BEYOND WIMPS: FUN WITH XENON

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May 30, 2015

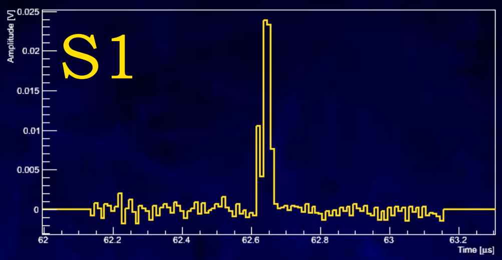
I Agree With Maxim's Lamppost

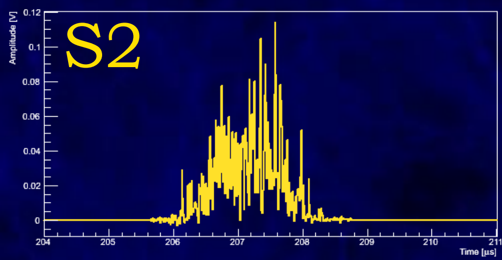
Extract maximum physics from experiments. Ton-scale detector XENON1T running this Fall! What can we do with it?

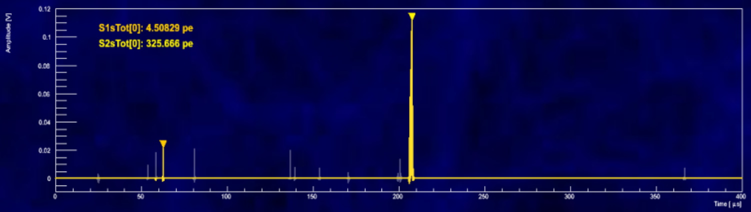
Candidate Event, E~3keV$_{nr}$

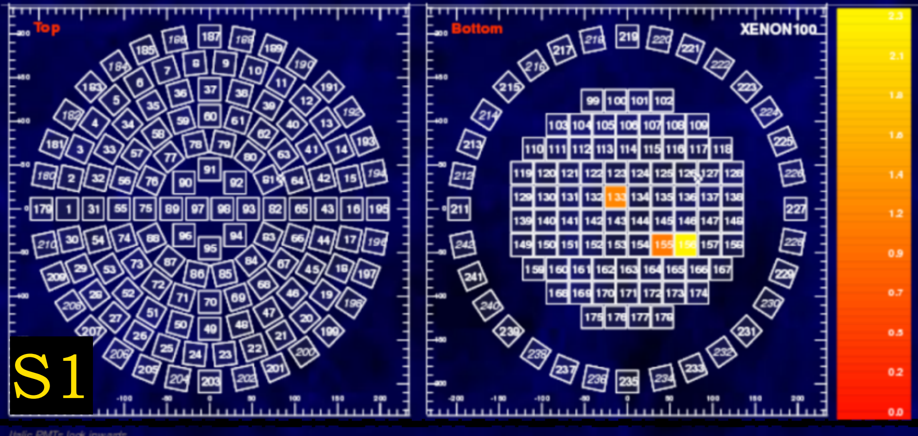
Ample information even at lowest energies:

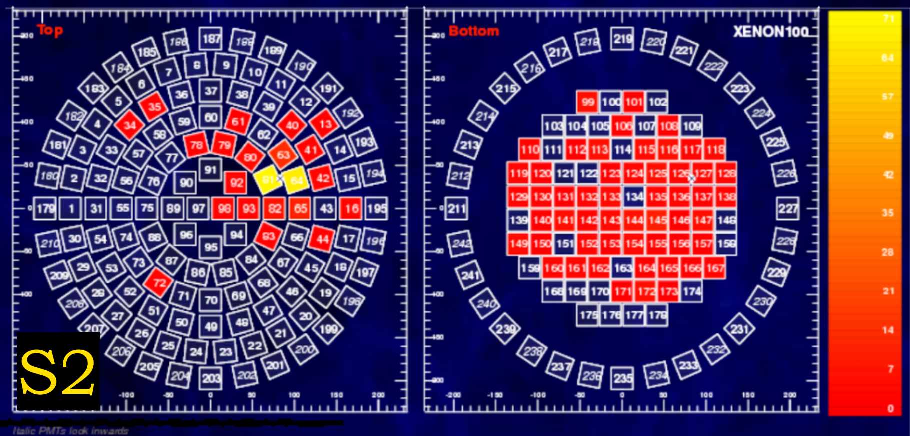
- S1 size and PMT hit pattern
- S2 size and PMT hit pattern
- Single/Multiple Scatter
- Electronic/Nuclear Recoil
- Vertex position
- S2 width
- Time





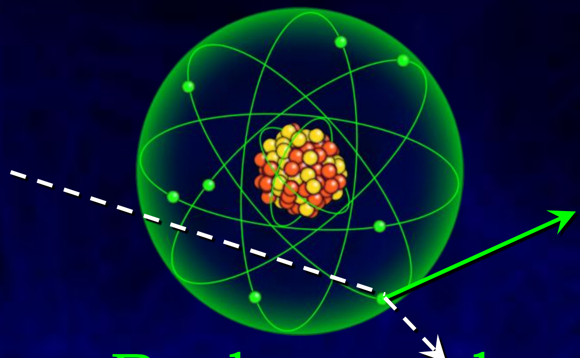






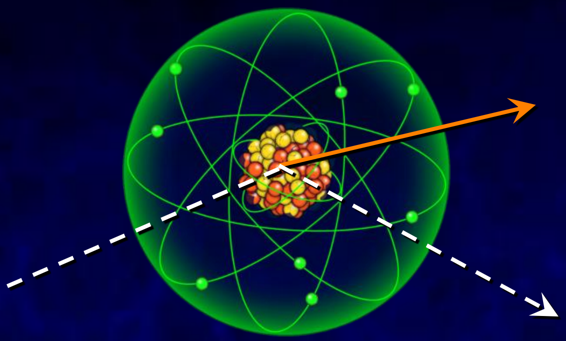
Discrimination: Need Information

e^-/γ: electronic recoil



Background

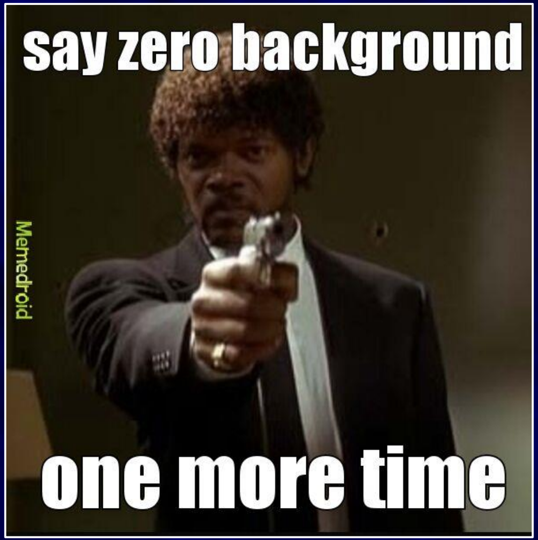
α/n/WIMPs: nuclear recoil



Signal

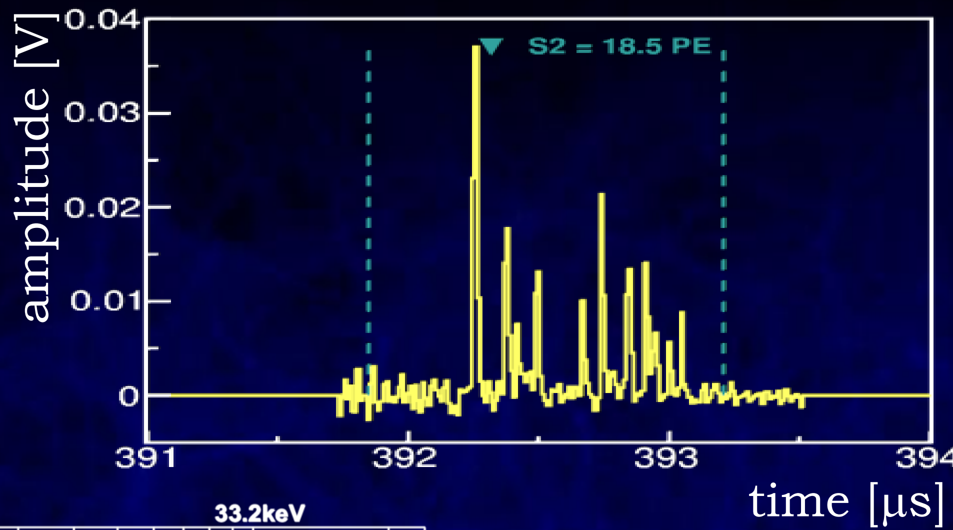
Most relevant though:
Detector artefacts!
→ Extract as much information as possible

How valuable is a limit-only analysis, *really*?

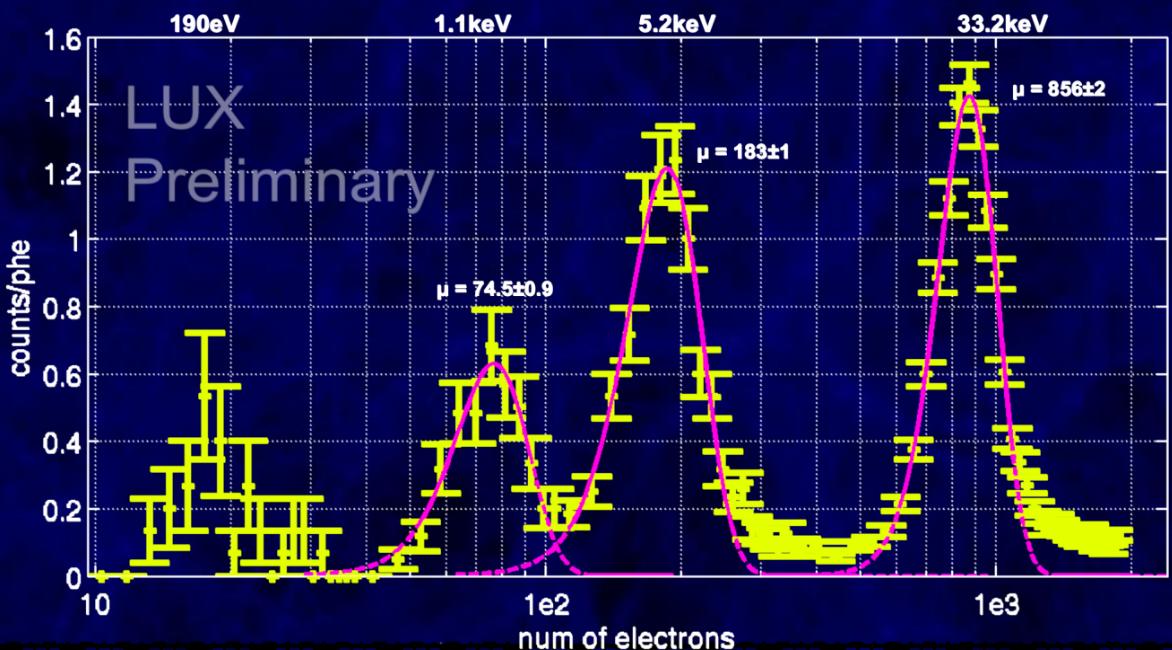


Extreme Low-Energy Sensitivity

Detect even individual electrons liberated in an interaction:



XENON100 1311.1088



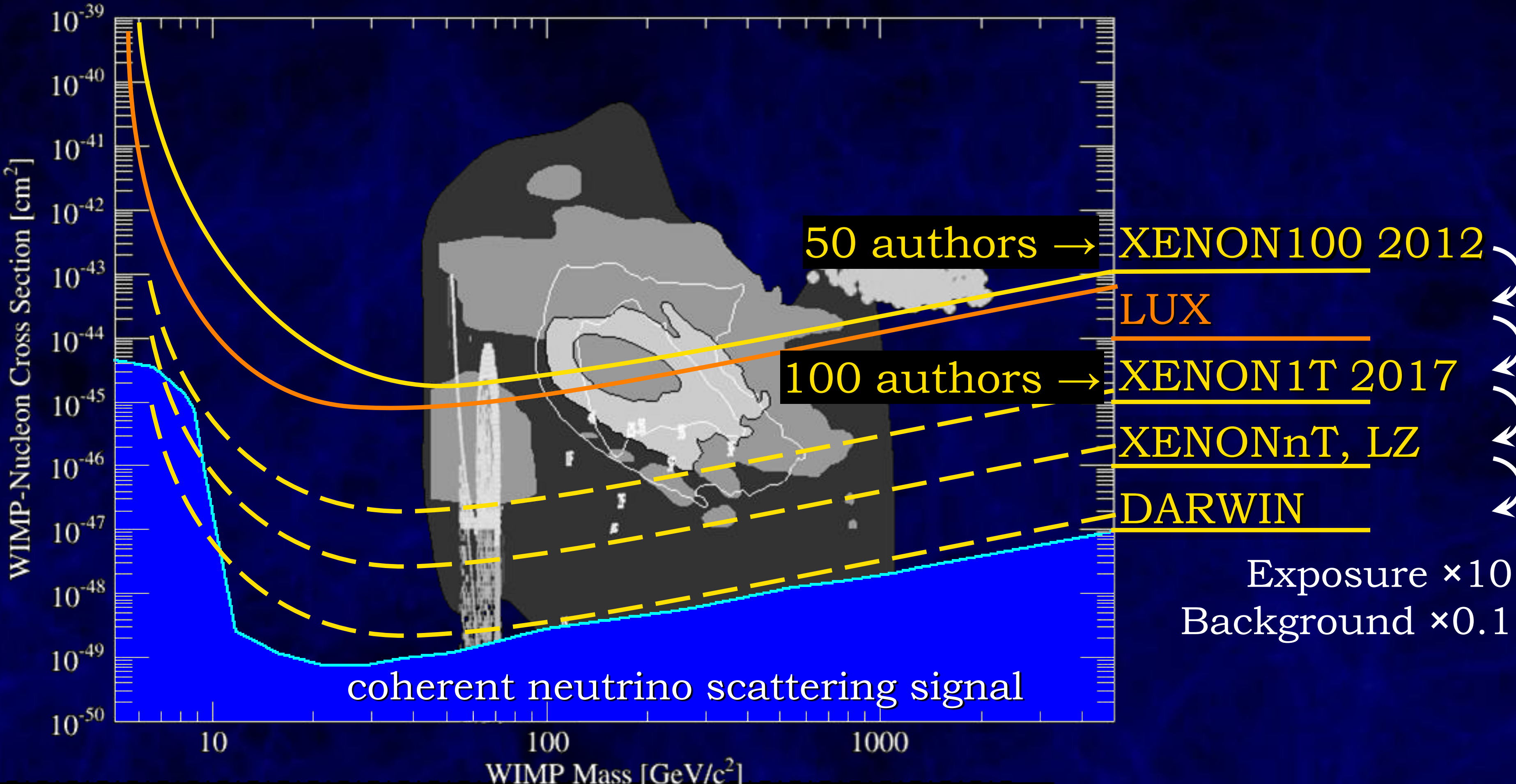
LUX D.Huang APS2015

^{127}Xe EC (from cosmic activation) calibration as low as 190eV

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

Spin-Independent WIMPs

Our main goal of course: SI WIMPs, m_χ~10GeV-10TeV limit or measure properties



$$\chi + N \to \chi + N$$

Many More Couplings

Transition from spin-dependent/independent to effective field theory approach

- Present results for each operator individually?
- Use relativistic or non-relativistic operators?

Fan, Reece & Wang 1008.1591

SI NR operators	SD NR operators
$\delta^3(\vec{r})$	$\vec{s}_\chi \cdot \vec{s}_N \delta^3(\vec{r})$
$\vec{s}_\chi \cdot \vec{\nabla}\delta^3(\vec{r})$	$\vec{s}_N \cdot \vec{\nabla}\delta^3(\vec{r})$
$\frac{1}{4\pi r}$	$\frac{\vec{s}_\chi \cdot \vec{s}_N}{4\pi r}$
$\frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3}$	$\frac{\vec{s}_N \cdot \vec{r}}{4\pi r^3}$

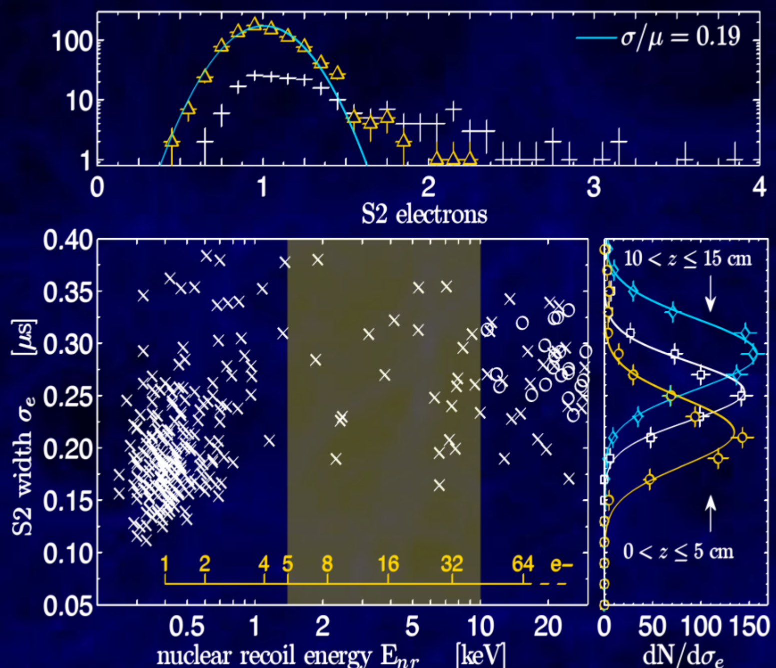
$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = -i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = -i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp_{\chi N}\right)$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp_{\chi N}$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp_{\chi N}$$
$$\mathcal{O}_9 = -i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_{10} = -i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = -i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

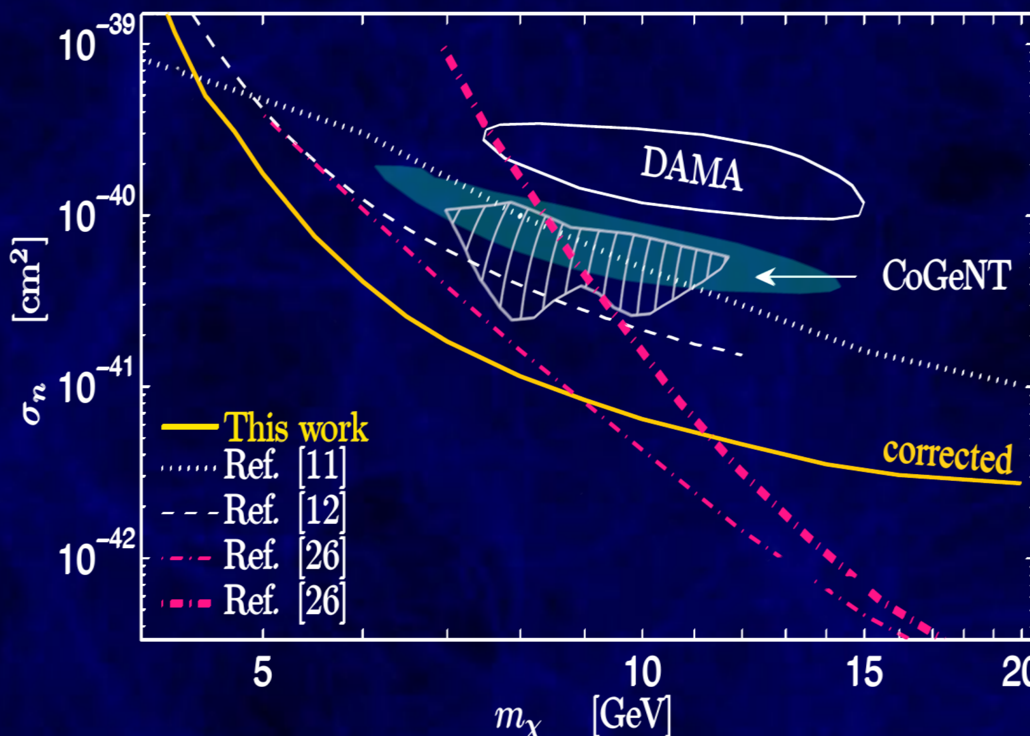
Fitzpatrick+ 1203.3542, 1211.2818
Anand, Fitzpatrick & Haxton 1405.6690, Catena 1406.0524
see also the code packages 1308.6288 and 1307.5955

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

Don't require S1s: GeV/c² WIMPs

- S1-requirement limits threshold
- Don't require S1: lower threshold, more background





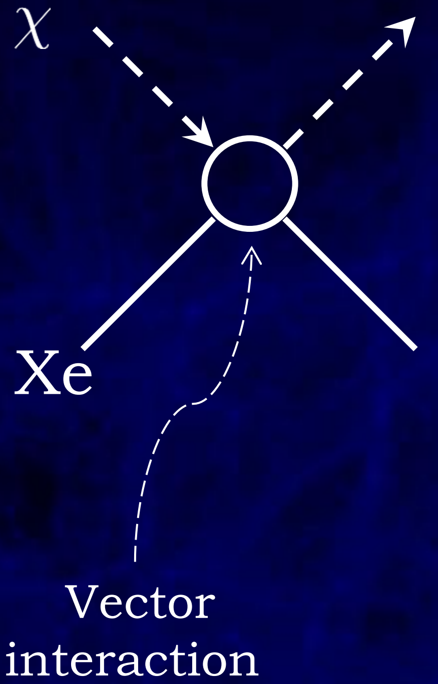
XENON10 1104.3088 (and errata)

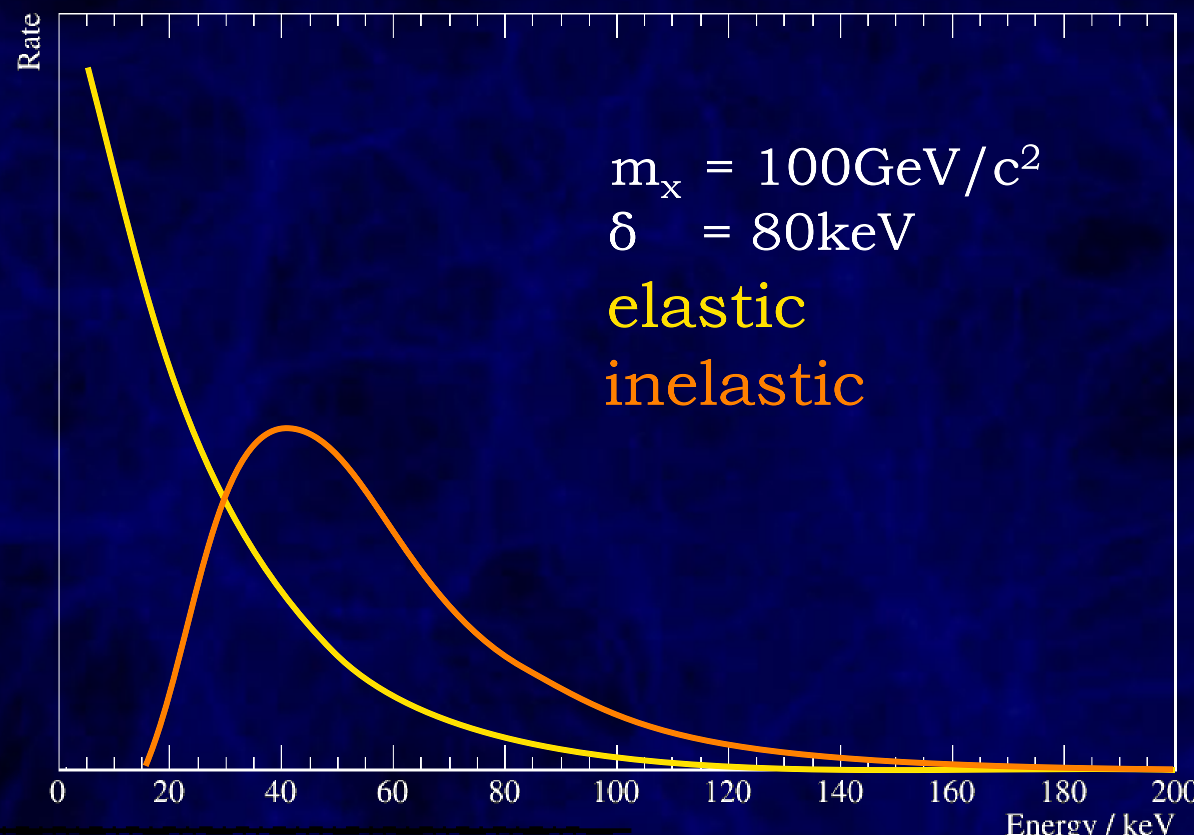
$\chi + N \rightarrow \chi^* + N$

Inelastic Dark Matter iDM

Originally proposed to reconcile DAMA with CDMS

χ^* excited state with energy δ



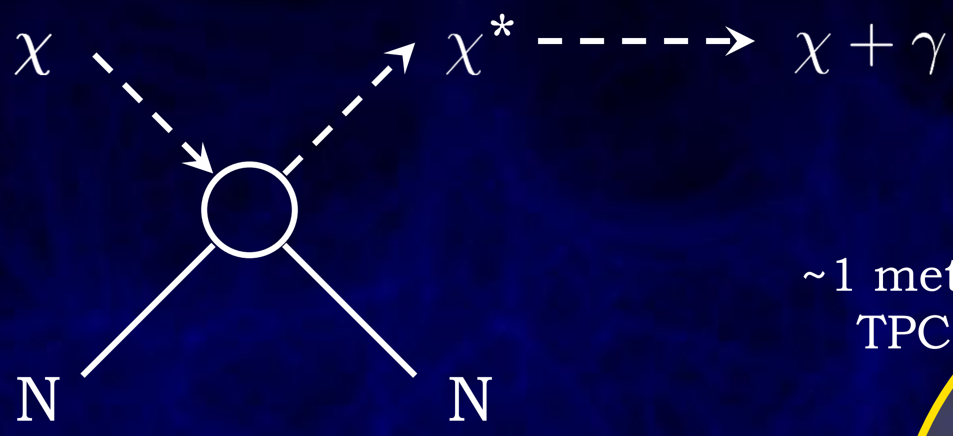


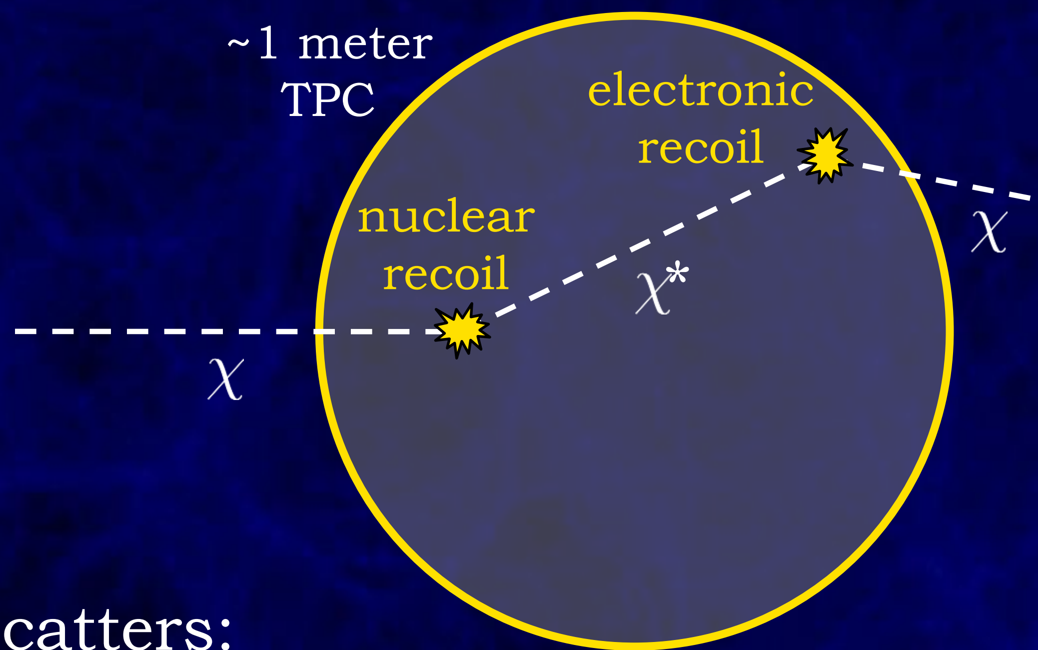
Tucker-Smith&Weiner hep-ph/0101138

$$\chi + N \rightarrow \chi^* + N \rightarrow \chi + \gamma + N$$

Magnetic Inelastic Dark Matter miDM

Assume (magnetic) dipole transition: excited state decays





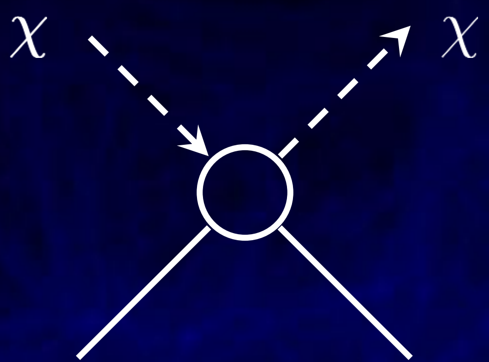
Chang, Weiner & Yavin 1007.4200
Lin & Finkbeiner 1011.3052

Looks like double-scatters:
So far completely un-searched for.

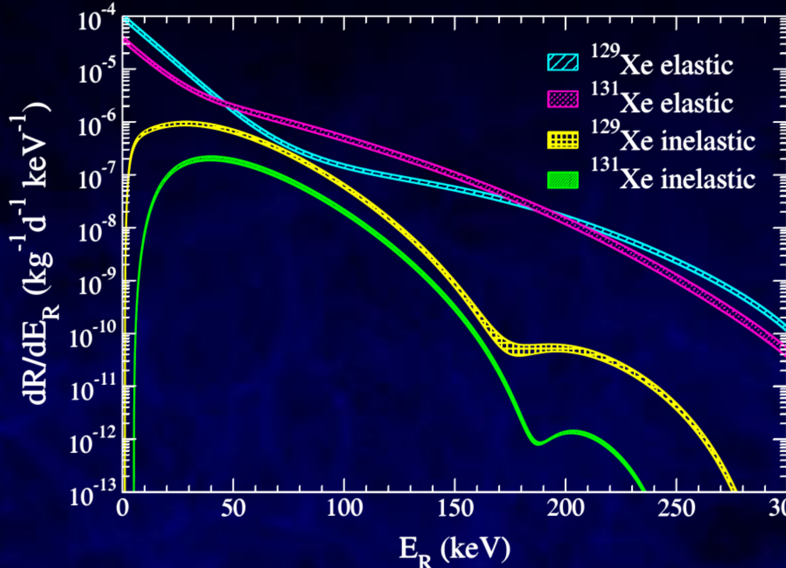
$$\chi + N \rightarrow \chi + N^*$$

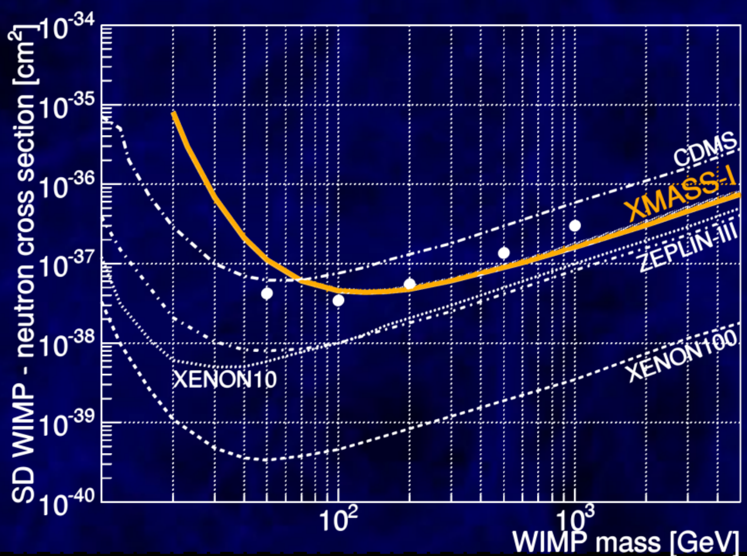
Inelastic Scattering

cross-check limit, measure halo

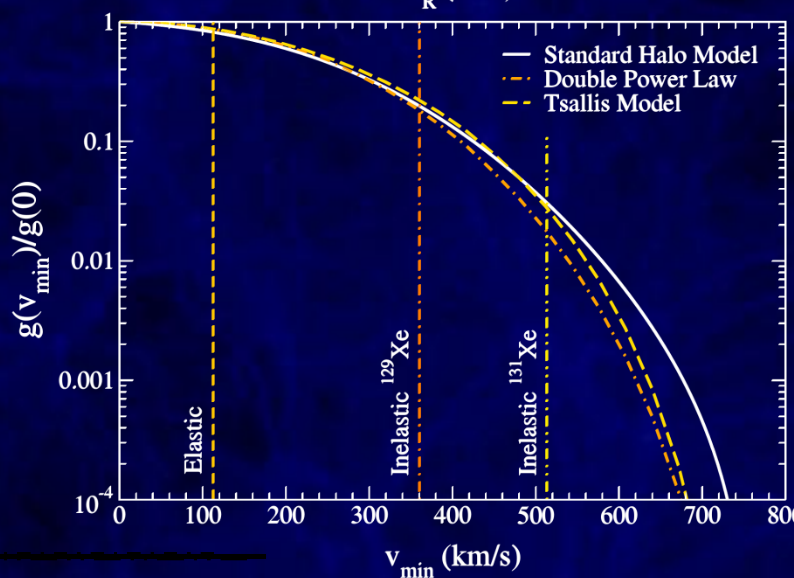


Xe $Xe^* \longrightarrow Xe + \gamma_{40keV}$





XMASS 1401.4737

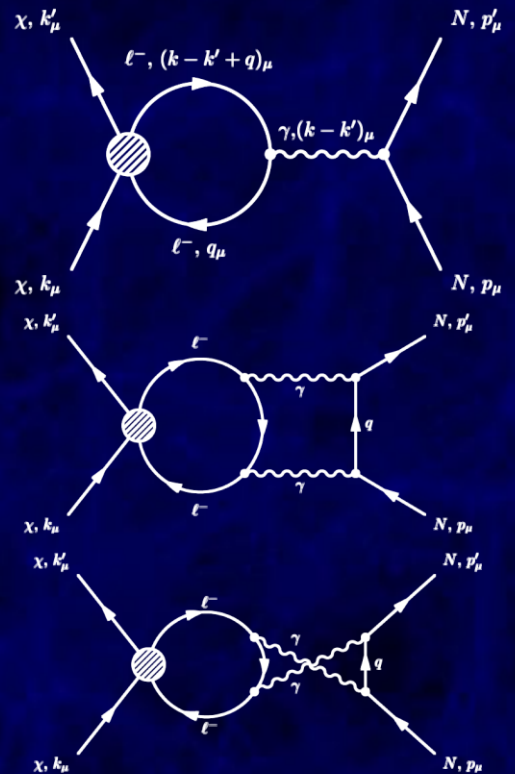


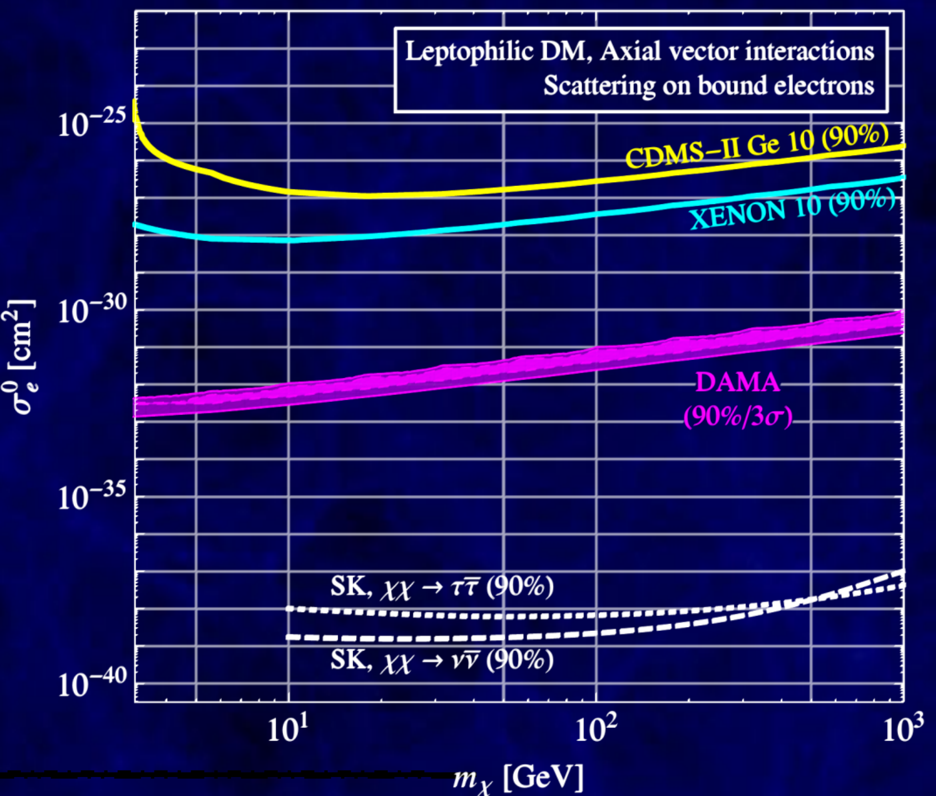
Baudis+ 1309.0825

$$\chi + e^- \rightarrow \chi + e^-$$

Axial-Vector Interactions

- Typically, keV electronic recoils require electron momenta of ~MeV: Highly suppressed
- Axial-vector interaction only channel where loop-induced nuclear recoils do not dominate





Kopp+ 0907.3159

$$e' + e^- \rightarrow e' + e^-$$

Mirror Dark Matter

- Kinetically mixed Dark Matter
- Get keV electronic recoils from halo with particles of mass ~ m_e and energy ~ keV

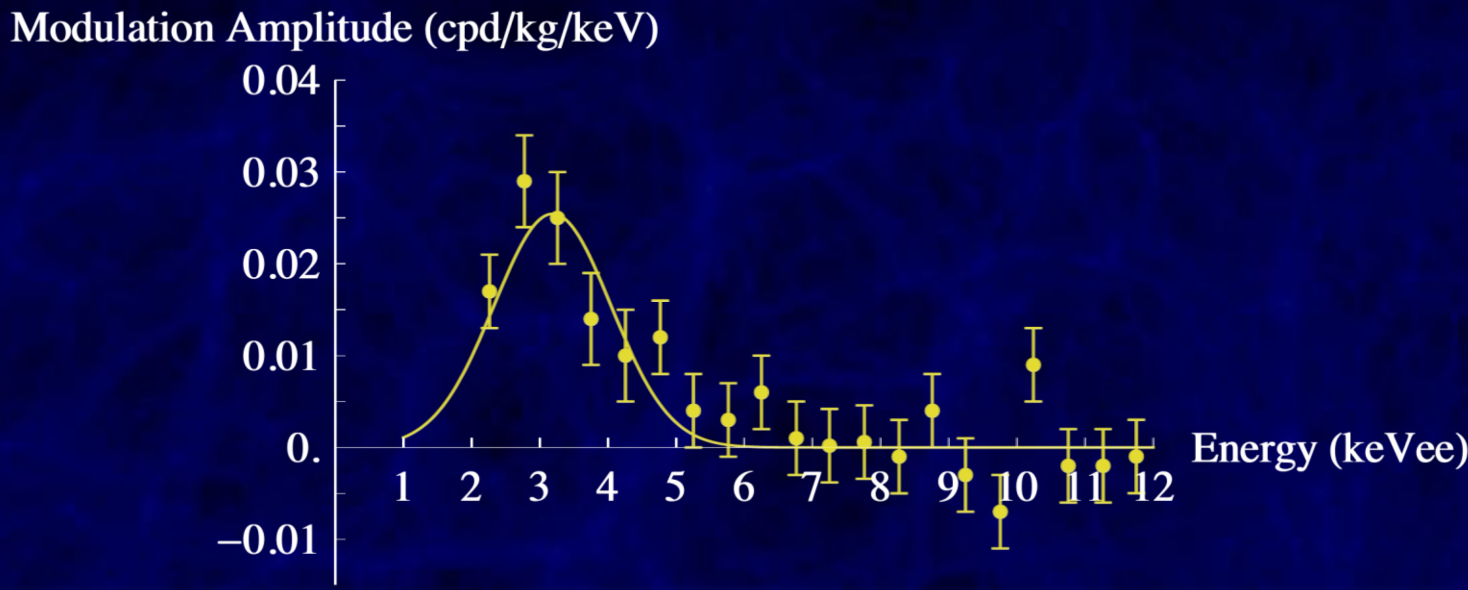
Foot e.g. 1407.4213

sampaikini.com

$\chi^* \rightarrow \chi + \gamma$

Luminous Dark Matter

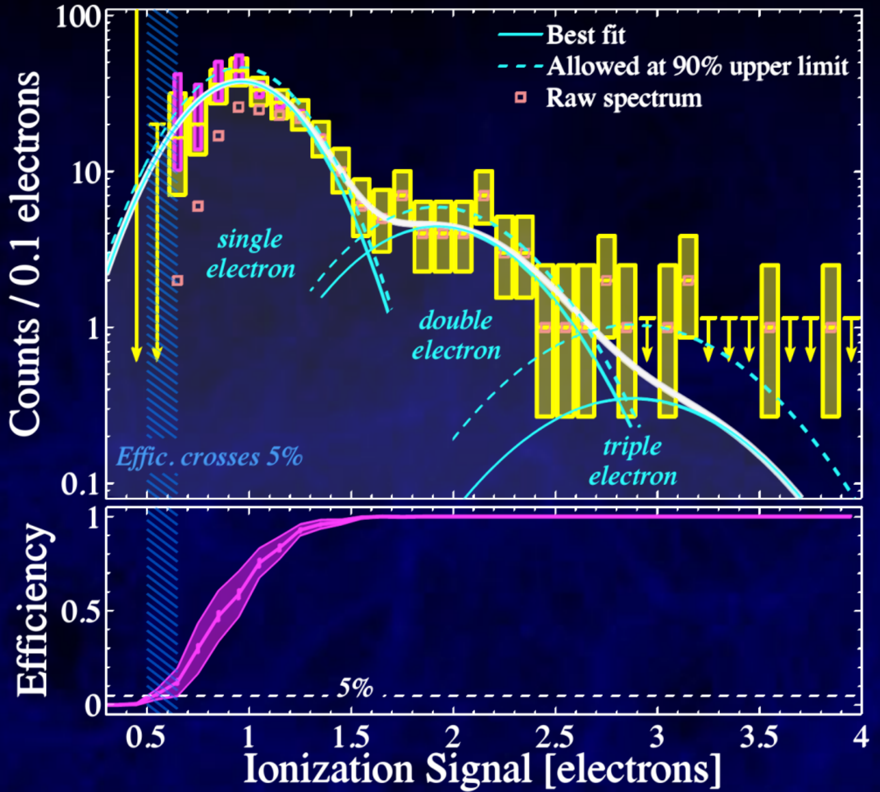
- Excited dark matter flys through detector and decays: see only de-excitation gamma
- E.g. fit of 3.3keV line to some infamous data:



Feldstein, Graham, Rajendran 1008.1988

$\chi + e^- \rightarrow \chi + e^-$

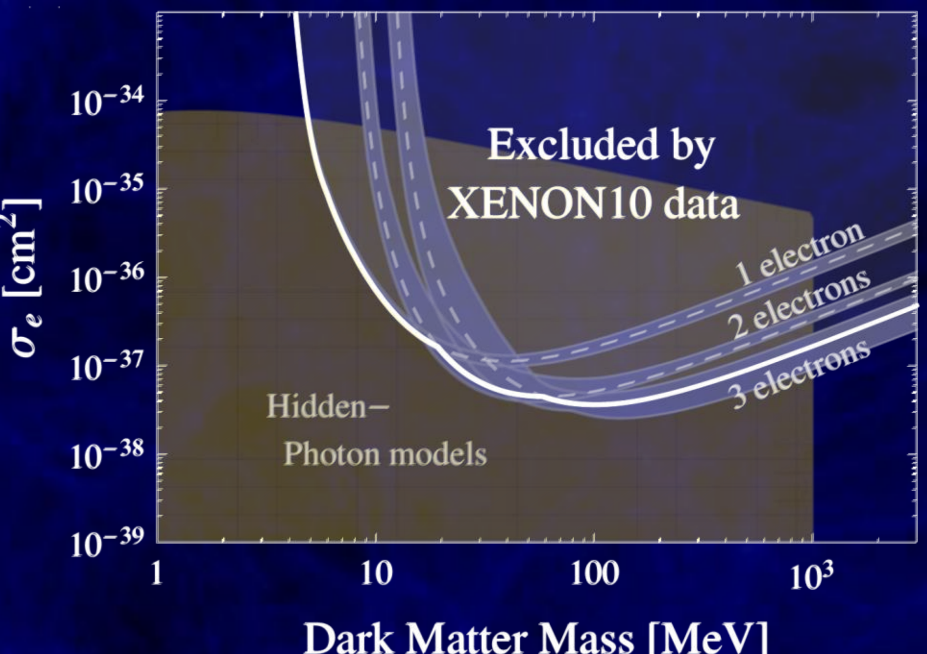
MeV/c^2 WIMPs Scattering Off e$^-$



Limit MeV Dark Matter:

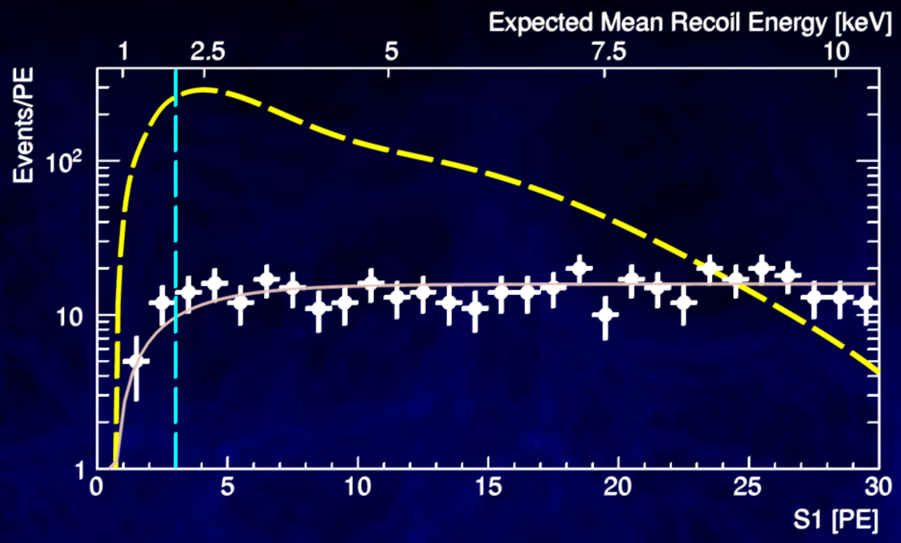
- Kinematics favor scattering off electrons
- We observe even single electrons!

Essig+ 1206.2644

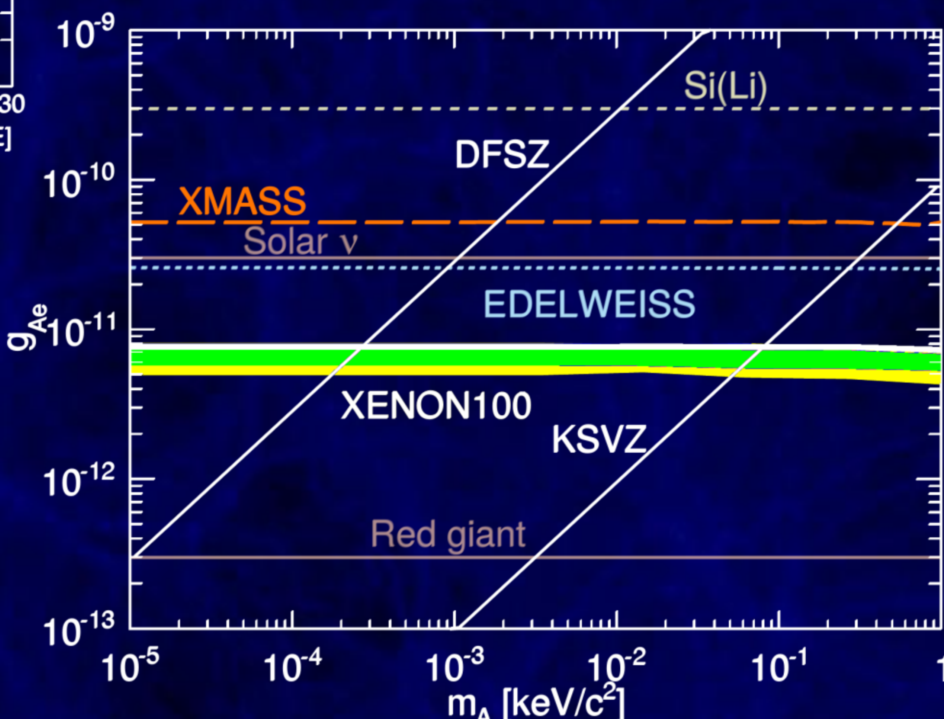


$a + e^- \rightarrow e^- + \gamma$

Solar Axion Search



Use electronic recoils to search for axions coupling via axio-electric effect g_{Ae}

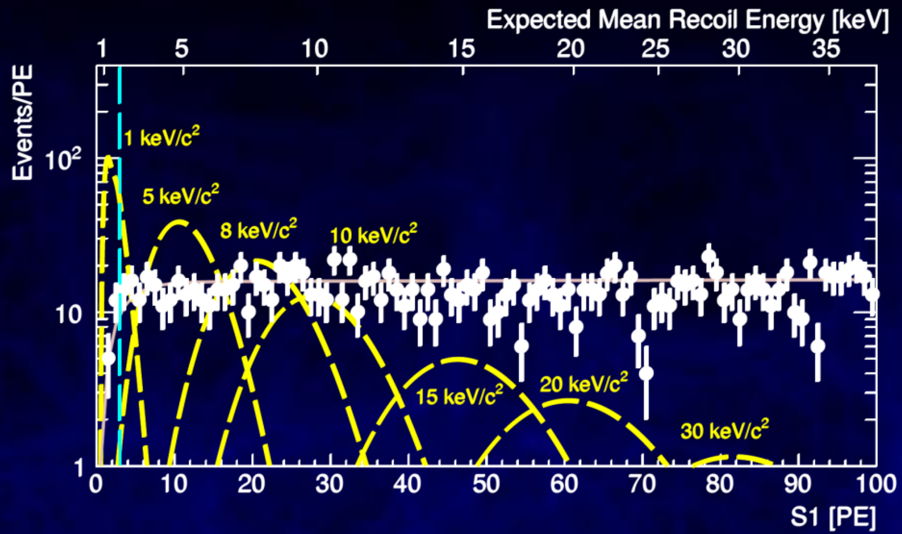


XENON100 1404.1455

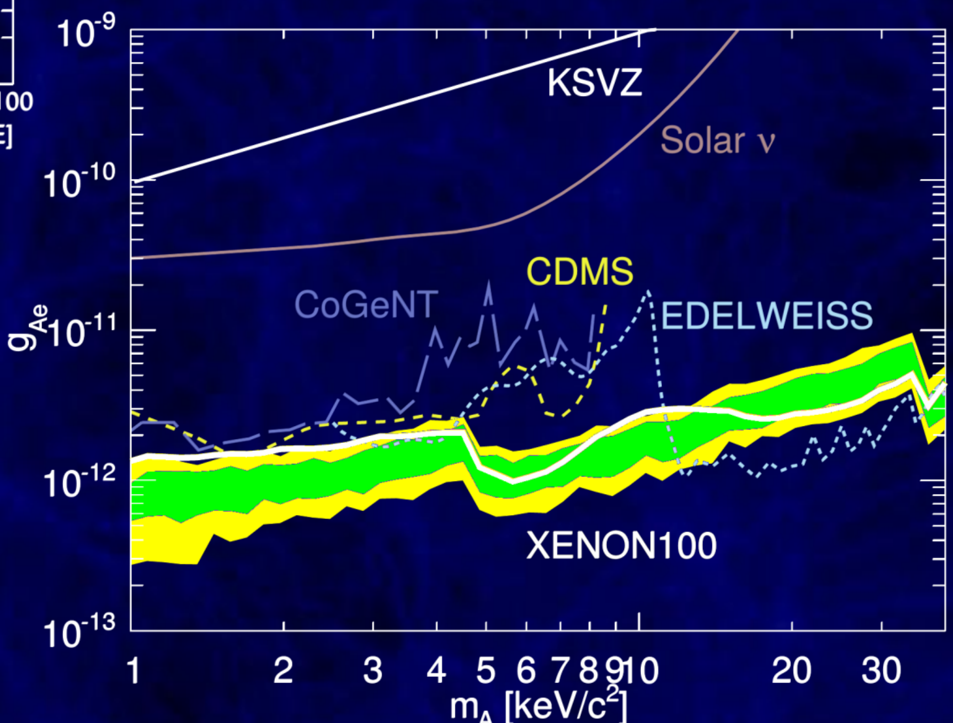
XENON100 excludes
QCD axions
> 0.3 eV (DFSZ)
> 80 eV (KSVZ)

$a + e^- \rightarrow e^- + \gamma$

Axion-Like Particles



Use electronic recoils to search for axions coupling via axio-electric effect g_{Ae}



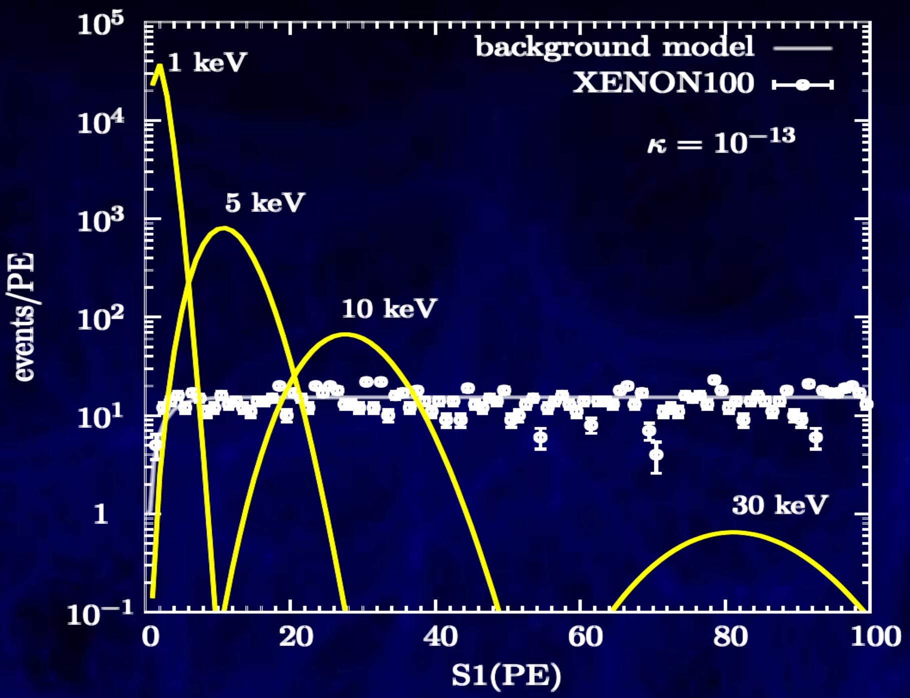
Also: bosonic Super-WIMPs

Pospelov, Ritz, Voloshin 0807.3279

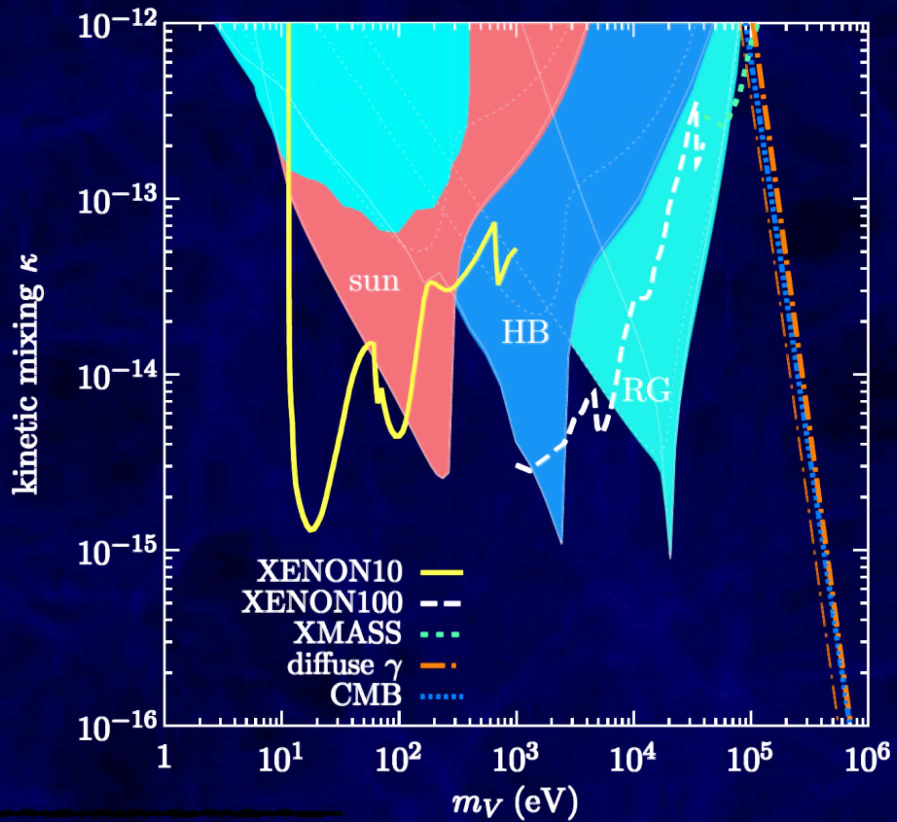
XENON100 1404.1455

$$Xe + V \rightarrow Xe^* + V \rightarrow Xe + \gamma + V$$

Dark Photons



Atomic ionization from dark vectors with energy above ionization threshold

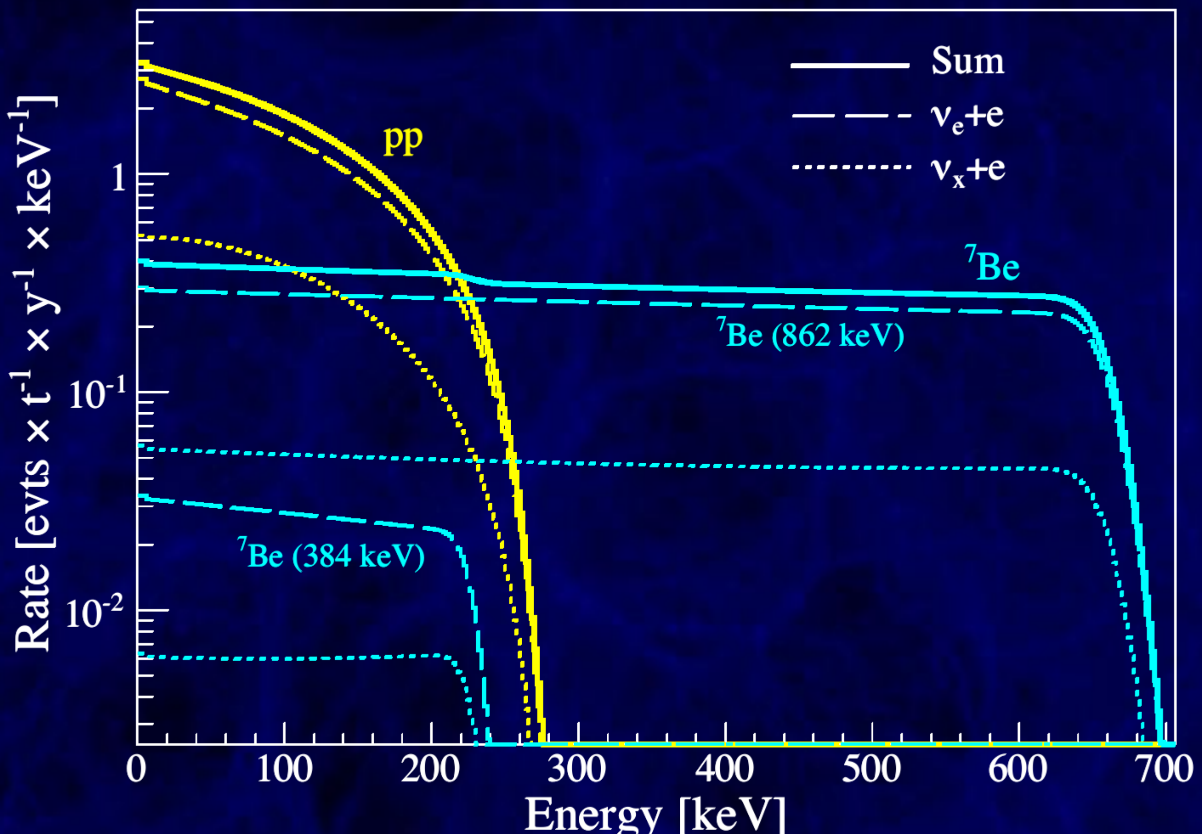


An+ 1412.8378

$$\nu_{e,\mu/\tau} + e^- \rightarrow \nu_{e,\mu/\tau} + e^-$$

Solar Neutrino Electronic Recoils

Mostly from pp process
About ¼ of background in XENON1T !
As signal: Measure flux to refine solar models



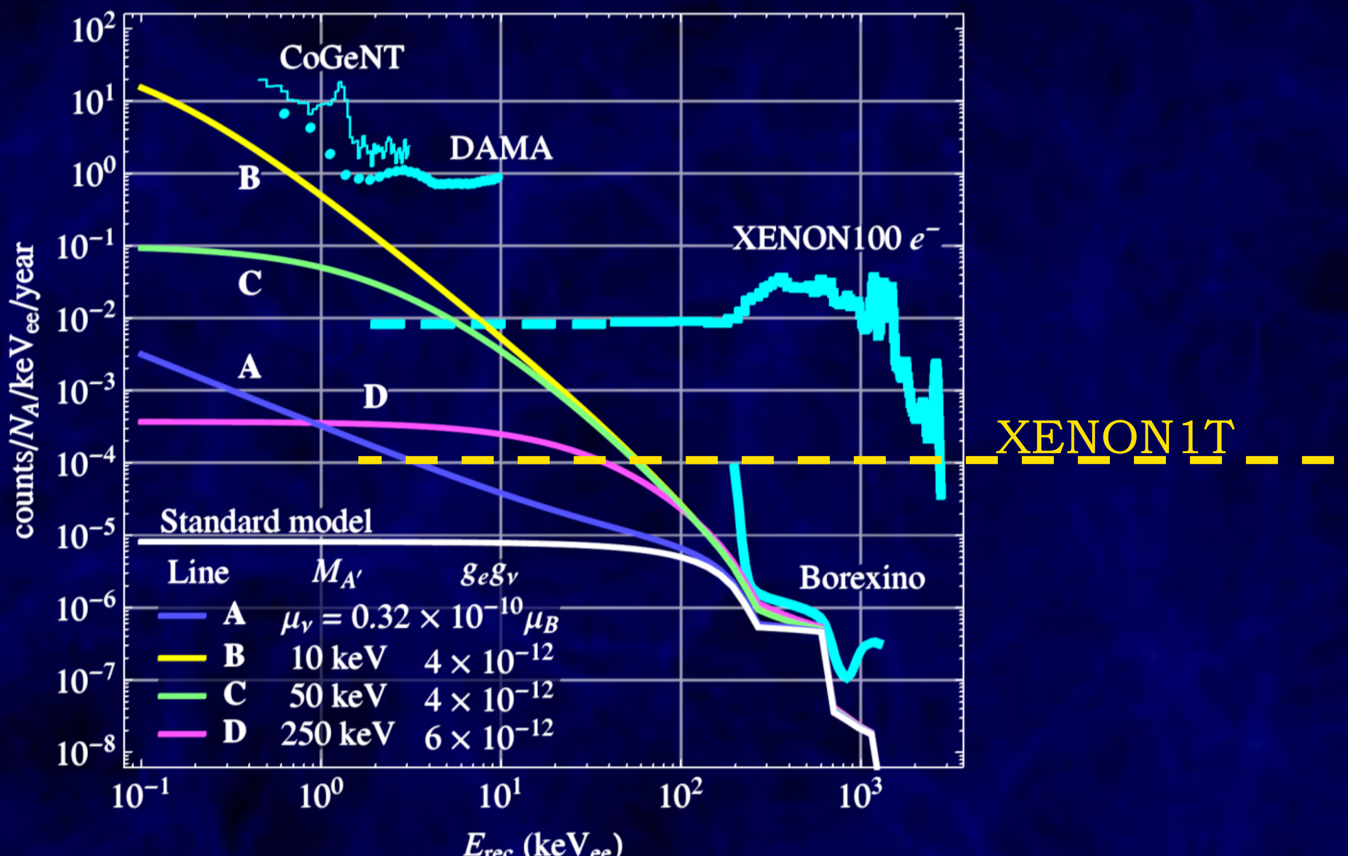
Baudis+ 1309.7024

$$\nu_{e,\mu/\tau} + e^- \to \nu_{e,\mu/\tau} + e^-$$

Add μ_ν or A’

Modified predictions

- Magnetic dipole moment of neutrino μ_ν = 3 x 10^{-11} μ_B
- Additional U(1)’ vector boson A’ of varying mass



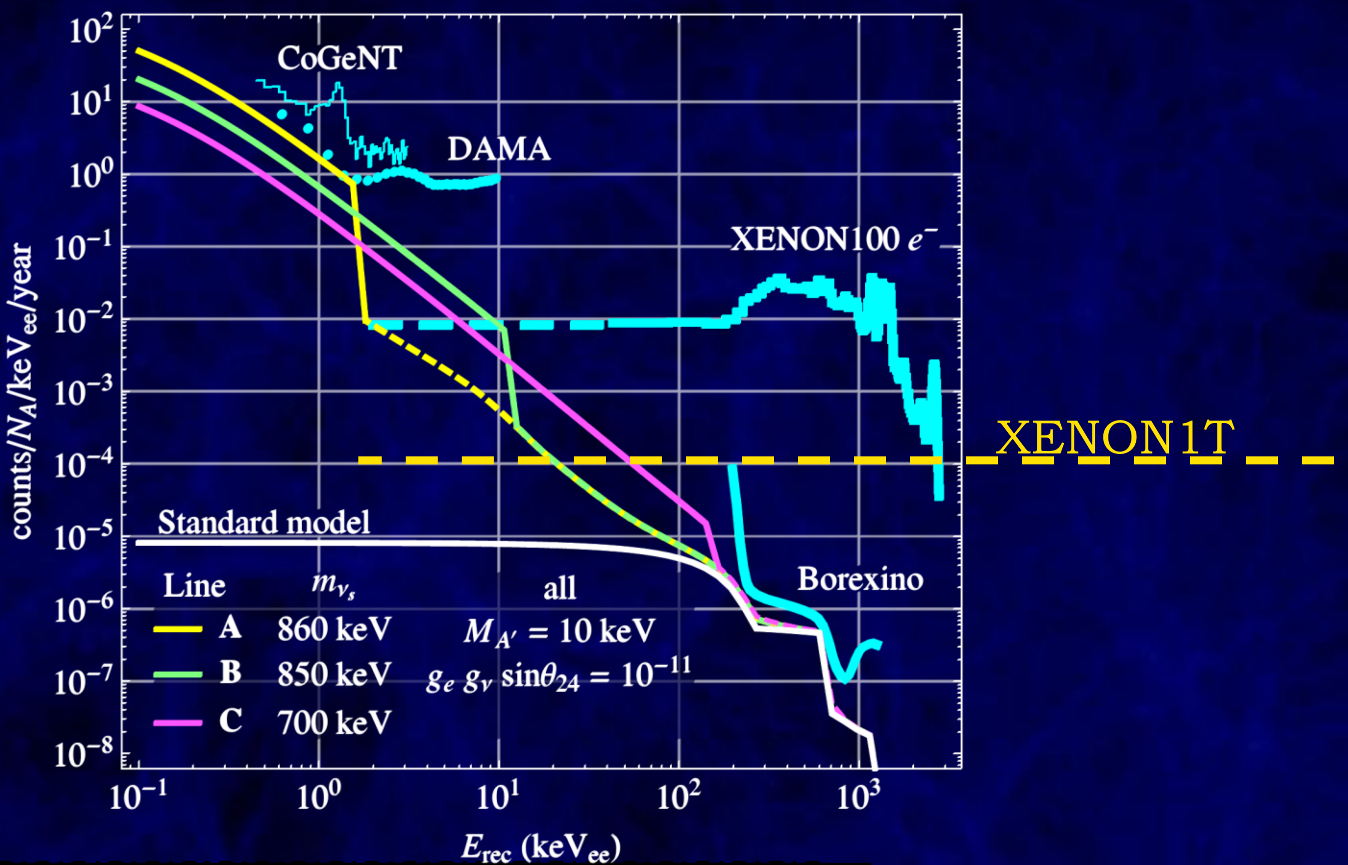
Harnik, Kopp & Machado 1202.6073

$\nu_x + e^- \rightarrow \nu_x + e^-$

Heavy Sterile Neutrinos

Modified predictions

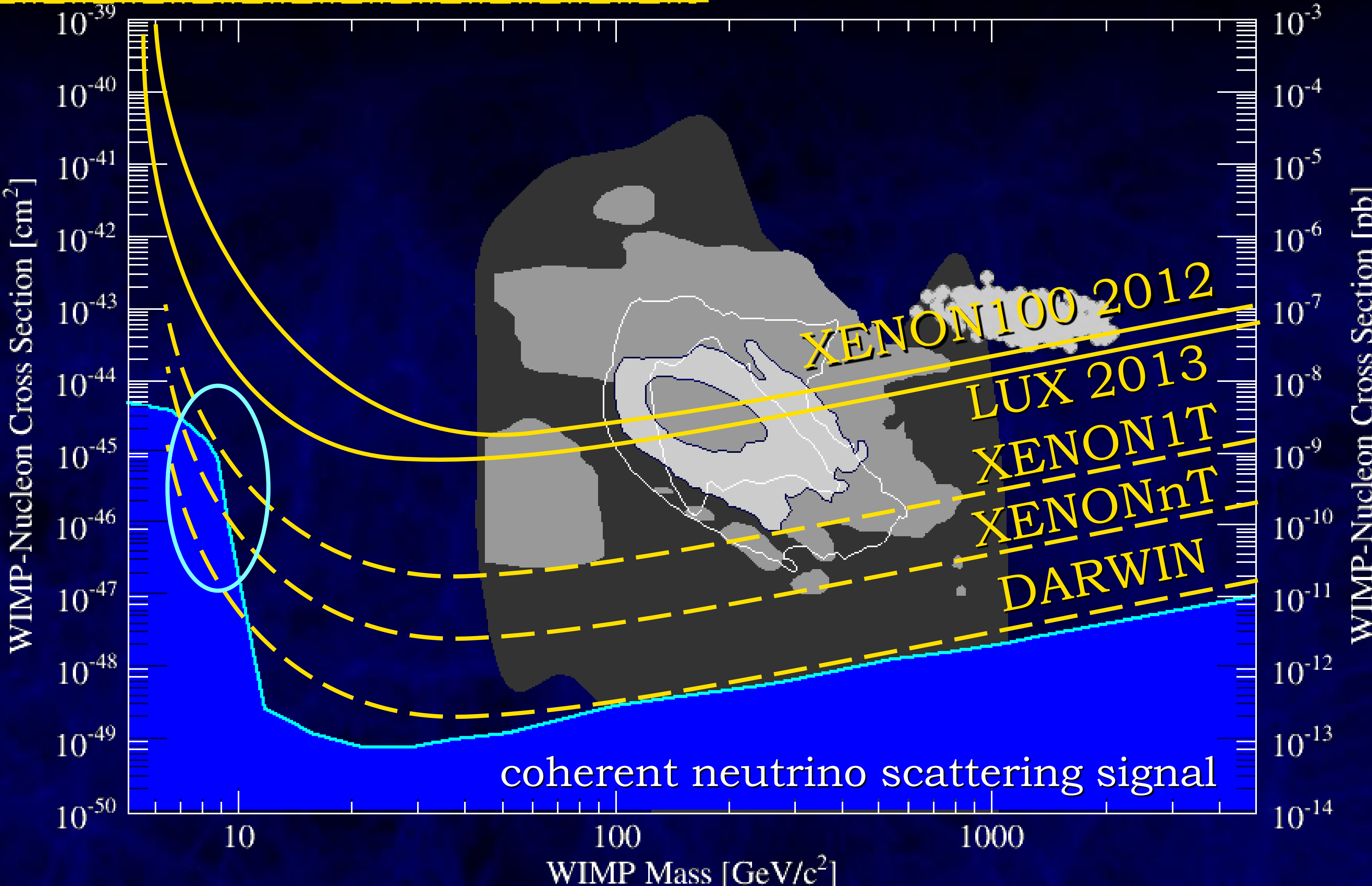
- Might enhance coherent rates below some threshold



Harnik, Kopp & Machado 1202.6073

$$\nu_x + N \rightarrow \nu_x + N$$

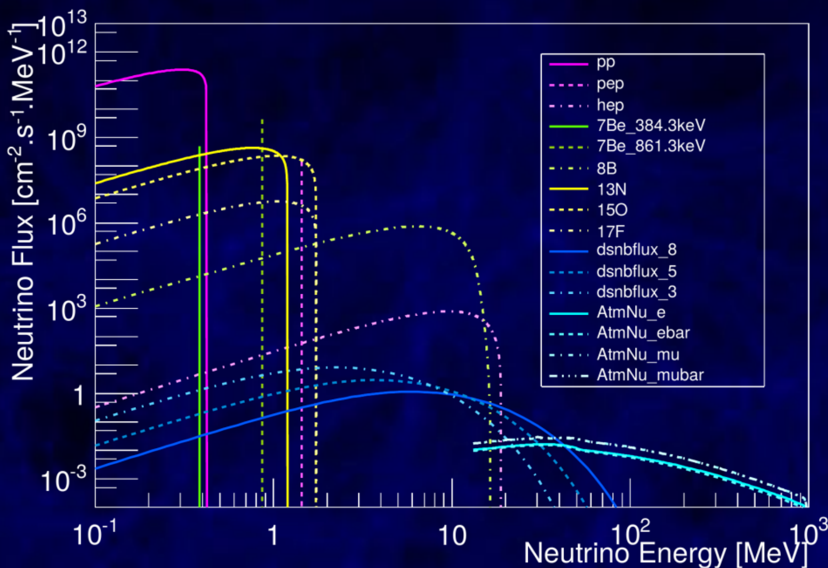
Coherent Neutrino-Nucleus Scattering

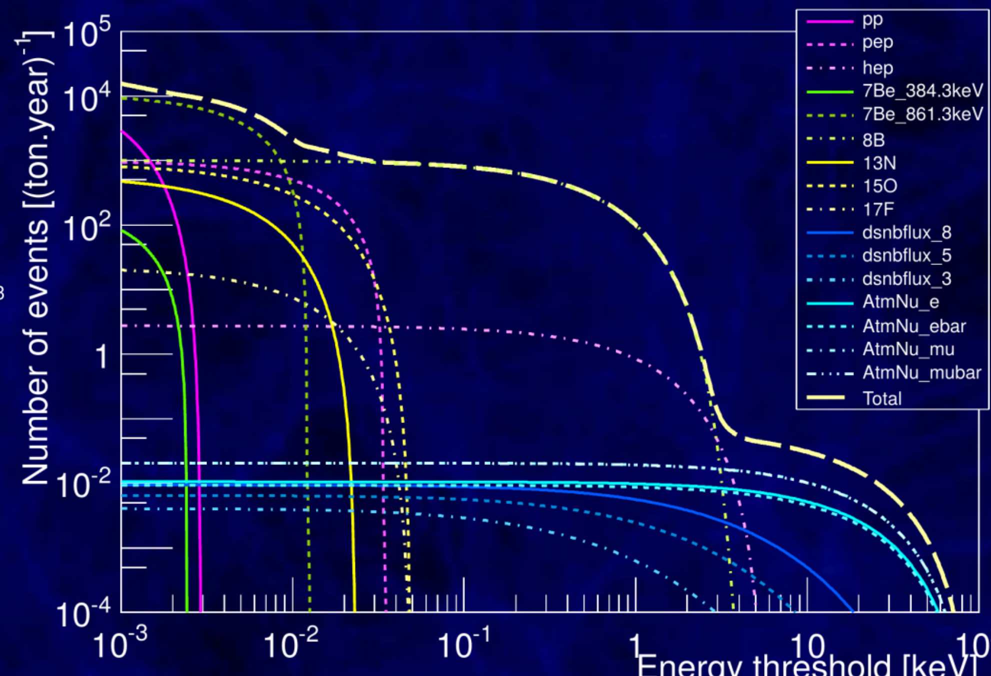


$\nu_x + N \rightarrow \nu_x + N$

Coherent Neutrino-Nucleus Scattering

- Expect first measurement already with XENON1T
- Constrain solar physics (^{8}B normalization)



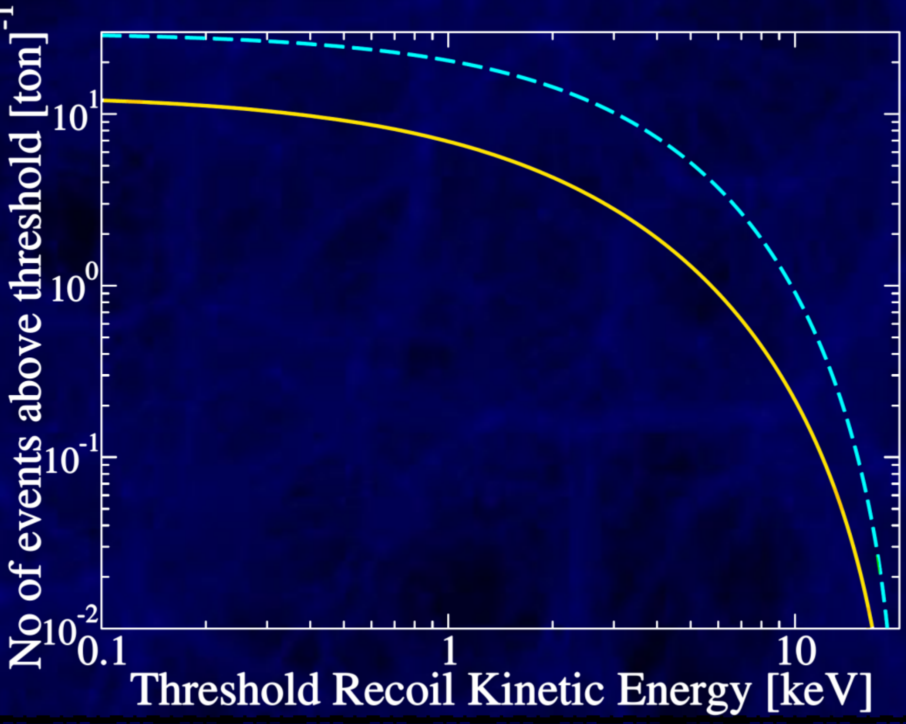


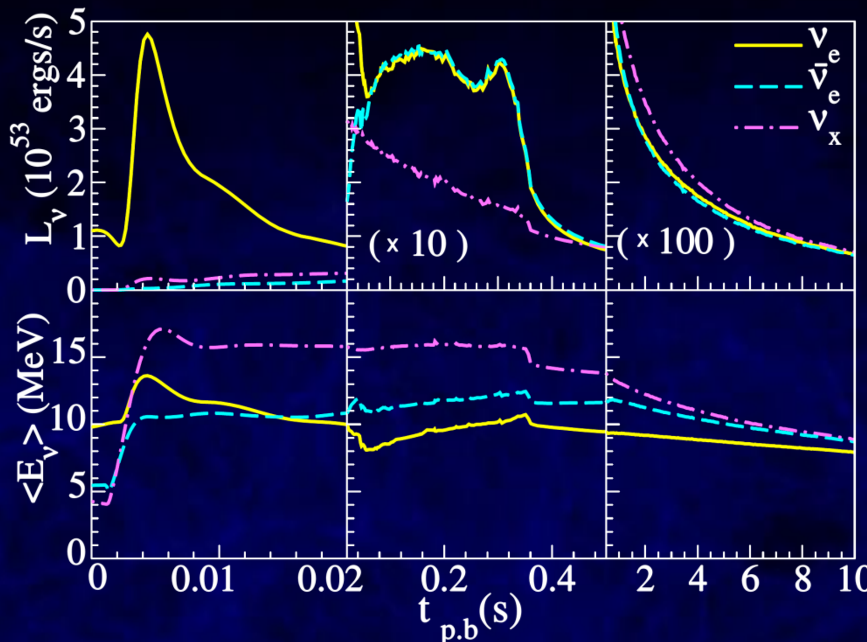
Billard, Strigari & Figueroa-Feliciano 1307.5458

Yes, Even Supernovas

Assume Galactic Supernova (10kpc, Basel/Darmstadt)

CC: $\mathcal{O}(0.1)\bar{\nu}_e$ per ton
CNNS: $\mathcal{O}(1)$ per ton





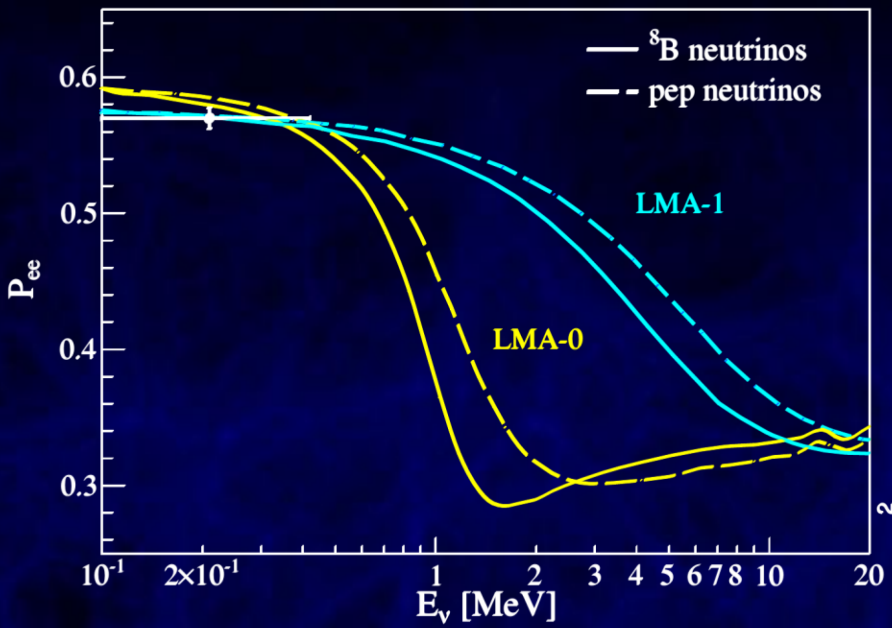
Flavor-independent: complementary information

Chakraborty, Bhattacharjee & Kar 1309.4492

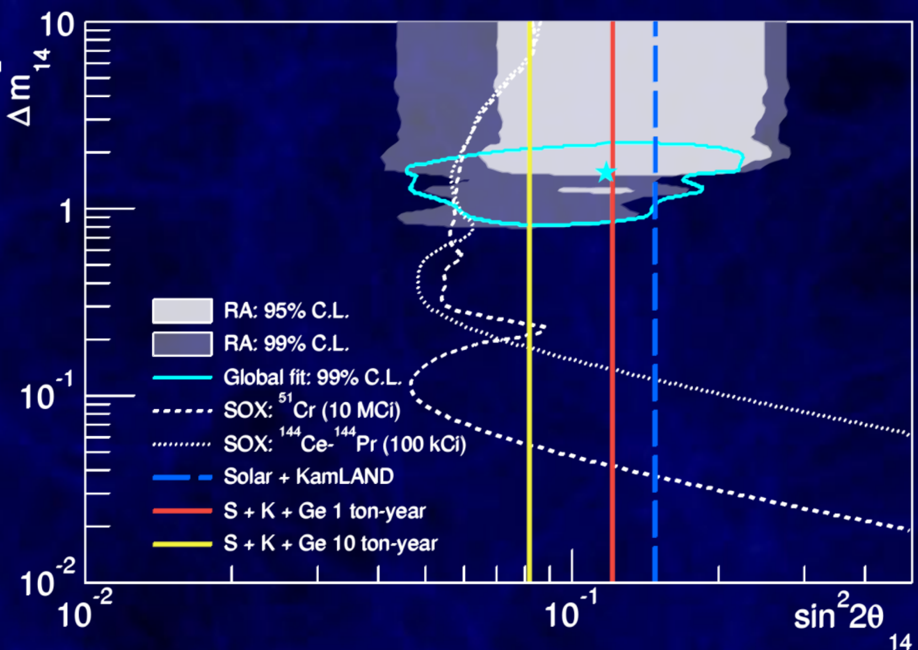
$$\nu_x + N \rightarrow \nu_x + N$$

Neutrino Oscillations

Baudis+ 1309.7024



Try to distinguish different neutrino oscillation scenarios? Probably requires >10 ton years



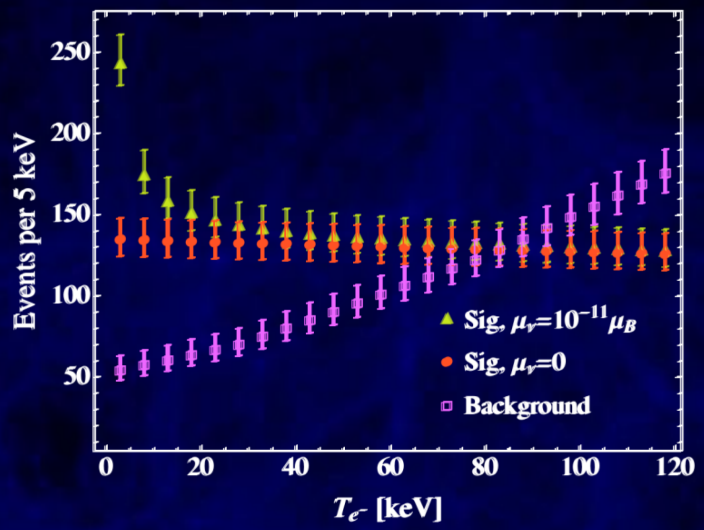
Billard, Figueroa-Feliciano & Strigari 1409.0050

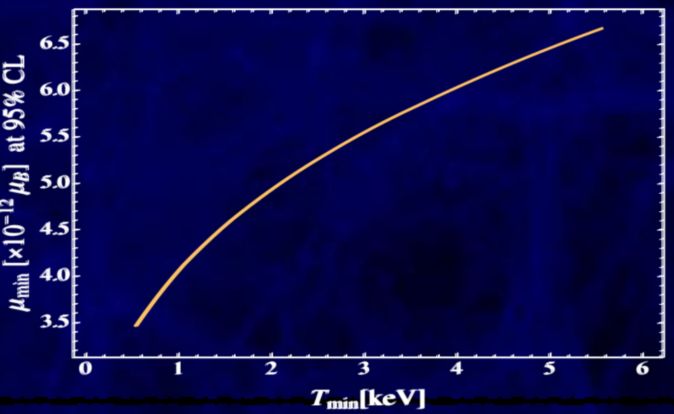
Coherent scattering is flavor-insensitive: Check for neutrino disappearance Here: Ge, 0.1keV threshold

$\nu_e + N \to \nu_e + N$

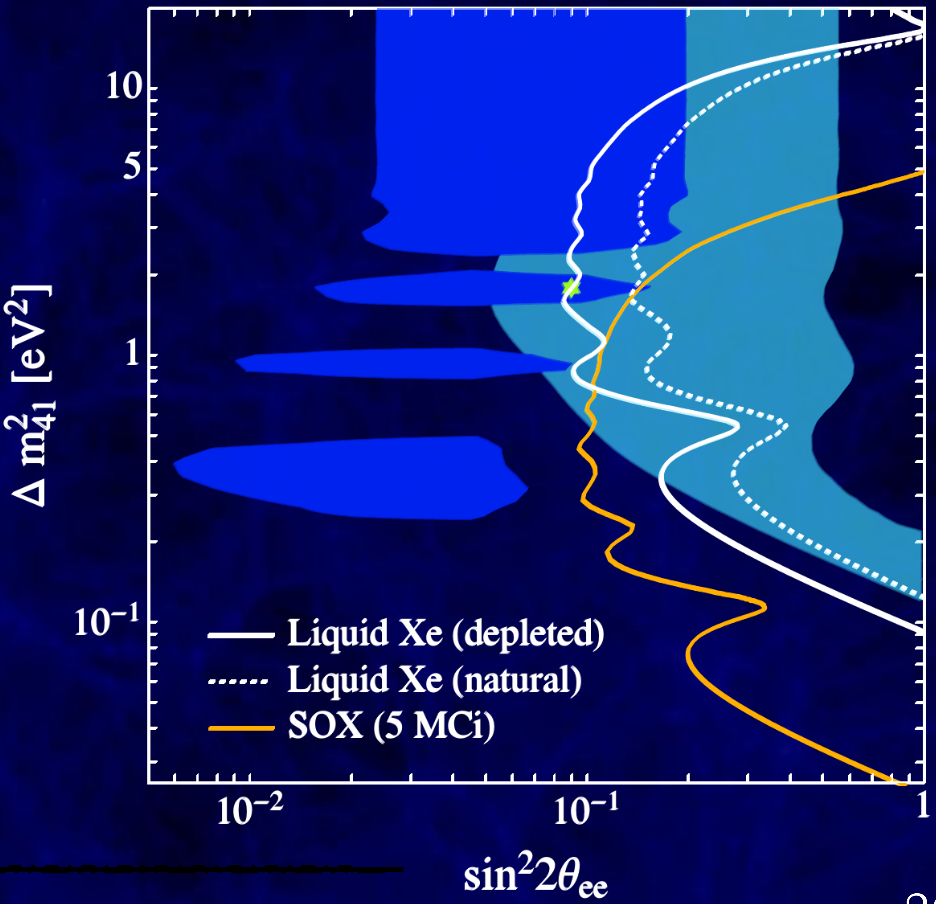
5MBq ^{51}Cr Anyone?

Sensitivity to neutrino magnetic moment





Complementary sterile ν sensitivity probably not with XENON1T



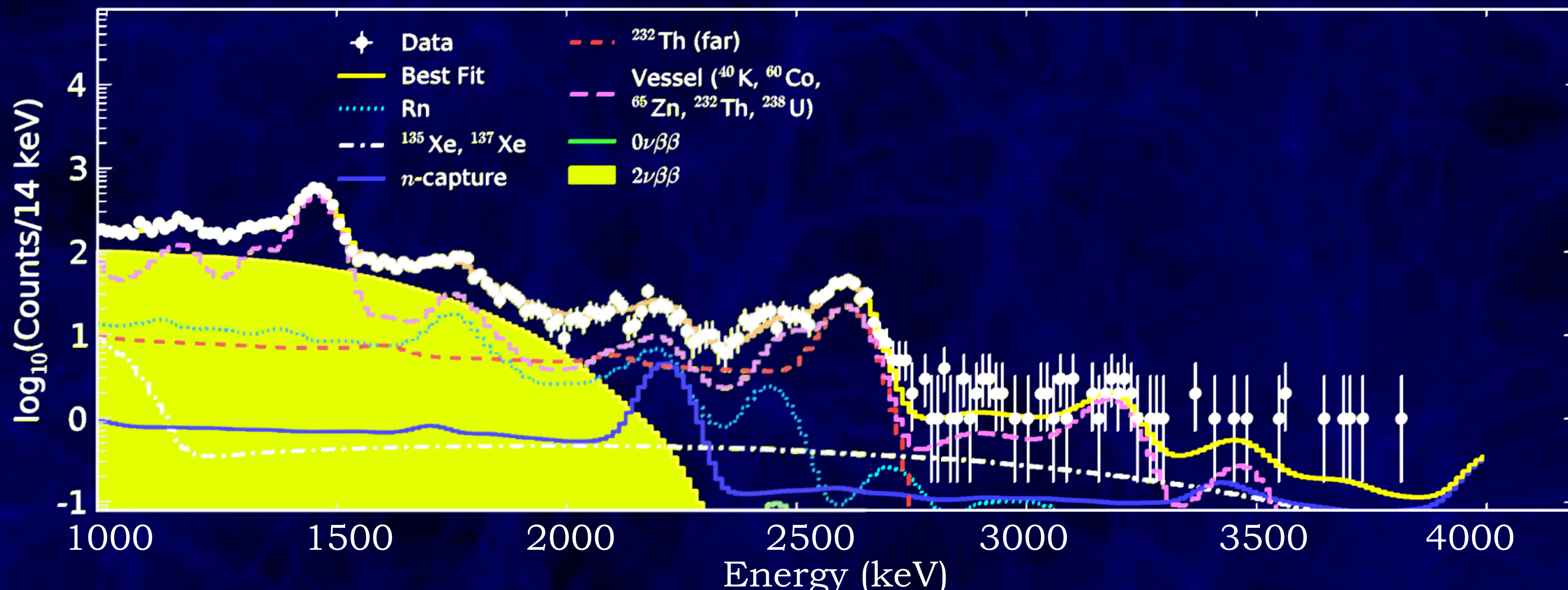
Coloma, Huber & Link 1406.4914

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^- + 2\bar{\nu}_e$$

^{136}Xe 2ν2β: Measure Half-Life

$T_{1/2}$ = (2.16±0.06) x 10^{21} a
Best-measured value, best-known matrix element

Dominant background overall for large Xe target, e.g. EXO-200 spectrum:

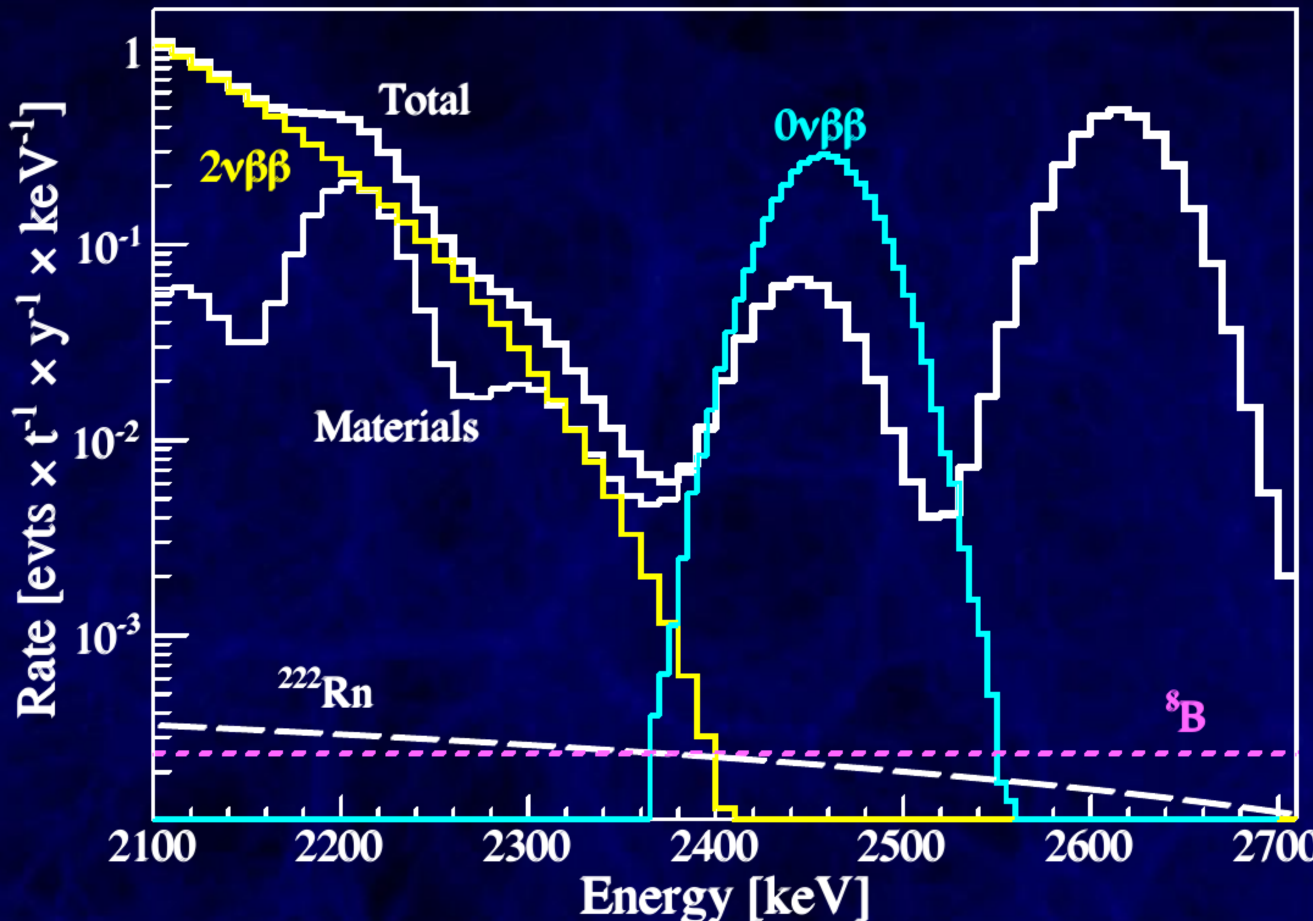


EXO-200 1402.6956

$^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

^{136}Xe 0ν2β With ^{nat}Xe Target

Requires TPC performing also at high energies
Hard with XENON1T… e.g. 20 ton DARWIN detector:

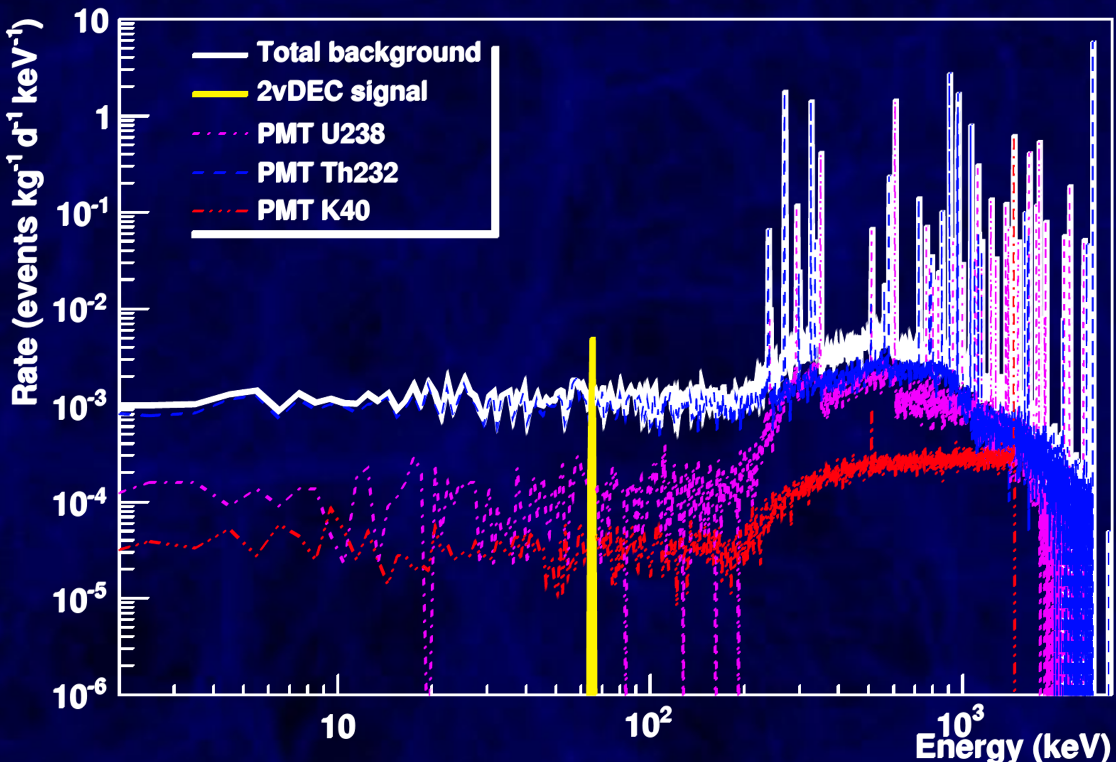


Baudis+ 1309.7024

$$2e^- + {}^{124}\mathrm{Xe} \rightarrow {}^{124}\mathrm{Te} + 2\nu_e$$

Double-Electron Capture of ^{124}Xe

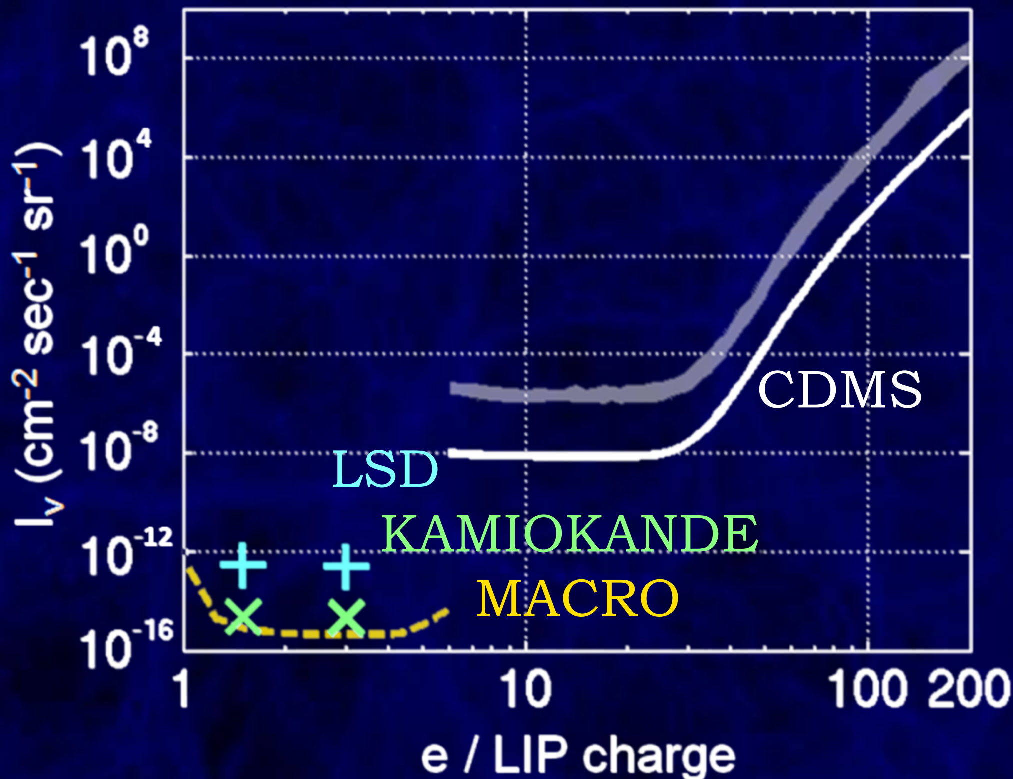
As 2ν2β, just the other way around
Expect $T_{1/2} = 2.9\mathrm{x}10^{21}$a
Calculated from XENON100 data: $T_{1/2} > 1.6\mathrm{x}10^{21}$a
LUX simulation:



Mei+ 1310.1946

Fractionally Charged Particles

- Also called Lightly Ionizing Particles: less than minimum ionizing
- Leave a track in the TPC
- Limit on flux:



CDMS 1409.3270

Much more than just a WIMP search!

Liquid Noble Physics

- Light and charge yield
- Properties of the liquids
- Radioactivity Assays
- Particle Interaction Modeling
- Pushing the Technology

Dark Matter

- Spin-independent WIMPs
- Various couplings
- GeV WIMPs ("S2-only")
- Inelastic WIMPs
- Magnetic Inelastic WIMPs
- Axial-Vector coupling
- Mirror, Luminous DM
- MeV WIMPs
- Axion-Like Particles

Astrophysics

- Measure solar pp ν
- Normalization of ^{8}B solar rate
- Supernovae

Double-Beta

- Two-Neutrino Decay of ^{136}Xe
- Neutrinoless Decay of ^{136}Xe
- Double-EC on ^{124}Xe

Particles Physics

- Coherent Scattering
- Neutrino Oscillations
- Sterile Neutrinos
- Solar Axions
- Fractionally Charged Particles