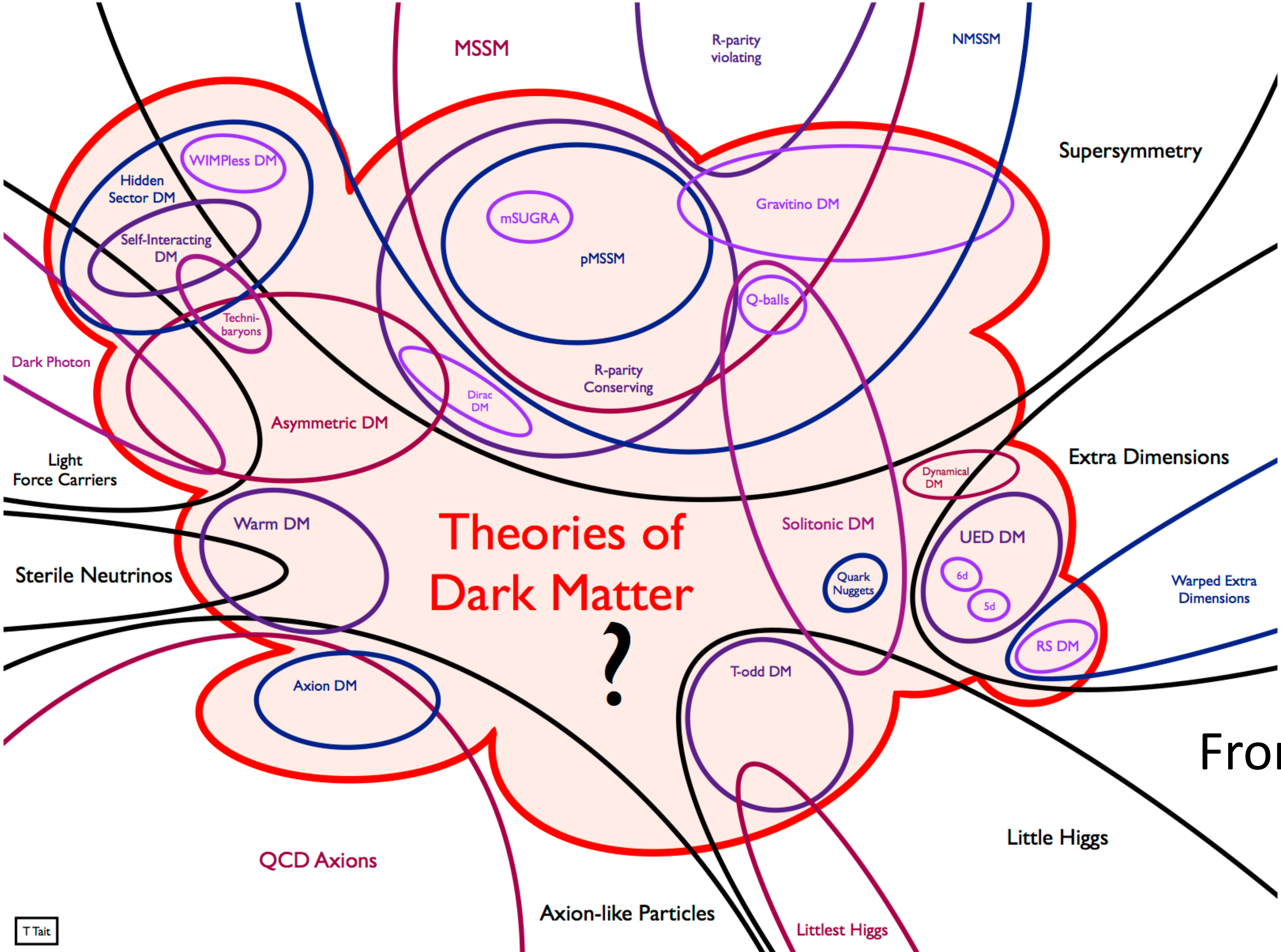
Dark Matter – The Next Phase

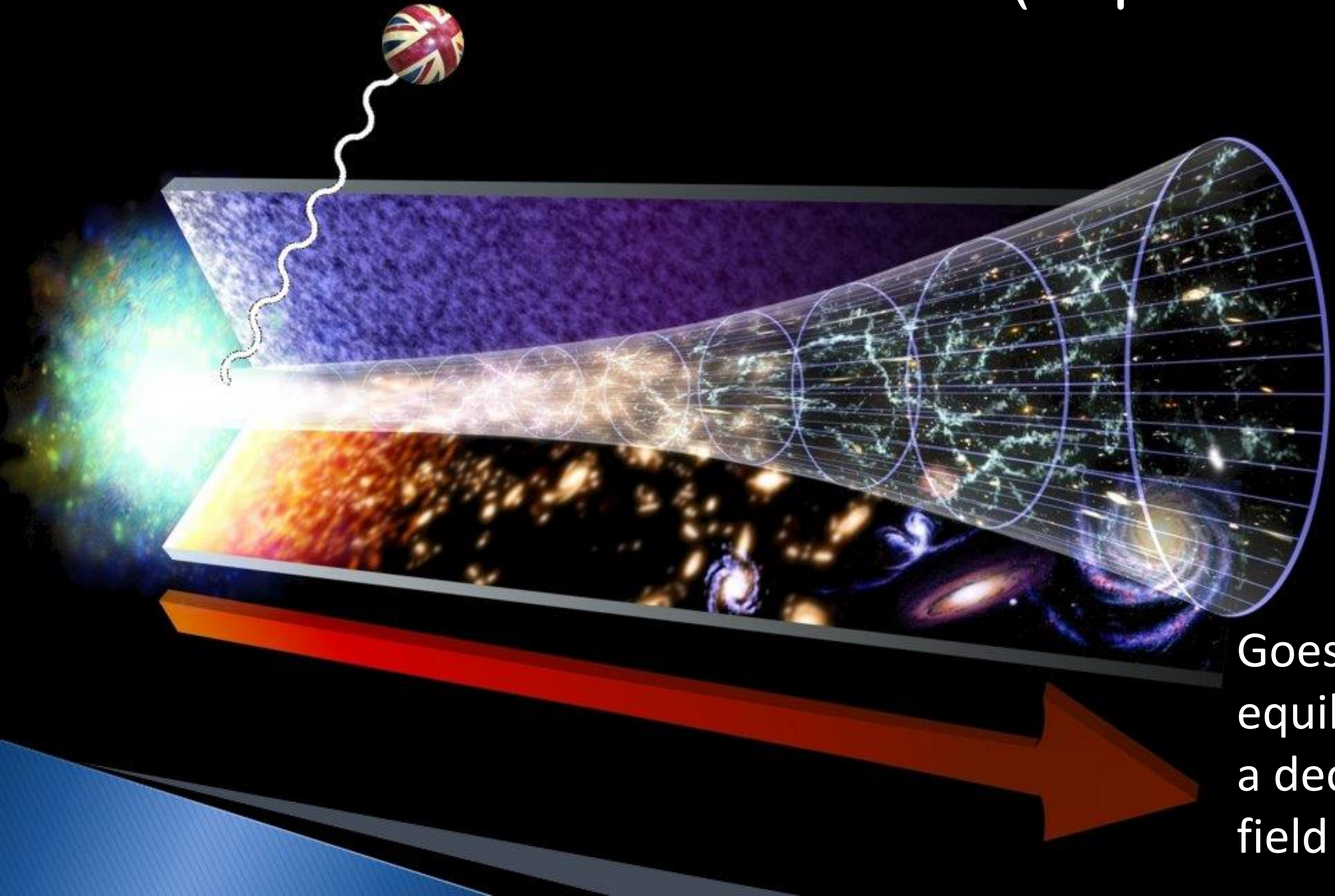
Malcolm Fairbairn

DESY – September 2017



From Tim Tait

The Brexiton (Enqvist 2017, Rajantie 2017)



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

Plan

- Neutrinos as background at dark matter detectors
- Neutrinos as signal at dark matter detectors
- Axion miniclusters and gravitational microlensing

Science & Technology Facilities Council
erc

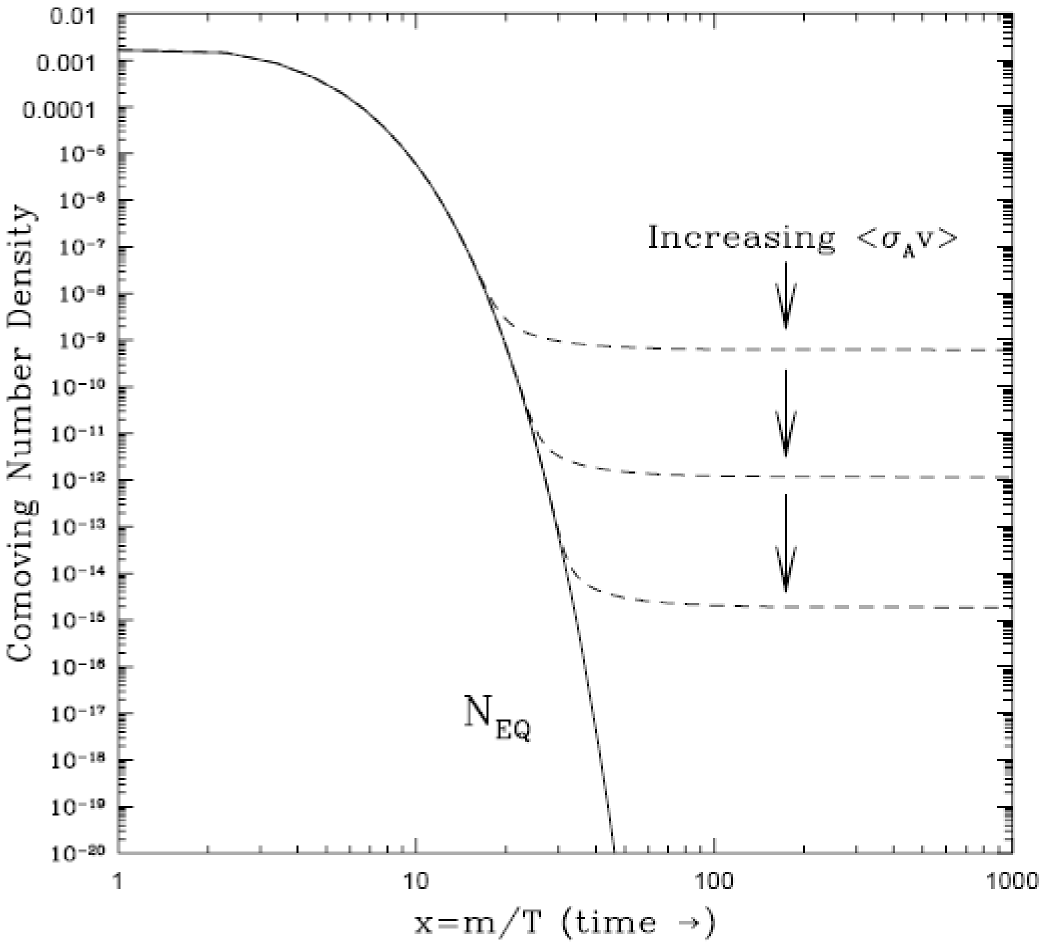
Part I

Thermal relic Dark Matter
and the
Neutrino Background

Thermal Relic Dark Matter

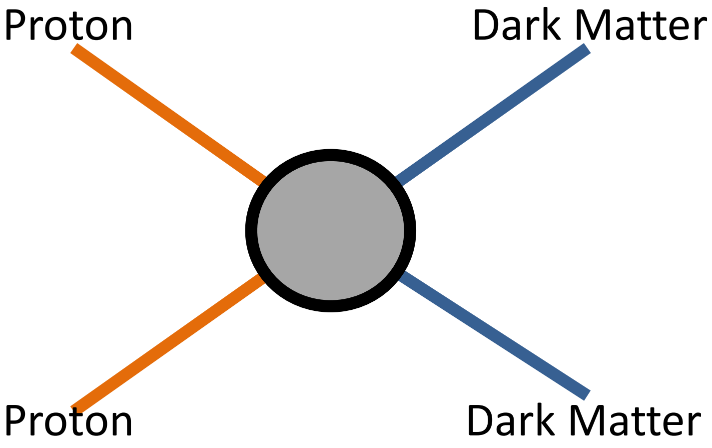
$<\sigma v> = 3 \times 10^{-26}\ cm^3 s^{-1}$

$$\Omega_\chi \sim 1$$

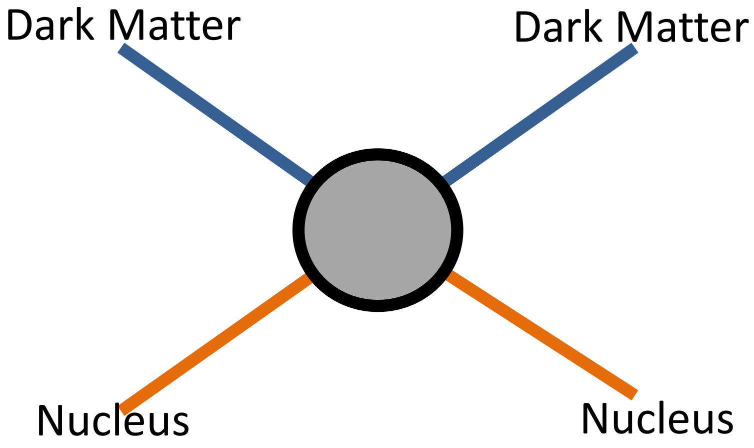


Right amount of dark matter if dark matter mass 100 MeV < M < 100 TeV

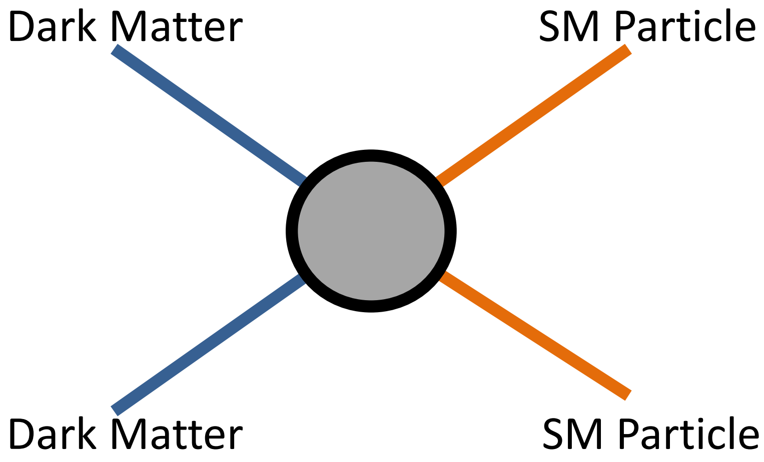
Ways to Detect Thermal Relic Dark Matter –
Make, Shake and Break



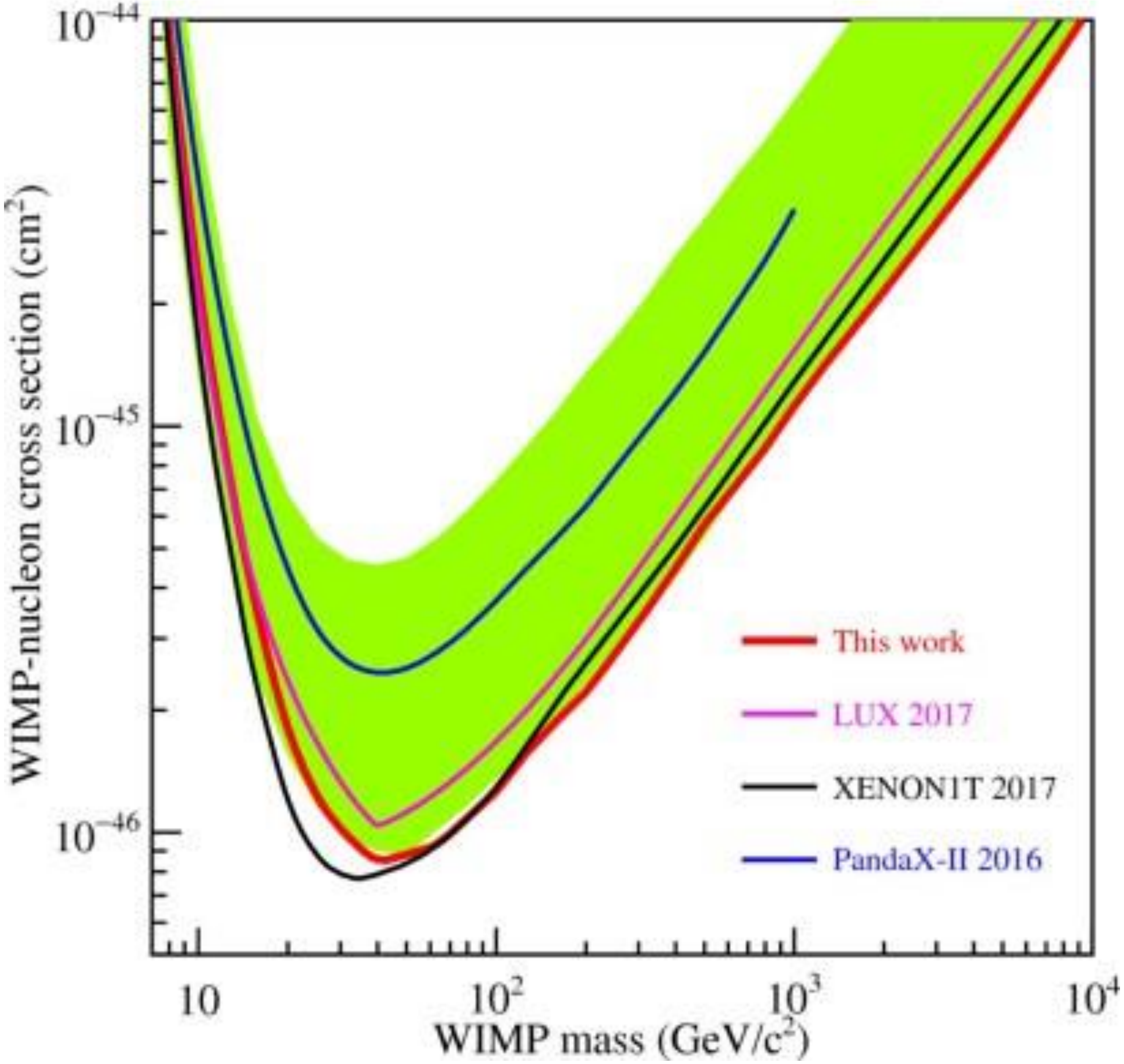
Make *– collider production*



Shake *– direct detection scattering*



Break *– indirect detection of annihilation*



Currently, entertaining race between LUX, PandaX-II and XENON1T

Notably all Xenon targets

lux.brown.edu

LZ- Lux Zeplin

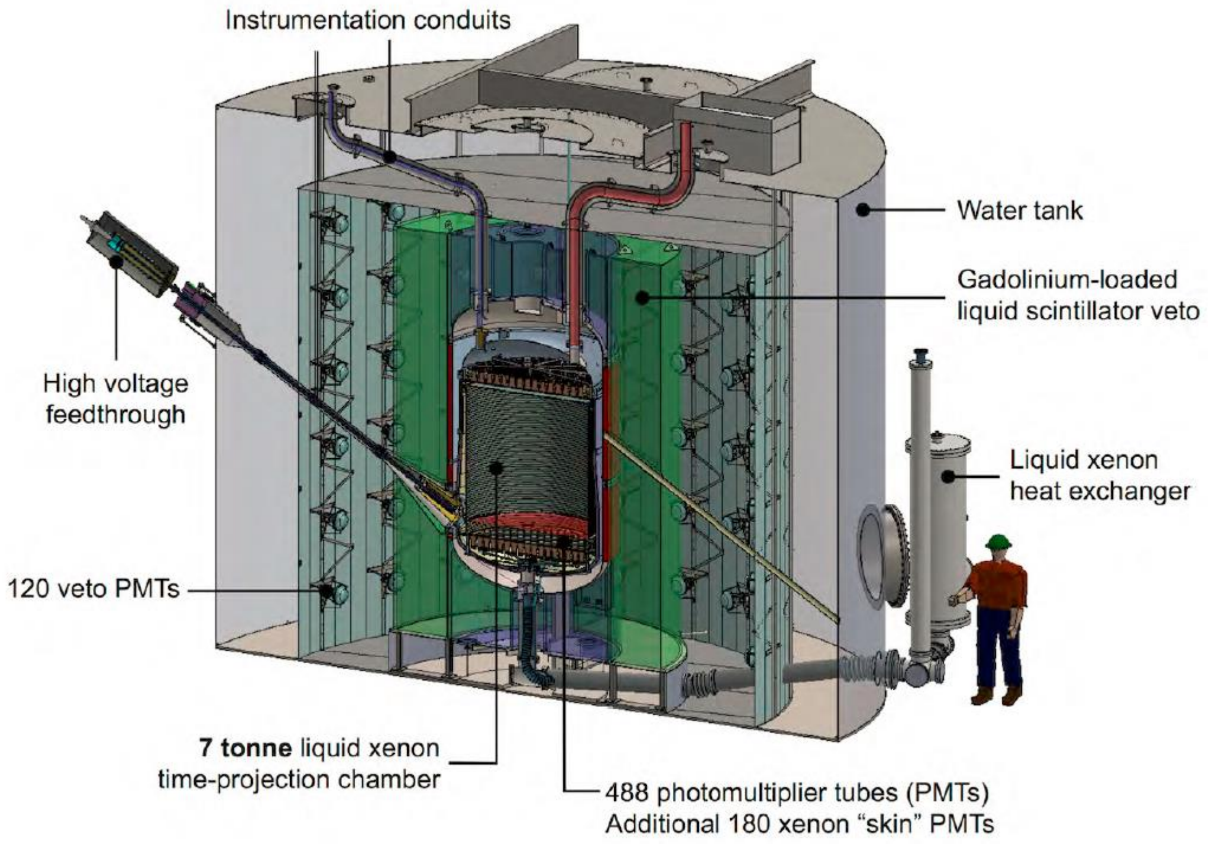


Figure 2.1. LZ detector concept.

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

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:

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

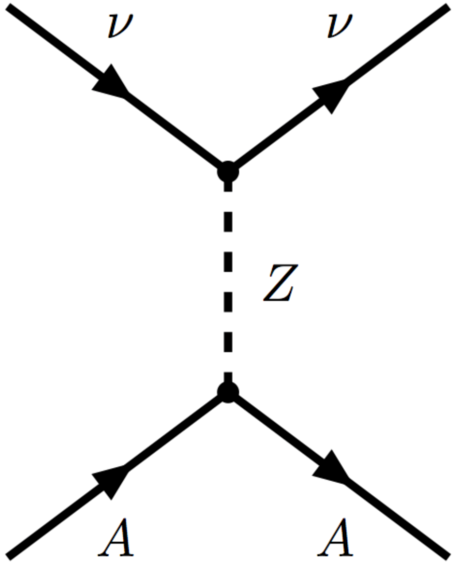
- $\cos\theta$: angle between in- and outgoing neutrino direction
- $2m_T E_r = q^2 = 2E_\nu^2(1-\cos\theta)$

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

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

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

$qR \ll 1$



Coherent Neutrino-Nucleon Interactions

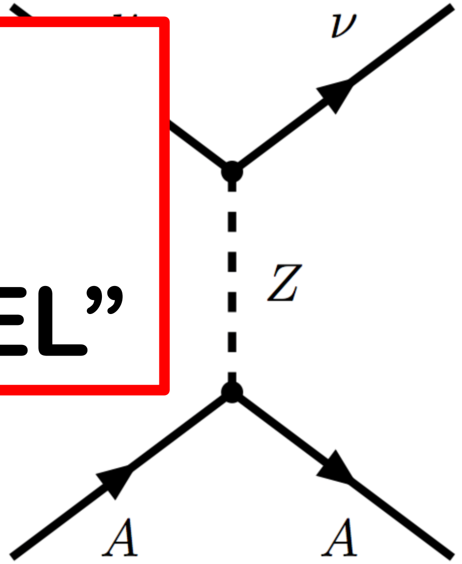
$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 \, E_\nu^2 \, (1+\cos\theta) \, F(Q^2)^2$$

- Enhanced by factor N^2:

$Q_W = N$ …

- $\cos\theta$: angle b…
- $2m_T E_r = q^2$ …

THIS IS THE ANIMATED POP UP THAT USED TO SAY "STILL NOT OBSERVED IN STANDARD MODEL"



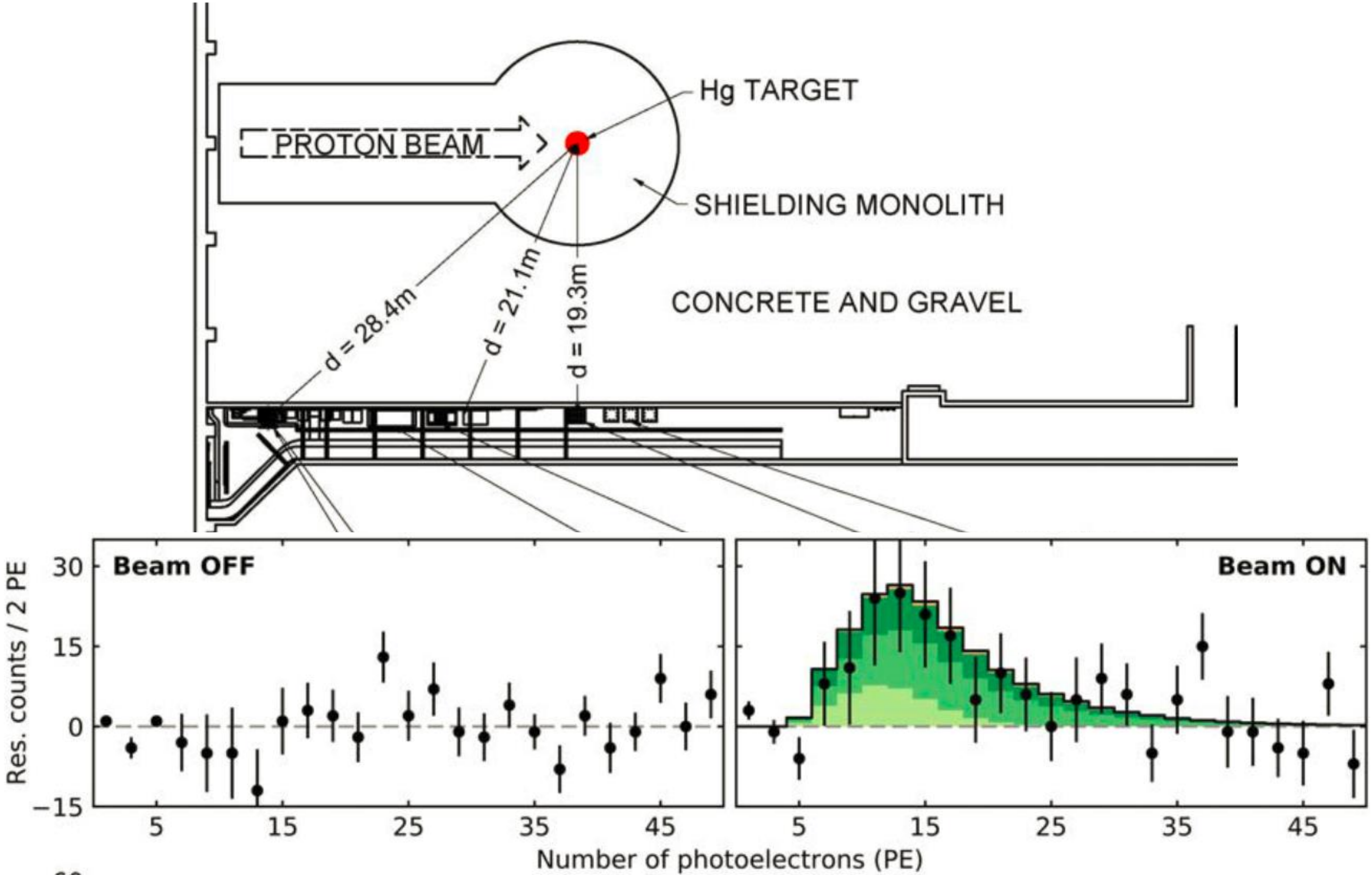
$$\Rightarrow \frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 \, m_T \, (1 - \frac{m_T E_r}{2E_\nu^2}) \, F(Q^2)^2.$$

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

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

Observation of Coherent Elastic Neutrino-Nucleus Scattering

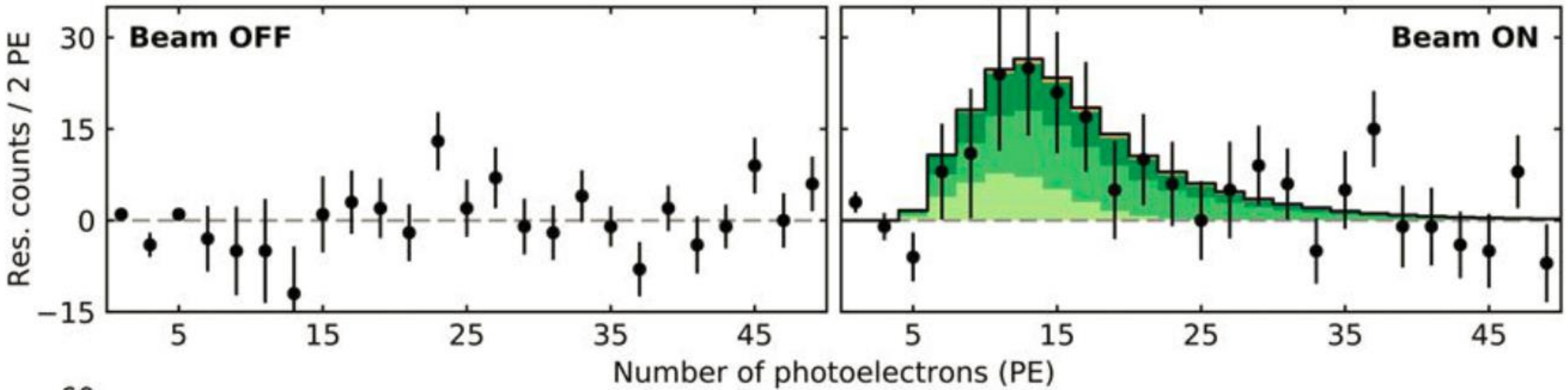
COHERENT COLLABORATION arXiv:1708.01294



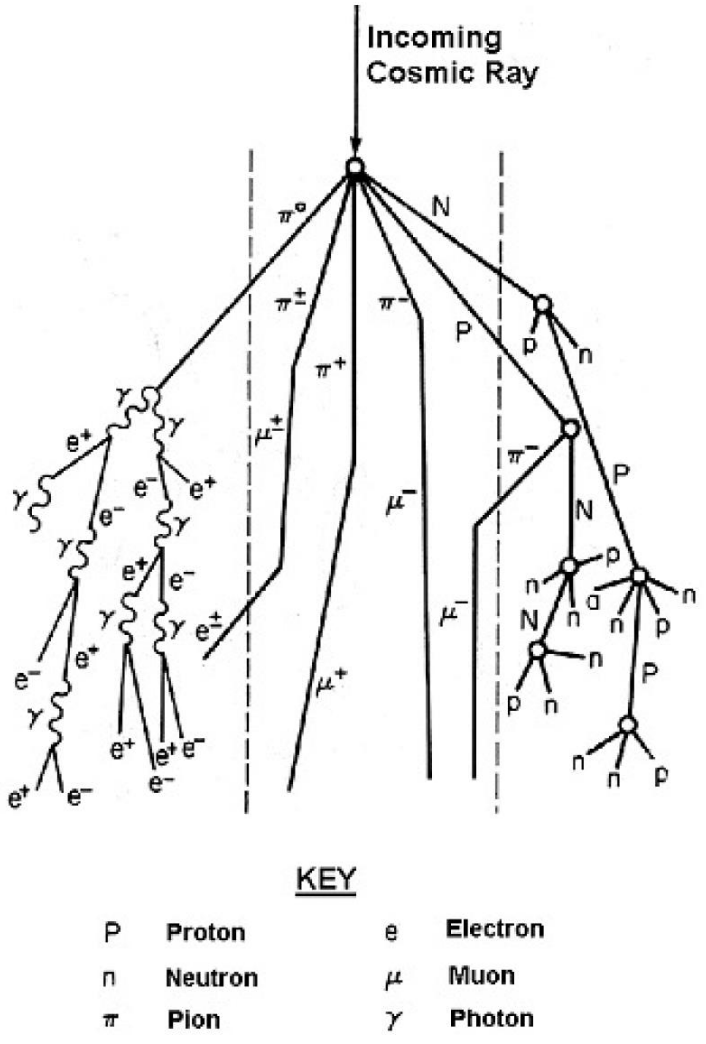
Observation of Coherent Elastic Neutrino-Nucleus Scattering

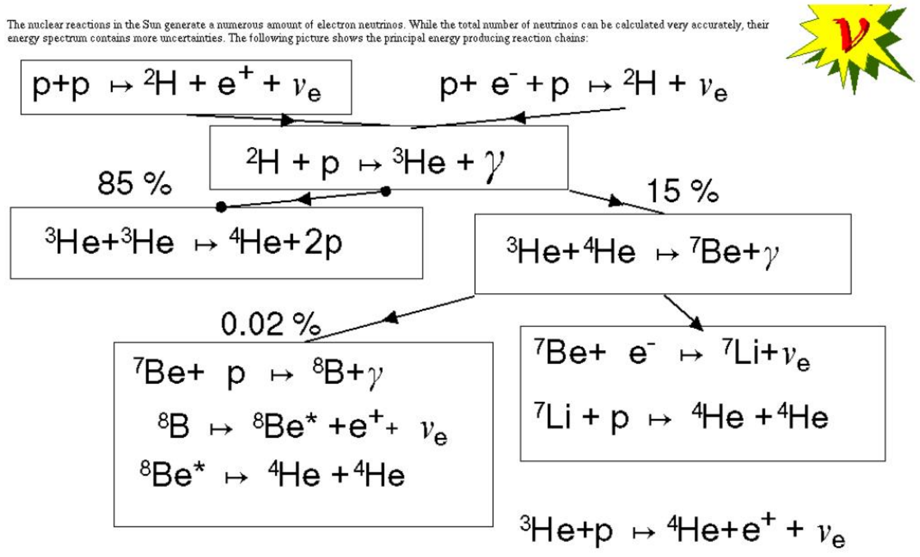
Abstract: The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross-section is the largest by far of all low-energy neutrino couplings. This mode of interaction provides new opportunities to study neutrino properties, and leads to a miniaturization of detector size, with potential technological applications. **We observe this process at a 6.7-sigma confidence level**, using a low-background, 14.6-kg CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the Standard Model for this process, are observed in high signal-to-background conditions. Improved constraints on non-standard neutrino interactions with quarks are derived from this initial dataset.

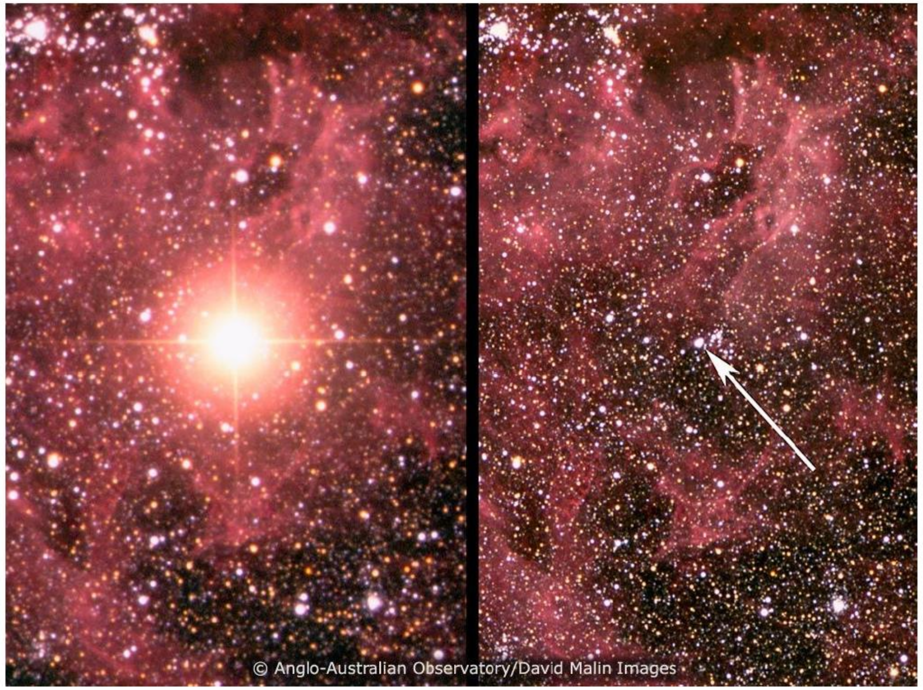
COHERENT COLLABORATION arXiv:1708.01294



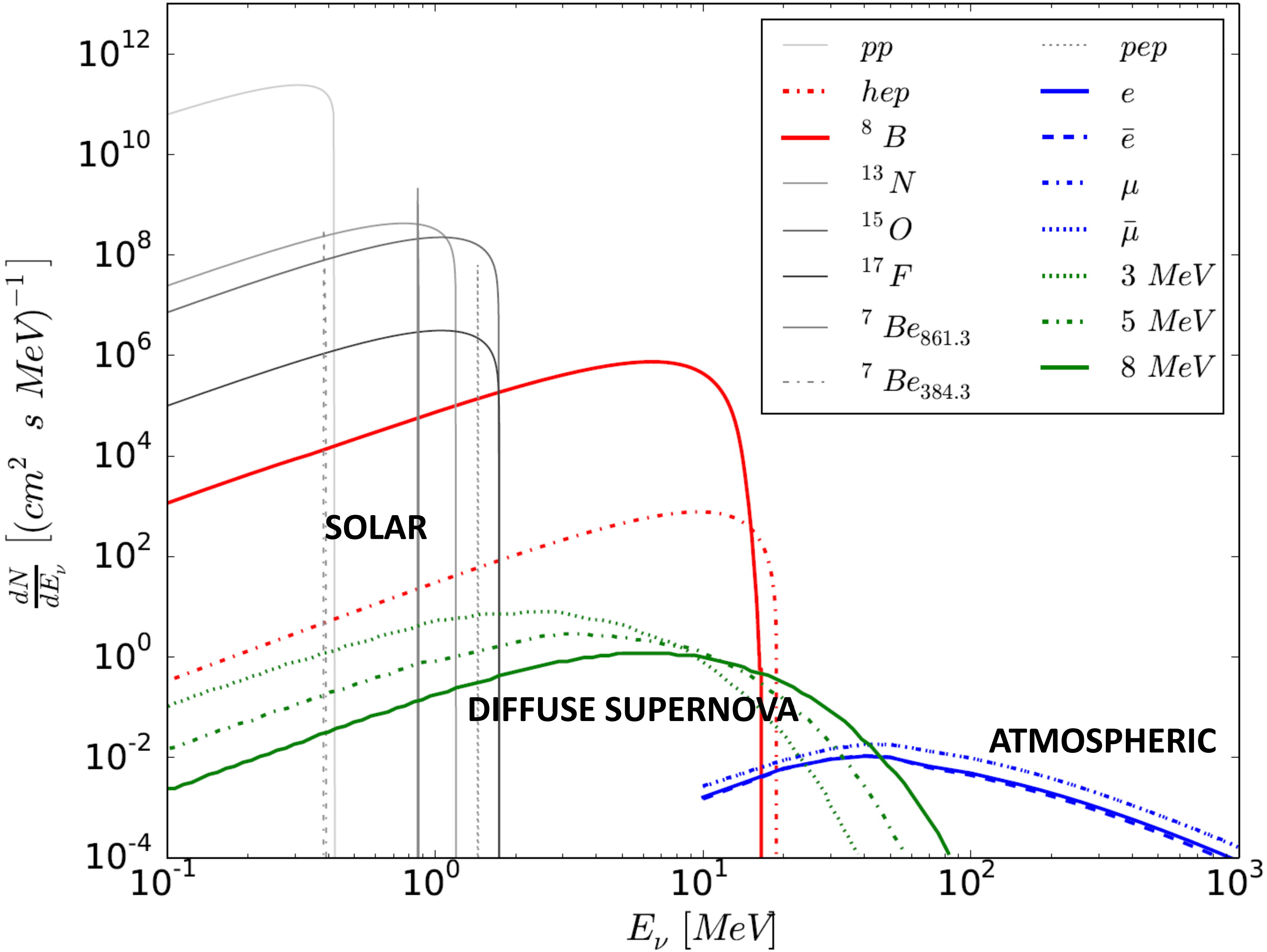
Astrophysical Neutrino Sources





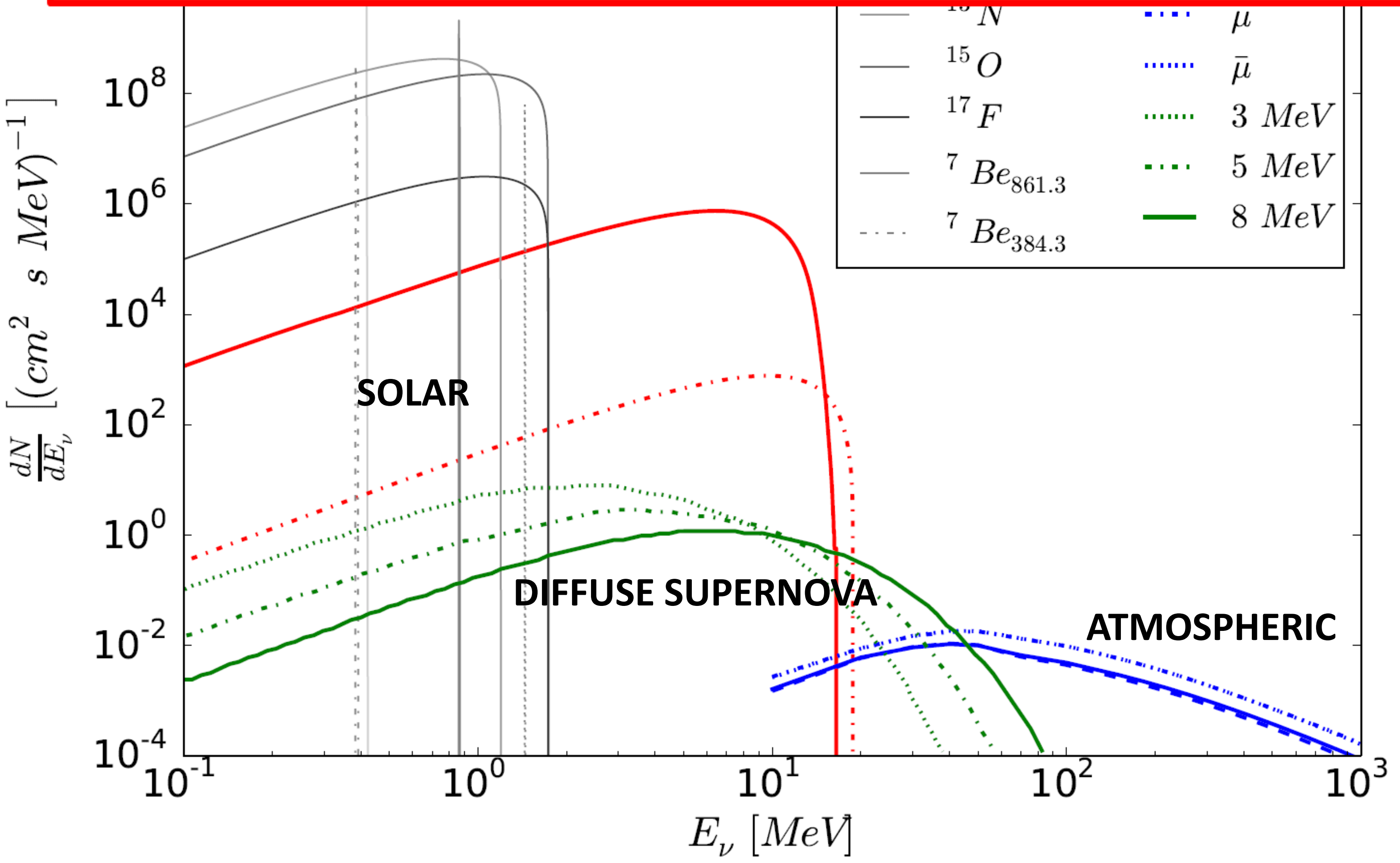


Neutrino Background

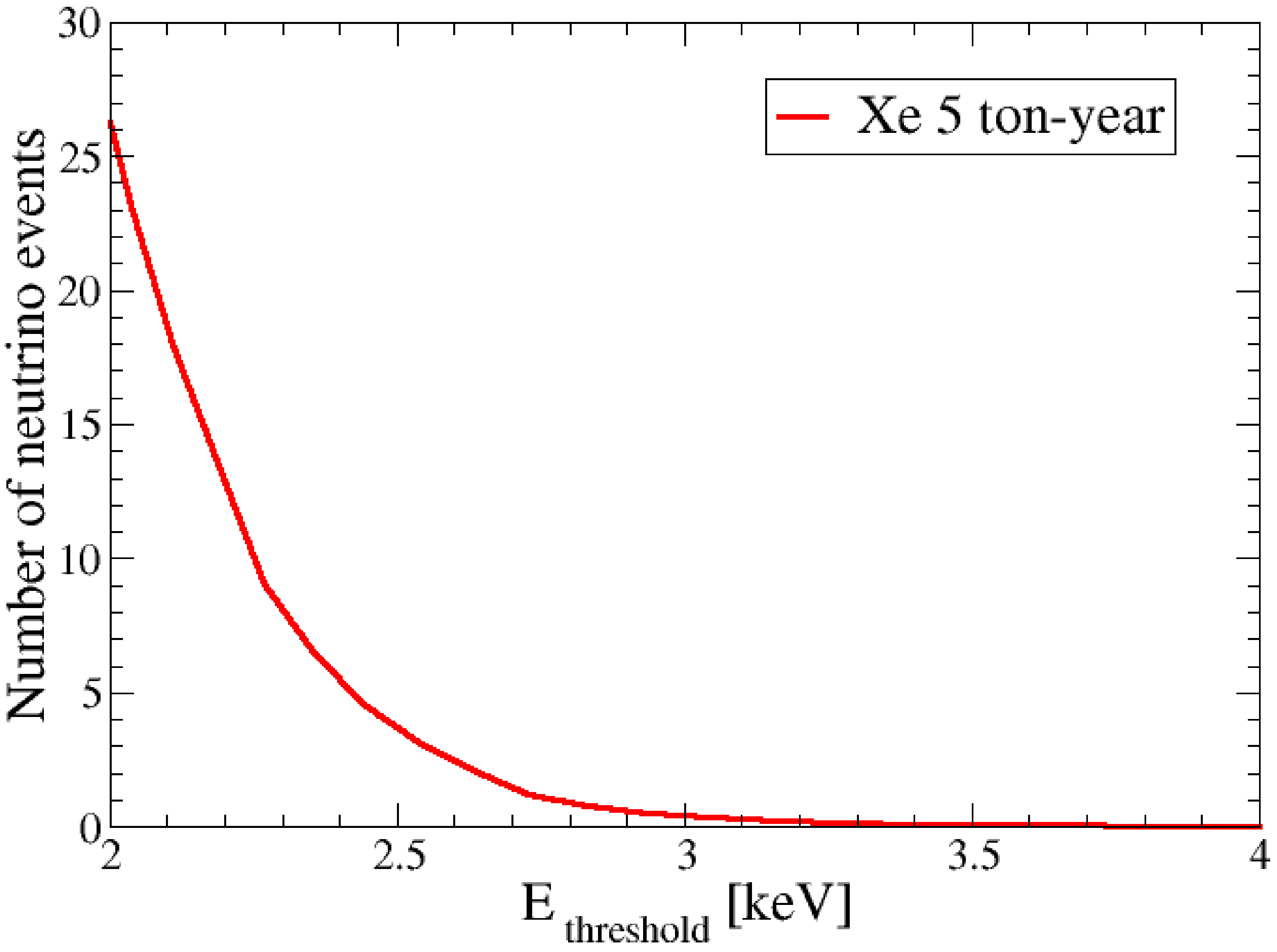


Neutrino Background

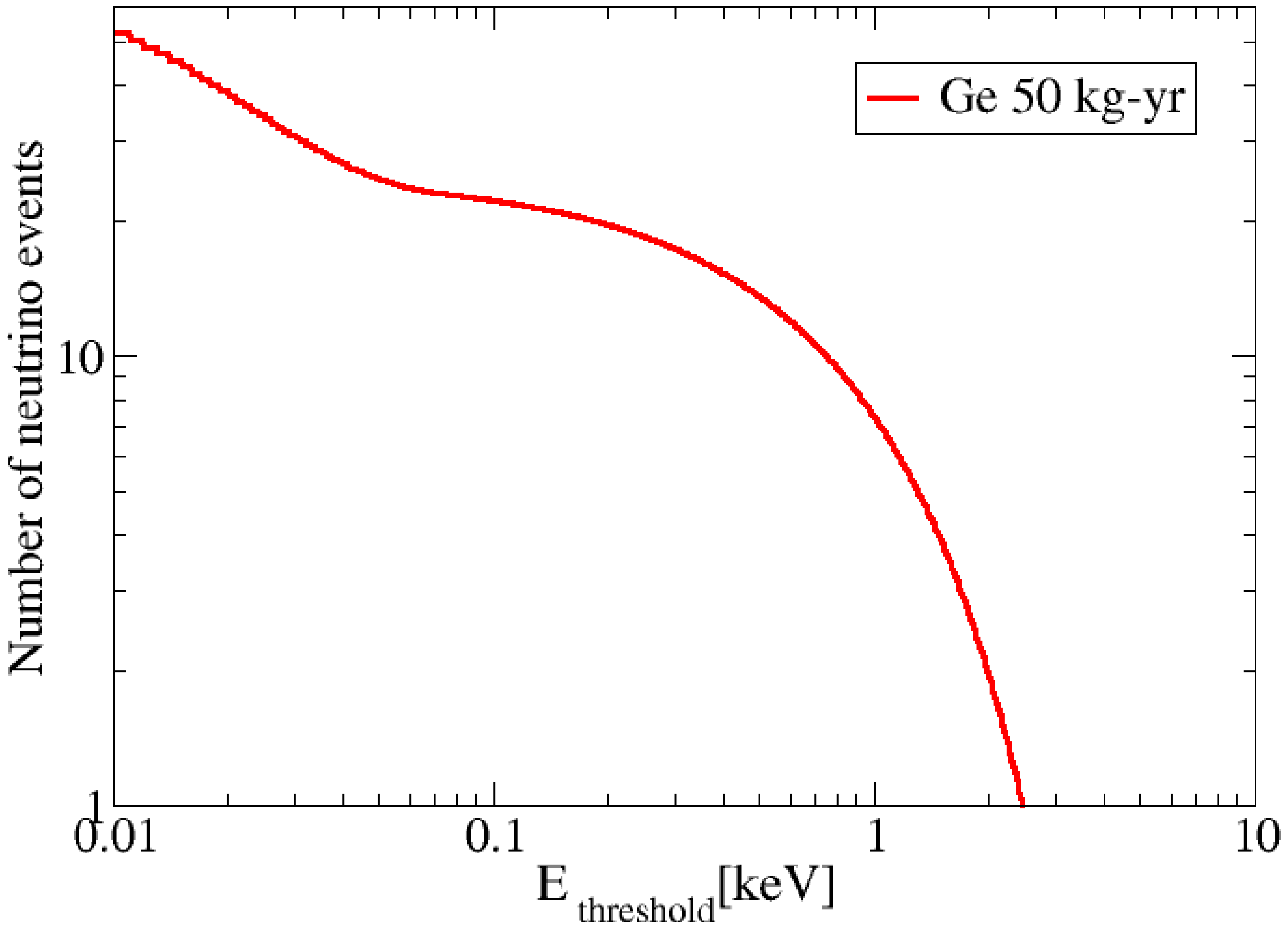
Not enough Neutrinos to be detected with COHERENT set-up
Need a much bigger detector sensitive to keV nuclear recoils
For example, a Dark Matter detector…



Integrated Event Rate in Xe detector above different Thresholds

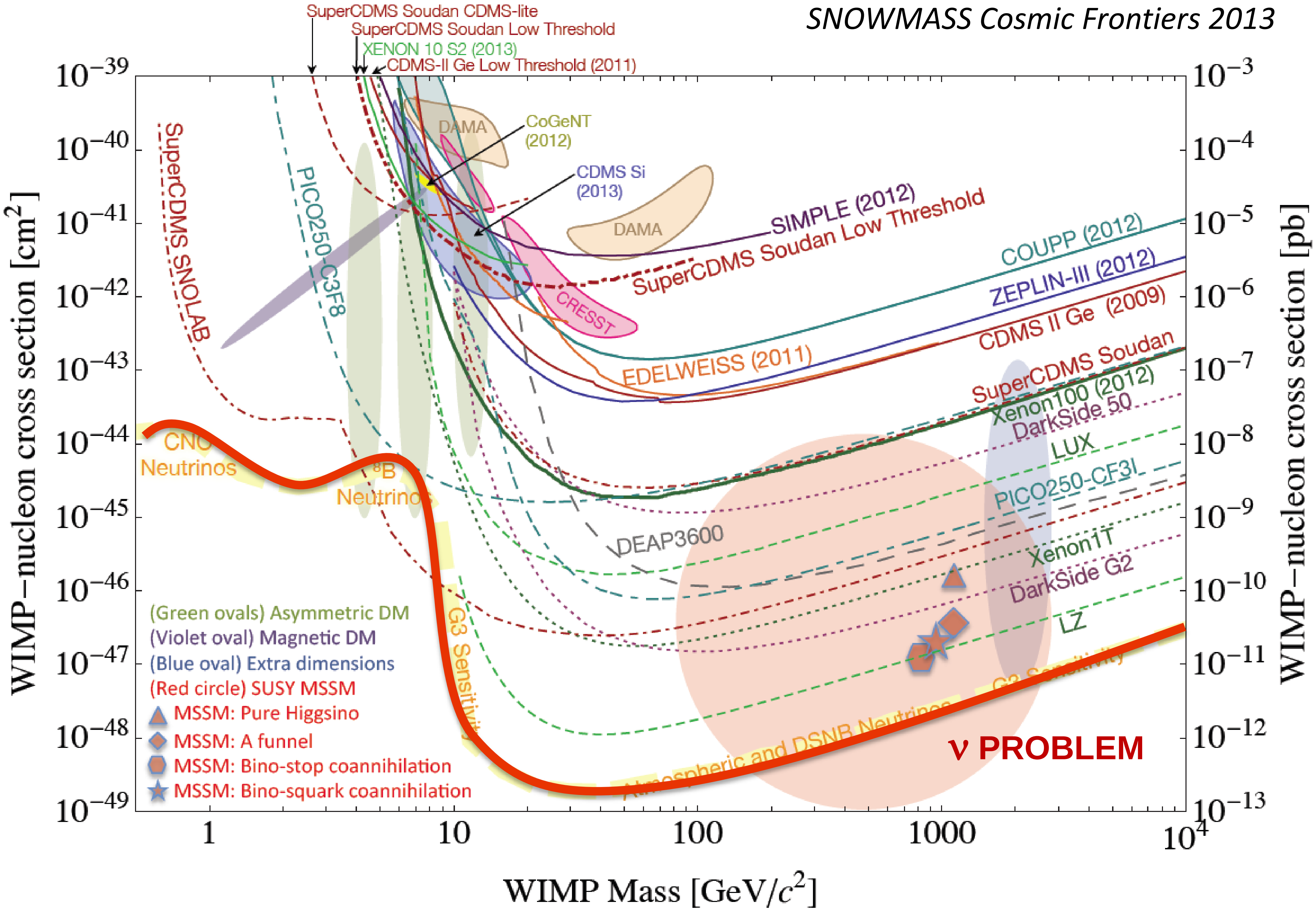


Integrated Event Rate in Ge detector above different Thresholds (B8, hep, N13, O15, F17 and Be7 lines)

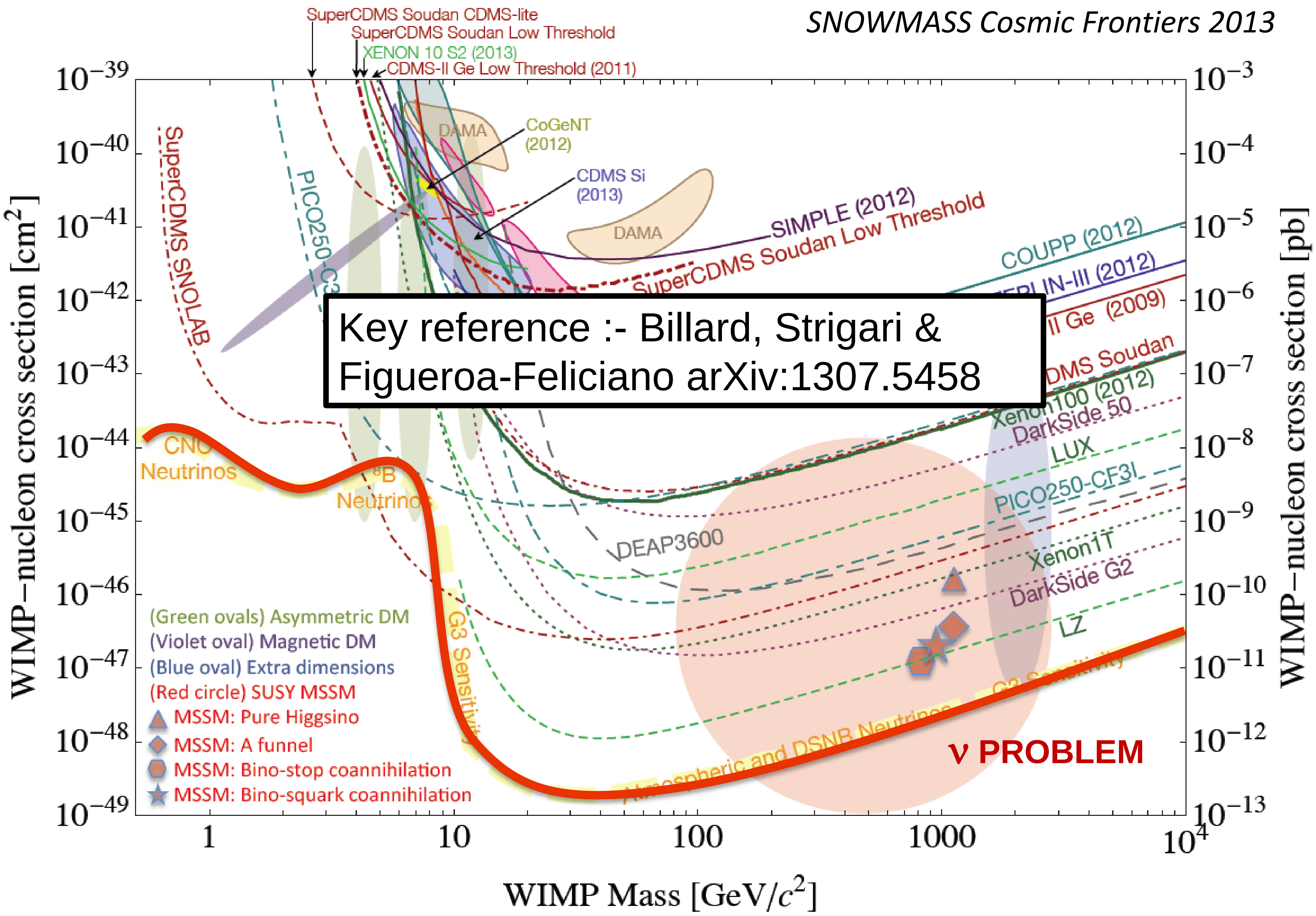


These Neutrinos create a floor…

SNOWMASS Cosmic Frontiers 2013



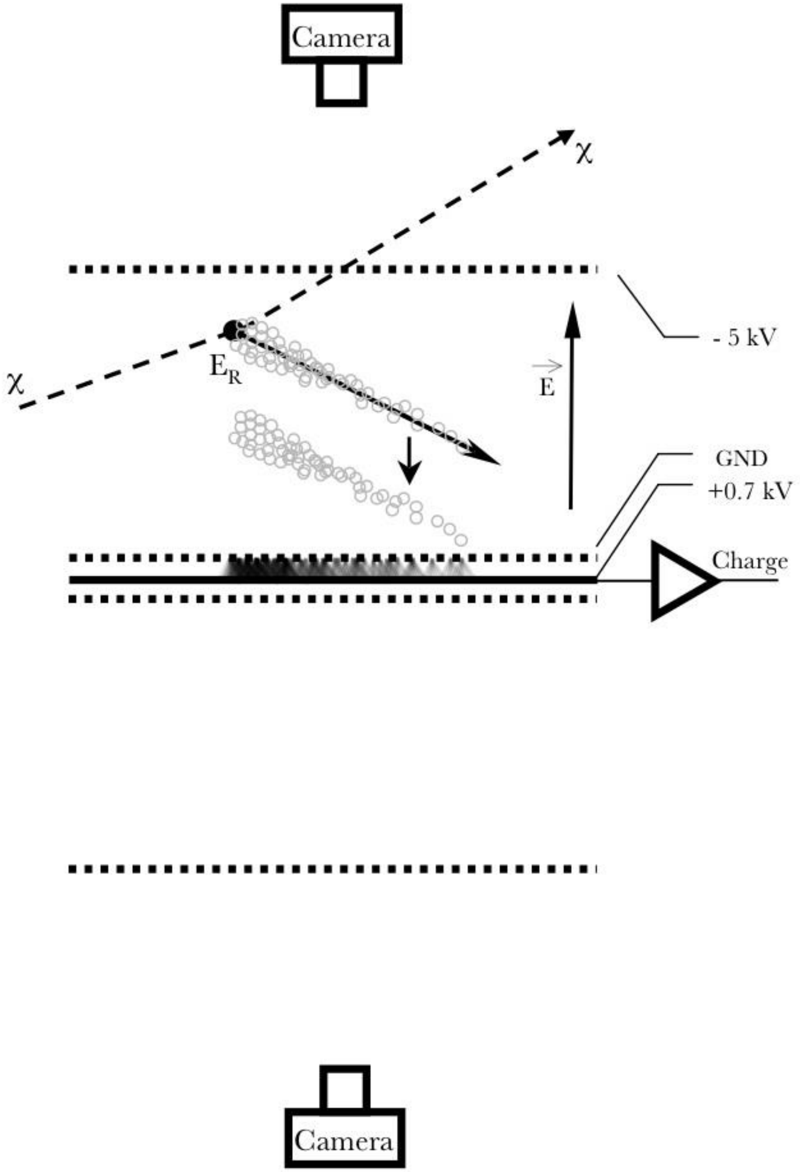
These Neutrinos create a floor…



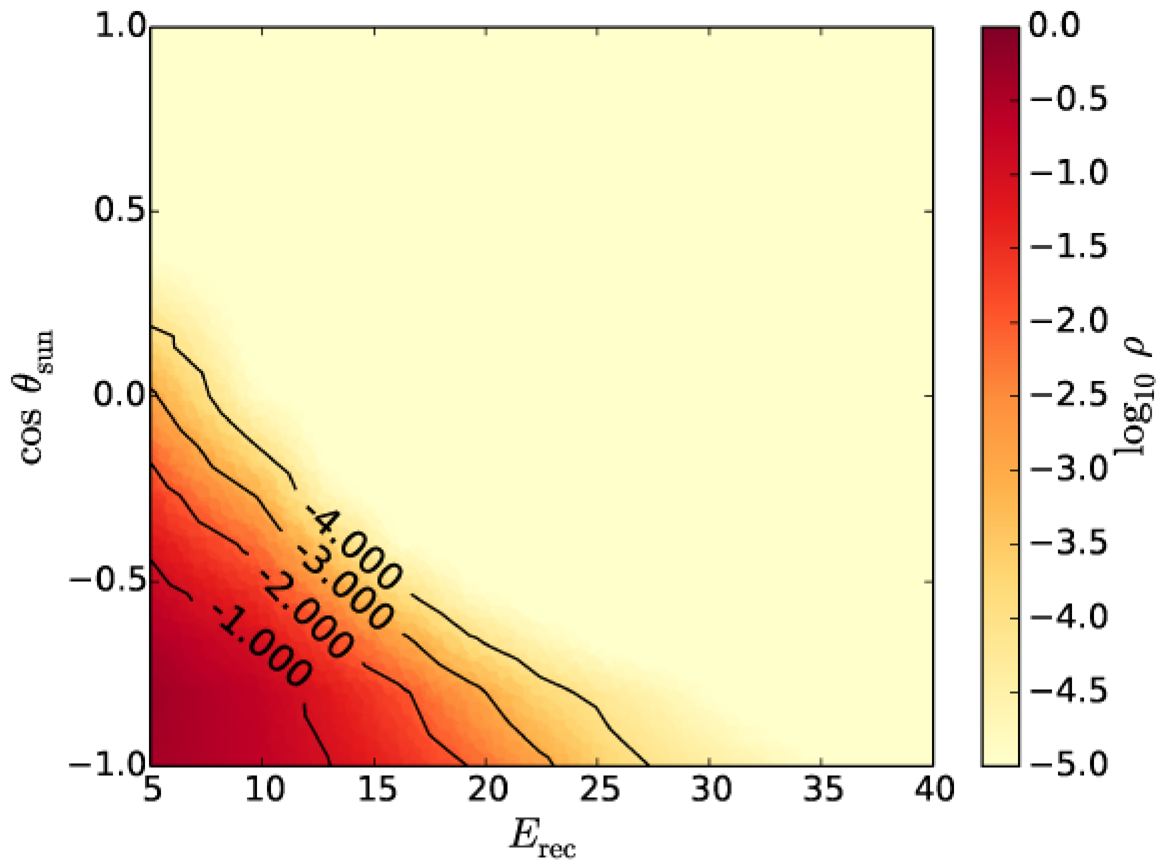
What if we can Tell which direction the dark matter is coming from?

DIRECTIONAL DARK MATTER DETECTION

e.g. DMTPC



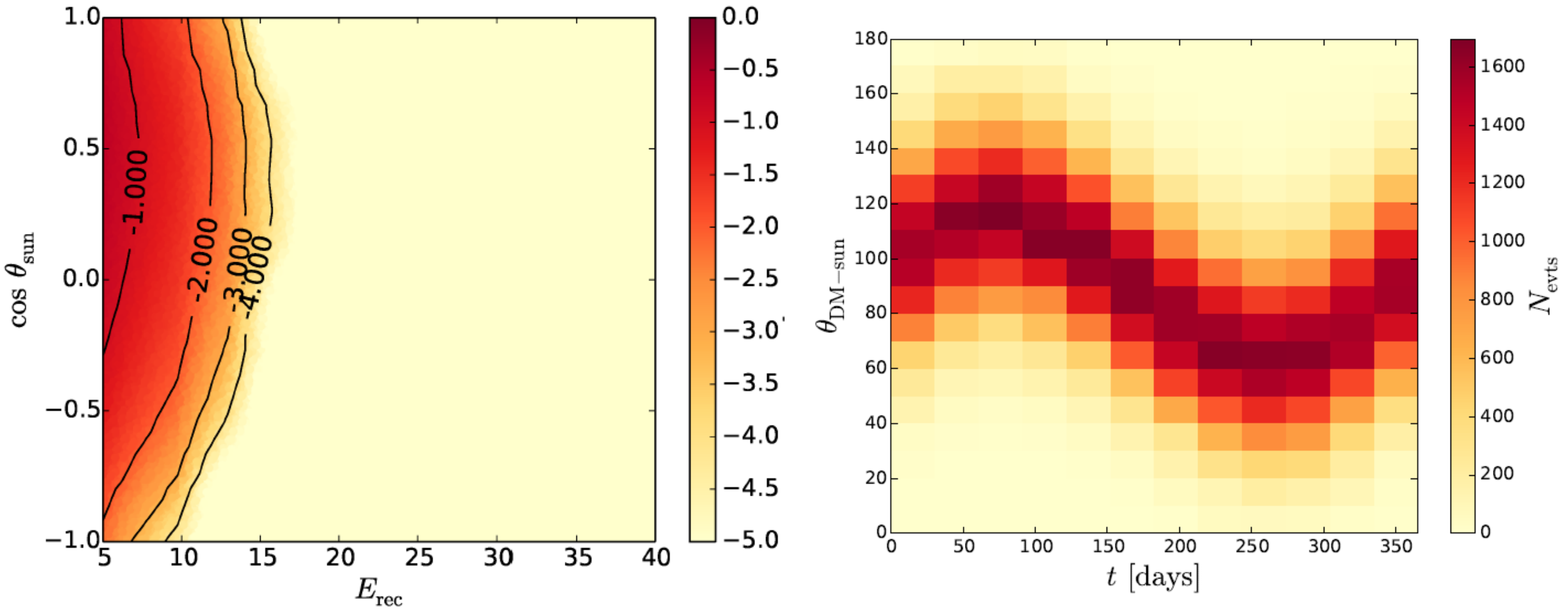
angle between recoil from Solar neutrino and sun



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

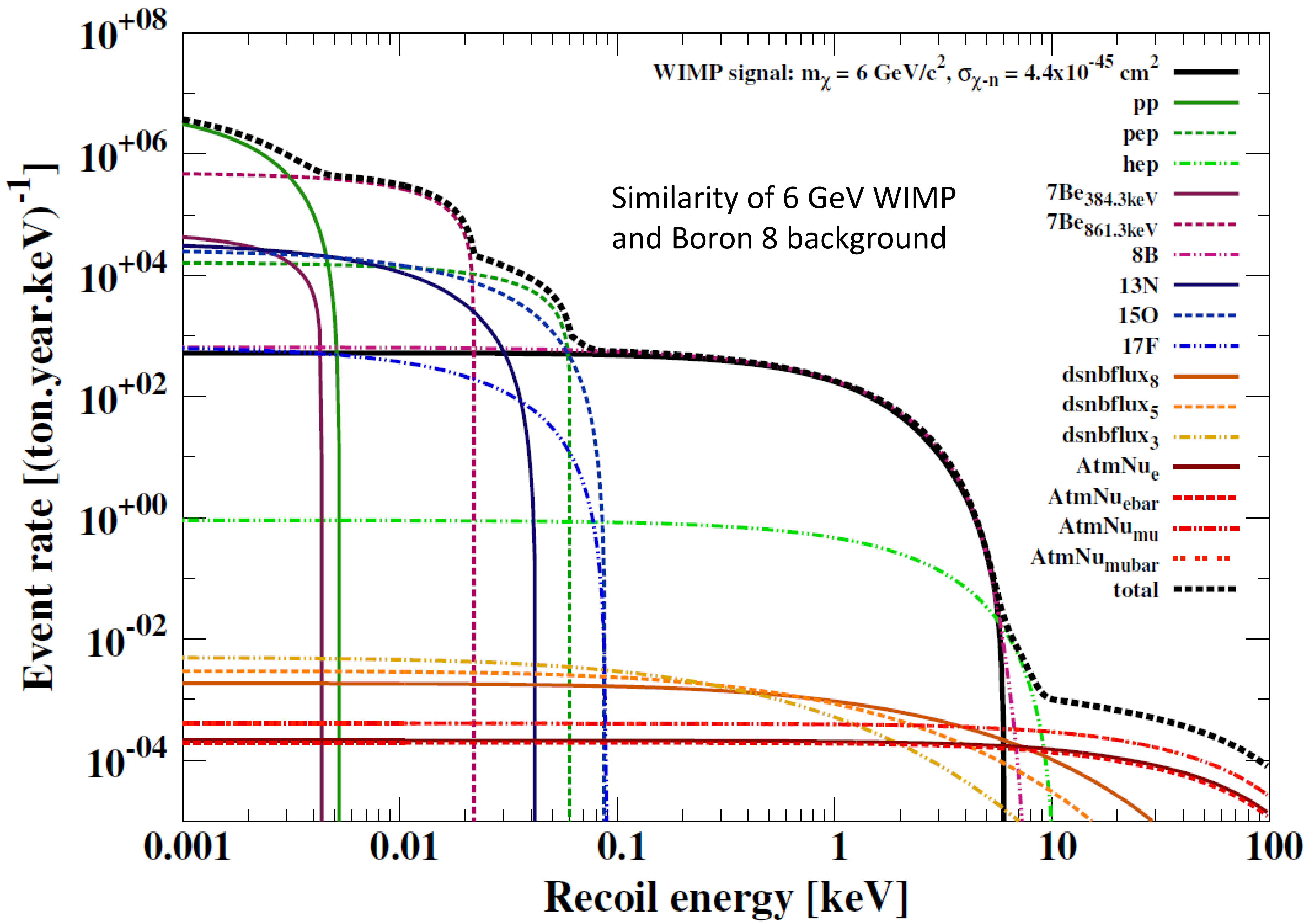
arXiv:1406.5047

angle between recoil from Dark Matter and sun

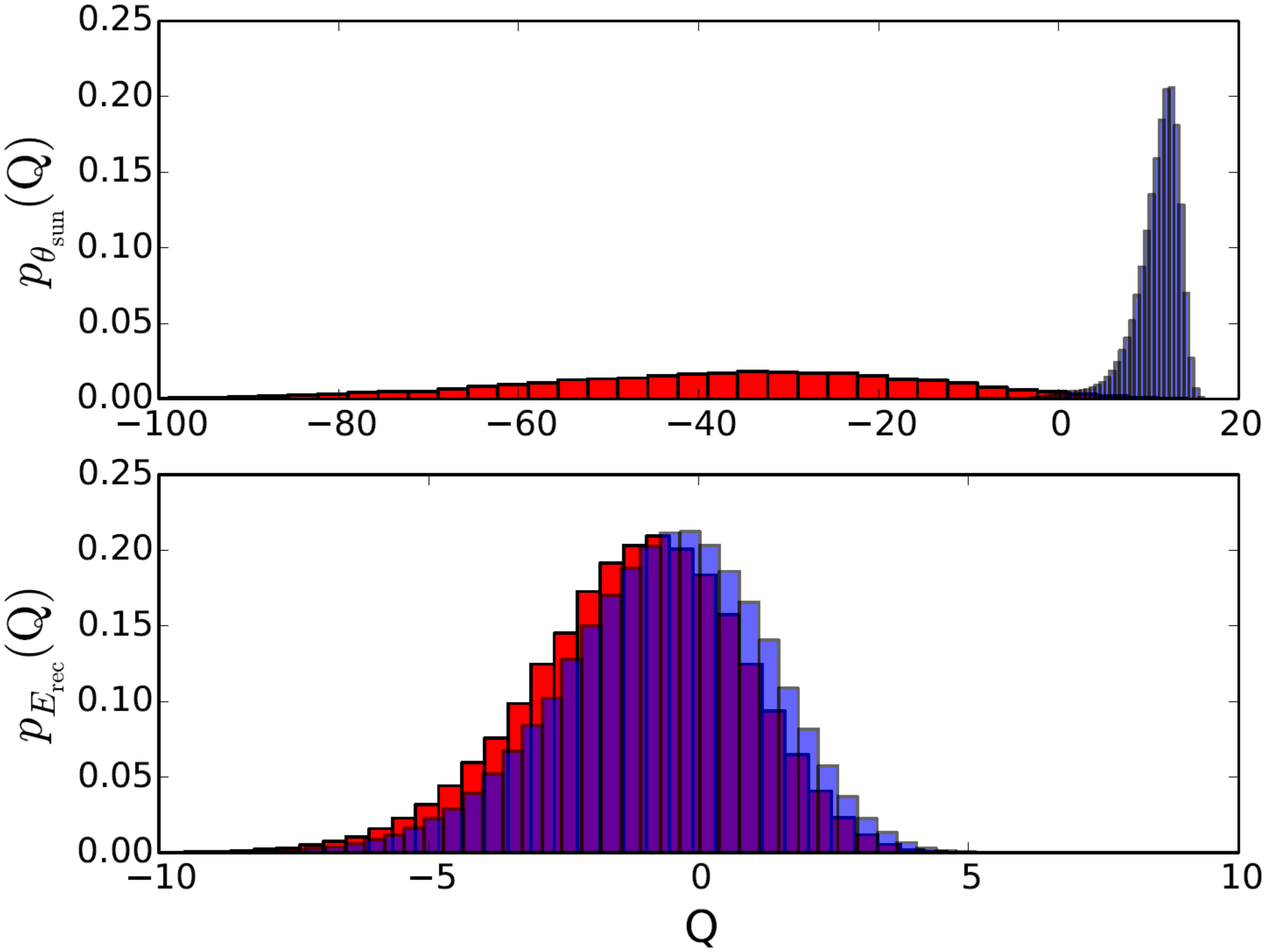


- Preferred arrival direction roughly from Cygnus A
- This changes during the year
- Lighter (heavier) dark matter more (less) directional above a given threshold

arXiv:1406.5047



Ruppin et al 1408.3581



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

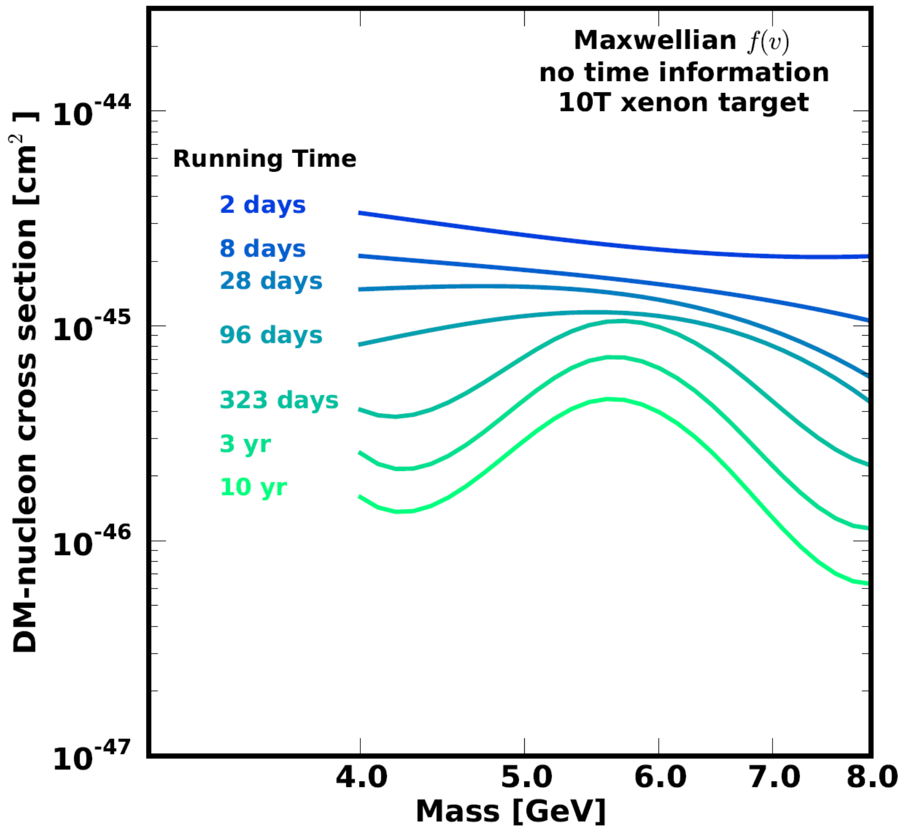
Various Effects, some of which compete with each other:-

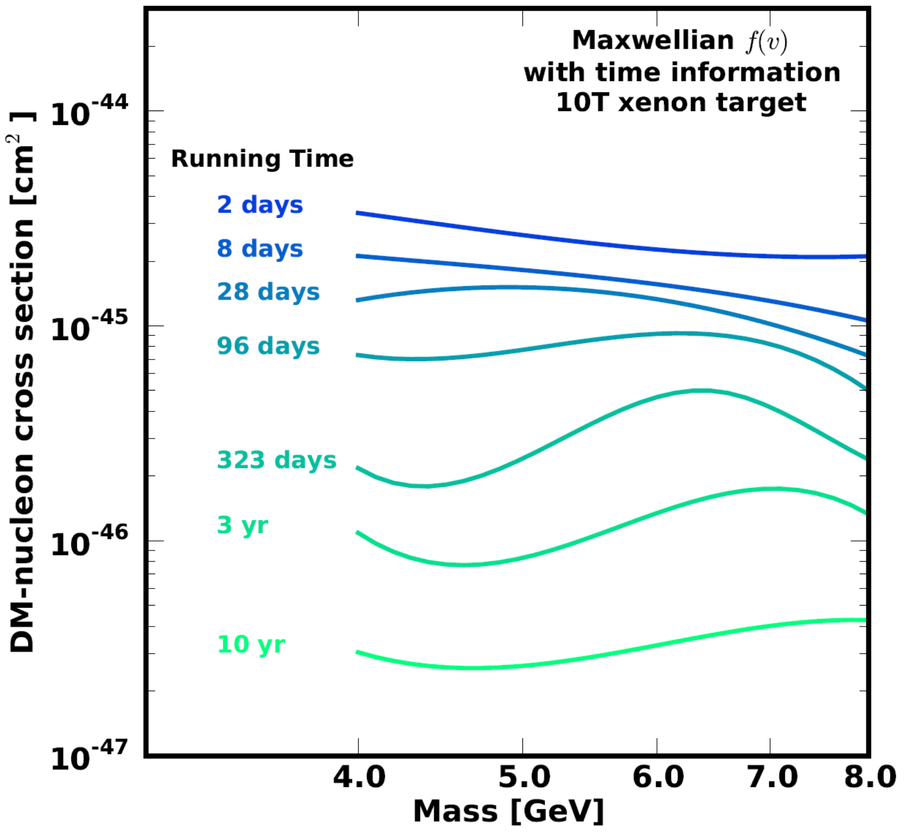
- For Low mass DM, only fastest moving particles will give a signal, so that points right back to Cygnus, easy to discriminate from the Sun

- 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

What about NO DIRECTIONALITY, only TIME information?

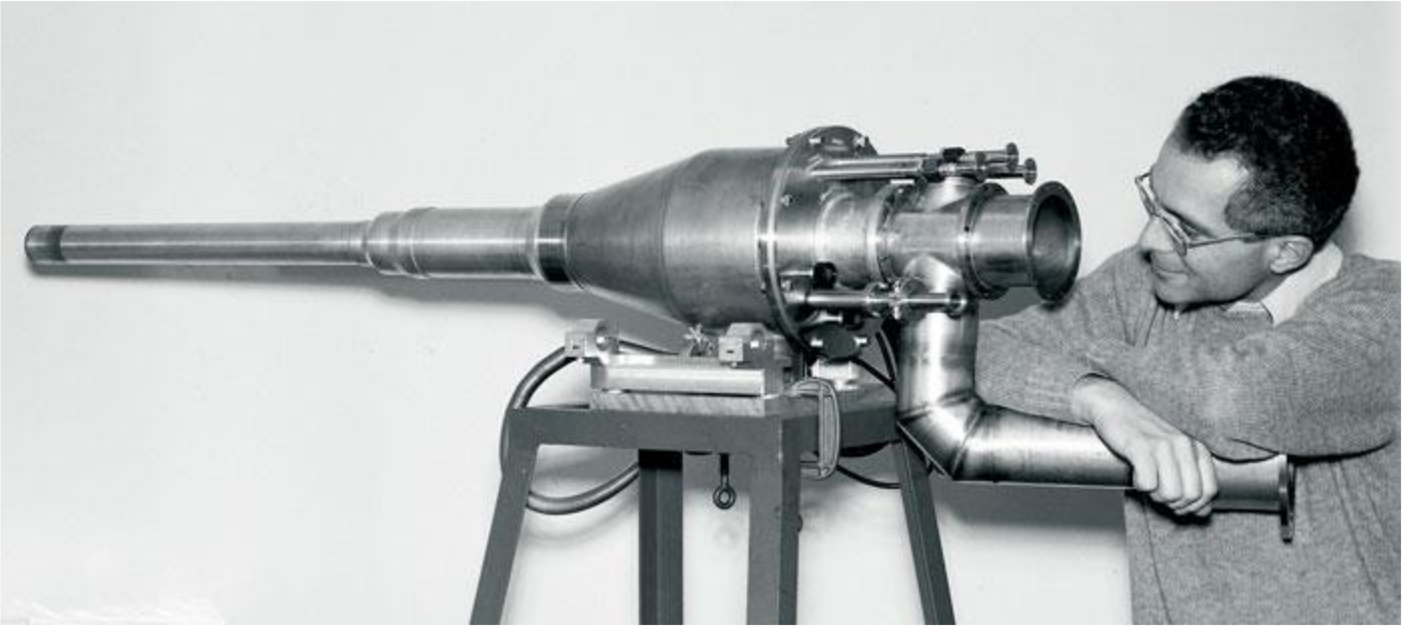




Davis arXiv:1412.1475

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

Interesting Possibility – Polarised targets



Michel Borghini with a polarized target at CERN in 1976.

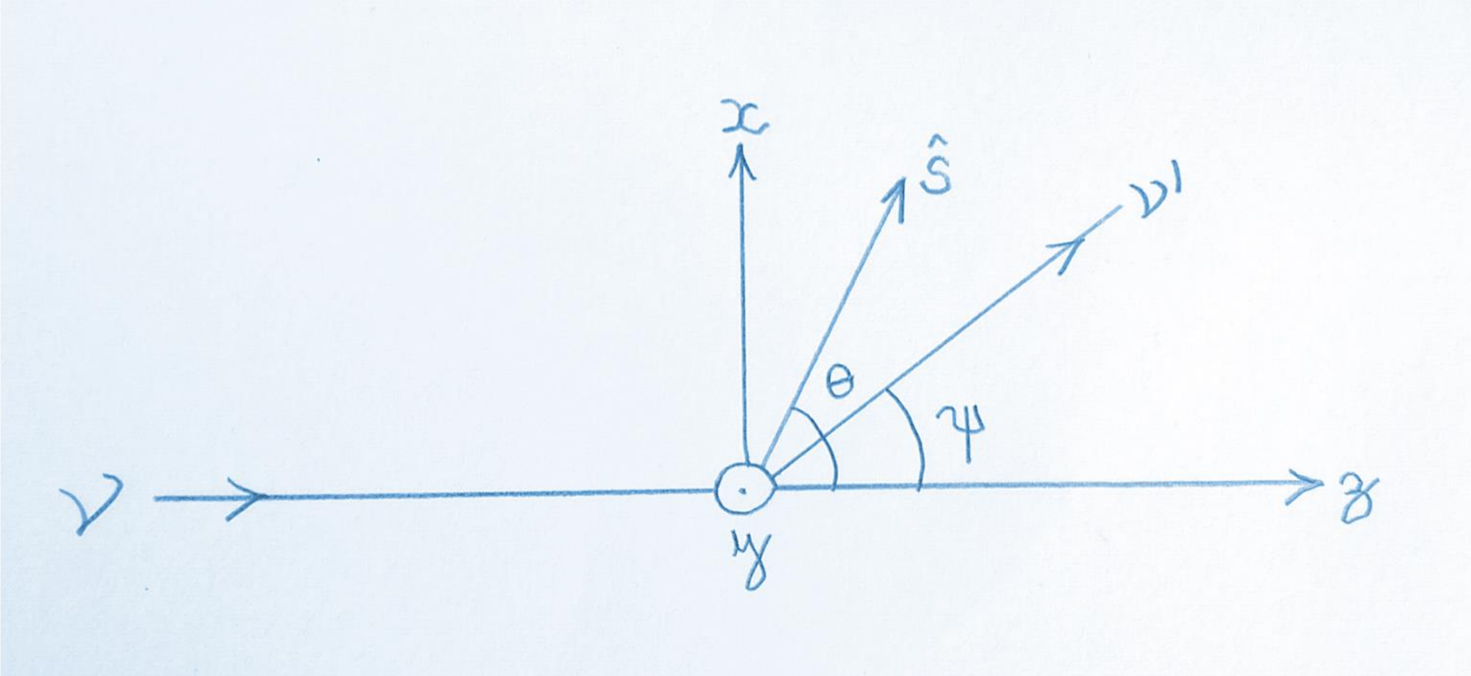
see also

“Dark Matter Detection with Polarized Detectors”

Chiang, Kamionkowski & Krnjaic, arXiv:1202.1807

Interesting Possibility – Polarised targets

- Polarised targets not very directional for dark matter
  (any 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
- Following work based on Franarin and Fairbairn **arXiv:1605.08727**



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

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

SI **SD**

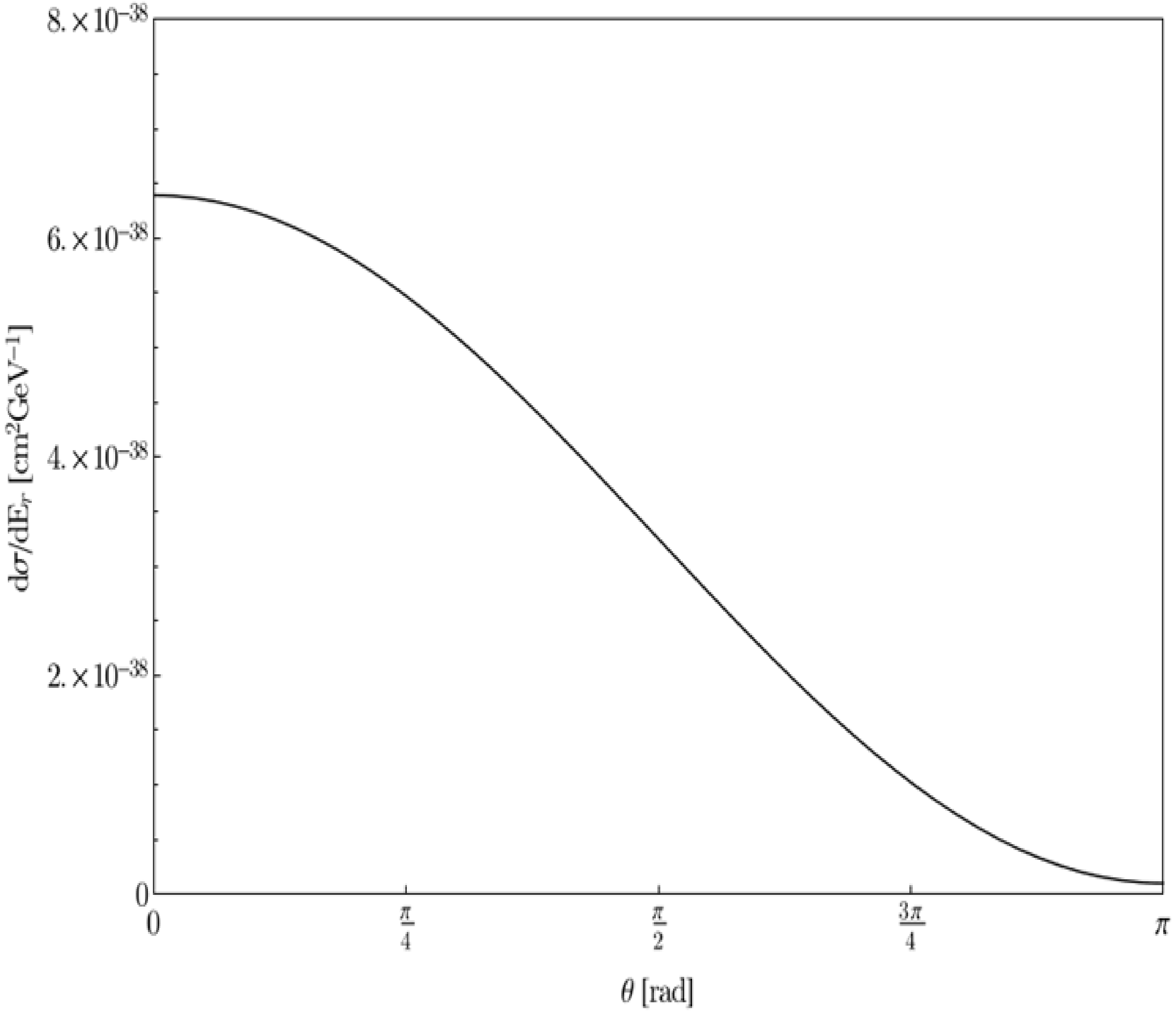
$$c_V^{\text{nucleus}} = Z c_V^p + N c_V^n$$

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

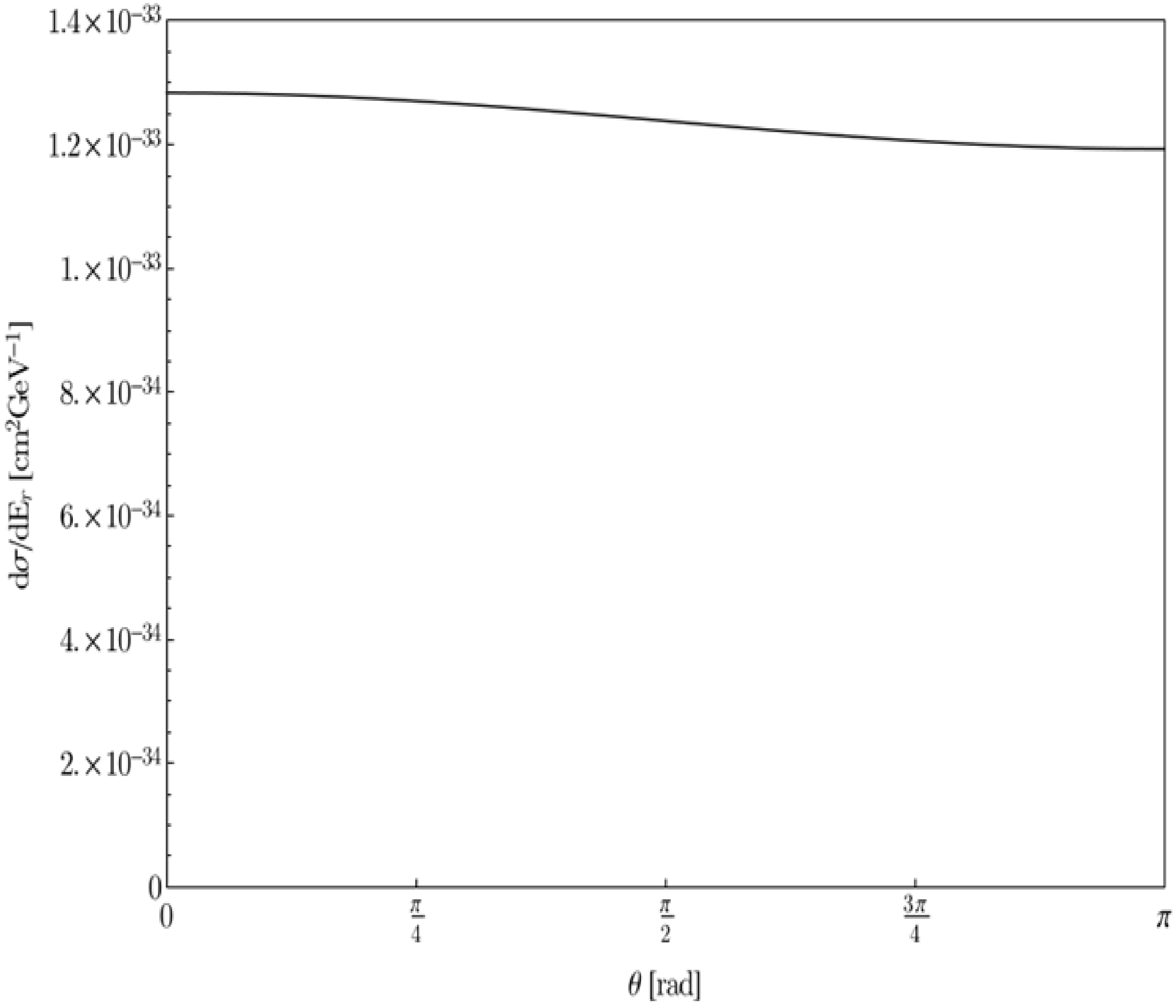
	c_V	c_A
Proton	$1 - 4\sin^2\theta_W$	1.26
Neutron	-1	-1.26

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

There are therefore ways of beating down the neutrino background, but they are difficult.

Many of them might only be well motivated if there is evidence from elsewhere of a dark matter particle in a certain mass range.

Some detectors which will come online in the next years

Darwin

Proposed 40(ish) ton Xenon experiment.

One suggested timeline is that construction begins 2020-ish. 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)	$R(pp)$	$R(^8\text{B})$
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?

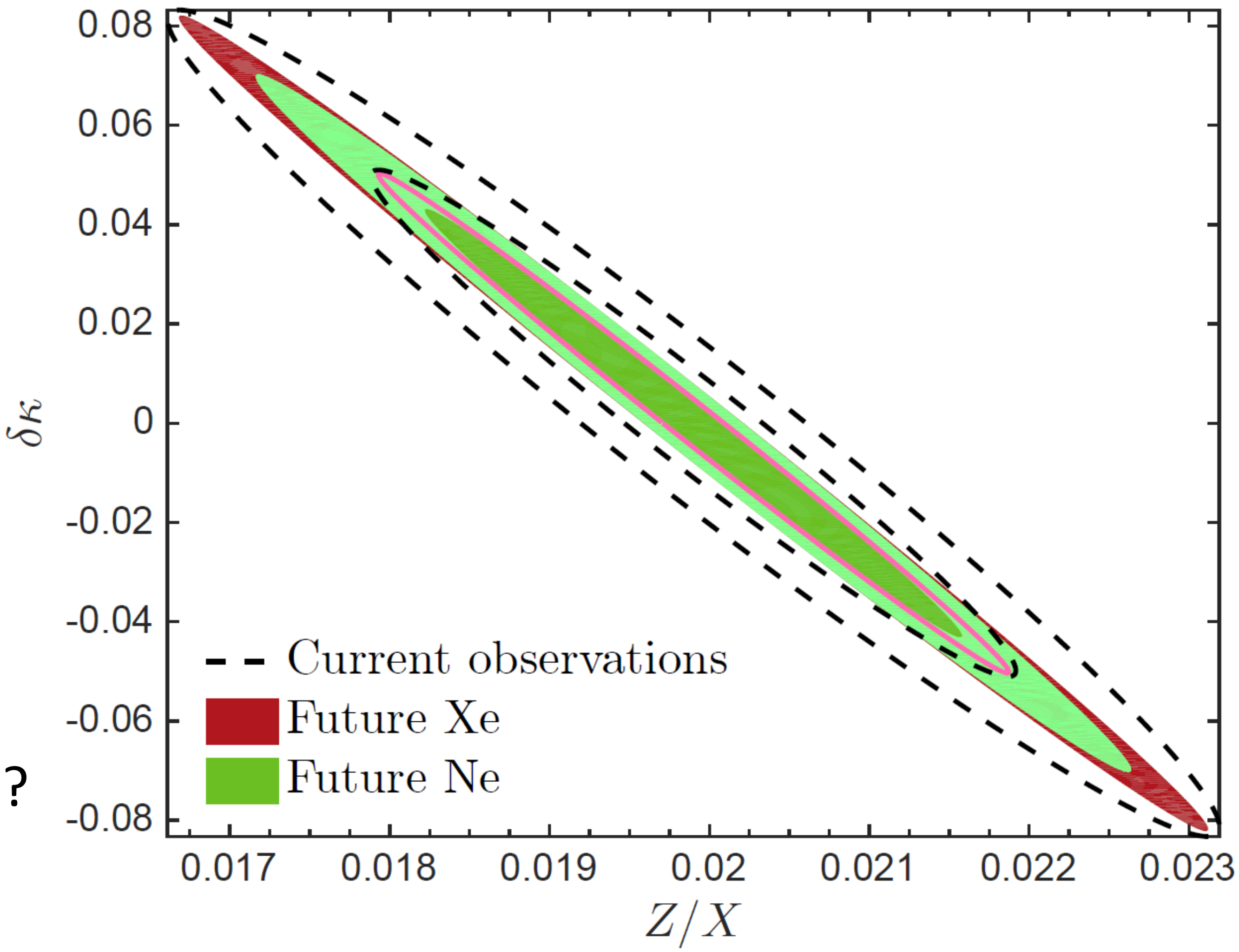
Limits average opacity vs. metallicity

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

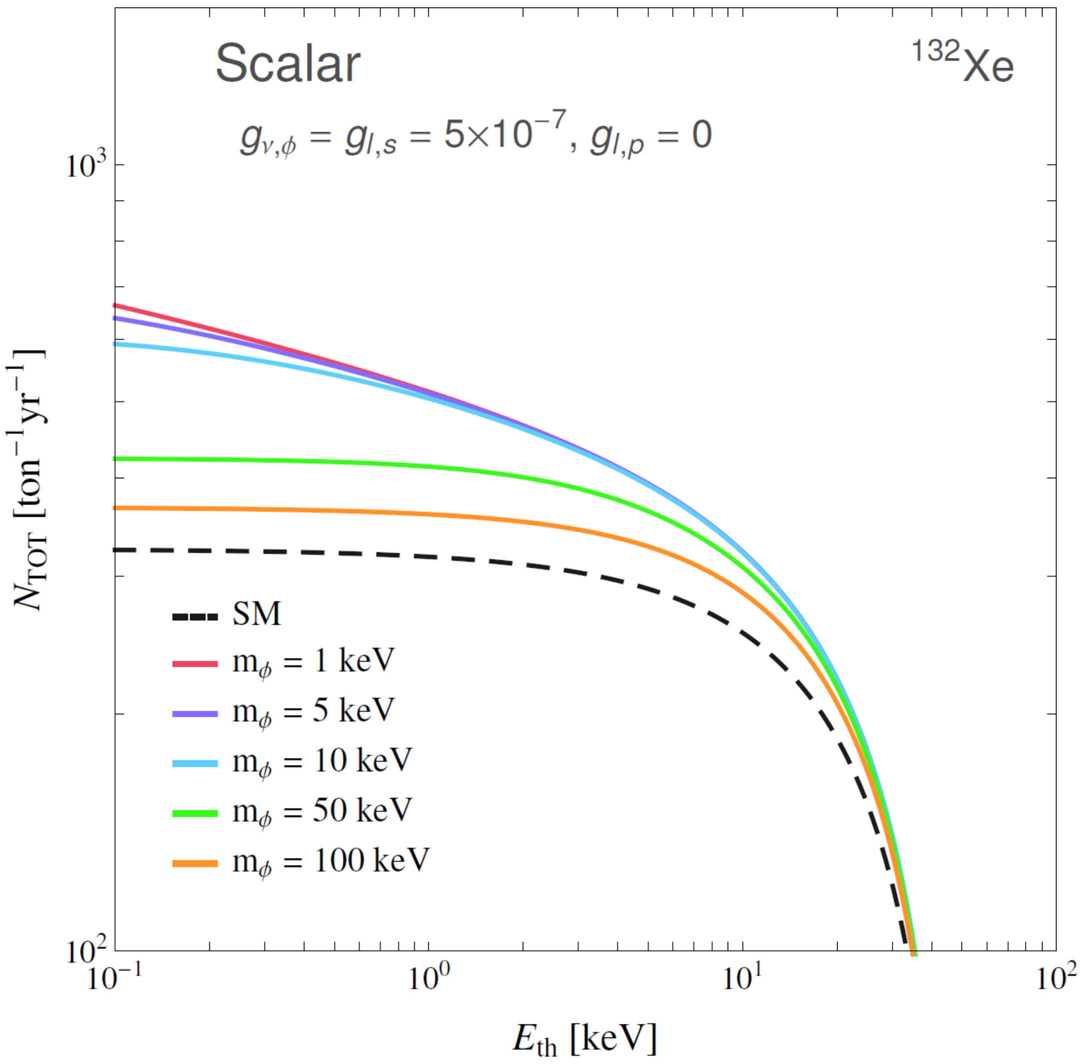
Momentum exchanged for pp-neutrino electron events is around 10 keV

Momentum exchanged for neutrino-nucleon events is about MeV scale

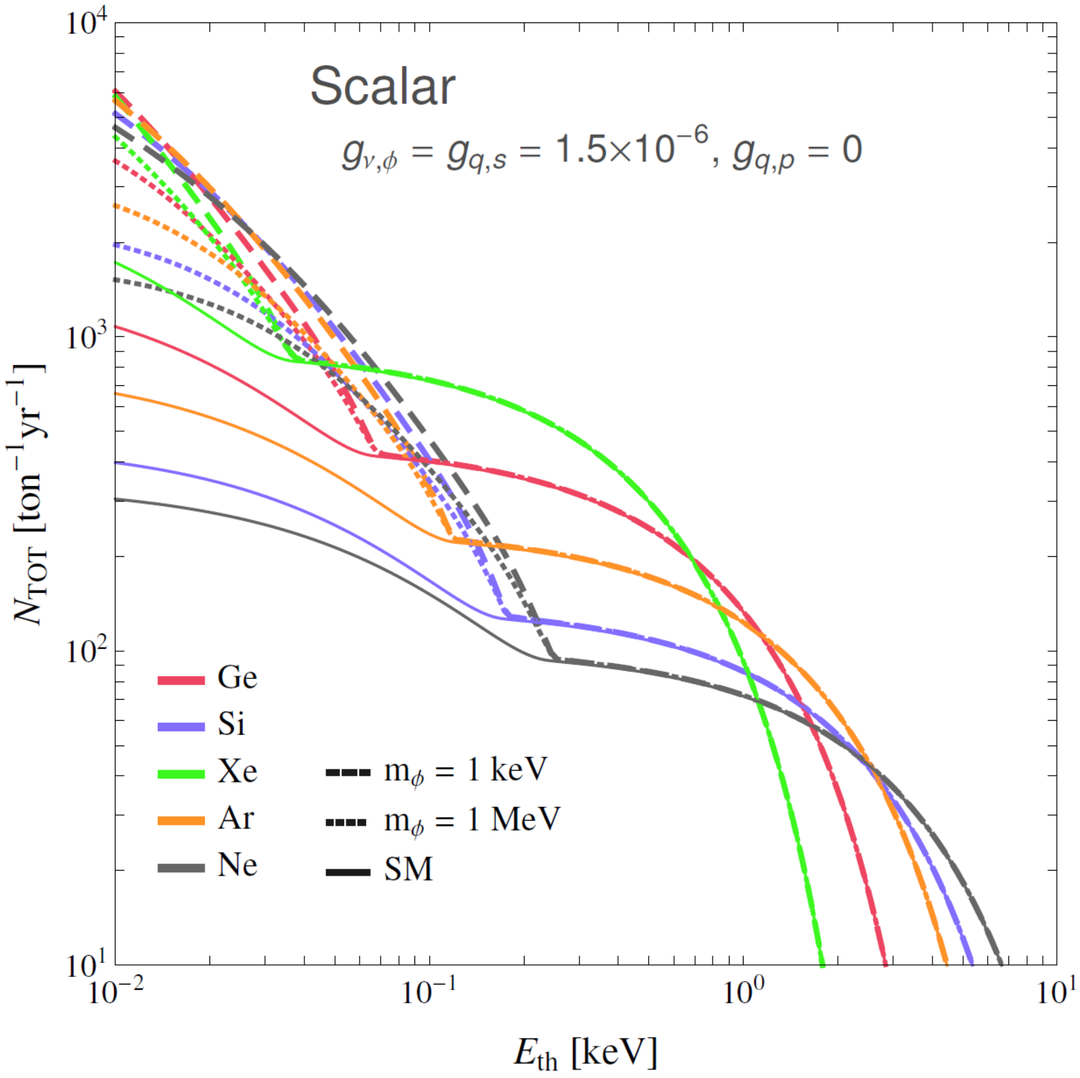
Both Q^2 unstudied in those settings, can probe new interactions.

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



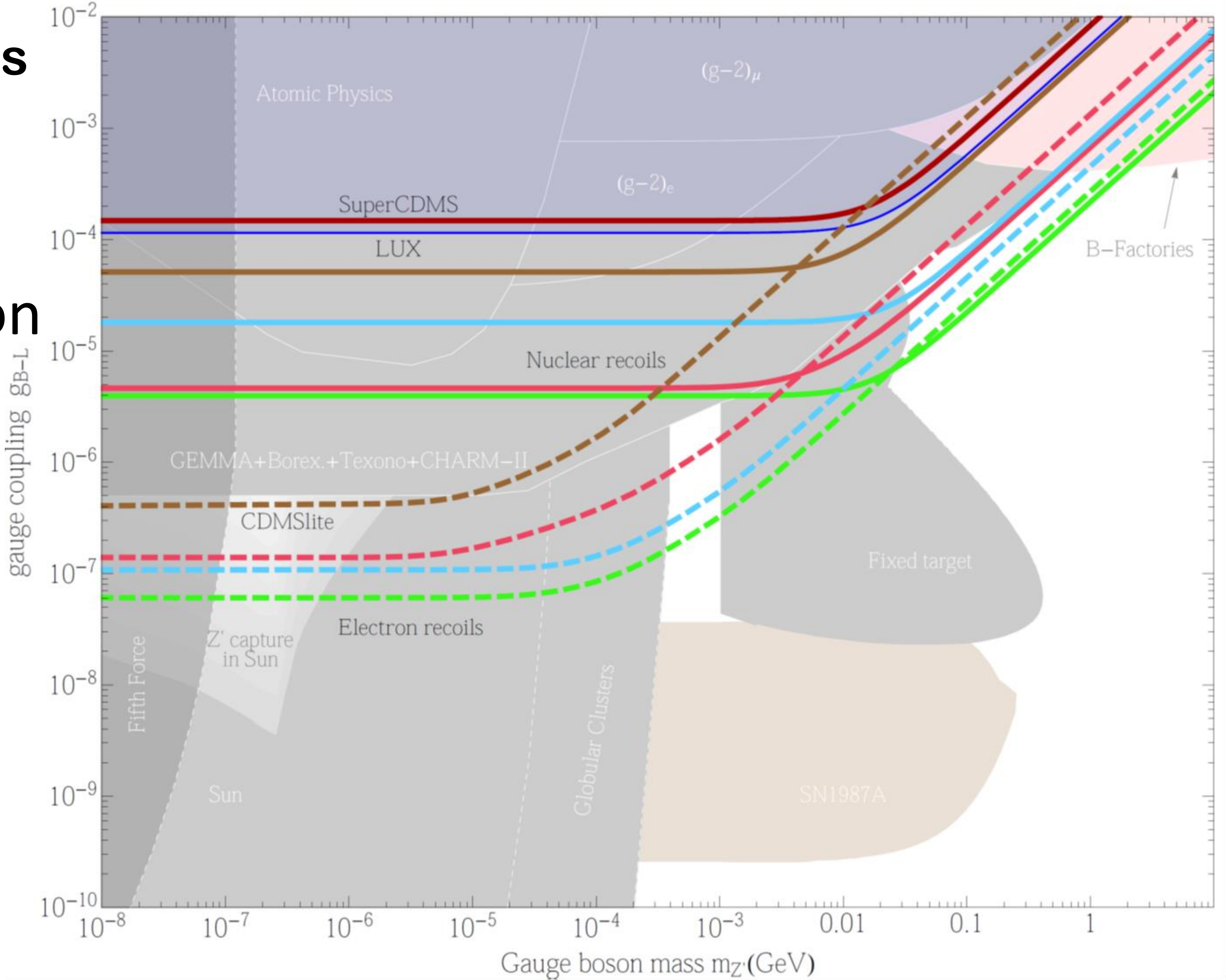
nuclear recoils

Tests of BSM Physics

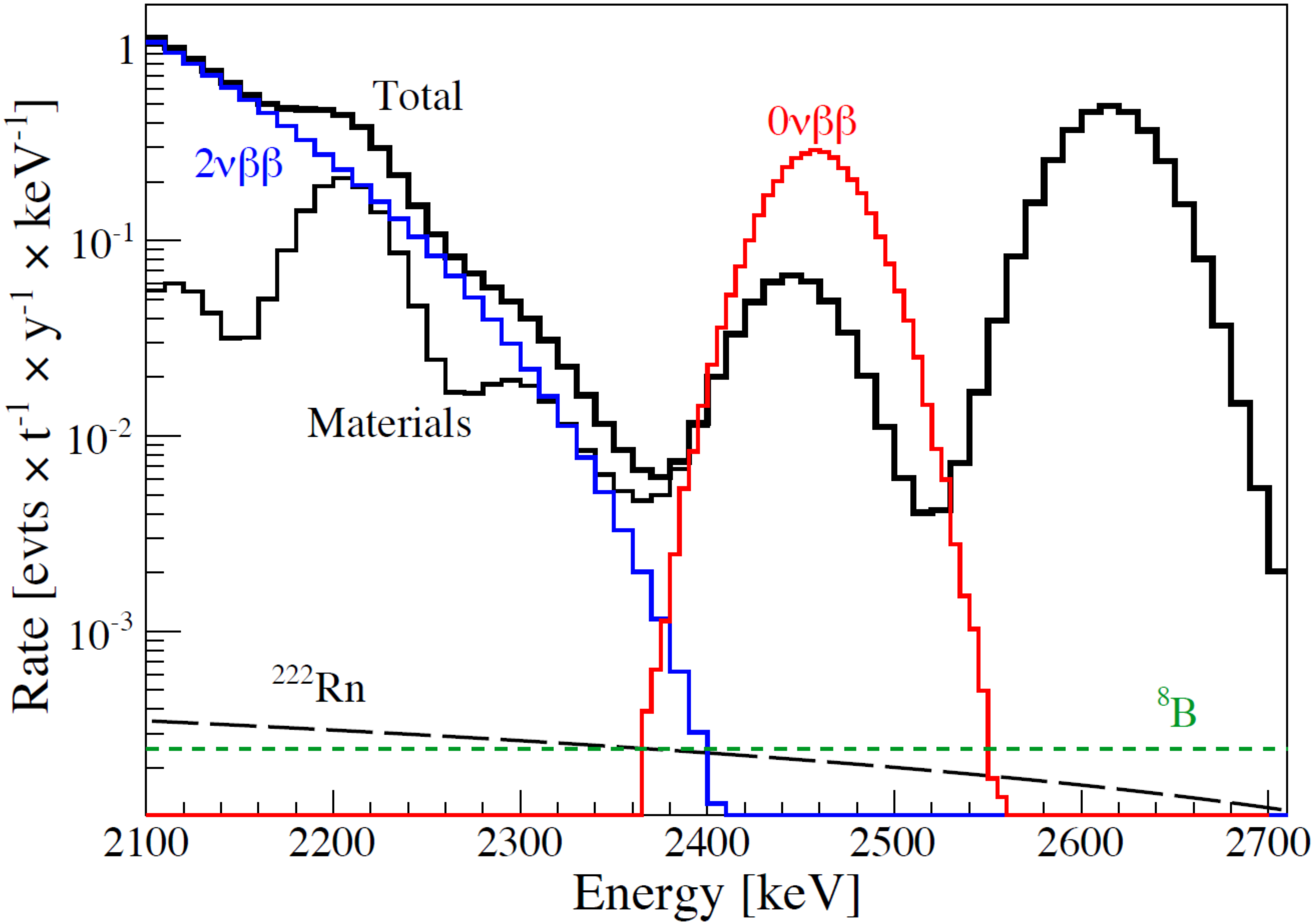
U(1)$_{B-L}$ gauge boson couples to B-L charge of SM particles

Dashed electron, solid nucleon.

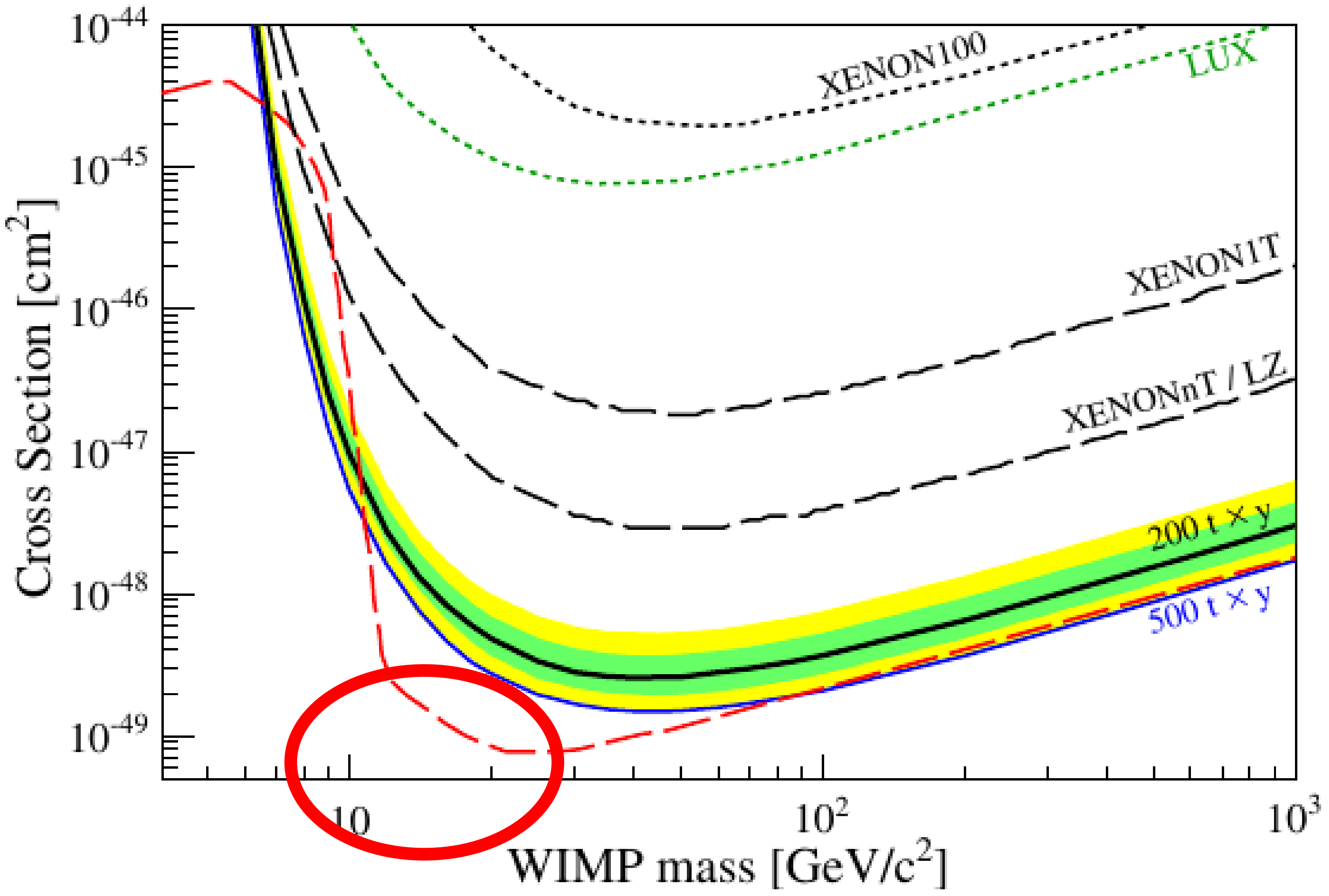
Green future xenon
Blue G2 xenon
Red G2 germanium



Darwin would also be sensitive to Neutrinoless Double Beta Decay



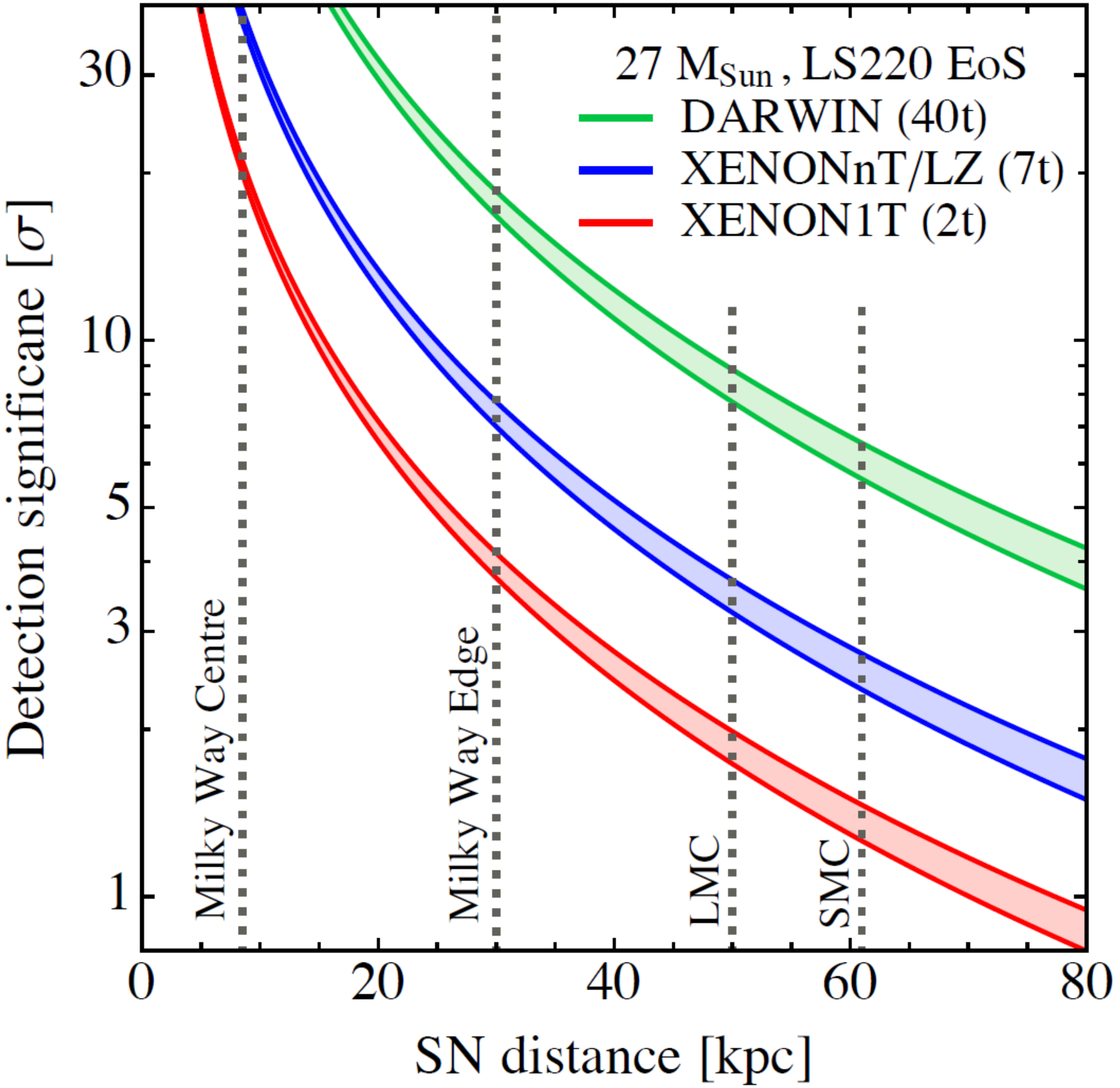
Doesn't seem possible to measure Diffuse Supernova Neutrino Background even with Darwin



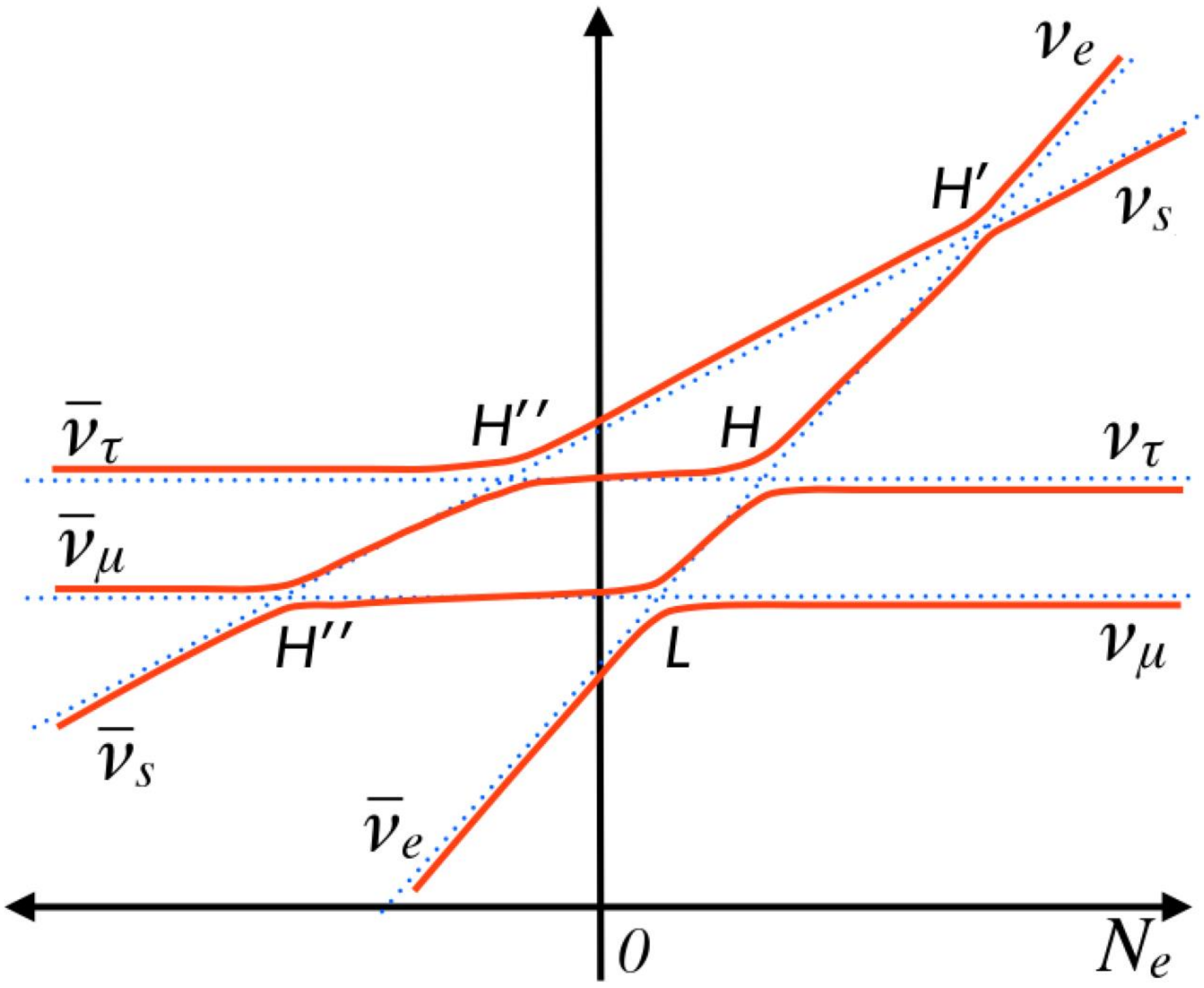
Observing a local supernova with DM detectors

Should be easily possible (see e.g. Lang, McCabe et al 1606.09243)

Question is, can we do new fundamental physics with such observations?



Mixing with Sterile Neutrino during Supernova Explosion



Normal hierarchy

At the first resonance:

$$\begin{pmatrix} F_1' \\ F_2' \\ F_3' \\ F_4' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1-p_{H'} & p_{H'} \\ 0 & 0 & p_{H'} & 1-p_{H'} \end{pmatrix} \begin{pmatrix} F^0_{\bar{\nu}_\mu} \\ F^0_{\bar{\nu}_\tau} \\ F^0_{\bar{\nu}_s} \\ F^0_{\bar{\nu}_e} \end{pmatrix}$$

Then:

$$\begin{pmatrix} F_1'' \\ F_2'' \\ F_3'' \\ F_4'' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-p_H & p_H & 0 \\ 0 & p_H & 1-p_H & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} F_1' \\ F_2' \\ F_3' \\ F_4' \end{pmatrix}$$

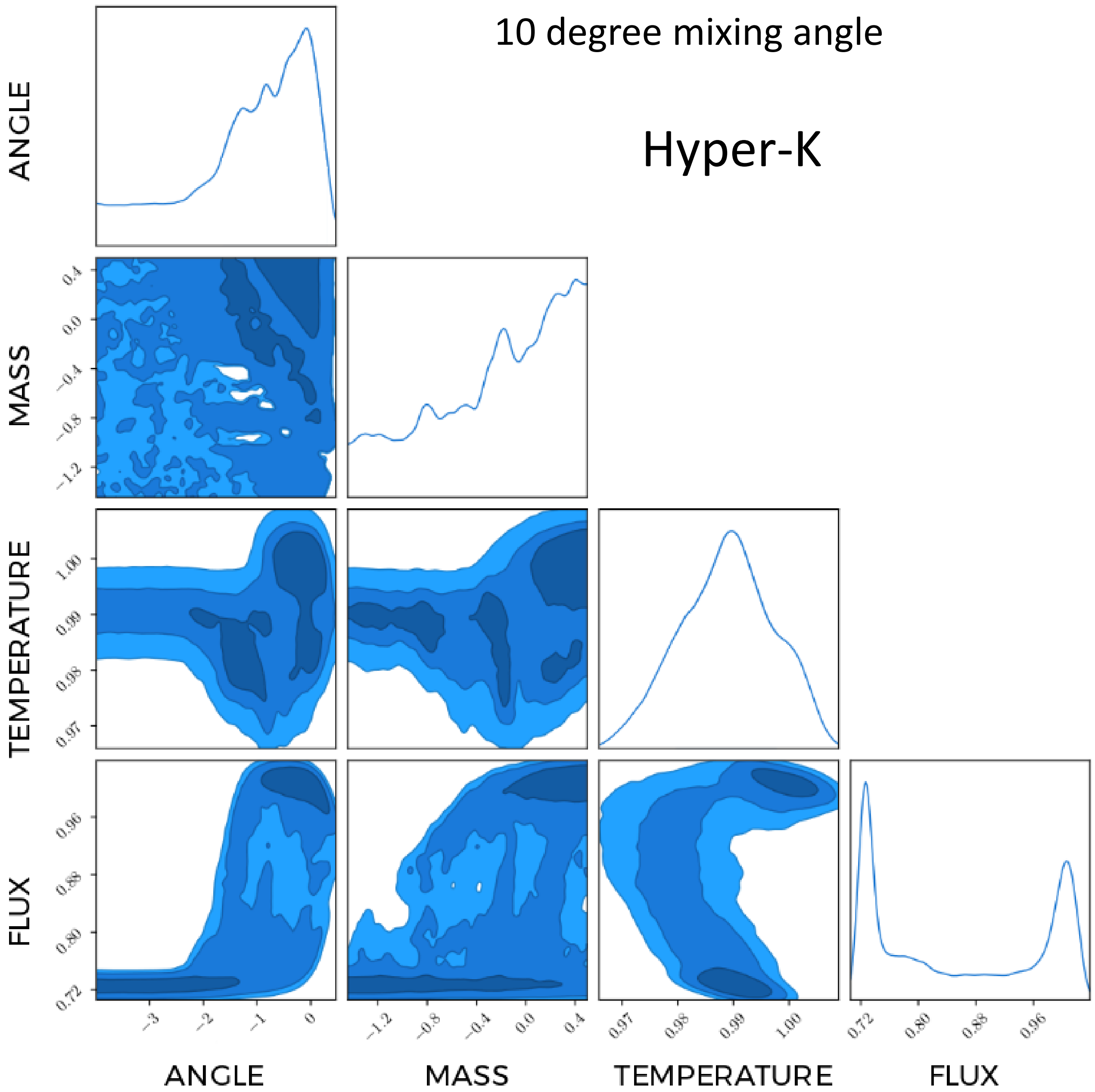
Finally:

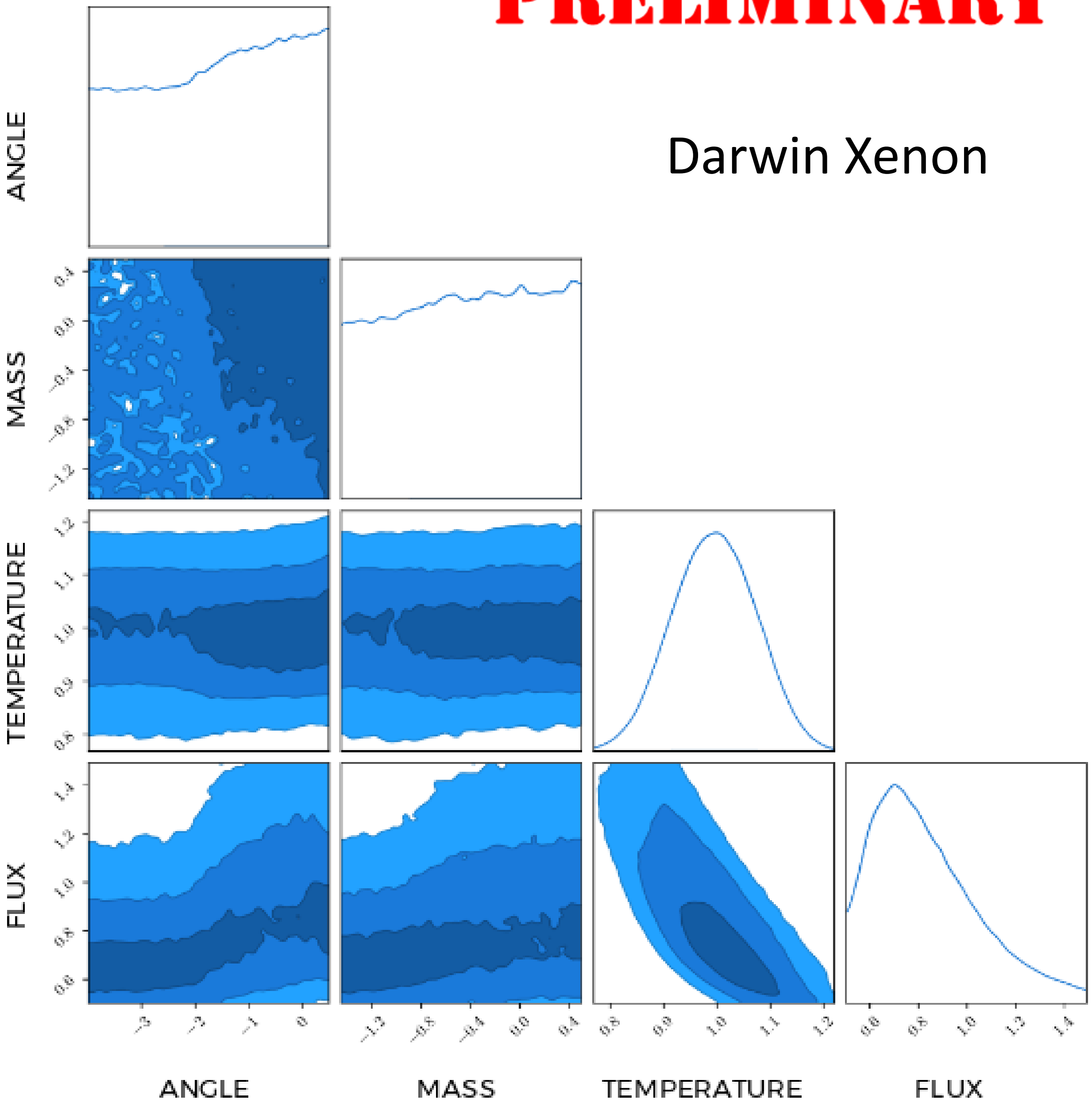
$$\begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{pmatrix} = \begin{pmatrix} 1-p_L & p_L & 0 & 0 \\ p_L & 1-p_L & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} F_1'' \\ F_2'' \\ F_3'' \\ F_4'' \end{pmatrix}$$

Sensitivity of Hyper-K and Darwin to Sterile mixing from Supernova at 10 kpc

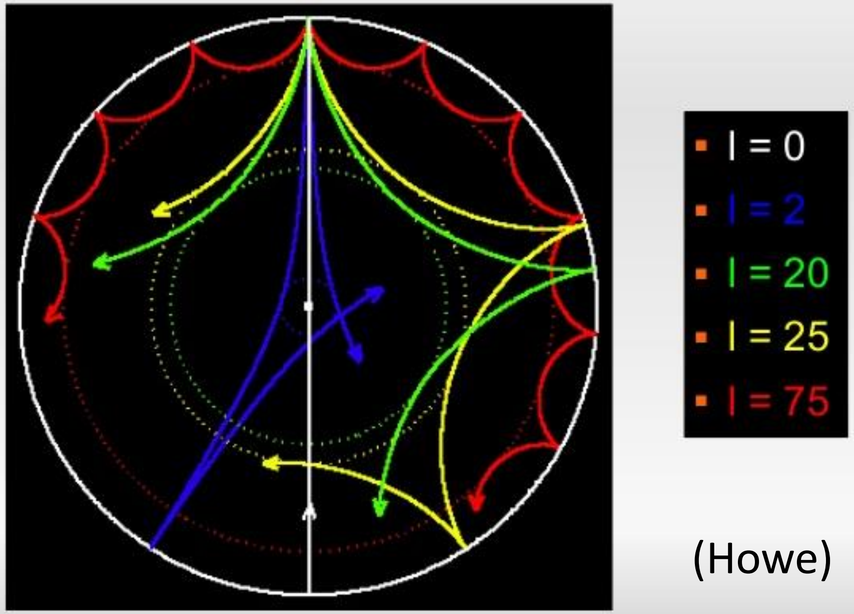
for eV neutrino with
10 degree mixing angle

PRELIMINARY



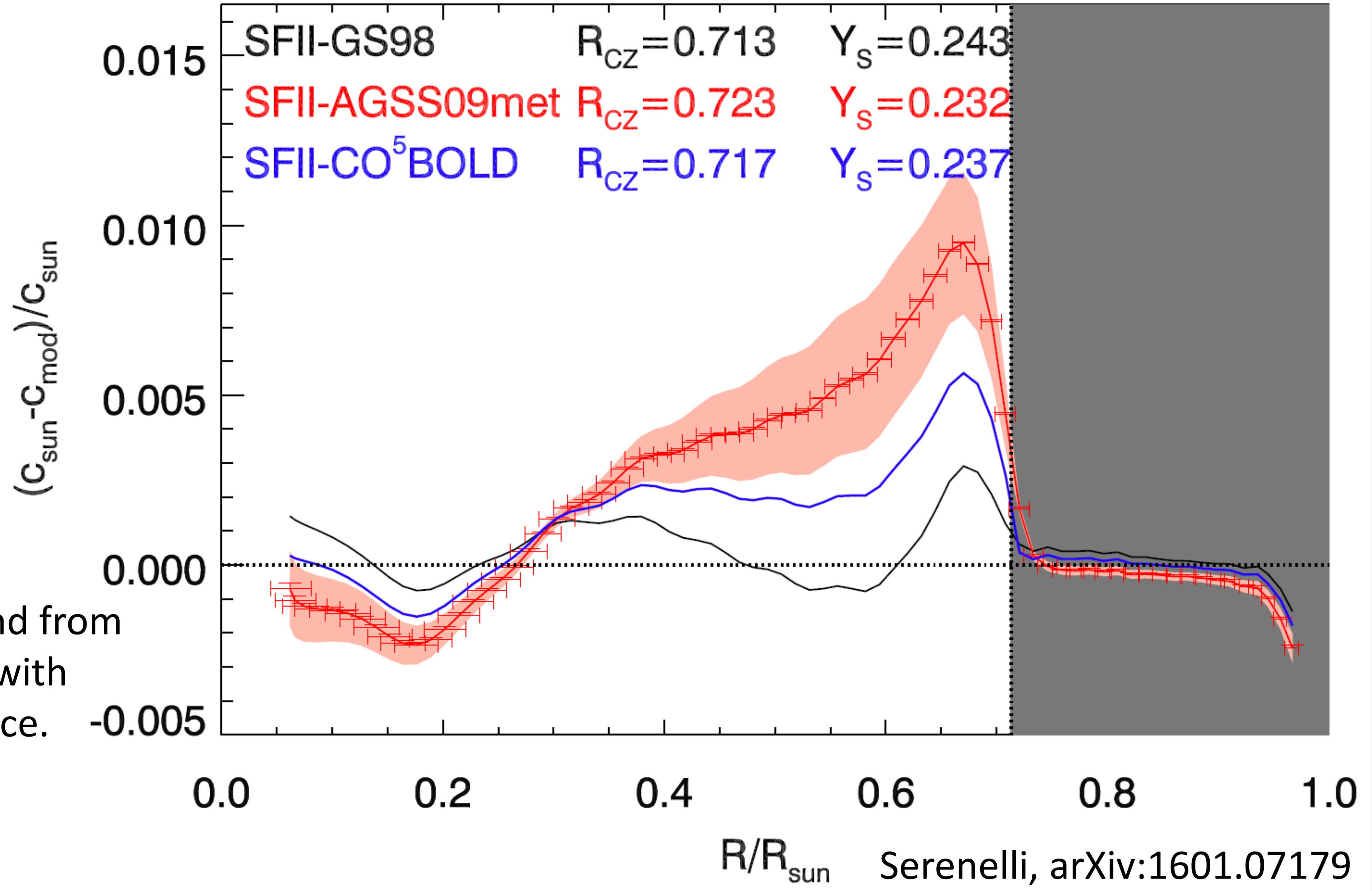


Solar Abundance Problem



(Howe)

Helioseismology measures the speed of sound of the sun as a function of depth.

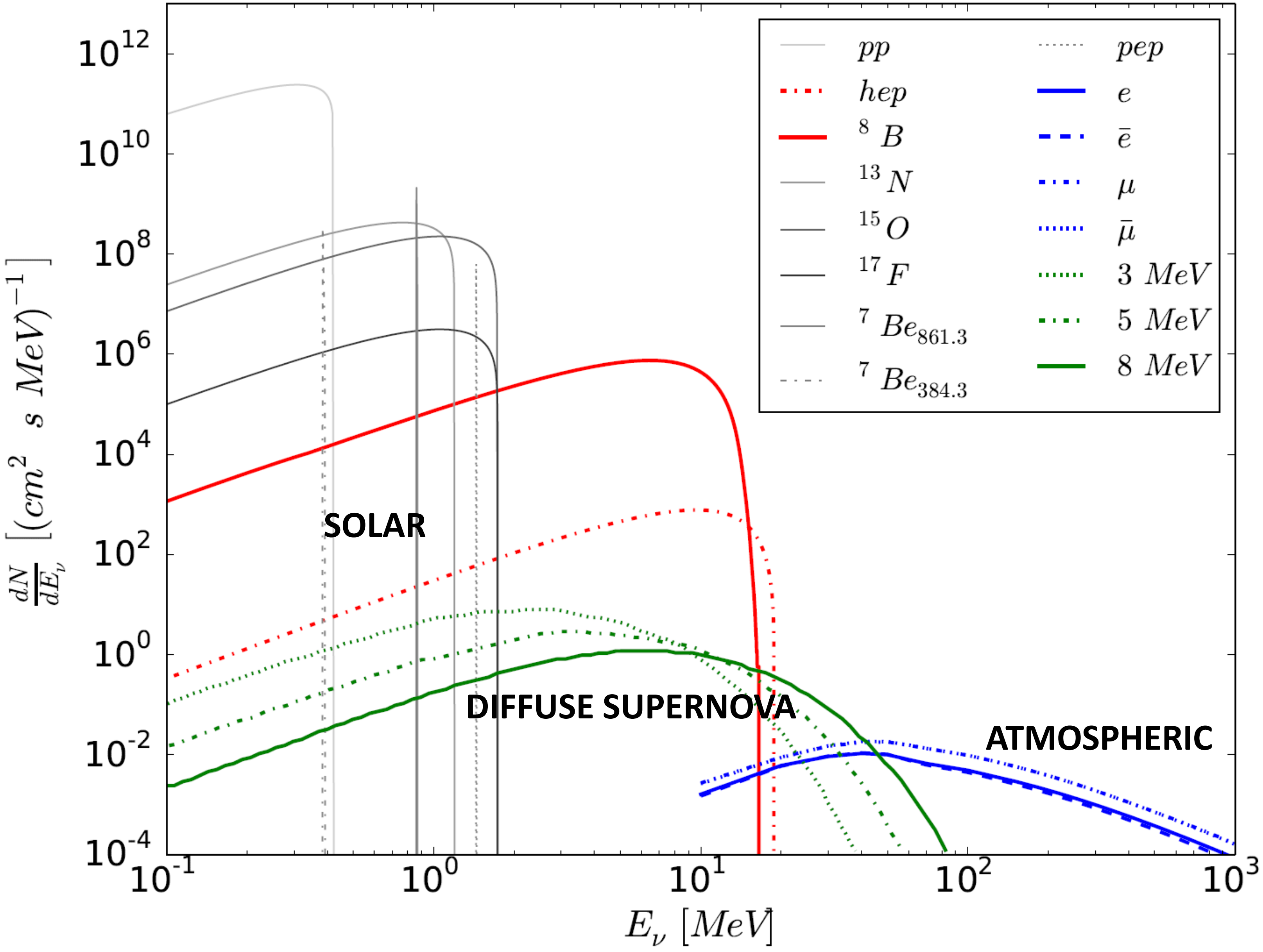


Serenelli, arXiv:1601.07179

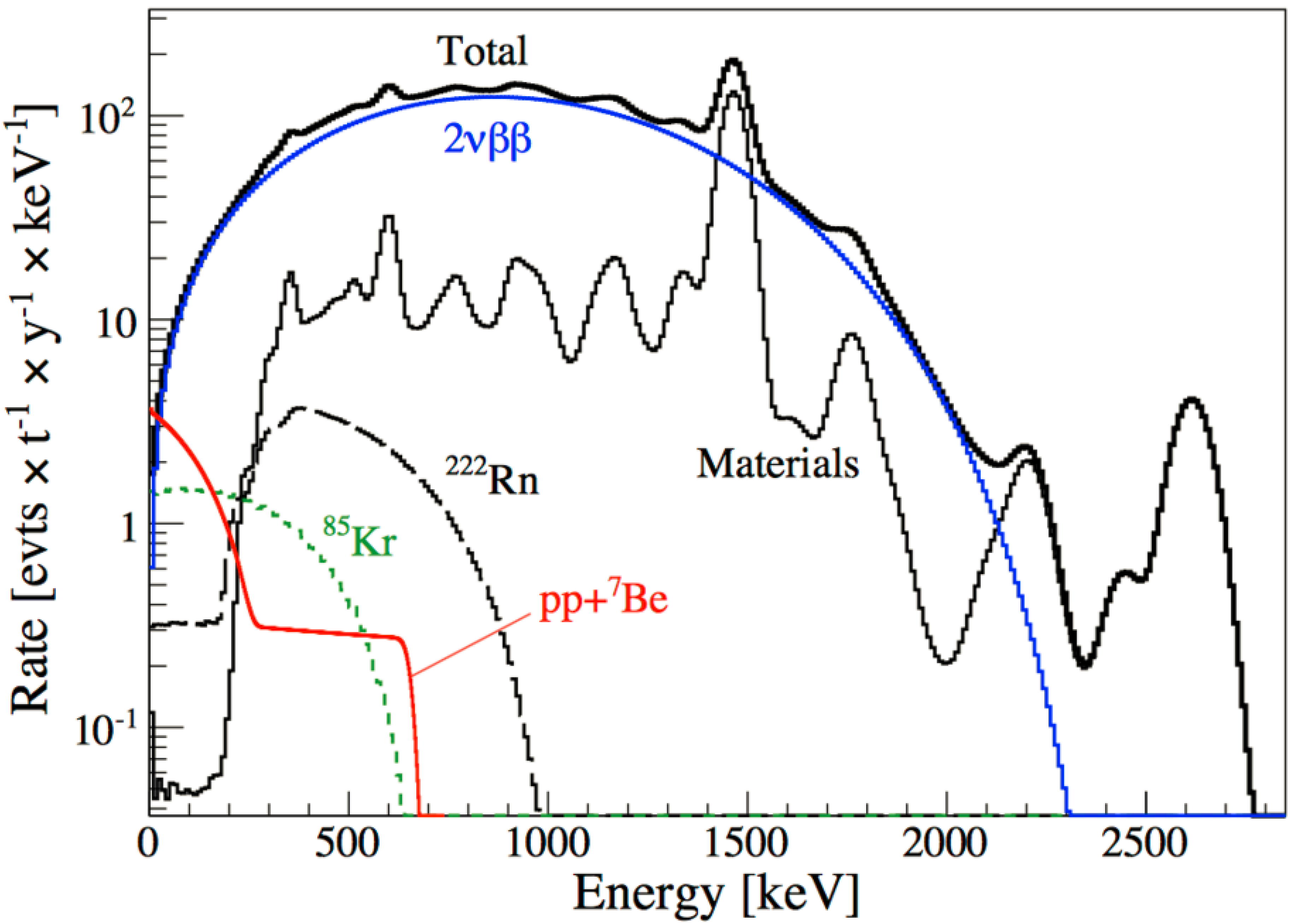
Discrepancy between the observed speed of sound from helioseismology and that inferred by the models with the same metallicity as that observed at the surface.

OBSERVING CNO NEUTRINOS WOULD HELP WITH THIS

Neutrino Background

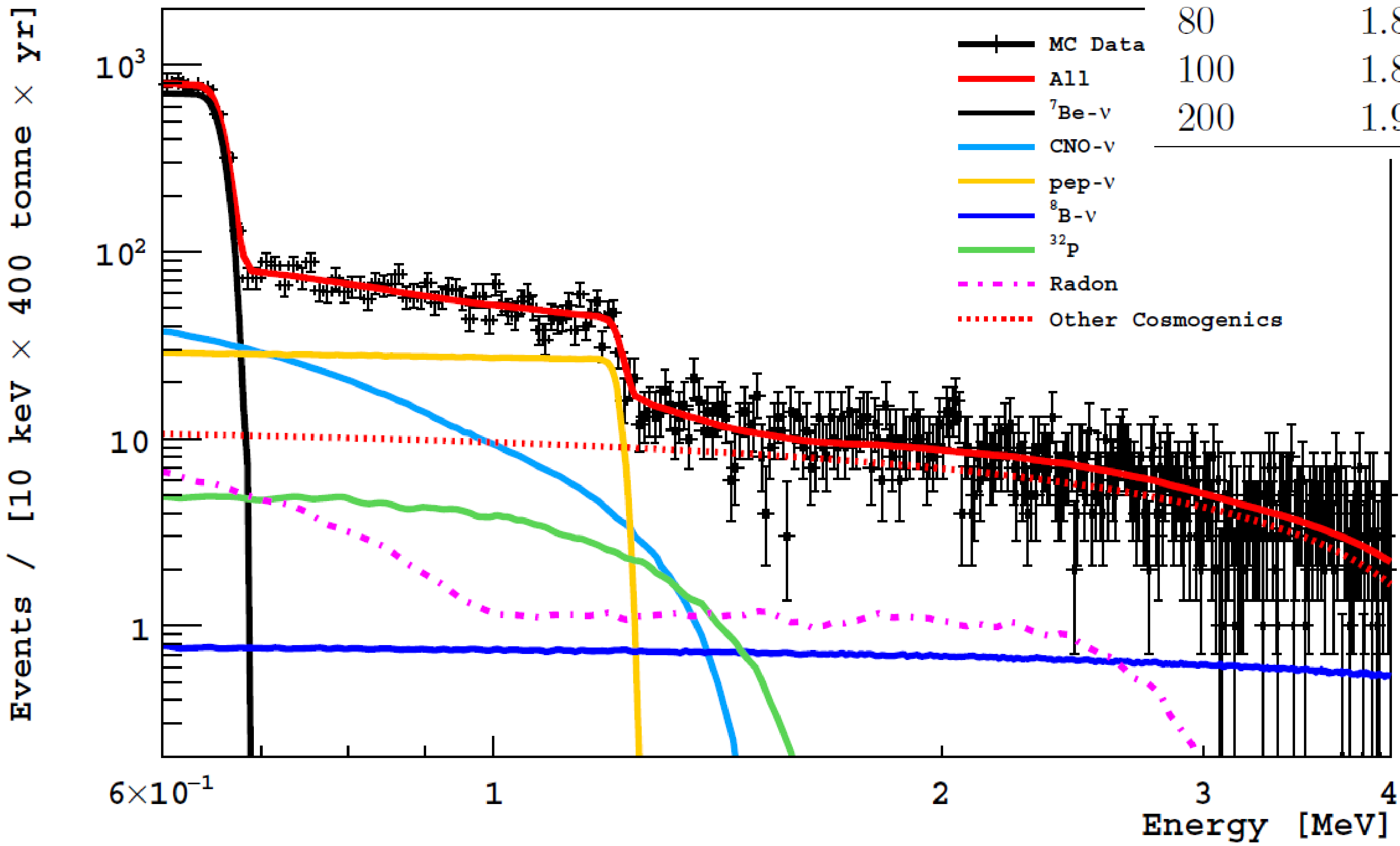


CNO neutrinos would be very difficult for a Darwin like experiment…



Future Argon Detectors could detect CNO neutrinos Using electron Recoils (Franco et al. arXiv:1510.04196)

^{222}Rn Activity	Low Metallicity $\sigma(^7Be)$	$\sigma(pep)$	$\sigma(CNO)$
10	1.77 ± 0.01	8.4 ± 0.1	16.7 ± 0.1
20	1.80 ± 0.01	8.7 ± 0.1	17.0 ± 0.1
40	1.82 ± 0.01	9.3 ± 0.1	17.9 ± 0.1
60	1.84 ± 0.01	9.7 ± 0.1	18.6 ± 0.1
80	1.85 ± 0.01	10.0 ± 0.1	19.6 ± 0.1
100	1.87 ± 0.01	10.5 ± 0.1	20.0 ± 0.1
200	1.96 ± 0.01	12.1 ± 0.1	23.2 ± 0.2



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

Potential for BSM and solar physics as well as DM

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Part II

Detecting Axion Mini-clusters through Microlensing

Axions as Dark Matter

What is this?

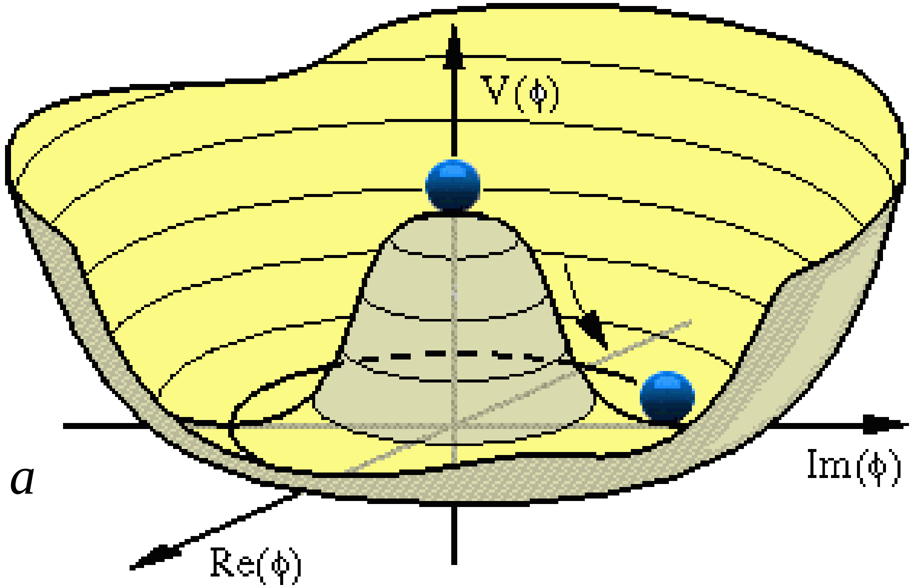
$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^a_{\mu\nu} + \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

Gluon kinetic energy

quark kinetic energy

quark mass

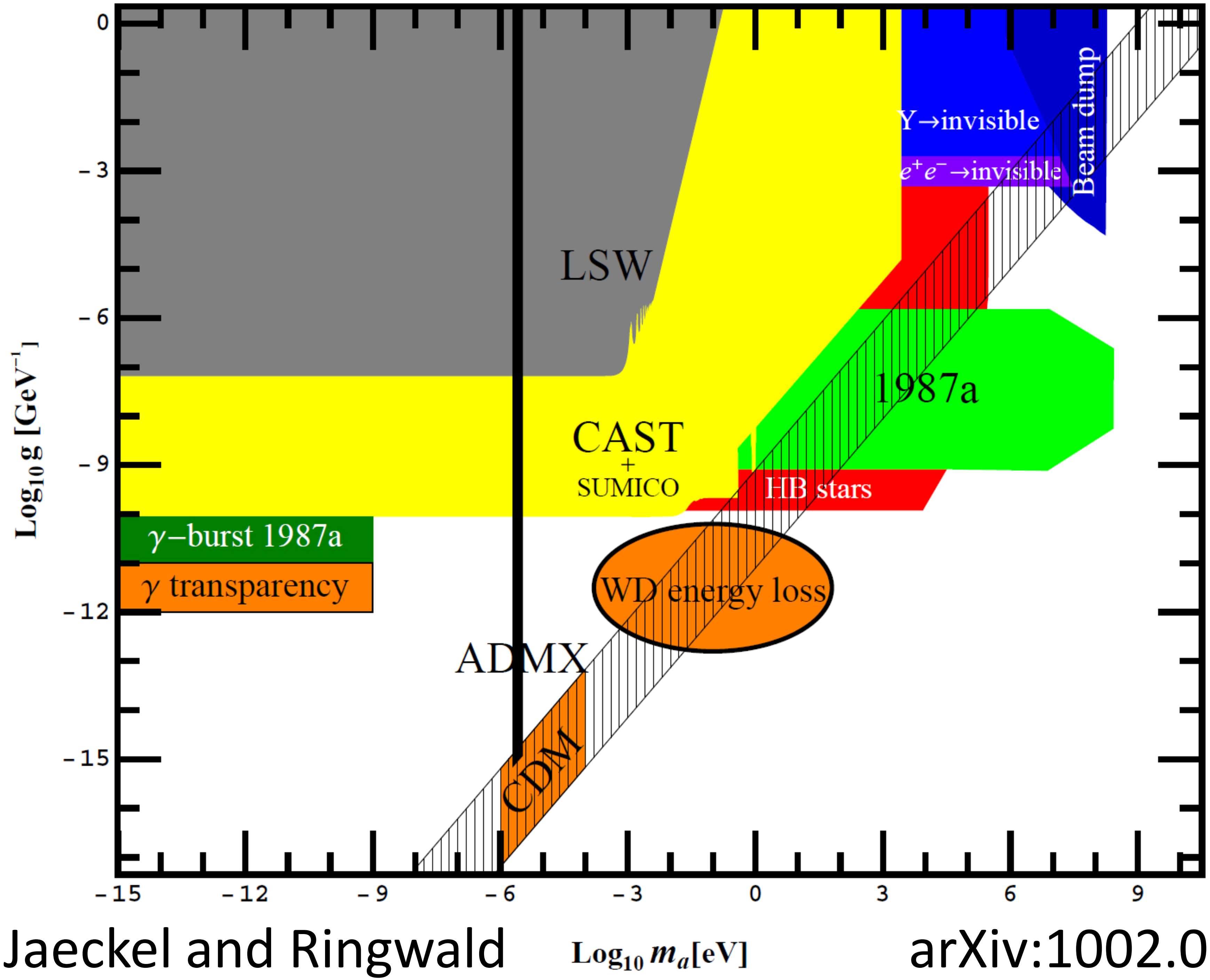
$$\theta \longrightarrow \theta - a/f_a$$



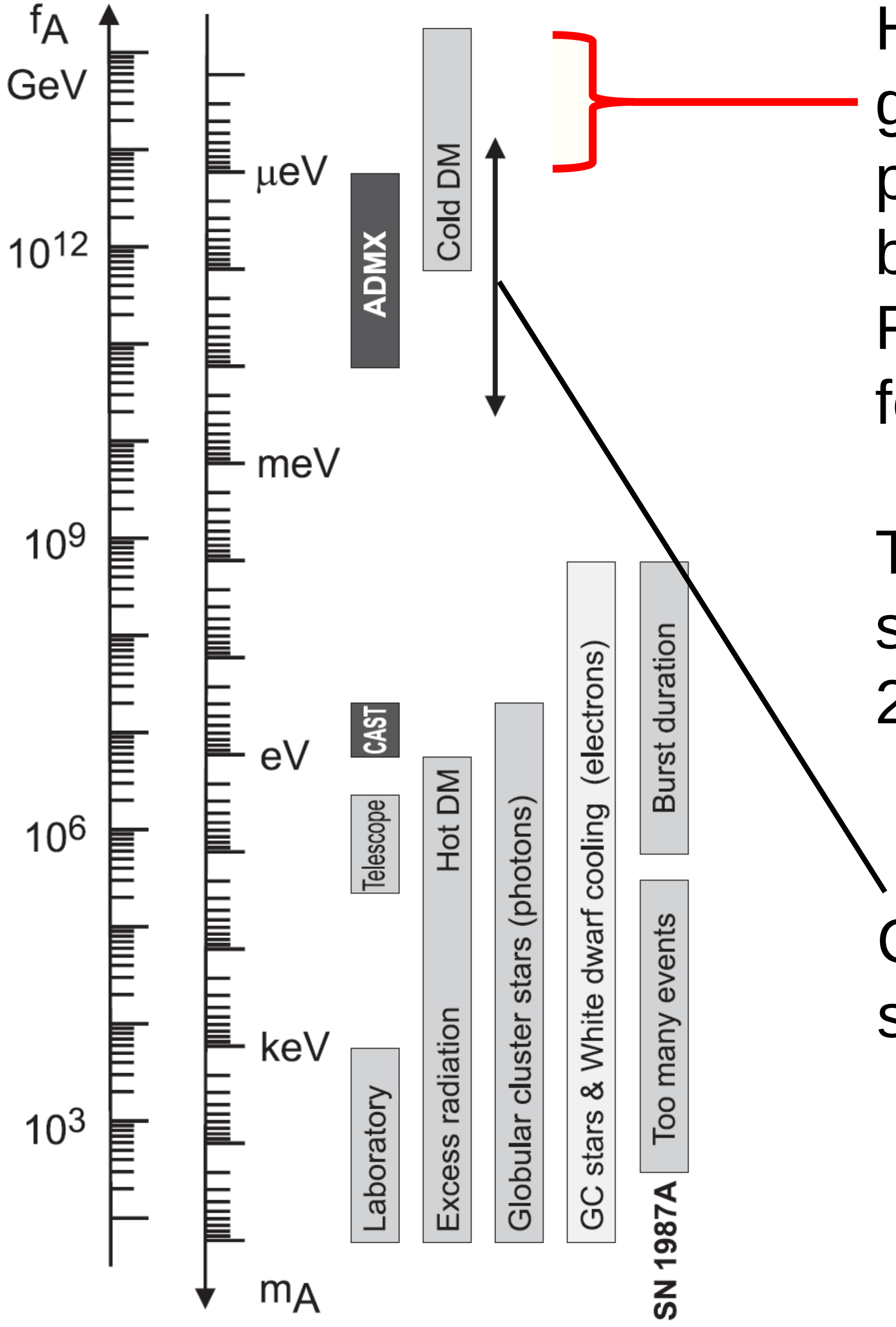
Promote θ to field a

$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

Also induces coupling to photons



Jaeckel and Ringwald arXiv:1002.0329



Here you can get good dark matter, but generically you get too many isocurvature perturbations if PQ symmetry was broken before inflation (although see Hogan, Fairbairn and Marsh and Ballesteros et al for ways around this.)

Tuning required to fix this worse than strong CP problem in first place (Mack 2009)

Can also get good relic abundance if PQ symmetry broken after inflation.

What Happens Step by Step

1. PQ phase transition after inflation – lots of different values in different regions
2. Field smooths itself out on horizon scale in the style of Kibble Mechanism
3. Axion acquires a mass, leading to big over-densities from place to place
4. Field now collapses to form (very) dense miniclusters with typical mass equal to that inside horizon
5. All of these isocurvature perturbations physics occurs on very small scales, on large scales they fall into adiabatic perturbations
6. We then try to observe the small scale miniclusters today with lensing

U(1) PQ symmetry broken by axion mass after inflation

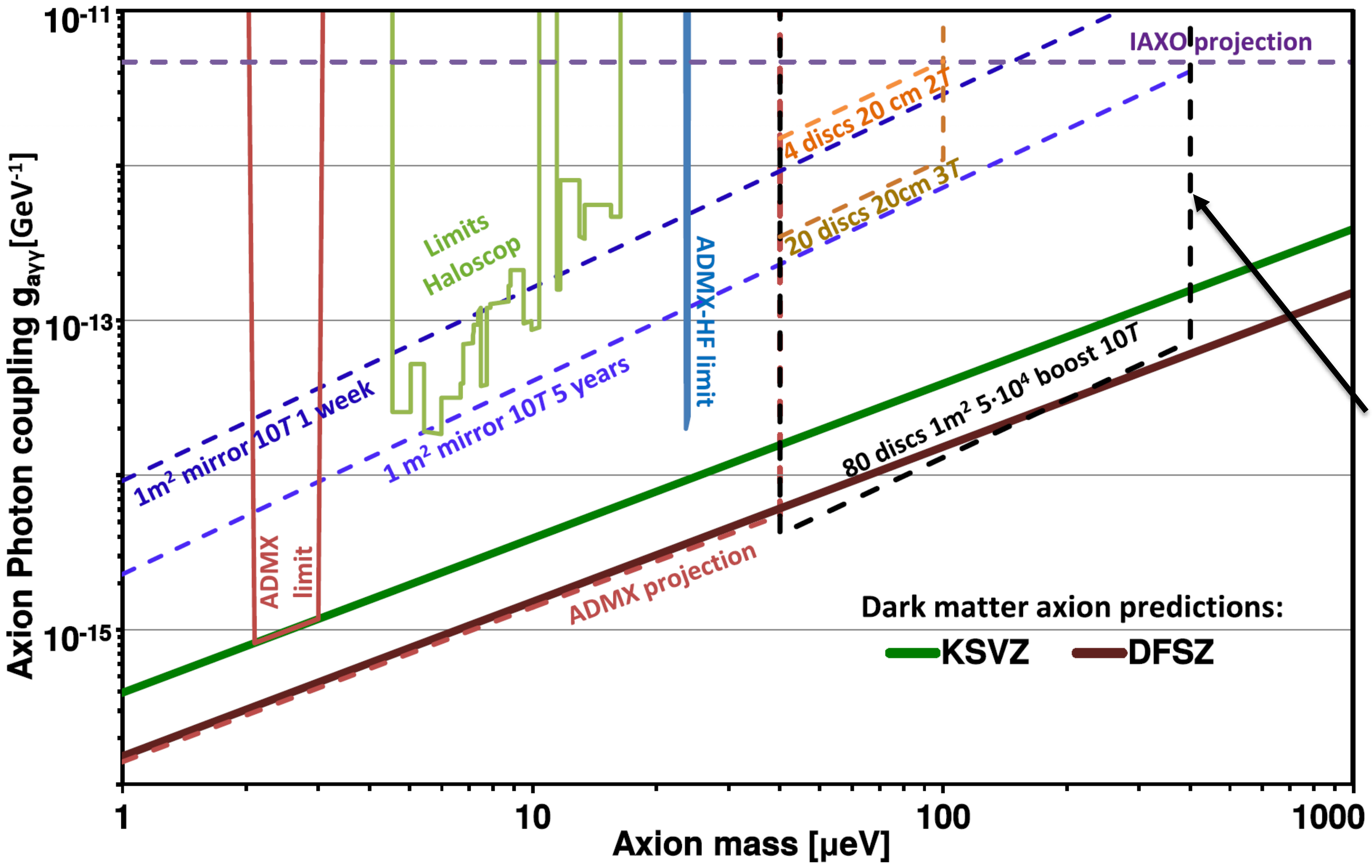
Relic abundance then set by different value of the axion field in different regions of the Universe

Generic answer (from particle data group) is given by

$$\Omega_A^{\rm real} h^2 \approx 0.11 \left(\frac{41\ \mu{\rm eV}}{m_A} \right)^{1.19}$$

On its own suggests that the axion mass is about 40 micro-eV but there is a range over perhaps a couple of orders of magnitude because the contribution from the decay of topological defects is uncertain.

Correlations in this field are on length scale of horizon at phase transition – very small- much smaller than cosmological Planck/galaxy scales etc.



Projection for MADMAX (Stefan Knirck, PATRAS presentation)

U(1) PQ symmetry broken by axion mass after inflation

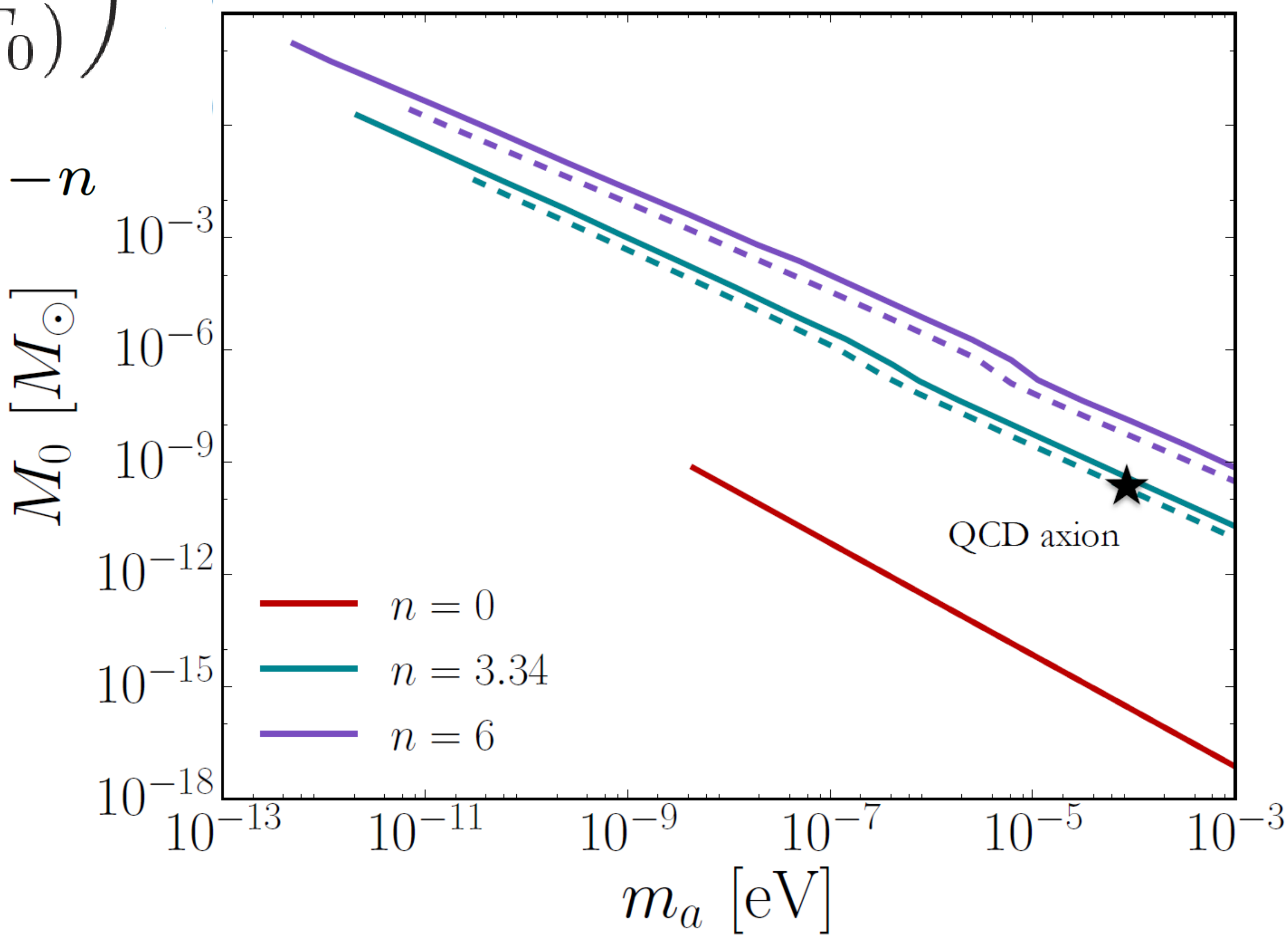
$$M_0 = \bar{\rho}_a \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3$$

$$m_a(T) = m_{a,0}(T/T_c)^{-n}$$

For QCD instantons, Theory and lattice simulations suggest that n=3.34. Wantz and Shellard, 0910.1066. Borsanyi et al., 1508.06917, 1606.07494.

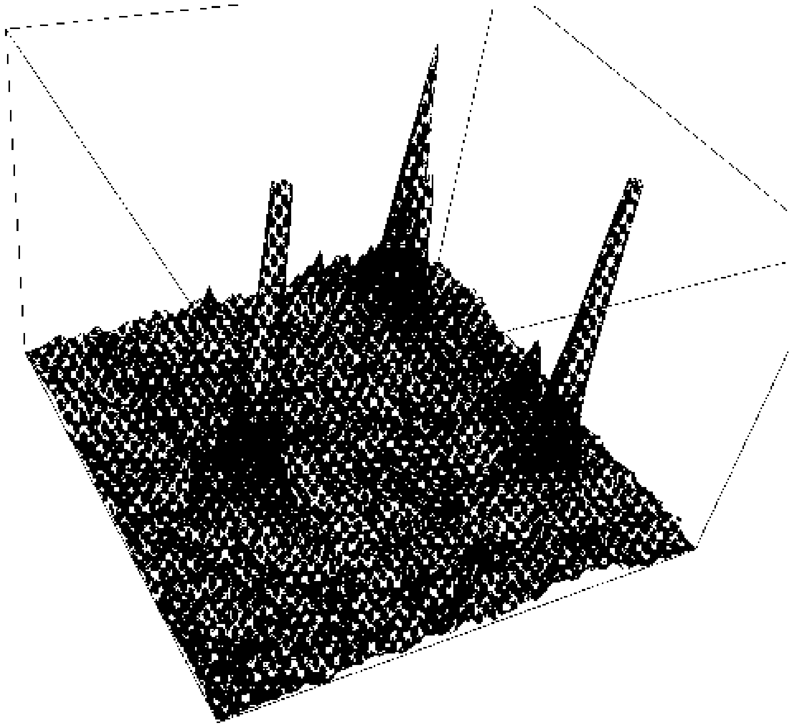
T_0 depends upon n

Mass inside horizon = M_0

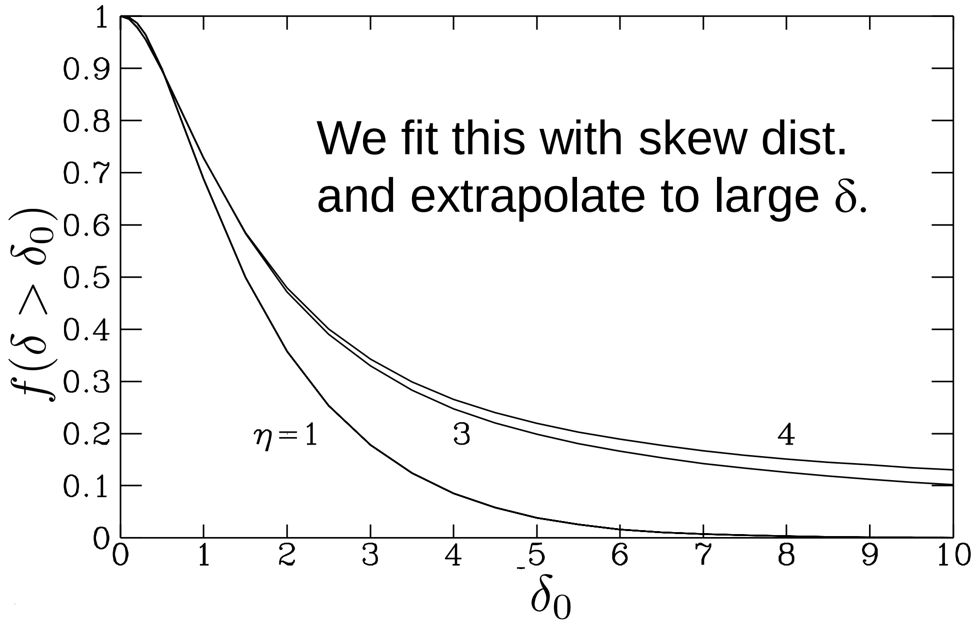


Simulations: Kolb & Tkachev (1990s)

See also Zurek et al (2007); Hardy (2016)



Minicluster formation simulated without gravity or phase transition.



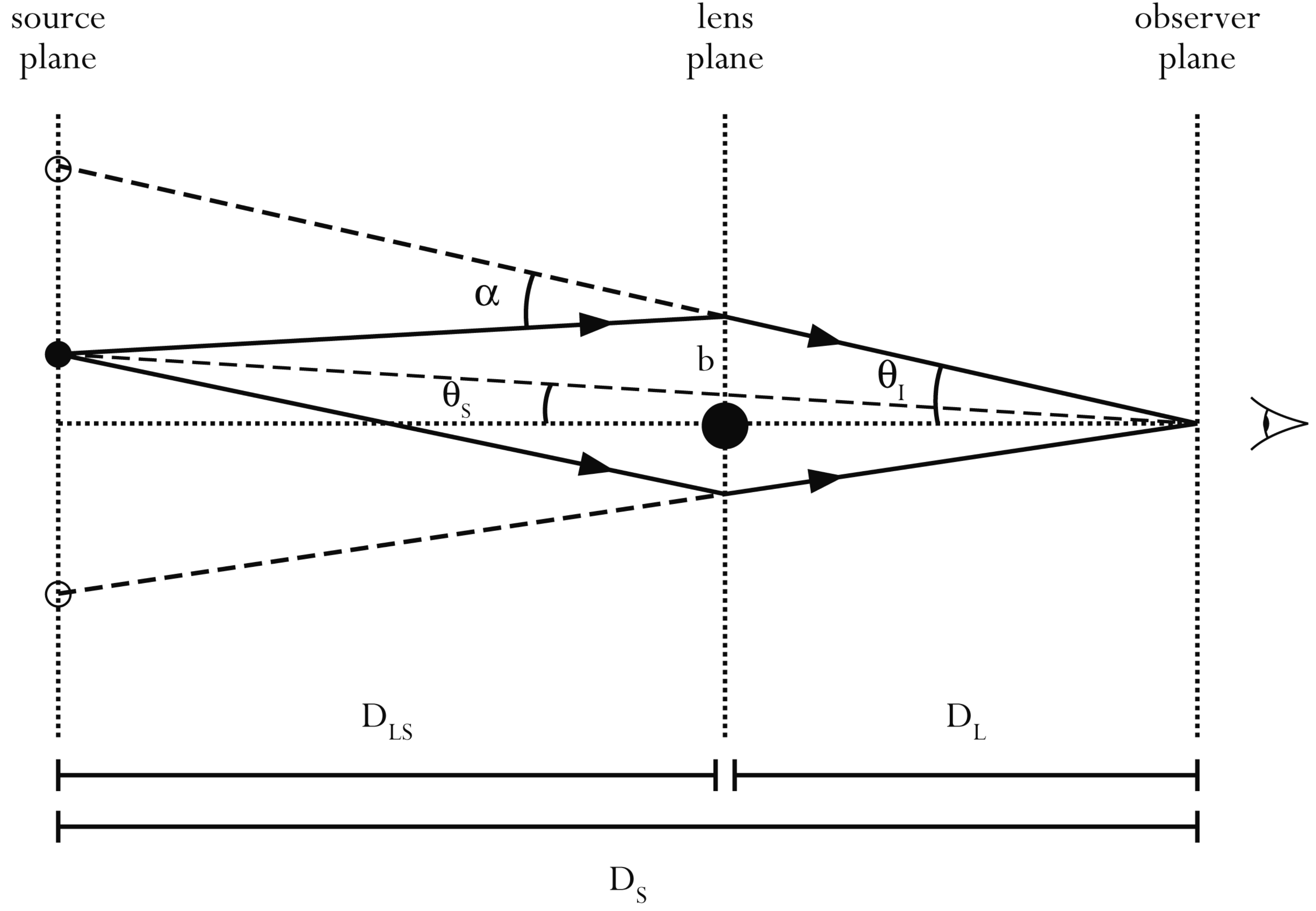
Fraction of MCs with density δ:

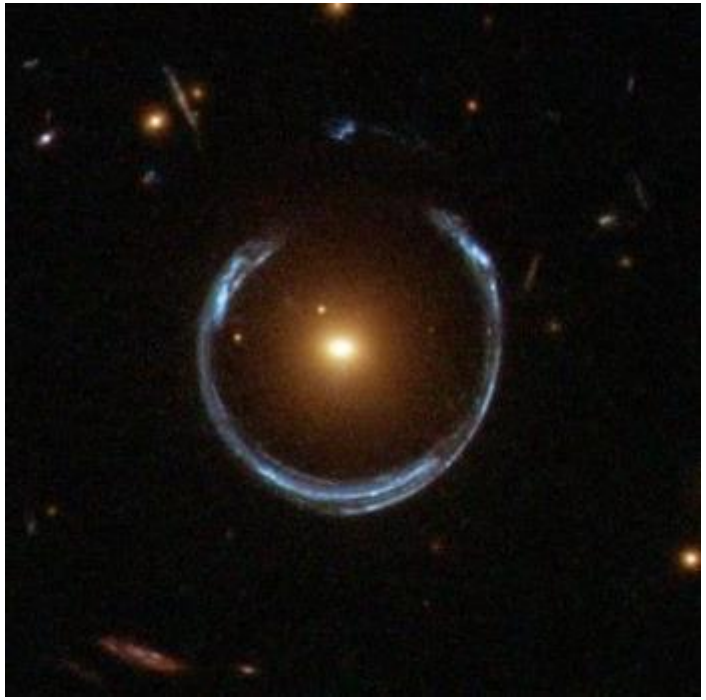
$$\rho_c = 140\delta^3(1+\delta)\rho_a(1+z_{\text{eq}})^3$$

The fraction of DM in miniclusters, f_{MC}, is not predicted.

<u>Our goal</u>: ***constrain f_{MC} observationally.***

Gravitational Lensing





$$R_{\mathrm{E}}(x, M) = 2\left[GMx(1-x)d_s\right]^{1/2}$$

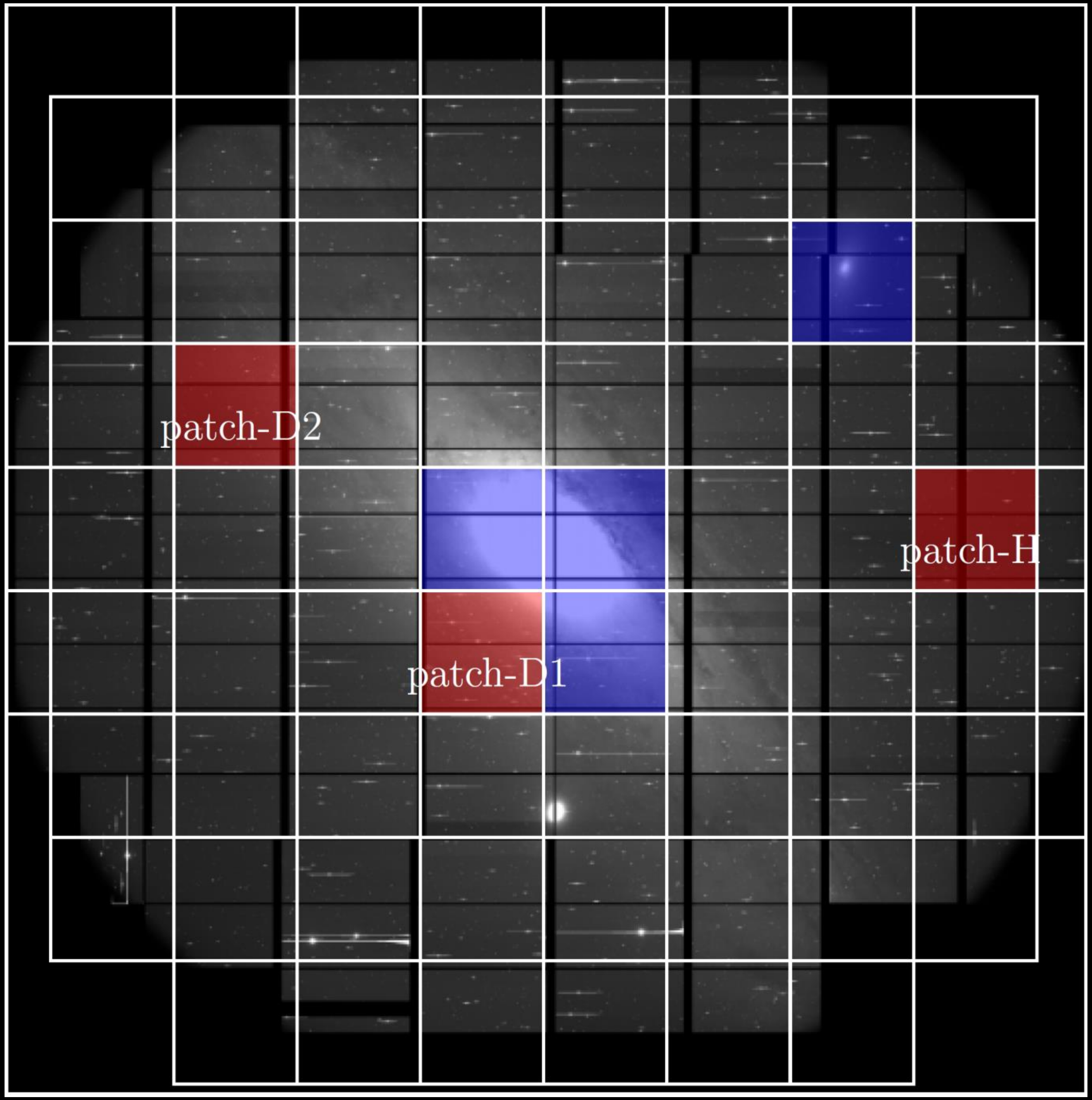
Subaru Hyper Suprime Cam (HSC)

1.5 degree coverage on sky, can cover whole of Andromeda Galaxy (M31)

Blue patches excluded due to too many objects

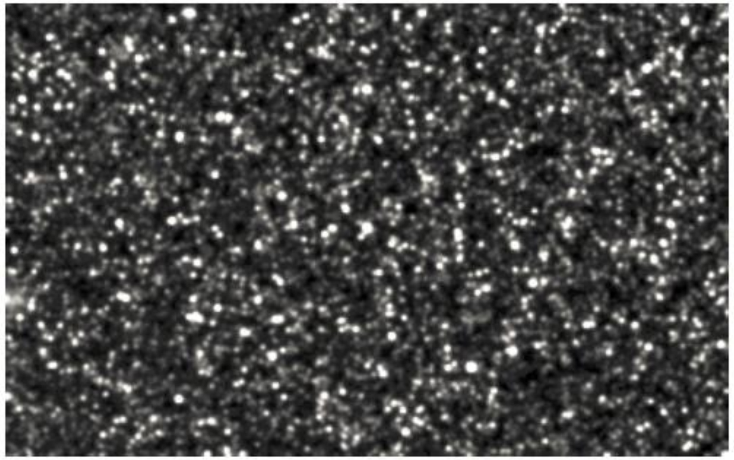
D1 representative of inner disk
D2 outer disk
H halo

Niikura et al, 1701.02151

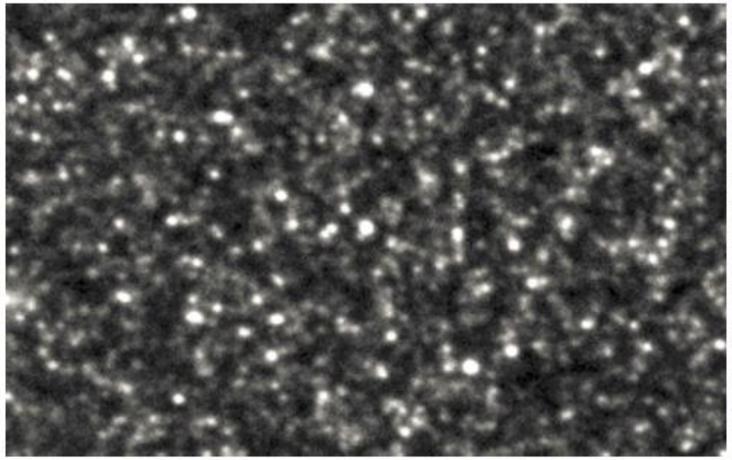


Subaru Hyper Suprime Cam (HSC)

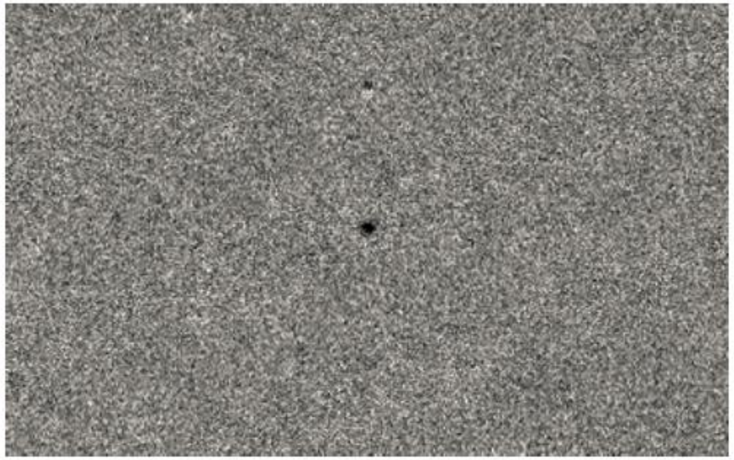
Has only collected 7 hours of data – already has very strong constraints on lensing events



Good stacked image



representative target image

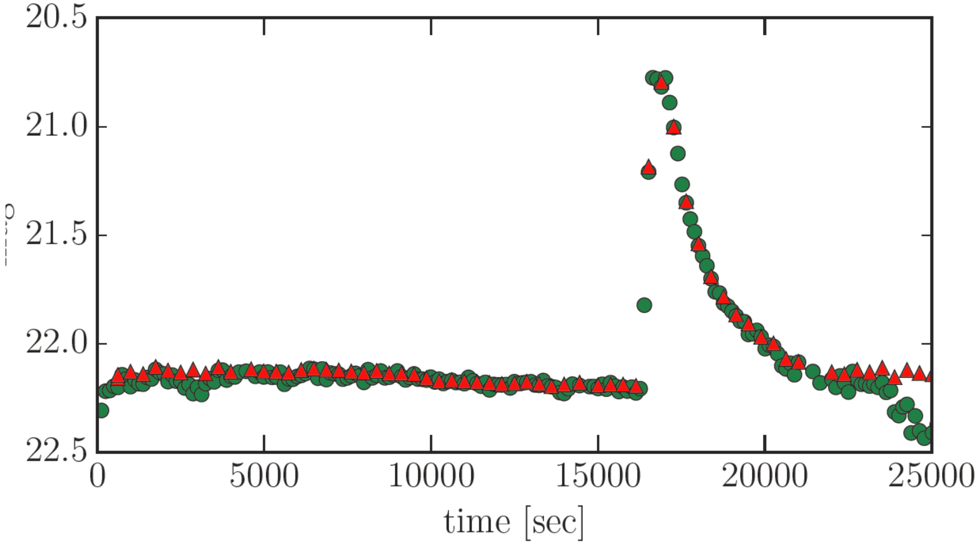


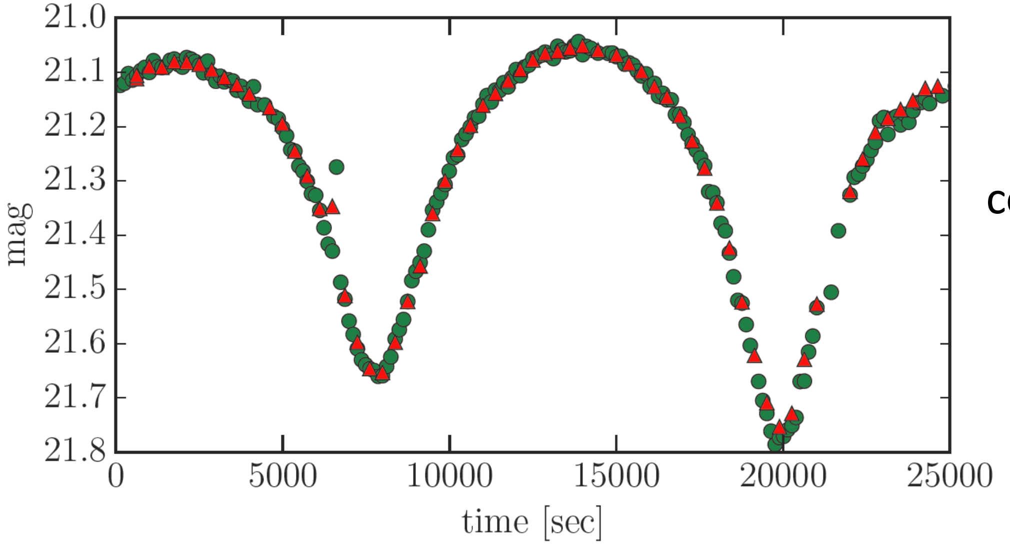
difference – change in one star's flux

Subaru Hyper Suprime Cam (HSC)

Niikura et al, 1701.02151

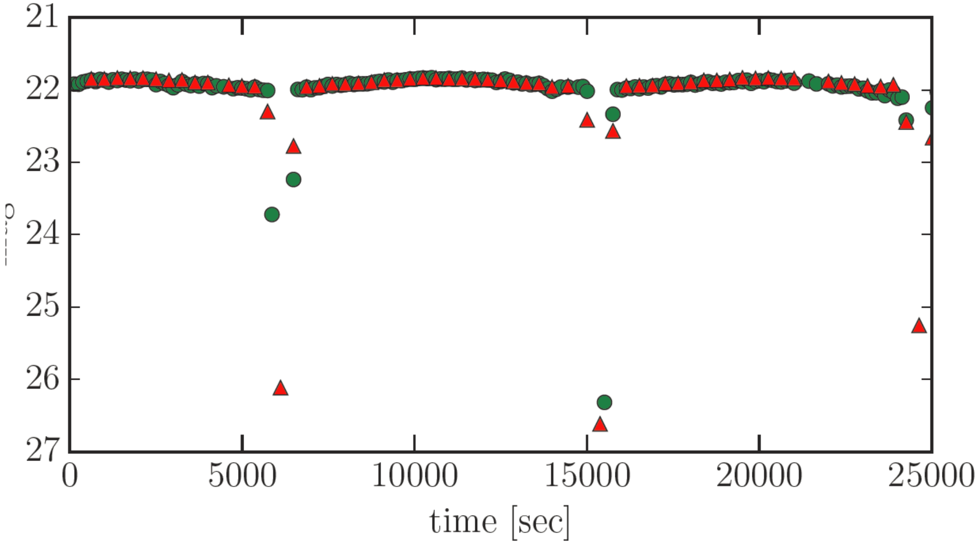
Stellar flare?

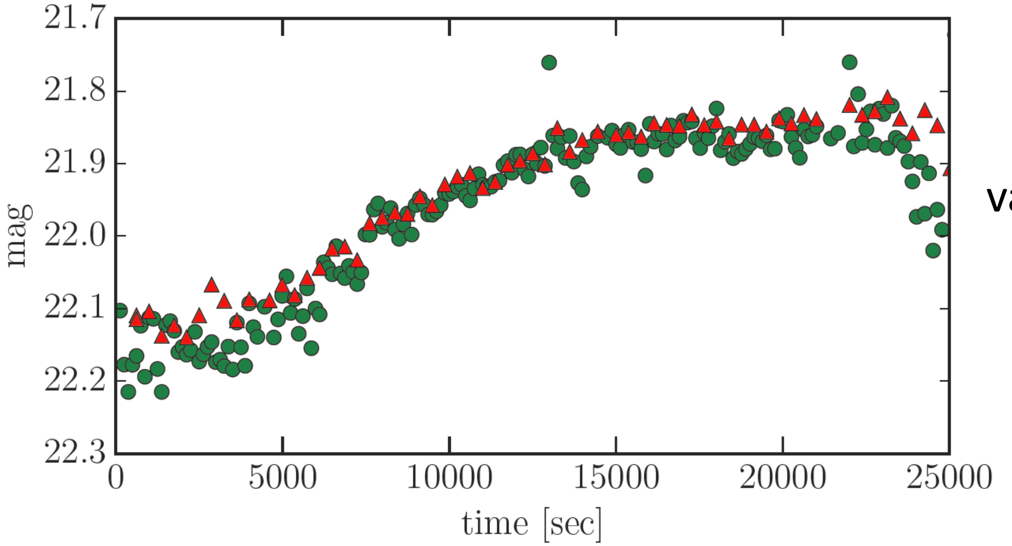




contact binary?

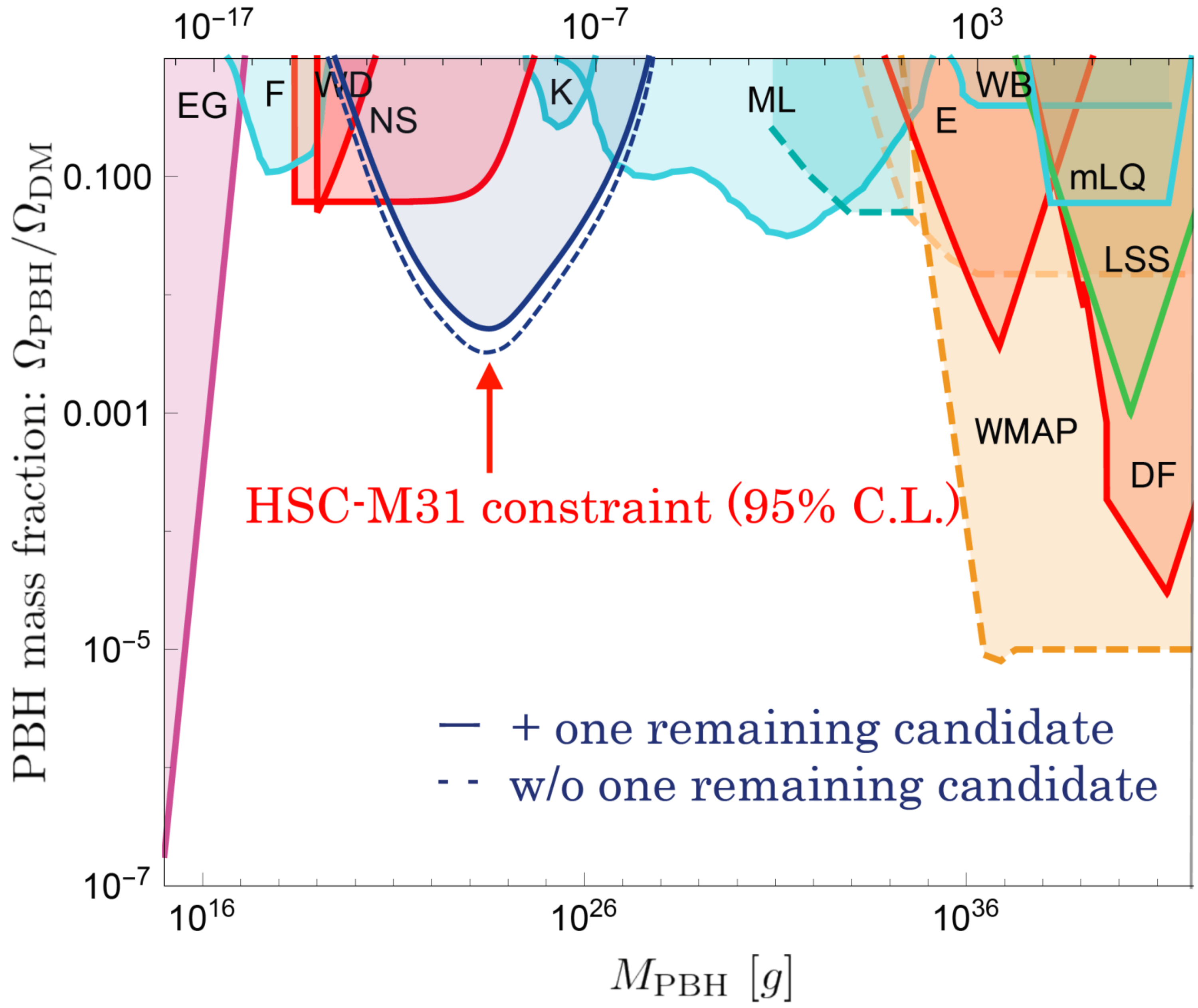
Eclipsing Binary?





variable star?

HSC constraint on Primordial Black Holes Niikura et al, 1701.02151



Magnification in the point mass vs. the extended mass case

Most haloes are very diffuse and therefore cause no lensing

Magnification for a distributed source

$$\mu = \left[(1-B)\,(1+B-C)\right]^{-1}$$

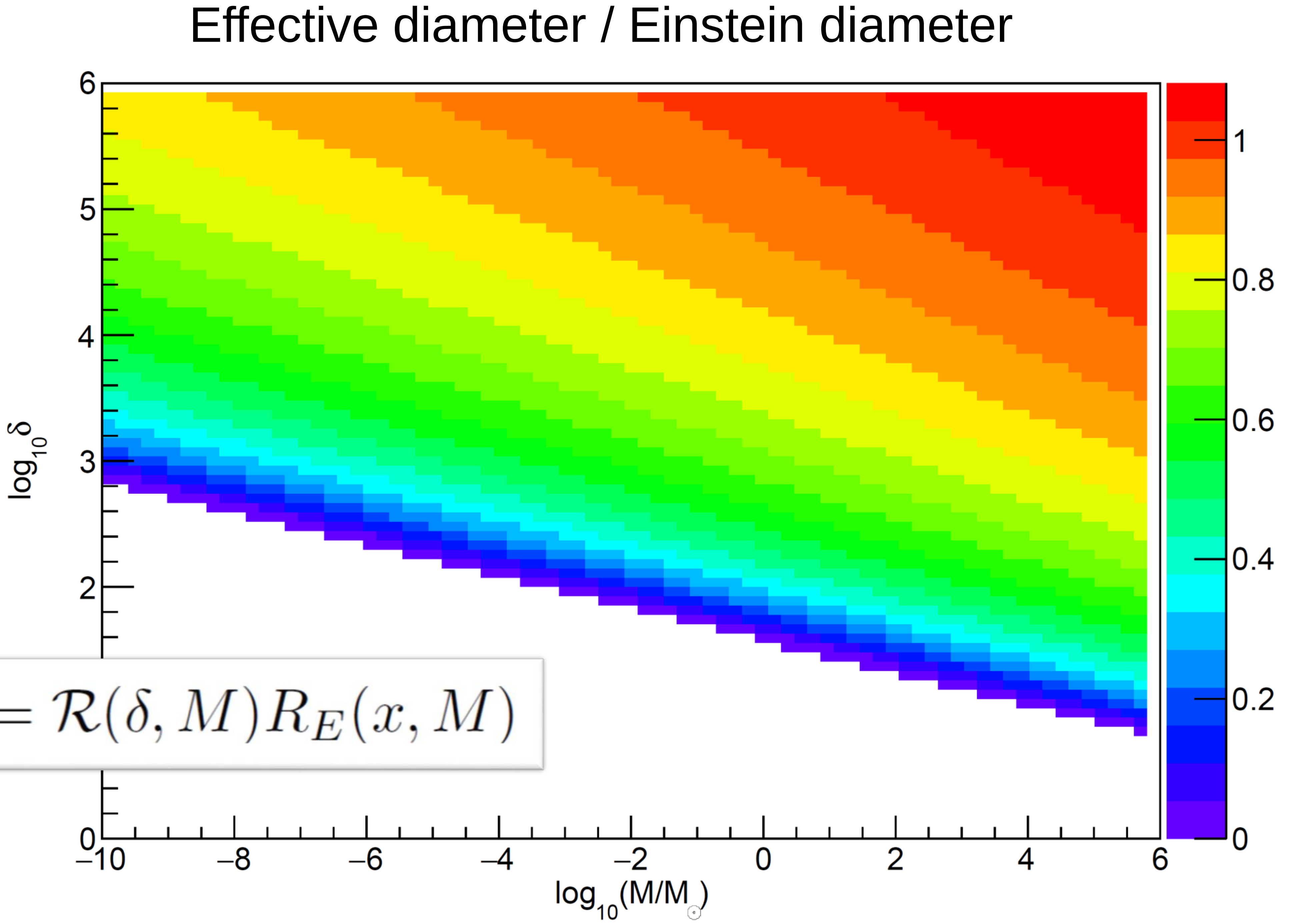
$$C = \frac{1}{\Sigma_c \pi r}\frac{dM(r)}{dr} \;;\; B = \frac{M(r)}{\Sigma_c \pi r^2} \;;\; \Sigma_c = \frac{c^2 D_S}{4\pi G D_L D_{LS}}$$

We have distributed density which, while dense, is not a point mass.

For each halo we need to integrate inwards to find value of *r* where μ=1.34.

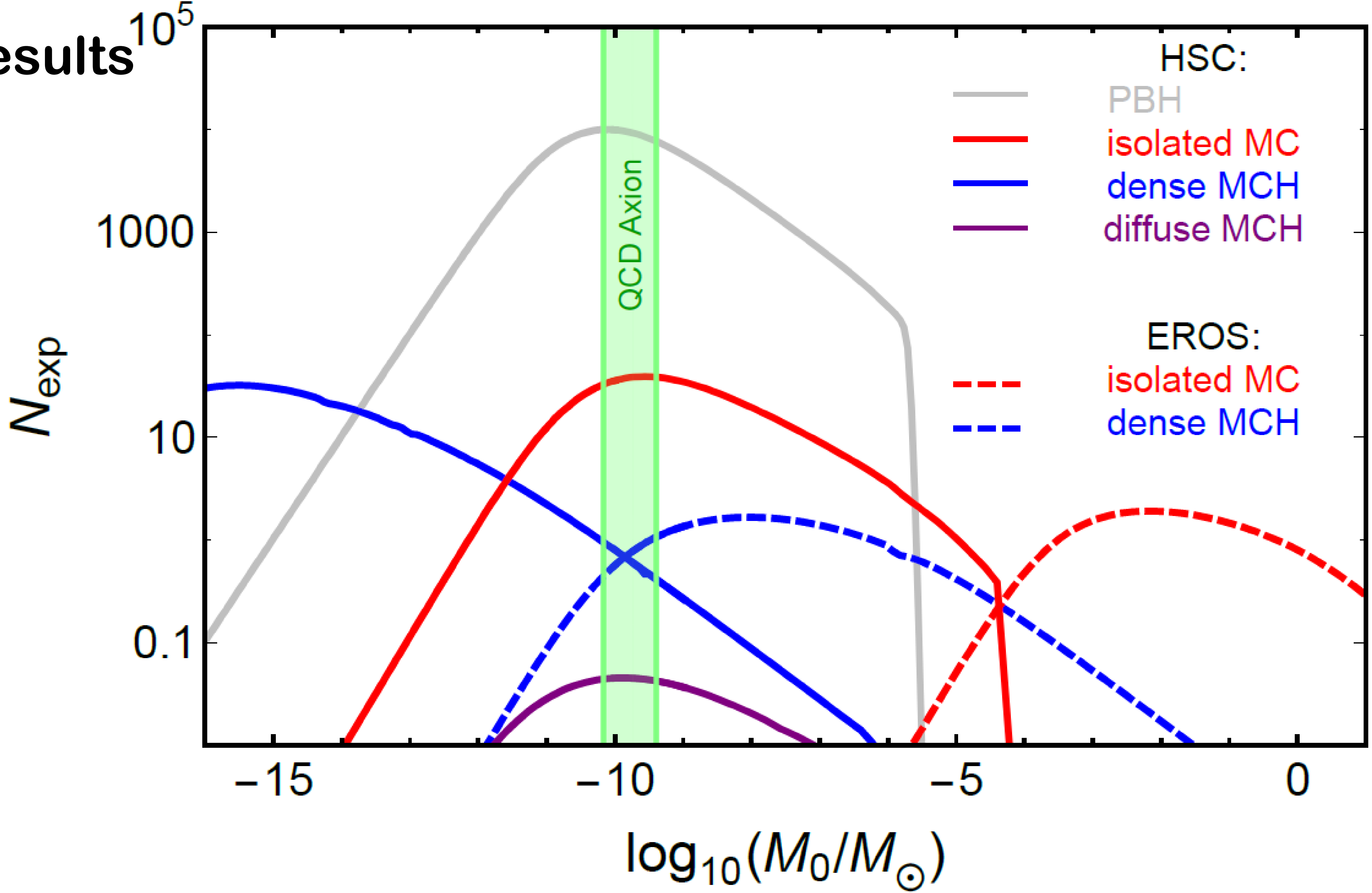
In practise the corresponds to outer image having magnification of 1.17.

Most haloes are very diffuse and therefore do not cause enough lensing



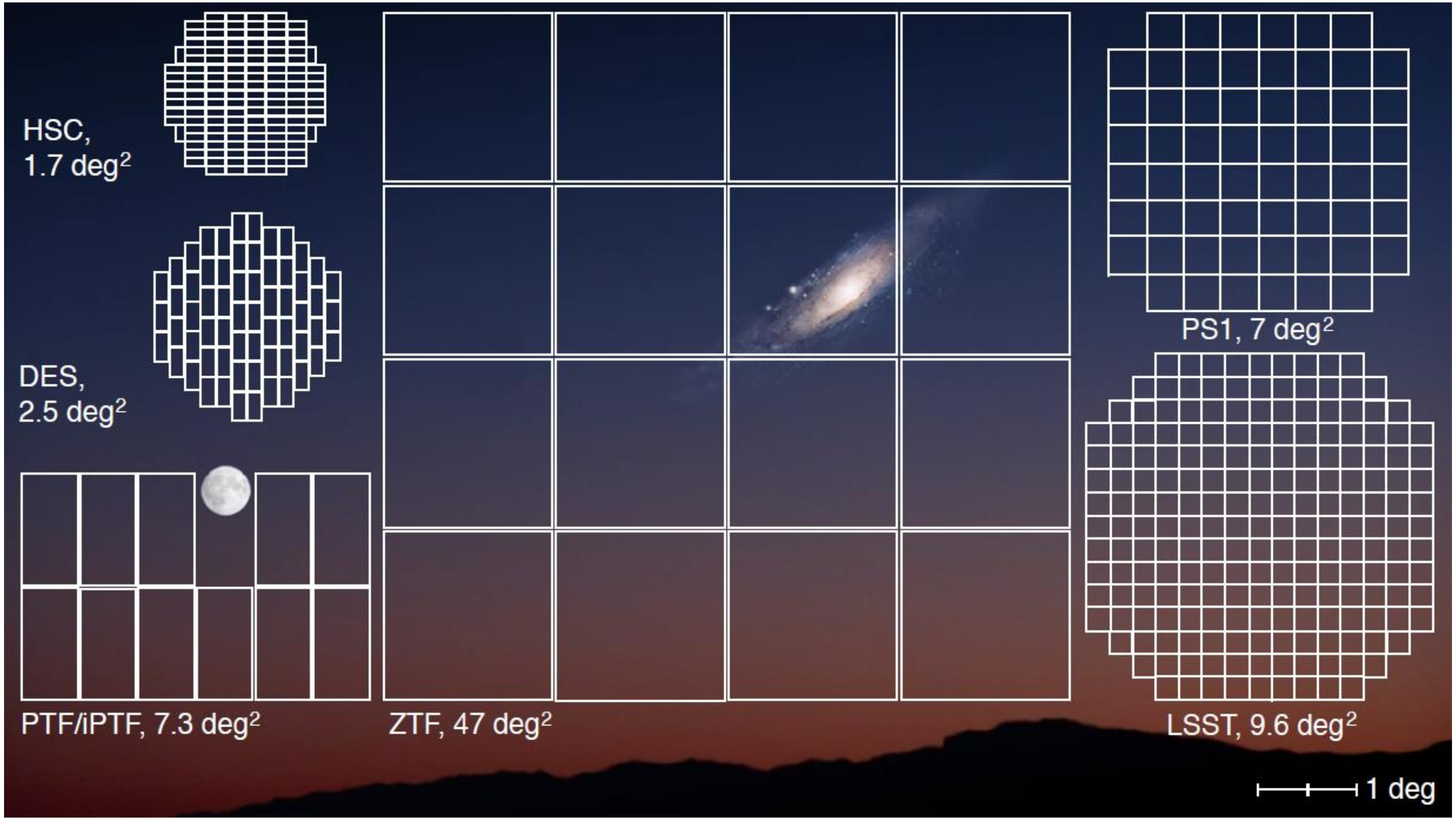
$$R_{\rm MC}(x, M, \delta) = \mathcal{R}(\delta, M) R_E(x, M)$$

Our Results



10^5
1000
10
0.1
N_{exp}
QCD Axion
HSC:
PBH
isolated MC
dense MCH
diffuse MCH
EROS:
isolated MC
dense MCH
−15
−10
−5
0
$\log_{10}(M_0/M_\odot)$

Upcoming Surveys - many of which are much better than HSC



Dark Matter Searches are no place for Dogma.

Could be WIMPs, sterile neutrinos, axions, hidden sector glueballs, KK particles, whatever….

Whenever we come up with an idea to test one of these we should do so. There will be lots of new ways to test these scenarios in the coming Years…

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