Dark Matter Detectors and Neutrinos

Malcolm Fairbairn

Content

- Directional dark matter to bypass the neutrino bound

- Polarised detectors and directional neutrino sensitivity

- BSM physics from neutrino interactions at DM detectors

Directional Dark Matter Detection Beyond the Neutrino Bound
Grothaus, Fairbairn & Monroe - arXiv:1406.5047
Reducing the Solar Neutrino Background Using Polarised Helium-3
Franarin, Fairbairn - arXiv:1605.08727
Physics from solar neutrinos in dark matter direct detection experiments
Cerdeño, Fairbairn, Jubb, Machado, Vincent & Bœhm - arXiv:1604.01025

Philosophy

- Understand and quantify problem of neutrino background

- Estimate the size of detectors required to fight the problem

- Try to come up with new ideas/technologies to bypass background

- Can we come up with ideas for viable detectors?

YES   *NO*
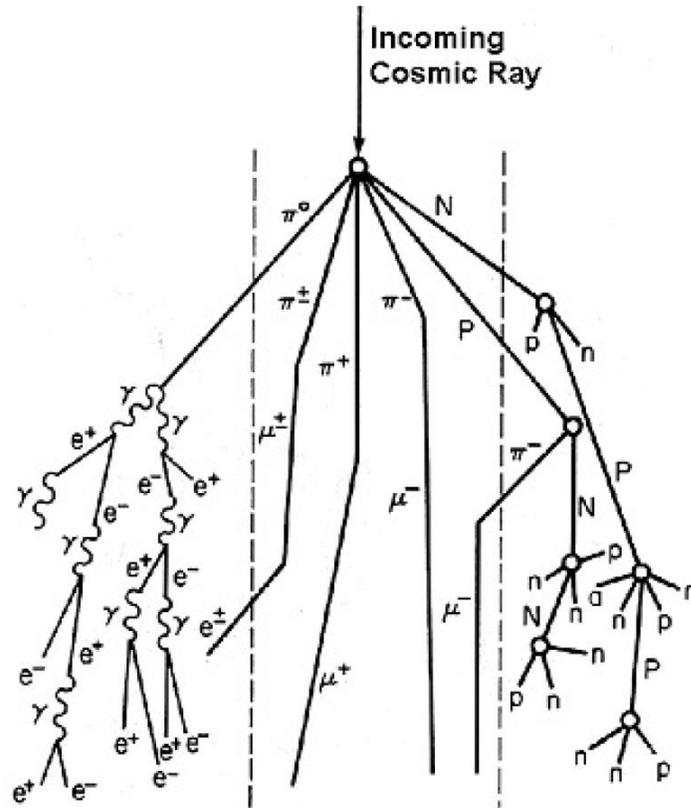
OK, should we build them?   *NO*   end of direct detection - BORING

YES

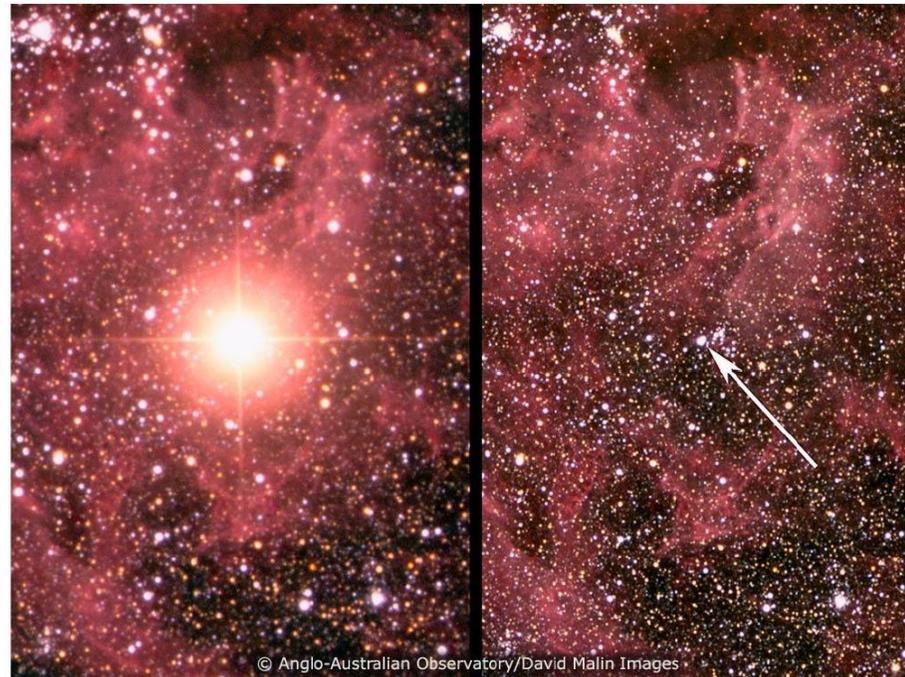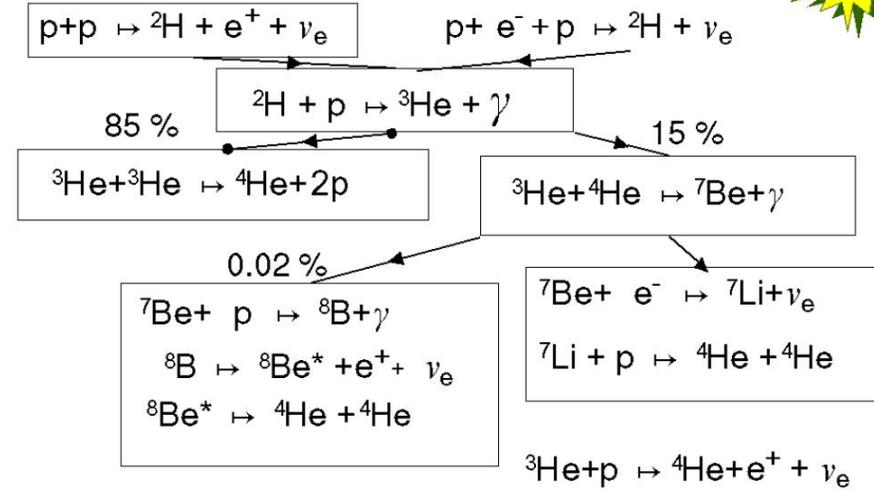- Can we do any neutrino/solar physics along the way -DEFINITELY!!!

Astrophysical Neutrino Sources

KEY

P	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

The nuclear reactions in the Sun generate a numerous amount of electron neutrinos. While the total number of neutrinos can be calculated very accurately, their energy spectrum contains more uncertainties. The following picture shows the principal energy producing reaction chains:
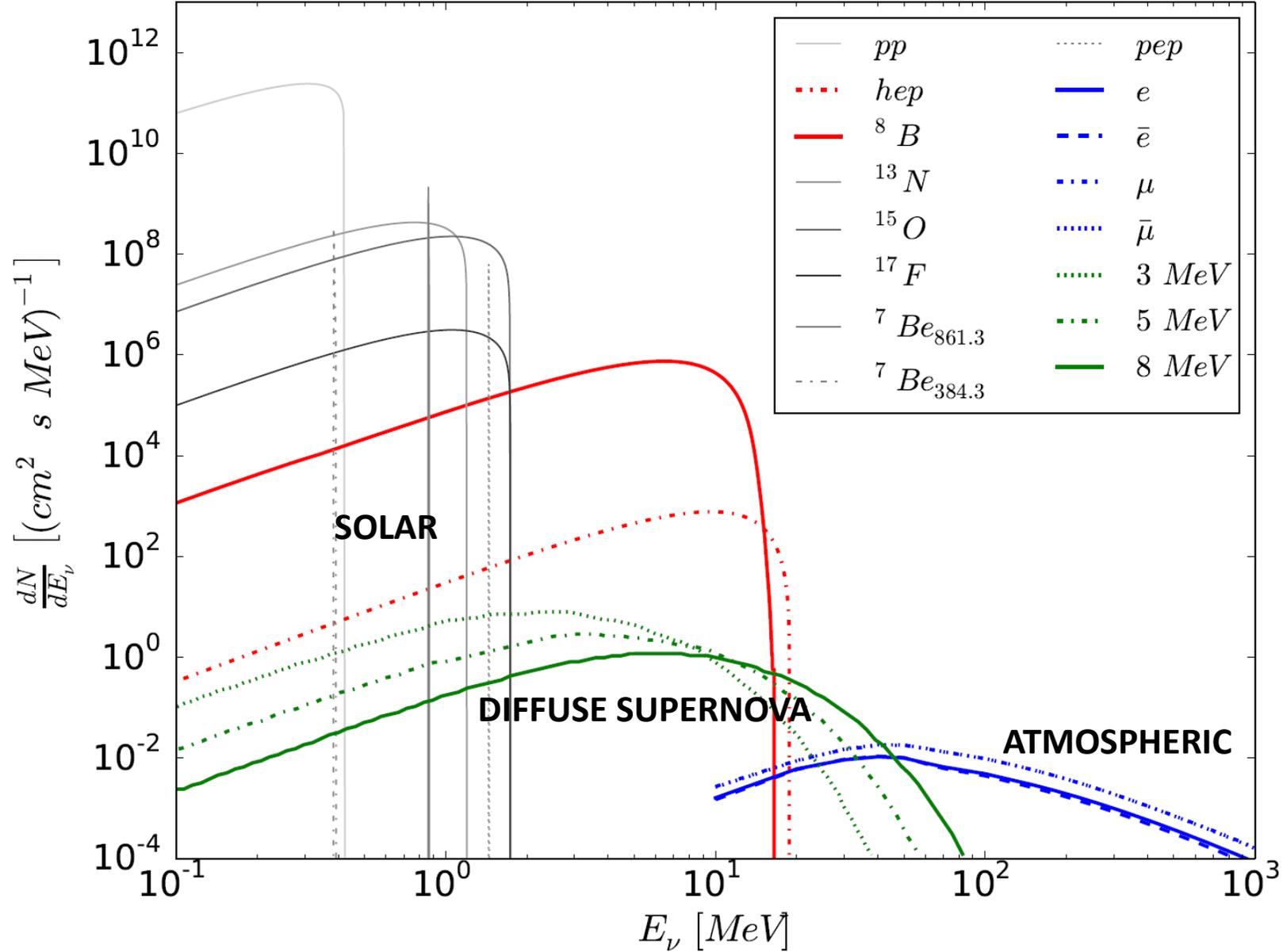
$$p+p \mapsto {}^2H + e^+ + \nu_e \qquad p+ e^- +p \mapsto {}^2H + \nu_e$$

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

85 % 15 %

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

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

0.02 %

$$^7Be + p \mapsto {}^8B + \gamma$$
$$^8B \mapsto {}^8Be^* + e^+ + \nu_e$$
$$^8Be^* \mapsto {}^4He + {}^4He$$

$$^7Be + e^- \mapsto {}^7Li + \nu_e$$
$$^7Li + p \mapsto {}^4He + {}^4He$$

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

© Anglo-Australian Observatory/David Malin Images

Neutrino Background

Coherent Neutrino-Nucleon Interactions

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1 + \cos\theta) F(Q^2)^2$$

o Enhanced by factor N^2:

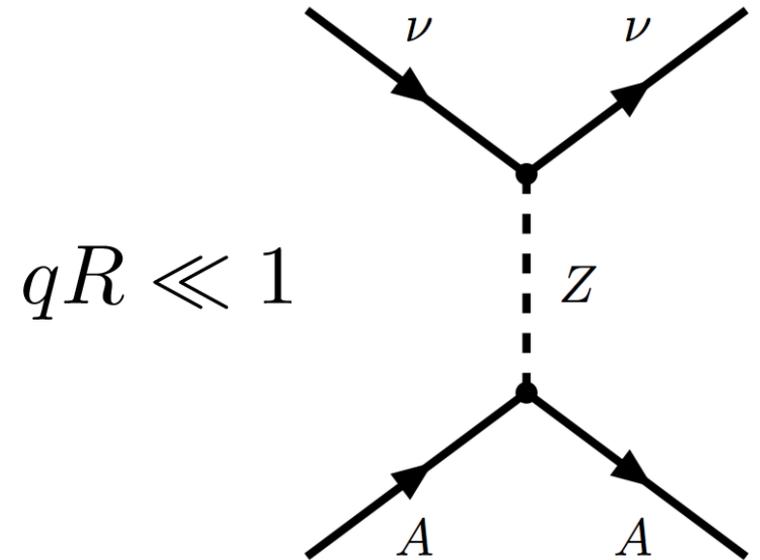$$Q_W = N - (1 - 4\sin^2\theta_W)Z \approx N - 0.08 \times Z \approx N$$

o $\cos\theta$: angle between in- and outgoing neutrino direction

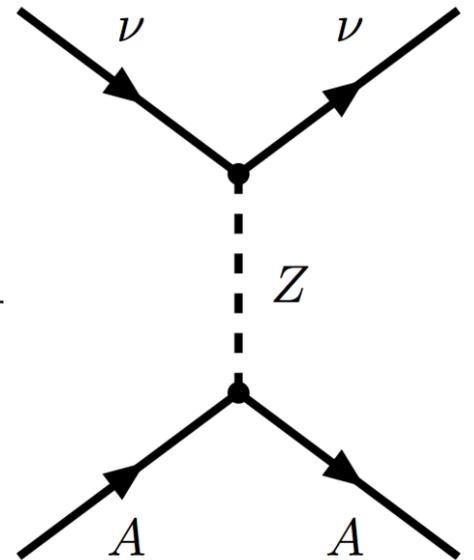o $2m_T E_r = q^2 = 2E_\nu^2(1 - \cos\theta)$

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

$$\frac{dR_\nu}{dE_r} = n_T \int_{t_0}^{t_1} \int_{E_\nu^{\min}}^{\infty} \frac{dN(t)}{dE_\nu} \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu\, dt$$

$$R_\nu = \int_{E_{\mathrm{thr}}}^{E_{\mathrm{up}}} \frac{dR_\nu}{dE_r} dE_r$$

$$qR \ll 1$$

Coherent Neutrino-Nucleon Interactions

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1 + \cos\theta) F(Q^2)^2$$

o Enhanced by factor N^2:

$$Q_W = N - (1 - 4\sin^2\theta_W)Z \simeq N - 0.08 \times Z \simeq N$$

o $\cos\theta$: angle between in-

o $2m_T E_r = q^2 = 2E_\nu^2(1 - \qquad \qquad \ll 1$

STILL NOT OBSERVED IN STANDARD MODEL

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

$$\frac{dR_\nu}{dE_r} = n_T \int_{t_0}^{t_1} \int_{E_\nu^{min}}^{\infty} \frac{dN(t)}{dE_\nu} \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu \, dt$$

$$R_\nu = \int_{E_{thr}}^{E_{up}} \frac{dR_\nu}{dE_r} dE_r$$

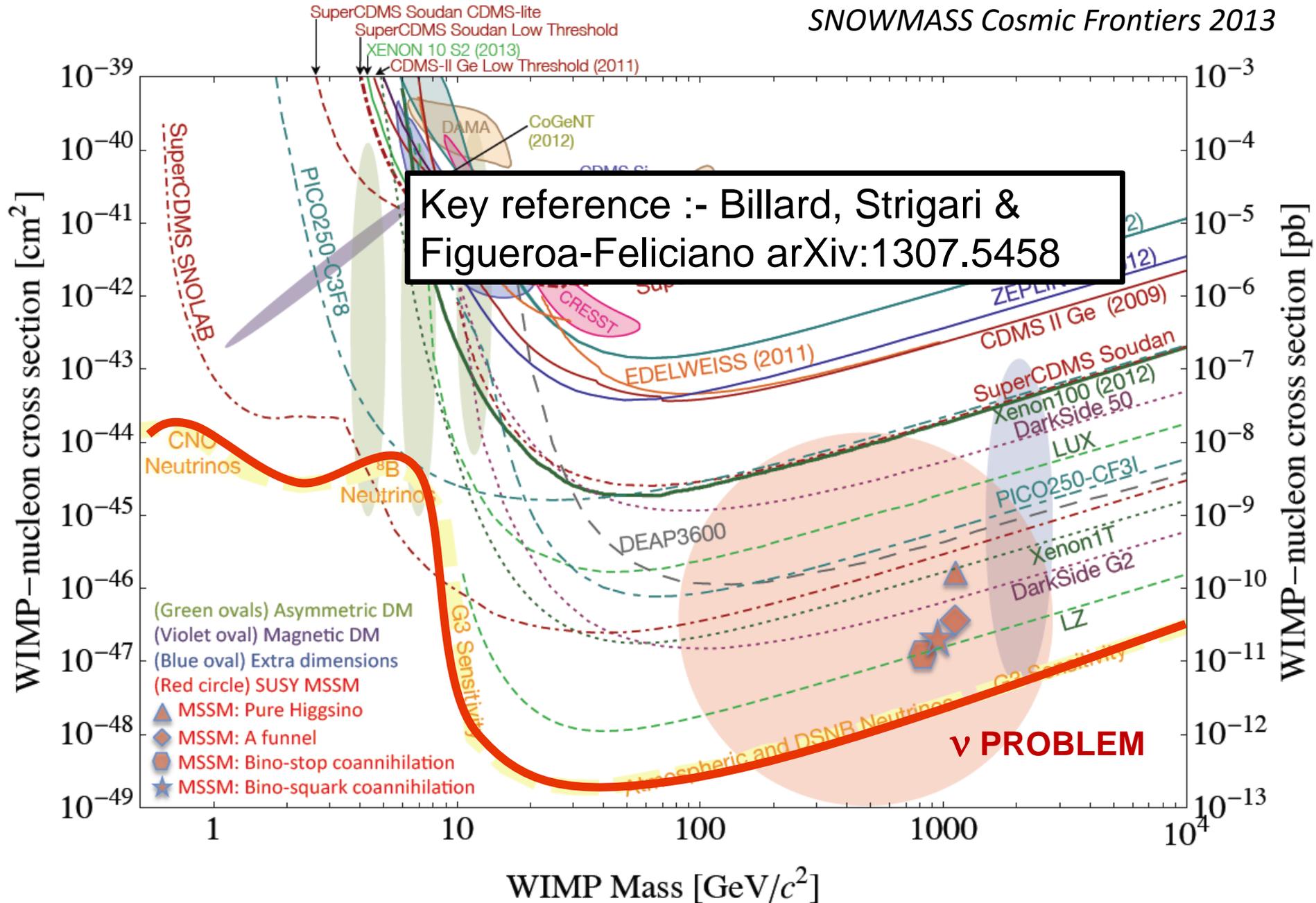# This now famous plot….

Key reference :- Billard, Strigari & Figueroa-Feliciano arXiv:1307.5458

Integrated Event Rate in Xe detector above different Thresholds
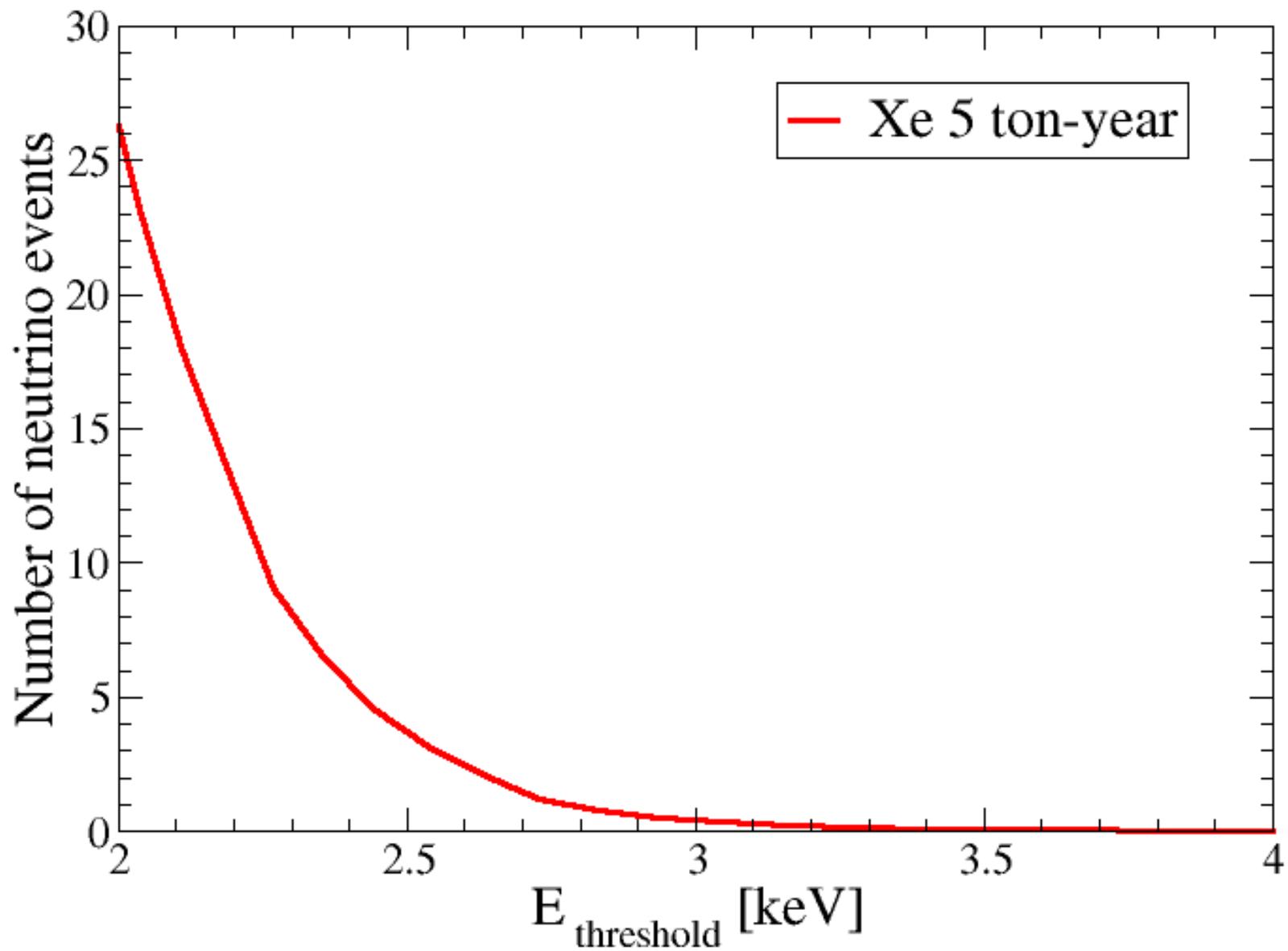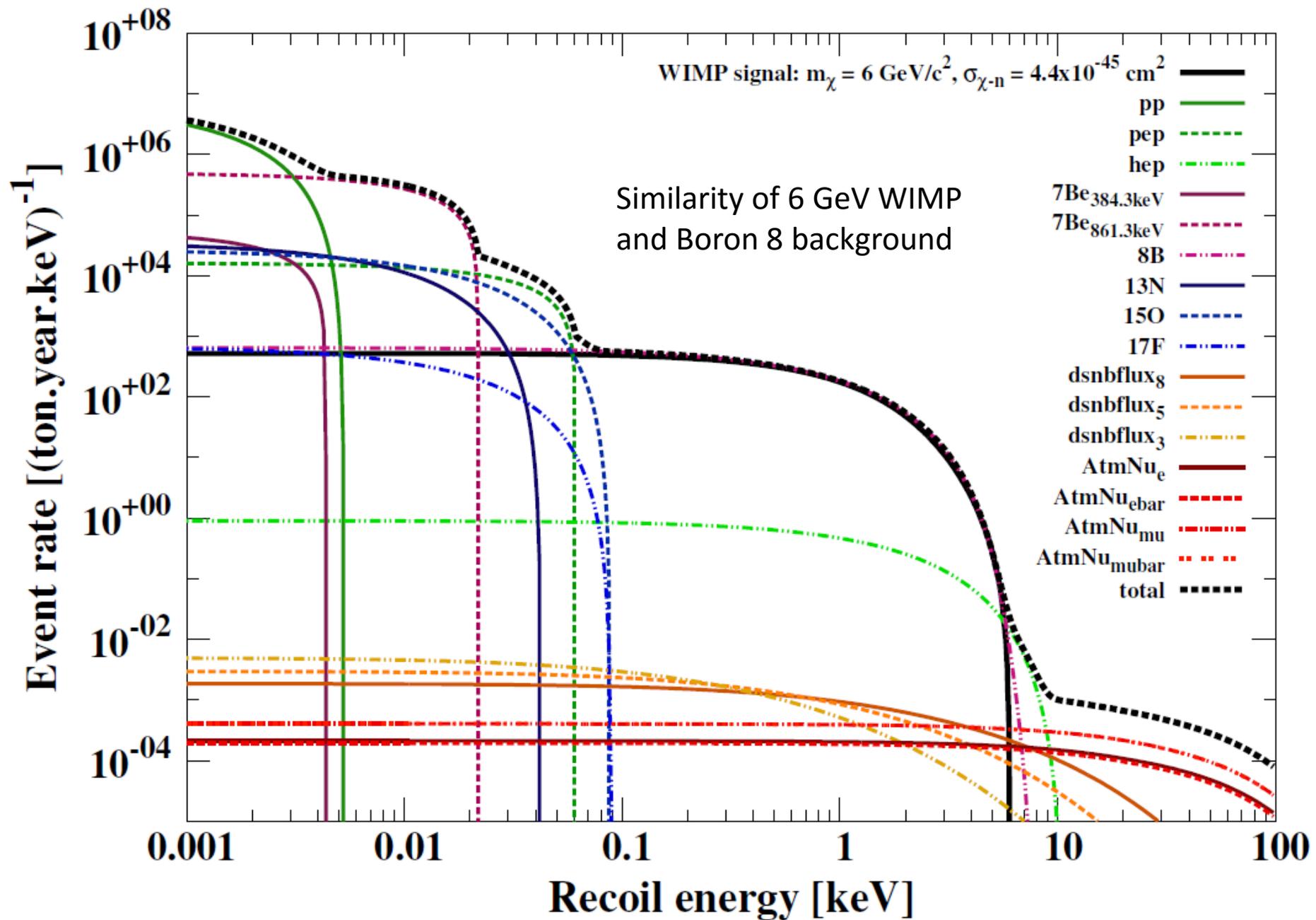
Integrated Event Rate in Ge detector above different Thresholds
(B8, hep, N13, O15, F17 and Be7 lines)

Similarity of 6 GeV WIMP and Boron 8 background

WIMP signal: $m_\chi = 6$ GeV/c^2, $\sigma_{\chi-n} = 4.4 \times 10^{-45}$ cm^2

- pp
- pep
- hep
- 7Be$_{384.3keV}$
- 7Be$_{861.3keV}$
- 8B
- 13N
- 15O
- 17F
- dsnbflux$_8$
- dsnbflux$_5$
- dsnbflux$_3$
- AtmNu$_e$
- AtmNu$_{ebar}$
- AtmNu$_{mu}$
- AtmNu$_{mubar}$
- total

Ruppin et al 1408.3581
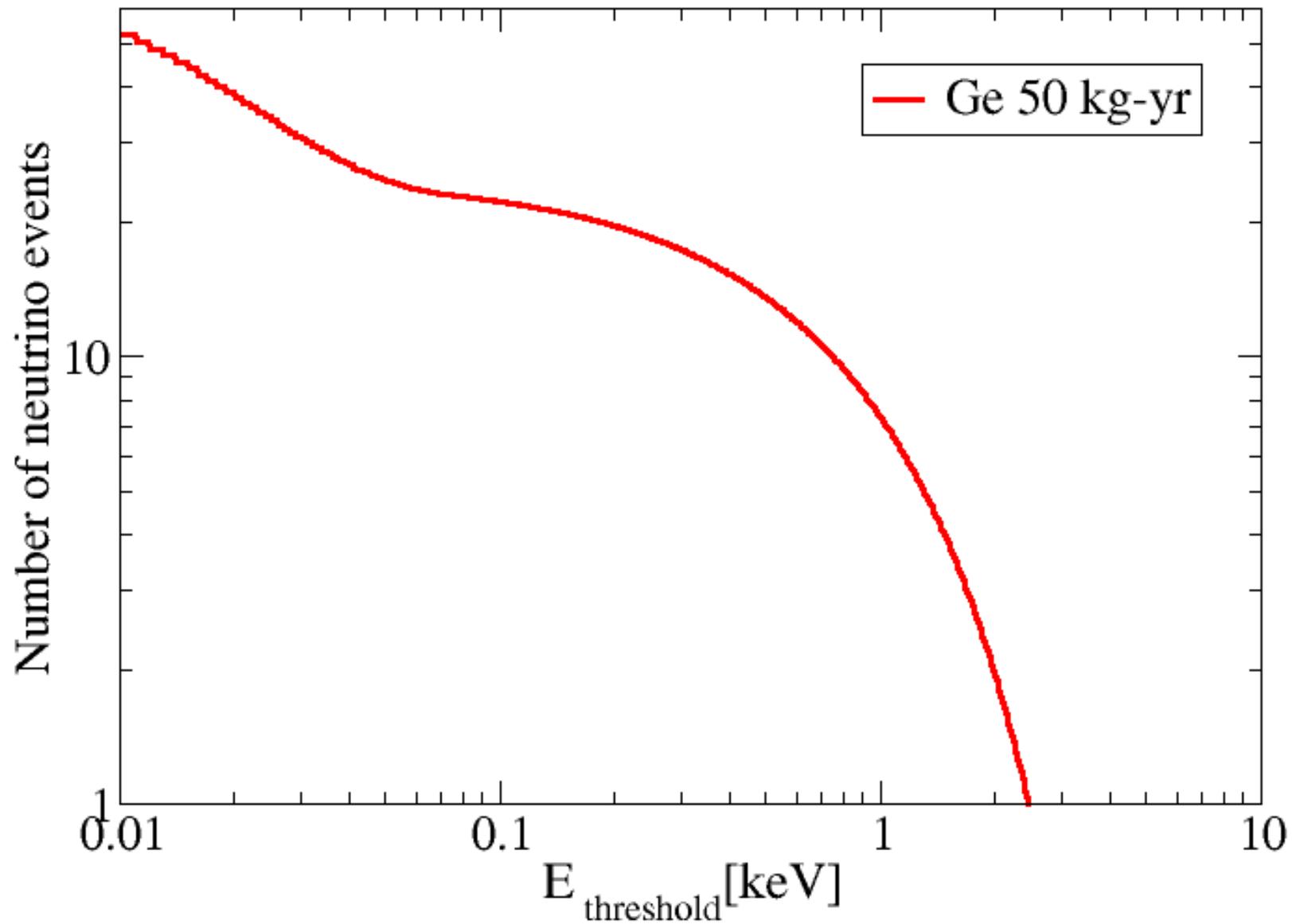
Effect of Energy and Time resolution on low mass case

Maxwellian $f(v)$
no time information
10T xenon target

Running Time

2 days
8 days
28 days
96 days
323 days
3 yr
10 yr

DM-nucleon cross section [cm^2]

Mass [GeV]

Maxwellian $f(v)$
with time information
10T xenon target

Running Time

2 days
8 days
28 days
96 days
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10 yr

DM-nucleon cross section [cm^2]

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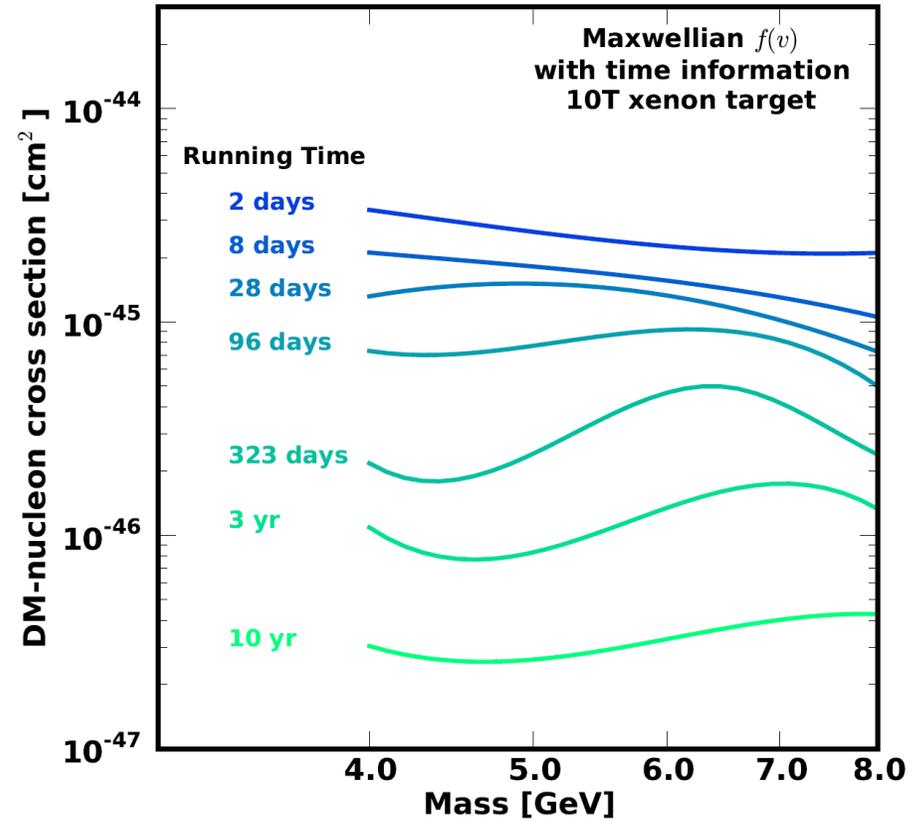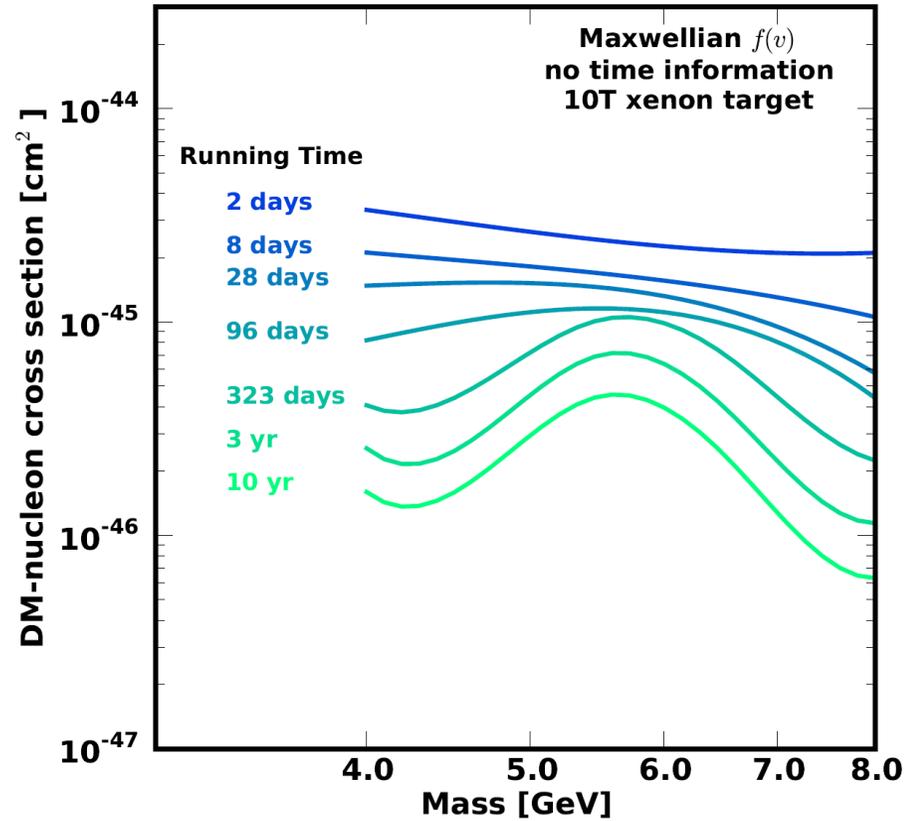
Davis arXiv:1412.1475

In principle, direction, energy and time information can discriminate neutrinos from dark matter.

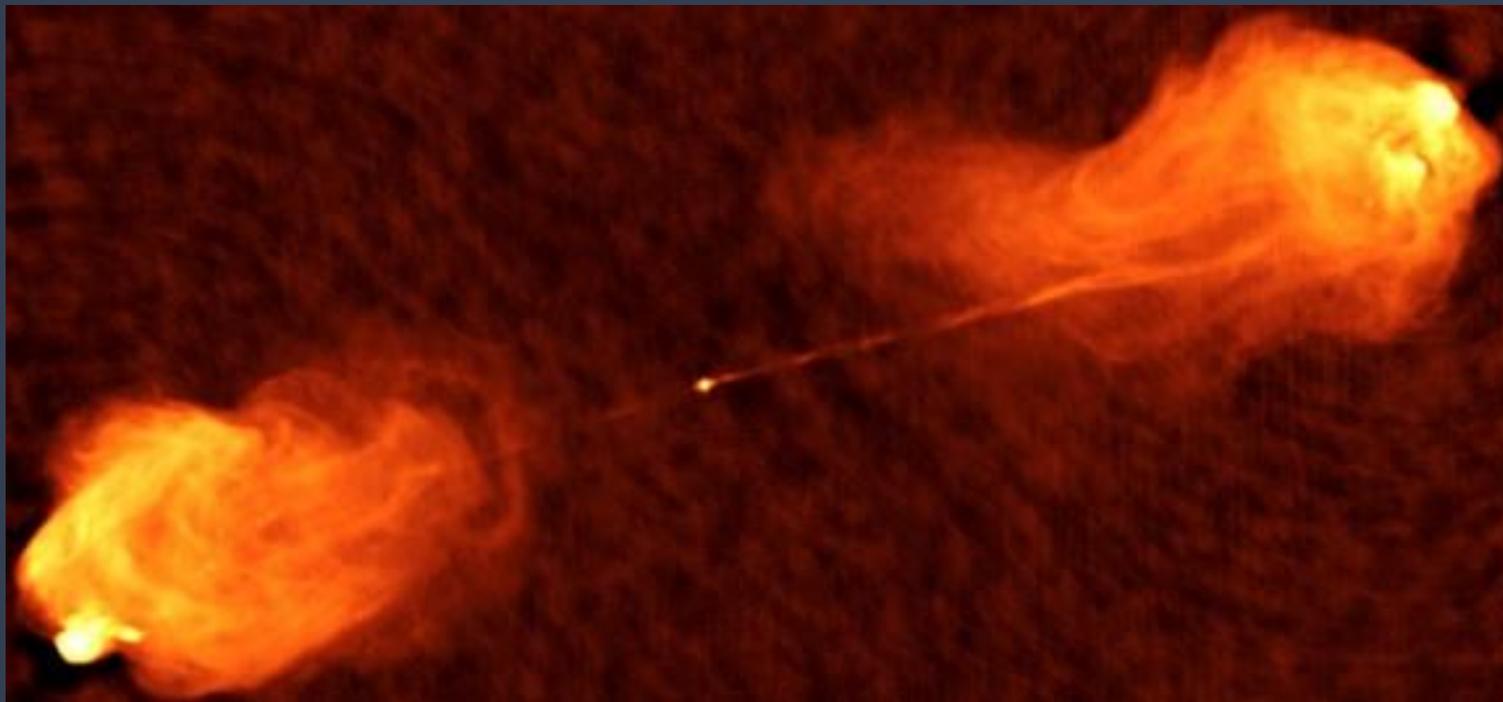# angle between recoil from Solar neutrino and sun

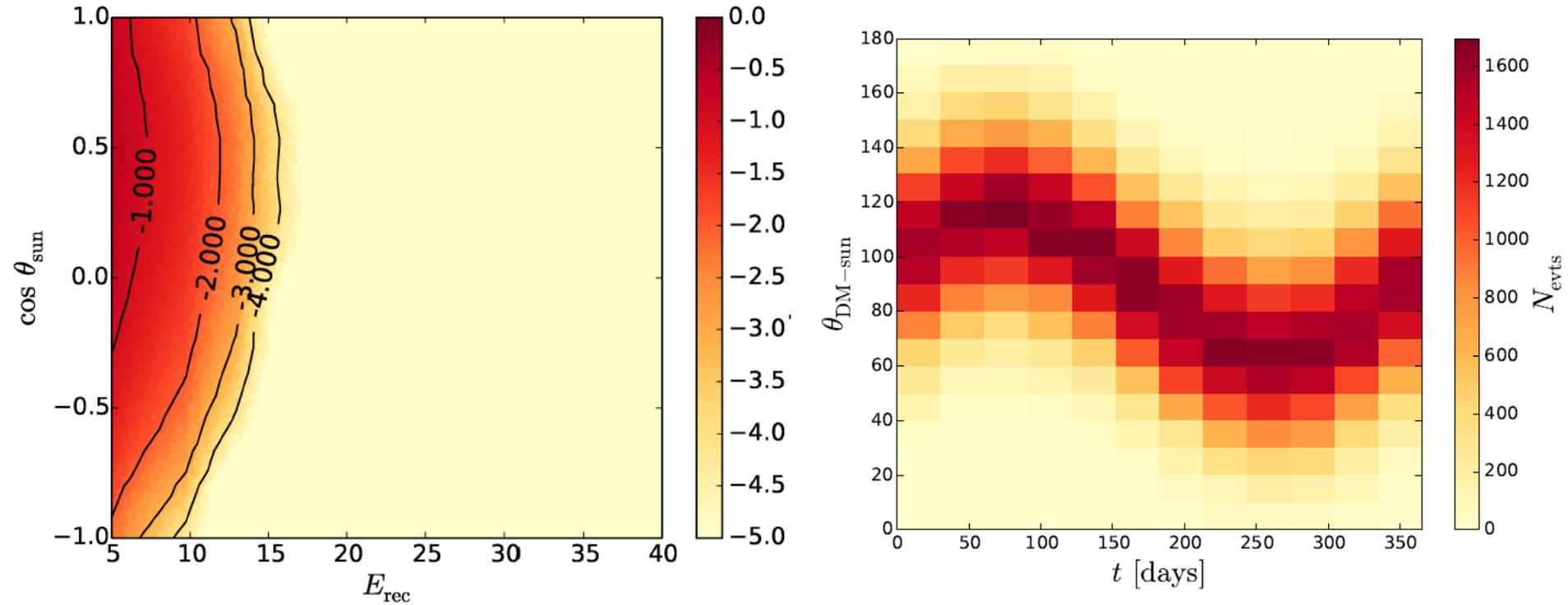$$\cos\theta' = \frac{E_\nu + m_T}{E_\nu}\sqrt{\frac{E_r}{2m_T}}$$

arXiv:1406.5047
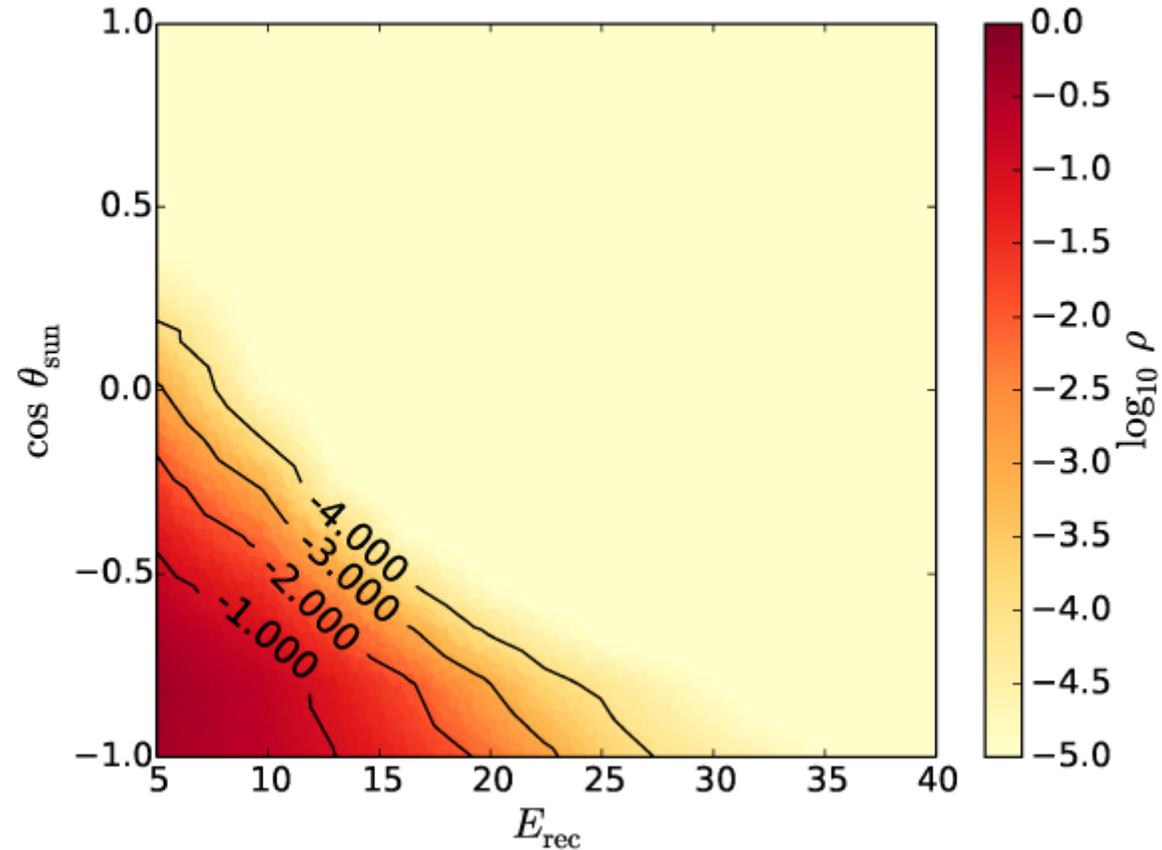
Motion of Sun Through Galaxy

towards
constellation of
Cygnus, ~220 km/s

Roughly in the
direction of active
galaxy Cygnus A

# angle between recoil from Dark Matter and sun

- Preferred arrival direction roughly from Cygnus A
- This changes during the year
- Lighter (heavier) dark matter more (less) directional above a given threshold

arXiv:1406.5047

$$\tilde{Q} = \frac{\frac{e^{-(s+b)}(s+b)^n}{n!}}{\frac{e^{-b}b^n}{n!}} \prod_{j=1}^{n} \frac{\frac{sS_t(t_j)+bB_t(t_j)}{s+b} \frac{sS_{\theta,E}(\theta_j,E_j)+bB_{\theta,E}(\theta_j,E_j)}{s+b}}{\prod_{j=1}^{n} B_t(t_j) B_{\theta,E}(\theta_j,E_j)}$$
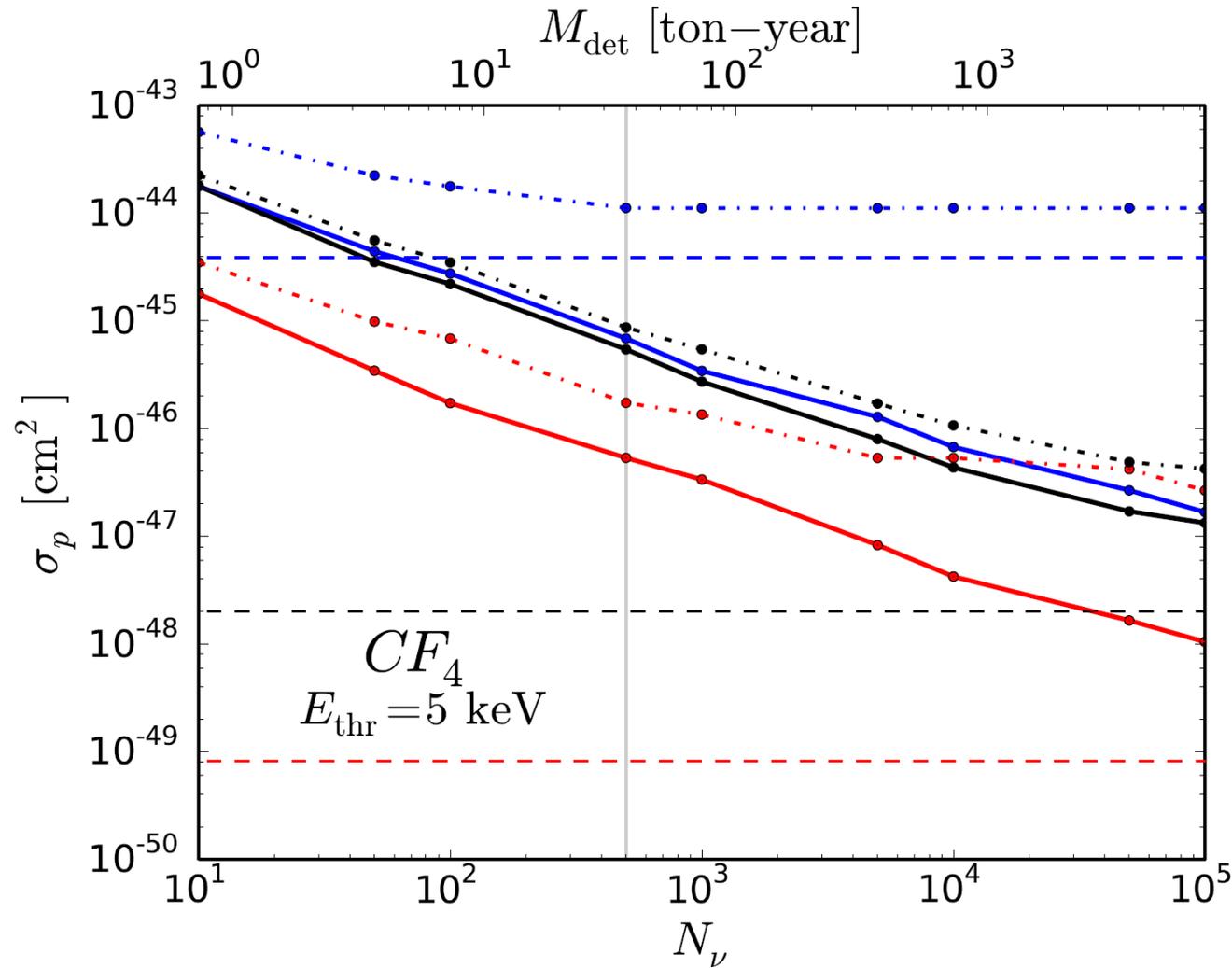
$$Q = -2\log\tilde{Q}$$

The normalised background only distribution $p_B(Q_B)$ (blue) and signal plus background distribution $p_{SB}(Q_{SB})$ (red) including angular information (top) and excluding angular information (bottom) for s=10 and b=500 for a 6 GeV dark matter particle in a CF_4 detector.

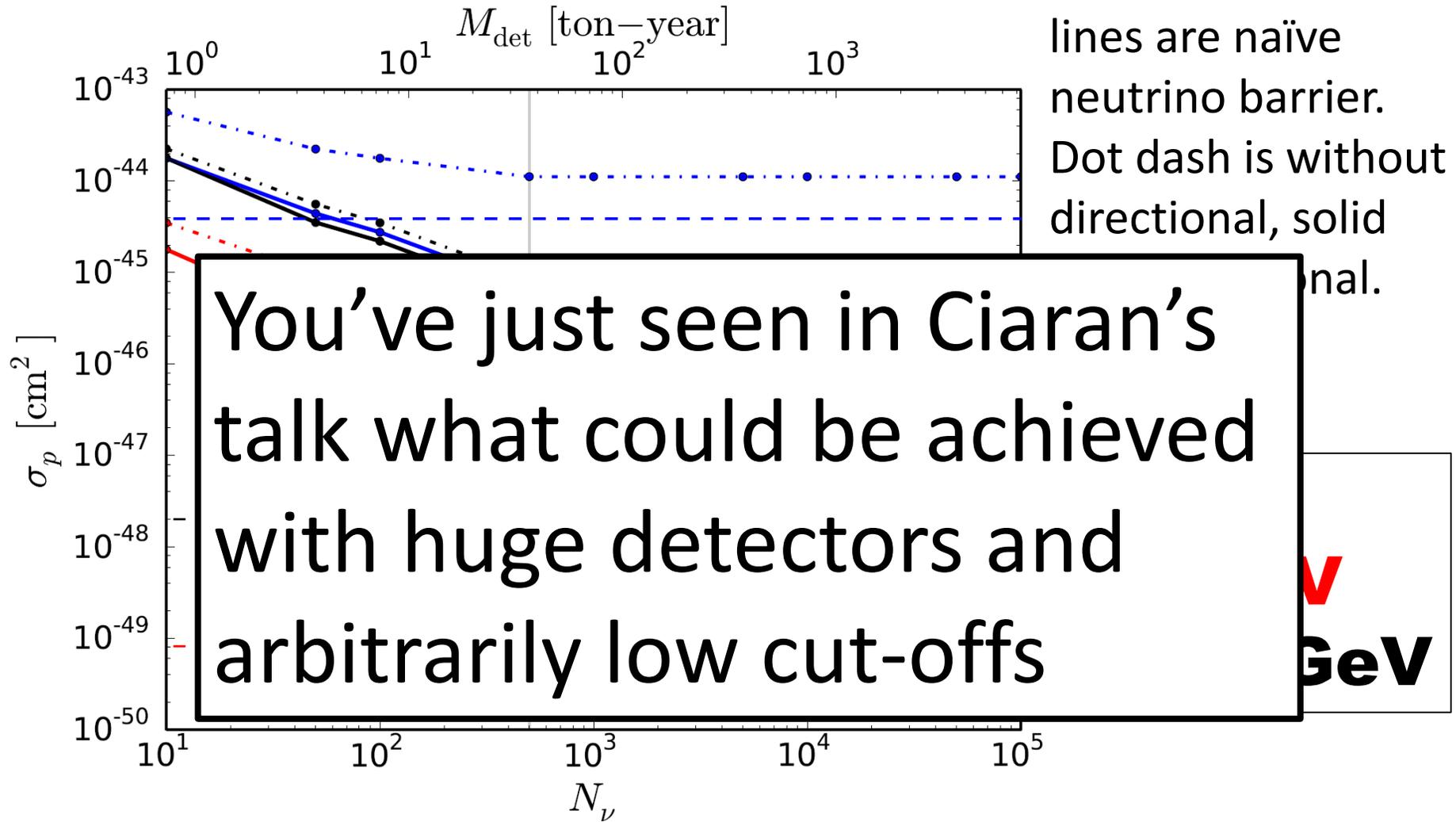arXiv:1406.5047
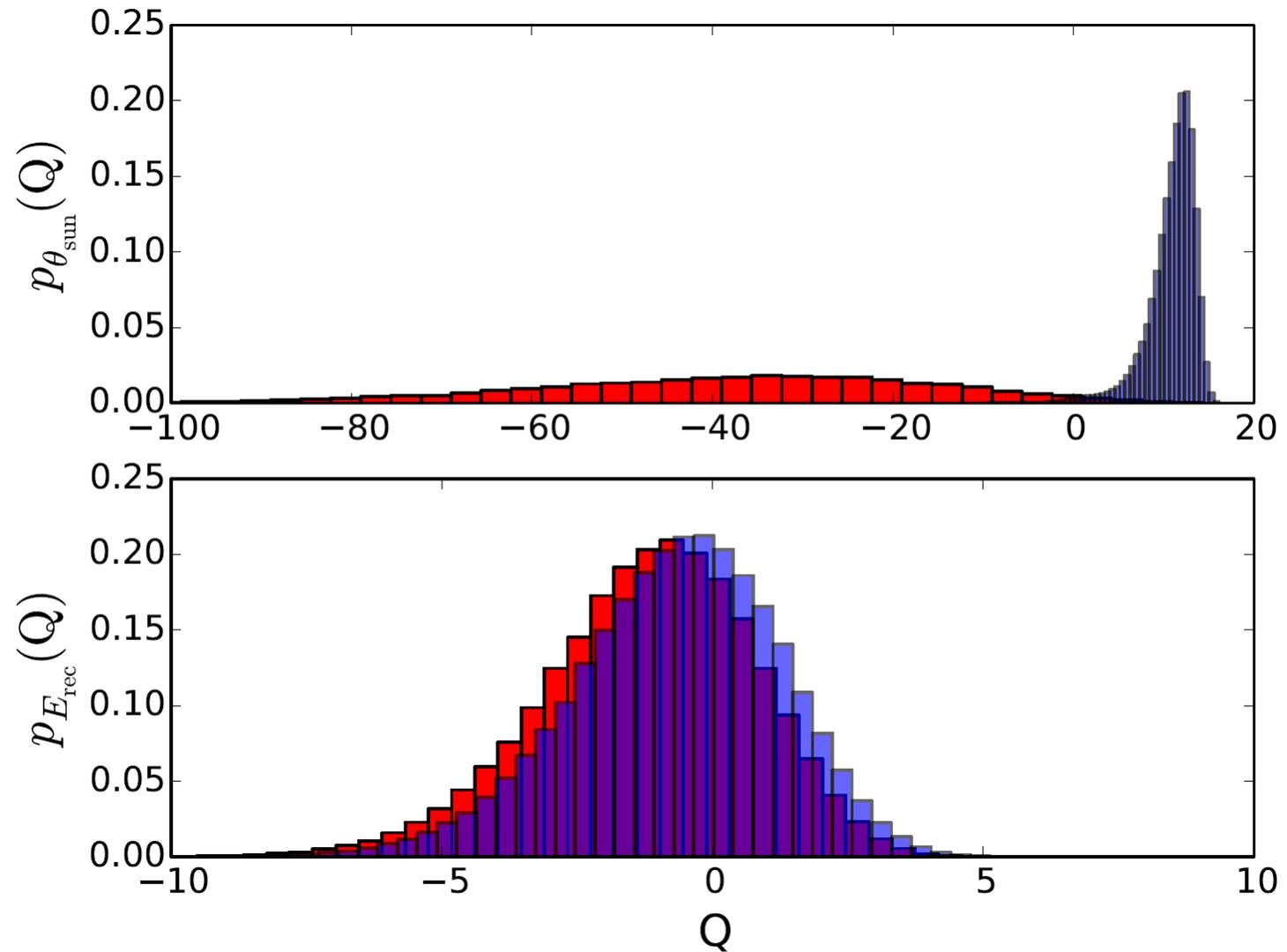
How far can we push things?

Horizontal Dashed lines are naïve neutrino barrier. Dot dash is without directional, solid with directional.

6 GeV
30 GeV
1000 GeV

Ultimately, this depends on how well we know the neutrino background

arXiv:1406.5047

How far can we push things?

M_{det} [ton−year]

σ_p [cm^2]

N_ν

Horizontal Dashed lines are naïve neutrino barrier. Dot dash is without directional, solid ~~~~~ional.

You've just seen in Ciaran's talk what could be achieved with huge detectors and arbitrarily low cut-offs

V

GeV

Ultimately, this depends on how well we know the neutrino background

arXiv:1406.5047

Interesting Possibility – Polarised targets
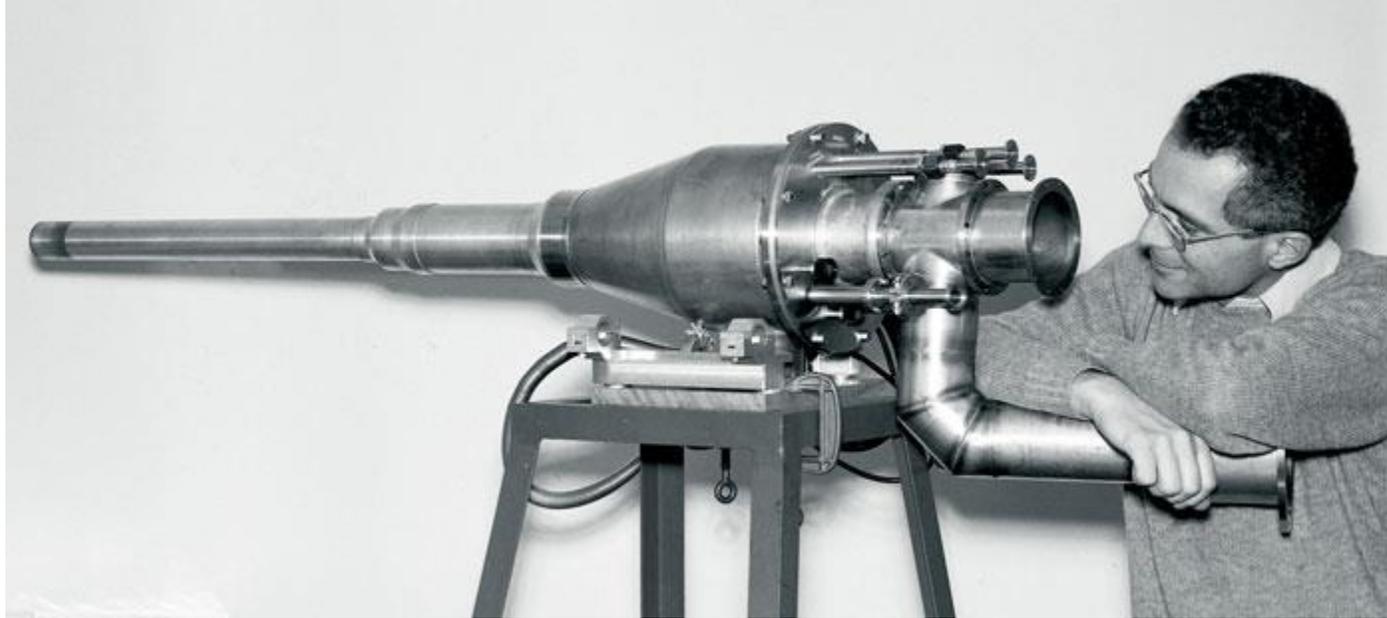
Michel Borghini with a polarized target at CERN in 1976.

see also
"Dark Matter Detection with Polarized Detectors"
Chiang, Kamionkowski & Krnjaic, arXiv:1202.1807

Interesting Possibility – Polarised targets

- Polarised targets not very directional for dark matter
  (effect is supressed when no preferred helicity)

- Polarised targets with unpaired neutrons ARE directional to axial coupling of neutrinos

- Effect usually dwarfed by vector coupling due to coherent enhancement

- Notable exception is Helium-3
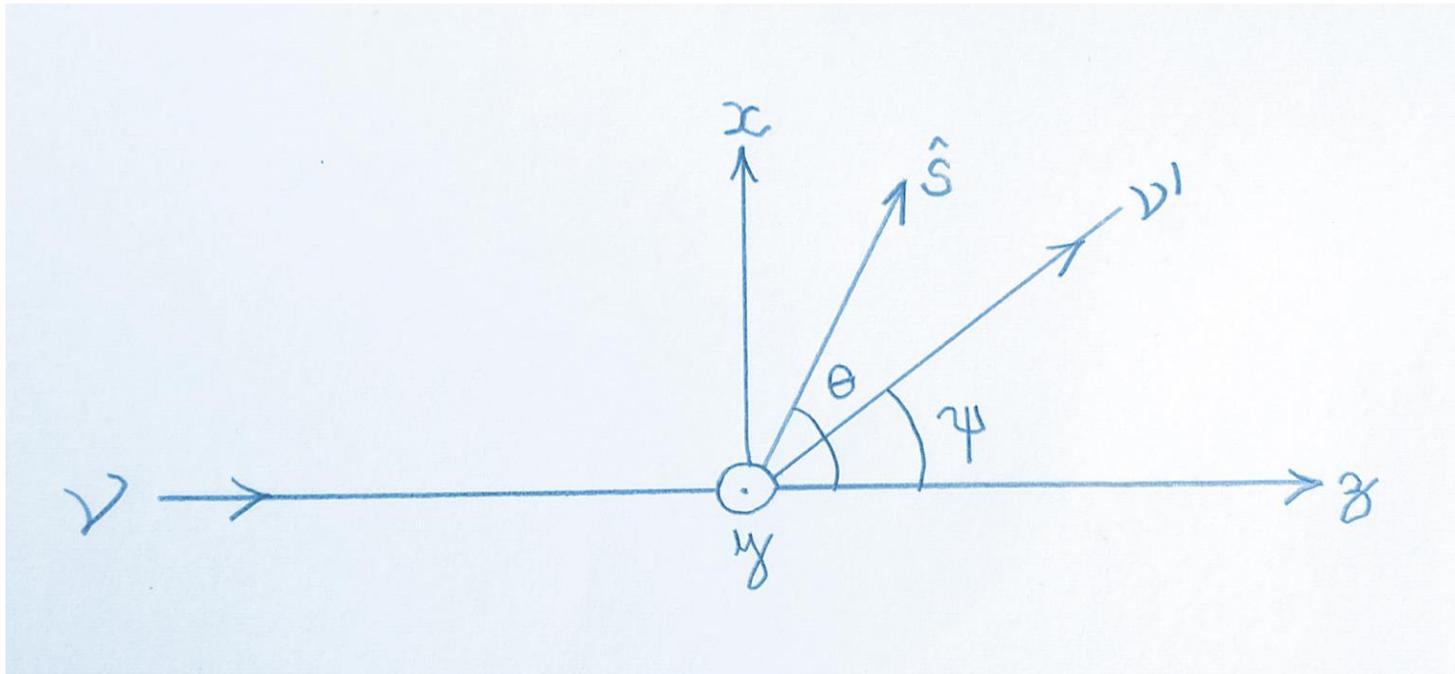
if N=1 and c_A due to unpaired neutron

cancellation between V and A for particular orientations of the spin and the arrival direction of the neutrino

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\{c_V^2 + 3c_A^2 + (c_V^2 - c_A^2)\cos\psi - 2c_A[(c_V - c_A)\hat{v}.\hat{s} + (c_V + c_A)\hat{v}'.\hat{s}]\}$$

SI

$$c_V^{\text{nucleus}} = Zc_V^p + Nc_V^n$$

$$c_A^{\text{nucleus}} = c_A^{\text{unpaired nucleon}}$$

SD

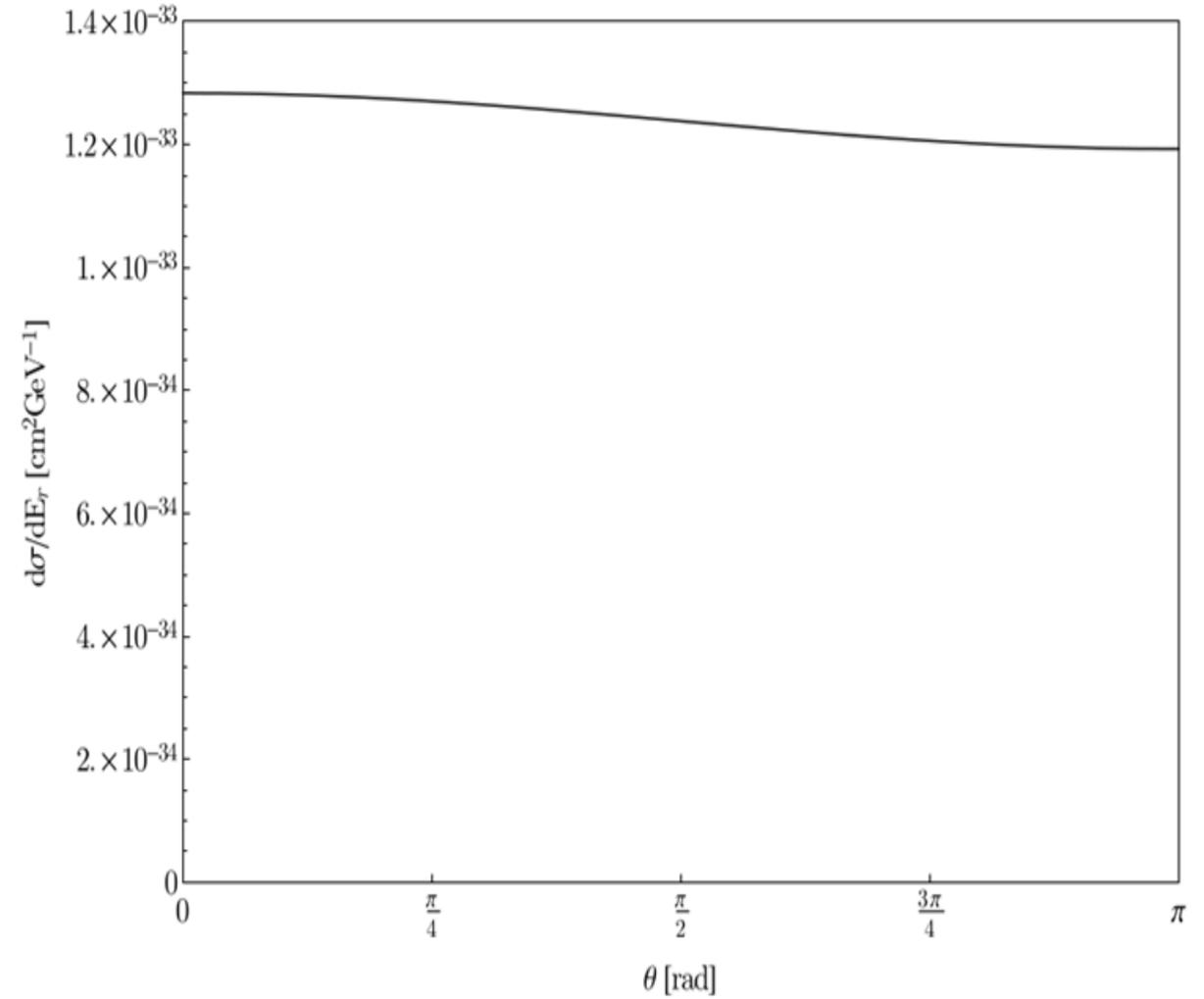|	c_V	c_A
Proton	$1 - 4\sin^2\theta_W$	1.26
Neutron	-1	-1.26

6.4 MeV Neutrino-nucleon cross section as function of angle

For Xenon there is a small effect while for Helium-3 there is almost a complete cancellation.
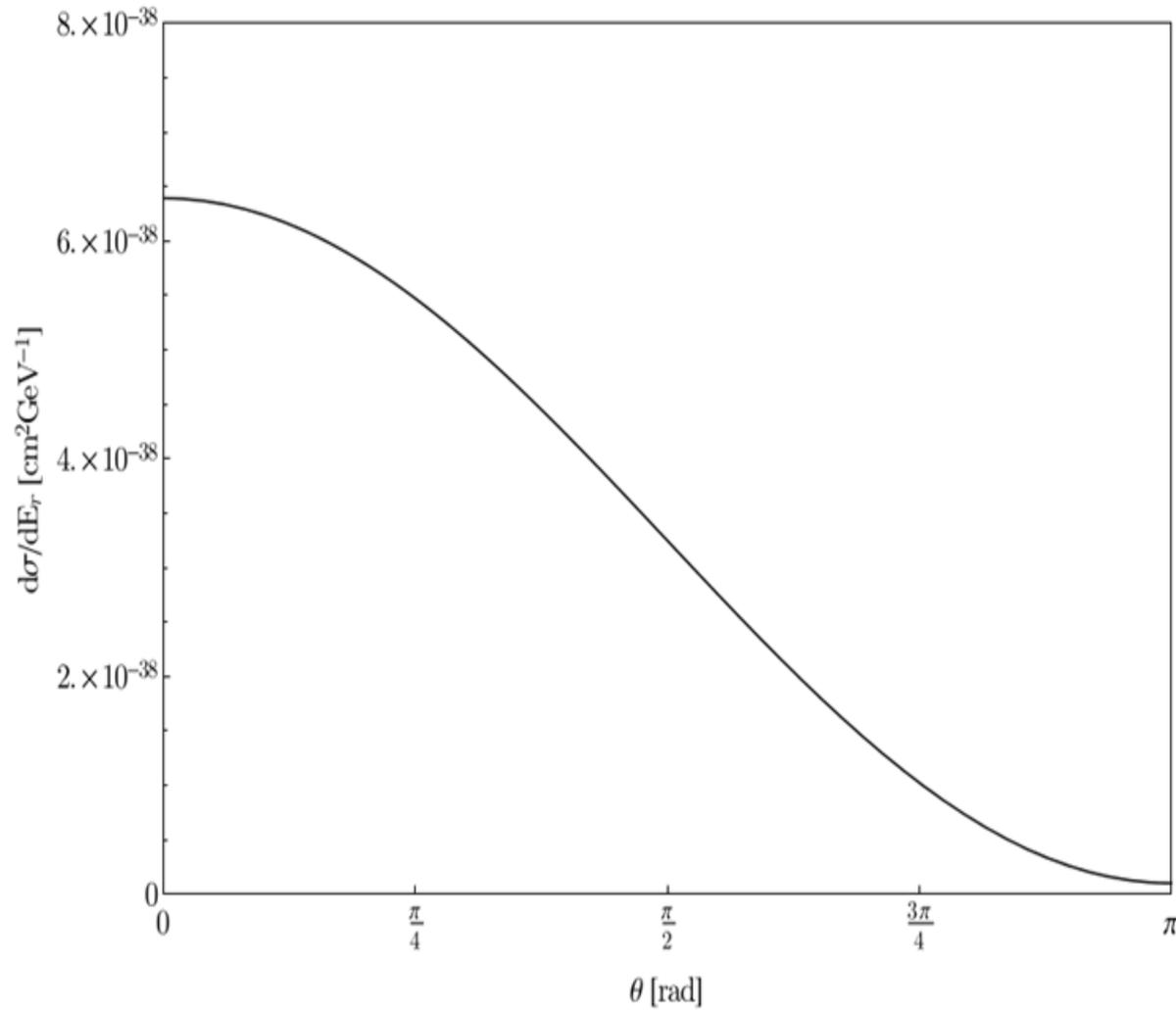
^{3}He

^{129}Xe

Event rates for solar neutrino scattering off Helium-3

| E_{thr} (keV)	2	1	0.5	0.2
$N_{\text{E}}(0)$	3.232	7.665	23.256	85.448
$N_{\text{E}}(\pi)$	0.072	0.099	0.188	0.851
$N_{\text{E,unpolarised}}$	1.652	3.882	11.722	43.150

100 kg-year exposure

$$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

For a threshold energy of 0.2 keV:
- P=0: 43 events
- P=1: 1 event
- P=-1: 85 events
- P=0.7: 13 events

100 kg year With different Levels of polarisation.

$E_{th}=2\ keV$

$E_{th}=0.2\ keV$

Green line is "traditional" Neutrino line for Xenon From Billard and Strigari CONVERTED NAIVELY to Spin dependent case
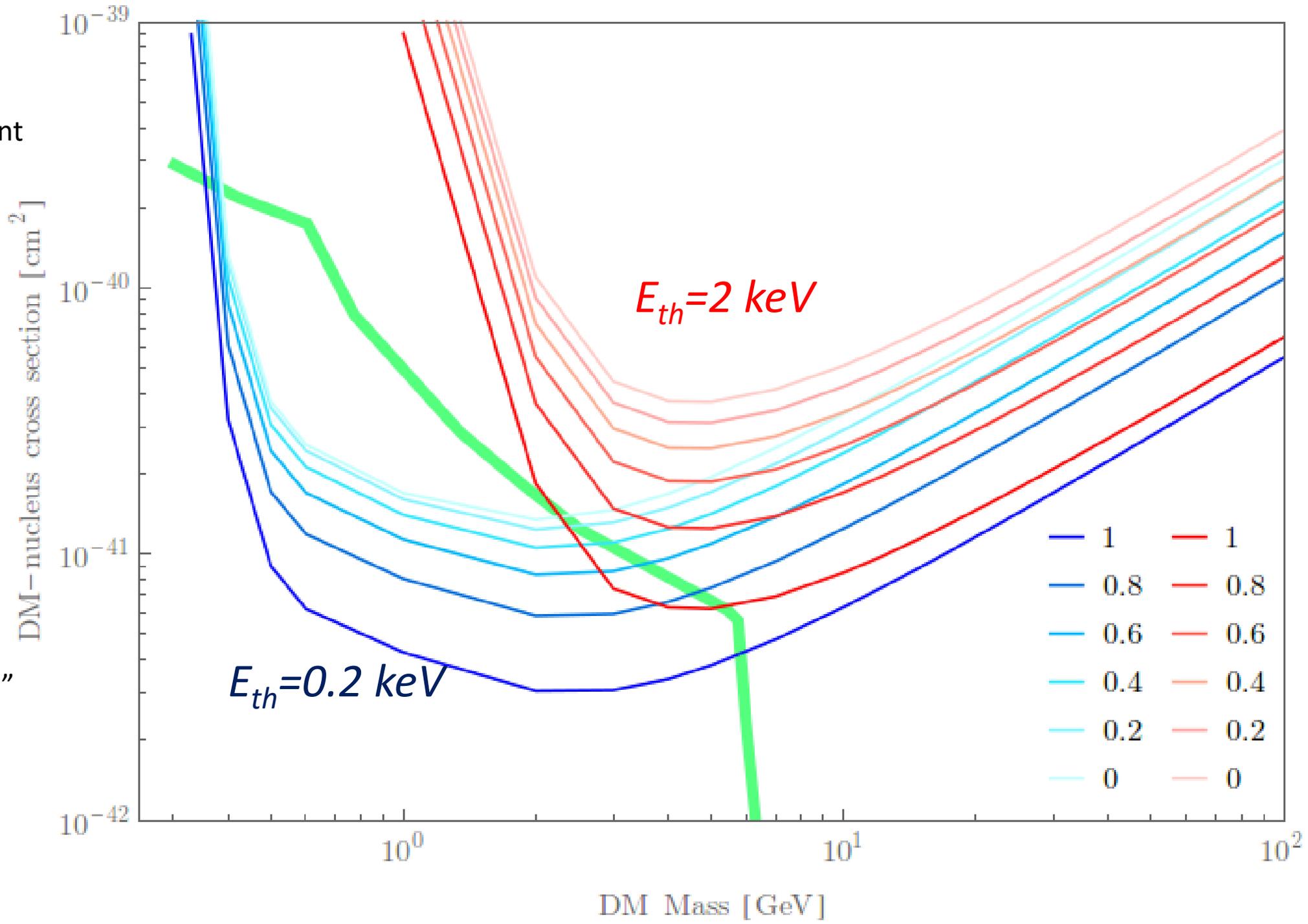
Some obvious problems with Helium-3

- Tritium contamination would be a major background

- Simplest Polarisation scheme for He-3 for NMR uses potassium and/or rubidium, both of which are potential contaminants

- Helium-3 makes Xenon look as cheap as water

$$\alpha = \frac{1}{2} \left| \frac{\frac{d\sigma}{dE_r}(0) - \frac{d\sigma}{dE_r}(\pi)}{\frac{d\sigma}{dE_r}(\pi/2)} \right|$$

	α
^3He	0.97
^{13}C	0.41
^{15}N	0.36
^{19}F	0.22
^{129}Xe	0.04

EMBRACING THE ENEMY
going to detect these neutrinos, can we learn anything new?

Nelson Mandela talking to PW Botha, former South Africa president and staunch supporter of apartheid, during the Truth and Reconciliation hearings

We expect to detect Neutrinos. What could we do with this information?

Experiment	ϵ (ton-year)	$E_{th,n}$ (keV)	$E_{th,o}$ (keV)	E_{max} (keV)	$R(pp)$	$R(^8B)$
G2-Ge	0.25	0.35	0.05	50	–	$[62 - 85]$
G2-Si	0.025	0.35	0.05	50	–	$[3 - 3]$
G2-Xe	25	3.0	2.0	30	$[2104 - 2167]$	$[0 - 64]$
Future-Xe	200	2.0	1.0	30	$[17339 - 17846]$	$[520 - 10094]$
Future-Ar	150	2.0	1.0	30	$[14232 - 14649]$	$[6638 - 12354]$
Future-Ne	10	0.15	0.1	30	$[1141 - 1143]$	$[898 - 910]$

We expect to detect Neutrinos. What could we do with this information?

- measure Weinberg angle at very low energies

Exp.	$\sin^2\theta_W$
Measured	
G2	4.6% (4.5%)
Future-Xe	1.7% (1.7%)
Future-Ar	1.5% (1.4%)
HyperK[c]	—

arXiv:1604.01025

We expect to detect Neutrinos. What could we do with this information?

- measure Weinberg angle at very low energies
- measure Boron-8 flux using nuclear recoils

Exp.	$\sin^2\theta_W$	$\phi_\nu^{^8\text{B}}$
Measured		2.0% [a]
G2	4.6% (4.5%)	1.9% (1.9%)
Future-Xe	1.7% (1.7%)	1.8% (0.9%)
Future-Ar	1.5% (1.4%)	1.0% (0.6%)
HyperK[c]	—	1.43%

We expect to detect Neutrinos. What could we do with this information?

- measure Weinberg angle at very low energies
- measure Boron-8 flux using nuclear recoils
- measure pp flux using electron recoils

Exp.	$\sin^2\theta_W$	$\phi_\nu^{^8\mathrm{B}}$	ϕ_ν^{pp}
Measured		2.0% [a]	10.6 % [b]
G2	4.6% (4.5%)	1.9% (1.9%)	2.5 % (2.5%)
Future-Xe	1.7% (1.7%)	1.8% (0.9%)	0.7% (0.7%)
Future-Ar	1.5% (1.4%)	1.0% (0.6%)	0.6% (0.5%)
HyperK[c]	—	1.43%	—

arXiv:1604.01025

We expect to detect Neutrinos. What could we do with this information?
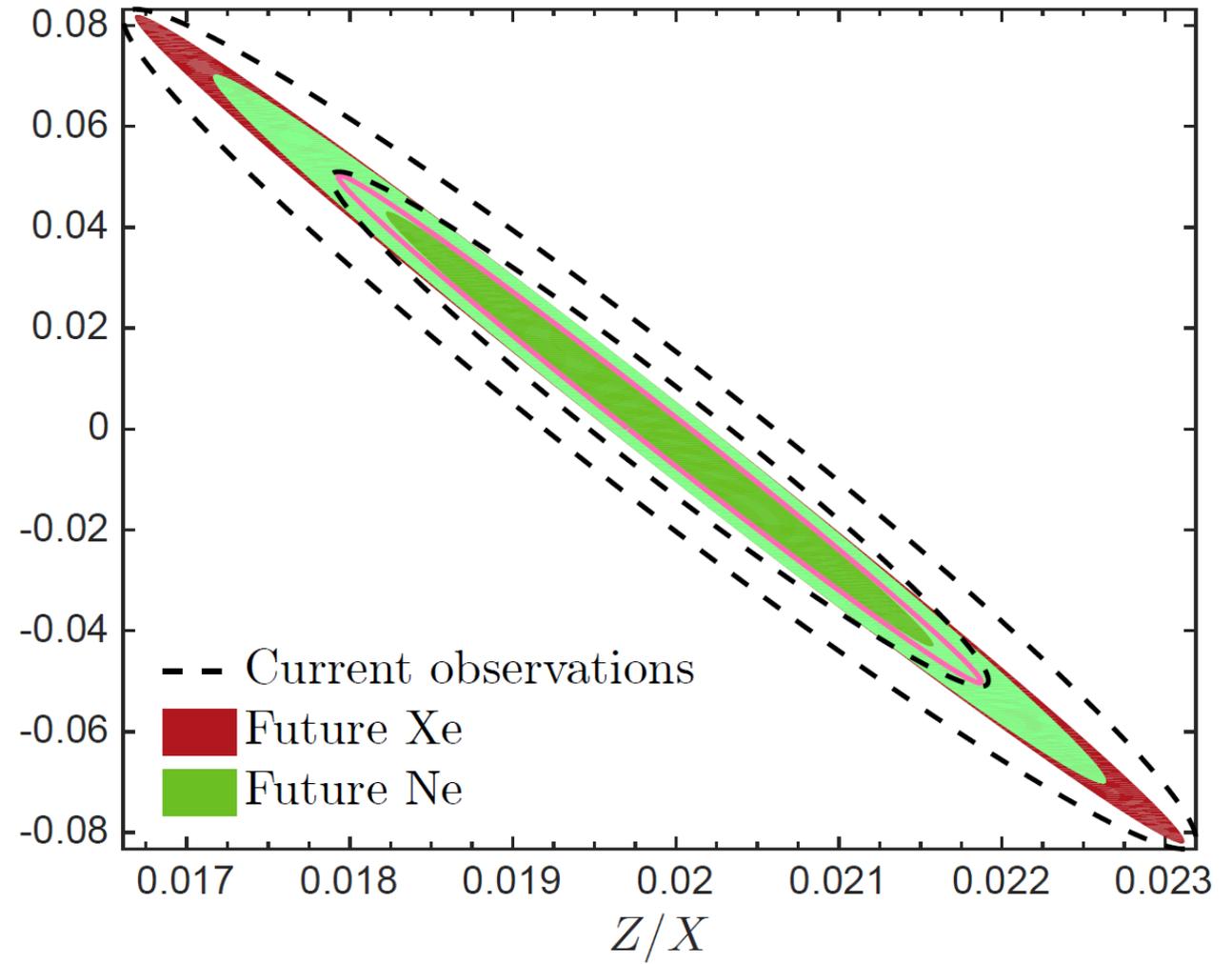
Limits average opacity vs. metallicity

Narrows line but still huge degeneracy

Needs to be broken by observation of CNO neutrinos –

SNO+ ???

Future direct detection experiments ???

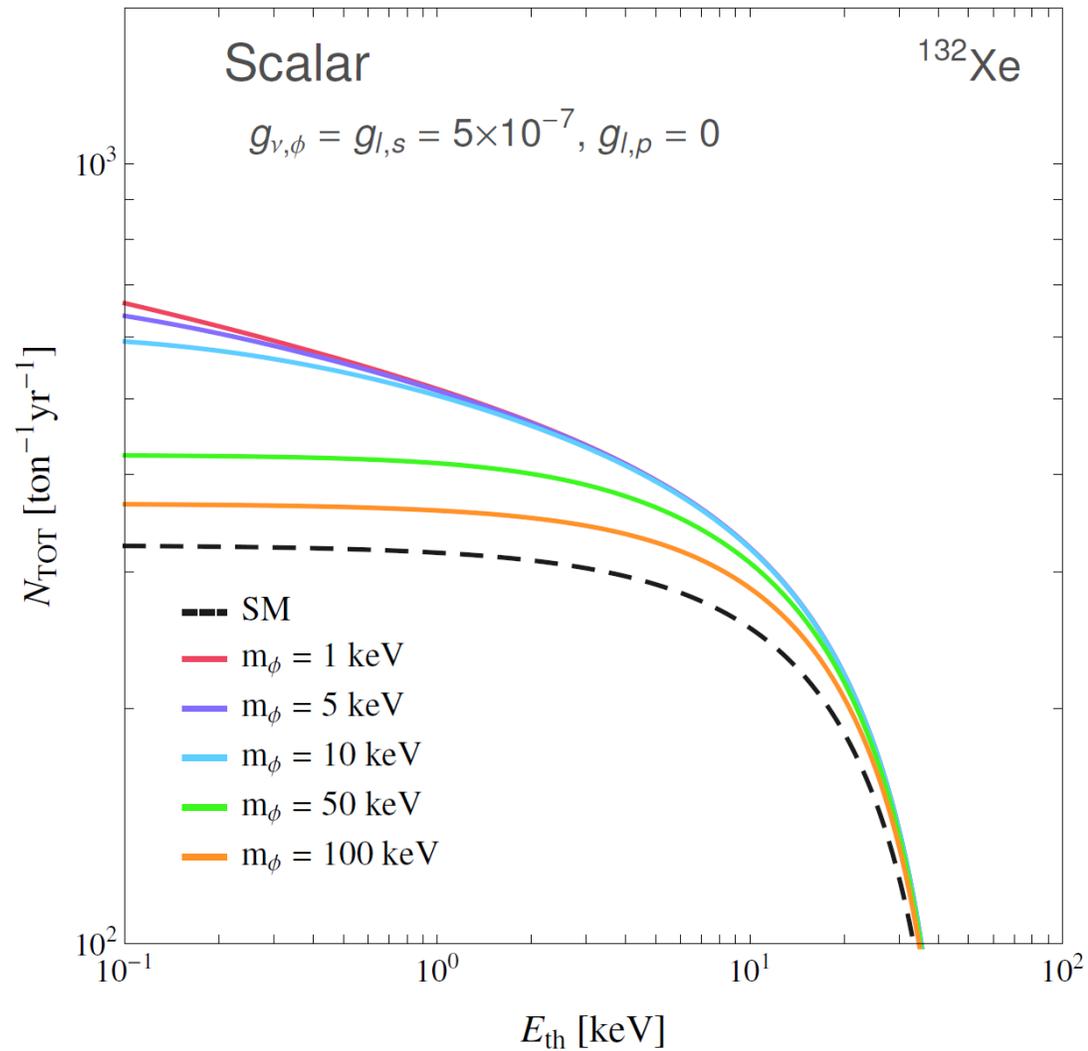
arXiv:1604.01025

Tests of BSM Physics

Momentum exchanged for pp-neutrino electron events around 10 keV

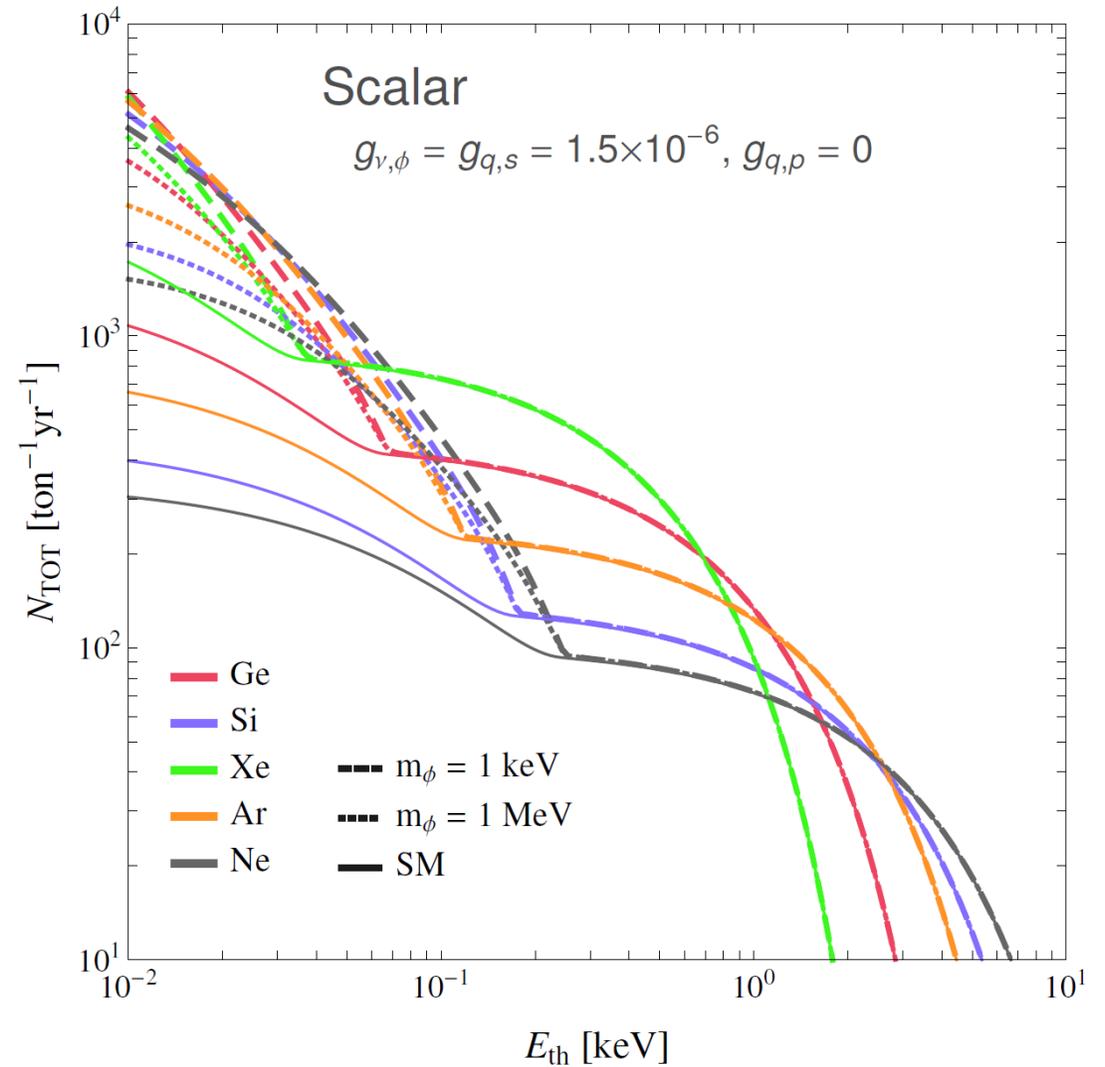Momentum exchanged for neutrino-nucleon events is MeV scale

Both Q^2 unstudied in those settings, can probe new interactions.

Tests of BSM Physics

$$(g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.)$$
$$+ \phi\bar{\ell}g_{\ell,s}\ell + \phi\bar{q}g_{q,s}q$$
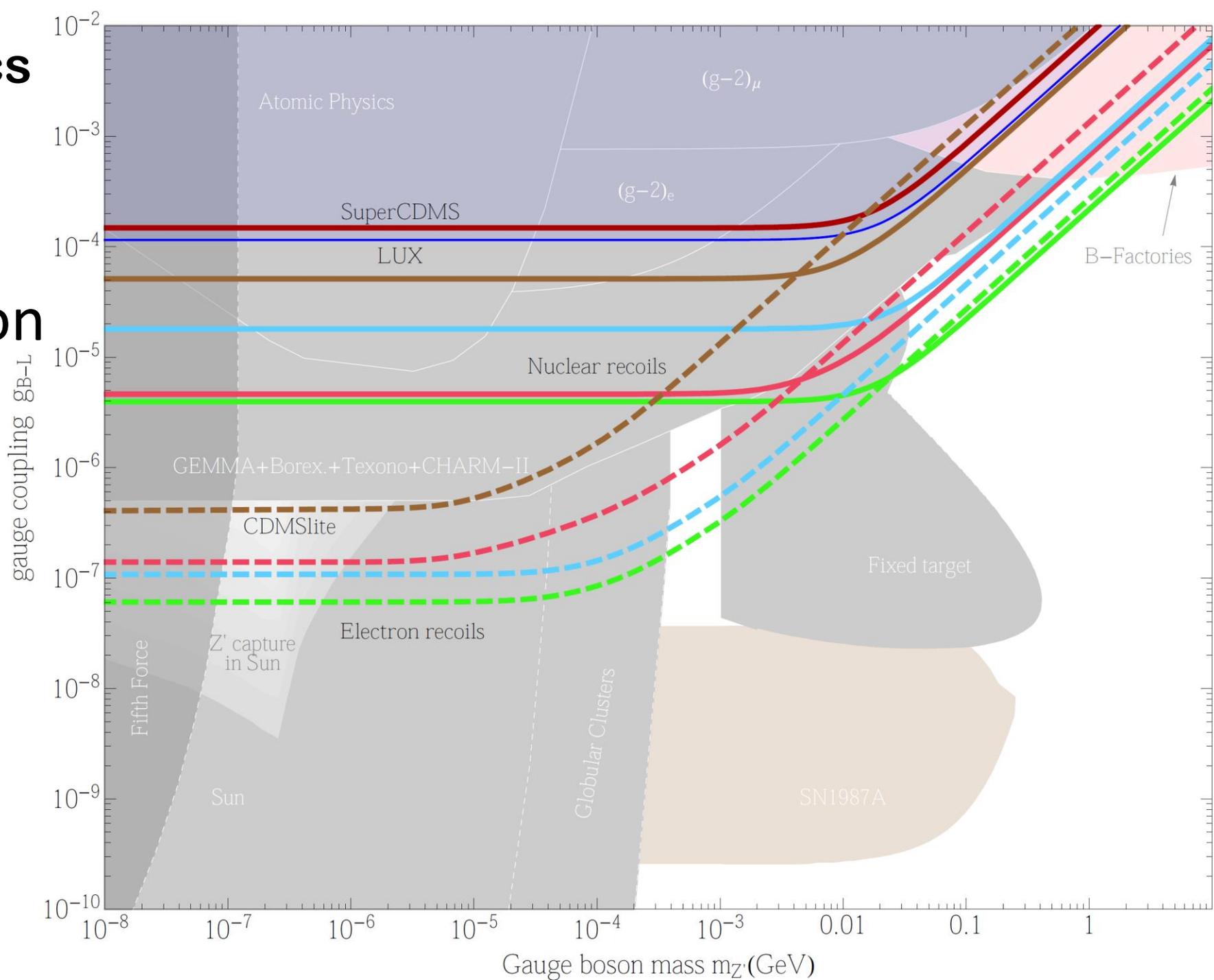

electron recoils

nuclear recoils

Tests of BSM Physics

$U(1)_{B-L}$ gauge boson couples to B-L charge of SM particles

Dashed electron, solid nucleon.

Green future xenon
Blue G2 xenon
Red G2 germanium

Conclusions

Neutrino events will increasingly shape the future of direct detection.

Right now the focus is on getting round the neutrino floor, but focus should shift to *ALSO* studying those neutrinos.

There are still new ideas to be found.