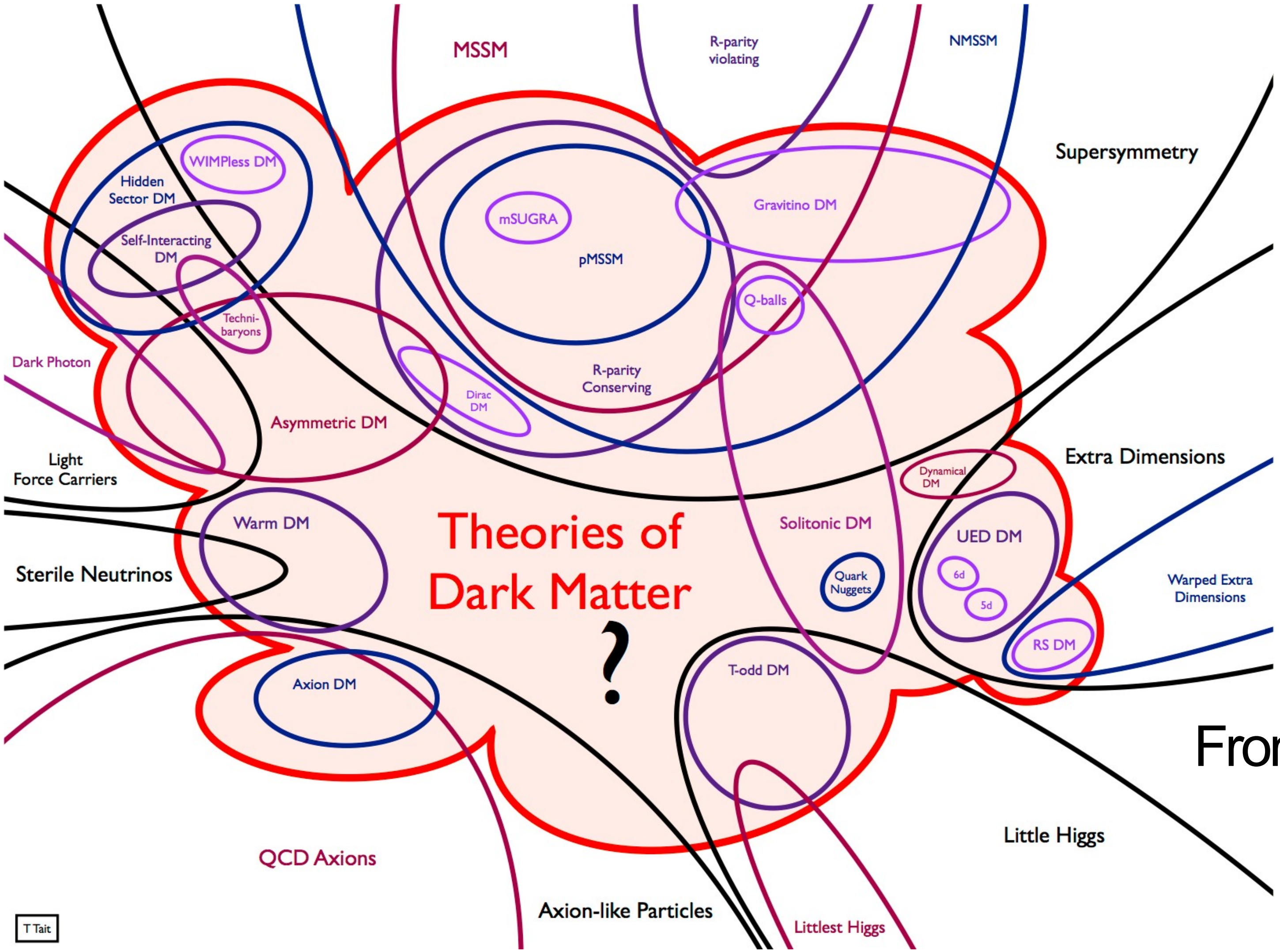
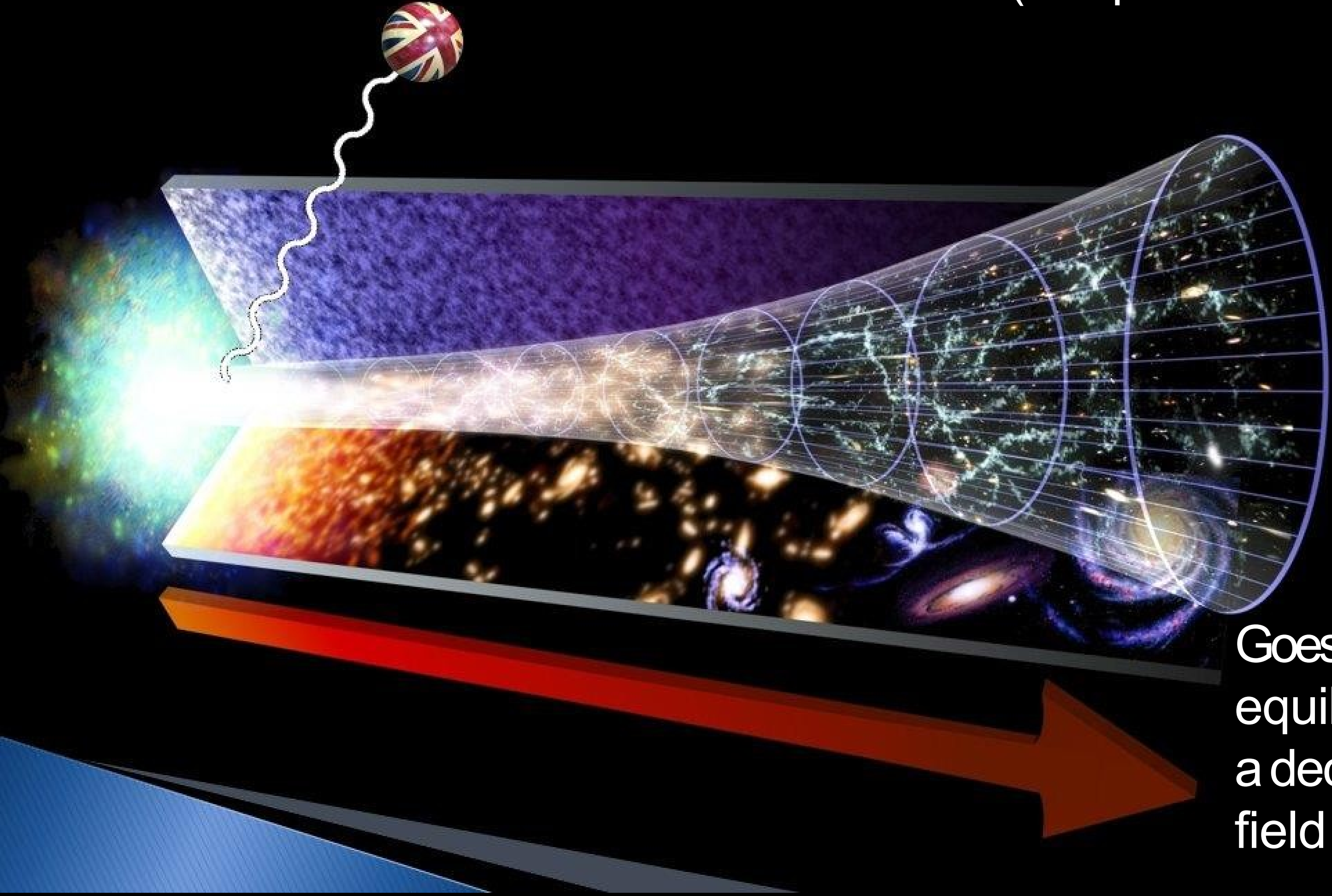
Theoretical Interpretations of the Xenon 1T excess

Malcolm Fairbairn
LDW2020



From Tim Tait

The Brexiton (Enqvist 2017, Rajantie 2017)



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

….. however I am sure that the Brexit talks are going well….

Dr Mike Galsworthy @mikegalsworthy · 14h

Which side looks like they've got their s*** together?

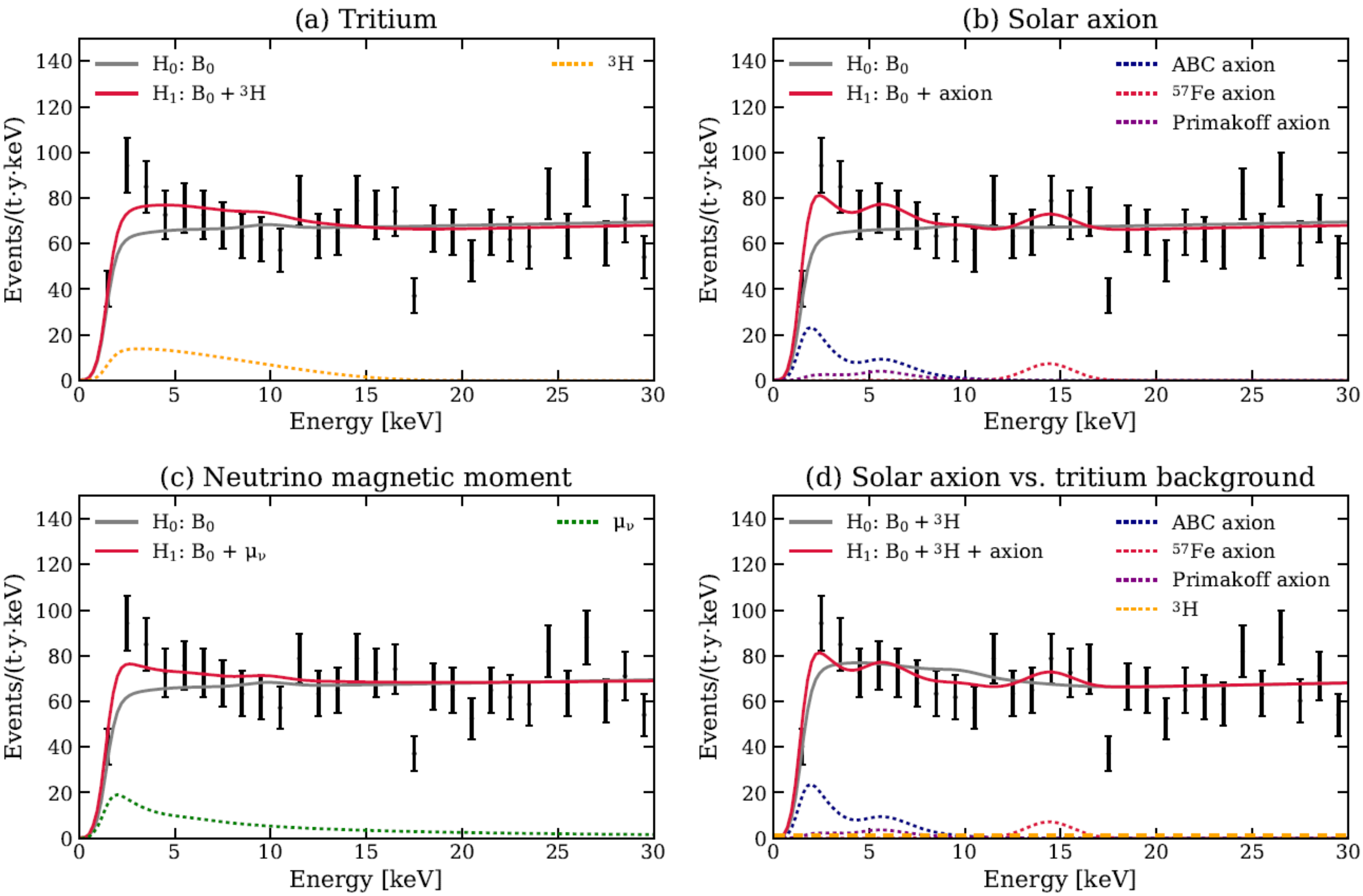
Outline

- Xenon 1T original theoretical interpretations
- Axion interpretations
- Our work on explaining the Xenon 1T results
- Astrophysical problems/challenges
- Very incomplete Survey of other attempts to model the excess
- General comments about some aspect of future uses of dark matter detectors

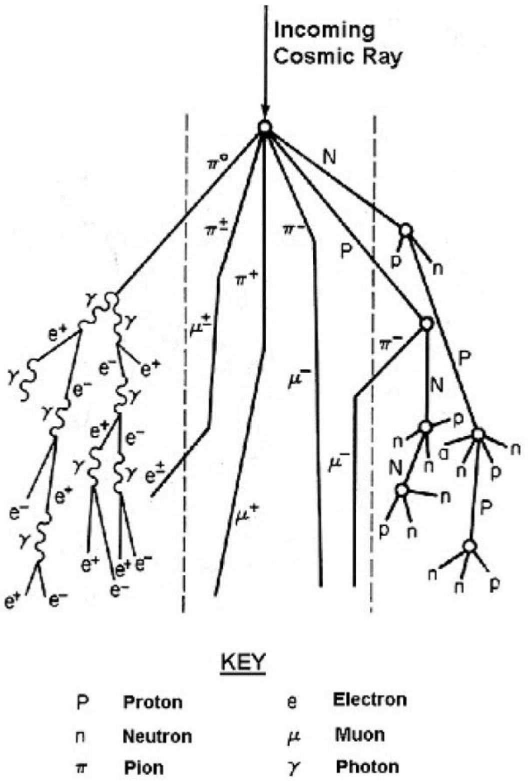
What are we talking about this for?

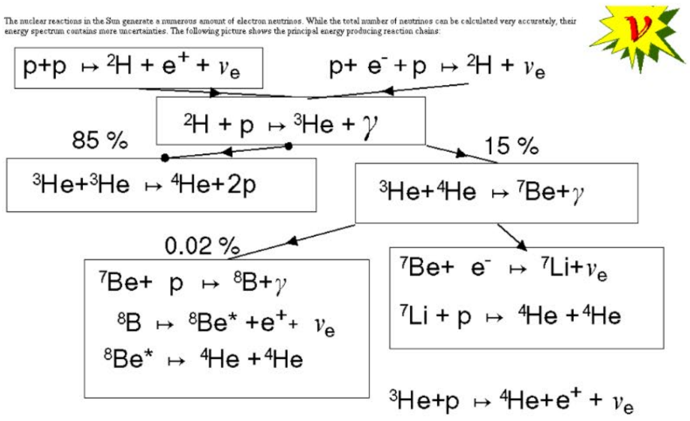
- Xenon 1T experiment did a search looking for electron recoils
- They tried to model their background carefully but still got an excess around 3 keV
- People are trying hard to understand what this means
- Can be explained by lots of different theories but explanations often face astrophysical problems

Xenon 1T results and fits



Dark Matter detectors for detecting neutrinos





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 %

${}^7Be + p \mapsto {}^8B + \gamma$

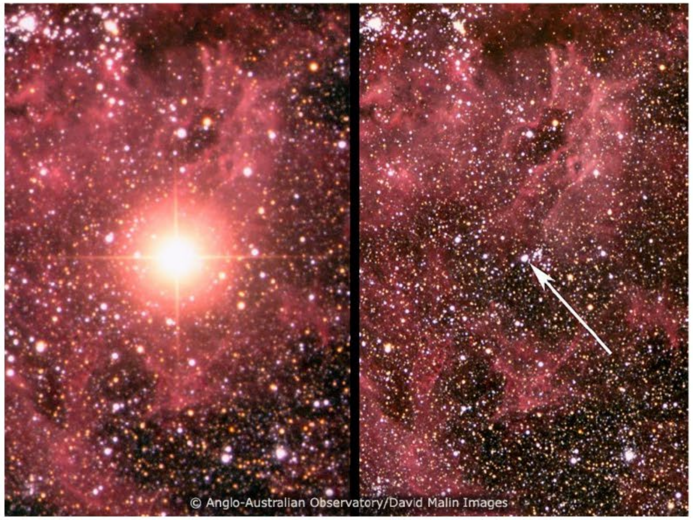
${}^8B \mapsto {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \mapsto {}^4He + {}^4He$

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

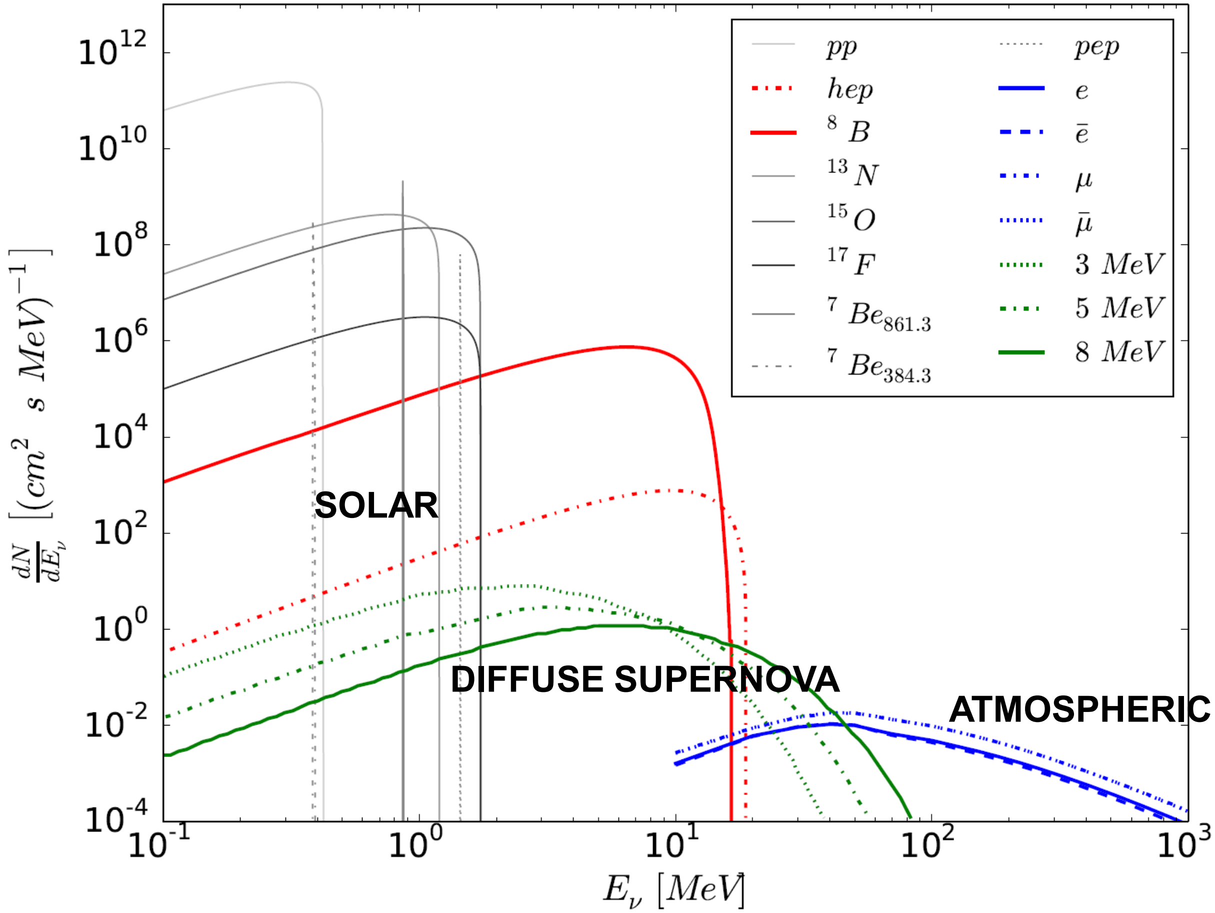
${}^7Li + p \mapsto {}^4He + {}^4He$

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



© Anglo-Australian Observatory/David Malin Images

Neutrino flux at Earth



Solar neutrinos give rise to

keV-MeV electron recoils (above pp)
&
keV nuclear recoils (below 8B)

Both can be detected with dark matter detectors

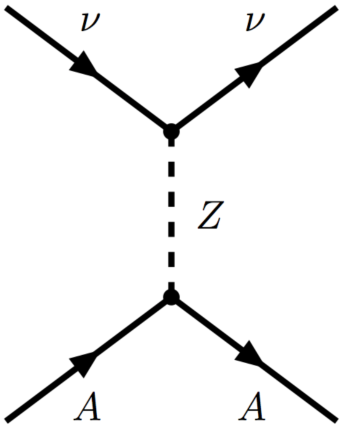
Coherent Neutrino-Nucleon Interactions….

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

- Enhanced by factor N^2:

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

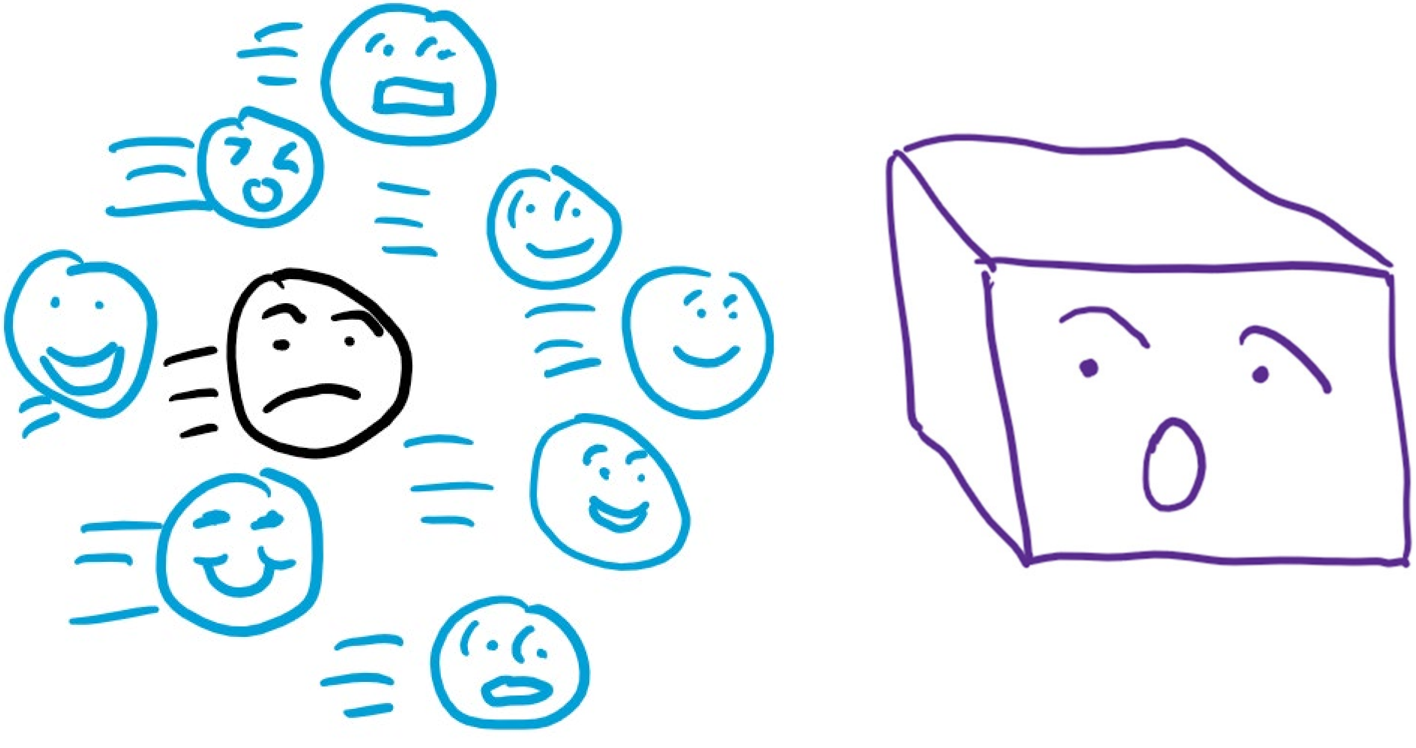
ONLY OBSERVED A COUPLE OF YEARS AGO IN STANDARD MODEL BY COHERENT EXPERIMENT



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

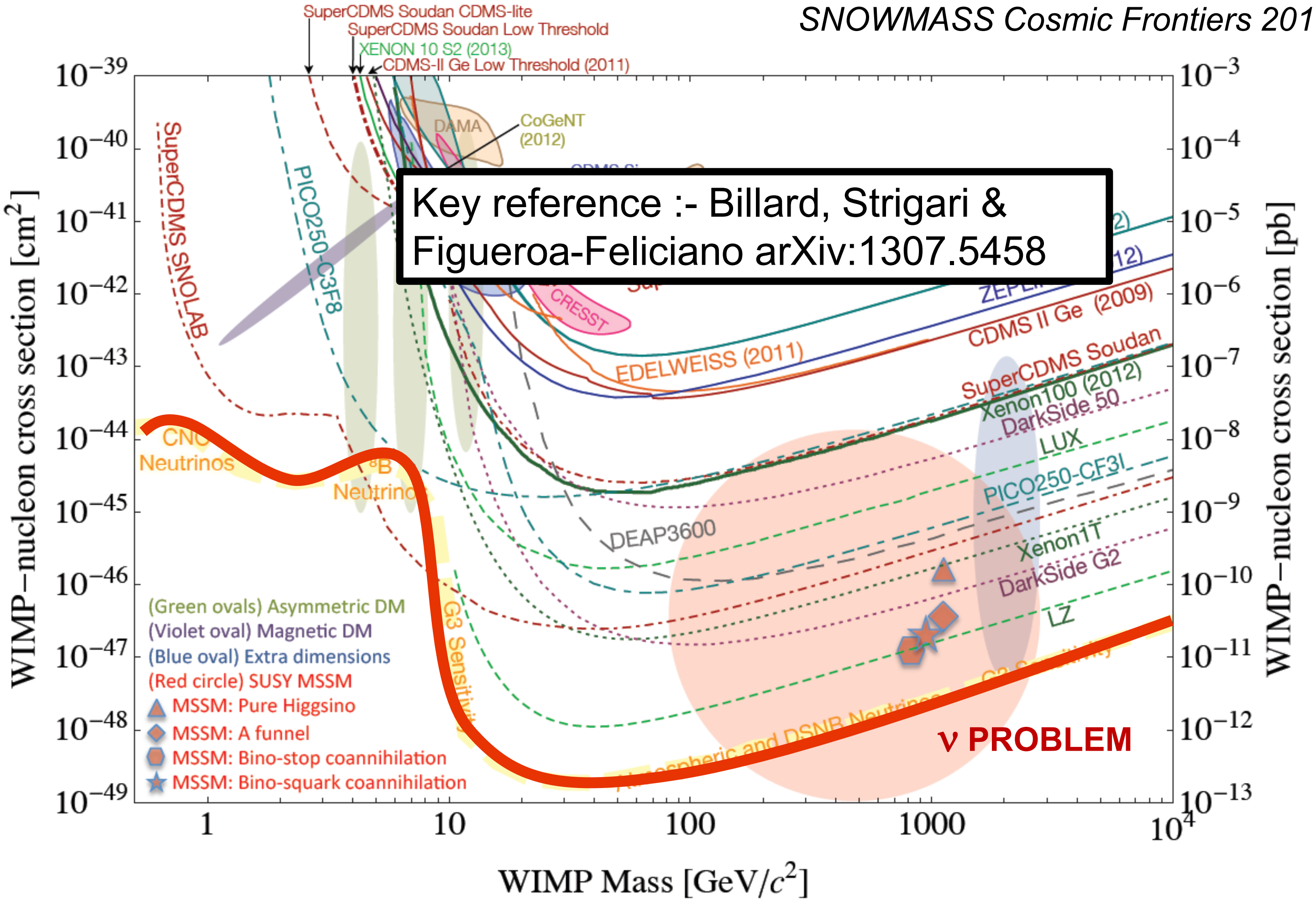
$$R_\nu = \int_{E_{\rm thr}}^{E_{\rm up}} \frac{dR_\nu}{dE_r} dE_r$$

… mean you might not see the dark matter for all the neutrinos…



….which leads to this now famous plot.

SNOWMASS Cosmic Frontiers 2013



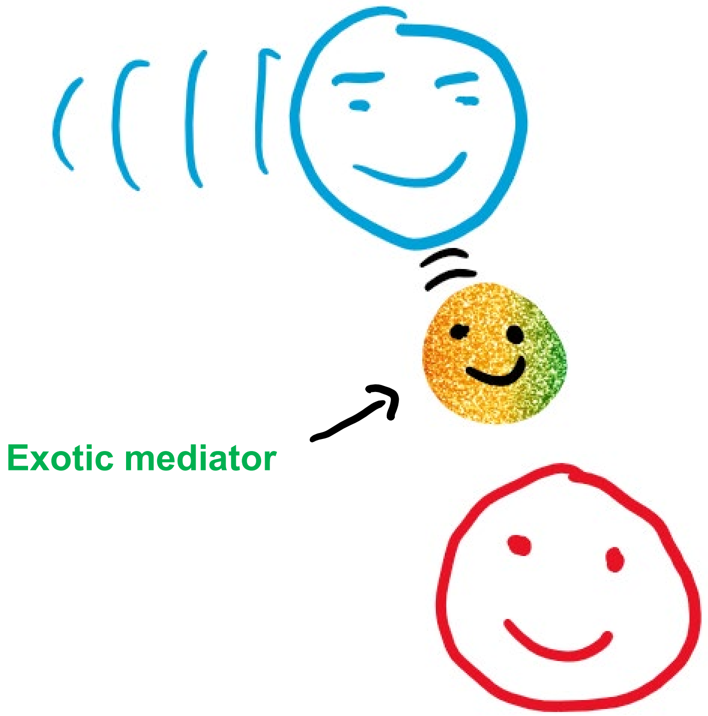
Key reference :- Billard, Strigari & Figueroa-Feliciano arXiv:1307.5458

Tests of BSM Physics

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

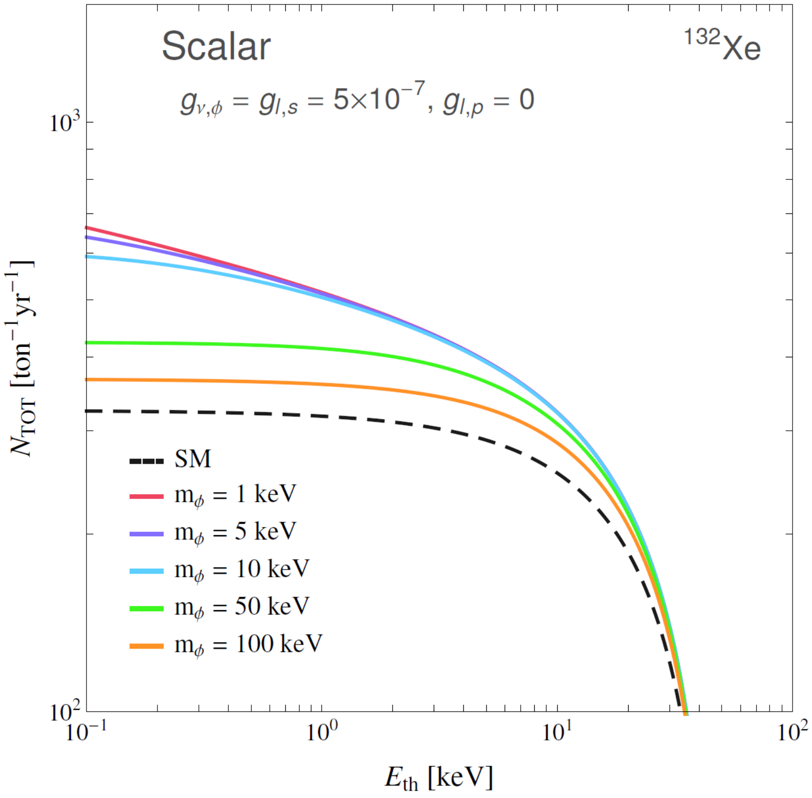
Momentum exchanged for neutrino-nucleon events is about MeV scale

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

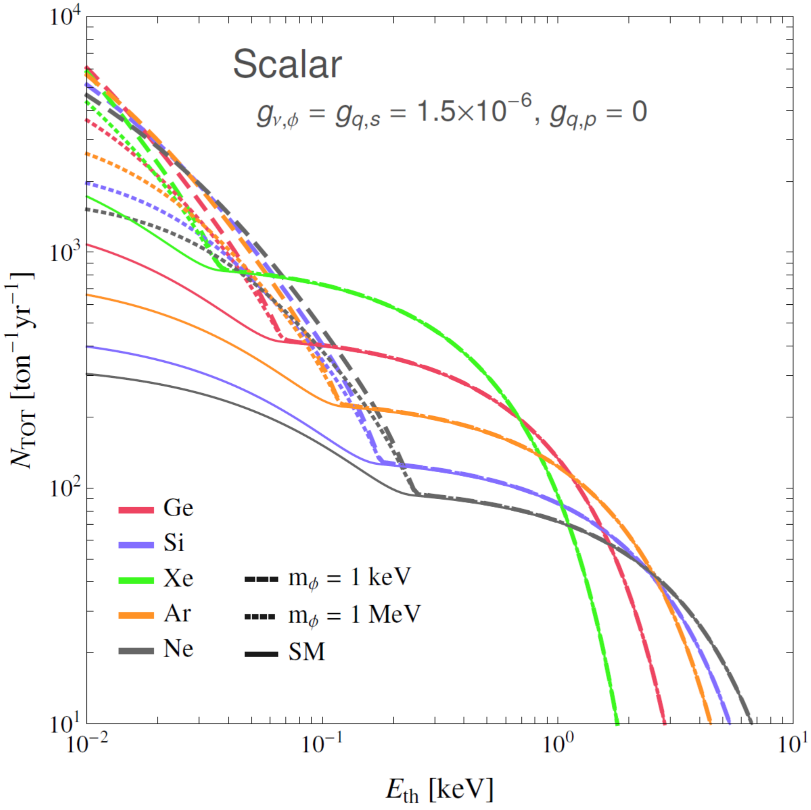


Tests of BSM Physics

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



electron recoils



nuclear recoils

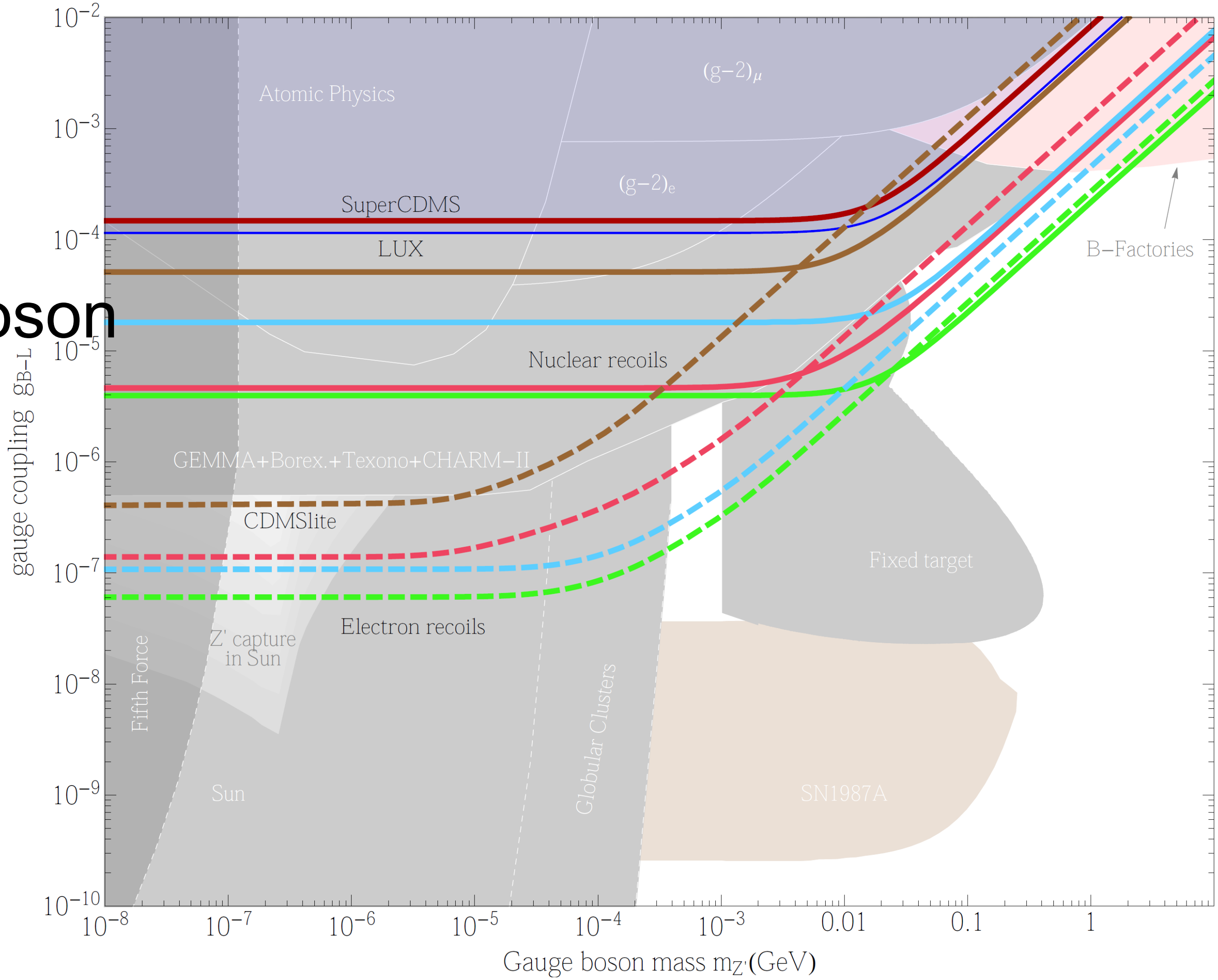
arXiv : 1604.01025

Tests of BSM Physics

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

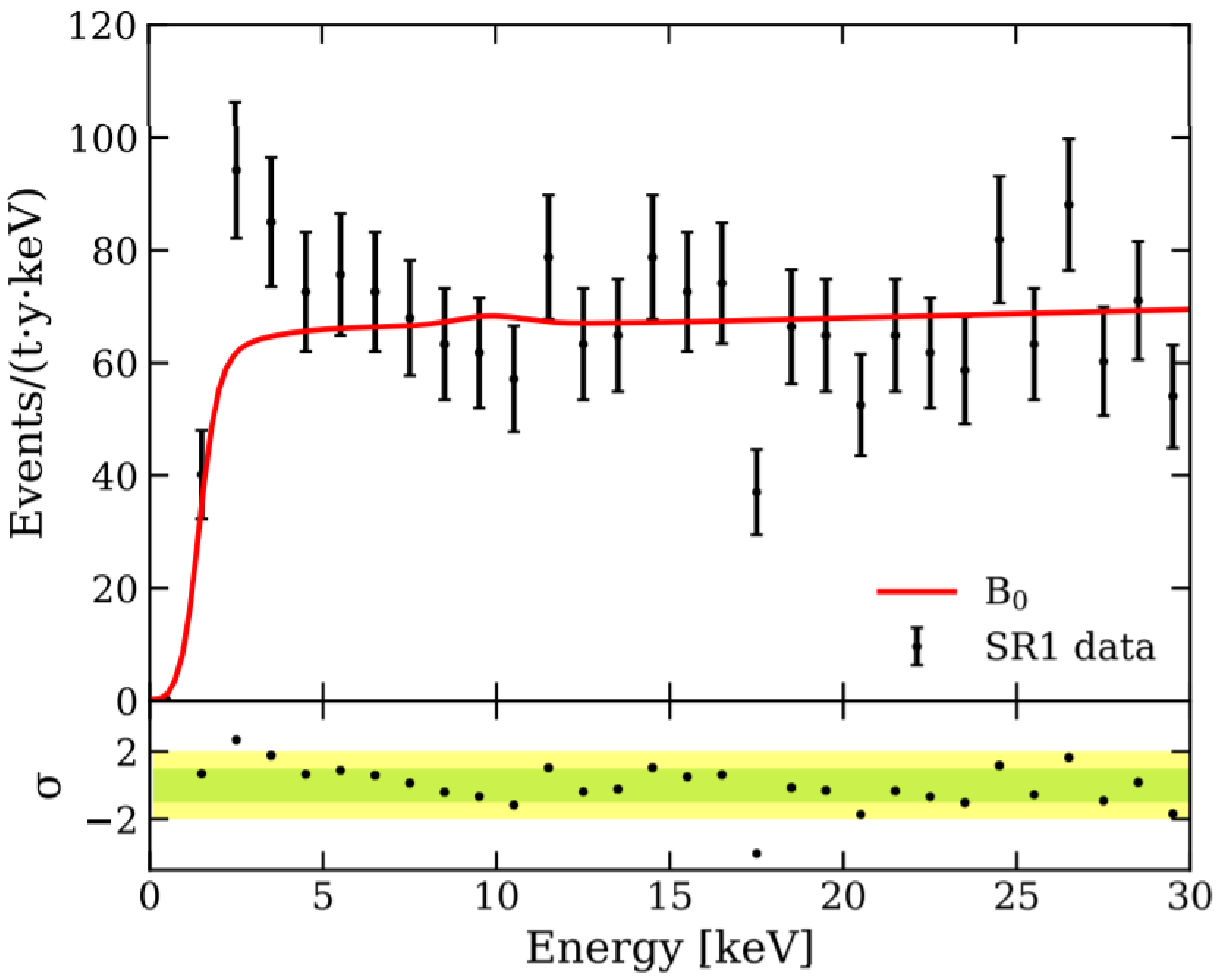
Dashed electron, solid nucleon.

Green future xenon
Blue G2 xenon
Red G2 germanium



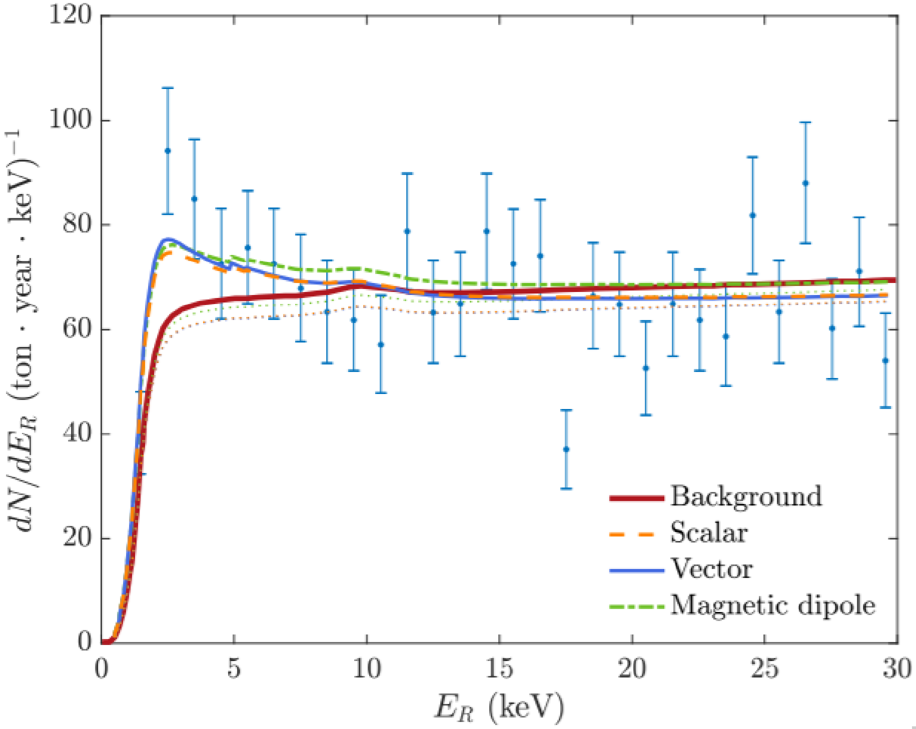
arXiv : 1604.01025

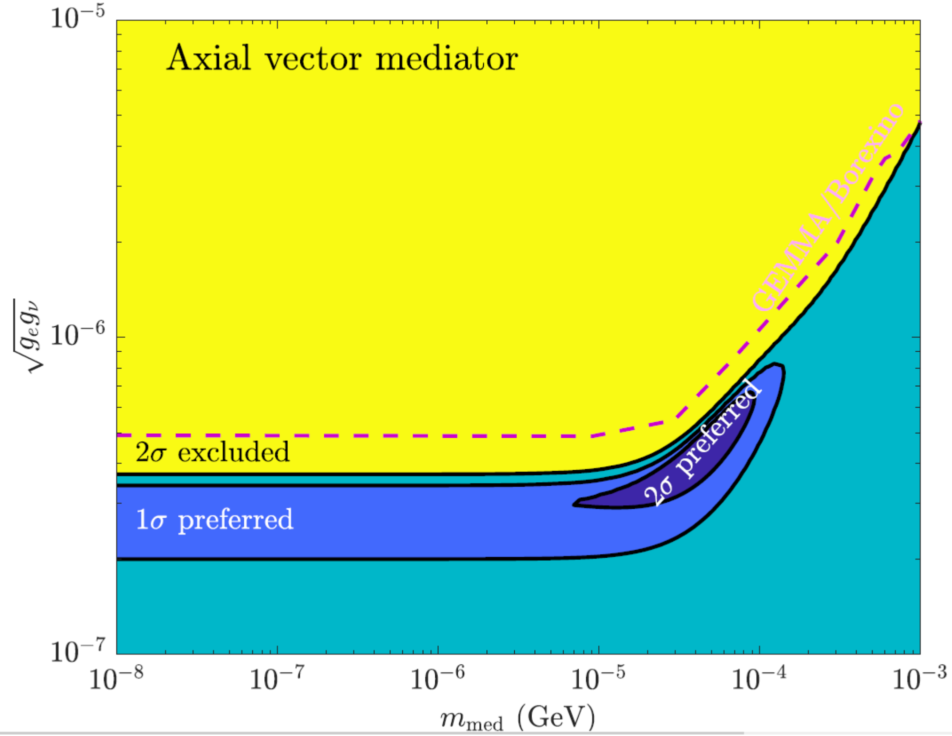
Fast forward to June 2020, a new result from electron recoils from XENON1T collaboration arXiv: 2006.09721



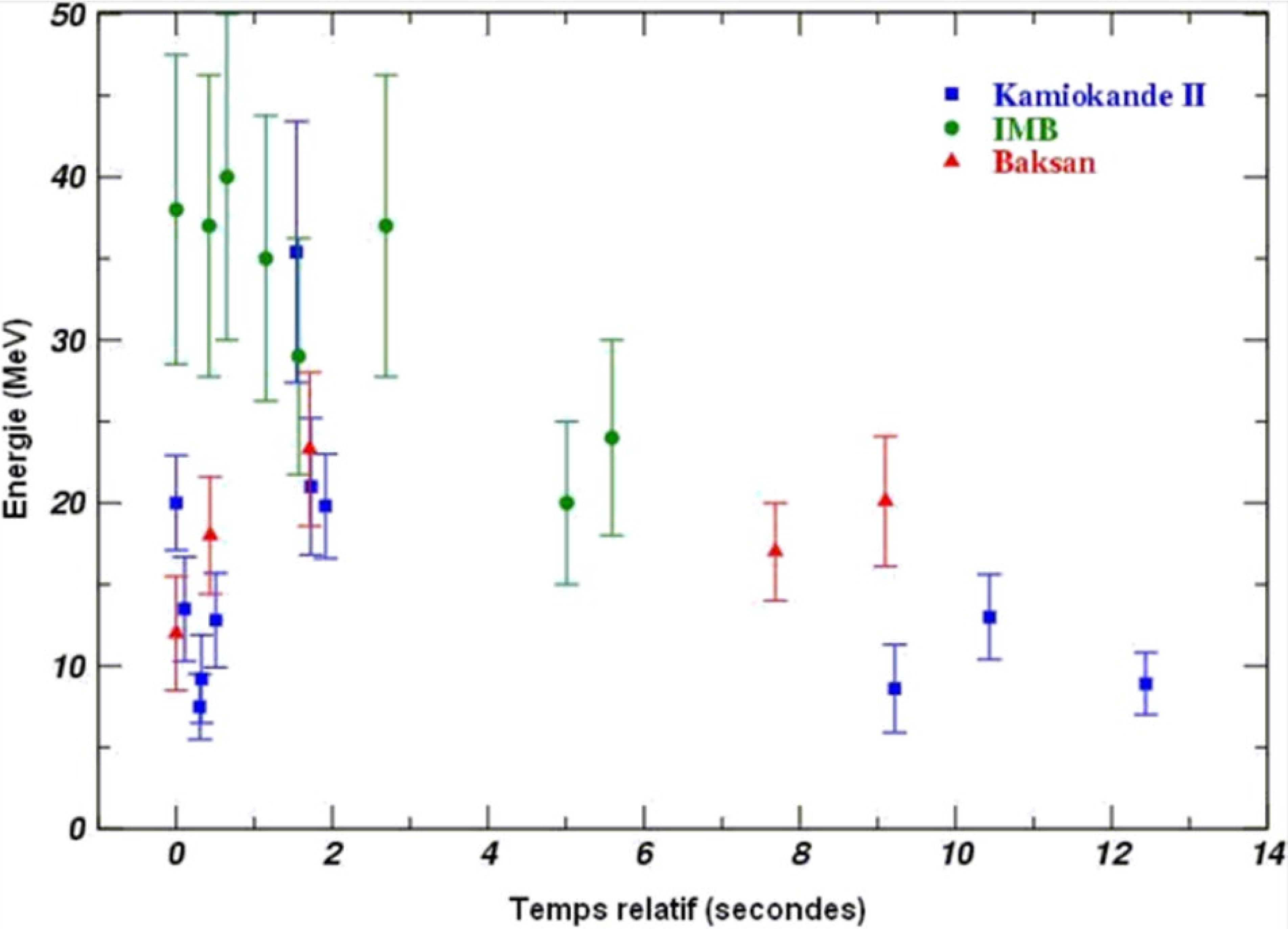
The signal has an excess over the background. This could be due to new physics, but it also could be due to Tritium or Argon.

We showed that the fit to the excess could be improved by various mediators between neutrinos and electrons, but that this faces difficult astrophysical constraints. arXiv:2006.11250





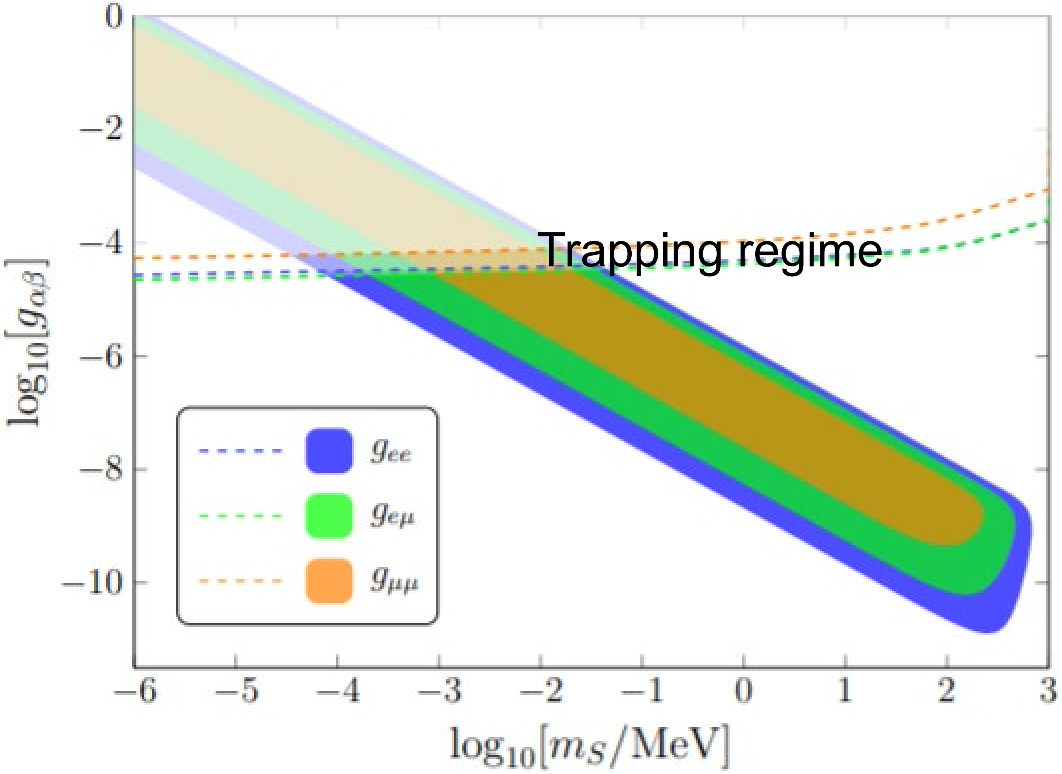
Important point is that dark matter detectors are able to probe some aspects of the neutrino sector with precision comparable or better to some neutrino detectors.


Kamiokande II
IMB
Baksan
Energie (MeV)
Temps relatif (secondes)
0
10
20
30
40
50
0
2
4
6
8
10
12
14

Constraints from SN1987A

For a massive scalar S or pseudoscalar J, the renormalizable couplings to neutrinos can be generally denoted by

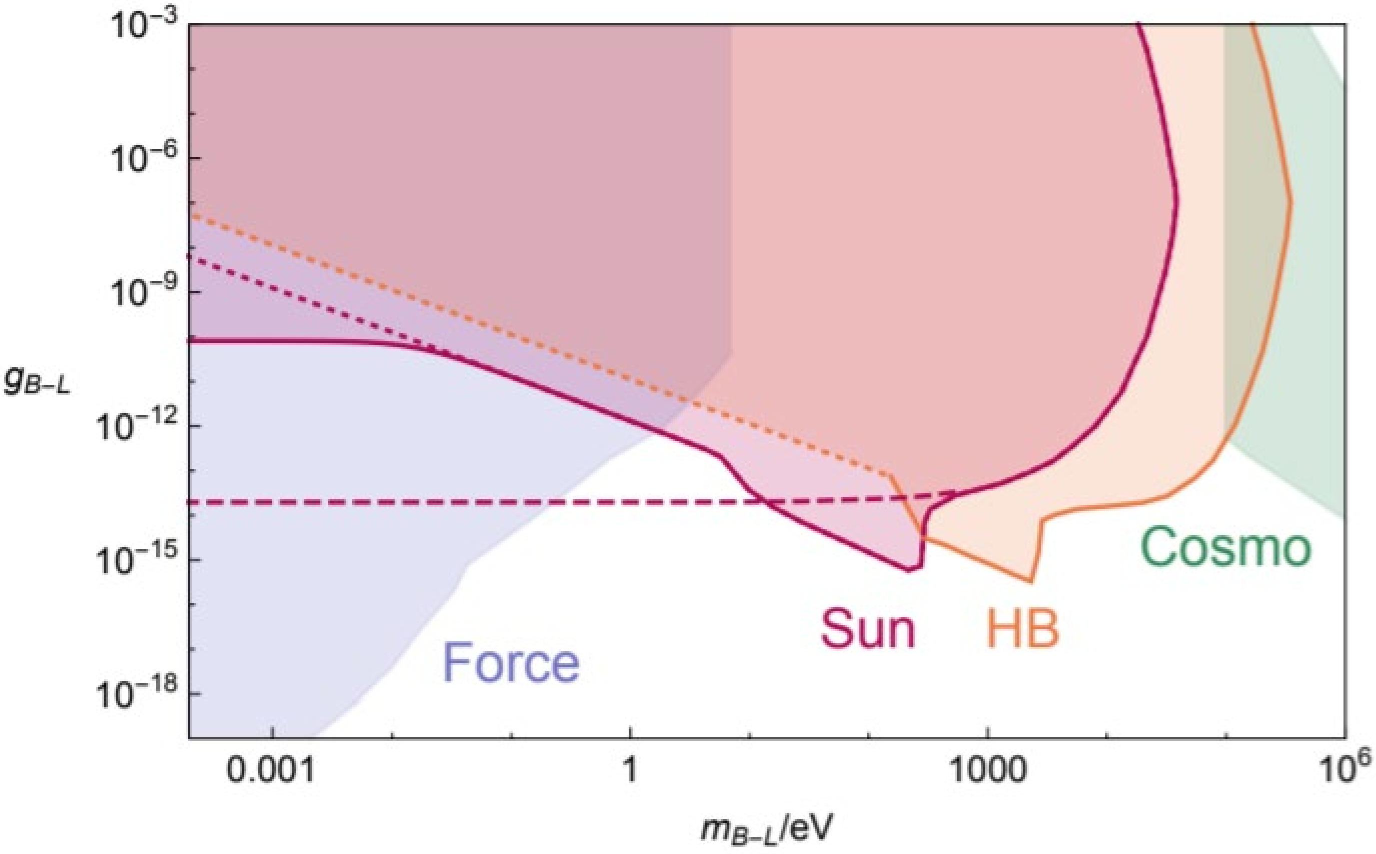
$$\mathcal{L} = \frac{1}{2} g_{\alpha\beta} S \left(\nu_\alpha^T i\sigma_2 \nu_\beta\right) + \frac{1}{2} g'_{\alpha\beta} J \left(\nu_\alpha^T \sigma_2 \nu_\beta\right) + \text{h.c.} \tag{2.1}$$



Heurtier & Zhang
1609.05882

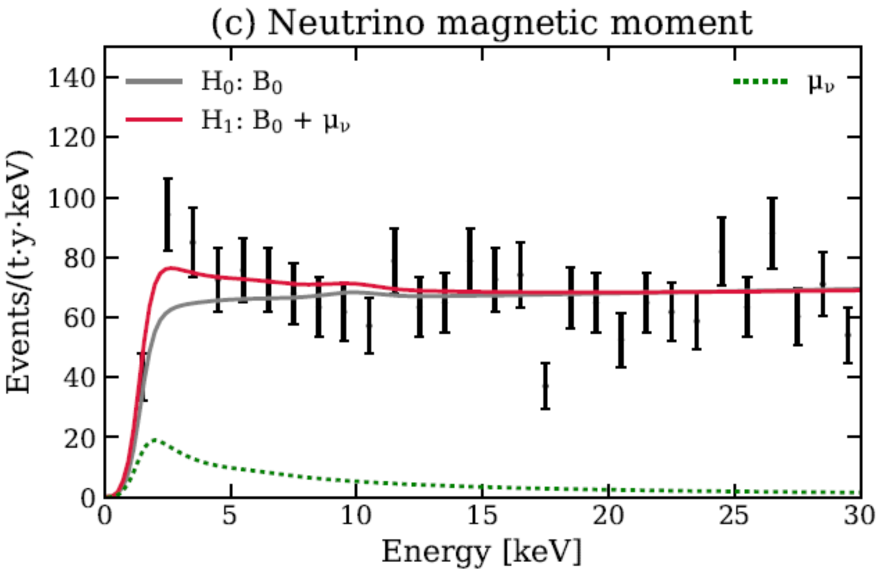
Can also affect propagation of neutrinos from 1987a

On the other side, the coupling between electrons and vectors is also tightly constrained… Will talk more about this later.



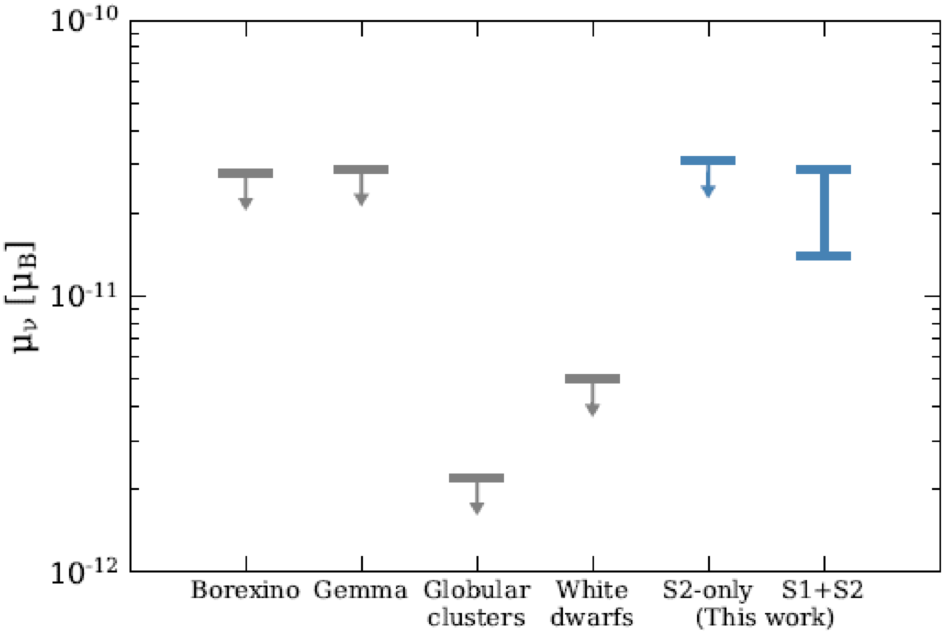
Hardy and Lasenby, 1611.05852

The neutrino magnetic moment Fit tightly constrained



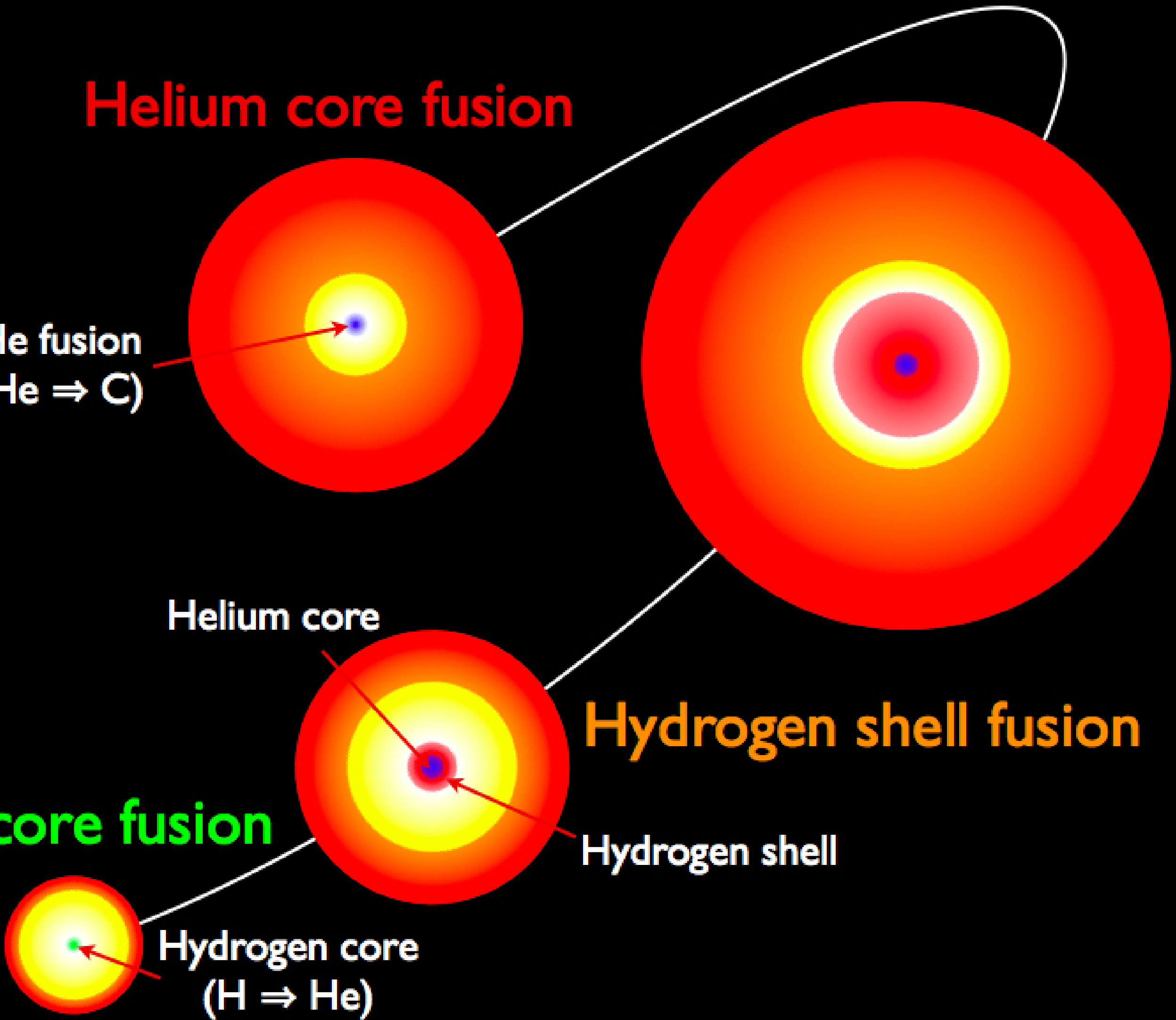
$$\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\,\mu_B$$

Where do these constraints come from?



Stellar evolution

(sizes not to scale!)



Helium core fusion

He fusion
(He ⇒ C)

Helium core

Hydrogen shell fusion

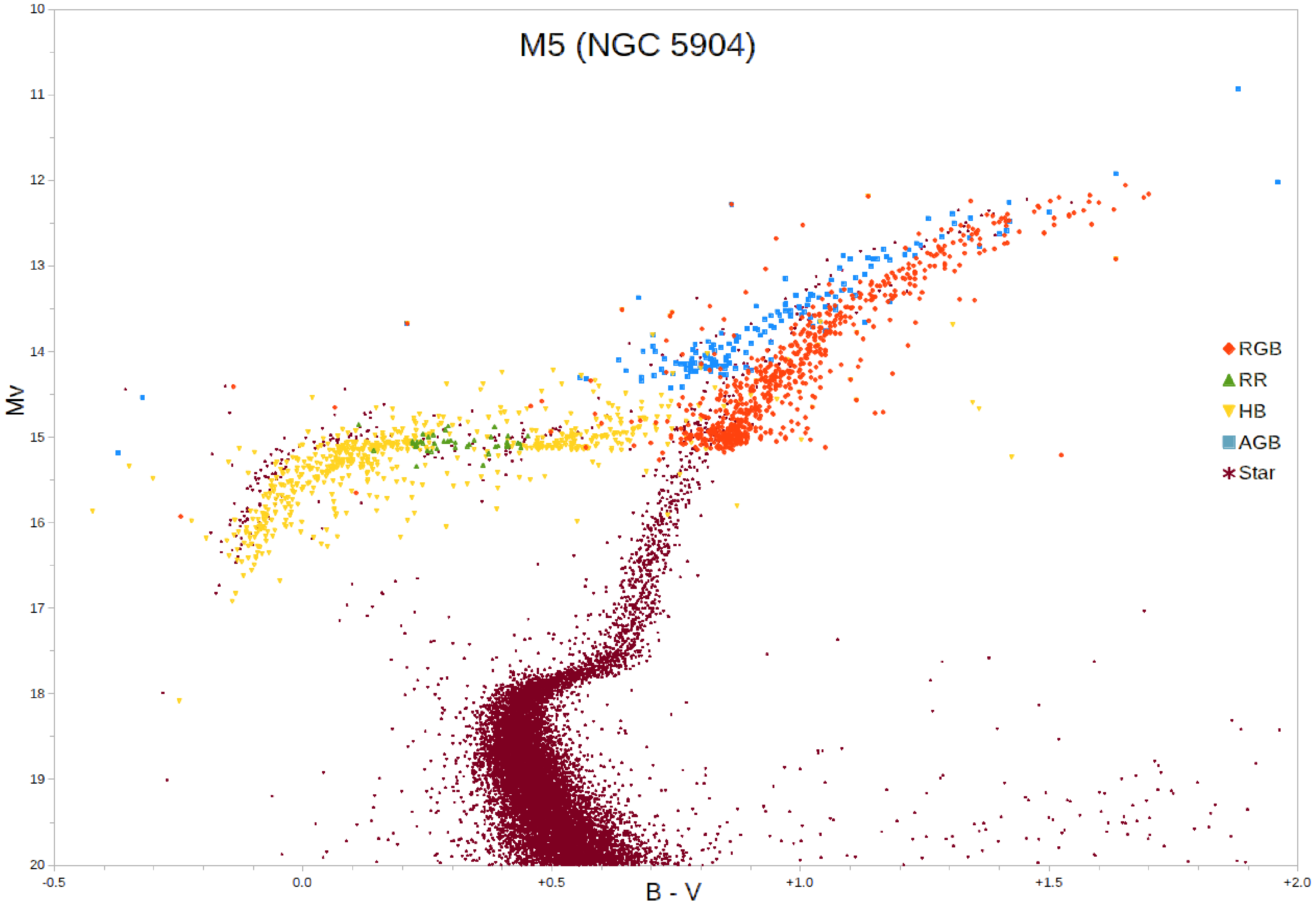
Hydrogen shell

Hydrogen core fusion

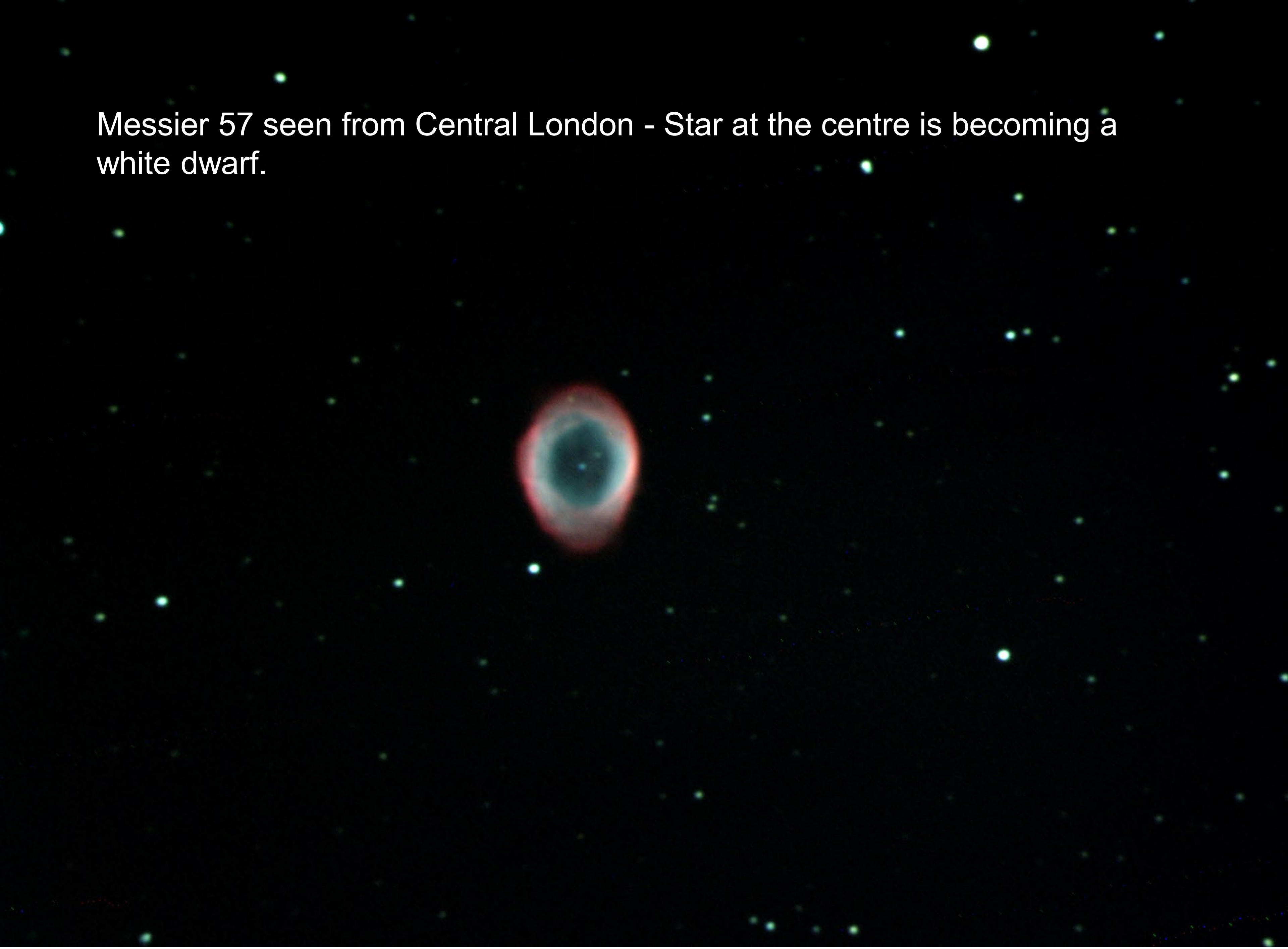
Hydrogen core
(H ⇒ He)

Thomas Kallinger, University of British Columbia and University of Vienna


Messier 5 from
Central London

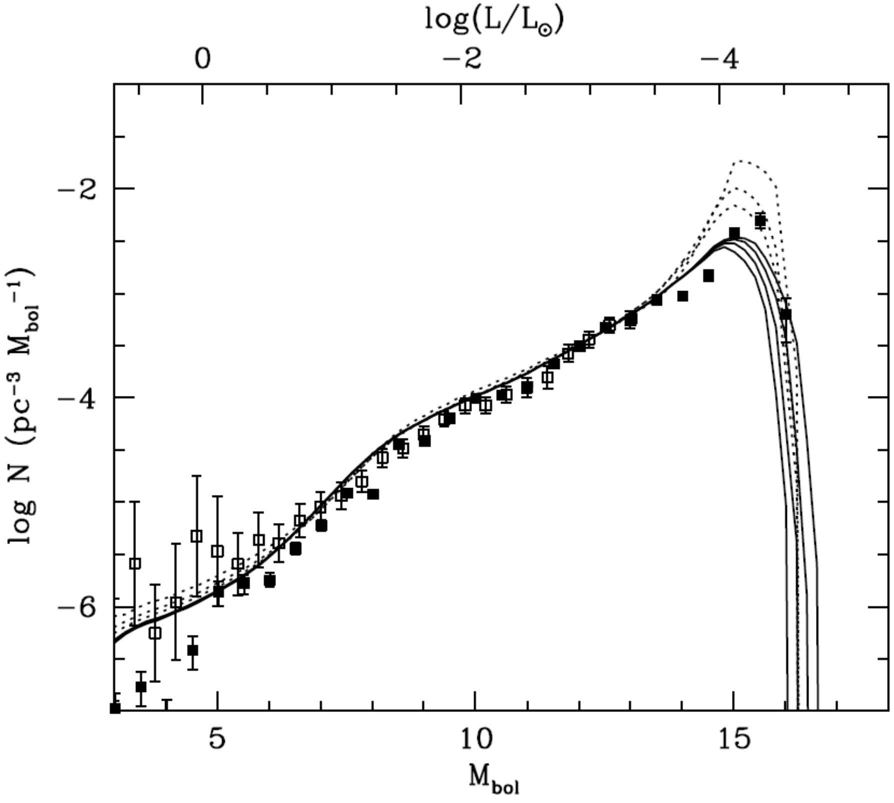


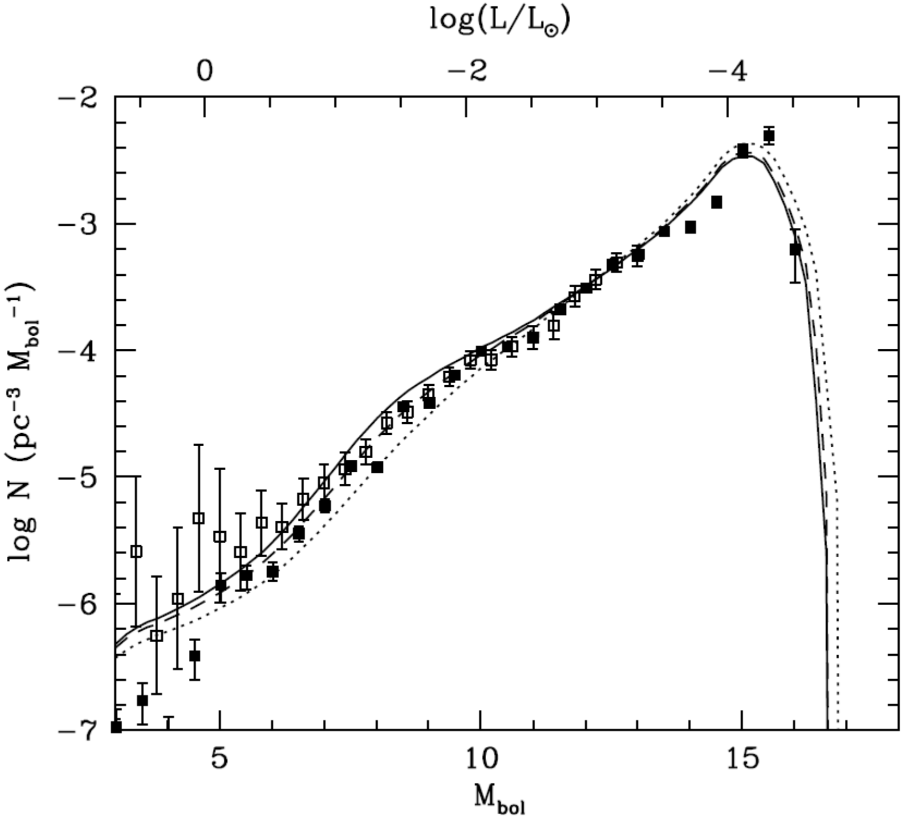
Tip of the Red Giant Branch is affected by cooling



Messier 57 seen from Central London - Star at the centre is becoming a white dwarf.

Hints for cooling from White Dwarf Luminosity functions

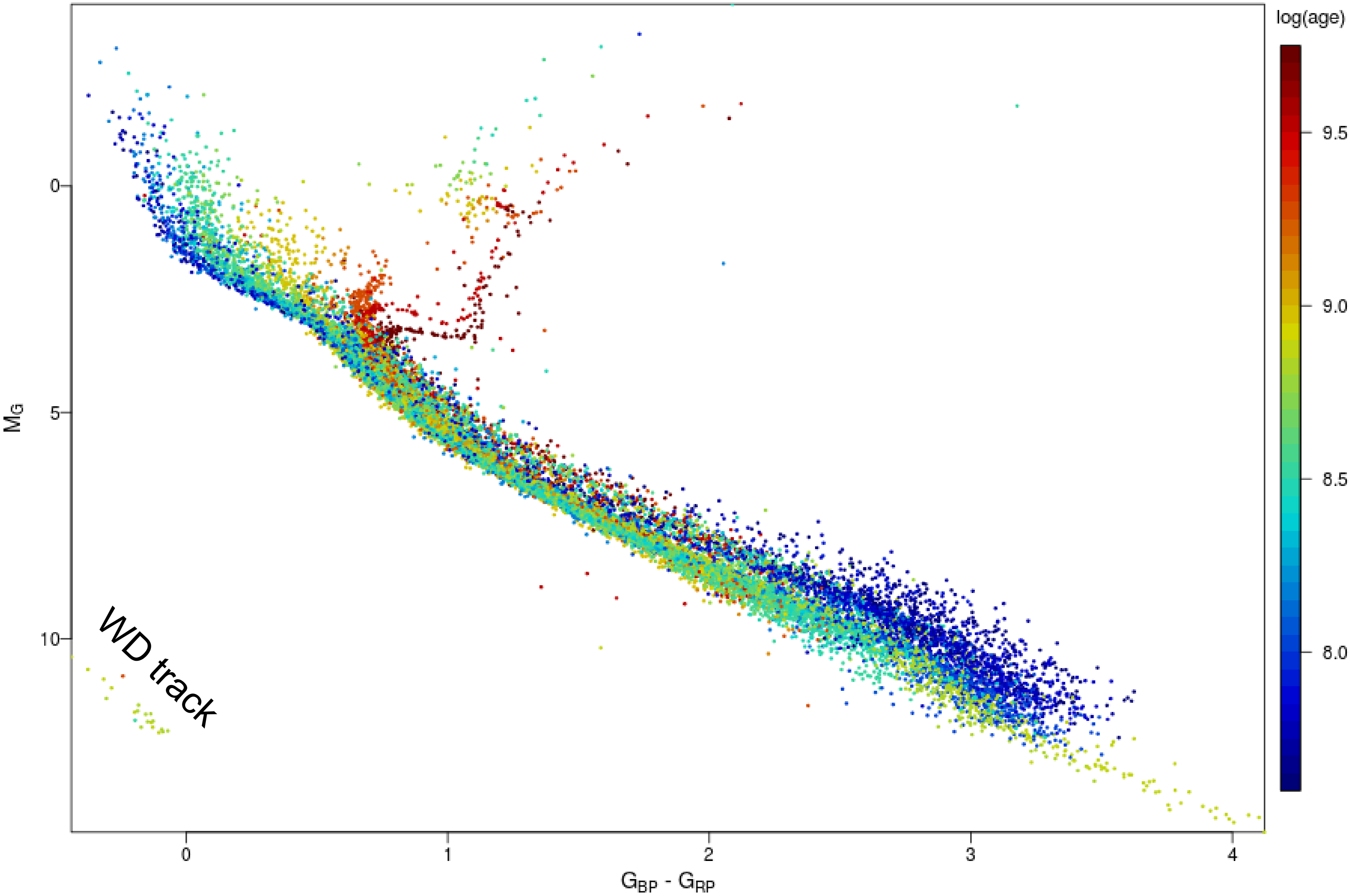




without axions

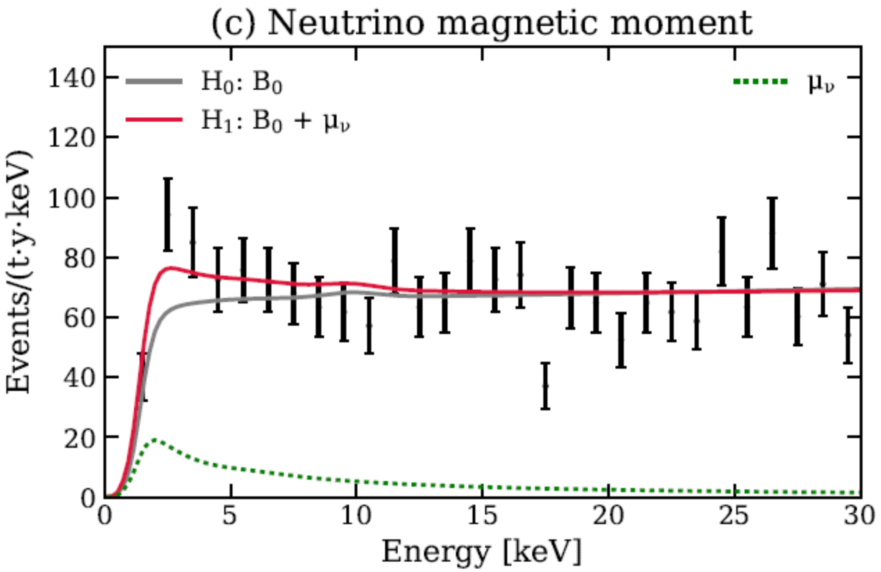
with axions

arXiv:0812.3043



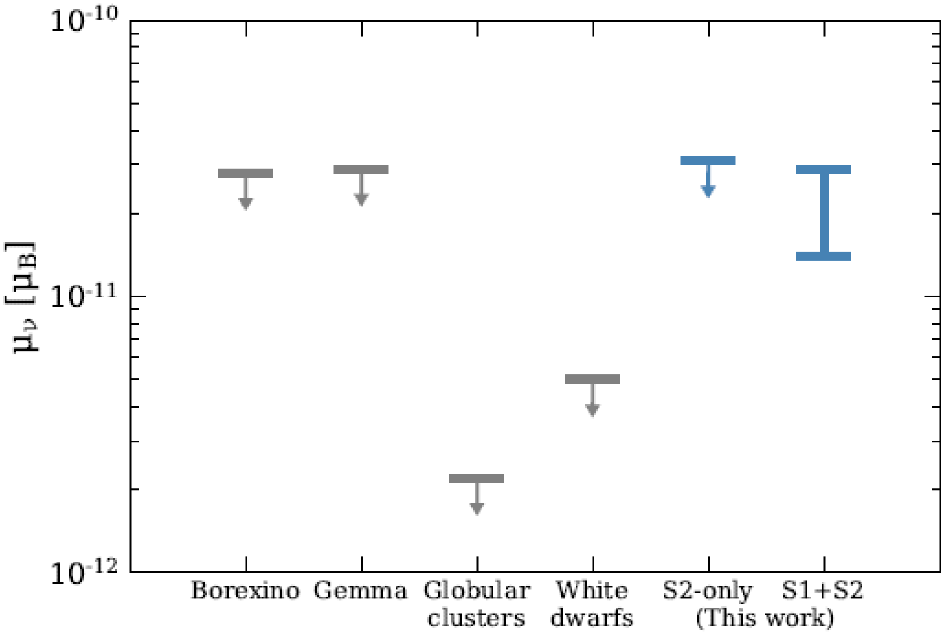
Combined HR diagram for 32 open clusters made with Gaia data.
Stars from younger clusters are blue, stars belonging to older clusters are red.
A10, A&A Volume 616, August 2018

The neutrino magnetic moment Fit tightly constrained

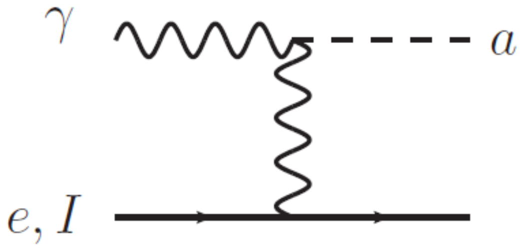


$$\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\,\mu_B$$

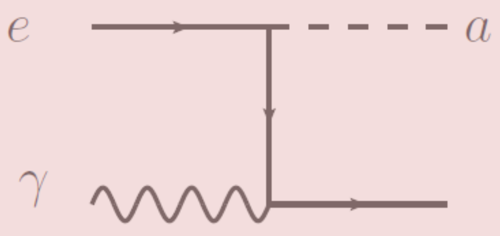
This interpretation is difficult to square with stellar observations



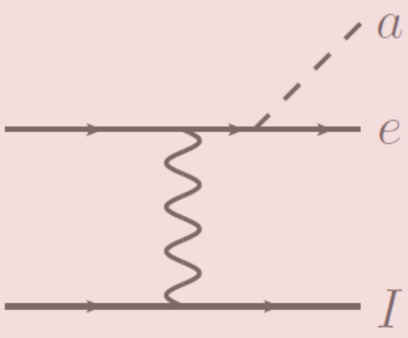
Axion production in the Sun



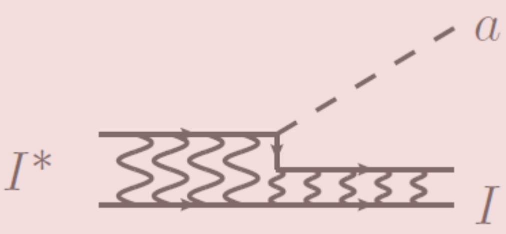
Primakoff



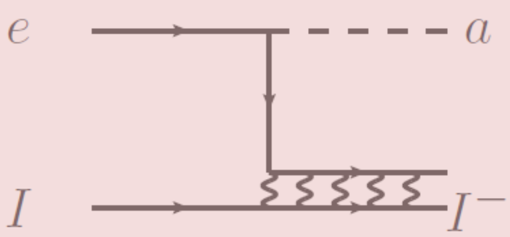
Compton



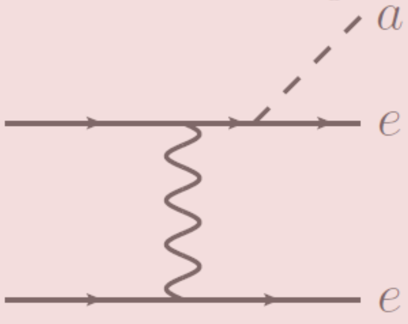
e − I bremsstrahlung



axio − deexcitation



axiorecombination

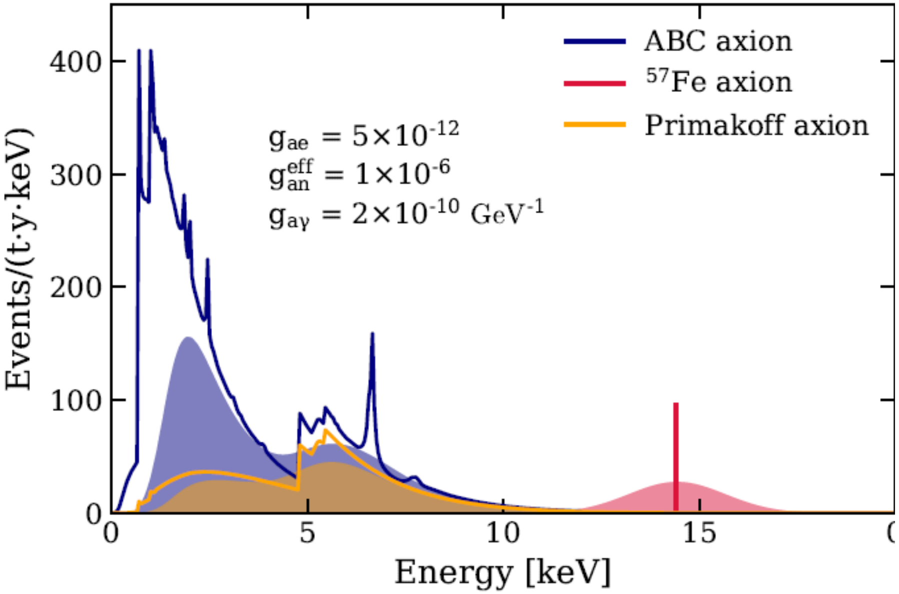


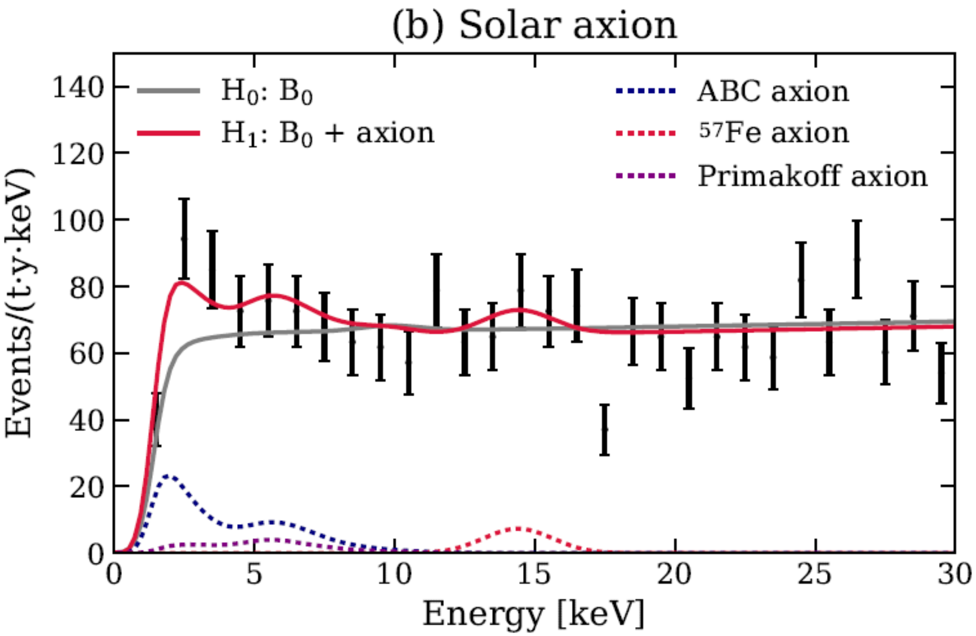
e − e bremsstrahlung

Redondo 1310.0823

ABC processes

Solar axion interpretation



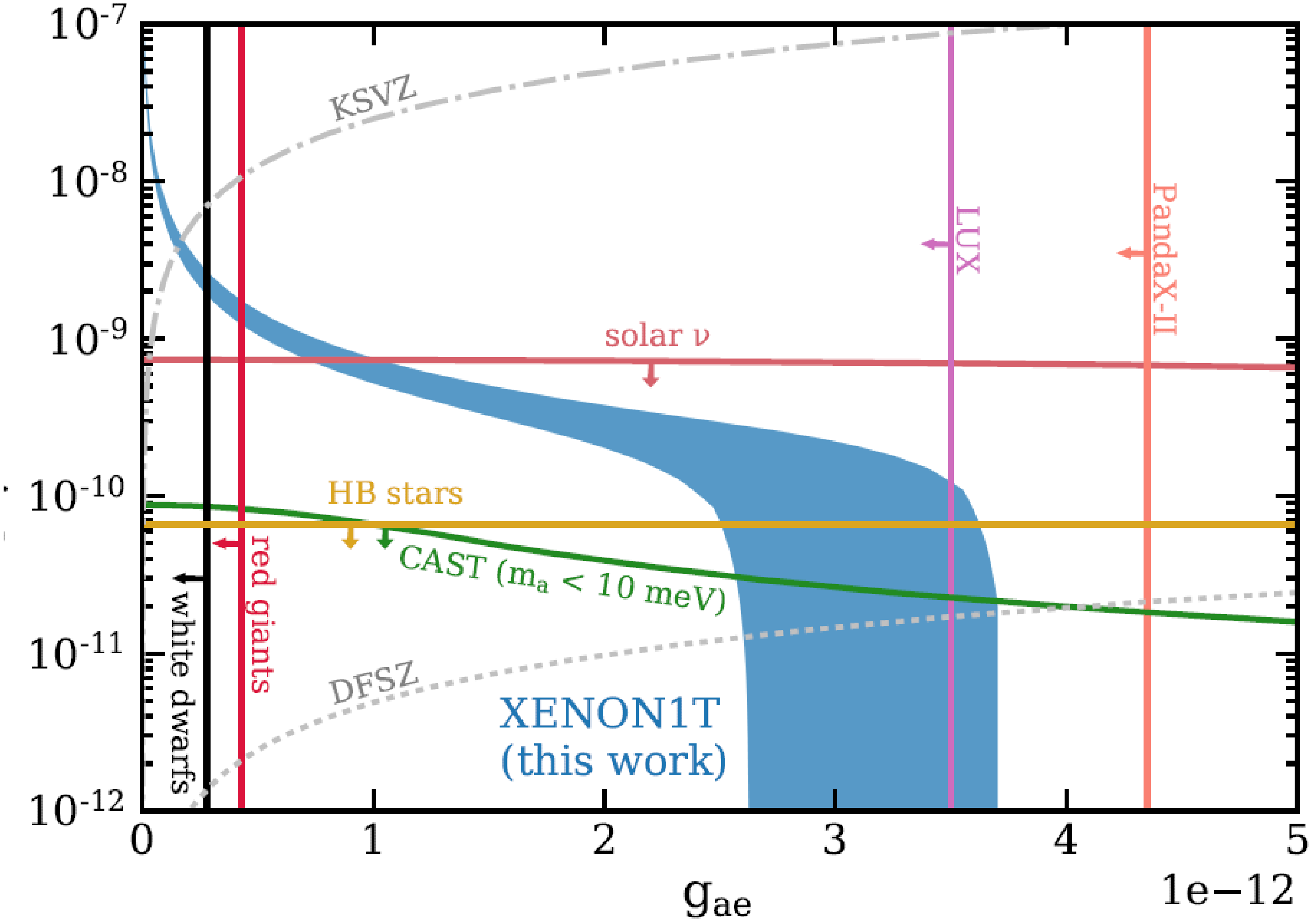

(b) Solar axion

$$\Phi_{\mathrm{a}}^{\mathrm{ABC}} \propto g_{\mathrm{ae}}^{2}$$

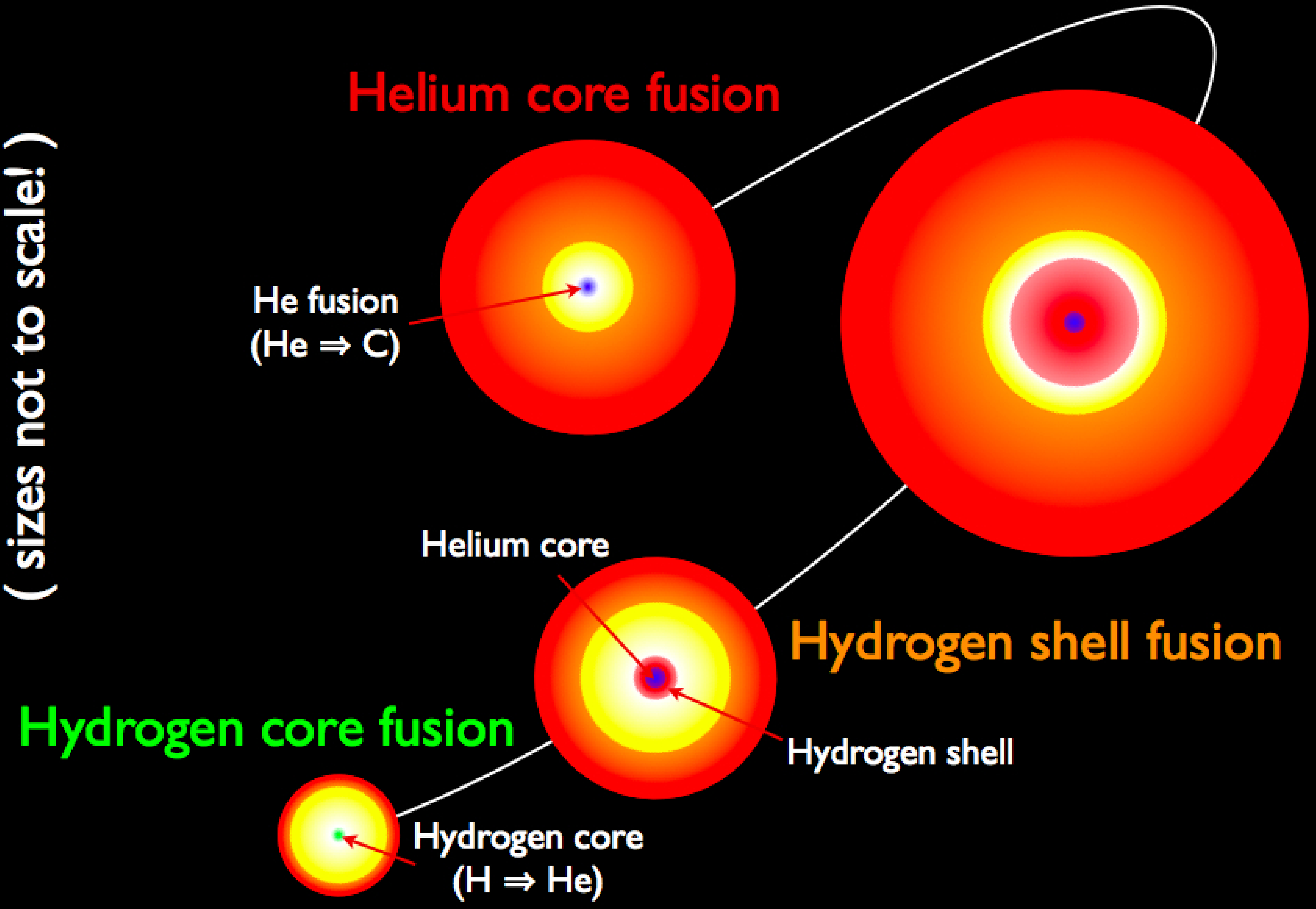
$$\Phi_{\mathrm{a}}^{57\mathrm{Fe}} = \left(\frac{k_{\mathrm{a}}}{k_{\gamma}}\right)^{3} \times 4.56 \times 10^{23} (g_{\mathrm{an}}^{\mathrm{eff}})^{2} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\frac{d\Phi_{\mathrm{a}}^{\mathrm{Prim}}}{dE_{\mathrm{a}}} = \left(\frac{g_{\mathrm{a}\gamma}}{\mathrm{GeV}^{-1}}\right)^{2} \left(\frac{E_{\mathrm{a}}}{\mathrm{keV}}\right)^{2.481} e^{-E_{\mathrm{a}}/(1.205\ \mathrm{keV})}$$
$$\times 6 \times 10^{30} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1},$$

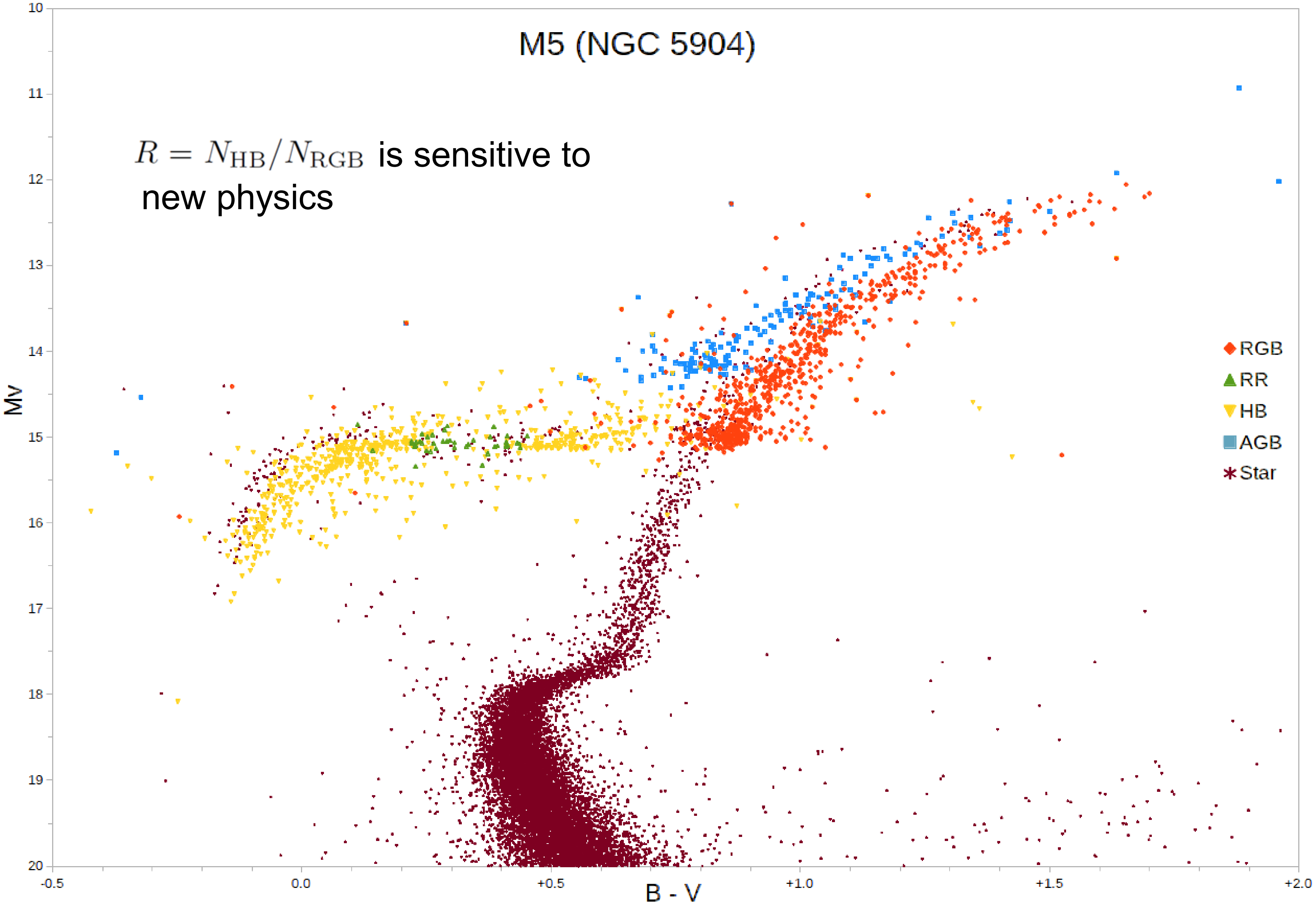
Favoured Axion Parameters to fit the excess



Stellar evolution

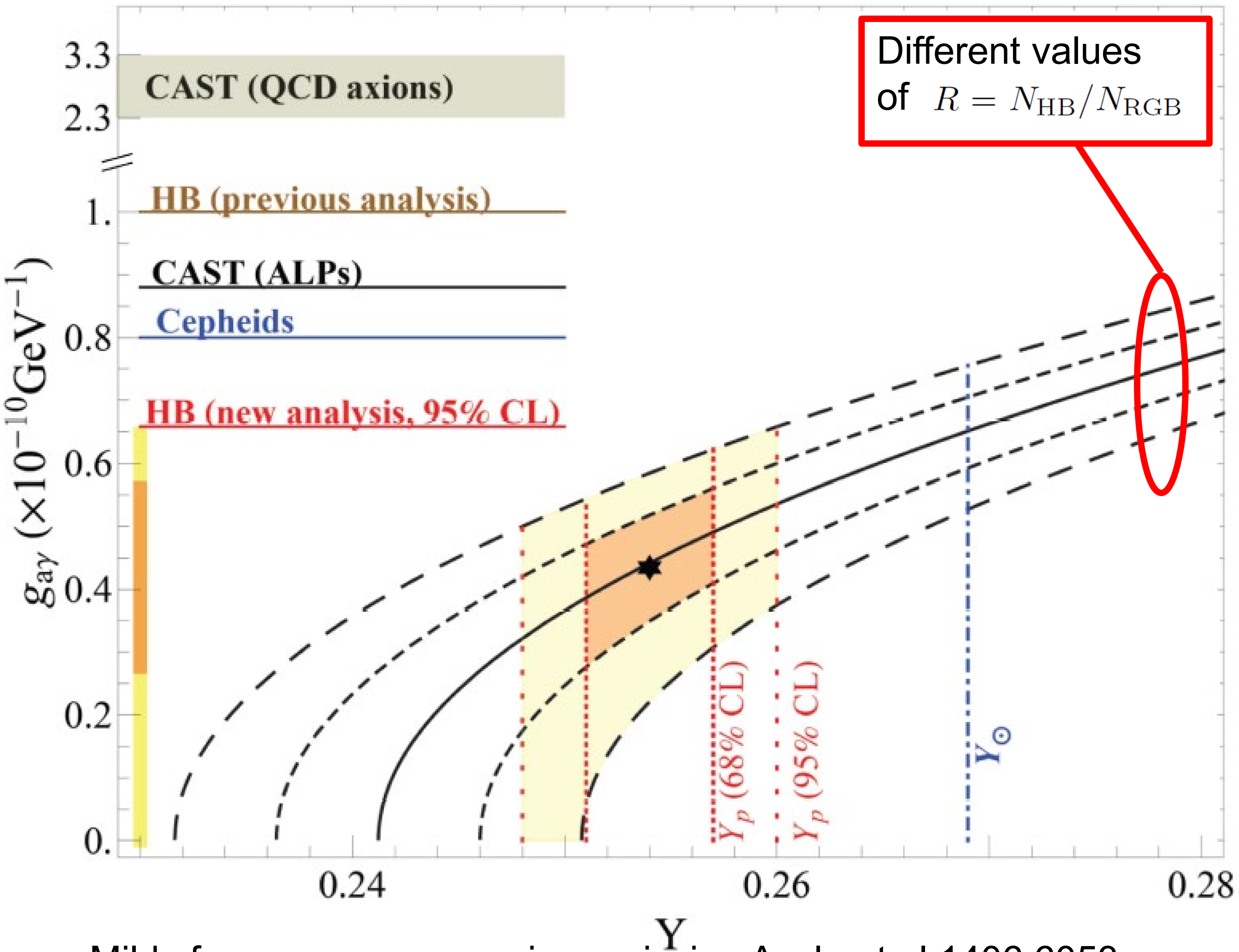


Thomas Kallinger, University of British Columbia and University of Vienna



$R = N_{\mathrm{HB}}/N_{\mathrm{RGB}}$ is sensitive to new physics

Ratio between number of HB to RGB stars sensitive to Helium and Cooling
Raffelt & Dearborn (1987)



Different values of $R = N_{\rm HB}/N_{\rm RGB}$

Mildy favours non-zero axion emission Ayala et al 1406.6053

Constraints on Axion parameters from RGB and HB stars

The cooling also depends upon the axion electron coupling.

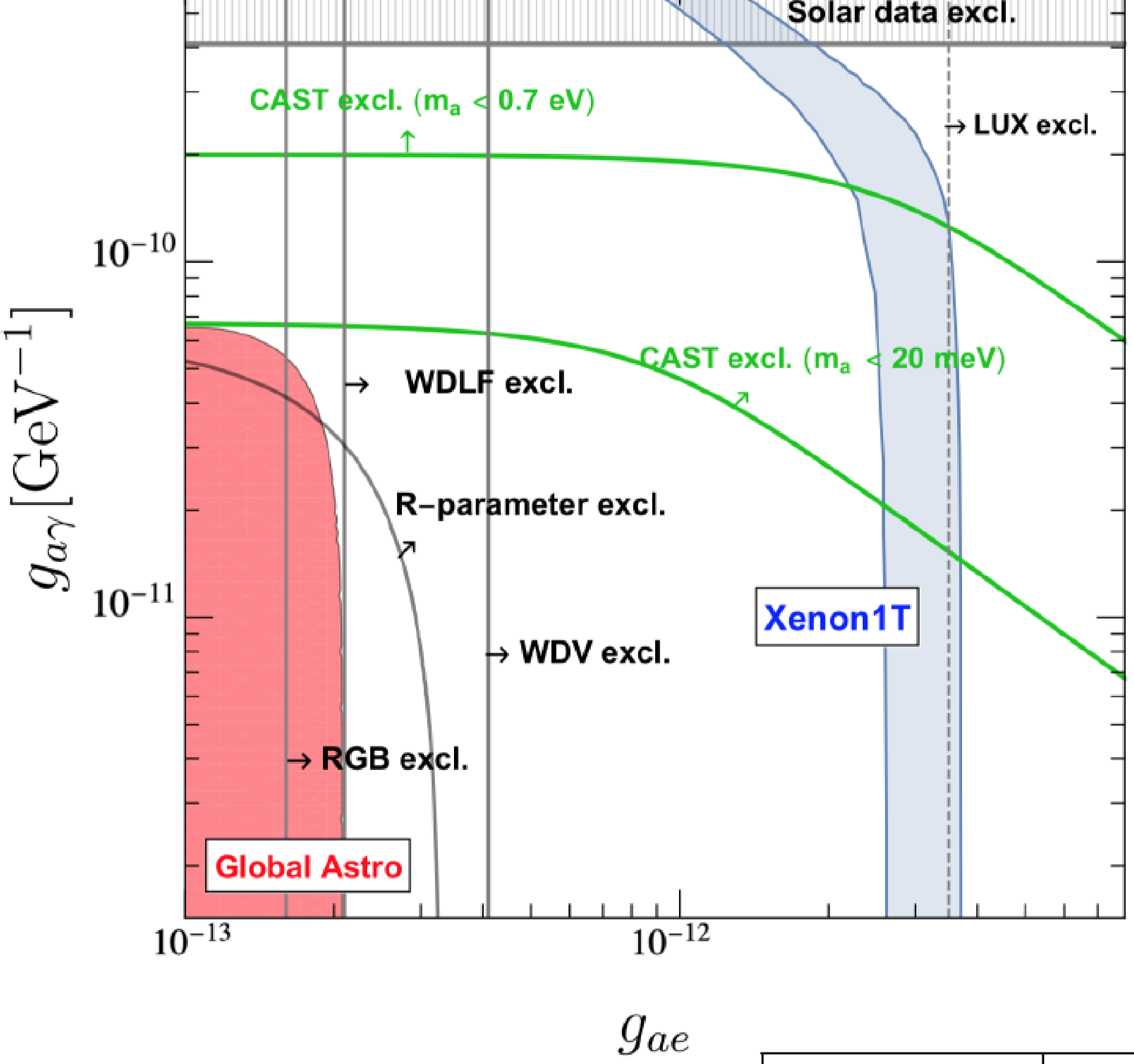
$$M_{I,\mathrm{TRGB}} = -4.047 \pm 0.045\ \mathrm{mag}$$

$$M_{I,\mathrm{TRGB}}^{\mathrm{theo}} = -4.08 \\ -0.25\left(\sqrt{g_{e13}^2 + 0.93} - 0.96 - 0.17 g_{e13}^{1.5}\right)$$

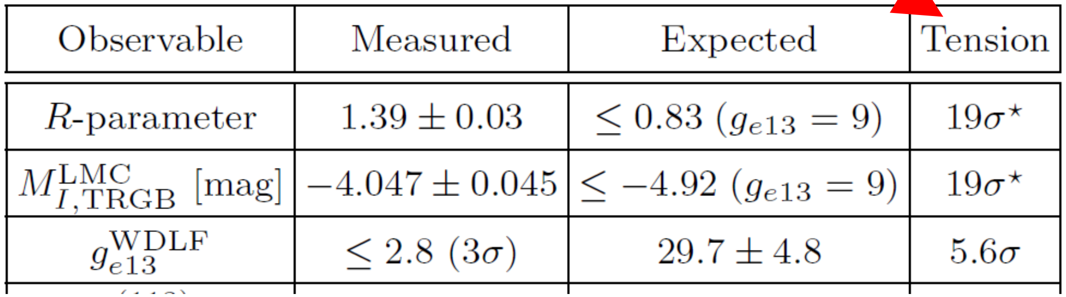
$$R^{\mathrm{theo}} = 7.33Y - 0.095\sqrt{21.86 + 21.08 g_{\gamma 10}} \\ + 0.02 - 1.61\delta\mathcal{M}_c - 0.005 g_{e13}^2\,,$$

$$\delta\mathcal{M}_c = 0.024\left(\sqrt{g_{e13}^2 + 1.23^2} - 1.23 - 0.138\, g_{e13}^{1.5}\right)$$

Di Luzio et al 2006.12487



Constraints independent of mass provided m_a<100 eV



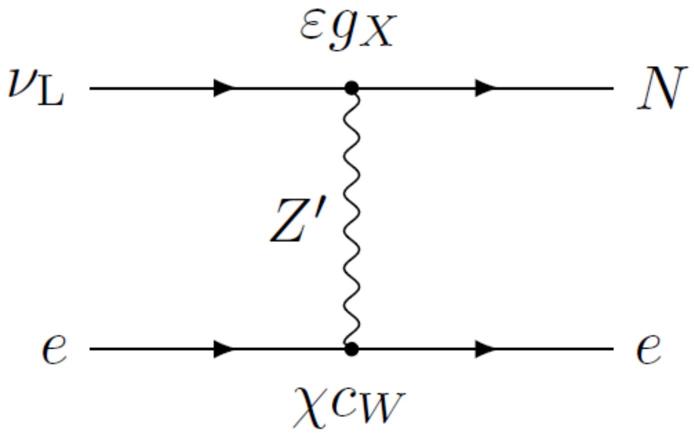
Observable	Measured	Expected	Tension
R-parameter	1.39 ± 0.03	$\leq 0.83\ (g_{e13} = 9)$	$19\sigma^{\star}$
$M_{I,\mathrm{TRGB}}^{\mathrm{LMC}}$ [mag]	-4.047 ± 0.045	$\leq -4.92\ (g_{e13} = 9)$	$19\sigma^{\star}$
g_{e13}^{WDLF}	$\leq 2.8\ (3\sigma)$	29.7 ± 4.8	5.6σ

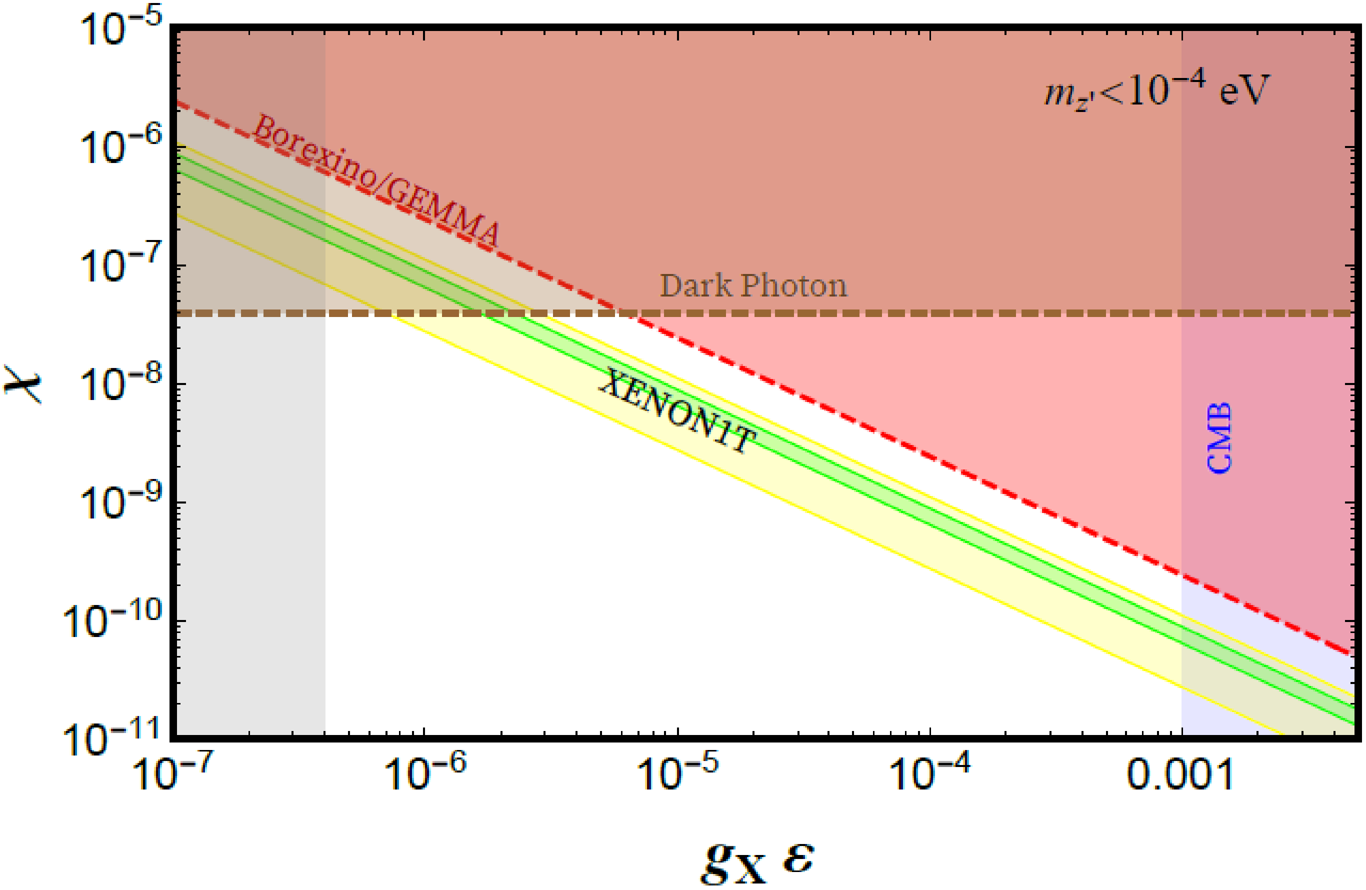
Di Luzio et al 2006.12487

Neutrino “self interactions” – hidden neutrino

$$\mathcal{L}_{\rm eff} \;=\; \varepsilon\, g_X\, Z'_\mu\, \overline{N}\gamma^\mu \nu_{\rm L} + \chi\, c_W\, Z'_\mu\, \mathcal{J}^\mu_{\rm e.m.}$$

Ballly et al 2006.11919





- It seems difficult to have solar axions as an explanation of the excess, not because of earth based constraints but mostly because of astrophysical constraints.
- This is probably also true for neutrinos with non standard interactions.

We know there is 6 times as much dark matter as normal matter. Can it be the Xenon 1T excess?

Axionic Dark matter be responsible for the signal

m_a~keV and g_{ae}~10^{-13} works OK!
might also fit cooling hint for HB stars???
However, tight constraints from decays into photons.
Can we evade?

$$\begin{aligned}\mathcal{L}_{\rm eff} \;&\simeq\; -(q_e+q_\mu+q_\tau)\frac{\alpha_{em}}{4\pi f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu}\\ &+\frac{\alpha_{em}}{48\pi f_a}\left(\frac{q_e}{m_e^2}+\frac{q_\mu}{m_u^2}+\frac{q_\tau}{m_\tau^2}\right)\left((\partial^2 a)F_{\mu\nu}\tilde{F}^{\mu\nu}+2aF_{\mu\nu}\partial^2\tilde{F}^{\mu\nu}\right)\end{aligned}$$

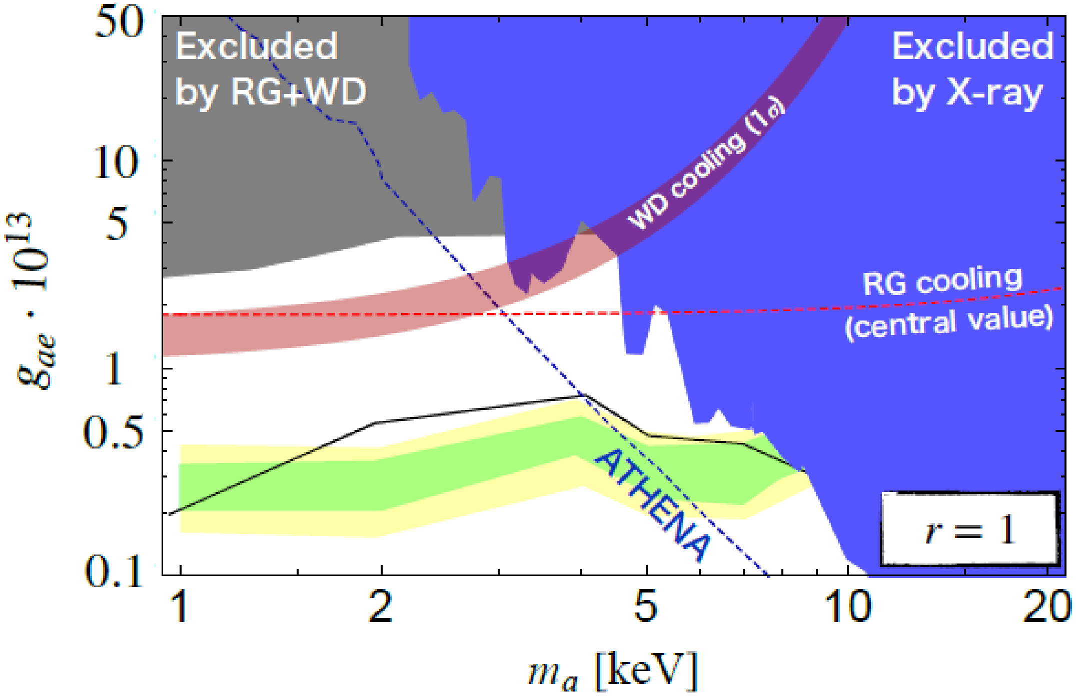
$$q_e+q_\mu+q_\tau=0$$

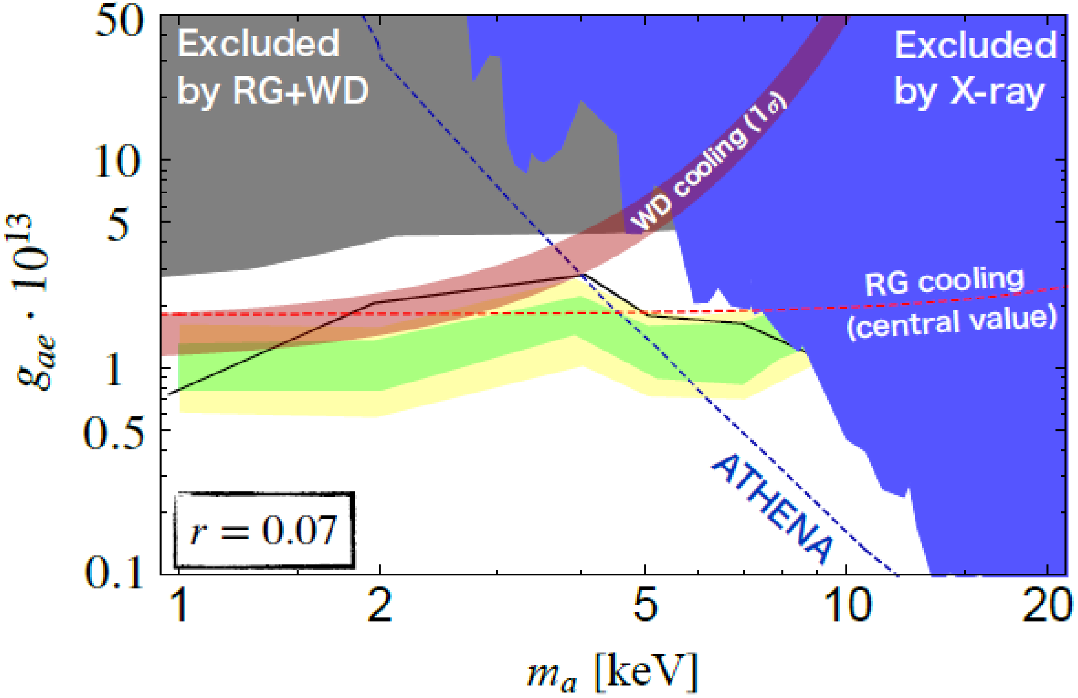
We are free to cancel this anomaly but then there are still supressed photon-axion couplings

$$\mathcal{L}_{\rm eff} \;=\; \frac{\alpha_{em}m_a^2}{48\pi f_a}\left(\frac{q_e}{m_e^2}+\frac{q_\mu}{m_\mu^2}+\frac{q_\tau}{m_\tau^2}\right)aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Gamma_{a\to\gamma\gamma} \;\simeq\; \frac{\alpha_{em}^2}{9216\pi^3}\frac{m_a^7}{f_a^2}\times\begin{cases} q_e^2/m_e^4 & \text{for } q_e\neq 0,\\ q_\mu^2/m_\mu^4 & \text{for } q_e=0\end{cases}$$

Nakayama et al. 1403.7390





$$r \equiv \Omega_{\rm ALP}/\Omega_{\rm DM}^{(\rm obs)}$$

Can be used to explain excess

Takahashi 2006.10035

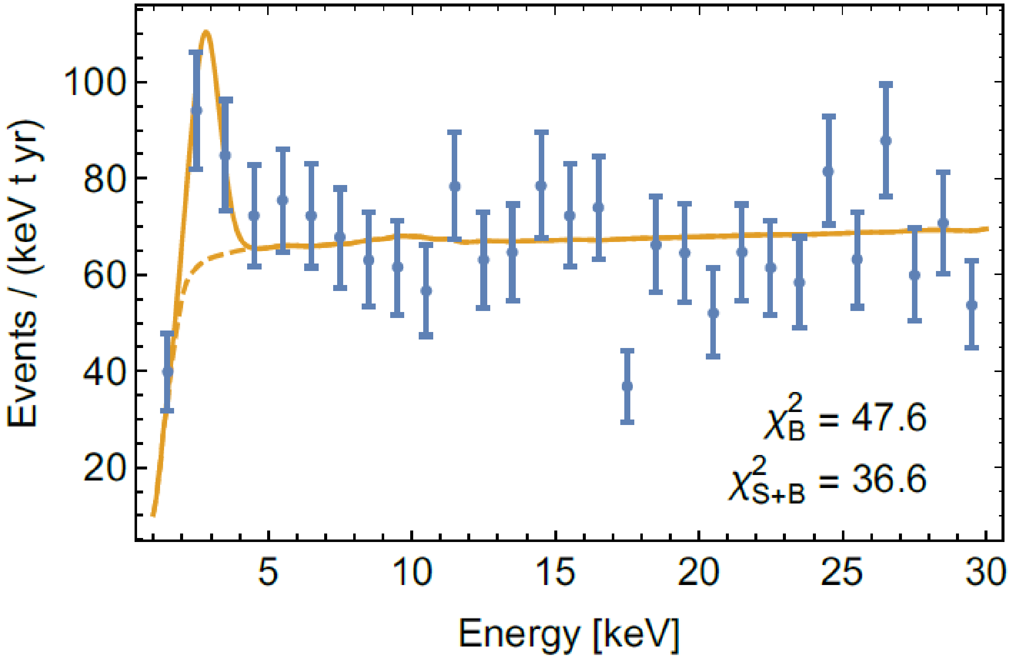
Hidden Photon Dark Matter Alonso-Alvarez et al 2006.11243

$$\mathcal{L} = -\frac{1}{4}(F^{\mu\nu})^2 - \frac{1}{4}(X^{\mu\nu})^2 - \frac{1}{2}\epsilon F^{\mu\nu}X_{\mu\nu} - \frac{1}{2}m_X^2(X^\mu)^2 - j^\mu A_\mu$$

Can explain excess with $\varepsilon=10^{-15}$ and m~2-3 keV

Relic abundance cannot be thermal – wrong abundance and too warm.

Alignment mechanism possible origin of abundance.



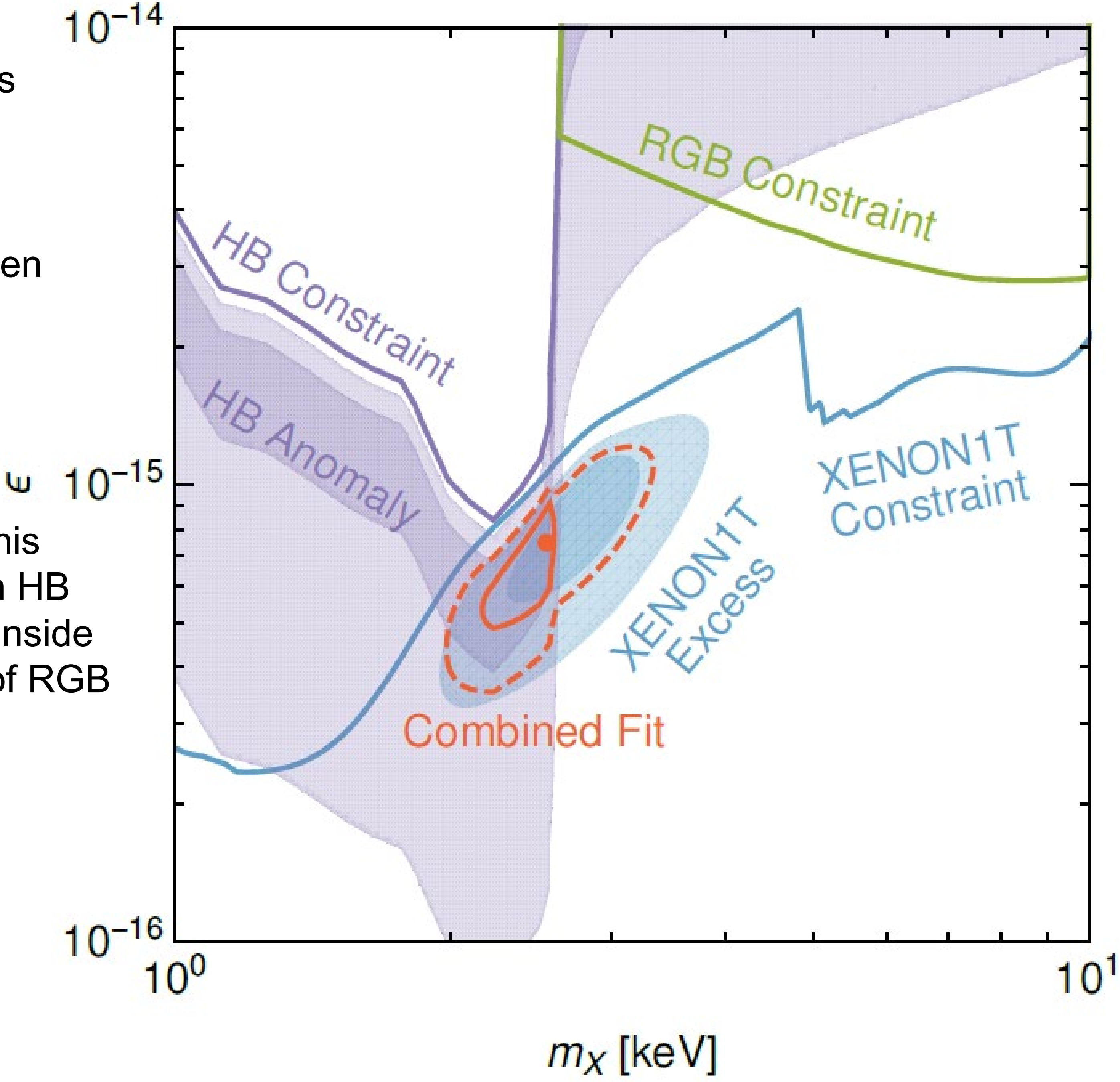
Photon gets effective mass

$\frac{1}{2}\omega_P^2 A^2$

Resonant conversion then occurs when

$m_X \sim \omega_P$

For 2.5 keV this takes place in HB stars but not inside hotter cores of RGB stars

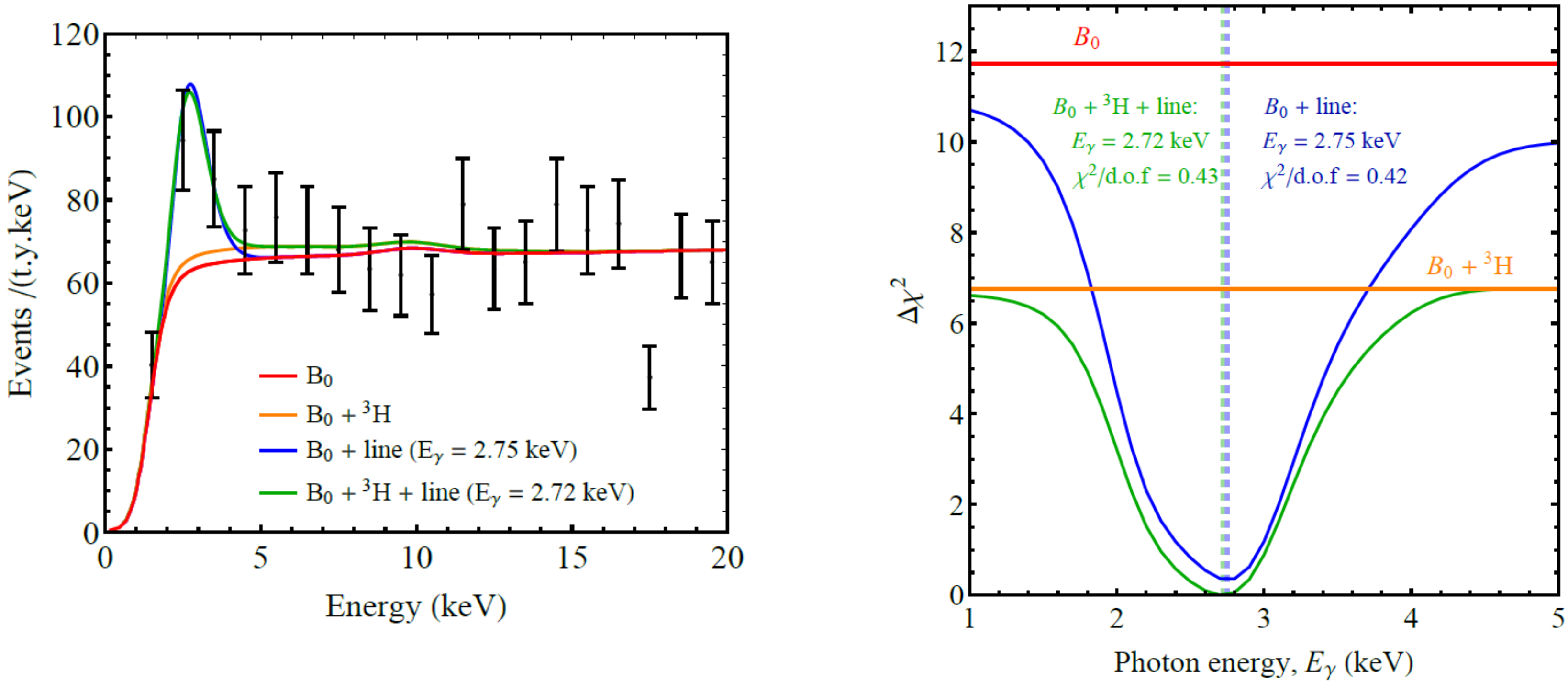


Luminous Dark Matter, Bell et al 2006.12461

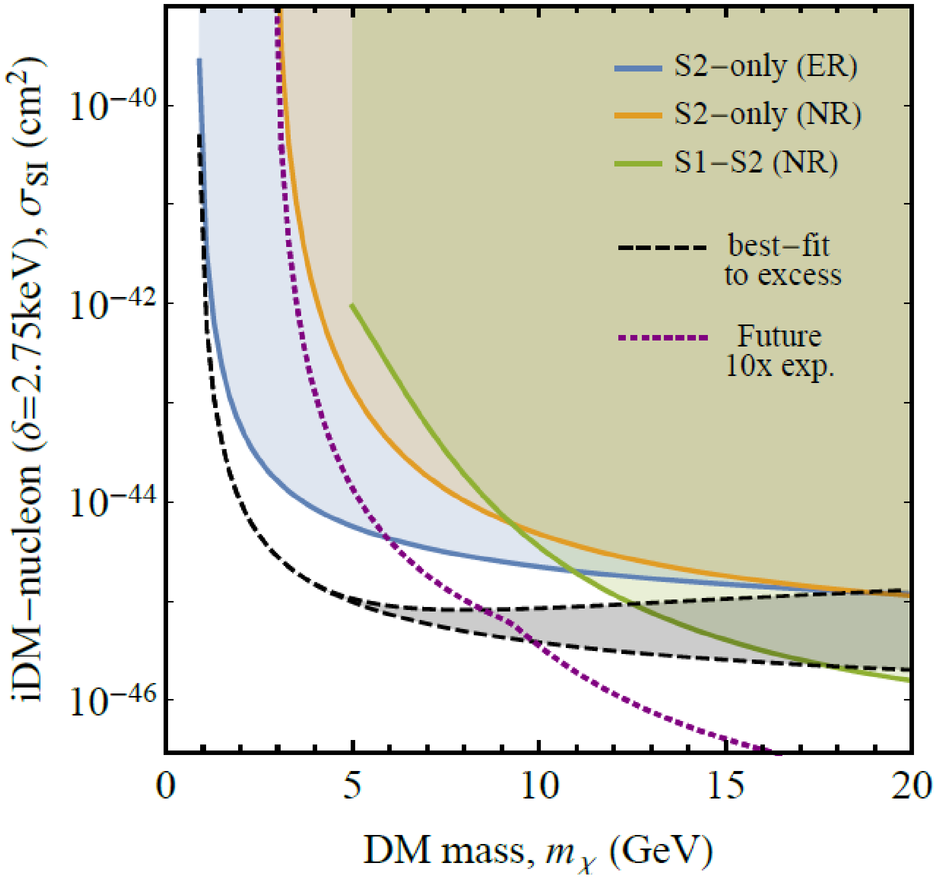
Dark Matter scatters in or around the detector

$$\delta = m_{\chi'} - m_{\chi} \ll m_{\chi}$$

$$\chi' \to \chi\gamma$$



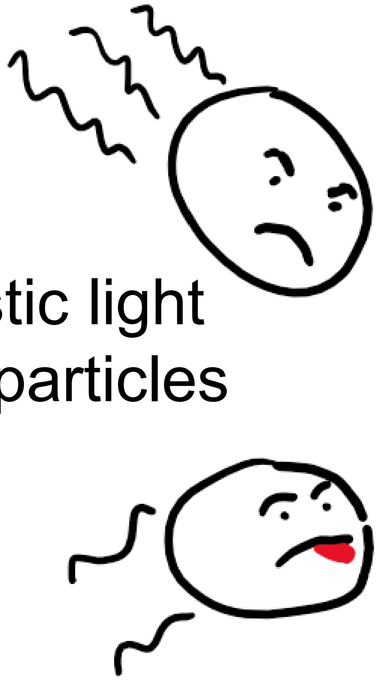
Luminous Dark Matter, Bell et al 2006.12461



- Improvements in detector resolution will sharpen the peak
- Dark Matter nuclear recoil could also be detected
- Daily modulation – when cygnus is below rather than above, more targets in rock for when the decay length is longer
- Beam Dump experiments – the particle can be produced at the LHC and then decay in FASER or SHiP

Bell et al 2006.12461

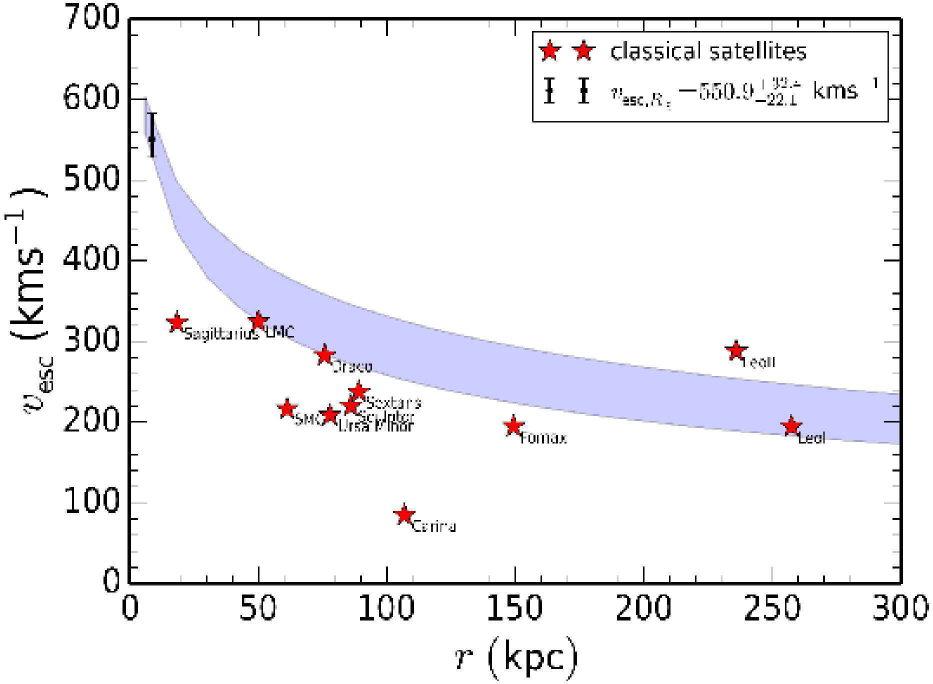
Idea - Bringmann and Pospelov 1810.07705



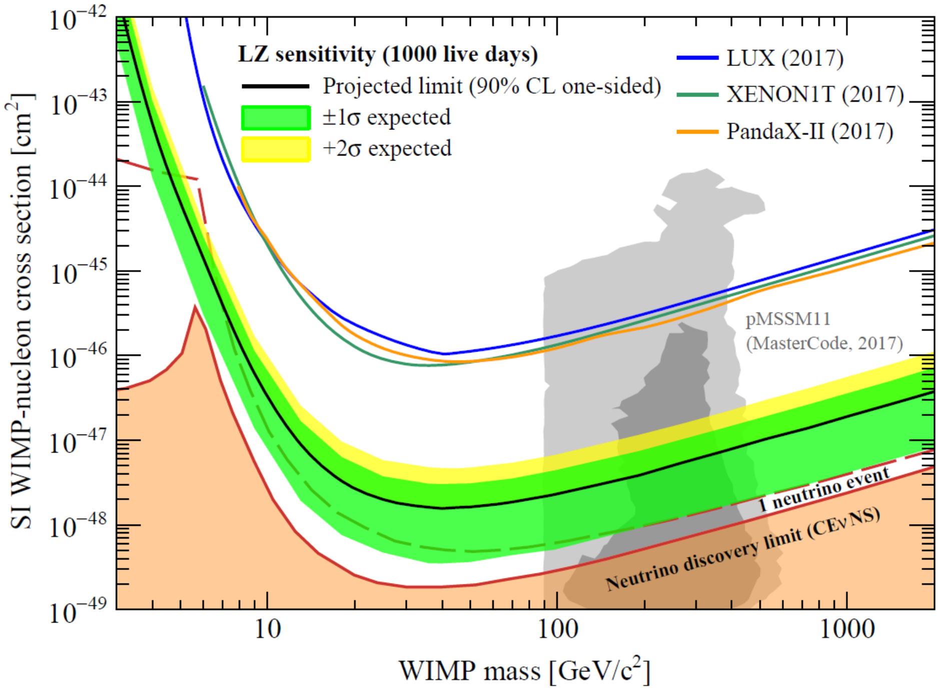
Non-relativistic light
dark matter particles

Dark Matter
Detector

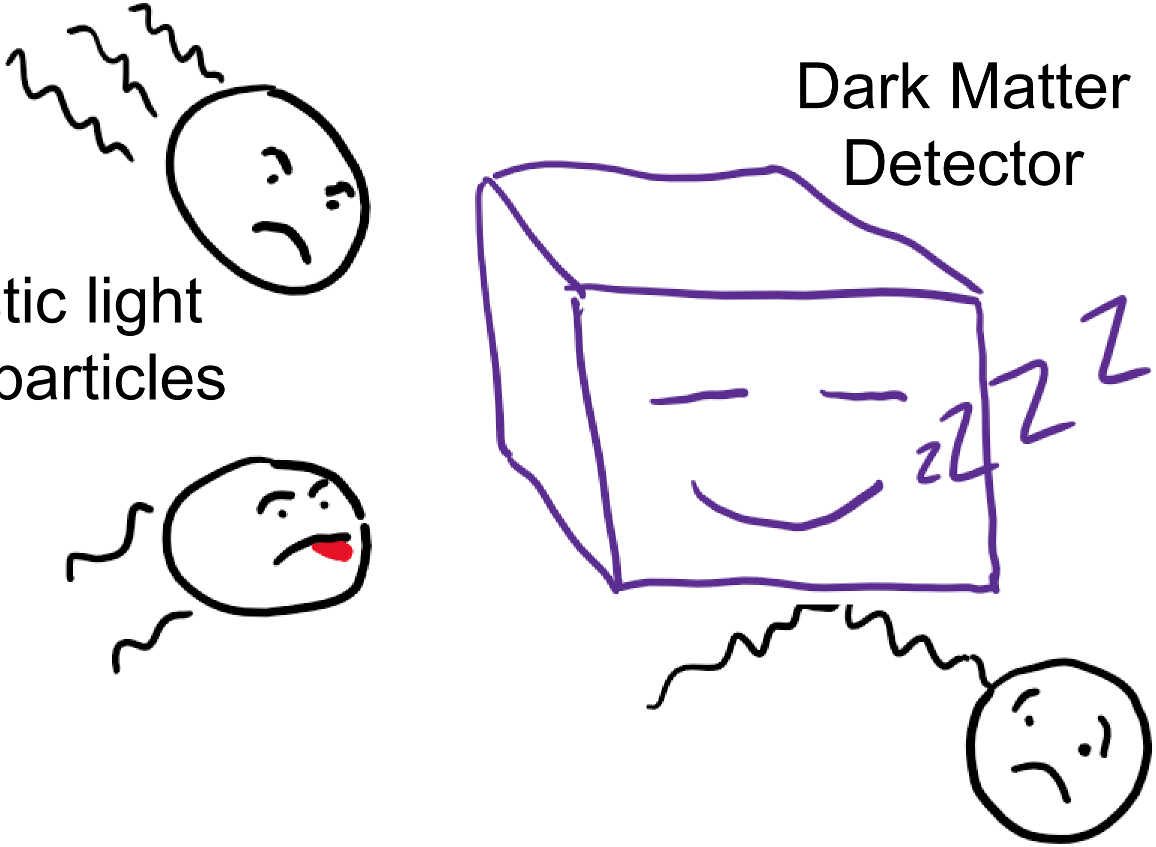
Milky Way Escape Velocity



LZ expected Sensitivity



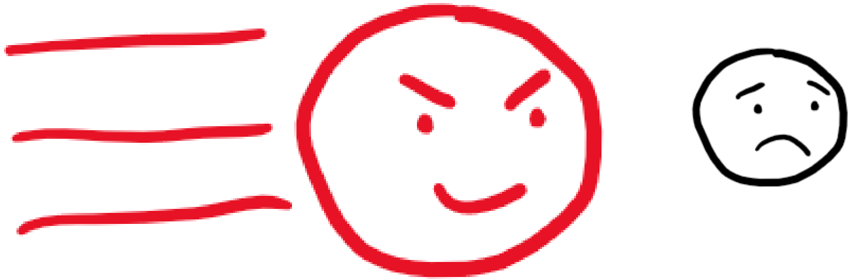
Idea - Bringmann and Pospelov 1810.07705



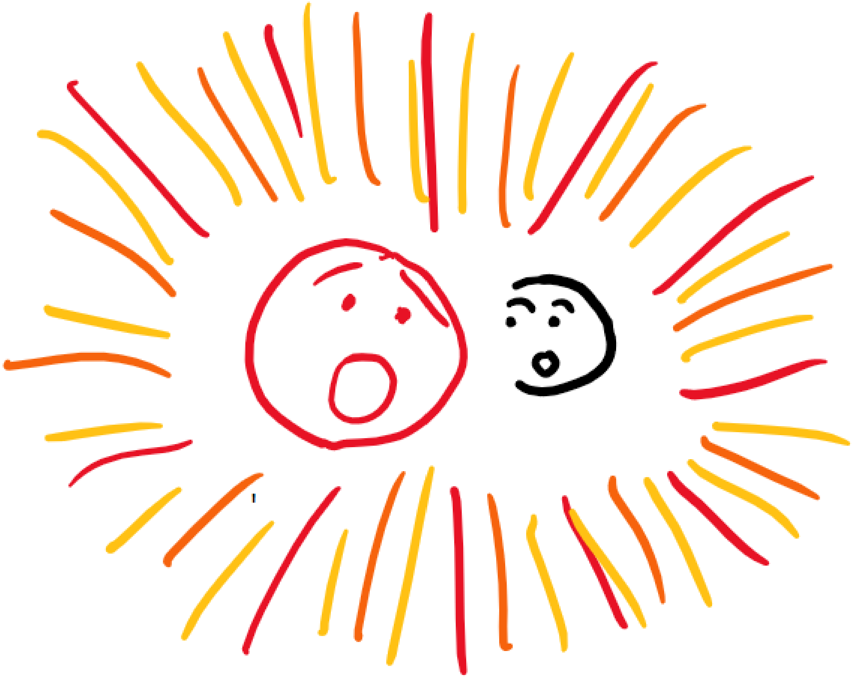
Non-relativistic light dark matter particles

Dark Matter Detector

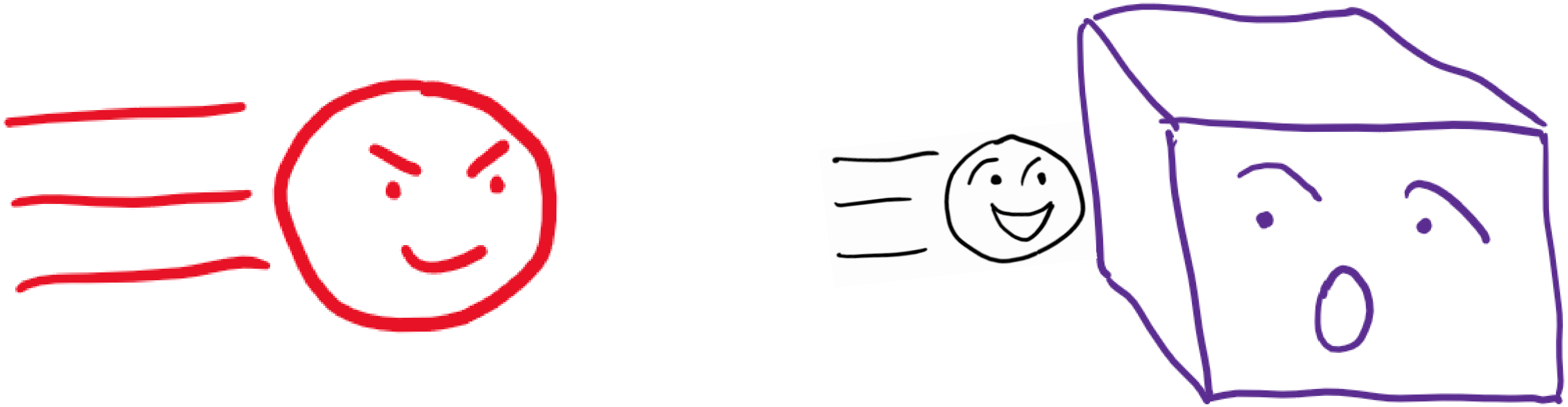
Idea - Bringmann and Pospelov 1810.07705



Idea - Bringmann and Pospelov 1810.07705

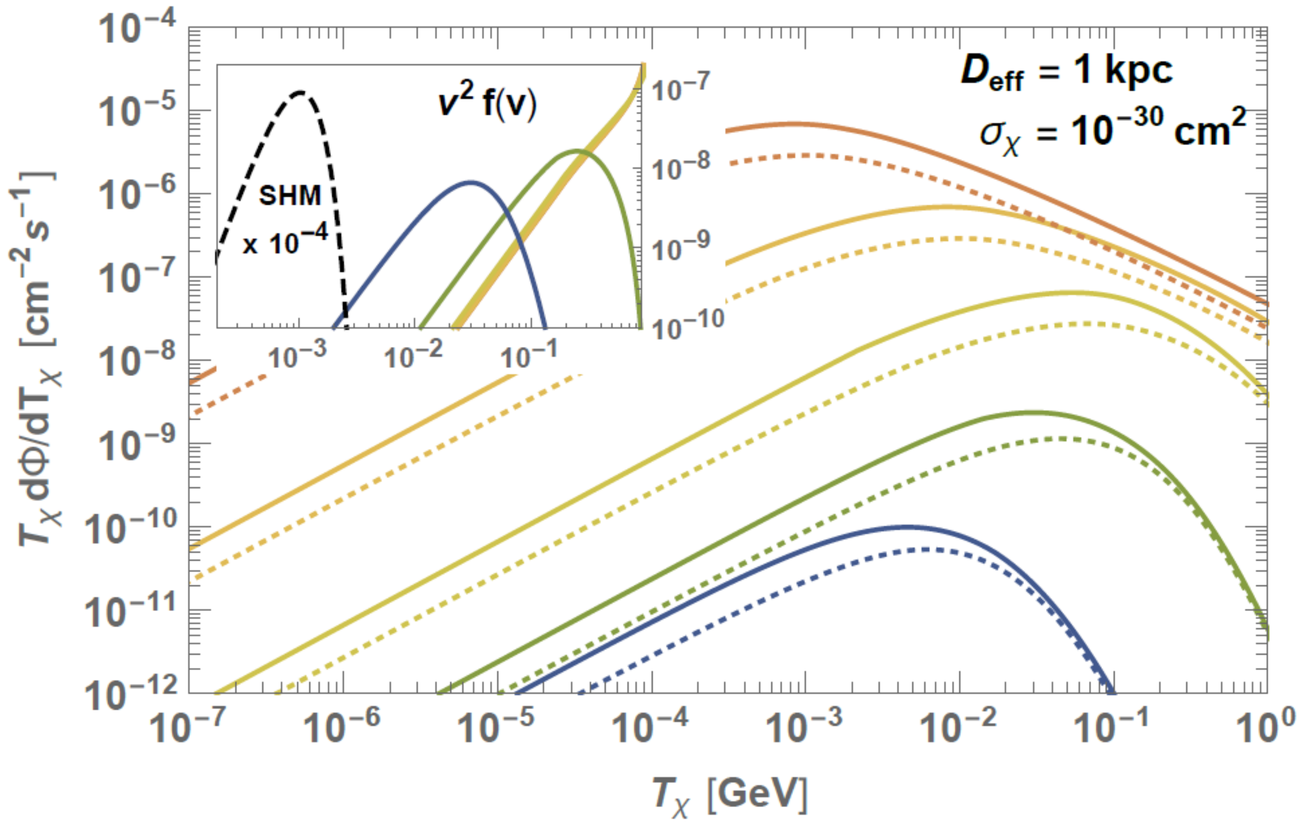


Idea - Bringmann and Pospelov 1810.07705

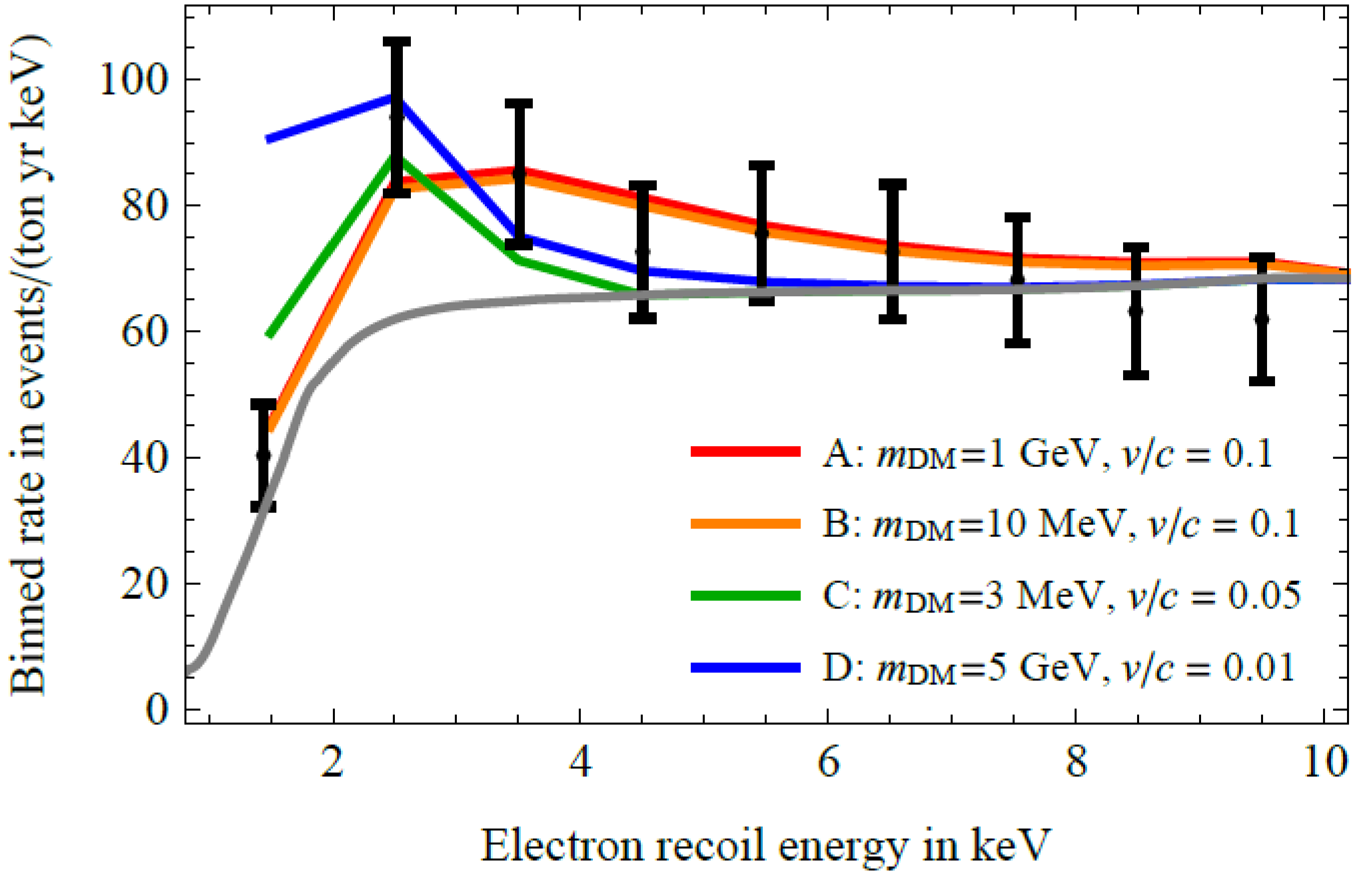


light dark matter particle now relativistic,
makes dark matter detector go “BONG”

Bringmann and Pospelov 1810.07705



Can in principle fit the Xenon 1T excess with boosted dark matter



Could be due to a clump of dark matter, a local overdensity passing through (although velocity would be a mystery)

Hannicke et al 2006.10764

Boosted Dark Matter, more detailed anaylsis

$$\chi + \chi \to \bar{\chi} + X.$$

X is standard model particle, DM has Z_3 symmetry.

$$\psi_A + \bar{\psi}_A \to \psi_B + \bar{\psi}_B$$

m_A is dominant component of dark matter with $m_A > m_B$

$$\begin{aligned}\Phi^{\rm BDM}_{\rm gal} &= 1.6 \times 10^{-6}\,{\rm cm}^{-2}{\rm s}^{-1} \\ &\times \left(\frac{\langle\sigma_{\rm ann} v\rangle}{5 \times 10^{-26}\,{\rm cm}^3{\rm s}^{-1}}\right)\left(\frac{10\,{\rm GeV}}{m_{\rm DM}}\right)^2\end{aligned}$$

$$\begin{aligned}\Phi^{\rm BDM}_{\rm Sun} &= \frac{C(m_{\rm DM}, \sigma_{\rm nucl})}{4\pi\,{\rm AU}^2} \\ &= 7.2 \times 10^{-6}\,{\rm cm}^{-2}{\rm s}^{-1}\left(\frac{\sigma_{\rm nucl}}{10^{-42}\,{\rm cm}^2}\right)\left(\frac{10\,{\rm GeV}}{m_{\rm DM}}\right)^2\end{aligned}$$

$$\sigma_{\rm elec} = 3 \times 10^{-29}\,{\rm cm}^2\left(\frac{10^{-6}\,{\rm cm}^{-2}{\rm s}^{-1}}{\Phi^{\rm BDM}}\right)\left(\frac{N_{\rm sig}}{100}\right)$$

So we need roughly 10^{-28} or 10^{-29} cm^2 cross section

Fornal et al 2006.11264

Inside the core of the sun, the mean free path

$$L_{fs,S} \simeq 1\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right)$$

While inside the Earth,

$$L_{fs,E} \simeq 60\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right)$$

Fornal et al 2006.11264

Gran Sasso mountain ~ 1600 metres deep

Inside the core of the sun, the mean free path

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While inside the Earth,

$$L_{fs,E} \simeq 60\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right)$$

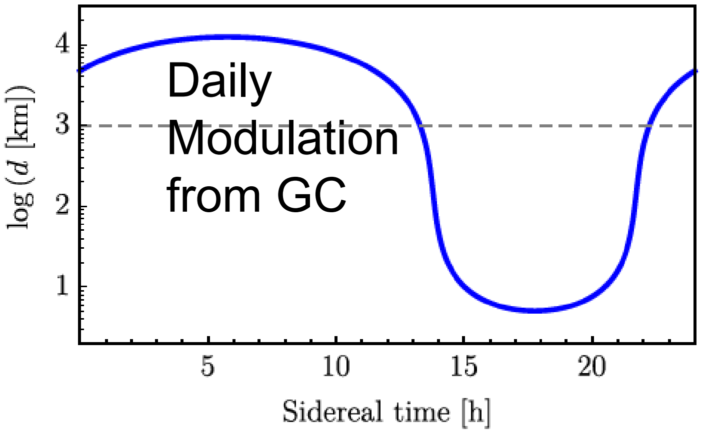
If the dark matter loses ~10 keV energies each interaction, it must have high mass to make it to the detector, and there will be a daily effect as the source of boosted moves relative to “up” at Gran Sasso.

$$d_e \gtrsim 1000\ \mathrm{km}\left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right)\left(\frac{m_{\mathrm{BDM}}}{10\ \mathrm{GeV}}\right)\left(\frac{v_{\mathrm{BDM}}}{0.1\ c}\right)^2$$

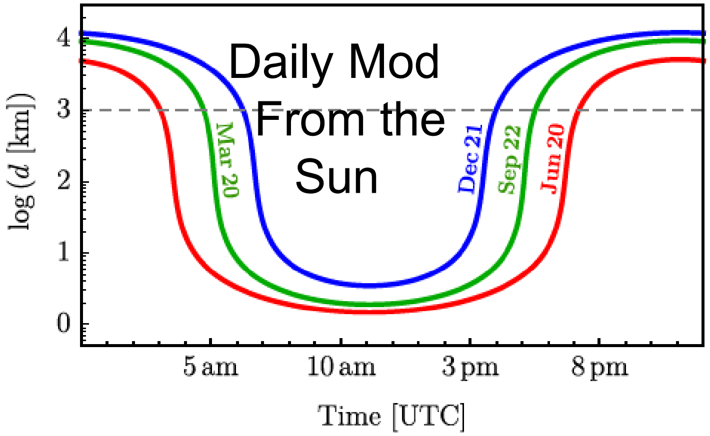
Fornal et al 2006.11264

$$\sigma_{\text{elec}} = \frac{g_{\text{BDM}}^2 g_e^2 m_e^2}{\pi\, m_{\text{med}}^4}$$

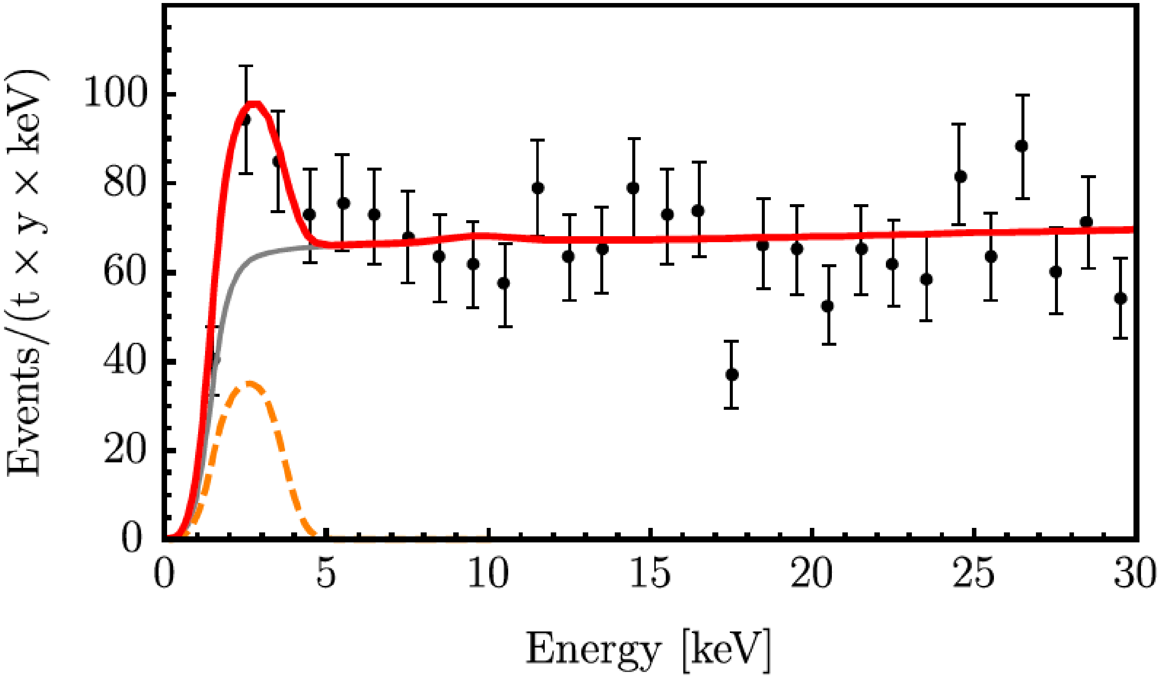
As a benchmark, consider $g_{\text{BDM}} = 1.1$, $g_e = 10^{-5}$, $m_{\text{BDM}} = 10$ GeV, and $m_{\text{med}} = 0.1$ MeV, which results in $\sigma_{\text{elec}} = 4 \times 10^{-29}\,\text{cm}^2$.



Daily Modulation from GC



Daily Mod From the Sun

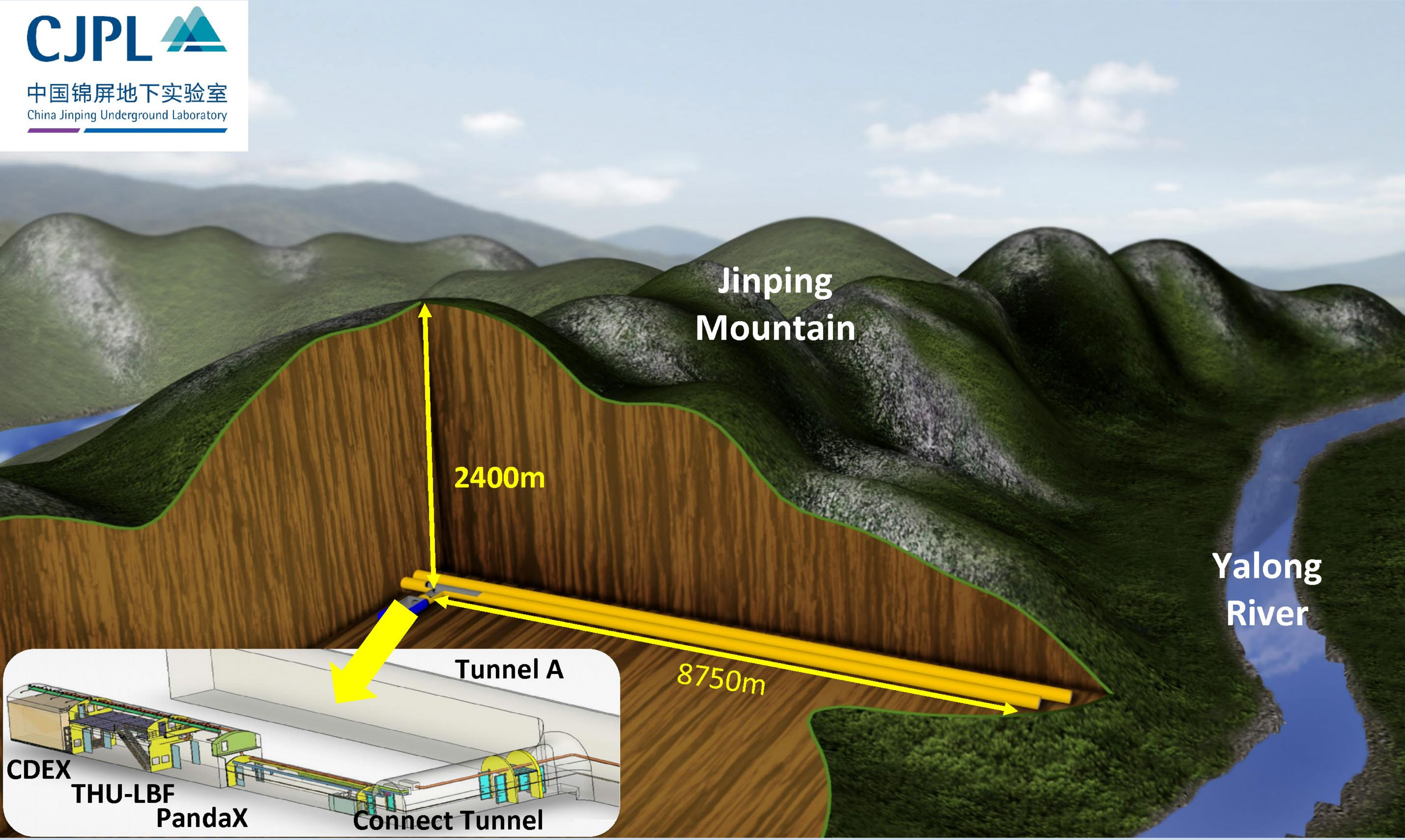


$$d_e \gtrsim 1000\ \text{km} \left(\frac{10^{-28}\,\text{cm}^2}{\sigma_{\text{elec}}}\right)\left(\frac{m_{\text{BDM}}}{10\ \text{GeV}}\right)\left(\frac{v_{\text{BDM}}}{0.1\ c}\right)^2$$

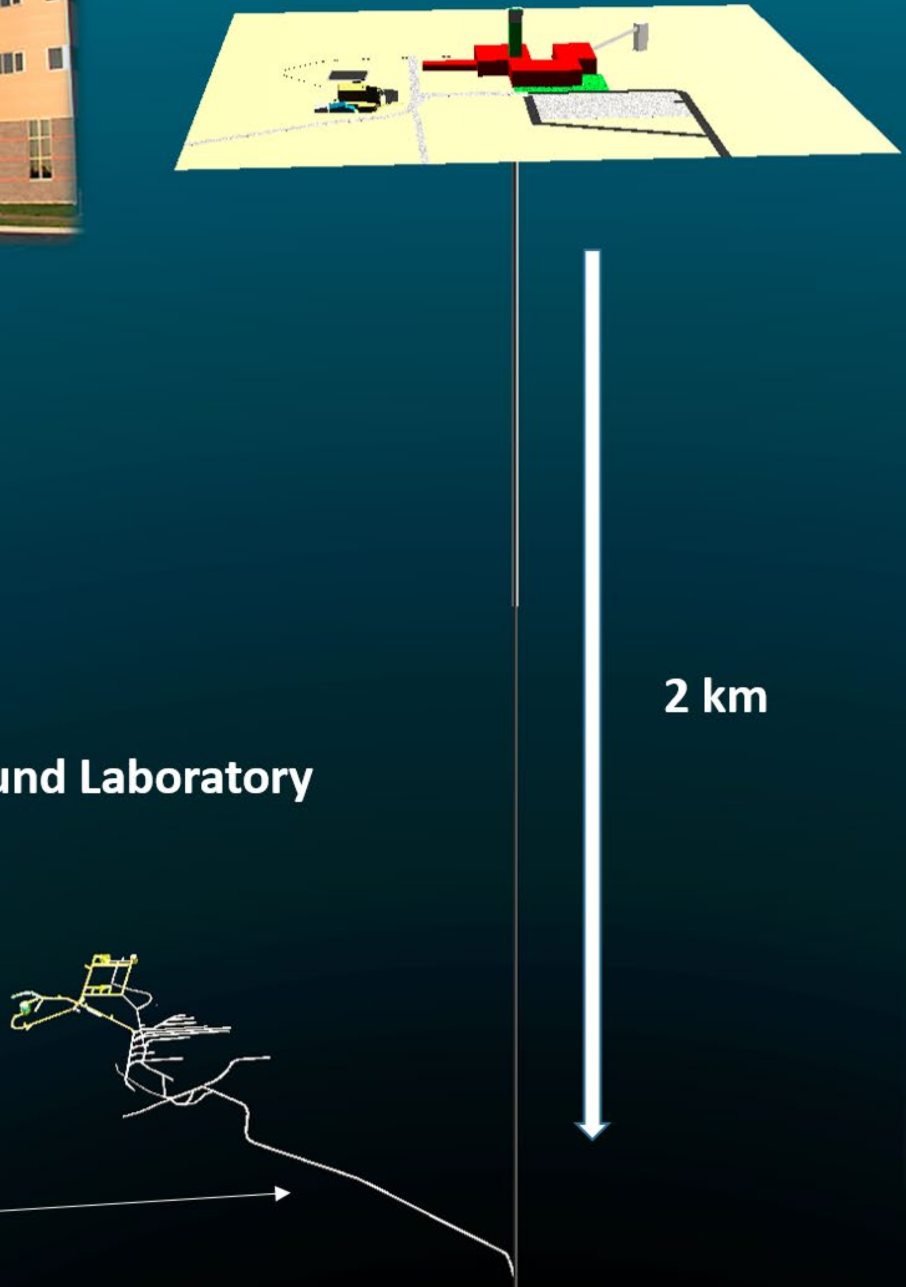
Fornal et al 2006.11264

Jinping Laboratory

CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory



Surface facilities at Creighton Mine



2 km

SNOLAB – Underground Laboratory

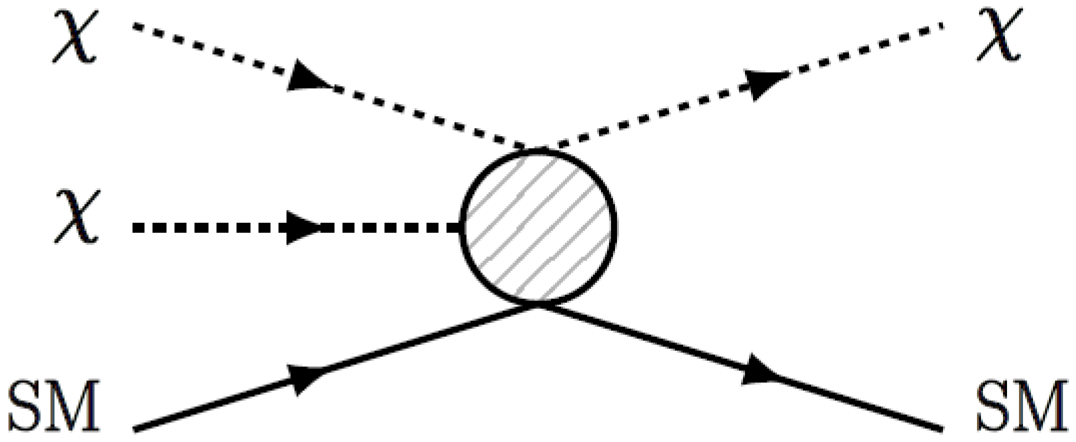
Tunnel

Photo by Randy Risling

Co-SIMP mechanism

$$\chi + \chi + \chi \rightarrow \chi + \chi$$

This works OK and can give good relic abundance for MeV scale DM, but typically the free-streaming length is too large.



This process keeps the dark matter in equilibrium with the SM particles, prevents velocity growing too high.

$$\chi + \chi \rightarrow \chi + \mathrm{SM} + \mathrm{SM}$$

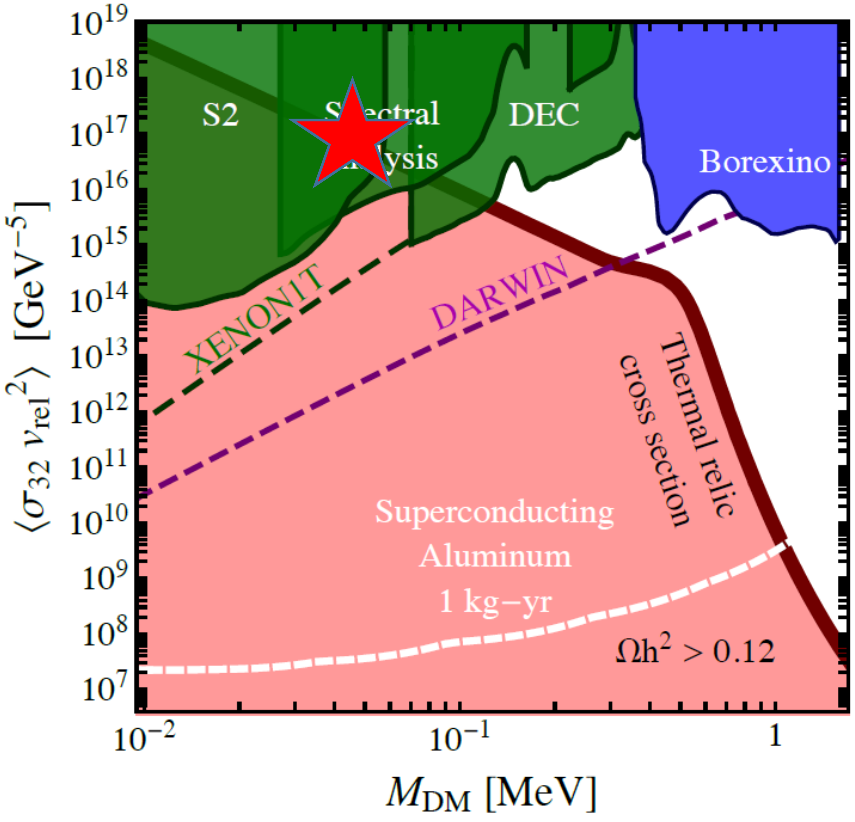
Is avoided by setting $M_{DM} < 2M_{SM}$

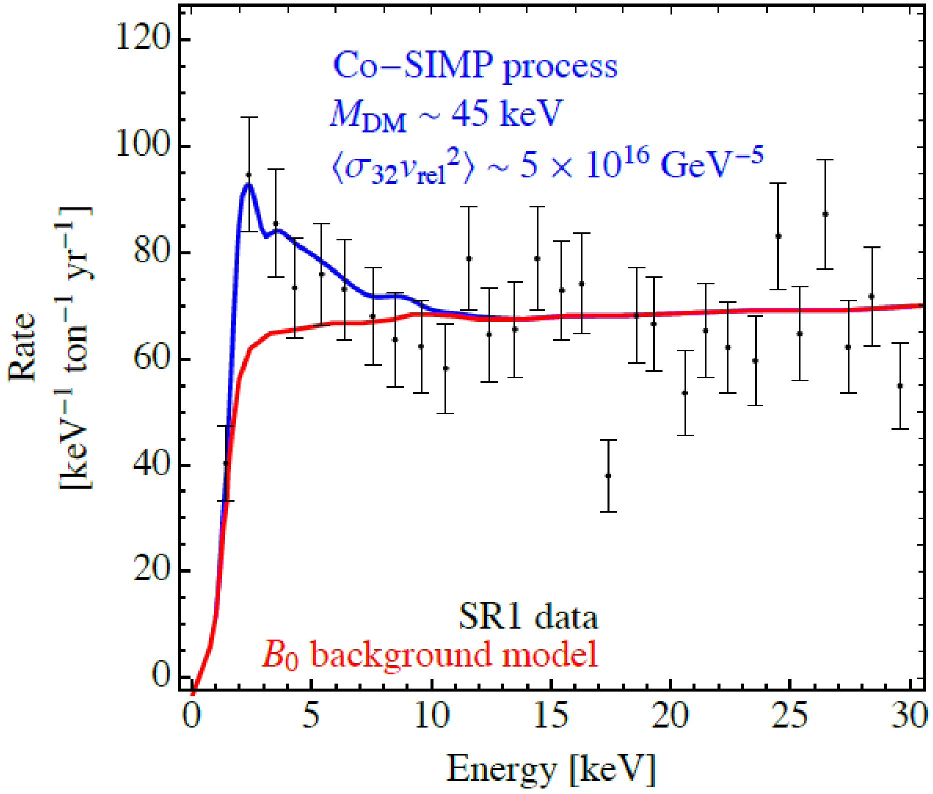
Beacom and Smirnov 2002.04038

$$\chi + \chi + \mathrm{SM} \rightarrow \chi + \mathrm{SM}$$

Is actually non negligible in detectors, thanks to large number of particles and high cross sections.

Turns out they predicted the correct mass-coupling relation for the electron recoil excess (so they're happy, good luck to them…)





Beacom and Smirnov 2002.04038

There are a variety of ways to explain the excess, all of which will be probed in the coming years by the next generation of experiments

New Scientist

WEEKLY 21 October 2017

SPECIAL REPORT

GRAVITATIONAL WAVES

All the fallout from the neutron star smash-up

SWIPE LEFT! How online dating is making society more liberal

SOMETHING STRANGE IS GOING ON INSIDE THE SUN

No3148 £4.10 US/CAN$6.99

PLUS LONG-LOST SPECIES / **CANCER AND NERVES** / SEX ADDICTION / **MOON VS MARS** / **FEMALE ORGASM** / EPIGENETIC EVOLUTION / **SOVIET SCIENCE** / MATHS BEATS THE BOOKIES

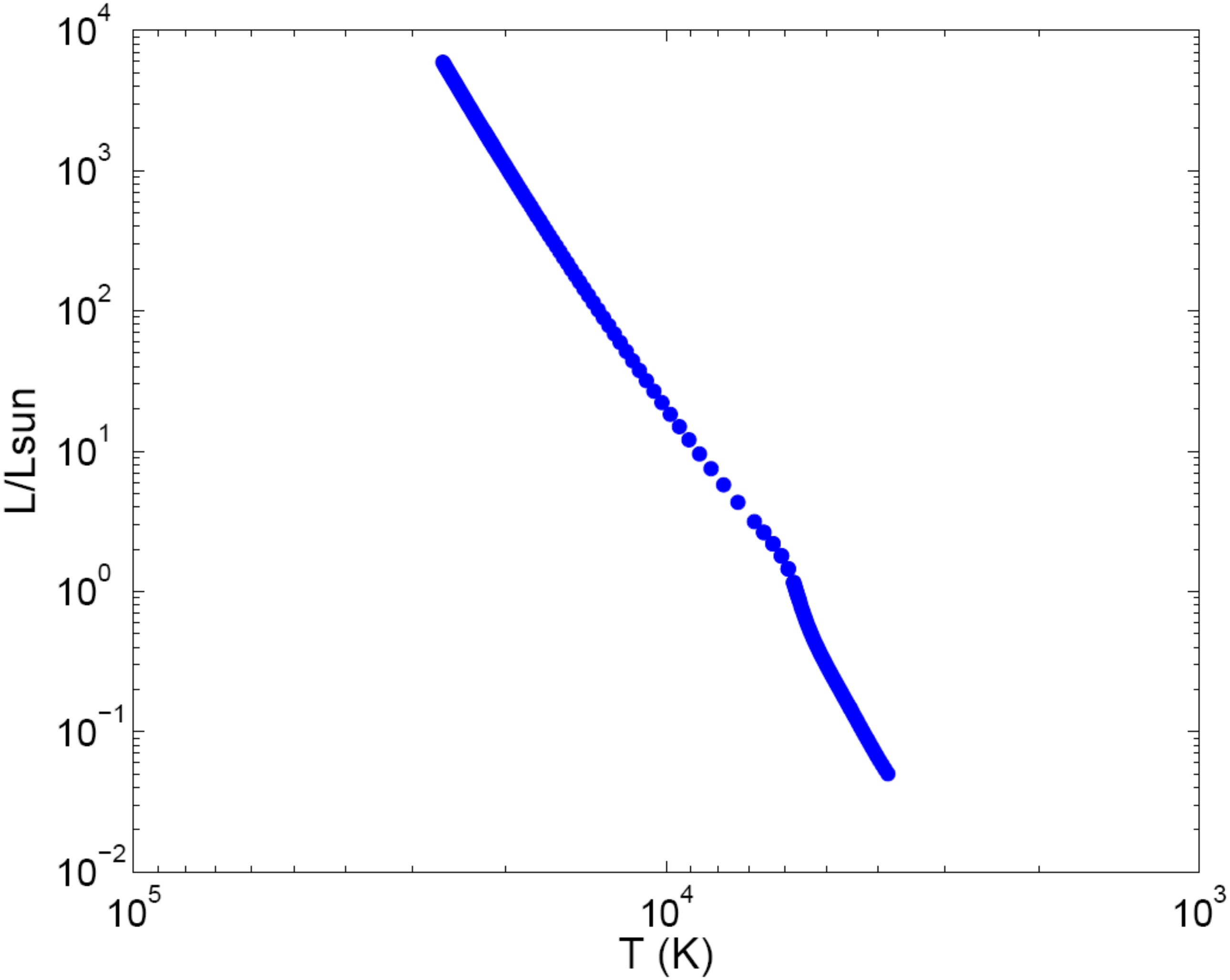
Equations of stellar structure have solutions which are stars

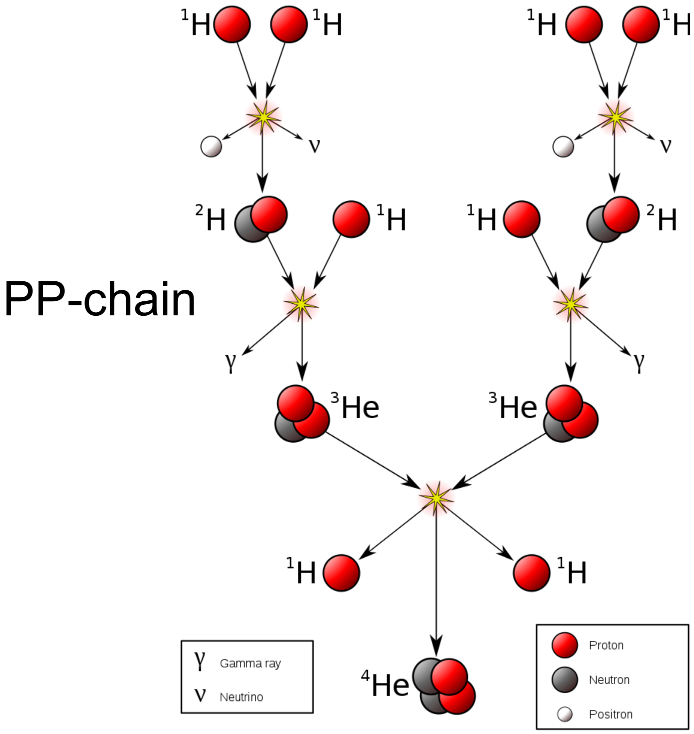
$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

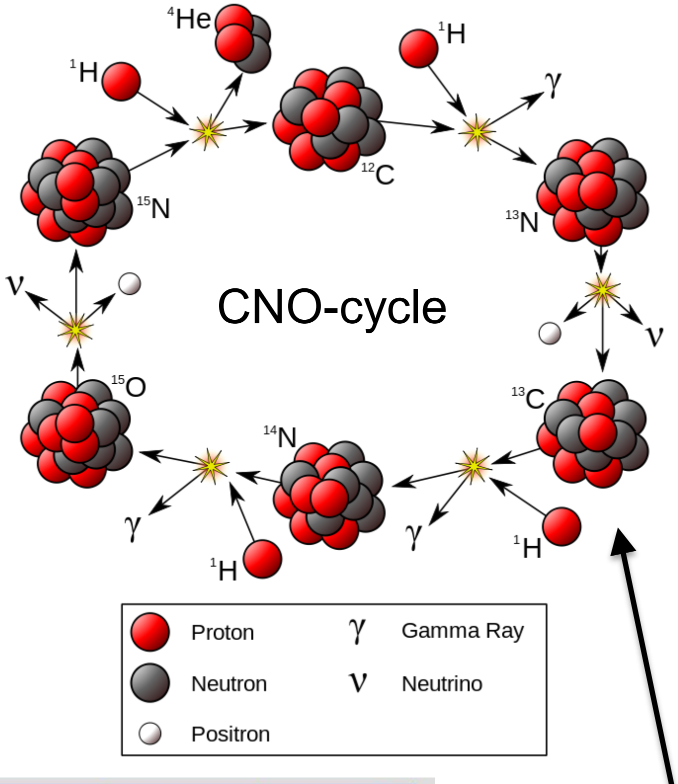
$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

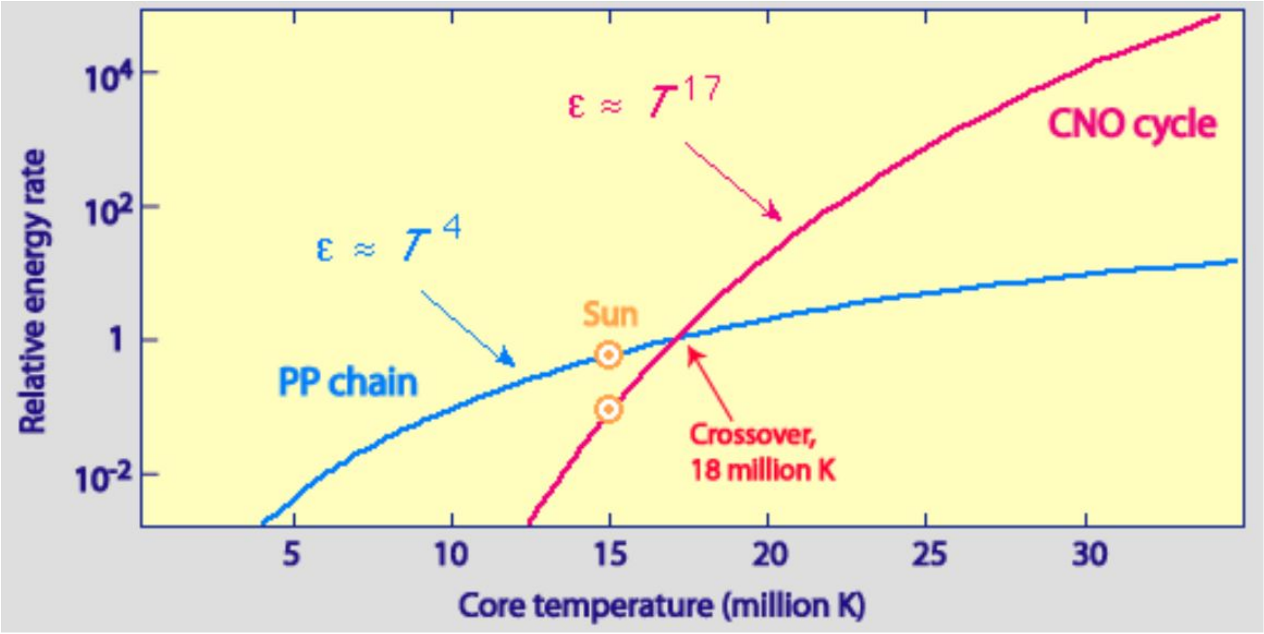
$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$





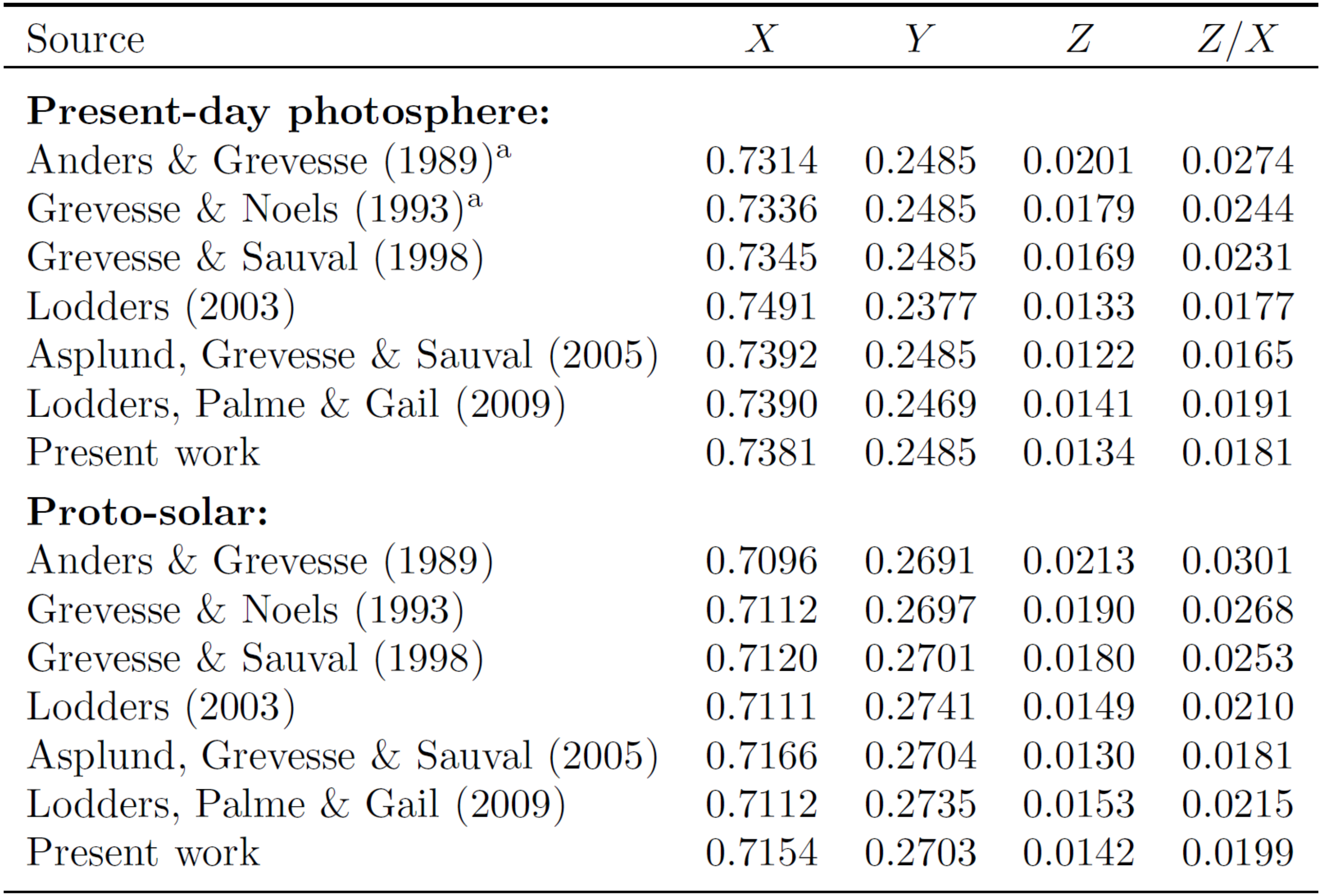




DEPENDS ON
METALLICITY
Z

Solar Spectral Abundance

This is taken from Asplund, Grevesse, Sauval and Scott 2009



Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

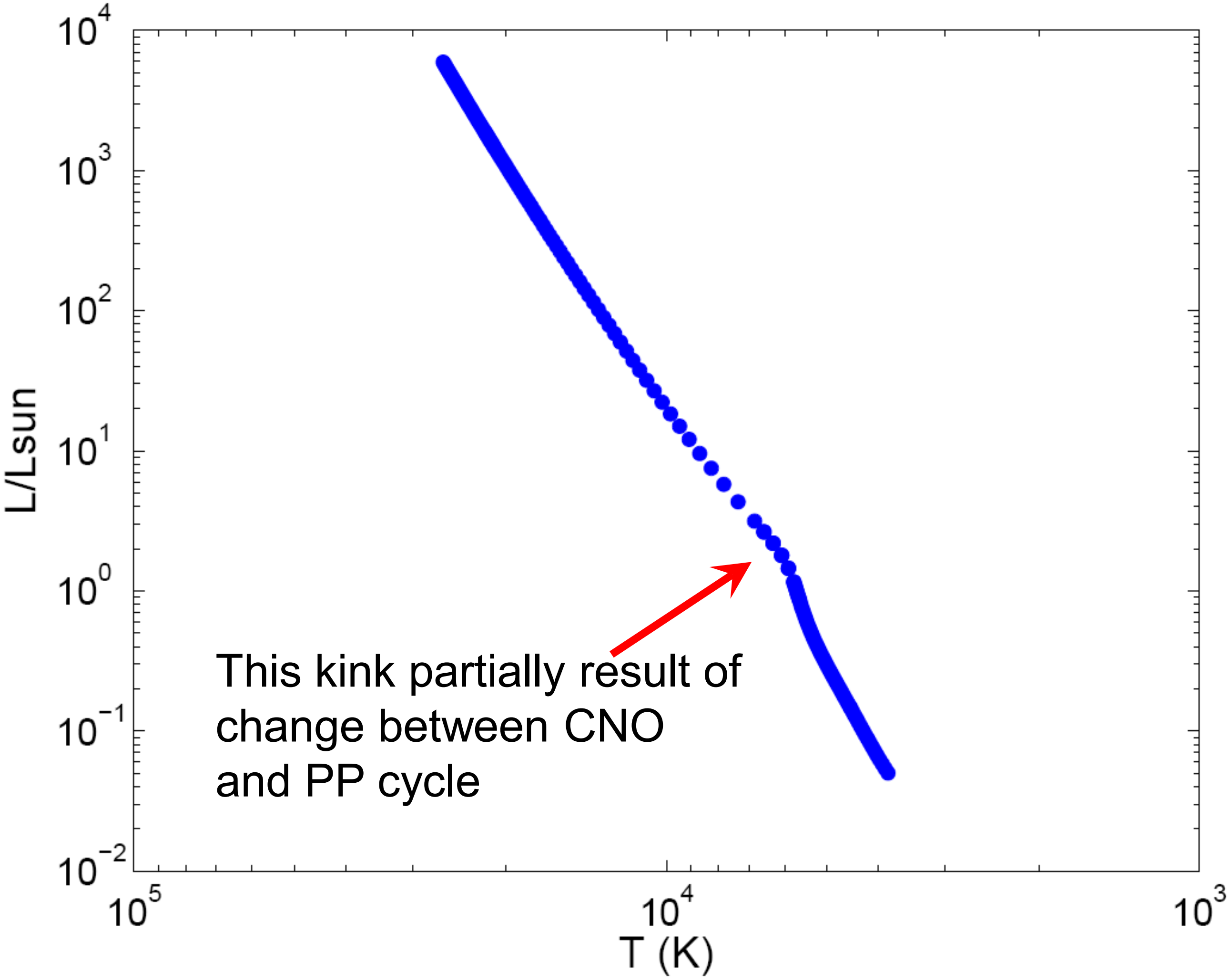
Equations of Stellar Structure have Solutions which are Stars

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

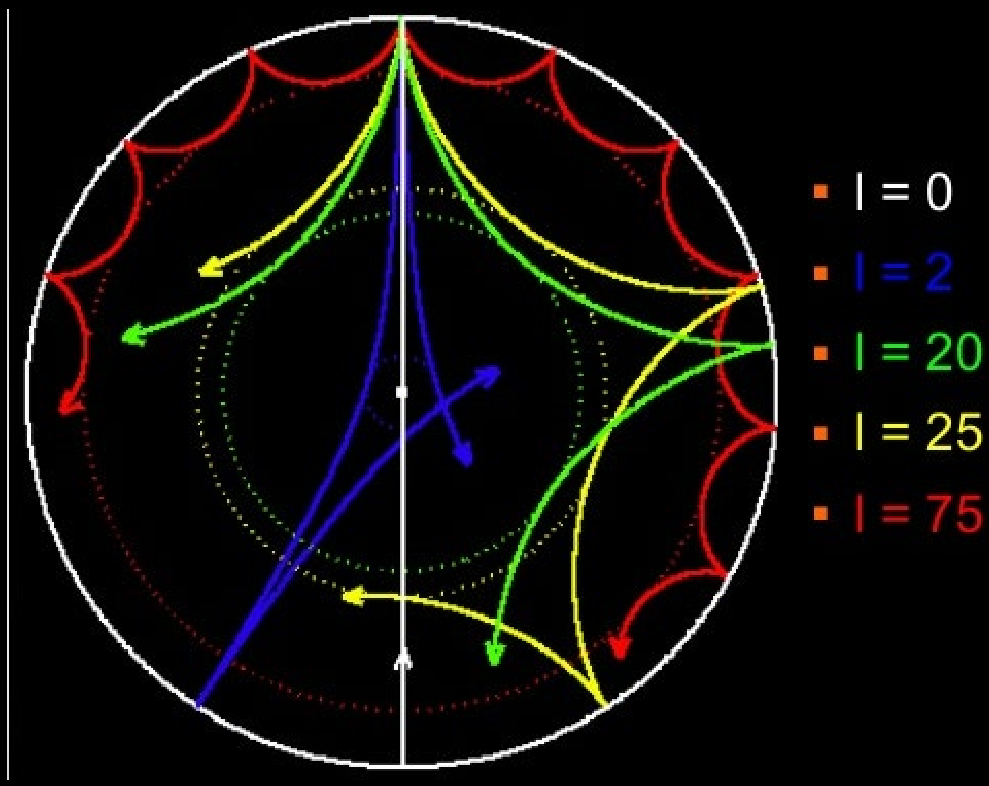
$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

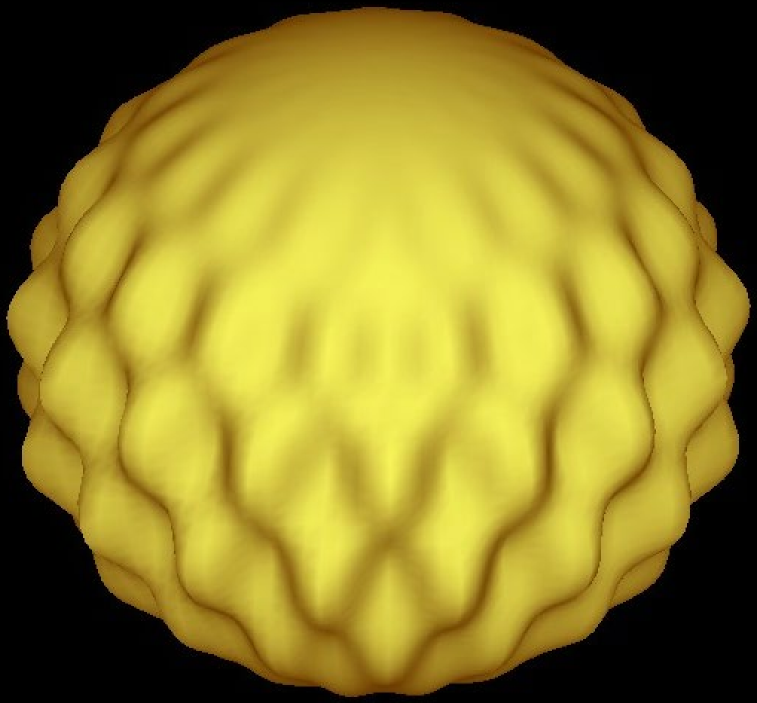
$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$



This kink partially result of change between CNO and PP cycle

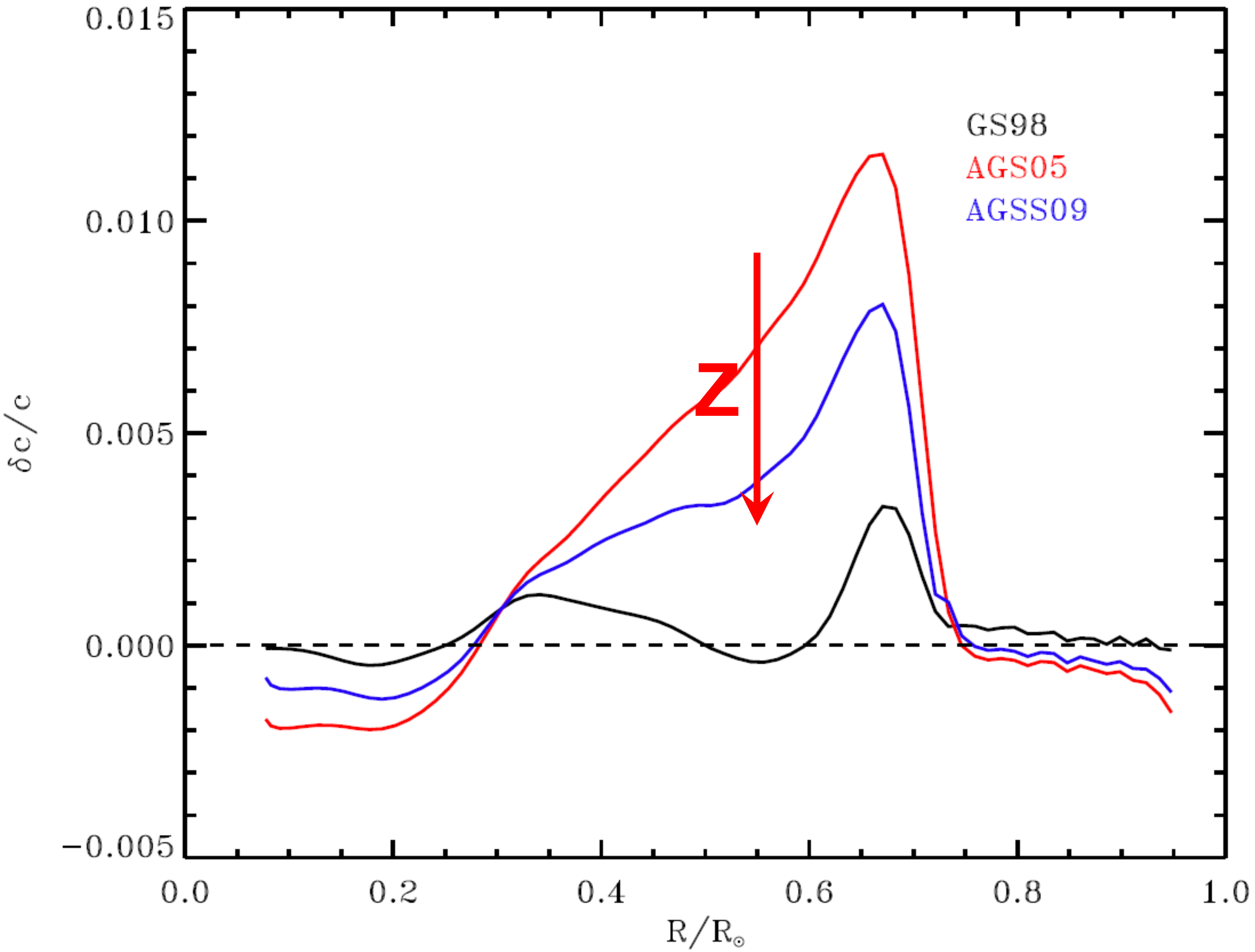
Helioseismology – vibrational modes of the Sun





By its very nature it samples the speed of sound in the Sun at different depths

Observed abundances are not consistent with Solar Models which match Helioseismology constraints on speed of sound.



As we make conclusions about DM and DE using stars should worry about this.

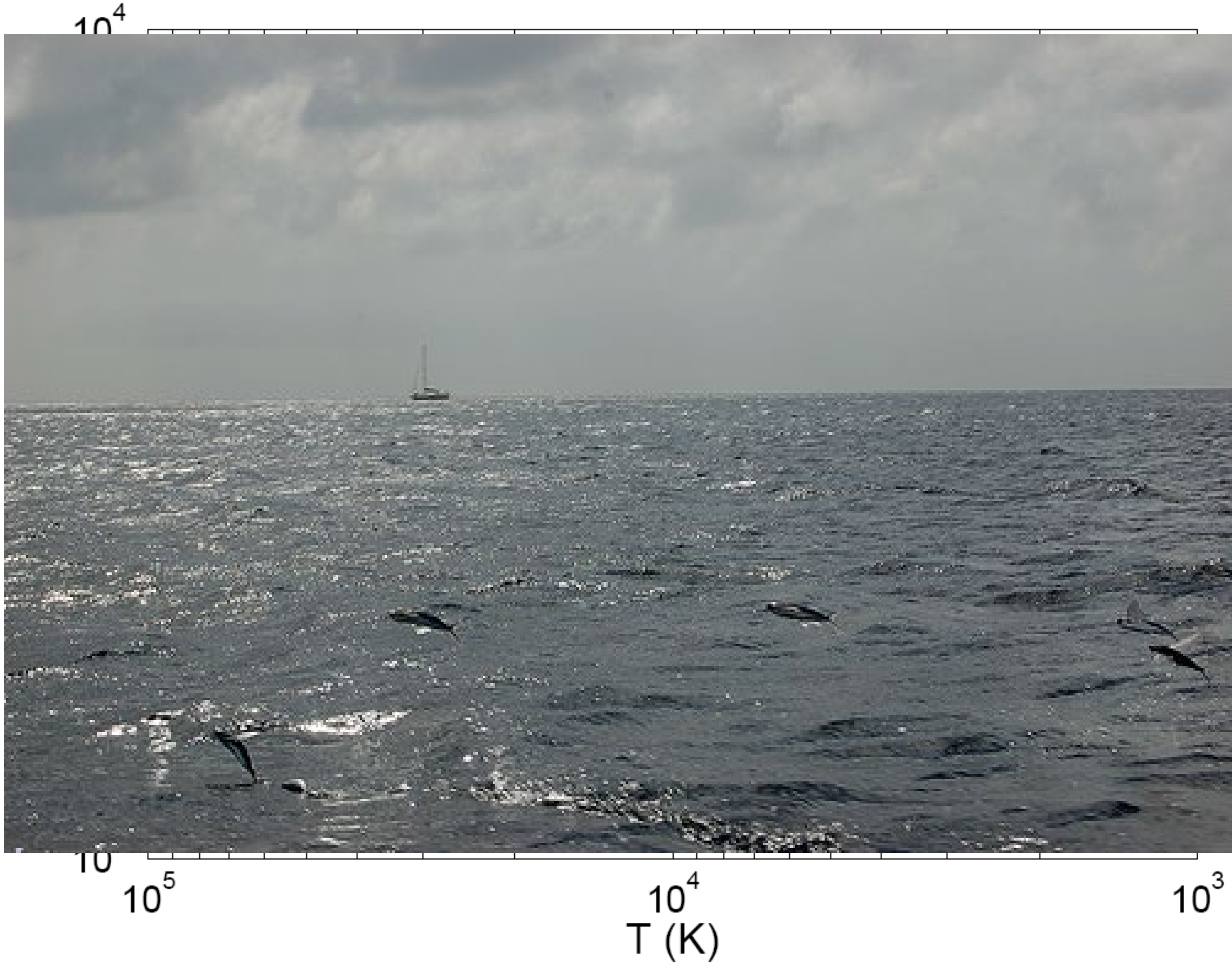
Equations of stellar structure have solutions which are stars

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

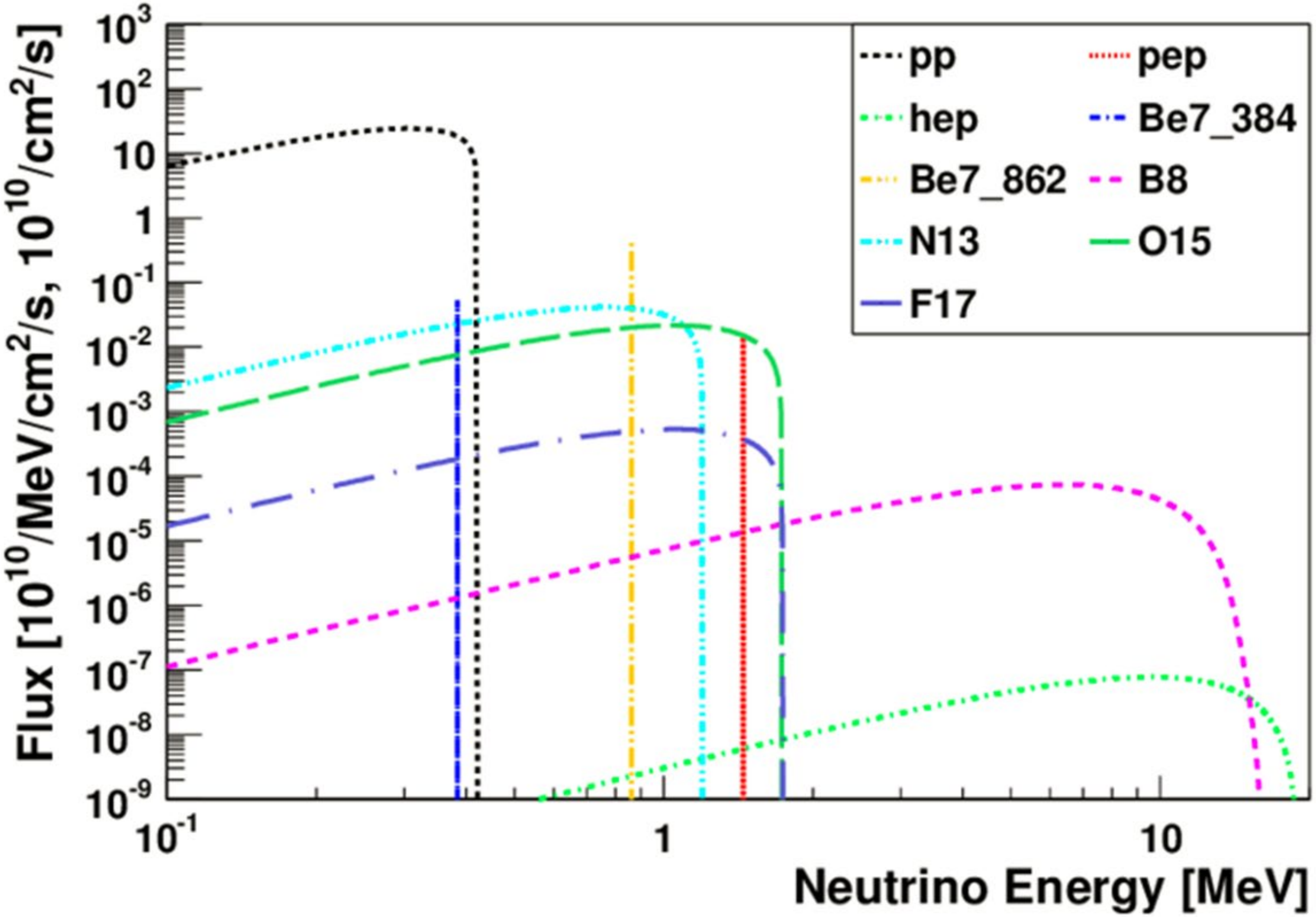
$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$



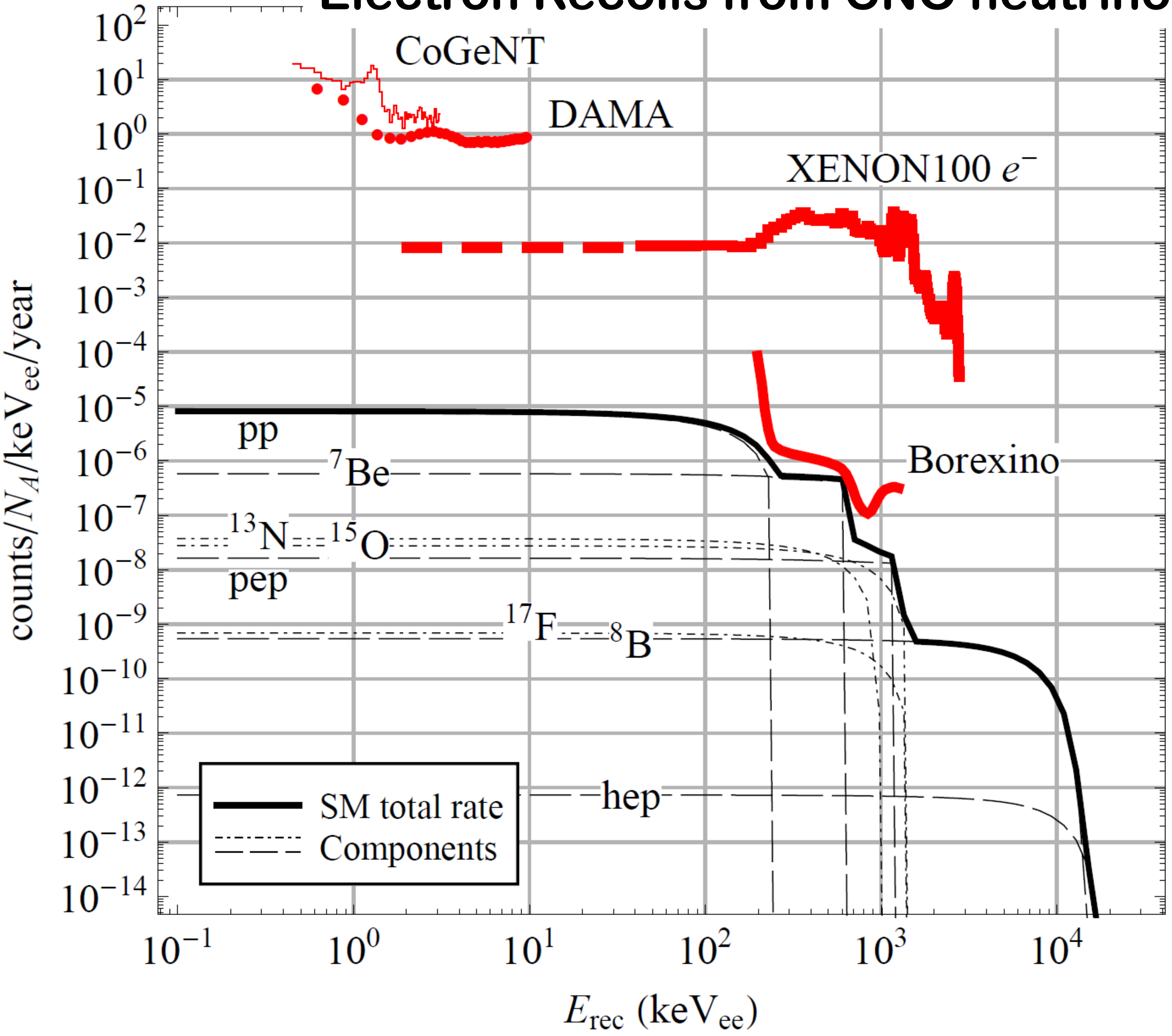
Scattering of dark matter can reduce opacity

Solar Metallicity	**CNO Neutrino Flux [$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$]**		
	^{13}N [10^8]	^{15}O [10^8]	^{17}F [10^6]
High	2.78 ± 0.42	2.05 ± 0.35	5.92 ± 1.06
Low	2.04 ± 0.29	1.44 ± 0.23	3.26 ± 0.59

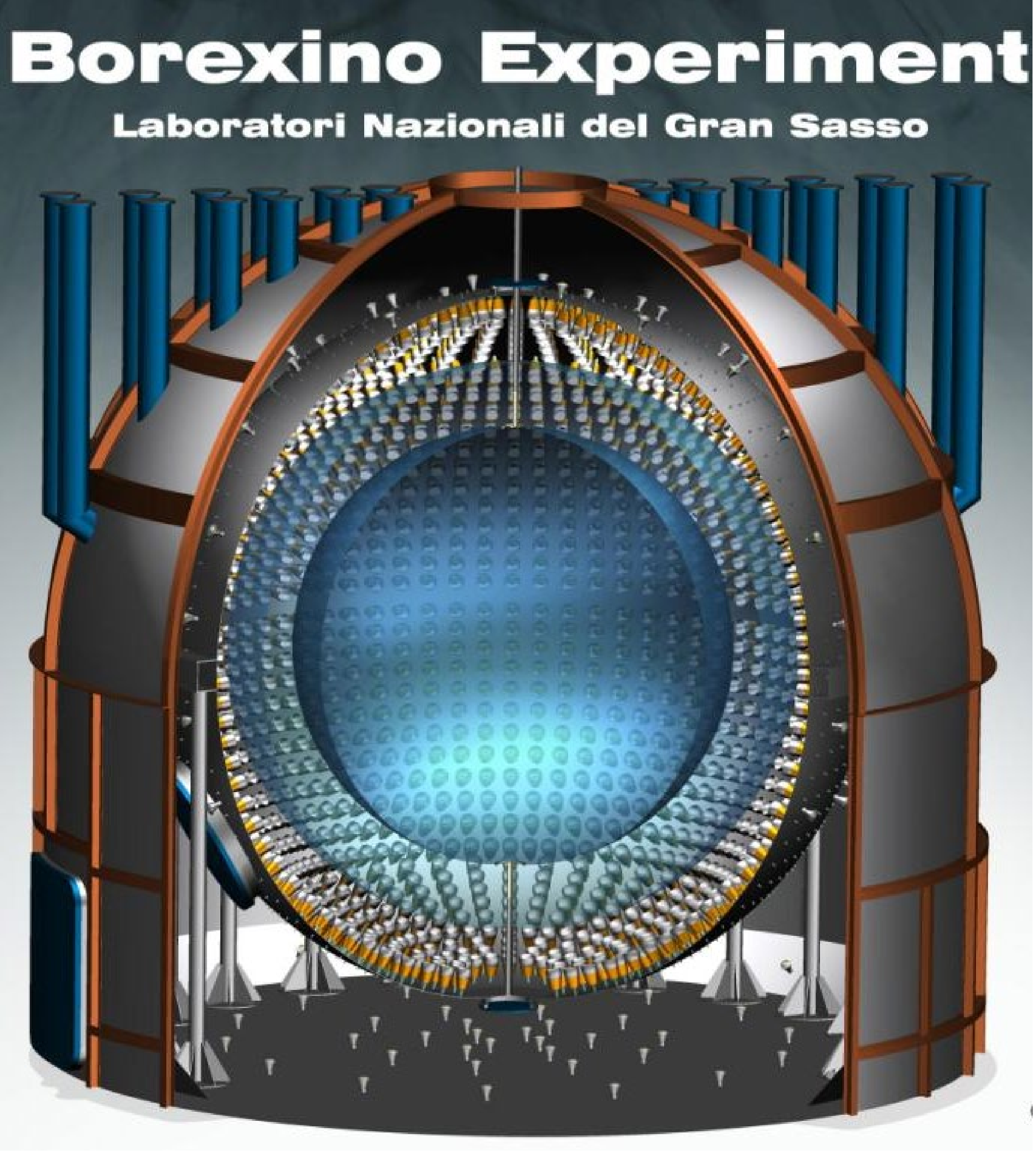
One way to get a better hold on this is by measuring CNO neutrinos



Electron Recoils from CNO neutrinos



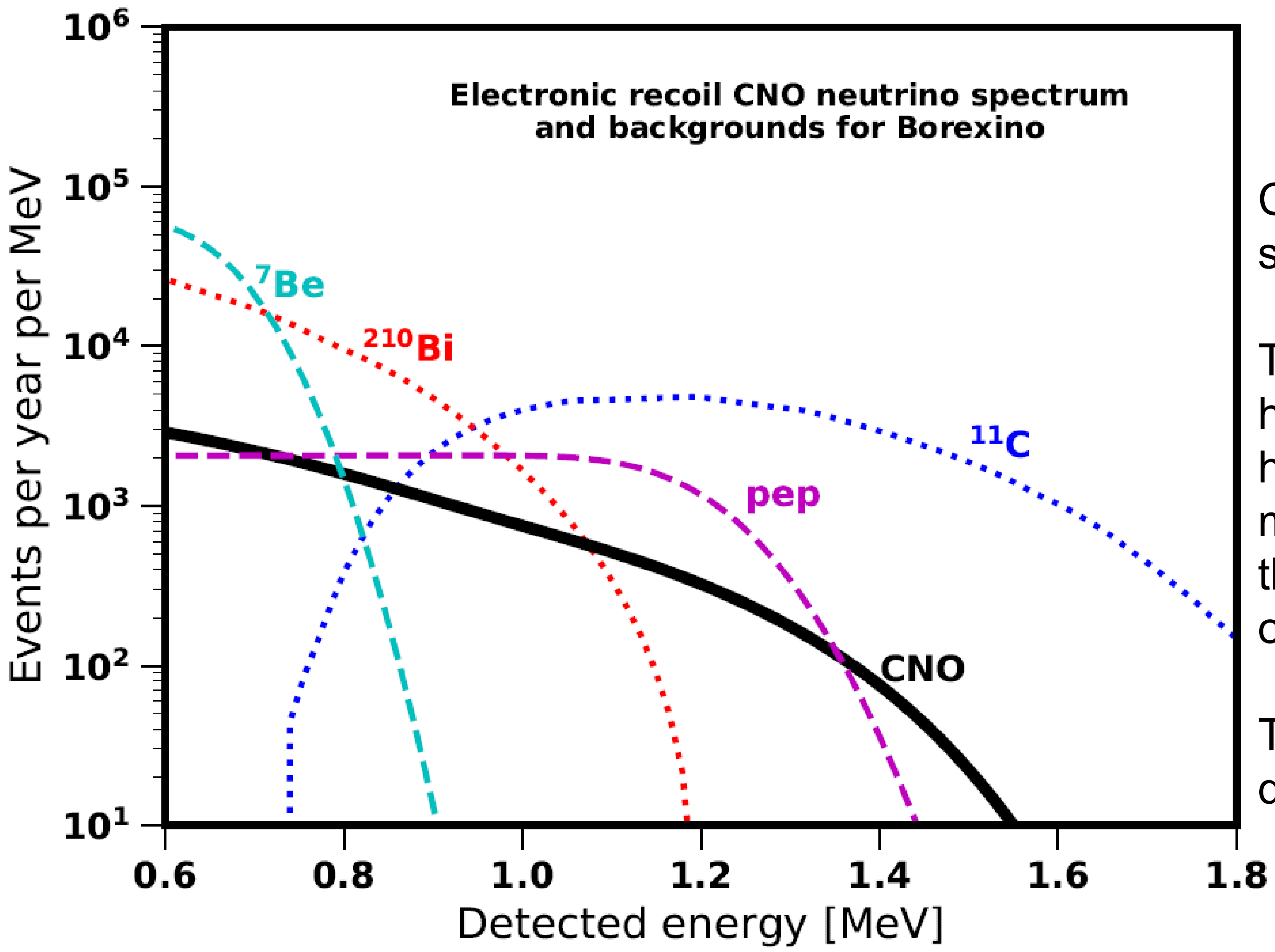
Harnik,
Kopp
& Machado
2009



Liquid scintillator with 71 tons fiducial mass located in Gran Sasso Laboratory.

The liquid is a doped aromatic hydrocarbon.

Borexino CNO recoil spectrum and relevant backgrounds



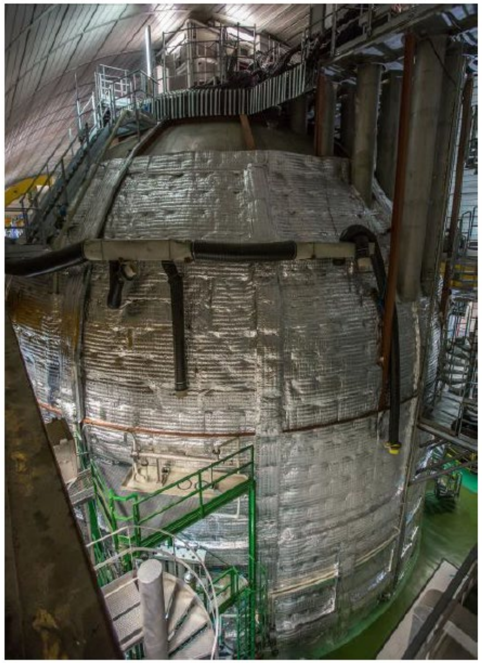
CNO flux is rather similar to ^{210}Bi flux

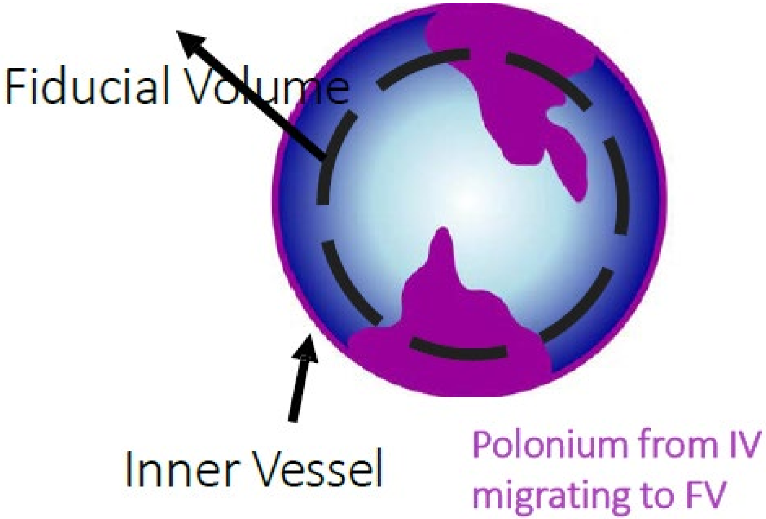
This is a problem, however Borexino hope to be able to measure ^{210}Bi flux through observation of daughter nuclei.

They may be able to do this at 10% level.

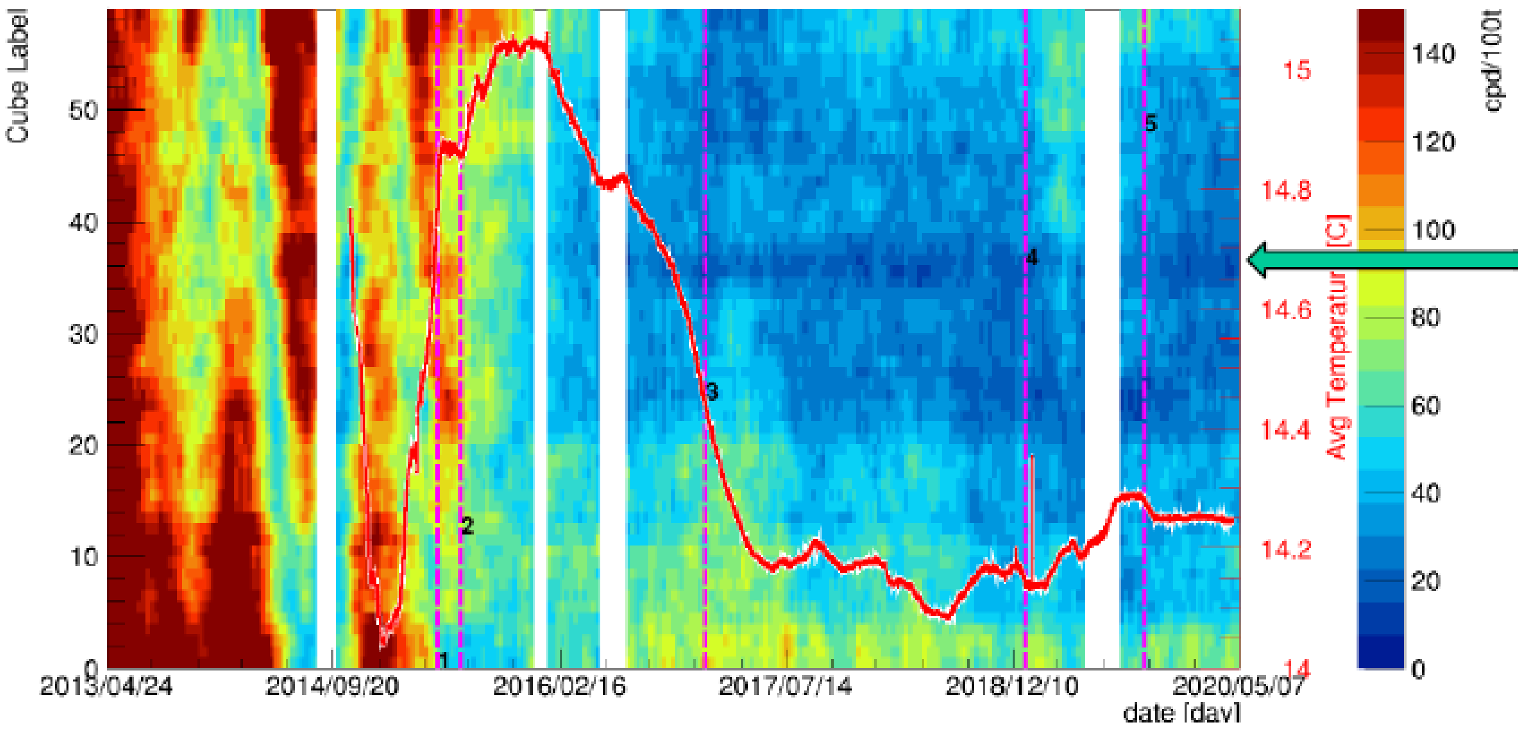
Borexino update 23rd June 2020

Thermal insulation & Active Gradient Stabilization System





A 2D detailed view - Polonium data spatial mapping vs. time



Crucial observation: "Low Polonium Field" 20 tons size from which we can infer the intrinsic ^{210}Po and hence the ^{210}Bi - **agreement with simulations see next slide**

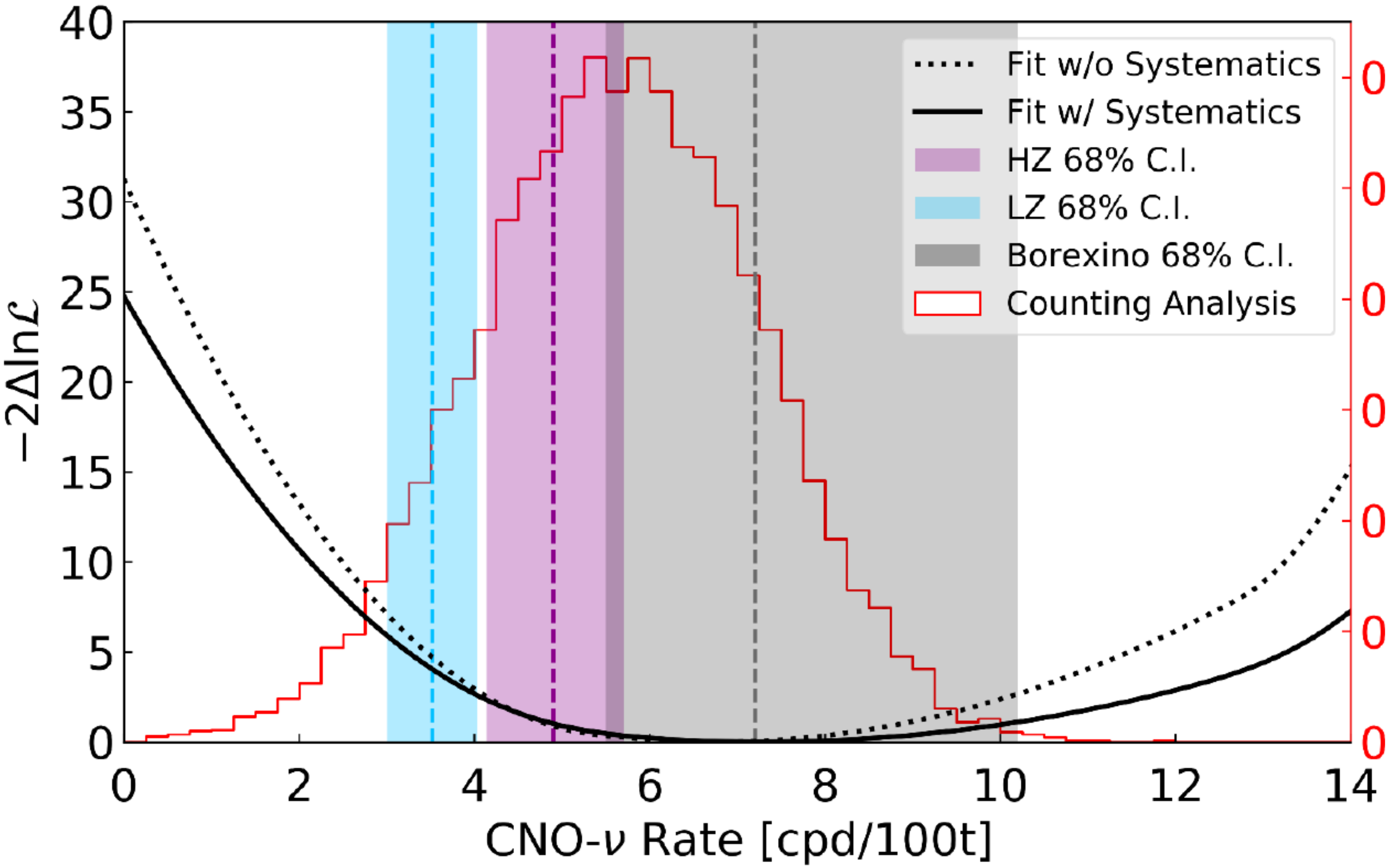
Convective condition before insulation

Quiet situation after insulation

1. Beginning of the Insulation Program
2. Turning off the water recirculation system in the Water Tank
3. Start of the active temperature control system operations
4. Change of the active control set points
5. Installation and commissioning of the Hall C temperature control system.

Stabilization measures were very effective at reducing the ^{210}Po motion

Borexino results, released 23rd June 2020

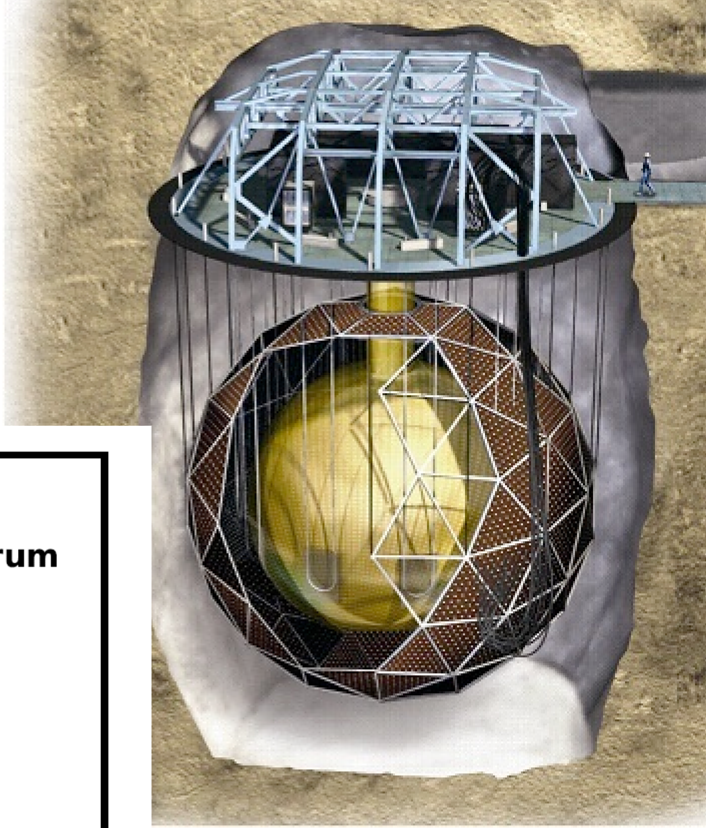


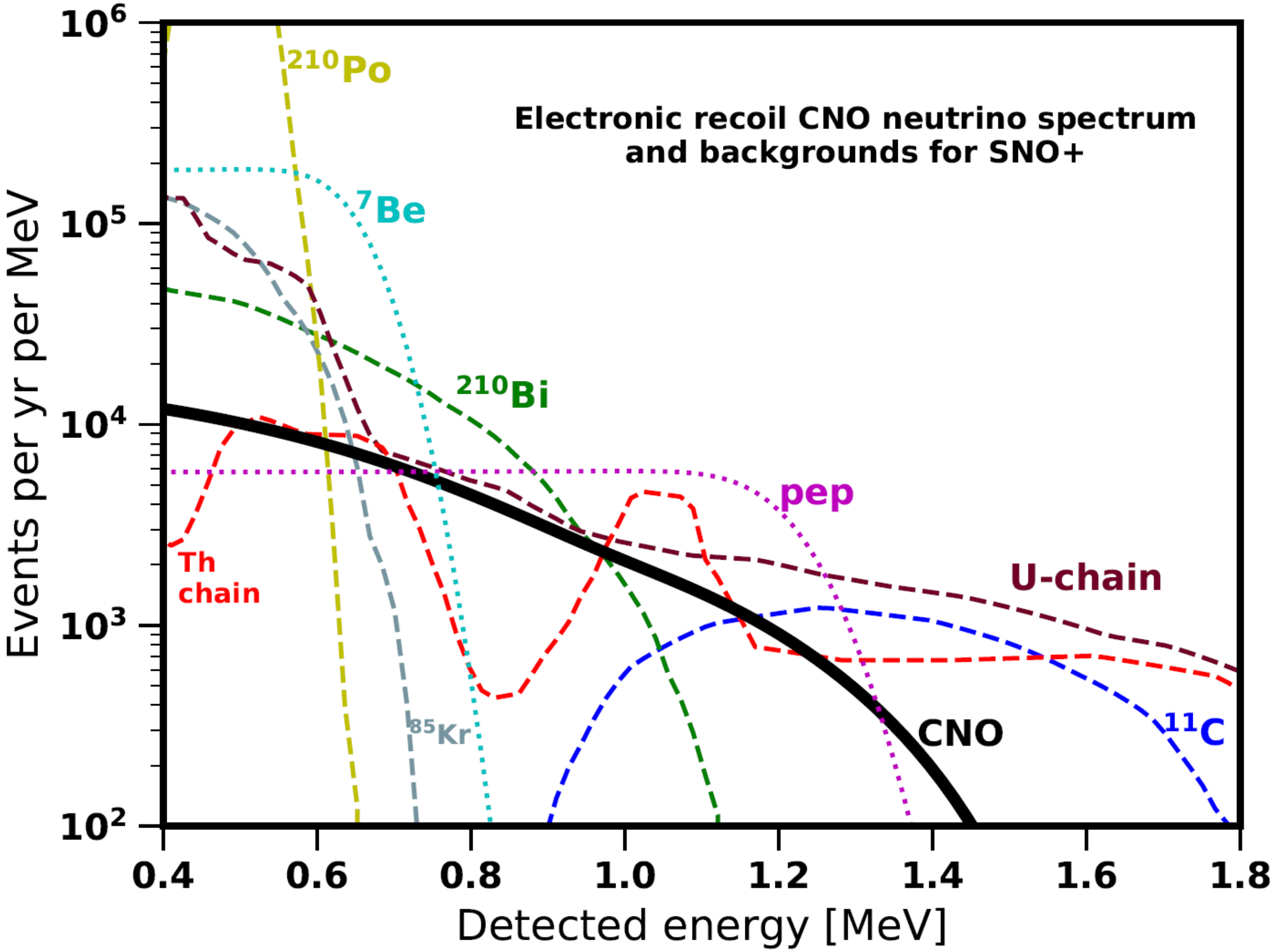
Has detected CNO neutrinos at 5σ

but cannot distinguish between high and low metallicity…

SNO+

Also has backgrounds but more importantly it is Starting it's run with ^{130}Te for $0\nu\beta\beta$





As it stands, SNO+ MAY detect CNO at low significance IF it decides to run without ^{130}Te for several years and they understand their backgrounds as well as they hope to.

However, they probably won’t be able to discriminate between low and high metallicities.

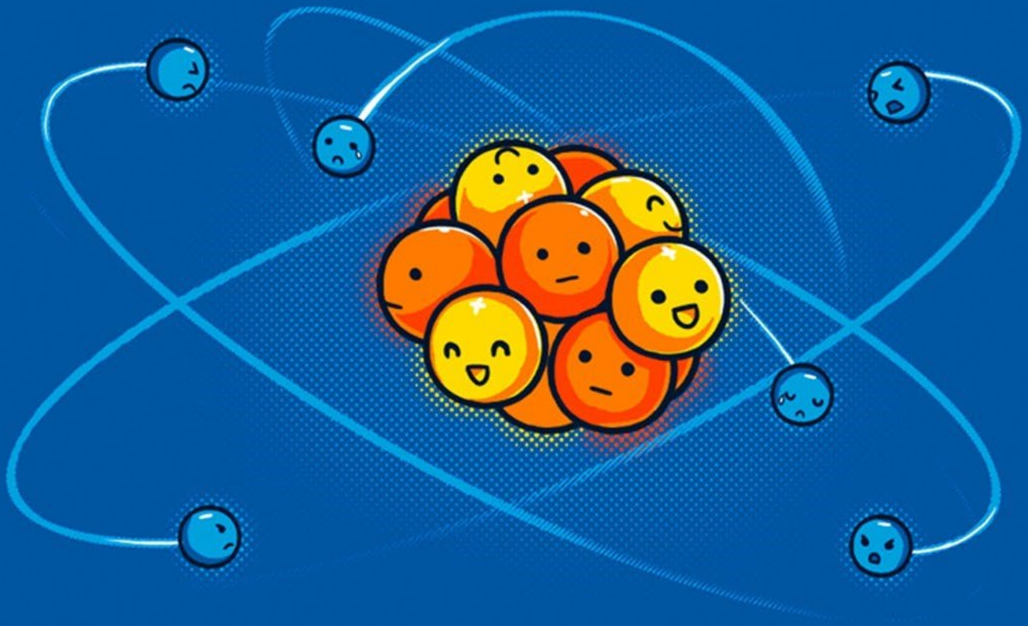
What about Dark Matter detectors?

CNO neutrinos give rise to

MeV electron recoils (above pp)
&
keV nuclear recoils (below 8B)

Lets start with electron recoils.

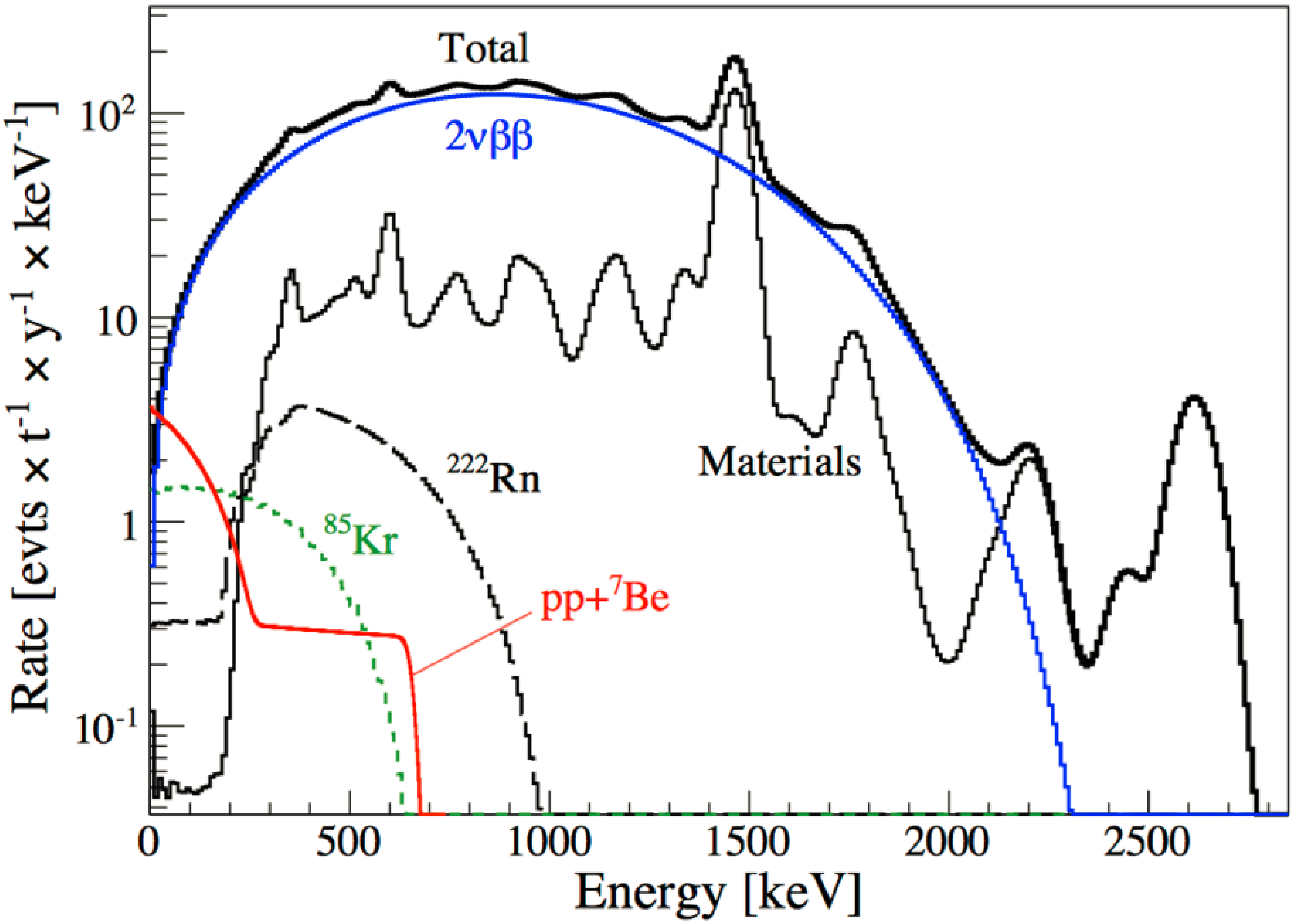
start with electron recoils



FUTURE ***XENON*** EXPERIMENTS (e.g. Darwin)

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

Electron recoils are in a region with a lot of background…

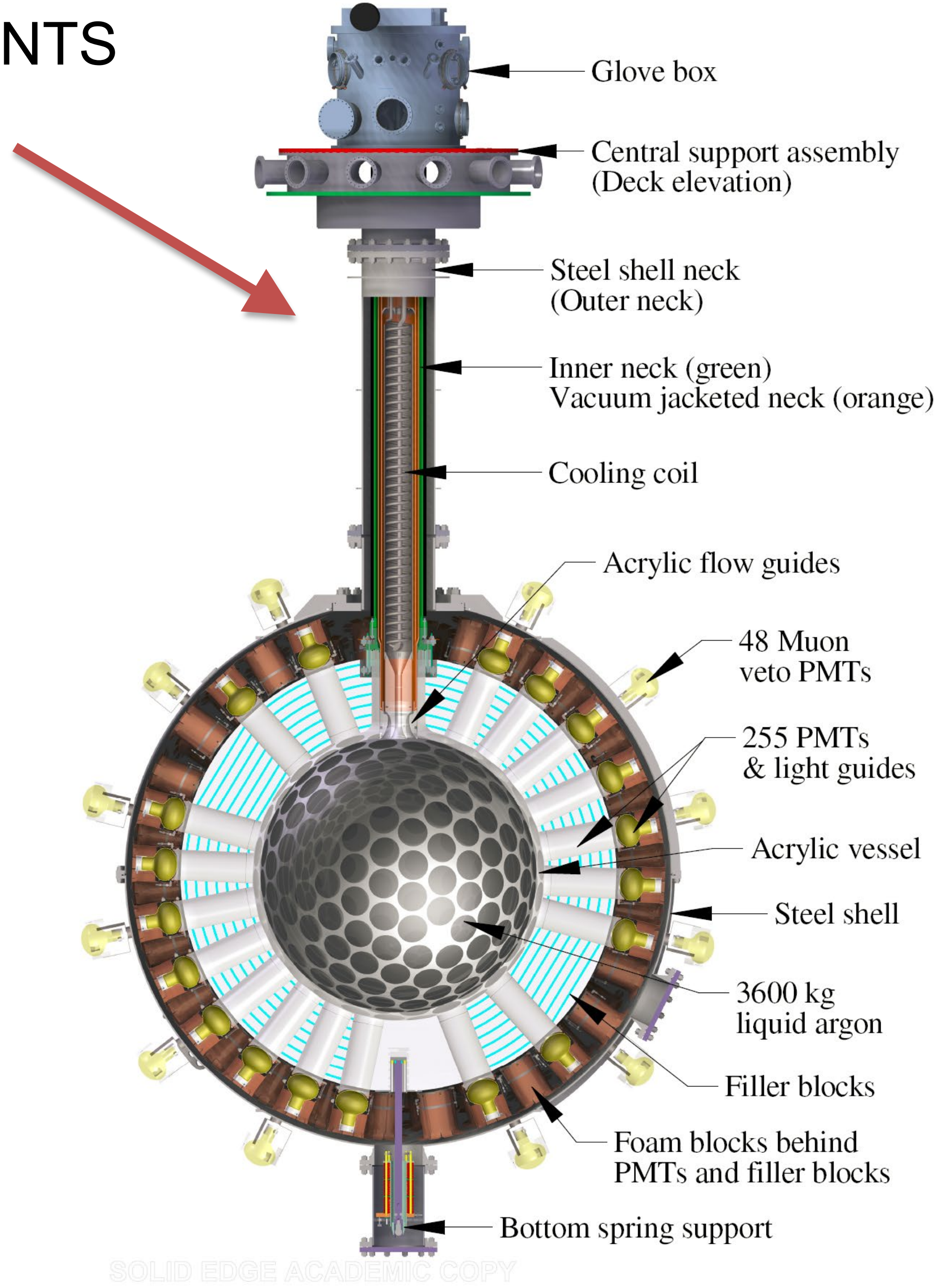


FUTURE ***ARGON*** EXPERIMENTS

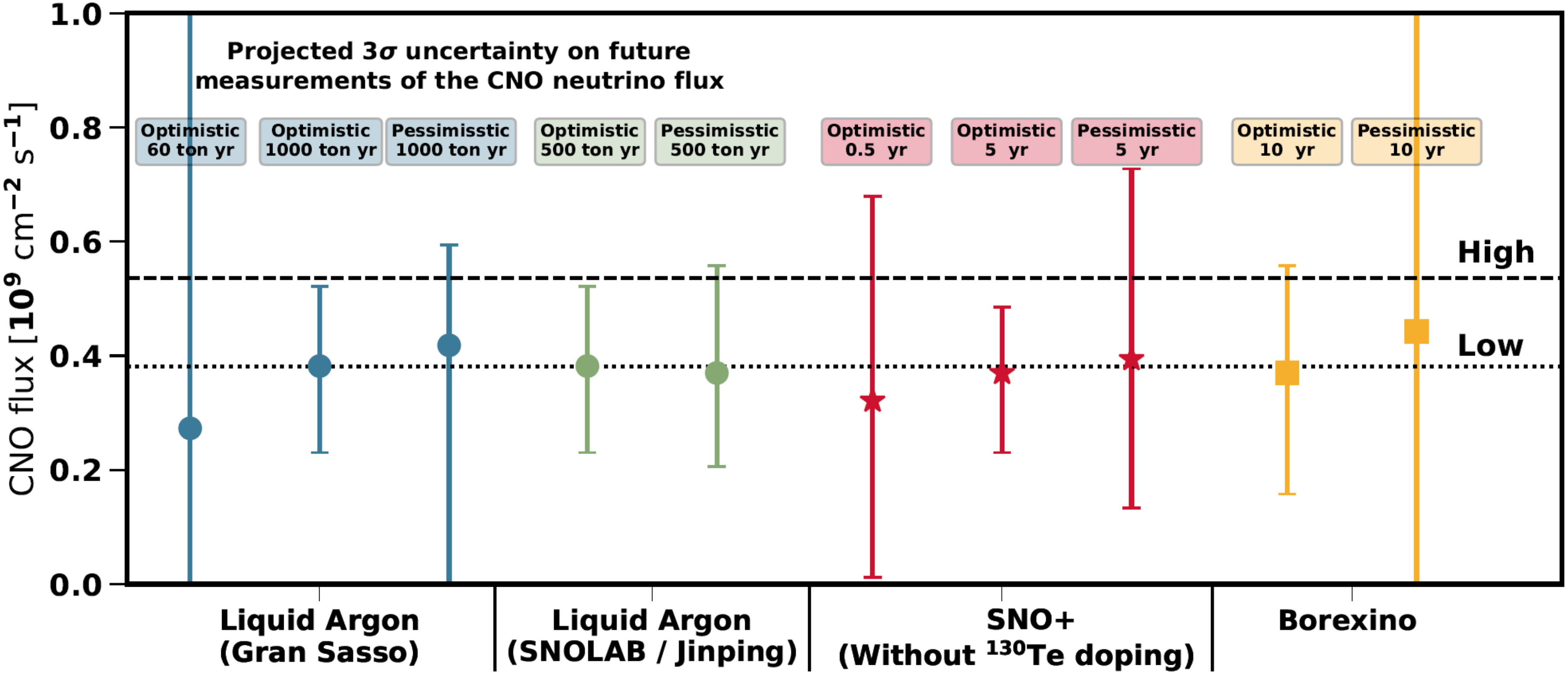
e.g. Deap 3600, already exists

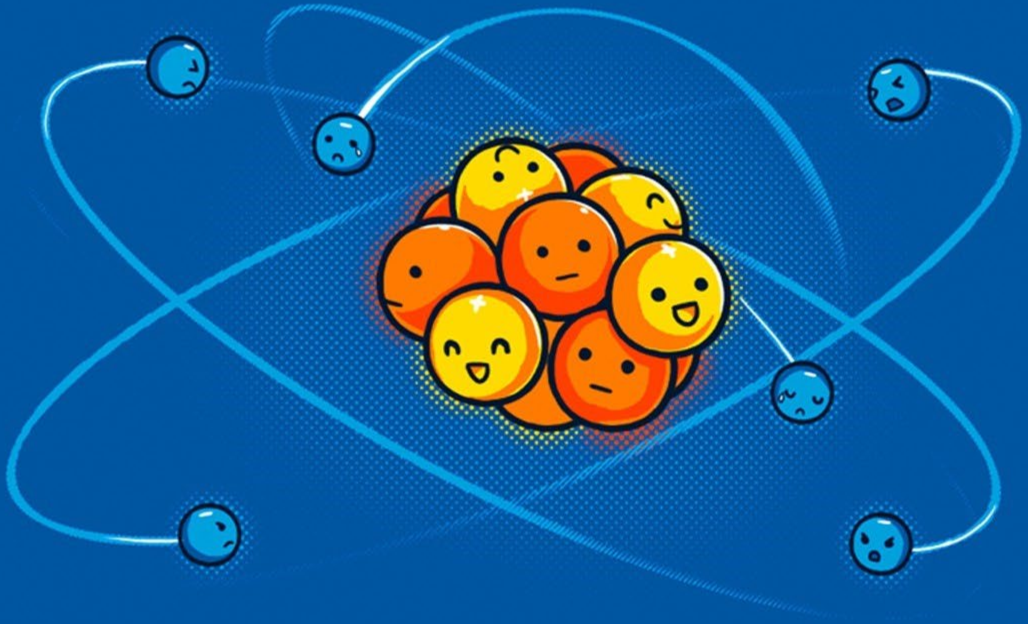
Darkside 20 tons
will probably happen.
Located at Gran Sasso

Argo 100 tons ????



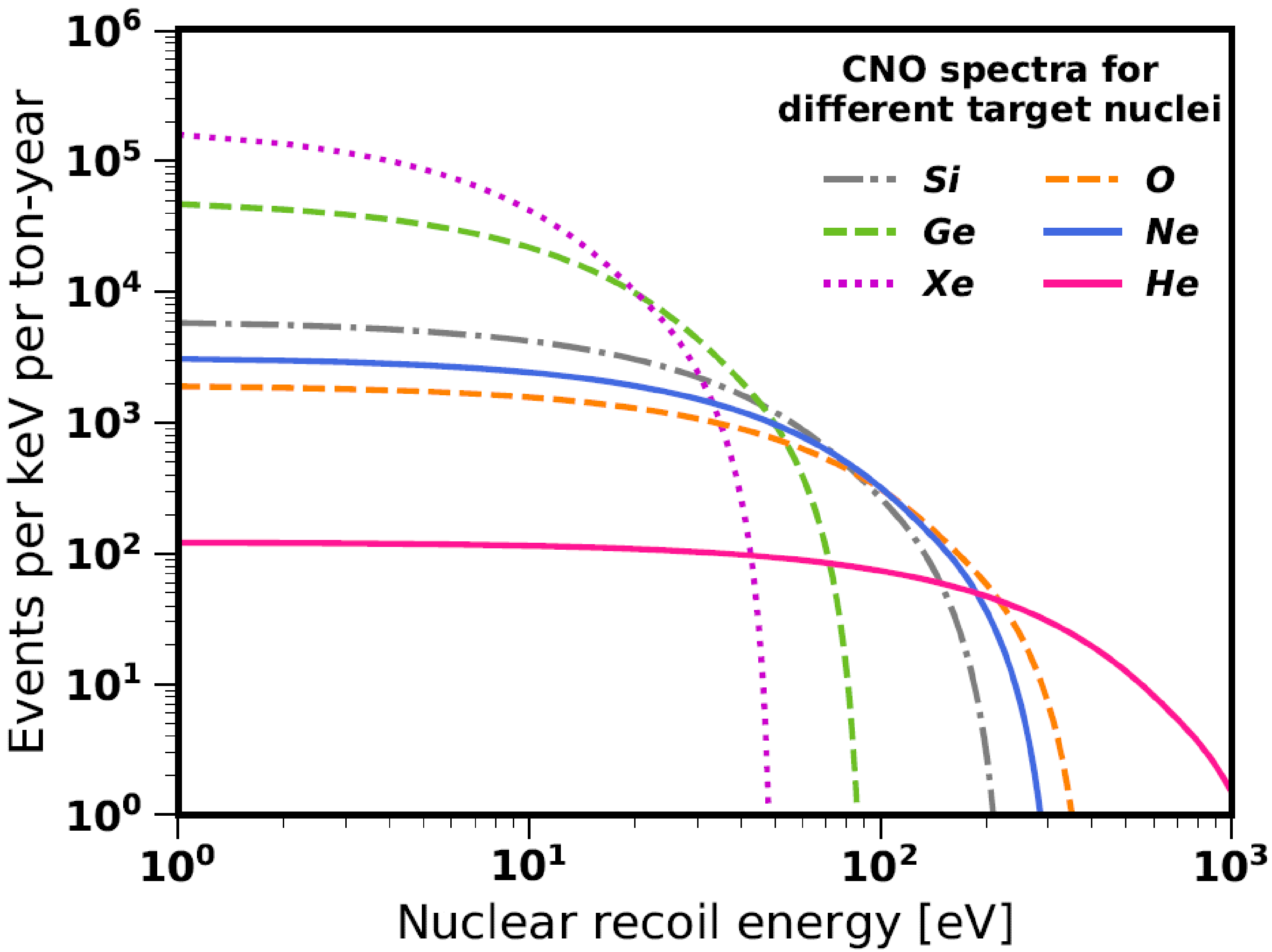
Summary of Electron Recoil Results



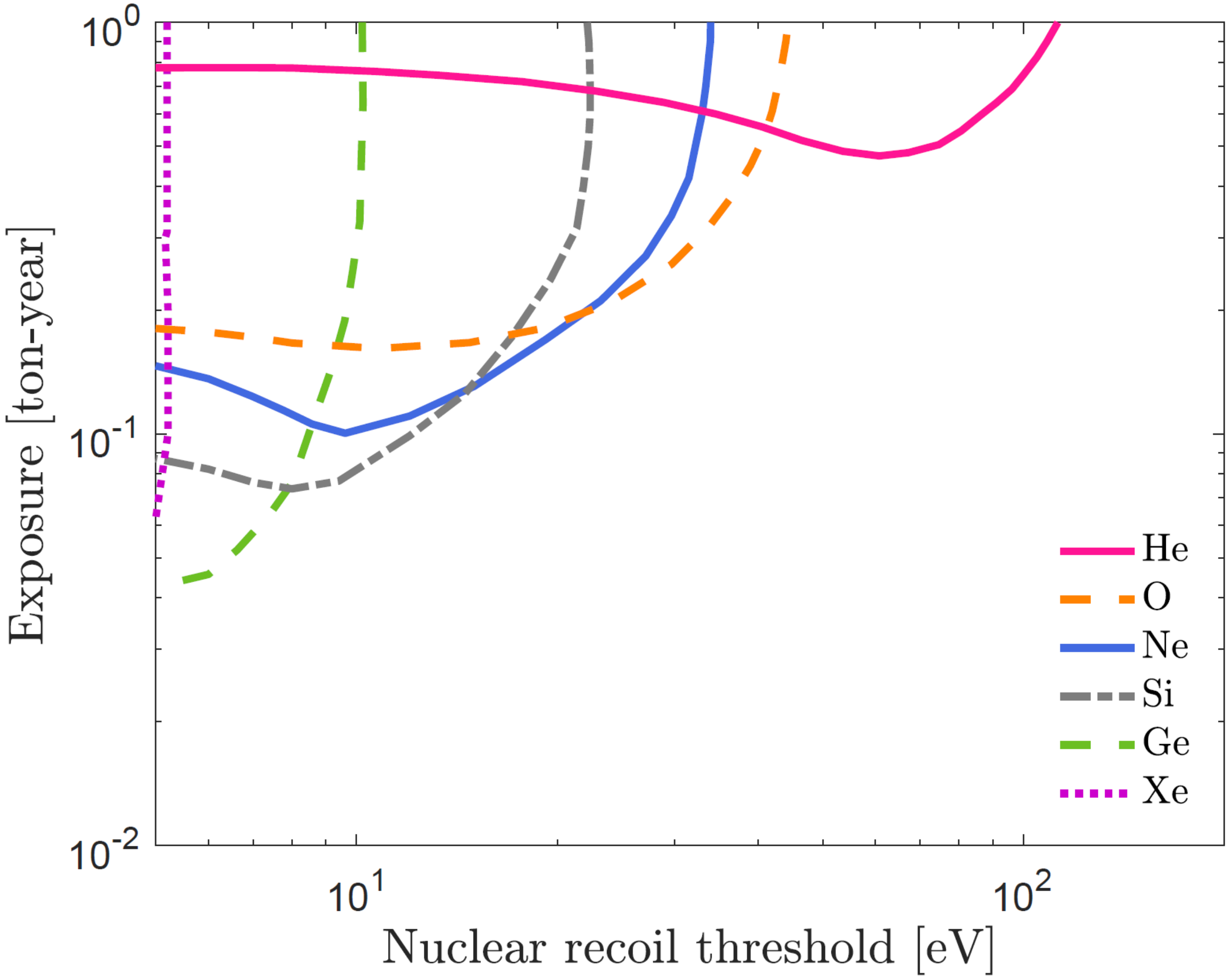


What about Nuclear recoils?

CNO Nuclear Recoil Energy Spectrum



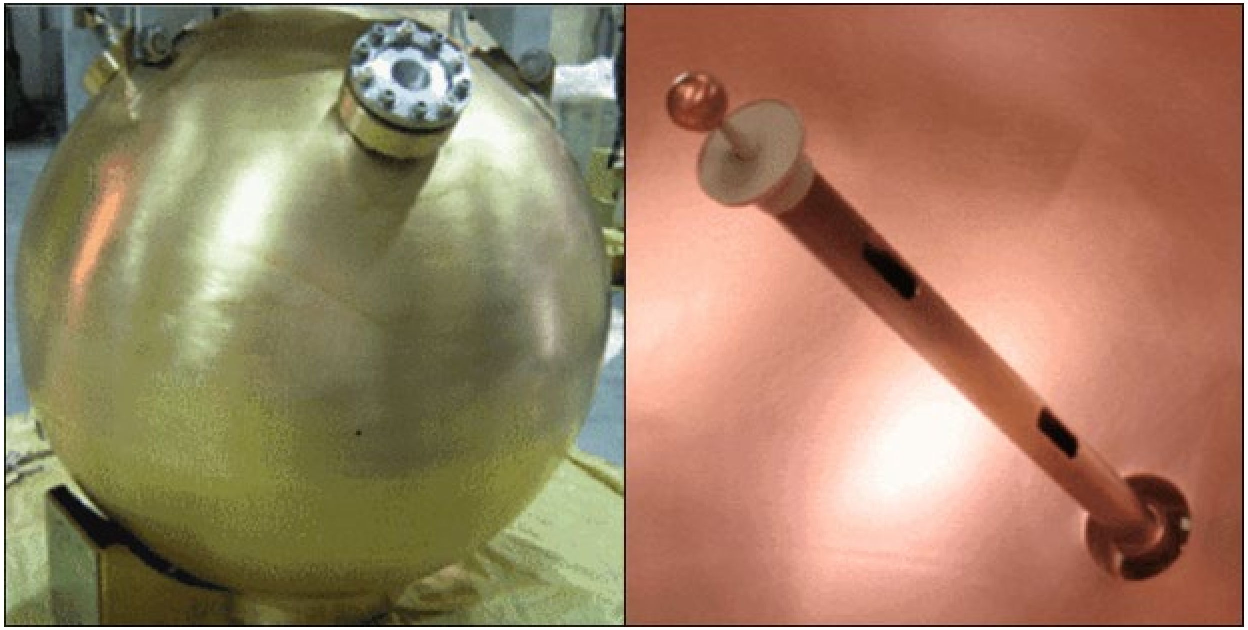
CNO Nuclear Recoil Sensitivity requirements



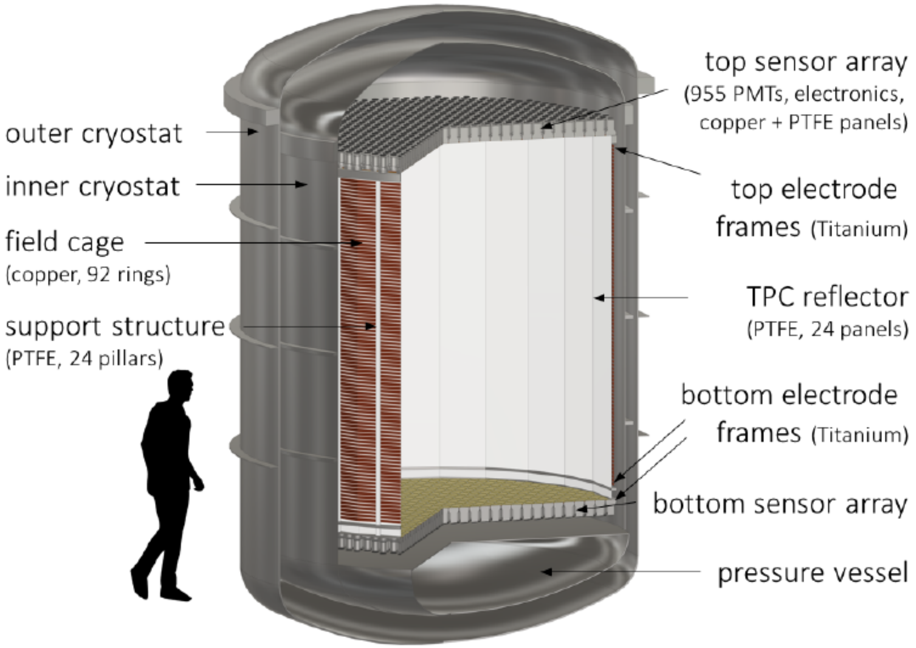
Required combination of high target mass and VERY low threshold is challenging!

There are low threshold, low mass target experiments

For example, the NEWS-G Experiment….



But they don't yet have low enough thresholds or high enough exposures (cheap to scale up to multiple units in the future?)



I have been Argon heavy here but the Xenon Darwin Experiment can also search for neutrinoless double beta decay, and as we have seen neutrino-interactions

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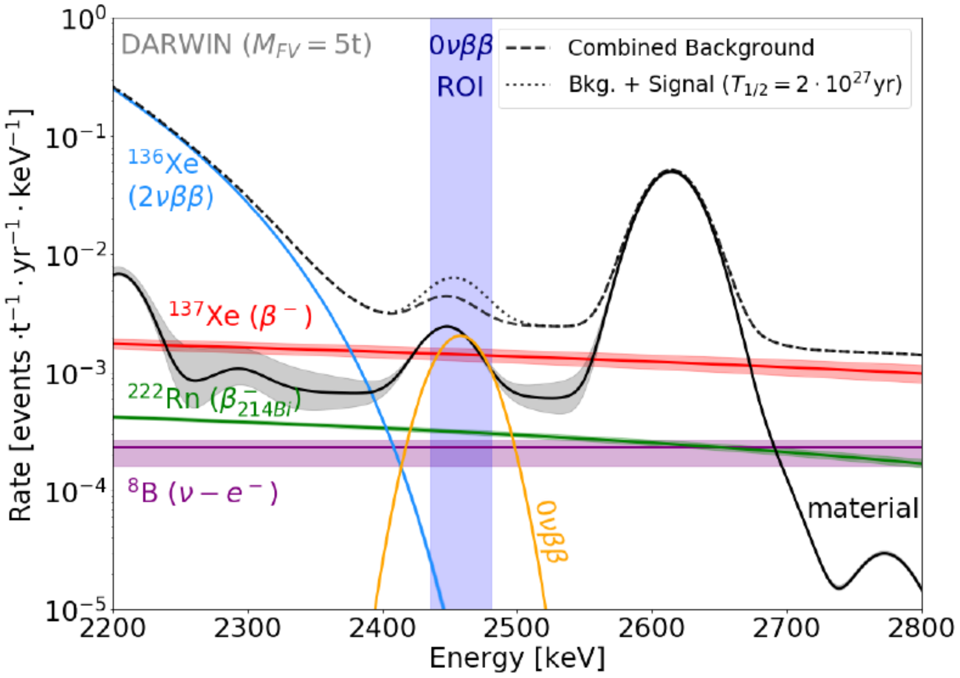

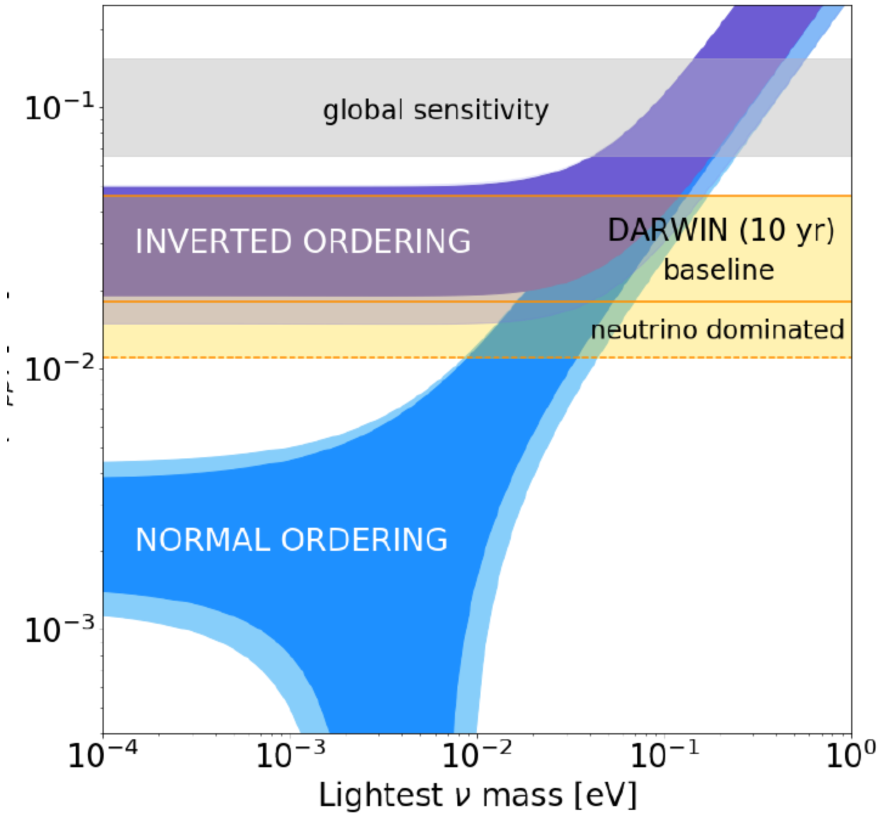

- Study of Solar neutrinos can place constraints on new physics in the neutrino sector
- Current experiment looking for CNO probably can’t see it (Borexino)
- Experiment which might be able to see it isn’t looking (SNO+)
- Future large argon experiments will be able to see it if they can understand their backgrounds
- If current low threshold nuclear recoil experiments could be improved and scaled up they might also see it.

PEOPLE SHOULD TRY HARDER TO LOOK FOR CNO NEUTRINOS

THE DARK MATTER COMMUNITY MIGHT ONE DAY GET INVOLVED

Conlusions

- For the time being we don’t know what the Xenon1T excess is
- We can explain it in a variety of different ways
- Most encouraging aspect of this entire discussion is that dark matter detectors are starting to shed light on a whole load of physics they were not built for (think about kamiokande)
- I believe that we are at the beginning of a new phase of constraints on Physics from dark matter detectors, both standard model and beyond, and I’m quite excited…

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