Dark Matter Direct Detection

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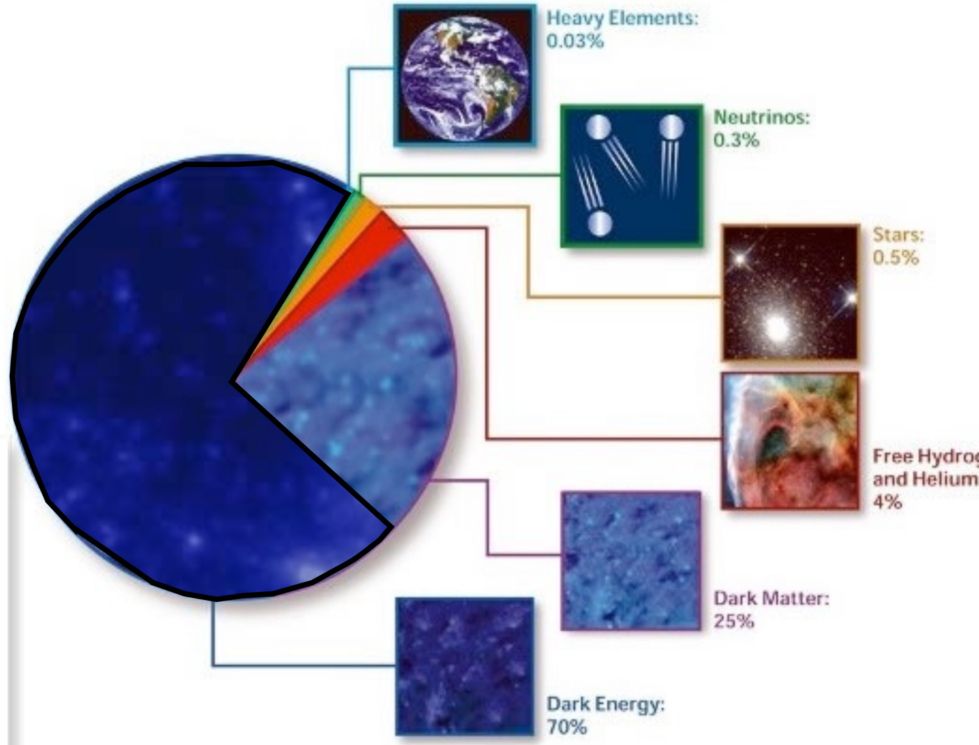
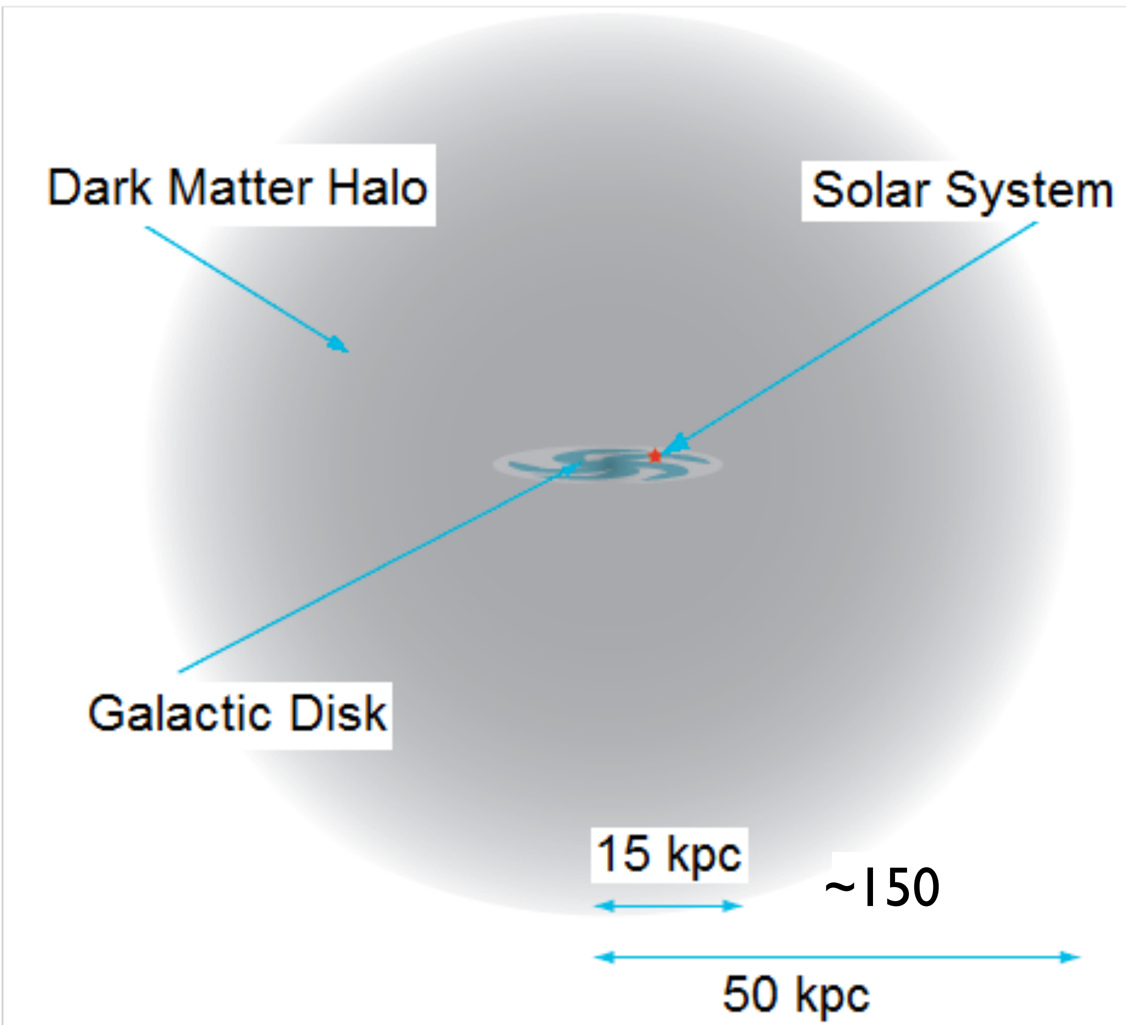
Naples, Italy

What do we know about Dark Matter?

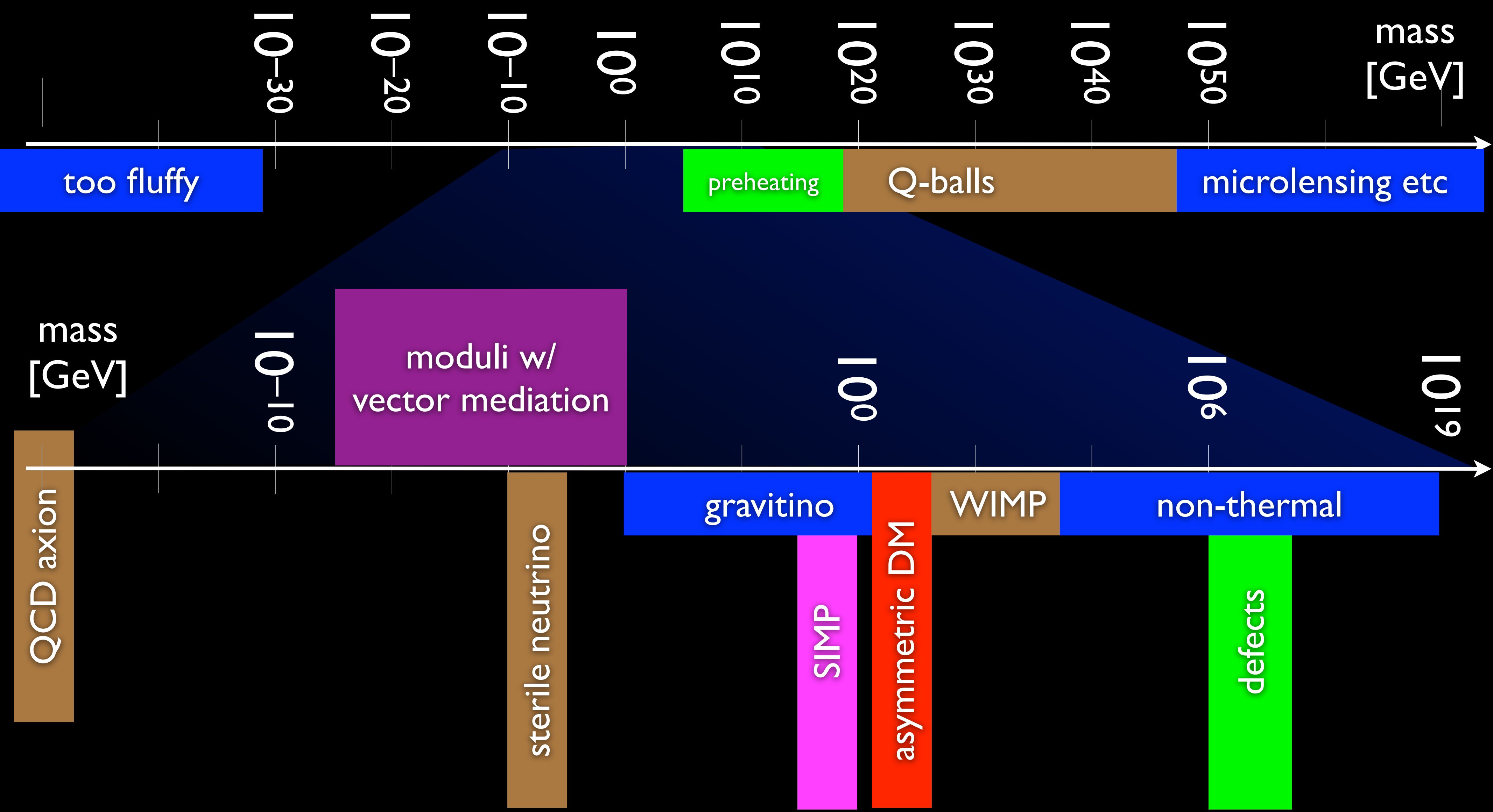




- optically dark
- bound to our galaxy
- density ~ 0.3 GeV/cm^3
- dark matter particle mass: ~unknown
- interactions: very weak, ~collision-less

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.

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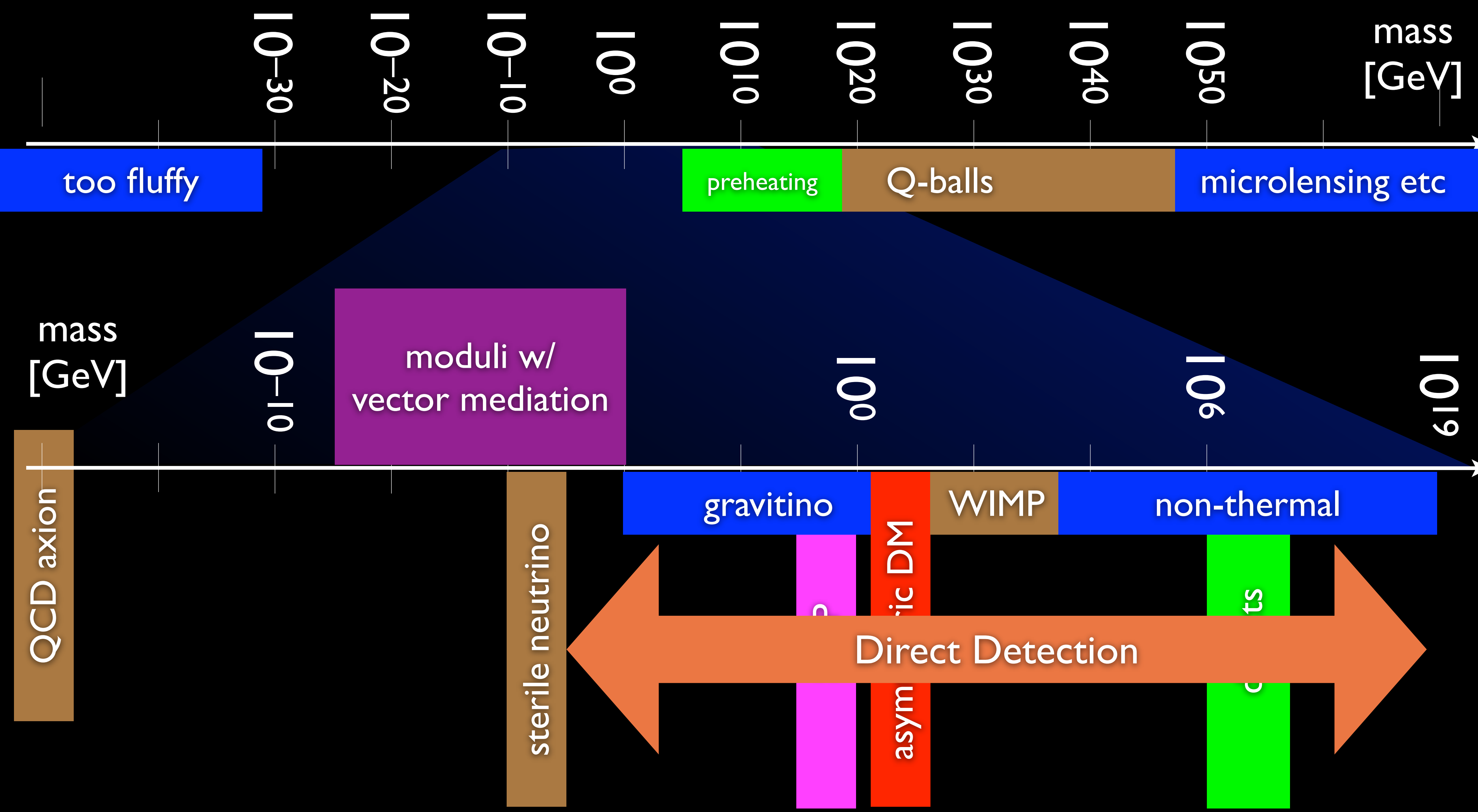

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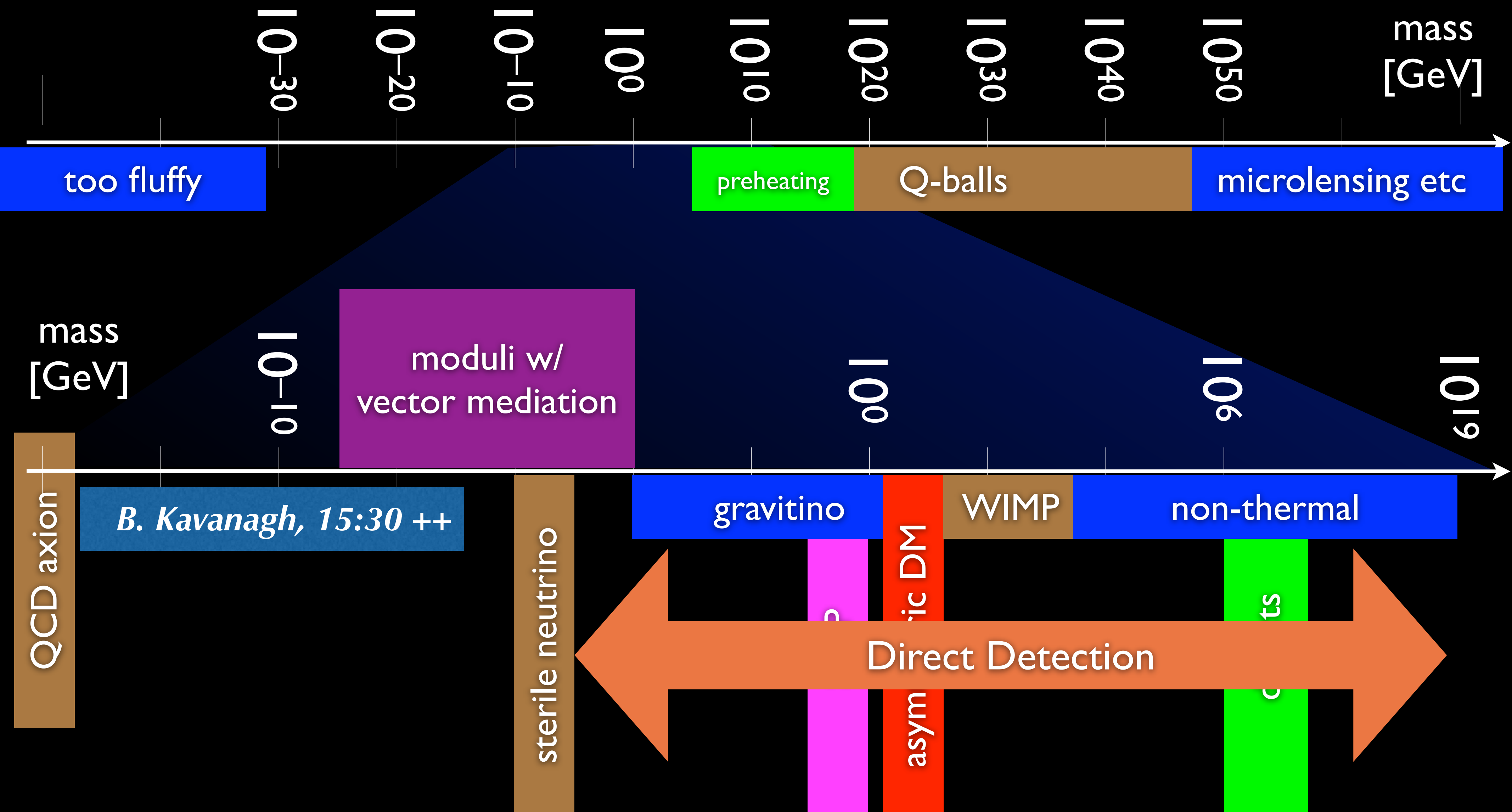

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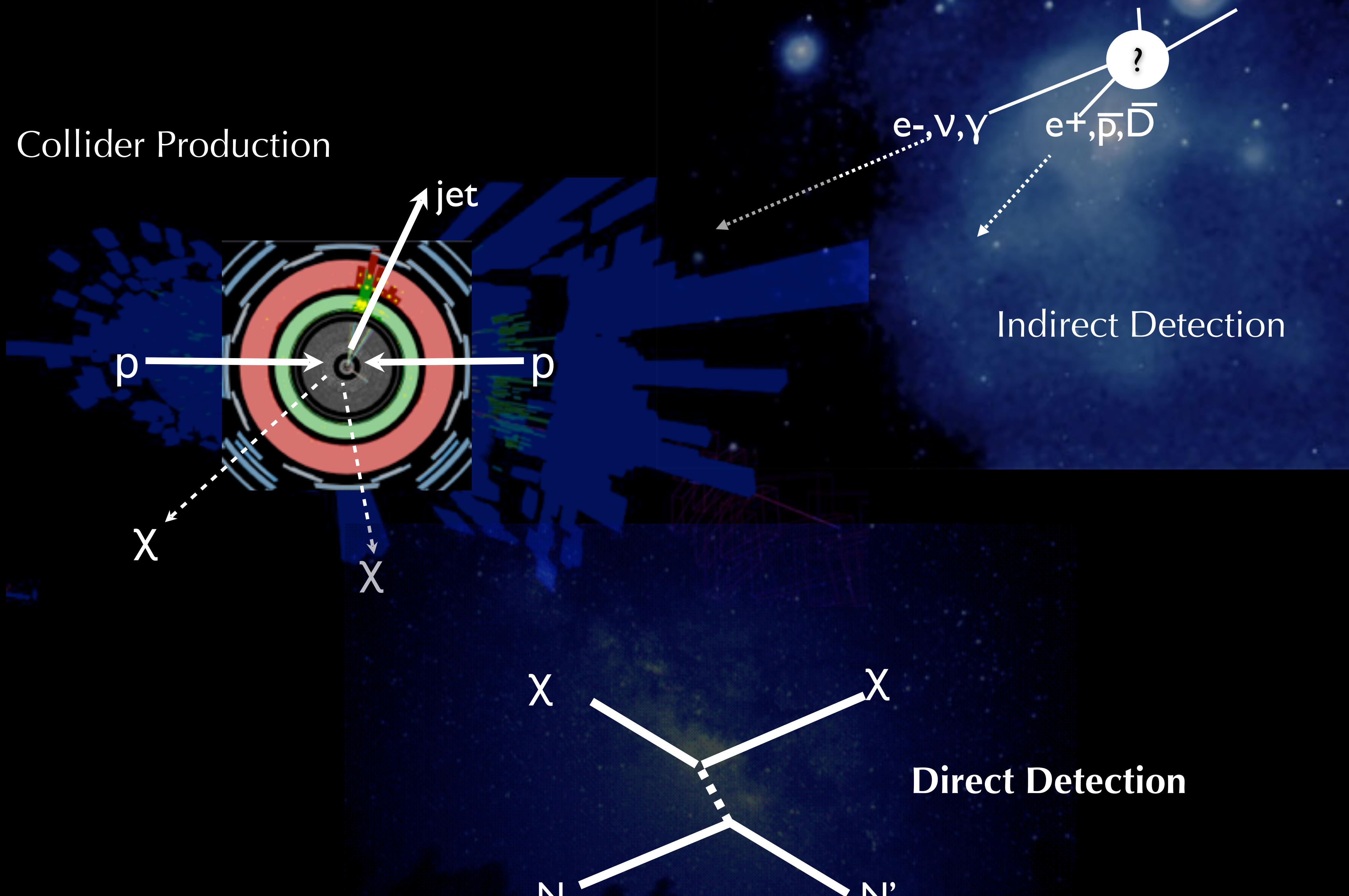
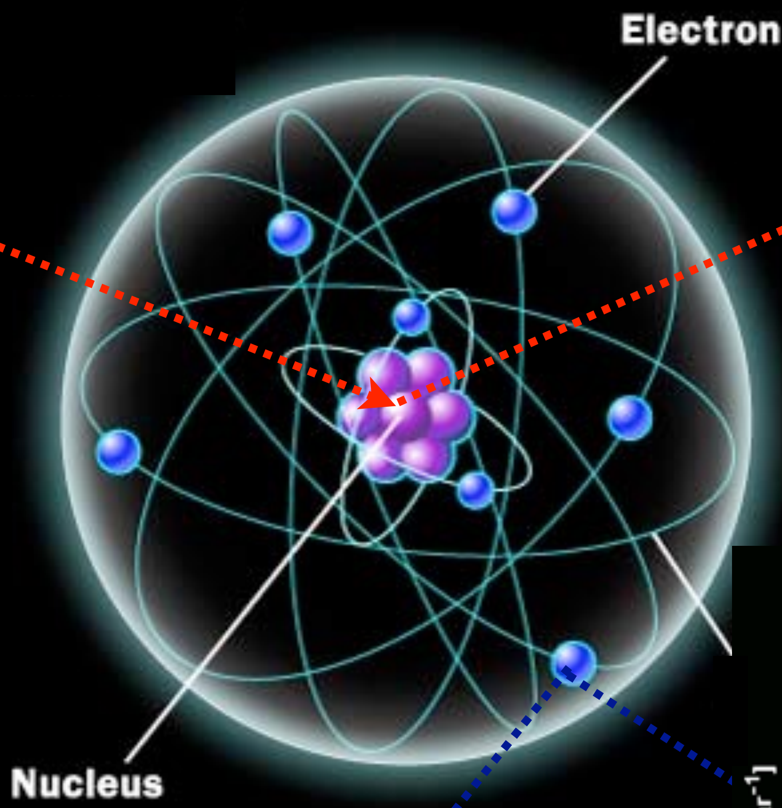
Experimentalist's View



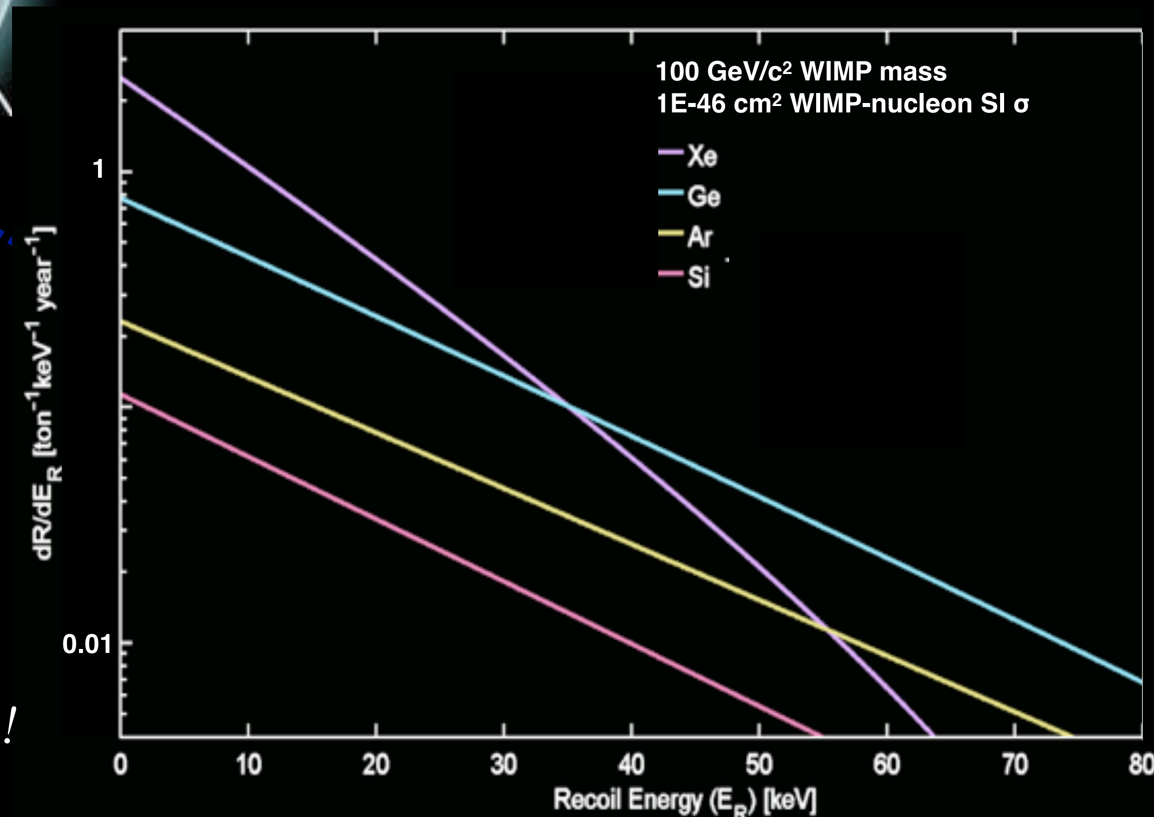
Direct Detection WIMP Signal

χ



χ

Signal: $\chi N \rightarrow \chi N$ (or $\chi e^- \rightarrow \chi e^-$)



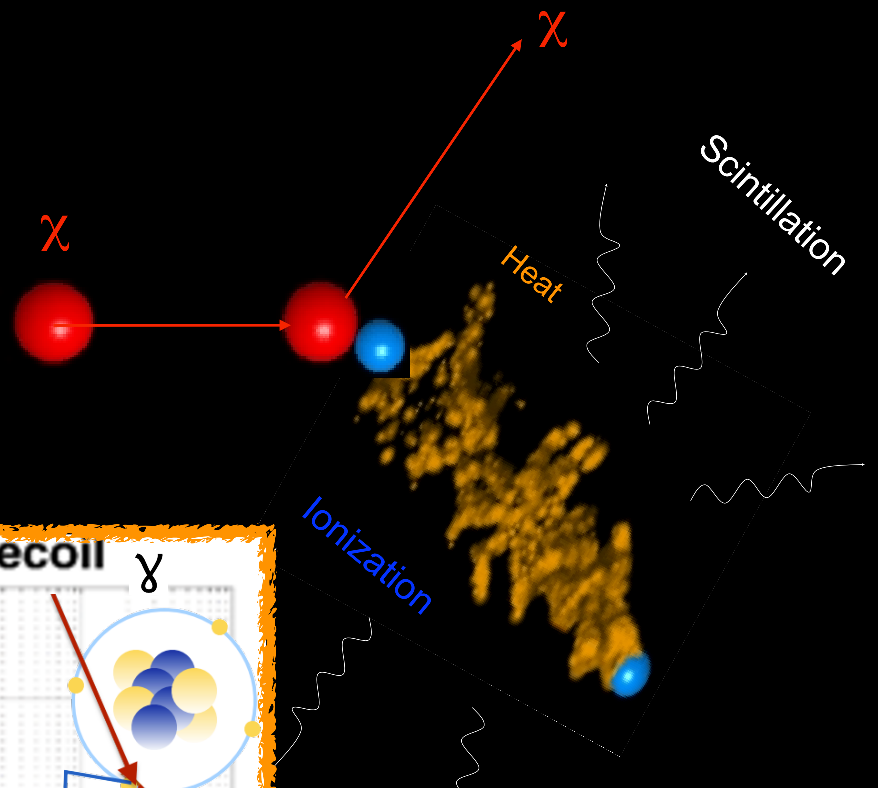
experimental challenges:

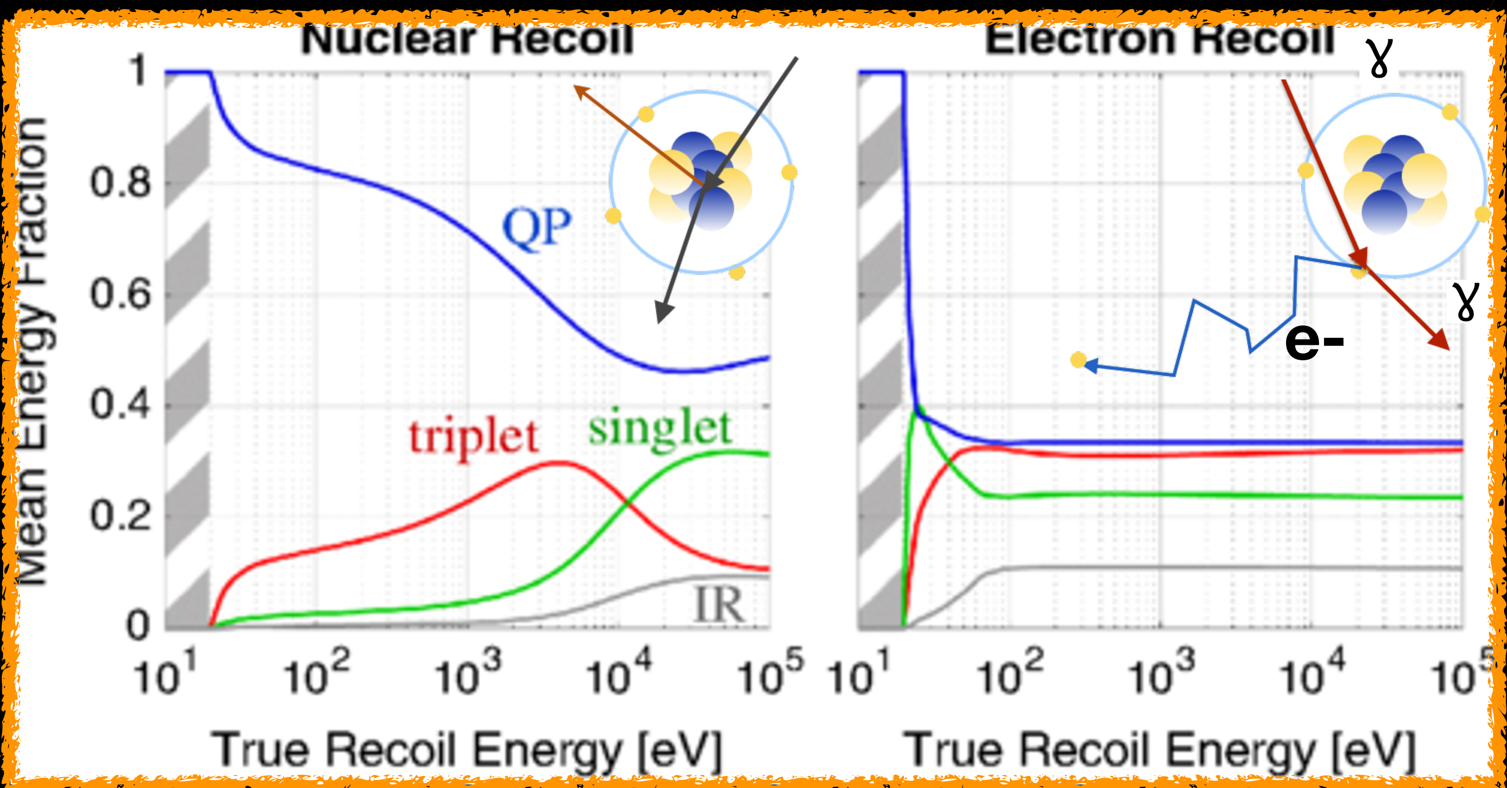
keV-scale energy threshold +
<1/t/y event rate
need particle ID at ppm-ppb-ppt-ppq!

Challenge 1: Low Energies!

Example in noble liquids:

Ionization energy per quanta:
~2 eV in Si
~10 eV in Xe
~20 eV in Ar, He





Energy partition depends on particle energy, and interaction with target microphysics

opportunity for particle ID: identify backgrounds via

- ionization vs. scintillation (Xe)
- + pulse shape vs. time difference (Ar)

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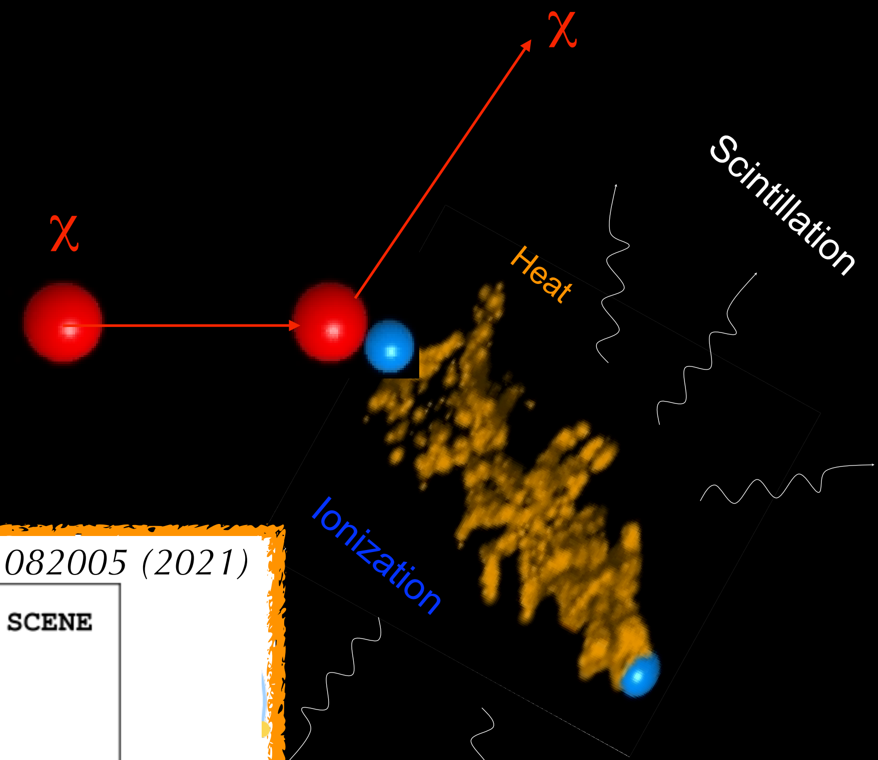
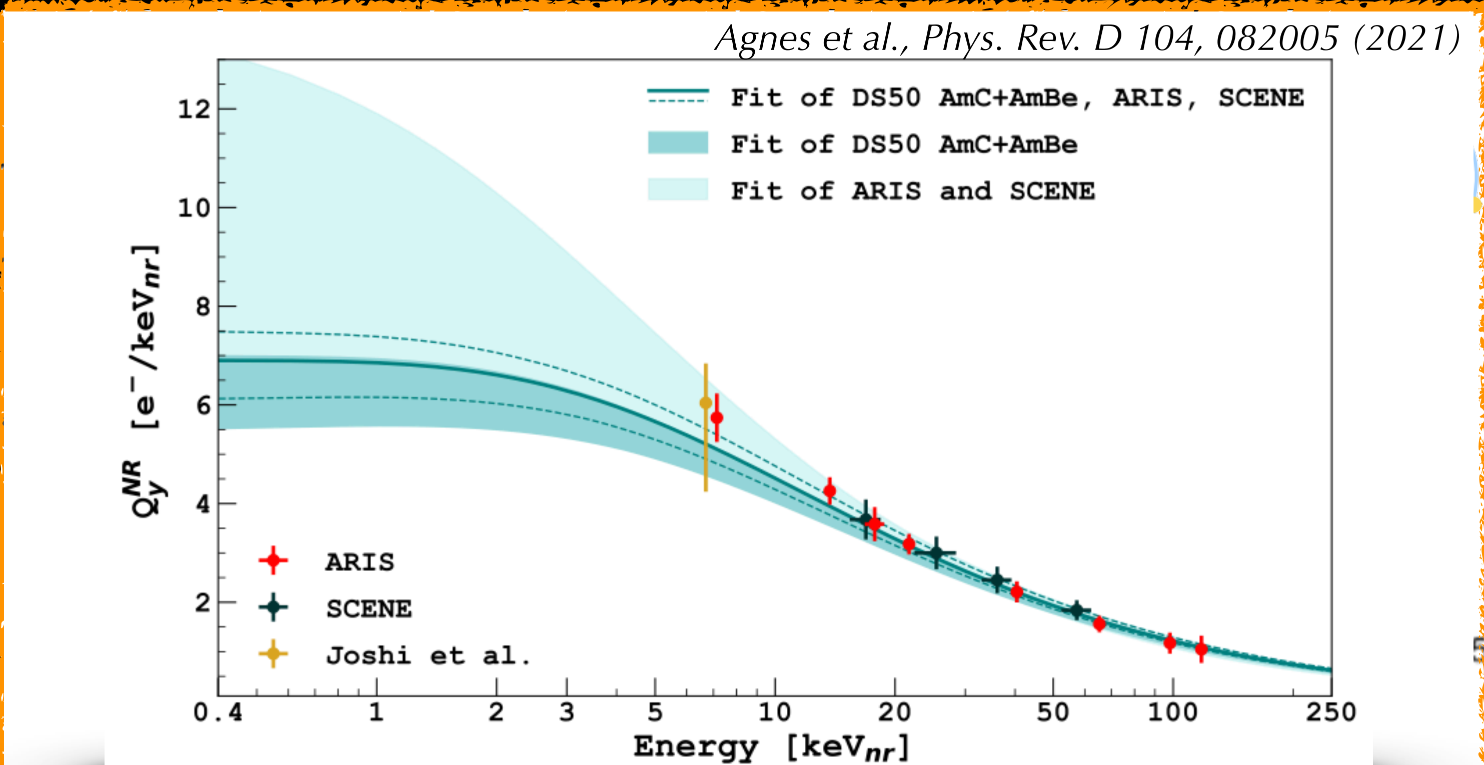


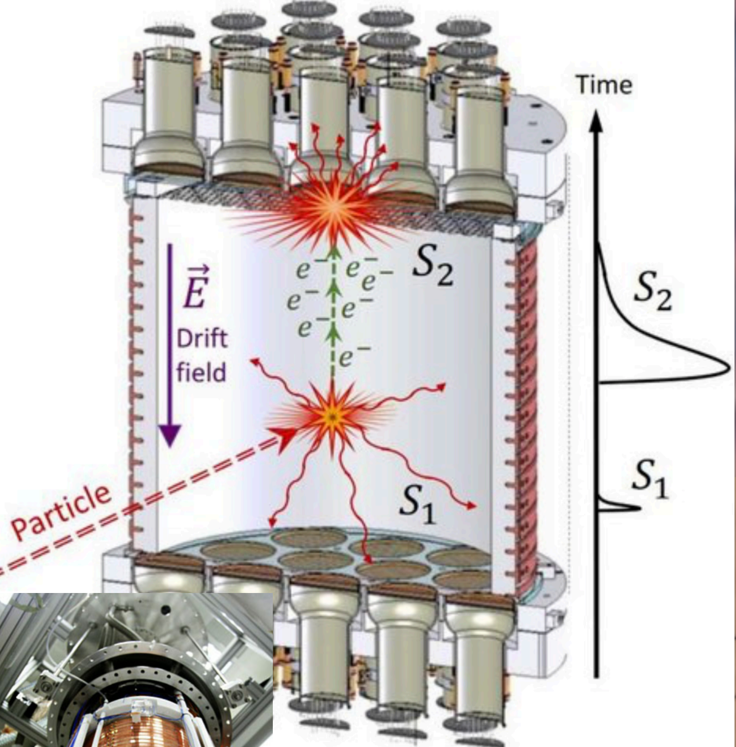


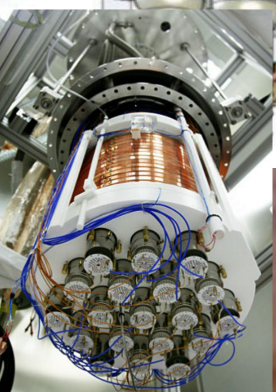
Energy partition depends on particle energy, and interaction with target microphysics

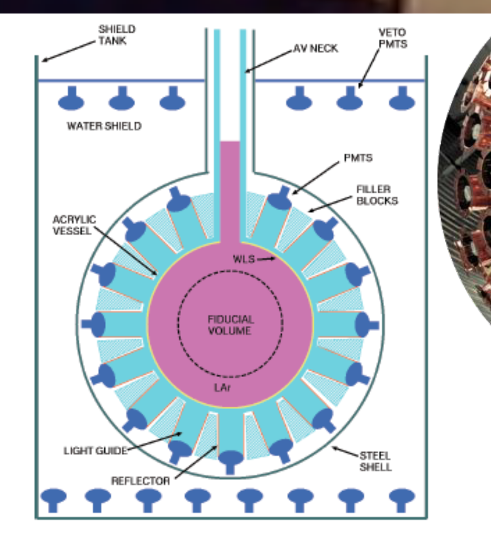
However! knowledge of ionisation fraction is a key systematic uncertainty

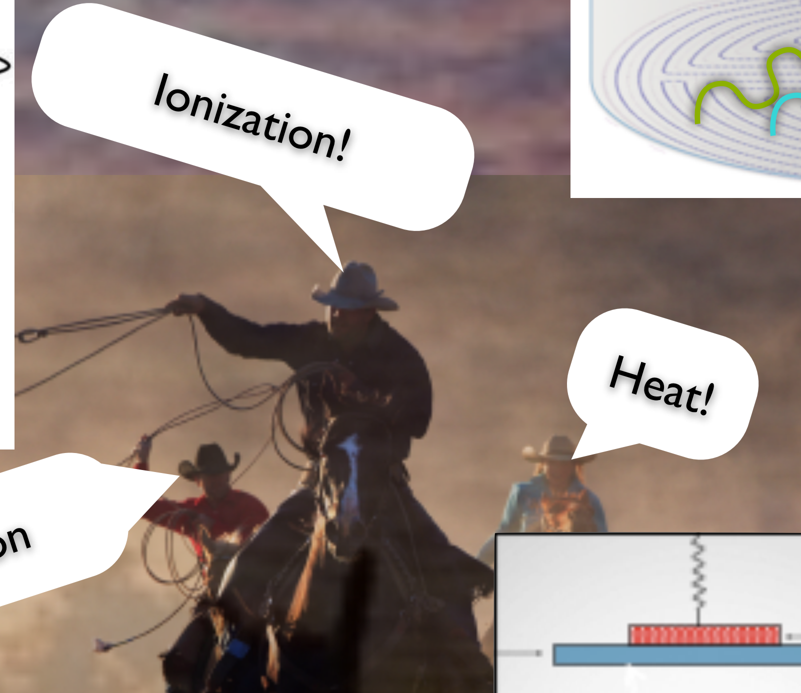
Detector Technologies

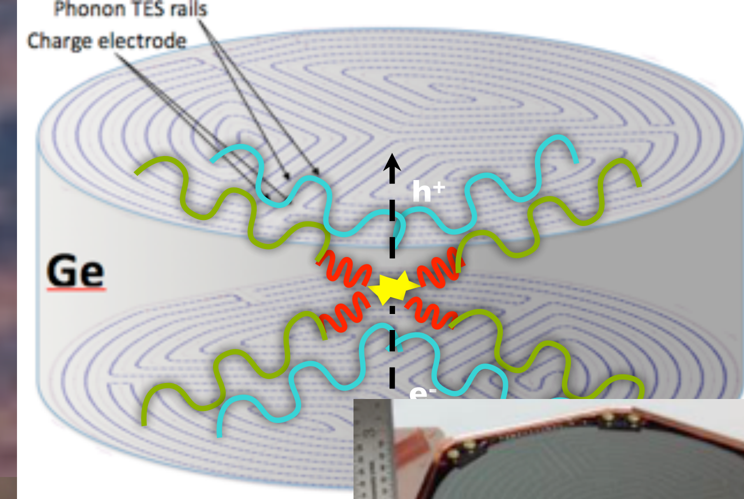
(not exhaustive!)

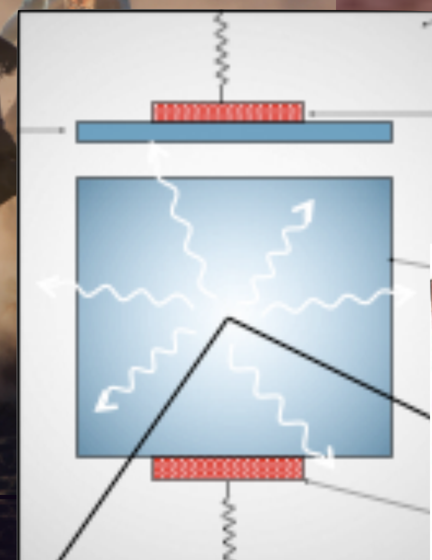


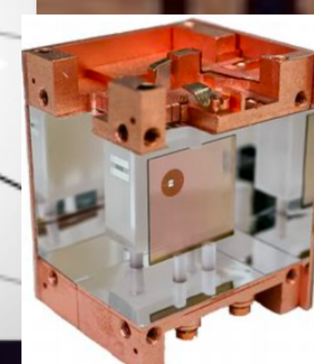










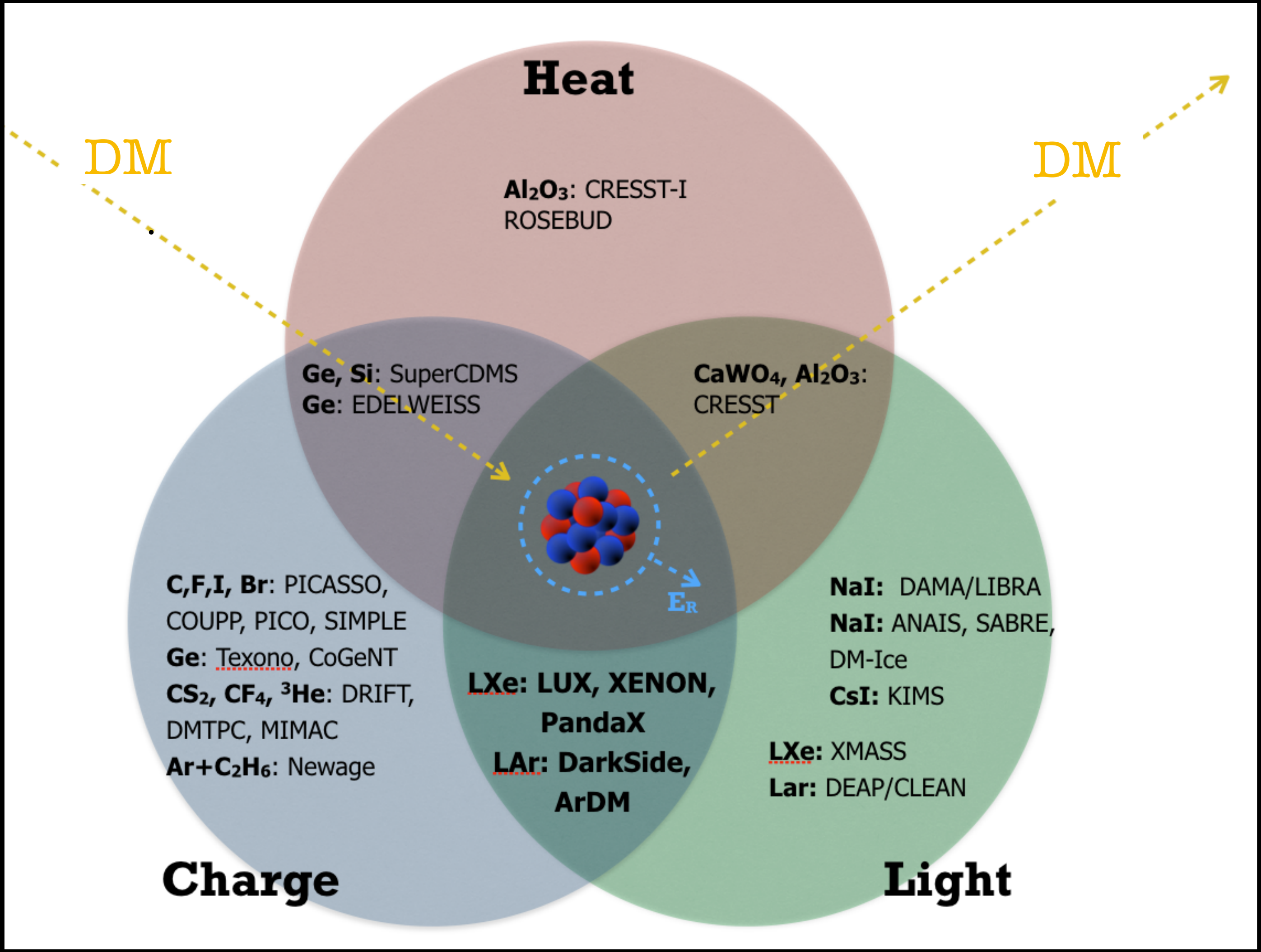


Nuclear recoil E_R ~ 1E-6 x m_{DM}

Challenge 1: Low Energies!

many experiments, many targets:
(Xe, Ge, Ar, NaI, CsI, $CaWO_4$, CF_3I, C_3F_8, F ...)

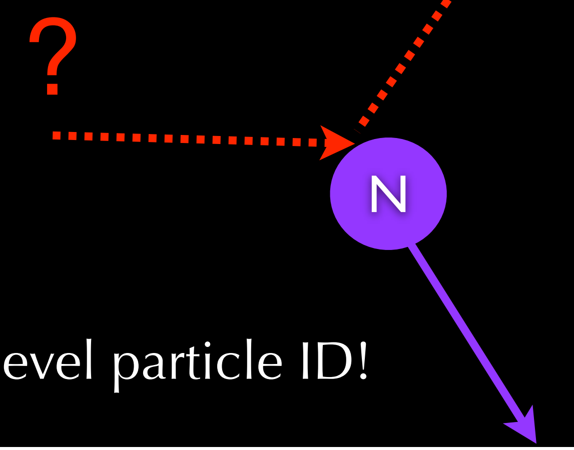
E_R threshold now O(10s eV), potential to reach meV



E_R threshold now O(10 eV), potential to reach eV

E_R threshold now O(keV), potential to reach 10 eV

Challenge 2: Low Rates!

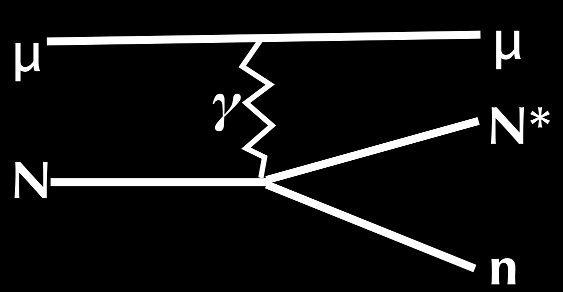


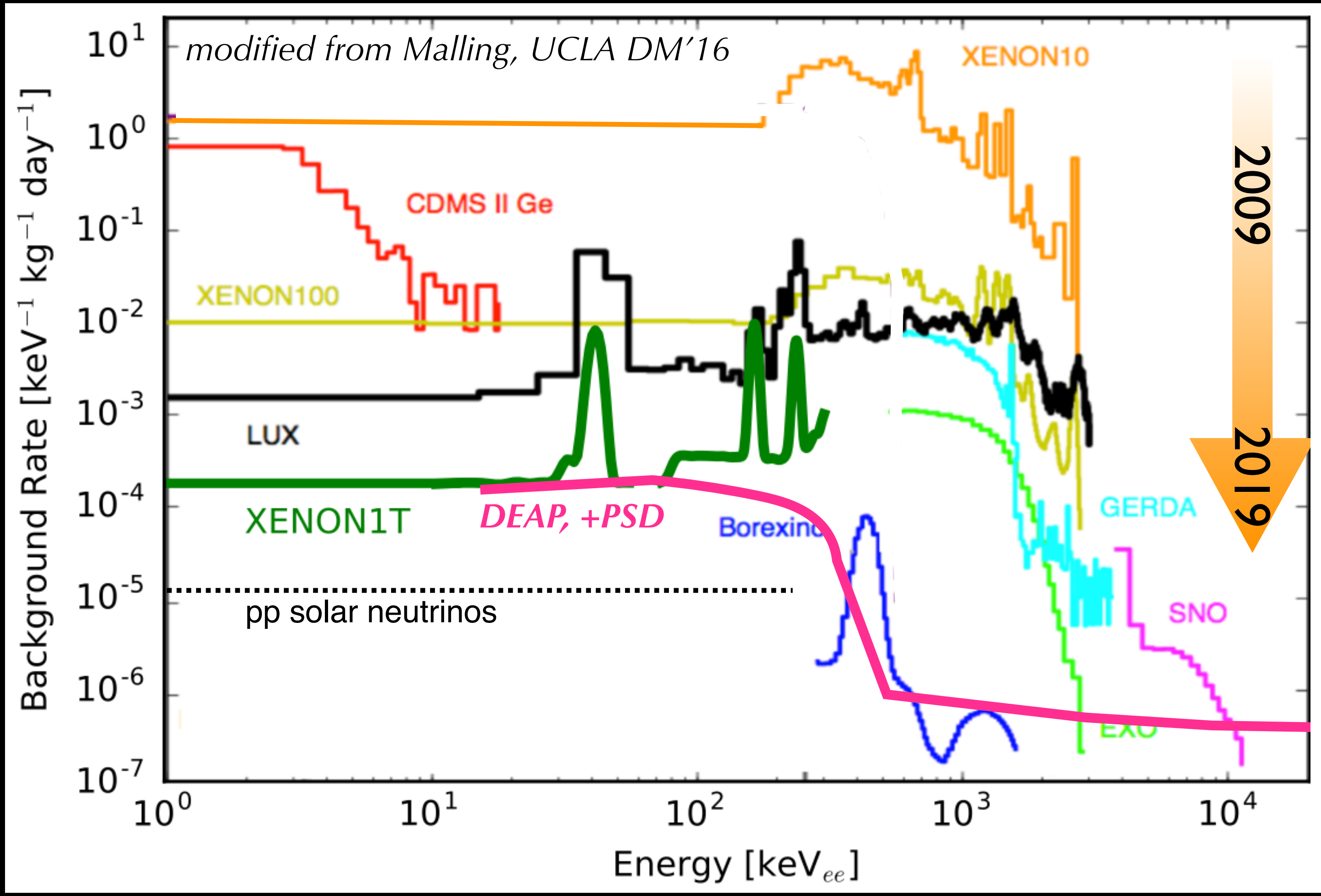
<u>Reducible Backgrounds:</u>

Gamma ray interactions: electron recoil final states
mis-identified electrons mimic nuclear recoils … part-per-billion level particle ID!

Contamination:
Mis-identified U, Th, Pb decays…
part-per-quadrillion++ control of materials

Neutrons:
Nuclear recoil final state.
(alpha,n), U, Th fission, cosmogenic spallation





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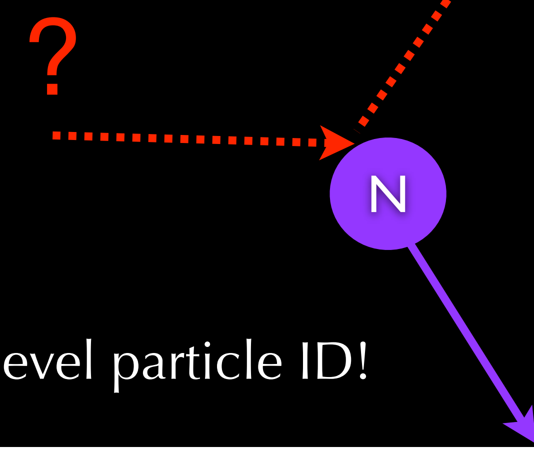

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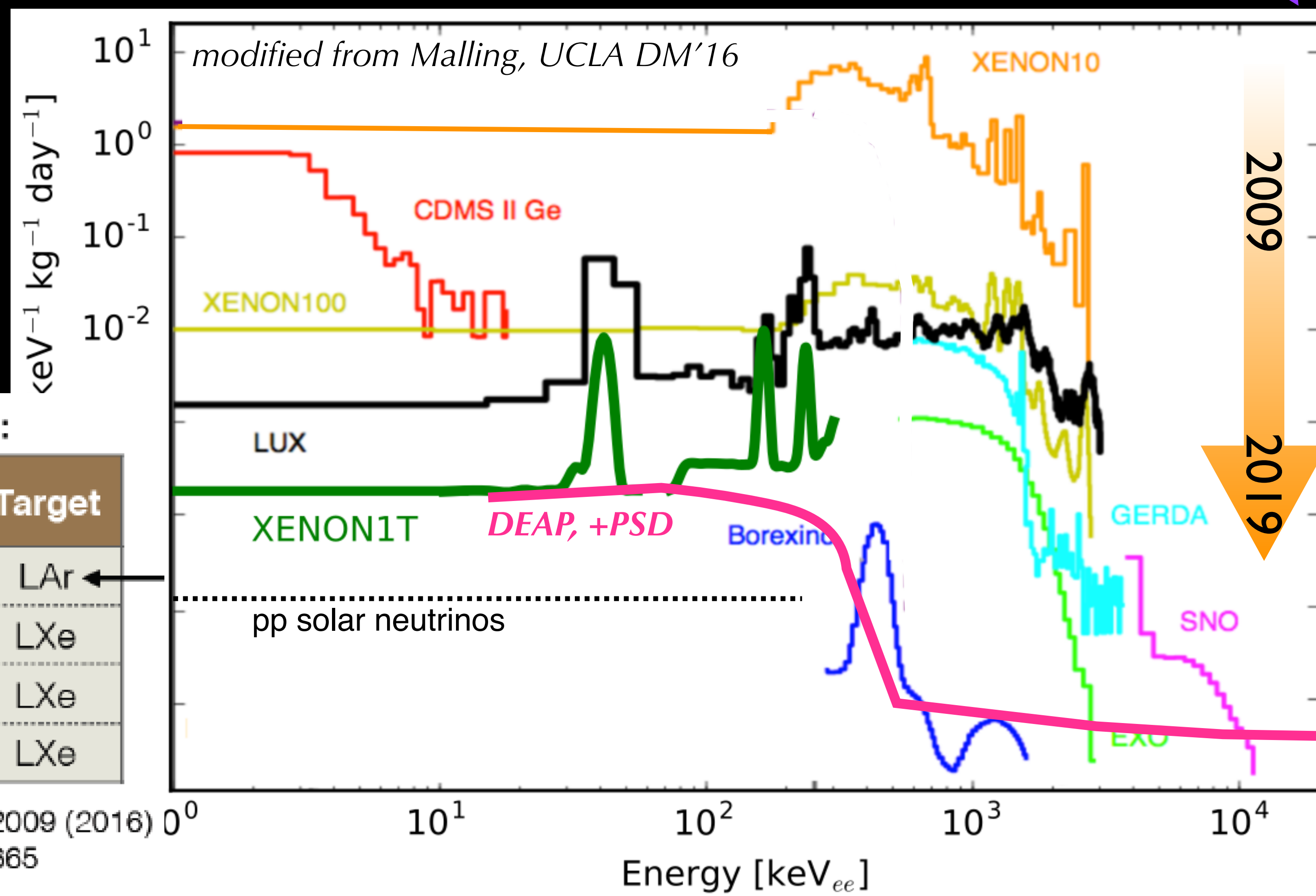
^{222}Rn in Dark Matter experiments:

Experiment	Activity / rate	Target
DEAP-3600	≈0.2 µBq / kg	LAr ←
PandaX-II	6.6 µBq / kg	LXe
LUX	66 µHz / kg	LXe
XENON1T	10 µBq / kg	LXe

- PandaX-II: PHYSICAL REVIEW D 93, 122009 (2016)
- LUX: Physics Procedia 61 (2015) 658 – 665
- XENON1T: XeSAT 2017 talk [link]



Amaudruz, et al, Phys.Rev.Lett. 121 (2018) no.7, 071801

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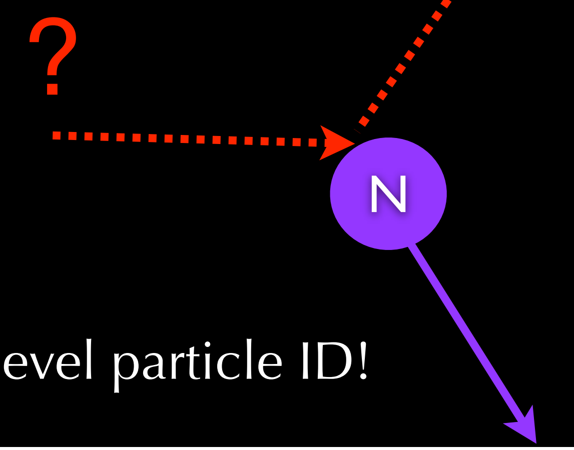

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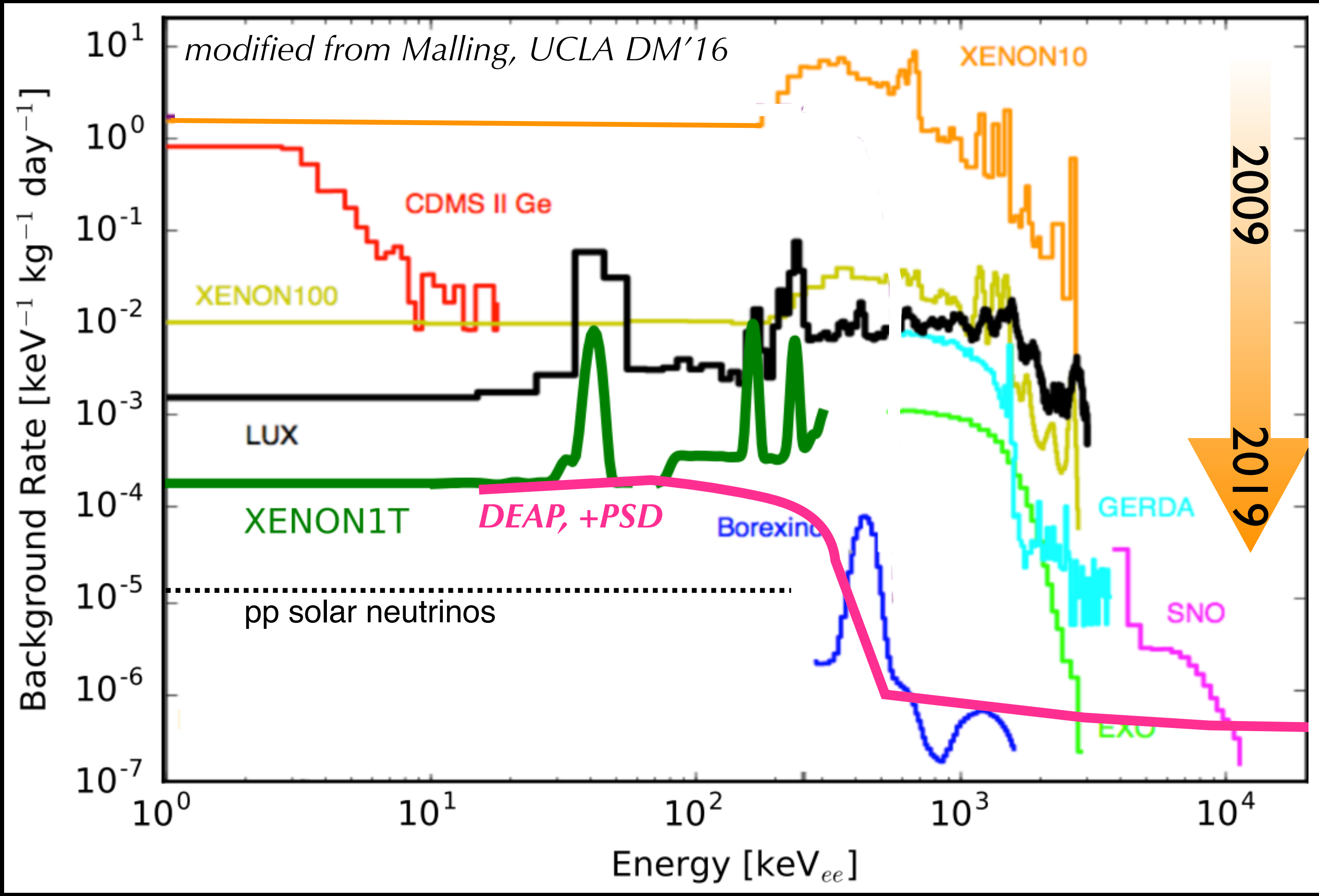

Neutrons:
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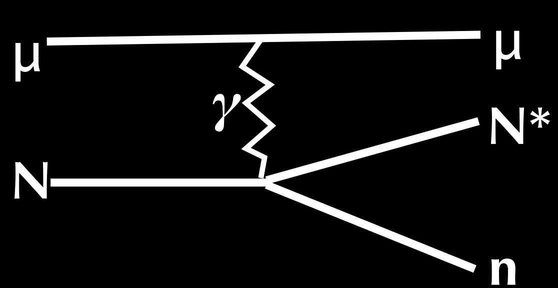

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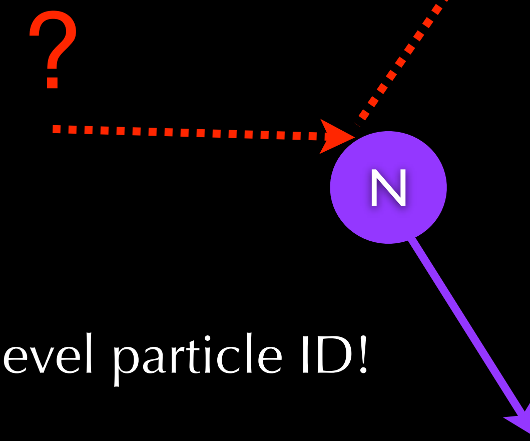

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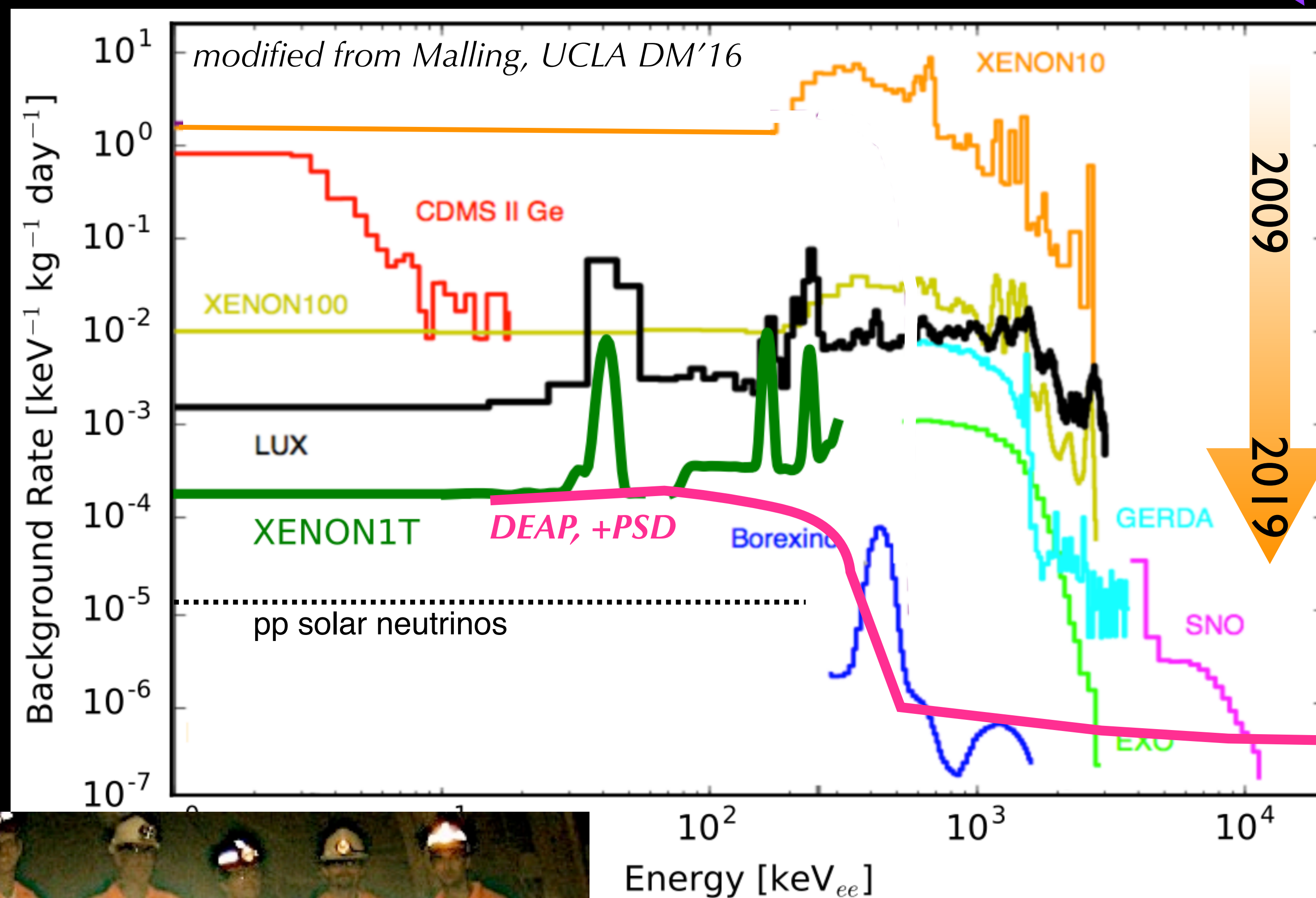

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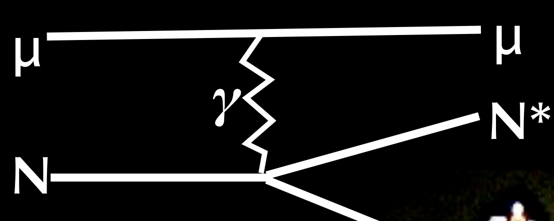
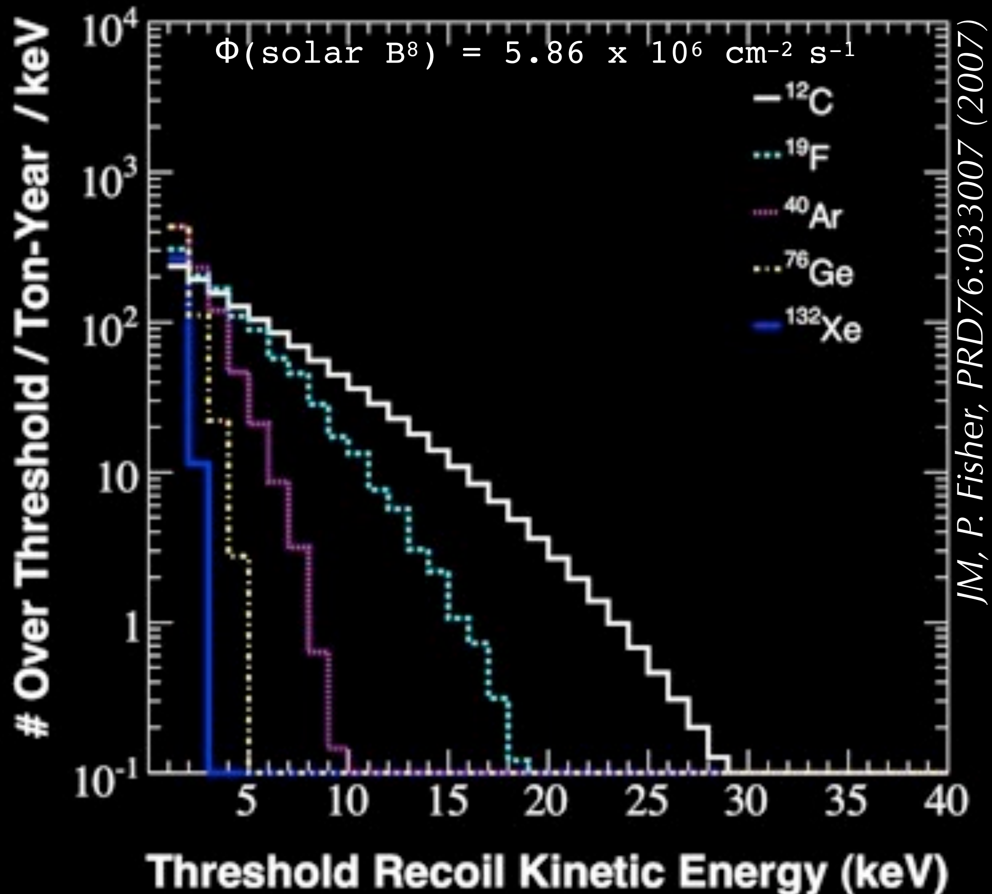


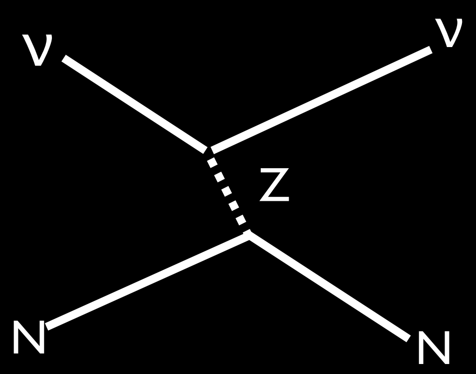
Challenge 2: Low Rates!

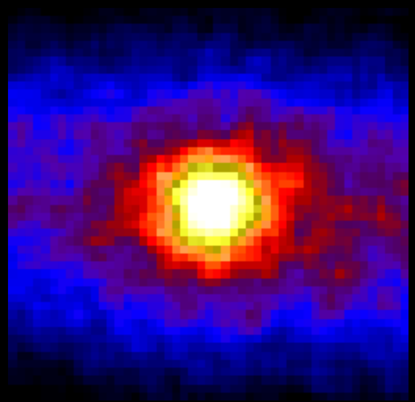
<u>Irreducible Backgrounds:</u>
impossible to shield a detector from coherent neutrino scattering!

A limiting background: neutrino floor/fog



JM, P. Fisher, PRD76:033007 (2007)





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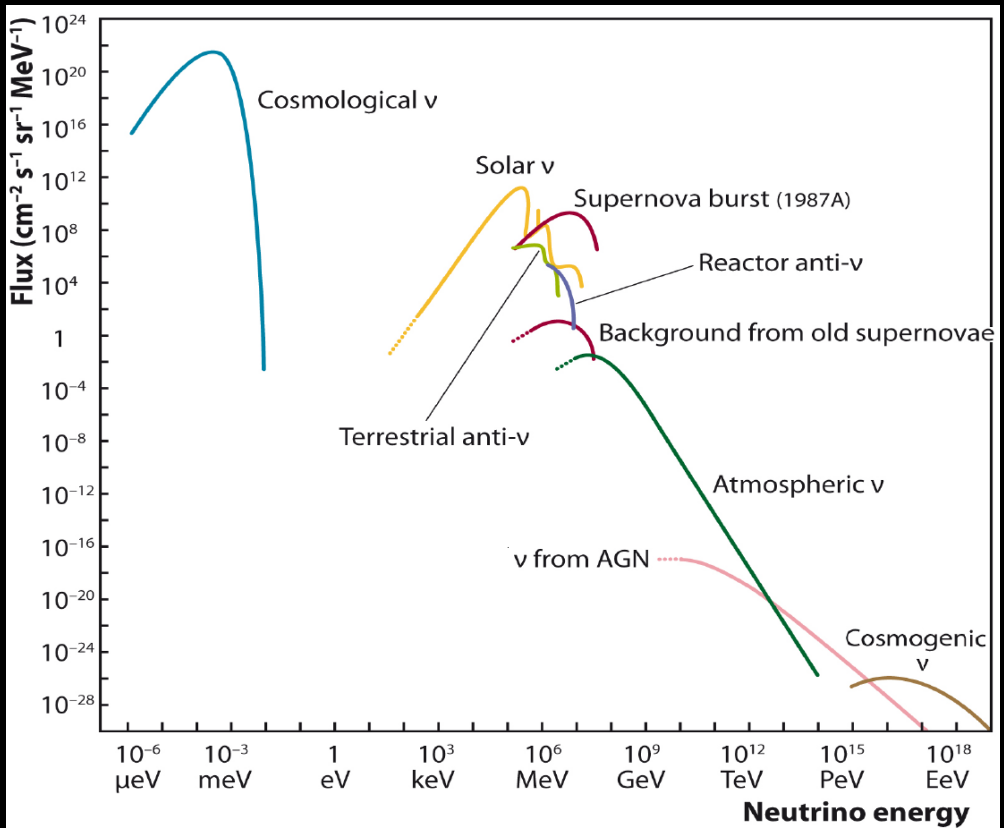
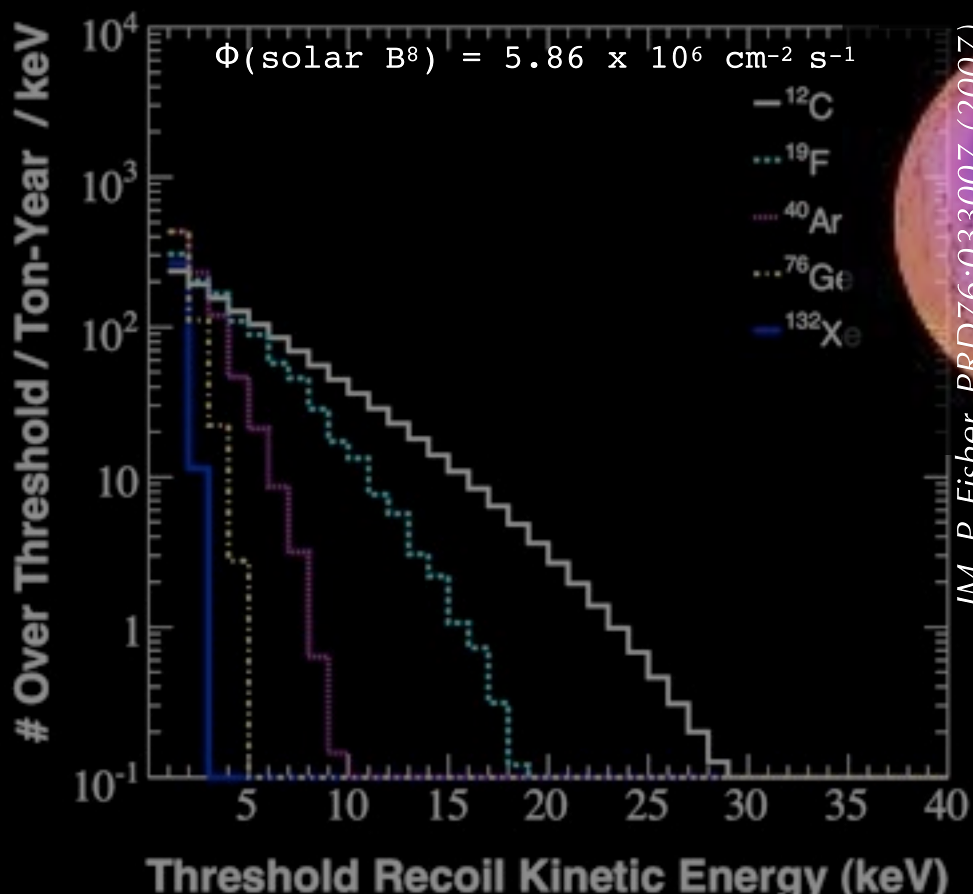


Challenge 2: Low Rates!

impossible to shield a detector from coherent neutrino scattering!

A limiting background at the neutrino floor



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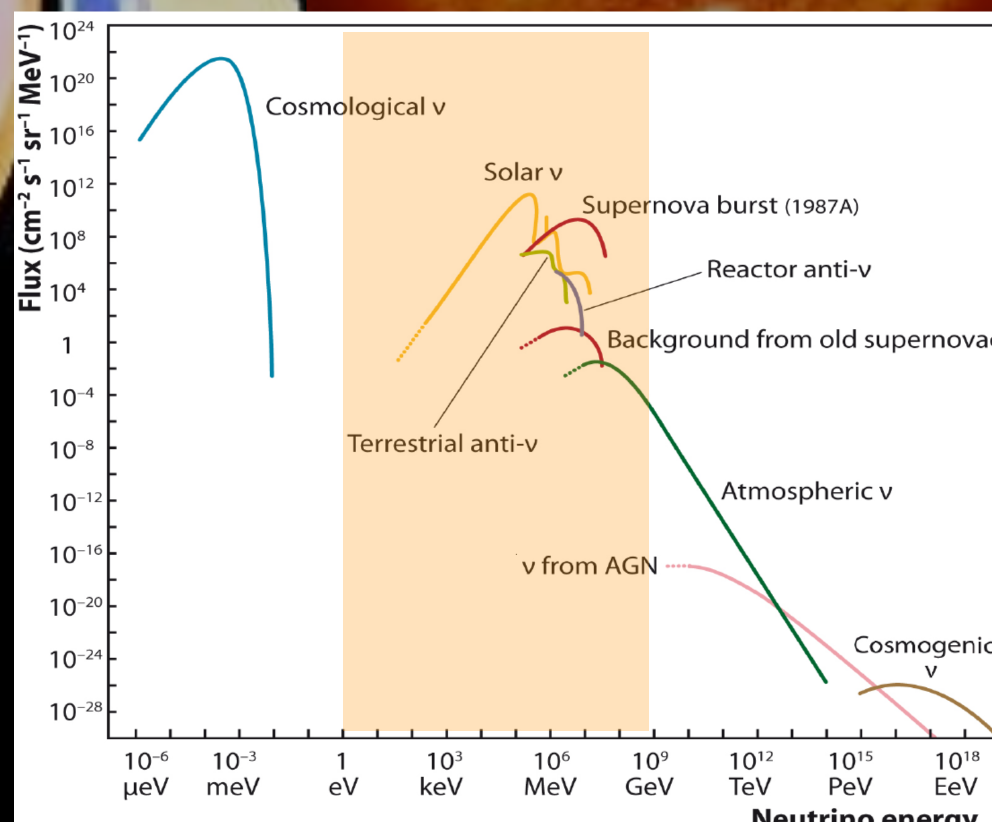
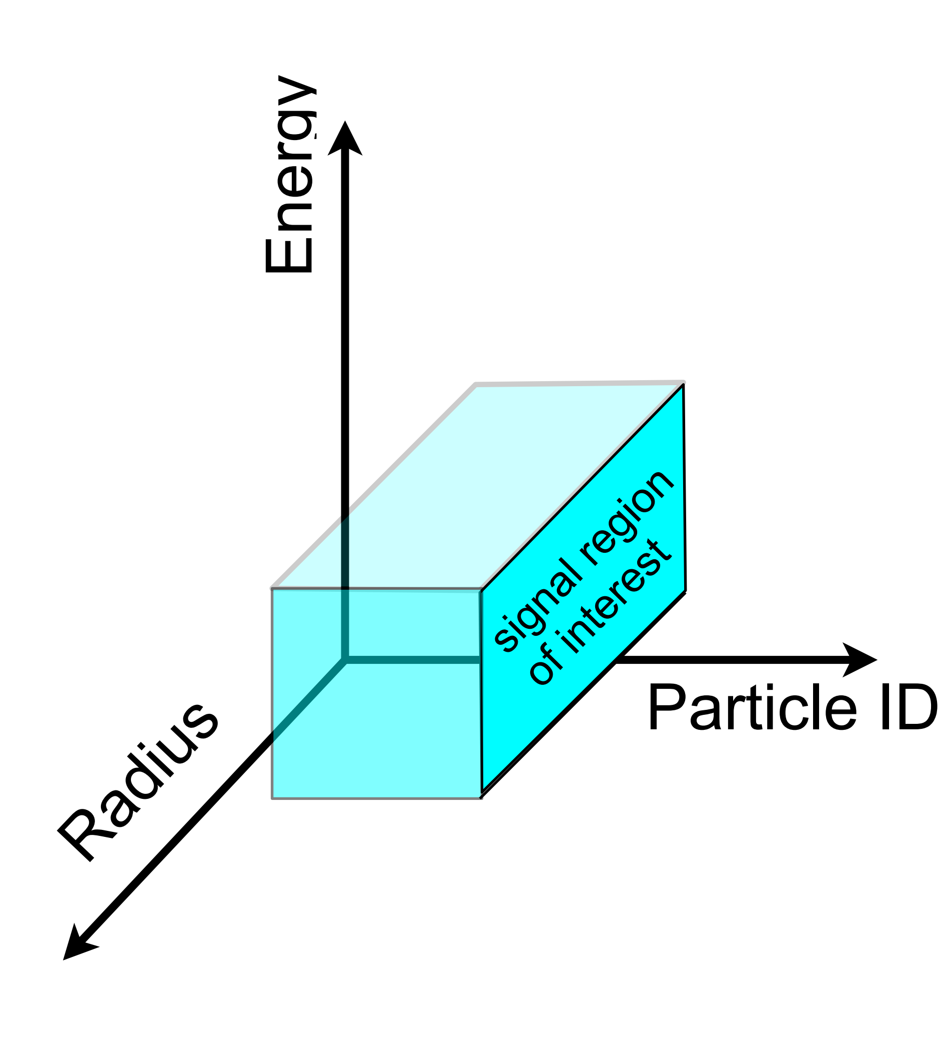


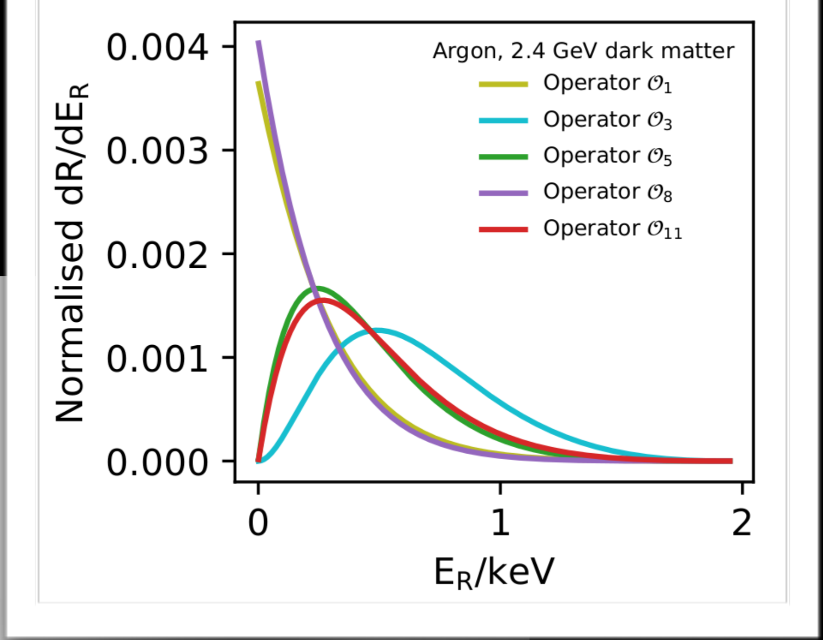
Challenge 3:
Signal Identification

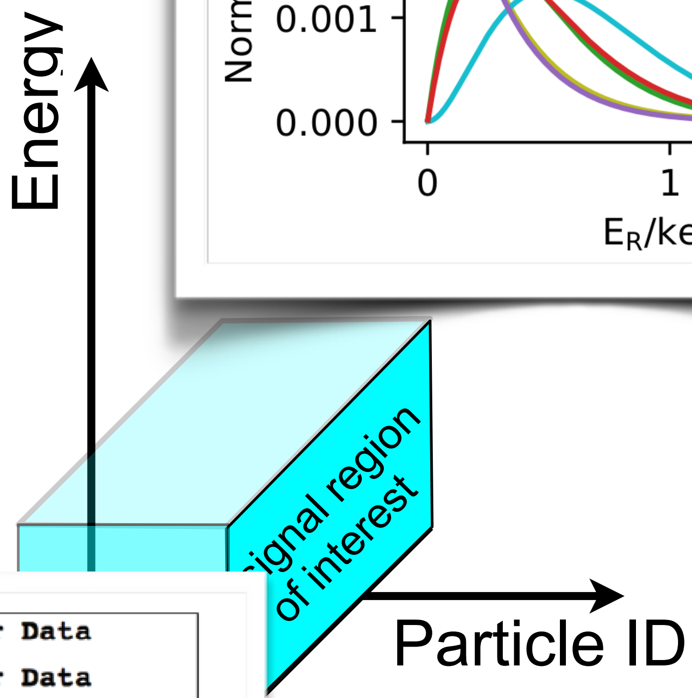


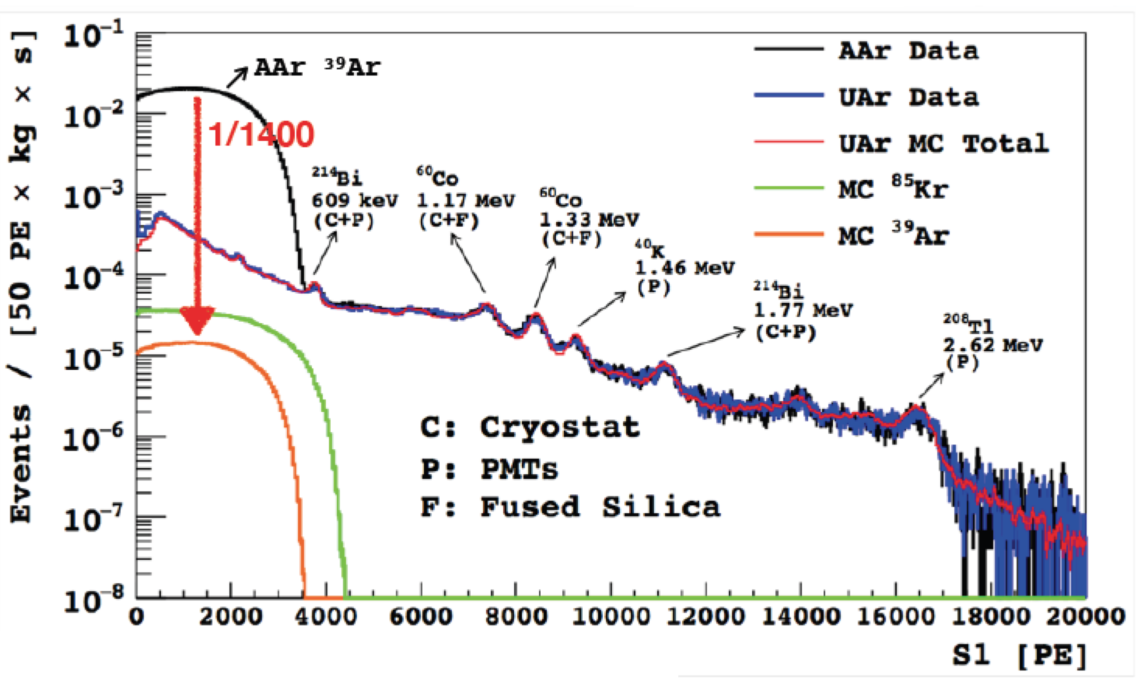
Challenge 3:
Signal Identification

Is the energy distribution consistent with the expected signal? Depends on interaction!

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





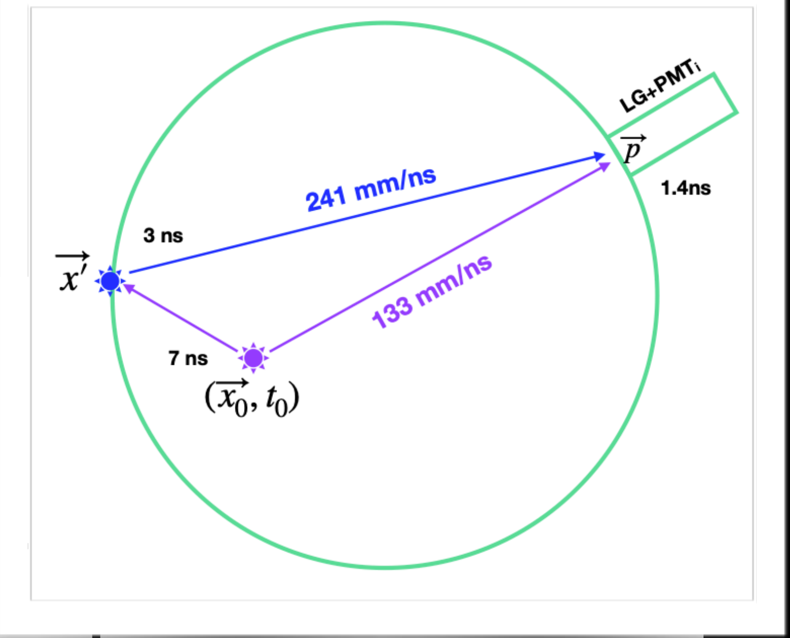


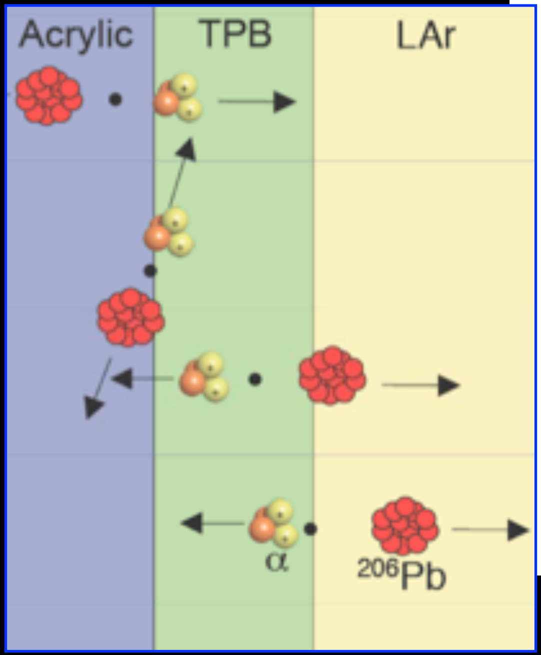
non-O1 and/or isospin-violating
Cheek et al., arXiv:2302.05458
Williams, TAUP'23
Ning et al., Nature 618, 47-50 (2023)
Adhikari et al., PRD 102. 082001 (20
++…

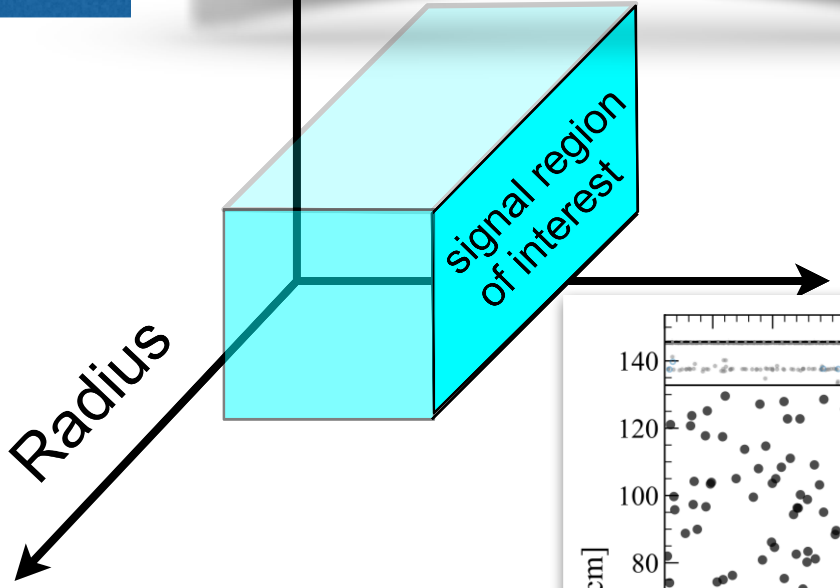
Is the energy partition consistent with the expected signal particle?

Challenge 3: Signal Identification

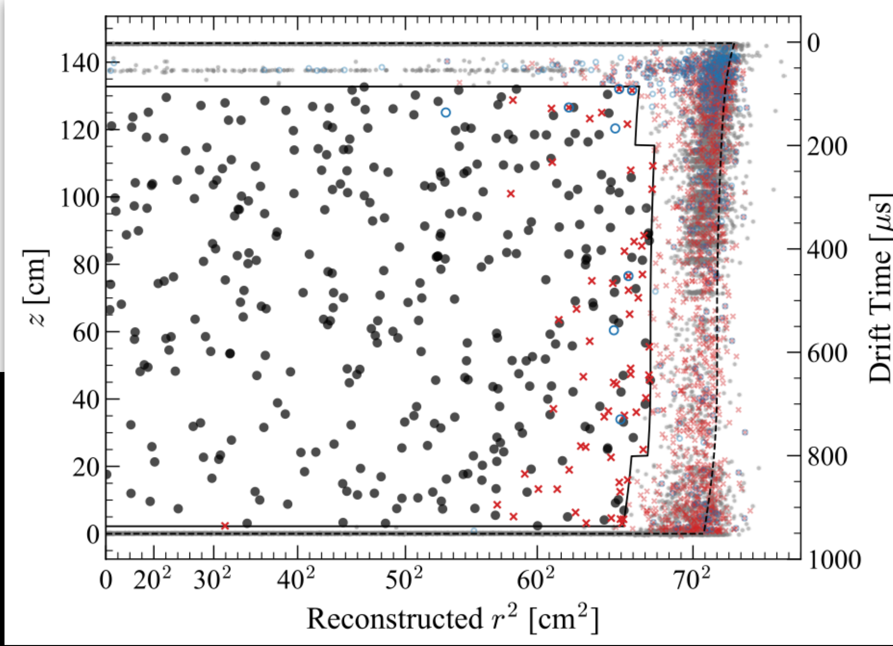
Is the reconstructed vertex consistent with the expected signal?





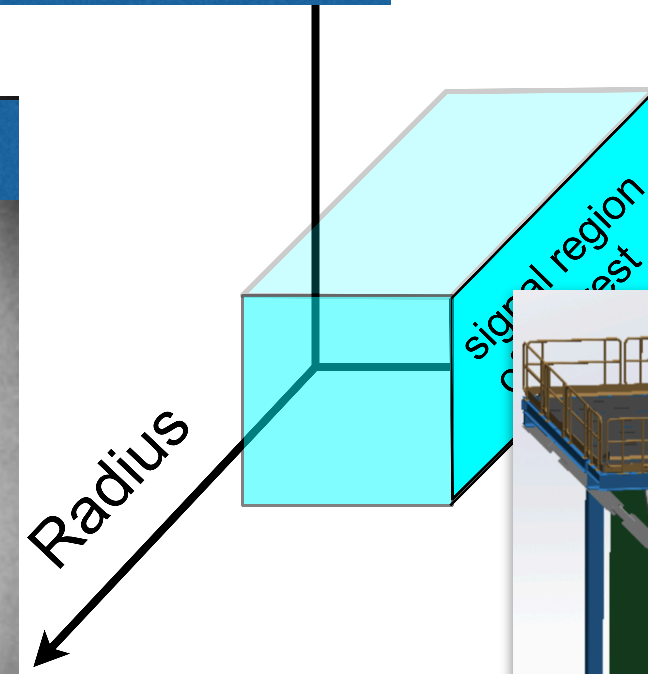


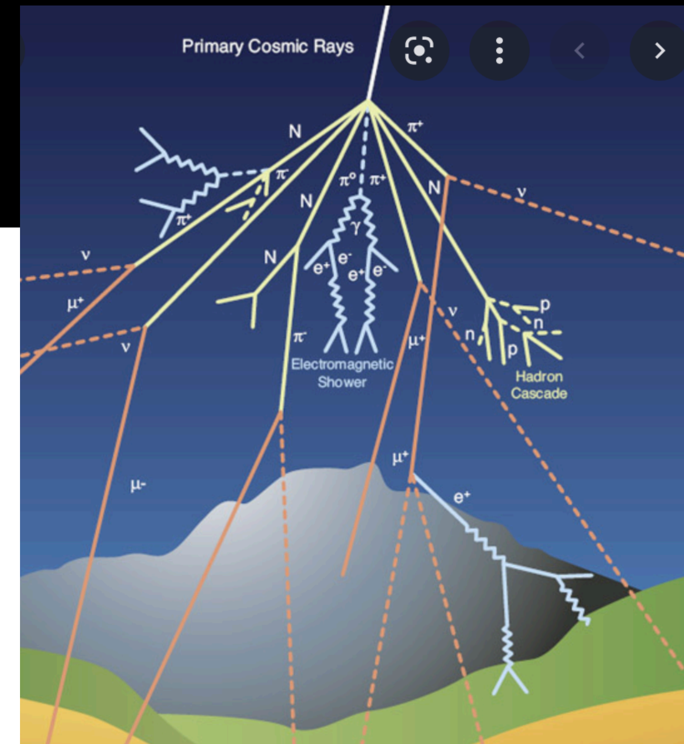
Aalberts et al., arXiv:2207.03764



Challenge 3: Signal Identification

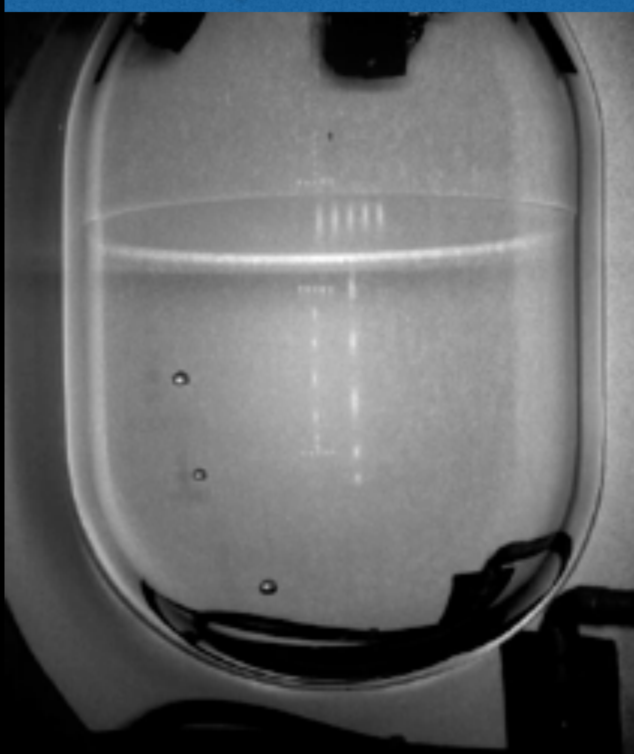
Is the event topology consistent with a tiny interaction cross section?

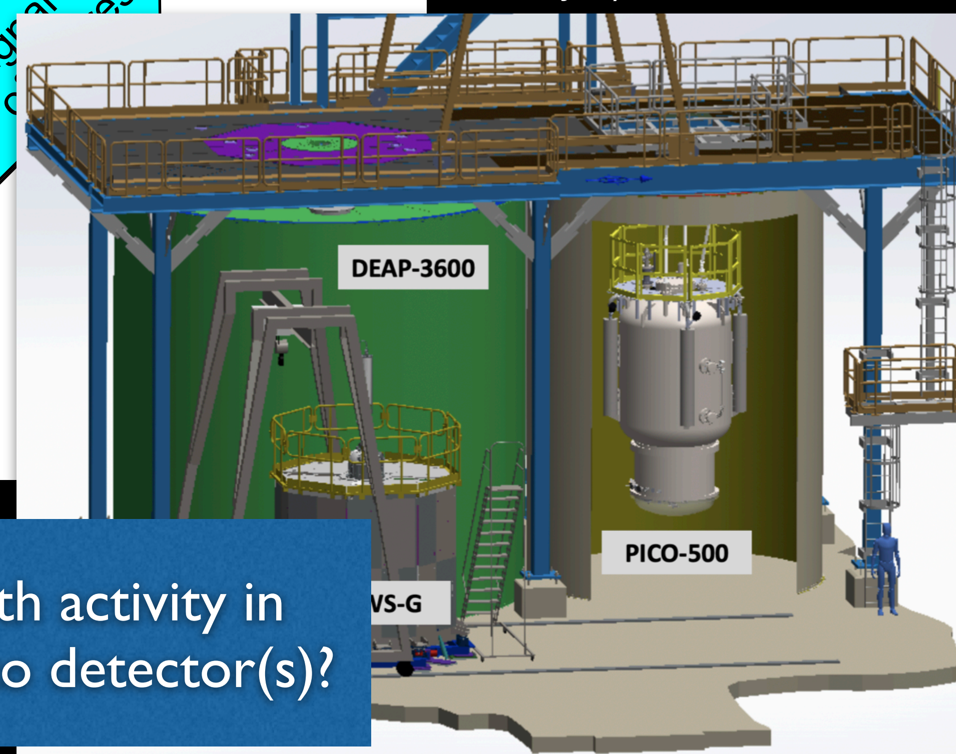




Giroux J. Phys.: Conf. Ser. 2156 012068

Multiple scatters?

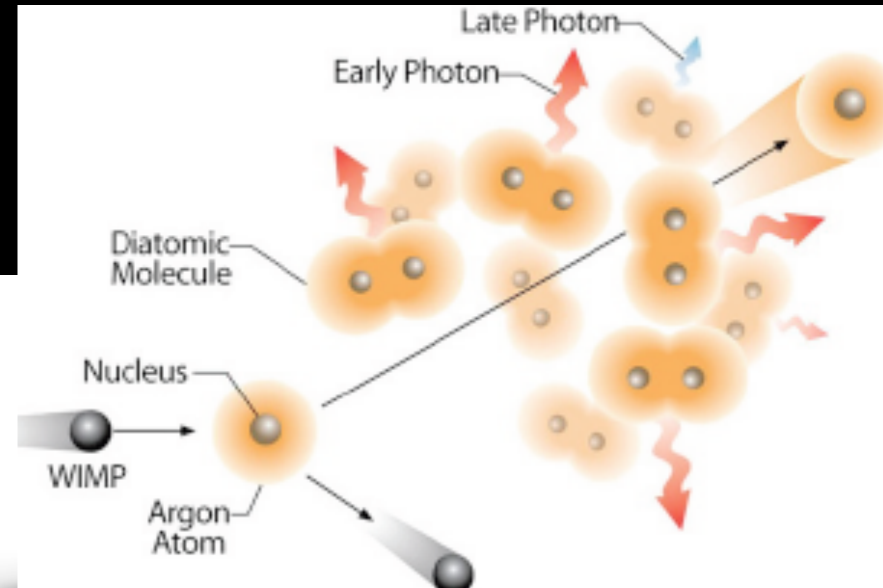


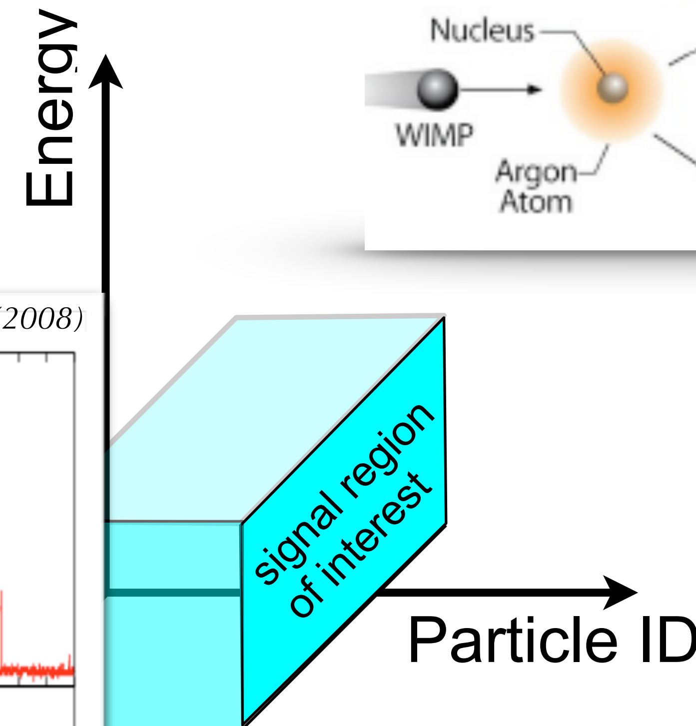


coincident with activity in surrounding veto detector(s)?

Challenge 3: Signal Identification

Is the timing distribution consistent with the expected signal particle?





Lippincott et al., Phys.Rev.C 78: 035801 (2008)

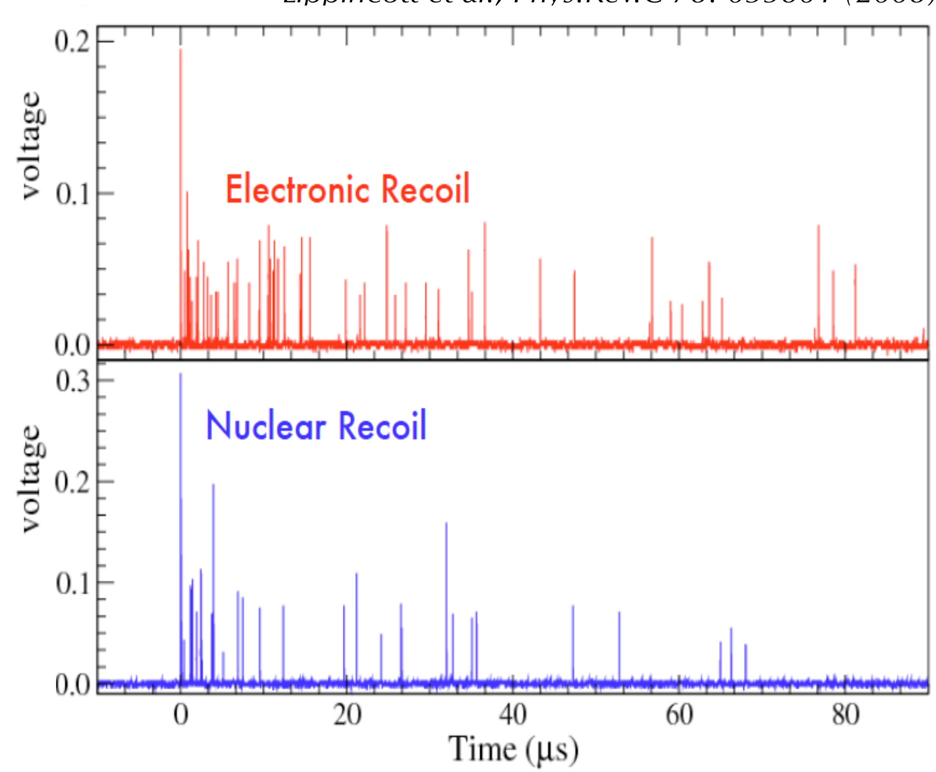


Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30

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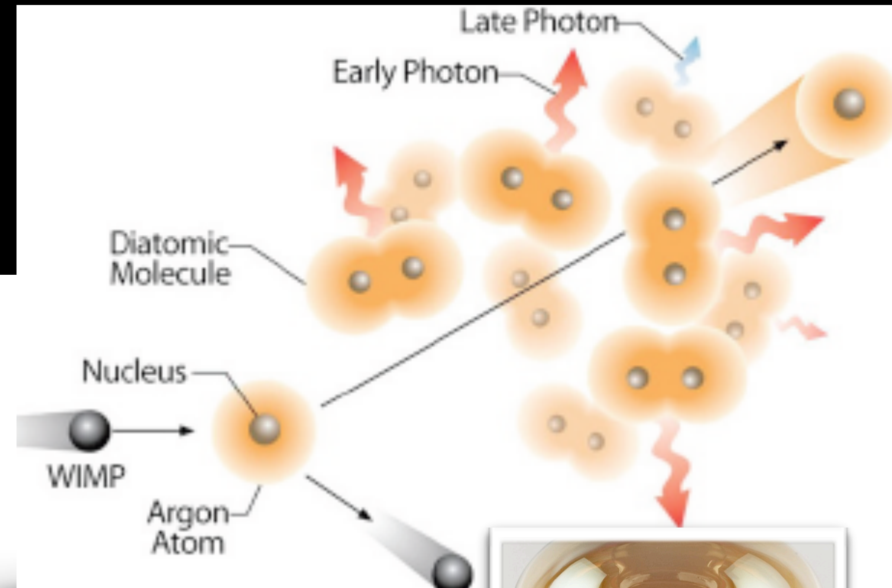
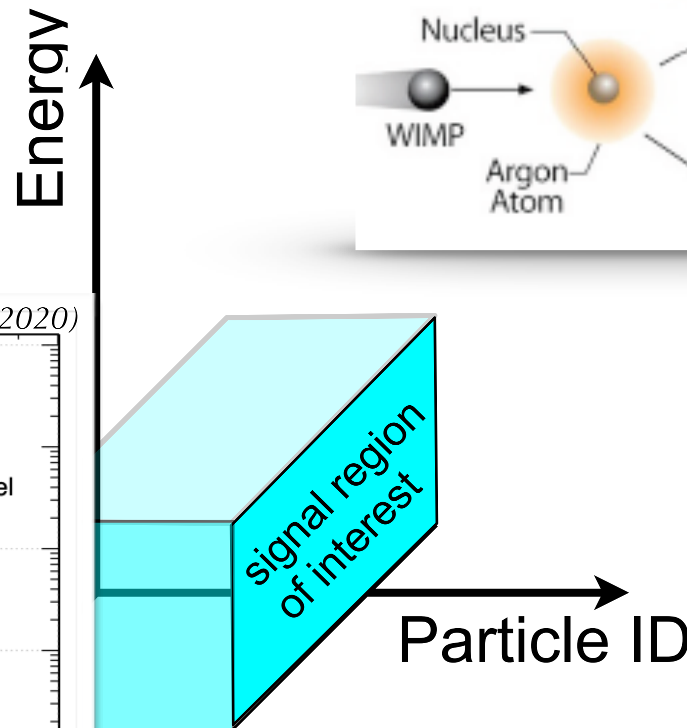
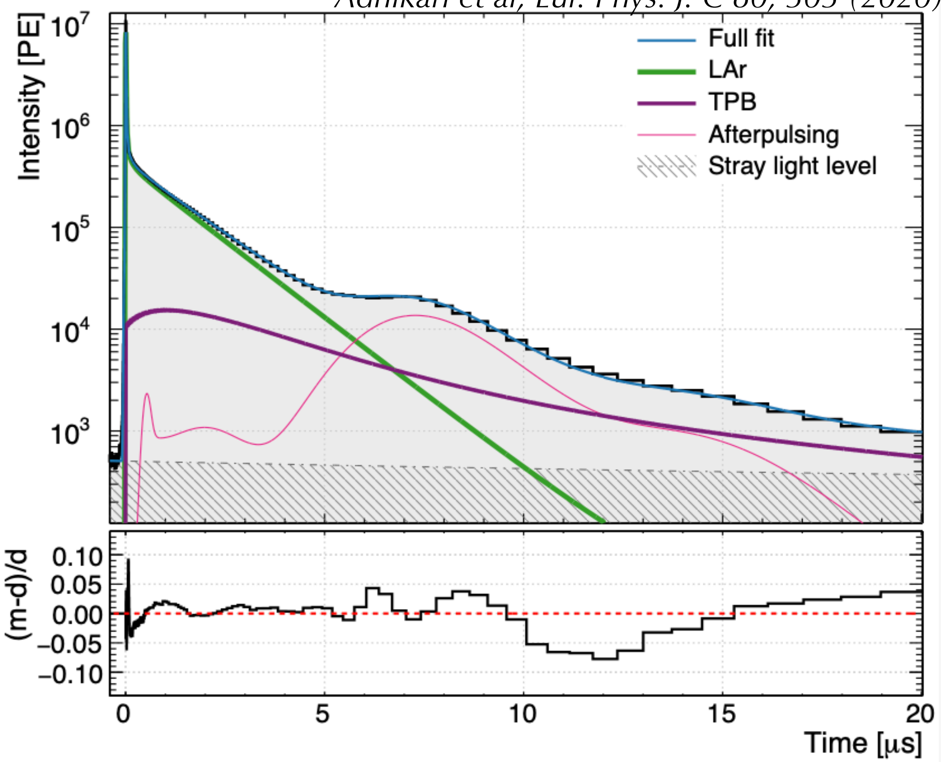




Adhikari et al, Eur. Phys. J. C 80, 303 (2020)



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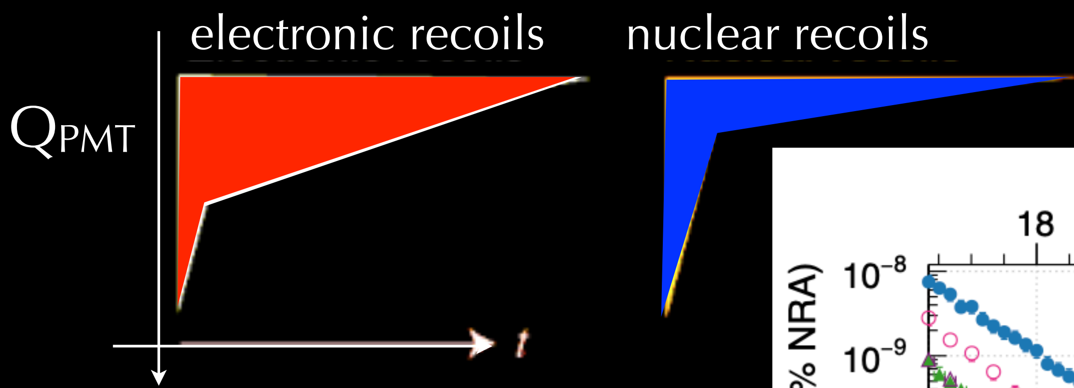
Pulse Shape Discrimination in Liquid Argon



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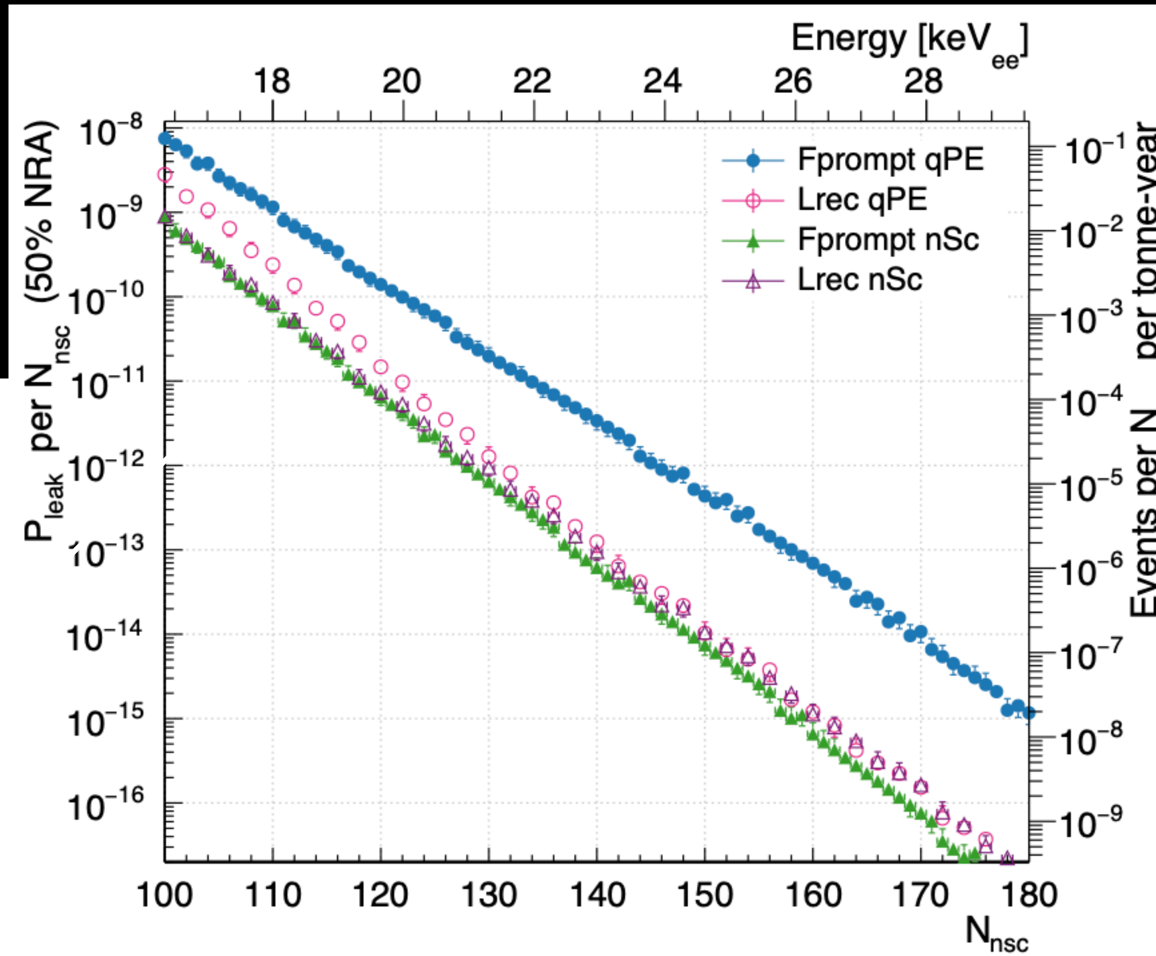

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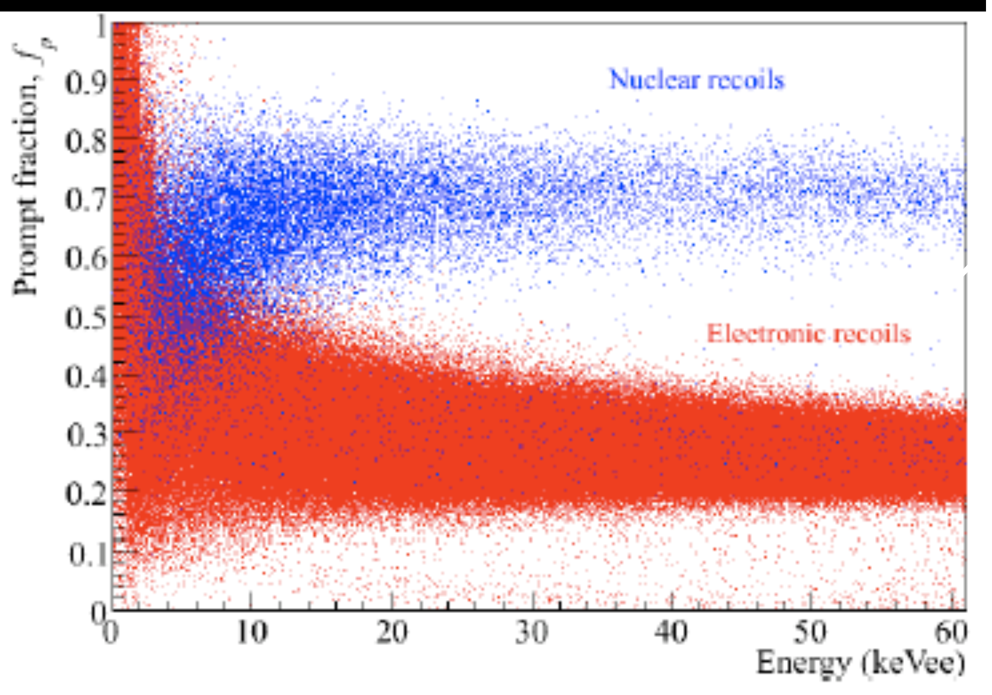
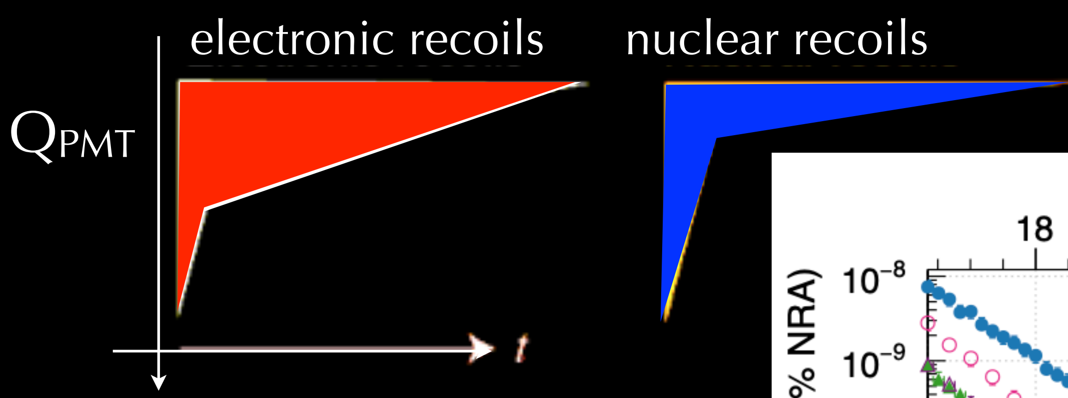
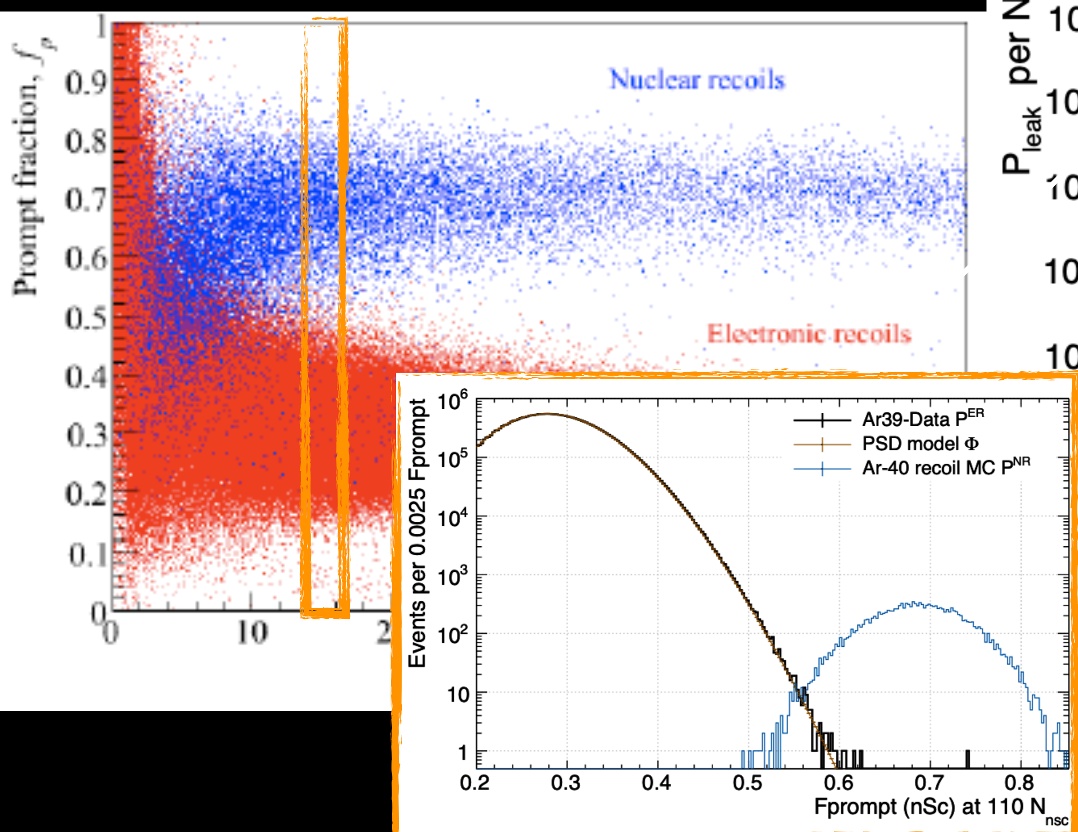


identify, reject electronic backgrounds via pulse shape vs. time difference at parts-per-billion level

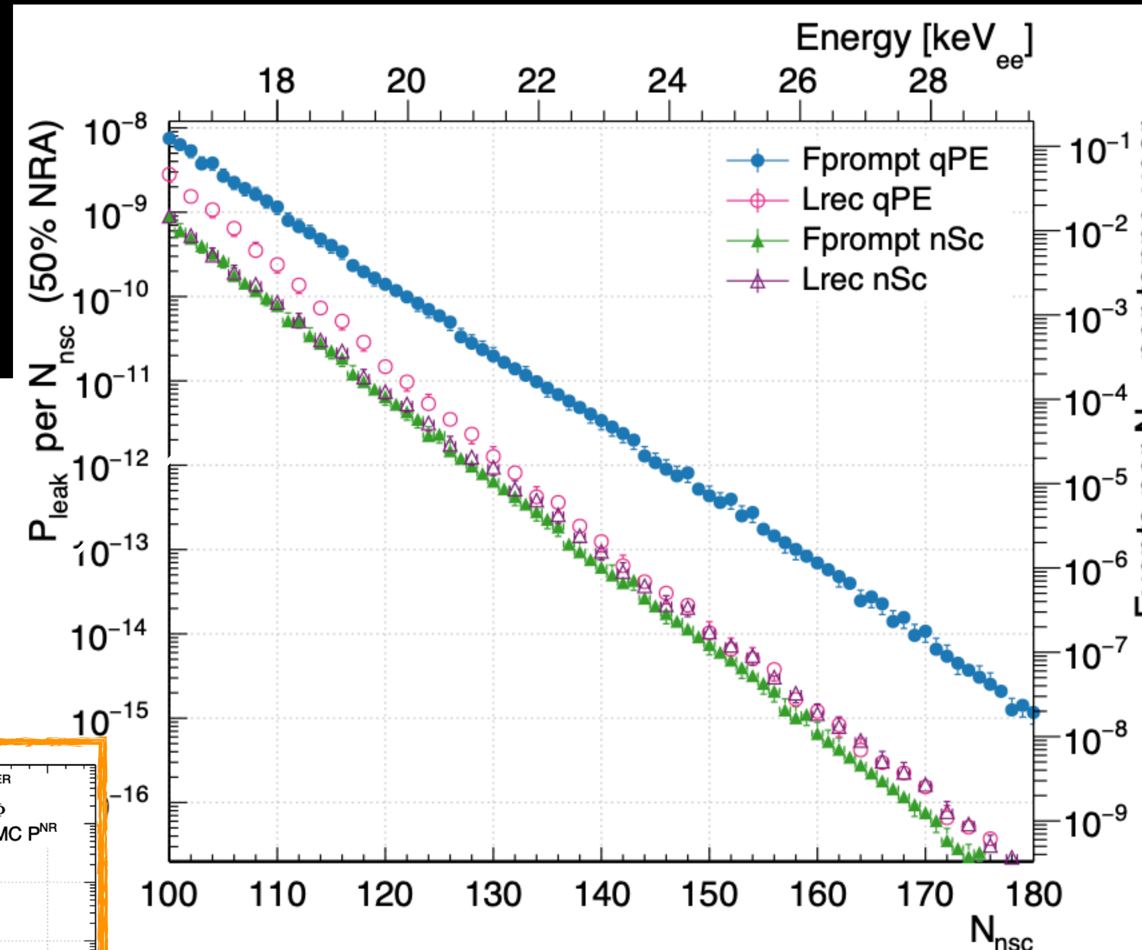
Pulse Shape Discrimination in Liquid Argon



Lippincott et al., Phys.Rev.C 78: 035801 (2008)



Adhikari et al, Eur. Phys. J. C 80, 303 (2020)



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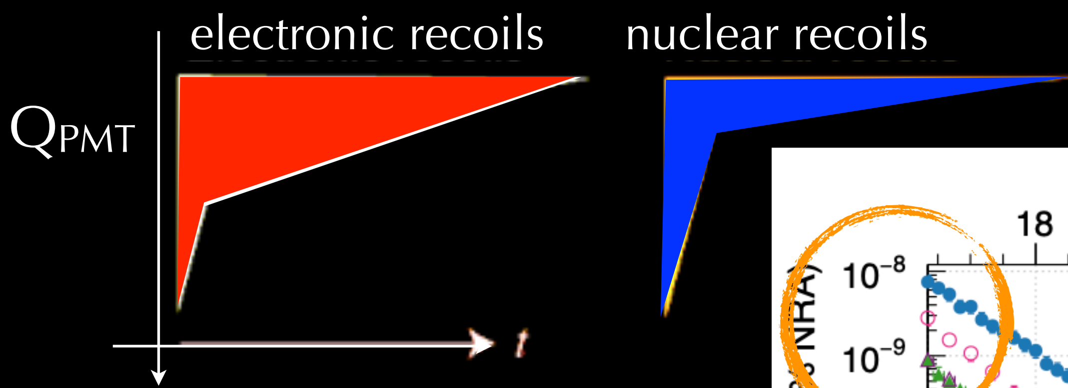
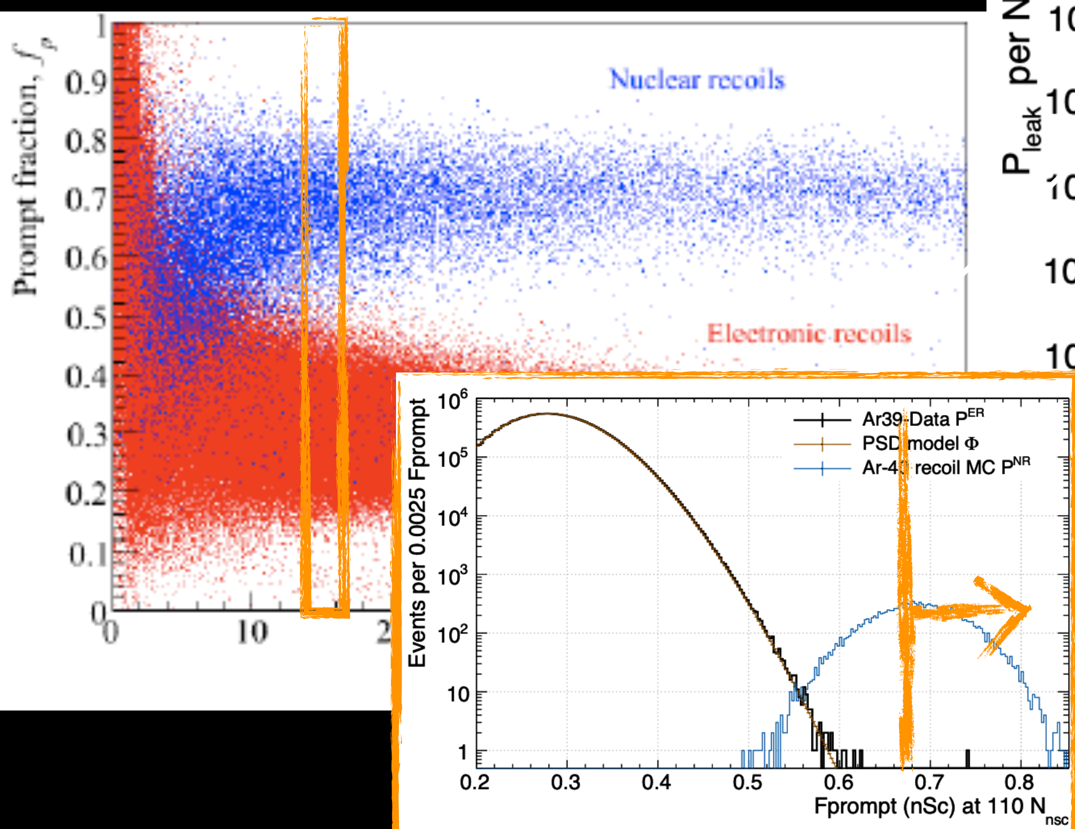
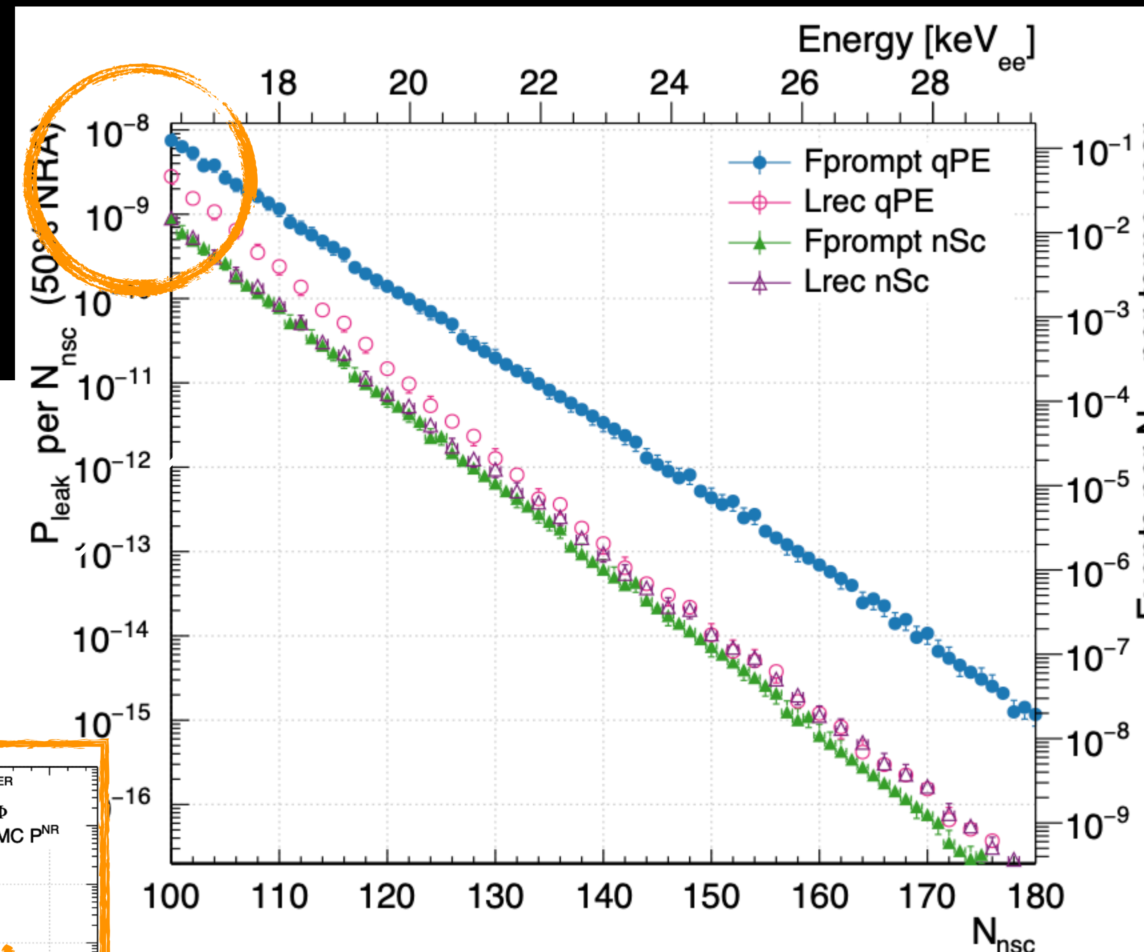


Lippincott et al., Phys.Rev.C 78: 035801 (2008)



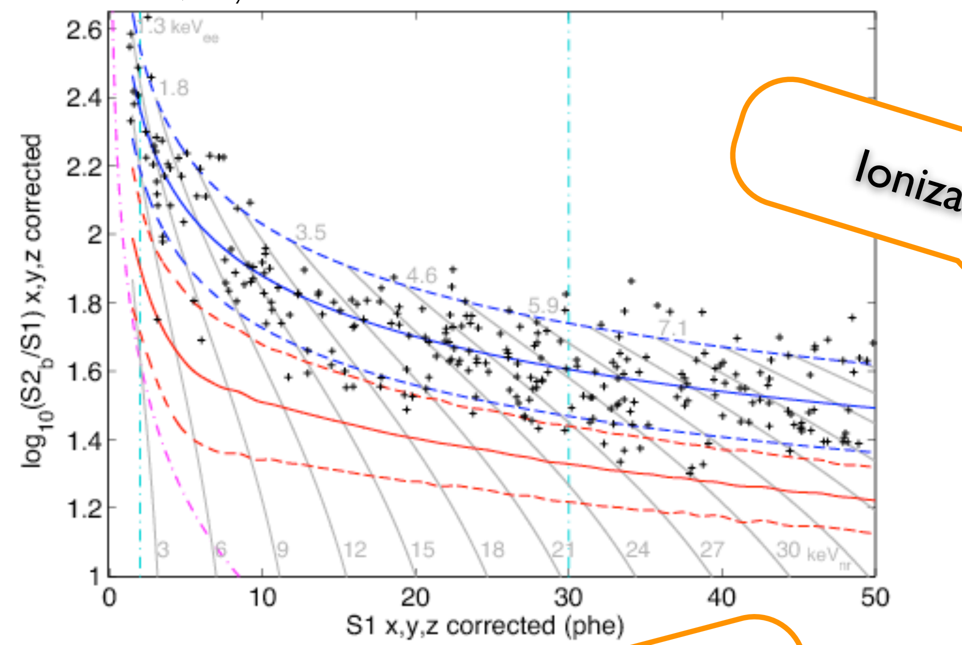
Adhikari et al, Eur. Phys. J. C 80, 303 (2020)



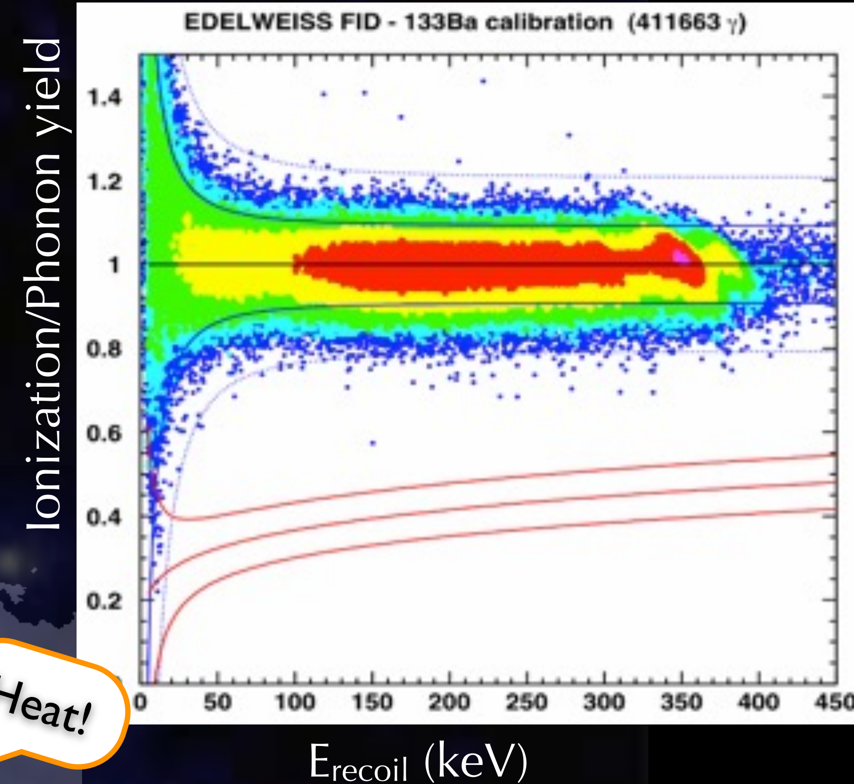
identify, reject electronic backgrounds via pulse shape vs. time difference at parts-per-billion level

Background Discrimination Strategies

Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



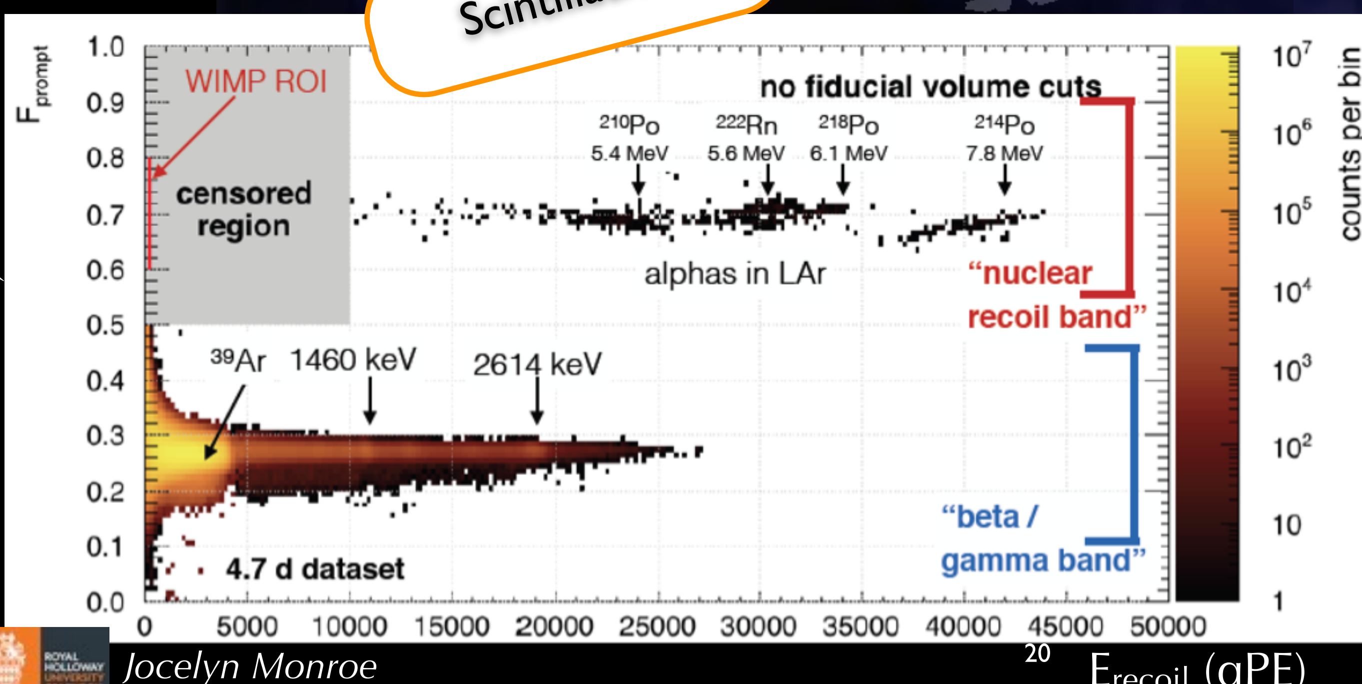
Ionization!

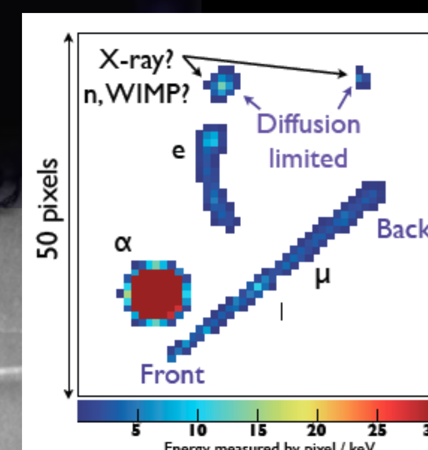


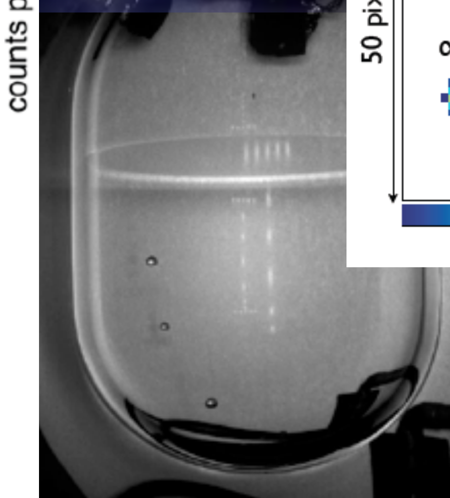
Heat!

Scintillation!

Amandruz et al., arXiv:1707.08042



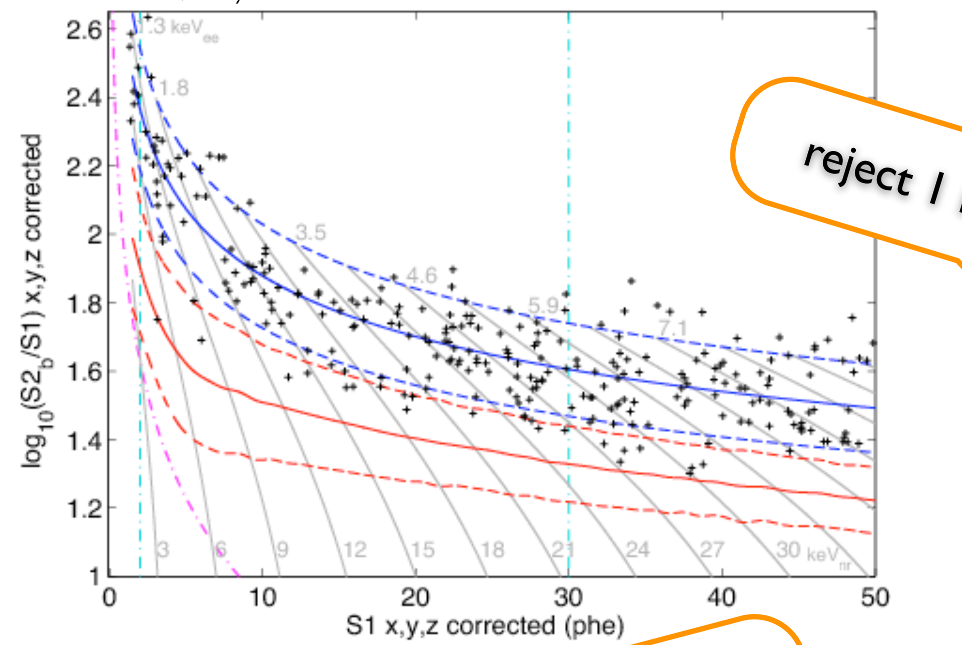




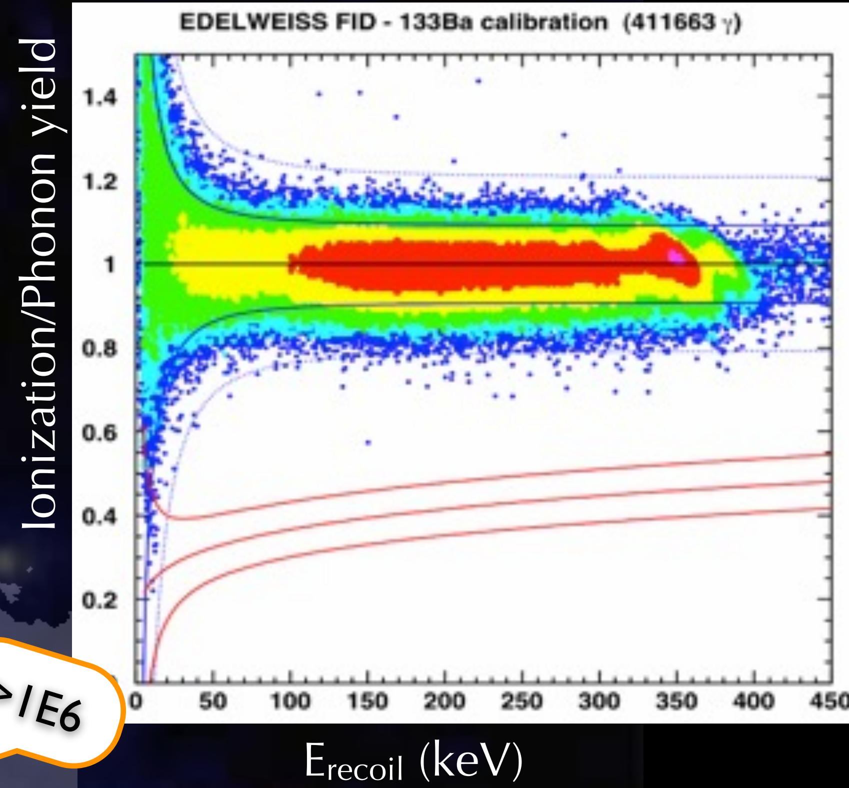
Topology

Background Discrimination Strategies

Akerib et al, Phys.Rev.Lett. 112 (2014) 091303



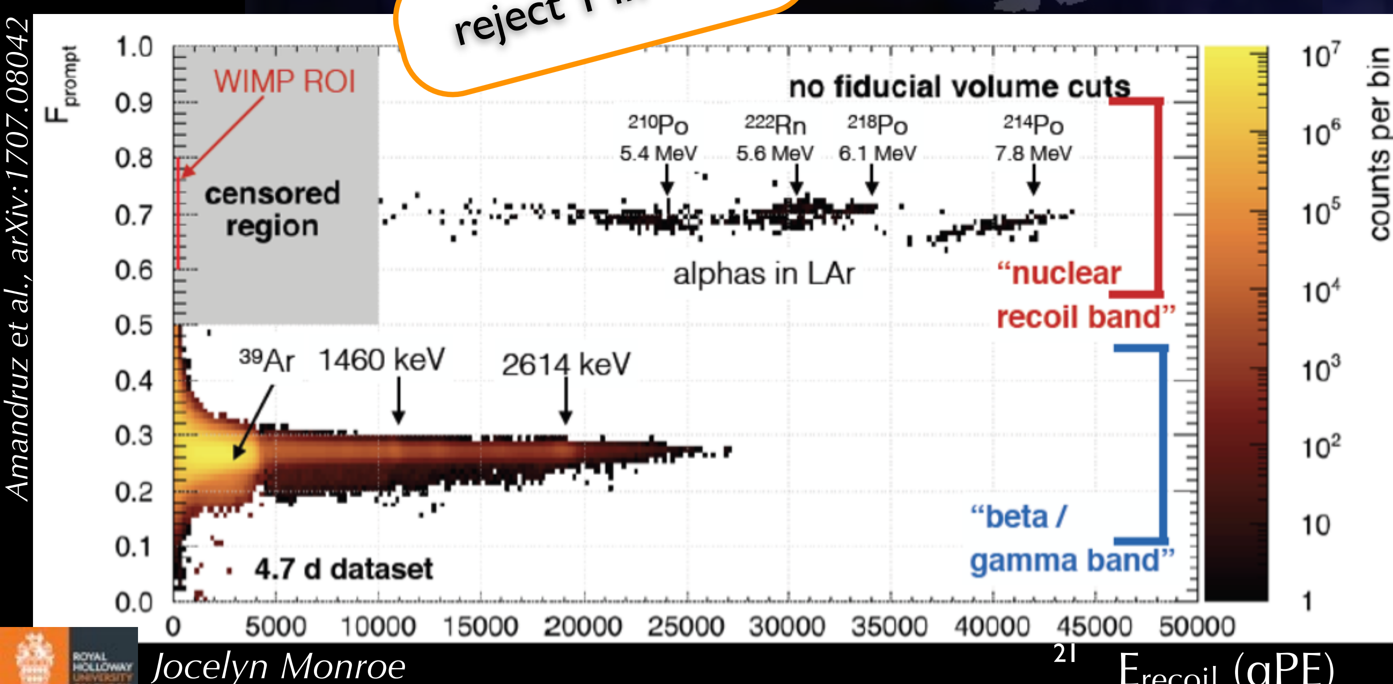
reject 1 in >1E3

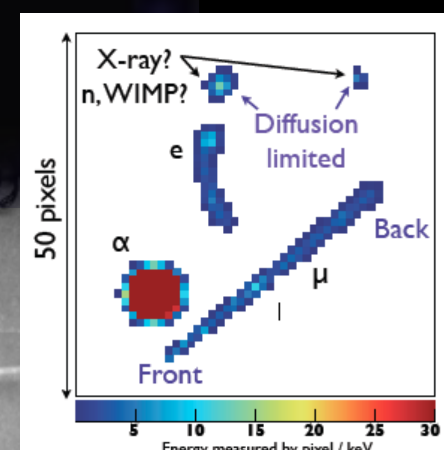


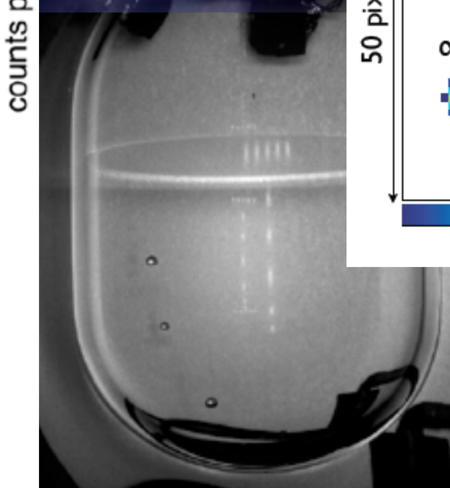
>1E6

reject 1 in >1E9

Amandruz et al., arXiv:1707.08042



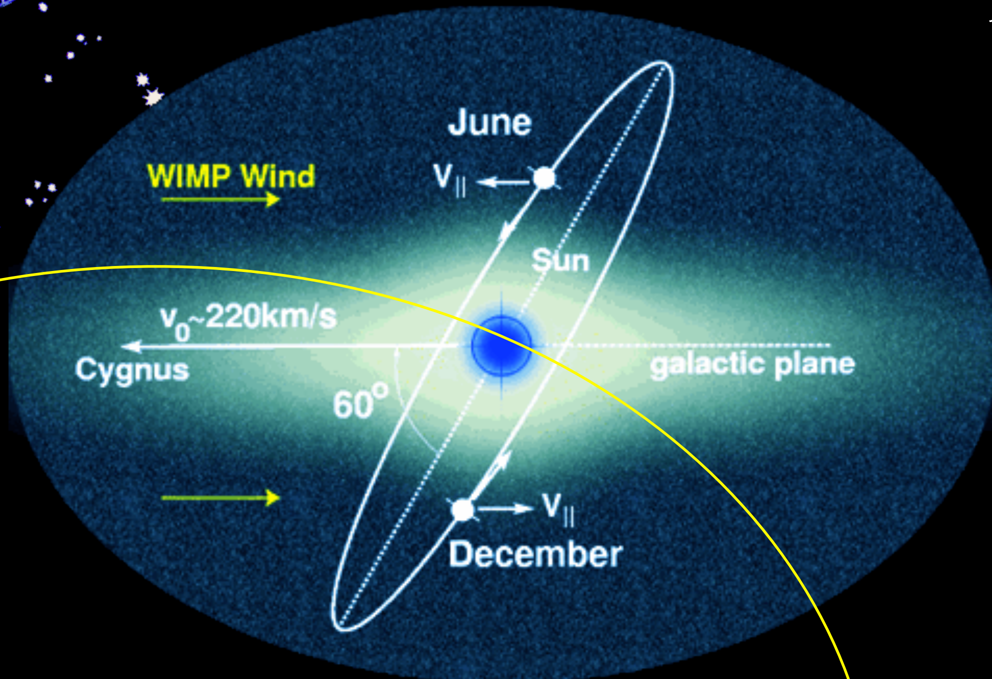


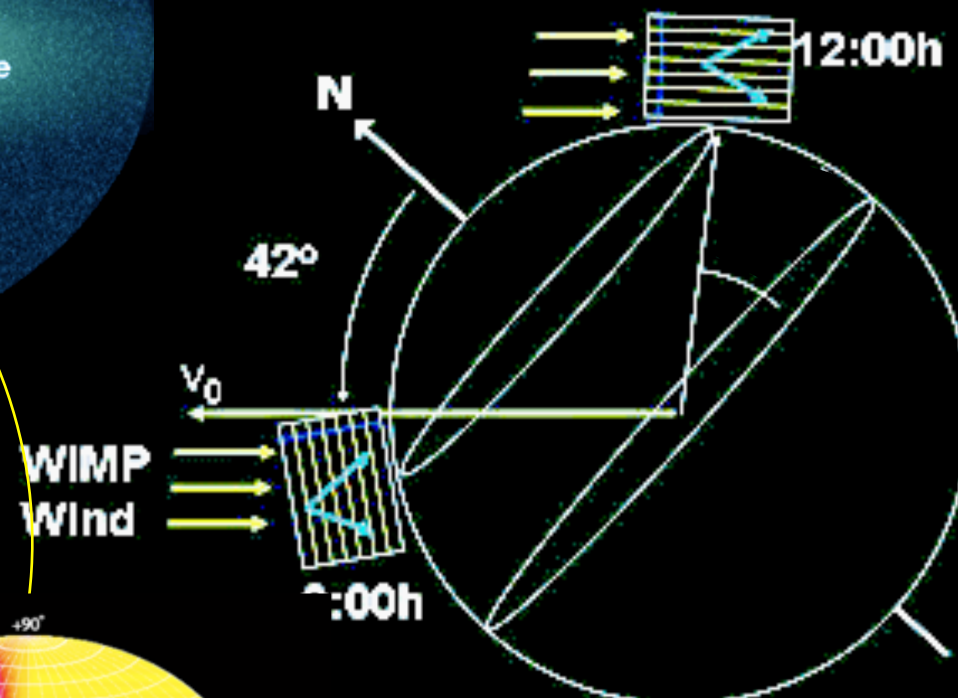


>1E2

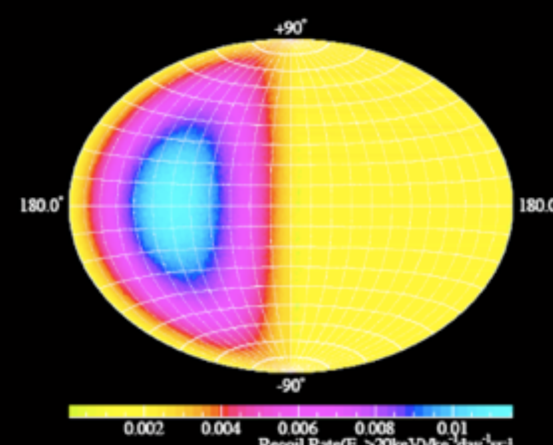
Modulation Signatures

Annual event rate modulation:
June-December asymmetry ~2%.
Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate.
Spergel, Phys. Rev. D36:1353 (1988)



Ultimate goal:
dark matter skymap
with ~100s of events

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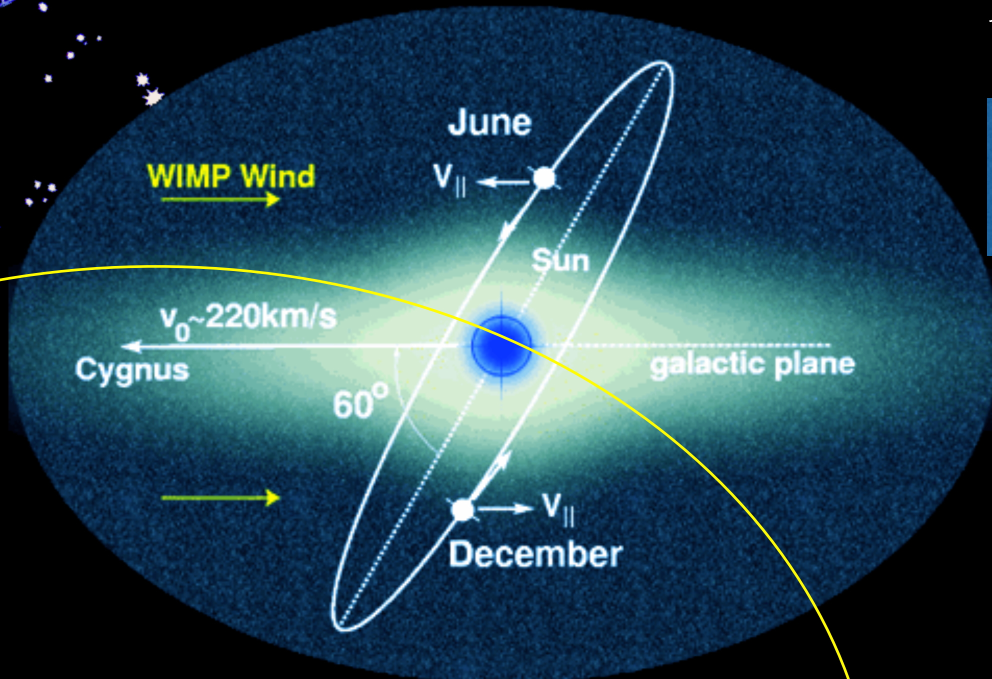
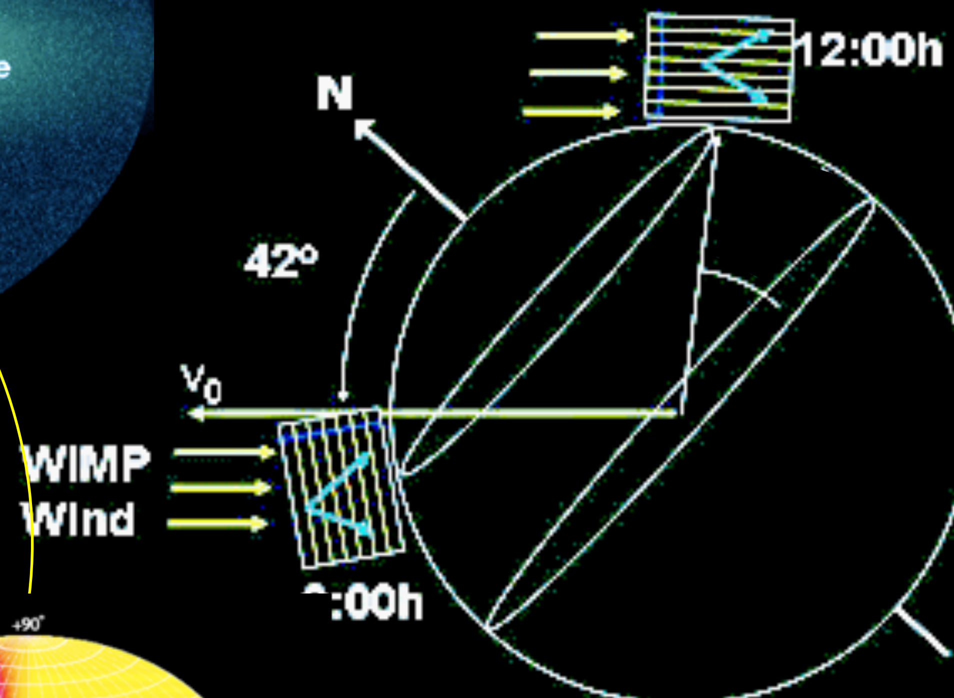
Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)

COSINUS: M. Bharadwaj, 14:40;
SABRE South: I. Bolognino, 16:30





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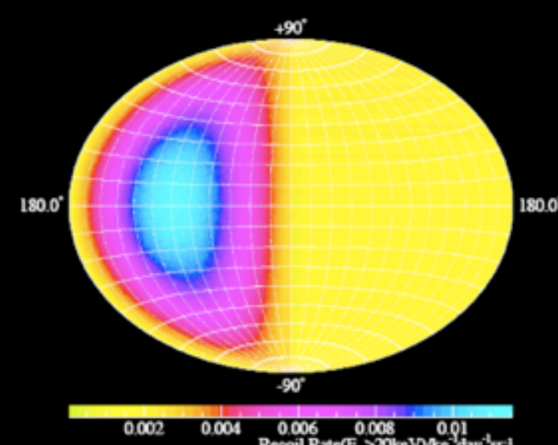

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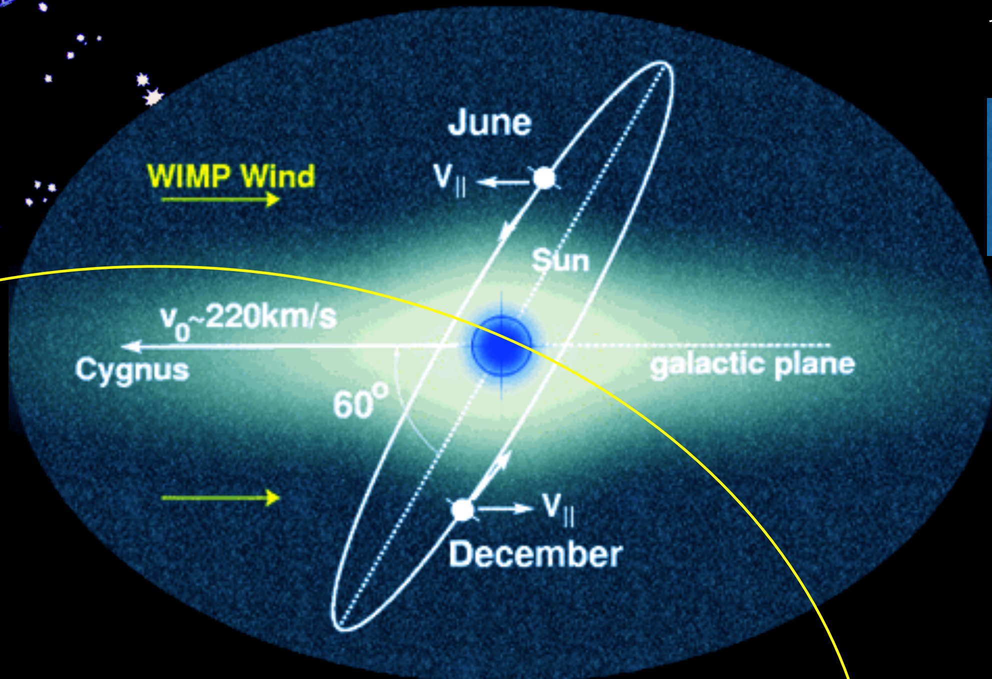

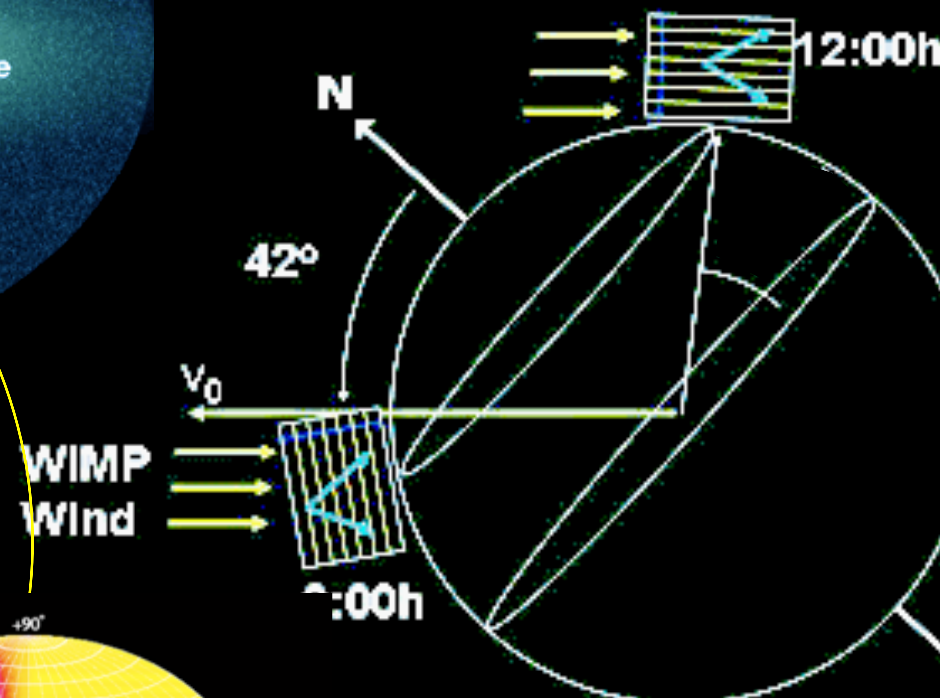

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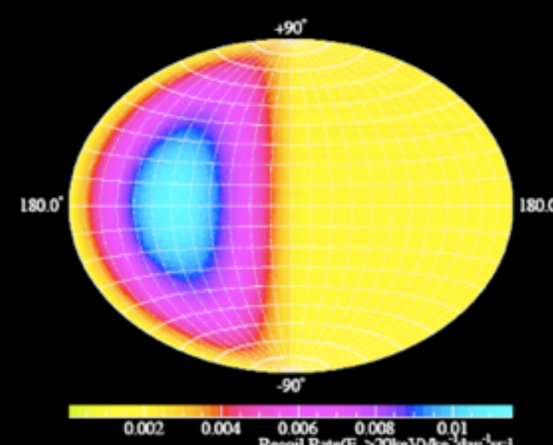
Spergel, Phys. Rev. D36:1353 (1988)

CYGNUS: E. Baracchini, 15:45
ReD: I. Albuquerque: 10:05
NEWSdm: Z. Sadykov: 9/14, 14:40



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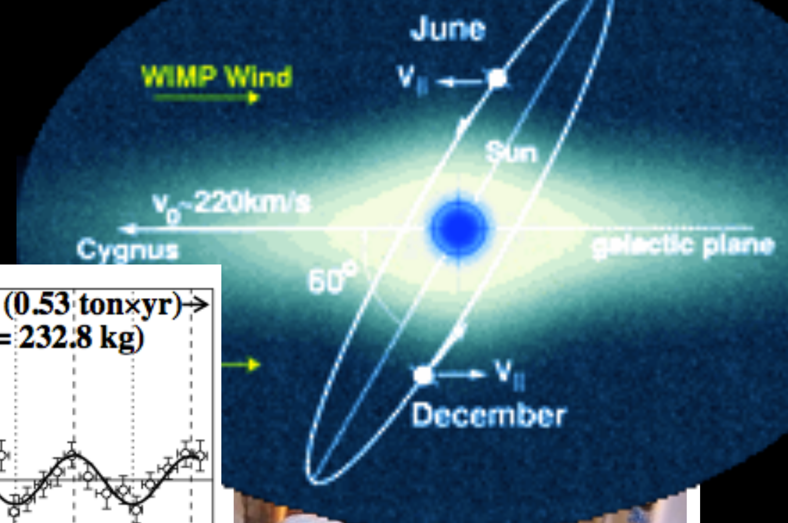
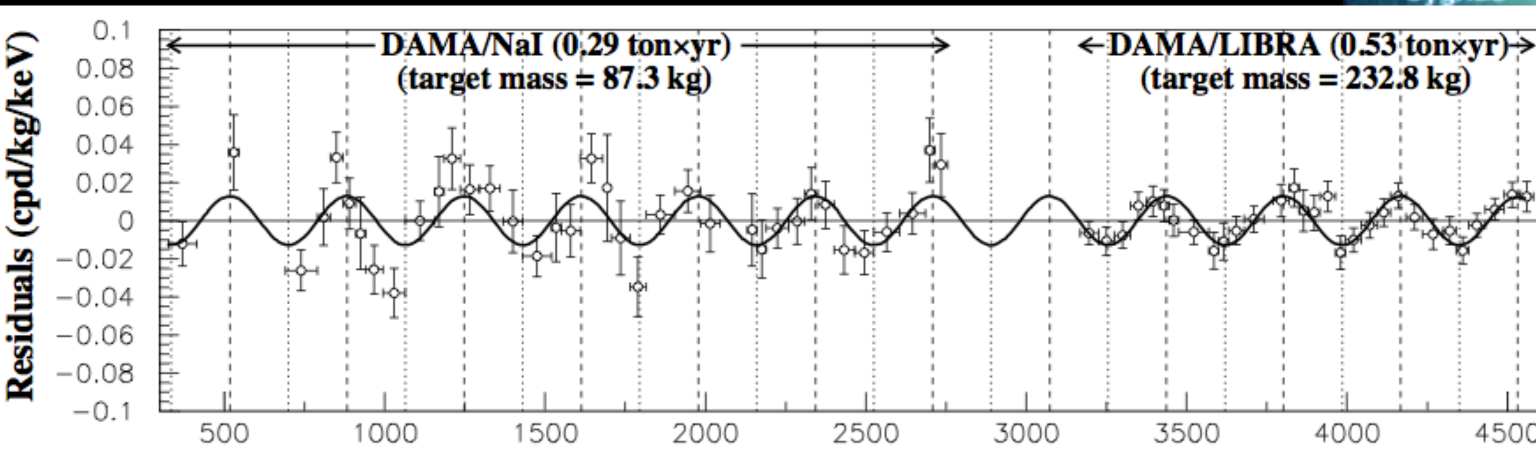
Annual Modulation Tests

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



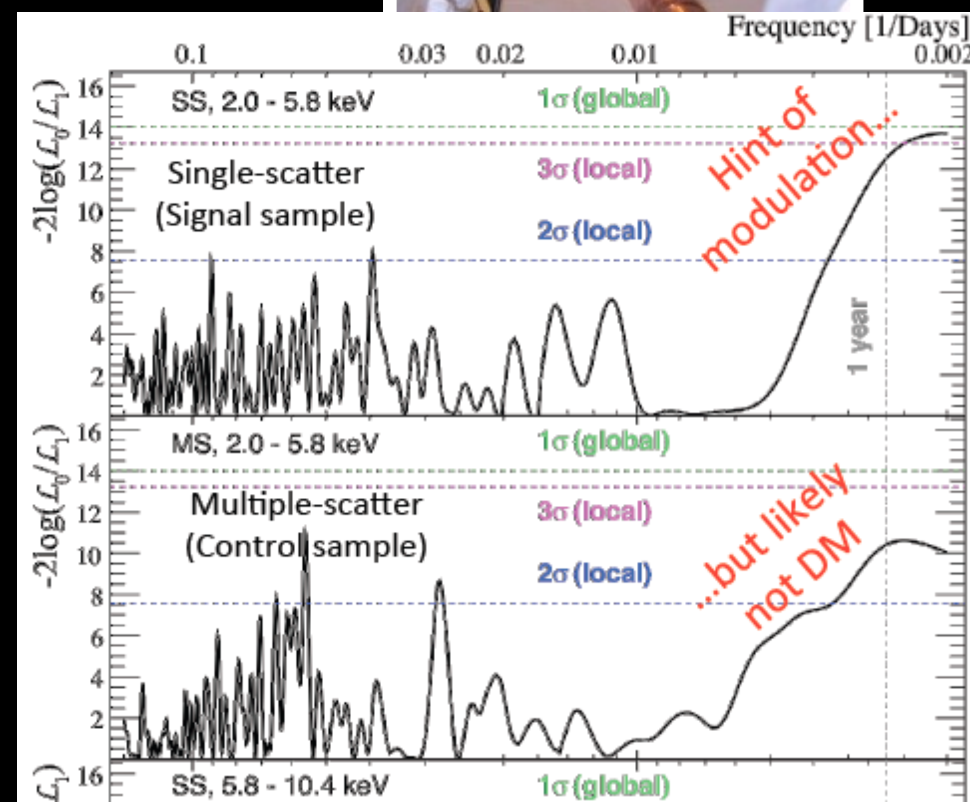


SciPost Phys. Proc. 12, 025 (2023)

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*



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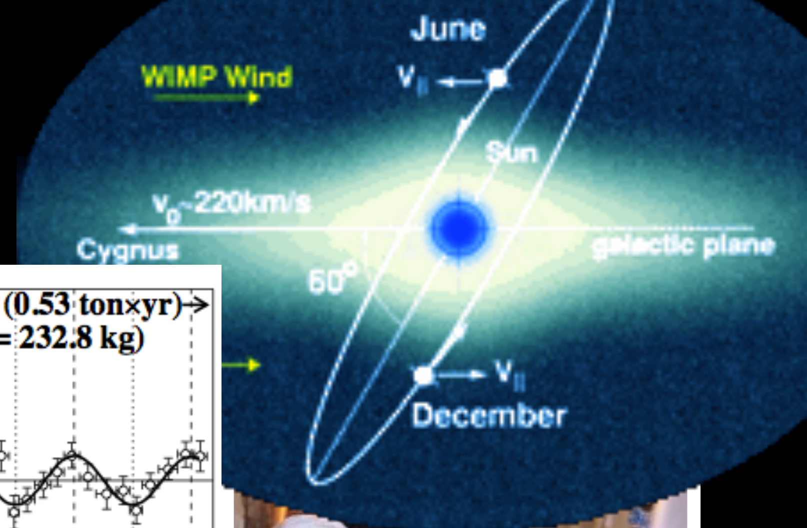

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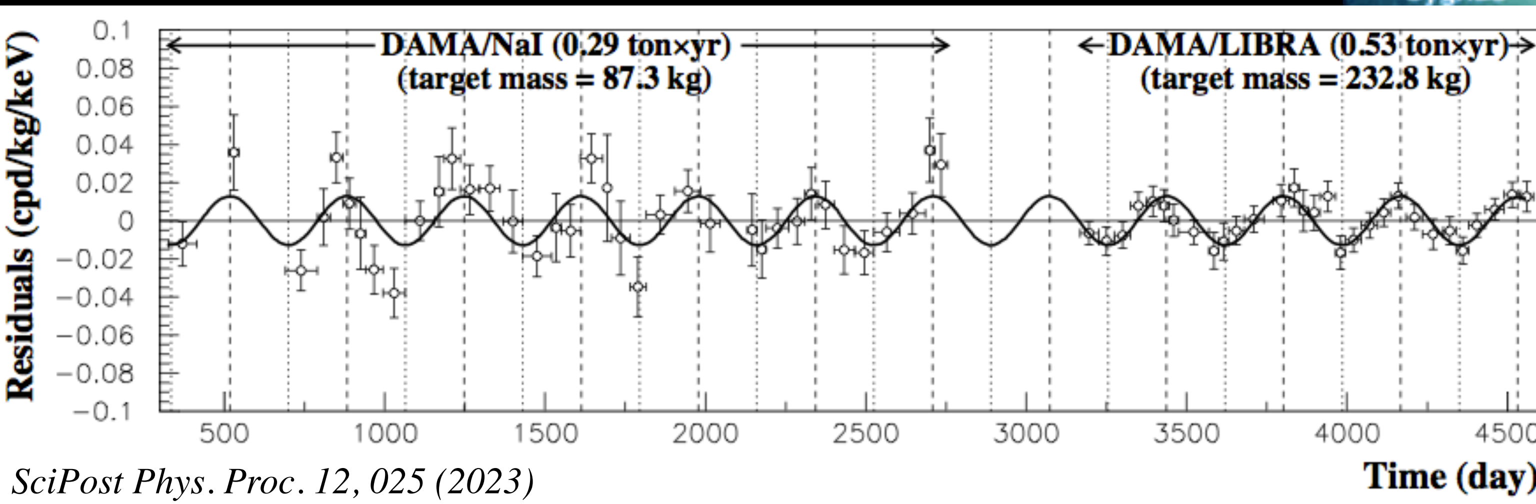

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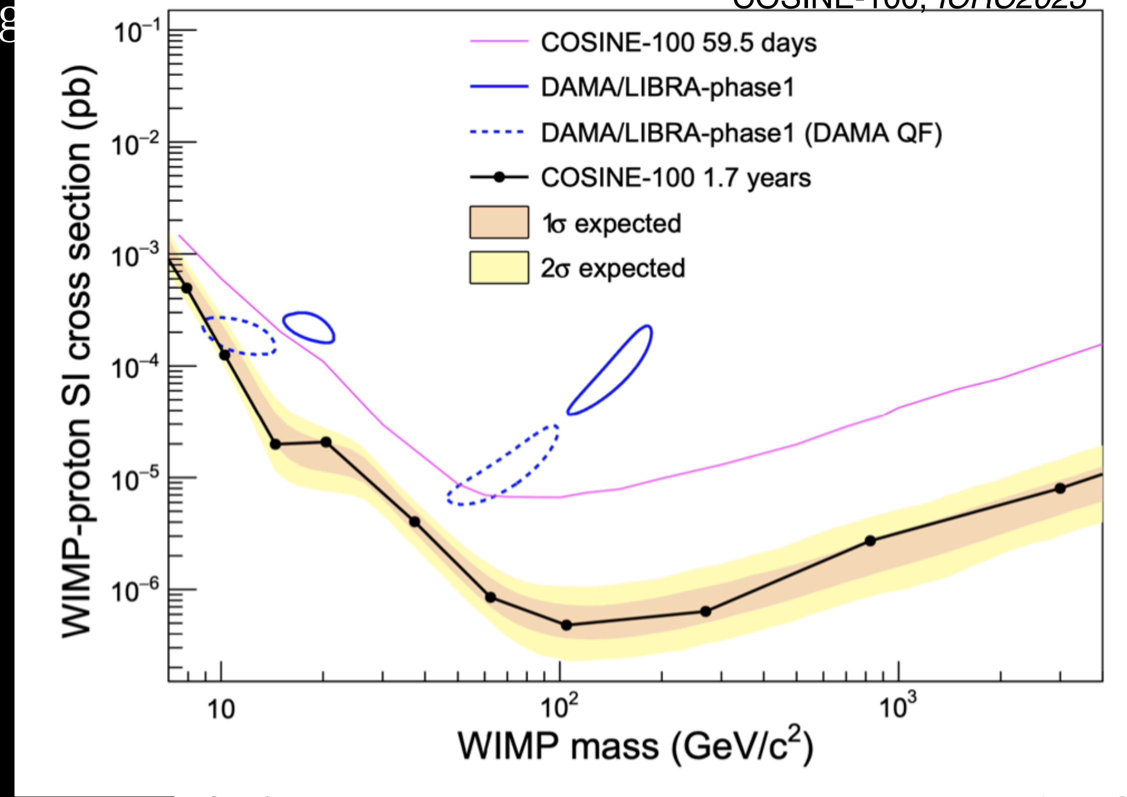
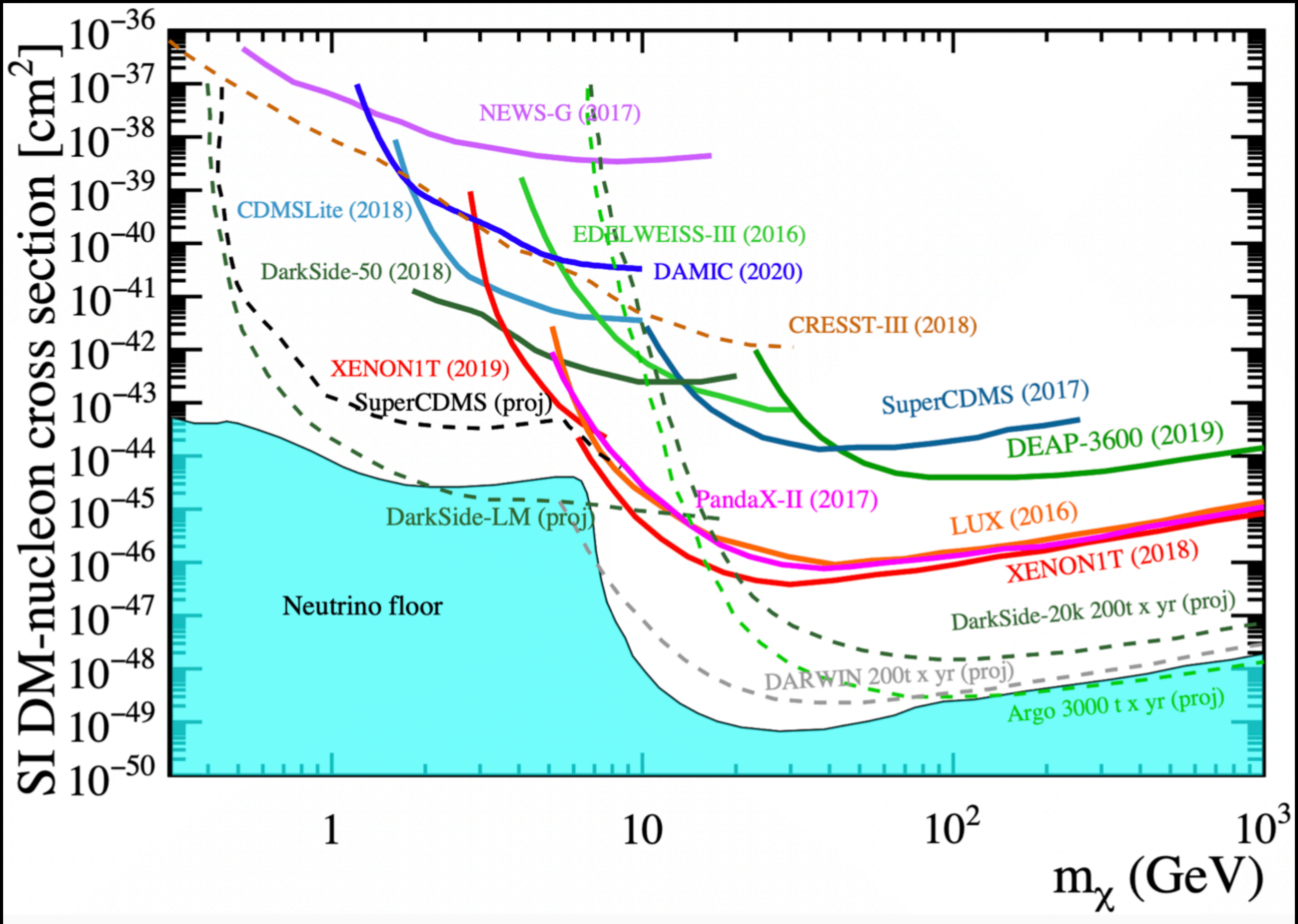
With the same target (different laboratories):
COSINE-100: no evidence of modulation
ANAIS: *PRD 103, 102005 (2021)*

COSINE-100, *ICRC2023*



WIMPs: Status and Prospects

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



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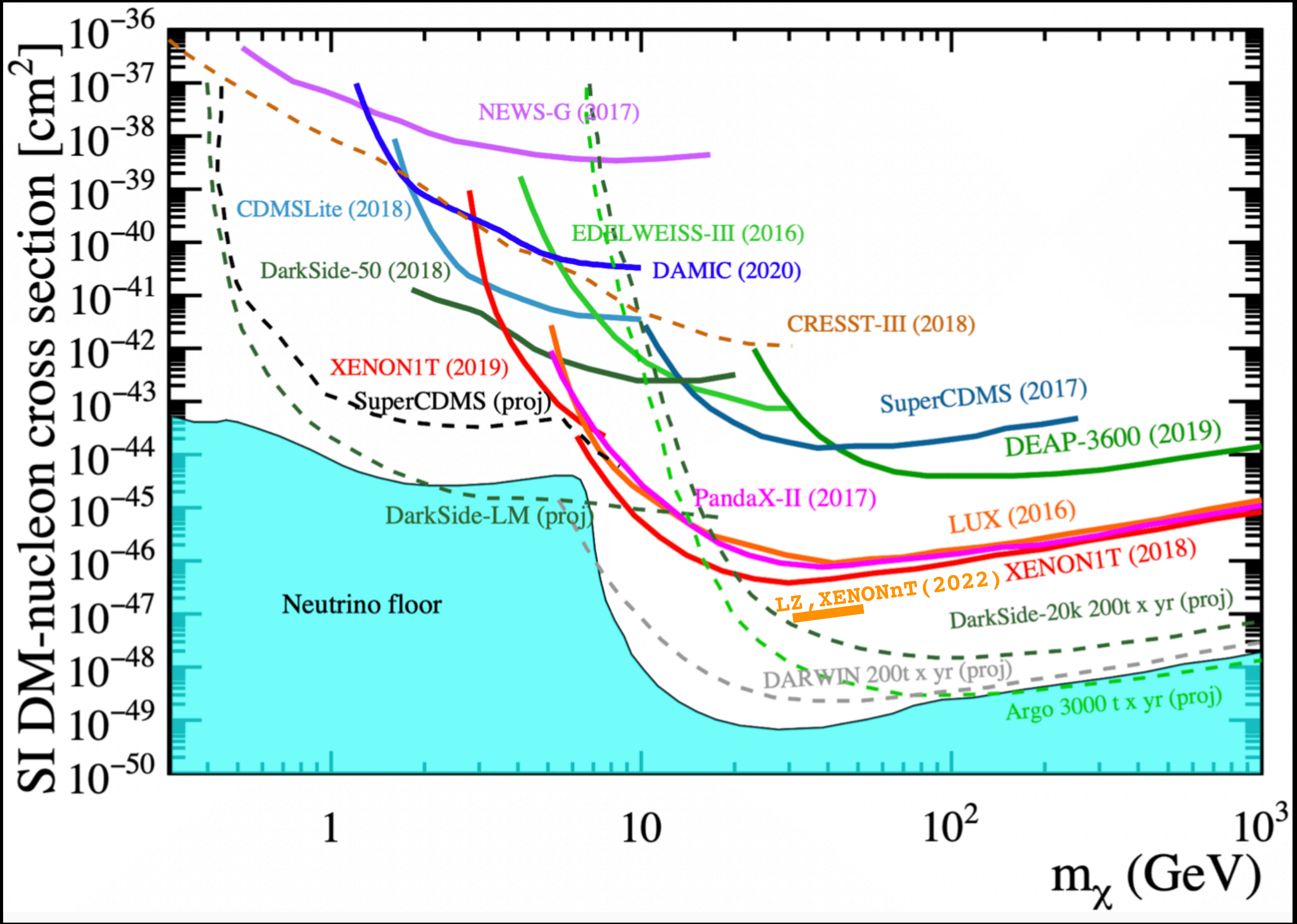
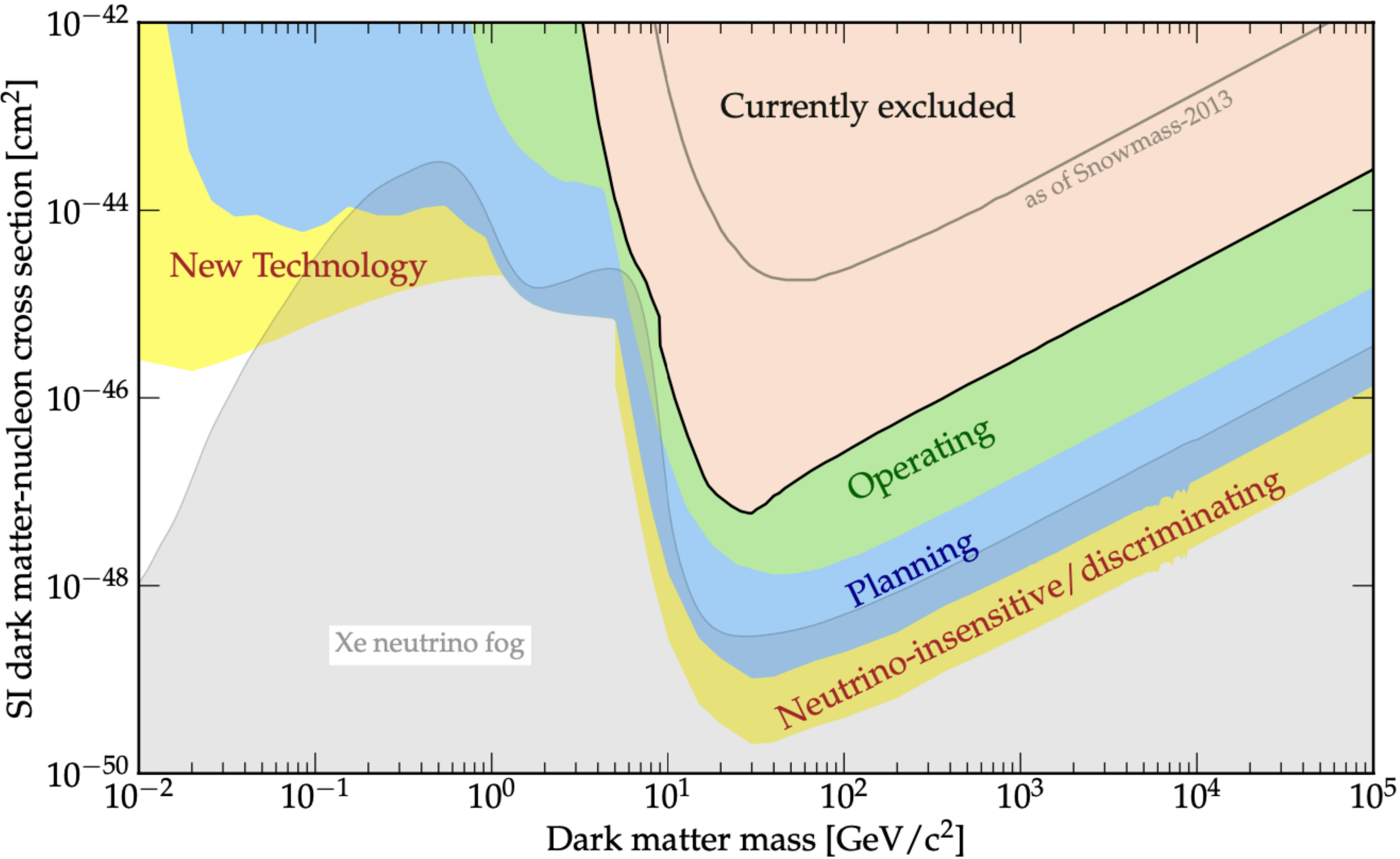
Agrawal et al., Eur. Phys. J. C 81, 11 (2021), 1015



WIMPs: Status and Prospects

Agrawal et al., Eur. Phys. J. C 81, 11 (2021), 1015
Snowmass Cosmic Frontier Report, arXiv:2211.09978



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

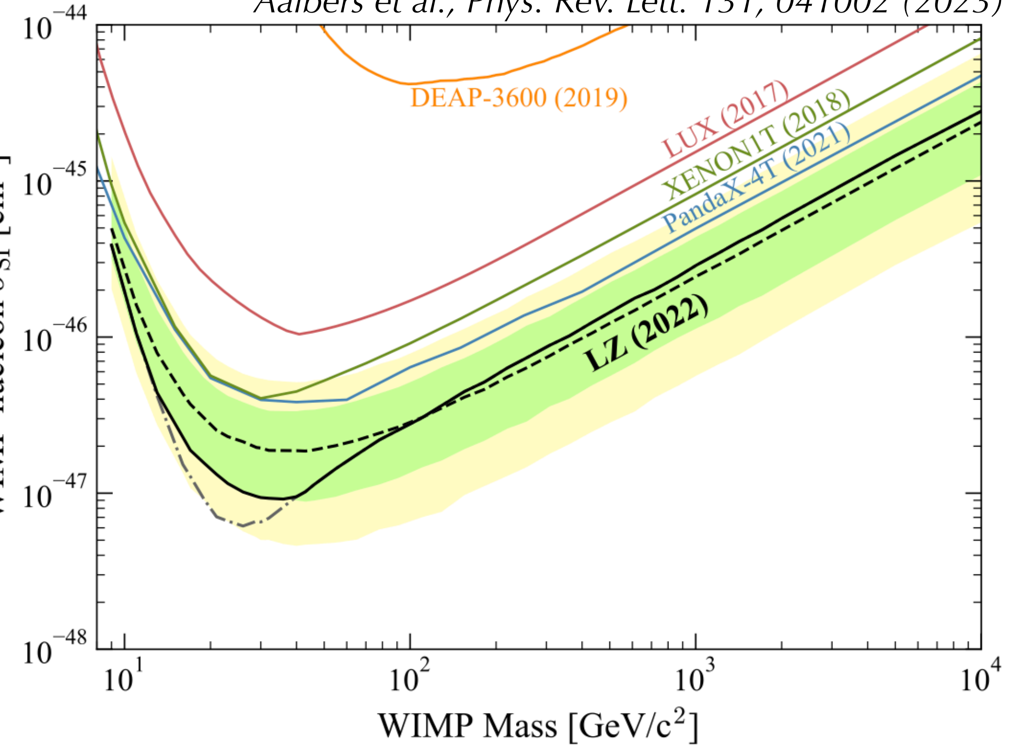
LUX (250 kg, SURF)

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/ XLZD

40/60 t

Xenon Detectors

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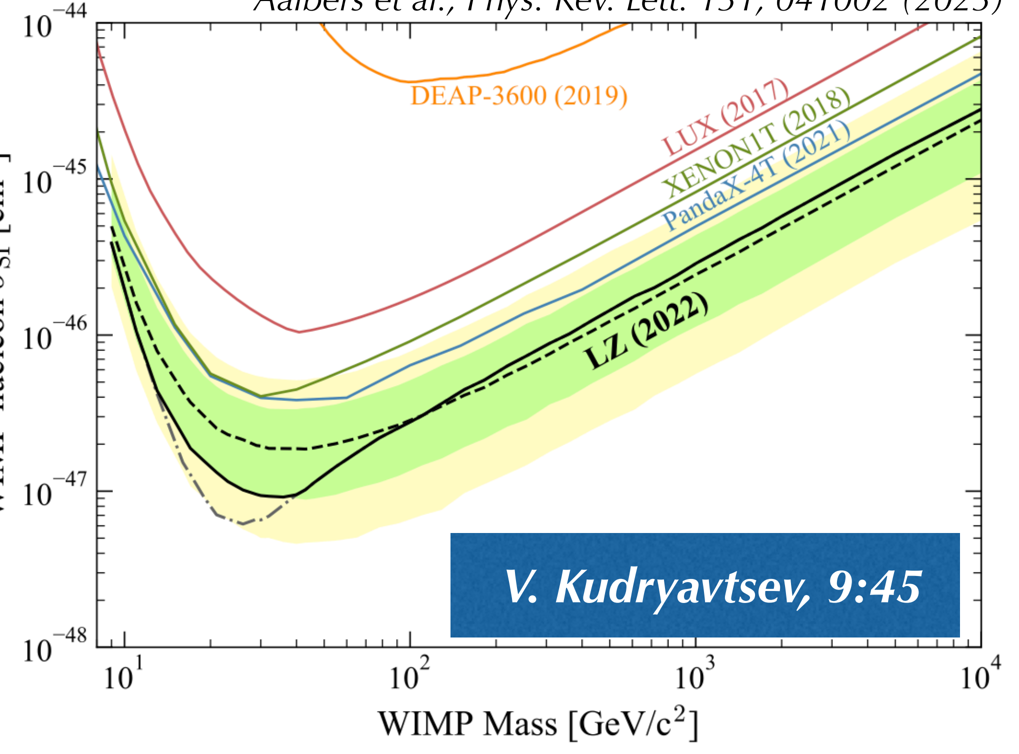

V. Kudryavtsev, 9:45

00 kg

ENON 1T (1t, LNGS)

C. Ferrari, 9:25

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

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10,000 kg

DARWIN/ XLZD

A. Scaffidi, 16:45

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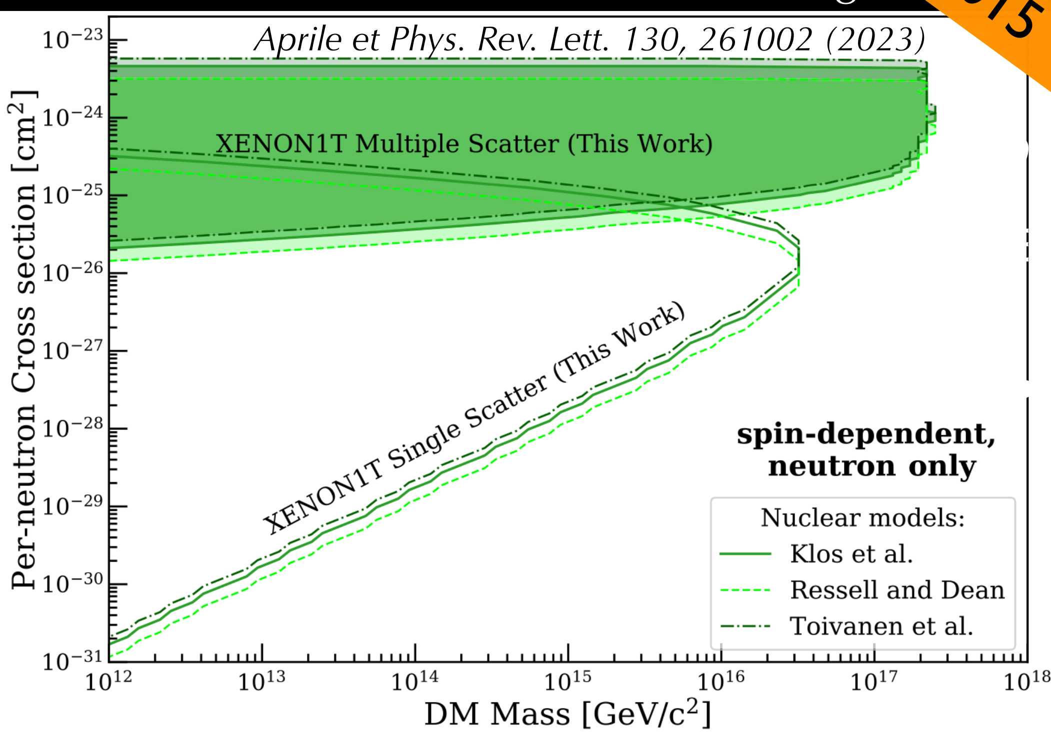


kg

ON 1T (1t, LNGS)

ndaX-4:(4t, CJPL)

2020

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

10,000 kg

DARWIN/ XLZD

40/60 t

LZ MIMPs, R. Smith 9/14, 14:00

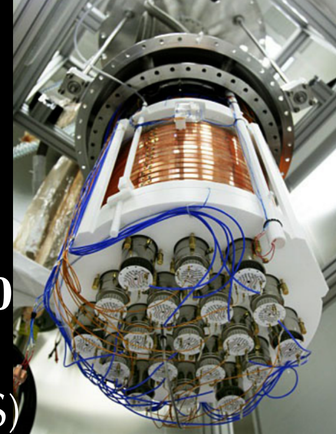
Argon Detectors

Astropart.Phys. 22 (2005) 355-368
New Astron.Rev. 49 (2005) 265-269

2010

10 kg

DarkSide-50 (50 kg, LNGS)



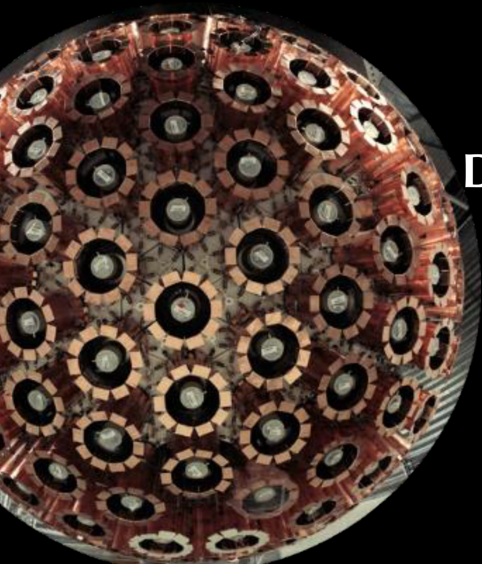
100 kg

ArDM (1t, LSC)

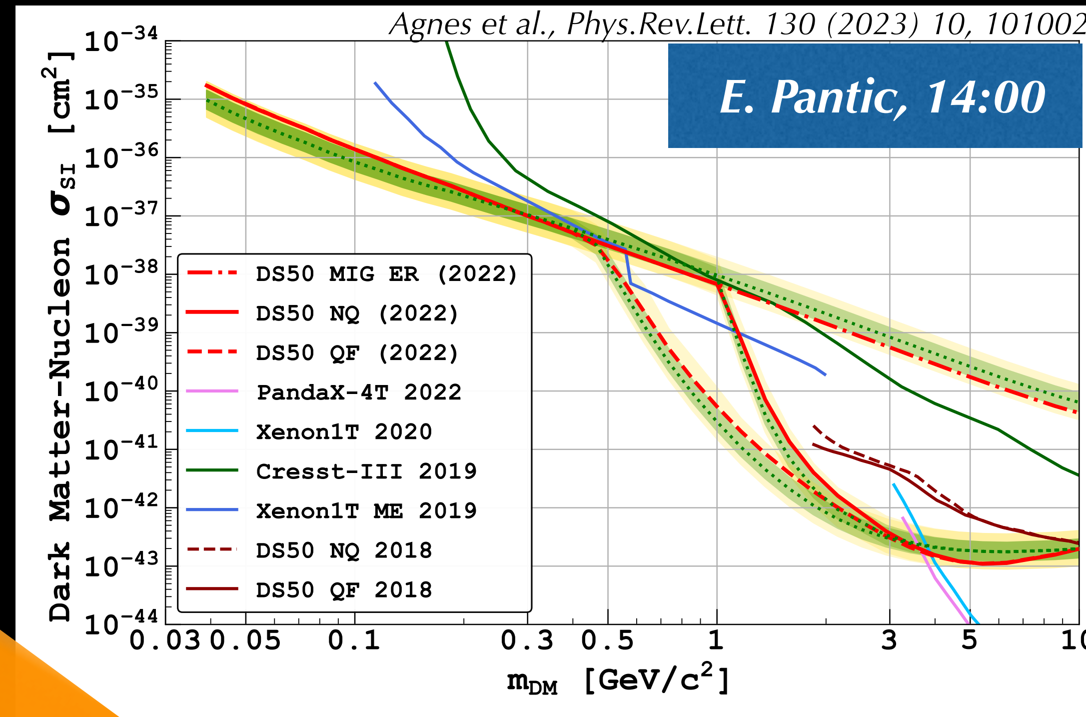
1,000 kg

2015

DEAP-3600 (3.6t, SNOLAB)



DS-50: leading SI limit for MeV -eV/c² DM, WIMP-nucleus and WIMP-e scattering



Global Argon Dark Matter Collaboration formed

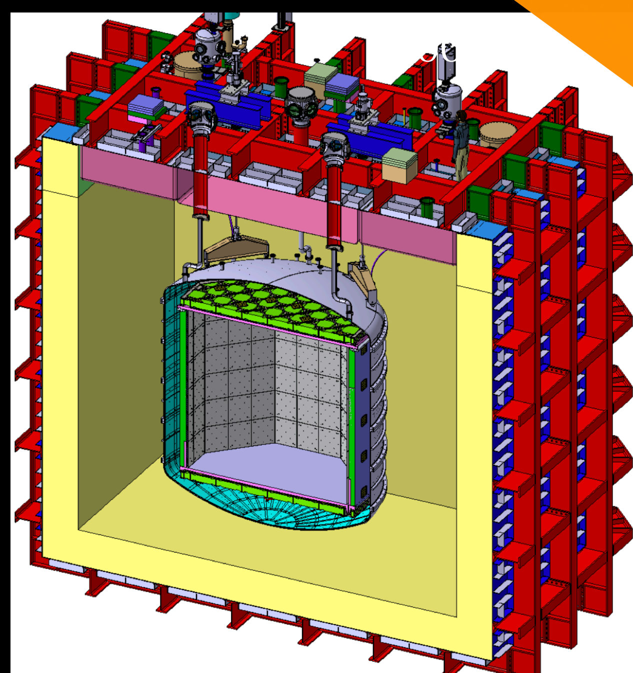
APPEC

10,000 kg

2020

100,000 kg

DarkSide-20k (50t, LNGS)



DEAP-3600: demonstrated PSD rejection of more MIPs than DarkSide-20k and even Argo will encounter from Ar-39

Future: ARGO kt-scale

Argon Detectors

Astropart.Phys. 22 (2005) 355-368
New Astron.Rev. 49 (2005) 265-269

2010

10 kg

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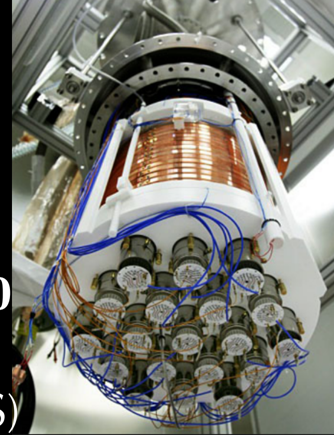


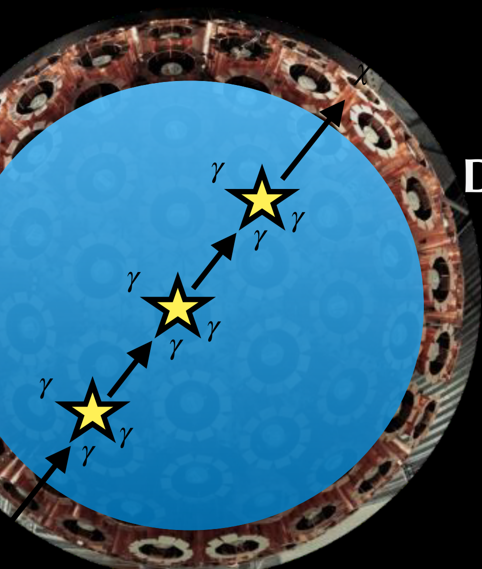
100 kg

ArDM (1t, LSC)

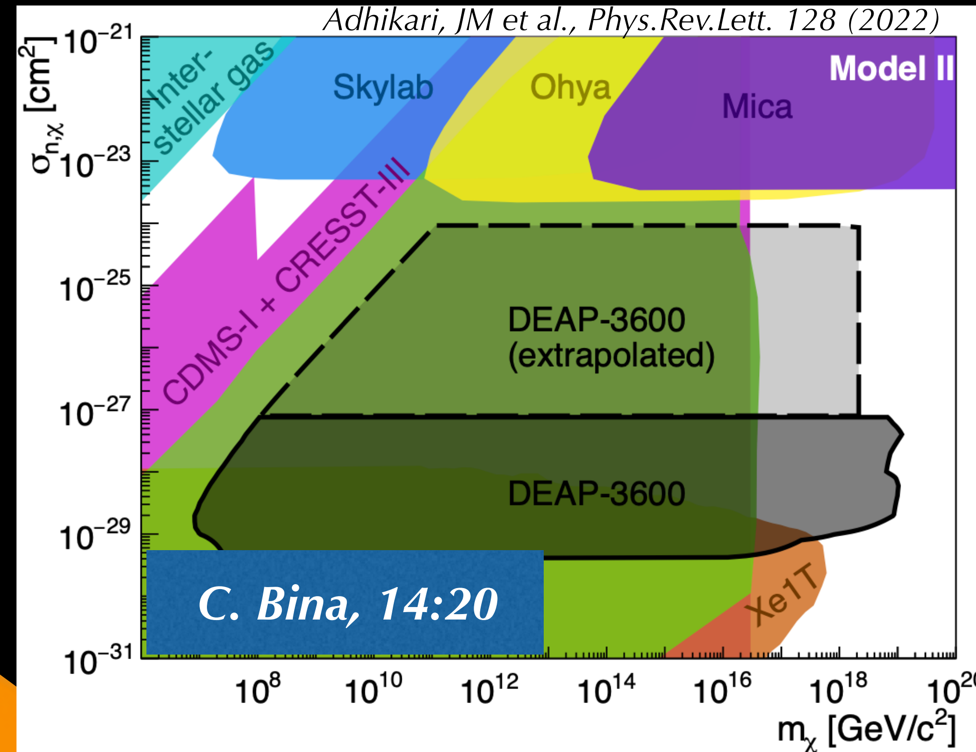
1,000 kg

2015

DEAP-3600 (3.6t, SNOLAB)



DEAP-3600: leading Planck-scale dark matter search result (can be produced in GUTs, PBHs …)



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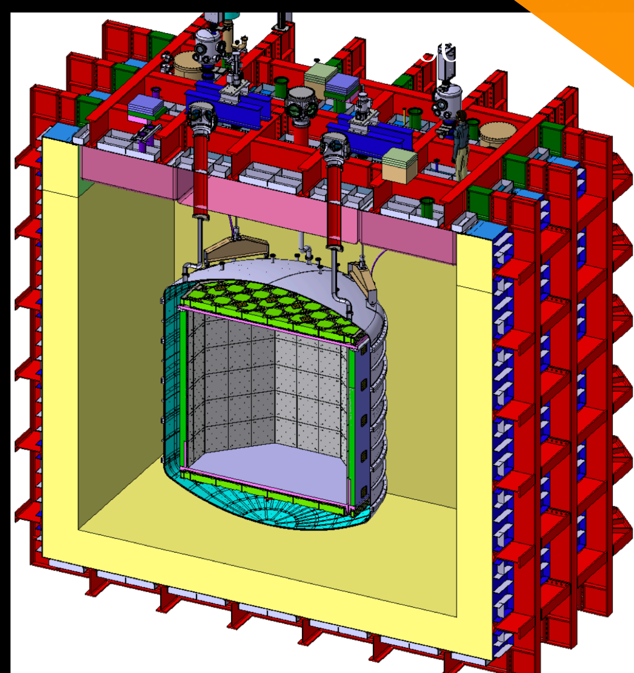
10,000 kg

APPEC

2020

100,000 kg

DarkSide-20k (50t, LNGS)



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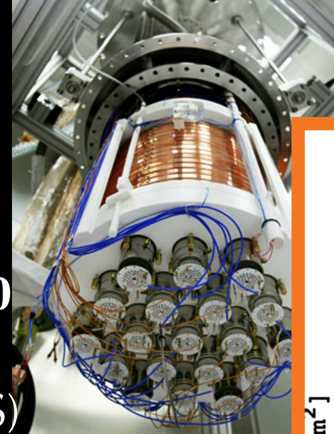
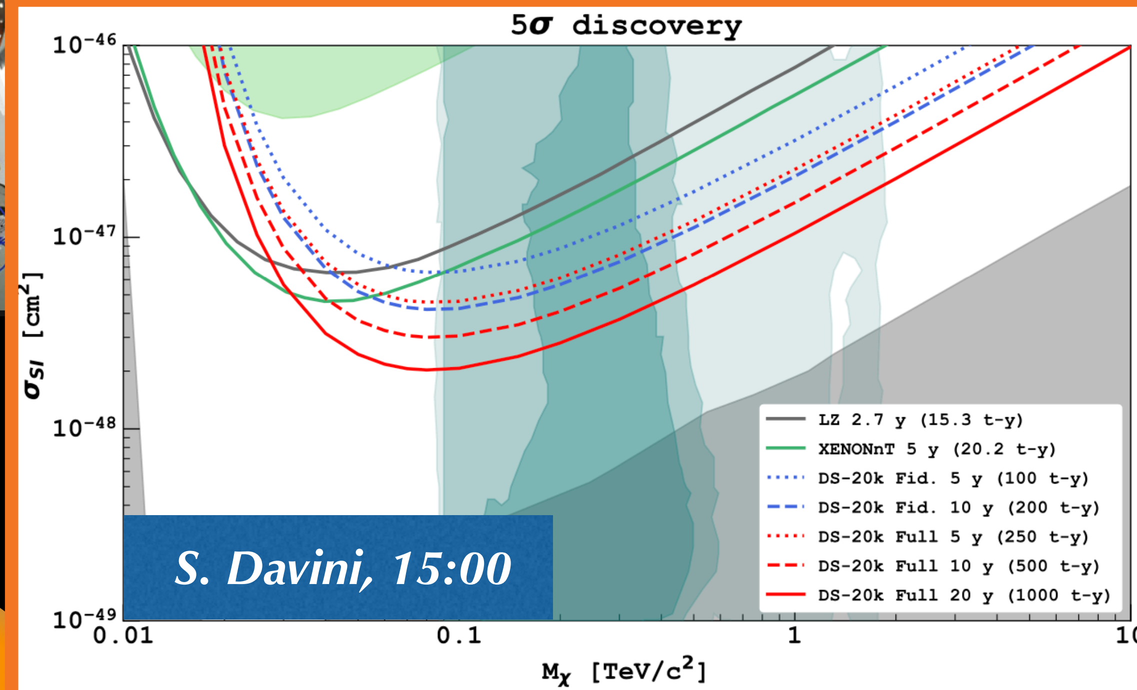
DarkSide-20k: observatory for dark matter and **ν**

2010

10 kg

DarkSide-50 (50 kg, LNGS)





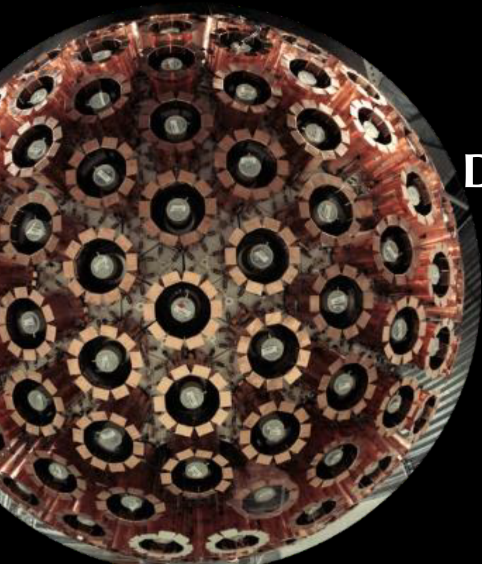
100 kg

ArDM (1t, LSC)

1,000 kg

2015

DEAP-3600 (3.6t, SNOLAB)



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APPEC

2020

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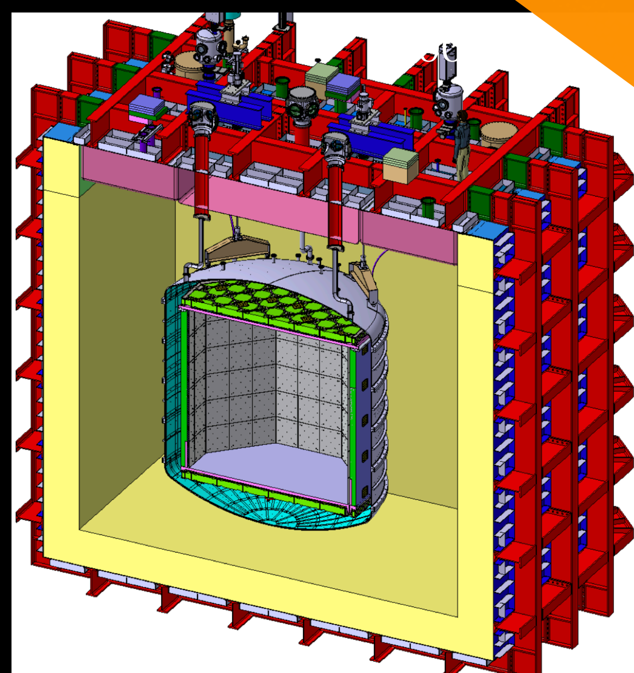

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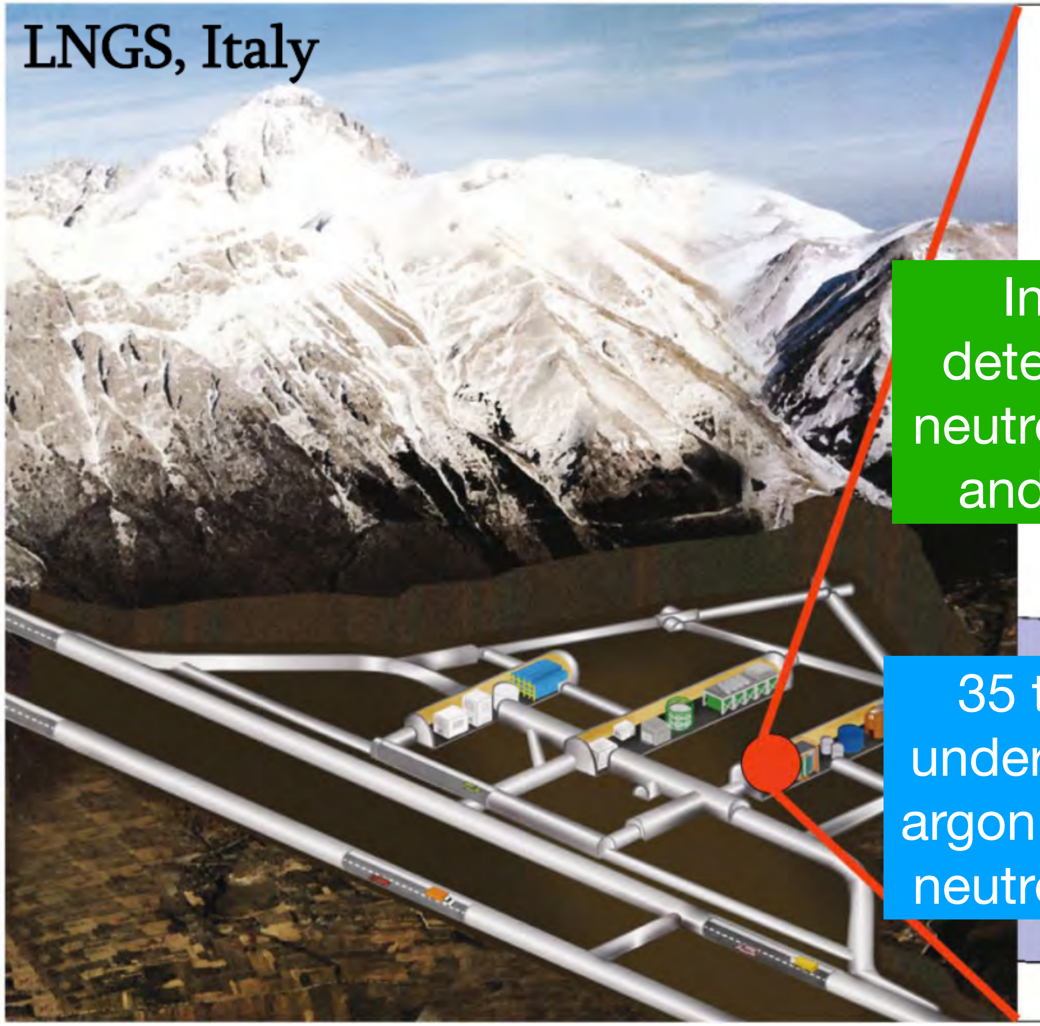
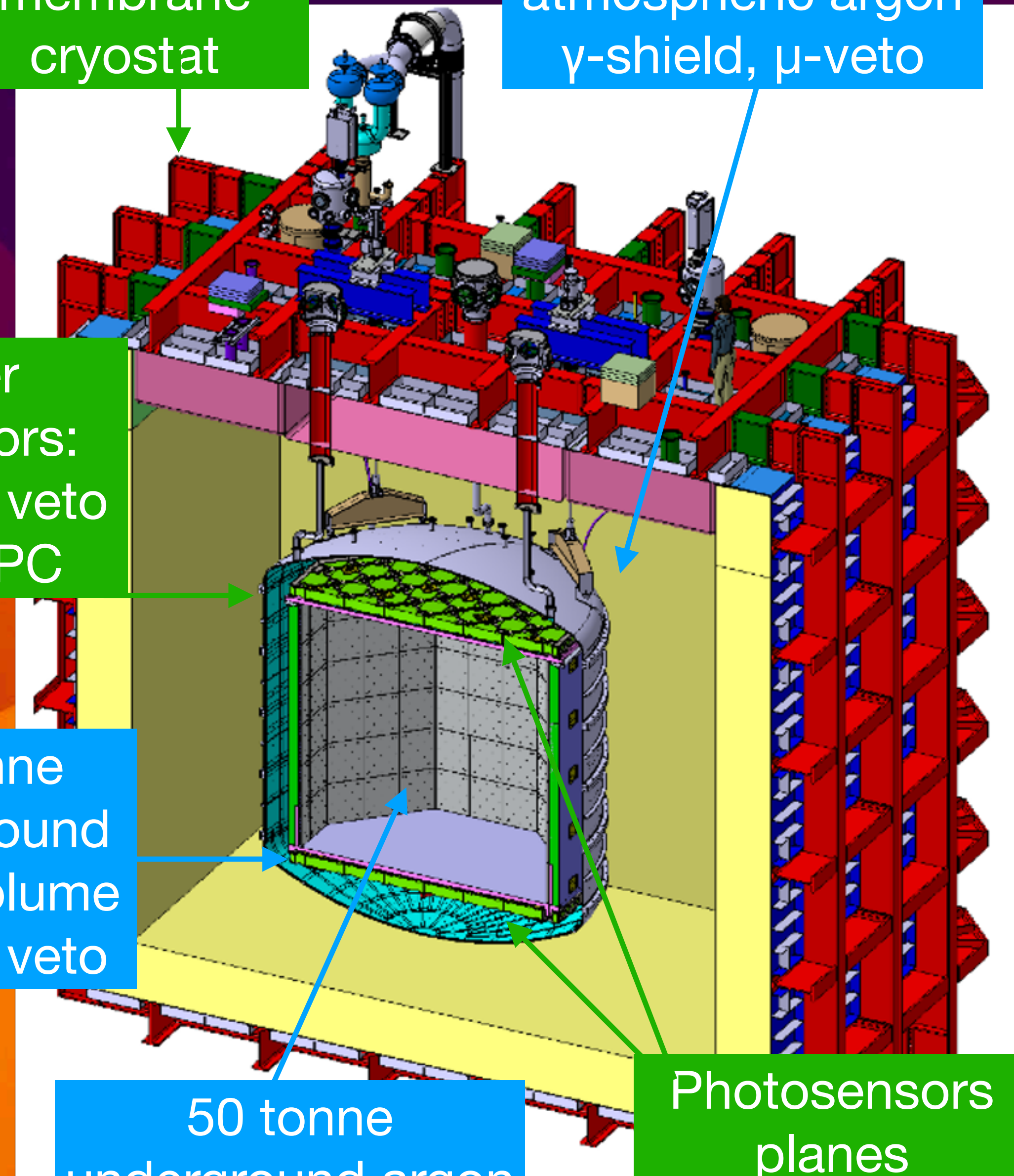
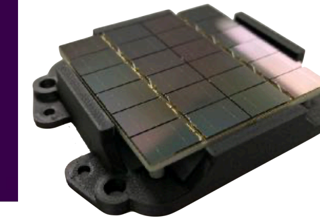
DarkSide-20k

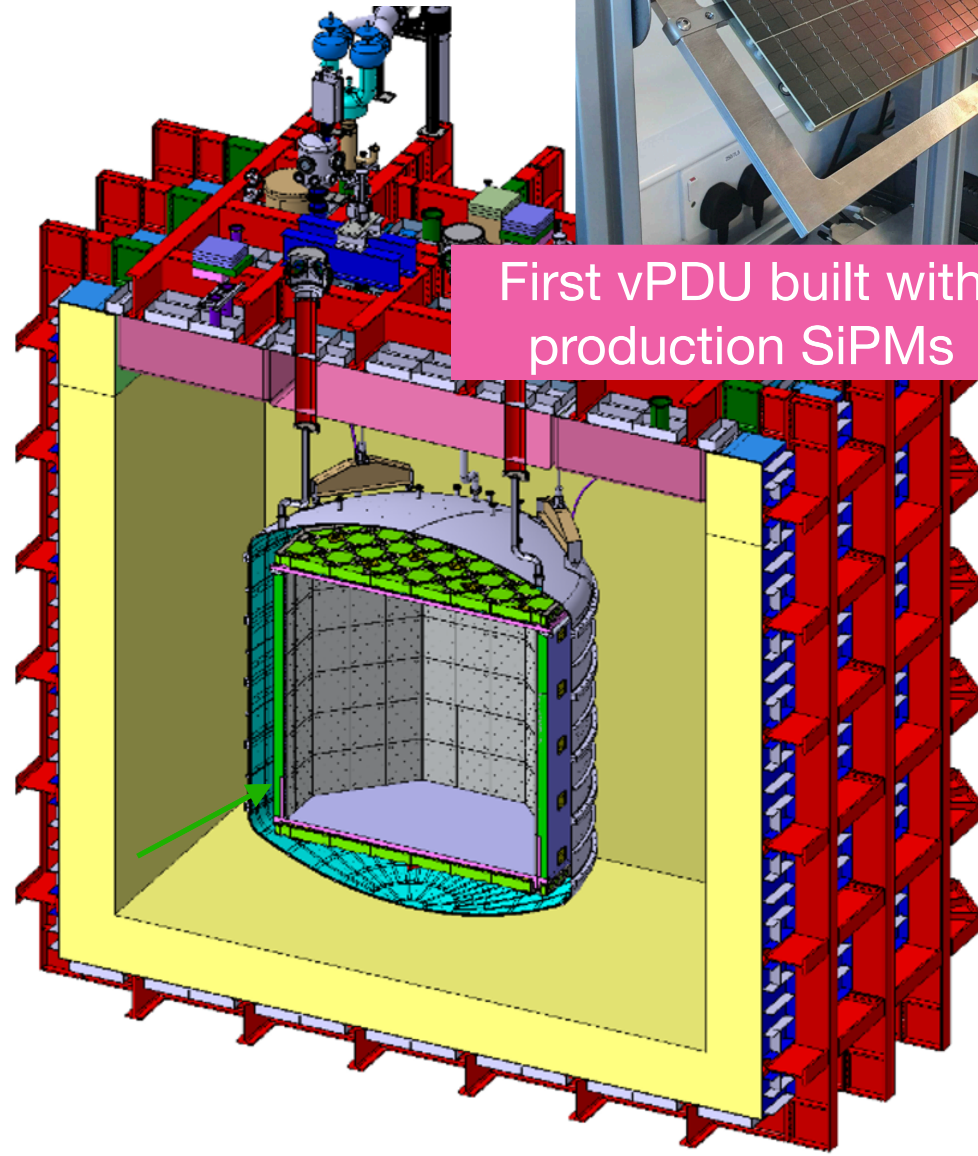




DarkSide-20k



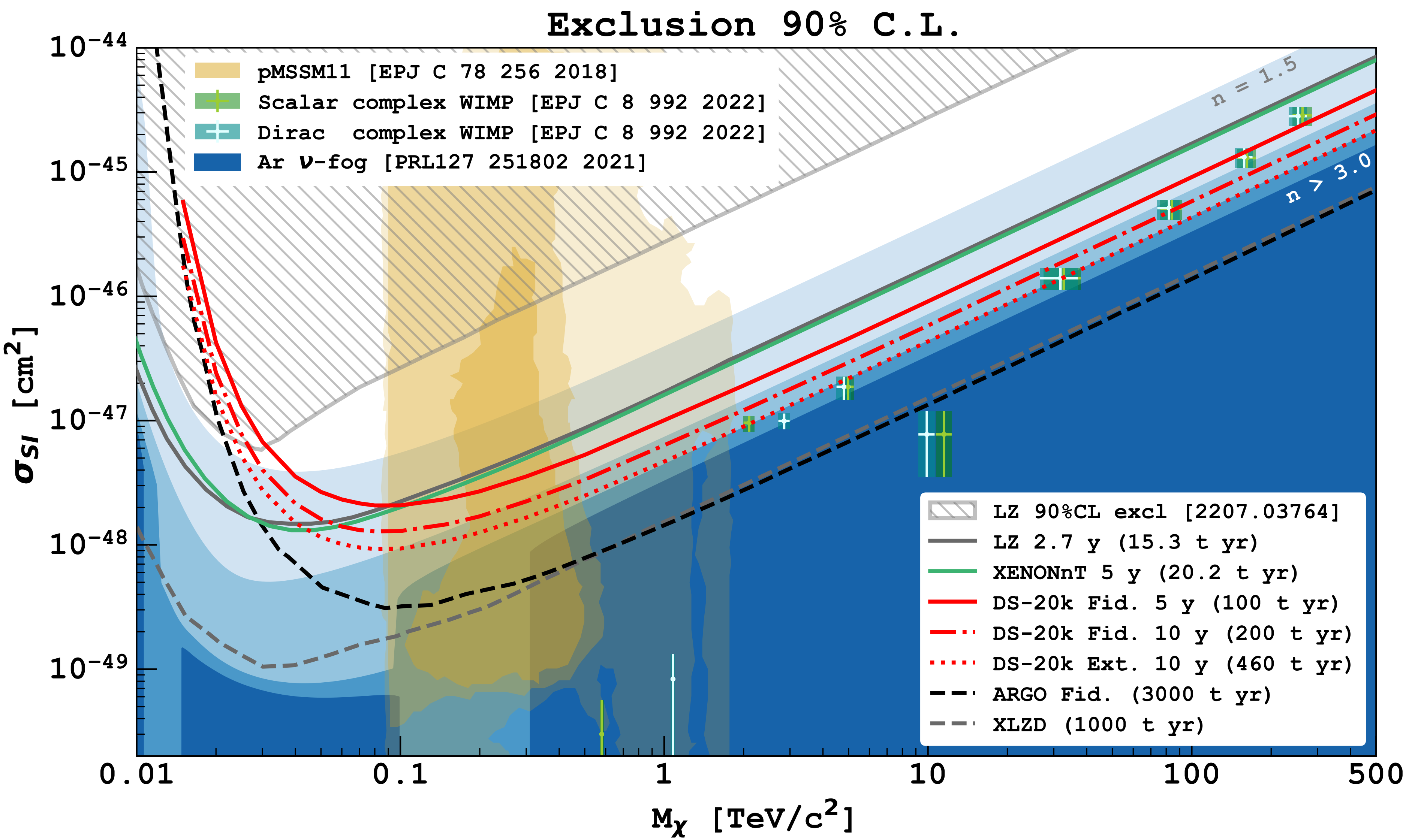
First vPDU built with production SiPMs



LNGS underground Hall C in August 2023

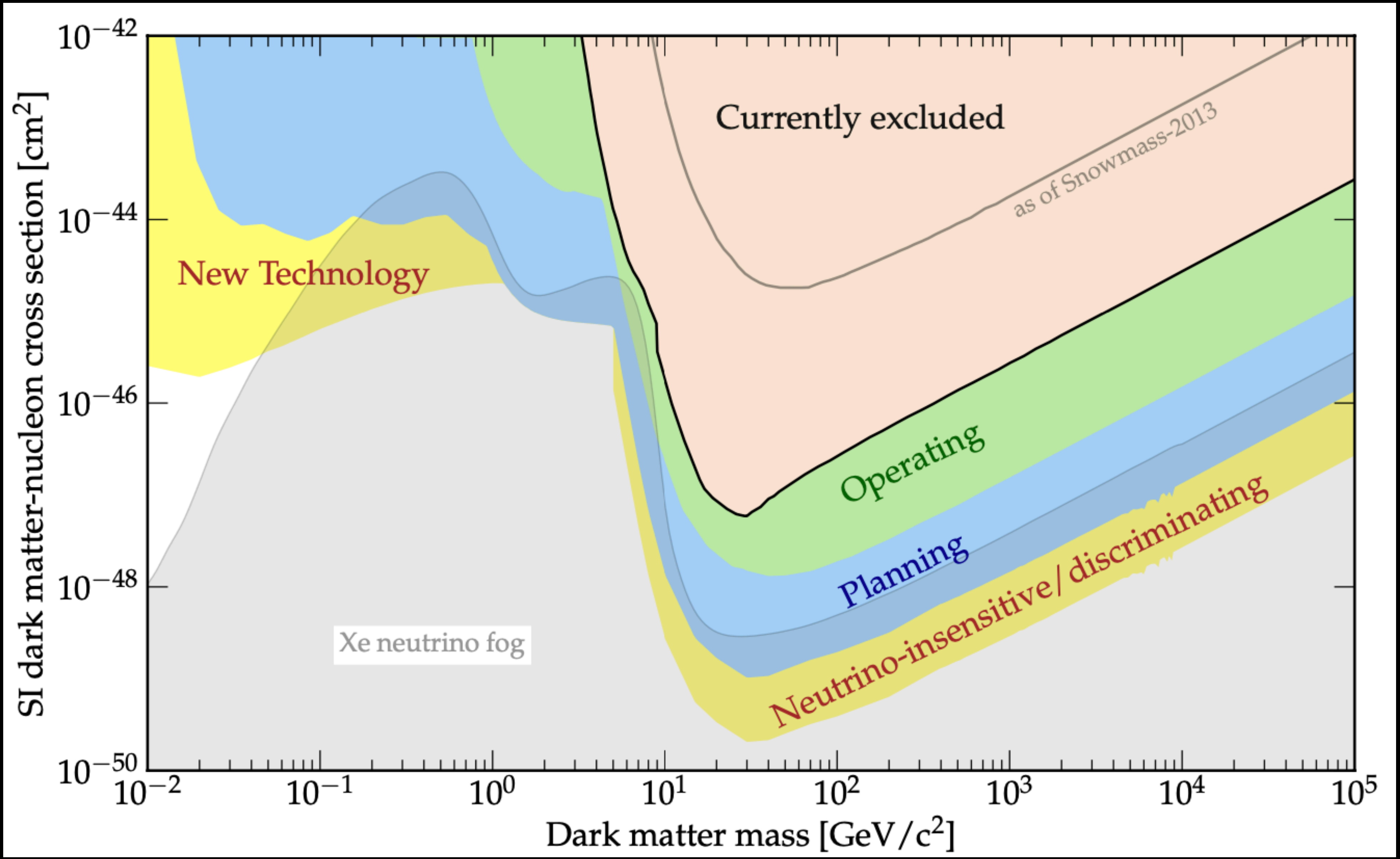
Collaborators to scale!

Heavy WIMP Prospects



Quo Vadis?

Snowmass Cosmic Frontier Report, arXiv:2211.09978



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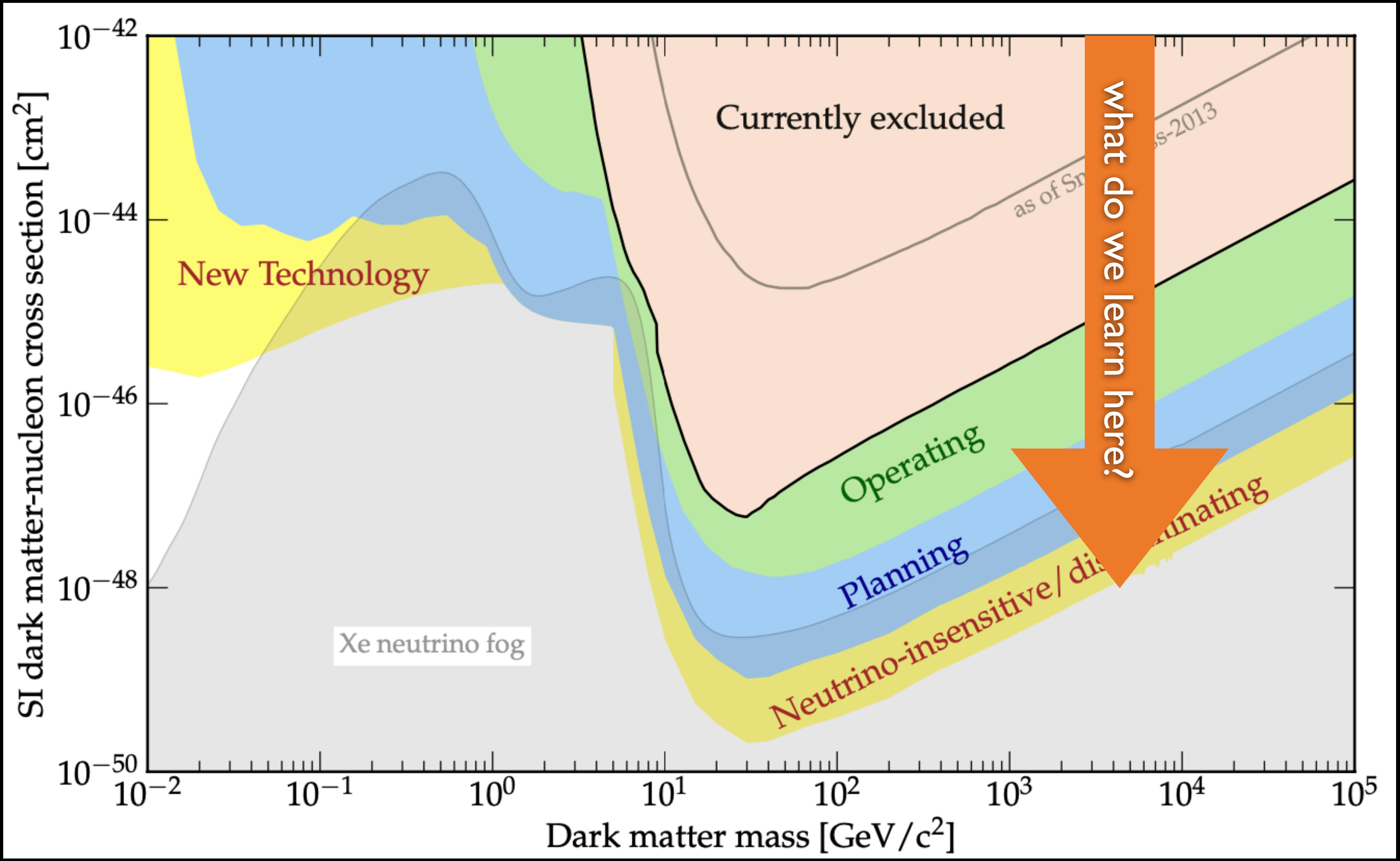
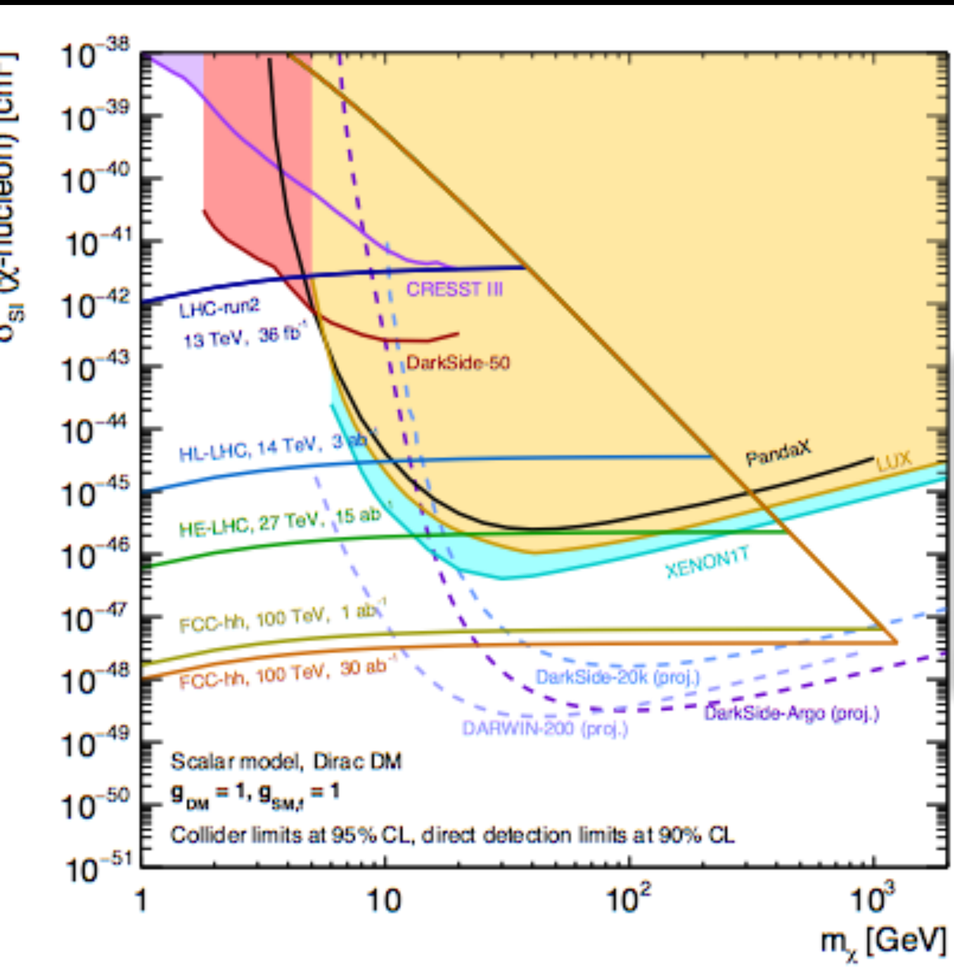
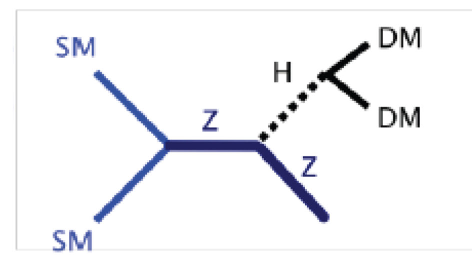


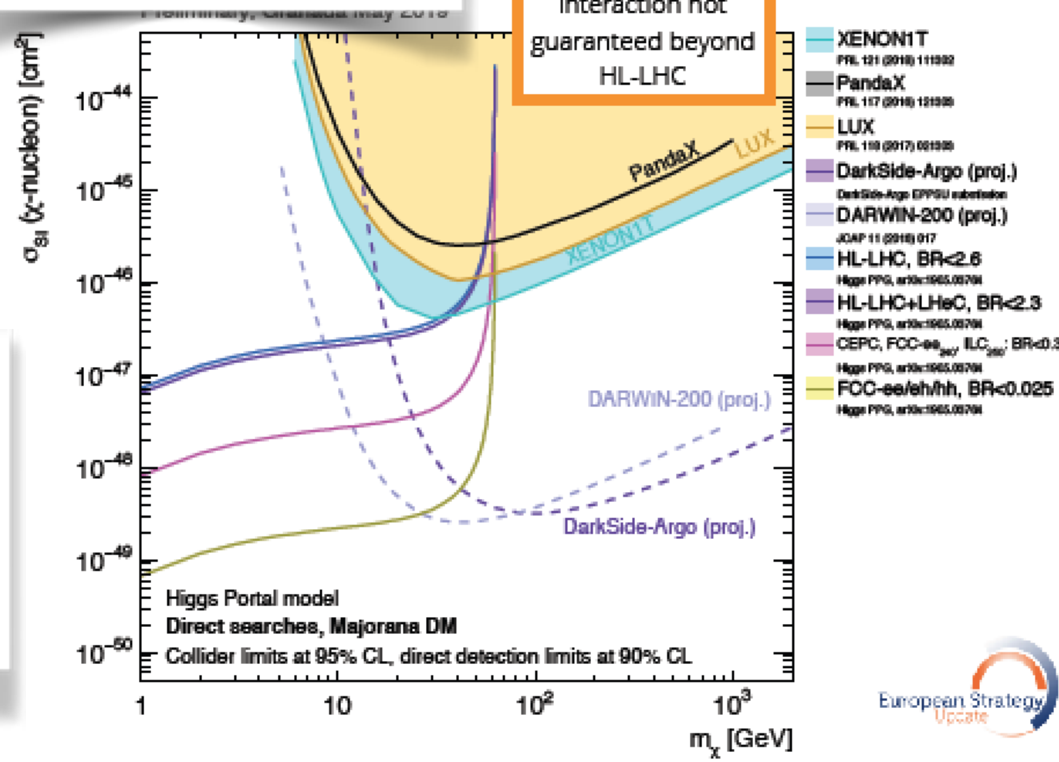
What do we learn here? (1)

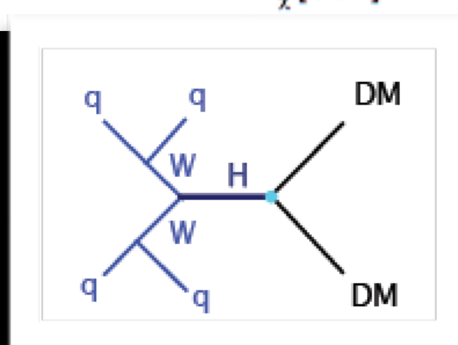
Ellis, JM et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)





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





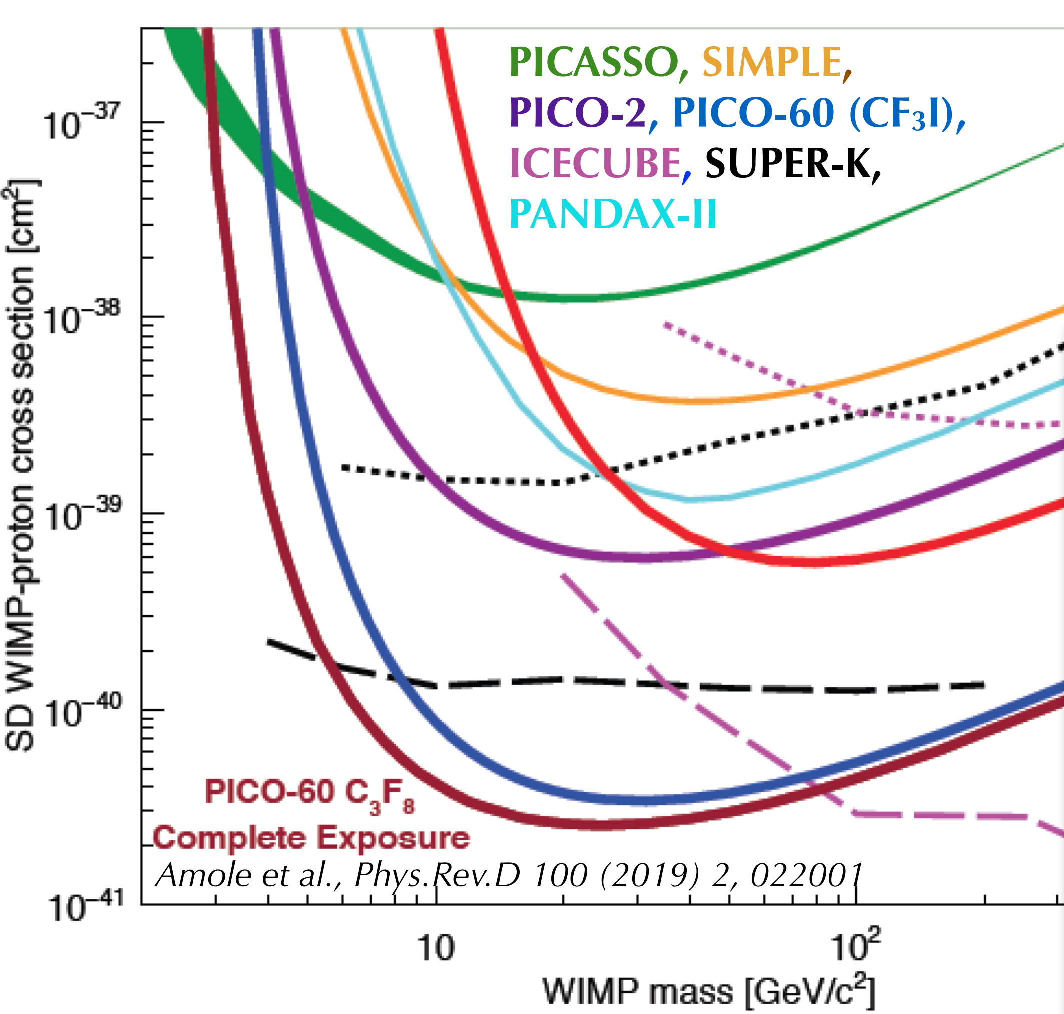
European Strategy Update

What do we learn here? (2)

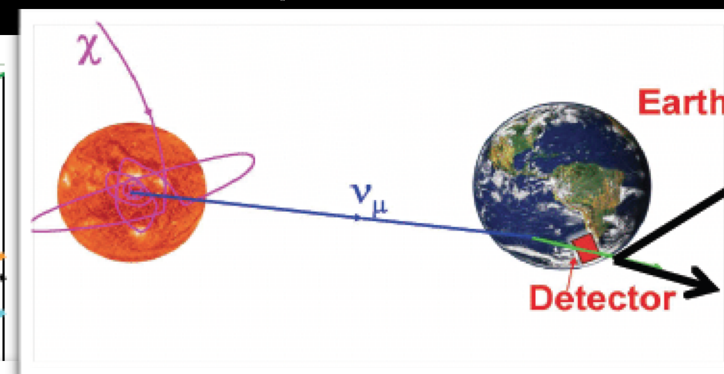
Spin-dependent interaction cross section constraints are 5 orders of magnitude weaker!

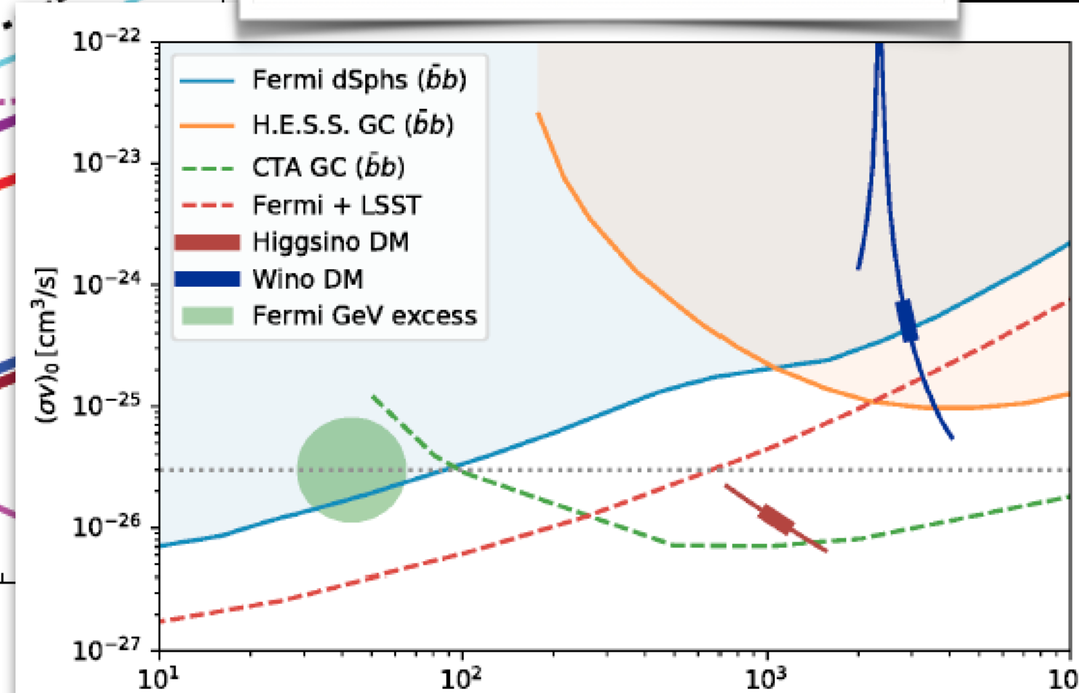
Leading WIMP-n constraints from LXe *PRL 131, 041002 (2023)*, WIMP-p constraints from PICO-60 bubble chamber. Next: PICO-500

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., Phys.Rev.D 100 (2019) 2, 022001

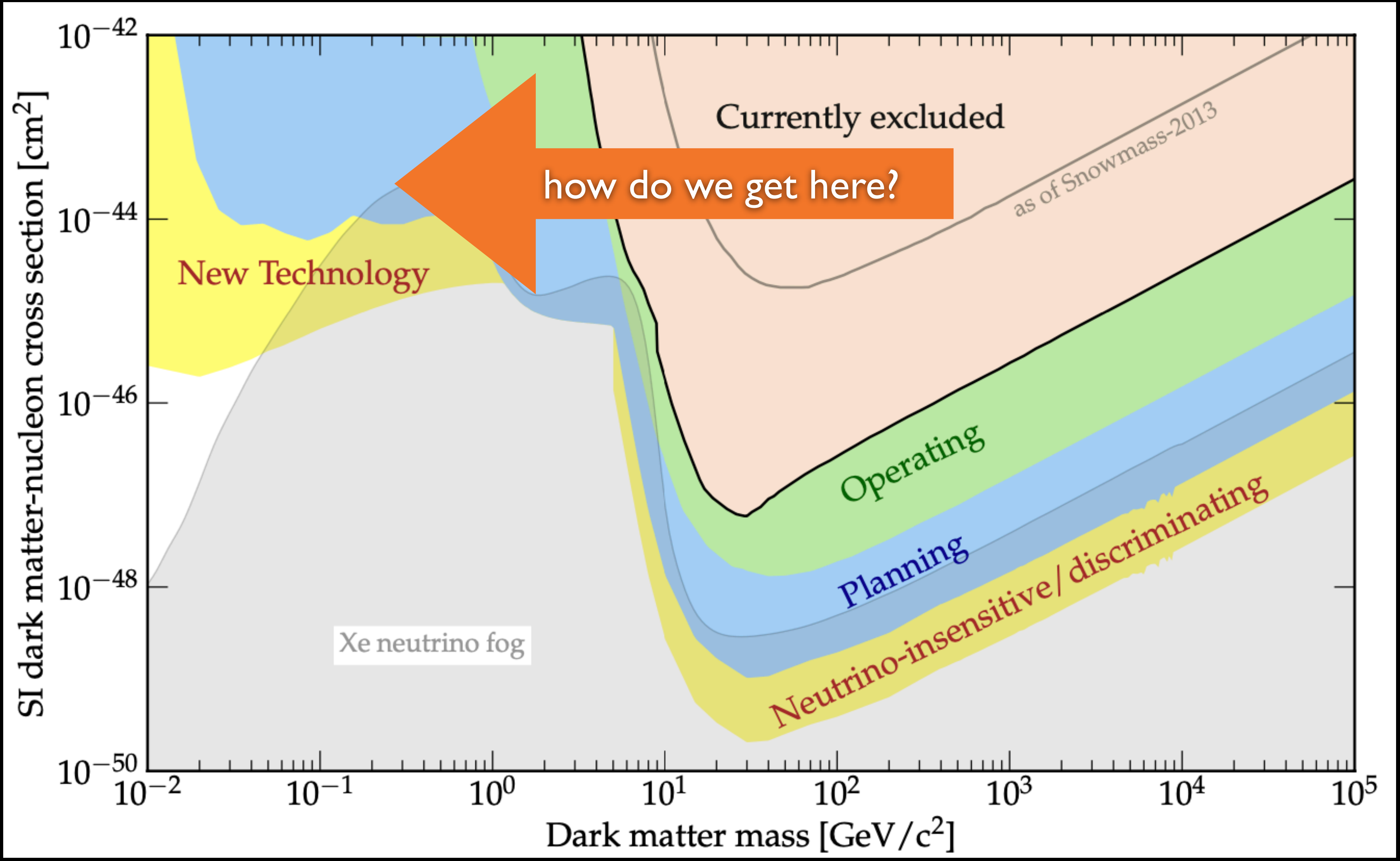




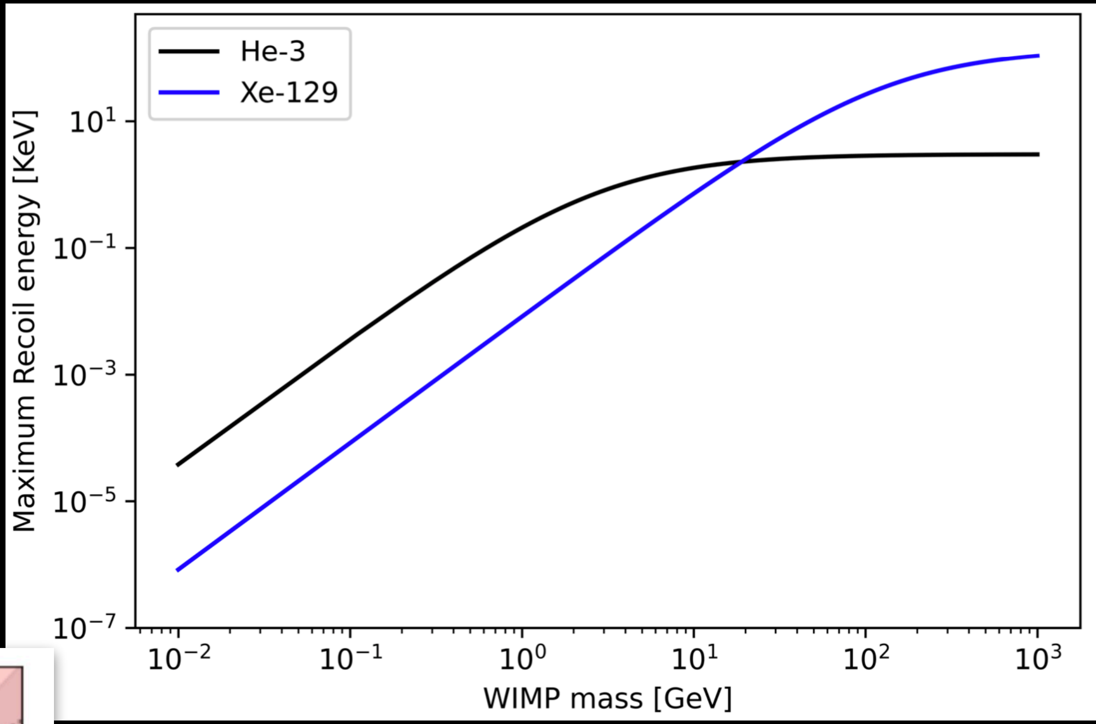
Ellis et al., CERN-ESU-004

Light Dark Matter Prospects

Snowmass Cosmic Frontier Report, arXiv:2211.09978

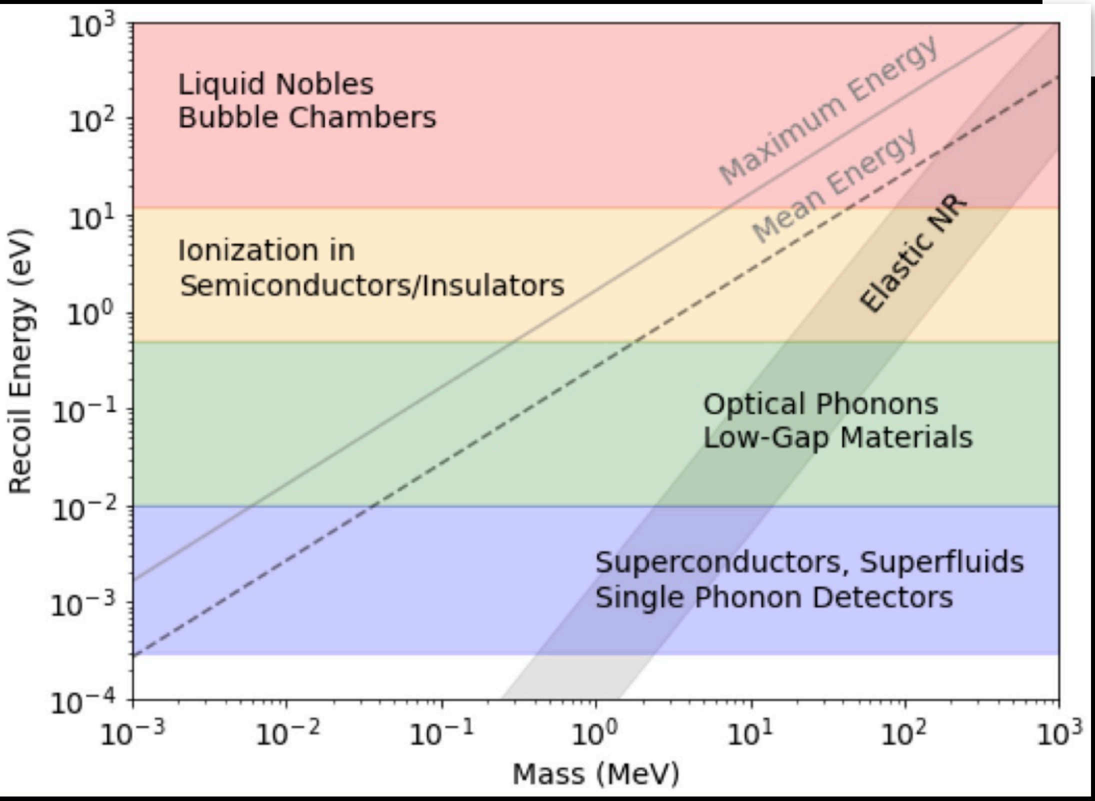


Light Dark Matter (1)



Detector Strategy:

- Light targets for kinematic match to light DM
- New detector materials, with low energy barrier (Si, He-4, He-3)
- Smaller detectors, optimised for lowest possible energy thresholds, *and* best possible energy resolution



Analysis Strategy:

- Liquid nobles: S2-only searches, w/o PID
- Include nuclear effects ("Migdal" in interpretation: adds electromagnetic energy due to nucleus' electron cloud acceleration
- Electron scattering as signal: recoil kinetic energy ~as large as DM mass

thanks to E. Leason

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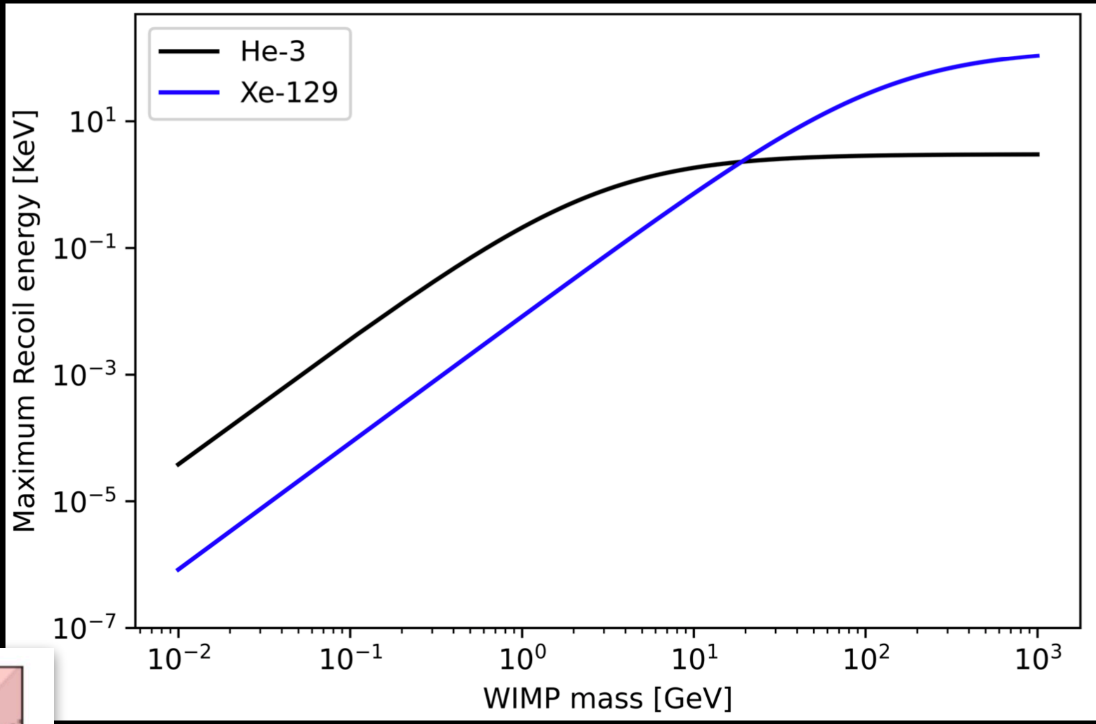

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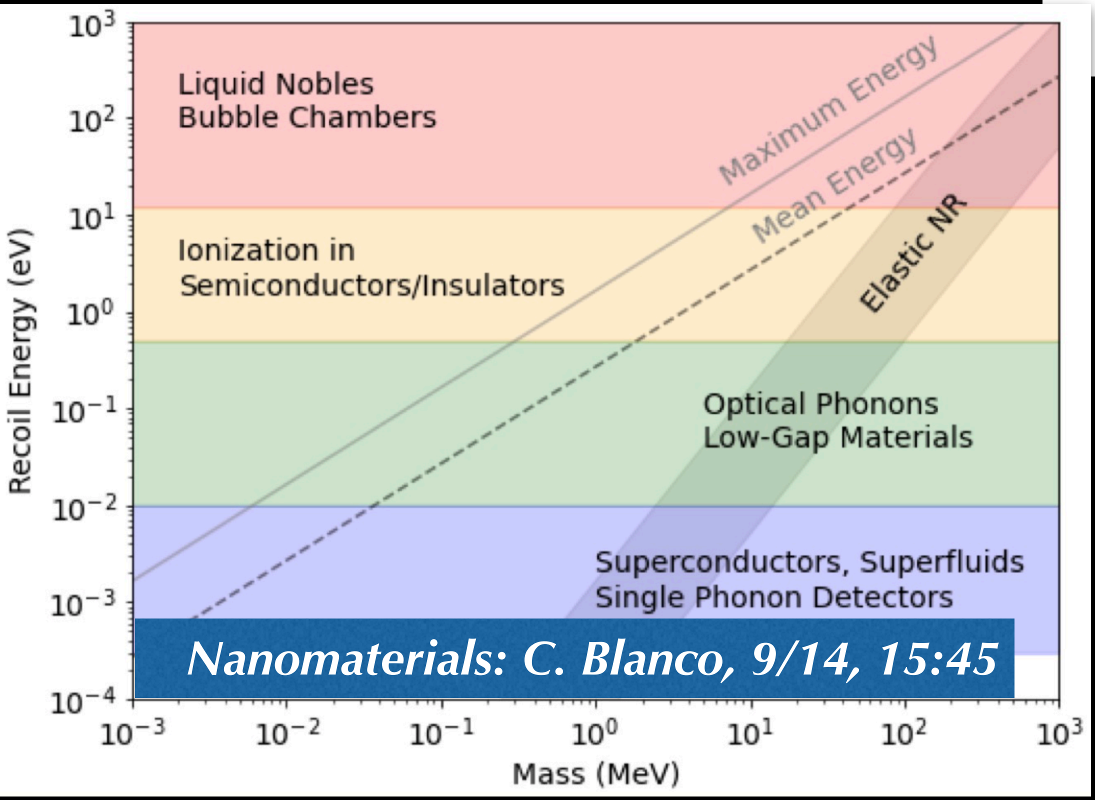

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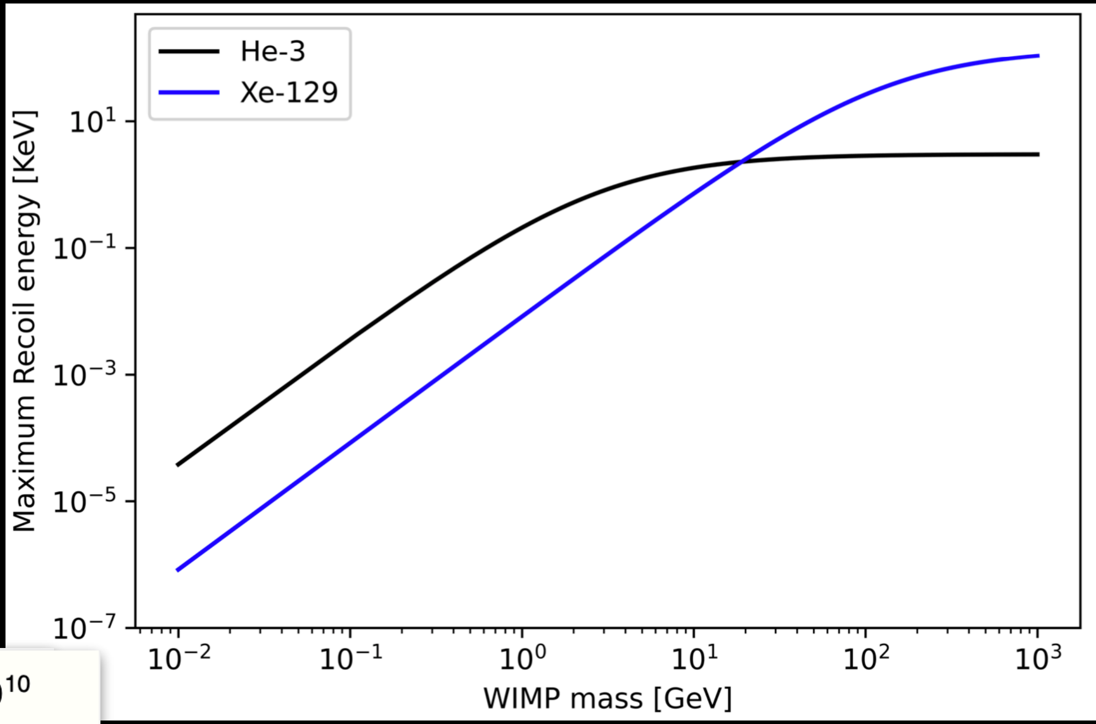

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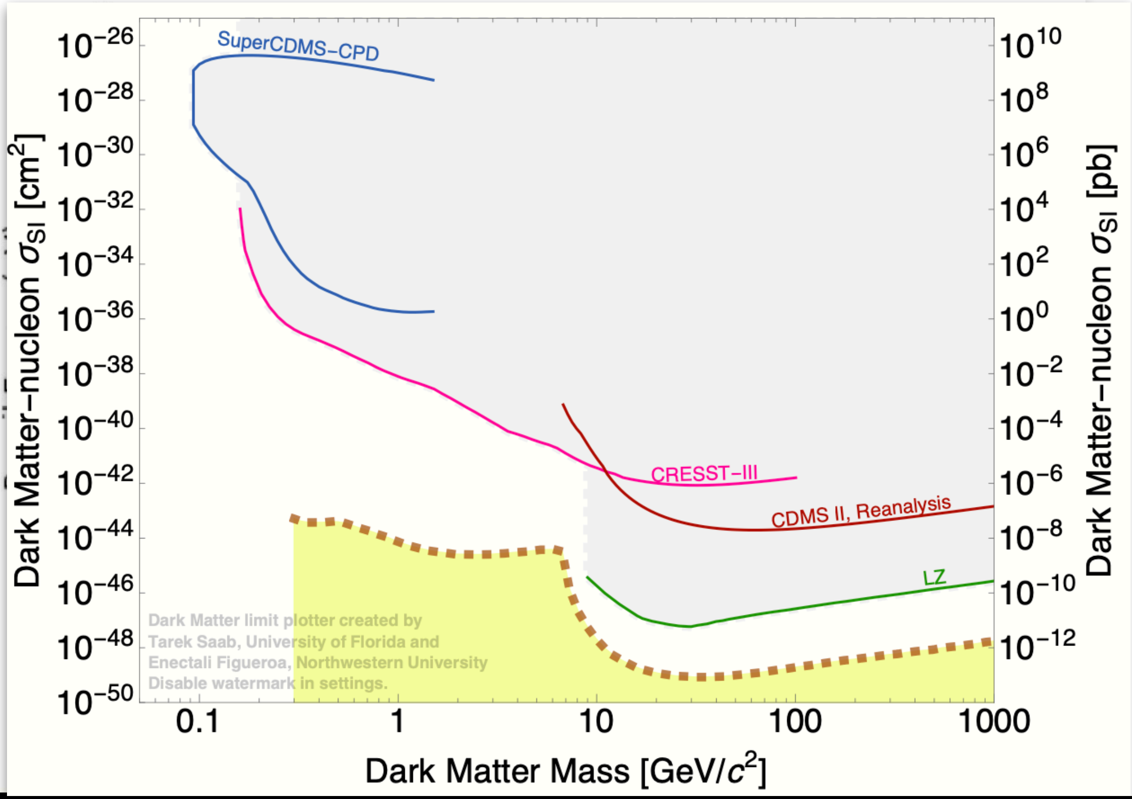

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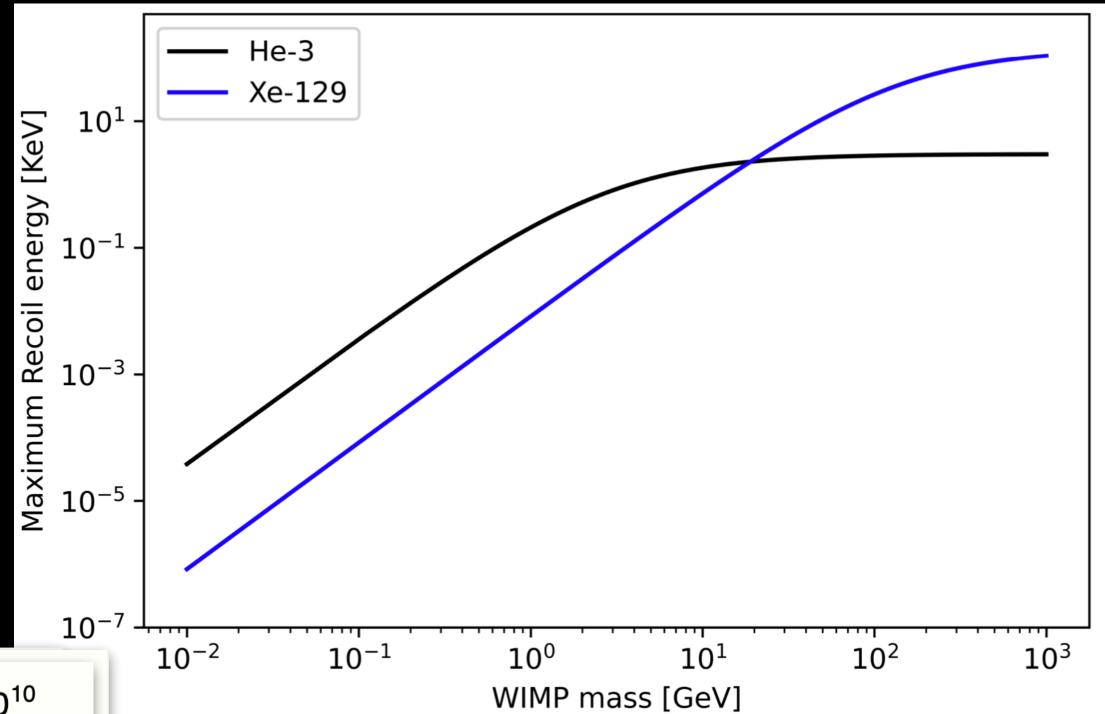

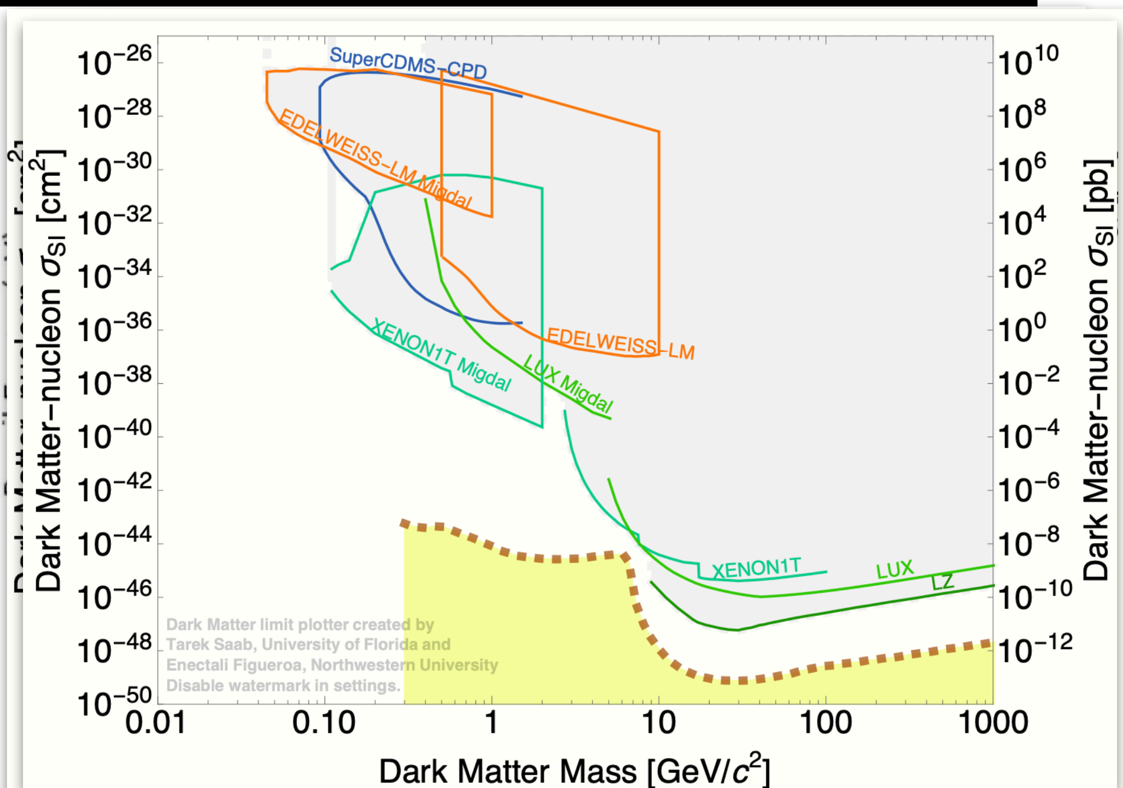

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Light Dark Matter (2)

EDELWEISS-III: Ge crystals with <0.3 keV FWHM for low mass search, R&D to lower background

CRESST-III: reaching 30 eV threshold in $CaWO_4$, with smaller crystals, R&D to lower background.
Phys.Rev.D 106, 092008 (2022)

SuperCDMS: 50 kg of 1.4 kg Ge (and Si) detectors, Installing 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, next: DAMIC-M. Aim for 1E-5 pb sensitivity, with 1 keV threshold. Related: **SENSEI**

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

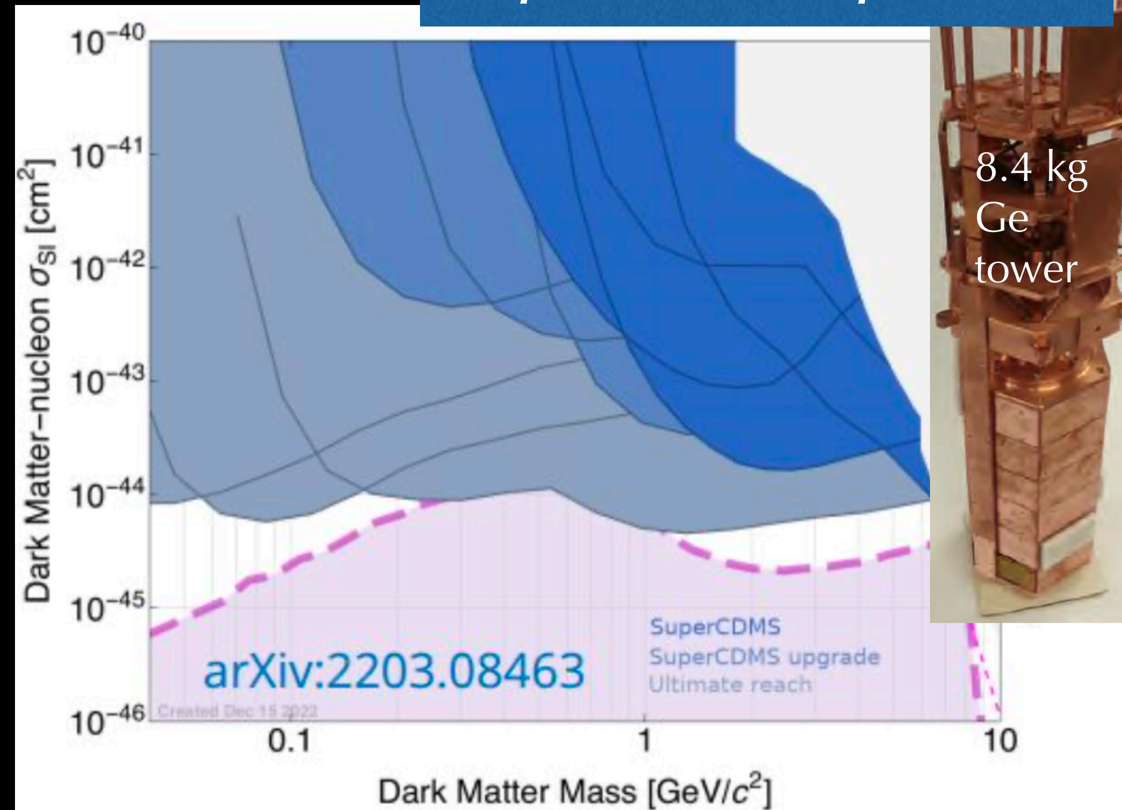
Quantum Sensors & Materials ++

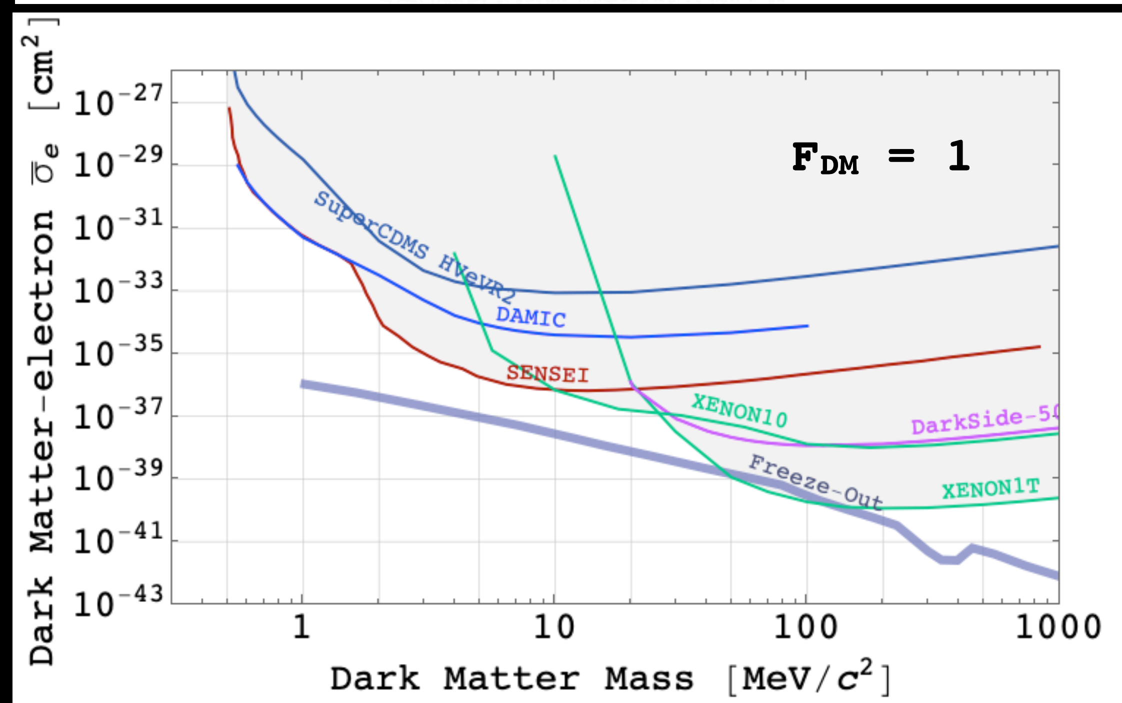
Superfluid He-4: HeRALD, DeLight, ++

Superfluid He-3: QUEST-DMC

QUEST-DMC: A. Kemp, 9/14, 15:15

SuperCDMS: E. Lopez, 15:15





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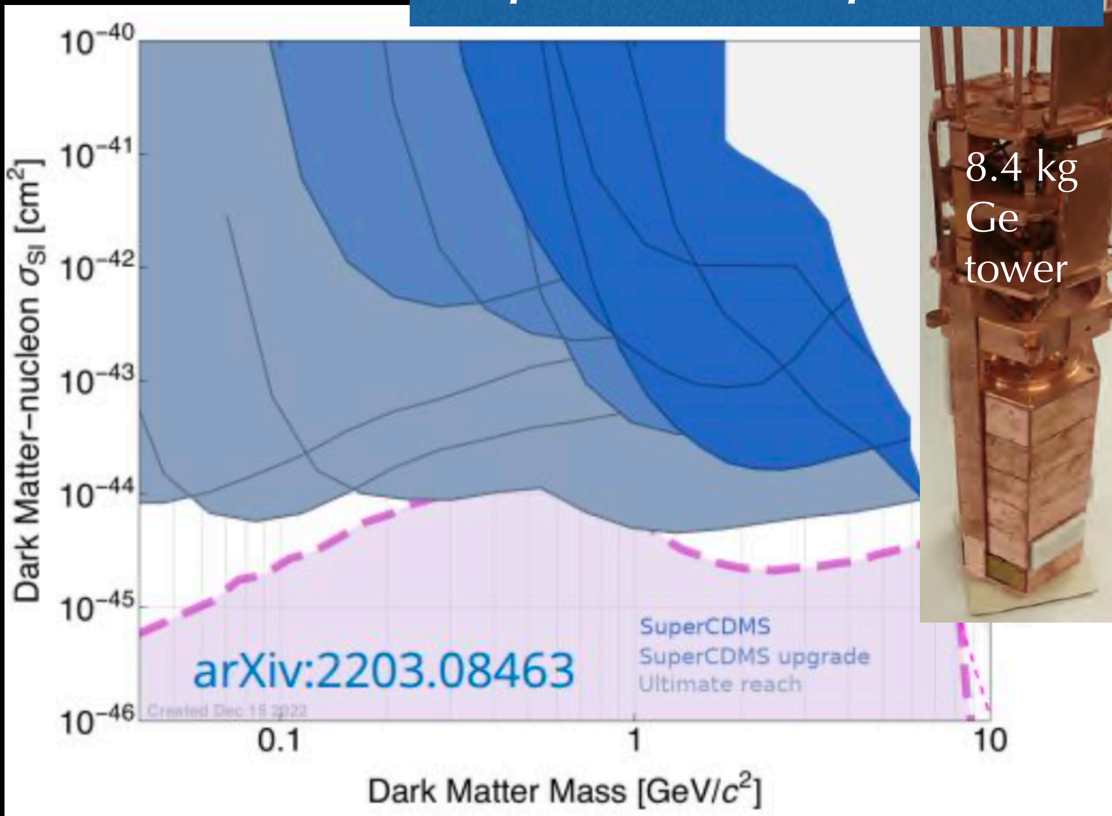
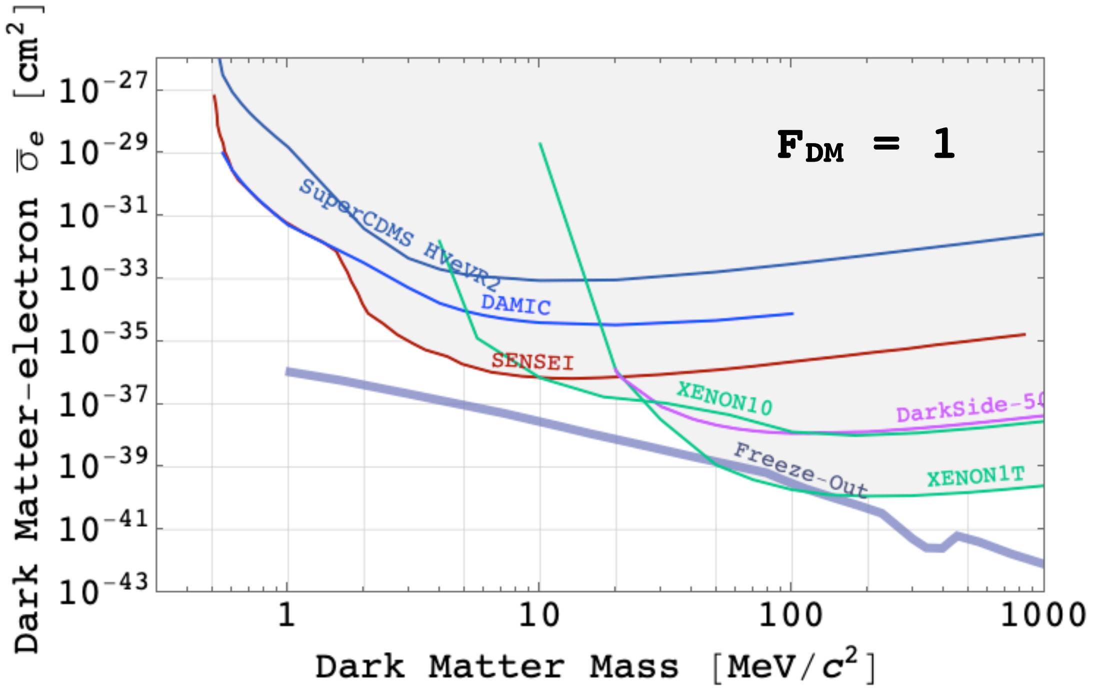




QUEST-DMC: A. Kemp, 9/14, 15:15

P. Stengel, 9/14, 16:00

Conclusions & Outlook

Exciting prospects at the low background frontier are driving technology development in inspiring directions.

Direct detection searches are rapidly expanding physics reach:

- to lower cross sections, probing new parameter space,
- to lower masses, testing new models and interaction types,
- to higher masses, complementary with the LHC!

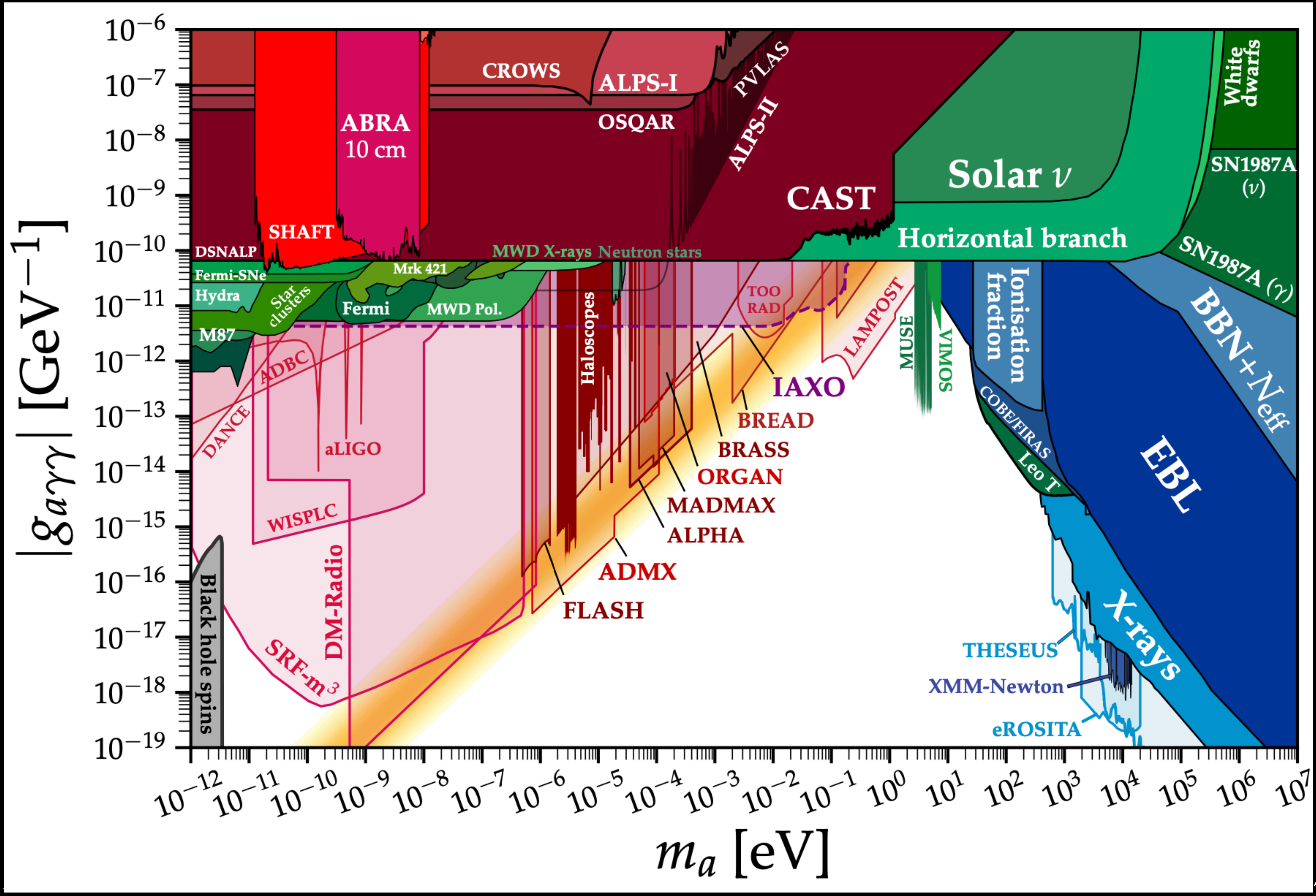
Experiments running now or under construction aim to continue to beat Moore's Law by 2x….

… and today's background may be tomorrow's signal. *(T. Kajita, 2015)*

Extra Slides

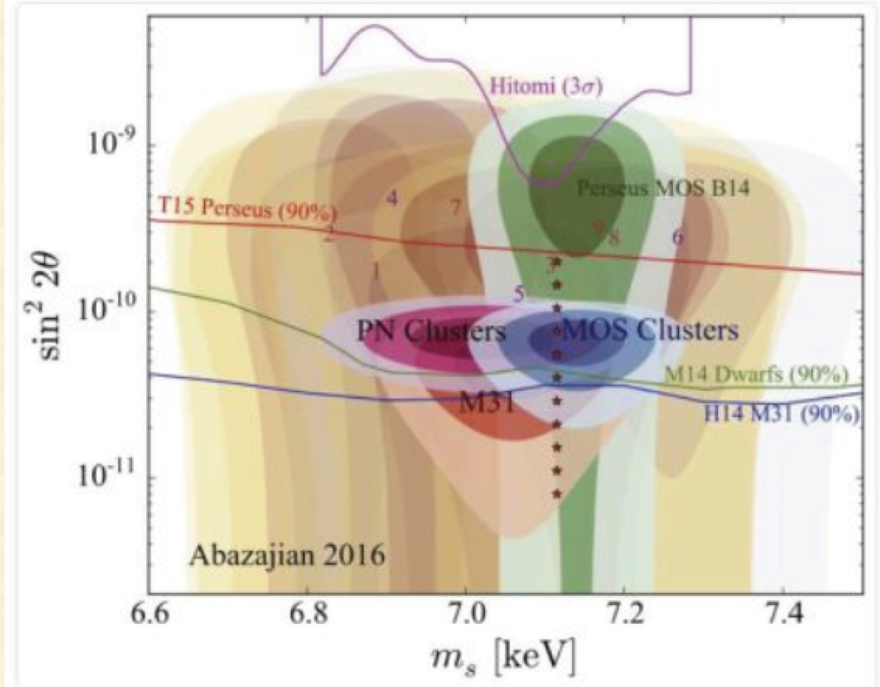
sub-eV: Axion/ALPs Searches

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

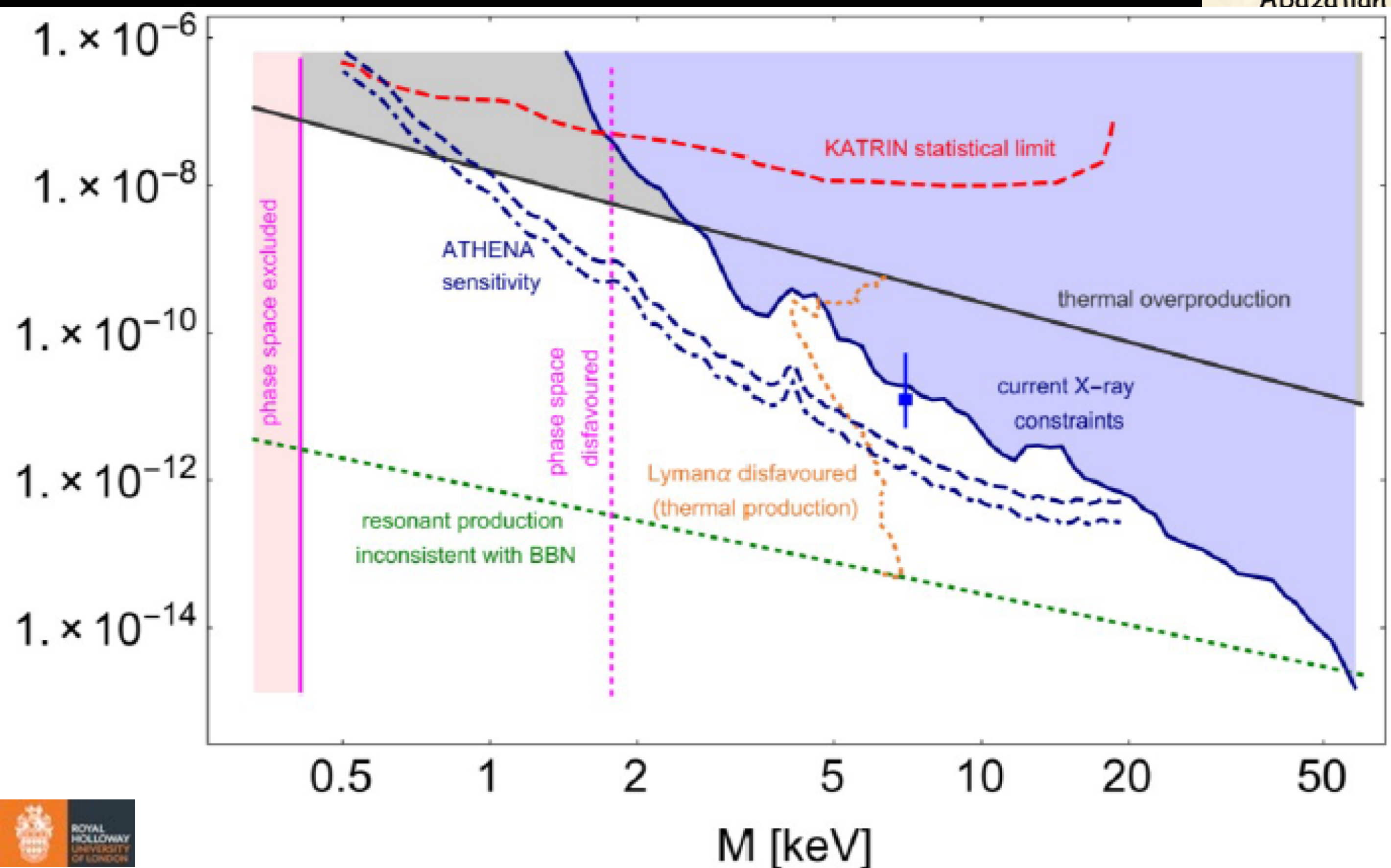


Sterile Nu Dark Matter Search

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



Sterile neutrino-electron scattering search channel for direct detection

$N_S\ e^- \rightarrow \nu_e\ e^-$

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

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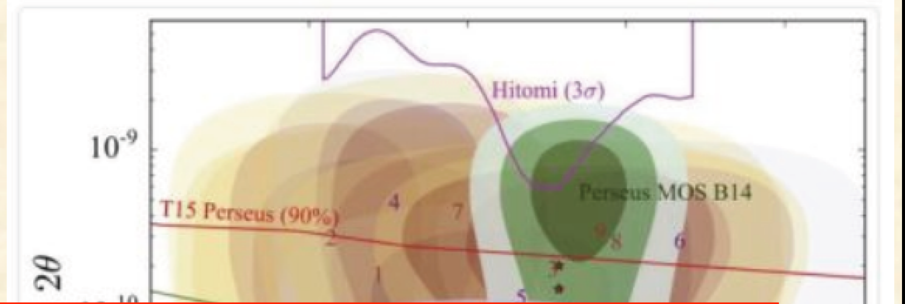
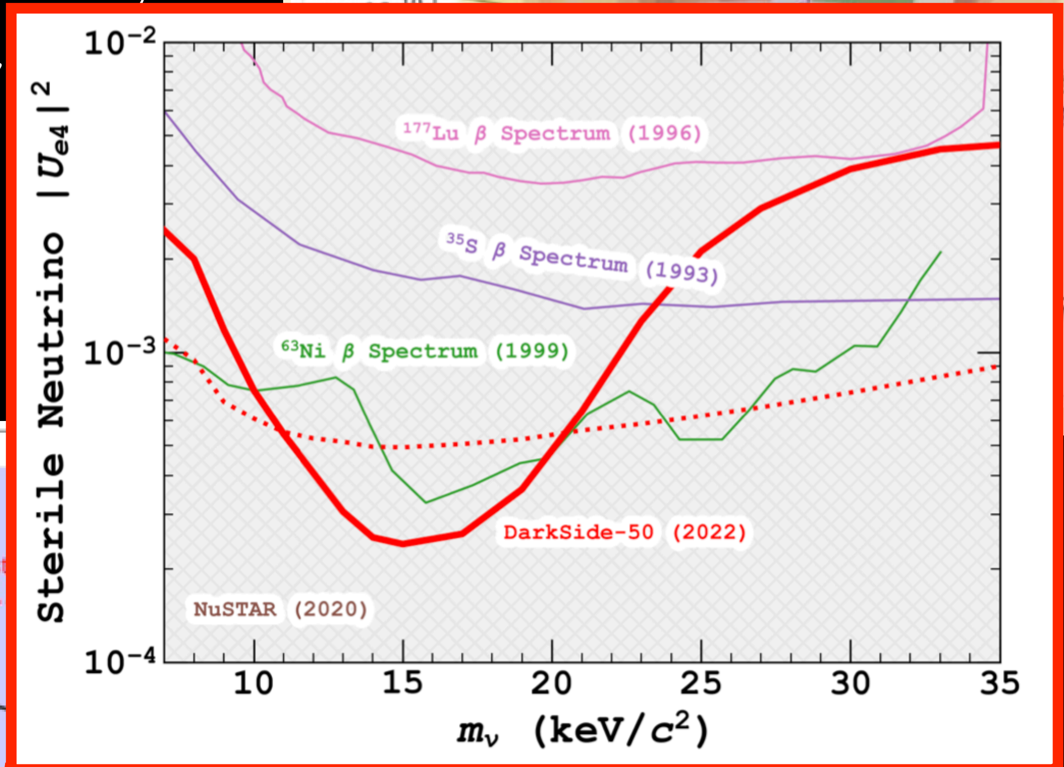
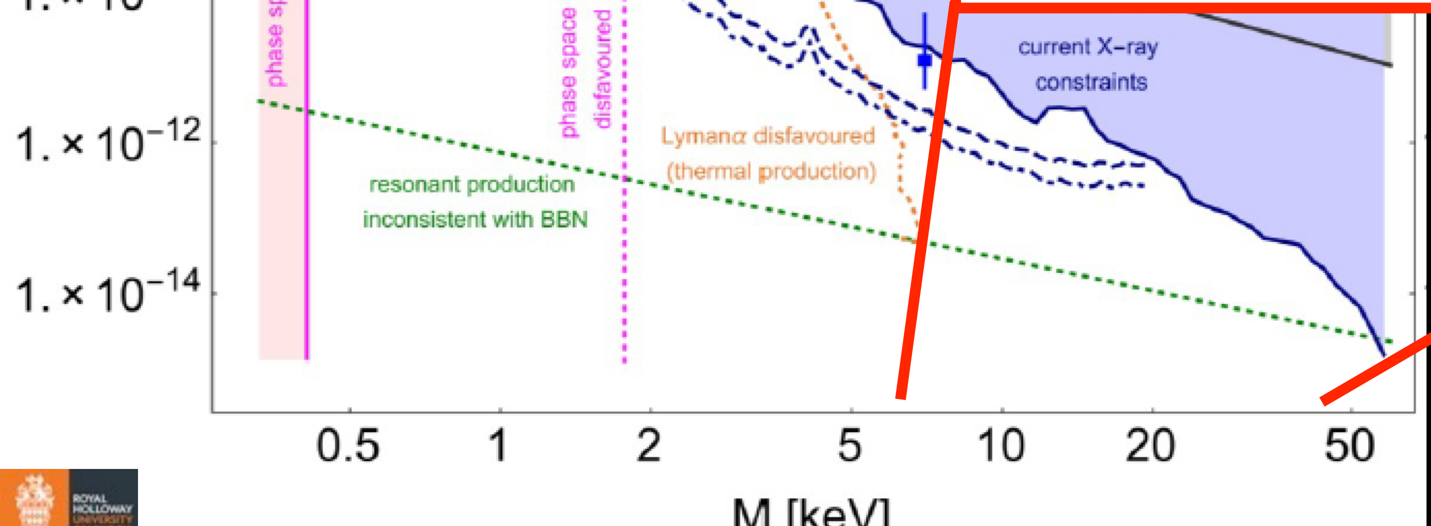
First direct detection search!
Phys.Rev.Lett. 130 (2023) 10, 101002







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Self-Interacting Dark Matter Search

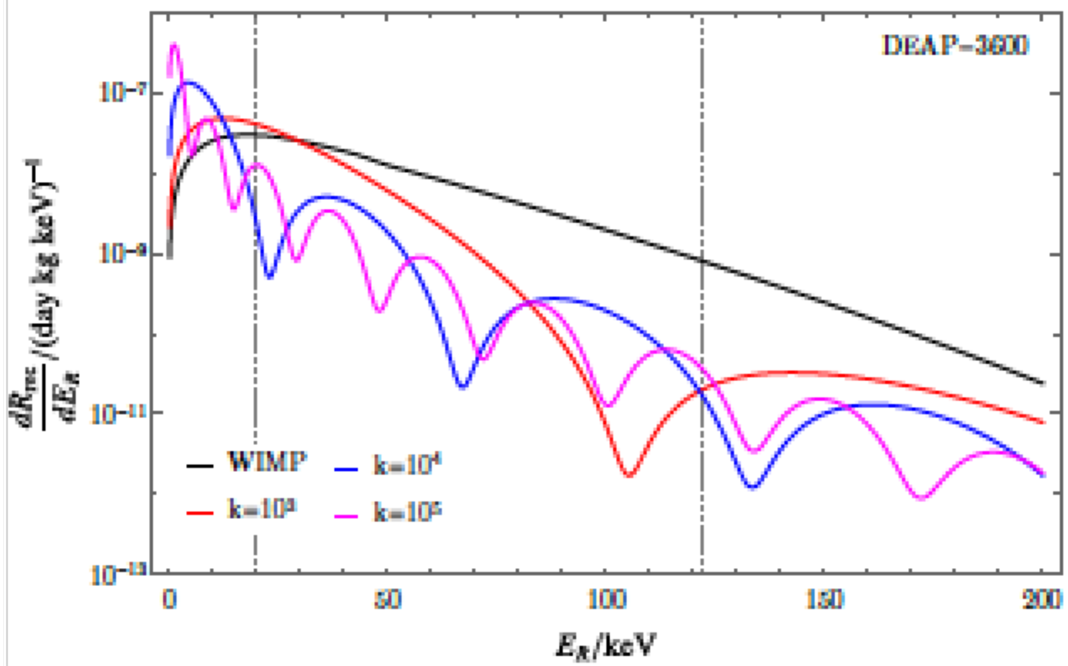
What if dark matter forms bound states?

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

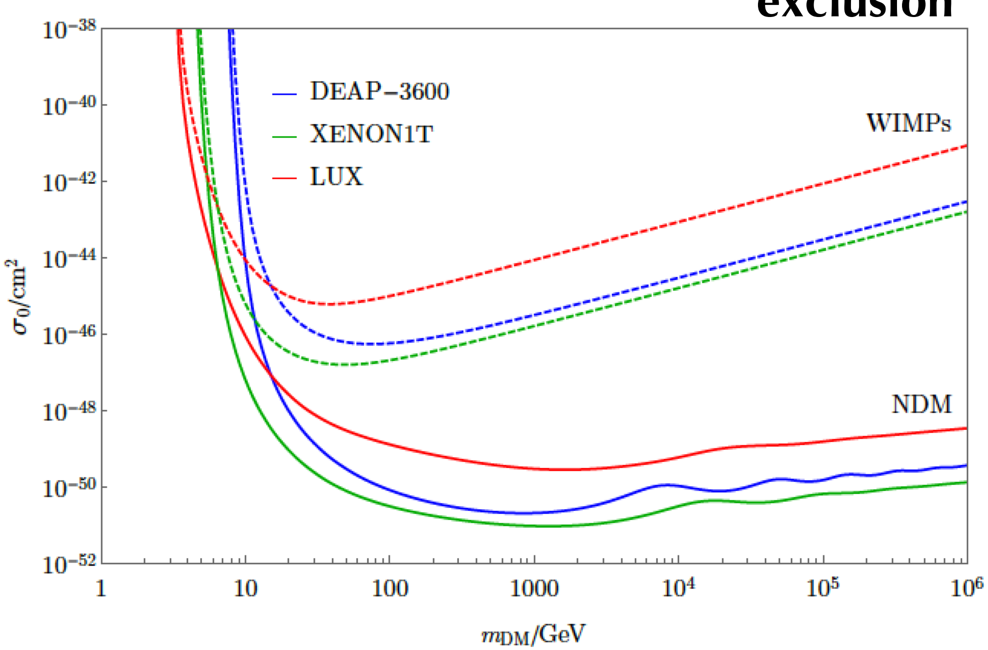
Scattering process now has a form factor from the nuclear dark matter and the target.

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

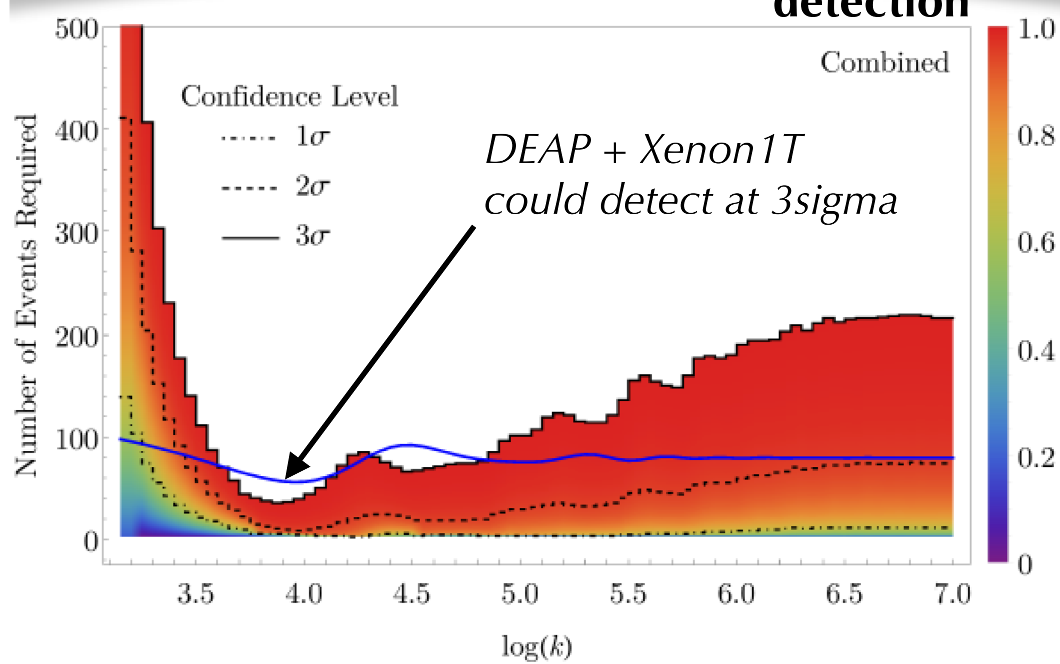
Kirk, Butcher, JM, West, JCAP 1710 (2017) 10, 035



exclusion

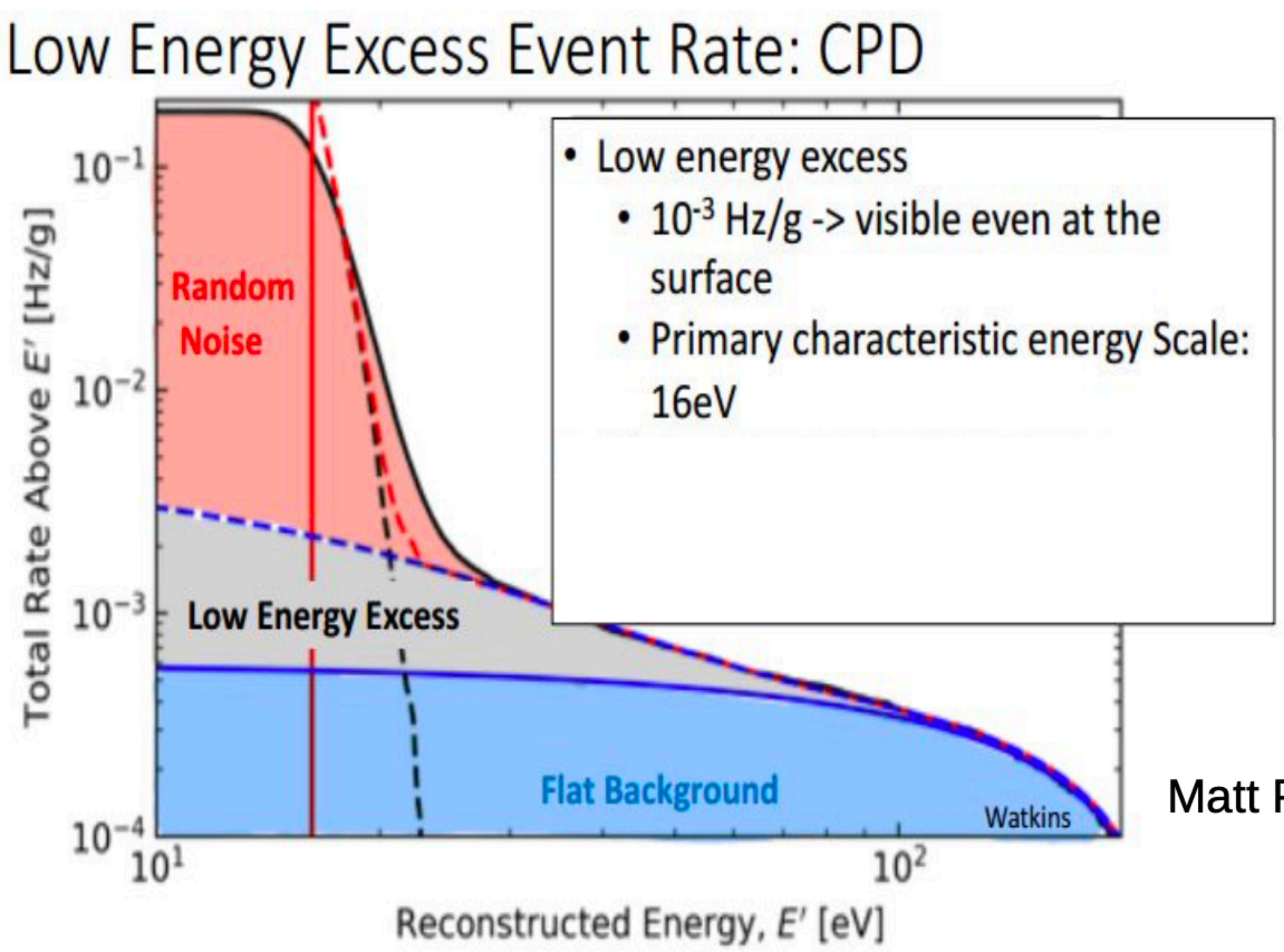


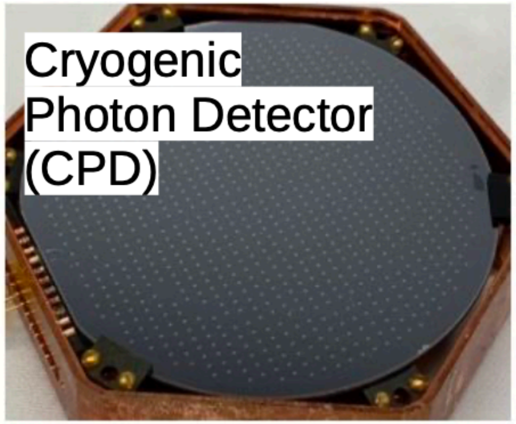
detection



Low energy excess

Observed in Edelweiss, CRESST, SuperCDMS-CPD ...





Matt Pyle, EXCESS 22

- Frequent cross-collaboration workshops (EXCESS) to tackle this issue, including at TAUP2023
- Great example for the community to follow when dealing with anomalies in the data
- No firm conclusion yet, but... not compatible with WIMPs and most likely not radiogenic

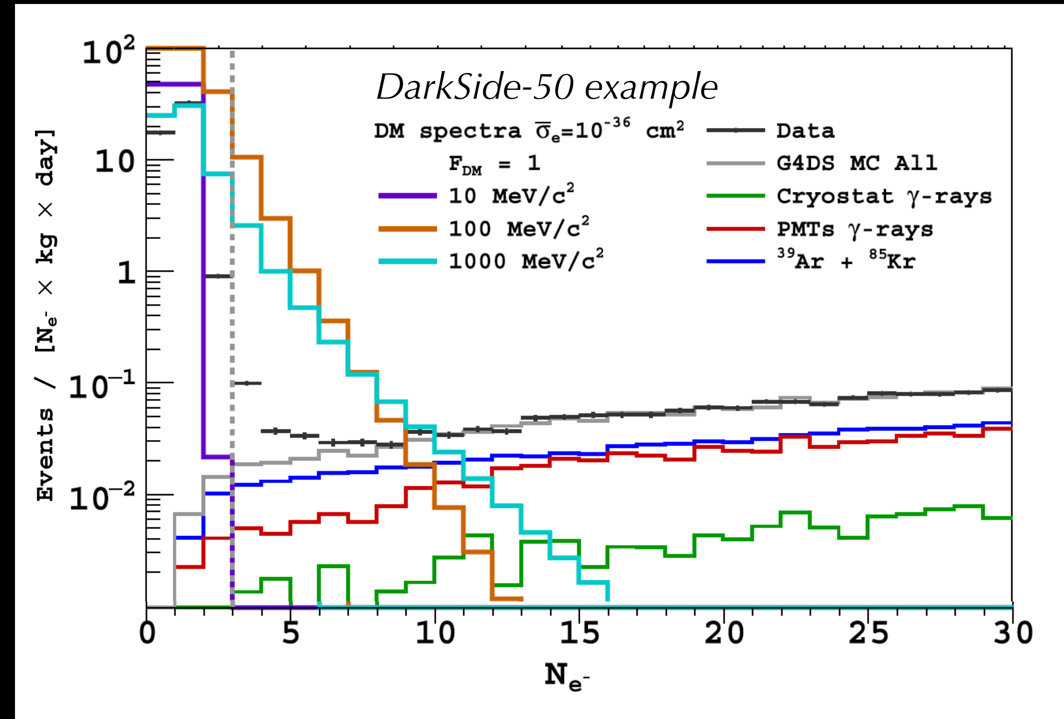
MeV-scale Direct Detection

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

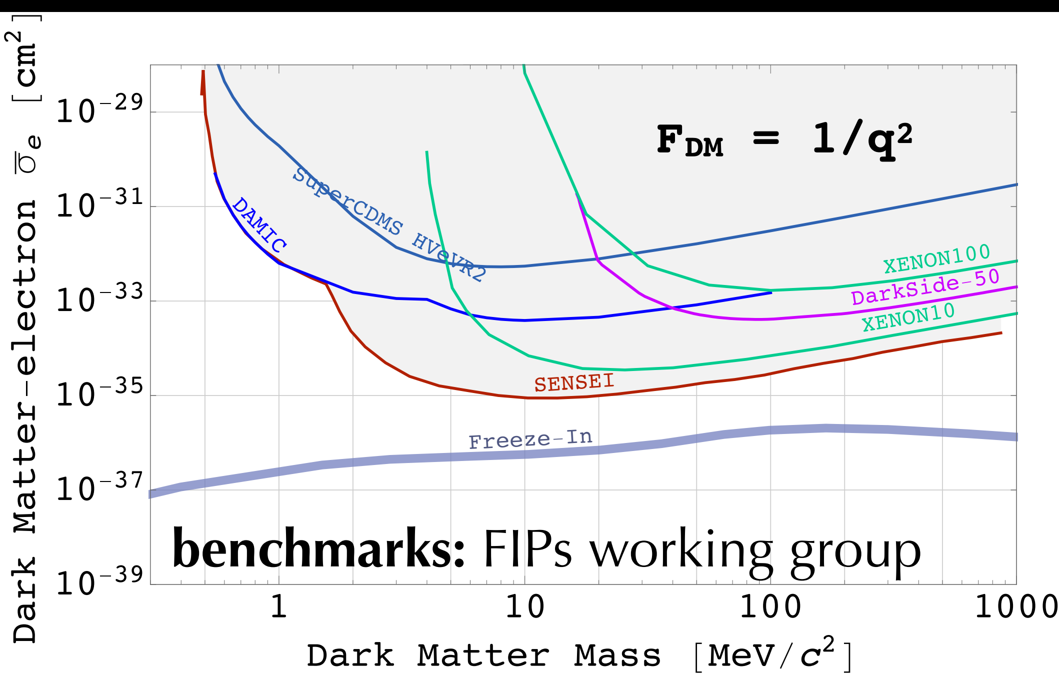
Backgrounds: ER ~ 0.1-1/(keV kg day).

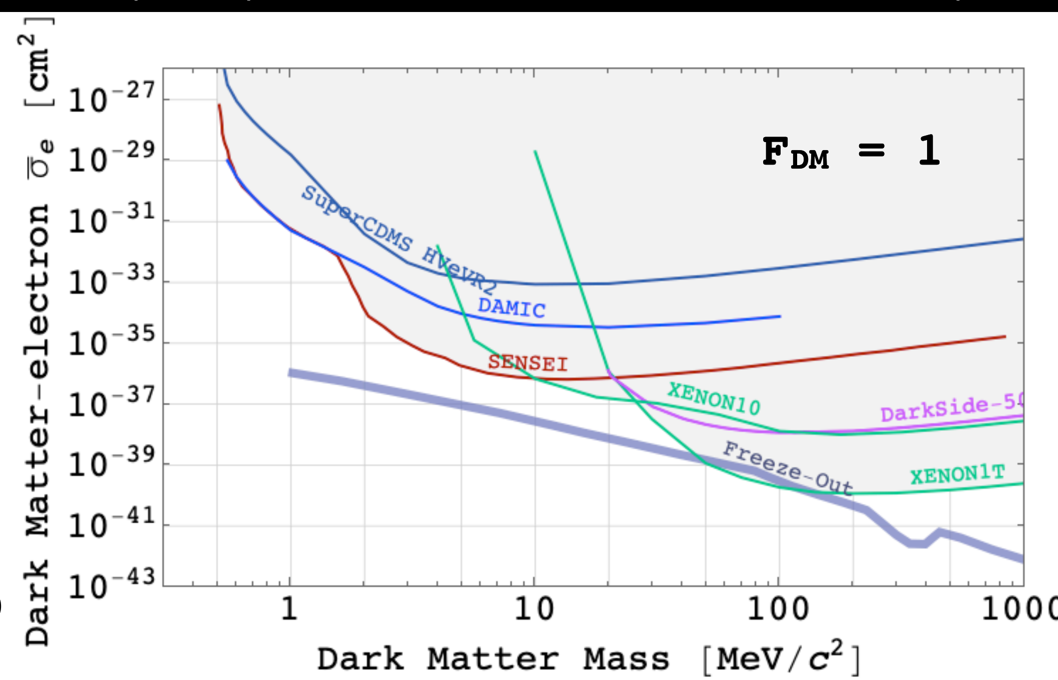
Analysis: PLR.

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



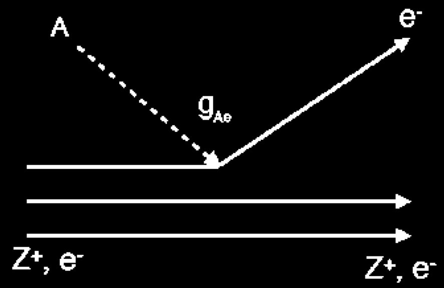
https://supercdms.slac.stanford.edu/dark-matter-limit-plotter





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).

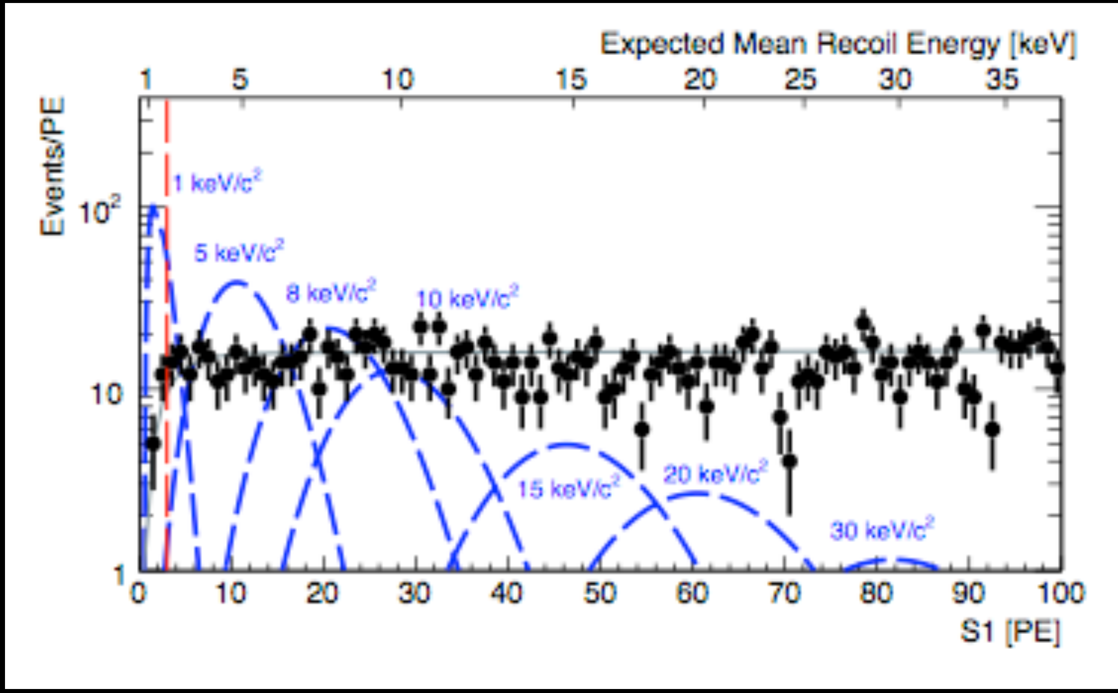
Analysis: bump hunt.

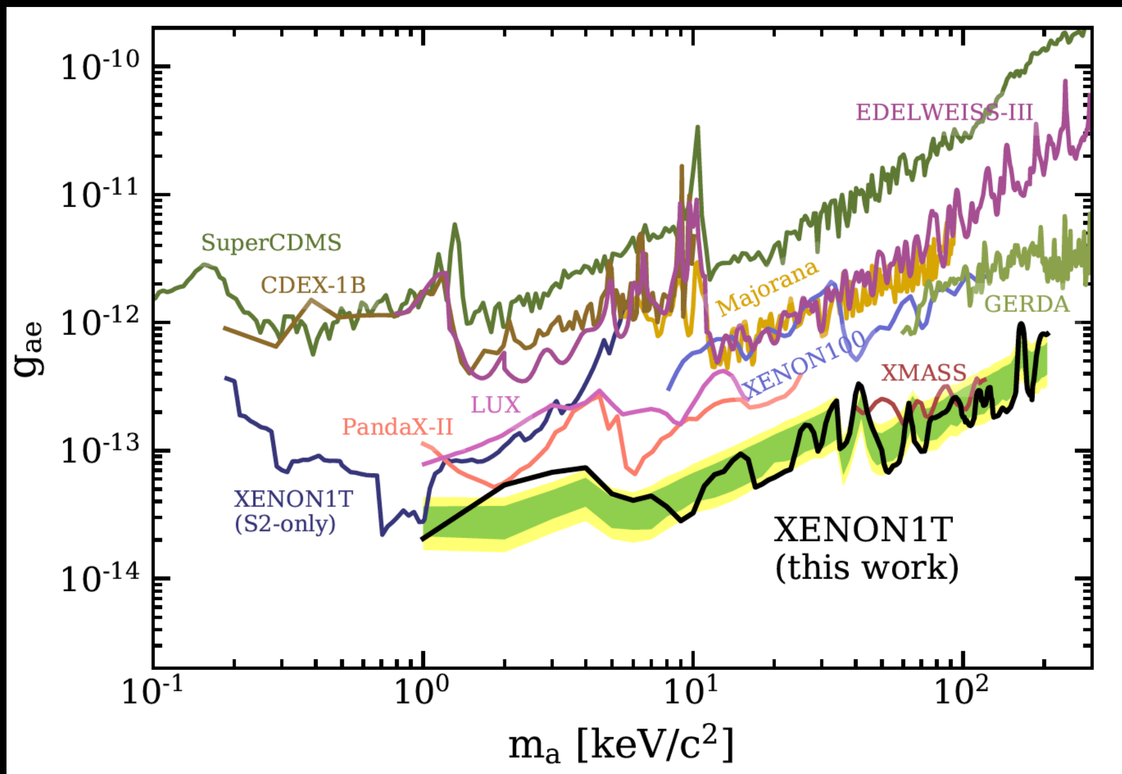
Constraints on new pseudoscalars at <MeV/c² via ALP-electron coupling.

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)*

***XENON100**, arXiv:1404.1455*





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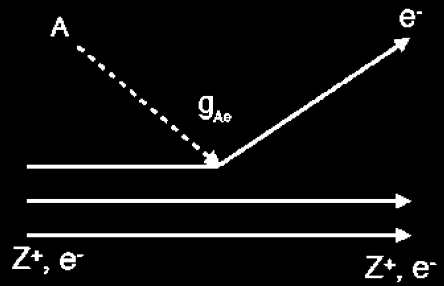

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