Direct Dark Matter Searches – Status and Perspectives

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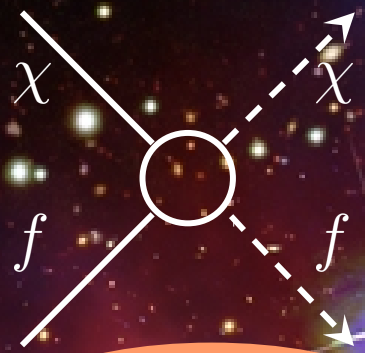
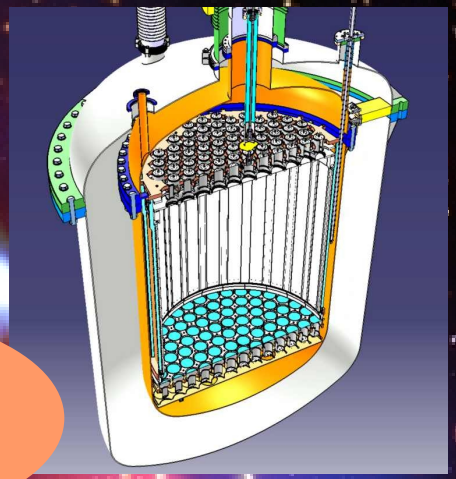
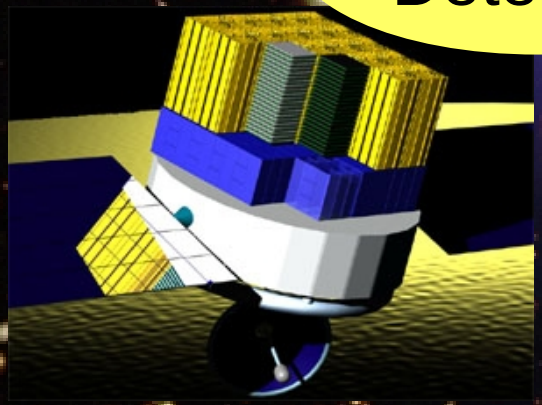
Dark Matter Search



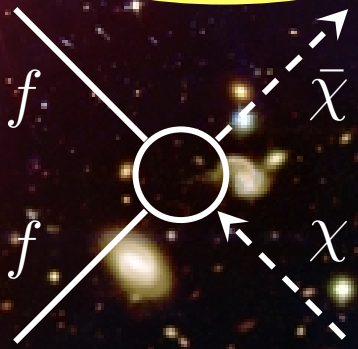


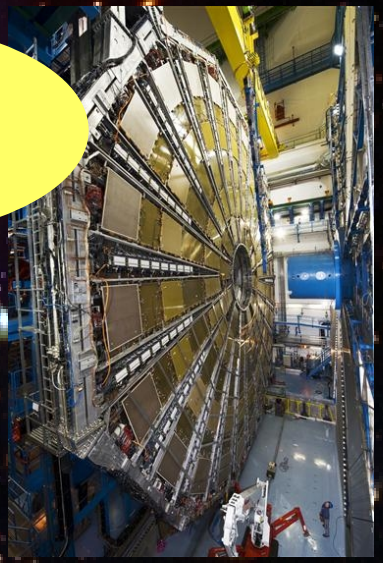
Direct Detection

Indirect Detection



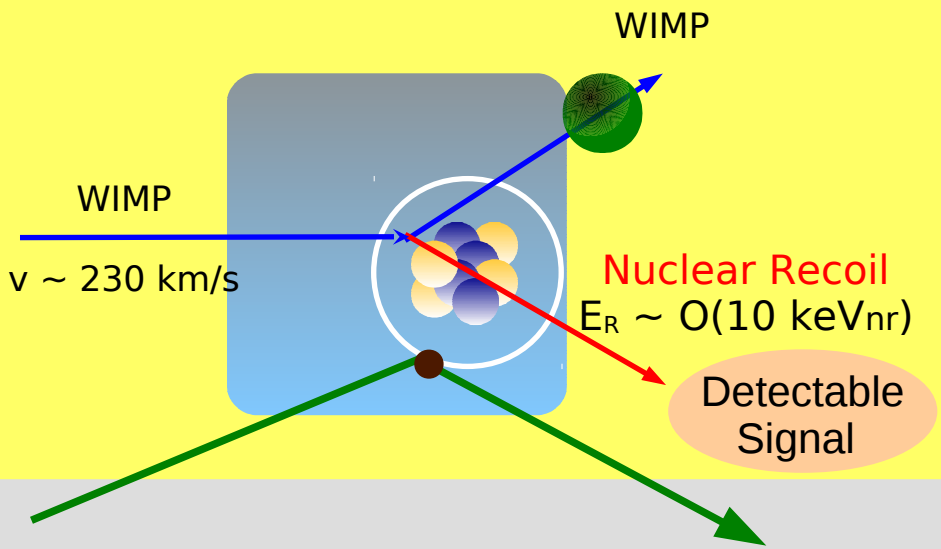
Production @Collider





Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



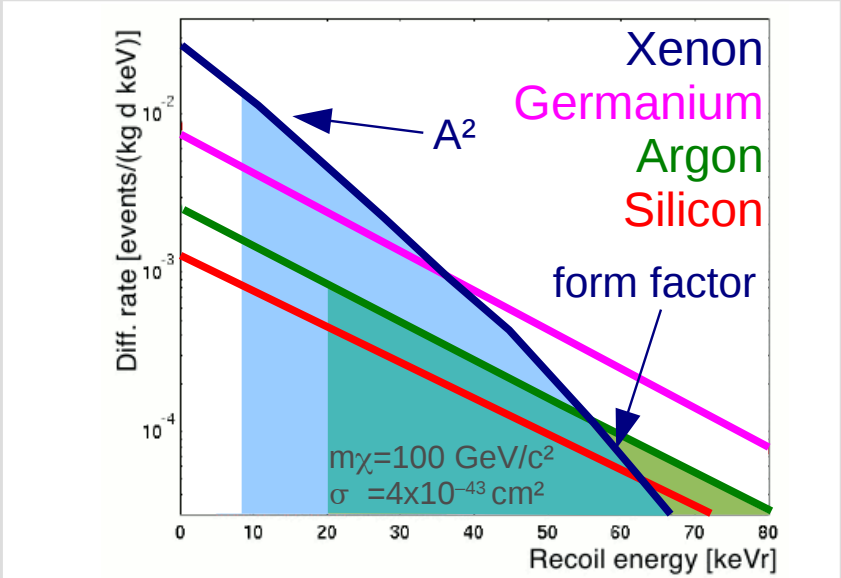
gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil** [in keVee]

Direct WIMP Search

Direct Detection:

$E_r < 100$ keV

$R < 1$ evt/kg/year



Recoil Energy: $E_r \sim \mathcal{O}(10\ \mathrm{keV})$

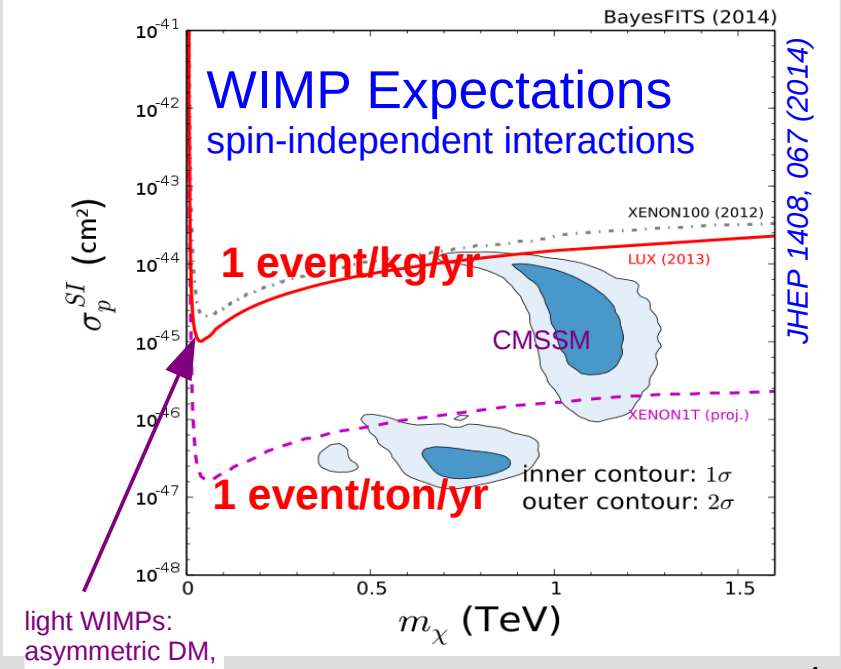
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

Detector

Local DM Density

ρ_χ~0.3 GeV/c^2

Physics



light WIMPs: asymmetric DM, sneutrinos, ...

Direct WIMP Search

Direct Detection:

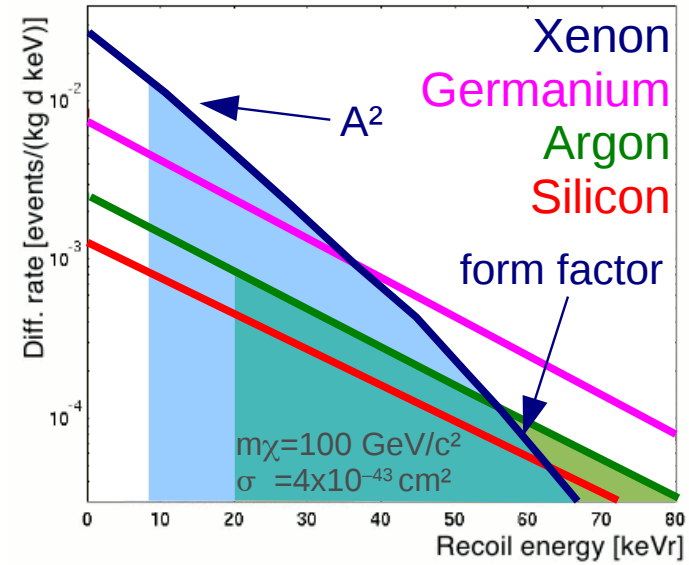
$E_r < 100$ keV
$R < 1$ evt/kg/year

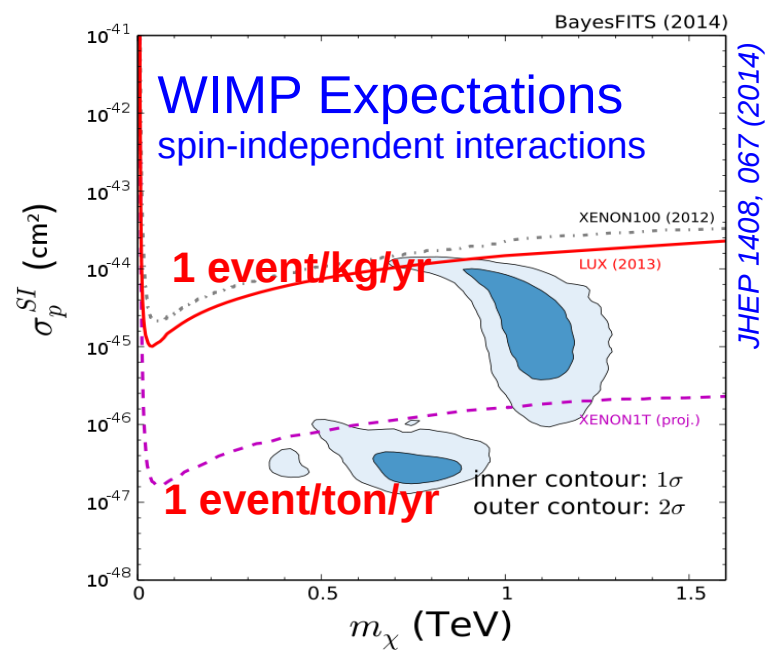
How to build a WIMP detector?

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

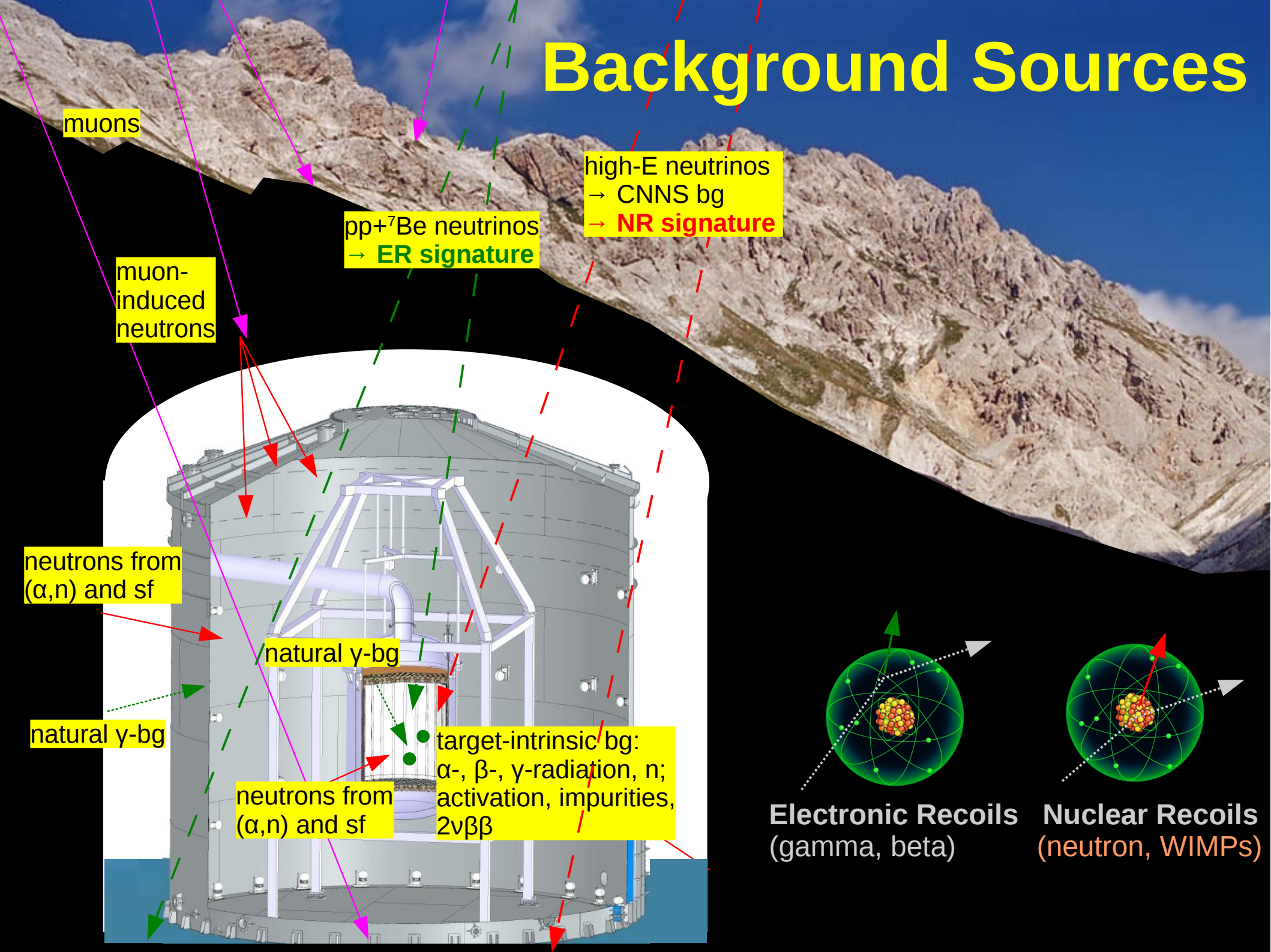
We are dealing with

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





Background Sources



Background Suppression

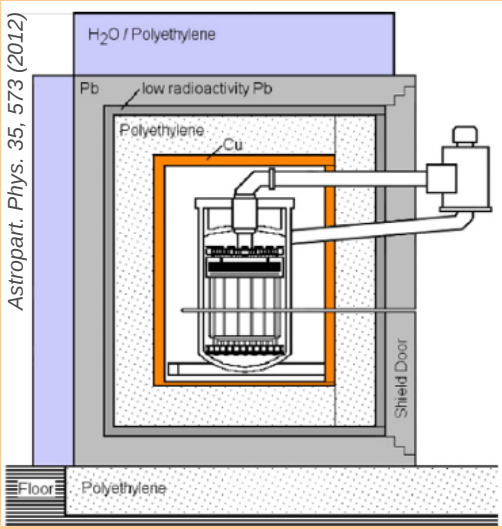
Avoid Backgrounds

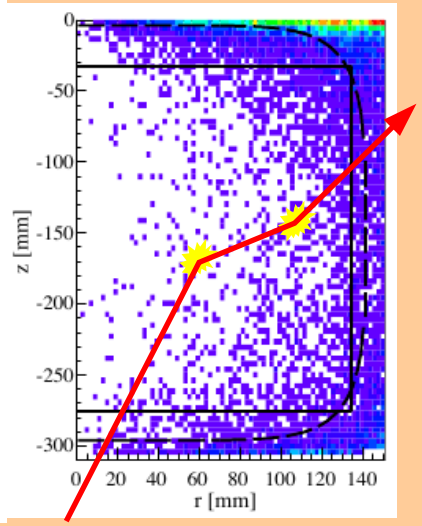
Shielding

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

self shielding → fiducialization

Use of radiopure materials





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*/d*x* from signal and background

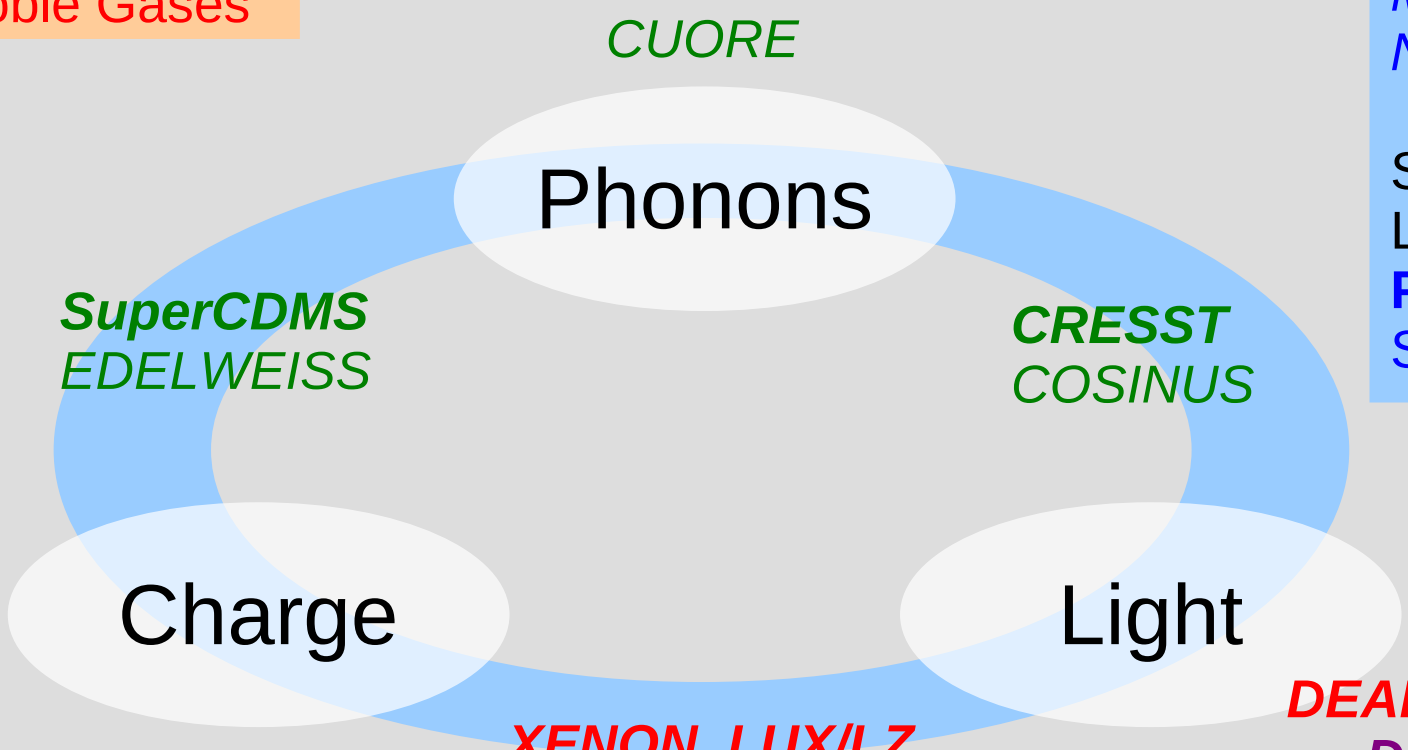
Examples:
- scintillation pulse shape
- charge/light ratio
- ionization yield

Direct WIMP Detection

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

Tracking:
DRIFT, DMTPC
MIMAC, NEWS
NEWAGE

Superheated Liquids:
PICO
SIMPLE



CUORE

SuperCDMS
EDELWEISS

CRESST
COSINUS

CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

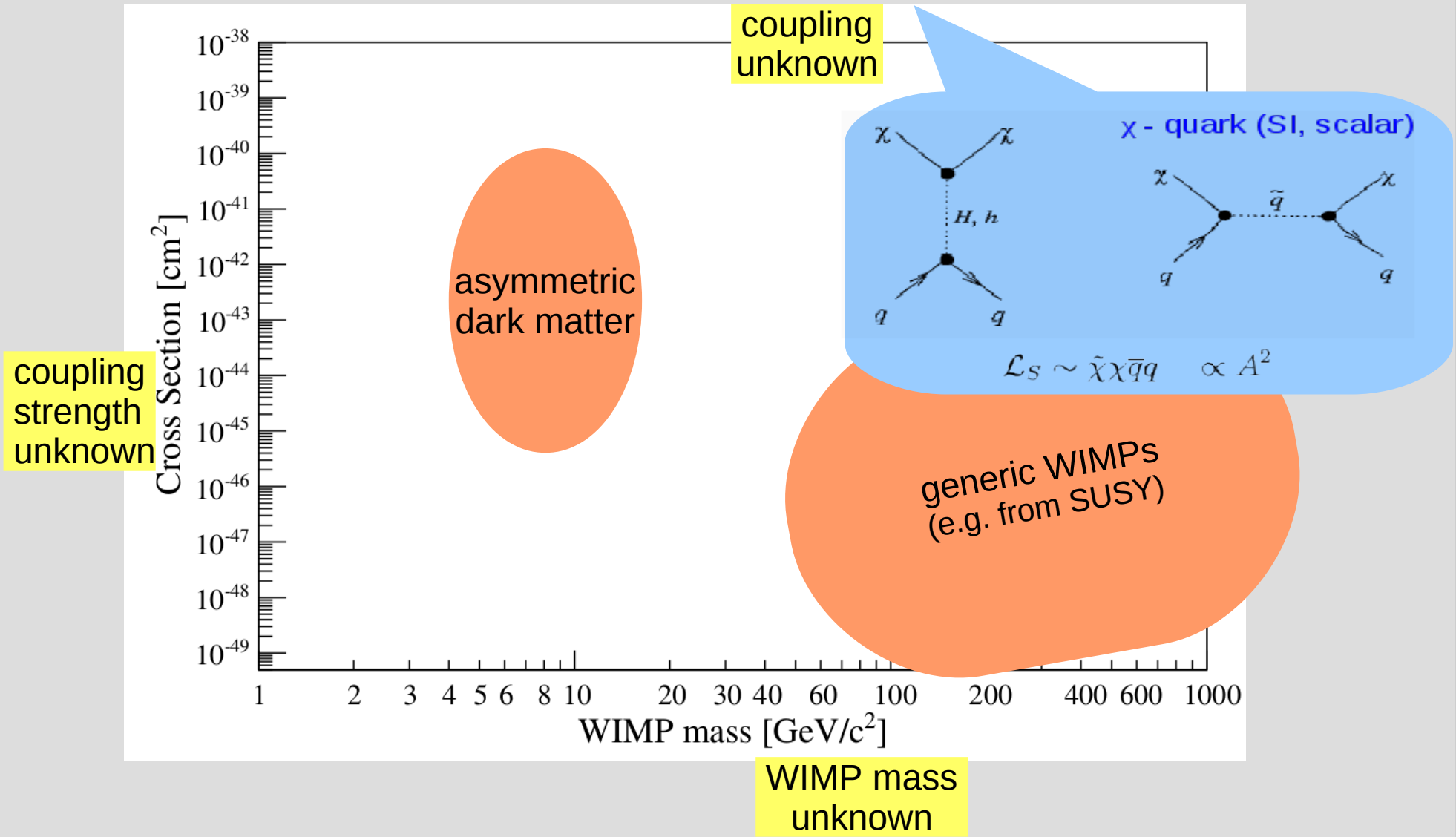
XENON, LUX/LZ
ArDM, ***Panda-X***
DarkSide, DARWIN

DEAP-3600*, CLEAN*
DAMA*, KIMS*
XMASS*, COSINE*
ANAIS, ***SABRE***

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

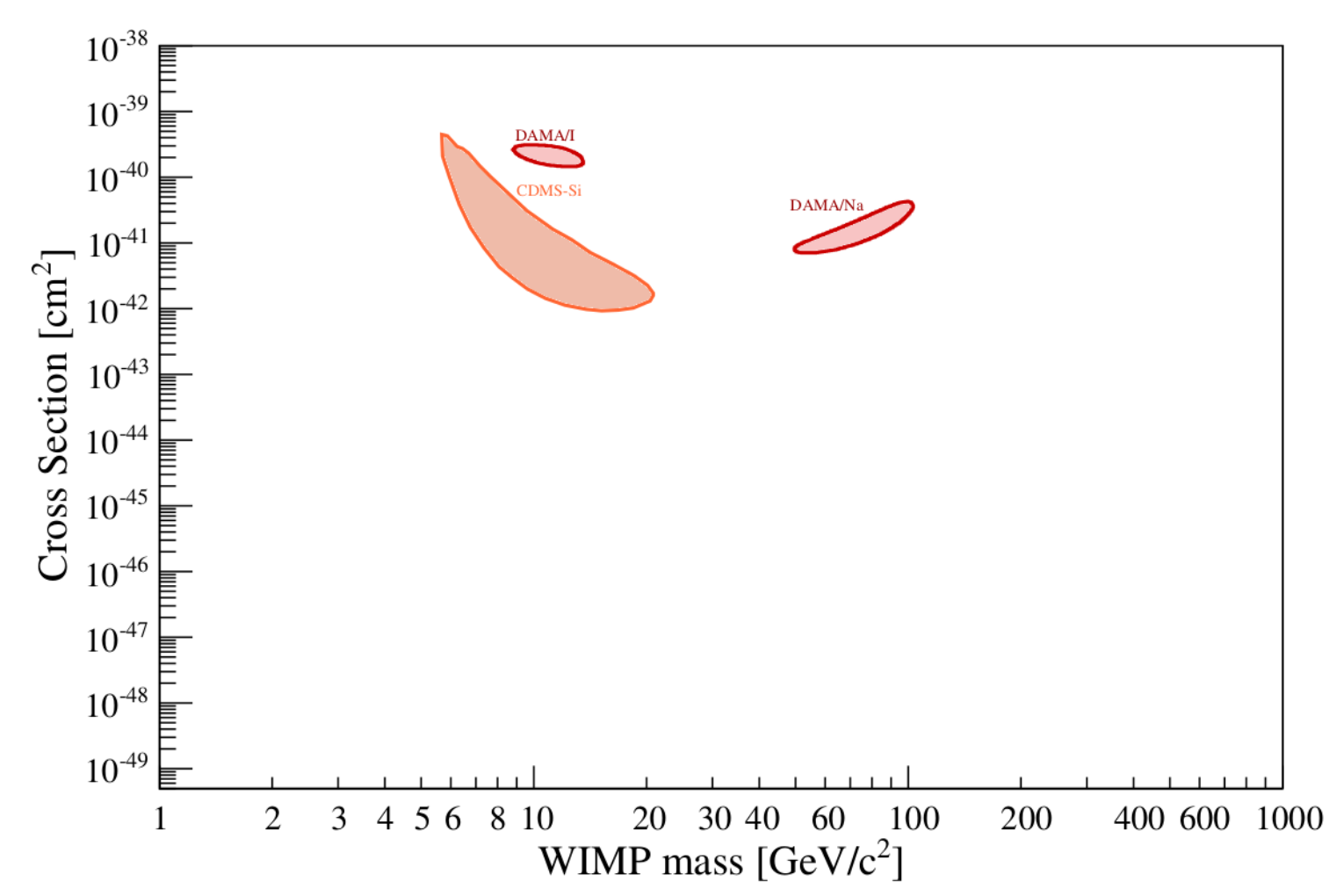
The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



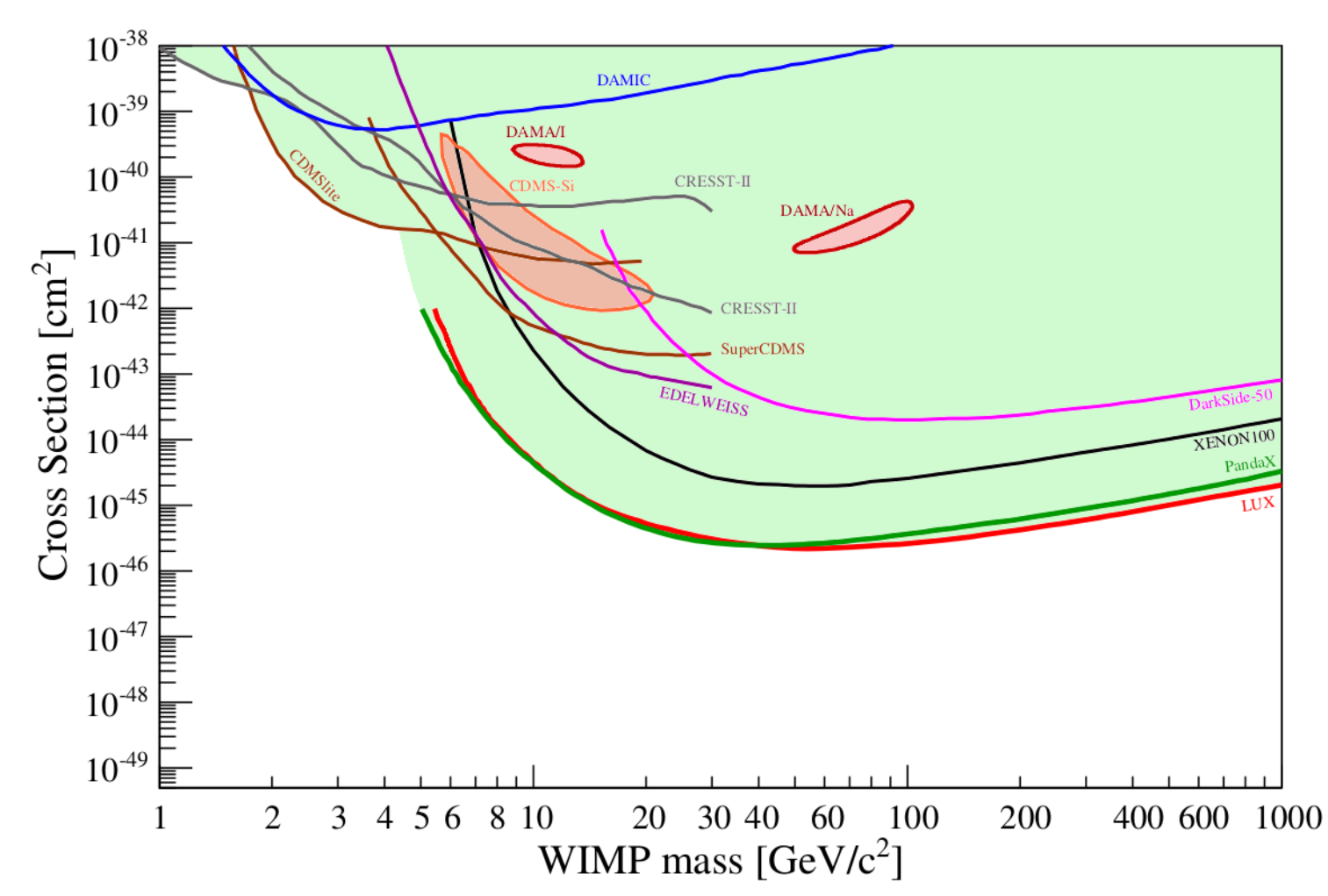
Detections?

spin-independent WIMP-nucleon interactions



Exclusions?

spin-independent WIMP-nucleon interactions

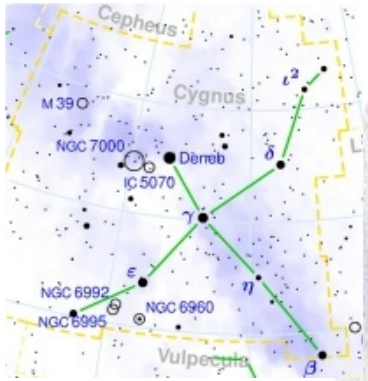


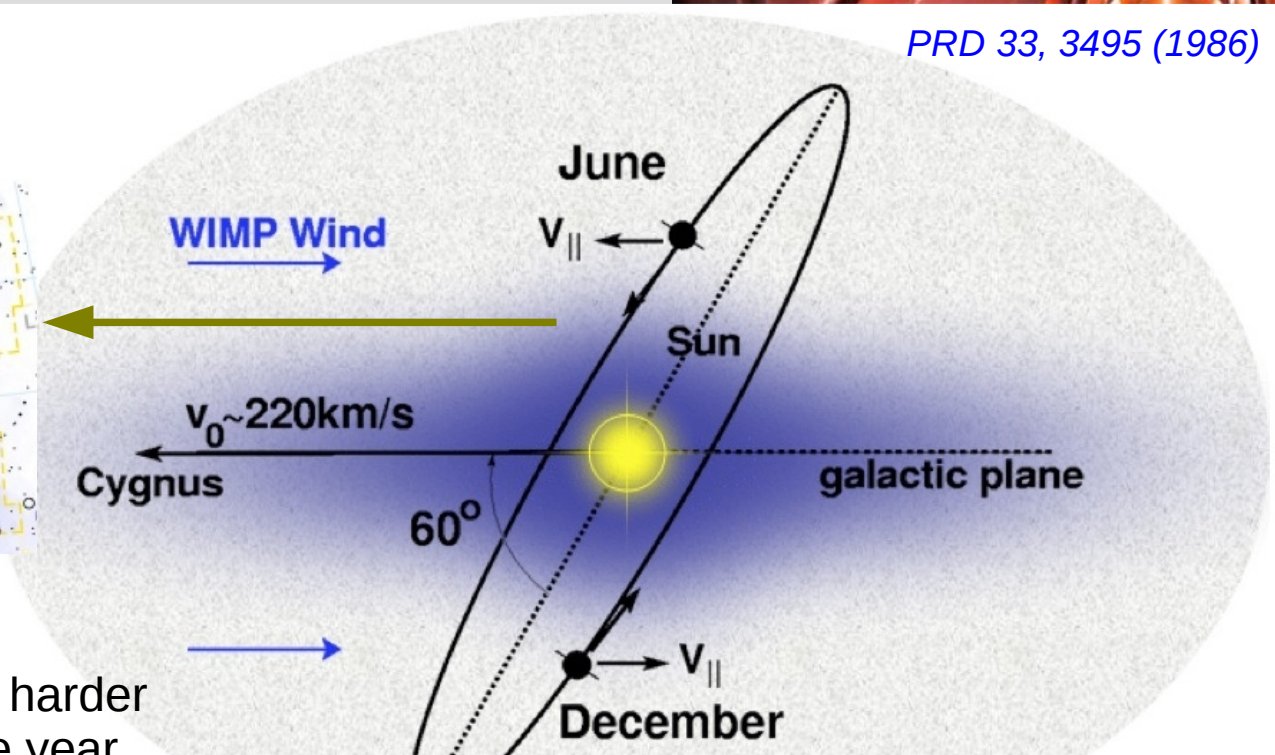
some results are missing...

Annual Modulation: DAMA/Libra

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

PRD 33, 3495 (1986)





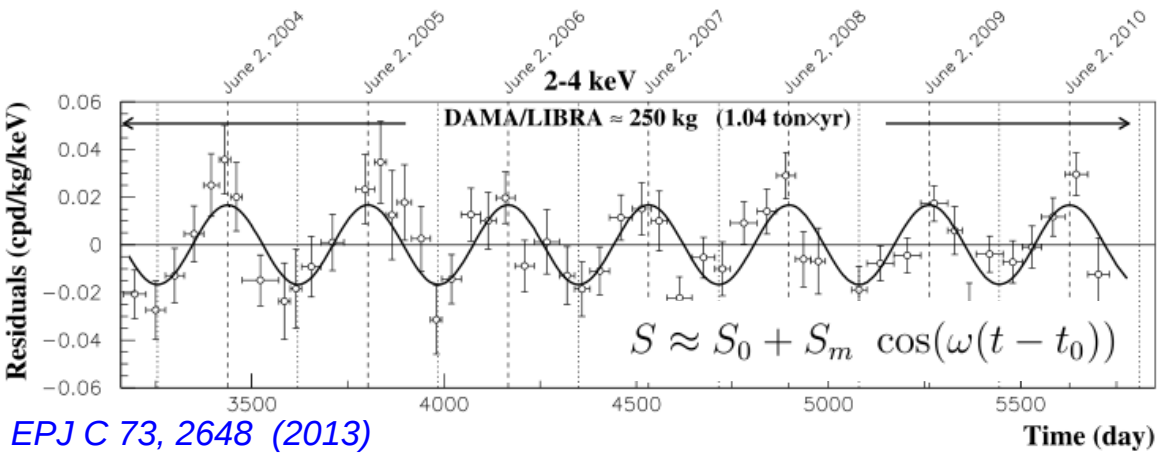
$$\frac{dR}{dE_{nr}} = \frac{\rho_0\, M}{m_{Xe}\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_{nr}}\, dv$$

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

Annual Modulation: DAMA/Libra

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

- DAMA finds annual modulation @ **9.3σ CL**
- BUT: no ER/NR discrimination!



EPJ C 73, 2648 (2013)

interpretation as (spin-(in)dependent, inelastic) WIMP-nucleon scattering challenged by many experiments

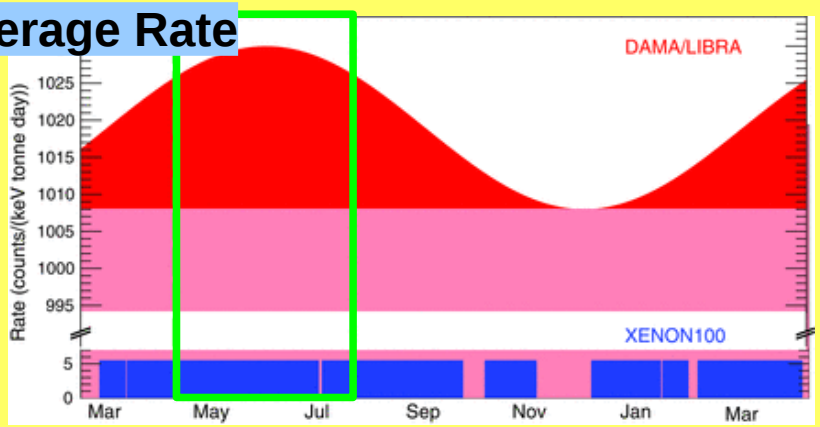
Reconcile DAMA/Libra with the null-results from other experiments assuming **leptophilic** dark matter?
→ DAMA might see electronic recoils

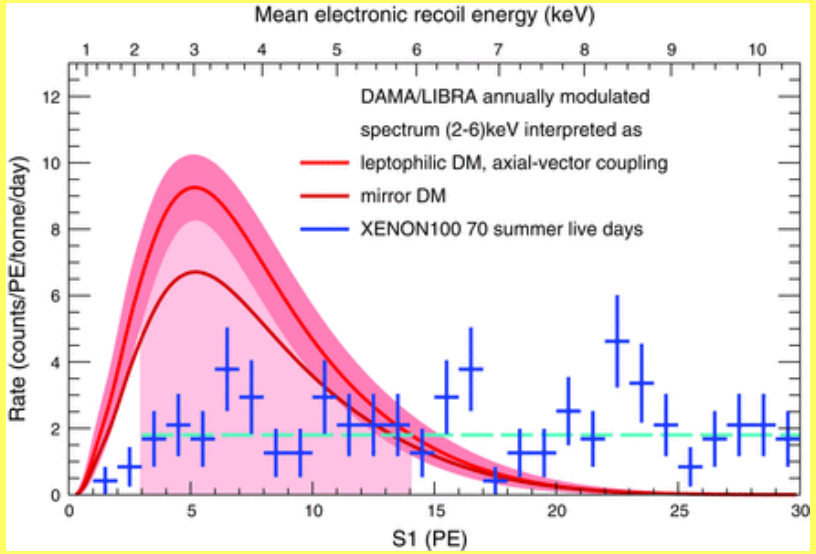
Examples:
Axial-vector couplings:
Kopp et al., PRD 80, 083502 (2009)
Changet al., PRD 90, 015011 (2014)
Bell et al., PRD 90, 035027 (2014)
Mirror dark matter:
Foot, Int.J.Mod.Phys. A29, 1430013 (2014)
Luminous dark matter:
Feldstein et al., PRD 82, 075019 (2010)

DAMA vs XENON

Science 349, 851 (2015) *PRL 115, 091302 (2015)*

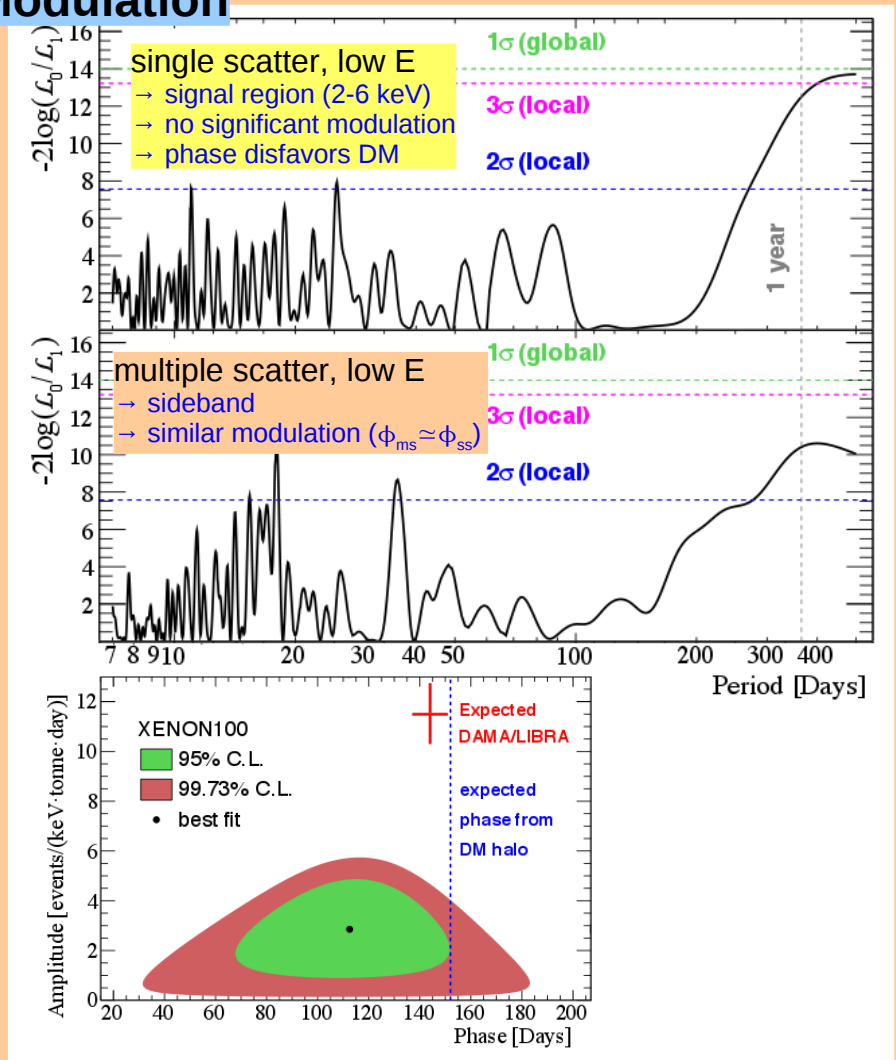
Average Rate





XENON100 excludes DAMA as being due to
– WIMP-e⁻ axial-vector couplings at **4.4σ**
– luminous dark matter at **4.6σ**
– mirror dark matter at **3.6σ**

Modulation



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

New NaI Projects to test DAMA

aim at testing the DAMA claim using the same target/detector

→ main challenges: crystal purity, low threshold, target mass

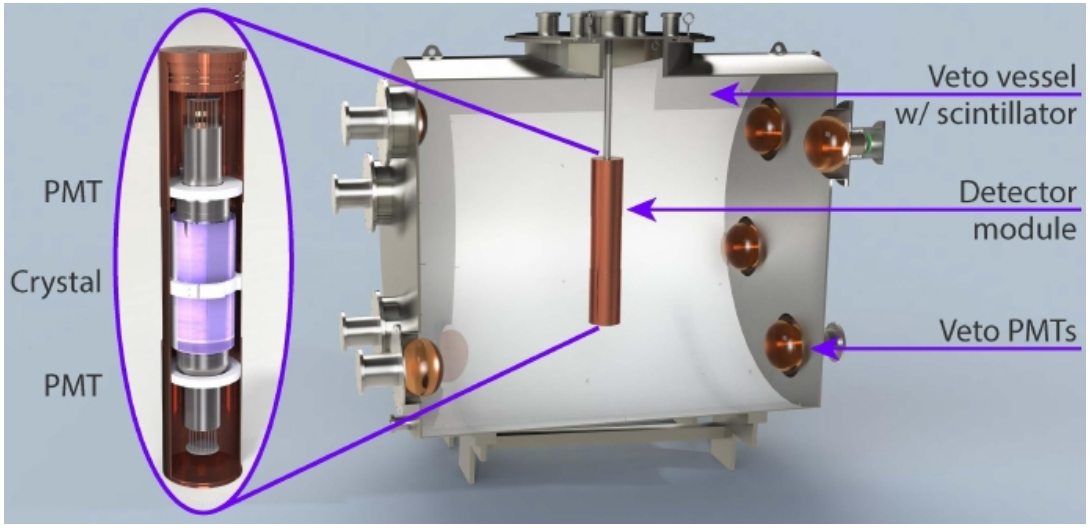
SABRE *P. Urquio (COSMO 2016)*

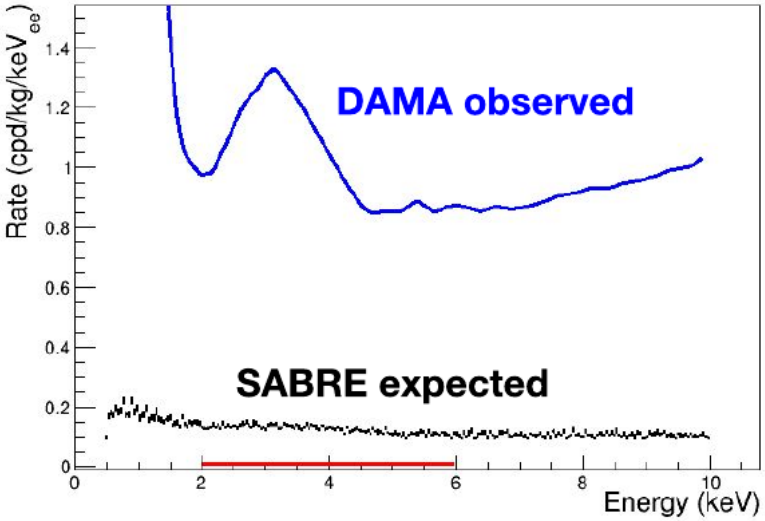
*S*odium-iodine with *A*ctive *B*ackground *RE*jection

Strategy:

- lower background: better crystals ✓, PMTs
- liquid scintillator veto against ^{40}K (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- North (LNGS) and South (Australia)

- *Status*: tests with 5 kg crystals ongoing at LNGS





DM-Ice: 17 kg @ South Pole
arxiv:1602.05939

COSINE = KIMS+DM-Ice
~100 kg @ Yangyang → start soon

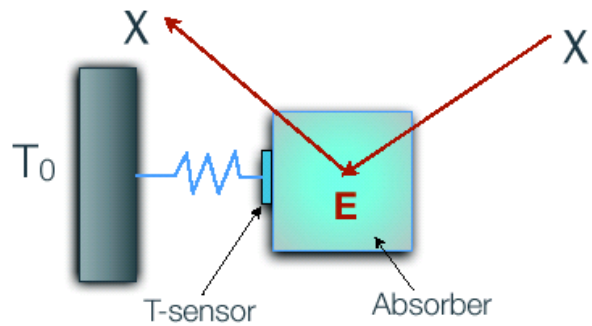
ANAIS: 112 kg @ Canfranc
→ background ~2-3x DAMA

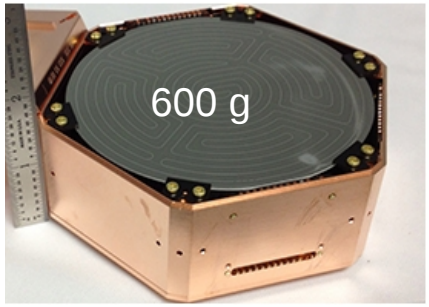
COSINUS R&D: *EPJ C 76, 441 (2016)*
NaI with bolometric+light readout

Cryogenic Detectors

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

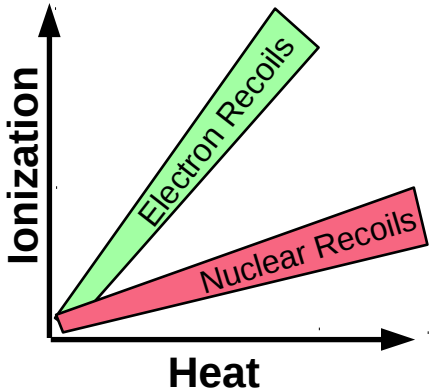
→ requires detecors at mK temperatures





Crystals: **Ge**, **(Si)** cooled to few mK
– low heat capacity
– $\Delta T \sim \mu K$ (→ TES)

Very good discrimination
→ BUT: need to reject surface events

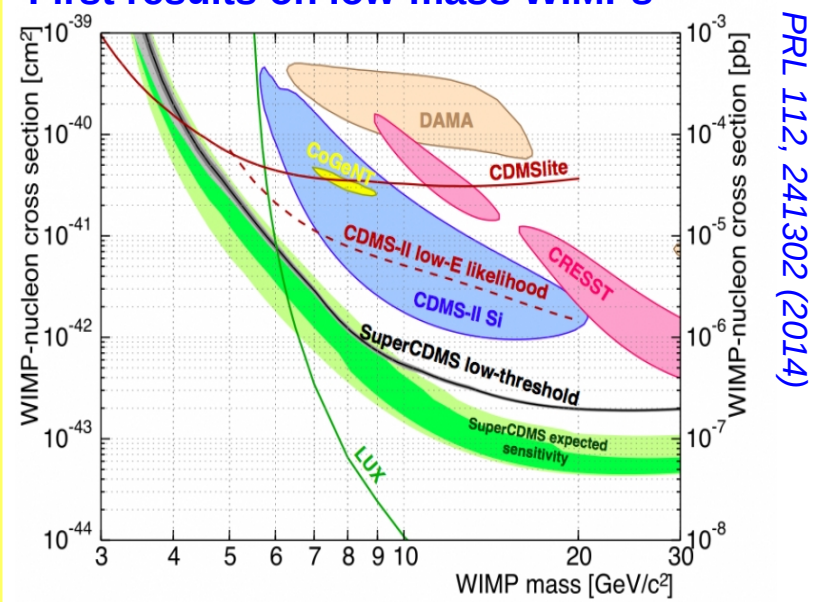


EDELWEISS (Modane)
→ new low-mass limit *arXiv:1607.03367*

SuperCDMS @ SNOLAB

- selected by NSF-DOE downselection
- ~50 kg (upgrade to 400 kg possible)
- low threshold
  → focus on 1-10 GeV/c² mass range
- deeper lab, better materials & shield, improved resolution, electronics, ...
- 100 x 33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si)

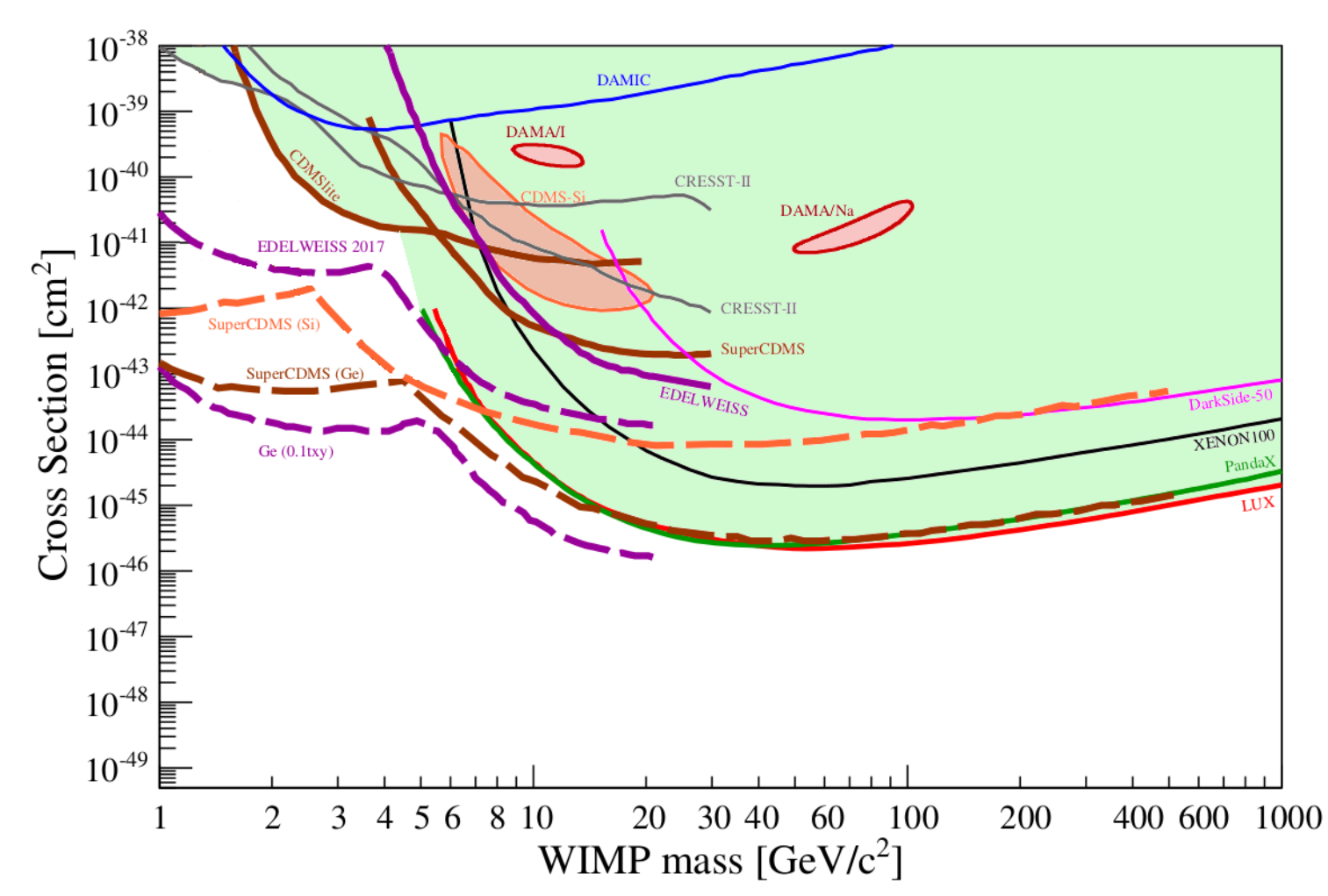
First results on low-mass WIMPs



PRL 112, 241302 (2014)

Ge / Si: Status and Prospects

spin-independent WIMP-nucleon interactions

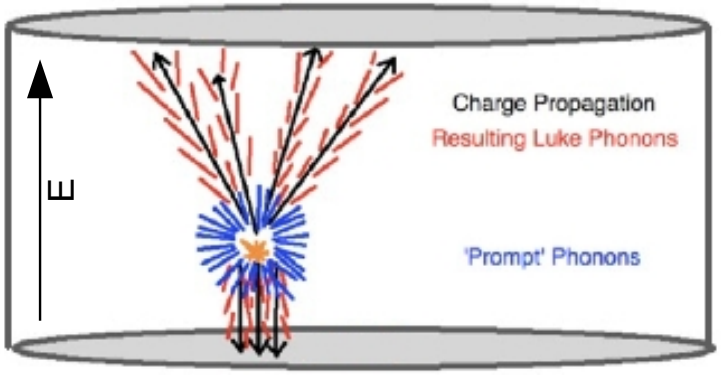


some projects are missing...

Very low WIMP masses

Exemely low threshold for sensitivity to very low-mass WIMPs:
amplify signal → HV operation: **Neganov-Luke effect** to amplify charge signal

convert work done by E-field on e^--hole pairs to phonons



$$E_{tot} = E_r + E_{luke}$$
$$= E_r + n_{eh} e V_b$$
$$= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)$$

bias voltage

initial recoil

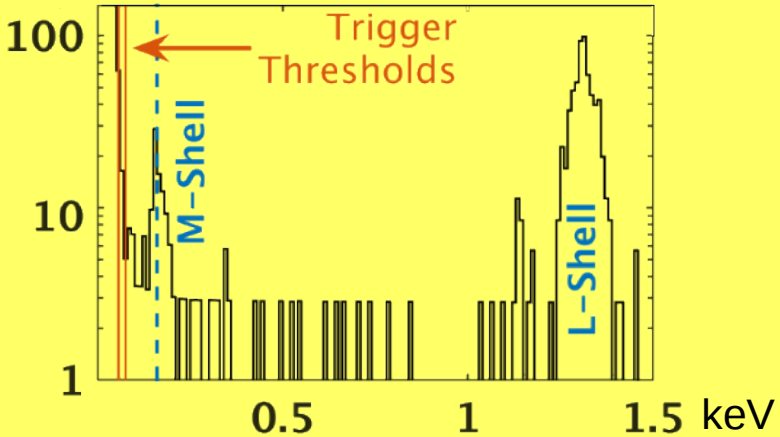
3 eV/pair

EDELWEISS plans:
2017:
350 kg×d in HV mode
afterwards:
join forces with CDMS

SuperCDMS plans:
2018-20: construction
2020: begin data taking

CDMSlite *PRL 116, 071301 (2016)*

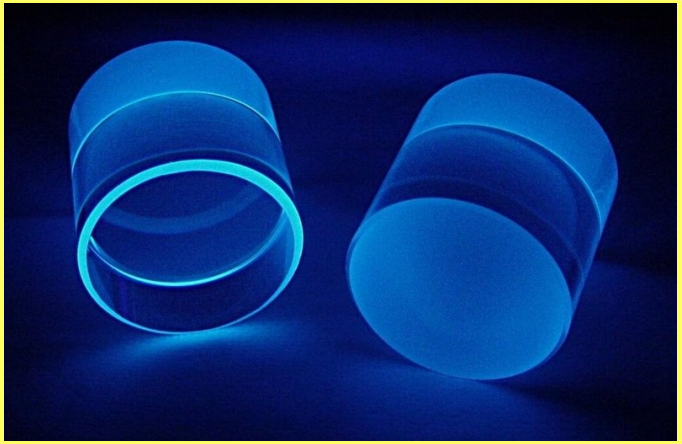
- 625 g iZIP detector, 70 kg×d exposure
- V_b=69 V, **56 eV_{ee} threshold!** 14 eV_{ee} resolution
- no ionization measured
  → no ER rejection

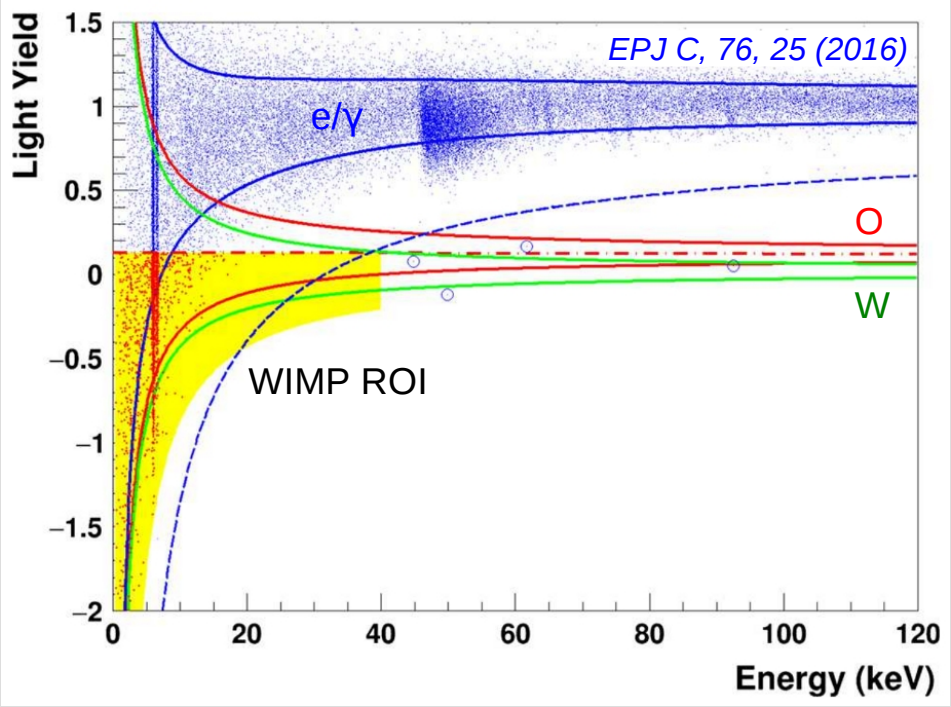


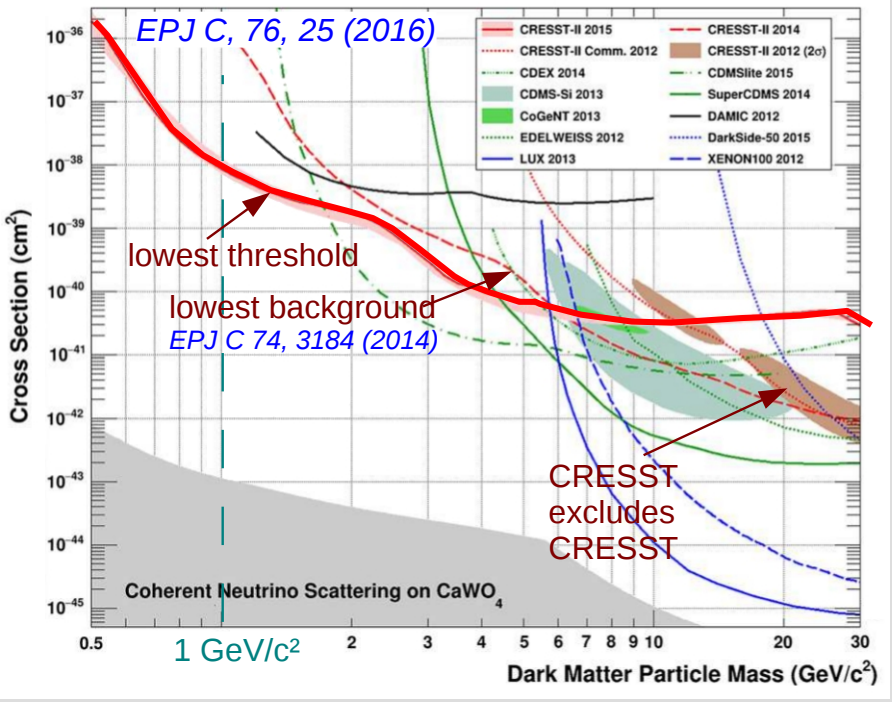
CRESST: the low-mass record

CRESST-II @ LNGS

- read phonons and scintillation light
- target: $CaWO_4$ → multi-element material
- successful background reduction;
  data taking 2013-2015, 52 kg×d
- new result *EPJ C, 76, 25 (2016)*
  detector with **300 eVnr** threshold







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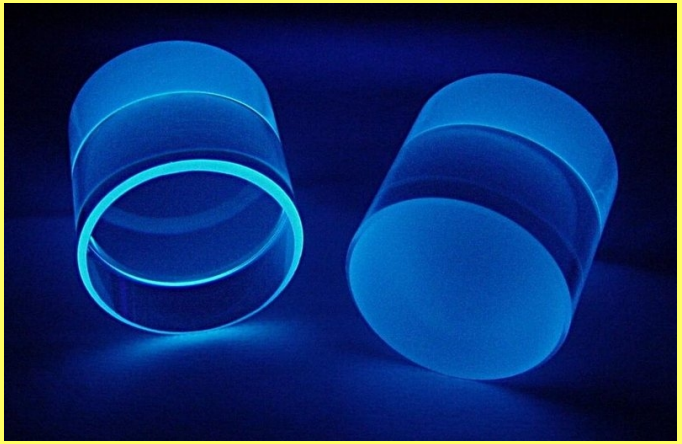


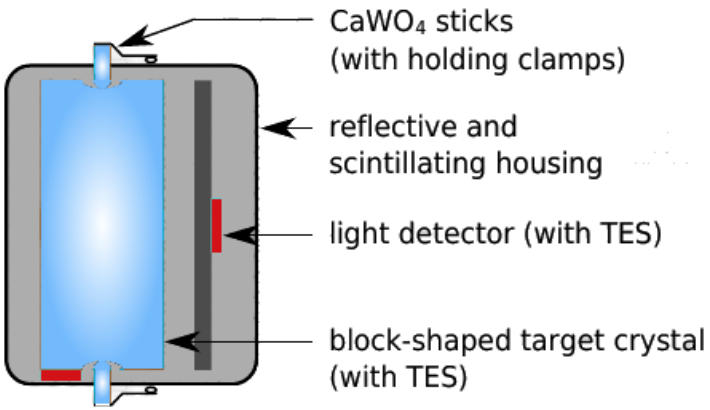
CRESST-III: lower threshold to 100 eV$_{nr}$

arXiv:1503.08065

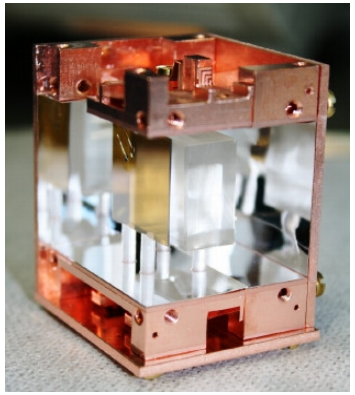
- smaller crystals (250 g → 24 g)
- all-scintillating detector design
  → avoid partial energy depositions
- improve signal-to-noise

Status:

- Prototype exceeds design goal:
  50 eV$_{nr}$ threshold
- commissioning and
  calibration started July 2016

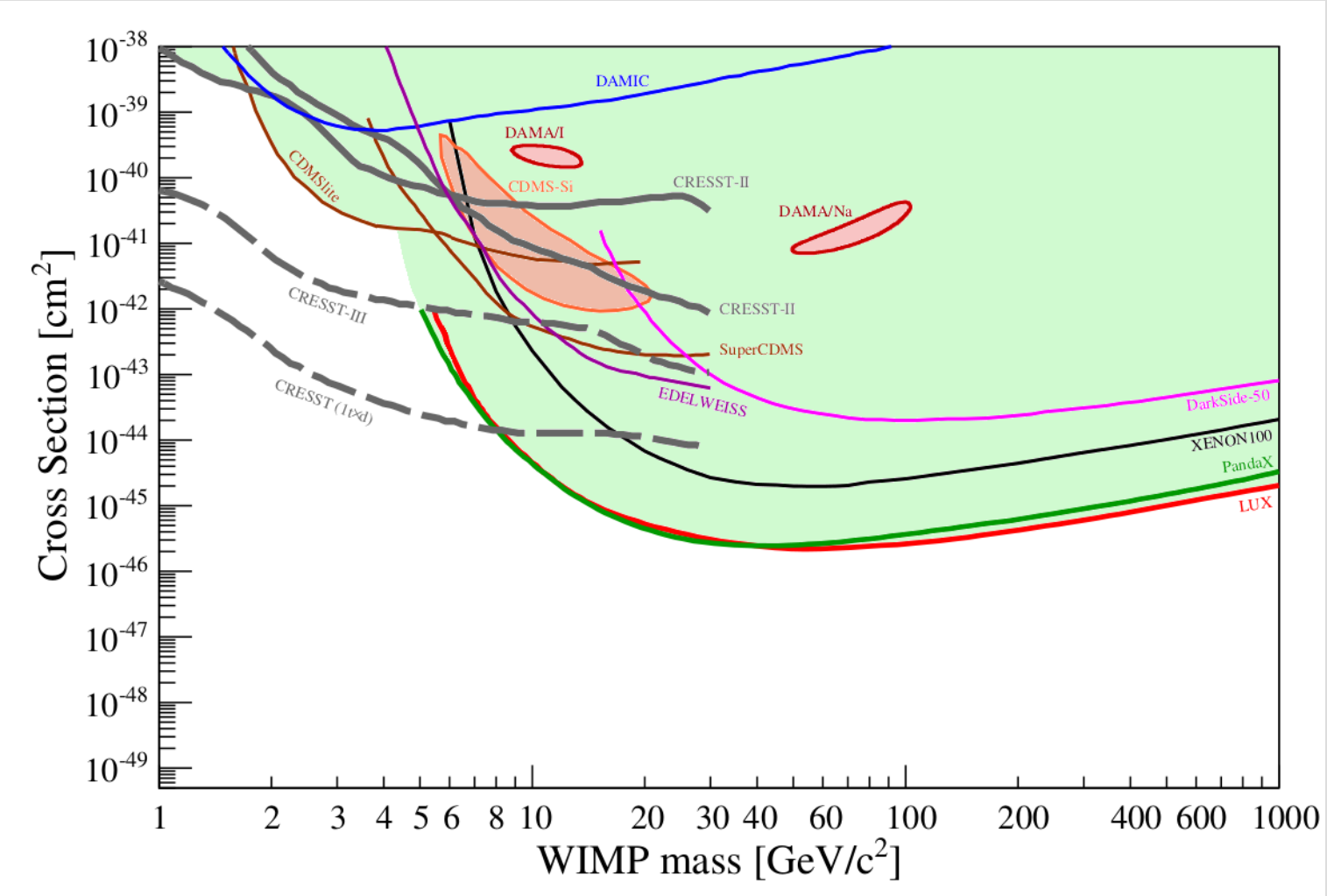


Reindl @ Lake Louise 2016



CRESST: Status and Prospects

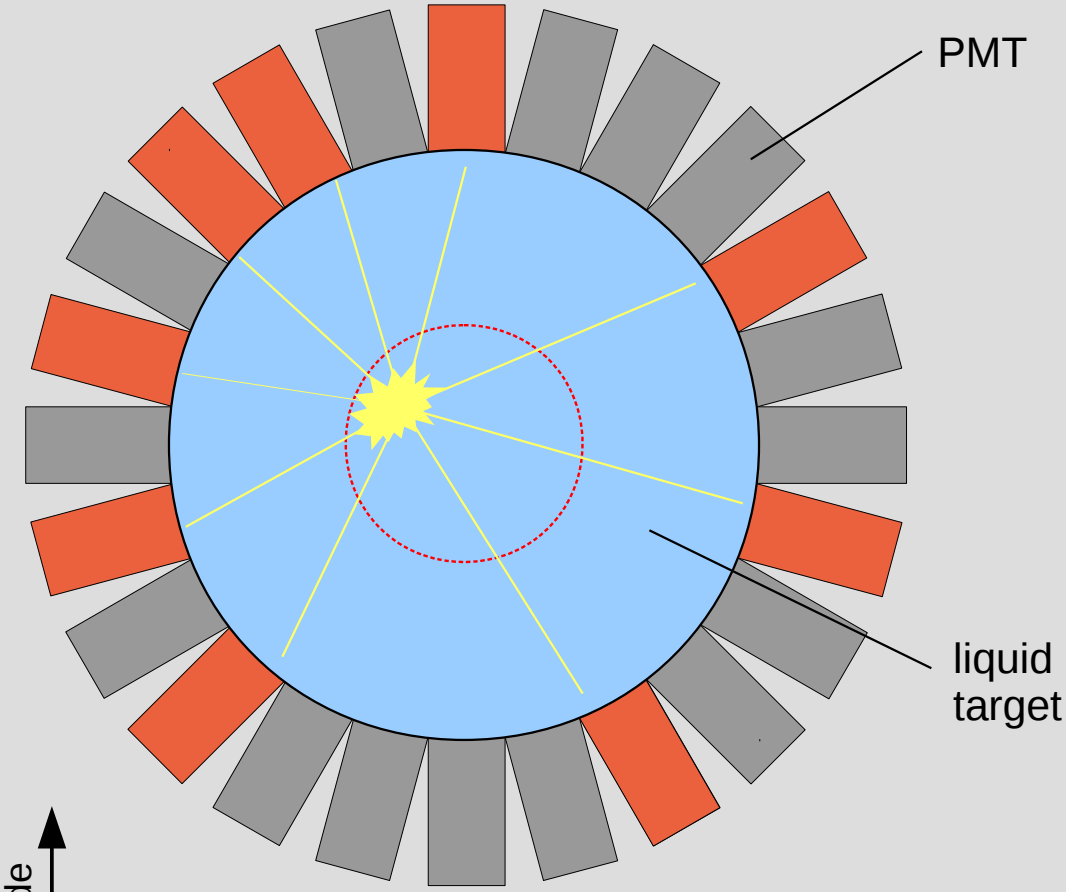
spin-independent WIMP-nucleon interactions

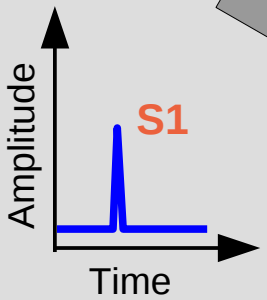


some projects are missing...

Liquid Noble Gases: Detector Concepts

Single Phase Detector





+ no high voltage, very high light yield

– O(cm) resolution, no double scatter rejection

Noble Gas: Single Phase Detectors

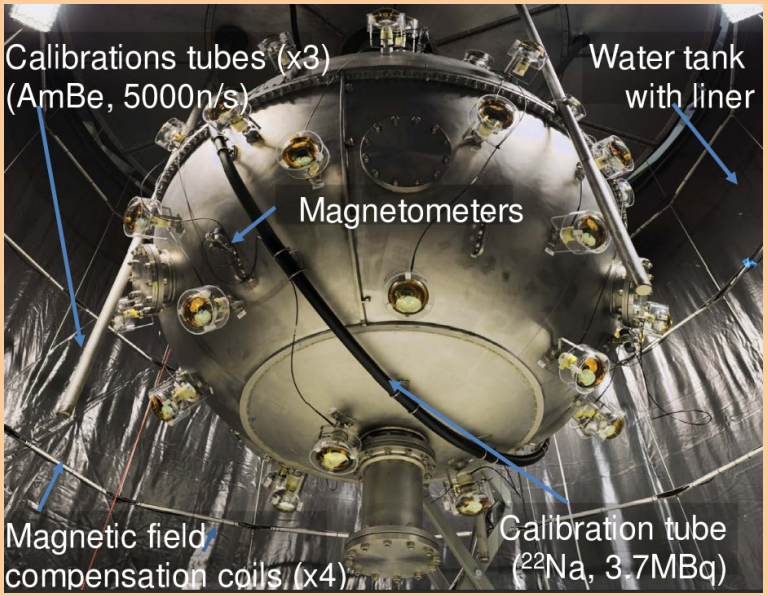
XMASS @ Kamioka (JP) **LXe**

– **832 kg** LXe target, 642 PMTs
– very high light yield, low threshold (0.5 keV$_{ee}$)
  BUT: **no possibility to reject NRs**
– many results: summary: *arXiv:1506.08939*

– background reduced after commissioning run
  → stable data taking since >2 years
– plans towards XMASS-1.5t and XMASS-II (24t)

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

– **3.6t** liquid argon target;
  high ^{39}Ar background when using ^{nat}Ar (~1 Bq/kg)
– filled with LAr since a few weeks
  start data taking...
– sensitivity: 1×10^{-46} cm² @ 100 GeV/c²
– **light pulse-shape for discrimination**
  3×10^{-8} achived in 43-86 keV$_{ee}$
  → prediction: 10^{-10} above 15 keV$_{ee}$ in DEAP-3600



F. Retiere (LIDINE 2015)

Noble Gas: Single Phase Detectors

XMASS @ Kamioka (JP) **LXe**

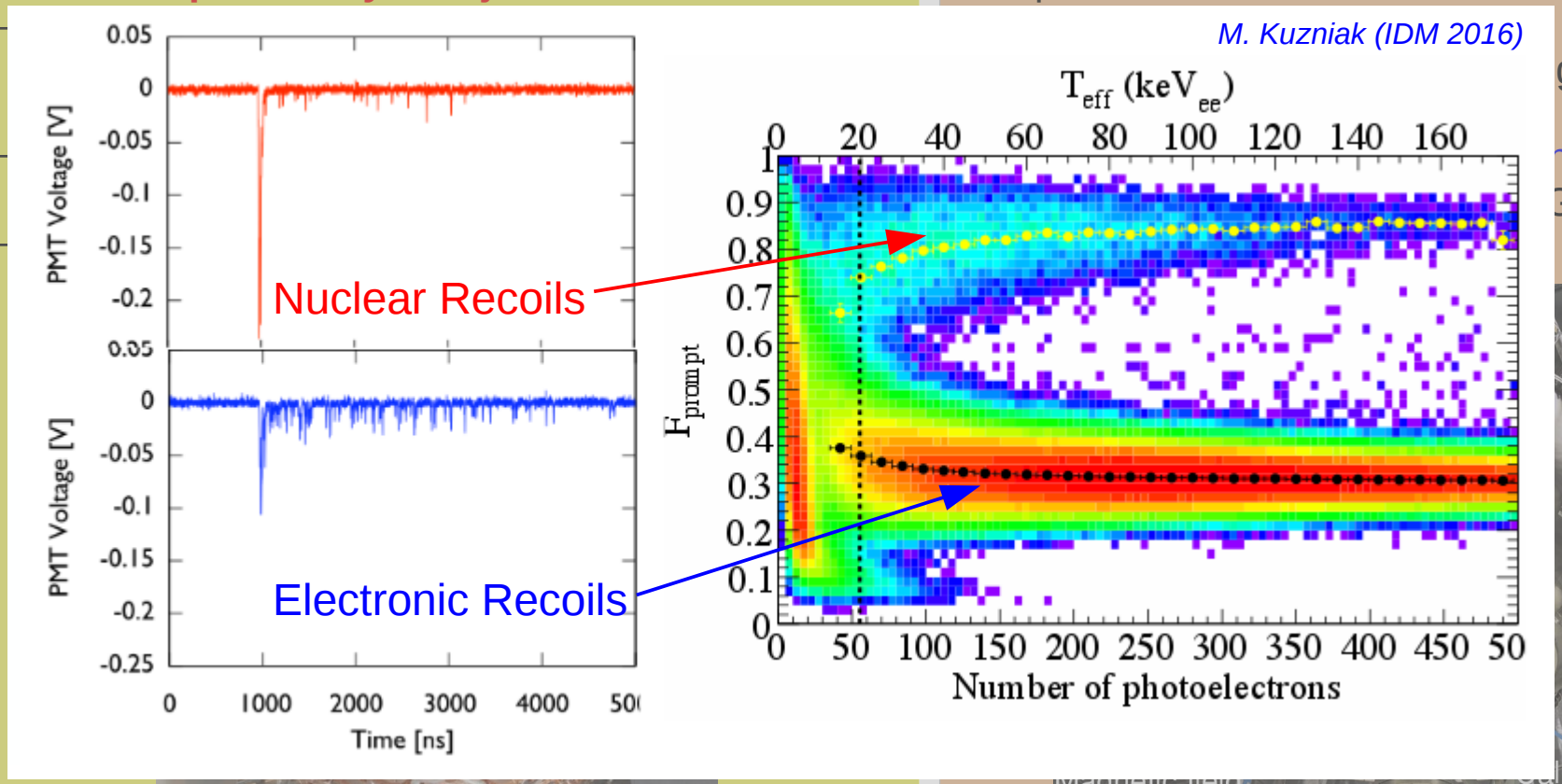
– 832 kg LXe target, 642 PMTs
– very high light yield, low threshold (0.5 keVee)
BUT: **no possibility to reject NRs**

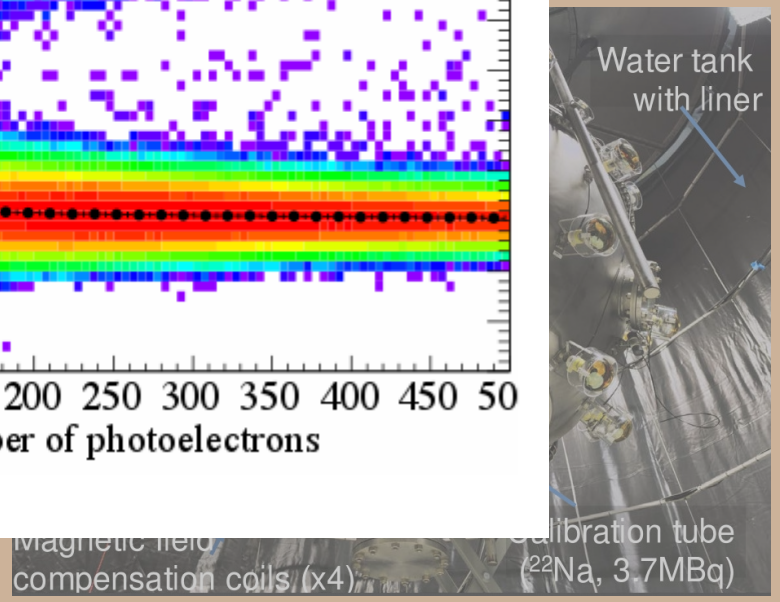
DEAP-3600 @ SNOLAB (CA) **LAr**

– **light pulse-shape for discrimination**
3×10^{-8} achived in 43-86 keVee
→ prediction: 10^{-10} above 15 keVee in DEAP-3600

g ^{nat}Ar (~1 Bq/kg)

n LAr...
GeV/c²

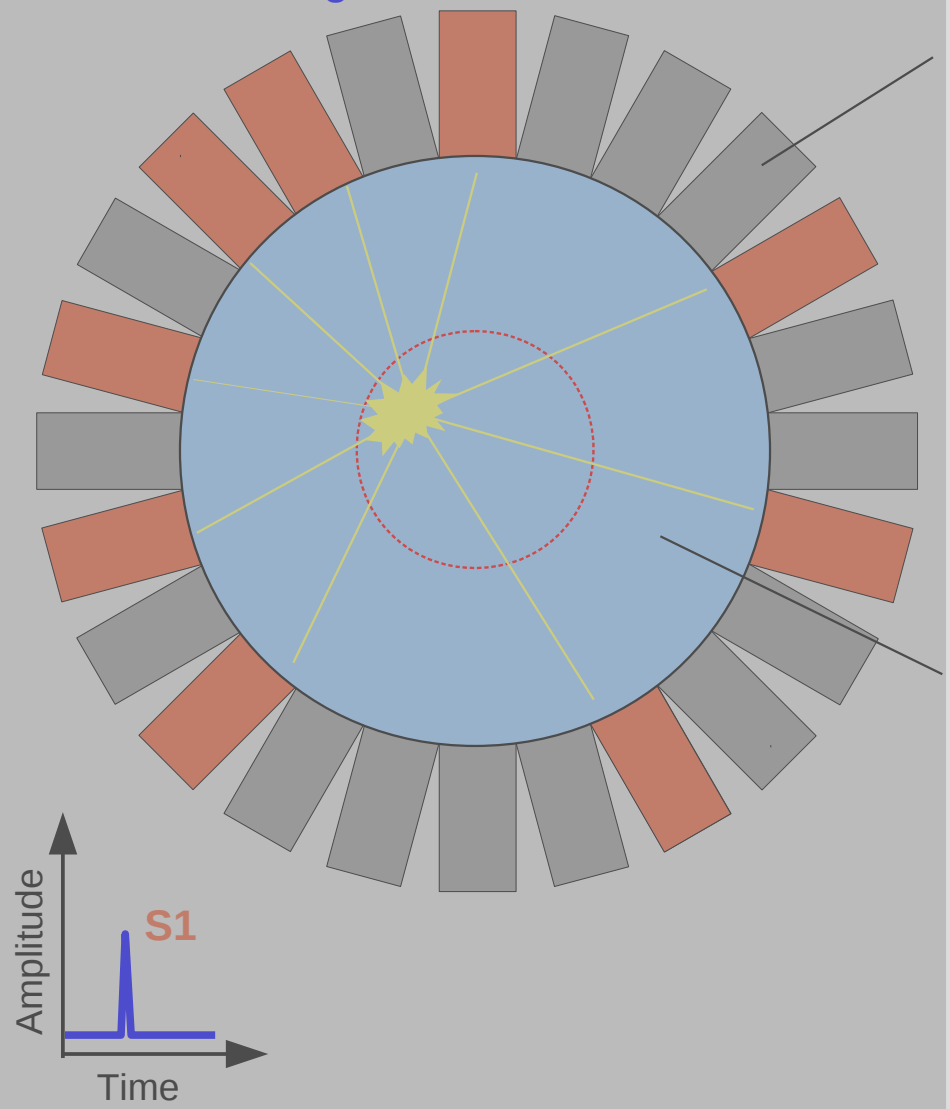




F. Retiere (LIDINE 2015)

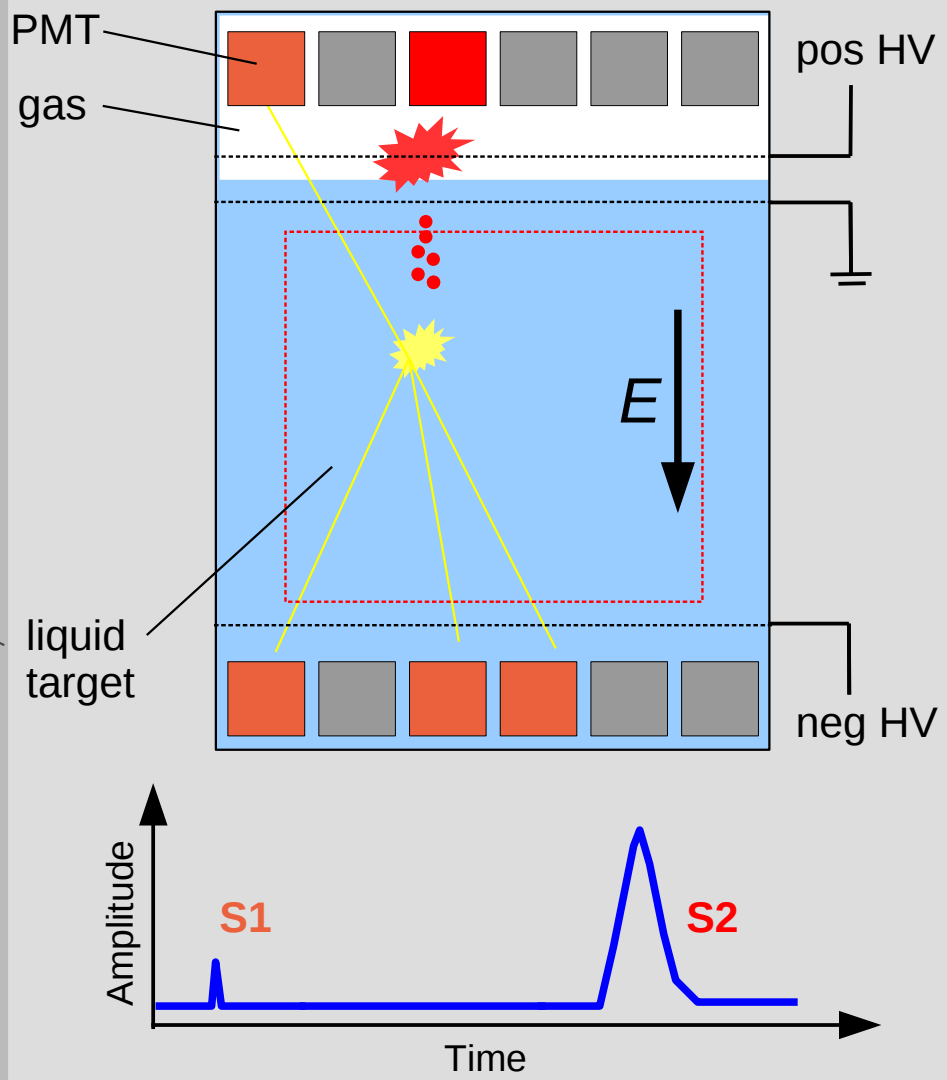
Liquid Noble Gases: Detector Concepts

Single Phase Detector



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

Time Projection Chamber



+ O(mm) resolution, S2/S1 NR rejection
– technical challenges (HV), less light

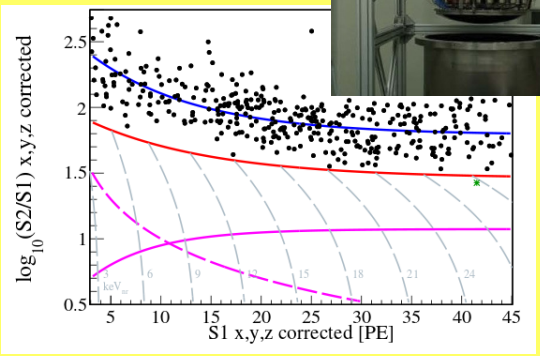
Existing dual phase detectors

LXe

PandaX-II @ CJPL (CN)
arXiv:1607.07400

- 60cm×60cm, **500 kg** target
- 2nd largest operational LXe TPC

New result July 2016:
- combines data from 2 runs (^{85}Kr differs by factor 10)
- 3.3×10^4 kg×d = 0.1 t×y exposure
- no signal excess
- best limit above ~4.5 GeV/c²
- taking more data

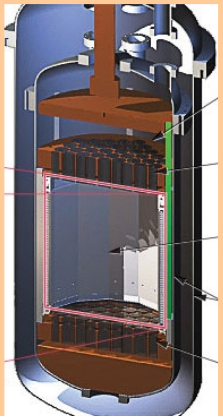


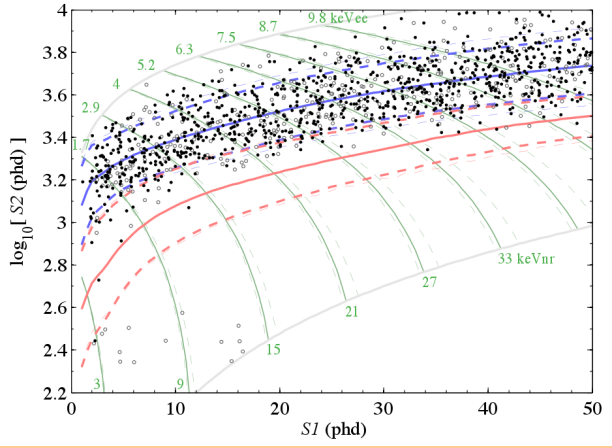
LXe

LUX @ SURF (USA)
arXiv:1608.07648

- 48cm×48cm, **251 kg** target
- in-situ NR calibration studies *arXiv:1608.05381*

New result July 2016:
- 332d exposure: 3.4×10^4 kg×d = 0.1 t×y
- no signal excess
- 2.2×10^{-46} cm² @ 50 GeV/c²



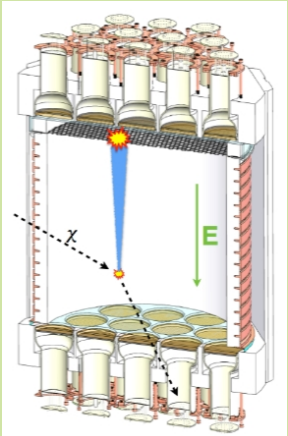


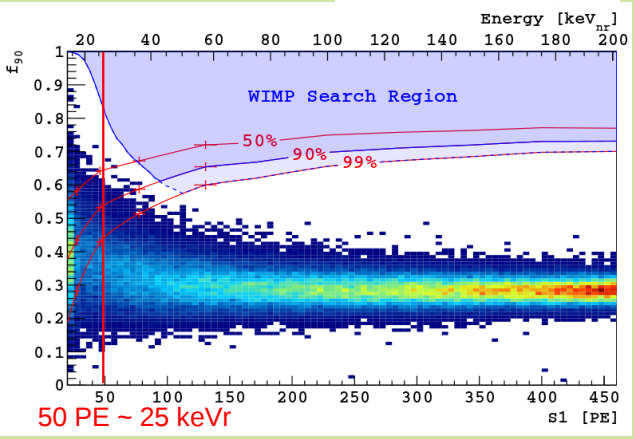
LAr

DarkSide-50 @ LNGS (IT)
PRD 93, 081101 (2016)

- **46 kg** LAr, which is ^{39}Ar-depleted by a factor 1400
- 71d×37kg exposure
- no event in search region
- taking data

- proposal for DarkSide-20k

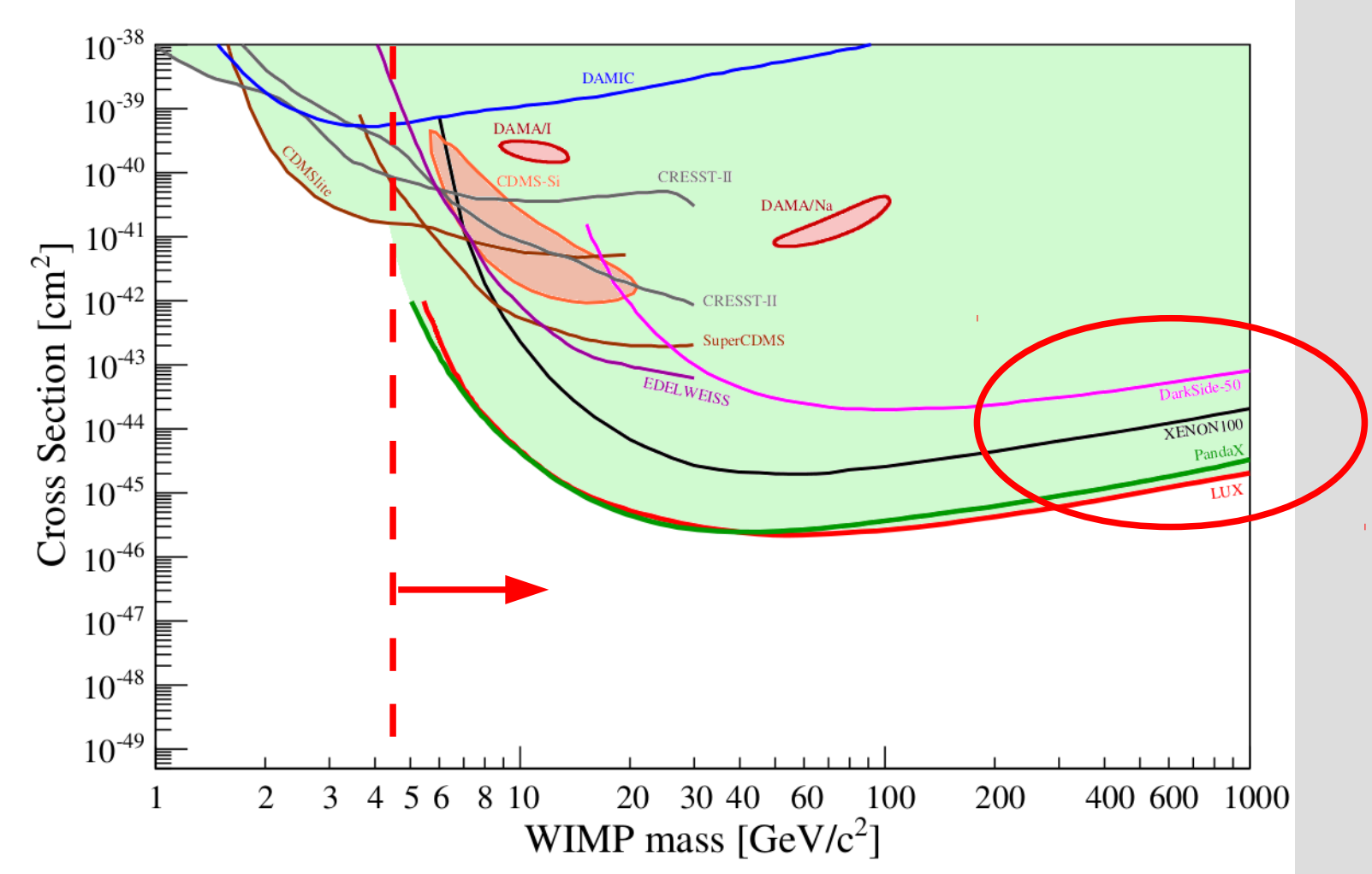




High WIMP-masses TPC dominated

→ ≥4.5 GeV/c²

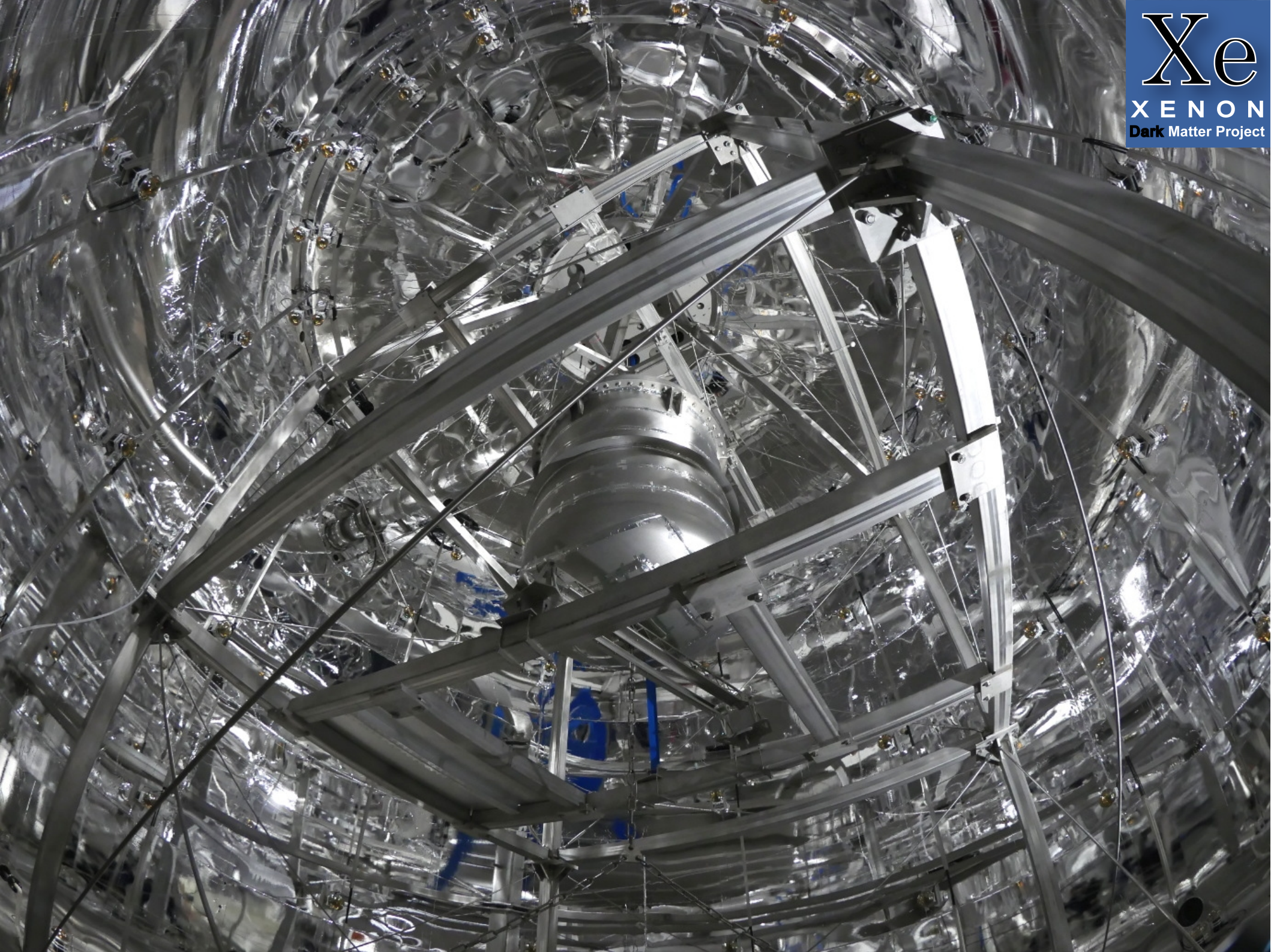
spin-independent WIMP-nucleon interactions



some projects are missing...

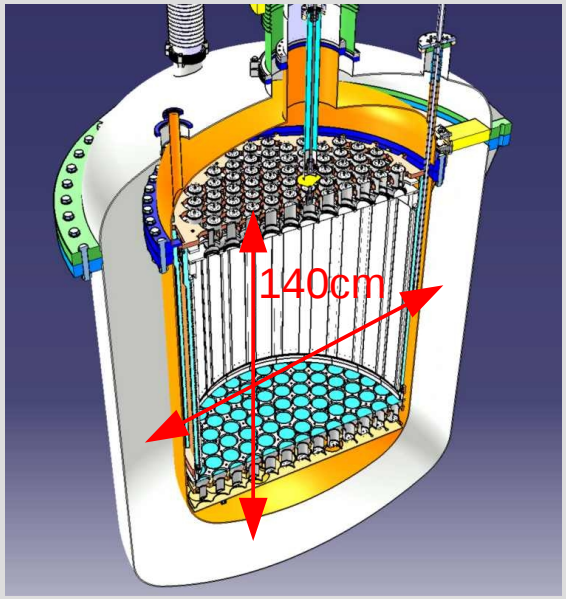
XENON1T @ LNGS

LXe


Xe
XENON
Dark Matter Project

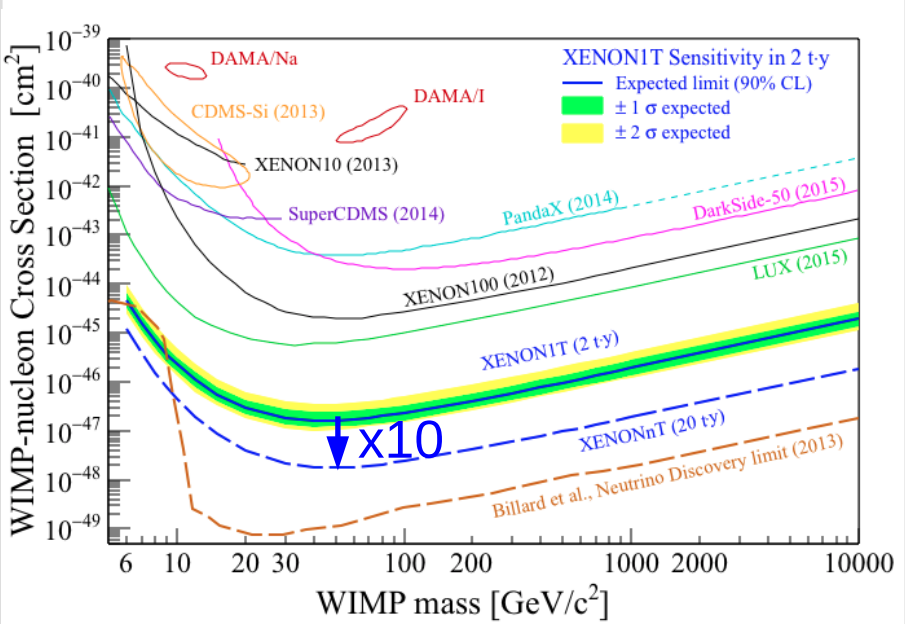
XENON1T → XENONnT

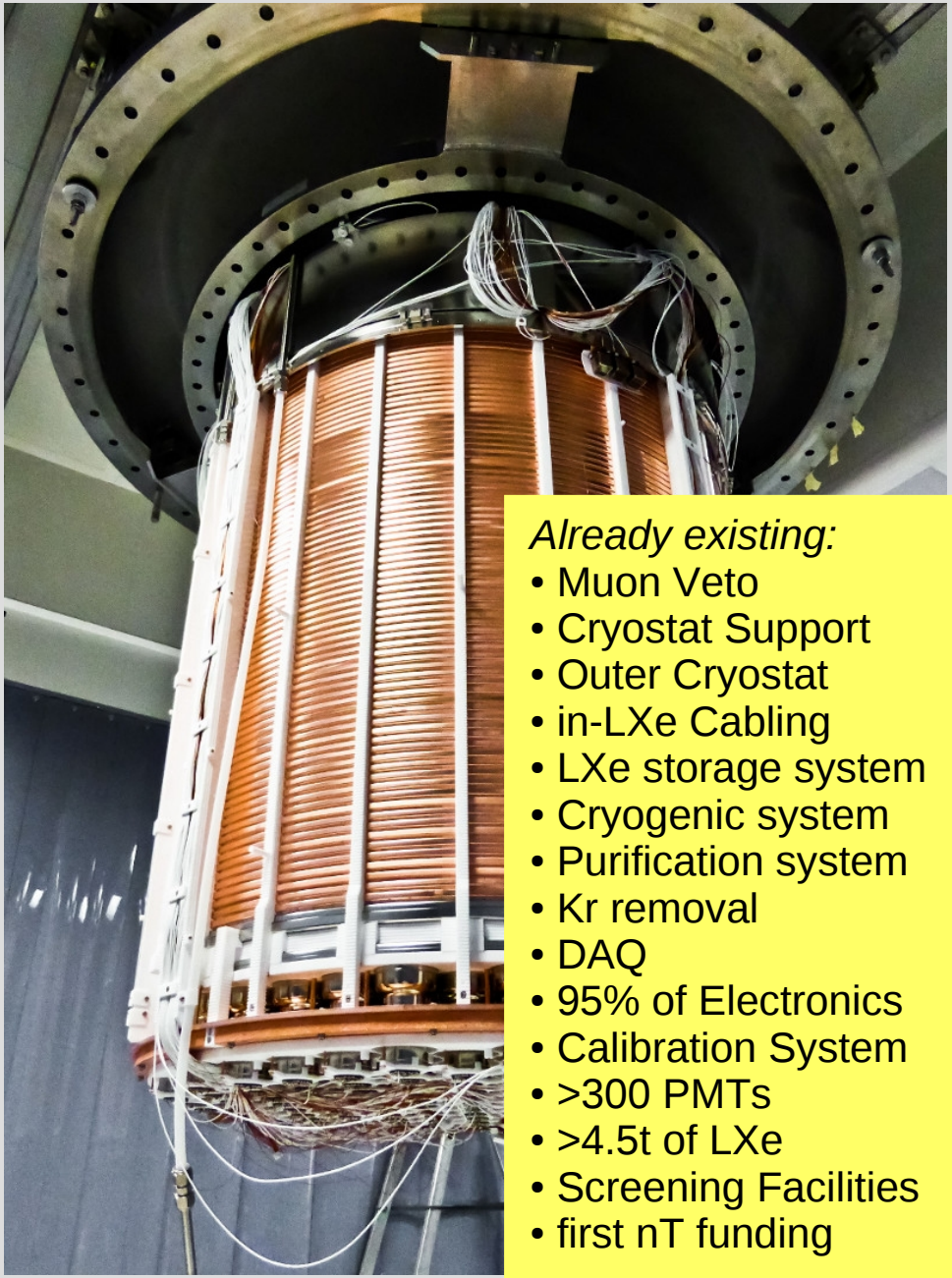
JCAP 04, 027 (2016)



XENON1T
- **2t** active LXe target
- **largest LXe TPC**
- @commissioning
- first science data in 2016

XENONnT
- **6t** active target
- projected to start in 2018





Already existing:
- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ
- 95% of Electronics
- Calibration System
- >300 PMTs
- >4.5t of LXe
- Screening Facilities
- first nT funding

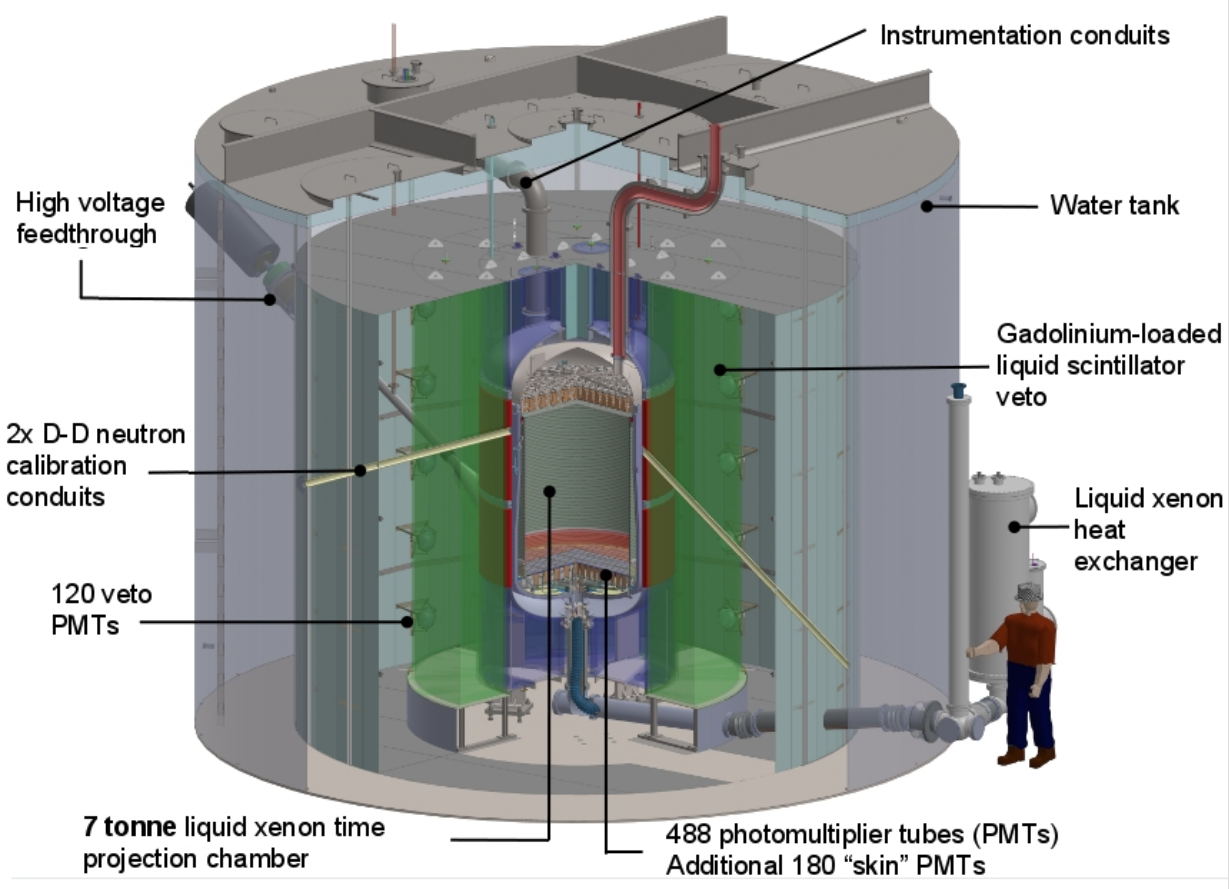
LZ – LUX/ZEPLIN

arXiv:1509.02910

LXe

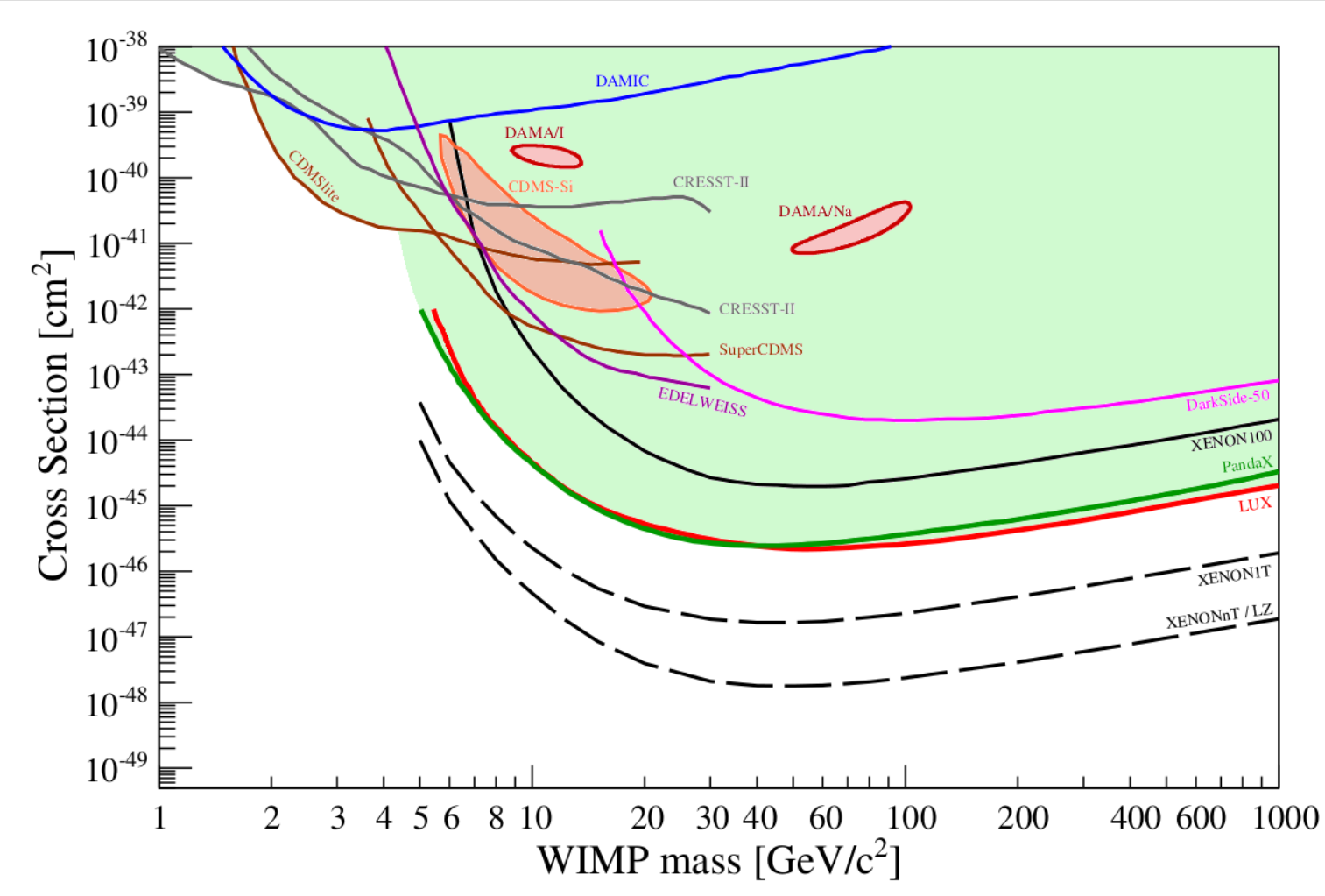
- **LZ = LUX+ZEPLIN**
  selected by 2014
  US DOE-NSF downselection
- to be installed @ SURF (USA)
- 50× larger than LUX

  10t total LXe mass,
  7t active target,
  5.6t fiducial target
- 488 R11410 PMTs
- *2015*: started procurement of xenon gas, PMTs, ...
  2020: start operations
- goal: 2×10^{-48} cm² @ ~50 GeV/c²
  after 15 t×y exposure



XENON Science Goals

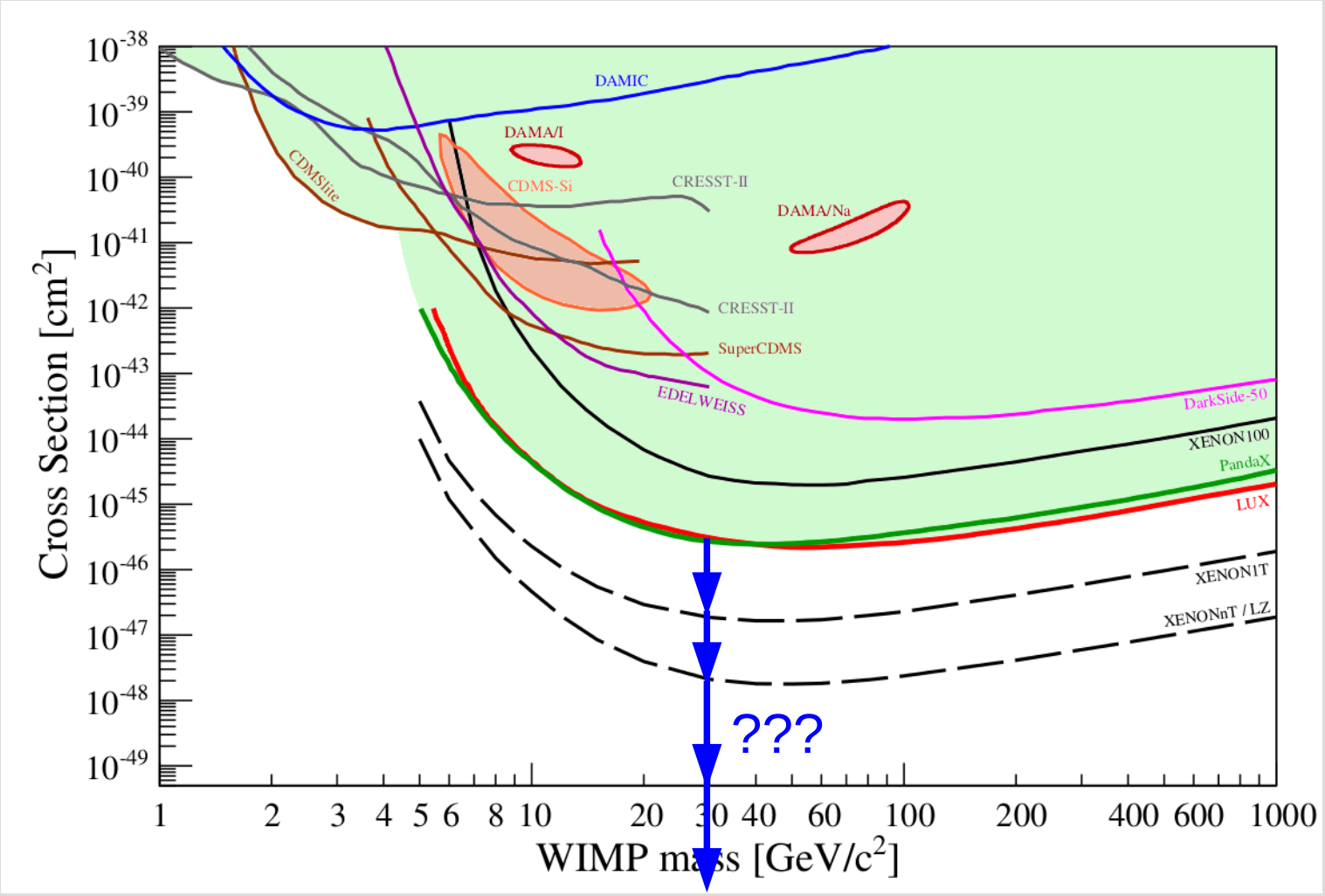
spin-independent WIMP-nucleon interactions



some projects are missing...

Dark Matter Searches: The Future

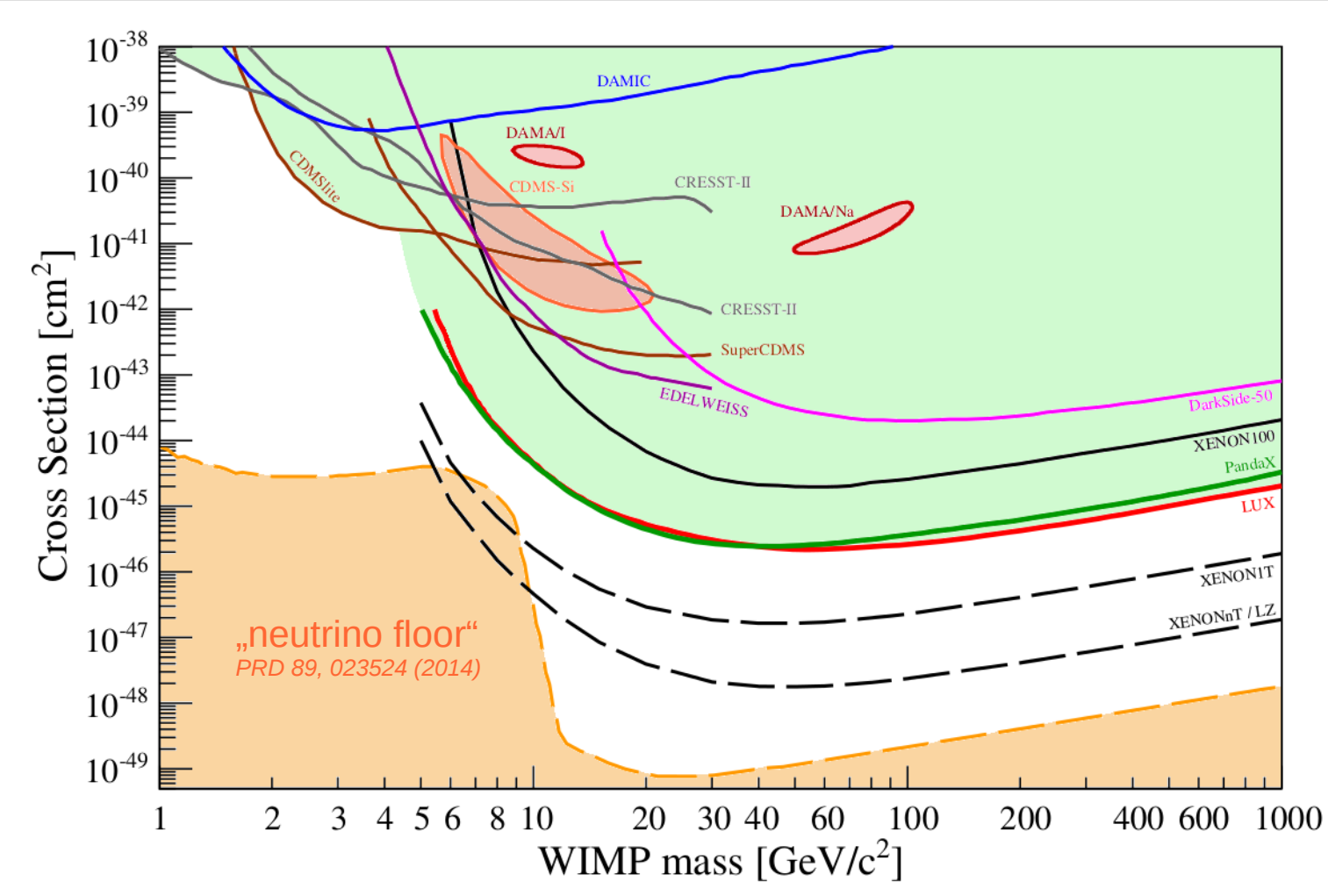
spin-independent WIMP-nucleon interactions



some projects are missing...

Dark Matter Searches: The Limit

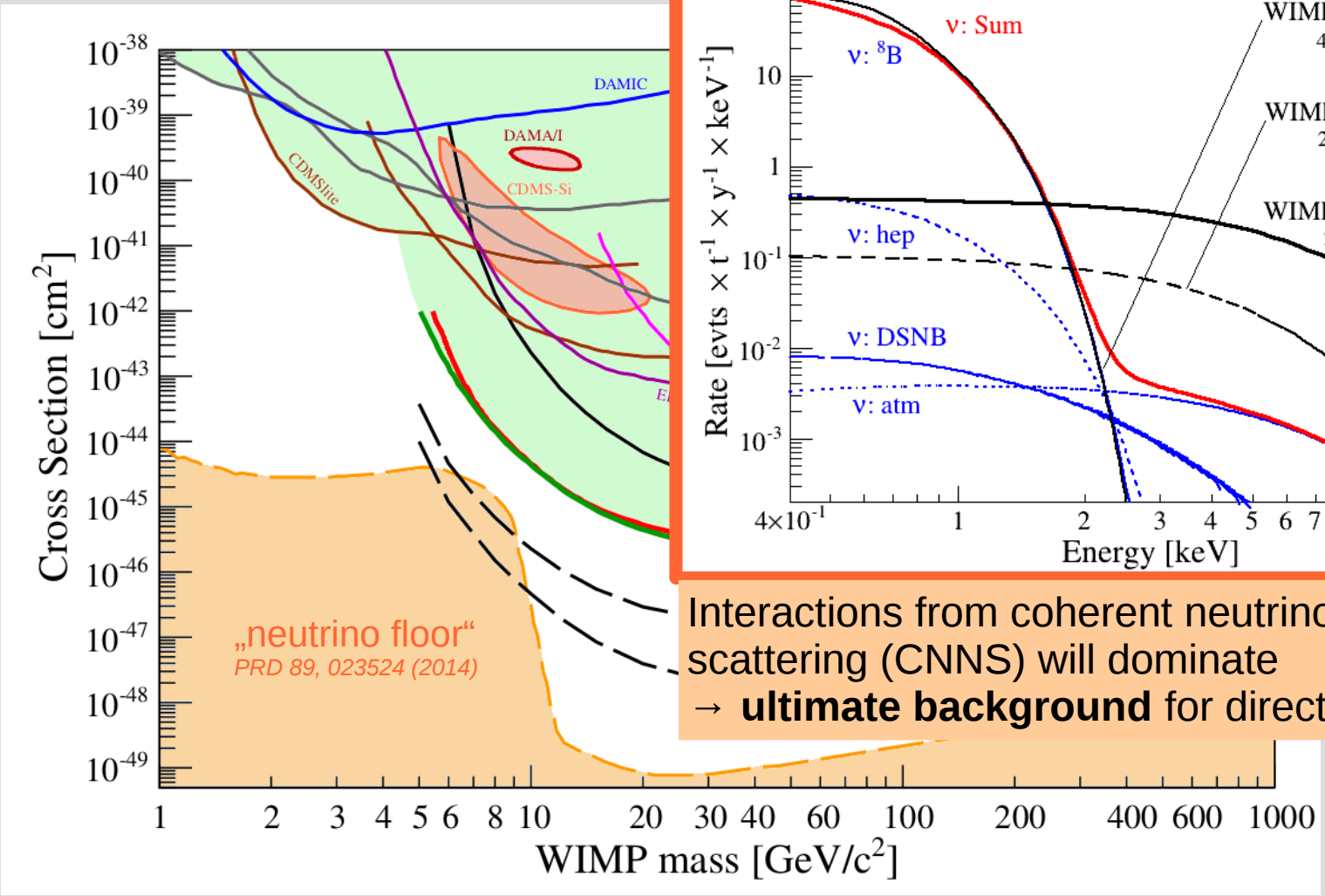
spin-independent WIMP-nucleon interactions

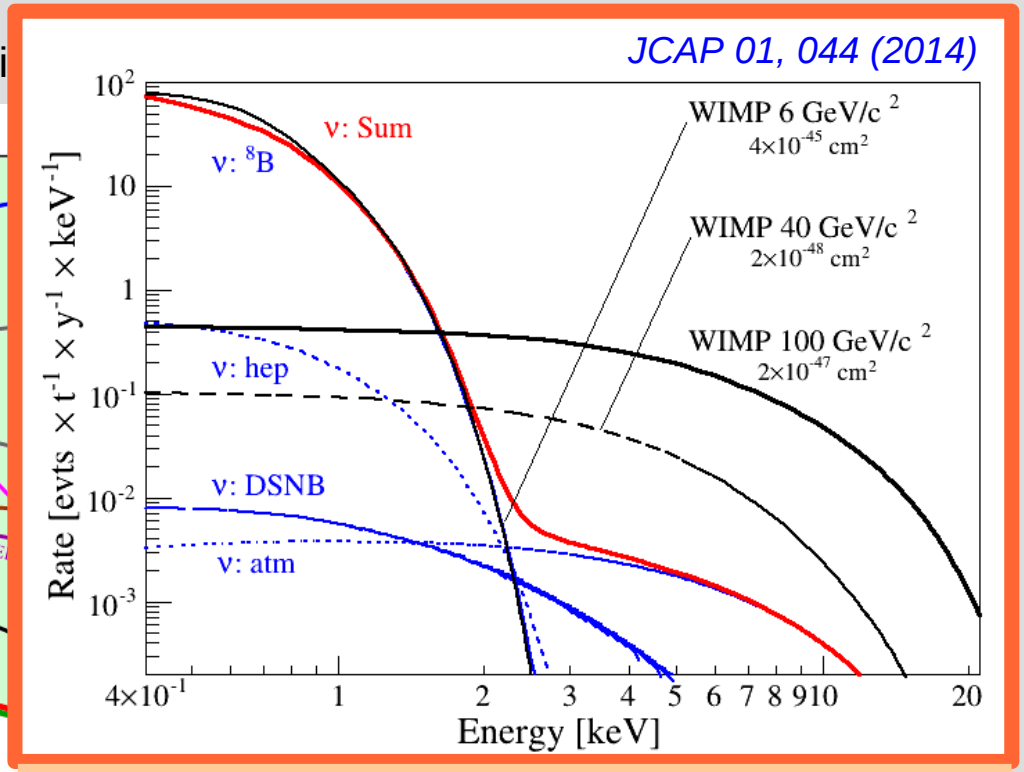


some projects are missing...

Dark Matter Searches: The Limit

spin-i



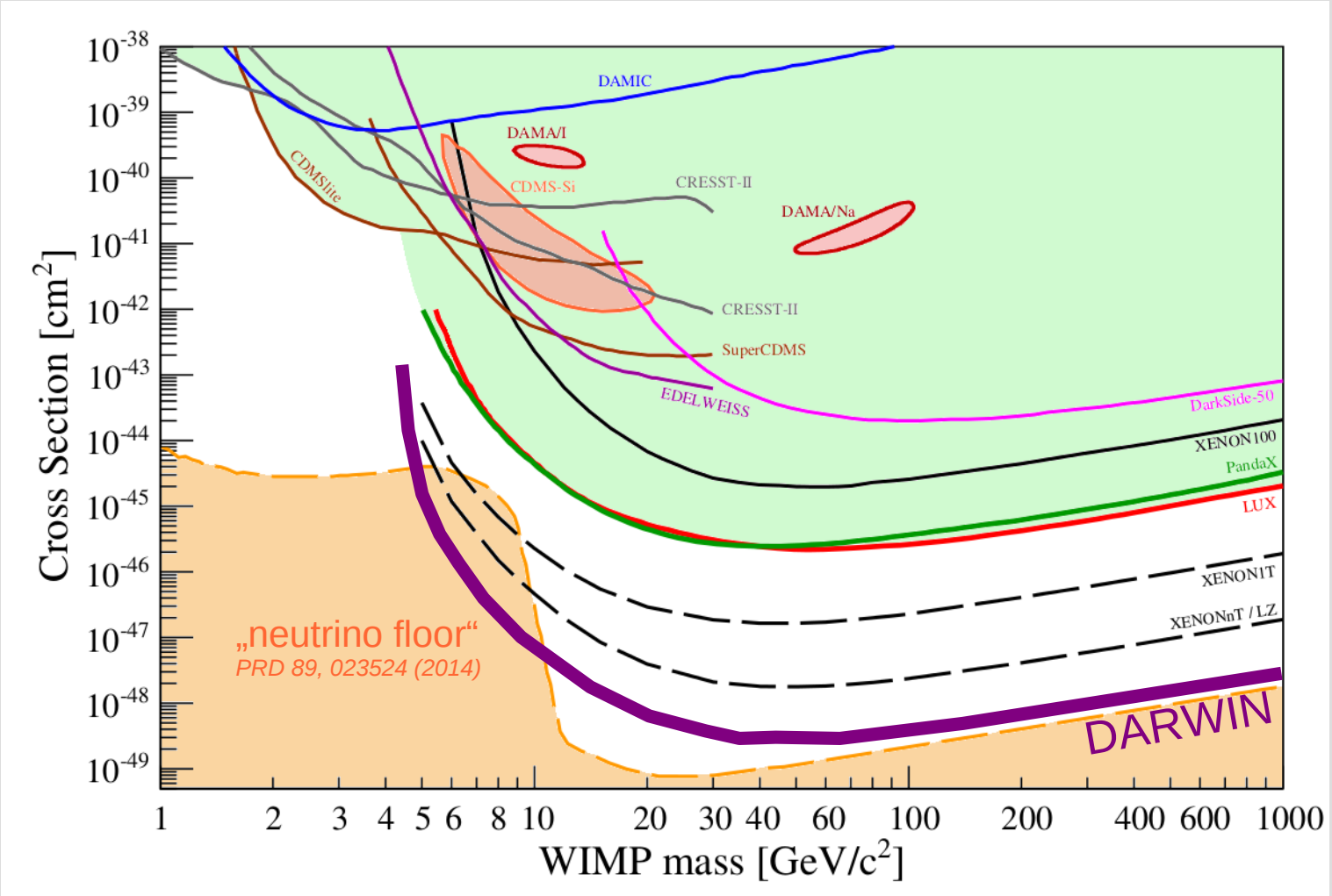


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection

some projects are missing...

DARWIN The ultimate WIMP Detector

spin-independent WIMP-nucleon interactions

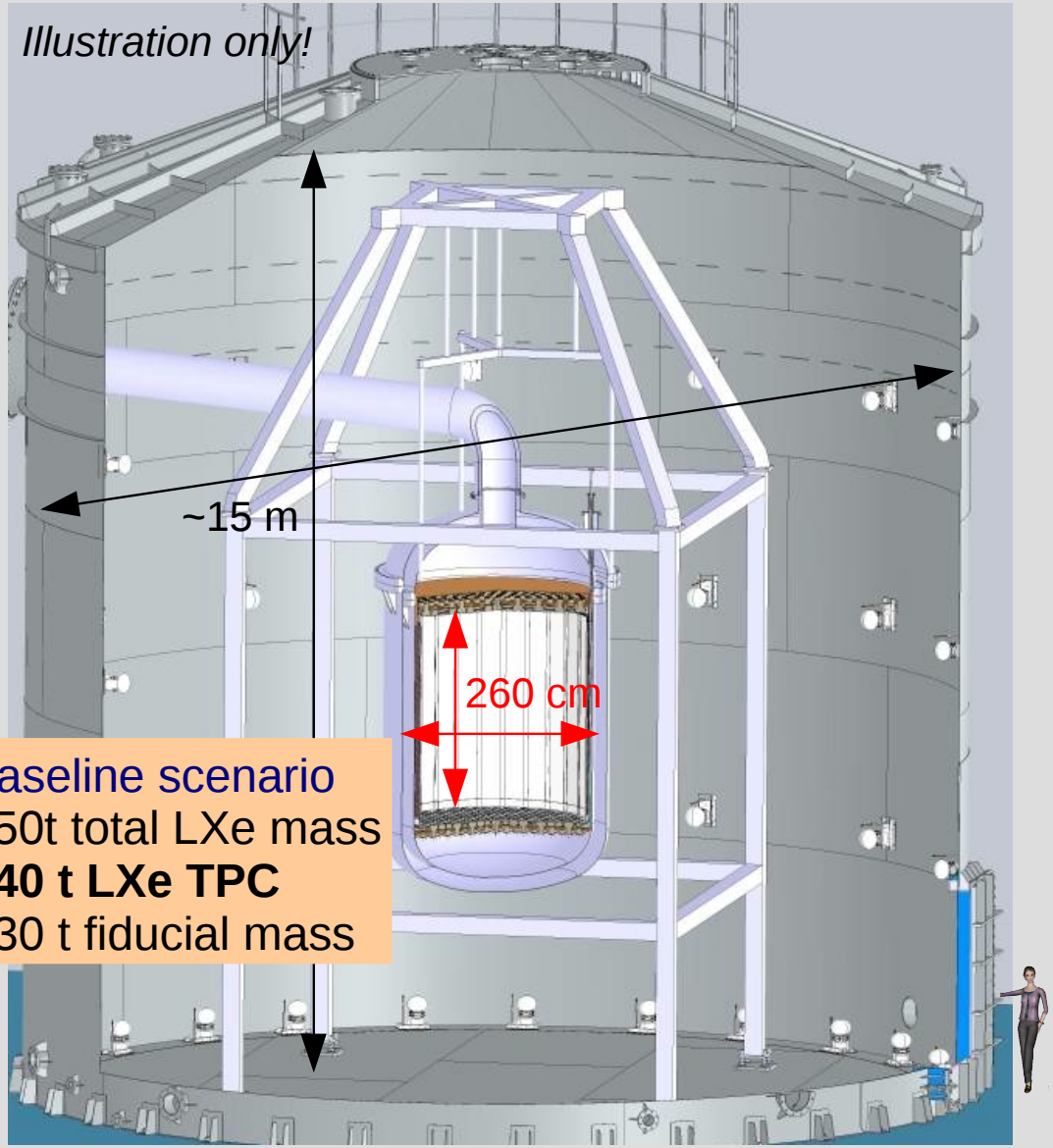


some projects are missing...

DARWIN The ultimate WIMP Detector

arXiv:1606.07001

LXe



Baseline scenario
~50t total LXe mass
~40 t LXe TPC
~30 t fiducial mass

- aim at sensitivity of a few 10^{-49} cm², limited by **irreducible ν-backgrounds**
- international consortium, 21 groups
  → R&D ongoing
- DARWIN is sensitive to
  - spin-independent,
  - spin-dependent,
  - inelastic WIMP interactions;
  - axions, ALPs
  - supernova neutrinos
  - CNNS
  - low-*E* solar neutrinos
  - neutrinoless double-beta decay
  - other rare nuclear processes...
- Timescale: start after XENONnT

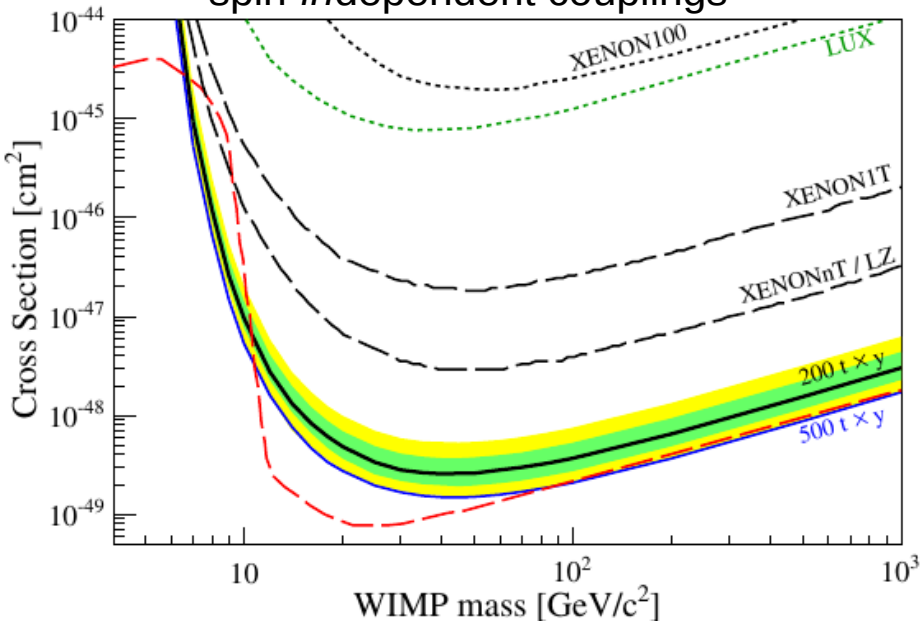
www.darwin-observatory.org

DARWIN WIMP Sensitivity

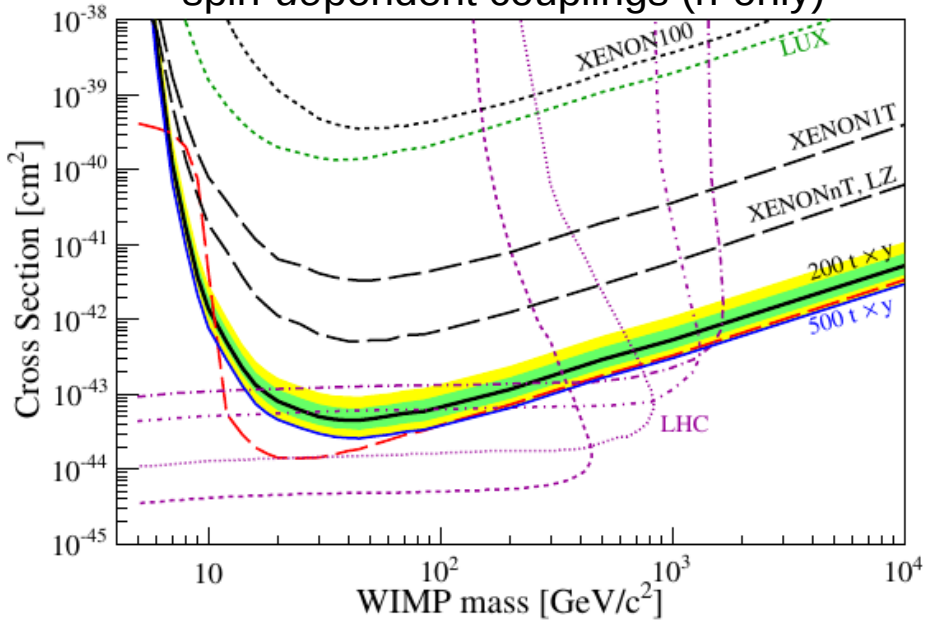
exposure: 200 t x y; **all backgrounds included**

JCAP 10, 016 (2015)

spin-*in*dependent couplings



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

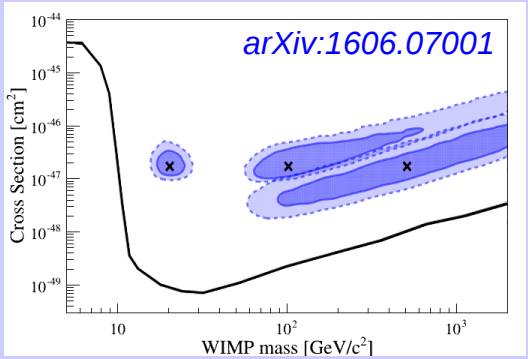


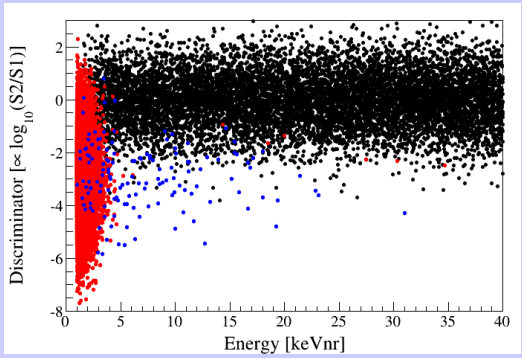
200 t×y: σ < 2.5 x 10^{-49} cm² @ 40 GeV/c²

excellent complementarity to LHC searches

Phys.Dark Univ. 9-10, 51 (2015)

if detection before DARWIN
→ **„WIMP spectroscopy“**





Spin dependence: Threshold Detectors

PICO =PICASSO + COUPP @ SNOLAB

- bubble chambers filled with superheated C_3F_8 or CF_3I
  → 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: particulate contamination, hysteresis effects

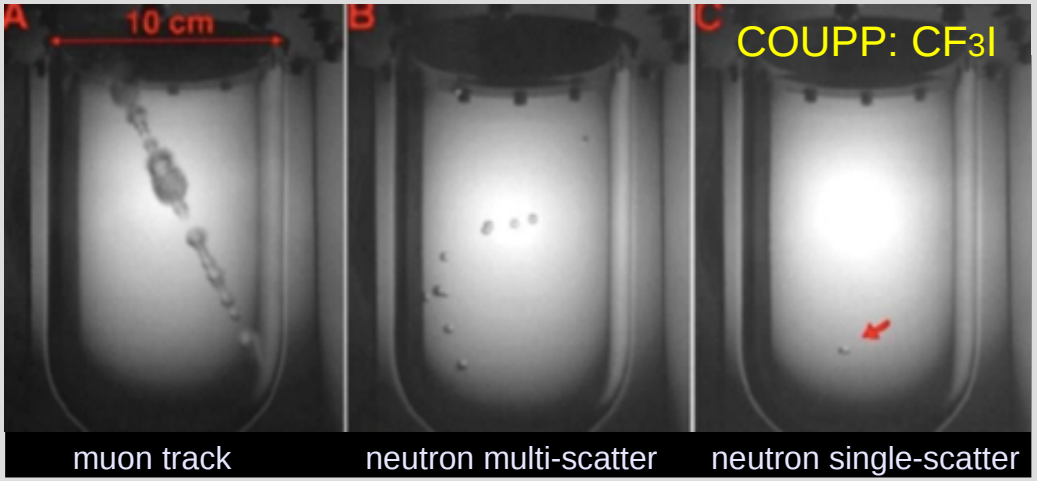
$$\sigma = \frac{32 G_F^2 m_r^2}{\pi} \frac{J+1}{J} \left[a_p \langle s_p \rangle + a_n \langle s_n \rangle \right]^2$$

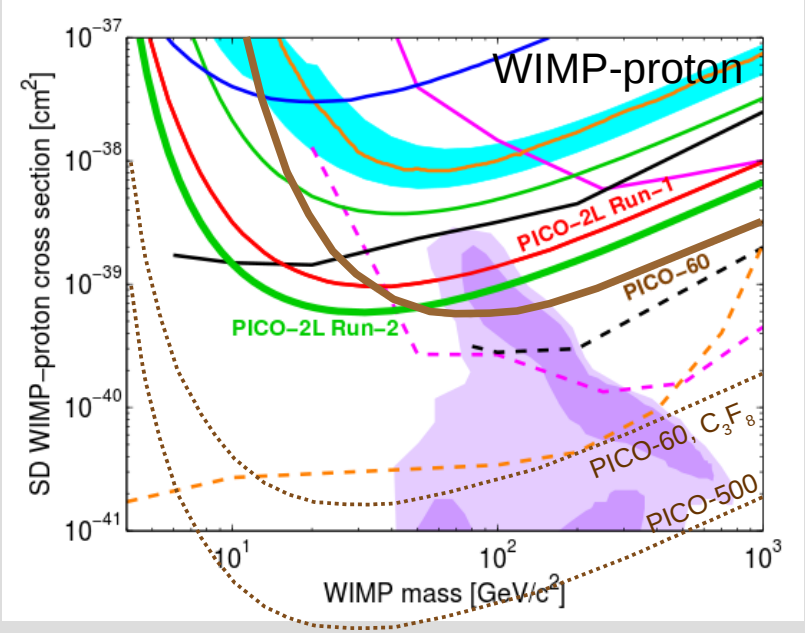
Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

Recent results:

PRD 93, 052014 (2016)
PRD 93, 061101 (2016)

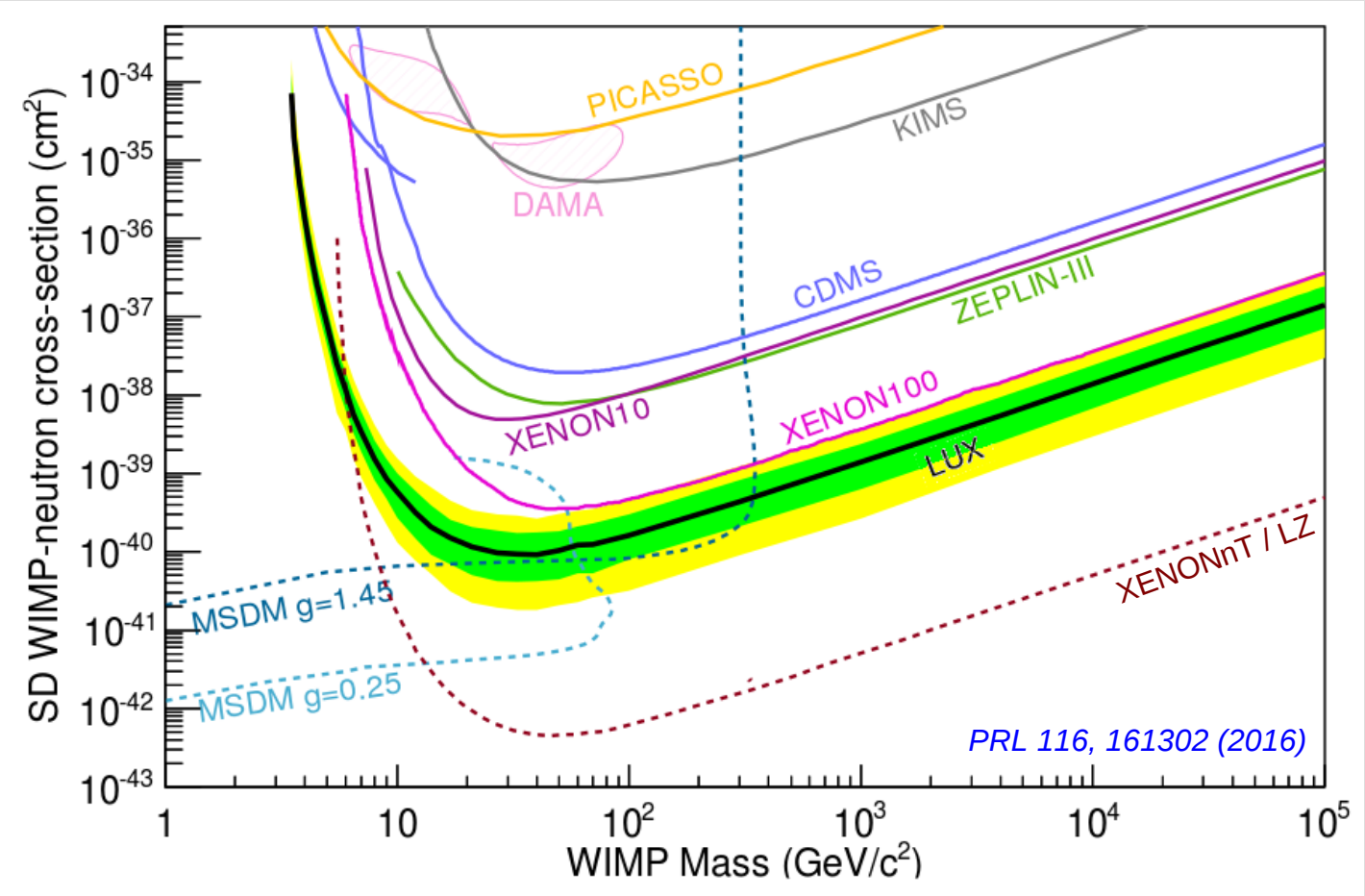
PICO-60: largest chamber; >2000 bg events
PICO-2L: cleaning solved bg problem in Run-2





Upgrade plan: PICO-500 → SD reach ~10^{-42} cm²

Spin-dependent: Neutron-Only



Liquid xenon detectors dominate neutron-only parameter space

Exciting times ahead of us