Direct Dark Matter Searches – Status and Perspectives

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LHCb Week Talk, Neckarzimmern, March 24, 2017

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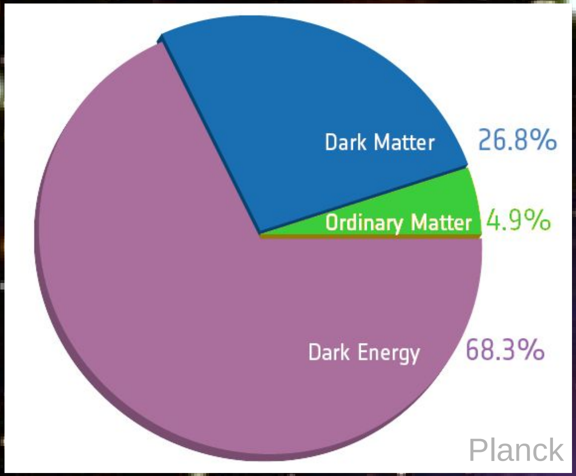
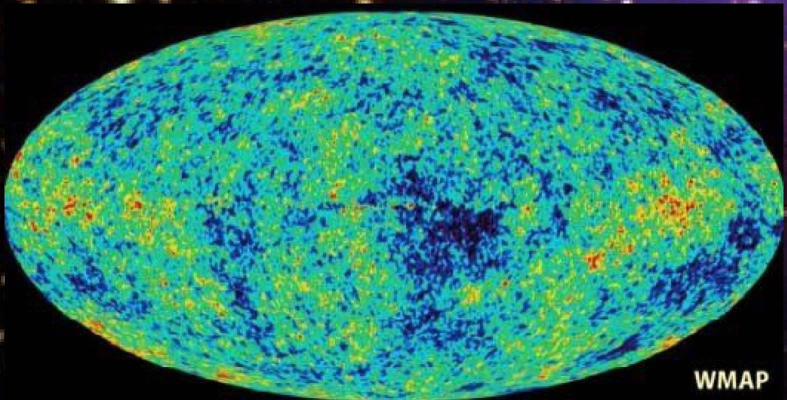
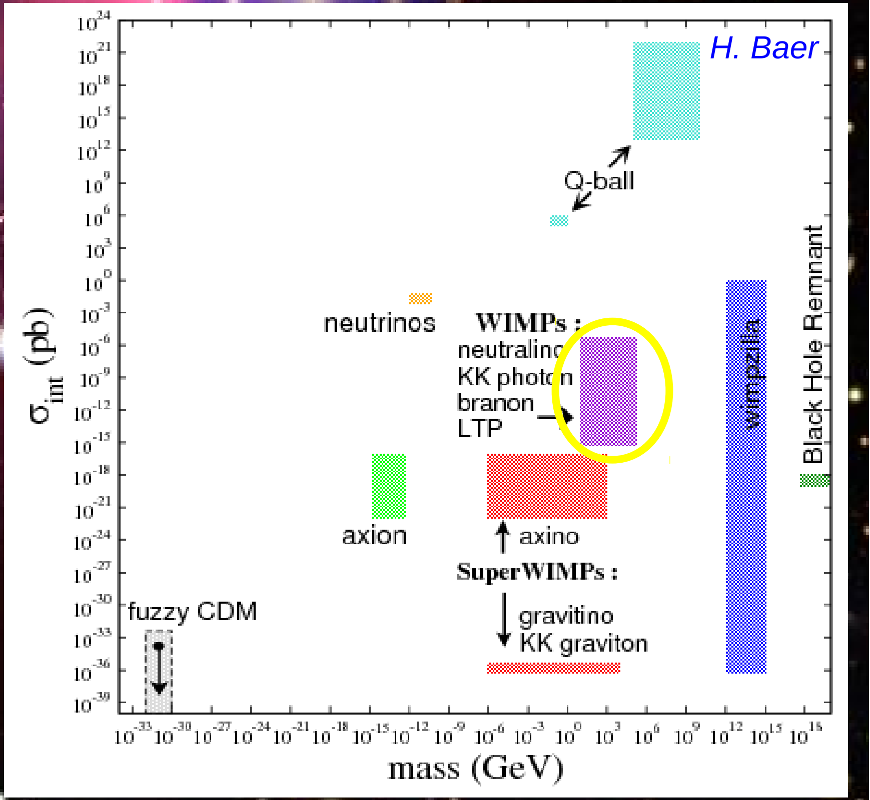
Dark Matter: (indirect) **Evidence**

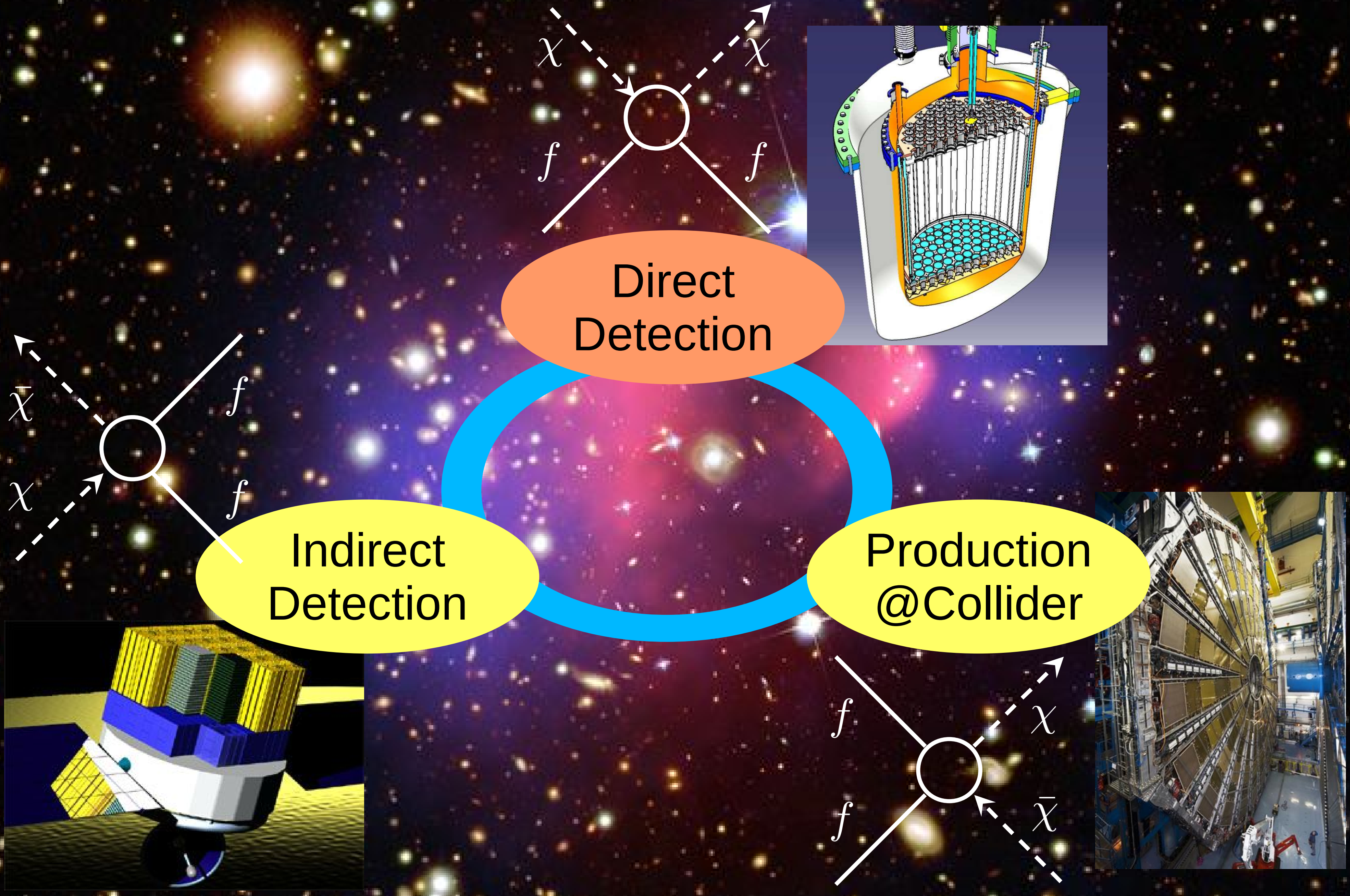


Particle Dark Matter Candidates:
- **WIMP** → *„WIMP miracle"*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...





Dark Matter Search

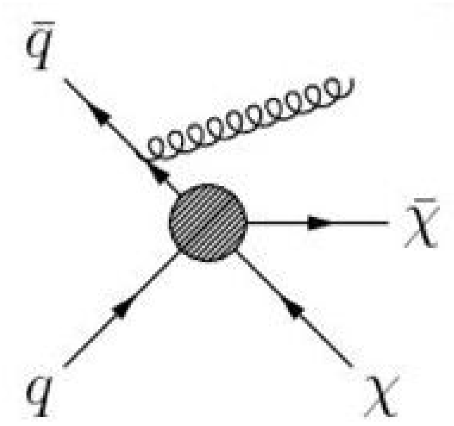


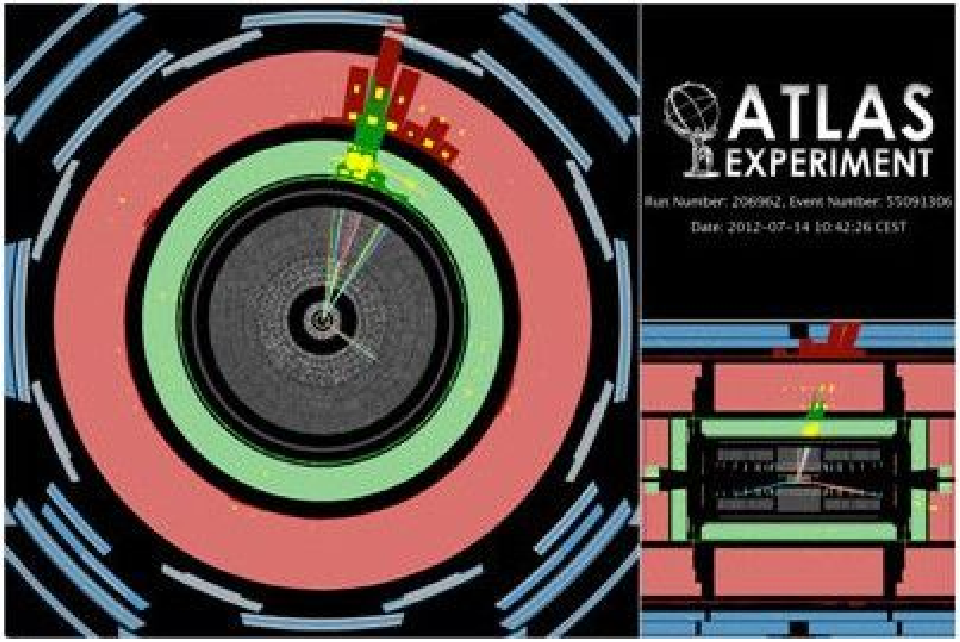
Direct Detection

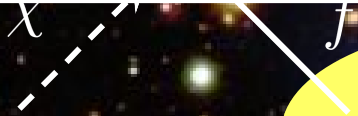
Indirect Detection

Production @Collider

Dark Matter Search

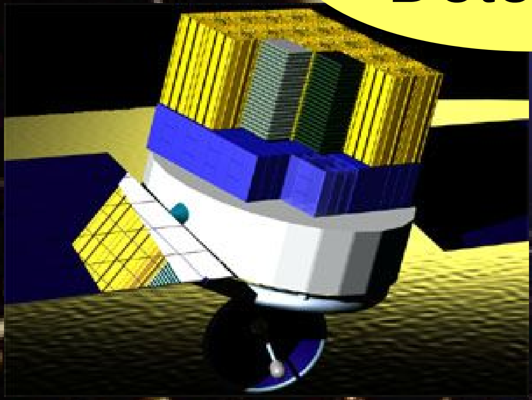


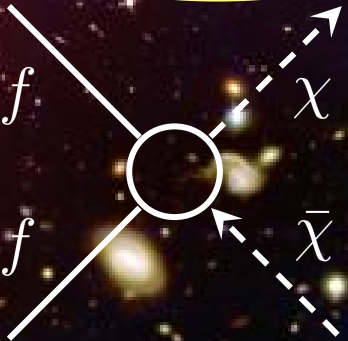


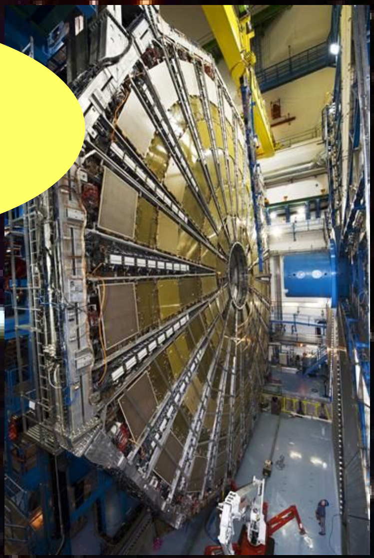


Indirect Detection

Production @Collider

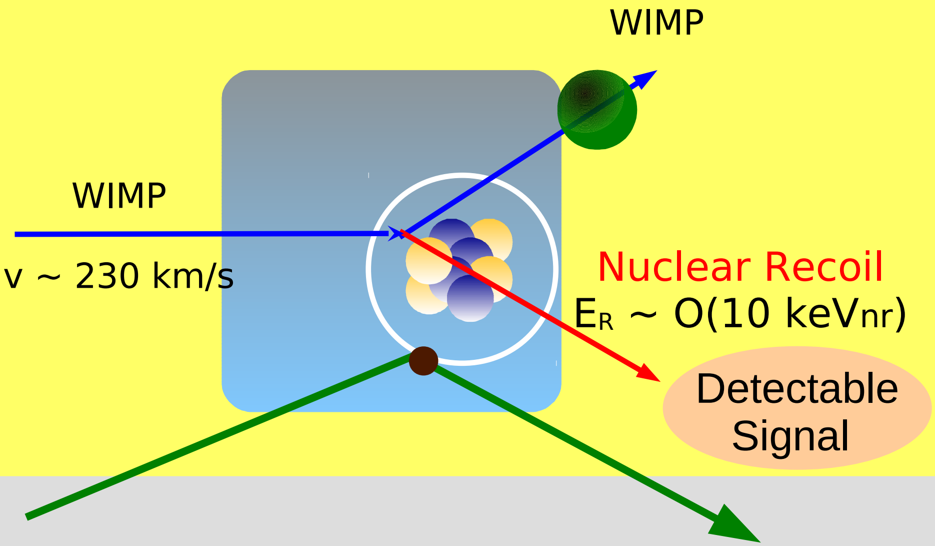


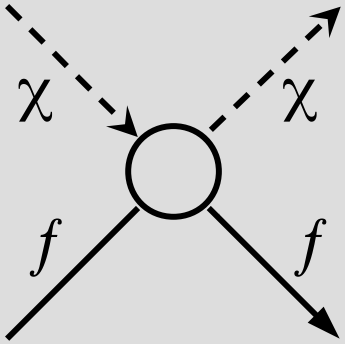




Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



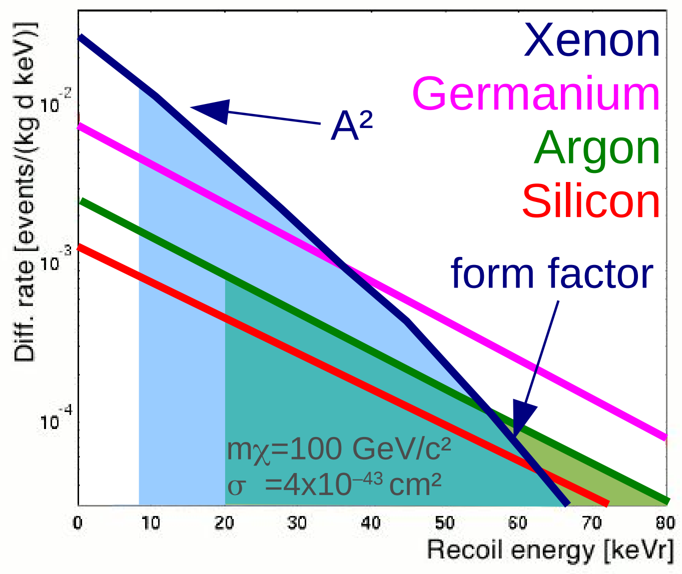


gamma- and beta-particles (background) interact with the atomic electrons
→ **electronic recoil** [in keVee]

Direct WIMP Search

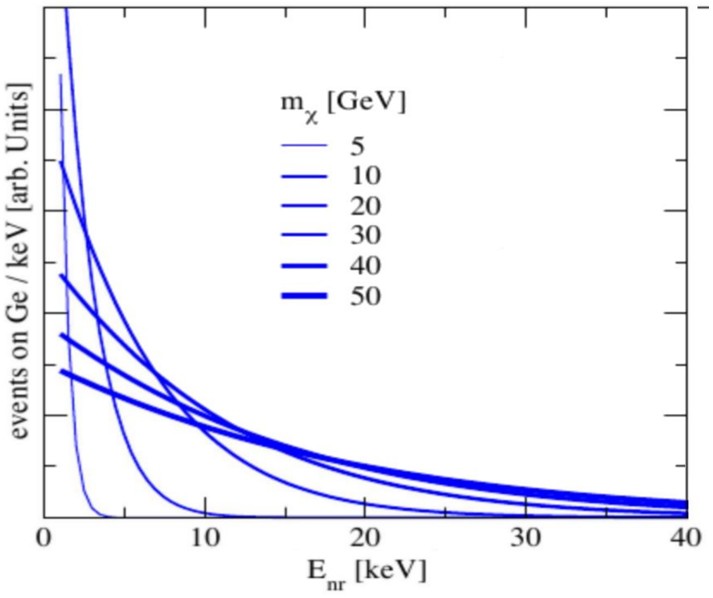
Direct Detection:

$E_r < 100$ keV



Recoil Energy:

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



Direct WIMP Search

Direct Detection:

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

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

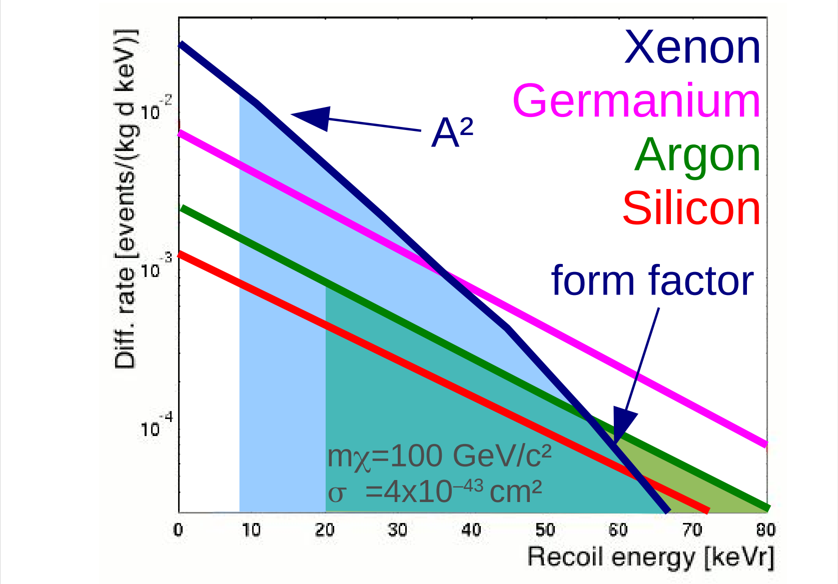
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

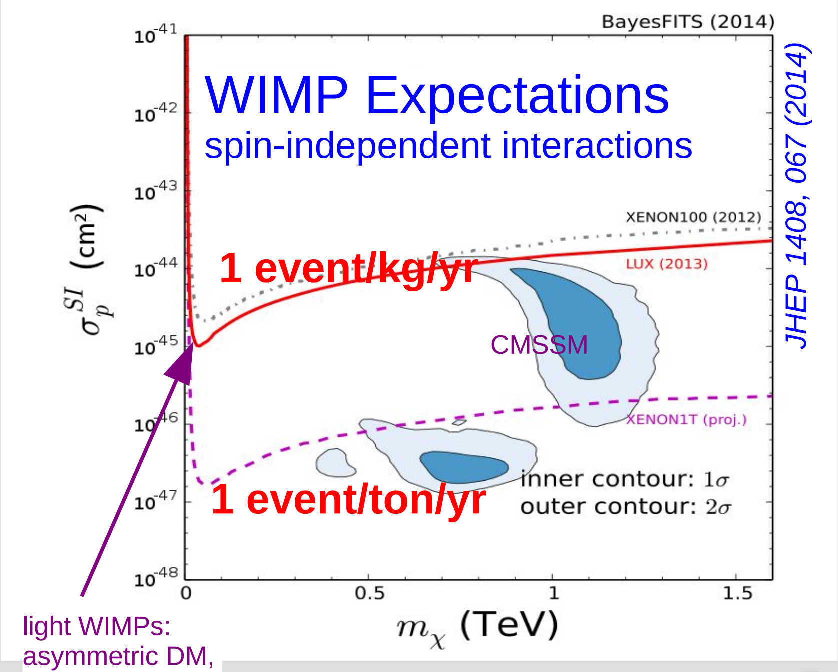
Detector

Local DM Density

$\rho_\chi \sim 0.3$ GeV/c²

Physics





light WIMPs:
asymmetric DM,
sneutrinos, ...

WIMP-Nucleon Interactions

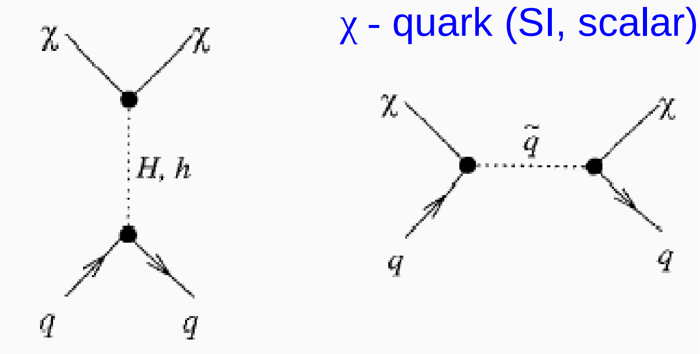
A priori, we do not know how dark matter WIMPs interact with ordinary matter

Parametrization of interactions leading to WIMP-nucleus scattering:

coupling to **mass**

Spin independent

χ - quark (SI, scalar)

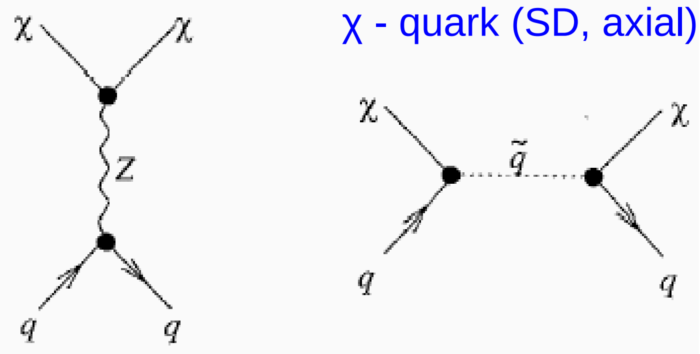


$$\mathcal{L}_S \sim \tilde{\chi}\chi\bar{q}q \quad \propto A^2$$

coupling to **nuclear spin**

Spin dependent

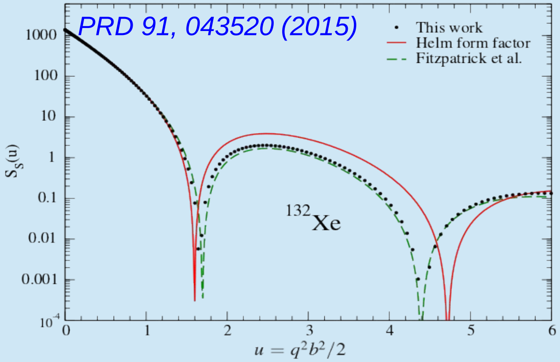
χ - quark (SD, axial)

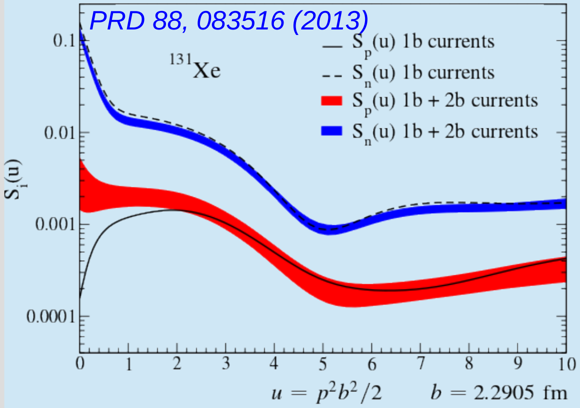


$$\mathcal{L}_A \sim \tilde{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$$

Jungmann et al. '96 Phys.Rep.

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





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

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

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

Direct WIMP Search

Direct Detection:

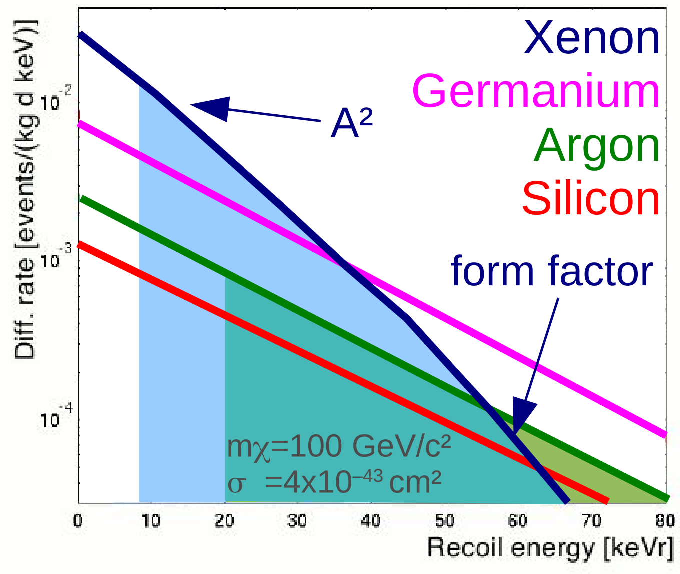
$E_r < 100$ keV
$R < 1$ evt/kg/year

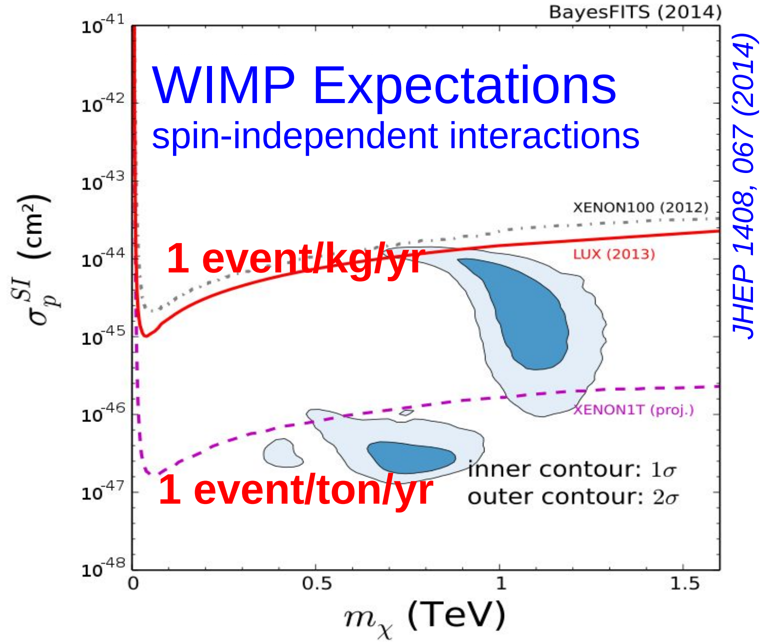
How to build a WIMP detector?

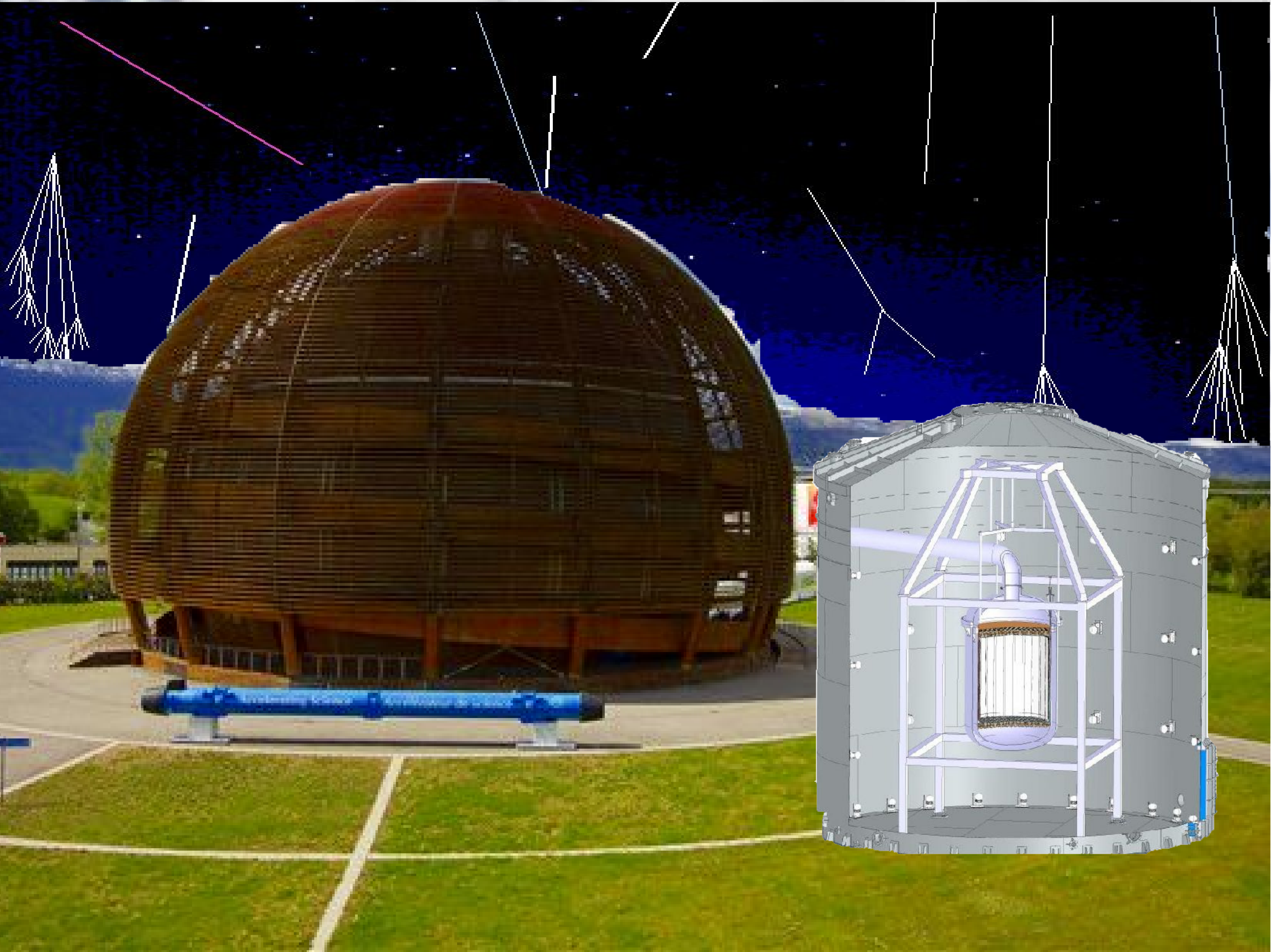
- large total mass, high *A*
- low energy threshold
- ultra low background
- good signal / background discrimination

We are dealing with

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



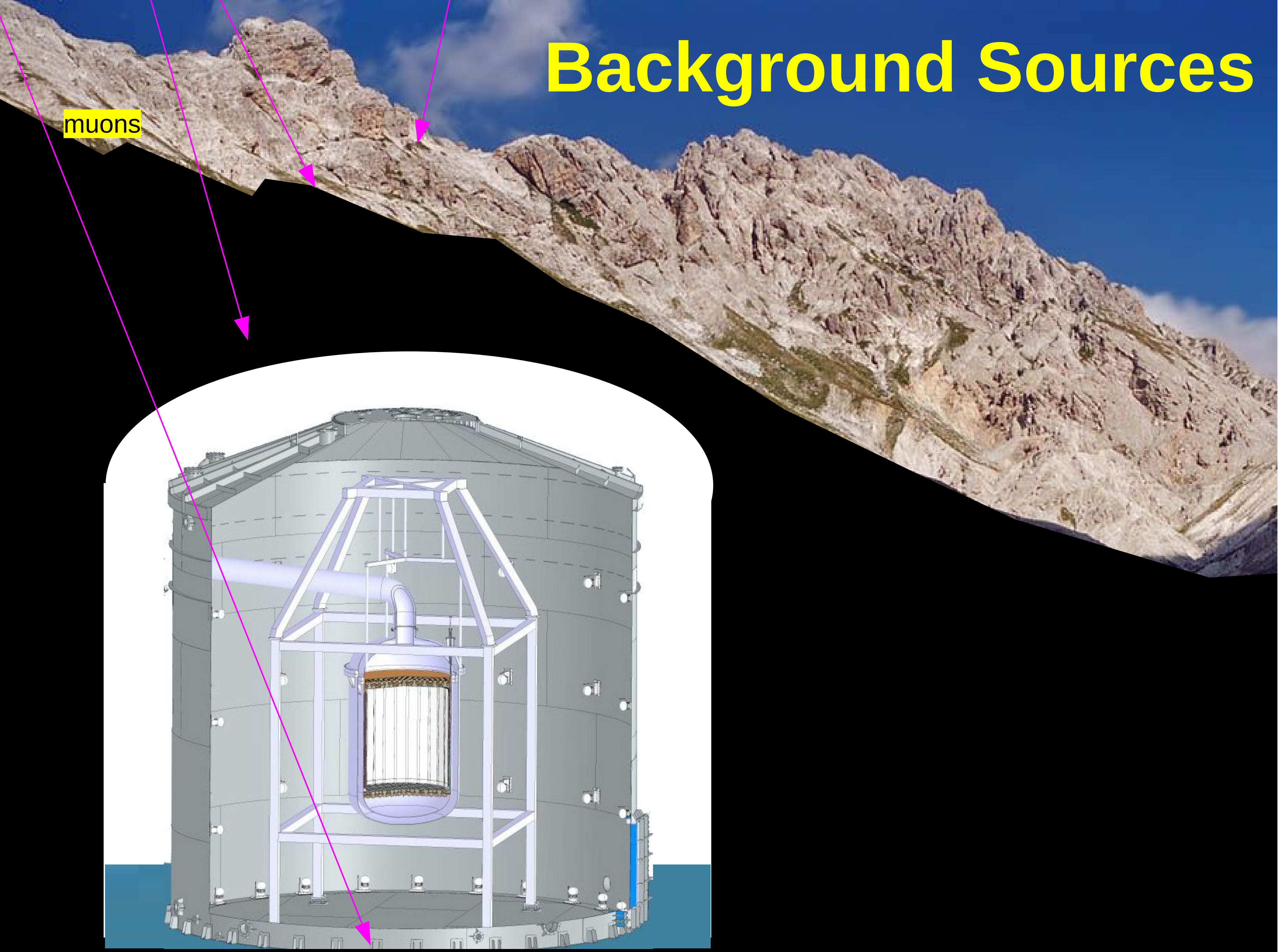




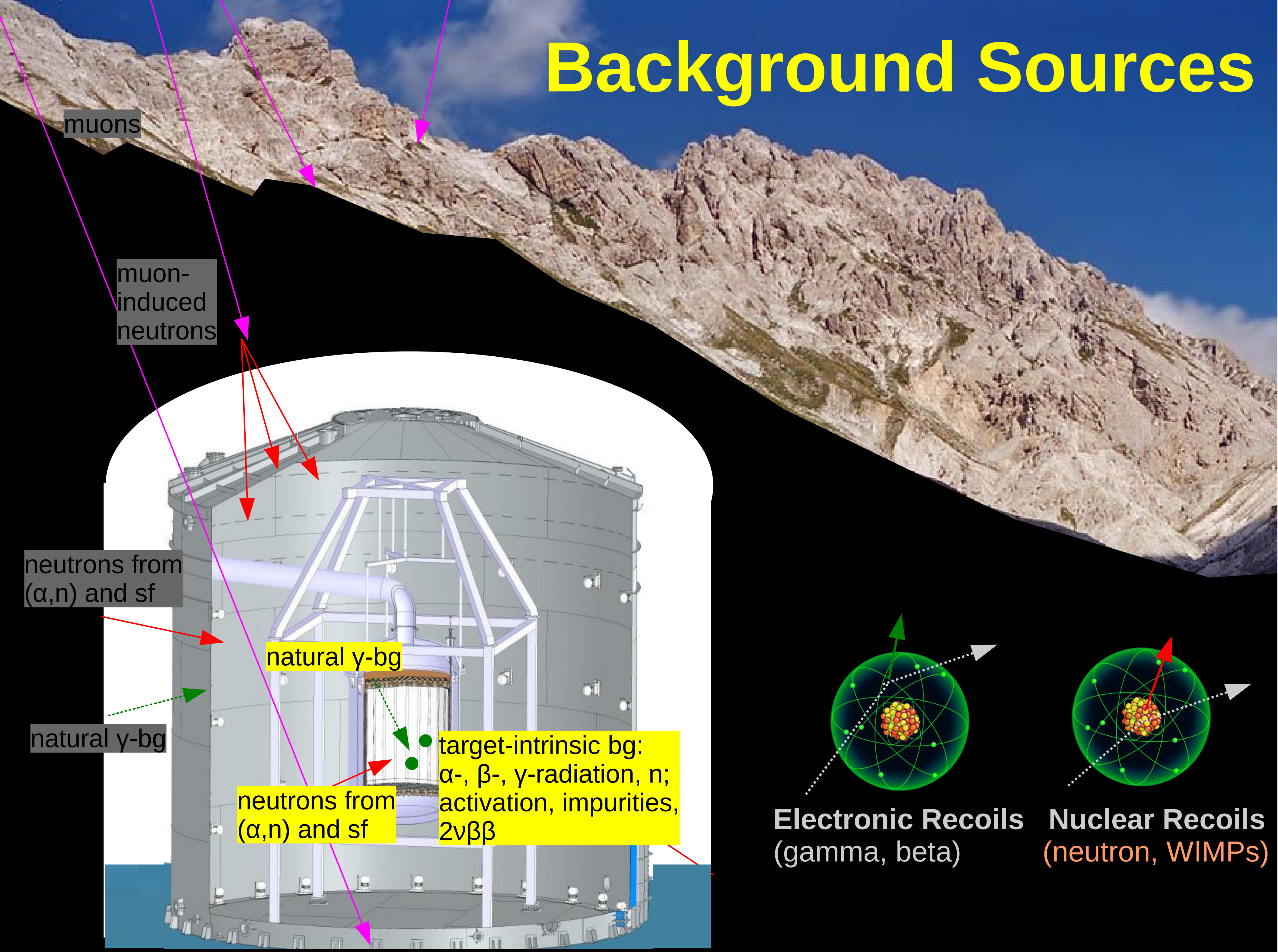
Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock
(3700 mwe)

Background Sources



Background Sources



muons

muon-induced neutrons

neutrons from (α,n) and sf

natural γ-bg

natural γ-bg

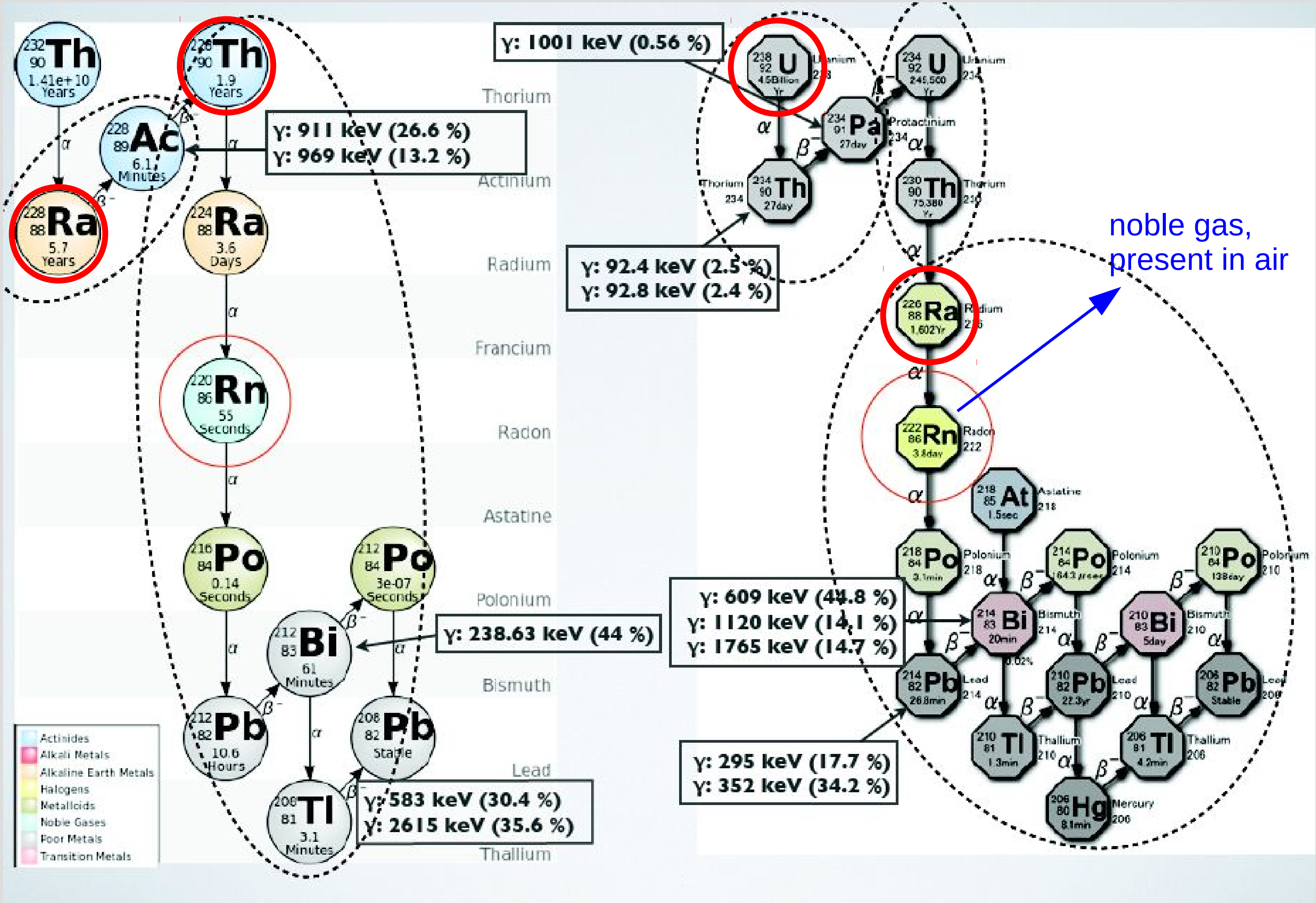
target-intrinsic bg:
α-, β-, γ-radiation, n;
activation, impurities,
2νββ

neutrons from (α,n) and sf

Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)

The U and Th Chains



γ: 1001 keV (0.56 %)

γ: 911 keV (26.6 %)
γ: 969 keV (13.2 %)

γ: 92.4 keV (2.5 %)
γ: 92.8 keV (2.4 %)

noble gas, present in air

γ: 609 keV (44.8 %)
γ: 1120 keV (14.1 %)
γ: 1765 keV (14.7 %)

γ: 238.63 keV (44 %)

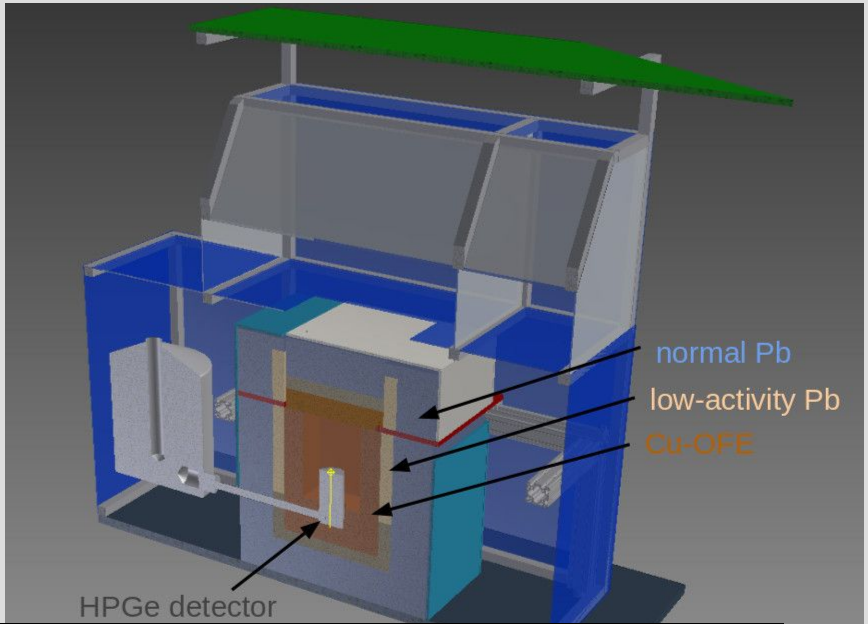
γ: 295 keV (17.7 %)
γ: 352 keV (34.2 %)

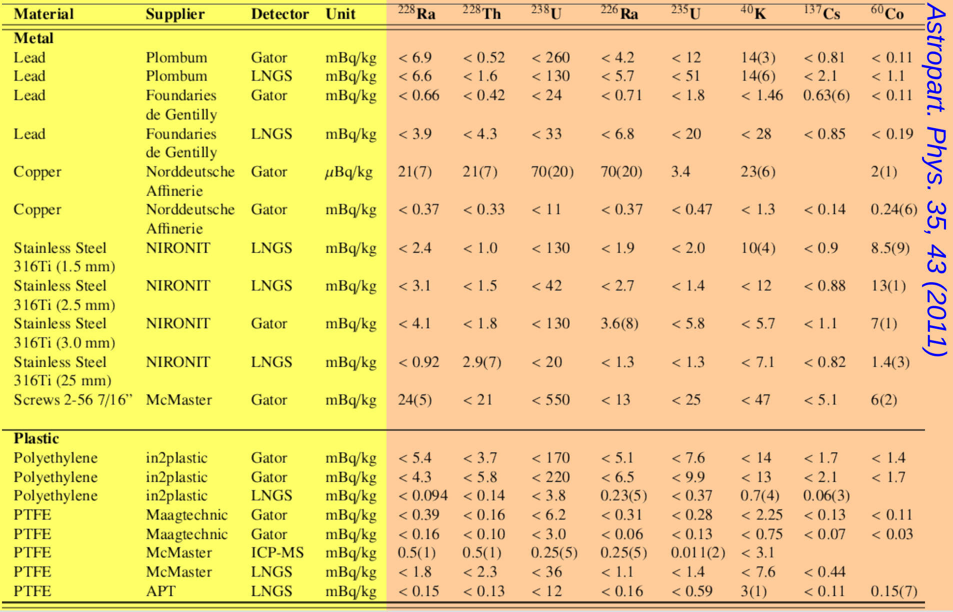
γ: 583 keV (30.4 %)
γ: 2615 keV (35.6 %)

Low-background Screening

GeMSE
Germanium Material and Meteorite Screening Experiment

JINST 11, P12017 (2016)





Material	Supplier	Detector	Unit	^{228}Ra	^{228}Th	^{238}U	^{226}Ra	^{235}U	^{40}K	^{137}Cs	^{60}Co
Metal											
Lead	Plombum	Gator	mBq/kg	< 6.9	< 0.52	< 260	< 4.2	< 12	14(3)	< 0.81	< 0.11
Lead	Plombum	LNGS	mBq/kg	< 6.6	< 1.6	< 130	< 5.7	< 51	14(6)	< 2.1	< 1.1
Lead	Foundaries de Gentilly	Gator	mBq/kg	< 0.66	< 0.42	< 24	< 0.71	< 1.8	< 1.46	0.63(6)	< 0.11
Lead	Foundaries de Gentilly	LNGS	mBq/kg	< 3.9	< 4.3	< 33	< 6.8	< 20	< 28	< 0.85	< 0.19
Copper	Norddeutsche Affinerie	Gator	μBq/kg	21(7)	21(7)	70(20)	70(20)	3.4	23(6)		2(1)
Copper	Norddeutsche Affinerie	Gator	mBq/kg	< 0.37	< 0.33	< 11	< 0.37	< 0.47	< 1.3	< 0.14	0.24(6)
Stainless Steel 316Ti (1.5 mm)	NIRONIT	LNGS	mBq/kg	< 2.4	< 1.0	< 130	< 1.9	< 2.0	10(4)	< 0.9	8.5(9)
Stainless Steel 316Ti (2.5 mm)	NIRONIT	LNGS	mBq/kg	< 3.1	< 1.5	< 42	< 2.7	< 1.4	< 12	< 0.88	13(1)
Stainless Steel 316Ti (3.0 mm)	NIRONIT	Gator	mBq/kg	< 4.1	< 1.8	< 130	3.6(8)	< 5.8	< 5.7	< 1.1	7(1)
Stainless Steel 316Ti (25 mm)	NIRONIT	LNGS	mBq/kg	< 0.92	2.9(7)	< 20	< 1.3	< 1.3	< 7.1	< 0.82	1.4(3)
Screws 2-56 7/16"	McMaster	Gator	mBq/kg	24(5)	< 21	< 550	< 13	< 25	< 47	< 5.1	6(2)
Plastic											
Polyethylene	in2plastic	Gator	mBq/kg	< 5.4	< 3.7	< 170	< 5.1	< 7.6	< 14	< 1.7	< 1.4
Polyethylene	in2plastic	Gator	mBq/kg	< 4.3	< 5.8	< 220	< 6.5	< 9.9	< 13	< 2.1	< 1.7
Polyethylene	in2plastic	LNGS	mBq/kg	< 0.094	< 0.14	< 3.8	0.23(5)	< 0.37	0.7(4)	0.06(3)	
PTFE	Maagtechnic	Gator	mBq/kg	< 0.39	< 0.16	< 6.2	< 0.31	< 0.28	< 2.25	< 0.13	< 0.11
PTFE	Maagtechnic	Gator	mBq/kg	< 0.16	< 0.10	< 3.0	< 0.06	< 0.13	< 0.75	< 0.07	< 0.03
PTFE	McMaster	ICP-MS	mBq/kg	0.5(1)	0.5(1)	0.25(5)	0.25(5)	0.011(2)	< 3.1		
PTFE	McMaster	LNGS	mBq/kg	< 1.8	< 2.3	< 36	< 1.1	< 1.4	< 7.6	< 0.44	
PTFE	APT	LNGS	mBq/kg	< 0.15	< 0.13	< 12	< 0.16	< 0.59	3(1)	< 0.11	0.15(7)

Astropart. Phys. 35, 43 (2011)

Identify materials with lowest radioactivity:

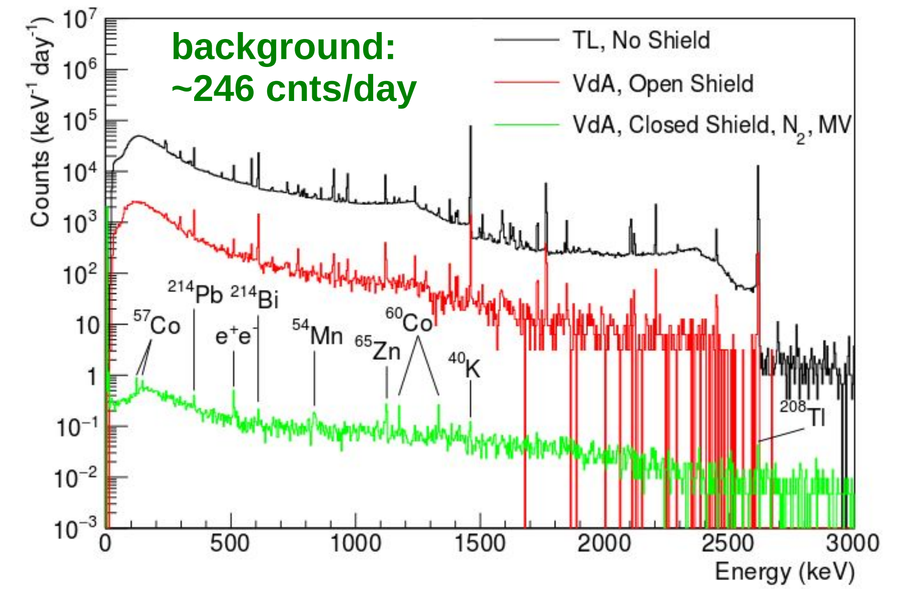
- γ-spectrometry using HPGe Detectors
- mass spectroscopy: ICP-MS, GDMS
- neutron activation analysis
- ^{222}Rn emanation

Low-background Screening

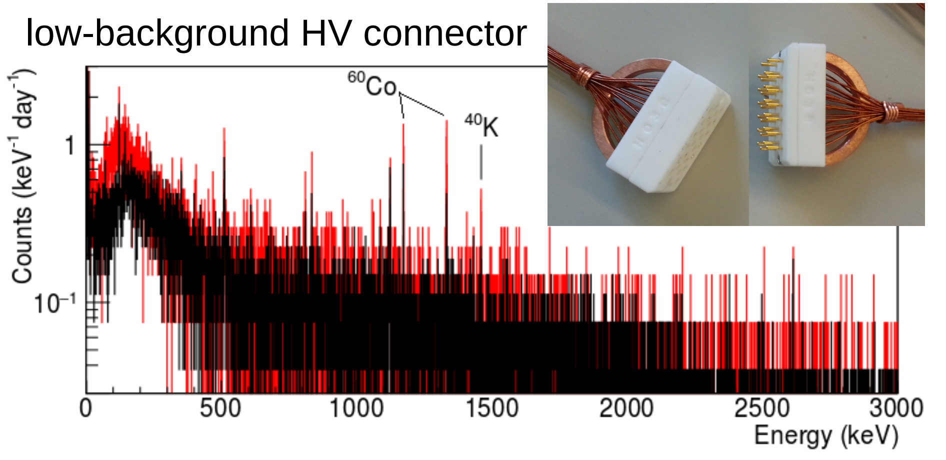
GeMSE
Germanium
Material and
Meteorite
Screening
Experiment

JINST 11, P12017 (2016)


Vue des Alpes Laboratory
(600 mwe)


background:
~246 cnts/day

low-background HV connector

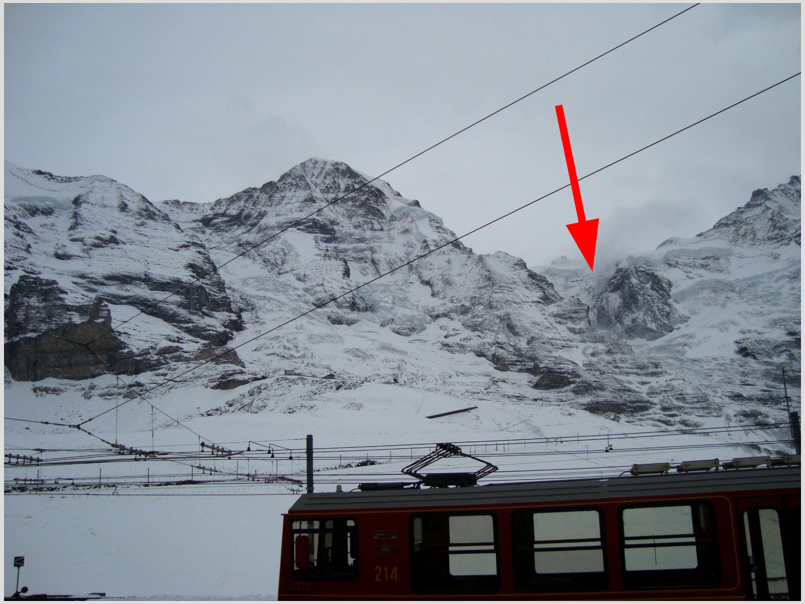


Identify materials with lowest radioactivity:

- γ-spectrometry using HPGe Detectors
- mass spectroscopy: ICP-MS, GDMS
- neutron activation analysis
- ^{222}Rn emanation

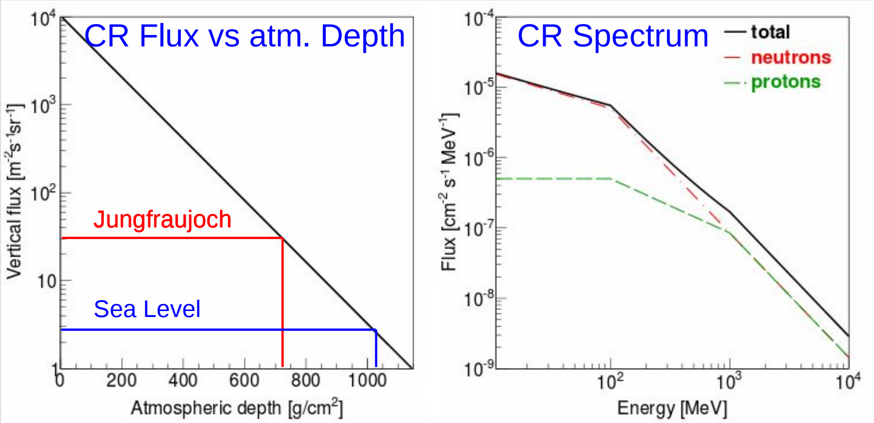
Measuring Xenon Activation

EPJ C75, 485 (2015)



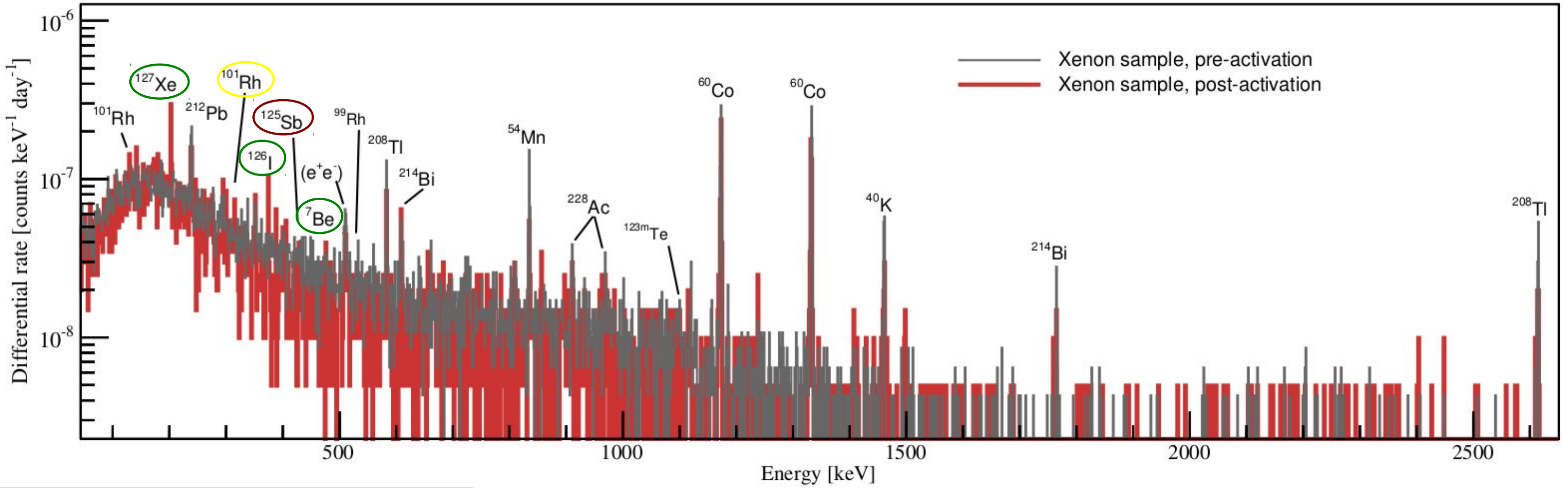
- study xenon activation by cosmic rays
- 2.04 kg ultra-pure xenon activated at Jungfraujoch for **345 days** `www.ifjungo.ch`
- CR flux @**3470m** 11.2× higher than at sea level
  → corresponds to >10 years sea-level exposure
- transport and cool-down times minimized
- gamma-ray spectra measured before and after activation with Gator HPGe spectrometer @ LNGS

Goals: (i) identification of isotopes from activation
(ii) comparison with activation codes
(Activia, Cosmo, TALYS)
(iii) impact for dark matter searches?



Xenon Activation: Results

EPJ C75, 485 (2015)

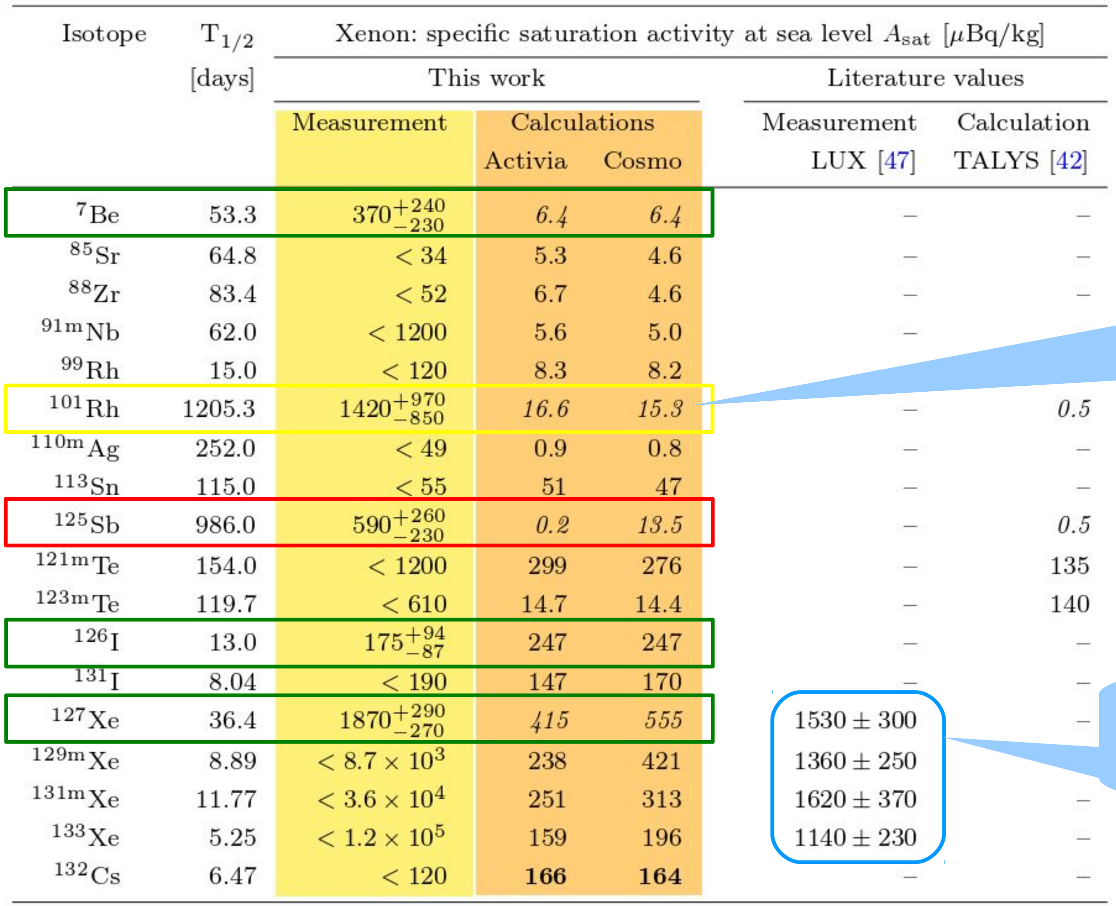


5 isotopes detected

^{7}Be, ^{126}I and ^{127}Xe are short-lived and therefore uncritical

^{101}Rh: no single low-E electrons or γ-rays

^{125}Sb: produces single low-E electrons
- → expected rate too high for LUX background
- → removed by getters?

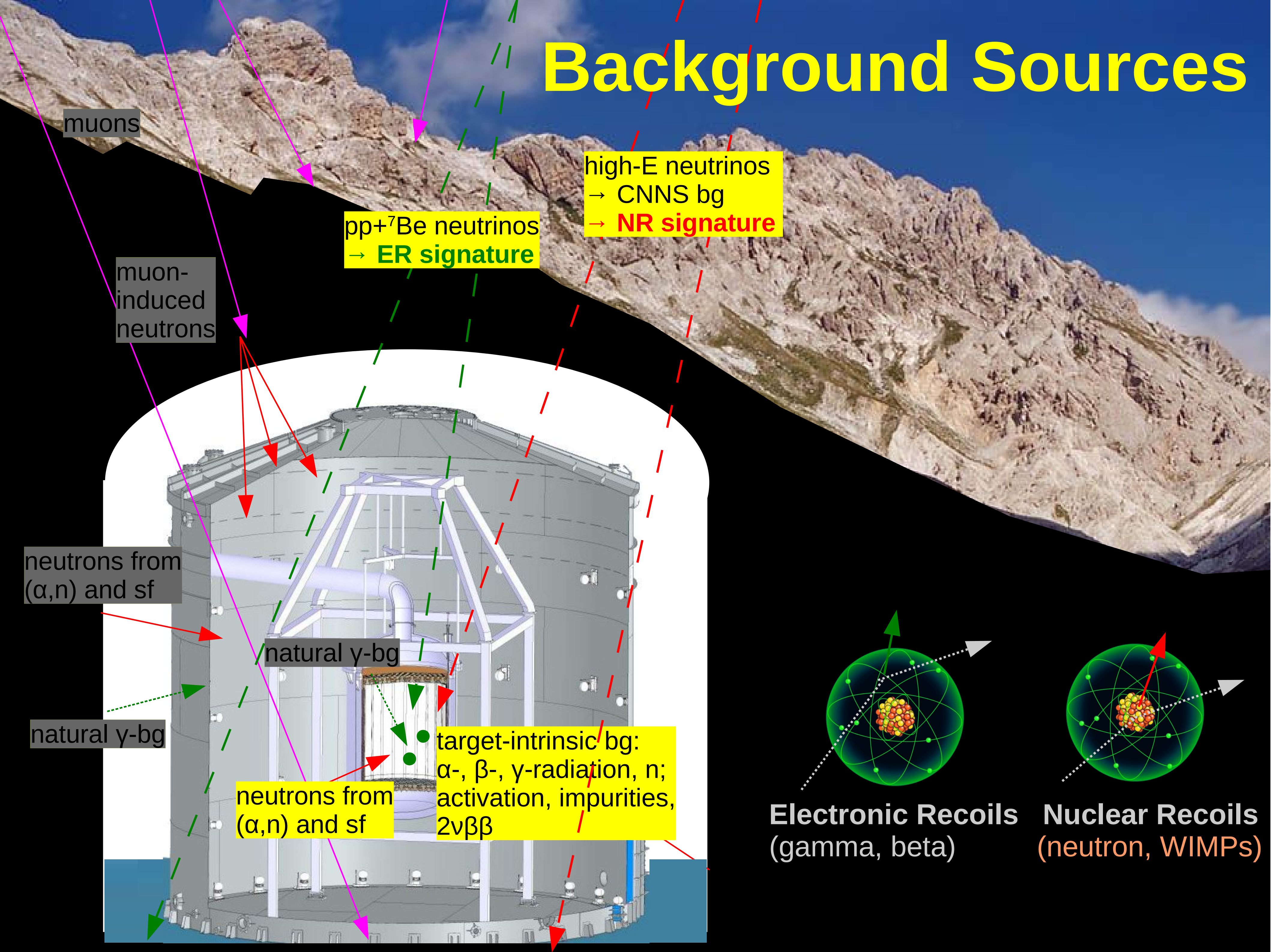


Isotope	$T_{1/2}$ [days]	Xenon: specific saturation activity at sea level A_{sat} [μBq/kg]				
		This work			Literature values	
		Measurement	Calculations Activia	Calculations Cosmo	Measurement LUX [47]	Calculation TALYS [42]
^{7}Be	53.3	370^{+240}_{-230}	*6.4*	*6.4*	–	–
^{85}Sr	64.8	< 34	5.3	4.6	–	–
^{88}Zr	83.4	< 52	6.7	4.6	–	–
^{91m}Nb	62.0	< 1200	5.6	5.0	–	
^{99}Rh	15.0	< 120	8.3	8.2		
^{101}Rh	1205.3	1420^{+970}_{-850}	*16.6*	*15.3*	–	*0.5*
^{110m}Ag	252.0	< 49	0.9	0.8	–	–
^{113}Sn	115.0	< 55	51	47	–	–
^{125}Sb	986.0	590^{+260}_{-230}	*0.2*	*13.5*	–	*0.5*
^{121m}Te	154.0	< 1200	299	276	–	135
^{123m}Te	119.7	< 610	14.7	14.4	–	140
^{126}I	13.0	175^{+94}_{-87}	247	247	–	–
^{131}I	8.04	< 190	147	170	–	–
^{127}Xe	36.4	1870^{+290}_{-270}	*415*	*555*	1530 ± 300	–
^{129m}Xe	8.89	$< 8.7 \times 10^{3}$	238	421	1360 ± 250	
^{131m}Xe	11.77	$< 3.6 \times 10^{4}$	251	313	1620 ± 370	–
^{133}Xe	5.25	$< 1.2 \times 10^{5}$	159	196	1140 ± 230	–
^{132}Cs	6.47	< 120	**166**	**164**	–	–

The majority of the calculated predictions are too low (*italic font*); agreement only for ^{126}I

Xe-isotopes: good agreement with LUX

Background Sources



muons

muon-induced neutrons

pp+^{7}Be neutrinos
→ **ER signature**

high-E neutrinos
→ CNNS bg
→ **NR signature**

neutrons from (α,n) and sf

natural γ-bg

natural γ-bg

neutrons from (α,n) and sf

target-intrinsic bg:
α-, β-, γ-radiation, n;
activation, impurities,
2νββ

Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)

Background Suppression

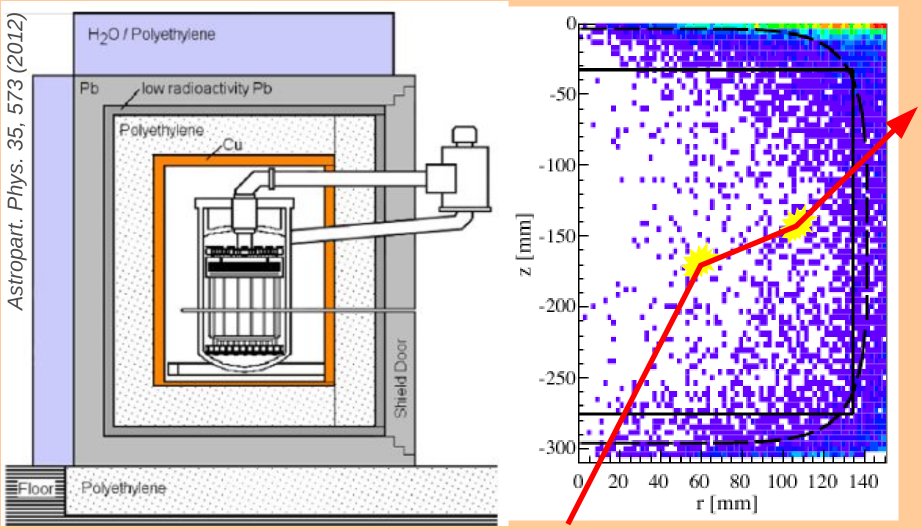
Avoid Backgrounds

Shielding

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

self shielding → fiducialization

Use of radiopure materials


Astropart. Phys. 35, 573 (2012)

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 →

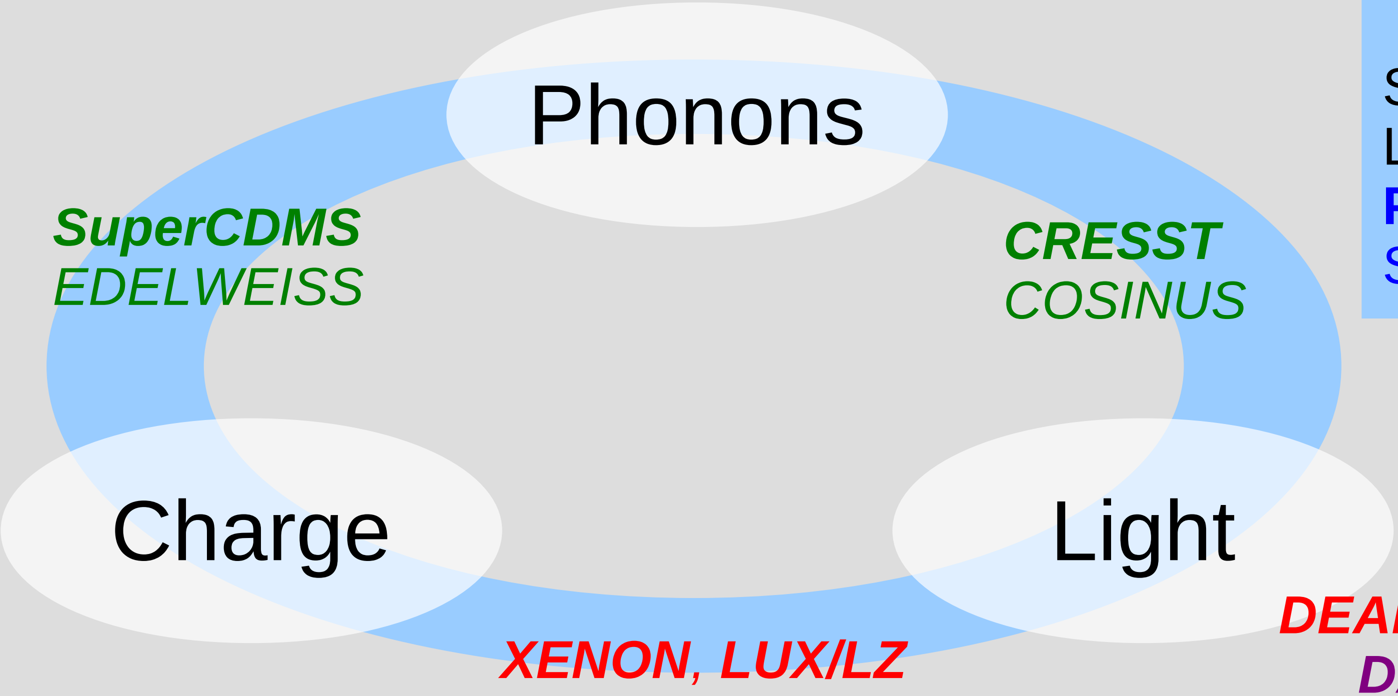
Examples:
- scintillation pulse shape
- charge/light ratio
- ionization yield

Direct WIMP Detection

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

Tracking:
DRIFT, DMTPC
MIMAC, NEWS
NEWAGE

Superheated
Liquids:
PICO
SIMPLE



CUORE

Phonons

SuperCDMS
EDELWEISS

CRESST
COSINUS

Charge

Light

CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

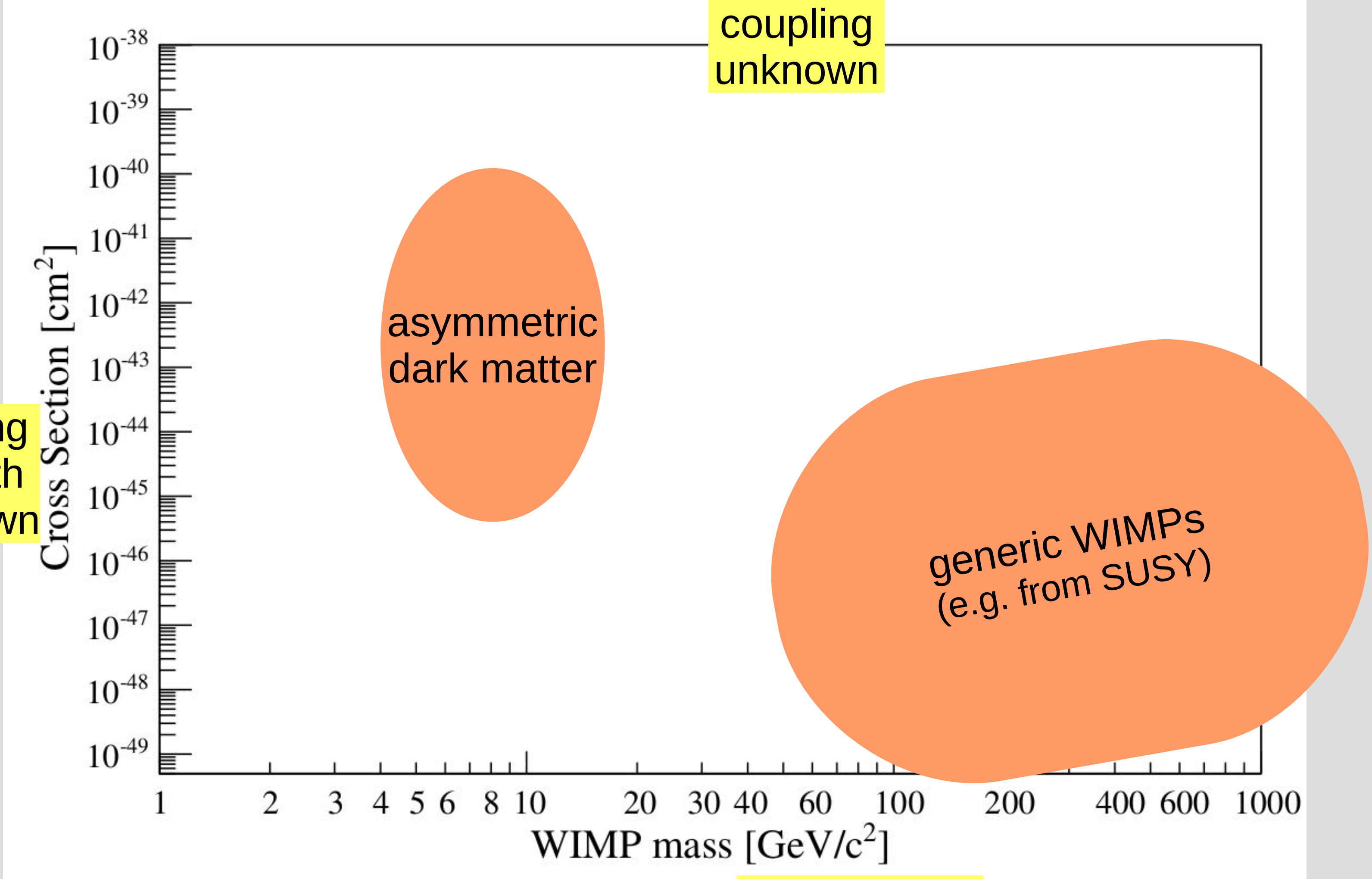
XENON**, **LUX/LZ
*ArDM, **Panda-X***
DarkSide, DARWIN

***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



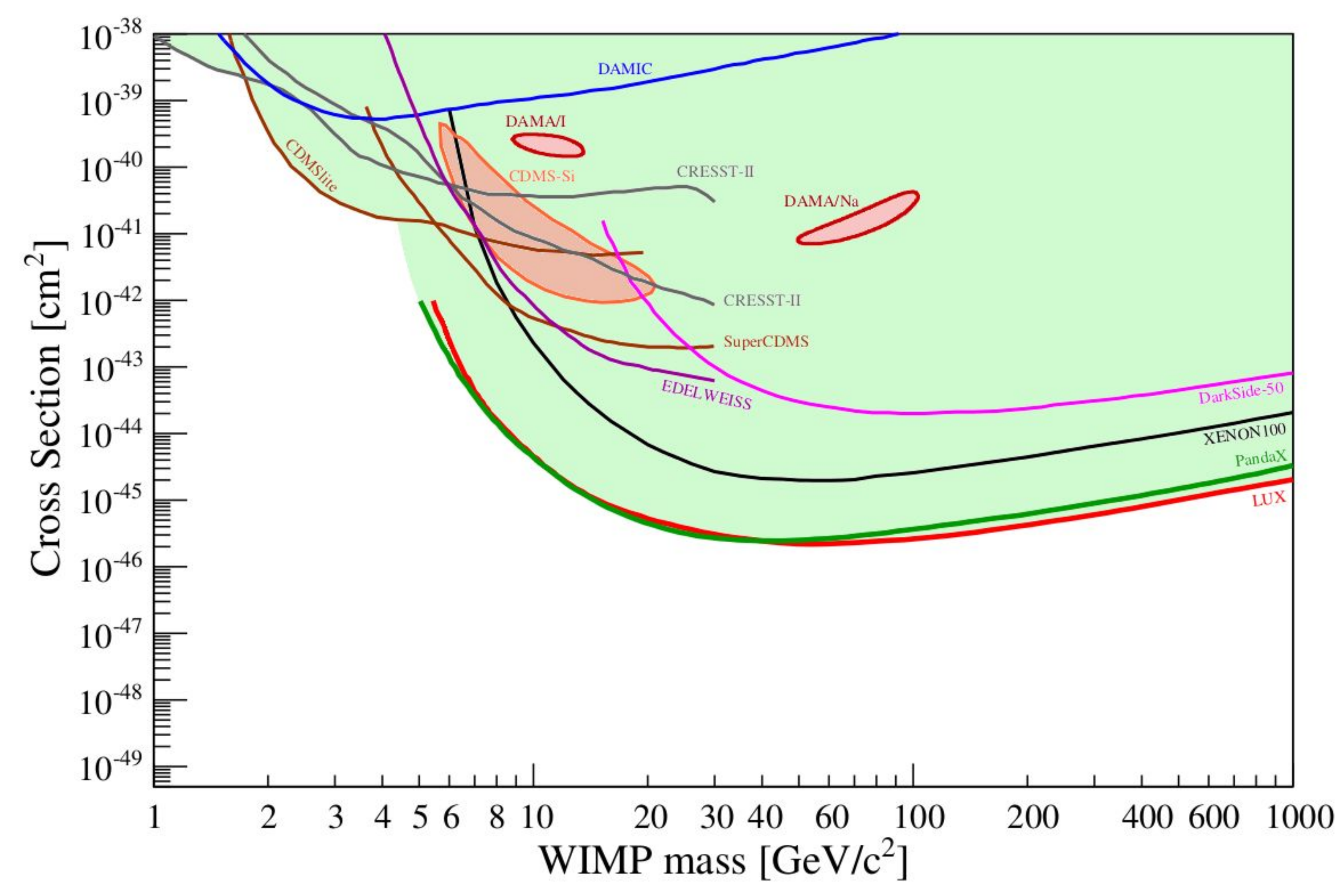
coupling unknown

coupling strength unknown

WIMP mass unknown

Detections? Exclusions?

spin-independent WIMP-nucleon interactions

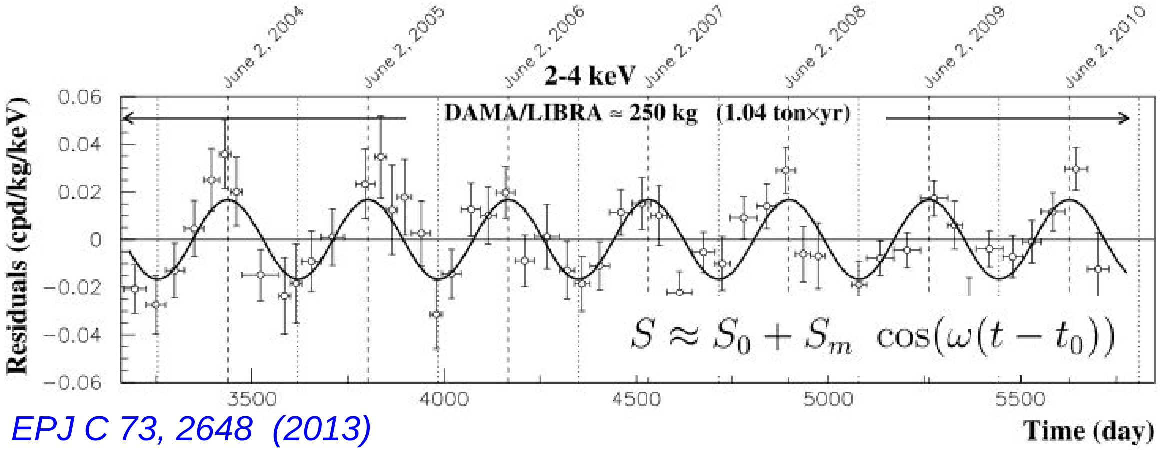


some results are missing...

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

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



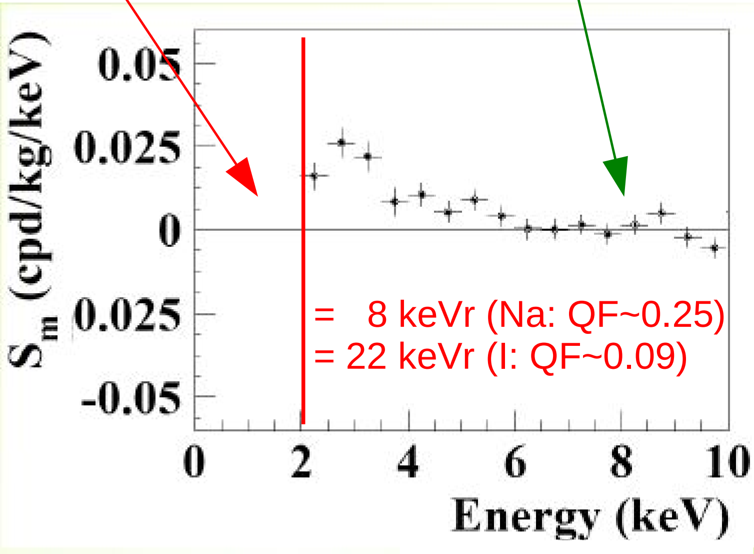
$$S \approx S_0 + S_m \cos(\omega(t - t_0))$$

EPJ C 73, 2648 (2013)

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

what is here?

no modulation above 6 keV

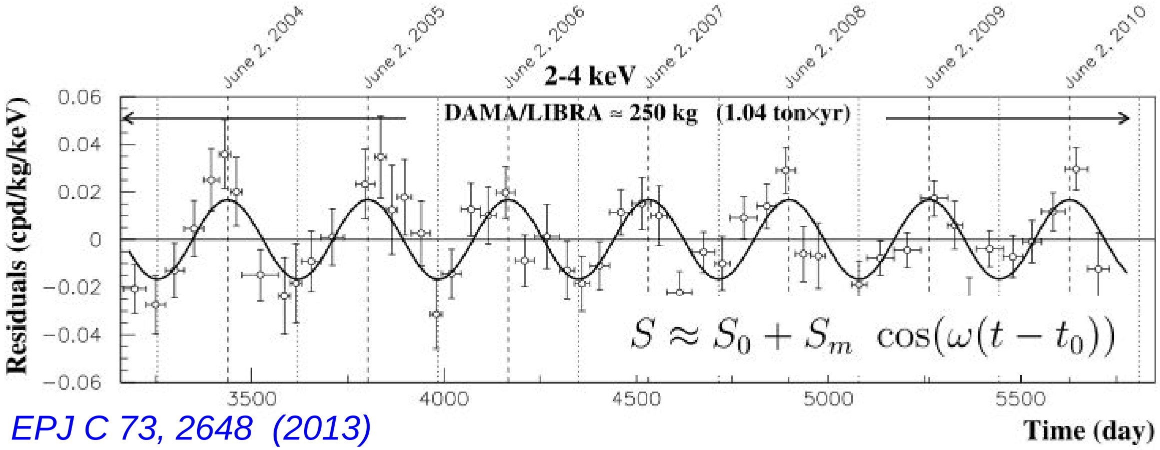


= 8 keVr (Na: QF~0.25)
= 22 keVr (I: QF~0.09)

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)

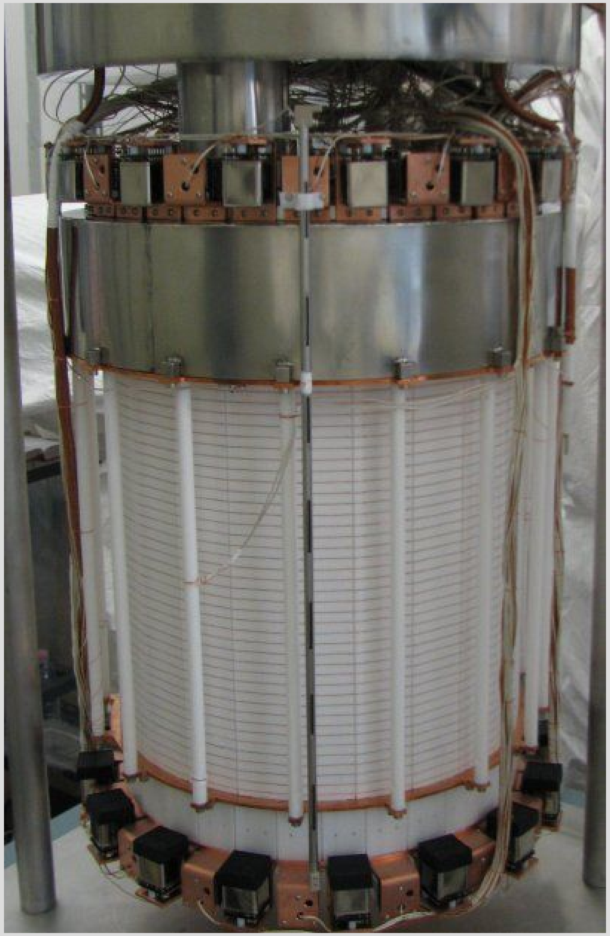
interpretation as (spin-(in)dependent, inelastic) WIMP-nucleon scattering challenged by many experiments

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)

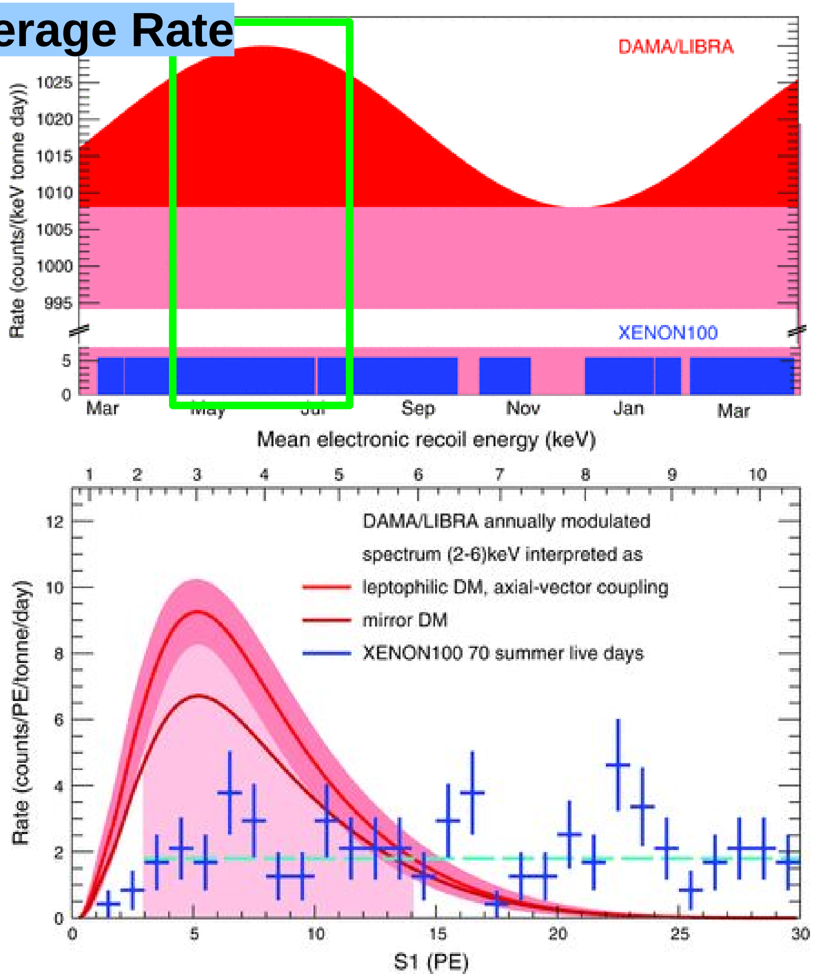


XENON100 @ LNGS

Astropart. Phys. 35, 573 (2012)

result from **XMASS** *PLB759, 272 (2016)*
→ exposure comparable to DAMA
→ result inconsistent with DAMA

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**

DAMA vs XENON

Modulation

PRL 118, 101101 (2017)

Detector

Pressure [bar]

Temperature [K]

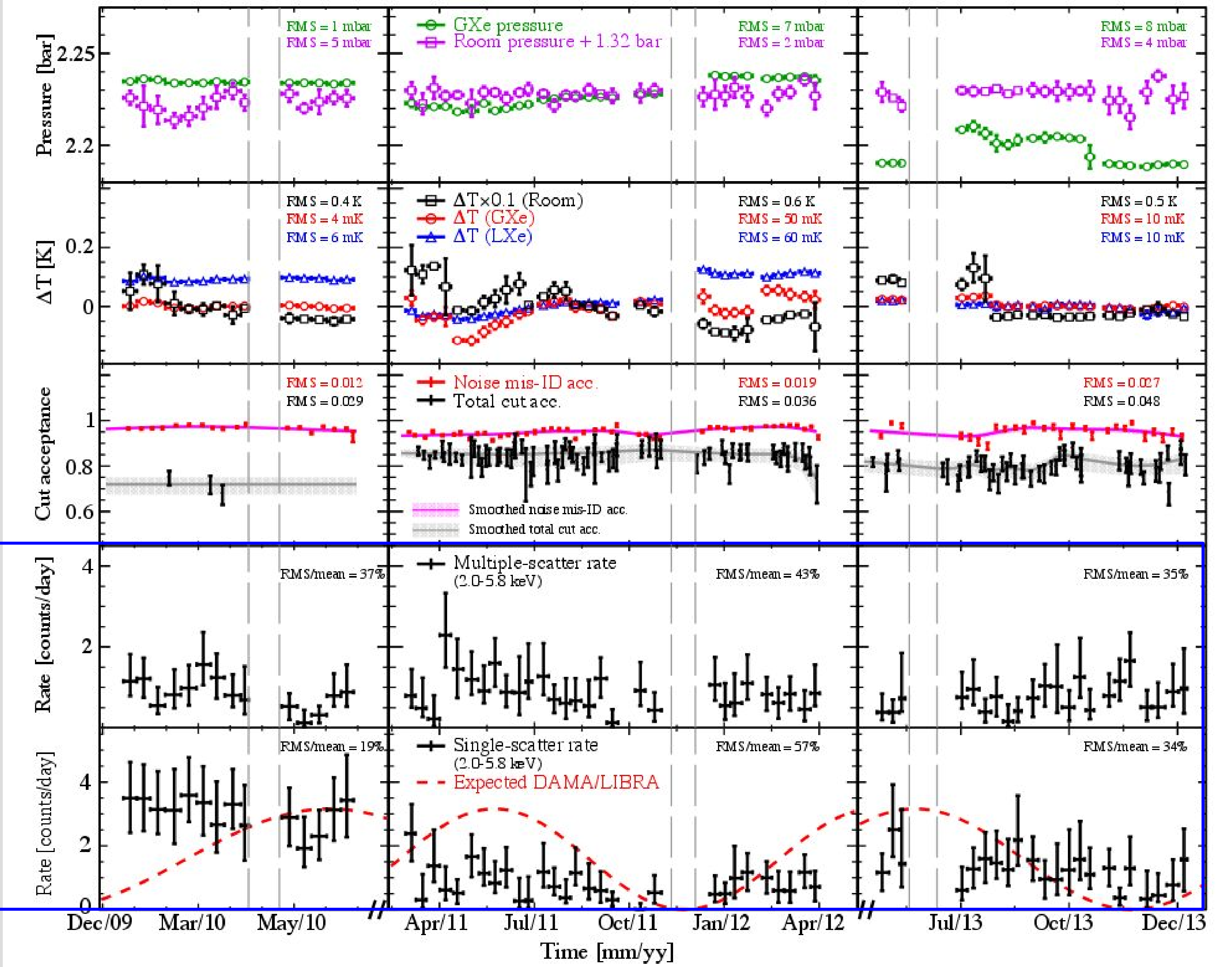
Analysis

Cut Acceptance

Rate

Multiples
(=background)

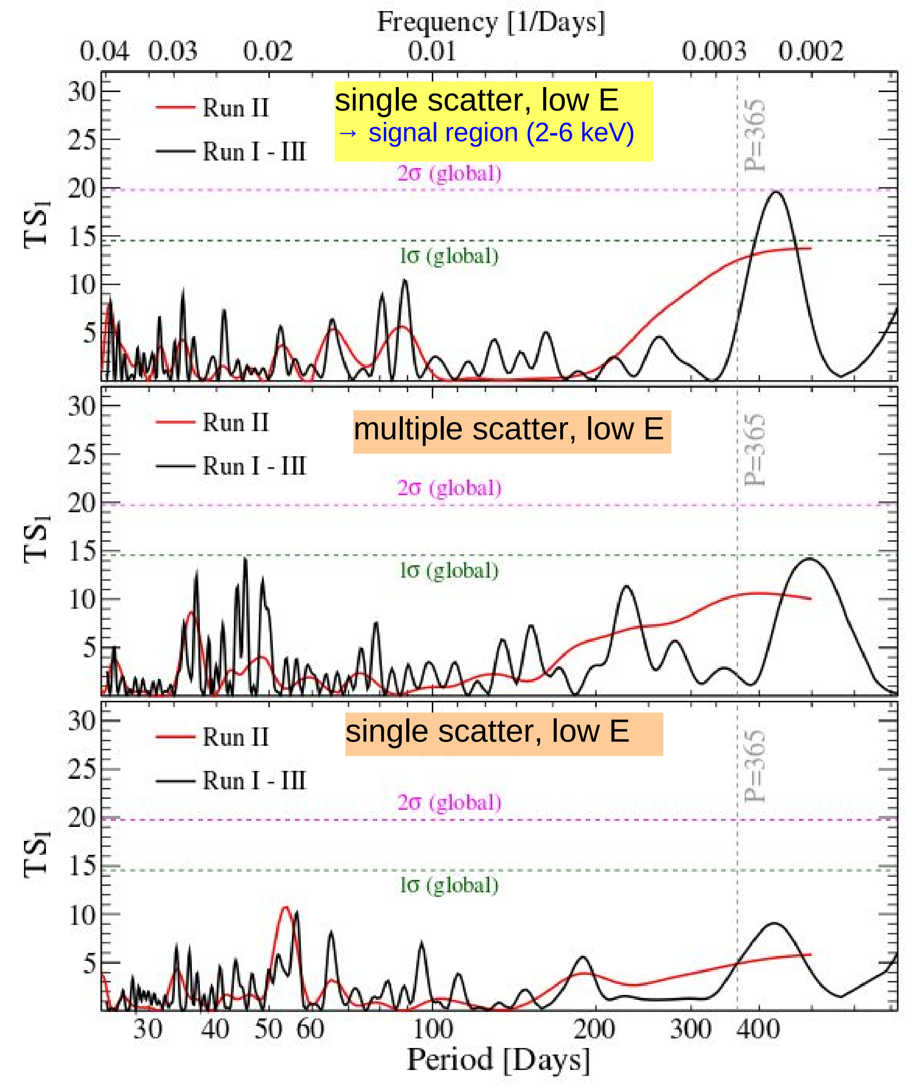
Singles
(=signal)



DAMA vs XENON

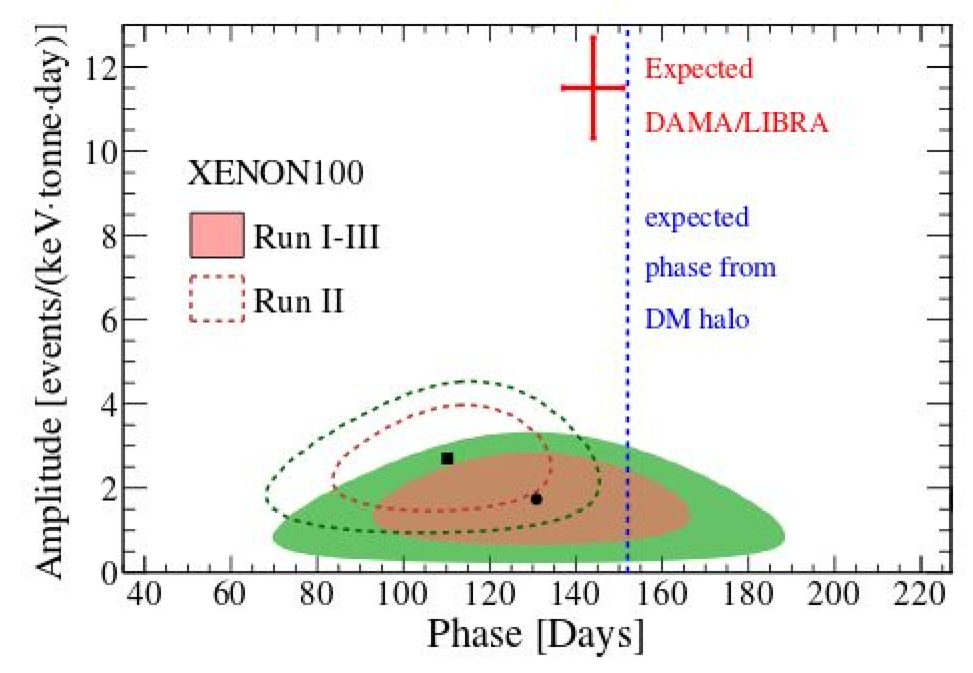
Modulation

PRL 118, 101101 (2017)


single scatter, low E
→ signal region (2-6 keV)

multiple scatter, low E

single scatter, low E



- additional data improves upon previous analysis *PRL 115, 091302 (2015)*
- no significant modulation observed
- Dark matter explanation of DAMA/LIBRA signal excluded @ **5.7σ**

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

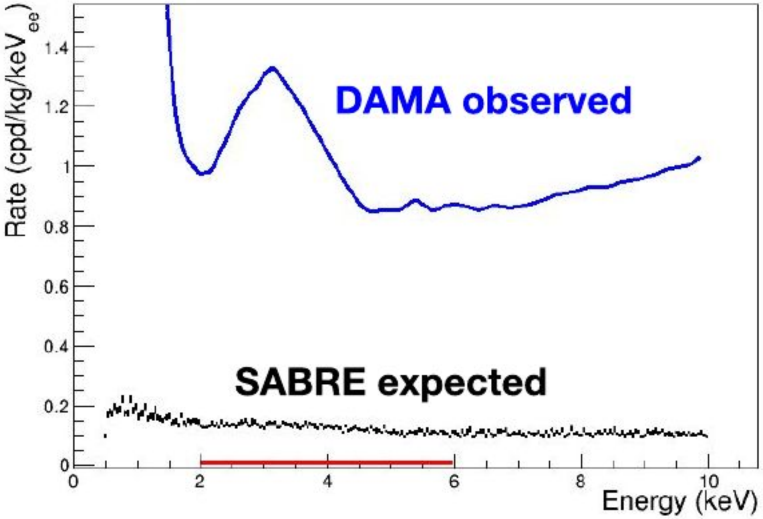
SABRE *NIM A 845, 418 (2017)*

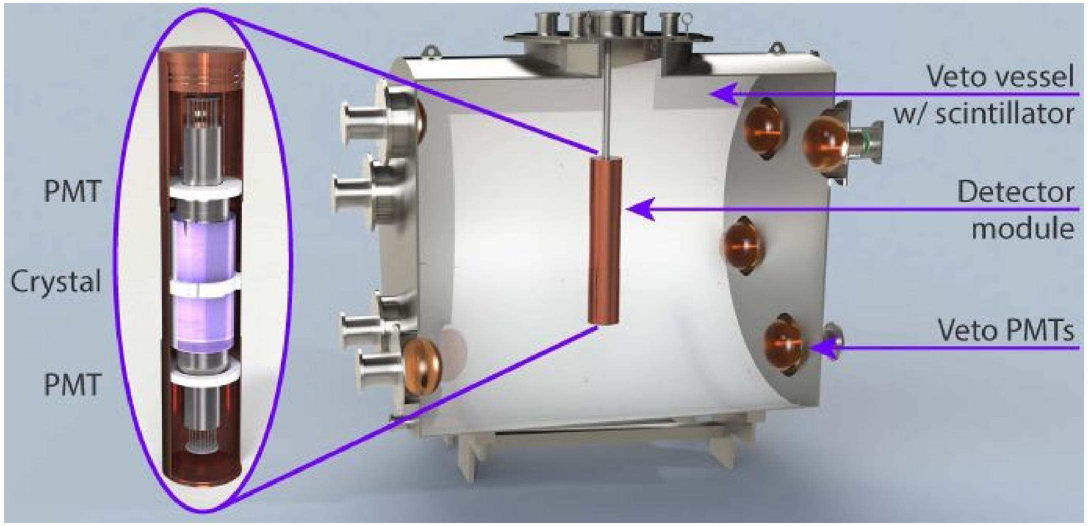
*S*odium-iodine with *A*ctive *B*ackground *RE*jection

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*: proof-of-principle prepared at LNGS (5 kg)





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

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

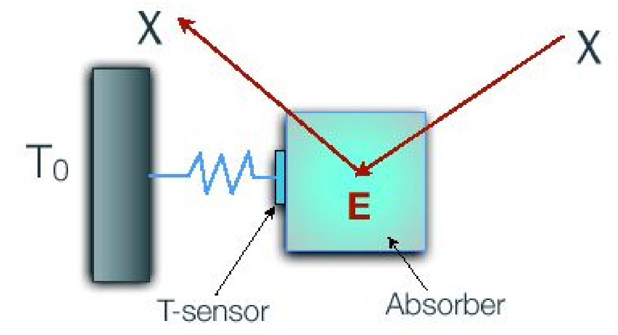
ANAIS: 112 kg @ Canfranc
→ background ~2-3x DAMA

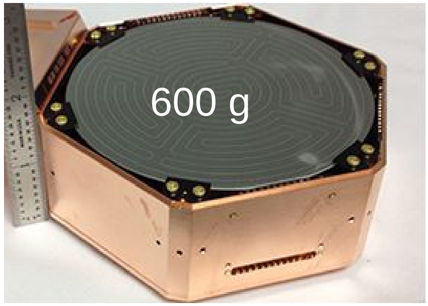
COSINUS R&D: *EPJ C 76, 441 (2016)*
NaI with bolometric+light readout

Cryogenic Detectors

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

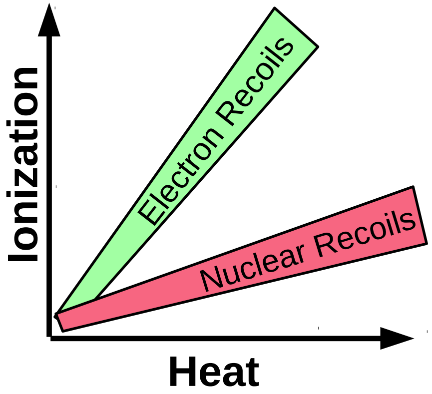
→ requires detecors at mK temperatures





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

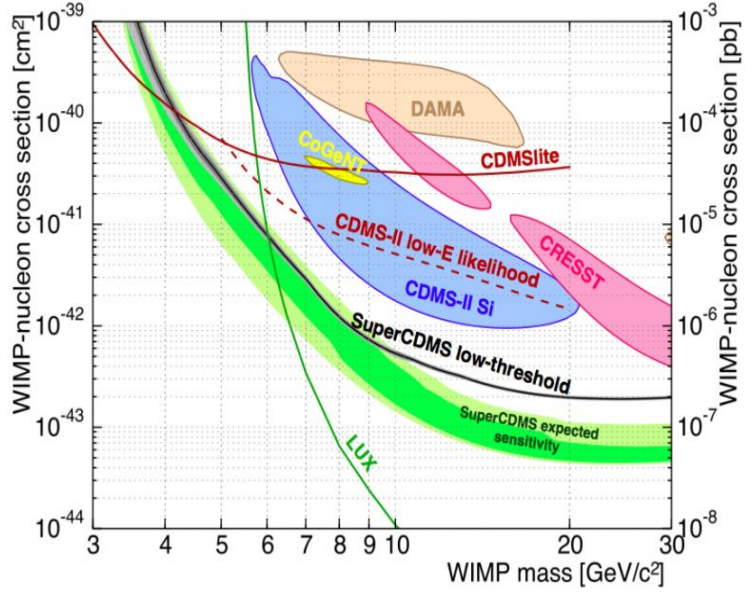
Very good discrimination
→ BUT: need to reject surface events



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)

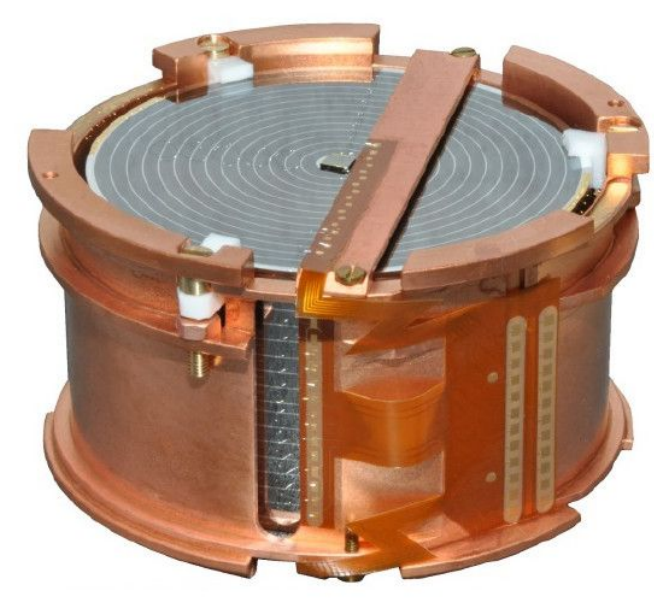
Sensitivity Study: *arXiv:1610.00006*

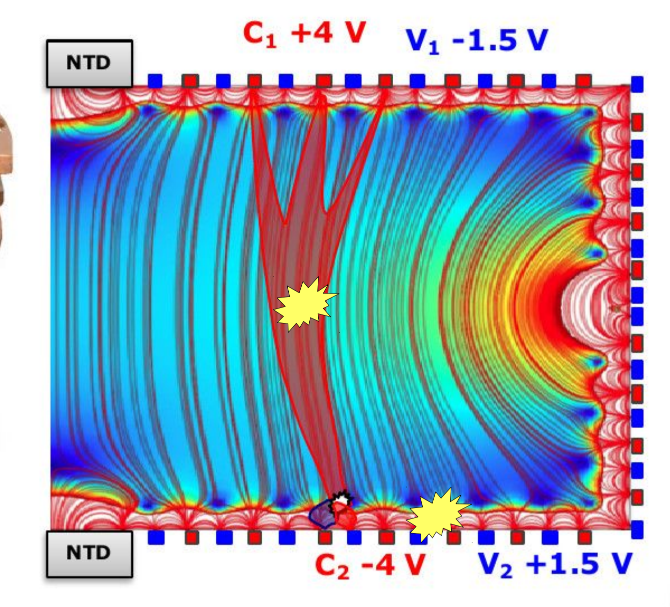
EDELWEISS-III

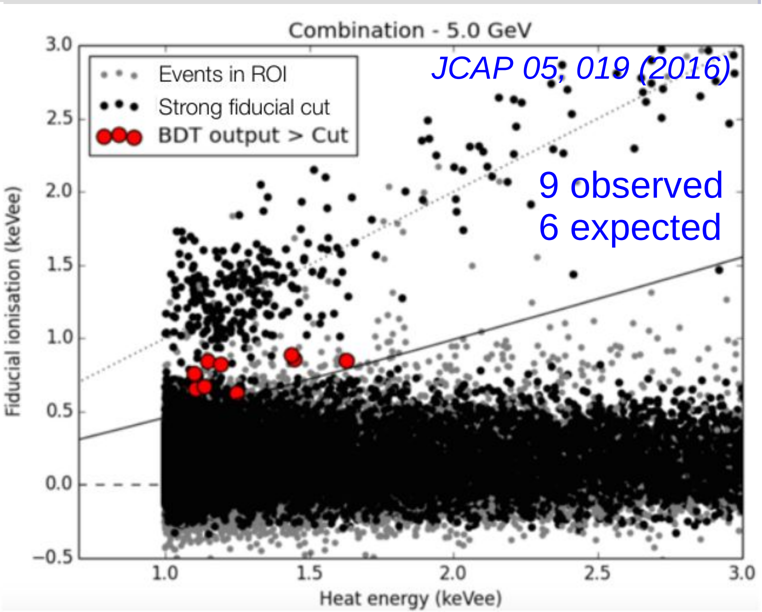
- operating 20 kg of Ge detectors in Modane Lab (F)
- 800 g Ge crystals measure ionization and heat (NTD sensors)

→ apply small voltage to extract charge

- interdigitized electrodes: fiducialization (~600 g)
- simultaneous measurement allows for NR/ER discrimination







JCAP 05, 019 (2016)

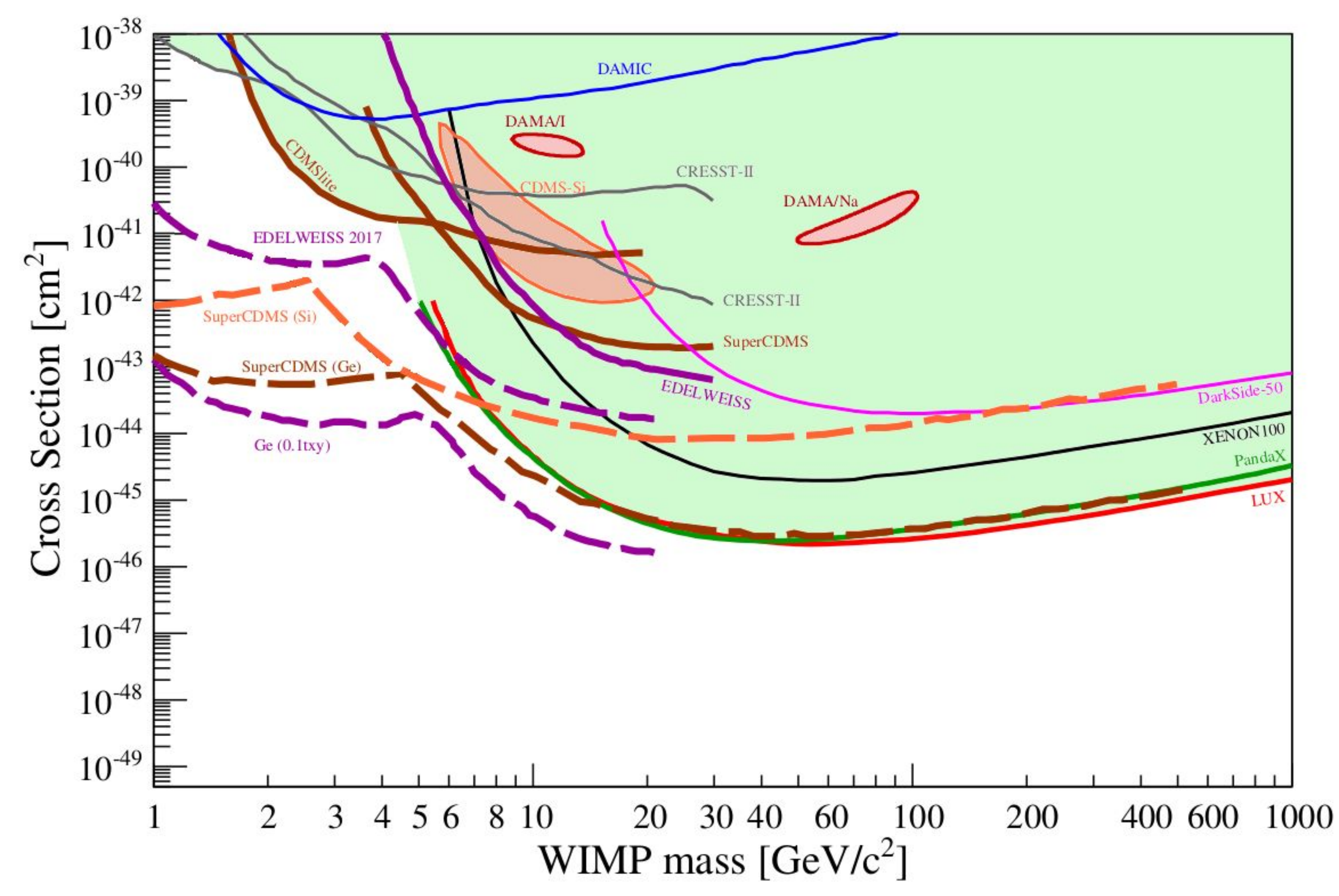
9 observed
6 expected

- new **low-threshold result**: 8 detectors with lowest thresholds (2.5–20 $\mathrm{keV_{nr}}$)
  → no statistically significant excess
  → 40× better limit than EDW-II @ 5 GeV/c²

BDT: JCAP 05, 019 (2016)
PL: EPJ C 76, 548 (2016)

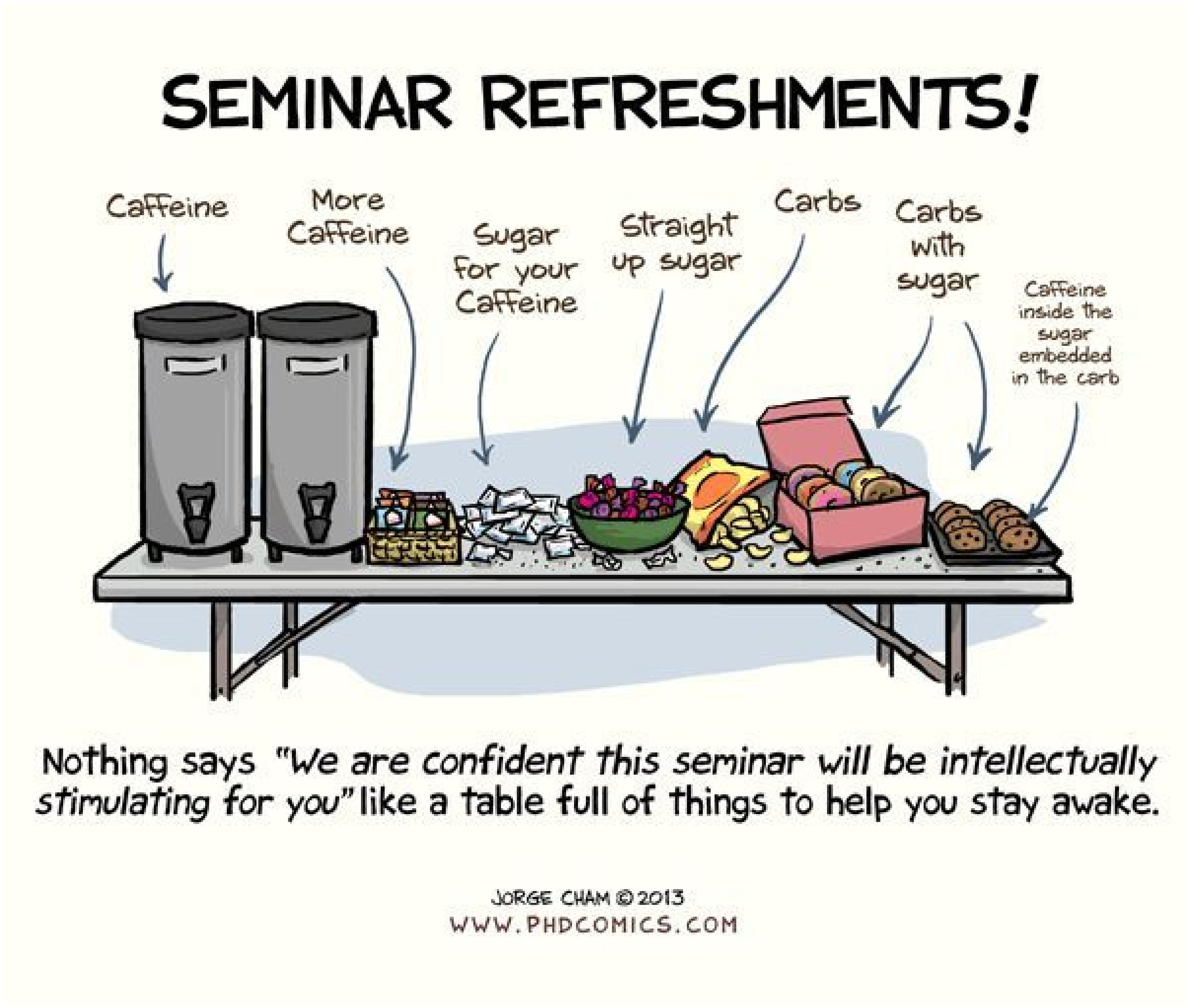
Ge / Si: Status and Prospects

spin-independent WIMP-nucleon interactions



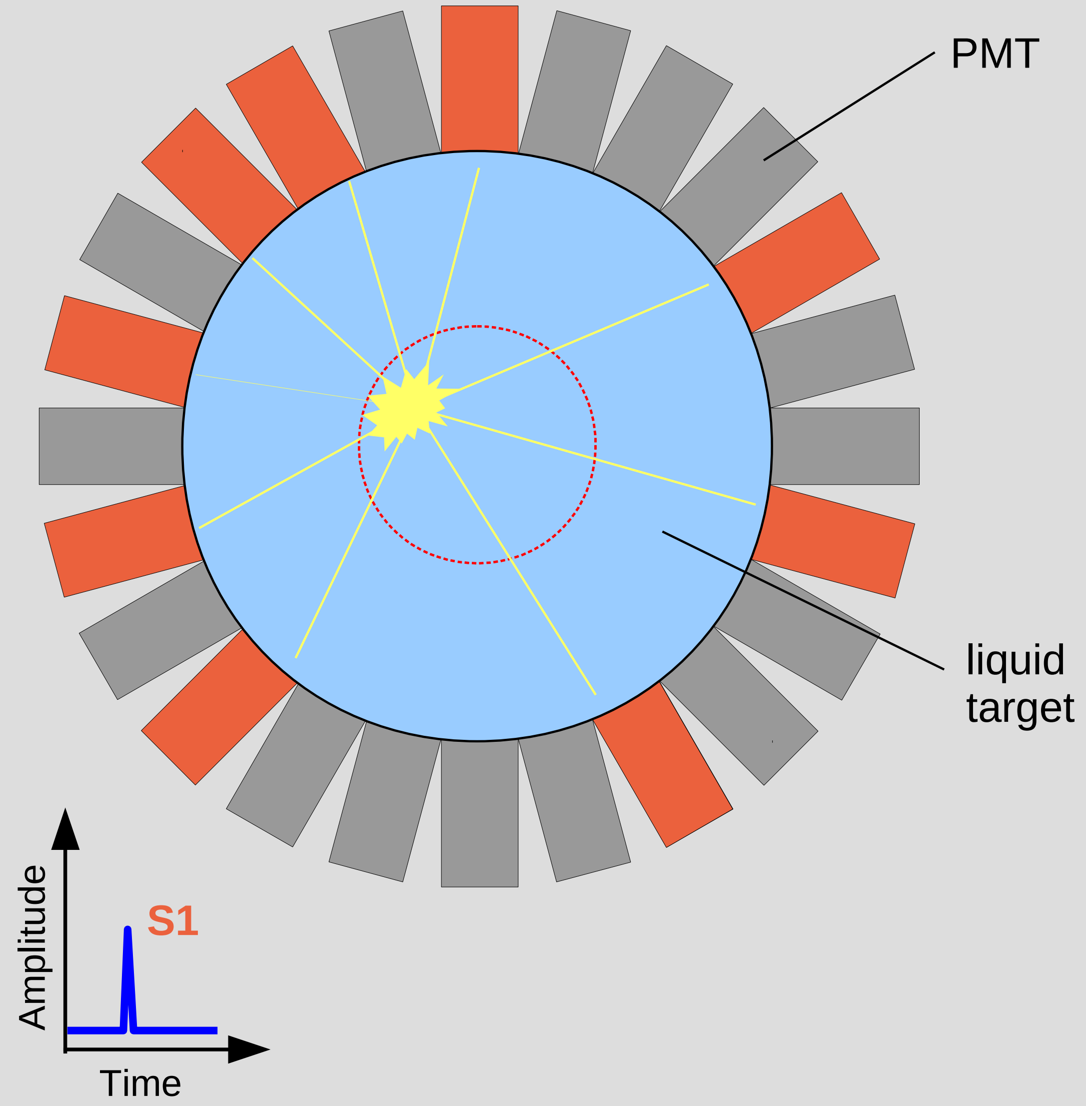
some projects are missing...

Time for a short break...



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

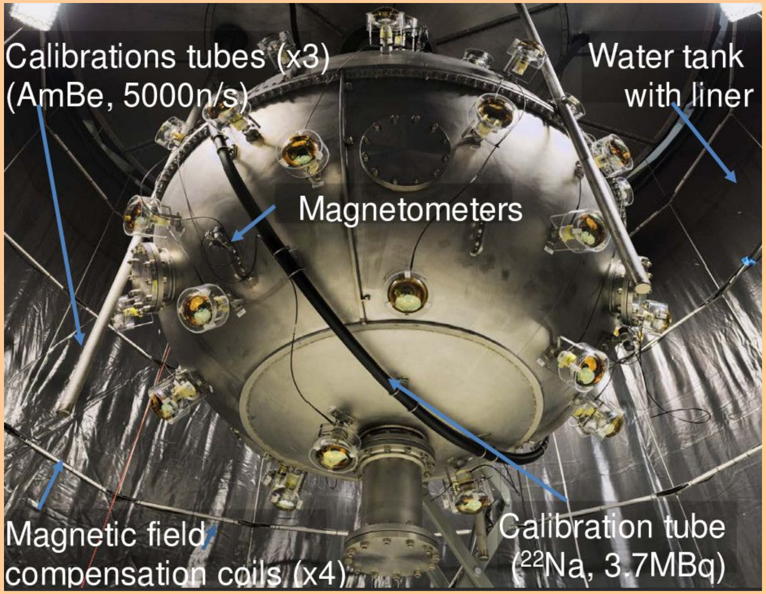
XMASS @ Kamioka (JP) **LXe**

- **832 kg** LXe target, 642 PMTs
- very high light yield, low threshold (0.5 keVee)
  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**

- **light pulse-shape for discrimination**
  3×10^{-8} achived in 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)
- data taking right now... high light yield,
  → results expected in spring 2017
- sensitivity: 1×10^{-46} cm² @ 100 GeV/c²



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**

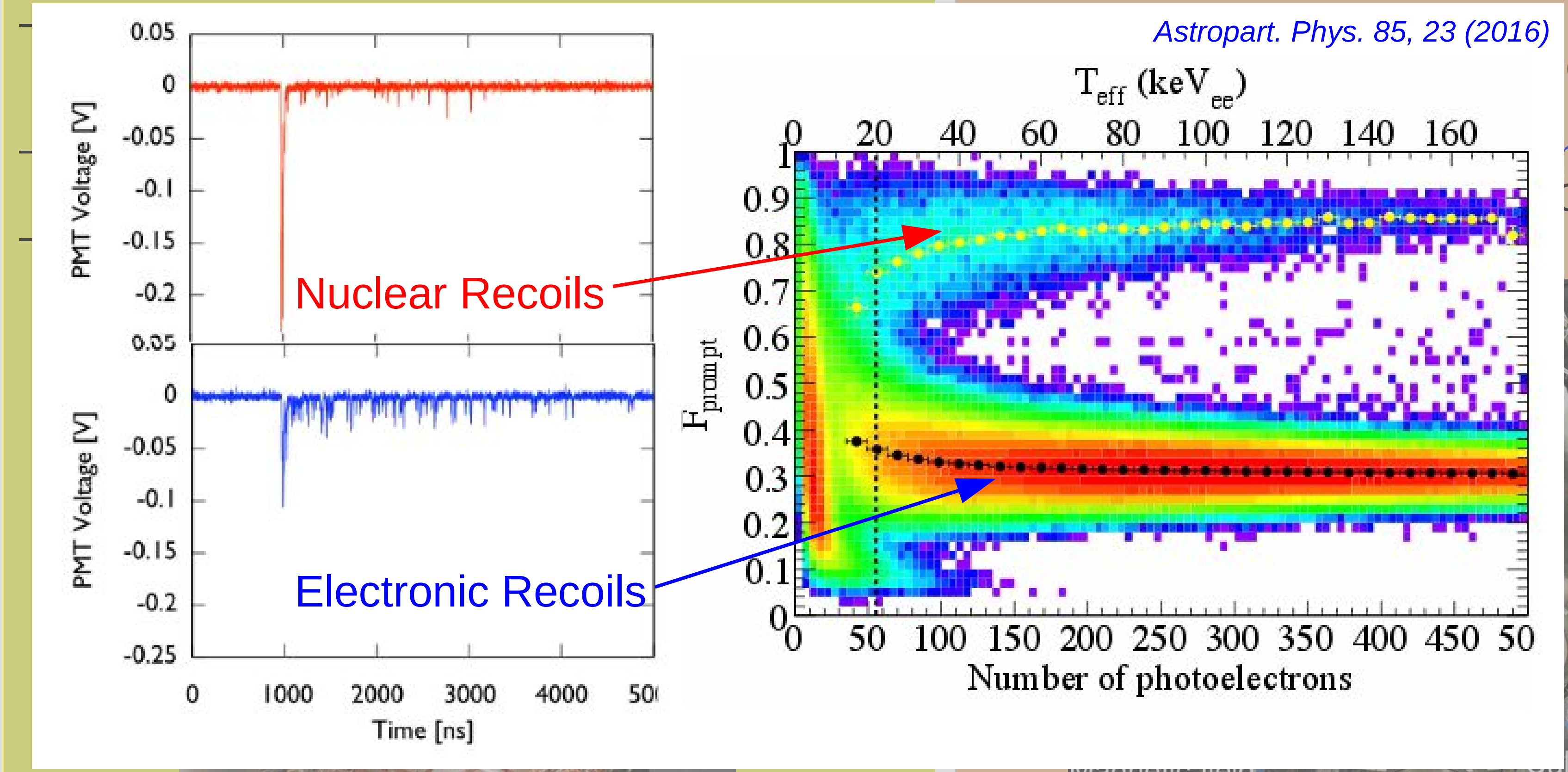
DEAP-3600 @ SNOLAB (CA) **LAr**

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

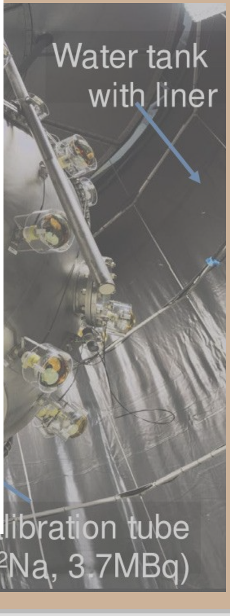
g ^{nat}Ar (~1 Bq/kg)

n LAr...

GeV/c²



Astropart. Phys. 85, 23 (2016)



F. Retiere (LIDINE 2015)

Why Xenon?

+ scintillation light in VUV (178nm)

+ high mass number *A*~131

SI: high WIMP rate @ low theshold

+ high *Z*=54, high ρ~3 kg/l:

self shielding, compact detector

+ 50% odd isotopes

+ "easy" cryogenics @ –100°C

+ scalability to larger detectors

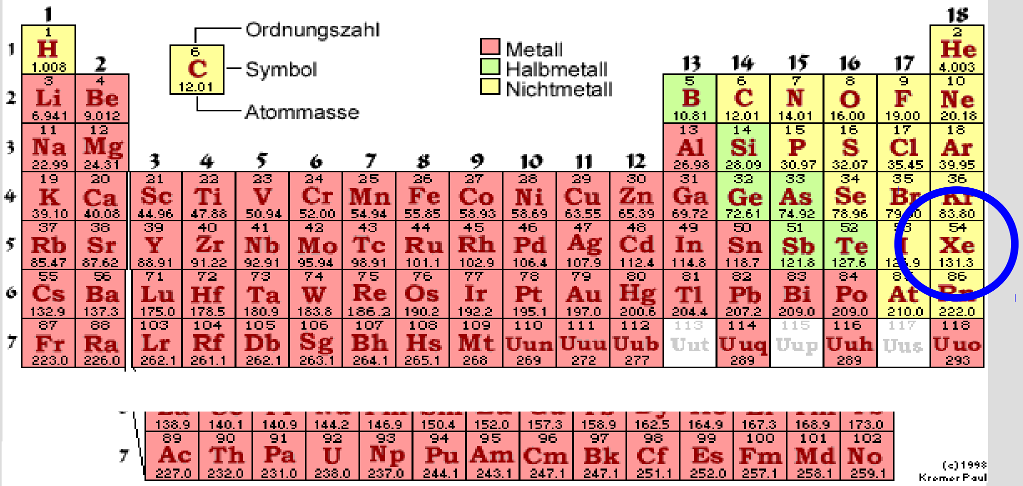
+ no long lived Xe isotopes

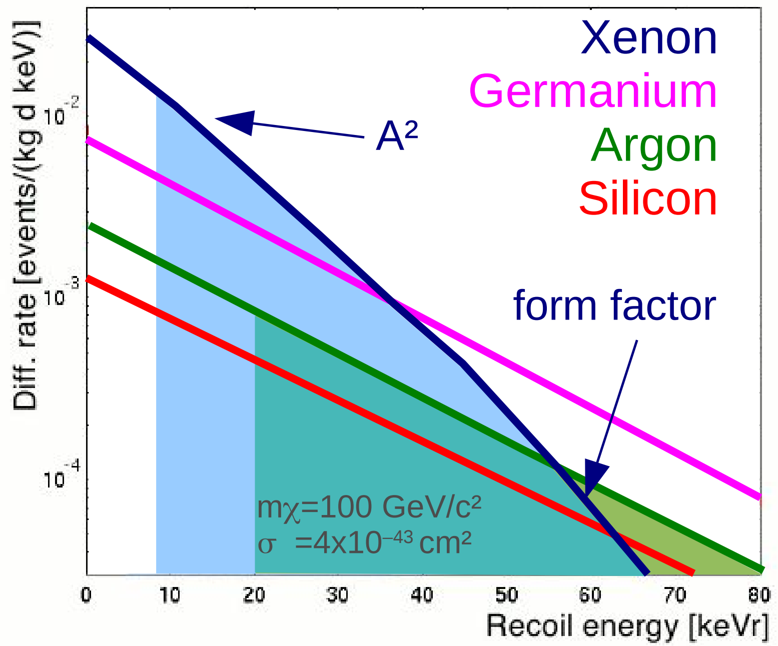
Kr-85 can be removed to below ppt level

+ background discrimination when measuring light and charge

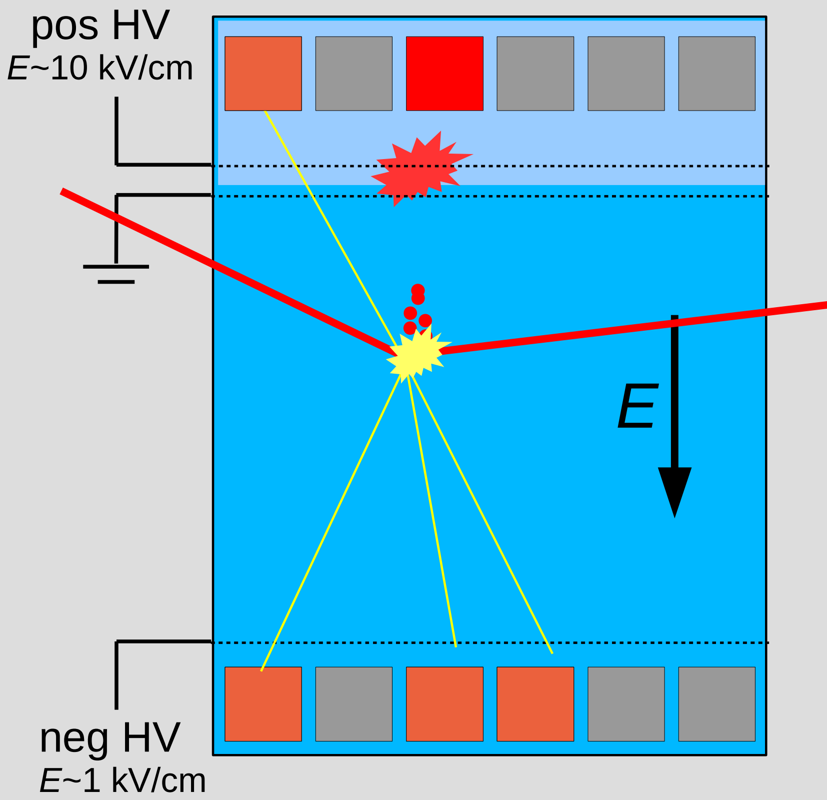
– expensive

– only fair background rejection





Dual Phase TPC

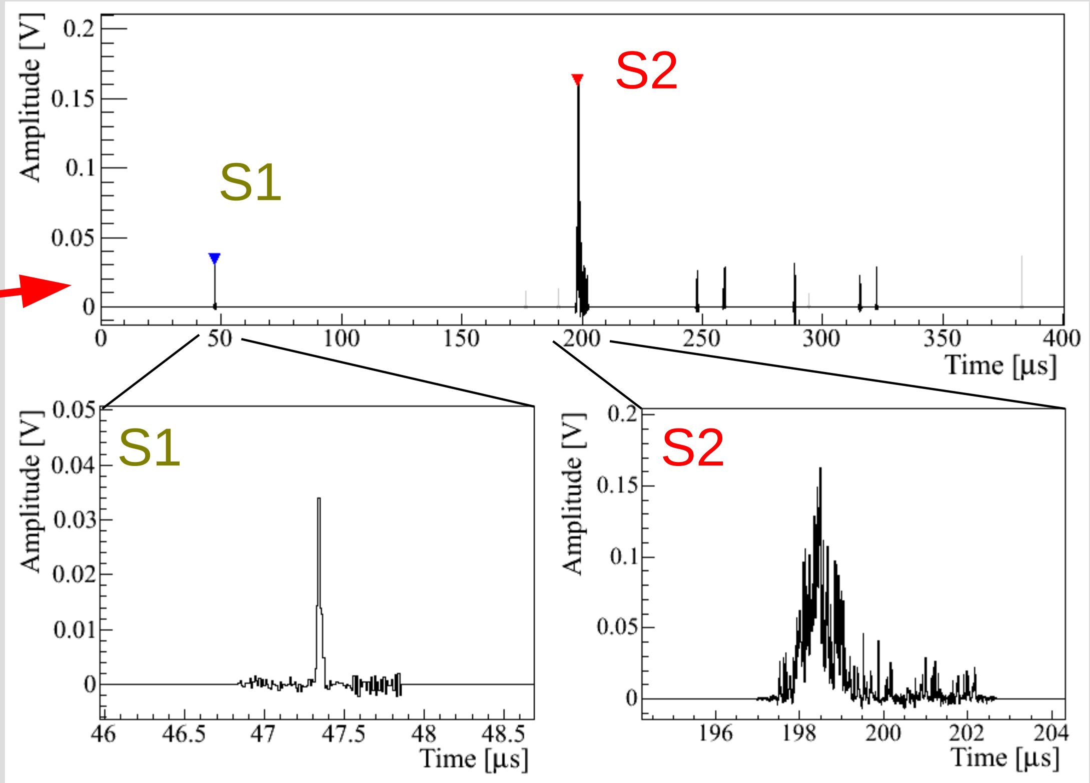


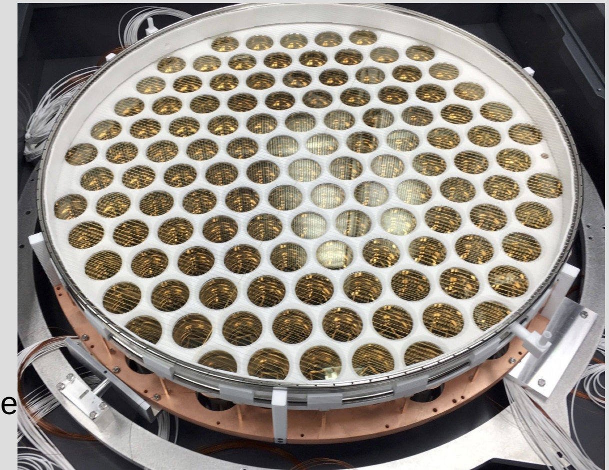
pos HV

E~10 kV/cm

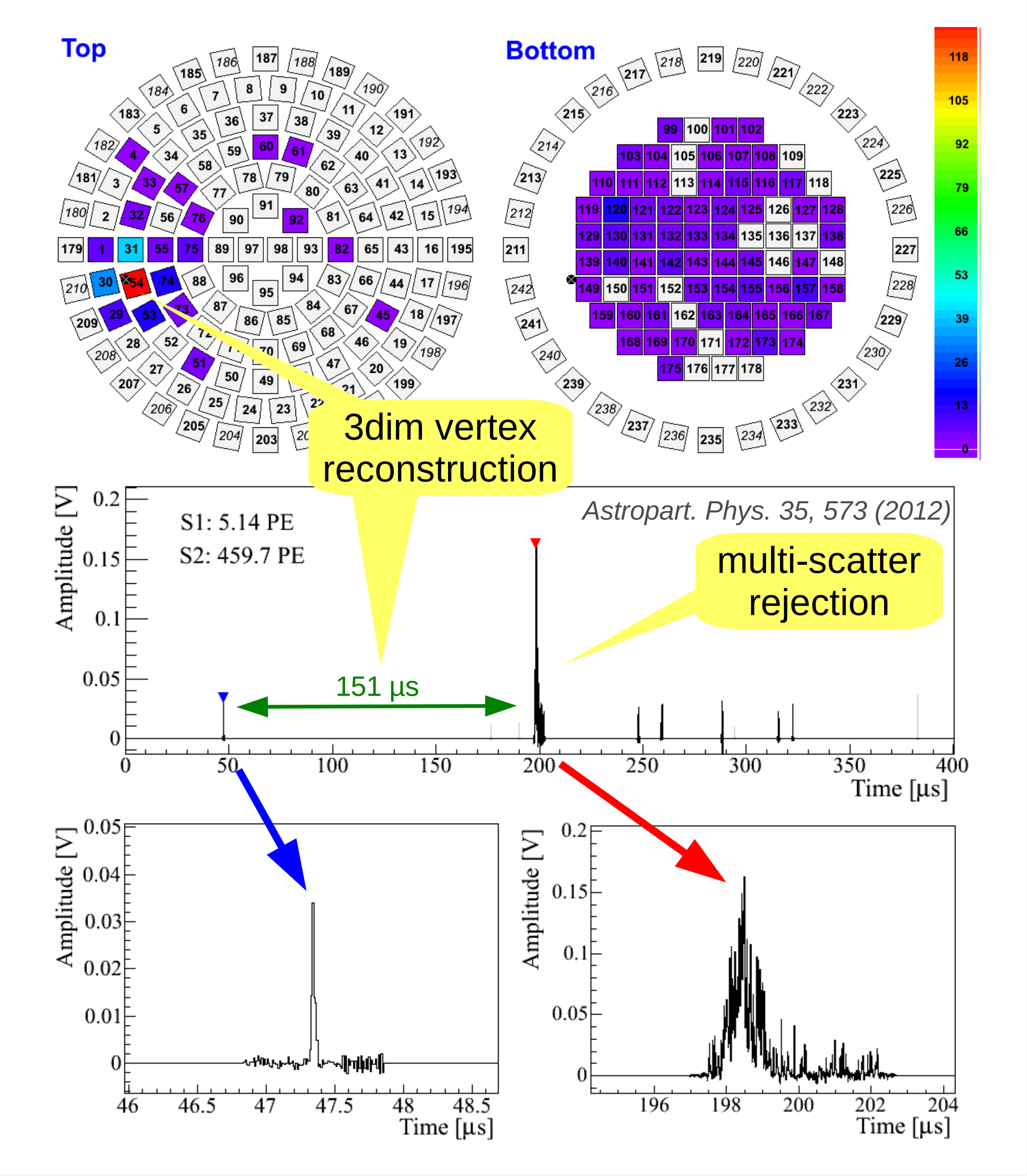
neg HV

E~1 kV/cm





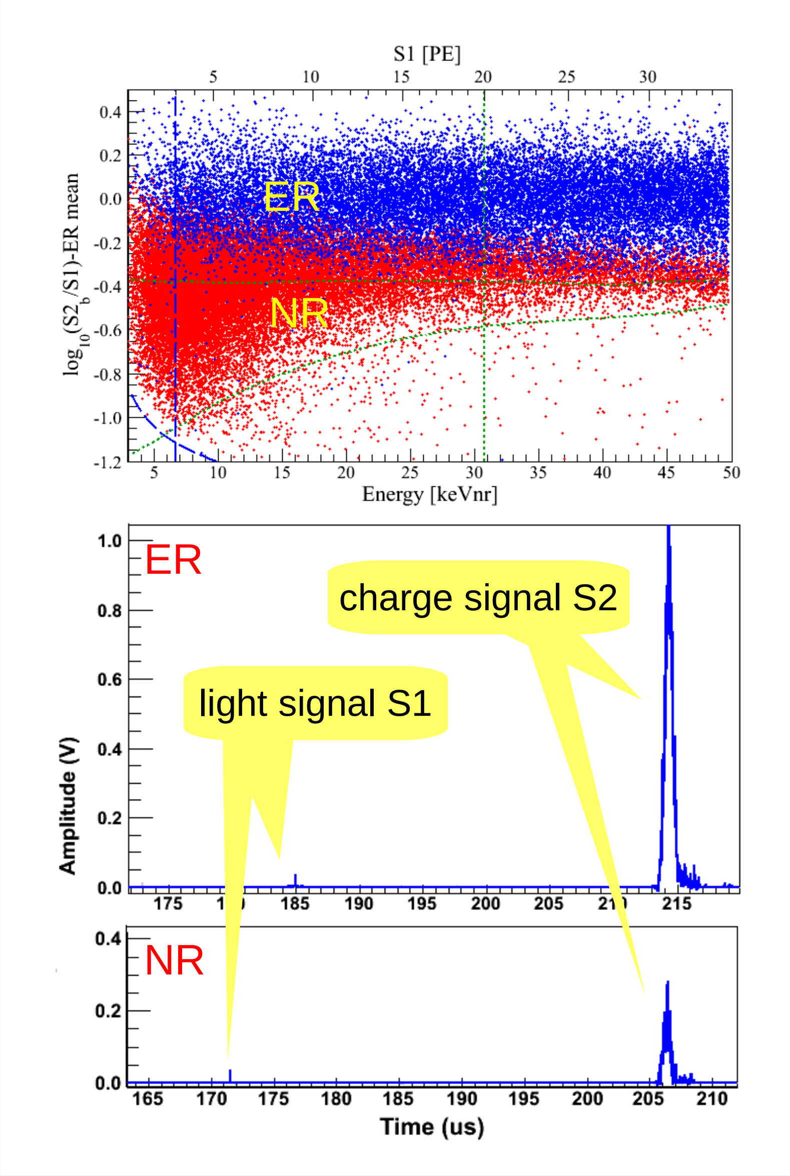
Dual Phase TPC



3dim vertex reconstruction

multi-scatter rejection

Astropart. Phys. 35, 573 (2012)



charge signal S2

light signal S1

Figures from XENON100

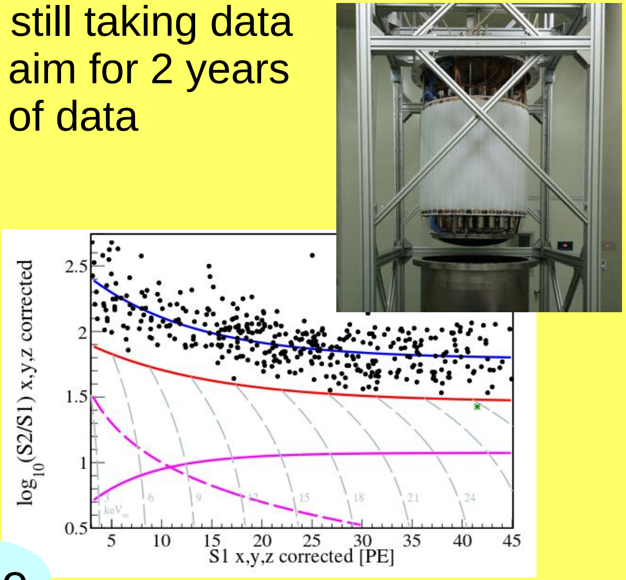
Existing dual phase detectors

LXe

PandaX-II @ CJPL (CN)
PRL 117, 121303 (2016)

- 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
- still taking data
  aim for 2 years
  of data

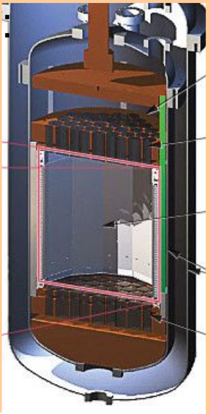


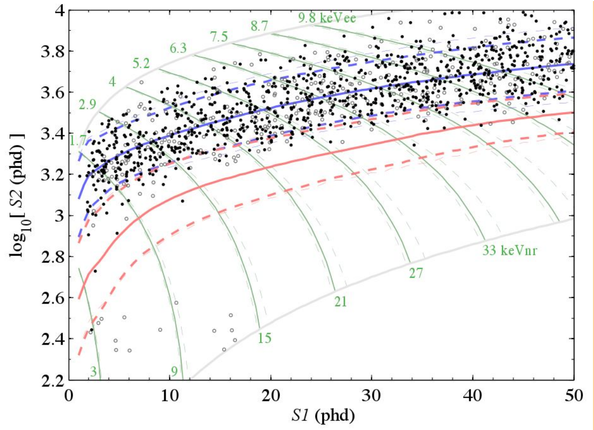
LXe

LUX @ SURF (USA)
PRL 118, 021303 (2017)

- 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
- stopped

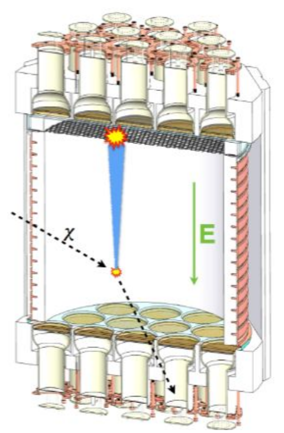


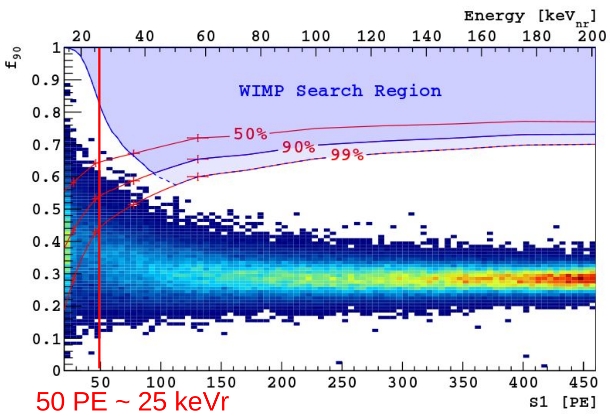


LAr

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 ROI
- taking data





50 PE ~ 25 keVr

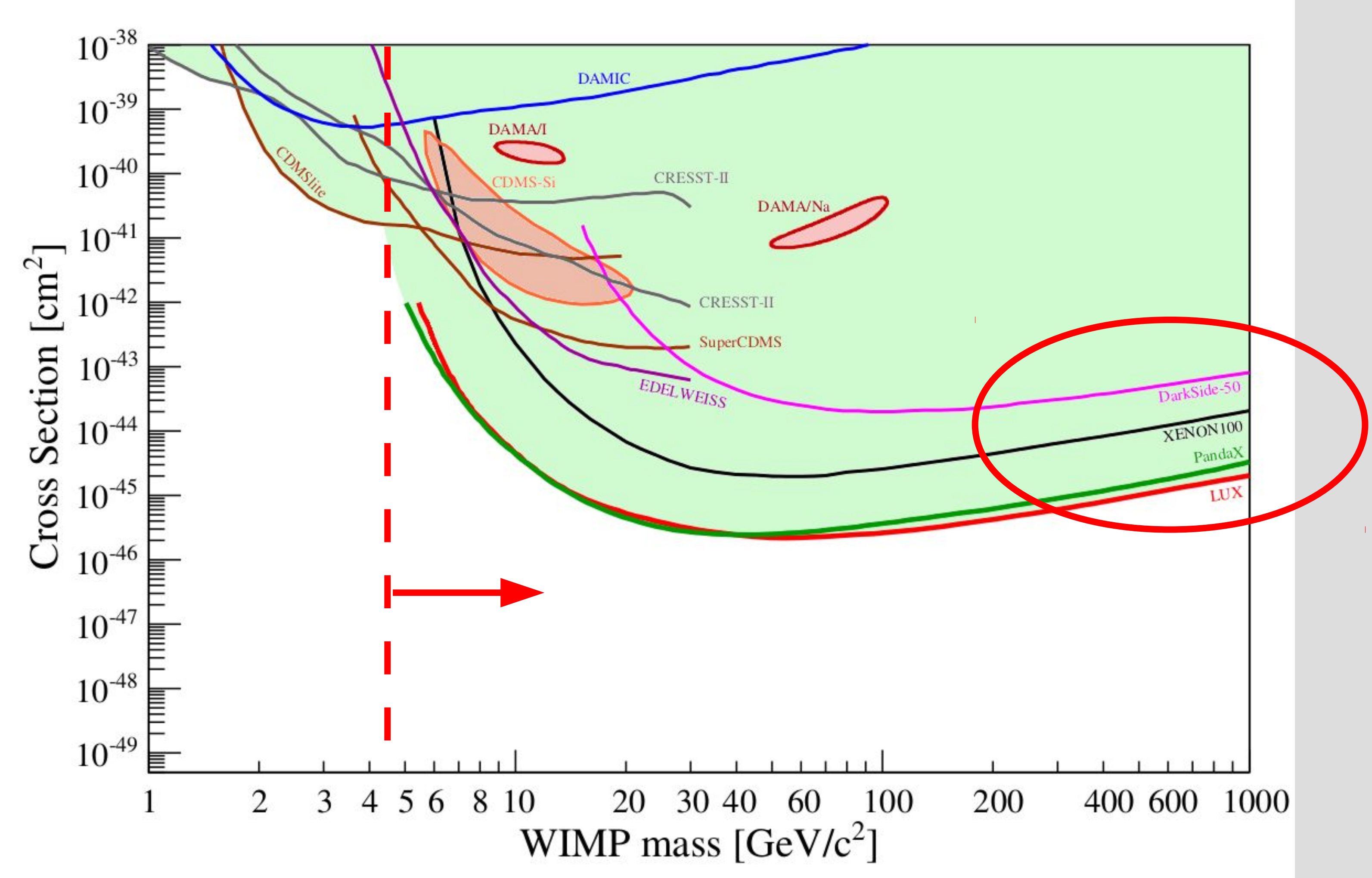
LXe

XENON100 @ LNGS (IT) **New:** 447 live days *PRD 94, 122001 (2016)* low-mass WIMPs *PRD 94, 092001 (2016)*

High WIMP-masses TPC dominated

≥4.5 GeV/c²

spin-independent WIMP-nucleon interactions



some projects are missing...

XENON1T @ LNGS

LXe

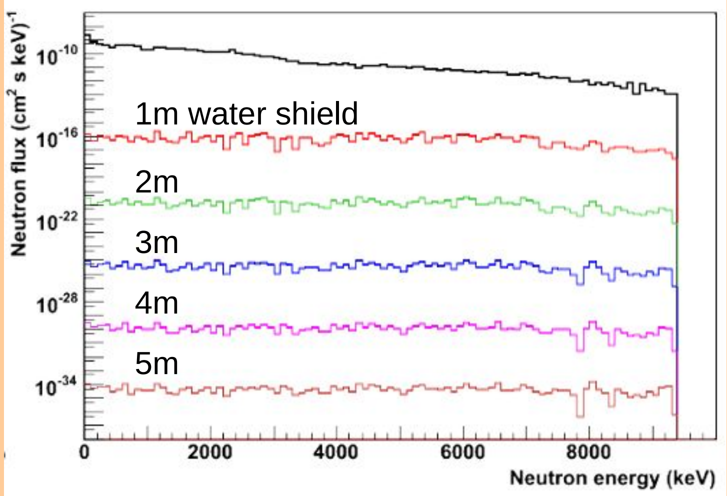
XENON1T @ LNGS

Water Cerenkov Shield

JINST 9, P11006 (2014)

- 9.6m diameter, 10m height
- external γ, neutrons irrelevant
- muon induced NRs irrelevant

→ dominating background of XENON1T will be intrinsic

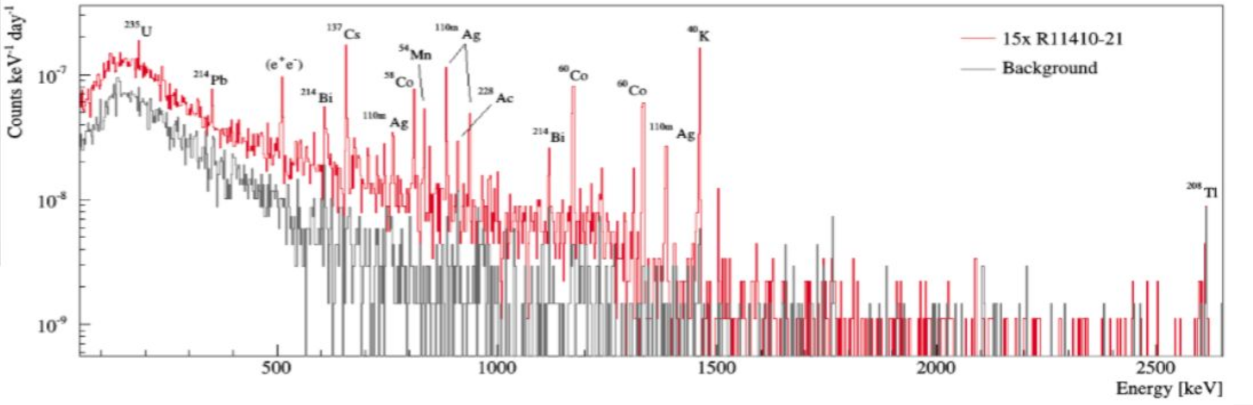


Xe
XENON
Dark Matter Project

PMTs: Hamamatsu R11410-21

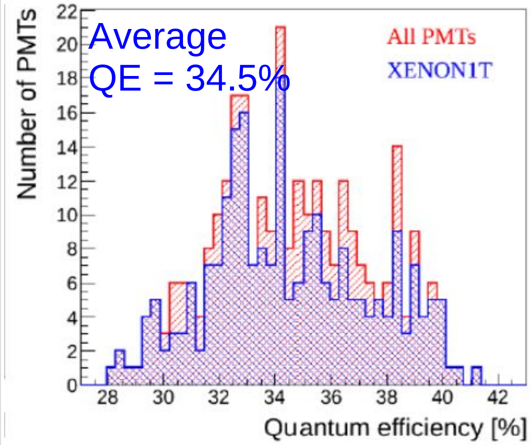
JINST 8, P04026 (2013)
EPJ C 75, 546 (2015)

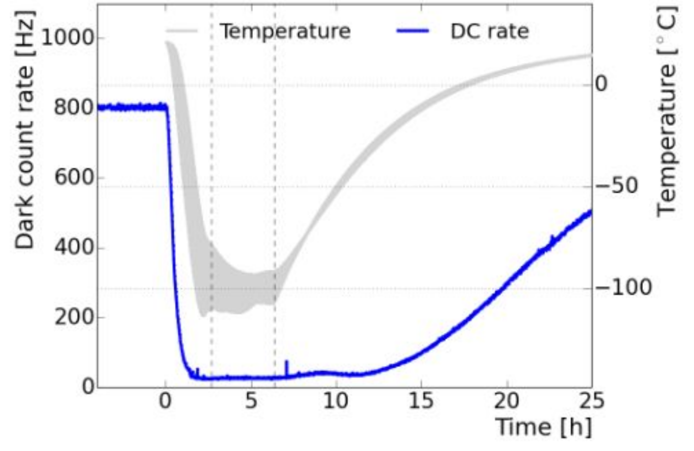
Low-background PMT developed with Hamamatsu



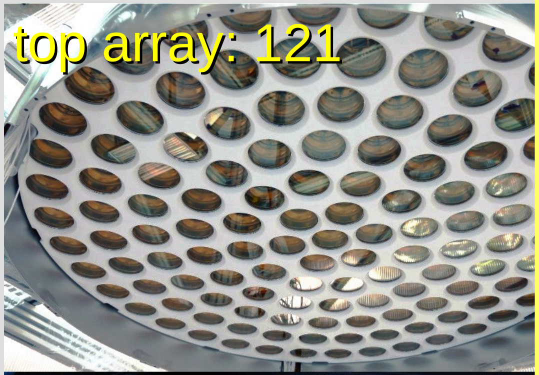
Extensive pre-testing/characterization campaign

arXiv:1609.01654

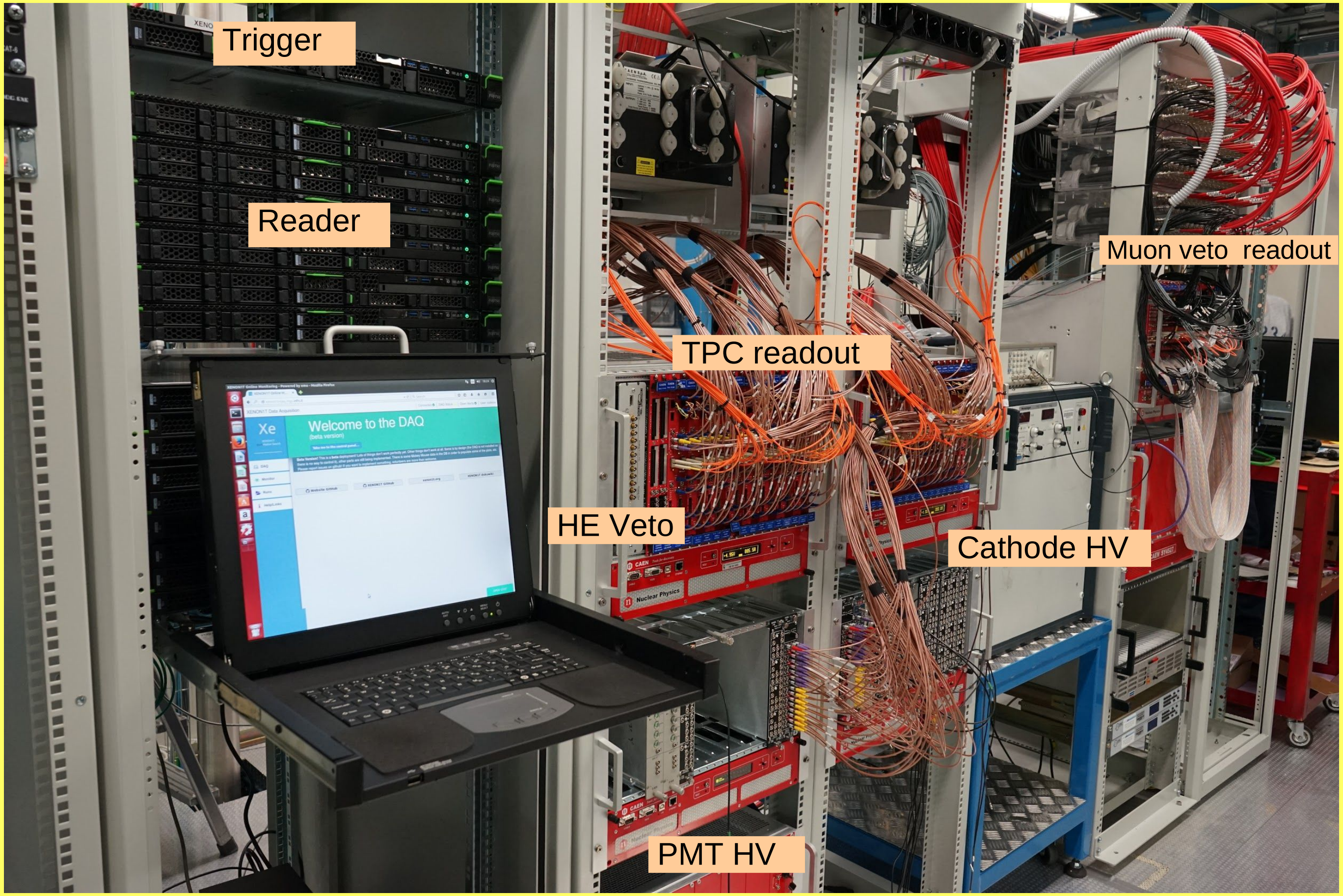




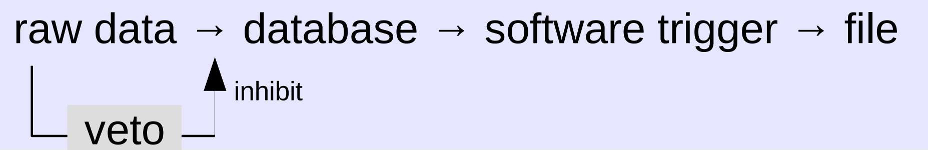
PMTs: Hamamatsu R11410-21



TPC Data Acquisition, Electronics



Parallel, trigger-less readout: → low threshold
→ high throughput (>300 MB/s achieved → 0.8 TB/d):

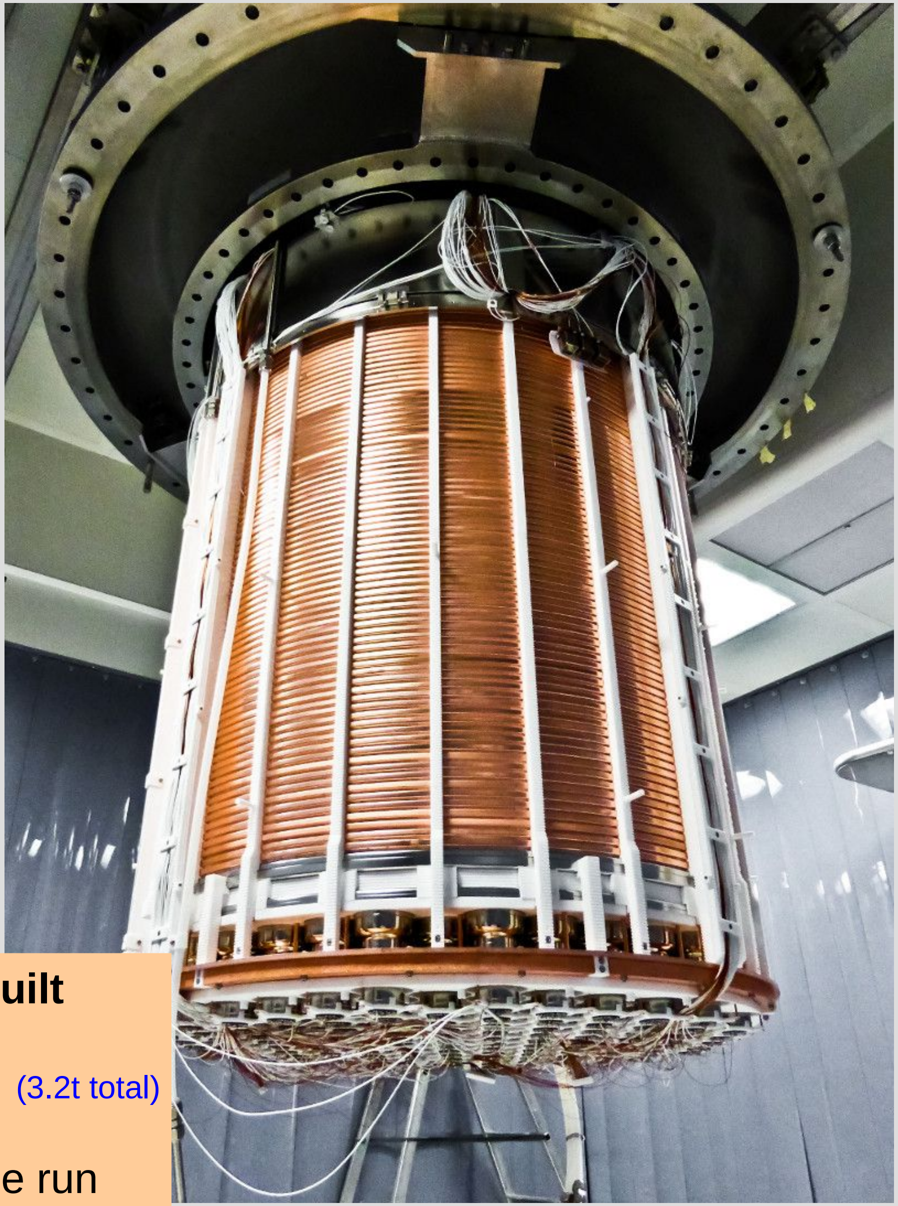

raw data → database → software trigger → file

inhibit

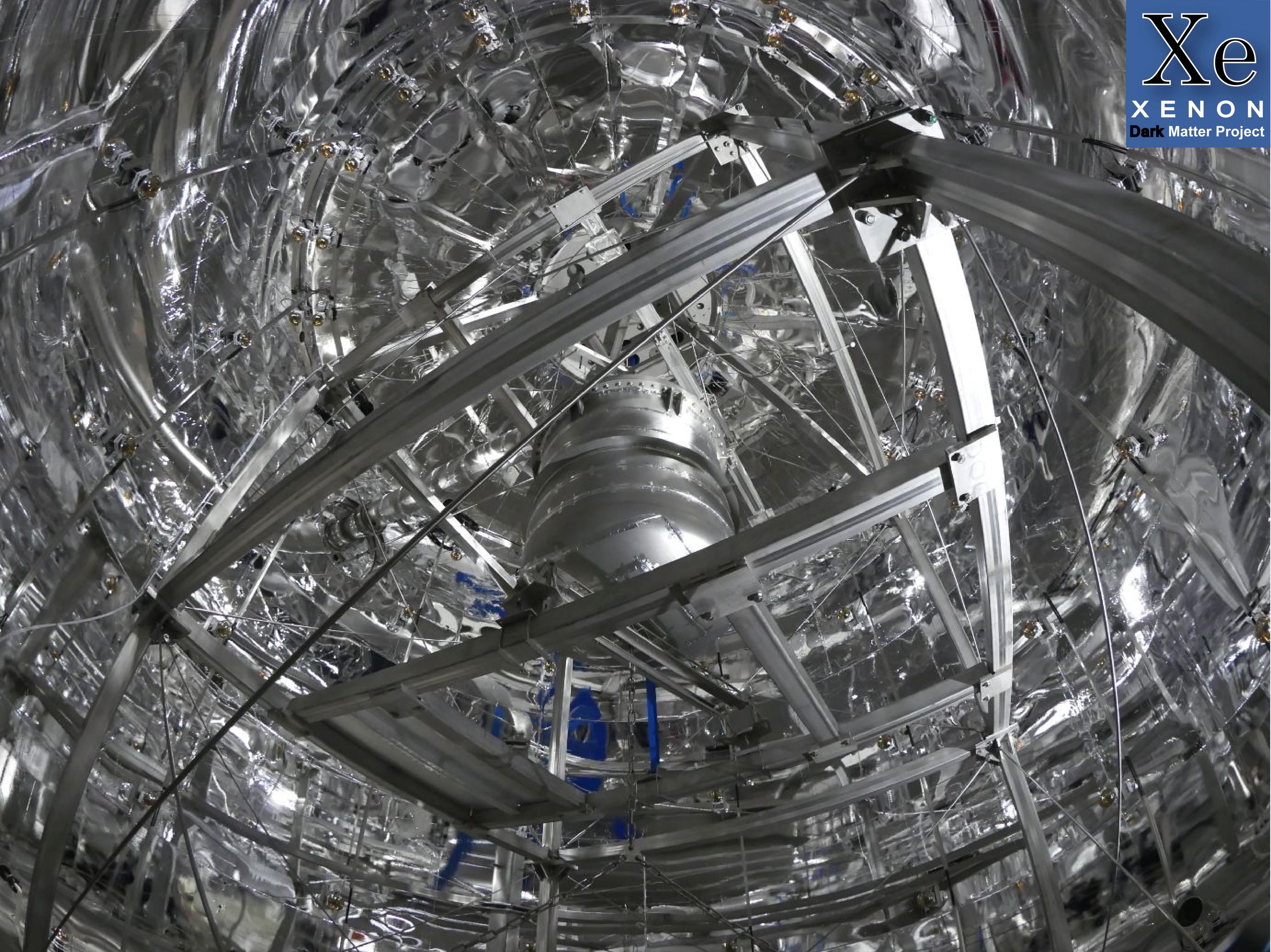
veto

Xe
XENON
Dark Matter Project

XENON1T

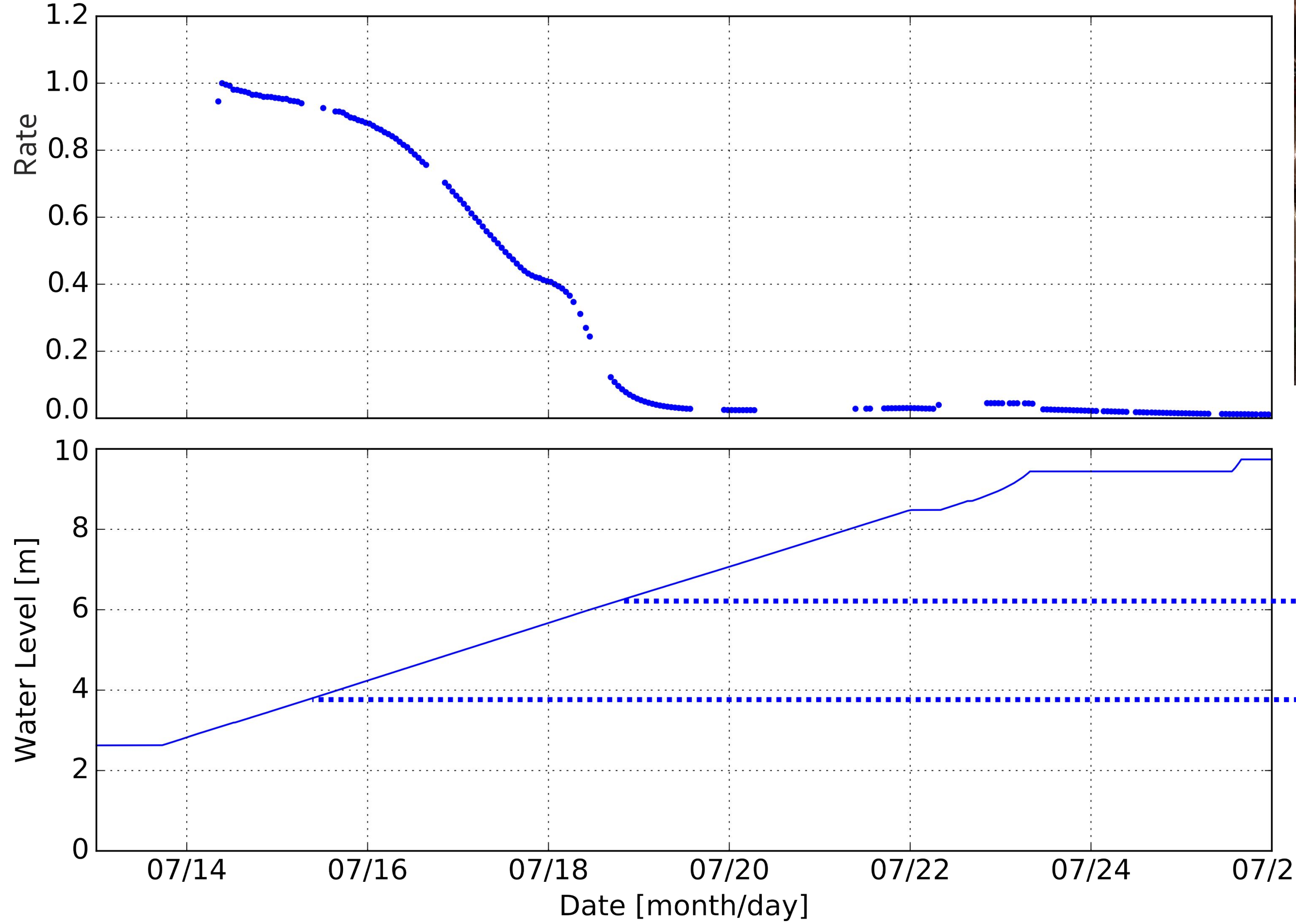


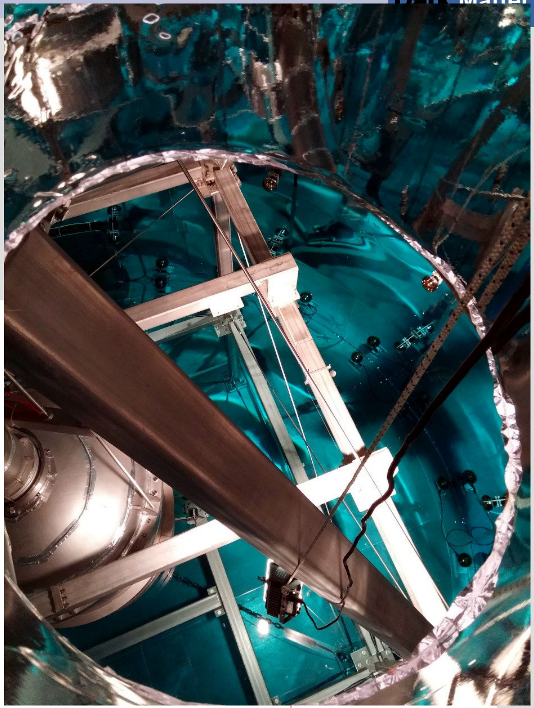
- **largest LXe TPC ever built**
  - **cylinder: 96 cm**
  - **active LXe target: 2.0t** (3.2t total)
  - **248 PMTs**
- operating: started science run

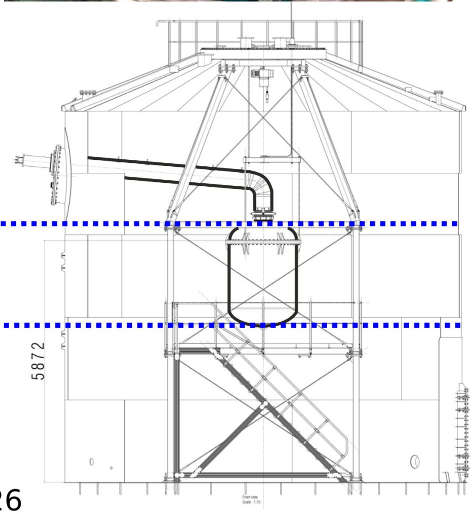

Xe
XENON
Dark Matter Project

XENON1T Performance

Water shield continuously filled since Summer...



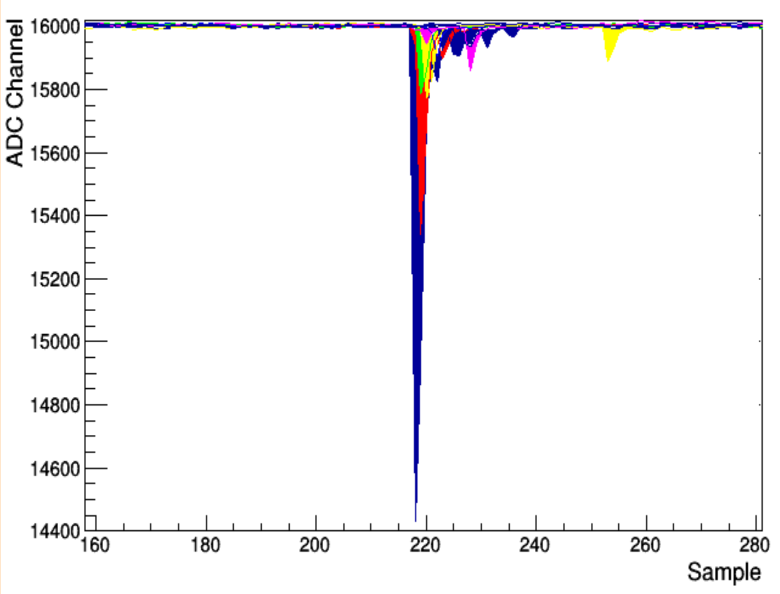


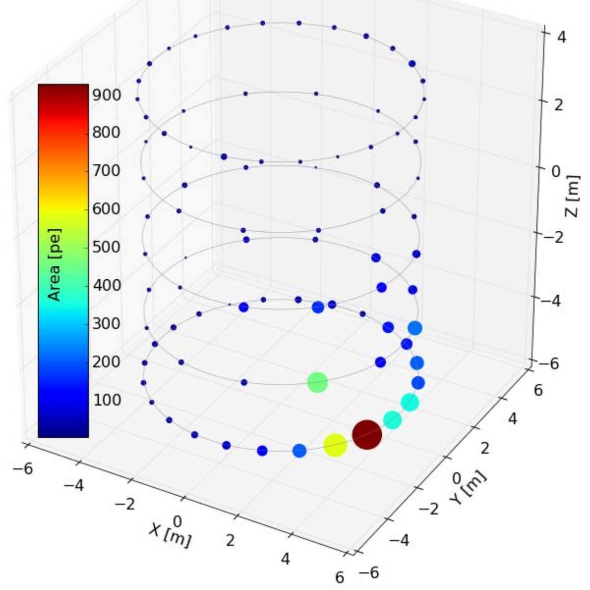


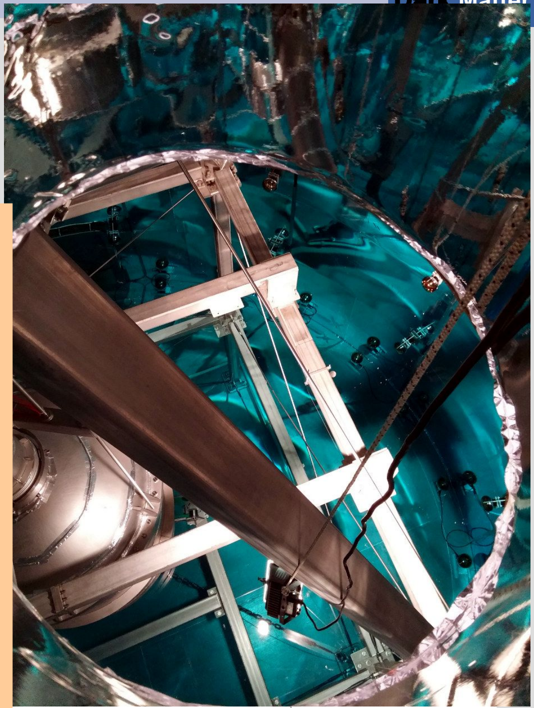
XENON1T Performance

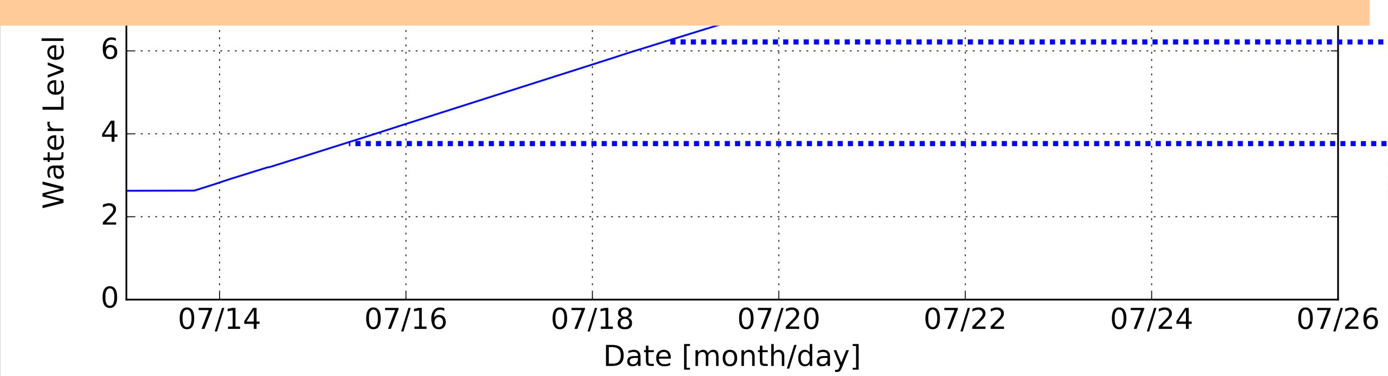
Water shield continuously filled since Summer...

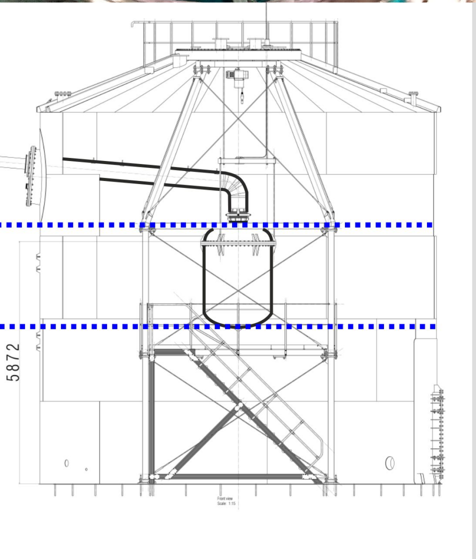
Cerenkov detector sees muons...





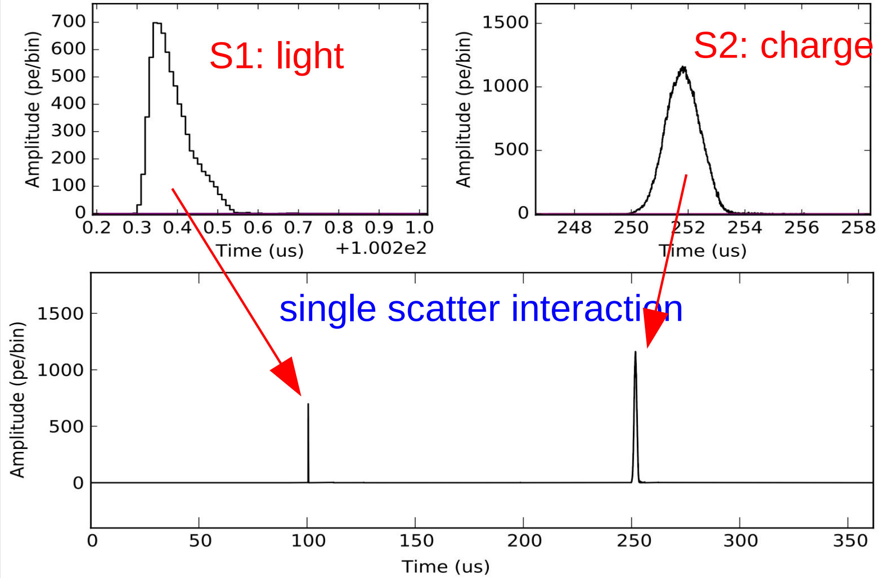


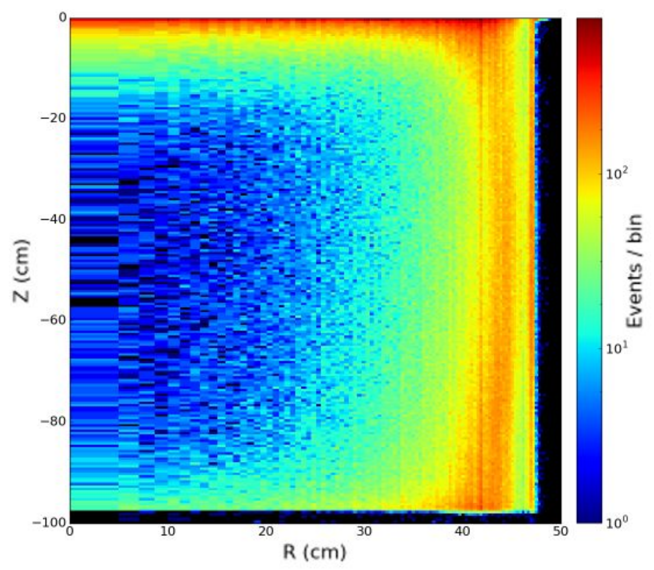




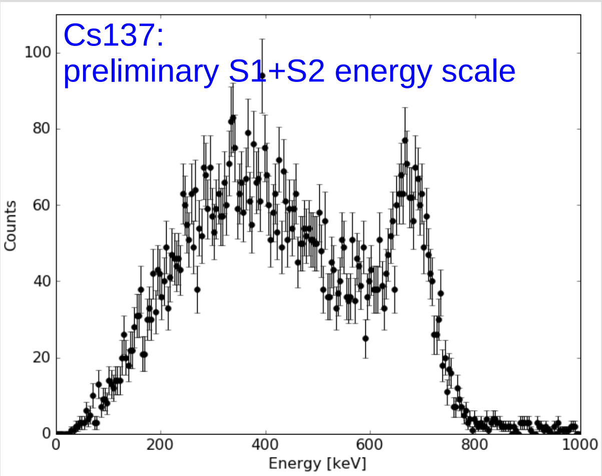
XENON1T Performance

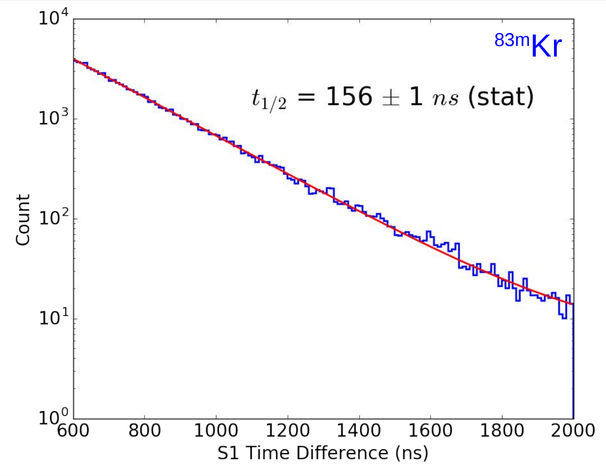
Recording light (S1) and light signals (S2) from the entire detector





Calibration: external (^{137}Cs, AmBe), internal (^{83m}Kr, ^{220}Rn)





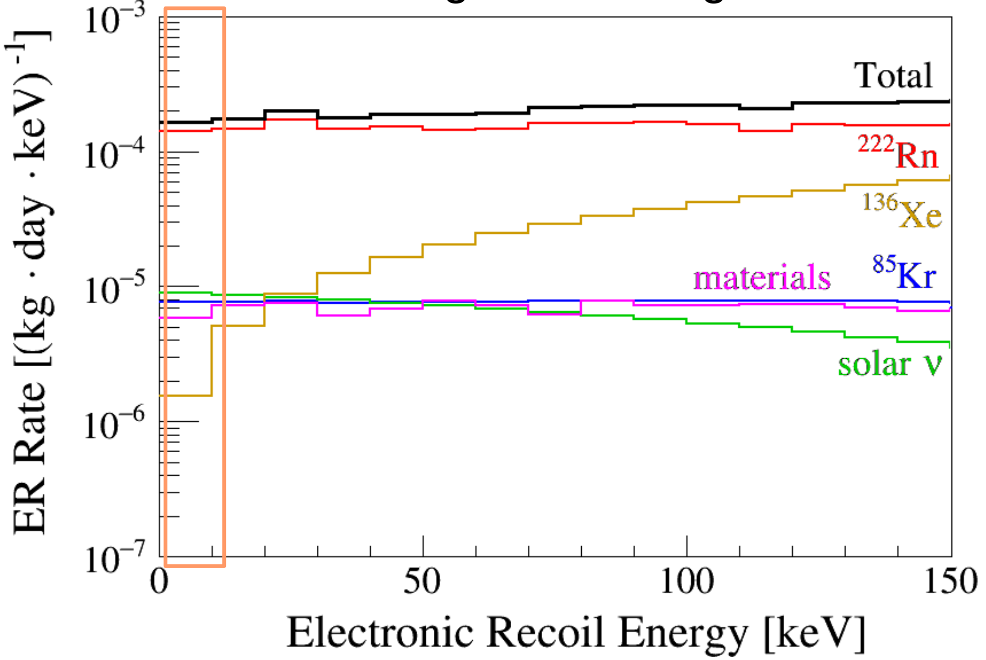
Backgrounds

- material background low, self-shielding effective
- ^{222}Rn background agrees with predictions
- online removal of ^{85}Kr via cryogenic distillation very successful

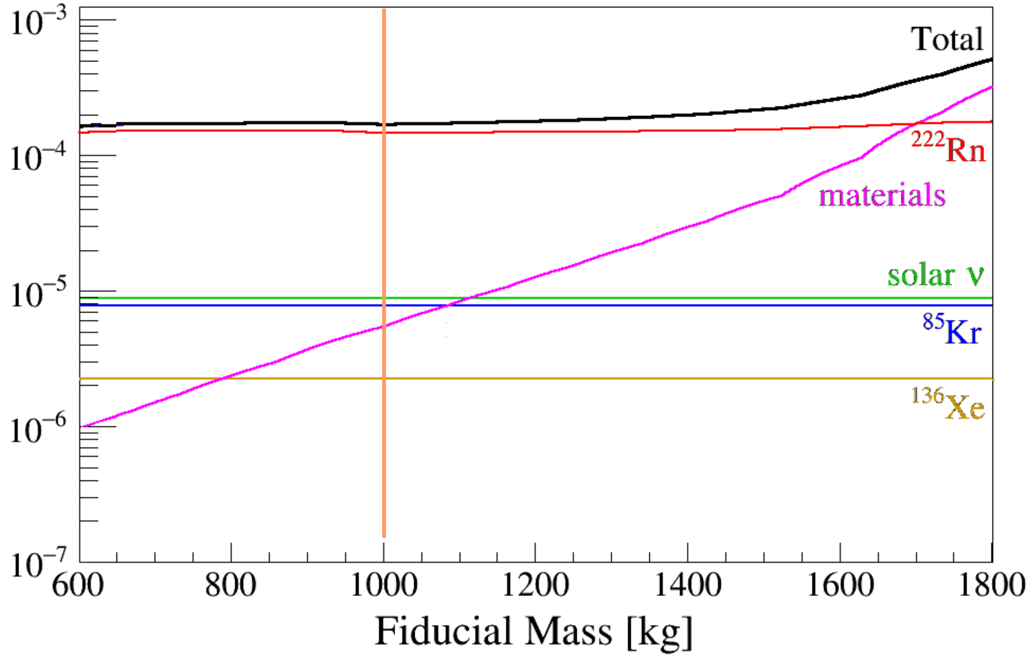
Background: Electronic Recoils

JCAP 04, 027 (2016)

1000 kg fiducial target



1–12 keV interval

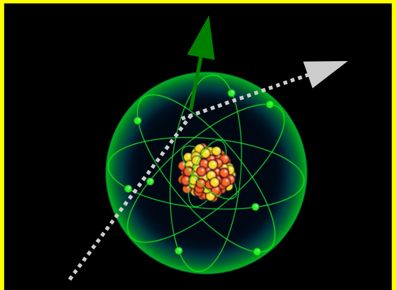


Assumed contamination:

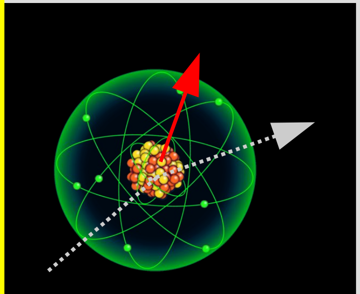
^{222}Rn: 10 µBq/kg

^{nat}Kr: 0.2 ppt

^{136}Xe: 8.9% natural abundance



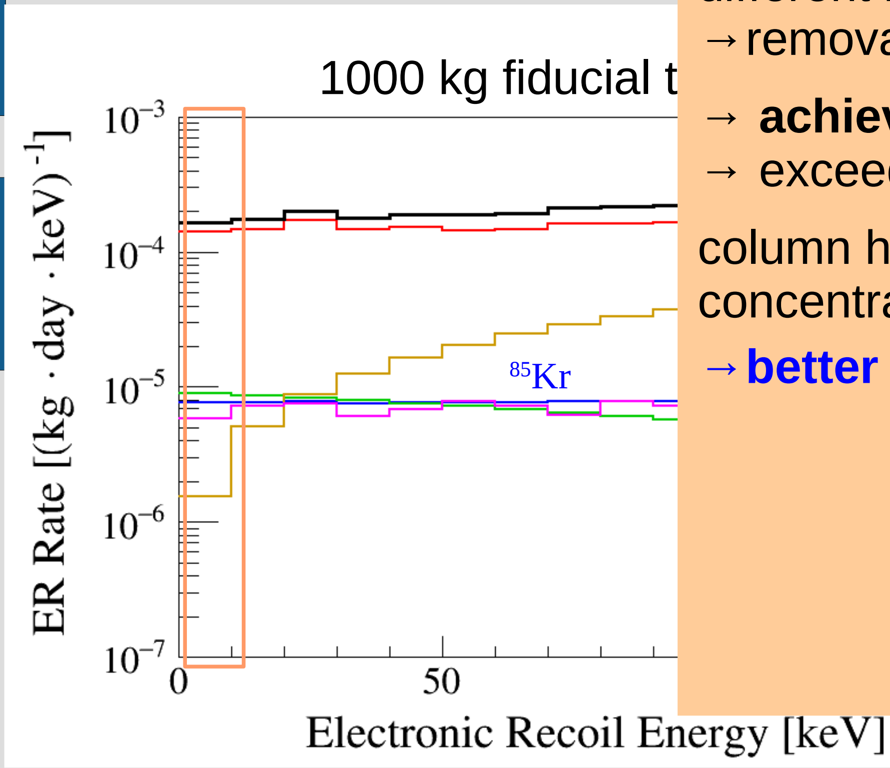
Electronic Recoils
(gamma, beta)



Nuclear Recoils
(neutron, WIMPs)

Background: Electronic Recoils

JCAP 04, 027 (2016)



different boiling points of Xe and Kr
→removal of Kr by cryogenic distillation

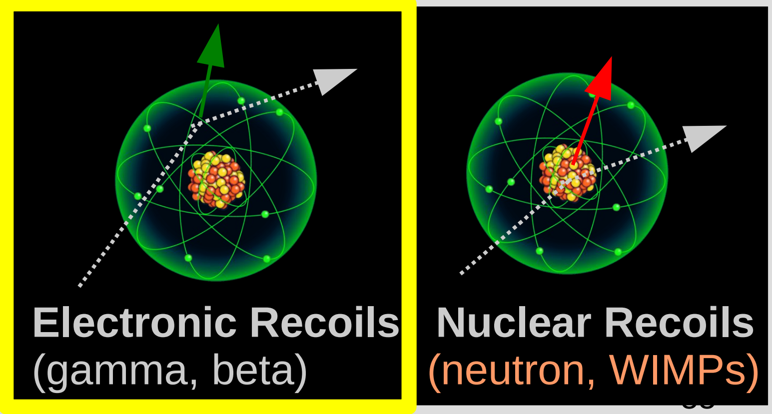
→ **achieved reduction factor $\sim 5\times10^5$**
→ exceeds the design goal of 10^4!

column has already delivered a concentration of **<0.026 ppt** = 2.6×10^{-14}

→**better than required for XENON1T**

Assumed contamination:

^{222}Rn: 10 µBq/kg
^{nat}Kr: 0.2 ppt
^{136}Xe: 8.9% natural abundance

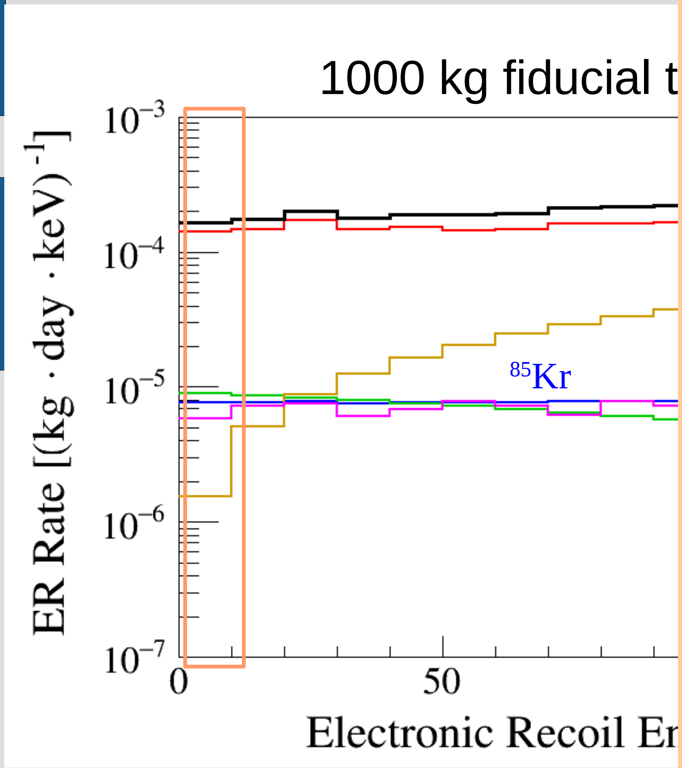


Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)

Background: Electronic Recoils

JCAP 04, 027 (2016)



Assumed contaminati

^{222}Rn: 10 µBq/kg

^{nat}Kr: 0.2 ppt

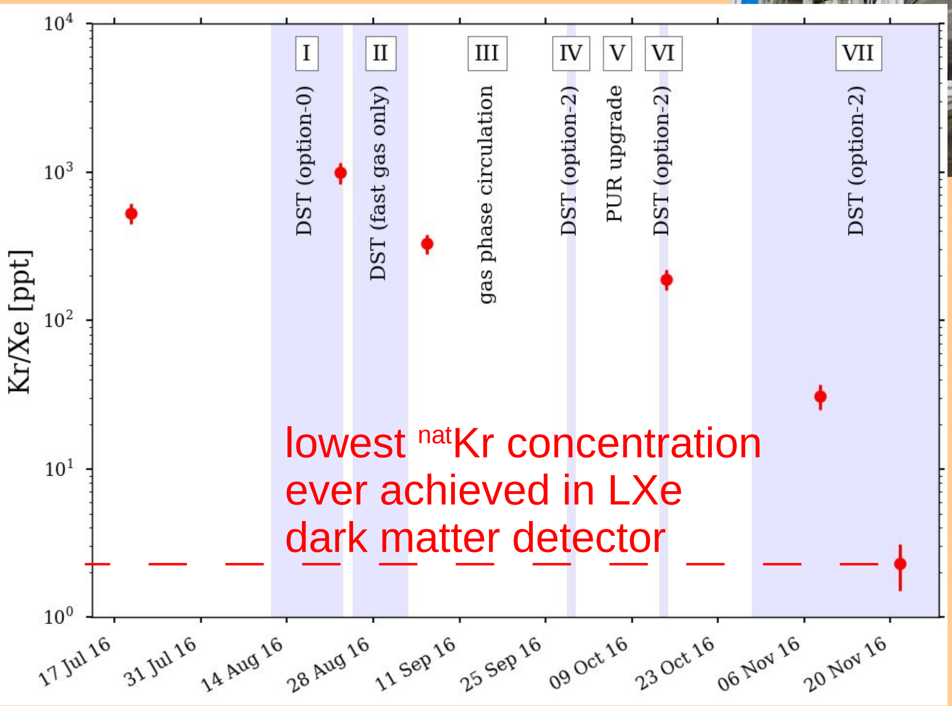
^{136}Xe: 8.9% natural ab

different boiling points of Xe and Kr
→ removal of Kr by cryogenic distillation

→ **achieved reduction factor ~5×10^5**
→ exceeds the design goal of 10^4!

column has already delivered a concentration of **<0.026 ppt** = 2.6×10^{-14}
→ **better than required for XENON1T**

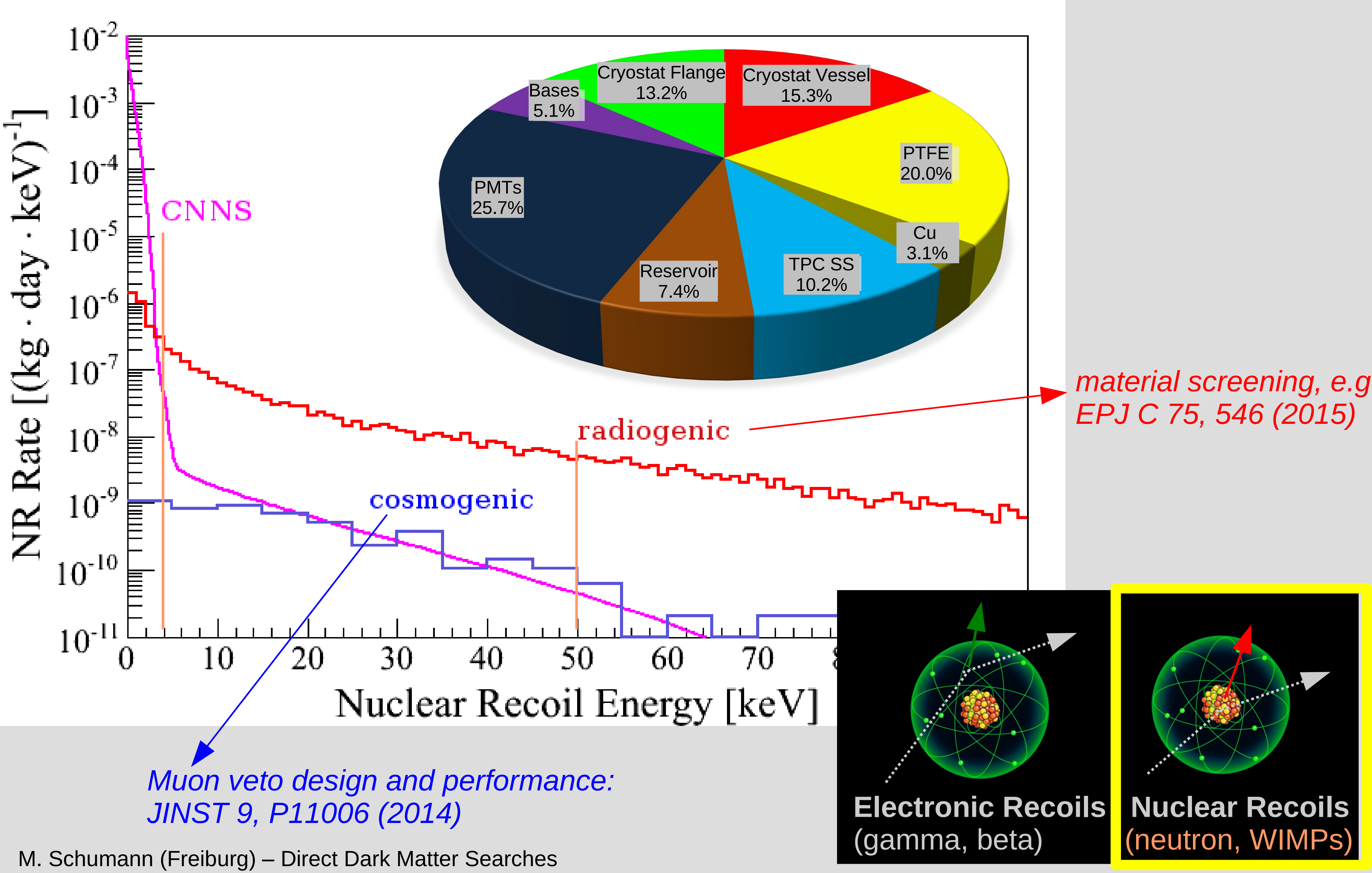
NEW: online distillation



lowest ^{nat}Kr concentration ever achieved in LXe dark matter detector

Background: Nuclear Recoils

JCAP 04, 027 (2016)



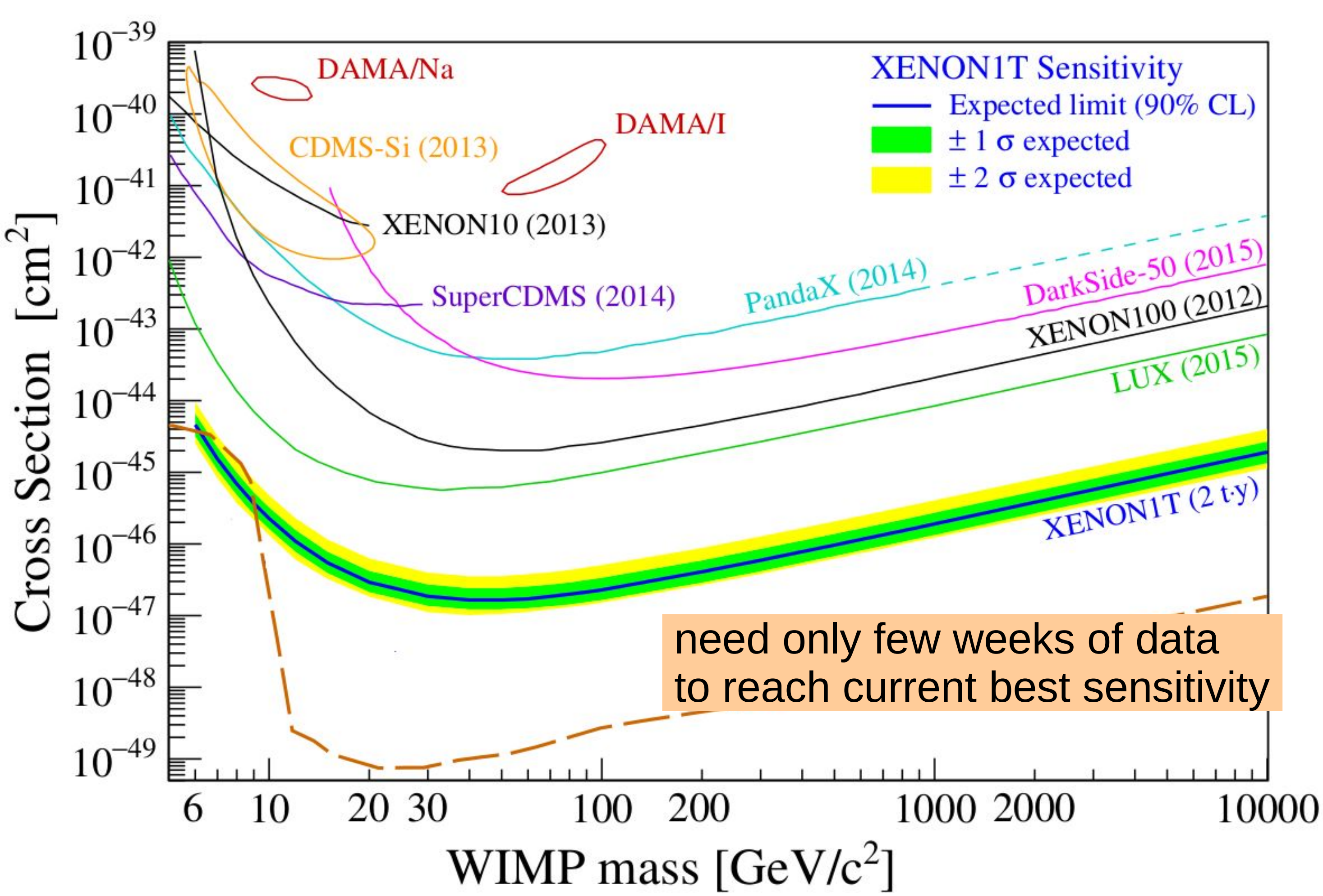
material screening, e.g.
EPJ C 75, 546 (2015)

Muon veto design and performance:
JINST 9, P11006 (2014)

XENON1T Sensitivity

JCAP 04, 027 (2016)

based on detailed background predictions, 2 t×y exposure:



need only few weeks of data to reach current best sensitivity

assumptions: energy interval: 4 – 50 keVr, ER rejection as XENON100: 99.5% @ 50% NR acc.

→ expected LY is 2x higher than in XENON100!

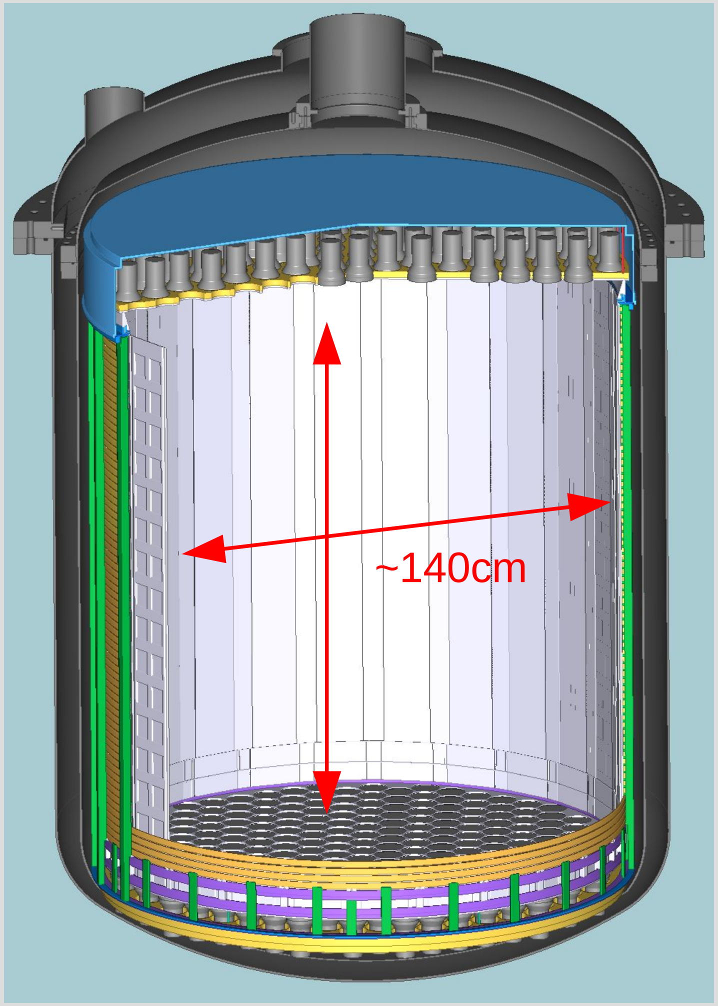
confirmed by measurement!

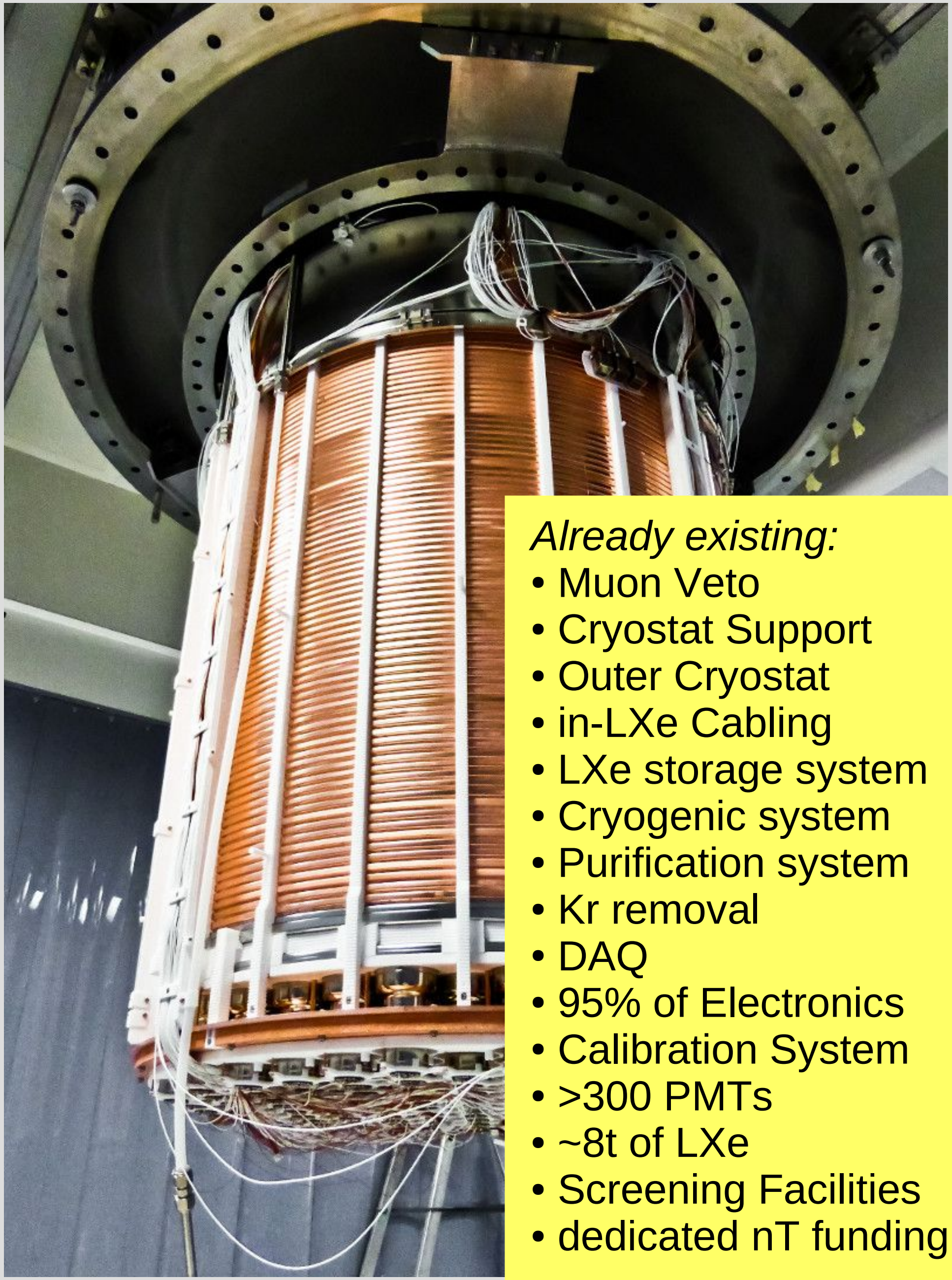
XENON1T → XENONnT

JCAP 04, 027 (2016)

XENON1T
- **2t** active LXe target
- operating
- science run started

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
- ~8t of LXe
- Screening Facilities
- dedicated nT funding

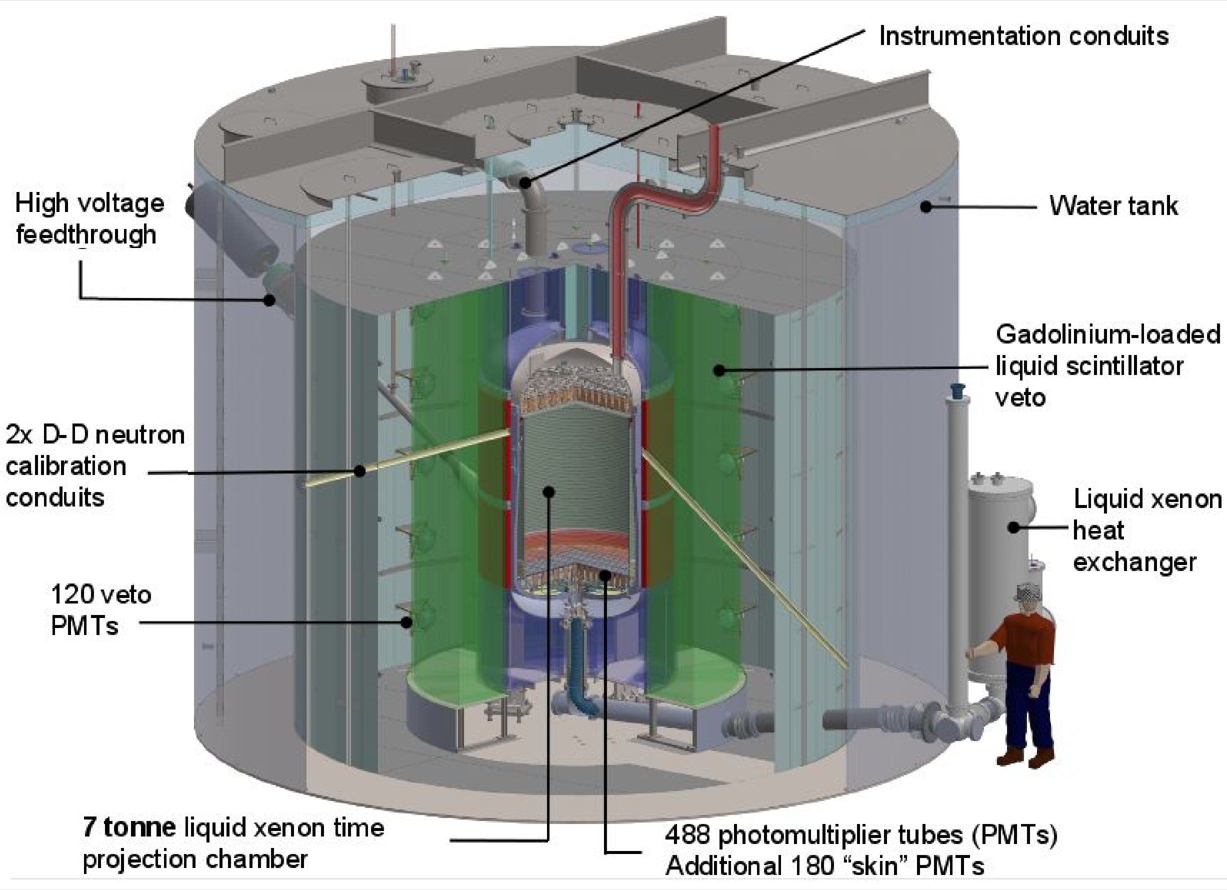
LZ – LUX/ZEPLIN

arXiv:1509.02910

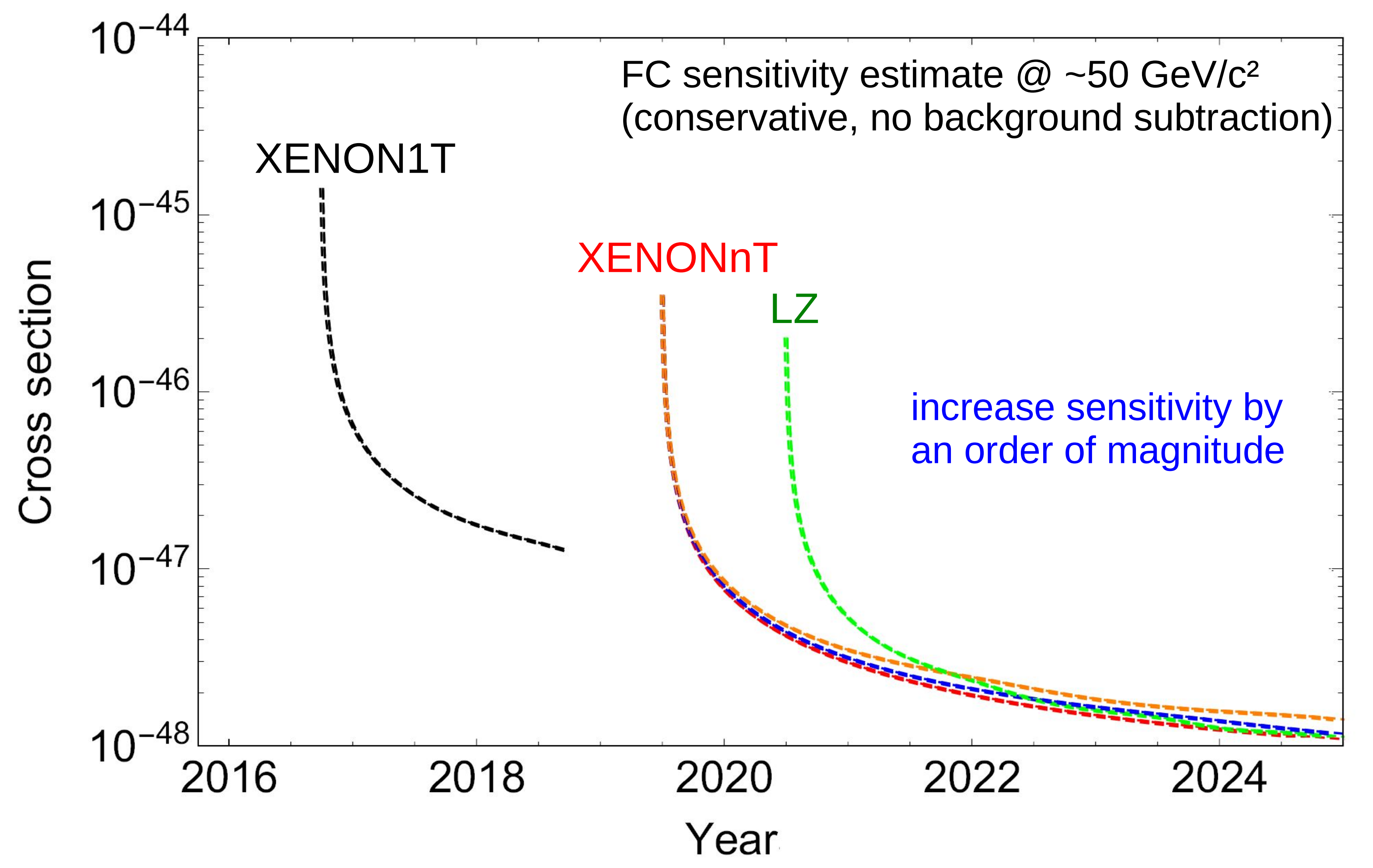
LXe

- **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, ...
  04/2020: end of construction
- goal: 2×10^{-48} cm^2 @ ~50 GeV/c^2
  after 15 t×y exposure



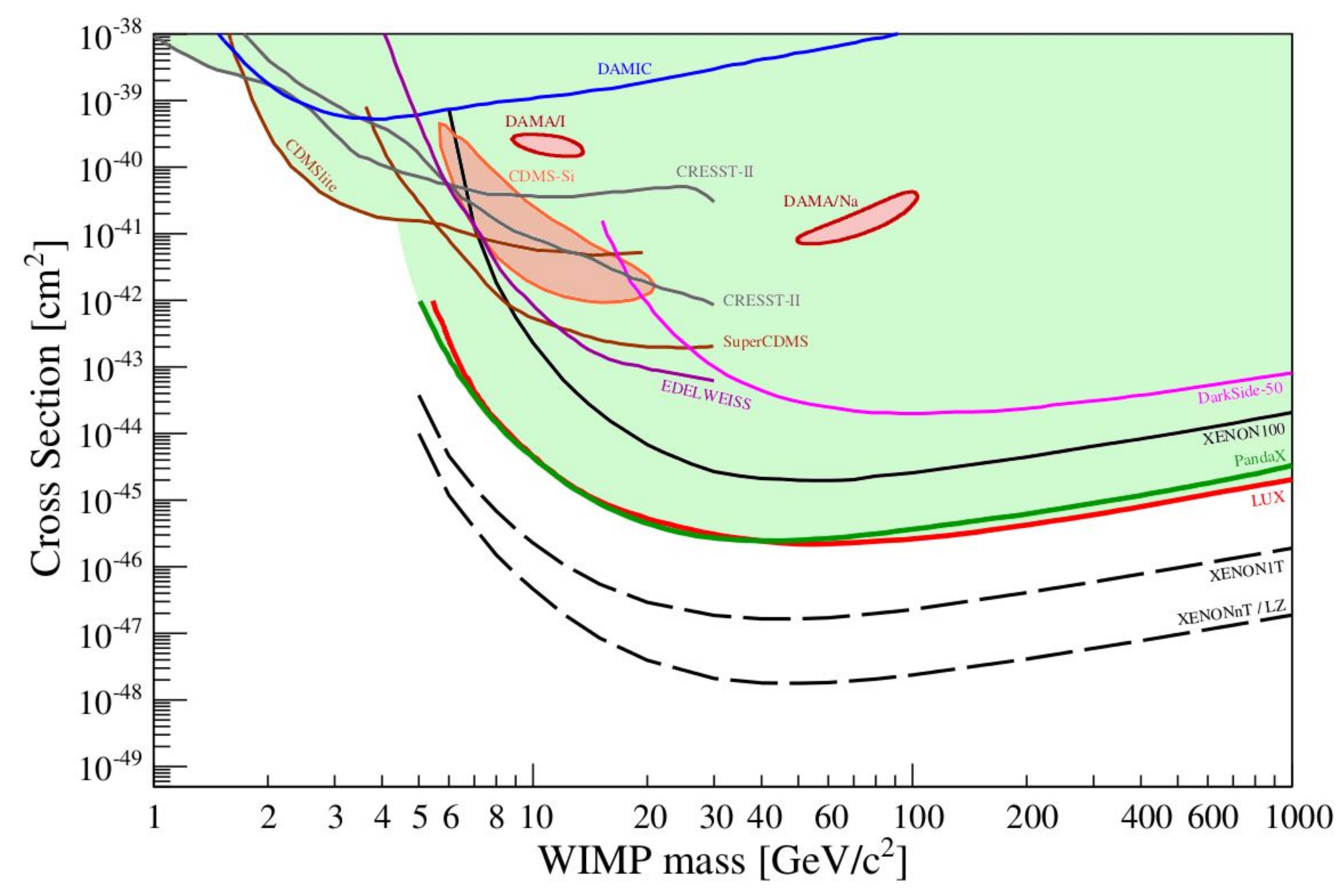
XENONnT: Sensitivity vs. time



LZ information taken from: https://idm2016.shef.ac.uk/indico/event/0/contribution/69/material/slides/0.pdf

XENON Science Goals

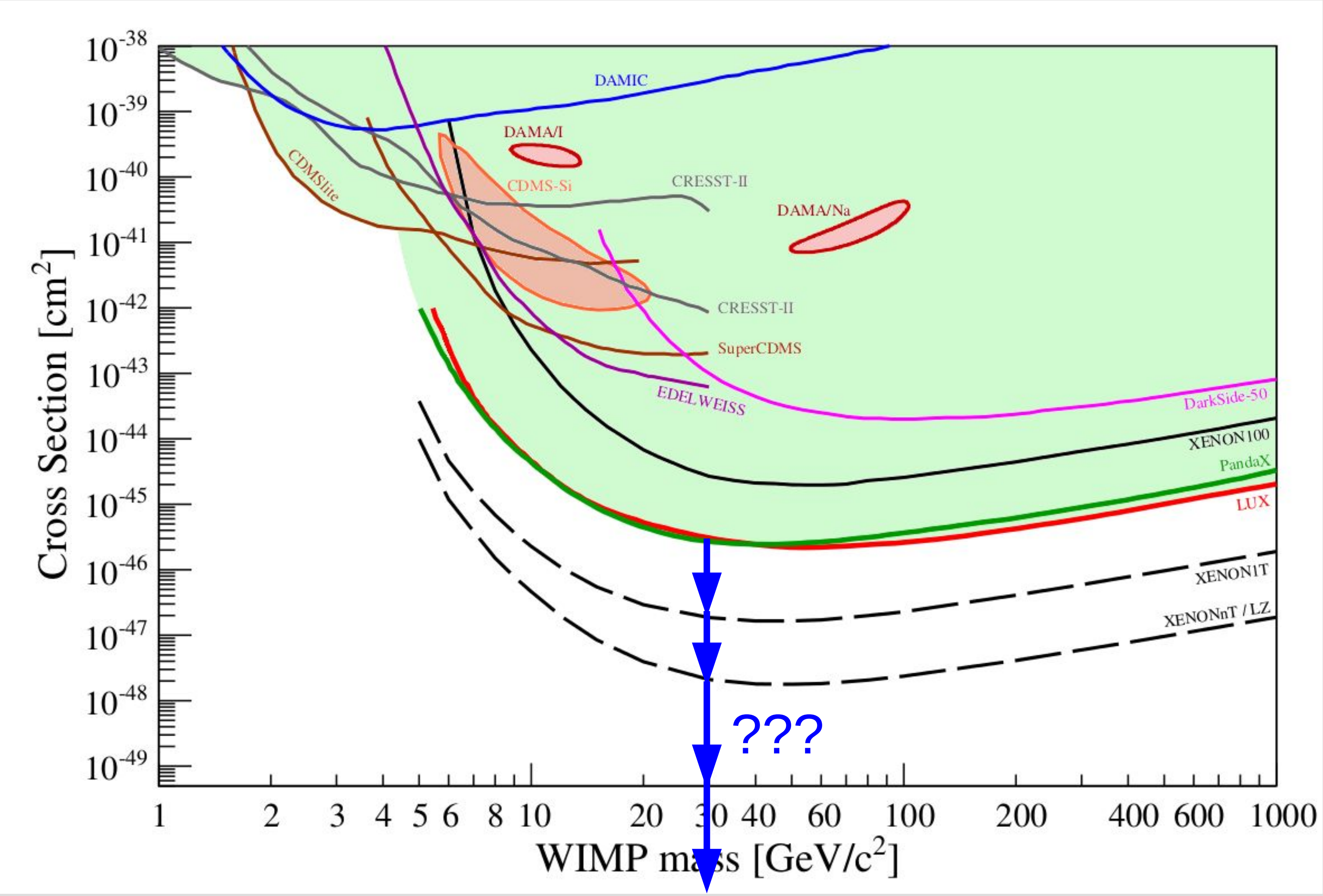
spin-independent WIMP-nucleon interactions



some projects are missing...

Dark Matter Searches: The Future

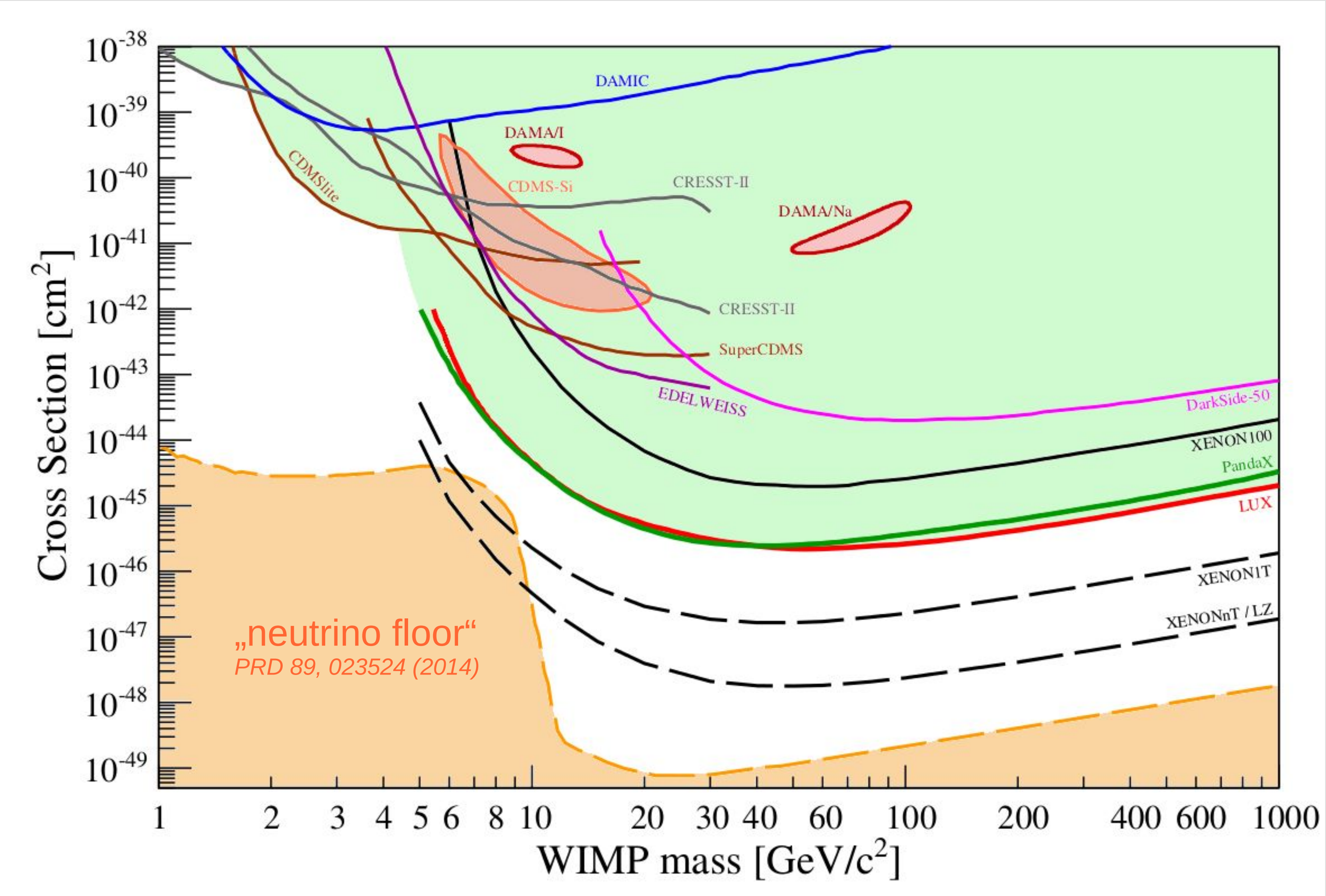
spin-independent WIMP-nucleon interactions



some projects are missing...

Dark Matter Searches: The Limit

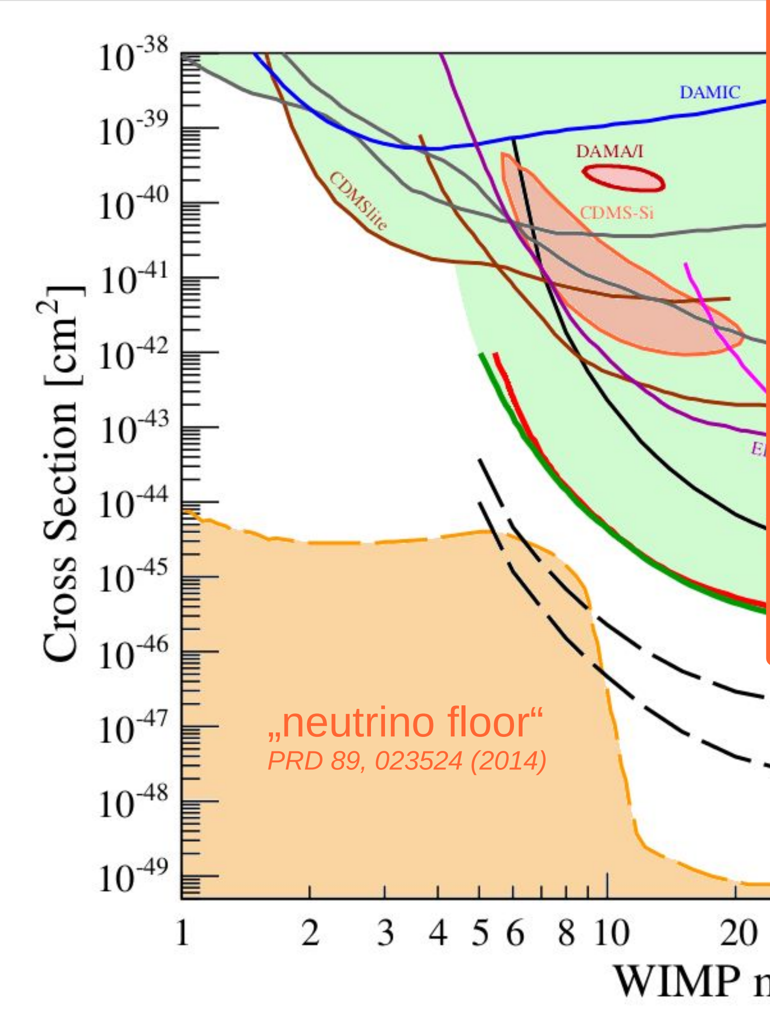
spin-independent WIMP-nucleon interactions



some projects are missing...

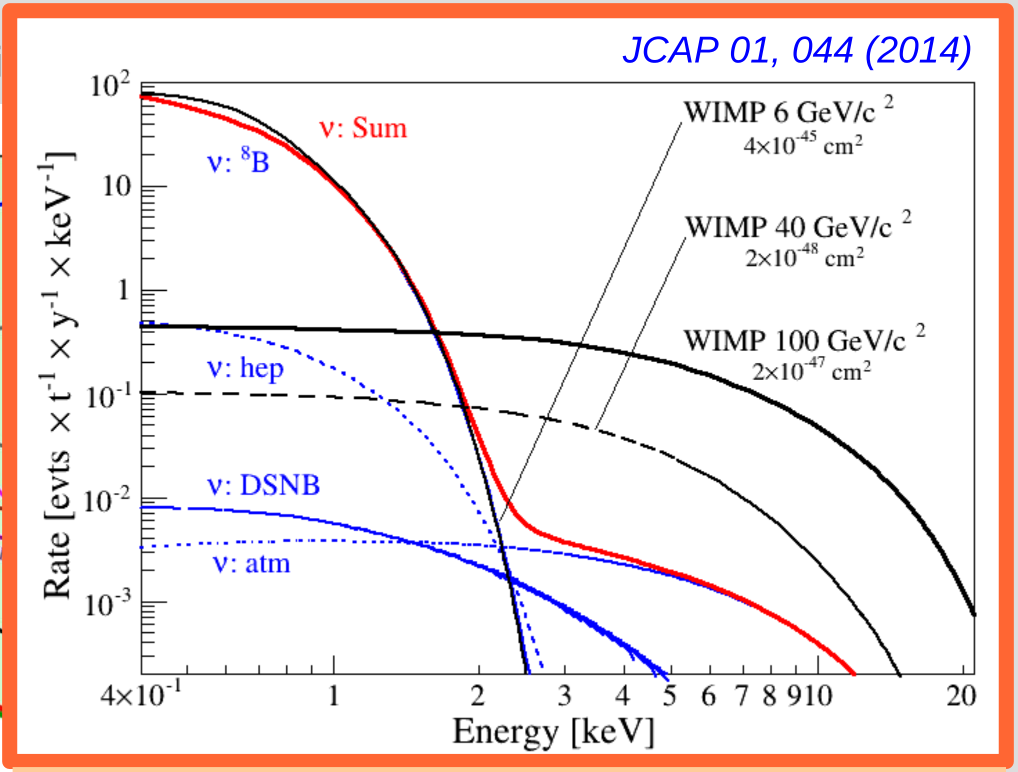
Dark Matter Searches: The Limit

spin-i

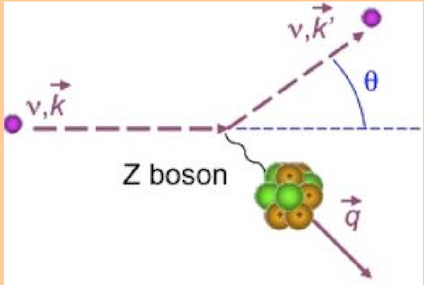


„neutrino floor“
PRD 89, 023524 (2014)

JCAP 01, 044 (2014)

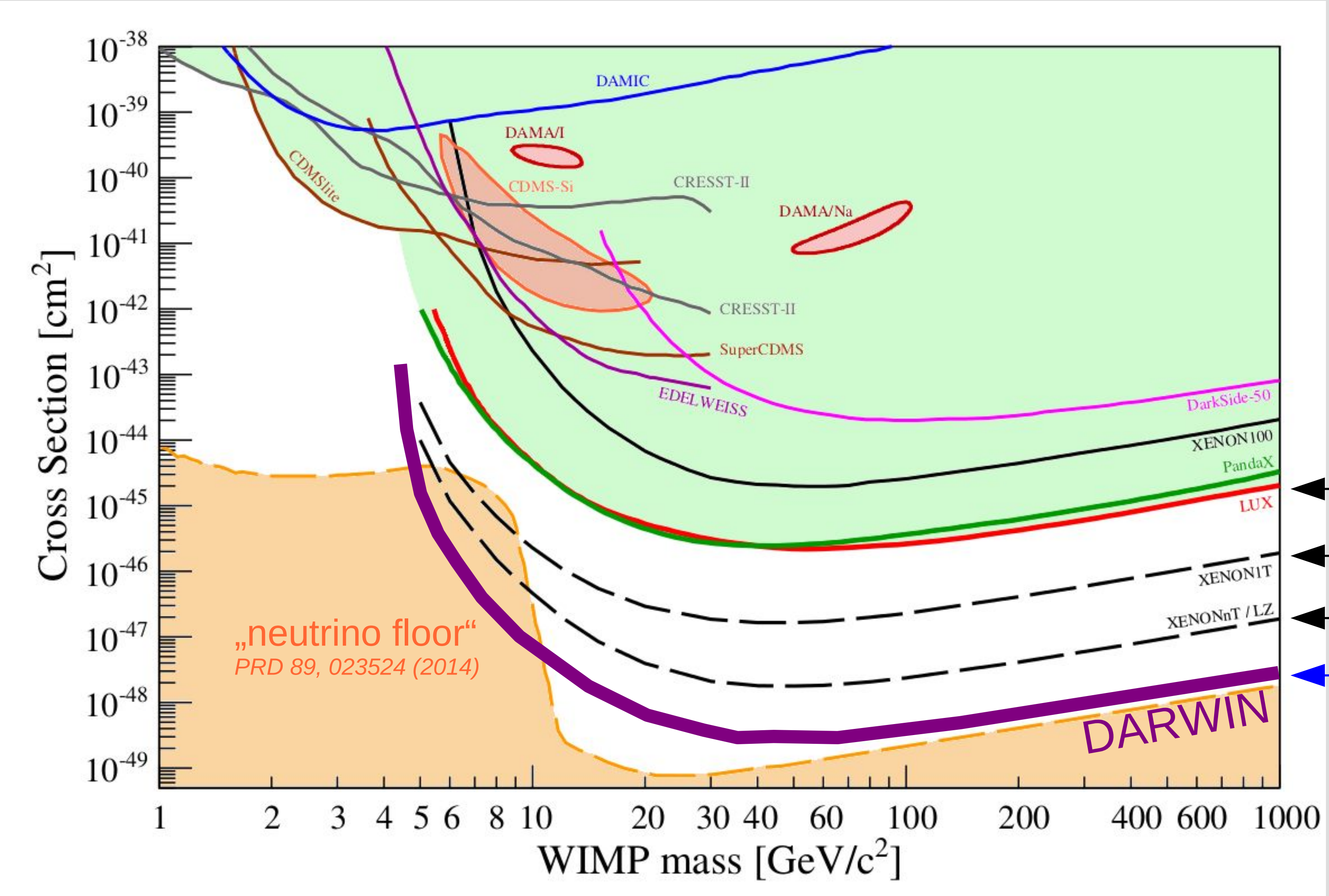


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



DARWIN The **ultimate** WIMP Detector

spin-independent WIMP-nucleon interactions



„neutrino floor“

PRD 89, 023524 (2014)

Exposure

0.1 t×y

2 t×y

20 t×y

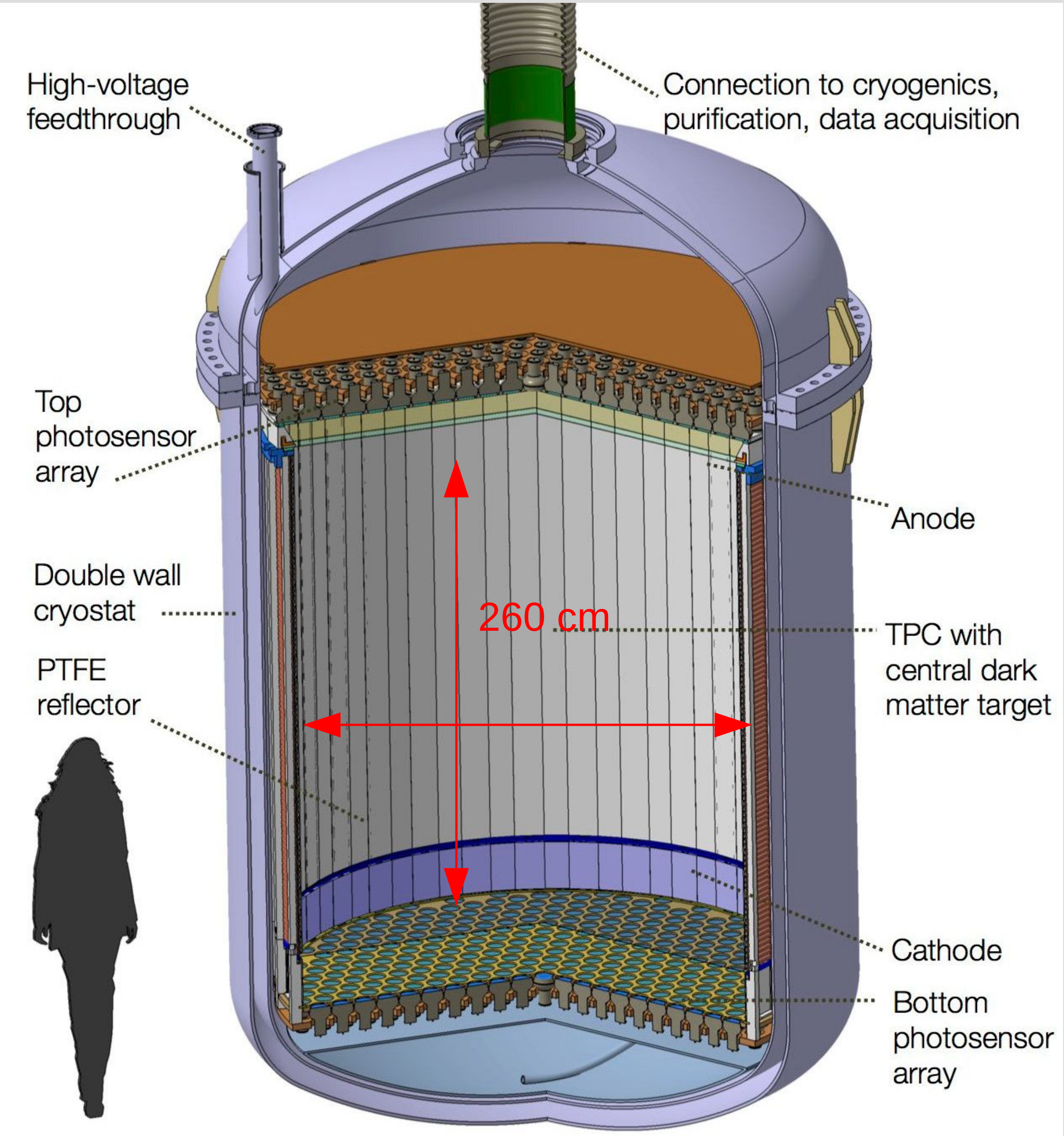
200 t×y

some projects are missing...

DARWIN The ultimate WIMP Detector

JCAP 11, 017 (2016)

LXe



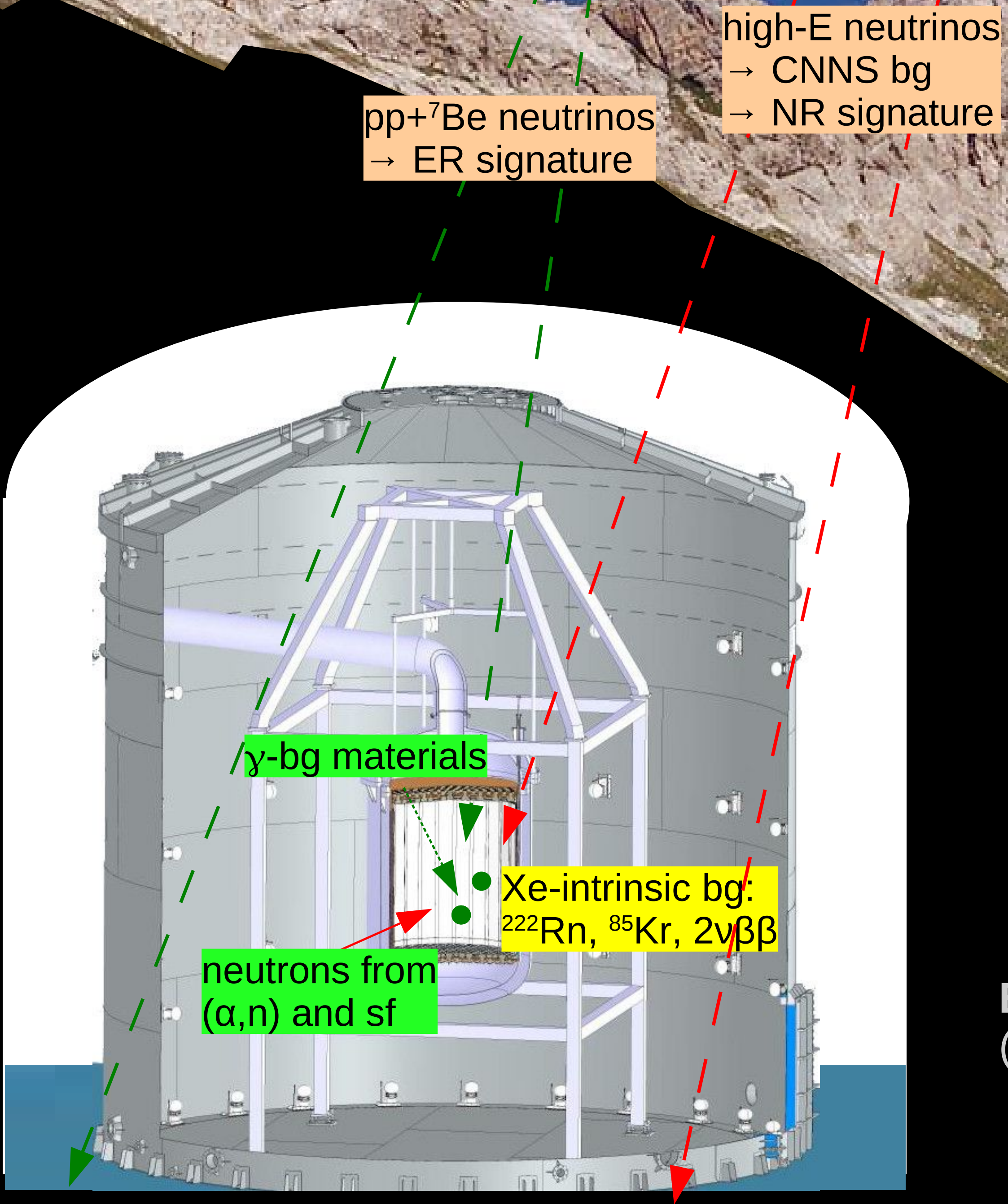
- aim at sensitivity of a few 10^{-49} cm², limited by **irreducible ν-backgrounds**
- international consortium, 21 groups
  → R&D ongoing

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

- Timescale: start after XENONnT

`www.darwin-observatory.org`

DARWIN Backgrounds

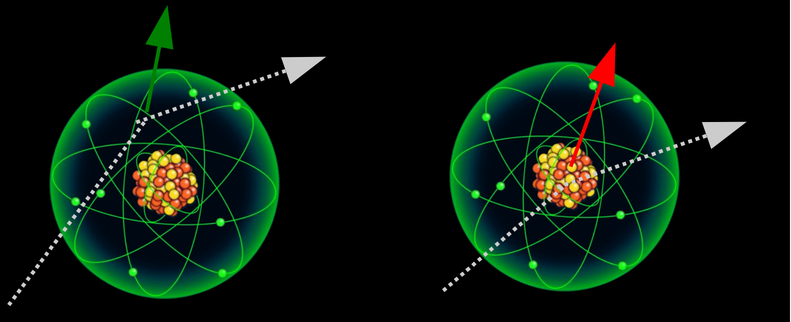


Remaining background sources:

– Neutrinos (→ ERs and NRs)
– Detector materials (→ γ, n)
– Xe-intrinsic isotopes (→ e$^-$)

(assume 100% effective shield (~15m) against µ-induced background)

JCAP 10, 016 (2015)



Electronic Recoils
(gamma, beta)

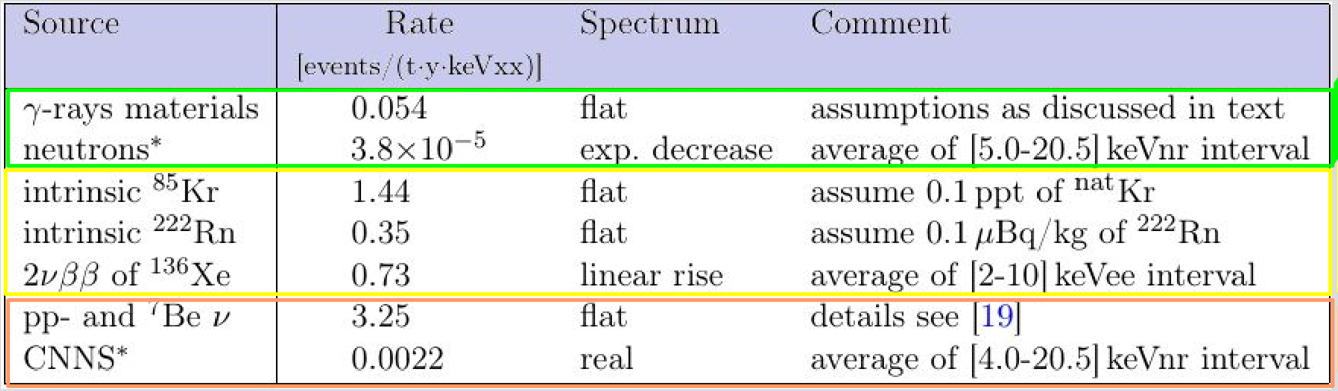
Nuclear Recoils
(neutron, WIMPs)

only single scatters

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

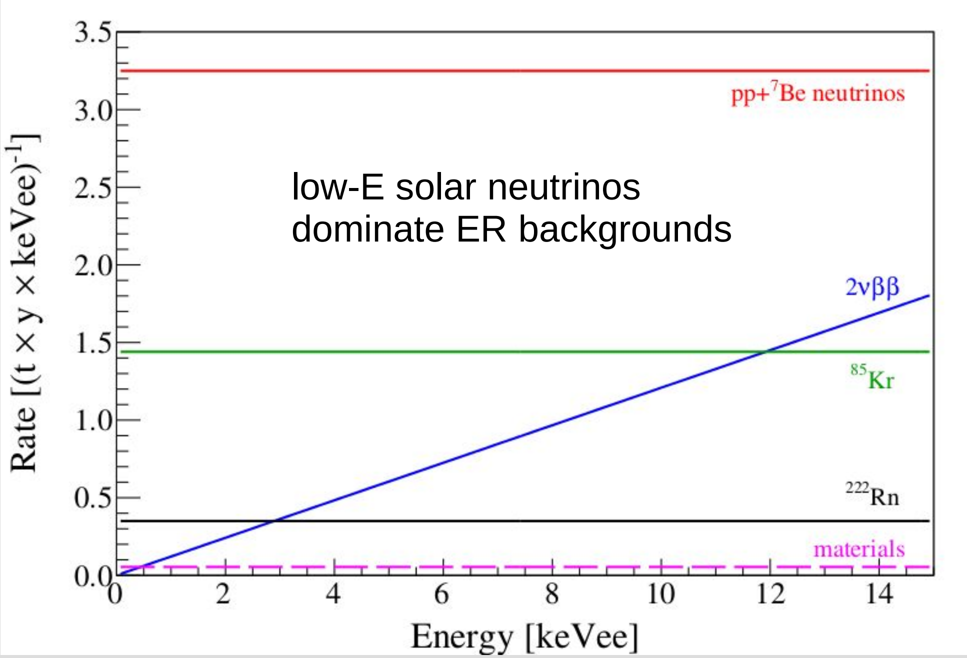
MC simulation of detector made of main components (PTFE, CU, PMTs): subdominant after ~15 cm fiducial cut

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

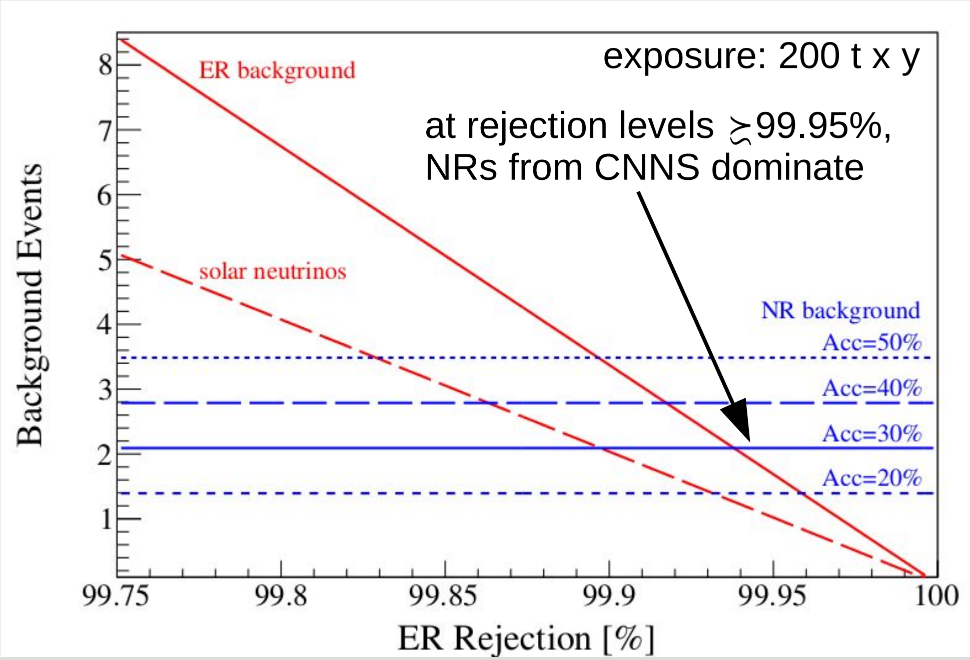
^{222}Rn: 100x below XENON1T design

^{136}Xe: assume natural xenon

consider all relevant neutrinos



low-E solar neutrinos dominate ER backgrounds



exposure: 200 t x y

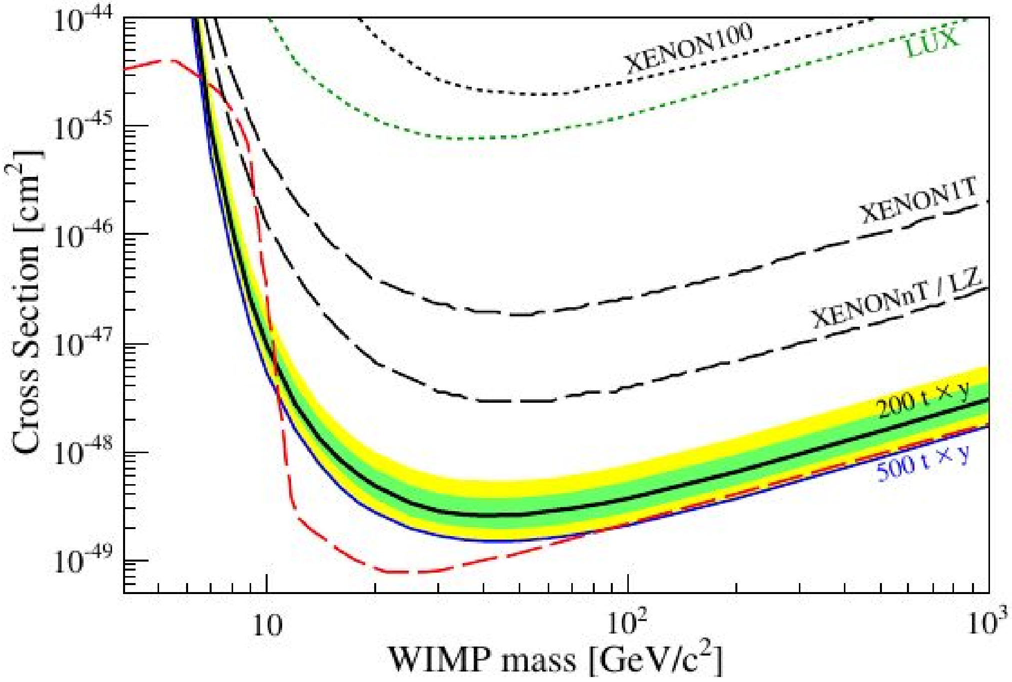
at rejection levels $\gtrsim$99.95%, NRs from CNNS dominate

DARWIN WIMP Sensitivity

JCAP 10, 016 (2015)

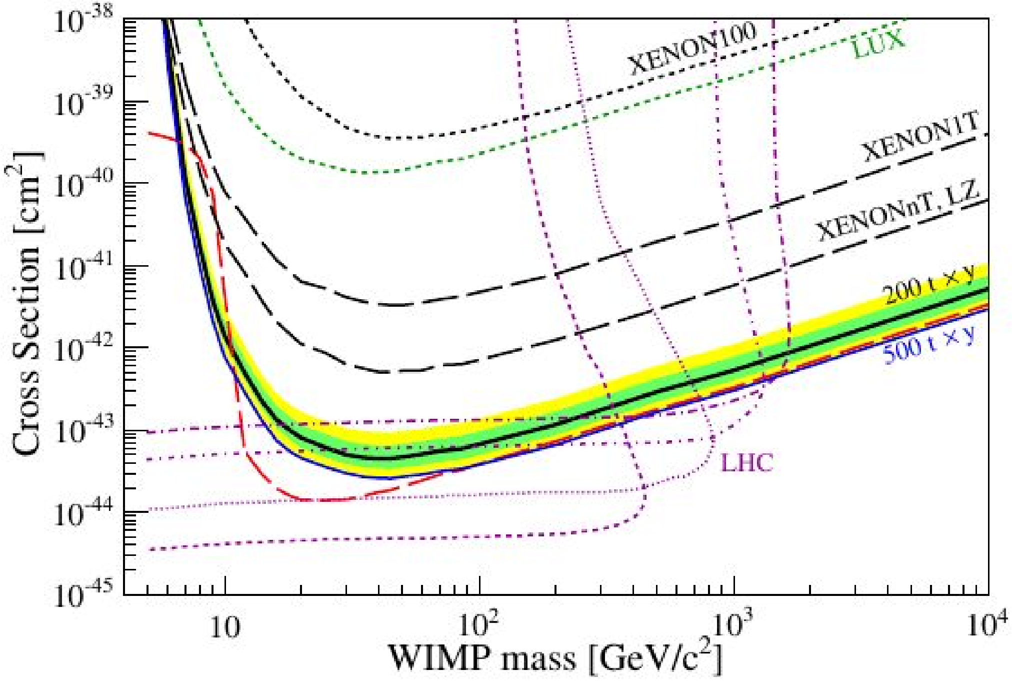
- exposure: 200 t × y; **all backgrounds included**
- likelihood analysis
- 99.98% ER rejection @ 30% NR acceptance, S1+S2 combined energy scale, LY=8 PE/keV, 5-35 keV$_{nr}$ energy window

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

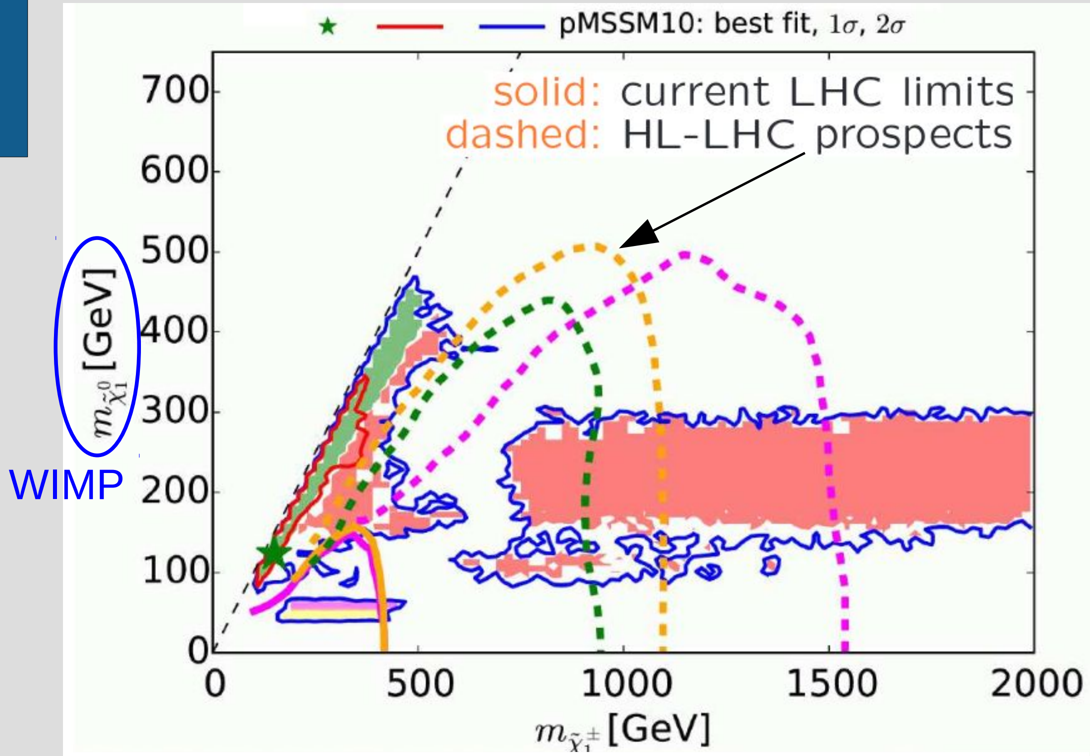
Phys.Dark Univ. 9-10, 51 (2015).

SUSY Dark Matter

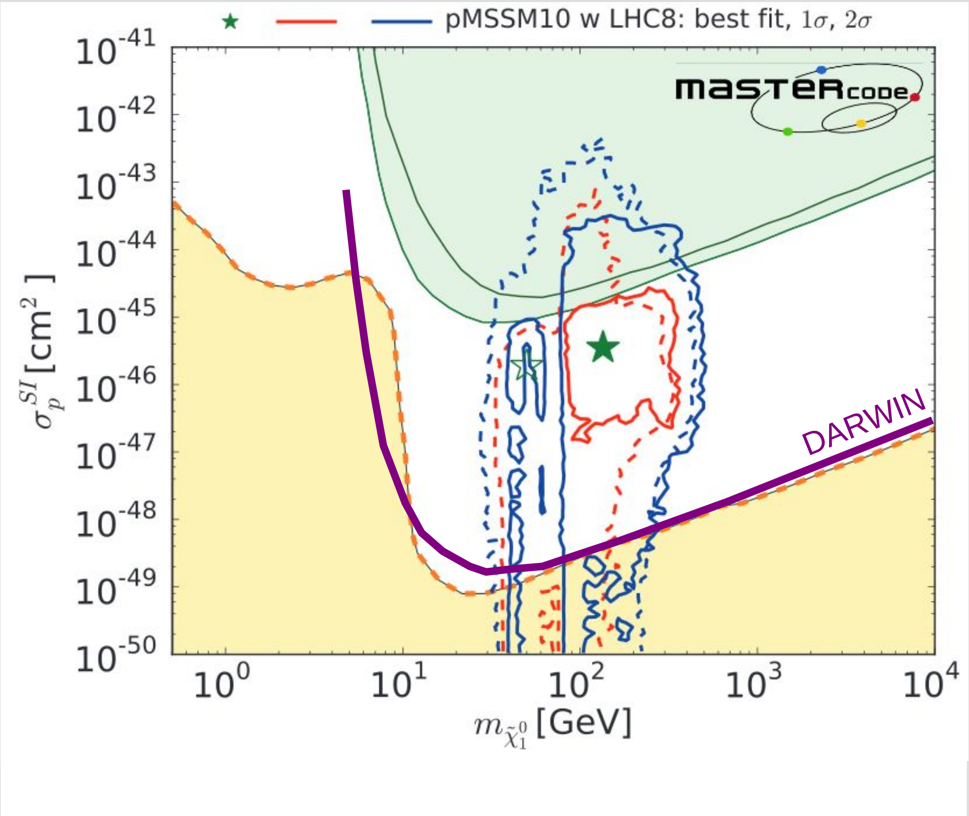
plots: Sven Heinemeyer (MasterCode 2015)

SUSY under pressure because not found at LHC?
→ true for some very constraint models (CMSSM etc.) but looks different
when more parameters are left unconstrained

Example: pMSSM10 ← 10 SUSY parameters, *e.g. EPJ C75, 422 (2015)*

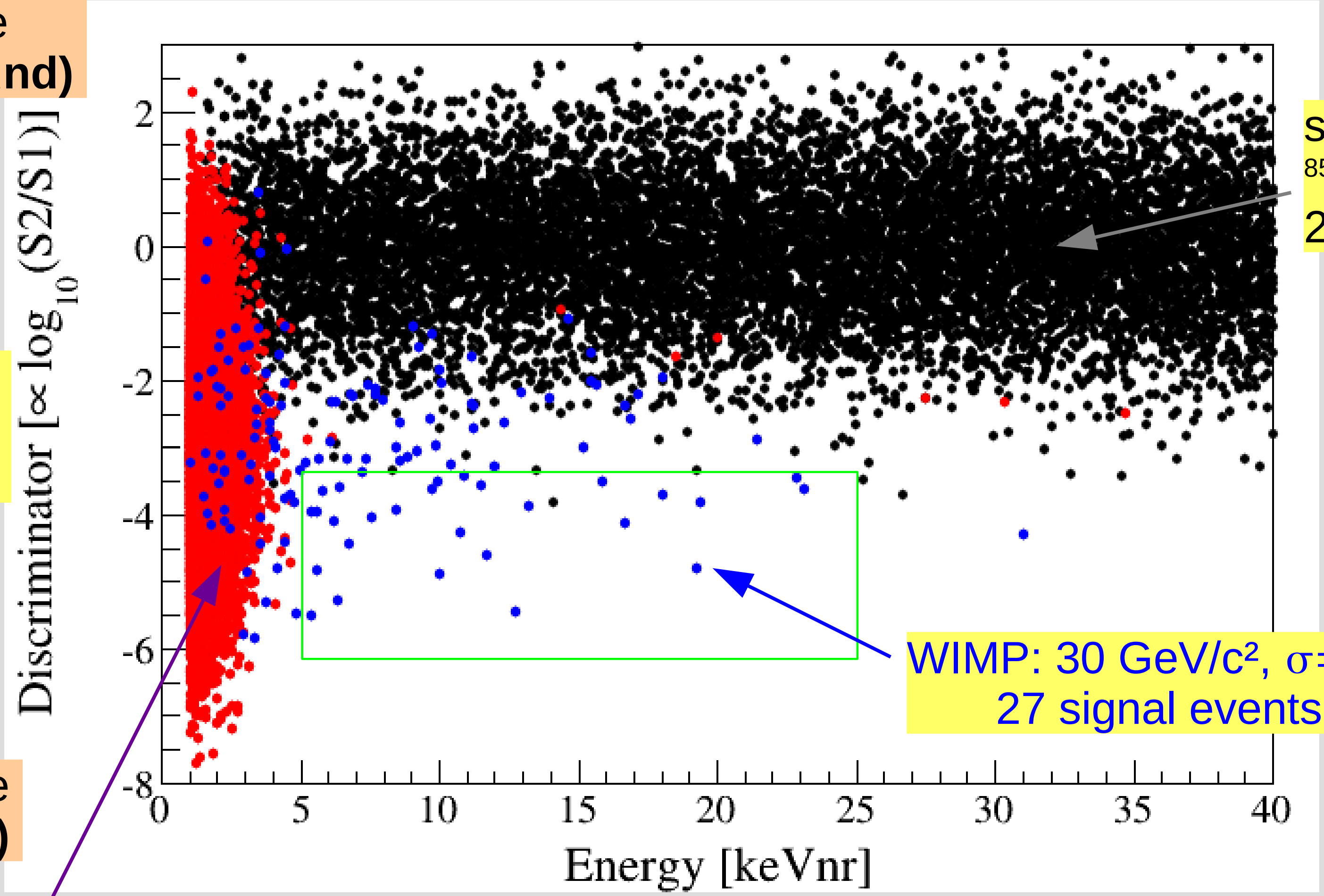


$m_{\text{neutralino}} \approx m_{\text{chargino}}$



WIMP out of reach of HL-LHC (best-fit regions not covered), but accessible by DARWIN

WIMP Detection



ER-like
(background)

discrimination variable;
based on S2/S1

NR-like
(signal)

CNNS+neutrons

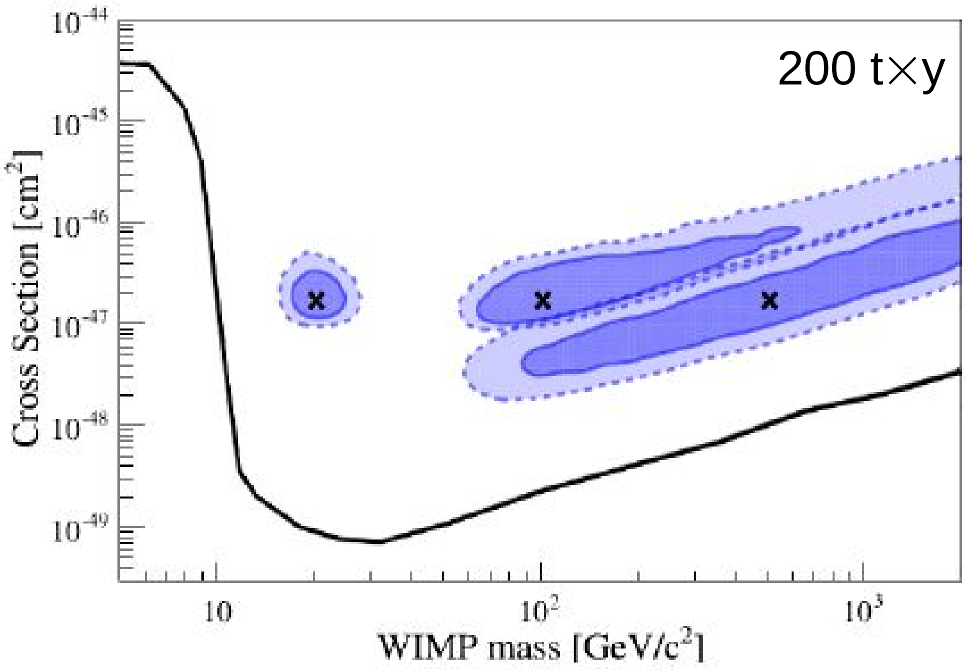
solar neutrinos,
^{85}Kr, ^{222}Rn,
2νββ, materials

WIMP: 30 GeV/c², σ=2×10^{-48} cm²
27 signal events in box

reconstructed energy,
based on S1 and S2 signal

WIMP Spectroscopy

Reconstruction: 2×10^{-47} cm²

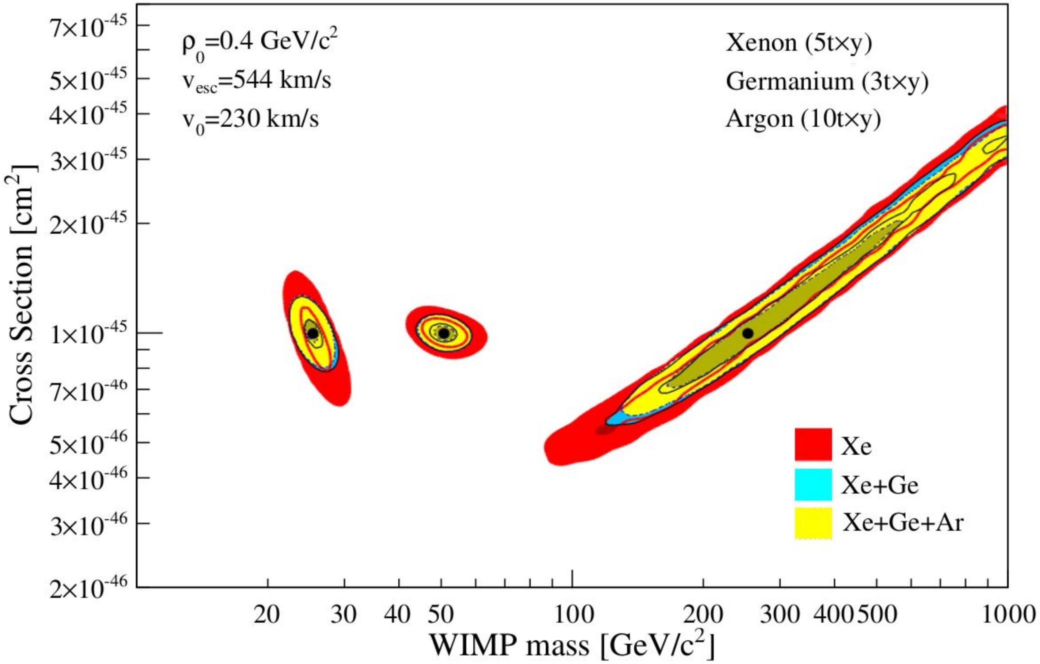


JCAP 11, 017 (2016)

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

Target Complementarity

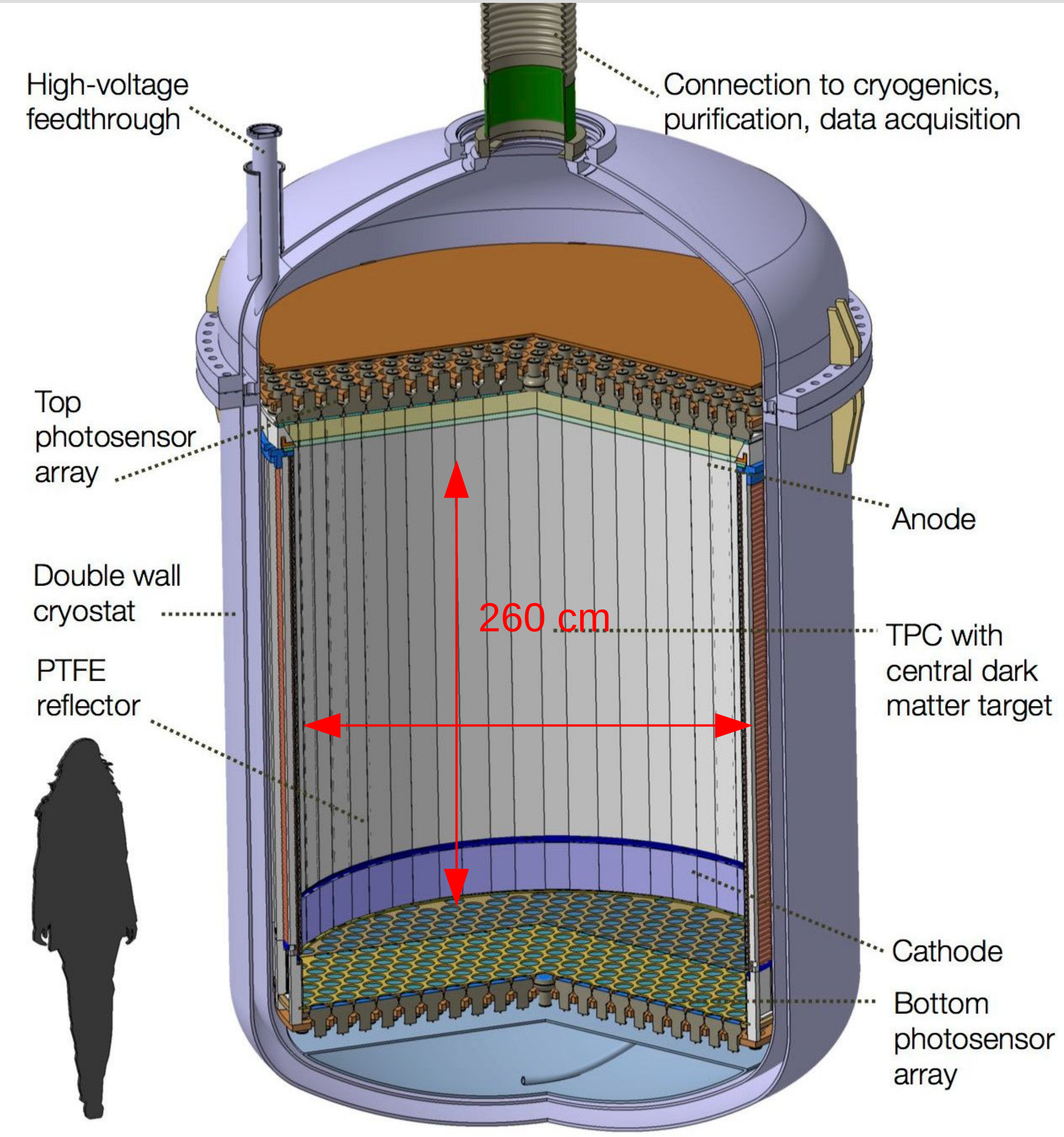


PRD 83, 083505 (2011)

Reconstruction improves considerably by adding Ge-data to Xe.

Only minimal improvement for Ar.

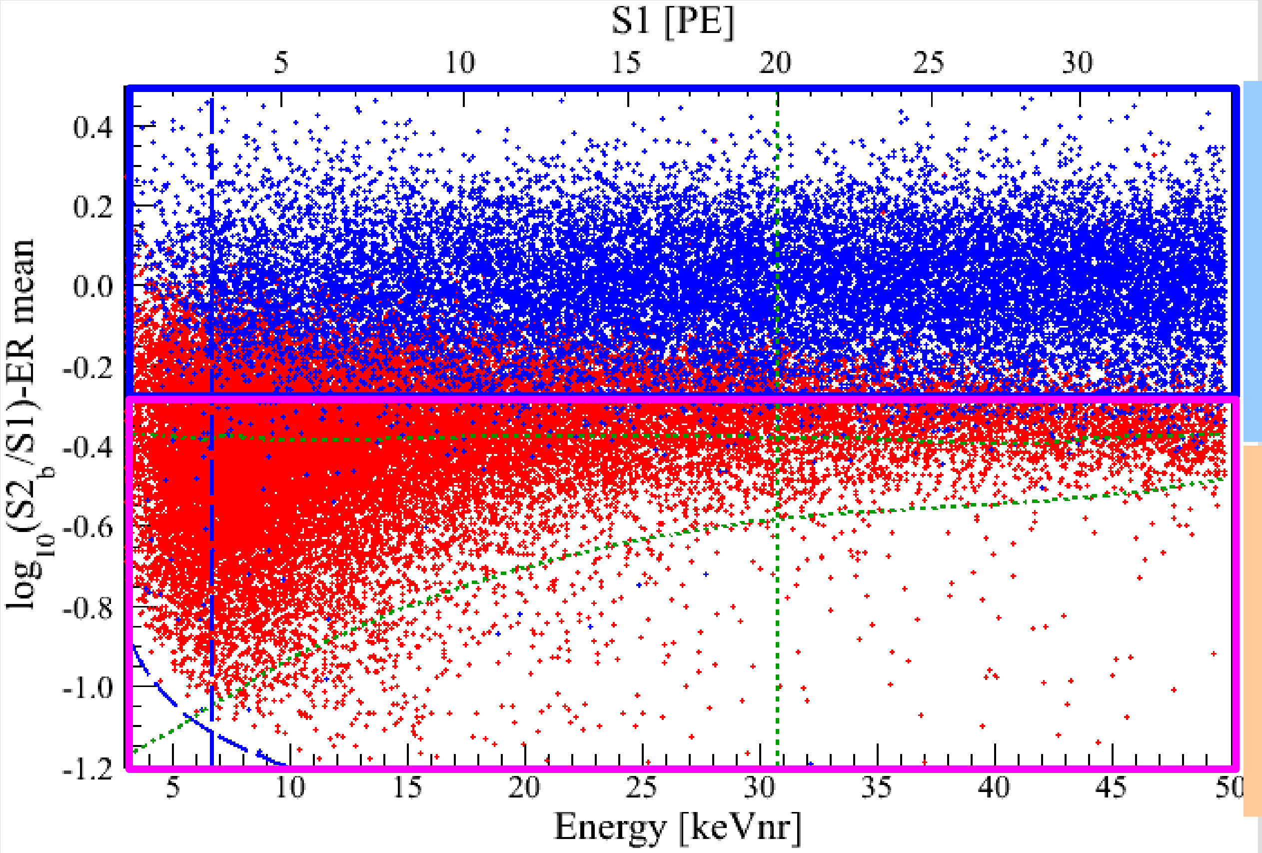
DARWIN The **ultimate** WIMP Detector



other than WIMPs

What (else) can we do with these instruments?

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

- rare processes detectable if ER background is low

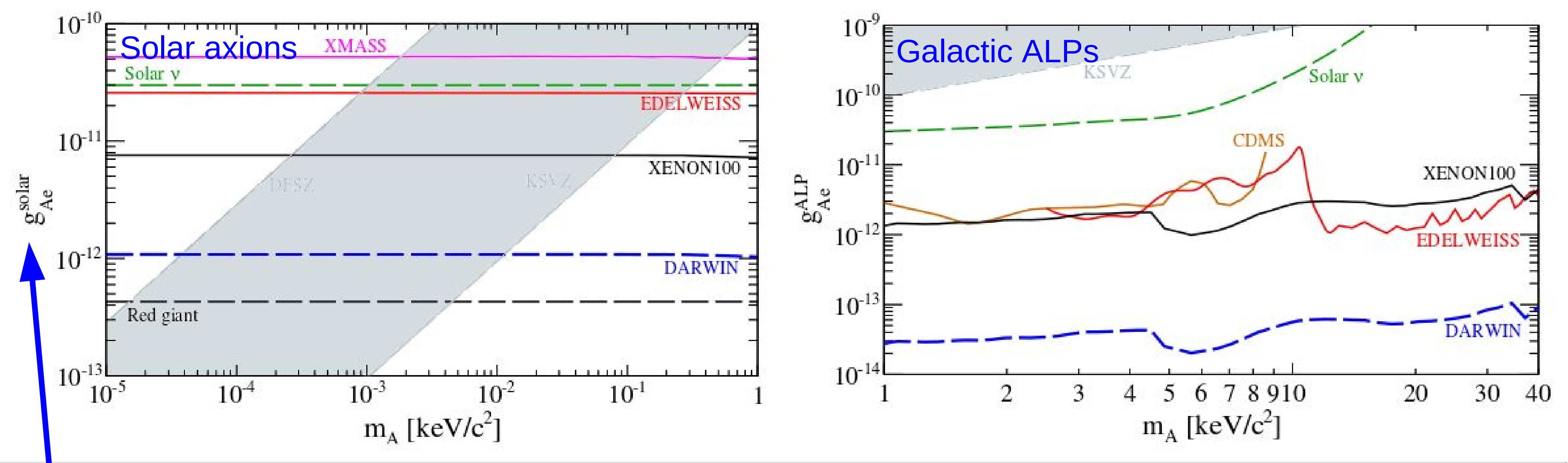
coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- CNNS

Many **science channels** are accessible with a multi-ton DARWIN detector thanks to its extremly low ER background.

Solar Axions, Dark Matter ALPs

JCAP 11, 017 (2016)



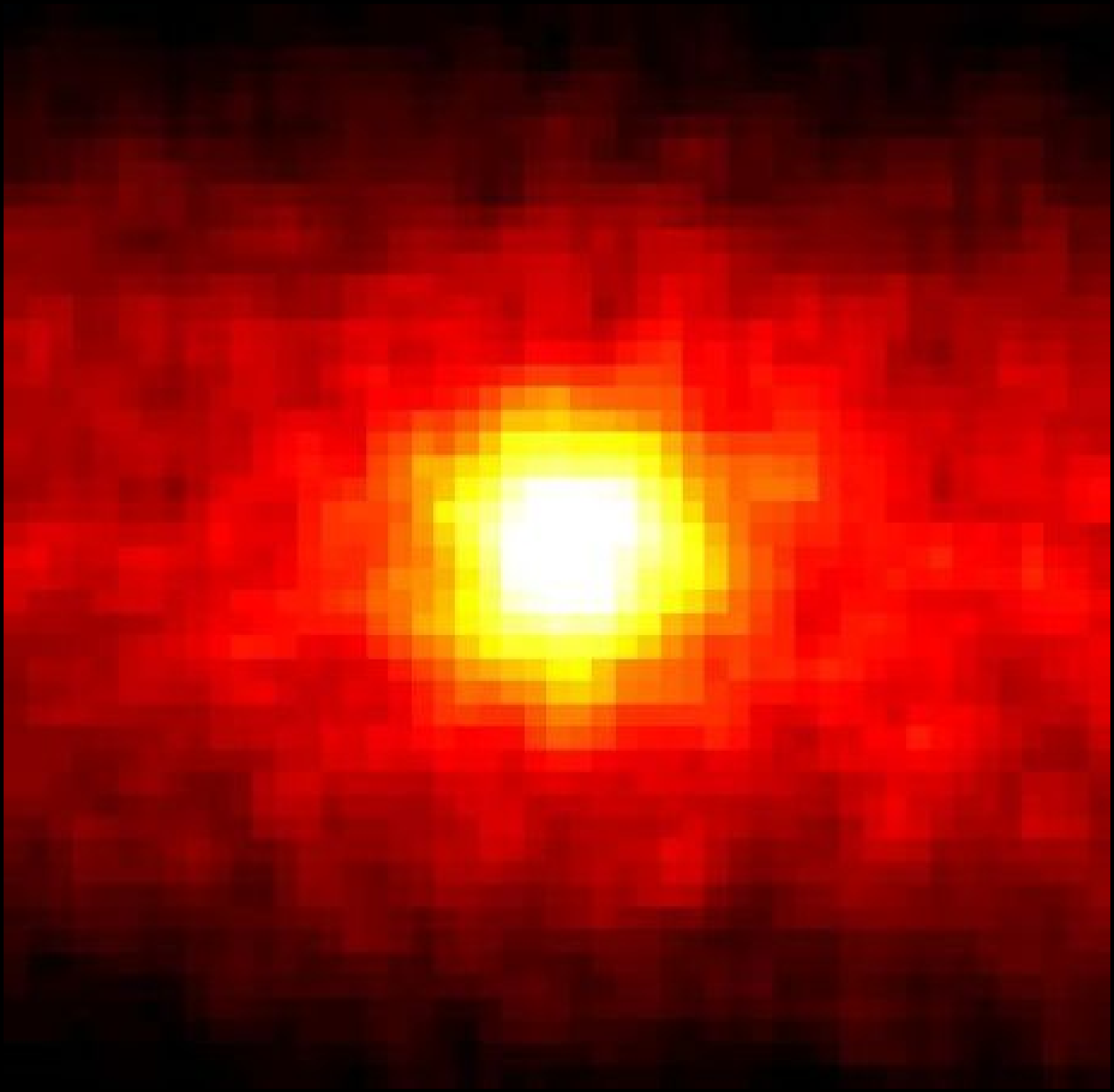
Axions and ALPs couple to xenon via **axio-electric-effect**

$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha\,{m_e}^2}\left(1-\frac{\beta_A}{3}\right)$$

→ axion ionizes a Xe atom

Axion
arises naturally in the Peccei-Quinn solution of the strong CP-problem
→ well-motivated dark matter candidate

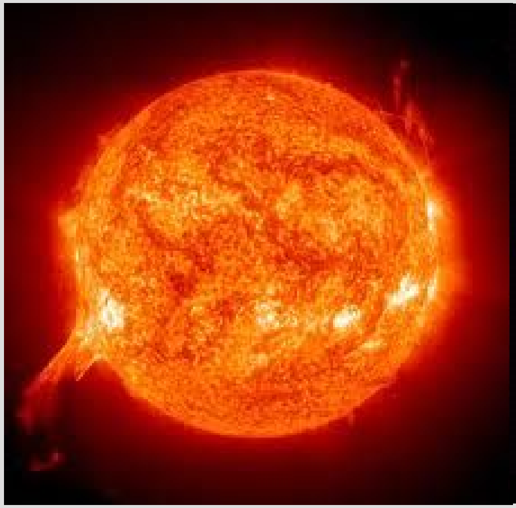
Axion-like particle (ALP)
generalization of the axion concept,
but without addressing strong CP problem
(ALPs = Nambu-Goldstone bosons from breaking of some global symmetry)

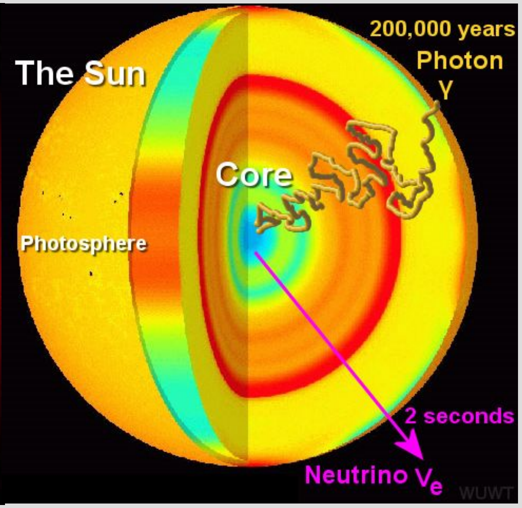


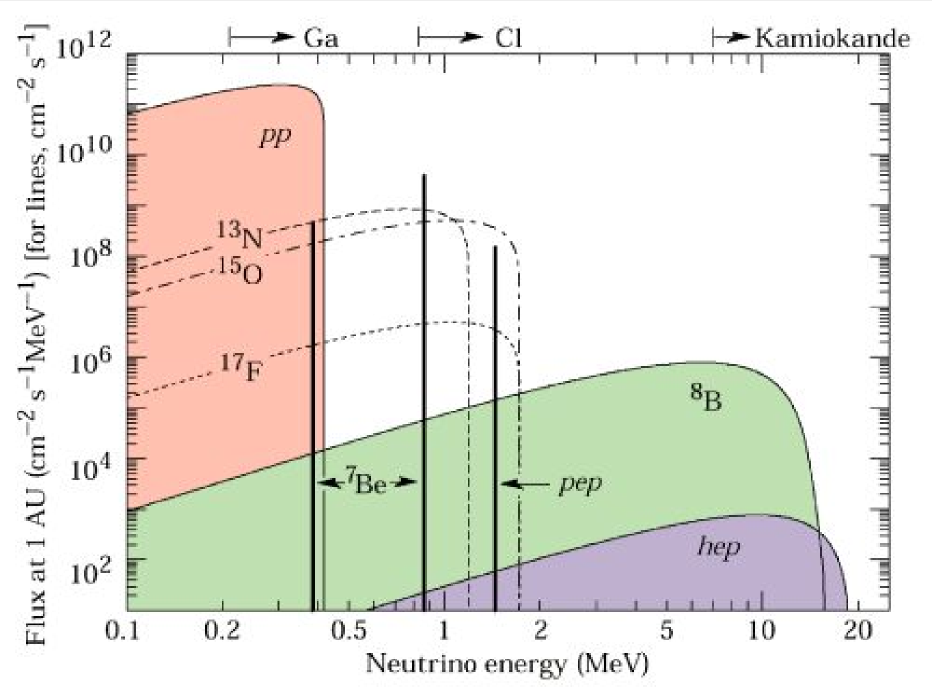
Low-E solar Neutrinos

Low-energy solar Neutrinos: pp, ^{7}Be

→ vast majority of solar neutrinos;
help to understand how the Sun works
→ very low energetic, hard to detect
→ mainly pp-neutrinos







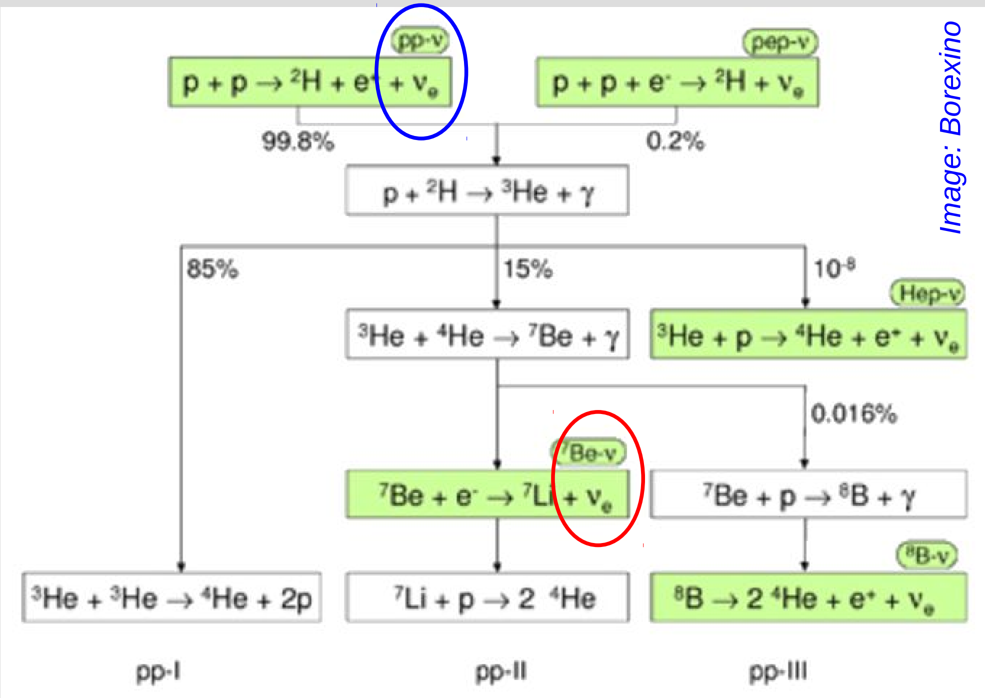


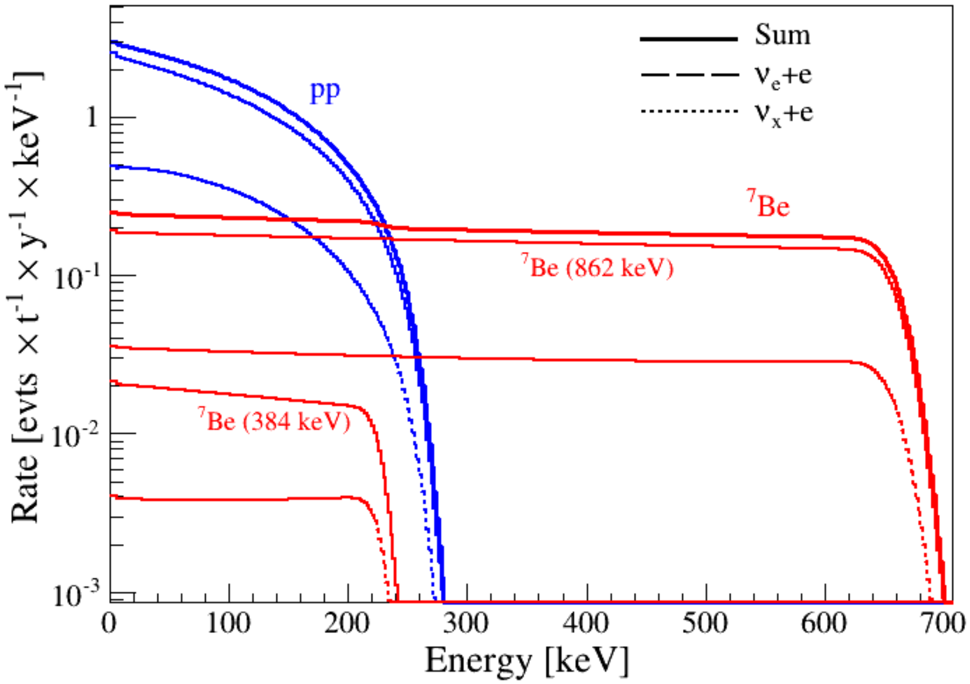
Image: Borexino

pp-Neutrinos in DARWIN

a background for the WIMP search

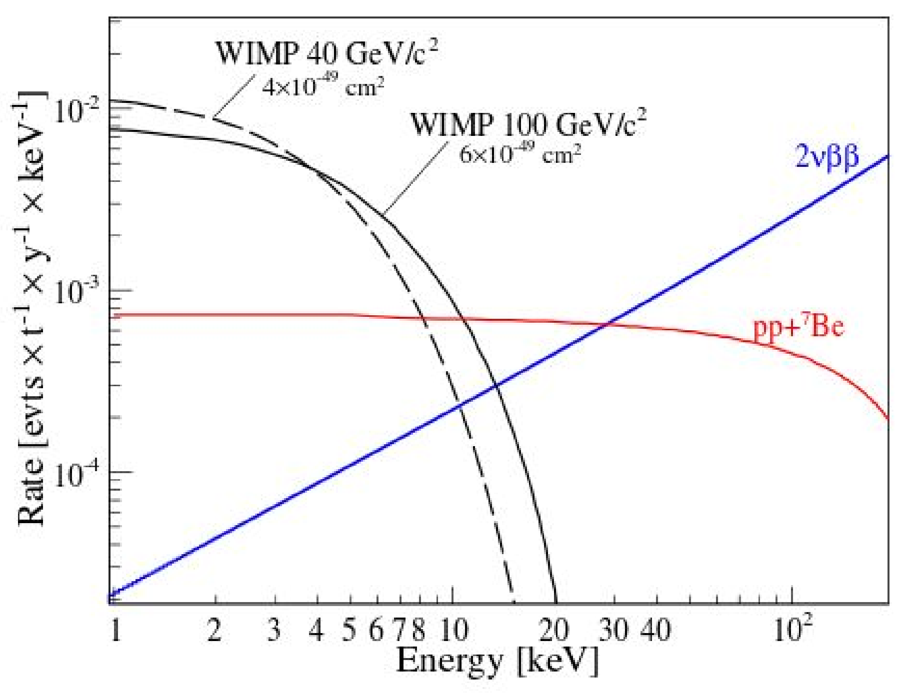
JCAP 11, 017 (2016)

Differential Recoil Spectrum in Xe



- neutrinos interact with Xe electrons
  →electronic recoil signature
- continuous recoil spectrum
  → largest rate at low E

Neutrino interactions



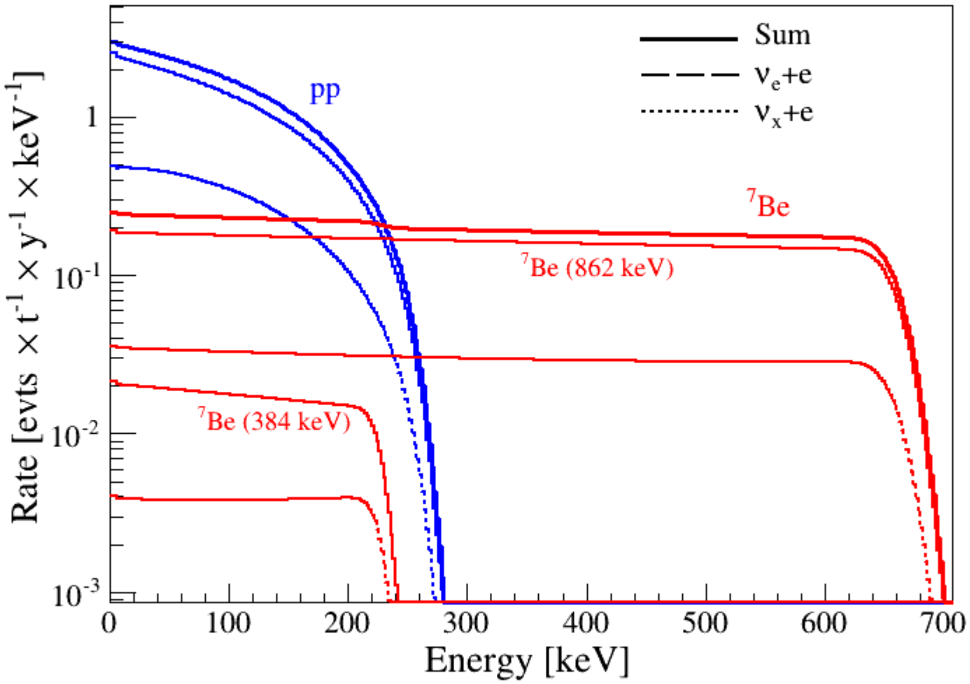
- ER rejection efficiencies ~99.98% at 30% NR efficiency are required to reduce to sub-dominant level

pp-Neutrinos in DARWIN

a new physics channel!

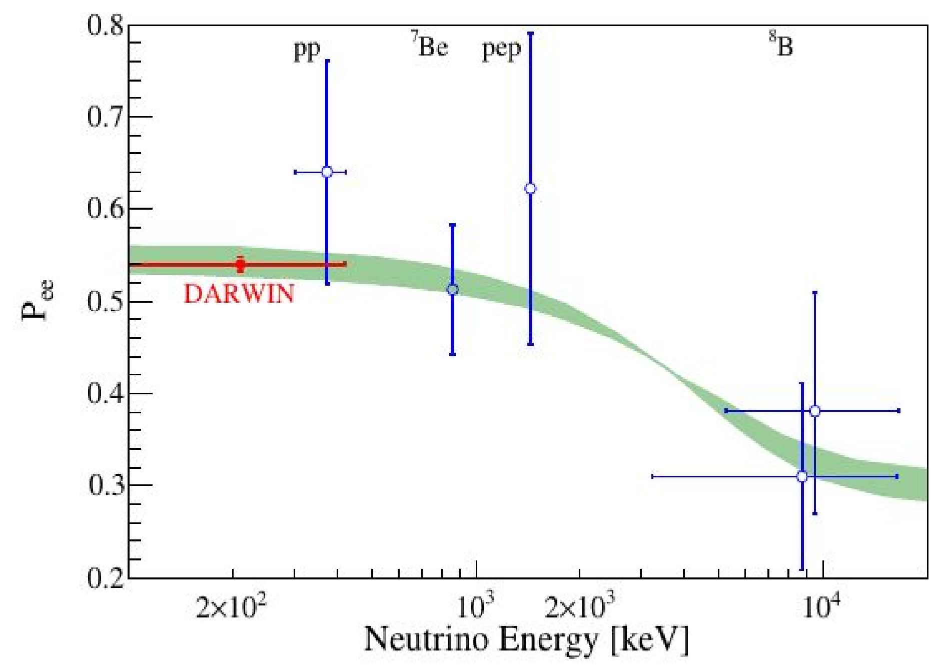
JCAP 11, 017 (2016)

Differential Recoil Spectrum in Xe



- neutrinos interact with Xe electrons
  →electronic recoil signature
- continuous recoil spectrum
  → largest rate at low E
  ~0.26 ν evts/t/d in low-E region (2-30 keV)

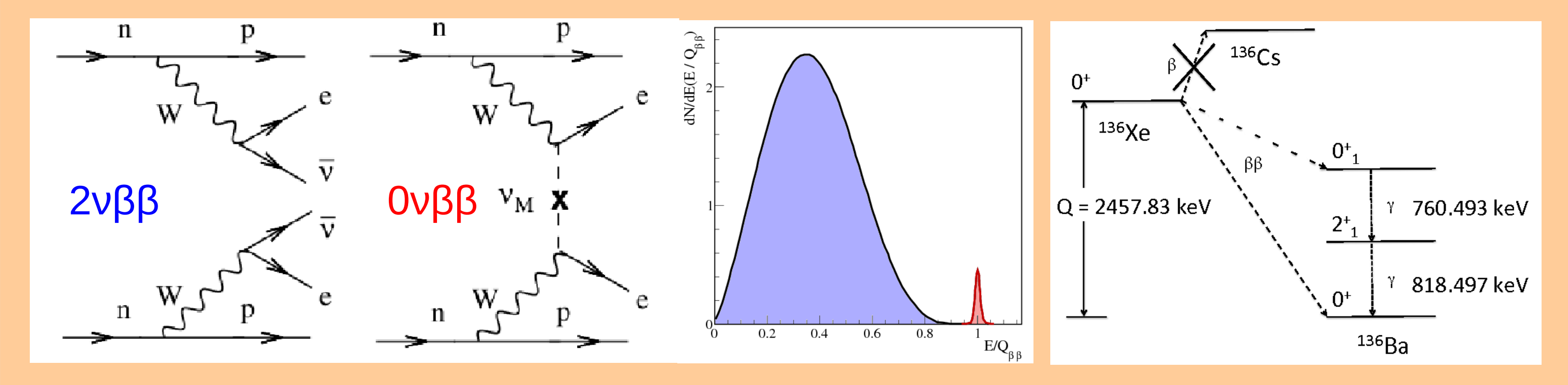
Neutrino interactions

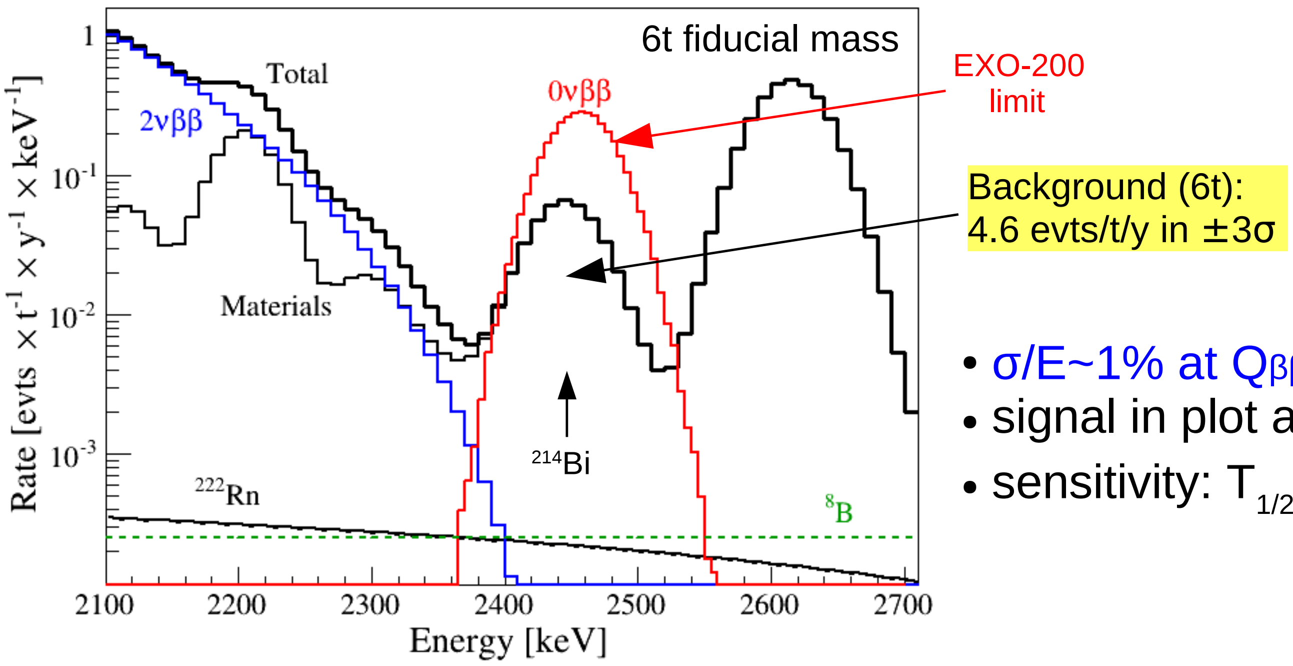


- 30t target mass, 2-30 keV window
  → 2850 neutrinos per year (89% pp)
  → achieve 1% statistical precision on pp-flux (→P_{ee}) with 100 t x y

^{136}Xe: 0ν double-beta Decay

JCAP 01, 044 (2014)





EXO-200 limit

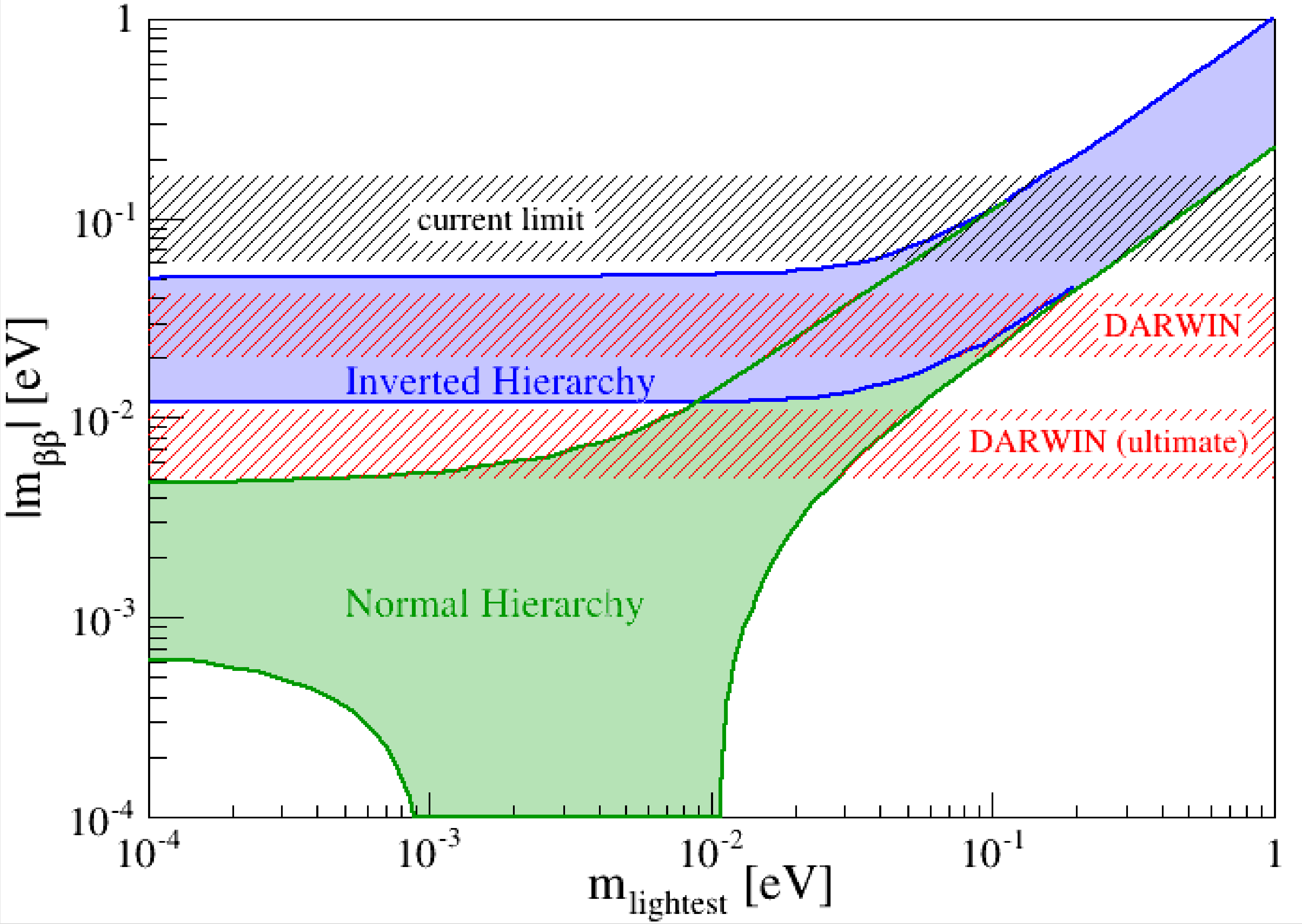
Background (6t): 4.6 evts/t/y in ±3σ

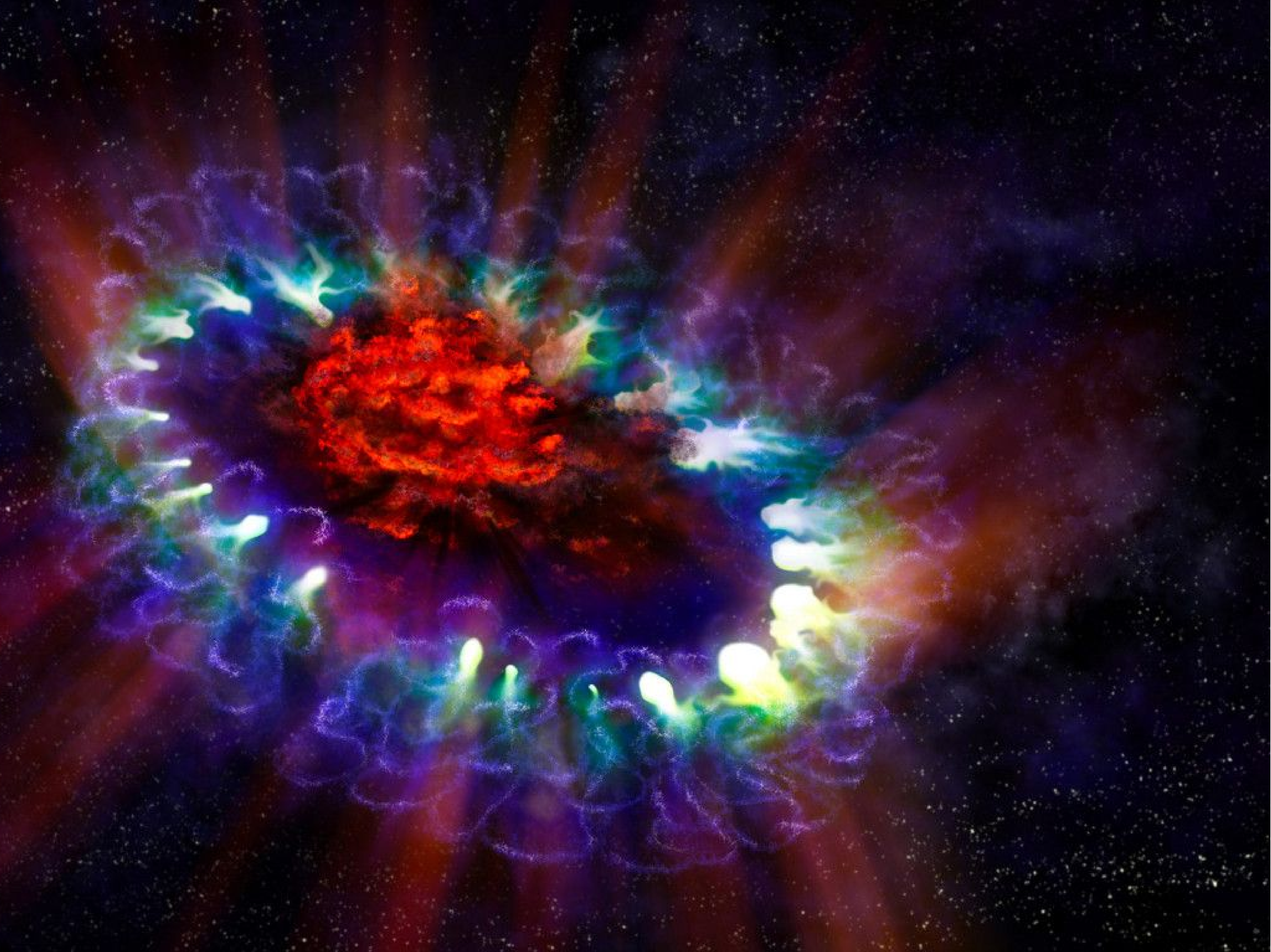
no ^{136}Xe enrichment!

- σ/E~1% at Qββ, combined *E*-scale
- signal in plot assumes $T_{1/2}$=1.6 x 10^{25} y
- sensitivity: $T_{1/2}$=5.6 x 10^{26} y (95% CL, 6t x 5y)

0ν Double-beta Decay

JCAP 11, 017 (2016)

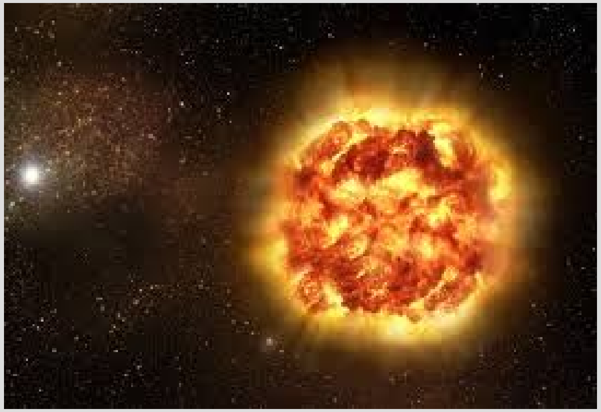




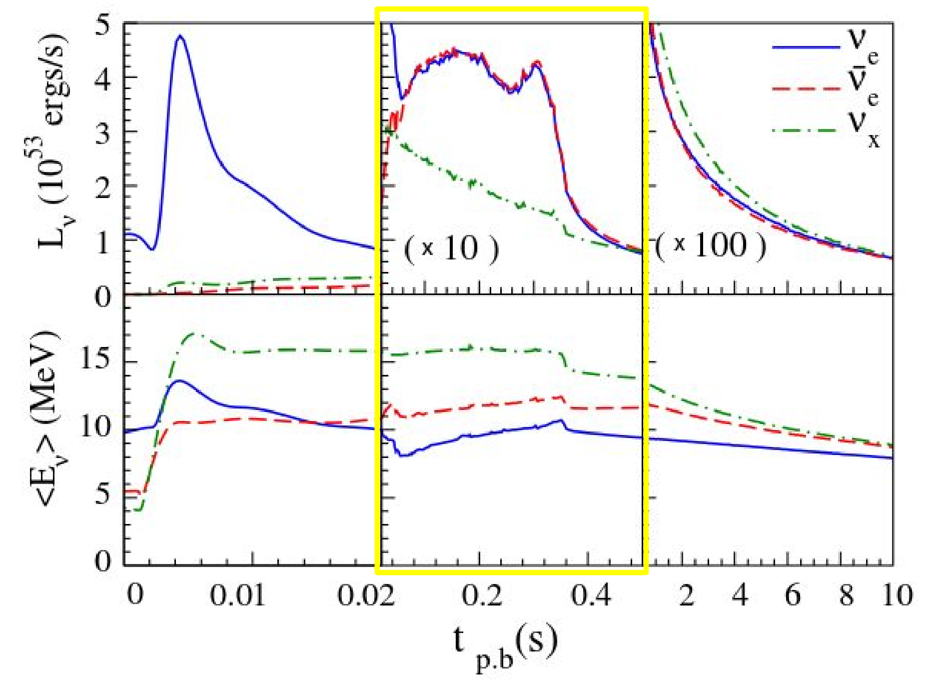
Supernova Neutrinos

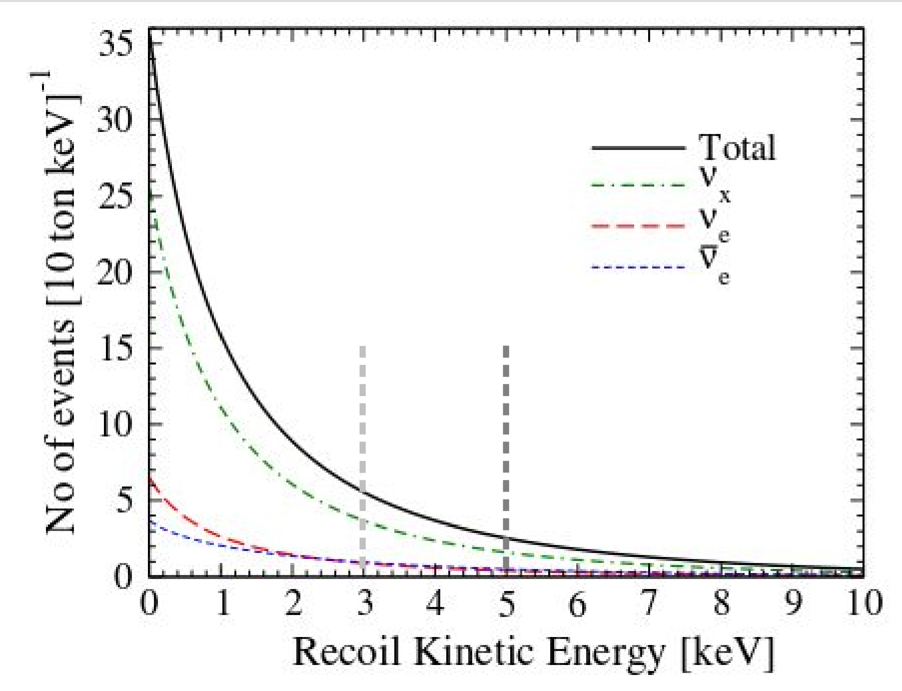
Chakraborty et al., PRD 89, 013011 (2014)
Lang et al., PRD 94, 103009 (2016)

- ν from supernovae could be detected via CNNS as well
- signal fom accretion phase of a ~18 M_{sun} supernova @ 10 kpc is clearly visible in DARWIN
- signal: NRs plus precise time information
- challenge: theshold

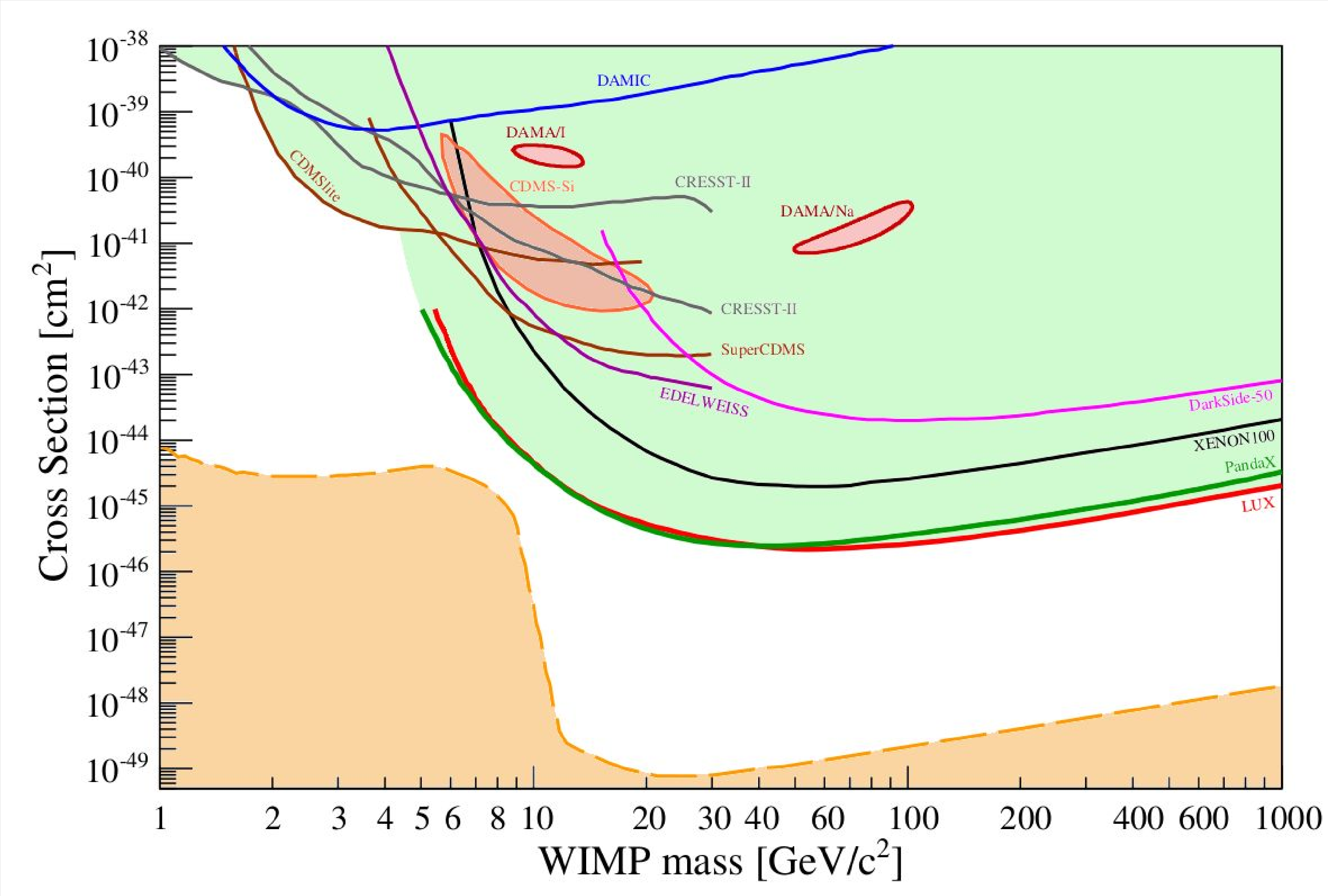


accretion phase



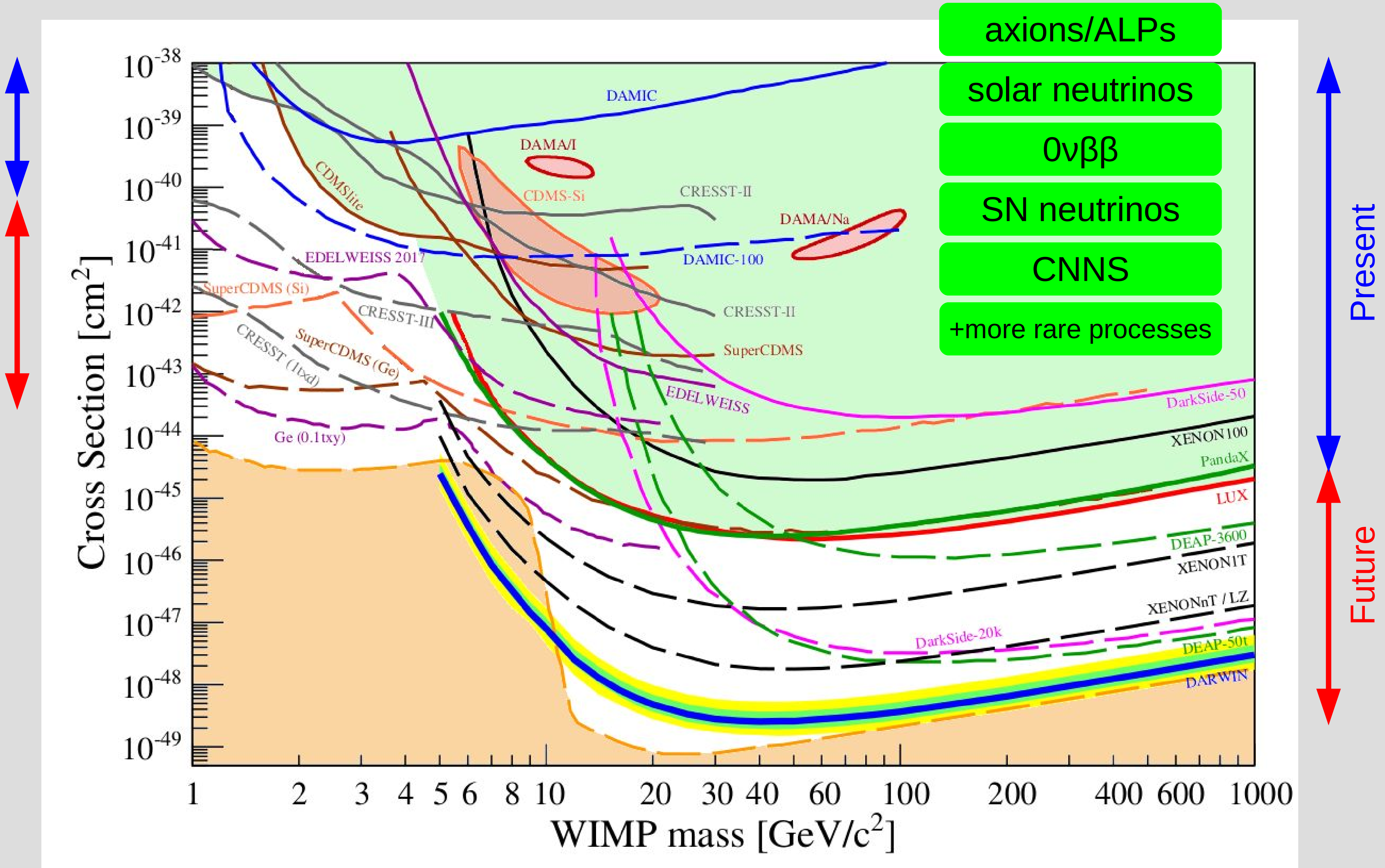


The WIMP Landscape today



Present

Exciting times ahead of us



- axions/ALPs
- solar neutrinos
- 0νββ
- SN neutrinos
- CNNS
- +more rare processes