Experimental Techniques in Dark Matter and Neutrino Physics
Rare Event Searches

Jocelyn Monroe

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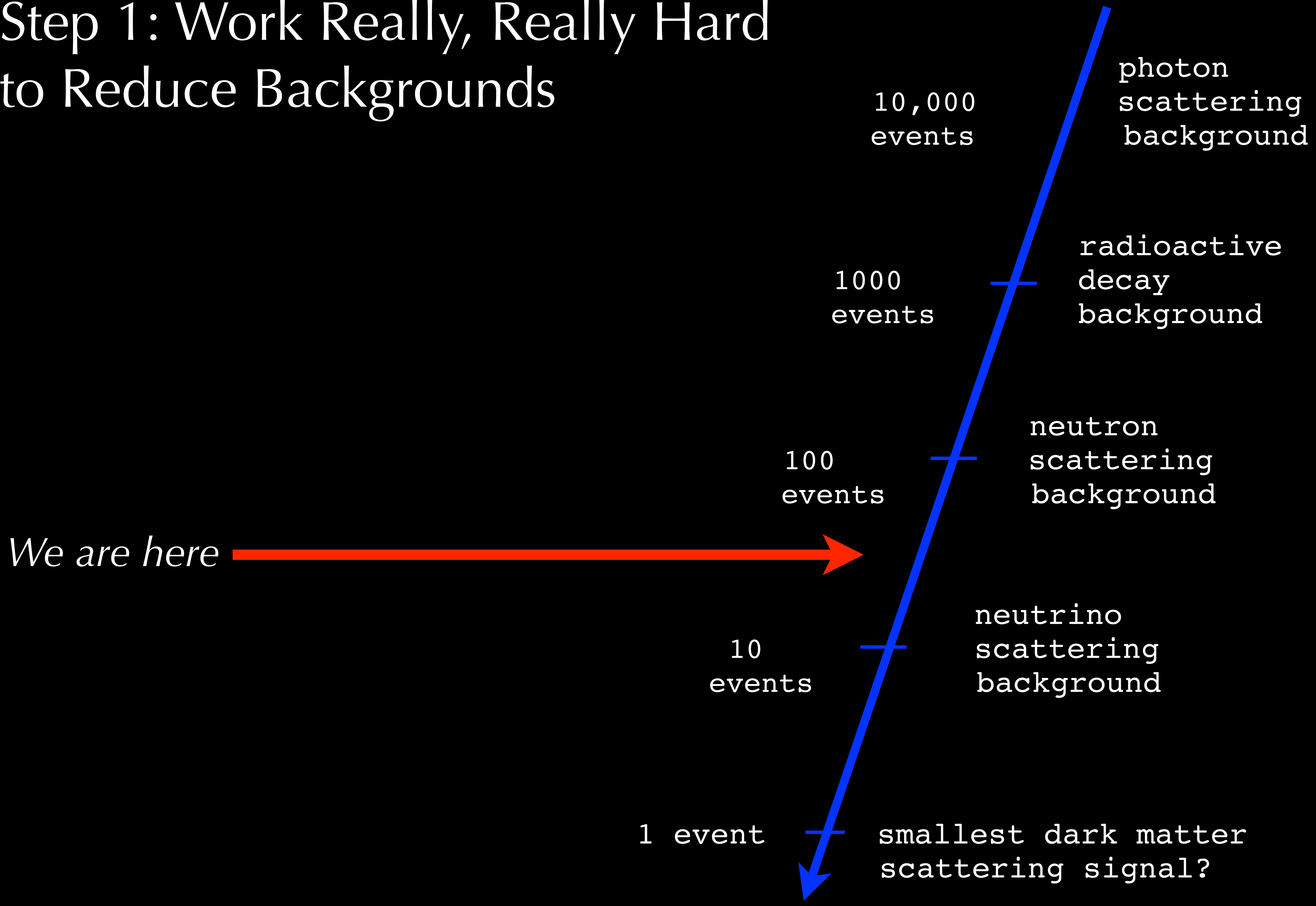
Invisibles School 2023
Bad Honnef, DE

Outline

1. The Evidence for Dark Matter
2. Dark Matter Detection Experimental Techniques
3. **Dark Matter Search Status and Prospects**
4. Neutrino Physics in Dark Matter Detectors

Experiment Strategy

Step 1: Work Really, Really Hard to Reduce Backgrounds



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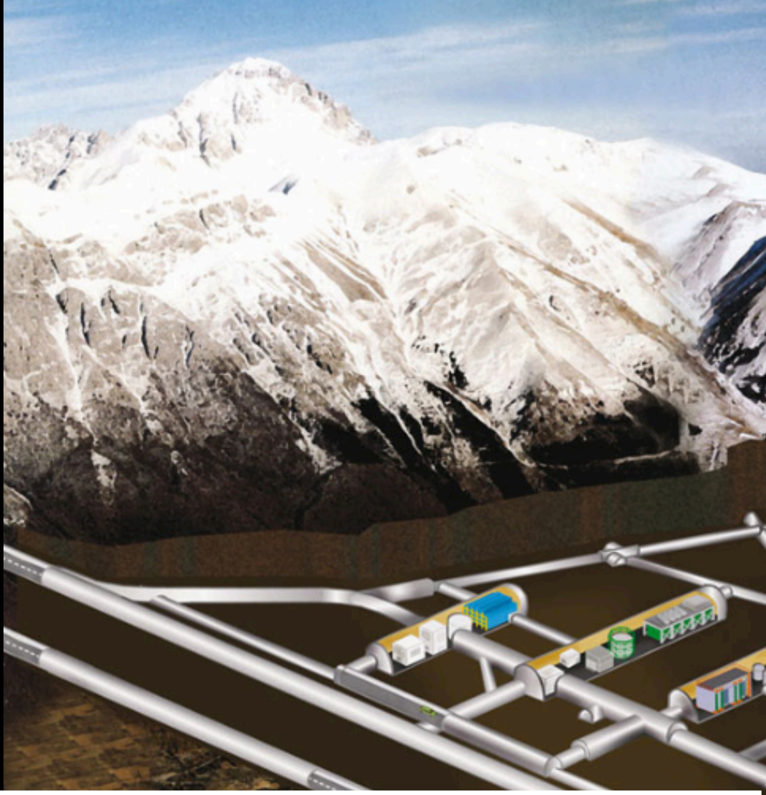

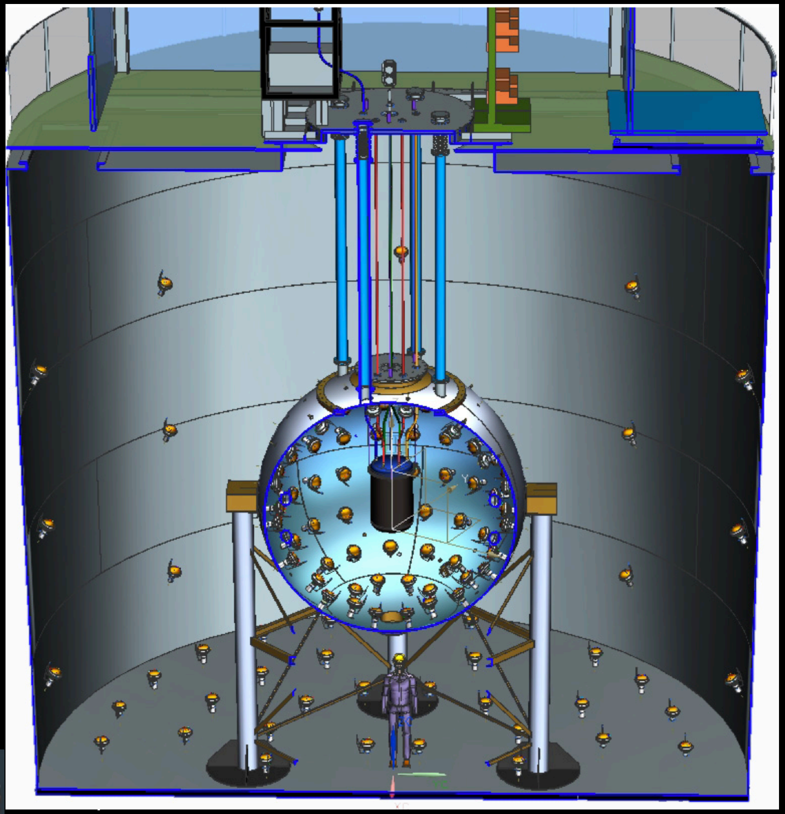

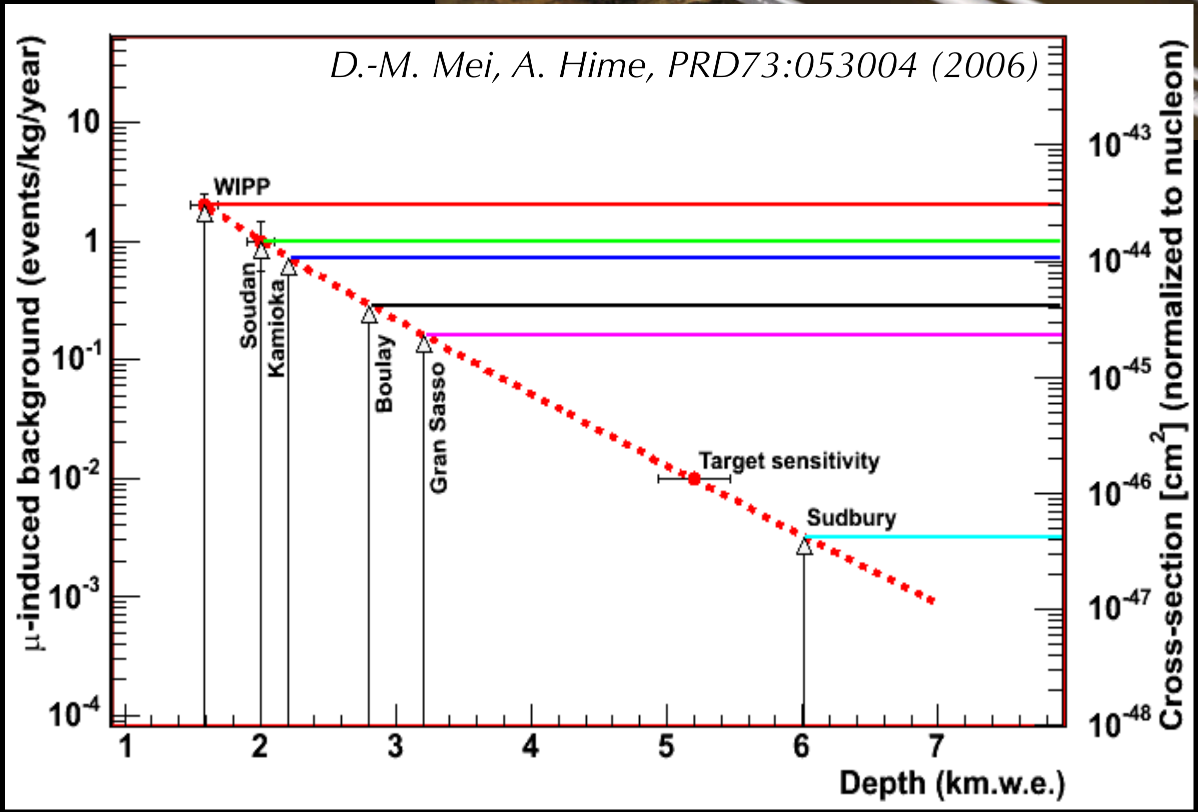

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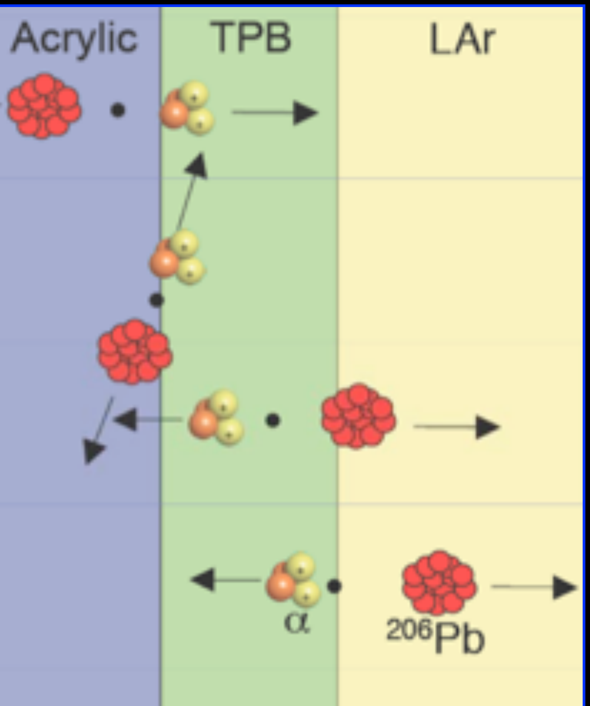

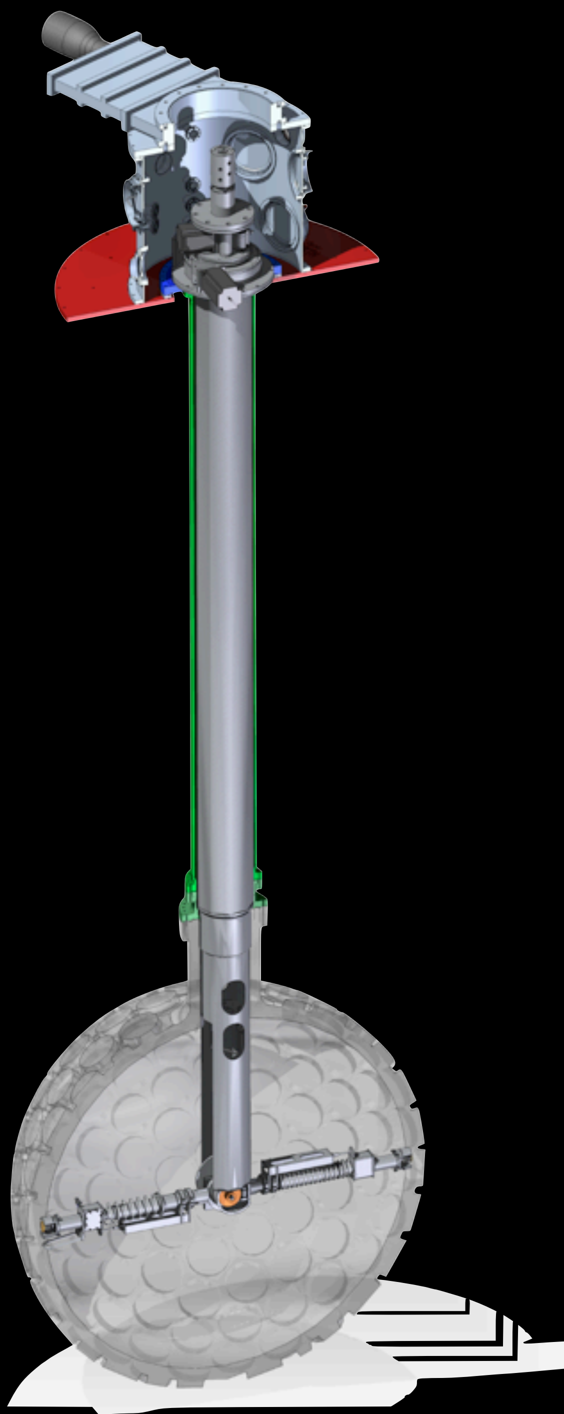

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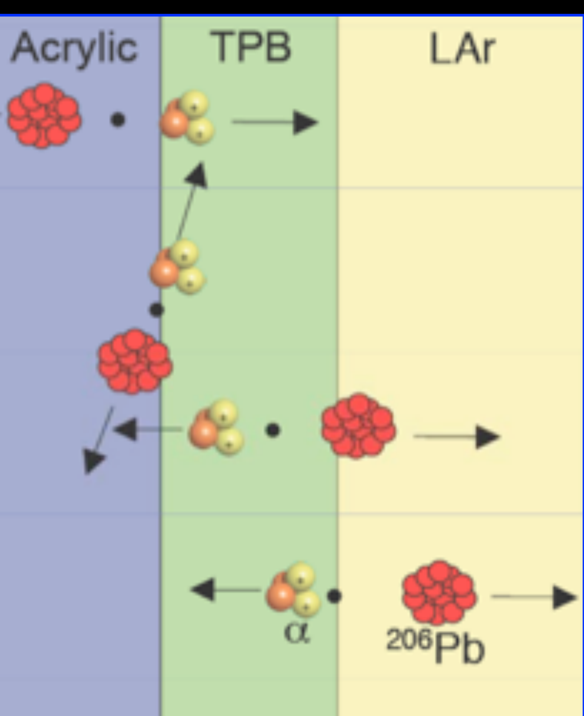

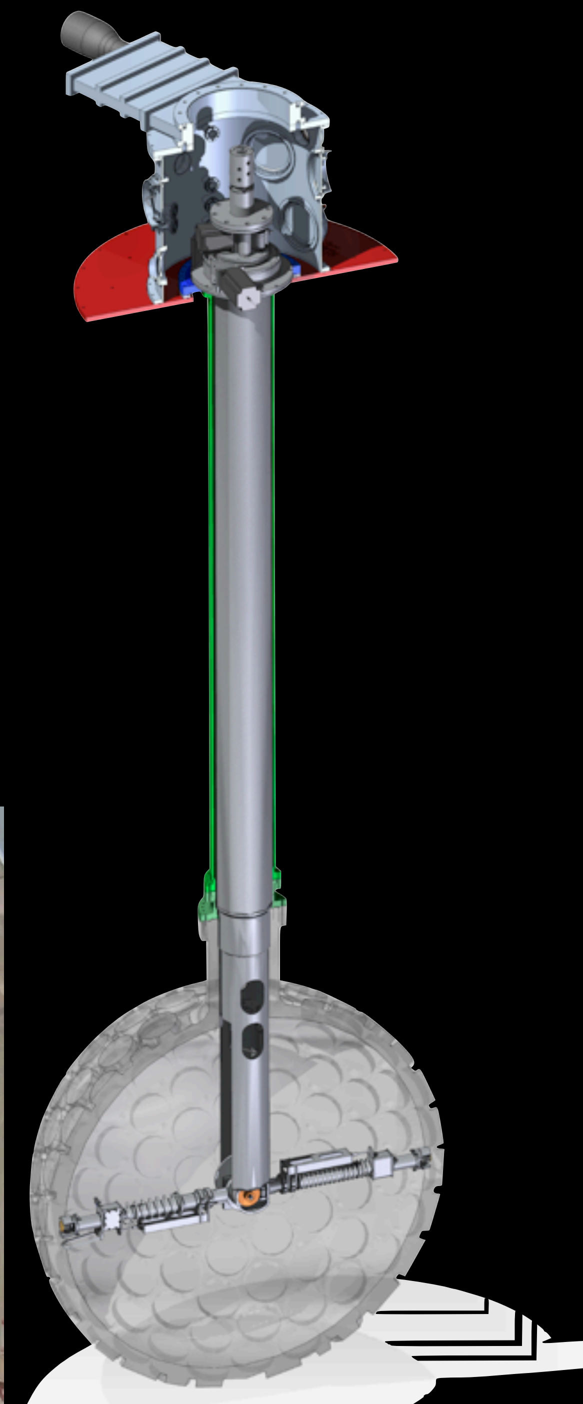

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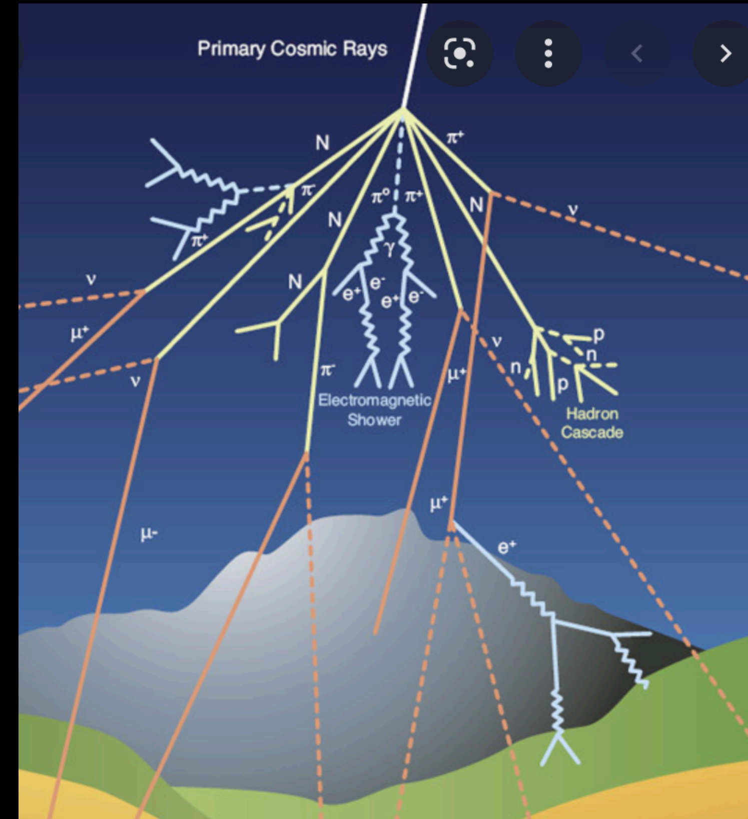

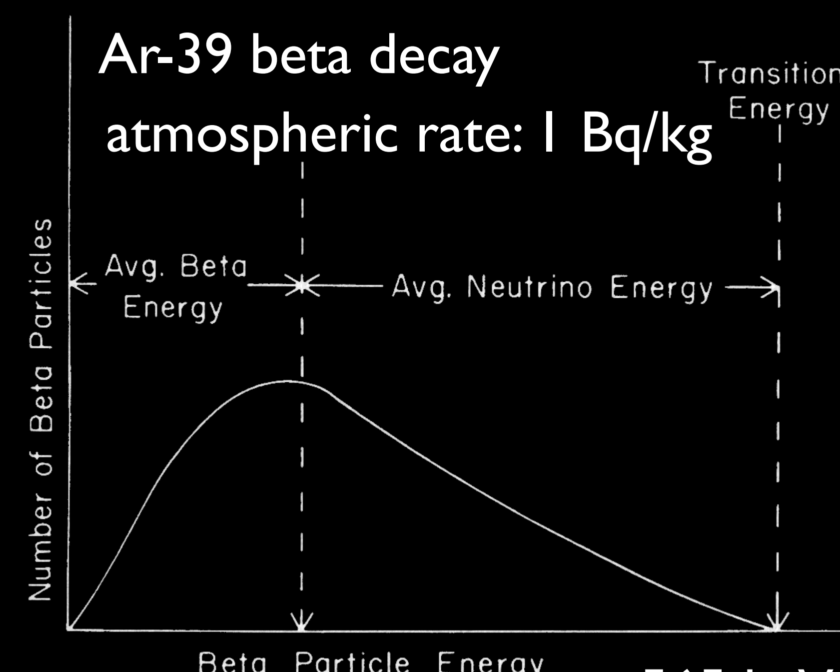

565 keV

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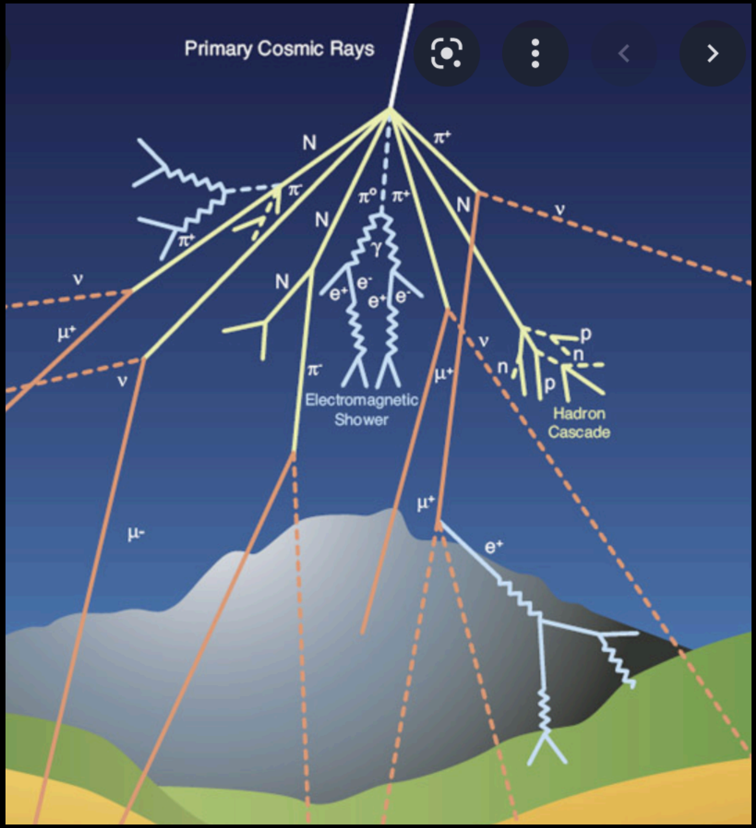

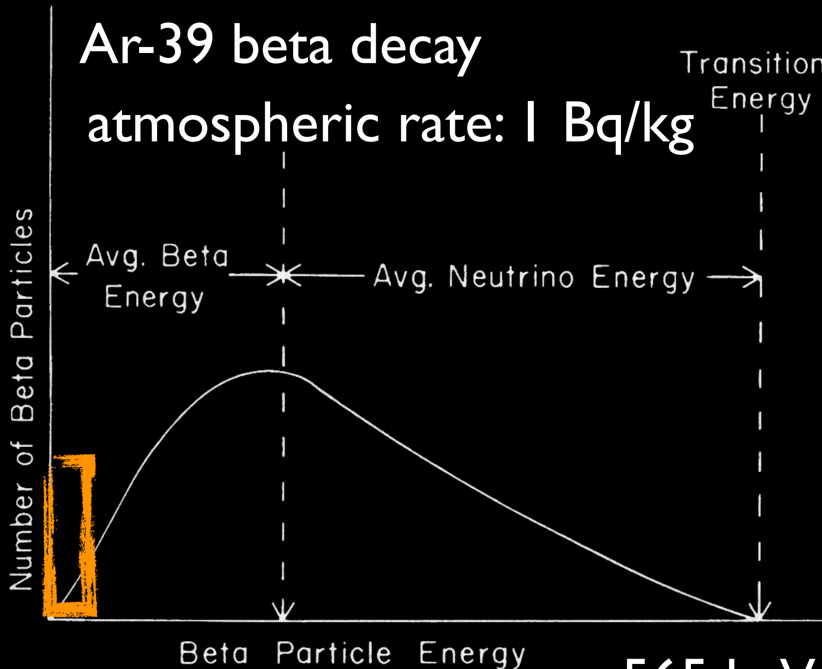

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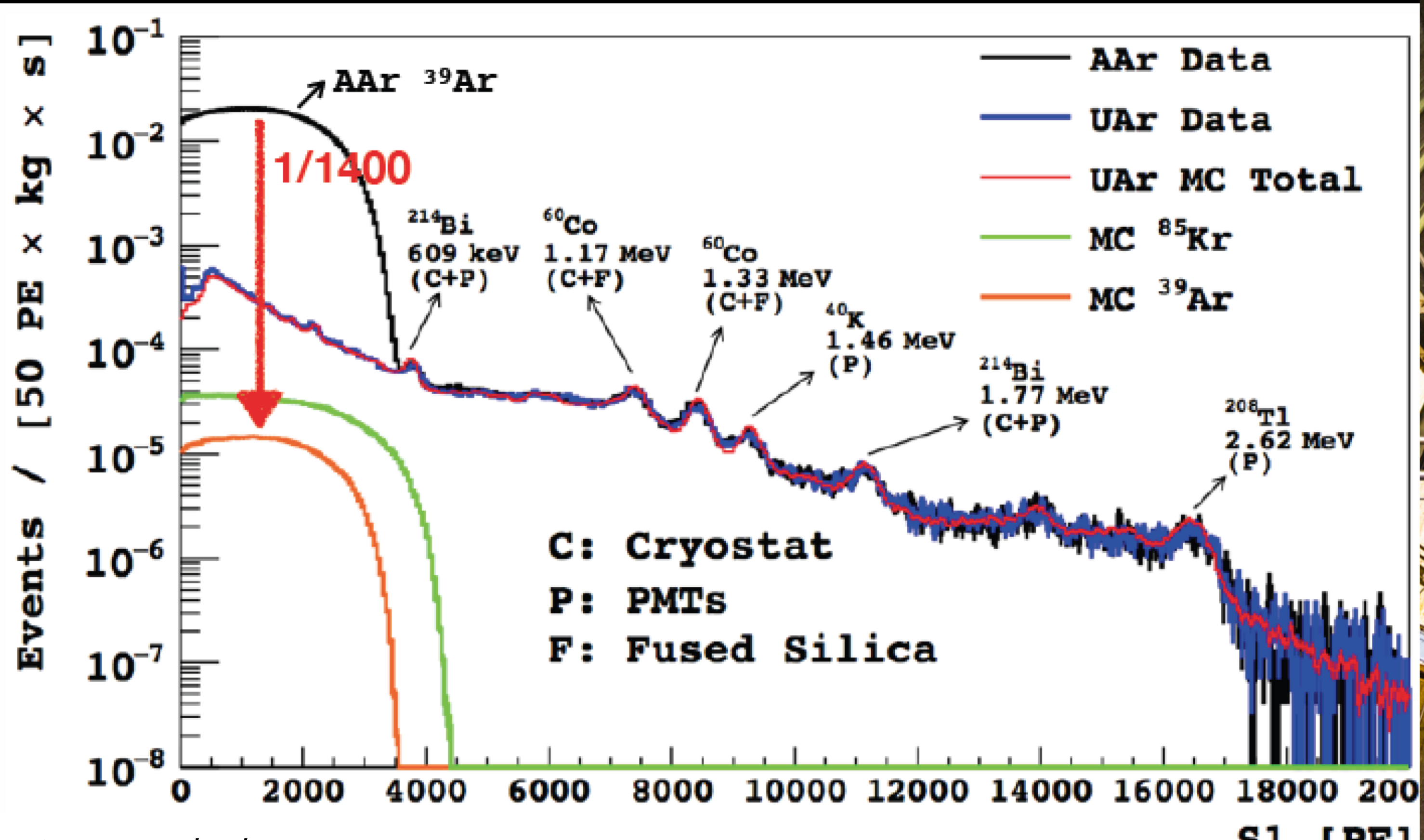
Agnes et al., Eur.Phys.J.C 81 (2021)



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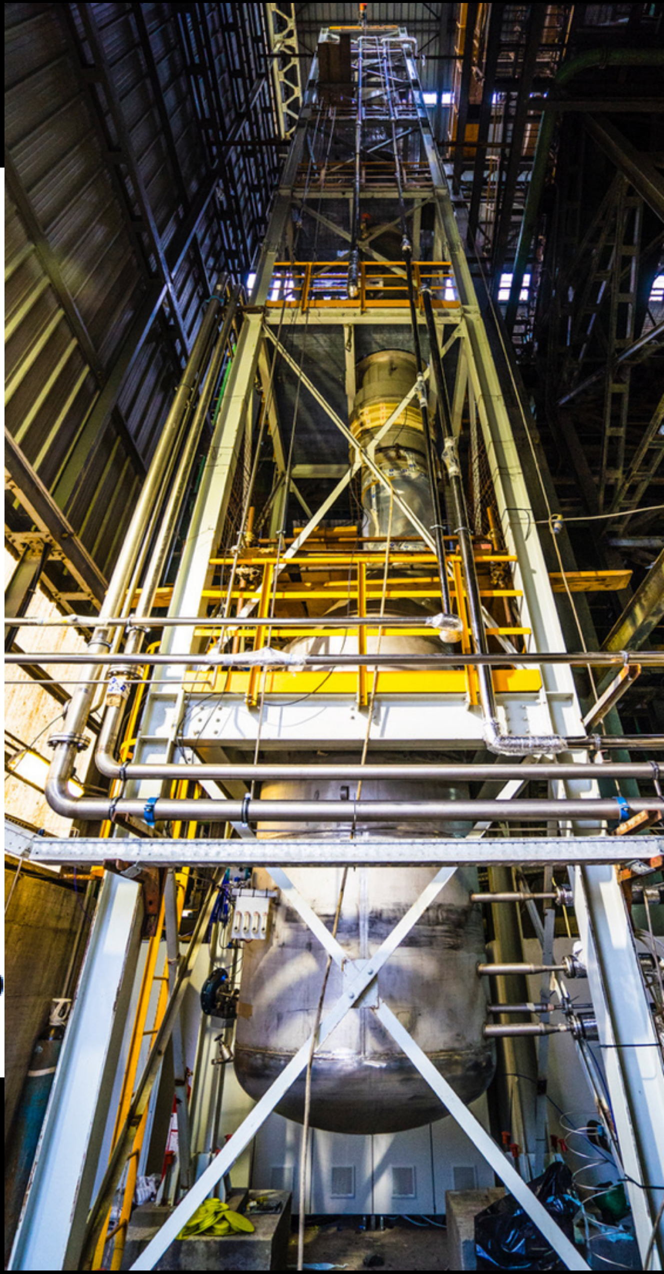

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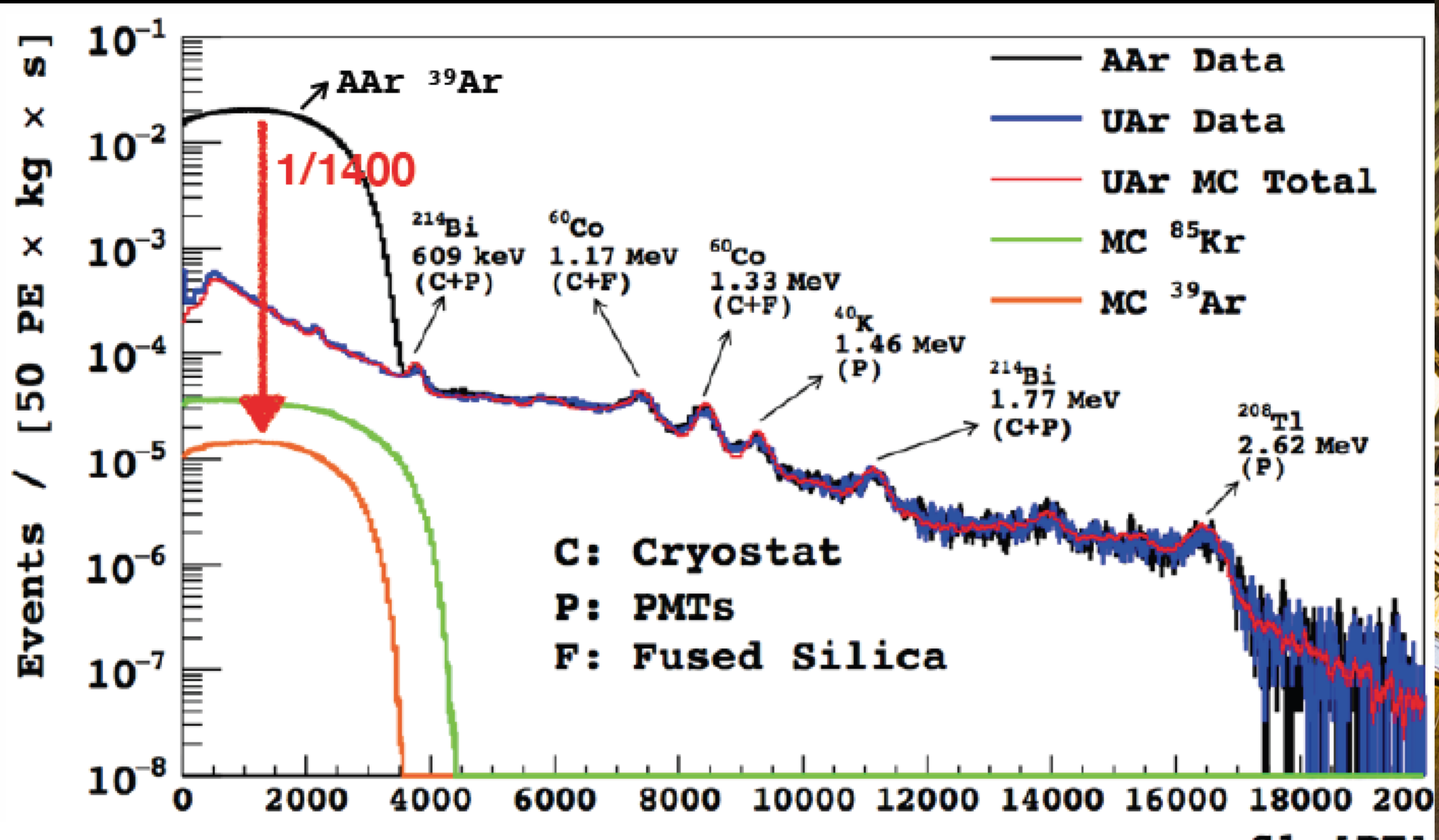

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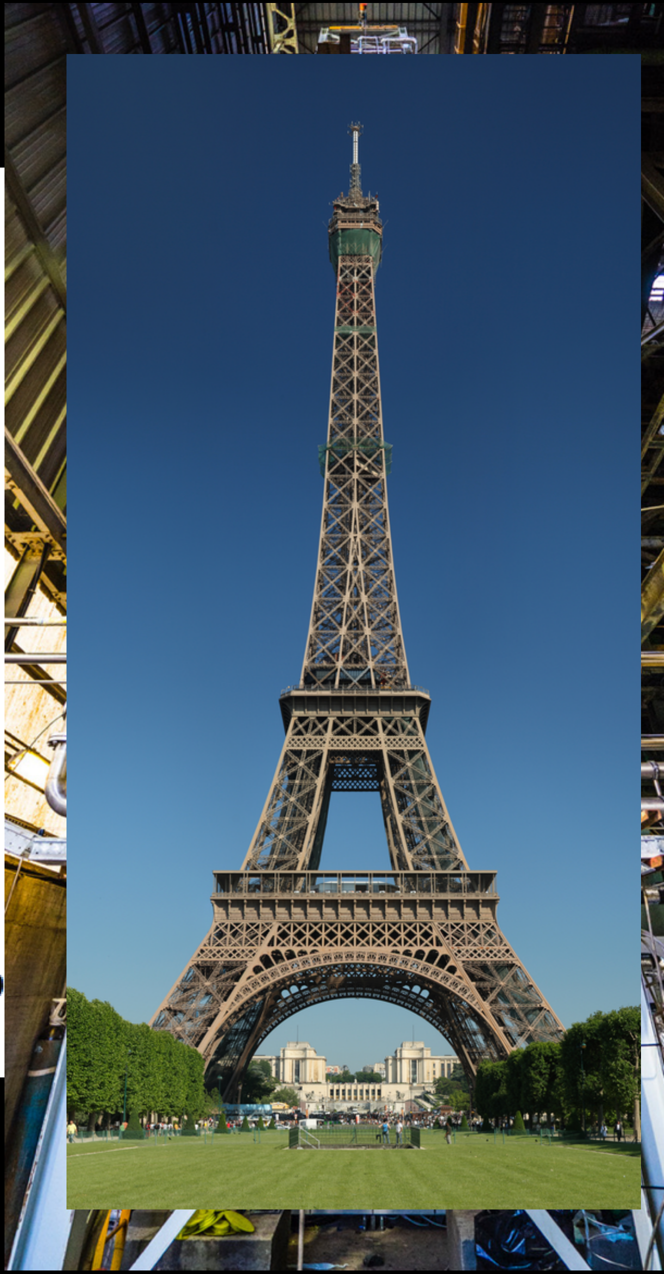
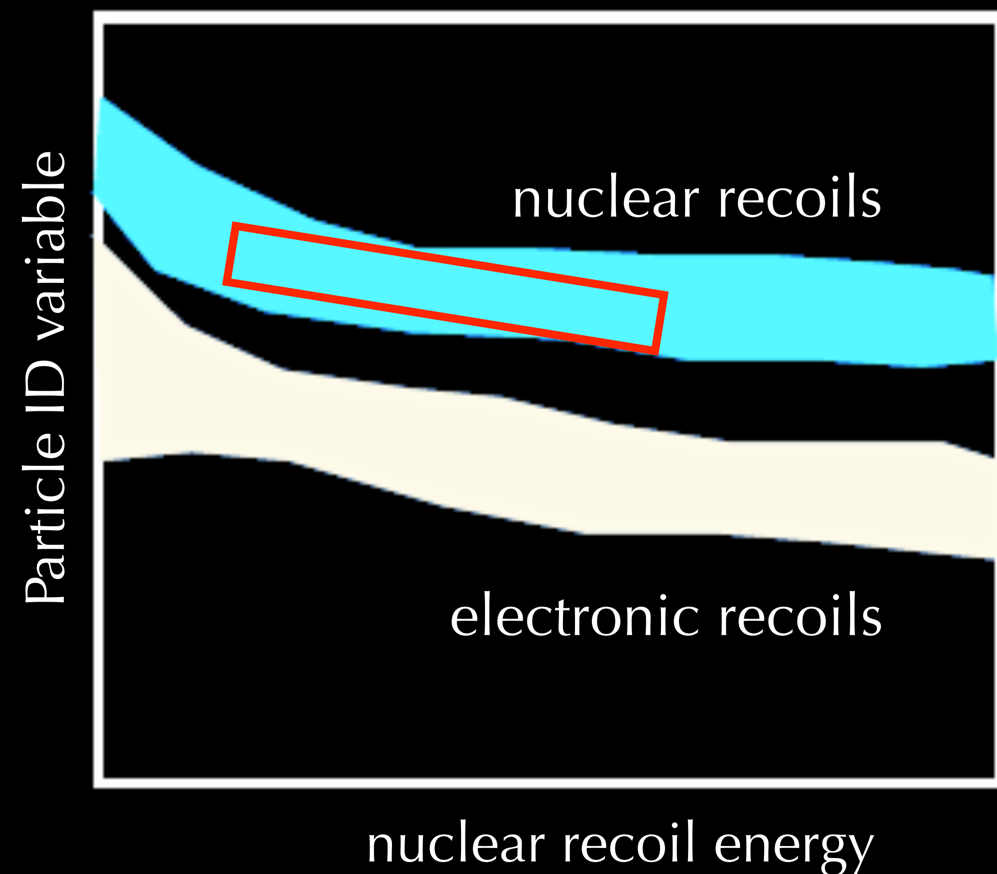


Step 2: Define Signal Region of Interest

1. using calibration data, define signal and background regions

2. using simulation, define a region with zero expected background events



(*any events* in the blind region are signal candidates)

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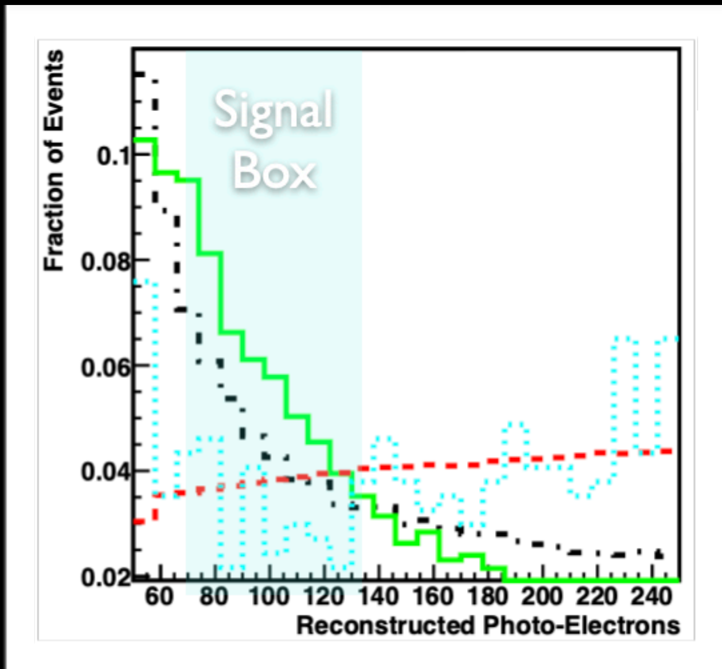
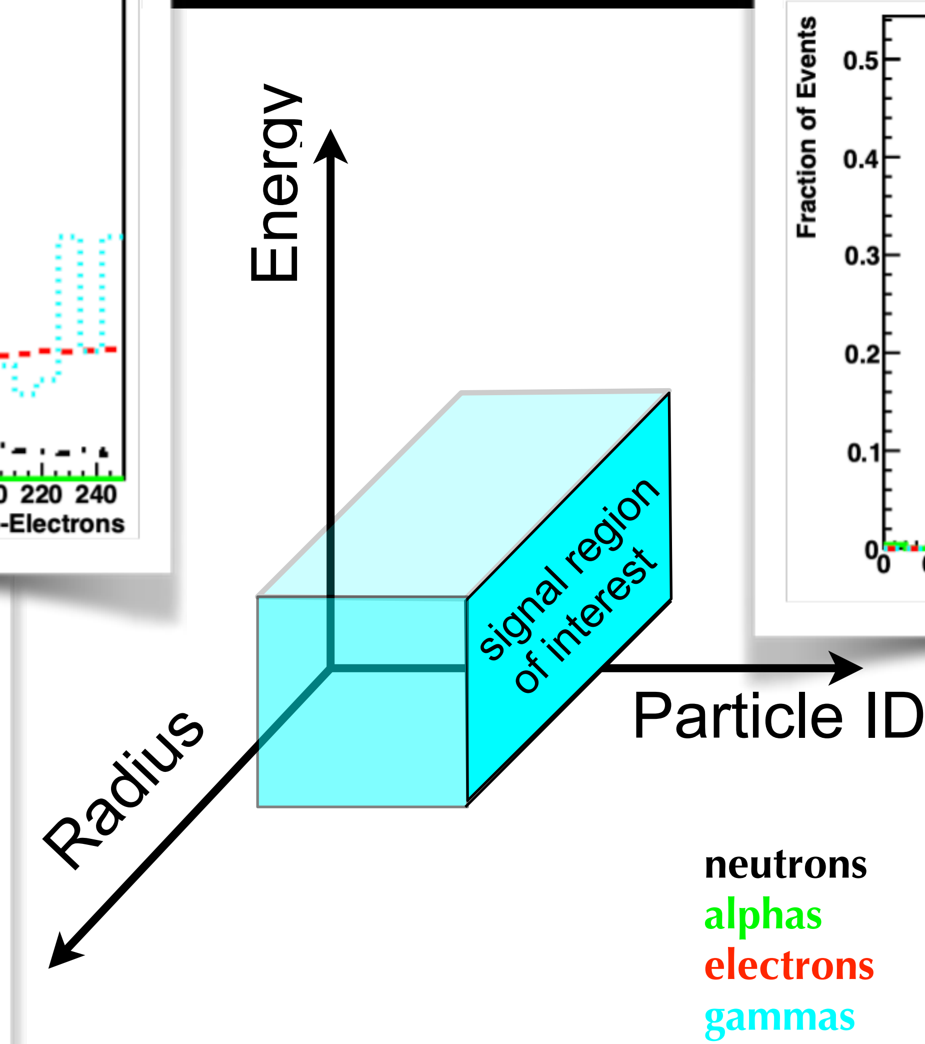
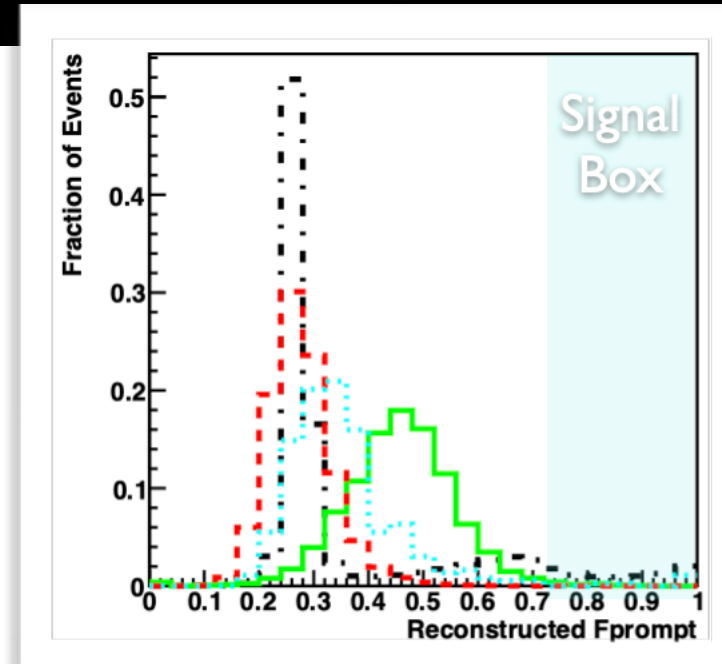
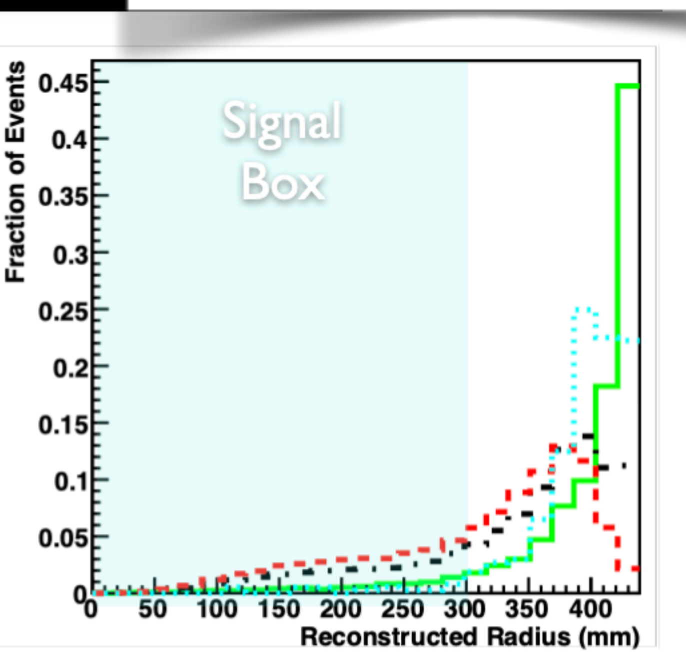








DEAP-3600 simulation of reconstructed background distributions, in energy, radius, PID (Fprompt)

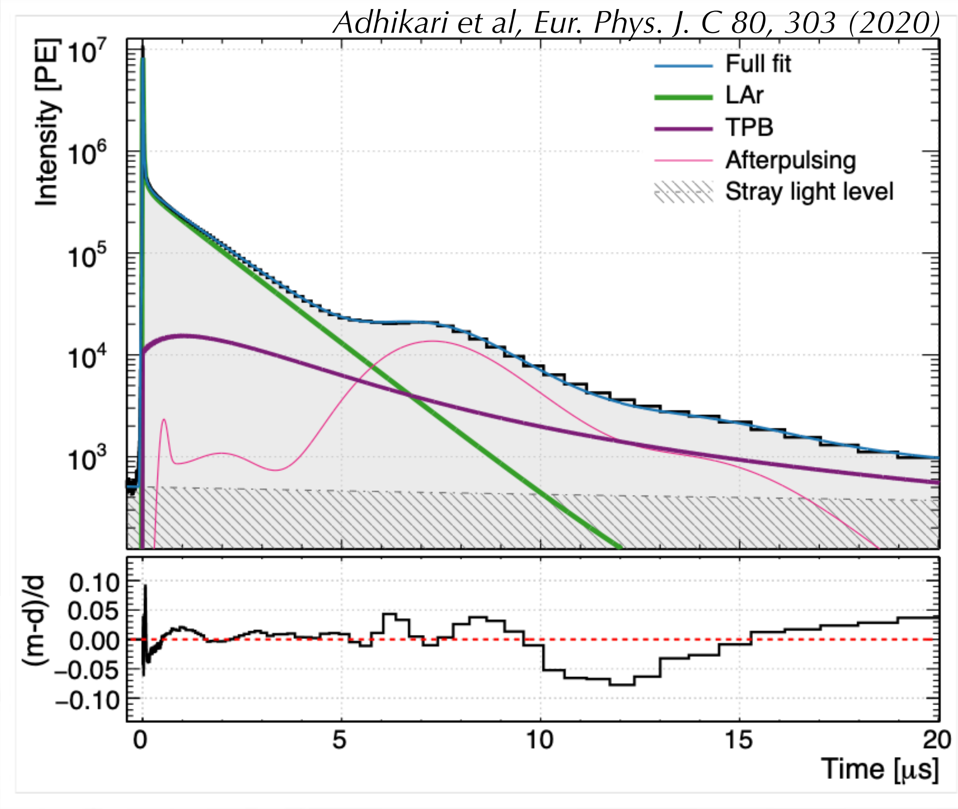
Step 2: Define Signal Region of Interest

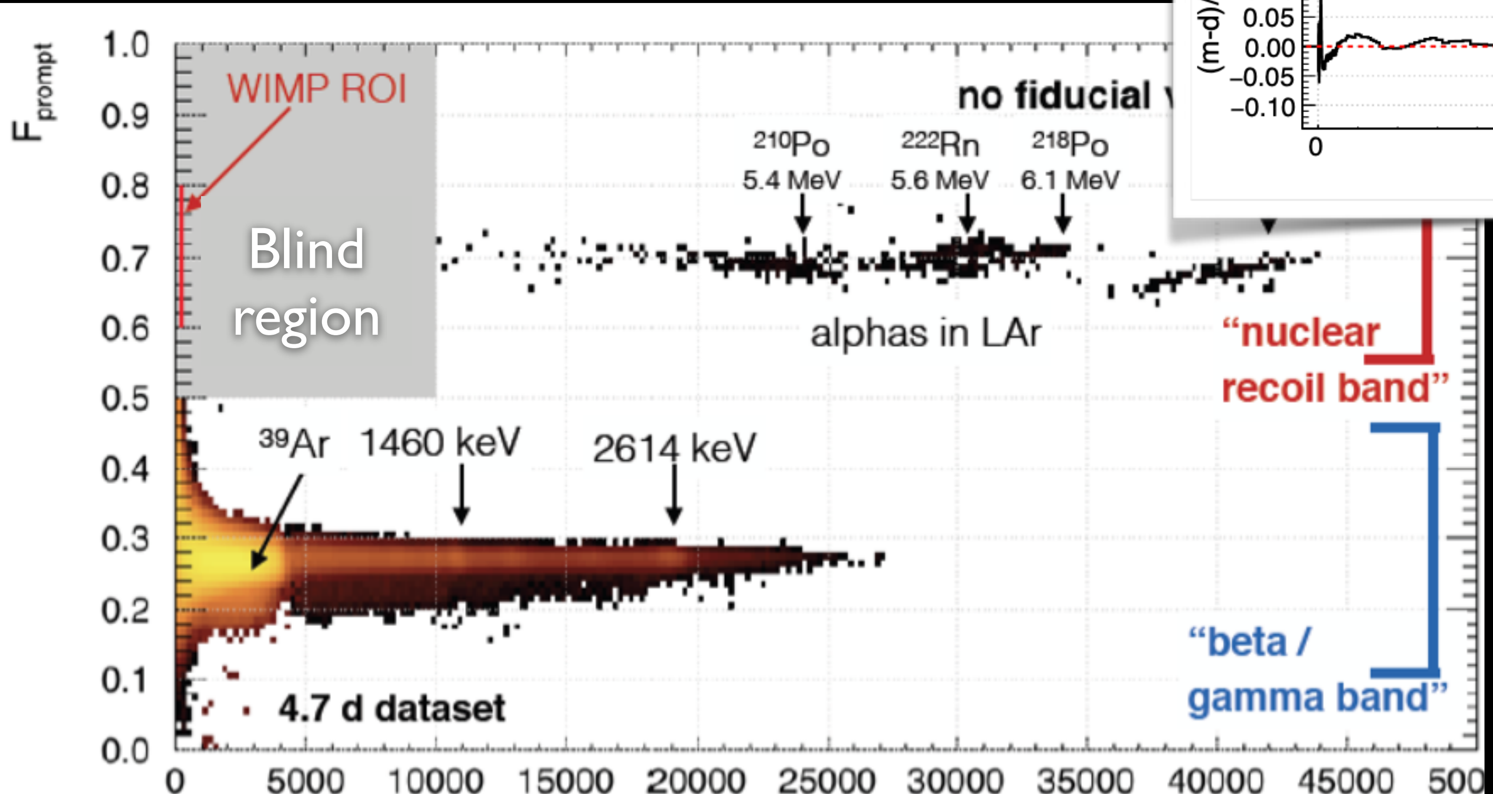
Particle ID reconstruction:

1. **S1**: count scintillation photons only — these contain the LAr physics!

   Akashi-Ronquest at al., Astropart.Phys. 65 (2015),
   Butcher et al., Nucl.Instrum.Meth.A 875 (2017) 87-91

2. Construct particle ID estimator from timing (e.g. prompt fraction vs. PE)

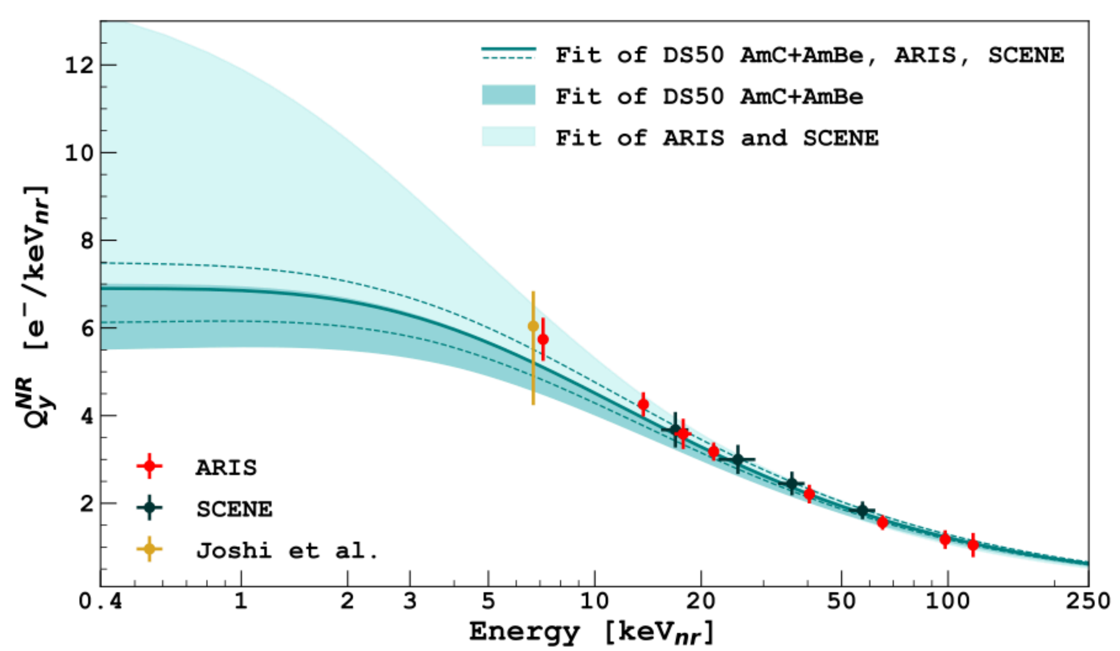




$$F_{\mathrm{prompt}} = \frac{\sum_{t>t_{\mathrm{start}}}^{t<t_{\mathrm{prompt}}} n(t)}{\sum_{t>t_{\mathrm{start}}}^{t<t_{\mathrm{total}}} n(t)}$$

Step 2: Define Signal Region of Interest

Agnes et al., Phys. Rev. D 104, 082005 (2021)



Energy reconstruction in dual phase:

S2: accesses lower energies via gain in gas (*g2* = 23+/-1 PE/e-)

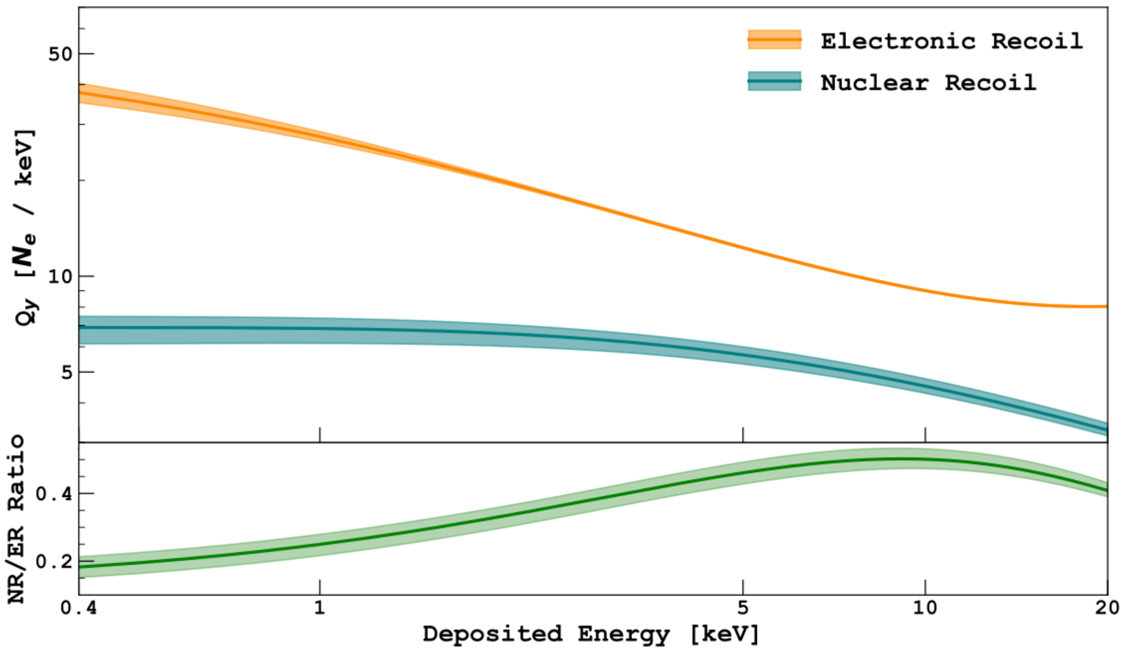
1. Measure S2 to infer number of e- extracted into the gas pocket, $N_{i.e.}$

$$N_{i.e.} = (1-r)N_i = \frac{S_2}{g_2} - 1$$

N_i = number of primary e-
= ionisation energy deposited / *w*
w = 19.5 eV: avg. work function
r = e- recombination probability

2. Reconstruct recoil kinetic energy:

$$E_{NR} = \frac{N_{i.e.}}{Q_y^{NR}}$$



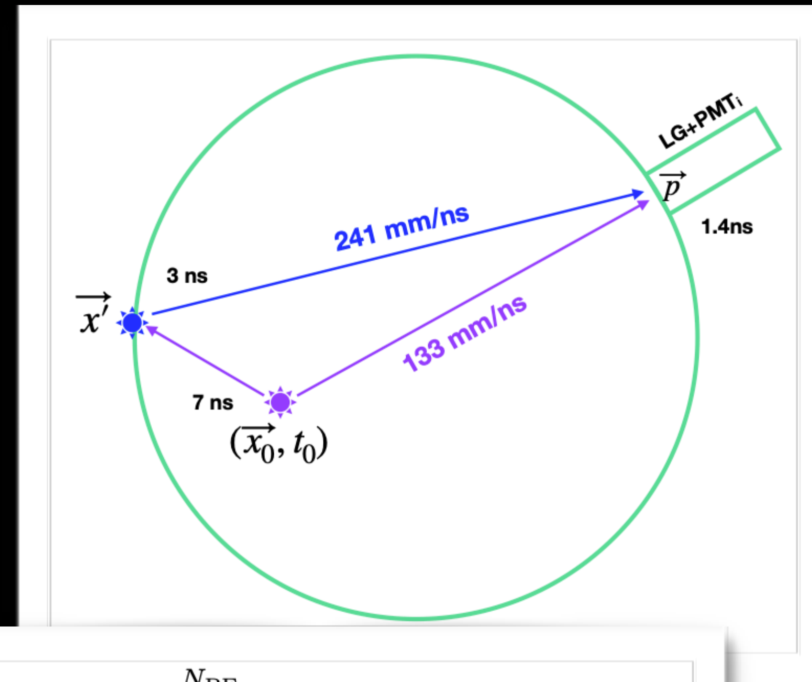
Step 2: Define Signal Region of Interest

Position reconstruction:

1. Single phase

   Compare expected $S1_i(\mathbf{x}_0,t_0)$ given event vertex hypothesis with measured $S1_i(\mathbf{x}_0,t_0)$

   At scale of DEAP-3600, resolution on $\mathbf{x}_0$ from $S1_i(\mathbf{x}_0)$ comparable with $S1_i(t_0)$: ~few cm

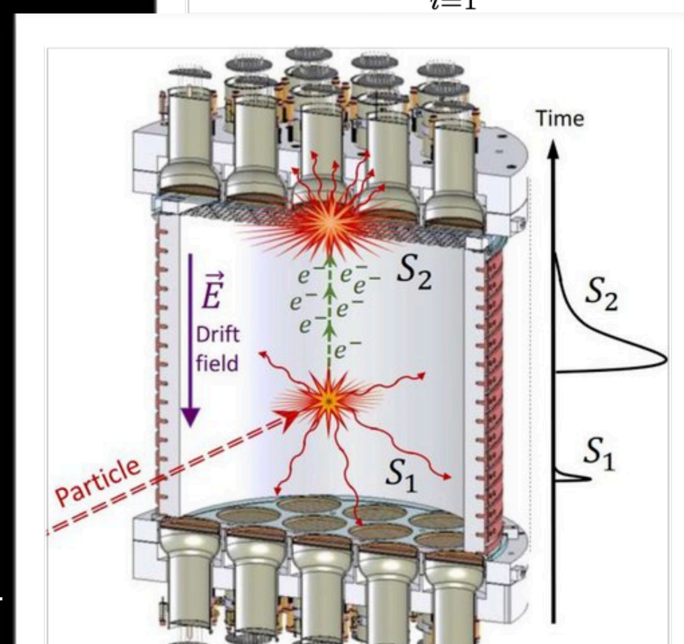


$$\ln \mathcal{L}(t_0, \vec{x}_0) = \sum_{i=1}^{N_{\mathrm{PE}}} \ln \mathcal{L}^{t\ \mathrm{res.}}(t_i - t_0; \vec{x}_0, \mathrm{PMT}_i),$$

2. Dual phase

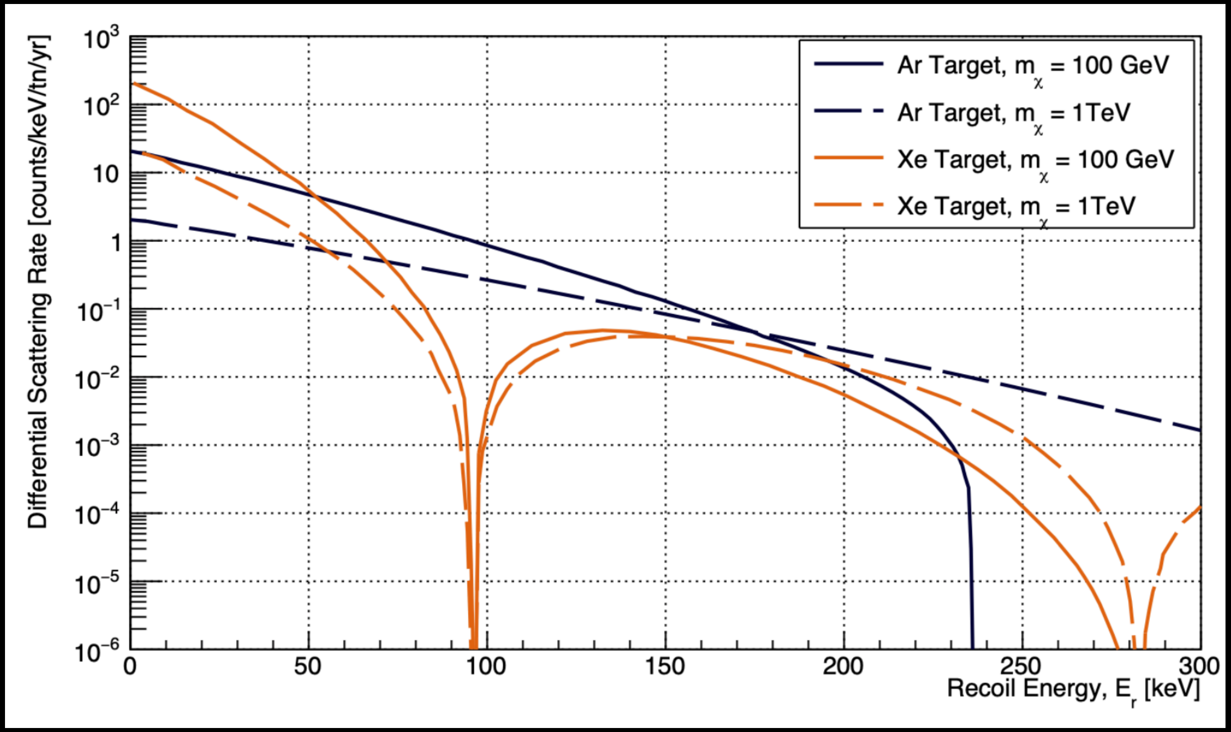
   Match S1 and S2 pulses in an event

   Plane perpendicular to **E** field: $S2_i(\mathbf{x}_0,t_0)$
   Plane parallel to **E** field: $z(t_{S2} - t_{S1})$
   resolution: ~cm (x,y) and ~mm (z)



"pixel pitch:"
⊥E: PMT radius
∥E: sampling rate in time

Step 3: Measure *the* Region of Interest



Two types of (blind) analyses:
1) counting events in region of interest

2) likelihood-based fit for signal above background distributions

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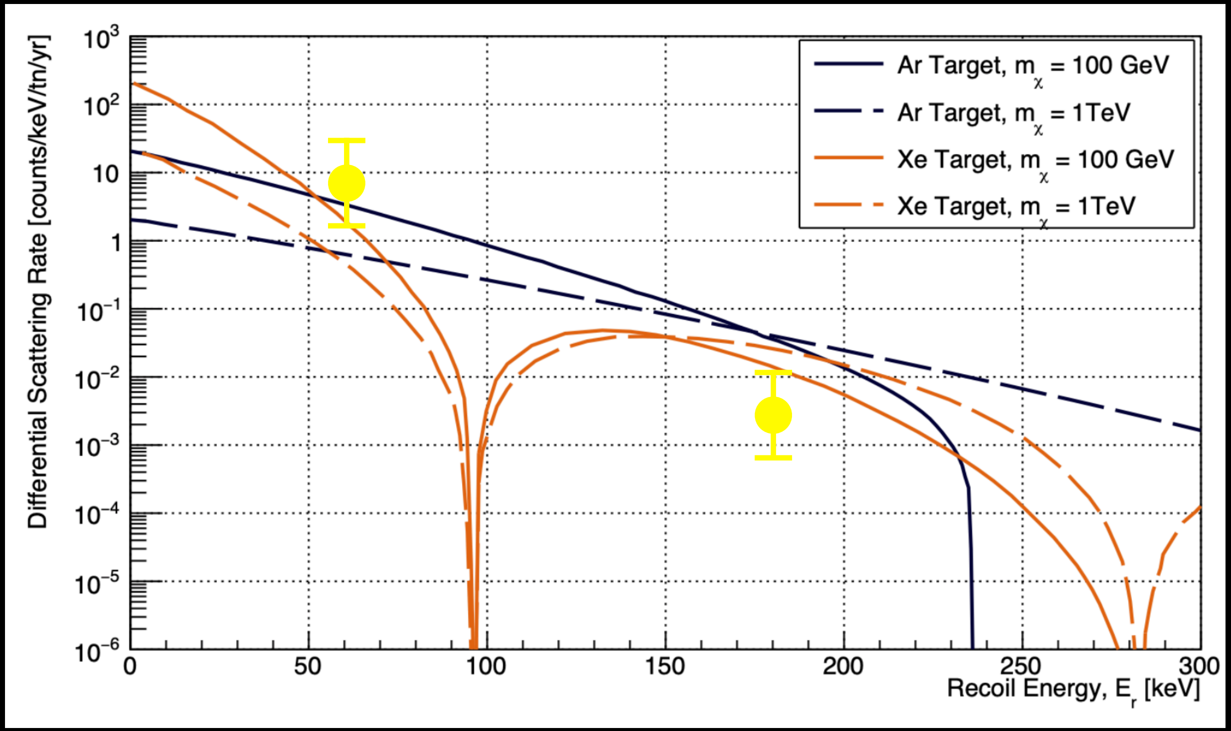

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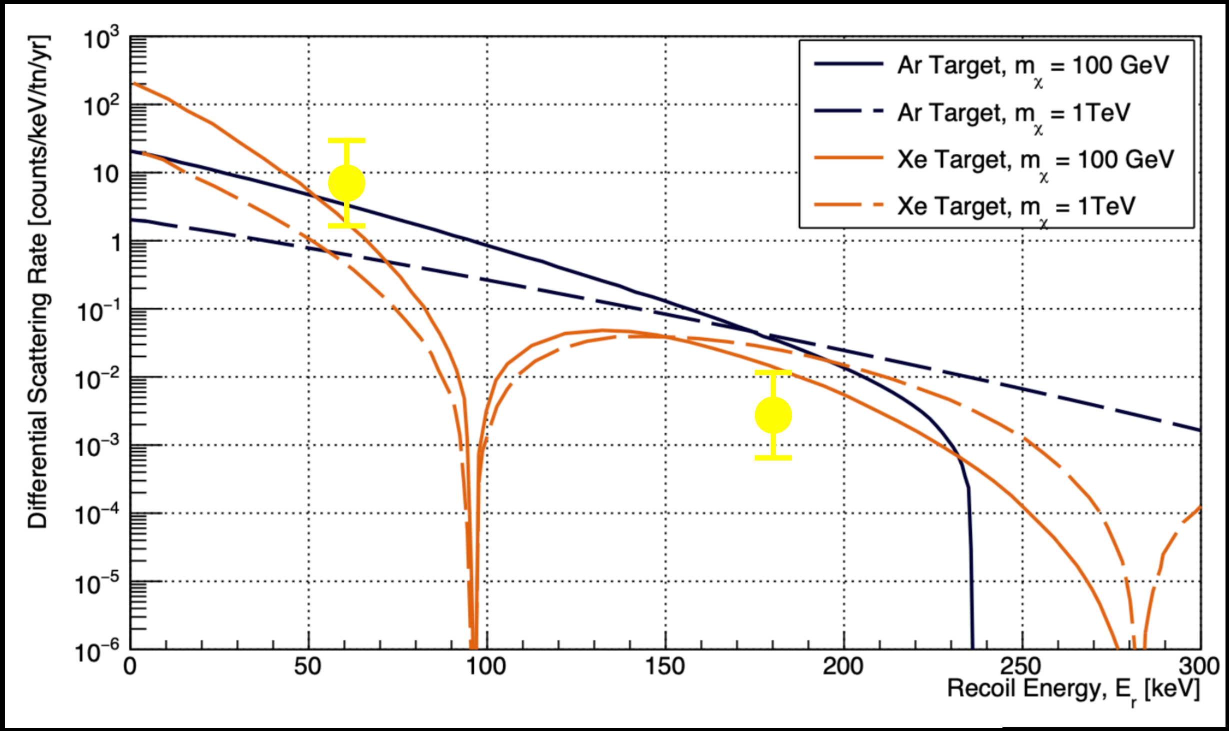

theorist:

what model explains this rate?

see a signal or set a limit?

experimentalist:

Jocelyn Monroe

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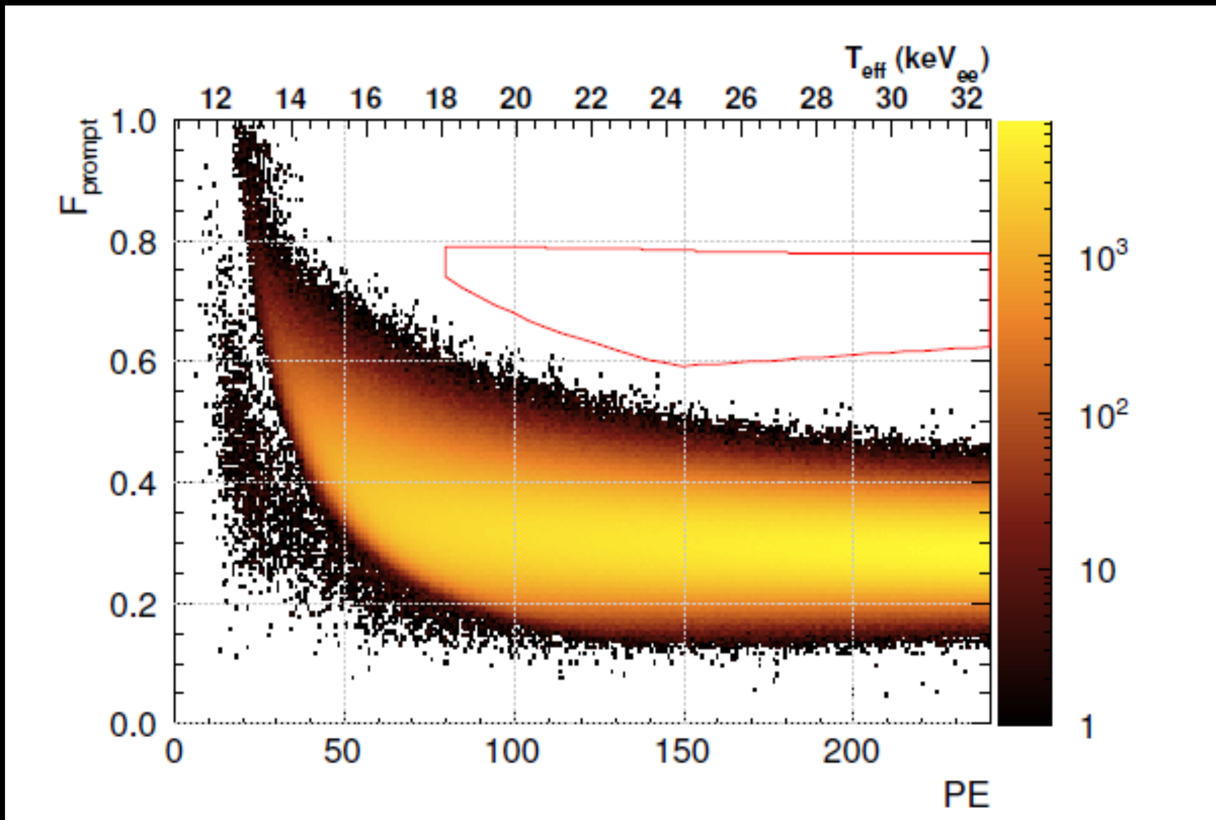

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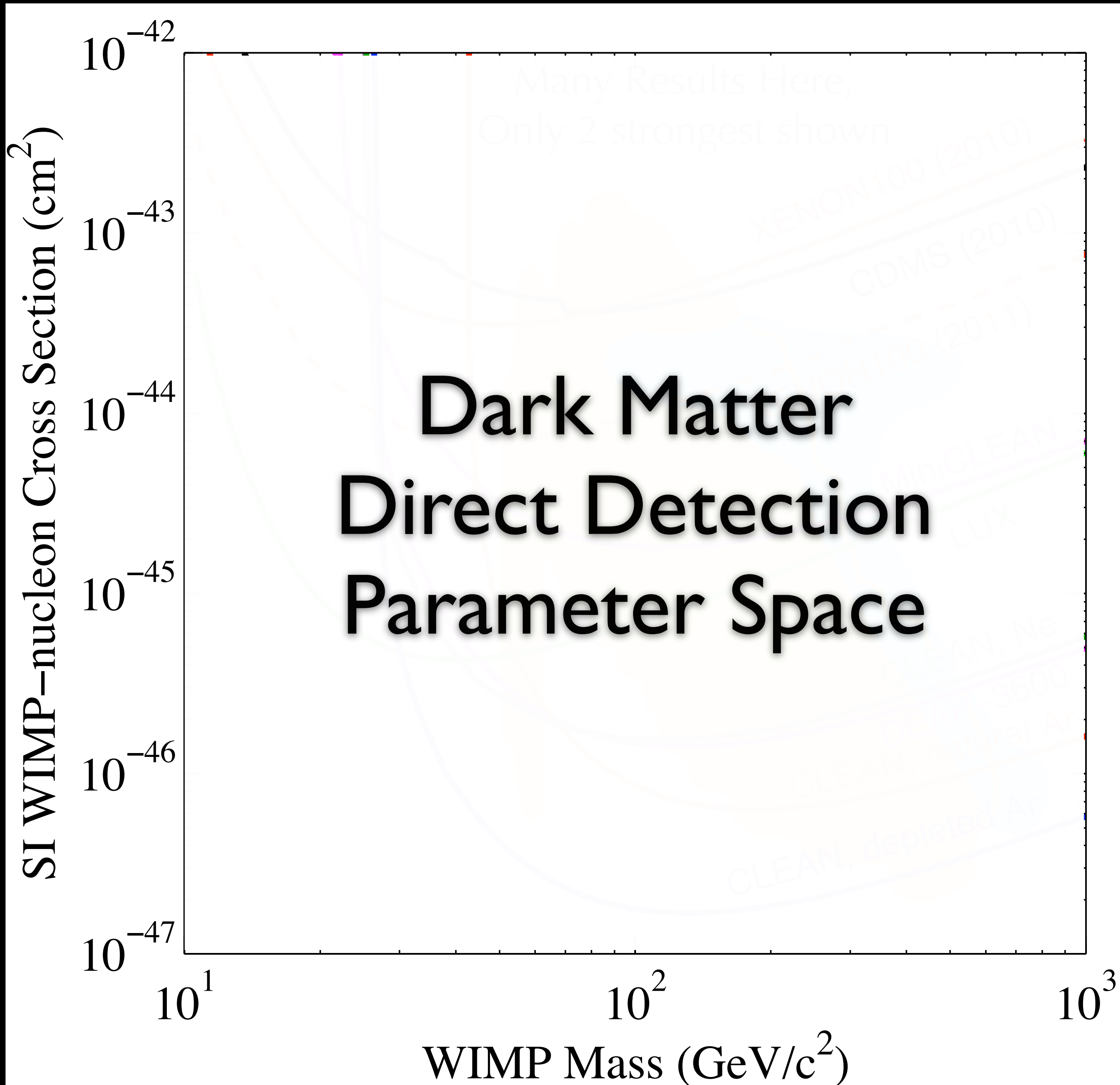

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← 1 event/ 100 kg/day

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need 100-1000 dark matter events to measure mass, cross section

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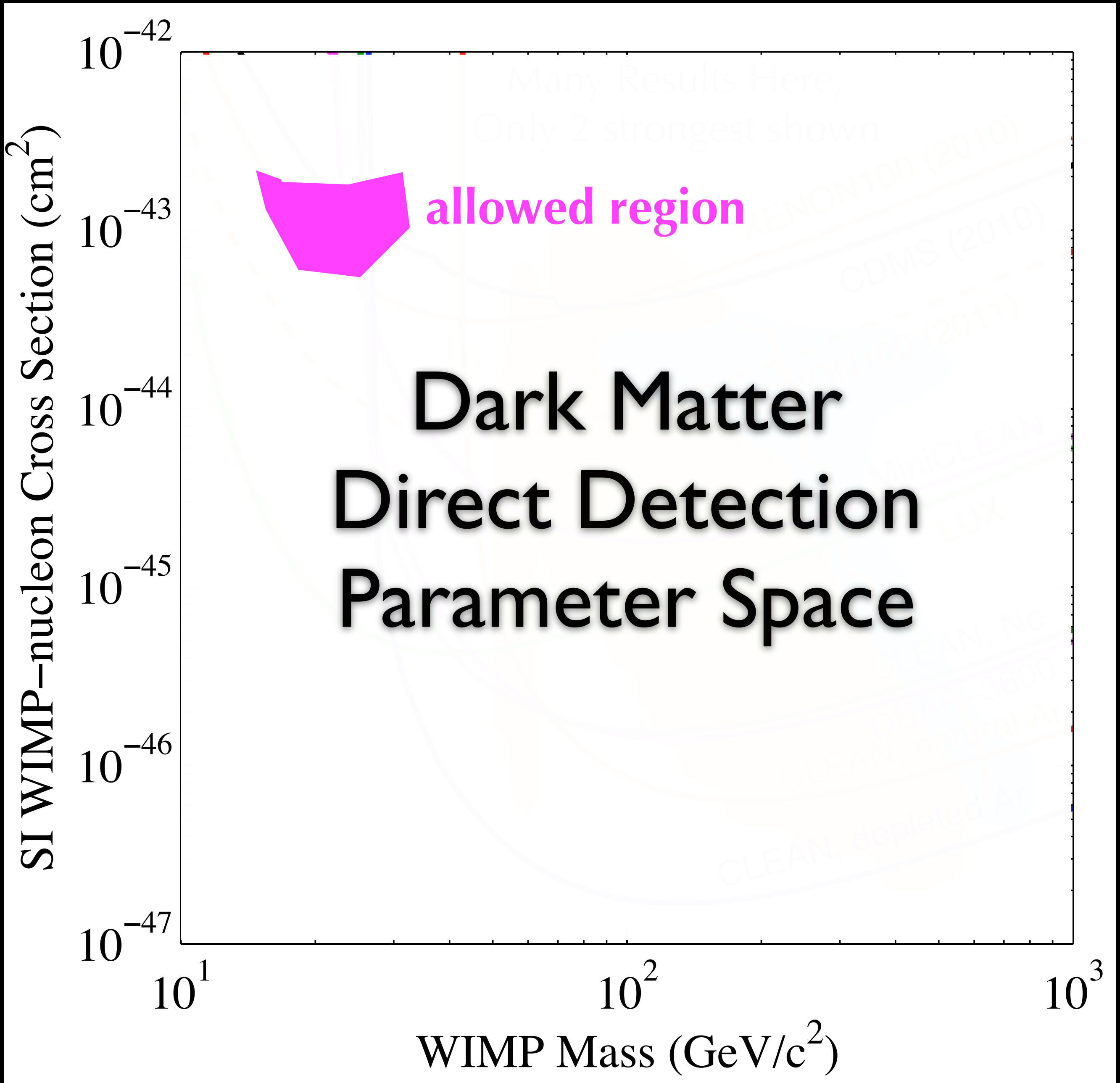

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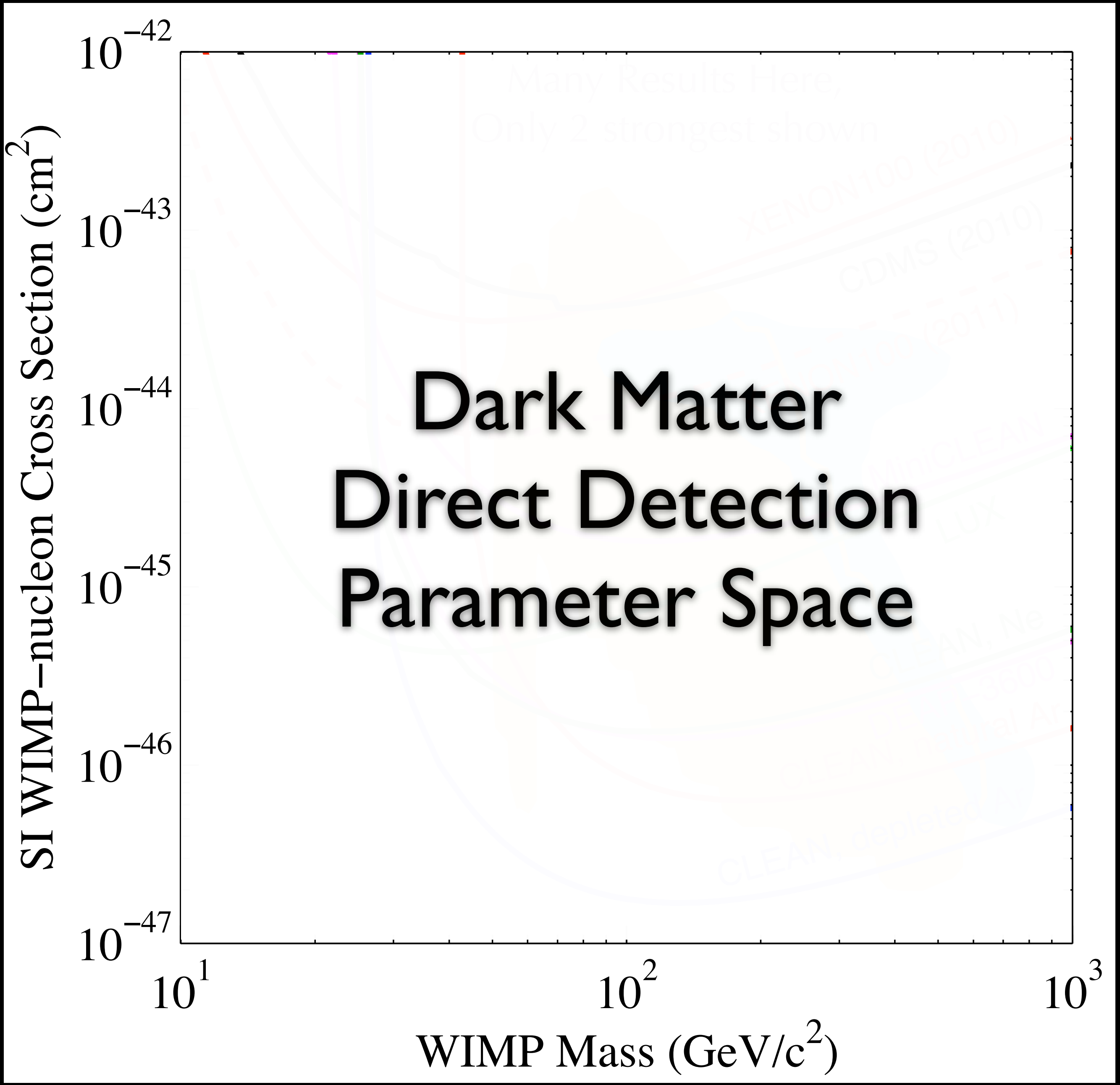

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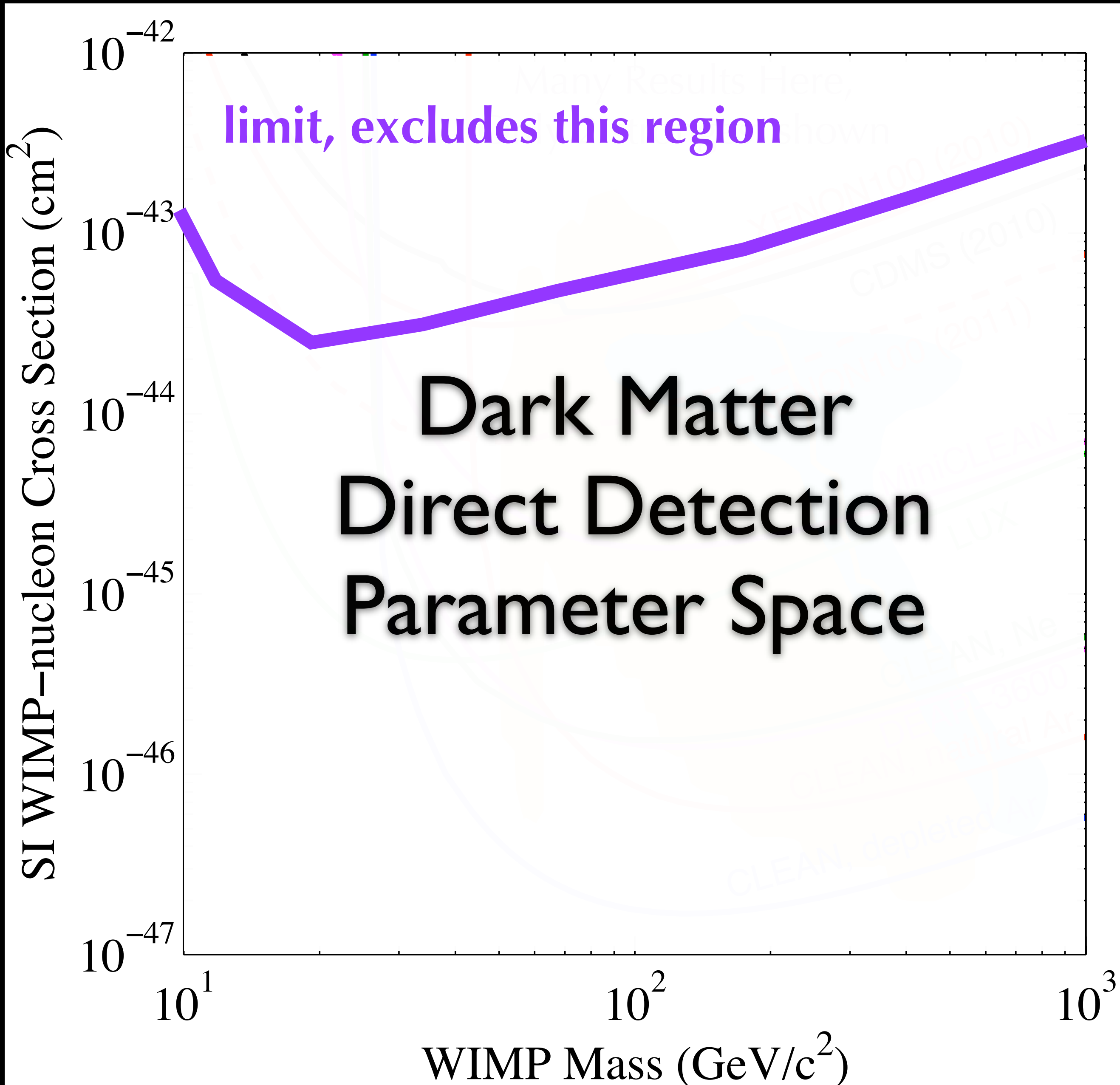

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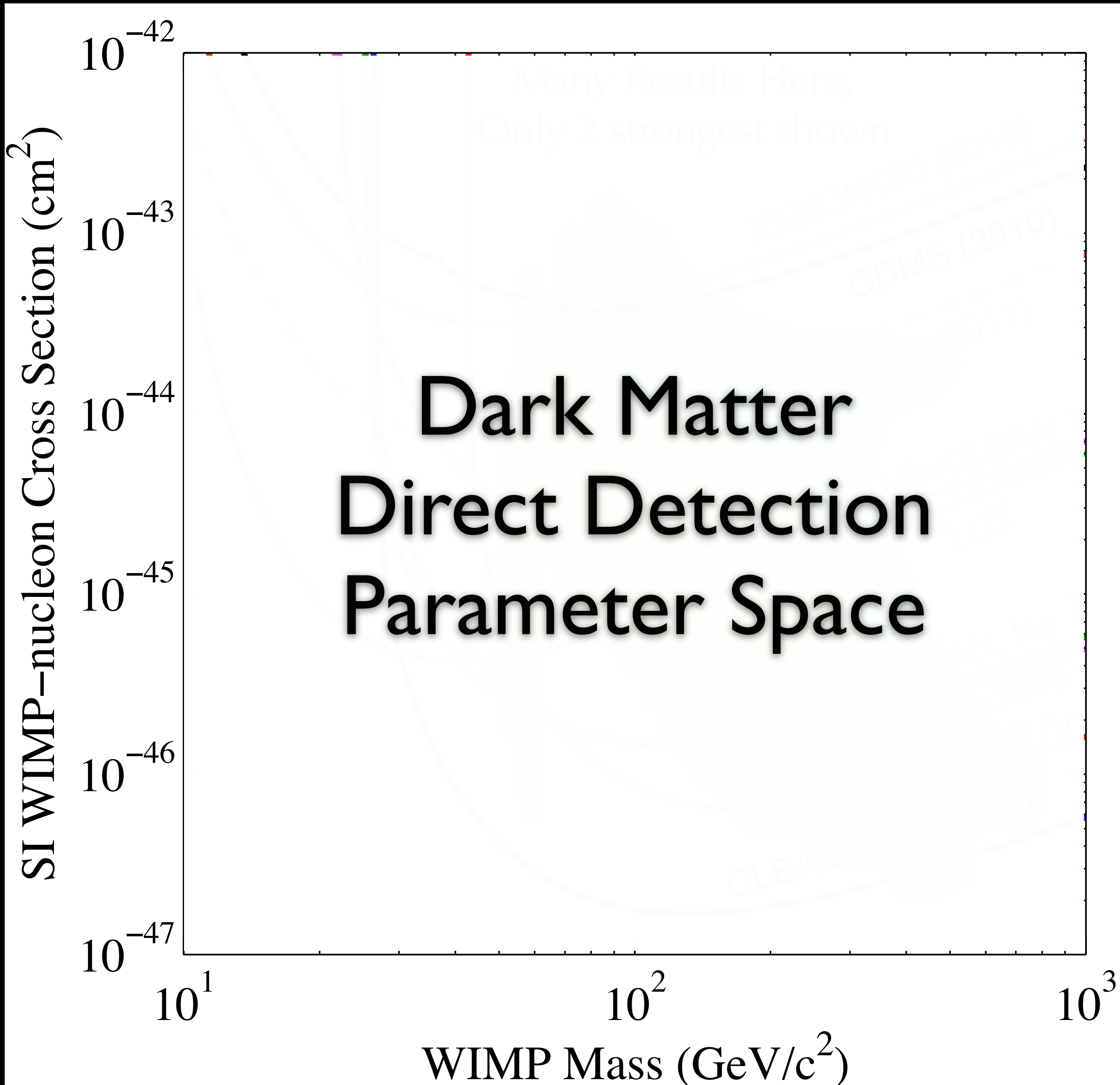

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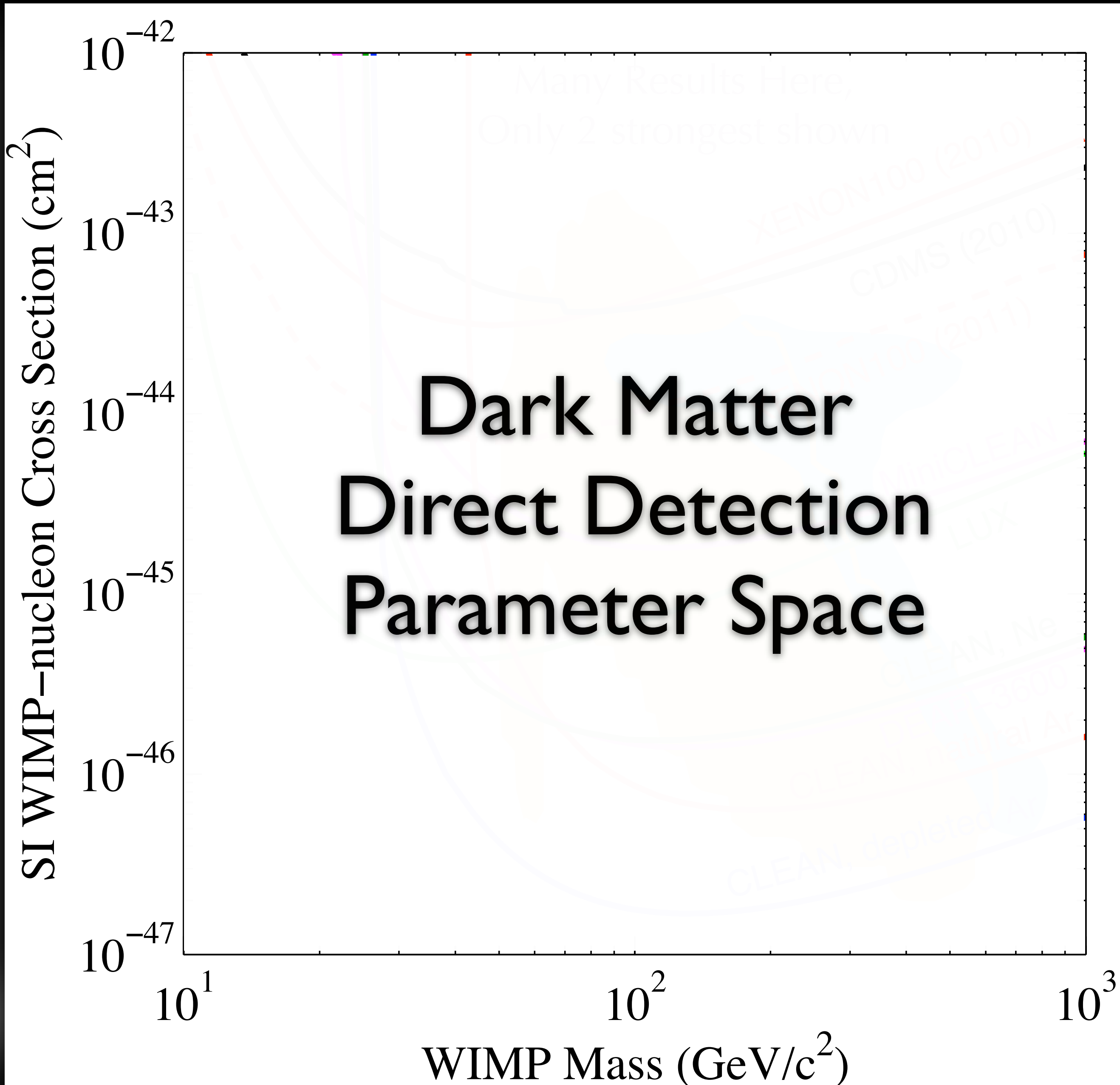
Scalability of Detector Technology



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New Techniques for Backgrounds

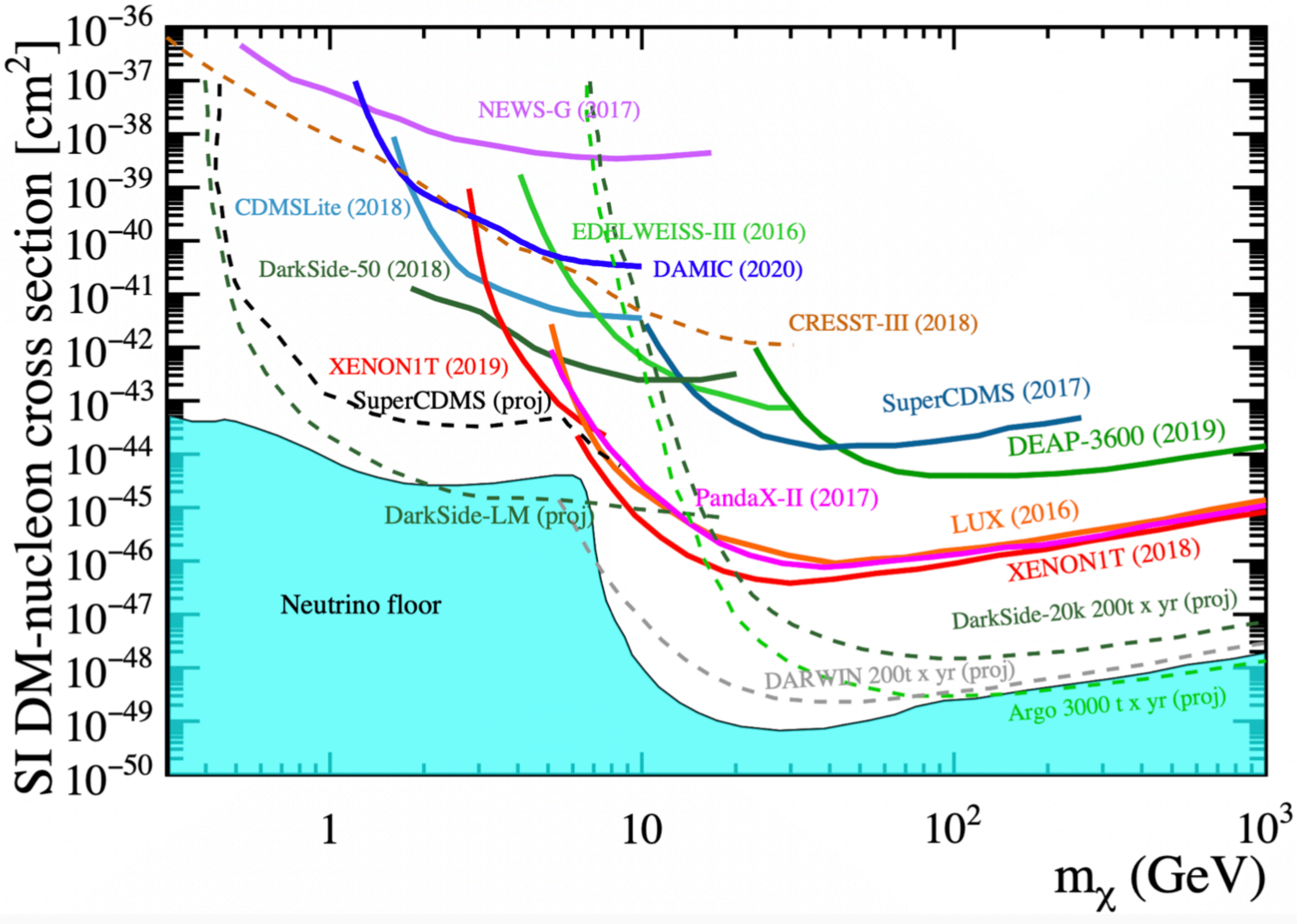
Complementary with High-Energy Frontier

need 100-1000 dark matter events to measure mass, cross section

Where are we now?

WIMPs: Status

Agrawal et al., Eur. Phys. J. C 81, 11 (2021), 1015



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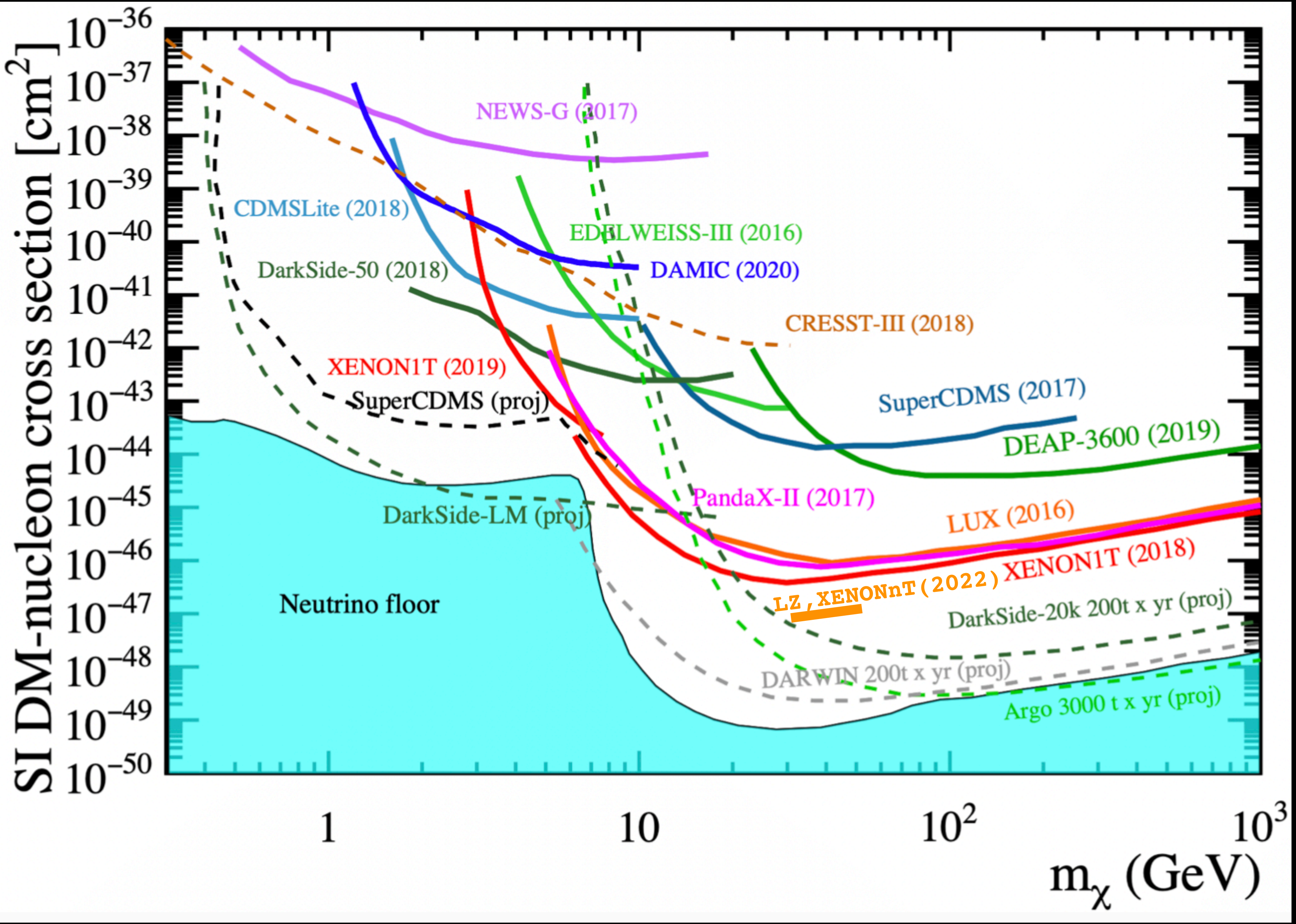
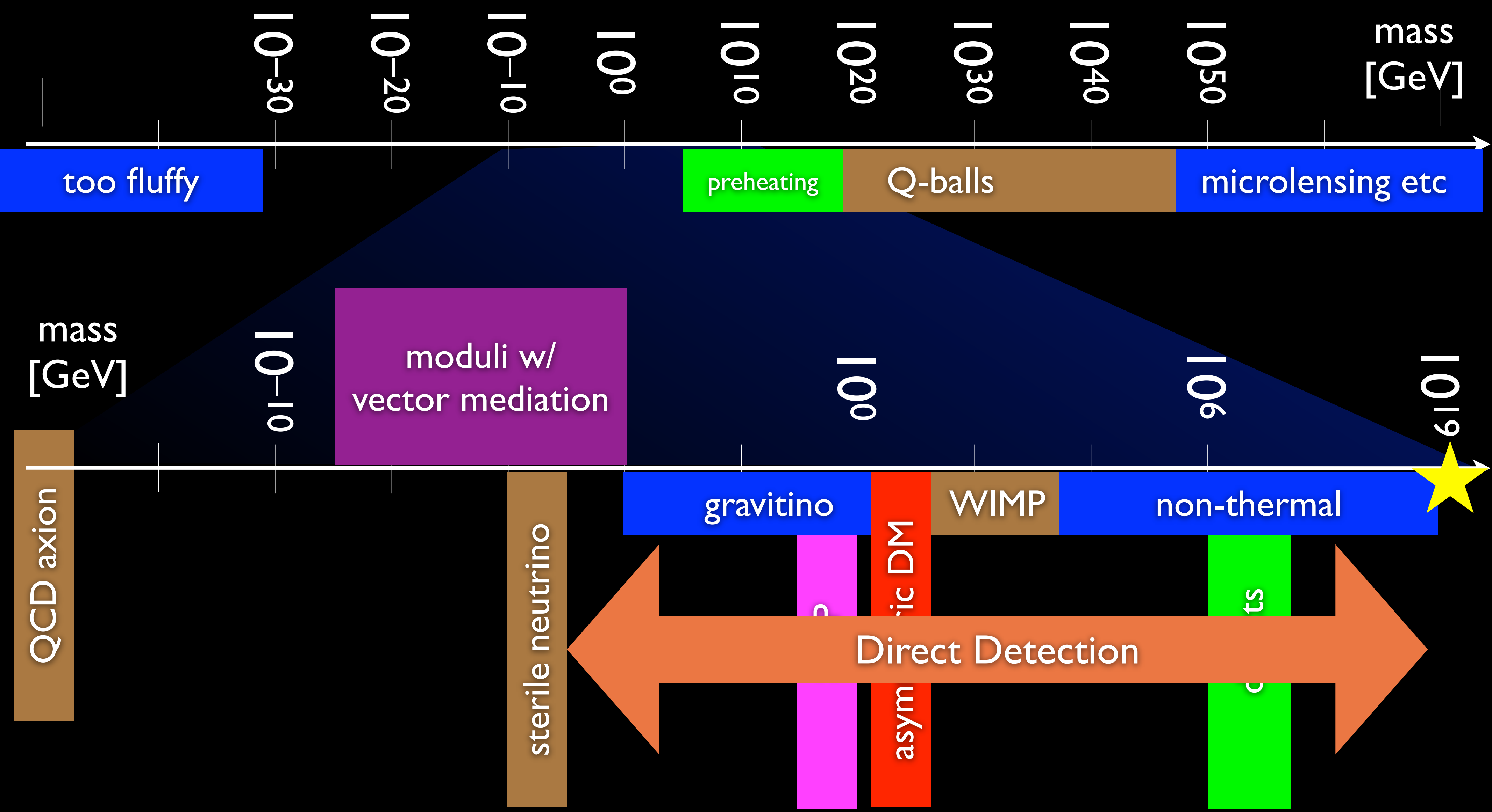


Model Space: Theorist's View

(thanks to H. Murayama)



New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.

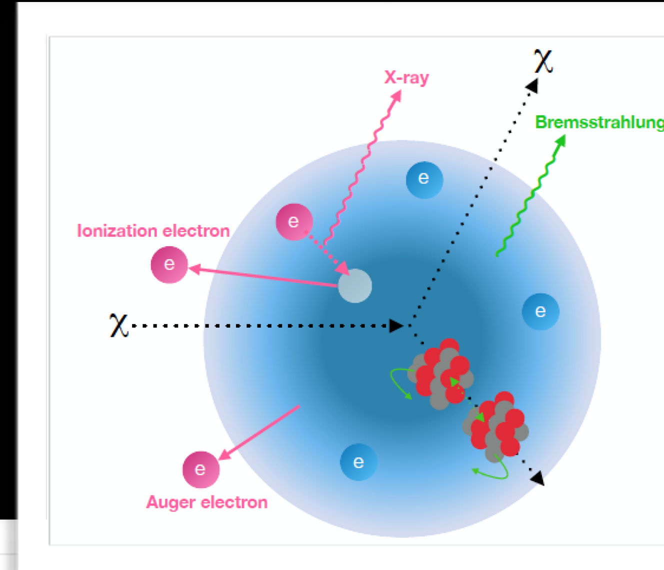
Light Dark Matter Search

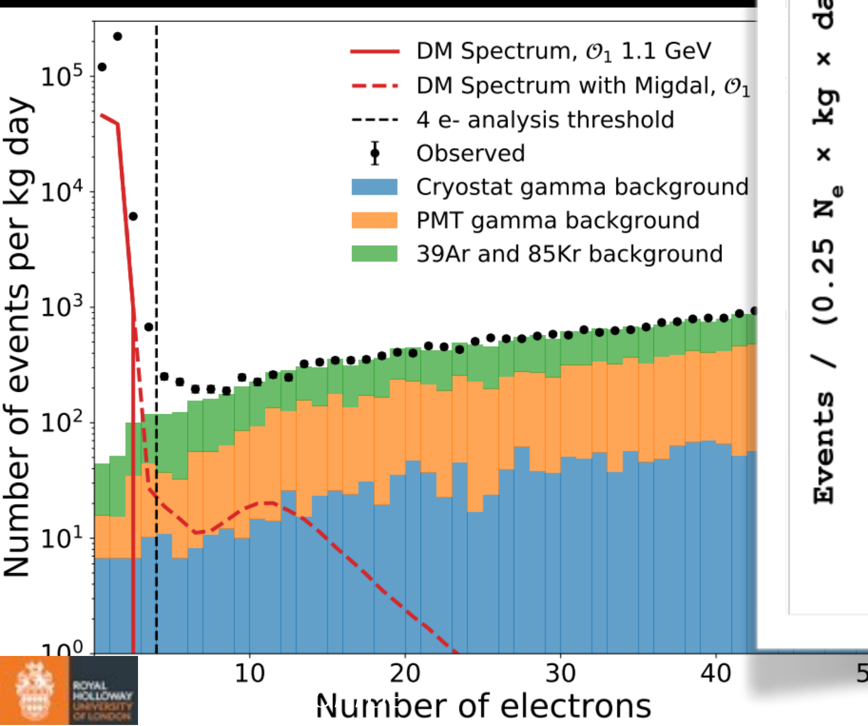
Electron + Nuclear Recoil Final States:

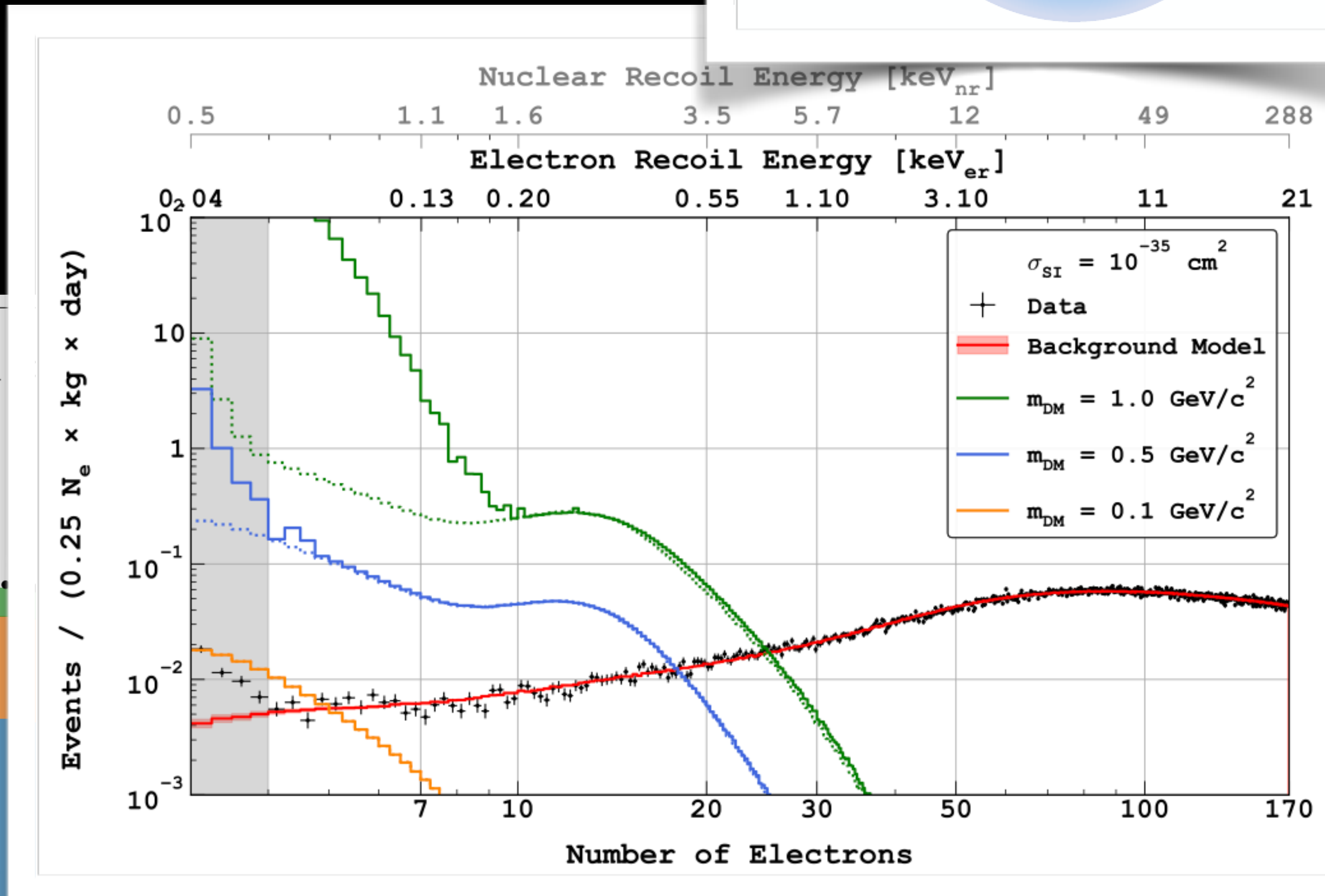
Additional energy associated with acceleration / de-excitation of target atom's electron cloud (Migdal effect) *(arXiv:1907.12771)*

Both nuclear recoil E_R (quenched) AND electronic recoil contribution (not quenched) up to ~keV

Reaches asymmetric dark matter model space sensitivity…







Light Dark Matter Search

arxiv:2207.11966, arxiv:2207.11967, arxiv:2207.11968

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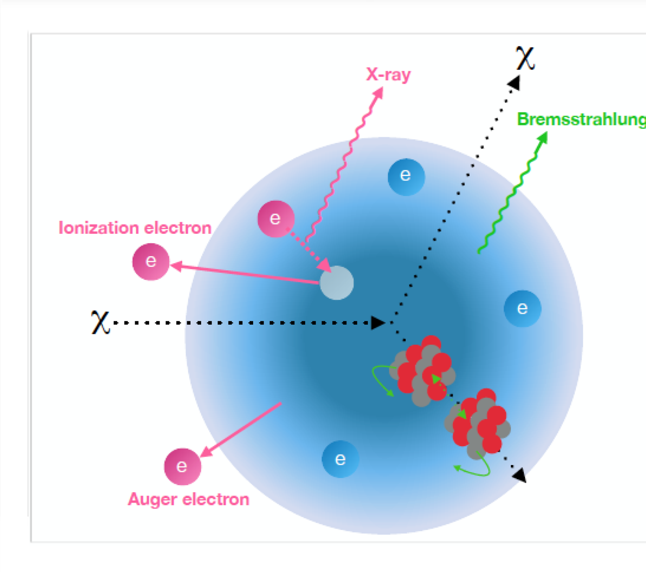
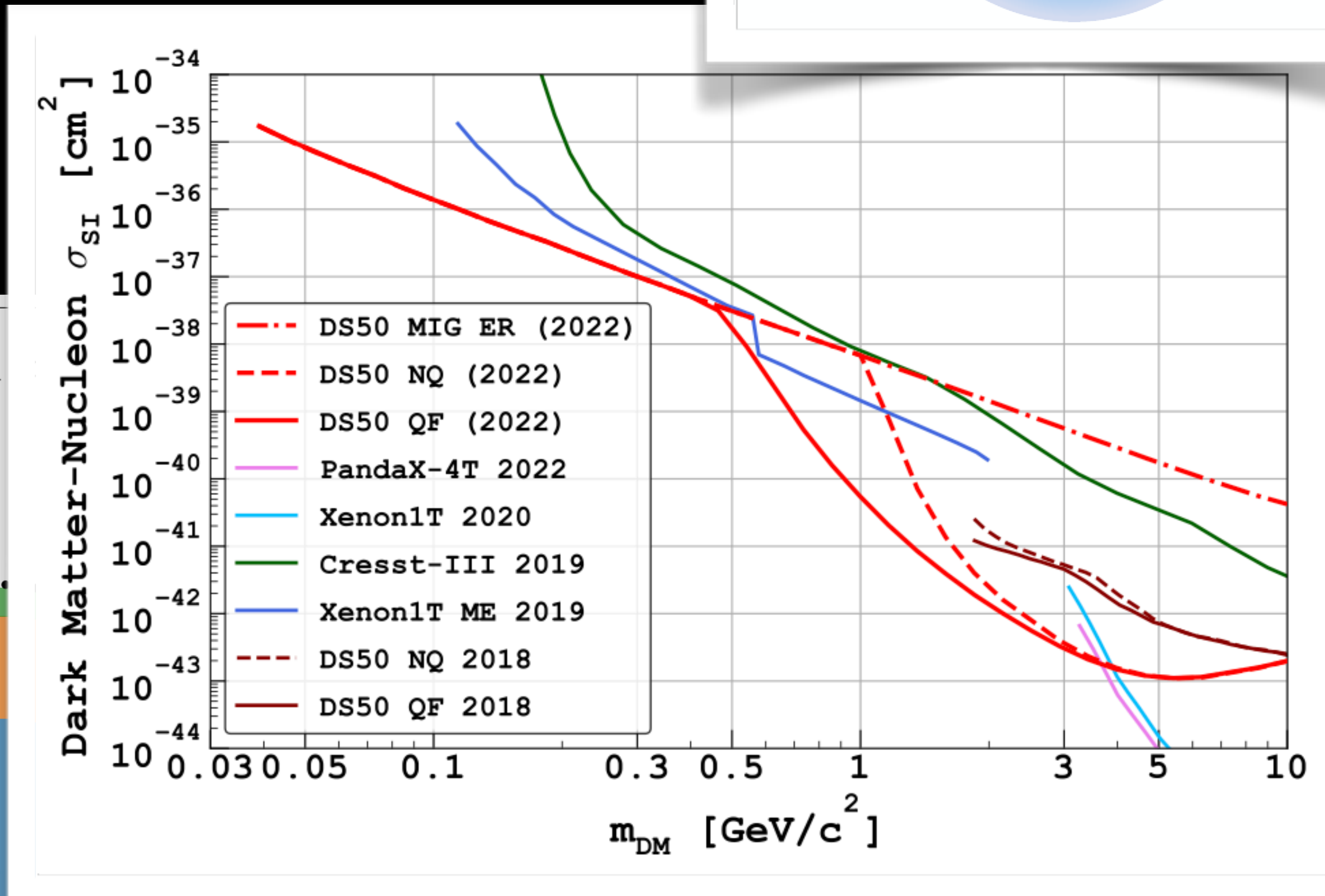
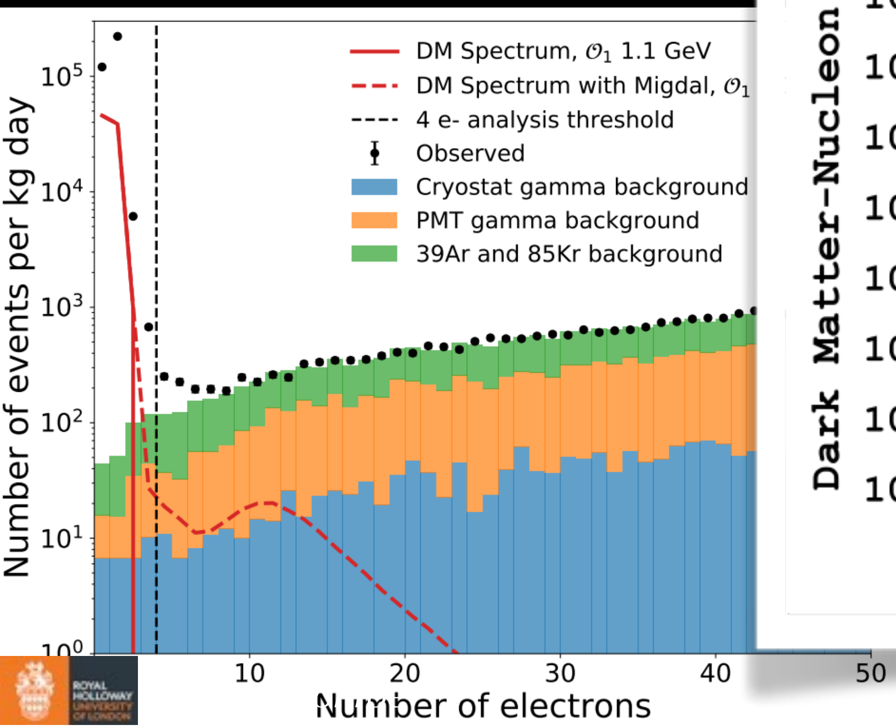






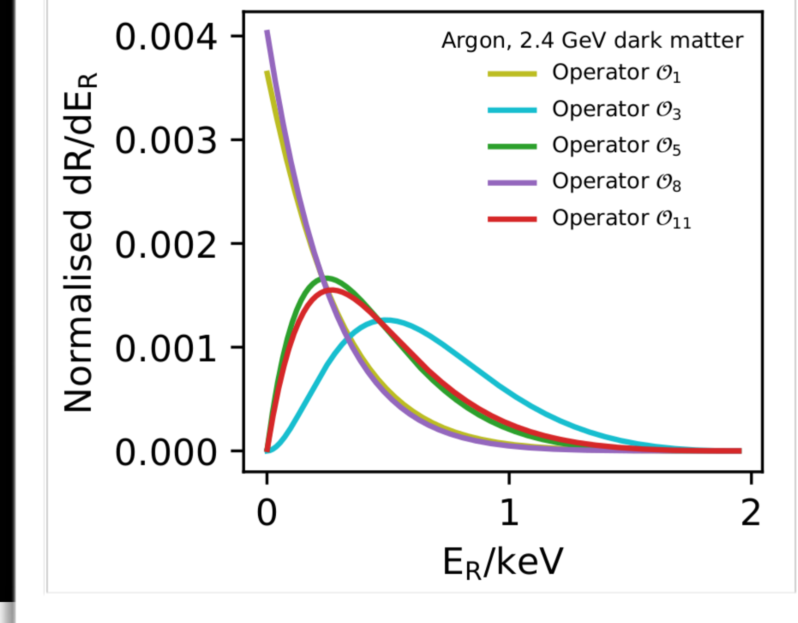
Light Dark Matter Search

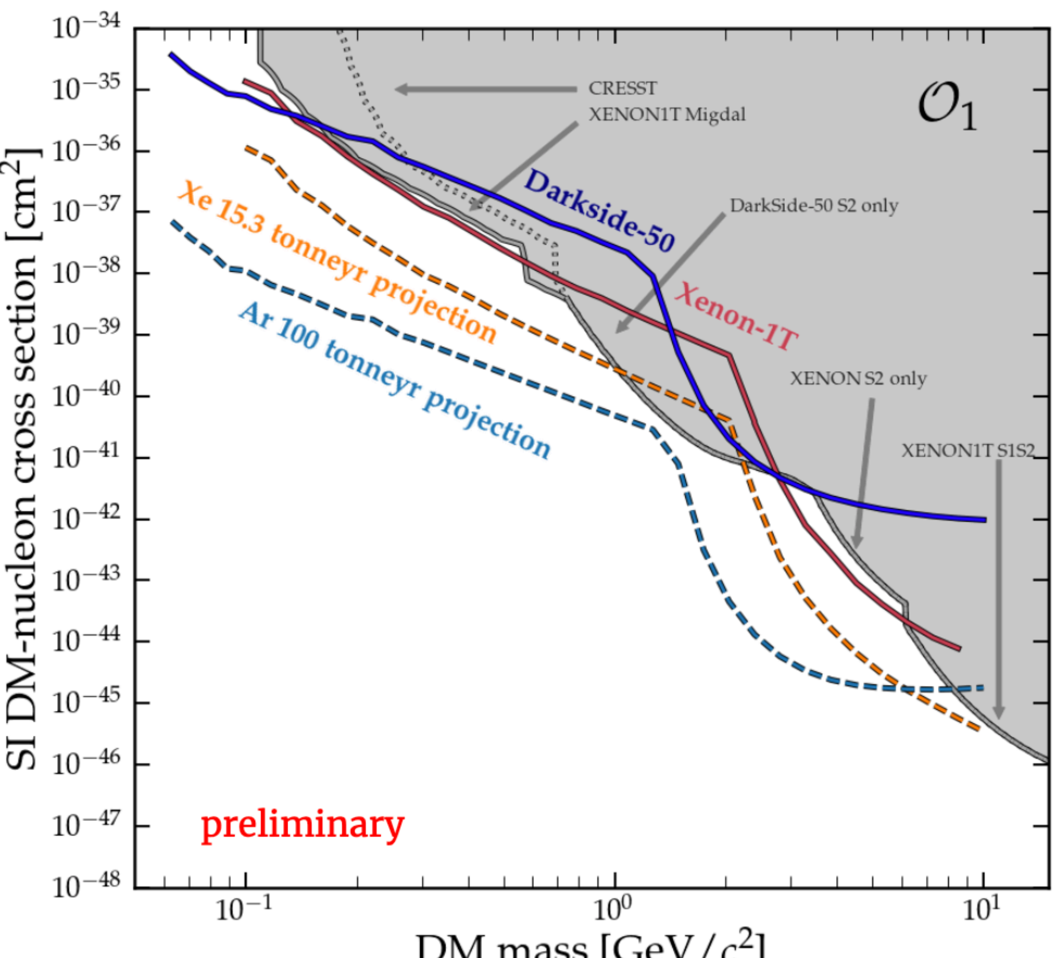
Beyond the usual assumptions…

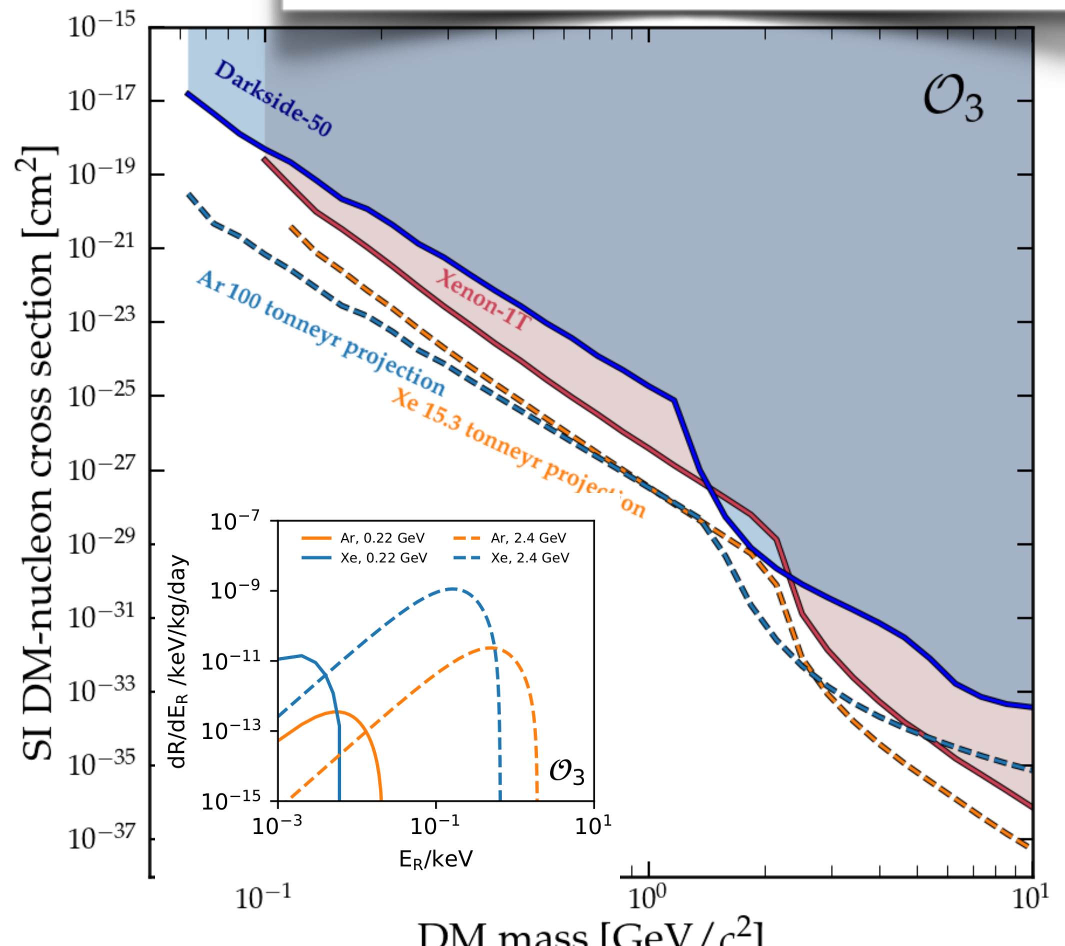
What if interaction is momentum or velocity dependent?

What if DM coupling to protons and neutrons not equal?

Test non-relativistic effective field theory operators beyond O(1), with global combination of results







Self-Interacting Dark Matter Signatures

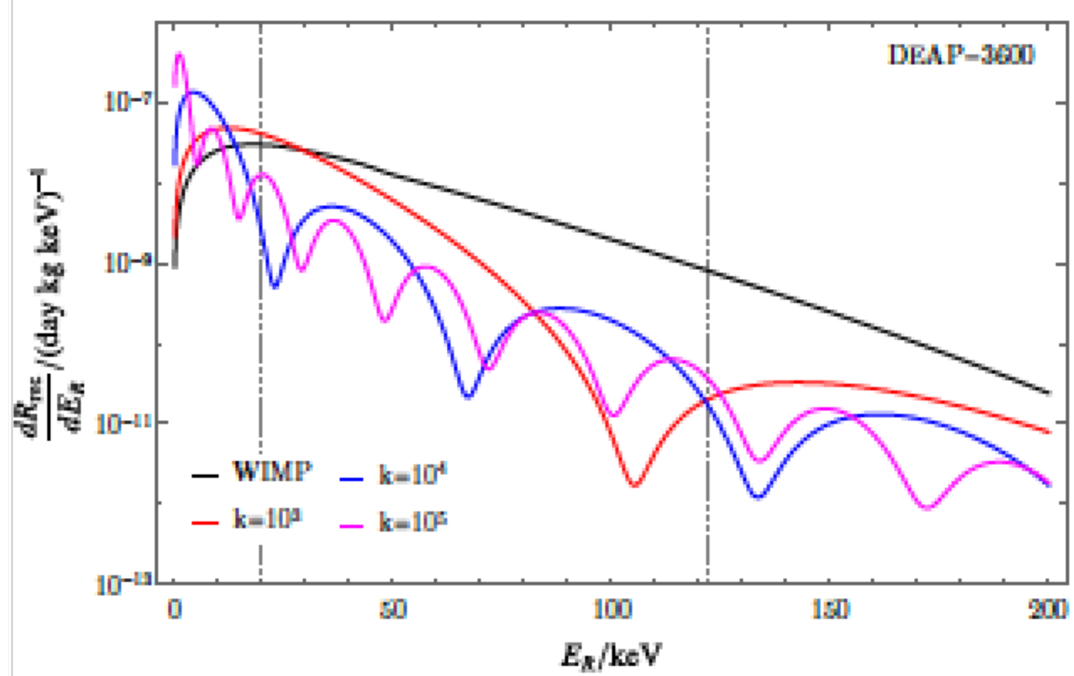
What if dark matter forms bound states?

Sensitivity to composite dark matter, e.g. dark nuclei, formed of *k* bound states of self-interacting light dark nucleons.

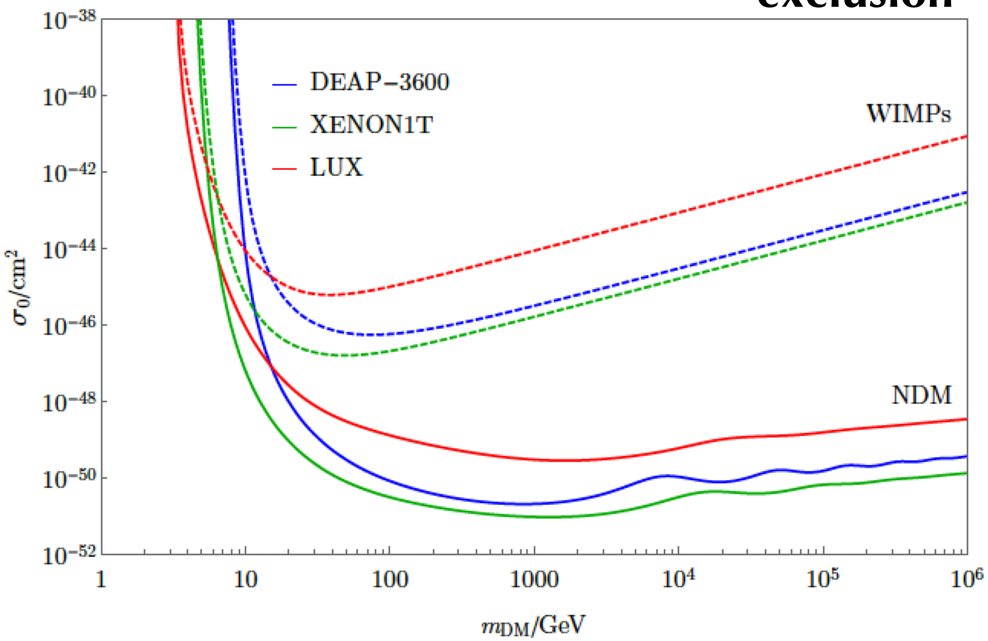
Scattering process now has a form factor from the nuclear dark matter and the target.

example: dark nucleon m = 1 GeV, r = 1 fm, and per-SM nucleon xsec = 1E-46 cm².

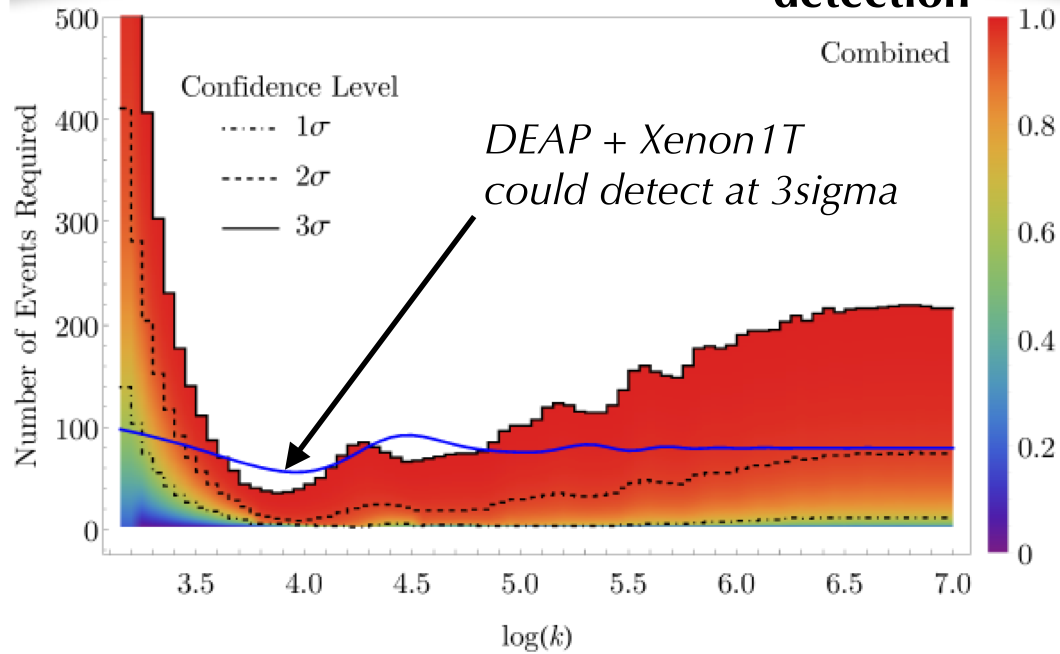
Kirk, Butcher, JM, West, JCAP 1710 (2017) 10, 035



exclusion



detection

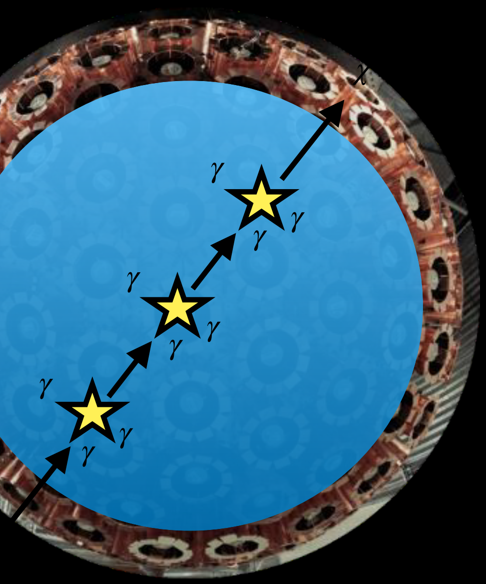


Planck-Scale Dark Matter Search

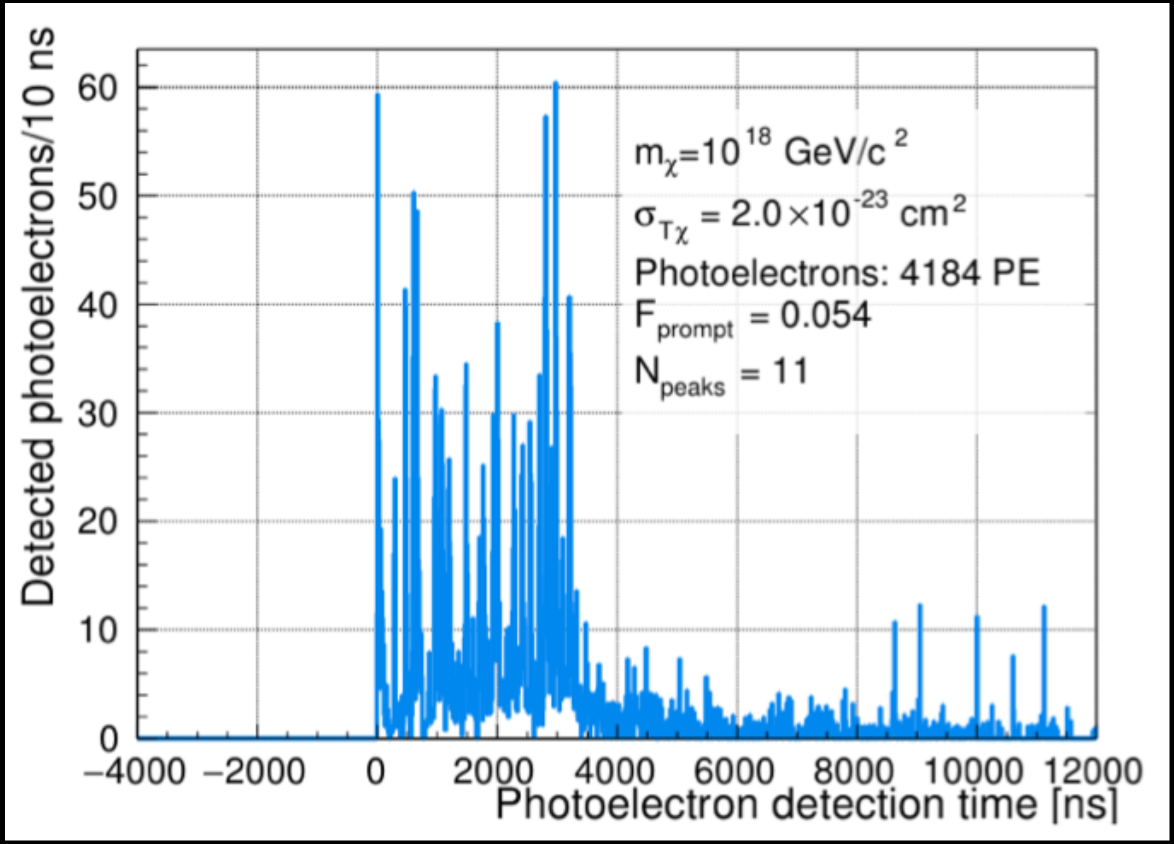
What if dark matter is super heavy?

Planck-scale DM may be produced non-thermally in GUTs, primordial black hole radiation or extended thermal production in a dark sector

Unlike standard WIMPs, which scatter at most once in a detector, Planck-scale DM has a high enough mass to scatter multiple times as it traverses a detector… **signal: multiple nuclear recoils**



Thanks: A. Kemp



Adhikari et al., PRL 128 (2022) 1, 011801

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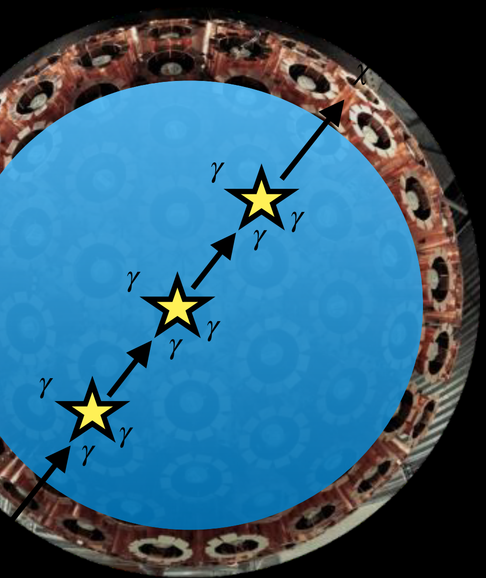

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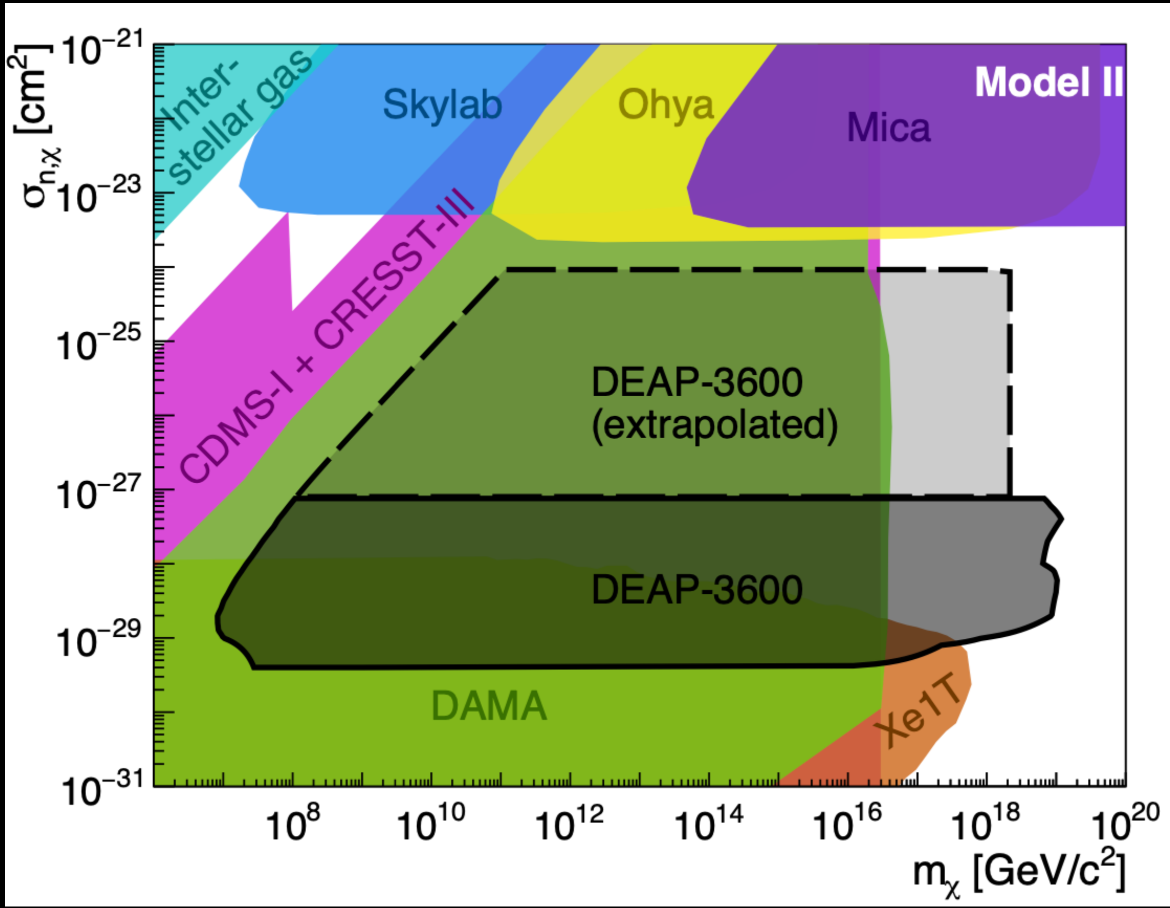


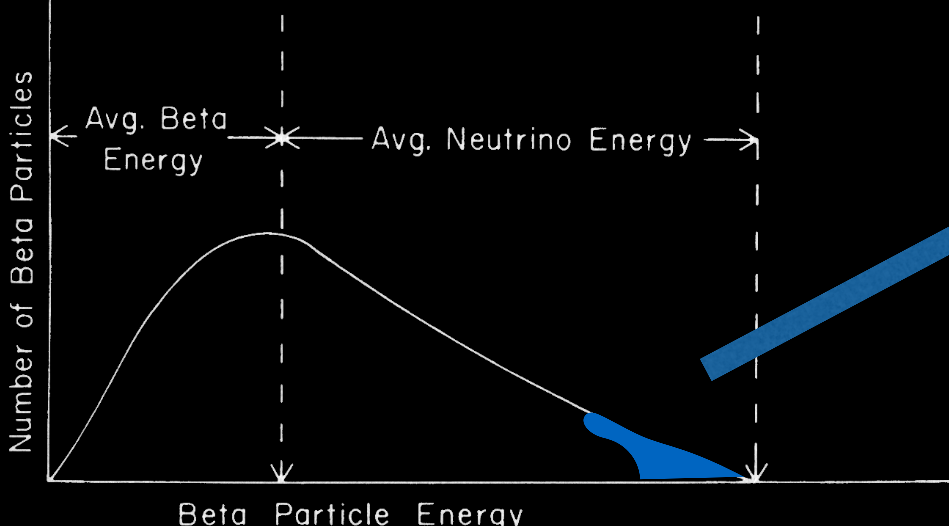
Adhikari et al., PRL 128 (2022) 1, 011801

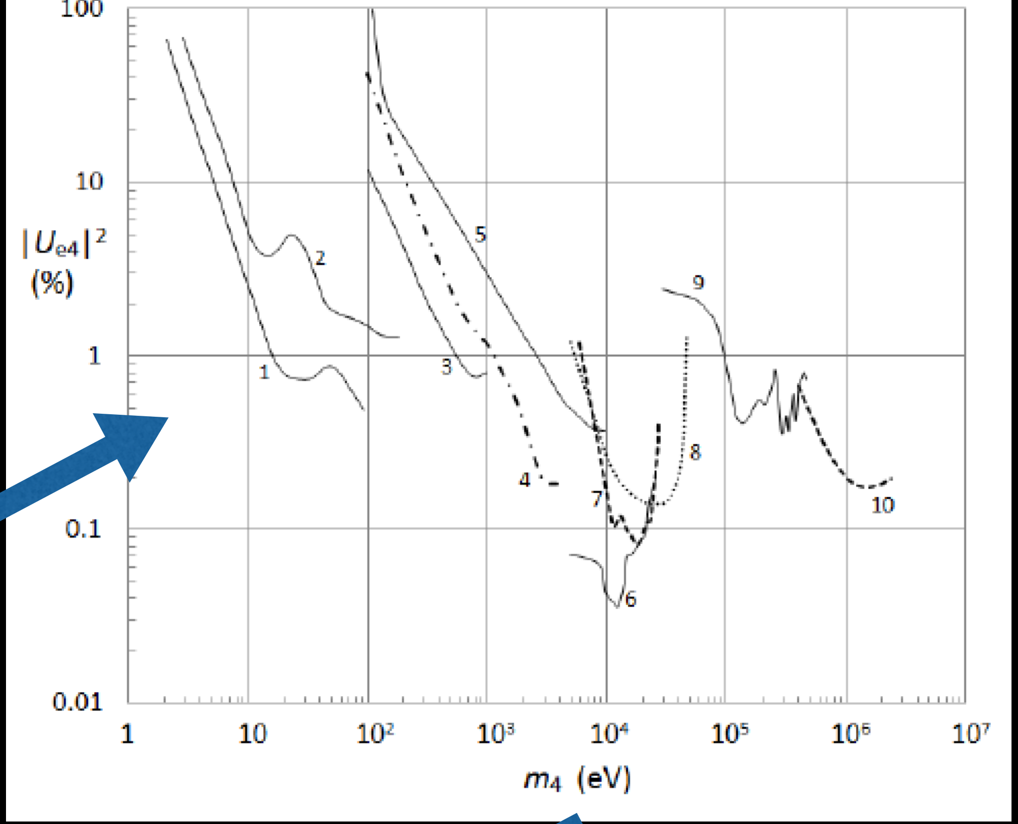
Extrapolation: scales flux with n_χ and regions of m_χ consistent with null result

Warm Dark Matter Signatures

What if dark matter is sterile νs?

1) beta decay energy spectrum is modified by ν mass and mixing.

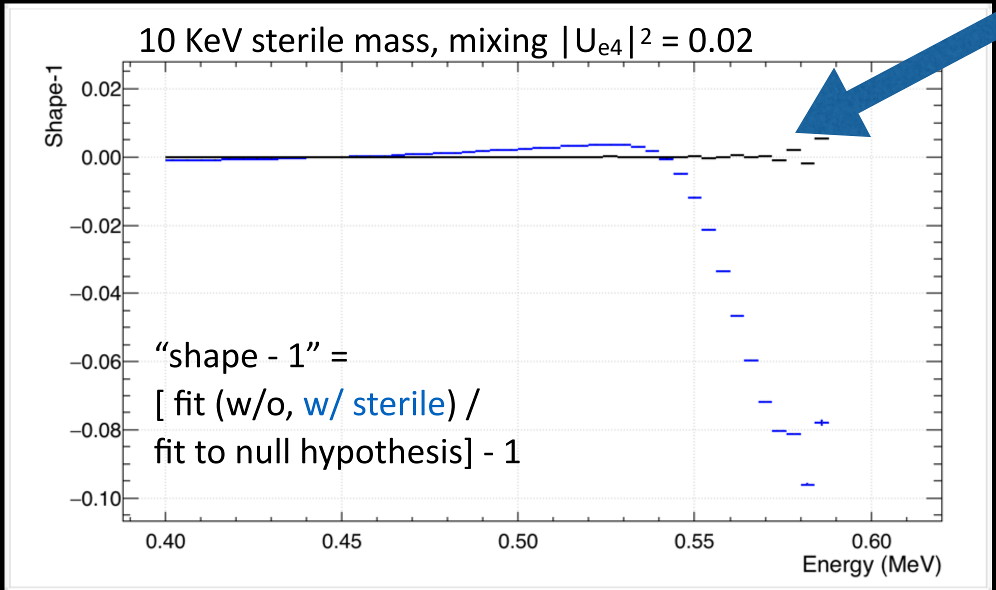




Dragoun, Venos, Phys. 3 (2016) 77-113

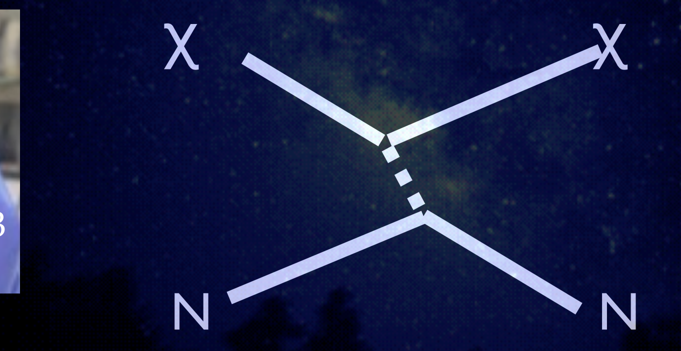
2) Sterile neutrino-electron scattering: $N_s\, e^- \rightarrow \nu_e\, e^-$

Campos & Rodejohann, Phys.Rev.D 94 (2016)

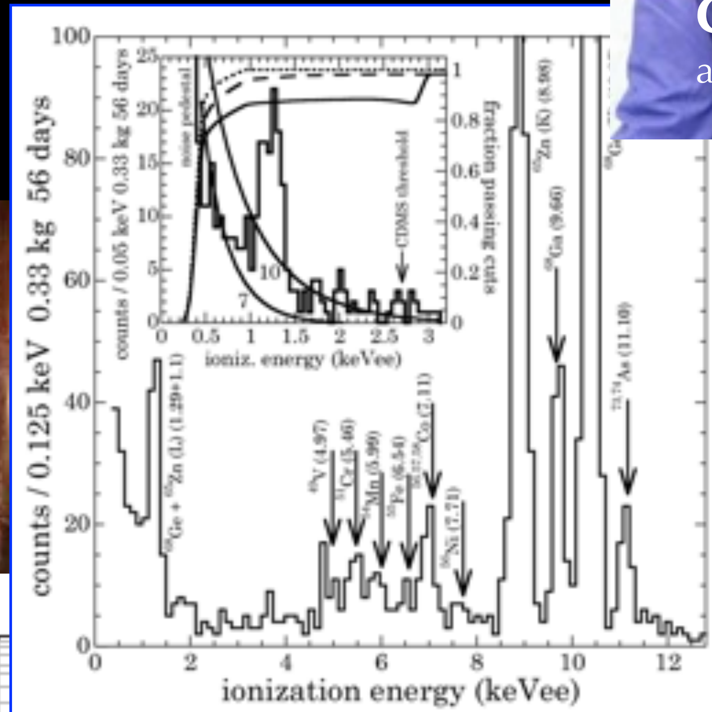


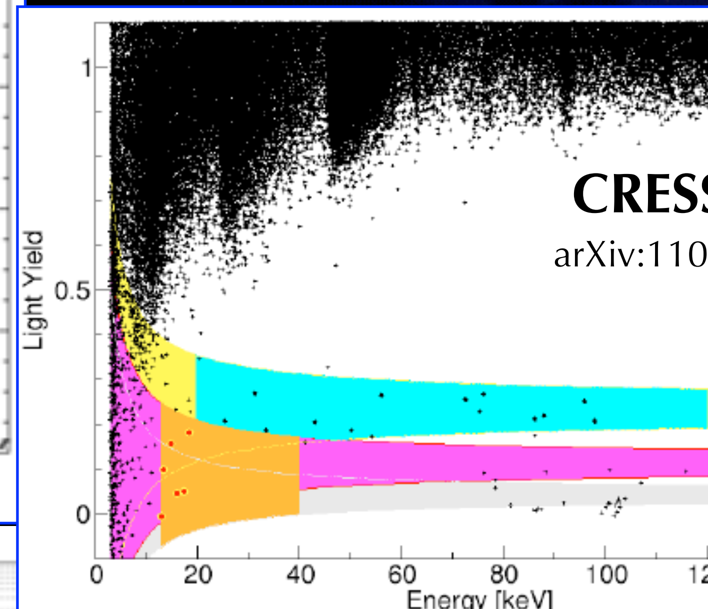
nb. astrophysical searches: limits on $|U_{e4}|^2$ at 10 keV ~1E-11 from x-ray signals

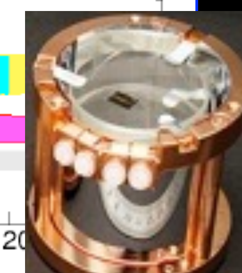
Direct Dark Matter Signals?

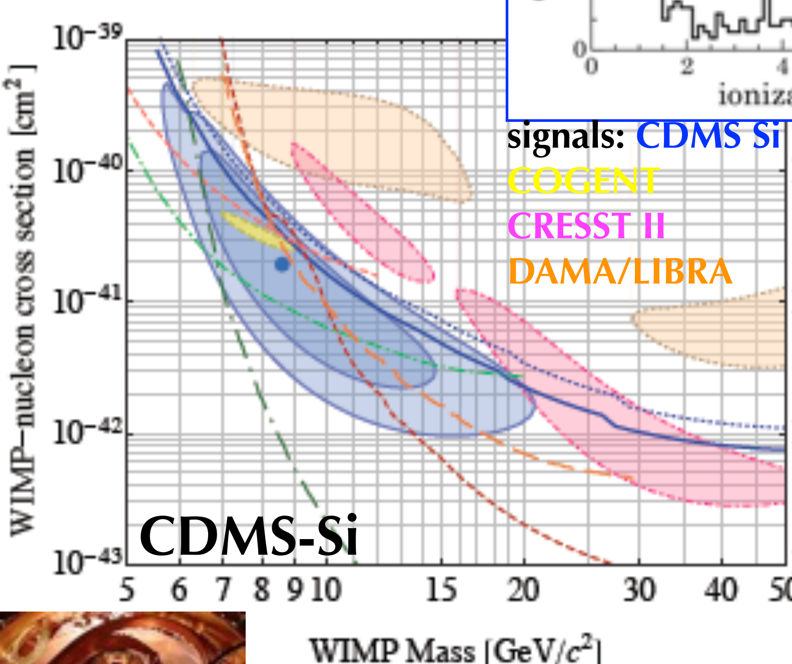


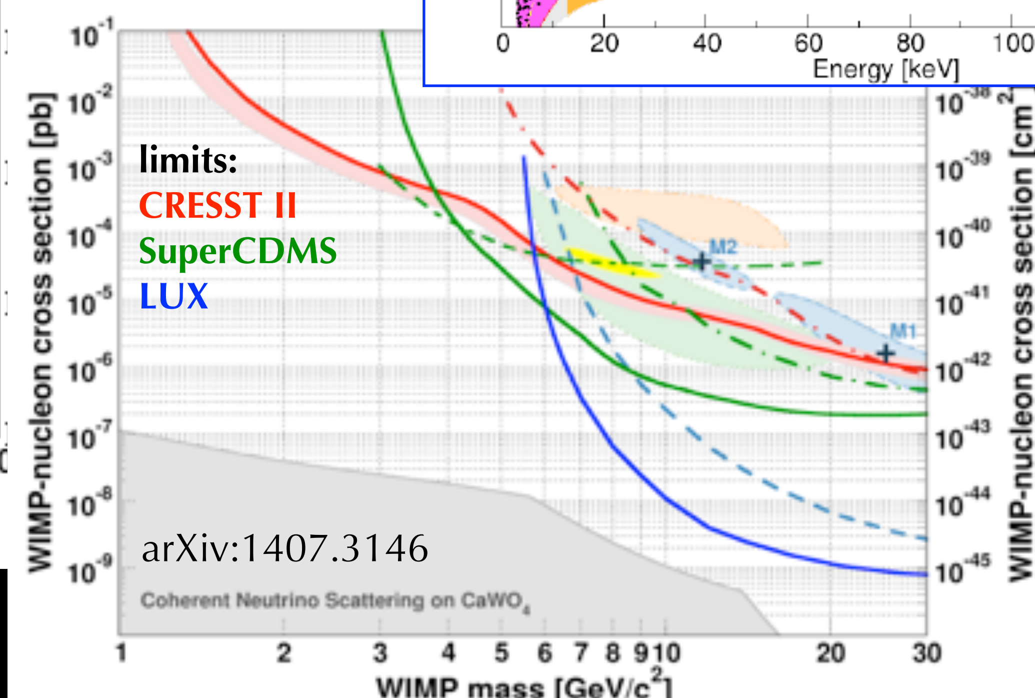
DAMA/Libra











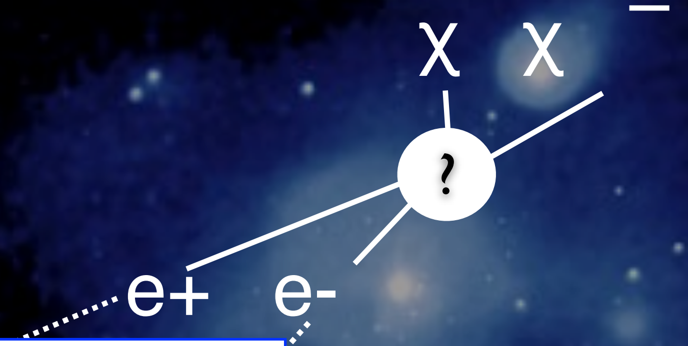
dark matter?

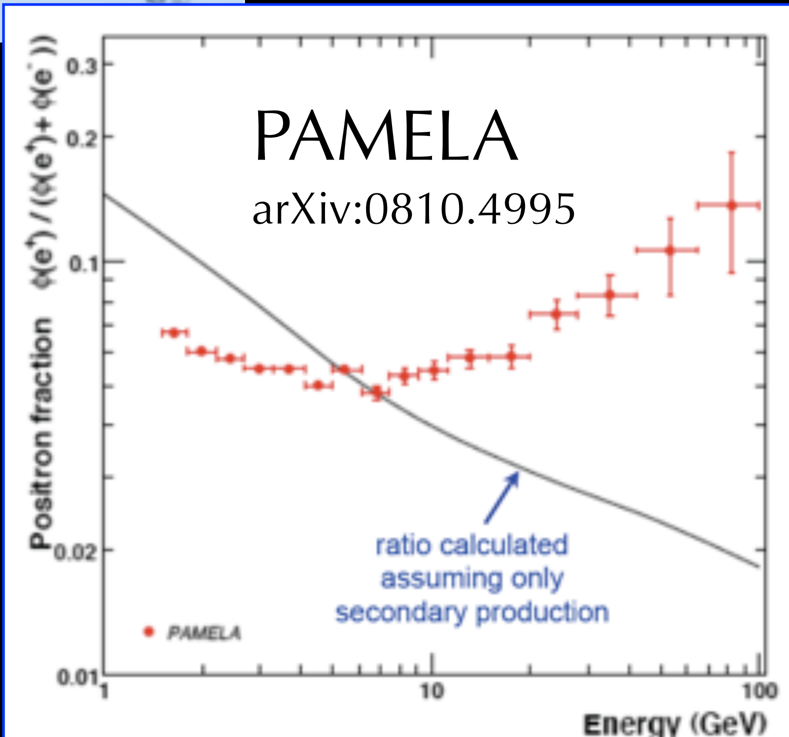
new back-grounds?

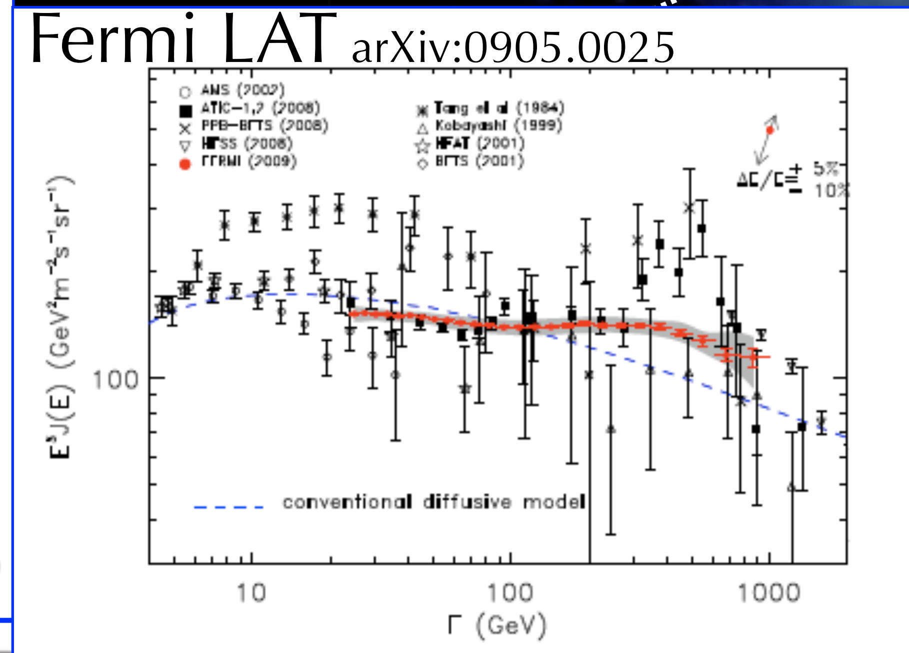
PRL 111 (2013) 251301

Jocelyn Monroe

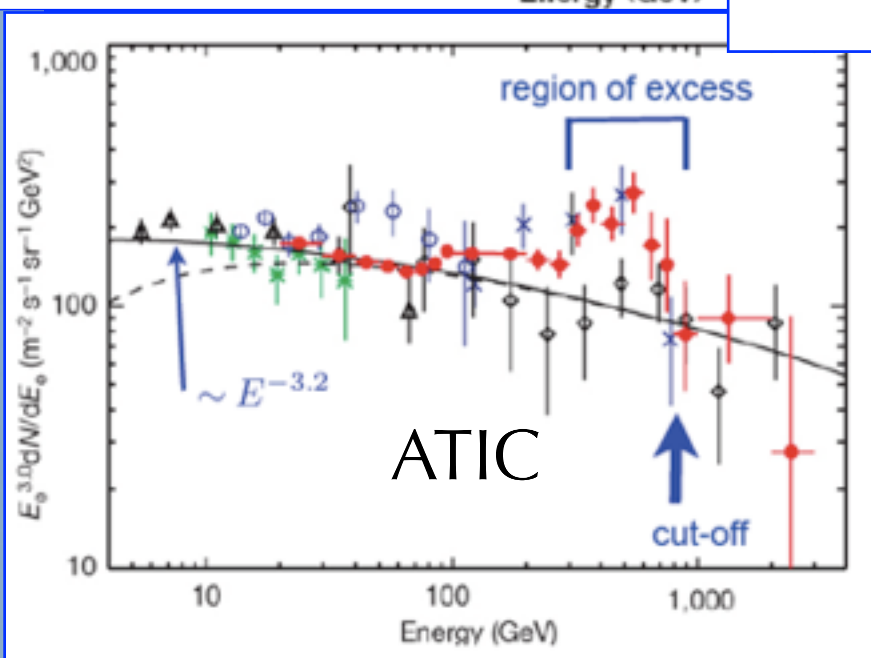
Indirect Dark Matter Signals?

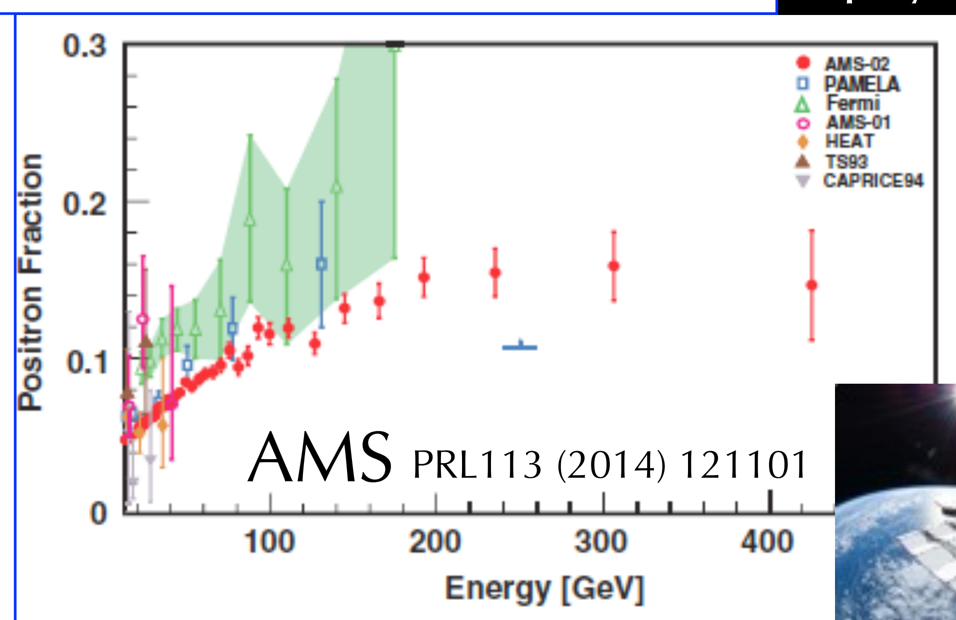






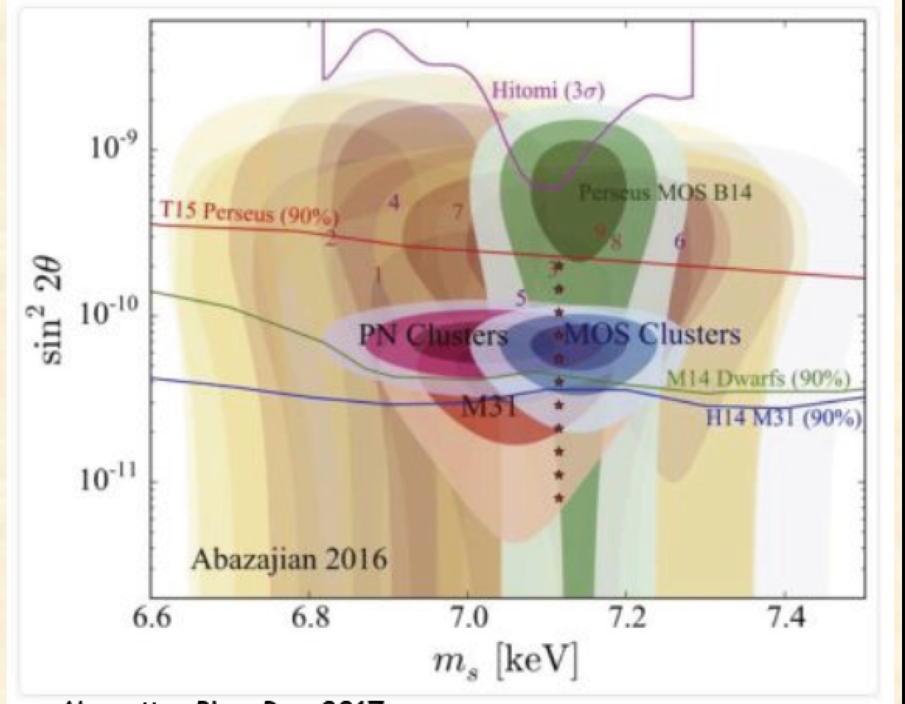
dark matter?
local astro-
physics?



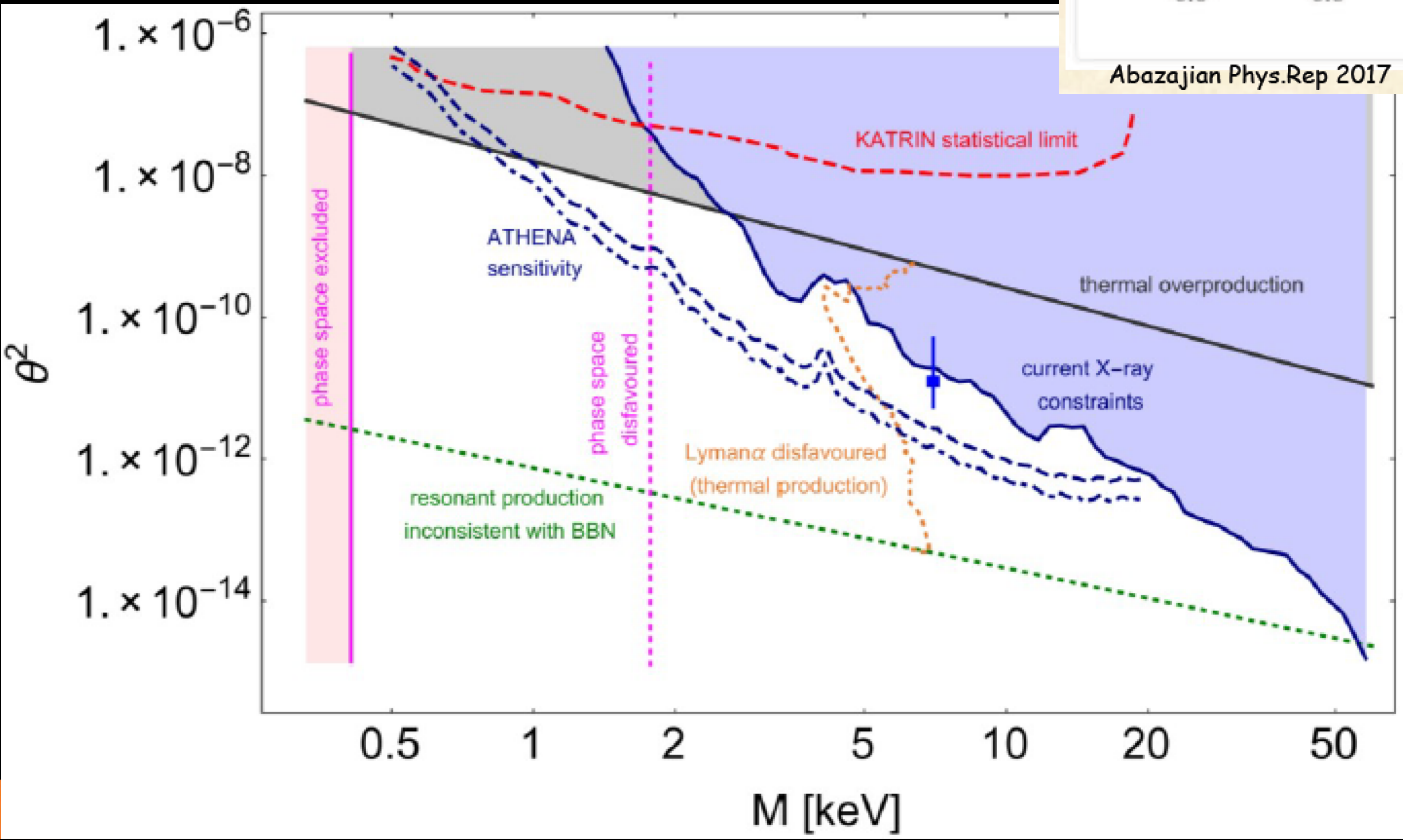


Sterile Nu Dark Matter Signal?

Excess x-ray flux at 3.5 keV observed by XMM-MOS/PN, Chandra, Suzaku, NuStar in some targets but not others.

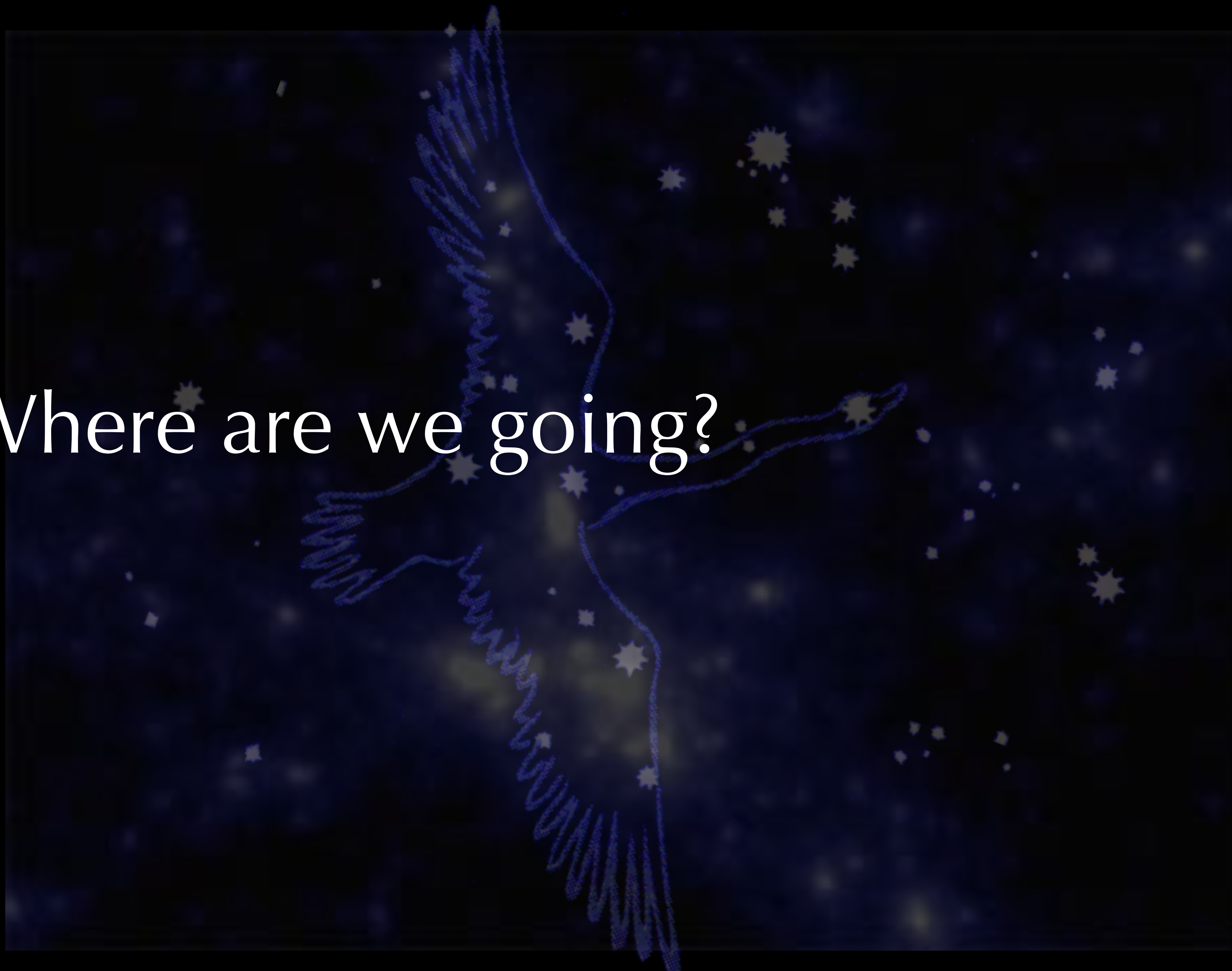


Abazajian Phys.Rep 2017



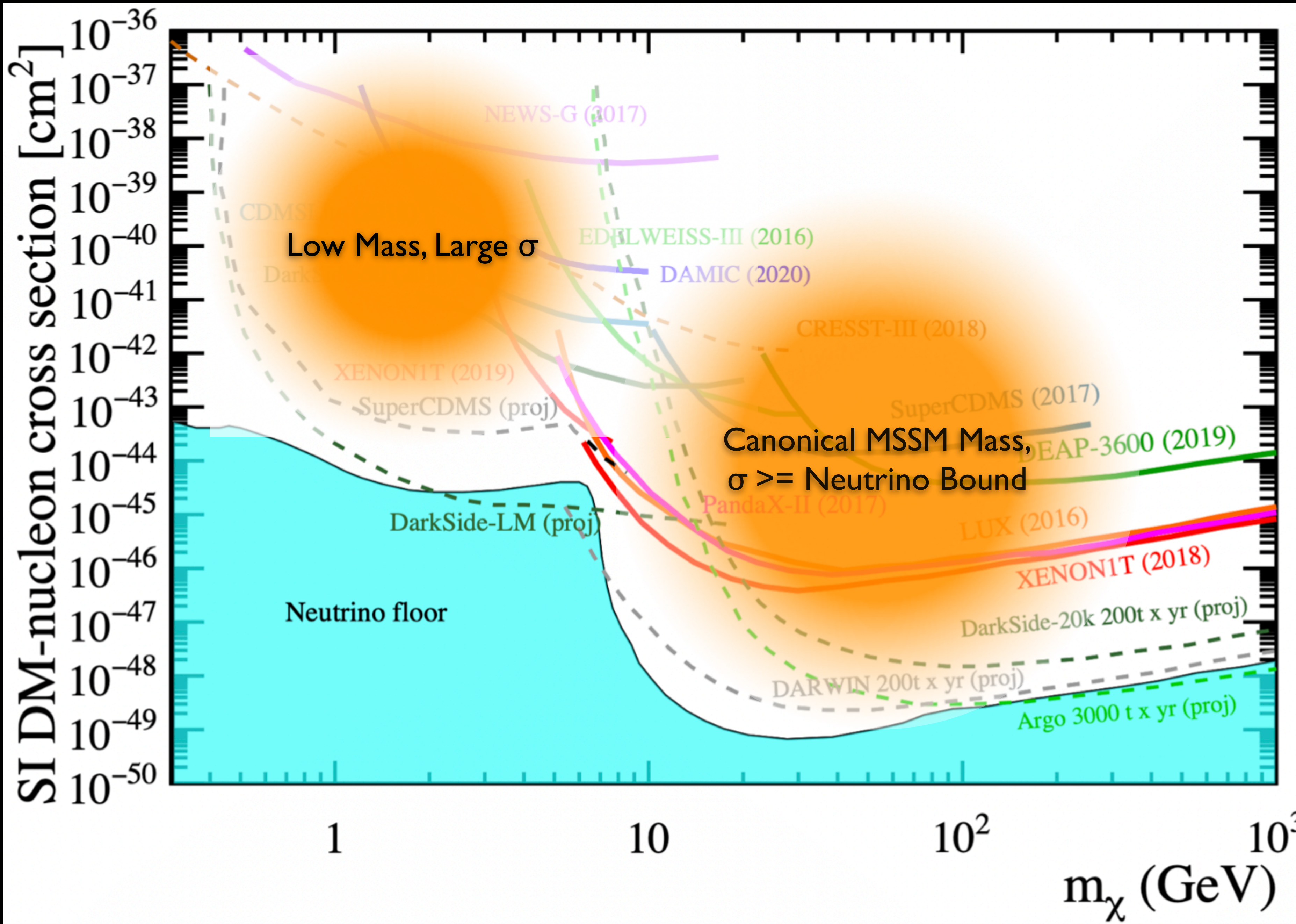
Prospect to test atomic line background hypotheses in near-future experiments (XRISM ++)

Where are we going?



WIMPs: Prospects

Agrawal et al., Eur. Phys. J. C 81, 11 (2021), 1015



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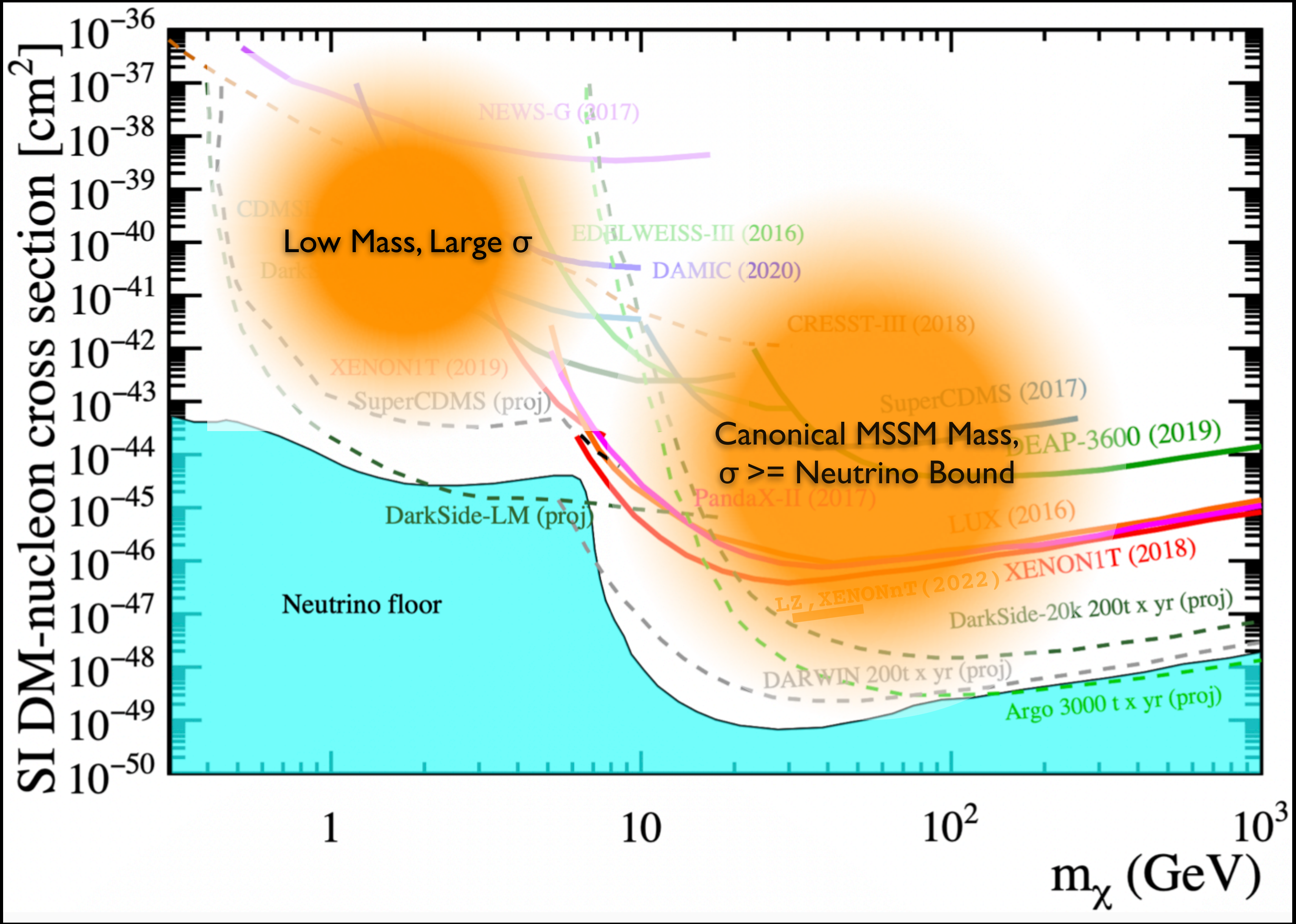


Low Mass, Large σ

Light Dark Matter Prospects

Goal: reach the neutrino bound!

DS-50: current leading result, at 1E-41 level.
Construction of 1000x larger detector underway.

EDELWEISS-III: new FIDs with <0.3 keV FWHM
for low mass search, with lower-background components

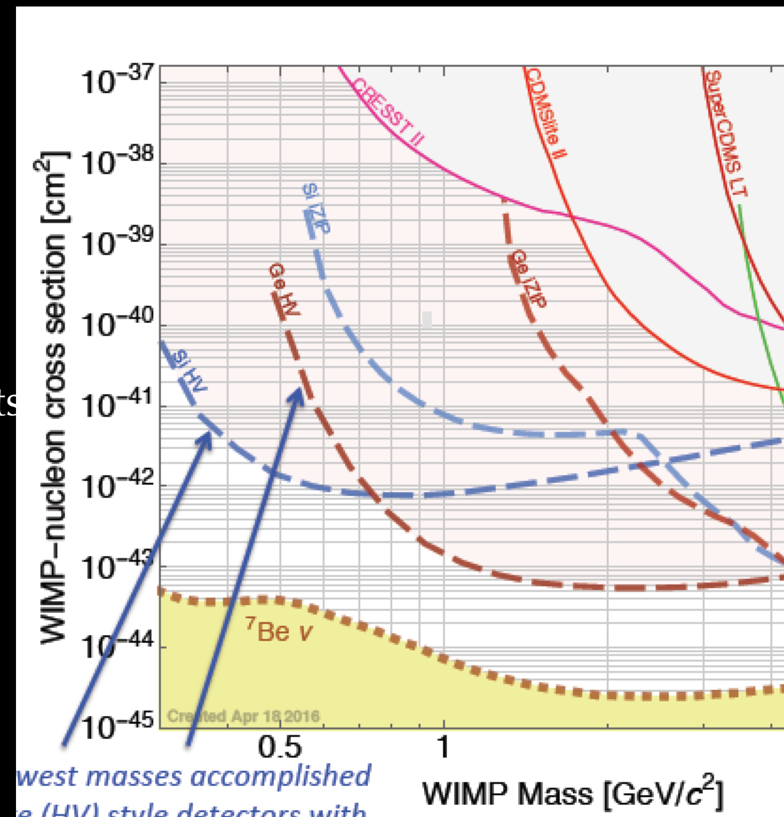
CRESST: R&D towards 0.1 keV threshold, with smaller crystals, lower background, leading SD constraints.

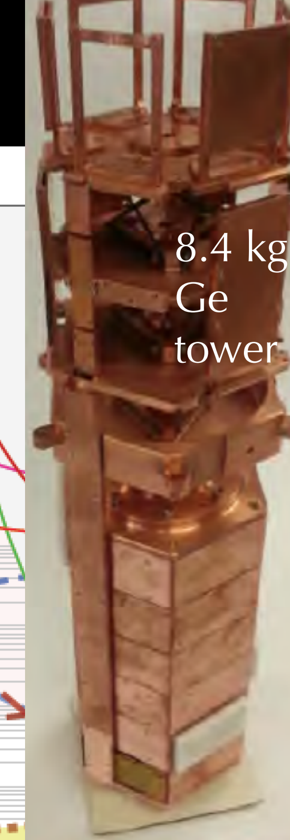
SuperCDMS: 50 kg of 1.4 kg Ge (and Si) detectors, construction/operation at SNOLAB. Can operate in HV mode, for 0.9 keV threshold. *PRL 112 (2014) 041302)*

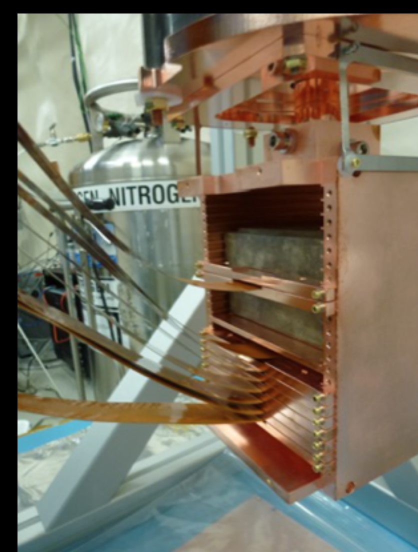
DAMIC: search for WIMP interactions in CCD Si,
36 gm now operating at SNOLAB, with 5 ev/keV/kg/day.
Aim for 1E-5 pb sensitivity, with 1 keV threshold.
arXiv:1506.02562

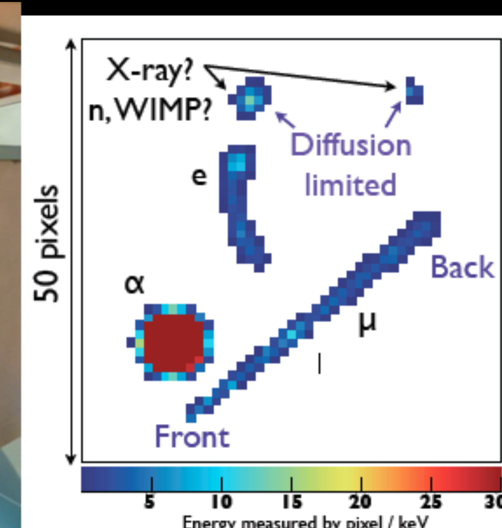
NEWS: spherical, high pressure gas detector with 0.1 keV threshold, under construction at SNOLAB, aim for 1E-5 pb sensitivity with Ar, Ne targets.

Quantum Sensors +++







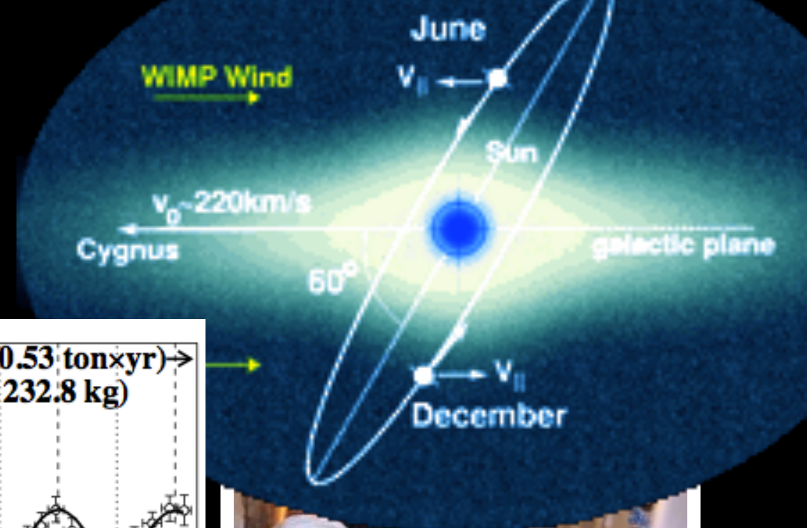


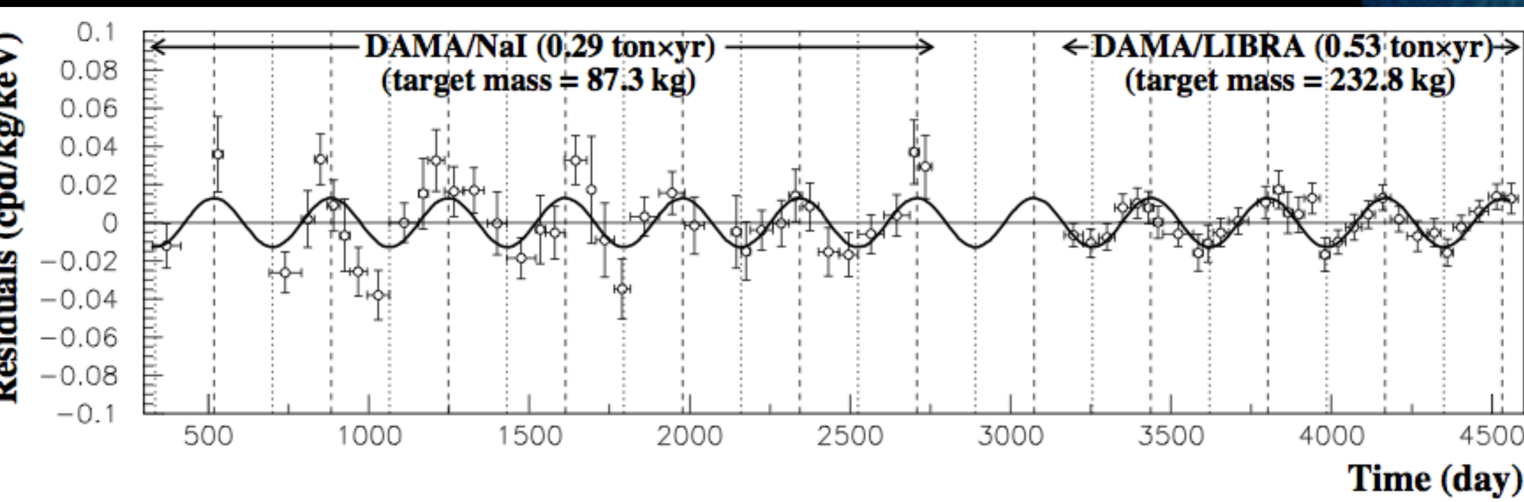
Low Mass, Large σ

Annual Modulation Tests

predicted modulation A~0.02-0.1, t_0=152.5 days

t_0 =

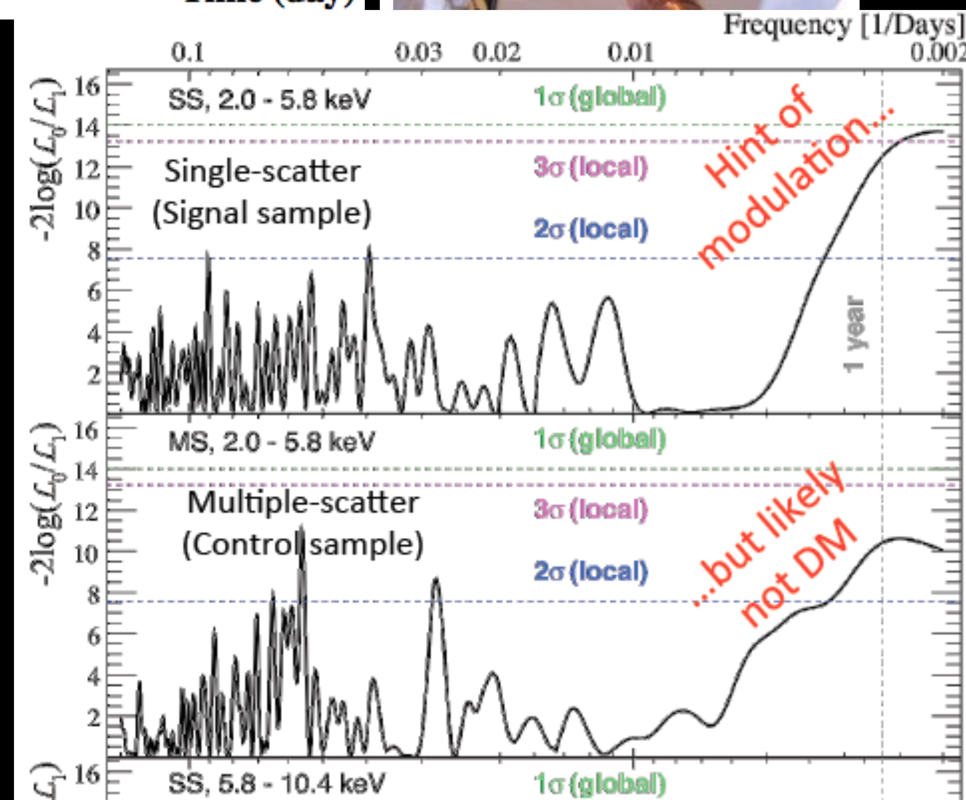




DAMA/LIBRA: measure (0.0112±0.0012) cpd/kg/keV, t_0 = (144±7) d in 1.33 T-yr.

many other searches, on Ge, CsI, Xe, etc. observe no evidence of modulation.

In the same underground laboratory:
XENON100: Xe, 4.8σ exclusion of DAMA, test of leptophilic dark matter *arXiv:1507.07748*



Low Mass, Large σ

Annual Modulation Tests

+**ANAIS** (Canfranc), **DM-Ice+KIMS** = **COSINE** (YangYang), **SABRE** (AU)

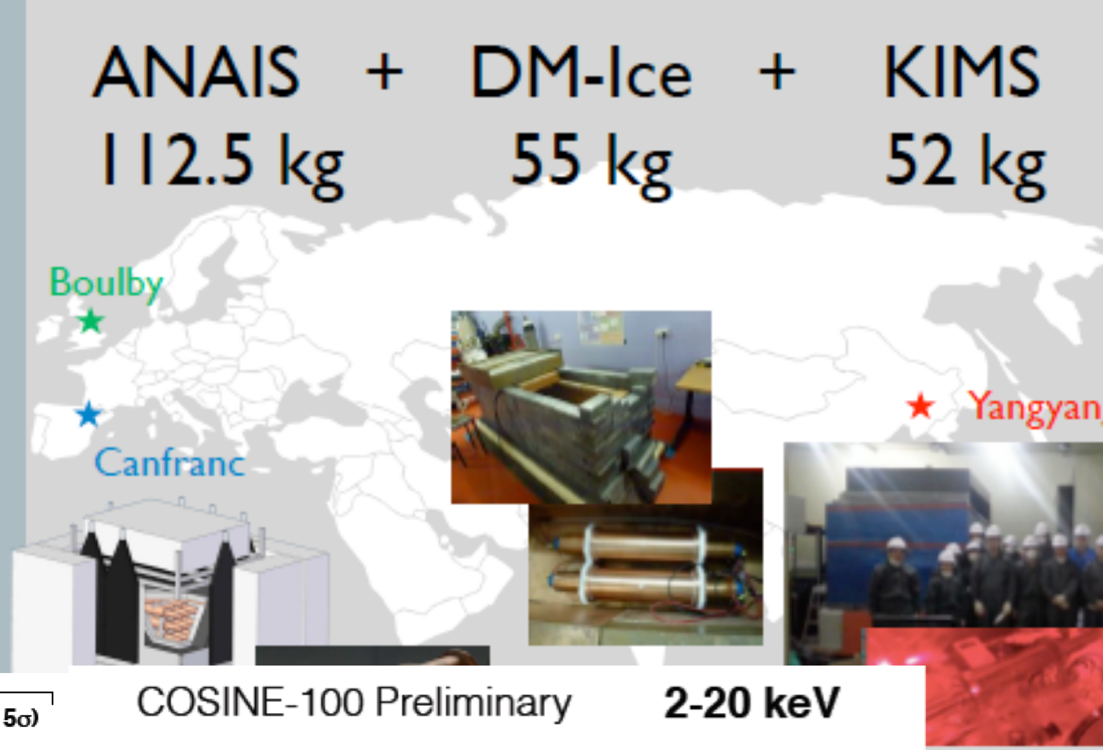
INTERNATIONAL NaI(Tl) COLLABORATIVE EFFORT

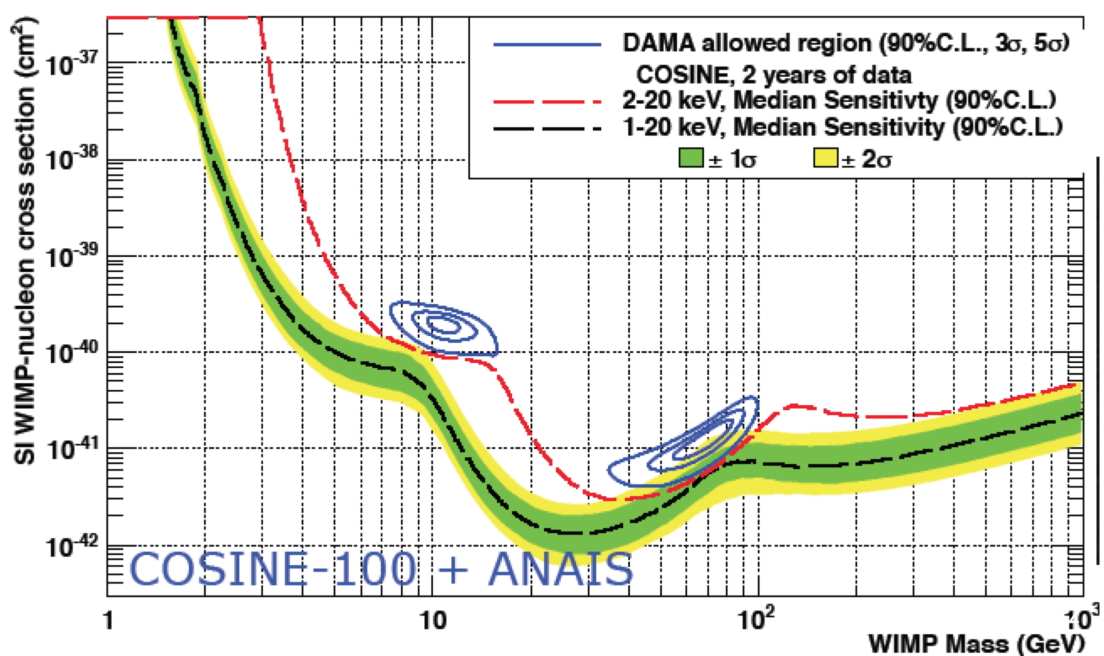
COMBINED ANALYSIS of 220 kg NaI(Tl) with present background levels

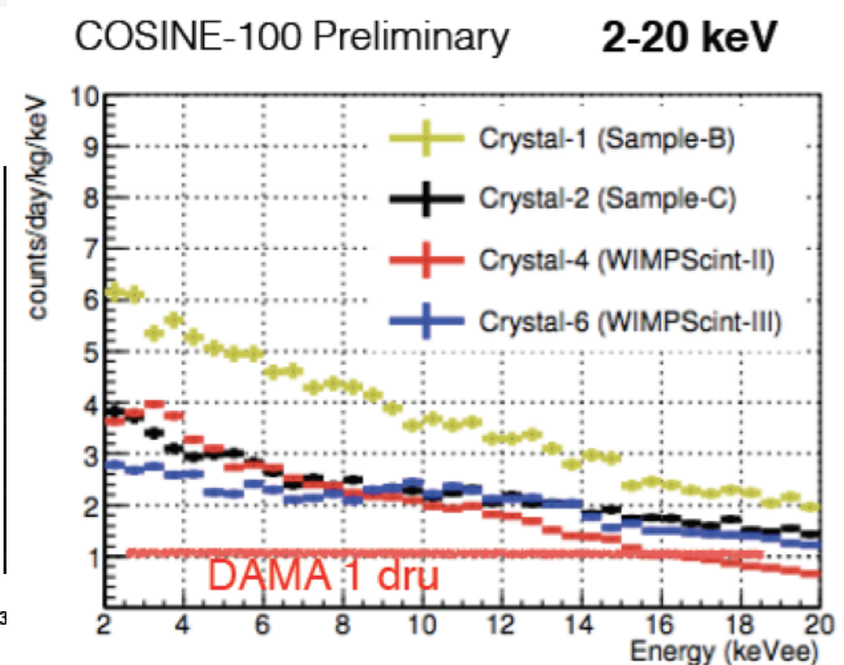
112.5 kg at Canfranc, Spain

+

107 kg at Yangyang, South Corea







R. Murayama, TAUP2017

Low Mass, Large σ

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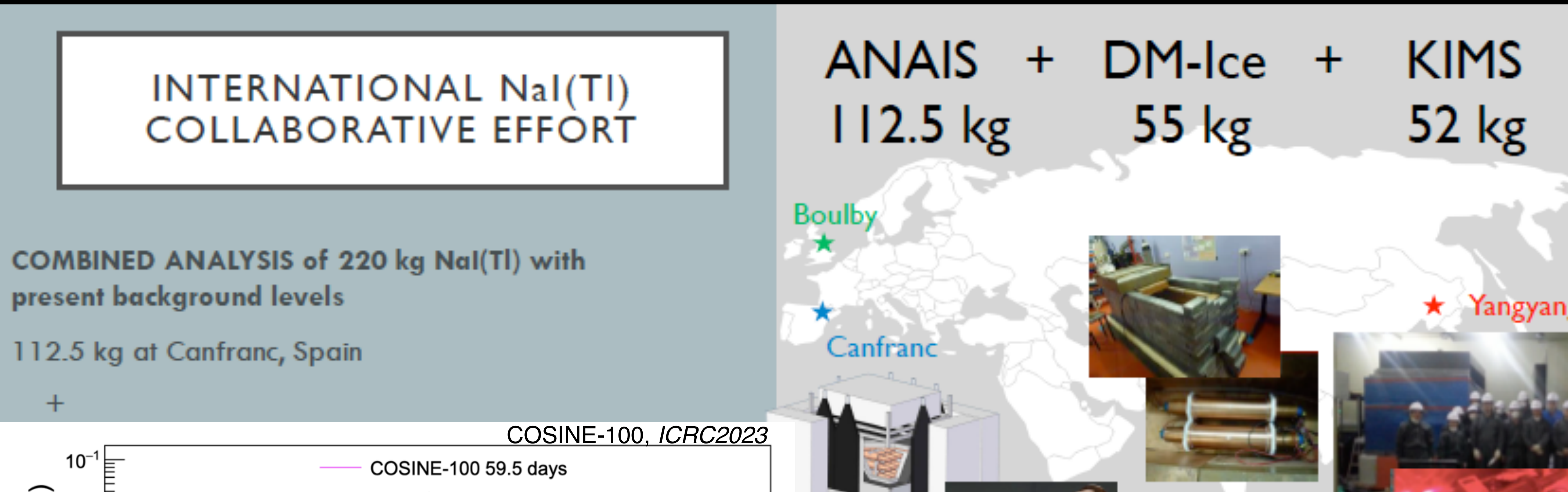
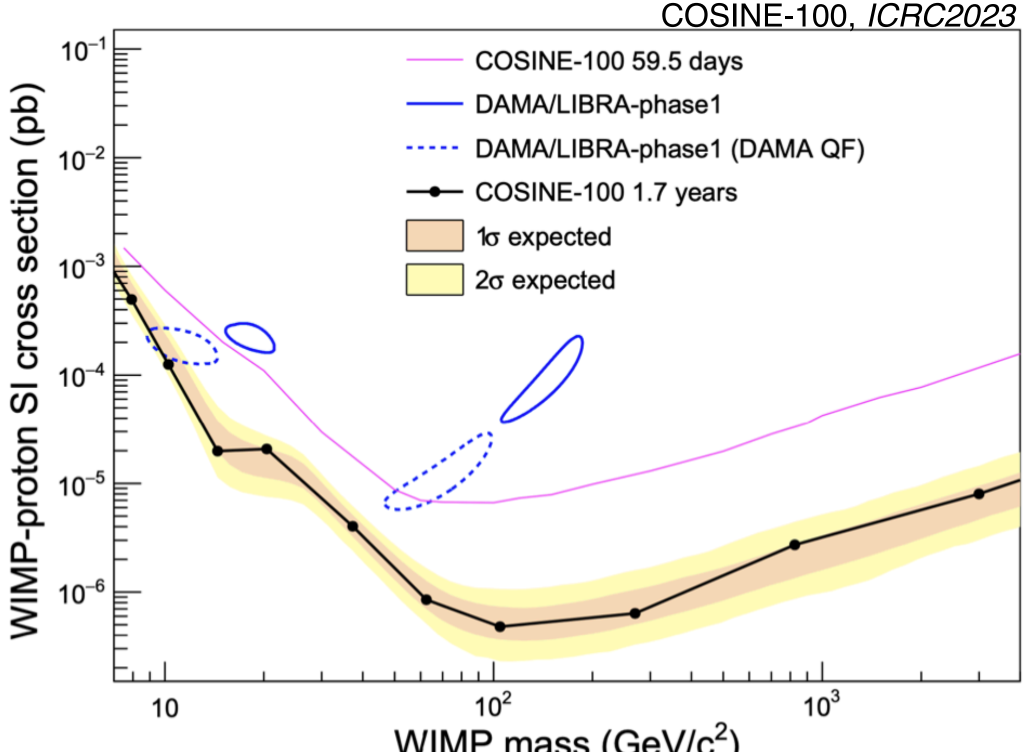
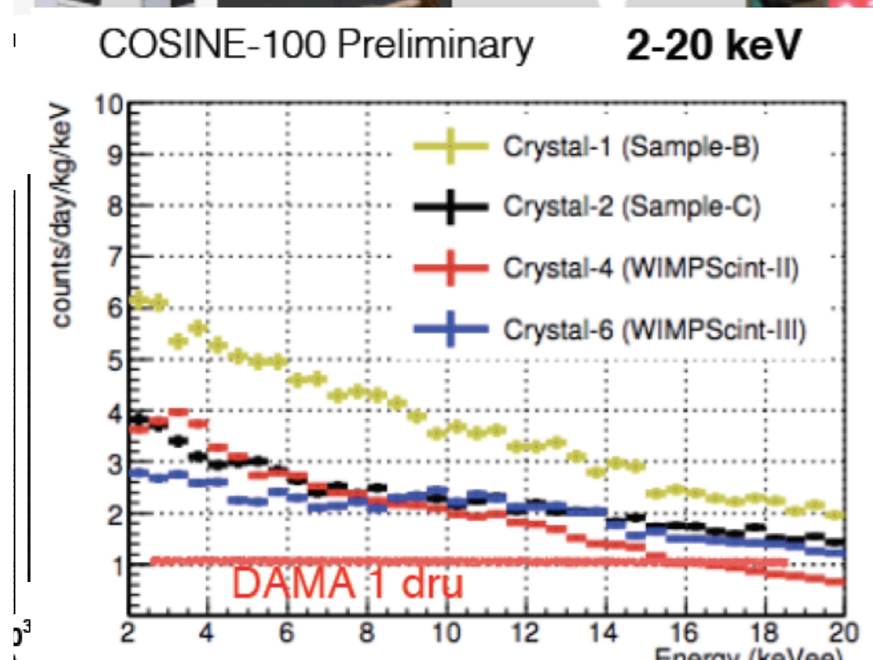


COSINE-100, *ICRC2023*





R. Murayama, TAUP2017

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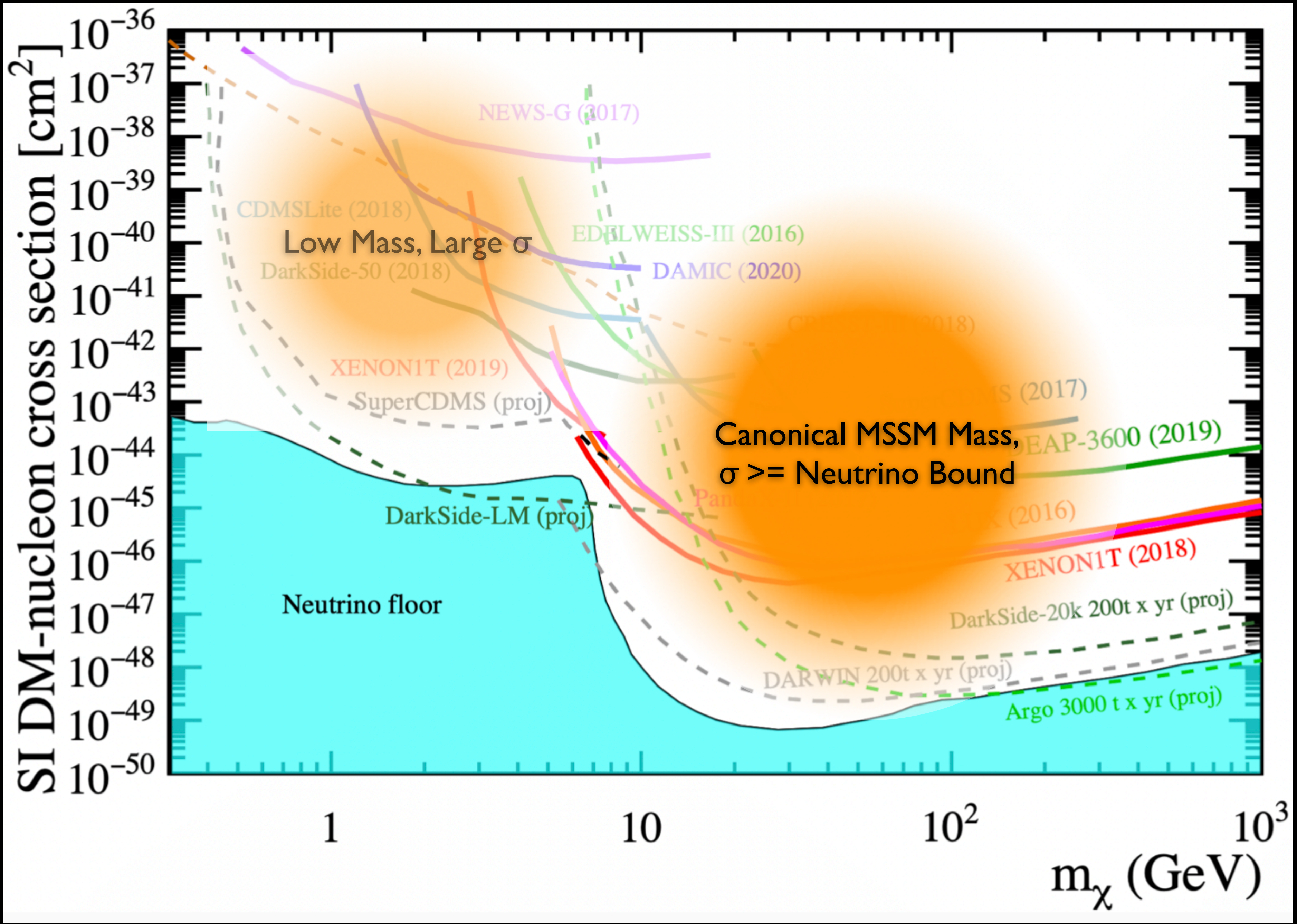

Jocelyn Monroe

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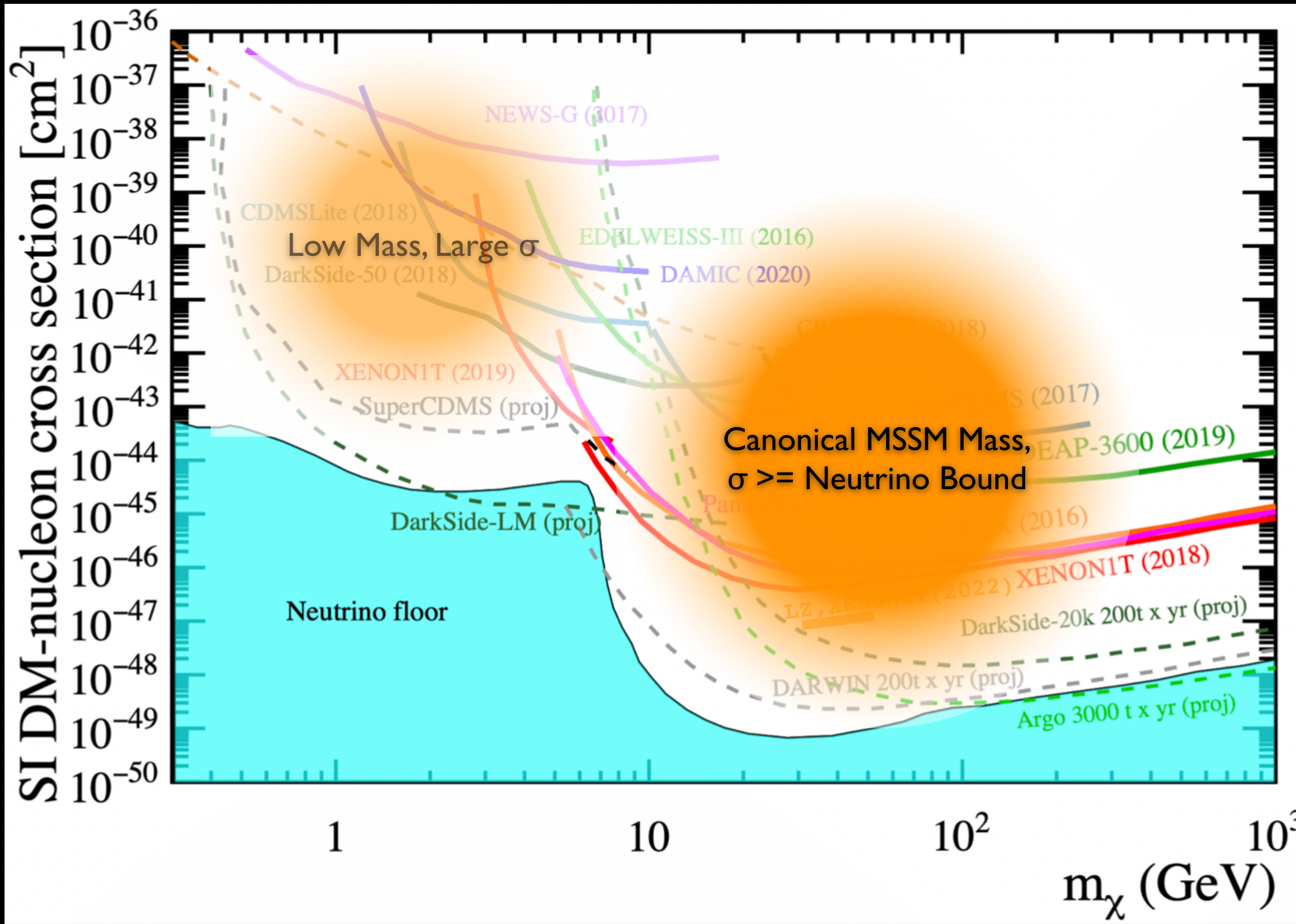


Xenon Detectors

Aprile E., et al. SPIE, Vol. No. 4140 (2000) **LXeGRIT**

10 kg

2010

XENON 10 (LNGS)

ZEPLIN I,II,III (Boulby)

XENON 100 (LNGS)

100 kg

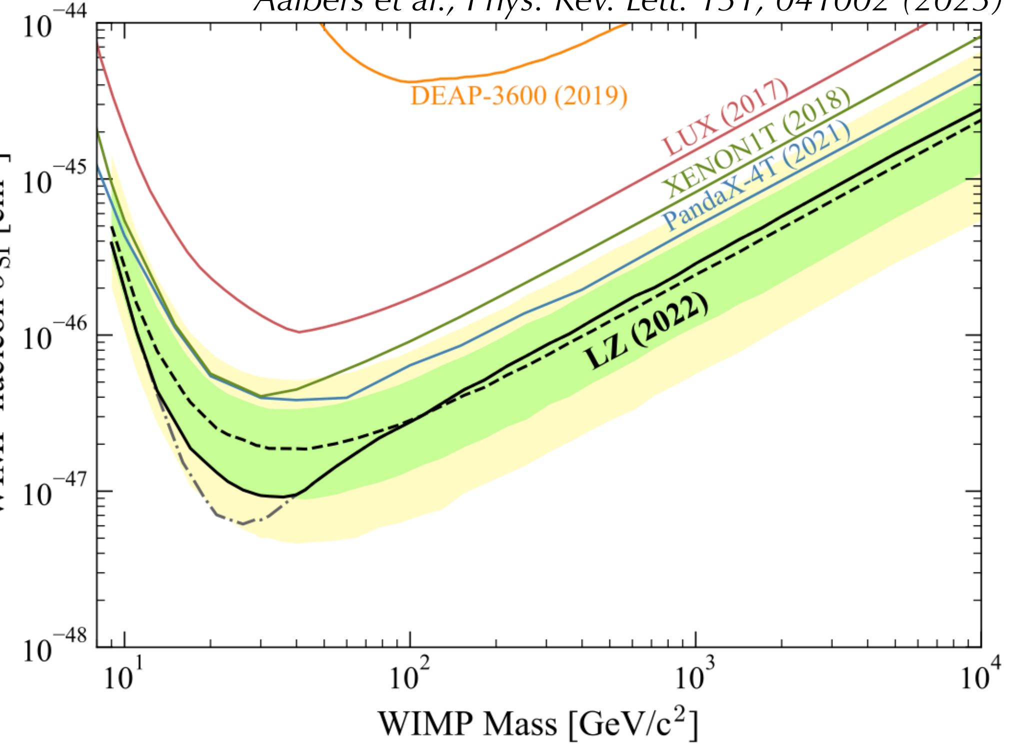
LUX (250 kg, SURF)

PANDA-X 500 kg, CJPL)

XMASS (800 kg, Kamioka)

2015

Aalbers et al., Phys. Rev. Lett. 131, 041002 (2023)



00 kg

ENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

2020

10,000 kg

DARWIN: 50 t

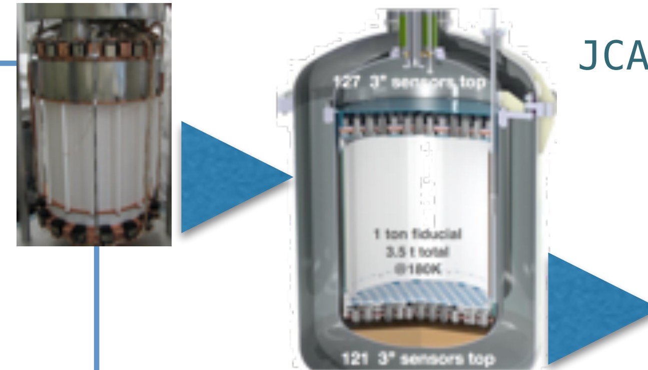
DARWIN

(thanks to L. Baudis)

High Mass,
Large # Events
$\sigma < \nu$ bound

Ultimate LXe TPC at LGNS.

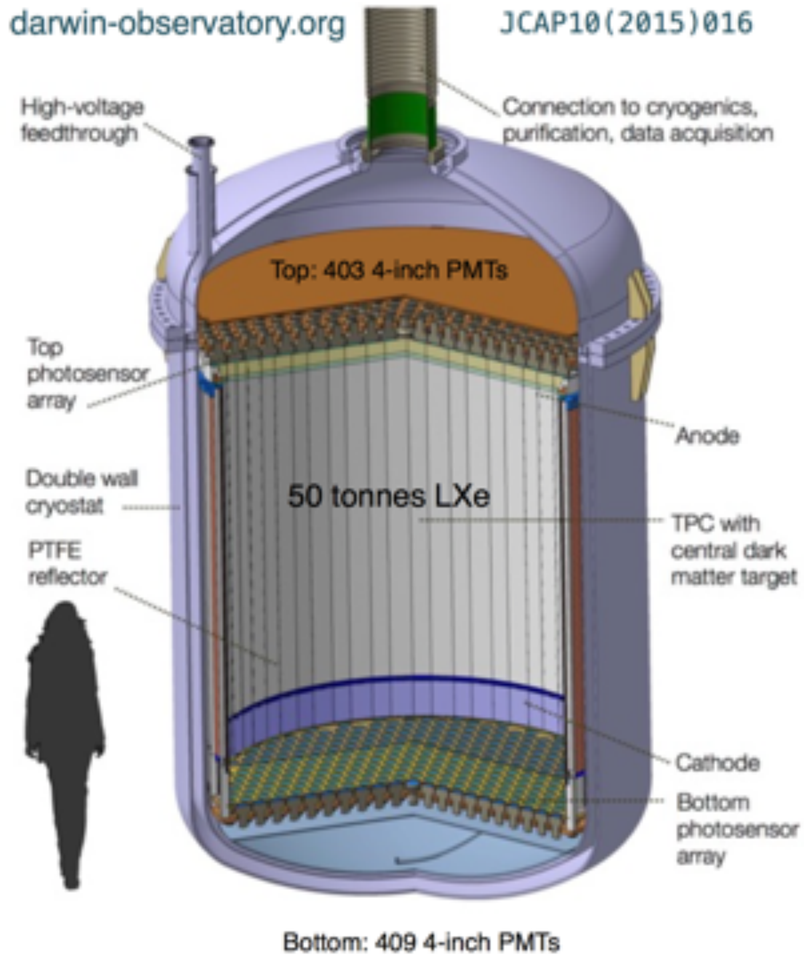
- ✓ 50 t (40 t) Lxe in total (in the TPC)
- ✓ $\sim 10^3$ photosensors
- ✓ 2.6 m drift length, 2.6 m diameter TPC
- ✓ Background: dominated by neutrinos
- ✓ WIMP spectroscopy, search + non-WIMP science: axion / ALP search, solar neutrinos, supernova neutrinos, sterile neutrinos, coherent neutrino – nucleus scattering, 0v2β decay of ^{136}Xe.



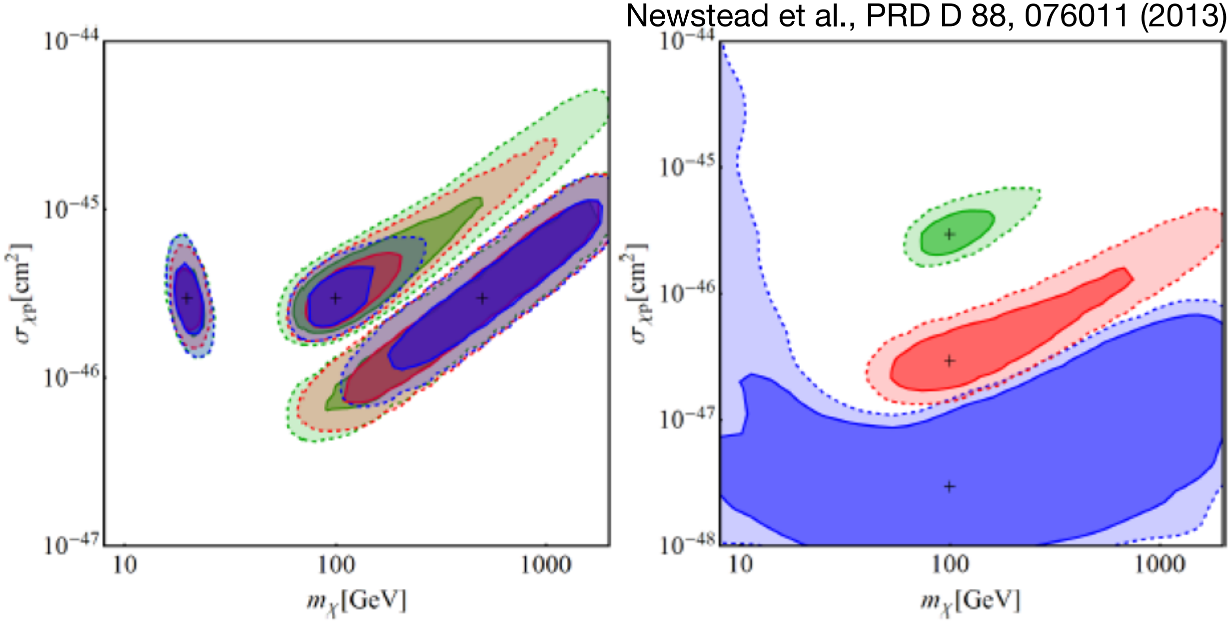
JCAP10 (2015) 016

darwin-observatory.org

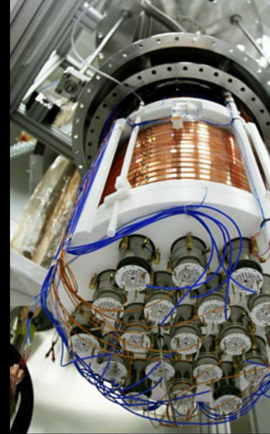
JCAP10(2015)016



Newstead et al., PRD D 88, 076011 (2013)



Argon Detectors



10 kg

2010

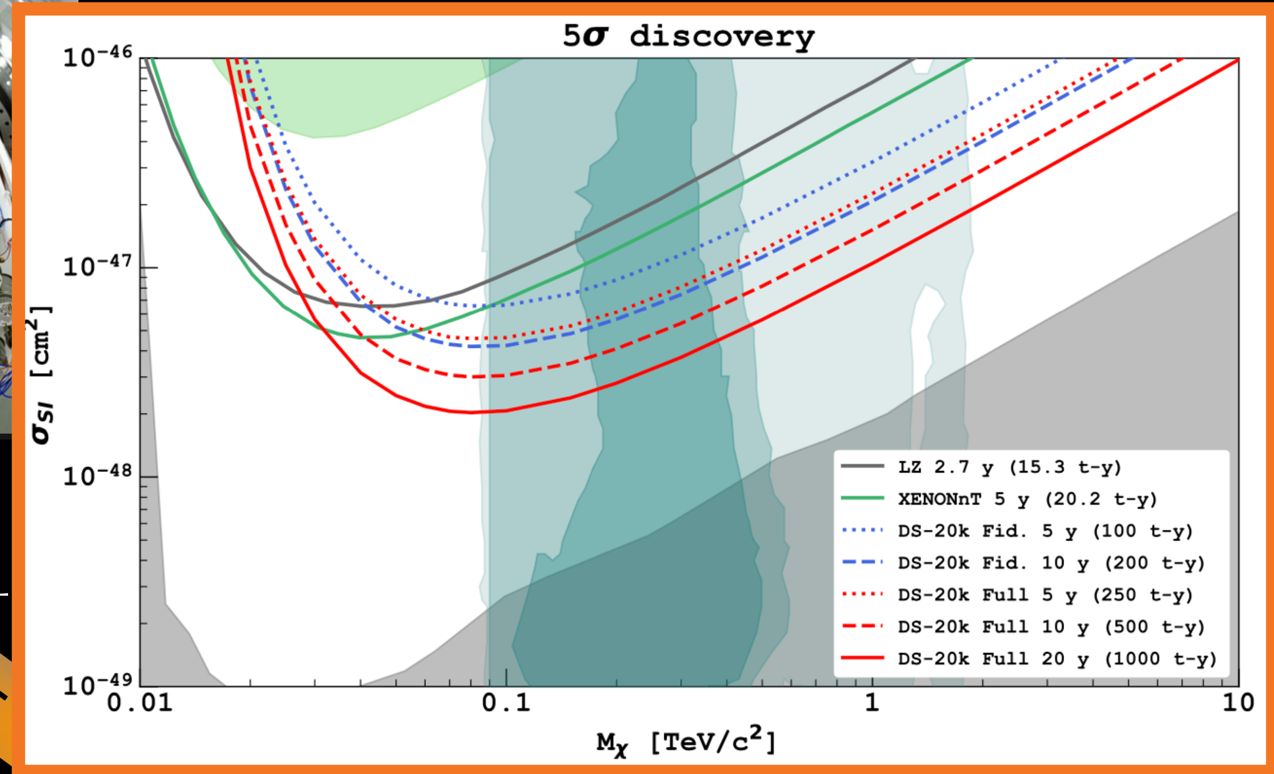
DarkSide-50 (50 kg, LNGS)

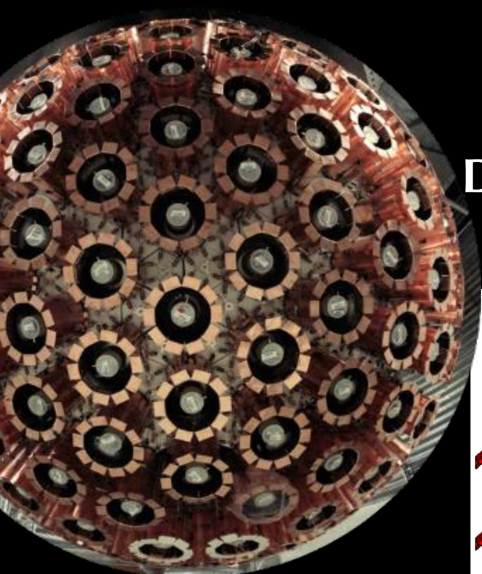
100 kg

ArDM (1t, L

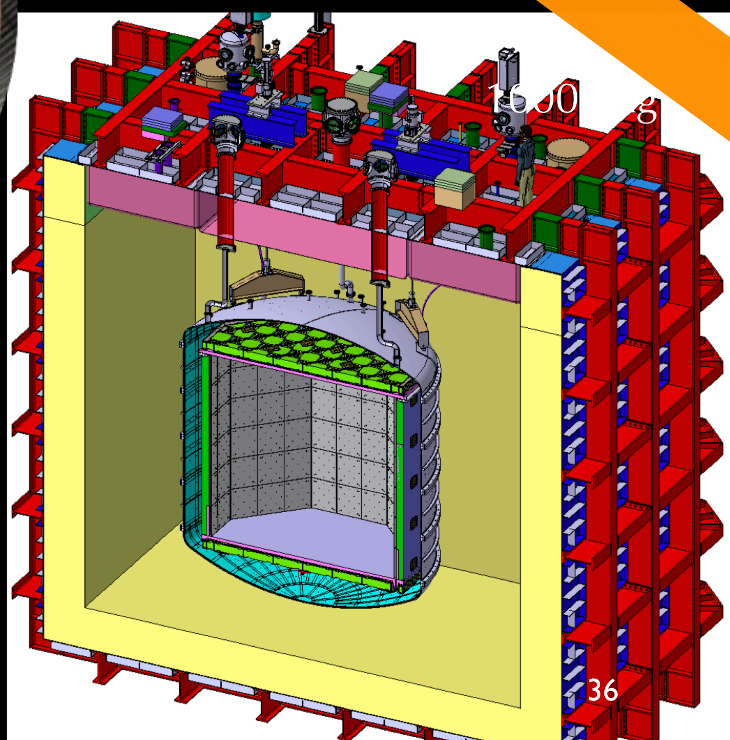
1,000 kg

2015





DEAP-3600 (3.6t, SNOLAB)



Global Argon Dark Matter Collaboration formed

APPEC

10,000 kg

2020

100,000 kg

DarkSide-20k (50t, LNGS)

Future: ARGO kt-scale

Jocelyn Monroe

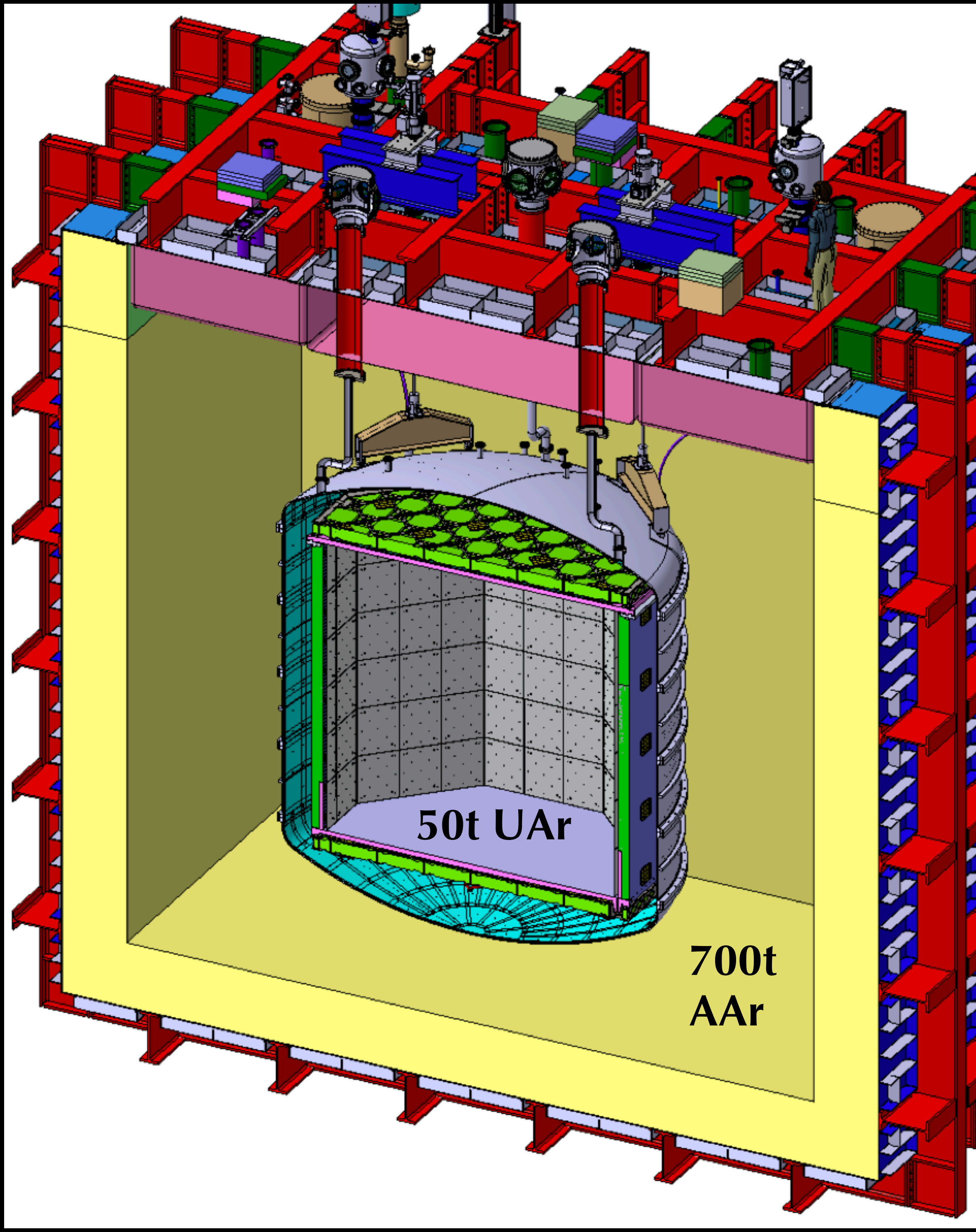
DarkSide-20k Detector

50 t liquid underground Ar (UAr) dark matter target, in a dual phase TPC. inside a 700 t liquid atmospheric Ar (AAr) outer detector

Two key innovations:

1. first large-scale use of large-area cryogenic Si photon detection modules (PDMs) instead of PMTs.

2. liquid AAr outer detector to veto the limiting background: neutrons



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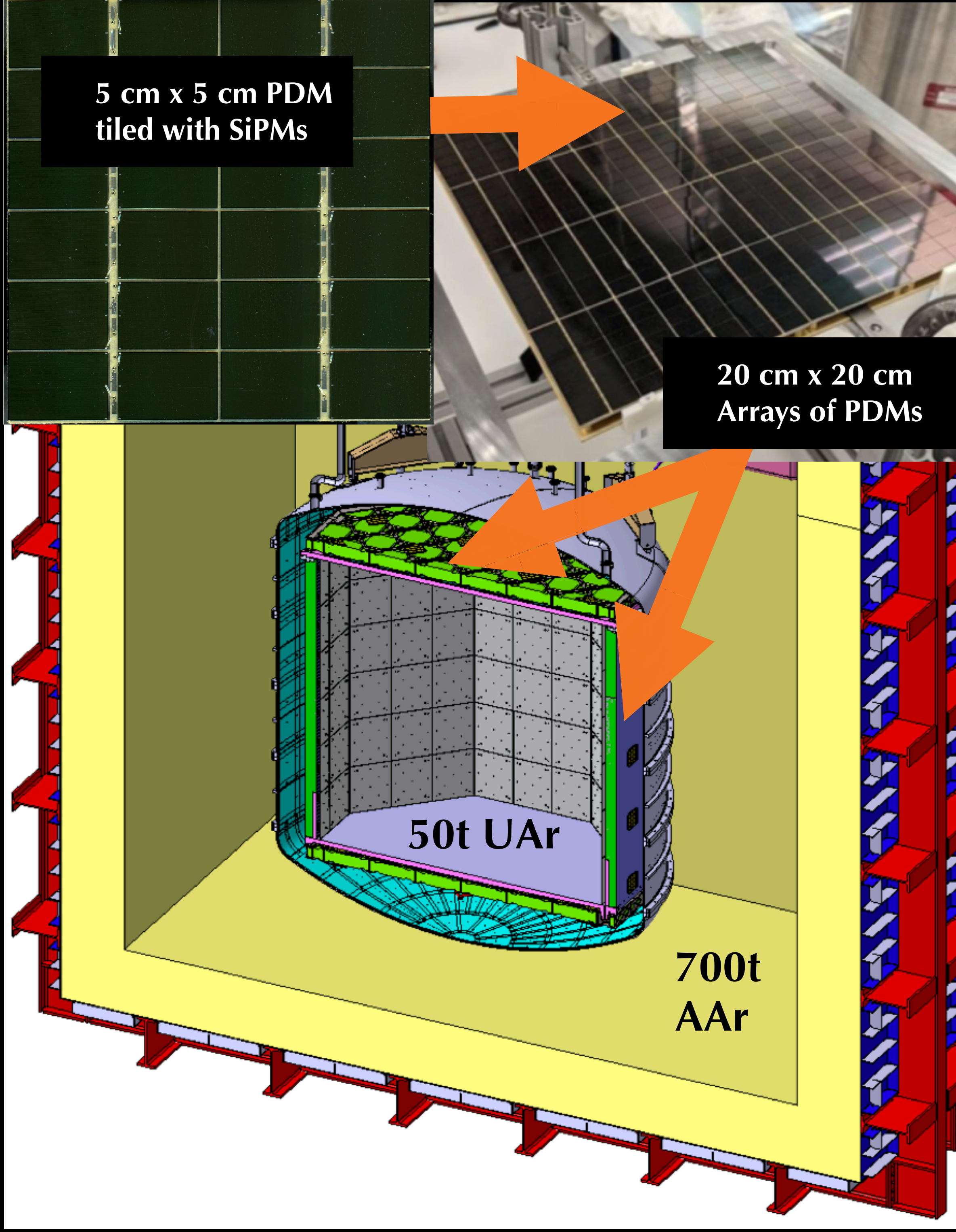
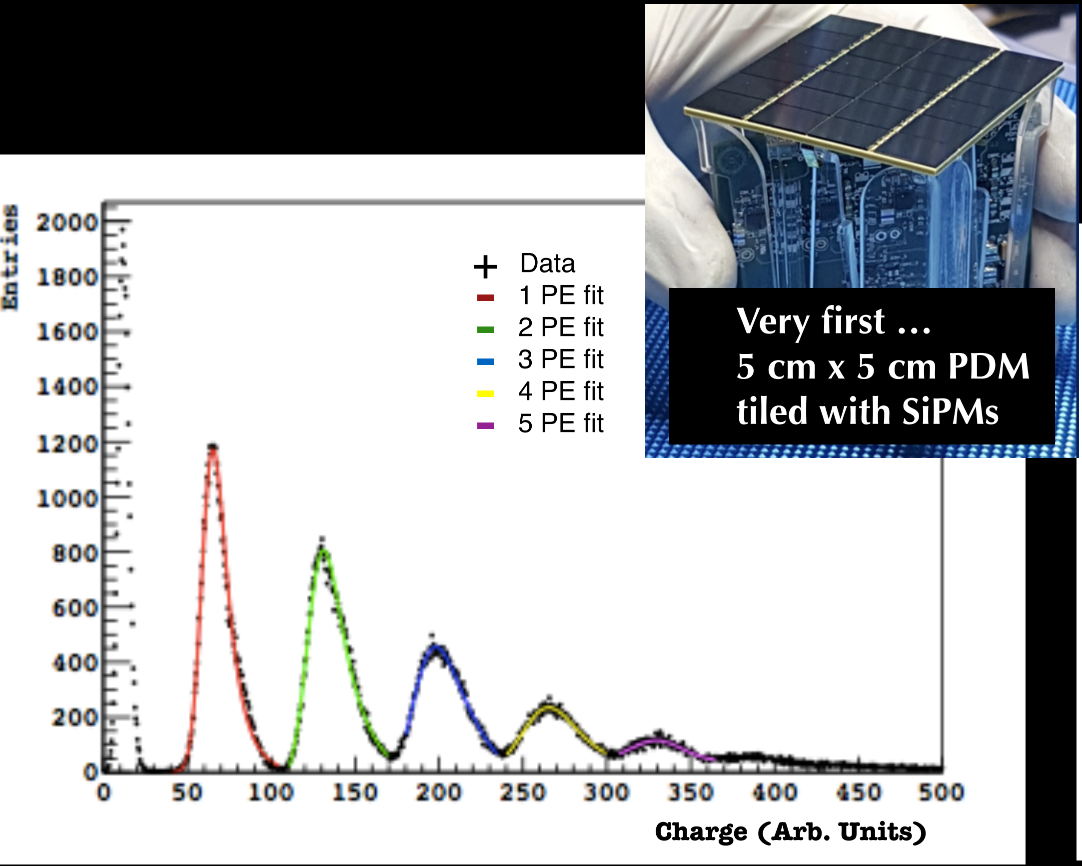


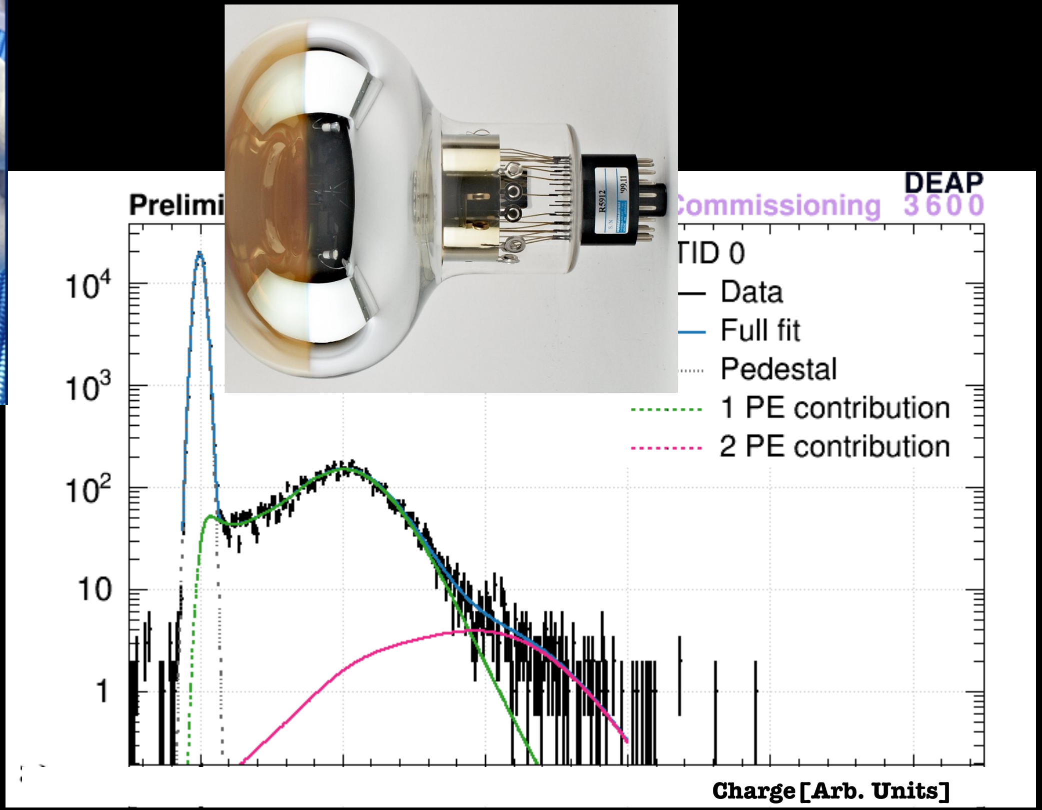
New Technology Collaborations

Photon Sensors: low noise, high efficiency, tiled arrays of cryogenic Si sensors developed in collaboration with FBK, achieving >45% PDE and 1 mHz/mm² dark noise



Aalseth, JM, et al. JINST 12 (2017) no.09, P09030

compared with:



Amaudruz, JM, et al. NIM A 922 (2019) 373

>3x photon detection efficiency, 10x lower noise, >50x lower radiogenic backgrounds than PMTs.

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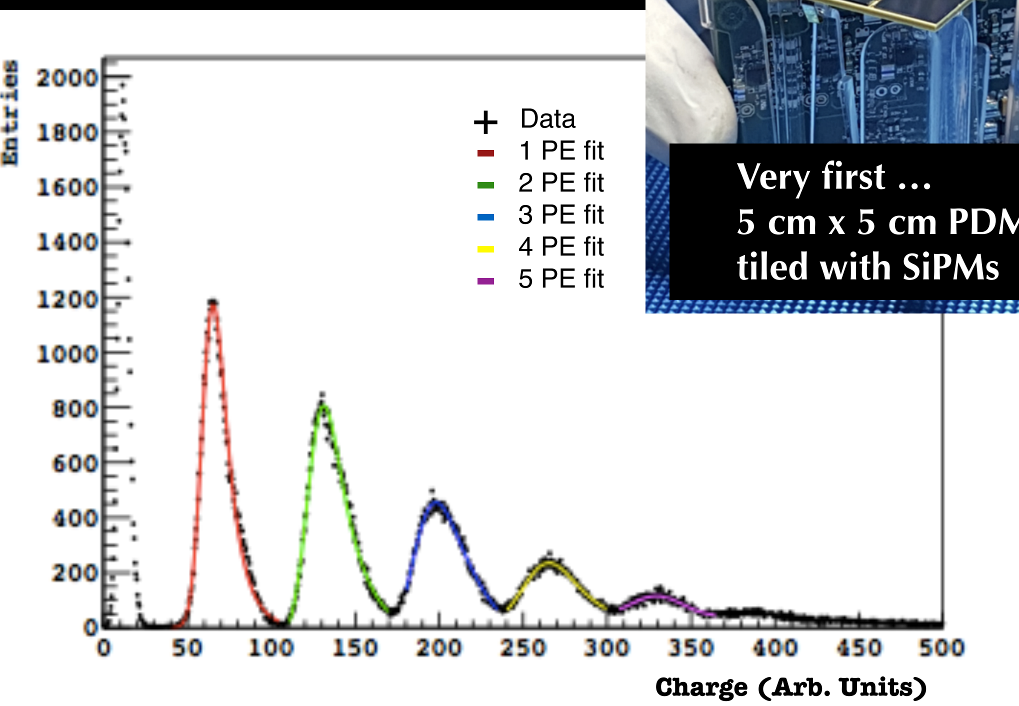
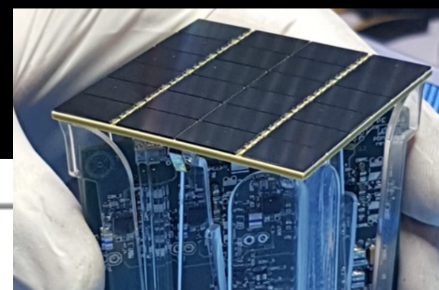
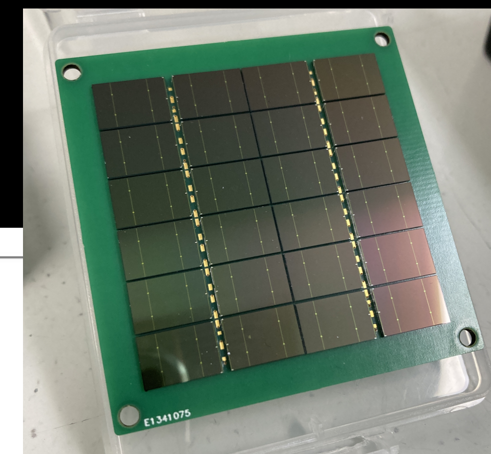


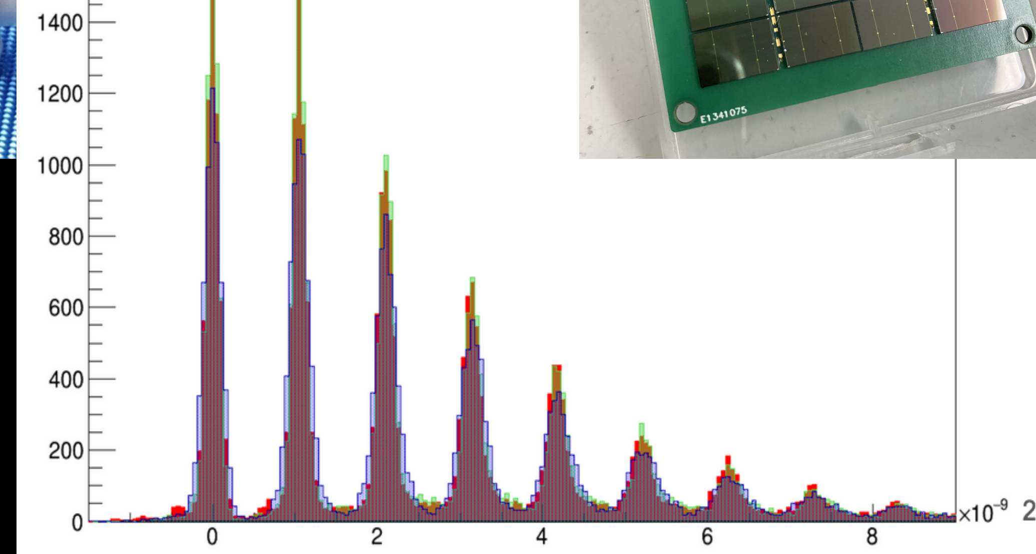
Aalseth, JM, et al. JINST 12 (2017) no.09, P09030



Very first …
5 cm x 5 cm PDM
tiled with SiPMs

Delivering
7 m^2 of PDMs,
25% of total,
in the UK!





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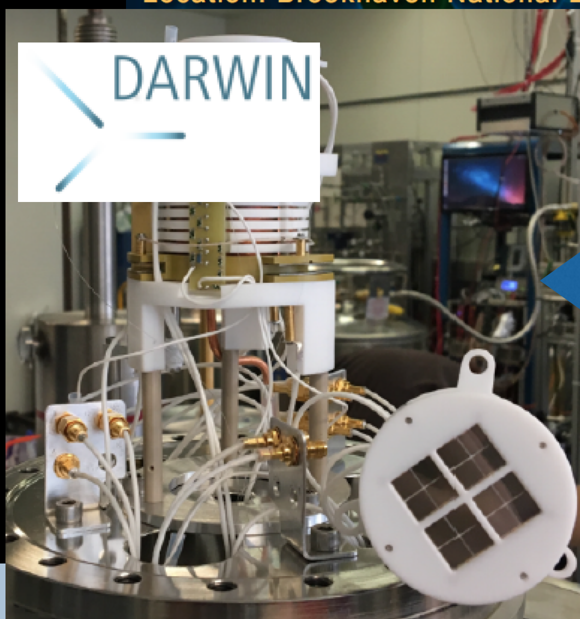
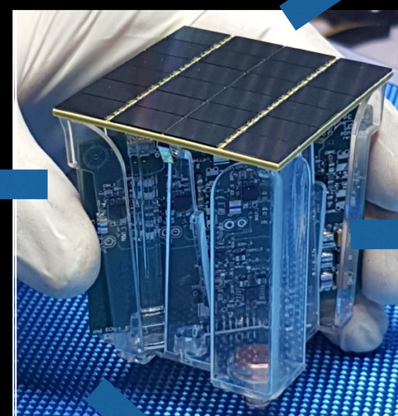
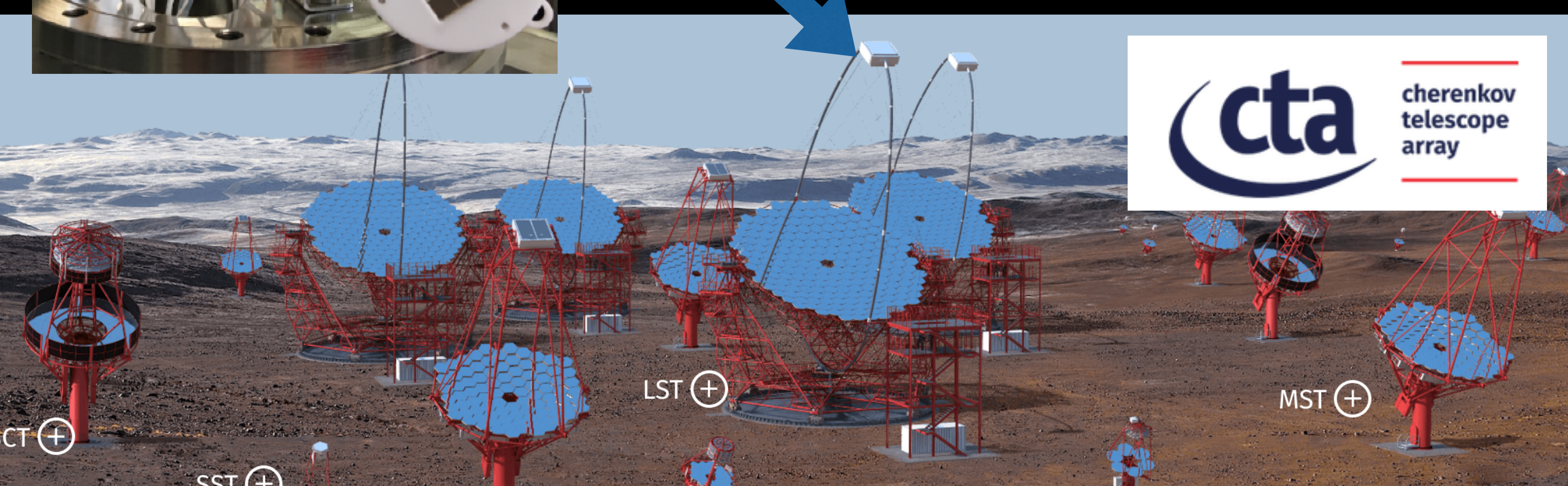
Experiments Exploring Cryogenic SiPM Technology





LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



+ environmental monitoring, medical imaging, automated navigation (LIDAR) …

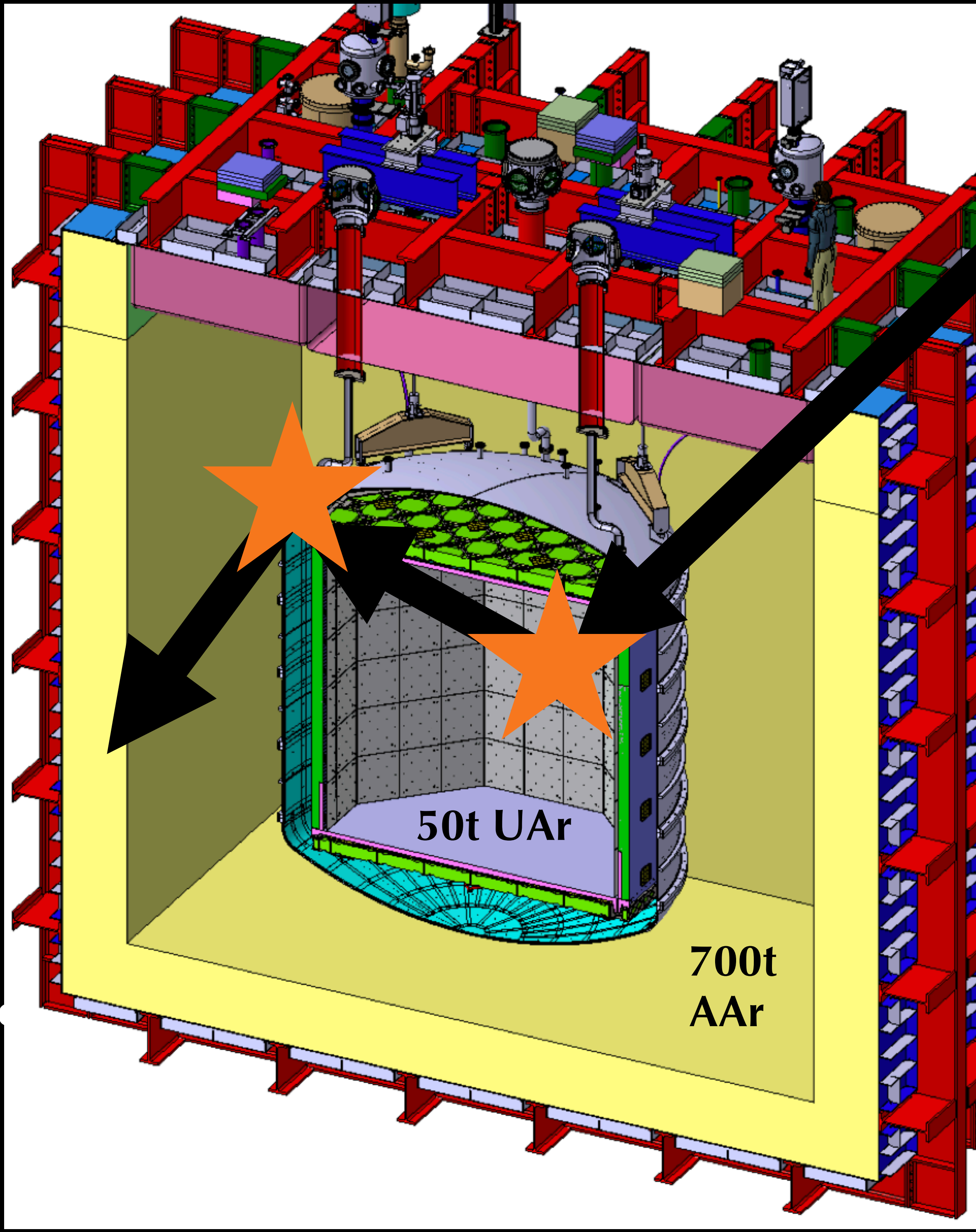
New Technologies: DarkSide-20k

50 t liquid Underground Ar (UAr) dark matter target, inside a 700 t liquid Atmospheric Ar (AAr) outer detector

Gran Sasso Underground Laboratory (LNGS) (outside L'Aquila, IT)

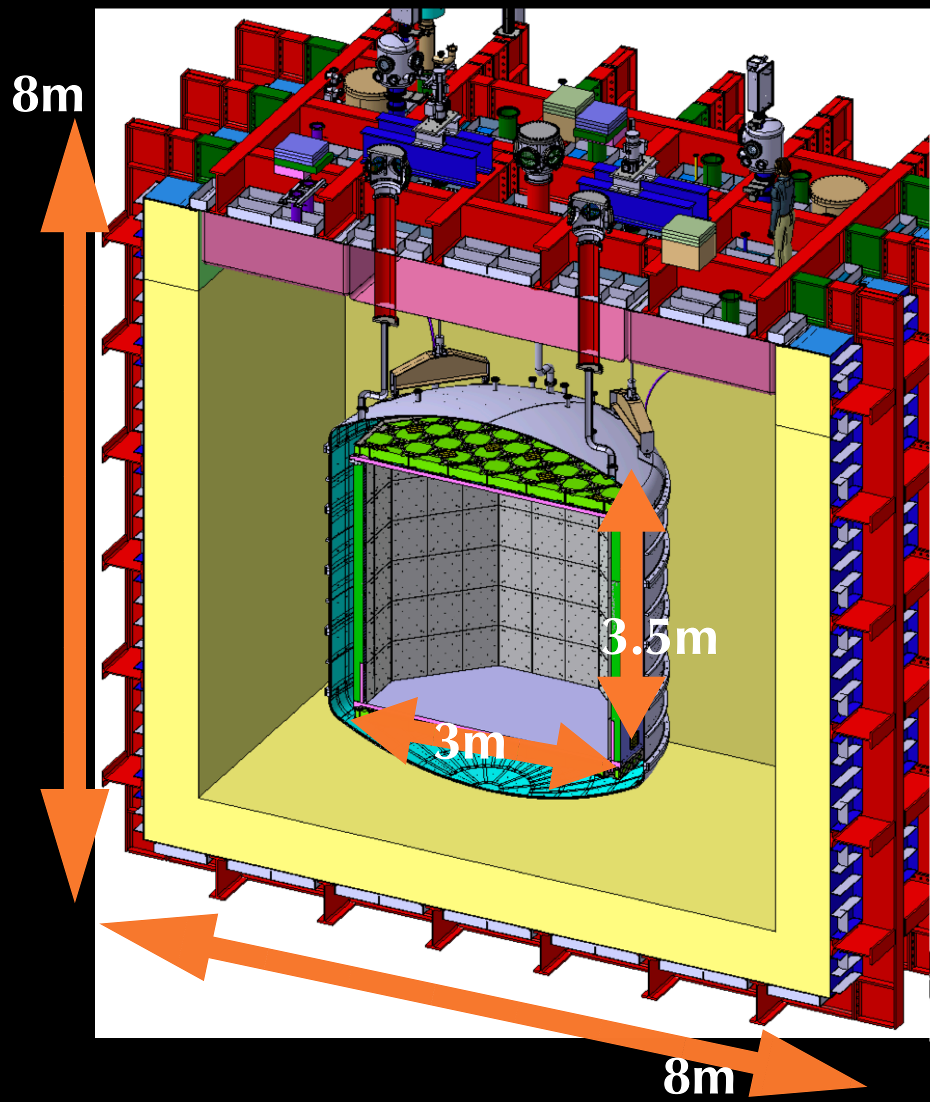
Two key innovations:

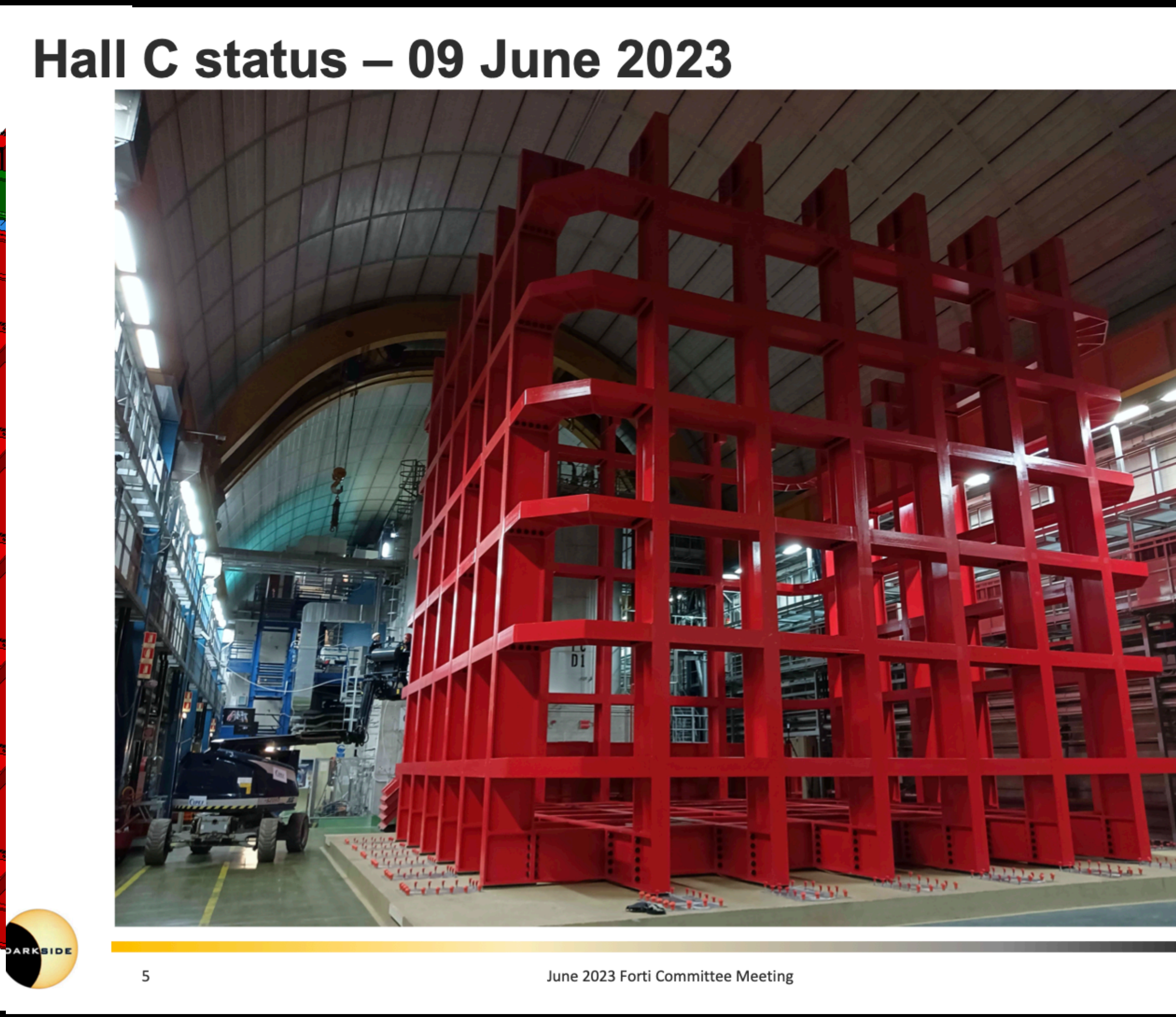
1. first large-scale use of large-area cryogenic Si photon detection modules (PDMs) instead of PMTs.
2. **liquid AAr outer detector to veto the limiting background: neutrons**



New Technology Collaborations

Cryostat technologies: DarkSide-20k cryostat + cryogenics systems use refrigeration, purification, recirculation and HV technology *demonstrated* by ProtoDUNE



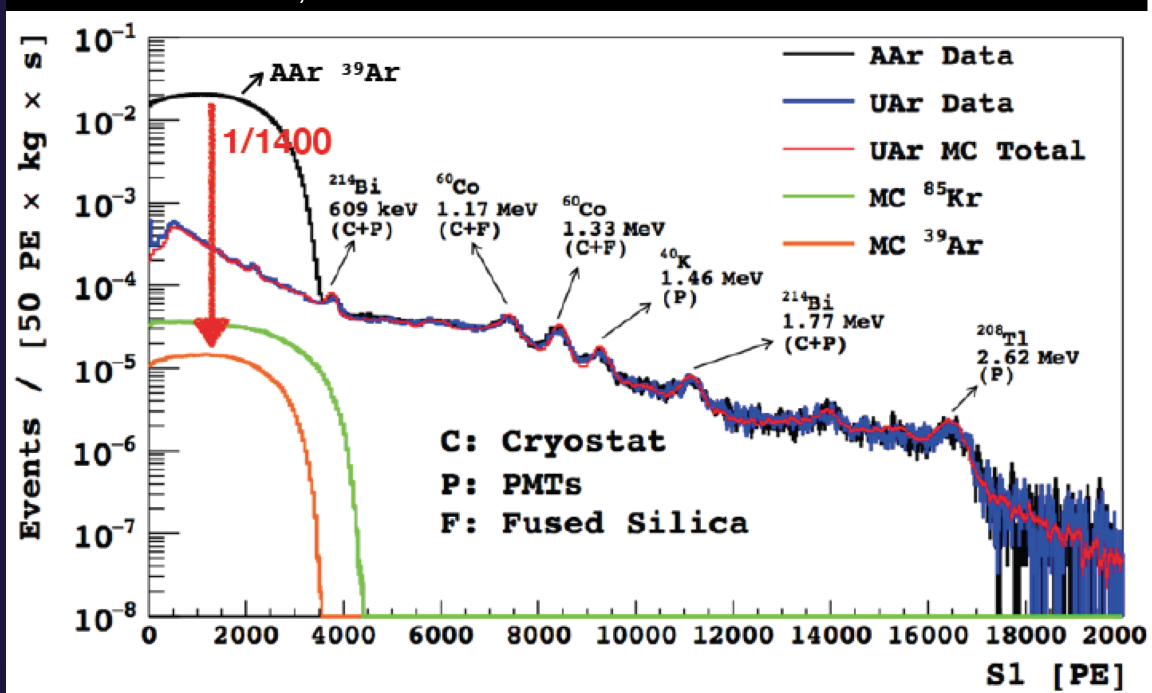


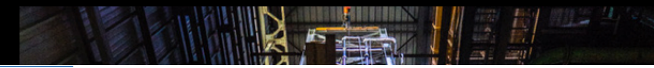
New Technology Collaborations

Agnes, JM et al., Eur.Phys.J.C 81 (2021) 4, 359

Isotopic enhancement: ARIA facility for x1000 depletion of Ar-39 in UAr, CERN Vacuum Group collaboration on distillation column for UAr, medical isotopes in Seruci mine.

Aalseth et al. Eur.Phys.J.Plus 133 (2018)





A 350-metre-tall tower to purify argon

CERN is participating in ARIA, a project to build a 350-metre column to produce extra pure argon to be used in a dark-matter search experiment

12 DECEMBER, 2017 | By Stefania Pandolfi

On Friday, 24 November, ARIA's top and bottom modules plus one standard module were brought to Building 180 and lined up to precisely test their alignment and interconnections. (Image: Max Brice/CERN)

CERN is taking part in a testing-phase project, called ARIA, for the construction of a 350-metre-tal distillation tower that will be used to purify liquid argon (LAr) for scientific and, in a second phase medical and possibly other uses.

New Technology Collaborations

Agnes, JM et al., Eur.Phys.J.C 81 (2021) 4, 359

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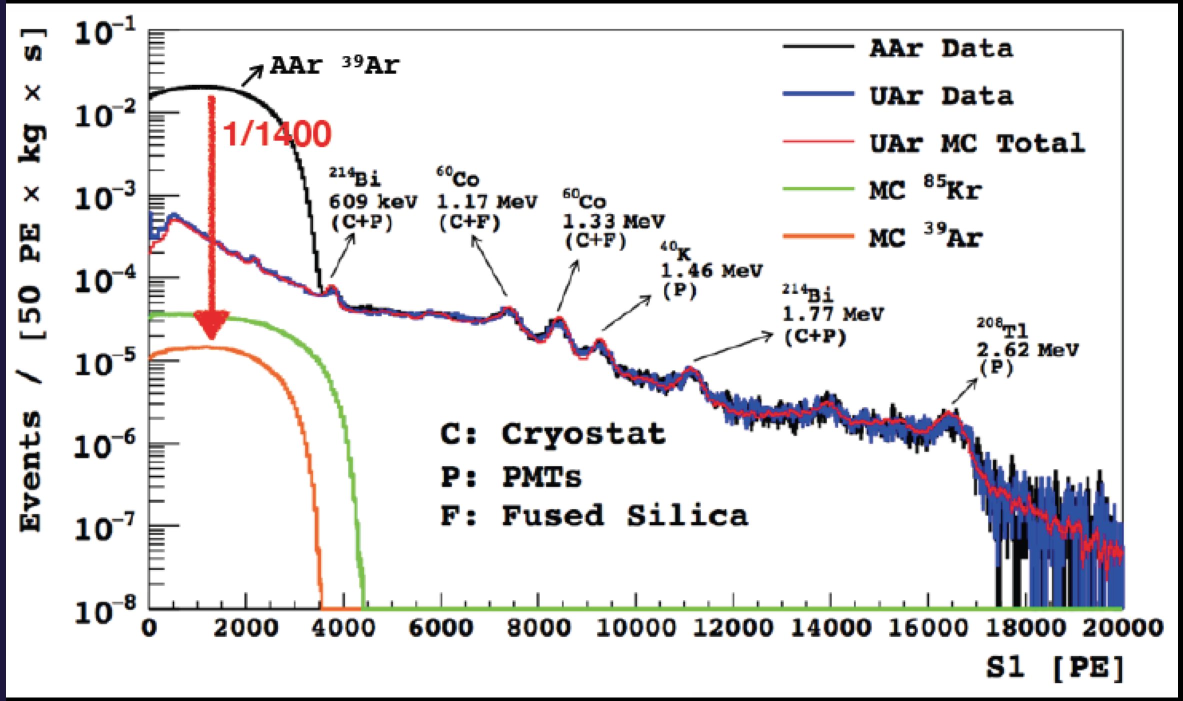

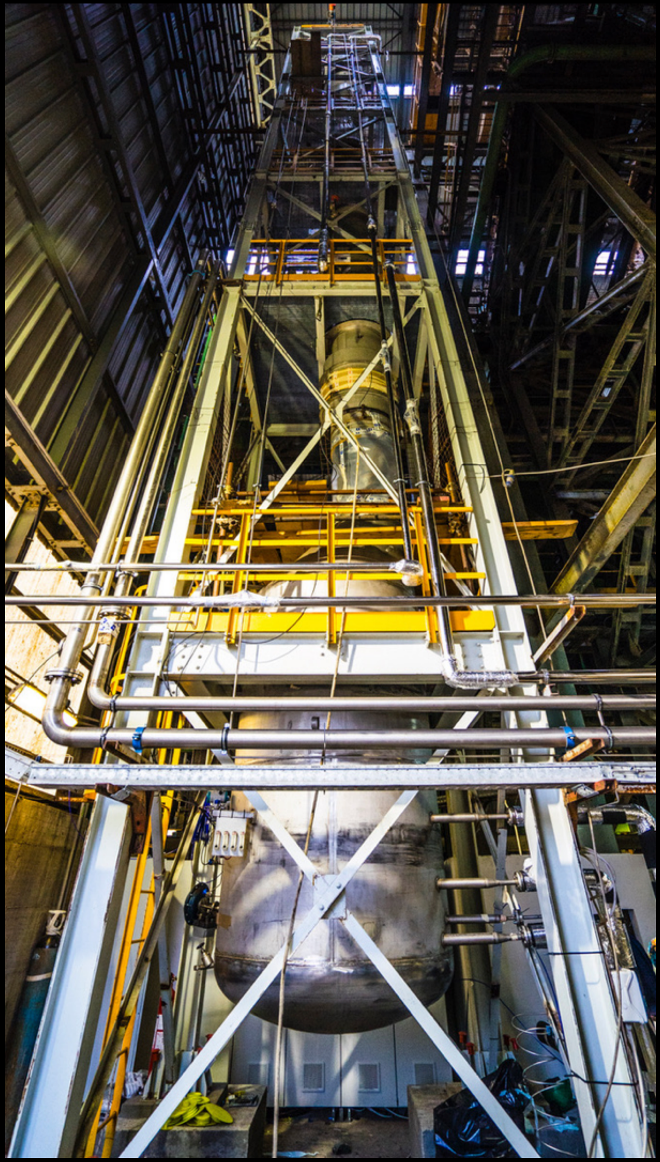

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New Technology Collaborations

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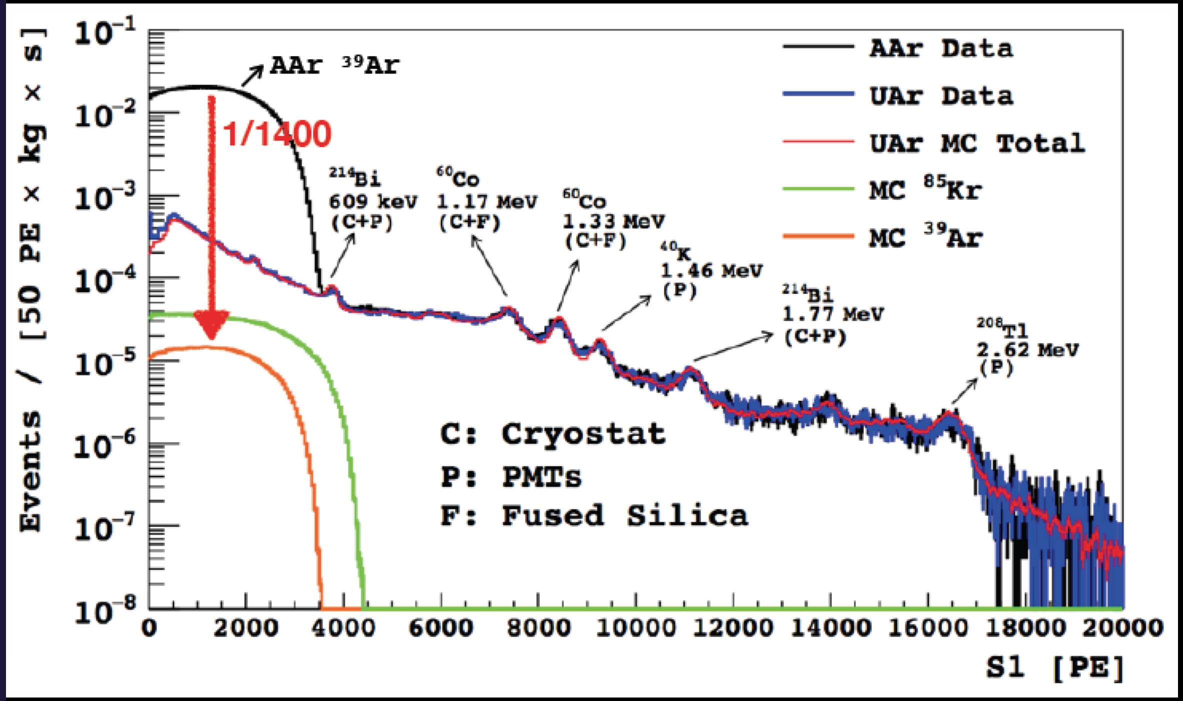


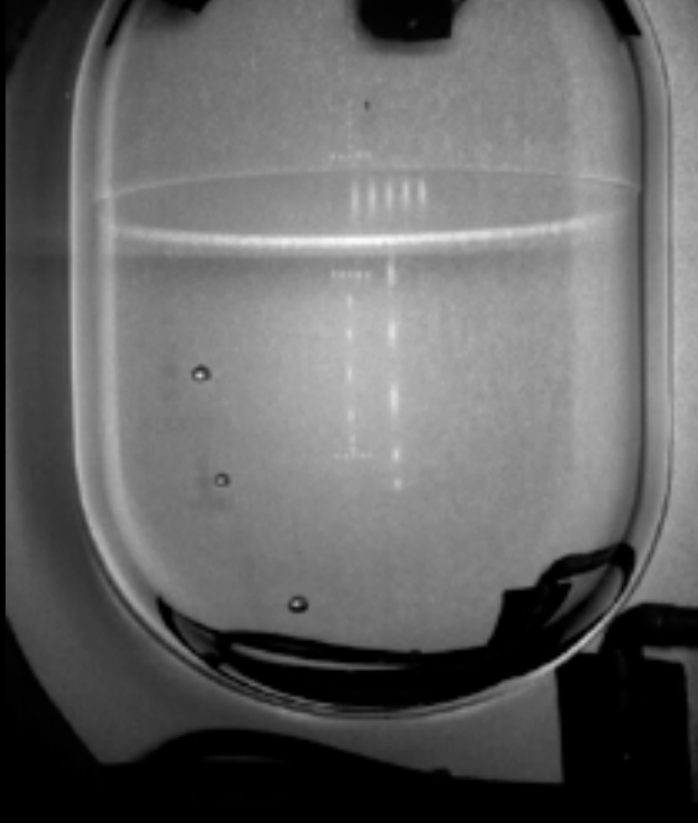
Bubble Chambers: Spin Dependent Search

SIMPLE (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)

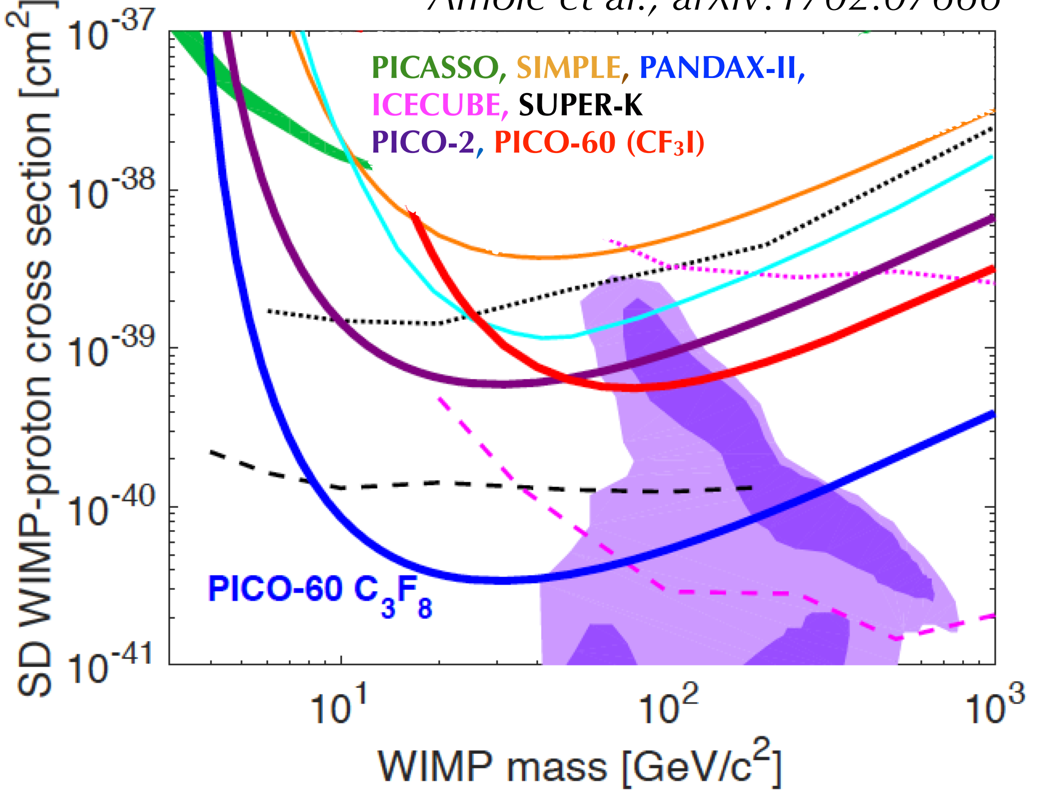
superheated target (CF_3I +), camera and piezo (acoustic) readout
measure integral counts above threshold when dE/dx > nucleation

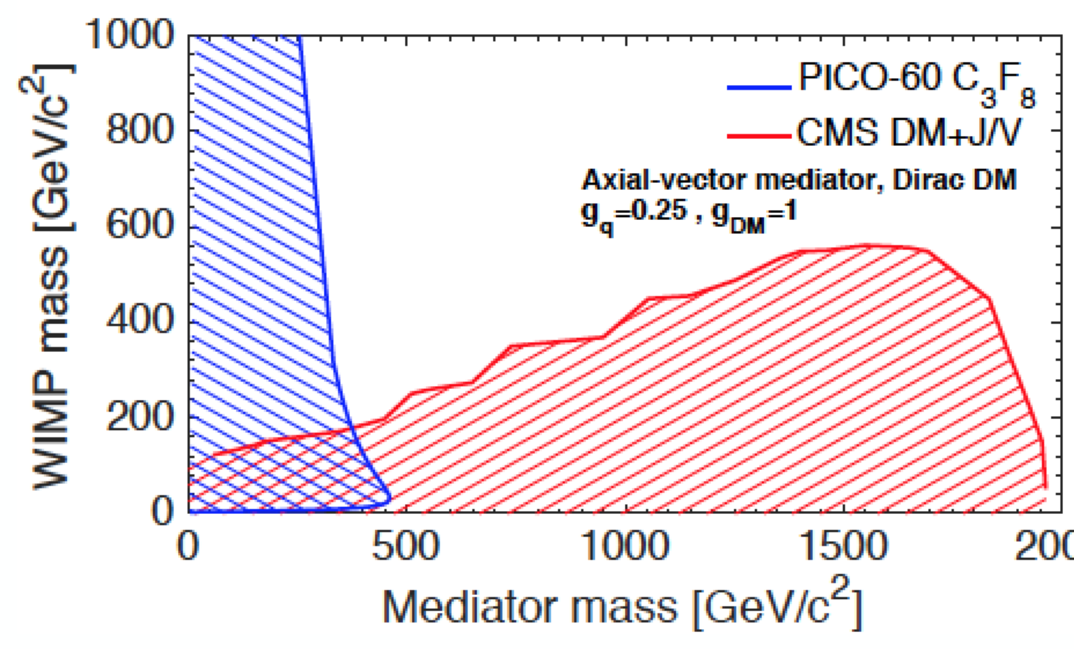
gamma rejection >1E-10, neutron discrimination from multiples,
1E-2 alpha rejection from acoustic readout

PICO-60: (PICASSO+COUPP) running since 2013 with CF_3I target upgraded in 2016 to C_4F_8 target. PICO-500 detector being deployed.



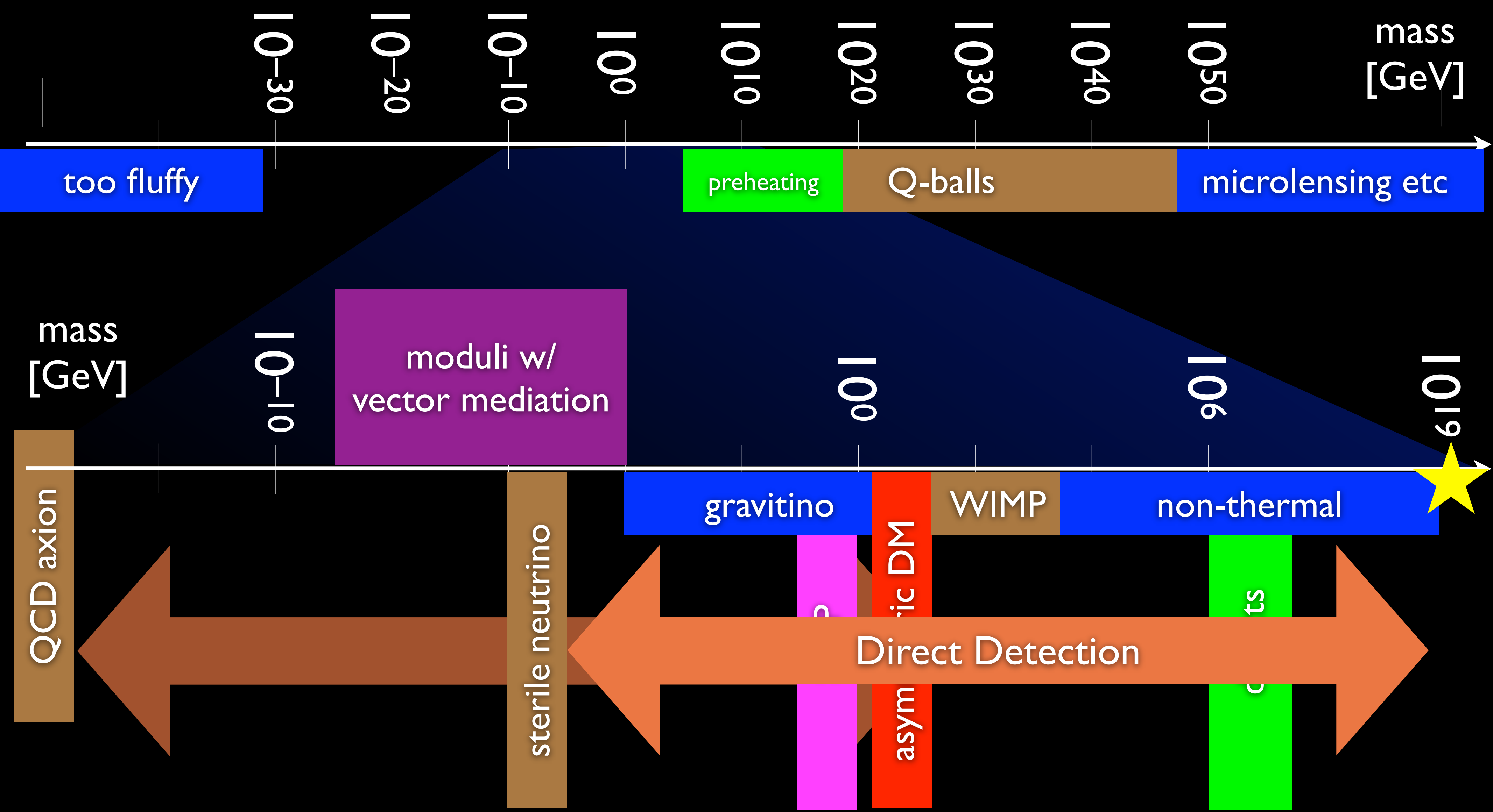
Amole et al., arXiv:1702.07666





Model Space: Theorist's View

(thanks to H. Murayama)



WIMPs producing nuclear recoils aren't the only possibility….

PRL 121 (2018) 11, 111303

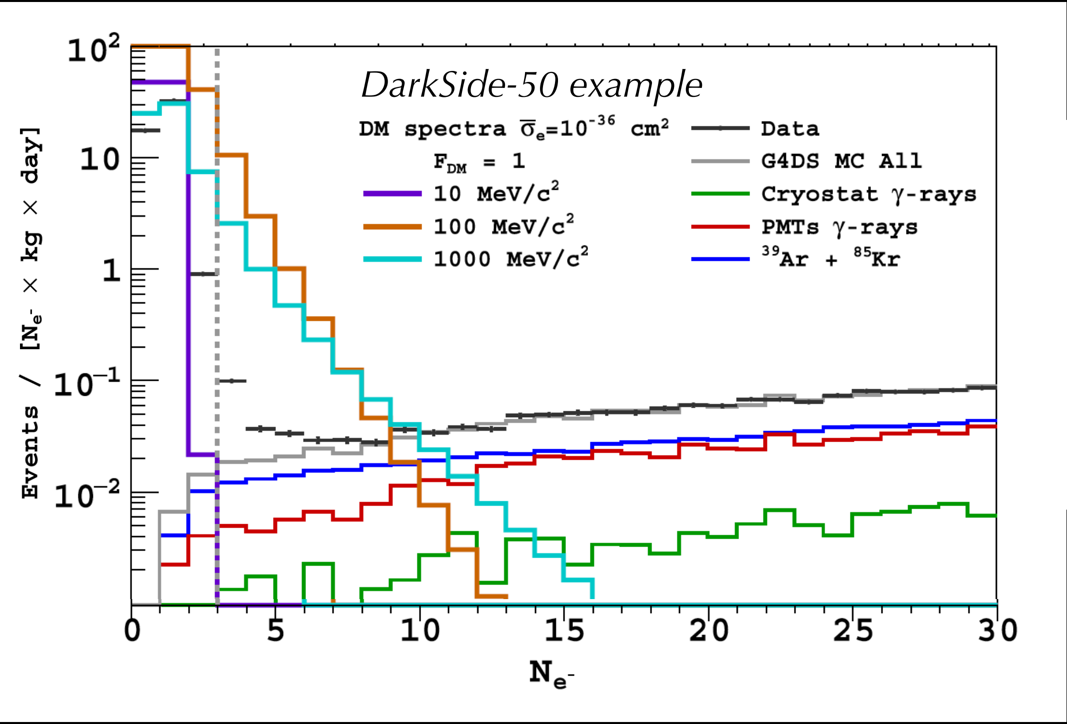
MeV-scale Direct Detection

Signal: dark matter-electron scattering, giving excess in electron recoil (ER) spectrum ~exponential distribution, depends strongly on assumed form factor for DM-e scattering.

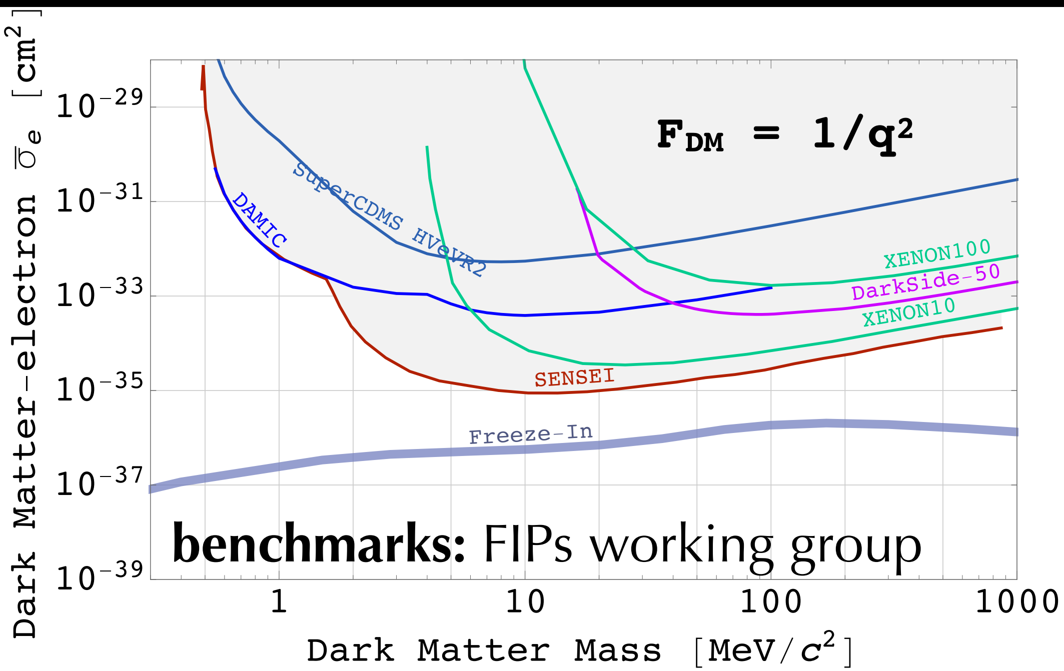
Backgrounds: ER ~ 0.1-1/(keV kg day).

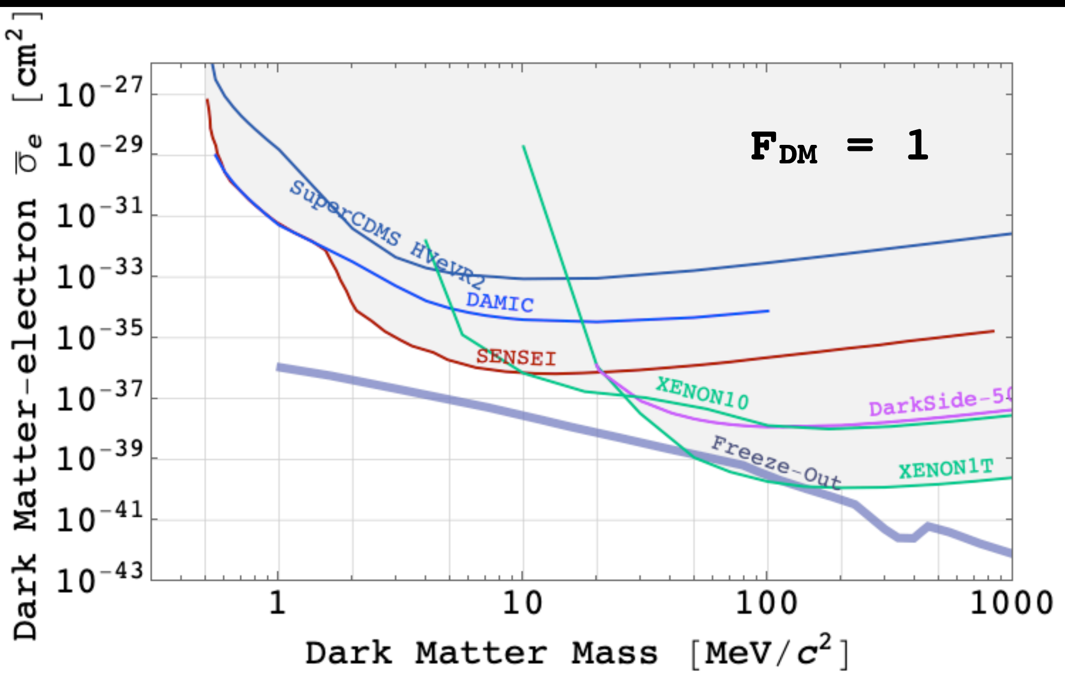
Analysis: PLR.

$$\frac{dR^{ER}}{dE_e} = \overline{\sigma}_e \frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2} \int q dq |F_{DM}(q)|^2 |f_{n,l}^{ion}(q, E_e)|^2 \eta(v_{min})$$



https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

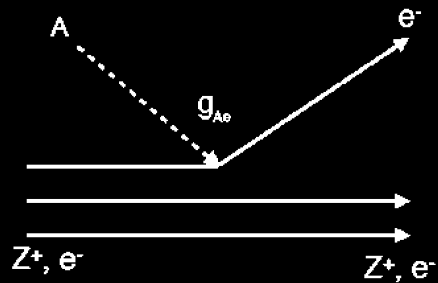




XENON100, *arXiv:1404.1455*

keV-scale Direct Detection

search for absorption:



Signal: peak in electron recoil (ER) spectrum at the new particle mass.

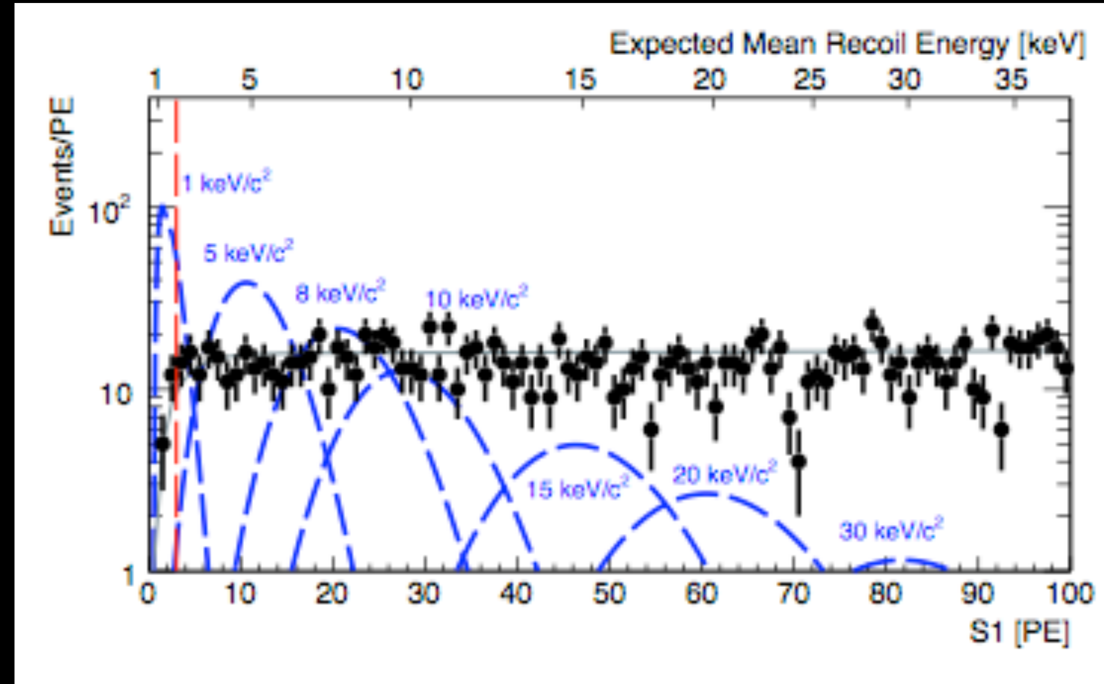
Backgrounds: ER ~1E-4/(keV kg day).

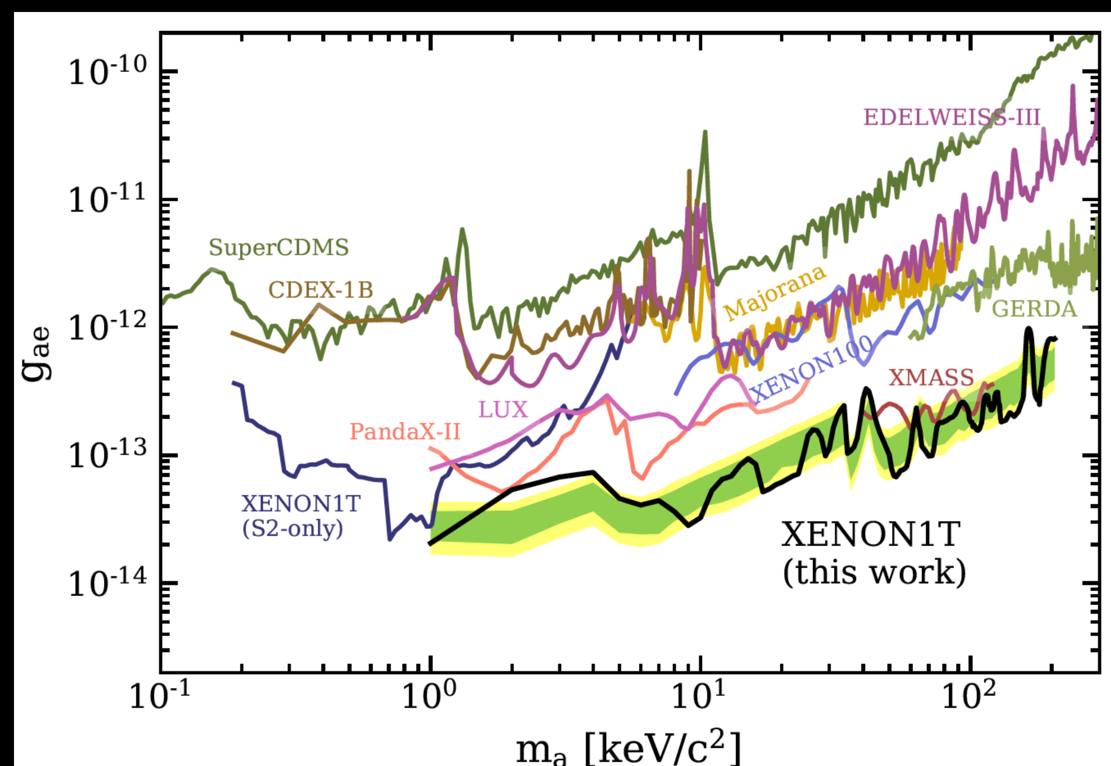
Analysis: bump hunt.

Constraints on new pseudoscalars at <MeV/c² via ALP-electron coupling.

Constraints on vector particles at 0.1-100 MeV/c² via kinetic mixing to hidden sector *(arXiv:1901.10478)*

Constraints on new scalar (and vector) bosonic SuperWIMPs in 10-100 keV/c² *(arXiv:1709.02222)*





keV-scale Direct Detection

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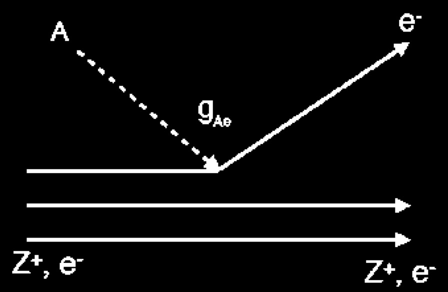

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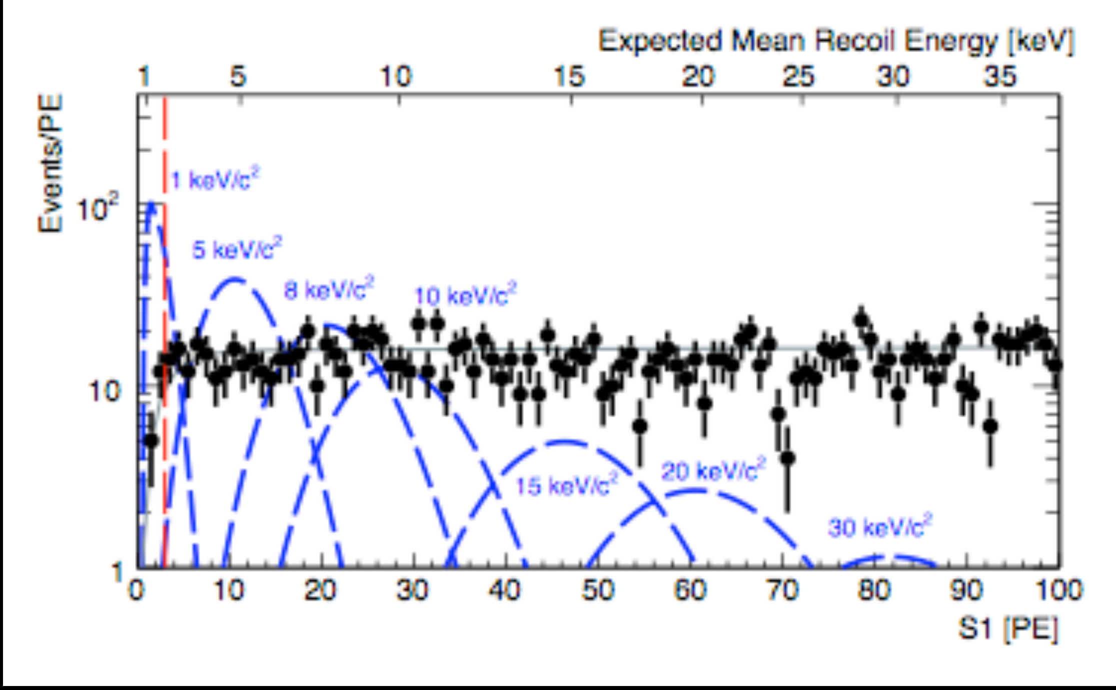
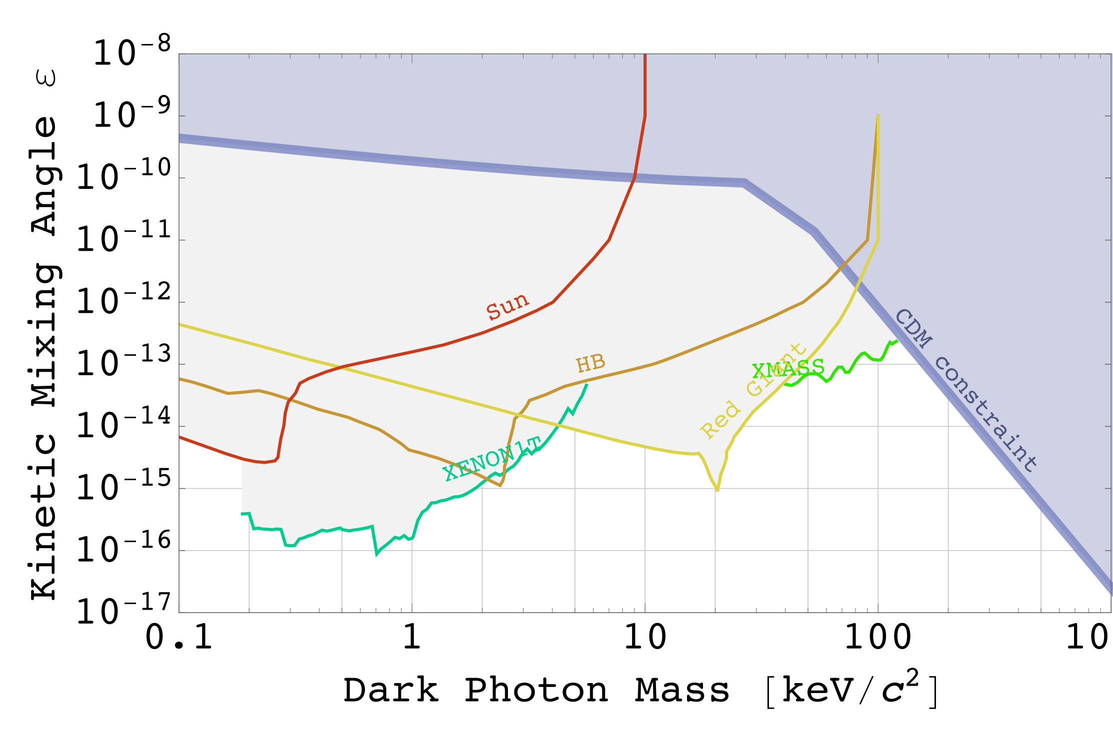
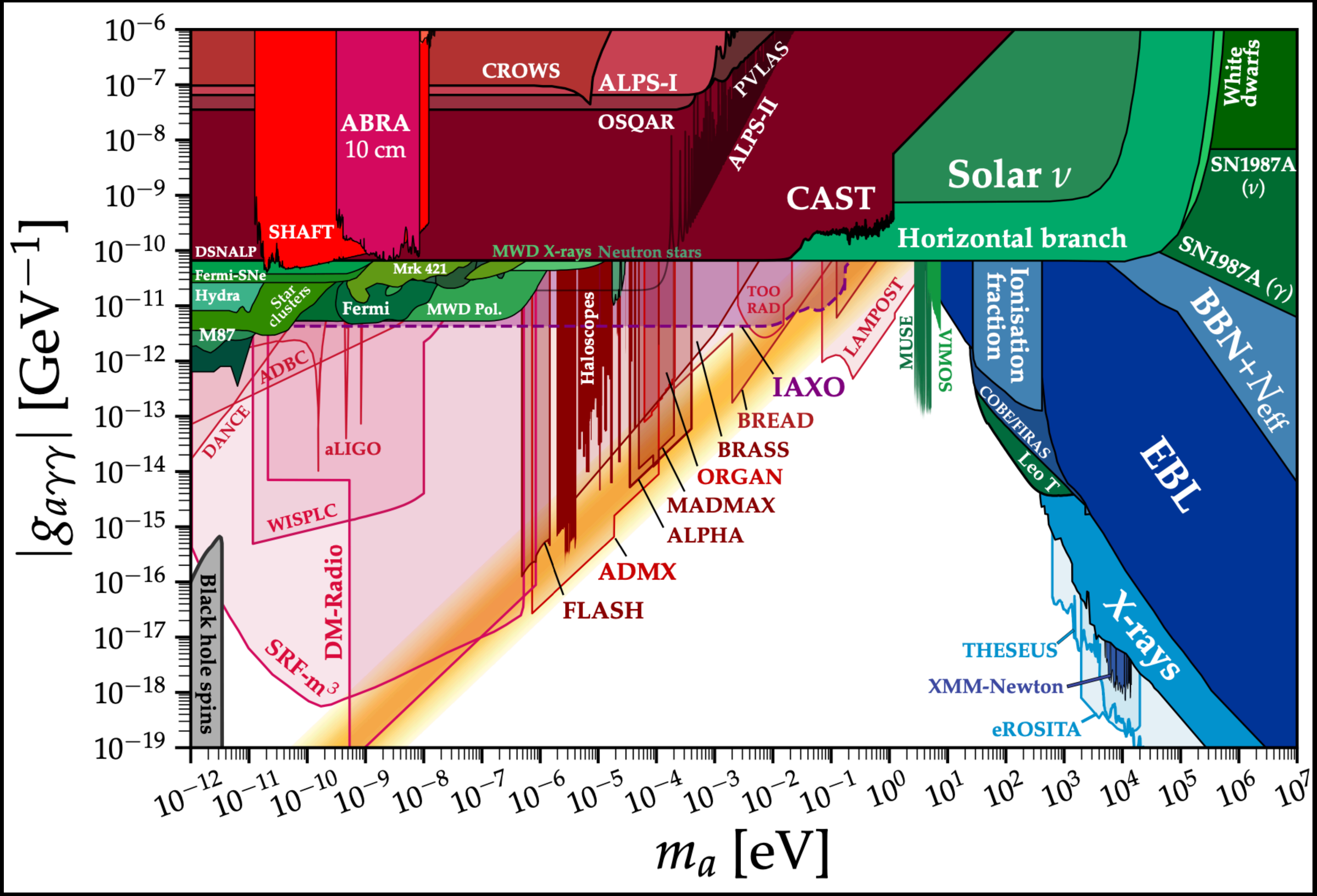




arXiv:2203.14923

sub-eV: Axion/ALPs Searches

Huge range of techniques to detect axion-photon coupling: halo/helioscopes, "light through a wall," axion cooling, axion-induced RF +++



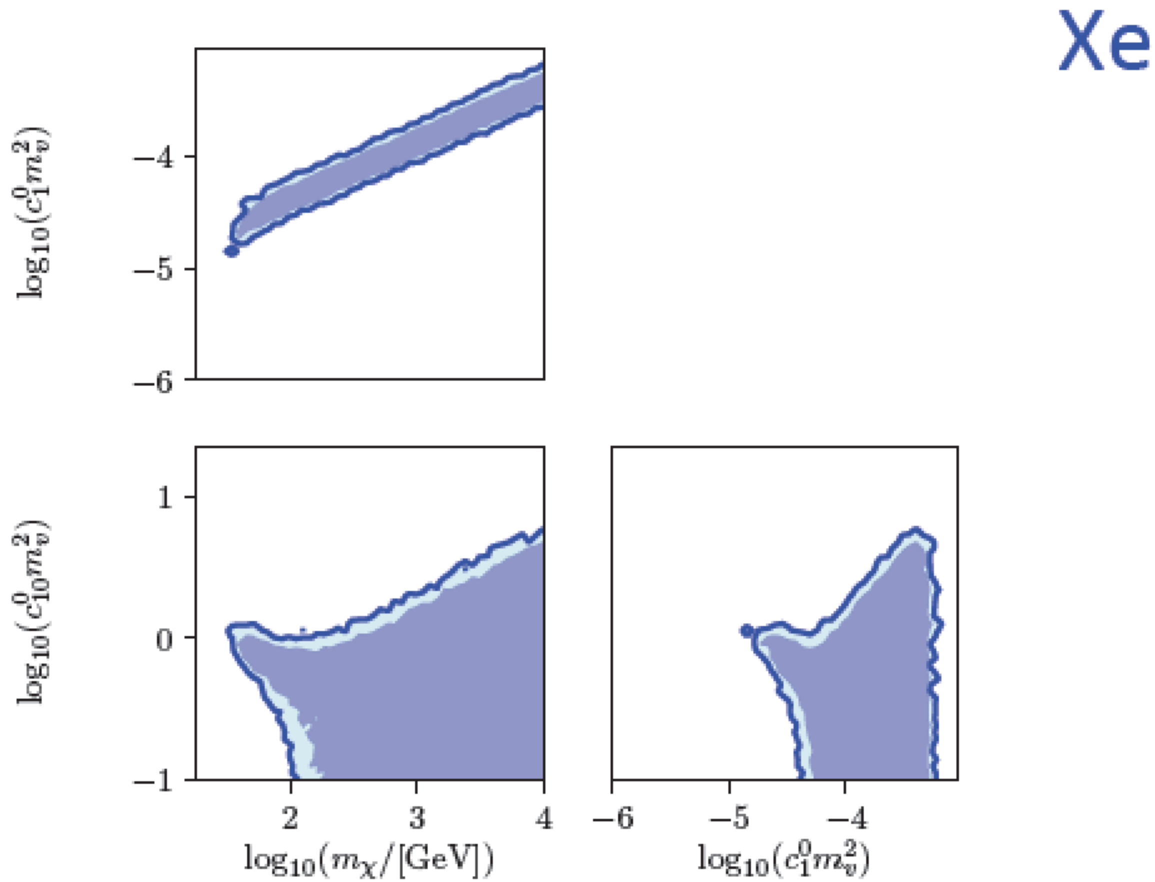
How Will We Know ~~If~~ When We Find Dark Matter?

Complementarity: Direct Detection

Newstead et al., PRD D 88, 076011 (2013)
DARWIN, JCAP 10 (2015) 016

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings



D. Cerdeno, IPPP April 2018

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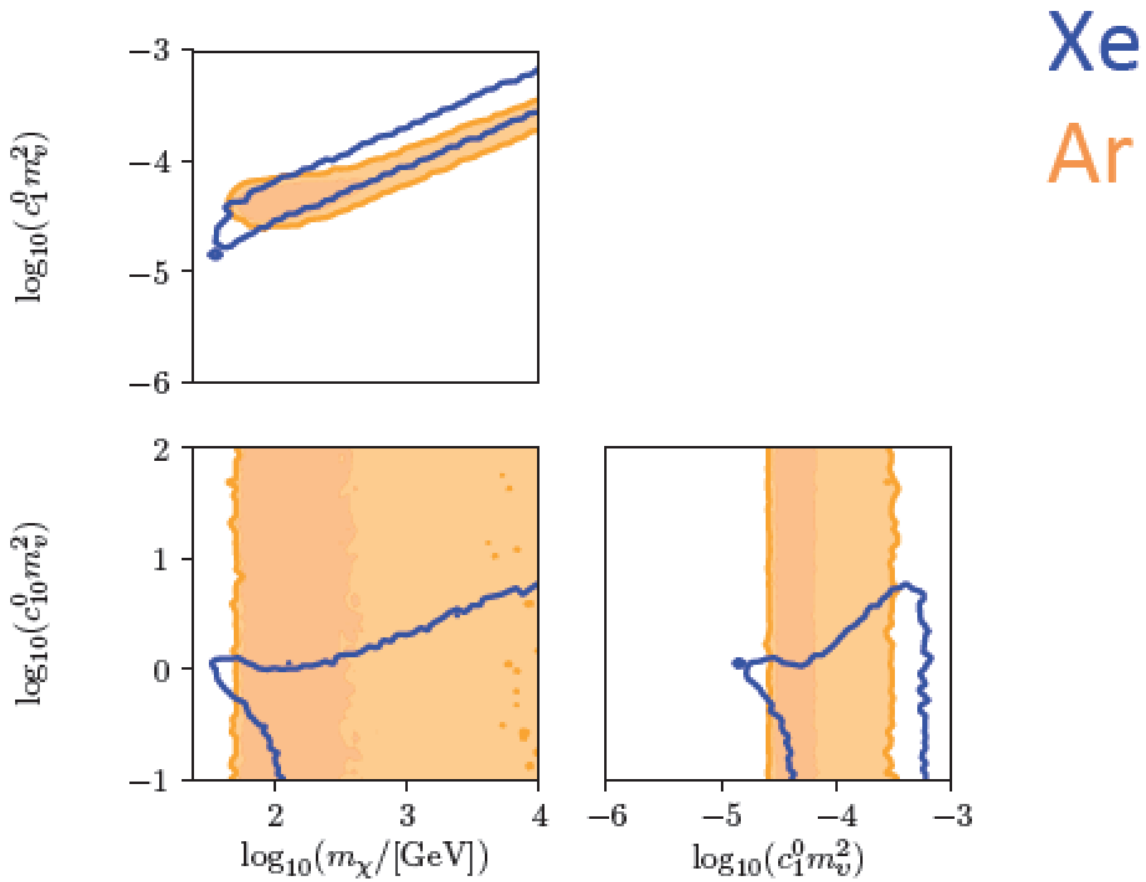

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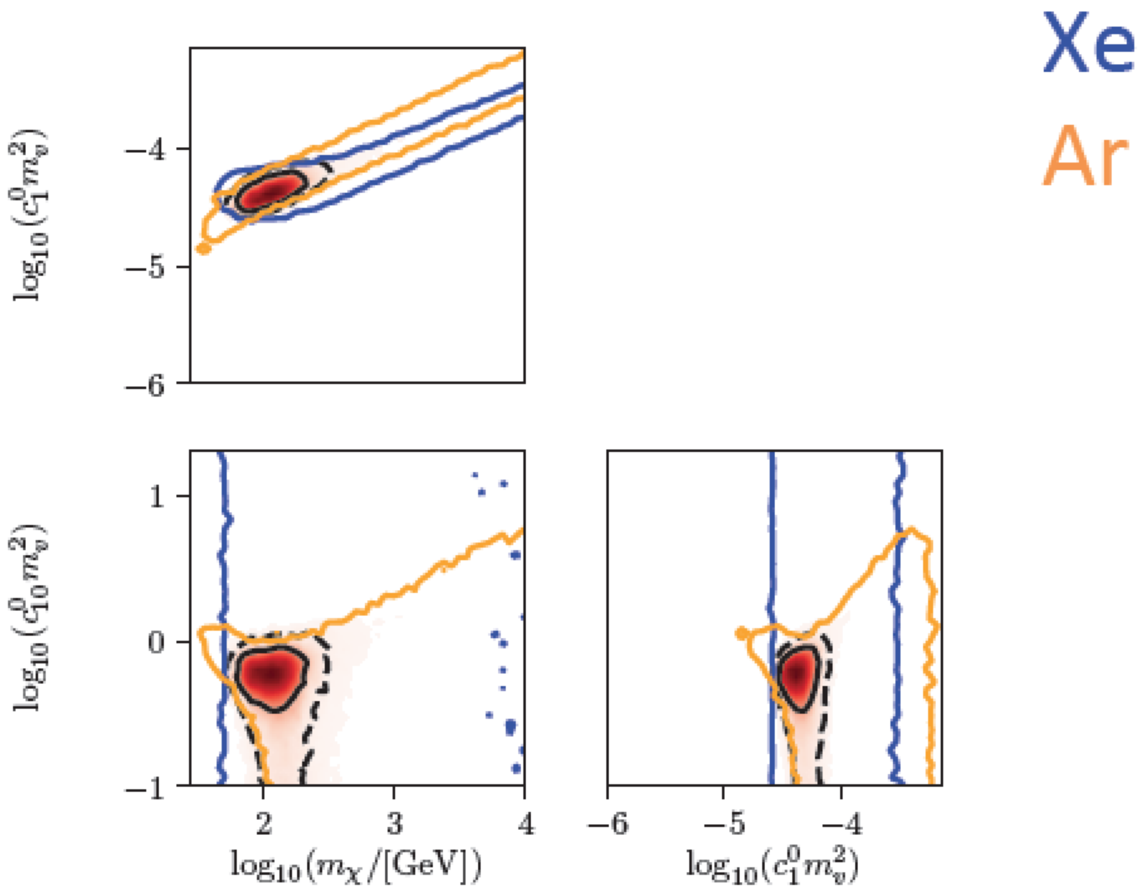
Combining data some degeneracies can be removed

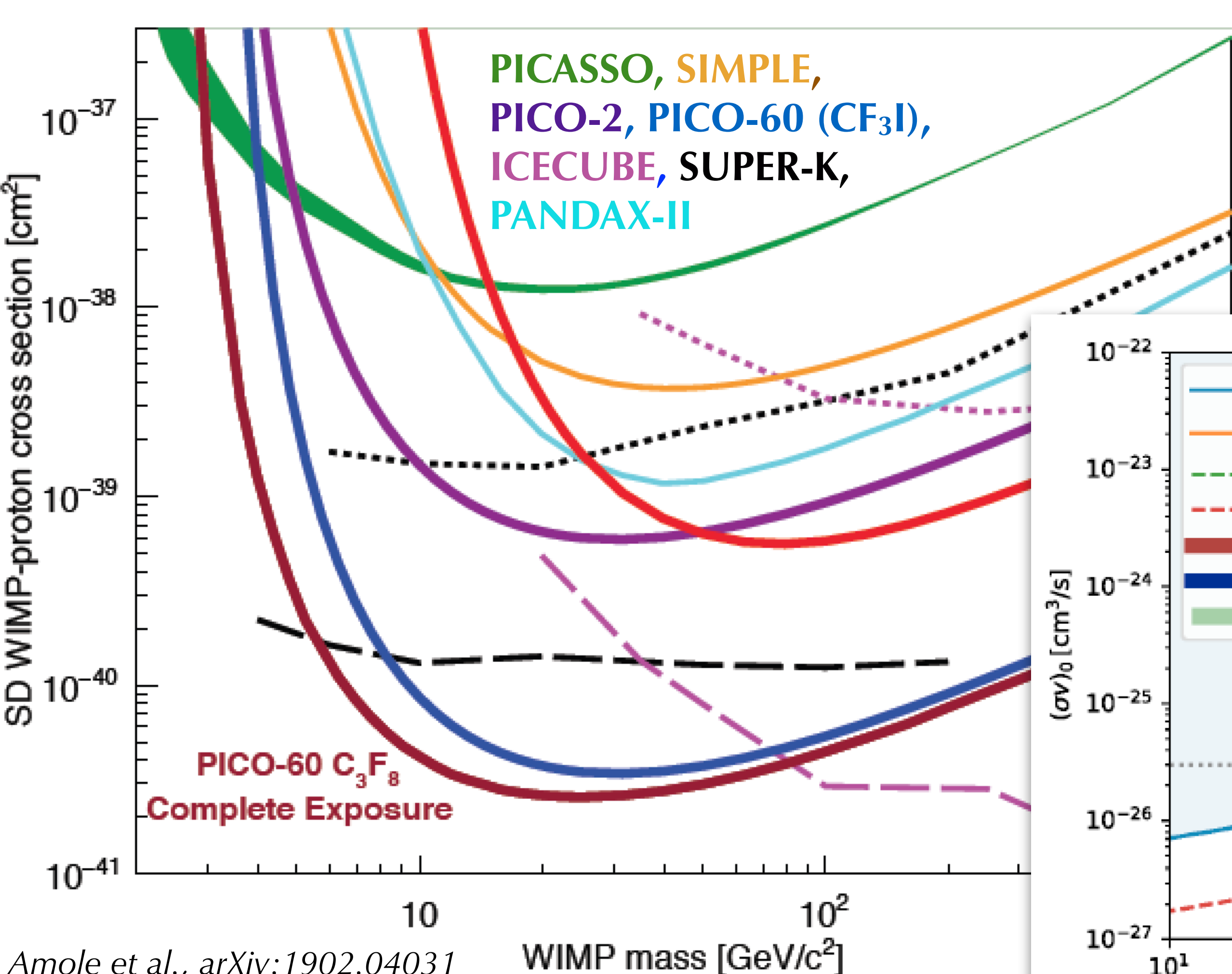


D. Cerdeno, IPPP April 2018

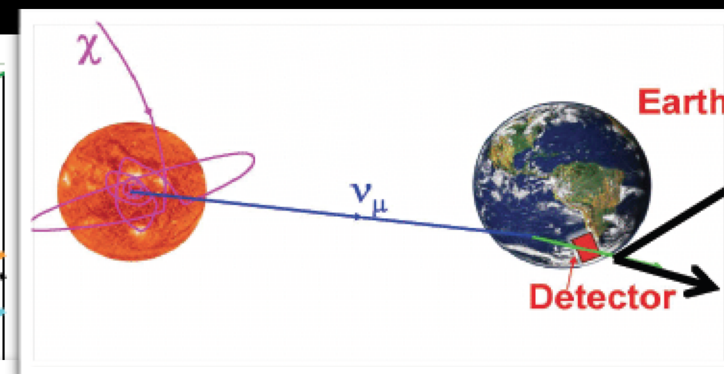
Complementarity: Indirect Detection

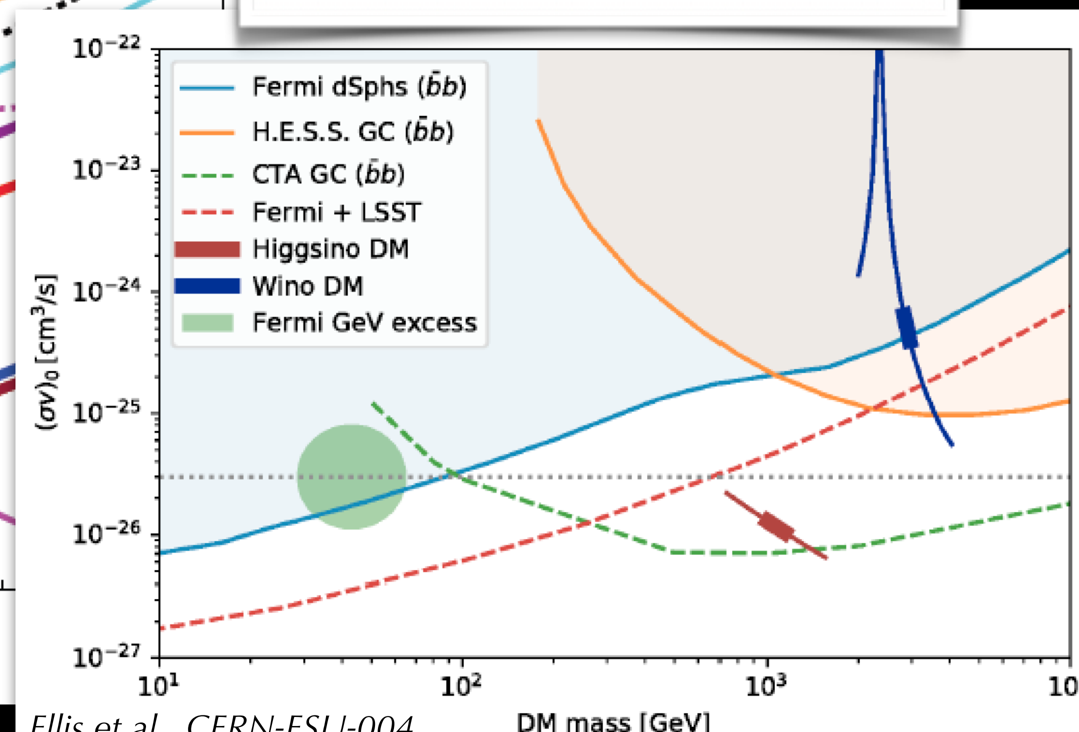
Spin-dependent interaction cross section constraints are 5 orders of magnitude weaker!

Complementarity with **Indirect Detection:** leading constraints at high mass from WIMP-p scattering +capture in the sun, leading to annihilation signatures in neutrino telescopes,.



Amole et al., arXiv:1902.04031

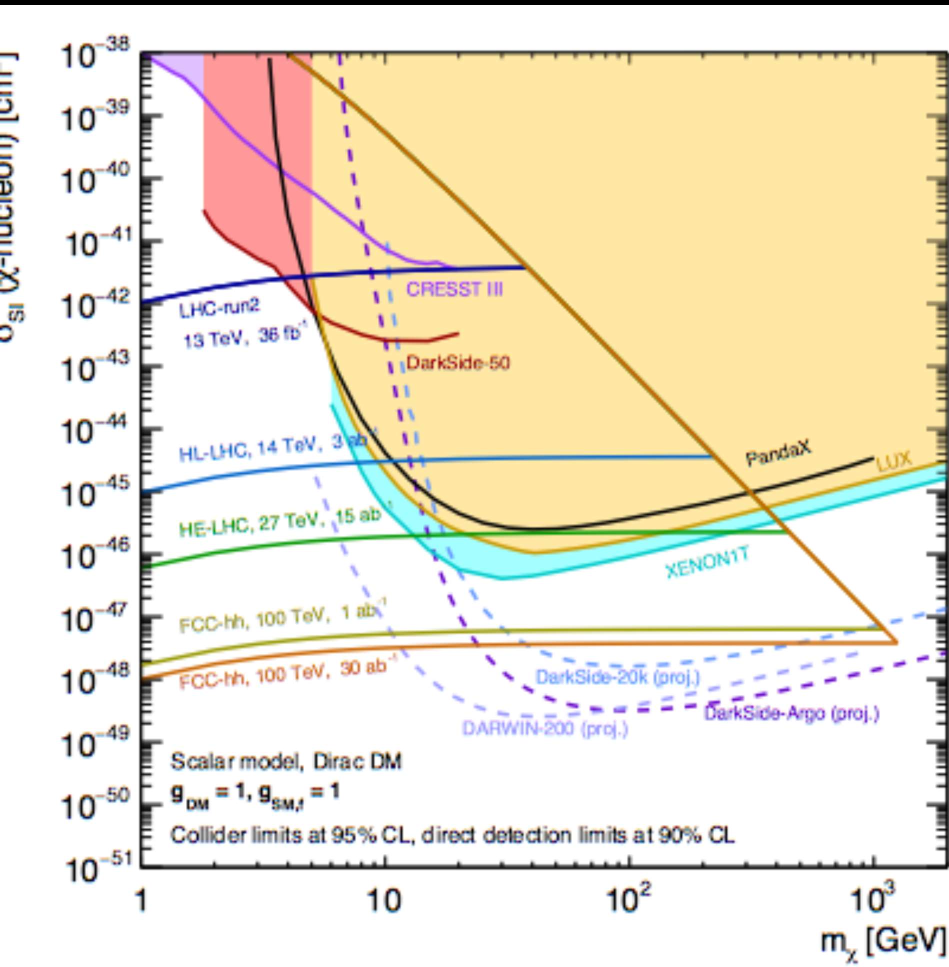




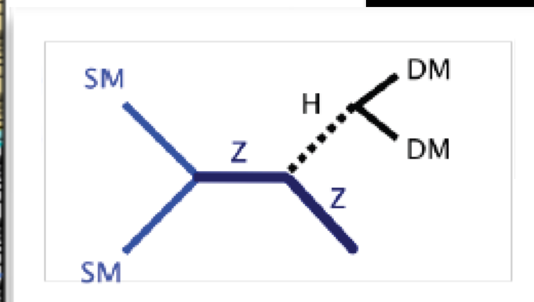
Ellis et al., CERN-ESU-004

Complementarity: Colliders

Ellis, JM et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)



limits on branching ratio translated to limits on cross section vs. mass



Caveat: EFT validity in Higgs-DM interaction not guaranteed beyond HL-LHC