Neutrino Physics
at
Dark Matter Detectors

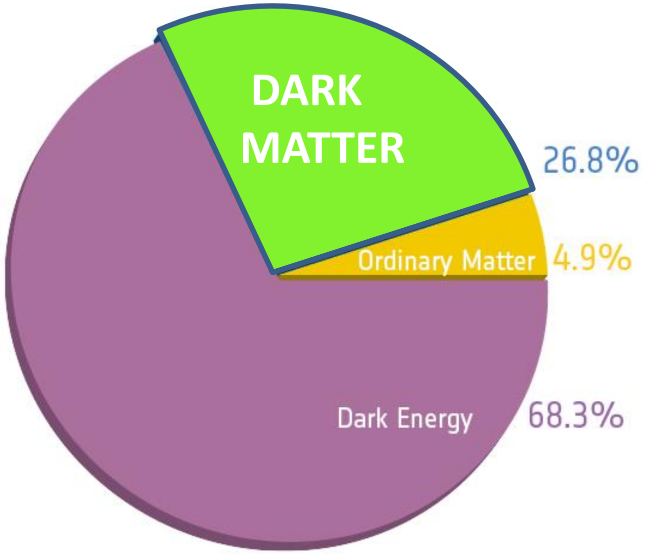
Malcolm Fairbairn

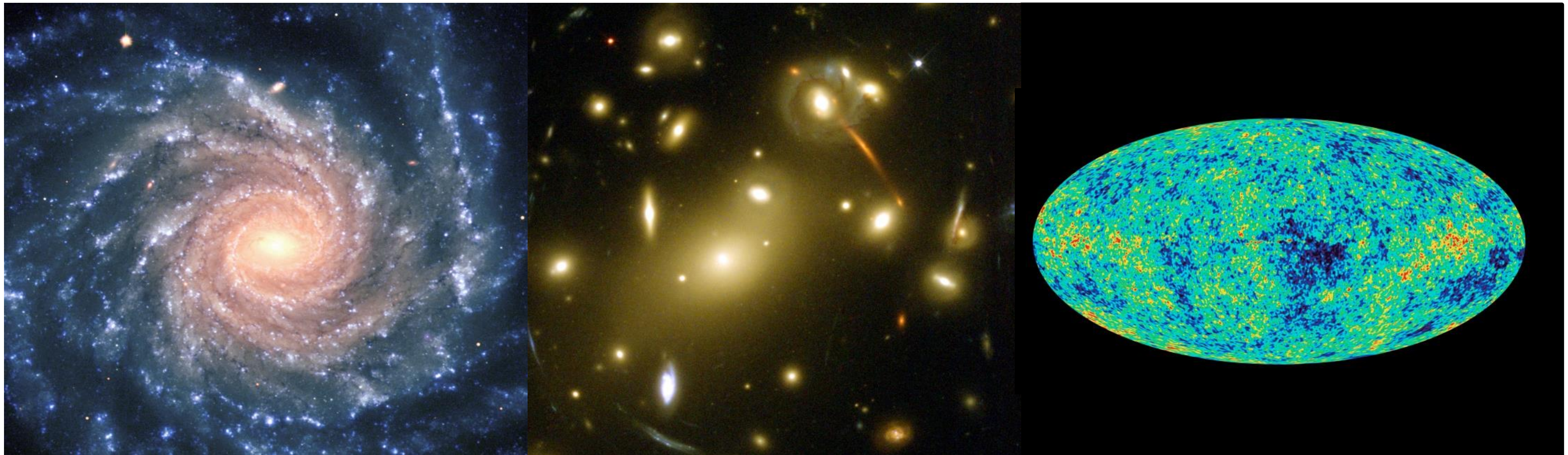
GDR Neutrino Meeting Paris – May 20th 2017

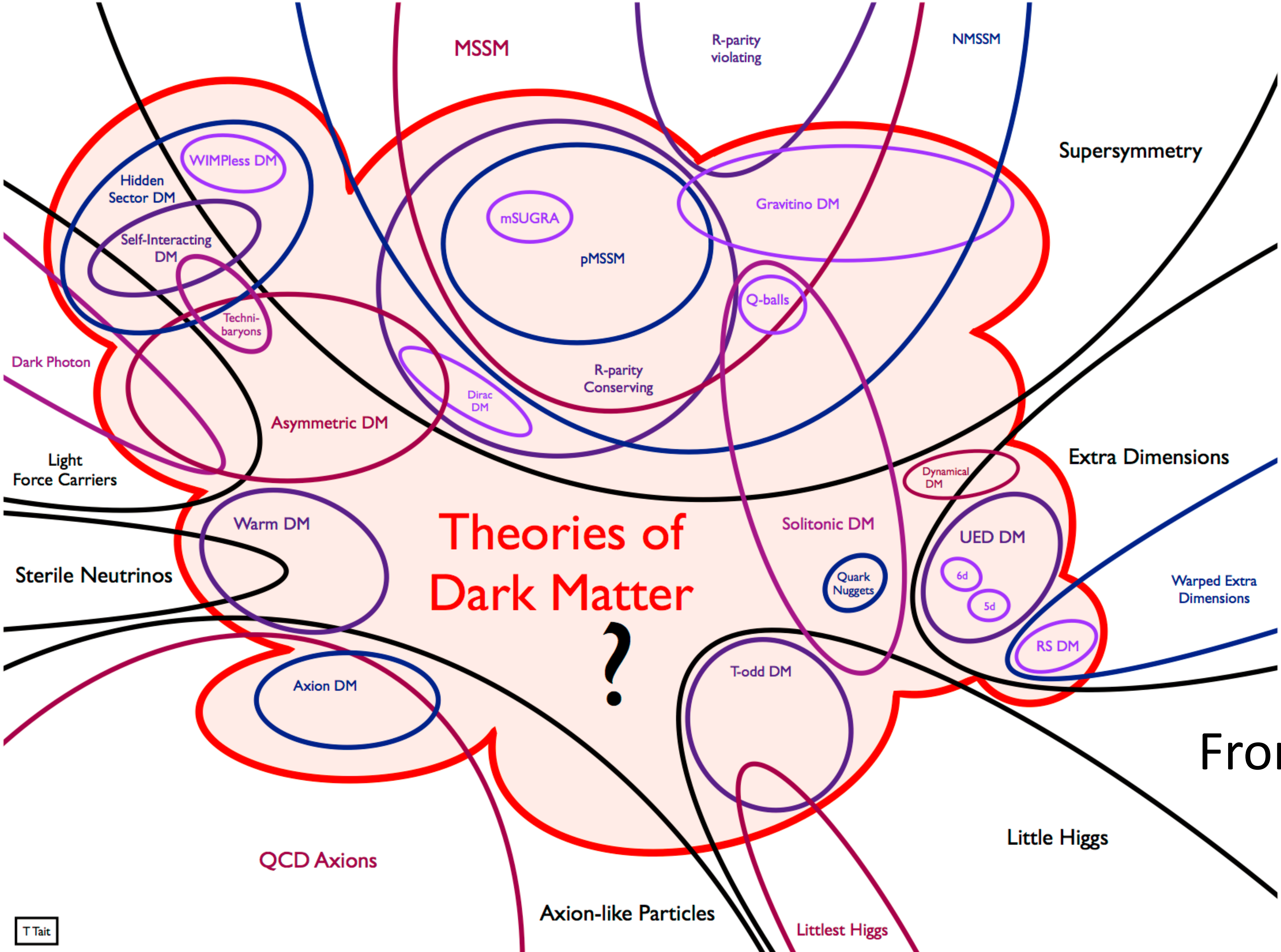
Dark Matter:

Much better at explaining missing matter in the Universe than modified gravity.

Still need dark energy but modified gravity doesn’t solve that problem..







Theories of Dark Matter ?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Dynamical DM

Extra Dimensions

Warm DM

Sterile Neutrinos

Solitonic DM

UED DM

6d

5d

Quark Nuggets

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

QCD Axions

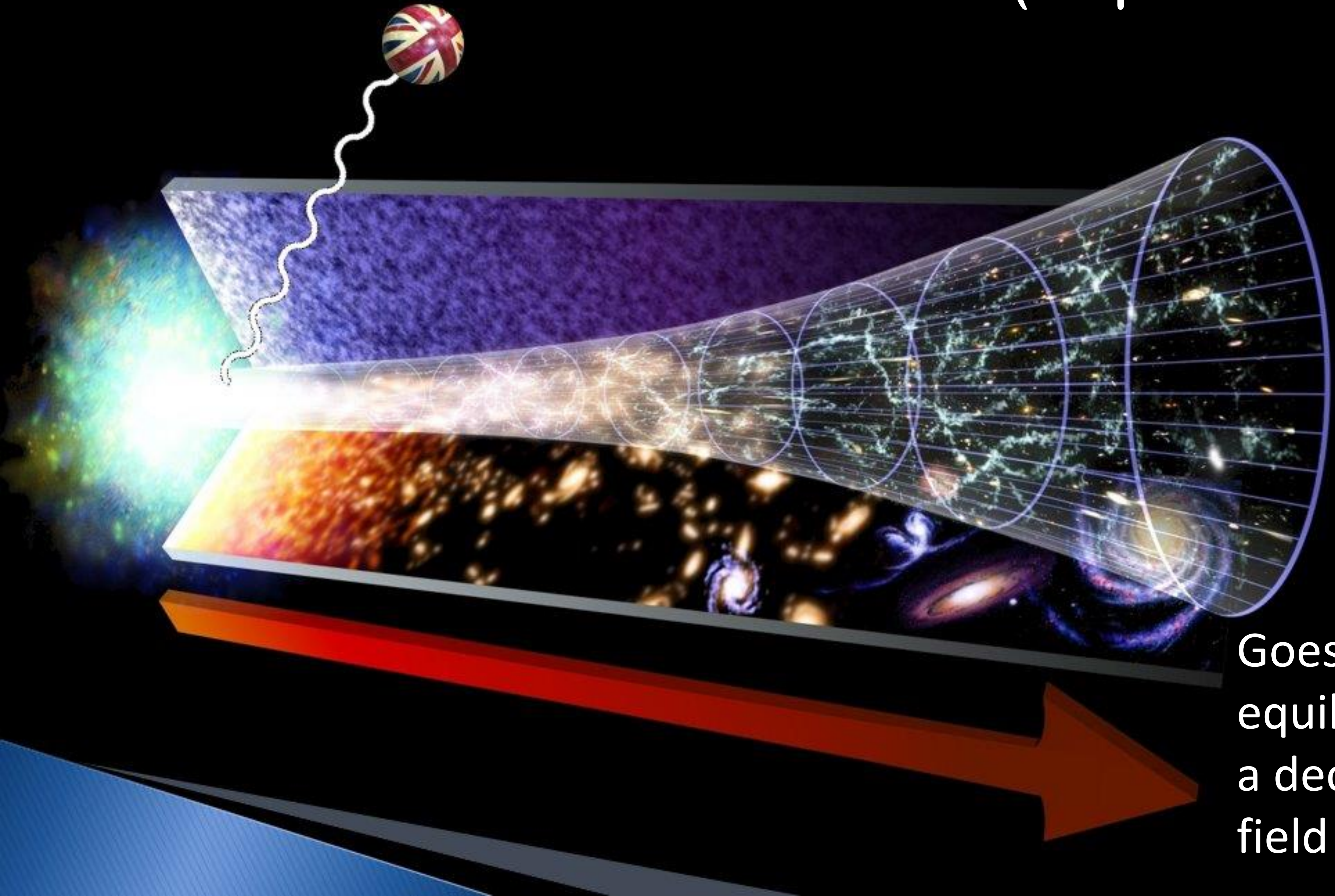
Axion-like Particles

Littlest Higgs

T Tait

From Tim Tait

The Brexiton (Enqvist 2017, Rajantie 2017)

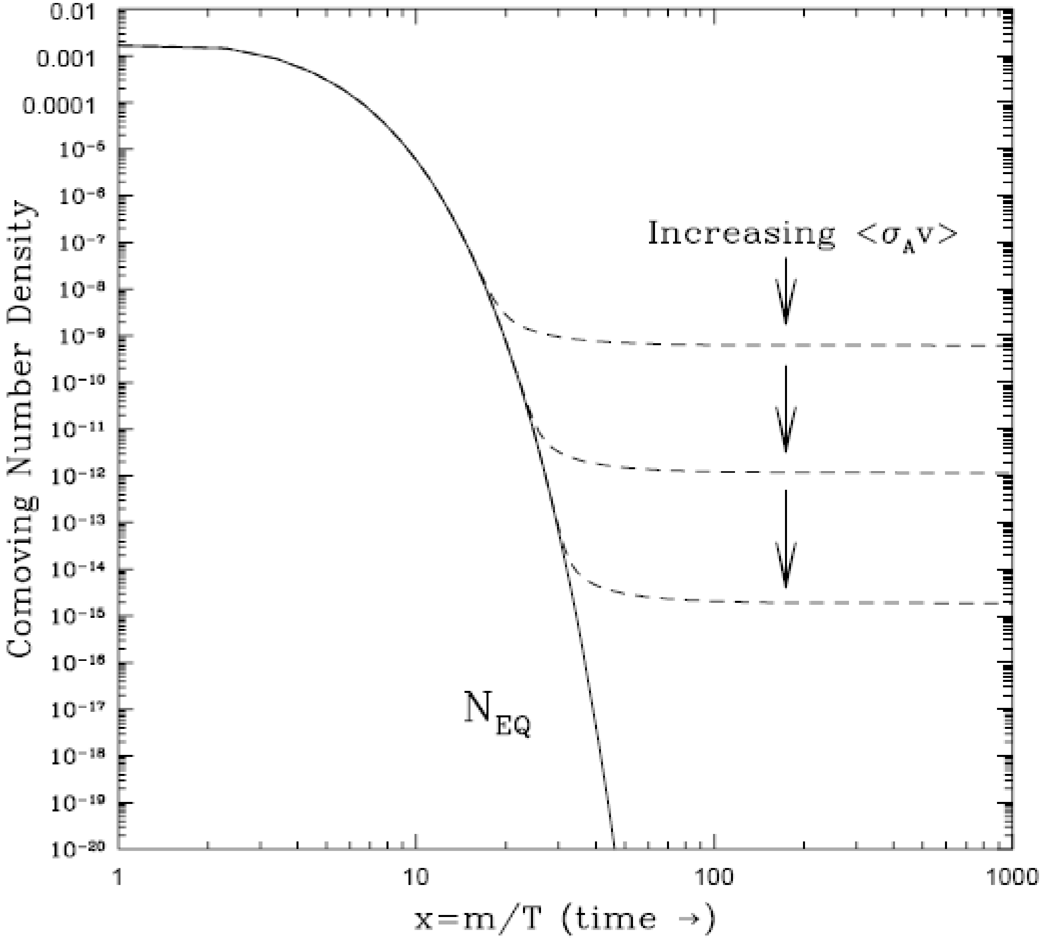


Goes out of thermal equilibrium then acts as a decoupled spectator field while it decays

Thermal Relic Dark Matter

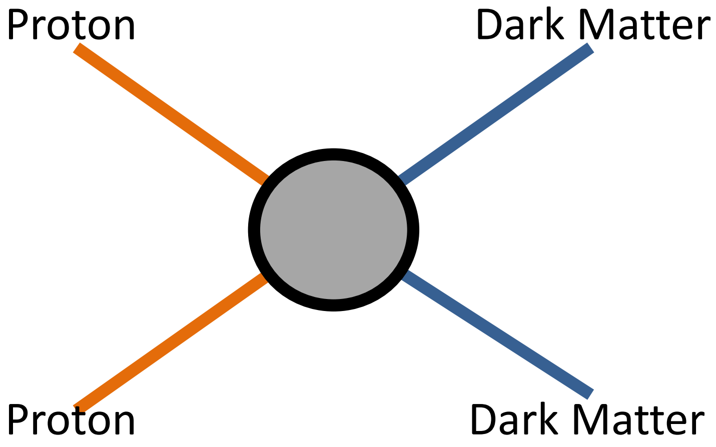
$\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$

$$\Omega_\chi \sim 1$$



Right amount of dark matter if dark matter mass 100 MeV < M < 100 TeV

Ways to Detect Thermal RelicDark Matter –
Make, Shake and Break

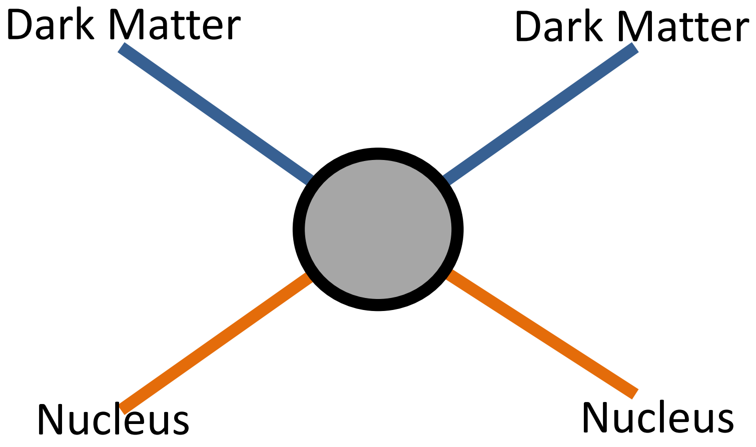

Proton

Dark Matter

Proton

Dark Matter

***Make** – collider production*

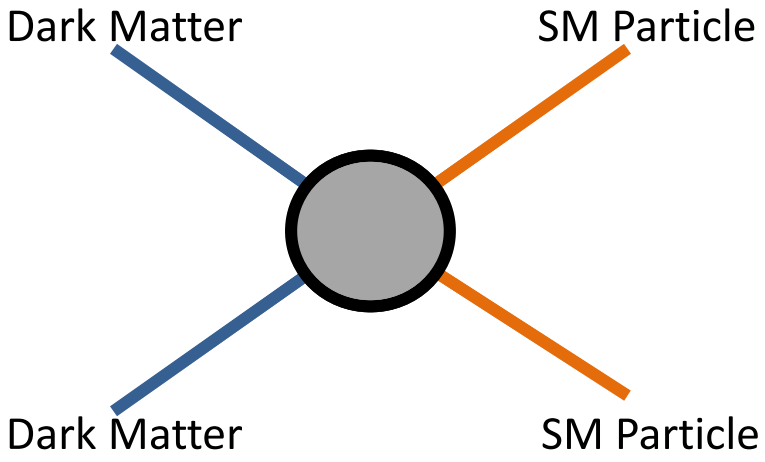

Dark Matter

Dark Matter

Nucleus

Nucleus

***Shake** – direct detection scattering*


Dark Matter

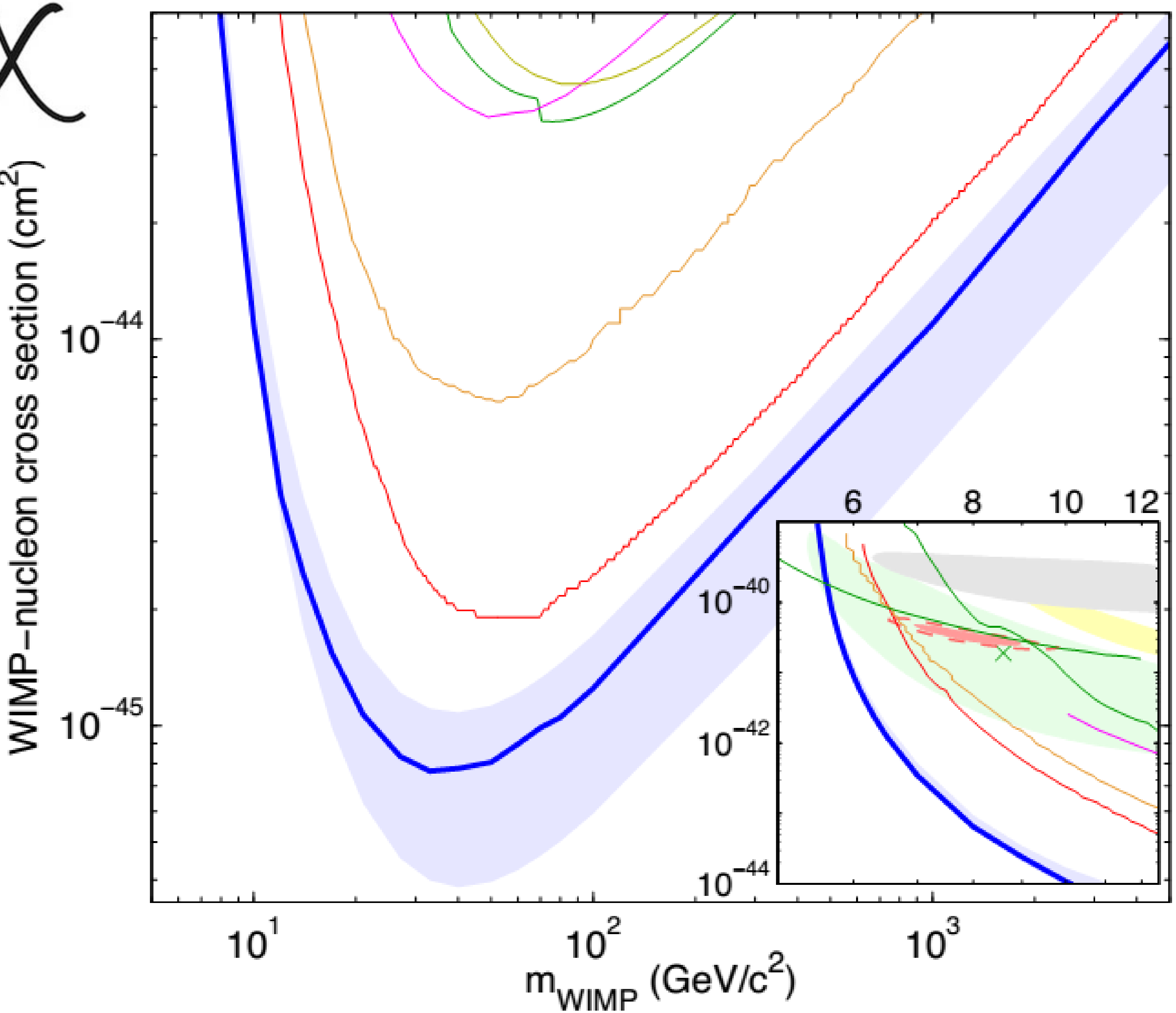
SM Particle

Dark Matter

SM Particle

***Break** – indirect detection of annihilation* lux.brown.edu

LUX



WIMP−nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^1
10^2
10^3
m$_{\mathrm{WIMP}}$ (GeV/c^2)
6
8
10
12
10^{-40}
10^{-42}
10^{-44}

LZ- Lux Zeplin

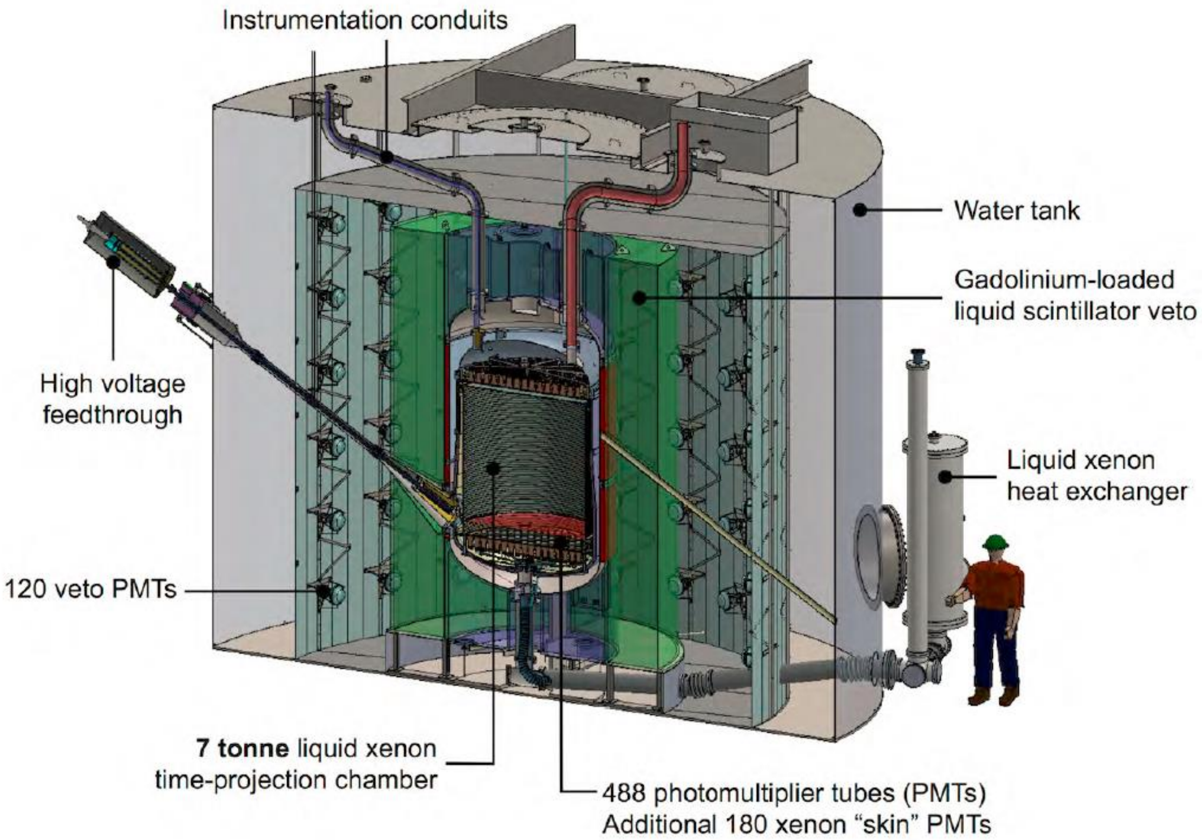
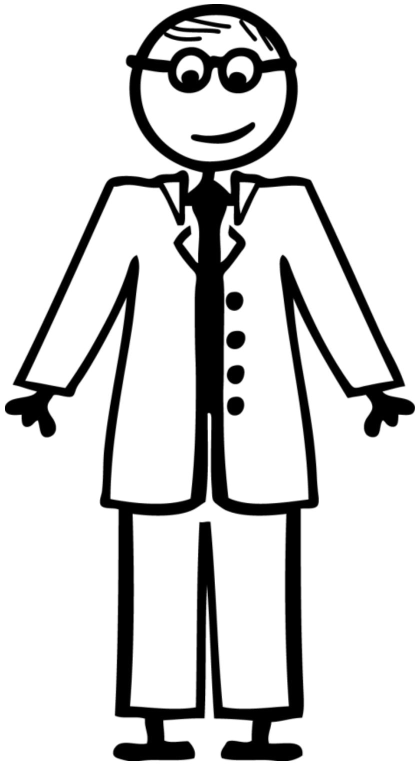


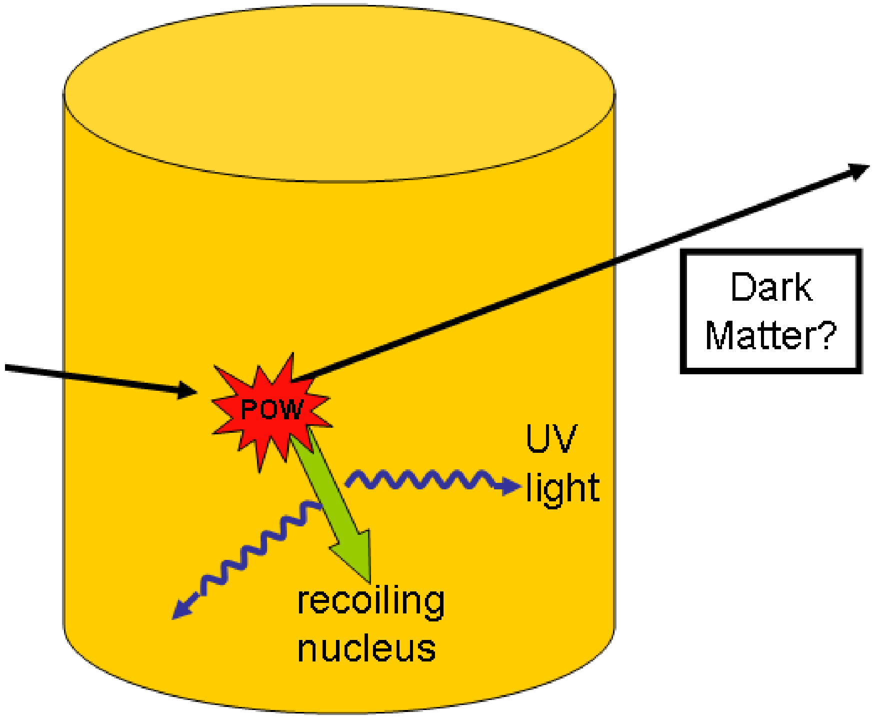
Figure 2.1. LZ detector concept.

Approximately 5 tons of Liquid Xenon, expands and improves on successful LUX design

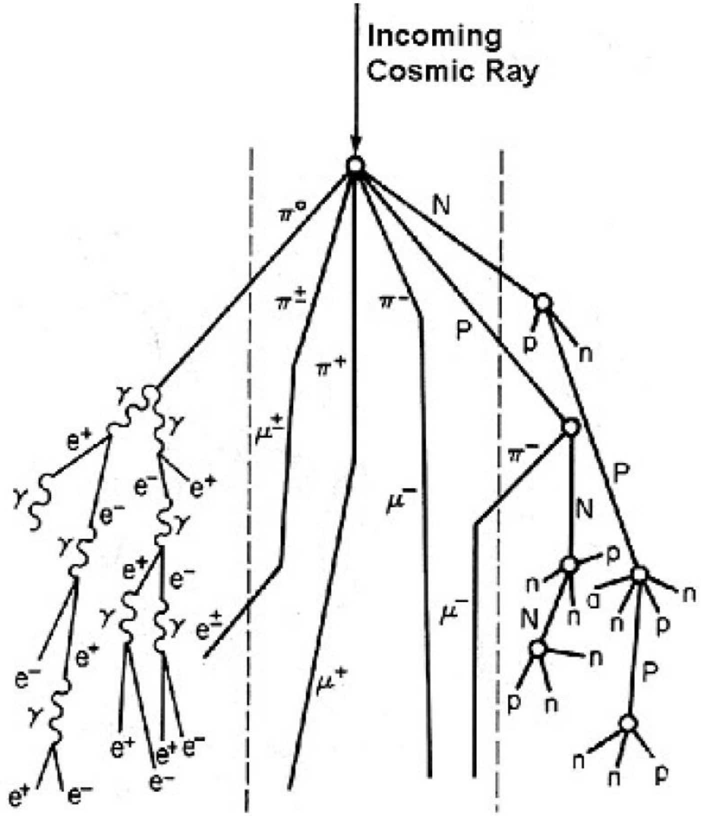
Looks for ionisation and scintillation signal – should start to be installed in 2018, commissioning begins in 2019 in Davis Cavern, Sanford, South Dakota

Surely just a problem of scale?





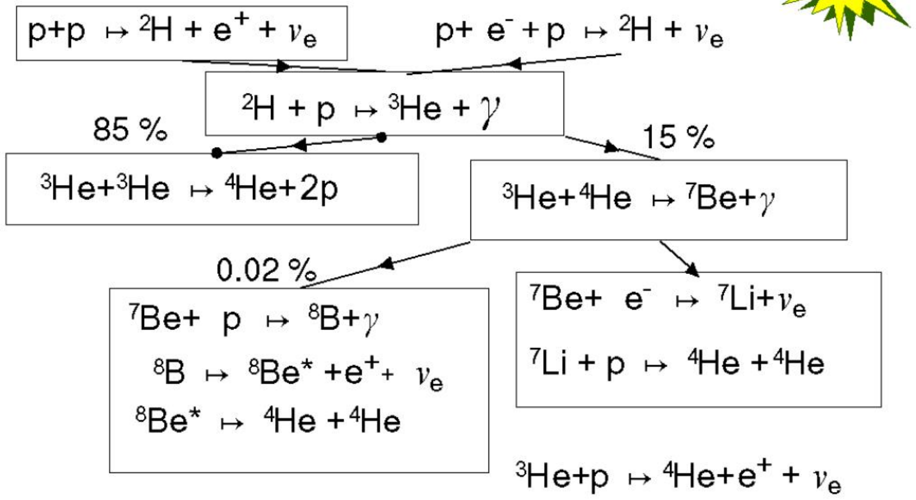
Astrophysical Neutrino Sources



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:



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

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

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

85 %

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

15 %

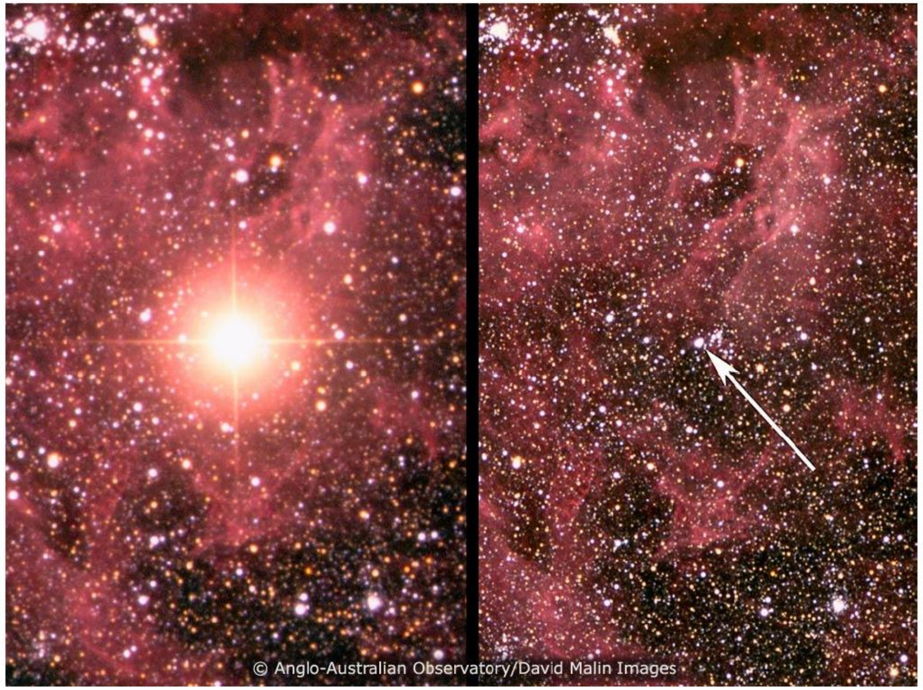
${}^3He+{}^4He \mapsto {}^7Be+\gamma$

0.02 %

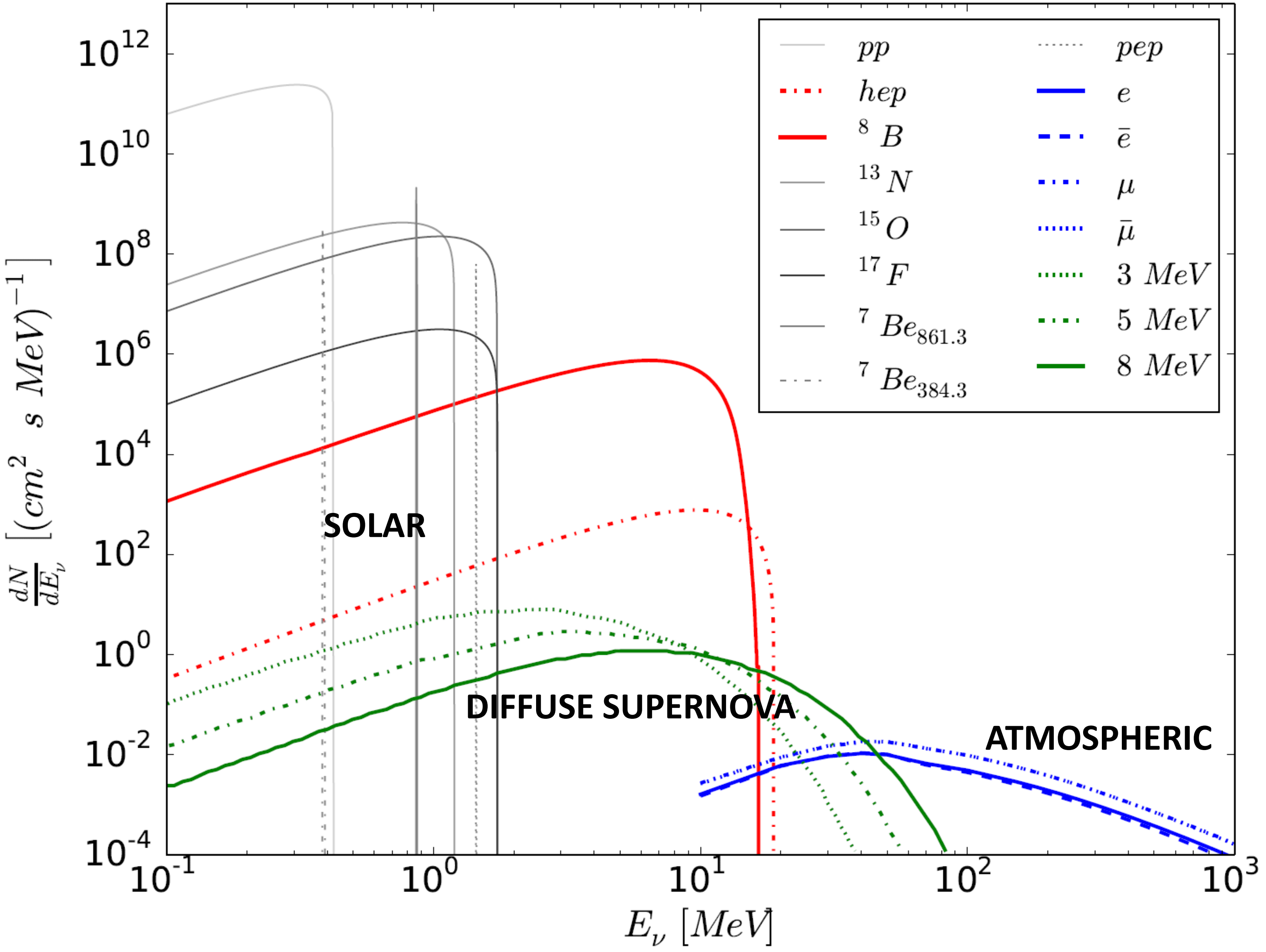
${}^7Be+ p \mapsto {}^8B+\gamma$
${}^8B \mapsto {}^8Be^* +e^+ + \nu_e$
${}^8Be^* \mapsto {}^4He + {}^4He$

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

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

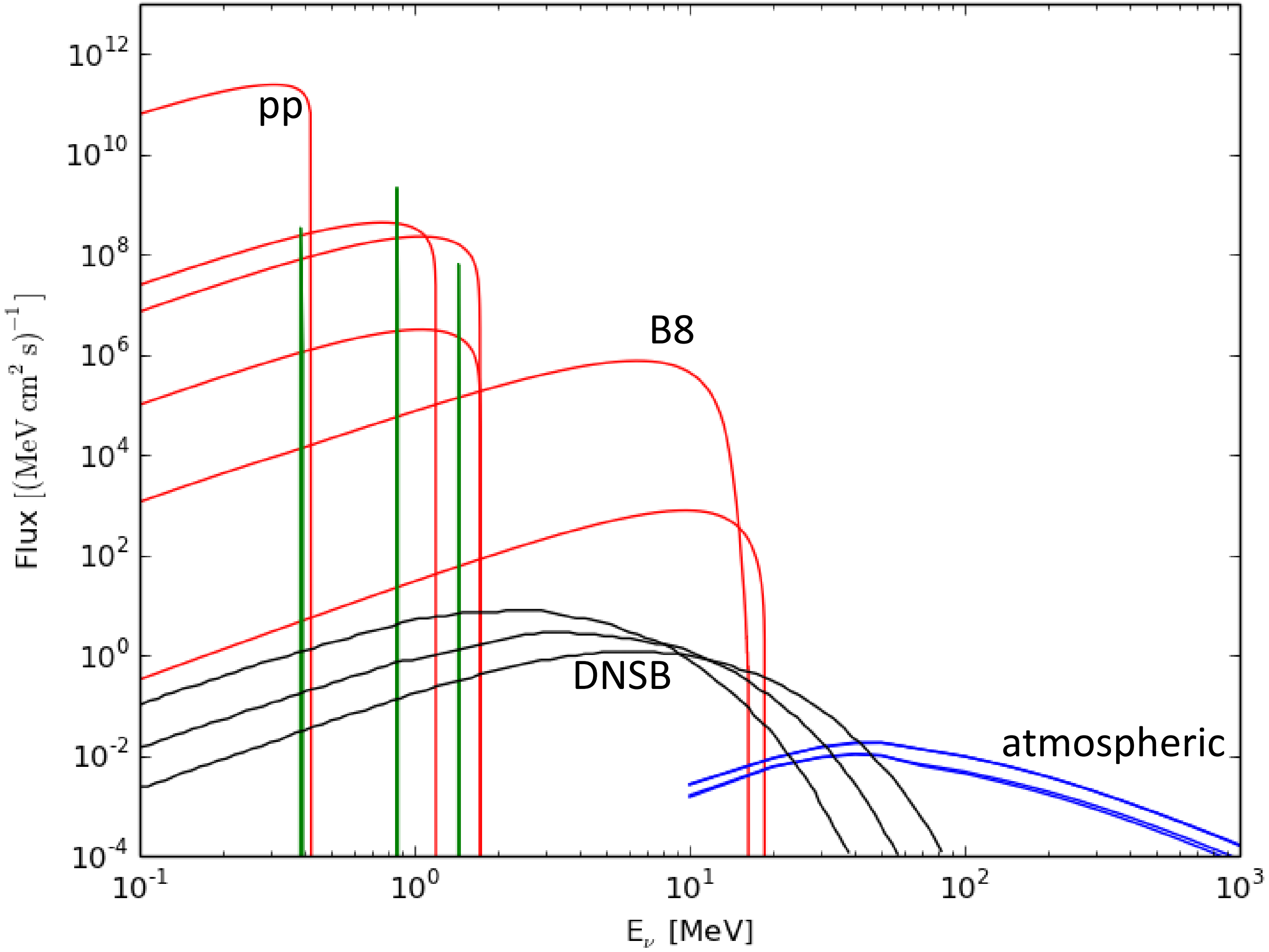

© Anglo-Australian Observatory/David Malin Images

Neutrino Background



Some Numbers

- pp neutrinos scattering off electrons will give recoils up to about 100 keV
- Boron 8 neutrinos scattering off electrons will give recoils up to about 10 MeV
- Boron 8 neutrinos scattering off 100 GeV nuclei will give recoils up to about a few keV (depends a lot on target)



Coherent Neutrino-Nucleon Interactions

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

- Enhanced by factor N^2:

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

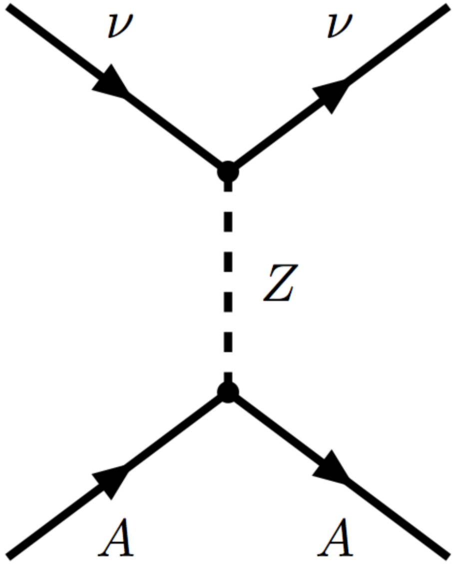
- $\cos\theta$: angle between in- and outgoing neutrino direction
- $2 m_T E_r = q^2 = 2E_\nu^2 (1 - \cos\theta)$

$$\Rightarrow \frac{d\sigma}{dE_{\rm r}} = \frac{G_F^2}{4\pi} Q_W^2 \, m_T \, (1 - \frac{m_T E_{\rm r}}{2E_\nu^2}) \, F(Q^2)^2.$$

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

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

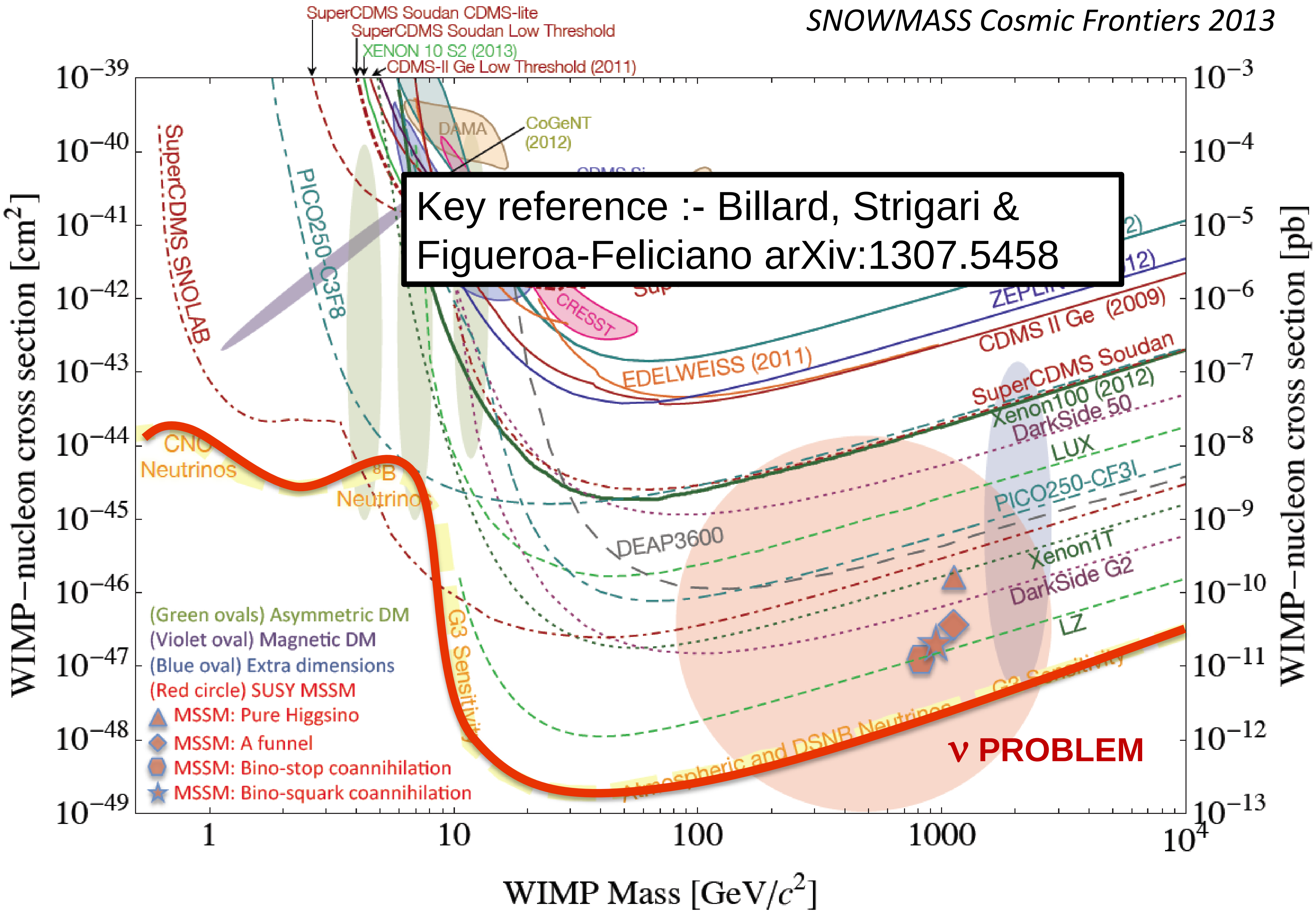
$qR \ll 1$



STILL NOT OBSERVED IN STANDARD MODEL

This now famous plot….

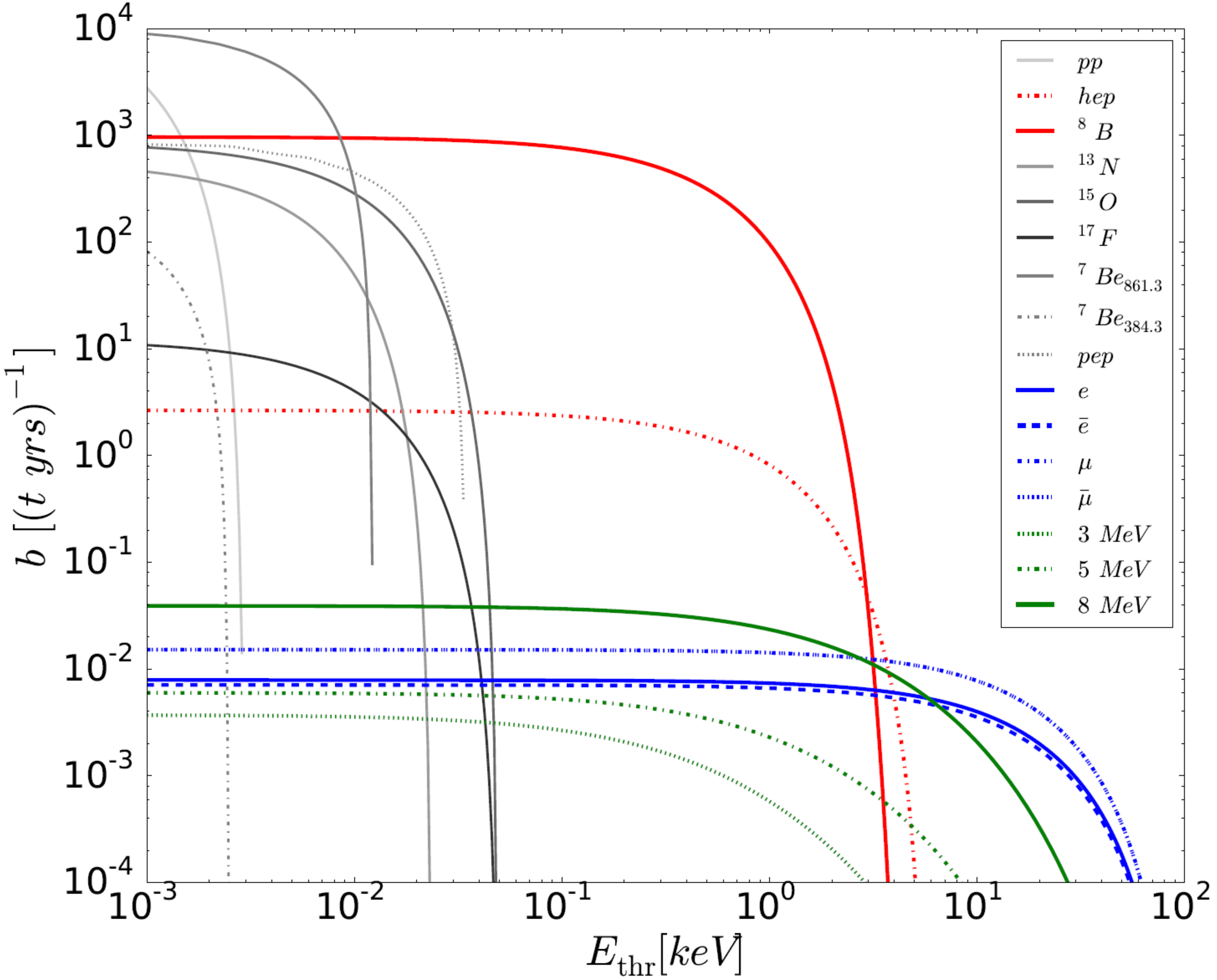
SNOWMASS Cosmic Frontiers 2013



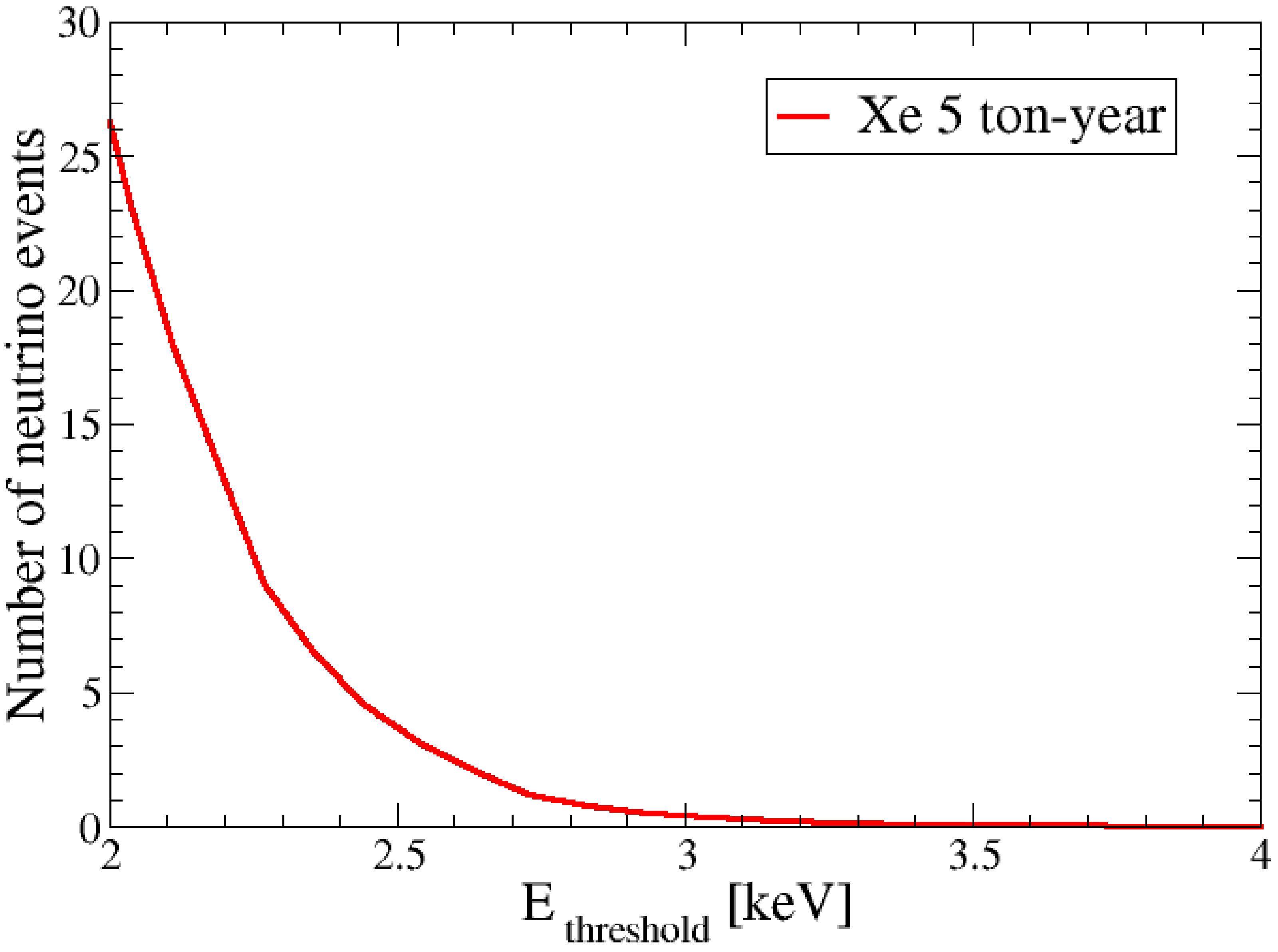
Key reference :- Billard, Strigari & Figueroa-Feliciano arXiv:1307.5458

ν PROBLEM

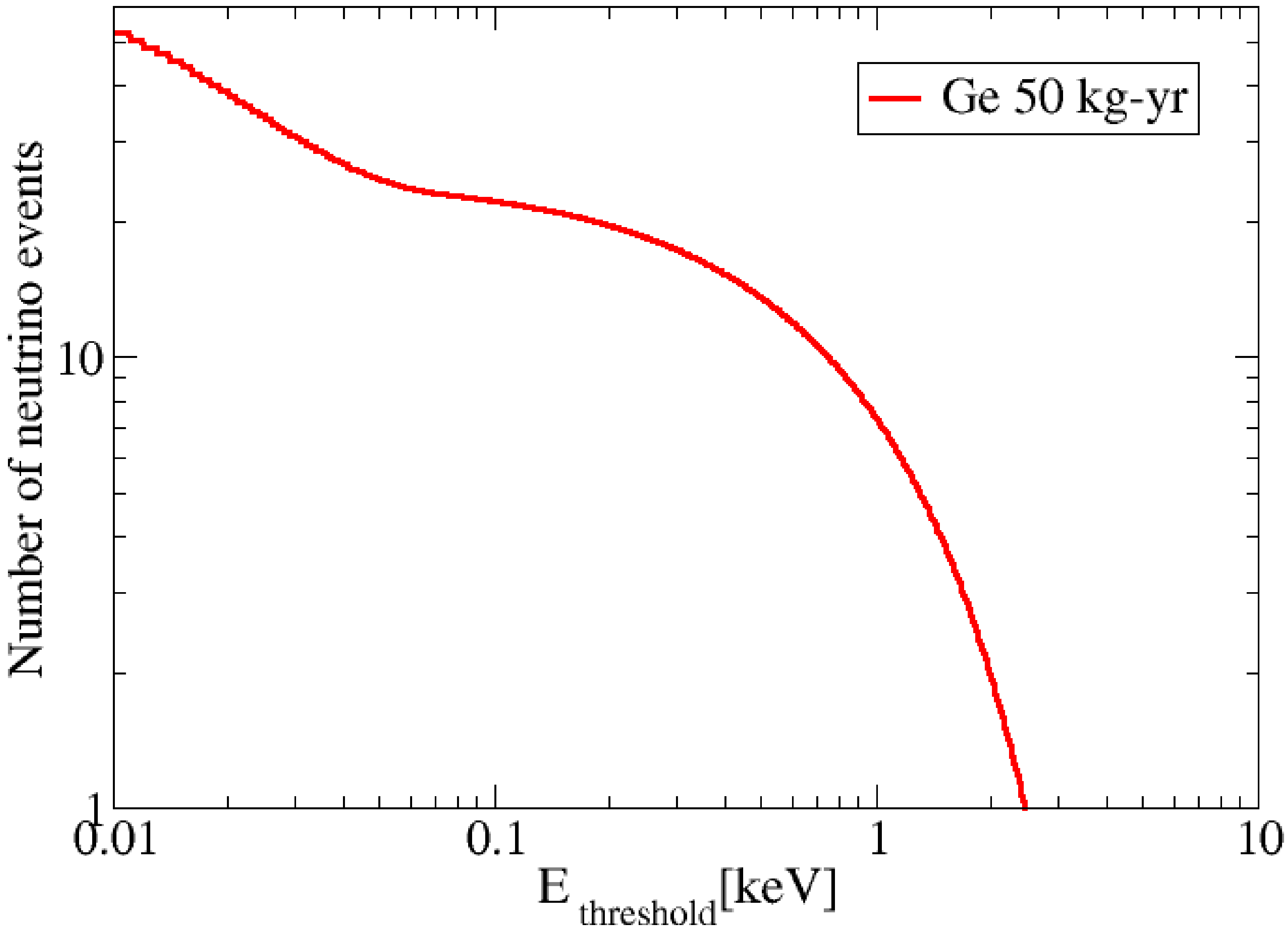
Integrated Event Rate in CF_4 detector above different Thresholds



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)



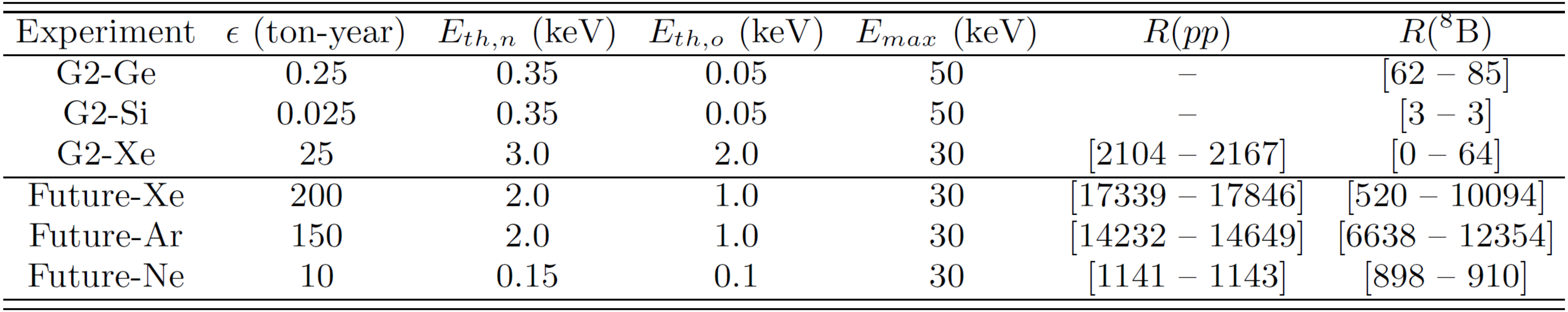
Some detectors which will come online in the next years

Darwin

Proposed 40(ish) ton Xenon experiment.

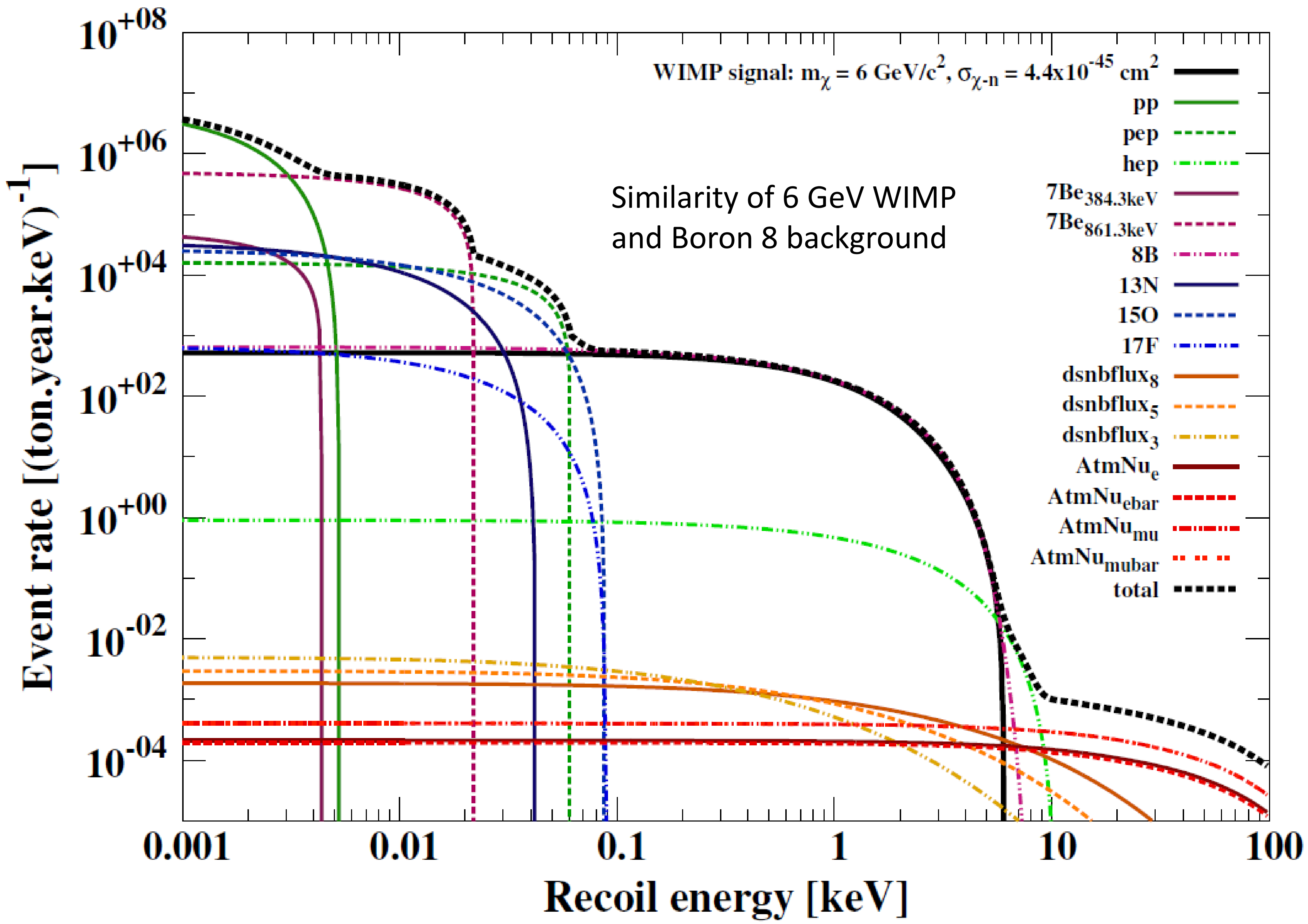
One suggested timeline is that construction begins in 2020+. Was originally going to have a liquid Argon detector with it but that will now be separated off.

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)	$R(pp)$	$R(^8\mathrm{B})$
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]

arXiv:1604.01025



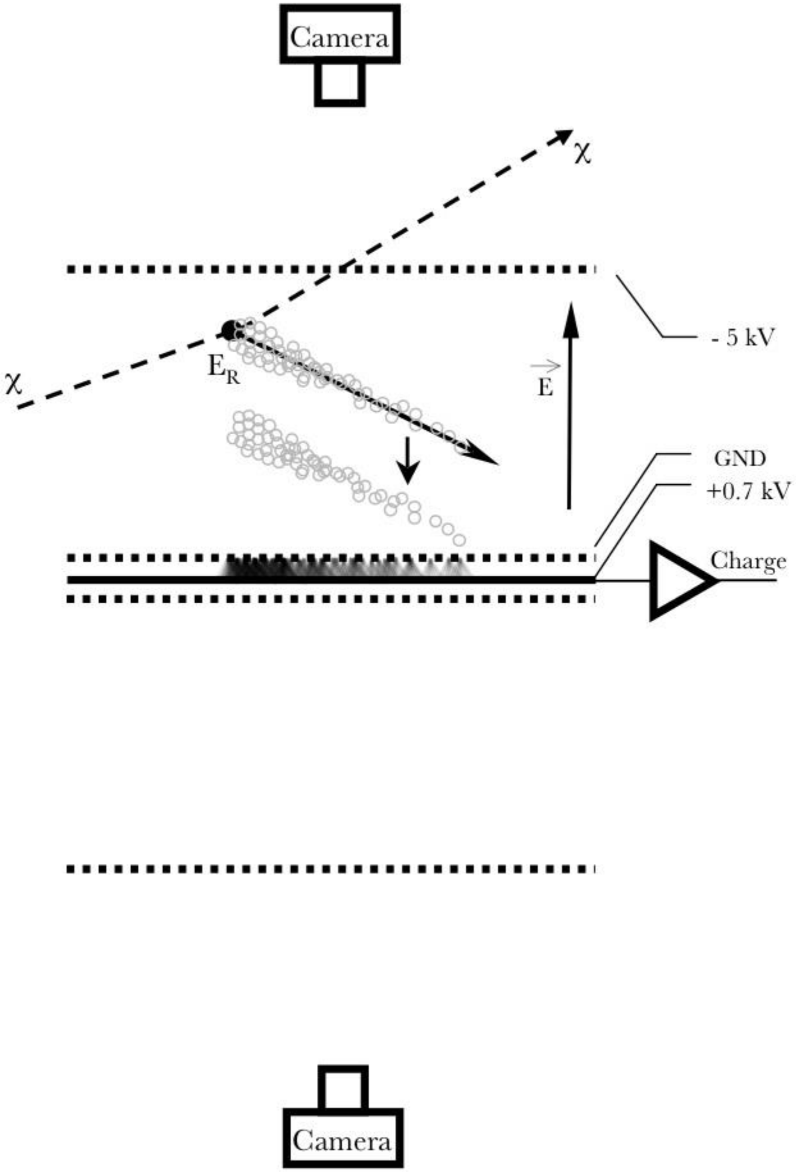
Similarity of 6 GeV WIMP
and Boron 8 background

Ruppin et al 1408.3581

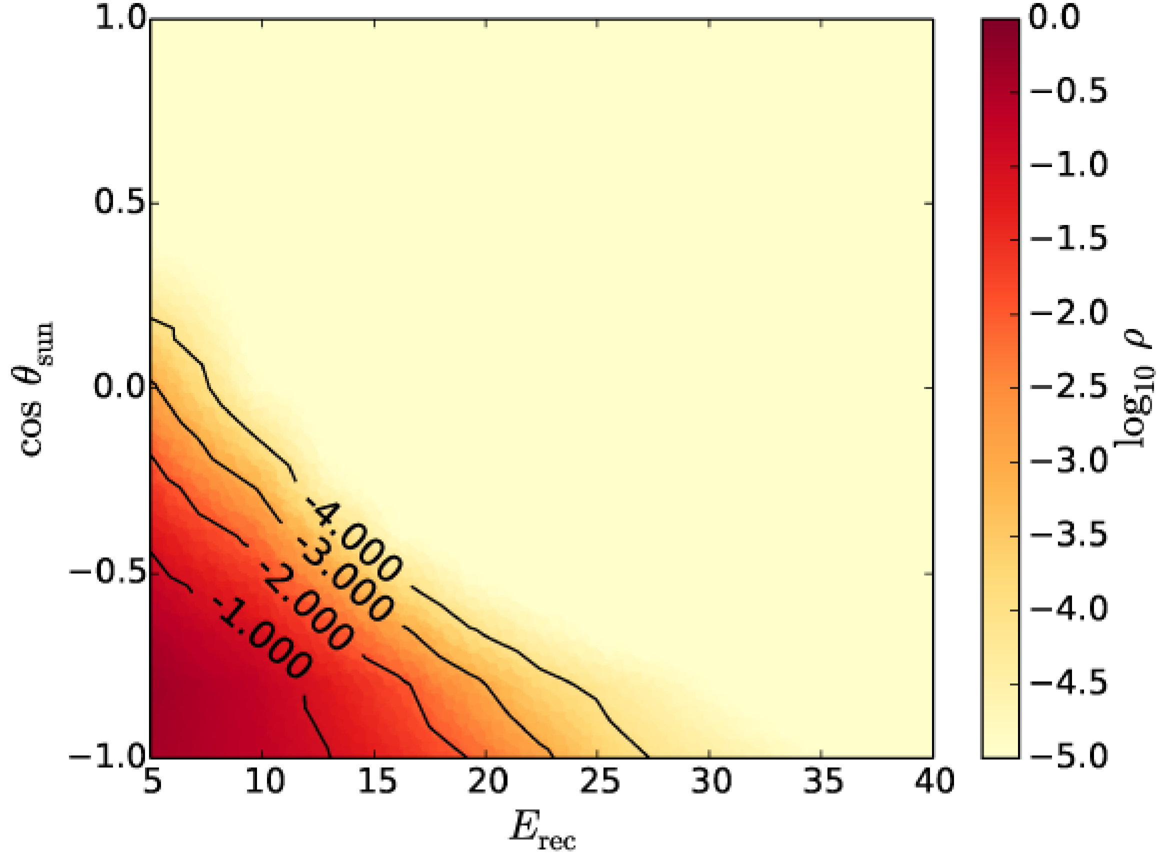
What if we can Tell which direction the dark matter is coming from?

DIRECTIONAL DARK MATTER DETECTION

e.g. DMTPC



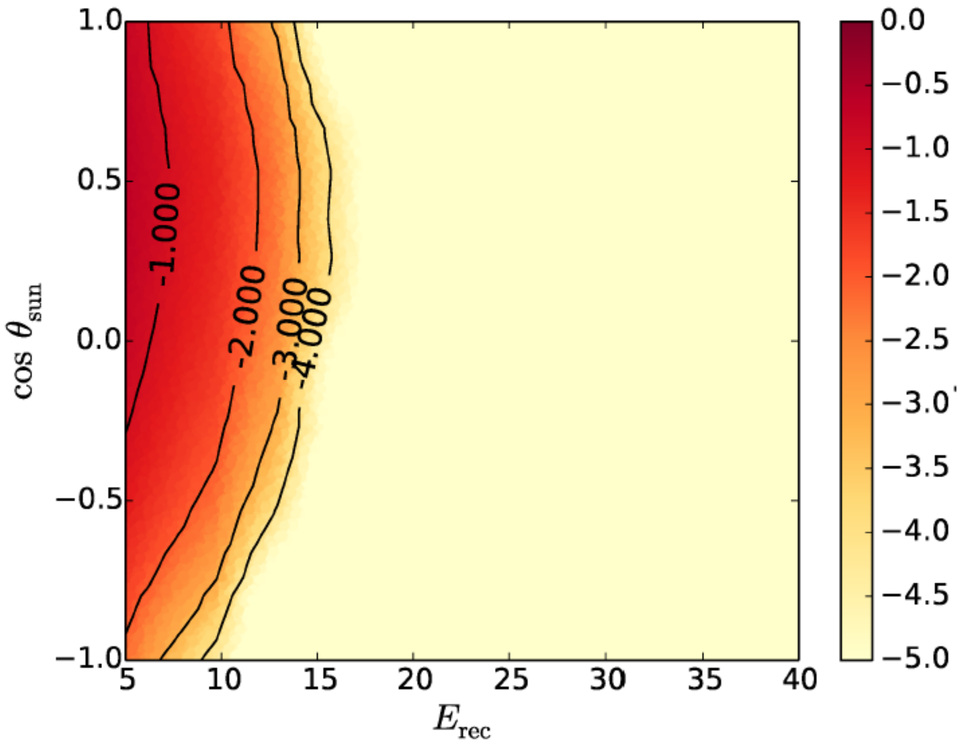
angle between recoil from Solar neutrino and sun

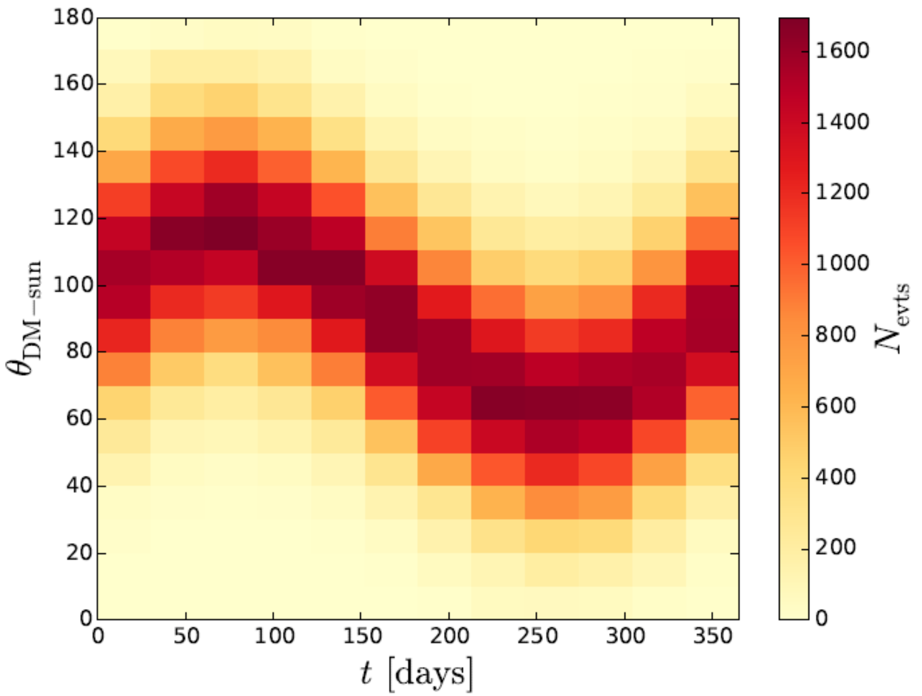


$$\cos\theta' = \frac{E_\nu + m_T}{E_\nu}\sqrt{\frac{E_{\mathrm{r}}}{2m_T}}$$

arXiv:1406.5047

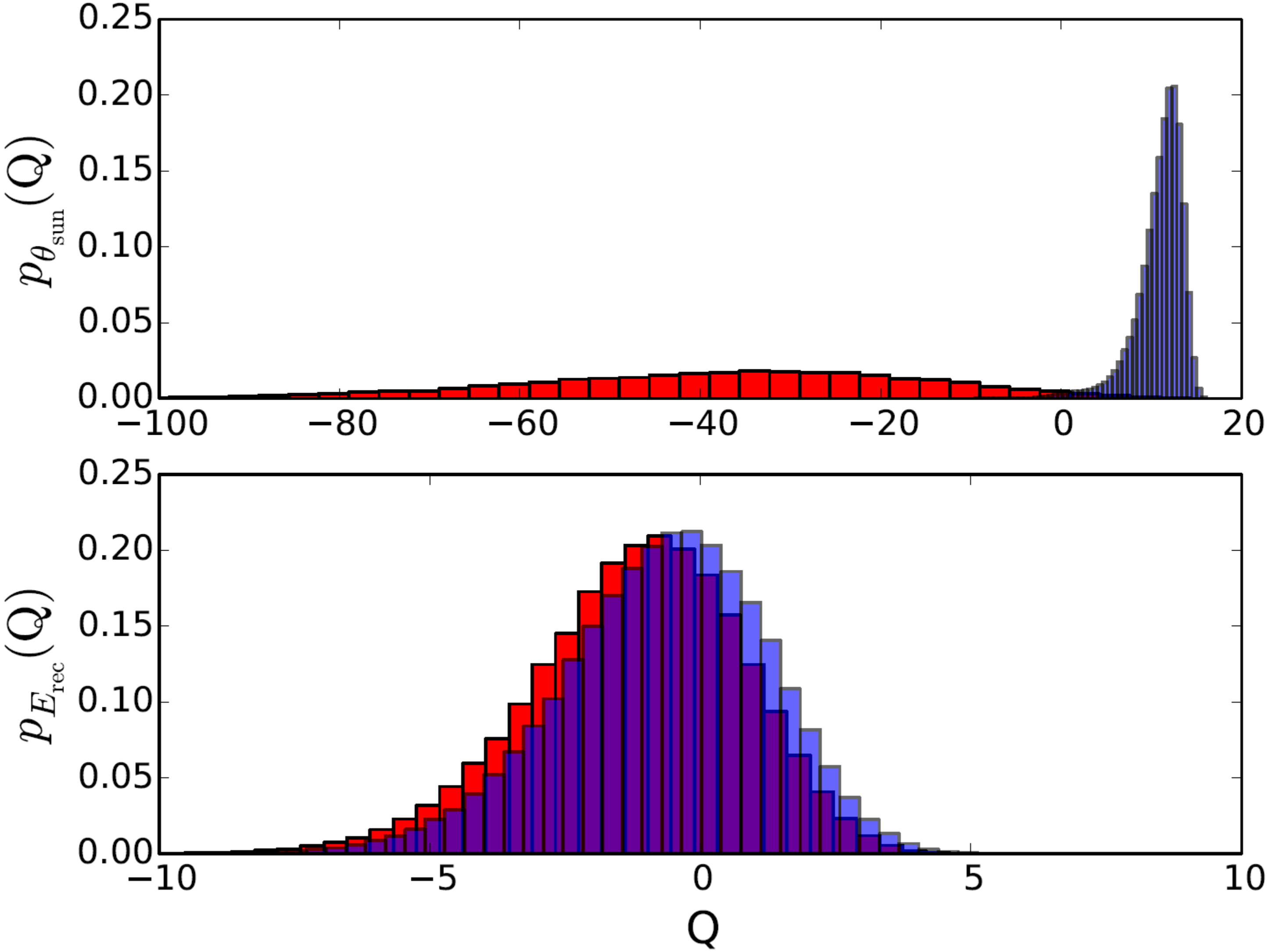
angle between recoil from Dark Matter and sun





- 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



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

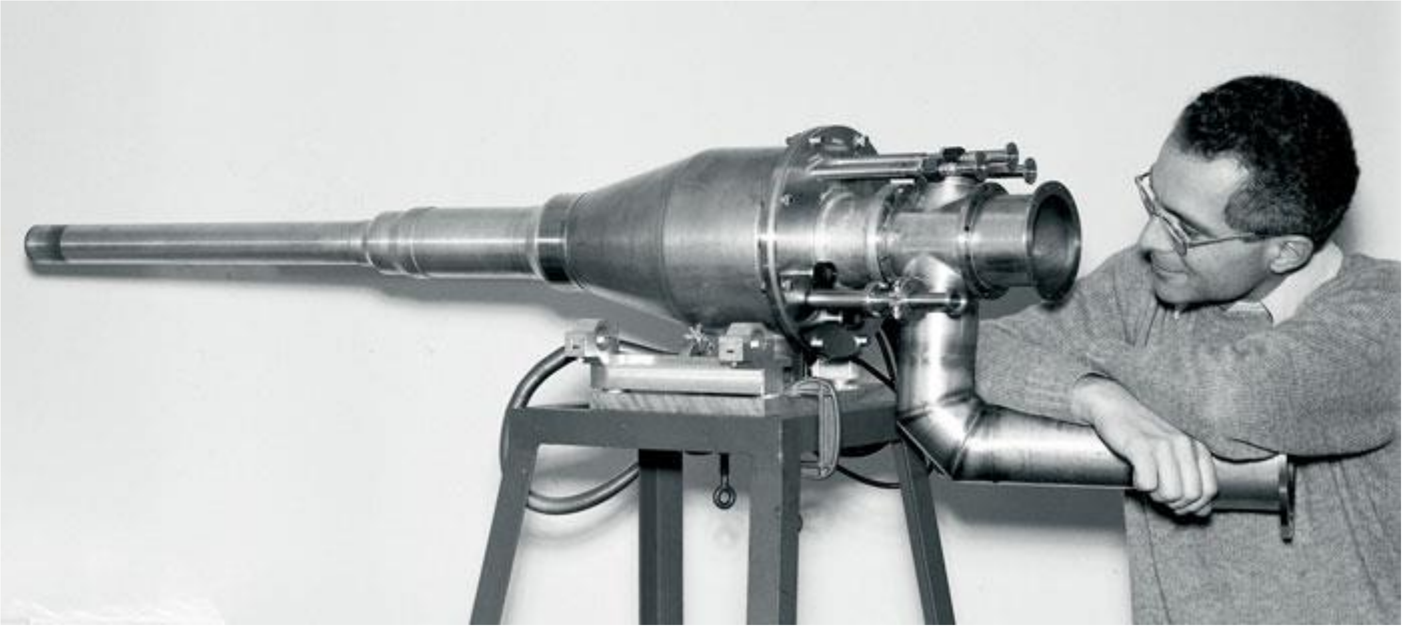
Various Effects, some of which compete with each other:-

- For Low mass DM, only fastest moving particles will give a signal, so that points right back to Cygnus, easy to discriminate from the Sun

- High mass DM can give a signal for DM coming from all directions so directionality less important, but it has an energy spectrum quite different from solar neutrinos

- Higher energy recoil tracks have a much better directional angle reconstruction

Interesting Possibility – Polarised targets



Michel Borghini with a polarized target at CERN in 1976.

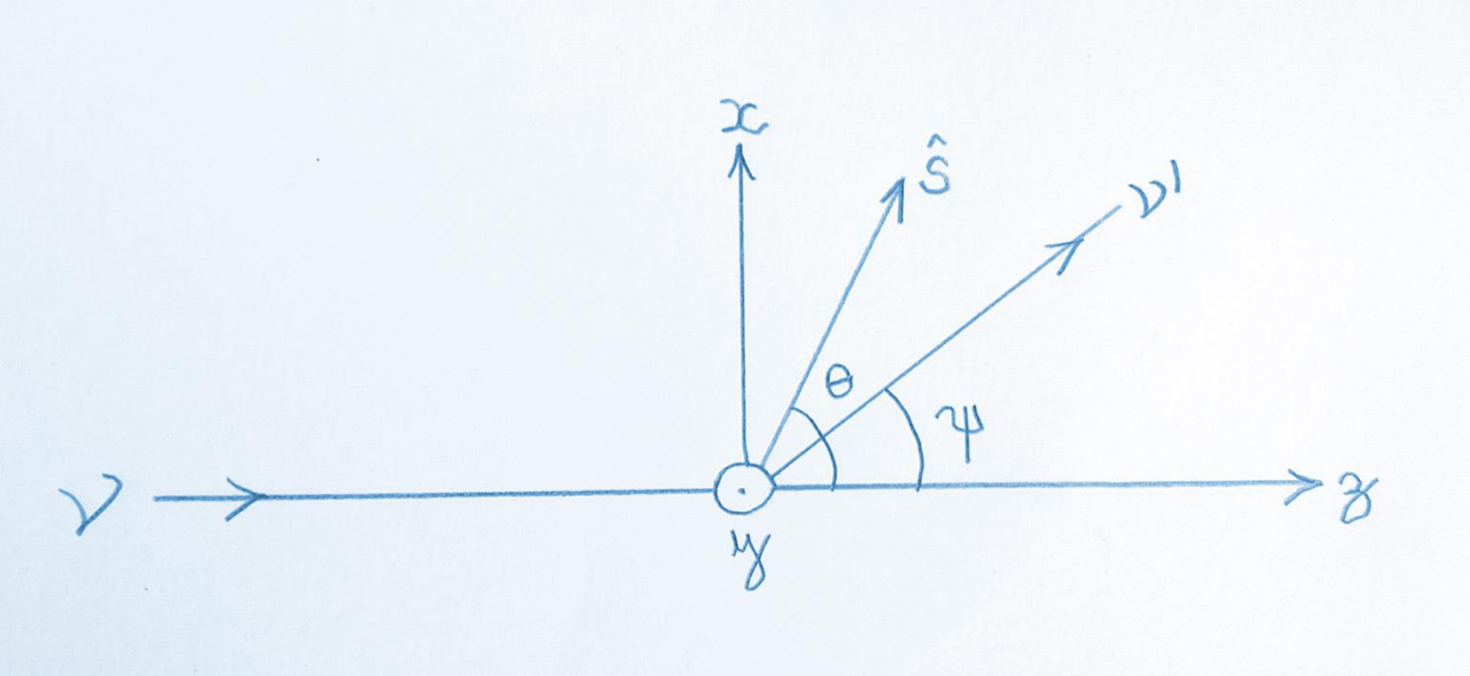
see also

“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

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

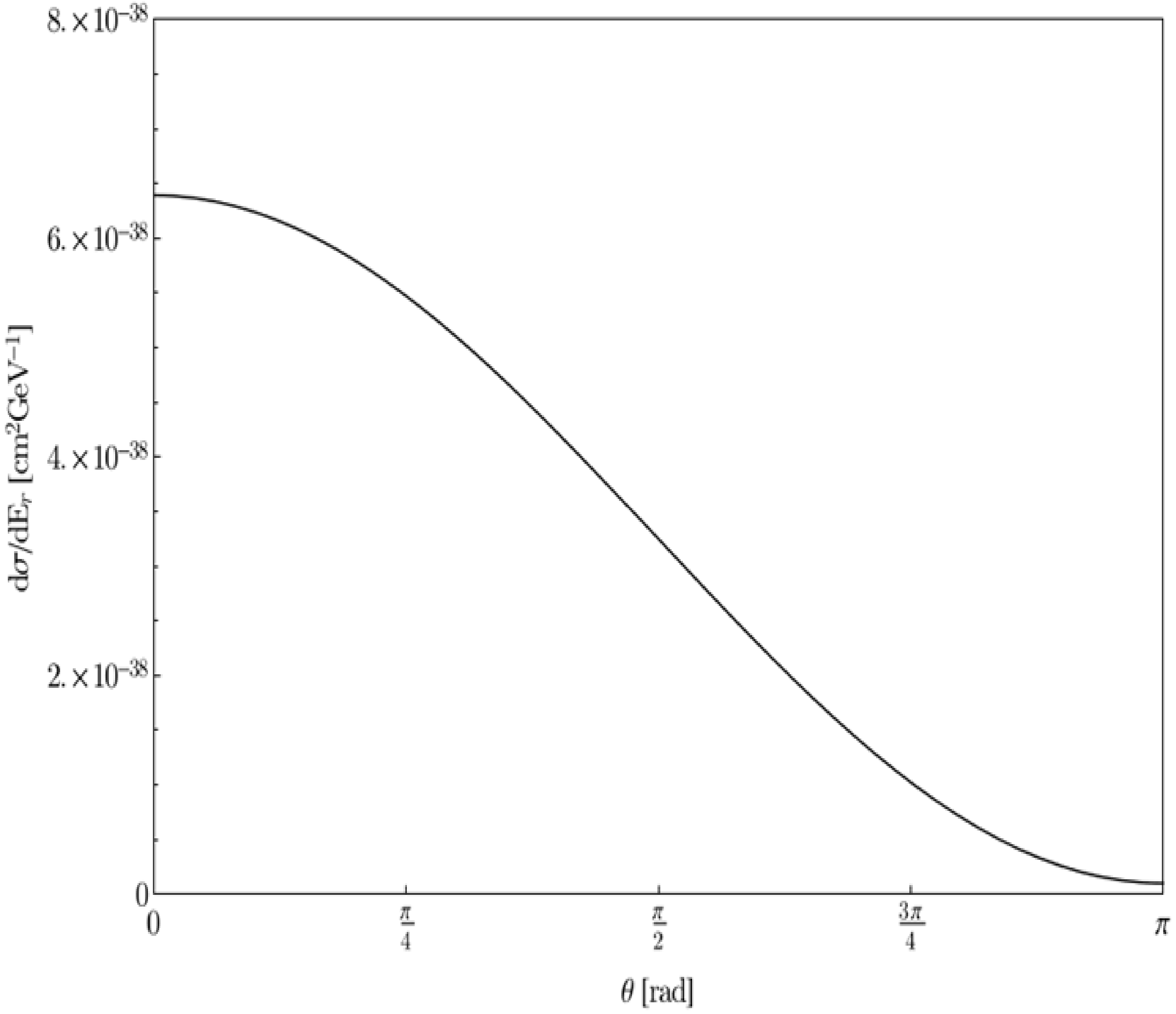
$$c_V^{\text{nucleus}} = Zc_V^p + Nc_V^n$$

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

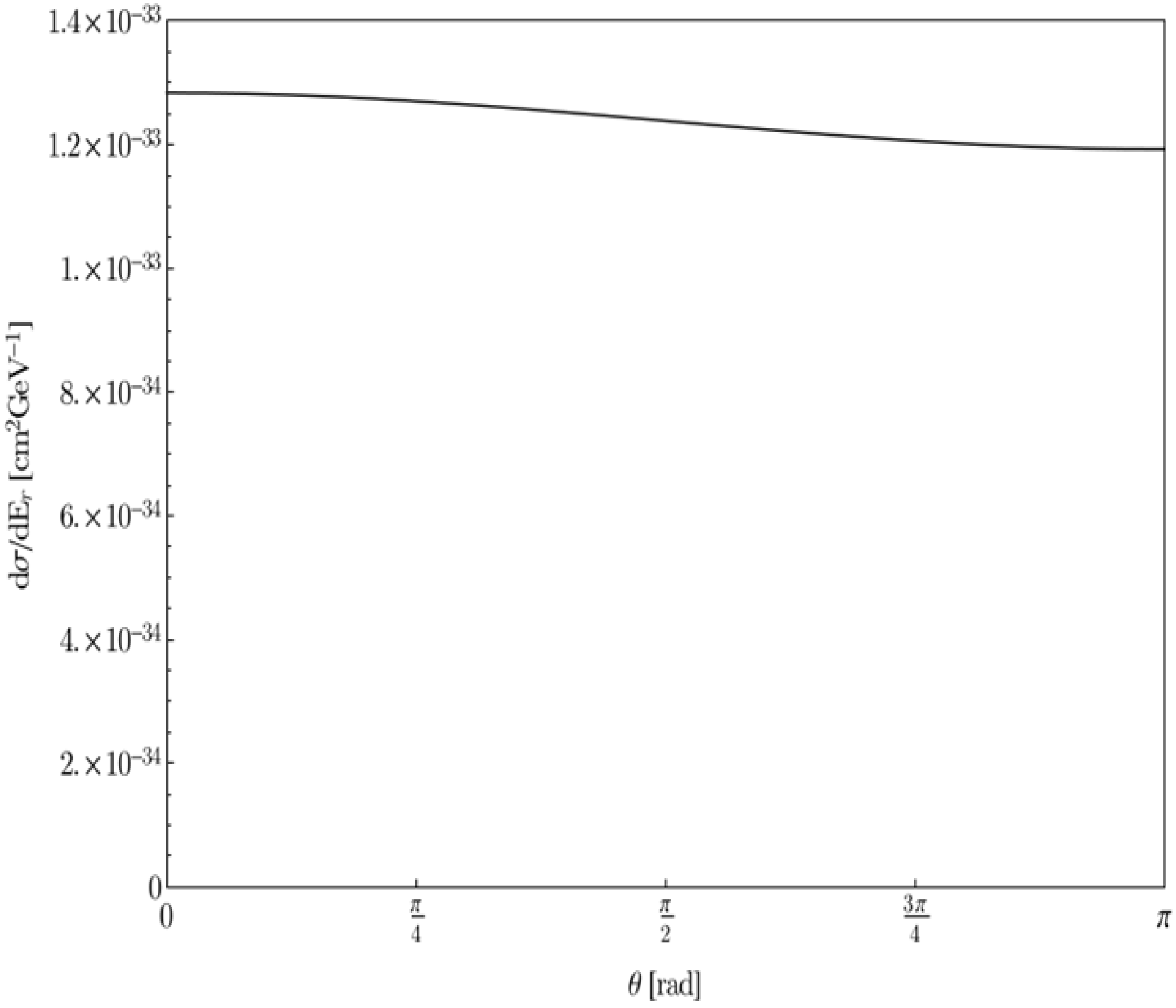
	c_V	c_A
Proton	$1 - 4\sin^2\theta_W$	1.26
Neutron	-1	-1.26

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

Some obvious problems with Helium-3

- Tritium contamination would be a major background

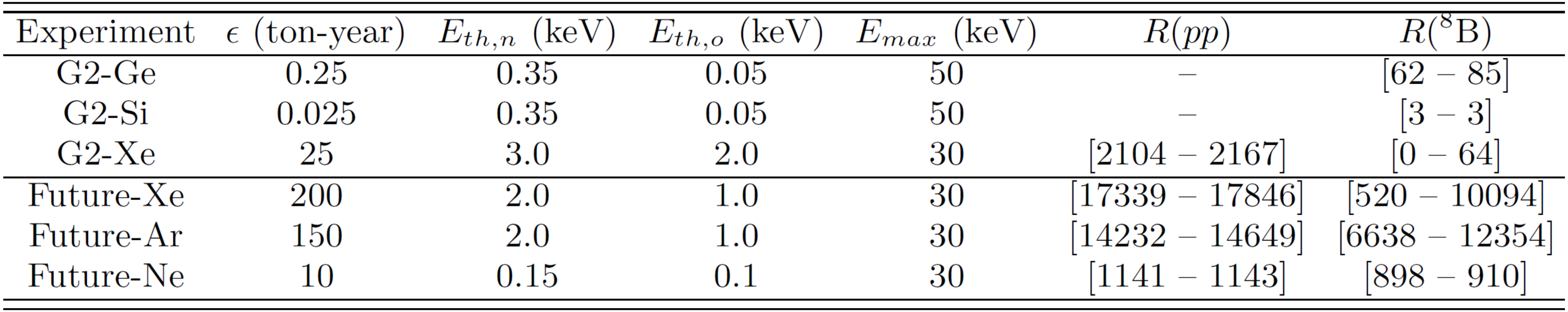
- Simplest Polarisation scheme for He-3 for NMR uses potassium and/or rubidium, both of which are potential contaminants

- 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
$^{3}\mathrm{He}$	0.97
$^{13}\mathrm{C}$	0.41
$^{15}\mathrm{N}$	0.36
$^{19}\mathrm{F}$	0.22
$^{129}\mathrm{Xe}$	0.04

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

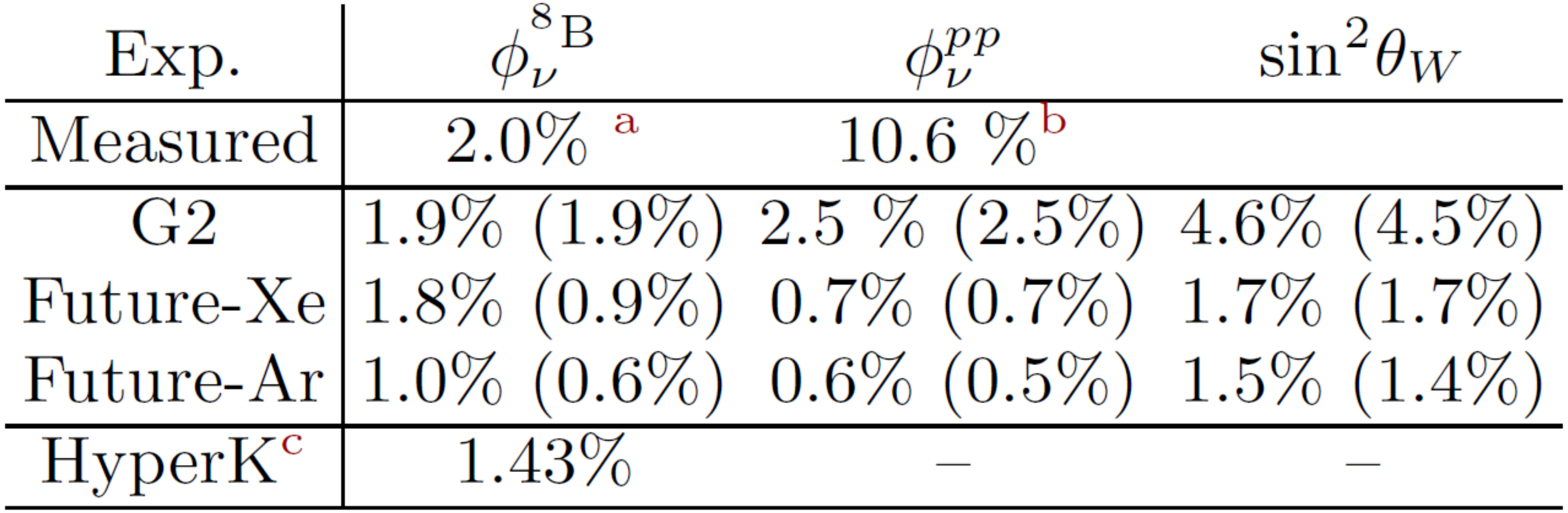


Experiment	ϵ (ton-year)	$E_{th,n}$ (keV)	$E_{th,o}$ (keV)	E_{max} (keV)	$R(pp)$	$R(^8\mathrm{B})$
G2-Ge	0.25	0.35	0.05	50	–	[62 – 85]
G2-Si	0.025	0.35	0.05	50	–	[3 – 3]
G2-Xe	25	3.0	2.0	30	[2104 – 2167]	[0 – 64]
Future-Xe	200	2.0	1.0	30	[17339 – 17846]	[520 – 10094]
Future-Ar	150	2.0	1.0	30	[14232 –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

arXiv:1604.01025

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

Can measure the Weinberg angle at very low energies



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

Measure Boron-8 flux using nuclear recoils and pp flux using electron recoils

arXiv:1604.01025

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

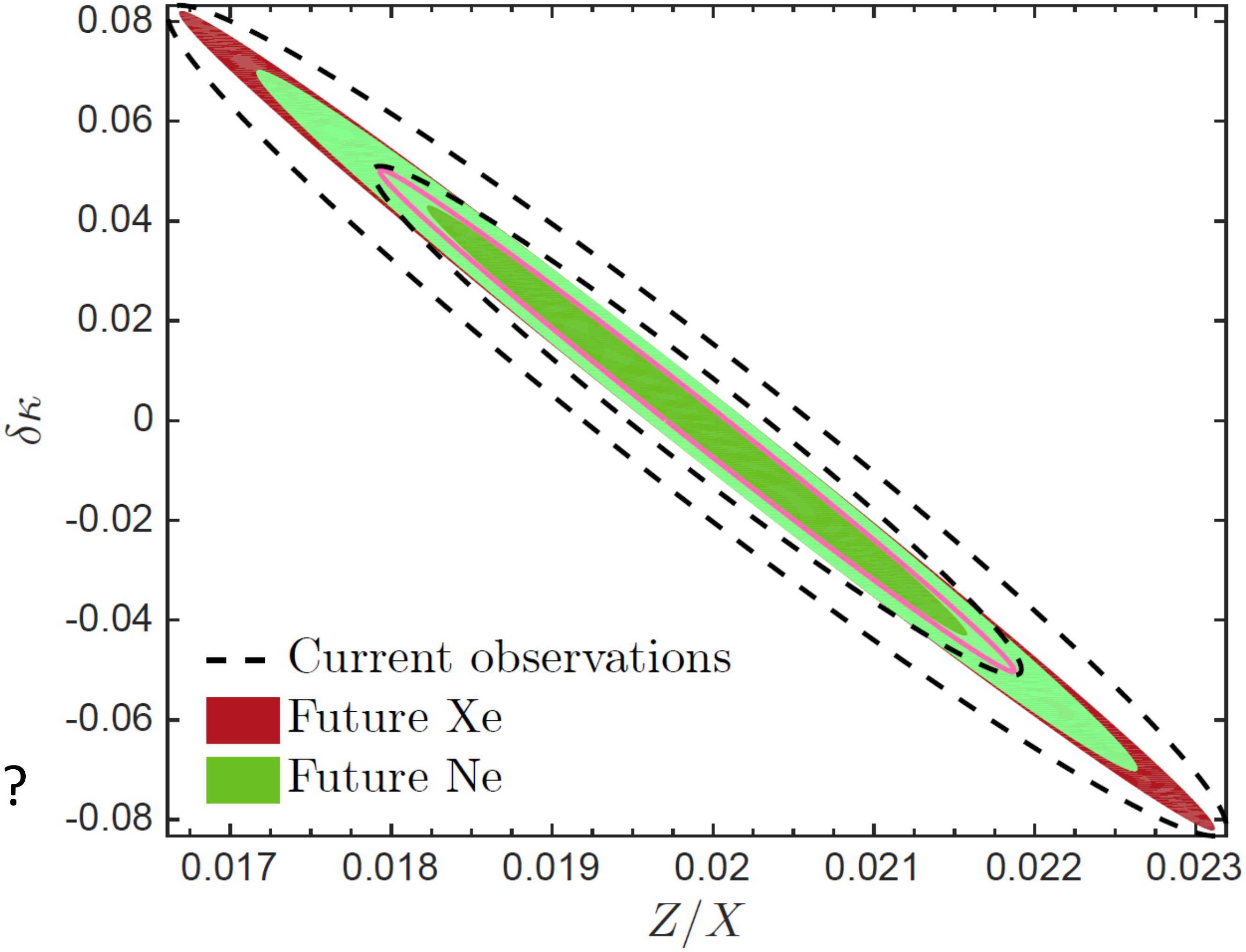
Limits average opacity vs. metallicity

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

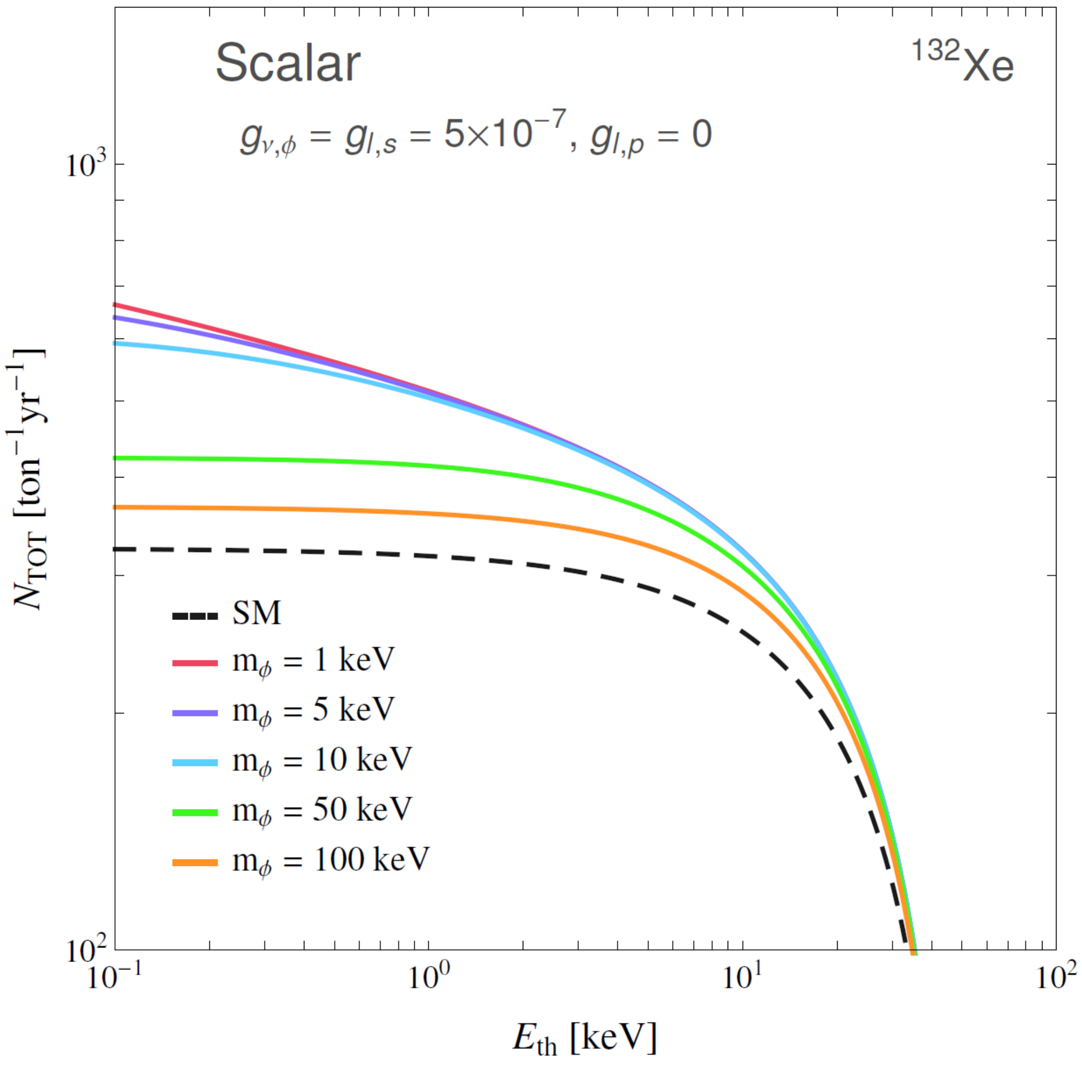
Momentum exchanged for pp-neutrino electron events is around 10 keV

Momentum exchanged for neutrino-nucleon events is about MeV scale

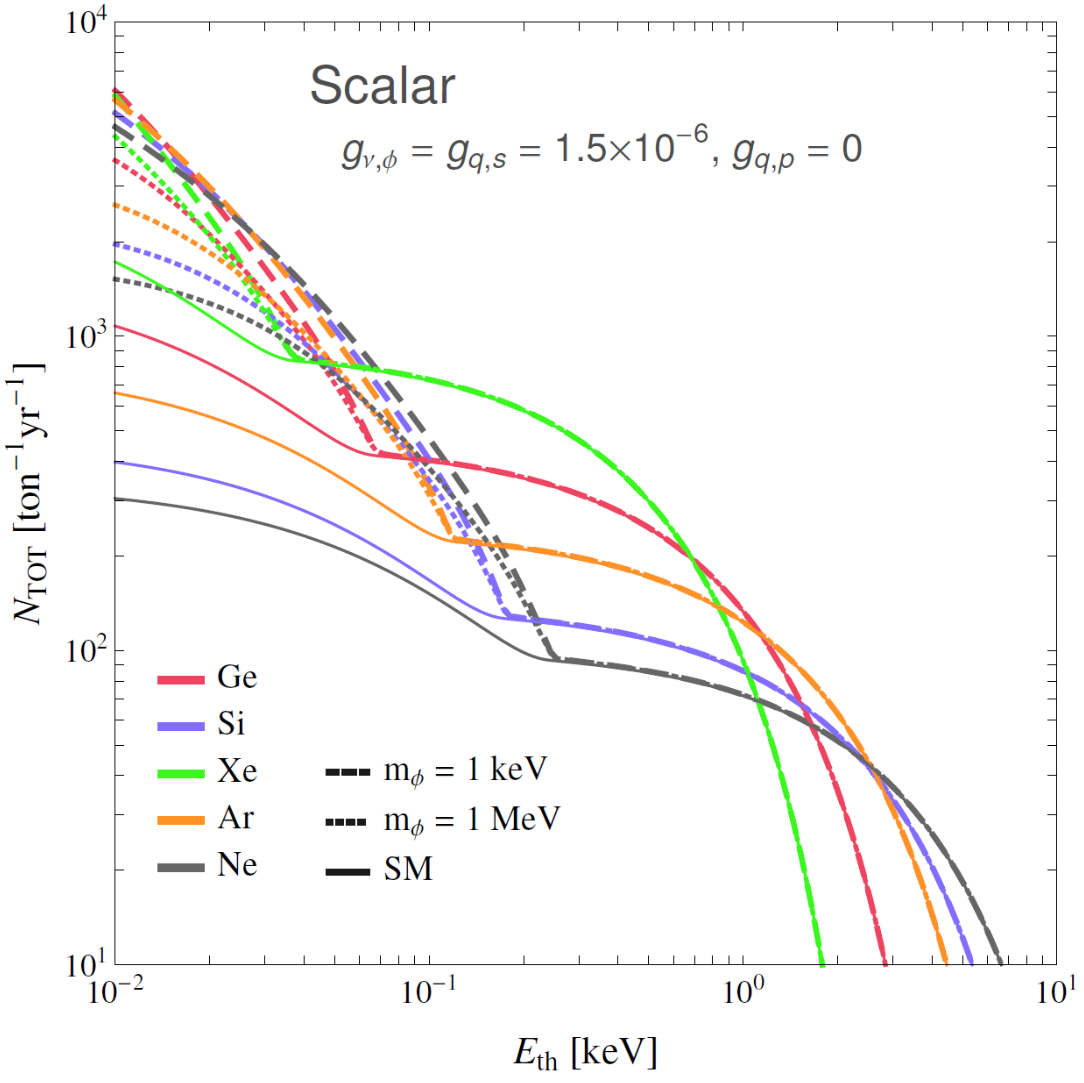
Both Q^2 unstudied in those settings, can probe new interactions.

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



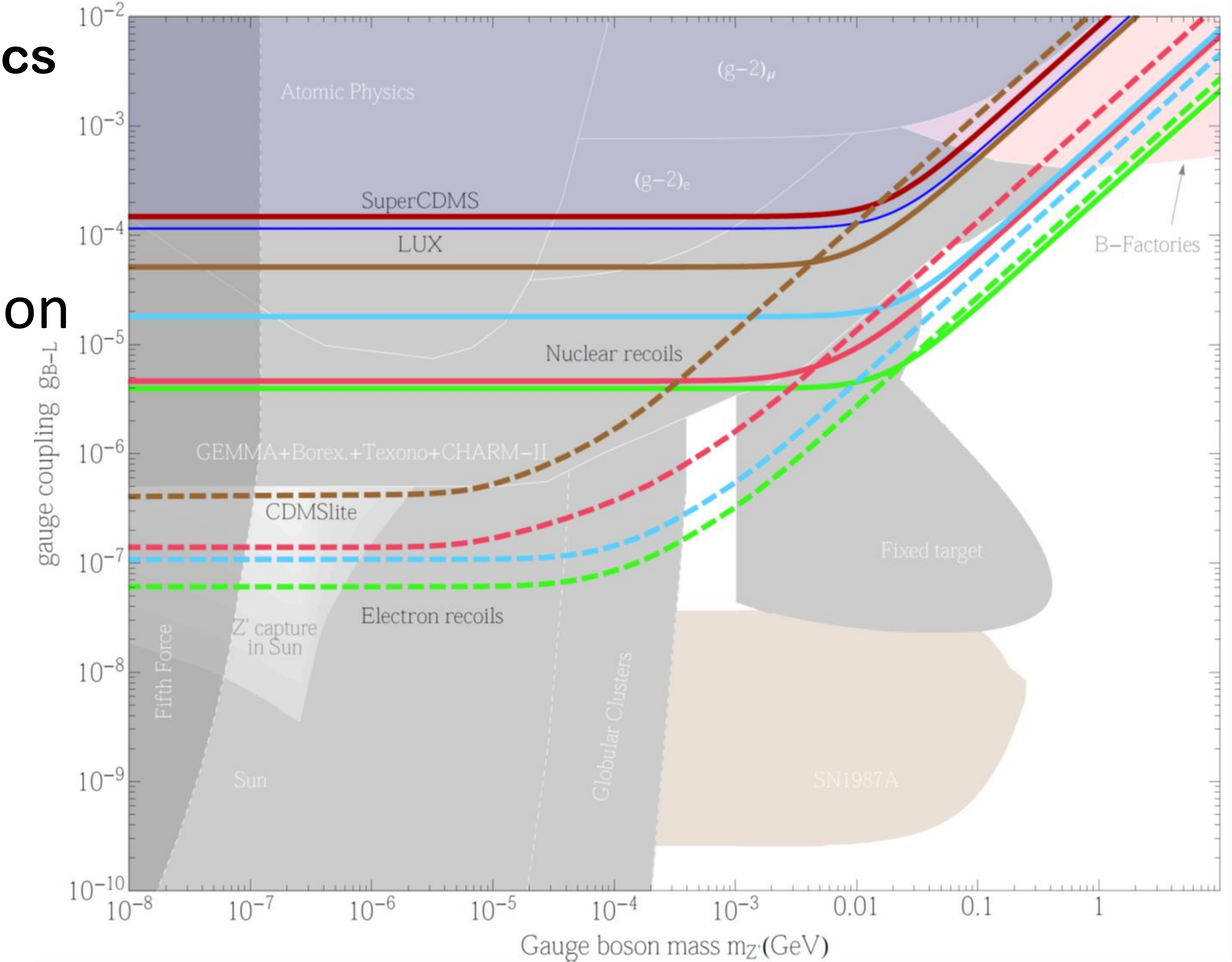
nuclear recoils

Tests of BSM Physics

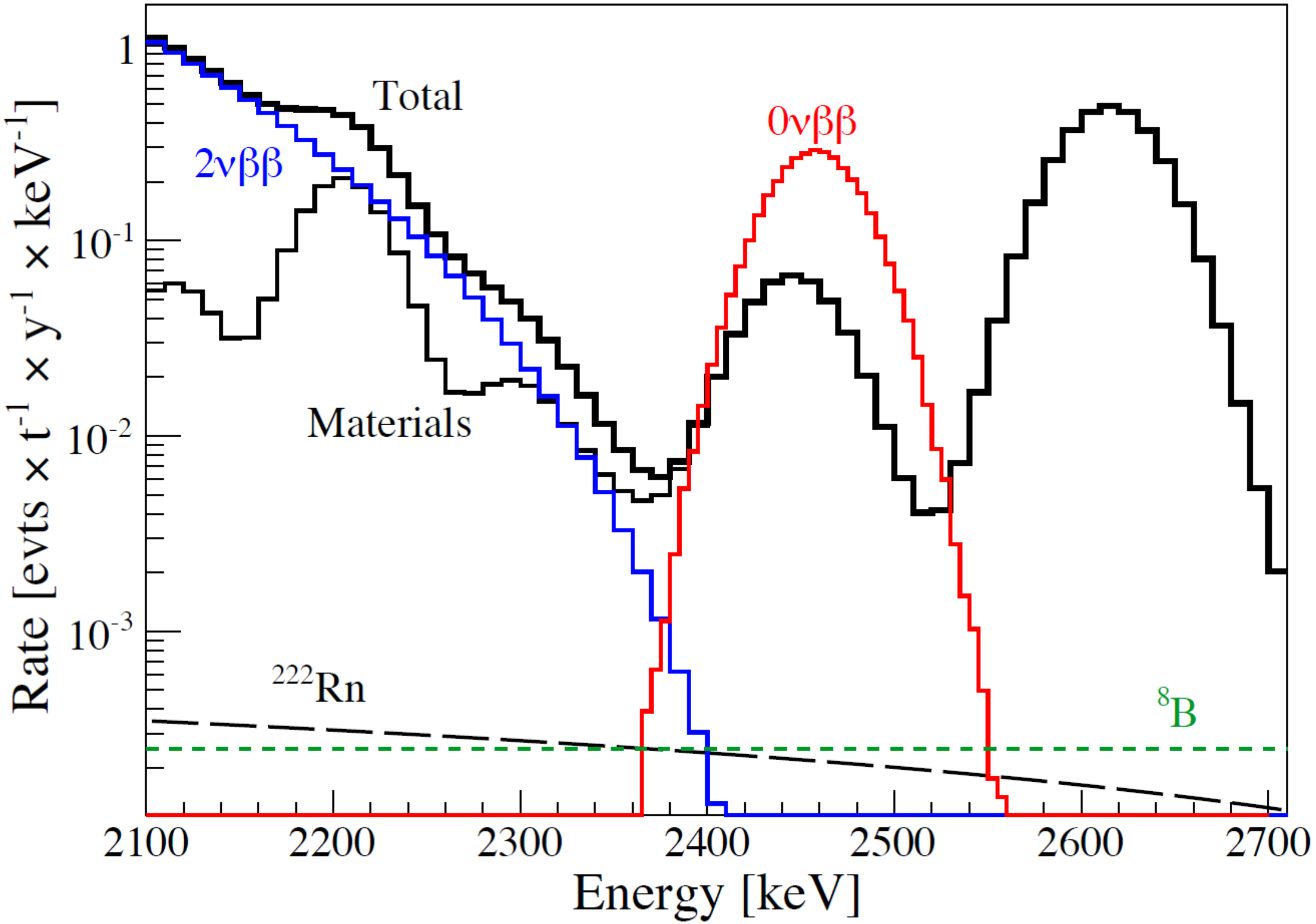
$U(1)_{B\text{-}L}$ gauge boson couples to B-L charge of SM particles

Dashed electron, solid nucleon.

Green future xenon
Blue G2 xenon
Red G2 germanium



Darwin would also be sensitive to Neutrinoless Double Beta Decay



Neutrinos will be detected very soon by Dark Matter Detectors

This will already on its own be new physics, will also probe regions of parameter space not probed by other experiments

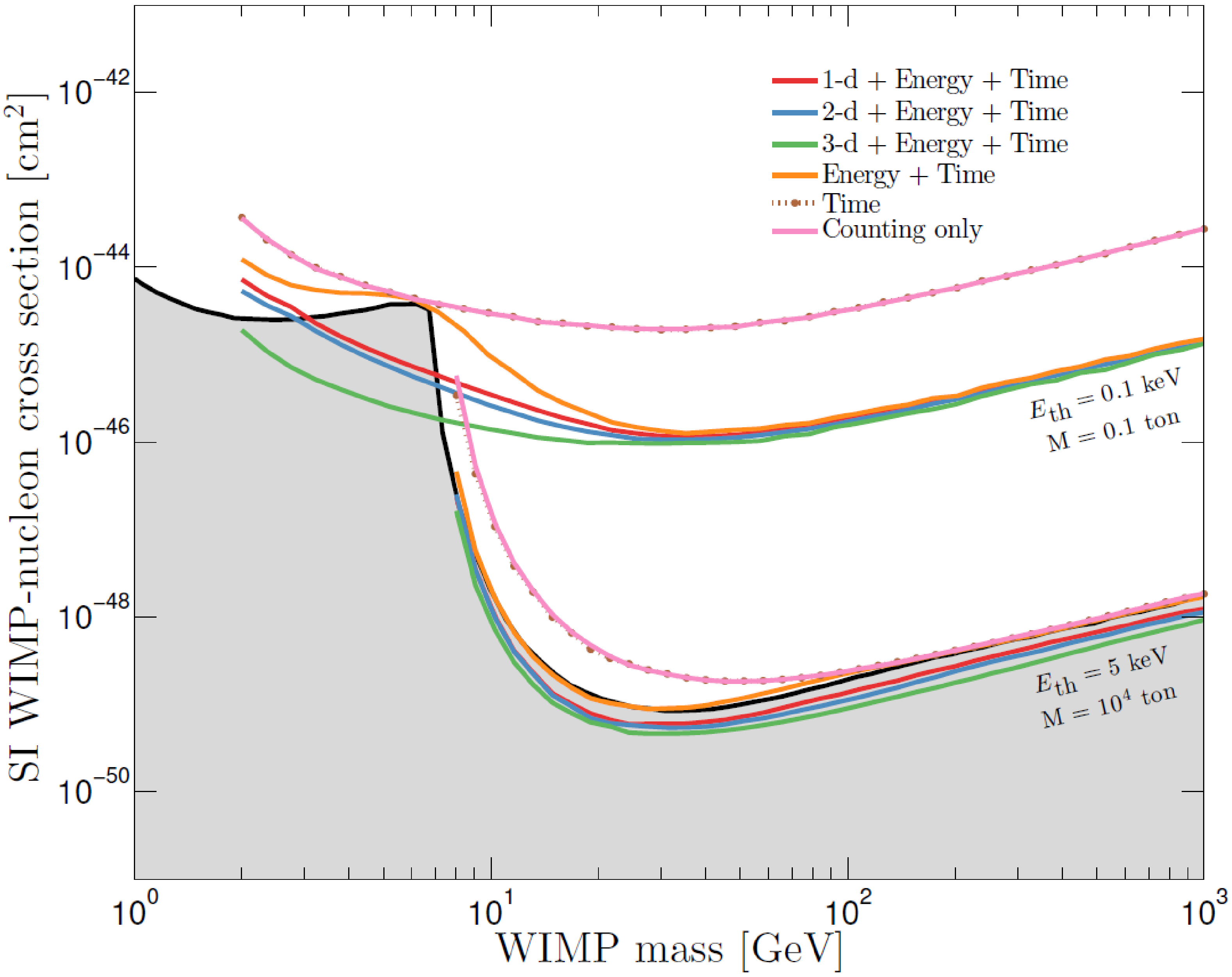
New channels will test for new experiments

Science & Technology
Facilities Council

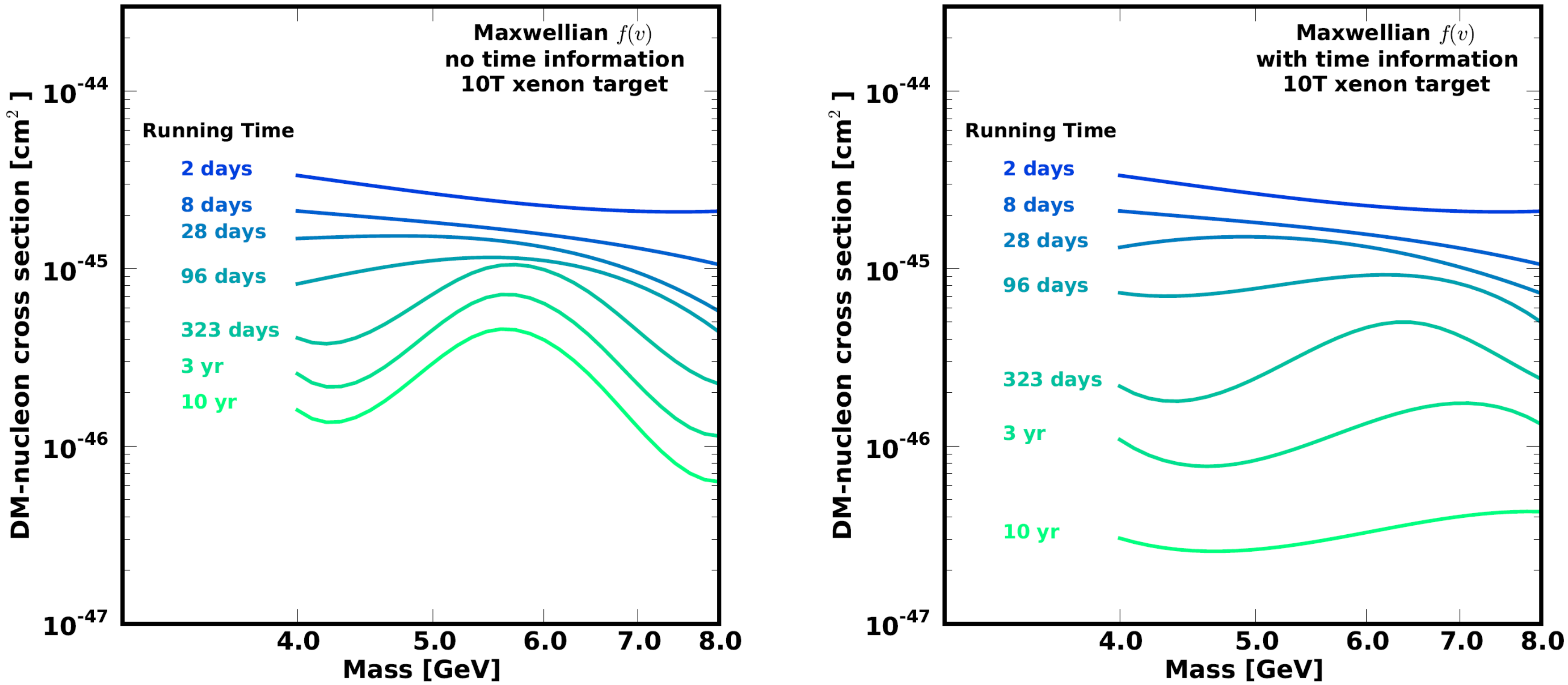
erc

Additional Material

results from O'Hare et al arXiv:1505.08061



What about NO DIRECTIONALITY, only TIME information?



Davis arXiv:1412.1475

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