Looking through the neutrino fog

Giovanni Grilli di Cortona

giovanni.grilli@lngs.infn.it

INFN LNGS

Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Gran Sasso

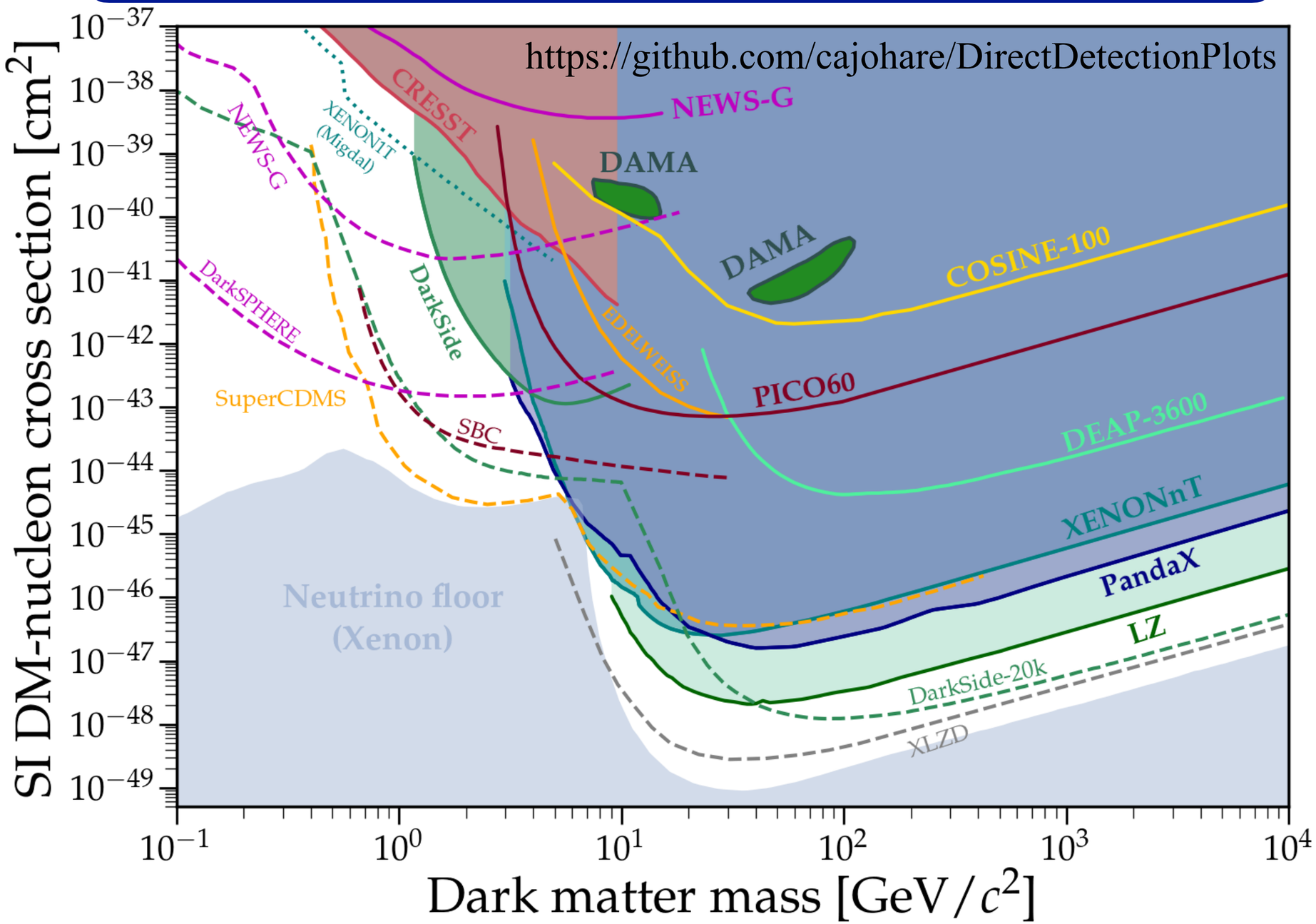
Sapienza - 2/12/2024

Outline

1. From the neutrino floor to the neutrino fog
2. Looking through the neutrino fog

Floor versus fog

Current status



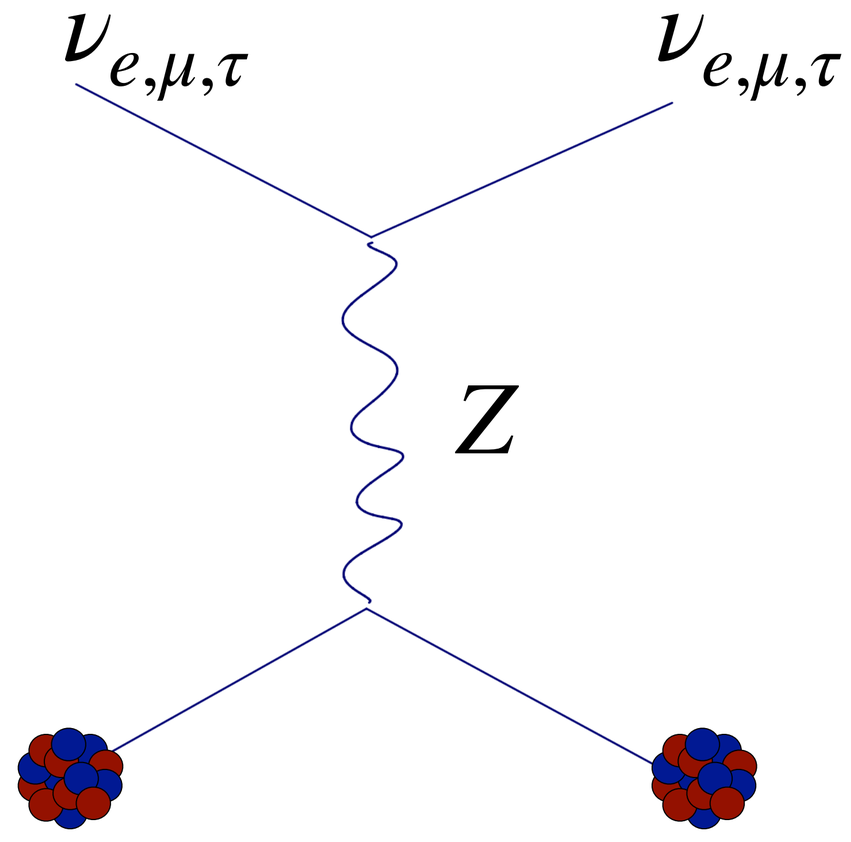
Coherent elastic neutrino-nucleus scattering

[Freedman 1974, COHERENT 1708.01294]

Fermi constant

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

Weak hypercharge



Coherent elastic neutrino-nucleus scattering

[Freedman 1974, COHERENT 1708.01294]

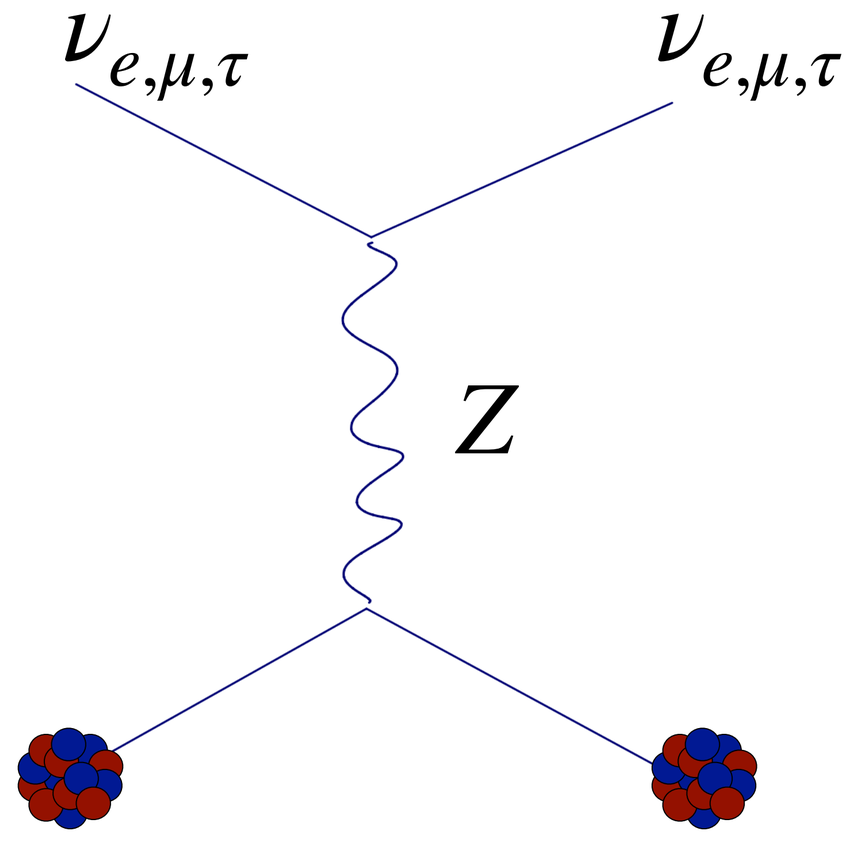
Fermi constant

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

Weak hypercharge

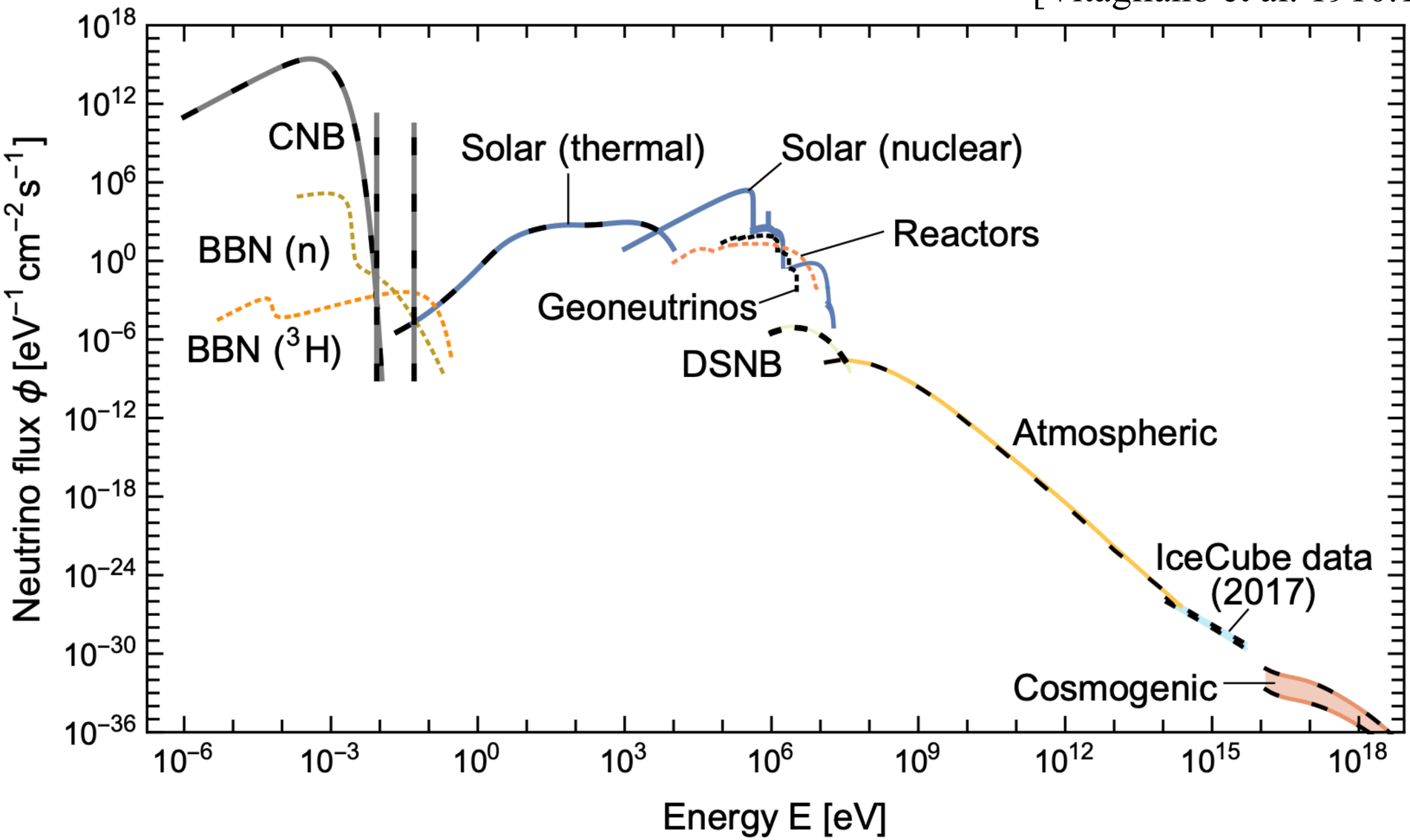
$$E_r \simeq \mathcal{O}(10\,\mathrm{keV})$$

$$E_\nu \sim \sqrt{\frac{m_N E_r}{2}} \simeq \mathcal{O}(1-10)\,\mathrm{MeV}$$



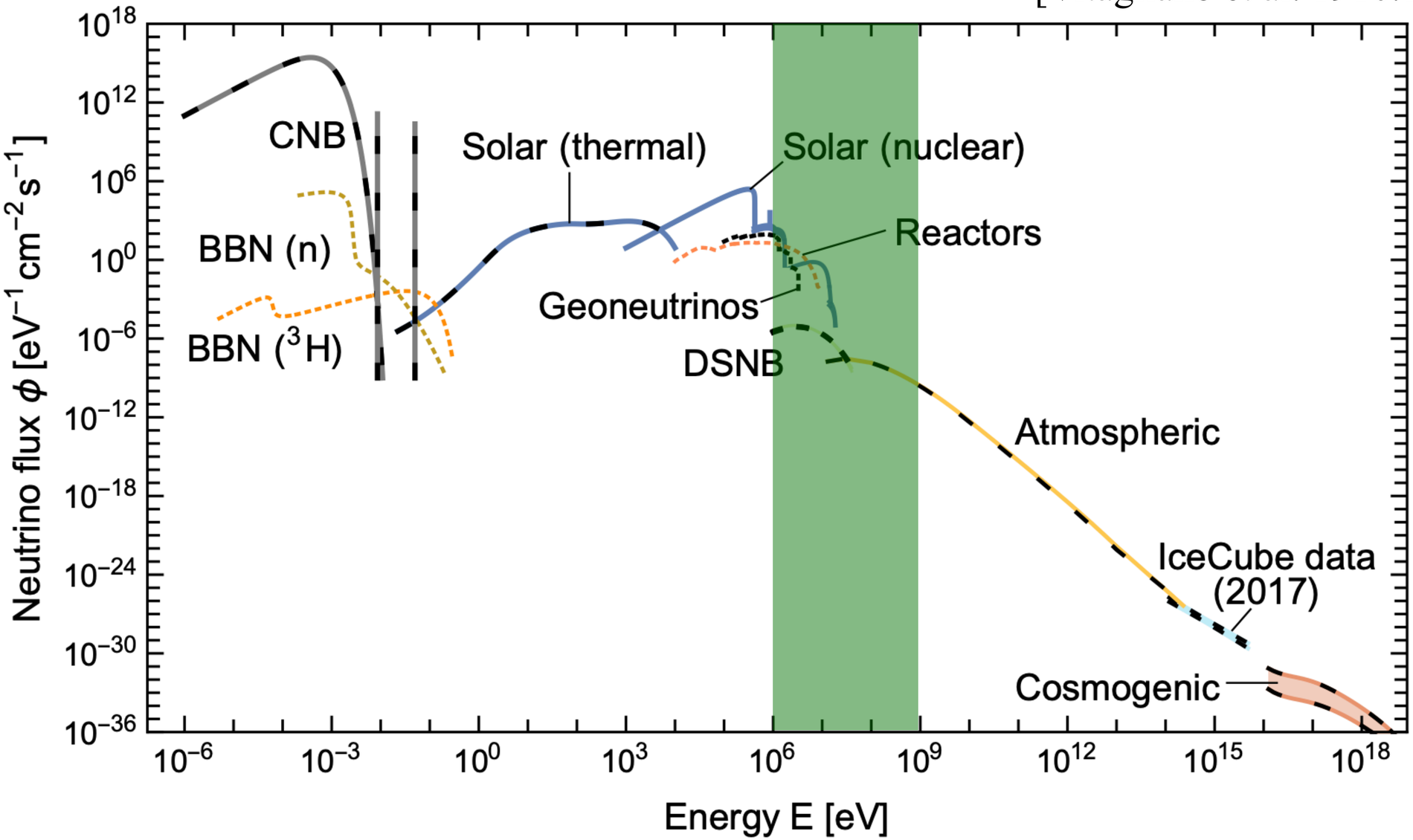
Neutrino sources

[Vitagliano et al. 1910.11878]



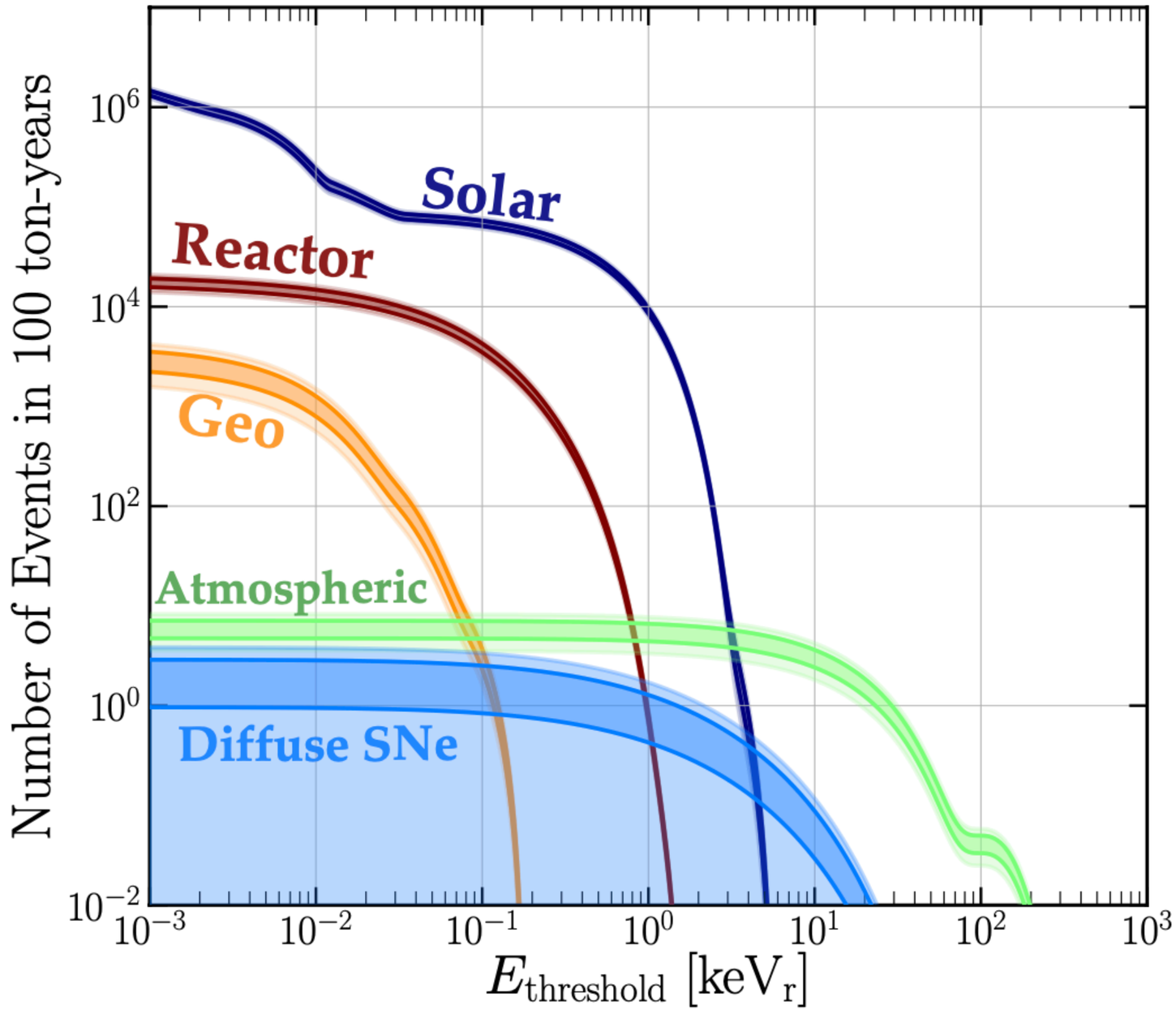
Neutrino sources

[Vitagliano et al. 1910.11878]



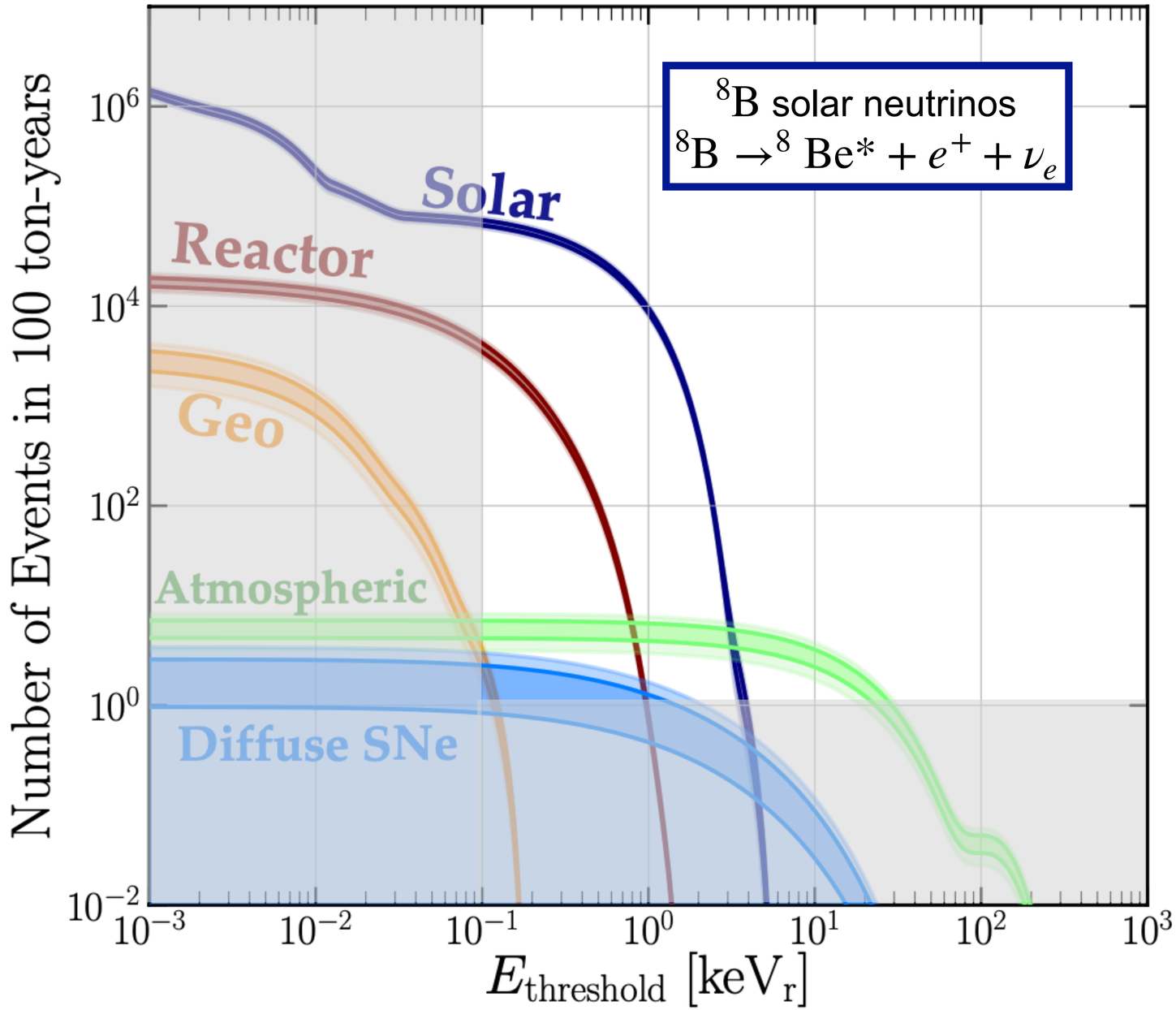
Neutrino sources

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N}\int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu}\frac{d\sigma}{dE_r} dE_\nu$$



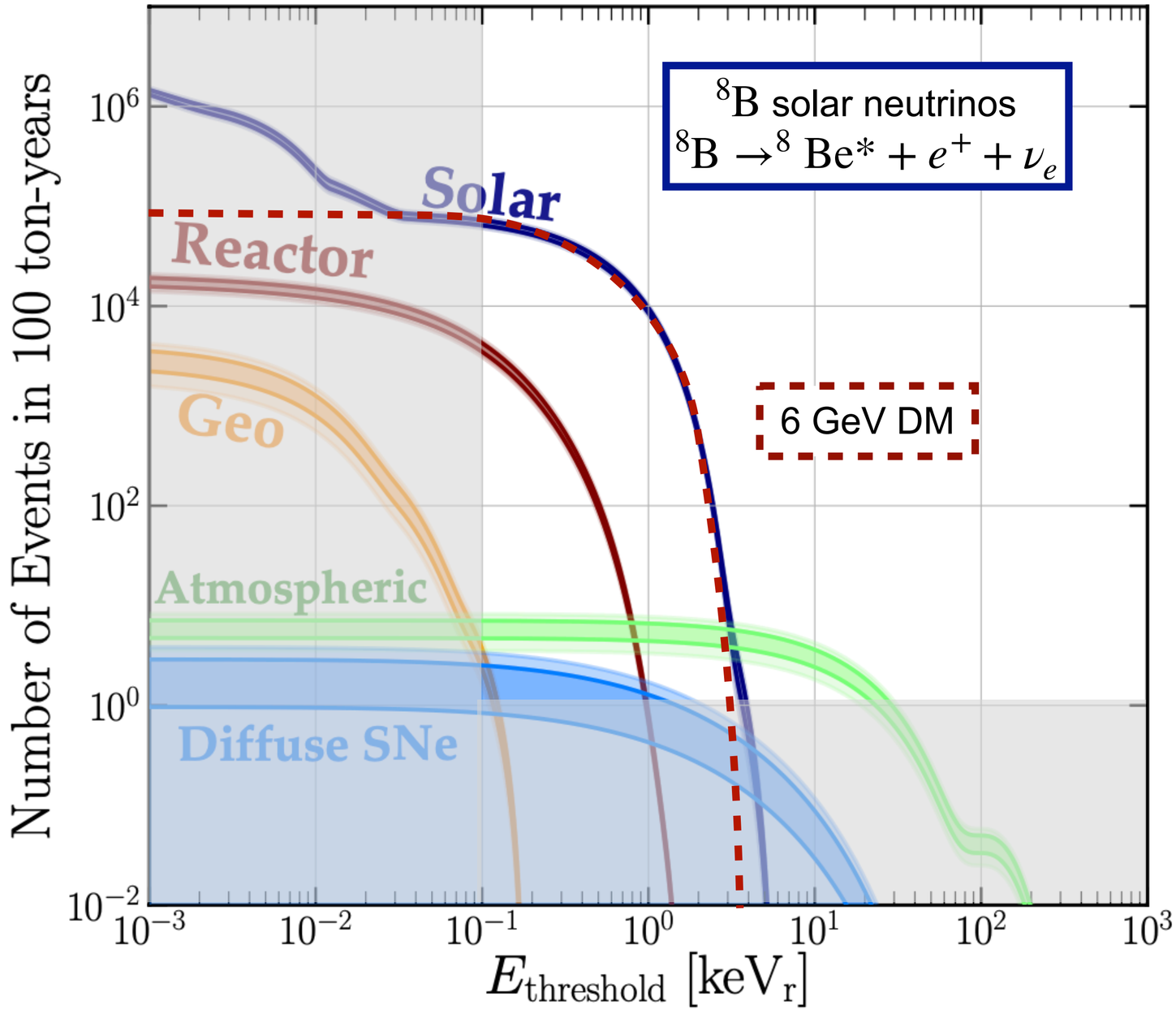
Neutrino sources

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N}\int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu}\frac{d\sigma}{dE_r} dE_\nu$$



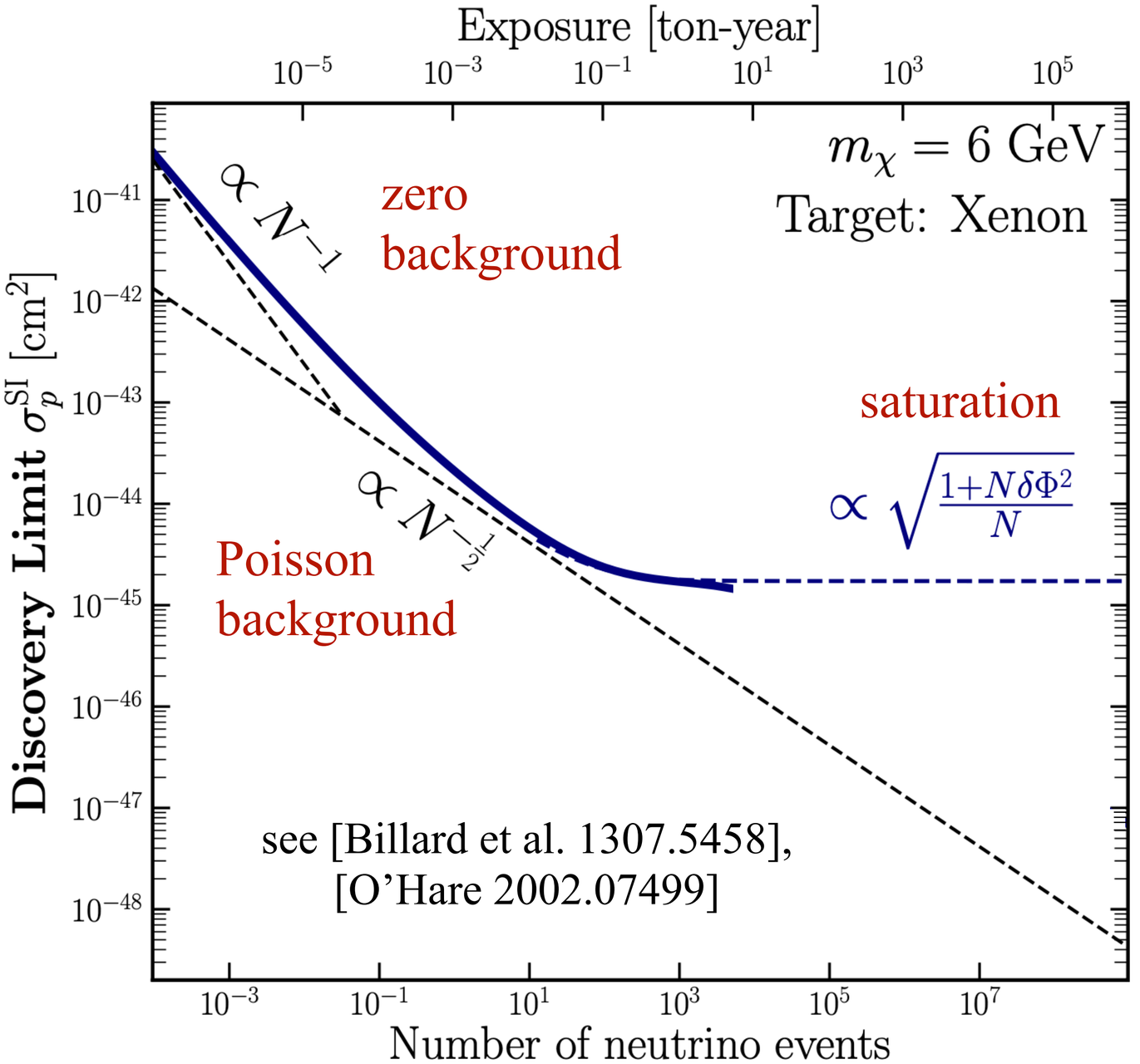
Neutrino sources

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N}\int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu}\frac{d\sigma}{dE_r} dE_\nu$$



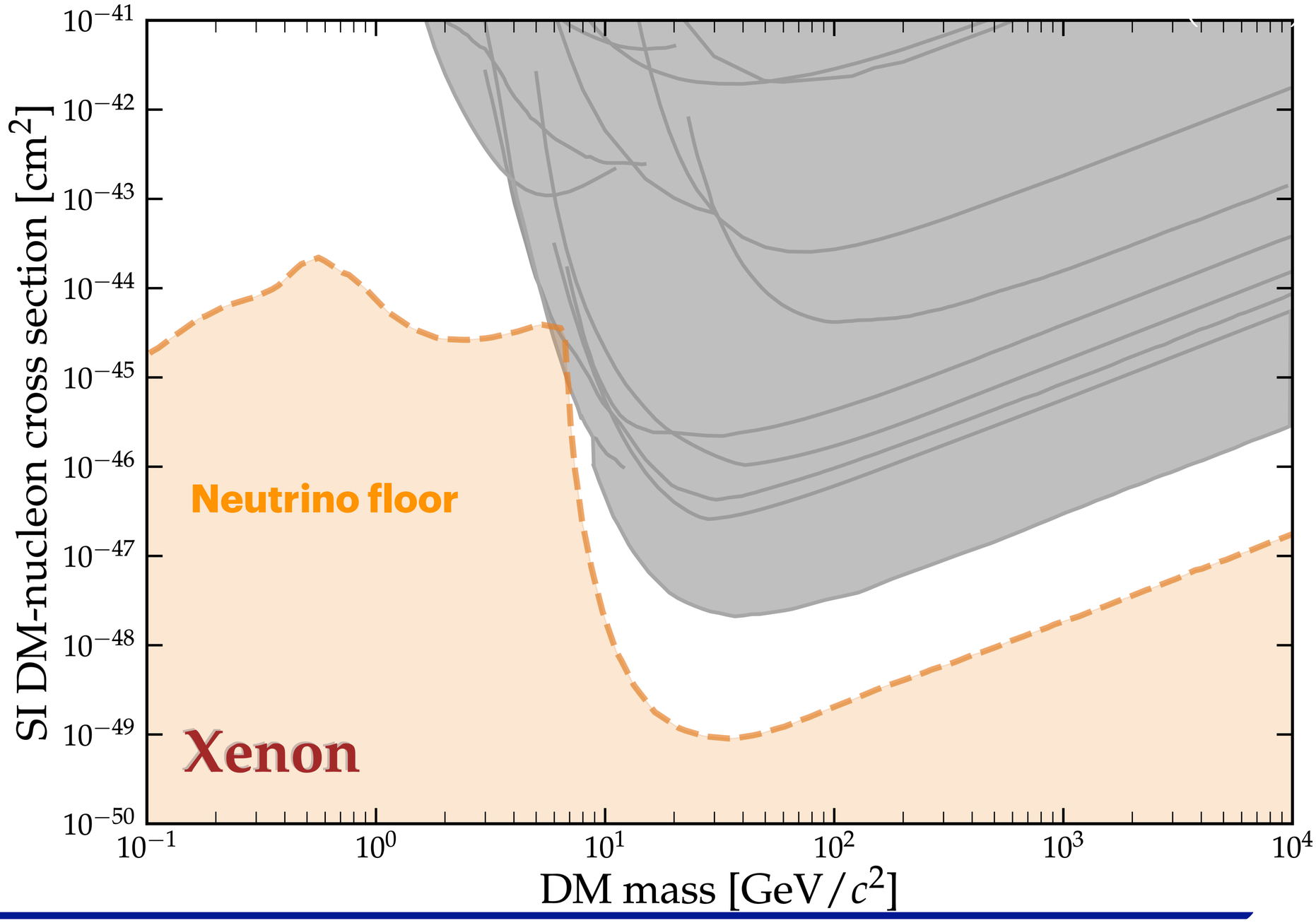
The neutrino floor

Scaling of a DM discovery limit for increasing exposure:
experiments cannot probe cross sections smaller than those that generate an event excess smaller than the estimated background fluctuations.

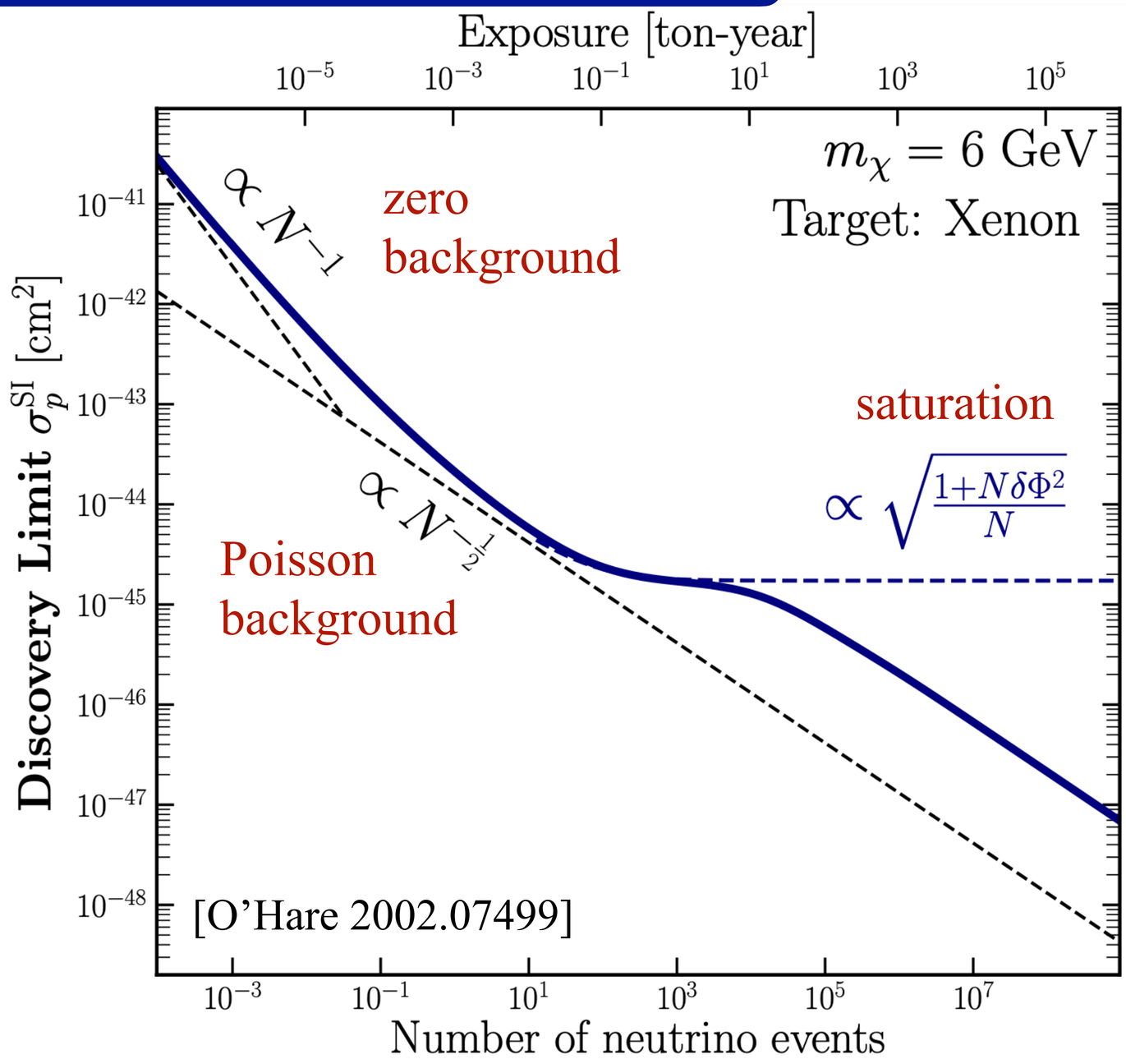


The neutrino floor

Done for the first time by
[Billard et al. ‘2013]



The neutrino fog



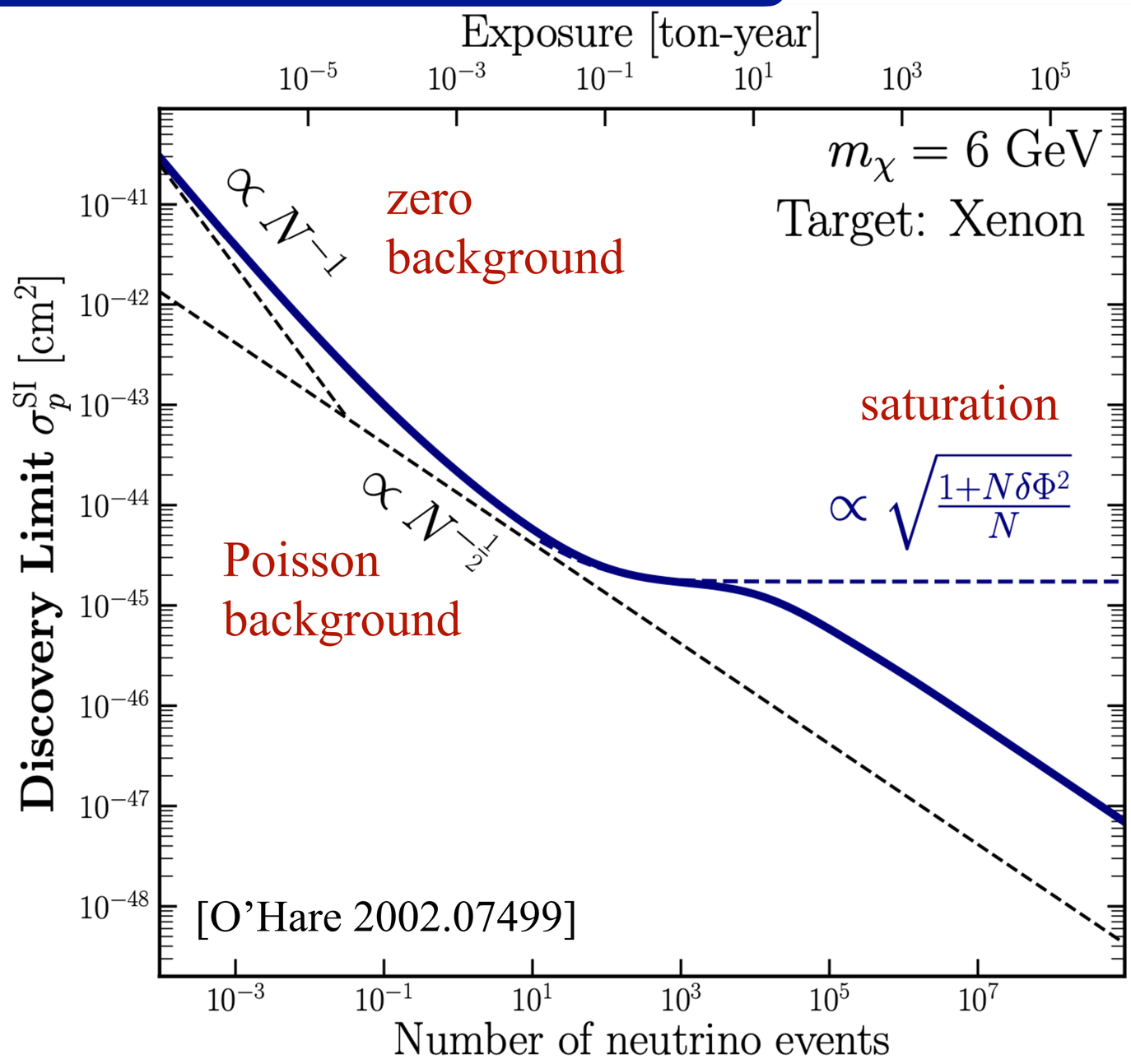
The neutrino fog

[O'Hare 2021]

Neutrino fog:
the boundary is given by the exposure for which the scaling departs from the Poissonian expectation

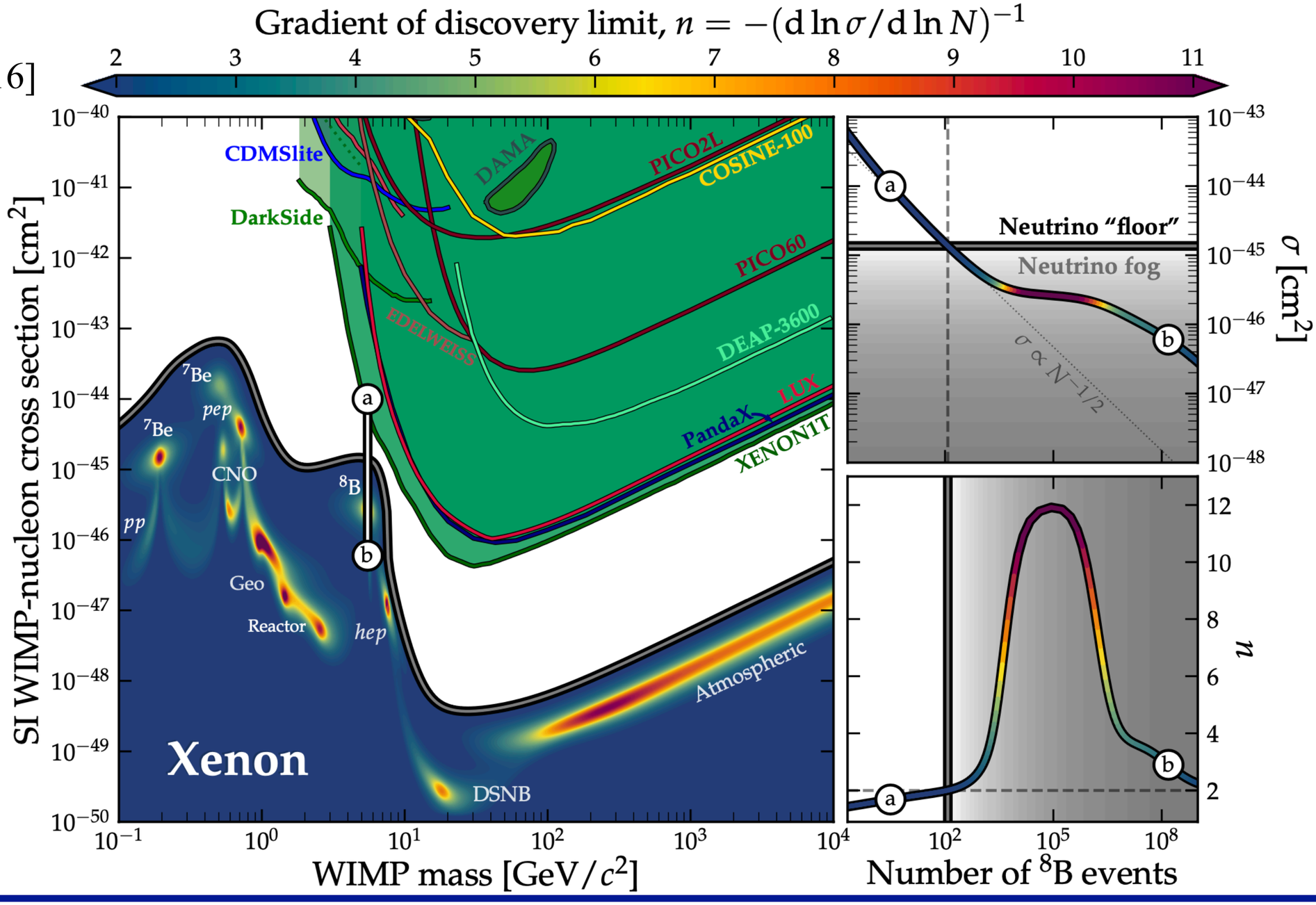
$$n = -\left(\frac{d\ln\sigma}{d\ln N}\right)^{-1}$$

$n = 2$: Poissonian scaling
$n > 2$: worse than Poissonian



The neutrino fog

[O'Hare 2109.03116]



Looking through the neutrino fog

Looking through the neutrino fog

If we want to

1. continue to search for DM into the neutrino fog

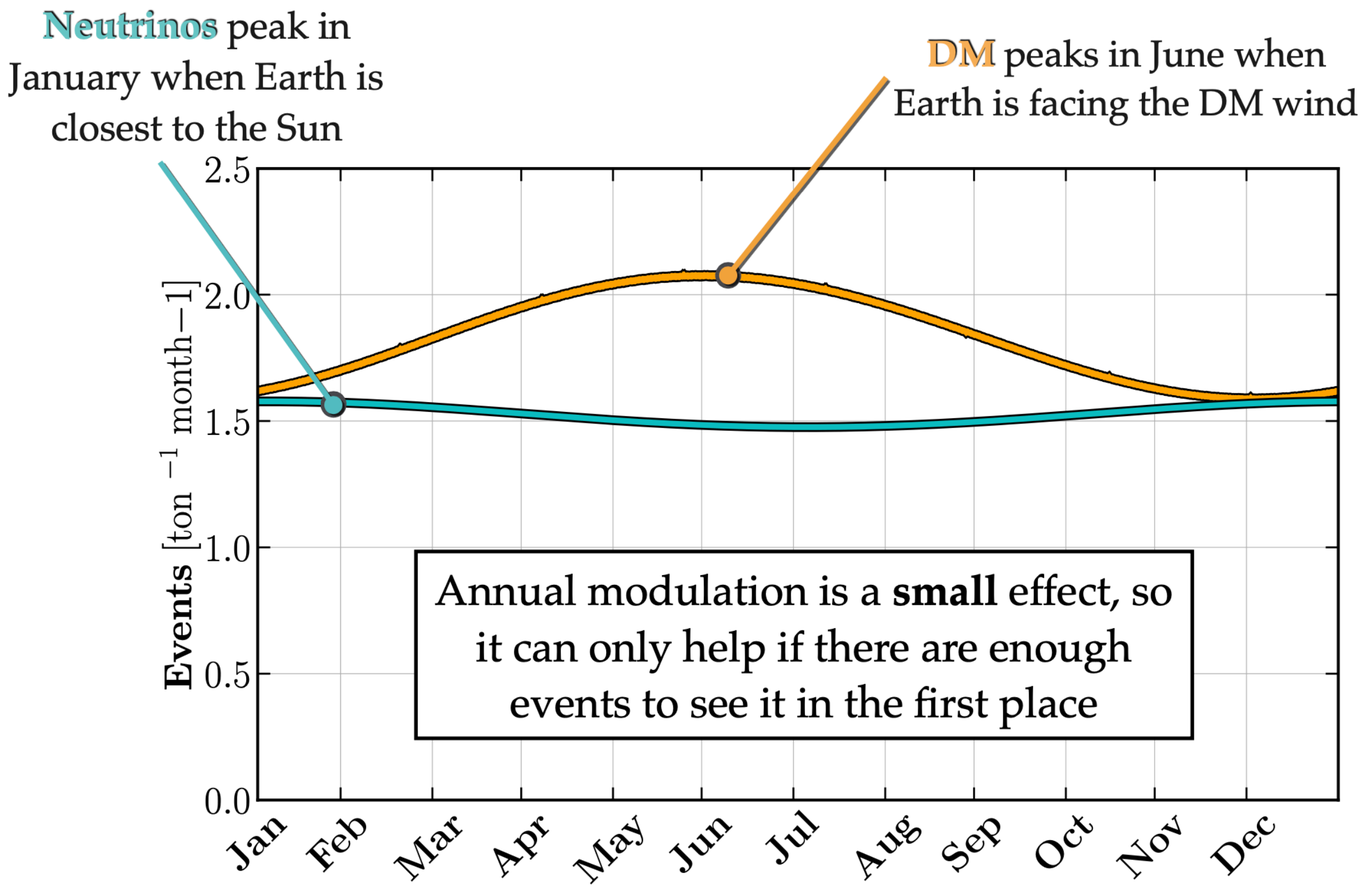
2. be able to study both DM and neutrino signals in direct detection experiments

we need strategies for dealing with the fog!

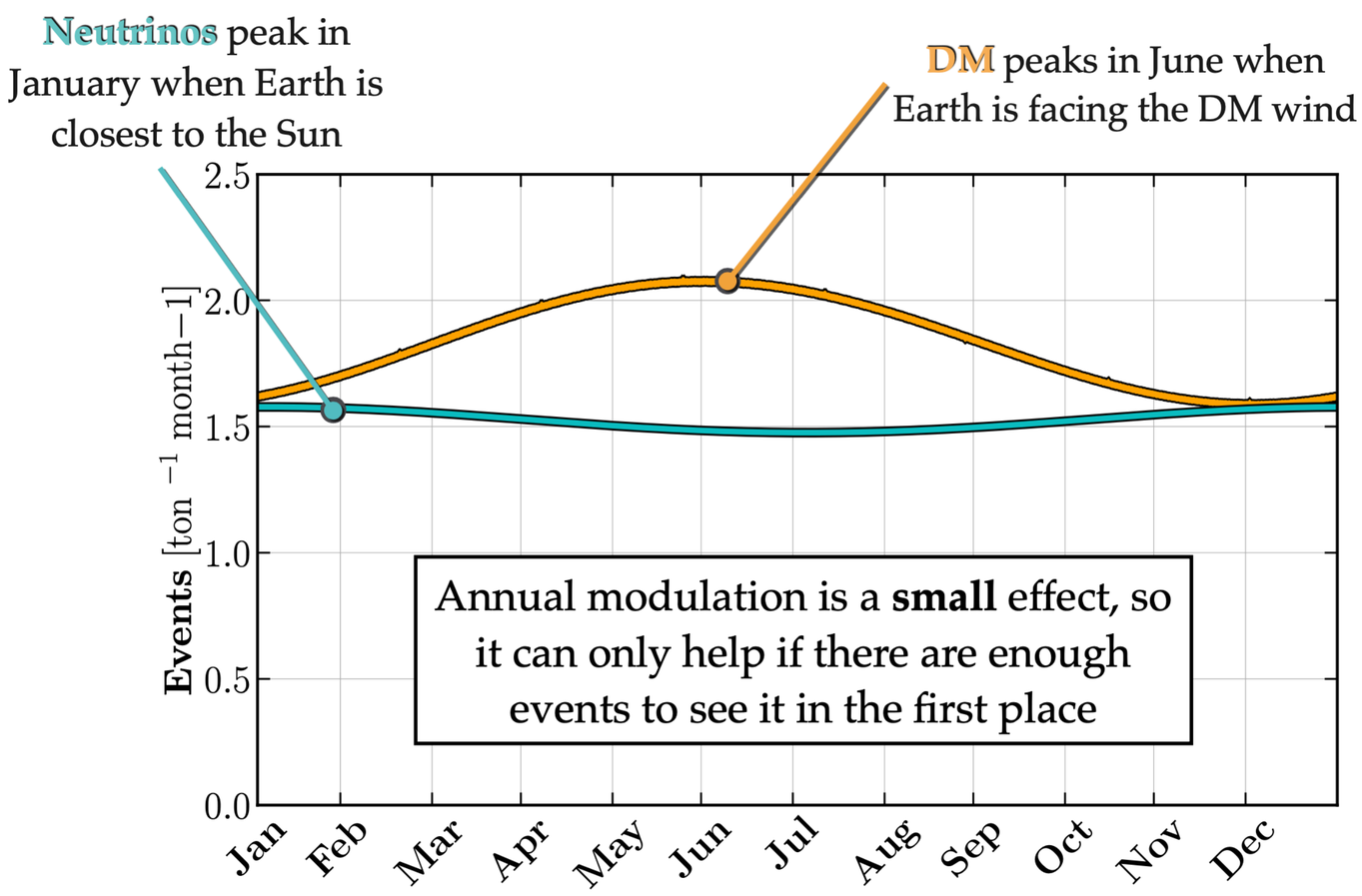
Strategies

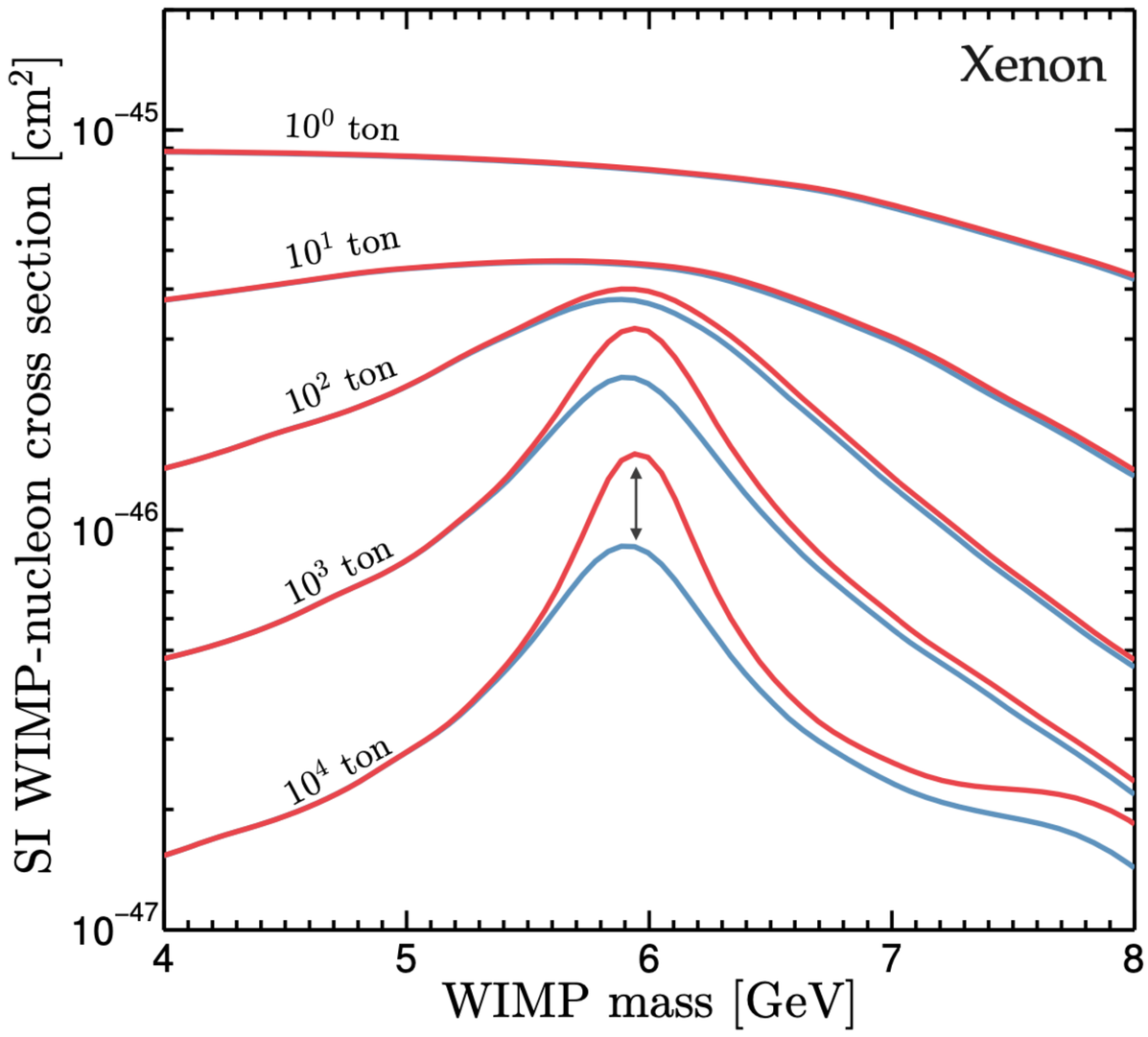
1. ~~Detect a lot of events~~
2. **Use annual modulation**
3. Improve the neutrino flux measurements
4. Target complementarity
5. Directional detectors

Annual modulation



Annual modulation

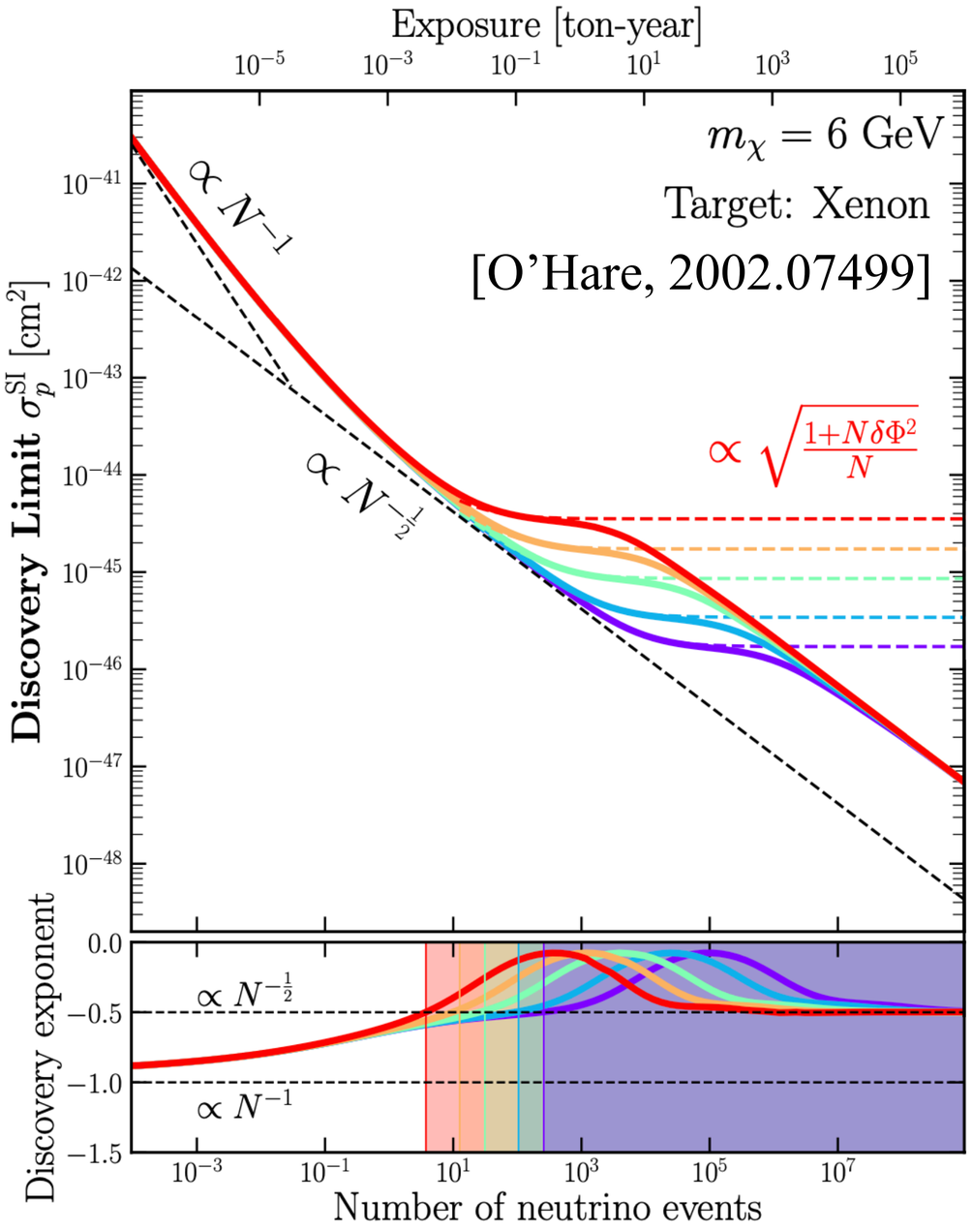




Strategies

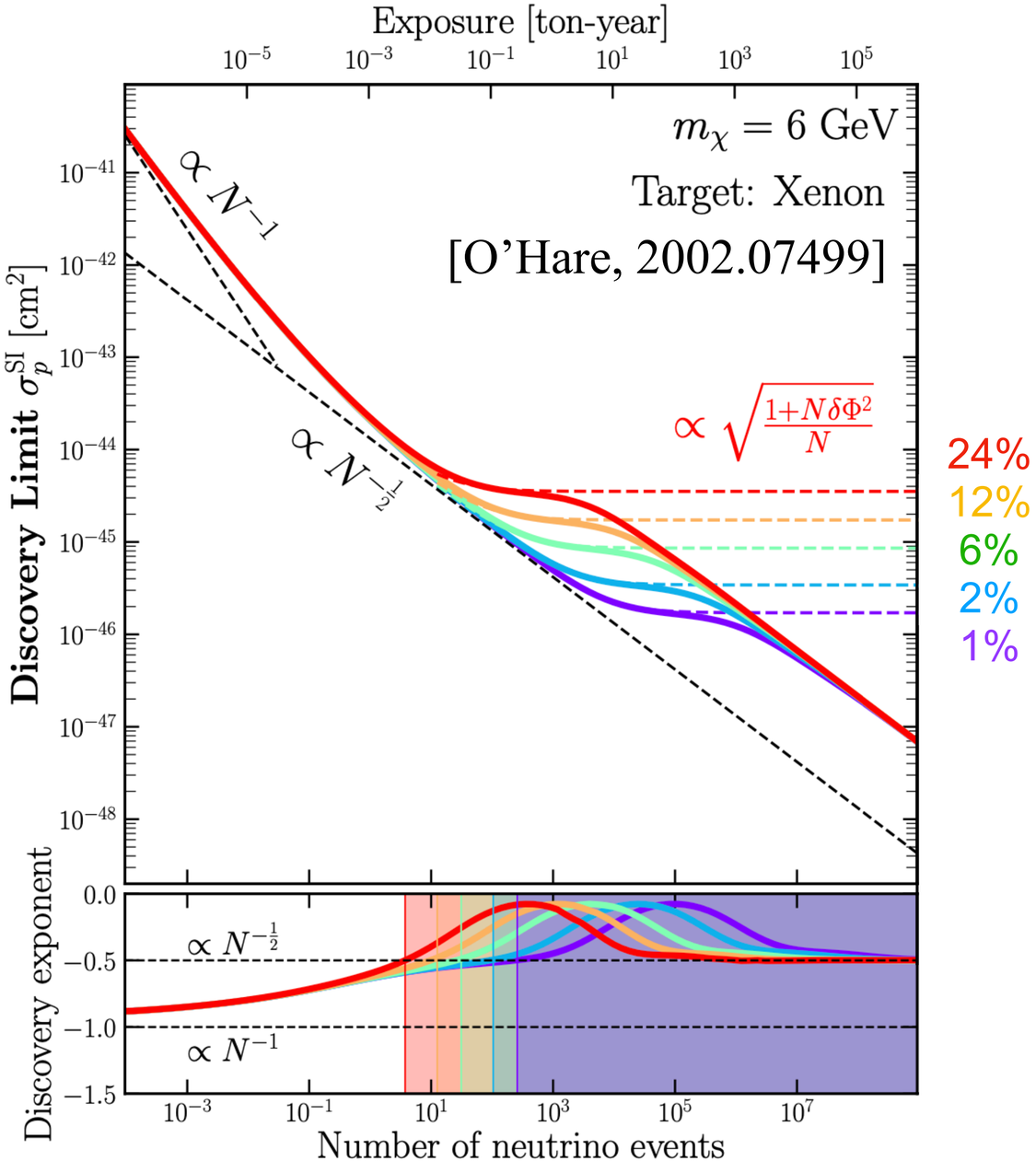
1. ~~Detect a lot of events~~
2. ~~Use annual modulation~~
3. **Improve the neutrino flux measurements**
4. Target complementarity
5. Directional detectors

Improve neutrino flux



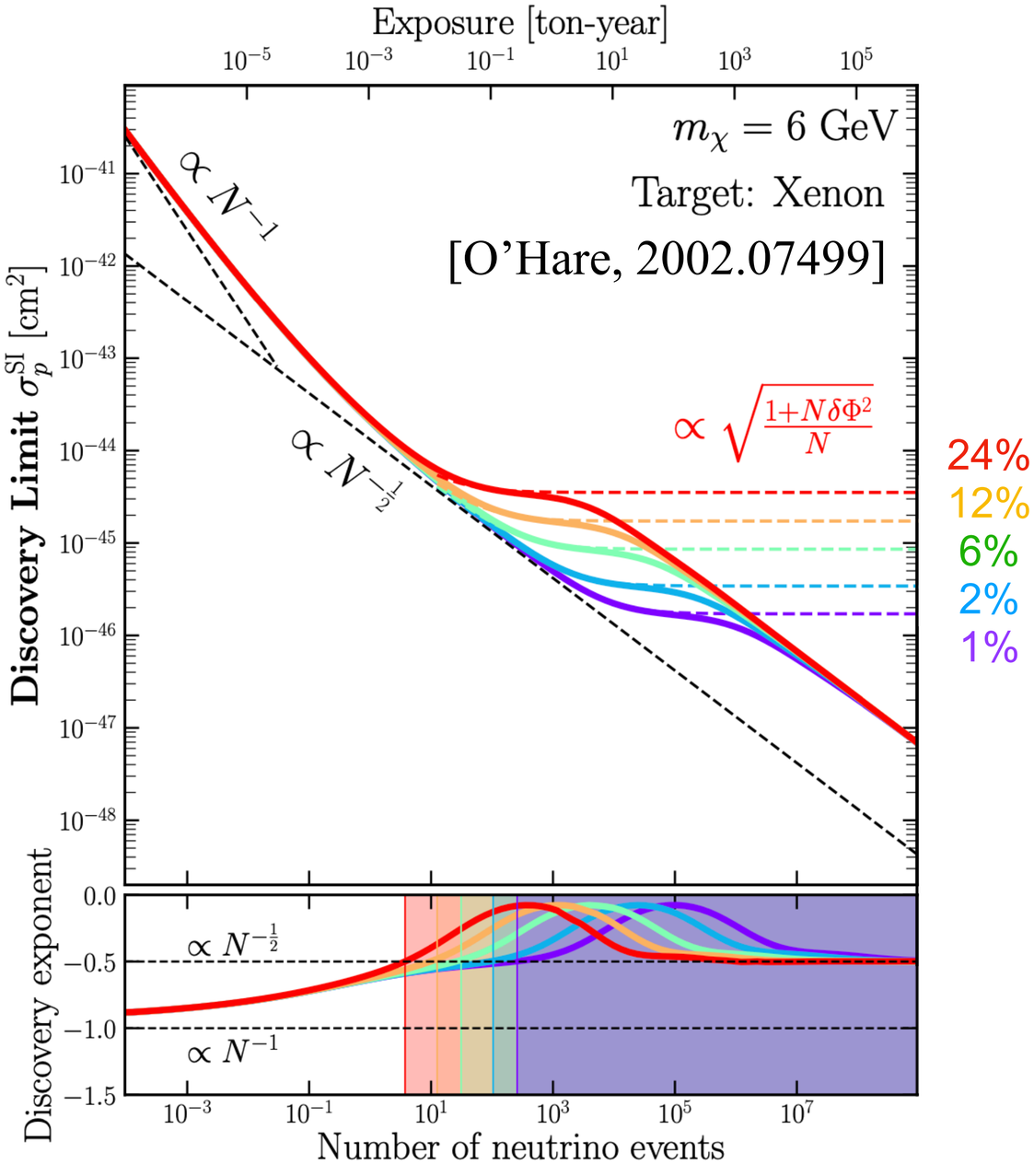
24%
12%
6%
2%
1%

Improve neutrino flux



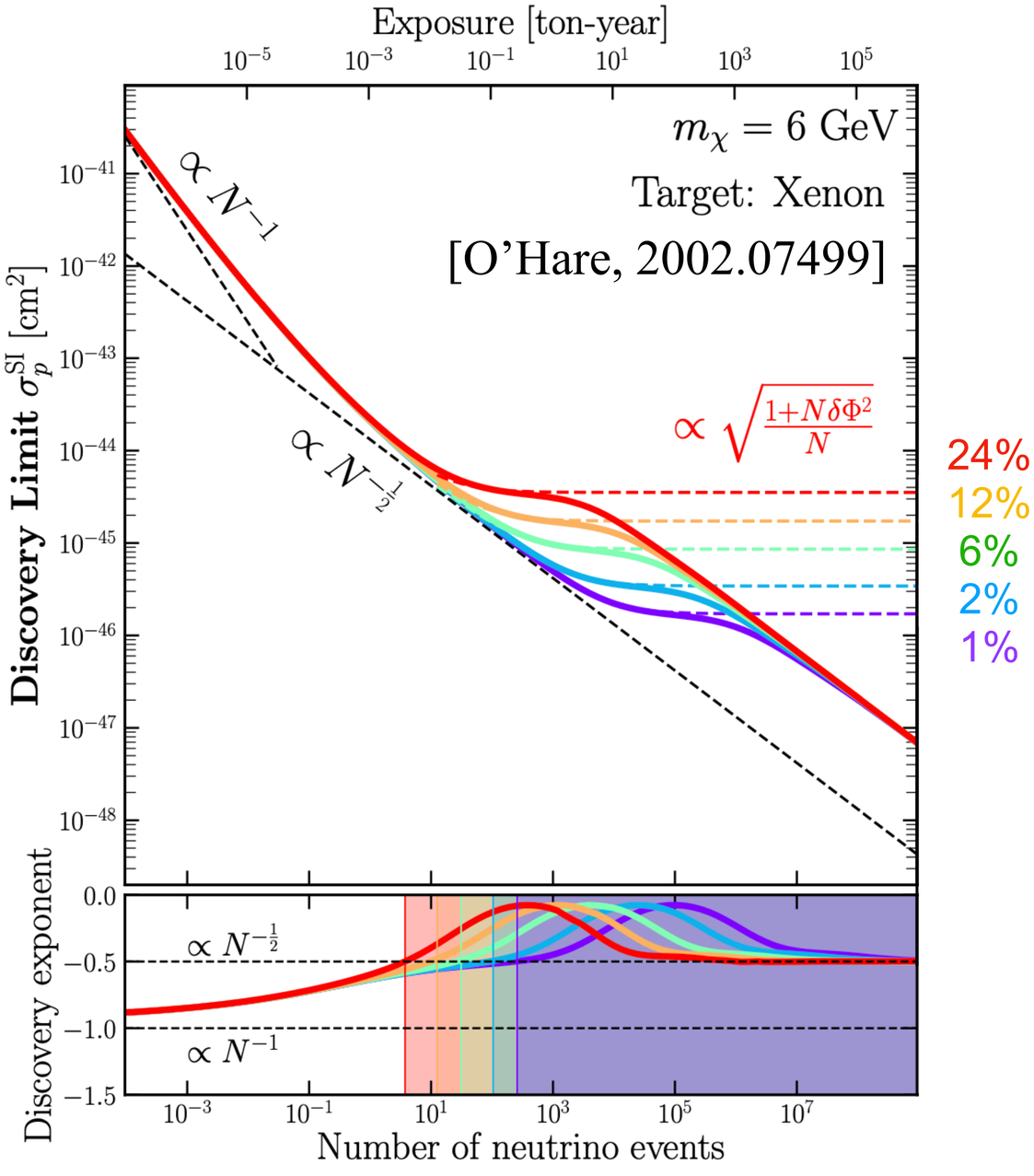
ν **type**		$\Phi(1 \pm \delta\Phi/\Phi)$ [cm^{-2} s^{-1}]	$\times 10^n$
Solar	*pp*	$5.98\,(1 \pm 0.006)$	10^{10}
	pep	$1.44\,(1 \pm 0.01)$	10^{8}
	hep	$7.98\,(1 \pm 0.30)$	10^{3}
	^{7}Be	$4.93\,(1 \pm 0.06)$	10^{8}
	^{7}Be	$4.50\,(1 \pm 0.06)$	10^{9}
	^{8}B	$5.16\,(1 \pm 0.02)$	10^{6}
	^{13}N	$2.78\,(1 \pm 0.15)$	10^{8}
	^{15}O	$2.05\,(1 \pm 0.17)$	10^{8}
	^{17}F	$5.29\,(1 \pm 0.20)$	10^{6}
Geo.	U	$4.34(1 \pm 0.20)$	10^{6}
	Th	$4.23(1 \pm 0.25)$	10^{6}
	K	$2.05(1 \pm 0.17)$	10^{7}
Reactor		$3.06(1 \pm 0.08)$	10^{6}
DSNB		$8.57(1 \pm 0.50)$	10^{1}
Atmospheric		$1.07(1 \pm 0.25)$	10^{1}

Improve neutrino flux



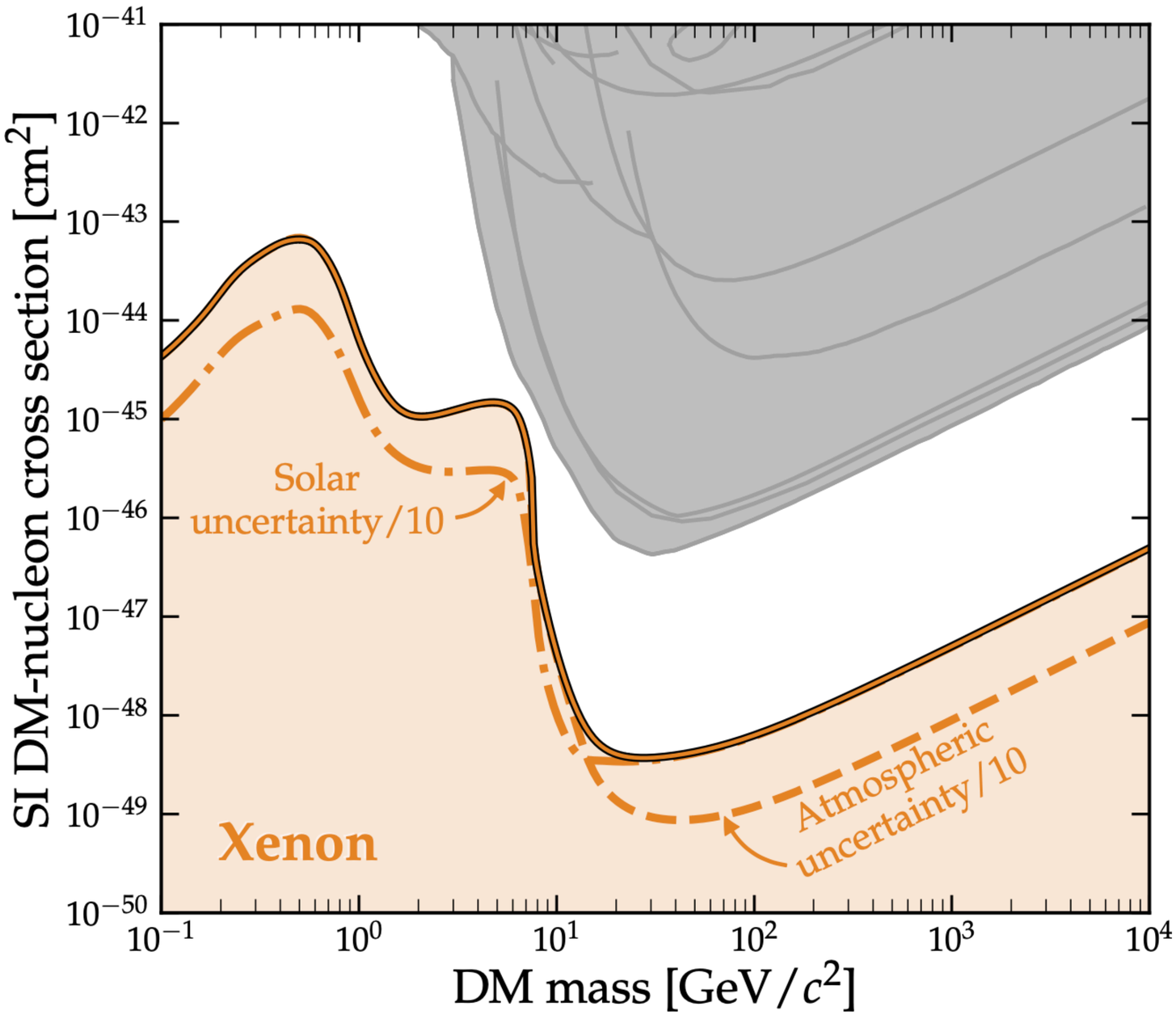
ν **type**		$\Phi(1 \pm \delta\Phi/\Phi)$ [cm^{-2} s^{-1}]	$\times 10^n$
Solar	*pp*	$5.98\,(1 \pm 0.006)$	10^{10}
	pep	$1.44\,(1 \pm 0.01)$	10^{8}
	hep	$7.98\,(1 \pm 0.30)$	10^{3}
	^{7}Be	$4.93\,(1 \pm 0.06)$	10^{8}
	^{7}Be	$4.50\,(1 \pm 0.06)$	10^{9}
	^{8}B	$5.16\,(1 \pm 0.02)$	10^{6}
	^{13}N	$2.78\,(1 \pm 0.15)$	10^{8}
	^{15}O	$2.05\,(1 \pm 0.17)$	10^{8}
	^{17}F	$5.29\,(1 \pm 0.20)$	10^{6}
Geo.	U	$4.34(1 \pm 0.20)$	10^{6}
	Th	$4.23(1 \pm 0.25)$	10^{6}
	K	$2.05(1 \pm 0.17)$	10^{7}
Reactor		$3.06(1 \pm 0.08)$	10^{6}
DSNB		$8.57(1 \pm 0.50)$	10^{1}
Atmospheric		$1.07(1 \pm 0.25)$	10^{1}

Improve neutrino flux



ν **type**		$\Phi(1 \pm \delta\Phi/\Phi)$ [cm^{-2} s^{-1}]	$\times 10^n$
Solar	*pp*	$5.98\,(1 \pm 0.006)$	10^{10}
	pep	$1.44\,(1 \pm 0.01)$	10^{8}
	hep	$7.98\,(1 \pm 0.30)$	10^{3}
	^{7}Be	$4.93\,(1 \pm 0.06)$	10^{8}
	^{7}Be	$4.50\,(1 \pm 0.06)$	10^{9}
	^{8}B	$5.16\,(1 \pm 0.02)$	10^{6}
	^{13}N	$2.78\,(1 \pm 0.15)$	10^{8}
	^{15}O	$2.05\,(1 \pm 0.17)$	10^{8}
	^{17}F	$5.29\,(1 \pm 0.20)$	10^{6}
Geo.	U	$4.34(1 \pm 0.20)$	10^{6}
	Th	$4.23(1 \pm 0.25)$	10^{6}
	K	$2.05(1 \pm 0.17)$	10^{7}
Reactor		$3.06(1 \pm 0.08)$	10^{6}
DSNB		$8.57(1 \pm 0.50)$	10^{1}
Atmospheric		$1.07(1 \pm 0.25)$	10^{1}

Improve neutrino flux



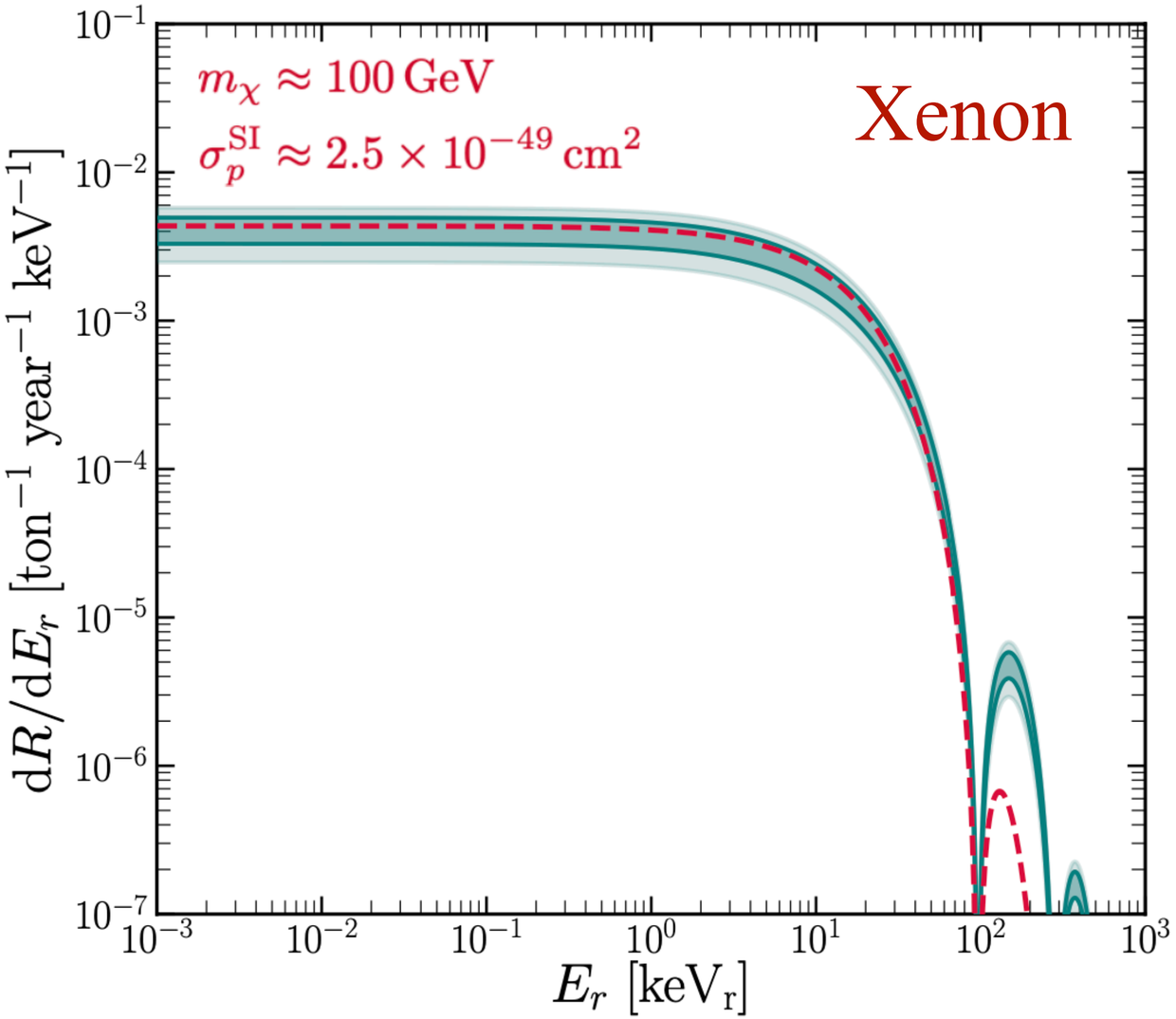
[O'Hare, 2002.07499]

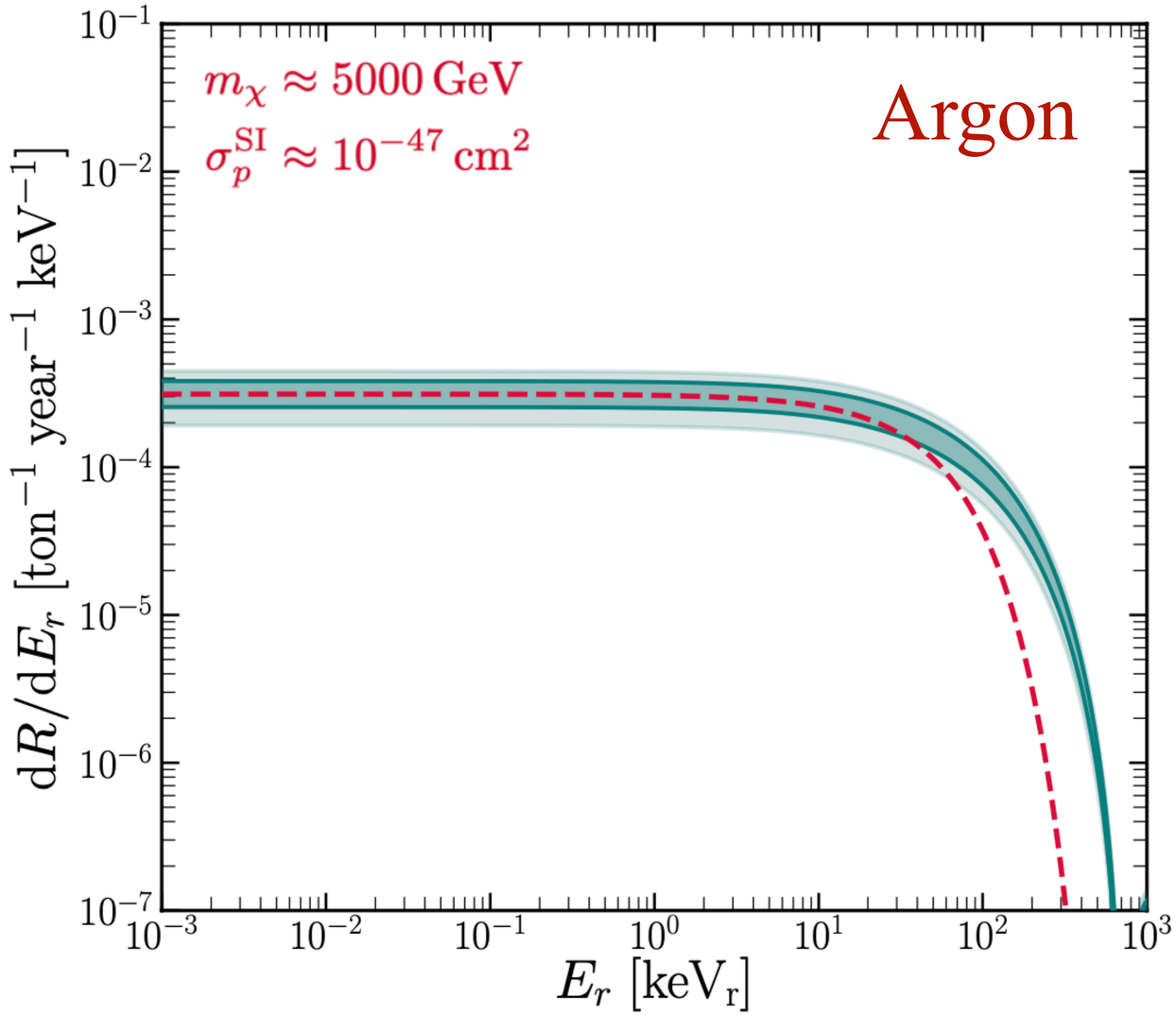
Strategies

1. ~~Detect a lot of events~~
2. ~~Use annual modulation~~
3. ~~Improve the neutrino flux measurements~~
4. **Target complementarity**
5. Directional detectors

Target complementarity

Heavy spin independent DM vs atmospheric neutrinos

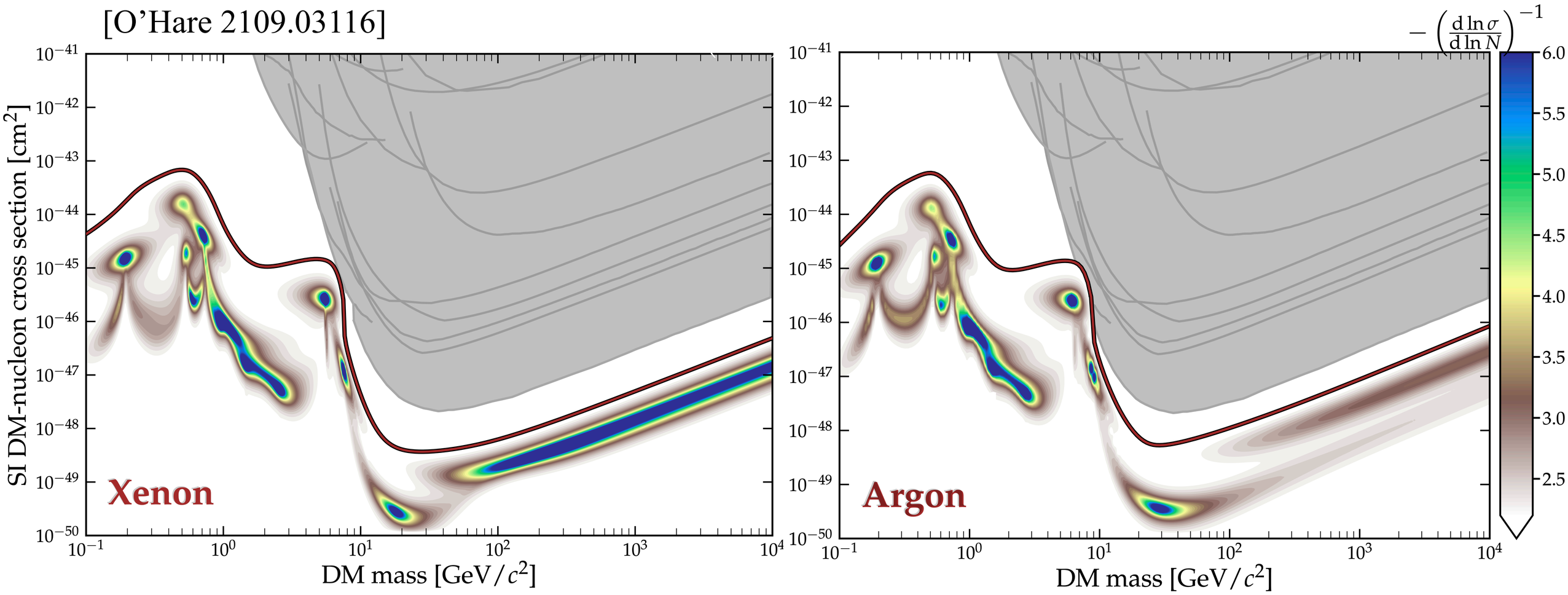




Target complementarity

Heavy spin independent DM vs atmospheric neutrinos

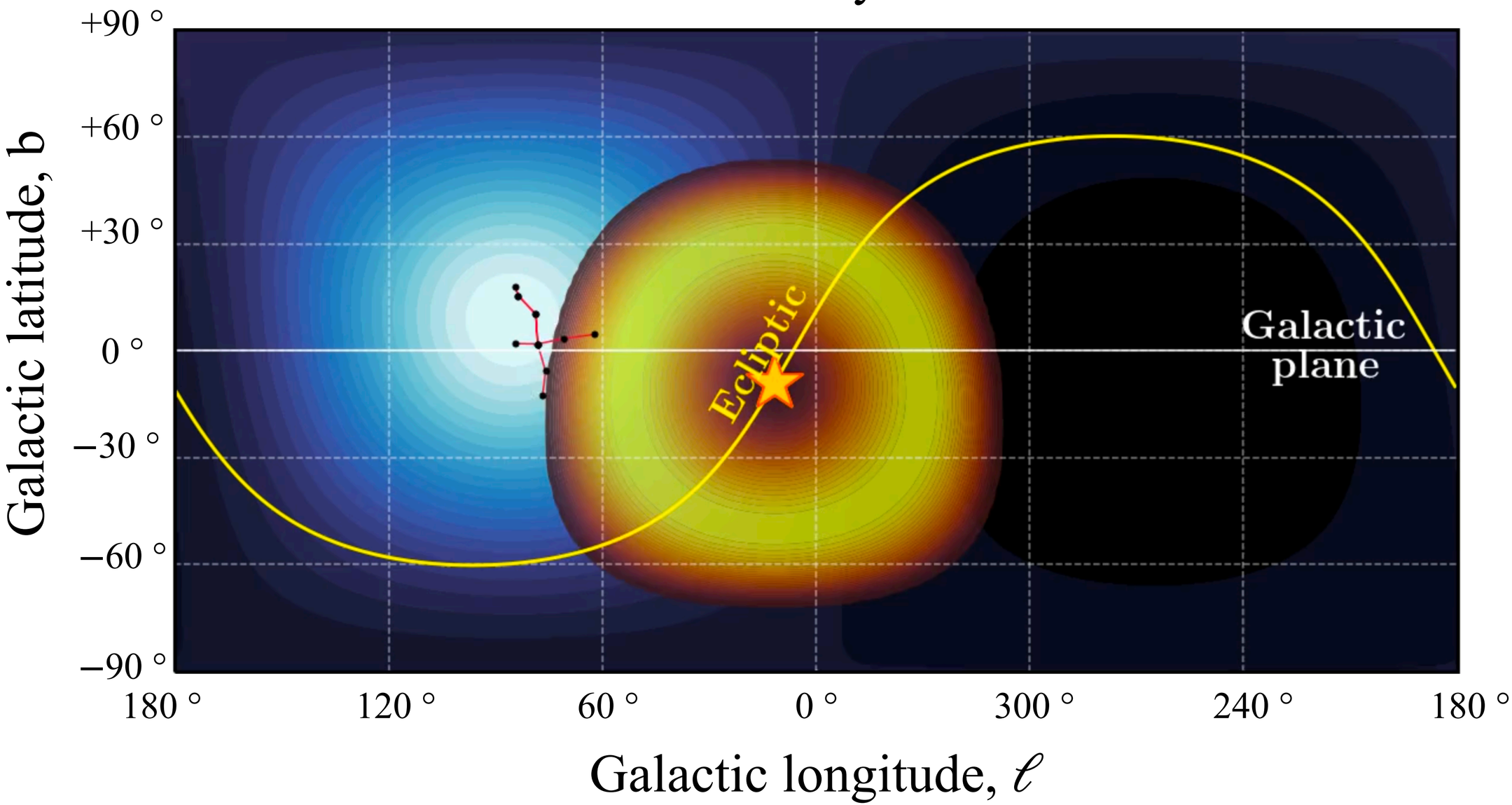
[O'Hare 2109.03116]



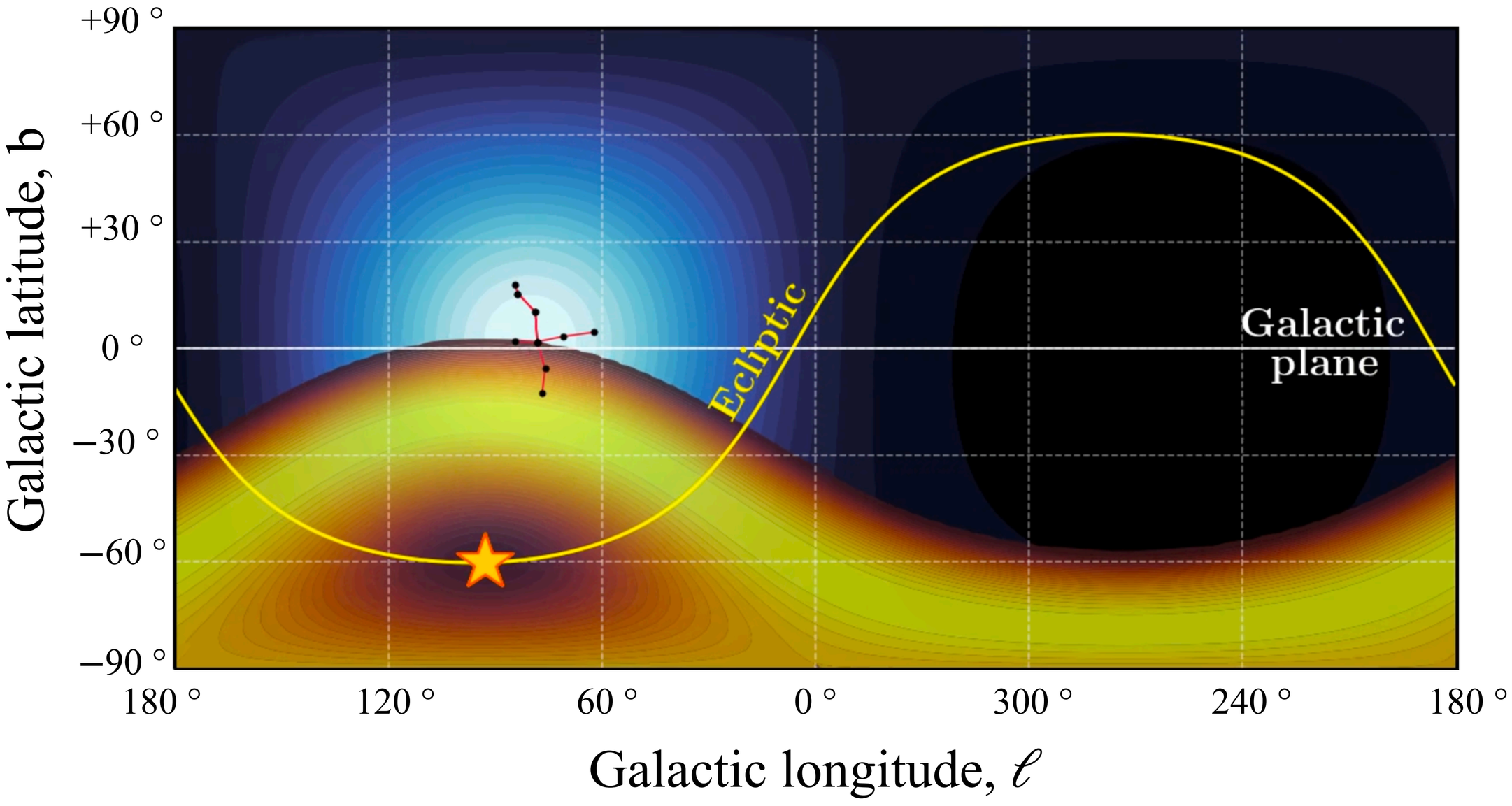
Strategies

1. ~~Detect a lot of events~~
2. ~~Use annual modulation~~
3. ~~Improve the neutrino flux measurements~~
4. ~~Target complementarity~~
5. **Directional detectors**

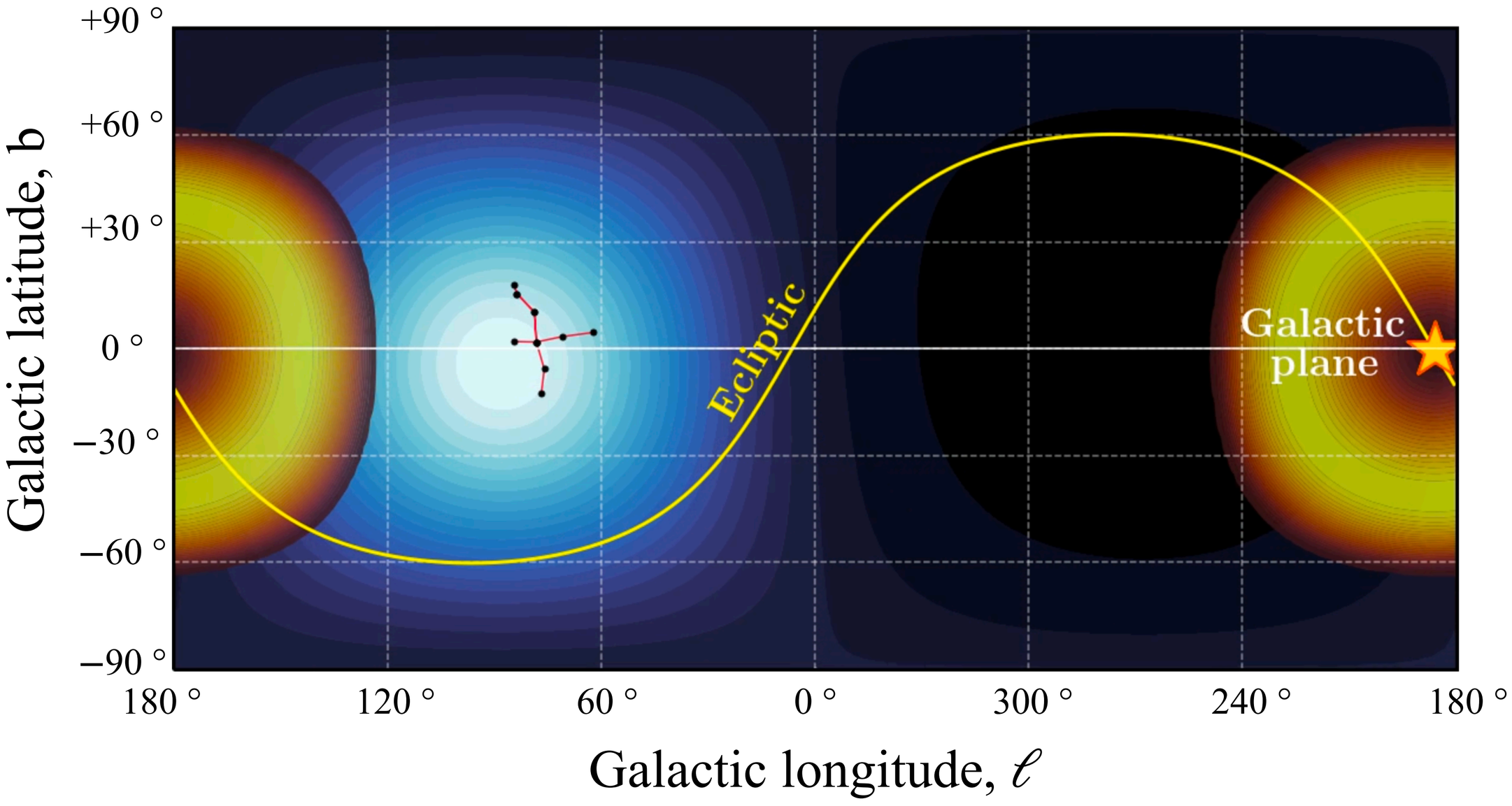
Directional detectors



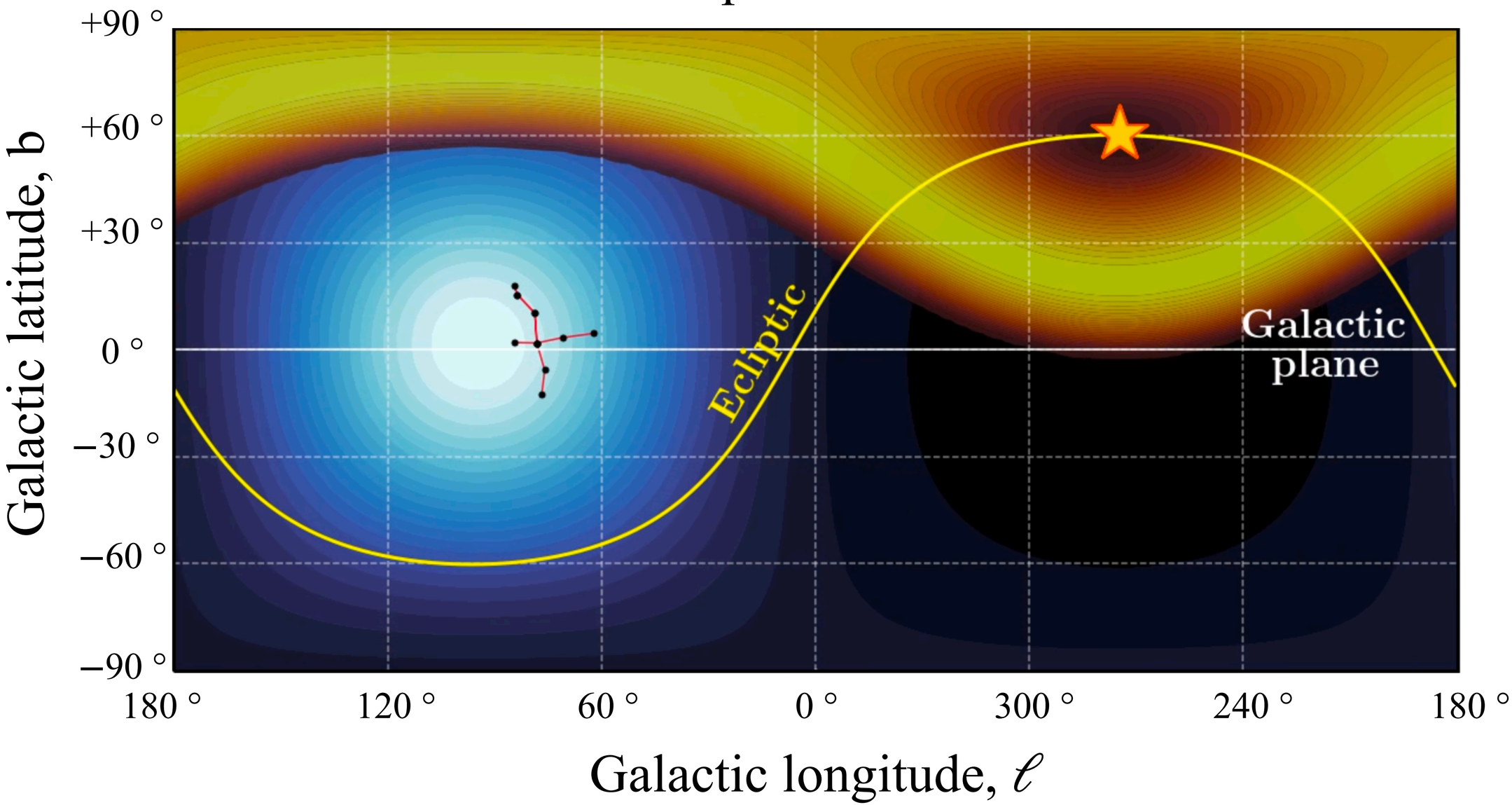
Directional detectors



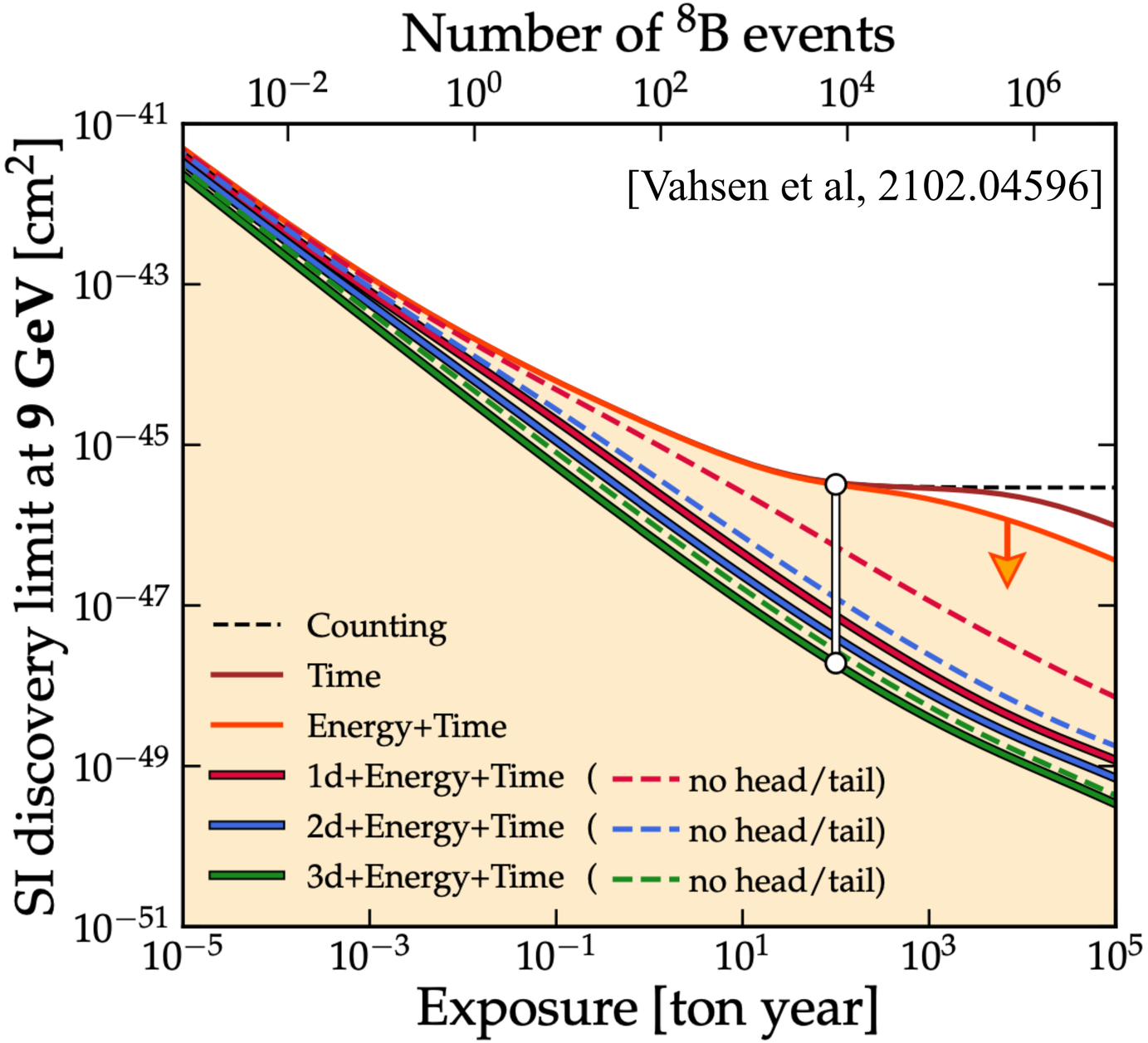
Directional detectors



Directional detectors

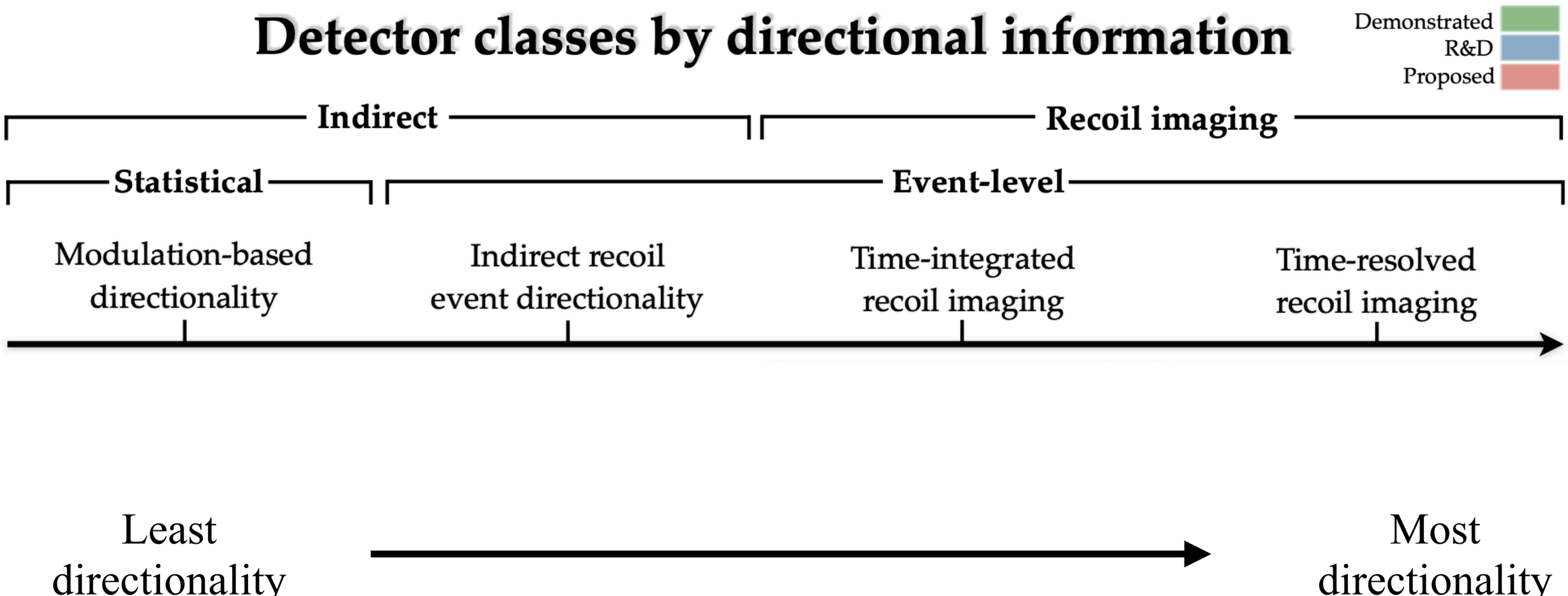


Directional detectors



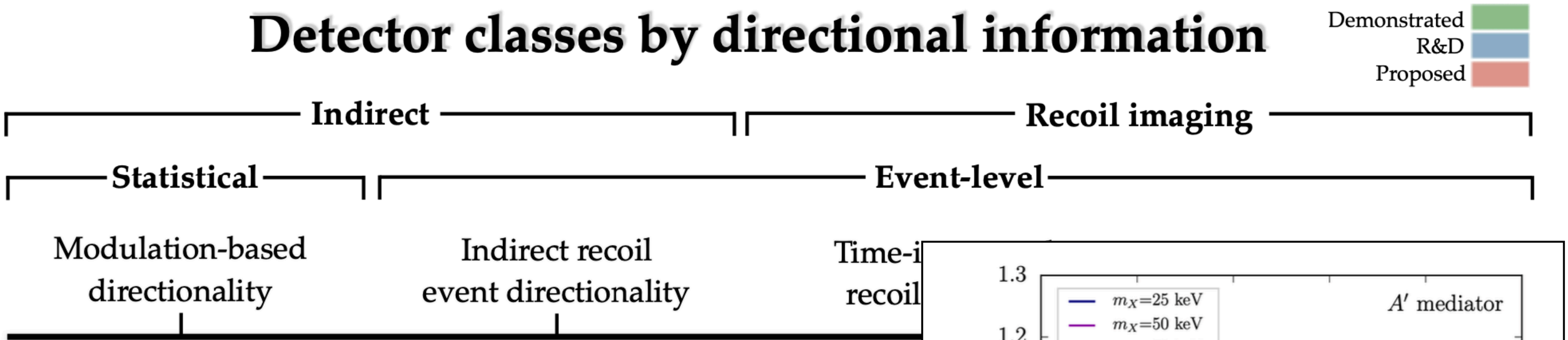
Directional detectors

[Vahsen et al, 2102.04596]

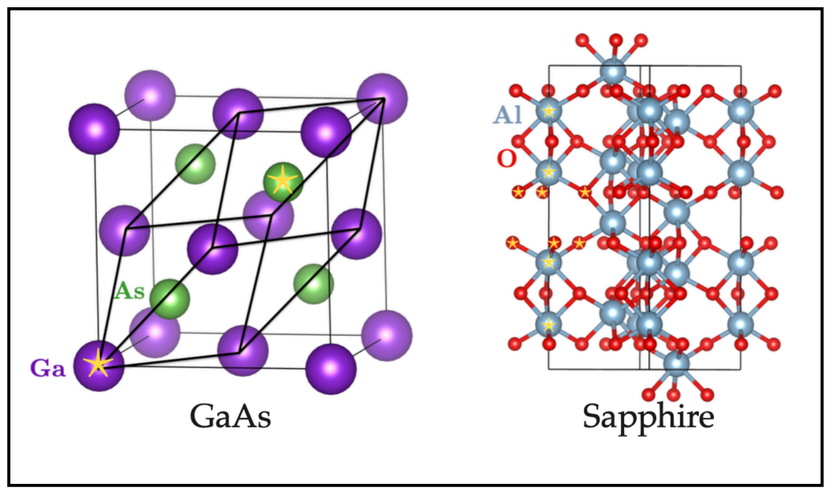


Directional detectors

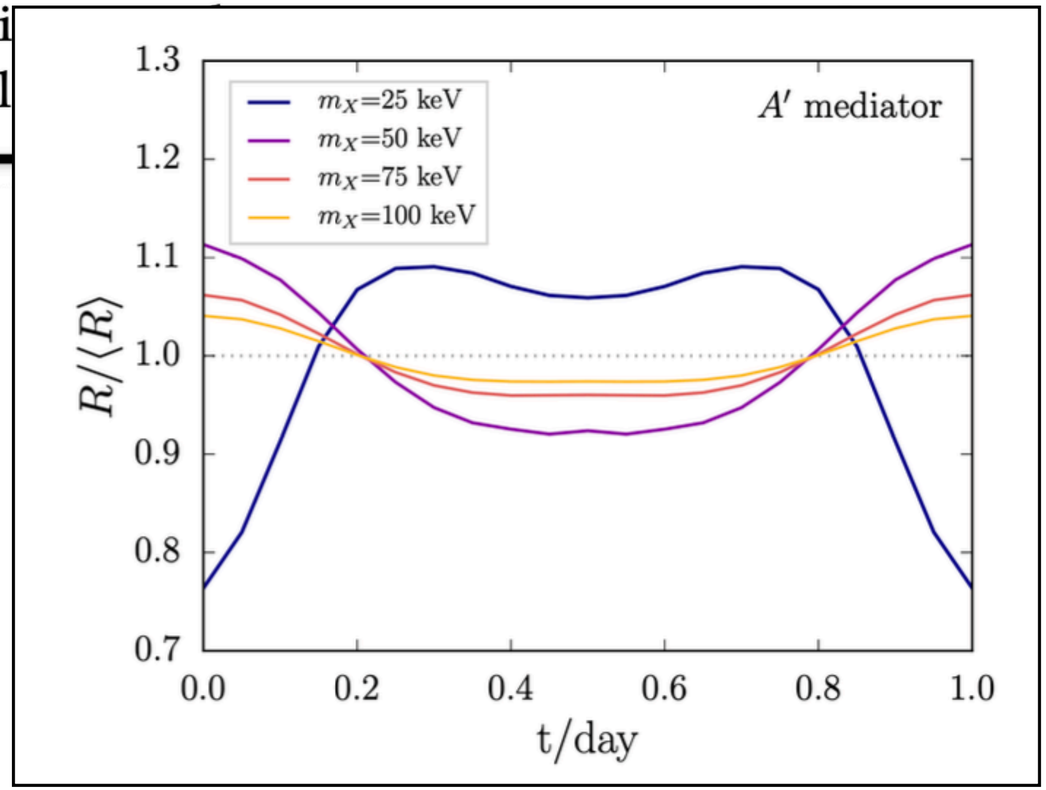
[Vahsen et al, 2102.04596]



Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

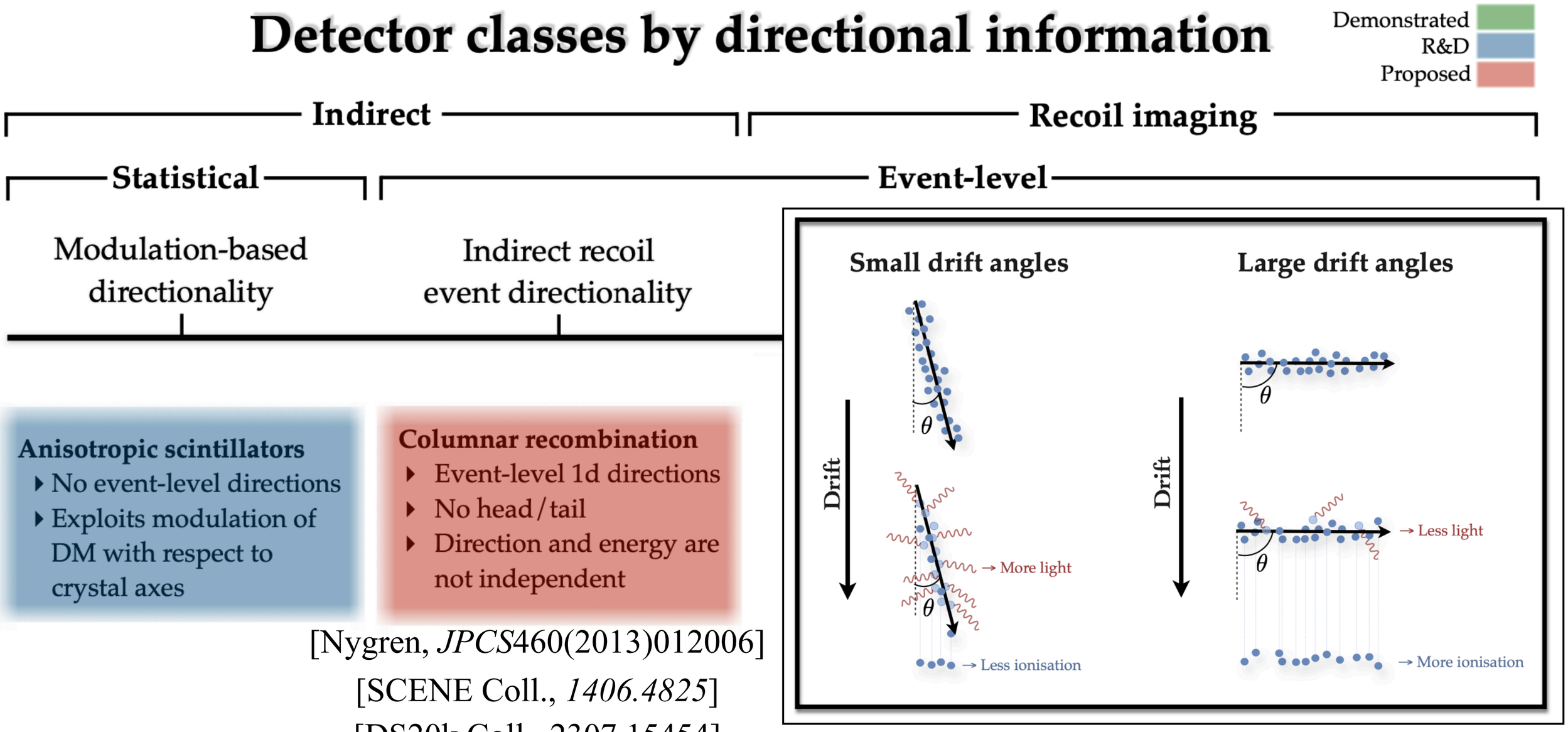


[Griffin et al, 1807.10291]



Directional detectors

[Vahsen et al, 2102.04596]



[Nygren, *JPCS*460(2013)012006]

[SCENE Coll., *1406.4825*]

[DS20k Coll., 2307.15454]

Directional detectors

[Vahsen et al, 2102.04596]

Detector classes by directional information

Demonstrated
R&D
Proposed

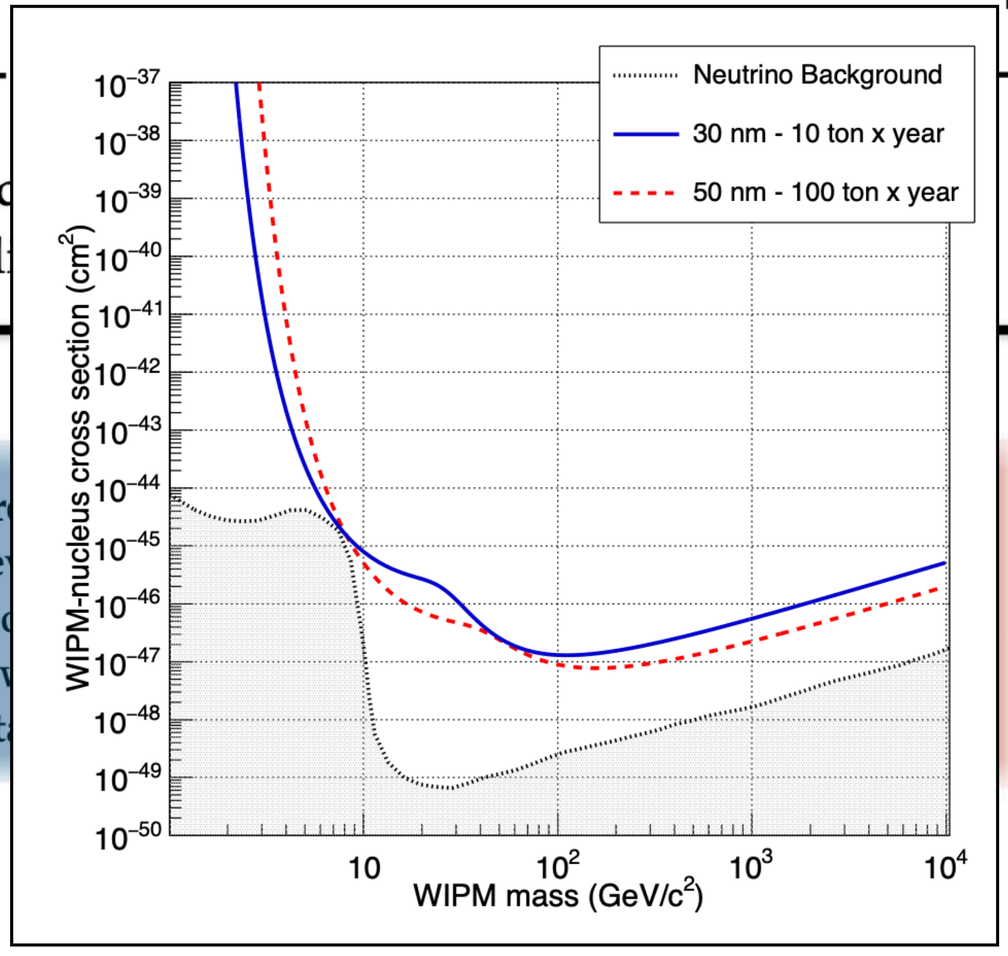
Indirect

Recoil imaging

Event-level

Time-integrated recoil imaging

Time-resolved recoil imaging



Anisotr
- No e
- Explo DM w cryst

Nuclear emulsions
- 2d recoil tracks, without head/tail
- No event times recorded

[NEWS-dm, 1705.00613]

Directional detectors

[Vahsen et al, 2102.04596]

Detector classes by directional information

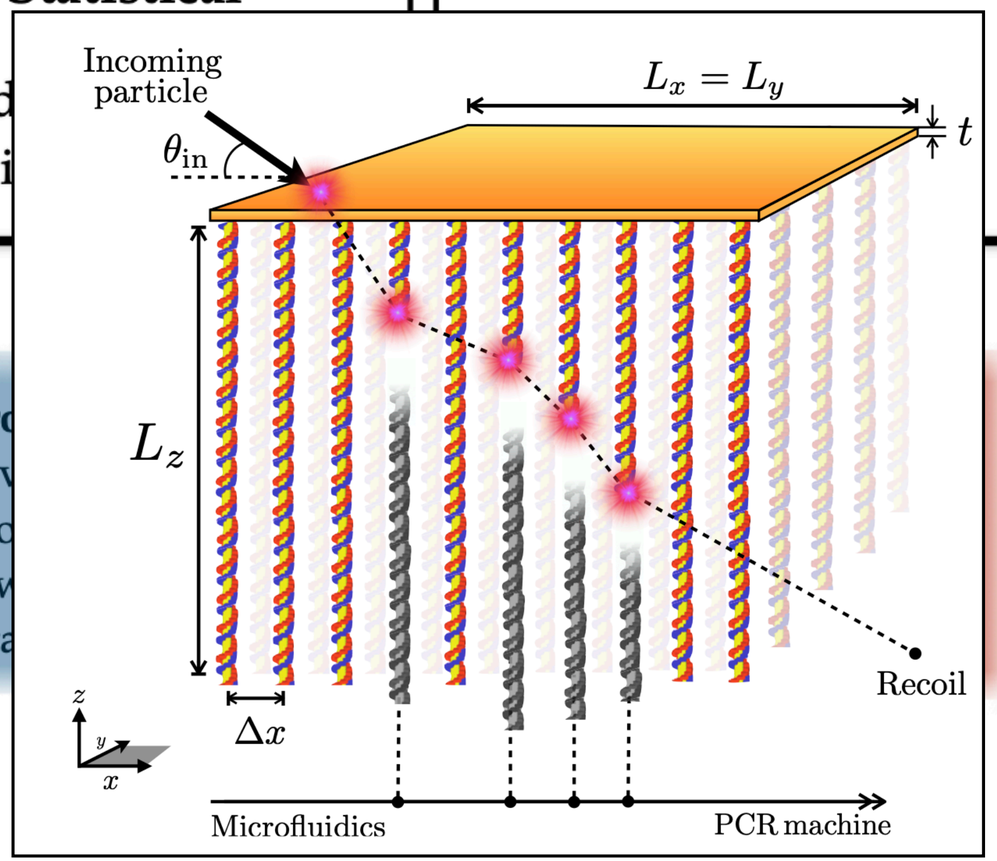
Demonstrated
R&D
Proposed

Indirect

Statistical

Mod
di

Anisotro
- No ev
- Explo
DM w
crysta



Recoil imaging

Event-level

Time-integrated recoil imaging

Time-resolved recoil imaging

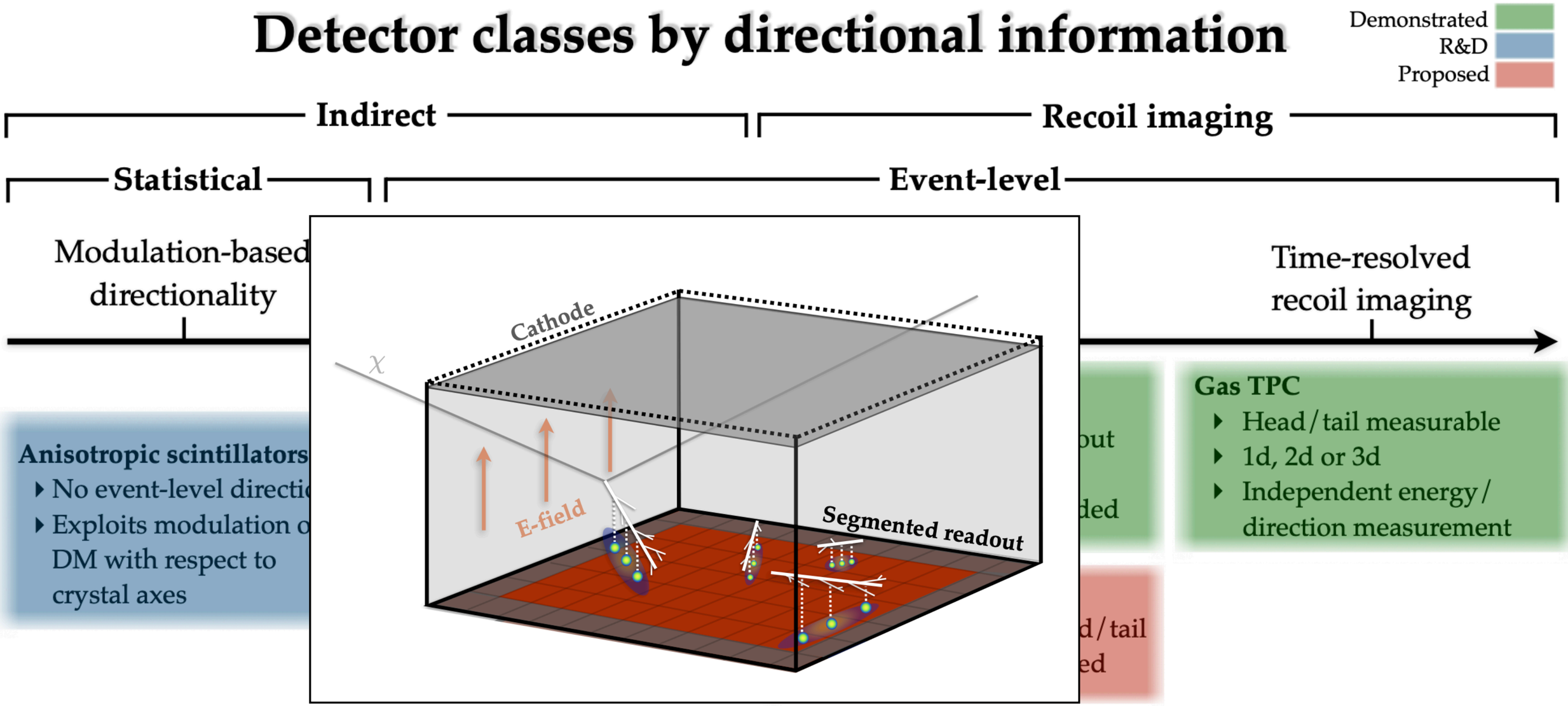
Nuclear emulsions
- 2d recoil tracks, without head/tail
- No event times recorded

DNA detector
- 3d recoils without head/tail
- No event times recorded

[Drukier et al, 1206.6809]

Directional detectors

[Vahsen et al, 2102.04596]



Directional detectors

[Vahsen et al, 2102.04596]

Detector classes by directional information

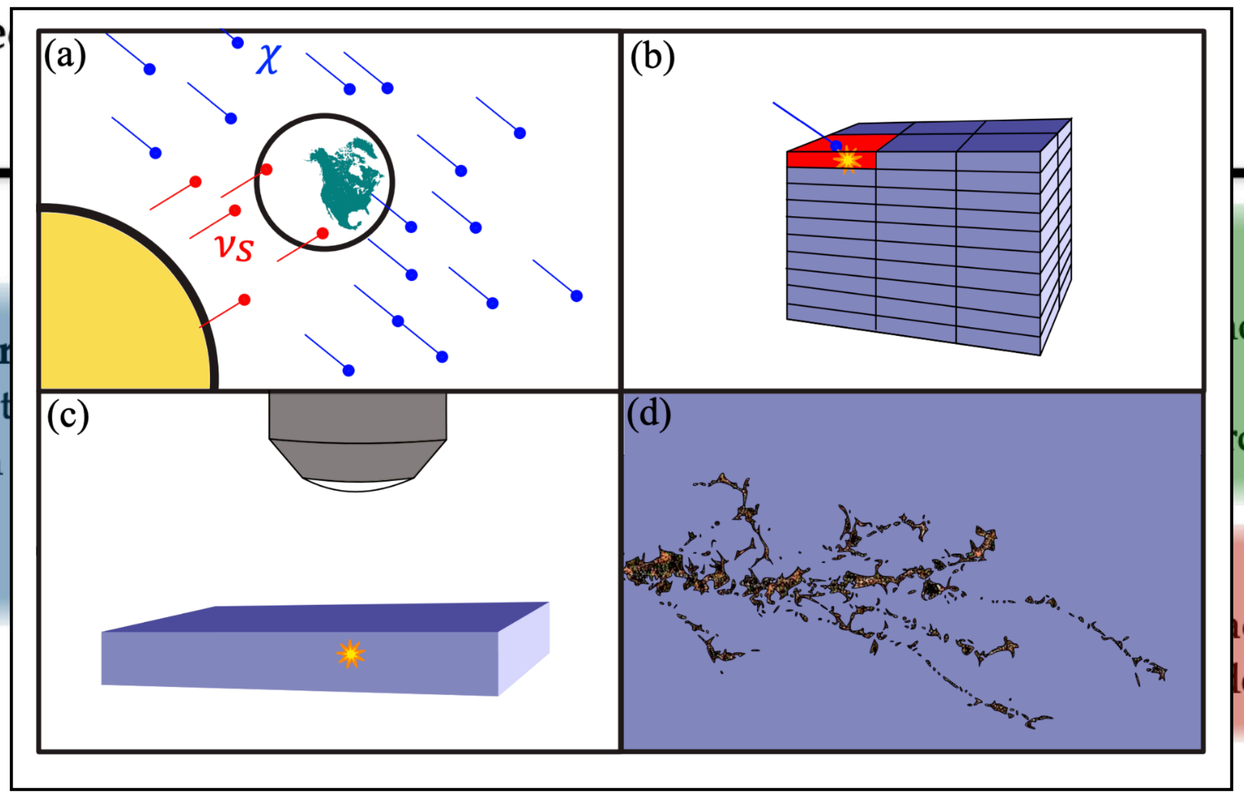
Demonstrated
R&D
Proposed

Indirect | **Recoil imaging**

Statistical | **Event-level**

Modulation-base directionality

Time-resolved recoil imaging



Anisotropic scintillator
- No event-level direct
- Exploits modulation DM with respect to crystal axes

Gas TPC
- Head / tail measurable
- 1d, 2d or 3d
- Independent energy / direction measurement

Crystal defects
- 3d track topology
- Head / tail measurable

[Marshall et al, 2009.01028]

Conclusions

Conclusions

- There is no neutrino floor, just a (sometimes thick) fog.

- Already approaching the neutrino fog, first measurements already published (XENONnt, PandaX), limiting the sensitivity to DM of direct detection experiments.

- Slight improvement from neutrino flux measurement and target complementarity

- Best option: directional detection!

- Several strategies theoretically feasible, some demonstrated already (Cygno, NEWSdm)