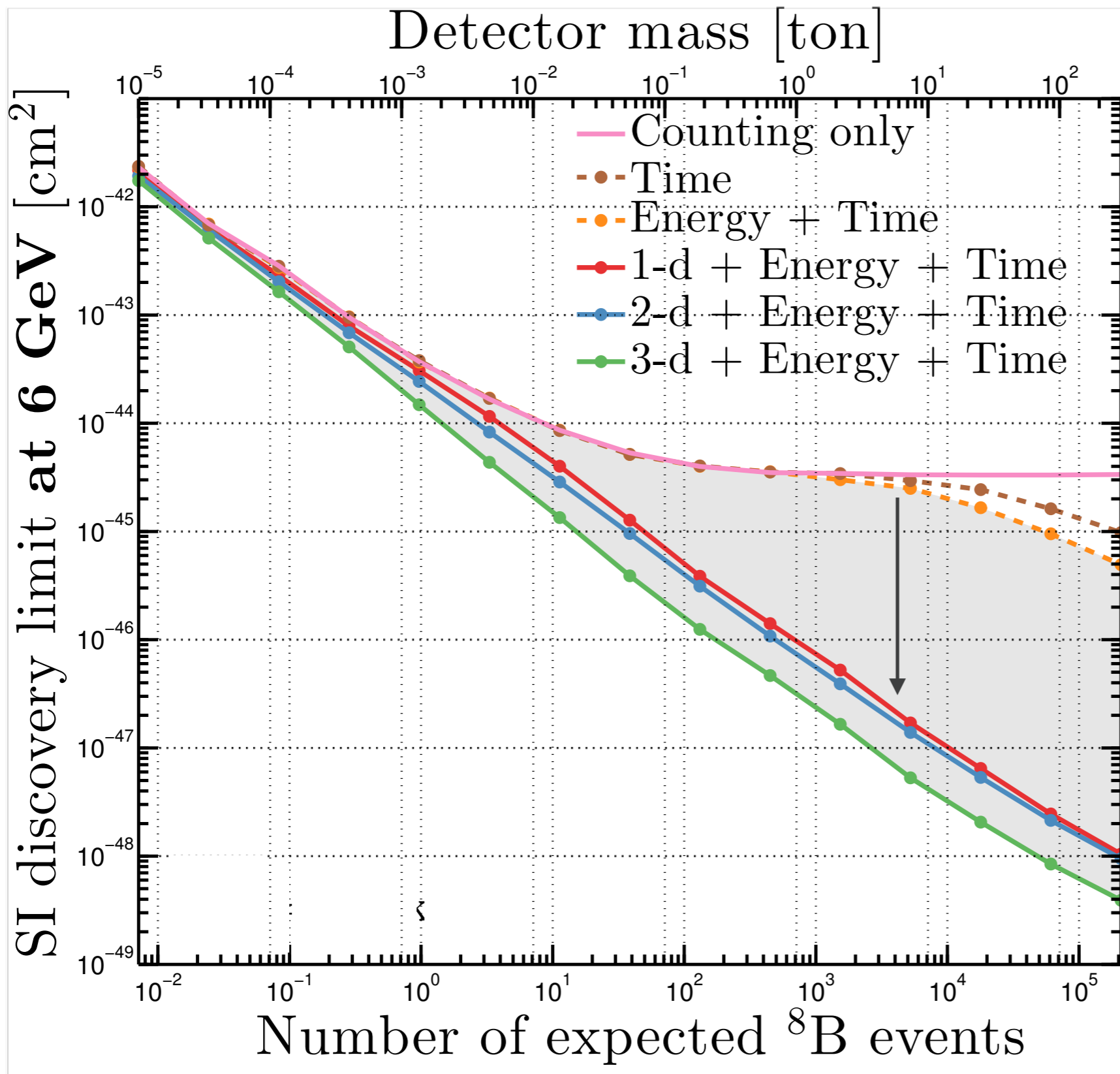


WIMP

Daily modulation

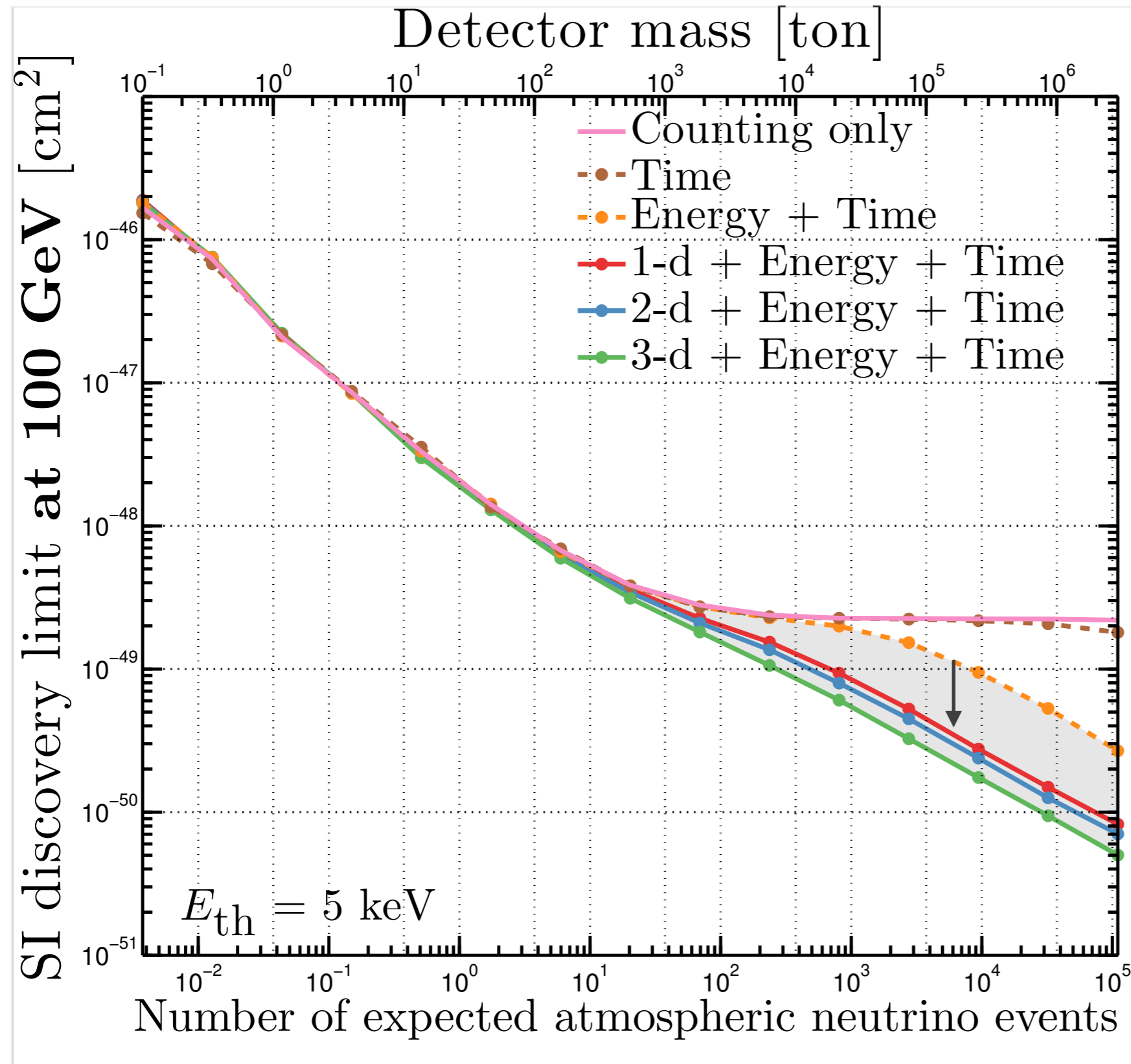
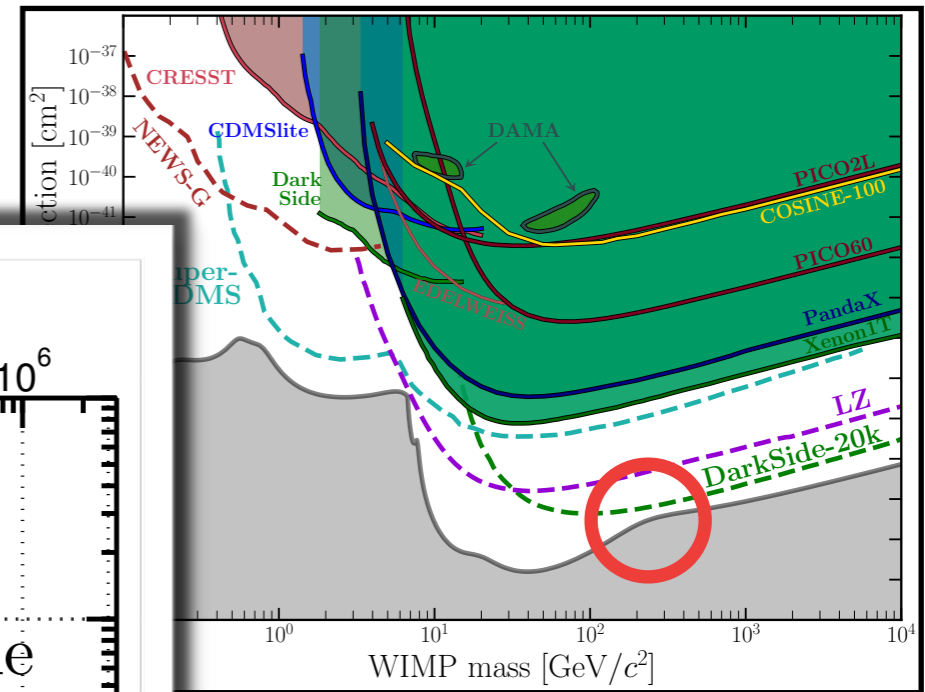


Comparing methods: Solar



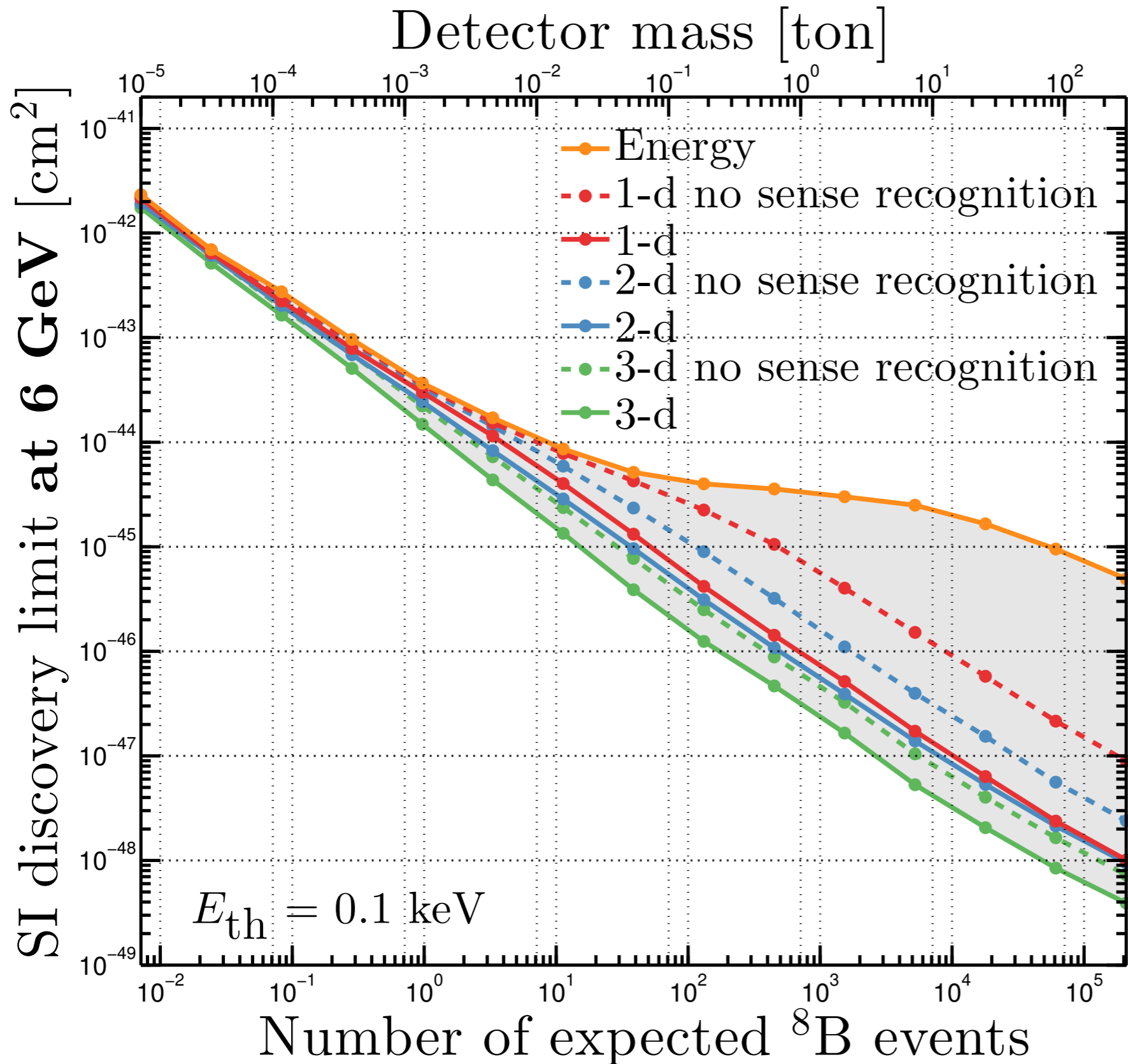
Directionality
powerful for
subtracting
Solar
neutrinos

Comparing methods: Atm.



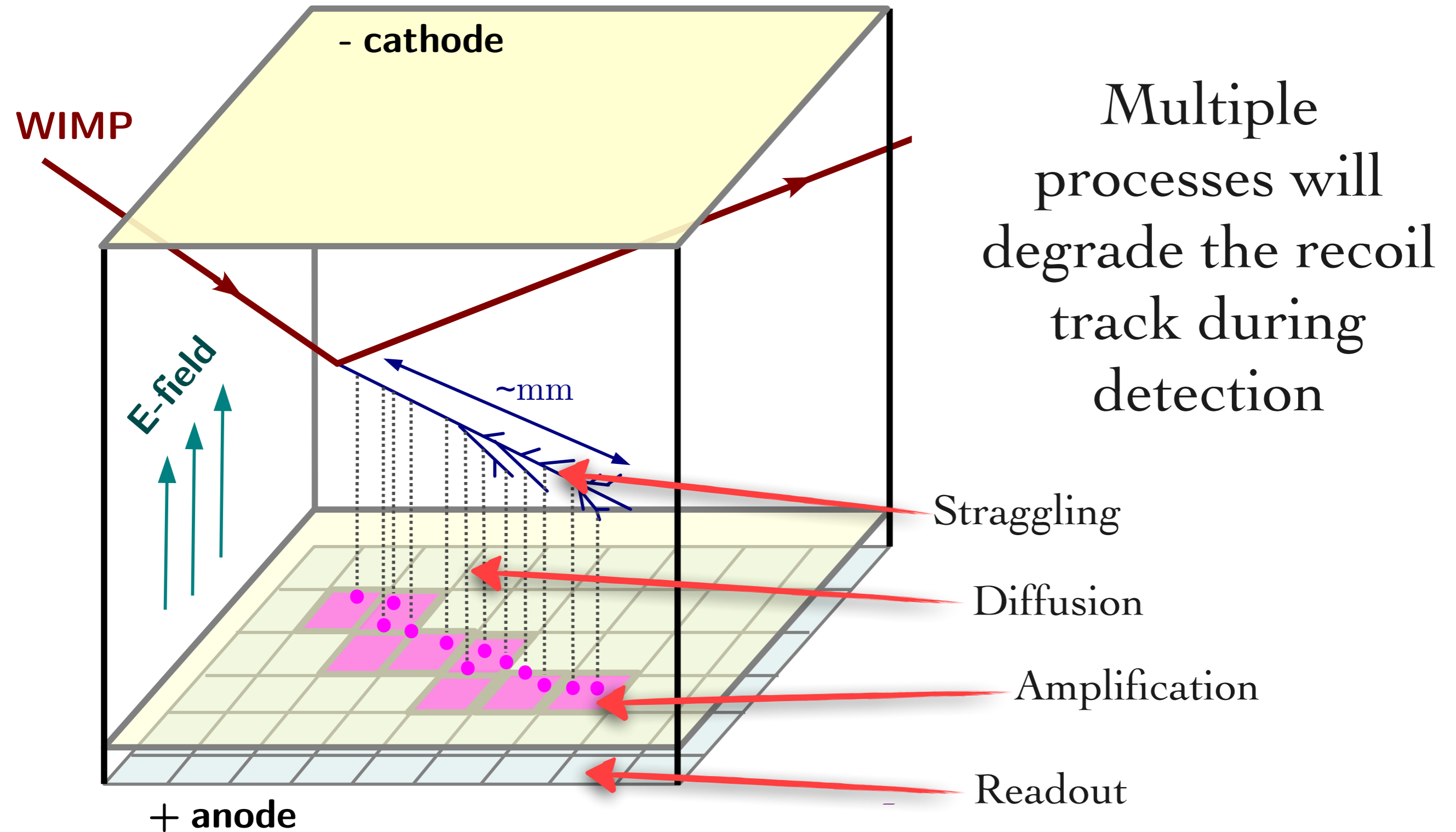
Directionality
less powerful
for subtracting
atmospheric
neutrinos

Is Head-tail or track dimensionality more important?



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

Real tracks are imperfect

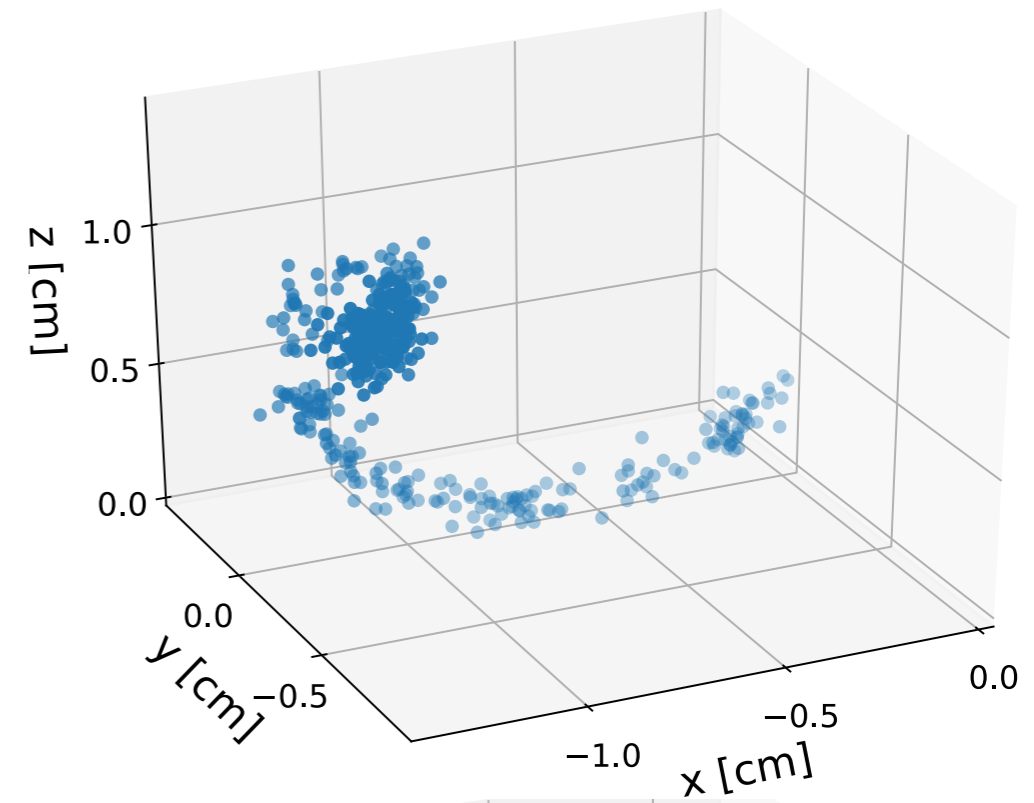
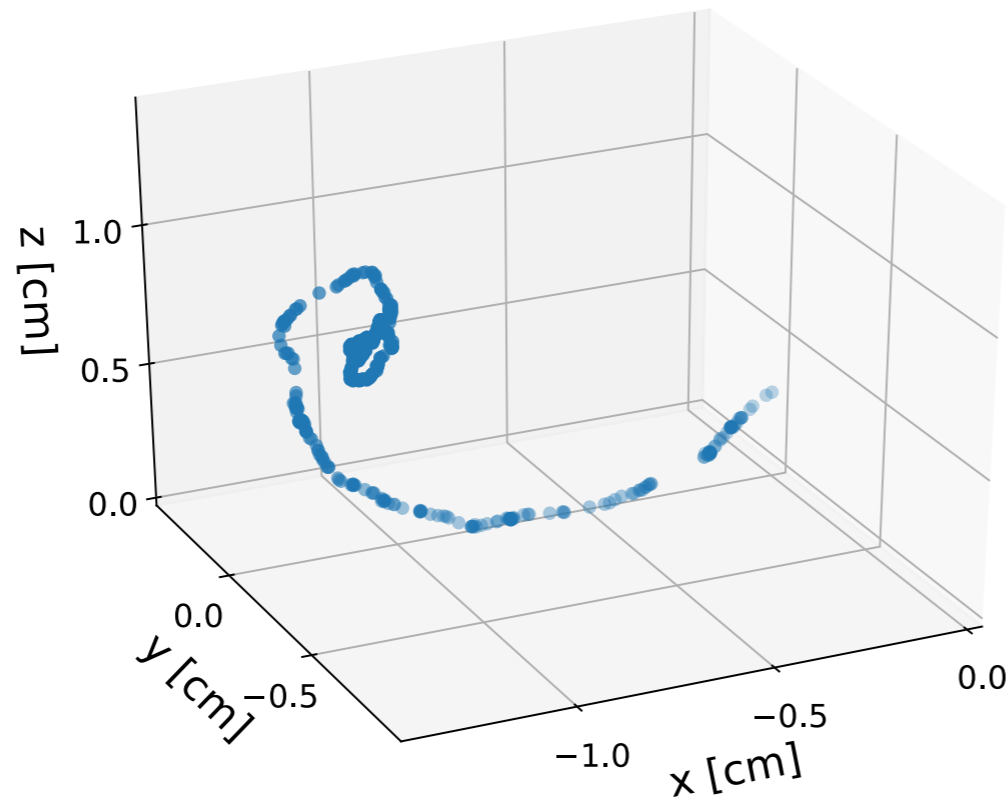


Recoil tracks (in He+SF₆ at 1 atm)

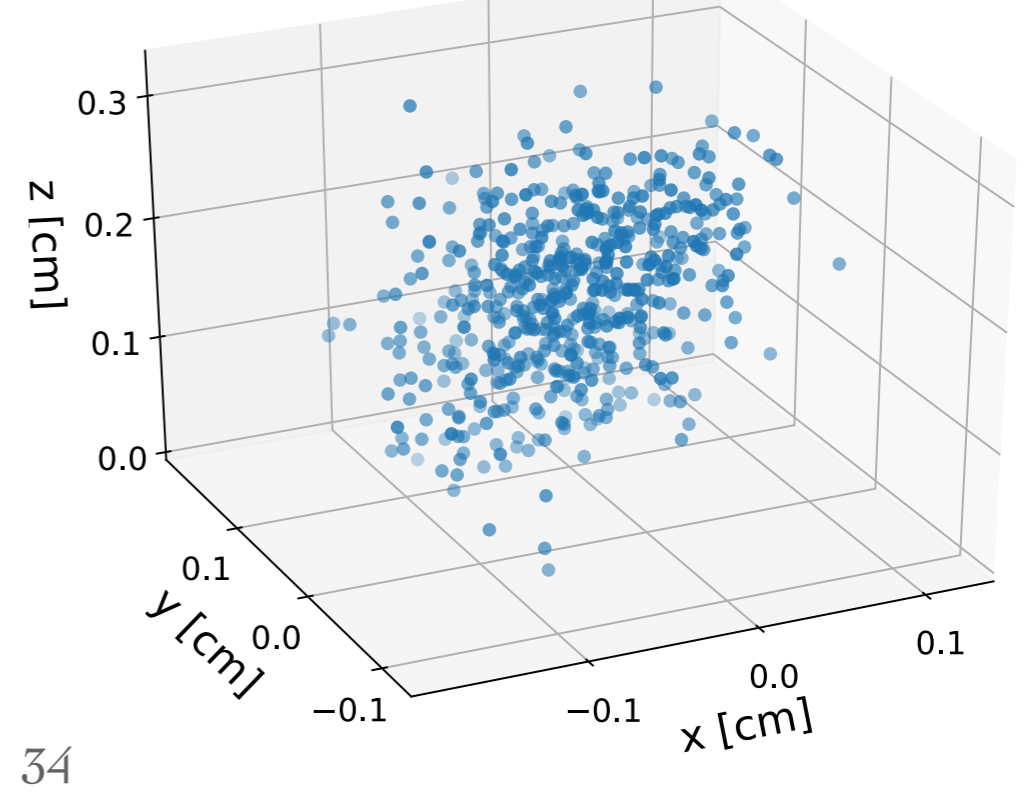
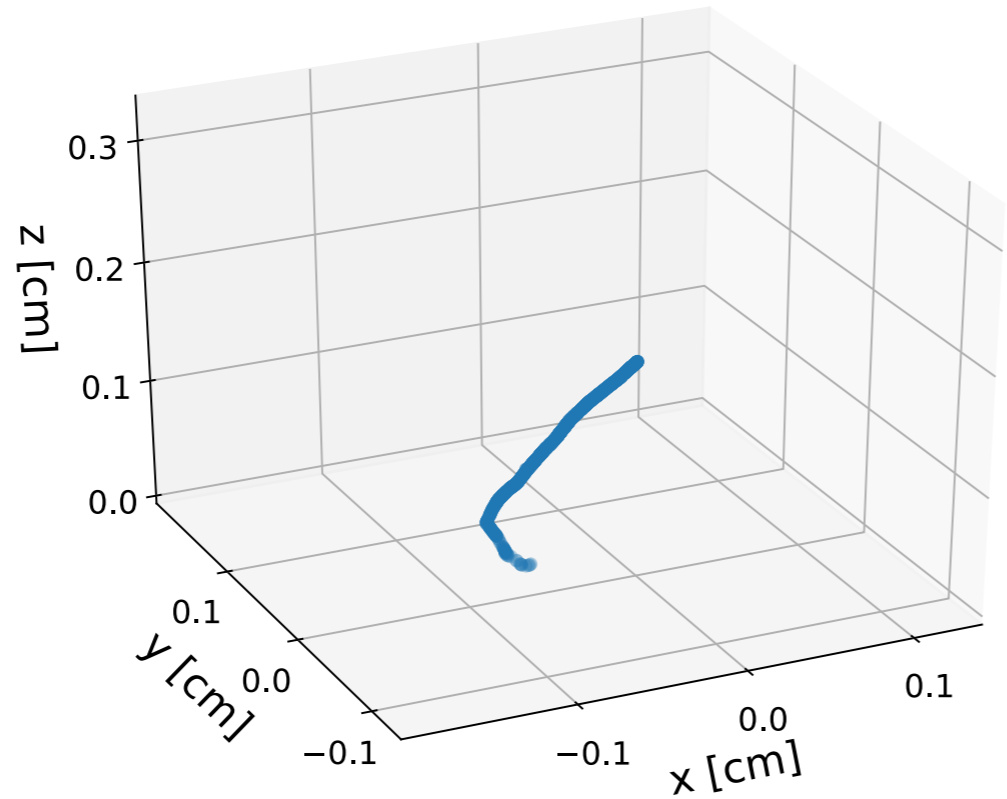
Before drift

After 25 cm drift

Electron:
20 keV



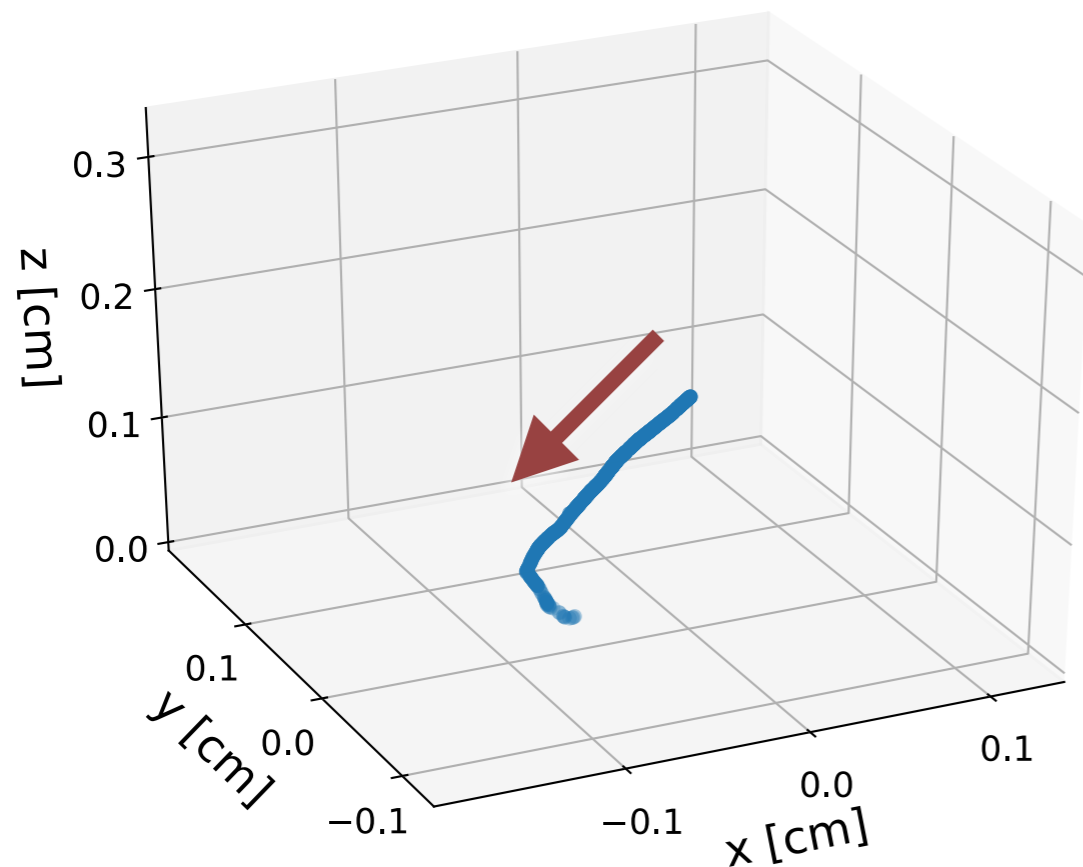
He Nucleus:
(25 keVr)



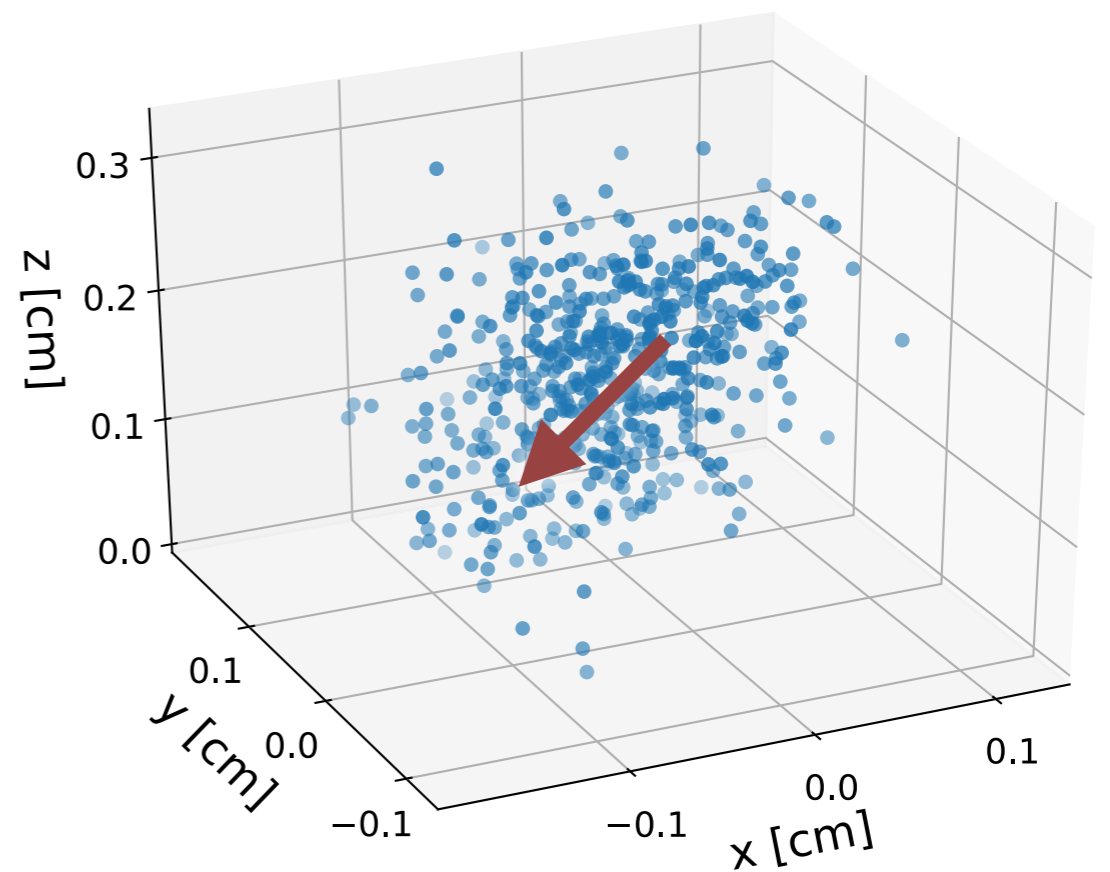
Angular resolution

Limited by two main effects: straggling & diffusion

Original track



Track after 25 cm drift

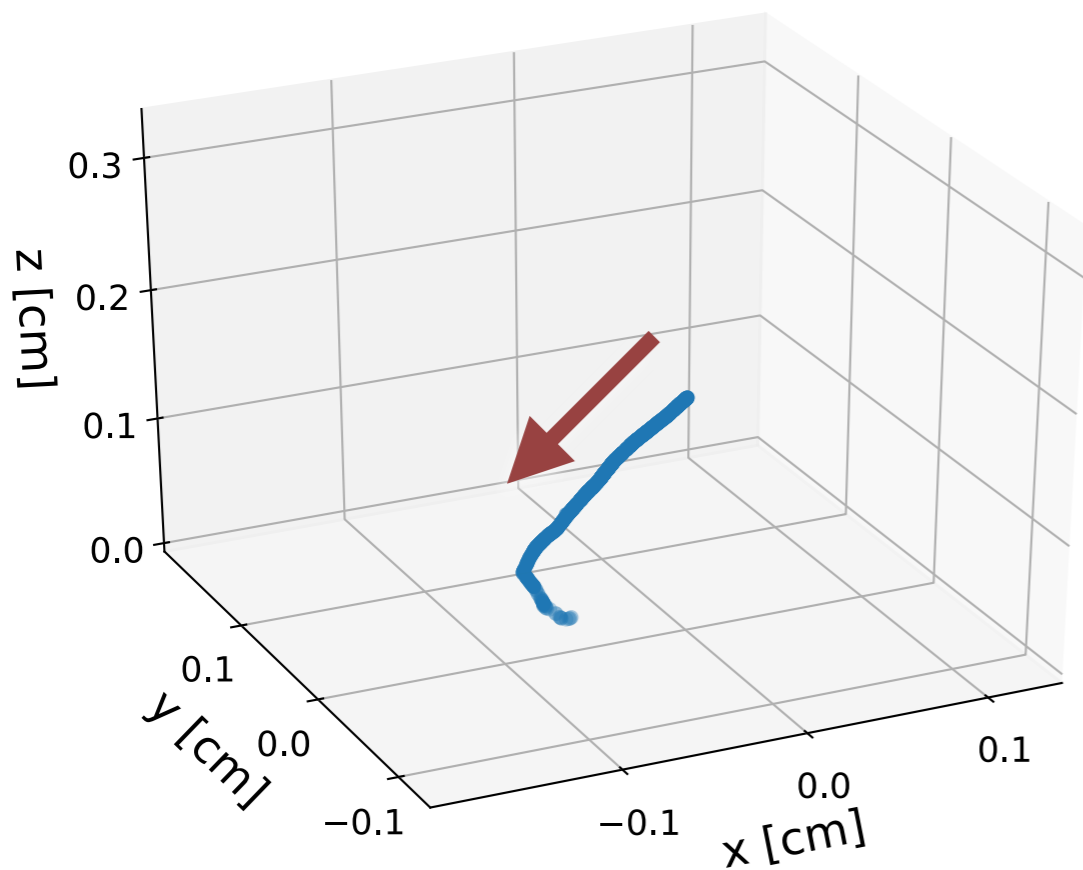


25 keVr Helium recoil in 1 atm of 755:5 He:SF₆

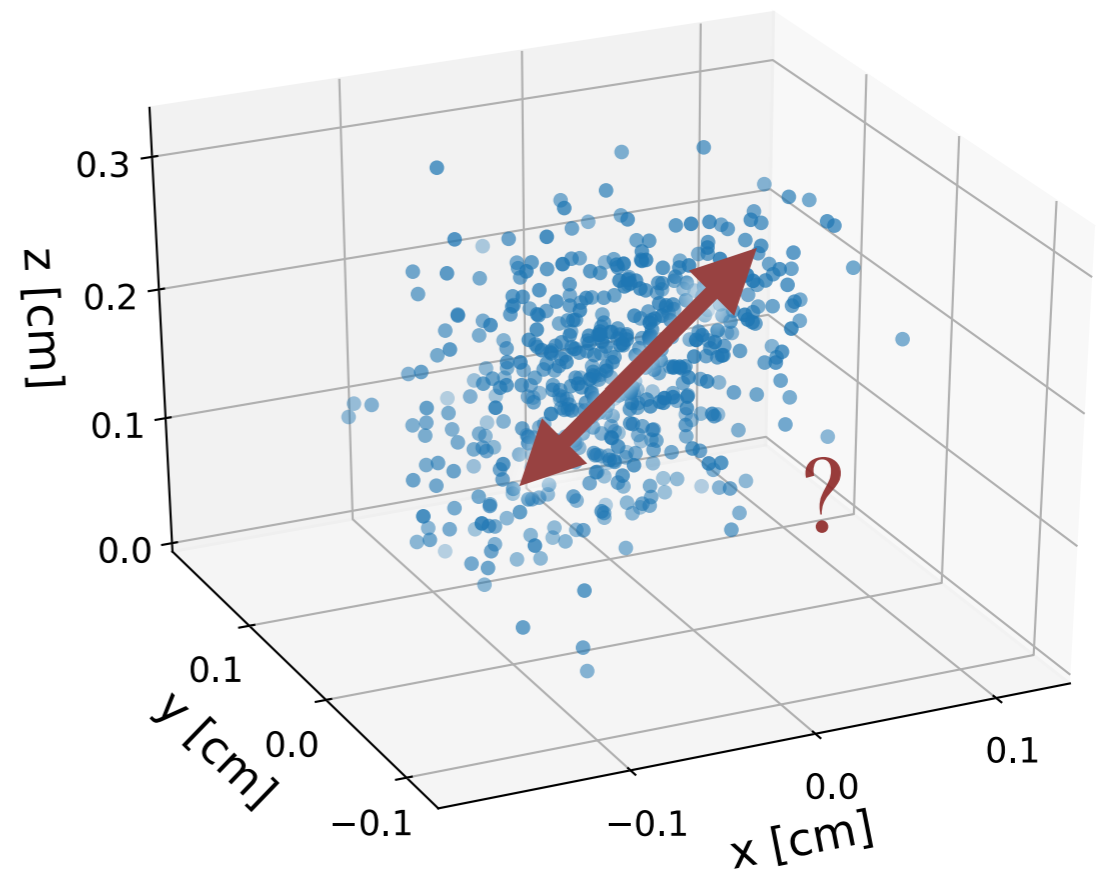
Head-tail recognition

Ability to recognise the forward-backward sense of a recoil

Original track



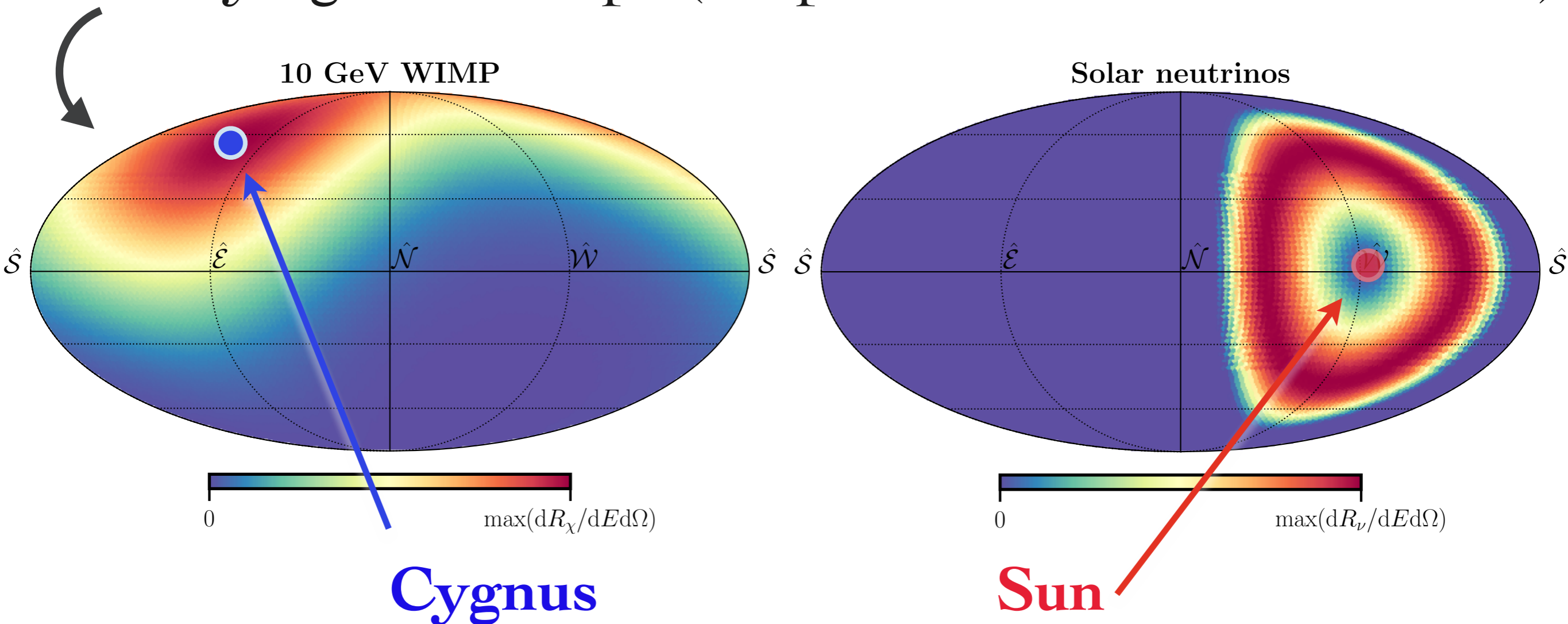
Track after 25 cm drift



**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

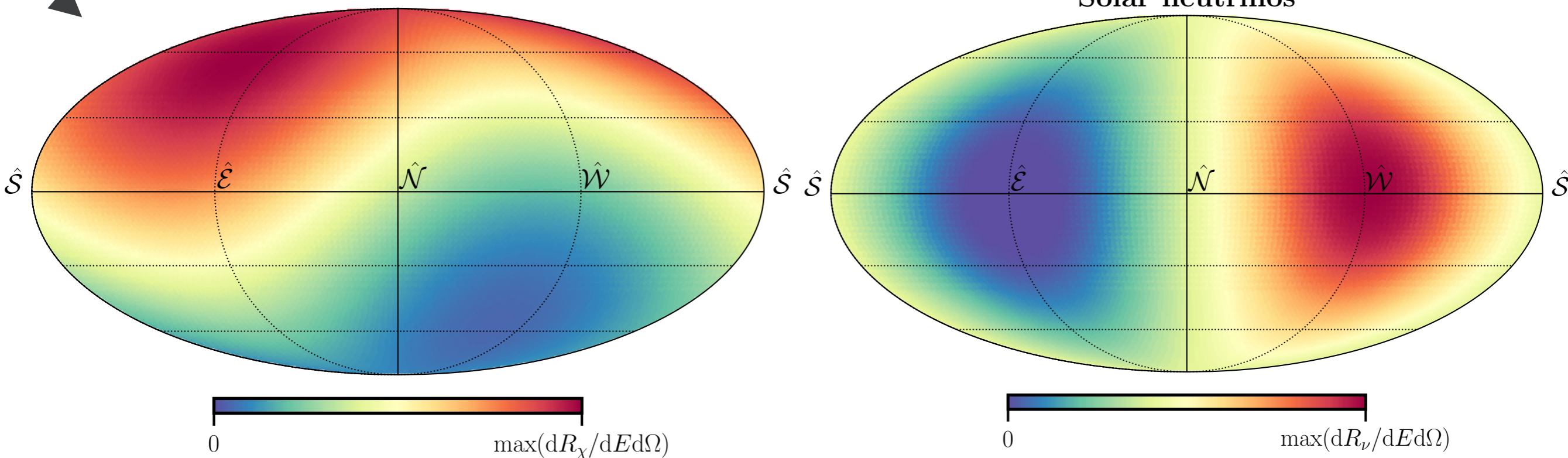
Angular resolution \rightarrow smears distributions in angle

No head-tail \rightarrow folds one half of sky on to the other

The same maps after 30° angular resolution applied

10 GeV WIMP

Solar neutrinos



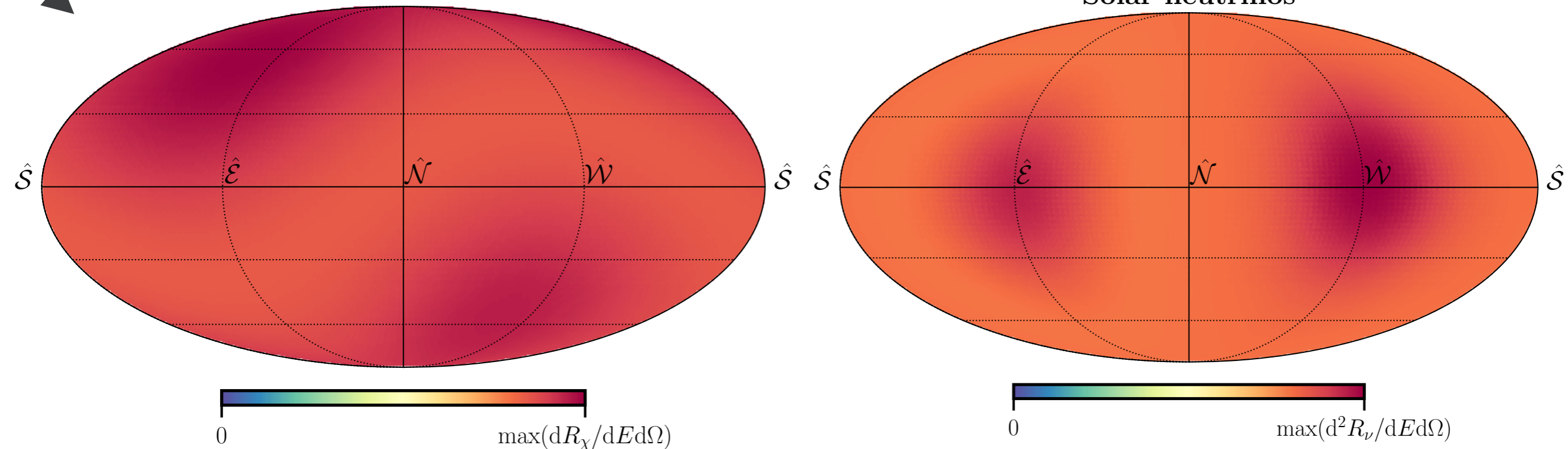
Signal in a “realistic” detector

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

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

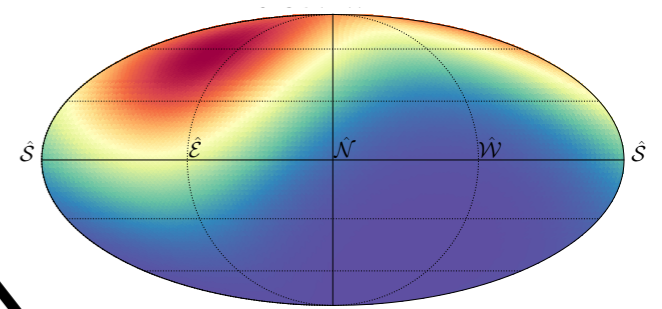
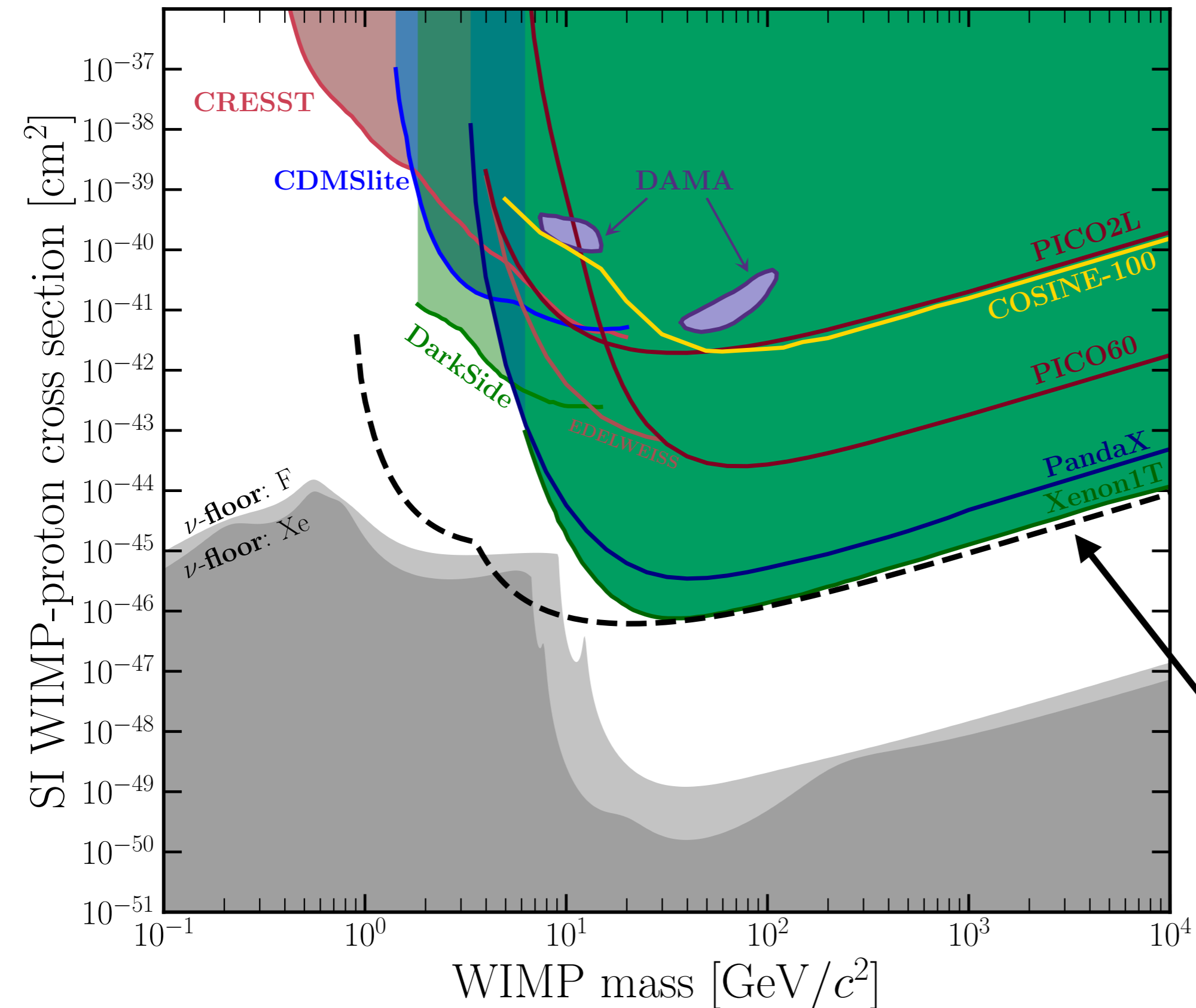
10 GeV WIMP

Solar neutrinos



How much does detector performance matter?

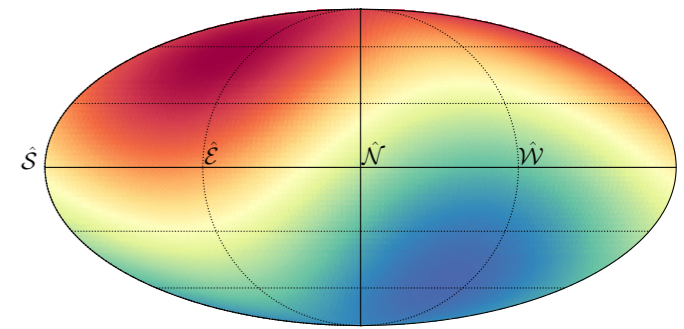
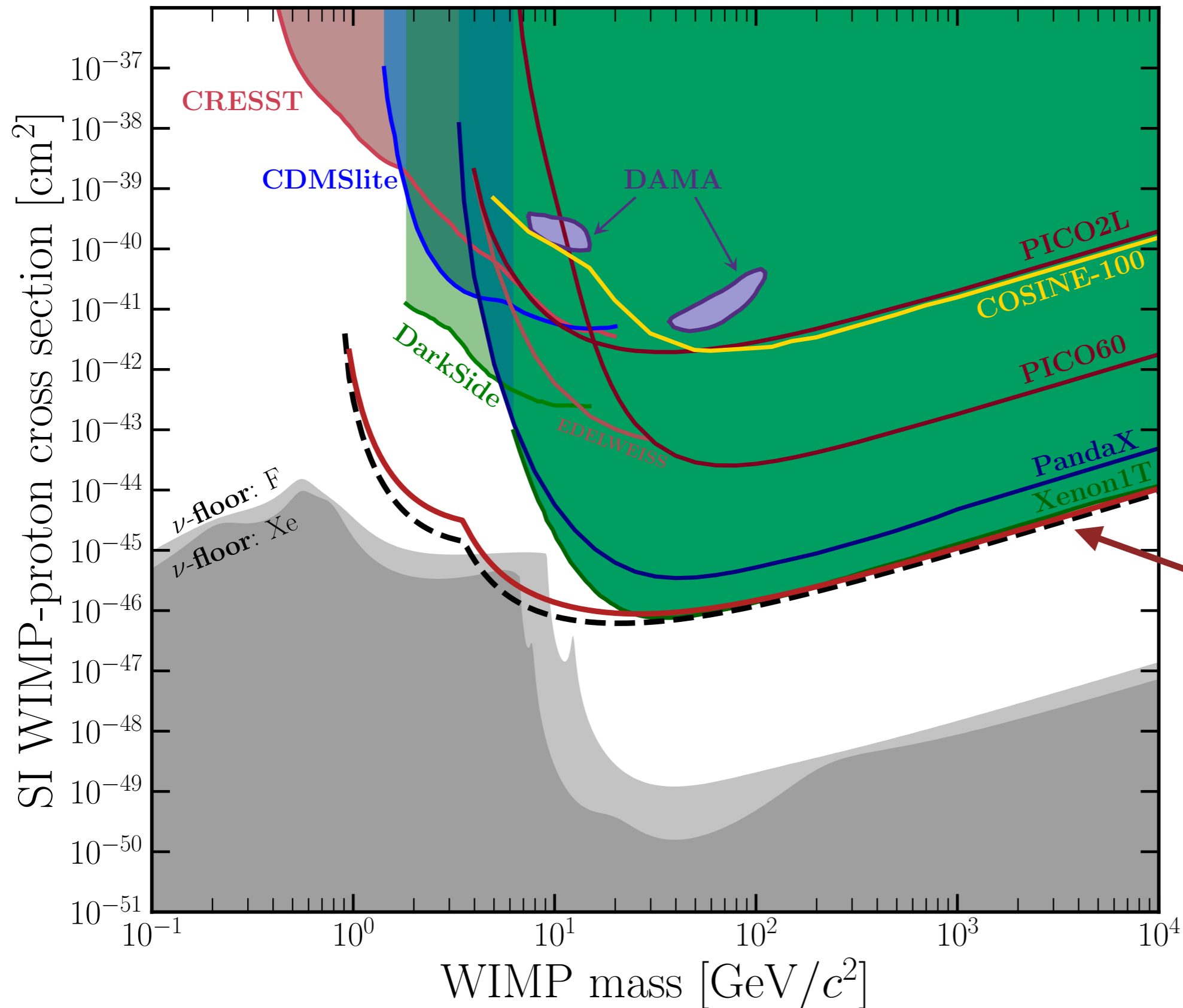
(1 atm He+SF₆ TPC, 1000 m³ × 6 years)



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

How much does detector performance matter?

(1 atm He+SF₆ TPC, 1000 m³ × 6 years)

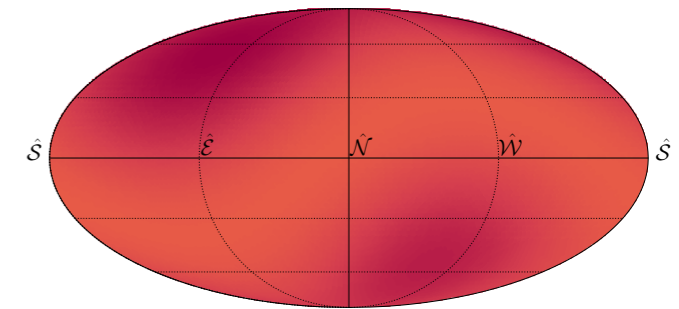
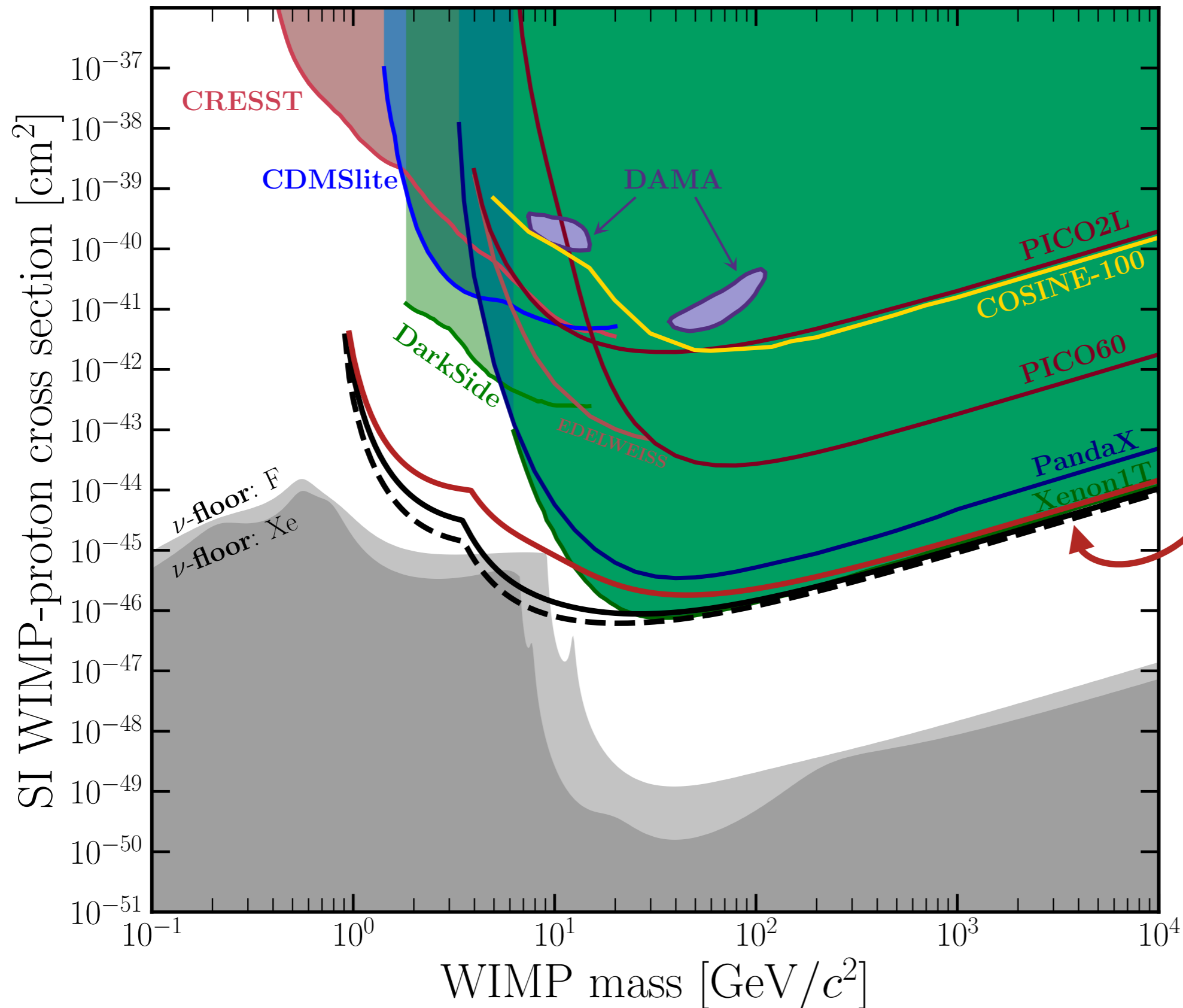


Case 2: Perfect HT
30° angular res.
100% head-tail

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

How much does detector performance matter?

(1 atm He+SF₆ TPC, 1000 m³ × 6 years)



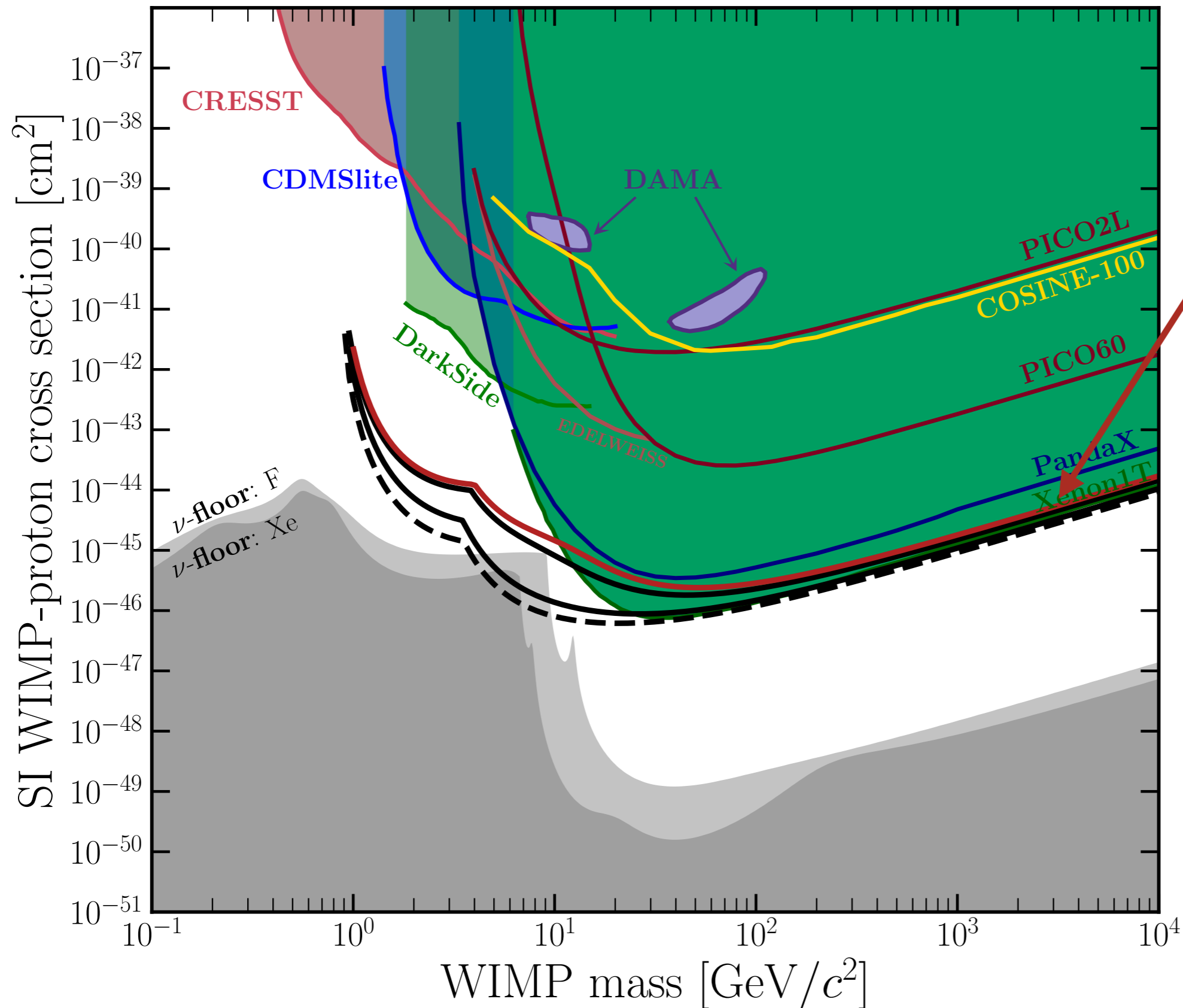
Case 3: Realistic
30° angular res.
75% head-tail

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+SF₆ TPC, 1000 m³ × 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

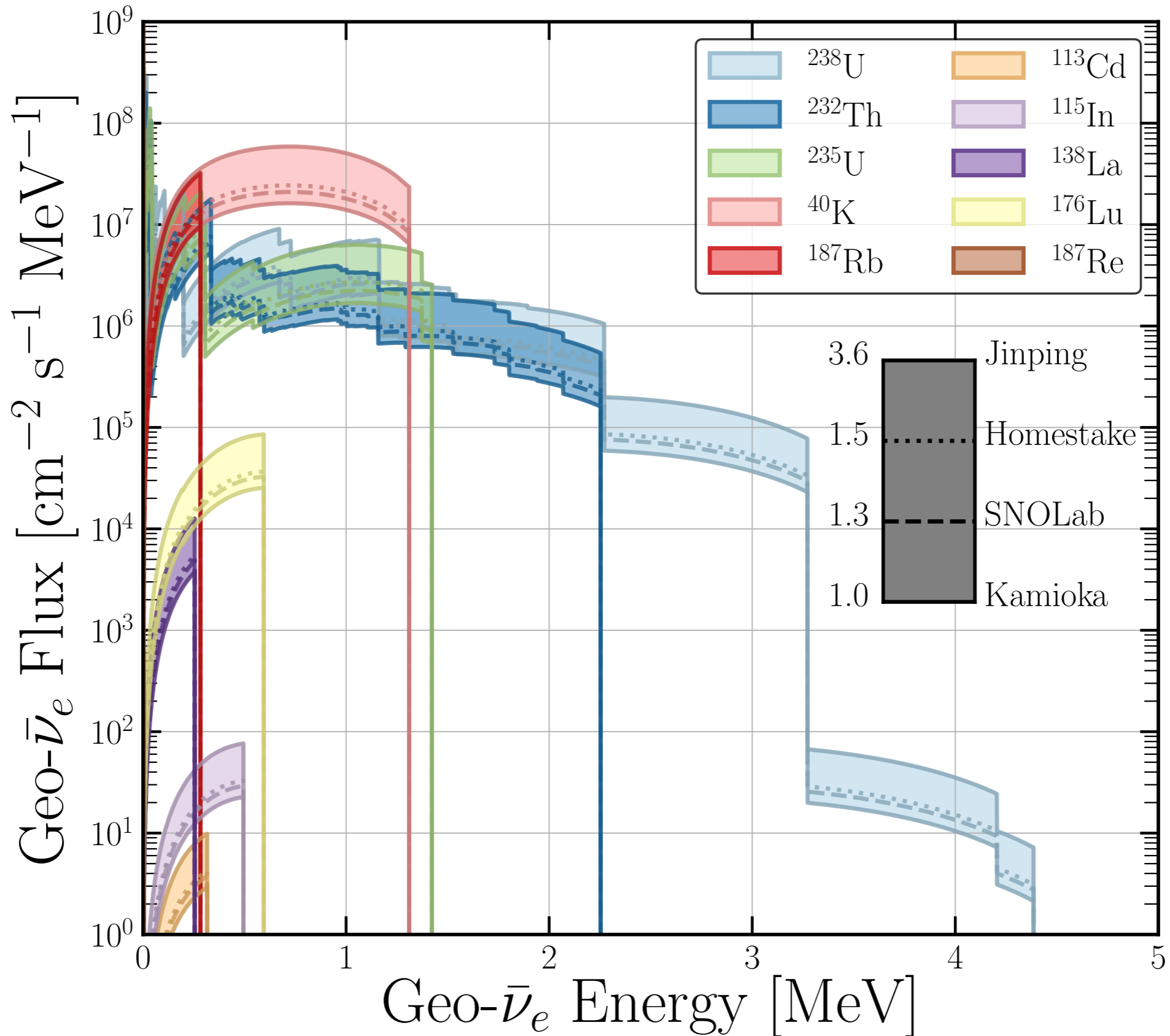
The most powerful way to remove the background

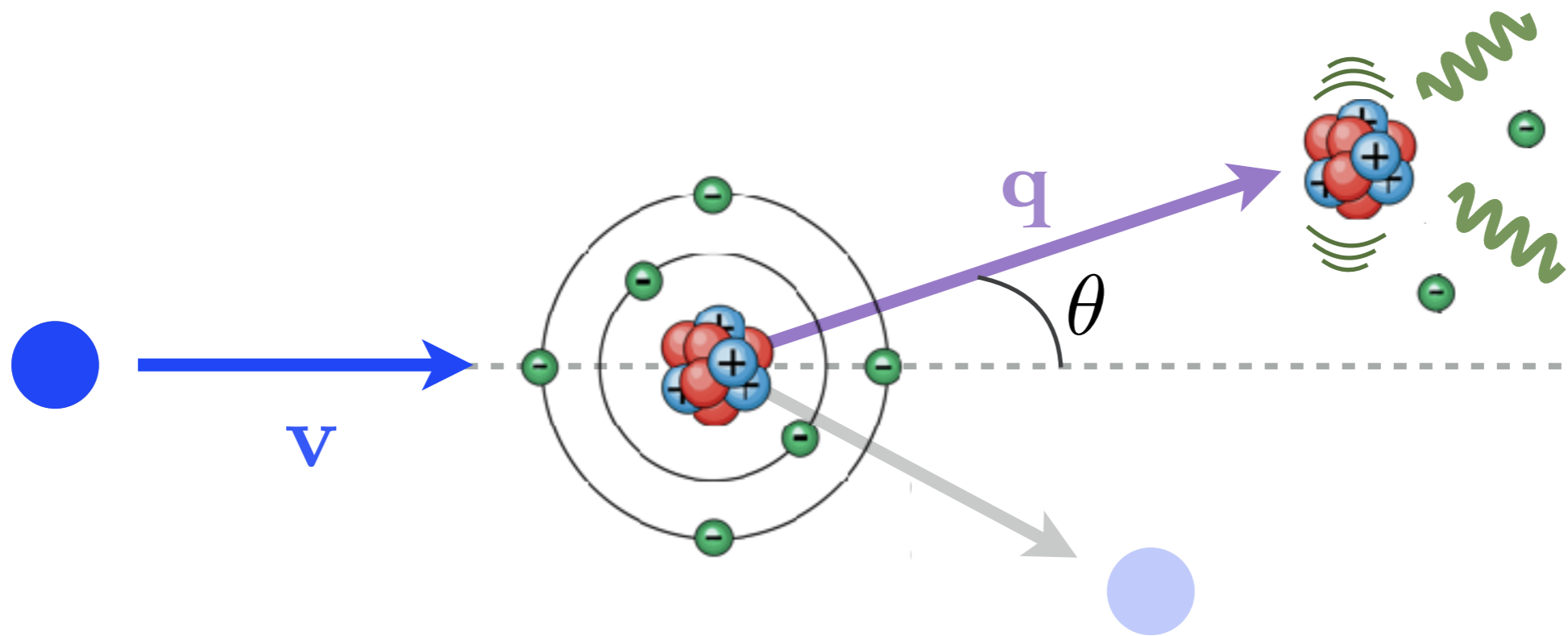
Idealised detector → Neutrino floor completely removed

Realistic detector → Need >30 deg. ang. res. and $<75\%$ Head-tail

Extra slides

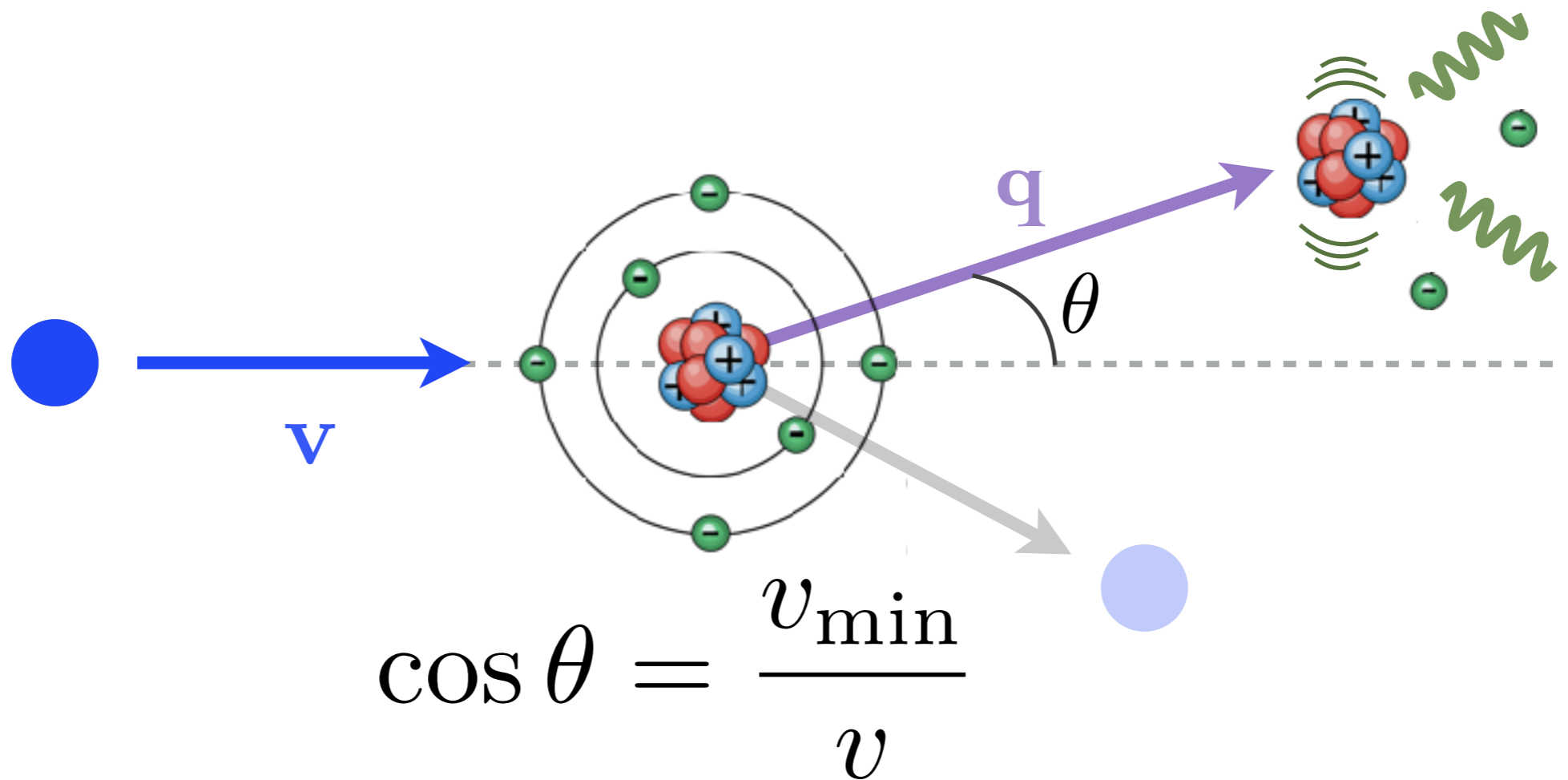
Geoneutrino flux depends on location





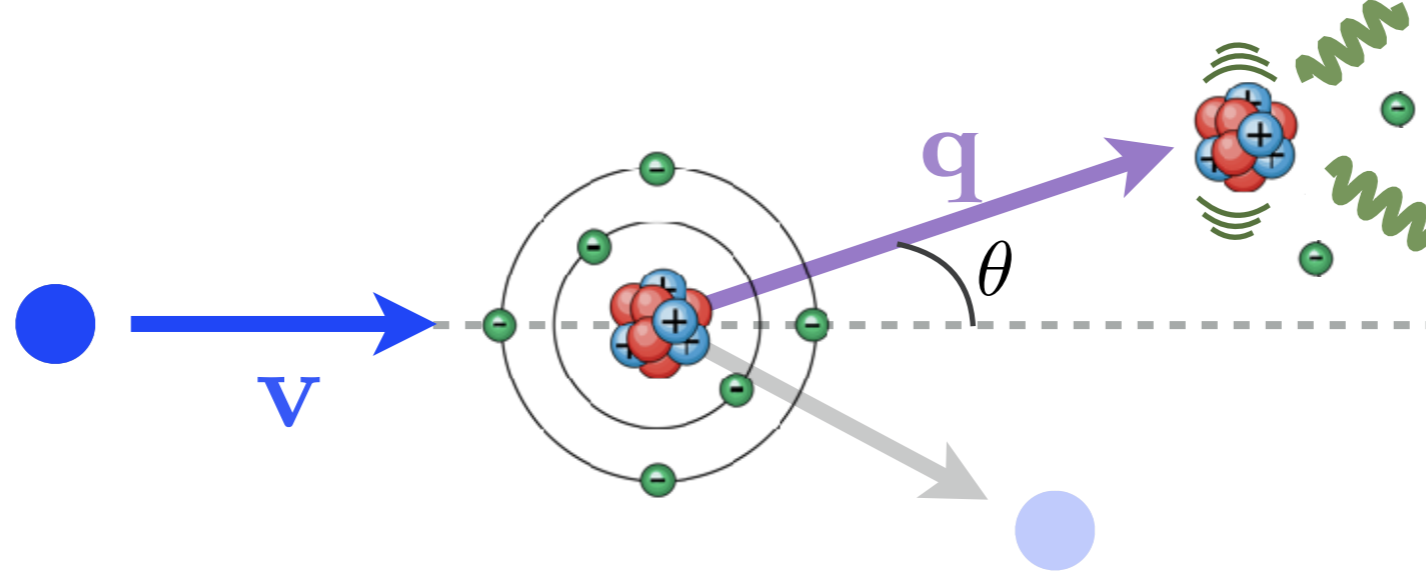
Momentum transfer: $q = 2\mu_N v \cos \theta$

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



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

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



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

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

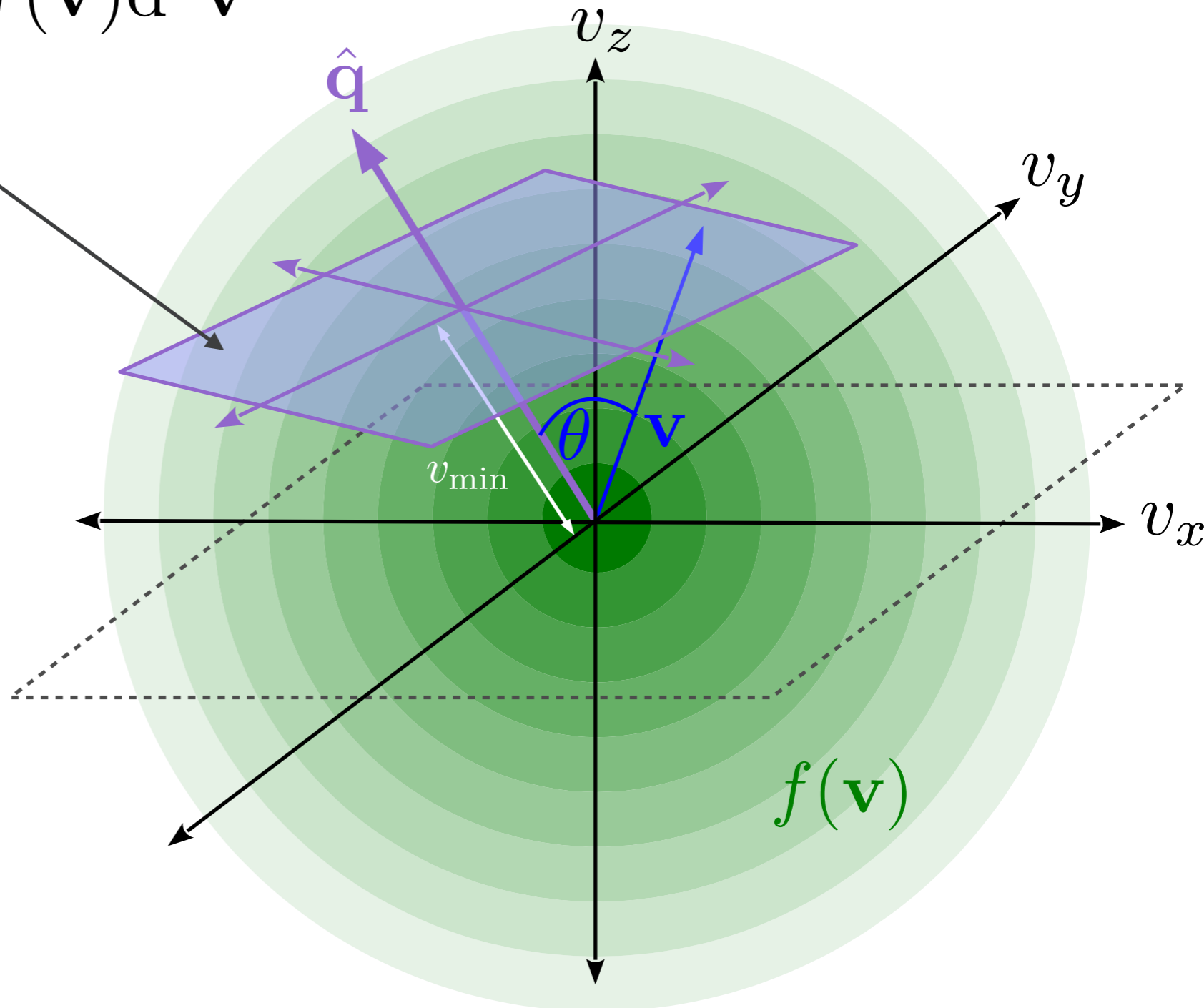
Energy dependence of most cross sections will look like: $\frac{d\sigma}{dE_r} = \frac{m_N \mathcal{C}_N \sigma_p}{2\mu_p^2 v^2} F^2(E_r)$

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

“Radon transform” encodes all direction sensitivity

Radon transform

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



Readout dimensionality depends on technology

1d - just drift direction (z)

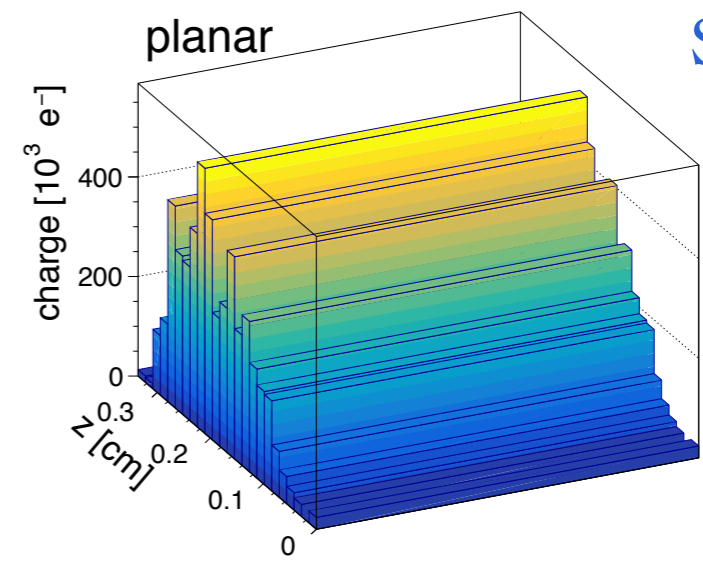
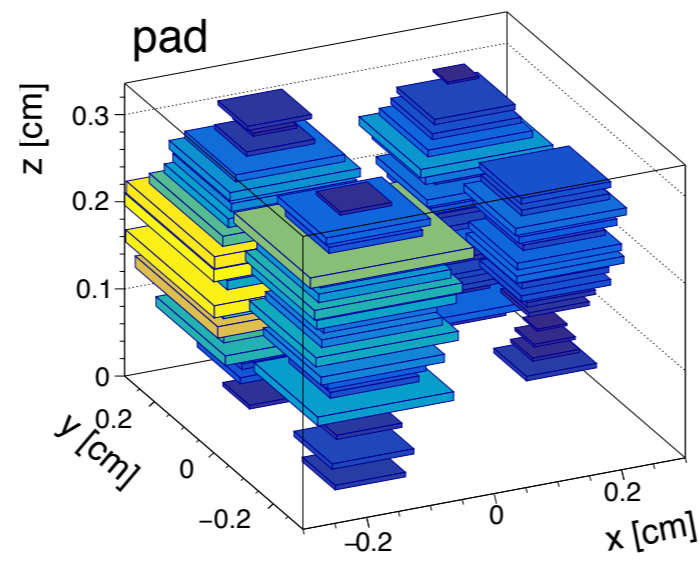
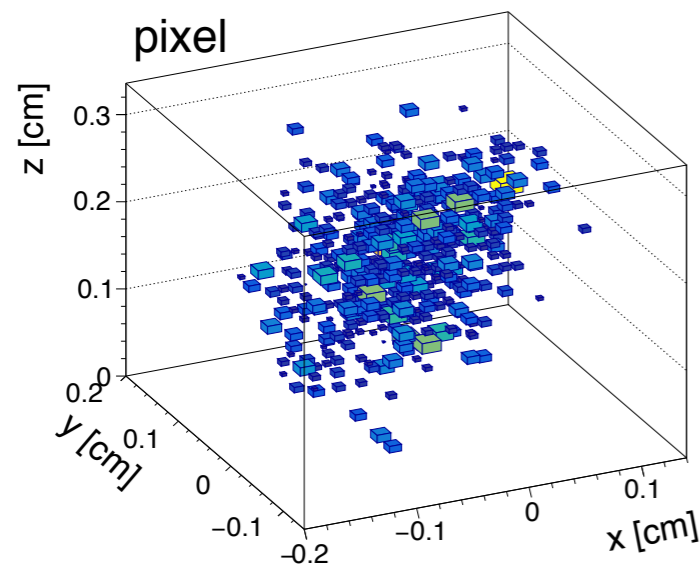
e.g. *planar* (just time dependence of charge), *wire* (e.g. DRIFT)

2d → just readout plane (x,y)

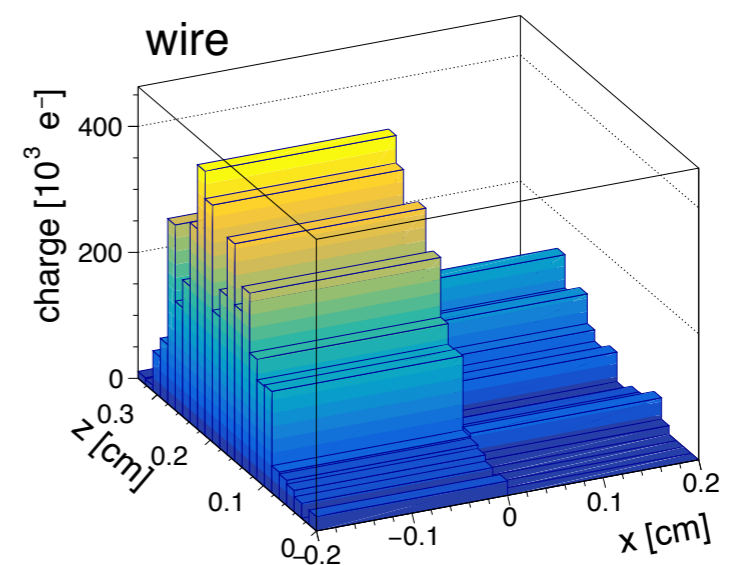
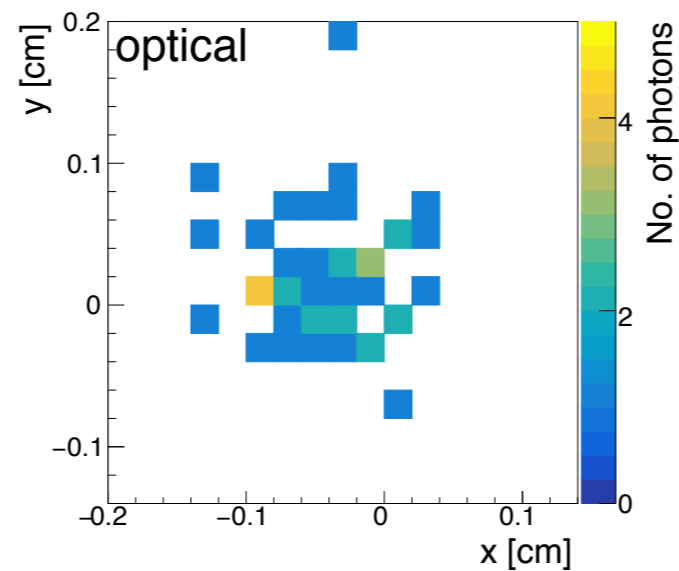
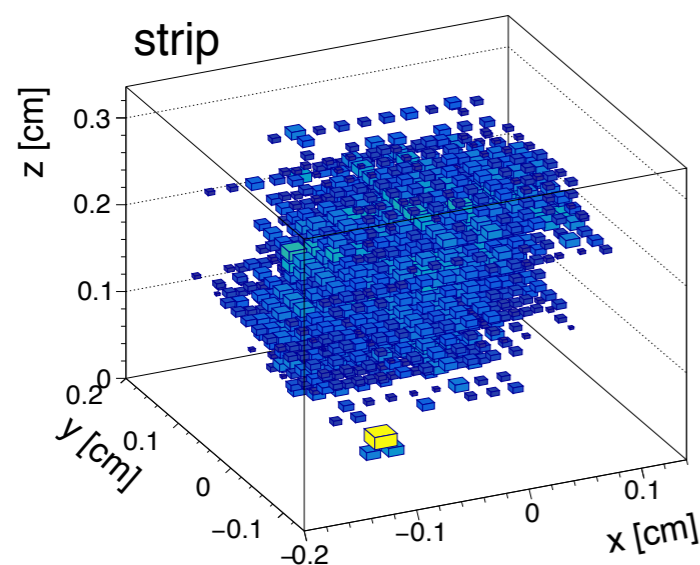
e.g. *optical* (CCDs)

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

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

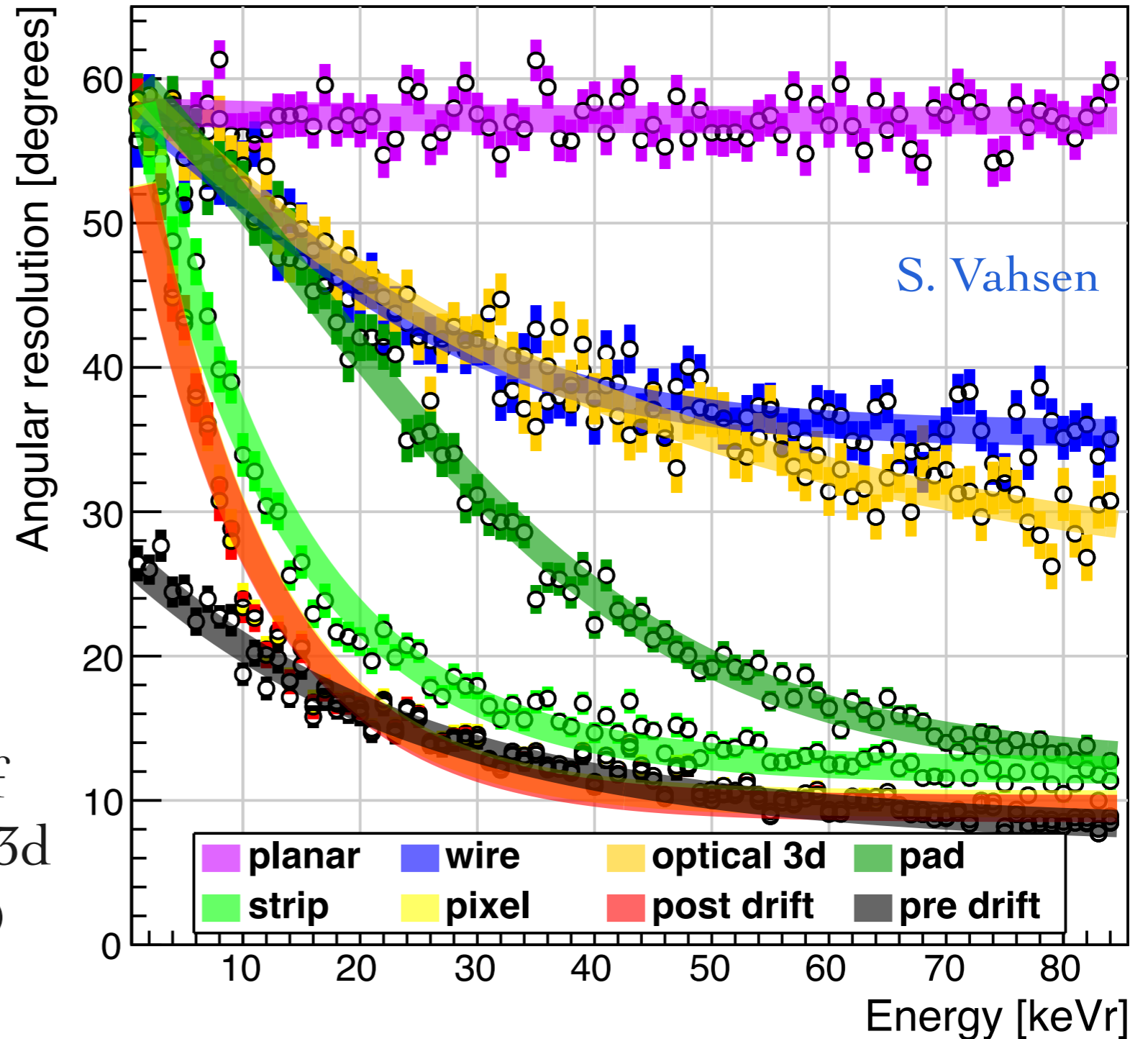


S. Vahsen



Angular resolution

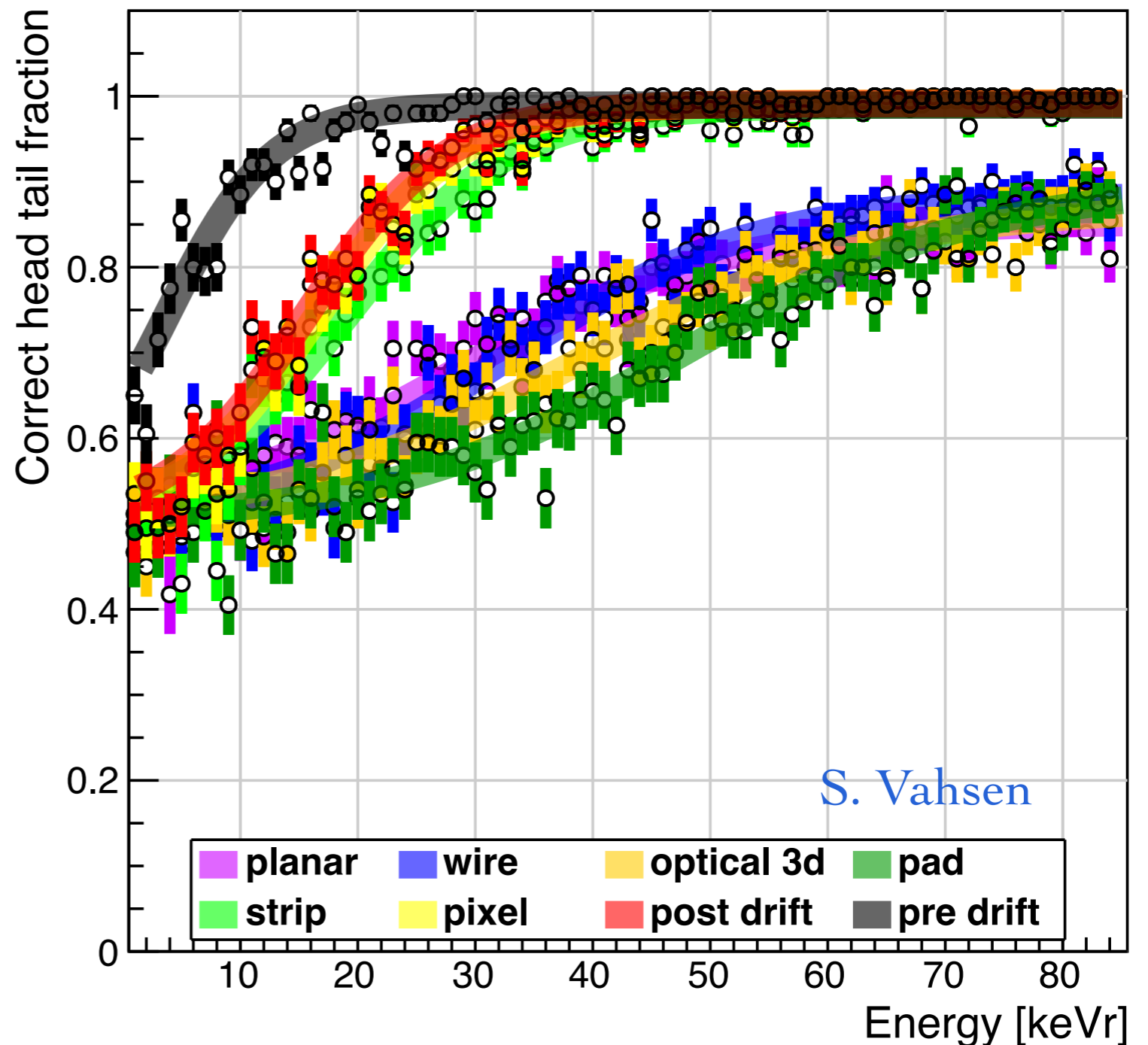
Angular resolution improves with energy because tracks are longer and more charge is generated



He recoils in 755:5 Torr of He:SF₆, (except for optical 3d which has 740:20 He:CF₄)

Head-tail recognition

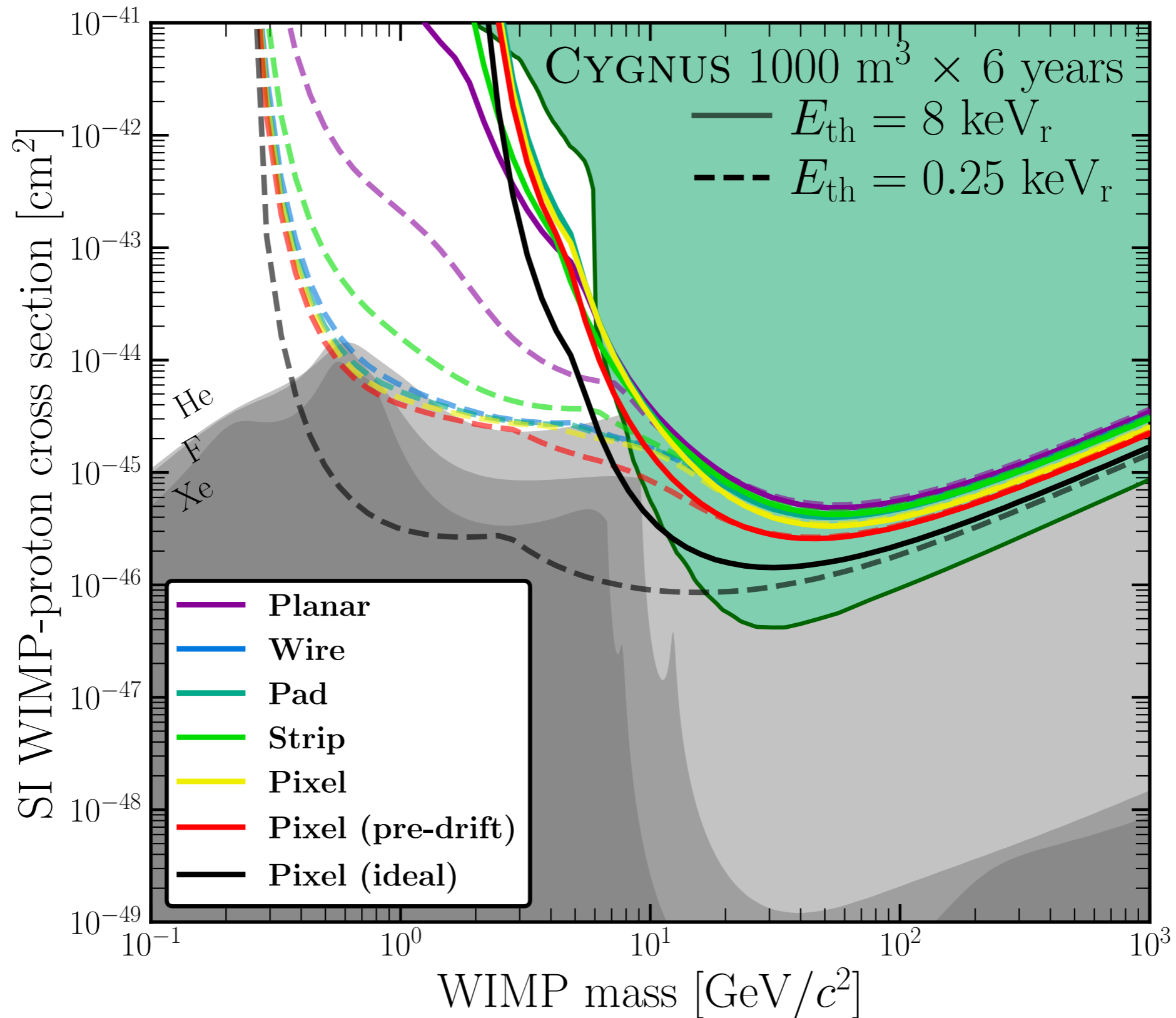
Head-tail recognition also improves with energy because tracks are longer and more charge is generated



He recoils in 755:5 Torr of He:SF₆, (except for optical 3d which has 740:20 He:CF₄)

Physics reach

(WIMP nuclear scattering vs neutrino background)



Physics reach

(WIMP nuclear scattering vs neutrino background)

