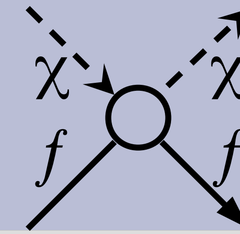
Dark Matter Detection with large LXe / LAr Detectors

Marc Schumann *University of Freiburg*

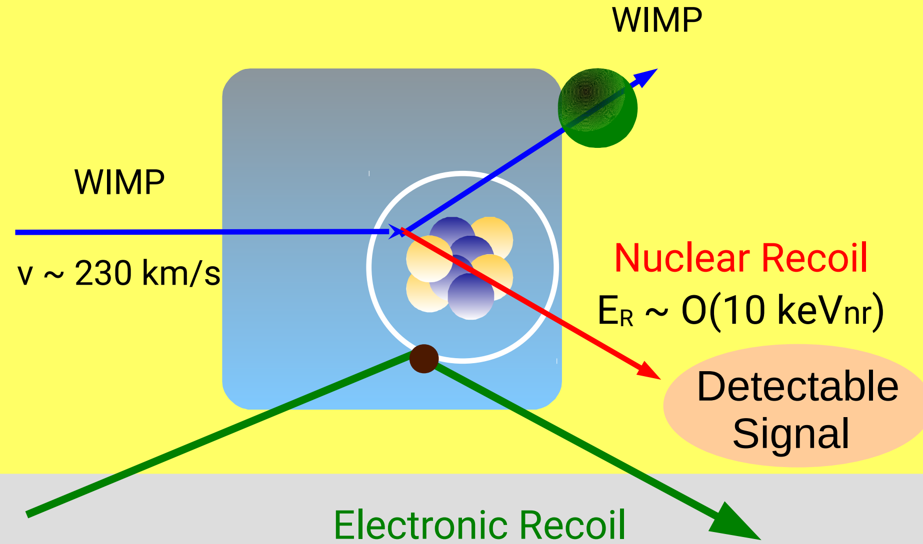
Dark Matter at the Dawn of Discovery, Heidelberg, April 10, 2018

www.app.uni-freiburg.de

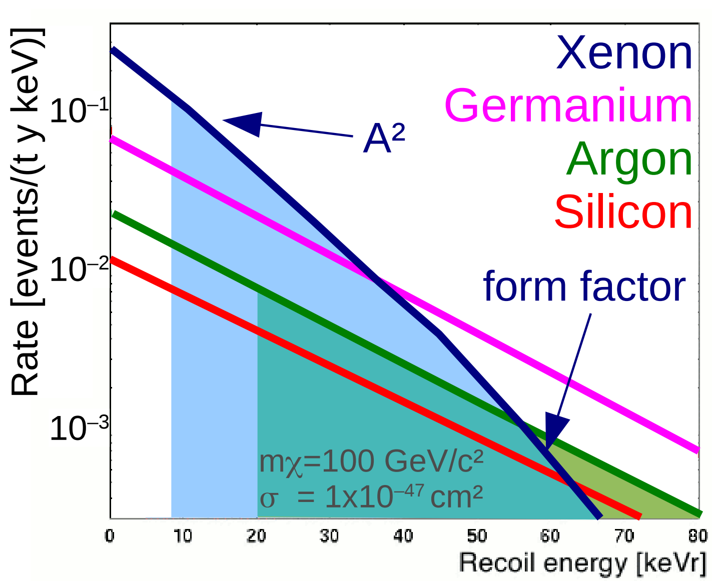
Direct WIMP Search

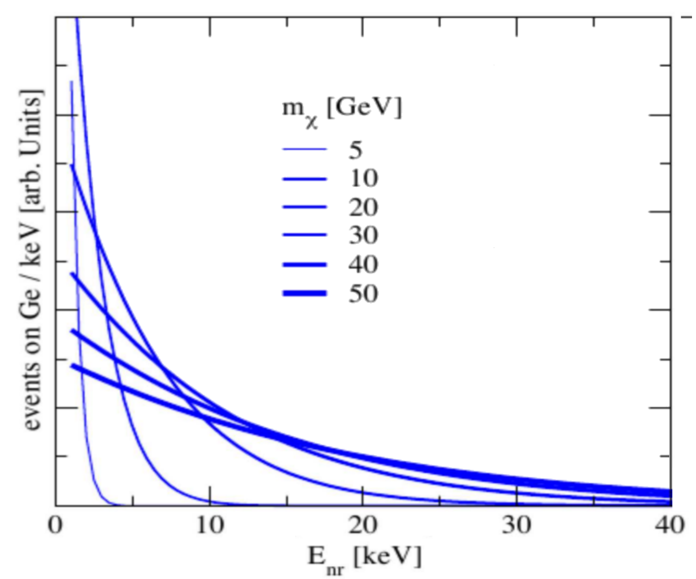


Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Spectra:





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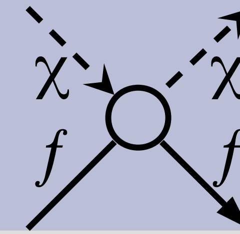

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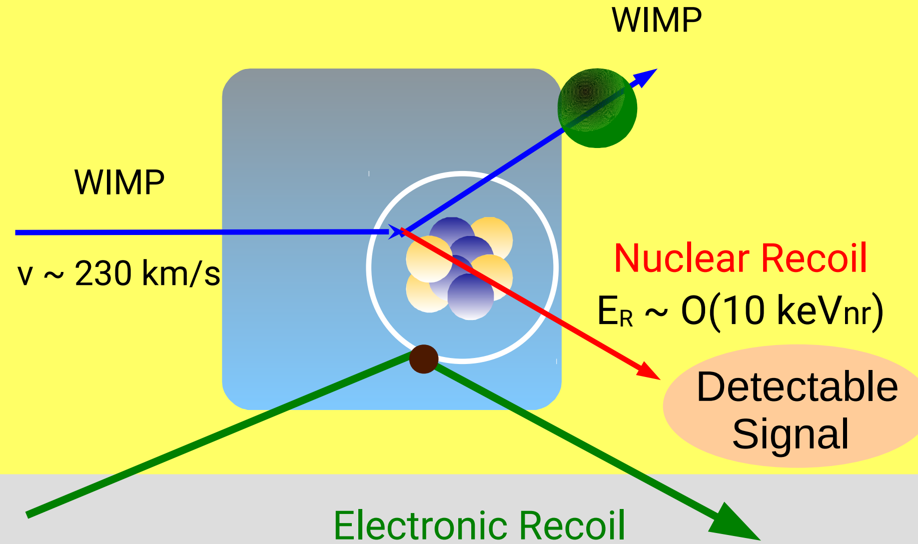

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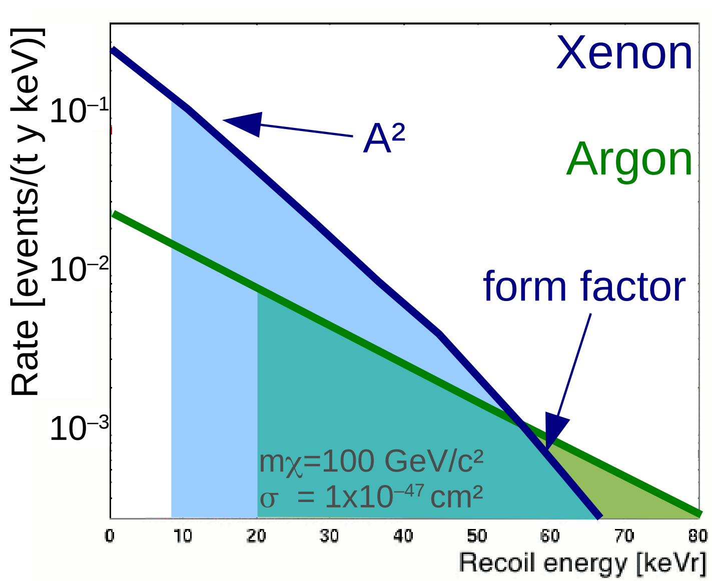
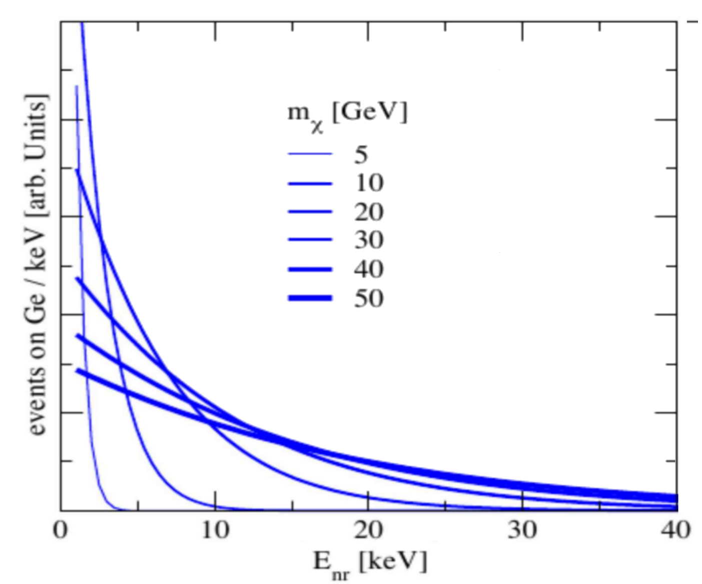


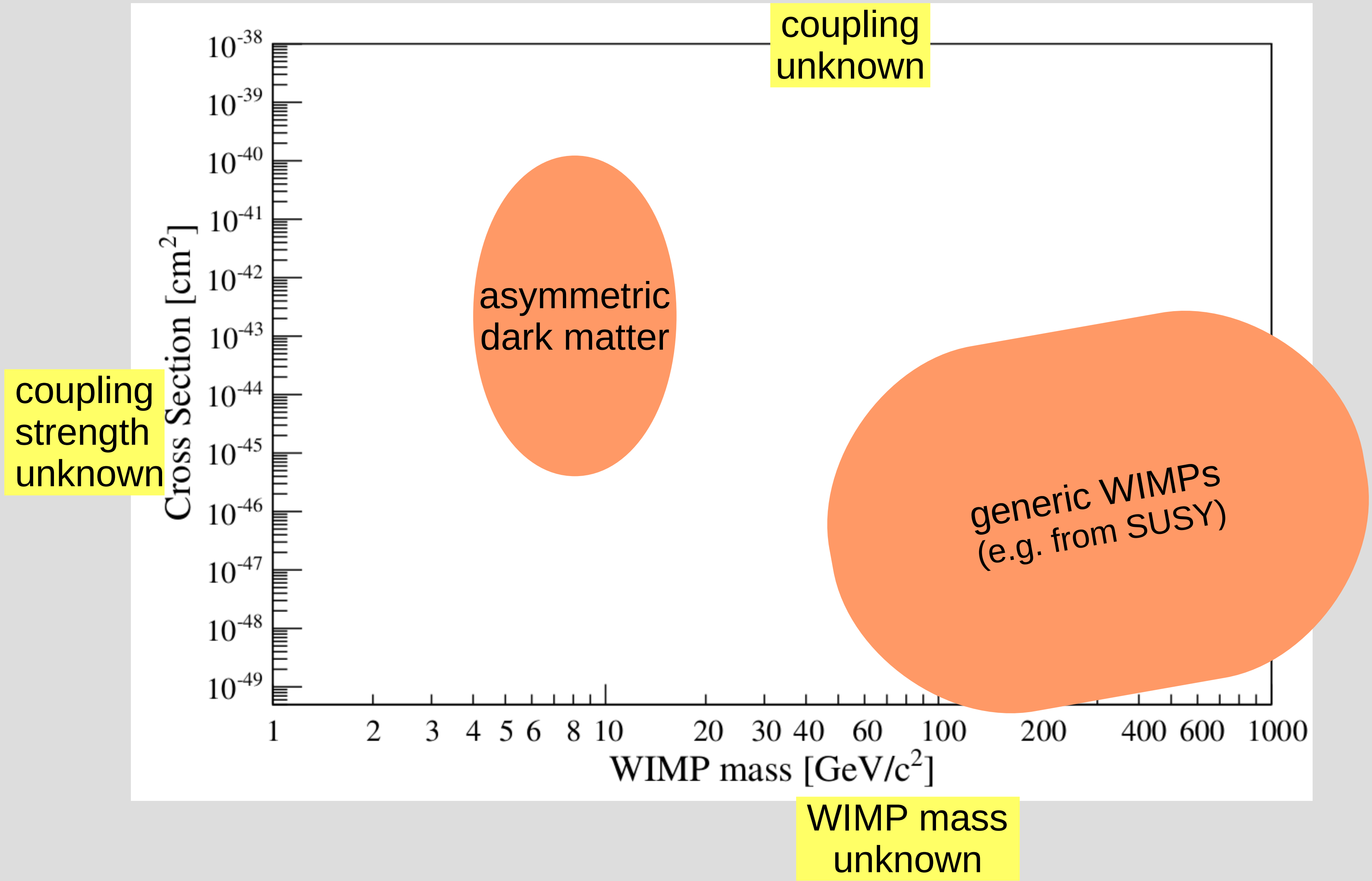


tiny!

tiny!

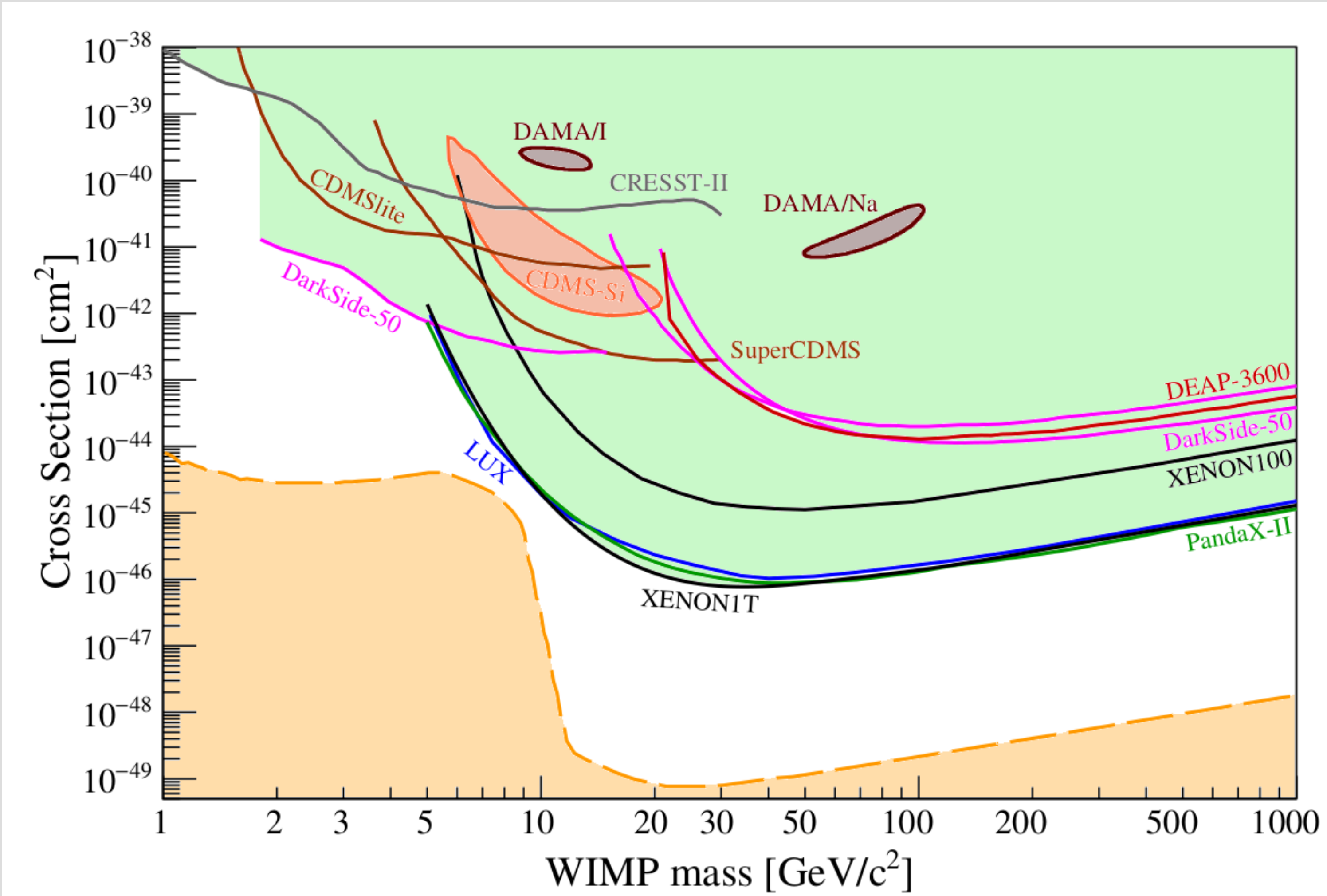
The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



Current Status

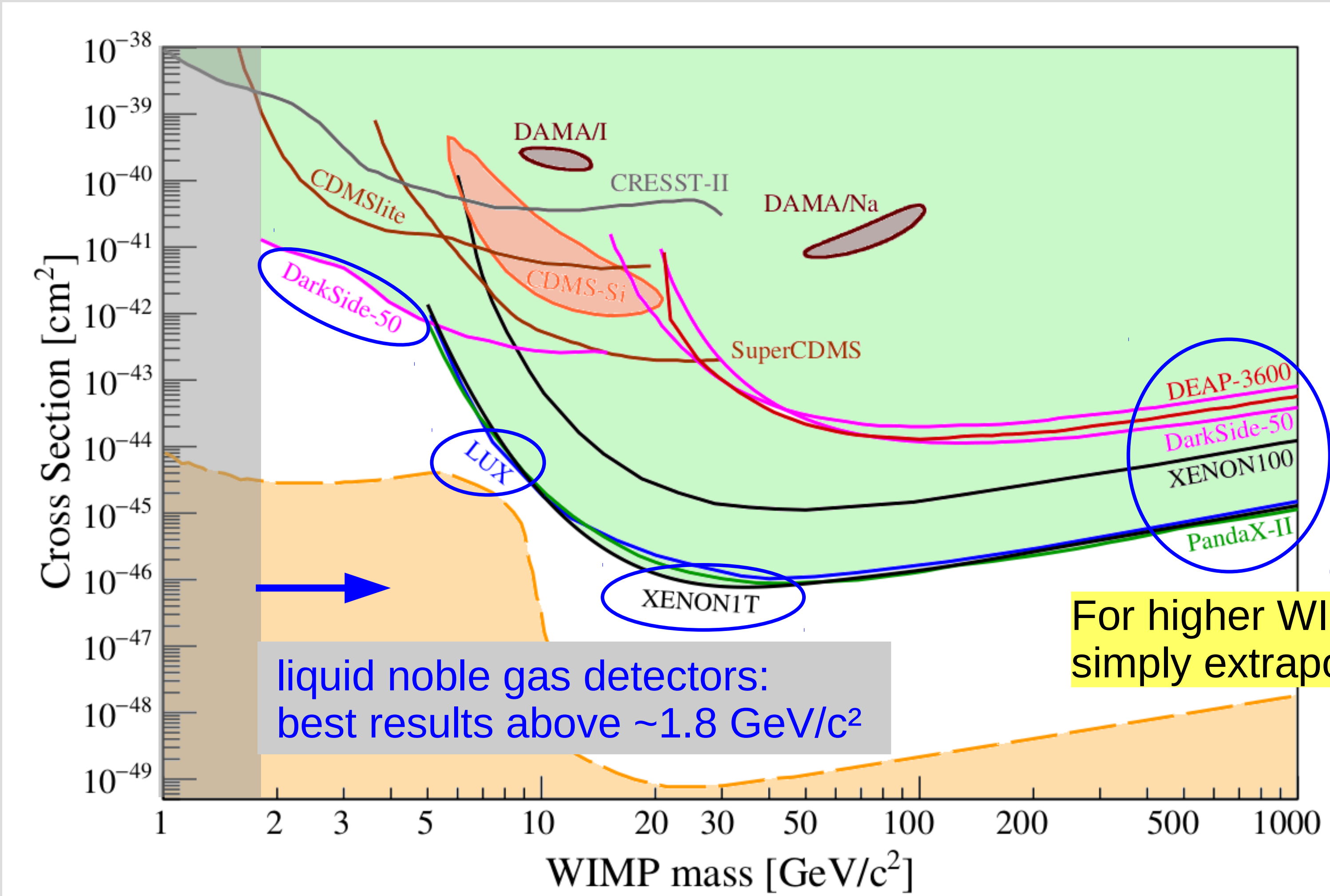
spin-independent WIMP-nucleon interactions



some results are missing...

Current Status

spin-independent WIMP-nucleon interactions

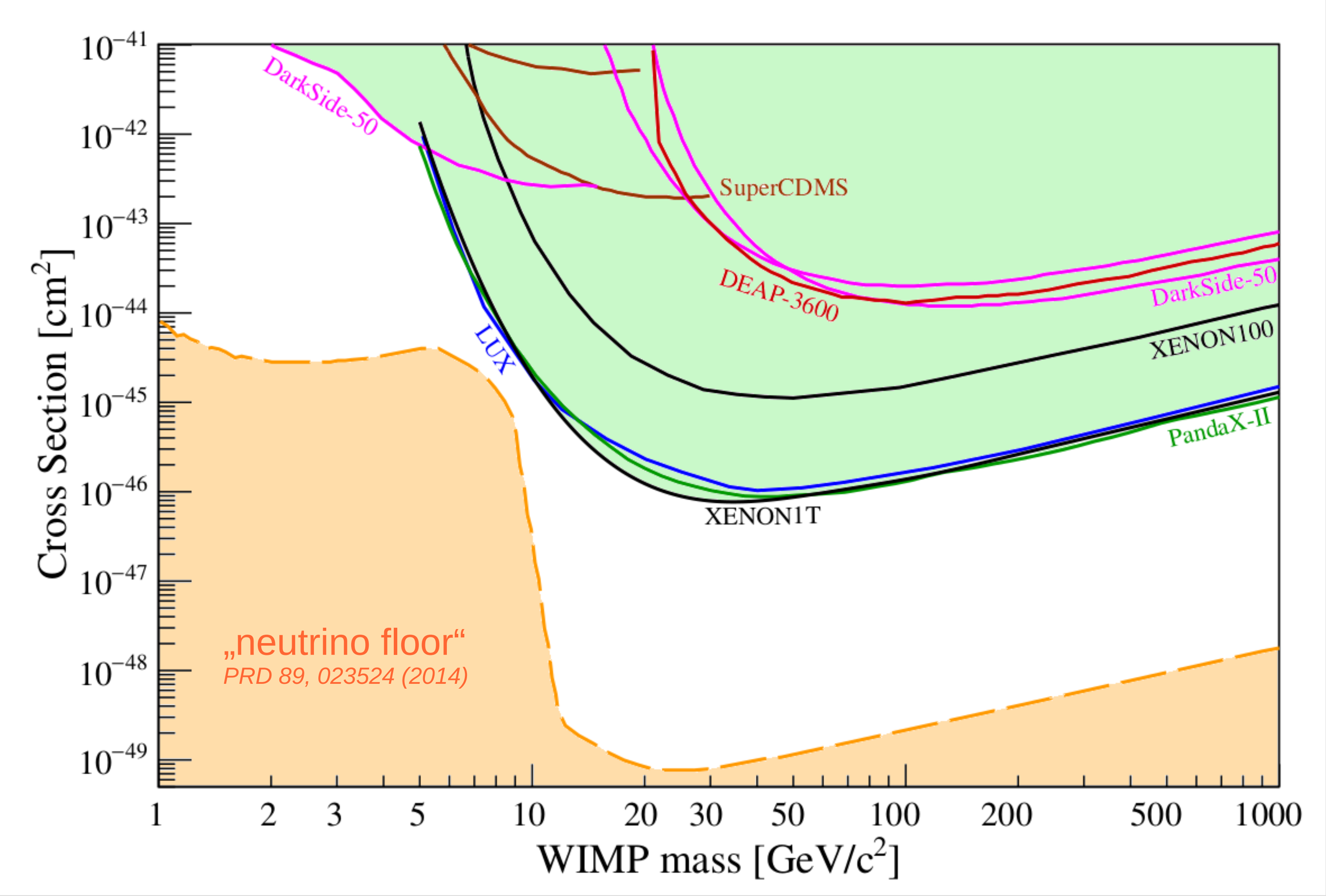


For higher WIMP masses, simply extrapolate limits

some results are missing...

The ultimate Limit

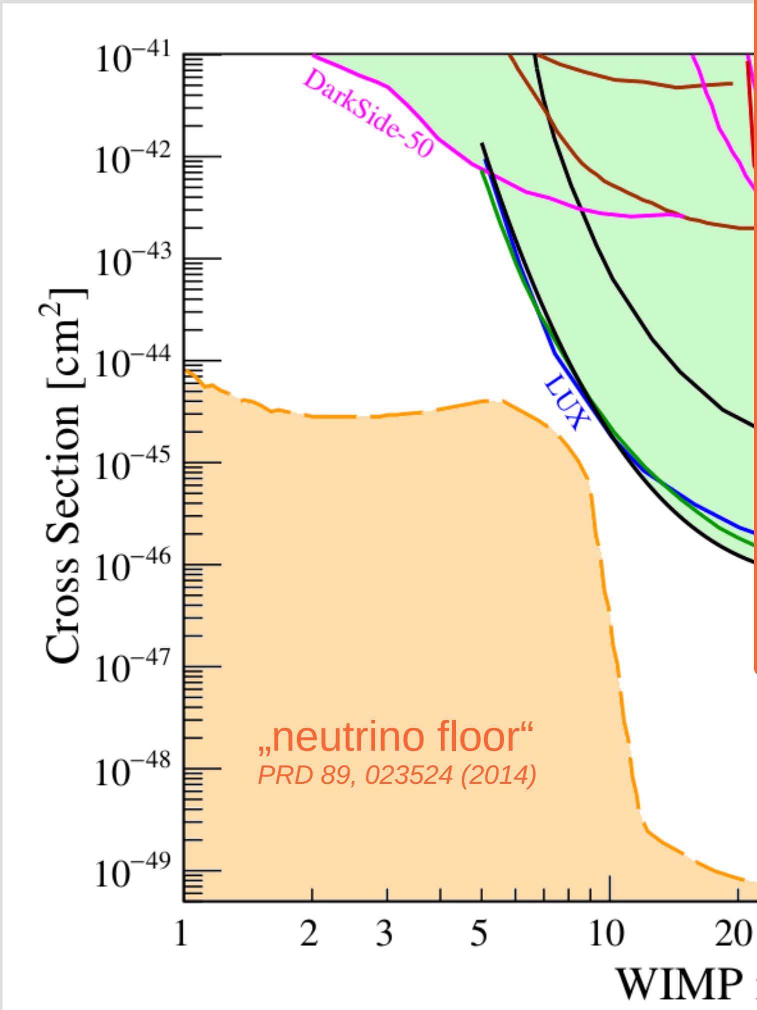
spin-independent WIMP-nucleon interactions

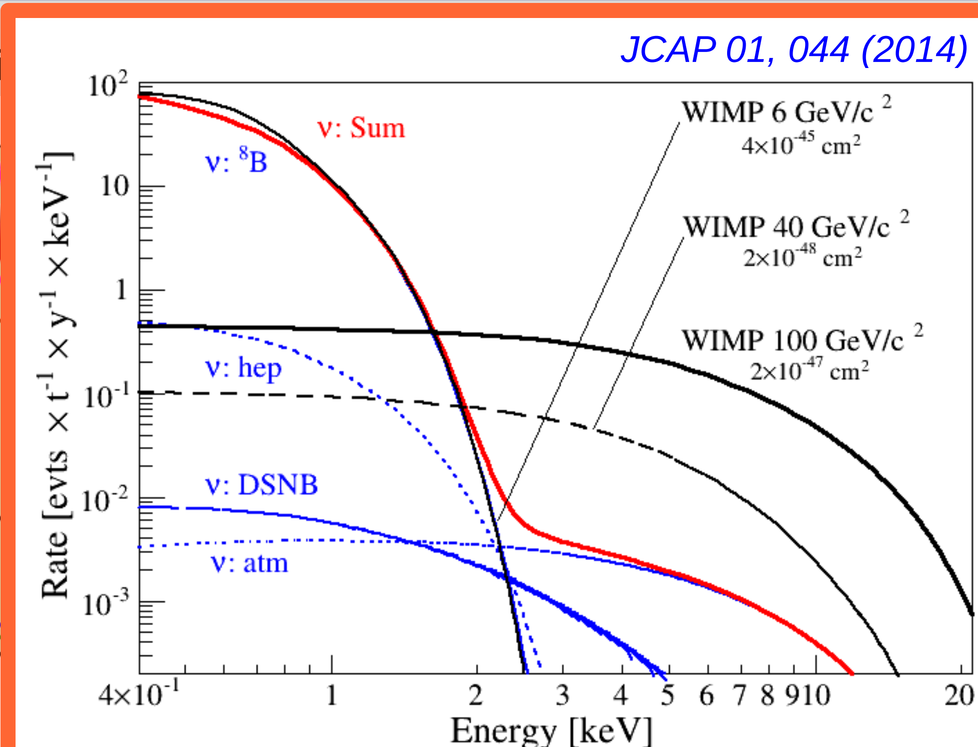


some results are missing...

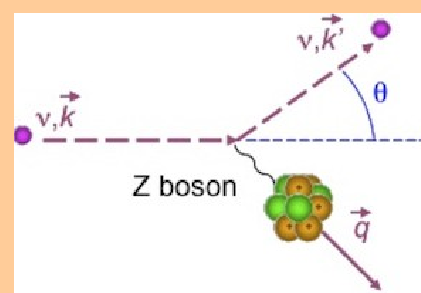
The ultimate Limit

spin-i



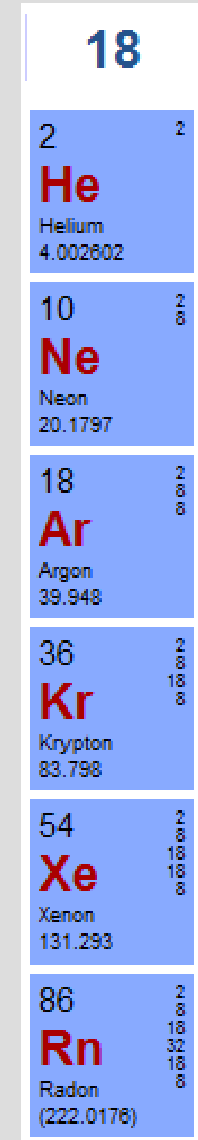


Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



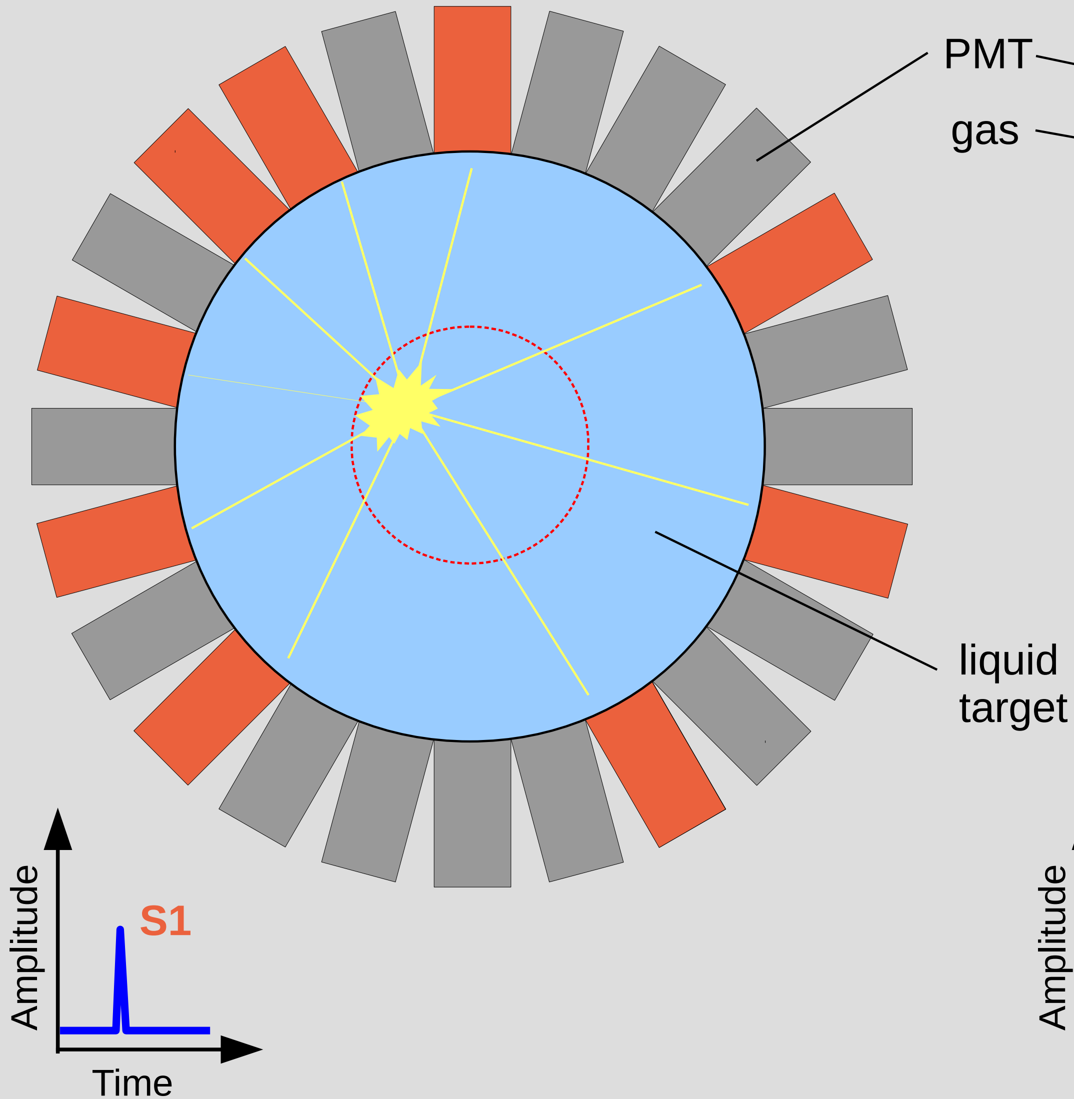
Noble Liquid Targets

Target	LXe	LAr
Atomic Number	54	18
Atomic mass	131.3	40.0
Boiling Point T_b [K]	165.0	87.3
Liq. Density @ T_b [g/cm^3]	2.94	1.40
Fraction in Atmosphere	0.09	9340
Price	$$$$	$

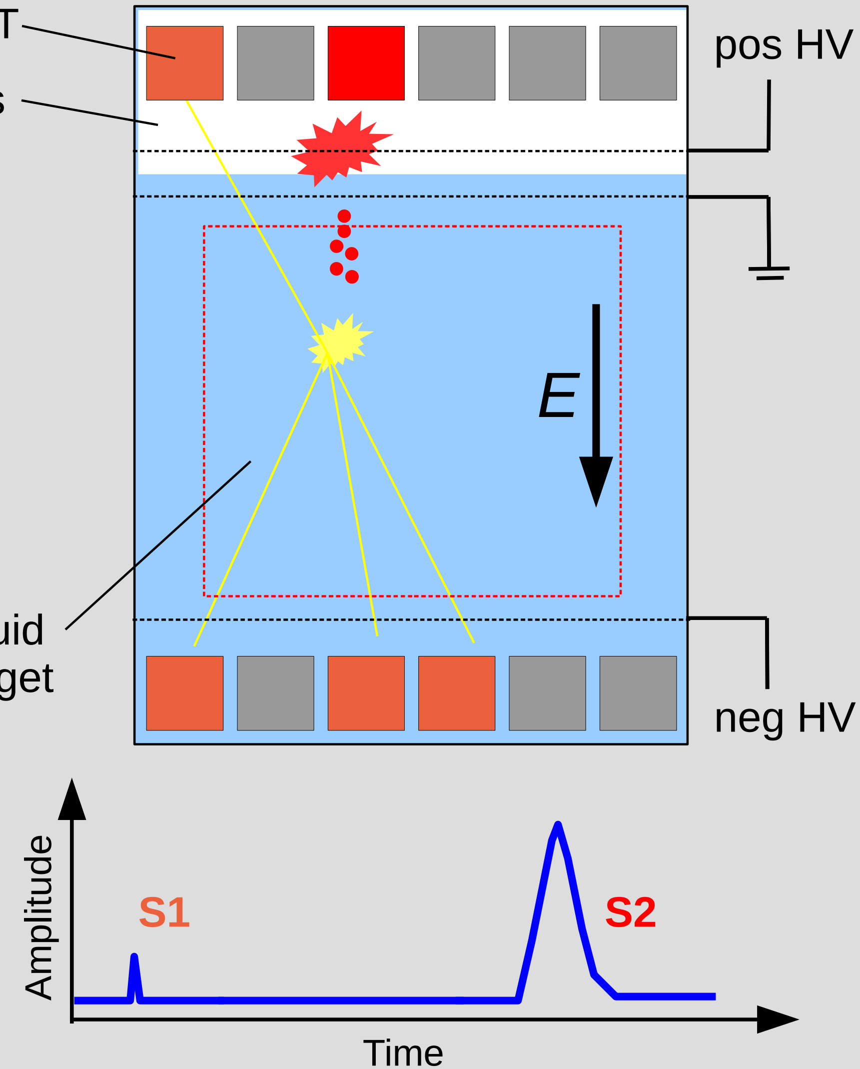


Liquid Noble Gases: Detector Concepts

Single Phase Detector



Time Projection Chamber



Liquid Noble Gases: Detector Concepts

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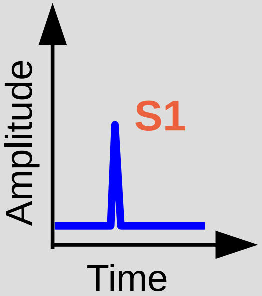
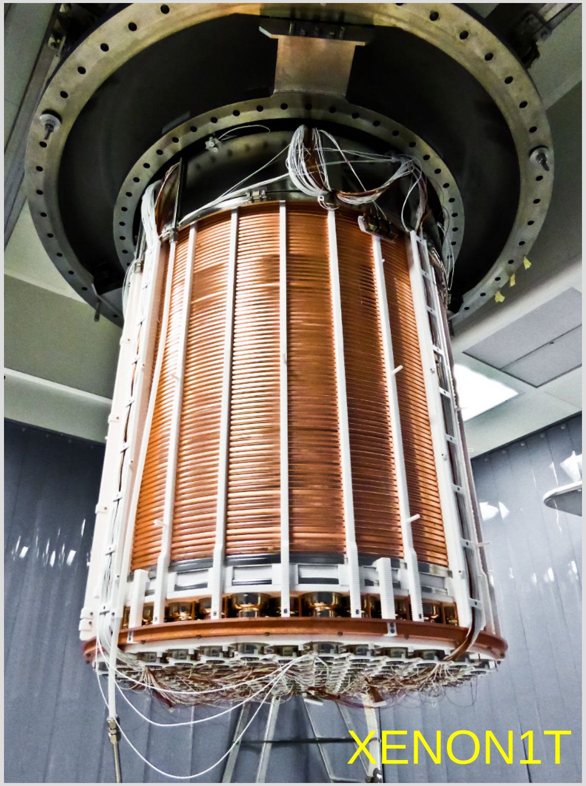
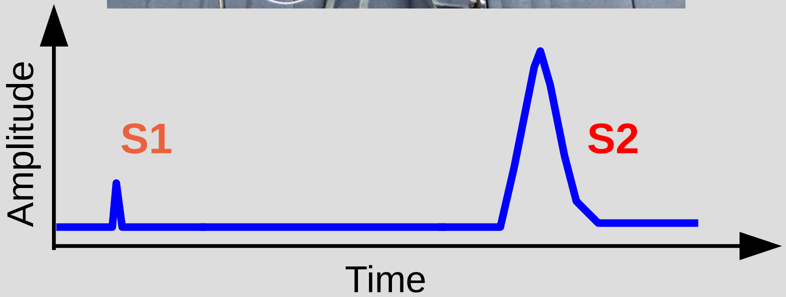


+ no high voltage, very high light yield
– O(cm) resolution, no double scatter rejection

Time Projection Chamber





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

Noble Liquid Targets

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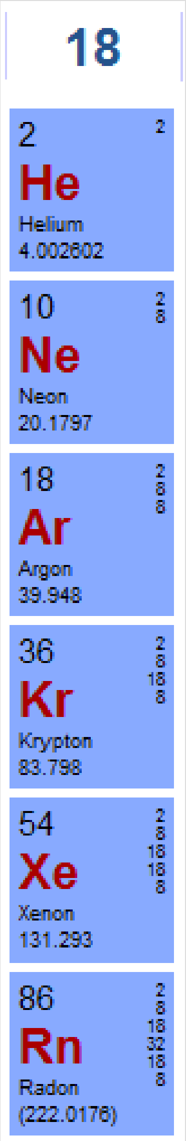
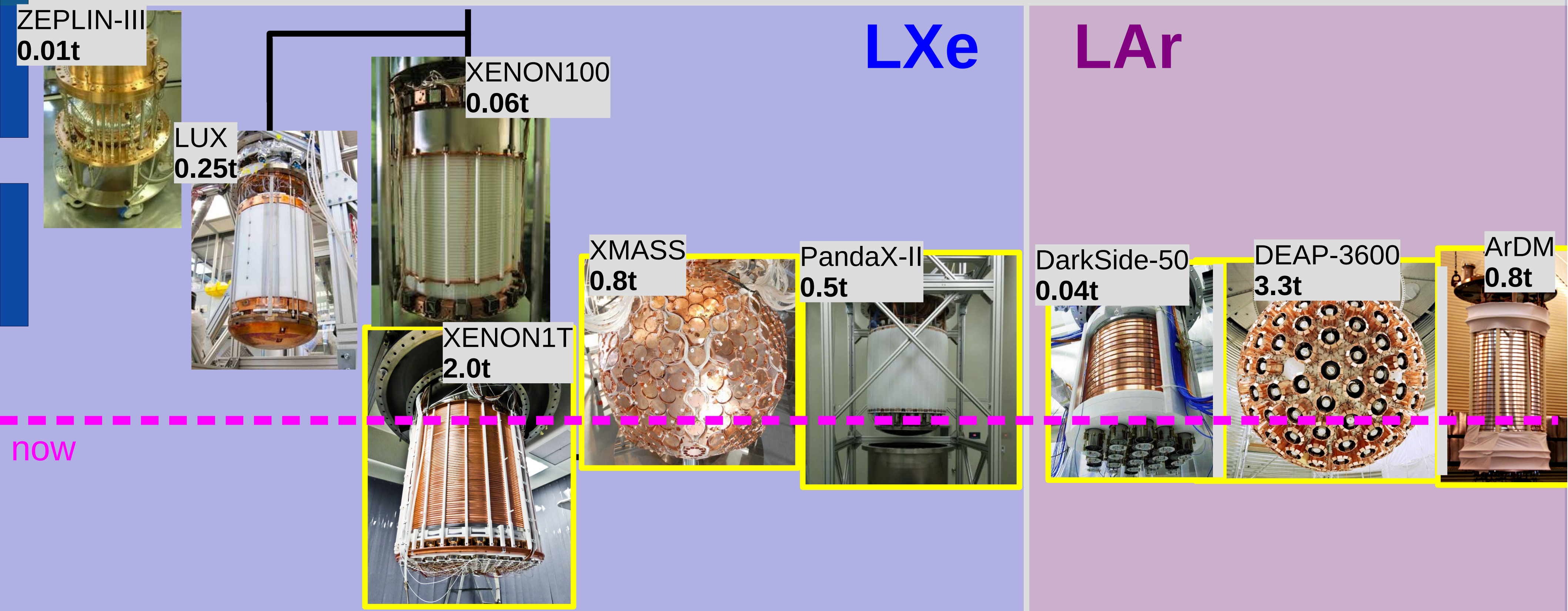
Liq. Density @ T_b [g/cm³]	2.94	1.40
Fraction in Atmosphere	0.09	9340
Price	$$$$	$
Scintillator	✔	✔
Scint. Wavelength [nm]	178	128
Ionizer	✔	✔
W (E to generate e-ion pair) [eV]	15.6	23.6
Scalability	✔	✔
Collaborations	4 → **3**	3 → **1**

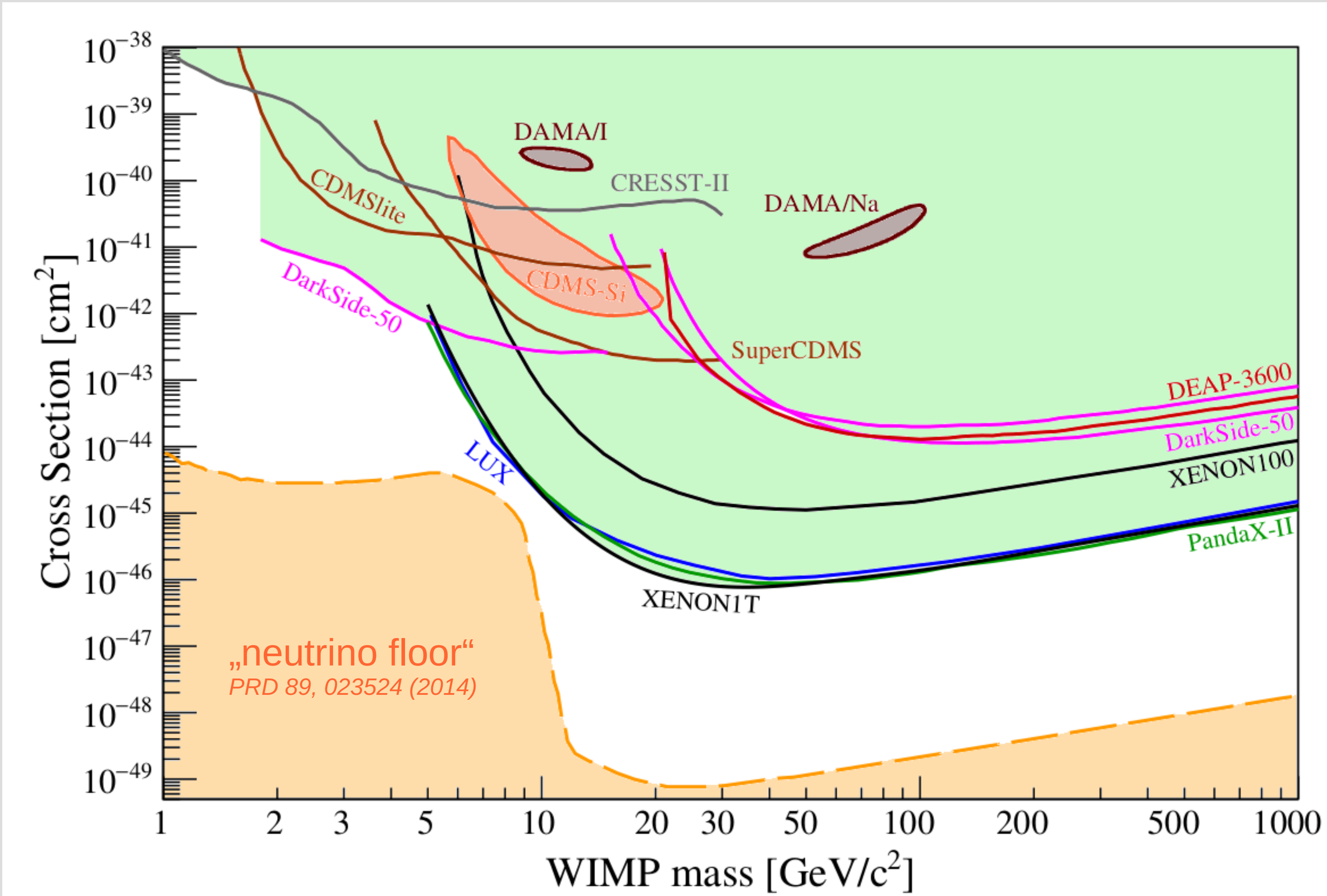


Operating Detectors



Current Status

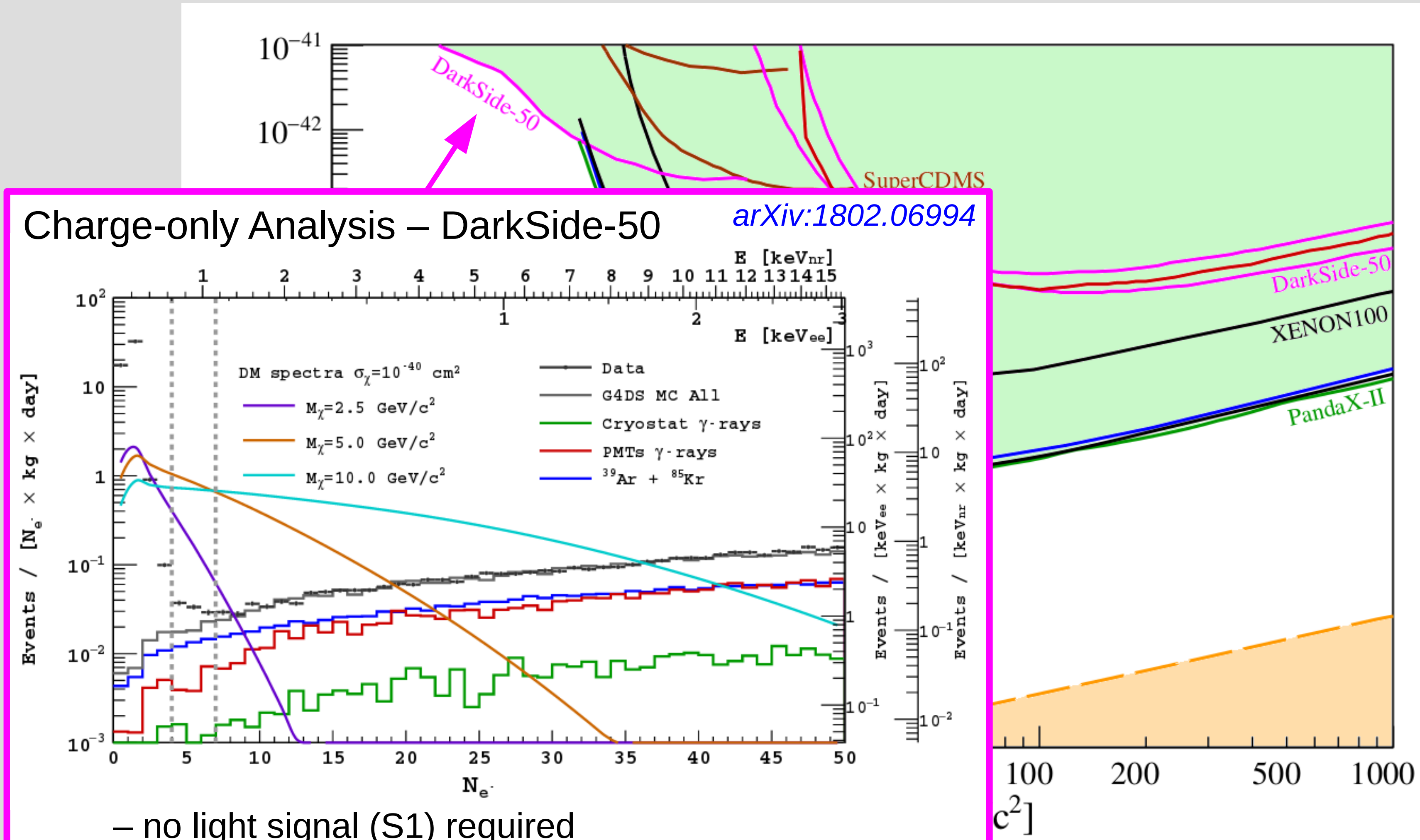
spin-independent WIMP-nucleon interactions



some results are missing...

New DS-50 Limit @ Low Mass

spin-independent WIMP-nucleon interactions



Charge-only Analysis – DarkSide-50

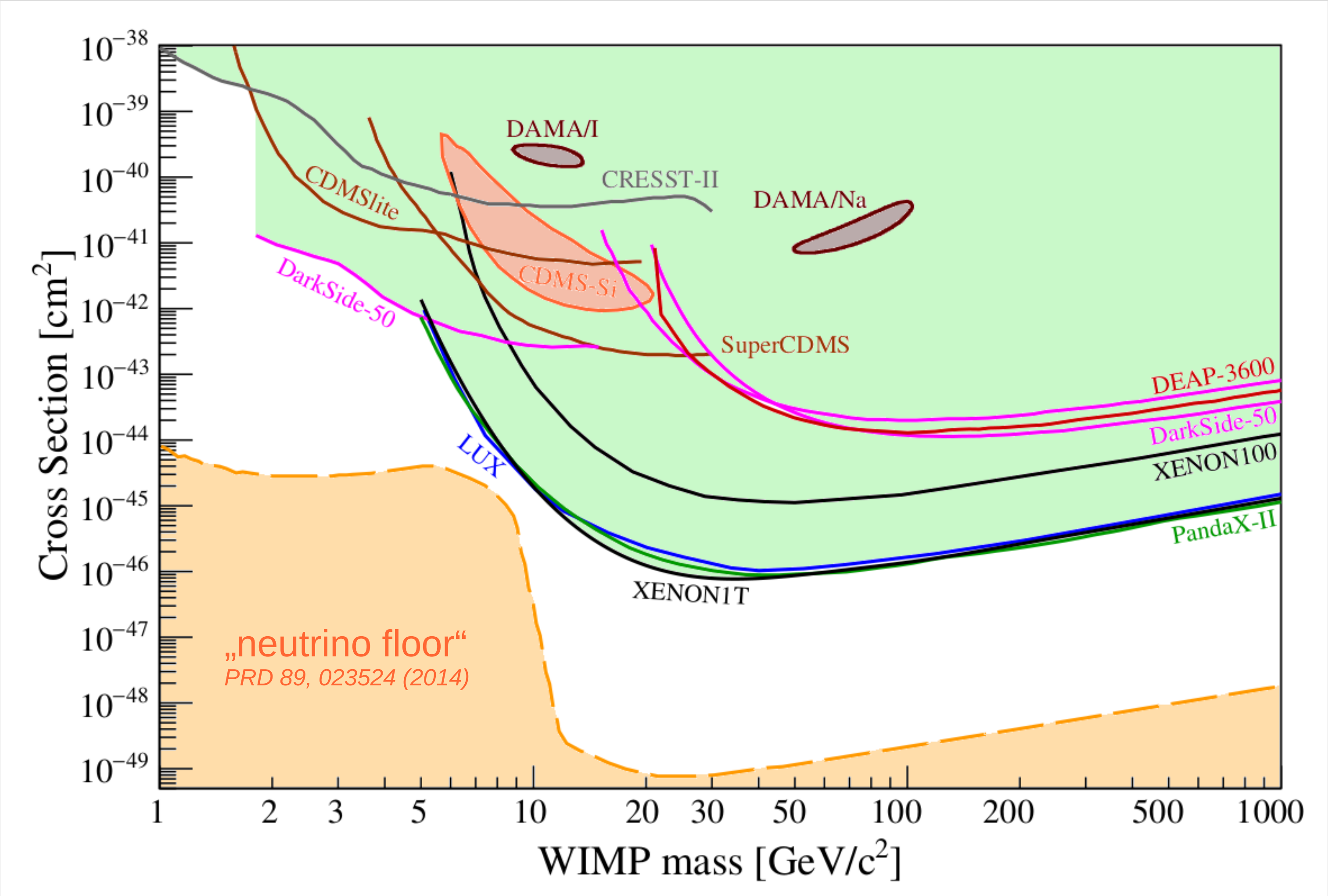
arXiv:1802.06994

– no light signal (S1) required
→ reduce threshold
– give up z-fiducialization, ER rejection

some results are missing...

Current Status

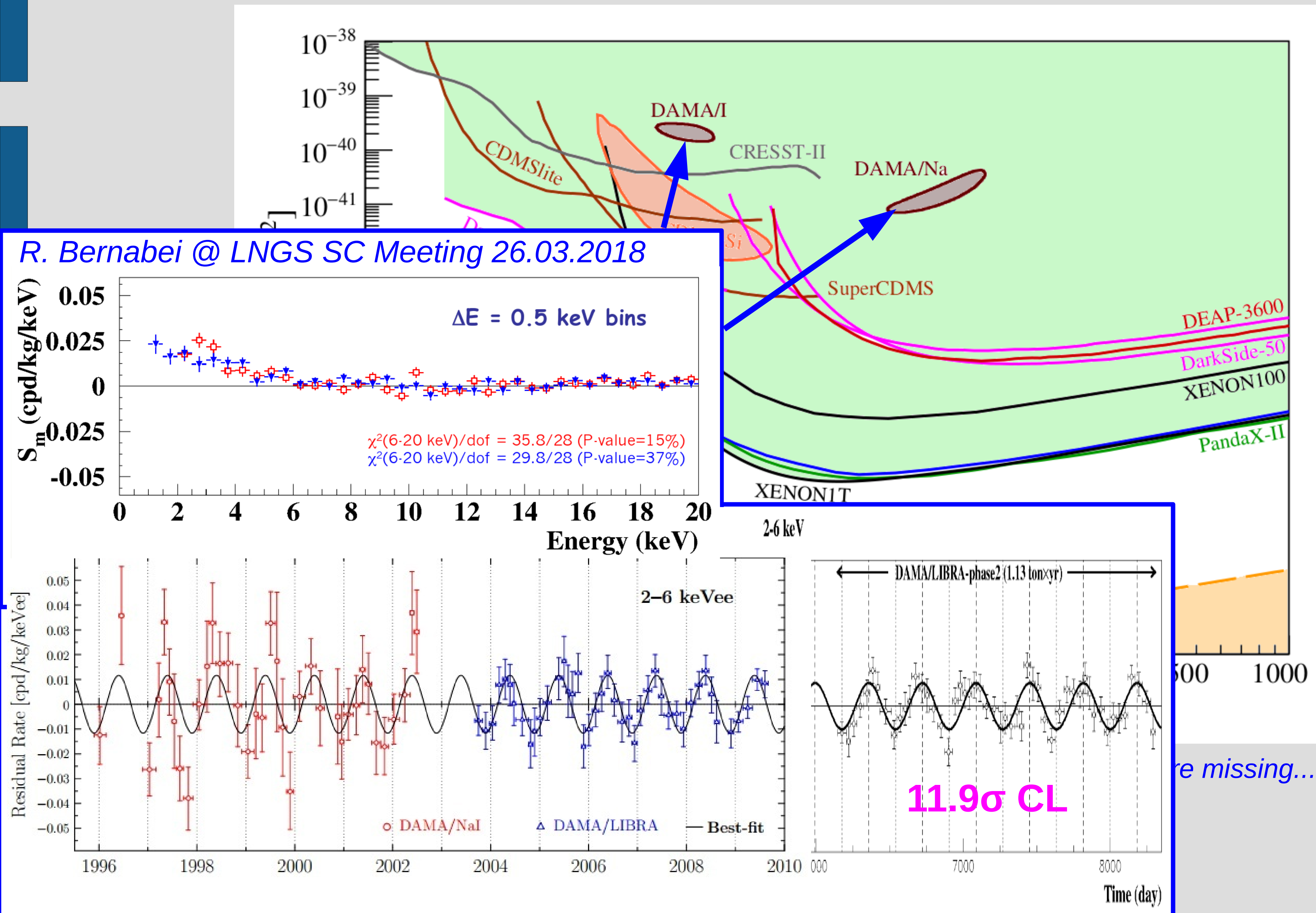
spin-independent WIMP-nucleon interactions



some results are missing...

New DAMA Result

spin-independent WIMP-nucleon interactions



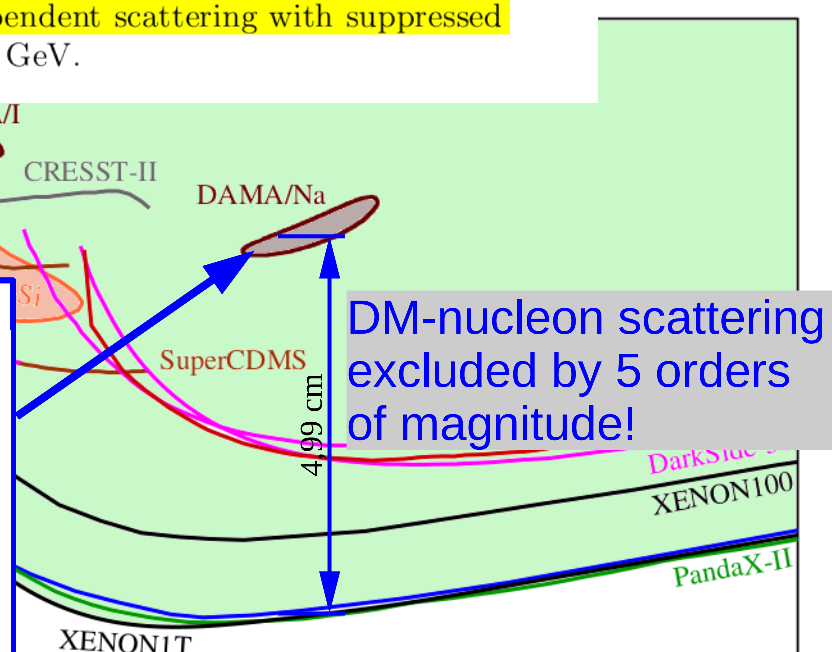
arXiv:1804.01231

Dark Matter implications of DAMA/LIBRA-phase2 results

Sebastian Baum,[1,2,*] Katherine Freese,[1,2,3,†] and Chris Kelso[4,‡]

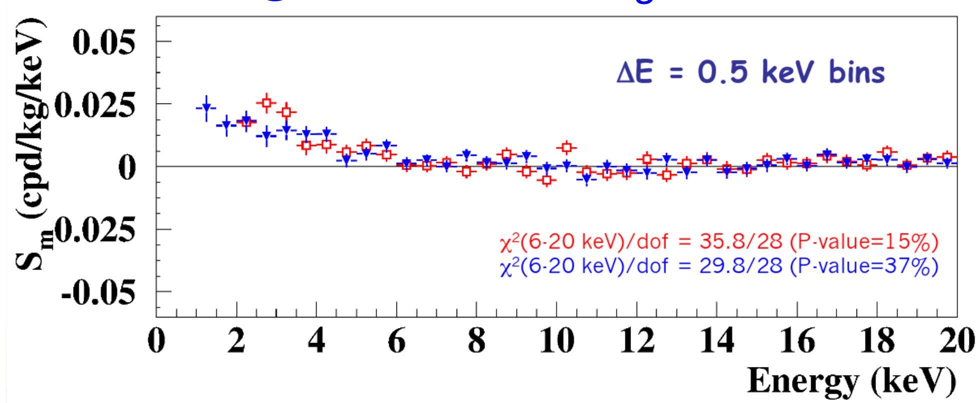
We find that canonical (isospin conserving) spin-independent DM-nucleon interactions are no longer a good fit to the observed modulation signal. The canonical spin-independent case is disfavored by the new data, with best fit points of a DM mass of ∼ 8 GeV, disfavored by 5.1 σ, or a mass of ∼ 53 GeV, disfavored by 3.2 σ. Allowing for isospin violating interactions, we find new best fit regions for spin-independent scattering with suppressed effective couplings to iodine for DM masses of ∼ 10 GeV or ∼ 45 GeV.

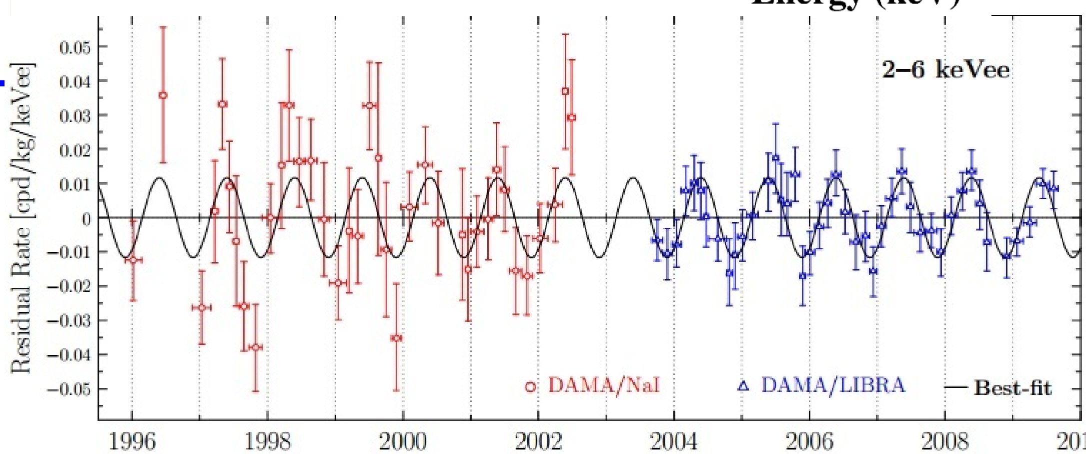
n interactions

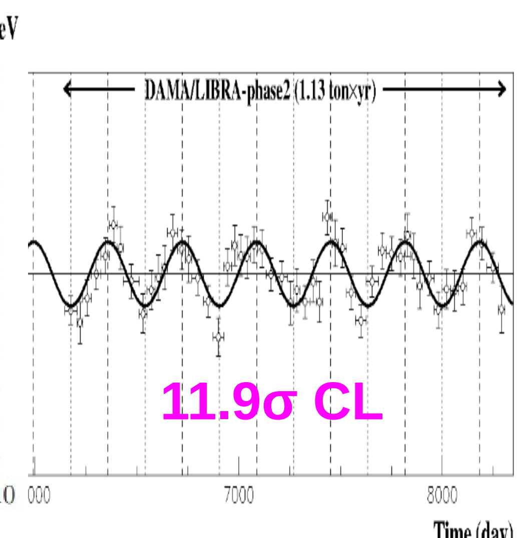


DM-nucleon scattering excluded by 5 orders of magnitude!

R. Bernabei @ LNGS SC Meeting 26.03.2018





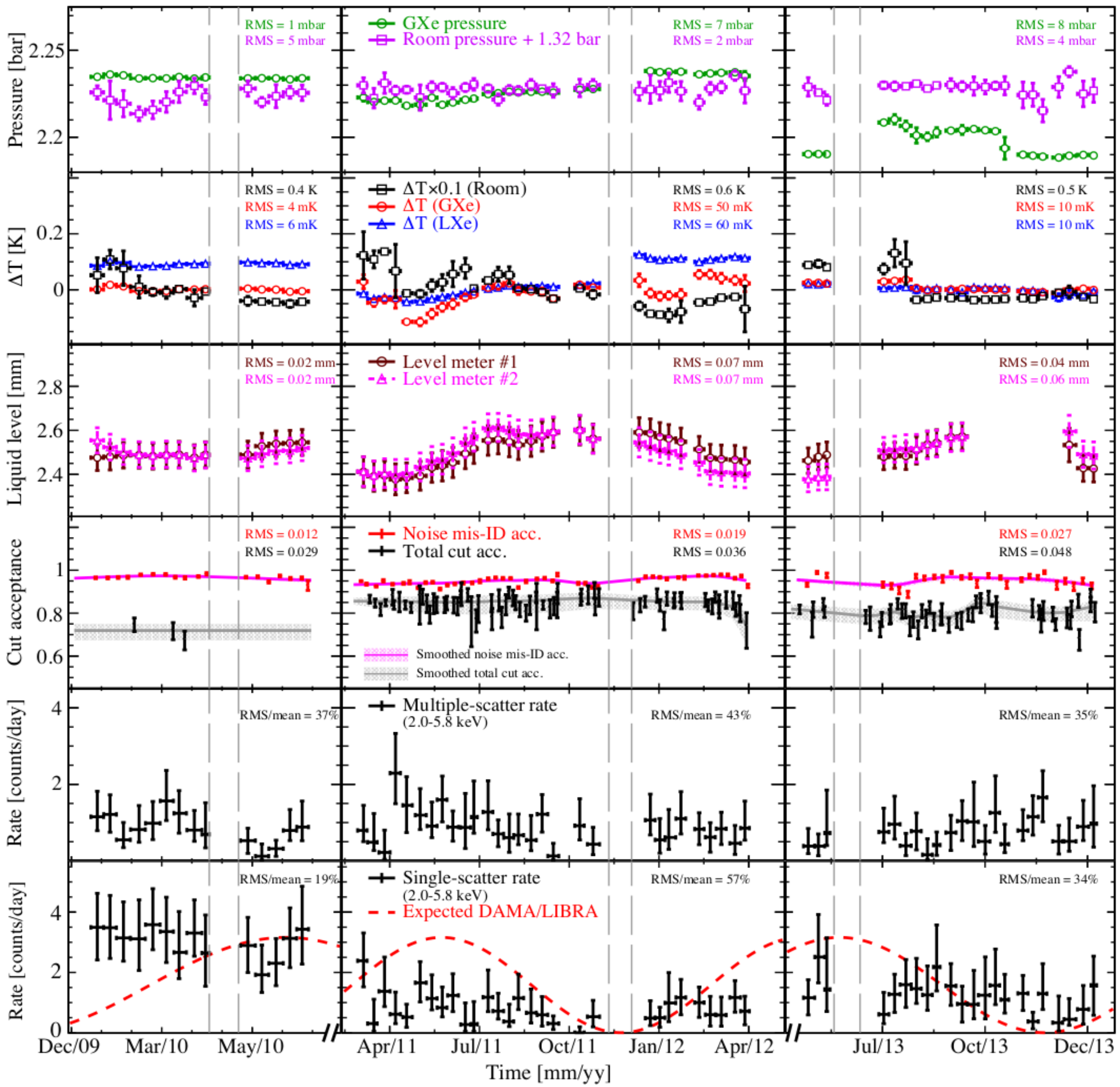


11.9σ CL

...re missing...

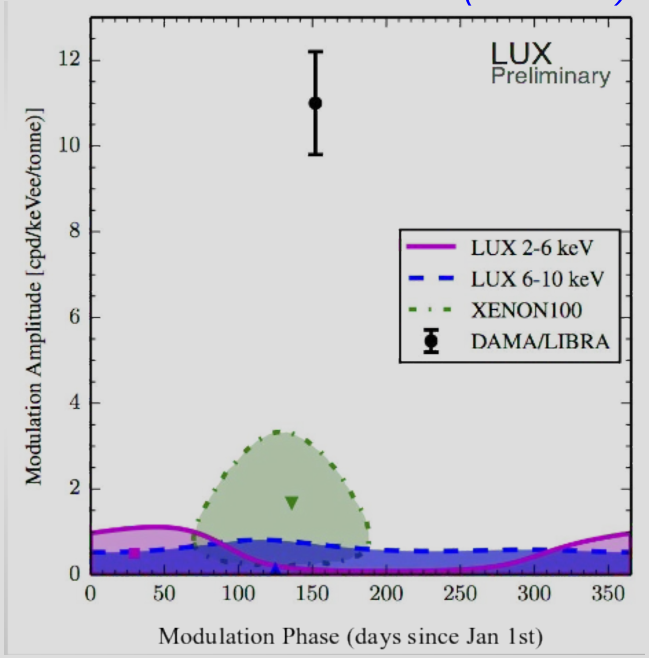
Annual Modulation Searches

XENON100: PRL 118, 101101 (2017)



- dark matter–electron scattering
- **2-phase LXe TPCs** operated stably over long periods
  XENON100: 4 years
  LUX: 2 years
- challenges DAMA/LIBRA
  XENON100: **5.7σ**
  LUX: ??

LUX: J. XU (UCLA DM)

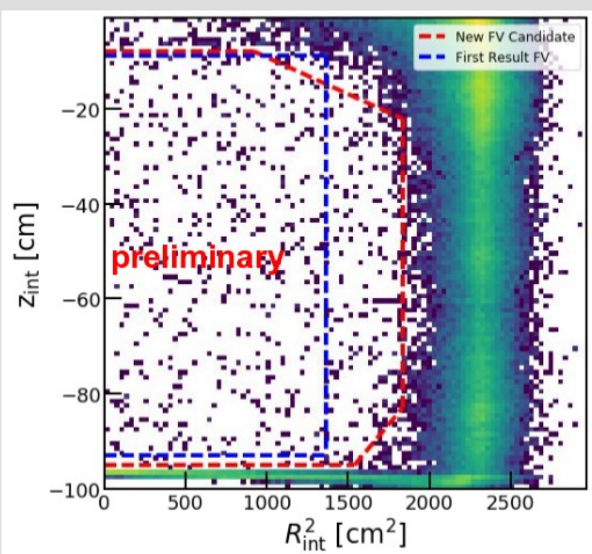


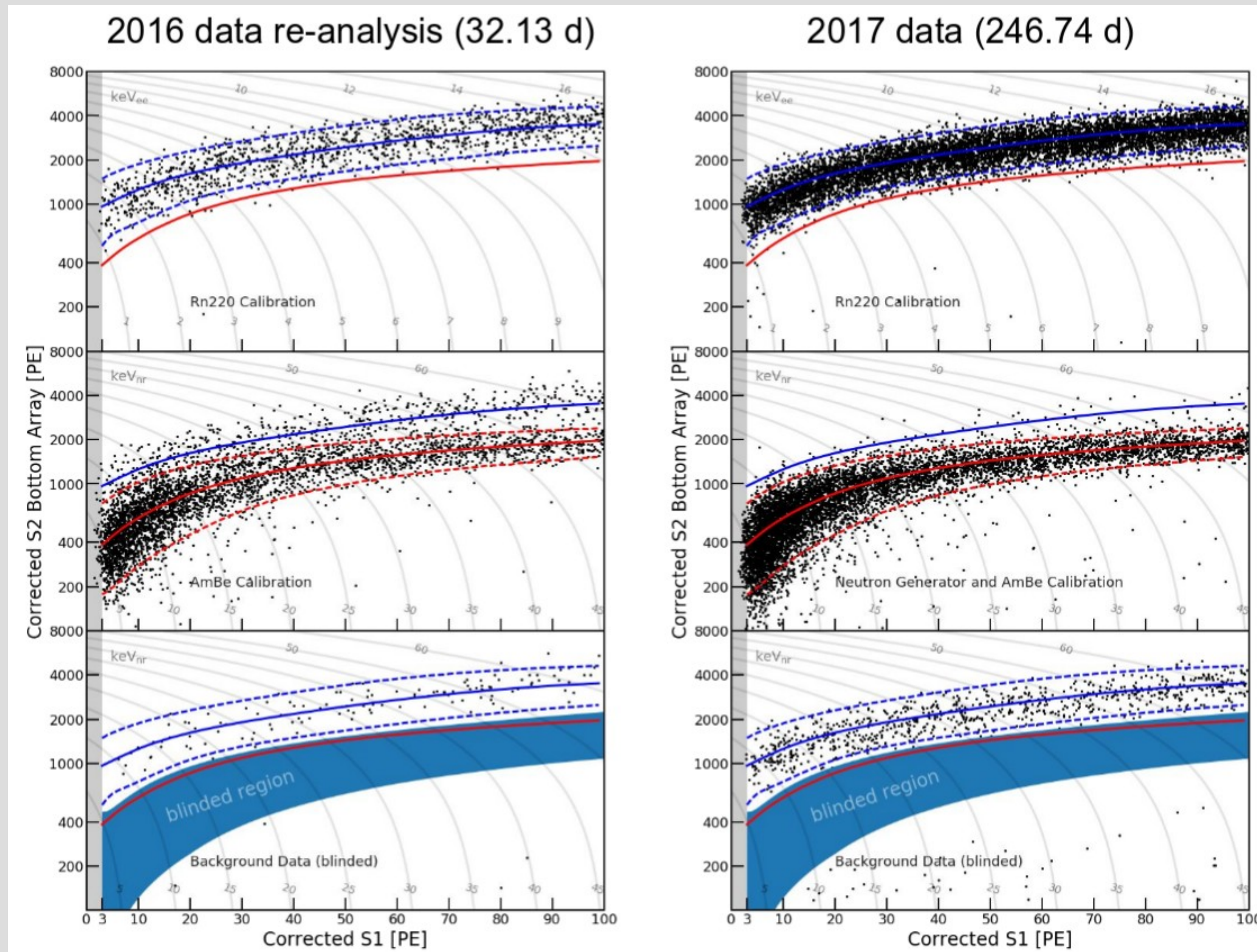
News from XENON1T

– release of new result soon
→ **8x more data than 2016**
→ 1 year of stable operation

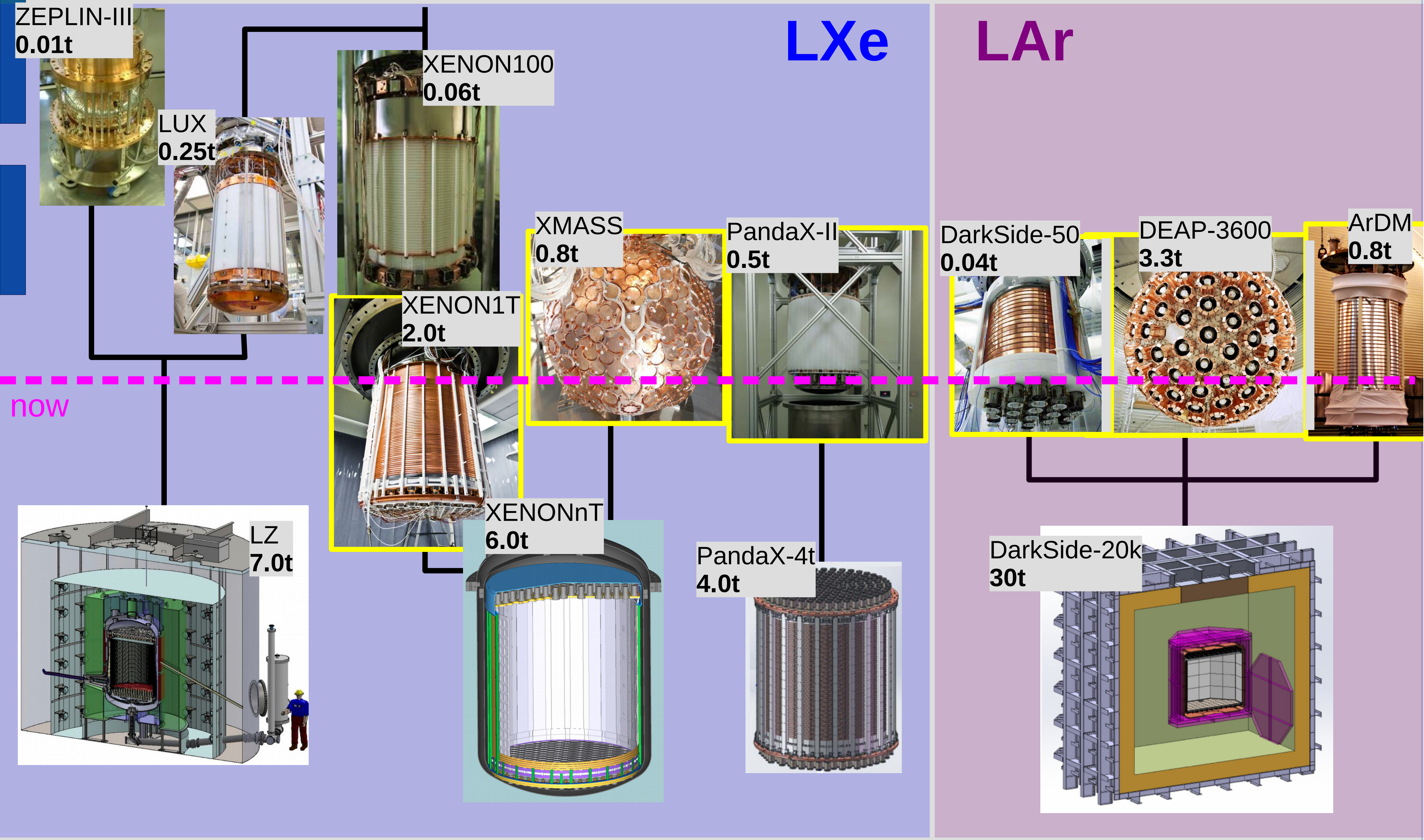
– larger FV: 1.0t → ~1.3t
→ event position in statistical interpretation

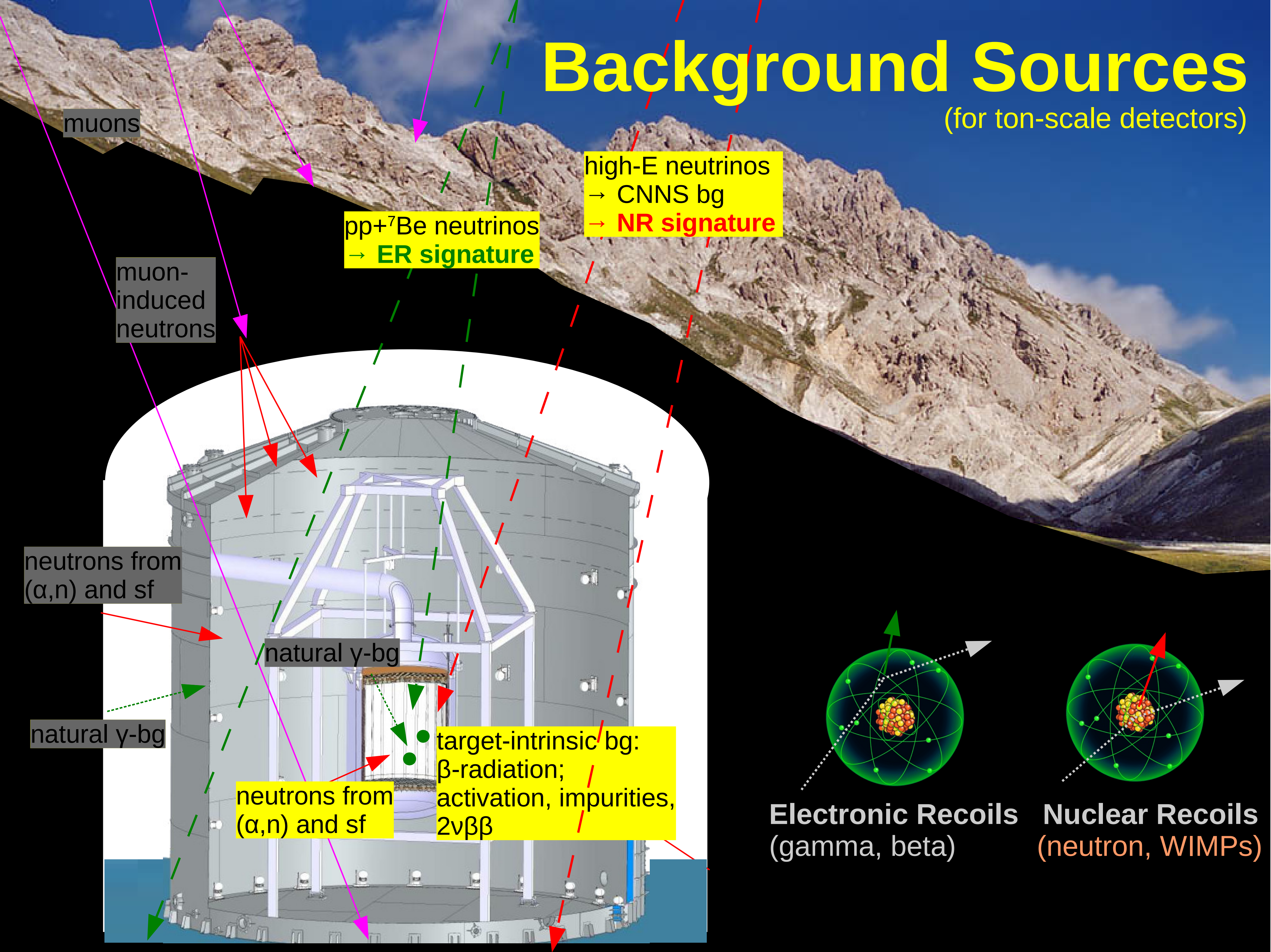
– ROI blinded and salted!





Consolidation of the Field




Background Sources
(for ton-scale detectors)
muons
muon-induced neutrons
pp+⁷Be 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:
β-radiation;
activation, impurities,
2νββ
Electronic Recoils
(gamma, beta)
Nuclear Recoils
(neutron, WIMPs)

Relevant Backgrounds

	LXe	LAr
Radioactivity Laboratory (ER, NR)	✘	✘
Muon-induced neutrons	✘	✘
Detector materials		
Gamma (ER)	✘	✘
Neutrons (NR)	✔	✔
Target Intrinsic isotopes (ER)		
^{39}Ar	–	✔
^{85}Kr	✔	✘
^{222}Rn	✔	✘
Neutrinos		
NR: ^{8}B, atmospheric	✔	✘ threshold too high for ^{8}B
ER: pp, ^{7}Be	✔	✘ ER rejection mandatory
Artefacts	??	??

– all experiments are underground and sufficiently shielded

– all TPCs employ fiducialization and multiple-scatter rejection

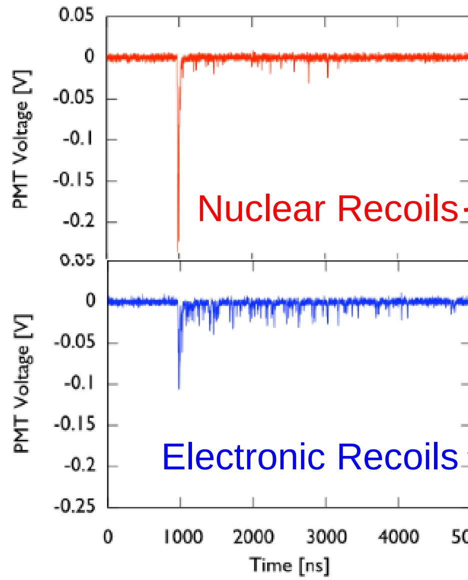
ER Background Rejection

Pulse shape discrimination (PSD):
Lifetimes of singlet and triplet states:

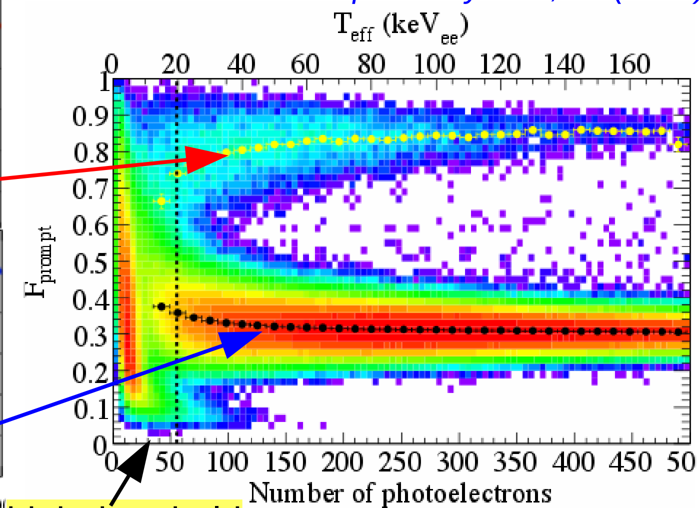
Ar: 5 ns, 1.6 μs
Xe: 4 ns, 22 ns

Ratio N_{trip}/N_{sing} depends on dE/dx
→ the interaction type

LAr: excellent ~3×10^{-8}
PRC 78, 035801 (2008)
LXe: irrelevant ~1×10^{-1}
NIM A 612, 328 (2010), arXiv:1803.07935



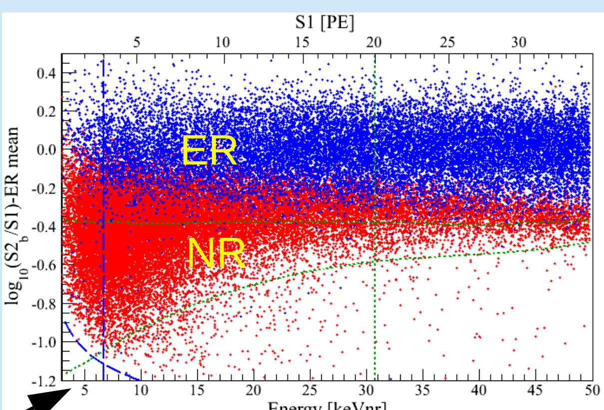
Astropart. Phys. 85, 23 (2016)



high threshold required

Charge-Light-Ratio (S2/S1):
Signal partition in light/charge depends on dE/dx → the interaction type

→ works for **LXe** and **LAr** (2-phase)
→ significant loss of acceptance



works down to low-E threshold

	E_{drift} [kV/cm]	LY @ 122 keV [PE/keV]	NR acc [%]	ER rej [%]
XENON100	0.53	3.8	40	2.5×10^{-3}
XENON100	0.53	3.8	30	1×10^{-3}
LUX	0.18	8.8	50	$1..10\times10^{-3}$
ZEPLIN-III	3.4	4.2	50	**1.3×10^{-4}**
K. Ni *APP14*	0.2-0.7	10	50	**$<1\times10^{-4}$**

Noble Liquid Targets

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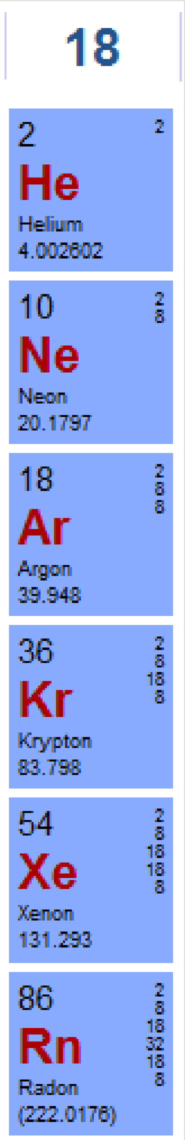
Atomic Number	54	18
Atomic mass	131.3	40.0
Boiling Point T_b [K]	165.0	87.3
Liq. Density @ T_b [g/cm^3]	2.94	1.40
Fraction in Atmosphere	0.09	9340
Price	$$$$	$ → $$$$
Scintillator	✔	✔
Scint. Wavelength [nm]	178	128
Ionizer	✔	✔
W (E to generate e-ion pair) [eV]	15.6	23.6
Scalability	✔	✔
Collaborations	4 → **3**	3 → **1**
Radioactive Isotopes	^{136}Xe (2νββ)	^{39}Ar (~1 Bq/kg)
ER Rejection	ok (2-phase only)	excellent
Odd Isotopes (→ SD couplings)	50% (^{129}Xe, ^{131}Xe)	✘

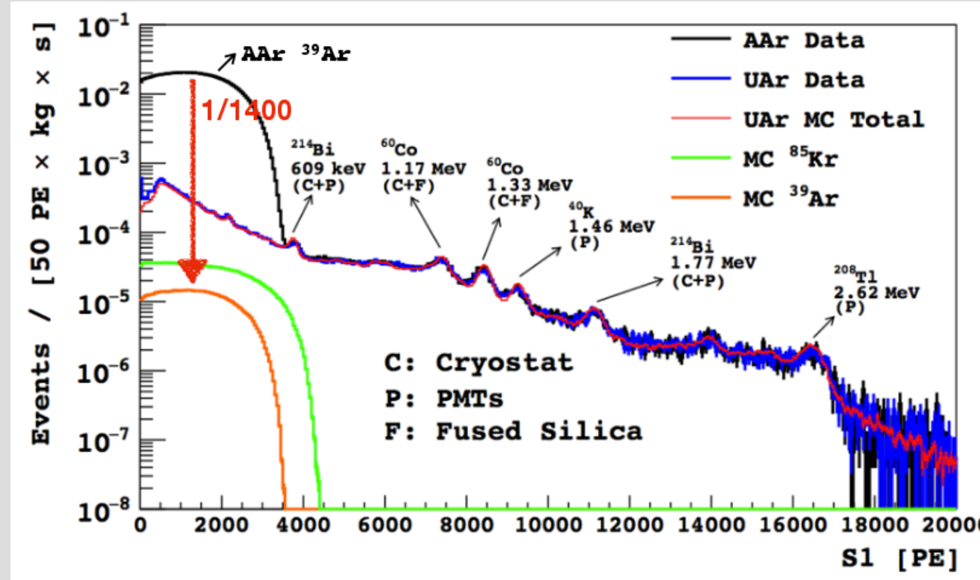


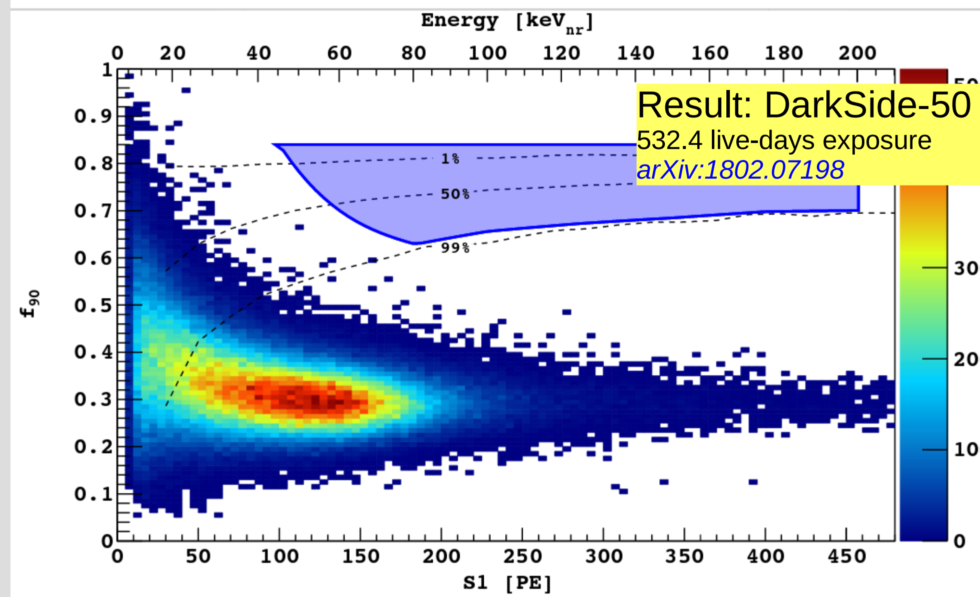
DarkSide: ^{39}Ar-depleted Argon

content: M. Wada, Moriond 2017

– extract underground Ar (UAr) in CO_2 well in Colorado
– cryogenic distillation @ FNAL

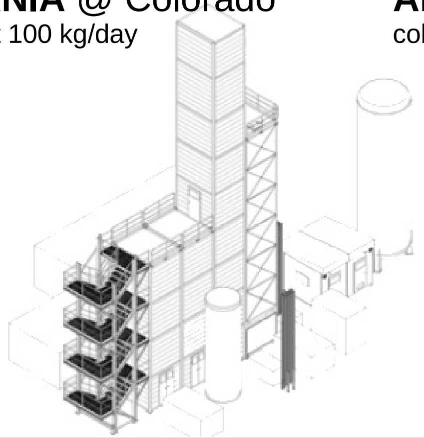
→ **^{39}Ar reduced by factor ~1400!**
→ 155 kg UAr produced in 6 years effort



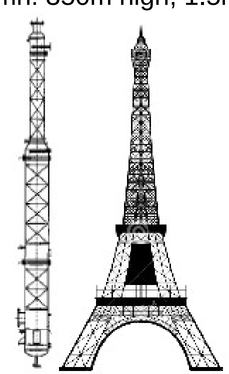


Future: mass-production planned

URANIA @ Colorado
extract 100 kg/day



Aria @ Sardegna
column: 350m high, 1.5m OD



content: M. Simeone (PNNL UAr Workshop 2018)

November 2017:
ARIA top+bottom+1 std module

Final: factor 10 ^{39}Ar reduction
(but lots of UAr lost)

LXe: Krypton Removal

Two methods: – cryogenic distillation (XMASS, XENON, PandaX)
– chromatography (LUX)

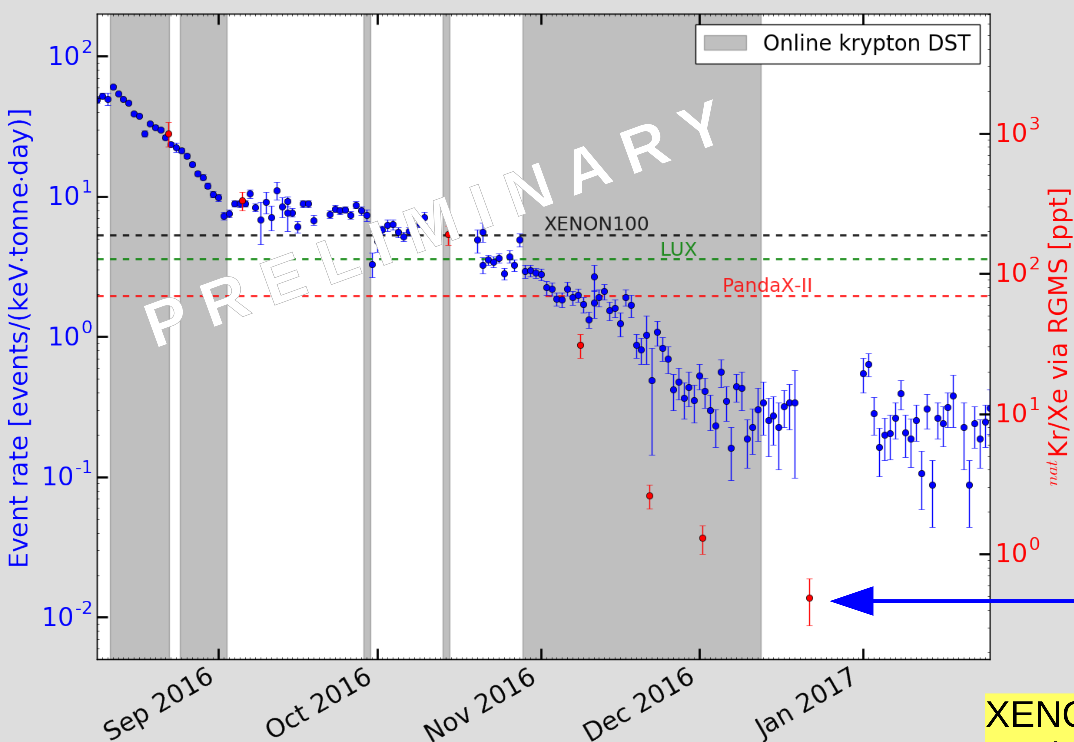
Example: **XENON1T**

goal: ^{nat}Kr/Xe = 0.2 ppt (below level of pp-neutrinos)

achieved by novel online distillation:

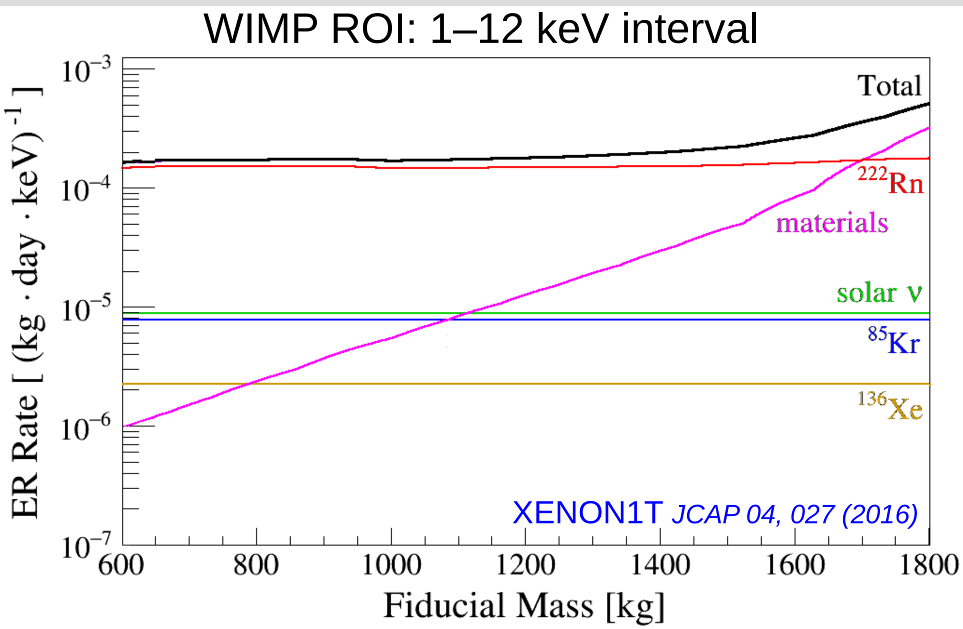
^{nat}Kr/Xe = (0.6±0.1) ppt achieved

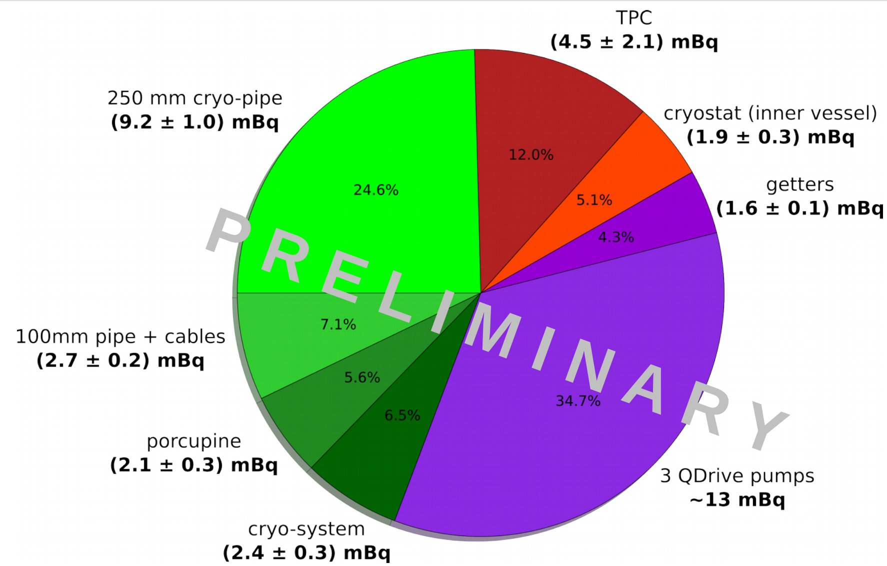
→ lowest value in LXe experiments ever



XENON1T column has produced a gas sample **<0.026 ppt** = 2.6×10^{-14} (90% CL)
→ 8x cleaner than needed

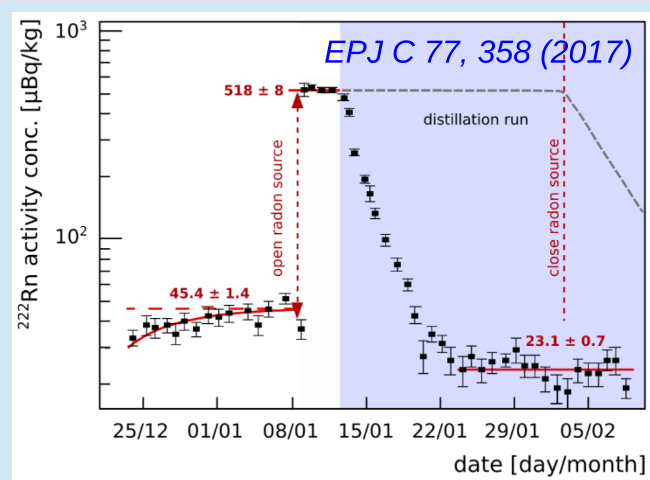
LXe: Radon Background





Current Strategy avoid Rn emanation by selecting clean materials

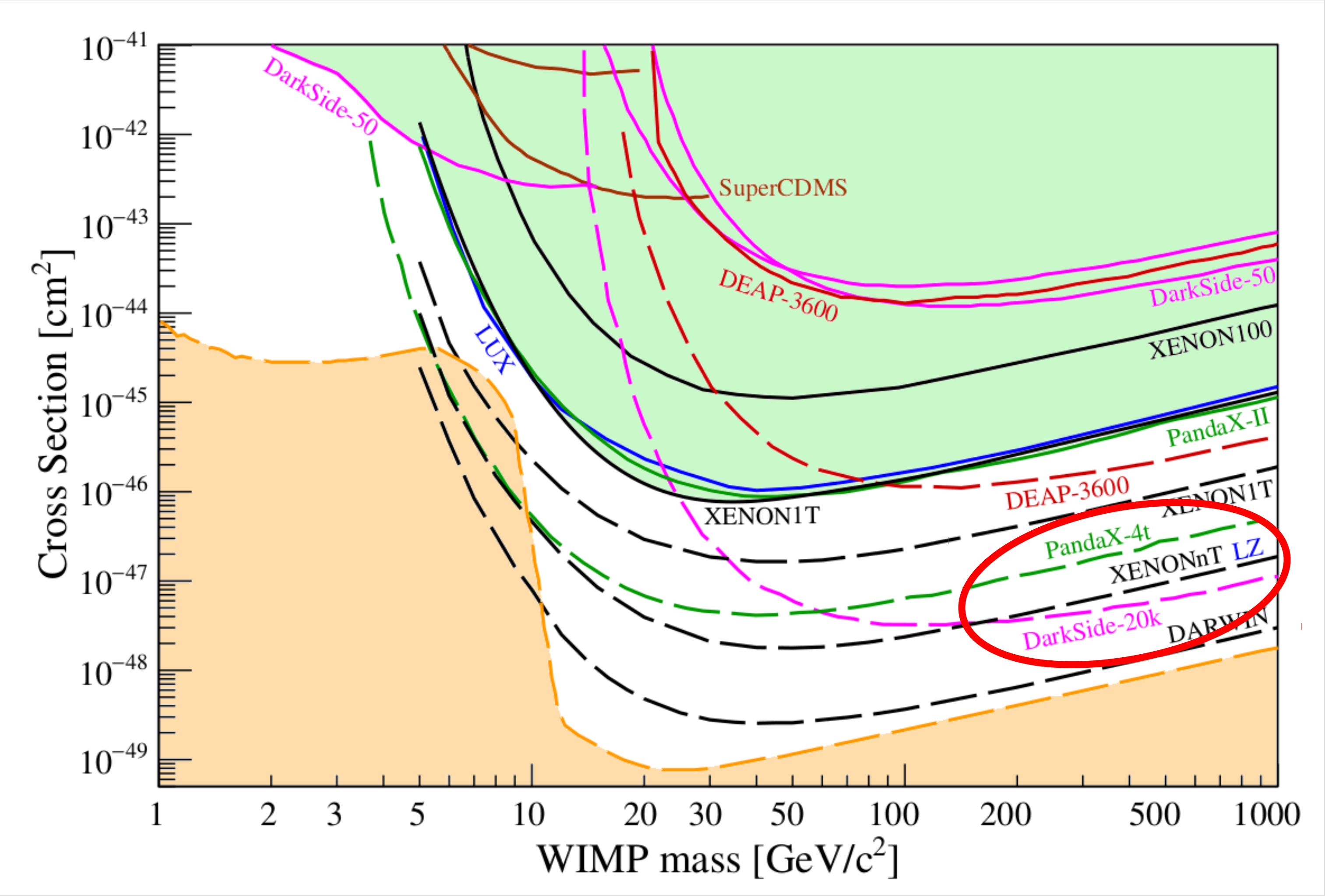
Example:	goal	10 µBq/kg
XENON1T	measured	**(11±2) µBq/kg** *prelim.*



Future Strategy XENONnT
– active Rn removal

– *Example*: **cryogenic distillation**
XENON1T distillation column installed @ XENON100
→ demonstrated **reduction factor >27** (@ 95% CL)

Upcoming Projects



some results are missing...

DarkSide-20k

G. Fiorillo @ UCLA-DM 2018

– scale up DS-50 by **factor 400**:

30t LAr total
20t fiducial

– focus on high-mass region >400 GeV/c^2

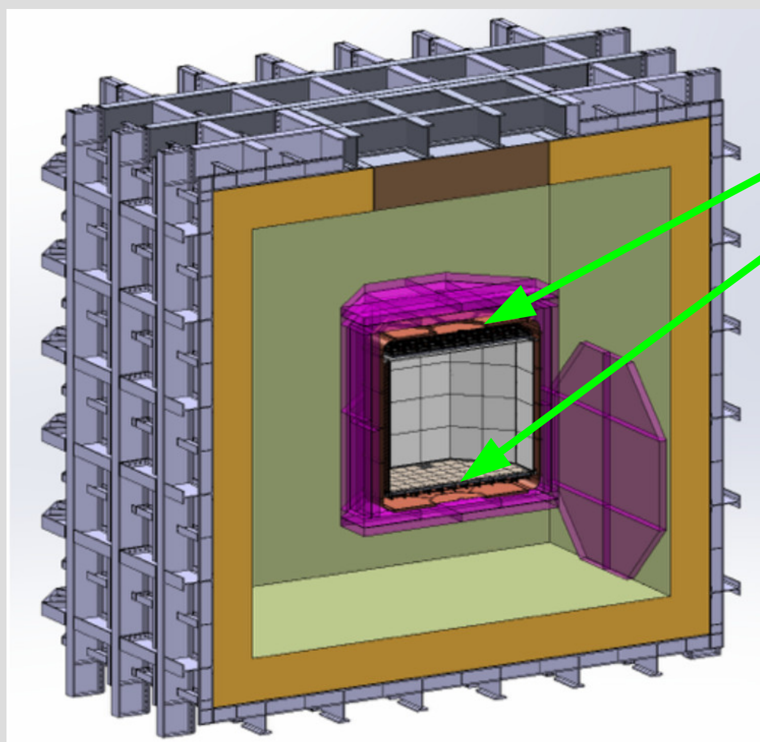
– keep strategy for background-free search with 100 t×y exposure

→ depleted underground Ar (URANIA+ARIA)

→ pulse-shape discrimination → high LY needed

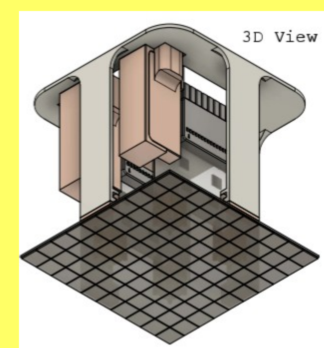
→ ~~liquid scintillator n-veto~~ → **NEW: LAr n-veto**

– start @ LNGS within 2021



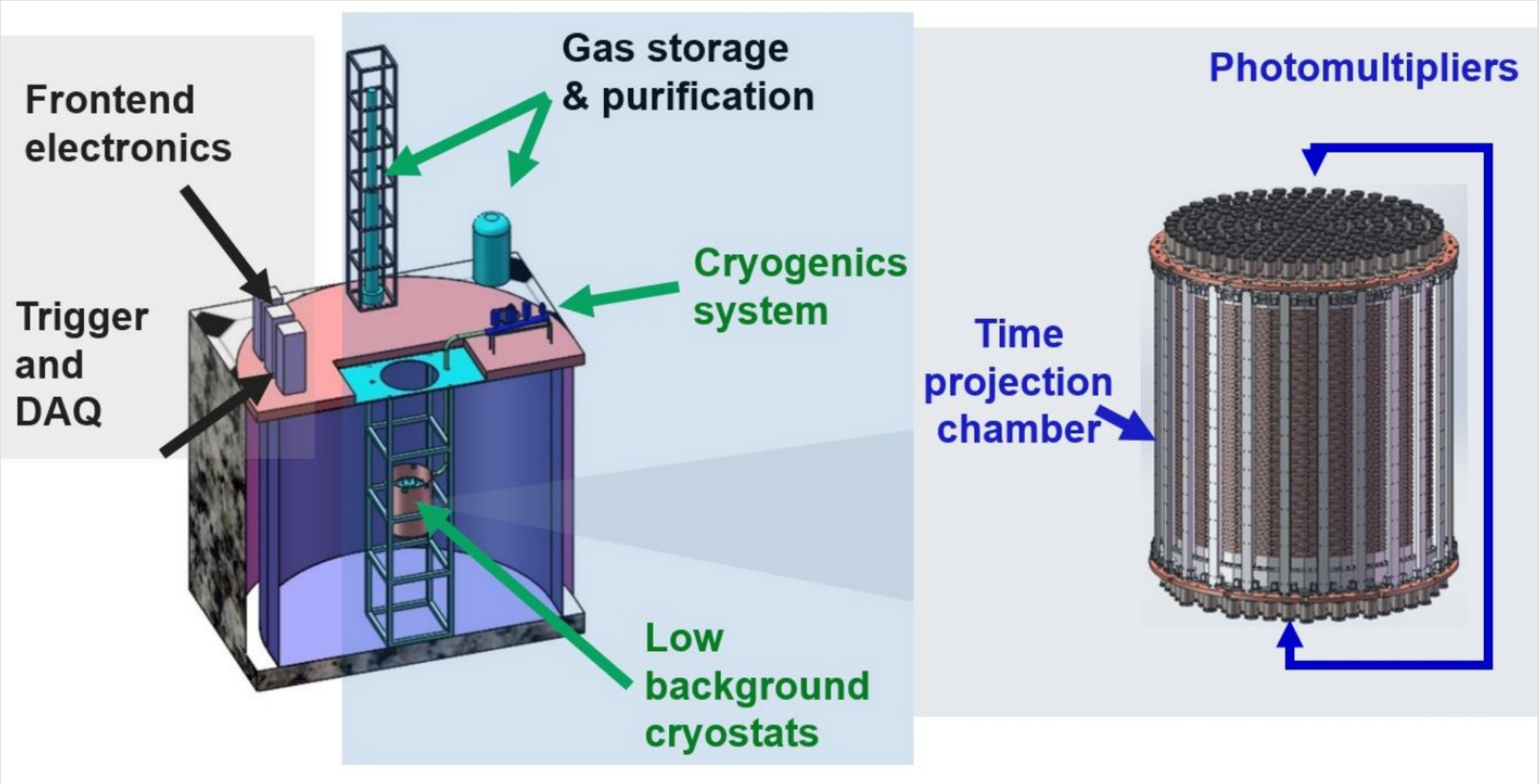
Readout by two arrays of grouped SiPMs:
14 m^2 total

Requirements:
– PDE: 45% ✔
– Dark Count Rate: 0.1 Hz/mm^2 ✔



PandaX-4t

J. Liu @ UCLA-DM 2018

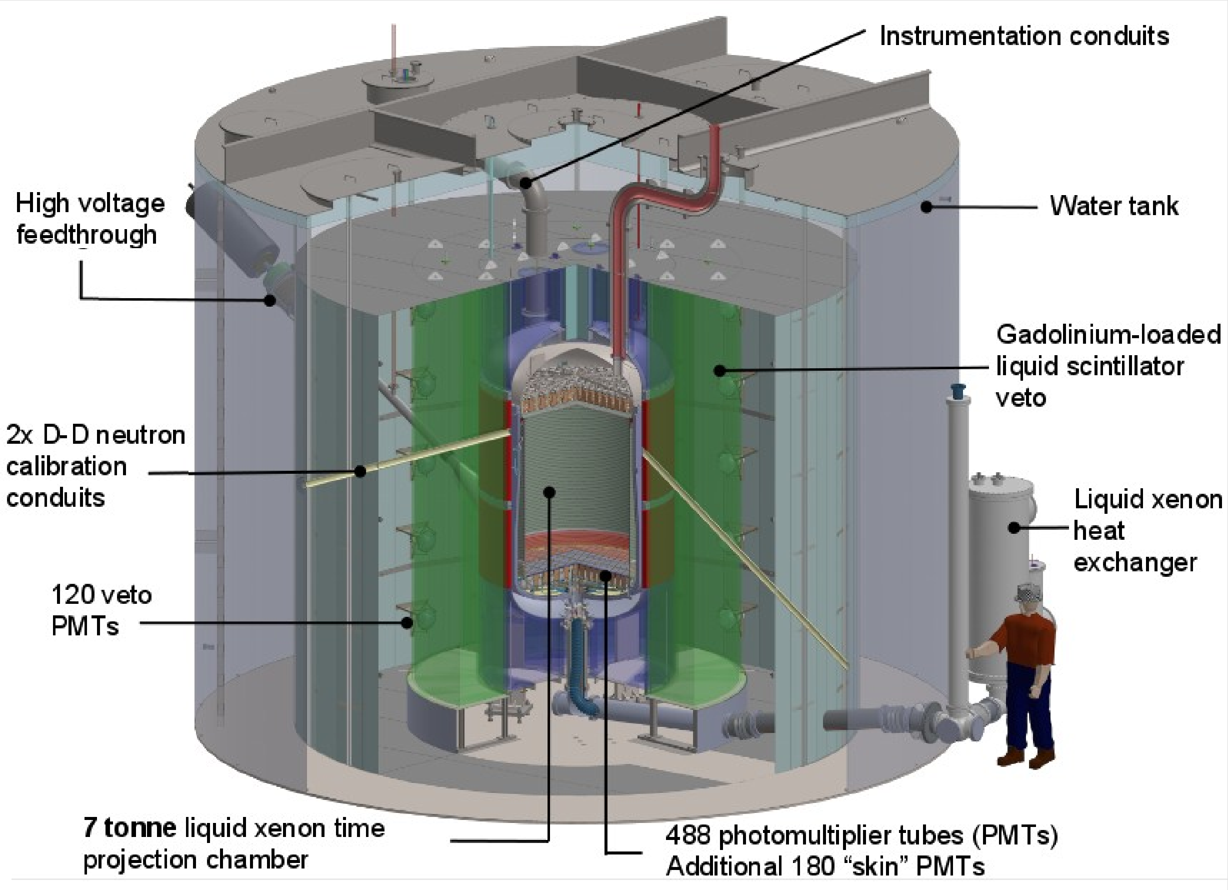


– to be installed at CJPL-II; scale-up by **factor 8**
– 4t LXe target with 10^{-47} cm^2 sensitivity to SI interactions
– assembly and commissioning: 2019-2020

LZ – LUX/ZEPLIN

arXiv:1703.09144

- **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,
- 488 R11410 PMTs
- *end 2019*: start cold commisioning
  spring 2020: first science data
- goal: 2×10^{-48} cm² @ ~50 GeV/c²
  after 15 t×y exposure



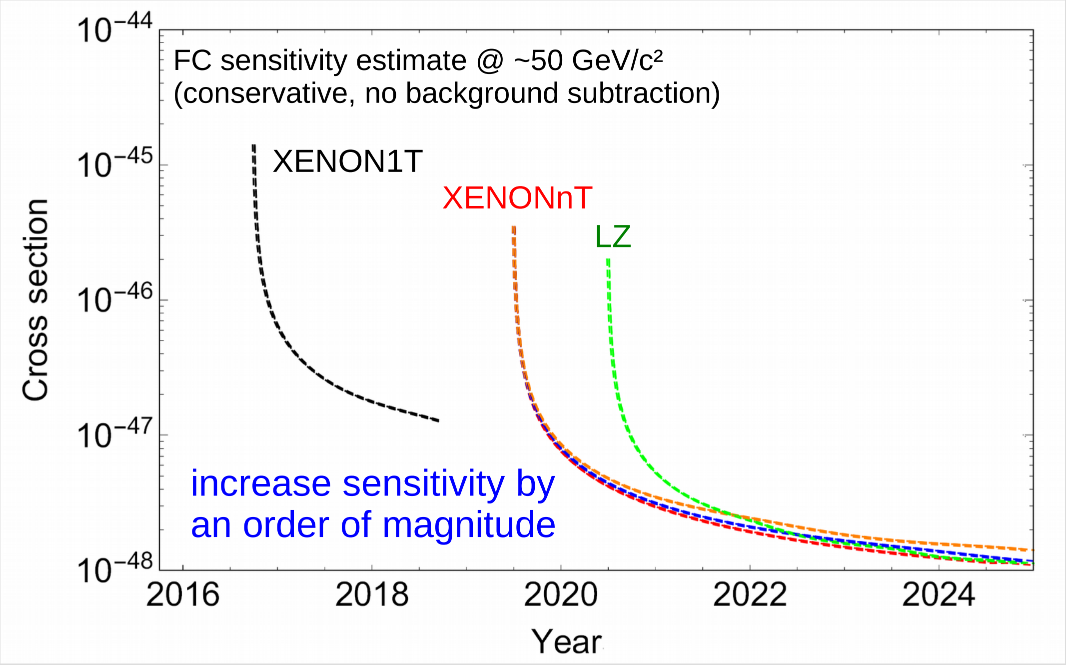
XENONnT

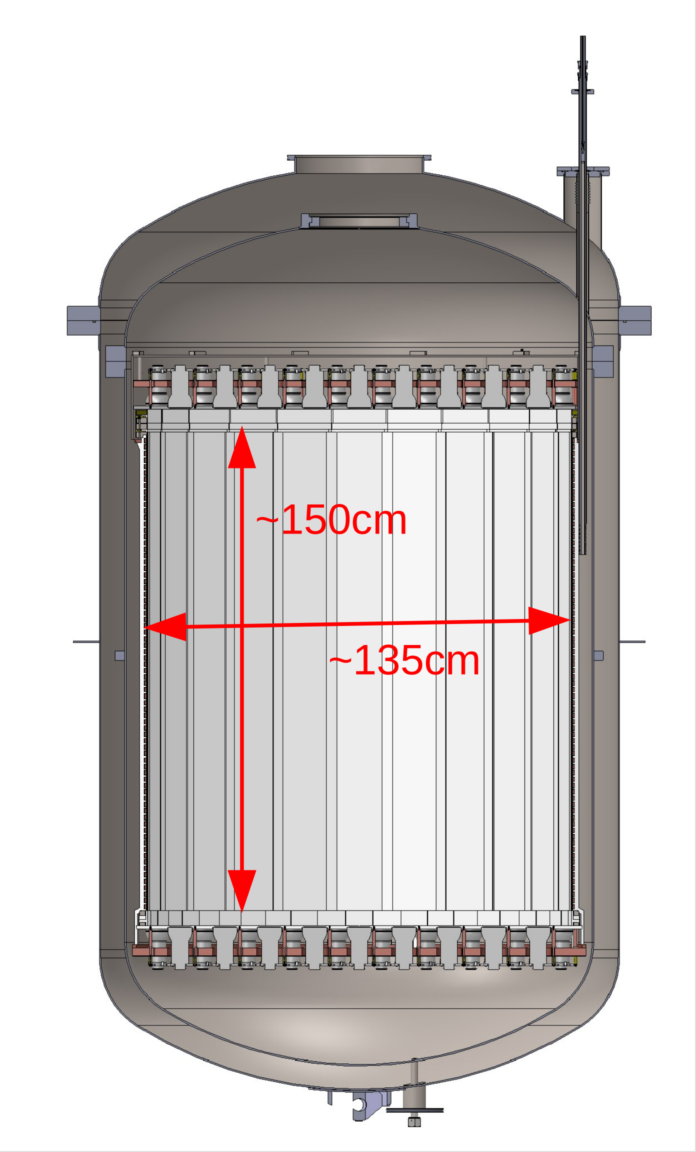
JCAP 04, 027 (2016)

- @ LNGS using existing XENON1T systems
  (existing µ-veto + new n-veto)
  → project funded!
- **3x larger** than XENON1T

6.0t active LXe target
~8t total mass

- 494 R11410 PMTs (XENON1T+new)
- start science by *mid 2019*
- goal: factor 10 better than XENON1T



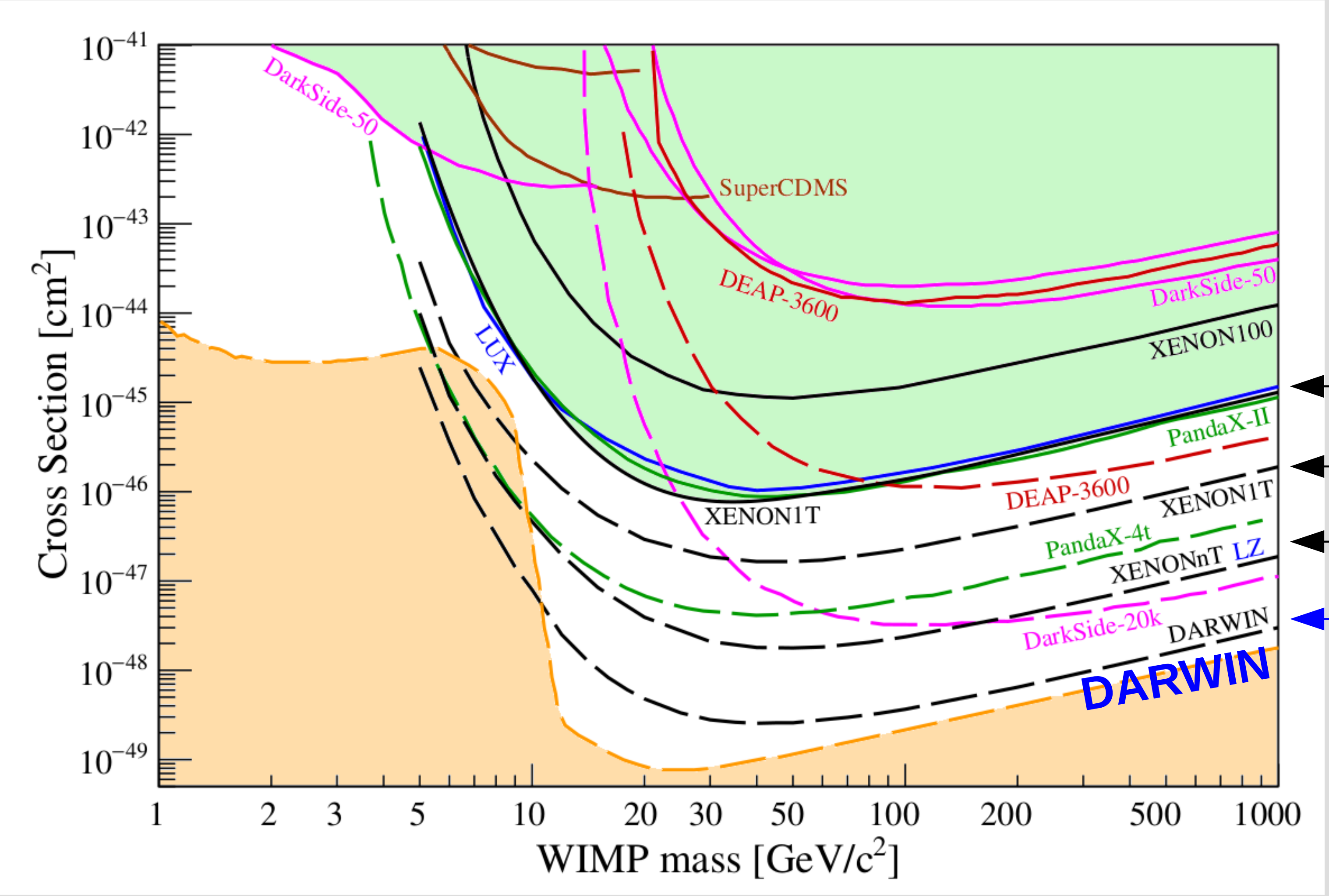


LZ information from: https://idm2016.shef.ac.uk/indico/event/0/contribution/69/material/slides/0.pdf

DARWIN The **ultimate** WIMP Detector

LXe-based

darwin-observatory.org



Exposure
0.1 t×y
2 t×y
20 t×y
200 t×y

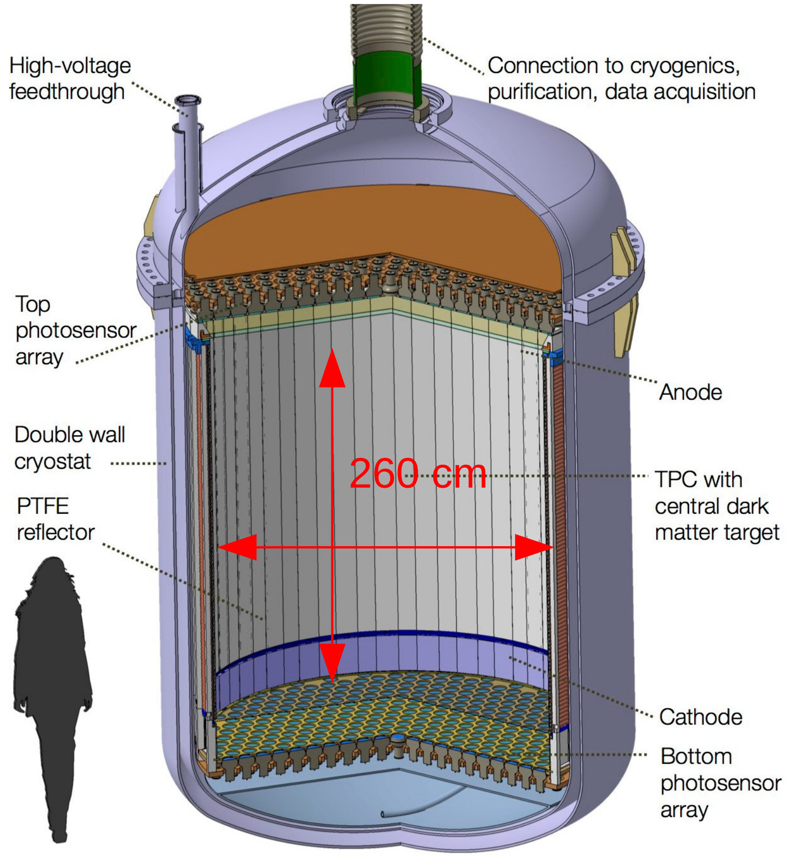
DARWIN The ultimate WIMP Detector

JCAP 11, 017 (2016)

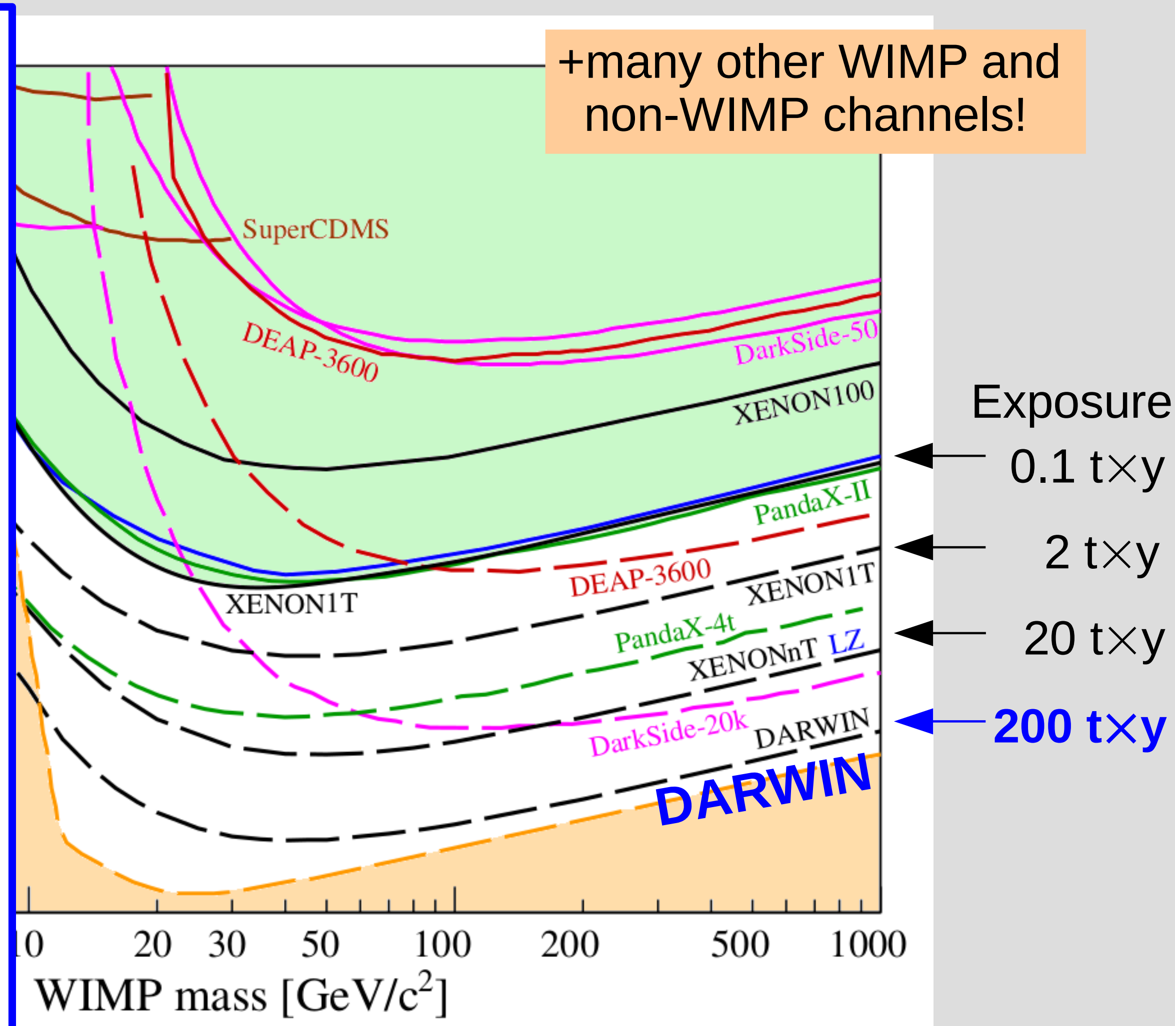
LXe-based

darwin-observatory.org

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

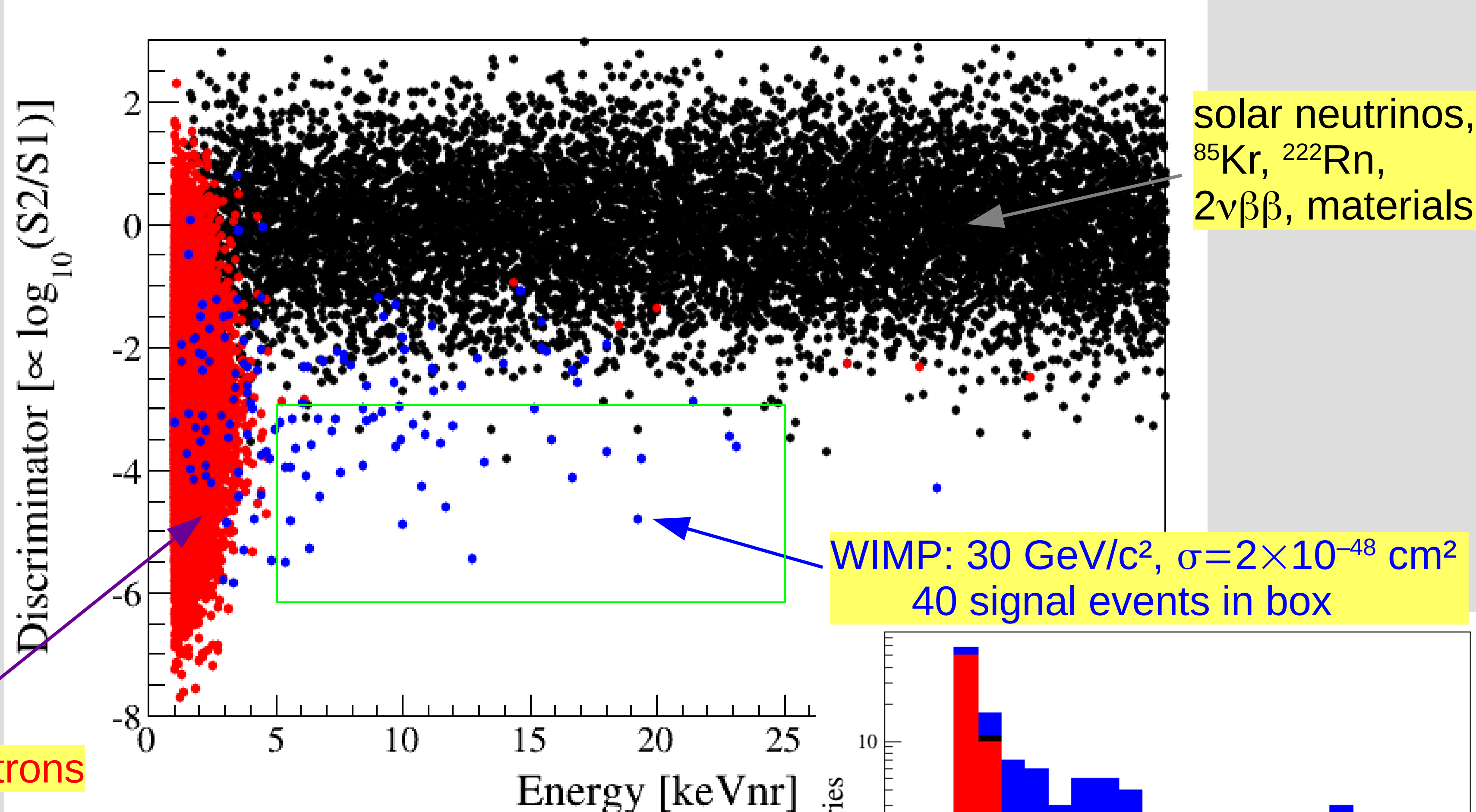


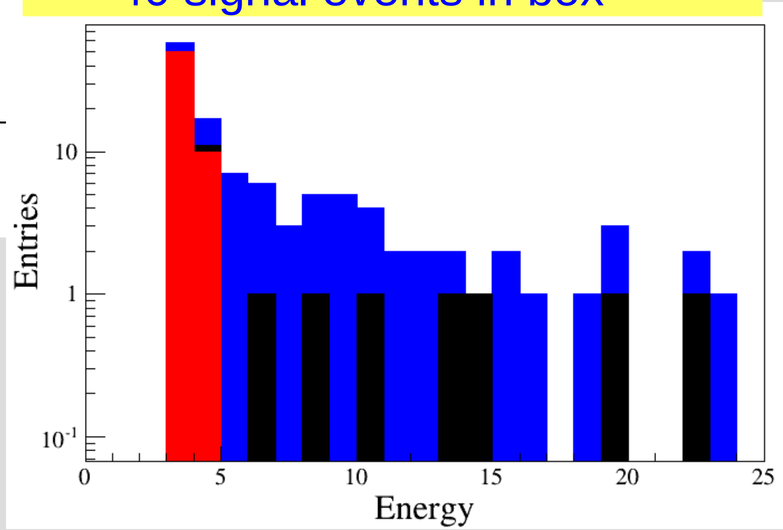
+many other WIMP and non-WIMP channels!



WIMP Detection

Backgrounds from JCAP 10, 016 (2015)

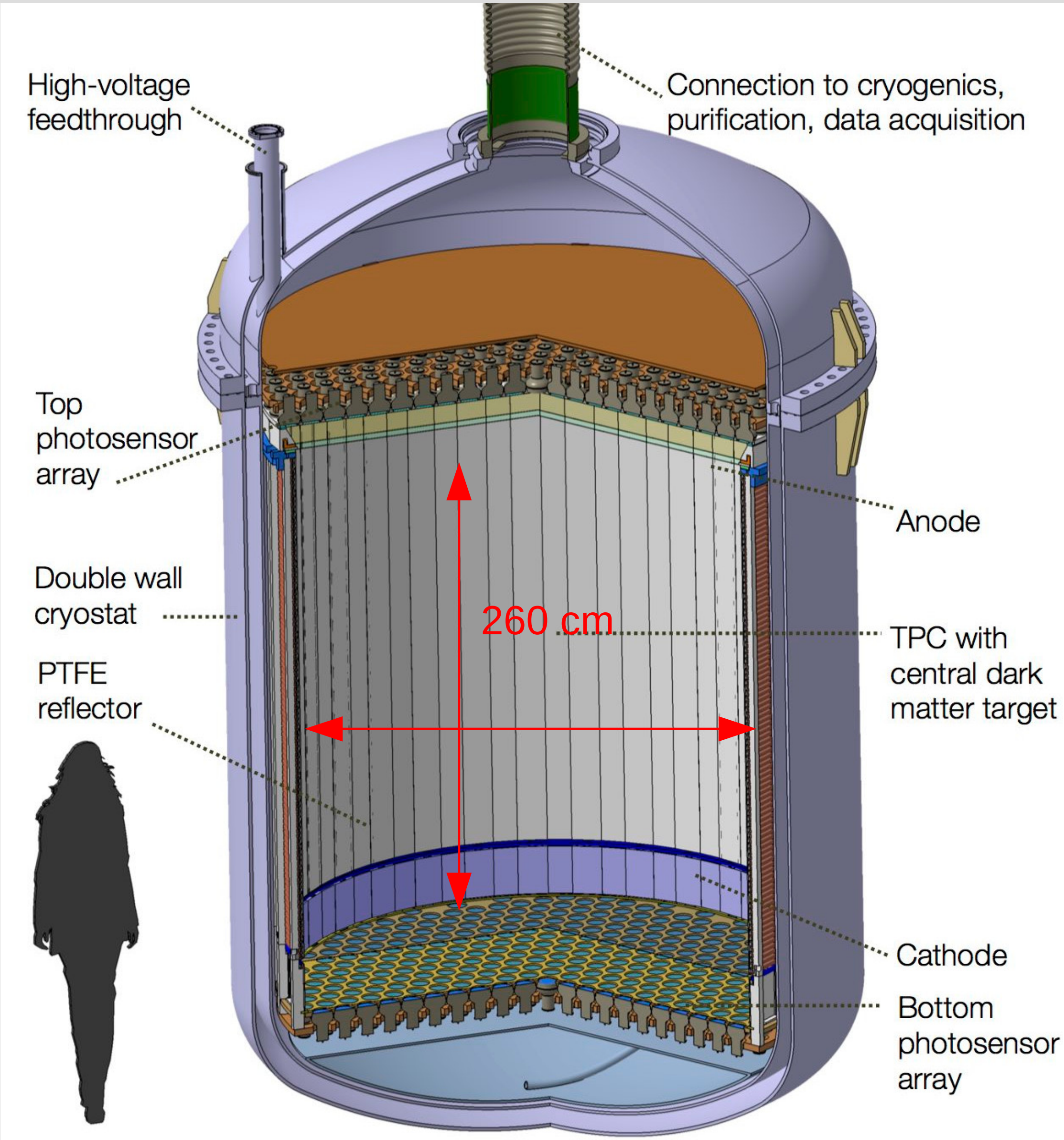




DARWIN The **ultimate** WIMP Detector

JCAP 11, 017 (2016)

darwin-observatory.org



Challenges

- Size
  - → electron drift (HV)
  - → diameter (TPC electrodes)
  - → mass (LXe purification)
  - → dimensions (radioactivity)
  - → detector response (calibration, corrections)
- Backgrounds
  - → ^{222}Rn: factor 100 required
  - → (α,n) neutrons (from PTFE)
- Photosensors
  - → high light yield (QE)
  - → low radioactivity
  - → long-term stability
- etc etc

R&D needed

erc ULTIMATE (Schumann, FR)

erc Xenoscope (Baudis, ZH)

Outlook: Lots of Science!

Large LXe TPC

LXe

Nuclear Recoil Interactions

WIMP dark matter *JCAP 10, 016 (2015)*
– spin-independent mid/high mass
– spin-dependent *Phys.Dark Univ. 9-10, 51 (2015)*
→ complementary with LHC, indirect det.
– various inelastic models (χ, n, MiDM, …)

Coherent neutrino-nucleon scattering (CNNS)
– ^{8}B neutrinos (low E), atmospheric (high E)
– supernova neutrinos *JCAP 1611, 017 (2016)*
PRD 89, 013011 (2014), PRD 94, 103009 (2016)

Electronic Recoil Interactions

Non-WIMP dark matter and neutrino physics
– axions, ALPs *JCAP 1611, 017 (2016)*
– sterile neutrinos
– pp, ^{7}Be: precision flux measurements
<1% *JCAP 01, 044 (2014)*

Rare nuclear events
– 0νββ (^{136}Xe), 2νEC (^{134}Xe), ... *JCAP 01, 044 (2014)*

Large LAr TPC

LAr

Nuclear Recoil Interactions:

WIMP dark matter
– spin-independent high mass

Coherent neutrino-nucleon scattering (CNNS)
– atmospheric (high E)

Electronic Recoil Interactions

Non-WIMP dark matter and neutrino physics

– ^{7}Be, pep , CNO flux measurements
2% 10% 15%
JCAP 1608, 017 (2016)

Backup

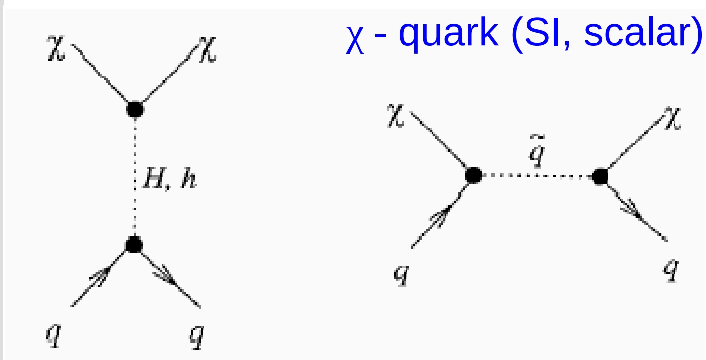
WIMP-Nucleon Interactions

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

Parametrization of interactions leading to WIMP-nucleus scattering:

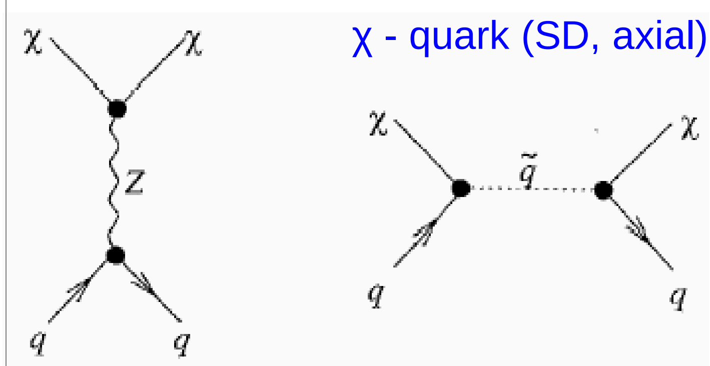
coupling to **nucleons** | coupling to **nuclear spin**

Spin independent



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

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

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

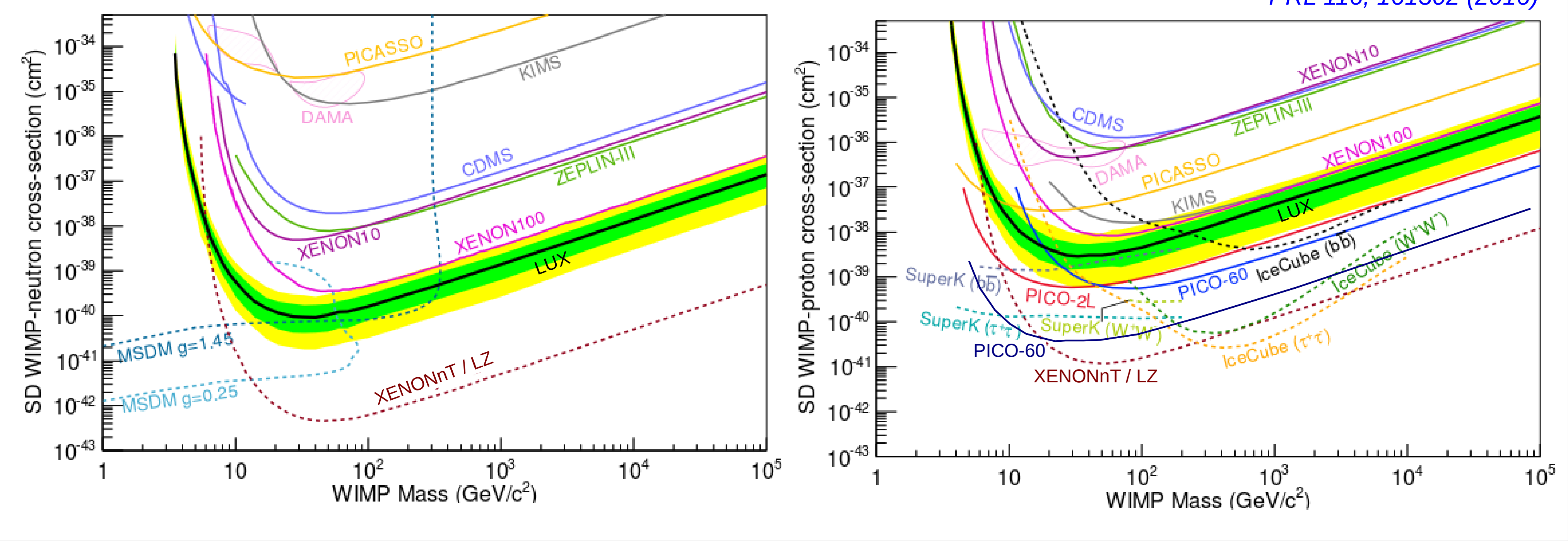
$$C_{spin} = \frac{8}{\pi}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 \frac{J+1}{J}$$

Spin-dependent WIMP Couplings

WIMP-neutron scattering:
– dominated by **LXe TPCs**
– also: Ge, NaI, CsI, CF_3I, C_3F_8

WIMP-proton scattering:
– dominated by **bubble chambers** (CF_3I, C_3F_8)
– also: Xe, NaI, CsI

PRL 116, 161302 (2016)



excellent complementarity to **LHC searches** (ATLAS, CMS)

excellent complementarity to **indirect searches** (IceCube, SuperK)