Dark Matter and Axion Searches

Jocelyn Monroe,

University of Oxford &
Rutherford Appleton Laboratory

ICHEP 2024

July 22, 2024
Prague, Czechia

42 Parallel Talks!

Searches for dark matter with CMS
Club E

Searches for dark sector particles at Belle and Belle$~$II
Club E

Search for Baryogenesis and Dark Matter in B-meson decays with the $BABAR$ detector
Club E

The Light Dark Matter eXperiment at 8 GeV
Club E

First measurement of antiproton cross section in p-He collisions at the AMBER Experiment at CERN
Mr Davide Giordano

ATLAS Latest Dark Matter Searches — *Elen*
Club E

The ALPHA axion dark matter experiment
Club A

The axion dark matter experiment MADMAX
Club A

Full Results from HAYSTAC's Phase II Operation with a Sq
Club A

Dark matter search in DEAP-3600: status and prospects
Club A

Exploring Low-Mass Dark Matter with the DarkSide Detect
Club A

Direct Dark Matter Search in the DarkSide-20k Experiment
Club A

Latest results from the XENONnT dark matter experiment
Club A

Status of the LUX-ZEPLIN (LZ) experiment: a direct searc
Club A

Background Modeling for the LUX-ZEPLIN Dark Matter Ex
Club A

DARWIN - The Ultimate Liquid-xenon-based Astroparticle
Club A

The CYGNO experiment
Club A

Light dark matter search at PandaX
Club A

Resonant dark sector production on crystals
Club E — 09:03 - 0

Hunting for Hypercharge Anapole Dark Matter — *Seong Youl Cho*
Club E — 09:21 - 0

Searching for the X17 with the PADME experiment — *Venelin Kozhuharov*
Club E — 09:39 - 0

Dark SHINE —— Search for Light Dark M Show the bookmarks in this folder ai — *Shu L*
Club E — 09:57 - 1

First results from testing SuperCDMS SNOLAB detectors in a low background environment at CUTE — *Aditi Pradee*
Club E — 10:45 -

The SuperCDMS at SNOLAB experiment, status and prospects — *Emanuele Michie*
Club E — 11:03 -

The search for light dark matter with DAMIC-M — *Radomir Smi*
Club E — 11:21 -

QUEST-DMC: detection of sub-GeV dark matter with nanowires in a superfluid He-3 calorimeter — *Dr Paolo Franch*
Club E — 11:39 - 11:57

Production, Purification and Assay of Underground Argon for DarkSide-20k
Club E

Directional dark matter searches with the NEWSdm Experiment — *Valeri Tioukov*
Club E — 16:45 - 17:03

Fabrication and Data Acquisition of the KAPAE Phase II Detector for Investigating Invisible Decay in Positronium Annih
HongJoo Kim

PICO: search for dark matter with bubble chambers
Club E

A novel approach for $\overline{He}$ research in cosmic rays wit
Club E

NEWS-G: Search for Light Dark Matter with a Spherical Propo Sh
Club E

ANAIS-112 updated results on dark matter annual modulation
Club A

Status on COSINE-100 experiment
Club A

The SABRE South Experiment at the Stawell Underground Physics Laboratory
Club A

Status of SABRE North at LNGS and radiopurity of SABRE NaI(Tl) crystals
Club A

Dark matter searches with the KM3NeT neutrino telescope — *Mr Adrian Šaina*
Club A — 15:41 - 15:59

Neutrino constraints on inelastic dark matter captured in the Sun
Club A

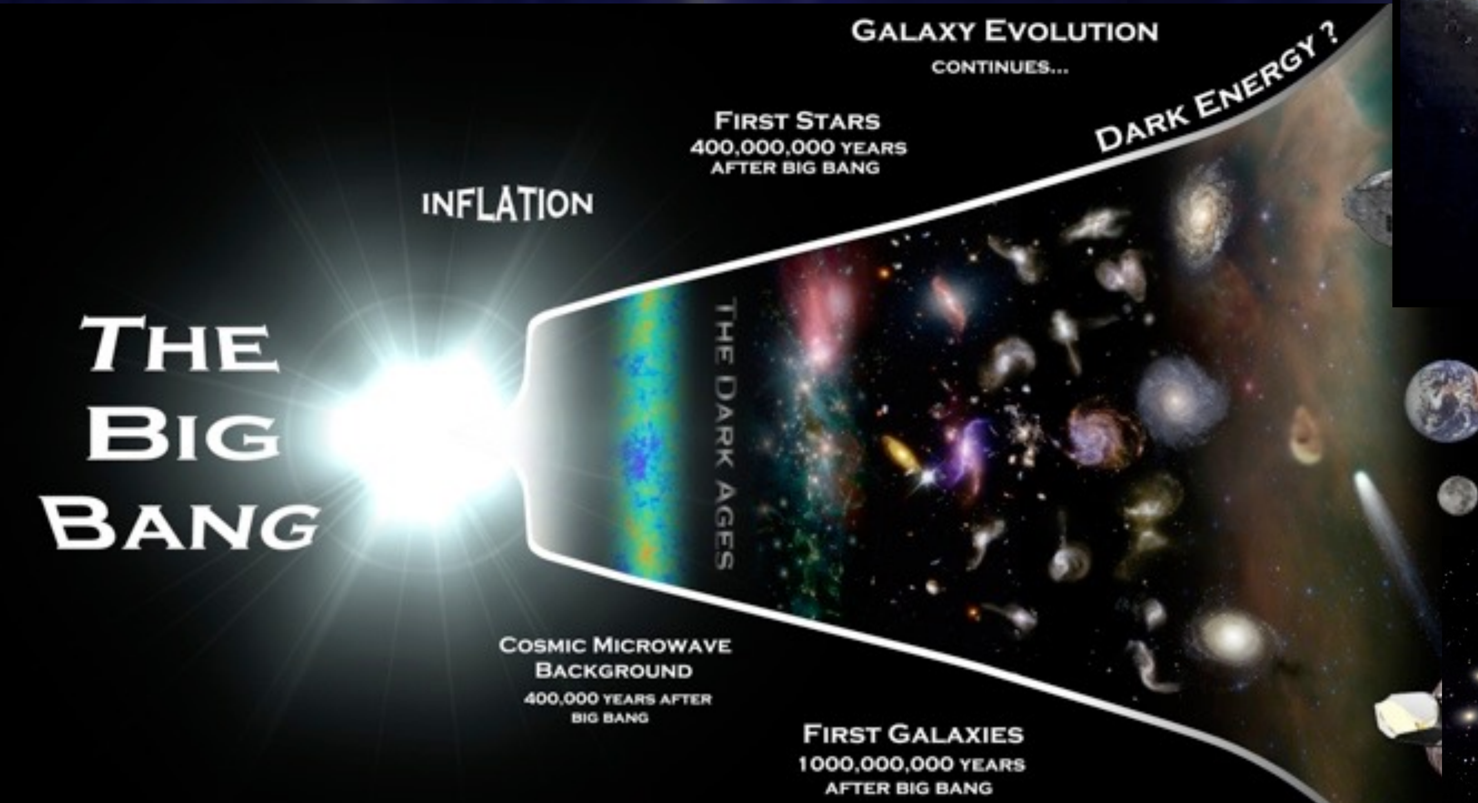
Dark sector and Axion-like particle search at BESIII
Club A

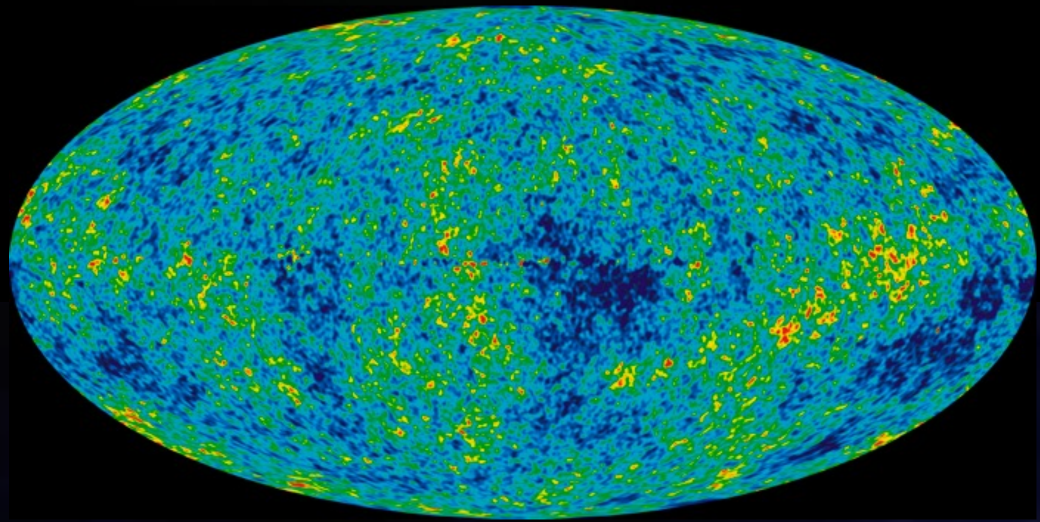
The Scintillating Bubble Chamber for Dark Matter and Neutrino detection
Club A

Recasting scalar-tensor theories of gravity for colliders
Club A

Boosting the production of sterile neutrino dark matter with self-interactions
Club A

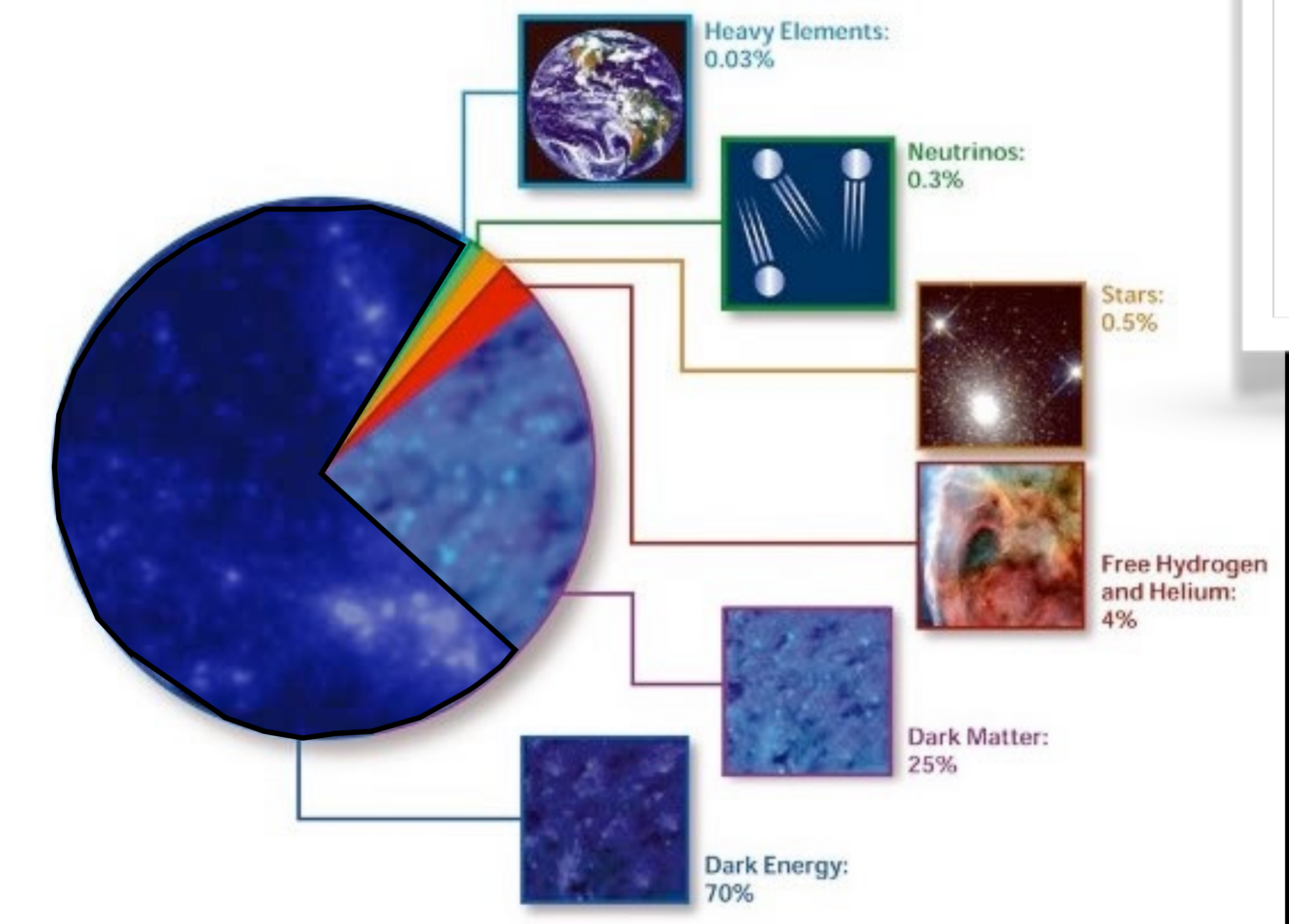
Evidence for Dark Matter

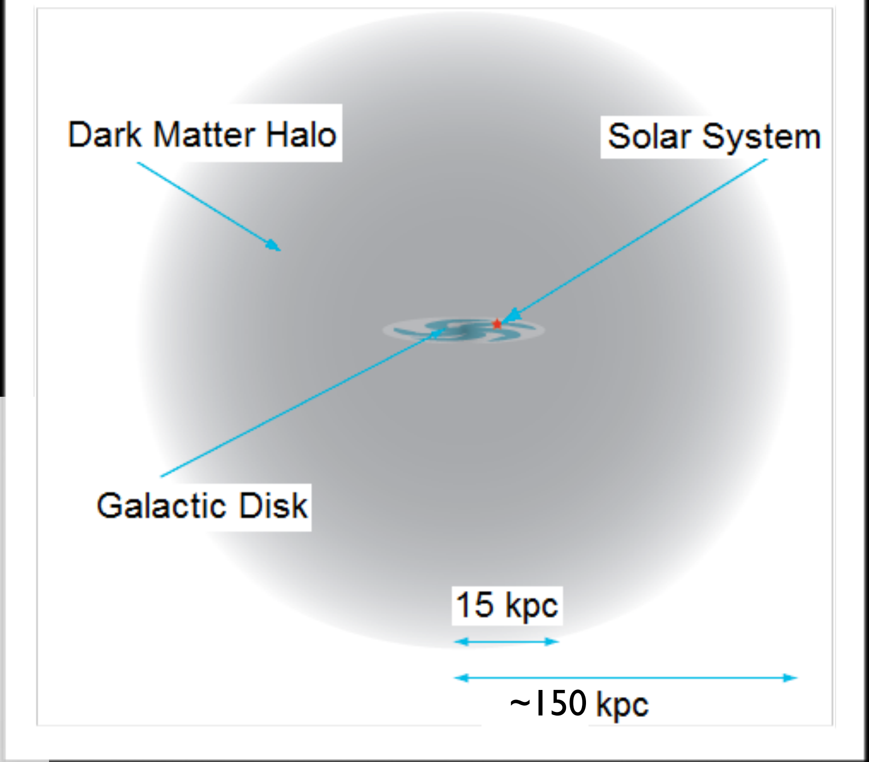




Evidence from a range of times,
from a range of scales

What do we know about Dark Matter?





optically dark

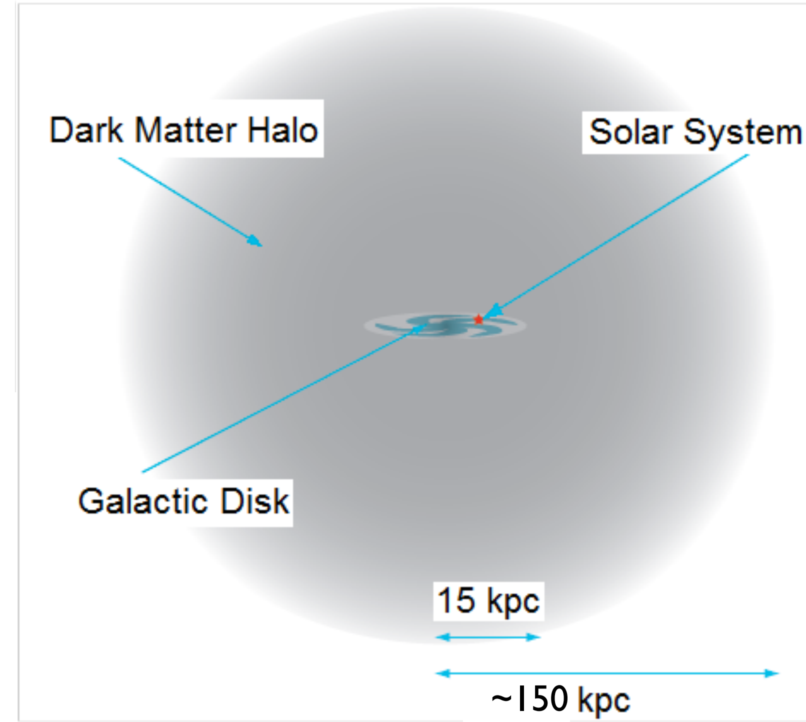
bound to our galaxy

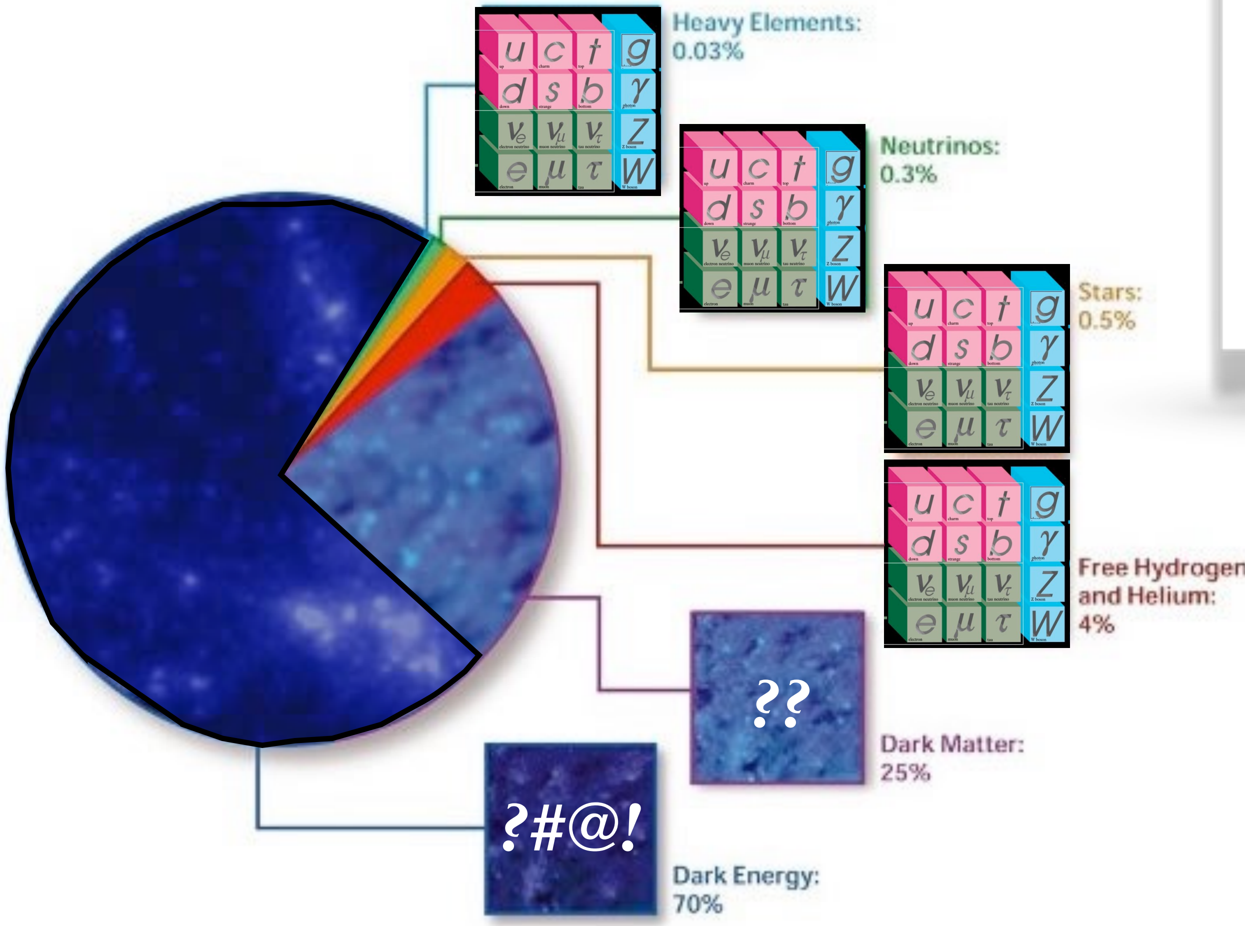
density ~ 0.3 GeV/cm^3

dark matter particle mass: ?

interactions: very weak

What do we know about Dark Matter?





optically dark

bound to our galaxy

density ~ 0.3 GeV/cm^3

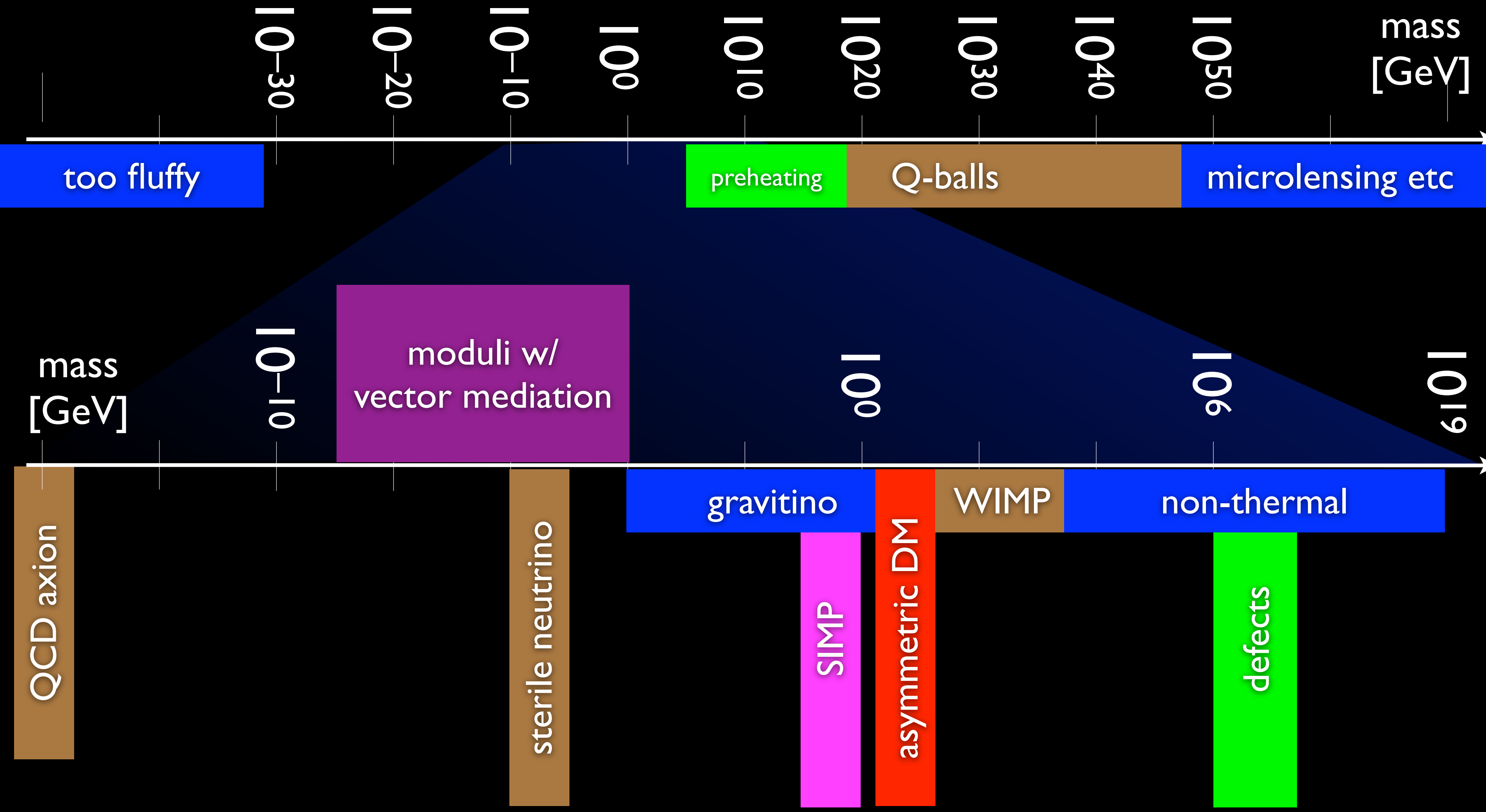
dark matter particle mass: ?

interactions: very weak

The Standard Model of Particle Physics describes <5% of the universe!

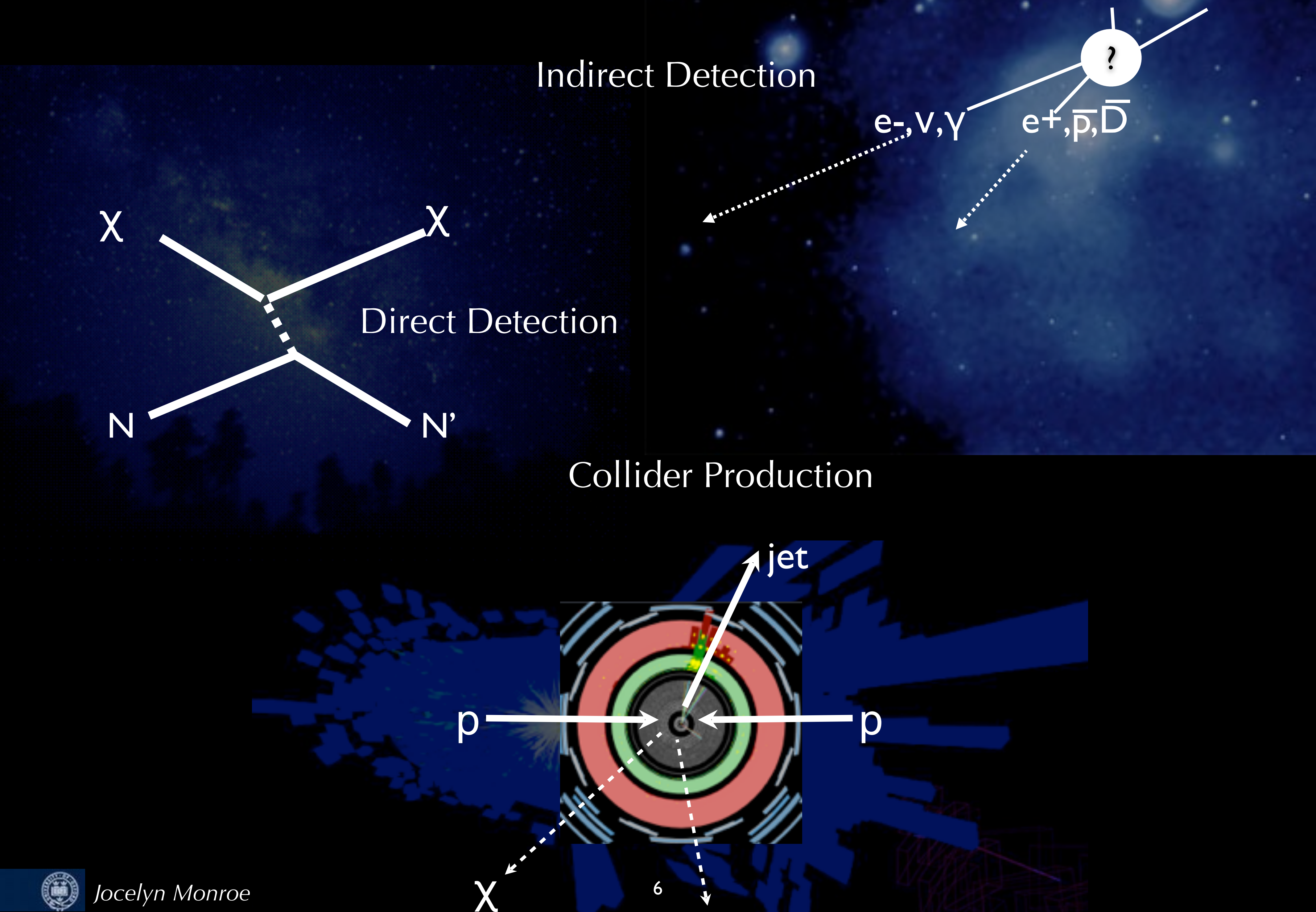
Theorist's View

(thanks to H. Murayama)

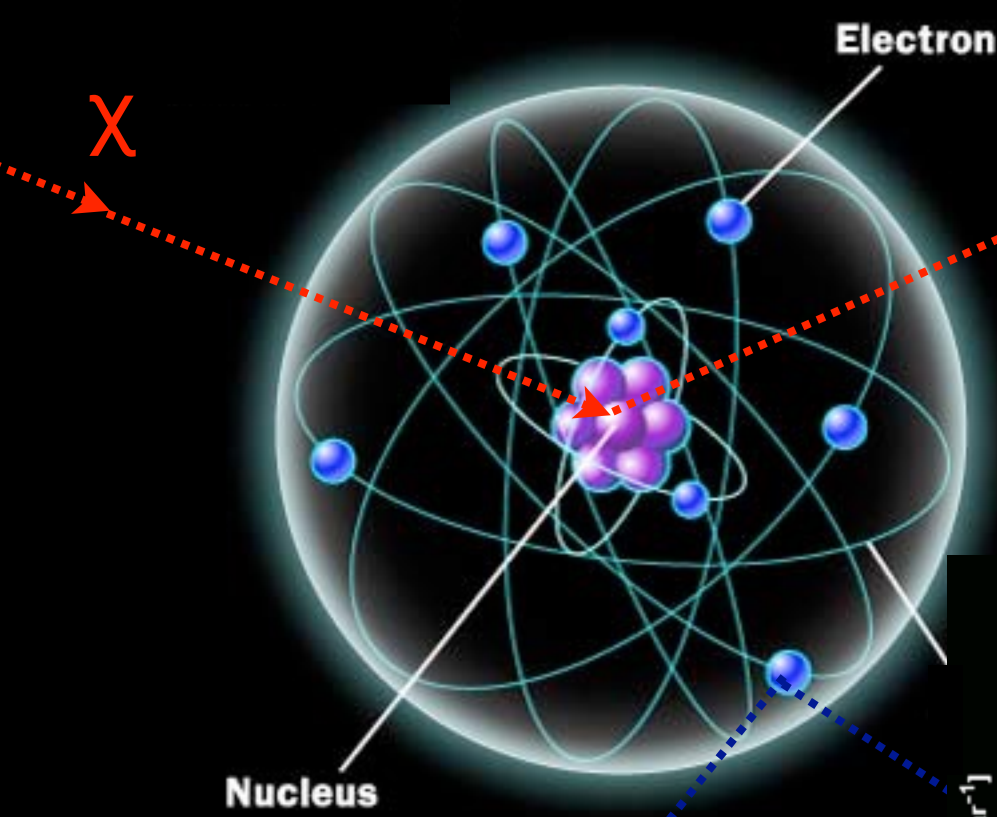


New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.

Experimentalist's View



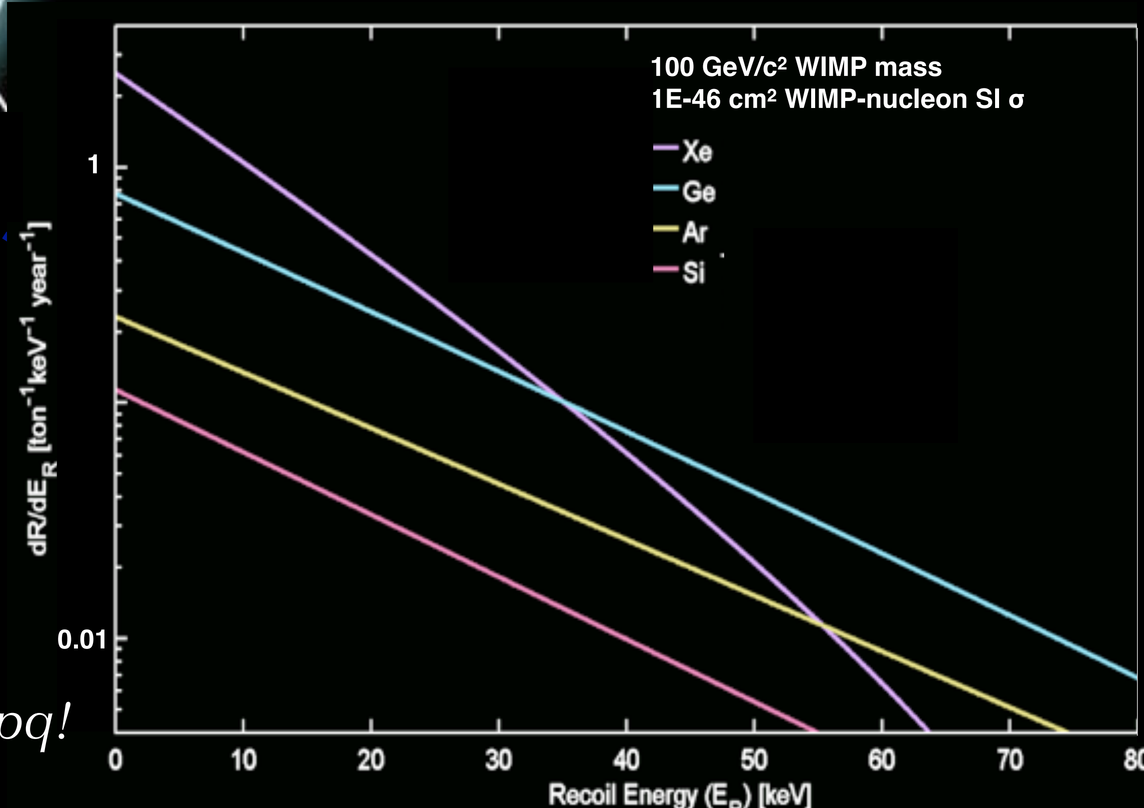
Direct Detection Scattering Signal



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

χ scatters coherently: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

scattering kinematics: *v/c ~ 8E-4!*



experimental challenges:

1. *keV-scale energy threshold +*
2. *<1/t/y event rate*
3. *need particle ID at ppm-ppb-ppt-ppq!*

Direct Detection Scattering Signal

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

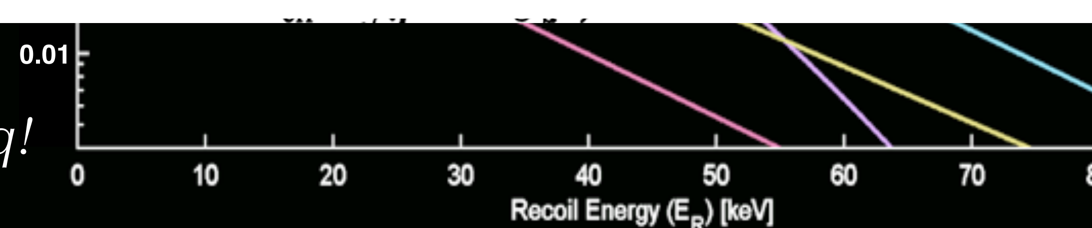
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

There is recent experimental evidence[1] from CERN and NAL which suggests the presence of a neutral current in neutrino-induced interactions.

important to interpret experimental results in a very broad theoretical framework.[4] We assume a general current-current effective Lagrangian

2. <1/t/y event rate
3. need particle ID at ppm-ppb-ppt-ppq!



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CEvNS: ~50 years from prediction to discovery

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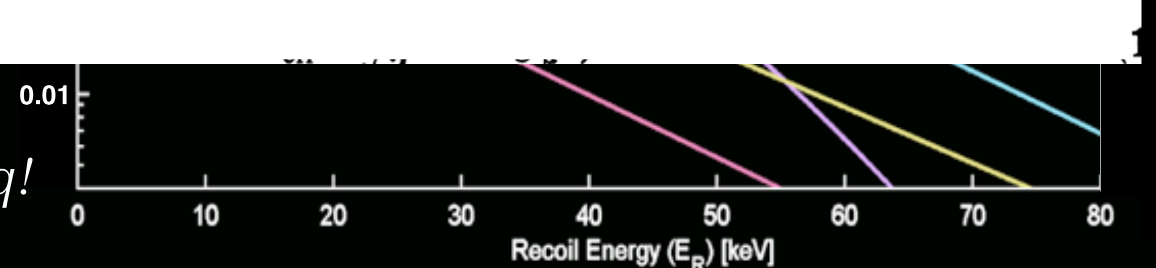
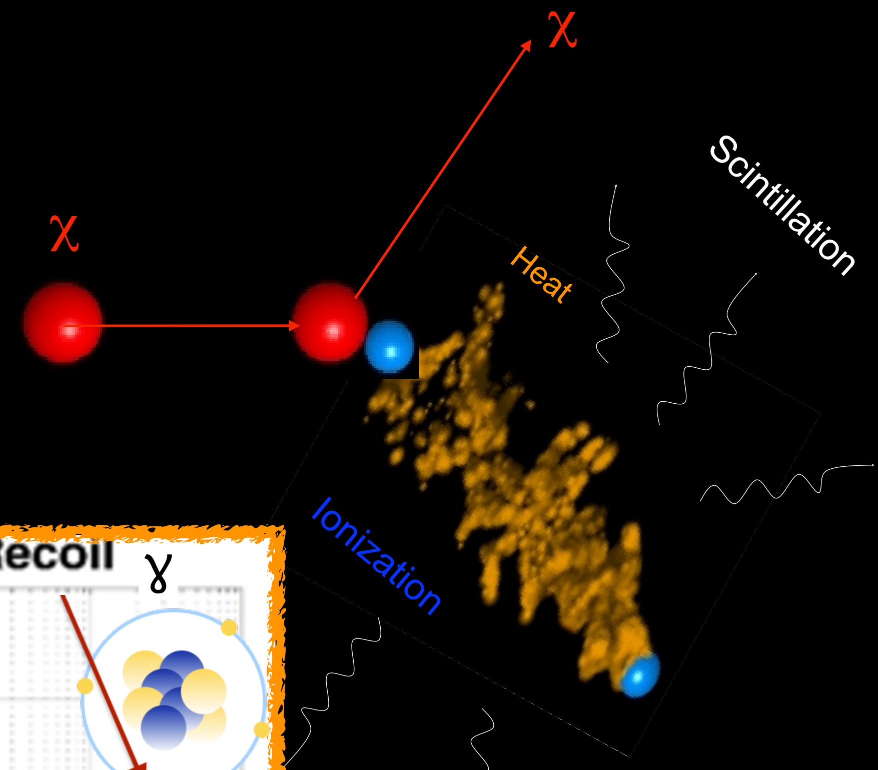
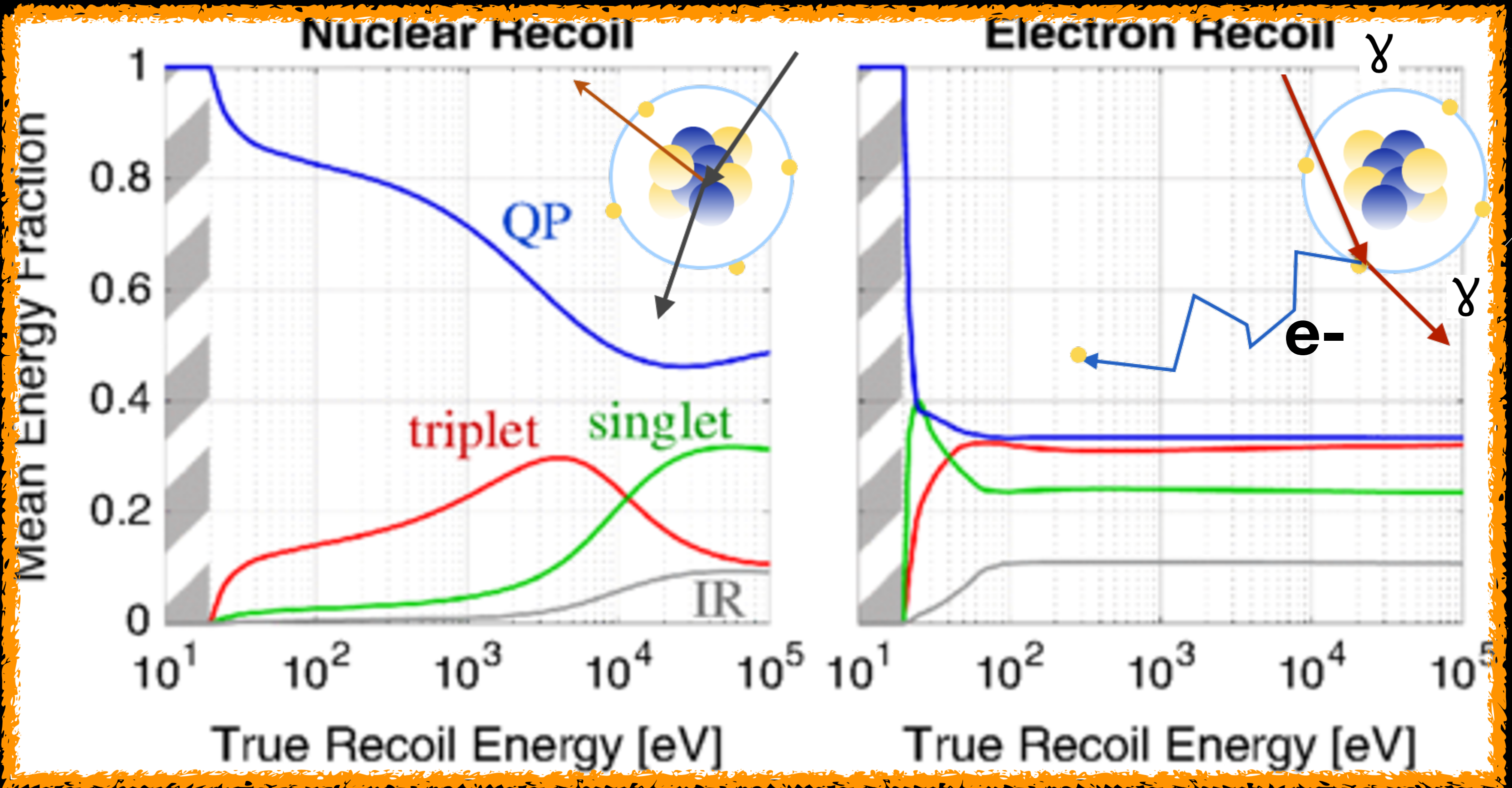


Challenge 1: Low Energies!

Recoil energy ~ 0.000001 x m_{DM}

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

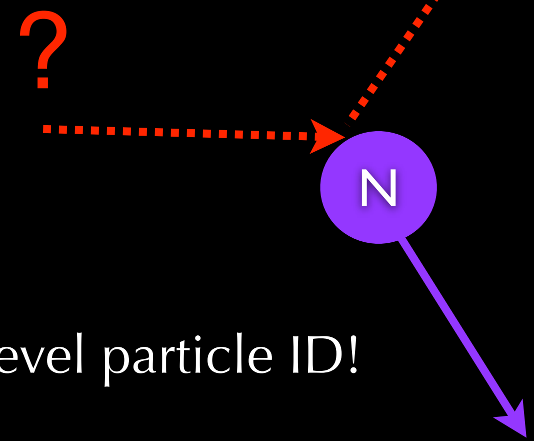




Energy partition depends on particle energy, and interaction with target microphysics

opportunity for particle ID: identify backgrounds via partition, light vs. time

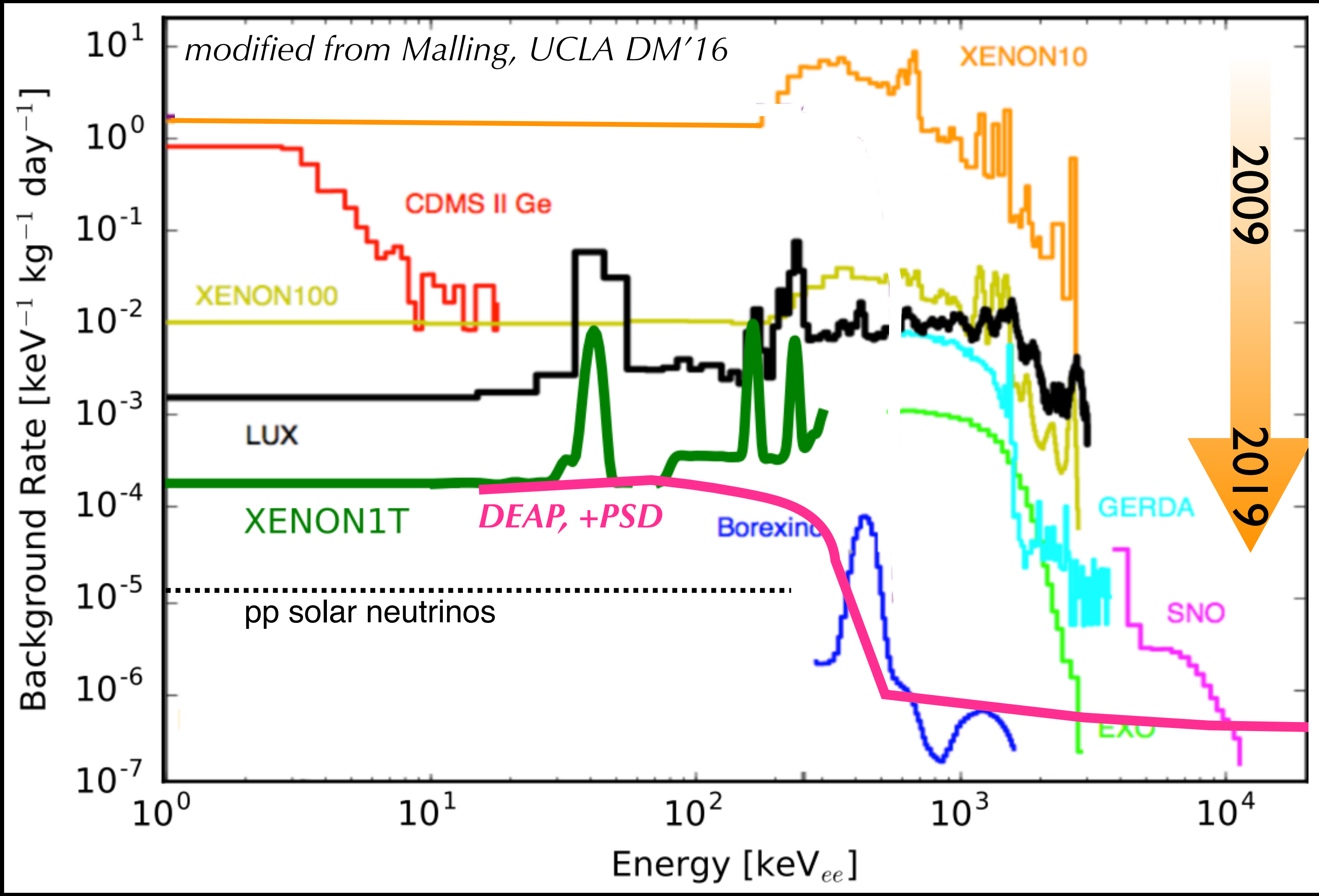
Challenge 2: Low Rates!



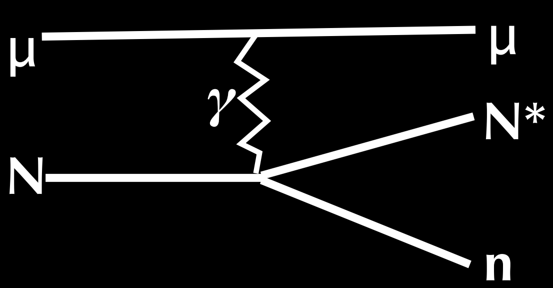
Reducible Backgrounds:

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

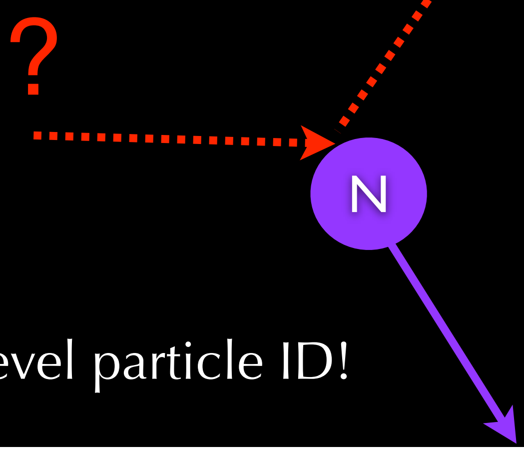
Contamination:
Mis-identified U, Th, Pb decays…
part-per-quadrillion++ control of materials



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



Challenge 2: Low Rates!



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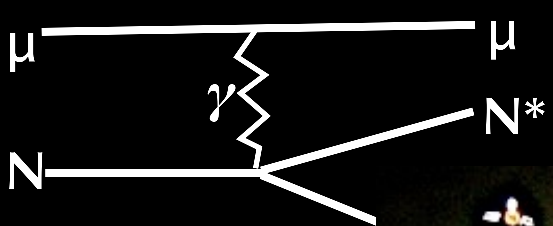
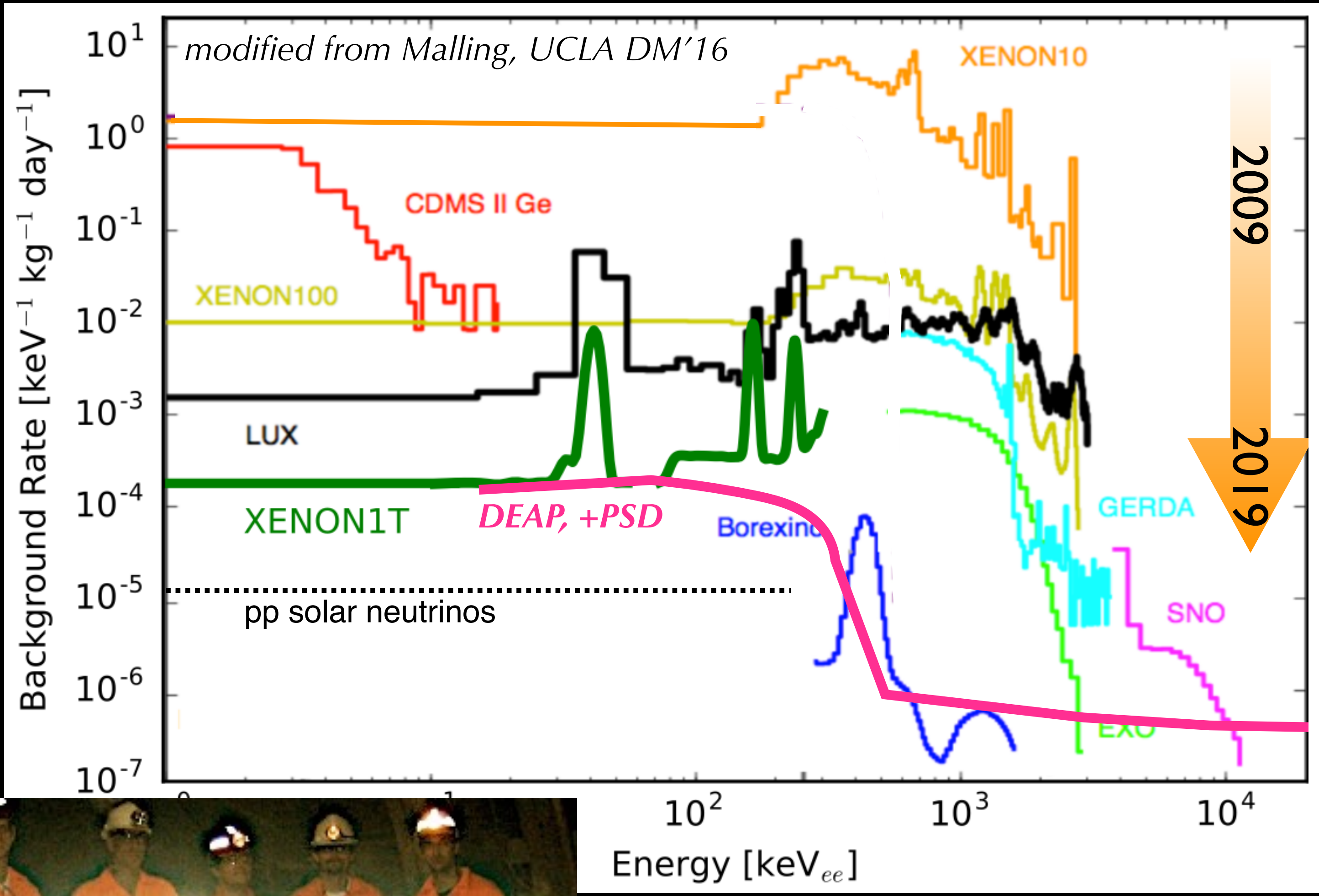


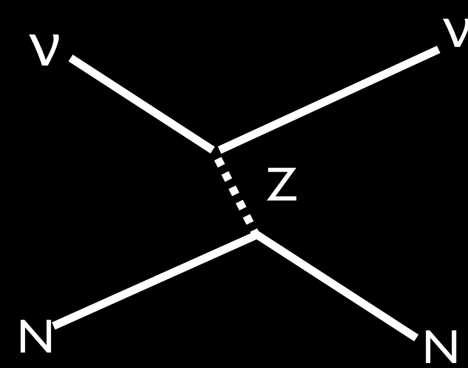


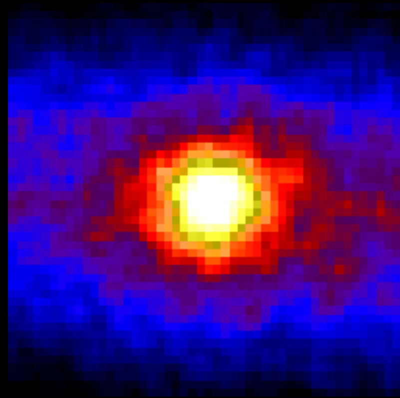
Challenge 2: Low Rates!

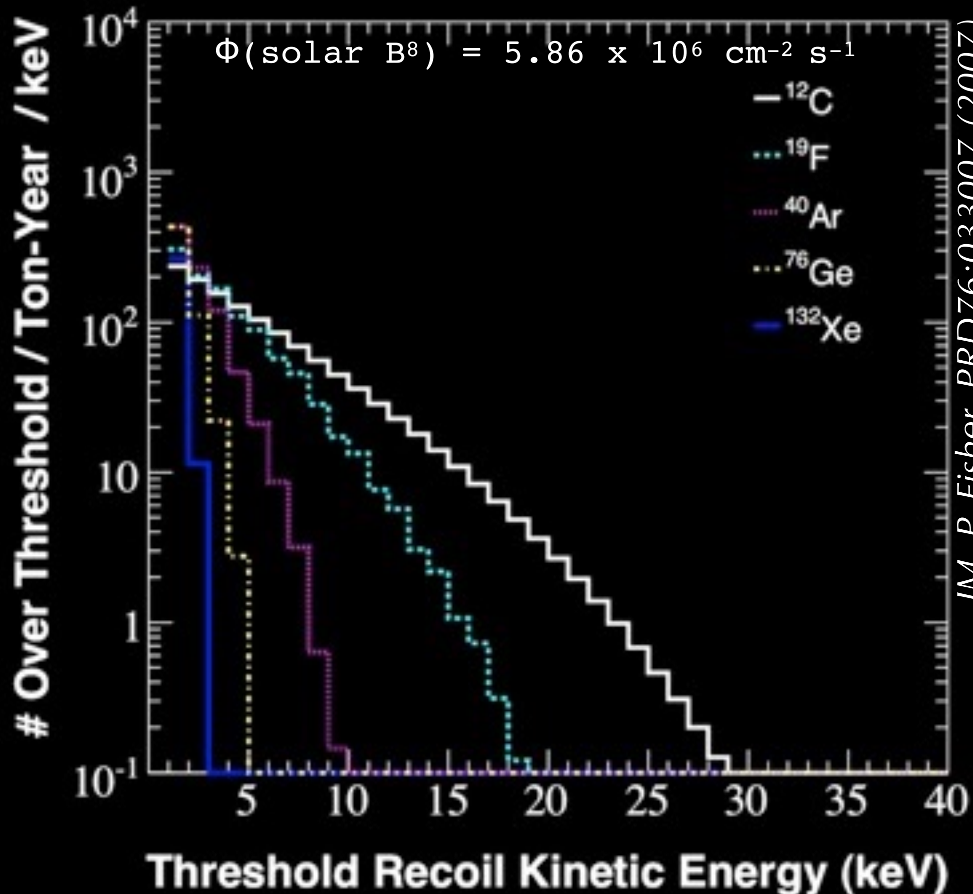
<u>Irreducible Backgrounds:</u>

impossible to shield a detector from coherent neutrino scattering!

A limiting background: neutrino floor/fog

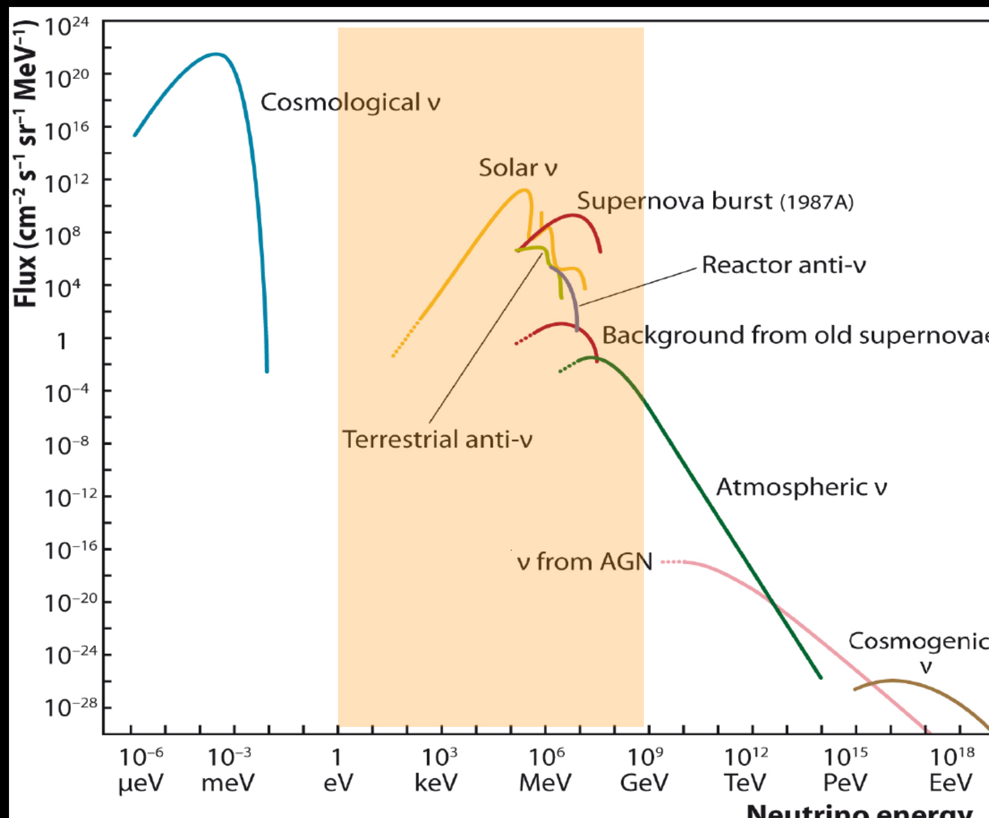






JM, P. Fisher, PRD76:033007 (2007)

…but also an *opportunity*.



Challenge 2: Low Rates!

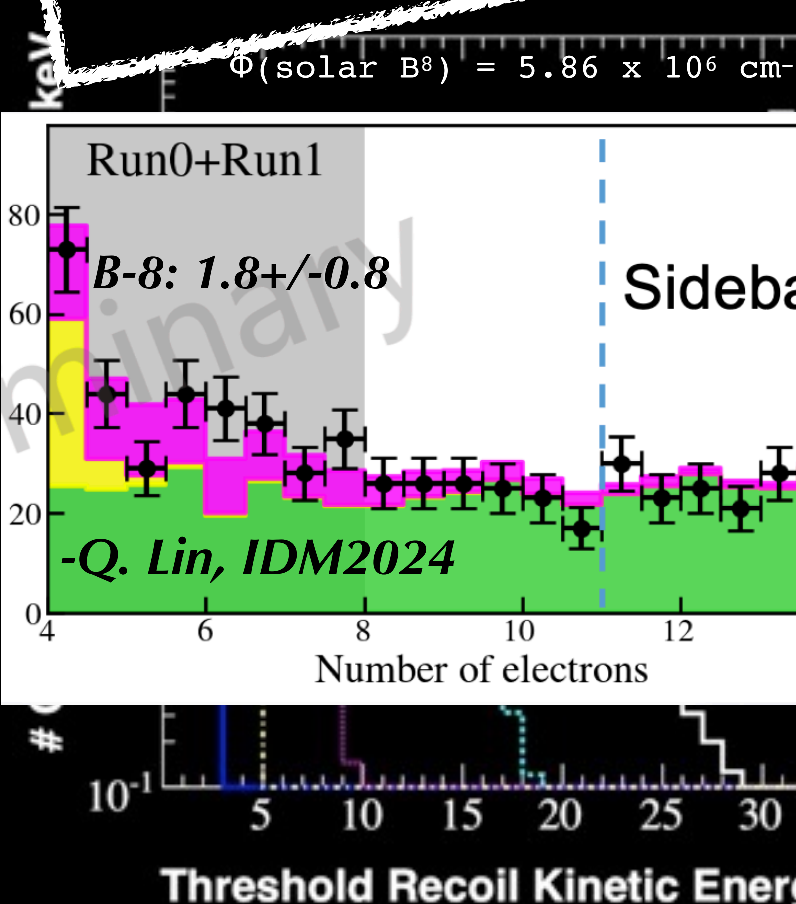
Irreducible Backgrounds:

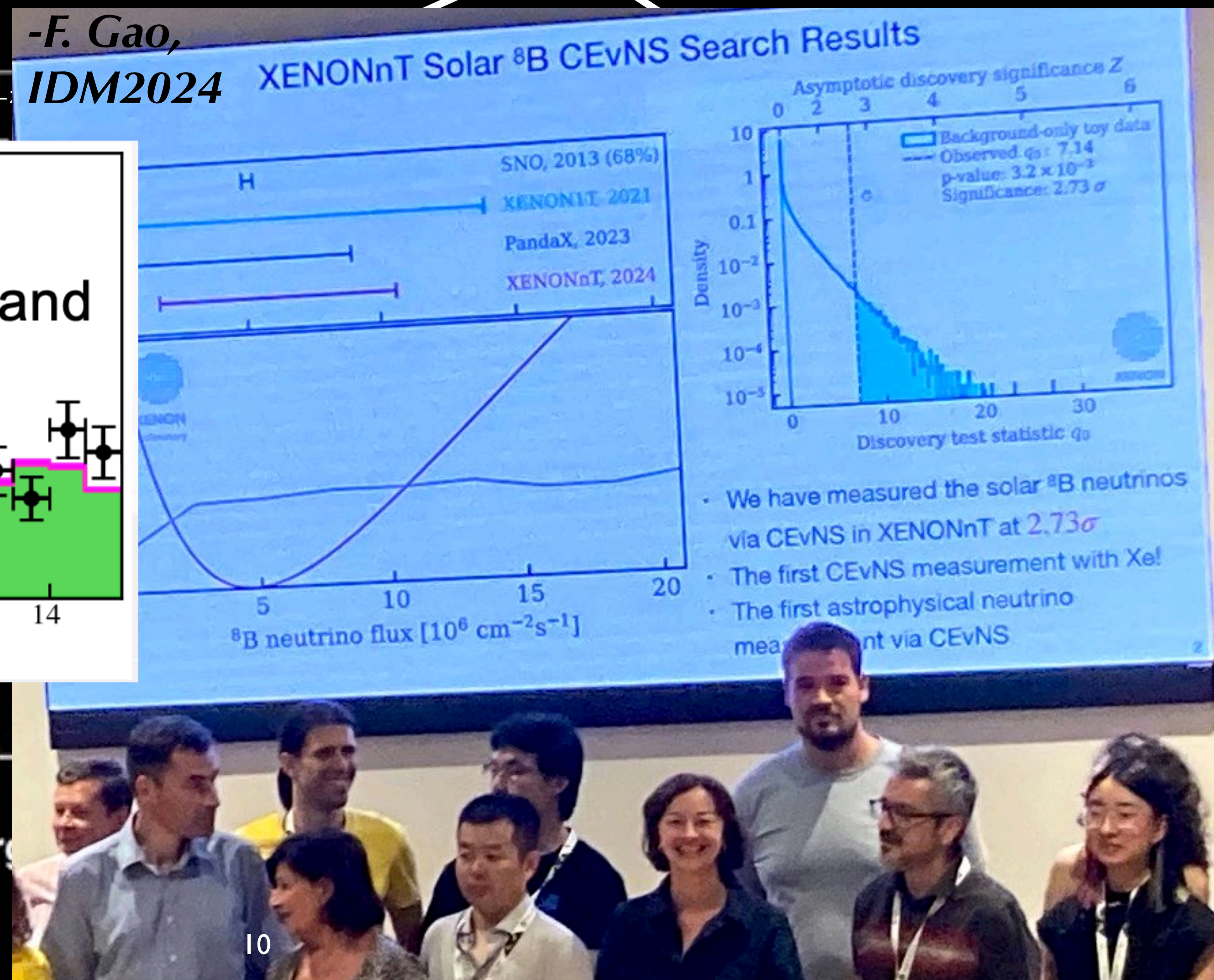
impossible to shield

coh

floor/fog

Yesterday's background is today's signal!

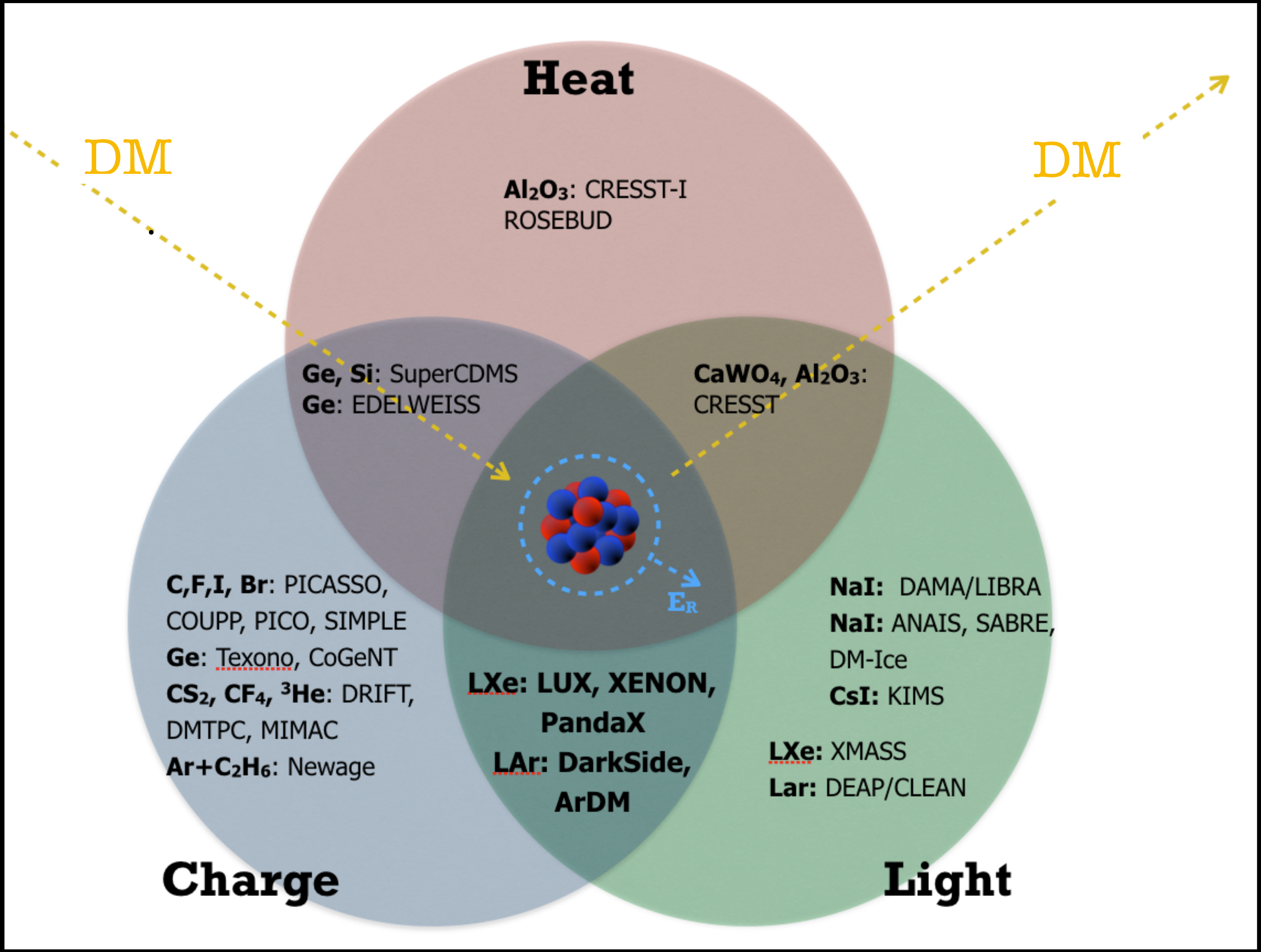




Challenge 3: Particle Identification

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

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

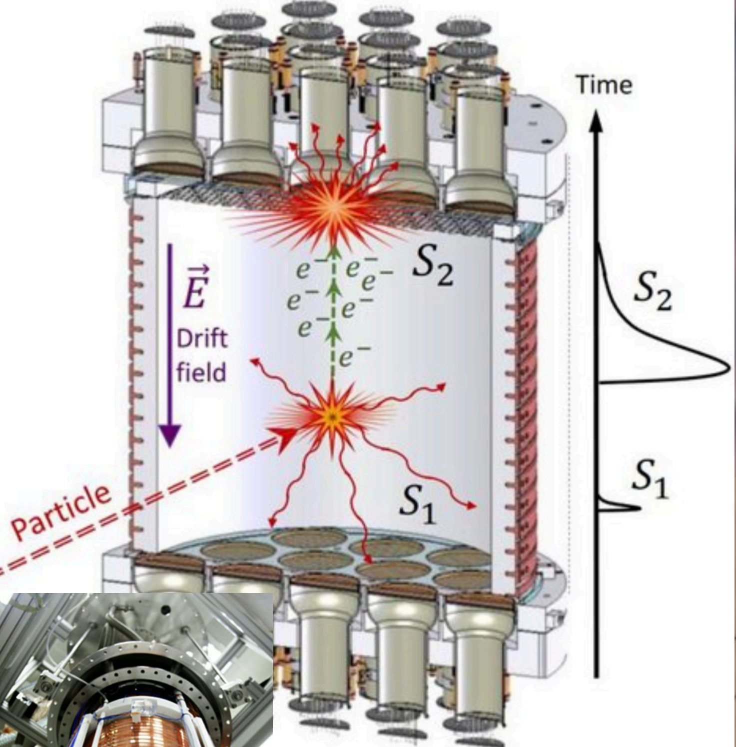


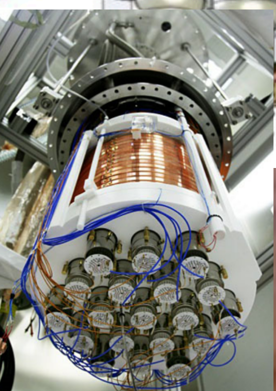
E_R threshold now O(10 eV), potential to reach eV

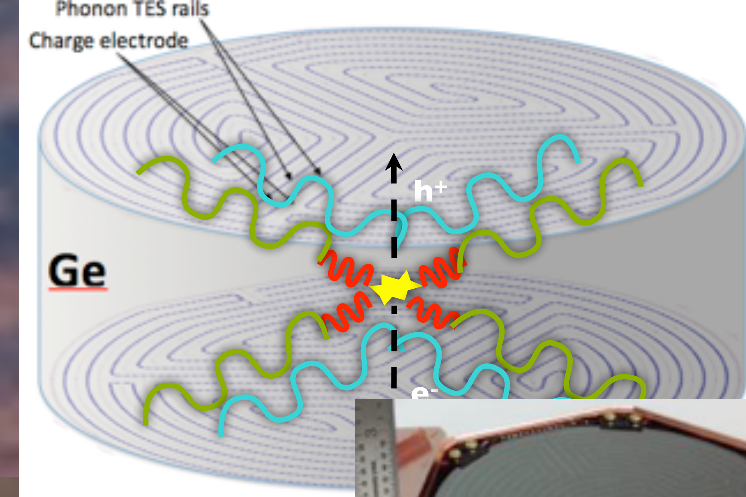
E_R threshold now O(keV), potential to reach 10 eV

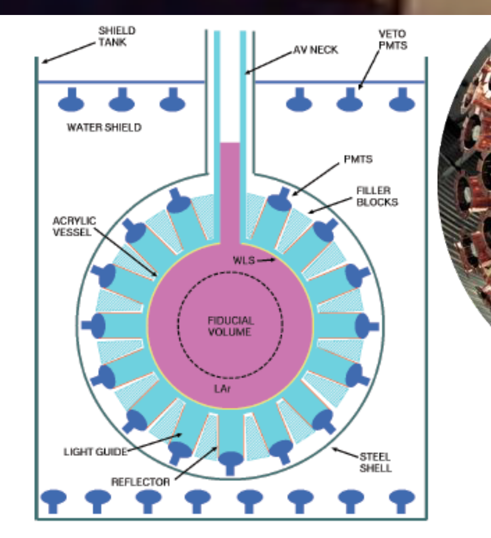
Detector Technologies

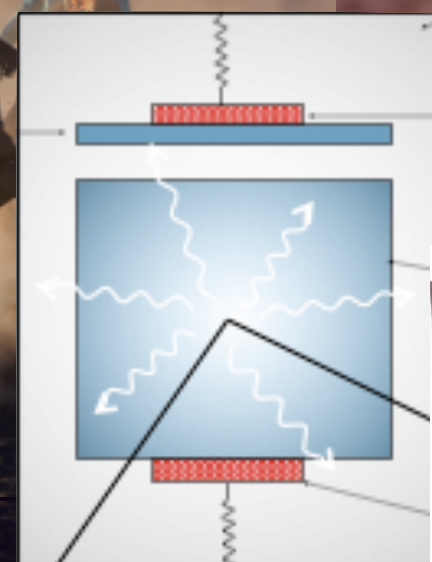
(not exhaustive!)

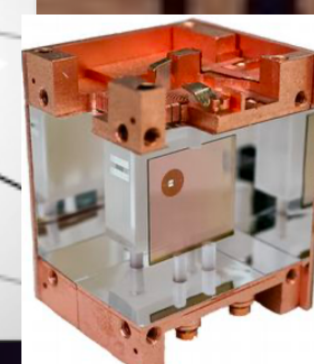








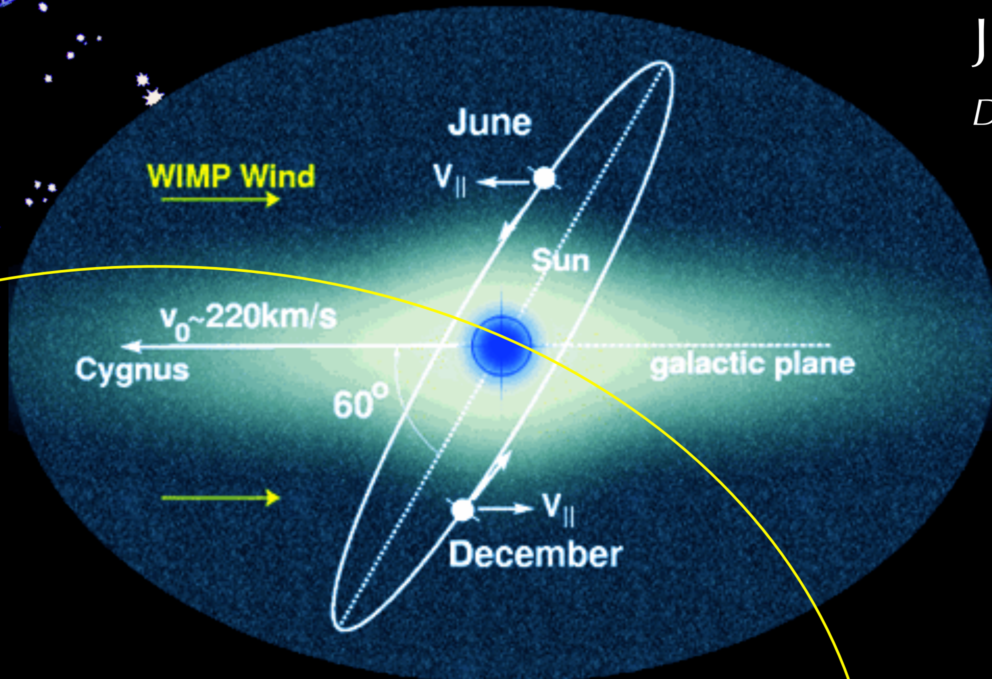


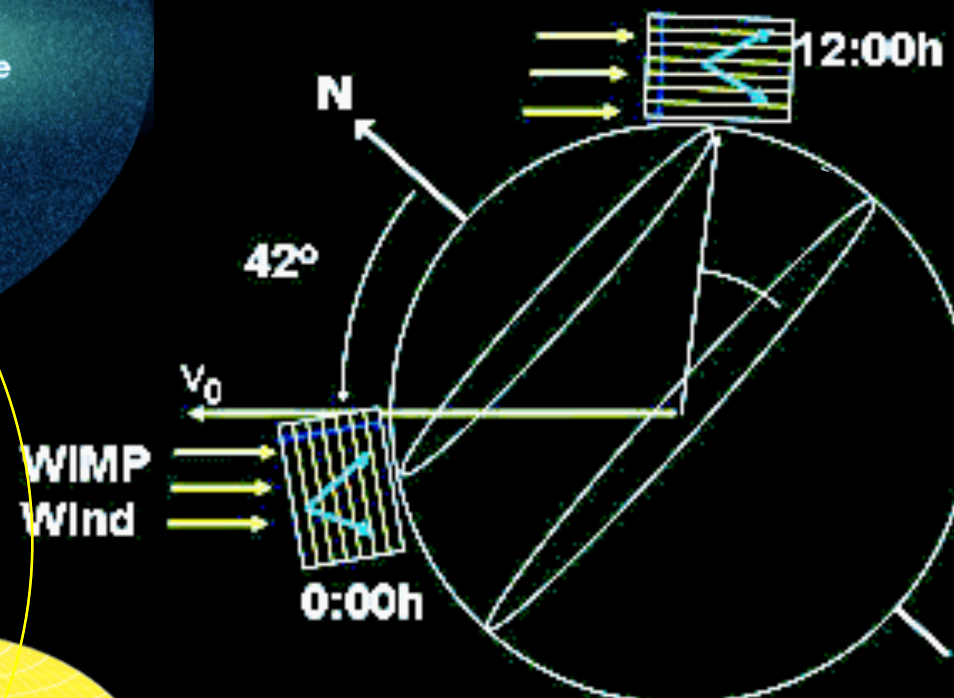


Modulation Signatures

Annual event rate modulation:
June-December asymmetry ~2%.

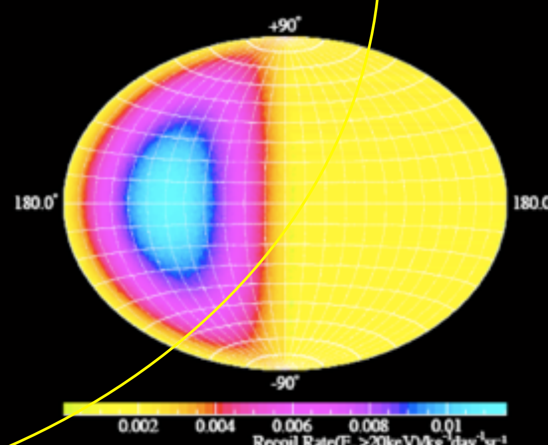
Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate

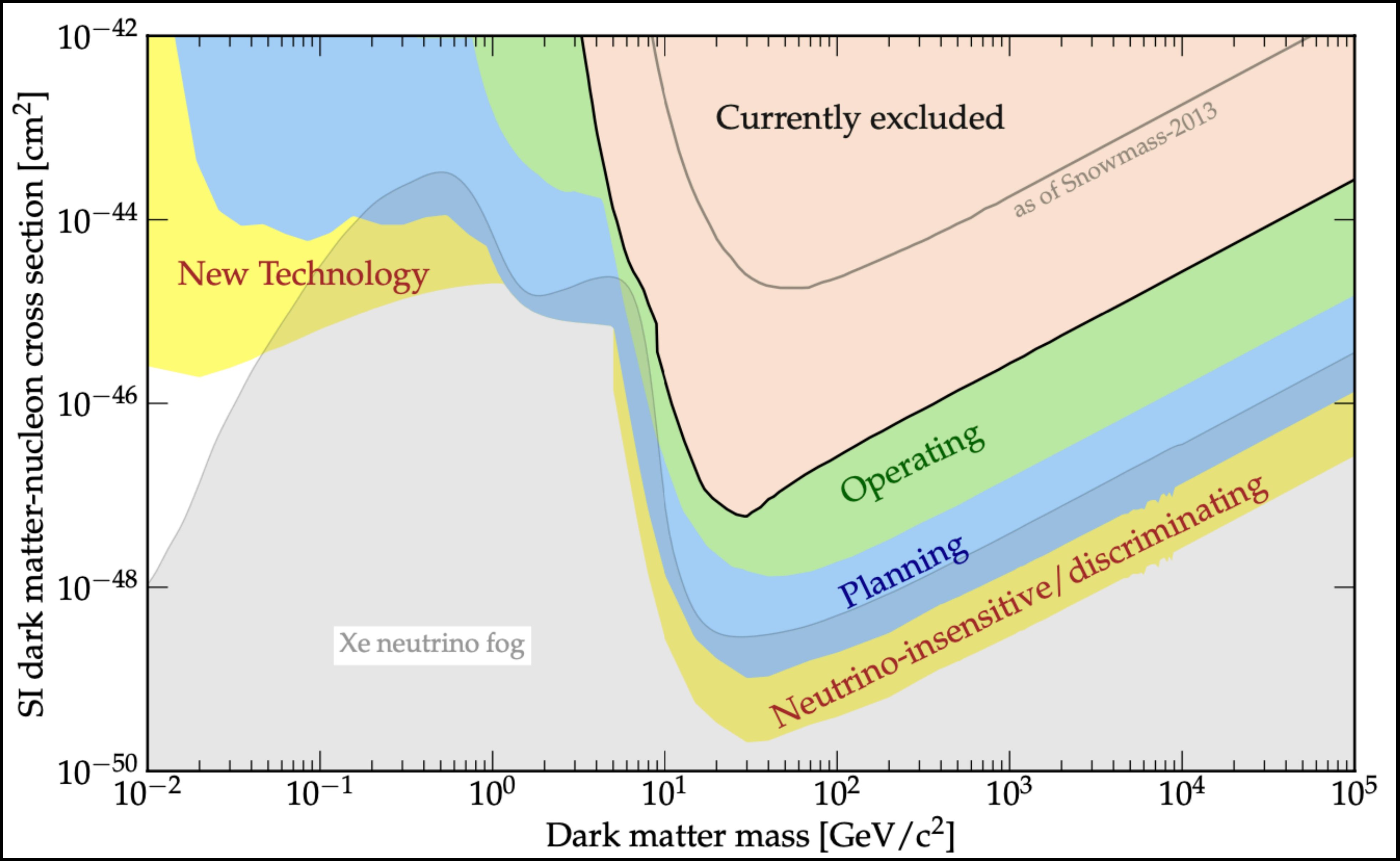
Spergel, Phys. Rev. D36:1353 (1988)



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

Direct Detection WIMP Searches

Snowmass Cosmic Frontier Report, arXiv:2211.09978



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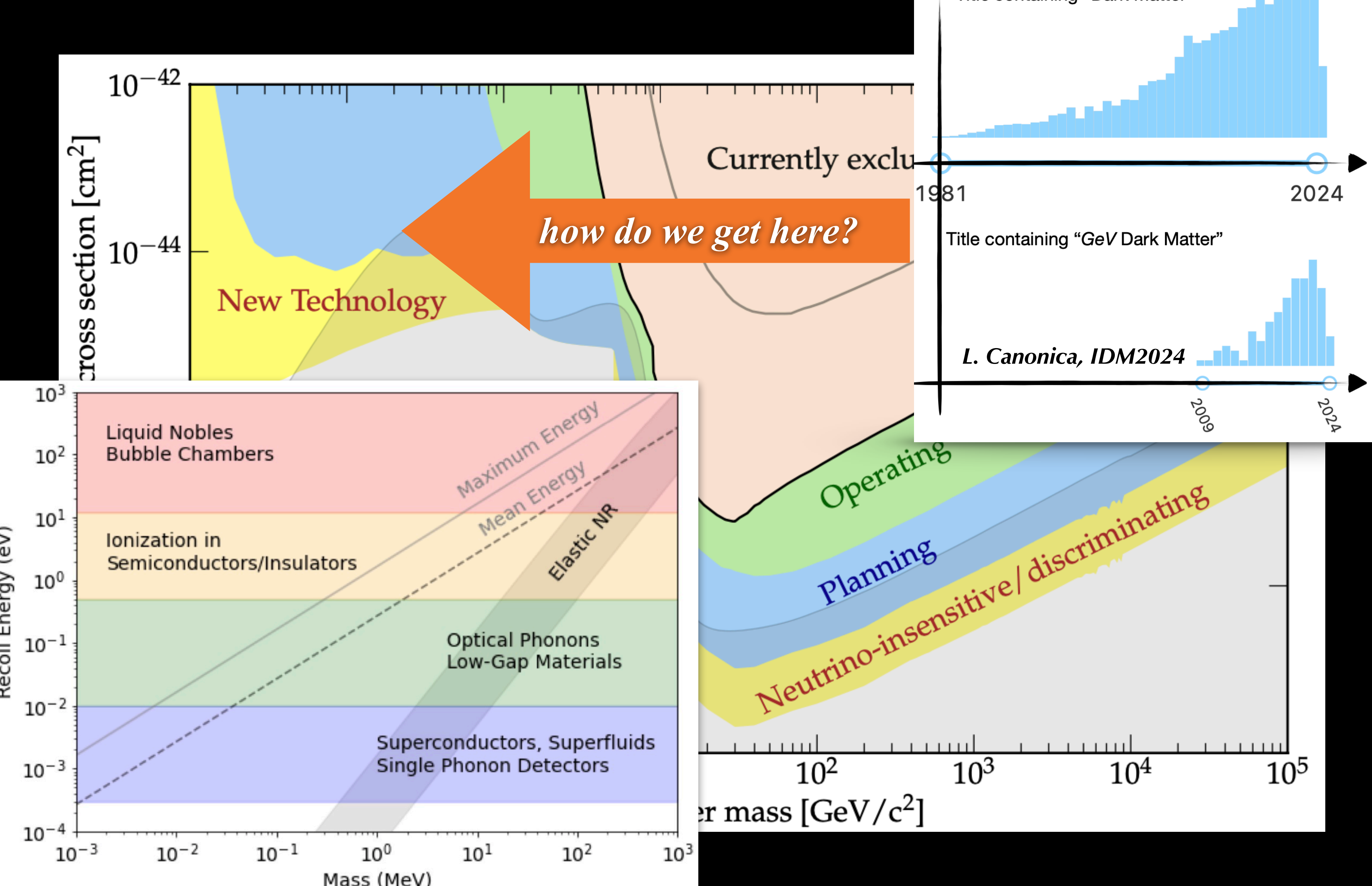

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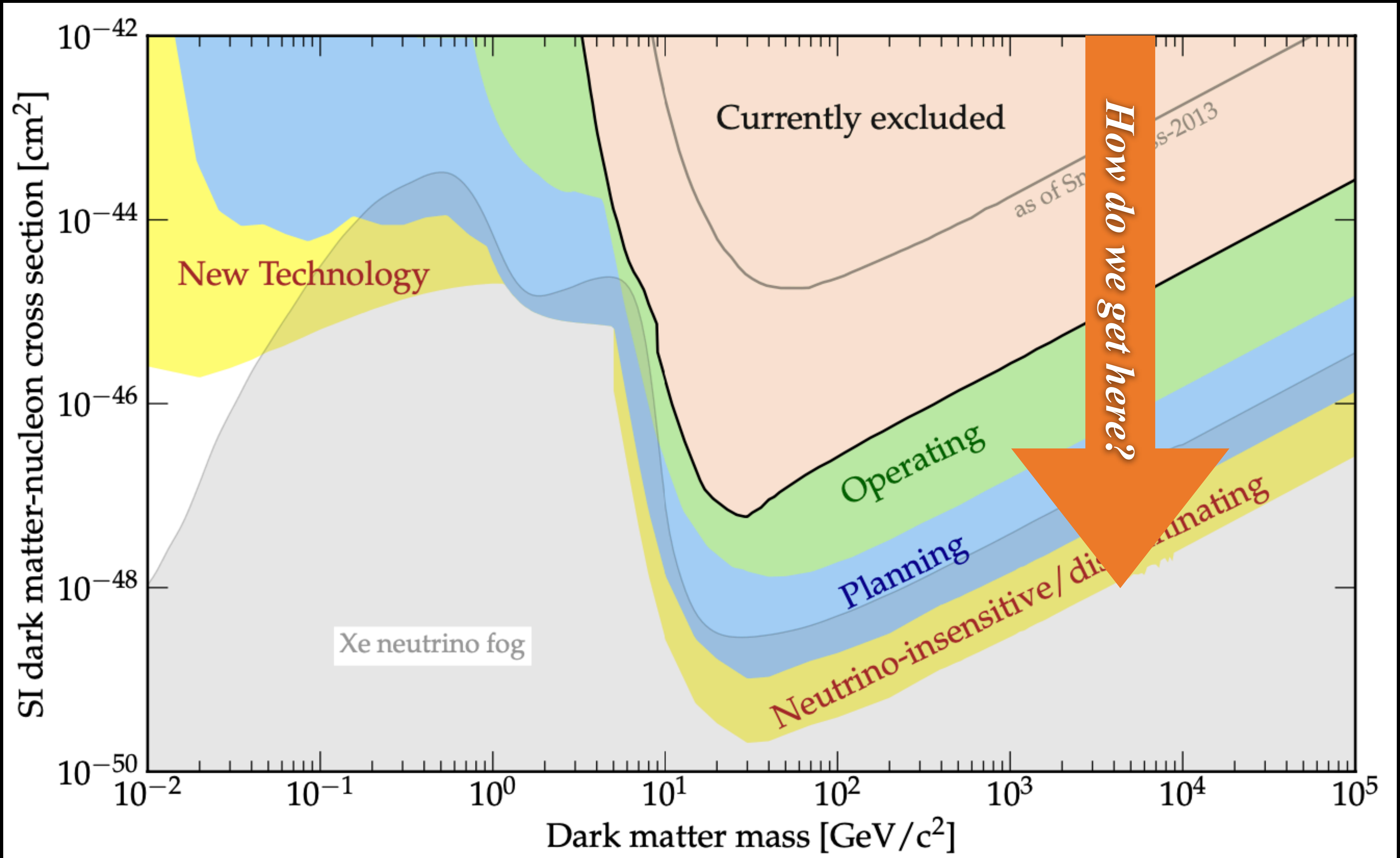


Xenon Detectors

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

2010

10 kg

XENON 10 (LNGS)

ZEPLIN I,II,III (Boulby)

100 kg

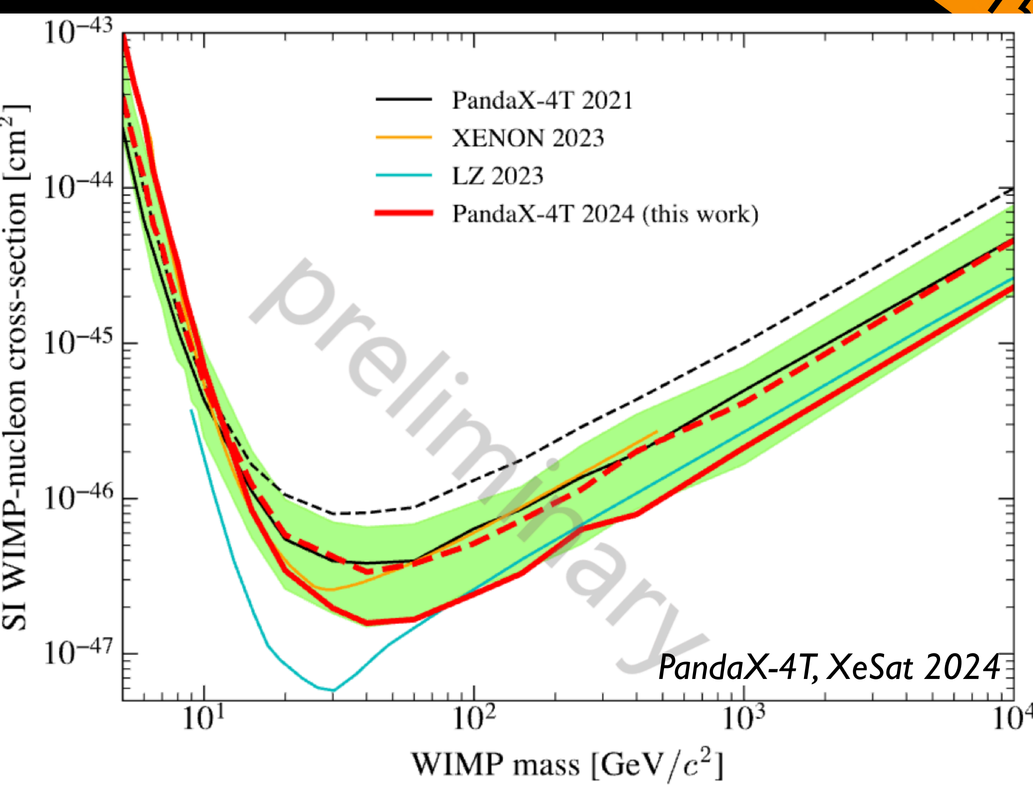
XENON 100 (LNGS)

LUX (250 kg, SURF)

PANDA-X 500 kg, CJPL)

XMASS (800 kg, Kamioka)

2015



1,000 kg

XENON 1T (1t, LNGS)

PandaX-4T: (4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

2020

10,000 kg

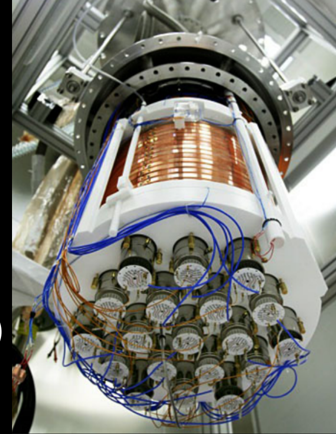
PandaX-20T: (20t, CJPL)

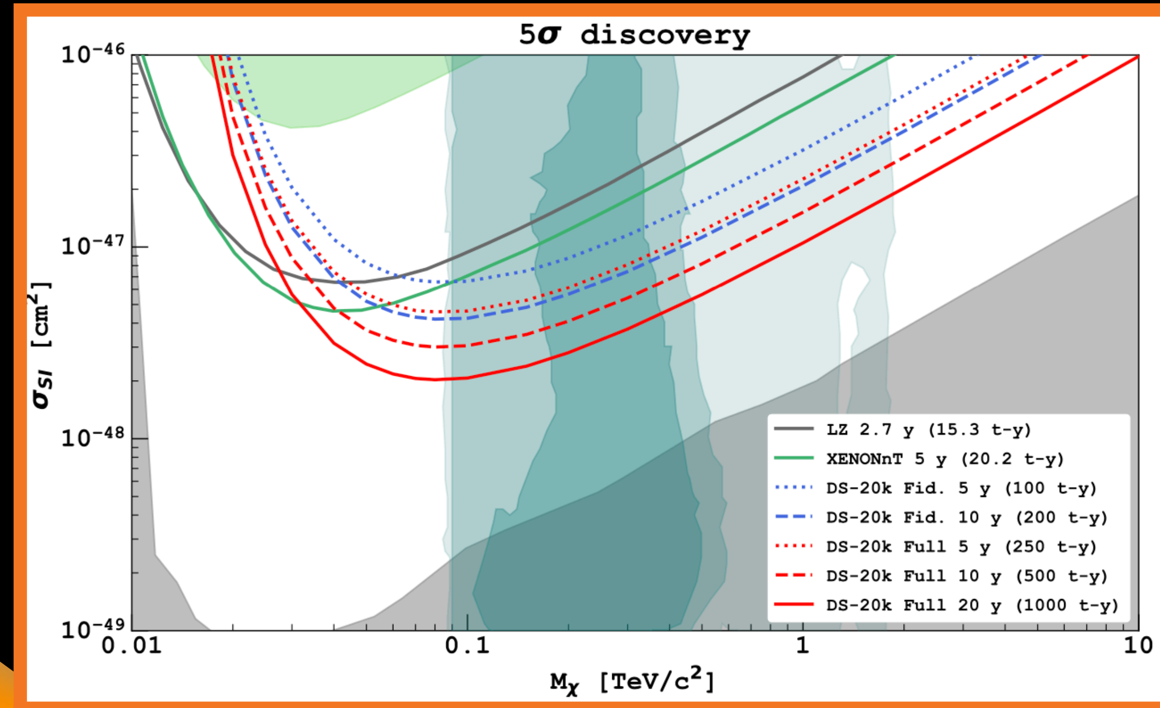
DARWIN/ XLZD

40-60 t

Argon Detectors

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





2010

10 kg

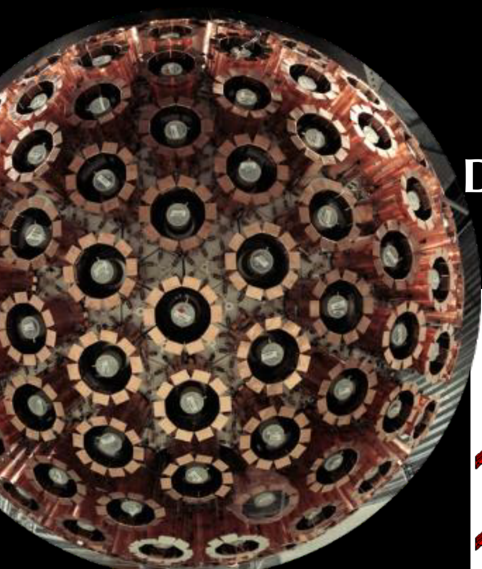
DarkSide-50 (50 kg, LNGS)

100 kg

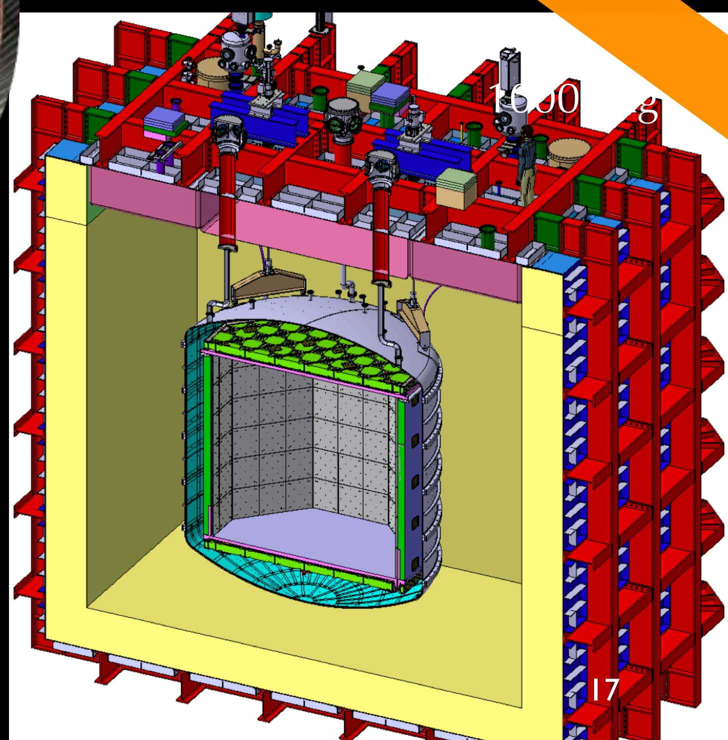
ArDM (1t, LSC)

2015

1,000 kg



DEAP-3600 (3.6t, SNOLAB)



Global Argon Dark Matter Collaboration formed

APPEC

10,000 kg

2020

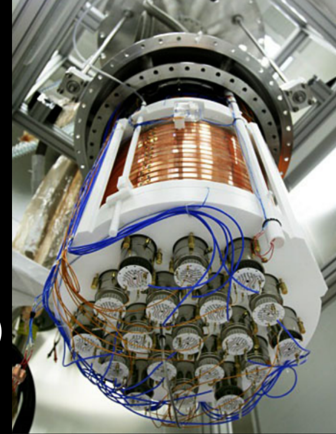
100,000 kg

DarkSide-20k (50t, LNGS)

Future: ARGO

kt-scale

Argon Detectors



DarkSide-50 (50 kg, LNGS)

10 kg

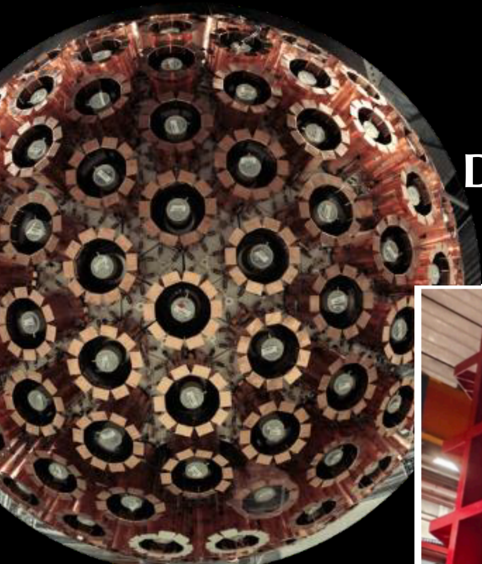
2010

100 kg

ArDM (1t, LSC)

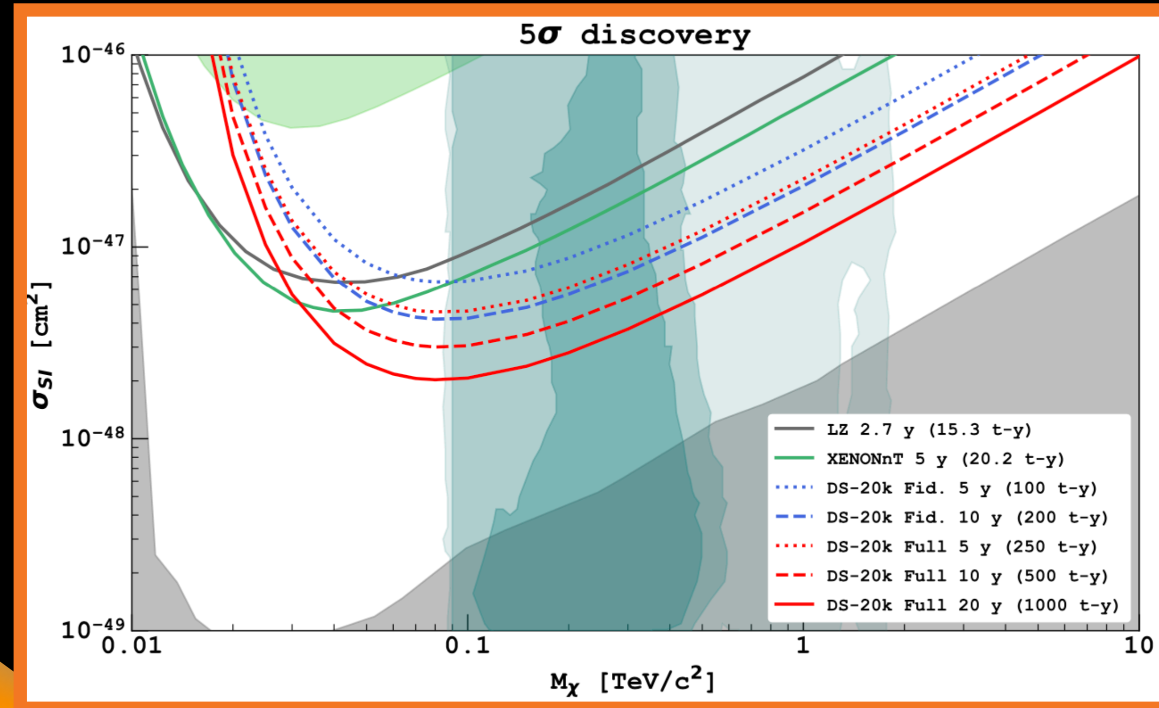
1,000 kg

2015



DEAP-3600 (3.6t, SNOLAB)

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



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10,000 kg

2020

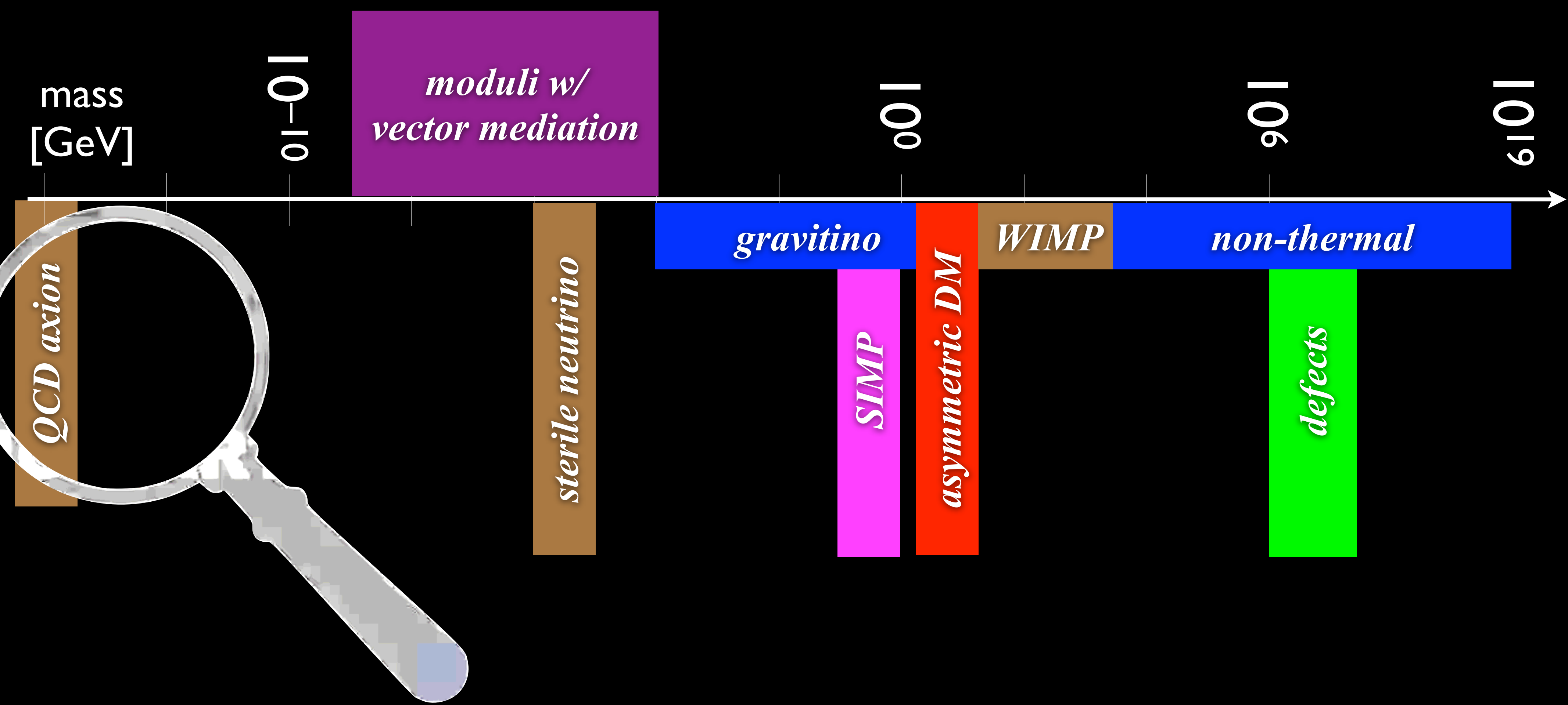
100,000 kg

DarkSide-20k (50t, LNGS)

Future: ARGO kt-scale

Jocelyn Monroe

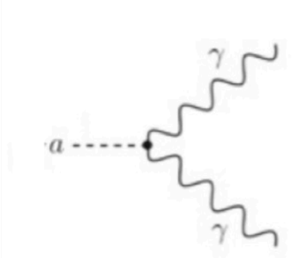
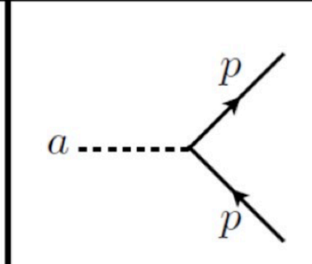
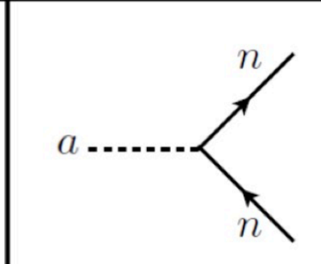
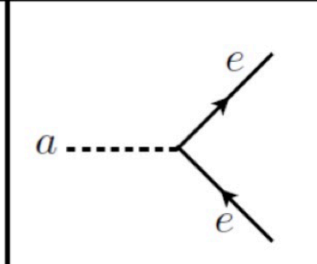
Theorist's View



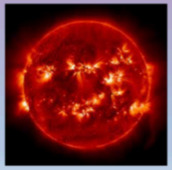
Axions

Motivated to solve strong CP Problem (KSVZ/DFSZ)

Detection Channels:

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap}m_p\frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an}m_n\frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae}m_e\frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			
$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a}$	$g_{ap} = C_{ap}\frac{m_p}{f_a}$	$g_{ap} = C_{an}\frac{m_n}{f_a}$	$g_{ap} = C_{ae}\frac{m_e}{f_a}$

Detection Strategies:

Source		Experiments	Model & cosmology dependency
Relic axions		Haloscopes	High (assume axions are all of the DM)
Lab axions		Light-Shining-Through-Wall Experiments	Very low
Solar axions		Helioscopes	Low

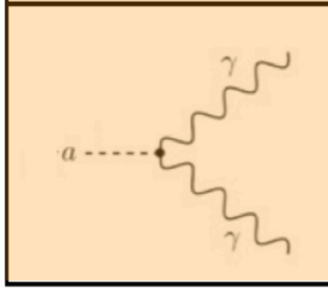
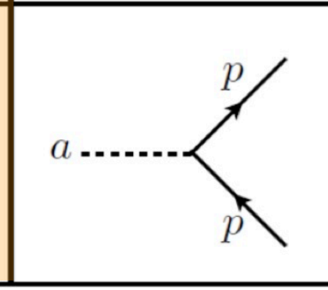
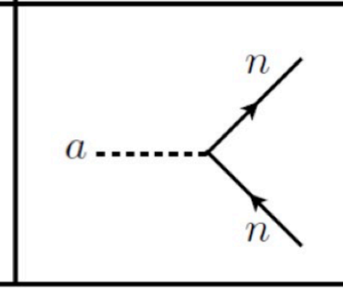
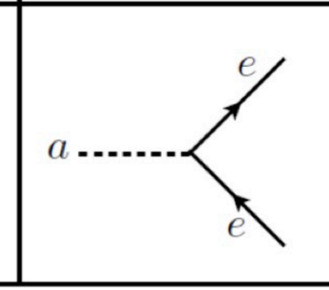
J. Vogel, IDM2024

Axions

Motivated to solve strong CP Problem (KSVZ/DFSZ)

Detection Channels:
Axion converts into a photon in a cavity in a ***B*** field, measure microwave power

Detection Strategies:

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			
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Source		Experiments	Model & cosmology dependency
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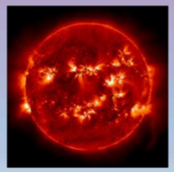
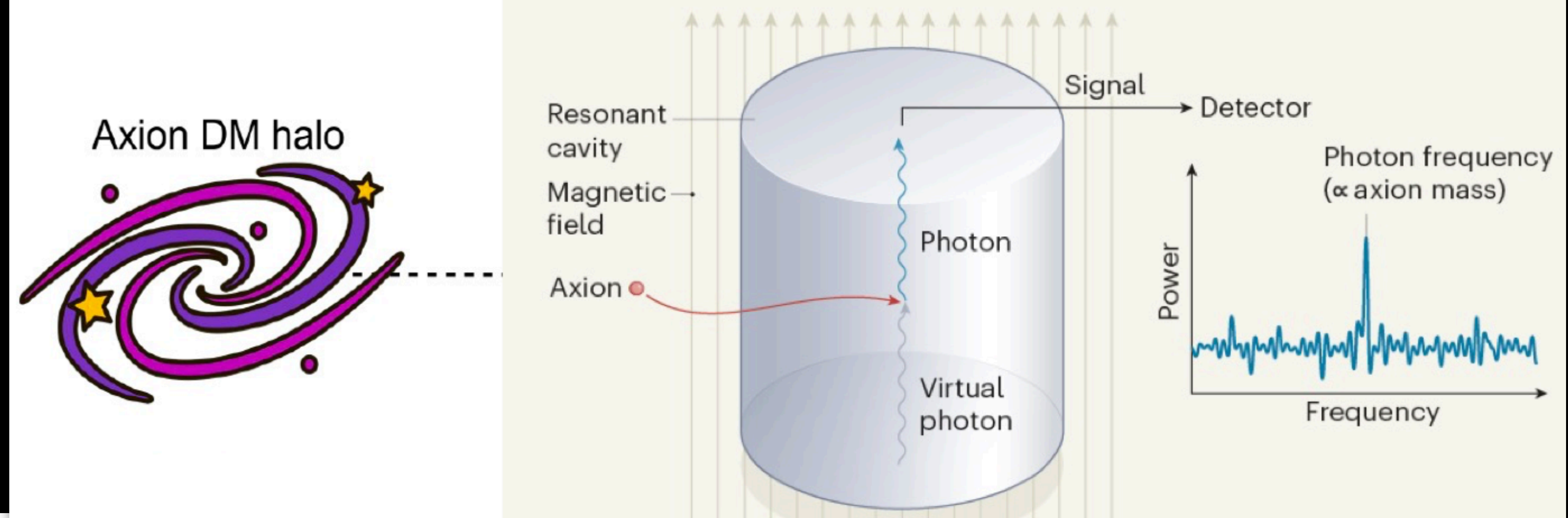
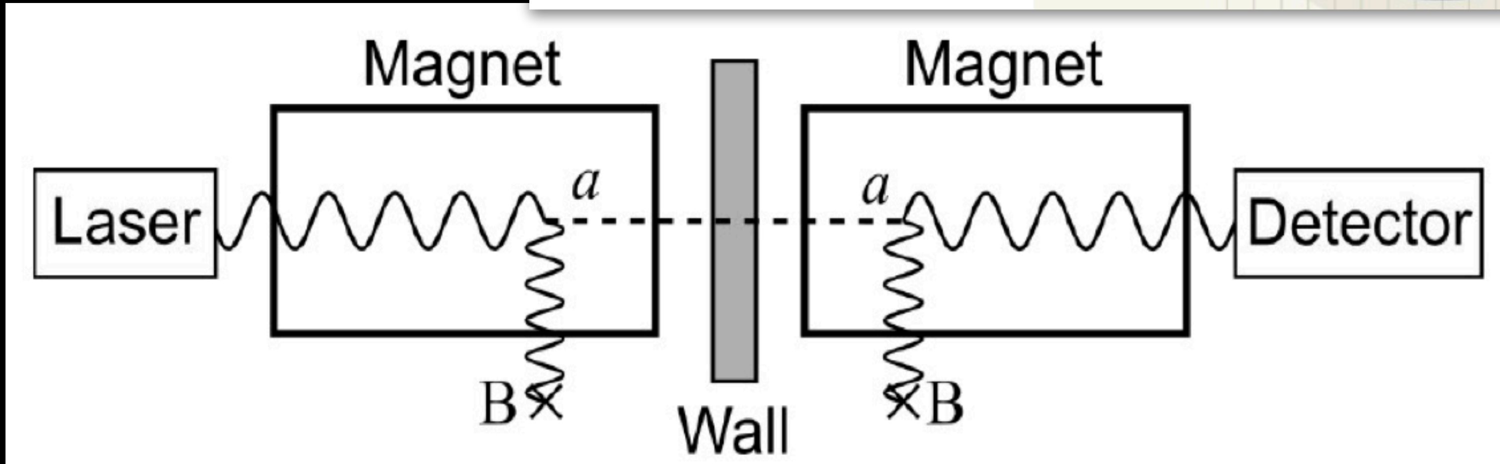
Solar axions		Helioscopes	Low

J. Vogel, IDM2024

Axions

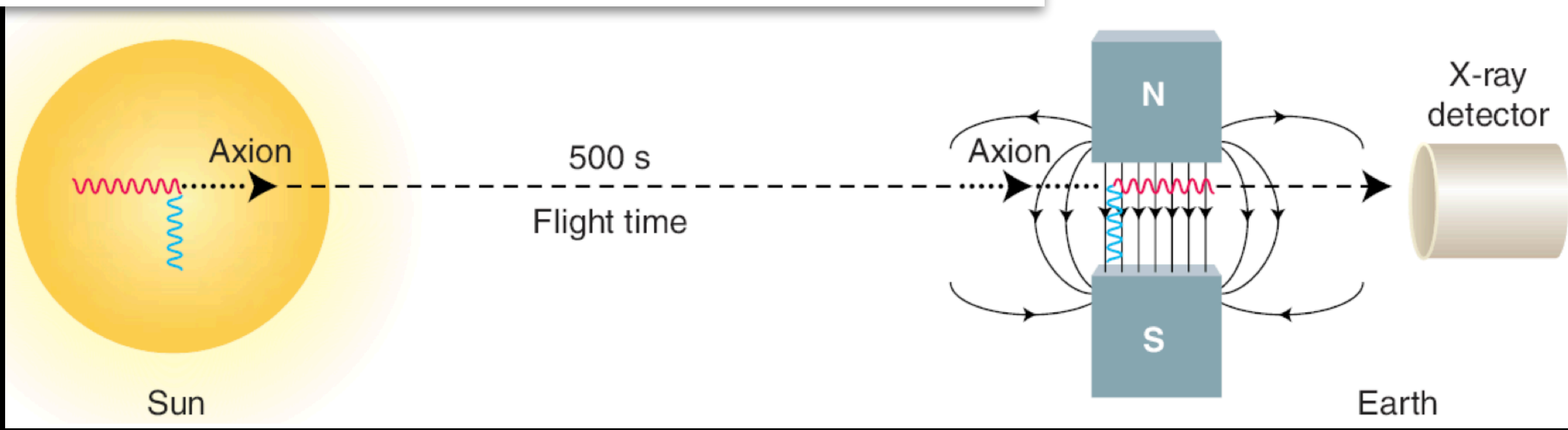
Haloscopes: ADMX, HAYSTAC, QUAX, CAST-CAPP, RADES+ many more …..





Light-Shining-through-a-Wall Experiments: ALPS, ALPS-II, OSQAR

Helio-Scopes SUMICO, CAST, IAXO

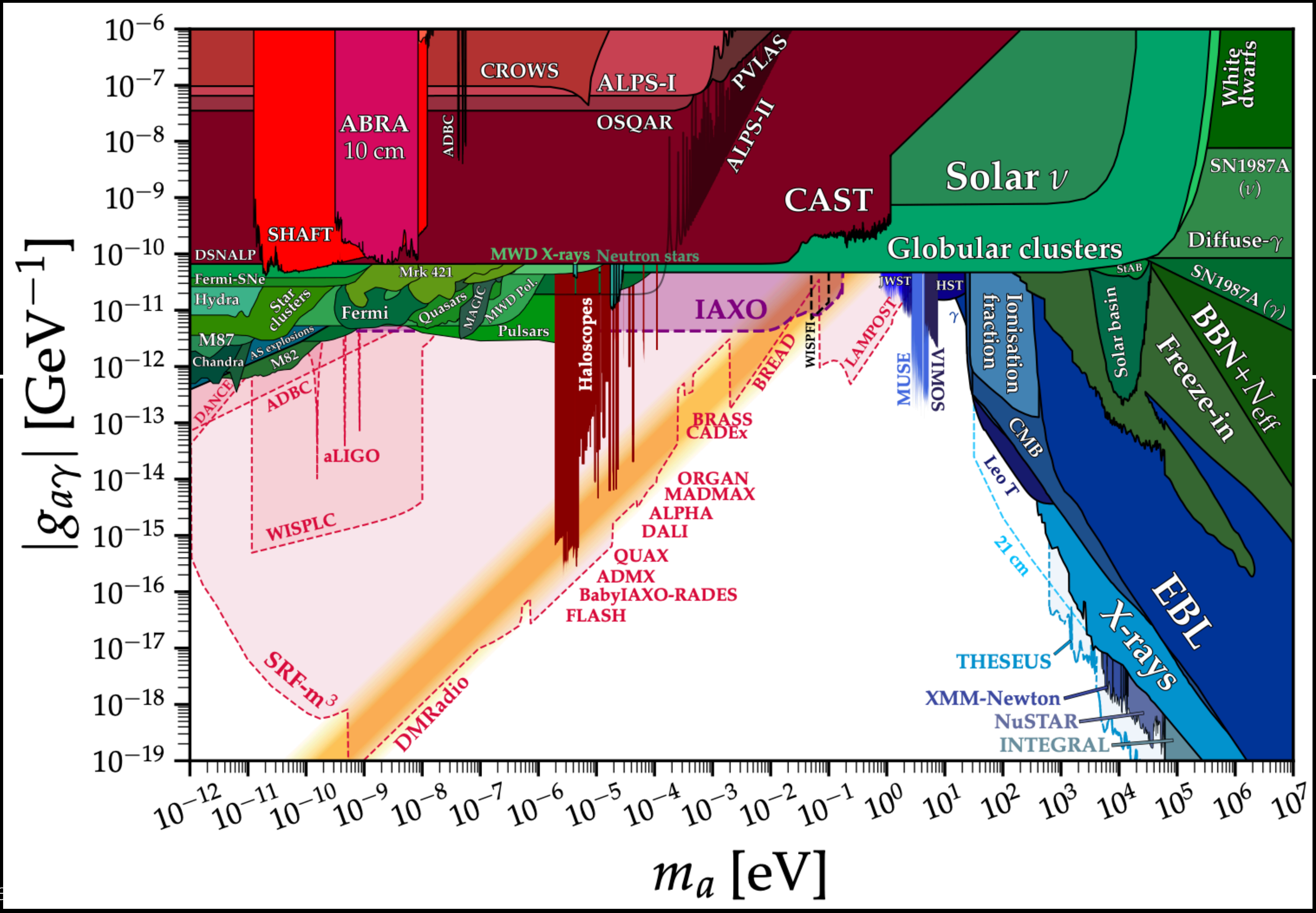


Axions

Huge range of techniques, strong overlap with quantum sensors development

mass [GeV]

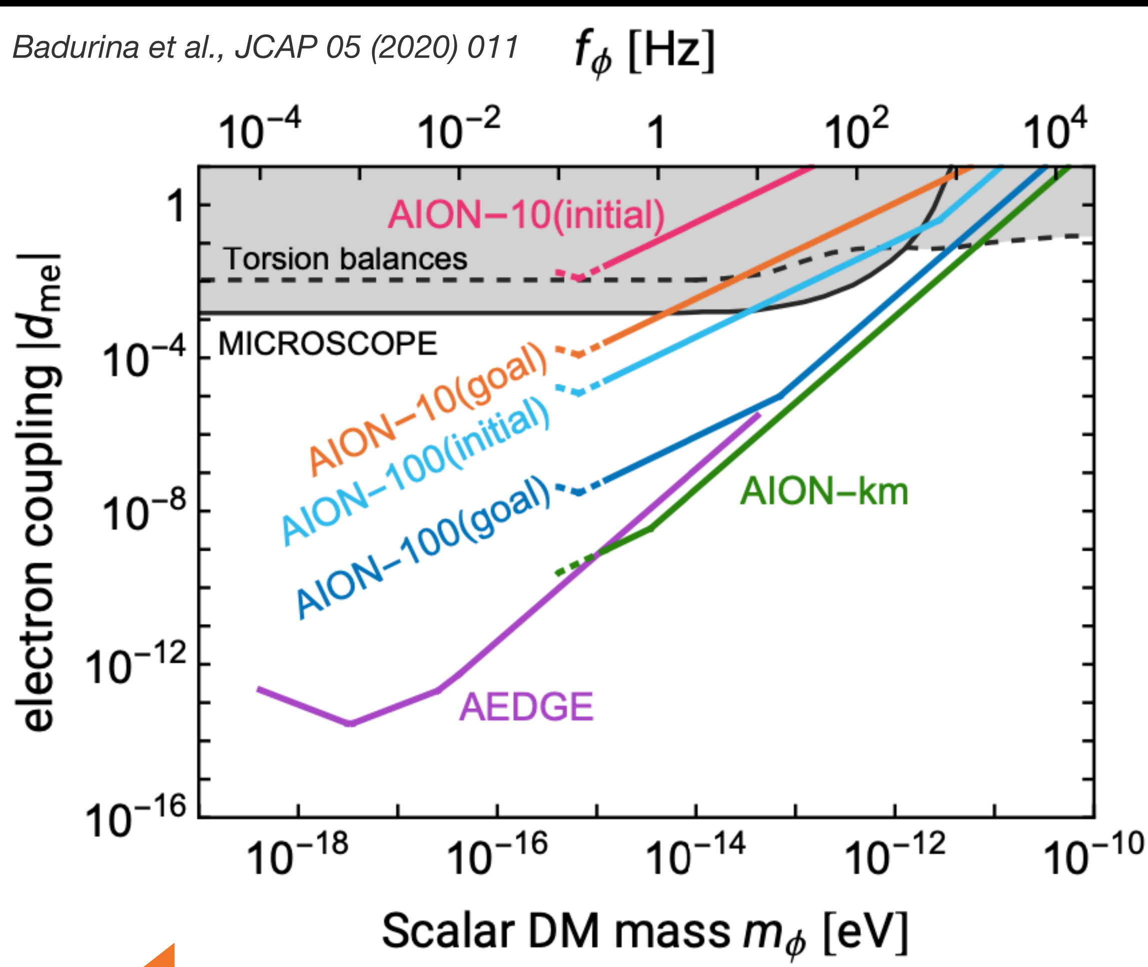
QCD axion

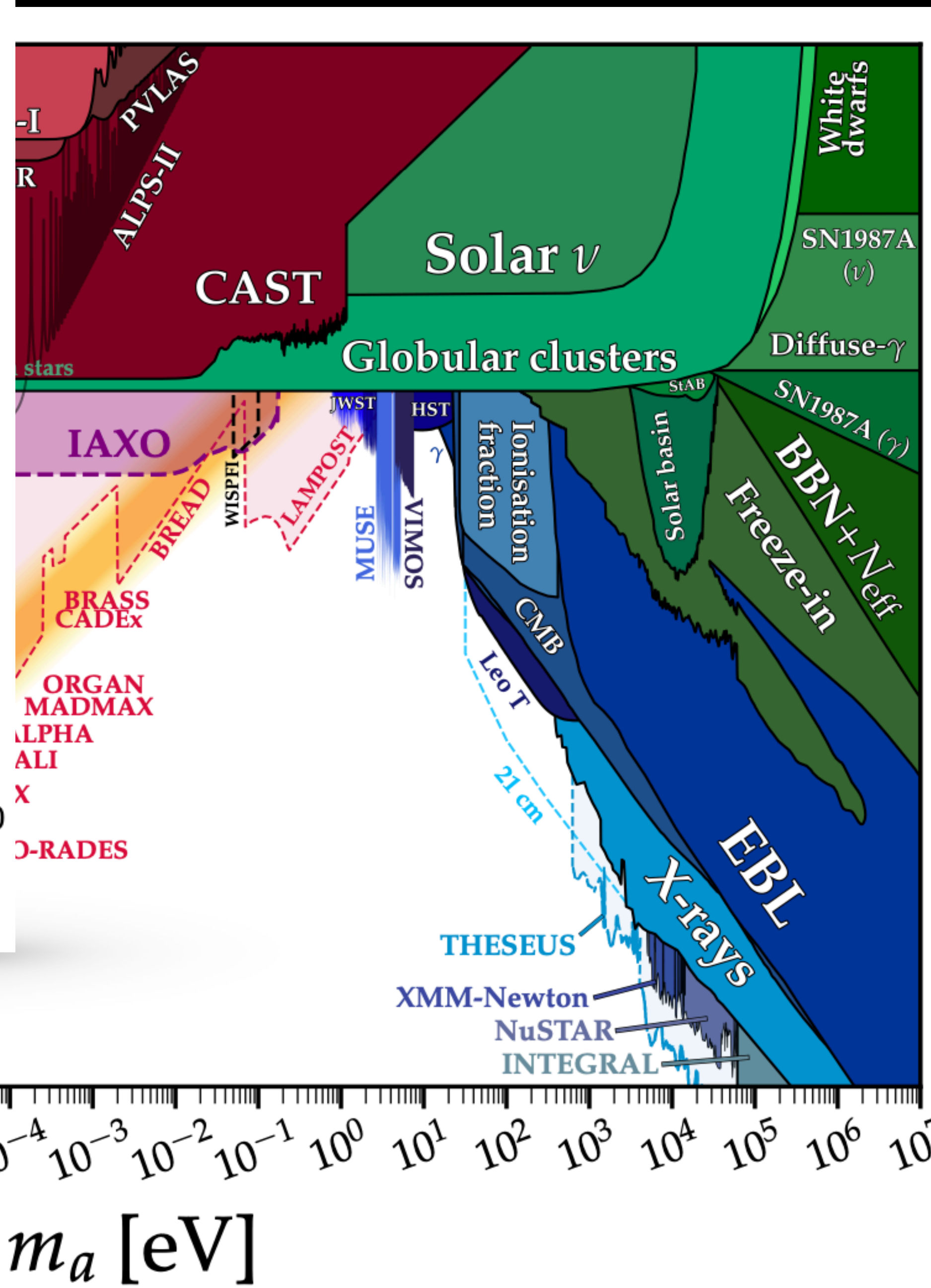


Joce

Axions

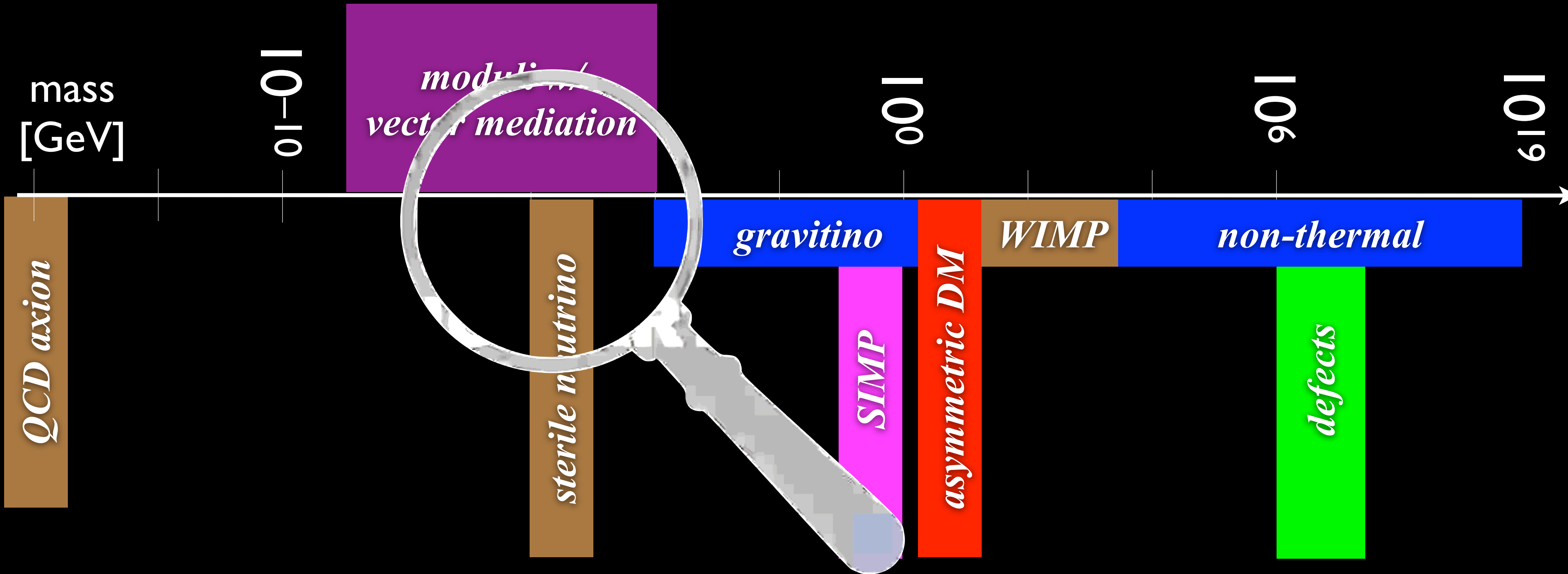
Huge range of techniques, strong overlap with quantum sensors development





how do we get here?

Theorist's View

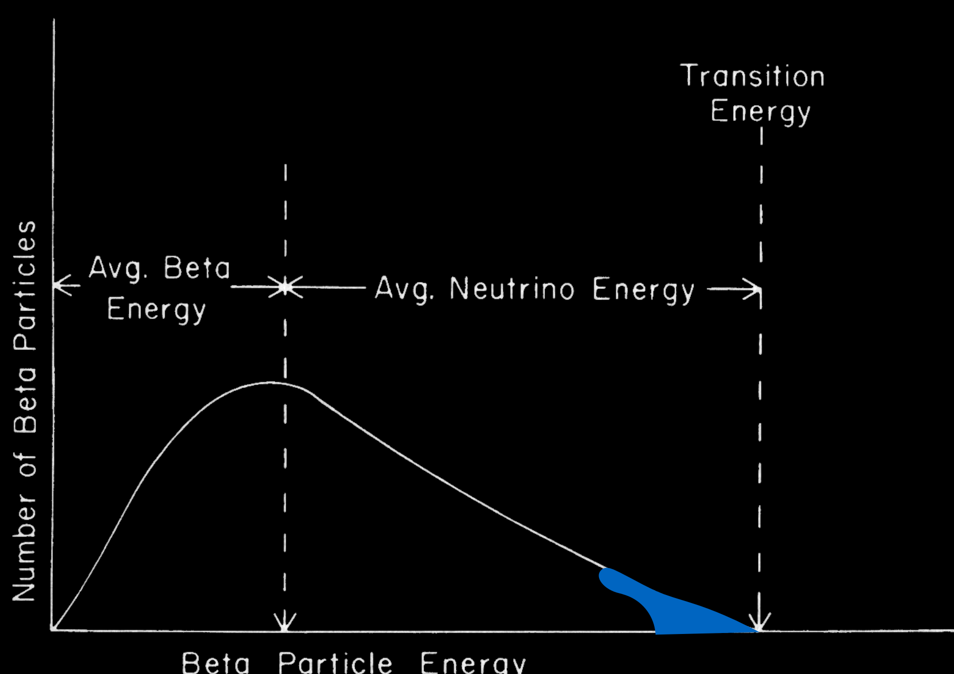


Warm Dark Matter

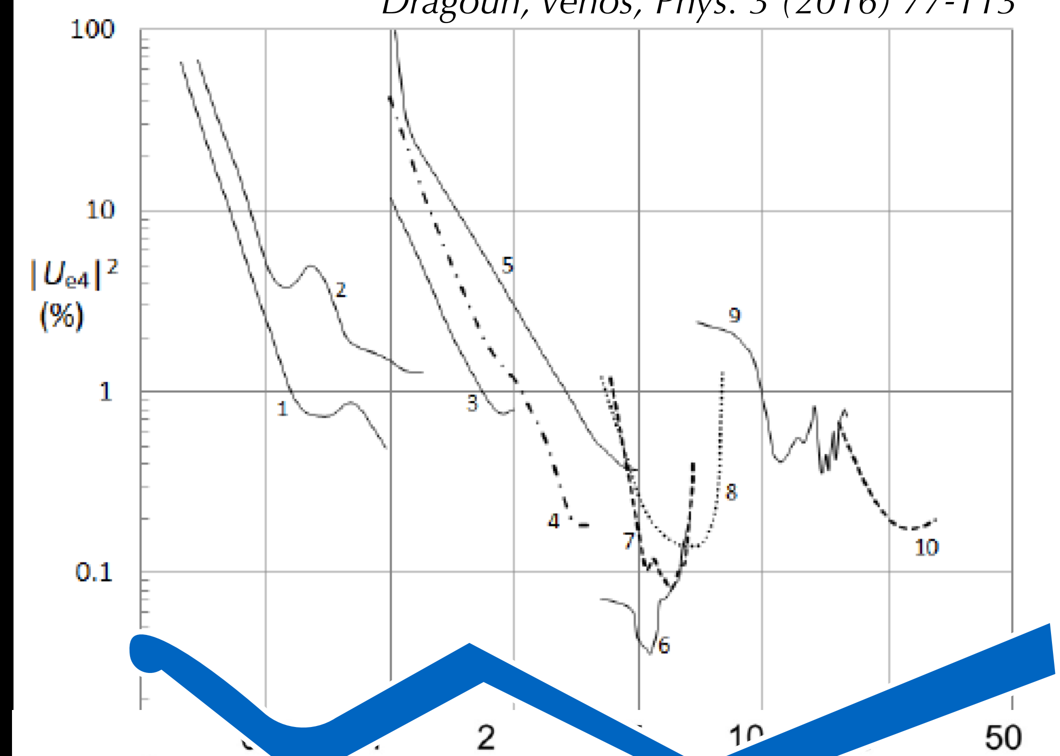
Sterile neutrino dark matter can scatter with electrons $N_S\ e^- \rightarrow \nu_e\ e^-$

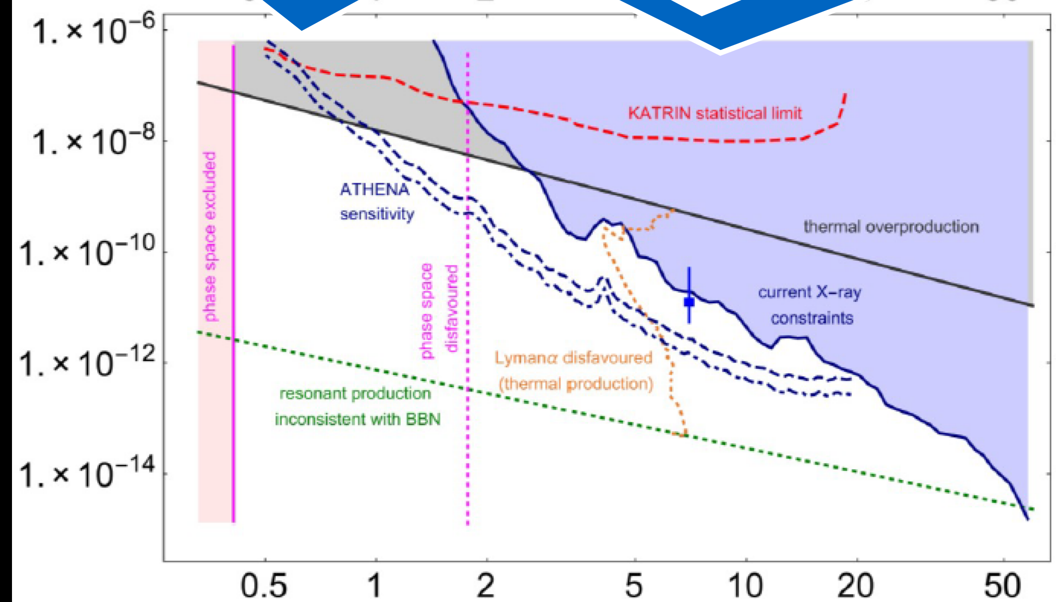
Constraints on $|U_{e4}|^2$ from beta decay: energy spectrum modified by sterile neutrino mixing.

Constraints from indirect detection: x-ray energy spectrum strongly limits $|U_{e4}|^2$



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





Weinheimer, ESPPU'19

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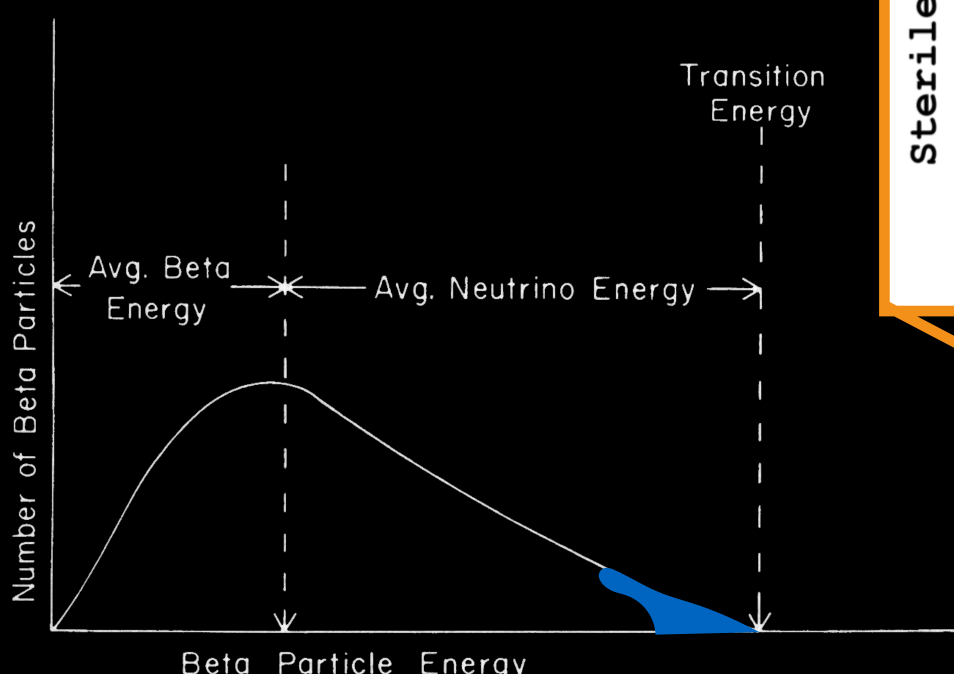
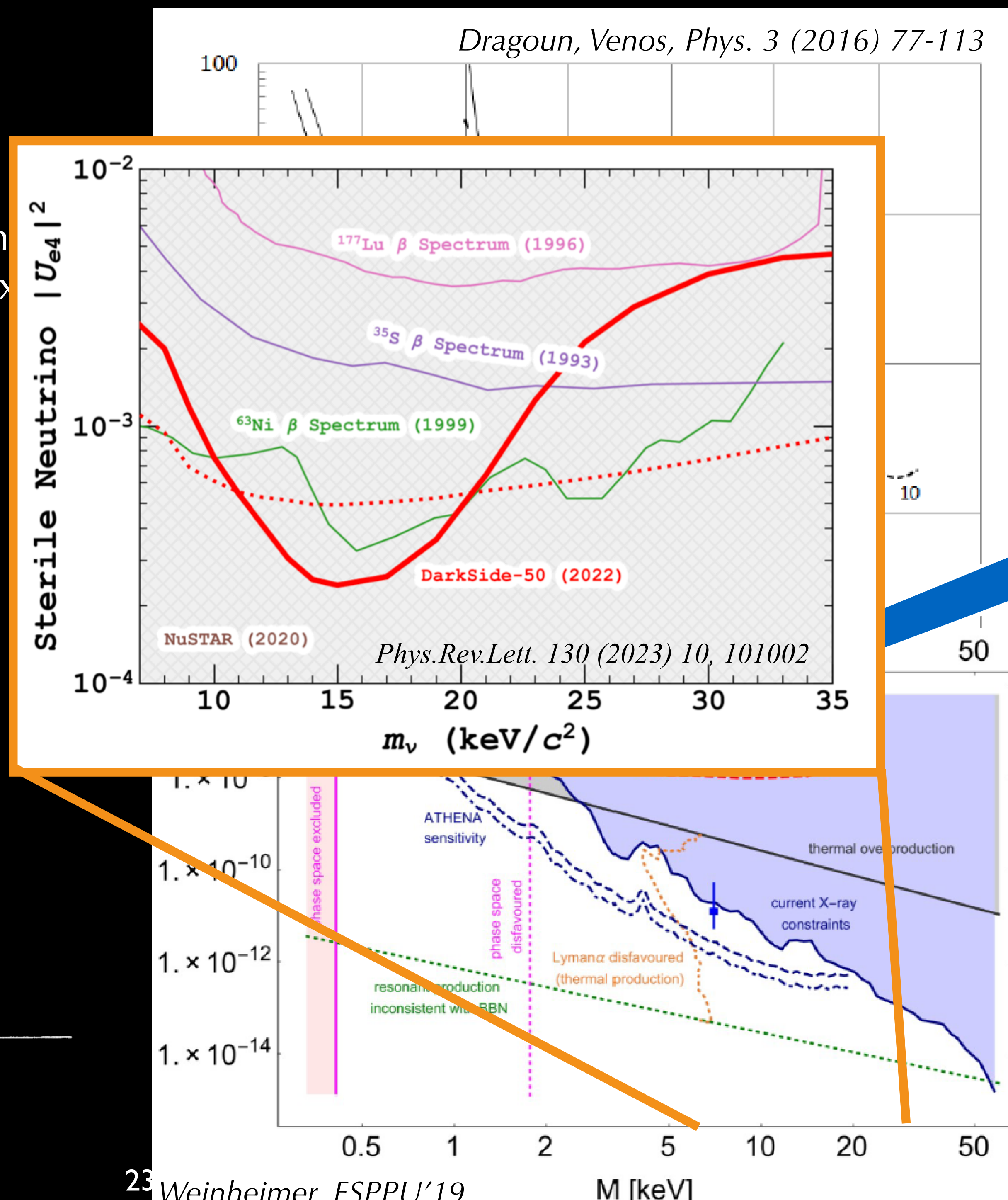
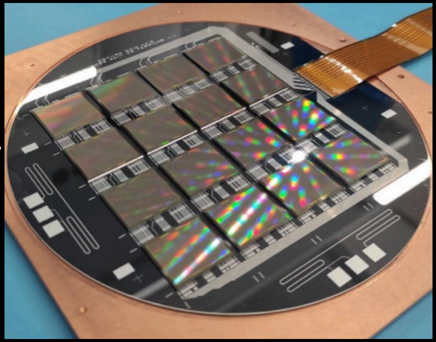
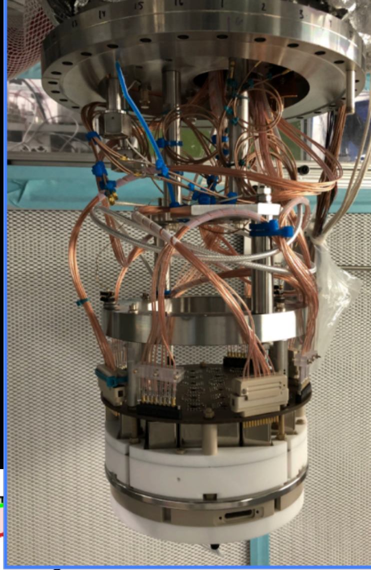
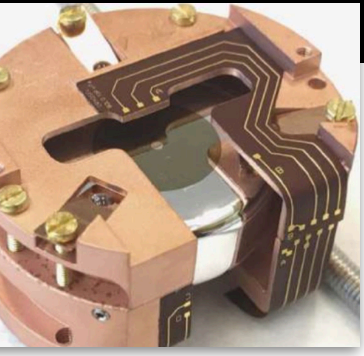
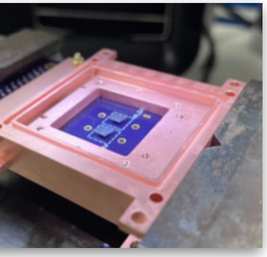
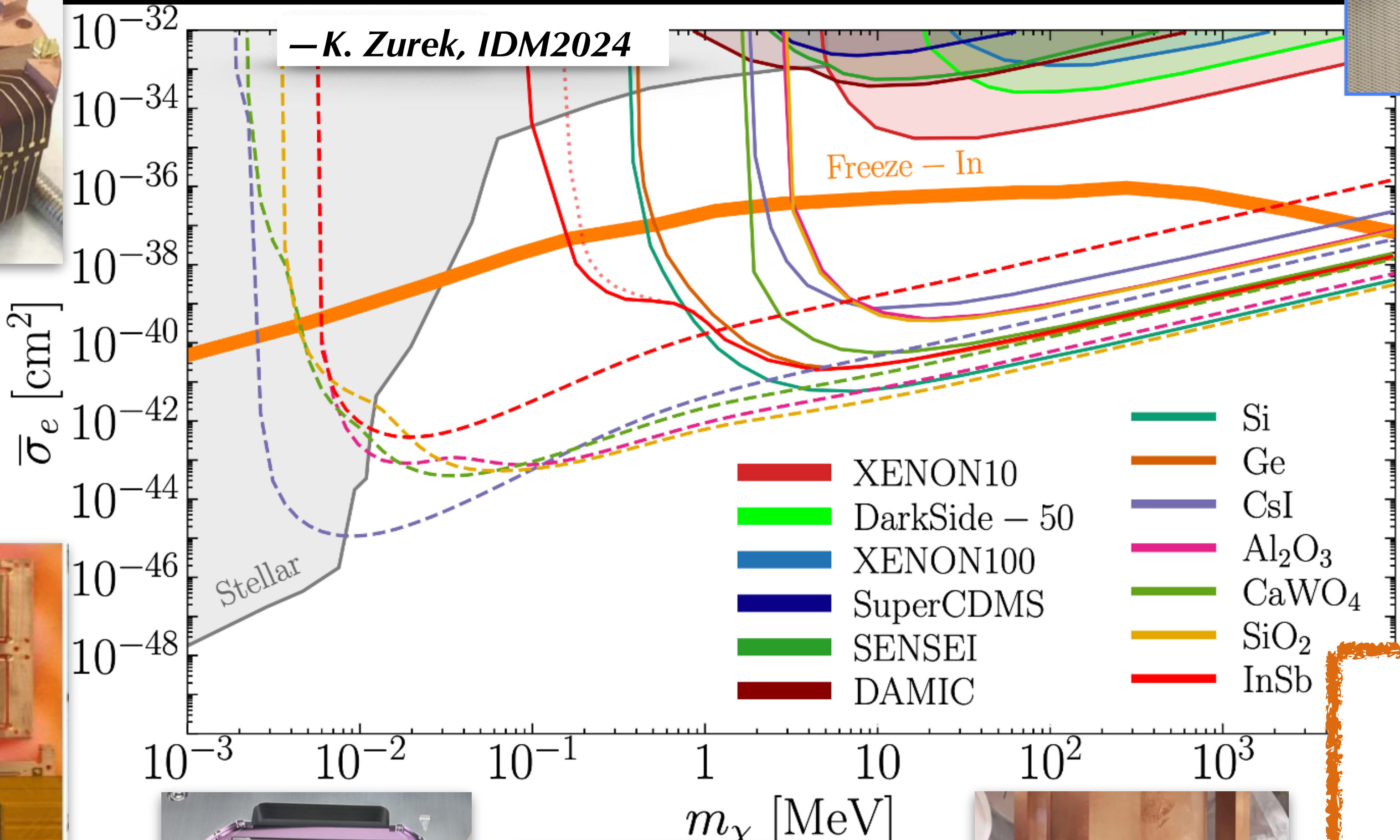


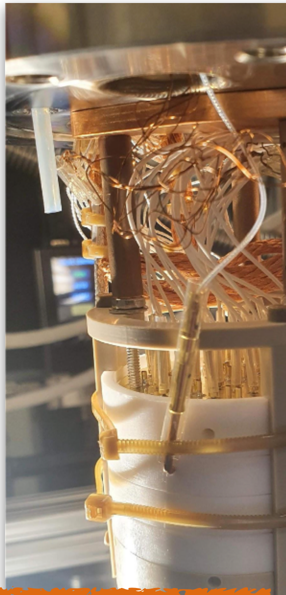
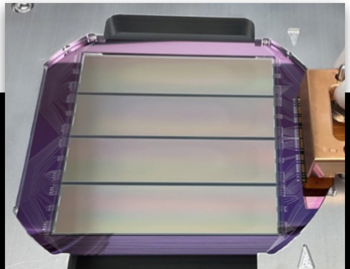
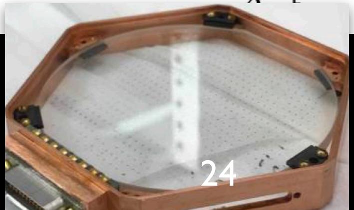
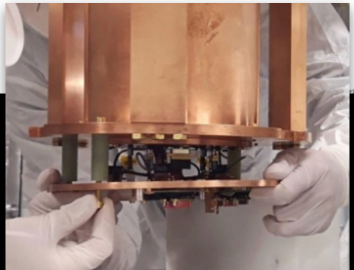


Explosion of Creativity in Detectors

Hidden sector dark matter: huge range of techniques… Strong incentive for experimentalists — well-motivated models can be tested with **1 kg-yr** exposures!

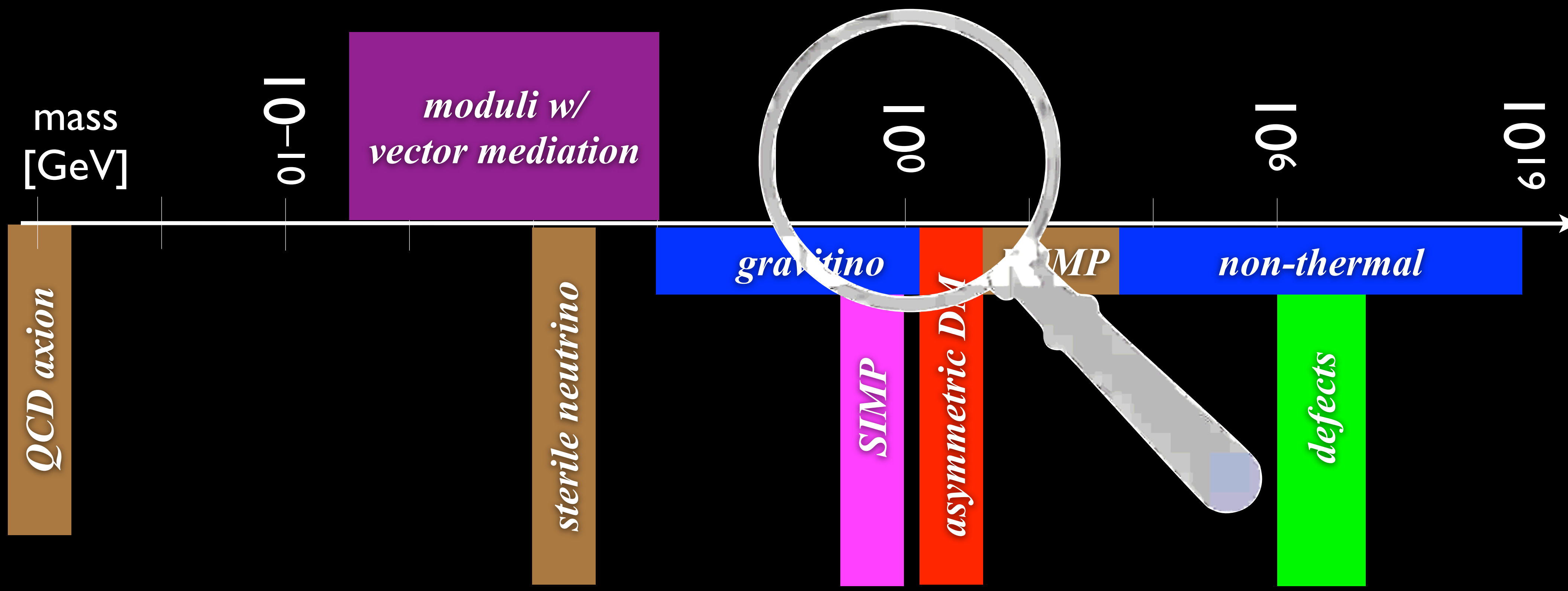







Your brilliant tiny detector here!

Theorist's View

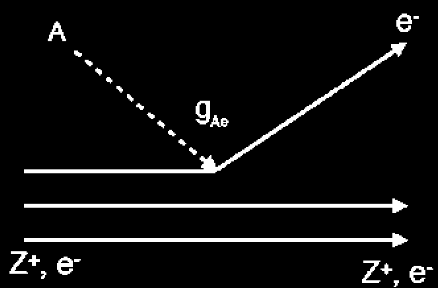


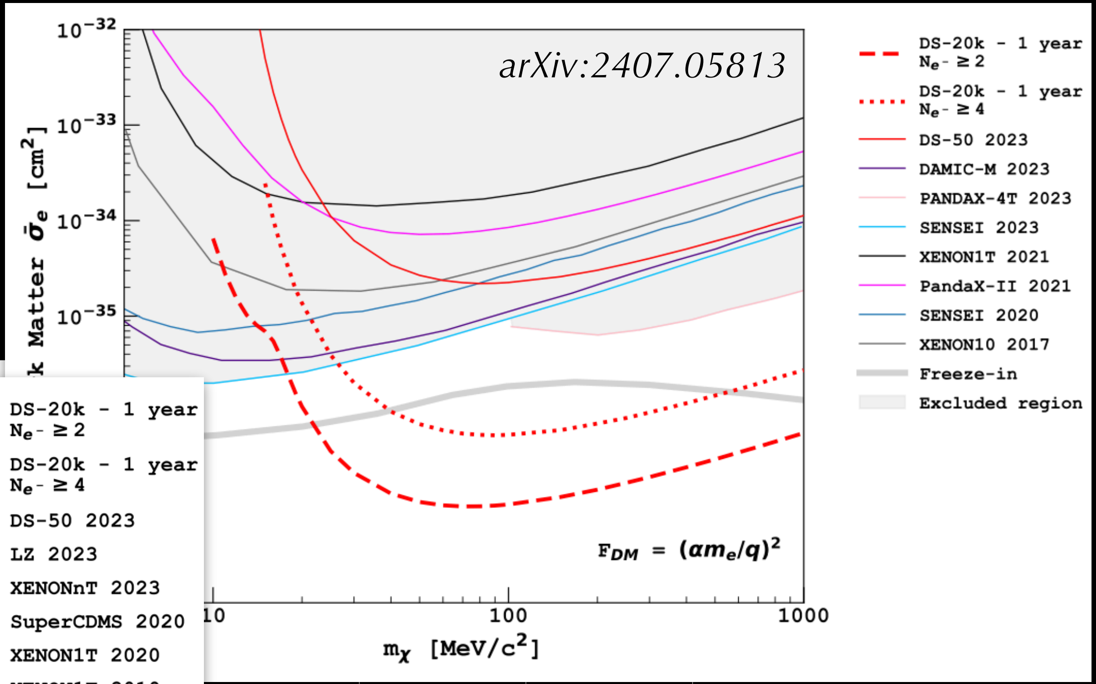
Direct Detection Beyond WIMPs

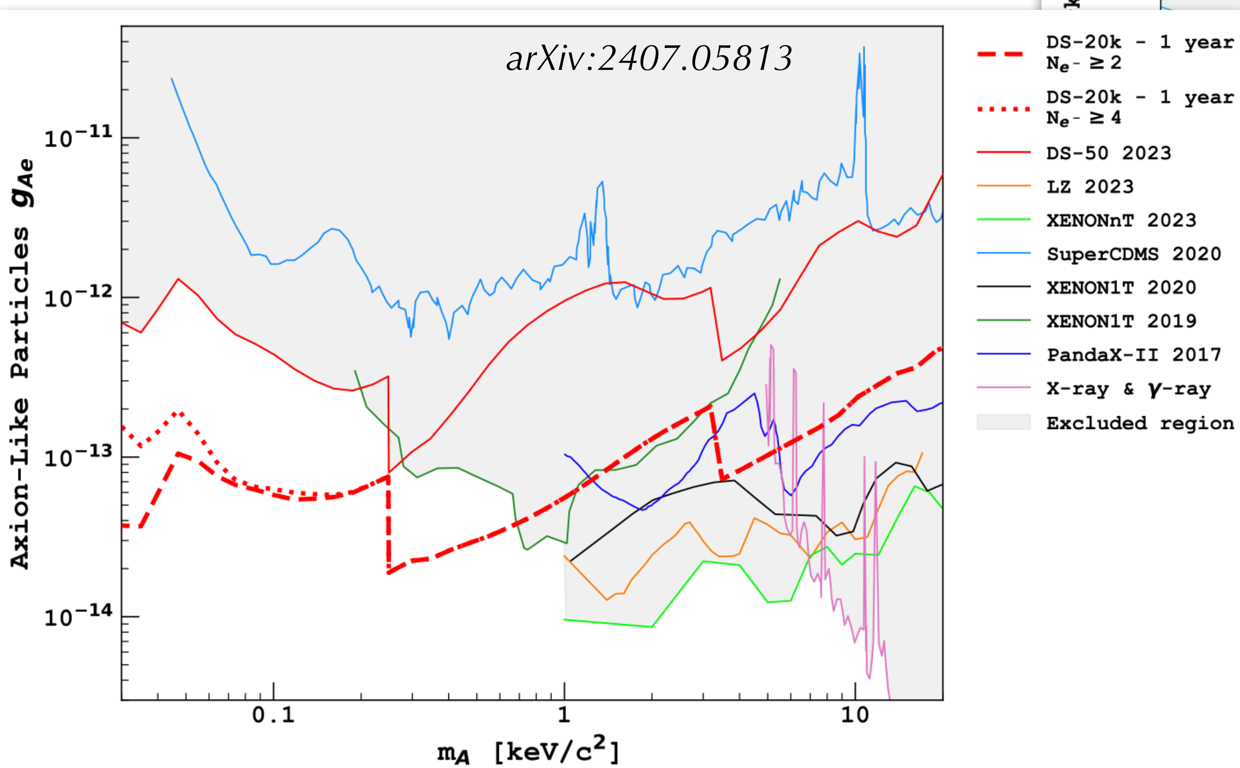
MeV-scale dark matter: search for scattering

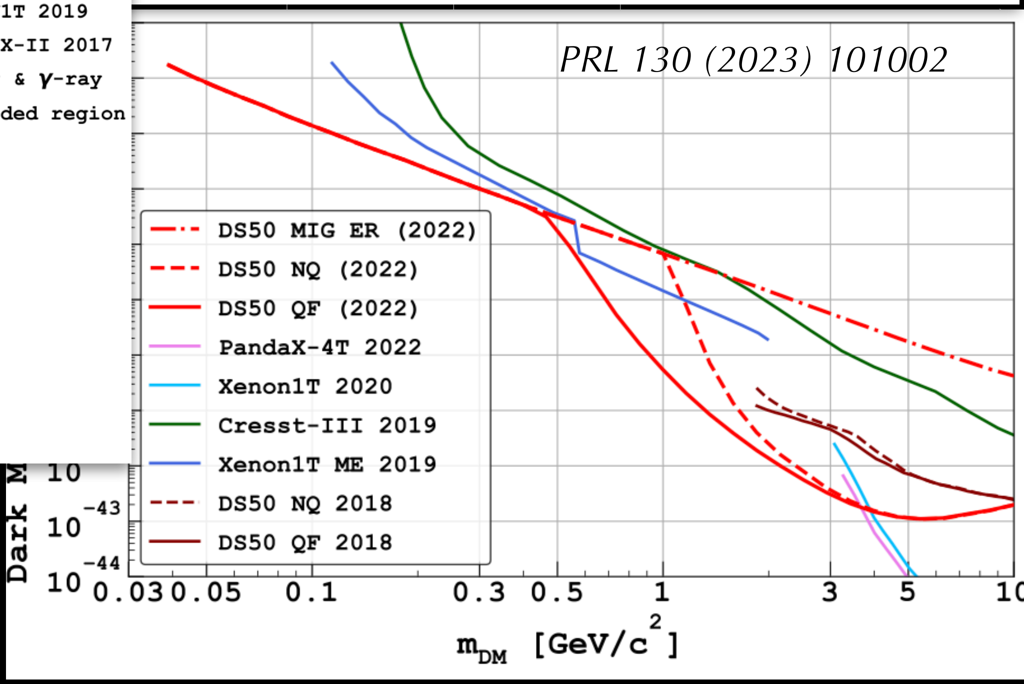
Liquid nobles++:

keV-scale dark matter:
search for absorption:







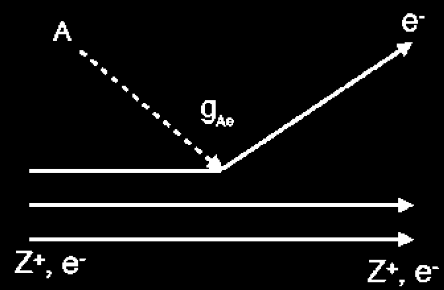


GeV-scale dark matter: search for scattering
with nuclear + electronic recoil final states

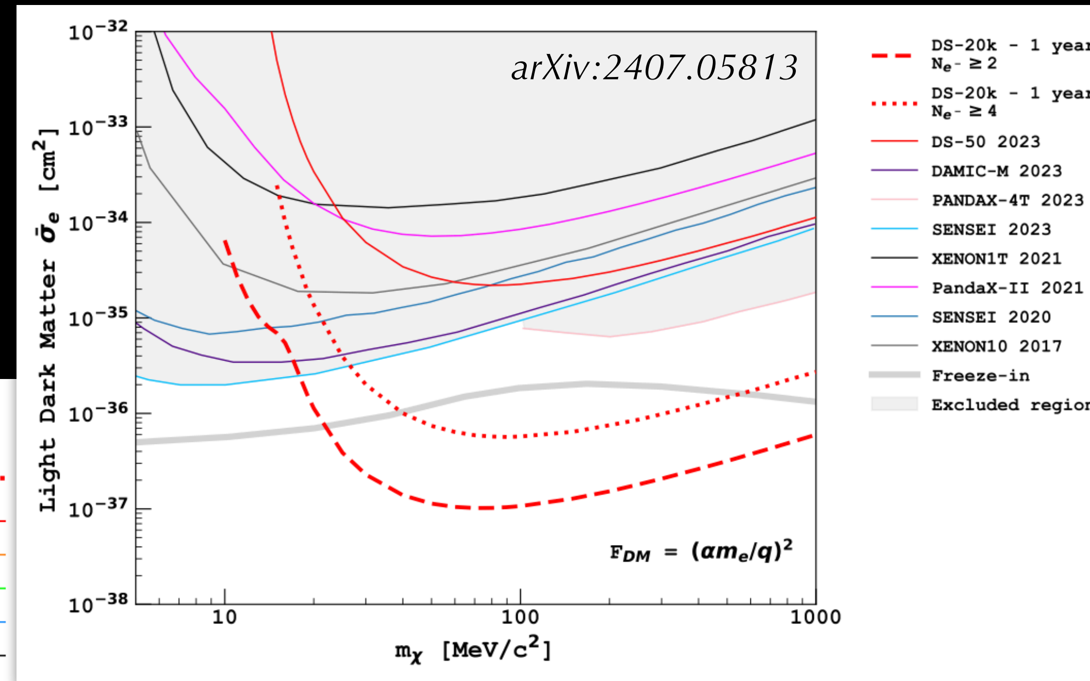
Direct Detection Beyond WIMPs

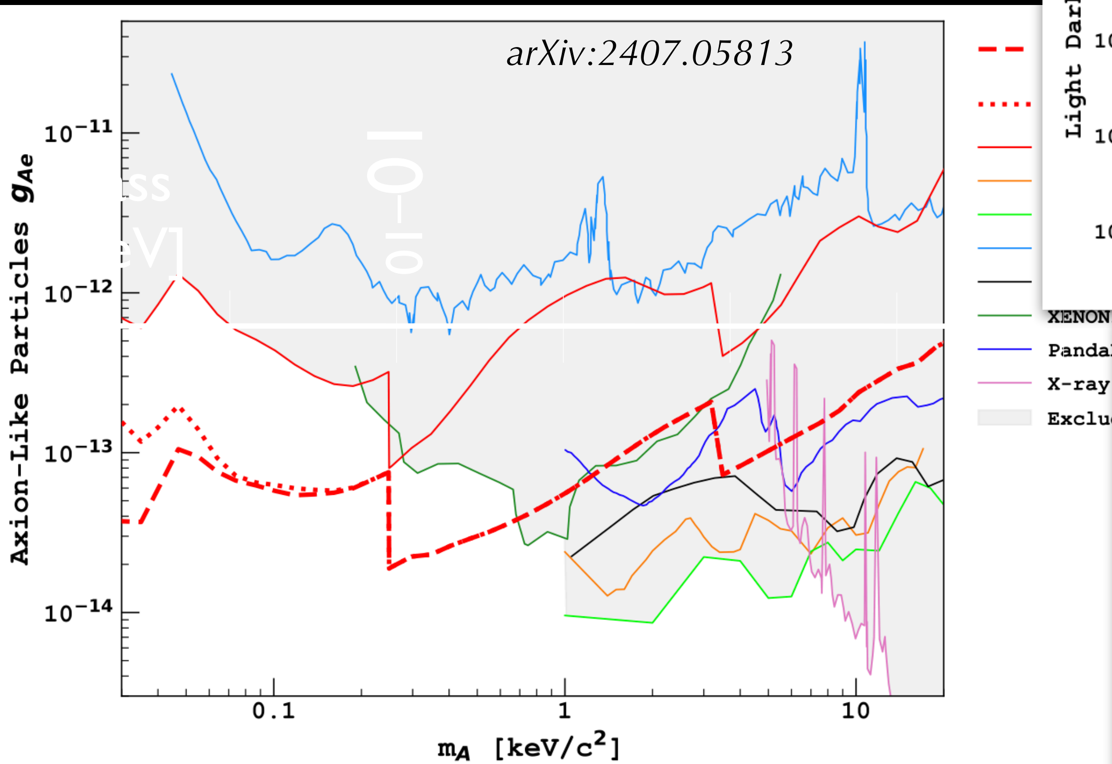
Liquid nobles++:

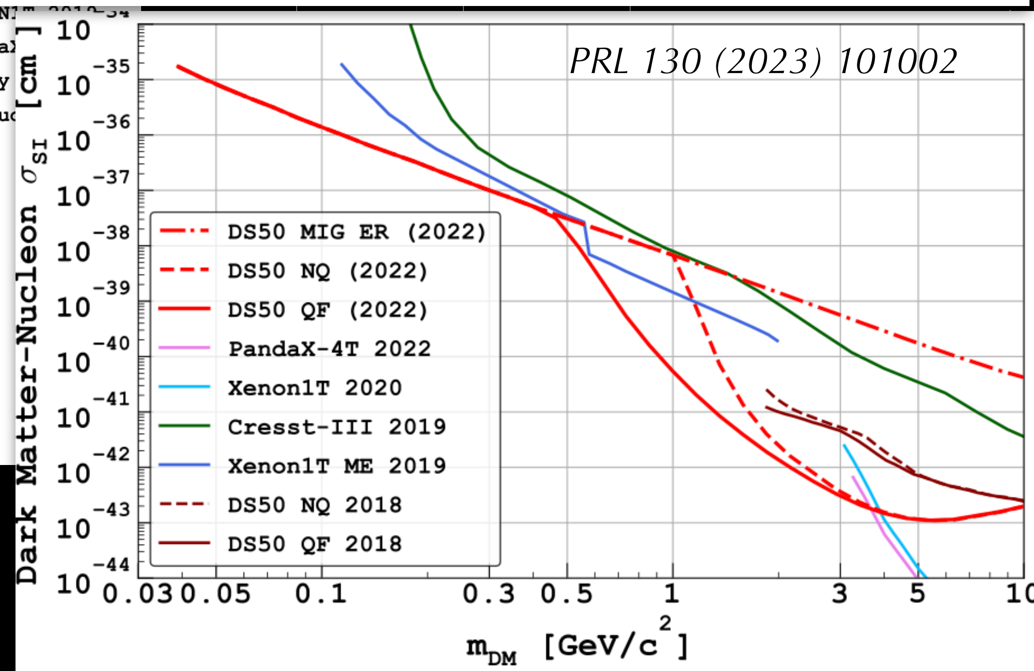
keV-scale dark matter:
search for absorption:



MeV-scale dark matter: search for scattering







GeV-scale dark matter: search for scattering
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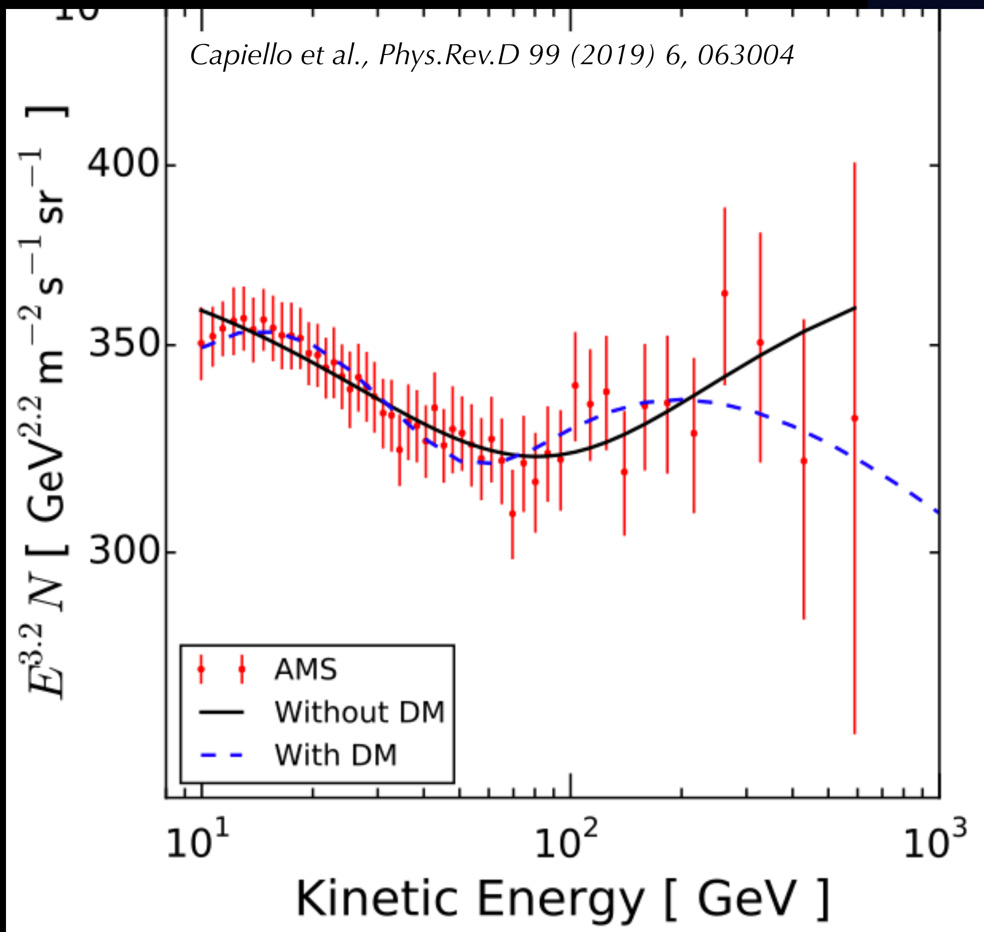
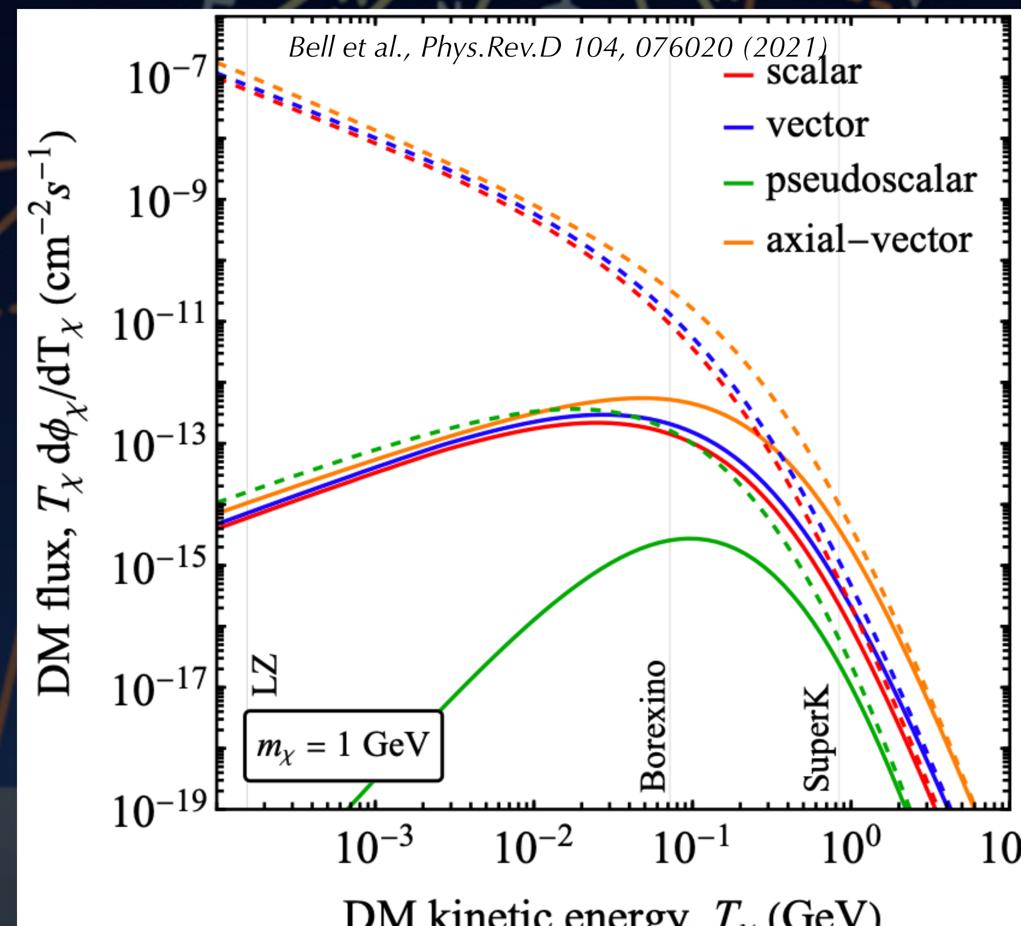
Explosion of Creative Ideas

What if dark matter and cosmic rays interact?

Cosmic ray "downscattering:"



Dark matter "upscattering:"



Explosion of Creative Ideas

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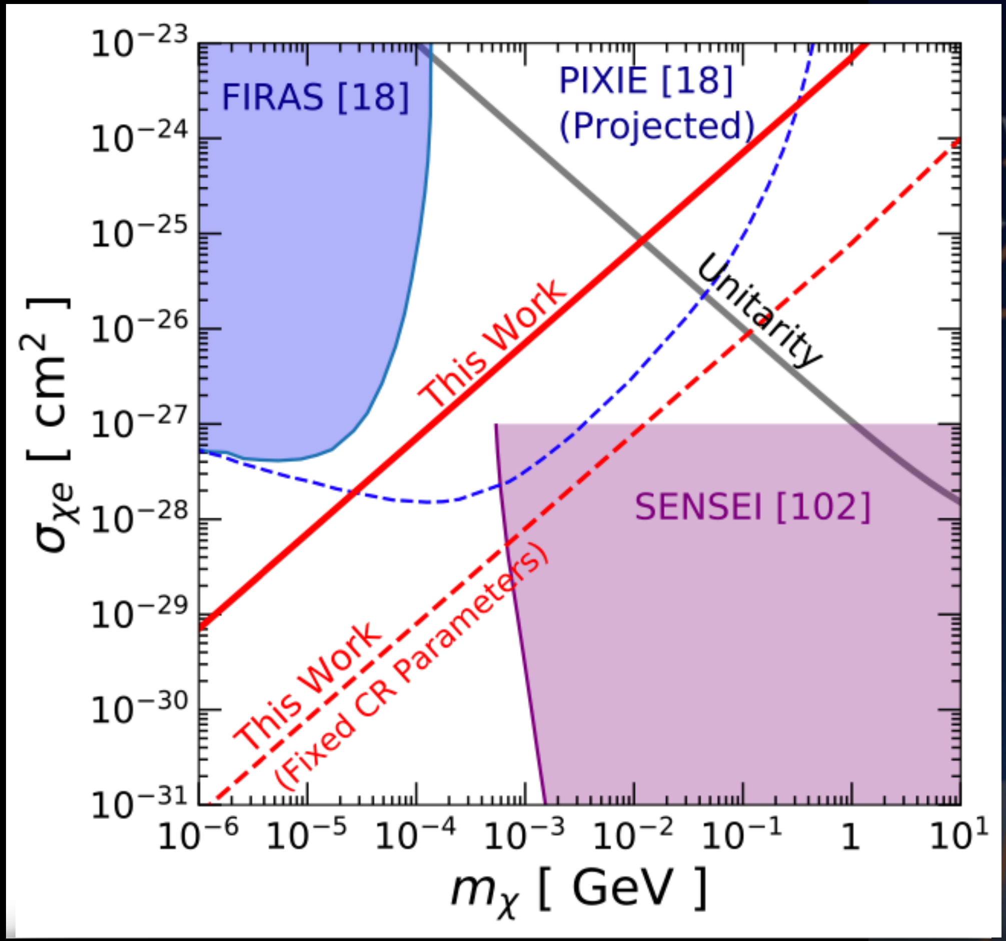
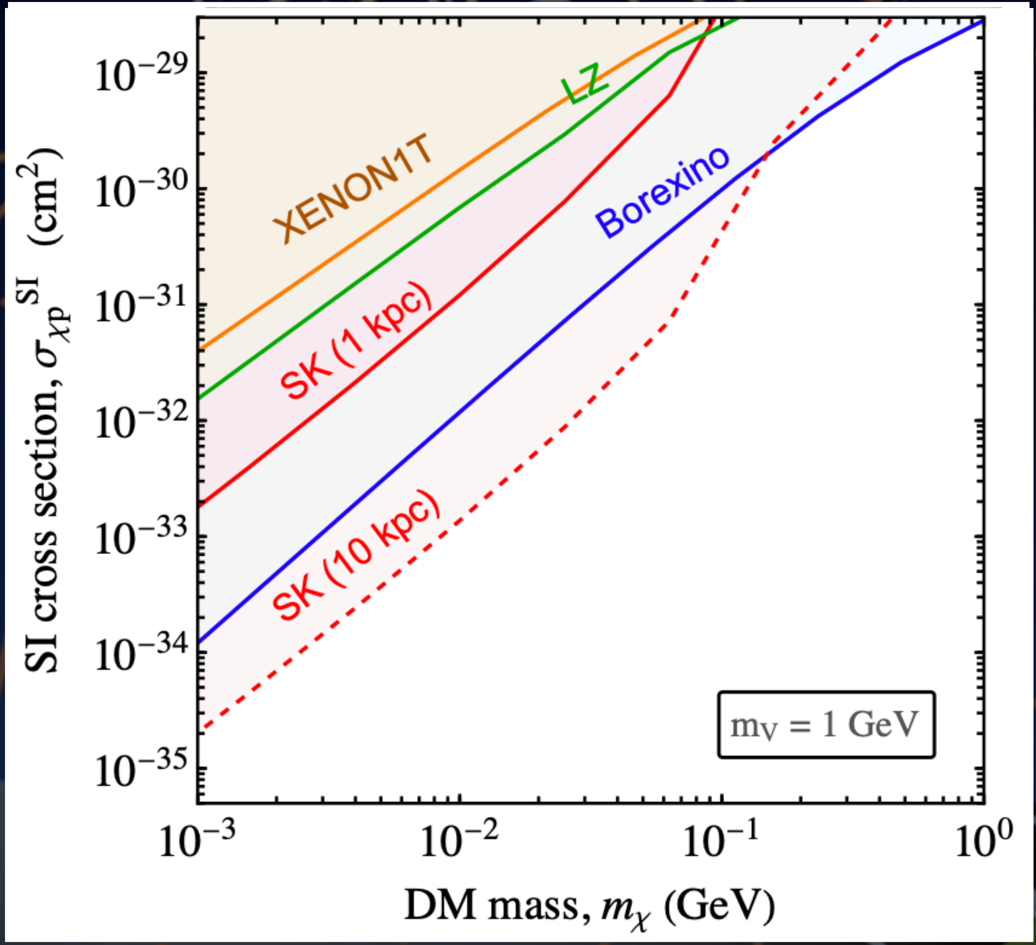


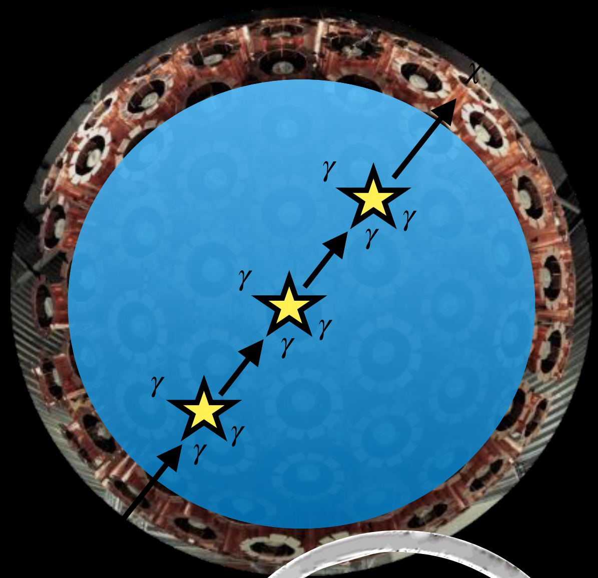


"Reverse Direct Detection"

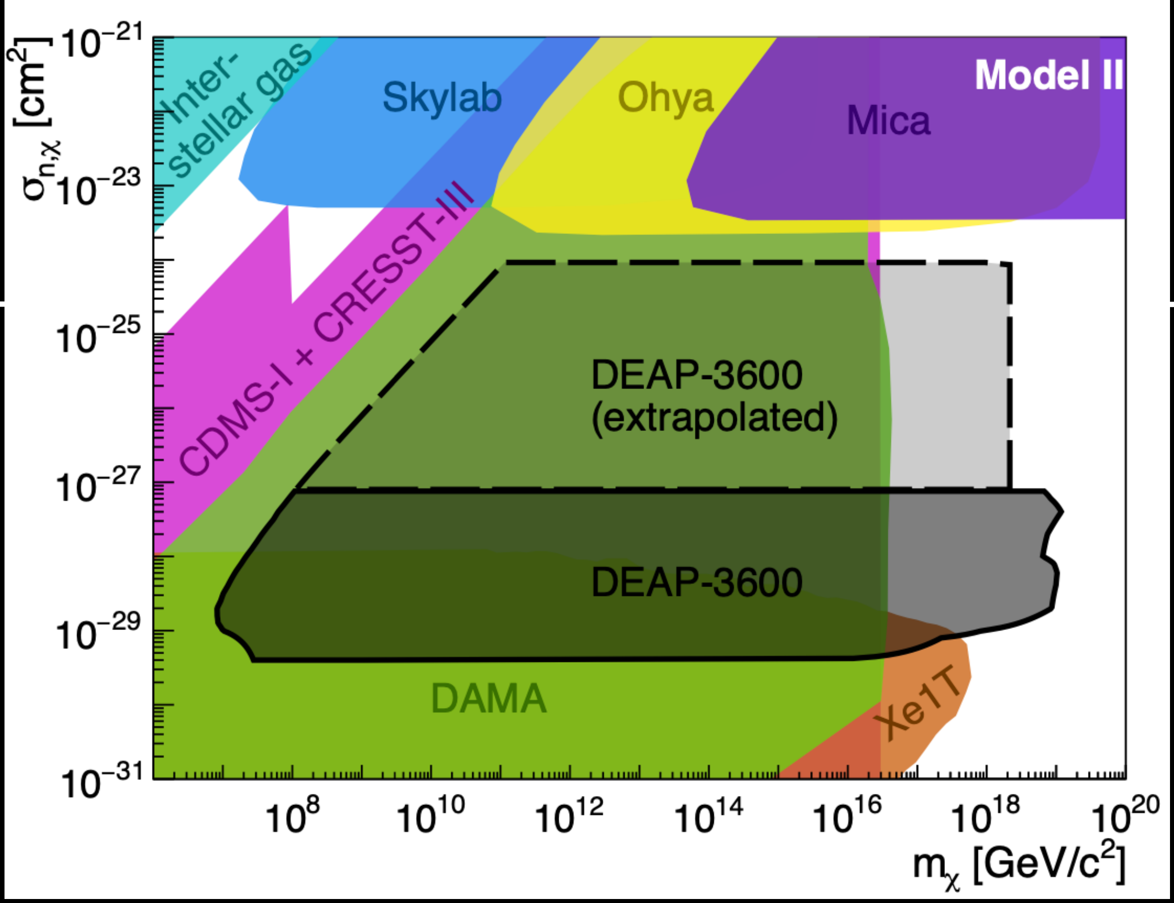
Very Heavy Dark Matter

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

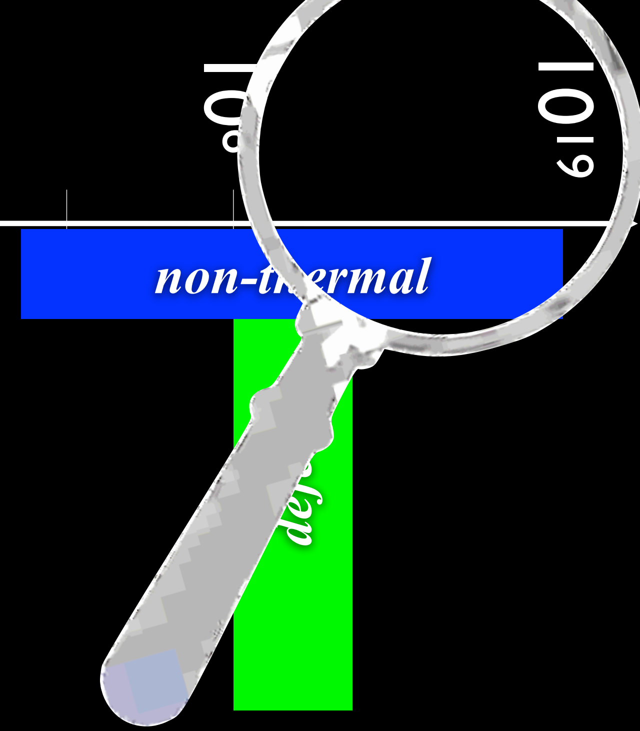
Unlike WIMPs, super heavy dark matter may scatter multiple it traverses a detector… signal: multiple nuclear recoils



mass [GeV]



PRL 128 (2022) 1, 011801



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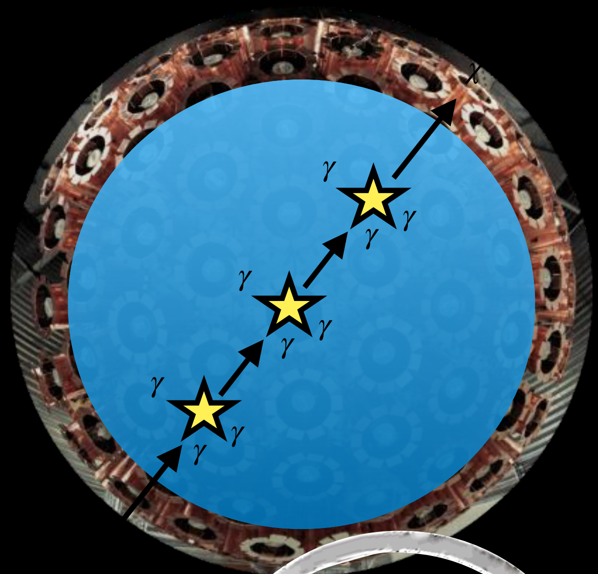
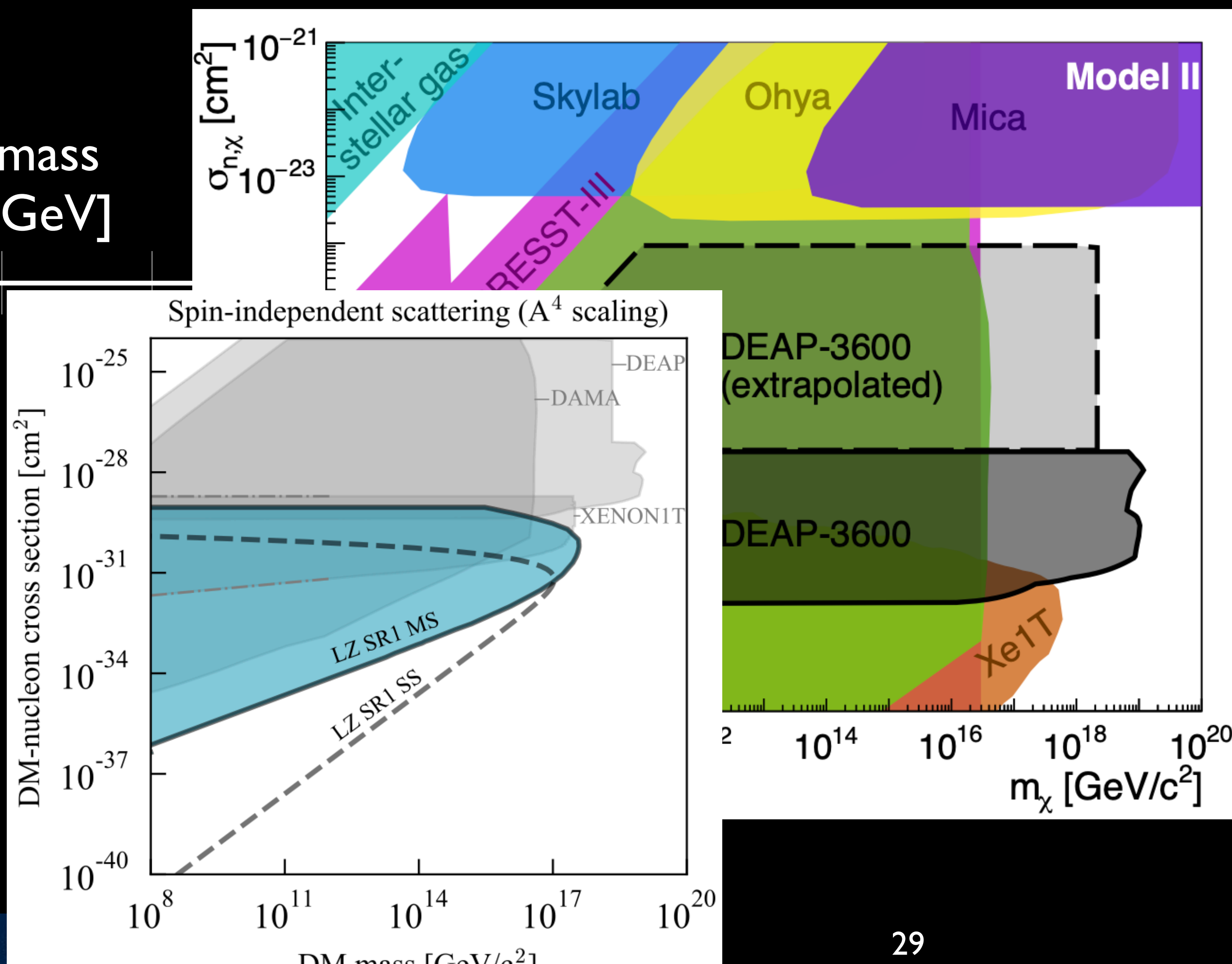
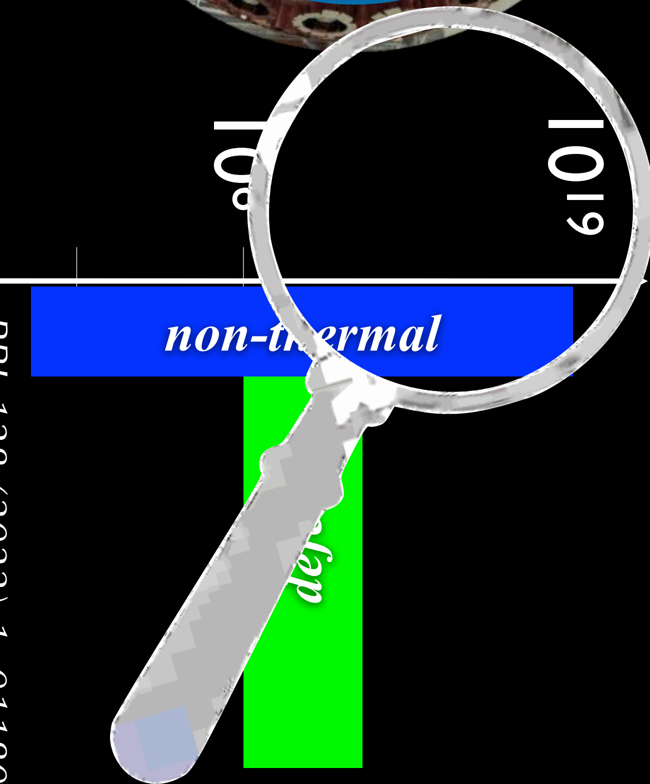


mass
[GeV]

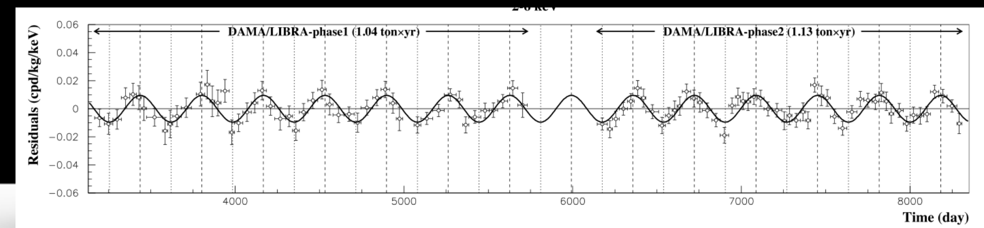


PRL 128 (2022) 1, 011801

arXiv:2402.08865



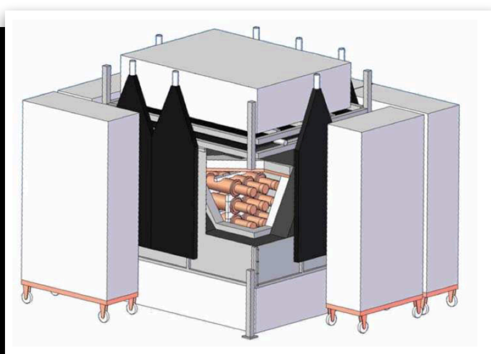
Direct Detection … any Signals?

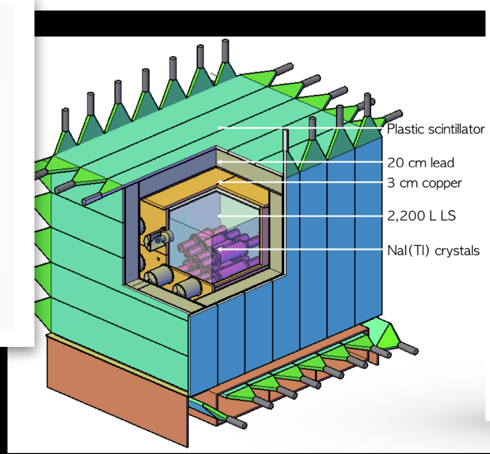


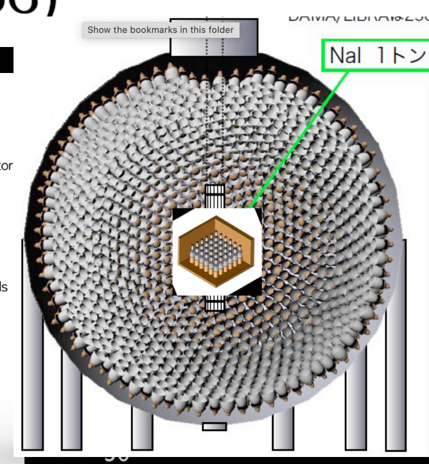
- **DAMA/LIBRA**: end of data taking by 2024
  - ✓ Outstanding crystal development achieved, still unmatched
  - ✓ A **crucial anomaly** in DM direct detection standing still
  - ✓ Currently taking data with new PMT dividers since 2021
  - ✓ Since 2021 in data taking without interruptions till Feb 2024 (Phase 2 empowered, ~0.5 ton x yr)
  - ✓ Crucial comprehensive analysis of background time dependence ongoing

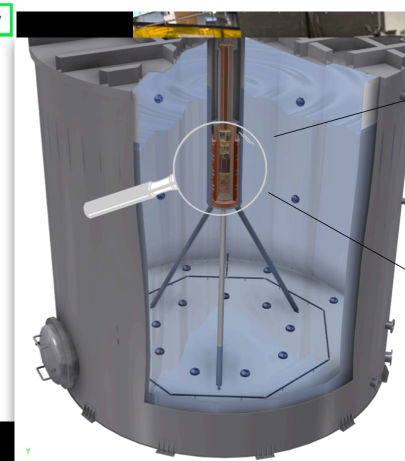
—A. Ianni, IDM2024

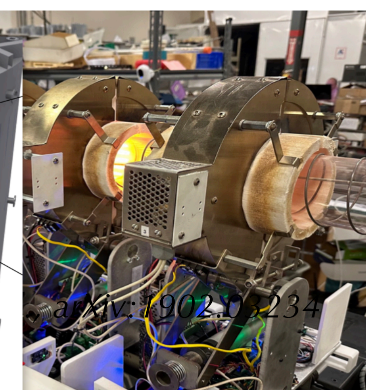
- **ANAIS-112 and COSINE-100**
  - ✓ Achieved outstanding noise events rejection in the ROI
  - ✓ Time-dependent background MC simulations: more details on systematics
  - ✓ Stronger **tests of DAMA/LIBRA accessible** from preliminary analysis reported at this meeting (goal: towards 5σ)











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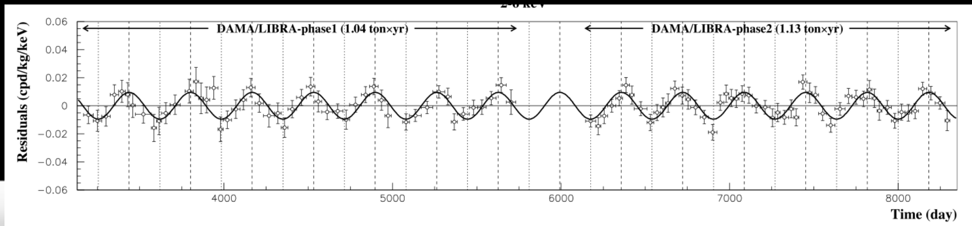

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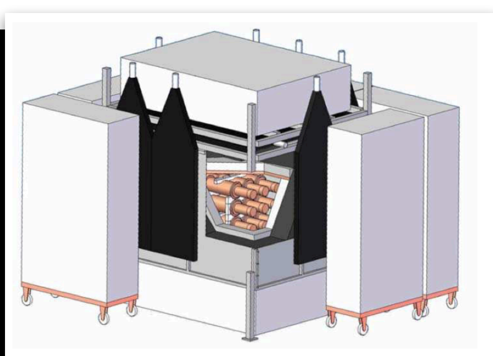
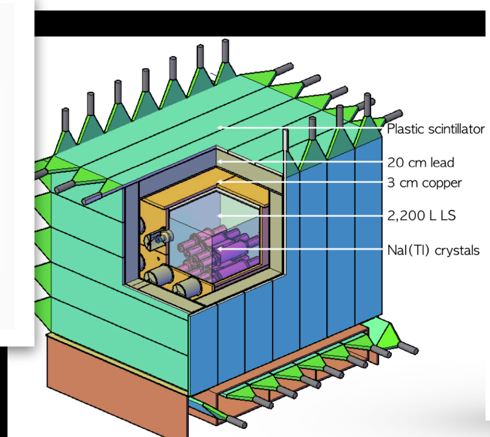
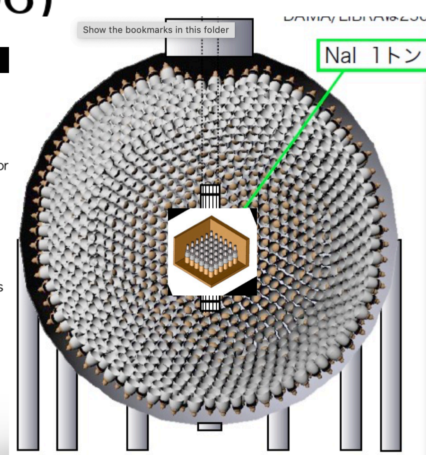
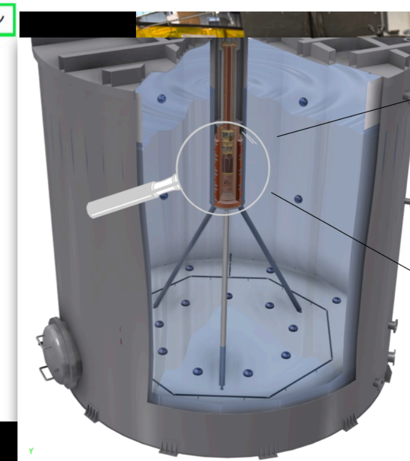
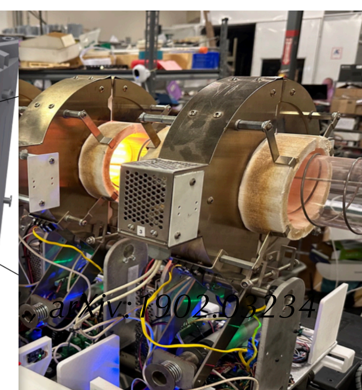
Exclude DAMA at >3 sigma



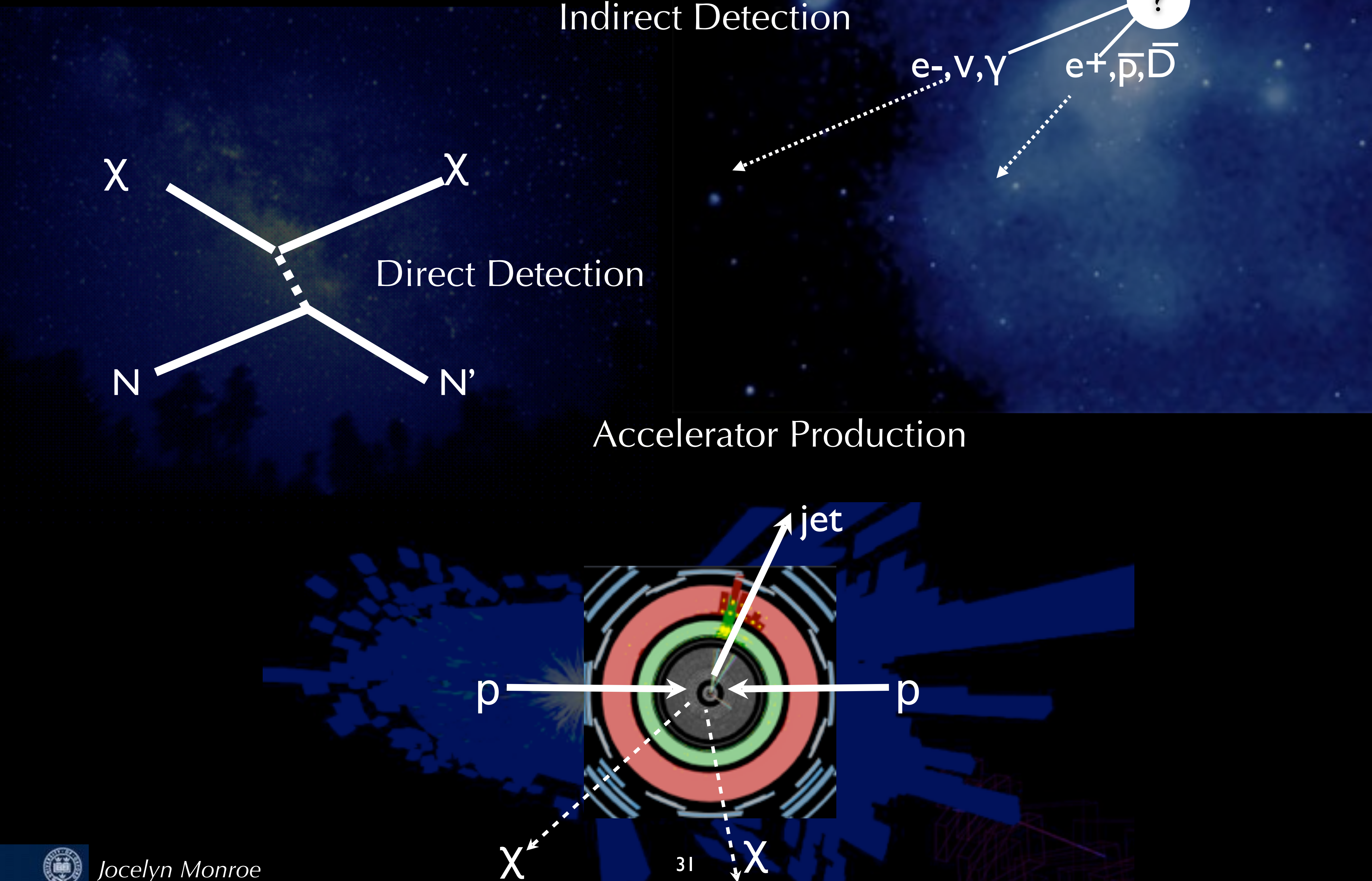






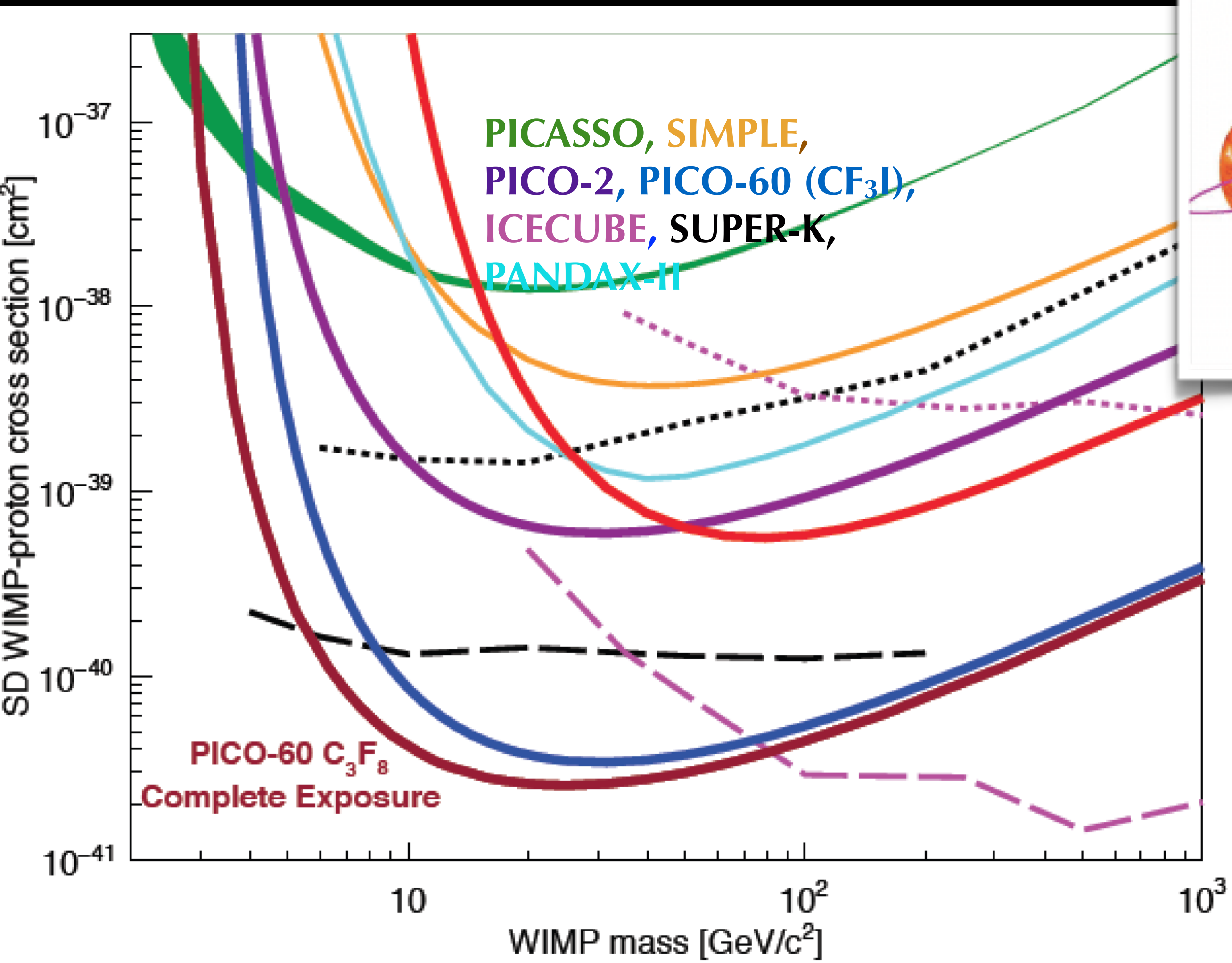


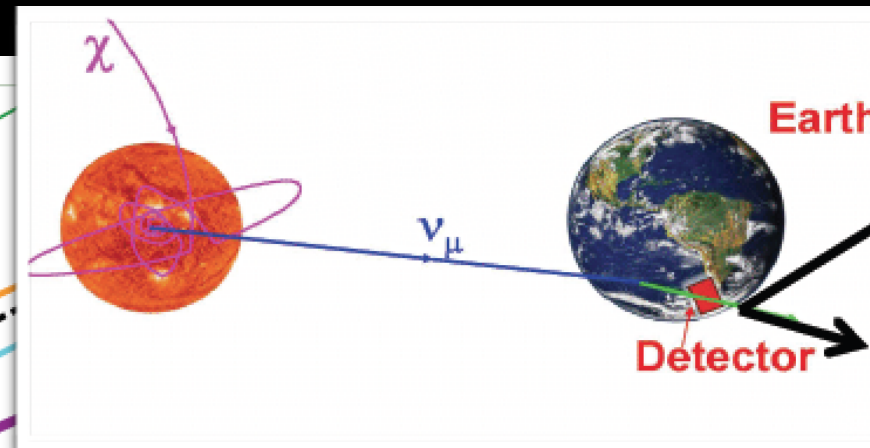
Experimentalist's View: Complementarity



Indirect Detection

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





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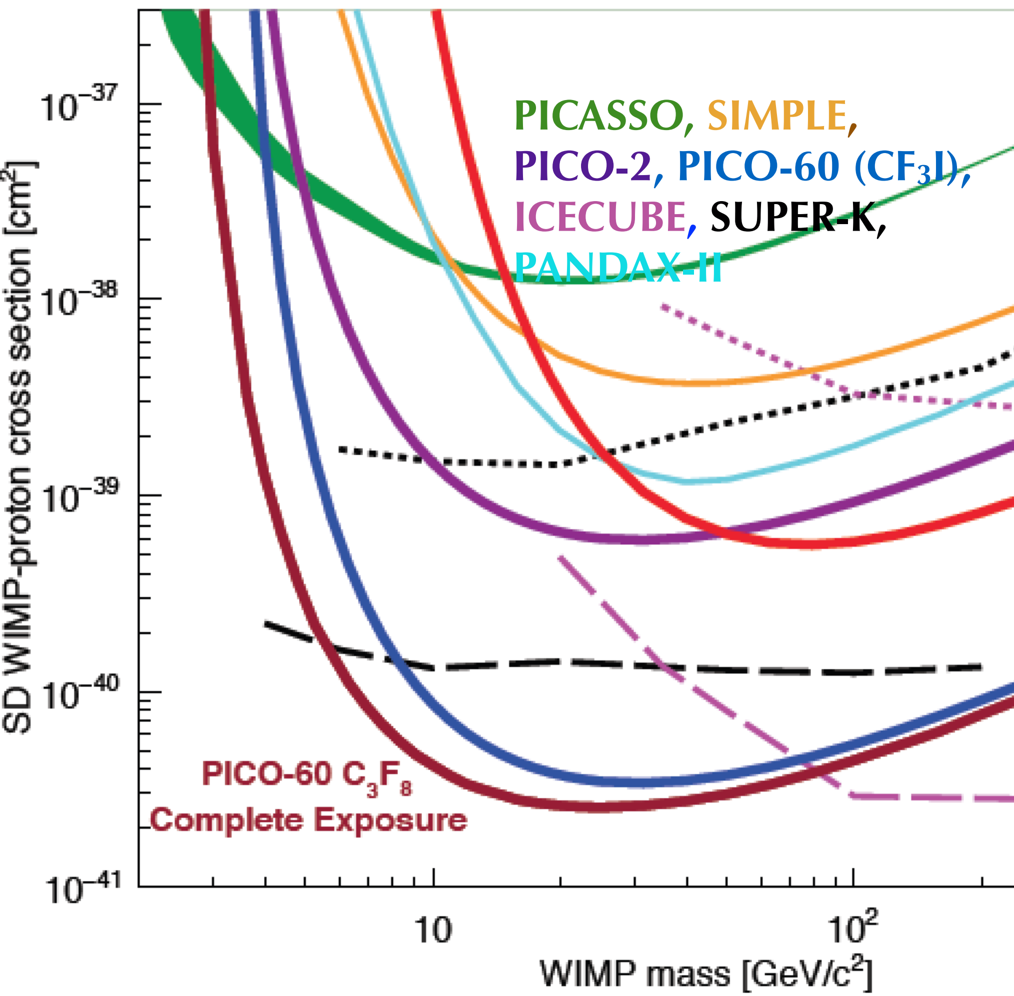
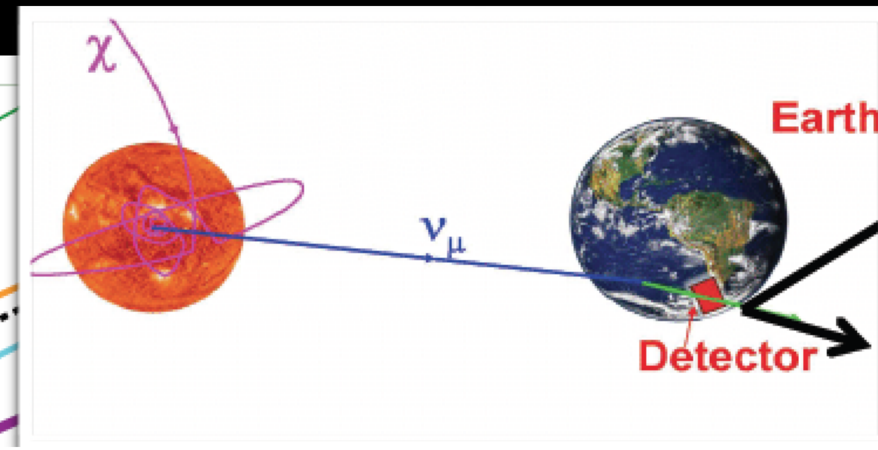
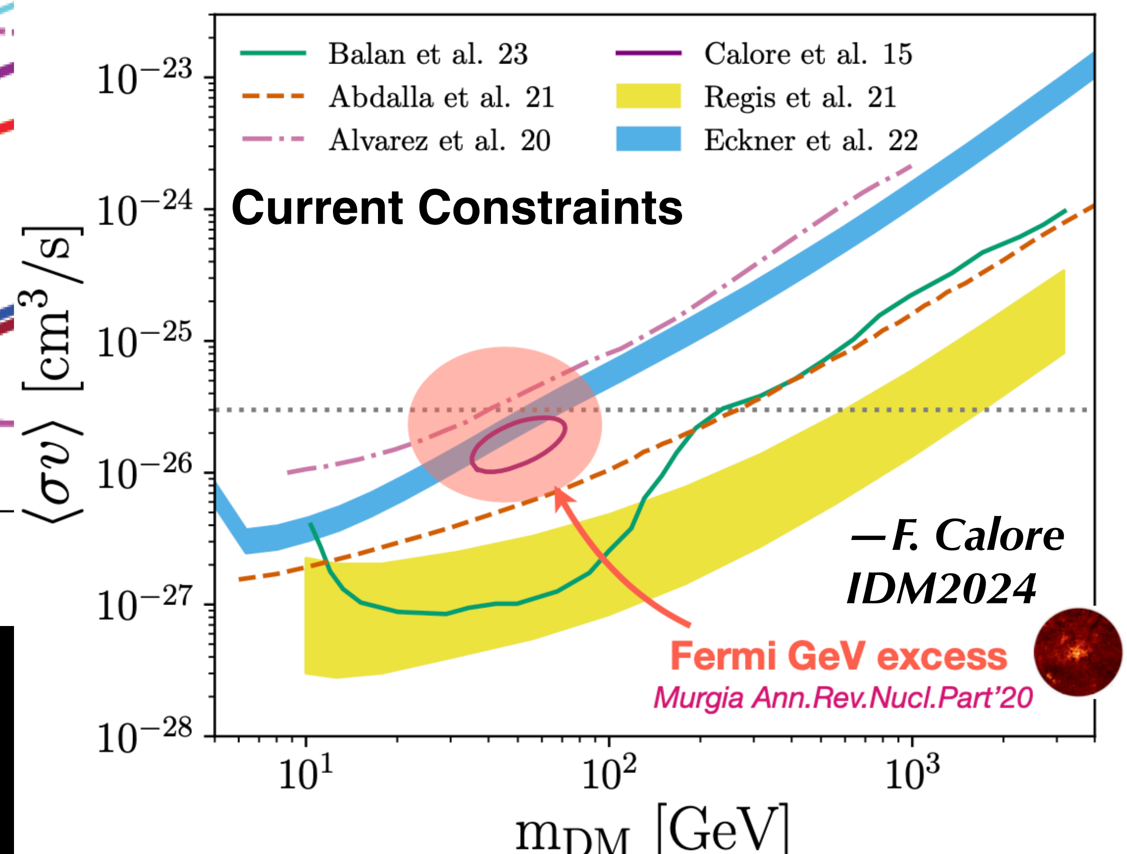


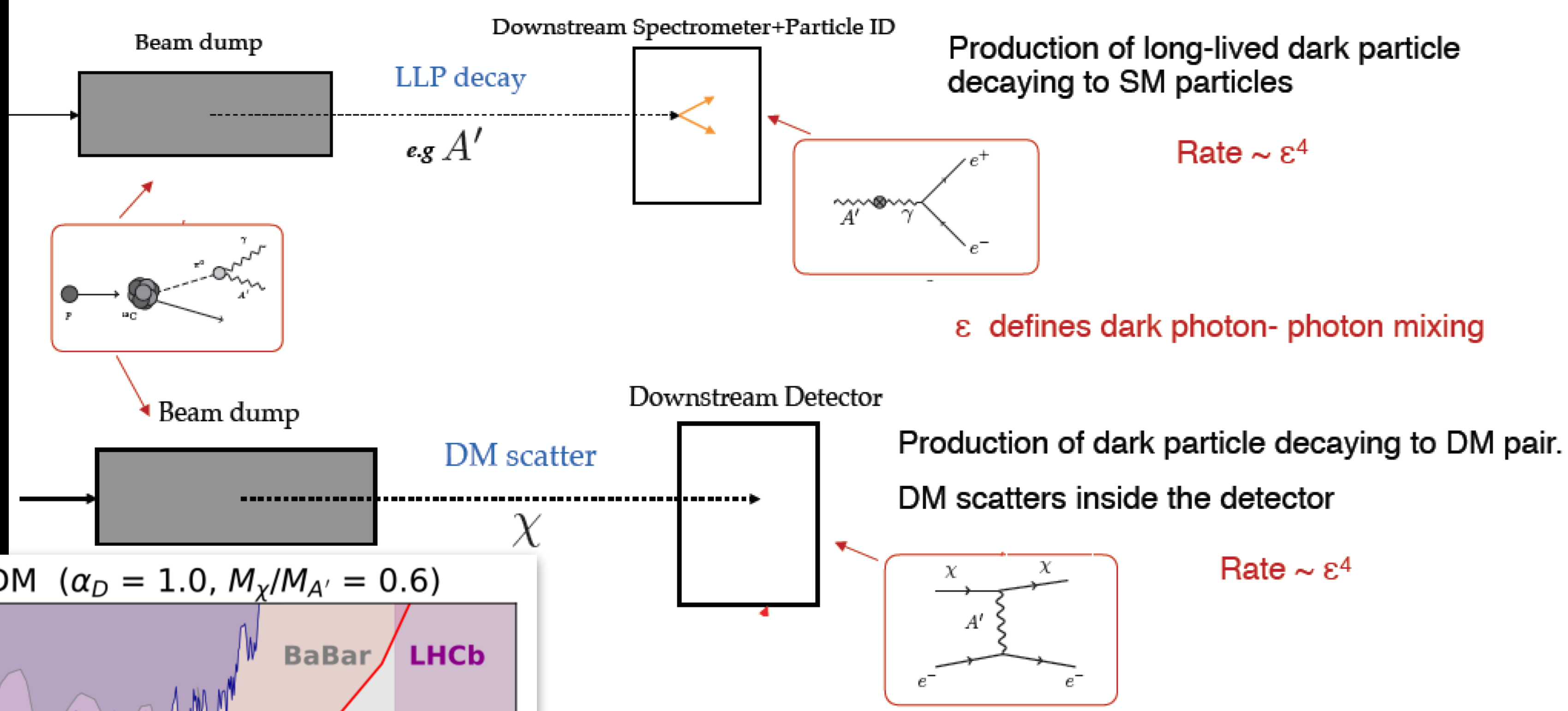


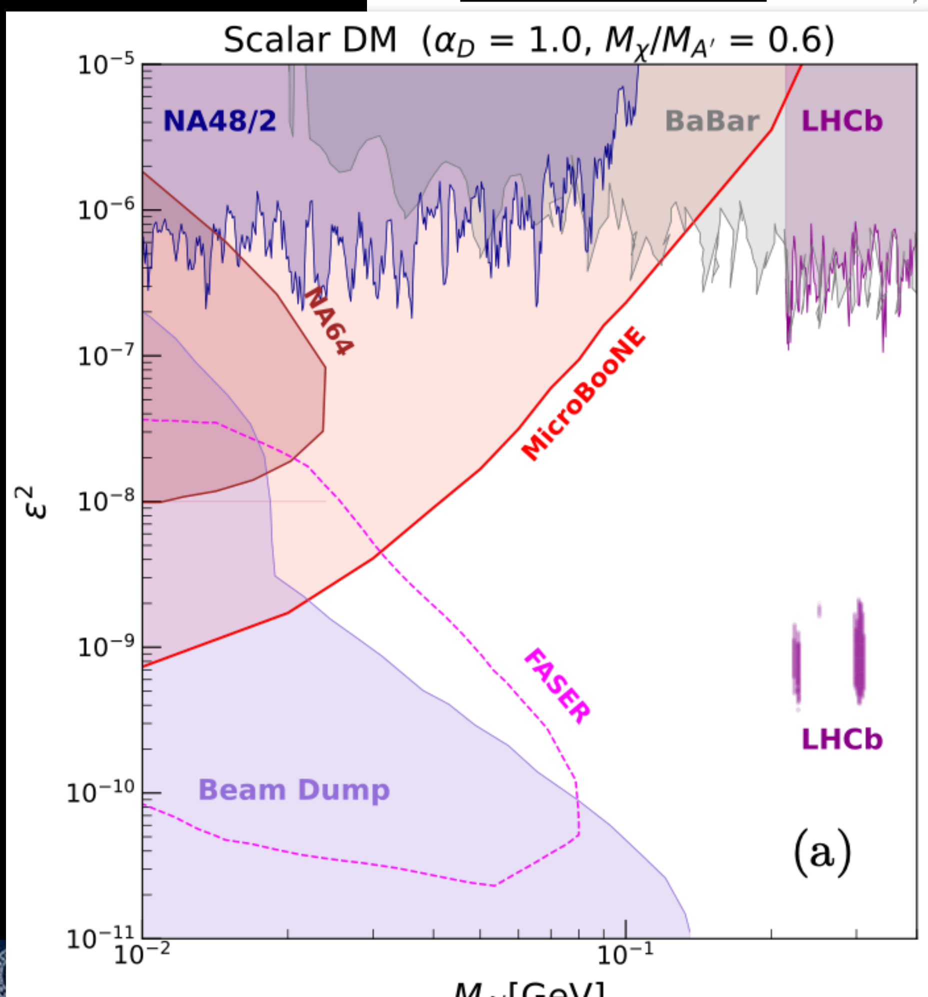


Indirect Detection … any signals?
Fermi GeV excess at galactic center…

Fixed-Target Strategies

Renaissance of the fixed-target!





Many new experiments planned, proposed, and going beyond original scope for hidden sector searches.

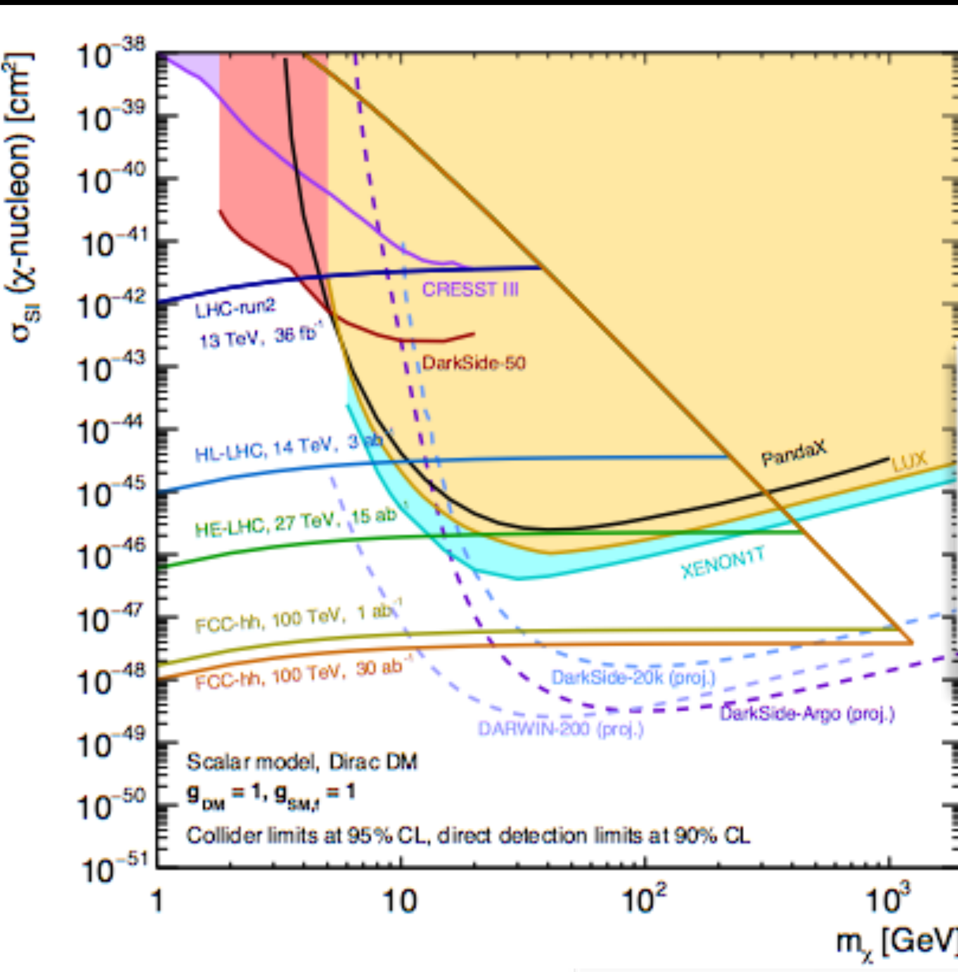
Major synergistic topic of Dark Sectors work at CERN

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

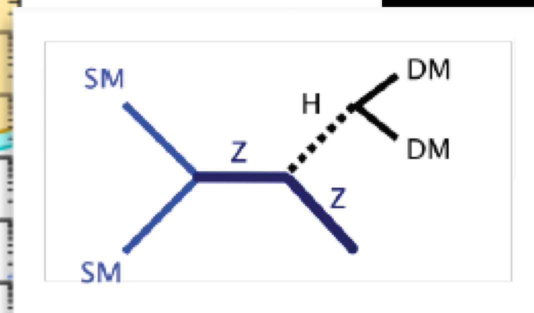
… and with neutrino experiments.

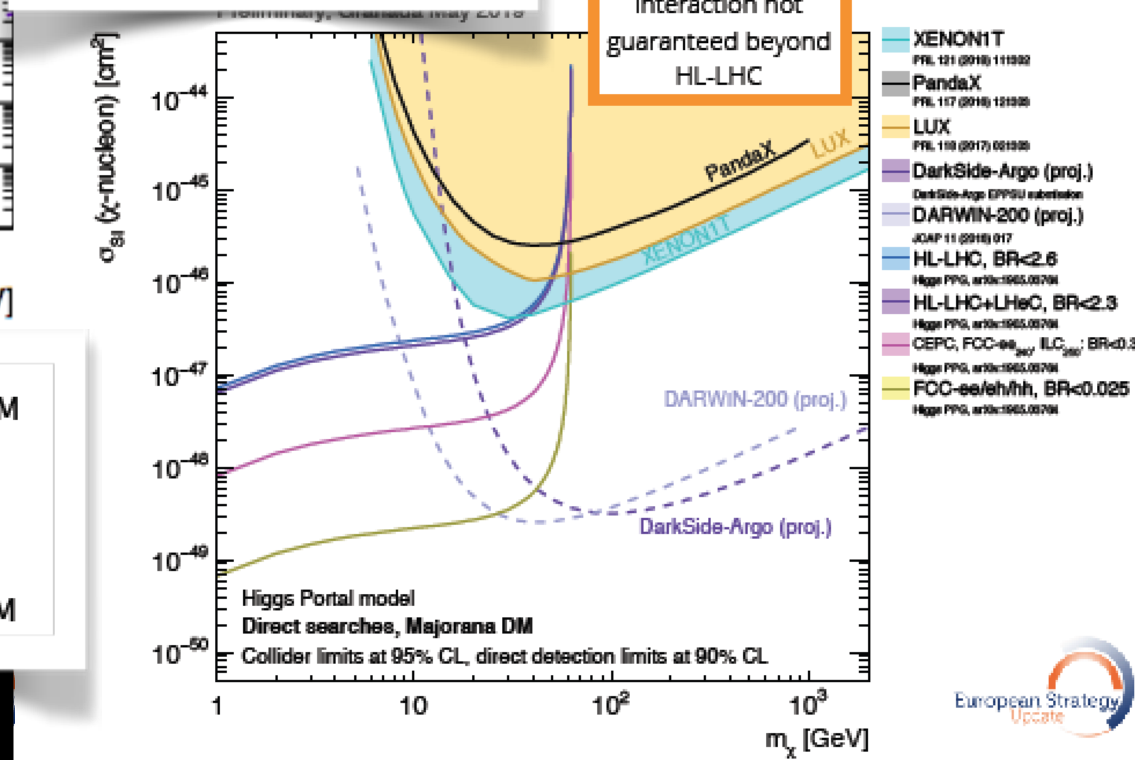
PRL 132 (2024) 241801

Accelerator Production

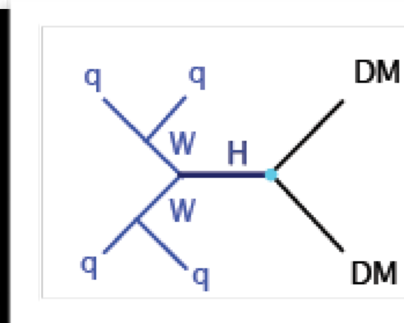


limits on branching ratio translated to limits on cross section vs. mass





ESPPU Physics Briefing Book, CERN-ESU-004 (2019)



Conclusions & Outlook

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

Direct detection searches are rapidly expanding physics reach:

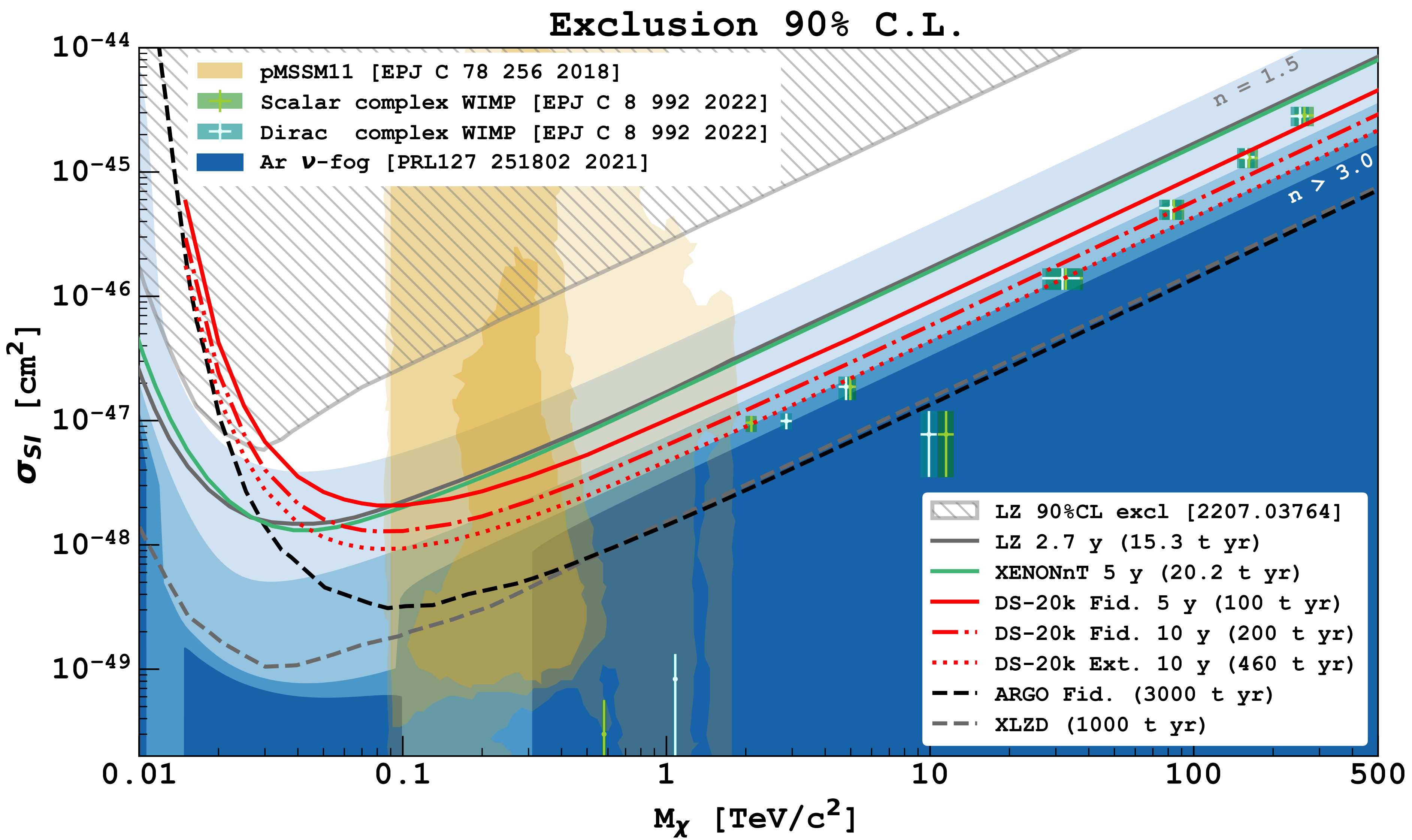
to lower cross sections, probing new parameter space,
to lower masses, testing new models and interaction types,
to higher masses, complementary with the energy frontier!

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

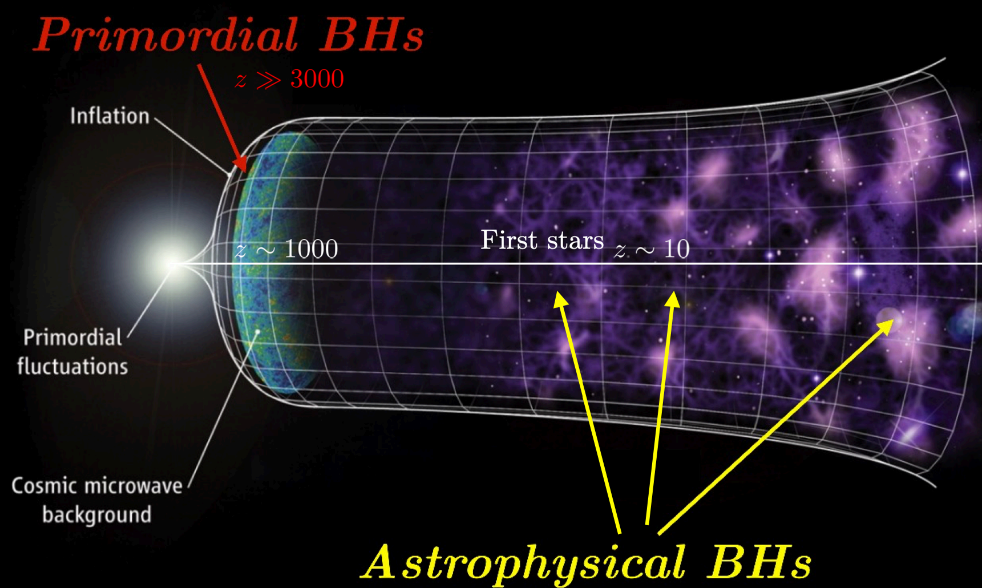
… and today's background may be tomorrow's signal. *(T. Kajita, 2015)*

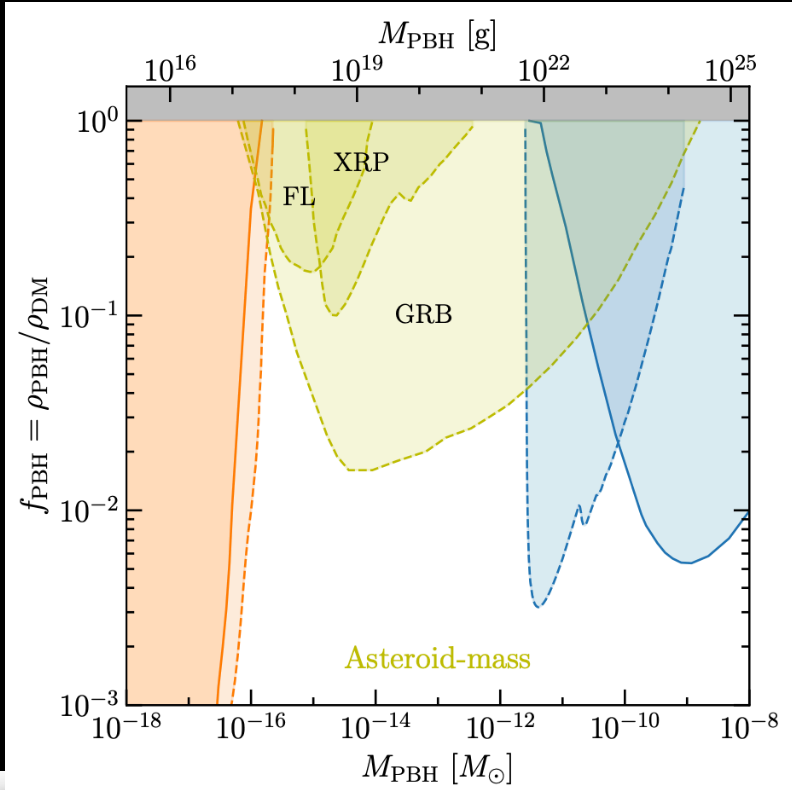
Extra Slides

Heavy WIMP Prospects

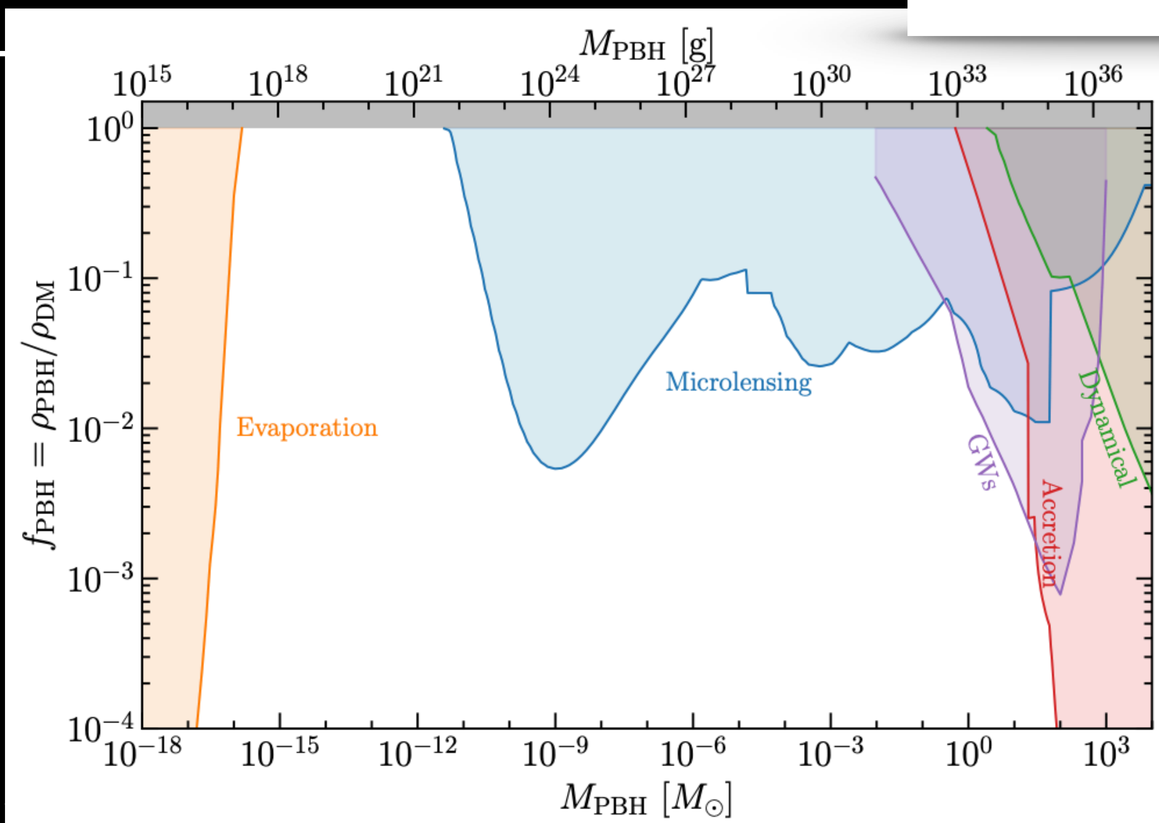


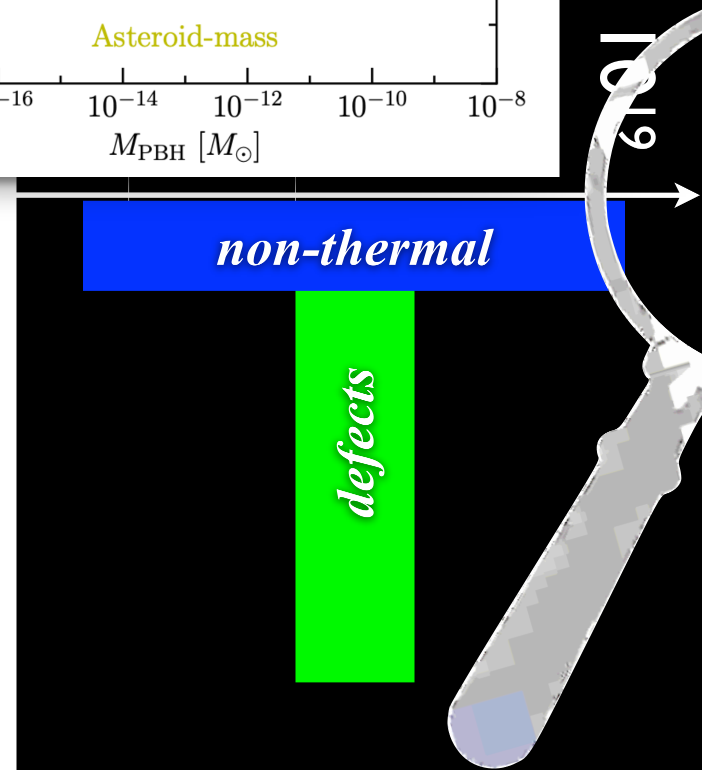
Very, Very Heavy Dark Matter





mass
[GeV]



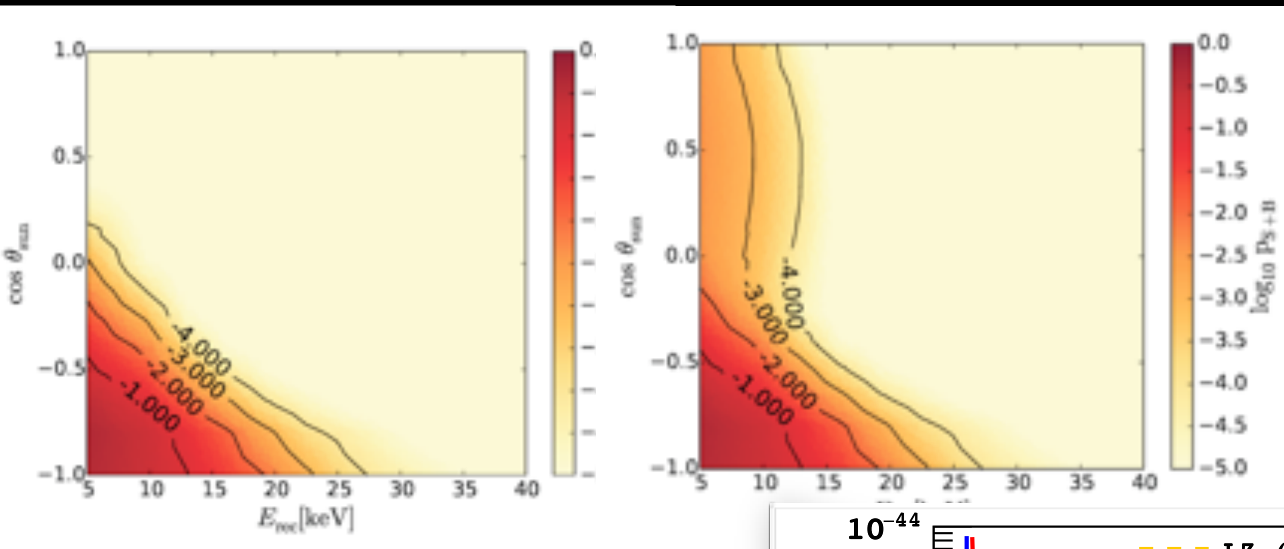


Green et al, 2402.15211

Jocelyn

Direct Detection: Is the Neutrino Bound the End? No.

- sensitivity scales with sqrt(time) instead of linearly in time (with zero background)



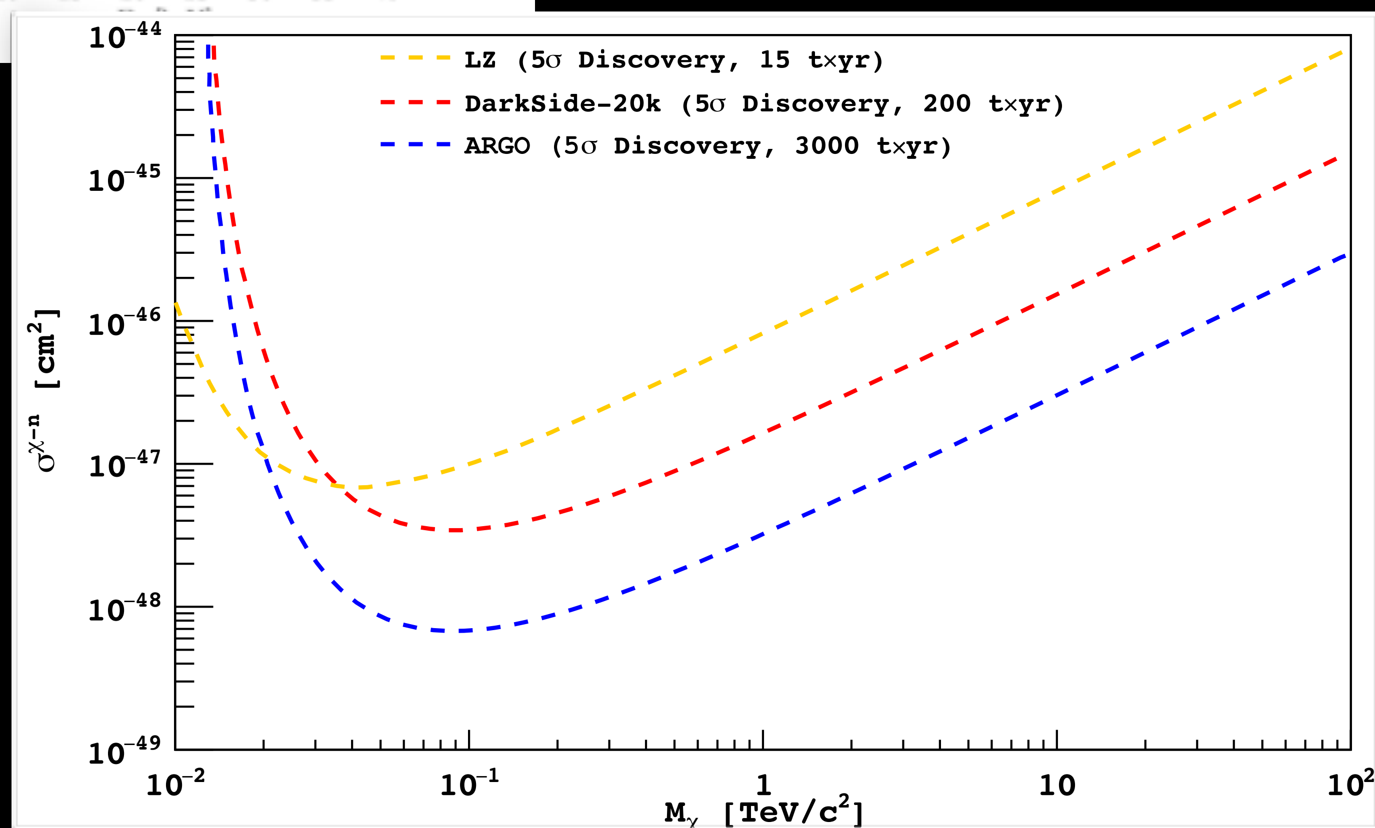
(energy, angle, time) of neutrino background vs. DM signal differ.

- no ν bound for directional detectors

Grothaus, Fairbairn, JM, Phys.Rev.D90 (2014)

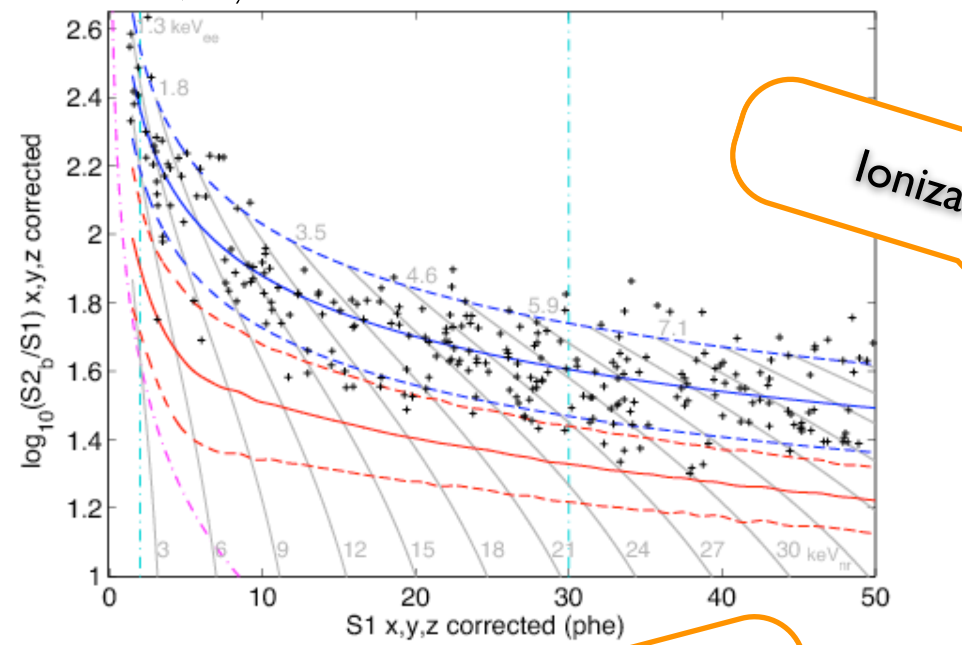
A ν background paradigm…
for non-directional detectors

the discovery reach
depends on ν flux errors
and on ν-e discrimination.

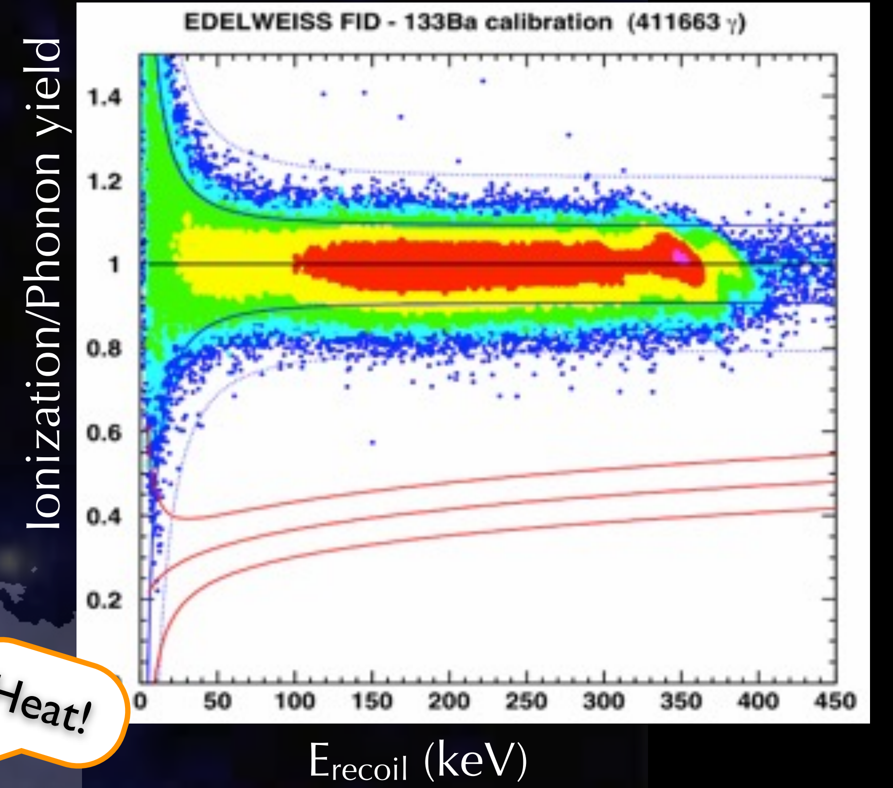


Background Discrimination Strategies

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



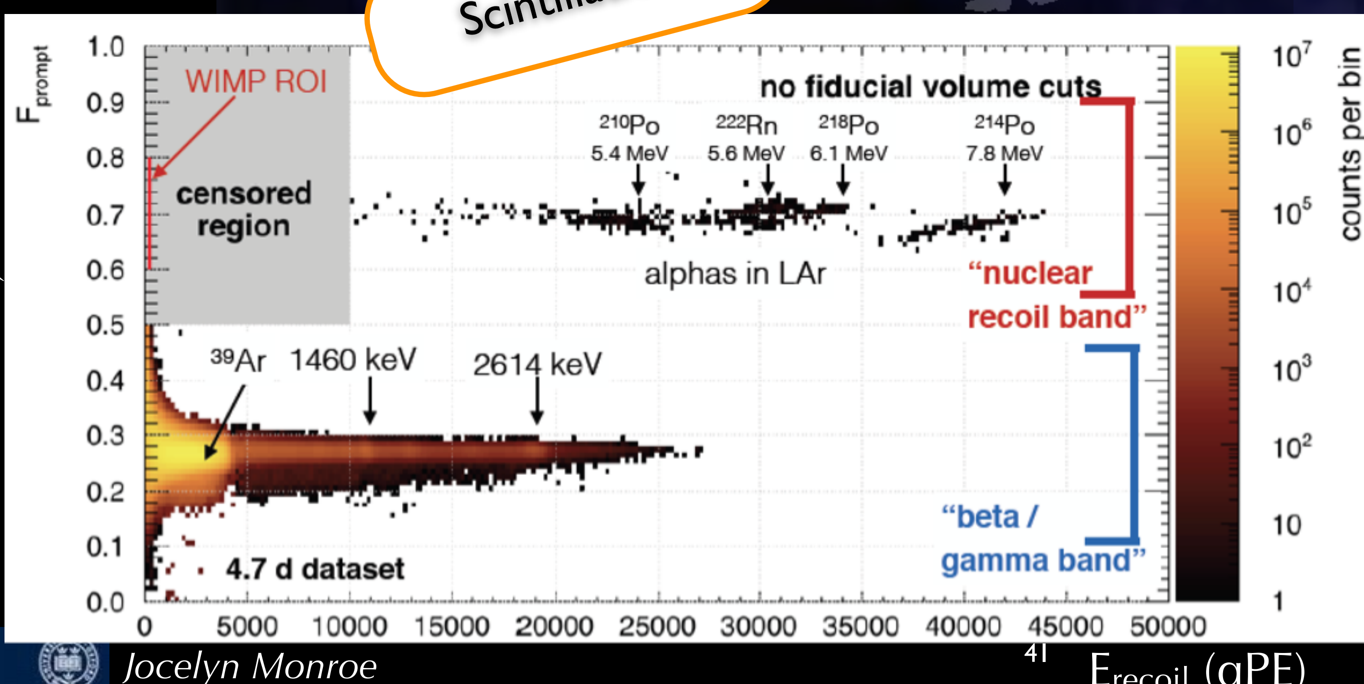
Ionization!

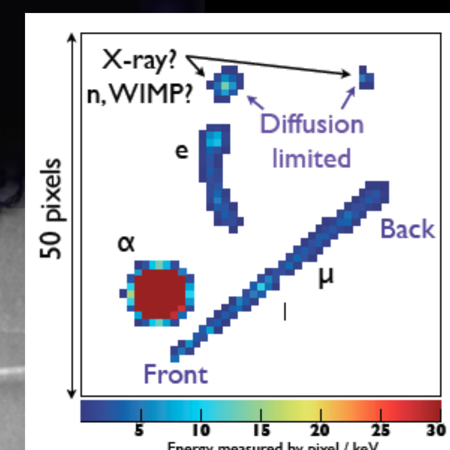


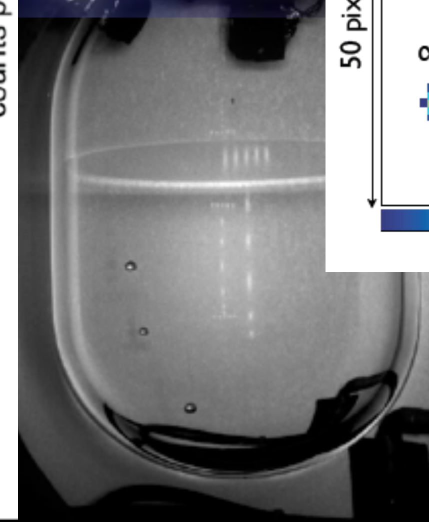
Heat!

Scintillation!

Amandruz et al., arXiv:1707.08042



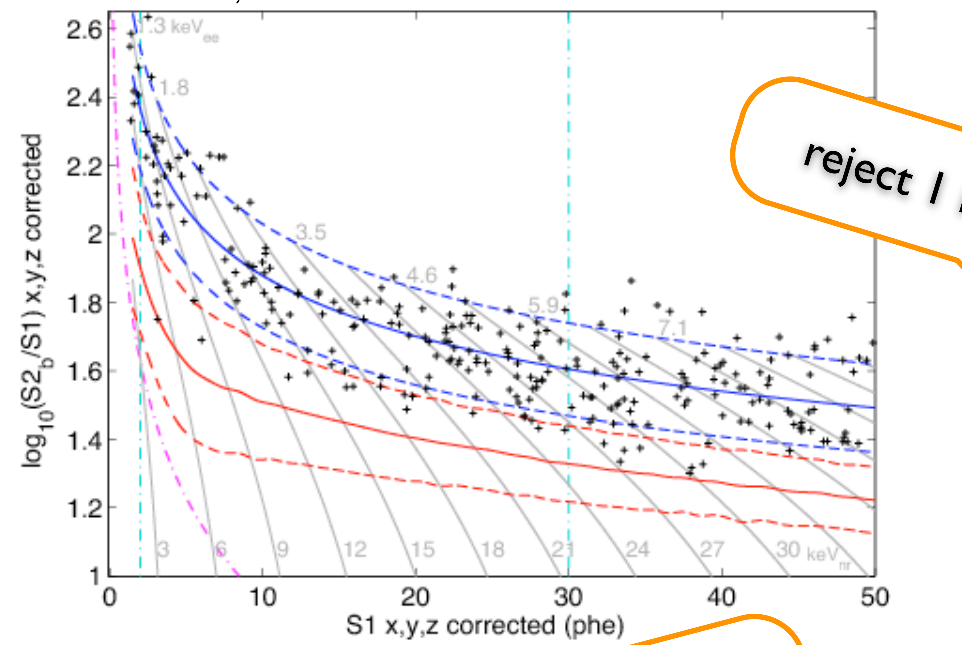




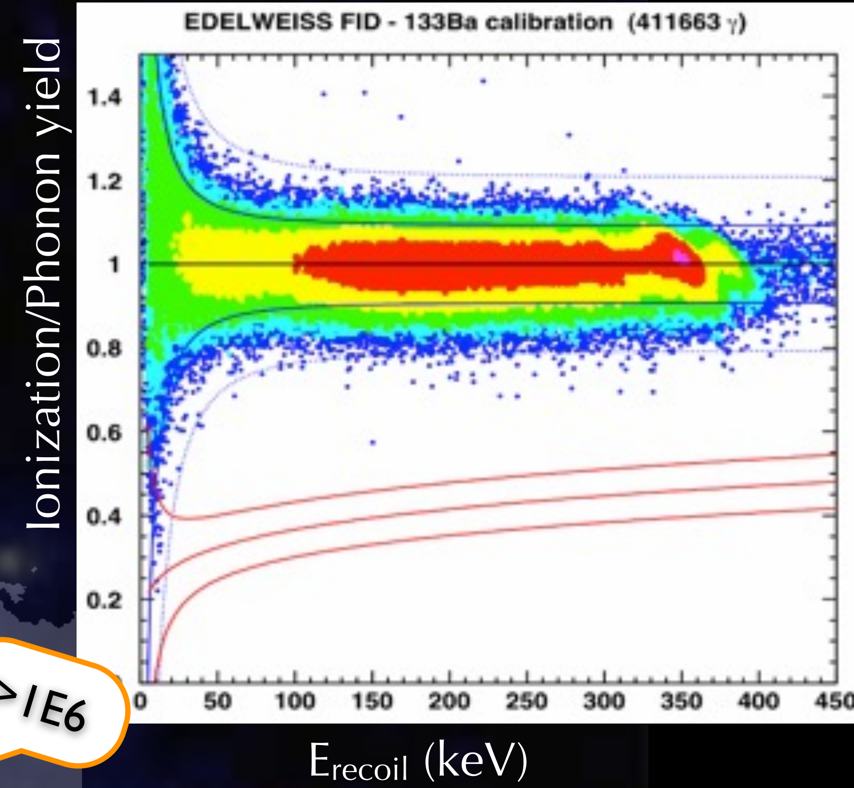
Topology

Background Discrimination Strategies

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



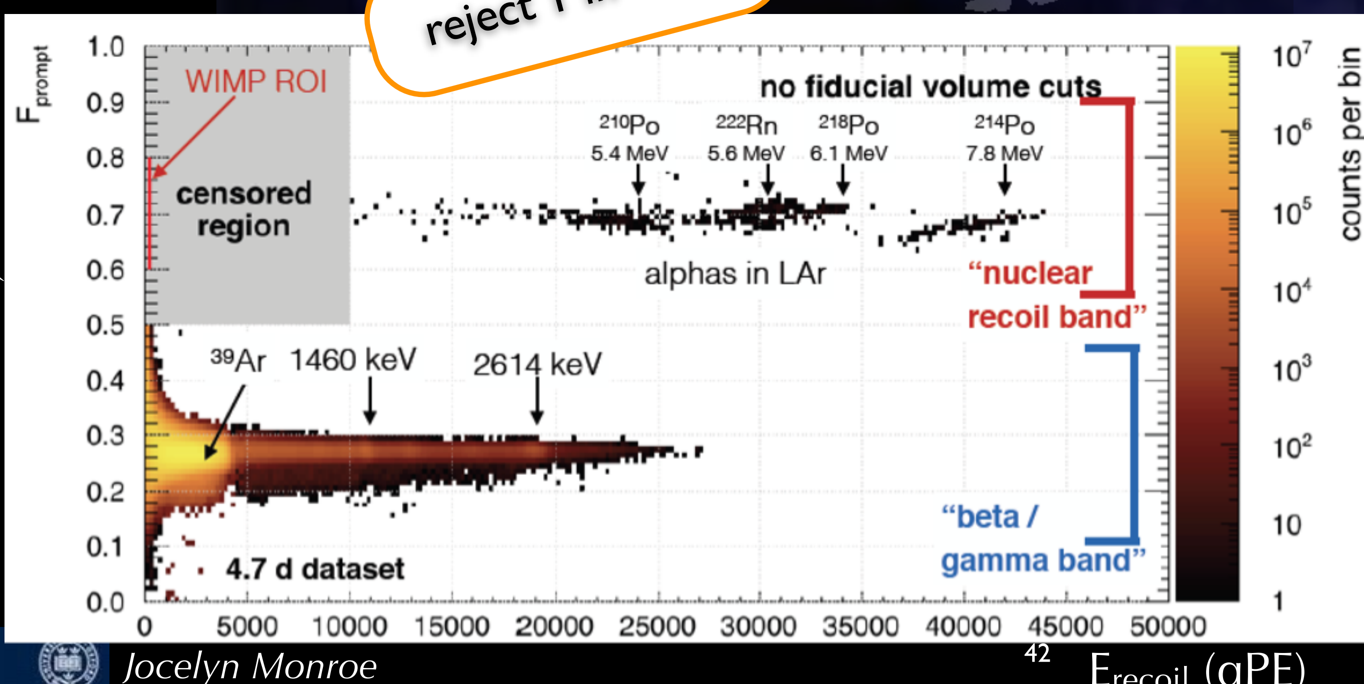
reject 1 in >1E3

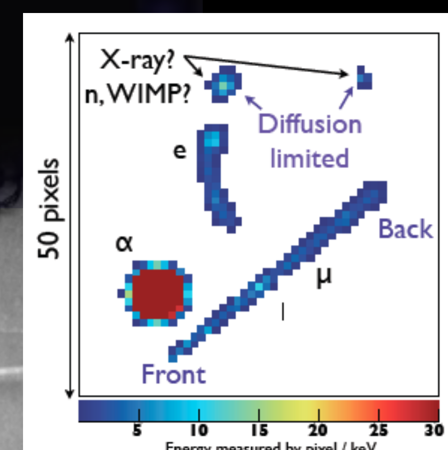


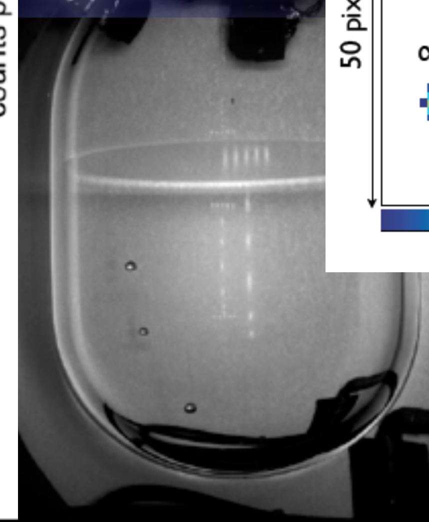
>1E6

reject 1 in >1E9

Amaudruz et al., arXiv:1707.08042







>1E2