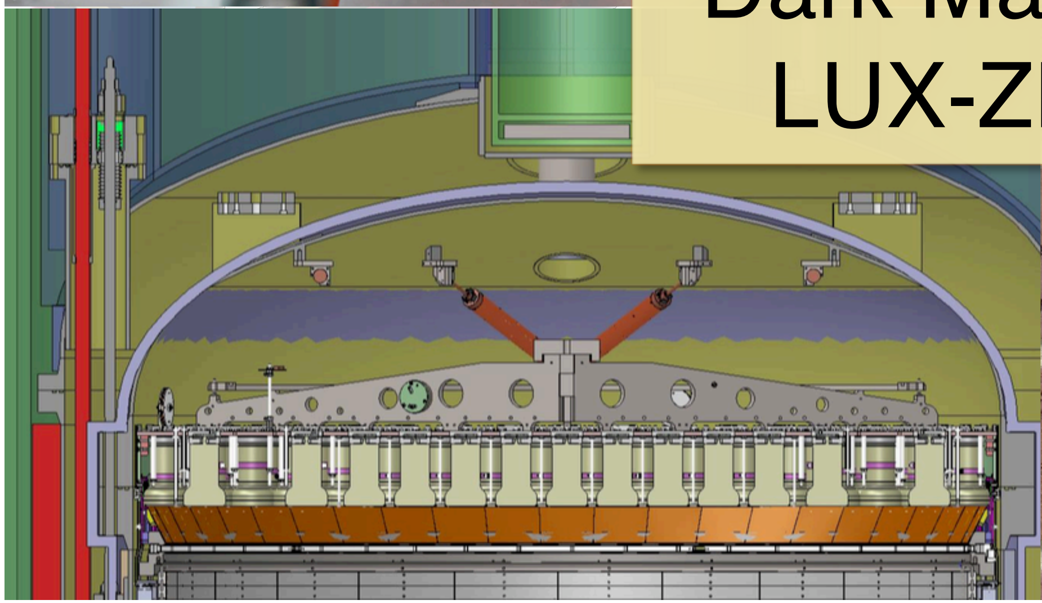
Direct Searches for Dark Matter with LUX-ZEPLIN

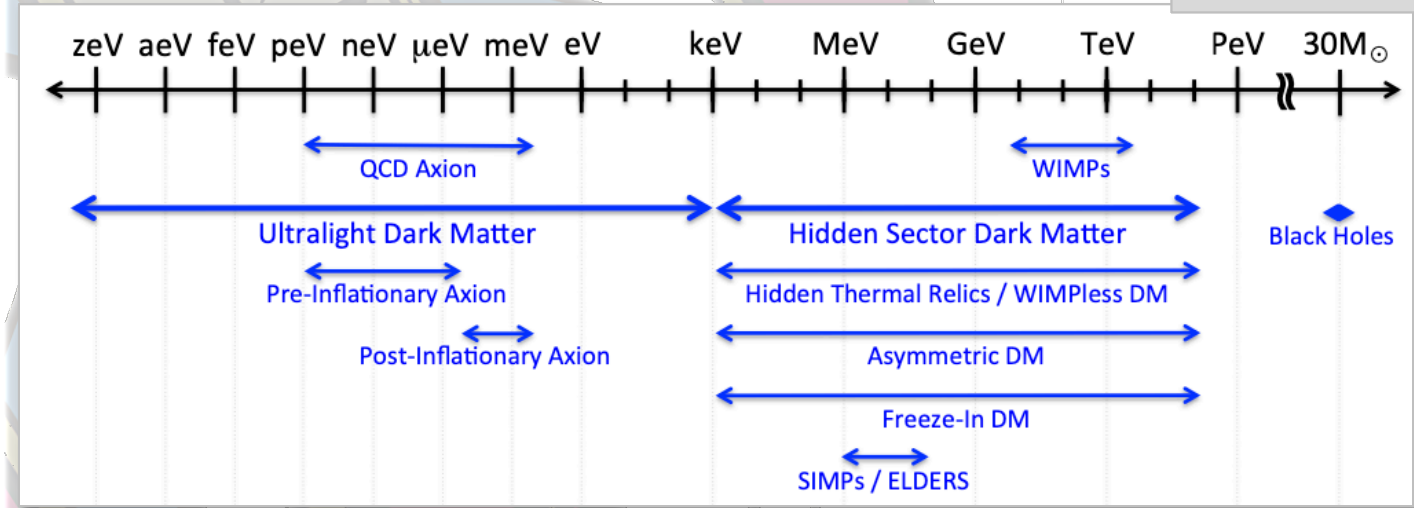


LZ UK

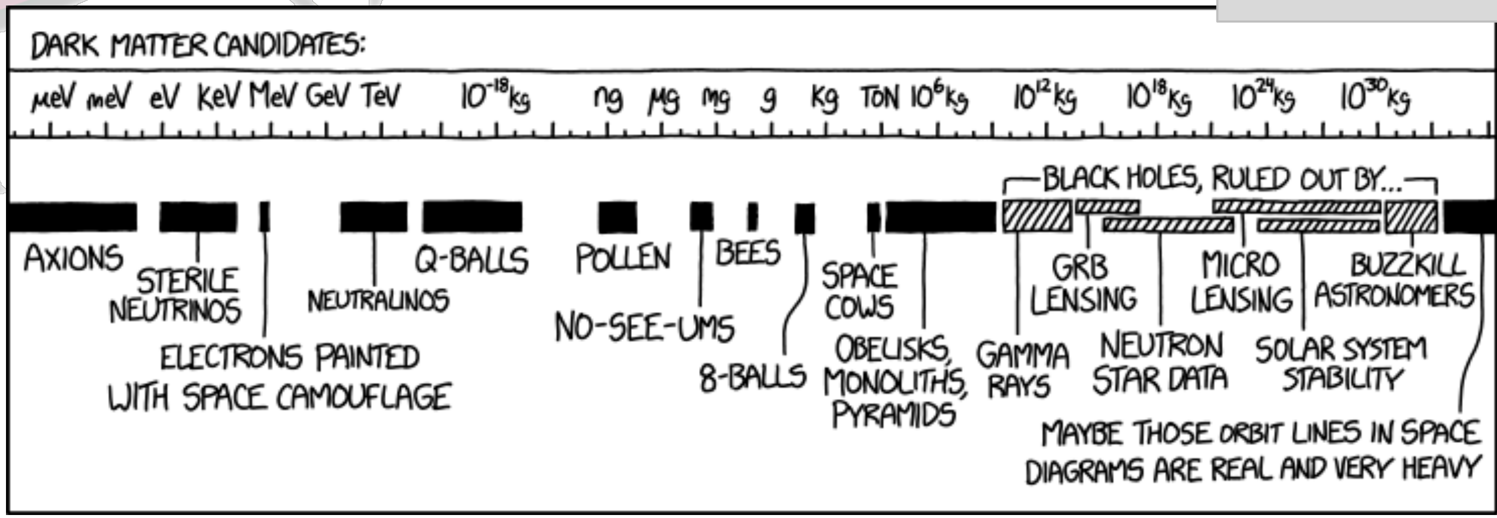
University of Bristol · The University of Edinburgh · Imperial College London · University of Liverpool · University of Oxford · Particle Physics Rutherford Appleton Laboratory · Royal Holloway University of London · The University of Sheffield · UCL

What are we looking for?

Cosmic Visions report (2017)

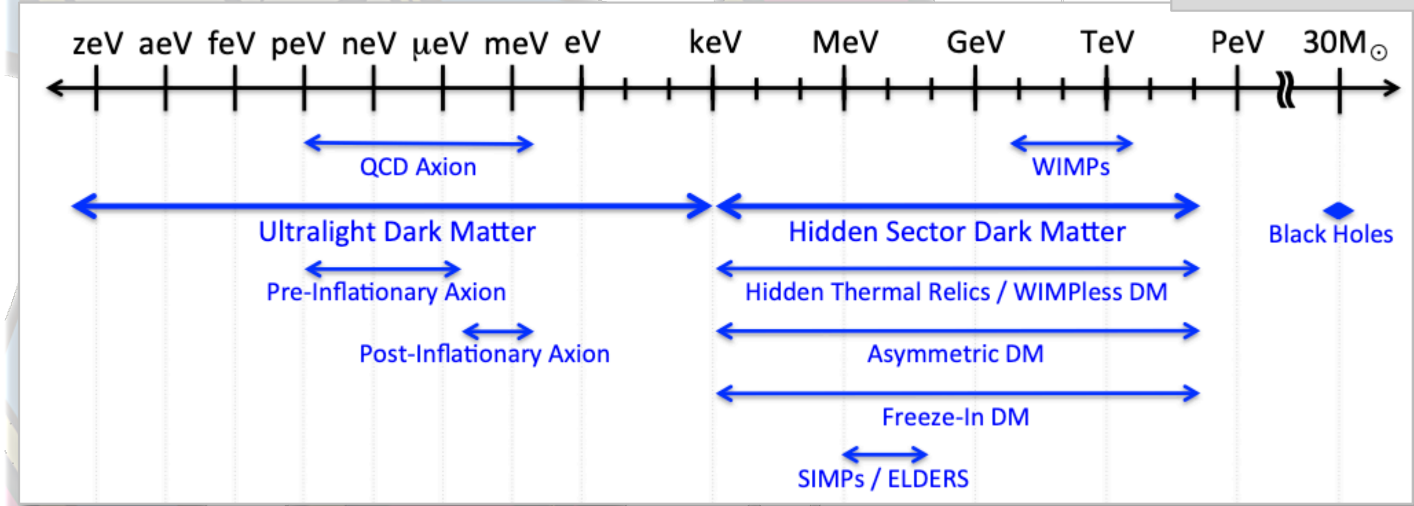


xkcd:2035



What are we looking for?

Cosmic Visions report (2017)



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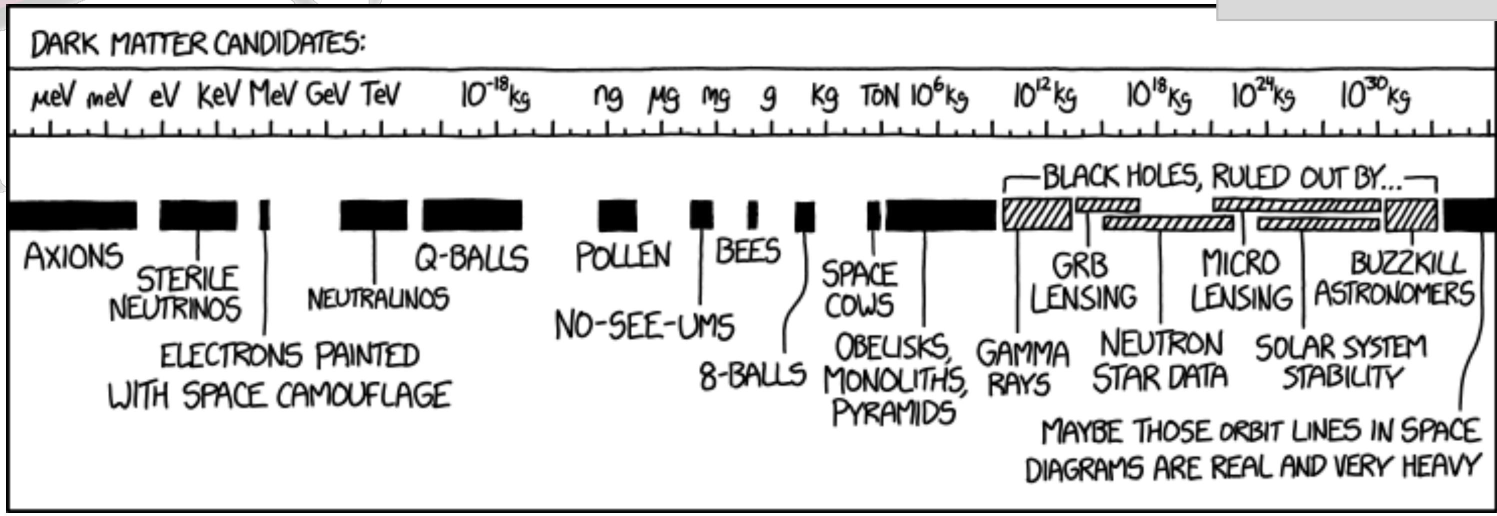
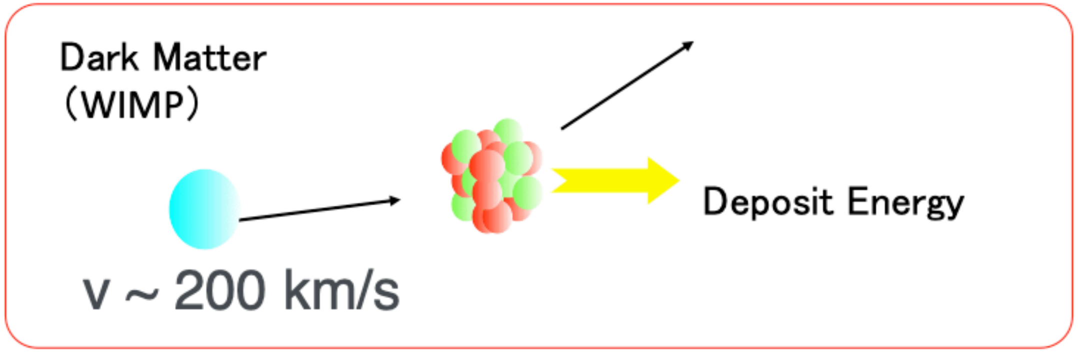


→ Strong incentive for searches to be as broad as possible


Arcturus
Deneb
Vega
Mars
Mercury
Altair
Sun
Antares
S
E
Iupiter
Right Now



$$\frac{dR}{dE_R} = R_0 F^2(E_R) \frac{1}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbb{v}, \mathbb{v}_E) d^3\mathbb{v}$$

Nuclear form factor

Astrophysics

$$R_0 = \frac{377}{M_\chi M_N} \left(\frac{\sigma_0}{1pb}\right) \left(\frac{\rho_D}{0.3\frac{GeV}{c^2}cm^{-3}}\right) \left(\frac{v_0}{230kms^{-1}}\right) kg^{-1} d^{-1}$$

SI

$$\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$$

SD

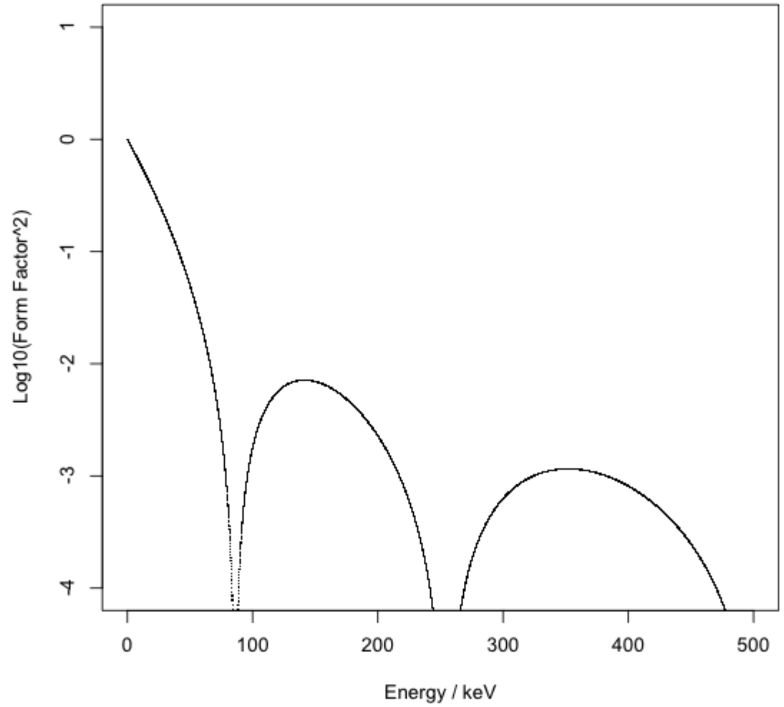
$$\sigma_0 = \frac{\lambda_{N,Z}^2}{\lambda_{p,Z}^2} \frac{J(J+1)^{Nuclear}}{J(J+1)^{proton}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$$

Other…

(Helm) Form Factor

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)} e^{-(qs)^2/2}$$

Relatively little uncertainty



(Helm) Form Factor

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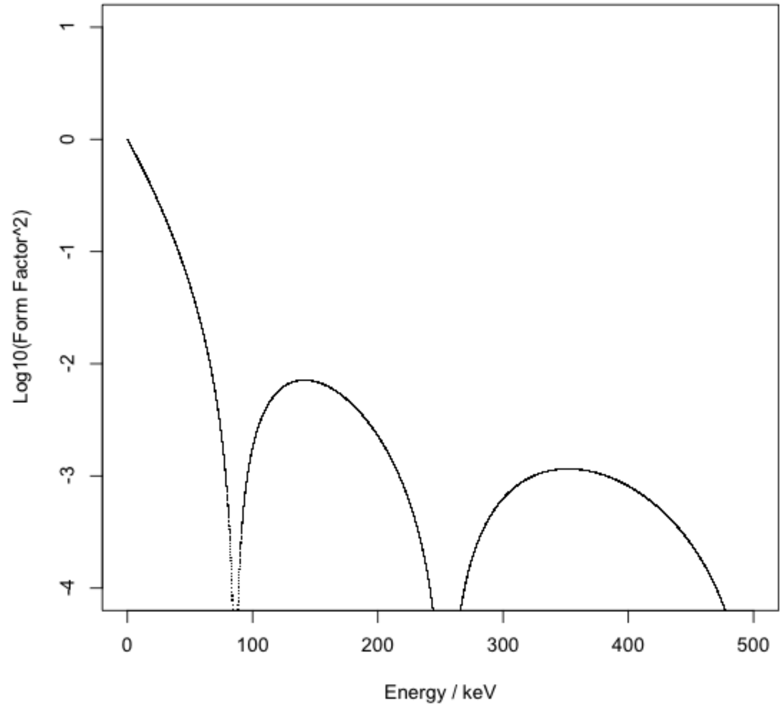

Relatively little uncertainty

Astrophysics…

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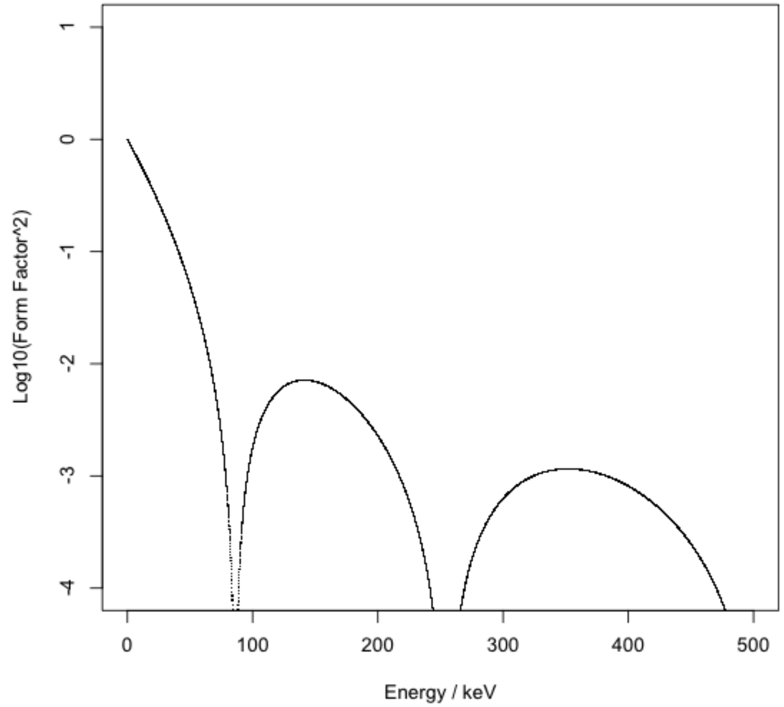
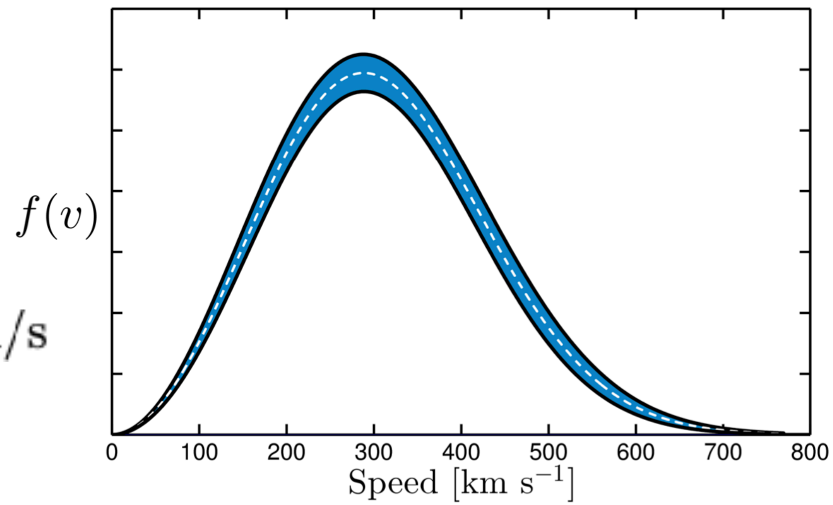


Relatively little uncertainty

Standard Halo Model

$$f(\mathbf{v}) = \frac{N}{2\pi\sigma_v^2}\exp\left(-\frac{\mathbf{v}^2}{2\sigma_v^2}\right)$$

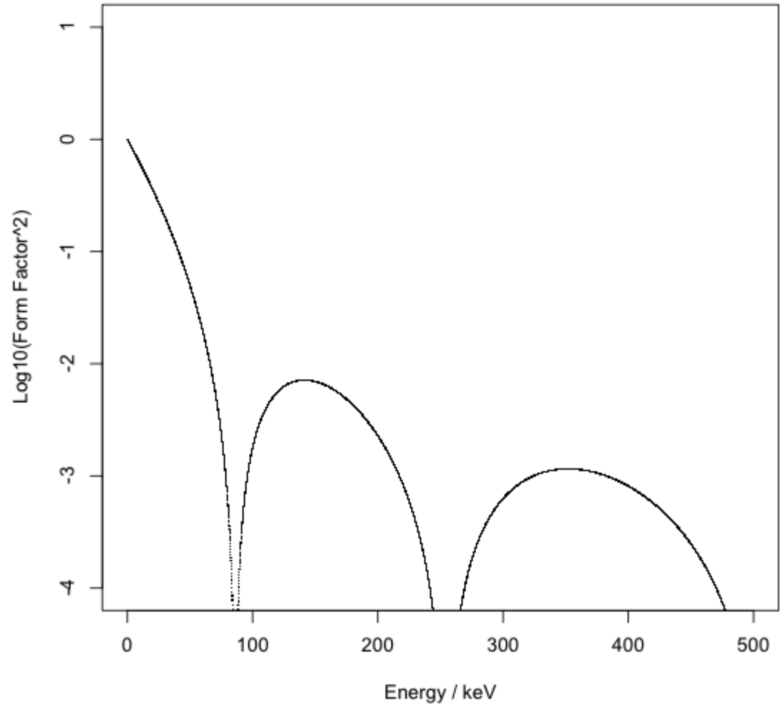
$\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}}$ $v_0 = 220\,\mathrm{km/s}$ $v_{esc} = 544\,\mathrm{km/s}$



Significant uncertainty

(Helm) Form Factor

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)} e^{-(qs)^2/2}$$



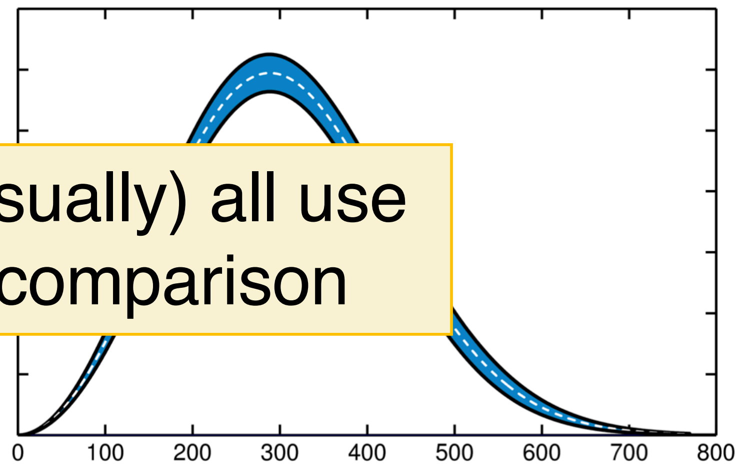
Relatively little uncertainty

Standard Halo Model

$$f(\mathbf{v}) = \frac{N}{\ \ } \left(\ \ \mathbf{v}^2 \right)$$

But experiments at least (usually) all use the same model to allow comparison

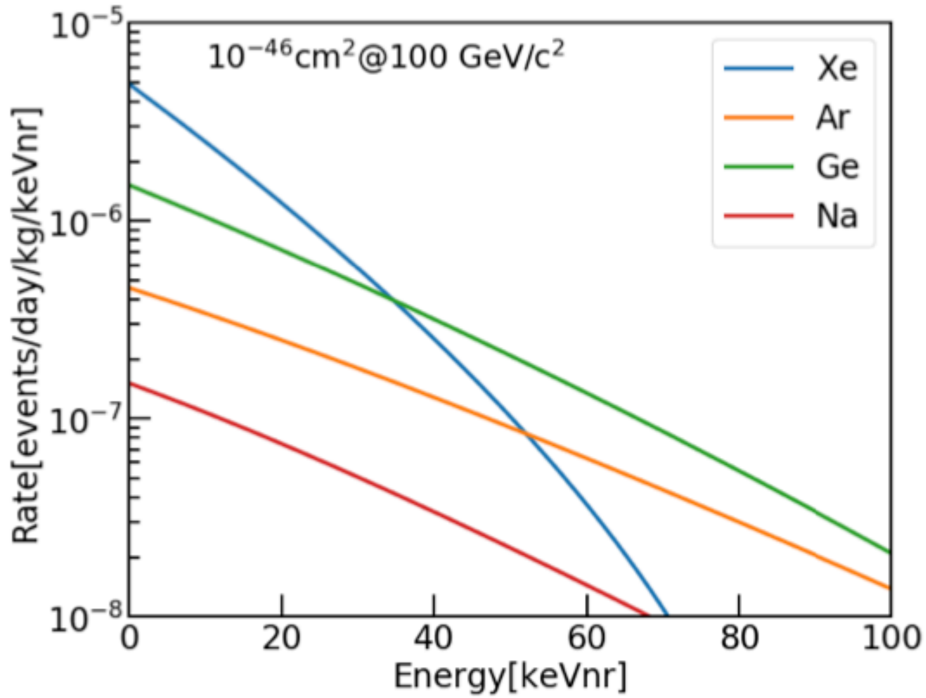
$\rho_0 = 0.3\,\mathrm{GeV\,cm}$ $v_0 =$ $v_{esc} =$

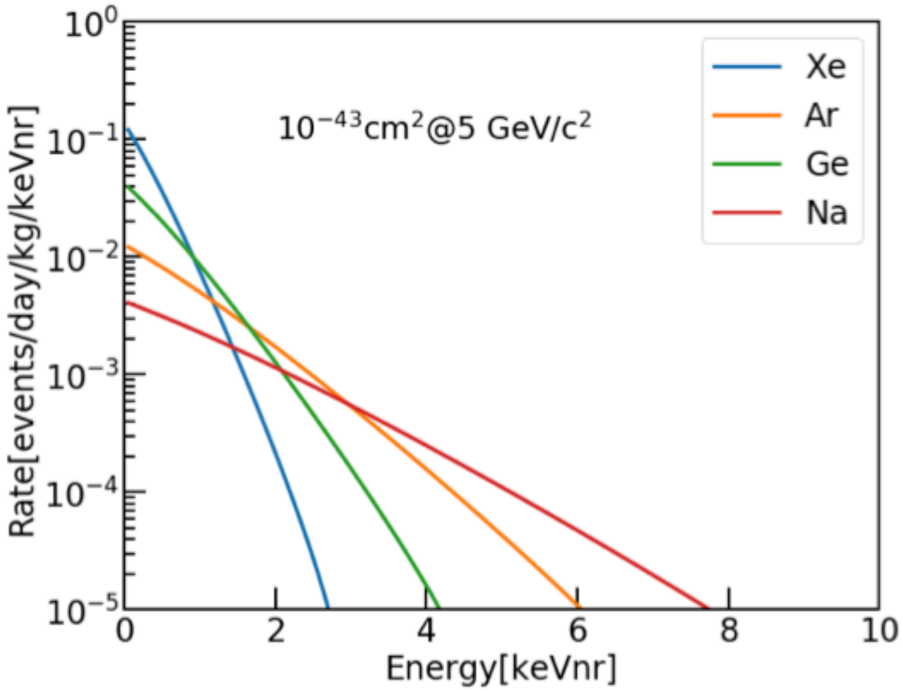


Significant uncertainty

Net result: Expected energy spectra

SI WIMP-nucleon, no efficiency applied





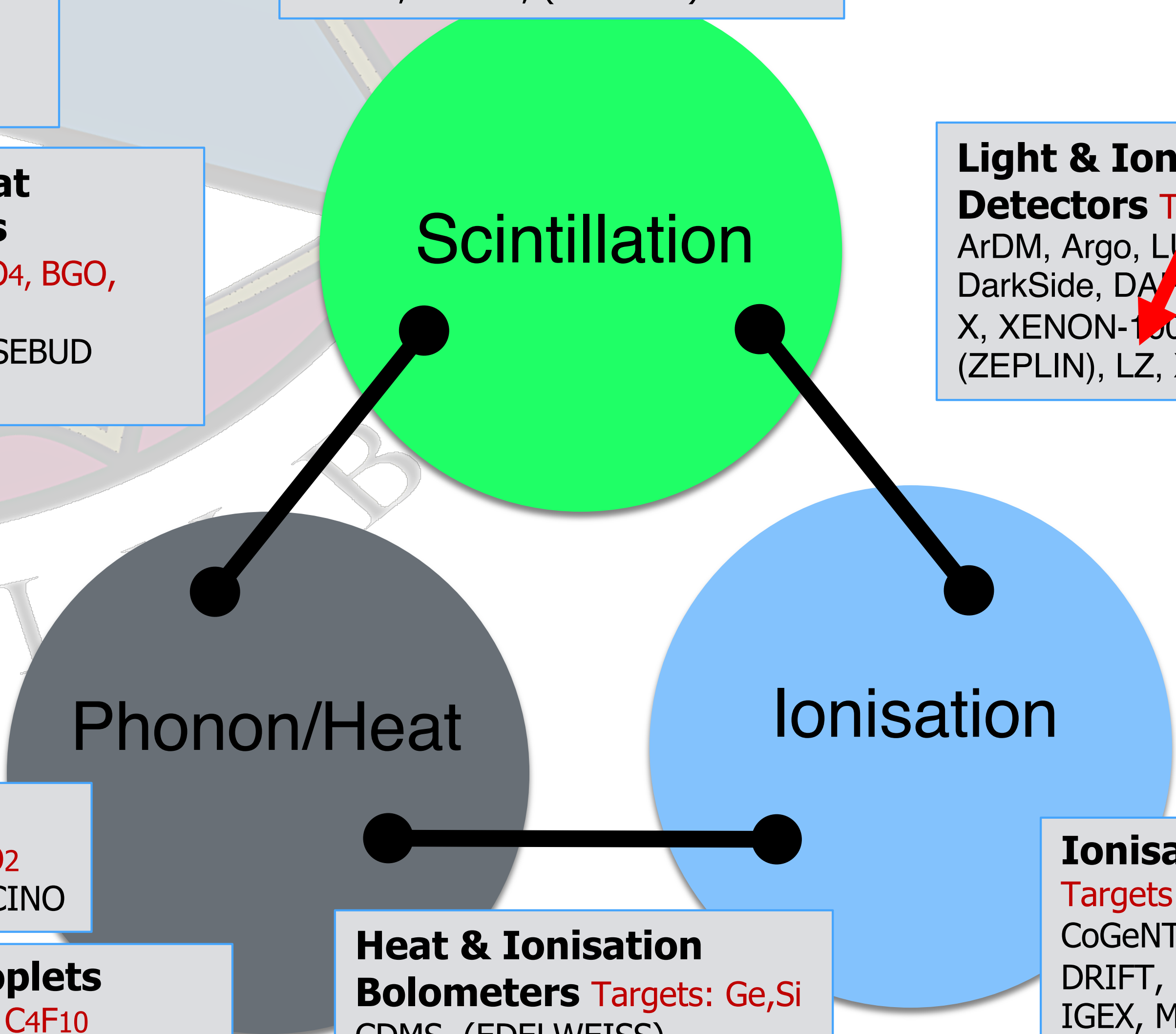
Scintillators
Targets: NaI, Xe, Ar
ANAIS, MiniCLEAN, DAMA, DEAP-3600, DM-ICE, KIMS, LIBRA, PICOLON, (NAIAD), SABRE, XMASS, (ZEPLIN-I)

Light & bubbles
Xe
arXiv:1702.08861
[PRL 118, 231301]

Light & Heat Bolometers
Targets: $CaWO_4$, BGO, Al_2O_3
(CRESST), ROSEBUD
cryogenic

This talk

Light & Ionisation Detectors Targets: Xe, Ar
ArDM, Argo, LUX, WARP, DarkSide, DARWIN, Panda-X, XENON-100, XENON-1T, (ZEPLIN), LZ, XENON-nT



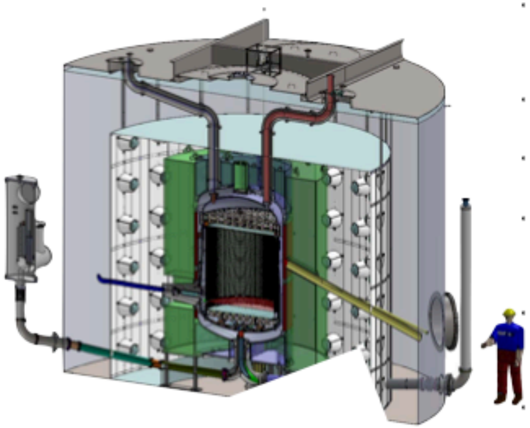
Bolometers
Targets: Ge, Si, Al_2O_3, TeO_2
CRESST-I, CUORE, CUORICINO

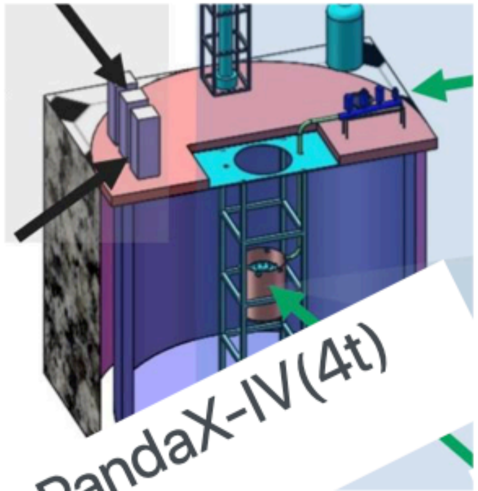
Bubbles & Droplets
CF_3Br, CF_3I, C_3F_8, C_4F_{10}
COUPP, PICASSO, PICO, SIMPLE

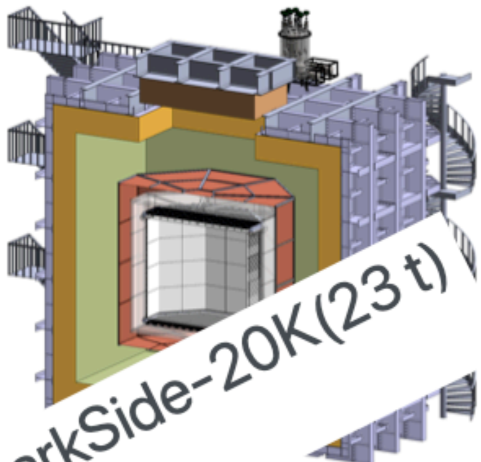
Heat & Ionisation Bolometers Targets: Ge,Si
CDMS, (EDELWEISS)
SuperCDMS, (EURECA)

Ionisation Detectors
Targets: Ge, Si, CS_2, CdTe
CoGeNT, CDEX, D3, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

New kids on the block…





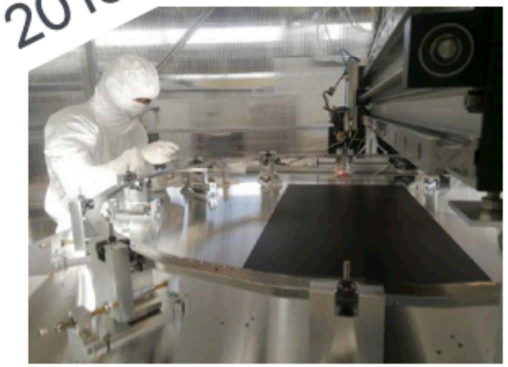


LZ(7t)
2020-

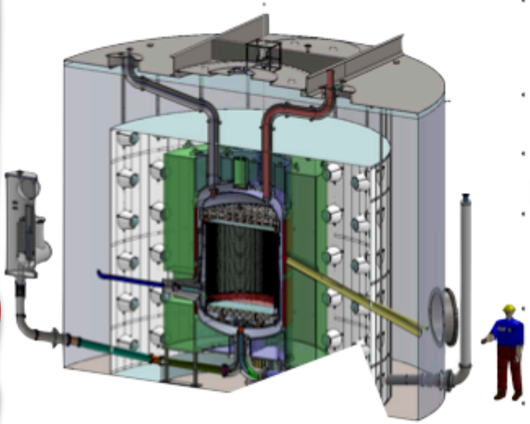
XENONnT (5.9t)
2019-

PandaX-IV(4t)
2020-

DarkSide-20K(23 t)
2022-

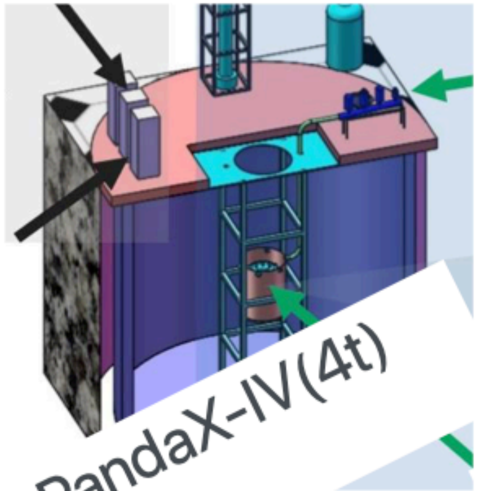


New kids on the block…

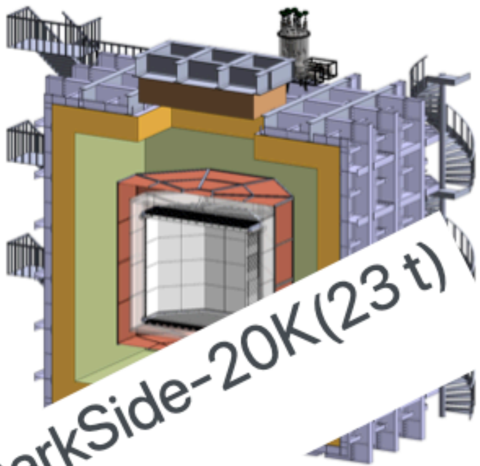


LZ(7t)
2020-

XENONnT (5.9t)
2019-

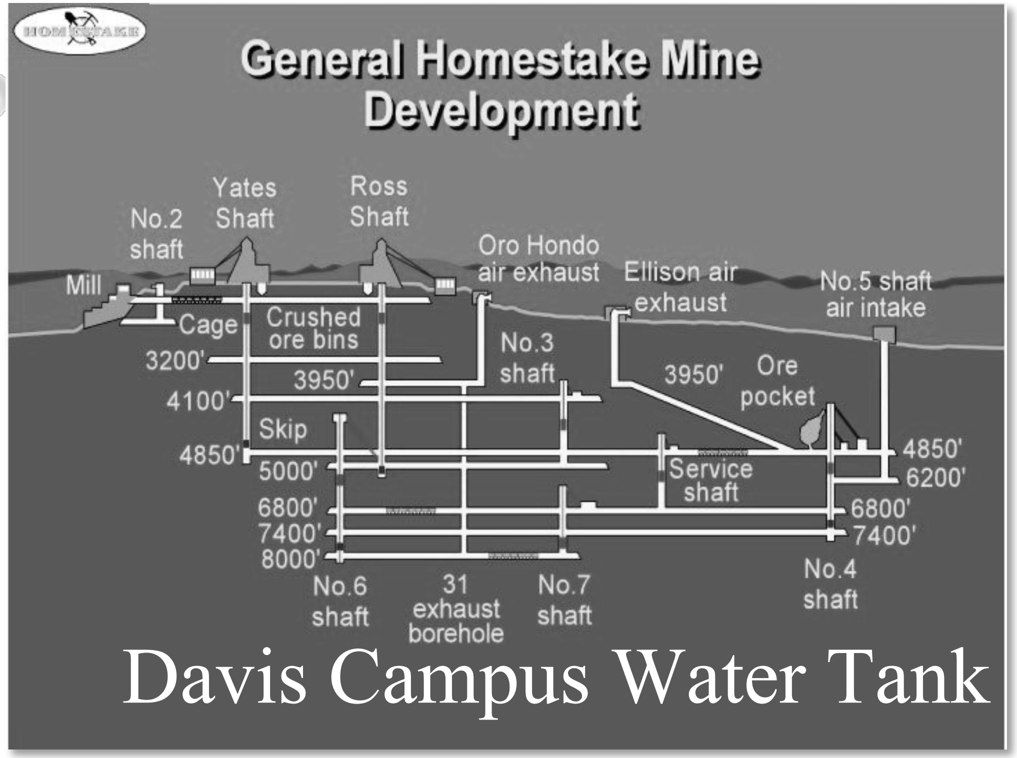


PandaX-IV(4t)
2020-



DarkSide-20K(23 t)
2022-

Sanford Underground Research Facility
Lead, South Dakota, USA



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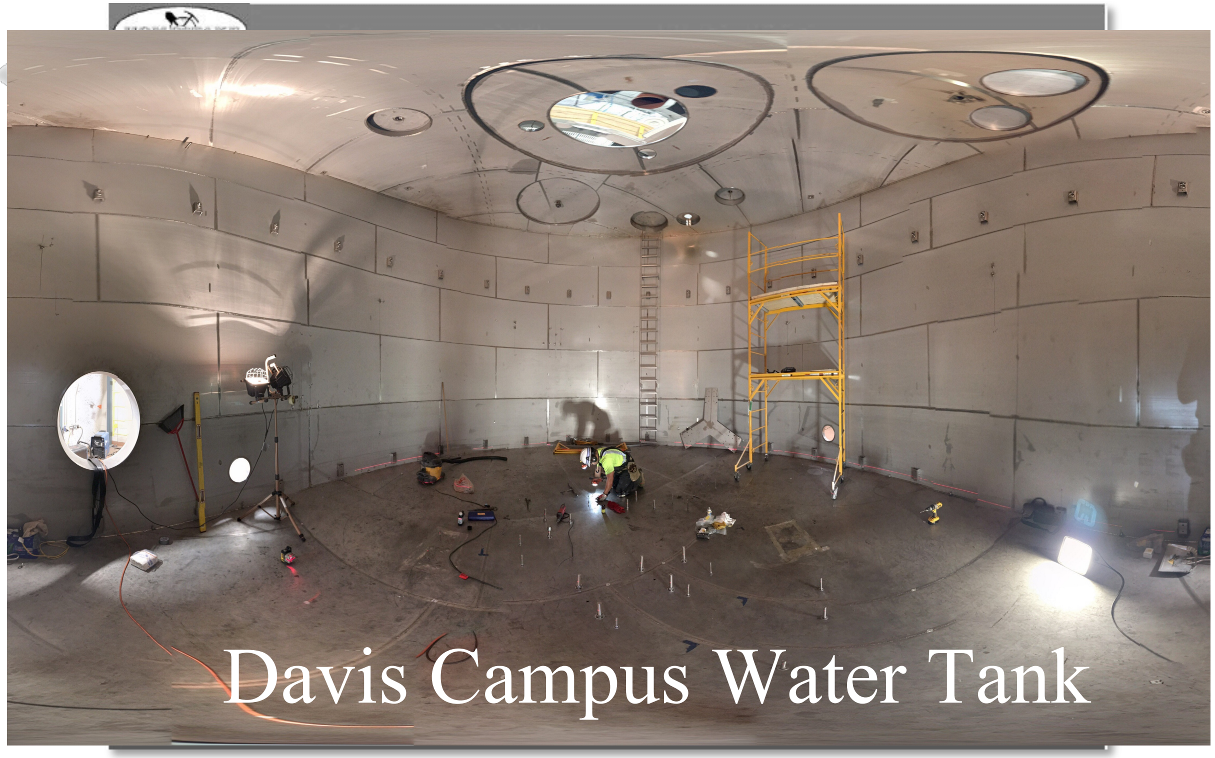
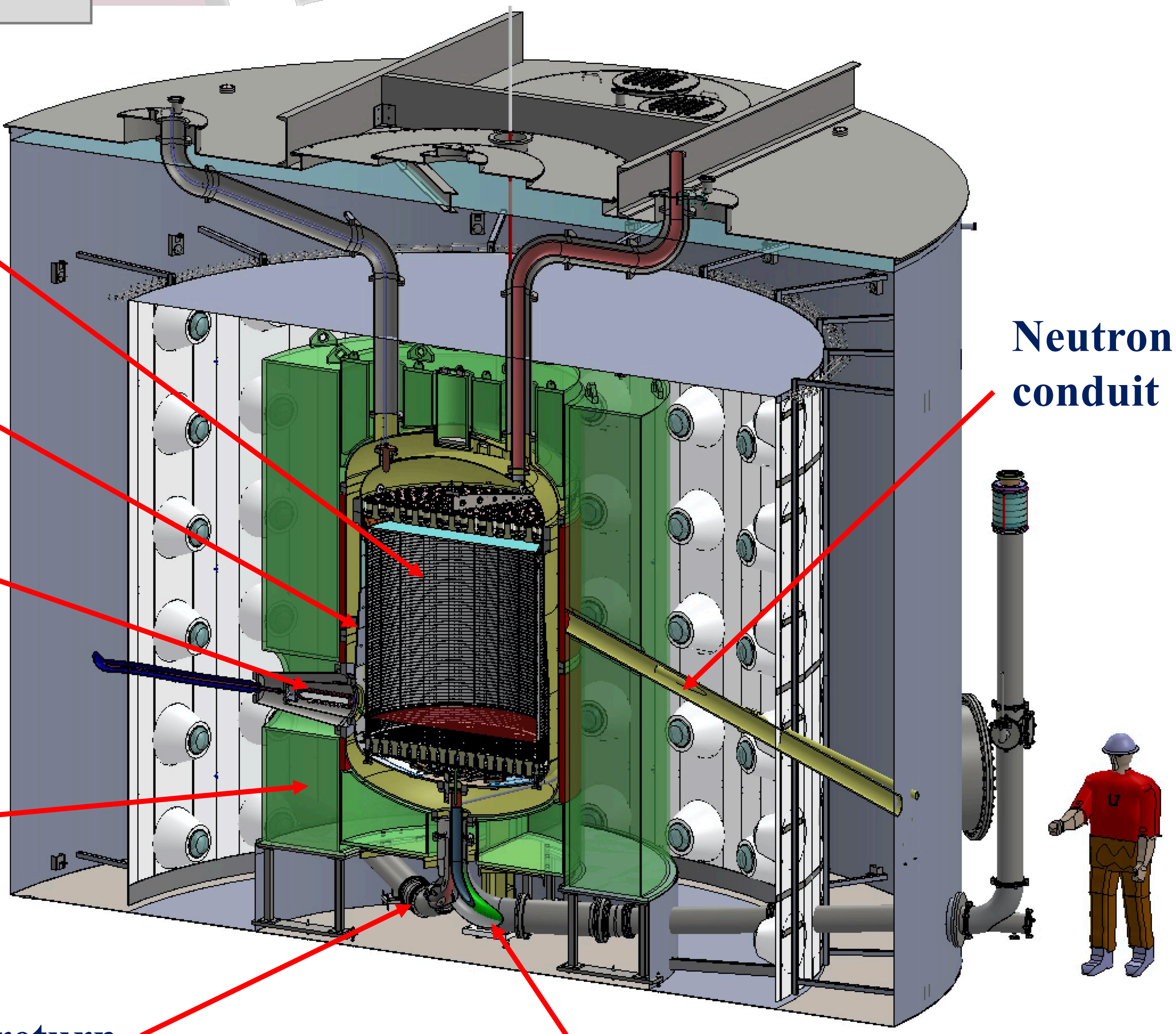


1/12/2019

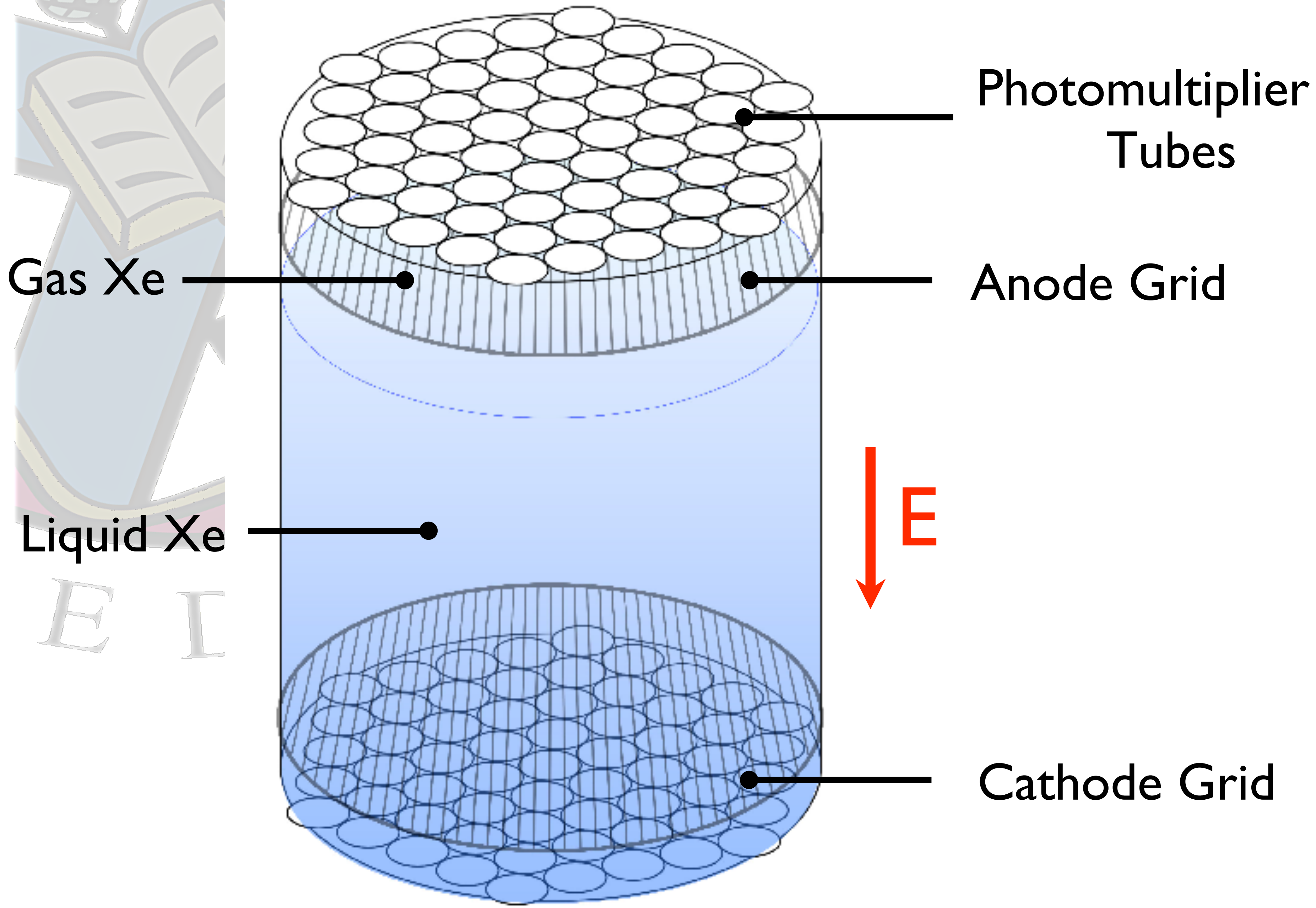
Science in an extreme environment

…

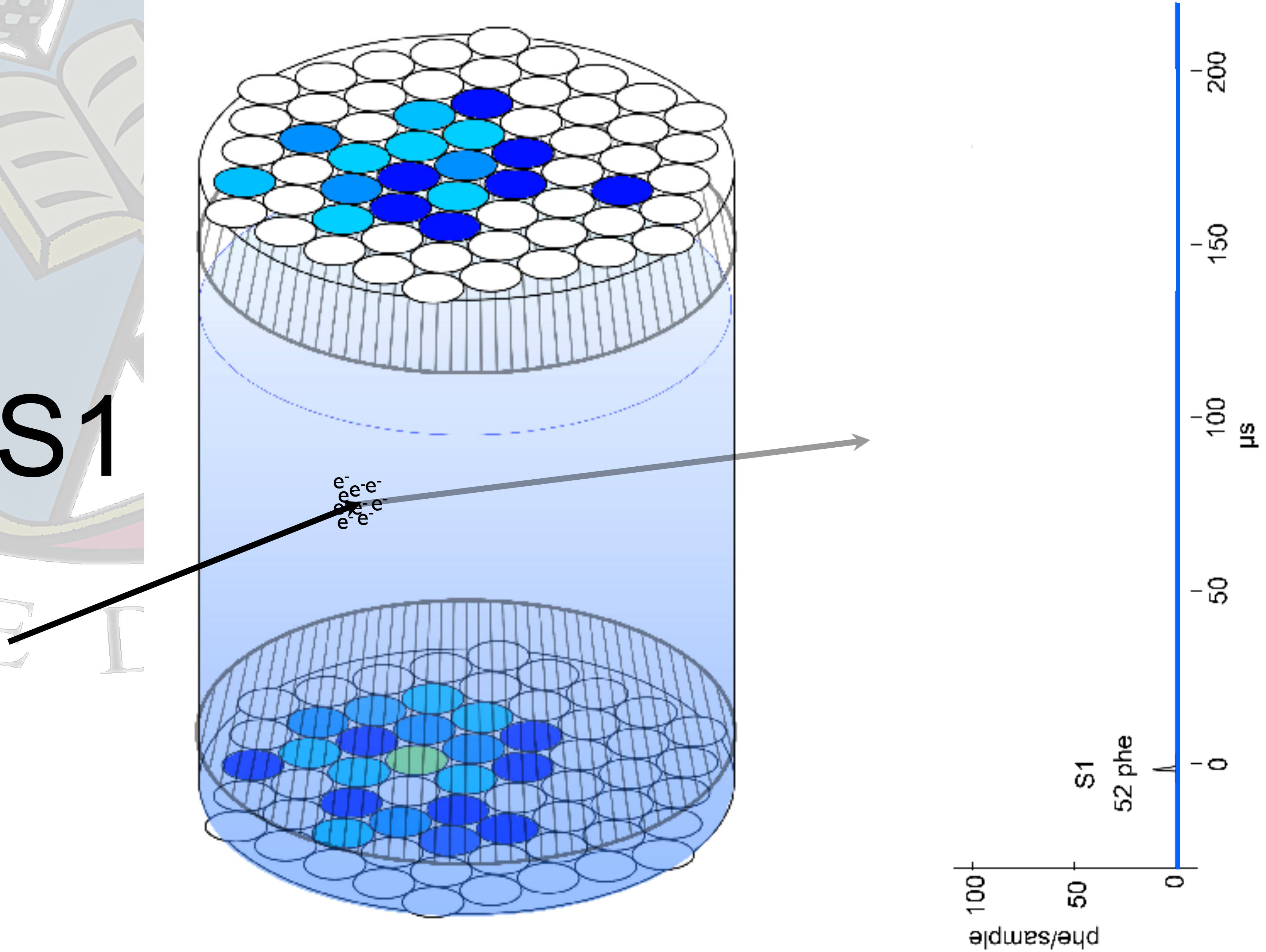
LUX-ZEPLIN (LZ)



arXiv:1910.09124

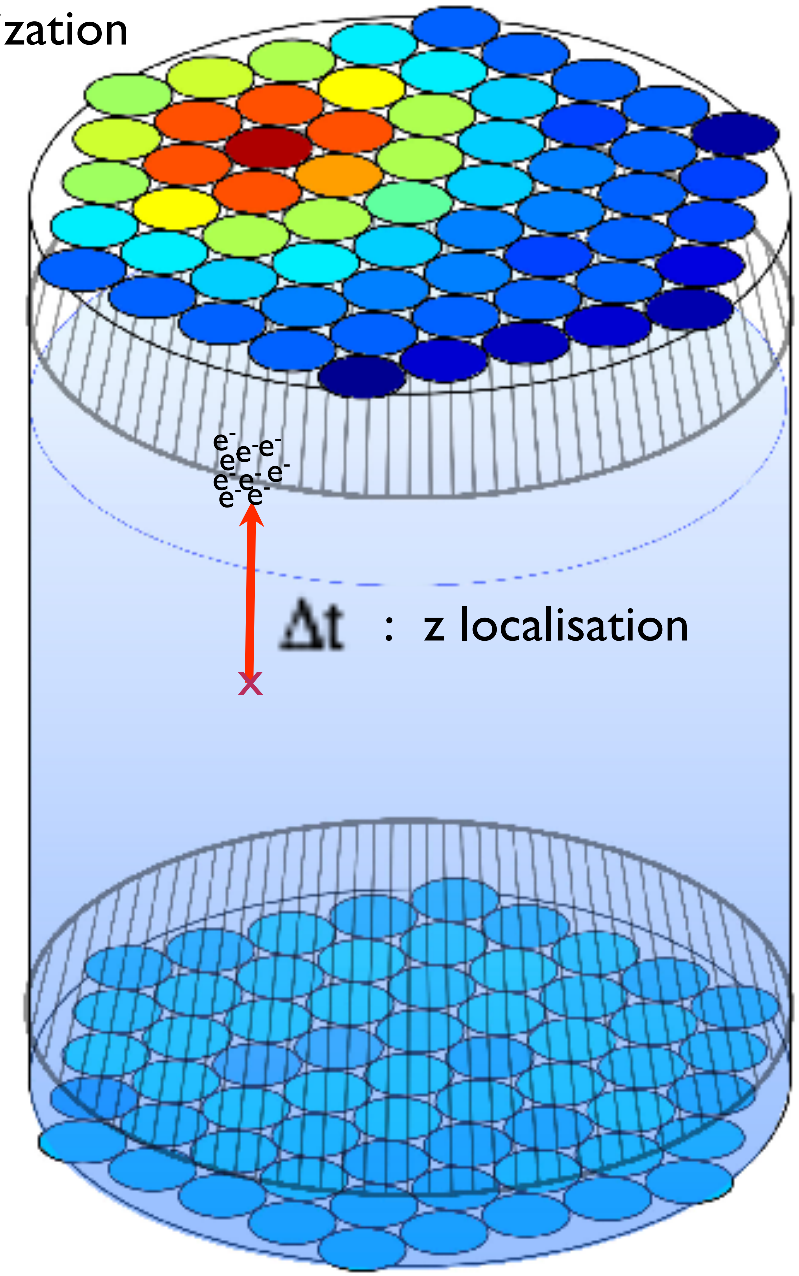

Photomultiplier Tubes
Gas Xe
Anode Grid
Liquid Xe
E
Cathode Grid

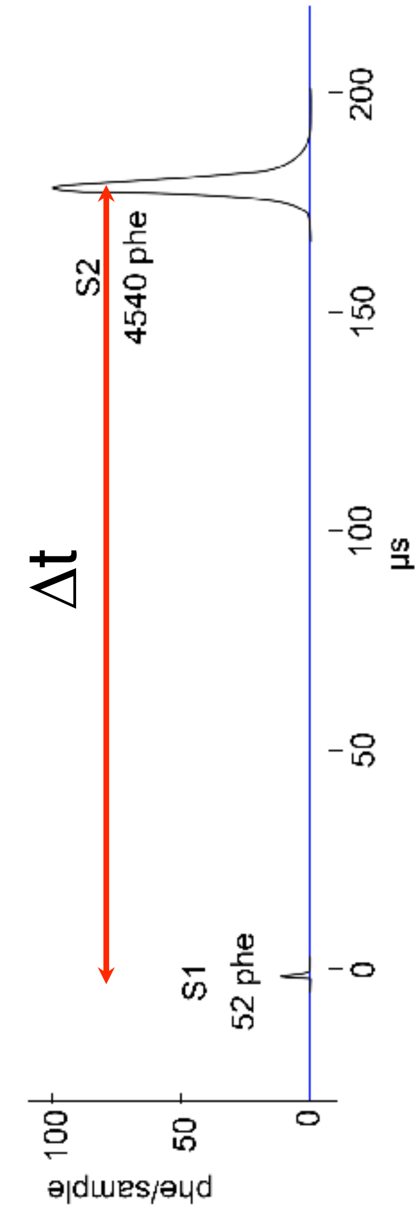
S1



top hit pattern:
x-y localization

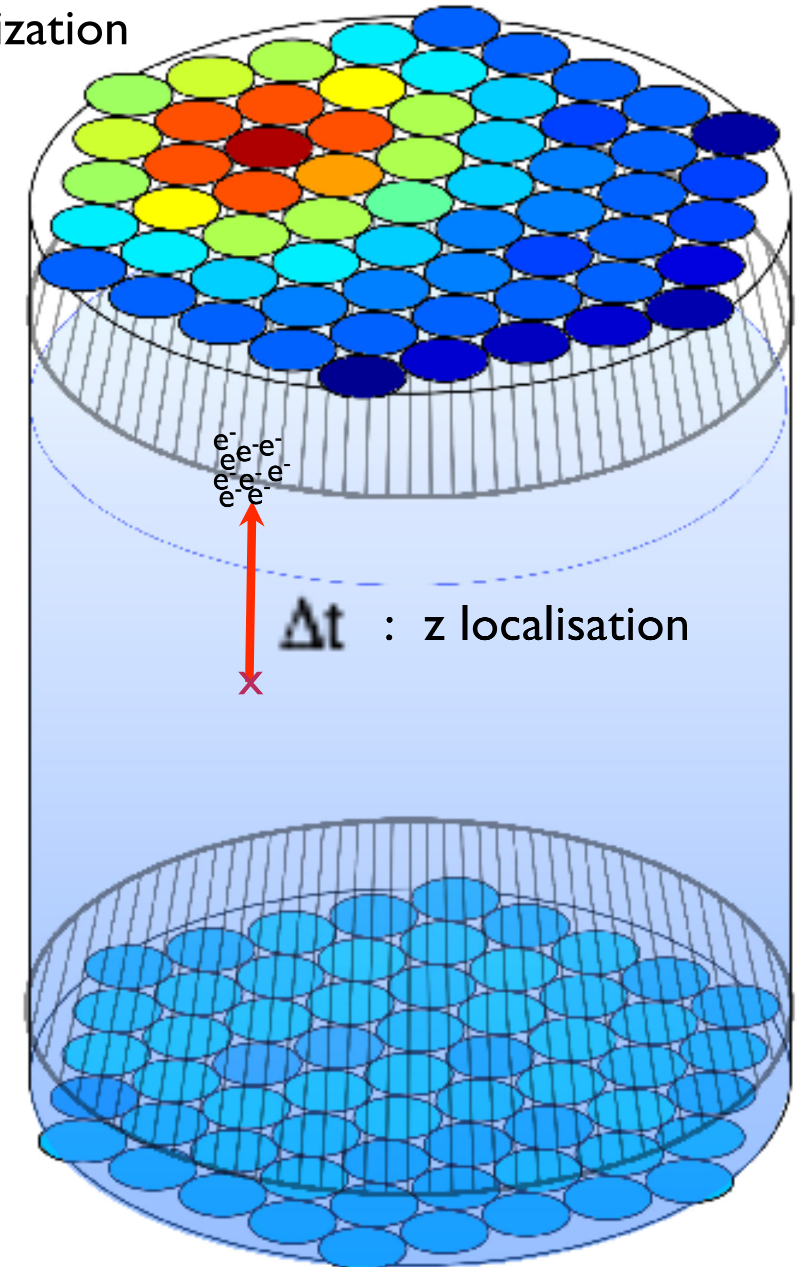
S2

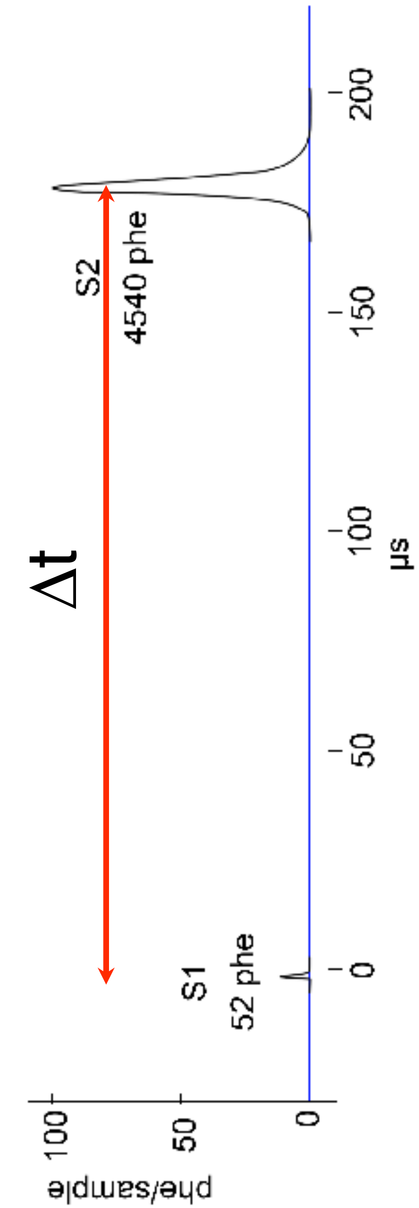




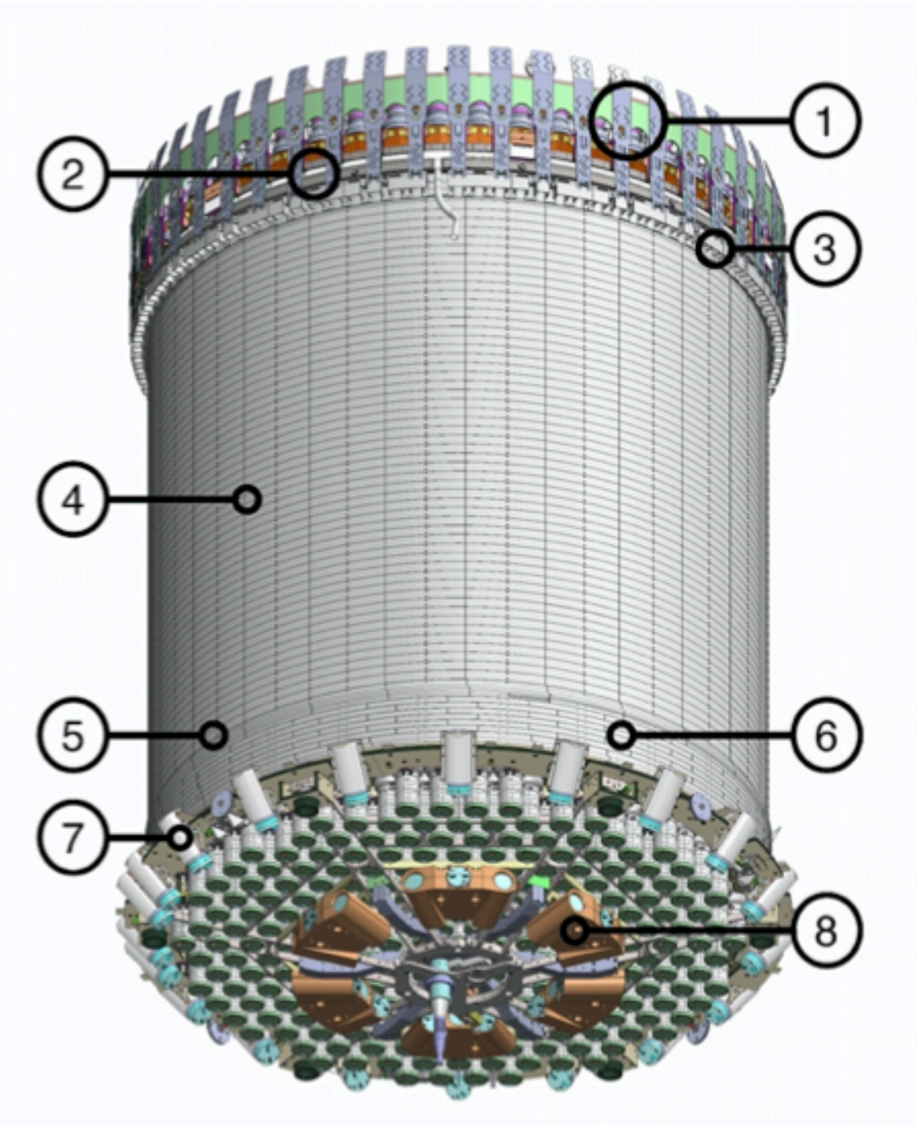
top hit pattern:
x-y localization

S2

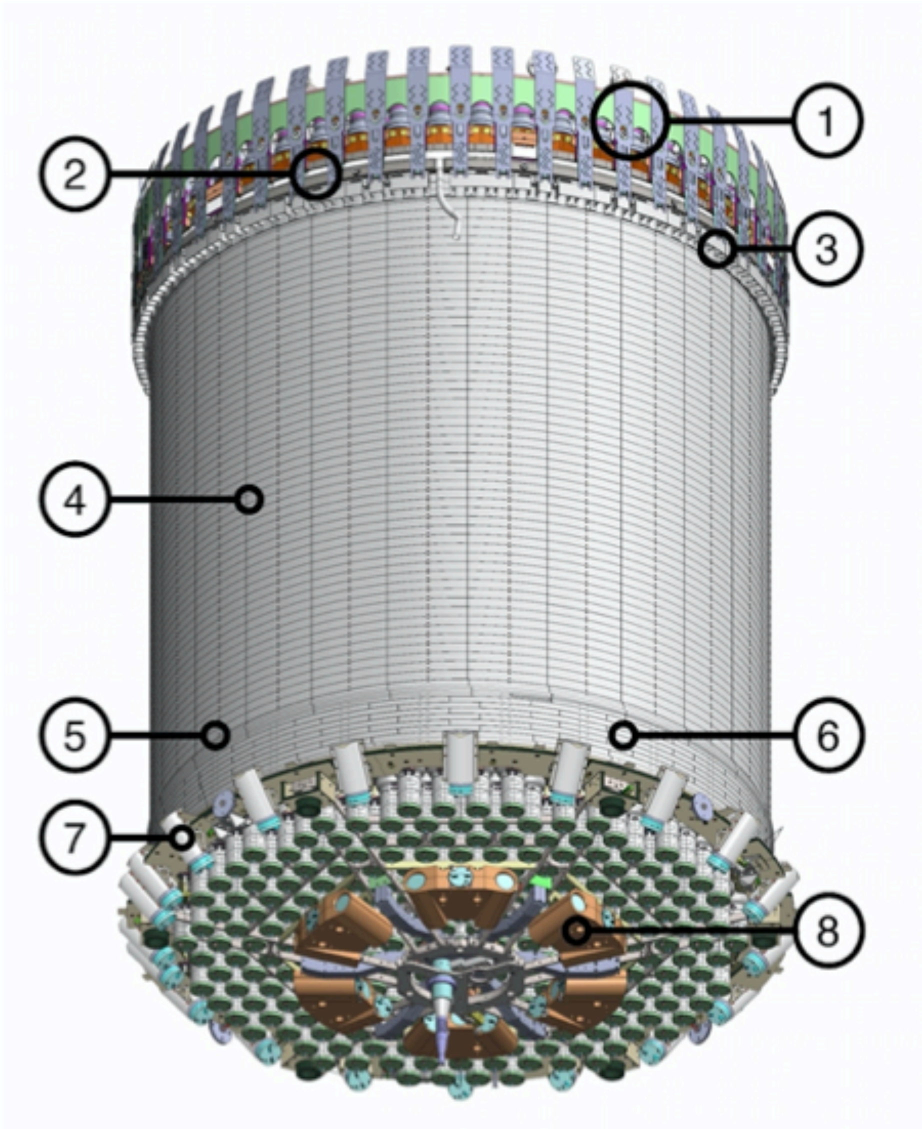




Ratio of S2 to S1 depends on the type of incident particle - allows ER (β, gamma) : NR (neutron, WIMP) discrimination >99.5%



arXiv:1910.09124

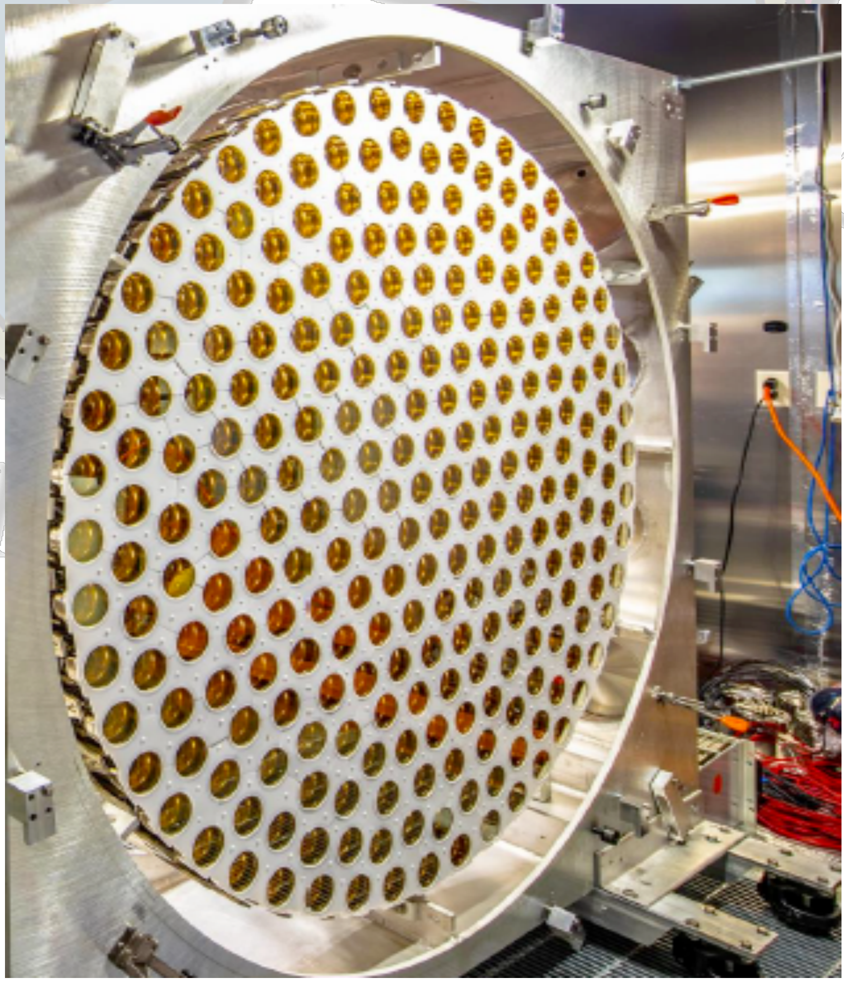


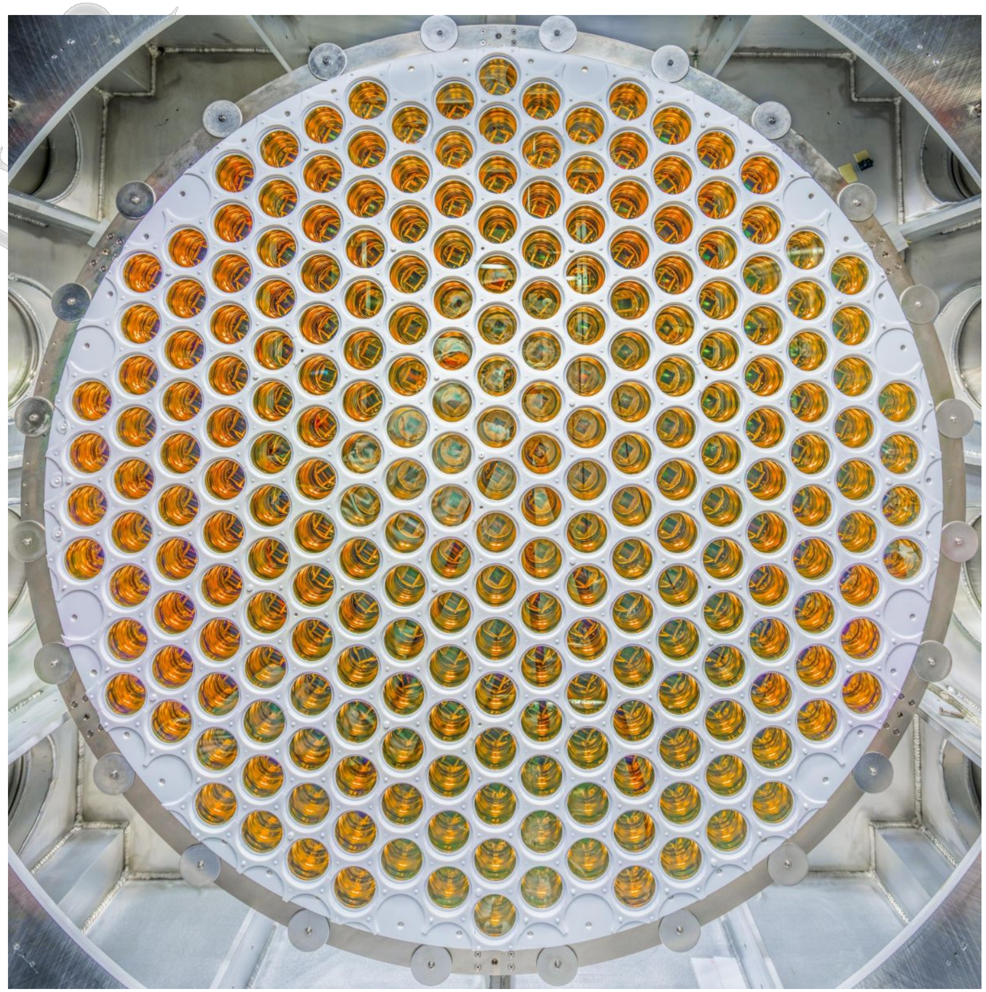
arXiv:1910.09124

PMTs

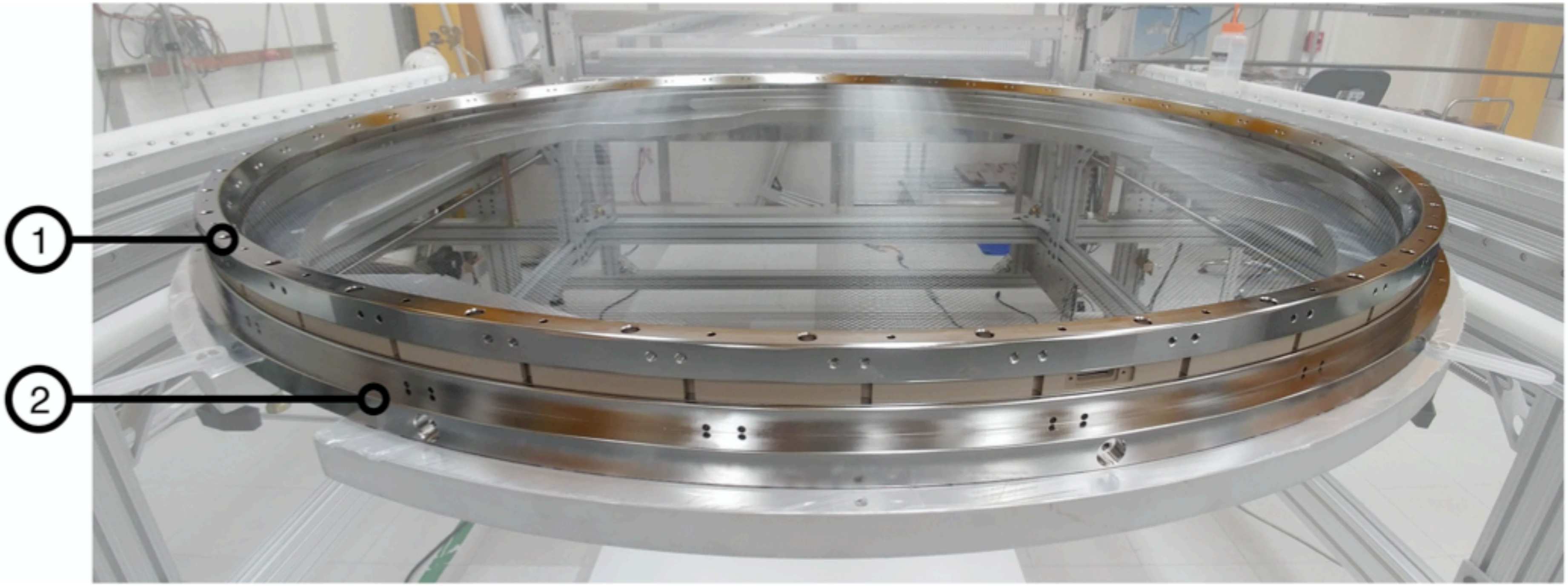
3” Hamamatsu R11410-22

Average QE: 31% (cold); Average Gain: $3.5x10^6$;Top array: 253 units; Bottom array: 241 units





Grids



Electrode	Voltage (kV)	Diam. (μm)	Pitch (mm)	Num.
Anode	+5.75	100	2.5	1169
Gate	−5.75	75	5.0	583
Cathode	−50.0	100	5.0	579
Bottom	−1.5	75	5.0	565

Cryostats (inner, outer)

Astroparticle Physics 96 (2017) 1–10

Contents lists available at ScienceDirect

Astroparticle Physics

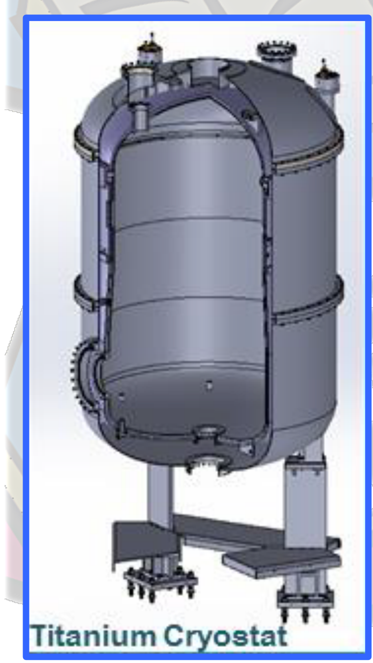
journal homepage: www.elsevier.com/locate/astropartphys

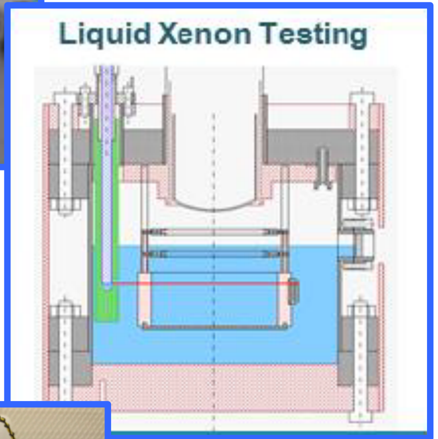
ELSEVIER

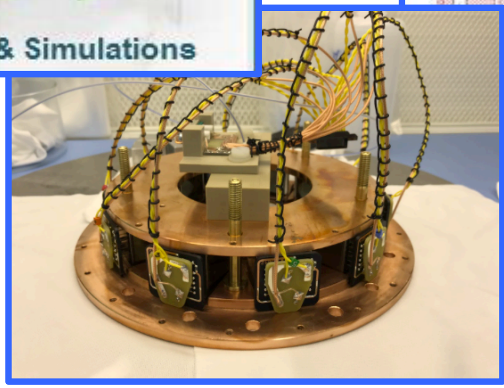
Identification of radiopure titanium for the LZ dark matter experiment and future rare event searches

CrossMark

LZ-UK status







All UK hardware contributions *complete* https://www.youtube.com/watch?v=dwoFeiqiNe0

ASSAY CAMPAIGN

+

MONTE CARLO SIMULATION

↓

Known source event rates

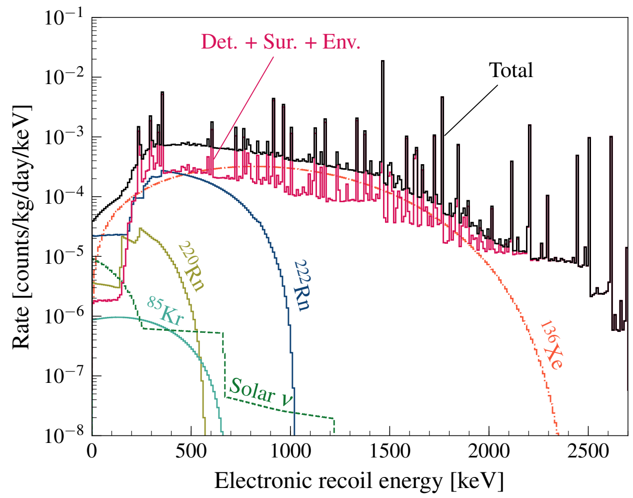
Assay campaign

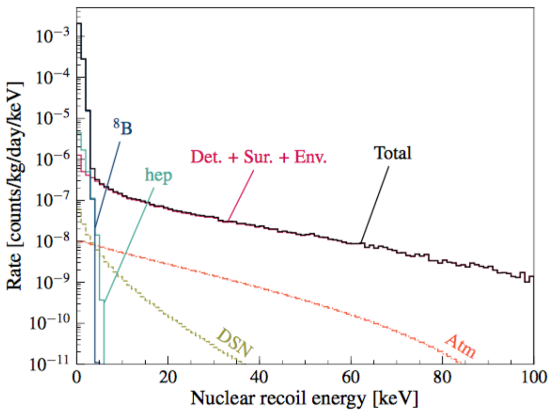
Technique	Isotopic Sensitivity	Typical Sensitivity	Sample Mass	Sampling Duration	Destructive/Non-destructive and Notes	Locations (and Number of Systems if > 1)	Samples Assayed
HPGe	^{238}U, ^{235}U, ^{232}Th chains, ^{40}K, ^{60}Co, ^{137}Cs any γ-ray emitter	5×10^{-11} g/g U, 10^{-10} g/g Th	kg	Up to 2 weeks	Non-destructive, very versatile, not as sensitive as other techniques, large samples	SURF ×6, LBNL ×1, U. Alabama ×2, Boulby ×7	926
ICP-MS	^{238}U, ^{235}U, ^{232}Th (top of chain)	10^{-12} g/g	mg to g	Days	Destructive, requires sample digestion, preparation critical	UCL, IBS, BHUC, U. Alabama	157
NAA	^{238}U, ^{235}U, ^{232}Th (top of chain), K	10^{-12} g/g to 10^{-14} g/g	g	Days to weeks	Destructive, useful for non-metals, minimal sample preparation	Irradiated at MITR-II, HPGe assay at U. Alabama	3
GD-MS	^{238}U, ^{235}U, ^{232}Th (top of chain)	10^{-10} g/g	mg to g	Days	Destructive, minimal matrix effects, cannot analyze ceramics and other insulators	National Research Council Canada	2
Radon Emanation	^{222}Rn	0.1 mBq	kg	1 to 3 weeks	Non-destructive, large samples, limited by size of emanation chamber	UCL ×2, U. Maryland, SDSM&T ×2, U. Alabama ×2	175
Surface α	^{210}Pb, ^{210}Bi, ^{210}Po	120 α/(m^2· day)	g to kg	<1 week	Non-destructive, thin samples, large surface area required	SDSM&T (Si), Brown (XIA), Boulby (XIA), U. Alabama (Si)	306

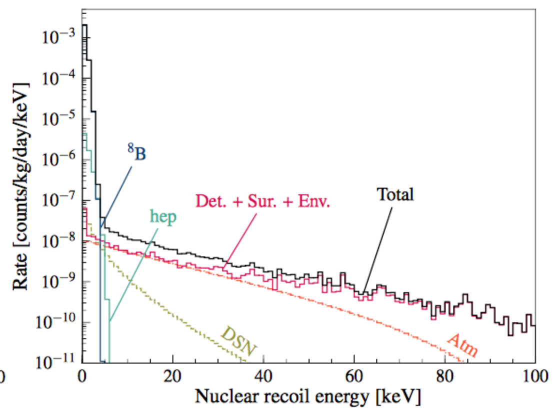
Sparing you the details!

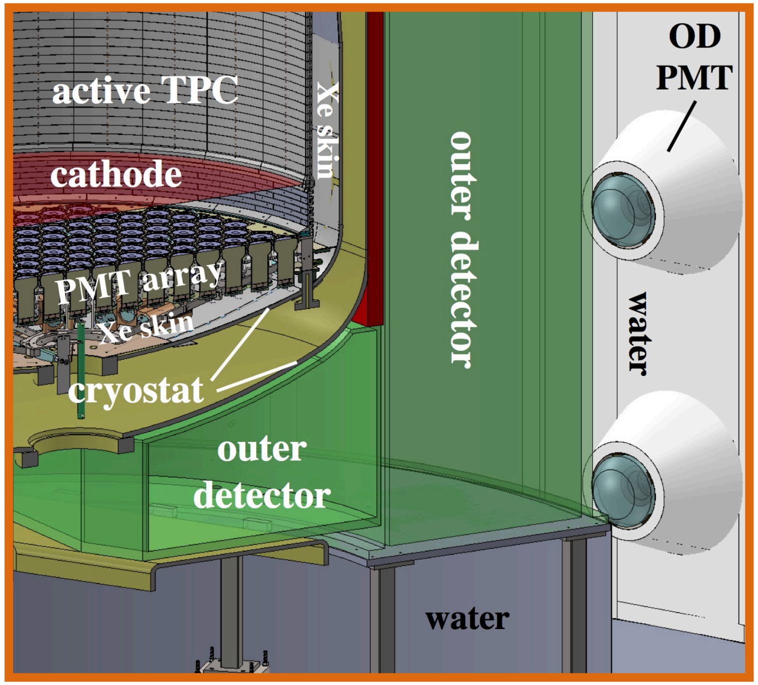
→ Complete understanding of ER and NR rates from known sources over the full relevant energy range

- Cosmics, external, internal, surfaces, β, γ, x, α, n, ν,…
- Includes f.v., LXe skin, OD, water veto
- Further details in *backup slides*









Backgrounds + Signal Model + PLR

Science Reach (Sensitivity)

What this means for WIMPs…

arXiv:1802.06039

039v1 [astro-ph.IM] 16 Feb 2018

Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment

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(The LUX-ZEPLIN Collaboration)

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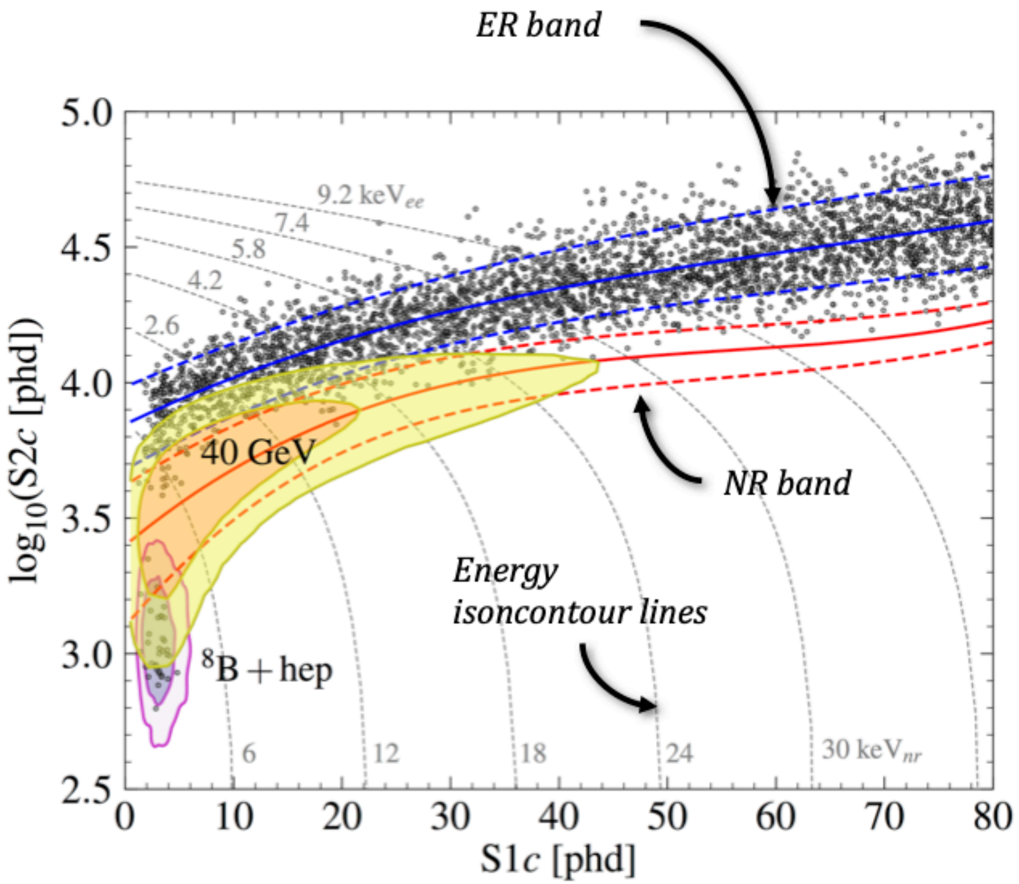
[2]*Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305-4085 USA*
[3]*University of Michigan, Randall Laboratory of Physics, Ann Arbor, MI 48109-1040, USA*
[4]*University of Wisconsin-Madison, Department of Physics, Madison, WI 53706-1390, USA*
[5]*Imperial College London, Physics Department, Blackett Laboratory, London SW7 2AZ, UK*
[6]*South Dakota School of Mines and Technology, Rapid City, SD 57701-3901, USA*
[7]*University of Maryland, Department of Physics, College Park, MD 20742-4111, USA*

Full simulation of event rates



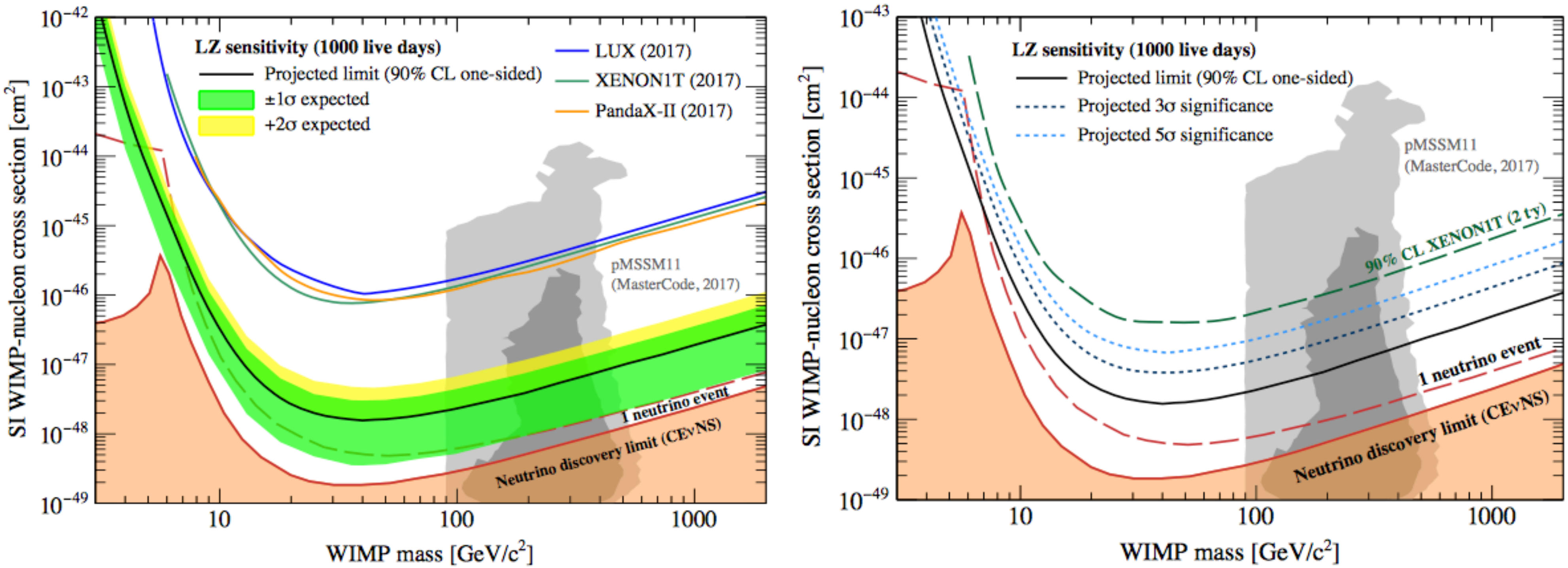
Simulated dataset inside the fiducial volume for the full LZ exposure (1000 days × 5600 kg)

ER: electron recoil
NR: neutron recoil

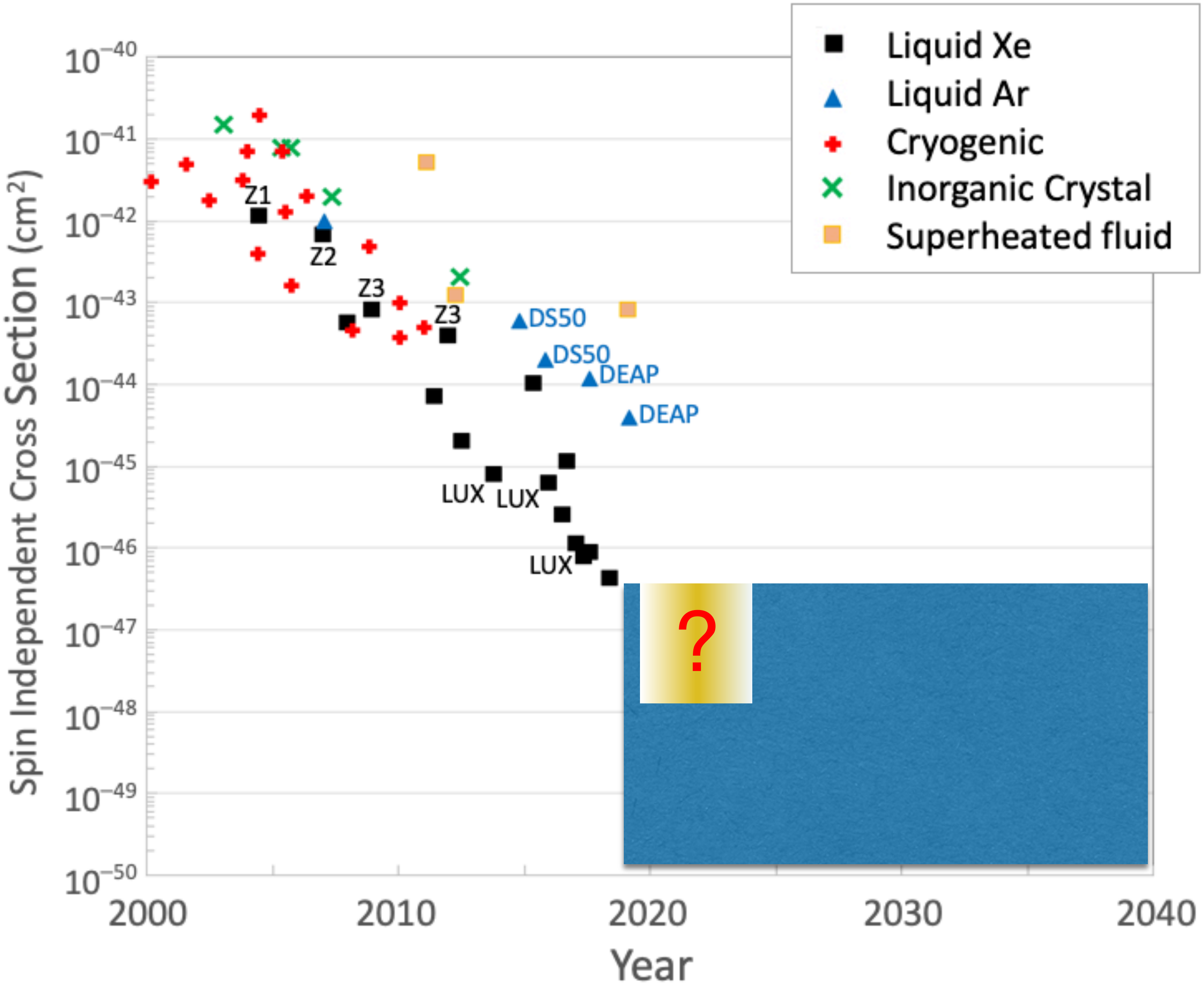
- ER and NR events discriminated from their different S2/S1 proportion
- ER and NR bands obtained through calibration
- Many γ and n events occur close to the TPC wall
  - ➢ Veto them: Xe skin and OD
  - ➢ Define a fiducial region: 5.6 t for the WIMP search
- ○ PLR analysis
- ○ Blinding via salt

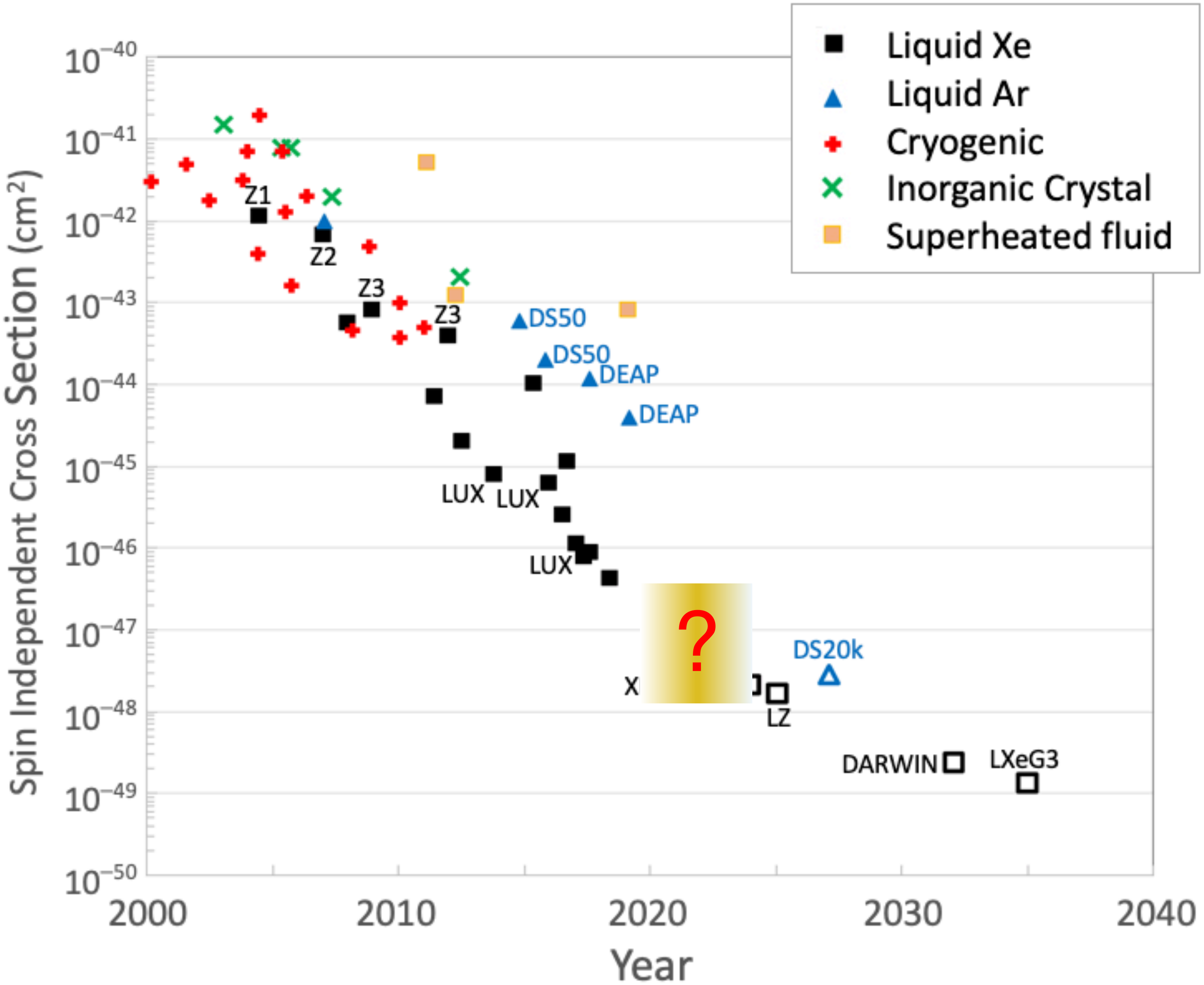
WIMP SI Sensitivity

https://arxiv.org/pdf/1802.06039.pdf



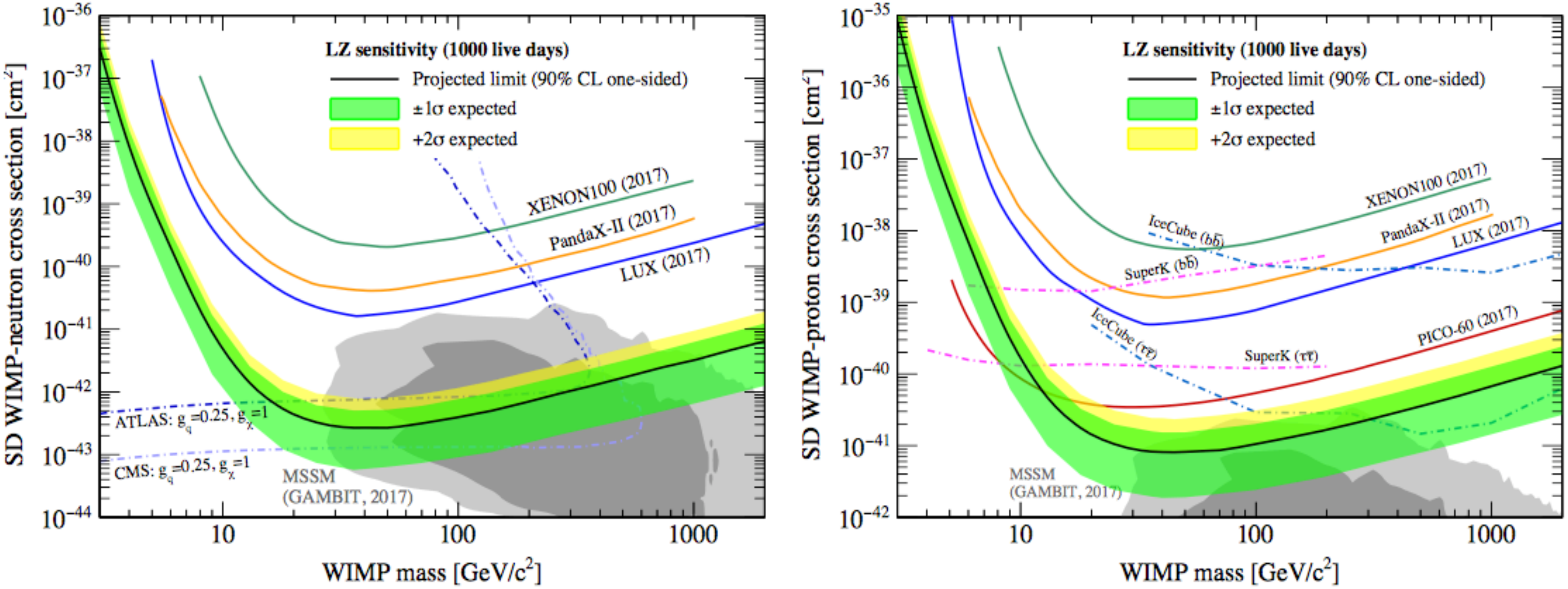
- Expected limits on spin-independent cross-sections for 1000 days of live time (left) and discovery potential (right).


Liquid Xe
Liquid Ar
Cryogenic
Inorganic Crystal
Superheated fluid
Spin Independent Cross Section (cm²)
Year
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10⁻⁵⁰
2000
2010
2020
2030
2040
Z1
Z2
Z3
Z3
DS50
DS50
DEAP
DEAP
LUX
LUX
LUX
?


Spin Independent Cross Section (cm²)
Year
Liquid Xe
Liquid Ar
Cryogenic
Inorganic Crystal
Superheated fluid
Z1
Z2
Z3
Z3
DS50
DS50
DEAP
DEAP
LUX
LUX
LUX
?
X
LZ
DS20k
DARWIN
LXeG3
2000
2010
2020
2030
2040

More Science

SD interactions, axions, axion-like particles (ALPs), sub-GeV dark matter, leptophillic axial vector DM, astrophysical neutrinos, $0\nu\beta\beta$'s, EFT analyses...

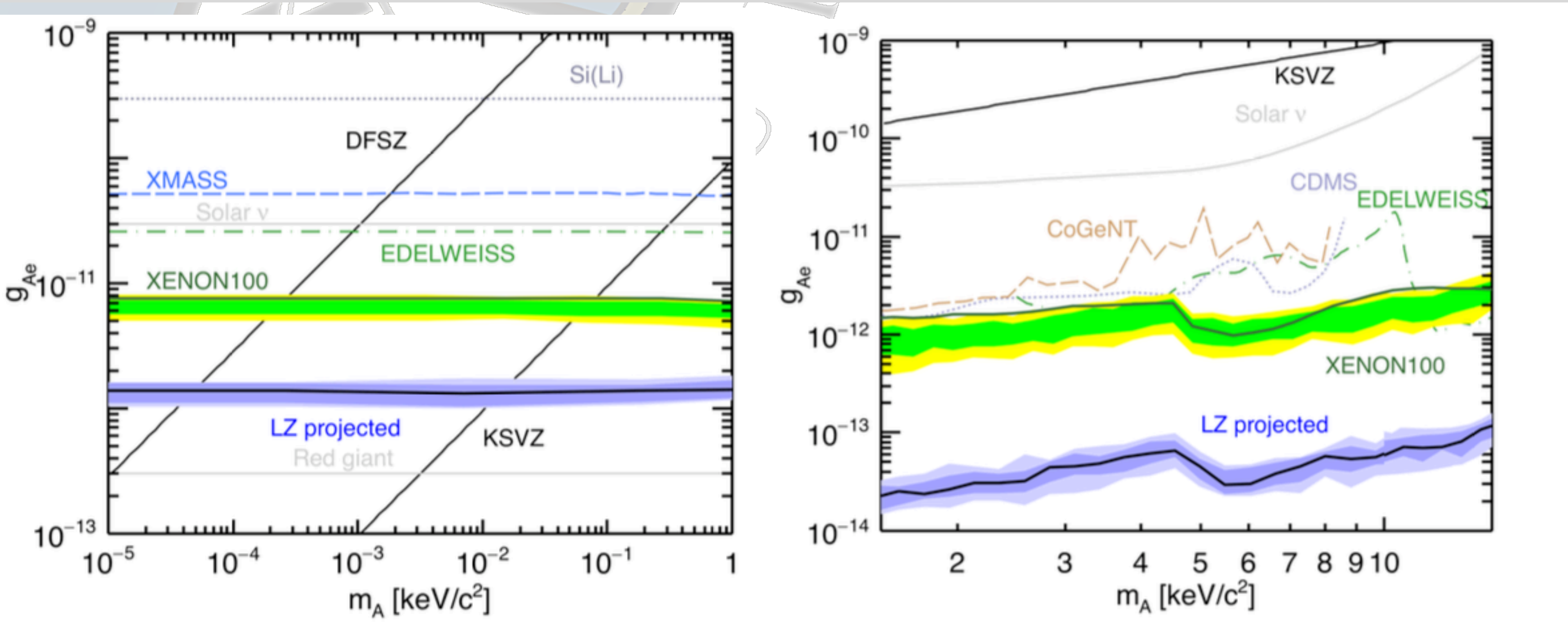


SD WIMP-neutron (left) and WIMP-proton (right) scattering for a 1000 live day run with a 5.6 tonne fiducial mass.

https://arxiv.org/pdf/1802.06039.pdf

More Science

SD interactions, **axions, axion-like particles (ALPs)**, sub-GeV dark matter, leptophillic axial vector DM, astrophysical neutrinos, $0\nu\beta\beta$'s, EFT analyses...



Solar QCD axions (left) and galactic axion-like particle (right) sensitivities for a 1000 live day run with a 5.6 tonne fiducial mass

https://arxiv.org/abs/1703.09144

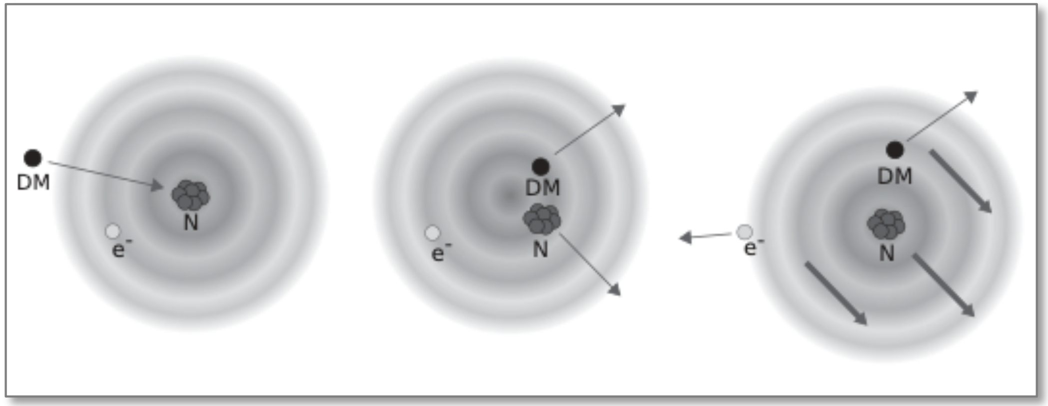
More Science

SD interactions, axions, axion-like particles (ALPs), **sub-GeV dark matter**, leptophillic axial vector DM, astrophysical neutrinos, $0\nu\beta\beta$'s, EFT analyses...

Migdal effect

Matthew J. Dolan, Felix Kahlhoefer, and Christopher McCabe
Phys. Rev. Lett. **121**, 101801

- χ-n scatter leads to *additional* ER signal
- ER quenching is << NR quenching
- Even if NR signal is below threshold, ER may still be visible
- Extends low mass sensitivity
- *Note: The reality of the Migdal effect is yet to be confirmed!*

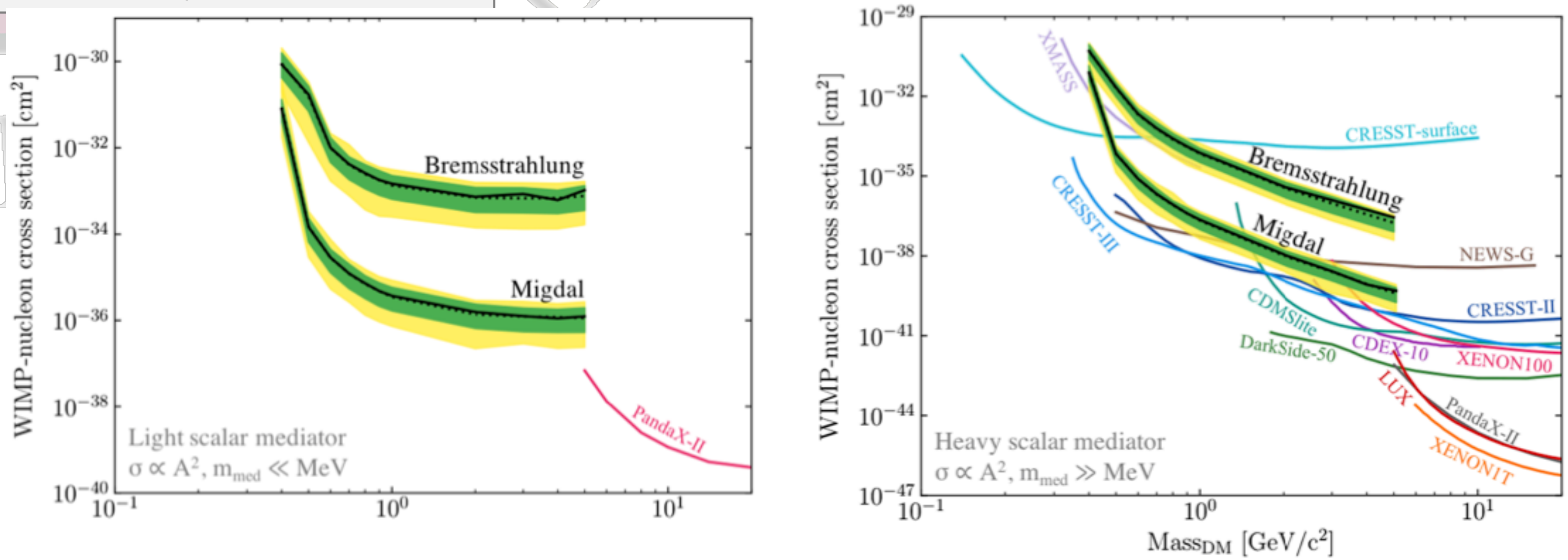


More Science

SD interactions, axions, axion-like particles (ALPs), **sub-GeV dark matter**, leptophillic axial vector DM, astrophysical neutrinos, $0\nu\beta\beta$'s, EFT analyses...

Migdal effect

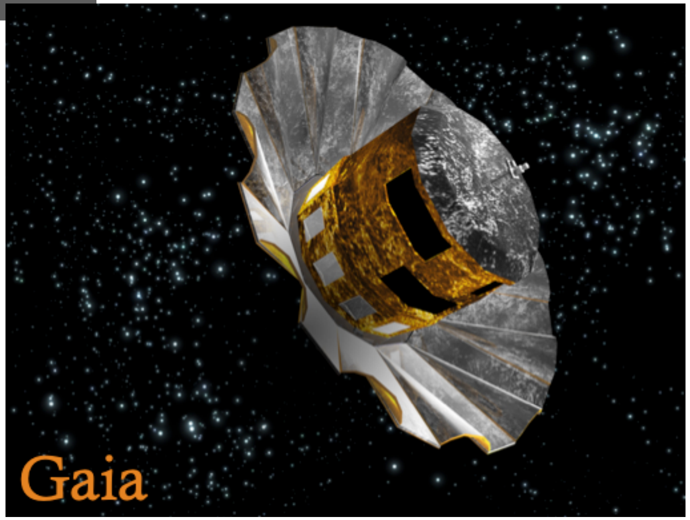
D. S. Akerib *et al.* (LUX Collaboration) Phys. Rev. Lett. **122**, 131301

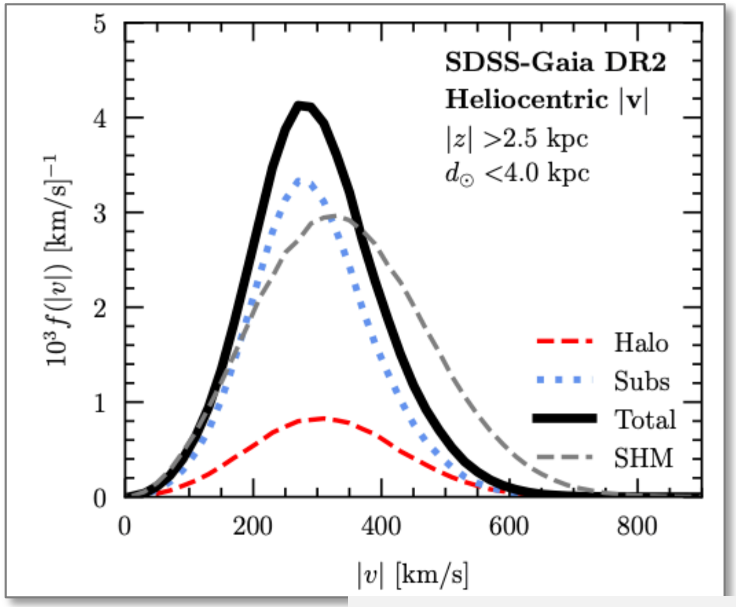


In the context of this meeting…

Updating the SHM

What is the impact on direct detection (with LZ)?

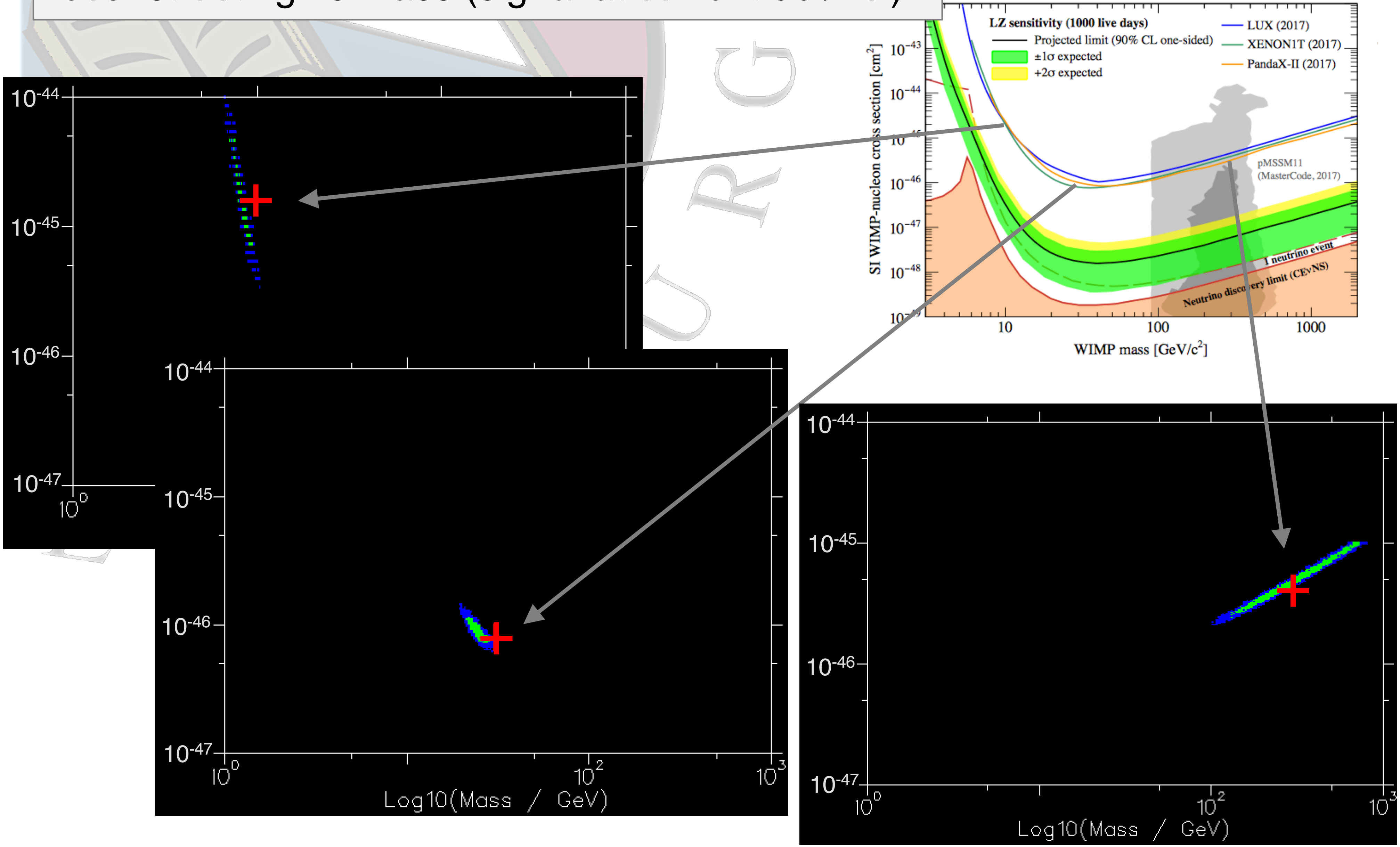




Necib et al. ApJ 874 (2019)

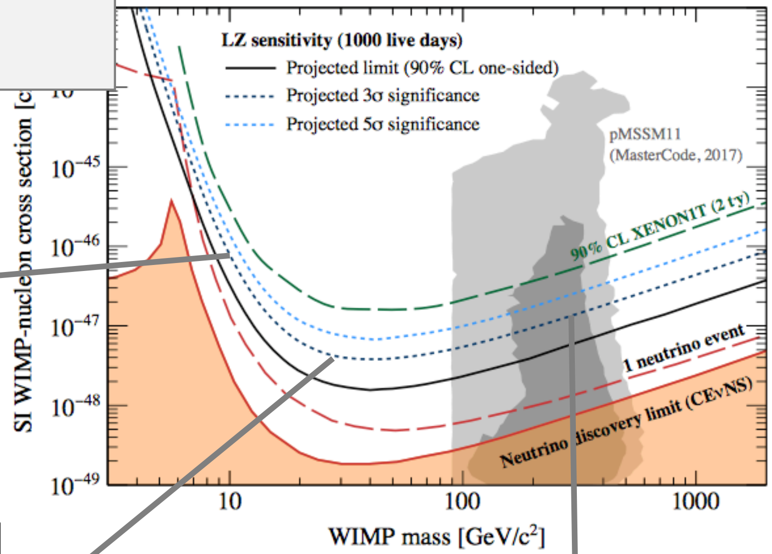
Necib et al. velocity distribution impact on reconstructing xs/mass (signal at current 90% cl)

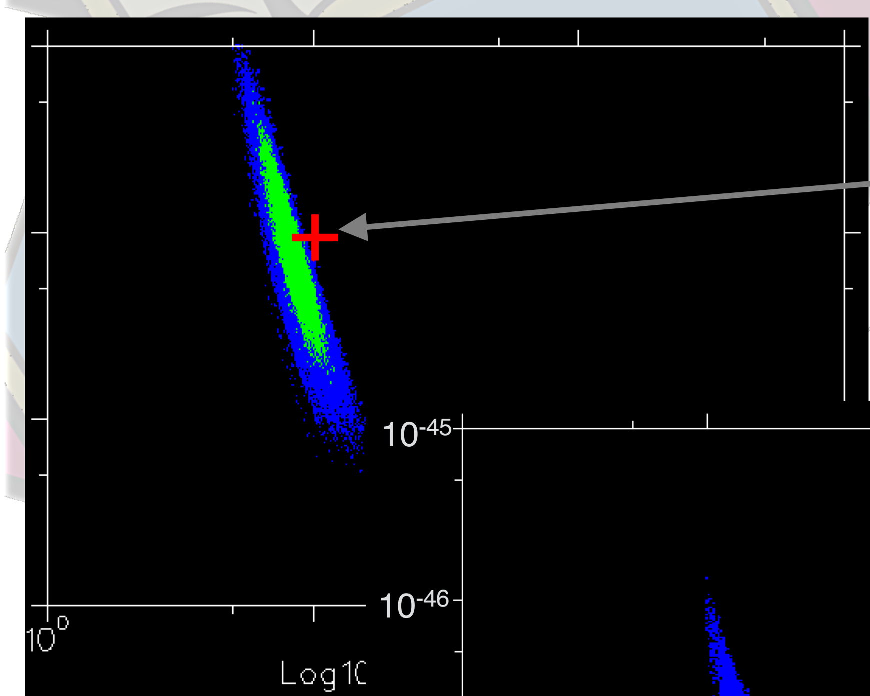
NOT LZ APPROVED PLOTS!!

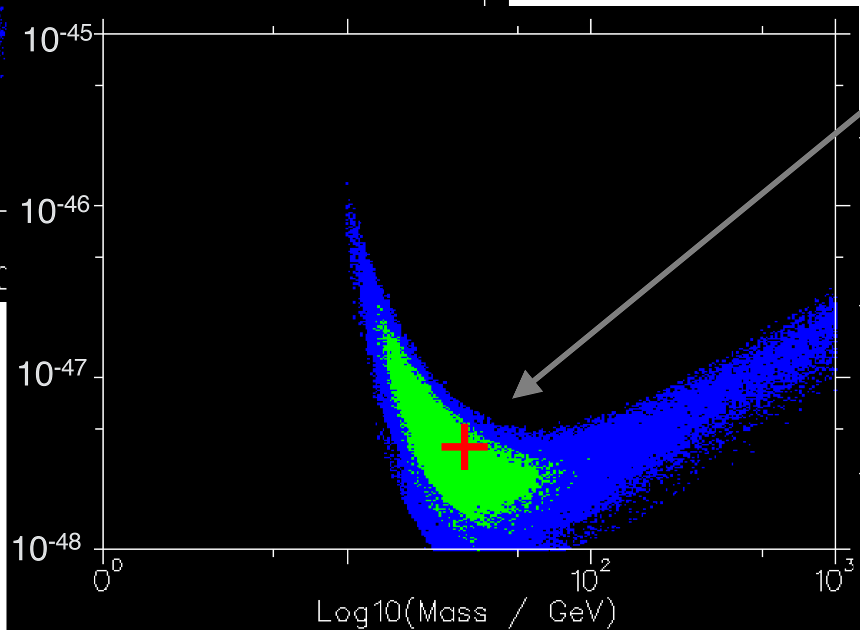


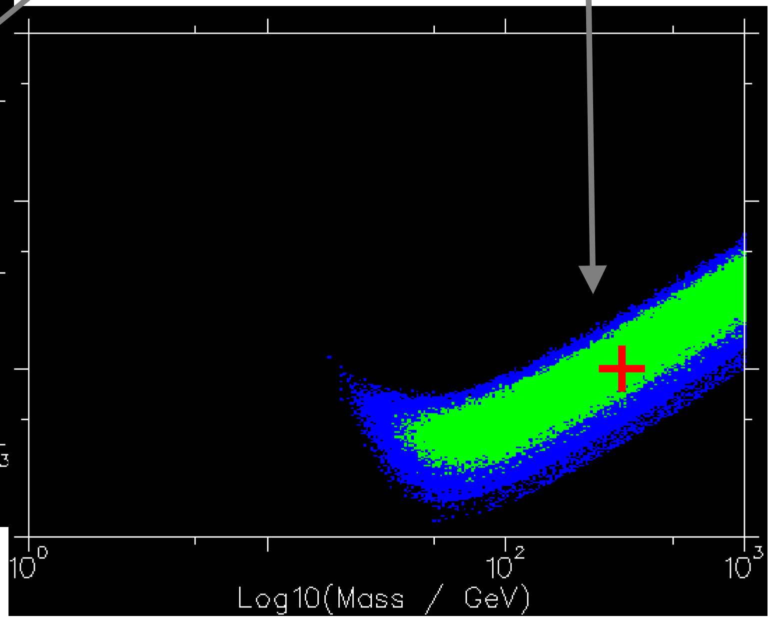
Necib et al. velocity distribution impact on reconstructing xs/mass (signal at current LZ 3σ discovery sensitivity)

NOT LZ APPROVED PLOTS!!









Looking ***beyond*** LZ…

G3Xe

XENON FUTURES:

R&D FOR A GLOBAL RARE EVENT OBSERVATORY

University of Bristol · The University of Edinburgh · Imperial College London · University of Liverpool · University of Oxford · Particle Physics Rutherford Appleton Laboratory · Royal Holloway University of London · The University of Sheffield · UCL

"Generation 3" dark matter

A ~50 ton LXe rare event observatory

- Expect to be operating by ~2030
- Broad science remit

Requires R&D ***now.*** UK Objectives:

- Direct observation of Migdal effect
- Enhanced liquid xenon technology & readout
- Cryogenic low background electronics
- Advanced radiopurity control techniques
- Design studies for a G3 experiment

'Phase 1' (18mo) just approved by STFC
'Phase 2' (24 mo) under evaluation.

In parallel…

STFC Opportunities Call 2019

Lead: Tim Sumner, Imperial College

Feasibility Study for Developing the Boulby Underground Laboratory into a Facility for Future Major International Projects

- Typical experiment requirements and expectations of facility support
- Use cases for 50-500 tonnes liquid targets for Dark Matter and 1000kg solid targets for 0vBB derived from existing experiments/proposals
- Consultation with wider community
- Recommendation for future developments with timescales and costs

To summarise…

Great Progress

To summarise…

Great Progress
Still lots to do

To summarise…

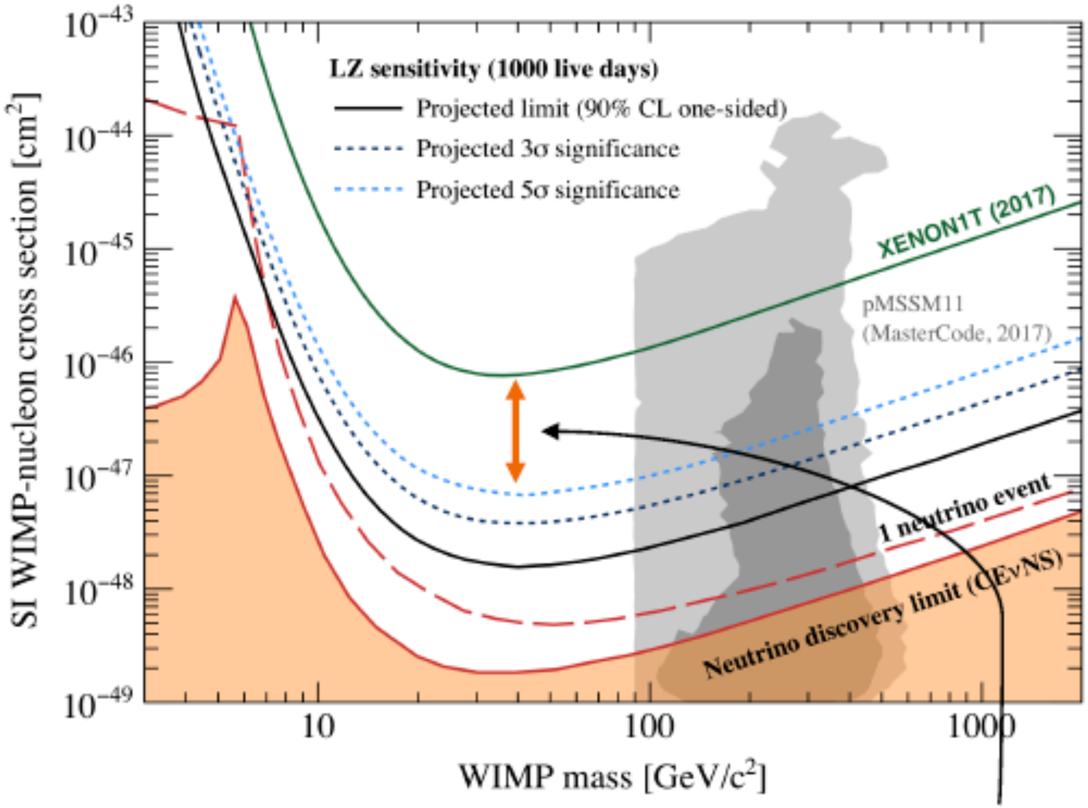
Great Progress
Still lots to do
Roll on 2020!

The LUX-ZEPLIN Collaboration

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics, Korea
- Fermi National Accelerator Laboratory
- Imperial College London
- LIP Coimbra, Portugal
- Lawrence Berkley National Laboratory
- Lawrence Livermore National Laboratory
- MEPhI-Moscow, Russia
- Northwestern University
- Pennsylvania State University
- Royal Holloway, University of London
- SLAC National Accelerator Laboratory
- South Dakota School of Mines and Technology
- South Dakota Science and Technology Authority
- STFC Rutherford Appleton Laboratory
- Texas A&M University
- University at Albany, SUNY
- University College London
- University of Alabama
- University of Bristol
- University of California, Berkeley
- University of California, Davis
- University of California, Santa Barbara
- University of Edinburgh
- University of Liverpool
- University of Maryland
- University of Michigan
- University of Massachusetts
- University of Oxford
- University of Rochester
- University of Sheffield
- University of South Dakota
- University of Wisconsin – Madison
- Washington University in St. Louis
- Yale University

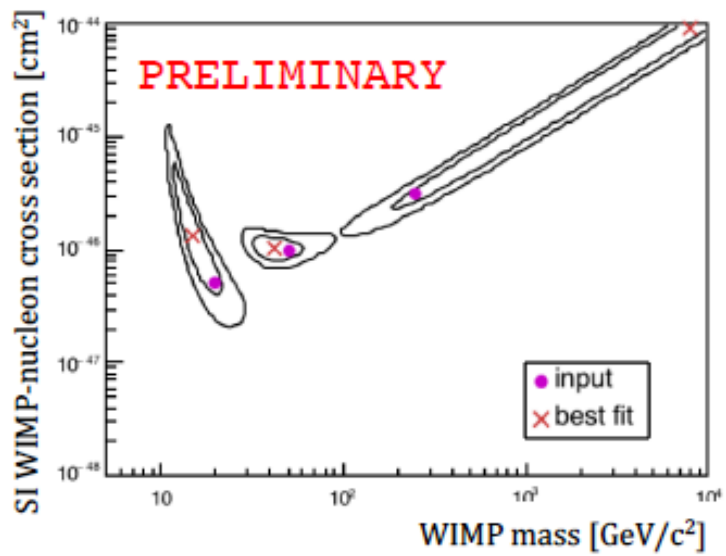
Back up slides

Projected discovery significance



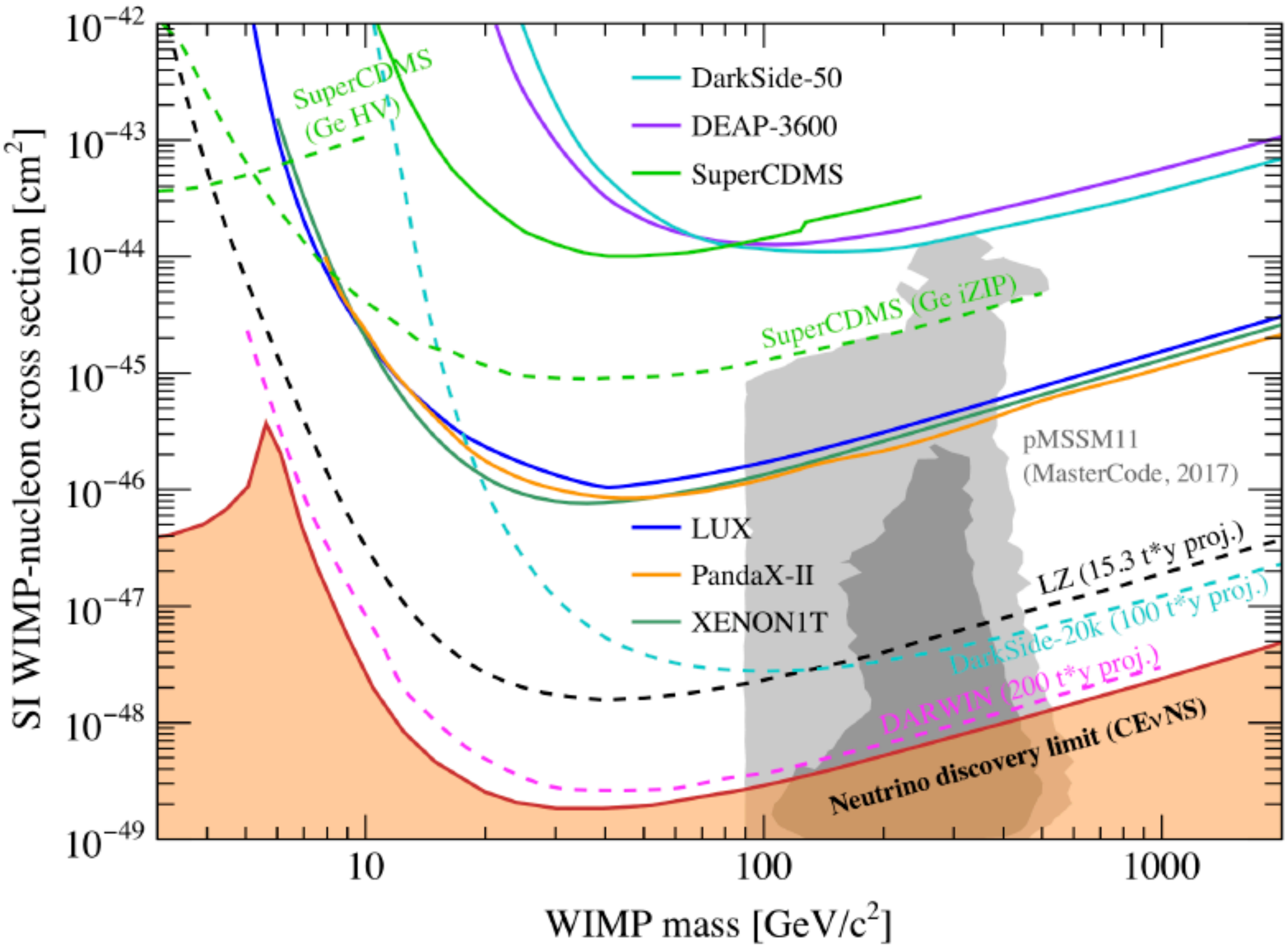
5σ discovery within reach!

Getting ready to characterise WIMP signals from the very start:



- Minimum points
  - 3.8×10^{-48} cm^2 @40 GeV/c^2 (3σ)
  - 6.7×10^{-48} cm^2 @40 GeV/c^2 (5σ)

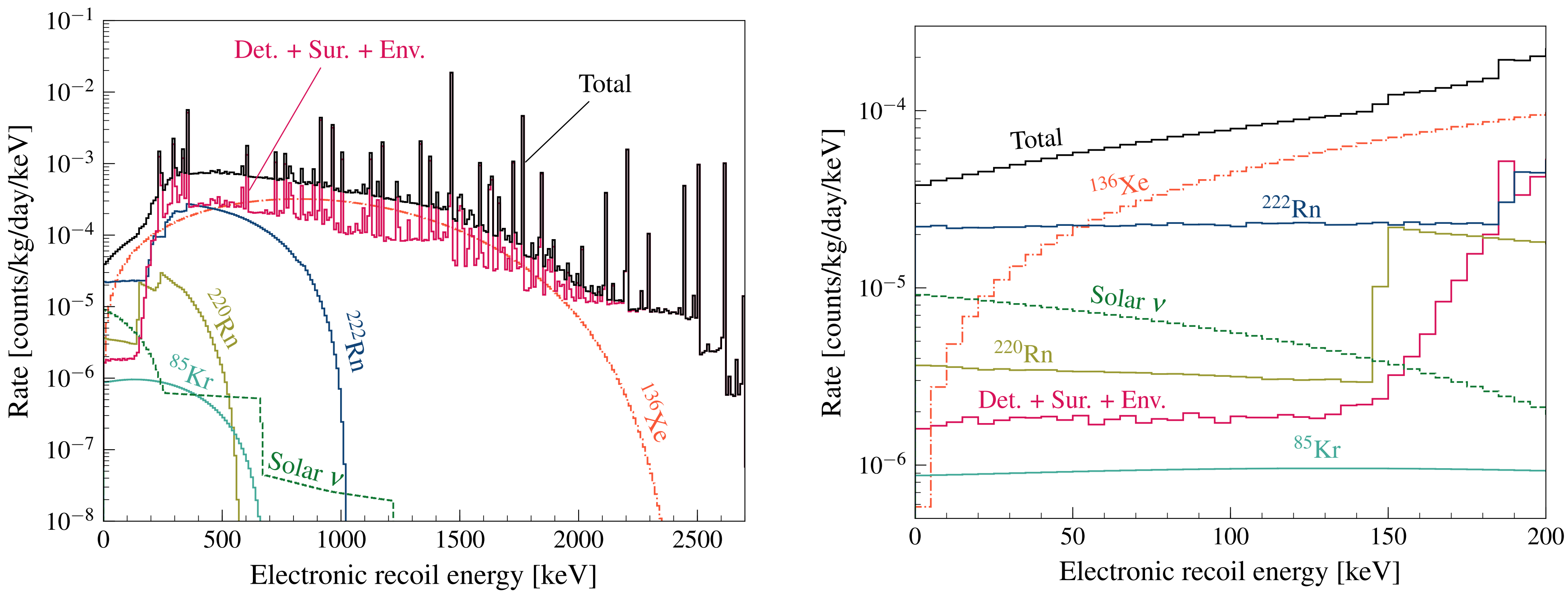
WIMP search: present and future



Detector parameters

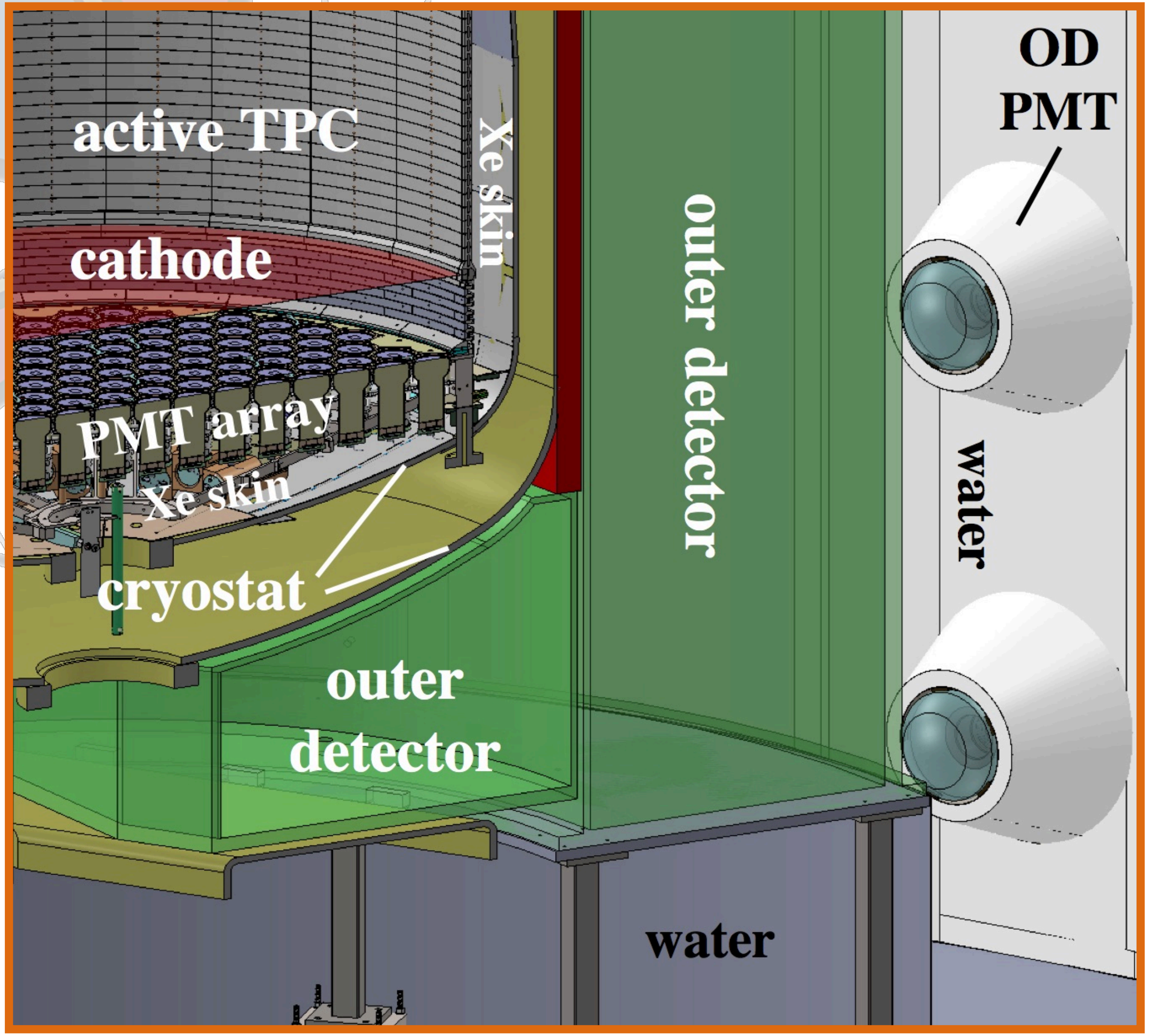
Detector Parameter	Value
Photon Detection Efficiency (PDE)	
PDE in liquid (g_1) [phd/ph]	0.119
PDE in gas ($g_{1,\mathrm{gas}}$) [phd/ph]	0.102
Single electron size [phd]	83
Effective charge gain (g_2) [phd/e]	79
PTFE-LXe reflectivity	0.977
LXe photon absorption length [m]	100
PMT efficiency at 175 nm	0.269
Other Key Parameters	
Single phe trigger efficiency	0.95
Single phe relative width (Gaussian)	0.38
S1 coincidence level	3-fold
S2 electron extraction efficiency	0.95
Drift field [V cm^{-1}]	310
Electron lifetime [μs]	850

Background Single Scatter **ER** events

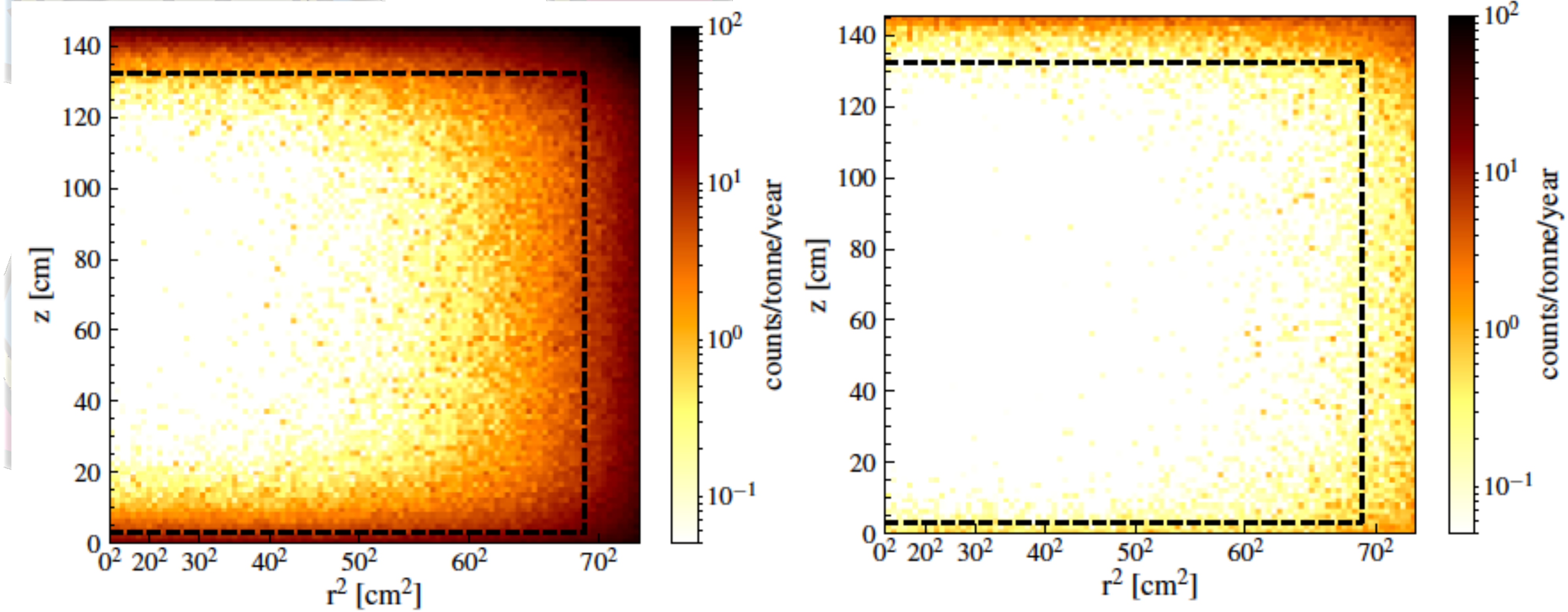


- Energy spectra of electron recoil background from various sources.
- ^{222}Rn dominates at low energies.
- Environmental background and components are not major sources of background events.

"…remembering that we have a skin region, outer detector and water tank for background suppression"

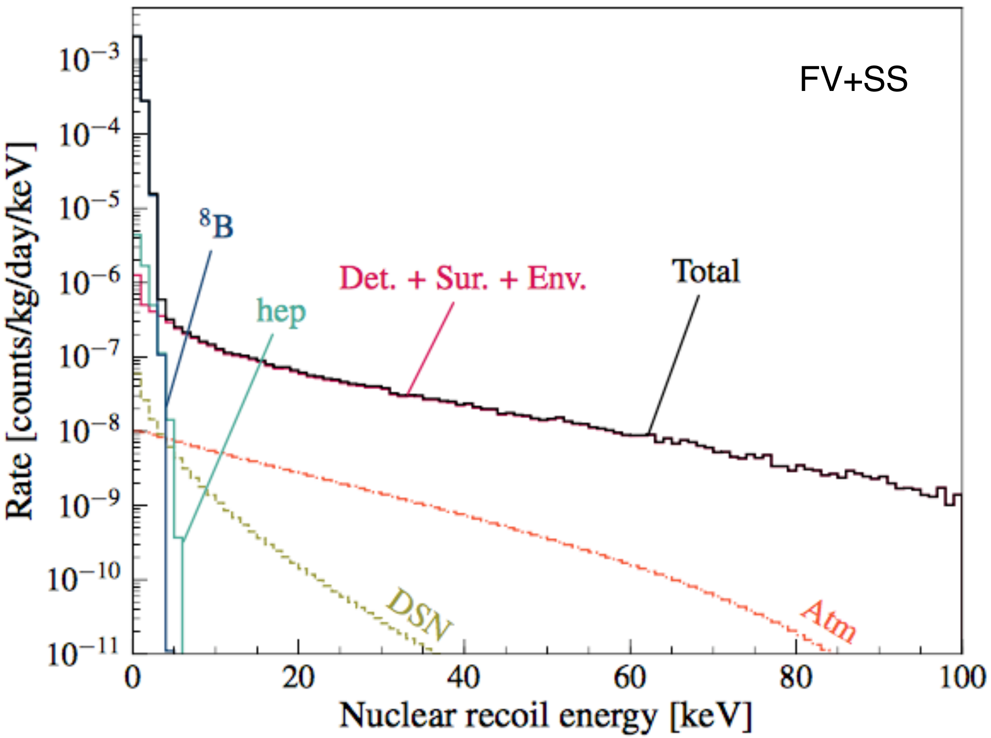


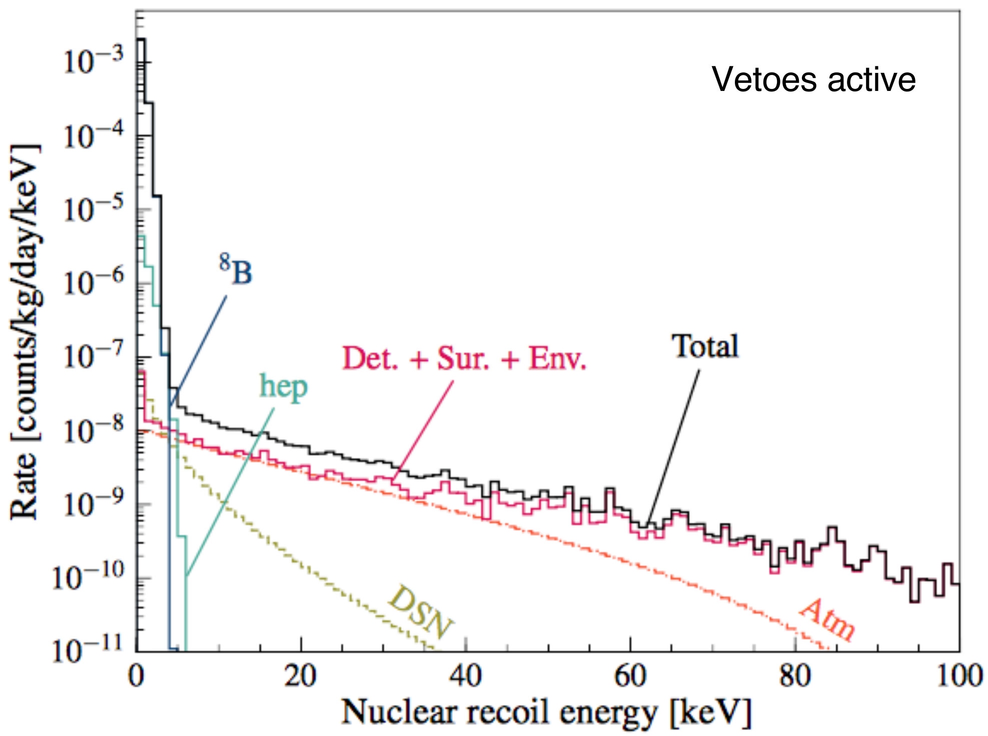
Background Single Scatter **NR** events



- Single scatter nuclear recoil events in the LXe active volume before (left) and after (right) rejecting events in coincidence with veto system (LXe skin and the Outer Detector (OD).

Background Single Scatter **NR** events





- Single scatter NR before (left) and after (right) skin and OD coincidence rejection
- Rate at low energy (<4 keV) dominated by ^{8}B CNNS

Event yields from known sources

- 5.6 tonnes
- 1000 days
- 1.5 to 6.5 keV

Background Source	ER (cts)	NR (cts)
Detector Components	**9**	**0.07**
Surface Contamination	**40**	**0.39**
Laboratory and Cosmogenics	**5**	**0.06**
Xenon Contaminants	**819**	**0**
222Rn	681	0
220Rn	111	0
natKr (0.015 ppt g/g)	24	0
natAr (0.45 ppb g/g)	3	0
Physics	**322**	**0.51**
136Xe 2νββ	67	0
Solar neutrinos (pp+7Be+13N)	255	0
Diffuse supernova neutrinos	0	0.05
Atmospheric neutrinos	0	0.46
Total	1195	1.03
with 99.5% ER discrim., 50% NR eff.	**5.97**	**0.51**

Event yields from known sources

- 5.6 tonnes
- 1000 days
- 1.5 to 6.5 keV

Radon dominates ER backgrounds

Neutrinos (atomic electron recoils)

Background Source	ER (cts)	NR (cts)
Detector Components	**9**	**0.07**
Surface Contamination	**40**	**0.39**
Laboratory and Cosmogenics	**5**	**0.06**
Xenon Contaminants	**819**	**0**
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Neutrons, including alpha-n on PTFE

Coherent scattering of atmospheric ν's on Xe nuclei

Event yields from known sources

- 5.6 tonnes
- 1000 days
- 1.5 to 6.5 keV

Background Source	ER (cts)	NR (cts)
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Simple WIMP search box "Cut & Count" type numbers