Direct Searches for WIMP Dark Matter – The XENON Perspective

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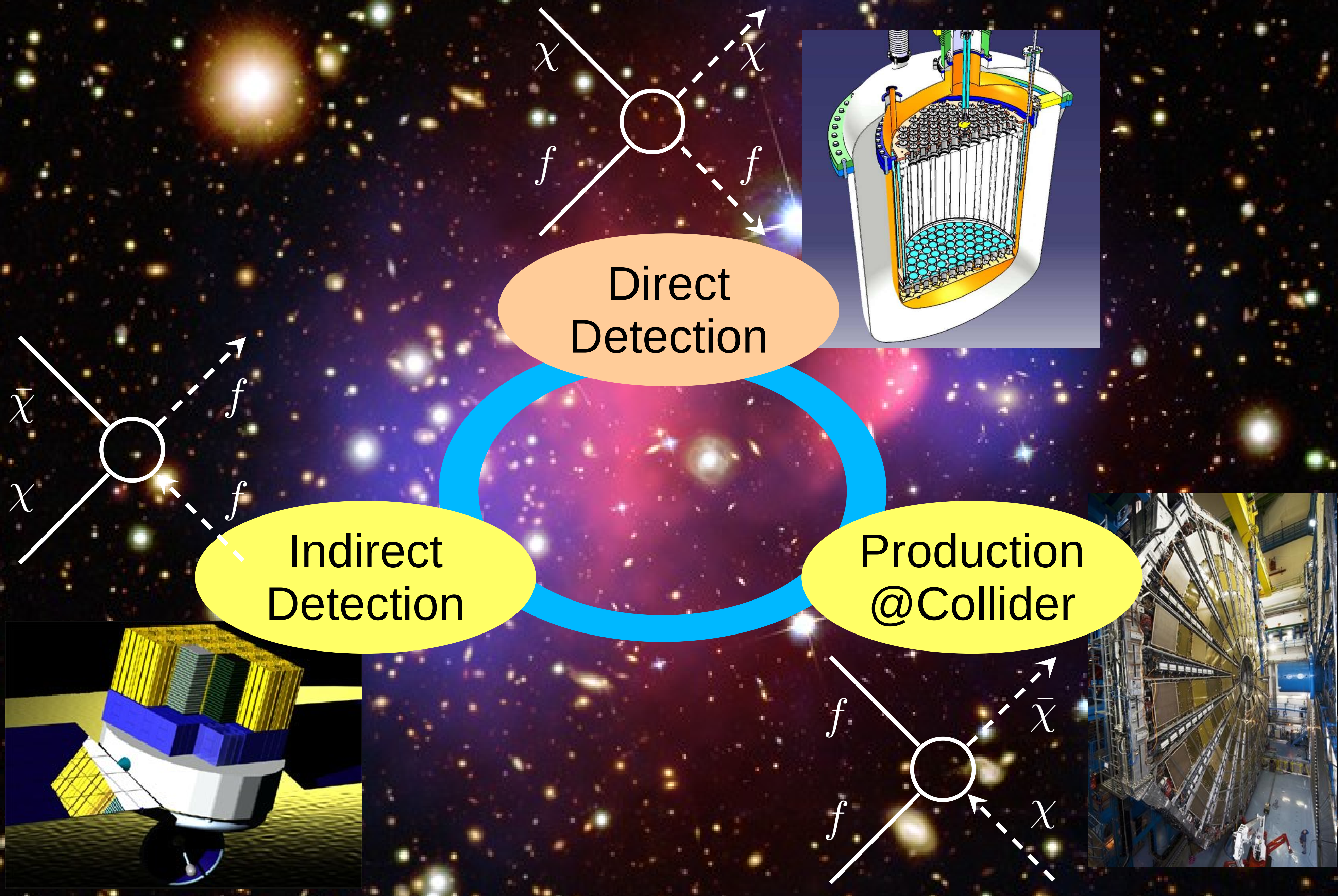
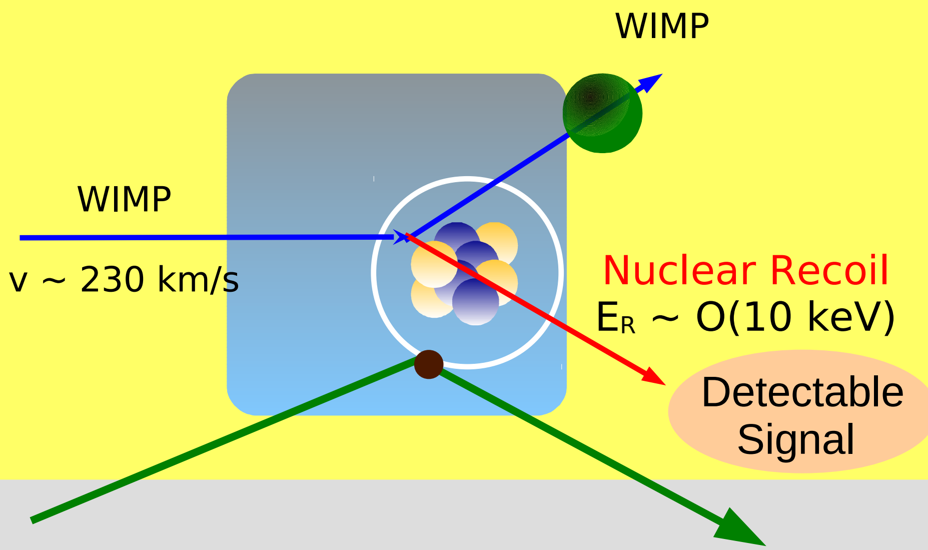
FOR FUNDAMENTAL PHYSICS

Dark Matter Search



Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei
➡ nuclear recoil



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

Direct WIMP Search

Summary: Tiny Rates

$R < 0.01$ evt/kg/day

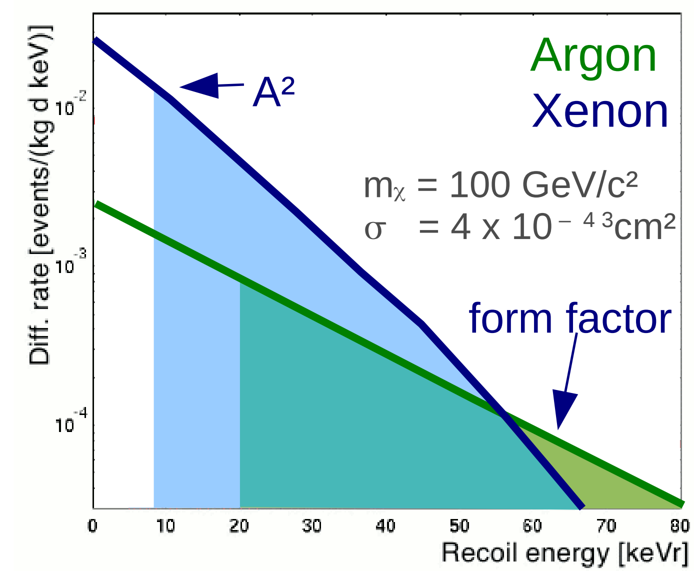
$E_R < 100$ keV

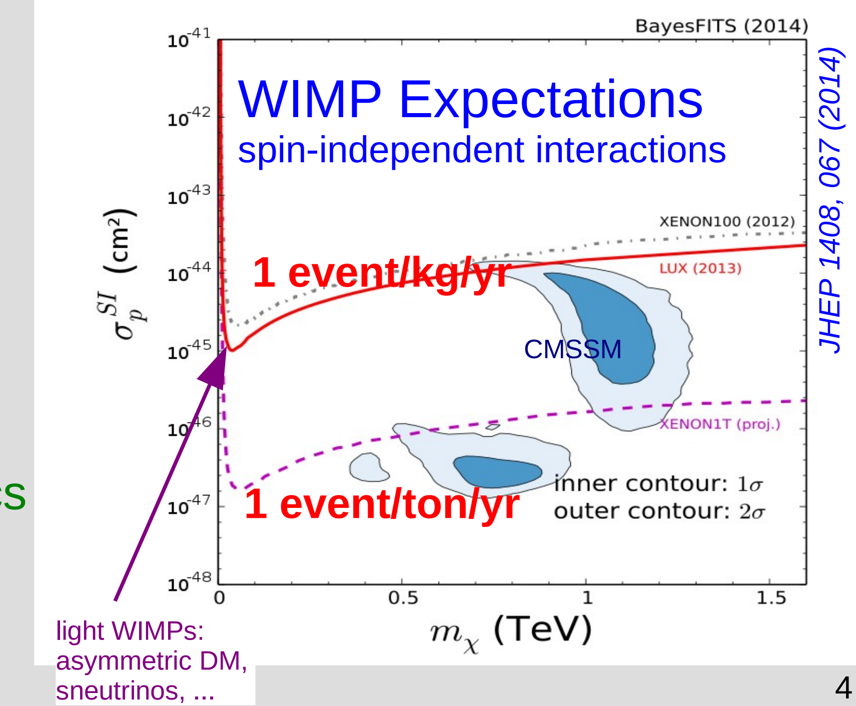
Recoil Energy: $E_r \sim \mathcal{O}(10\ \mathrm{keV})$

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

Detector — Local DM Density — Physics

$\rho_\chi \sim 0.3$ GeV/c^2





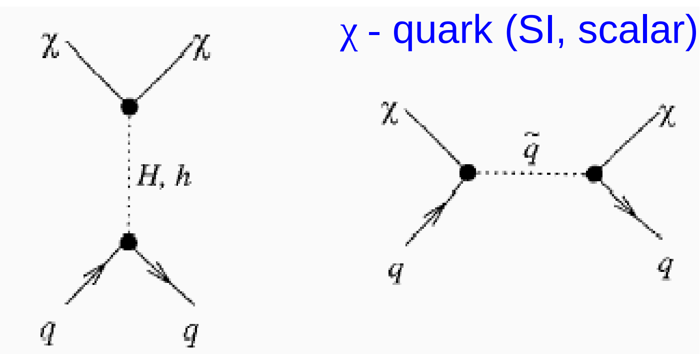
WIMP-Nucleon Interactions

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**

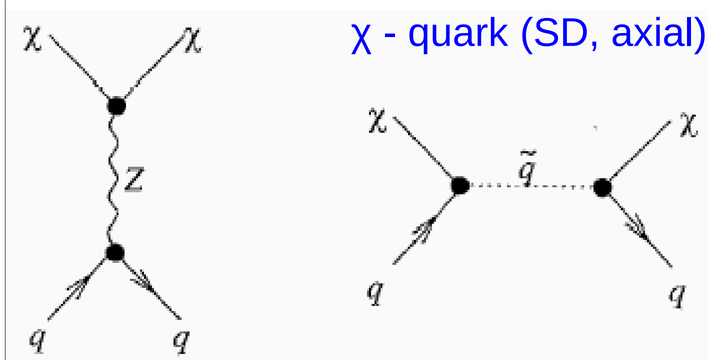
Spin independent



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

coupling to **nuclear spin**

Spin dependent



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

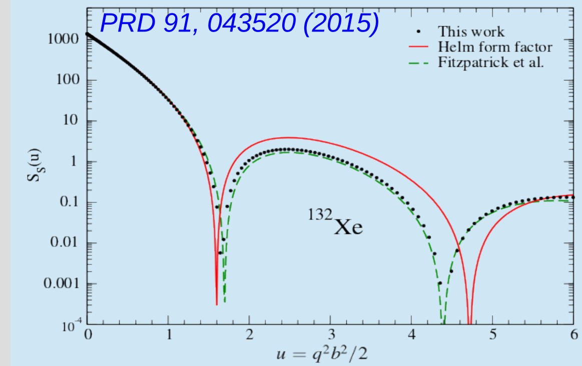
Jungmann et al. '96 Phys.Rep.

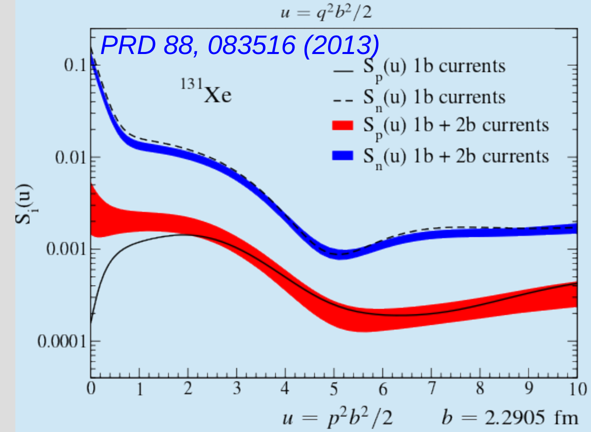
often: express SD results in proton-only or neutron-only

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

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

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





Direct WIMP Search

Summary: Tiny Rates

R < 0.01 evt/kg/day

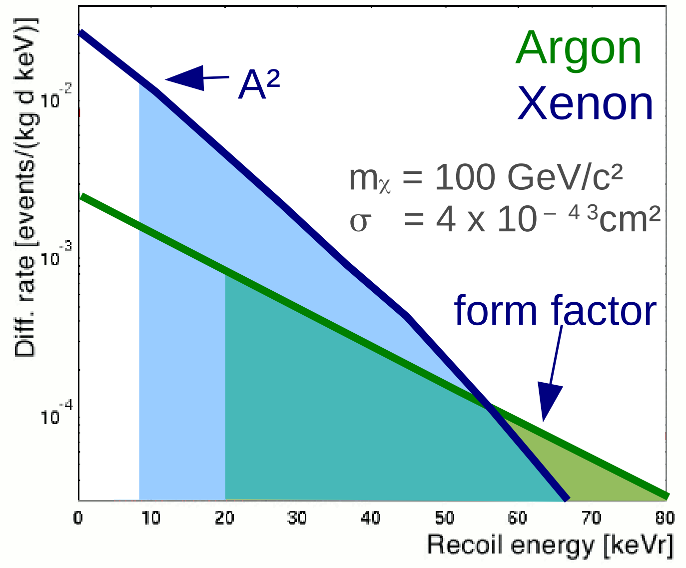
E_R < 100 keV

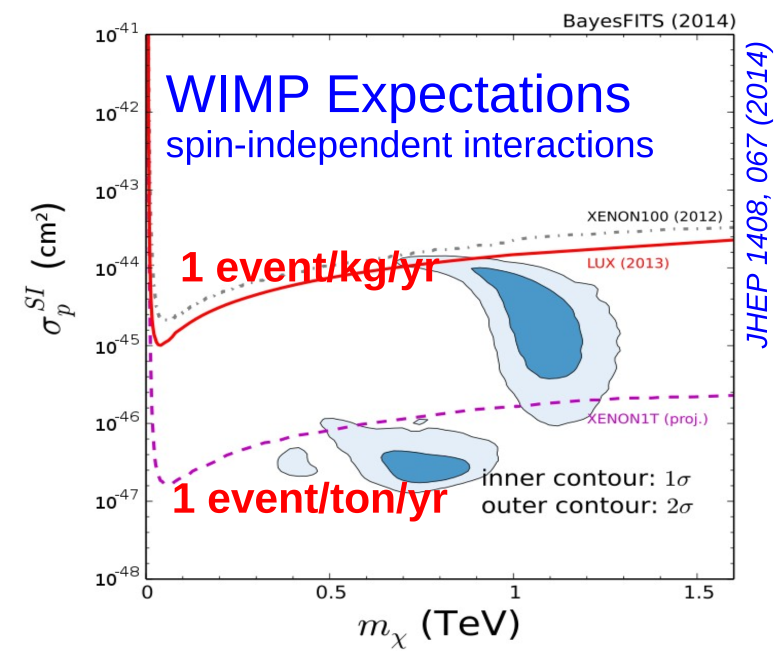
How to build a WIMP detector?

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

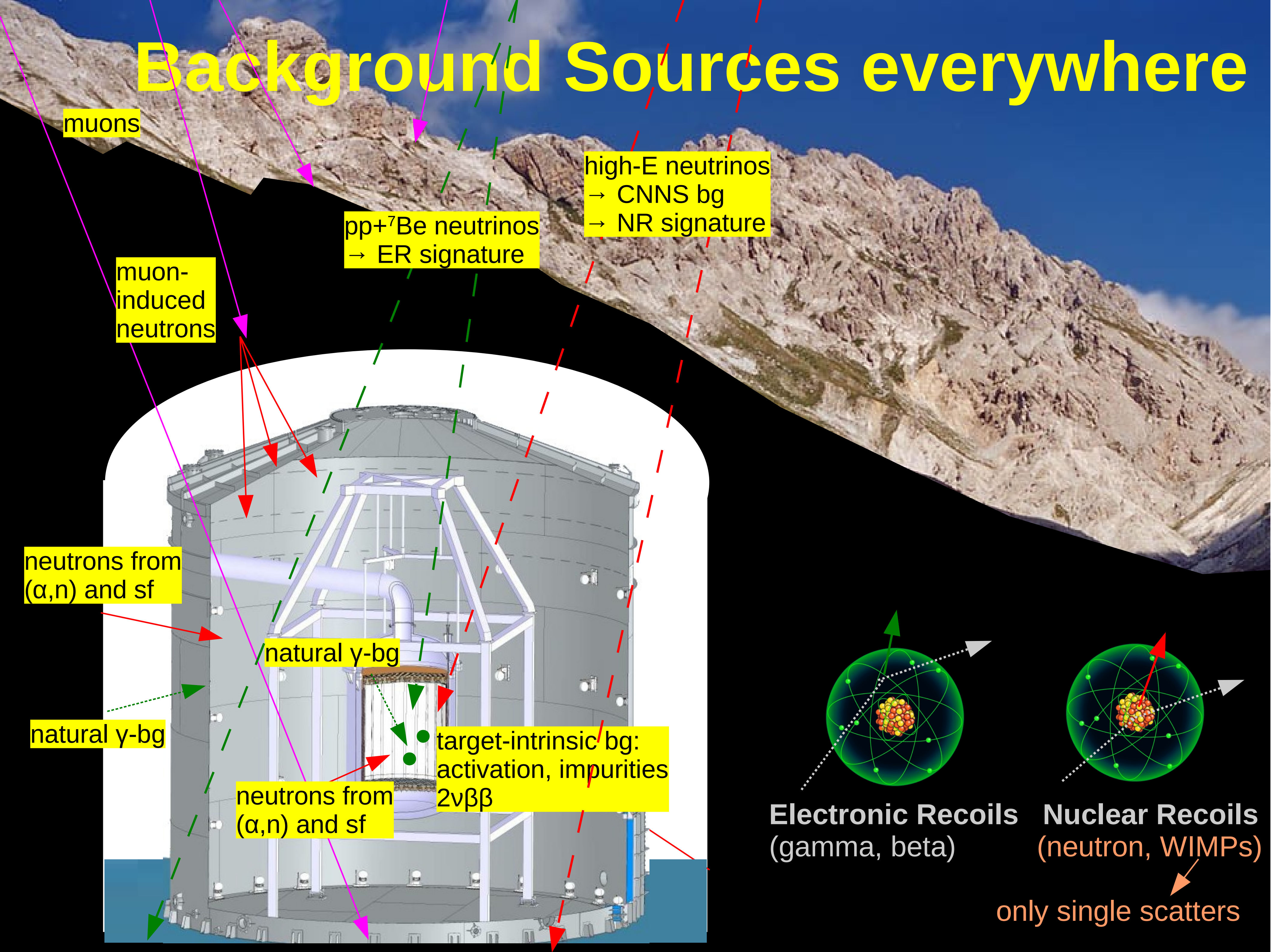
We are dealing with

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





Background Sources everywhere



Background Suppression

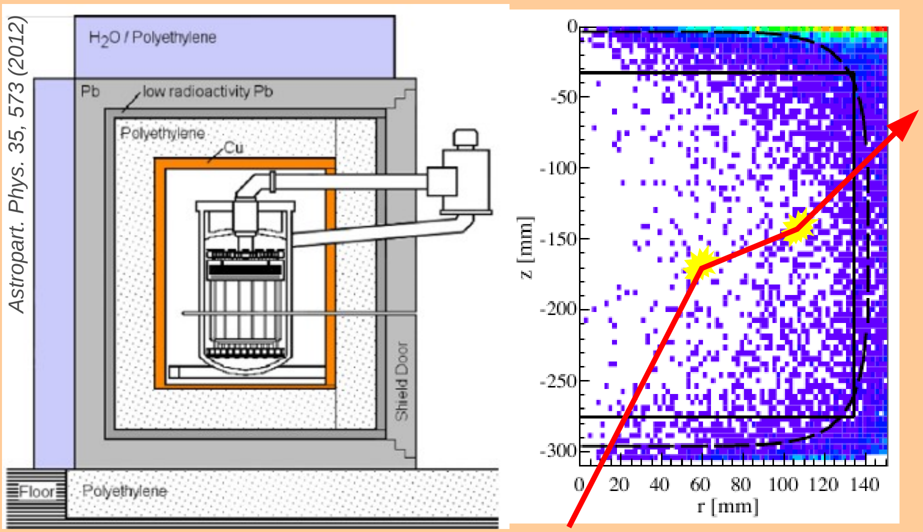
A Avoid Backgrounds

Use of radiopure materials

Shielding

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

self shielding → fiducialization



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*/d*x* from signal and background

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

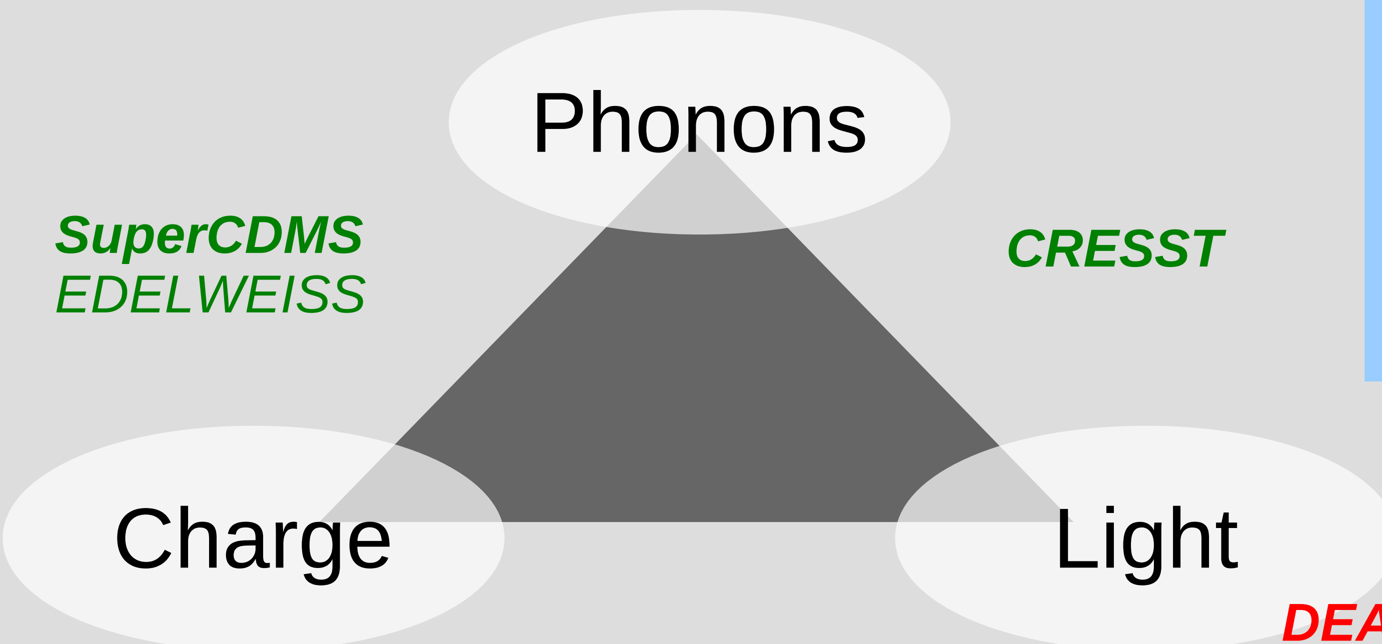
Direct WIMP Detection

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

Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE

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

CRESST-I
CUORE



SuperCDMS
EDELWEISS

CRESST

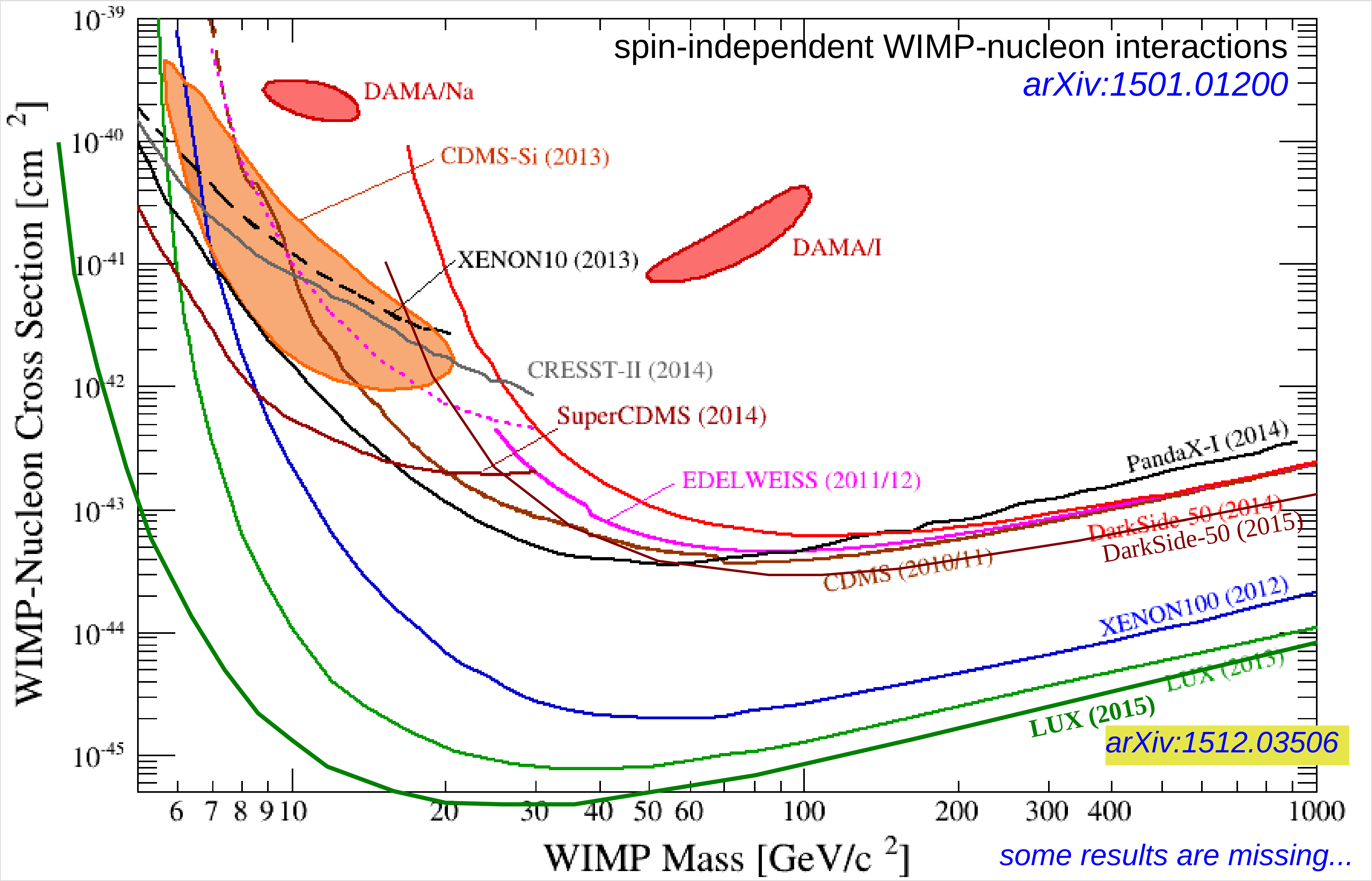
CoGeNT
CDEX
Texono
Malbek
DAMIC

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

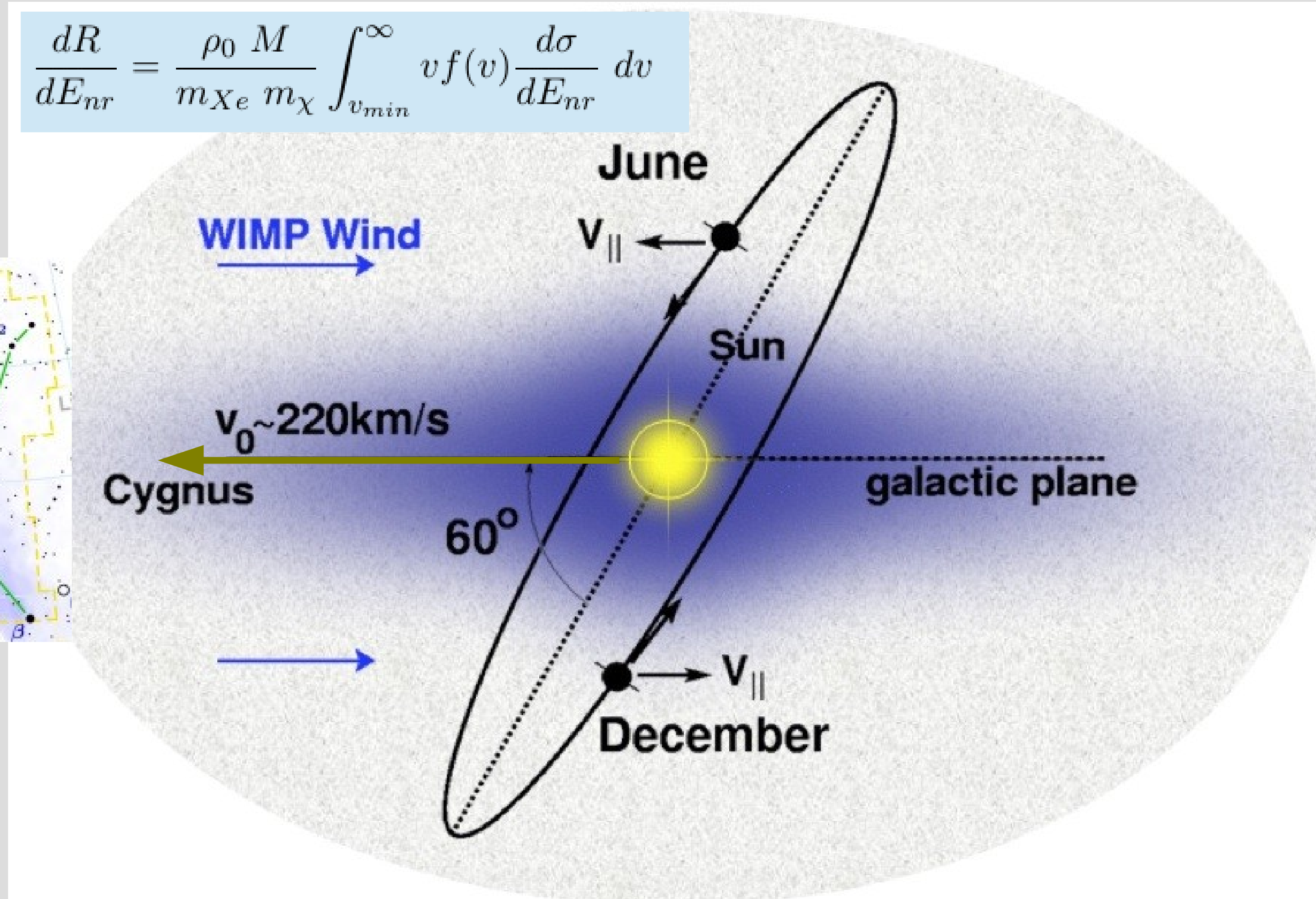
The current WIMP landscape

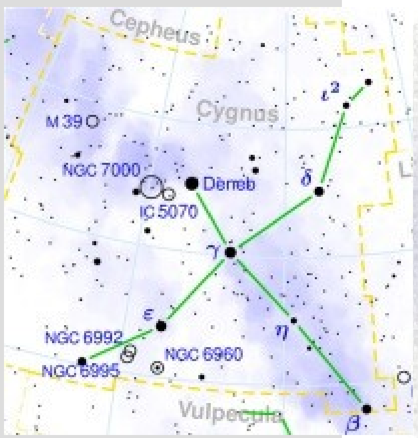


Annual Modulation

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

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



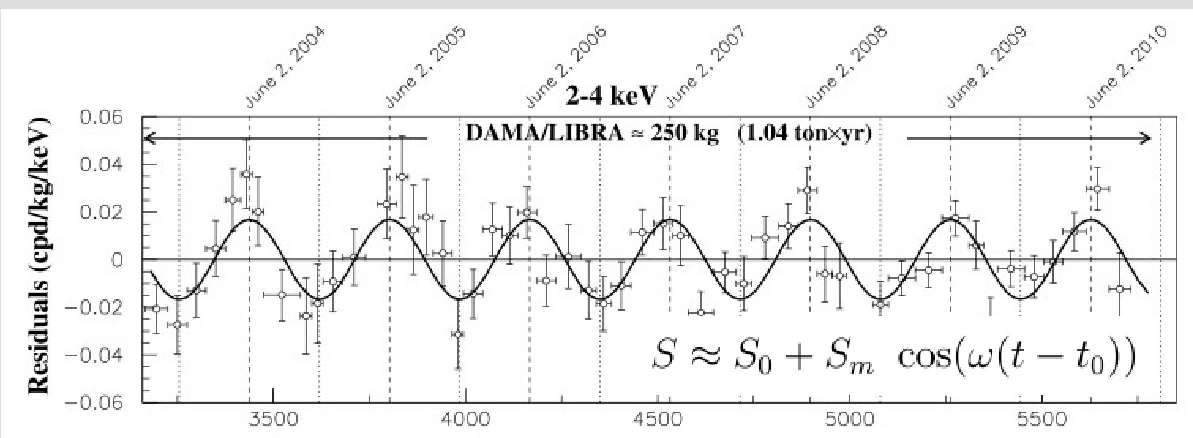


→ recoil spectrum gets harder and softer during the year
→ search for annually modulating signal (3% effect)
→ does not require many physical assumptions

Annual Modulation: DAMA/Libra

- PMTs coupled to **NaI(Tl)** Scintillators @ LNGS
  → extremely clean background necessary
- looks for annual modulation (~3% effect)
- large mass and exposure: 1.17 t×y

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

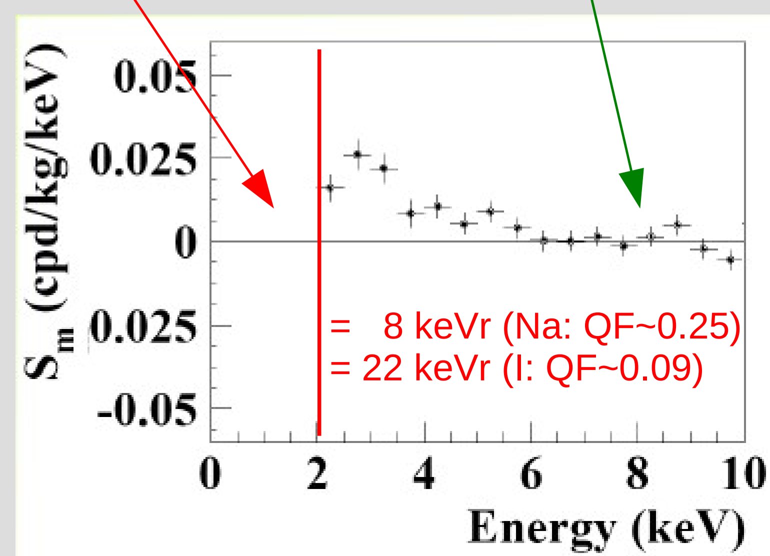


Eur. Phys. J. C 73, 2648 (2013)

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

what is here?

no modulation
above 6 keV



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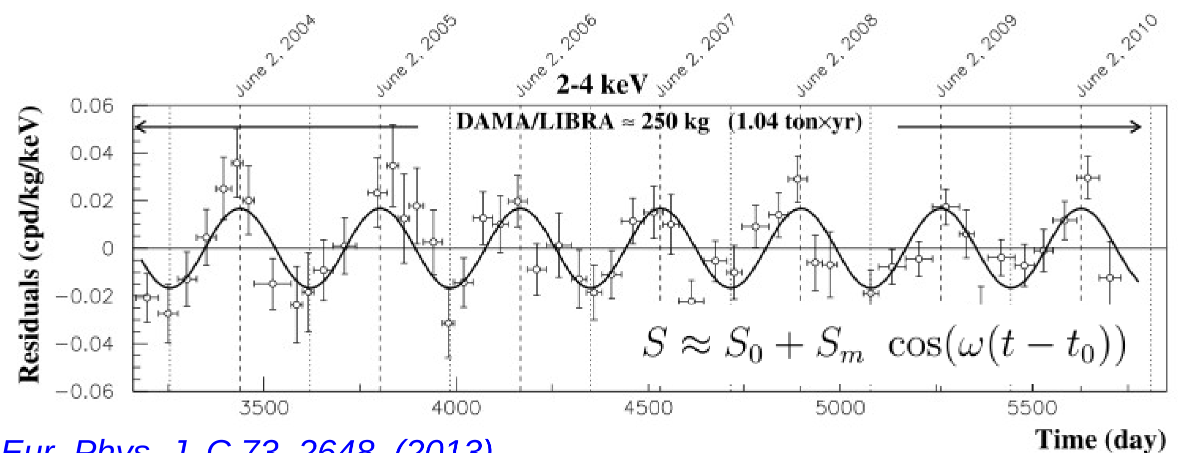

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Interpretation as Dark Matter interaction
is in conflict with numerous other experiments
→KIMS, ANAIS, DM-Ice, Sabre will check directly

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

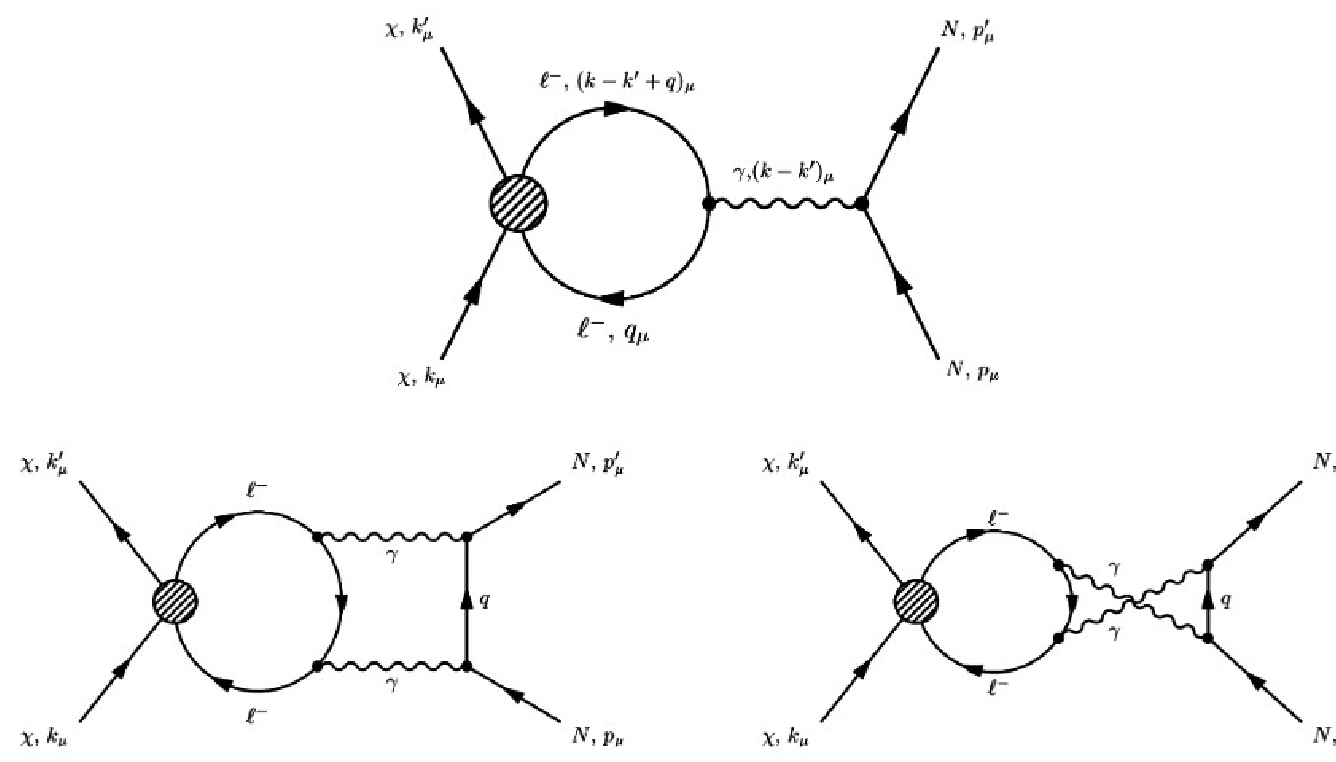
Examples:
Kopp et al., PRD 80, 083502 (2009)
Changet al., PRD 90, 015011 (2014)
Bell et al., PRD 90, 035027 (2014)
Mirror dark matter:
Foot, Int.J.Mod.Phys. A29, 1430013 (2014)
Luminous dark matter:
Feldstein et al., PRD 82, 075019 (2010)

DAMA vs XENON: Modulation

XENON100, PRL 115, 091302 (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



PRD 80, 083502 (2009)

FIG. 2. DM-nucleus interaction induced by a charged lepton loop and photon exchange at one loop (top) and two loop (bottom).

DAMA vs XENON: Average Rate

XENON100, Science 349, 851 (2015)

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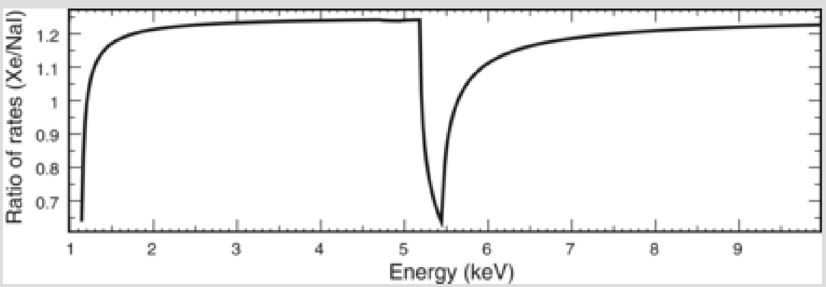
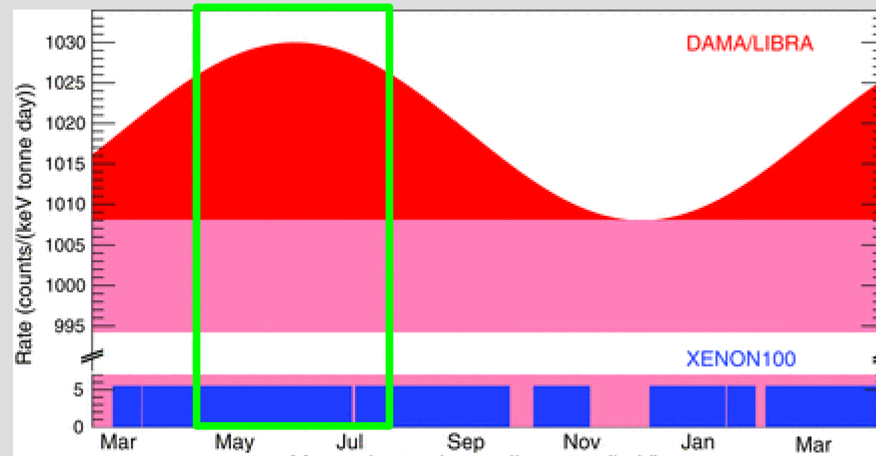


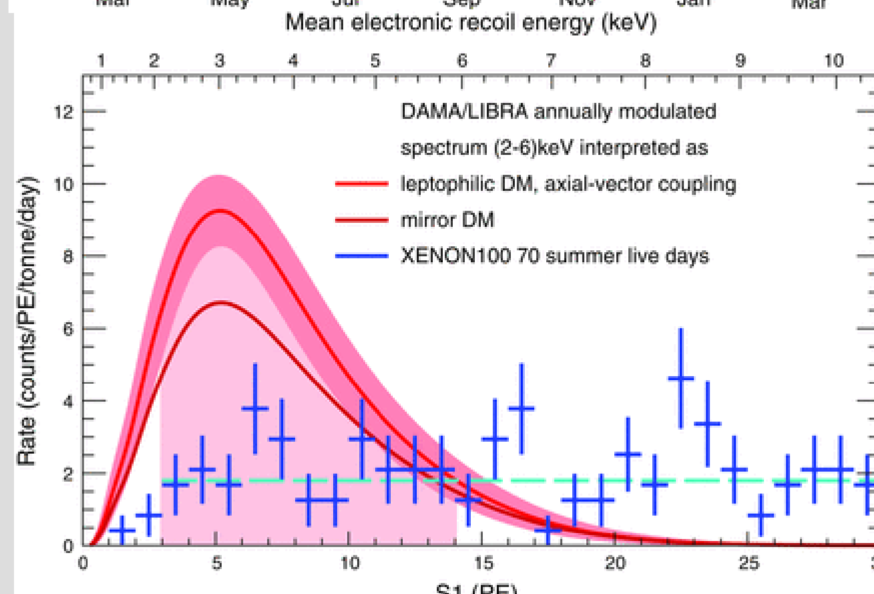
Analysis

– 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

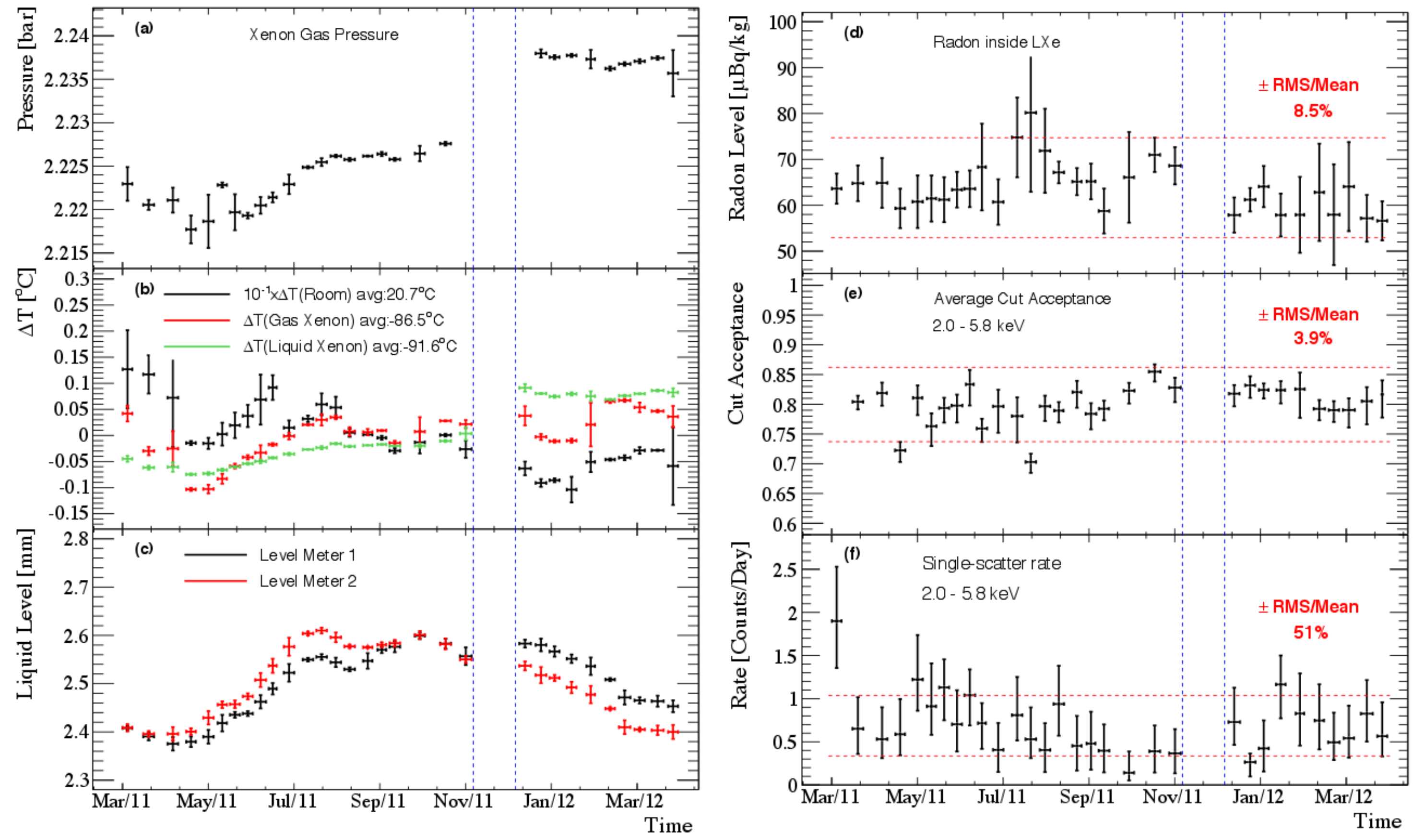
XENON100, PRL 115, 091302 (2015)

- 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

Xe Pressure

Temperature

LXe Level



Rn Level

Cut Acceptance

Count Rate

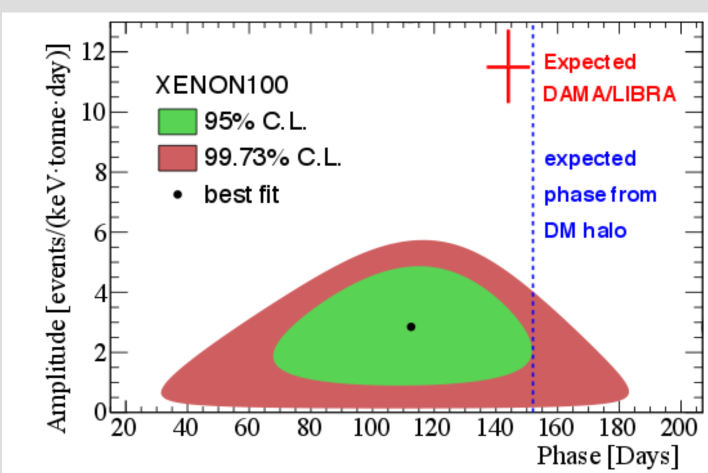
DAMA vs XENON: Modulation

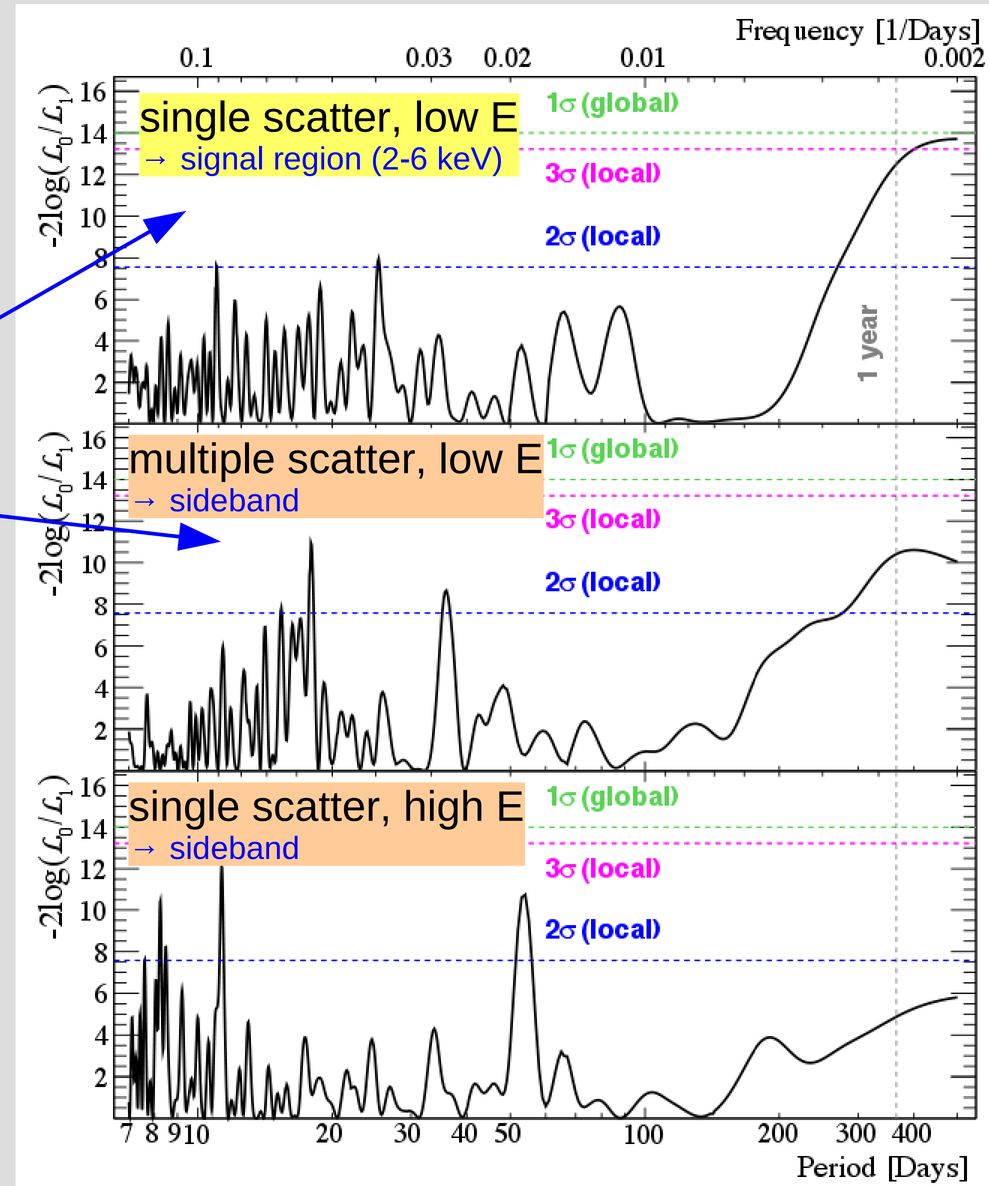
XENON100, PRL 115, 091302 (2015)

- 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**

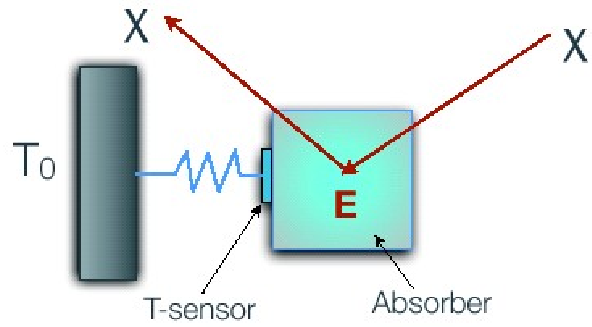




Cryogenic Detectors: SuperCDMS

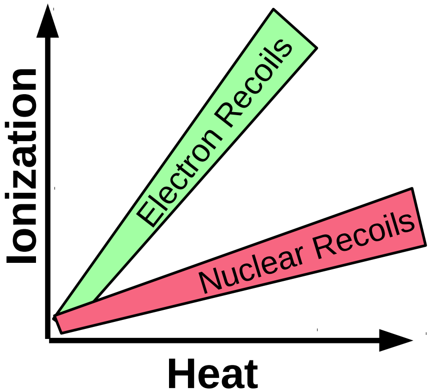
@ Soudan Lab (USA) → later: SNOLAB

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



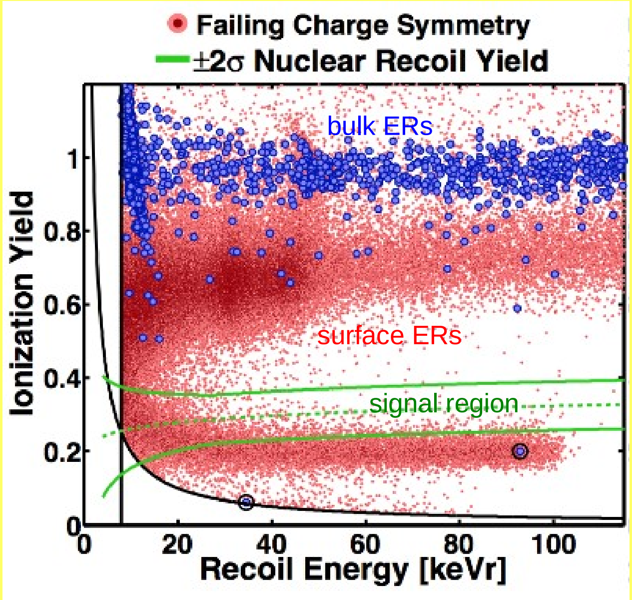
Crystals: **Ge**, **(Si)** cooled to few mK
– low heat capacity
– Δ*T* ~ μK

Very good discrimination
→ BUT: need to reject surface events



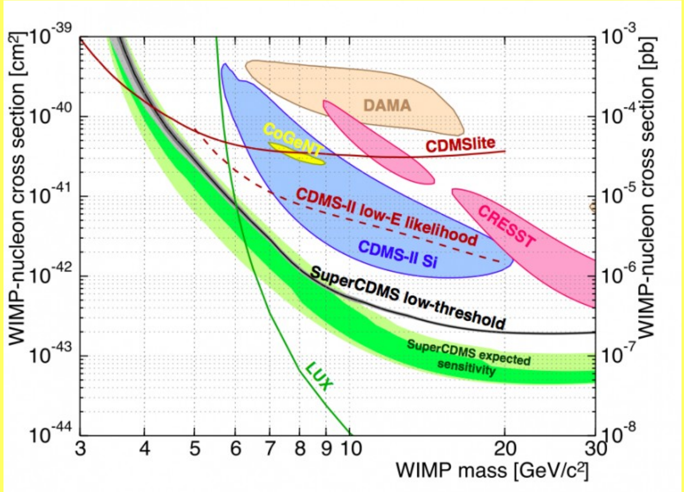
similar: **EDELWEISS** @ Modane
new low-mass limit also challenges CDMS-II-Si
arXiv:1504.00820

Rejection of Surface Events



Appl.Phys.Lett. 103 (2013) 164105

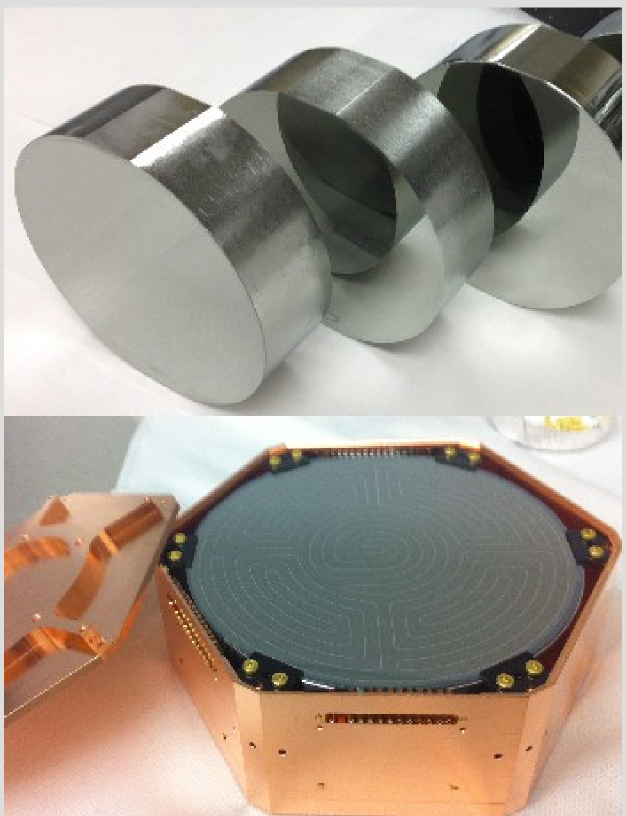
First results on low-mass WIMPs

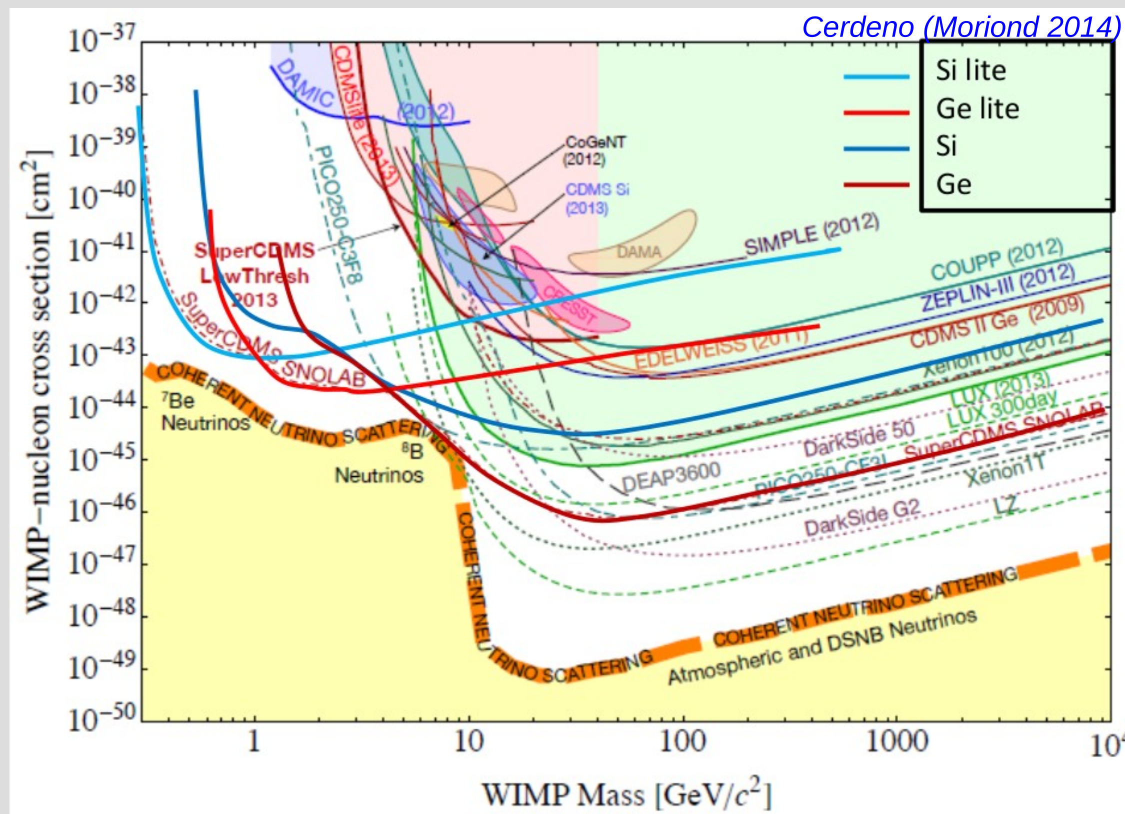


PRL 112, 241302 (2014)

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

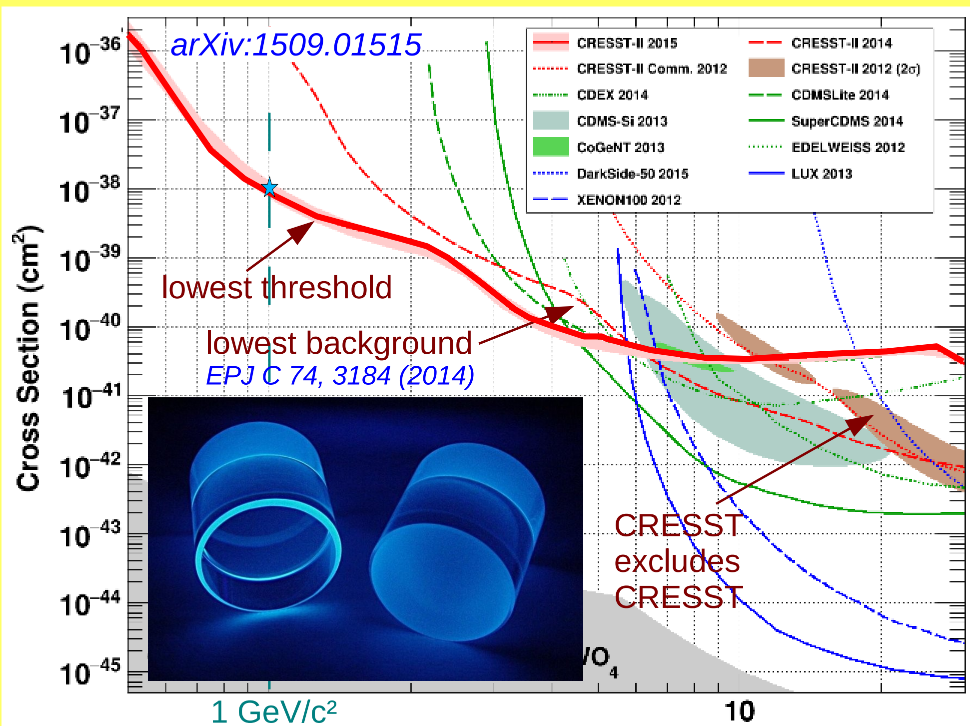




Towards lowest WIMP masses

CRESST @ LNGS

- reads phonons and scintillation light
- target: $CaWO_4$ → multi-element material
- successful background reduction; data taking since 2013
- new result 2015: detector with 300 eV threshold
- focus on low-mass WIMPs

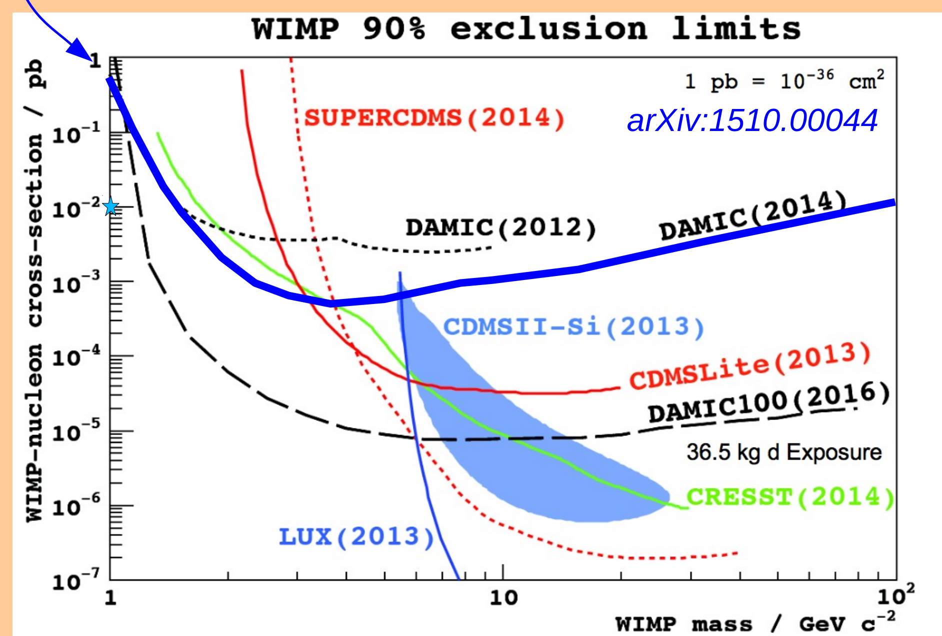


DAMIC @ SNOLAB

- 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

new (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



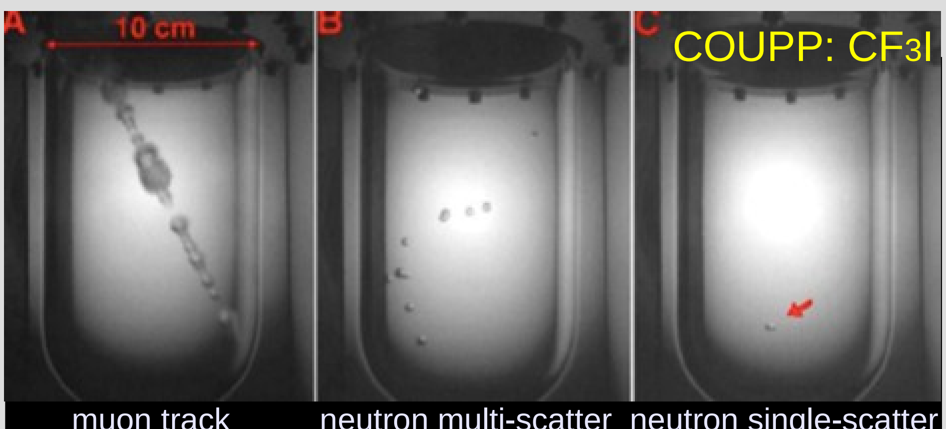
Spin dependence: Threshold Detectors

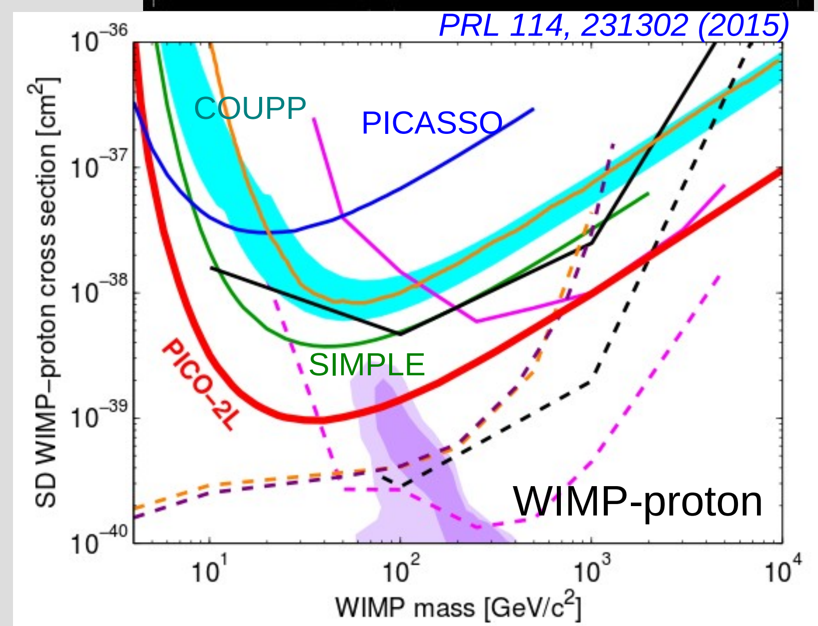
PICO @ SNOLAB

- 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

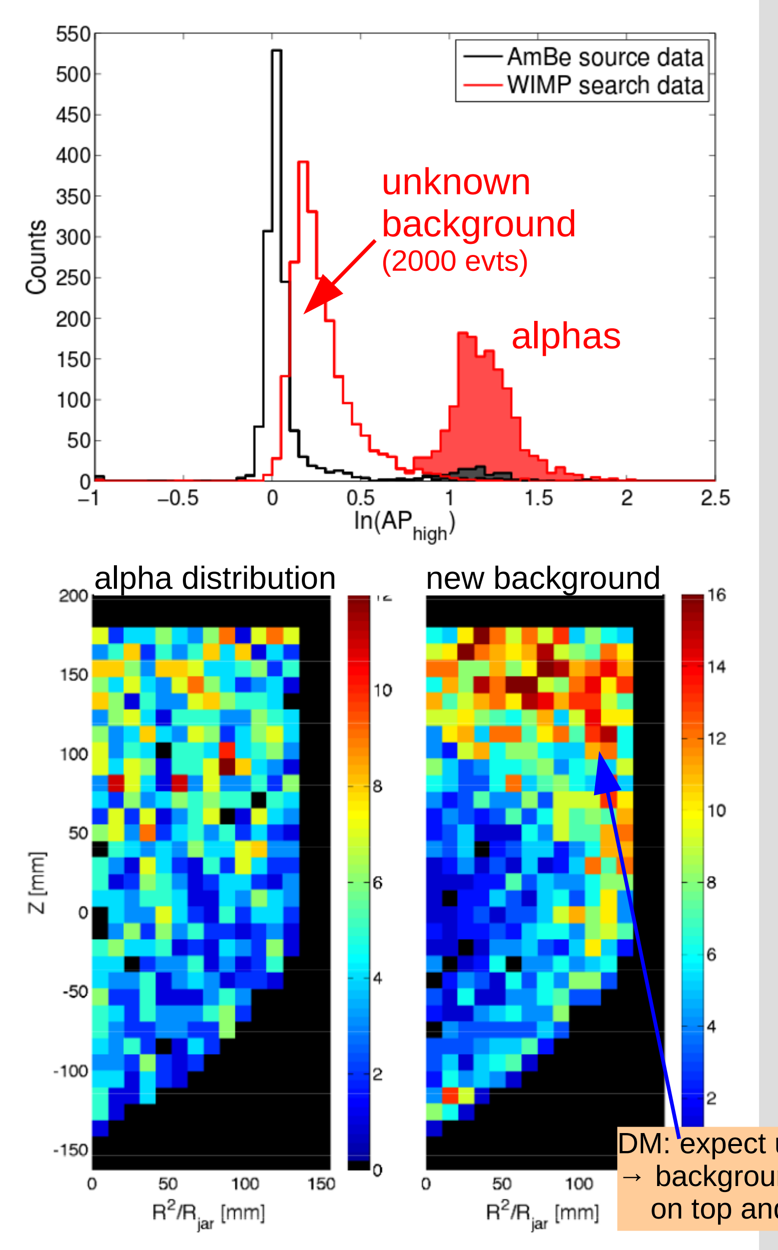




PICO-60: CF_3I data analysis finalized → C_3F_8
Upgrade plan: PICO-250 → SD reach ~10^{-42} cm²

PICO-60: New Result

arXiv:1510.07754



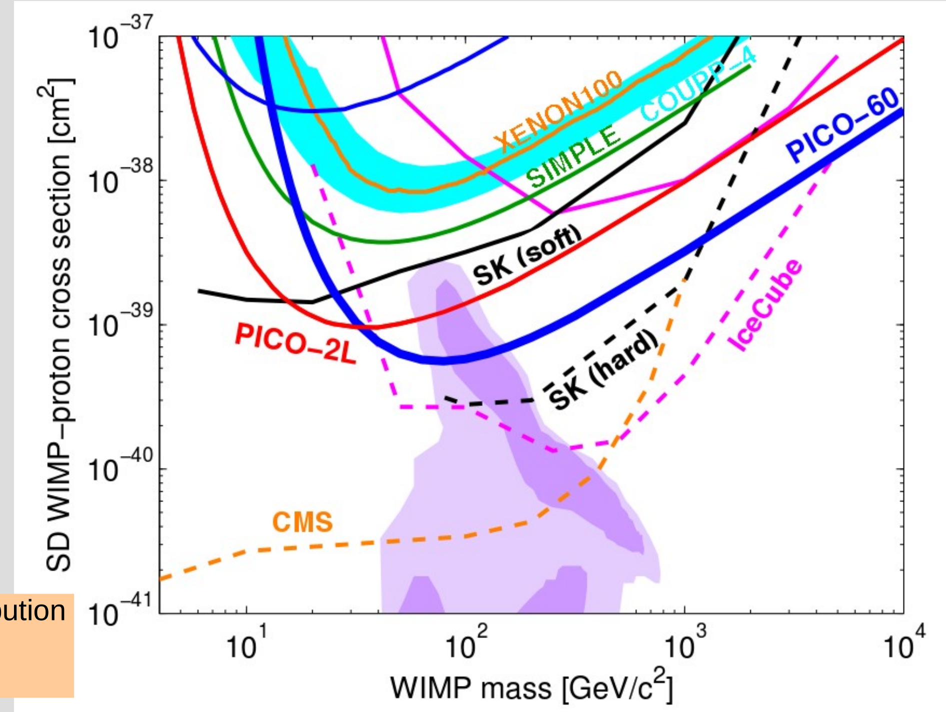
PICO-60 is largest bubble chamber to date

- 36.8 kg x 92.8 days exposure @ SNOLAB
- filled with CF_3I
- observe large background: acoustic, spatial and time distribution inconsistent with WIMP expectation

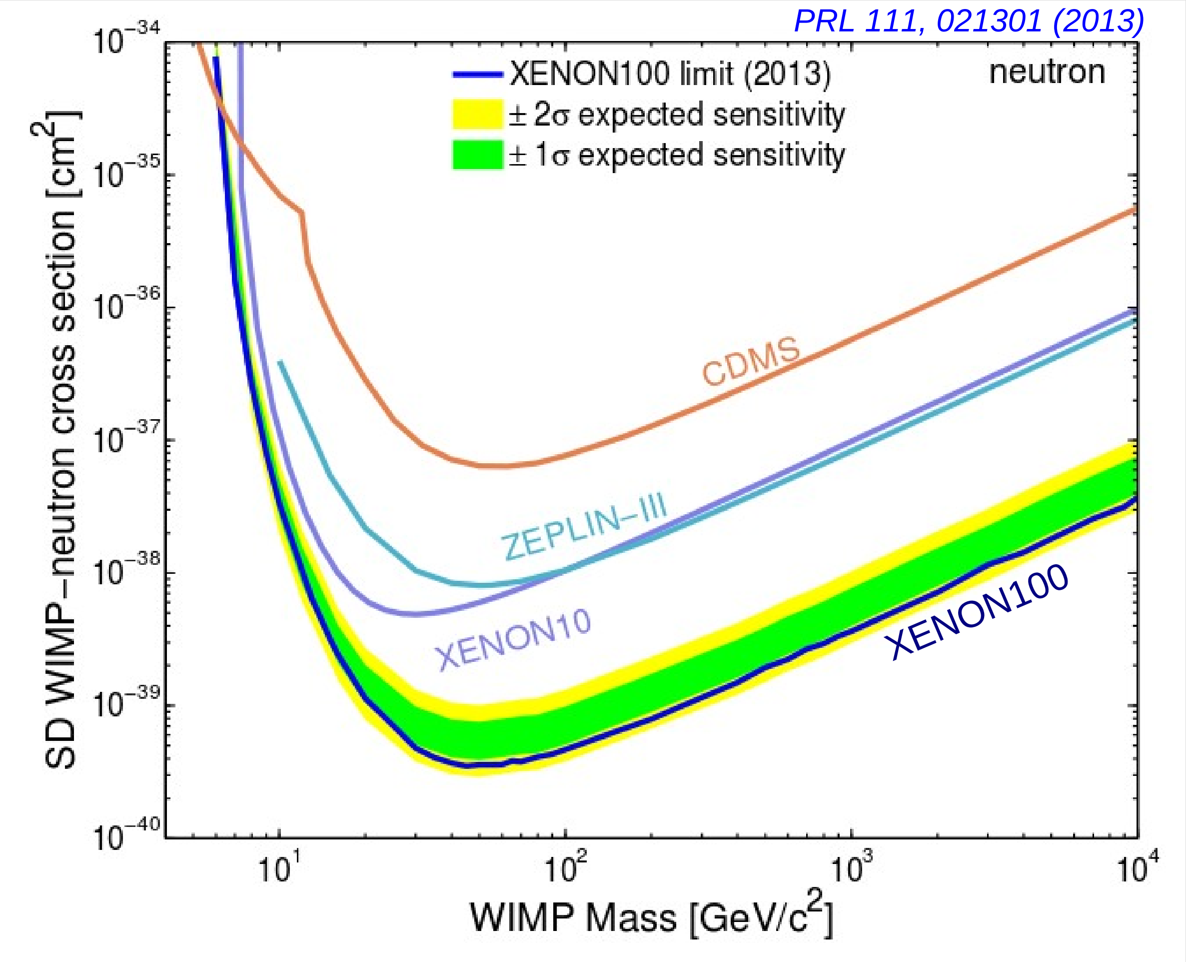
→ use cuts to reject background (48.2% acceptance)

→ new best limit for SD WIMP-proton couplings

DM: expect uniform distribution
→ background clustered on top and walls



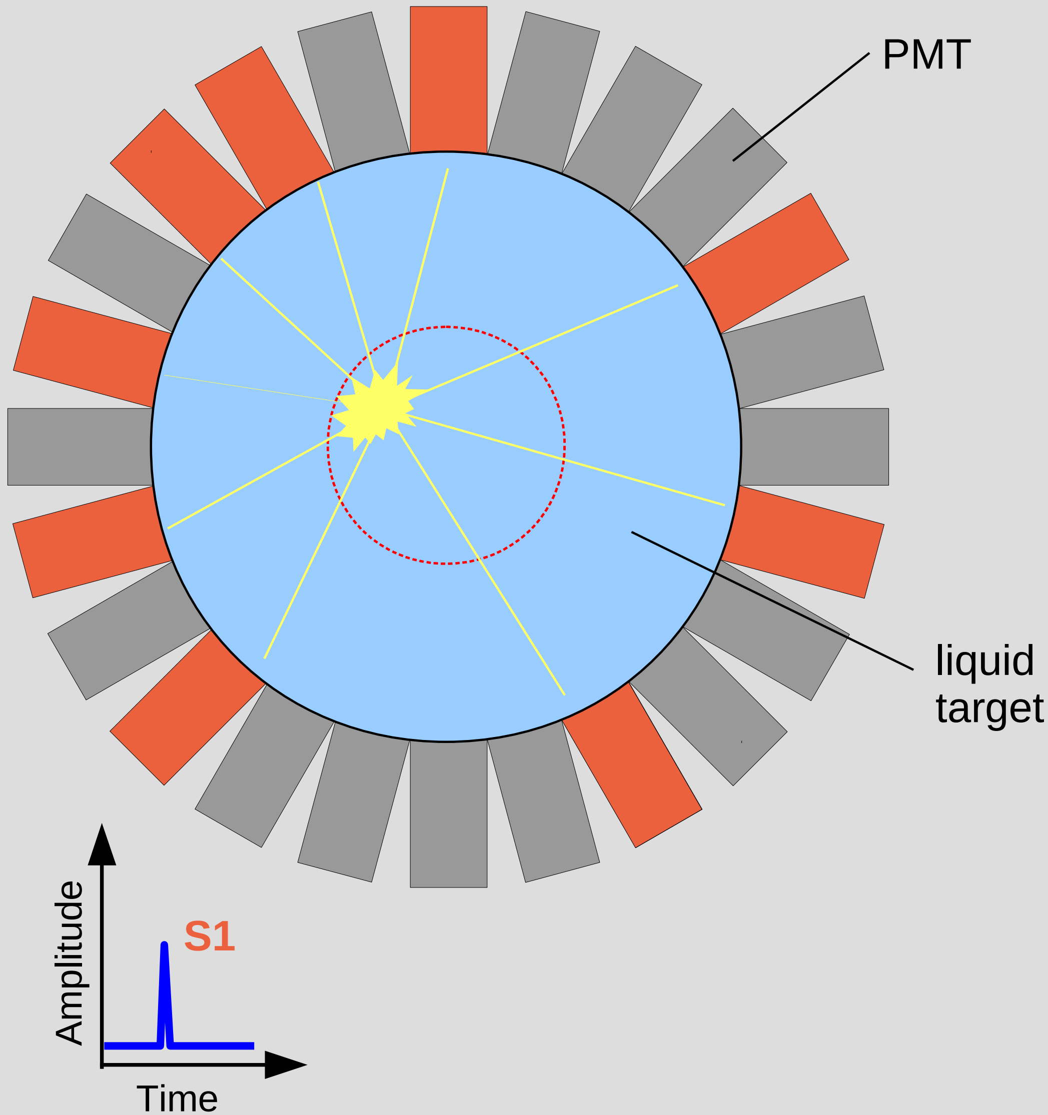
Spin-dependent: Neutron-Only



Liquid xenon detectors dominate neutron-only parameter space

Liquid Noble Gases: Detector Concepts

Single Phase Detector



Noble Gas: Single Phase Detectors

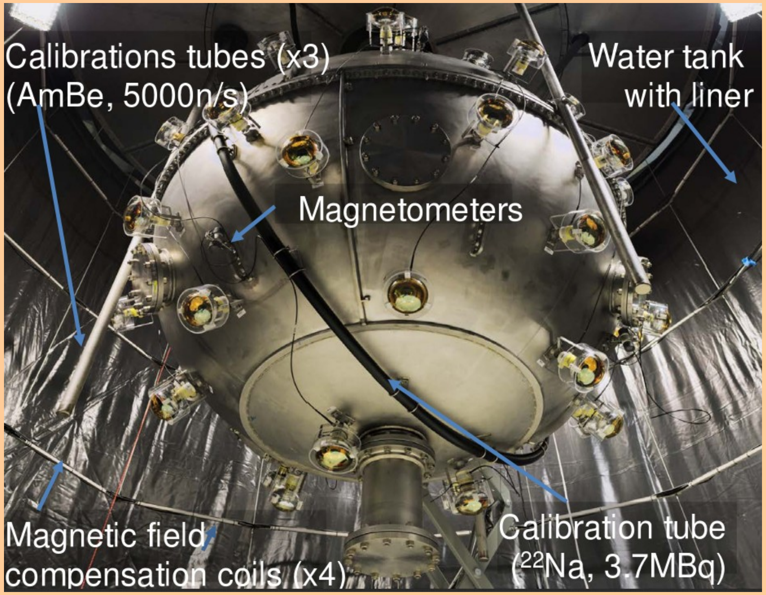
+ no high voltage, very high light yield **–** O(cm) position resolution, no double scatter rejection

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)

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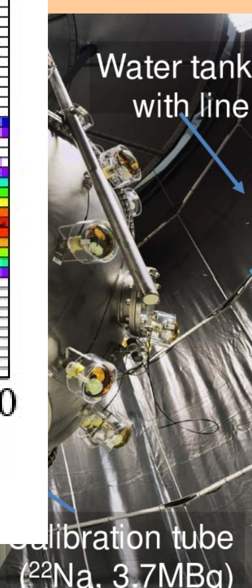
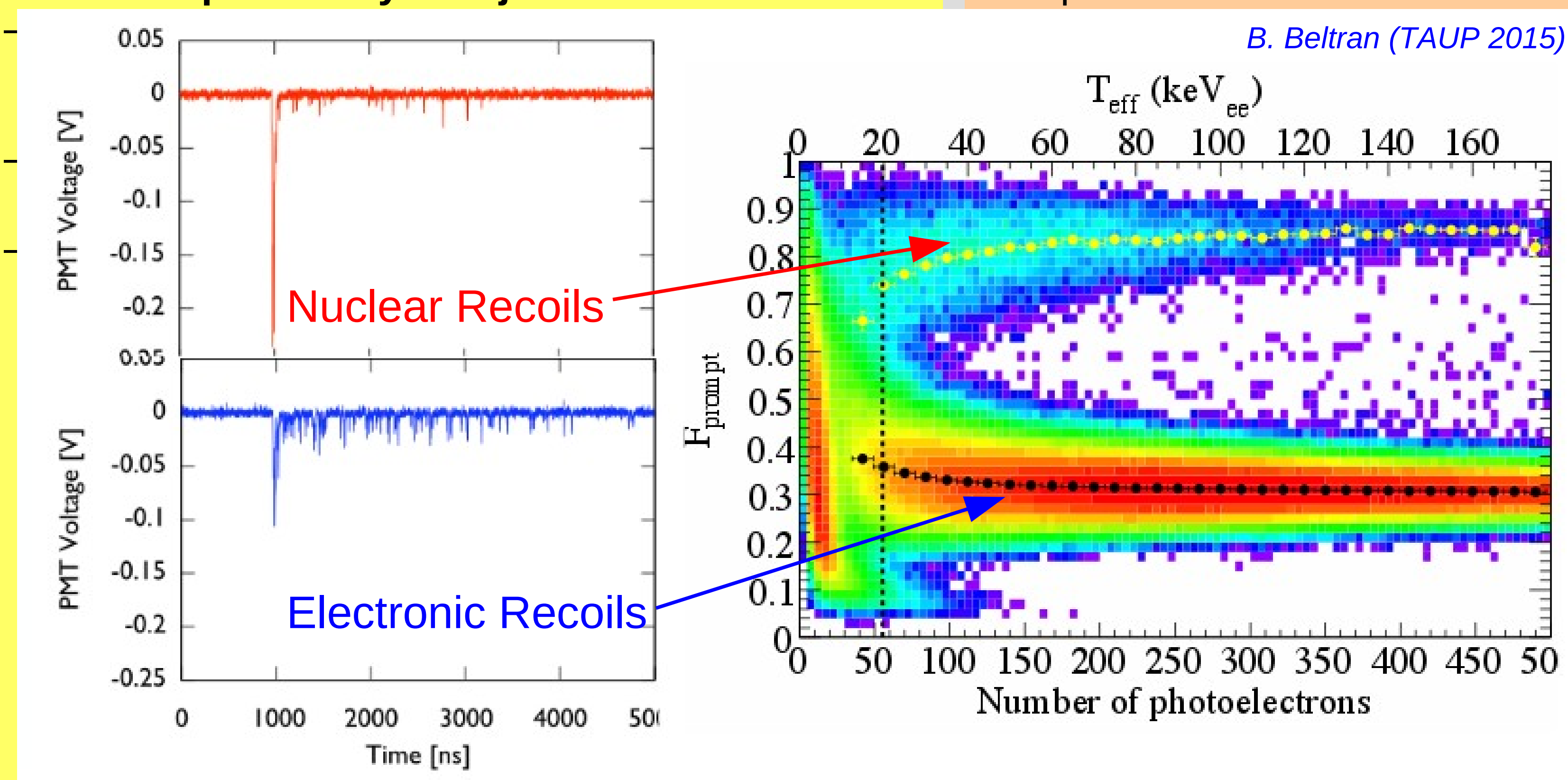
g ^{nat}Ar (~1 Bq/kg)
Ar in summer
result in 2016
GeV/c²
grade“ to 50t

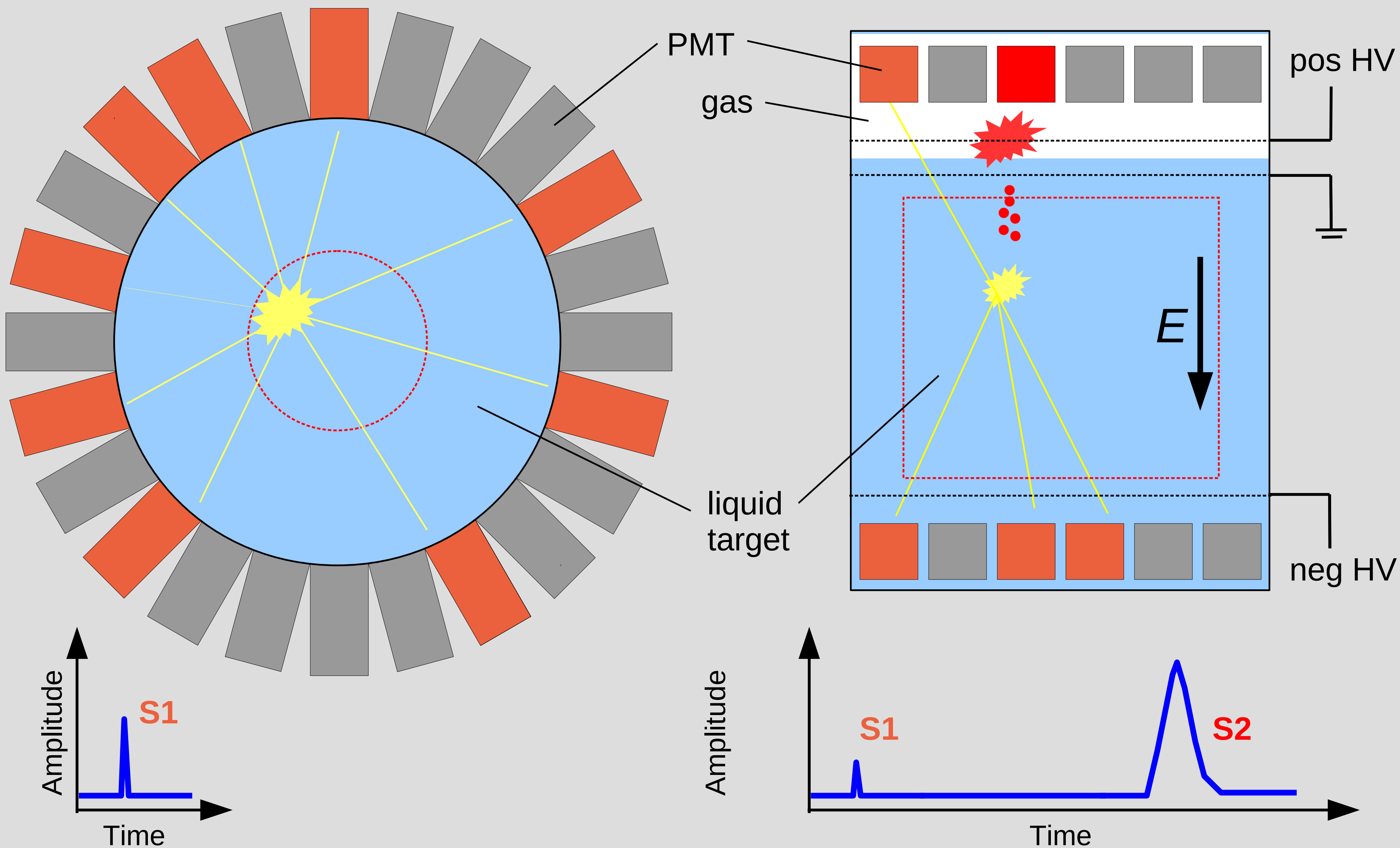


F. Retiere (LIDINE 2015)



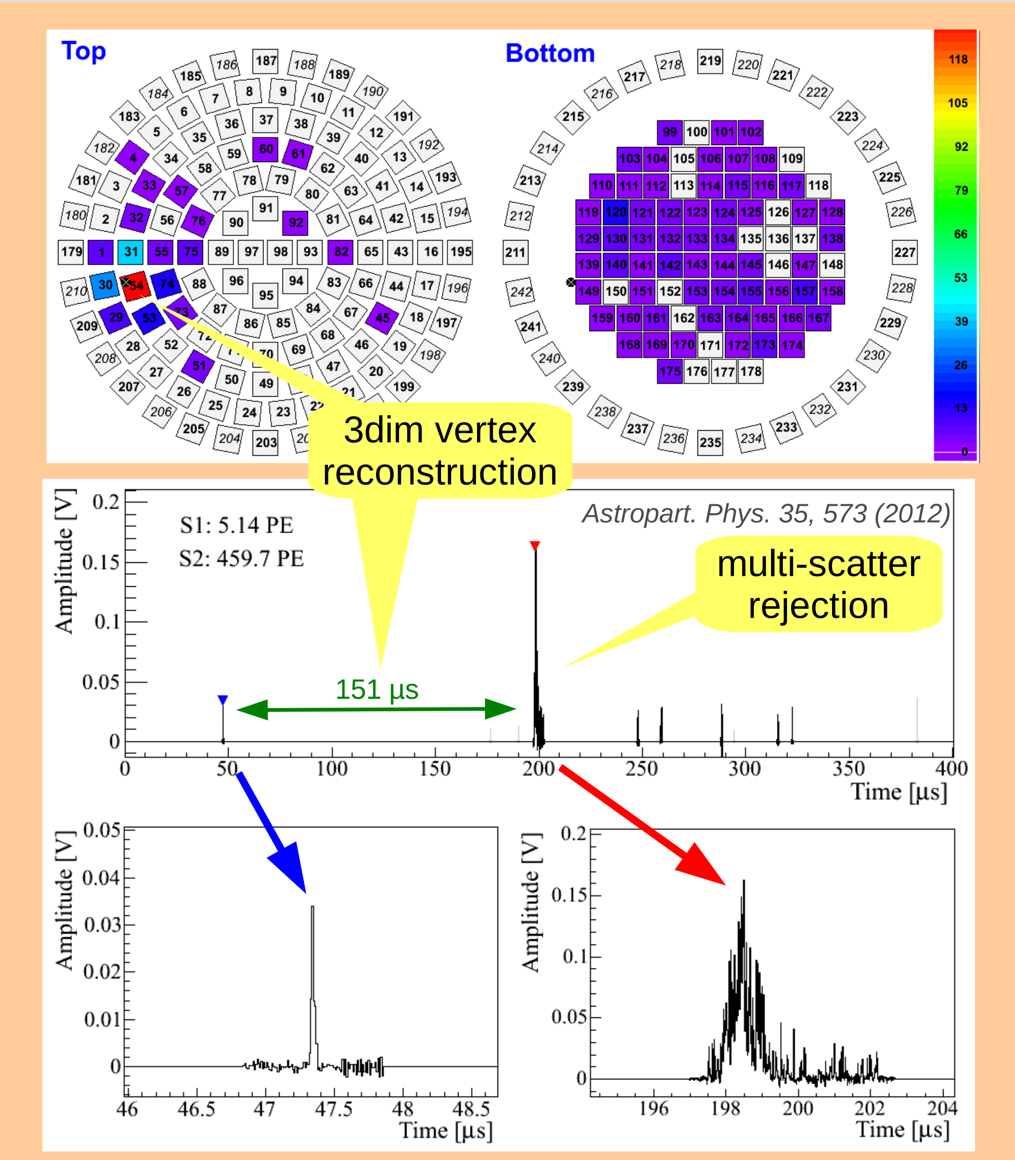
Liquid Noble Gases: Detector Concepts

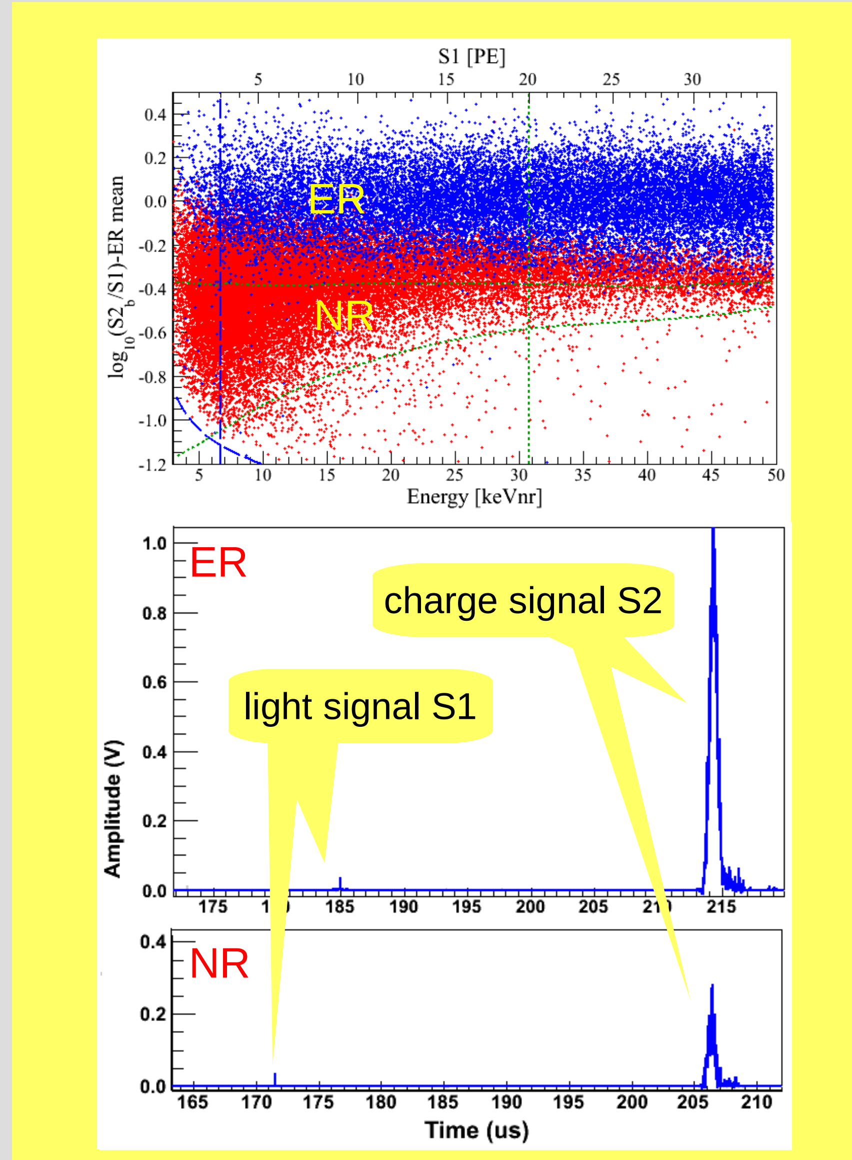
Single Phase Detector | Time Projection Chamber



Dual Phase TPC

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





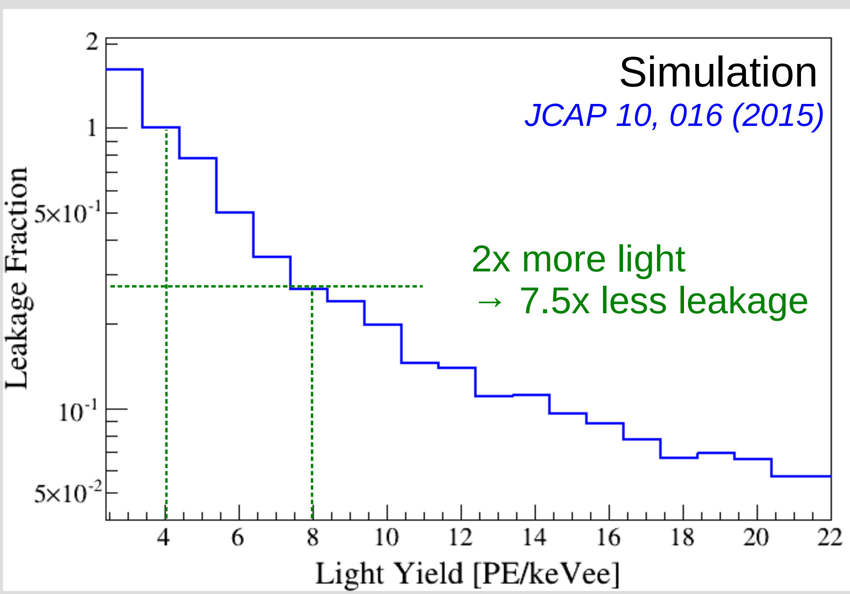
Figures from XENON100

Dual Phase TPC

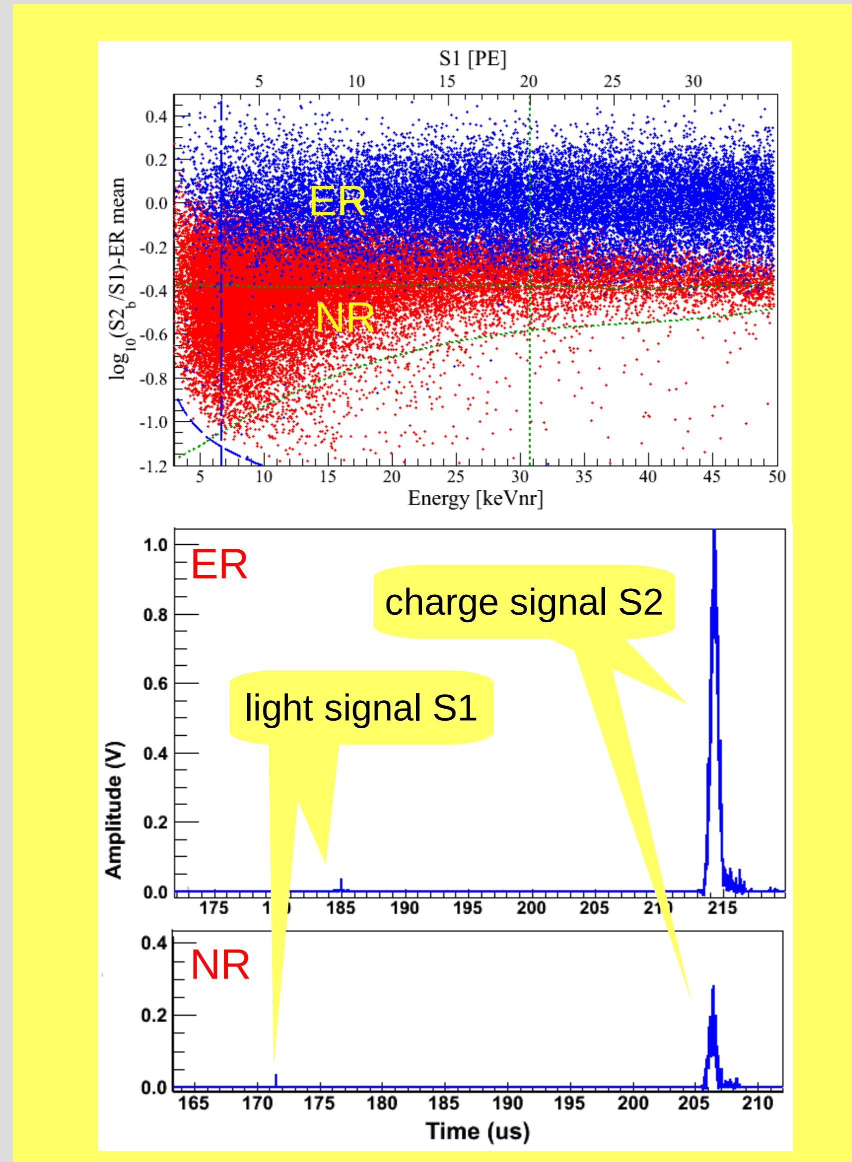
ER Rejection	NR Acceptance
99.50%	~50%
99.75%	~40%
99.90%	~30%

XENON100 achieved

Improve rejection (at a given acceptance)
→ need more S1 light!



→ rejection levels of 99.98% are in reach!

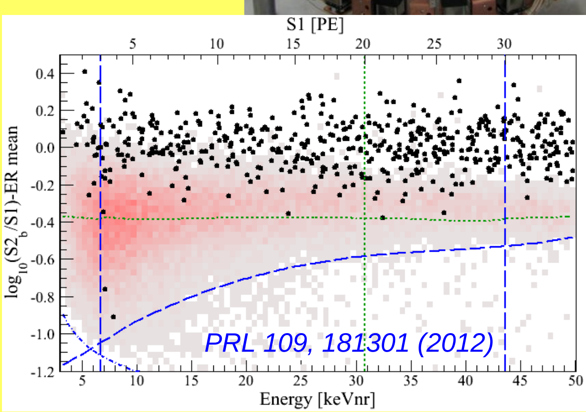


Figures from XENON100

LXe: Existing dual phase detectors

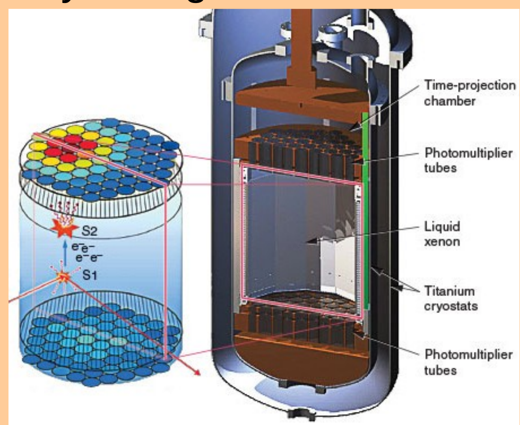
XENON100 @ LNGS (IT)
Astropart. Phys. 35, 573 (2012)

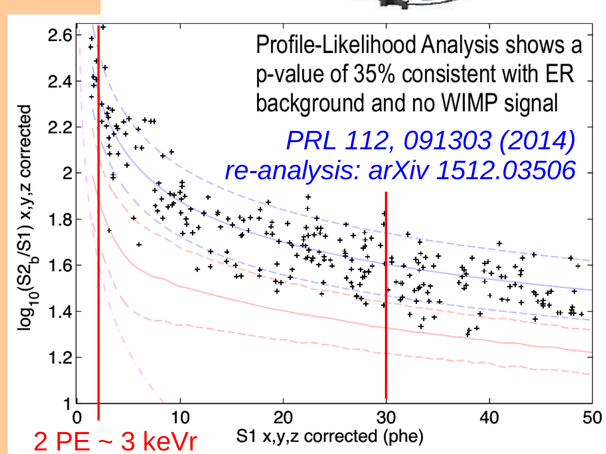
- 62 kg LXe, 225×34kg exposure
- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, ...
- still running as testbench



LUX @ SURF (USA)
NIM A 704, 111 (2013)

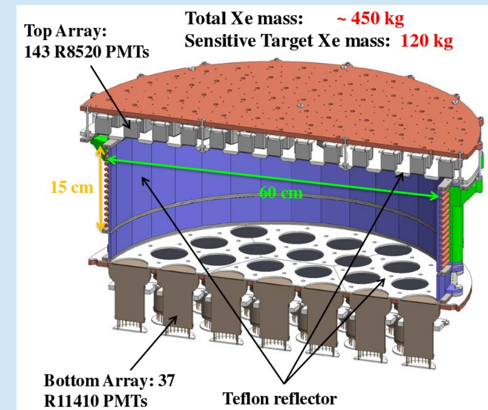
- best sensitivity above ~6 GeV/c²
- 250 kg LXe: 85d×118kg exp.
- high LY, inside water shield
- currently taking data

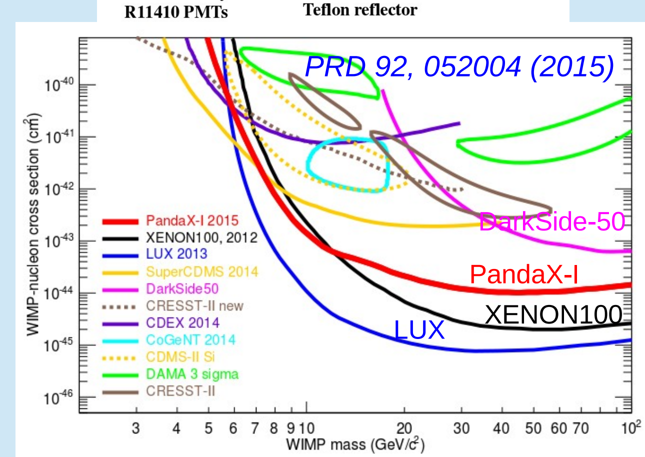




PandaX-I @ CJPL (CN)
Sci.China Phys.Mech.Astron. 57 (2014) 1476

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



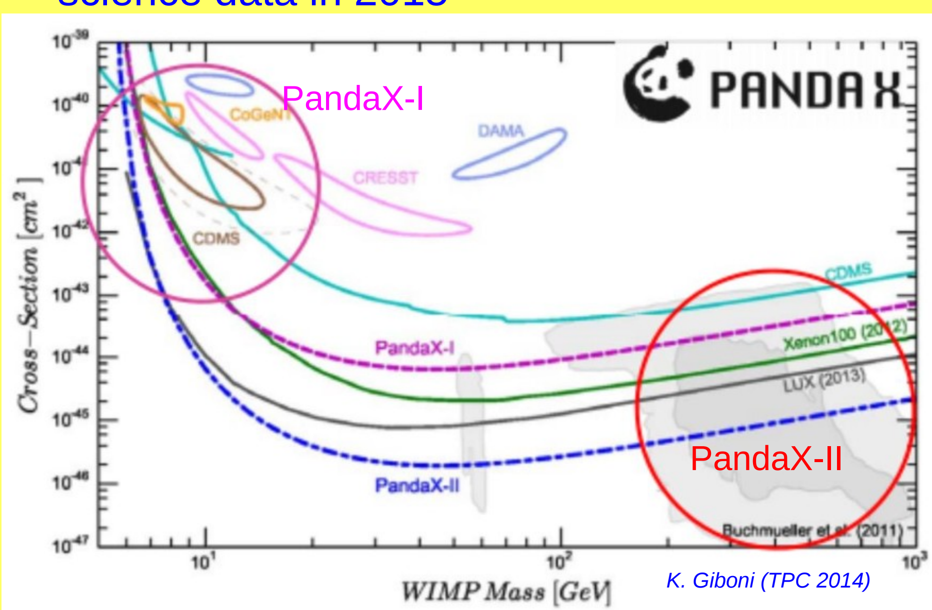


LAr TPC: **DarkSide-50** @ LNGS *arXiv:1510.00702*
→ first results with ^{39}Ar-depleted target (factor ~1400)

Upcoming Detectors

PandaX-II @ CJPL

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

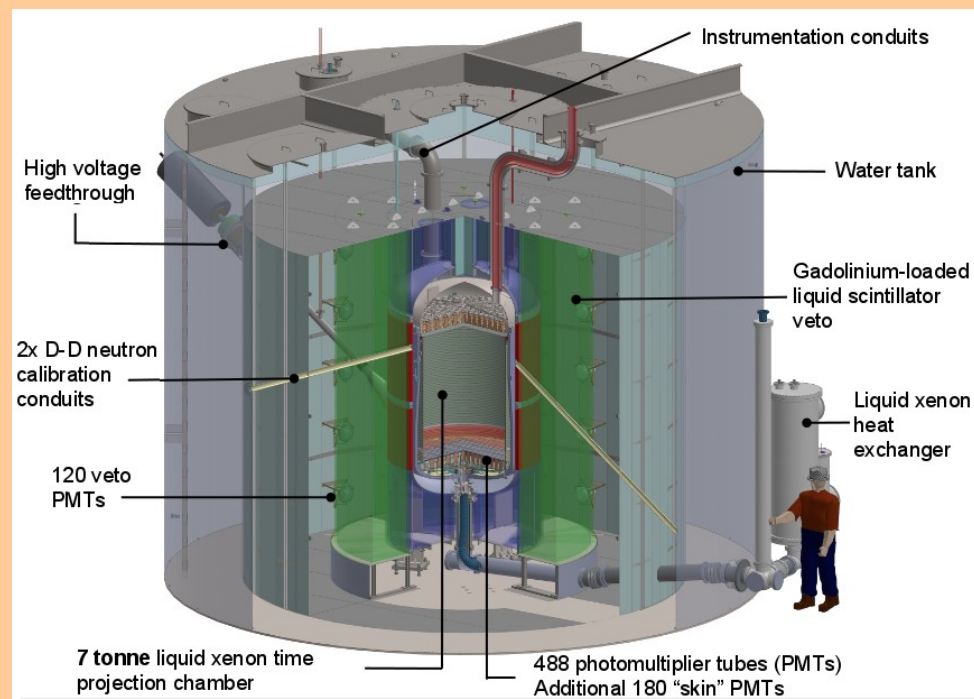


K. Giboni (TPC 2014)

LZ @ SURF

arXiv:1509.02910

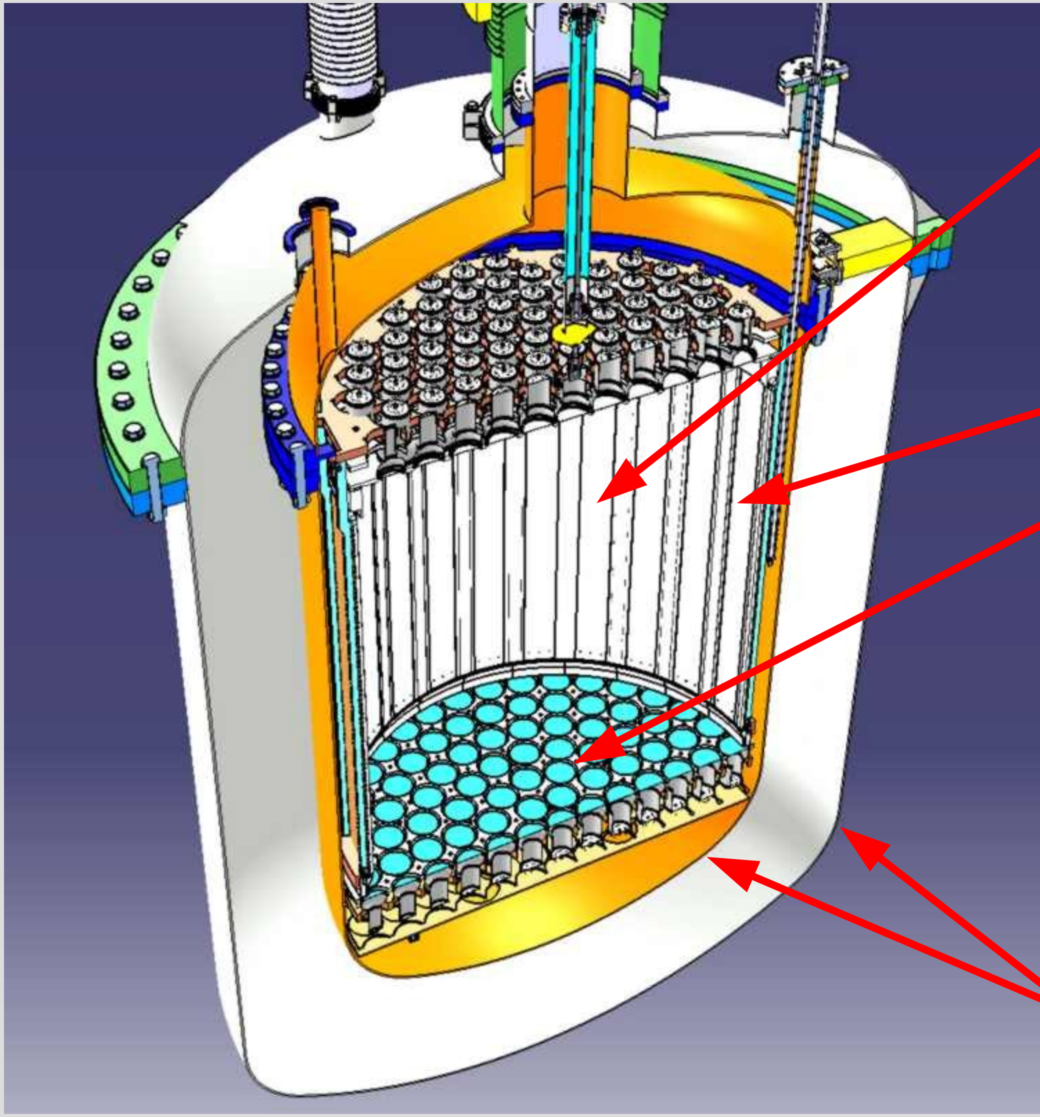
- LZ = LUX+ZEPLIN
  selected by 2014 US DOE-NSF downselection
- 50× larger than LUX
  10t total, 7t active target, 5.6t fiducial target
- 488 R11410 PMTs
- 2015: started procurement of Xe, PMTs, ...
  2019: expected start of comissioning
- goal: 2×10^{-48} cm² @ ~50 GeV/c² after 15 t×y exp



XENON1T @ LNGS


Xe
XENON
Dark Matter Project

XENON1T



dual-phase LXe TPC
- total mass ~3.5 t
- active mass ~2.0 t
- fiducial mass: ~1 t

TPC made from OFHC and PTFE

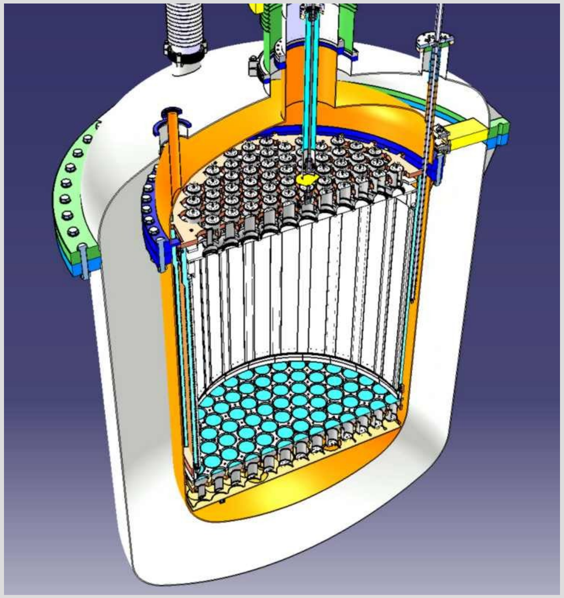
248 photomultipliers
- Hamamatsu R11410-21
- low background
  arXiv:1503.07698
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments
  JINST 8, P04026 (2013)

Low-background stainless steel cryostats

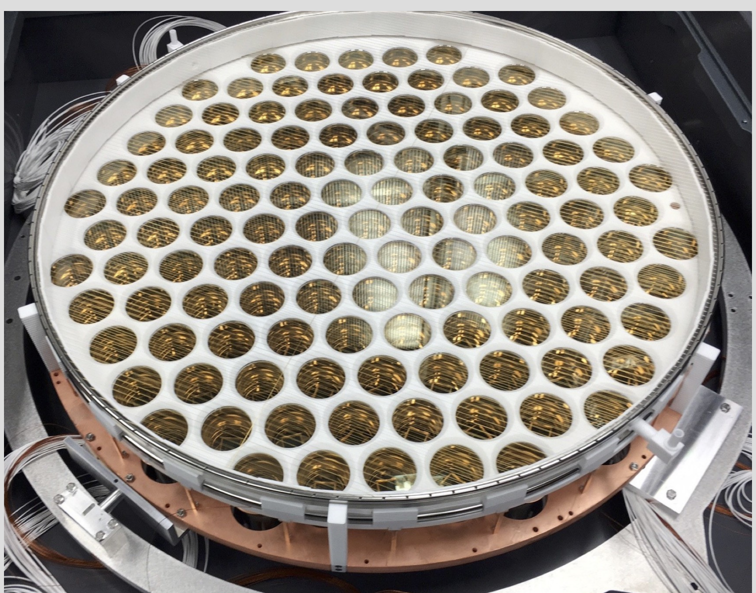

Xe
XENON
Dark Matter Project


Xe
XENON
Dark Matter Project

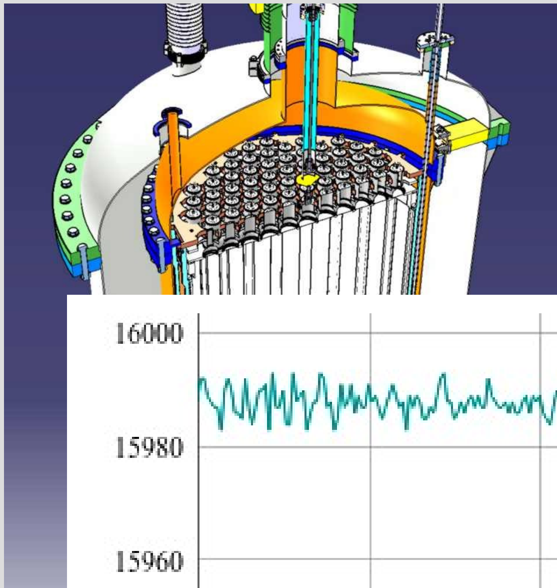
XENON1T



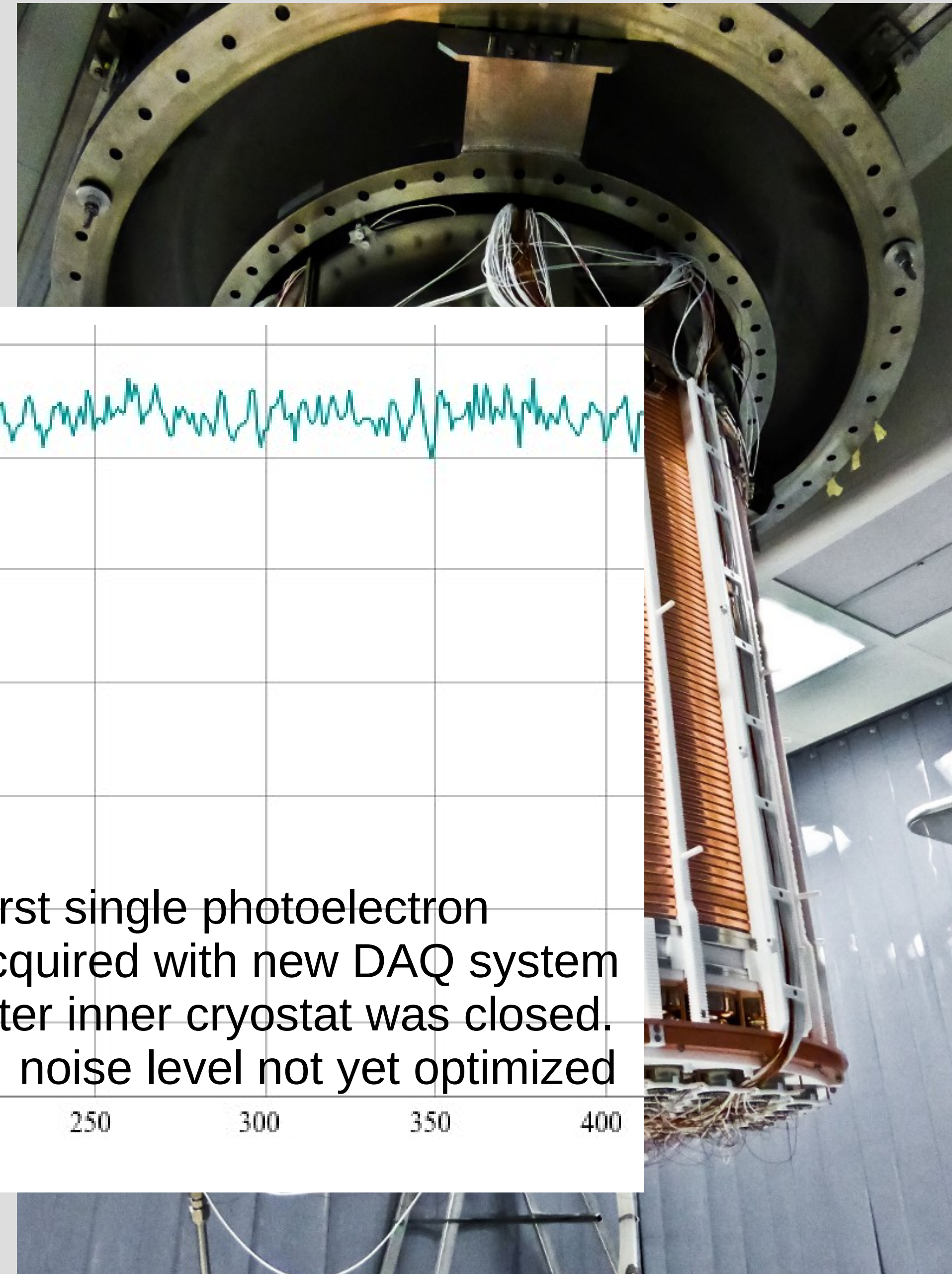
XENON1T
- 2t active target
- @commissioning
- first science data early 2016

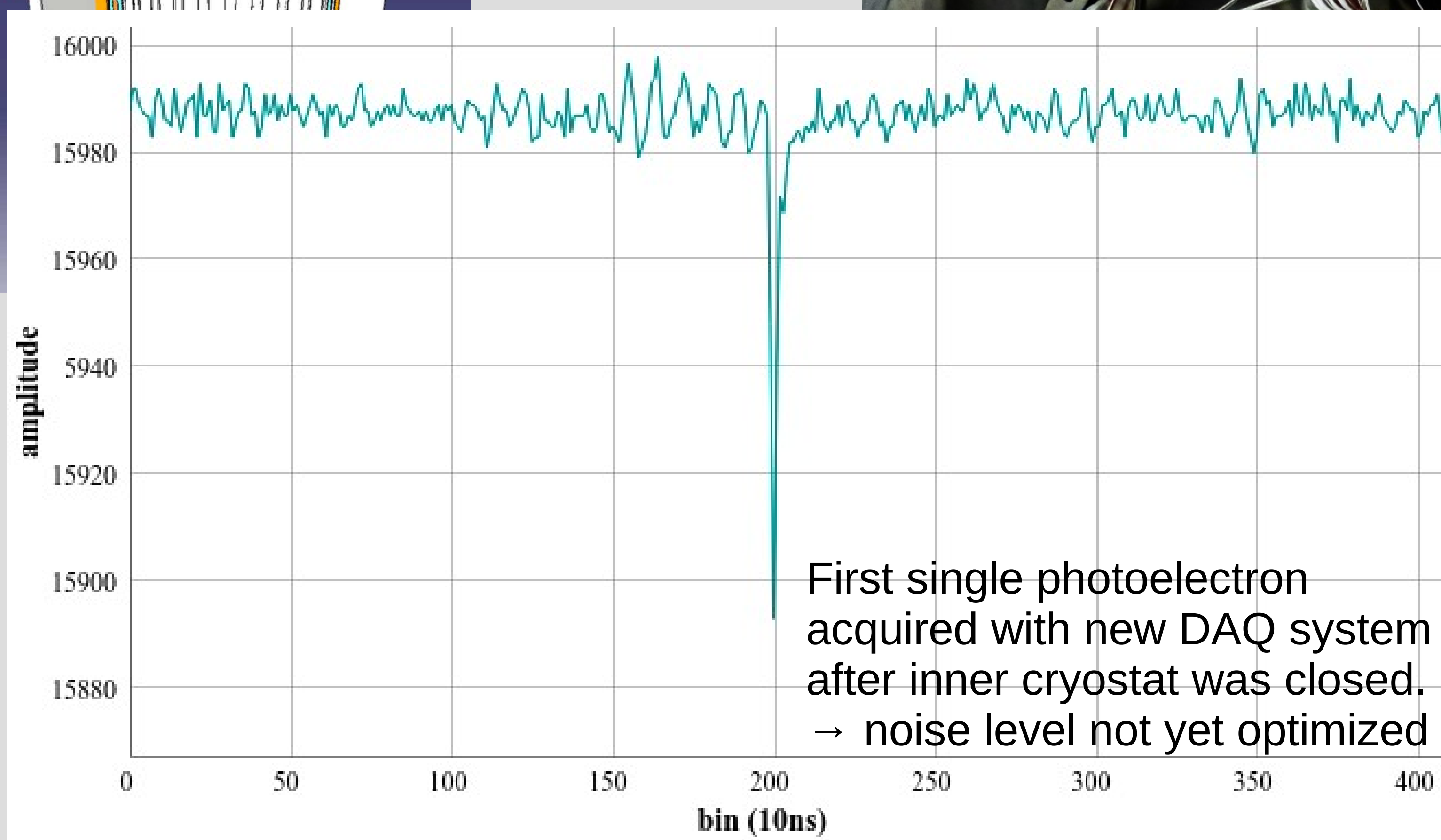


XENON1T



XENON1T
- 2t active target
- @commissioning
- first science data
  early 2016





First single photoelectron acquired with new DAQ system after inner cryostat was closed.
→ noise level not yet optimized

XENON1T Sensitivity

in preparation

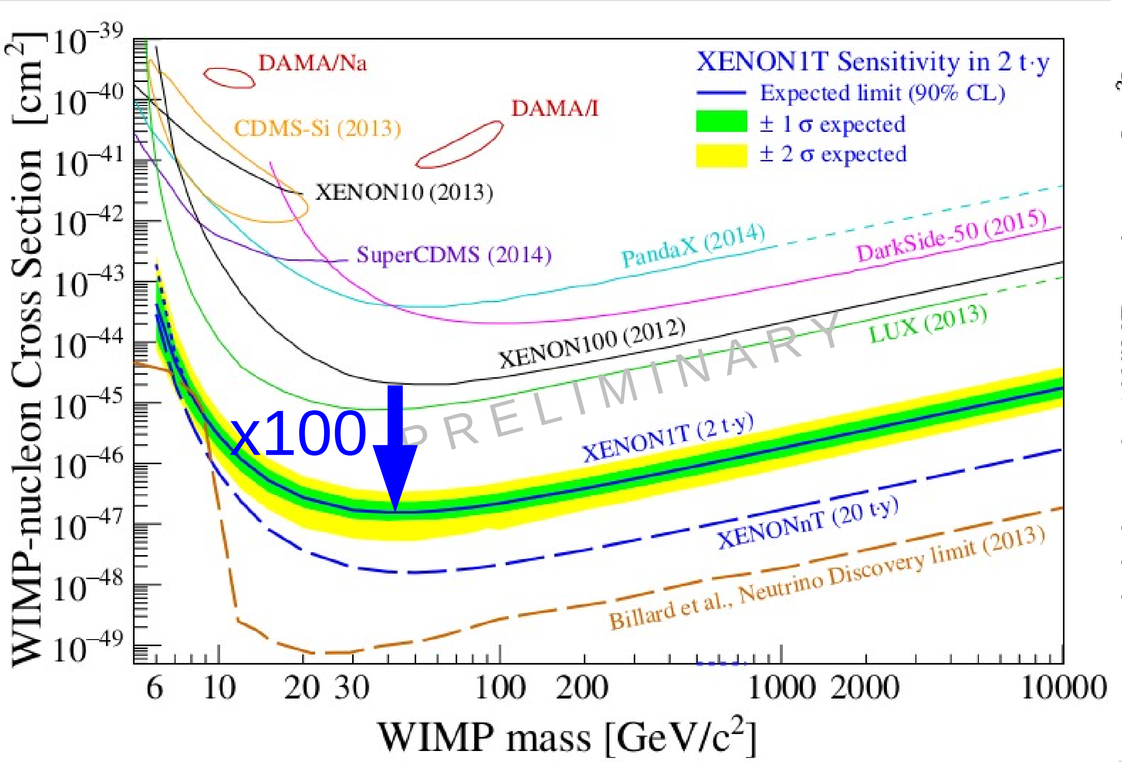
sensitivity study based on realistic background assumptions:

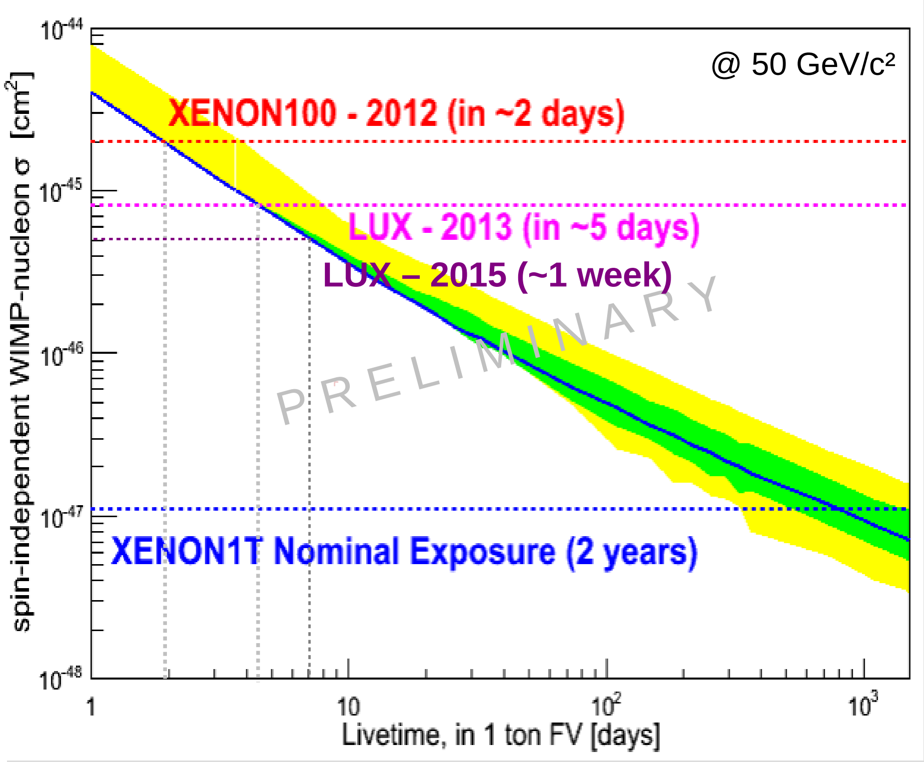
ER: materials (CAD and screening)
^{222}Rn: 10 µBq/kg
^{85}Kr: 0.2 ppt ^{nat}Kr/Xe
solar pp-, ^{7}Be neutrinos

NR: materials (CAD and screening)
CNNS (mainly from ^{8}B solar neutrinos)
µ-induced backgrounds irrelevant

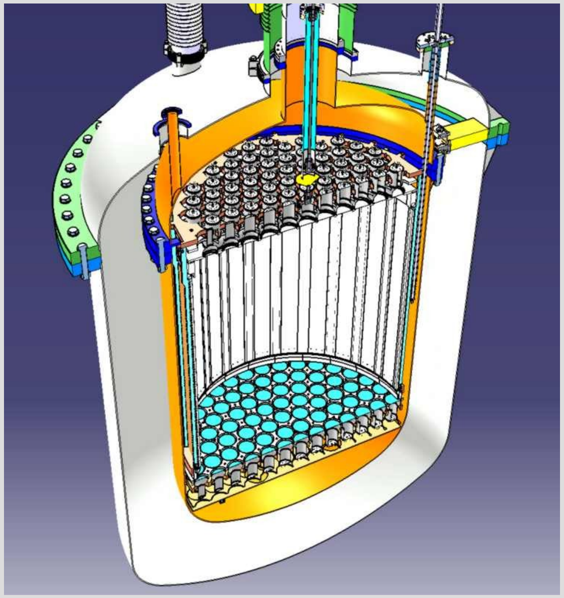
JINST 9, P11006 (2014)

LCE, light yield (7.7 PE/keV @ zero field), S1/S2 signal response, etc. also simulated



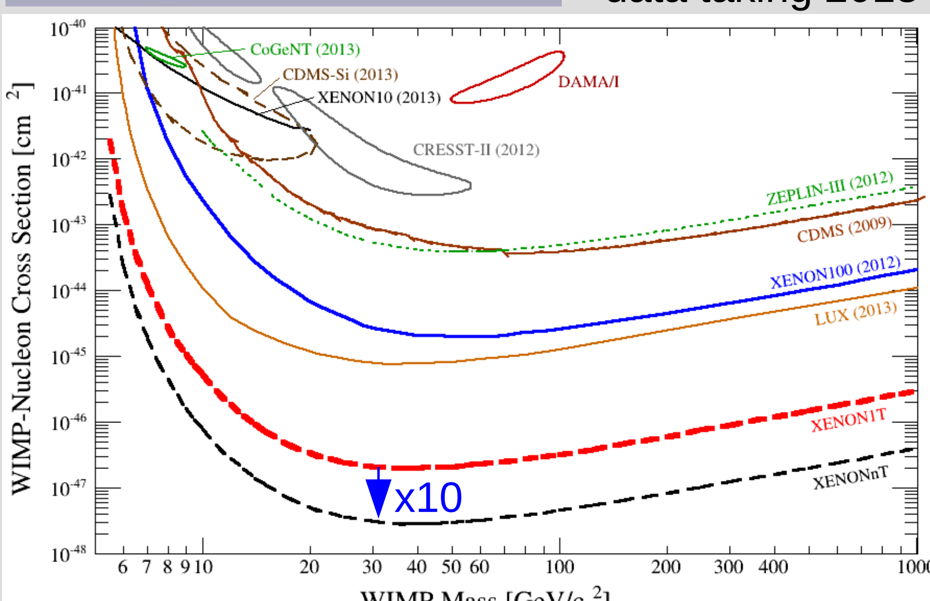


XENON1T → XENONnT



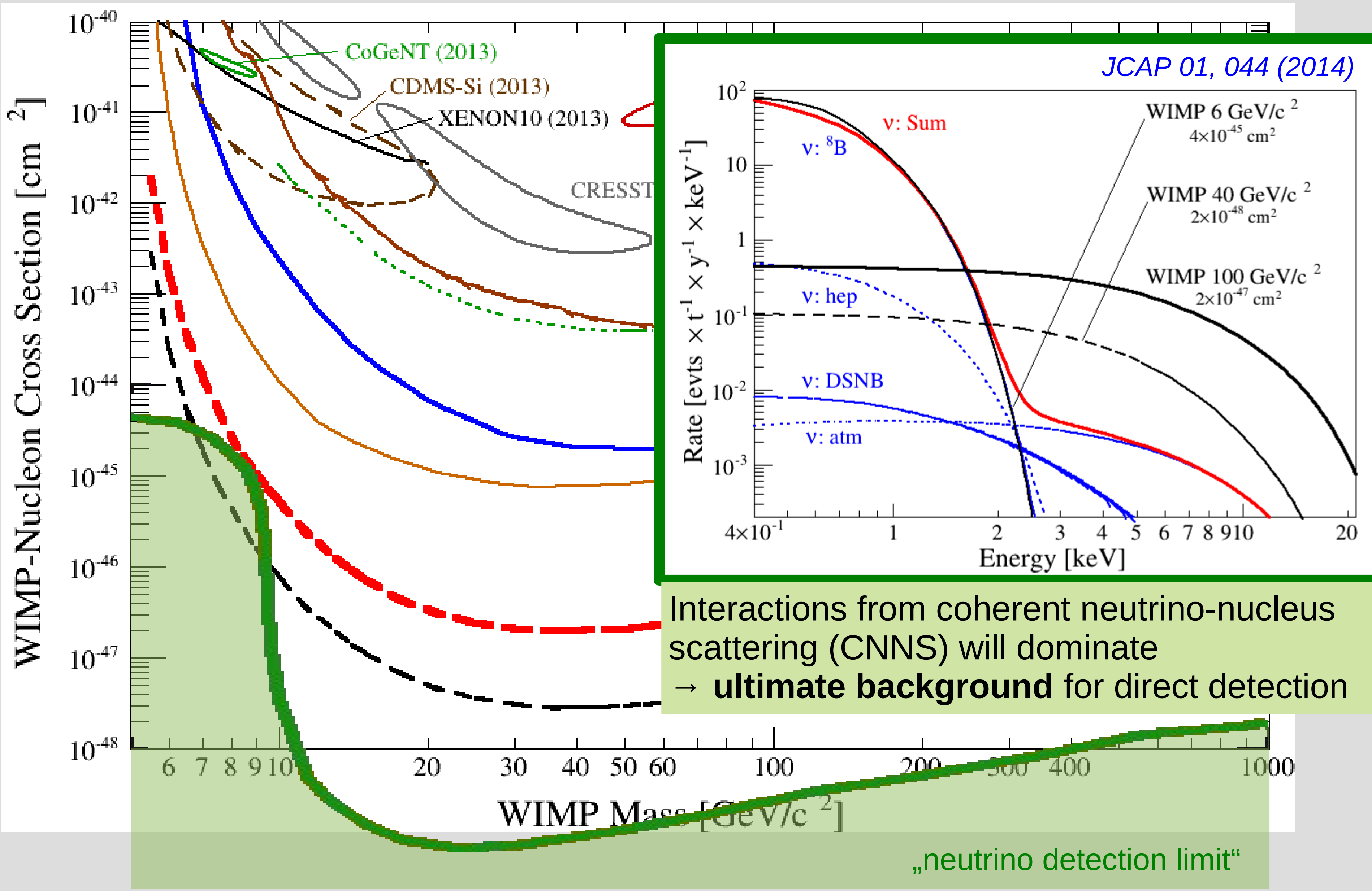
XENON1T
- 2t active target
- @commissioning
- first science data early 2016

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



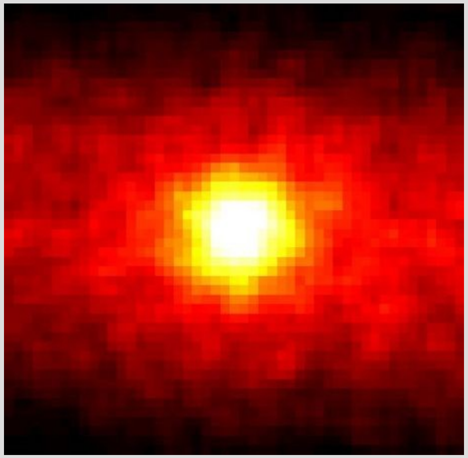
The XENON Future

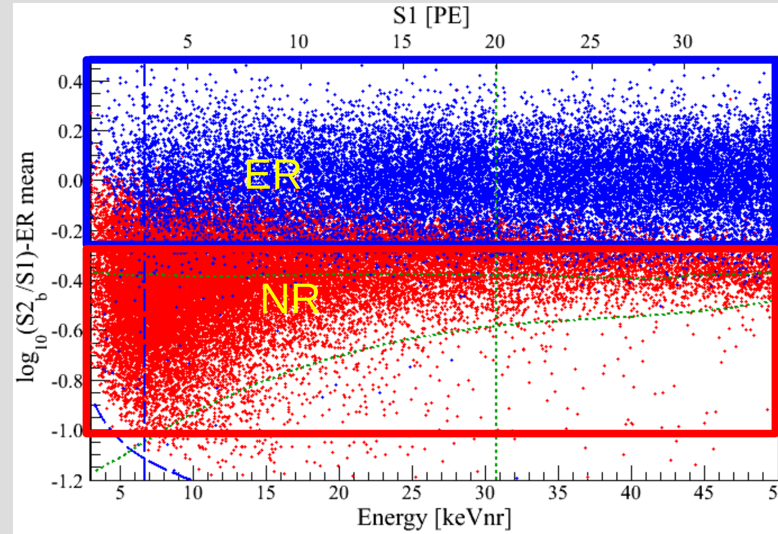
DARWIN



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

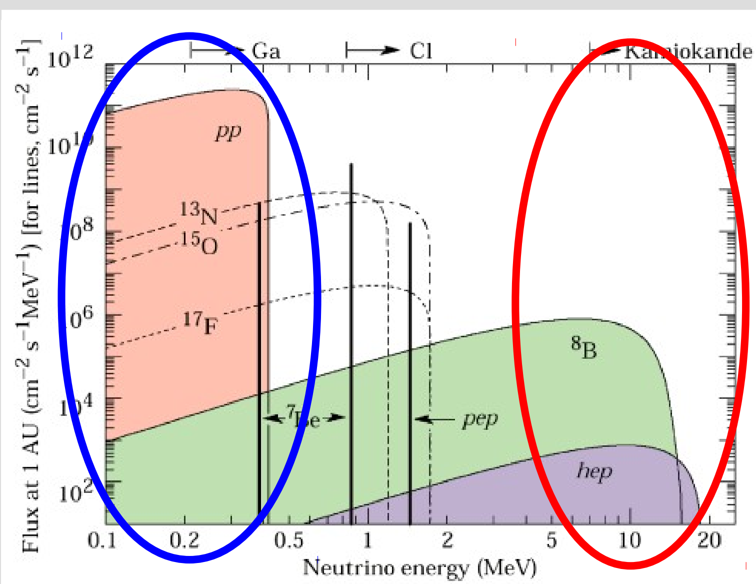
Cosmic Neutrino Sources

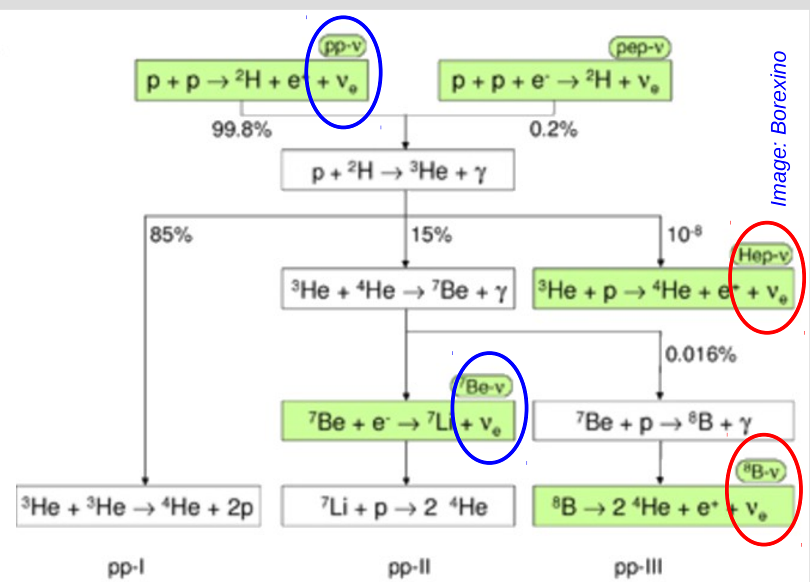




Solar neutrinos:
pp, ^{7}Be – ^{8}B, hep

Atmospheric neutrinos
+ diffuse SN background

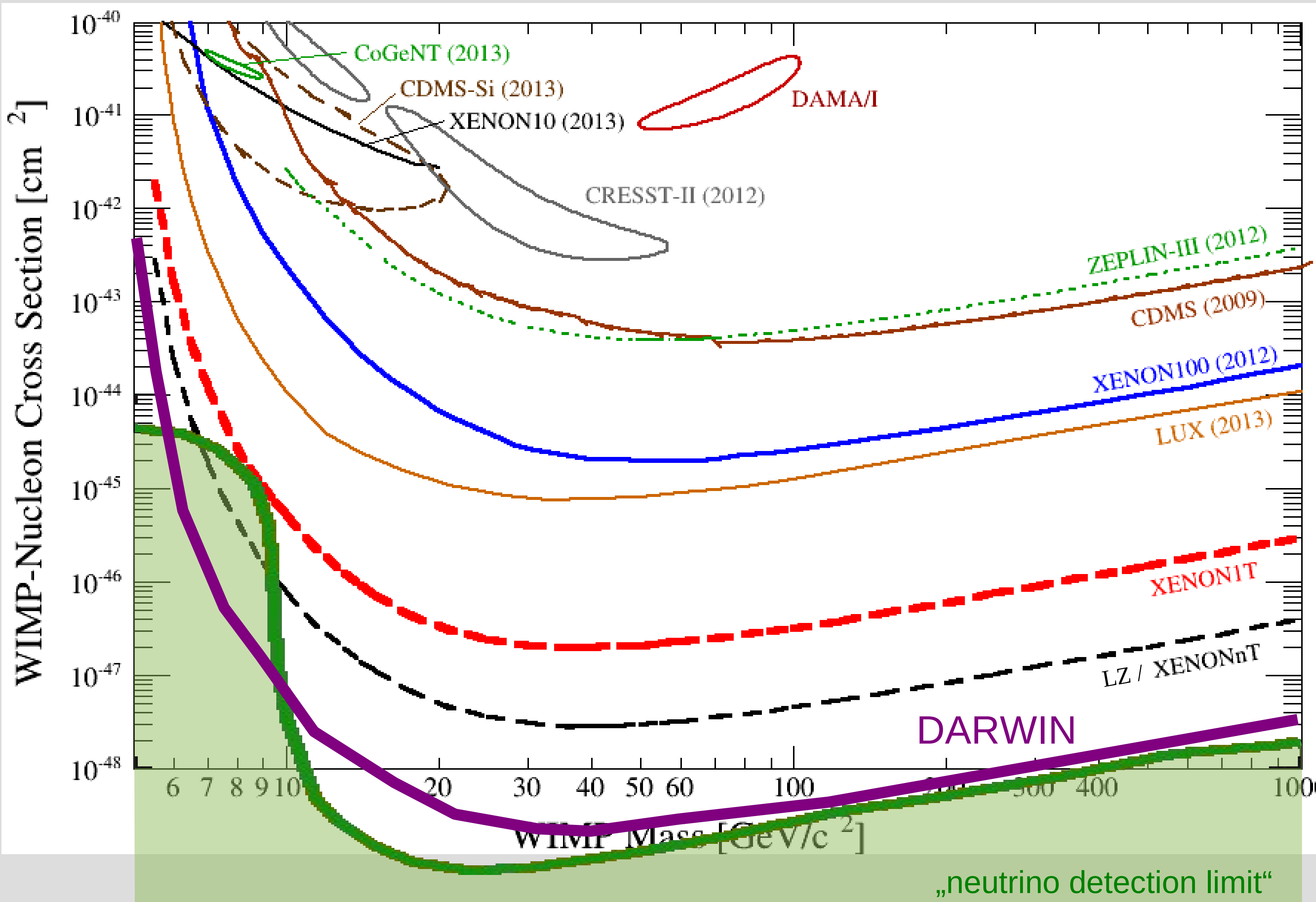




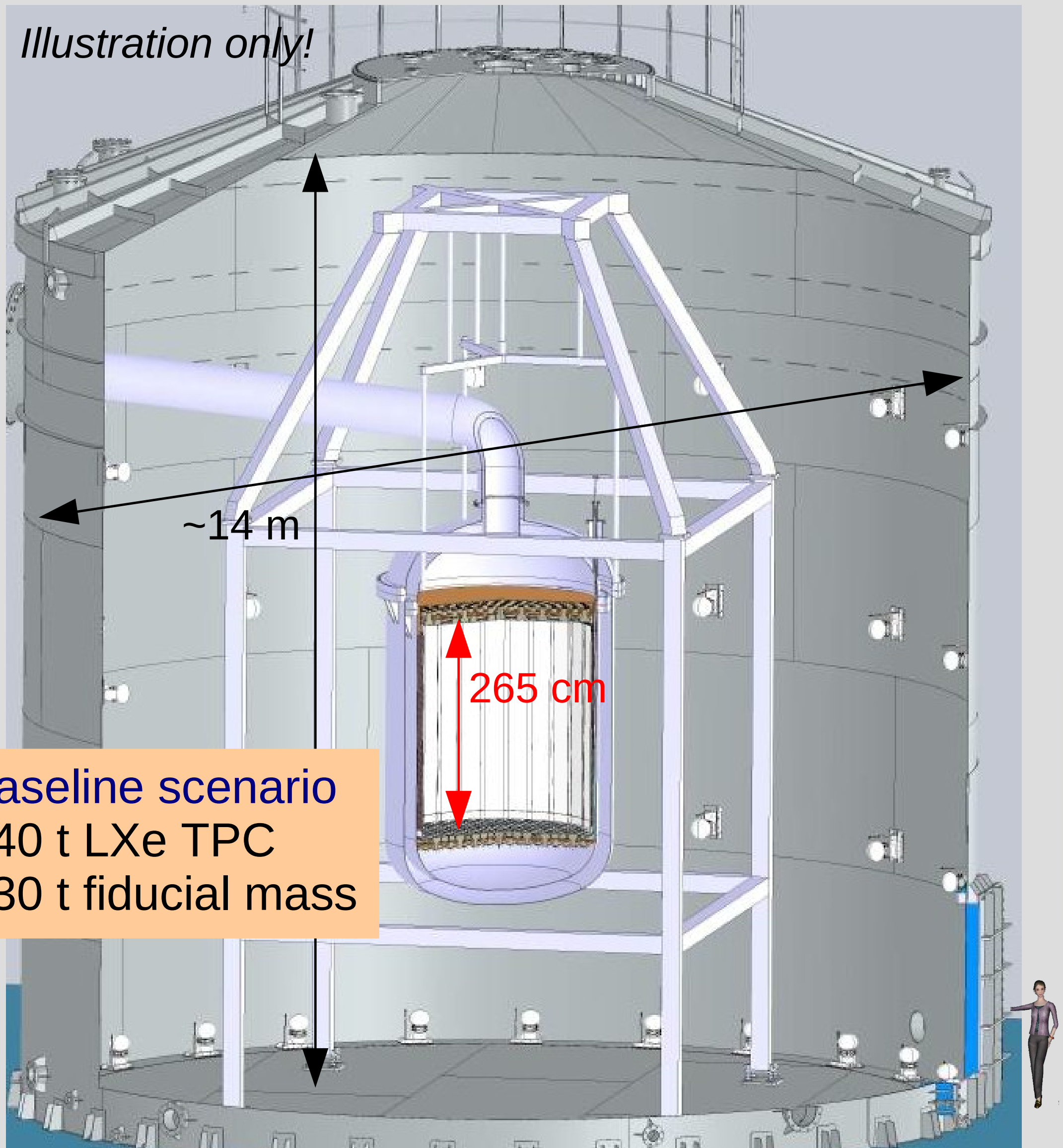
low-E solar neutrinos interact with electrons
→ electronic recoil
→ **can be rejected**

high E neutrinos (solar+DSNB) interact with Xe nuclei
→ nuclear recoil
→ **looks like a WIMP**

The DARWIN goal



DARWIN The ultimate WIMP Detector

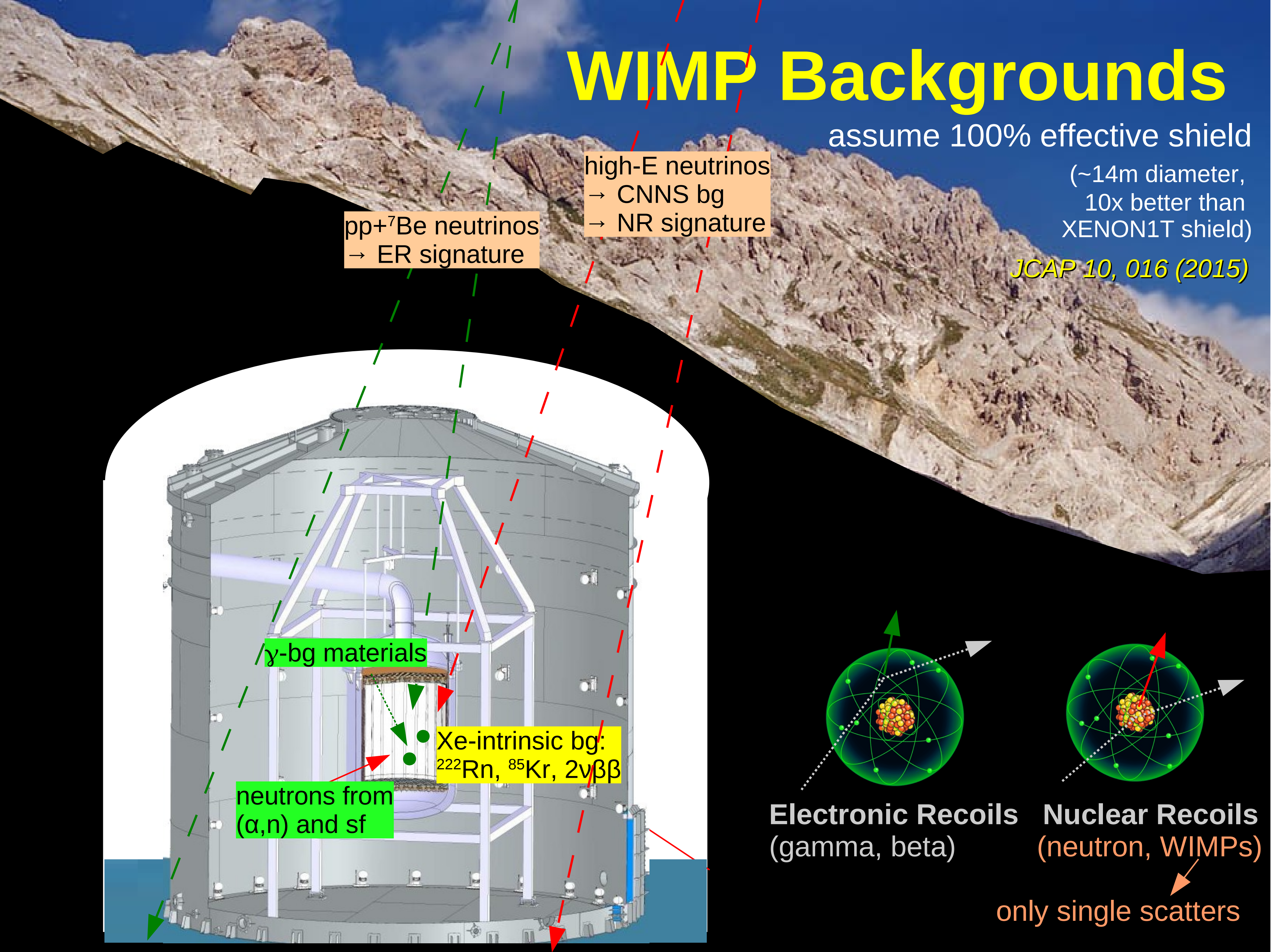


Baseline scenario
~40 t LXe TPC
~30 t fiducial mass

- 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

WIMP Backgrounds



Backgrounds

JCAP 10, 016 (2015)

All relevant backgrounds are considered:

Source	Rate [events/(t·y·keVxx)]	Spectrum	Comment
γ-rays materials	0.054	flat	assumptions as discussed in text
neutrons*	3.8×10^{-5}	exp. decrease	average of [5.0-20.5] keVnr interval
intrinsic ^{85}Kr	1.44	flat	assume 0.1 ppt of ^{nat}Kr
intrinsic ^{222}Rn	0.35	flat	assume 0.1 μBq/kg of ^{222}Rn
$2\nu\beta\beta$ of ^{136}Xe	0.73	linear rise	average of [2-10] keVee interval
pp- and ^{7}Be ν	3.25	flat	details see [19]
CNNS*	0.0022	real	average of [4.0-20.5] keVnr interval

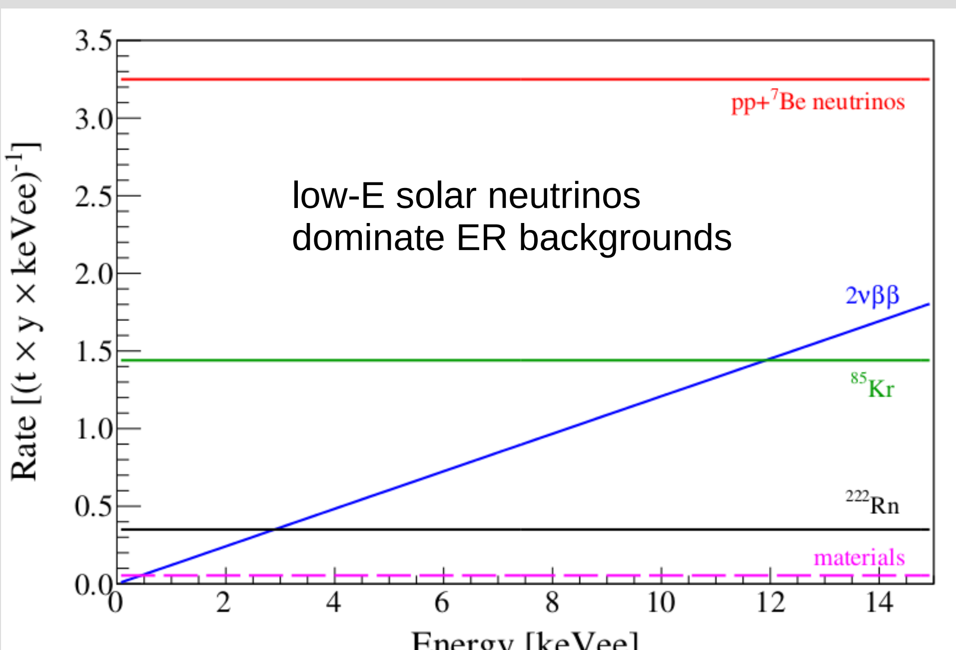
MC simulation of detector made of main components (PTFE, CU, PMTs): subdominant after ~15 cm fiducial cut

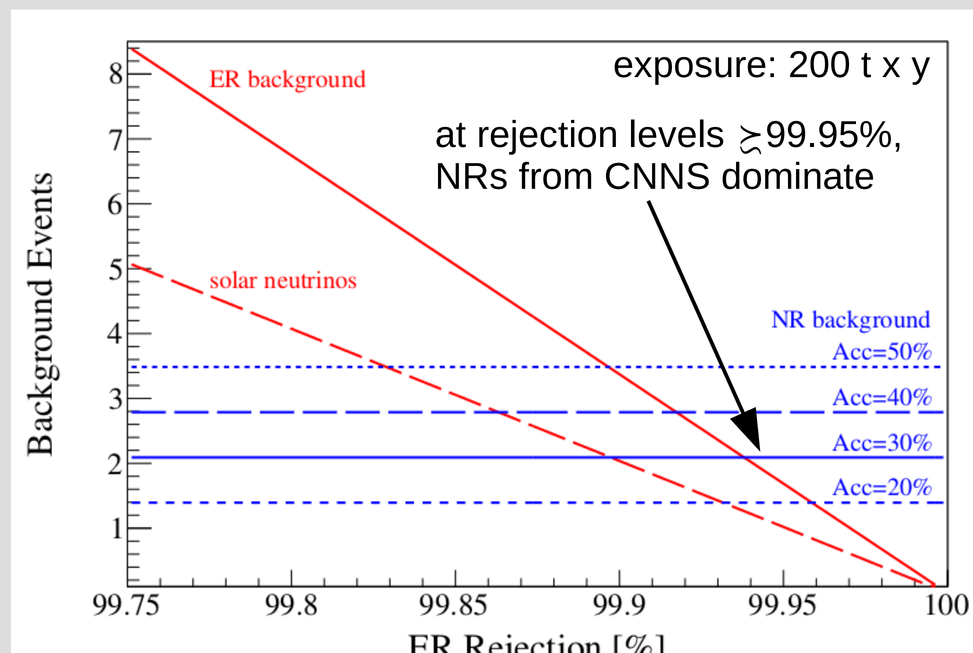
^{85}Kr: 2x below XENON1T design (0.03 ppt achieved: *EPJ C 74 (2014) 2746*)

^{222}Rn: 100x below XENON1T design

^{136}Xe: assume natural xenon

consider all relevant neutrinos



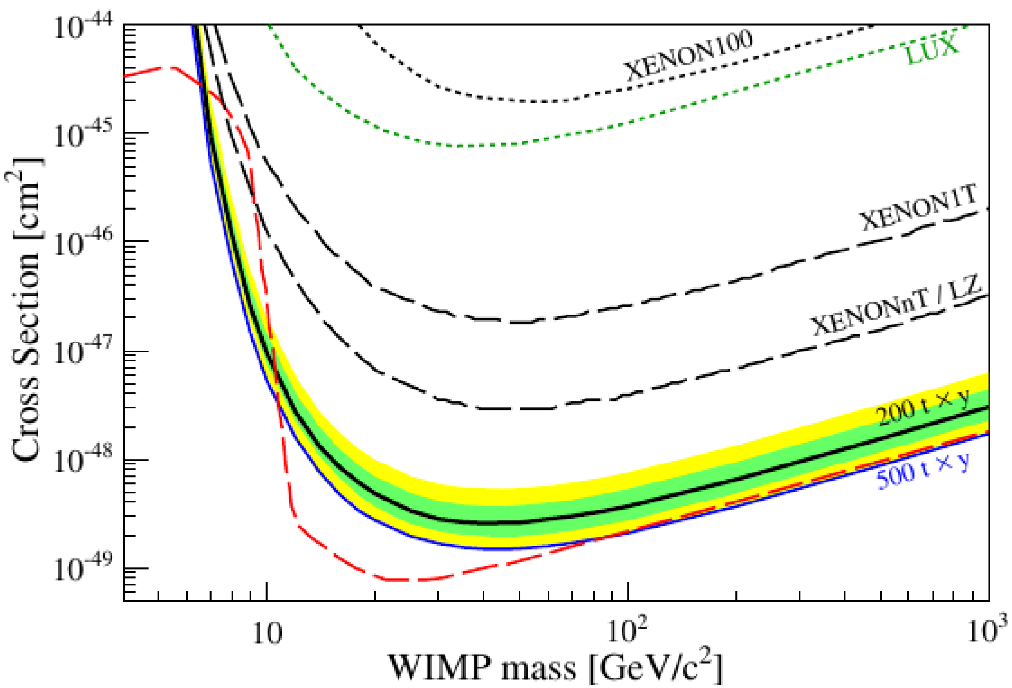


DARWIN WIMP Sensitivity

JCAP 10, 016 (2015)

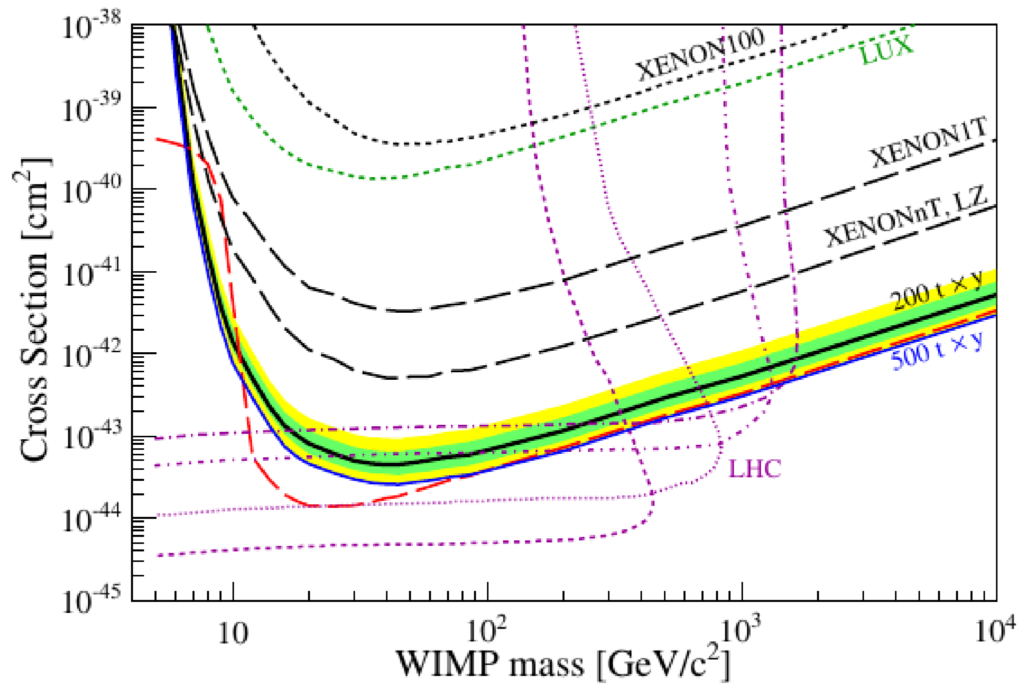
- exposure: 200 t x y; **all backgrounds included**
- likelihood analysis (~99.98% ER rejection @ 30% NR acceptance)
- S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keVnr energy window

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

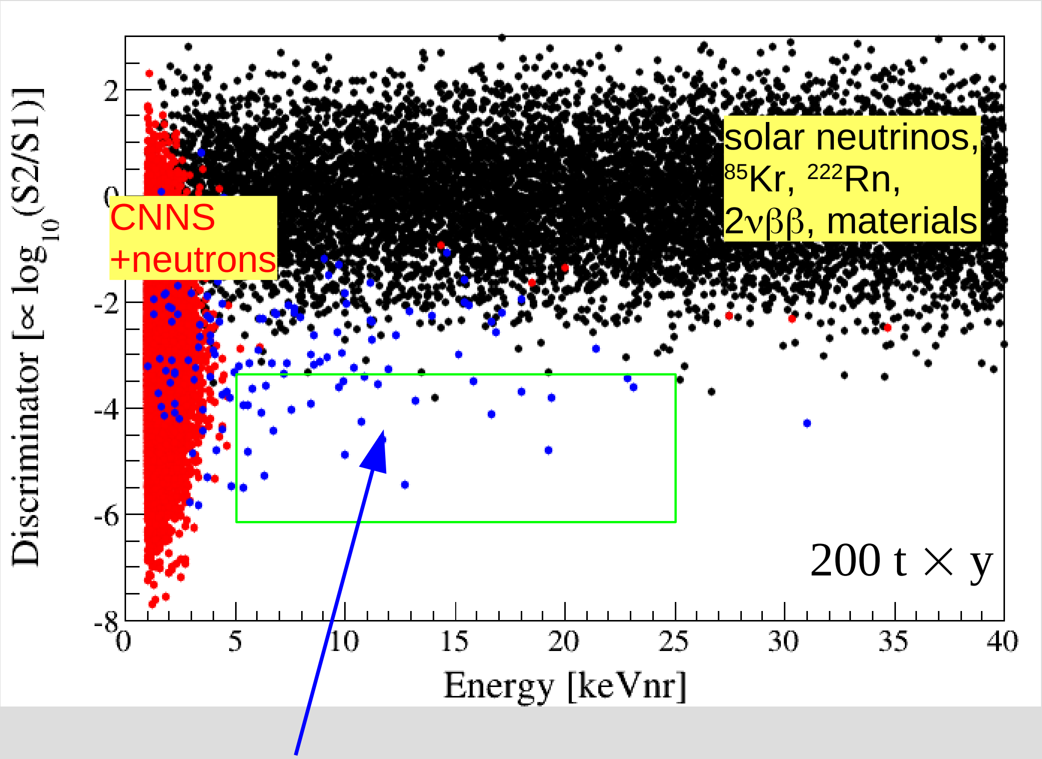
arXiv:1409.4075

→ also sensitive to inelastic WIMP interactions

WIMP Spectroscopy

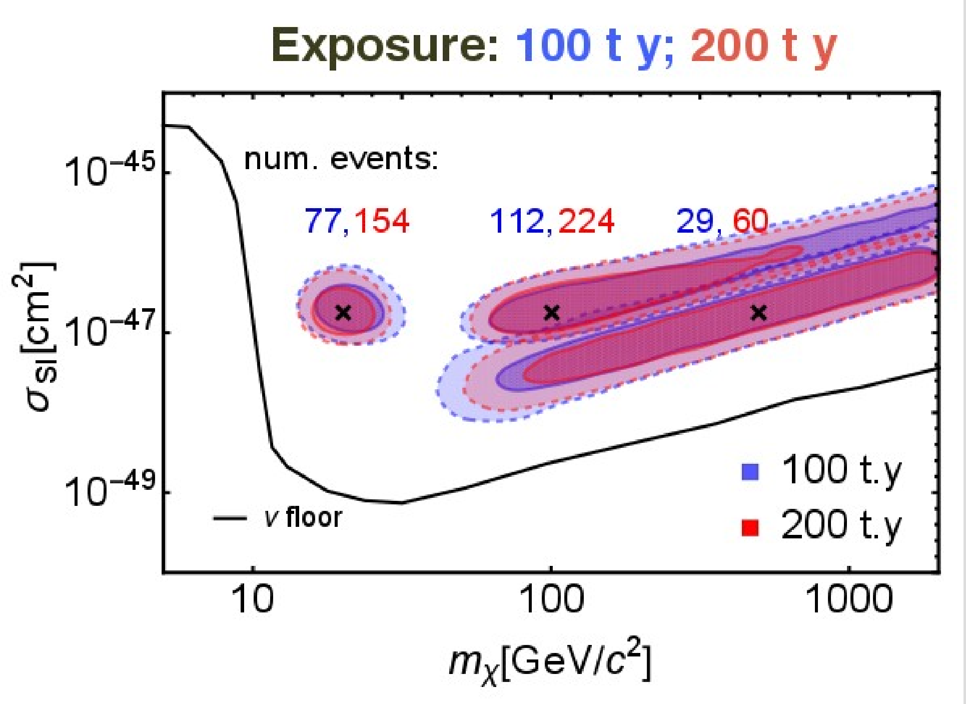
DARWIN

2×10^{-48} cm²



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

2×10^{-47} cm²



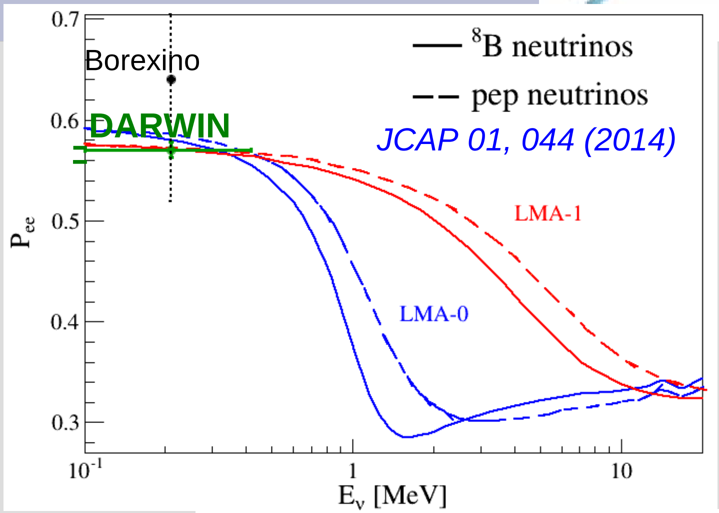
Update of Newstead et al., PRD 8, 076011 (2013)

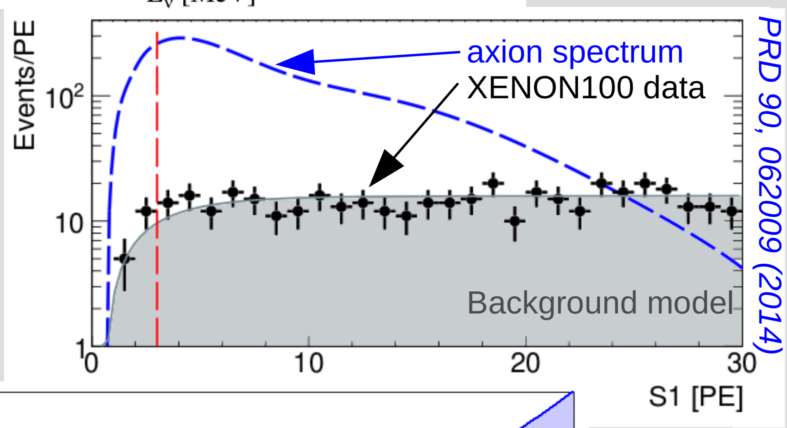
Capability to reconstruct WIMP parameters

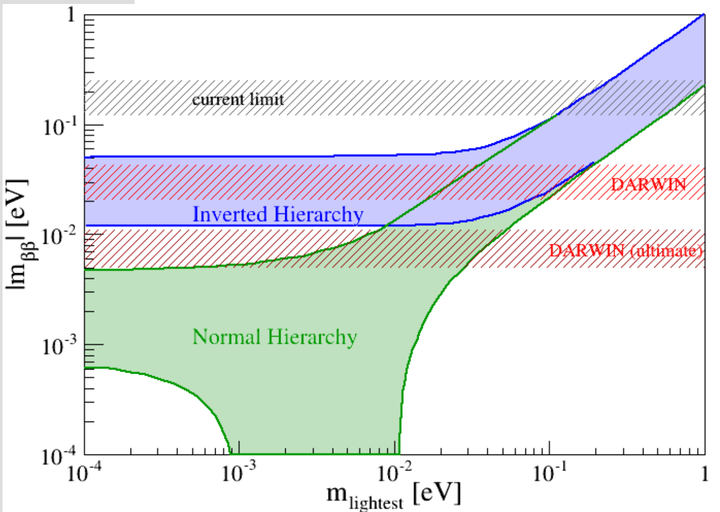
- m_χ=20, 100, 500 GeV/c²
- 1σ/2σ CI, marginalized over astrophysical parameters
- due to flat WIMP spectra, no target can reconstruct masses >500 GeV/c²

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







Exciting times ahead of us