Direct Dark Matter Searches

Context

Techniques

Status of current experiments

New results

Prospects

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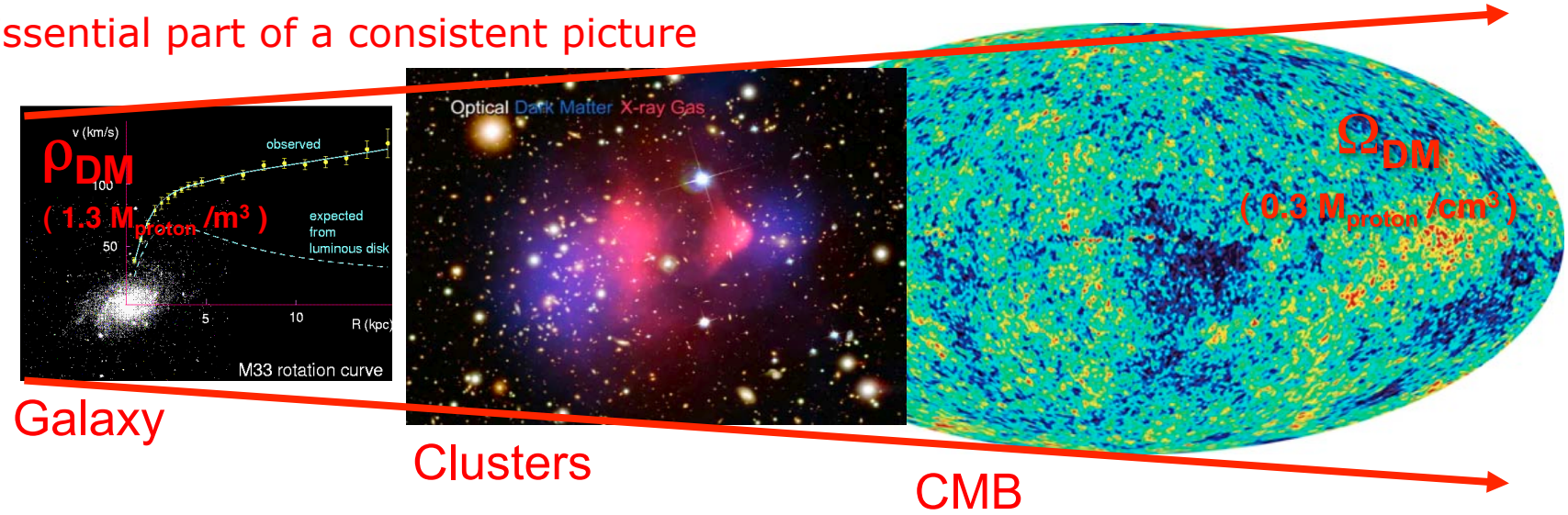
DIRECT SEARCH: CONTEXT

Cold Dark Matter in the Universe

- Cold Dark Matter present at all scales in the Universe…

Essential part of a consistent picture



- Searched as a new particle at LHC

See many talks this week

- Searched via the remains of its decay in cosmic rays (γ, ν, e+, antimatter)
- *… Direct seach: collision of WIMPs from our galactic halo on target nuclei I a laboratory on Earth*
  - Proof that Dark Matter is present in our environment
  - After discovery: observatory for WIMP velocity distribution in our environment?
  - Sensitive to local WIMP density ρ_{DM} (not to the cosmological density Ω_{DM})

Can we detect WIMPs?

- Cosmology: $\Omega_{DarkMatter}$ ~ 0.268 +- 0.02 **(1.3 M_{proton} /m^3)**
- Astrophysics: Localy, ρ_{DM} ~ 0.4 GeV/cm^3 **(0.3 M_{proton} /cm^3)**

Hypothesis: thermal production in the Big Bang

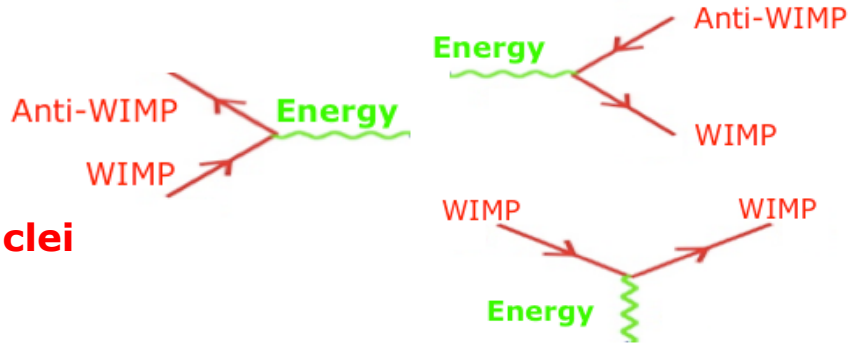
- *Particle physics*: pair production (and annihilation)
- *Big Bang Thermodynamics*: $\Omega_{DarkMatter}$ proportional to $\sigma_{annihilation}$:

$$\langle\sigma_{annihilation} v\rangle \;/\; (\Omega_{DM} h^2) \quad \sim \quad 0.3 \times 10^{-27}\ cm^3/s$$

- *Miracle WIMP*: For Ω = 0.27, $\sigma_{annihilation}$ ~ Weak Nuclear Force.
- *Big Bang Thermodynamics +Weak Force*: M_{WIMP} ~ 10 – 10 000 GeV/c^2

➔ *Predictions are possible for identifying WIMPs in 3 channels* :

1. **Creation at LHC ($\sigma_{creation}$)**
2. **Annihilation producs in cosmic rays ($\sigma_{annihilation}$)**
3. **Elastic Scattering on target nuclei ($\sigma_{scattering}$)**

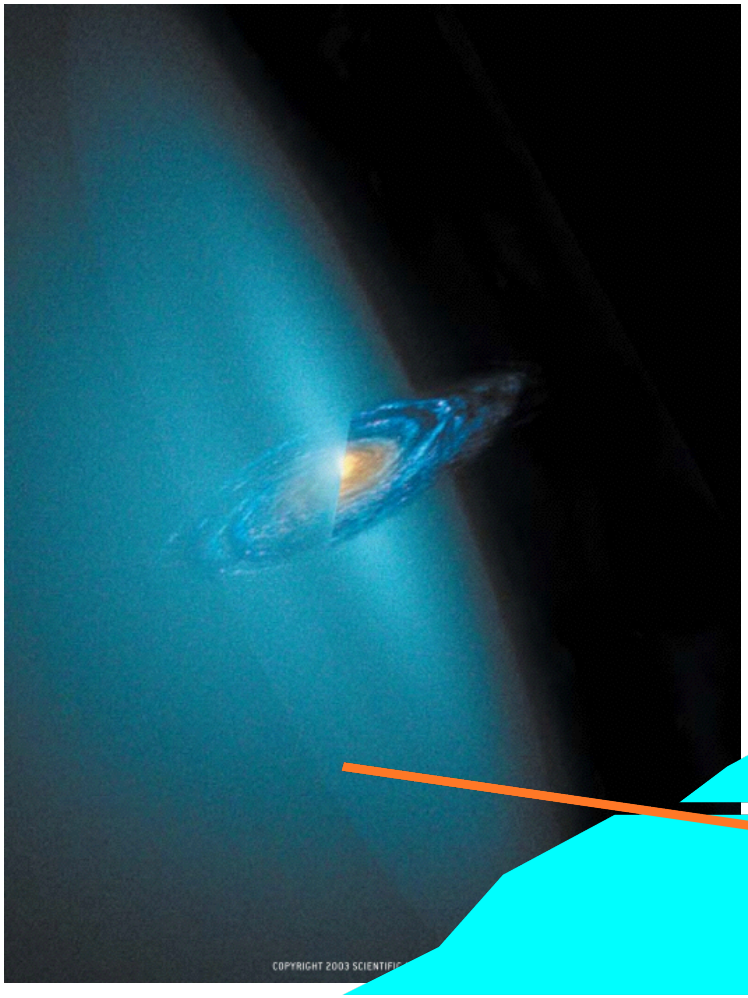


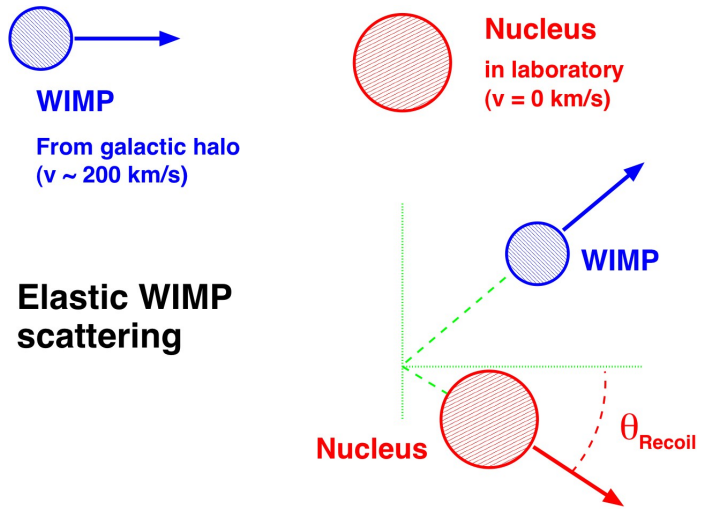
(shortened) list of candidates

- Axions
  - *Non-thermal* relics (μeV->meV, CDM->HDM)

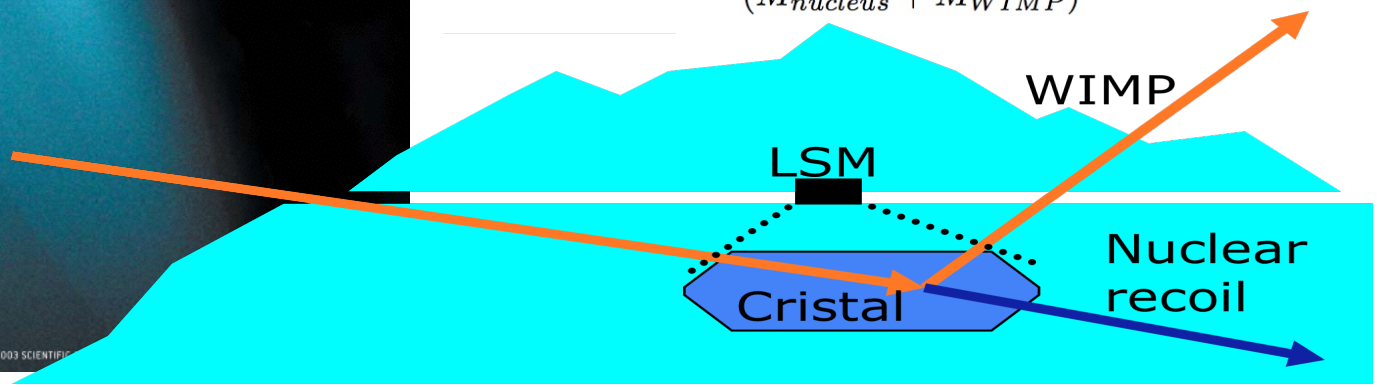
    Recent results by XENON, Edelweiss, XMASS…
    [arXiv:1404.1455;1307.1488;TeVPA2014]
- WIMPs
  - Stable thermal relics
  - Electroweak physics (~ prediction on annihilation/ creation/scattering cross-sections)
  - Mass 10-100-1000 GeV/c^2 (atomic nucleus are interesting targets: maximal momentum transfer)
- Other models
  - Many are also covered by WIMP search (KK…)
  - Models without detectable particles are not excluded!

Direct search schematics



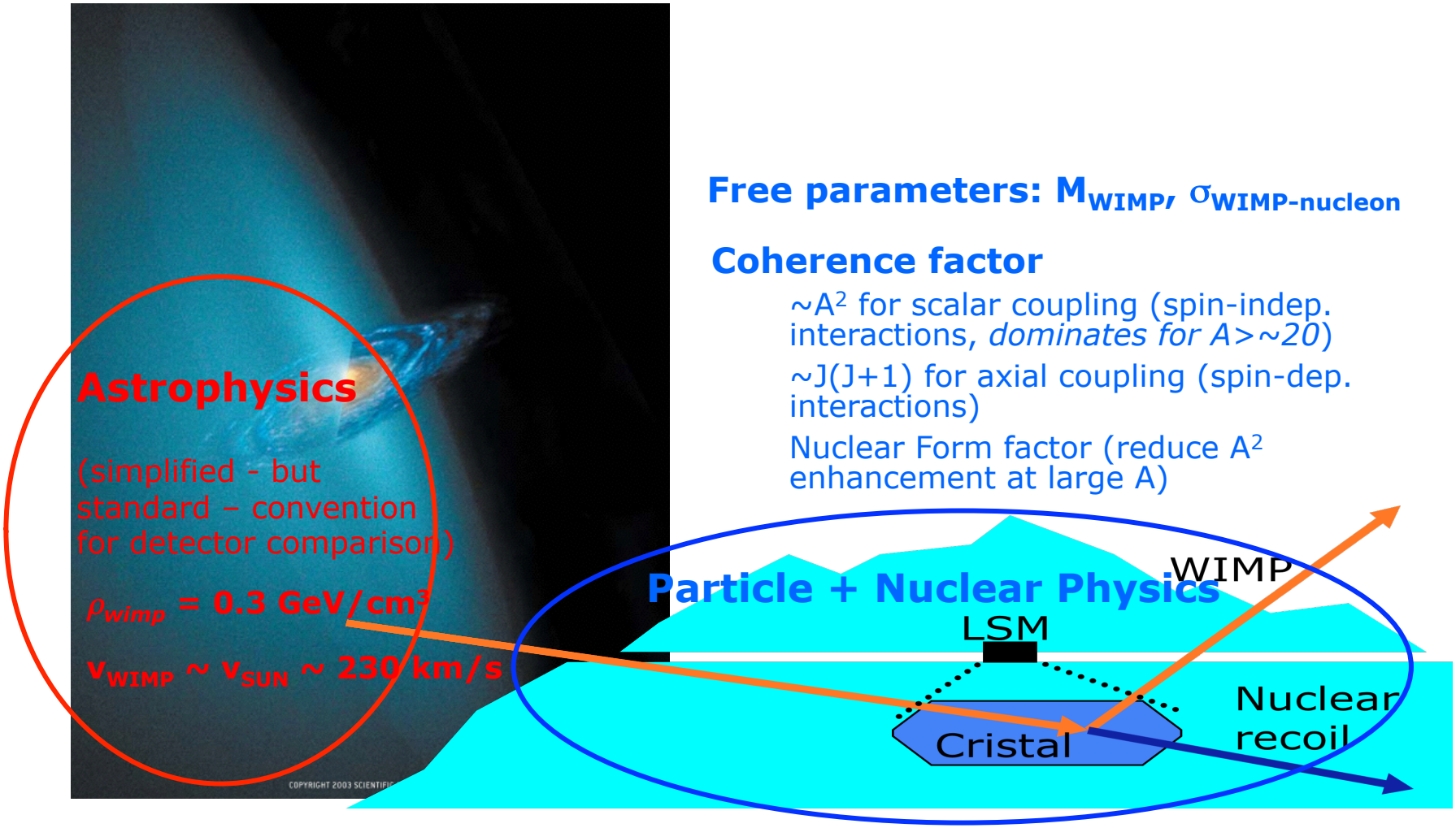


$$E_{recoil} = E_{WIMP} \frac{4 M_{nucleus} M_{WIMP}}{(M_{nucleus} + M_{WIMP})^2} \cos^2 \theta_{recoil}$$



Observables: Event rate, E_{recoil} , θ_{recoil} (recoil range is related to E_{recoil})

WIMP-nucleon collision



Free parameters: M_{WIMP}, $\sigma_{WIMP\text{-}nucleon}$

Coherence factor

- $\sim A^2$ for scalar coupling (spin-indep. interactions, *dominates for A>~20*)
- $\sim J(J+1)$ for axial coupling (spin-dep. interactions)
- Nuclear Form factor (reduce A^2 enhancement at large A)

Historical notes

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Method suggested in 1985 (28 years ago!) by Goodman + Witten

- Predict rates between 4 and 1400 events/kg/day for heavy ν.
  $M\nu$ = 100 TeV ↵ ↳ $M\nu$ = 100 GeV

- As early as 1987, first significant constraints (*exclusion of a heavy ν*) with ionization Ge and Si detectors: sensitivity to ~ few evts/kg/day
  - Ge: S. P. Ahlen, et al., Phys. Lett. B 195 (1987) 603
  - Ge: D. O. Caldwell, et al., Phys. Rev. Lett., 61 (1988) 510
  - Si: D. O. Caldwell, et al., Phys. Rev. Lett. 65 (1990) 1305

- To do better, need better rejection of radioactive backgrounds
  - Competition between techniques: Pulse-shape discrimination in NaI? Phonon+ Ionization detectors *[Shutt et al, PRL 69 (1992) 3531]*? CsI? Liquid Ar? 2-phase Xenon? Bubbles? Etc …

Experimental progress vs time

Irregular, but systematic, improvement with time

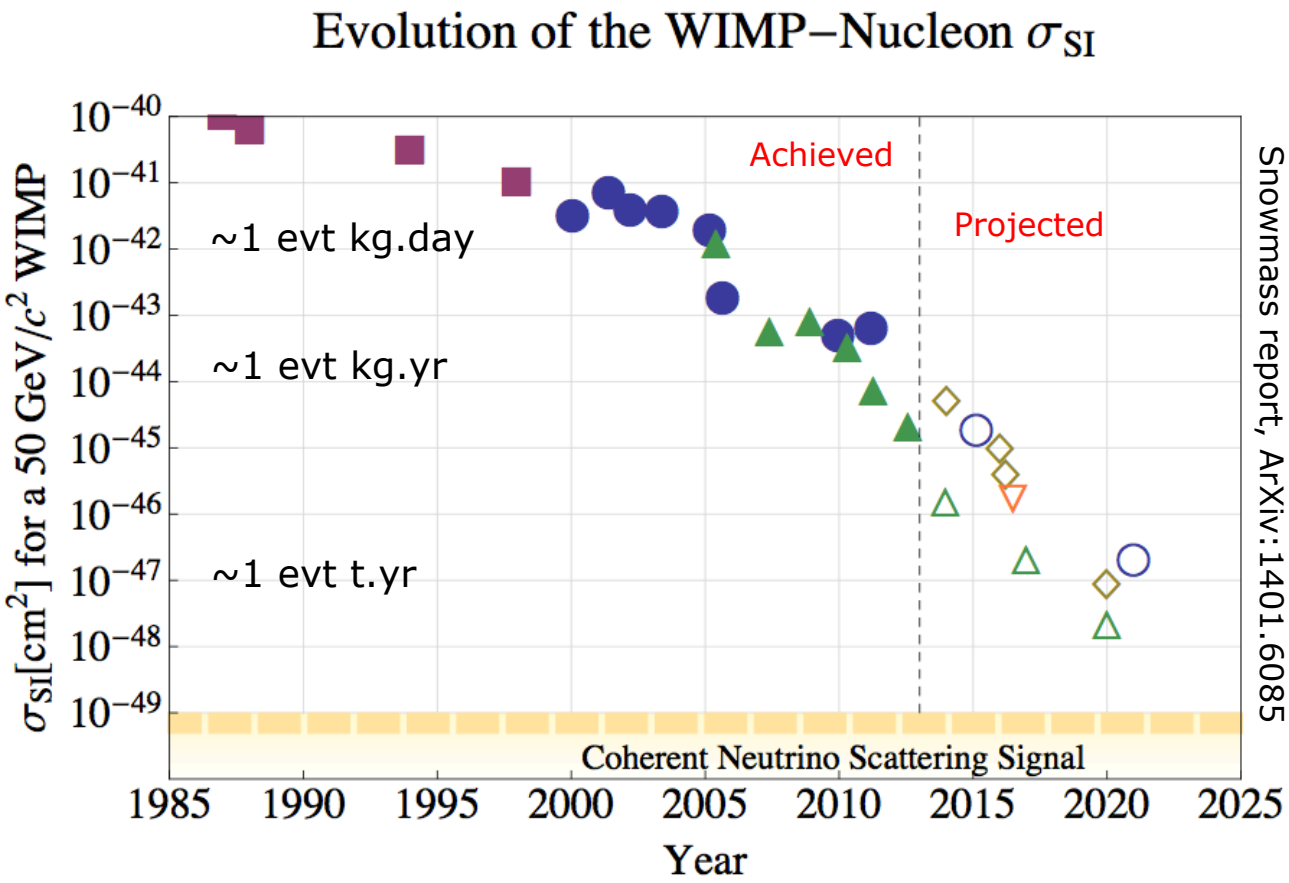


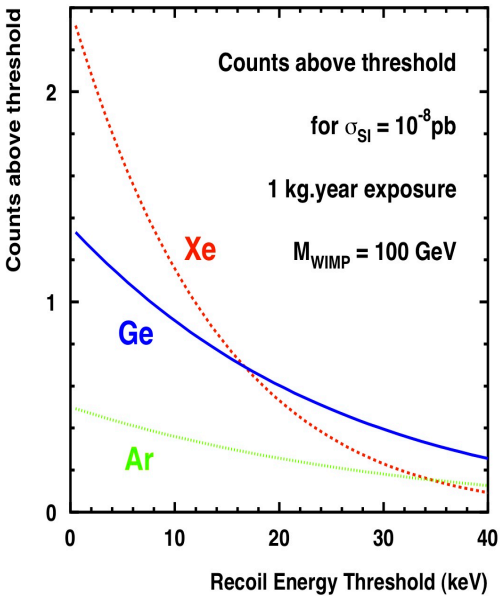
Figure 4-3. *Spin-independent limits for the major WIMP direct detection experiments (solid) and their projected sensitivity (open) for spin independent cross sections for a 50 GeV/c^2 mass WIMP. The shapes correspond to technologies: cryogenic solid state (blue circles), crystal detectors (purple squares), liquid argon (brown diamonds), liquid xenon (green triangles) and threshold detectors (orange inverted triangle).*

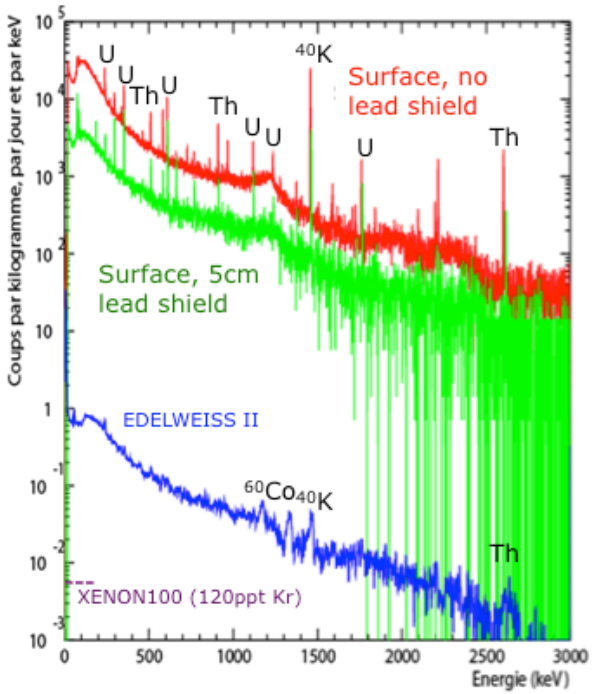
Experimental challenges

Direct Dark Matter searches = simple experiment:

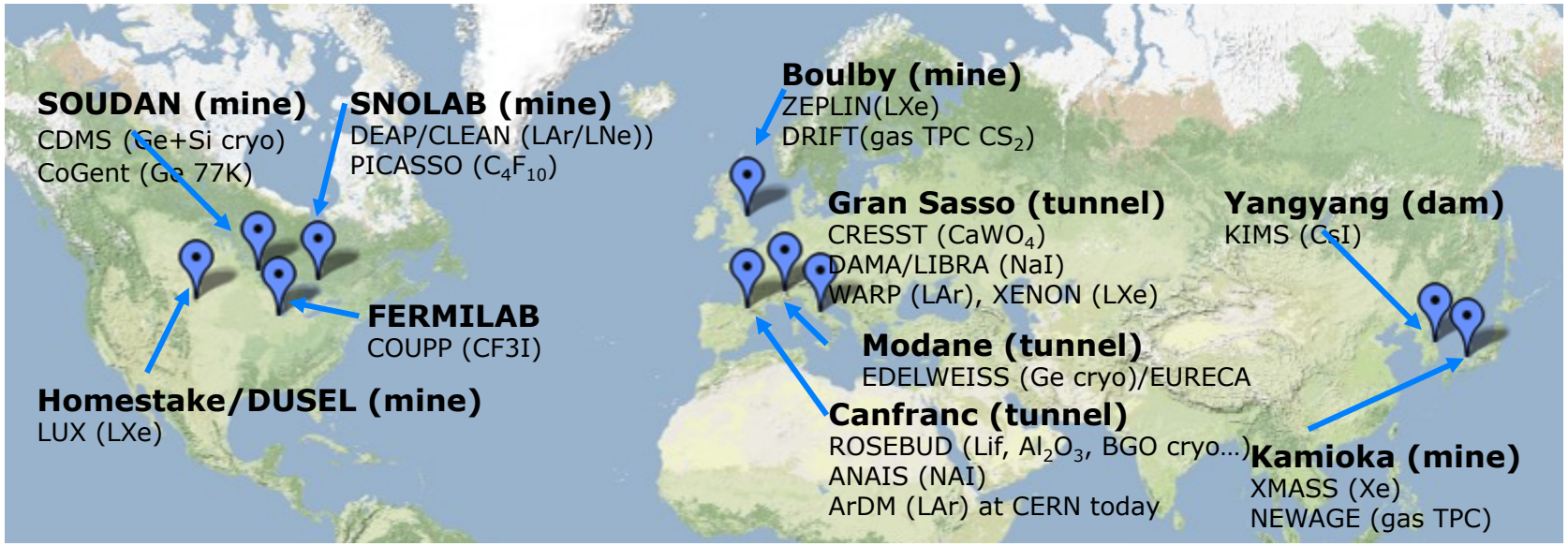
- look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision caused by a WIMP… but:

- Small event rate per unit time and per number of target nuclei (as low as 1 per ton per year?)
- Small kinetic energy involved in such collisions
- Need very strong rejection of radioactive backgrounds

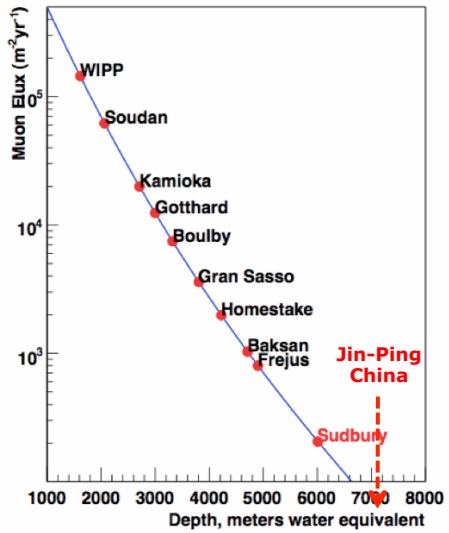




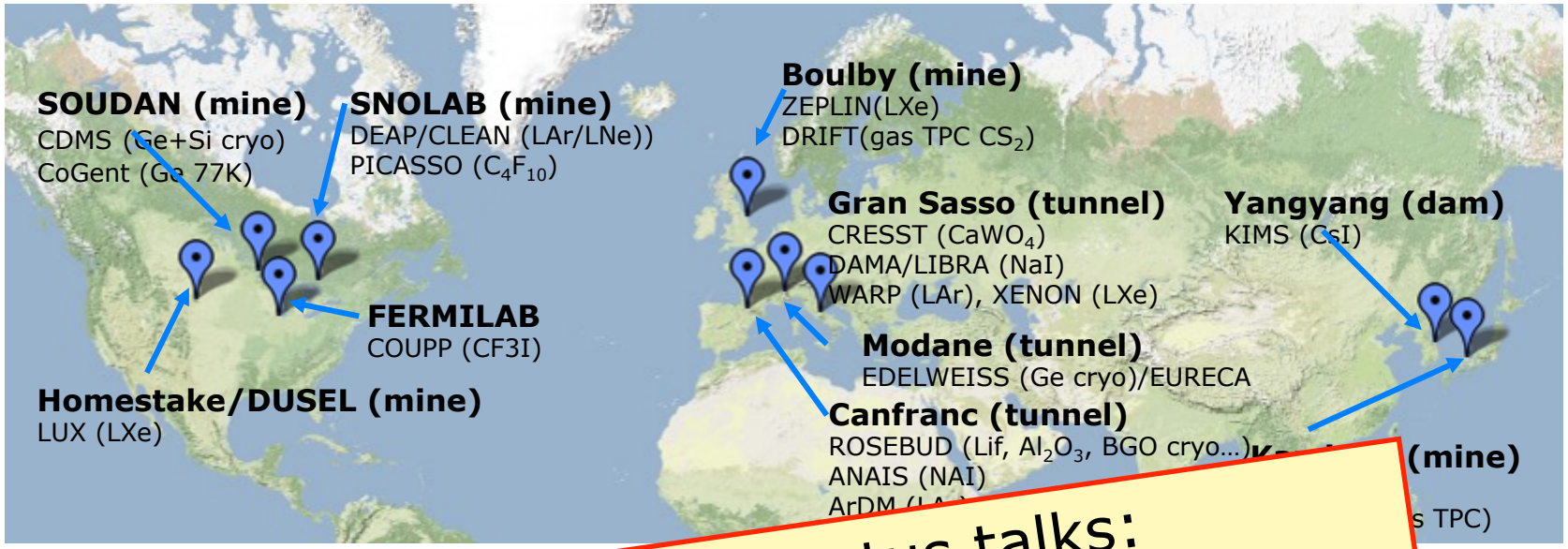
Dark Matter Searches around the world



- Underground sites (cosmic rays)
- Combine signals for ion/electron recoil identification
  - Heat (or thermalized phonons): "true" calorimetric energy
  - Ionization Yield
  - Scintillation Yield
  - Pulse shape discrimination: useful in some cases (Ne, Ar)
  - Also: dE/dx in superheated medium: COUPP, PICASSO



Dark Matter Searches around the world



- Underground si
- Cor
  -
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  - S
  - P
  - Al COUPP, PICASSO

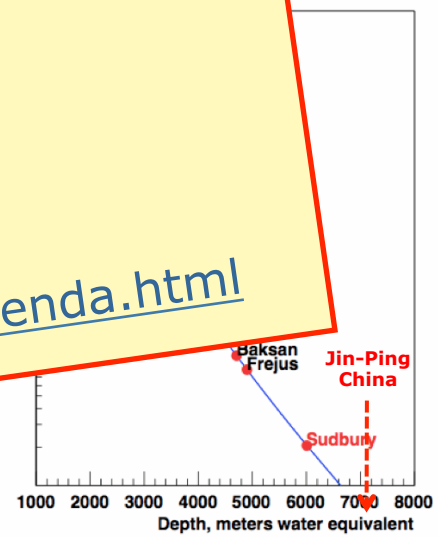
Most recent detailed status talks:

TeVPA-IDM 2014, Amsterdam

http://indico.cern.ch/event/278032/

Dark Matter 2014, UCLA

https://hepconf.physics.ucla.edu/dm14/agenda.html

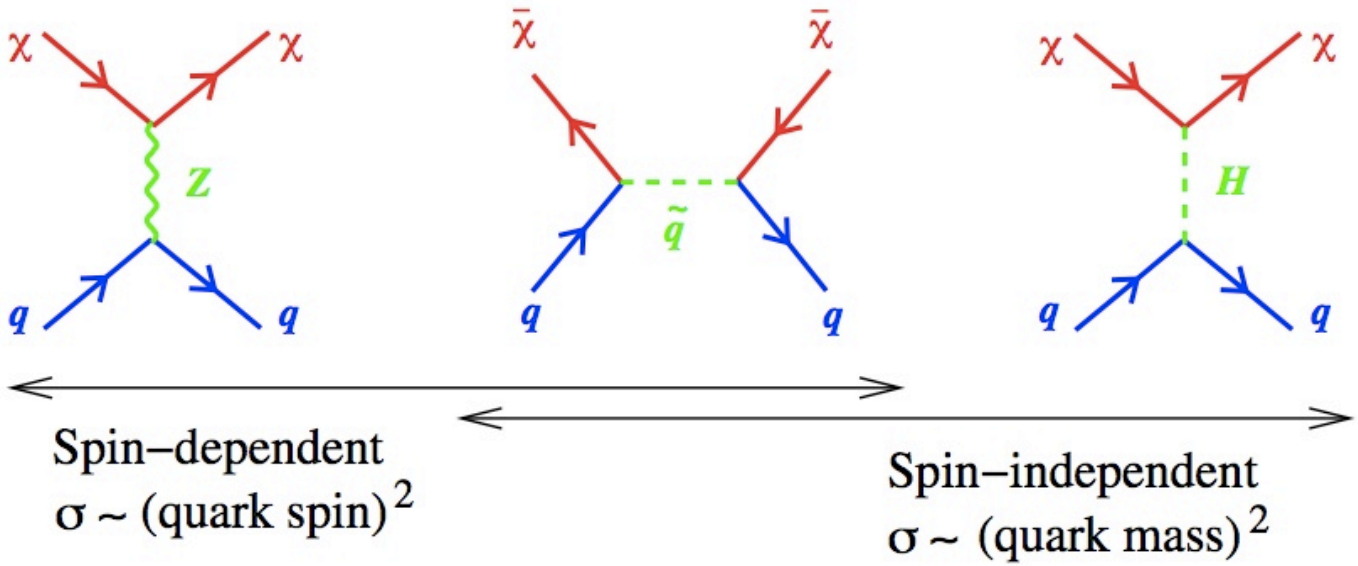


WIMP signatures

- Directionality (correlation with v_{sun})
  - Challenge: ~20 nm recoil in solid, ~30μm in gas
  - Low-pressure TPC? -> Still in R&D [DRIFT, DMTPC, MIMAC…]
  - *Small annual modulation of flux (~2%) requires large statistics + depends more on velocity distribution details.*
- Nuclear (and not electron = dominant bkg) recoils
  - **Particle identification**
- A^3 dependence of coherent scattering rate/kg
  - Motivates **diversity of target materials**
- Large scattering length
  - **Self-shielding** *[Xenon, Argon]* or **segmentation+multiplicity** *[Ge, Scintillators]*
- Control of systematics also favours target/expt. diversity

WIMP-nucleon interaction

- Neutralino-nucleon scattering cross-section can be calculated within SUSY



- Separation spin dependent (SD) / independent (SI): general expression for most types of interactions, even beyond SUSY
- Quark/nucleon spin mostly cancel out, but quark/mass add coherently: scattering rate enhancement

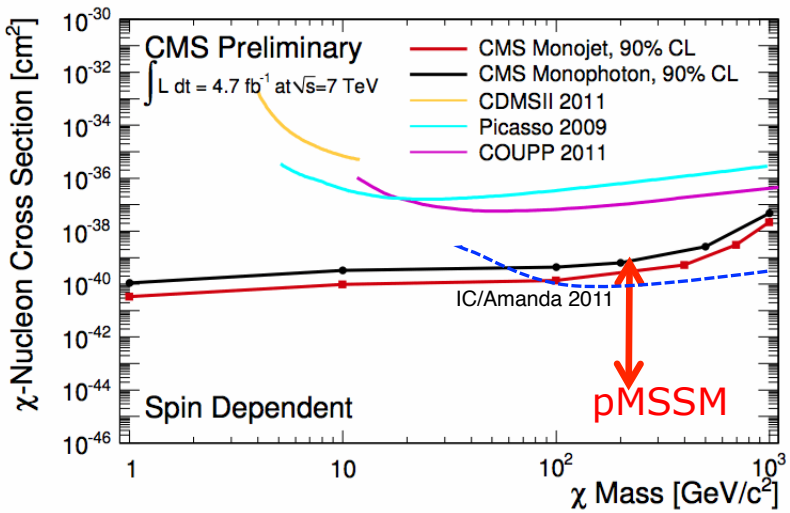
Spin-dependent interactions

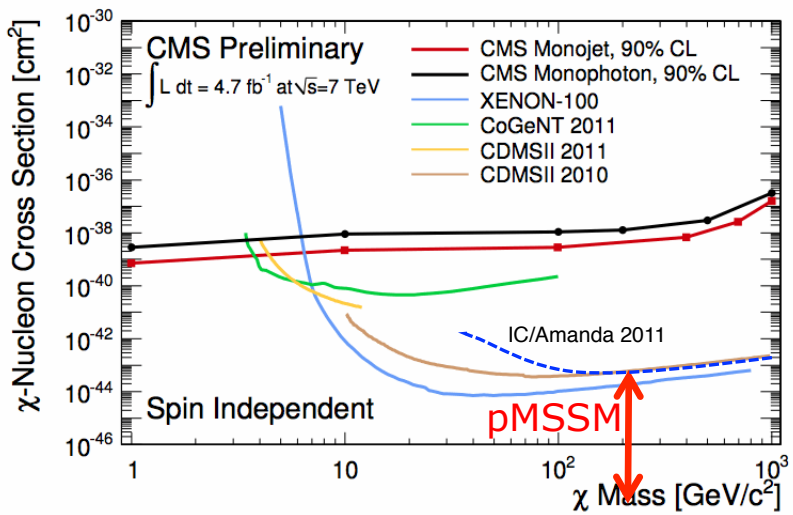
- In many models (like SUSY) axial, spin-dependent (SD) interaction are either already excluded, or mixed with spin-independent (SI) component.

  (… but this statement is model-dependent)

- SI component amplified by A^2 coherence tends to dominate.
- SD most efficiently probed by indirect searches (ν detectors) or even LHC, as SD searches don't benefit from A^2 coherence factor.

See AMS, IceCube talks this week

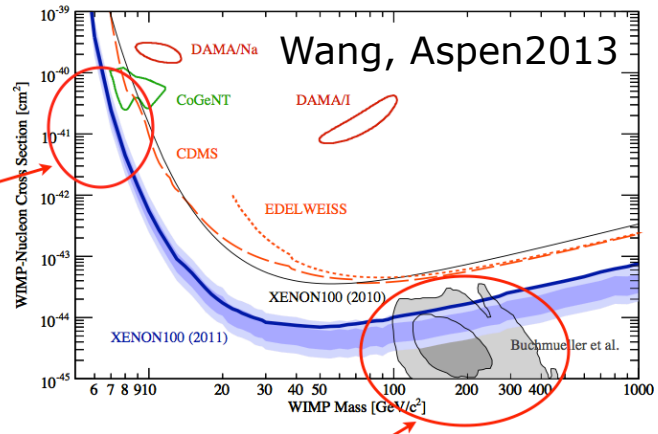




CMS Moriond EW 2012 + PRD85 (2012) 042002

Light or Heavy? - predictions

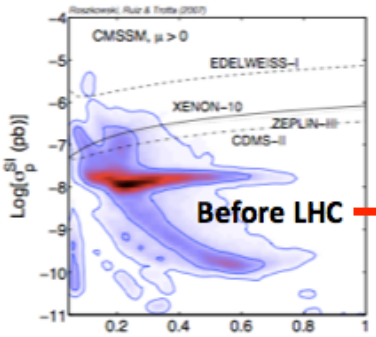
- Absence of "minimal" SUSY at LHC opens SUSY phase space
- Less predictive in terms of M_{WIMP}
- Two (opposing?) biases:
  - heavy SUSY suggests heavy WIMPs
  - absence of SUSY calls for something new
  - … lighter than conventional SUSY?



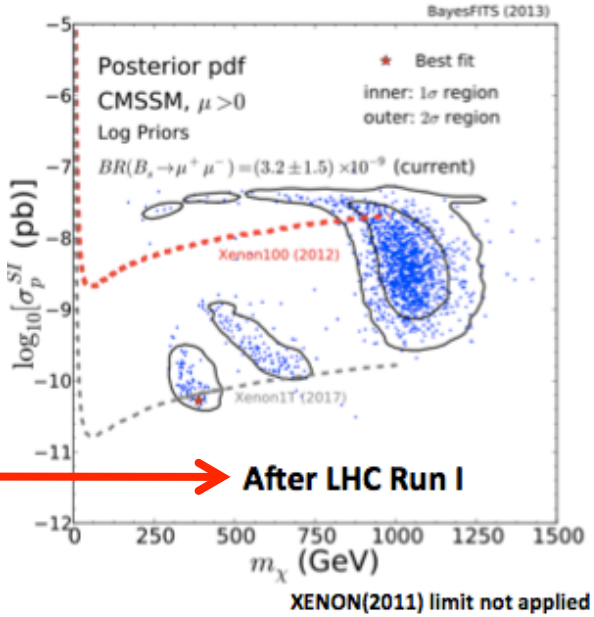
Light DM spin-1 mediator.

SUSY, typically Higgs mediated.

Roszkowski, Moriond QCD2013

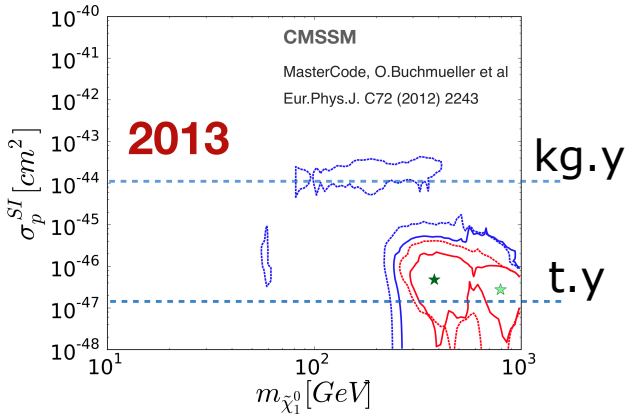


Before LHC

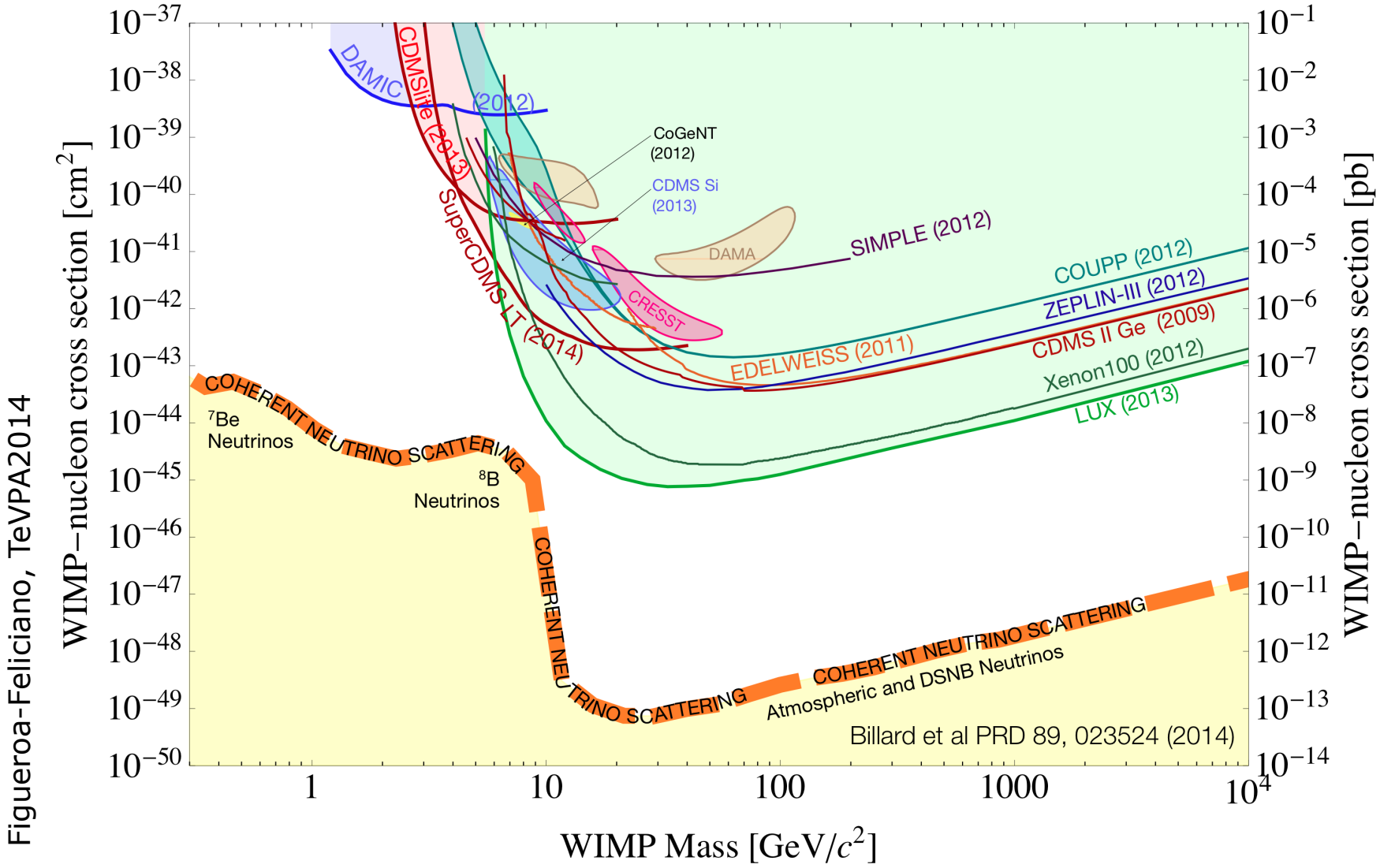


After LHC Run I

Baudis,TAUP2013

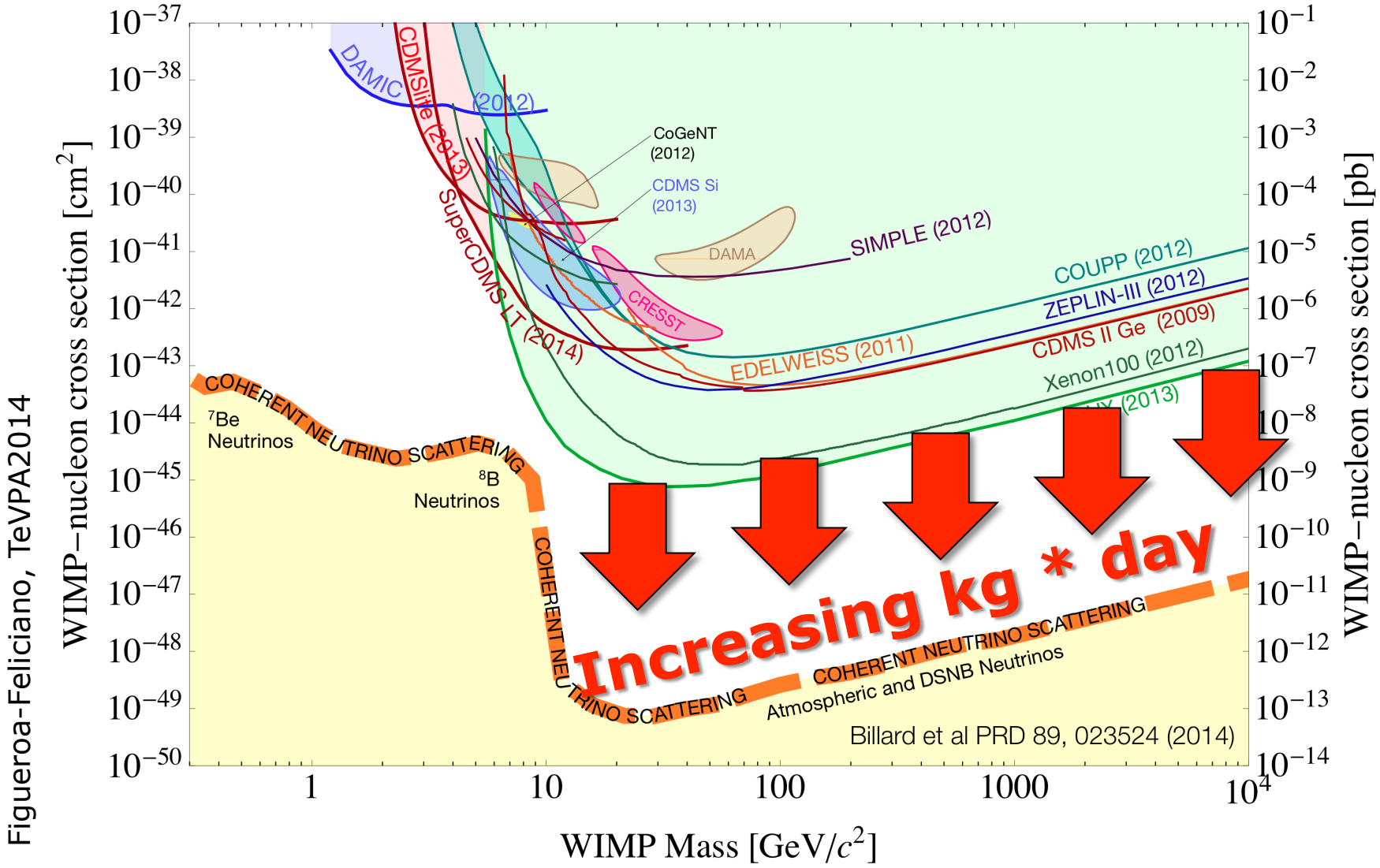


The experimental search domain



Figueroa-Feliciano, TeVPA2014

The experimental search domain



Figueroa-Feliciano, TeVPA2014

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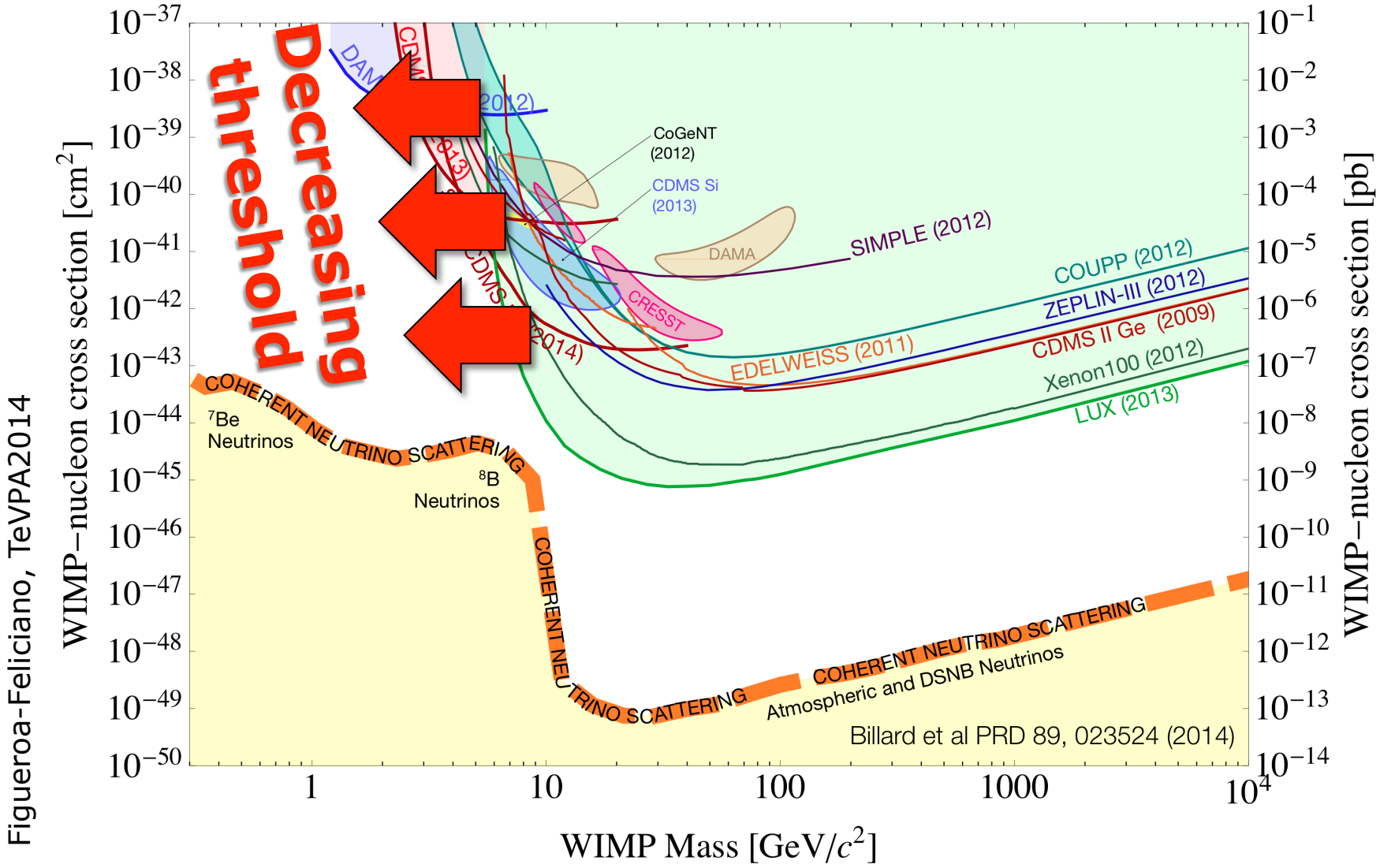

Figueroa-Feliciano, TeVPA2014

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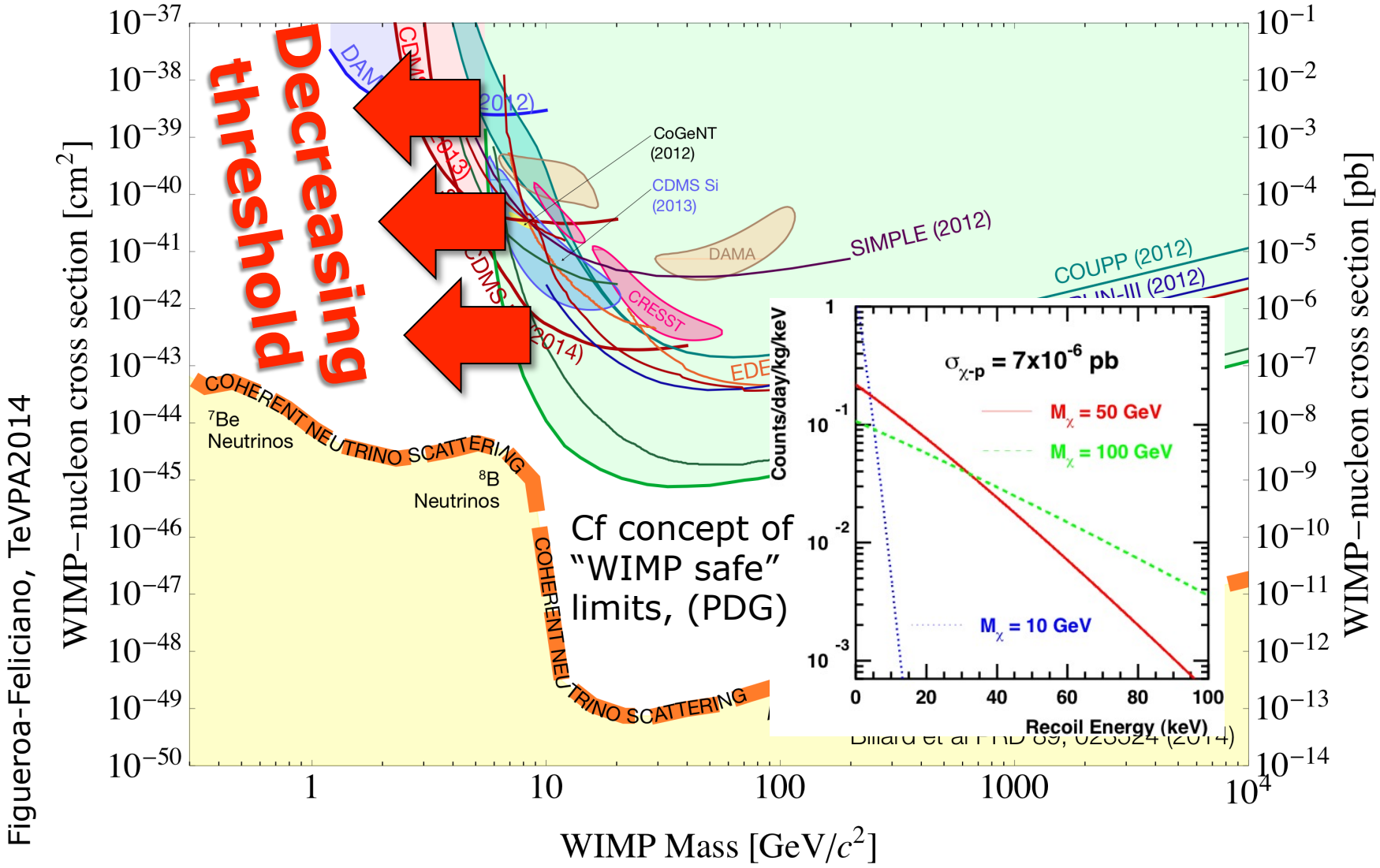

Figueroa-Feliciano, TeVPA2014

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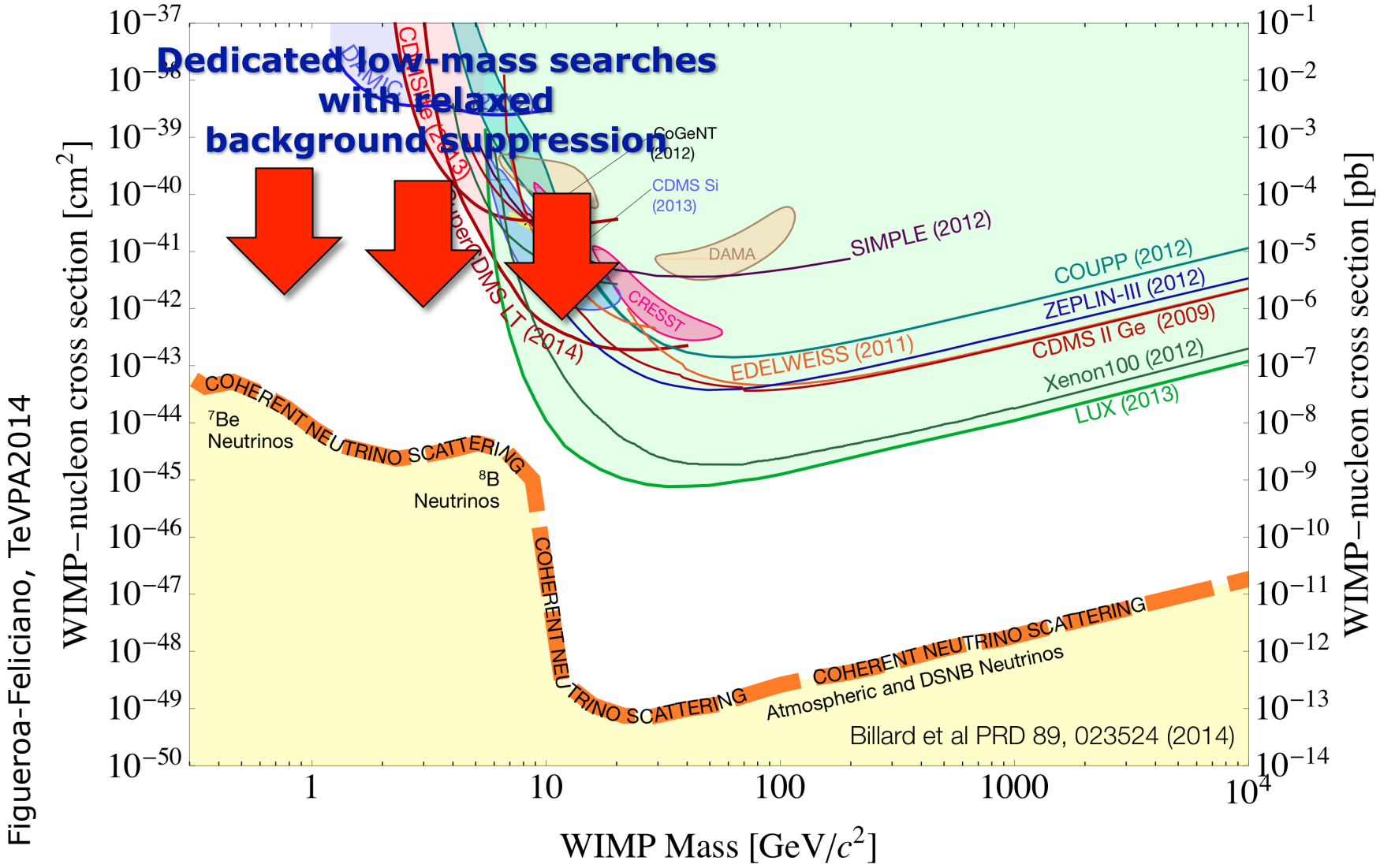


Figueroa-Feliciano, TeVPA2014

2- DETECTION TECHNIQUES

Signals in direct searches

- Exponential recoil spectrum
- A^3 dependence of rate

It's not a neutron-induced nuclear recoil ($\sigma = \pi R^2 \propto A^{2/3}$)

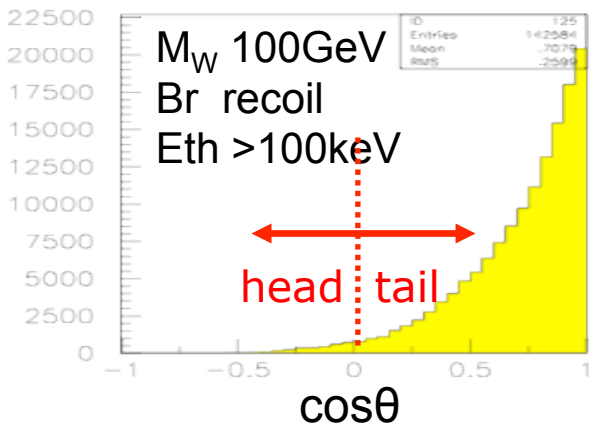
- No coincidence between adjacent detectors (detector array)
- Uniform rate within the fiducial volume (large detectors)

- Directionality (correlation with $\vec{v}_{SUN}$ direction): need to measure nuclear recoil trajectory
- Annual modulation (large statistics needed)

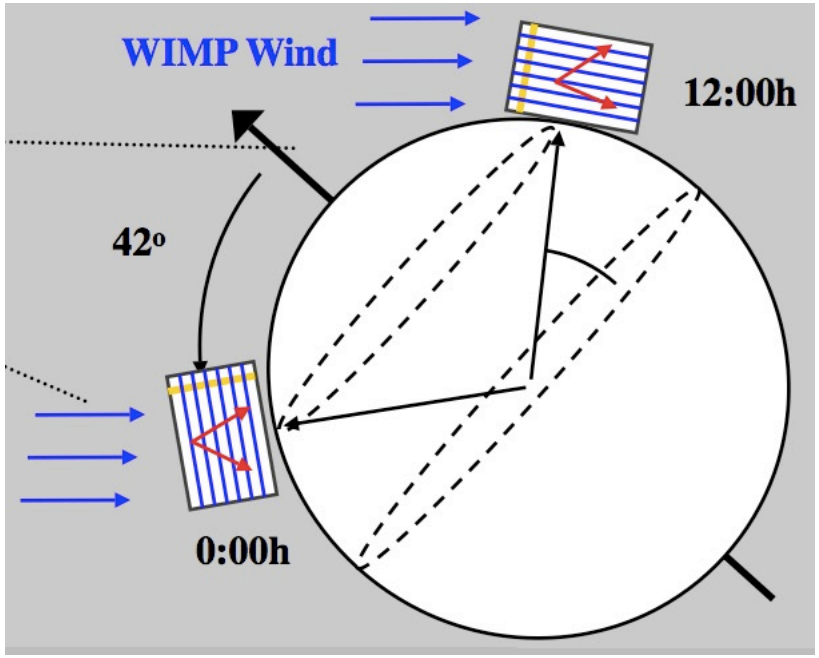
- ***Identification of nuclear recoils (vs electron recoils)***

Directionality: use v_{Earth} to detect WIMP wind

- Average WIMP wind direction due to v_E
- $\theta_{RECOIL} \neq \theta_{WIMP}$ but $<\theta_{RECOIL}> = <\theta_{WIMP}>$



Naka, IDM2008

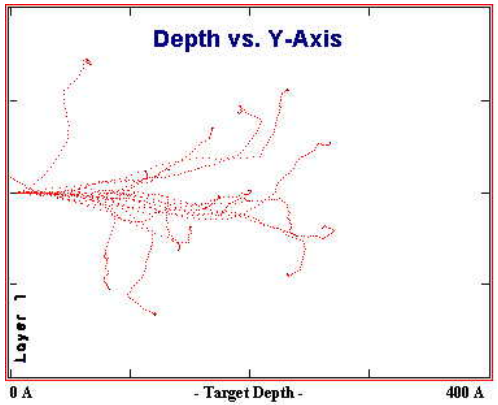


Spooner, IDM2008

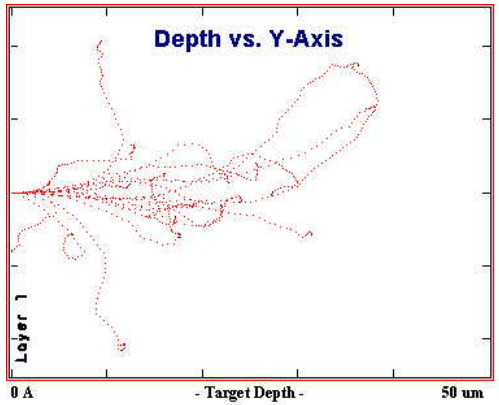
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

Range of nuclear recoils in matter

20 keV Ge recoils
in crystal Ge:
Range ~20 nm

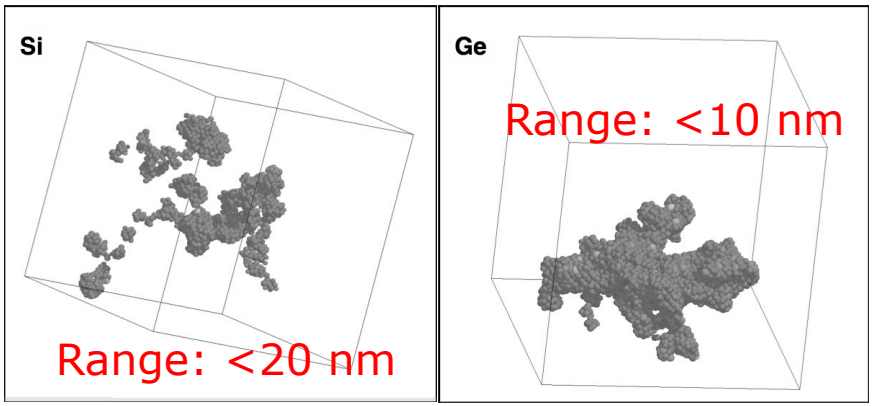


20 keV Kr recoils
in gaseous Kr:
Range ~30 µm



SRIM

- *Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)*



R&D on direction-sensitive techniques

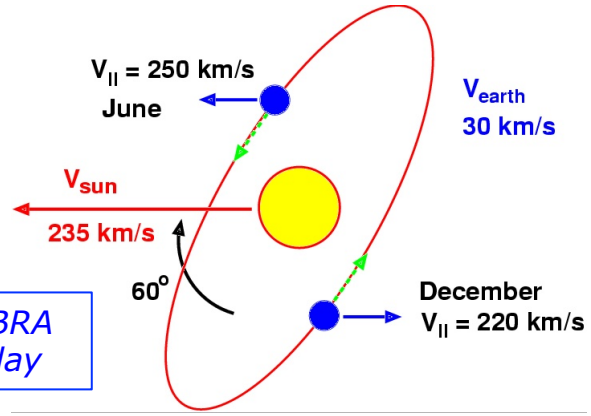
- Idea: check for recoil tracks in ancient mica, $\theta_{recoil} \sim -v_{sun}$
  - *Problem: direction of v_{sun}, v_{earth} changes constantly, continental drift…*
- Idea: low-pressure gas TPC detector

Expt		Target (bar)	F mass (g)	Vol. (L)	Thresh. (keV)
DRIFT	UK	CS_2 (0.04) CF_4 (0.01)	33	800	50
NEWAGE	JPN	CF_4 (0.2)	9	15	140
MIMAC	F	CF_4+CHF_3 (0.05)	1	5	20
DM-TPC	US	CF_4 (0.1)	3	9	80

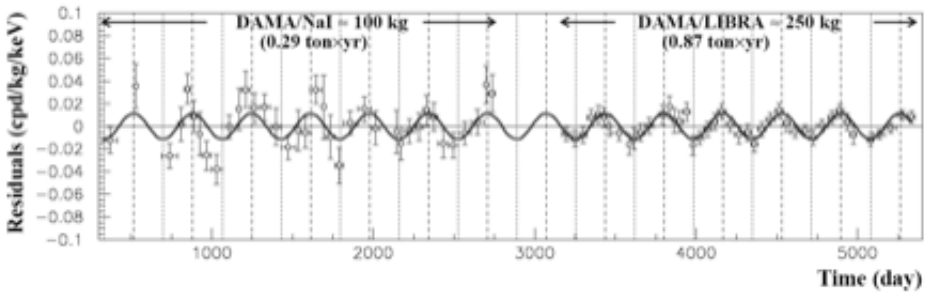
  - *Problems: low-density target to expand track length to ~cm, reduce diffusion of e−/ion (negative CS_2 ions instead of e^-)*
- Idea: scan tracks in emulsions
  - *~100 nm resolution; ~200 keV threshold for Br recoils (200 nm)*

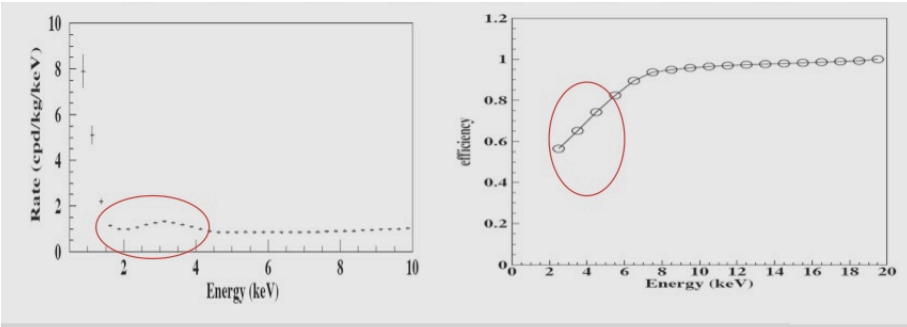
Annual modulation in DAMA

- Need large statistics: flux modulation is ~±3%, or less when considering experimental thresholds
- Claimed to be observed (~±2%) at low-energy in NaI (DAMA)
- Non-modulating component (~1 evt/kg/day) is ~total rate in NaI, but not observed in Ge, Xenon, $CaWO_4$ and CsI (KIMS).
- Signal in low-efficiency, near-threshold region
- NaI modulation expt. checks: SABRE (use DarkSide veto) DM-ICE (Antartic site, deep in ice)



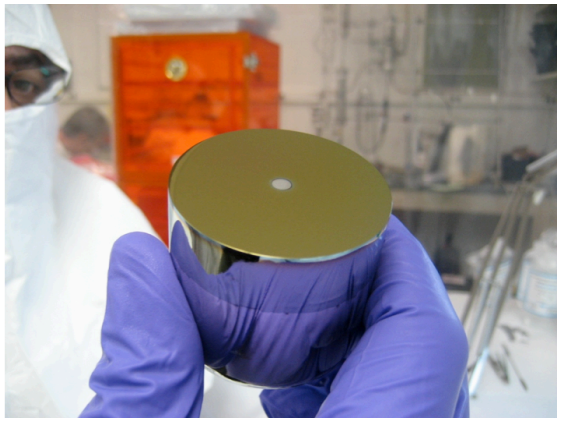
See DAMA-LIBRA talk on Saturday

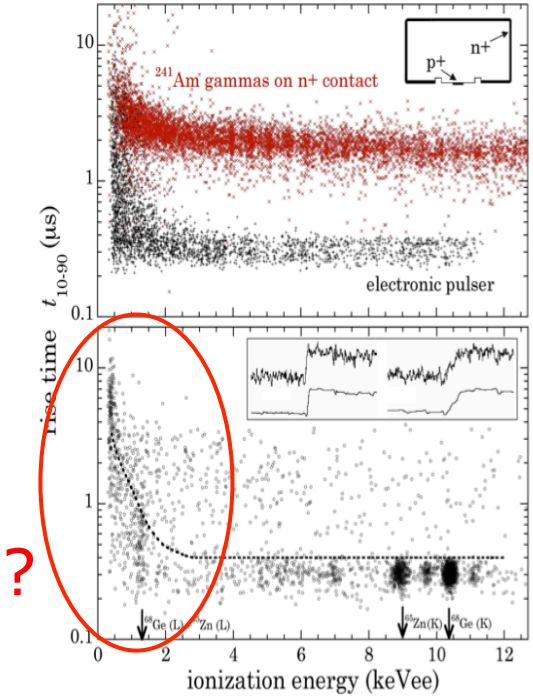


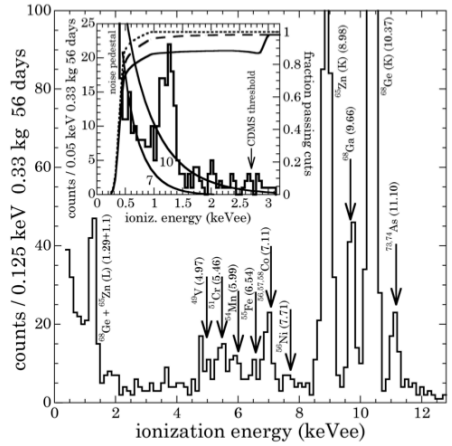


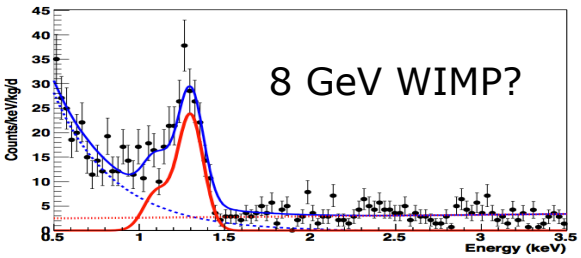
CoGeNT Modulation

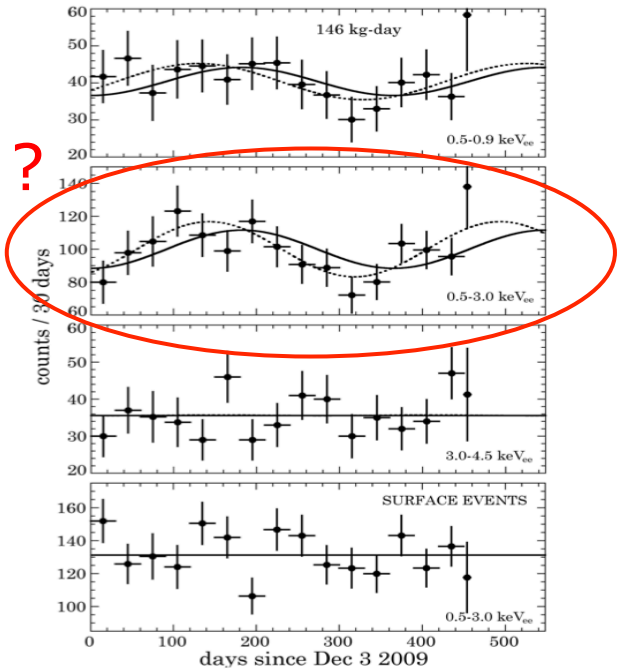
- 440 g Ge diode, point-contact electrode
- Arxiv:1002.4703 (Risetime discr. of surface evts)
- Arxiv:1106.0650 (Annual modulation)
- Arxiv:1208.5737 (Revised evaluation of surface rejection, *reduction of annual modulation*)



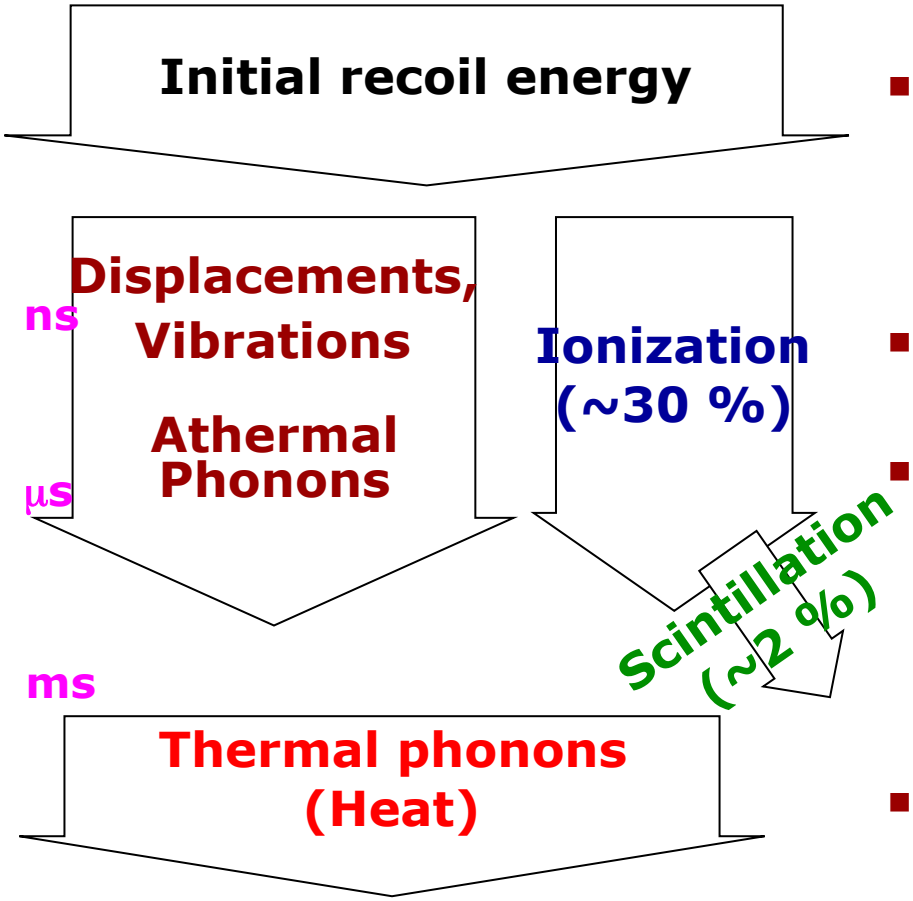








Effect of a nuclear recoil in matter

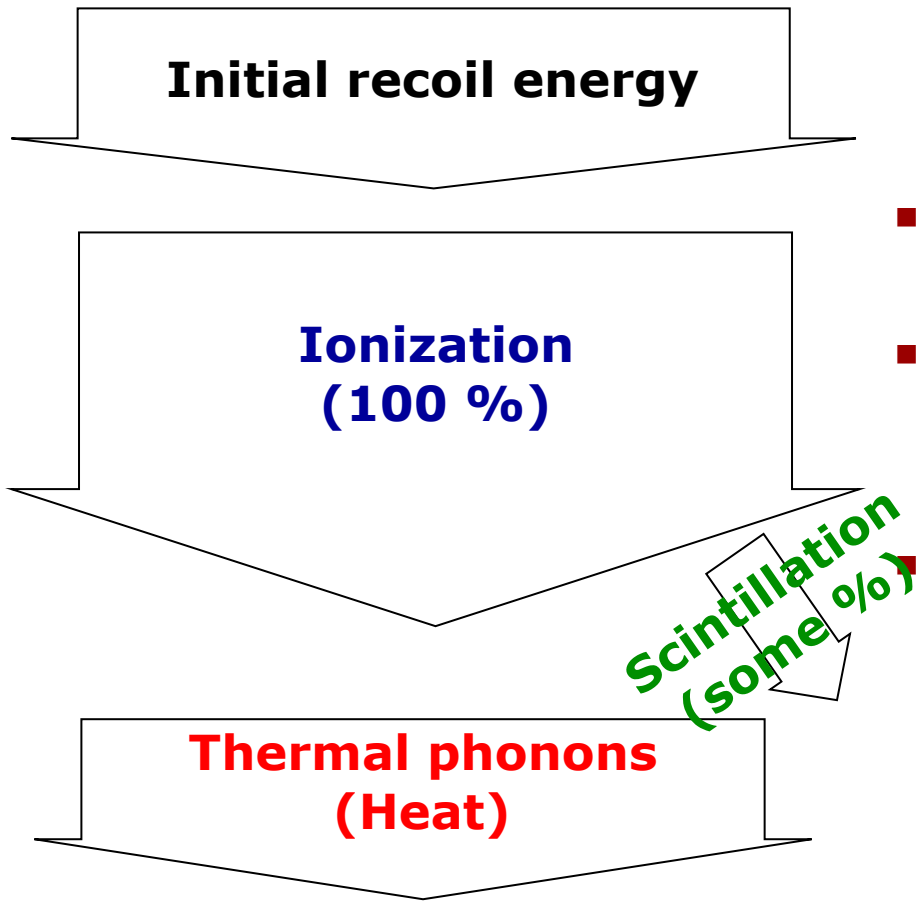


(+ Permanent crystaline defects?)

Two type of energy losses:

- Ion-ion collisions (producing displacements and vibrations in the crystal: athermal phonons): nuclear dE/dx.
- Ionization (electronic dE/dx)
- Cascade of collisions and mix of nuclear & electronic dE/x well described by Lindhard's theory + measured dE/dx
- In a closed system, after a while, all excitation decays into thermal energy -> rise in temperature

Effect of an electron recoil in matter



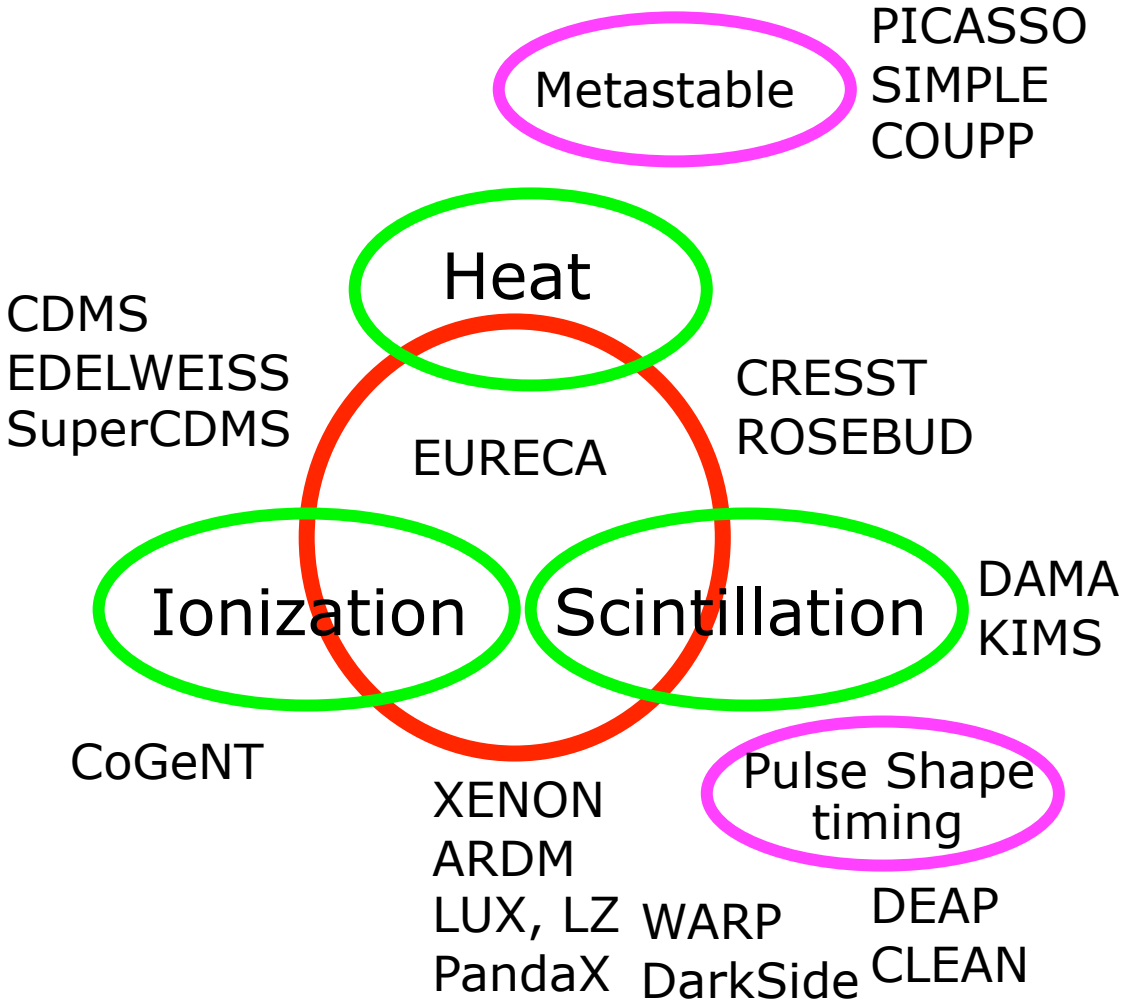
- Most common (long range) radioactive background: γ-rays, producing electron recoils (photoelectron, Compton)
- No ion-ion collisions only electronic dE/dx
- Comparing ionization and scintillation yields is a powerful tool to separate nuclear and electron recoils
- Other effects due to difference in dE/dx: density of energy deposit are not the same. This may also affect the risetime of the scintillation signal (pulse shape discrimination)

(+ No permanent crystaline defects?)

Detection techniques

γ, β discrimination:

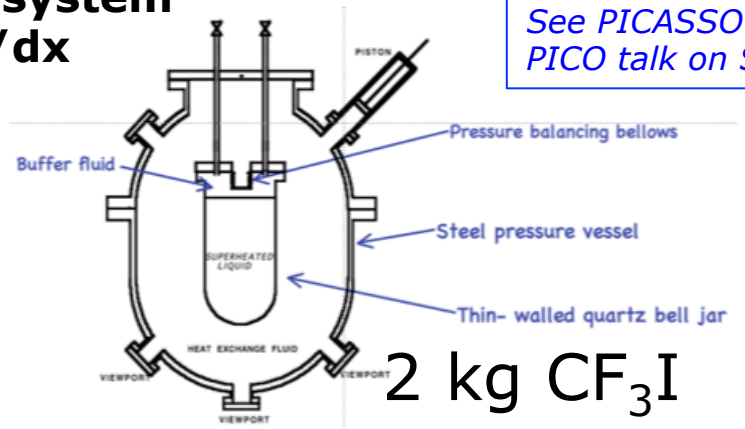
- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation
- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal
- Other "dE/dx" related ideas



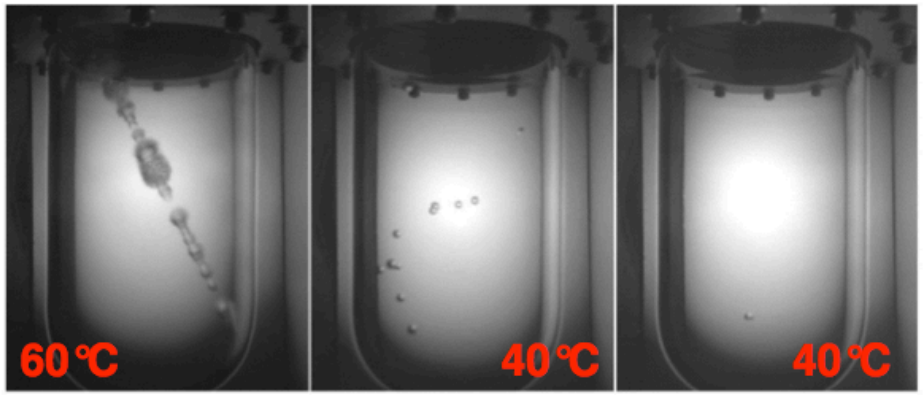
Discrimination « dE/dx» : COUPP+Picasso (PICO)

Bubble formation in metastable system triggered by large+localized dE/dx

See PICASSO-COUPP-PICO talk on Saturday



2 kg CF_3I



muon Neutron(s) WIMP

Spin-dependent:
Light target (^{19}F) with spin

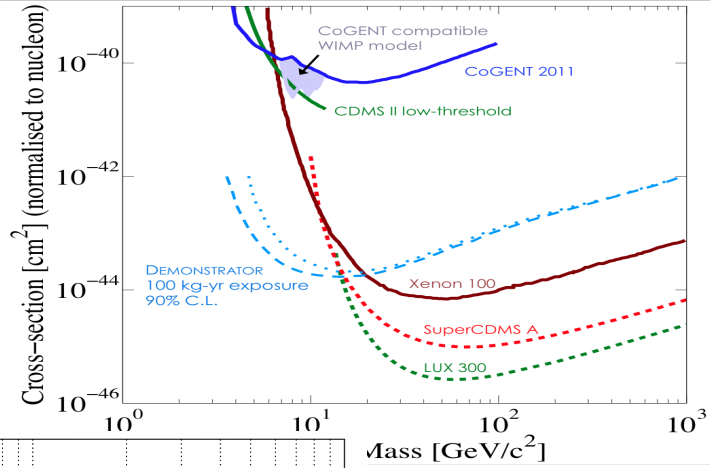
A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.

Low-threshold semiconductors

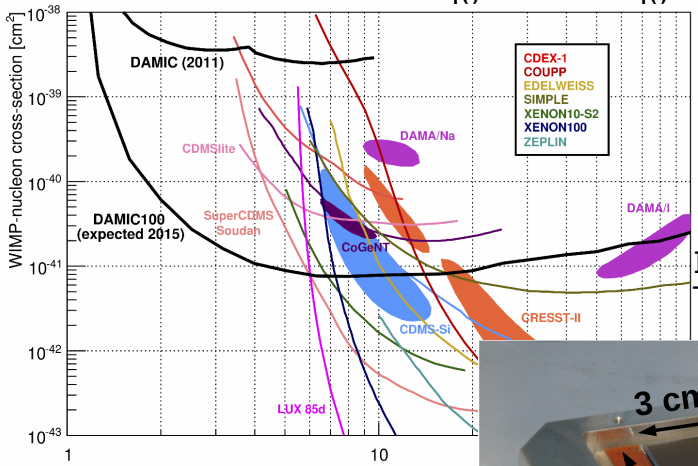
- **Majorana**: plans for 40 kg Ge detectors by end 2014 (primarily for $0\nu\beta\beta$)
- Bkg goal of ~0.001 event/kg/day/keV
- 0.6 keV threshold achieved with MALBEK single-detector test

TAUP2011, J. Phys. Conf. Series 375 (2012) 012014

Projections with 0.3-0.5 keV threshold

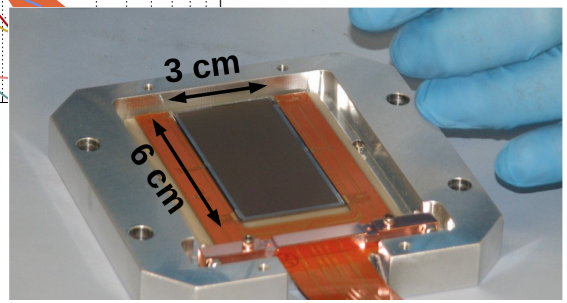


- **TEXONO/CDEX:** PC Ge with pulse shape discrimination down to ~0.4 keV



Izraelevitch, TeVPA-IDM2014

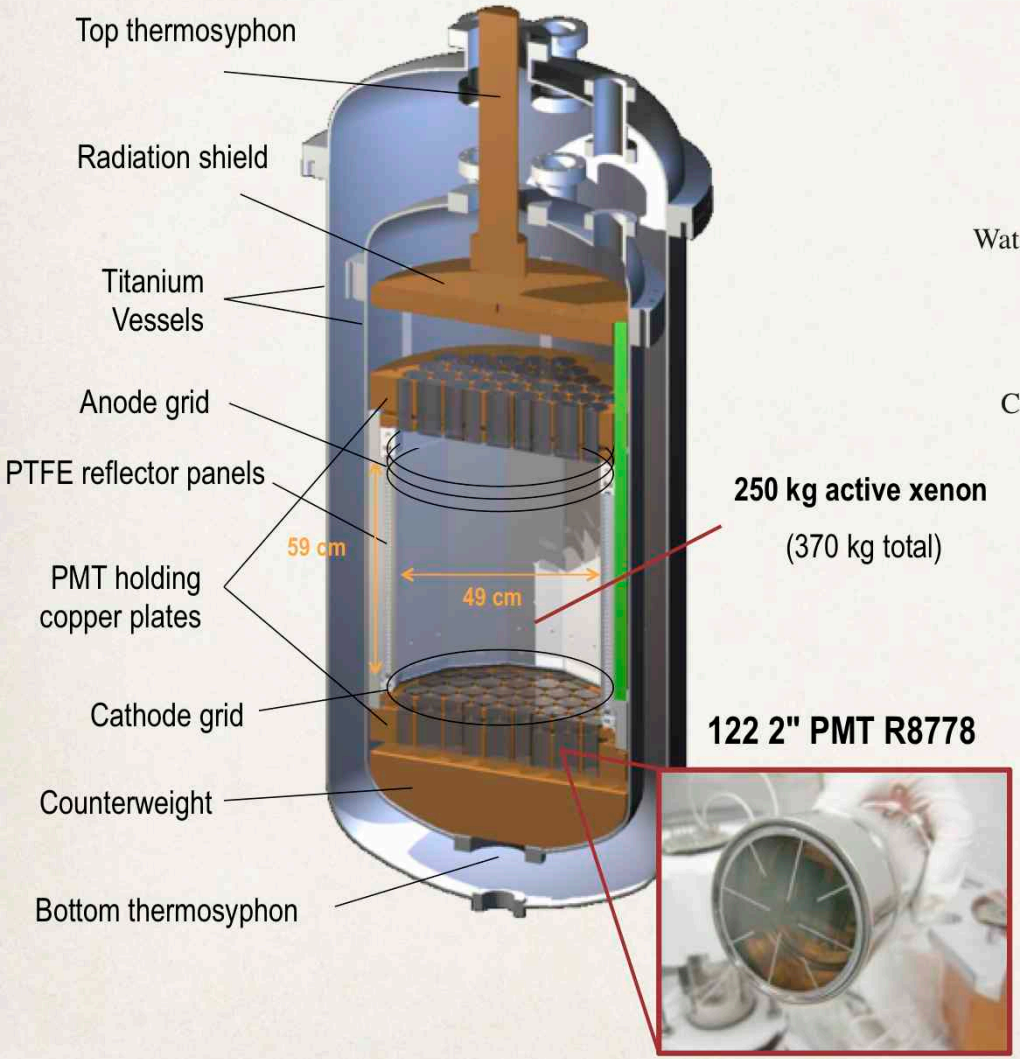
- **DAMIC**: 1-g Si CCDs with <50 eV_{ee} thresholds
- "dEdx" discrimination (15 μm x 15μm pixels)
- Best limits presently for WIMP masses 1.5-3 GeV (~4×10^{-39} cm^2)

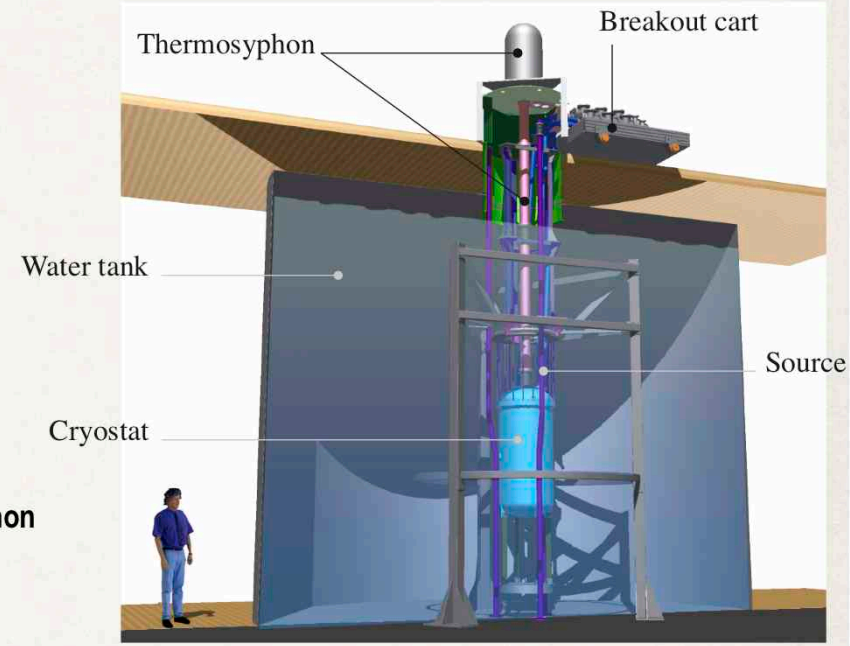


See XENON-100 talk on Saturday, and noble liquid review on Monday

NOBLE LIQUID & GAS

Example setup: LUX



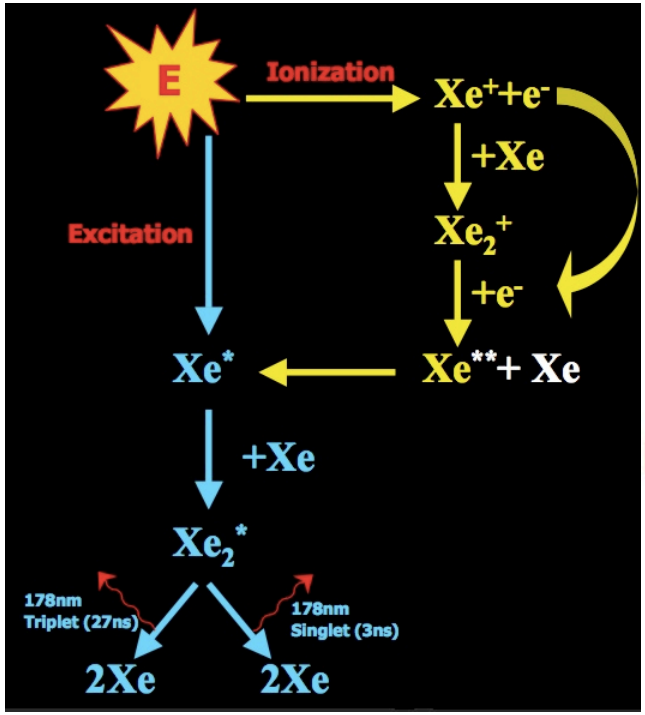


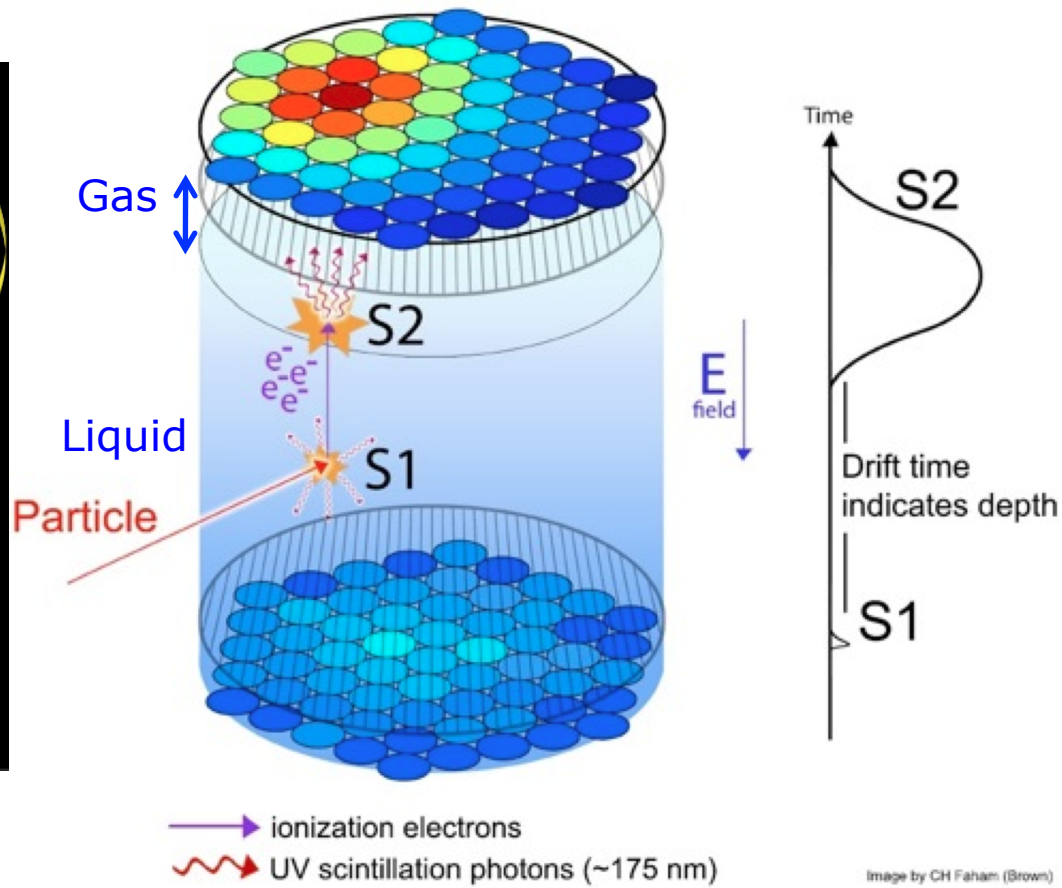
- 300 tonnes water tank
  - 3.5 m thickness on the sides
- Cherenkov muon veto
  - 20 PMTs (10″ diameter)
- All external backgrounds subdominant

LUX, TeVPA/IDM2014

Xenon S1/S2 discrimination

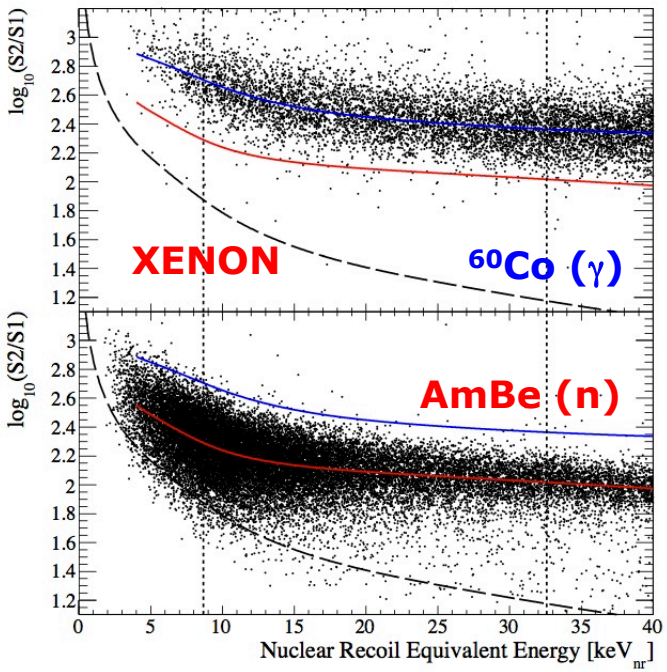
- Different scintillation (S1) and ionisation (S2) yields for nuclear / electronic recoils
- PMT array for (x,y), drift time for z : 3-D fiducial volume

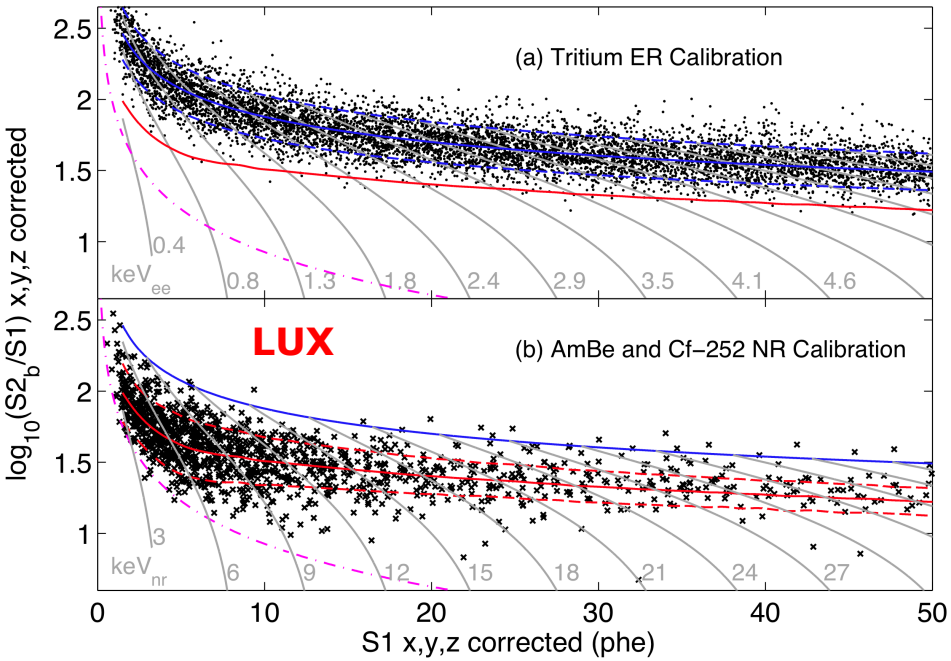




Xenon and LUX S1/S2 discrimination

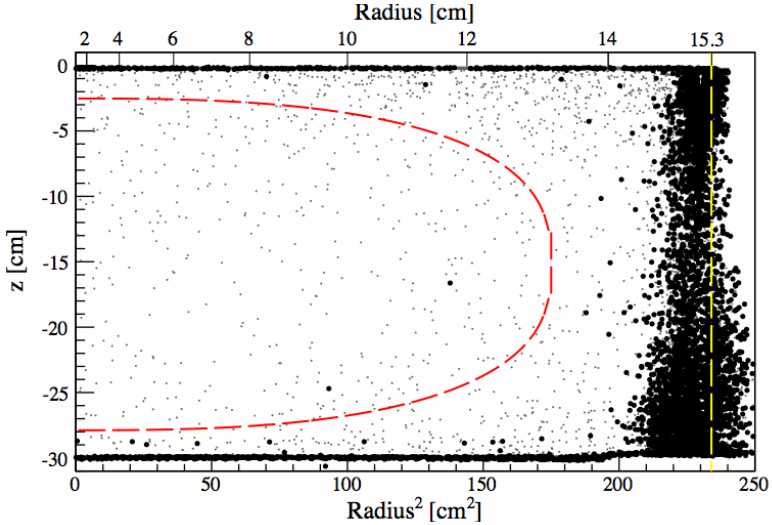
- **Xenon 100**: **170 kg LXe**, 34 kg fiducial, 30 cm drift, 98(top)+80(bottom) PM's
- Trigger on 3 PM coincidence: poor energy resolution, excellent noise suppression
- *10 keV nuclear recoil: S1 ~ 5 P.E. S2 ~ 800 P.E. (from ~30 ionization e^-)*
- **LUX**: **370 kg LXe**, 118 kg fiducial, 59 cm drift, 122 PM's + active water veto
- Trigger on 2 PM coincidence: excellent noise suppression + 3 keV threshold
- *10 keV nuclear recoil: S1 ~ 7 P.E. S2 ~ 800 P.E.*

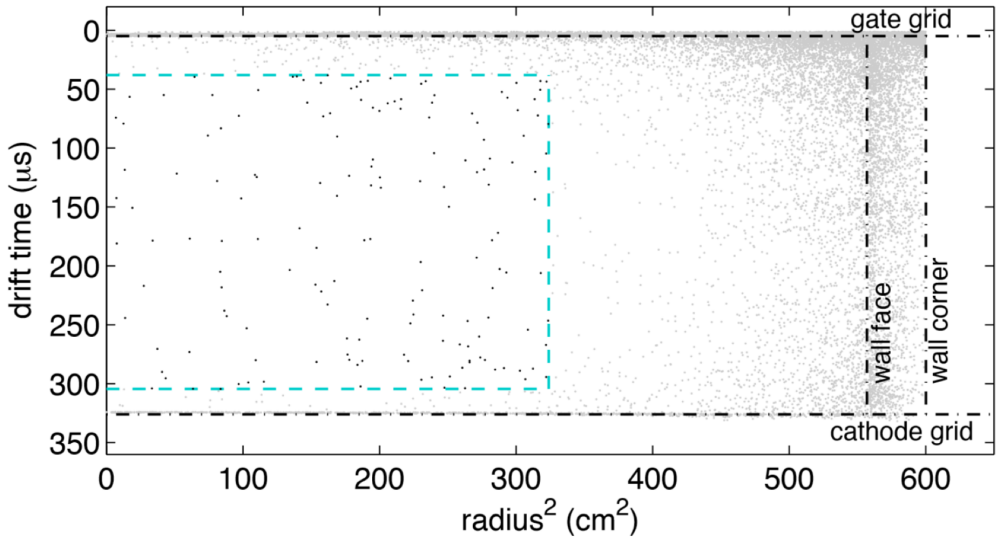




XENON and LUX fiducialization

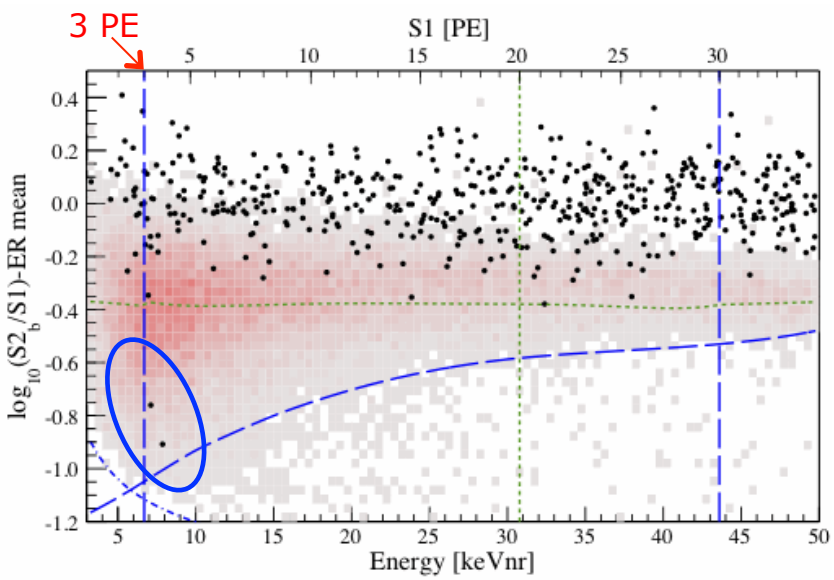
- XENON-100 2012: 34kg Xe fiducial, 225 day exposure
- Low γ background (19 ppt ^{85}Kr)
- Observe 2 evts, compatible with expected bkg = 1.0±0.2 evt (0.2 n + 0.8 Compton)
- LUX 2013 [PRL 112 091303]: 118kg Xe fiducial, 85 day exposure

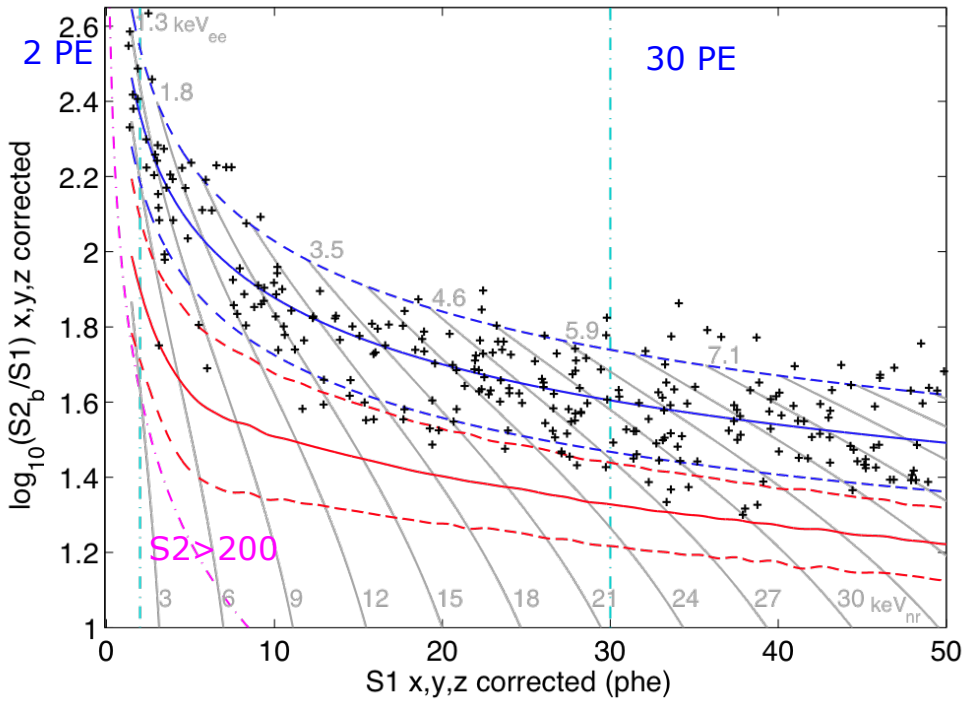




XENON and LUX data

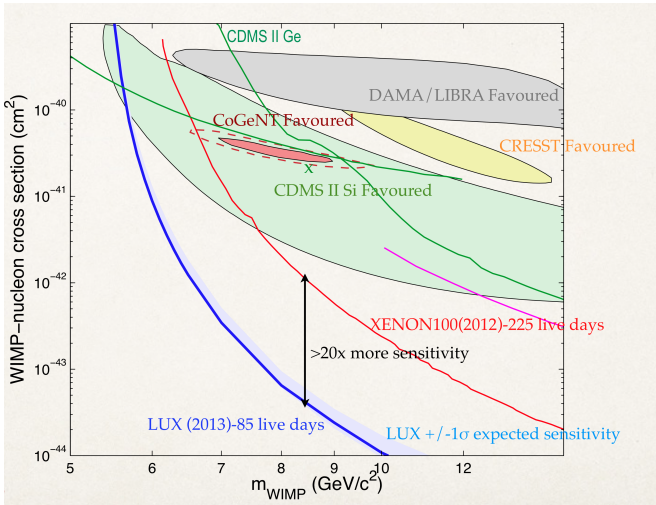
- XENON-100 2012: 34kg Xe fiducial, 225 day exposure
- Observe 2 evts, compatible with expected bkg = 1.0±0.2 evt (0.2 n + 0.8 Compton)
- LUX 2013 [PRL 112 091303]: 118kg Xe fiducial, 85 day exposure
- Observed rate compatible with γ-background estimates

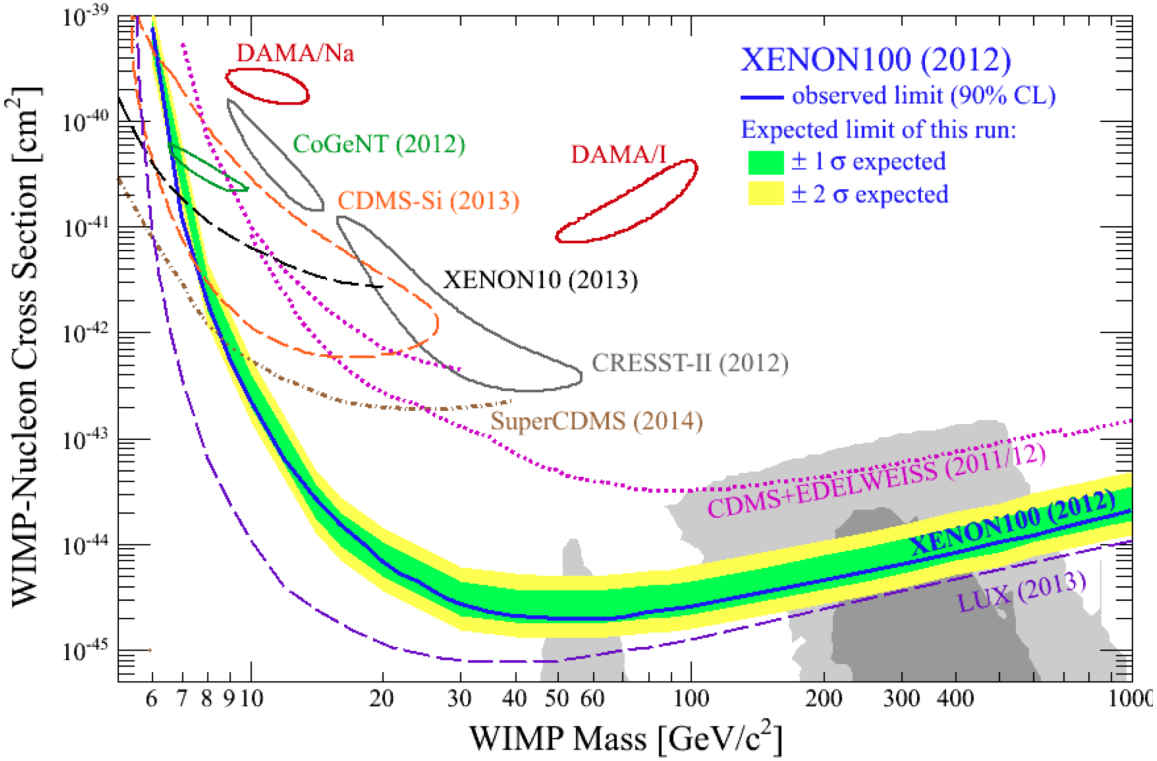




XENON and LUX limits

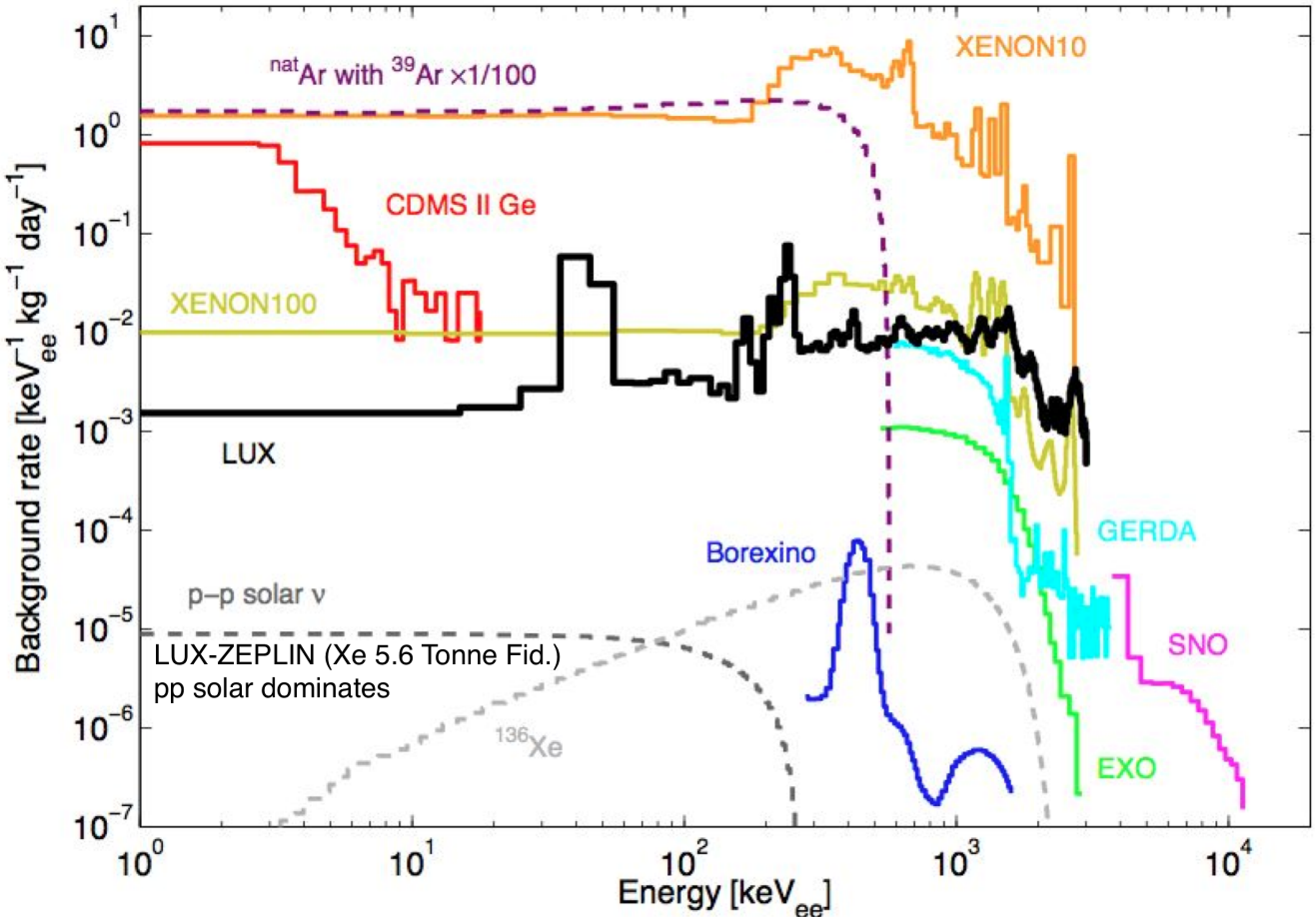
- LUX first experiment to reach 10^{-45} cm^2 (10^{-9} pb) sensitivity (~10 kg-year)
- Incompatible with some "hints" seen for low WIMP mass





Xe/Ar low radioactive background

- Backgrounds in fiducial (center) volume, before rejection of e^- recoils: *benefits from large self-shielded volume*



Gaitskell, TeVPA-DM 2014

Some LXe and LAr projects

- XENON 1t: in construction
  Reduction of radioactive background (cryostat, PM, purification).

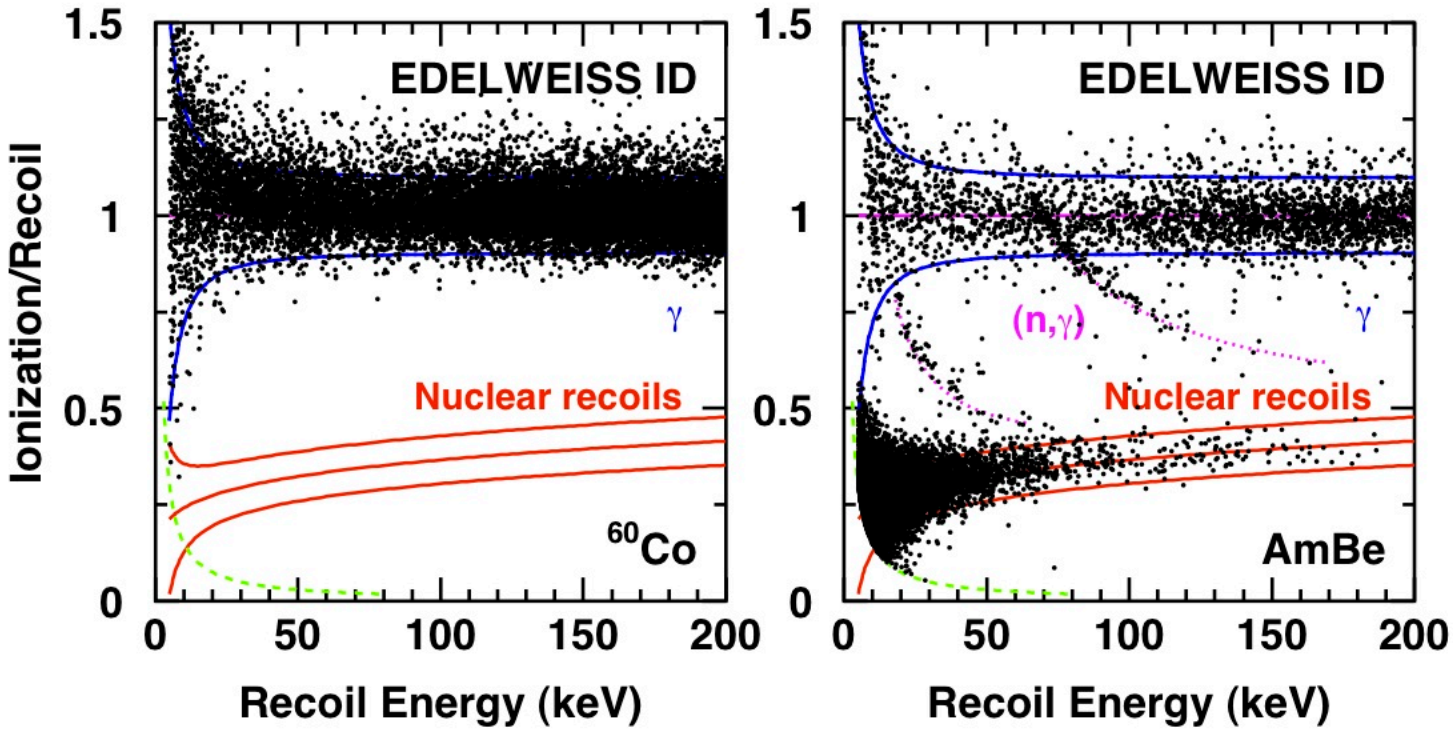
XENON-1t
in Gran Sasso

- LZ: next generation LUX+ZEPLIN
- XMASS (Kamioka): 100 kg + 642 PMs. Monophase, rejection based on fiducialization. Need to study and reduce internal radioactive background.
- DEAP-CLEAN (SNOLAB): 100 kg Ar, *need 10^8 rejection of radioactive ^{39}Ar* (pulse shape discr., τ = 1.6 μs)
- DarkSide-50: 33 kg fiducial Ar, *depleted in ^{39}Kr* (underground source, depletion 10^{-2} to 10^{-3})
- PandaX: 125 kg Xe in JinPing tunnel, China

GE IONIZATION + PHONON

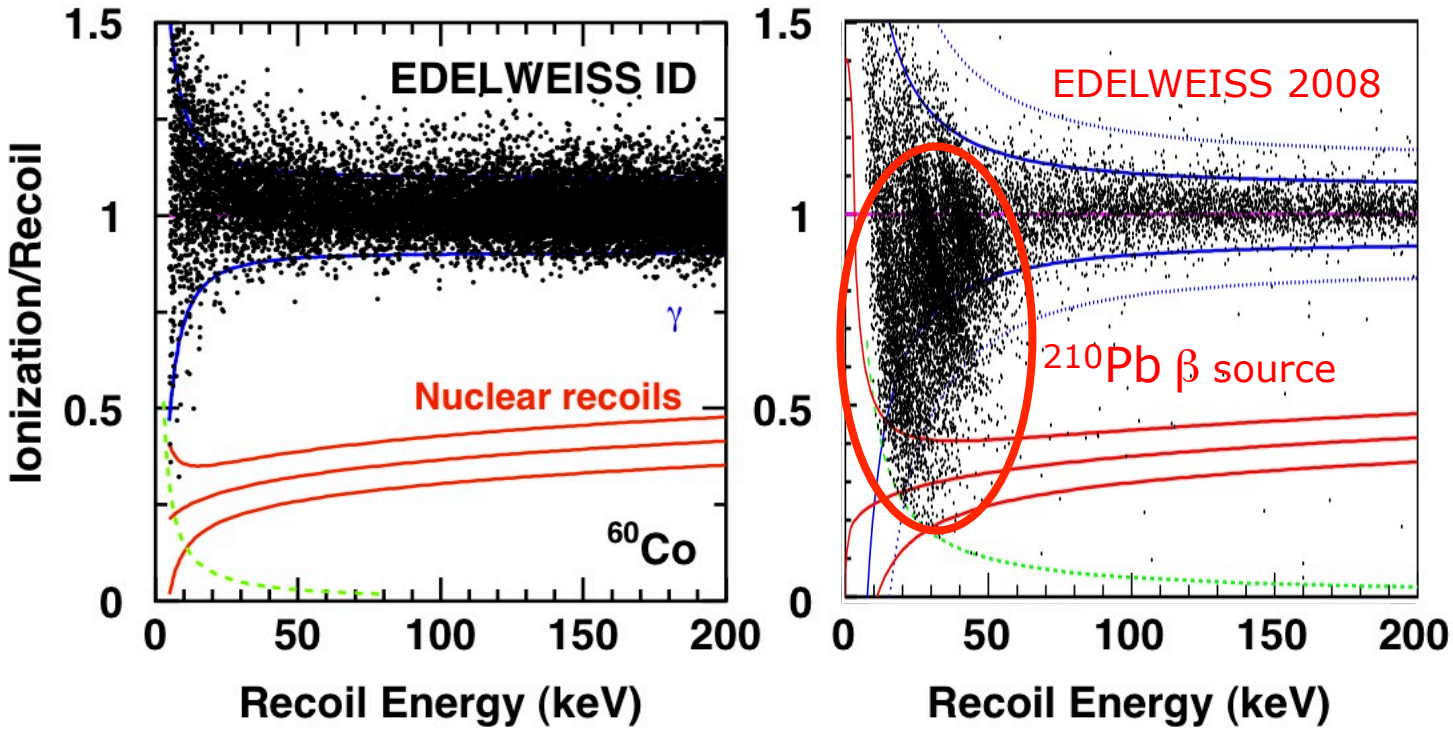
Nuclear recoil / gamma discrimination

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
  - discrimination of dominant background
  - Stable and reliable rejection performances



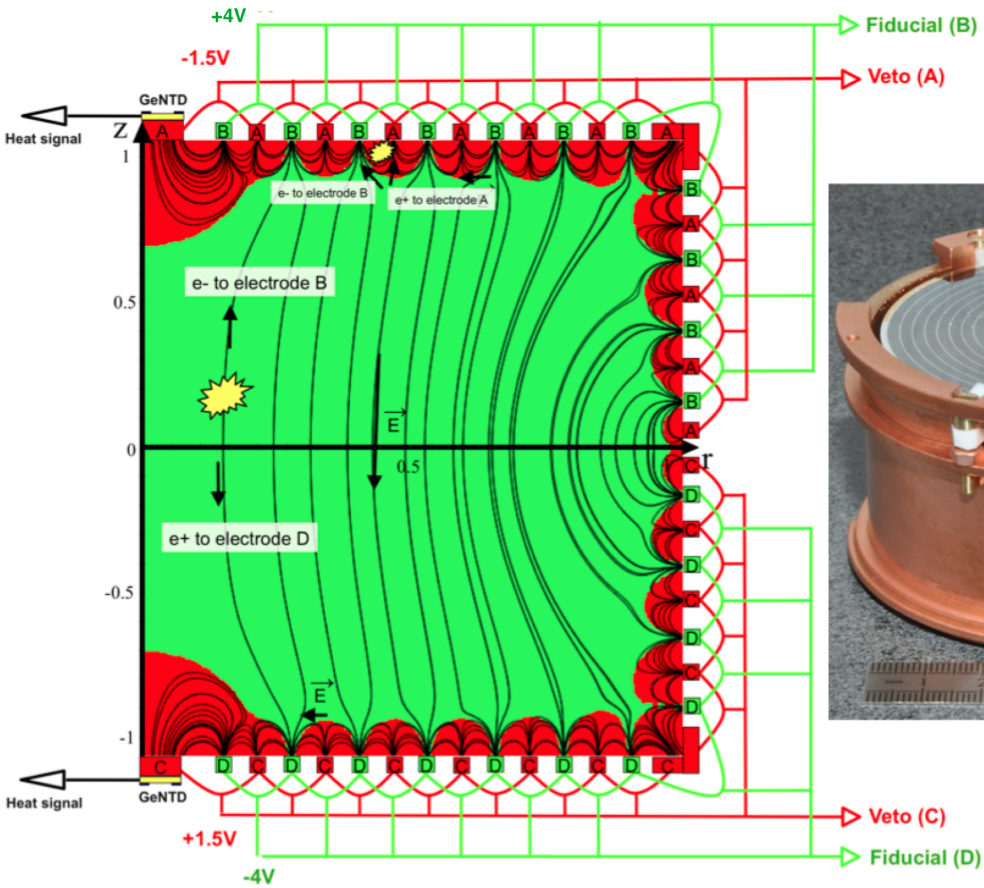
Limitation: poor ionization yield for surface events

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
- *Limitation: deficient charge collection near surface (trapping, dead layer)*
  => different surface rejection strategy for CDMS & EDELWEISS

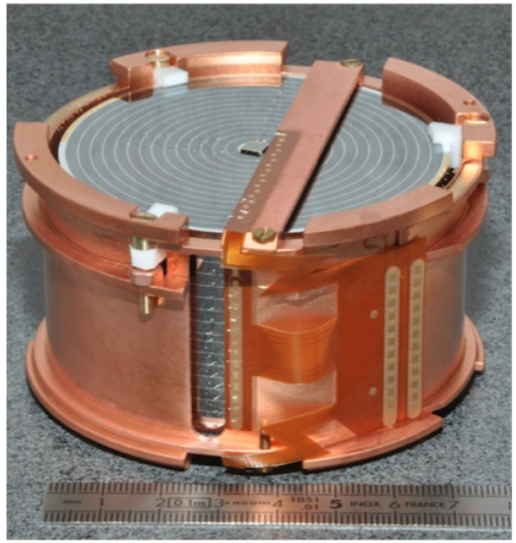


EDELWEISS Interleaved detectors

- Interleaved electrodes with alternate potential, to separate surface and bulk events



Full Inter-Digitized
800 g HP-Ge Detector

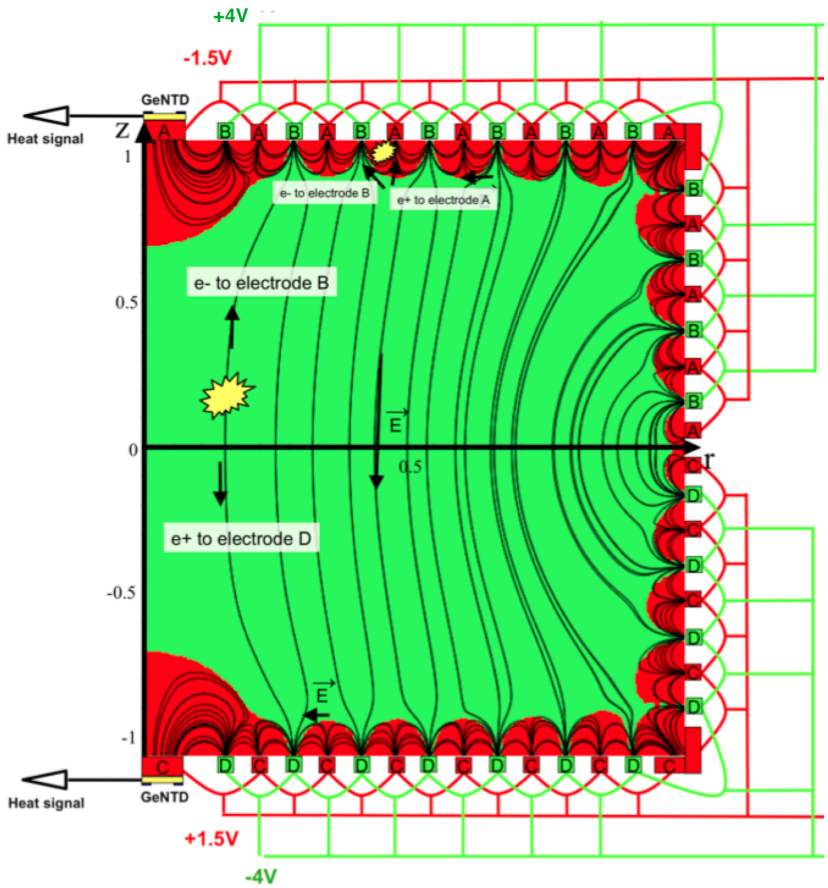


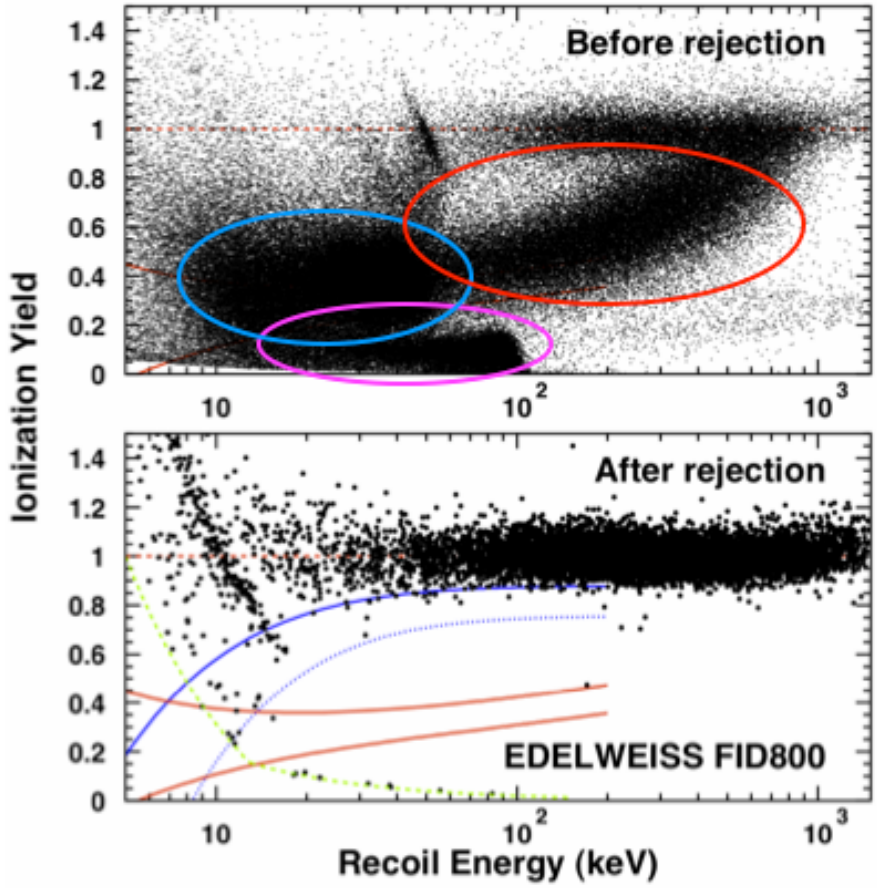
Height: 4 cm

Width: 7 cm

EDELWEISS Interleaved detectors

- Test of rejection of 10^5 β from ^{210}Bi, 10^5 β from ^{210}Pb and 10^5 ^{206}Pb recoils from ^{210}Po α decays (>> years of WIMP searches)

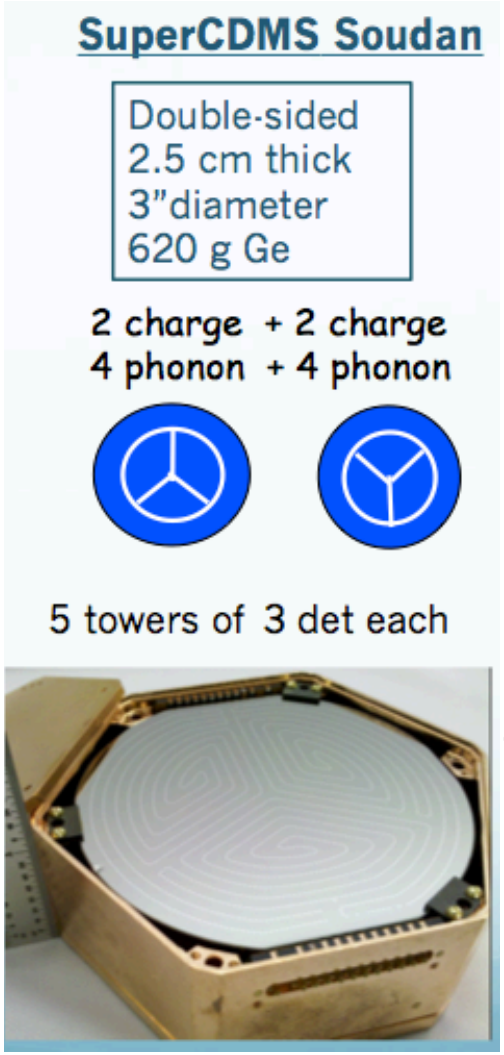




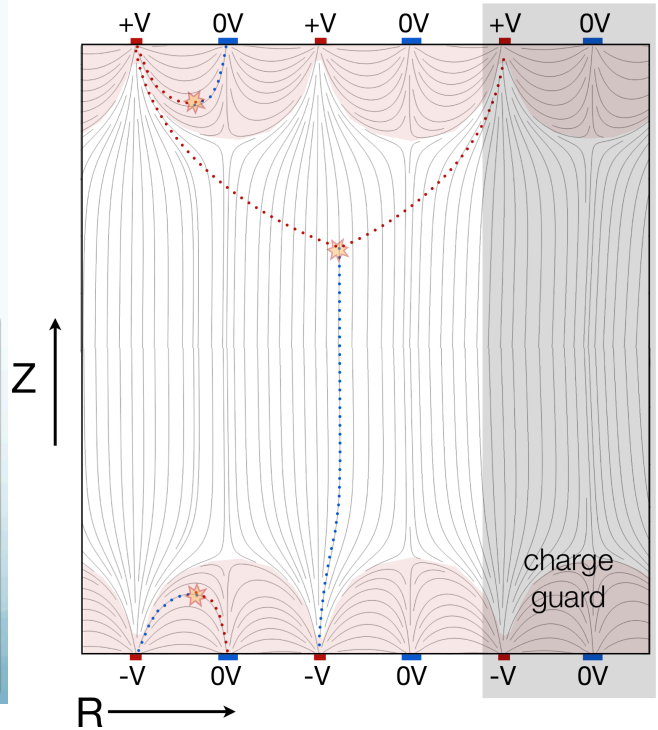
EDELWEISS 2014 status

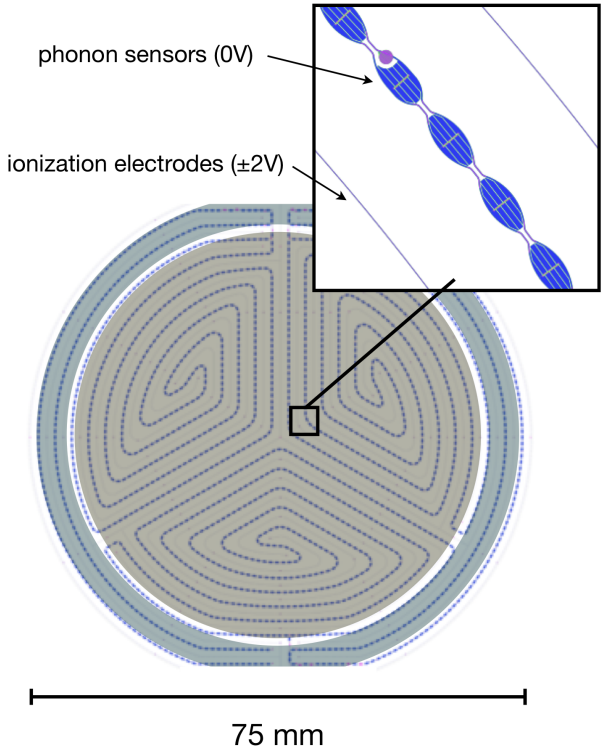
- 36x800 g detectors installed
- Facility able to collect 3000 kgd per 6 months, expect 10^{-9} pb sensitivity in coming 2 years

CDMS iZIP detectors

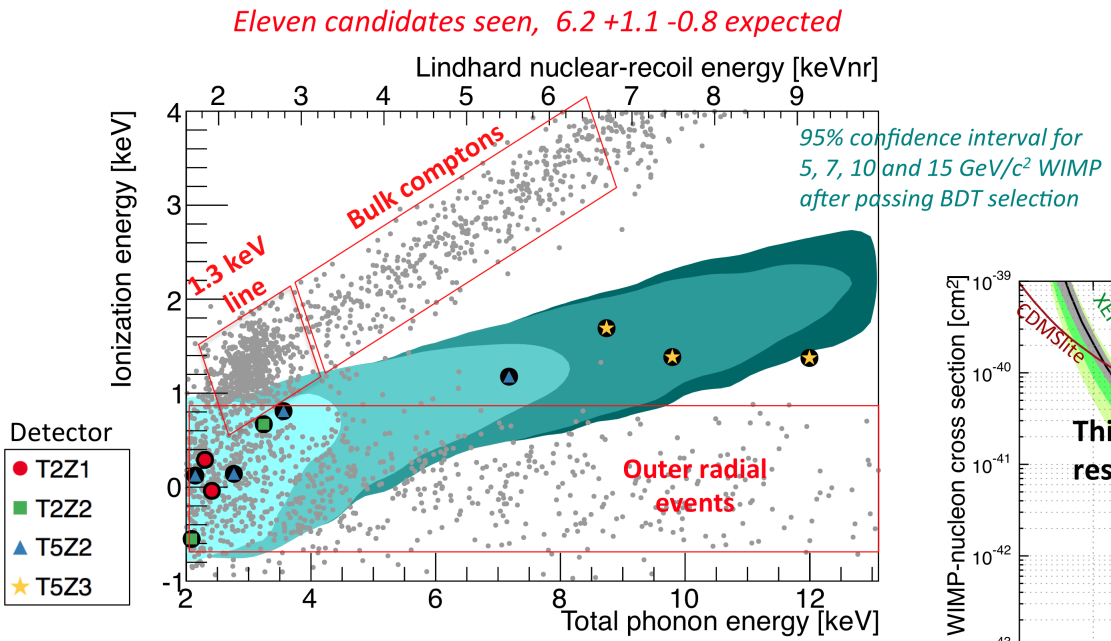


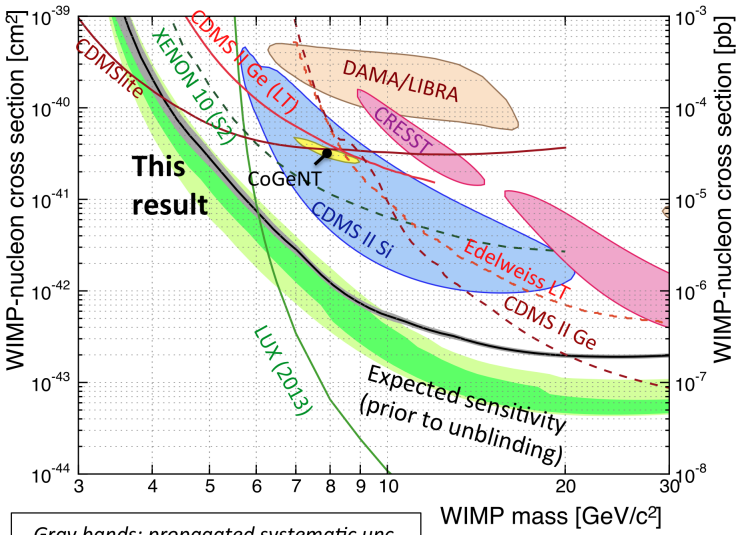
- Photolithographic patterns of W-TES + Al collector
- Large area: sensitivity to athermal phonons
- *Use phonon partition (outer/inner, top/bottom) and ionization partition to fiducialize*





SuperCDMS Soudan: 650g iZIPs





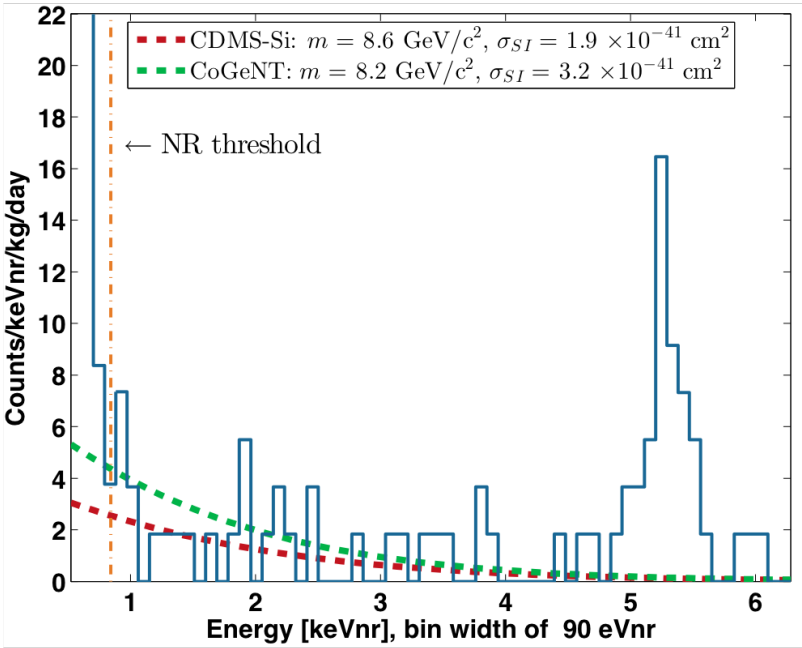
Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency

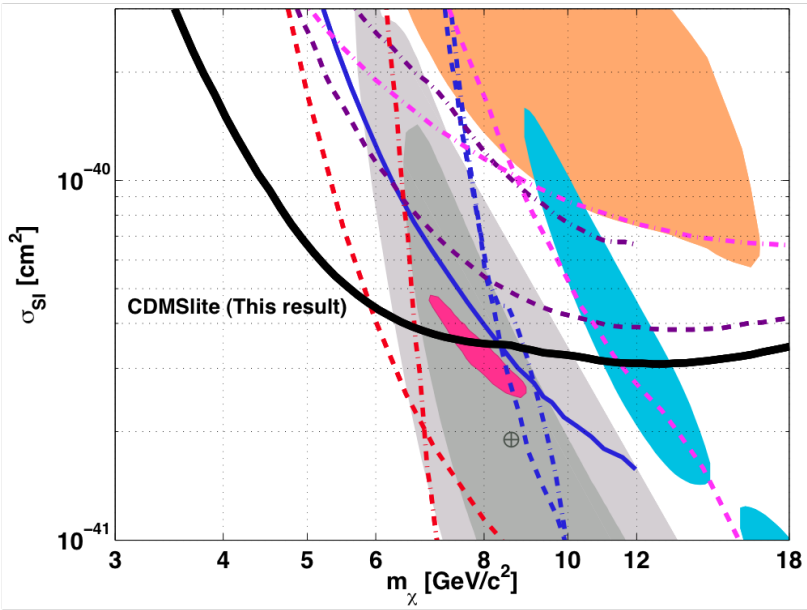
UCLA February 2014

- Data started in 2012 with 9 kg (6 kg fiducial)
- Recent results: 577 kdg WIMP search with low thresholds: record sensitivity despite smaller target mass than Xe expts.

Dedicated low mass WIMPs

- Using Luke-Neganov amplification, can lower the threshold
- Price to pay: no nuclear recoil discrimination (but can test it by varying V_{polar})
- Current threshold on $E_{electron\text{-}equivalent}$ ~ 1 keV_{ee} with V_{polar} = 3.2V
- Biasing at 70V reduces threshold by (1+3.2/3)/(1+70/3) = 12
- 840 $eV_{NuclRecoil}$ threshold on (standard iZIP) Ge detector





Future projects: USA

- SuperCDMS at SNOLab: improved cosmic protection
- 10 cm radius: double iZIP detector mass to 1.38 kg
- Goal: ~200 kg Ge 140 000 kgd (4 year run) 10^{-10} pb in ~2017

Cushman, IDM2012

Future cryogenic project EU

- European priority: completion of EDELWEISS-III (physics 2014-2015) and present CRESST runs
- EURECA: ~1 t combining Ge and $CaWO_4$ targets (see later)
- EURECA CDR recently completed
- 2013: EURECA discussions with SuperCDMS-SNOLAB: discussion on common strategy, collaboration for the cryogenics.

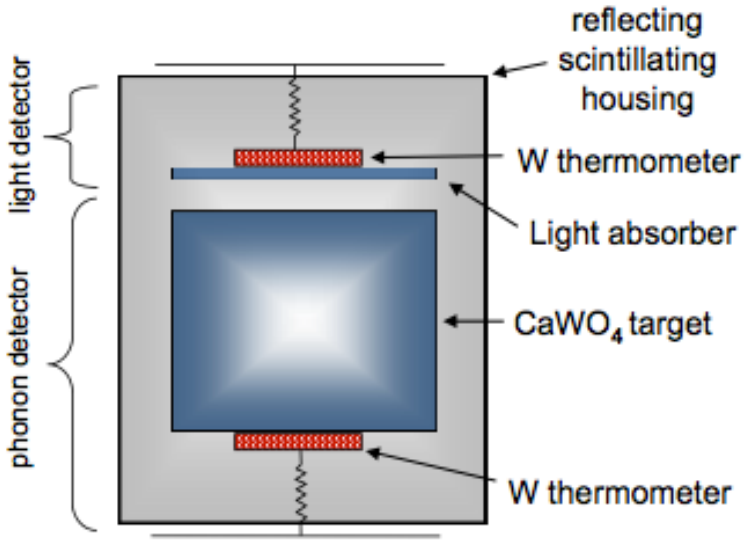
SCINTILLATION+HEAT

Heat-scintillation: CRESST

- 18x300 g $CaWO_4$ Crystals with Tungsten film thermometer
- Light detector = thin Si wafer + same type of thermometer
- 3 targets in same detector

  A = 16, 40 and 184

  Q = 0.10, 0.06 and 0.04

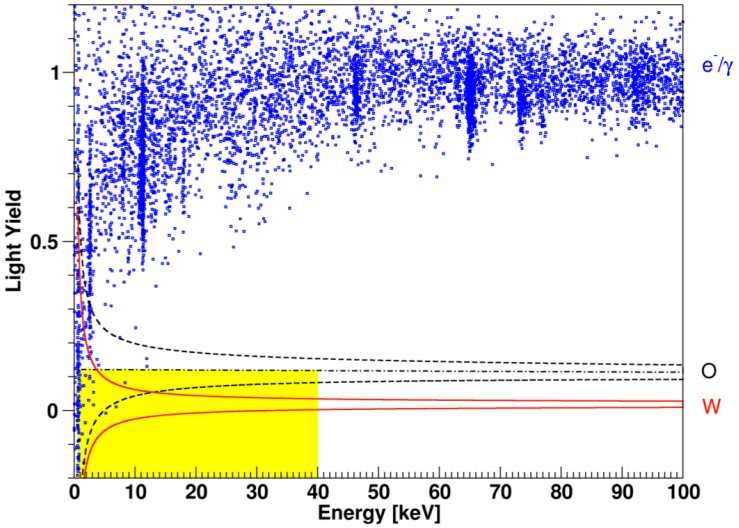


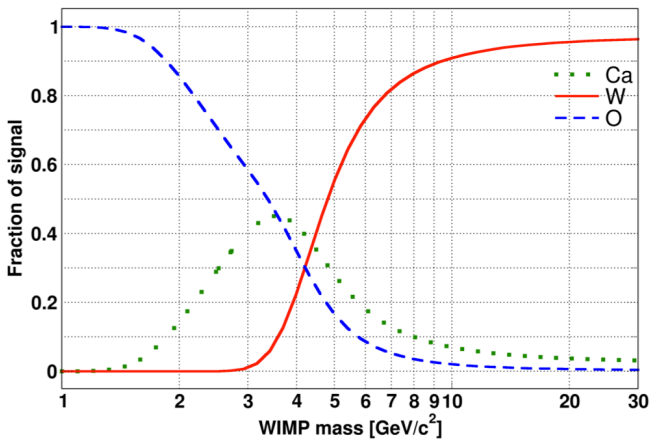
New: 6 detectors with radiopure clamps & fully reflecting scintillating housing to increase light yield

BONUS: tags $^{210}Po \rightarrow \alpha + ^{206}Pb$ 2-body decays

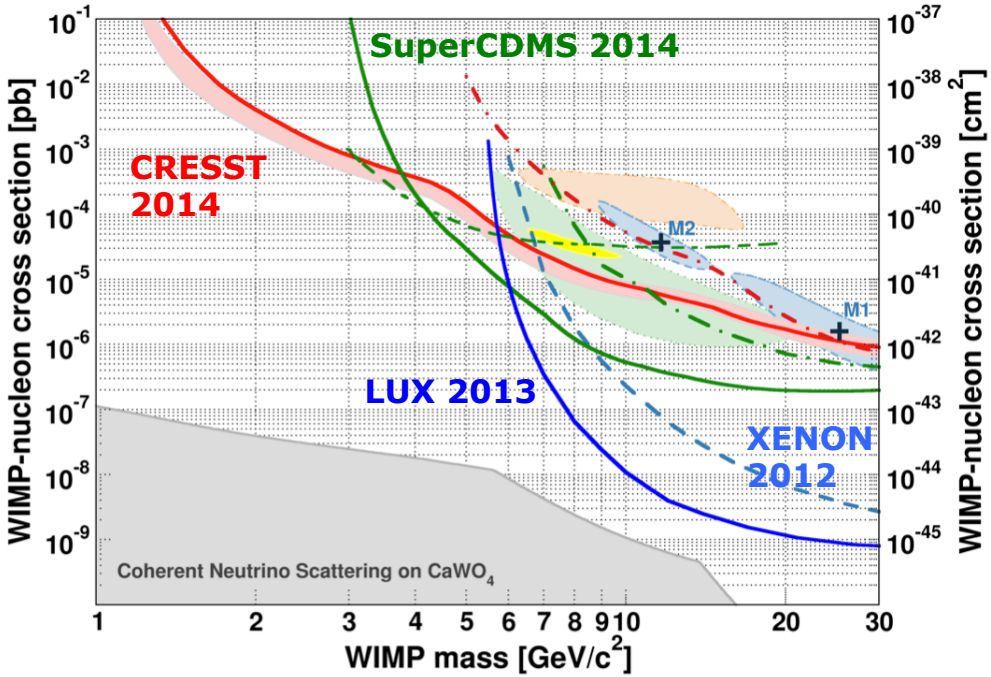
^{206}Pb recoil ~ W recoil

New CRESST limits at low mass





- 29.35 kgd of low-threshold data (0.6 keV), 1x250g detectors with support in $CaWO_4$
- Sensitivity from W recoils at high mass, and from O recoils at low mass
- Successful reduction of previous background of light-only events + neutrons



CONCLUSIONS

Future experiments (recent news)

APS physics

Is this message scattered? View it online.

The DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the "second generation" of direct detection dark matter experiments. We are pleased to announce that the joint DOE/NSF second-generation program will include the LZ and SuperCDMS-SNOLAB experiments with their collective sensitivity to both low and high mass WIMPS, and ADMX-Gen2 to search for axions. It will also include a program of R&D to test and develop technologies for future experiments, consistent with the recent P5 recommendations. The agencies will work with the proponents to develop project plans that can achieve their compelling science goals as expeditiously as possible.

Conclusions

- Direct Dark Matter Searches: crucial experiments to attest the presence of WIMPs in our galaxy; complementary to LHC and indirect searches
- *Apparently simple, but the required extreme low-backgrounds are challenging and they foster constant technological innovations.*

- Need variety of targets (essential to validate possible discovery) and broaden mass range sensitivity
- Intense world-wide competition of R&D efforts to *reduce backgrounds* and *increase the mass of the arrays*