Direct detection of WIMPs

COSMO 2014

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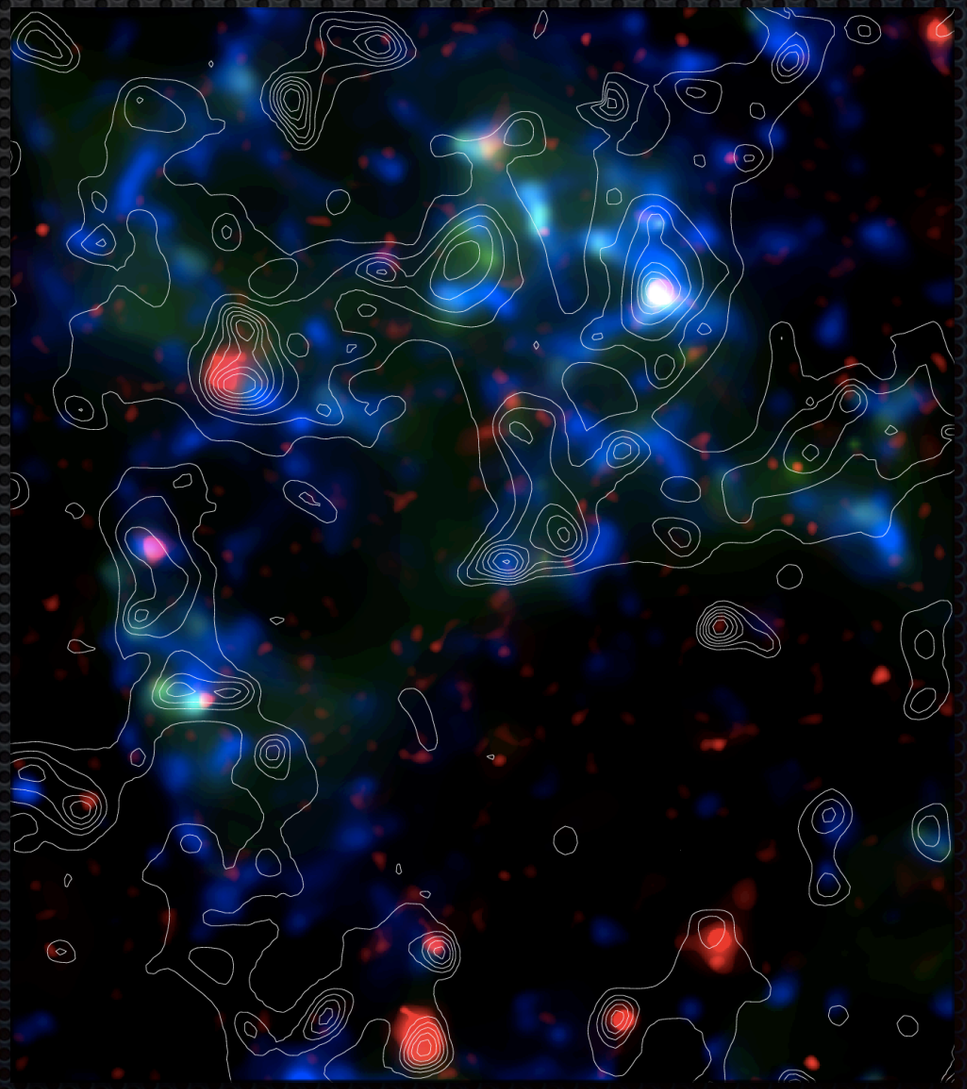
The dark matter puzzle

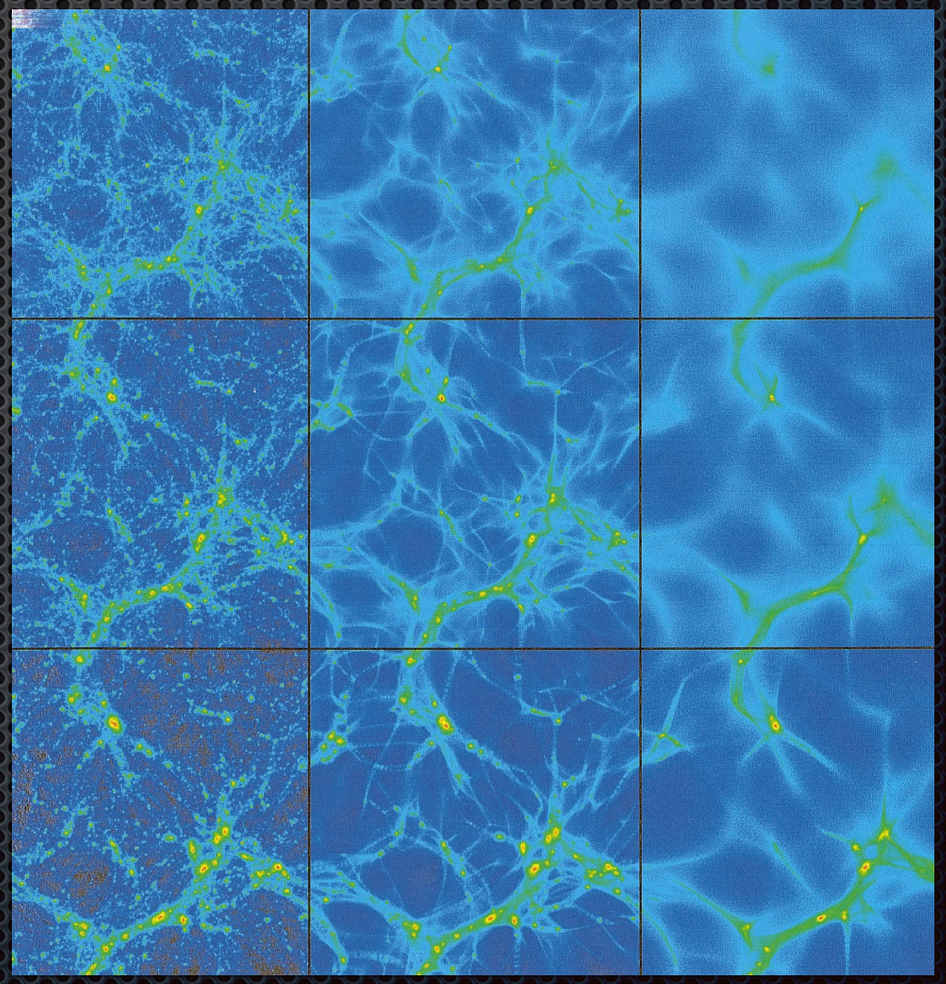
- The dark matter puzzle is fundamental: dark matter leads to the formation of structure and galaxies in the universe
- We have a so-called “standard model” of CDM, from “precision cosmology”: however, measurement ≠ understanding
- For 85% of matter in the universe is of unknown nature



What do we know about dark matter?

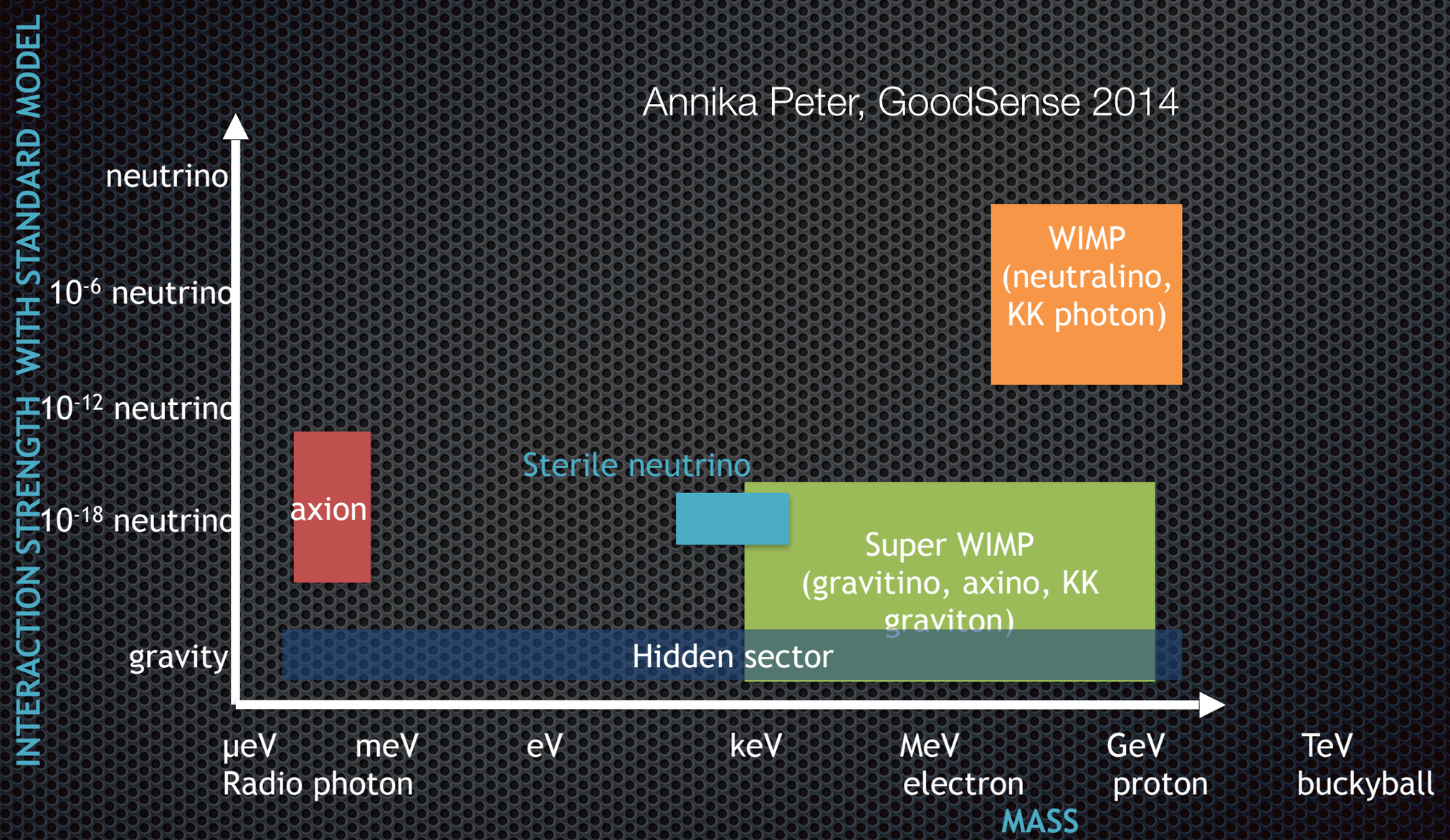
- So far, we mostly have “negative” information
- No color charge
- No electric charge
- No strong self-interaction
- Not a particle in the Standard Model of particle physics

Cold Warm Hot



What do we know about dark matter?

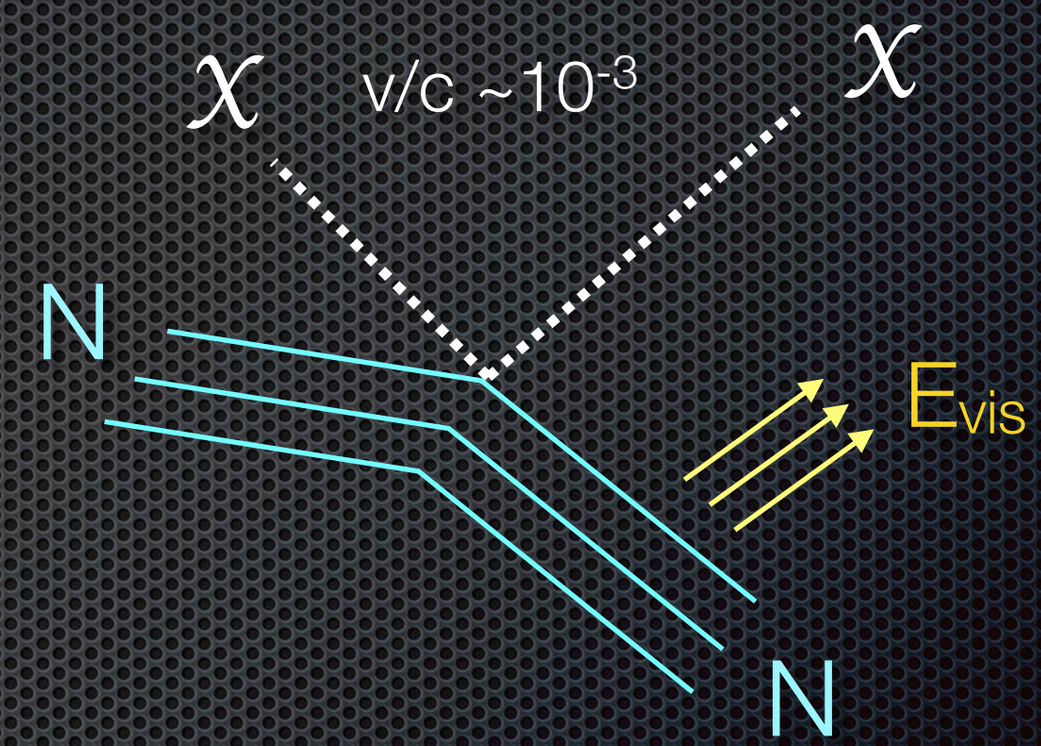
- The mass range spans merely 90 orders of magnitude



In this talk I will focus on the **weak scale,** and on direct detection

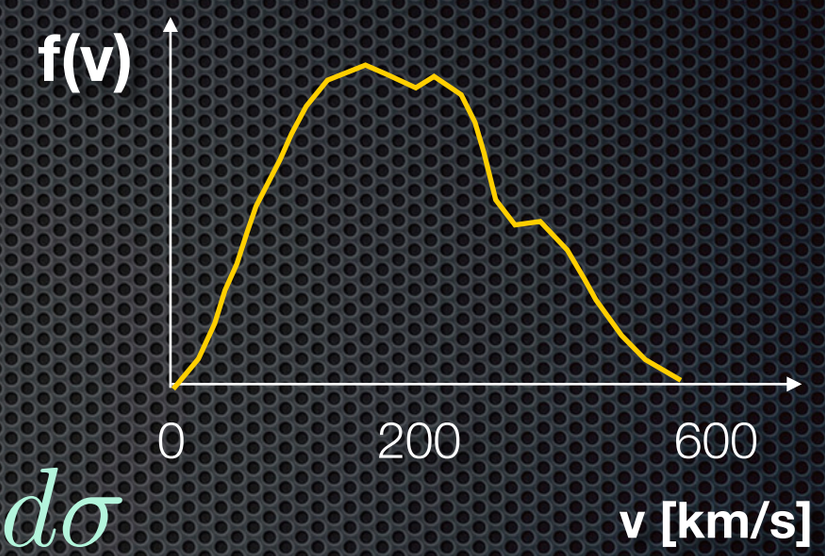
How to directly detect it in the lab?

- By searching for collisions of invisibles particles with atomic nuclei => E_{vis} (q ~ tens of MeV)
- Need *very low energy thresholds*
- Need *ultra-low backgrounds*, good background understanding (no "beam off" data collection mode) and discrimination
- Need *large detector masses* (remember neutrino detectors)



$$E_R = \frac{q^2}{2m_N} < 100\,\mathrm{keV}$$

What do we expect in a detector?



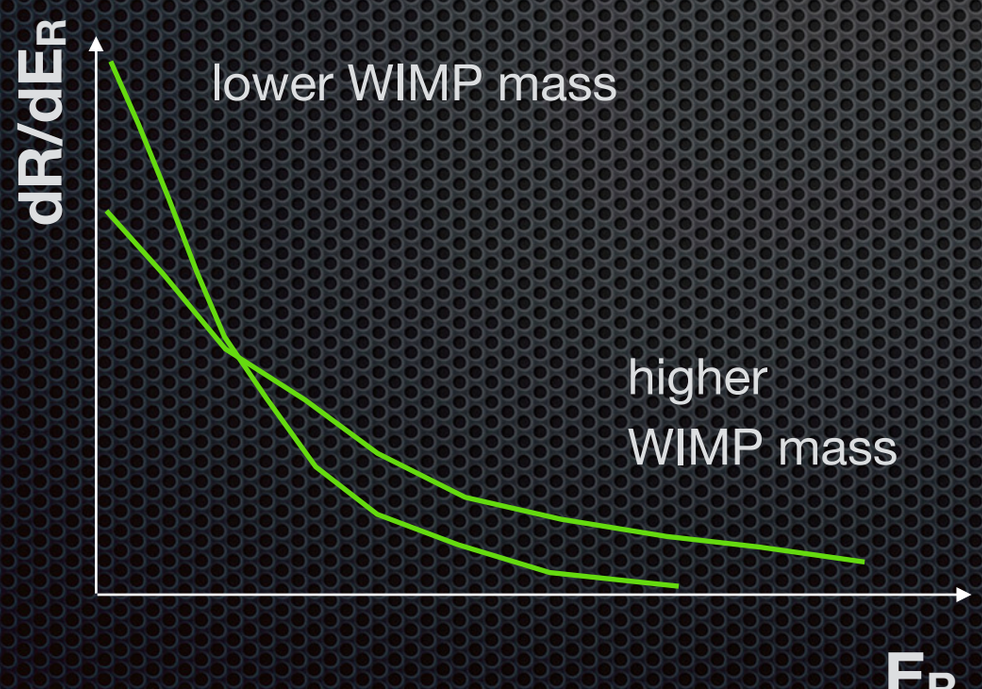
Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}$$

Detector physics

Particle/nuclear physics

$$v_{\min} = \sqrt{\frac{m_N E_{th}}{2 m_{\mathrm{r}}^2}}$$



$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

Justin Read, arXiv:1404.1938

WIMP scattering cross section

Scalar (S) $\mathcal{L} = \frac{G_S}{\sqrt{2}}\bar{\chi}\chi\bar{f}f$

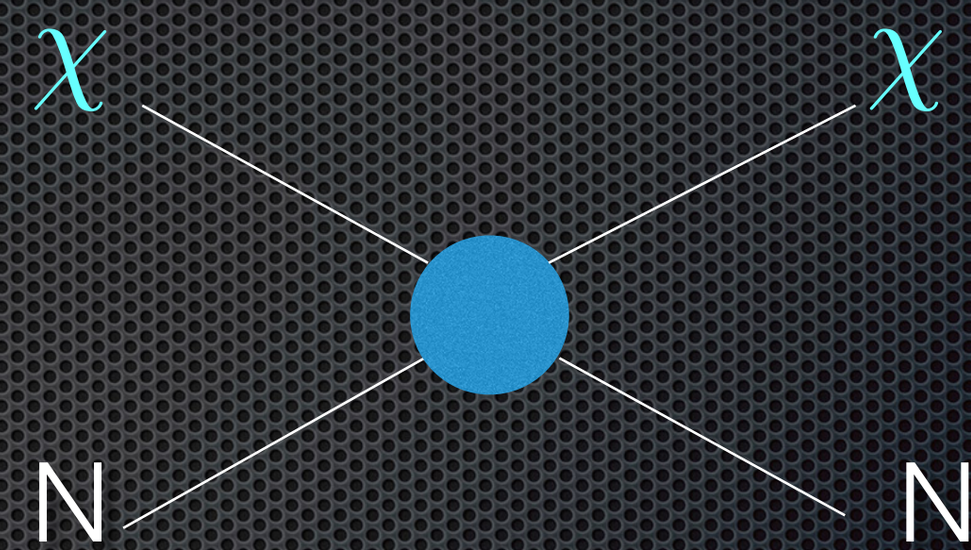
Pseudoscalar (P) $\mathcal{L} = \frac{G_P}{\sqrt{2}}\bar{\chi}\gamma^5\chi\bar{f}\gamma_5 f$

Vector (V) $\mathcal{L} = \frac{G_V}{\sqrt{2}}\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$

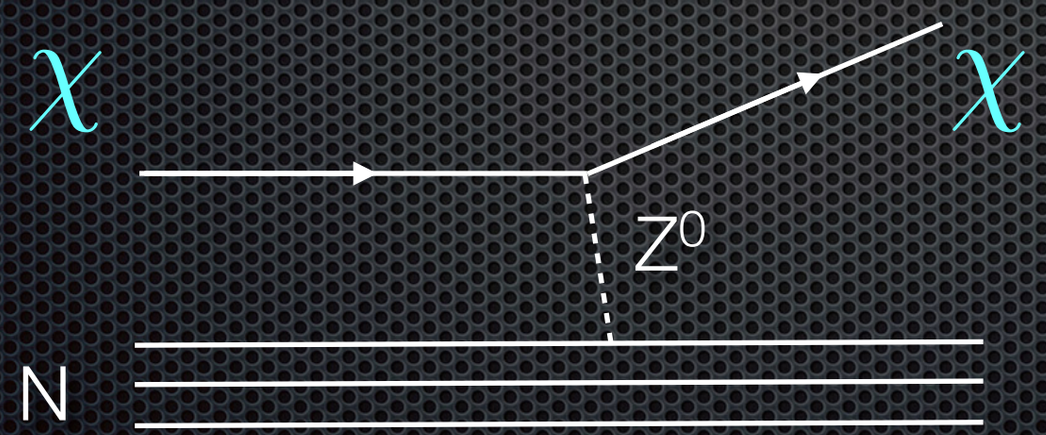
Axialvector (A) $\mathcal{L} = \frac{G_A}{\sqrt{2}}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{f}\gamma_\mu\gamma^5 f$

Tensor (T) $\mathcal{L} = \frac{G_T}{\sqrt{2}}\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi\bar{f}\sigma_{\mu\nu}\gamma^5 f$

Effective field theory approach, always valid for direct detection

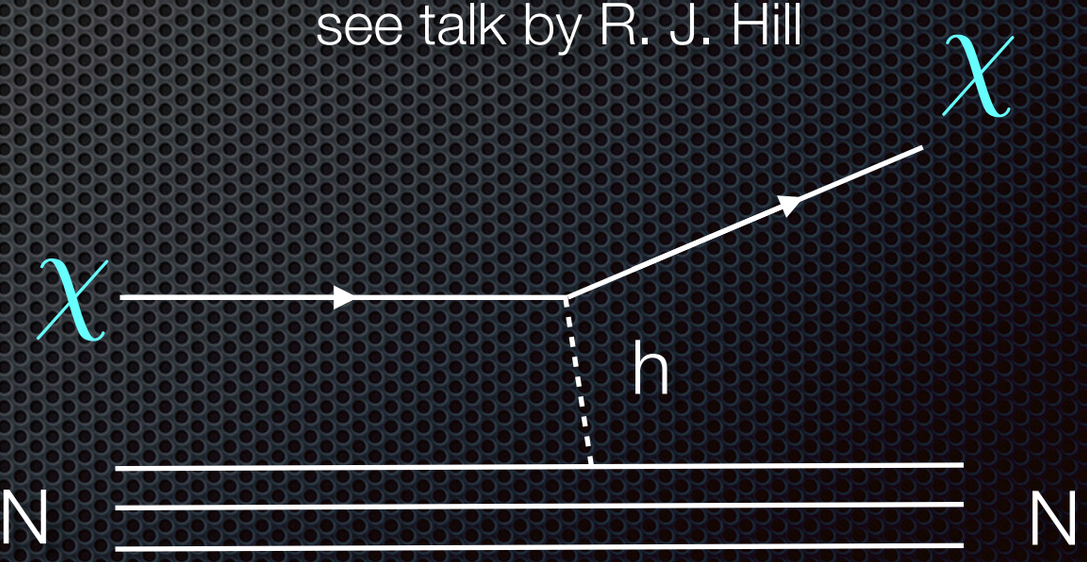


see talk by R. J. Hill



$\sigma_0 \sim 10^{-39}\,\mathrm{cm}^2$

see talk by Neal Weiner

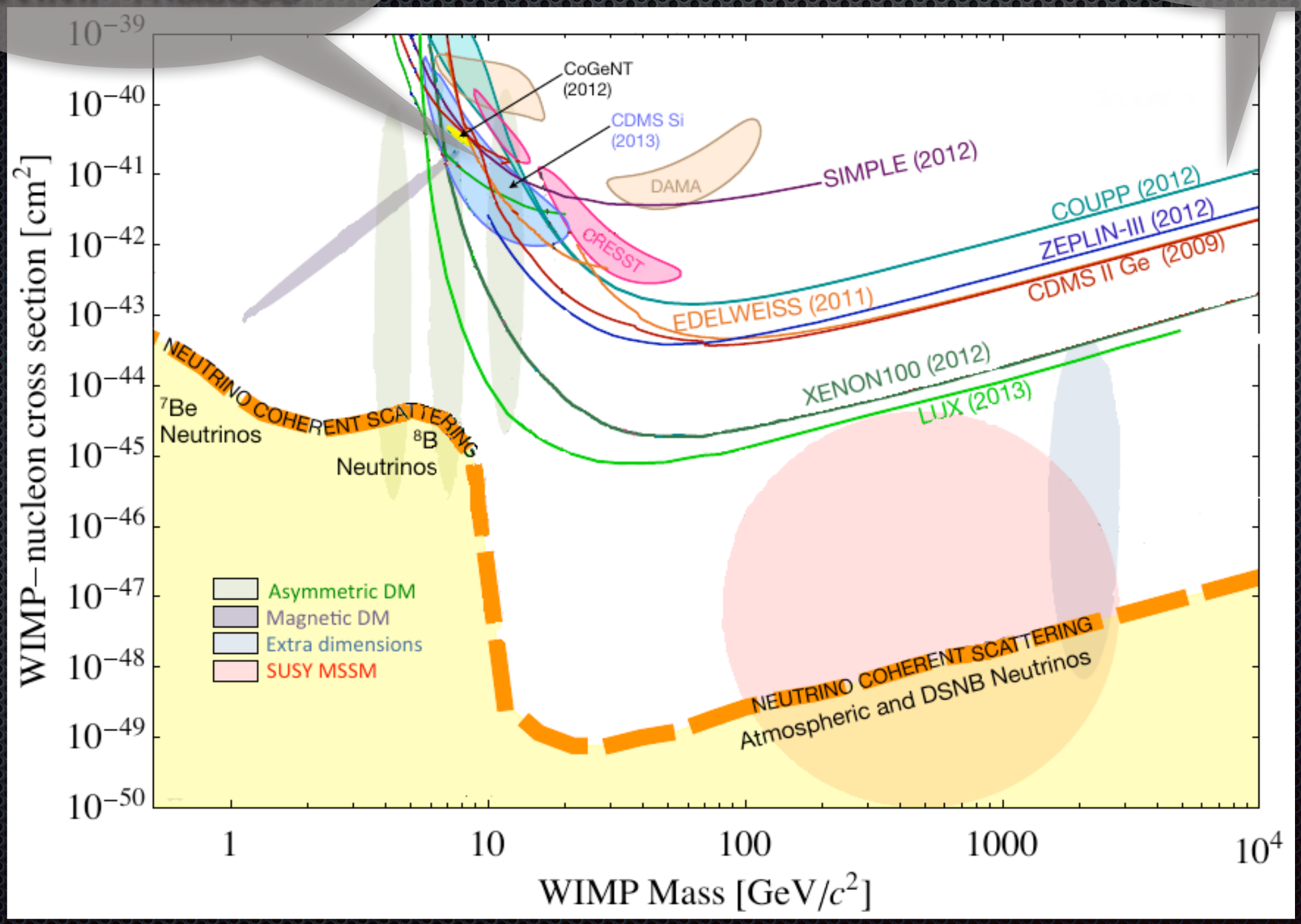


$\sigma_0 \sim 10^{-45}\,\mathrm{cm}^2$

The WIMP landscape in 2014

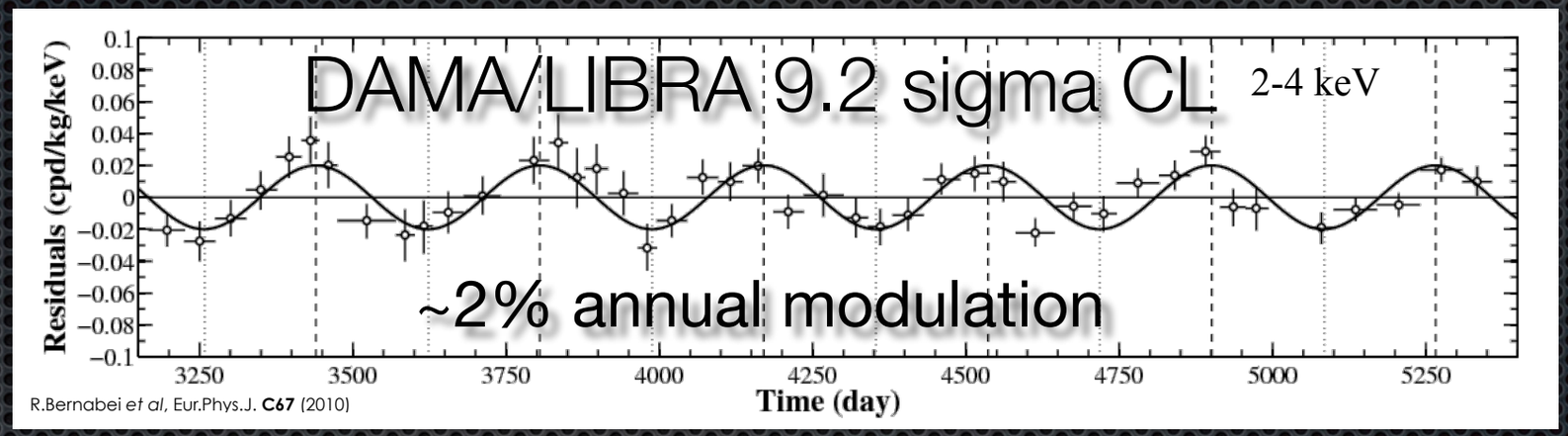
"Anomalies" at low WIMP masses

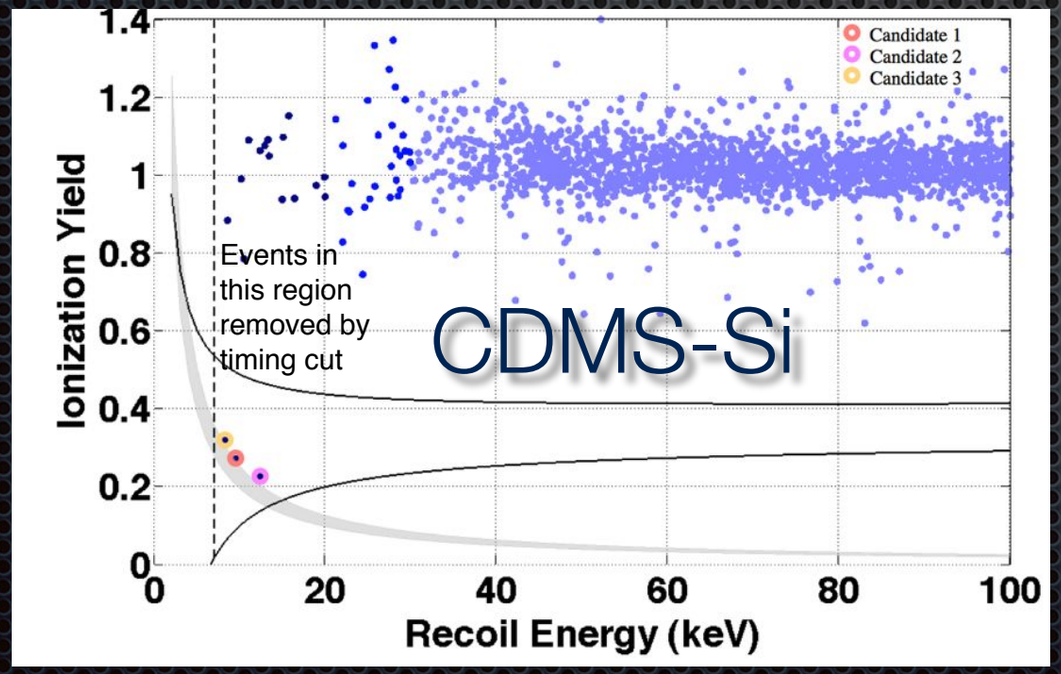
Sensitivity to masses up to 10 TeV and above!

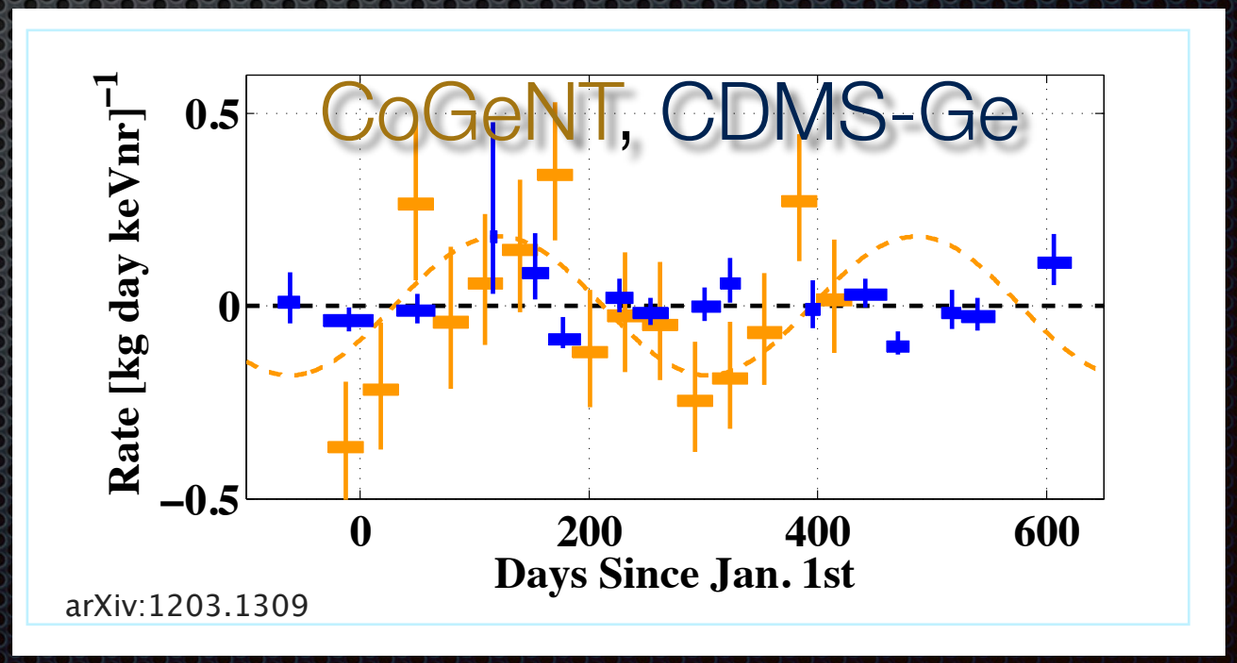


Have we observed low-mass WIMPs?

CDMS-Si, DAMA/LIBRA,
CoGeNT, CRESST: excess of events
above the *known* backgrounds







Have we observed low-mass WIMPs?

Or merely "*thresholdinos*"?

The Practical Matter of a Low Energy Rare Event Search

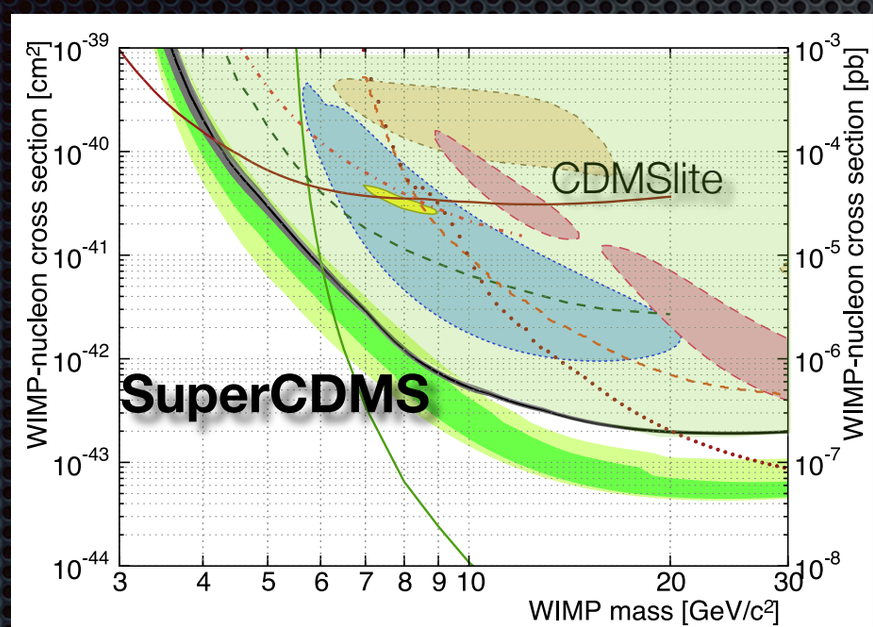
- Dark Matter signals will be expected to appear first in the lowest energy bins of an experiment that is still in search mode
- Unfortunately, that is also where the first indications that systematics are starting to dominate

Thresholdinos

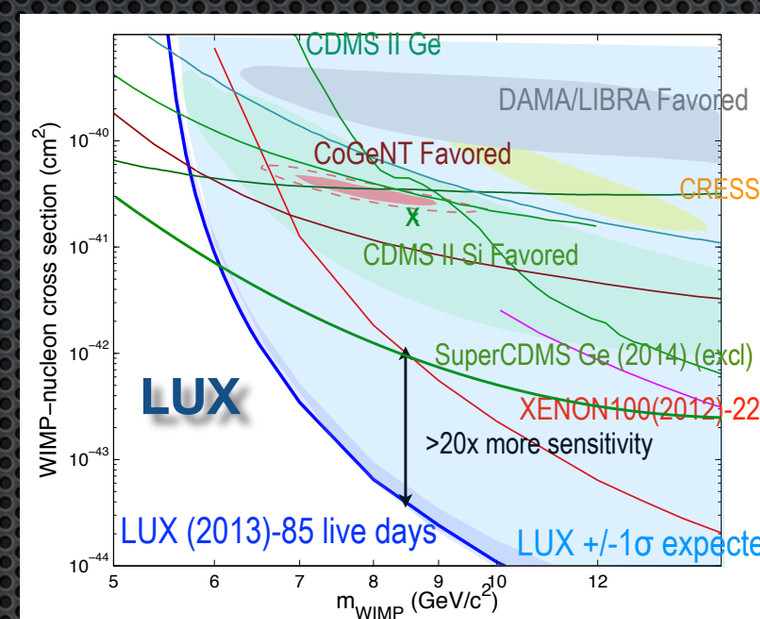
- You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram - Attributable, in spirit to Rutherford (I believe)
- It is difficult to control systematics that may cause events to be in edge bins/tails
  - This is particularly important when a result is dependent on subtle effects
- And we will need to push the detectors by another 10^4 before we reach the irreducible coherent scattering atm. neutrino backgrounds

Low-mass region: *heavily constrained* by CDMS-Ge, XENON10, XENON100, LUX, EDELWEISS, CRESST, CoGeNT, PandaX,....

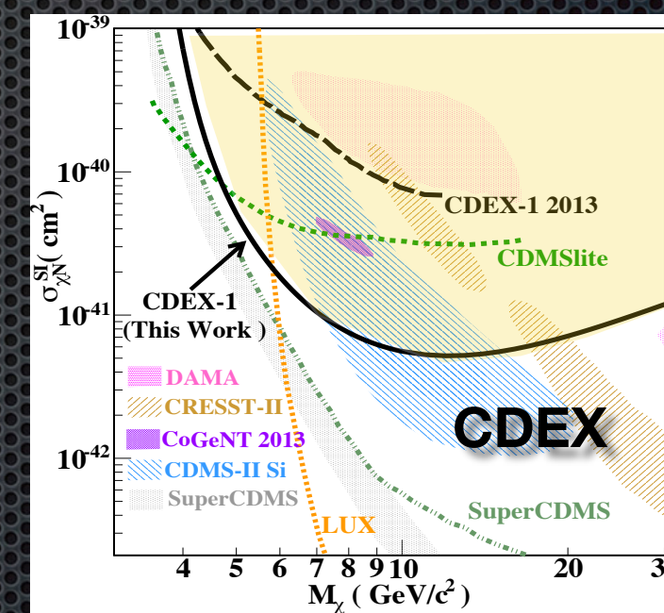
CDMS, PRL 112, 2014

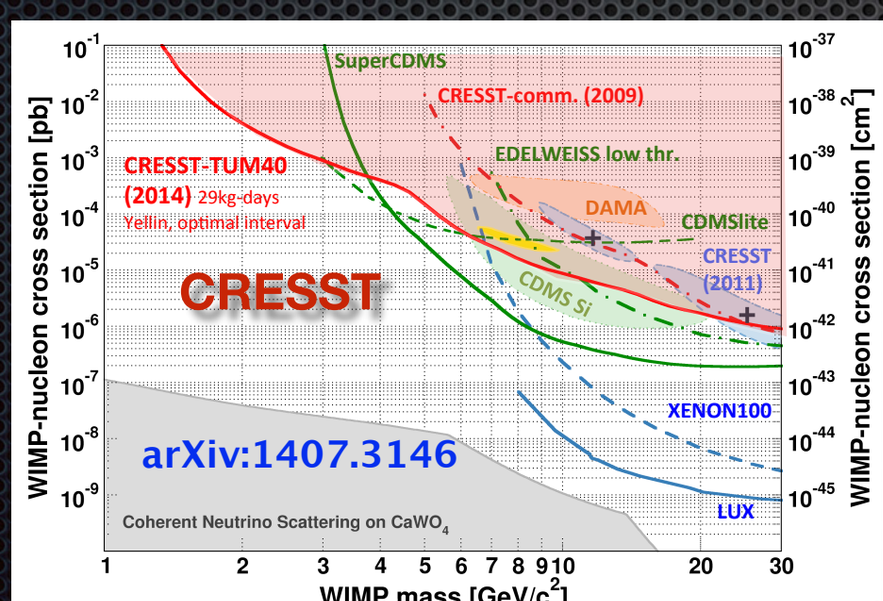


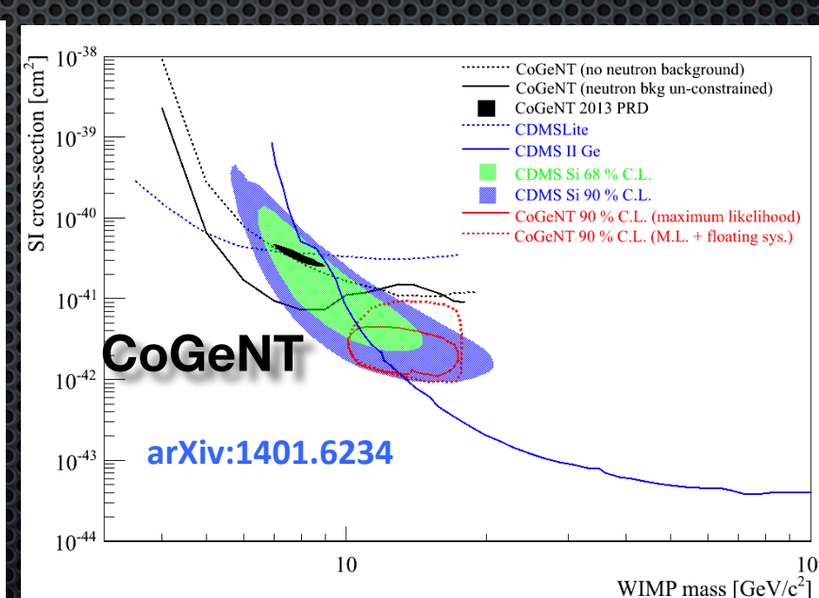
LUX, PRL, arXix: 1310.8214

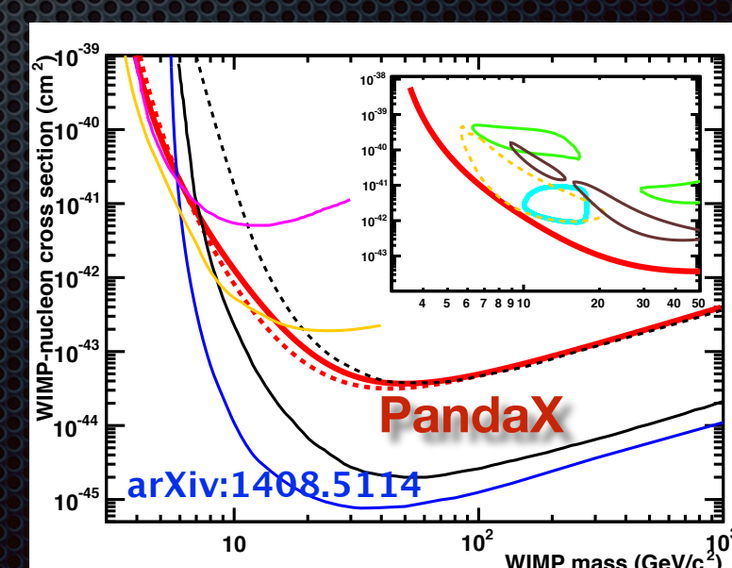


CDEX, arXiv:1404.4946





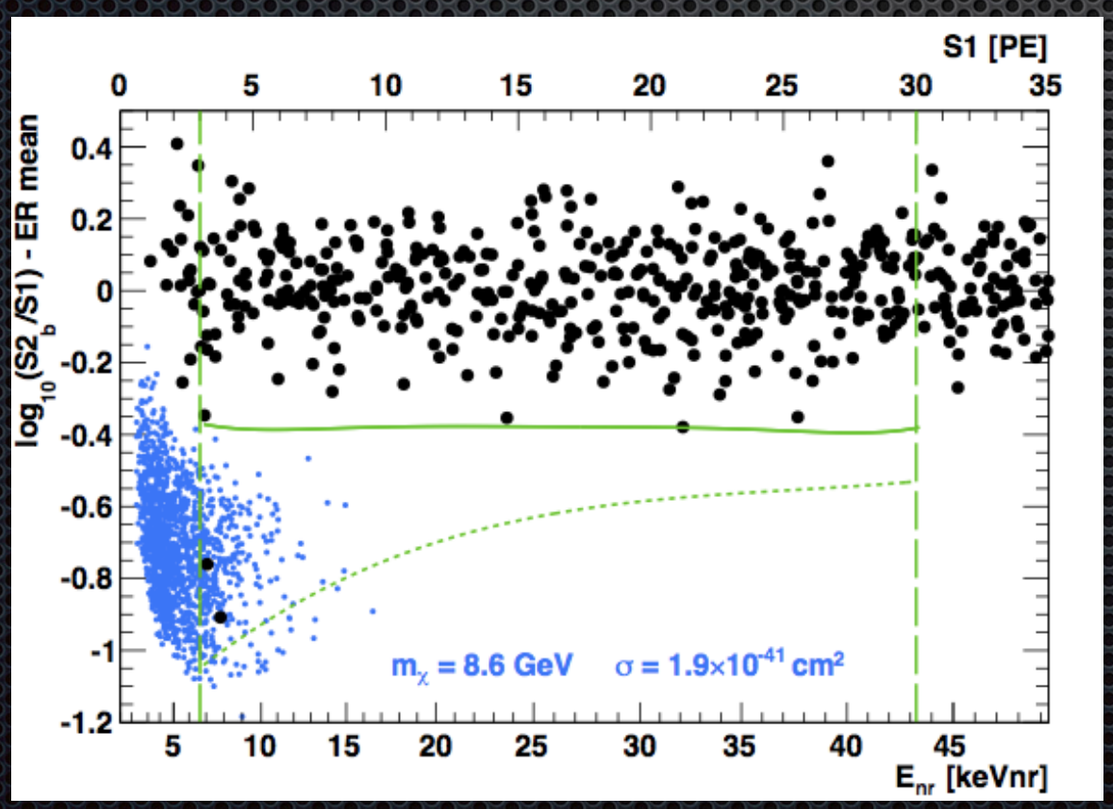




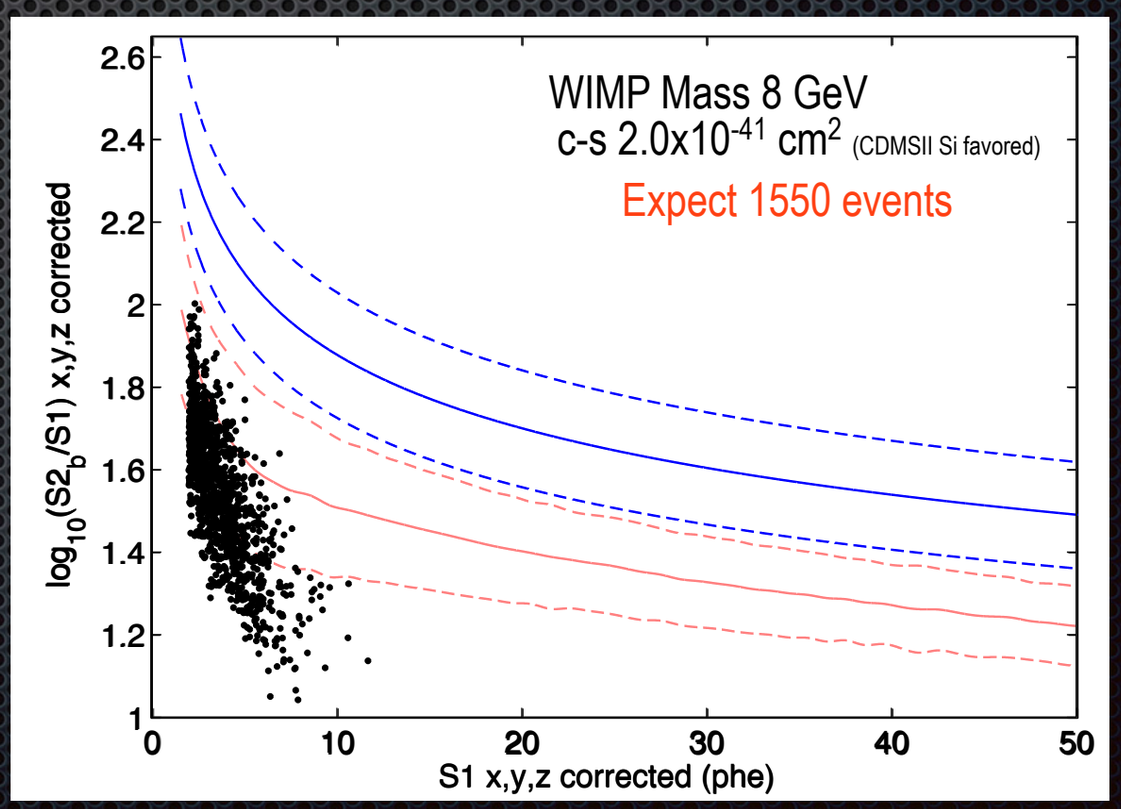
How would a CDMS-Si like signal look like in XENON100 and LUX?

Assumption:
m_W = 8.6 GeV and WIMP-nucleon cross section of 1.9 x 10^{-41} cm^2

XENON100 Run10
expect: ~ 220 events

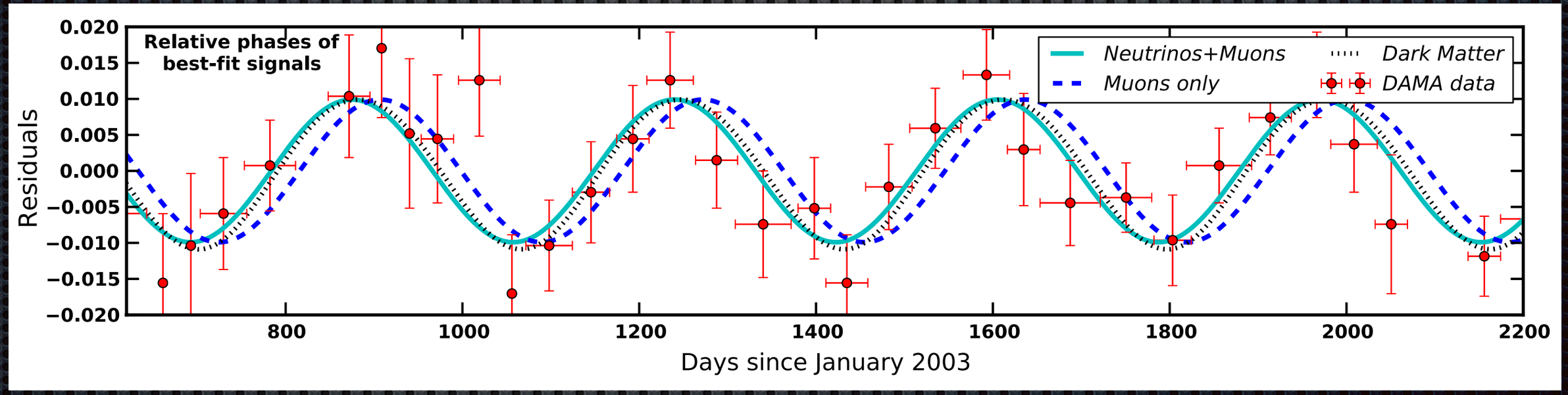


LUX first run
expect: ~ 1550 events



What is the origin of the DAMA signal?

- Possible explanation: a combination of neutrinos and muons
- Solar ^{8}B neutrino- and atmospheric muon-induced neutrons
- *Combined phase of muon and neutrino components*: good fit to the data*



Jonathan Davis, PRL 113, 081302 (2014)

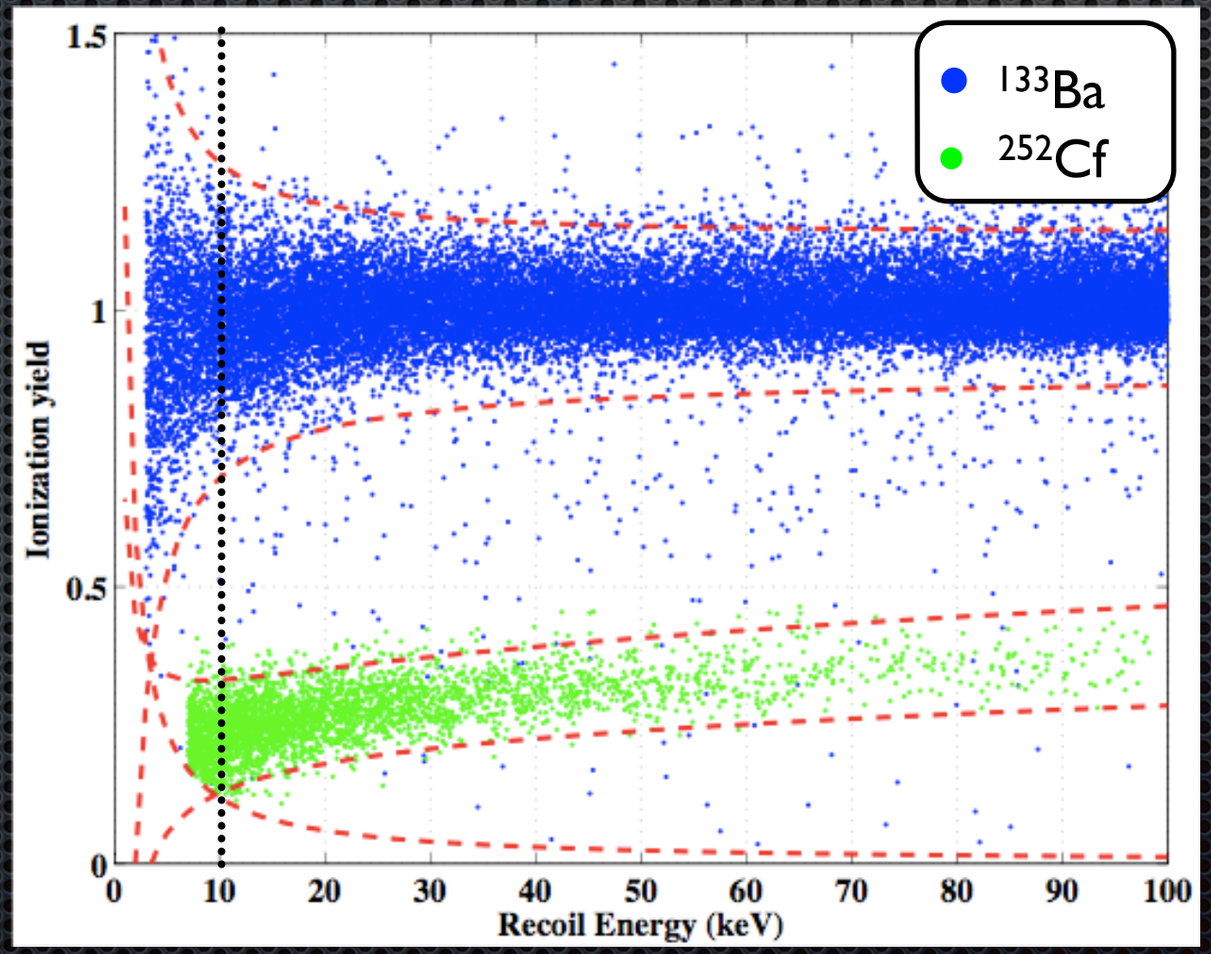
*Muons: flux correlated with T of atmosphere; period is ok but phase is 30 d too late
*Neutrinos: flux varies with the Sun-Earth distance; period is ok but phase peaks in early Jan

What next? We need *a variety of techniques* to convincingly discover and constrain WIMPs!

Cryogenic Experiments at T~ mK

- **High** sensitivity to nuclear recoils, good energy resolution, **low energy threshold (keV to sub-keV) => low-mass WIMPs**
- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination **-> separation of S and B**

Ratio of charge (or light) to phonon

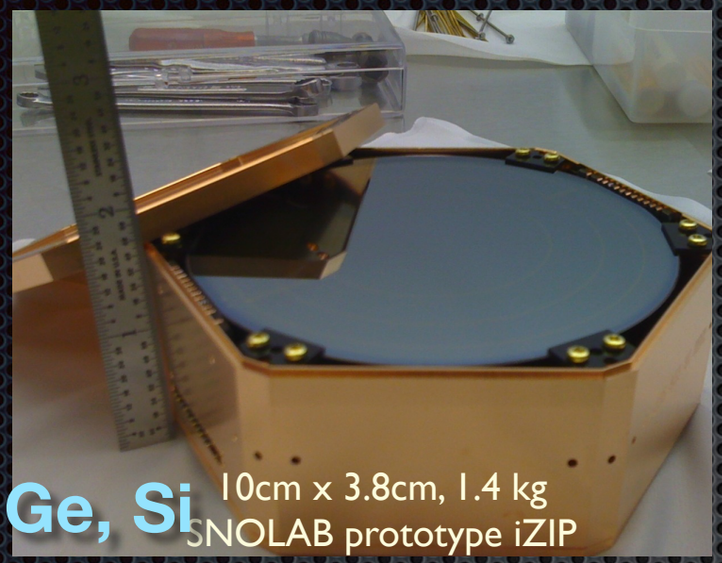


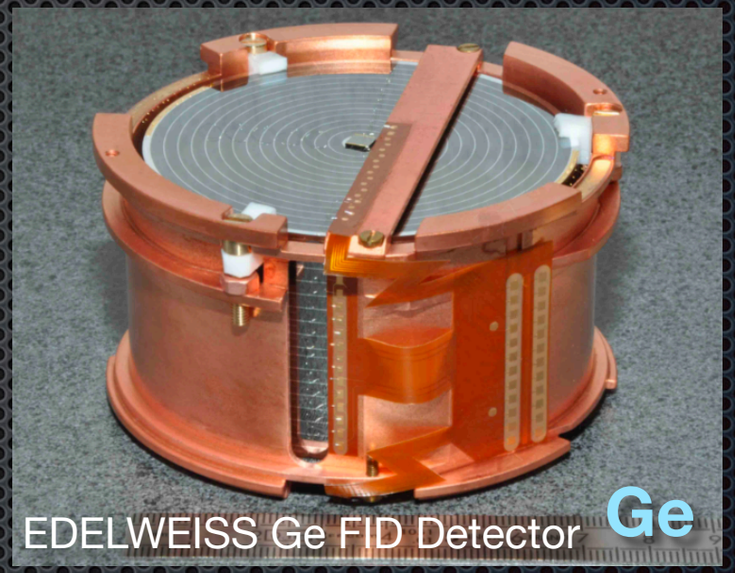
Background region

Expected signal region

New data from cryogenic experiments

- Absorber masses from ~ 100 g to 1400 g





SuperCDMS

new, leading results at low masses

proposed for SNOLAB:
Std: ~92 kg Ge, 11 kg Si
Lite: 5 kg Ge, 1.2 kg Si

CRESST

18 $CaWO_3$ detector modules (5 kg) installed at LNGS in 2013

low-background run in 2014, recent results and taking more data

EDELWEISS-III

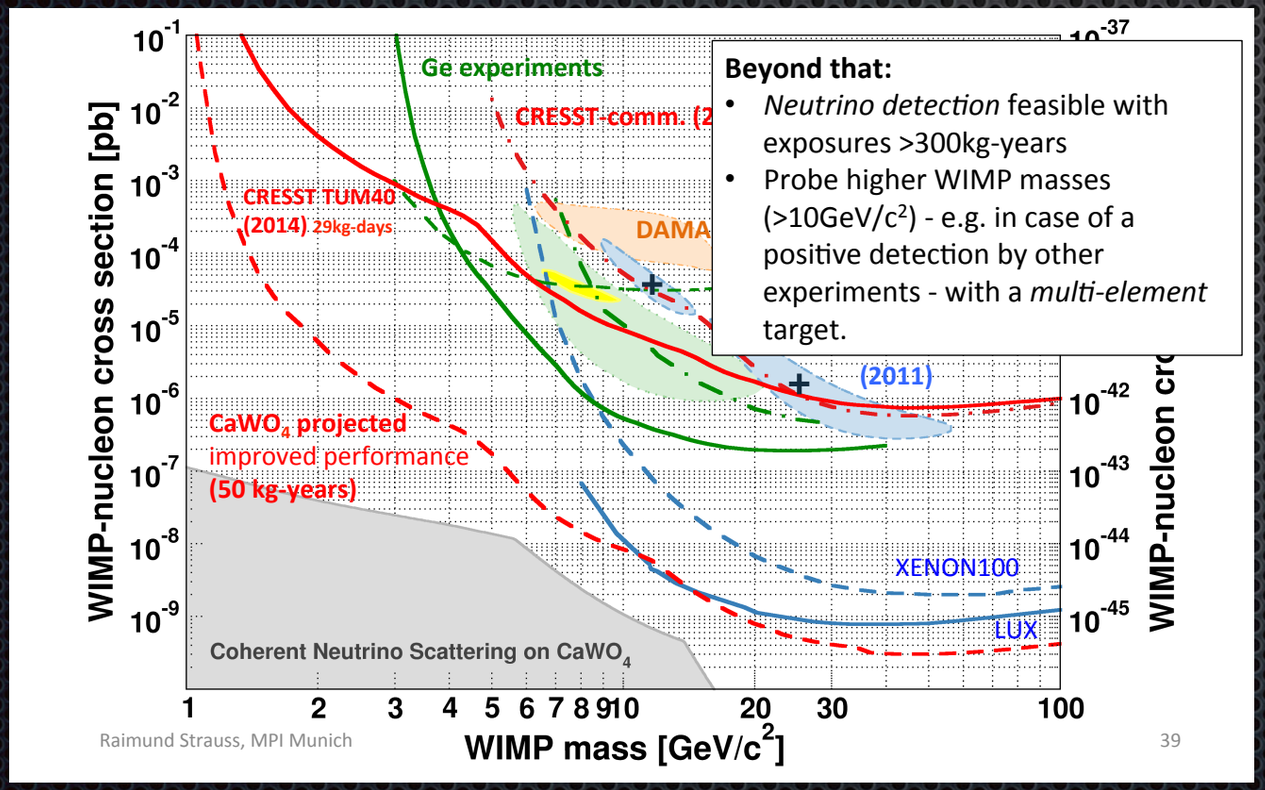
new run with 36 Ge FID800 (~ 30 kg) detectors since June 2014

End 2014/early 2015: reach 3000 kg x d (125 live days)

2016: reach 1.2 ton x days (500 live days)

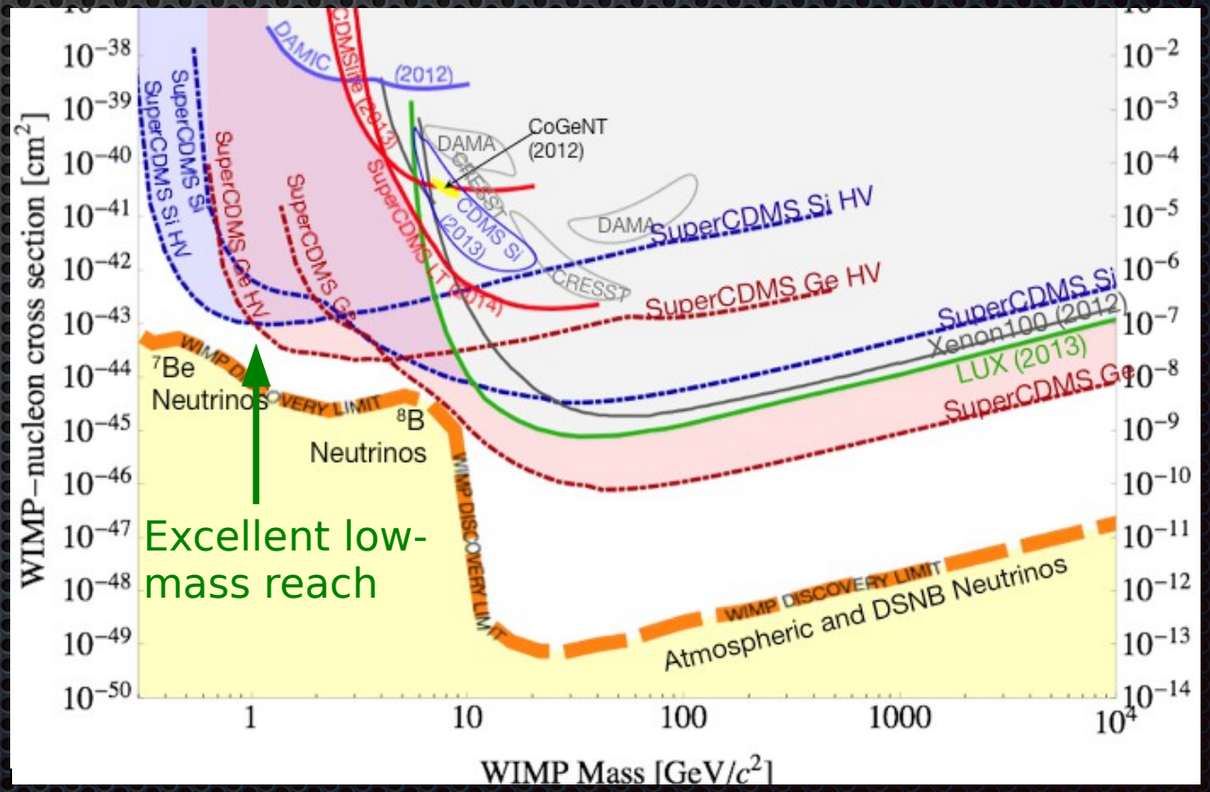
Future Cryogenic Experiments at T~ mK

- SuperCDMS at SNOLab: approved by NSF&DoE
- Collaboration between SuperCDMS and EURECA, at the ~100 kg level (cryostat can house up to 400 kg target material)
- Multi-target approach ($CaWO_3$, Ge), start data taking in 2018
- Reach for SI cross sections: 8×10^{-47} cm^2



Beyond that:

- *Neutrino detection* feasible with exposures >300kg-years
- Probe higher WIMP masses (>10GeV/c^2) - e.g. in case of a positive detection by other experiments - with a *multi-element* target.

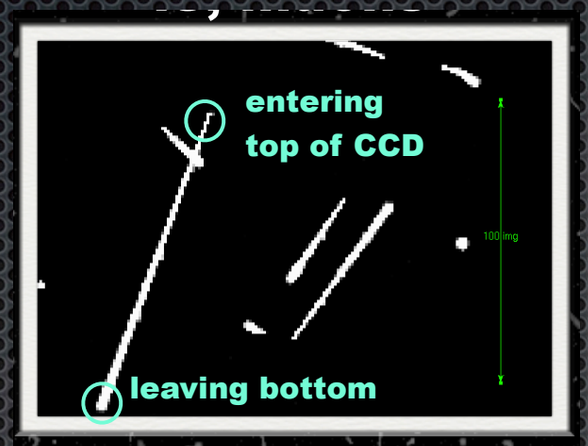


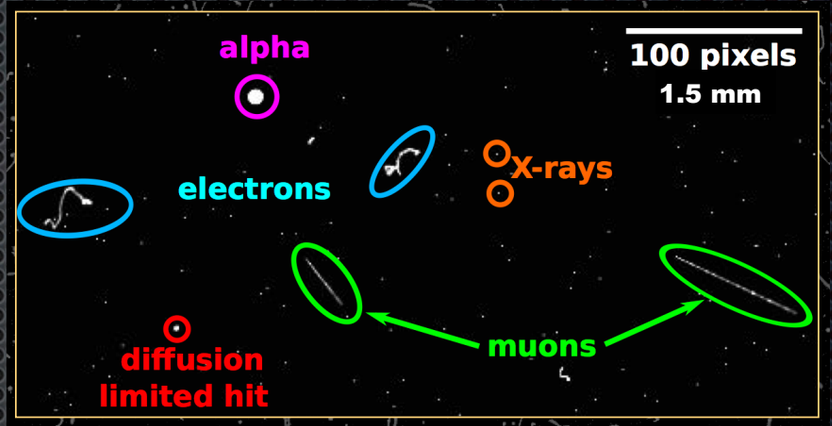
see talks by B. Loer, A.J. Anderson

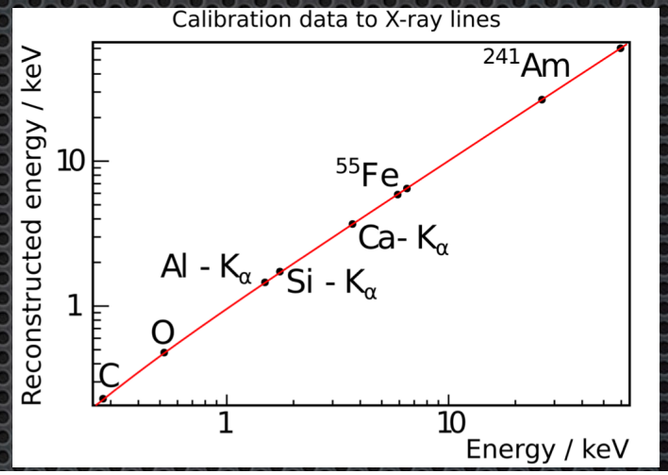
CCDs for low-mass WIMPs: DAMIC

see talk by P. Privitera

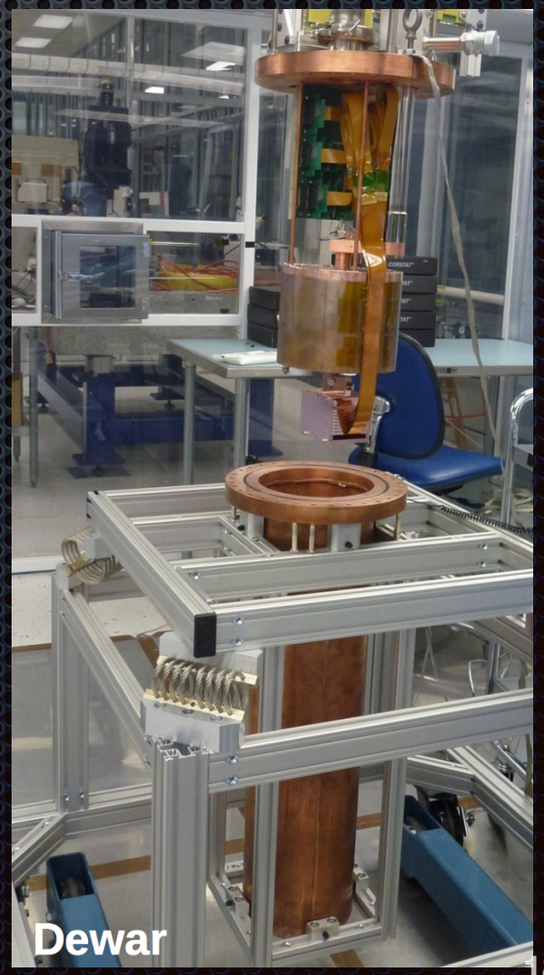
- Particle identification
- Fiducialisation to reject surface events (X-rays)
- DAMIC100 (100 g Si active mass) under construction at SNOLAB; results in 2015



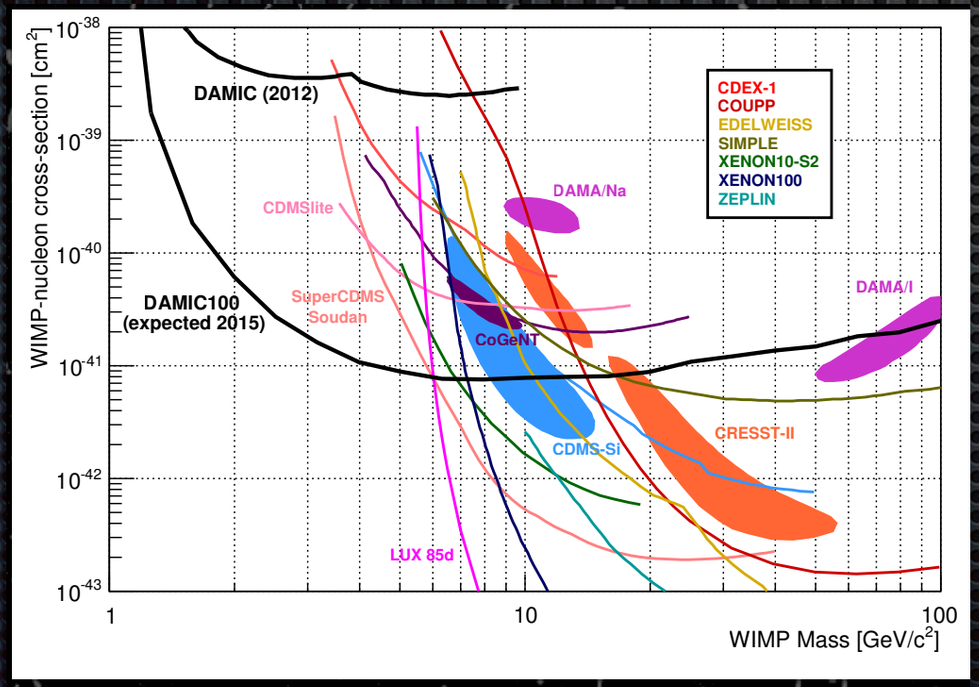


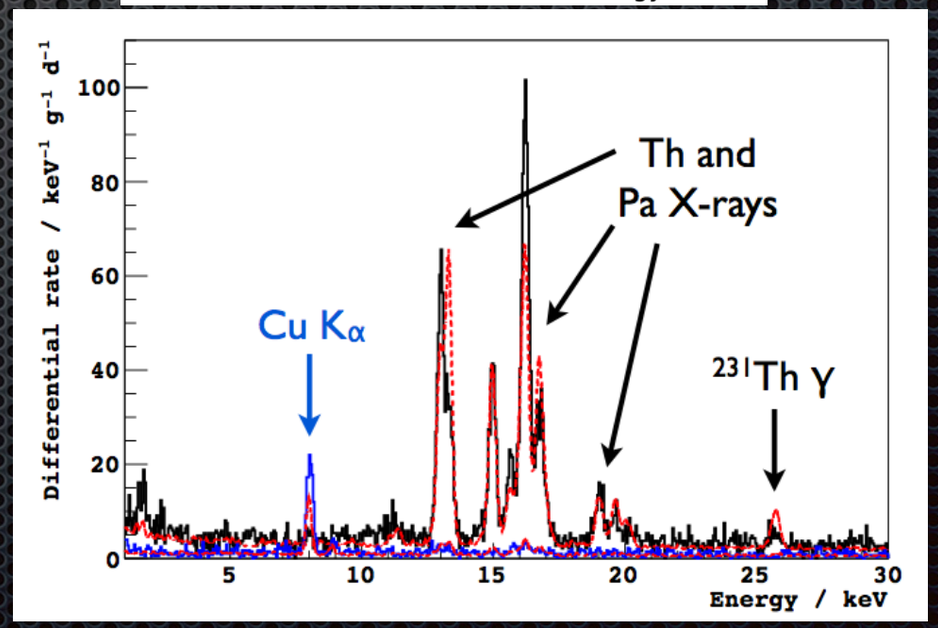


Ben Kilminster, PATRAS 2014



2012 DAMIC limit 107 g-days with 0.04 keV energy threshold Phys.Lett. B711 (2012) 264-269

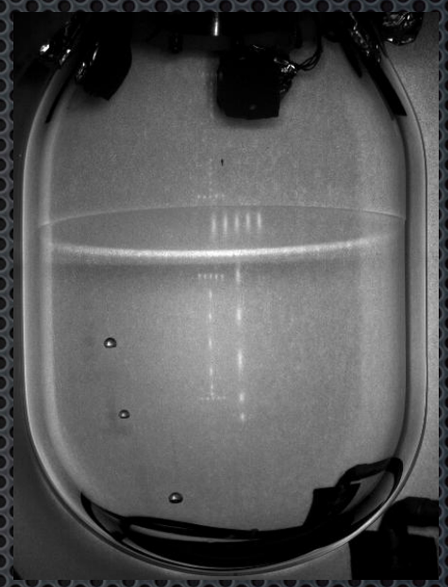




Bubble chambers

see talk by O. Harris

- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs (10^{10}), scalable to large masses, high spatial granularity
- Existing detectors: SIMPLE, COUPP, PICASSO, PICO 2 L
- Future: PICO (PICASSO + COUPP) -> 250 l detector detector at SNOLAB, C3F8 with 3 keV threshold



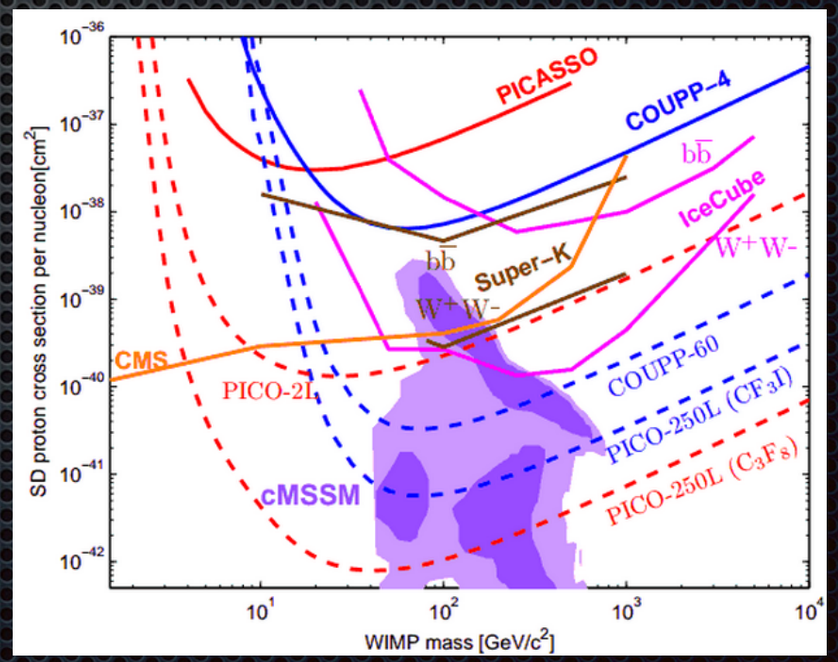
n-induced event (multiple scatter)

WIMP: single scatter

COUPP 60 kg CF_3I detector installed at SNOLAB; physics run until May 2014

PICASSO at SNOLAB

PICO 2L

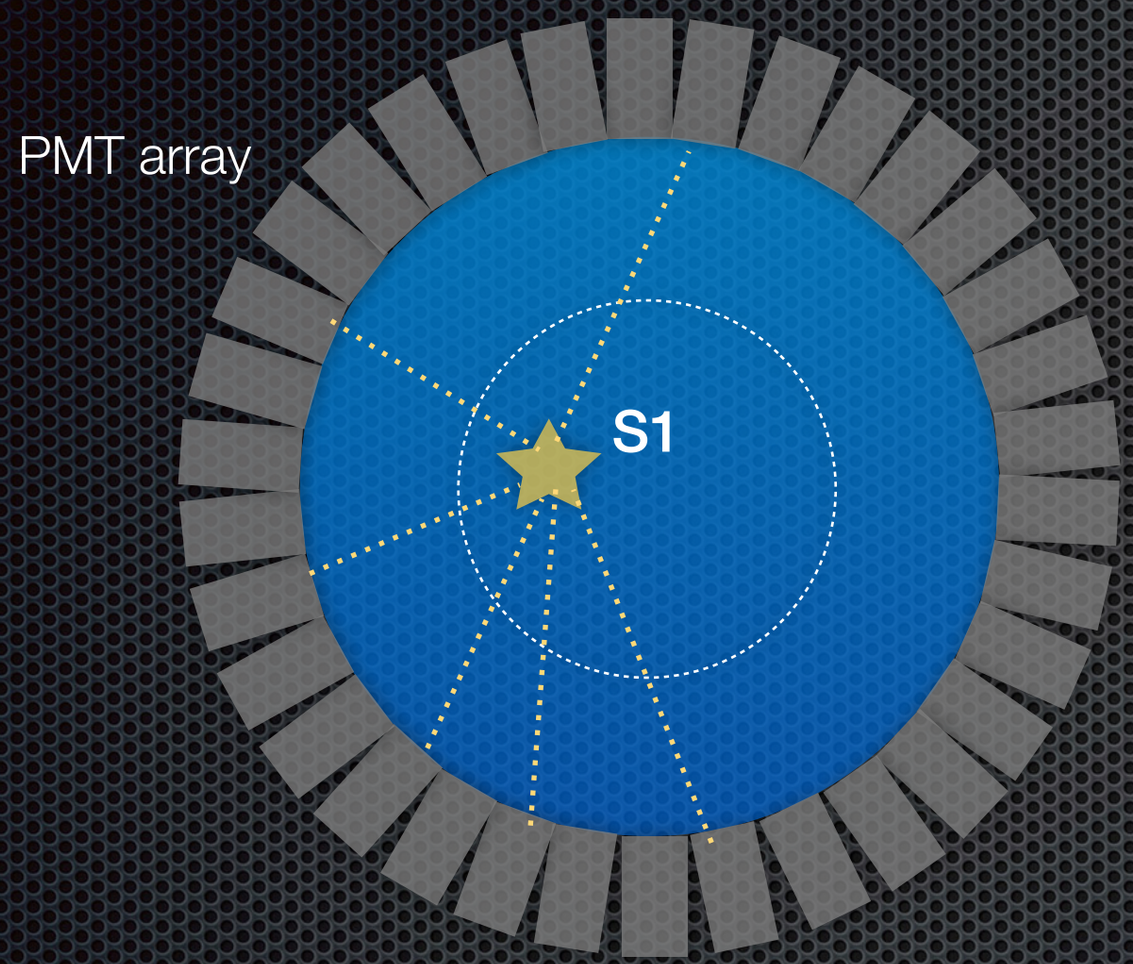


Spin-dependent limits

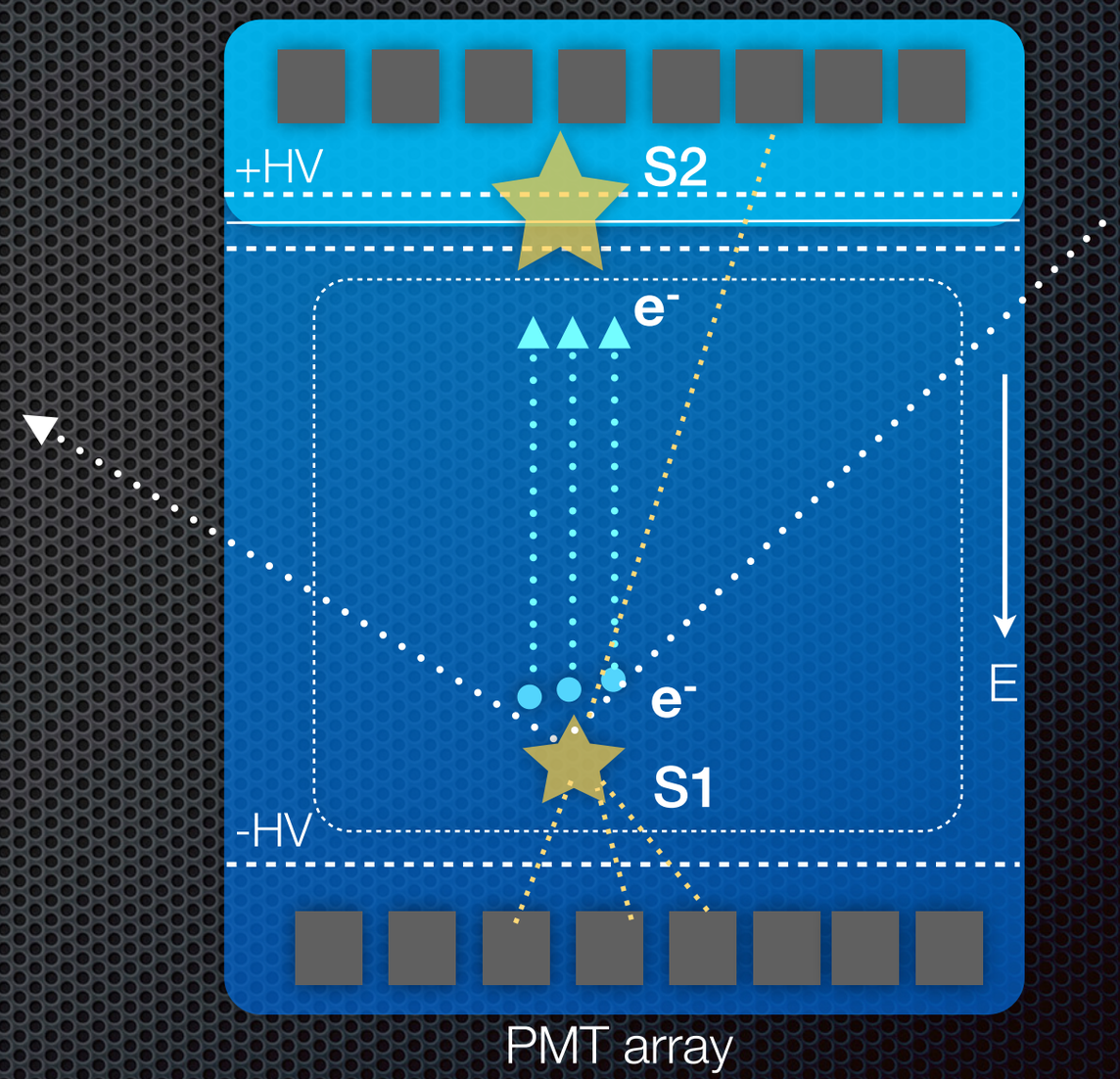
Recoil range << 1 μm in a liquid - very high dE/dx

Noble liquid detector concepts

Single phase



Double phase (TPC)



New data from Xe and Ar single-phase

- XMASS at Kamioka (LXe), DEAP and CLEAN at SNOLab (LAr)

XMASS at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished
new run since Nov 2013

CLEAN at SNOLab:

500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014

DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
under construction
first data expected in fall 2014

New data from Ar and Xe TPCs

see talk Y. Guardincerri

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
close to unblinding of new data set

LUX at SURF:

370 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run and first results in 2013
new run in 2014

PandaX at CJPL:

125 kg LXe
(37 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
first results in August 2014

ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

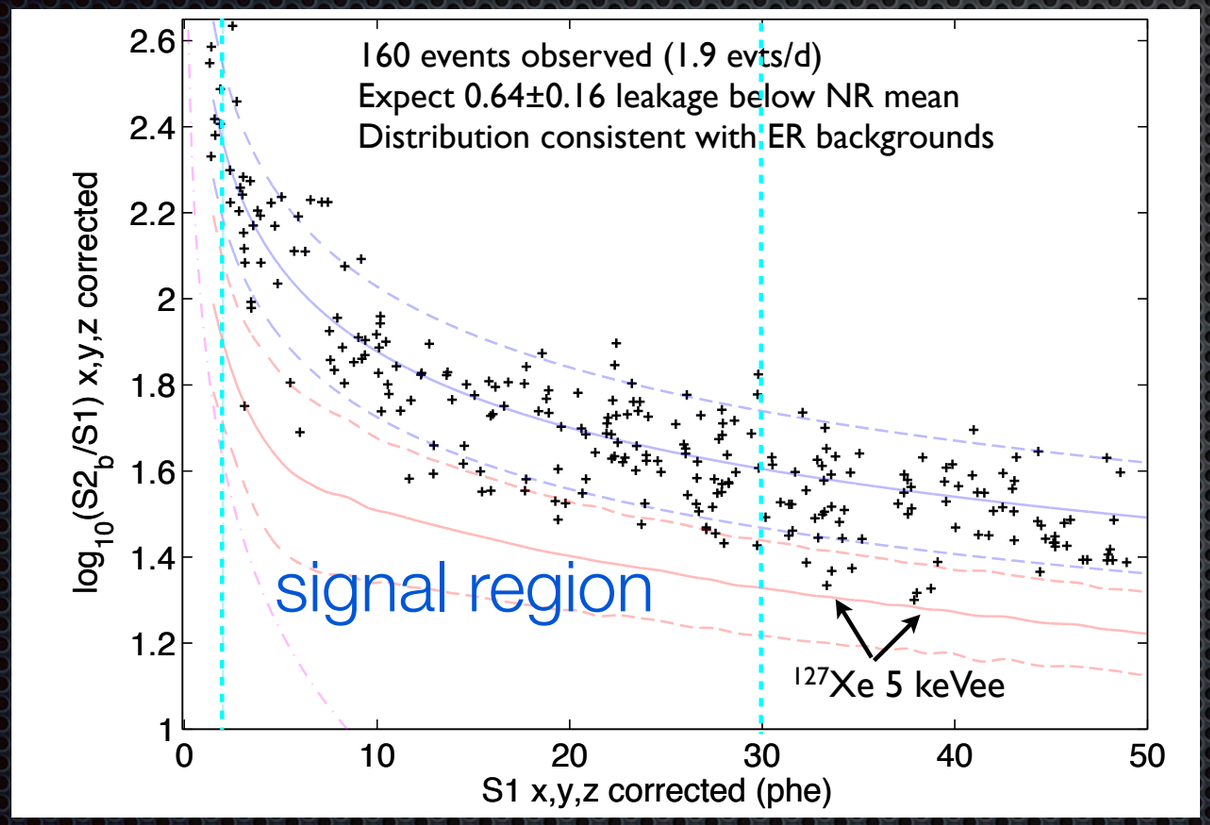
DarkSide at LNGS:

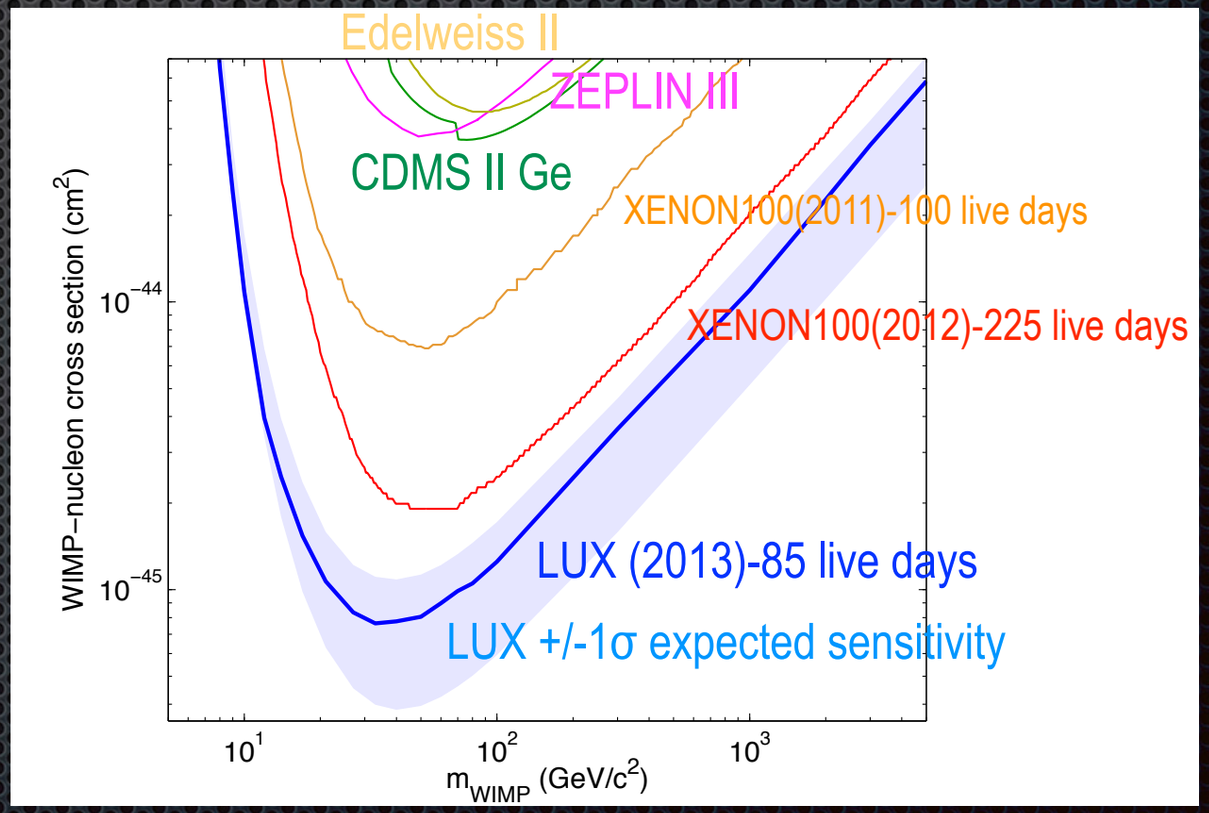
50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs
first data with non-depl Ar in 2014

Example: LUX dark matter data

- First run: 85.3 live-days, 118 kg fiducial mass
- No sign of dark matter, observed distribution consistent with backgrounds
- New run of 300 live-days planned for 2014/15, sensitivity increase by a factor of 5

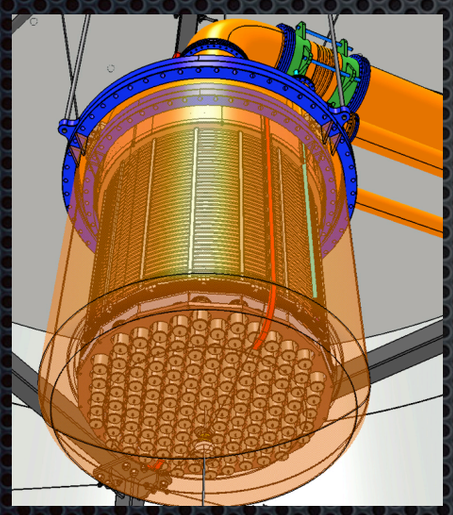




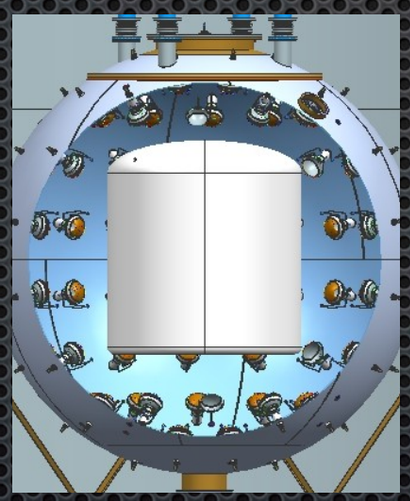
Accepted in PRL, arXix: 1310.8214

Future noble liquid detectors

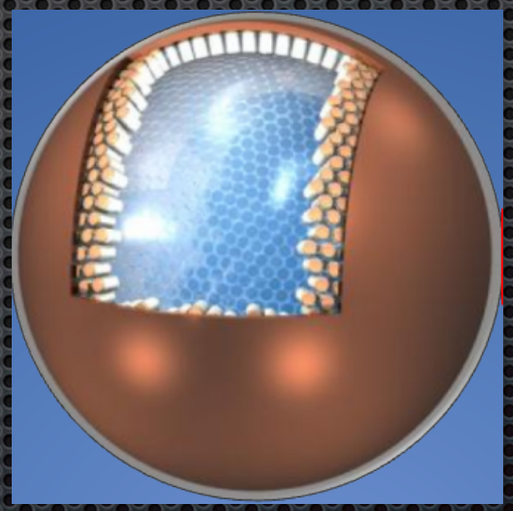
- **Under construction**: XENON1T at LNGS, 3.1 t LXe in total
- **Future:** LUX-ZEPLIN (7 t LXe) (approved by NSF&DoE), XENONnT (n=6-7 t LXe) (to be proposed), XMASS (5 t LXe), DarkSide (5 t LAr) (R&D funds)
- **Design and R&D:** "ultimate detector" DARWIN (~20 t LXe and/or 50 t LAr)



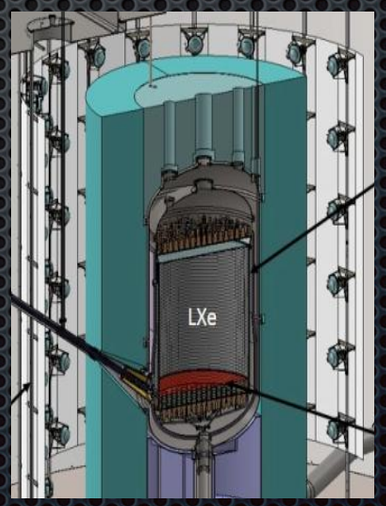
XENON1T: 3.3 t LXe



DarkSide: 5 t LAr



XMASS: 5t LXe



LZ: 7t LXe

DARWIN: 20 t LXe/LAr

The XENON1T Experiment

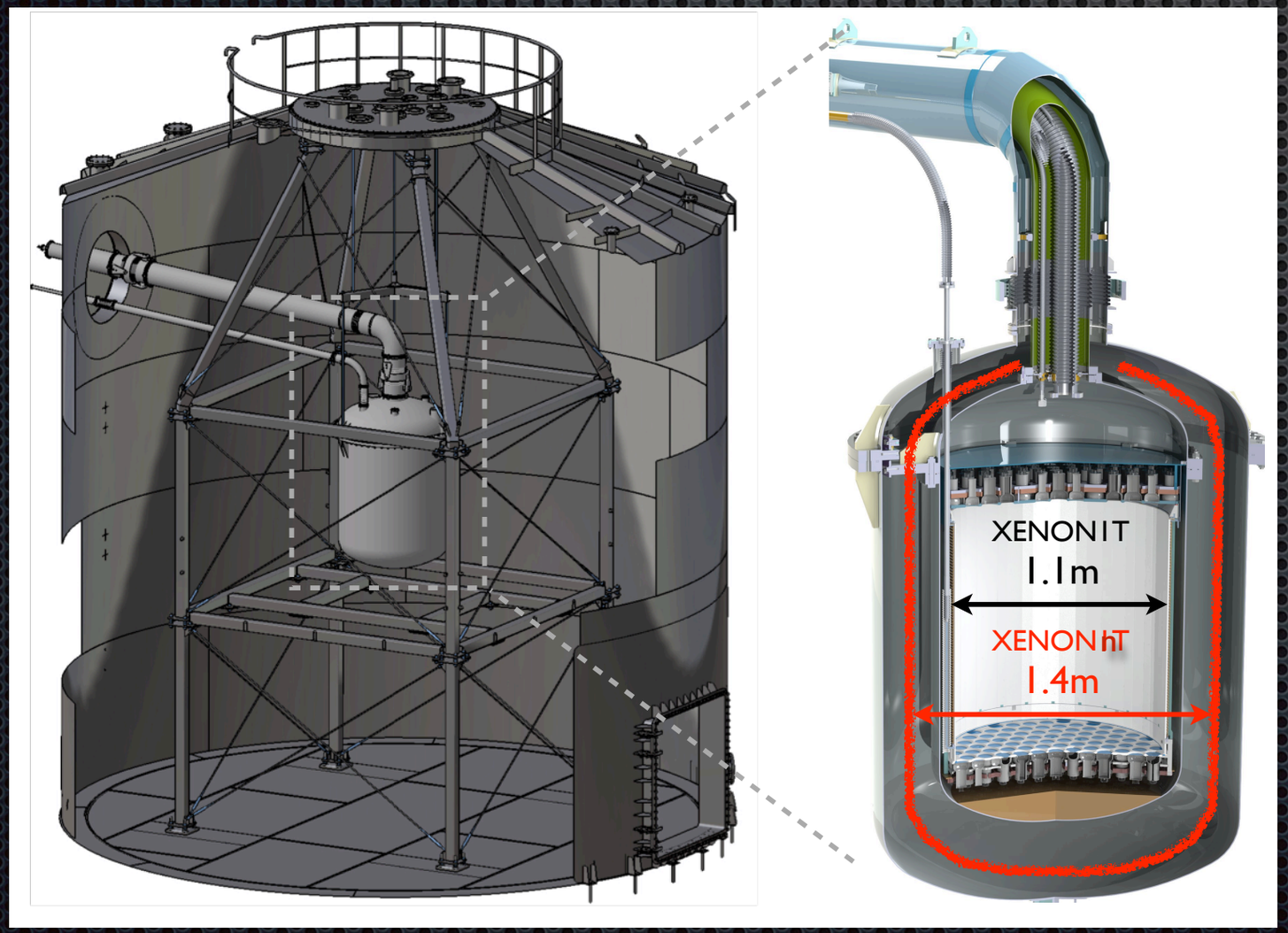
- Under construction at LNGS since fall 2013
- Total LXe mass: 3.1 t, 1 m charge drift; 248 3-inch PMTs; background goal:*100 x lower than XENON100, ~5 x 10^{-2} events/(t-d-keV)*
- Commissioning and science run: mid and late 2015
- Goal: 2 x 10^{-47} cm^2 at a WIMP mass of ~ 50 GeV

XENON1T construction at LNGS

- Water tank completed, service building ready
- Integration of several subsystems (cryostat, cryogenics, storage, purification, cable pipe etc) accomplished by August 2014
- PMTs screened and tested in cold gas and LXe; TPC under prototyping

XENONnT: 2018 - 2020

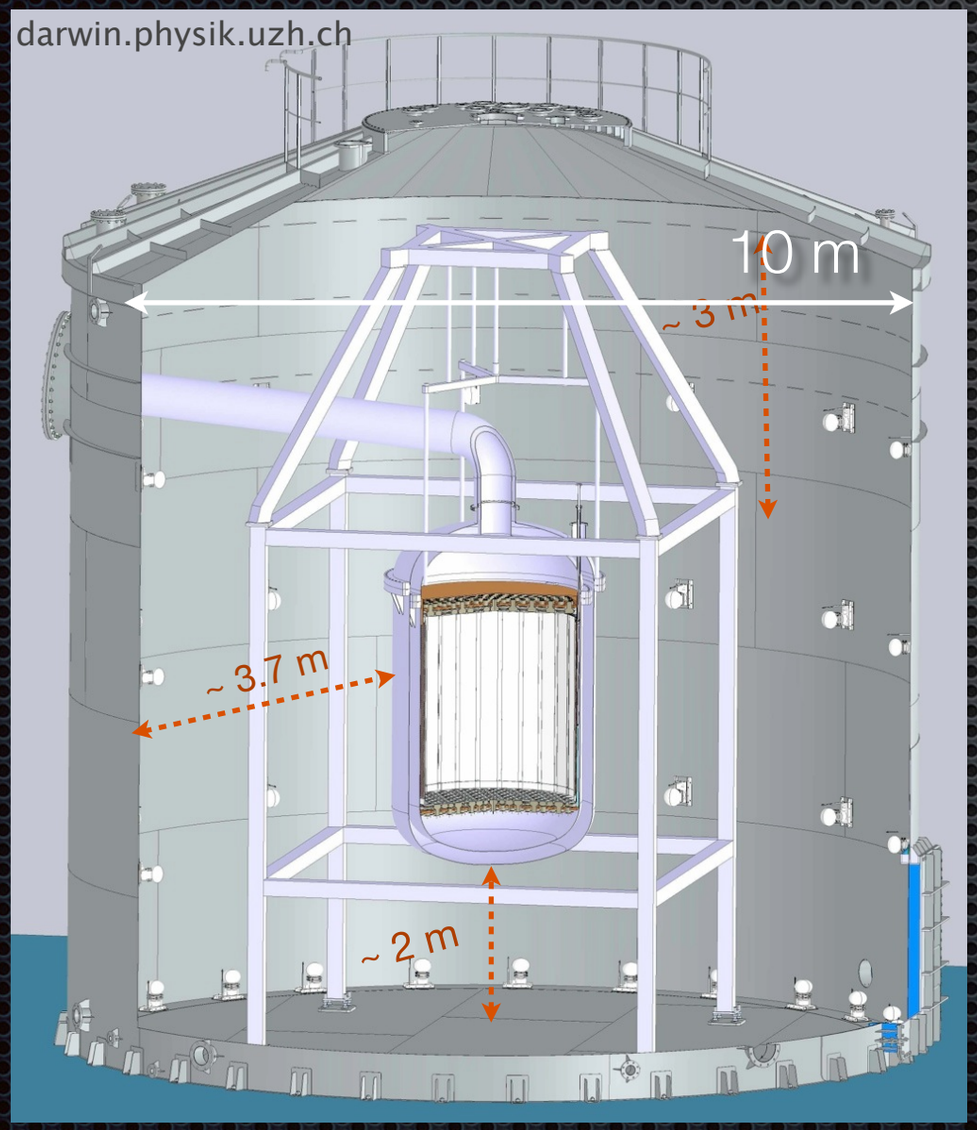
- Double the amount of LXe (~7 tons), double the number of PMTs
- XENON1T is designed such that many sub-systems will be reused for the upgrade:



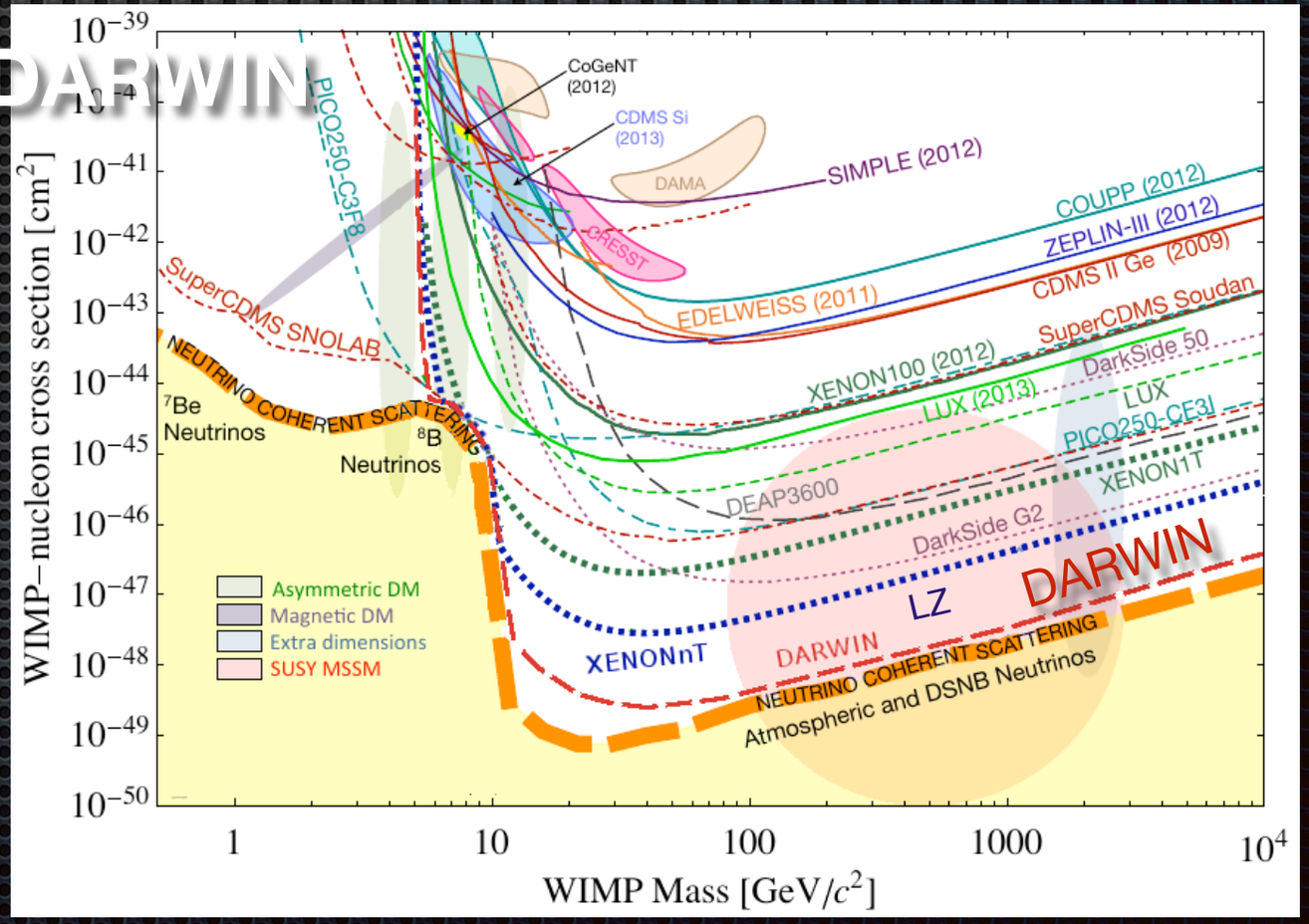
- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- More LXe, PMTs, electronics will be needed

DARWIN DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector for $m_W > 6$ GeV
- Physics goal: build the "ultimate WIMP detector", before the possibly irreducible neutrino background takes over; probe WIMP cross sections down to ~10^{-49} cm^2



DARWIN: 25 groups from 9 countries



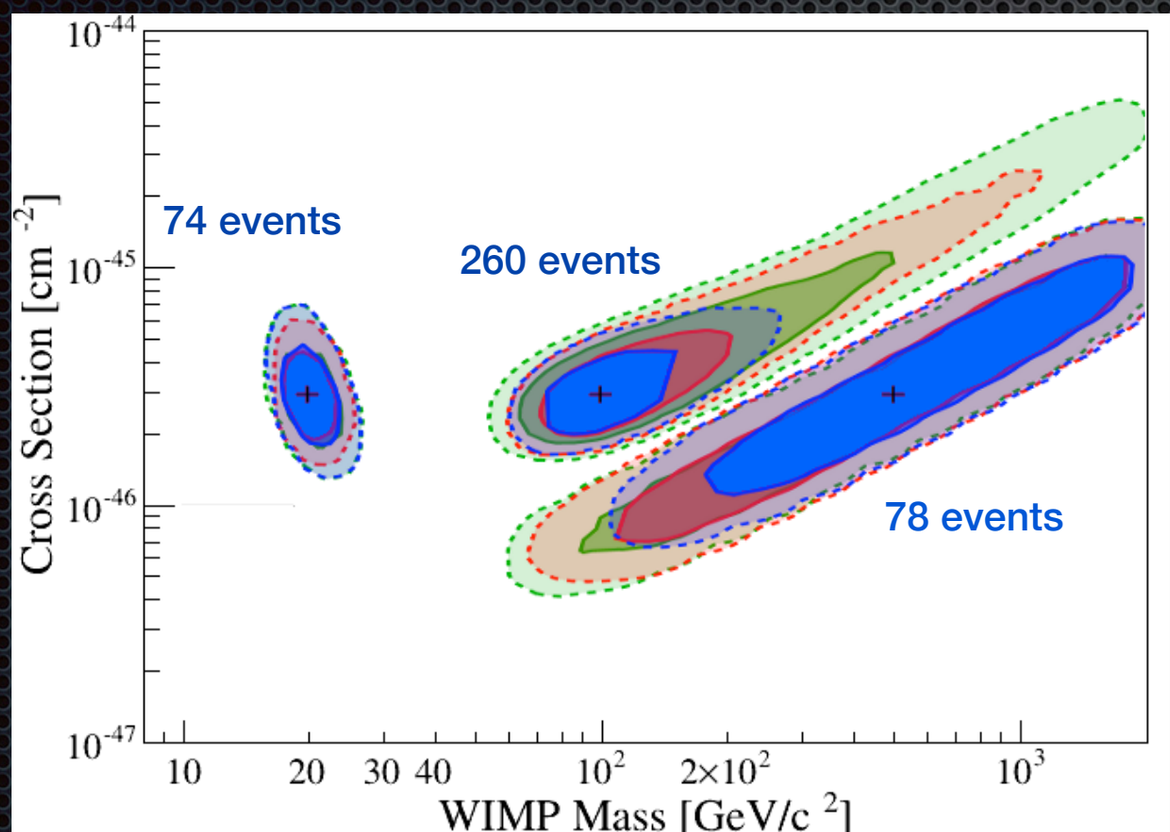
~20 t LXe (and/or 50 t LAr) cryostat in large water Cherenkov shield

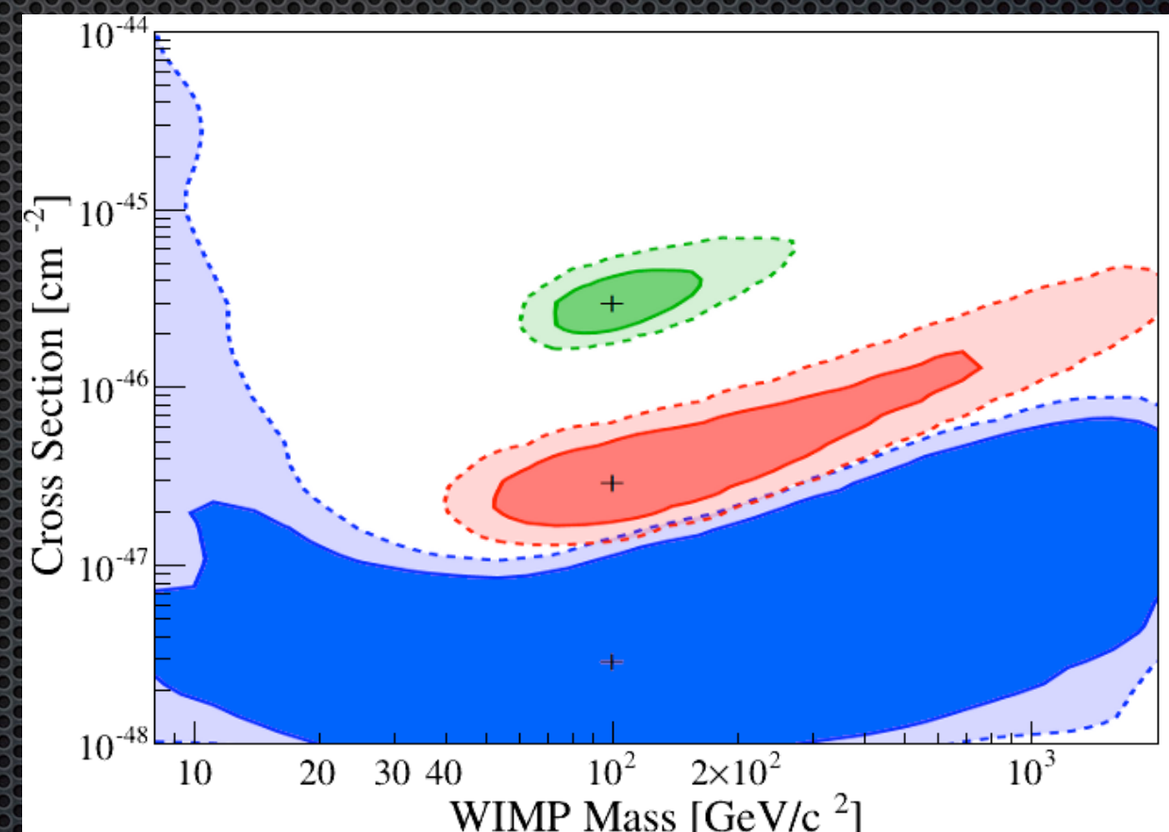
What can we say about the dark matter?

Newstead et al., PHYSICAL REVIEW D 88, 076011 (2013)

Xe 10 t yr, Xe 20 t yr
Xe 10 t yr + Ar 20 t yr

Xe 10 t yr + Ar 20 t yr for XS of:
3×10^{-46} cm^2, 3×10^{-47} cm^2, 3×10^{-48} cm^2



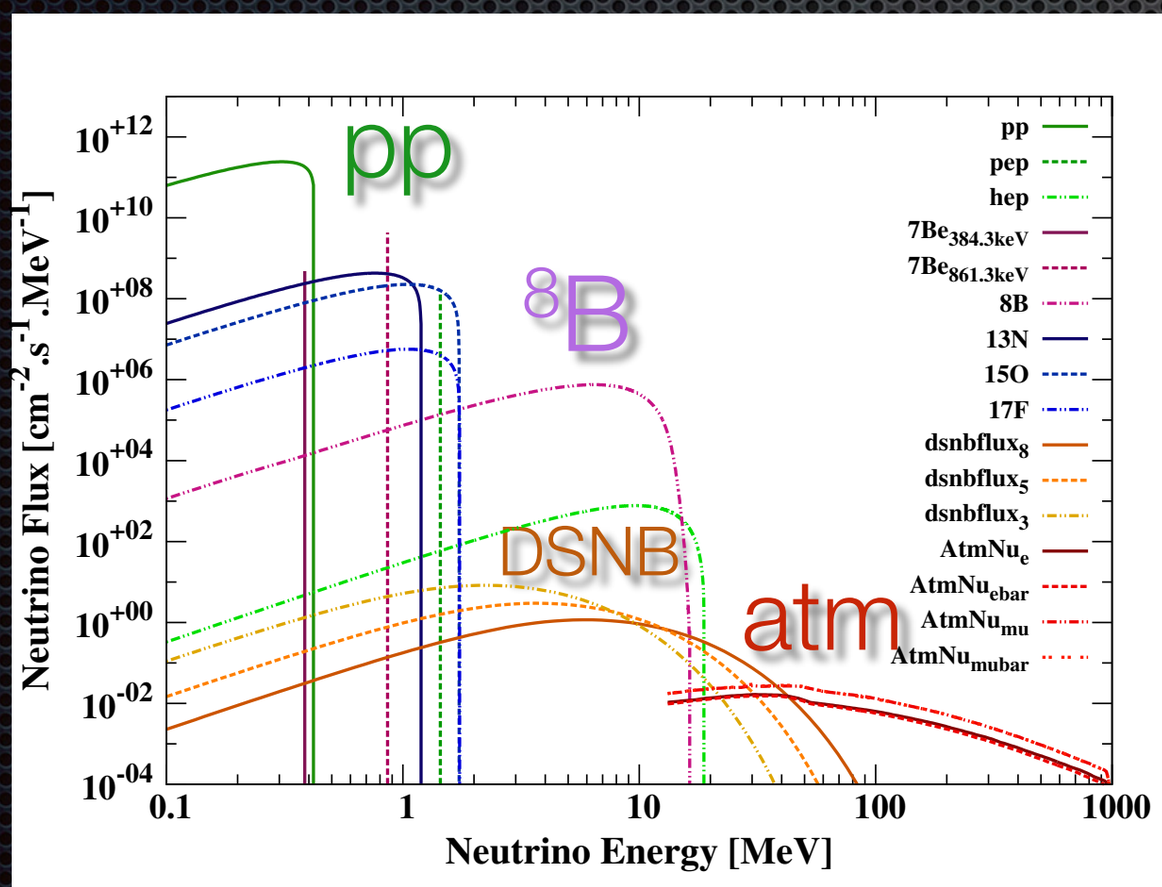


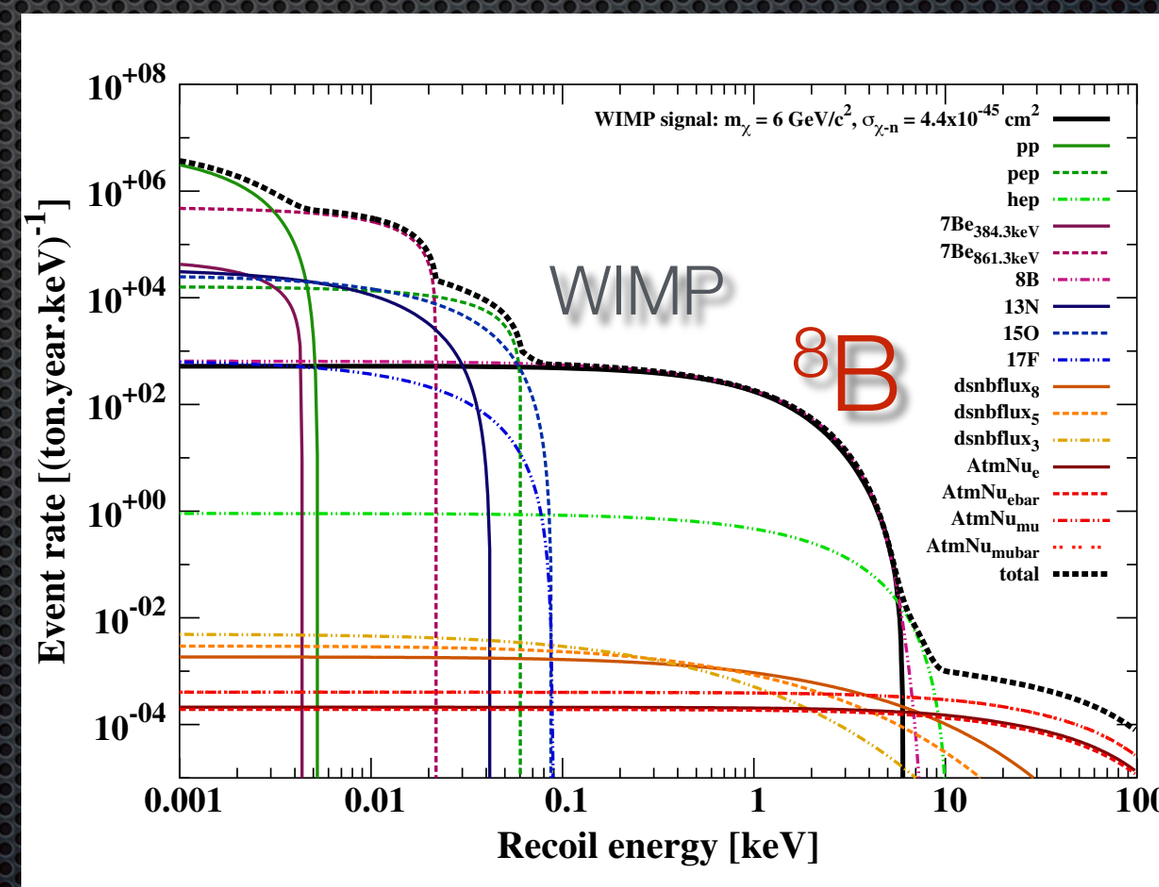
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV\,cm^{-3}}$$

$$v_{esc} = 544 \pm 40\,\mathrm{km/s} \qquad v_0 = 220 \pm 20\,\mathrm{km/s}$$

Will we turn into neutrino physicists?

- Electronic recoils from solar neutrinos: neutrino - electron scattering
- Nuclear recoils from ^{8}B solar neutrinos: neutrino - nucleus coherent scattering
- Nuclear recoils from atmospheric + DSNB: neutrino - nucleus coherent scattering

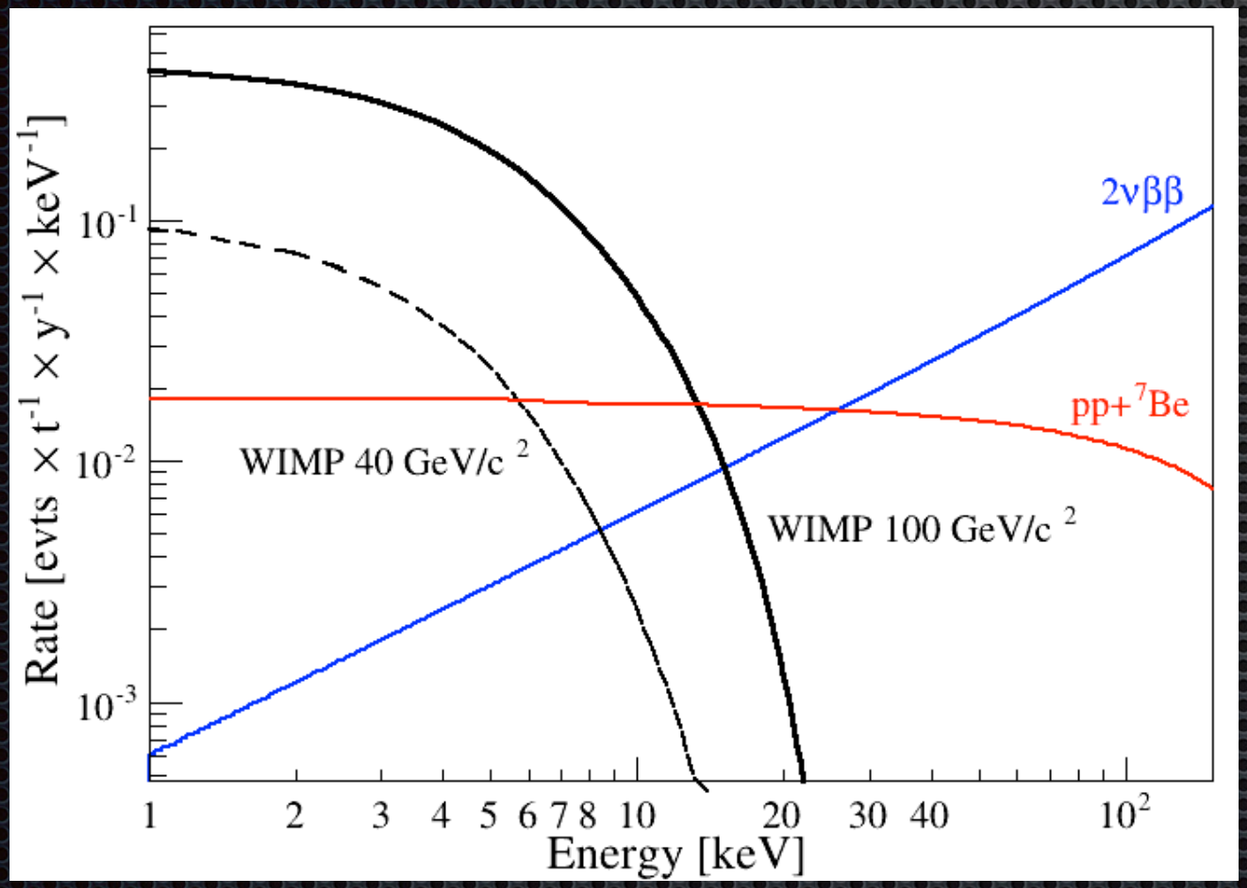


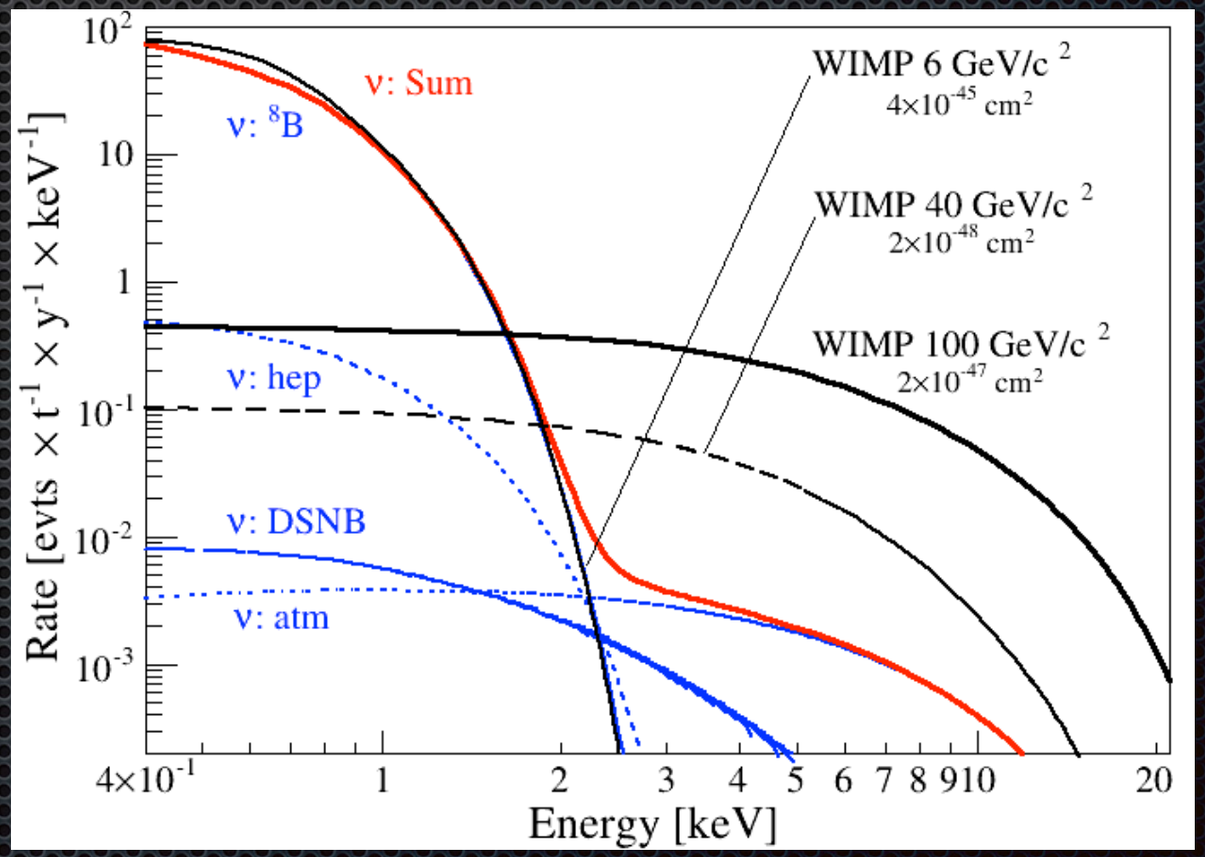


F. Ruppin J. Billard E. Figueroa-Feliciano L. Strigari arXiv:1408.3581

Will we turn into neutrino physicists?

- Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2 (depending on ER vs NR discr.)
- Nuclear recoils from ^{8}B solar neutrinos: below ~ 4 x10^{-45} cm^2 for low-mass WIMPs
- Nuclear recoils from atmospheric + DSNB: below 10^{-49} cm^2





$$\nu + e^- \rightarrow \nu + e^-$$

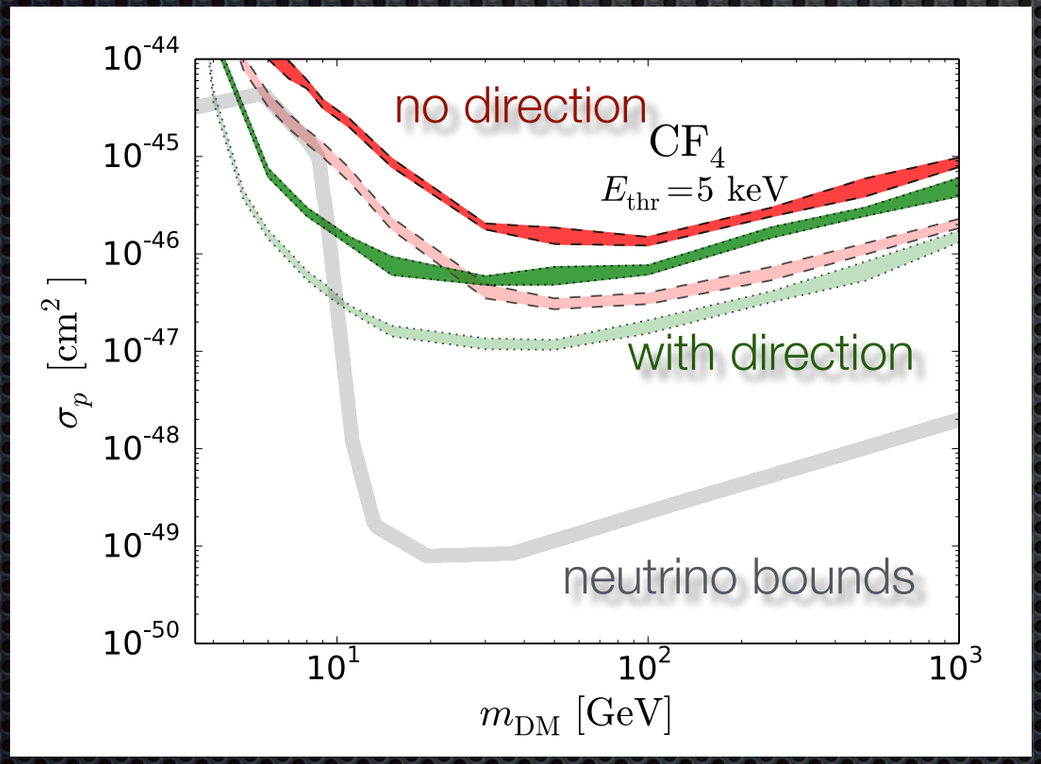
$$\nu + N \rightarrow \nu + N$$

LB et al., JCAP01 (2014) 044

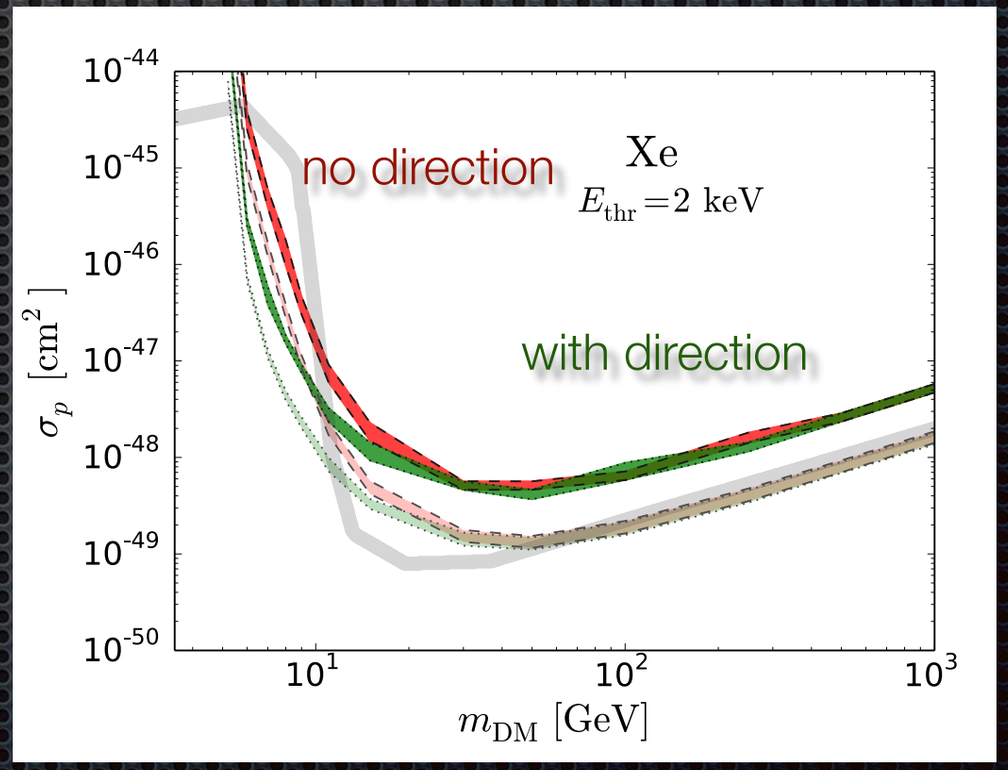
Will directional information help?

- Yes, but mostly for low WIMP masses
- Many directional techniques currently in R&D phase
- Might be difficult to reach the 10^{-48} - 10^{-49} cm^2 cross section with this technique

36.6 t yr exposure, 500 (solar) nu events



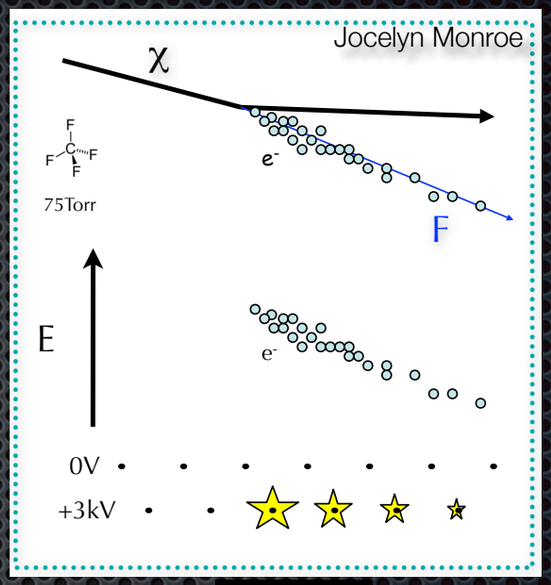
367 t yr exposure, 500 nu events

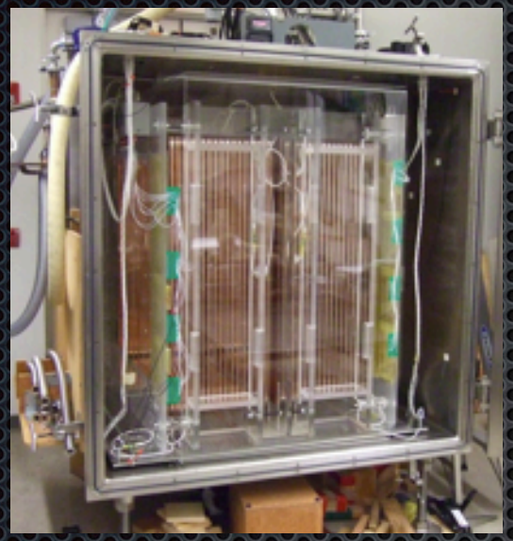


P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

Directional detectors

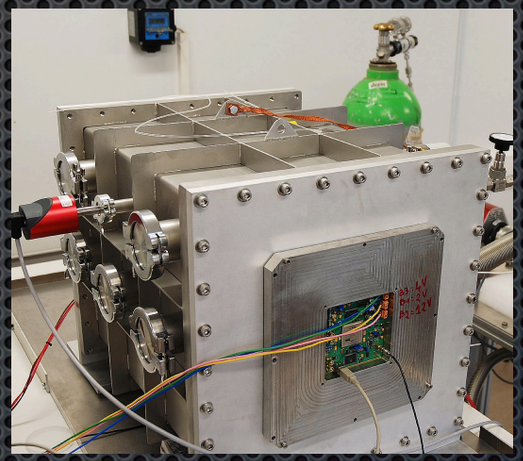
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- Challenge: good angular resolution + head-tail at E_{thr} (~30-50 keV)



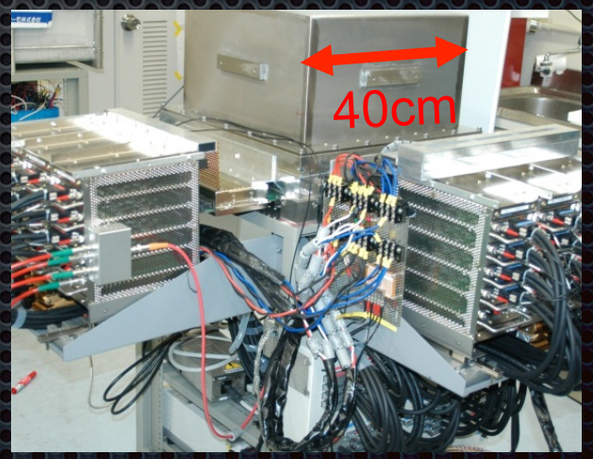


DRIFT, Boulby Mine
1 m3, negative ion drift
CS_2, CF4, O2 gas
DRIFTIII plans:
24 m^3 (3 x 8 m3 cells)
at Boulby
4 kg target mass

DMTPCino TPC at MIT
CCD readout
1 m3 prototype, CF4 gas
commissioning fall 2014



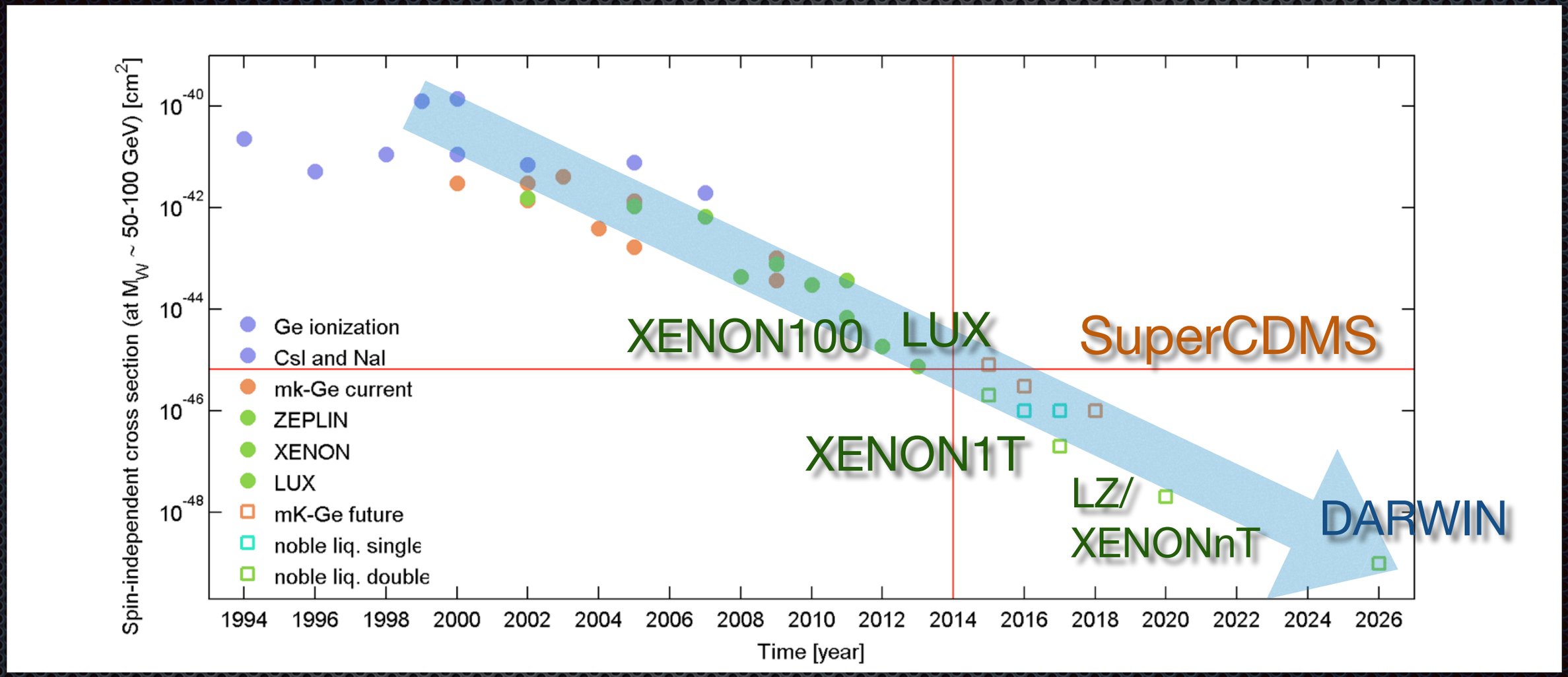
MIMAC 100x100 mm^2
5l chamber at Modane
CF_4, CHF_3, H gas



NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

Will we detect WIMP dark matter soon?

L. B., Physics of the Dark Universe 4, Sept 2014



About a factor of *10 increase in sensitivity every 2 years*

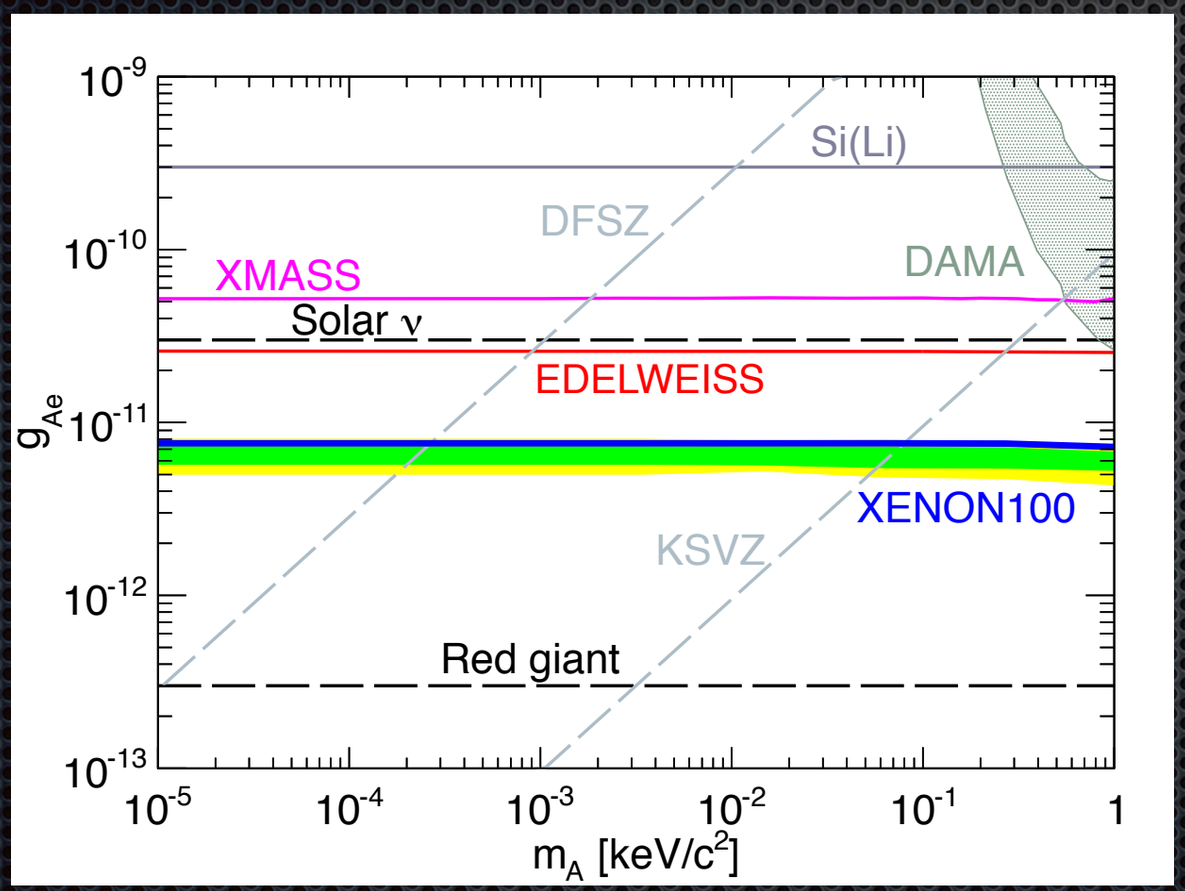
Who knows! Perhaps (hopefully?!) by 2026…

The End

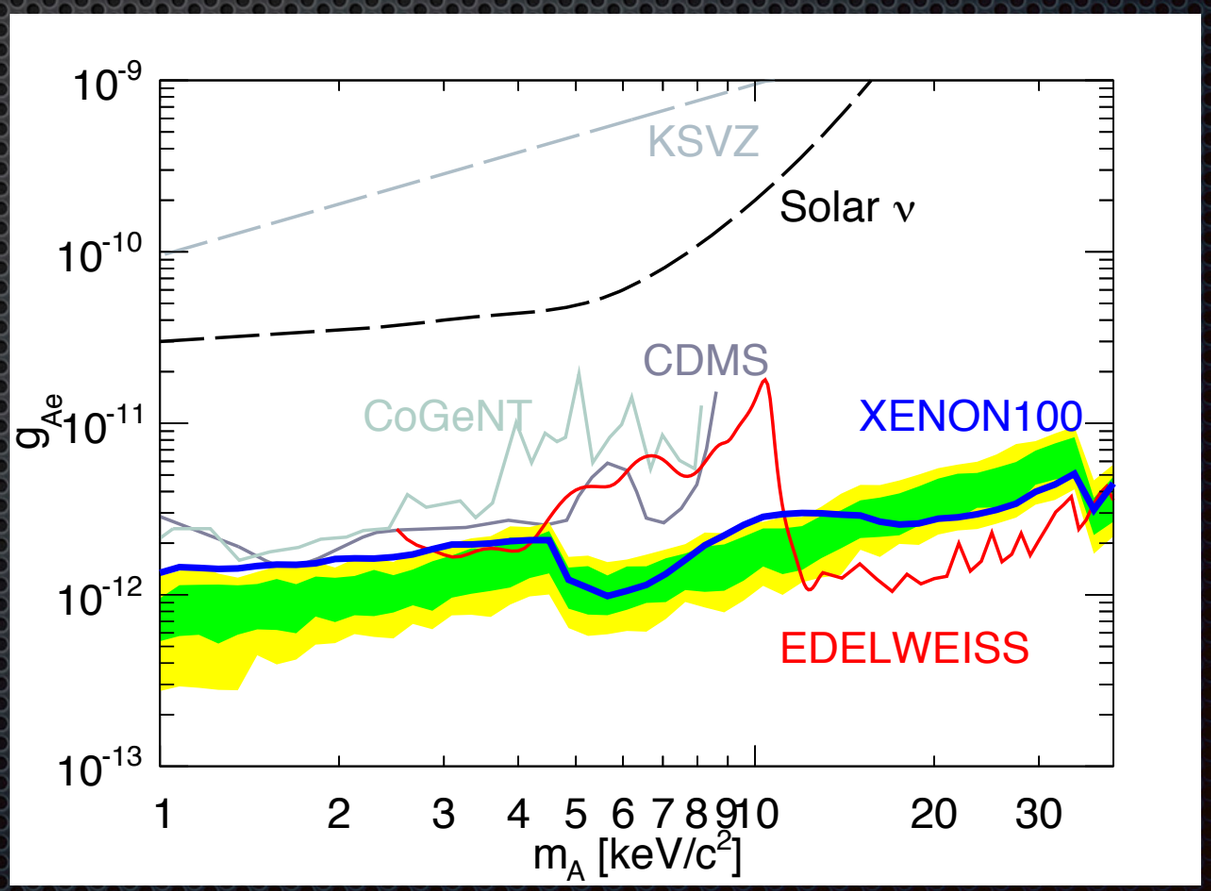
Direct-detection experiments can also search for solar axions, ALPs, vector…

- Limits on axions and ALPs from CDMS, DAMA, CoGeNT, XMASS, EDELWEISS, XENON100

Solar axions



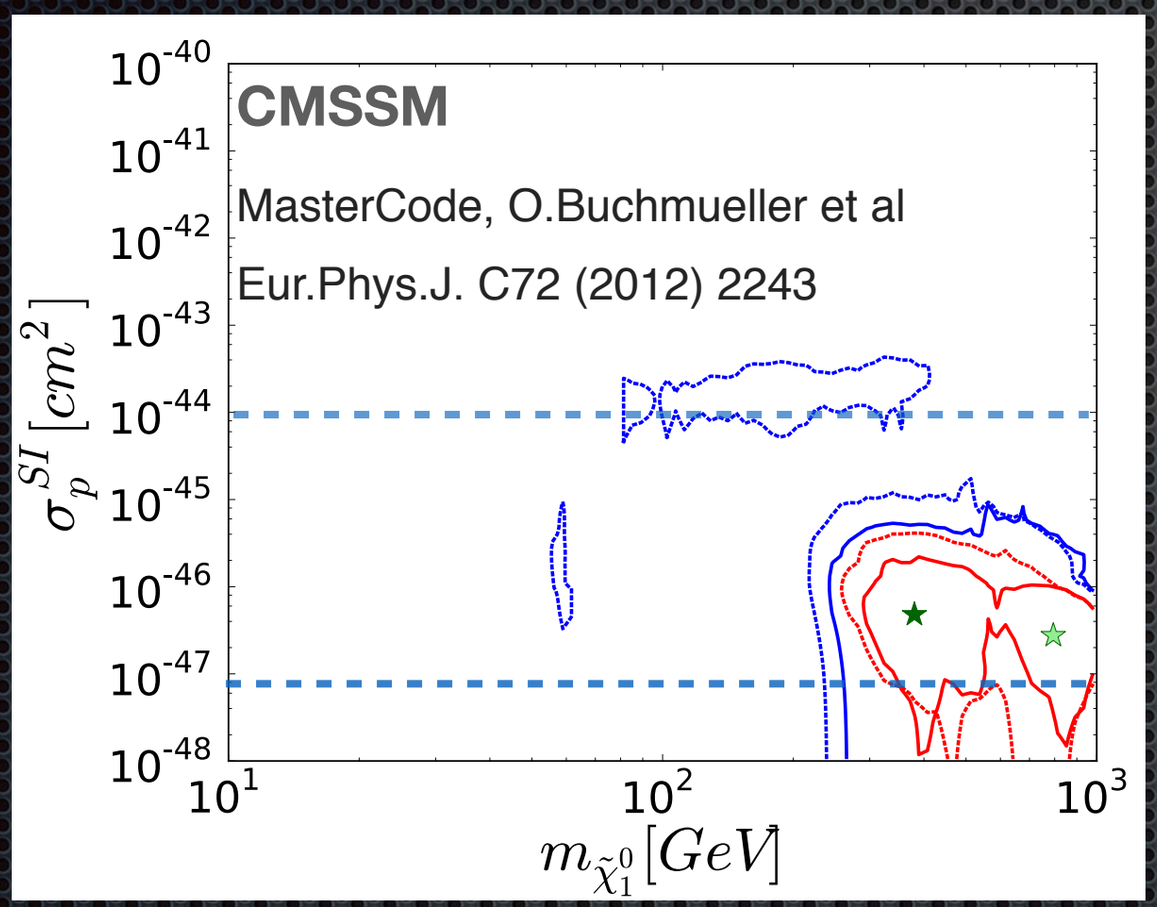
Galactic ALPs

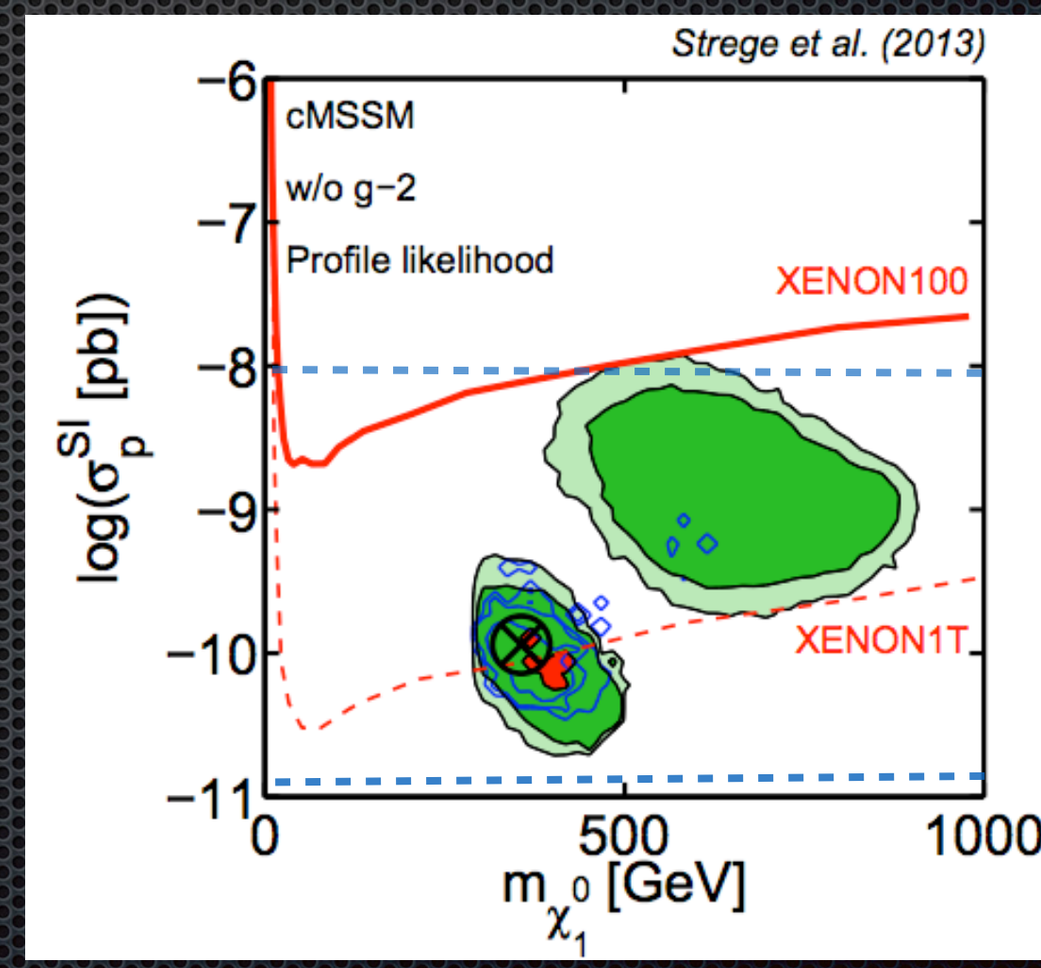


Particle physics

- SUSY: scattering cross sections on nucleons down to < 10^{-48} cm^2(10^{-12} pb)

10^{-44} cm^2: ~ 1 event kg^{-1} year^{-1}

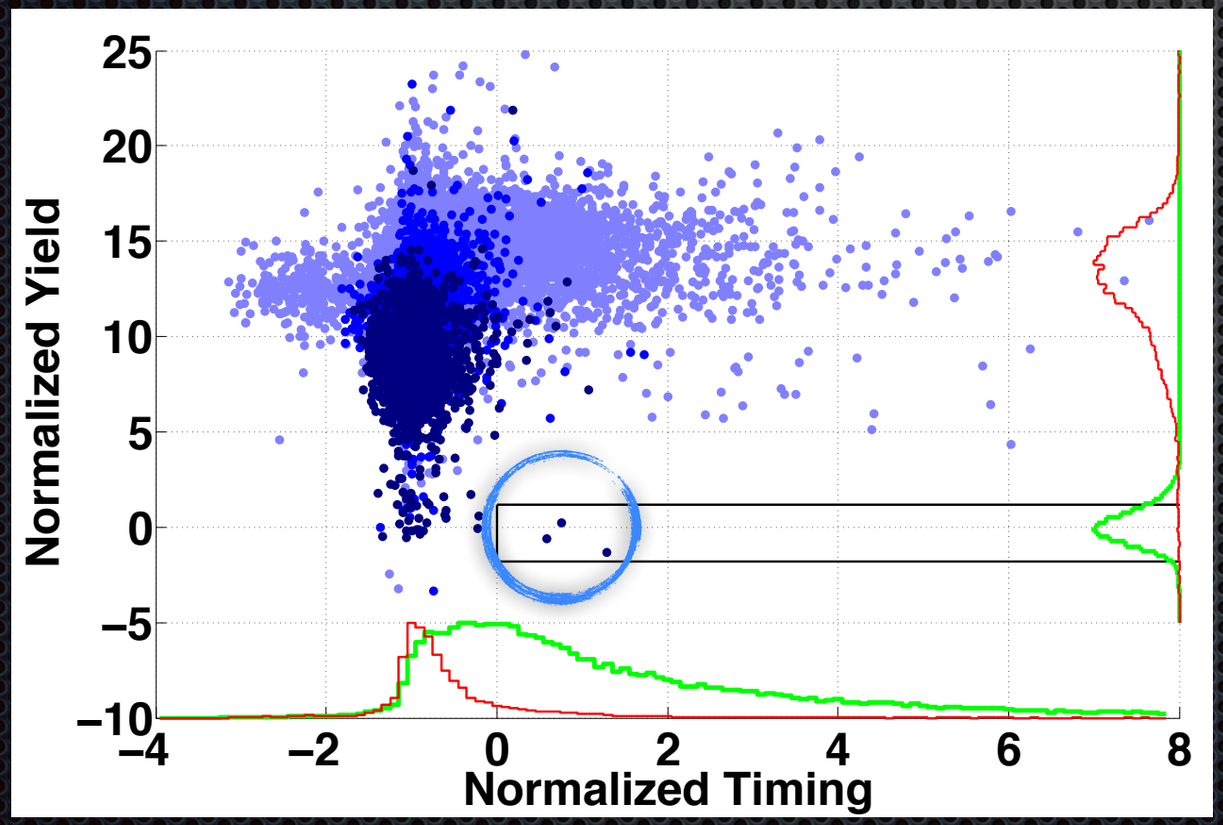


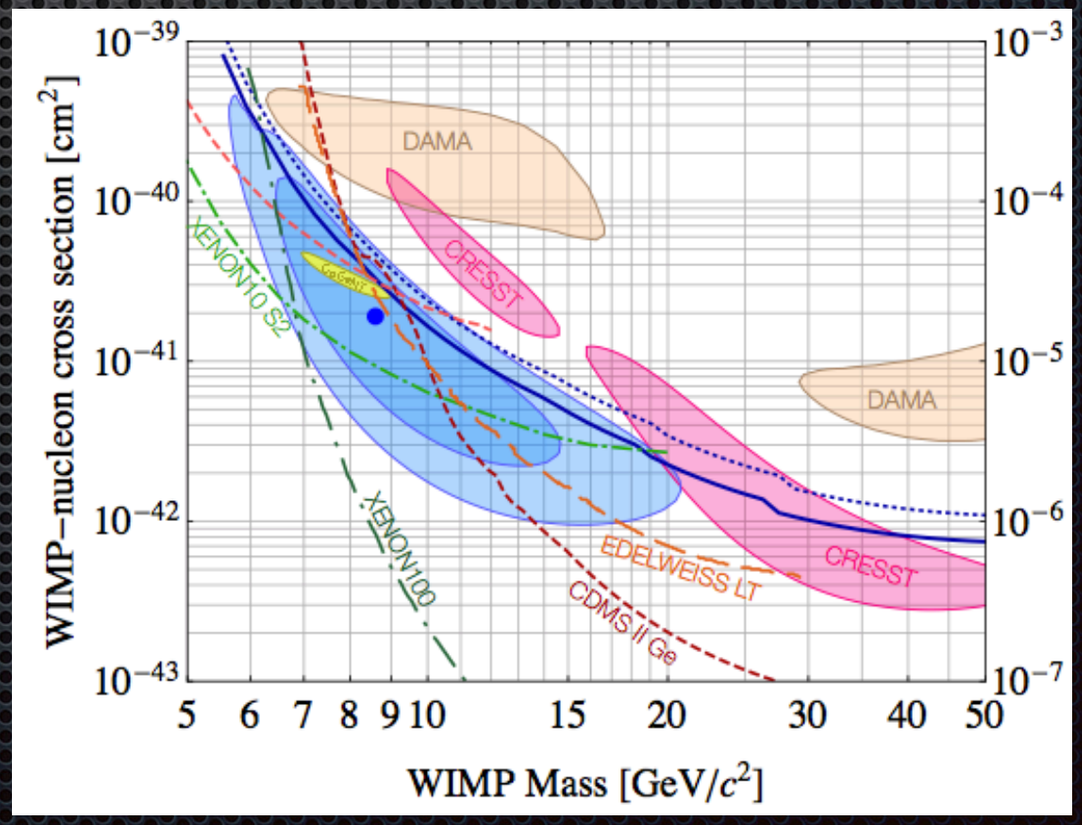


10^{-47} cm^2: ~ 1 event t^{-1} year^{-1}

Recent results from CDMS-Si

- Data from 11 x 0.106 kg Si crystals, for 140 kg-days exposure
- Energy region: 7- 100 keV_{nr} analyzed
- 3 events observed upon unblinding, 0.7 events expected
- Likelihood analysis: 0.19% probability for known background-only hypothesis
- ***best fit: 8.6 GeV, 1.9 x 10^{-42} cm^2***

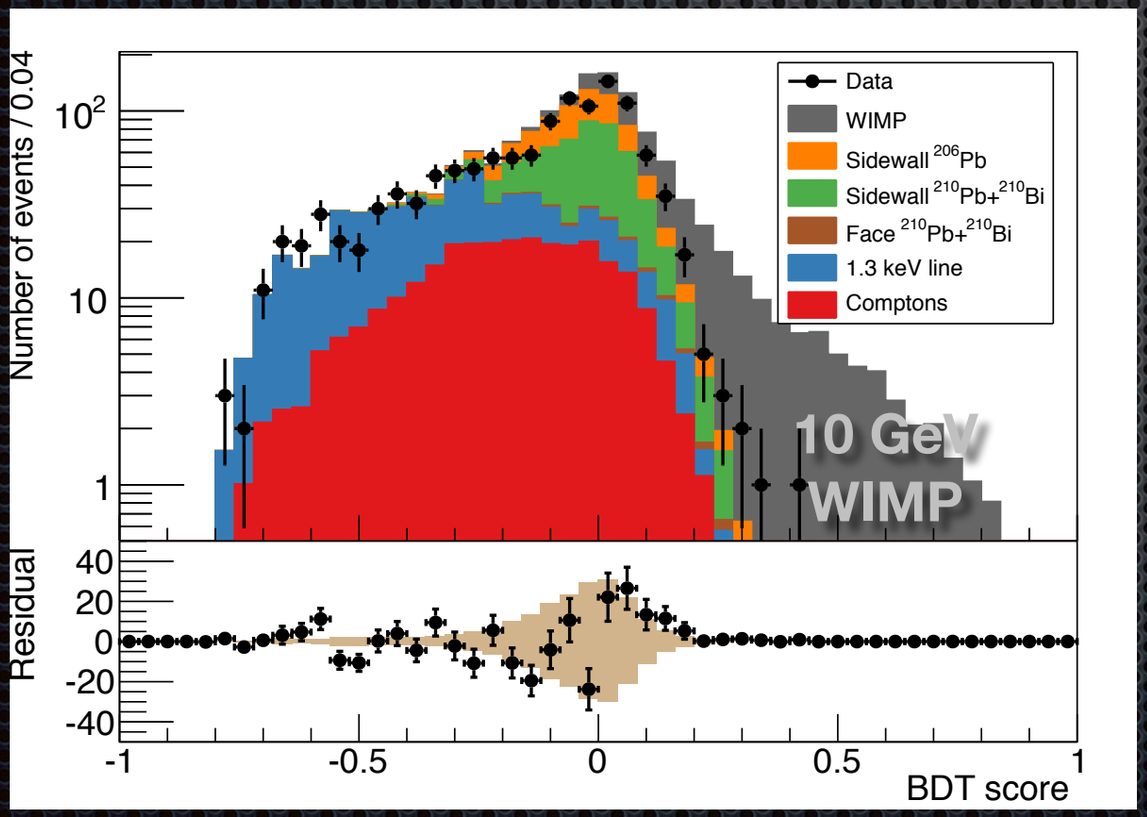


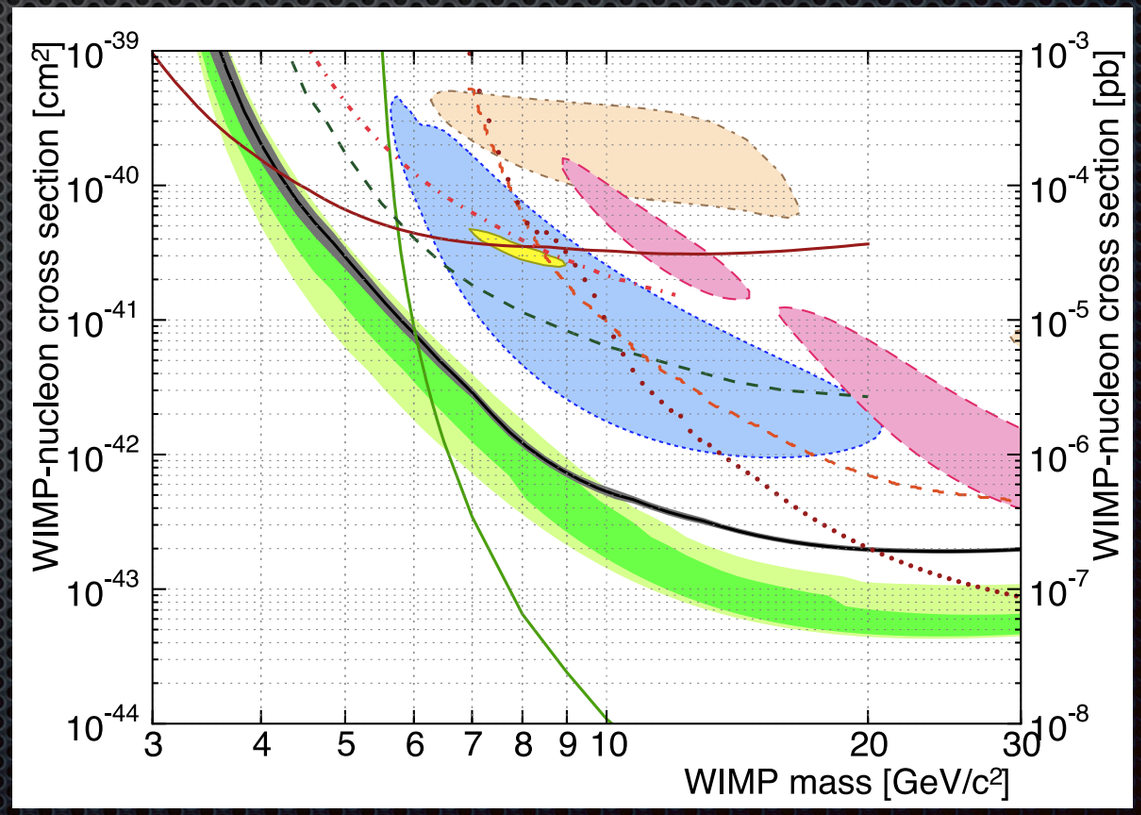


Phys.Rev.Lett. 111 (2013) 251301

New results from SuperCDMS

- Data from 15 x 0.6 kg Ge crystals, for 577 kg-days exposure
- Low energy region: 1.6 - 10 keV_{nr} analyzed
- 11 events observed upon unblinding, consistent with background model
- **New upper limit inconsistent with previous "excesses", including CDMS-Si**

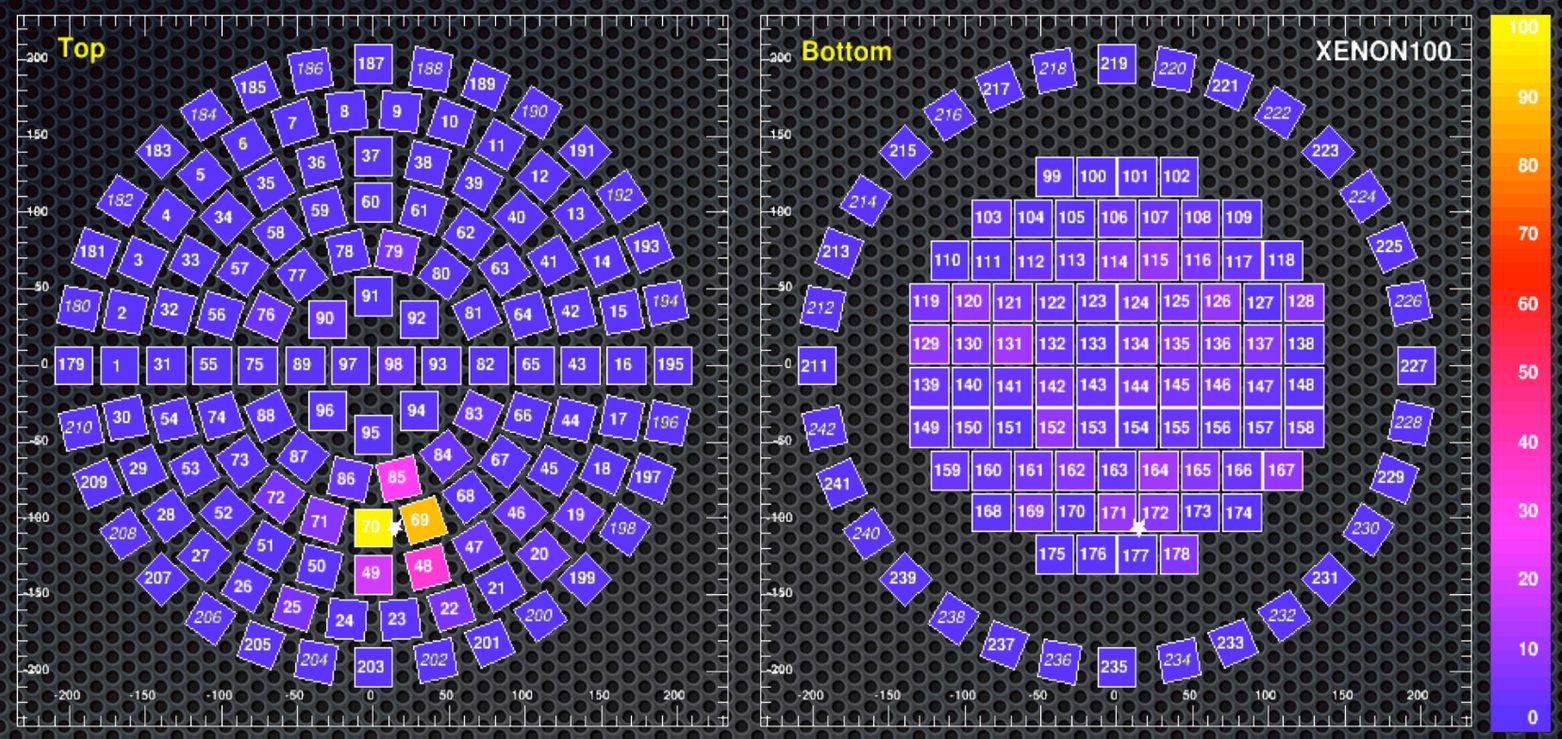




arXiv:1402.7137

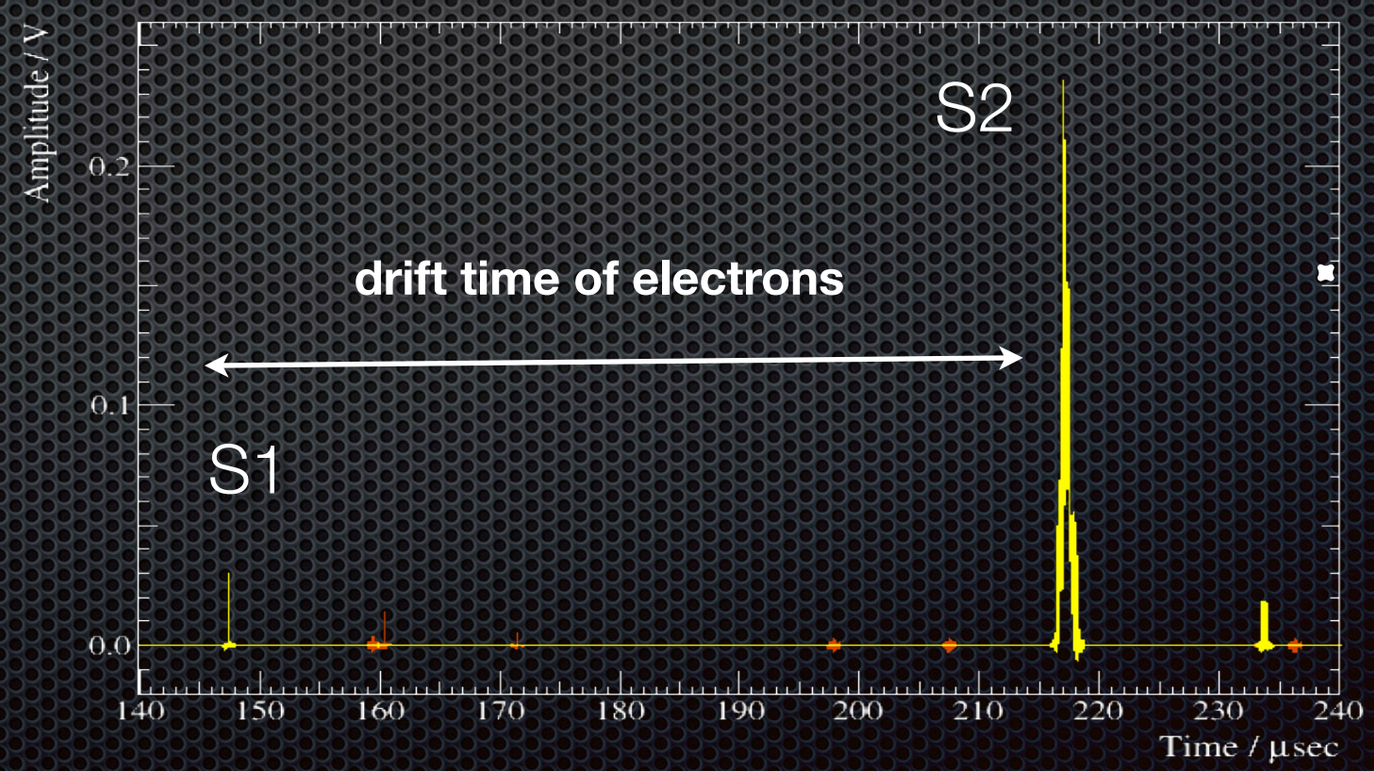
Example of a 9 keV nuclear recoil event

XENON100
top
PMT array



XENON100
bottom
PMT array

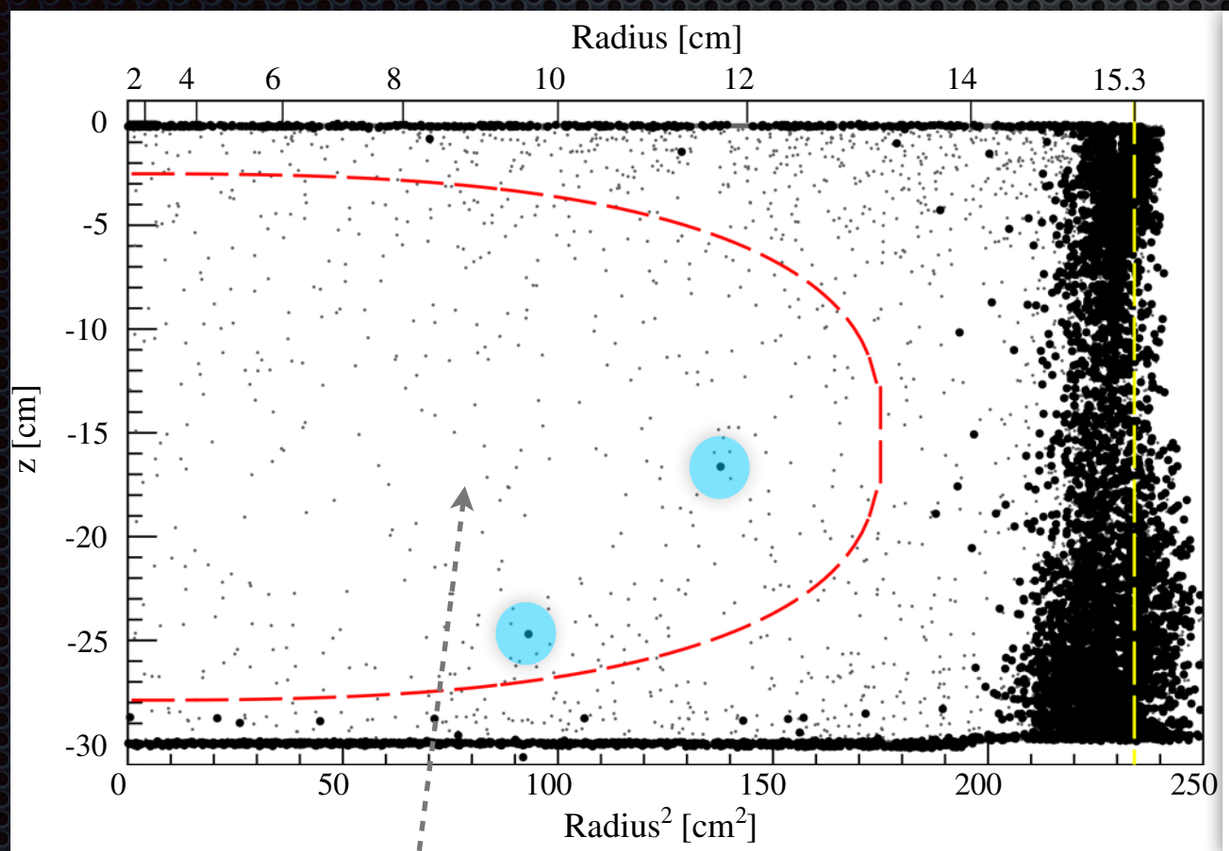
S1: 4 photoelectrons detected from about 100 S1 photons

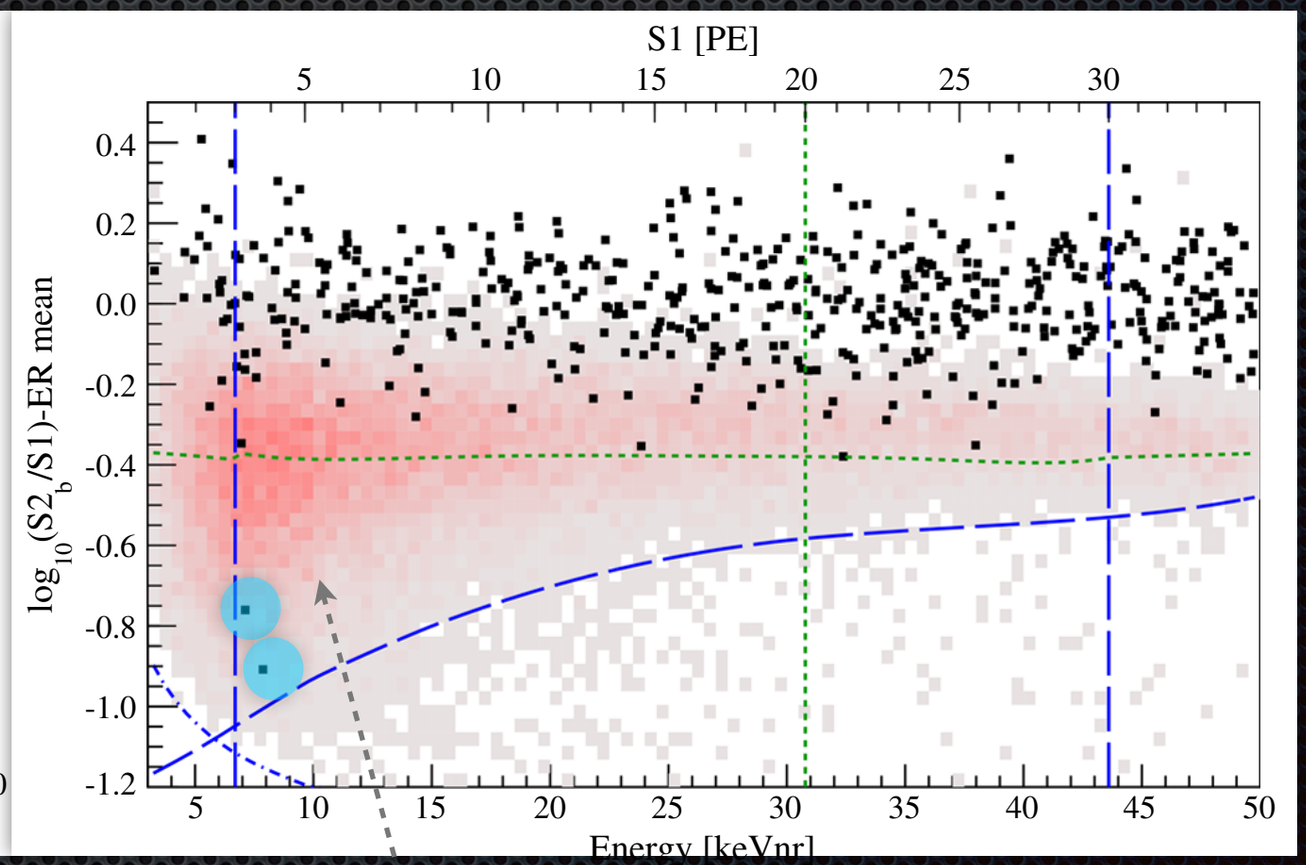


S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Example: XENON100 dark matter data

- Exposure: ~ 225 days x 34 kg fiducial liquid xenon mass





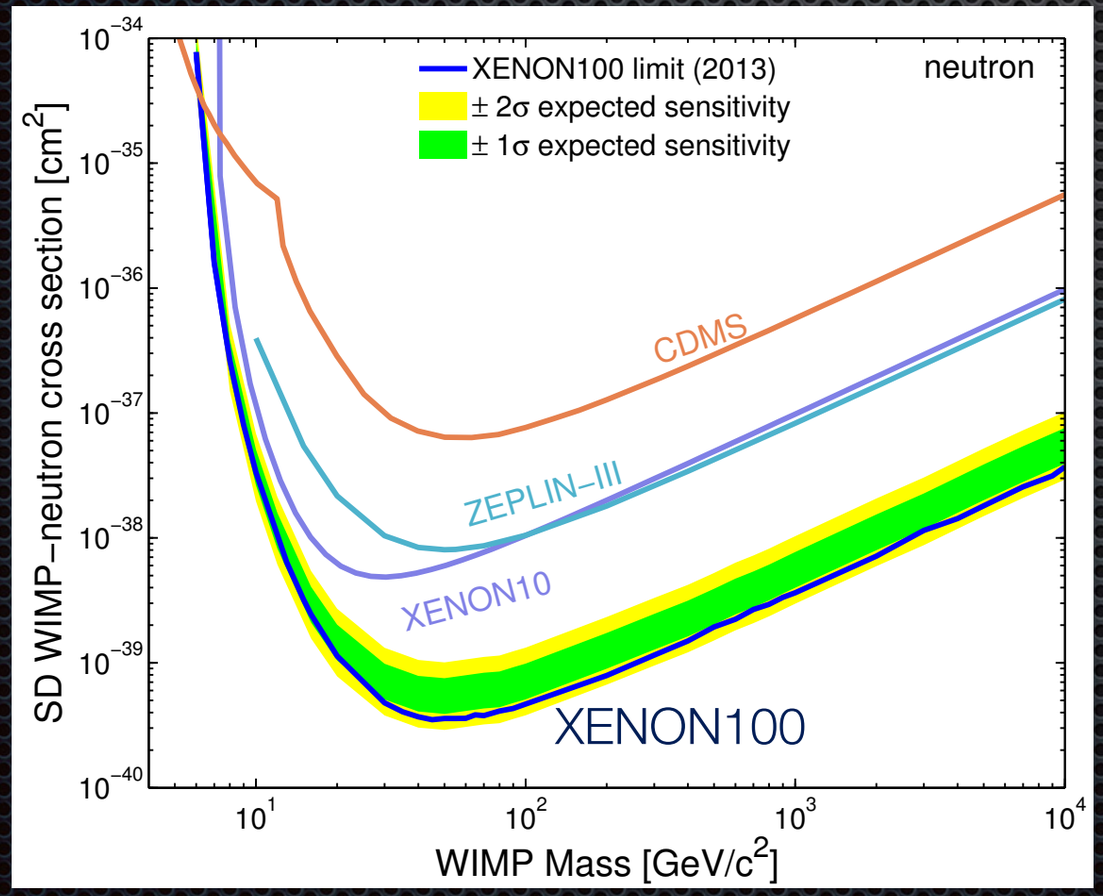
Fiducial mass region:
34 kg of liquid xenon
406 events in total

Signal region:
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected

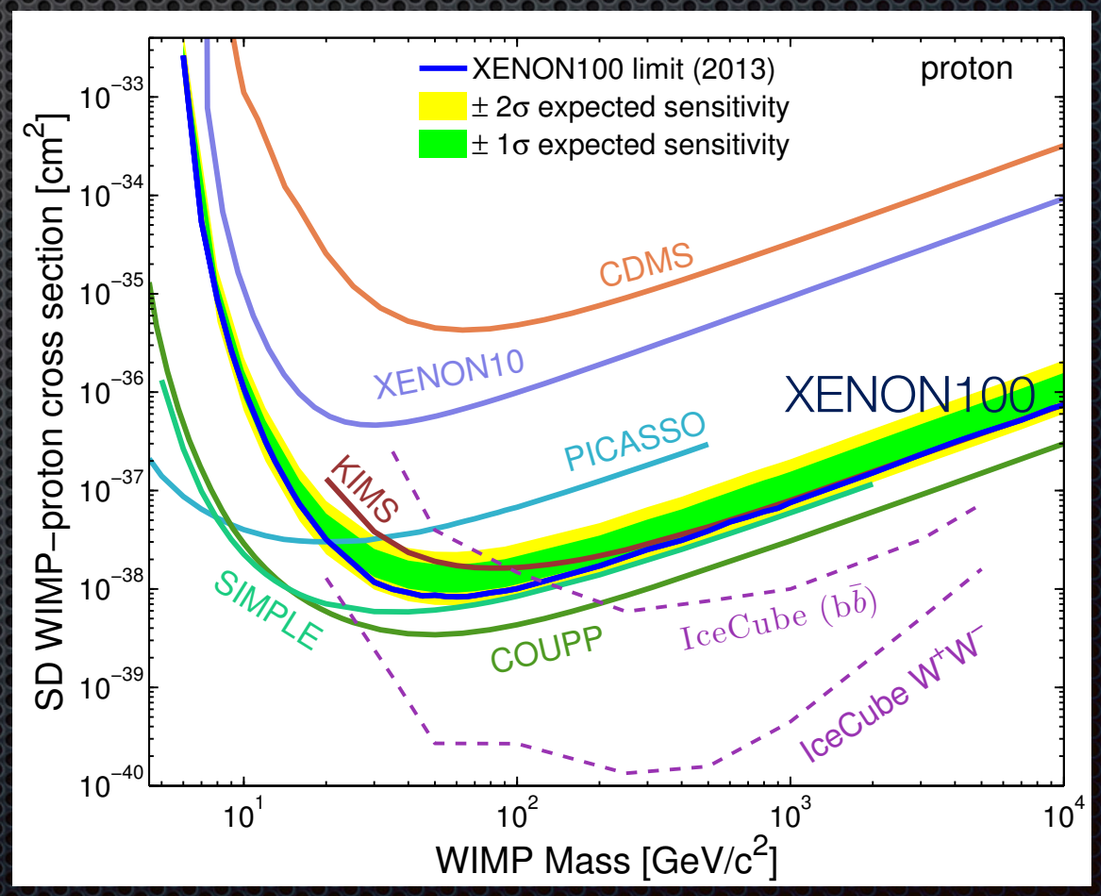
Spin-dependent results

$$\frac{d\sigma_{\rm SD}(q)}{dq^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(q) \qquad S_A(0) = \frac{(2J+1)(J+1)}{\pi J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

WIMP-neutron coupling



WIMP-proton coupling



Phys. Rev. Lett. 111 (2013)

Expected Scattering Cross Sections

- The WMP-nucleus scattering is NR for galactic WIMPs (**v/c ~10^{-3}**) -> simple NR effective theory, q ~ O(10-100 MeV)

- Interactions leading to **WIMP-nuclei scattering** are parameterized as:
  - **scalar interactions** (coupling to nuclear mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A - Z) f_n\right]^2$$

f_p, f_n: scalar 4-fermion couplings to protons and neutrons

  - **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

a_p, a_n: effective couplings to protons and neutrons

$$\sigma_{SD} \sim \mu^2 \frac{J_N + 1}{J_N}\left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

$\langle S_p \rangle$ and $\langle S_n \rangle$

expectation values of the p and n spins within the nucleus