Direct Searches for WIMP Dark Matter

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COSMO 2015, Warsaw, September 7, 2015

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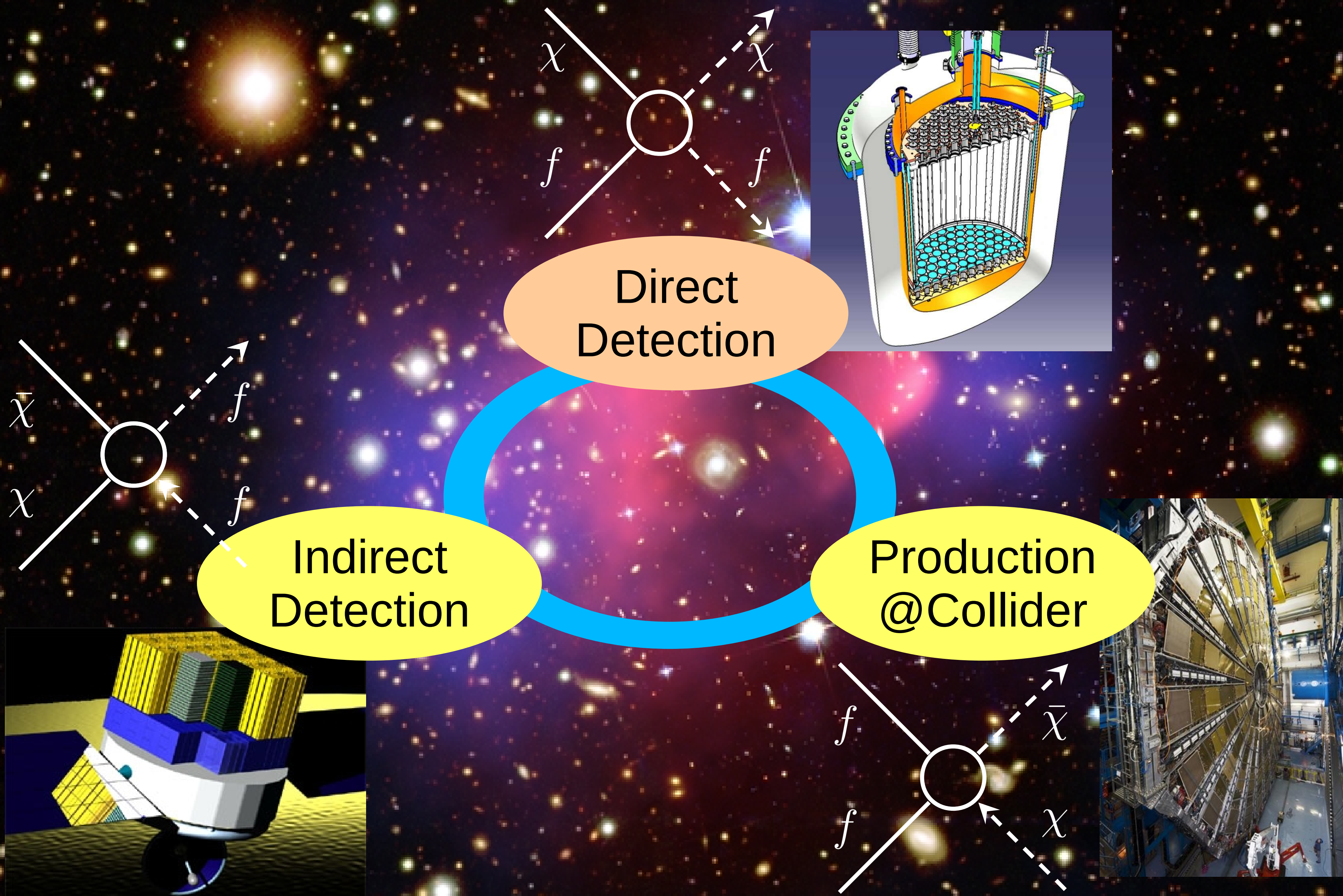
Dark Matter Search



Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

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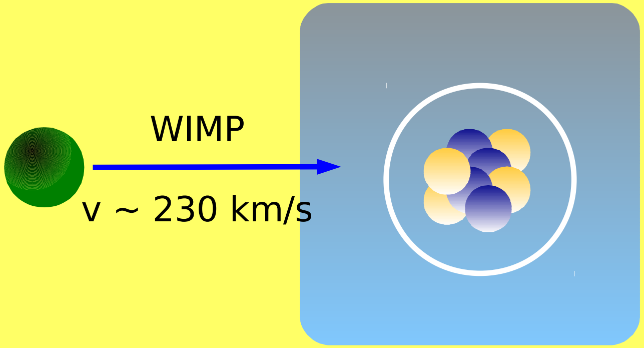

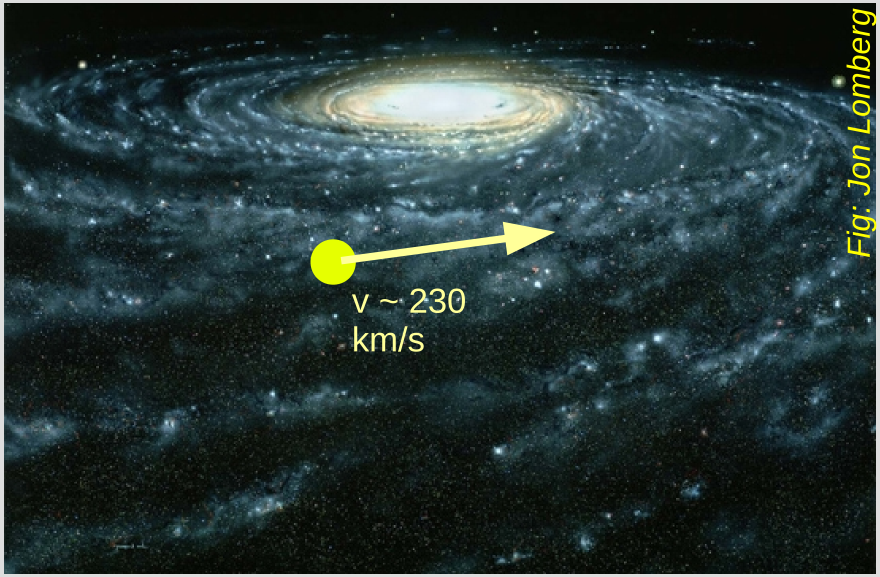

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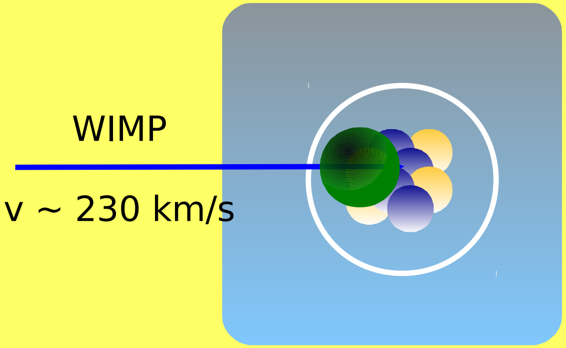
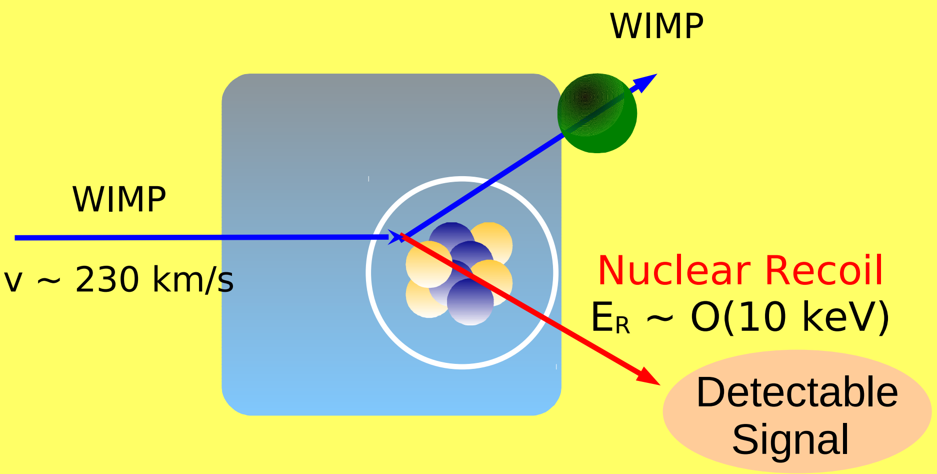


Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



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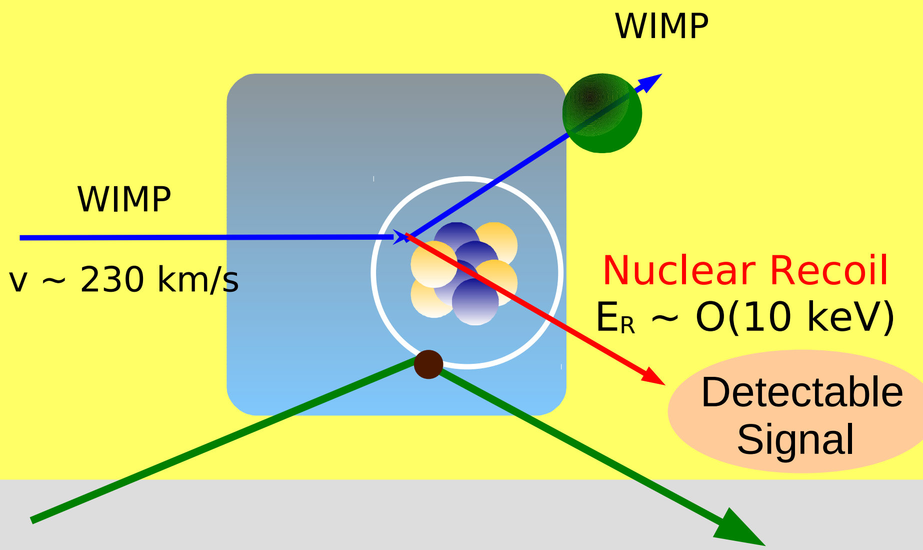

gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil**

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
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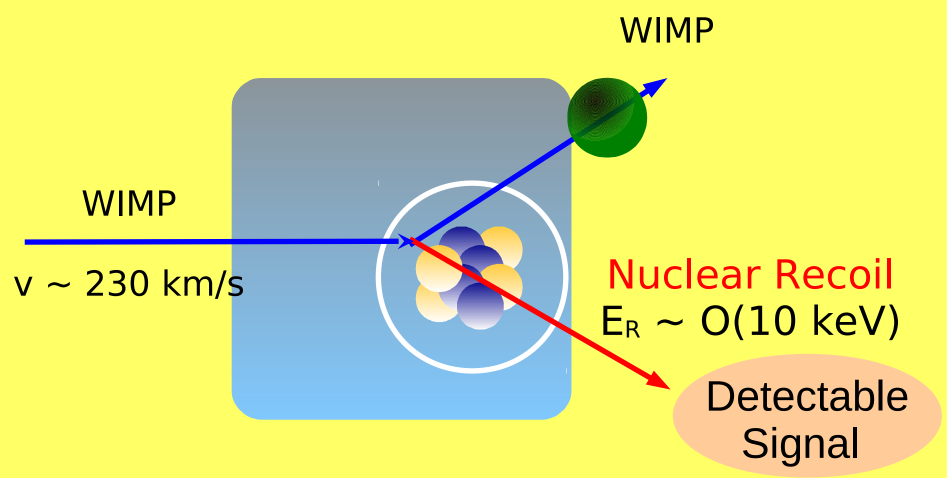


Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

Detector

Local DM Density

Physics

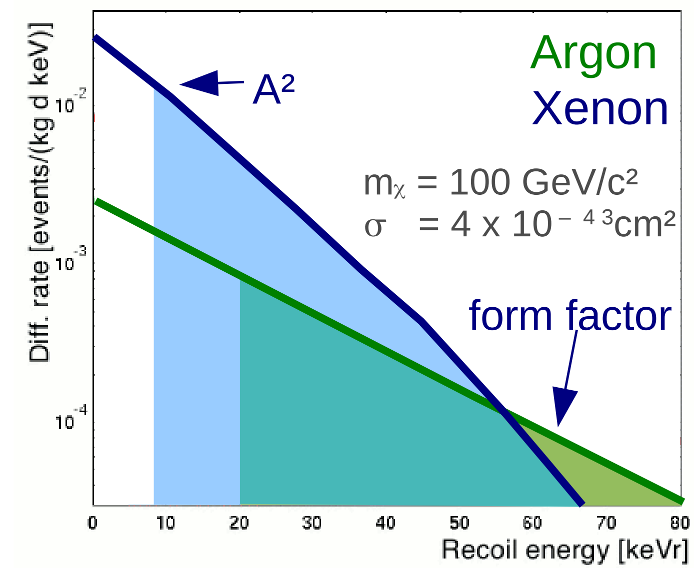
ρ_χ~0.3 GeV/c²

N number of target nuclei
ρ_χ / m_χ local WIMP number density
$<\sigma>$ velocity-averaged scatt. X-section

Direct WIMP Search

Summary: Tiny Rates

$R < 0.01$ evt/kg/day
$E_R < 100$ keV



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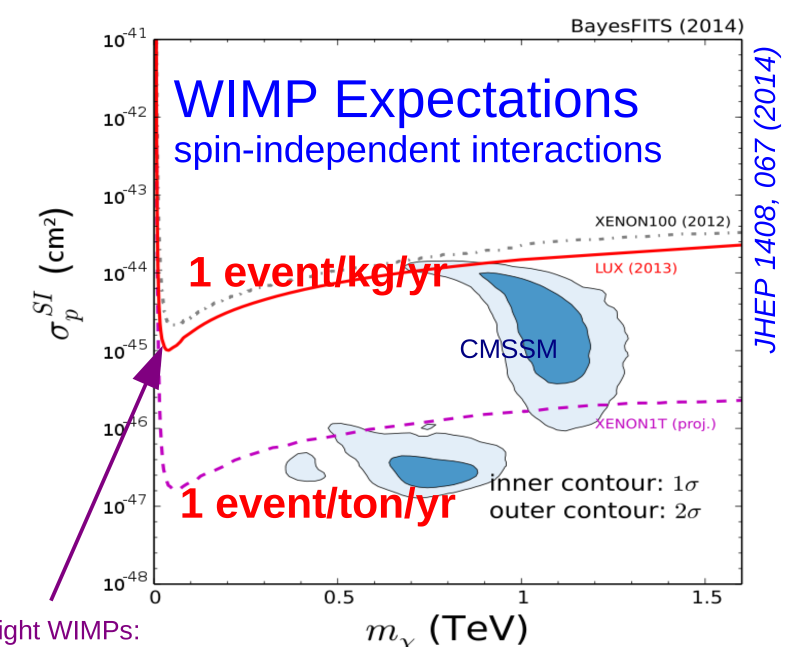


light WIMPs:
asymmetric DM,
sneutrinos, ...

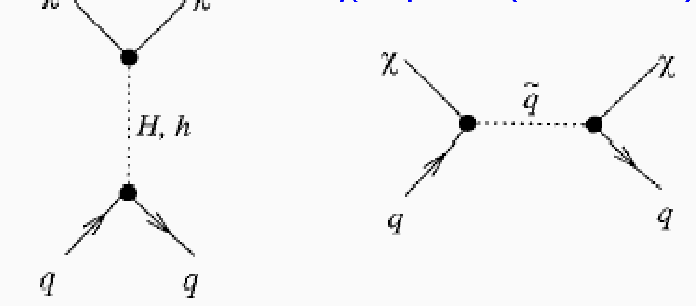
WIMP-Nucleon Interactions

A priori, we do not know how dark matter WIMPs interact with ordinary matter

Parametrization of interactions leading to WIMP-nucleus scattering:

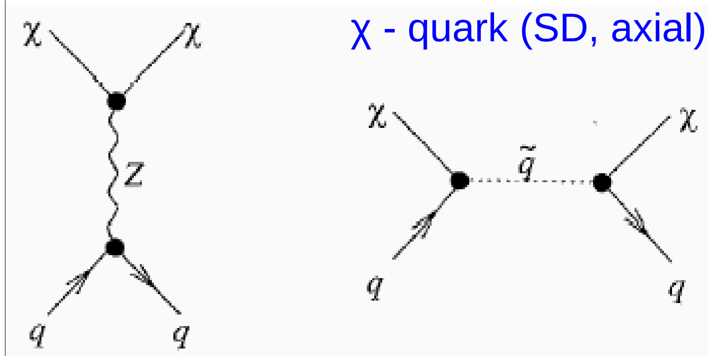
coupling to **mass**	coupling to **nuclear spin**
Spin independent	Spin dependent

χ - quark (SI, scalar)



$$\mathcal{L}_S \sim \tilde{\chi}\chi\overline{q}q \quad \propto A^2$$

χ - quark (SD, axial)



$$\mathcal{L}_A \sim \tilde{\chi}\gamma_\mu\gamma_5\chi\overline{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$$

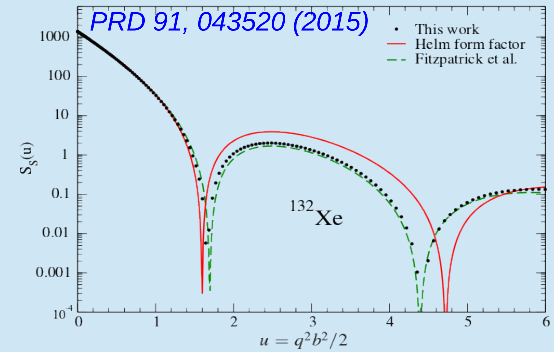
Jungmann et al. '96 Phys.Rep.

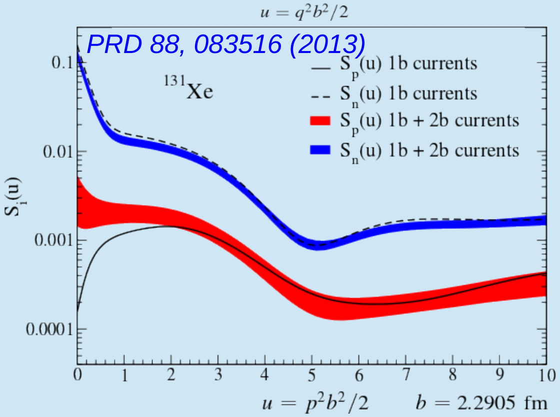
$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}$$

$$C_{spin} = \frac{8}{\pi}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 \frac{J+1}{J}$$

often: express SD results in proton-only or neutron-only

Form factors describe loss of coherence
→ mainly for heavy targets and tail of v-distribution





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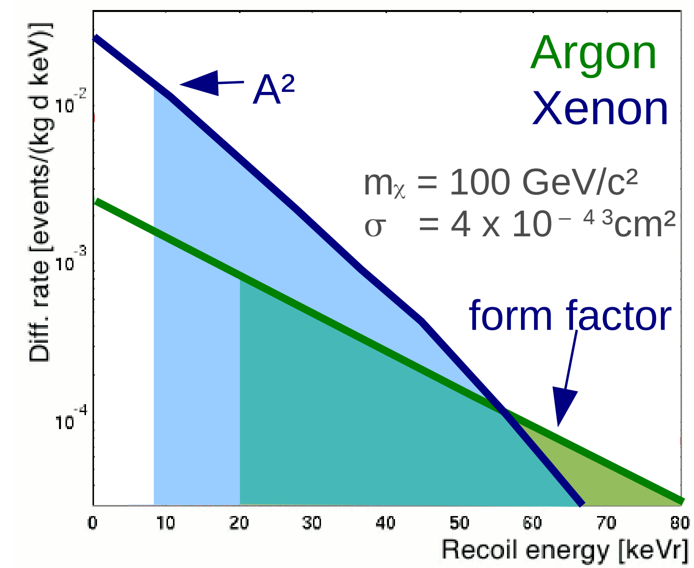
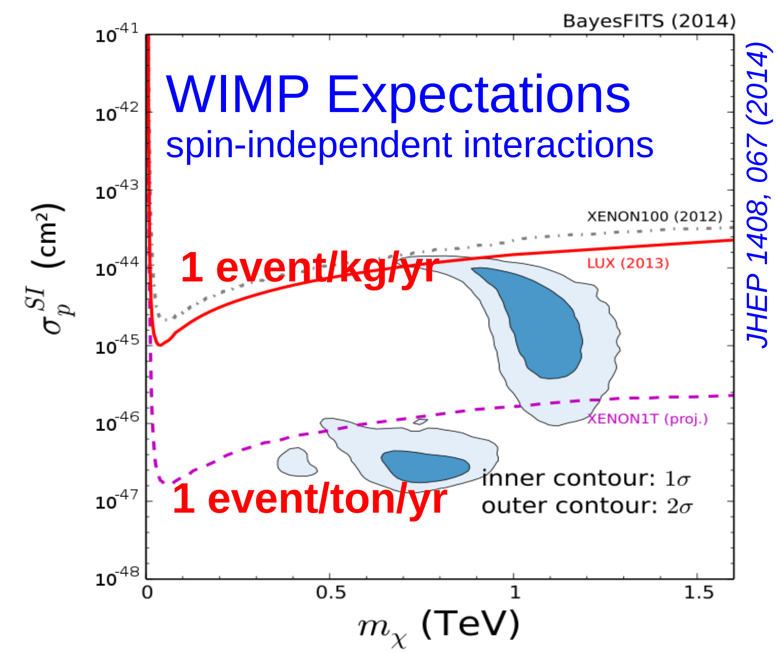


How to build a WIMP detector?

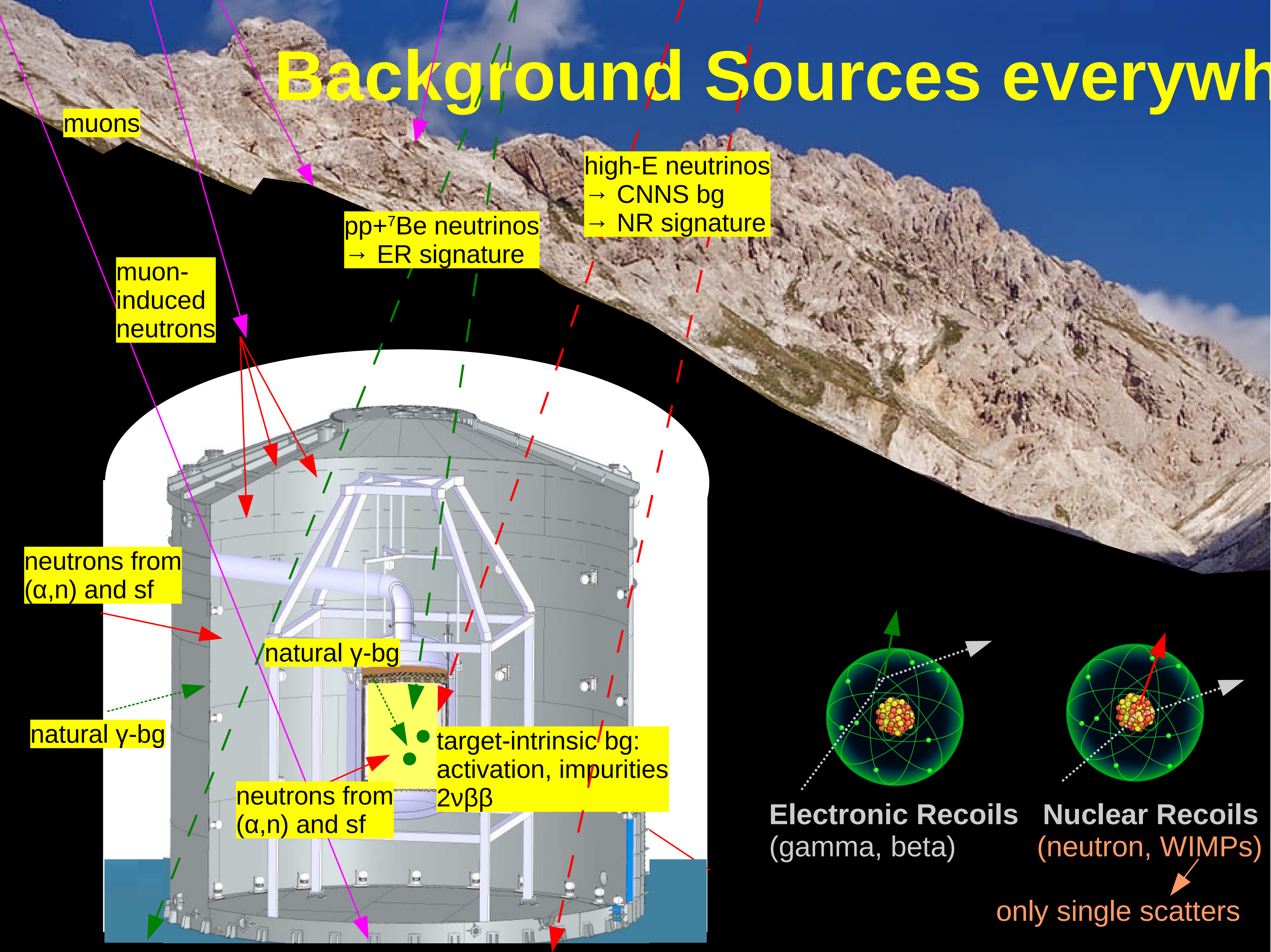
- large total mass, high *A*
- low energy threshold
- ultra low background
- good signal / background discrimination



We are dealing with

- extremely **low rates** (1 – 1000 Hz)
- extremely **low thresholds** (~2 keV)
- extremely **low radioactive** backgrounds

Background Sources everywh



Background Suppression

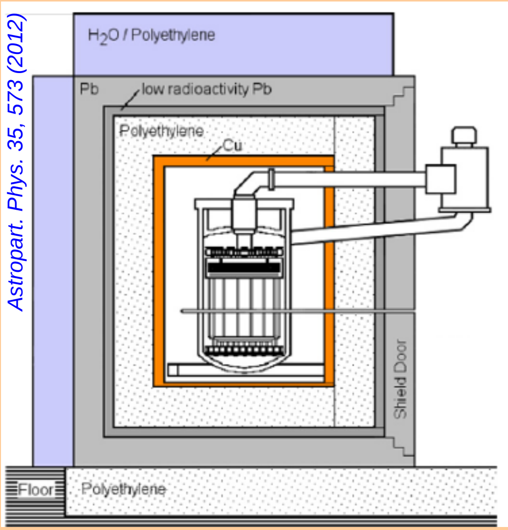
A Avoid Backgrounds

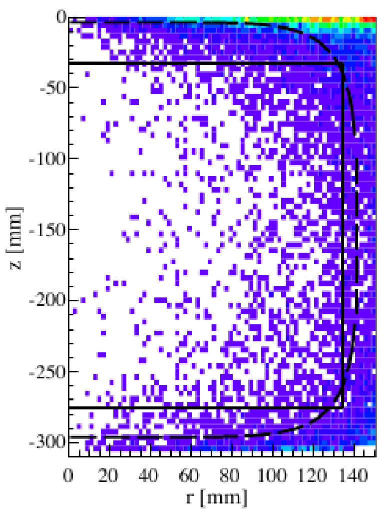
Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self shielding → fiducialization





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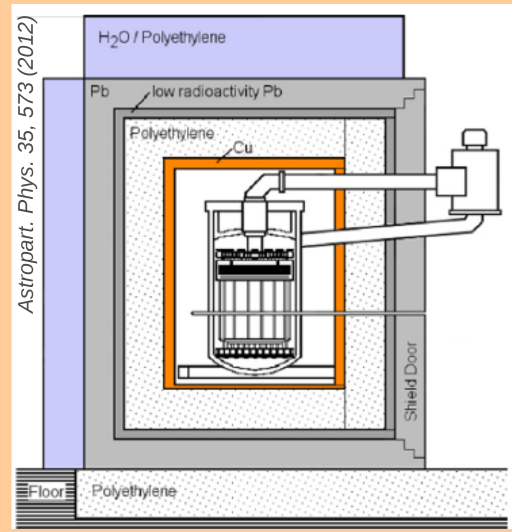
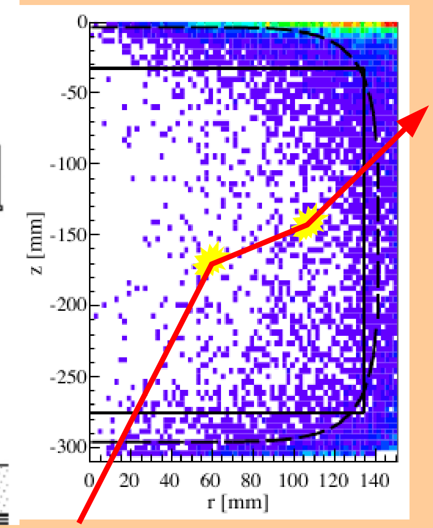




B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
requires some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different d*E*/dx from signal and background

Examples:
- scintillation pulse shape
- charge/light ratio
- ionization yield

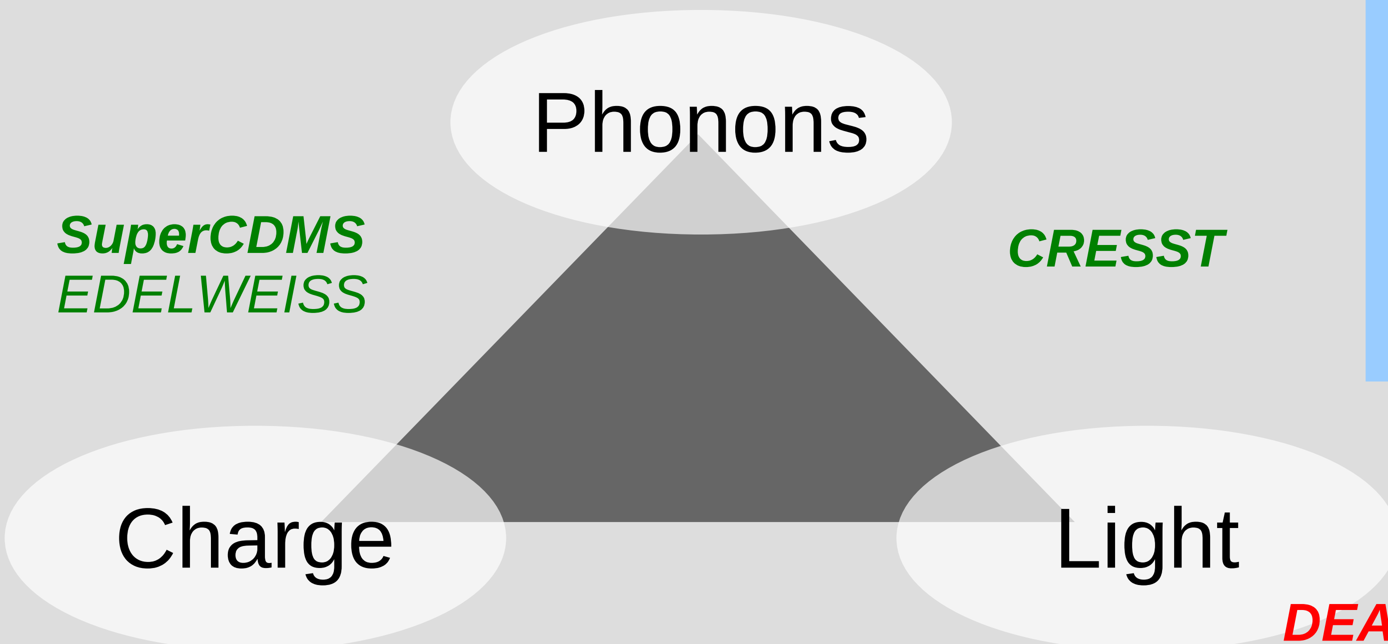
Direct WIMP Detection

Crystals (NaI, Ge, Si)
Cryogenic Detectors
Liquid Noble Gases

Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE

Superheated Liquids:
COUPP → **PICO**
PICASSO
SIMPLE

CRESST-I
CUORE



SuperCDMS
EDELWEISS

CRESST

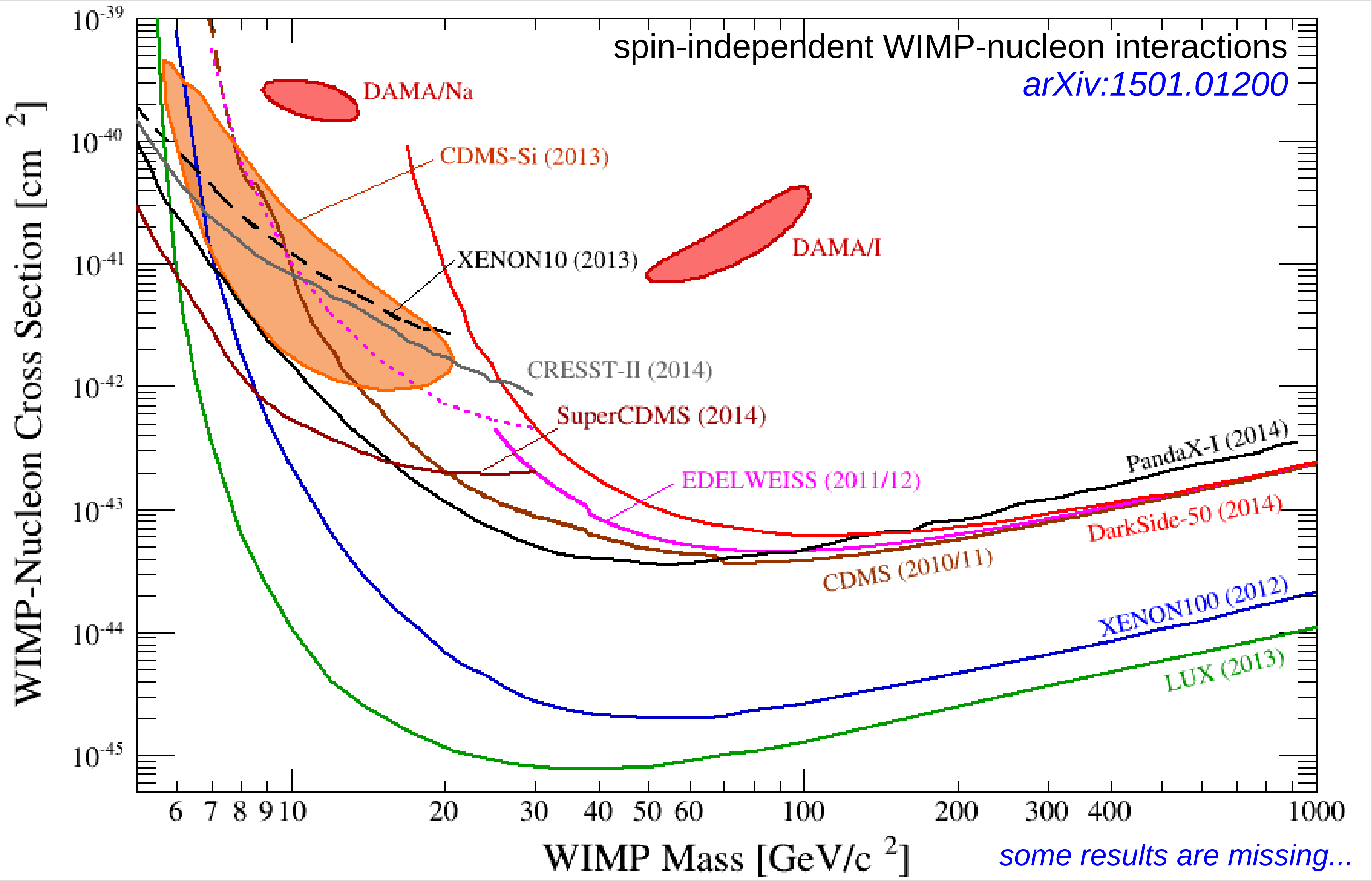
CoGeNT
CDEX
Texono
Malbek
DAMIC

XENON**, **LUX
*ArDM, **Panda-X***
*Darkside, **DARWIN***

***DEAP-3600**, CLEAN*
***DAMA**, KIMS*
***XMASS**, DM-Ice,*
ANAIS, Sabre

too many experimental efforts to report on → you will see a biased selection

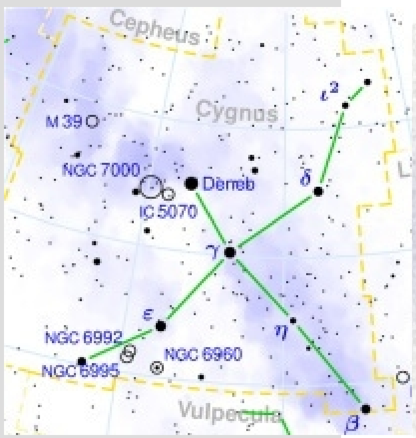
The current WIMP landscape

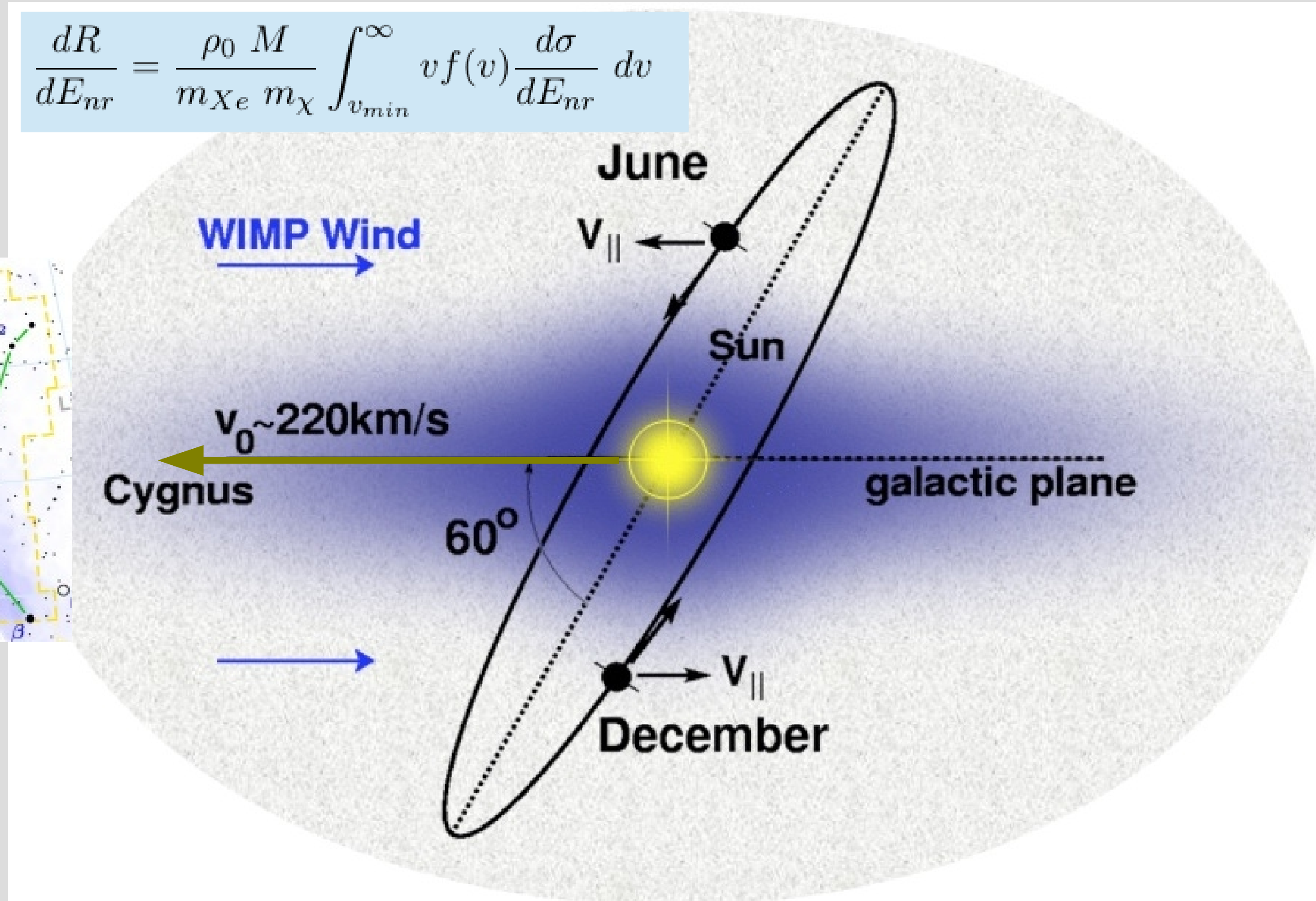


Annual Modulation

Drukier, Freese, Spergel, PRD 33, 3495 (1986)

$$\frac{dR}{dE_{nr}} = \frac{\rho_0\ M}{m_{Xe}\ m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_{nr}}\ dv$$



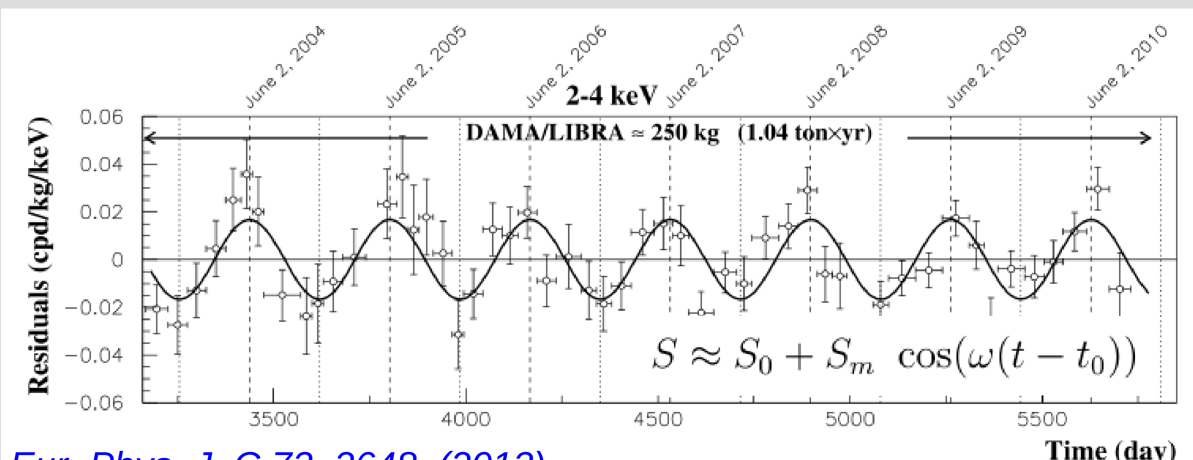


→ recoil spectrum gets harder and softer during the year
→ search for annually modulating signal (3% effect)
→ does not require many physical assumptions

Annual Modulation: DAMA/Libra

- PMTs coupled to **NaI(Tl)** Scintillators @ LNGS
  → extremely clean background necessary
- looks for annual modulation
- large mass and exposure: 1.17 t×y

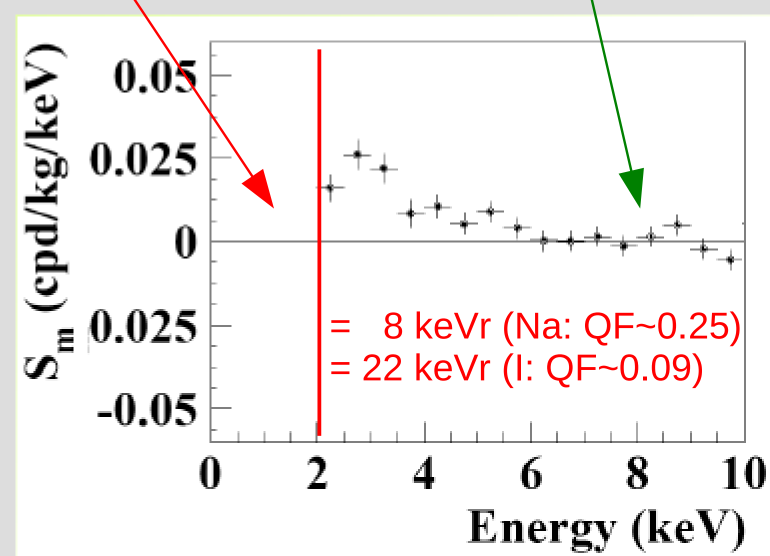
- DAMA finds annual modulation @ 9.3σ C.L.
- BUT: no ER/NR discrimination!



Eur. Phys. J. C 73, 2648 (2013)

what is here?

no modulation above 6 keV



Interpretation as Dark Matter interaction
is in conflict with numerous other experiments
→ KIMS, ANAIS, DM-Ice, Sabre will check directly

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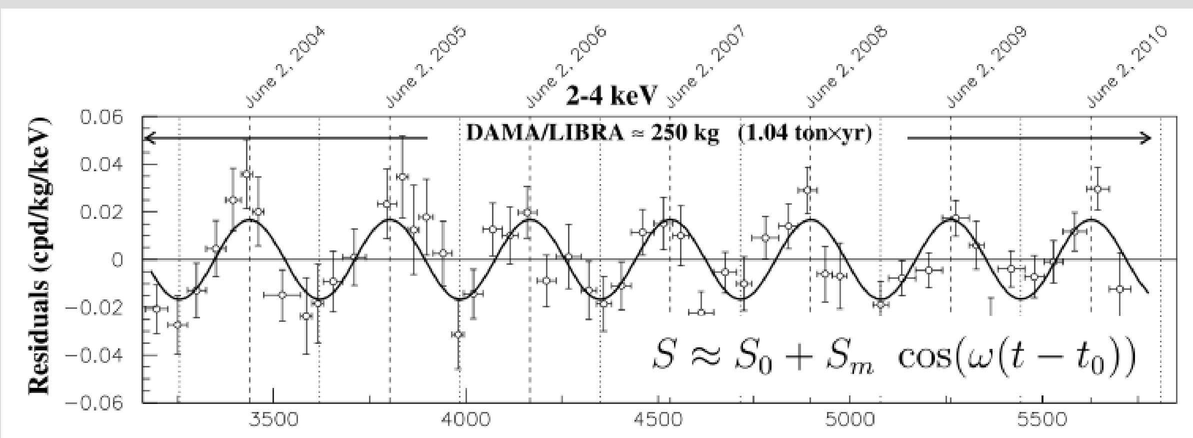

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Reconcile DAMA/Libra with the null-results from other experiments assuming **leptophilic** dark matter?
→ DAMA might see electronic recoils

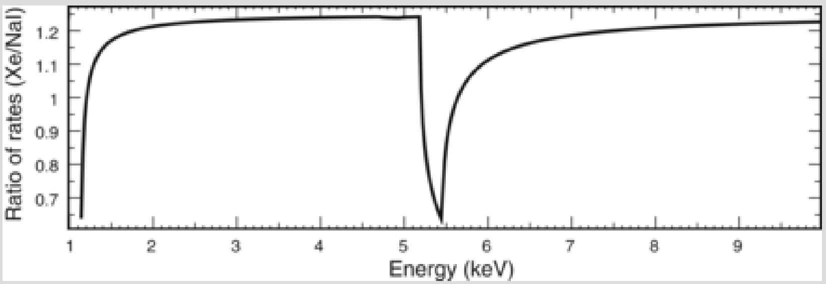
Examples:
Kopp et al., PRD 80, 083502 (2009)
Changet al., PRD 90, 015011 (2014)
Bell et al., PRD 90, 035027 (2014)
Mirror dark matter:
Foot, Int.J.Mod.Phys. A29, 1430013 (2014)
Luminous dark matter:
Feldstein et al., PRD 82, 075019 (2010)

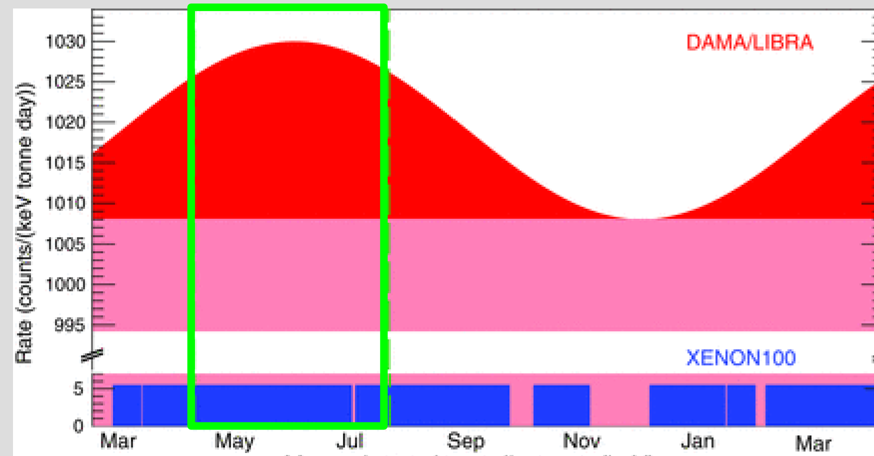
DAMA vs XENON: Average Rates

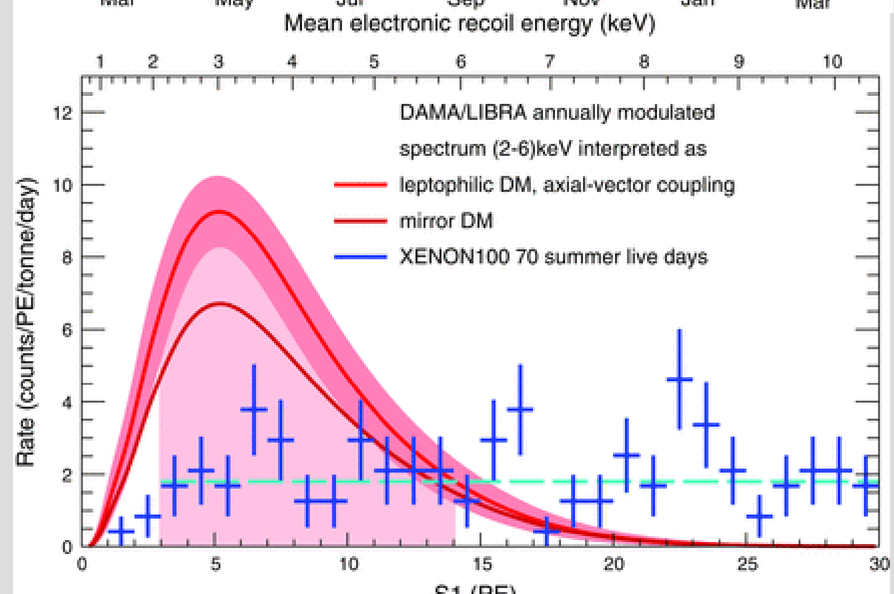
XENON100, Science 349, 851 (2015)

even if dark matter only interacts with electrons at tree-level, loop induced dark matter-hadron interactions dominate → back the the usual NR limits *PRD 80, 083502 (2009)*

Axial-vector couplings $\vec{A}\otimes\vec{A}$: loop-effects vanish, WIMP-electron couplings are not suppressed







Analysis

– assume 100% modulation
(conservative but hard to find a model)

– convert DAMA modulation spectrum to Xe;
I and Xe have very similar electron structure

– compare rates during 70 days in Summer

XENON100 excludes DAMA as being due to

– WIMP-electron axial-vector couplings at **4.4σ**
(interpreting all XENON100 events as signal)

– luminous dark matter at **4.6σ**

– mirror dark matter at **3.6σ**

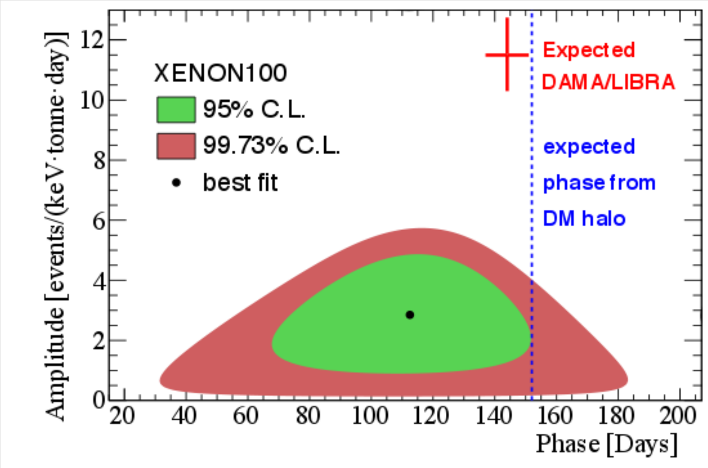
DAMA vs XENON: Modulation

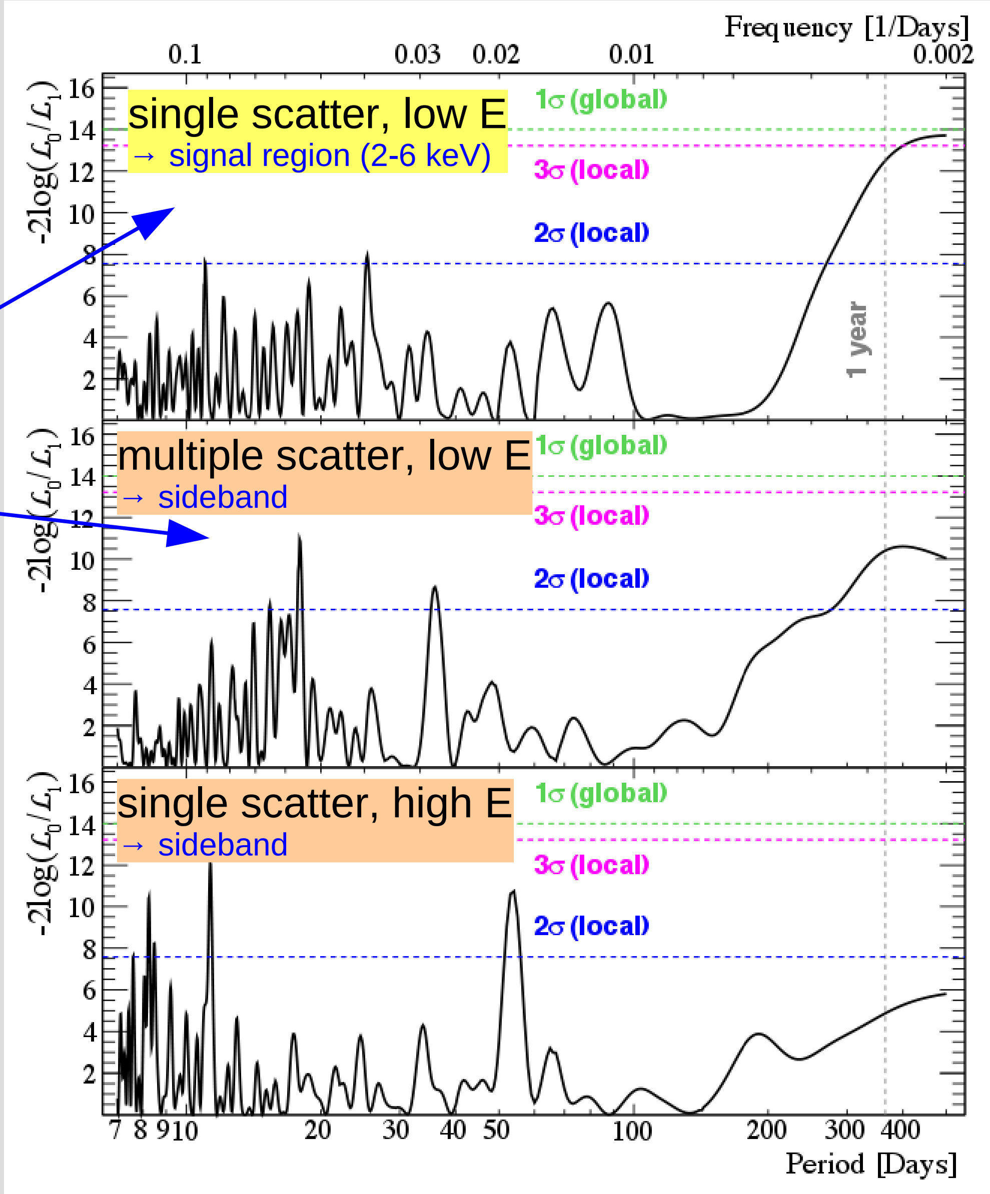
XENON100, PRL 115, 091302 (2015)

- 225 live days acquired over **13 months**
- first demonstration that 2-phase TPCs can be operated stably for modulation analysis
- did not find significant correlation with operation/detector parameters

- single scatters: no significant modulation at P=365d; phase disfavors DM interpretation
- multiple scatters: similar modulation ($\phi_{ms} \simeq \phi_{ss}$)

→ exclude DAMA/Libra as being induced by axial-vector WIMP-electron couplings at **4.8σ**

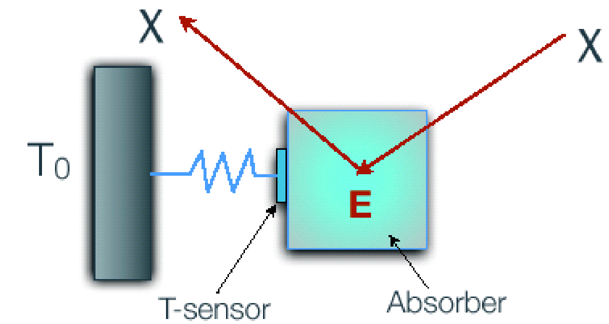


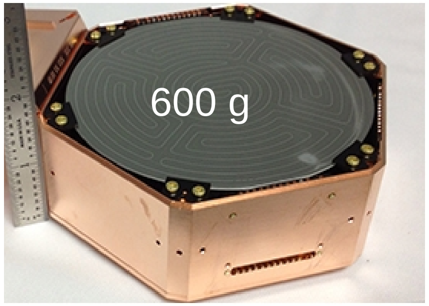


Cryogenic Detectors: SuperCDMS

@ Soudan Lab (USA) → later: SNOLAB

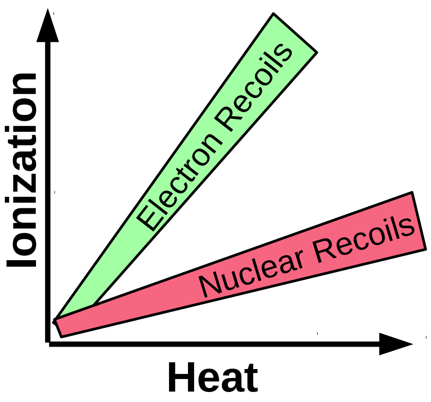
measure charge and heat (phonons):
  E deposition → temperature rise *ΔT*





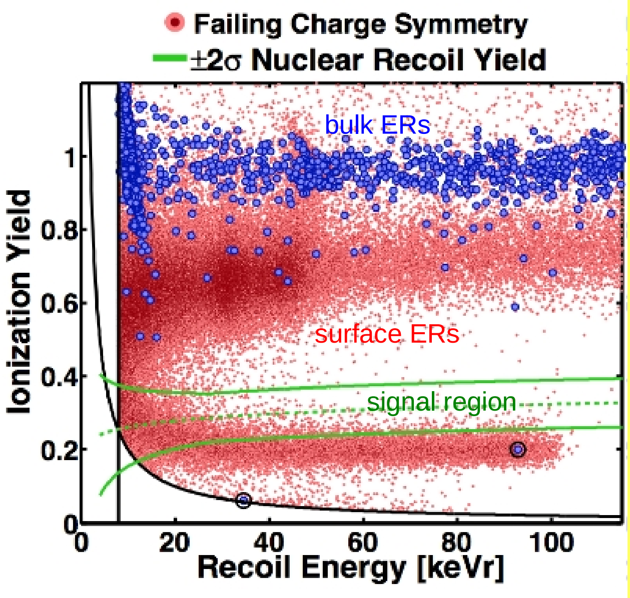
Crystals: **Ge**, **(Si)** cooled to few mK
– low heat capacity
– ΔT ~ μK

Very good discrimination
→ BUT: need to reject
surface events



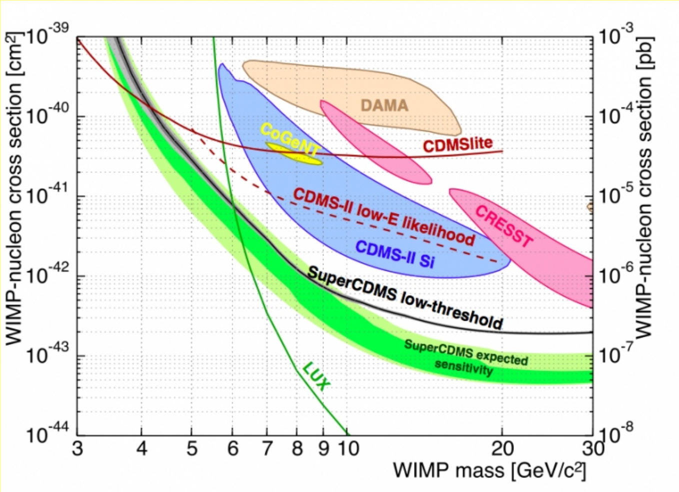
similar: **EDELWEISS** @ Modane
new low-mass limit also challenges CDMS-II-Si
arXiv:1504.00820

Rejection of Surface Events



Appl.Phys.Lett. 103 (2013) 164105

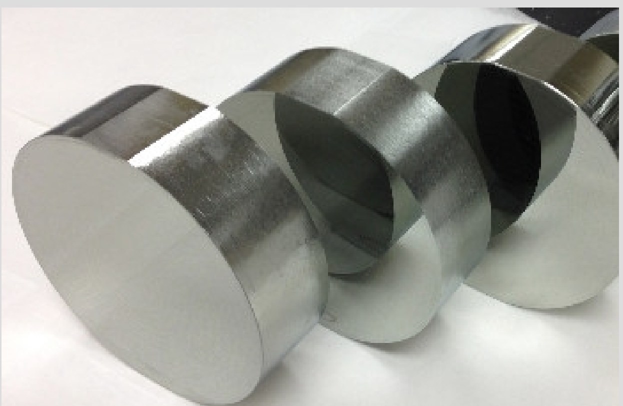
First results on low-mass WIMPs

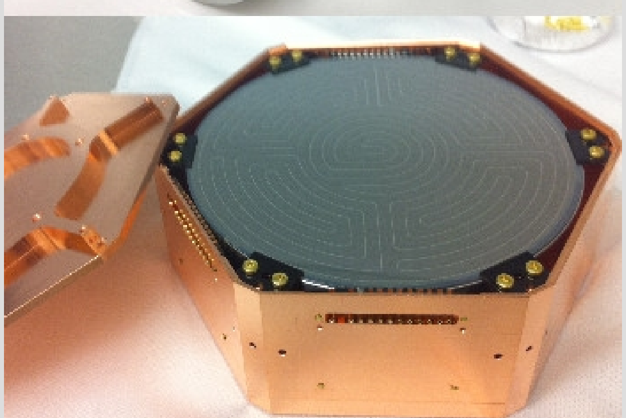


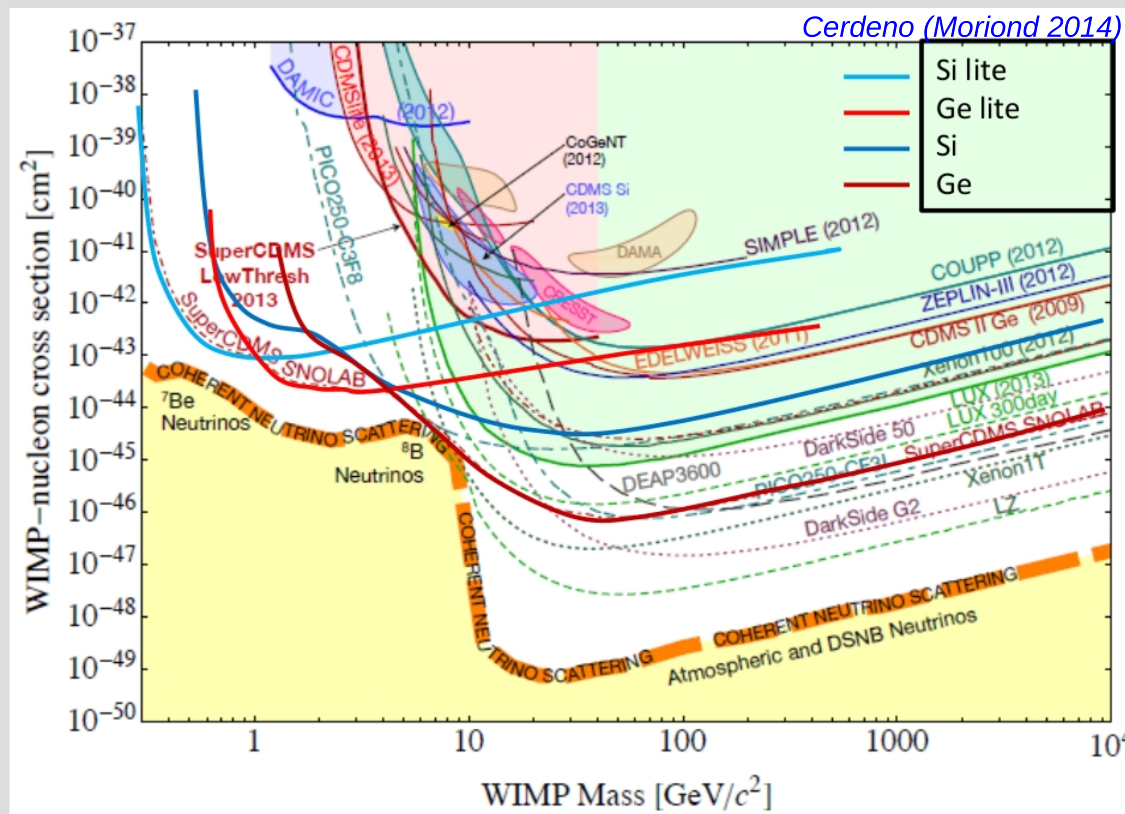
PRL 112, 241302 (2014)

SuperCDMS @ SNOLAB

- selected by US NSF-DOE downselection in 2014
- aim for 50 kg-scale experiment (cryostat can accomodate 400 kg)
  low threshold → focus on 1-10 GeV/c² mass range
- Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
- 100 x 33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established



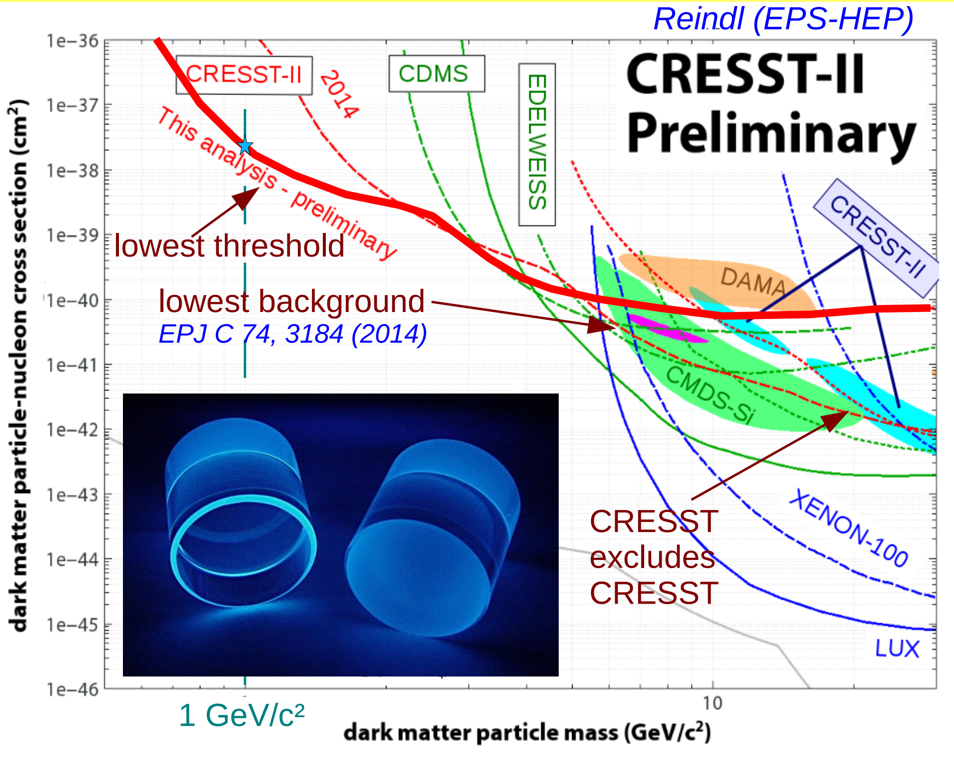




Towards lowest WIMP masses

CRESST @ LNGS

- reads phonons and scintillation light
- target: $CaWO_4$ → multi-element material
- successful background reduction; data taking since 2013
- EPS-HEP preliminary result: detector with 300 eV threshold
- focus on low-mass WIMPs

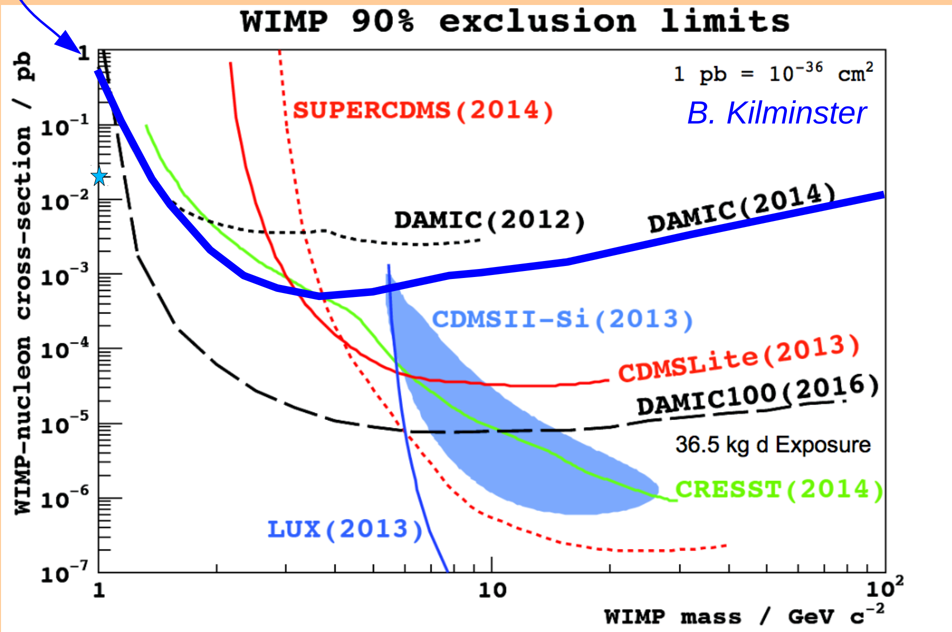


DAMIC @ SNOLAB

- target: Si → use thick CCDs
  → need only 3.6 eV to create e⁻-hole pair
- low target mass but very low thresholds
  → low mass WIMPs
- particle ID via track information

preliminary result:

- 36 days of 3 CCDs up to 675 µm thick (2.9 g)
  → @ 3 GeV/c²: 10x better than DAMIC (2012)
- DAMIC100 will start data taking in 2015



Spin dependence: Threshold Detectors

PICO @ SNOLAB

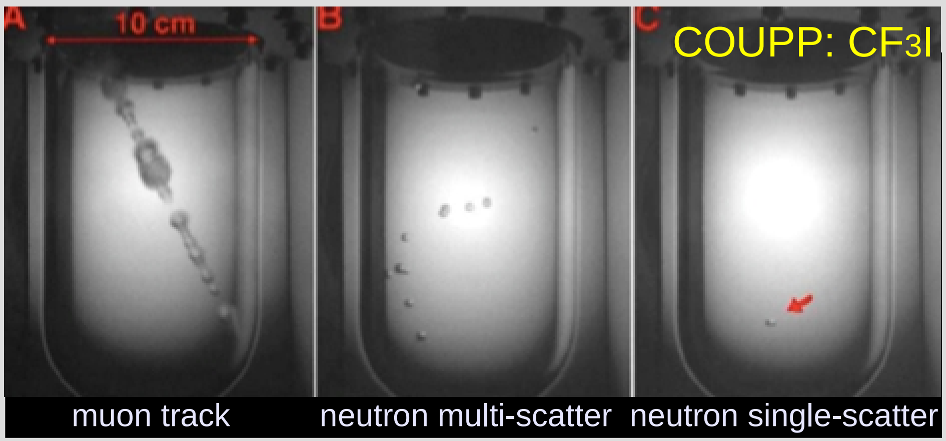
- PICO = PICASSO + COUPP
- bubble chamber filled with superheated C_3F_8
  → very good sensitivity to spin-dependent interactions
  → bubble forms only above a threshold energy

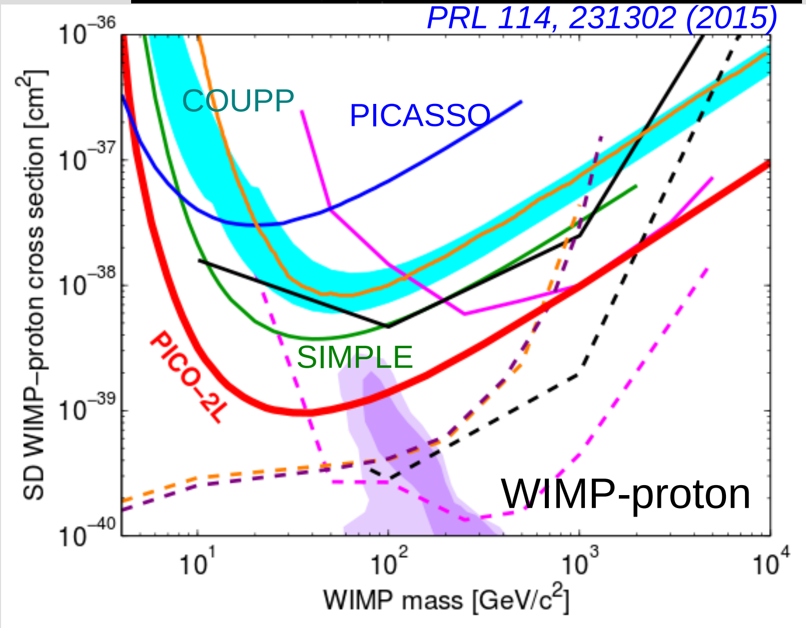
- almost „immune“ to electronic recoils;
  reject alphas by acoustic discimination *N. J. Phys.10, 103017 (2008)*
- challenge: correlation of candidate events
  with events in previous expansions

- PICO-2L: low threshold down to 3 keVnr

$$\sigma = \frac{32 G_F^2 m_r^2}{\pi} \frac{J+1}{J} \left[a_p \langle s_p \rangle + a_n \langle s_n \rangle \right]^2$$

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

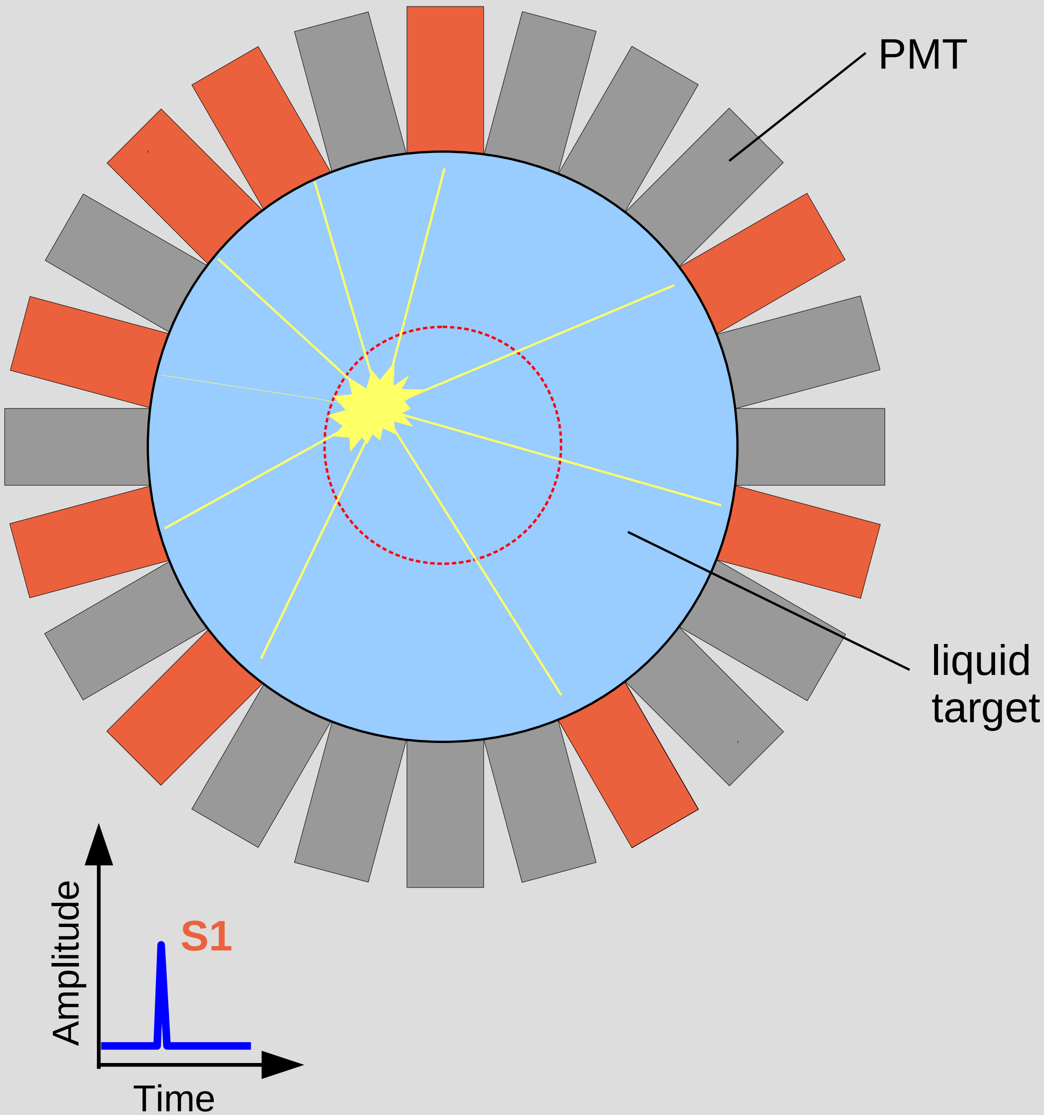




PICO-60: CF_3I data analysis ongoing → C_3F_8
Upgrade plan: PICO-250 → SD reach ~10^{-42} cm²

Liquid Noble Gases: Detector Concepts

Single Phase Detector



Noble Gas: Single Phase Detectors

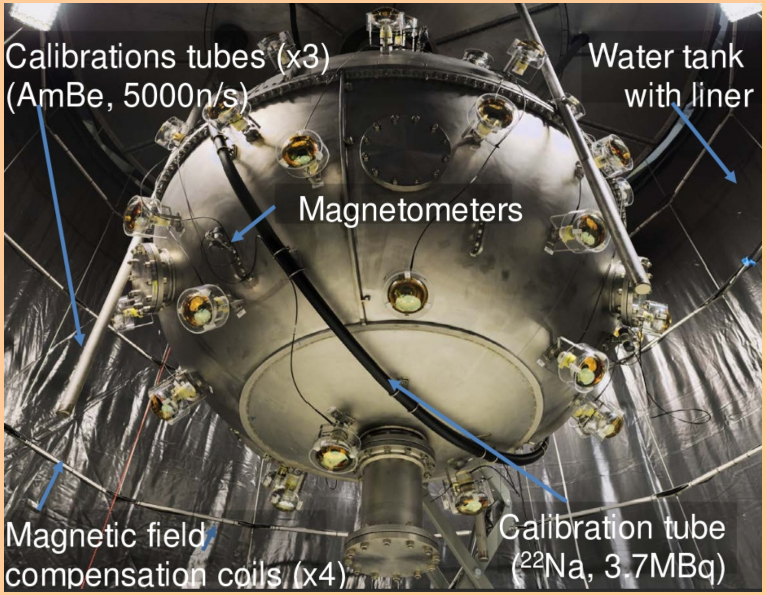
+ no high voltage, very high light yield **–** O(cm) position resolution, no double scatter rejection

XMASS @ Kamioka (JP) **LXe**

– 832 kg LXe target, 642 PMTs
– very high light yield, low threshold (0.5 keVee)
BUT: **no possibility to reject NRs**
– results: (low-mass) WIMPs, inelastic WIMP scat., axions, bosonic superWIMPs, rare decays
→ summary: *arXiv:1506.08939*
– background reduced after commissioning run
→ stable operation since 2 years
– plans towards XMASS-1.5t and XMASS-II (24t)

DEAP-3600 @ SNOLAB (CA) **LAr**

– **light pulse-shape for discrimination**
3×10^{-8} achived 43-86 keVee
→ prediction: 10^{-10} above 15 keVee in DEAP-3600
– 3.6t liquid argon target;
high ^{39}Ar background when using ^{nat}Ar (~1 Bq/kg)
– under commissioning; fill with LAr in summer
first data by late 2015; first DM result in 2016
– sensitivity: 1×10^{-46} cm² @ 100 GeV/c²
– if experiment successful → „upgrade“ to 50t



F. Retiere (LIDINE 2015)

Noble Gas: Single Phase Detectors

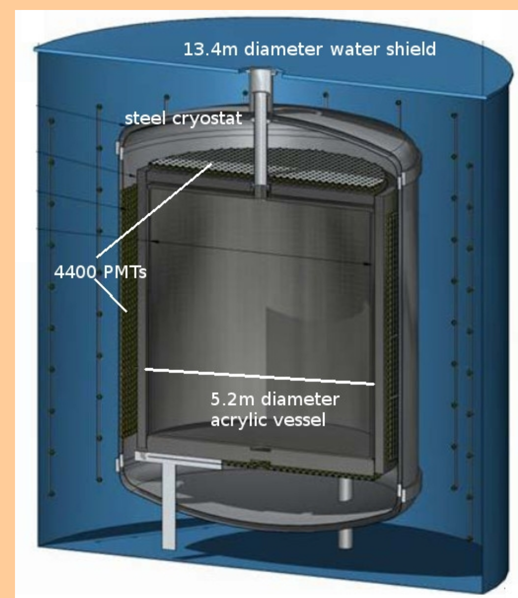
+ no high voltage, very high light yield **–** O(cm) position resolution, no double scatter rejection

XMASS @ Kamioka (JP) — LXe

– 832 kg LXe target, 642 PMTs
– very high light yield, low threshold (0.5 keVee)
BUT: **no possibility to reject NRs**
– results: (low-mass) WIMPs, inelastic WIMP scat., axions, bosonic superWIMPs, rare decays
→ summary: *arXiv:1506.08939*
– background reduced after commissioning run
→ stable operation since 2 years
– plans towards XMASS-1.5t and XMASS-II (24t)

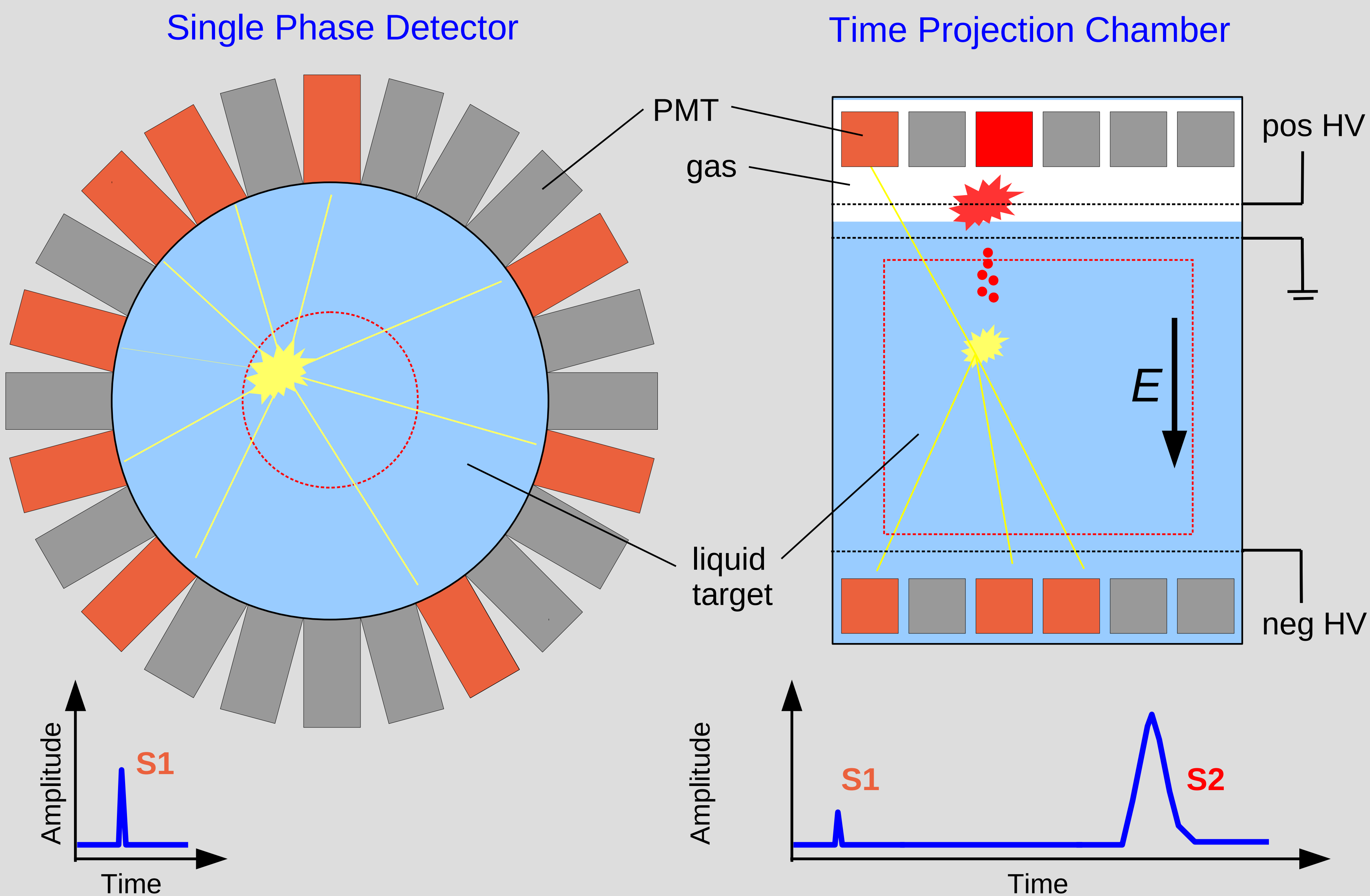
DEAP-3600 @ SNOLAB (CA) — LAr

– **light pulse-shape for discrimination**
3×10^{-8} achived 43-86 keVee
→ prediction: 10^{-10} above 15 keVee in DEAP-3600
– 3.6t liquid argon target;
high ^{39}Ar background when using ^{nat}Ar (~1 Bq/kg)
– under commissioning; fill with LAr in summer
first data by late 2015; first DM result in 2016
– sensitivity: 1×10^{-46} cm² @ 100 GeV/c²
– if experiment successful → „upgrade“ to 50t

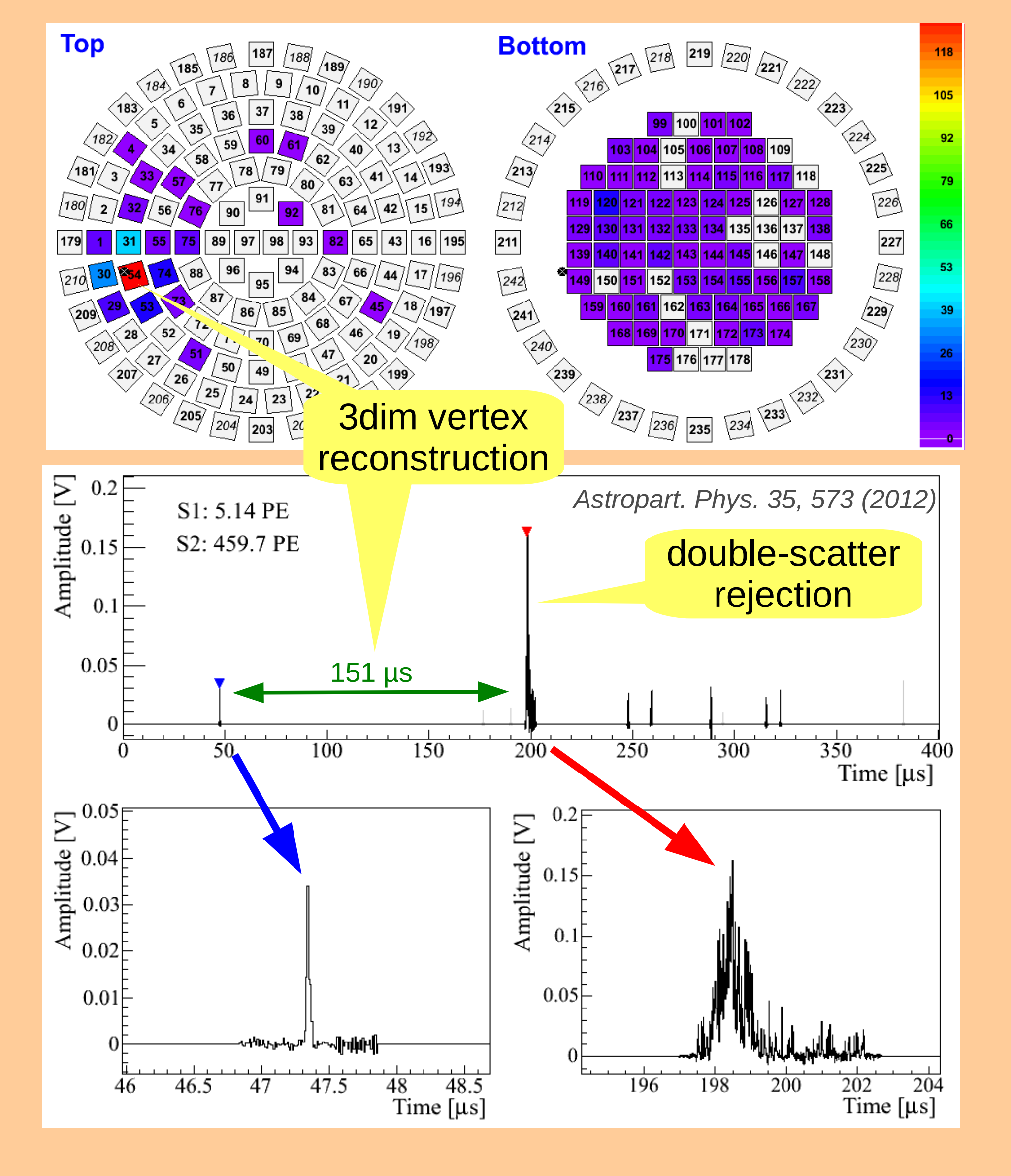


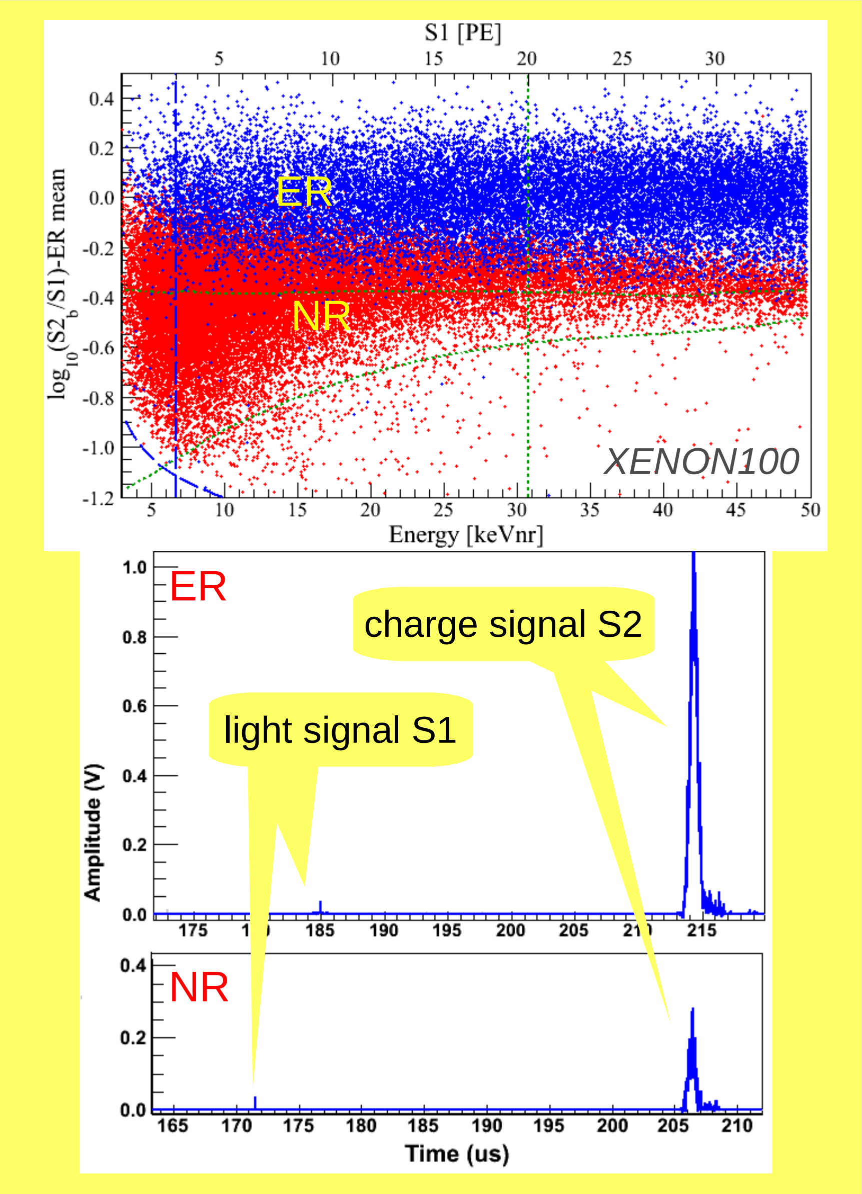
F. Retiere (LIDINE 2015)

Liquid Noble Gases: Detector Concepts



Dual Phase TPC



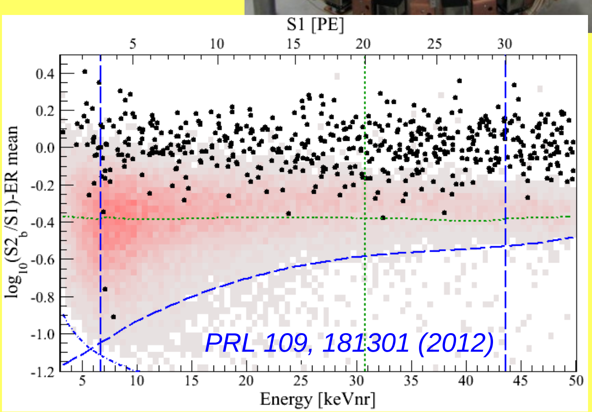


LXe: Existing dual phase detectors

XENON100 @ LNGS (IT)

Astropart. Phys. 35, 573 (2012)

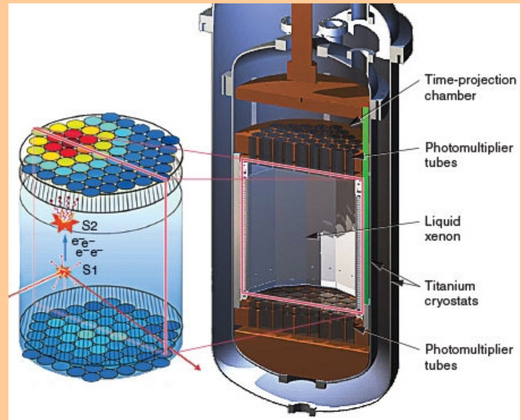
- 62 kg LXe, 225×34kg exposure
- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, ...
- still running as testbench

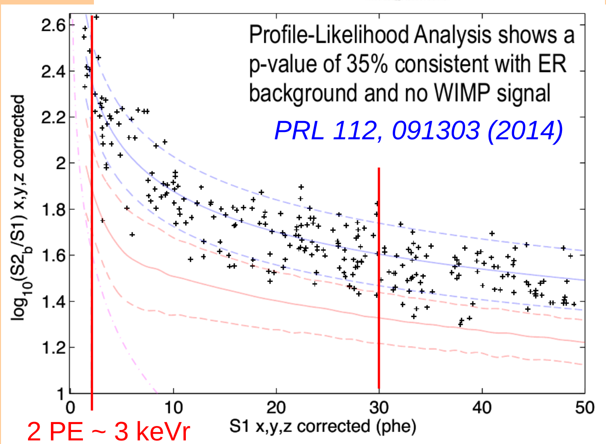


LUX @ SURF (USA)

NIM A 704, 111 (2013)

- best sensitivity above ~6 GeV/c²
- 250 kg LXe: 85d×118kg exp.
- high LY, inside water shield
- currently taking data

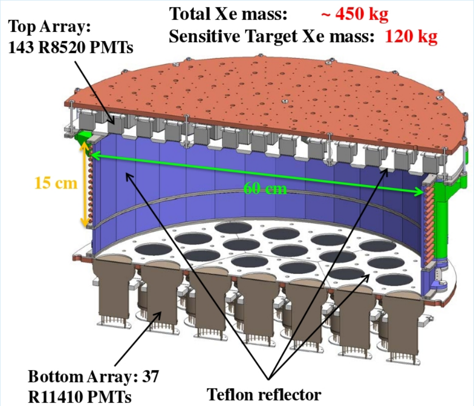


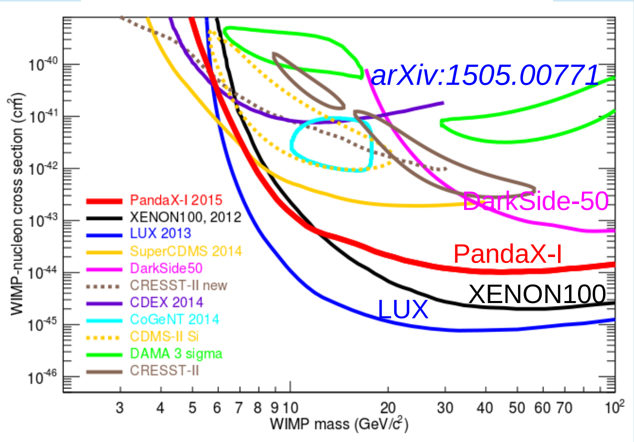


PandaX-I @ CJPL (CN)

Sci.China Phys.Mech.Astron. 57 (2014) 1476

- optimized for low-mass WIMPs
- 120 kg LXe: 80d×54kg exposure
- final low-mass limit published;
- experiment stopped for upgrade





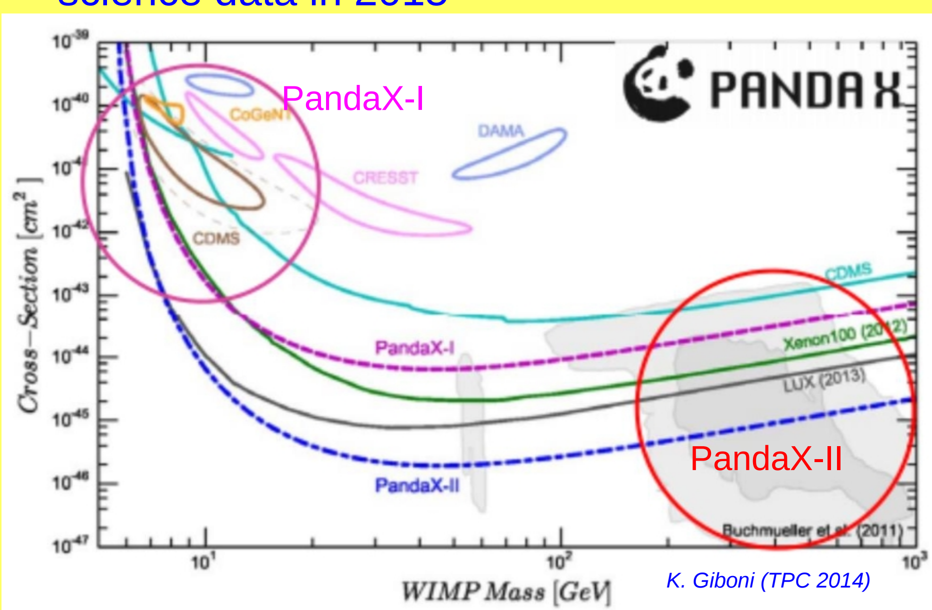
LAr TPC: **DarkSide-50** @ LNGS *PLB 743, 456 (2015)*

→ working towards a ^{39}Ar-depleted target (factor ~300)

Upcoming Detectors

PandaX-II @ CJPL

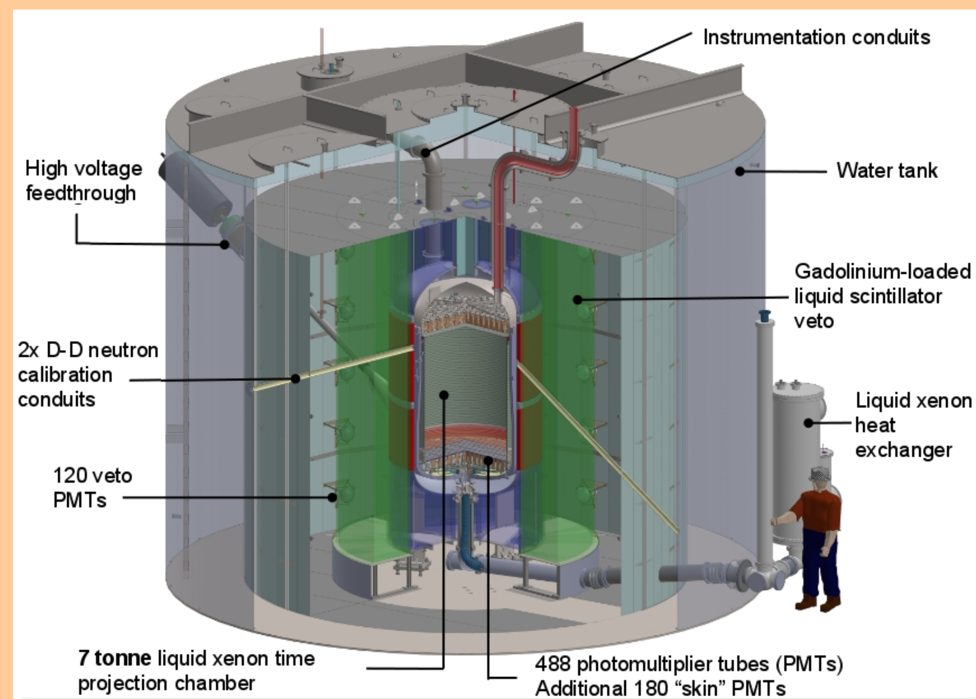
- new SS cryostat with lower radioactivity
- 1.3 tons total mass
  TPC: 60cm×60cm,
  600 kg active target
  ~300 kg fiducial target
- 110 R11410 PMTs,
  active veto
- aim for improved light yield
- under commissioning
  → science data in 2015



K. Giboni (TPC 2014)

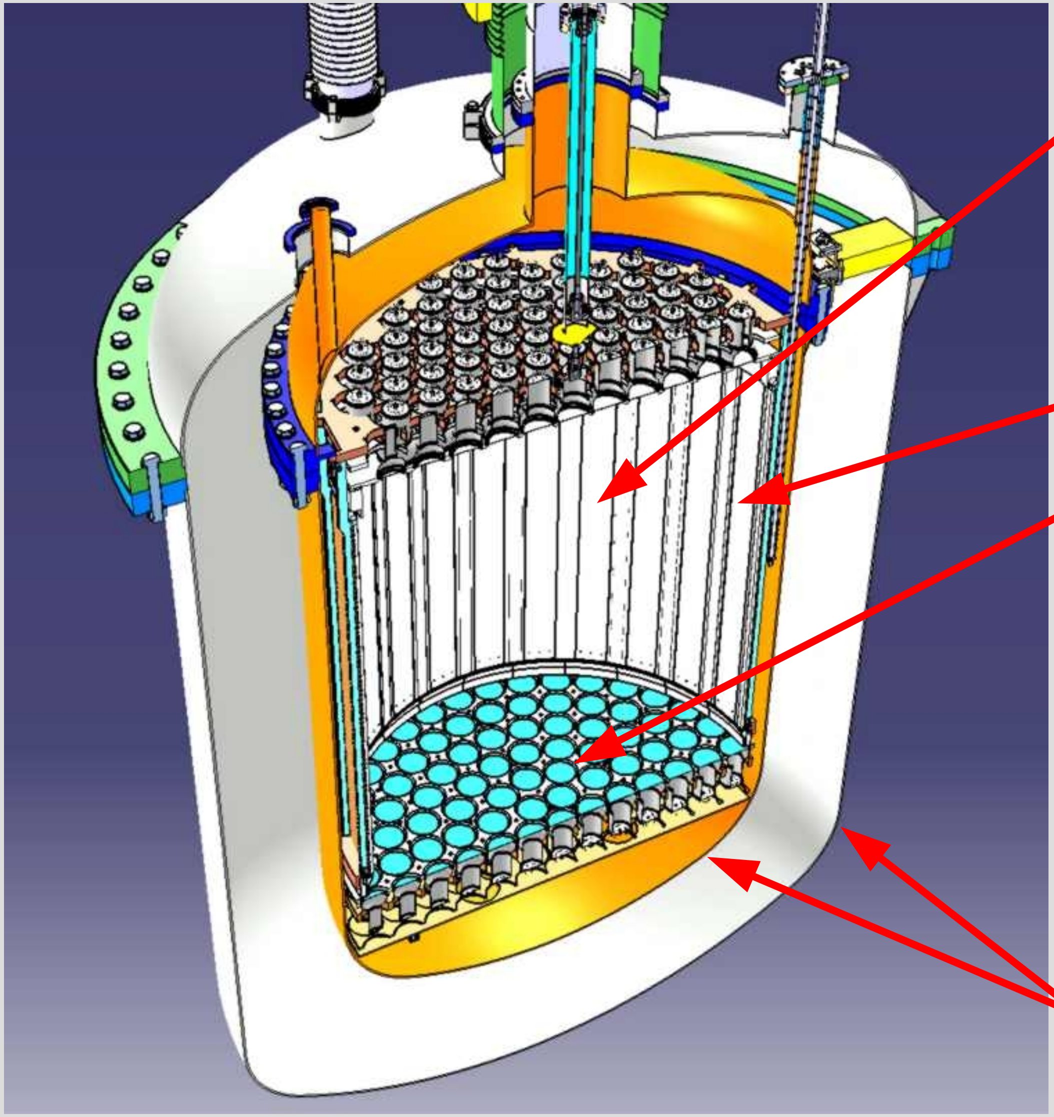
LZ @ SURF

- LZ = LUX+ZEPLIN
  selected by 2014 US DOE-NSF downselection
- 50× larger than LUX
  10t total, 7t active target, 5.6t fiducial target
- 488 R11410 PMTs
- 2015: started procurement of Xe, PMTs, ...
  2019: expected start of comissioning
- goal: 2×10^{-48} cm² @ ~50 GeV/c² after 15 t×y exp



XENON1T @ LNGS

XENON1T



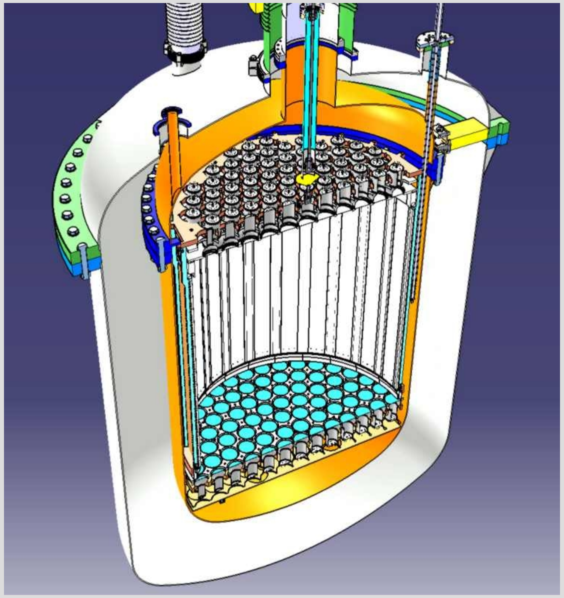
dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1 t

TPC made from OFHC and PTFE

248 photomultipliers
- Hamamatsu R11410-21
- low background
  arXiv:1503.07698
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments
  JINST 8, P04026 (2013)

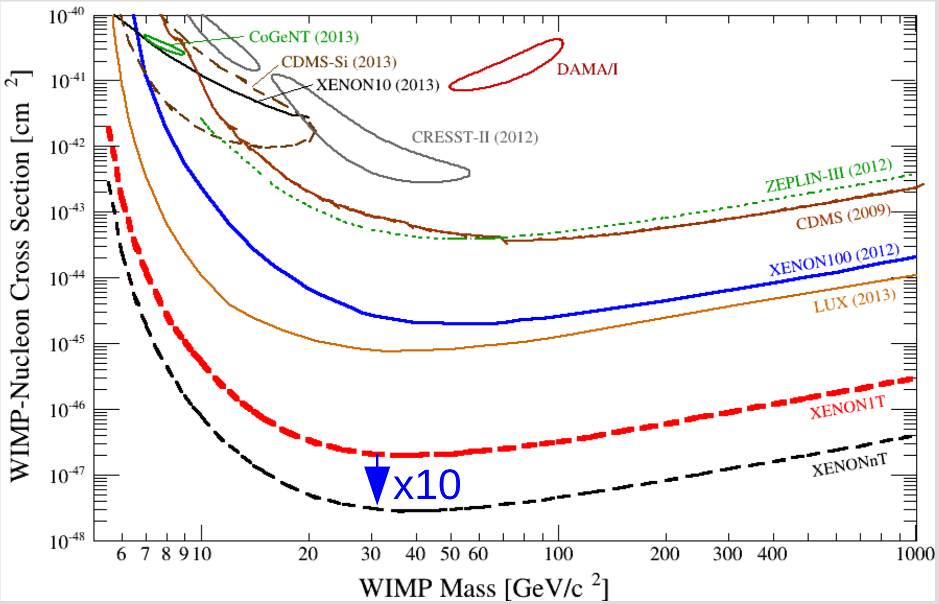
Low-background stainless steel cryostats

XENON1T → XENONnT

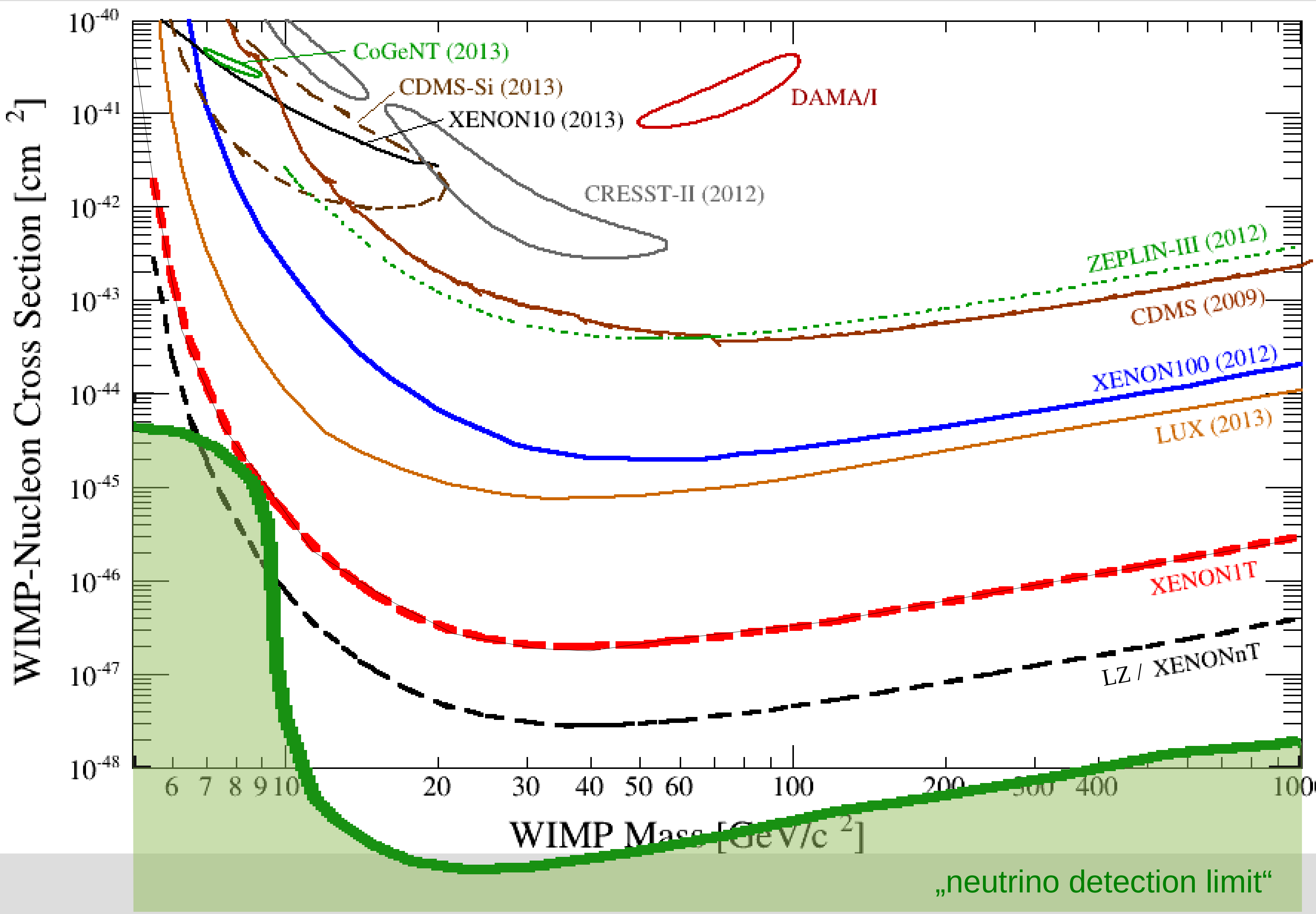


XENON1T
- 2t active target
- under construction
- first data 2015

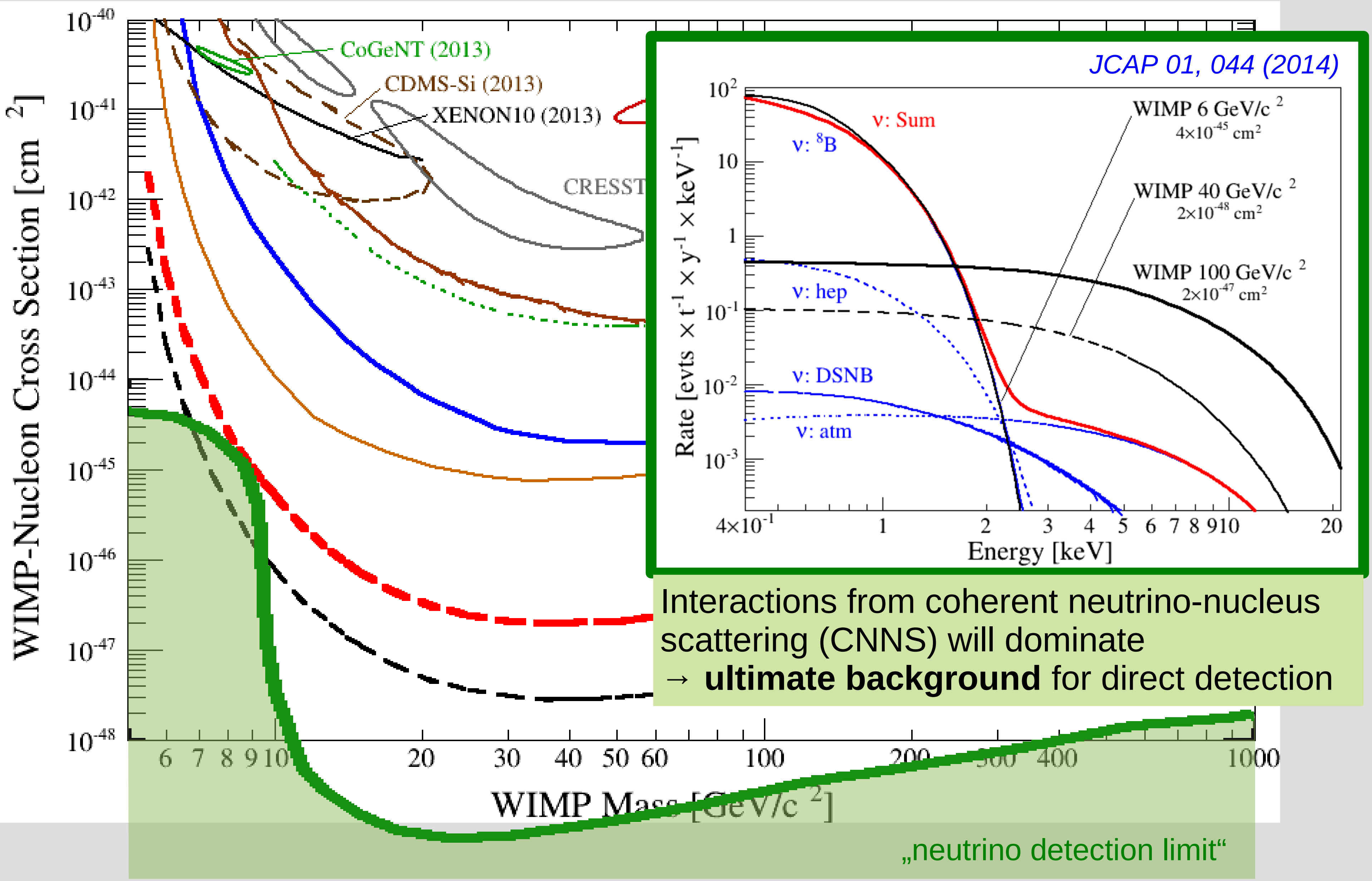
XENONnT
- >5t active target
- most components already in place from XENON1T
- projected to start data taking 2018



The XENON Future



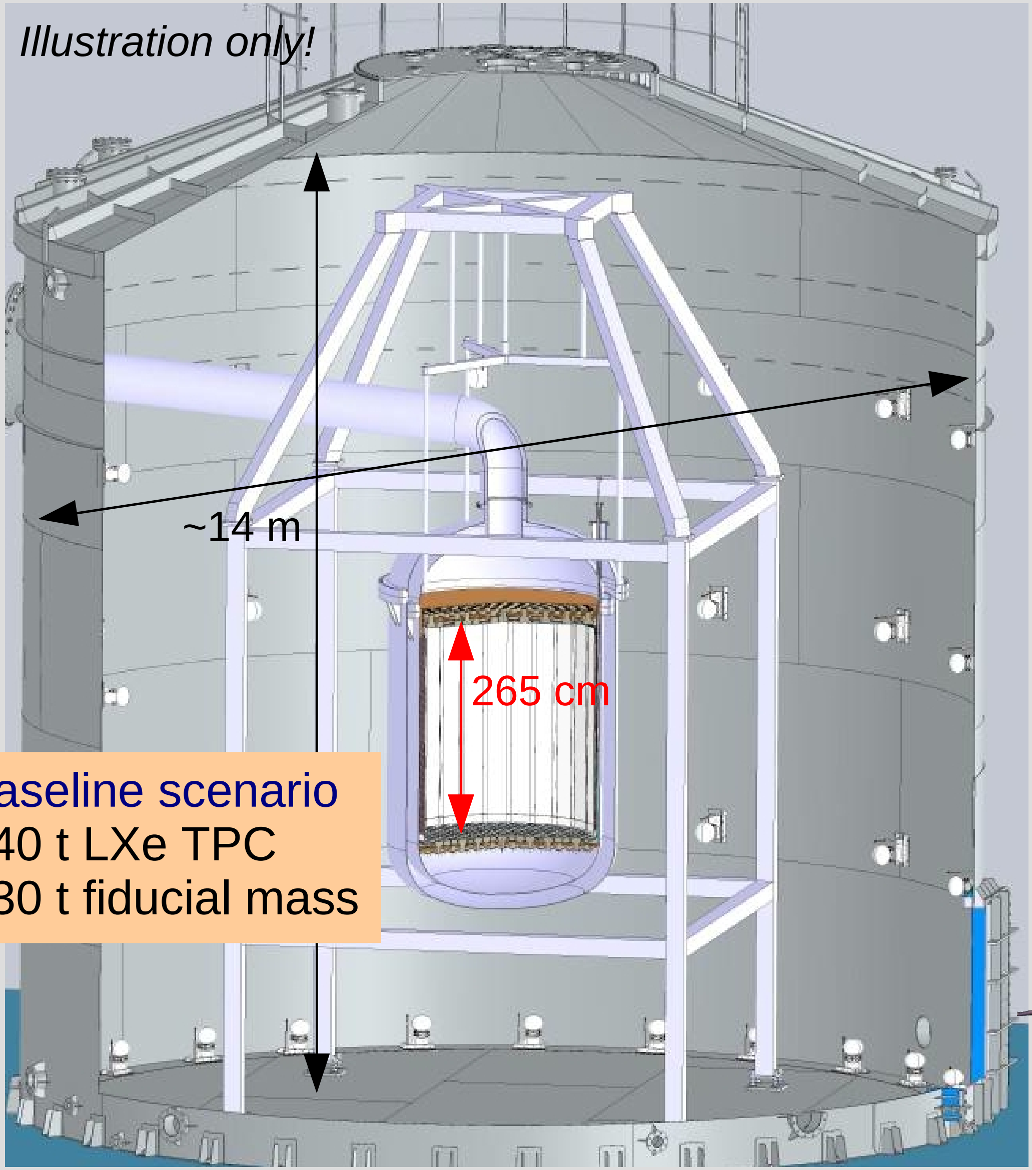
The XENON Future



Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection

„neutrino detection limit“

DARWIN The ultimate WIMP Detector



Baseline scenario
~40 t LXe TPC
~30 t fiducial mass

- aim at sensitivity of a few 10^{-49} cm², limited by **irreducible ν-backgrounds**
  → many non-WIMP science channels (e.g., neutrinos, axions, SN, ...)
- international consortium, 21 groups
  → R&D ongoing
- DARWIN is on the European astroparticle physics APPEC roadmap and endorsed by the Swiss State Secretariat (SERI)
- Timescale: start after XENONnT

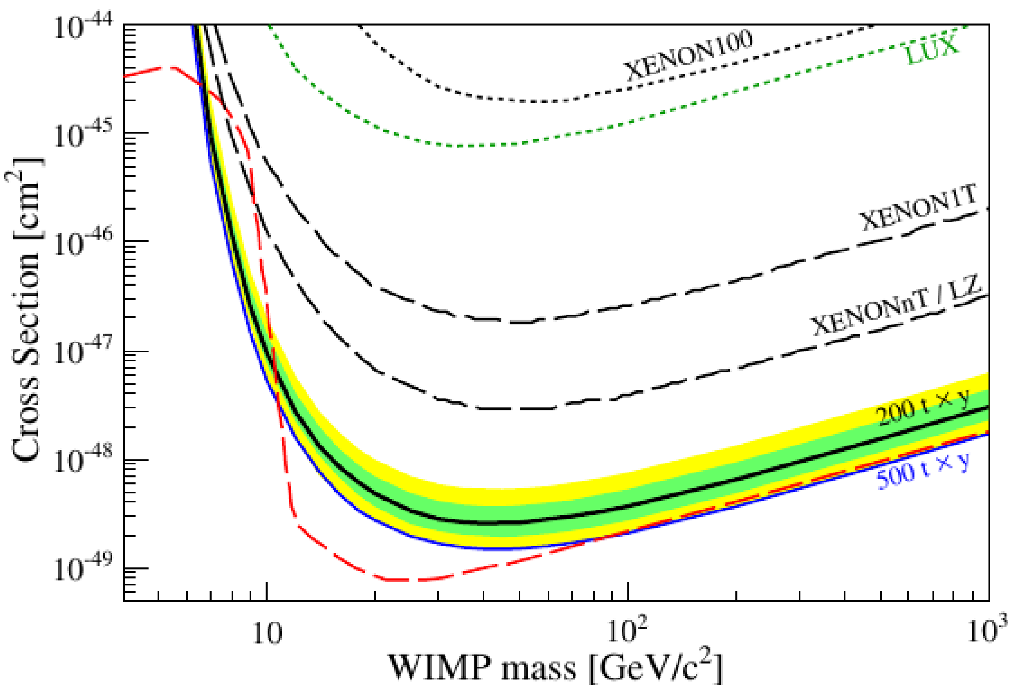
www.darwin-observatory.org

DARWIN WIMP Sensitivity

arXiv:1506.08309
accepted by JCAP

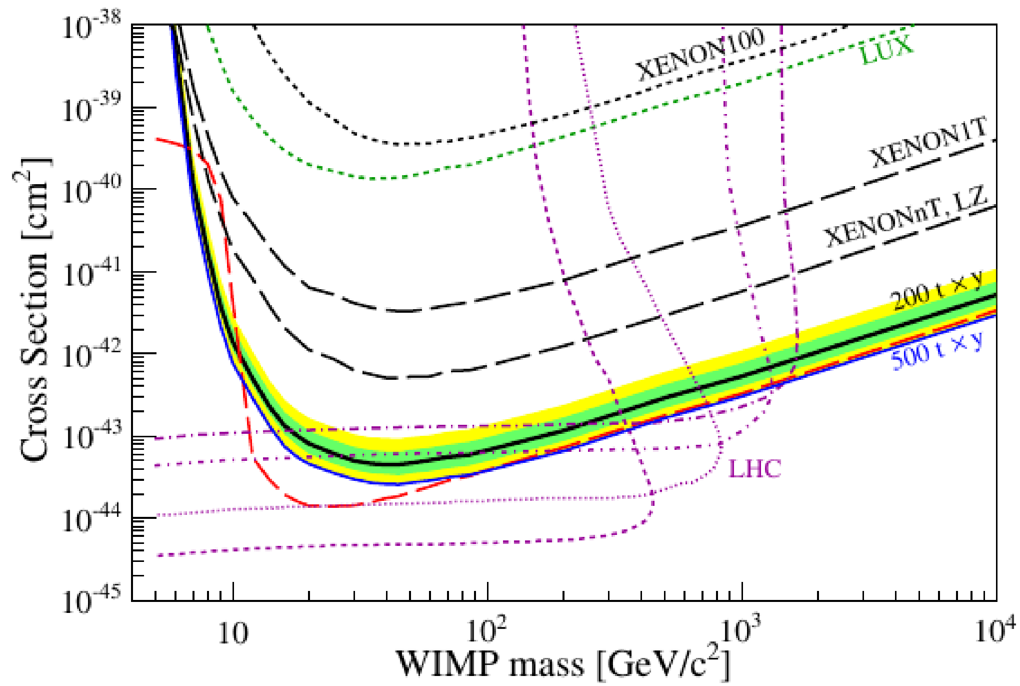
- exposure: 200 t x y; **all backgrounds included**
- likelihood analysis (~99.98% ER rejection @ 30% NR acceptance)
- S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keVnr energy window

spin-*in*dependent couplings



200 t×y: $\sigma < 2.5 \times 10^{-49}$ cm² @ 40 GeV/c²

spin-*de*pendent couplings (n-only)



excellent complementarity to LHC searches

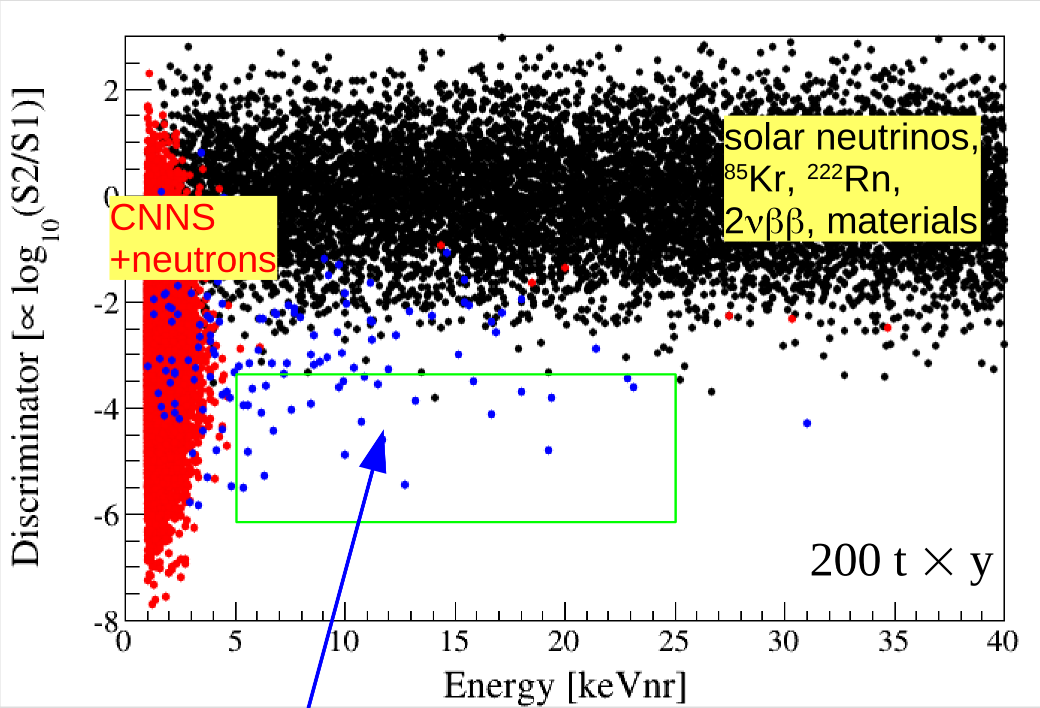
arXiv:1409.4075

→ also sensitive to inelastic WIMP interactions

WIMP Spectroscopy

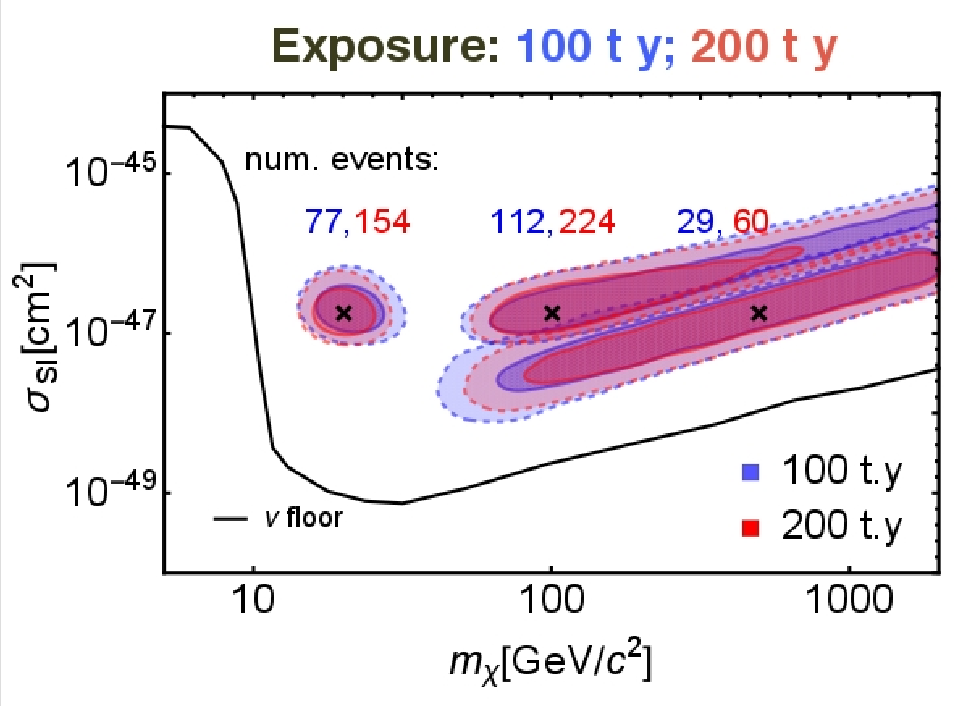
DARWIN

2×10^{-48} cm²



WIMP: 30 GeV/c², $\sigma=2\times10^{-48}$ cm²
27 signal events in box

2×10^{-47} cm²

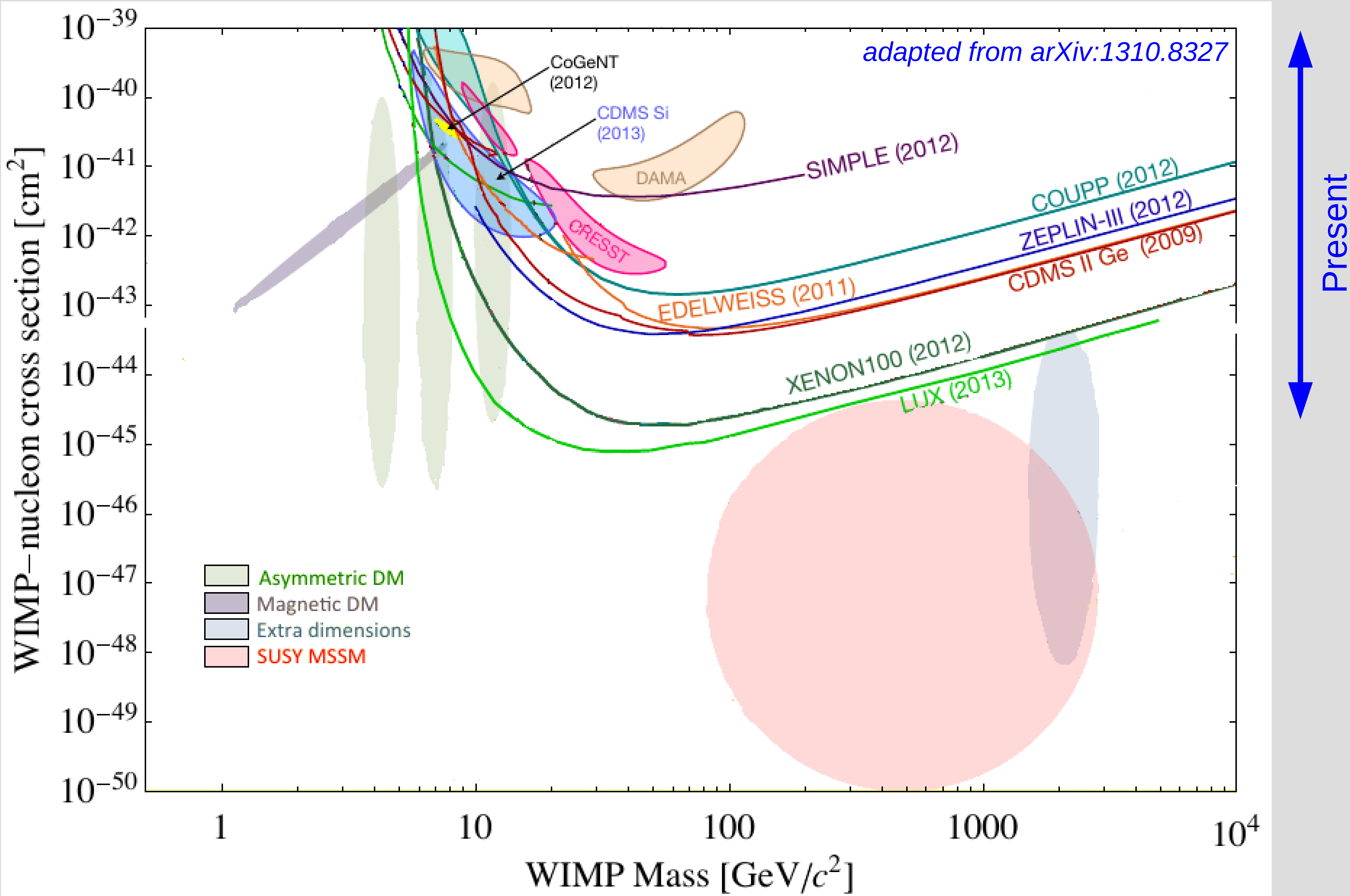


Update of Newstead et al., PRD 8, 076011 (2013)

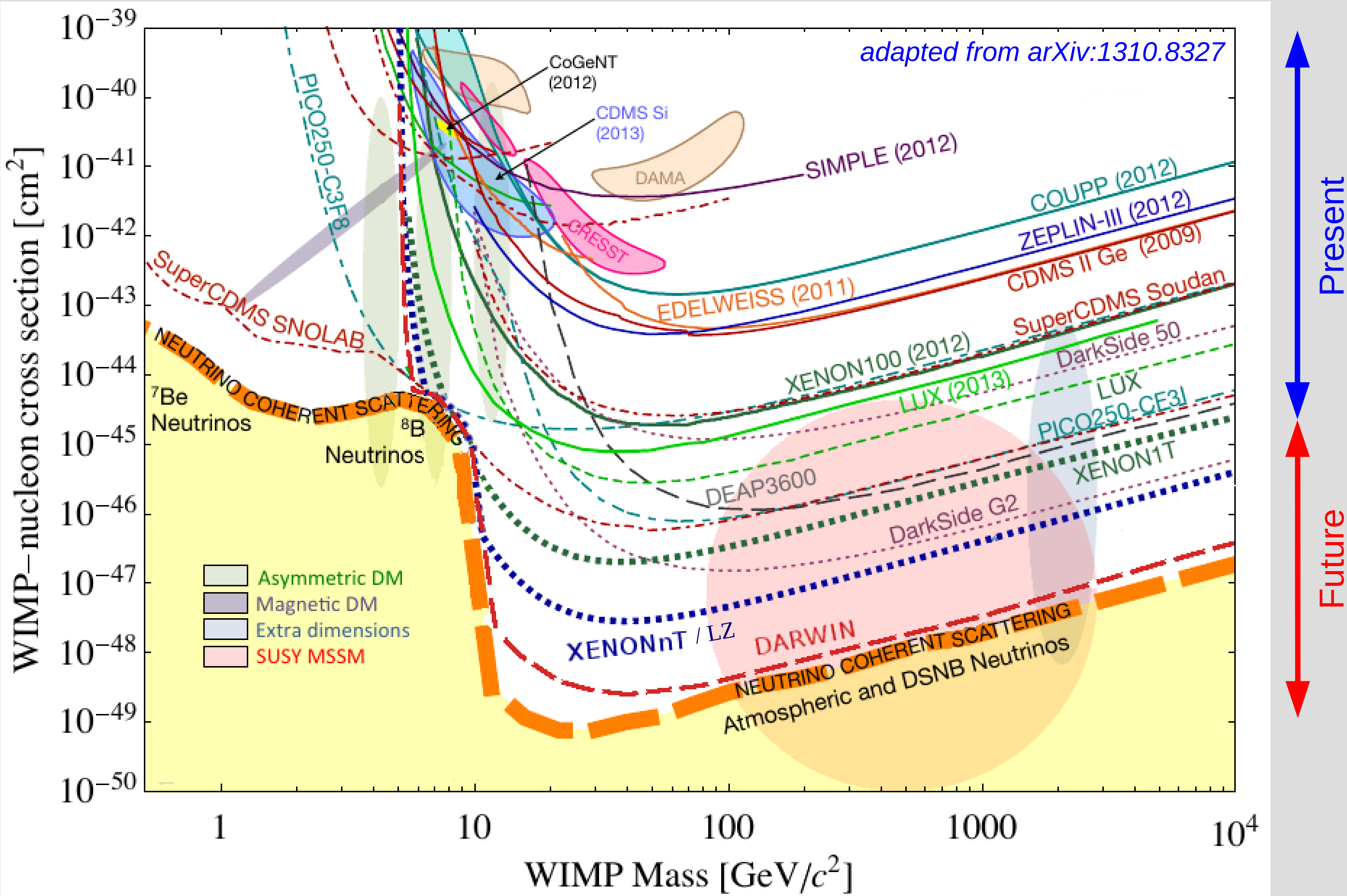
Capability to reconstruct WIMP parameters

- m_χ=20, 100, 500 GeV/c²
- 1σ/2σ CI, marginalized over astrophysical parameters
- due to flat WIMP spectra, no target can reconstruct masses >500 GeV/c²

The WIMP Landscape today

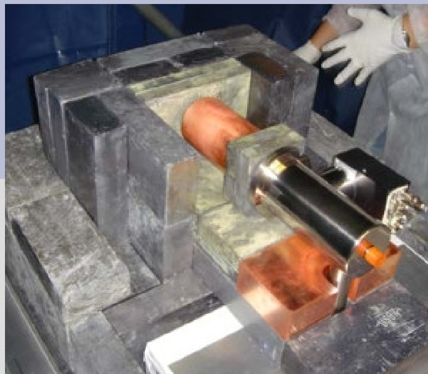


Exciting times ahead of us

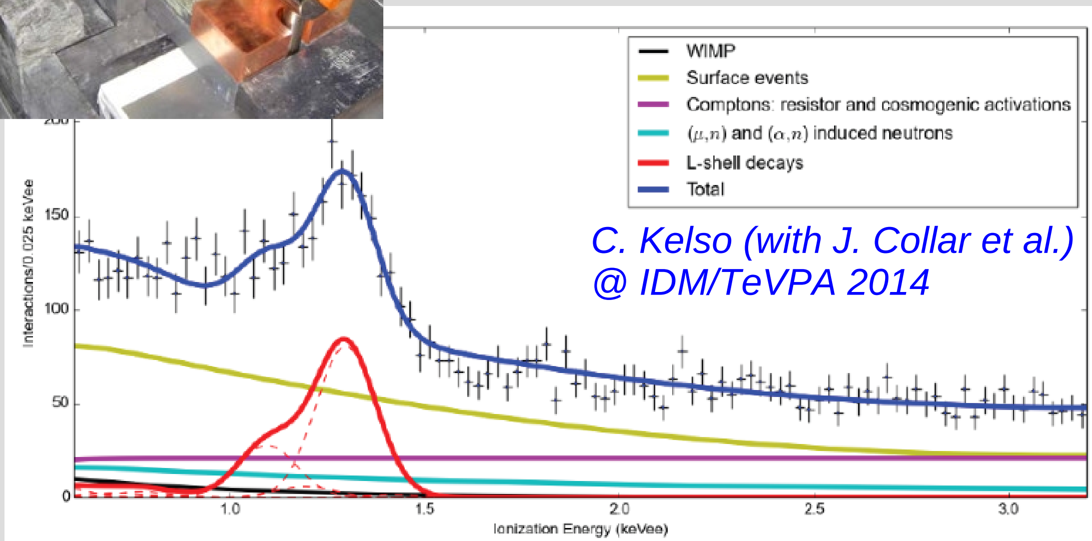


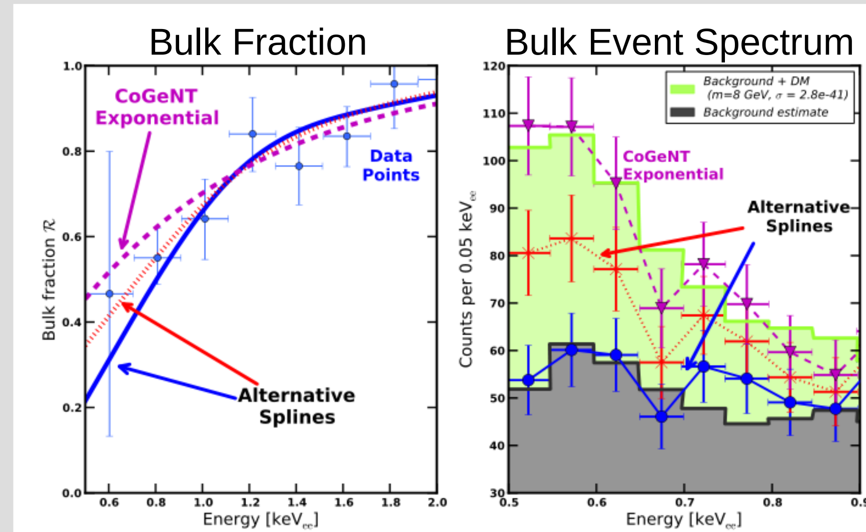
Backup

CoGeNT: excess gone

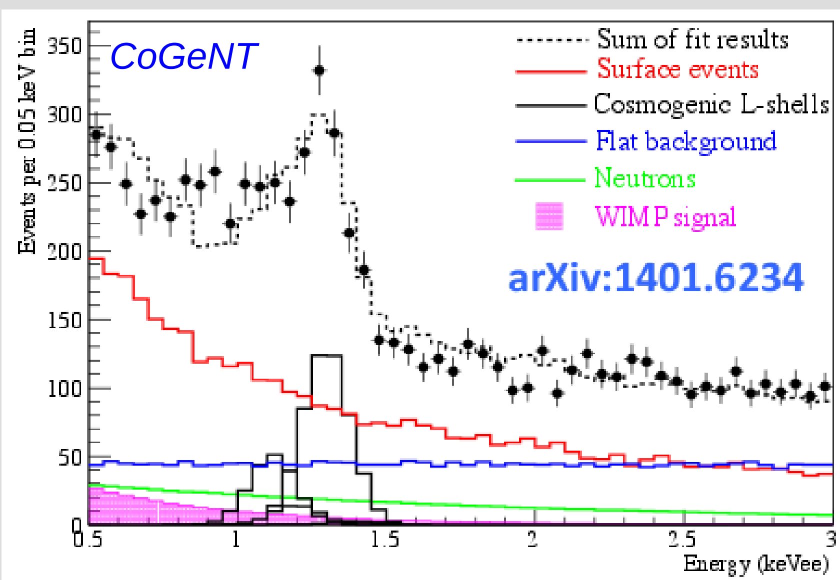


440 g HPGe p-type detector





J. Davis et al., JCAP 08, 014 (2014)



CoGeNT: NULL result excluded by 1.9σ

Kelso: best fit achieved w/o signal
(no improvement when considering streams)

Davis: detection crucially depends on equally-well motivated choices for the fraction of bulk events
→ marginalize over possibilities
→ end up with <1σ evidence

LXe: Non-WIMP Channels

- **Coherent Neutrino Nucleus Scattering**
  → not observed yet
  → 200 t×y: ~200 evts > 3 keVnr
  ~25 evts > 4 keVnr
- **Low E solar neutrinos: pp, ^{7}Be**
  → test solar model; test neutrino models
  → 1% stat. precision in 100 t x y
- **Solar axions and dark matter ALPs**
  → alternative dark matter candidates
  → couple to electrons via axio-electric effect
- **Supernova Neutrinos**
  → sensitive to all neutrino species (CNNS)
  (→ complementary information to large-scale neutrino detectors)
  → O(10) events for ~18 Msun SN @ 10 kpc
- **Neutrinoless Double-Beta Decay**
  → leption number violating process
  → access to neutrino mass, neutrino hierarchy
  → no ^{136}Xe enrichment required