Dark Matter Direct Detection:
Experimental Results

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UK HEP Forum
From Laboratories to the Universe and Back
November 23, 2021

Outline

1. Direct Detection Context

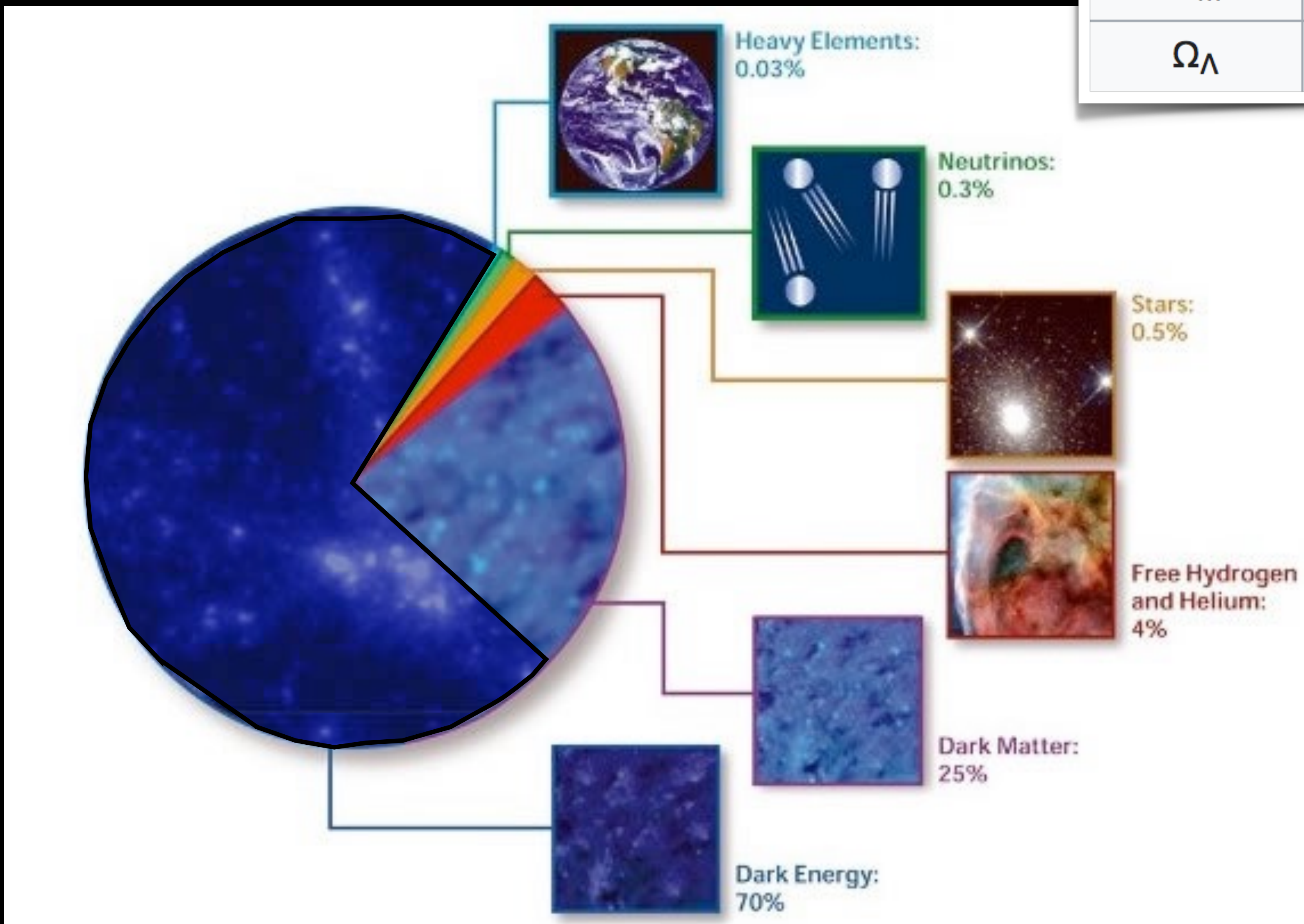
2. Current Searches

3. New Strategies

The Standard Model of Cosmology

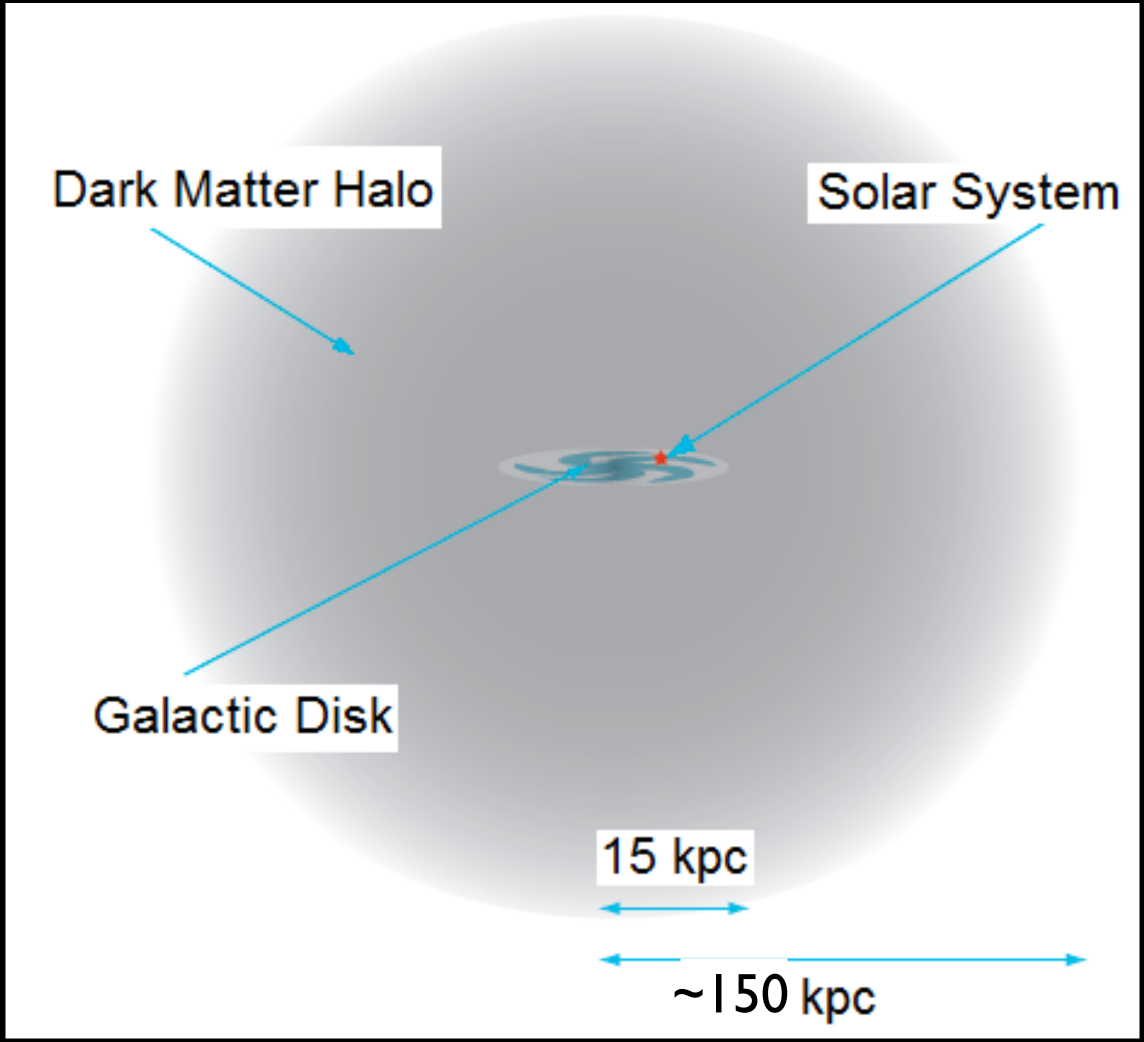
Ω_b	0.0486 ±0.0010[e]
Ω_c	0.2589 ±0.0057[f]
Ω_m	0.3089 ±0.0062
Ω_Λ	0.6911 ±0.0062

Planck (2016). Astronomy & Astrophysics. 594 (13): A13



Dark Matter is ~25% of the universe.

What do we know about Dark Matter?



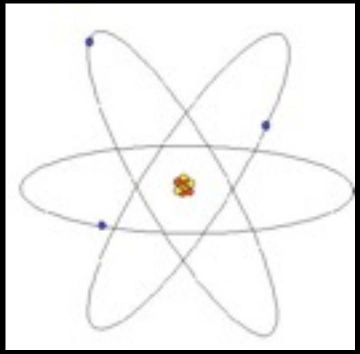
optically dark

density ~ 0.3 GeV/cm^3

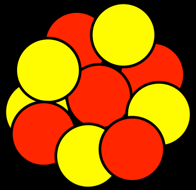
dark matter particle mass: ~unknown

interactions: very weak, ~collision-less

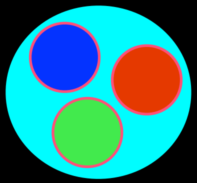
The Standard Model of Particle Physics



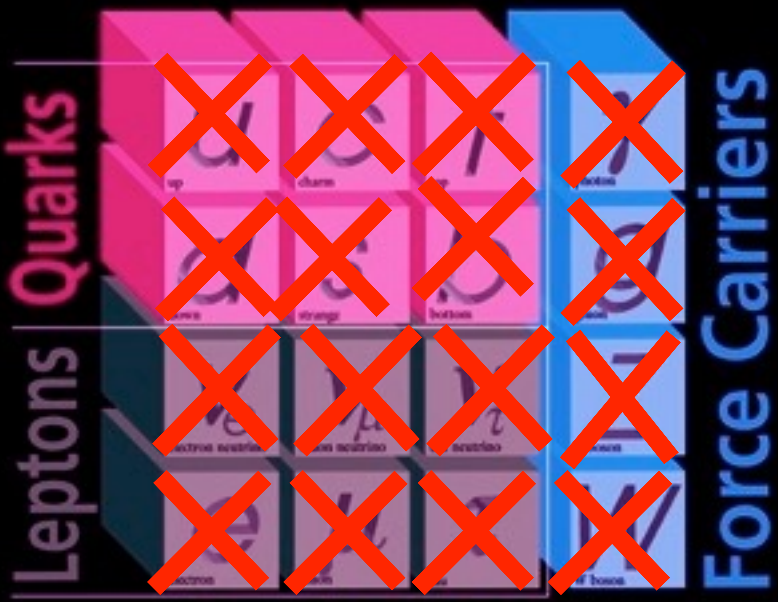
Atoms are made of electrons and a nucleus



The nucleus is made of protons and neutrons



Protons and neutrons are made up of quarks

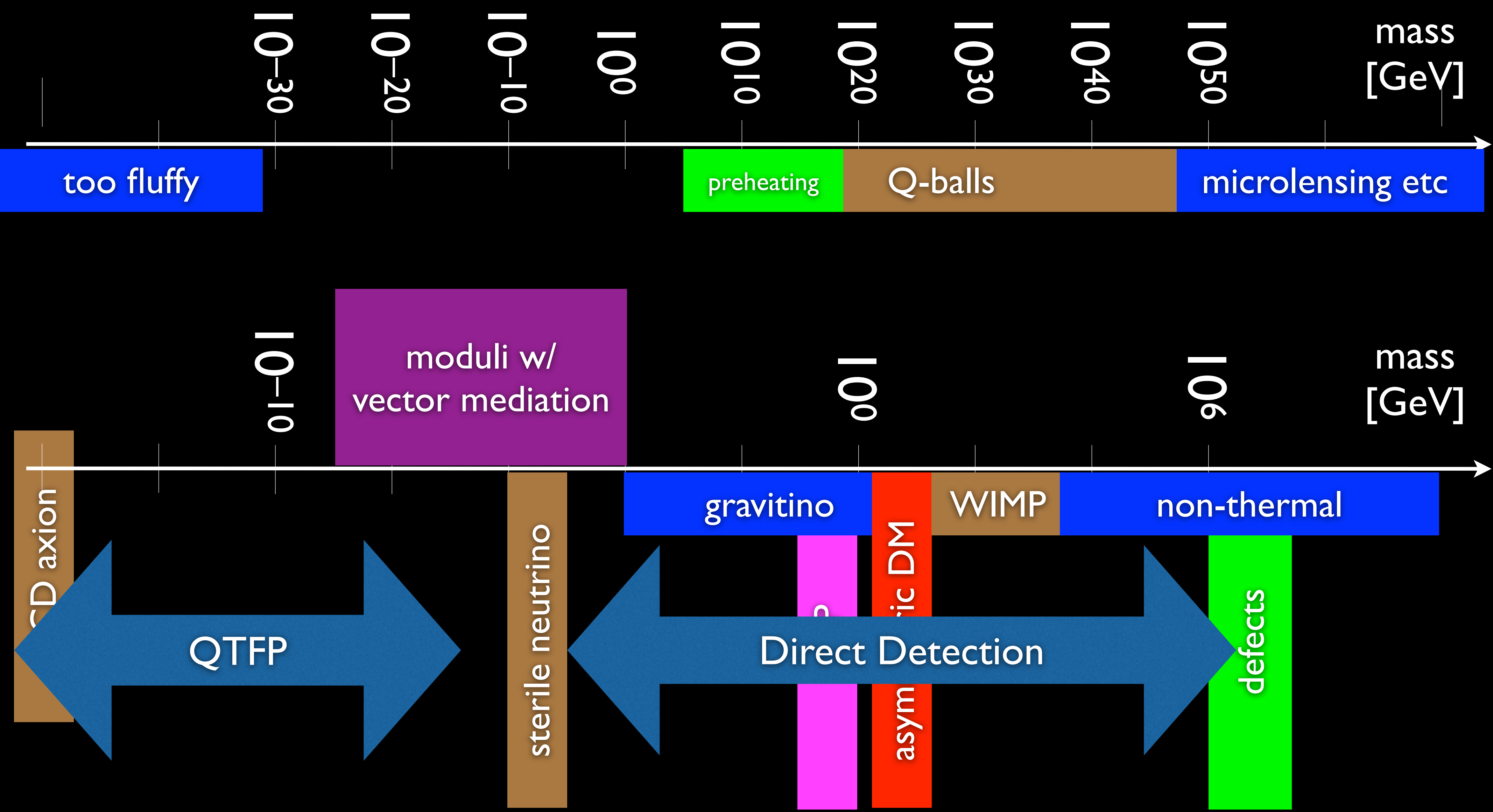


The Standard Model: point-like "elementary particles"

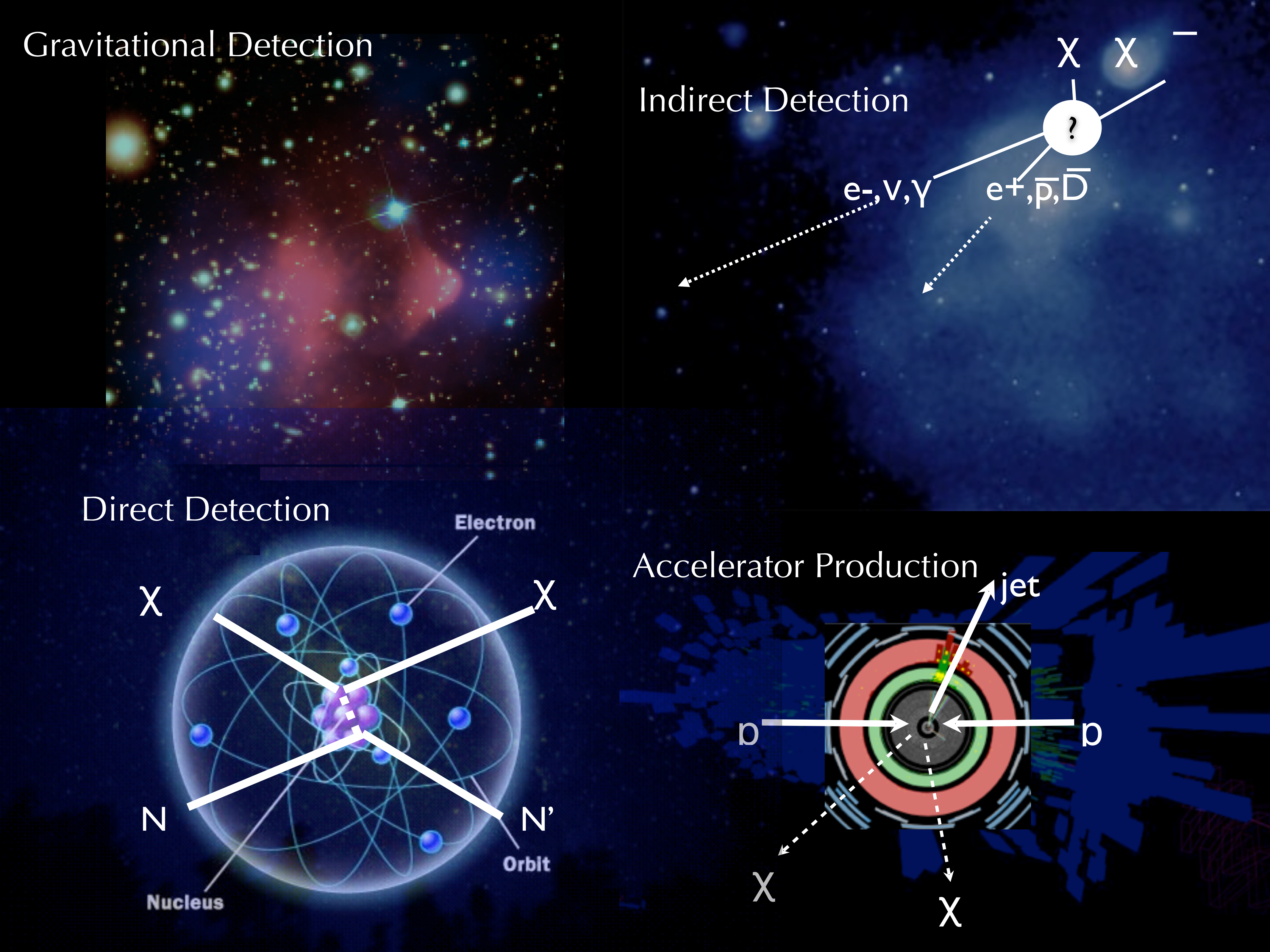
Dark Matter? **None of the above.**

Model Space: Theorist's View

(thanks to H. Murayama)



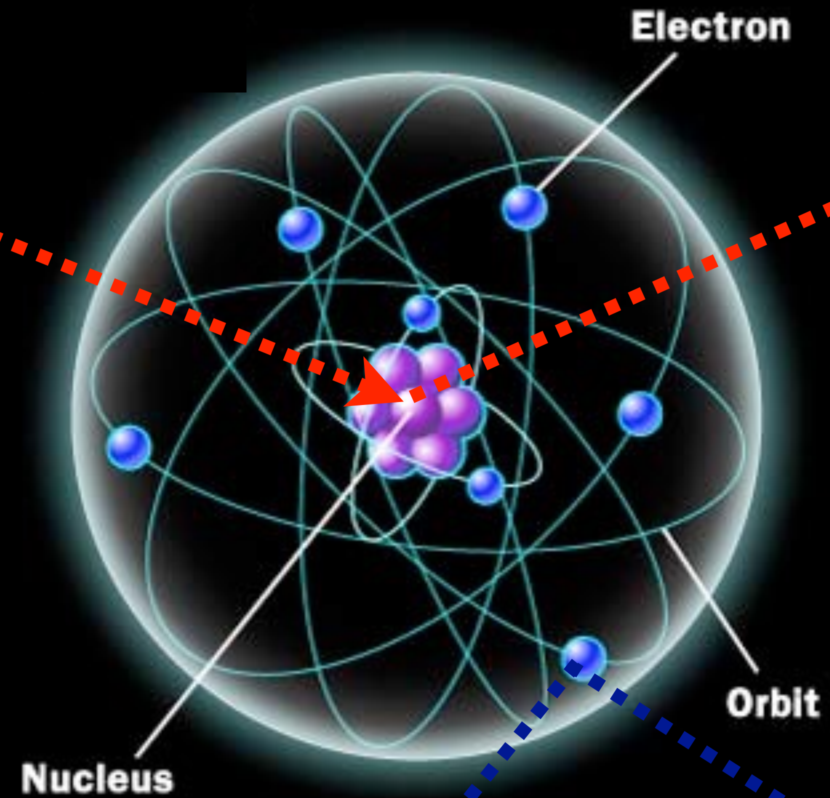
New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.



Gravitational Detection
Indirect Detection
χ χ̄
?
e-,ν,γ
e+,p̄,D̄
Direct Detection
Electron
χ
χ
N
N'
Orbit
Nucleus
Accelerator Production
jet
p
p
χ
χ

Dark Matter Direct Detection

Signal: $\chi N \rightarrow \chi N$



Backgrounds:

$\gamma\, e^- \rightarrow \gamma\, e^-$

$n\, N \rightarrow n\, N$

$N \rightarrow N' + \alpha, e^-$

$\nu\, N \rightarrow \nu\, N$

Detection

Number of Events = (Flux) x (Cross Section) x (Exposure)

(how much dark matter)

(how likely it is to interact)

(how long you look)

Astrophysics

Particle Physics

Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

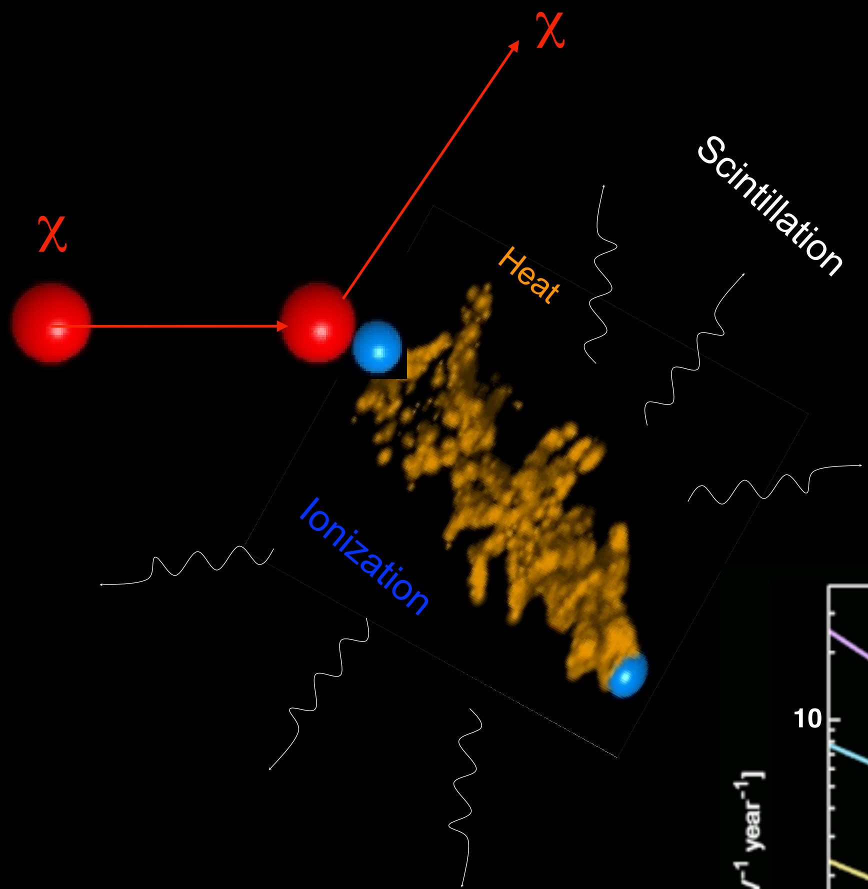
$$dR/dQ = (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

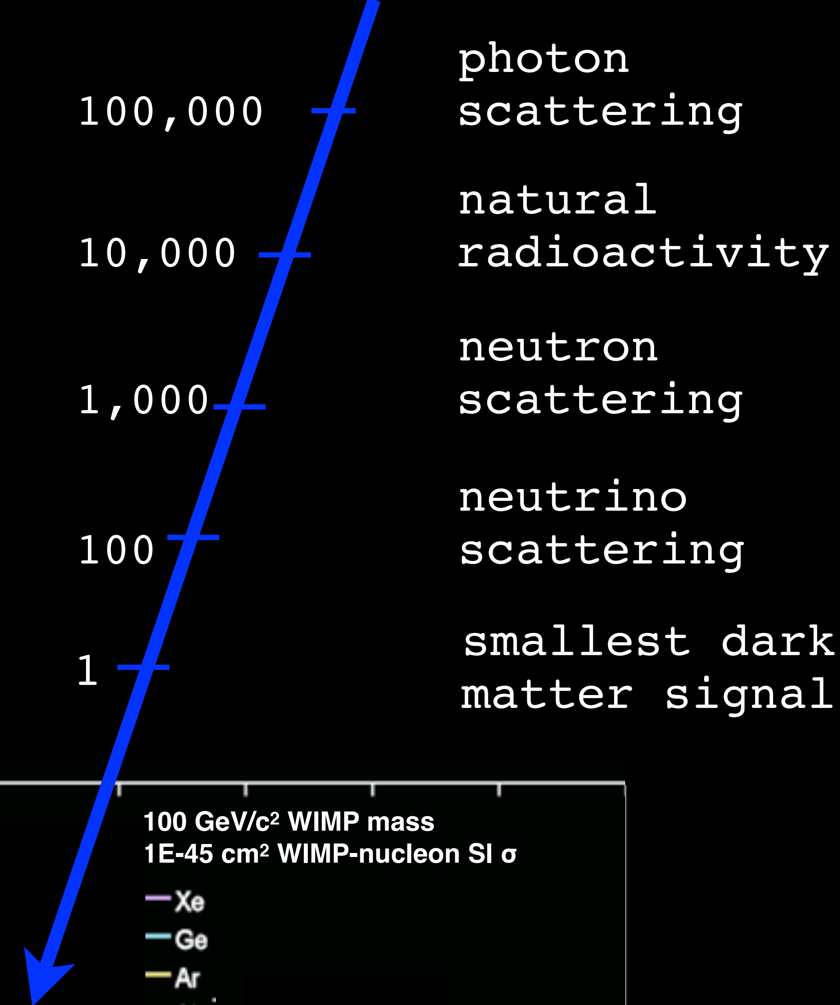
WIMP energy density, 0.3 GeV/cm^3

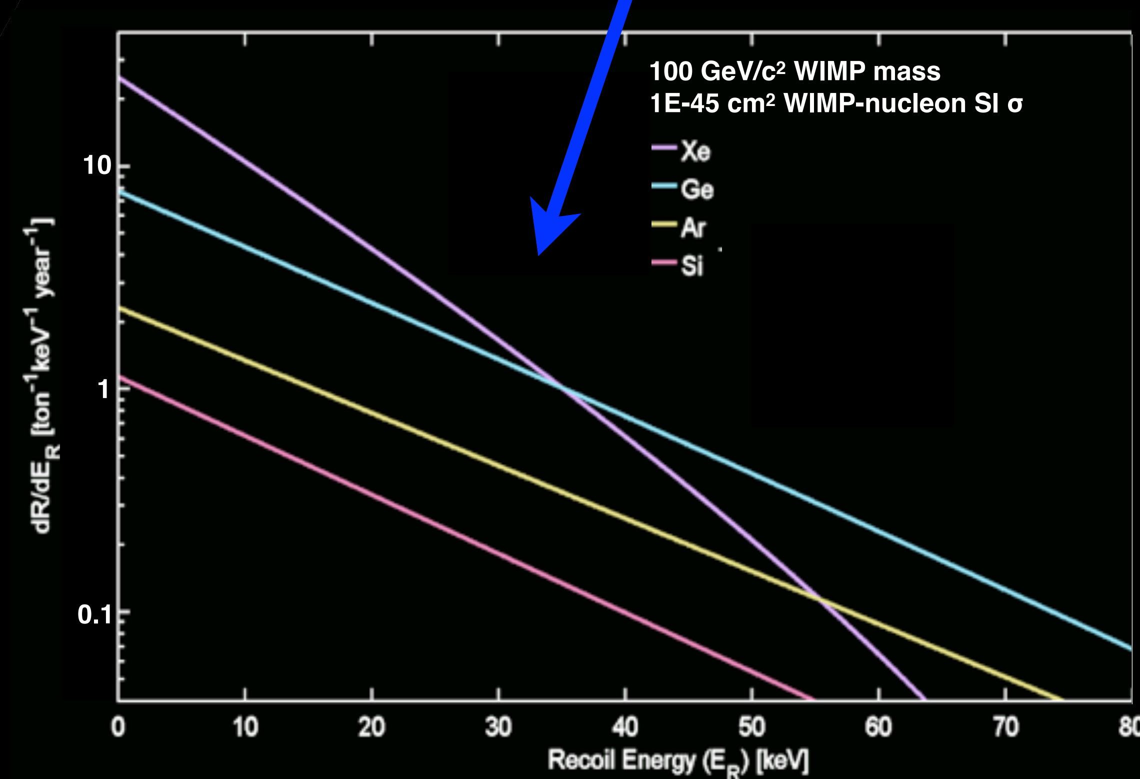
Form factor

Nuclear Physics

Measurement







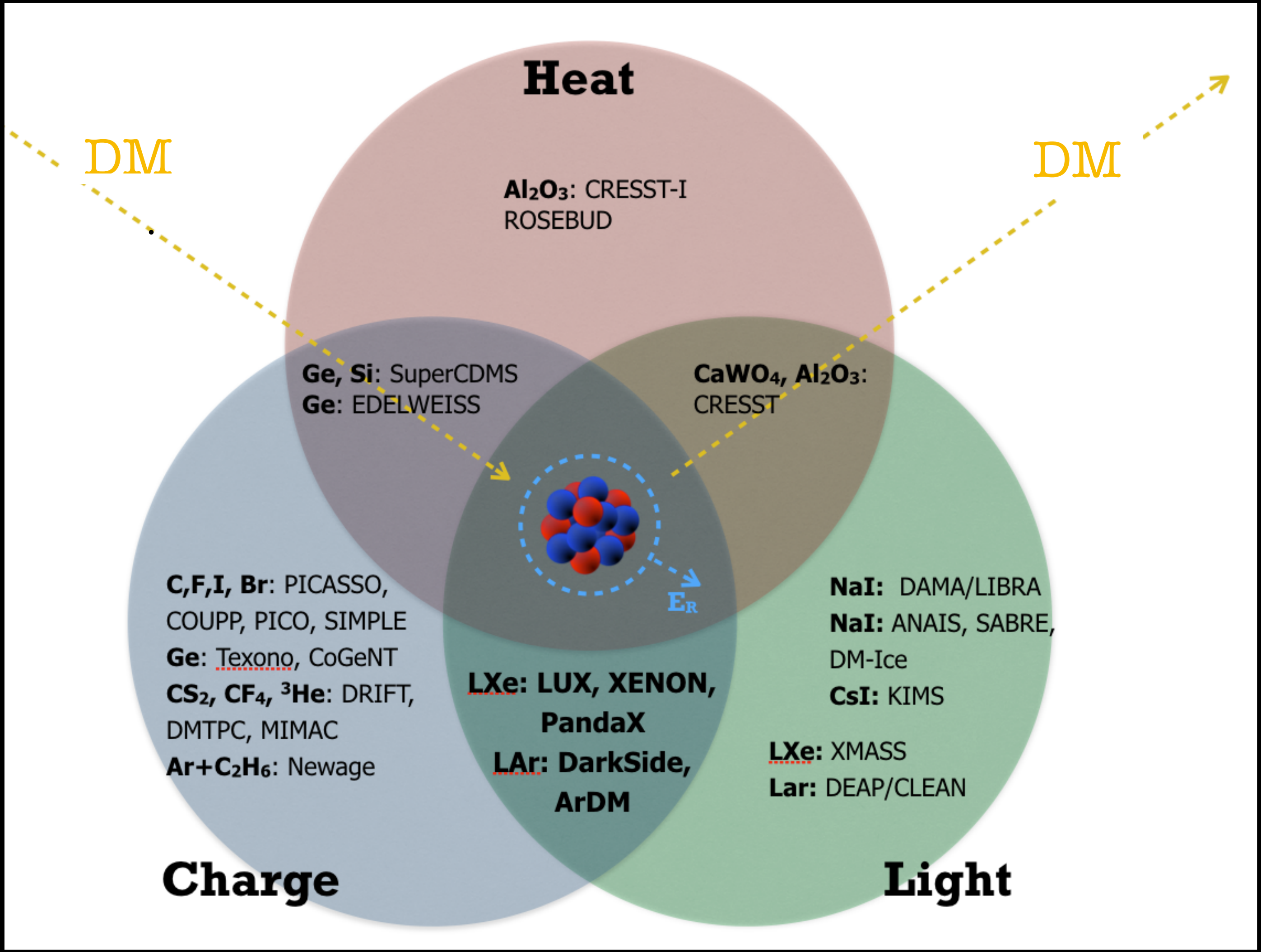
experimental requirements:

keV-scale energy threshold + background discrimination at the ppm-ppb level

Observables

$E_R \sim$ 1E-6 x m_{DM}

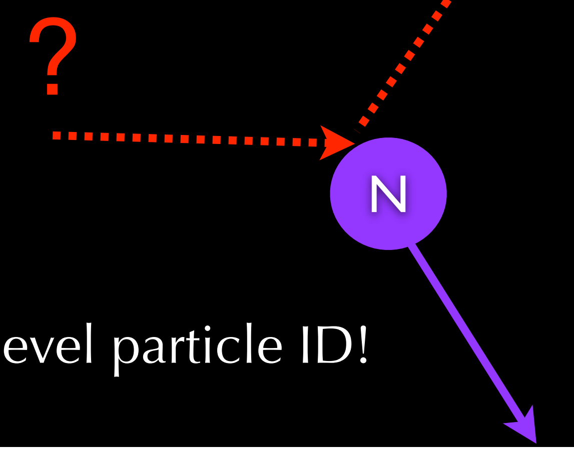
E_R threshold now O(10s eV), potential to reach meV



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

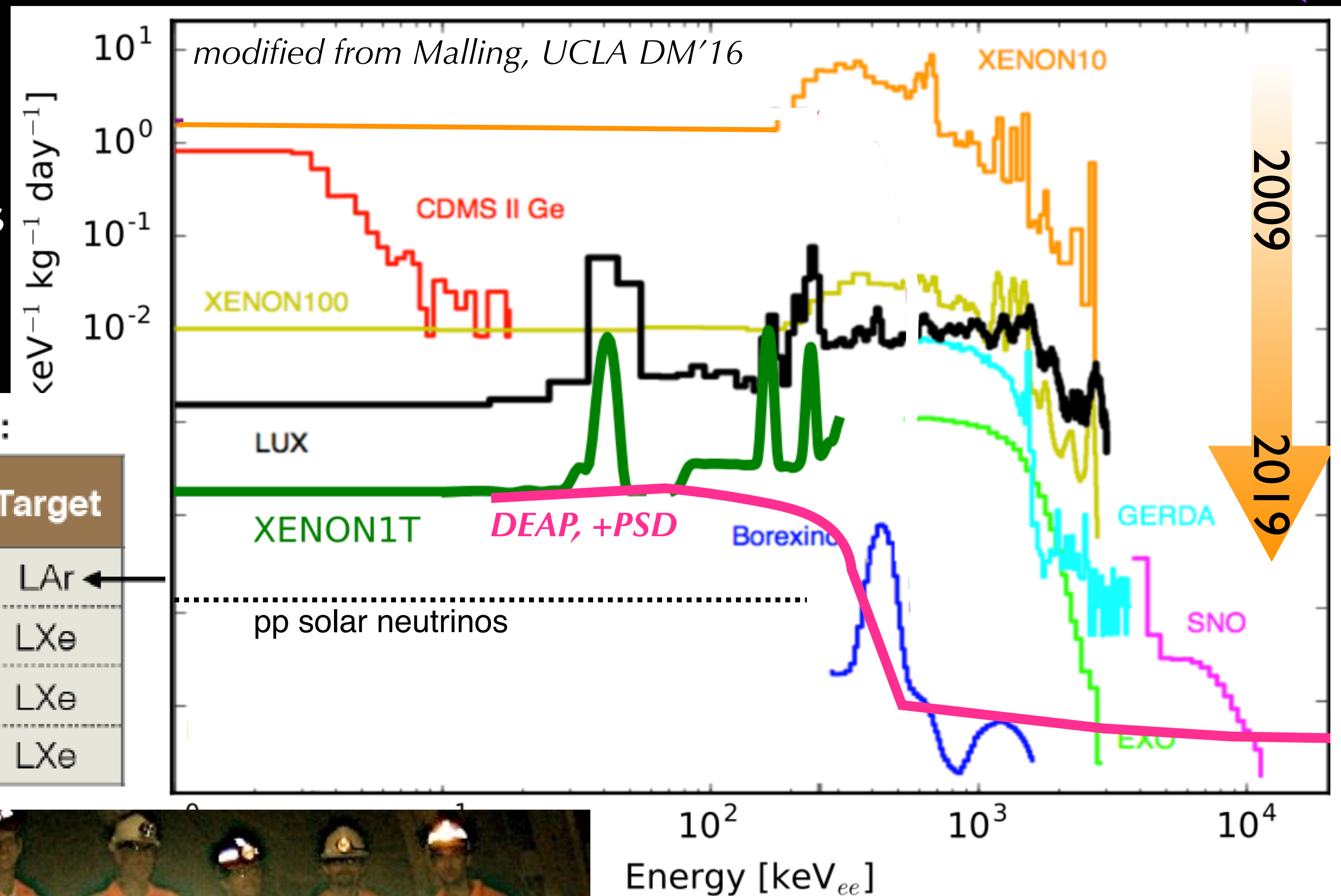
E_R threshold now O(keV), potential to reach 10 eV

Backgrounds



Gamma ray interactions: electron recoil final states
rate ~ N_e x (gamma flux), O(1E7) events/(kg day)
mis-identified electrons mimic nuclear recoils … part-per-billion level particle ID!

Contamination:
^{238}U and ^{232}Th decays,
recoiling progeny and
mis-identified alphas, betas
mimic nuclear recoils



^{222}Rn in Dark Matter experiments:

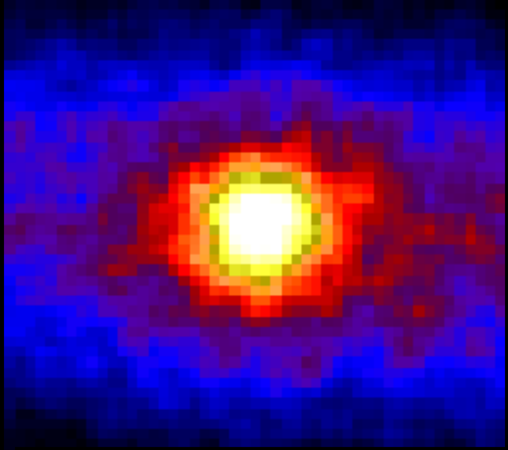
Experiment	Activity / rate	Target
DEAP-3600	≈0.2 μBq / kg	LAr ←
PandaX-II	6.6 μBq / kg	LXe
LUX	66 μHz / kg	LXe
XENON1T	10 μBq / kg	LXe

- PandaX-II: PHYSICAL R
- LUX: Physics Procedia
- XENON1T: XeSAT 2017

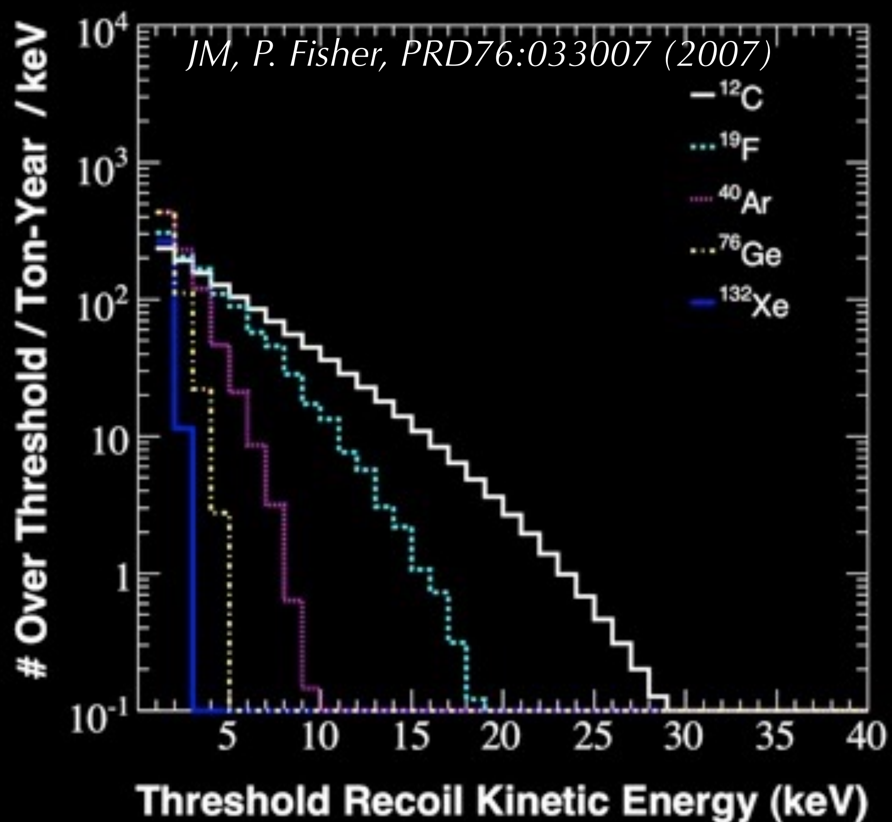
Amaudruz et al, Phys.Rev.

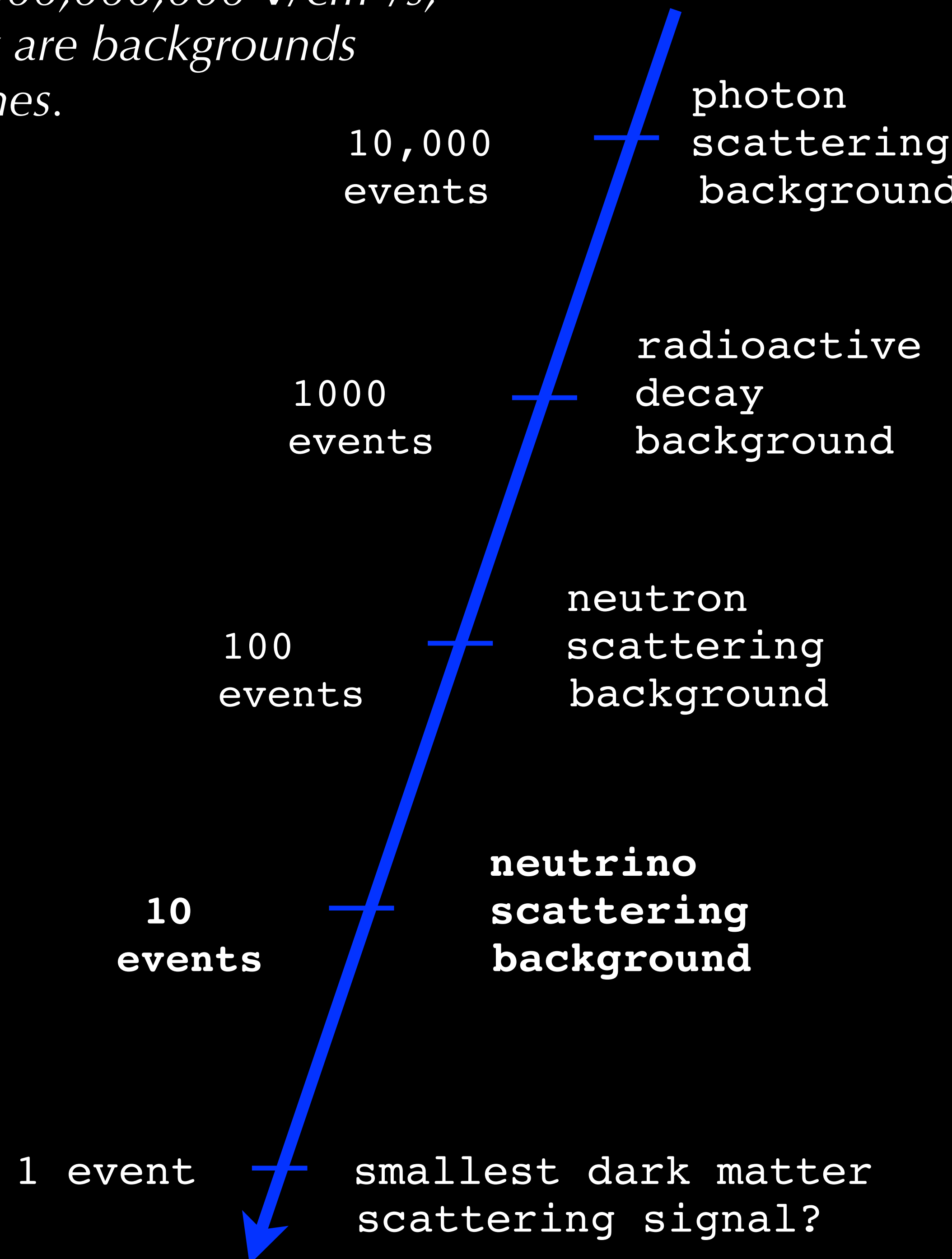
+ large, active veto detectors

The sun shines 100,000,000,000 ν/cm²/s, 1 in a million/kg/day are backgrounds to dark matter searches.



(Super-Kamiokande)

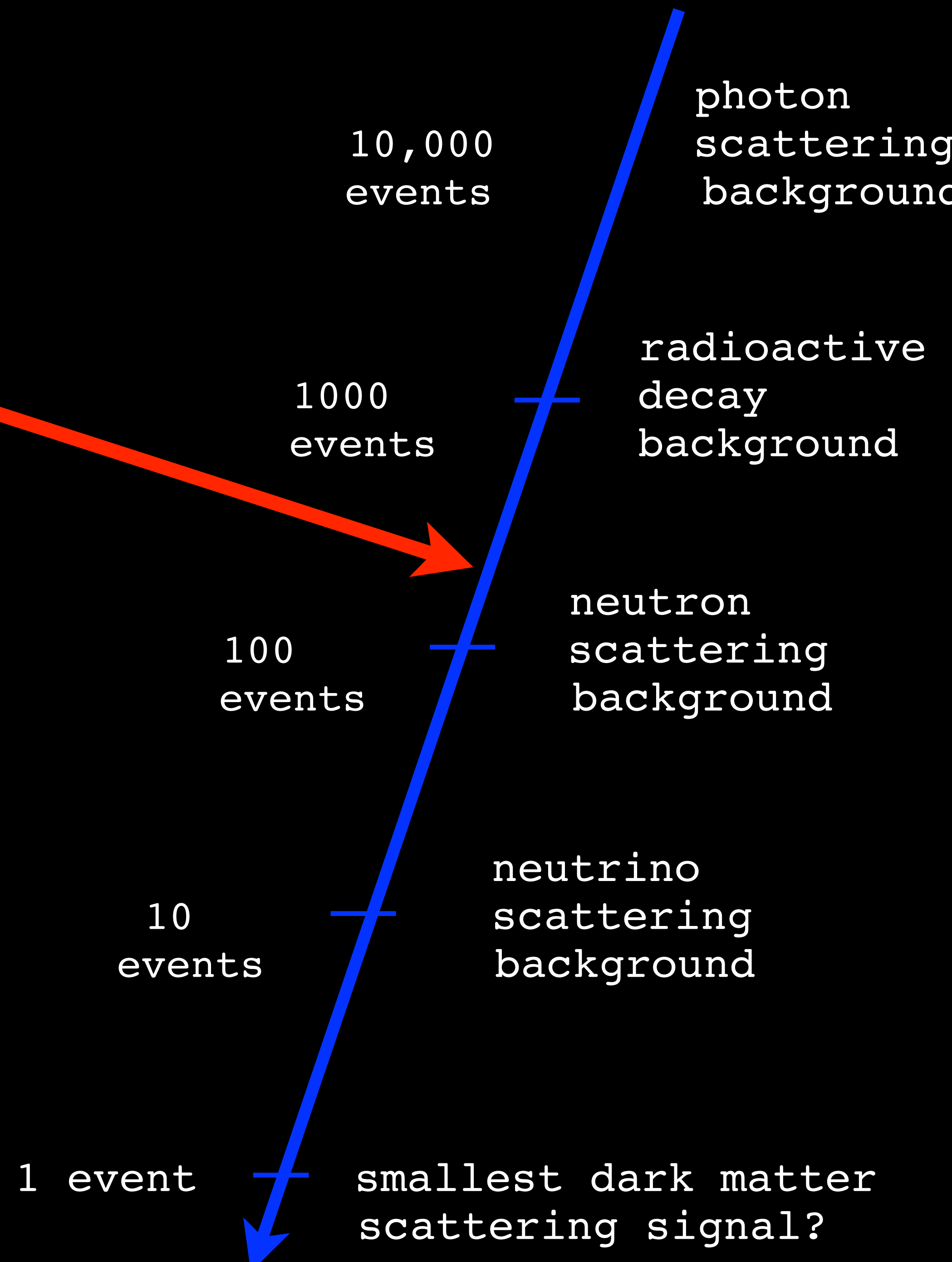




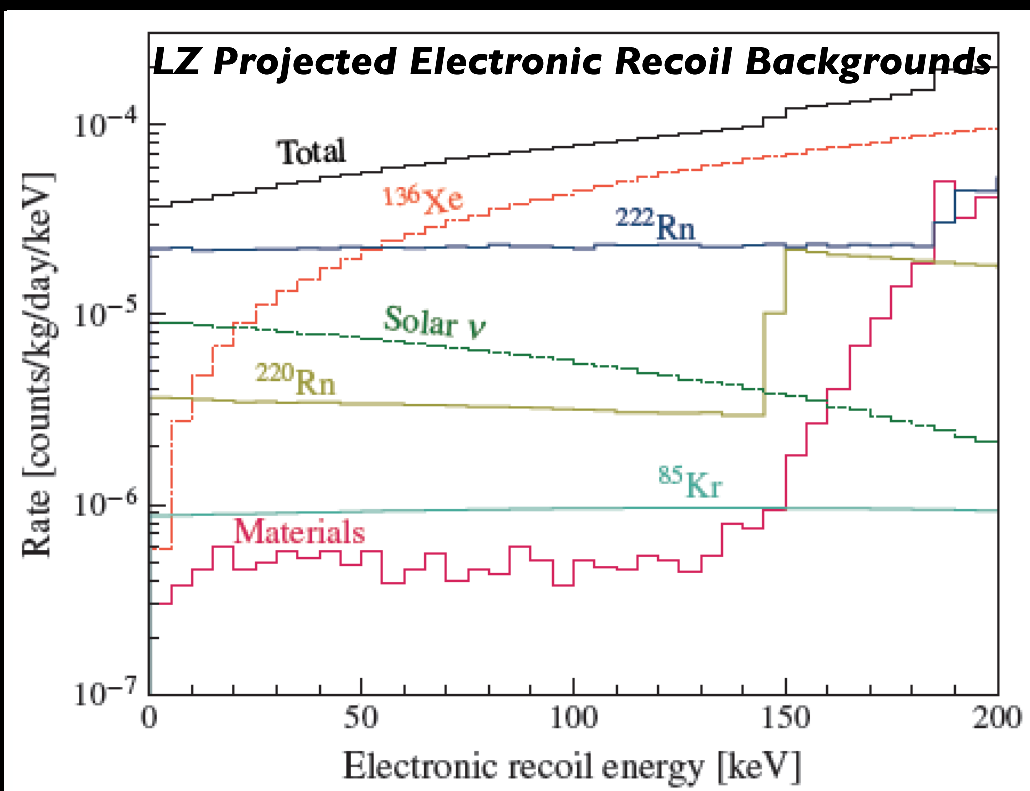
neutrino floor: impossible to shield a detector from neutrino scattering!

Backgrounds

experiments are here



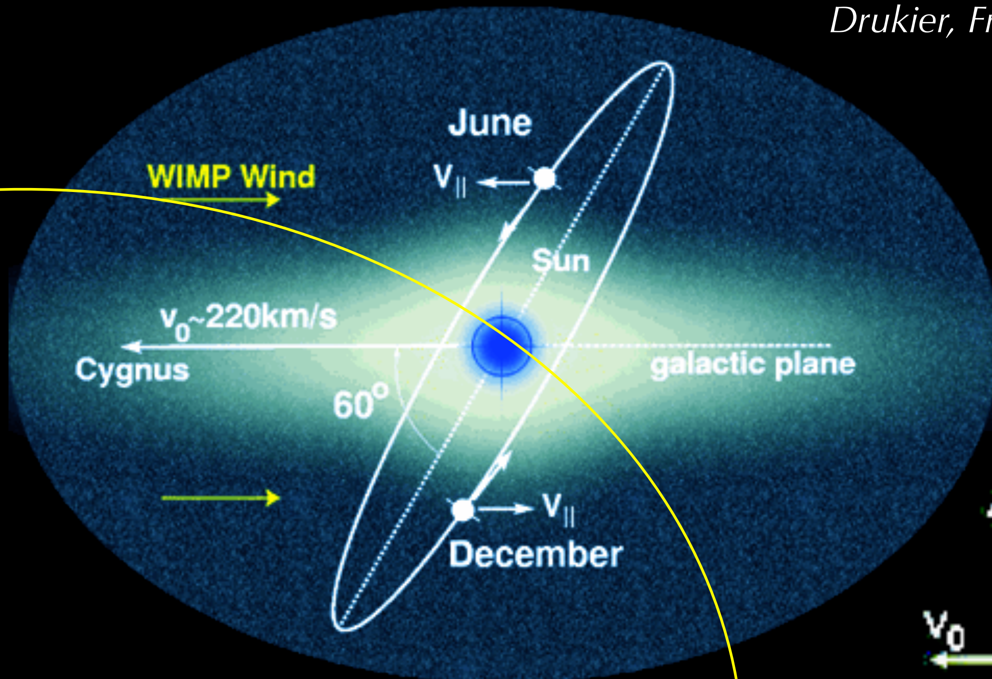
neutrino floor: depends on electron recoil discrimination, both ν-N and ν-e contribute!

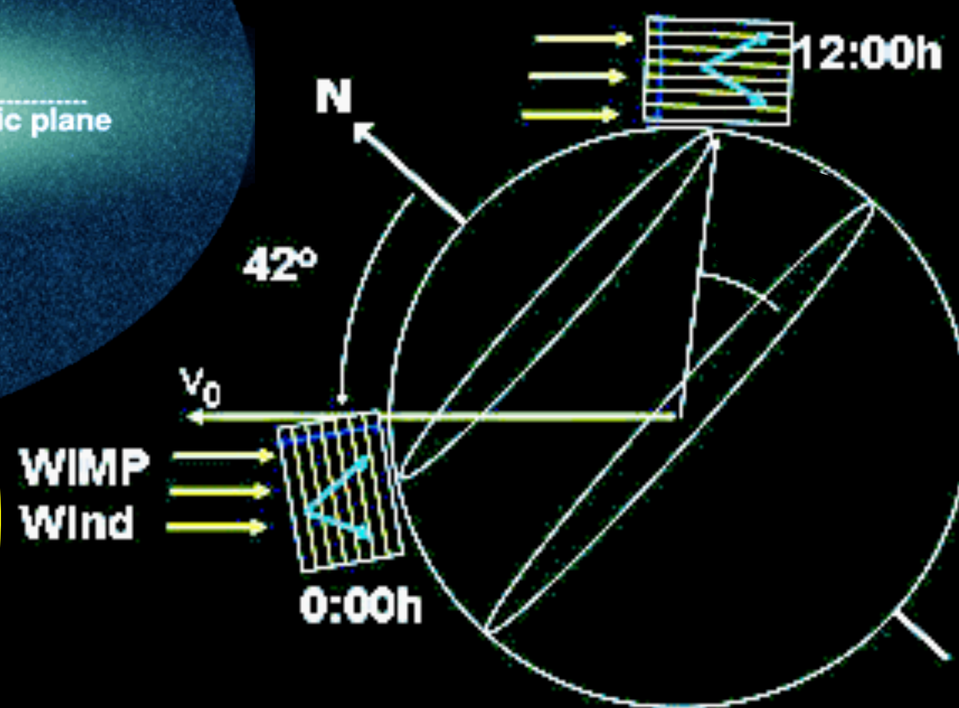


Modulation Signatures

Annual event rate modulation:
June-December asymmetry ~2-10%

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)

Outline

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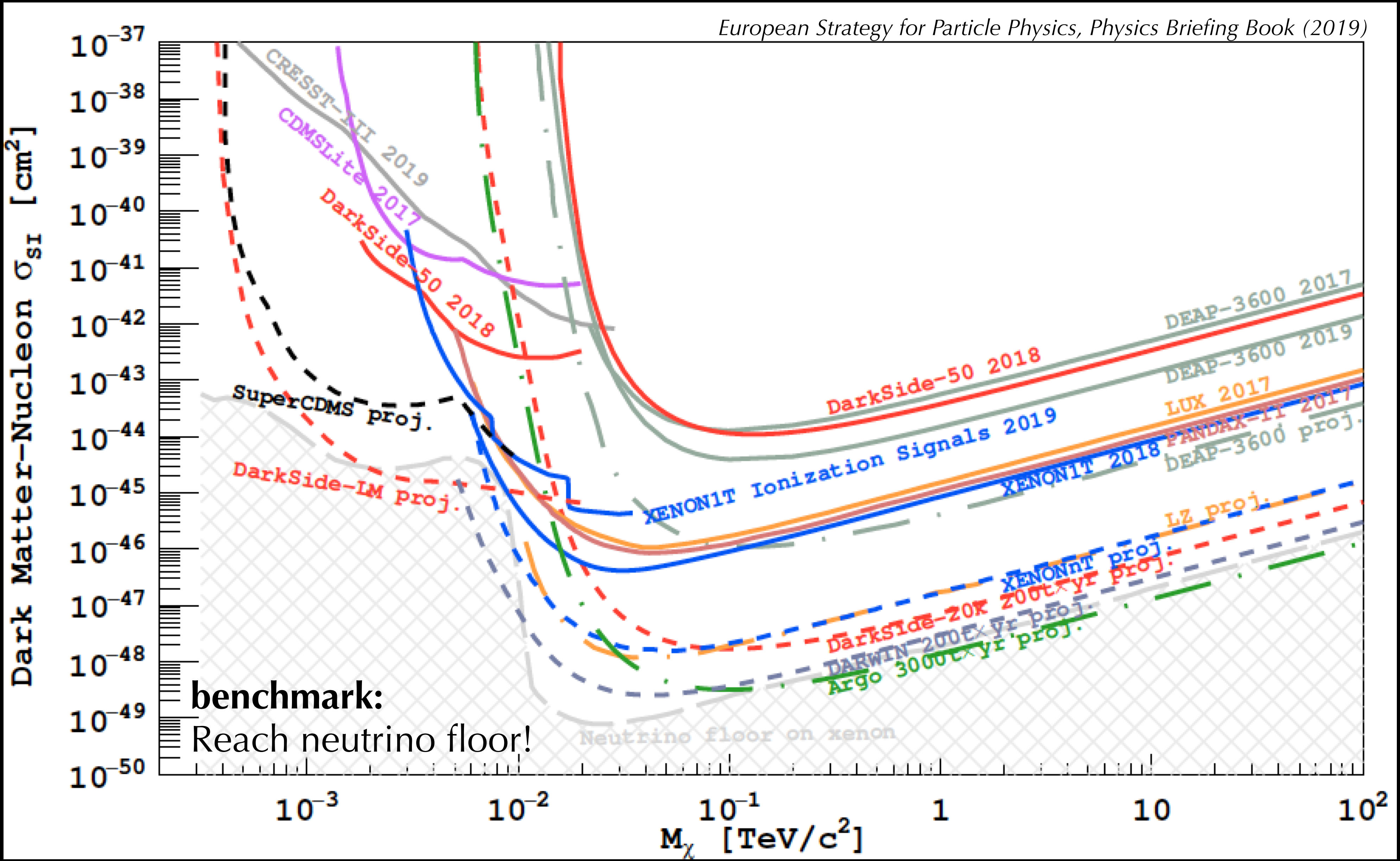
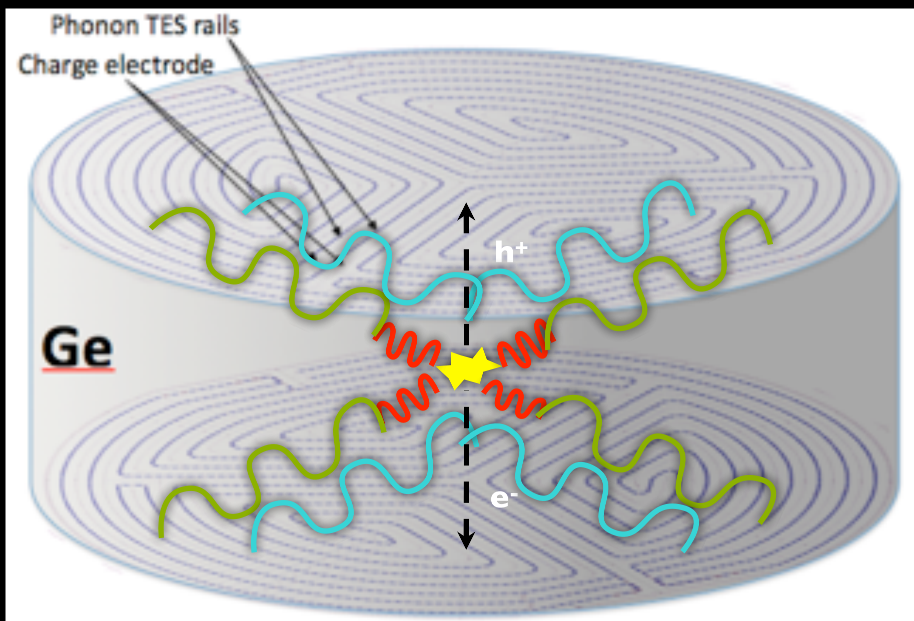
3. New Strategies

Direct Detection Status



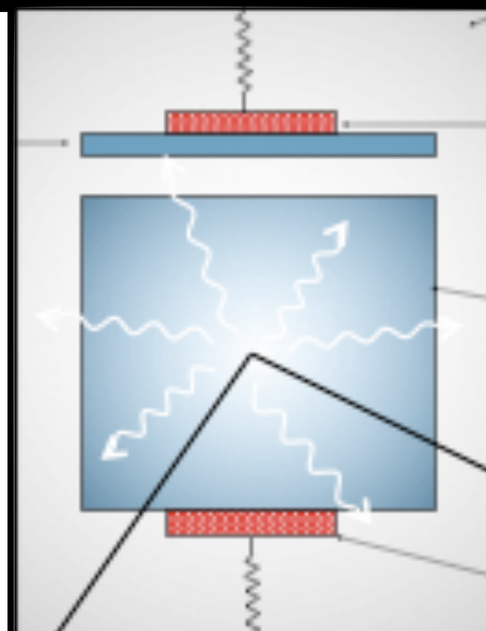
Heat ++

1400 / 800 gm Ge (**SuperCDMS / EDELWEISS**)
Phonon rails: TES for E_{recoil} & R (timing)



Charge electrodes: biased at +/- 2V, measure E_{recoil}, configured to reject surface events

300 gm $CaWO_4$ **(CRESST)**
Phonon side: **TES for E_{recoil}**



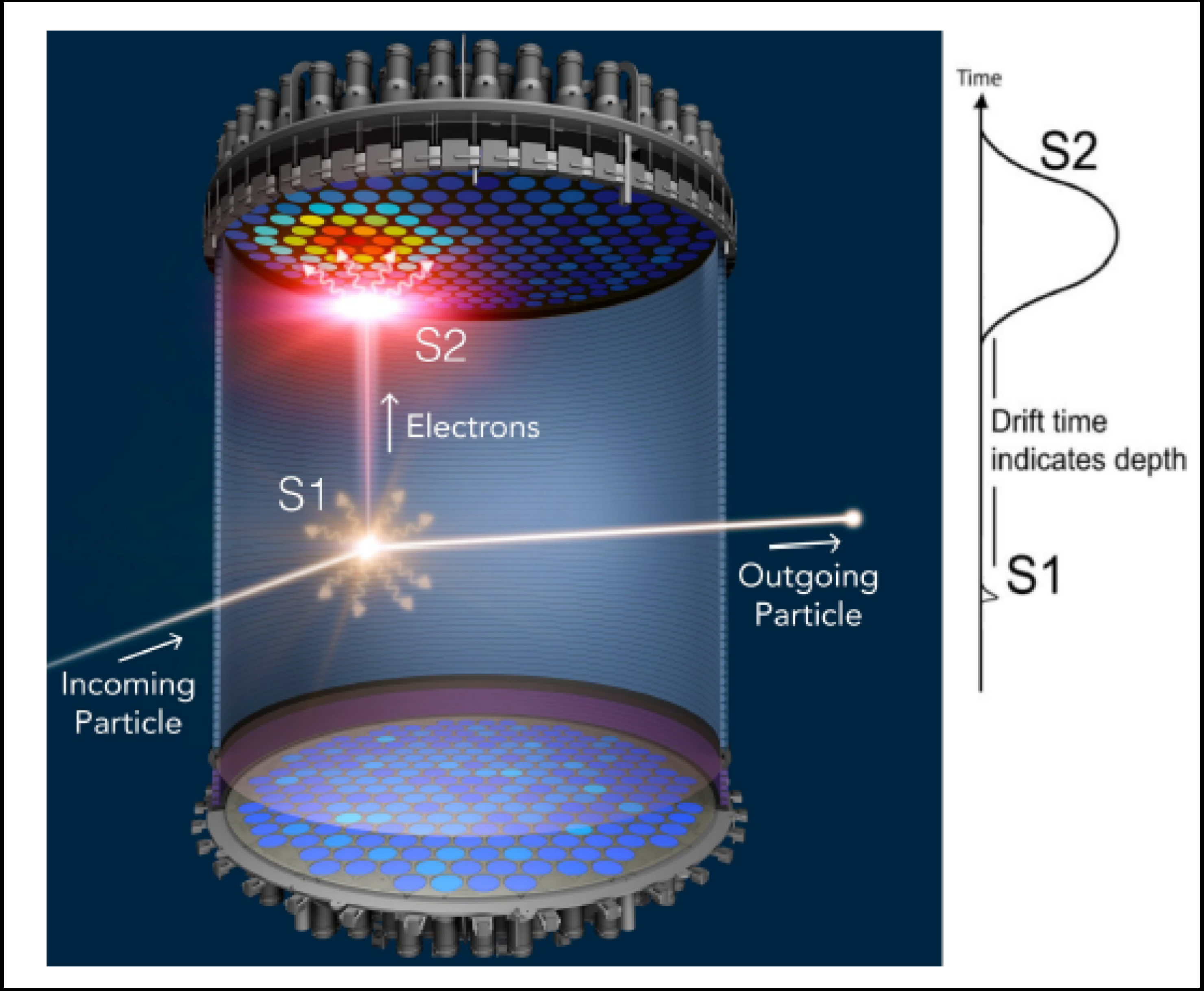
Scintillation side:
TES for particle ID

Detector Technology

crystals with eV-scale band gap instrumented with Transition Edge Sensor readout at O(10 mK) for phonon + scintillation/ionization signal detection

detectors reach energy thresholds of 30 eV_{nr} (CRESST)
70 eV_{nr} (CDMSlite)

Charge + Light



https://lz.slac.stanford.edu/our-research/lz-research

Detector Technology:
dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets

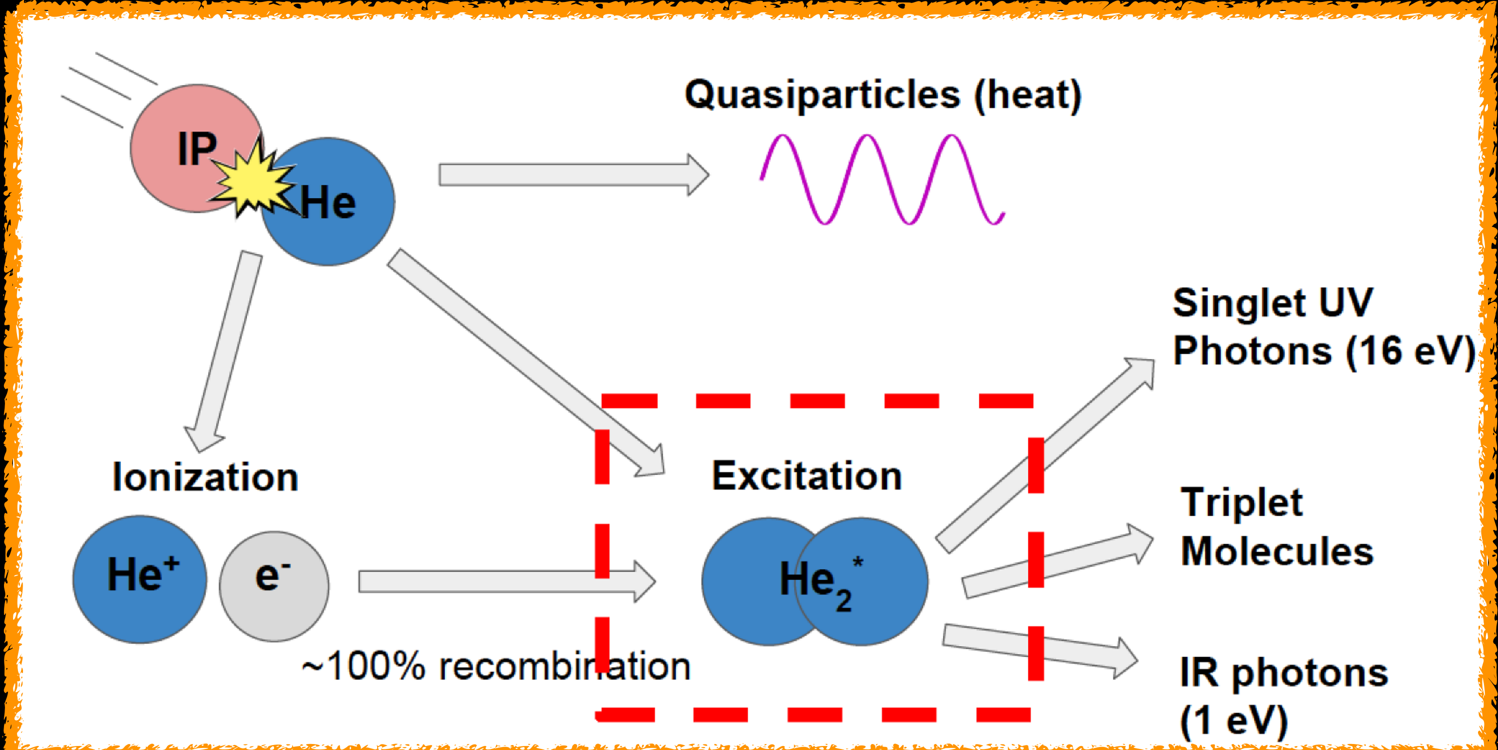
read out primary scintillation: “S1” + proportional gas scintillation from drifted electrons: “S2”

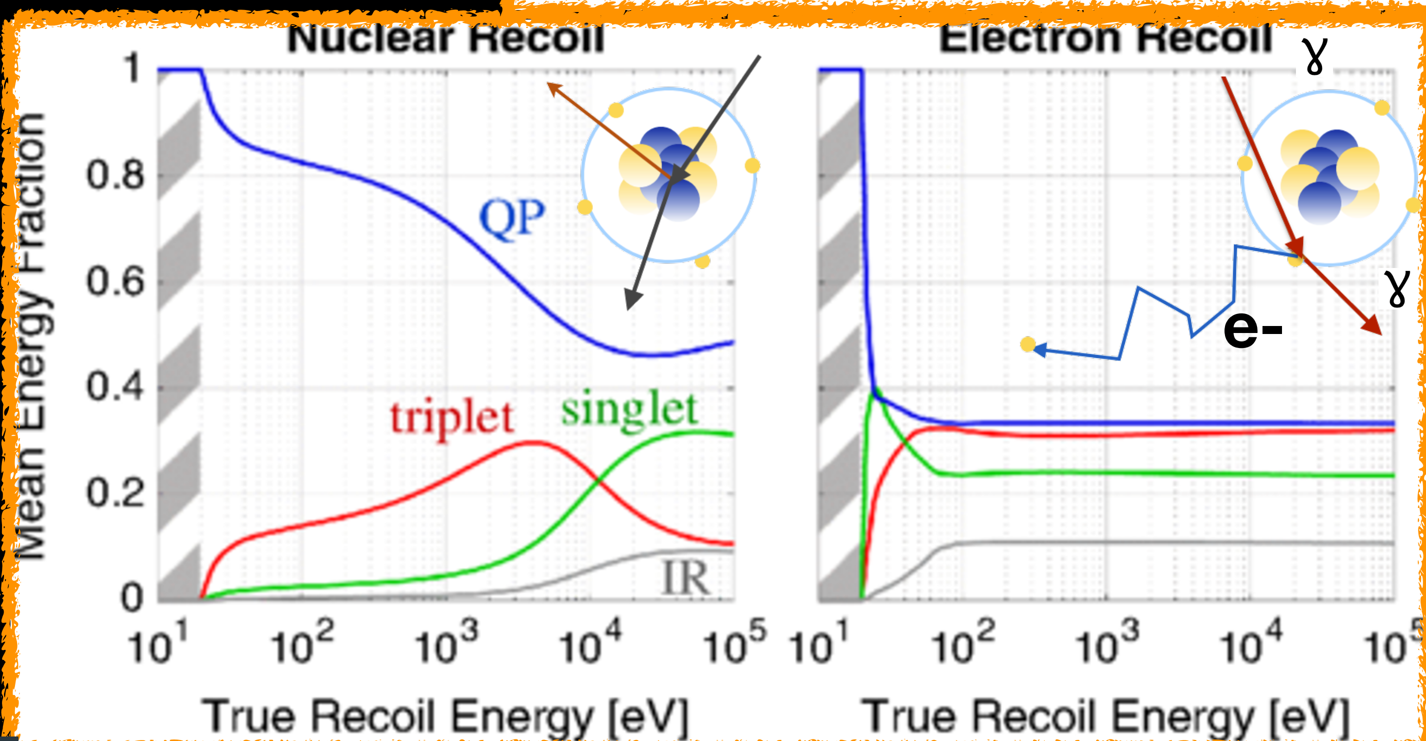
Goal: zeptobarn -> yoctobarn sensitivity to dark matter!

Energy Partition

He example

(Thanks: S. Hertel, D. McKinsey)



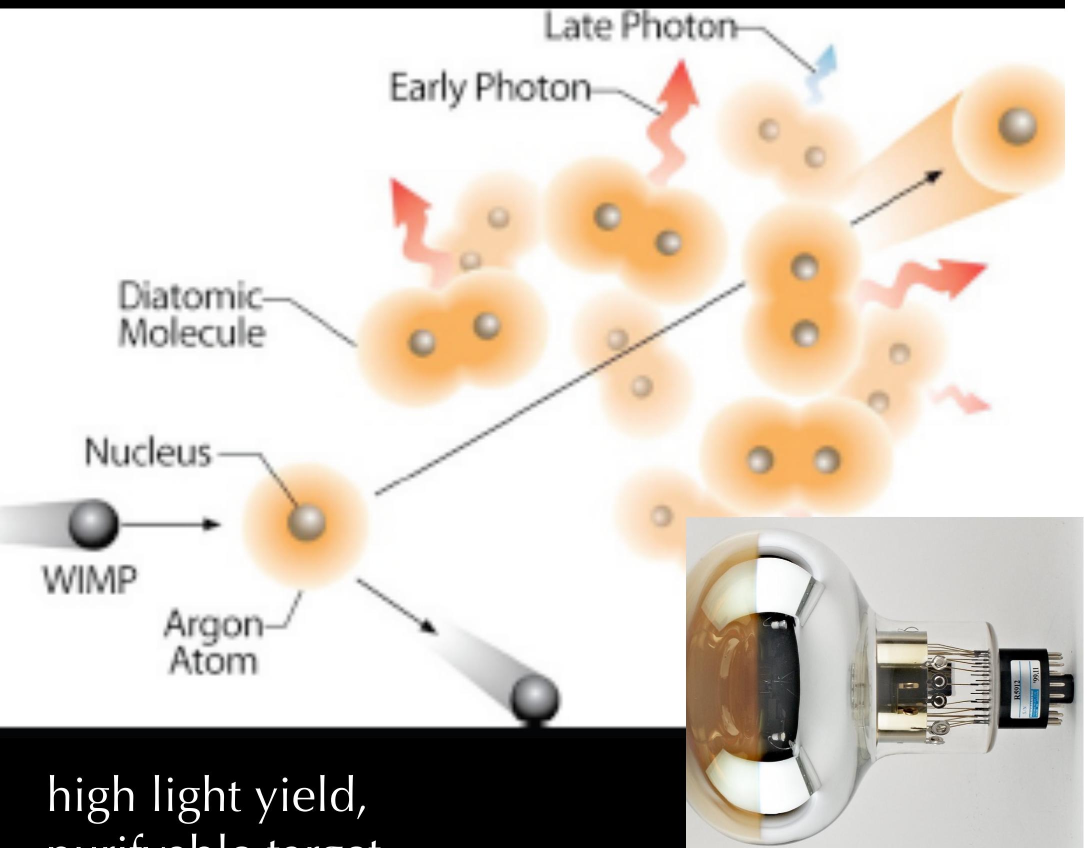


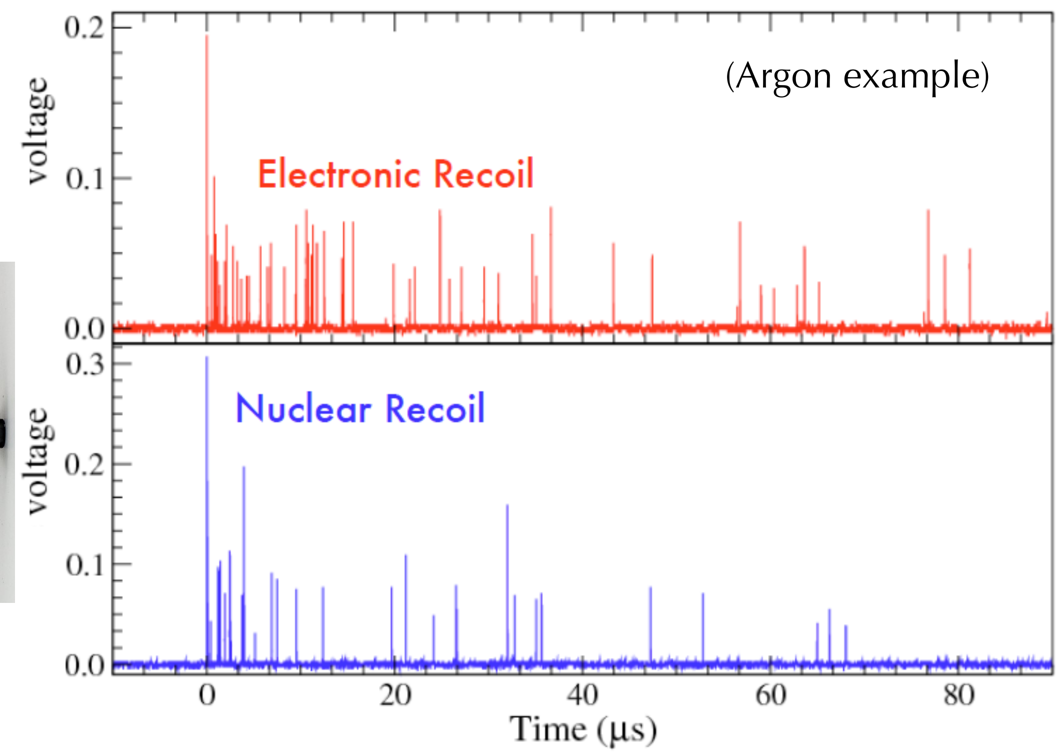
Liquid Noble Targets: S1

particle identification:
light vs. time depends on ionization density.

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





high light yield,
purifyable target,
self-shielding,
transparent to VUV scintillation,
…

Amaudruz et al. Astropart.Phys. 85 (2016) 1-23

Main dark matter backgrounds: target radiopurity, cryostat, PMTs.

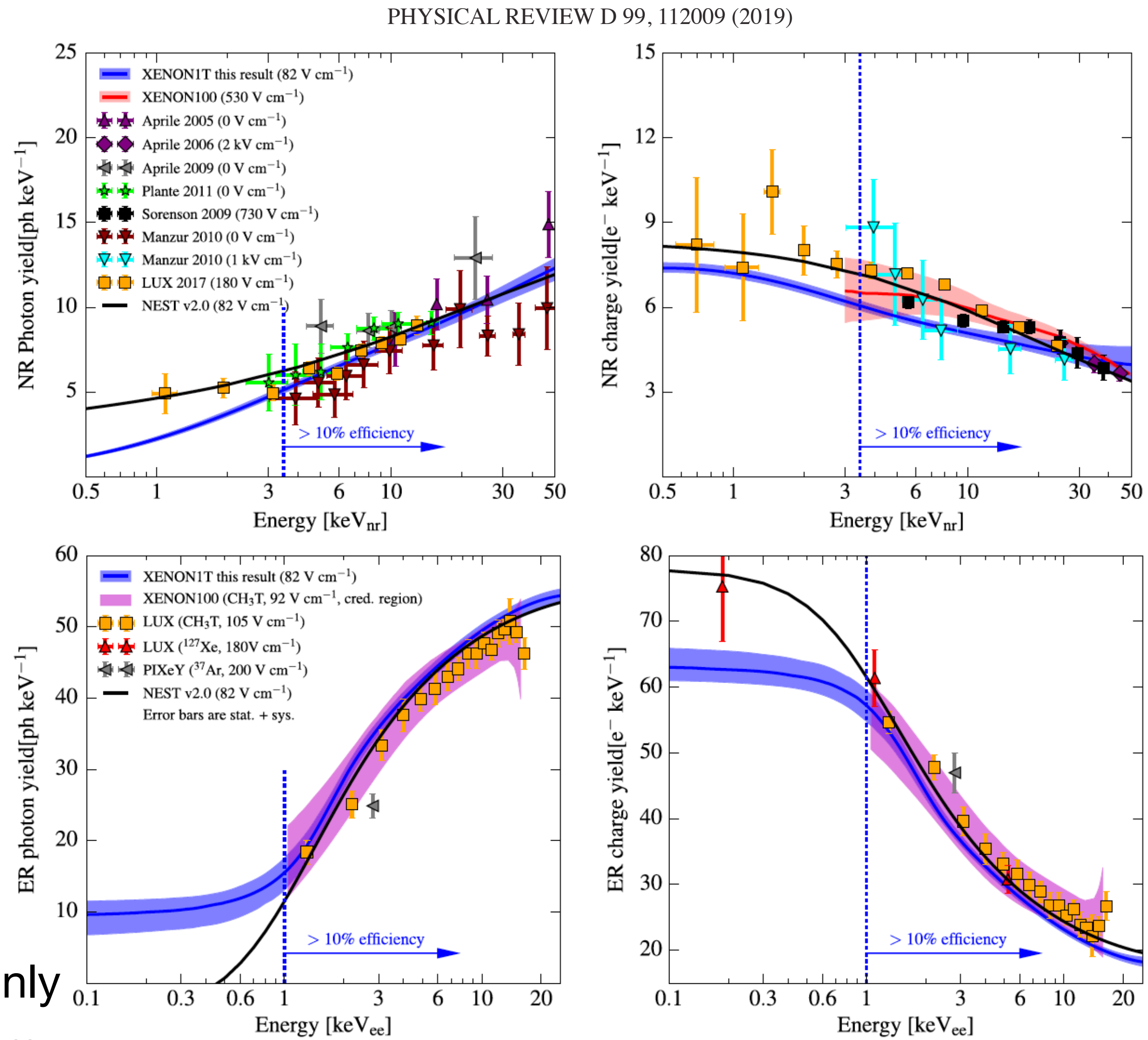
From Deposited Energy to Observable … S1+S2

Thanks: P. Agnes

Ar example:
W_{ion} = 23.5 eV

photon detection efficiency
~ 0.1 - 0.15
LY_{ER} ~ 7 PE / keV_{ee}
LY_{NR} ~ 2.5 PE/keV_{NR}
(high energy)

charge is multiplied in the gas,
with typical gain of 10-20
g2 ~ 10-20 PE/e-



light DM nuclear recoil searches: S2-only
look at the **ionization only** S2 spectrum
Below 3 keV_{ee}: give up the scintillation S1 signal
(too small to trigger the detector), thus **minimal fiducialization** (only radial), no **particle ID**

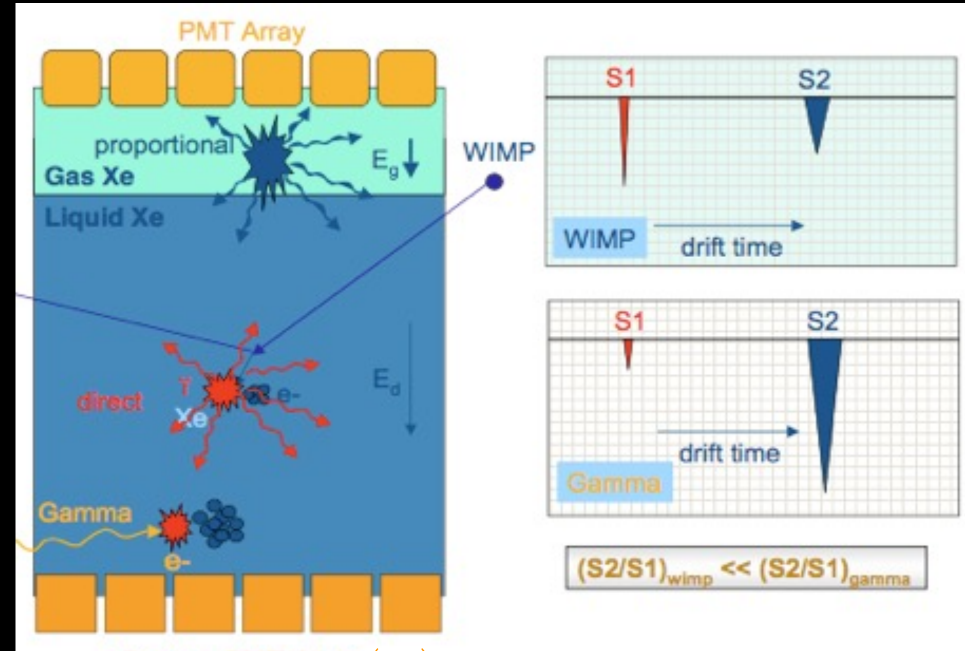
Xenon Detectors

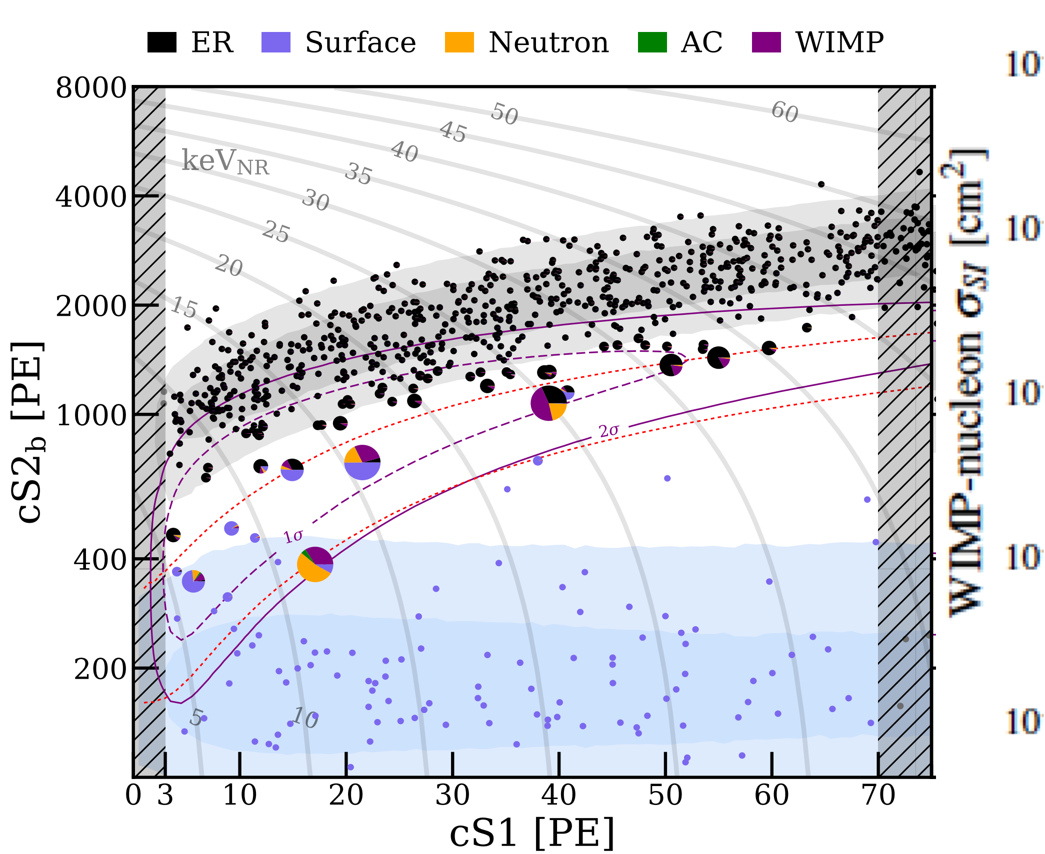
developed for gamma ray astrophysics (LXeGRIT)

Aprile et al., IEEE Trans.Nucl.Sci. 37 (1990),

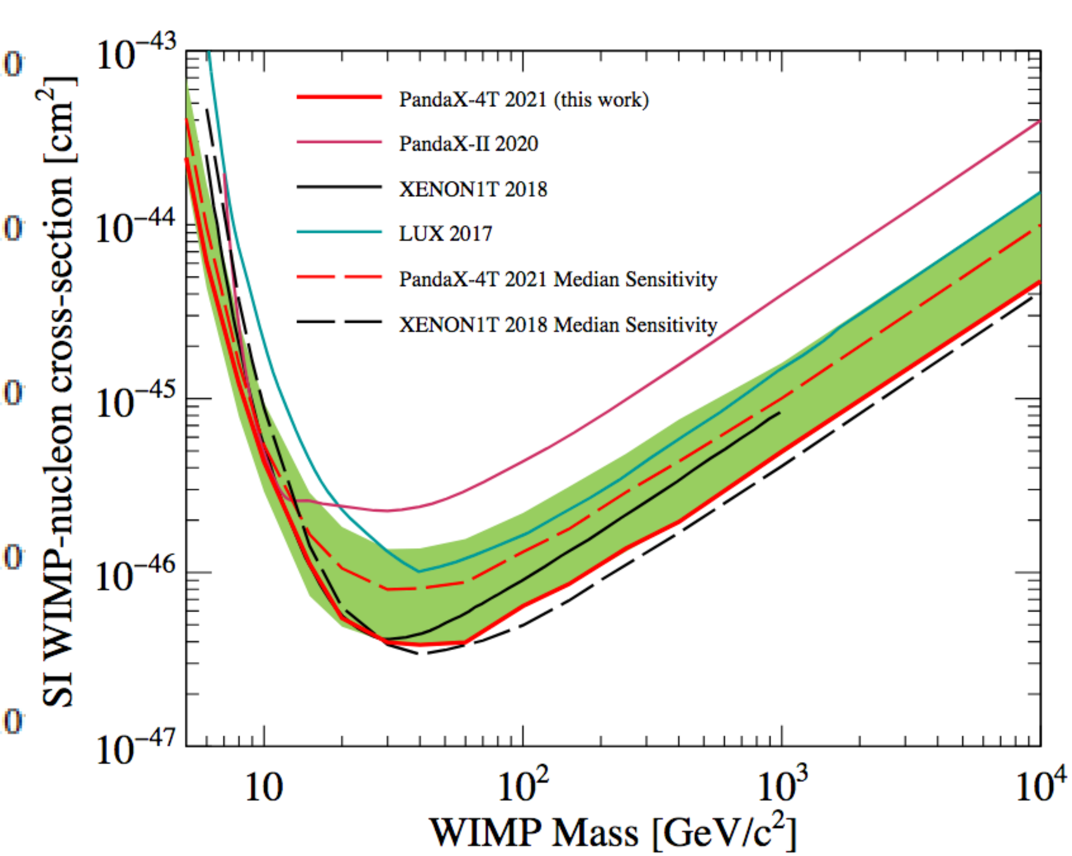
Challenge: electronic backgrounds (Rn, Kr++)
electron-nuclear recoil discrimination from S1/S2
of **$3x10^{-2}$** at 1.4 keVee threshold (**XENON1T**)

leading SI constraint at >5 GeV/c²





Aprile et al, arXiv:1805.12565



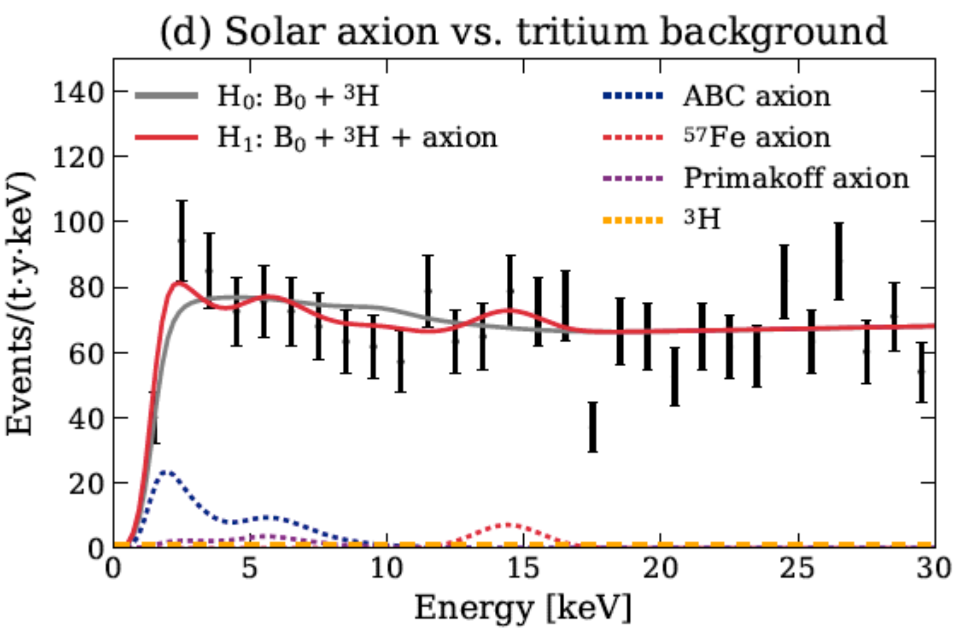
Meng et al., arXiv:2107.13438v2

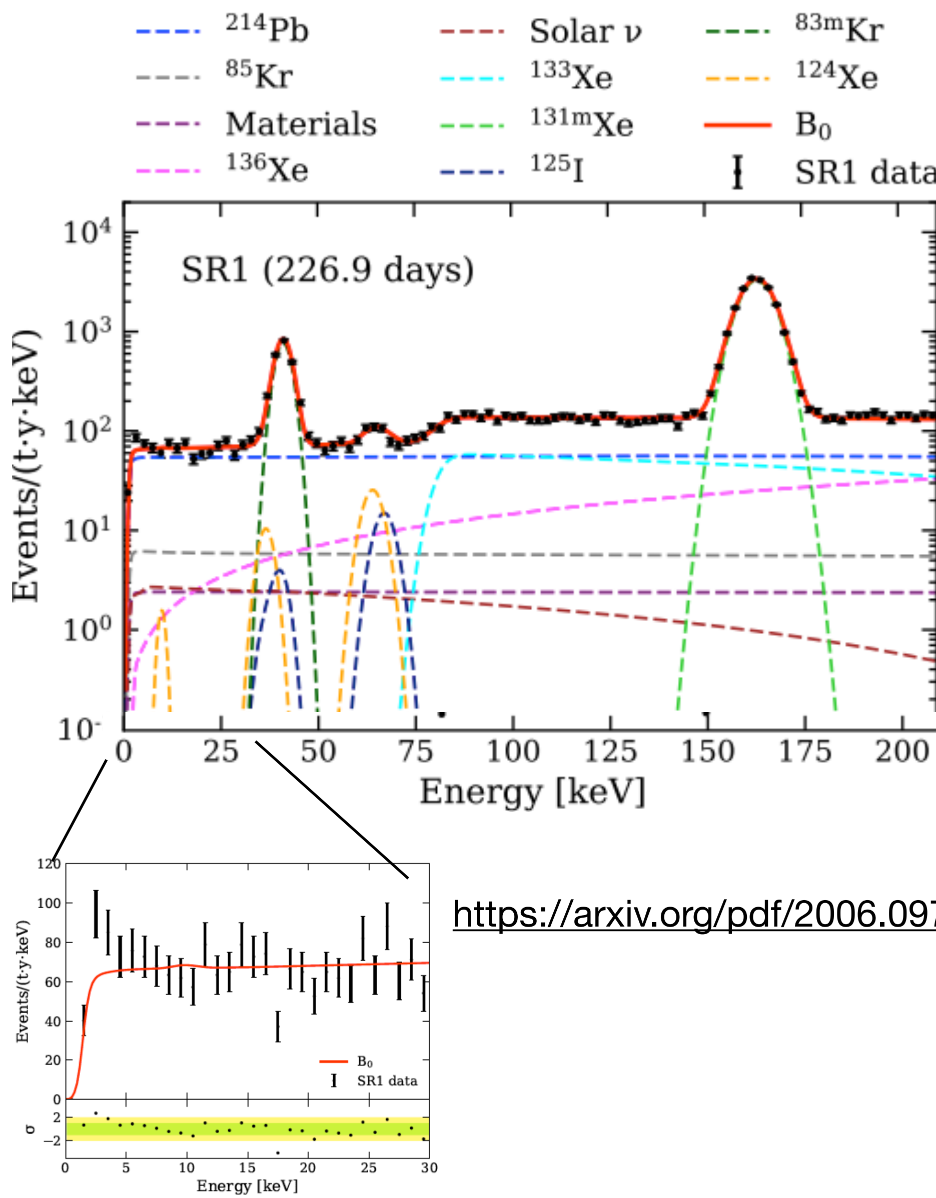
Xenon Detectors

Thanks: P. Agnes

Example: Xenon-1t projections vs real data

Beautiful agreement in most rates with predicted backgrounds…. but with a surprise!





https://arxiv.org/pdf/2006.09721.pdf

Xenon Detectors

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

10 kg

2010

XENON 10 (LNGS)

ZEPLIN I,II,III (Boulby)

XENON 100 (LNGS)

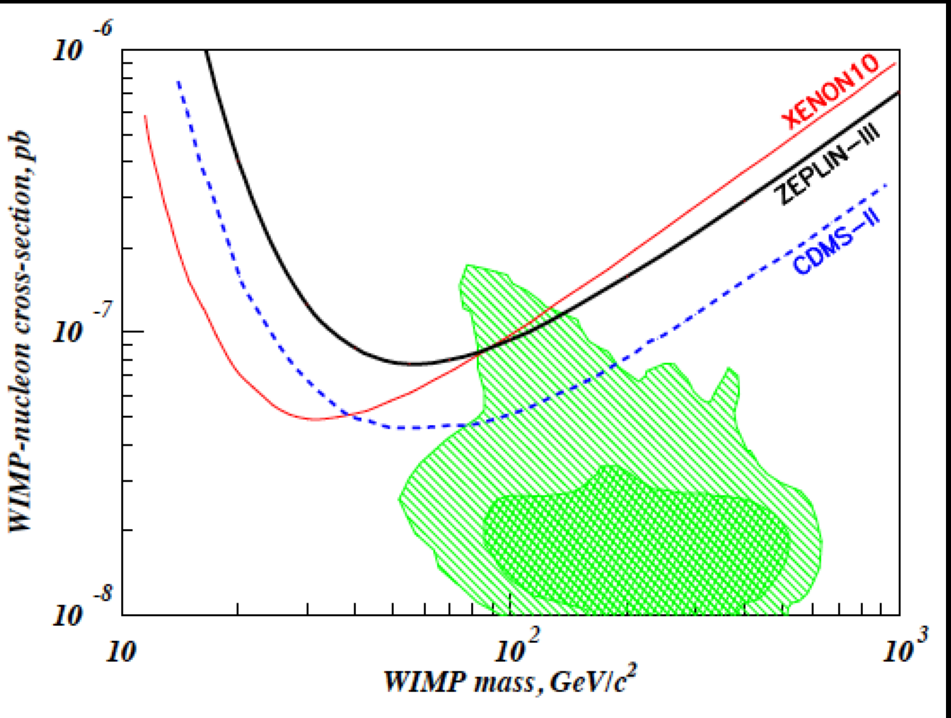
100 kg

LUX (250 kg, SURF)

PANDA-X 500 kg, CJPL)

XMASS (800 kg, Kamioka)

2015



1,000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

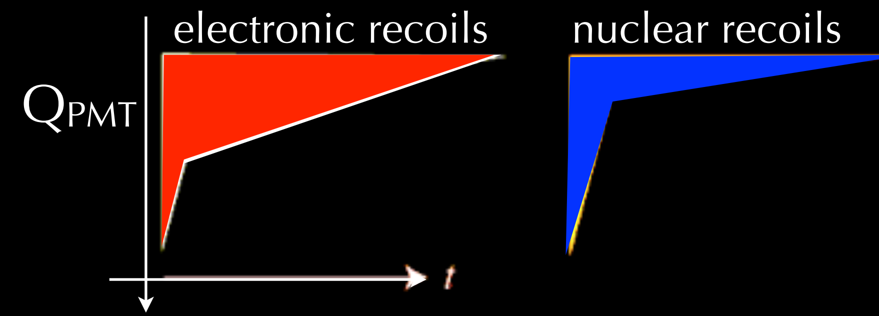
2020

10,000 kg

DARWIN: 30-50 t

2009:
end of Ge dominance!
Era of liquid nobles begins….

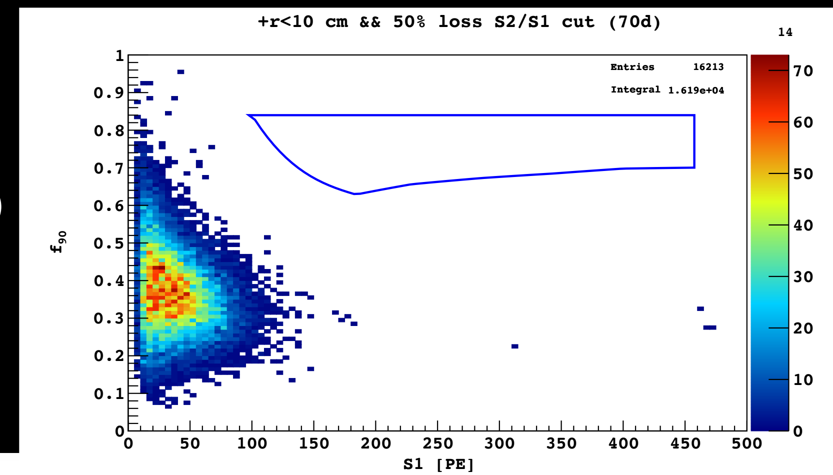
Argon Detectors



Liquid Ar TPCs developed for neutrino oscillation searches

Rubbia C., CERN-EP-INT-77-08 (1977)

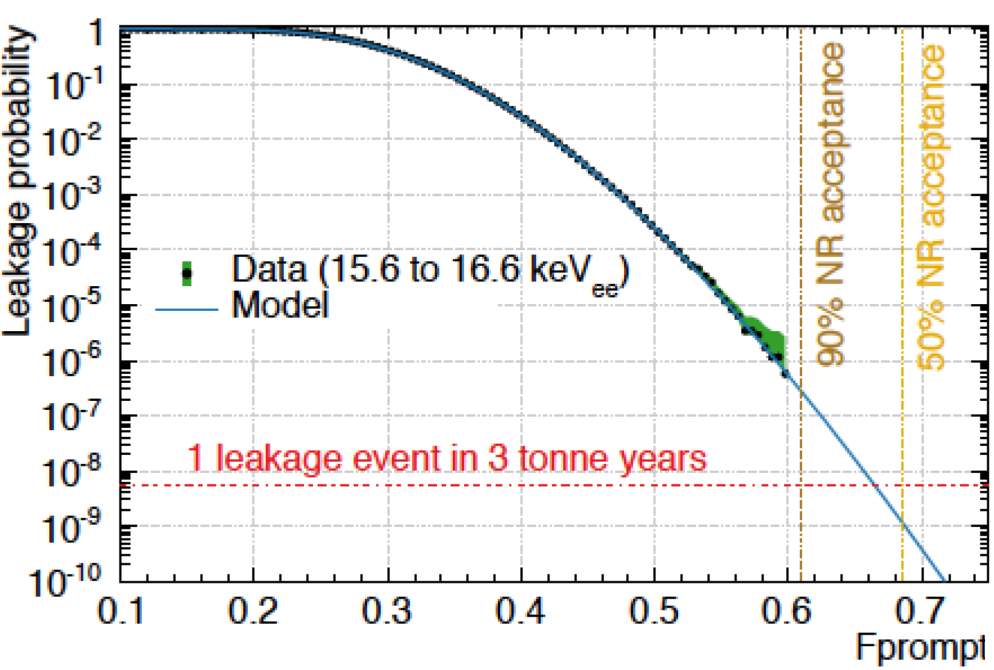
Challenge: intrinsic Ar-39 at 1 part per 10^{15} in natural Ar

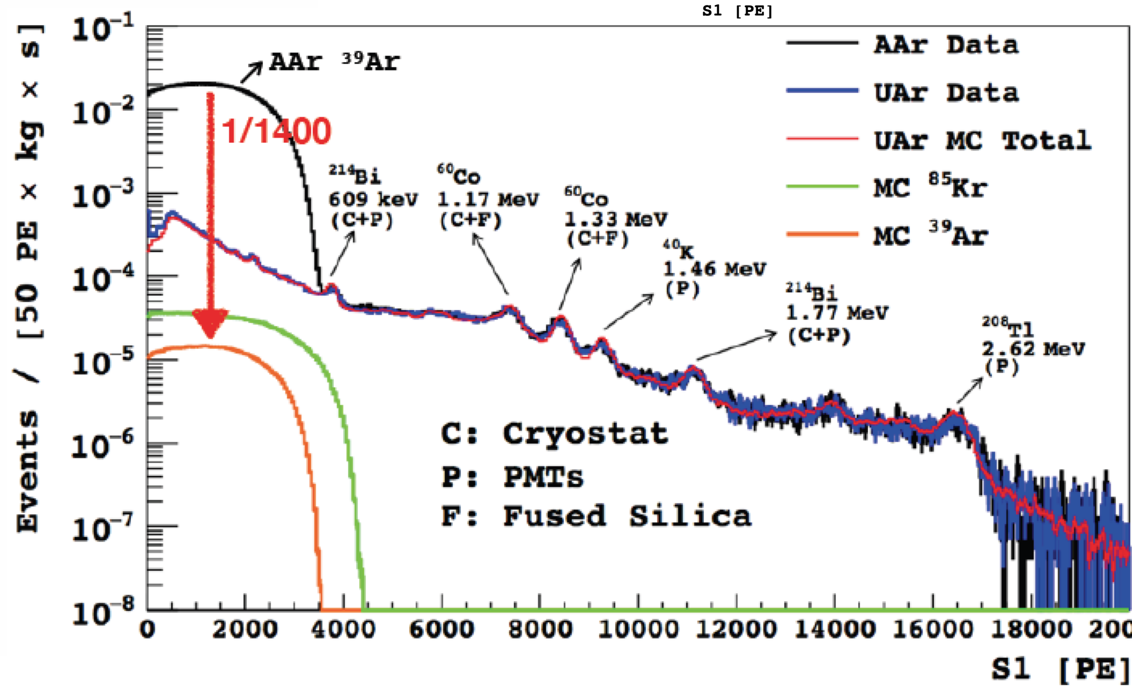


DM searches: particle ID power from light vs. time

DEAP: electron-nuclear recoil discrimination at 15 keVee threshold is **3.5E-11** (50% nuclear recoil acceptance)

DS-50: developed underground argon (UAr) extraction & distillation to deplete Ar in Ar-39 by >x1400





Ajaj et al, arXiv:1902.04048

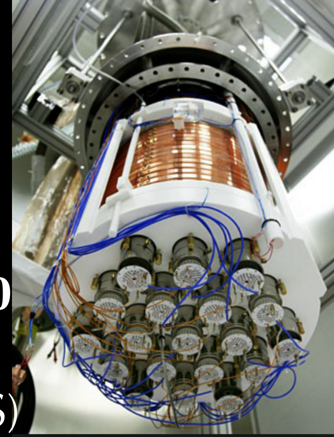
Agnes et al, Phys. Rev. D.93.081101 (2015)

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

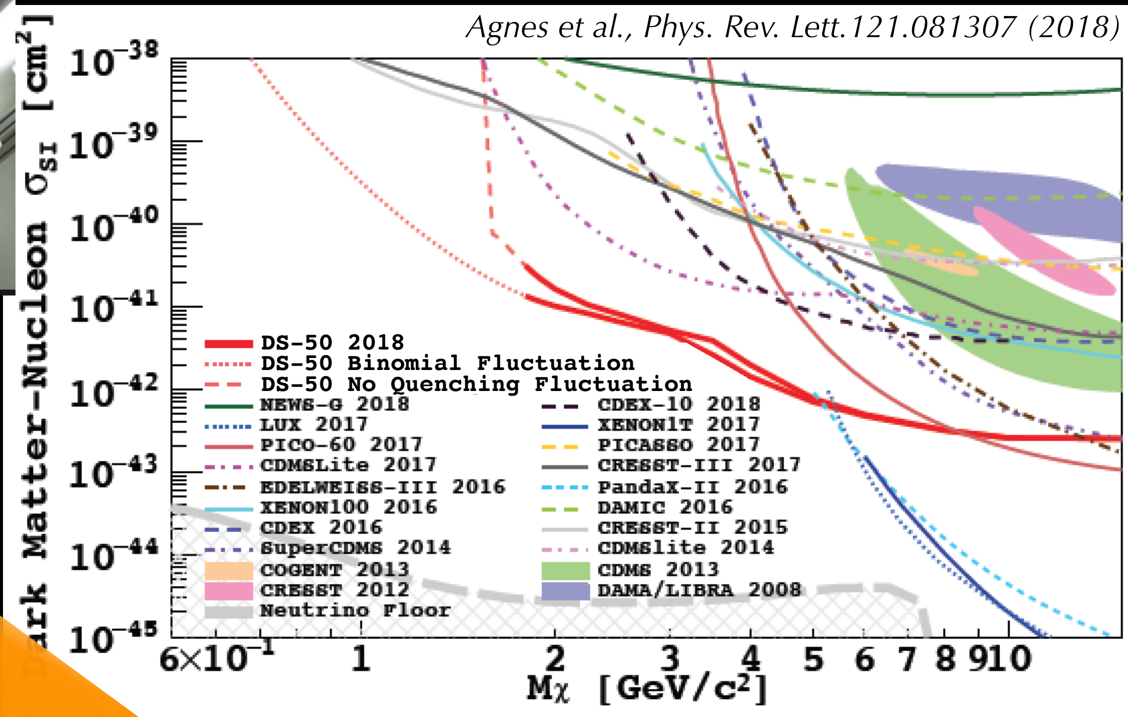
ArDM (1t, LSC)

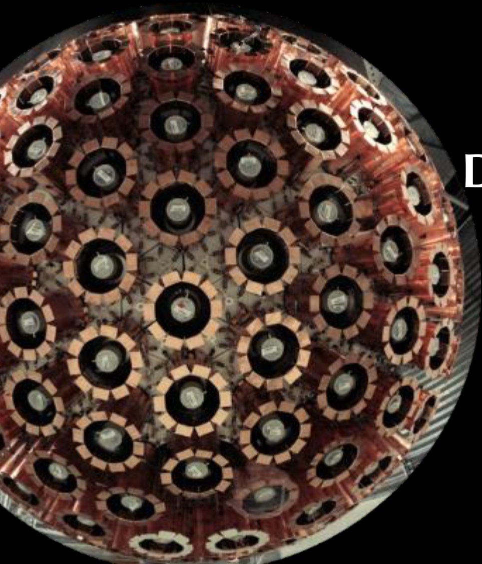
2015

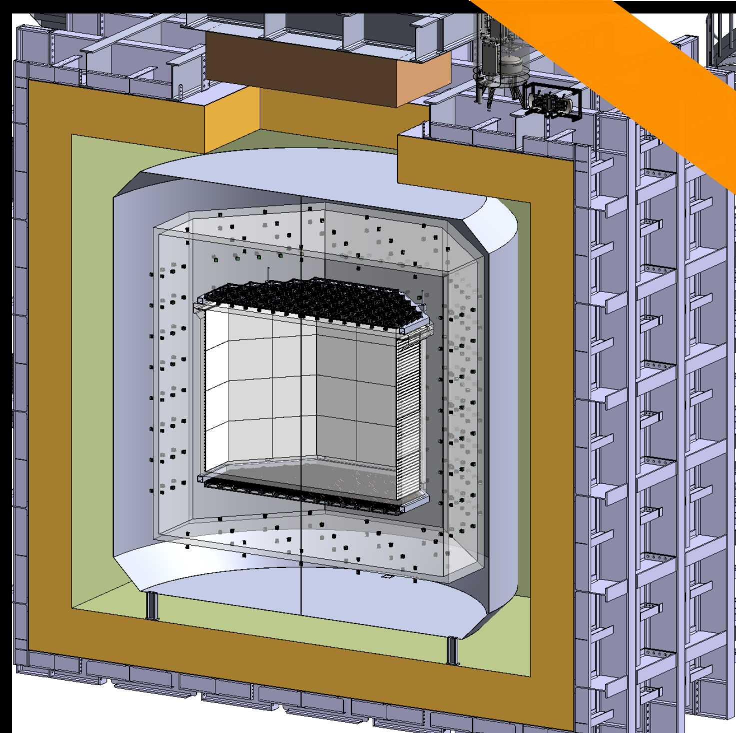
1,000 kg

DEAP-3600 (3.6t, SNOLAB)

DS-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering







DEAP-3600: demonstrated "S1" particle ID, and ultrapure acrylic cryostat (x100 lower radioactivity)

Global Argon Dark Matter Collaboration formed

10,000 kg

APPEC

2020

DarkSide-20k (50t, LNGS)

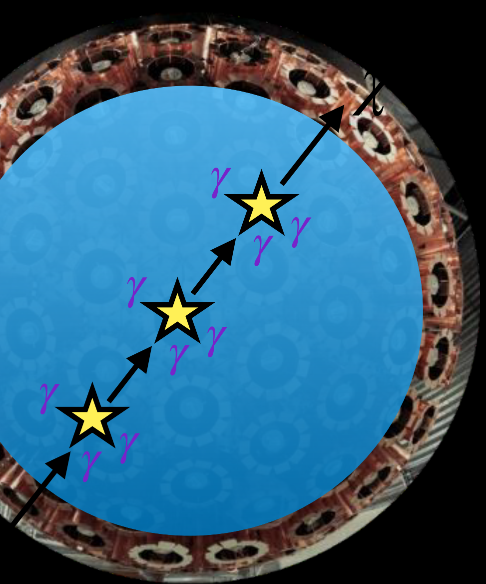
100,000 kg

Future; ARGO
kt-scale

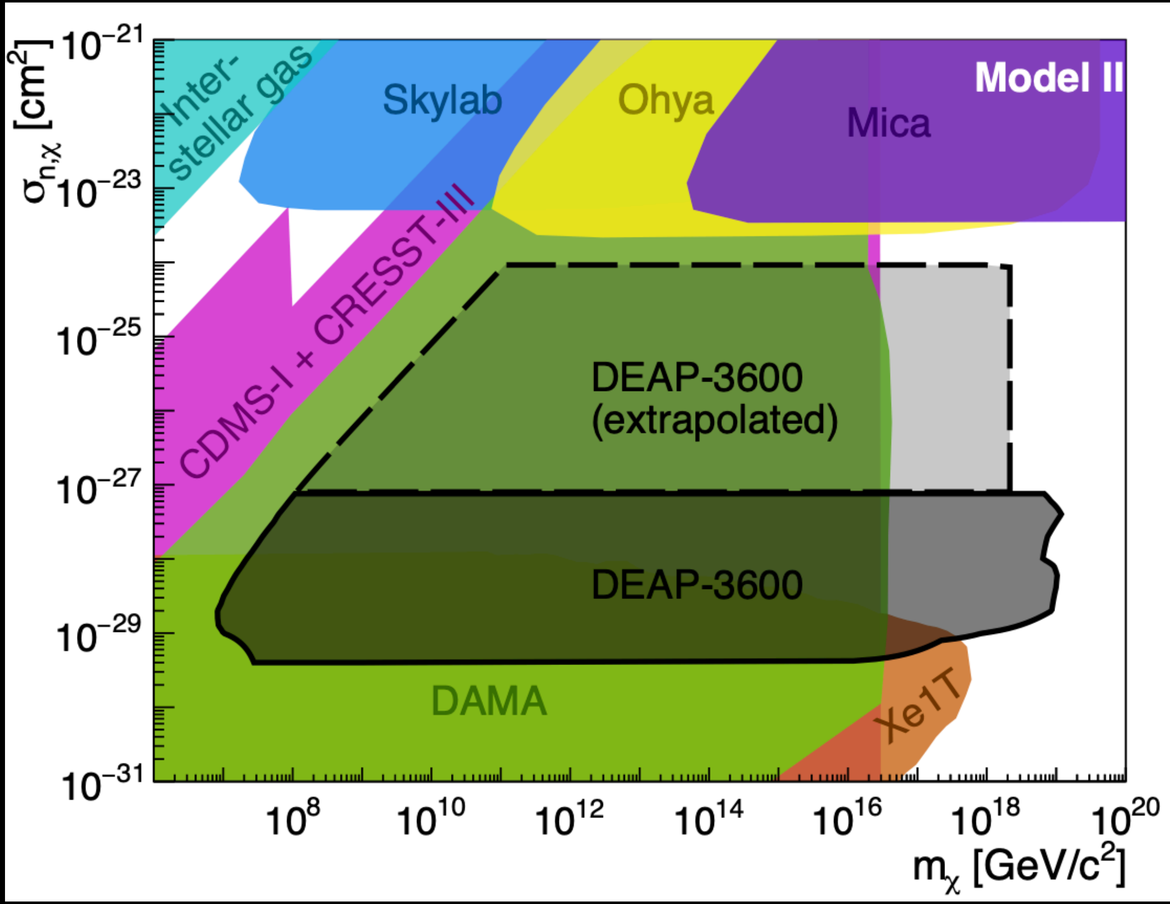
DEAP Planck-Scale Dark Matter Search

Planck-scale DM ($m_\chi = 10^{19}\mathrm{GeV/c^2}$) may be produced non-thermally through 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…



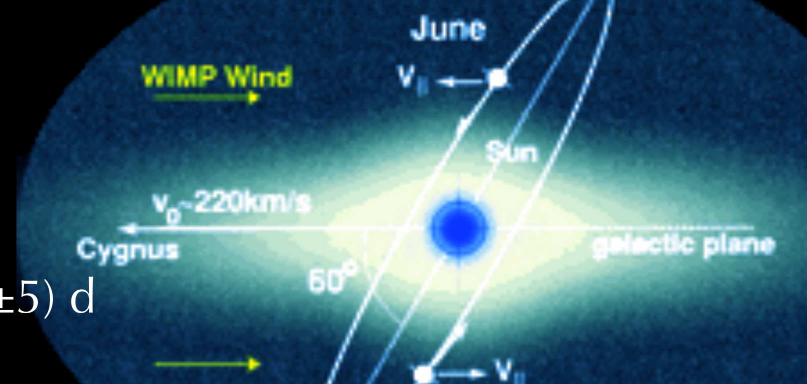
Thanks: A. Kemp



arXiv:2198.09405

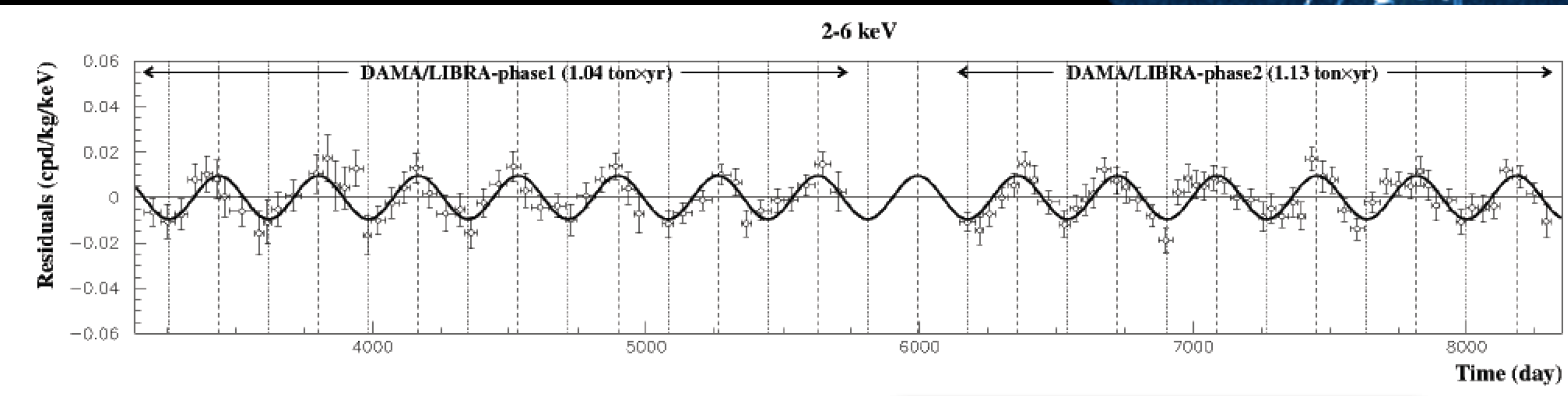
Extrapolation: scales flux with n_χ and regions of m_χ consistent with null result

Direct Detection: Candidate Signal



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

DAMA/LIBRA: measure (0.0095±0.0008) cpd/kg/keV, t_0 = (145±5) d



CSLNGS, March 2018

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

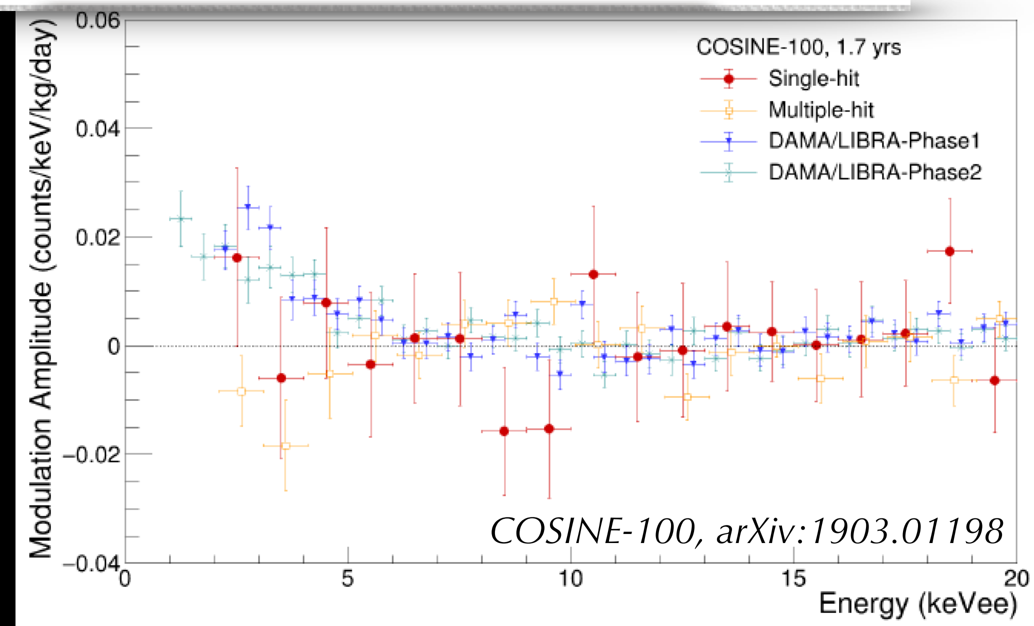
In the same underground laboratory:

XENON100: Xe, 4.8σ exclusion *(arXiv:1507.07748)*

Using the same target (NaI):

ANAIS (LSC), **SABRE** (AU), **COSINE-100** (Y2L)

~consistent at 1σ, project 3σ test in 5 years.



COSINE-100, arXiv:1903.01198

Complementarity (1): Direct Detection

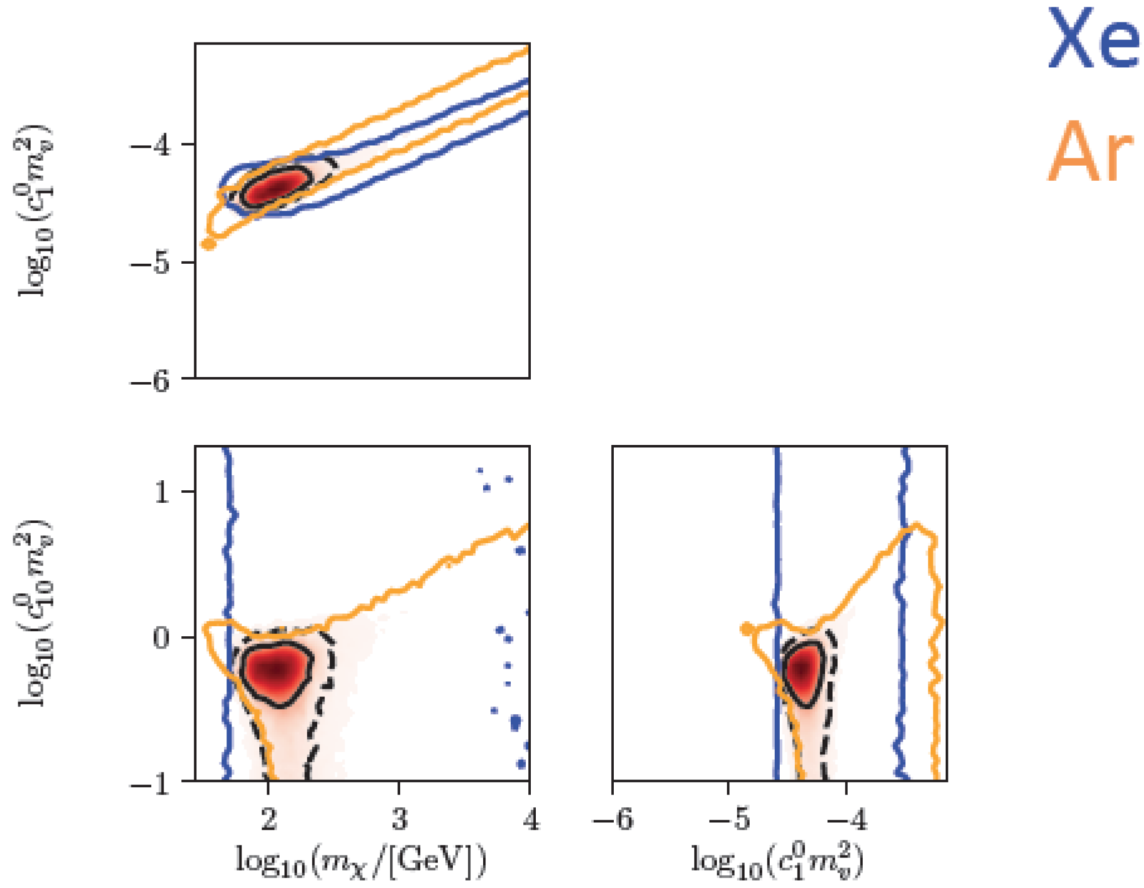
Newstead et al., PRD D 88, 076011 (2013)
DARWIN, JCAP 10 (2015) 016

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

The experimental response is very sensitive to the target

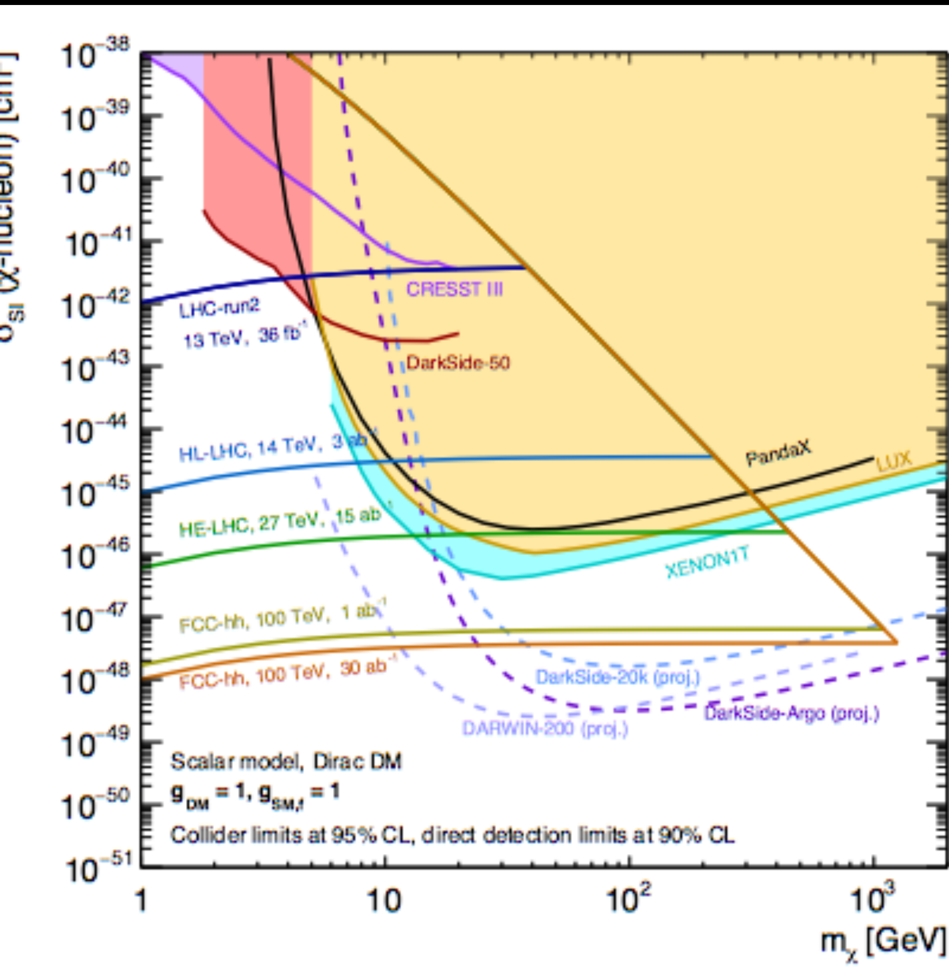
Combining data some degeneracies can be removed



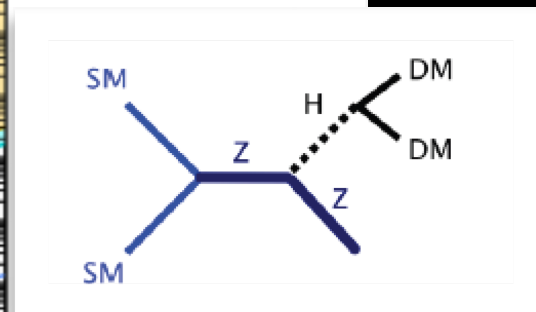
D. Cerdeno, IPPP April 2018

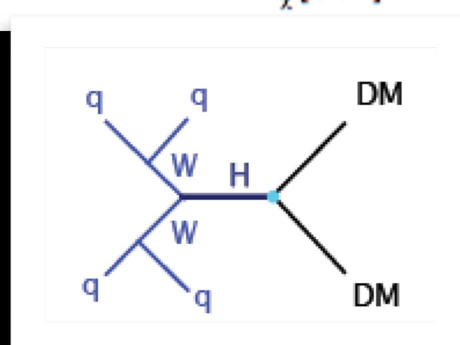
Complementarity (2): Collider Searches

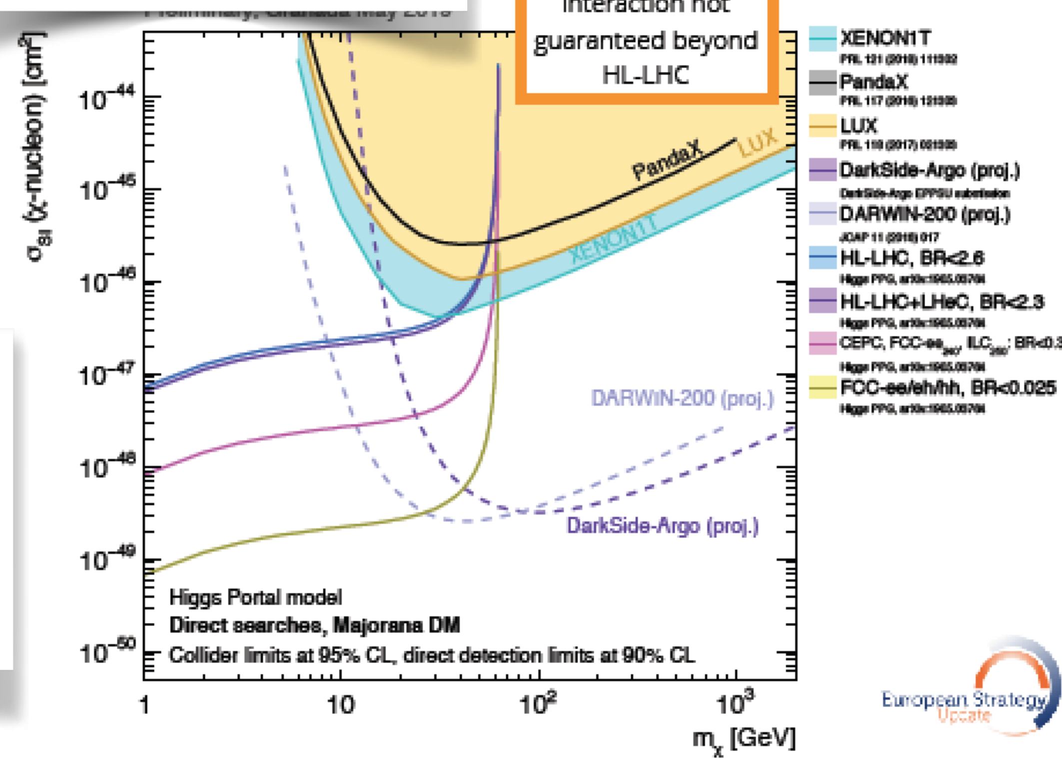
Ellis et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)



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





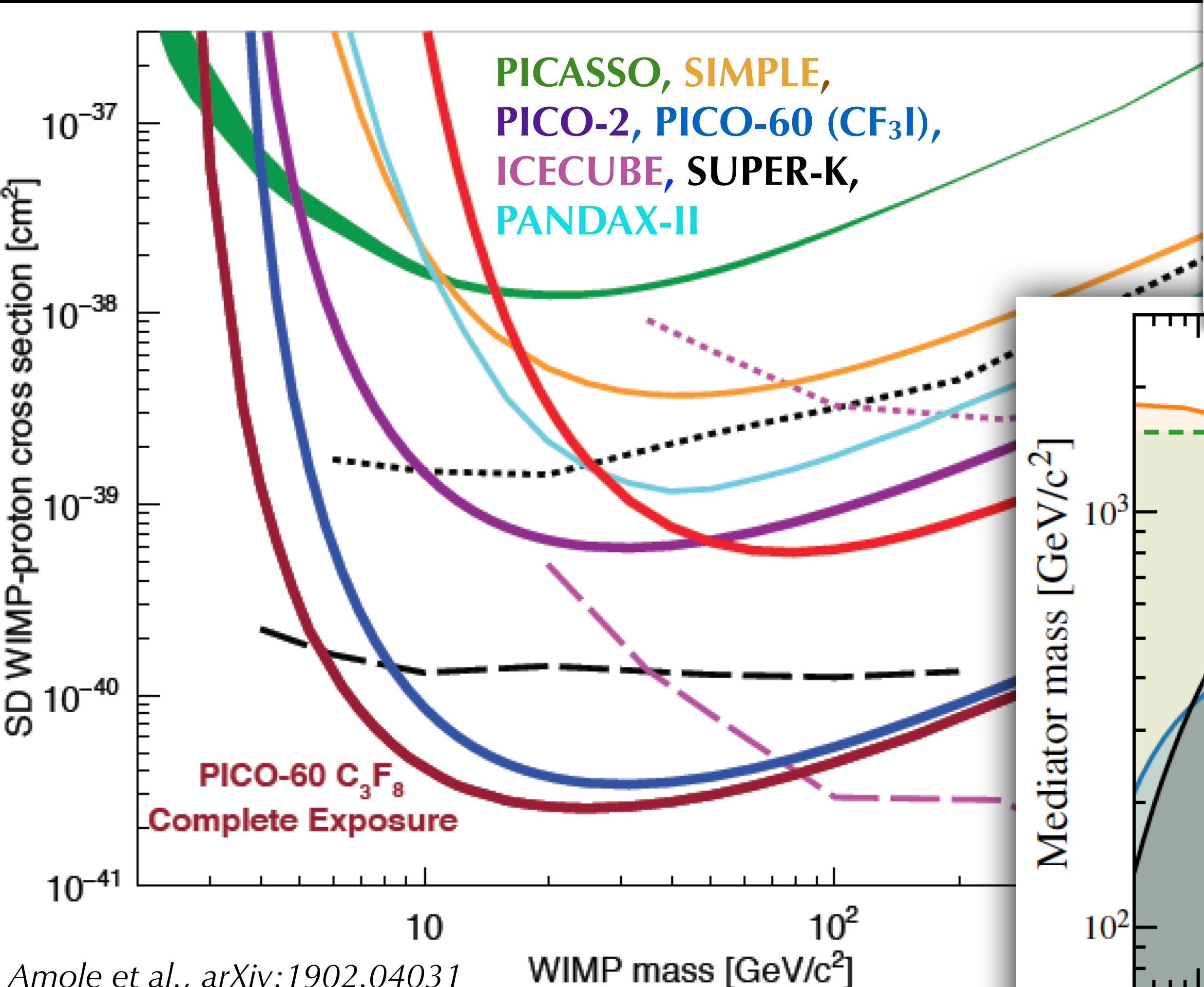


Doglioni - 2019/05/13 - European Strategy Update

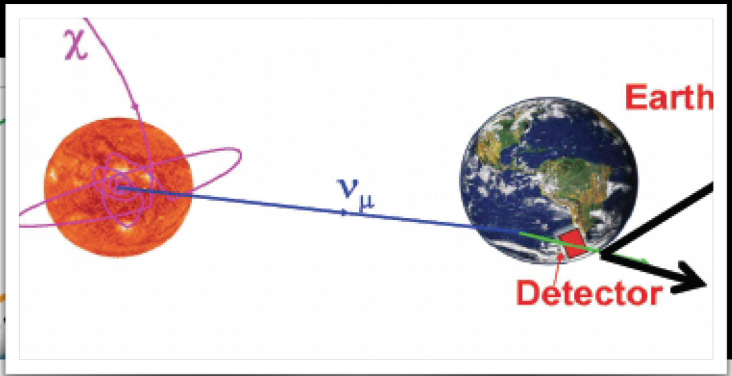
Complementarity (3): Indirect Detection

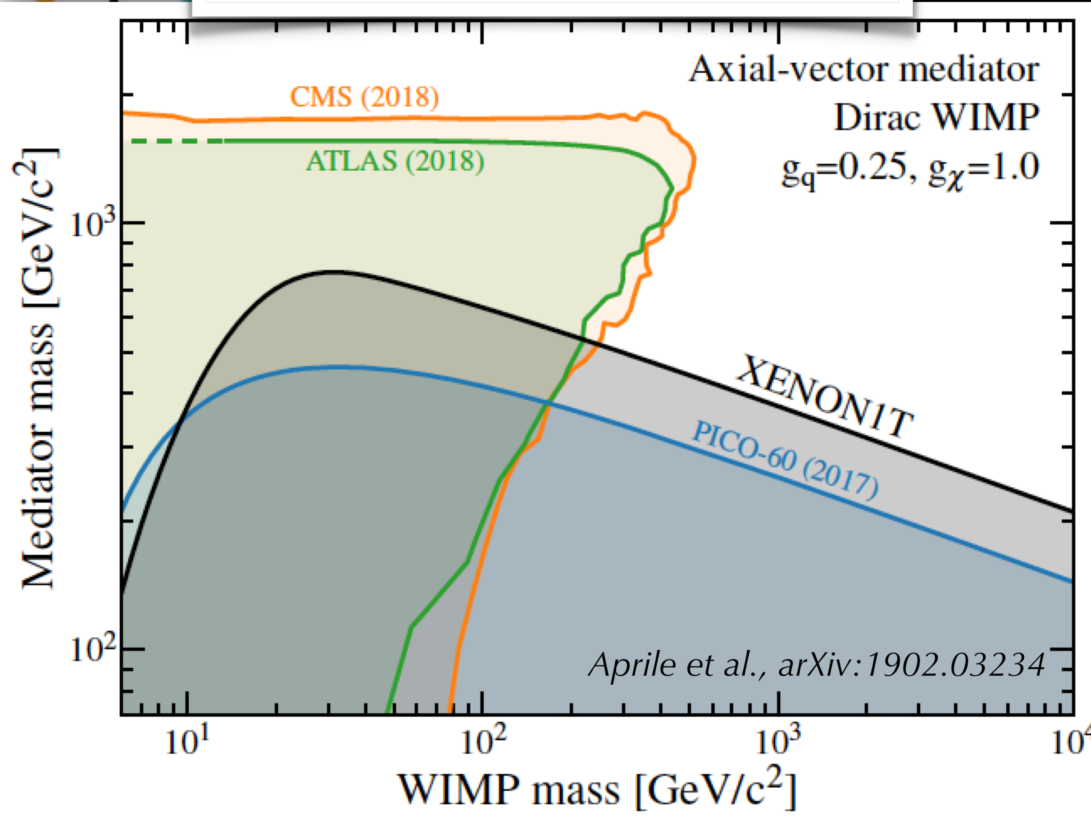
Direct Detection: leading WIMP-p constraints at low mass from PICO-60 kg. Best WIMP-n limits at high mass from Xenon-1T, at low mass from collider searches (for specific operators)

Indirect Detection: leading WIMP-p limit at high mass from neutrino telescopes, via WIMP scattering on p, +capture in the sun, leading to annihilation signatures.



Amole et al., arXiv:1902.04031





Aprile et al., arXiv:1902.03234

Outline

1. Direct Detection Context

2. Current Searches

3. New Strategies

New Technologies: DarkSide-20k

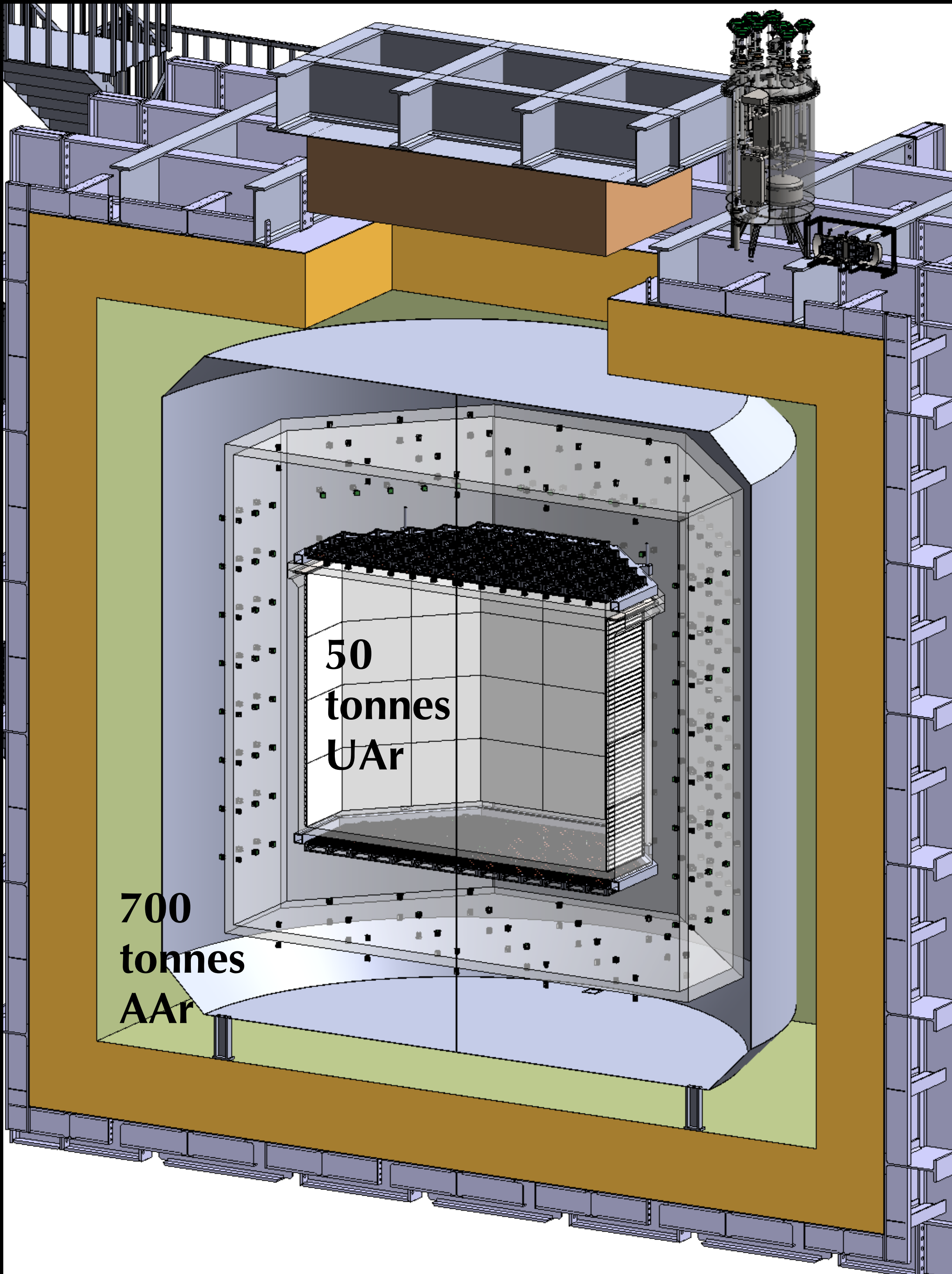
50 t liquid Underground Ar (UAr) dark matter target, inside a 700 t liquid Atmospheric Ar (AAr) outer detector

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



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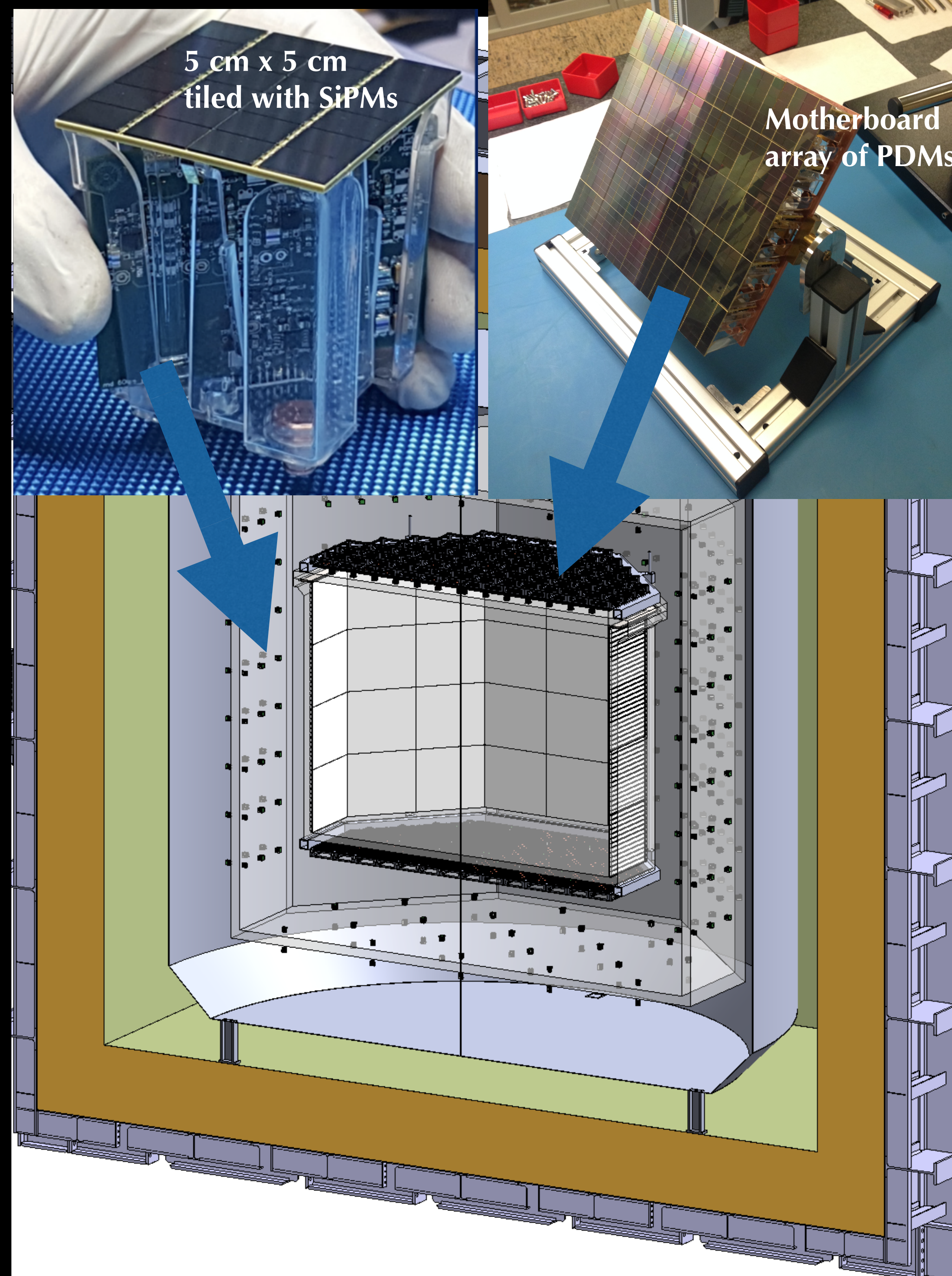

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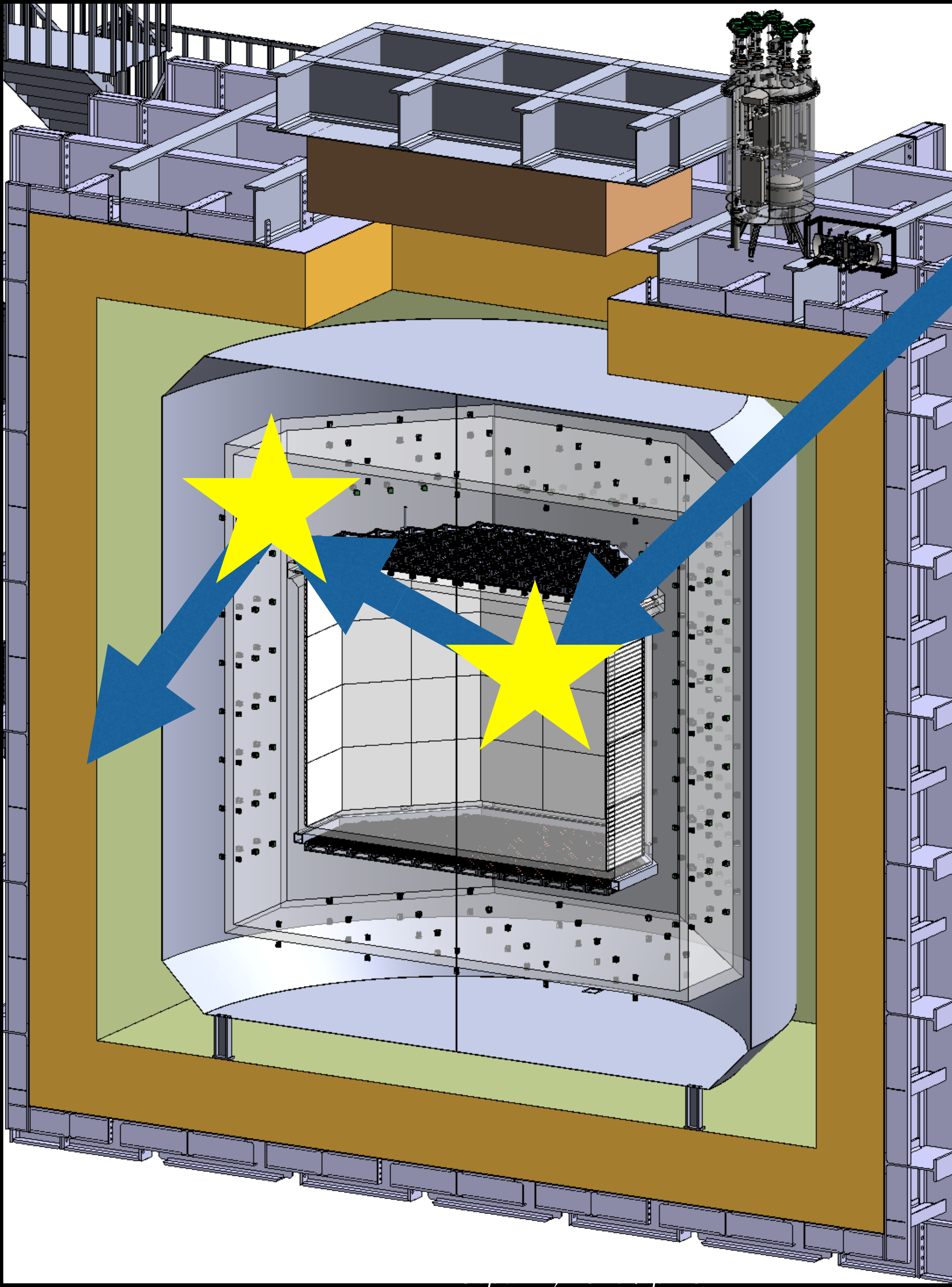
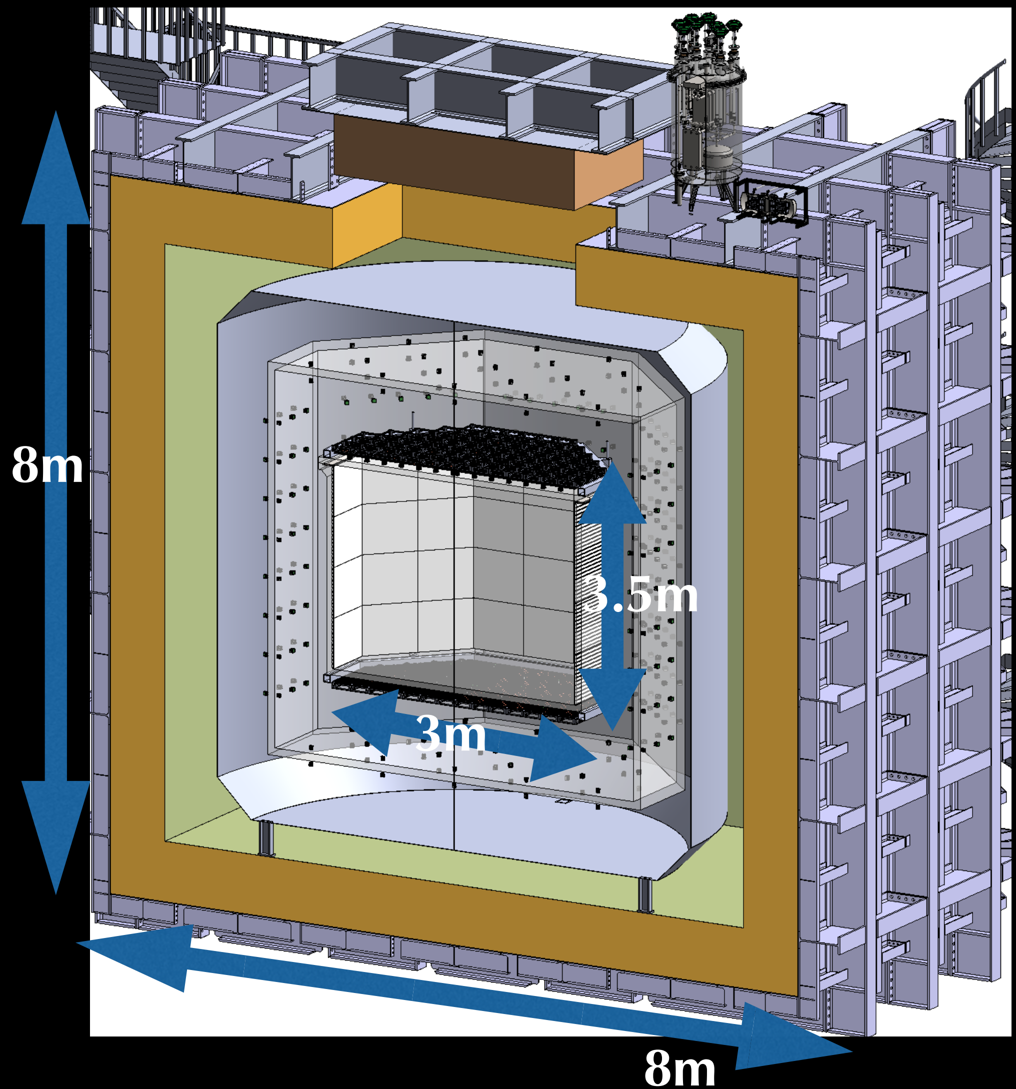
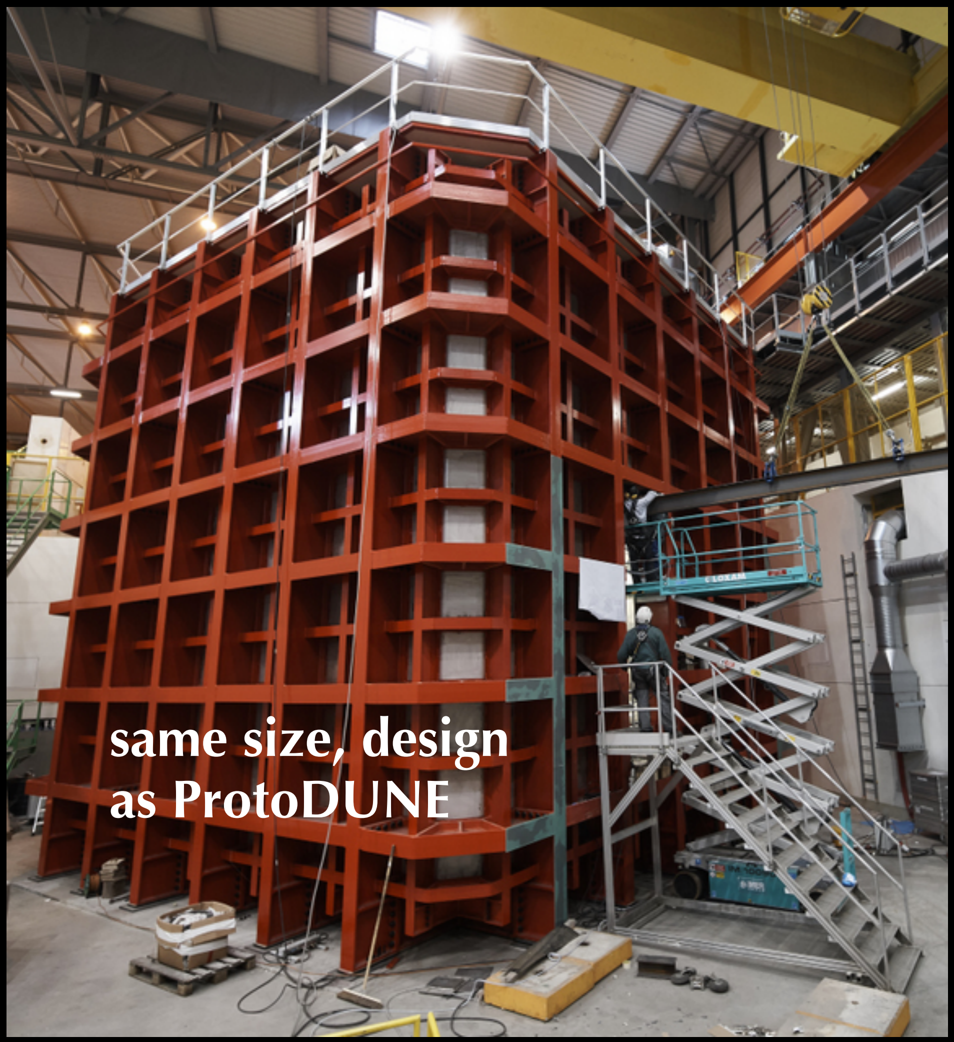


New Technology Collaborations

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

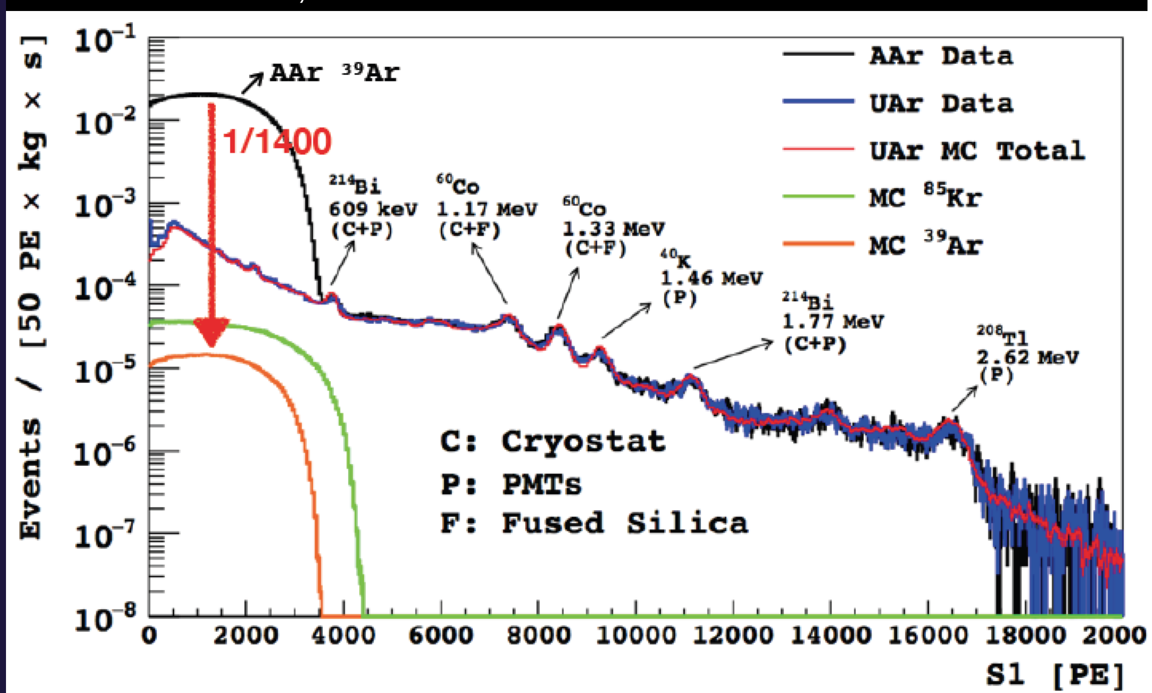




New Technology Collaborations

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

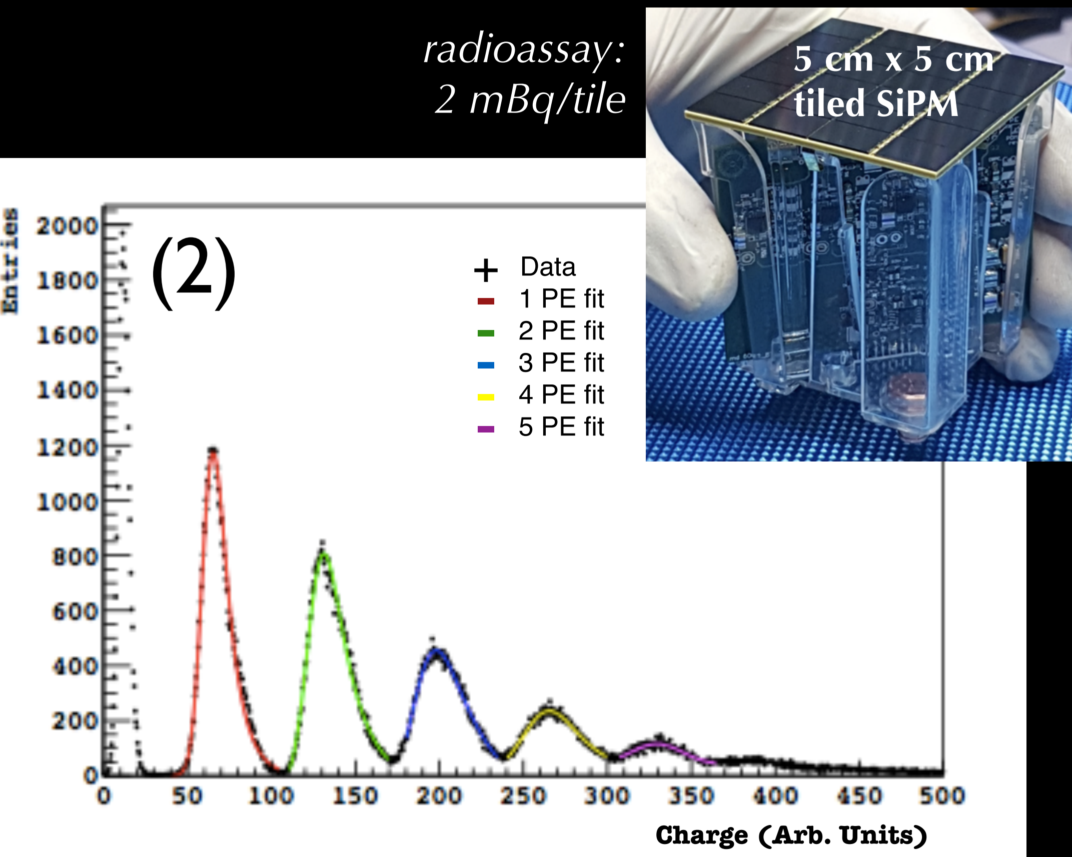
On Friday, 24 November, ARIA's top and bottom modules plus one standard module were brought to Building 180 and lined up to precisely test their alignment and interconnections. (Image: Max Brice/CERN)

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

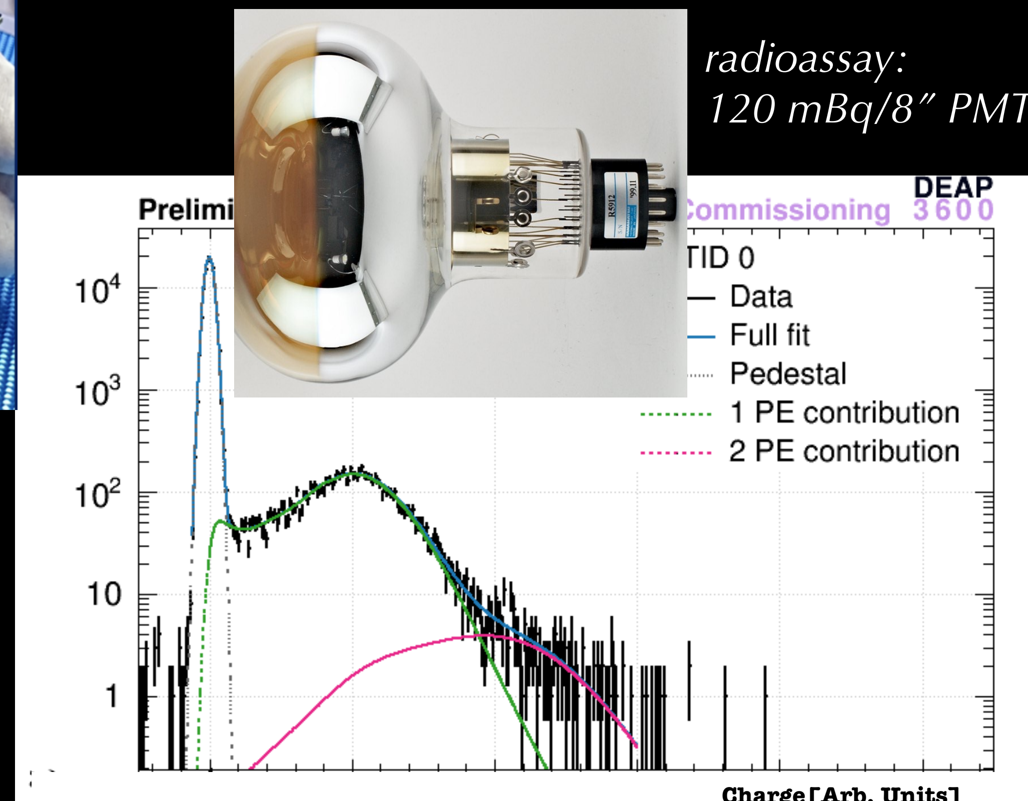
Photon Sensors: low noise, high efficiency, tiled arrays of cryogenic Si sensors developed in collaboration with FBK, achieving 45% PDE and 1 mHz/mm² dark noise

radioassay:
2 mBq/tile



compared with::

radioassay:
120 mBq/8" PMT

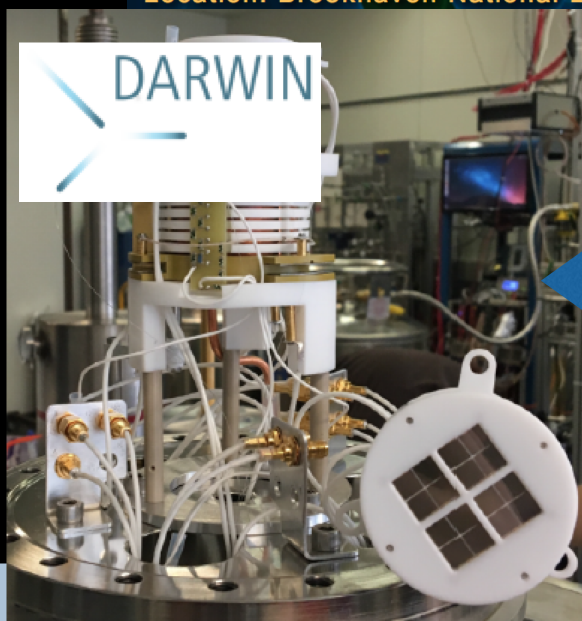


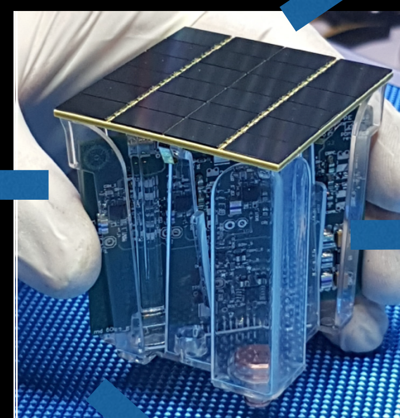
Aalseth, JM, et al. JINST 12 (2017) no.09, P09030

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

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

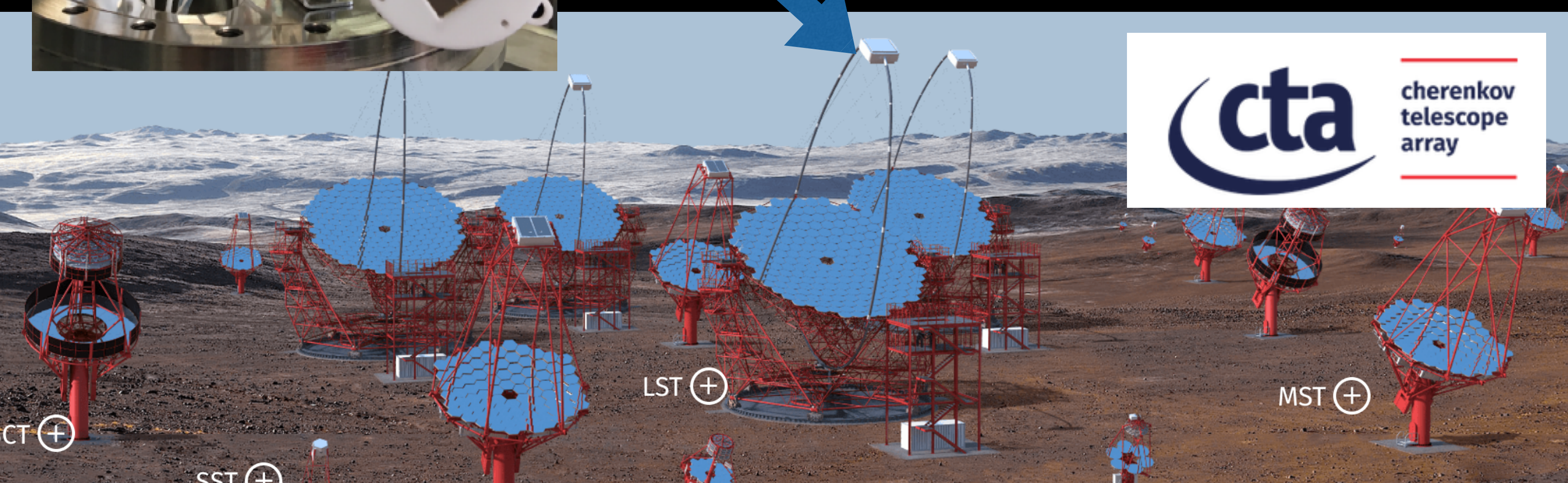
Experiments Exploring Cryogenic SiPM Technology





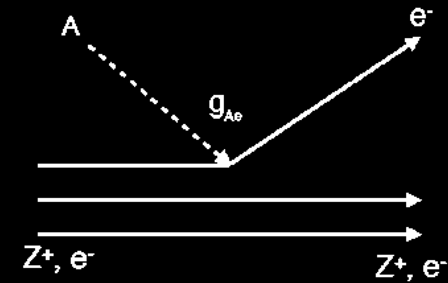
LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



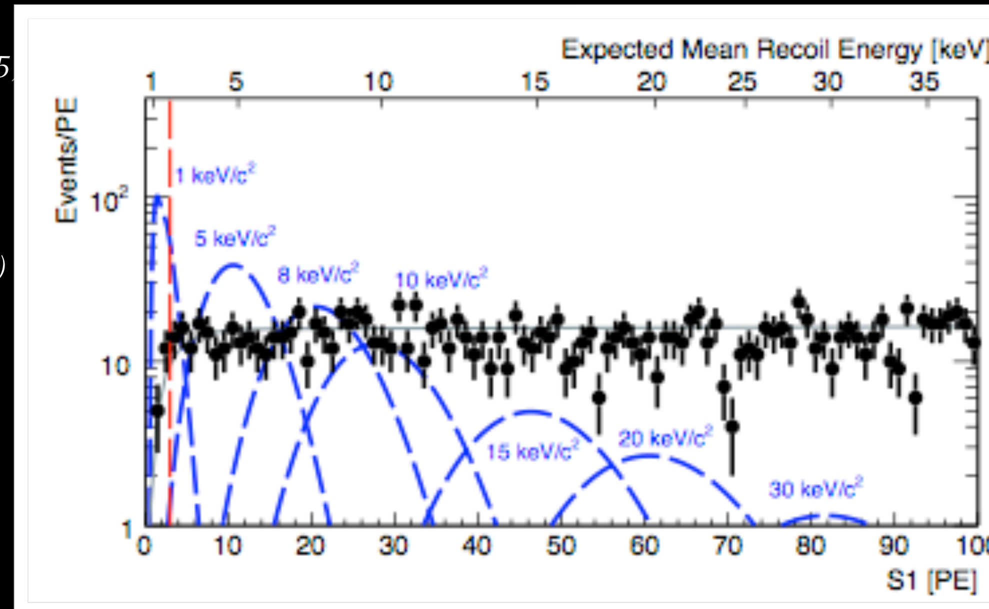
+ environmental monitoring, medical imaging, automated navigation (LIDAR) …

New Signatures



DM-Electron Absorption/Mixing:

- search for keV-scale axion-like particles interacting via the axio-electric effect *(arXiv:1404.1455)*



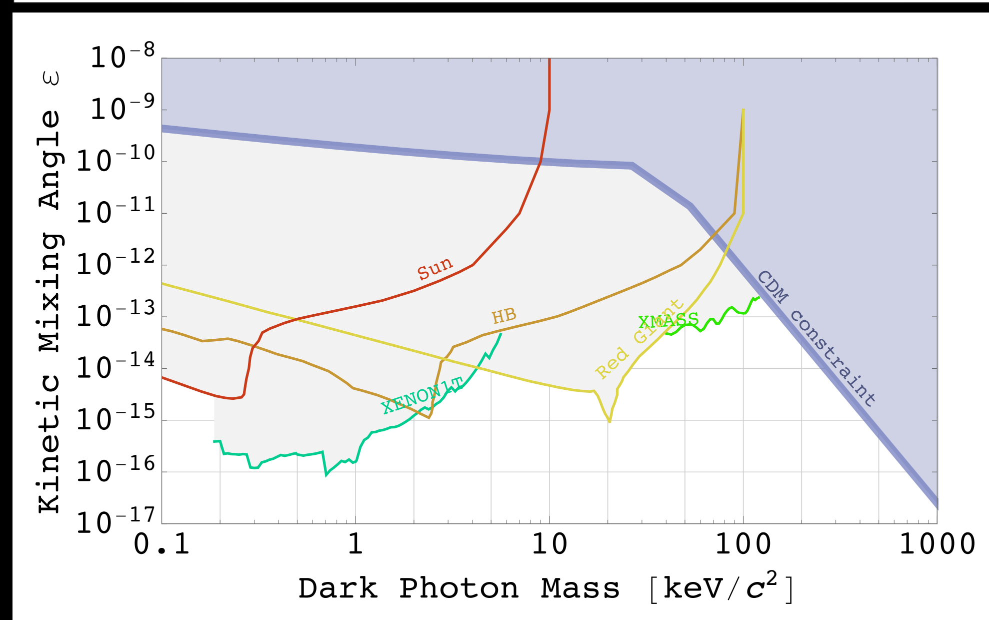
- search for 0.1-100 MeV-scale vector particles via kinetic mixing to hidden sector *(arXiv:1901.10478)*

- search for 10-100 keV-scale sterile neutrinos via coupling to ν_e in background beta decays, or scattering with electrons *(arXiv:1605.02918)*

- search for strongly interacting sub-GeV dark matter using electronic recoils *(arXiv:1905.06348)*

DM-Electron Scattering:

- Search for excess in electron recoil spectrum, ~exponential distribution, sensitivity depends strongly on DM-e scattering form factor assumed!



(arXiv:1901.10478)

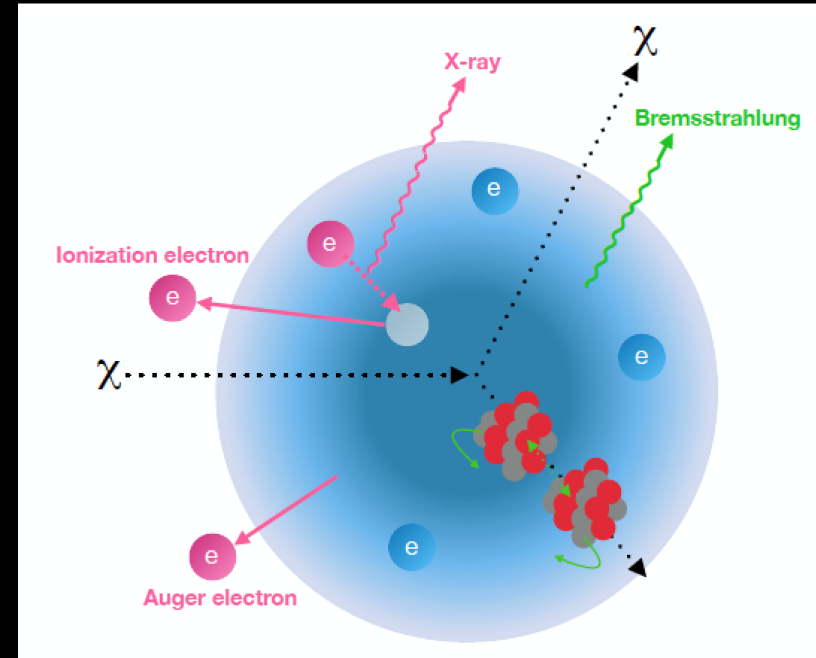
New Signatures

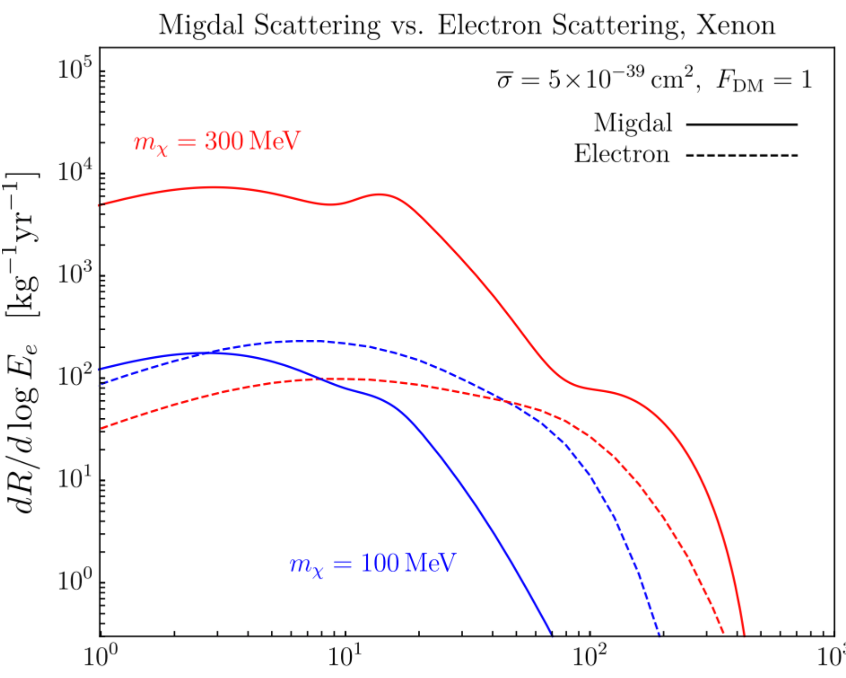
Electron + Nuclear Recoil Final States:

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

Both nuclear recoil E_R (quenched) AND electronic recoil contribution (not quenched) up to ~keV *(arXiv:1707.07258)*

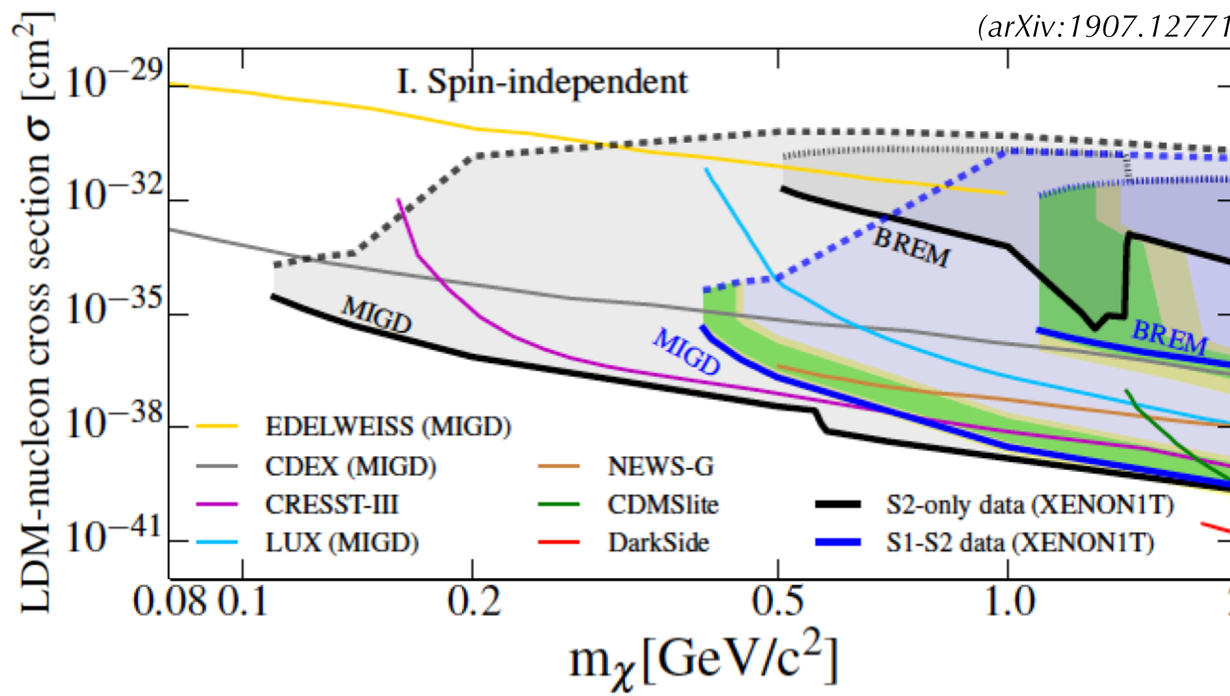
Reaches ~0.1 GeV dark matter sensitivity…





(arXiv:1908.00012)

(arXiv:1907.12771)



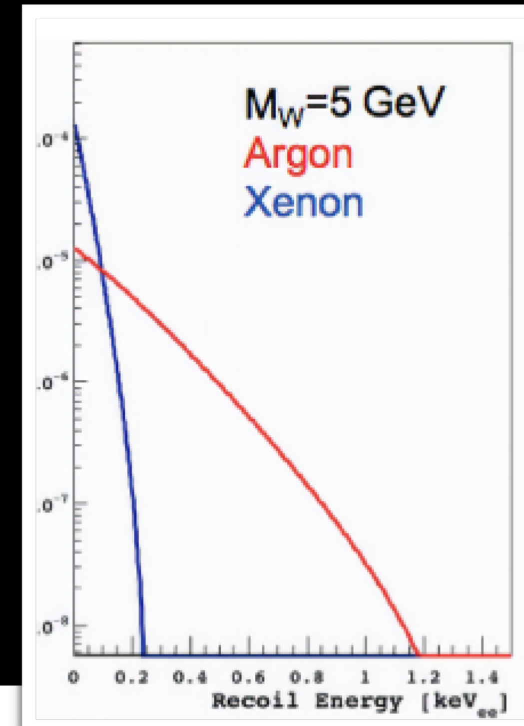
Lighter Targets

kinematic advantage to detect *low-mass* dark matter scattering on a *lighter* target

In noble liquids:

1) detectors optimised to reduce single e- backgrounds (LBECA, DarkSide-LowMass ++)
2) dope Xe target with a lighter species (He or Ne), to improve kinematic matching

PoS ICHEP2016 (2017) 275 ++



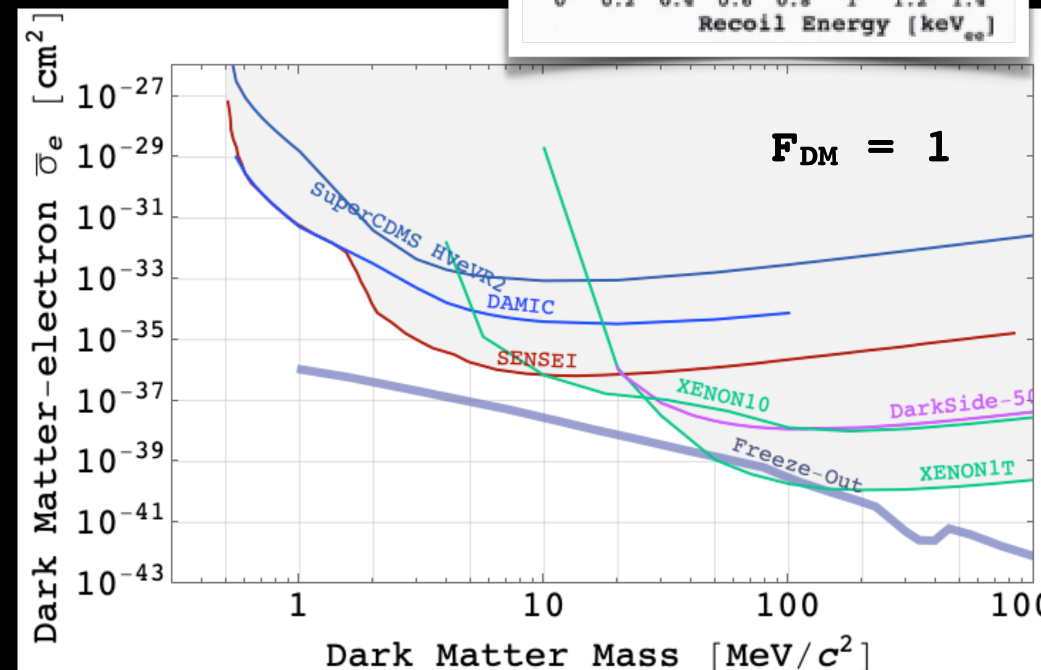
Use the lighter species as the target:

1) Si: DAMIC, SENSEI +new ideas
2) Helium

- gas: NEWS-G
- liquid:

—HeRALD: superfluid He-4 at ~1 mK temperature *(Phys. Rev. D 100, 092007 (2019))*

—QUEST-DMC: superfluid He-3 at 0.1 mK temperature with quantum sensors



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   PoS ICHEP2016 (2017) 275 ++

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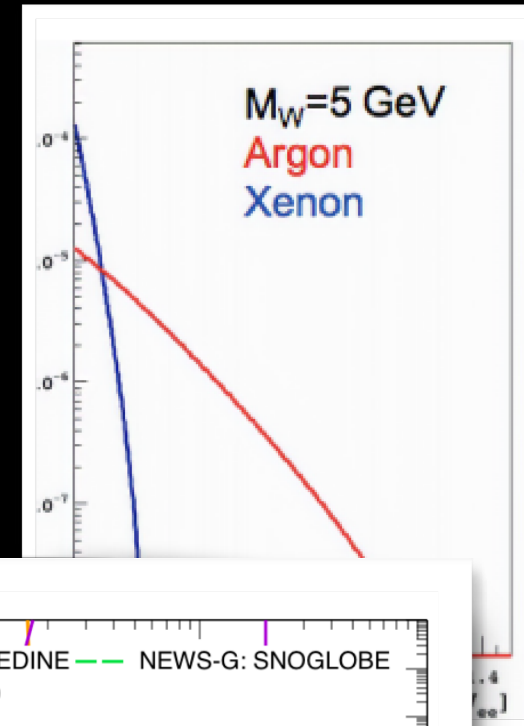
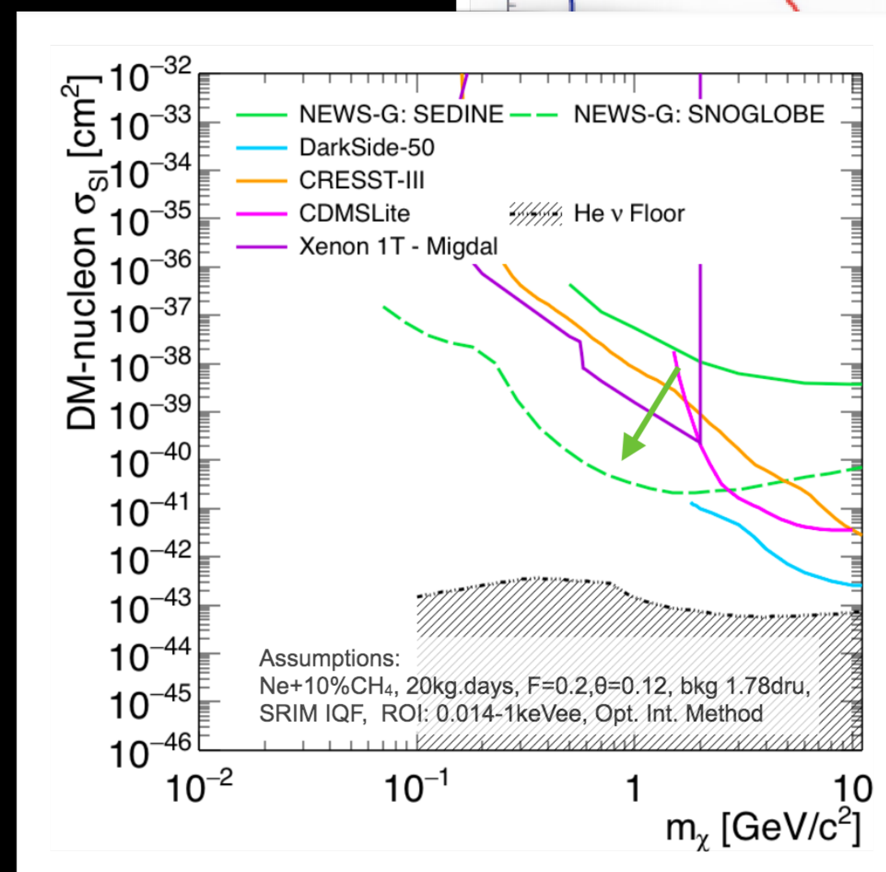




Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Goal: reach 10 eV recoil energy threshold in spin-dependent (SD) dark matter search for scattering in Superfluid He-3 (pairing energy ~1E-7 eV)

-current constraint at 1 GeV in SD scattering is ~1E4 pb *(CRESST-III, PRD100, 10200 (2019))*

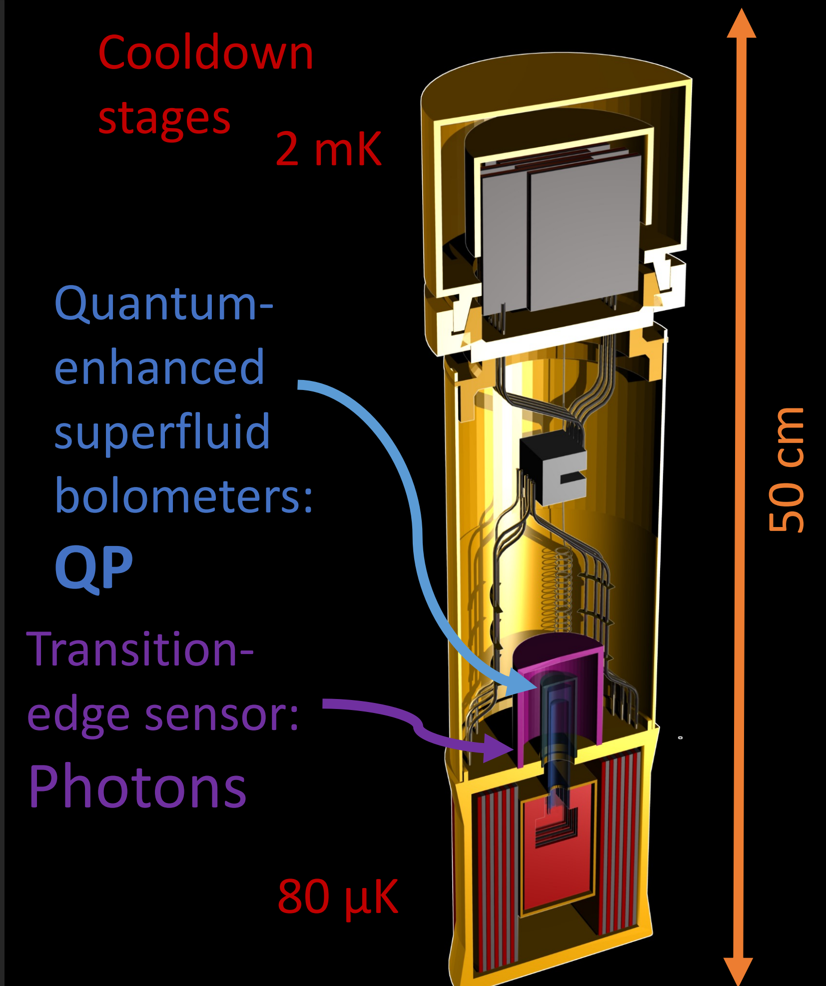
Heat partition measurement

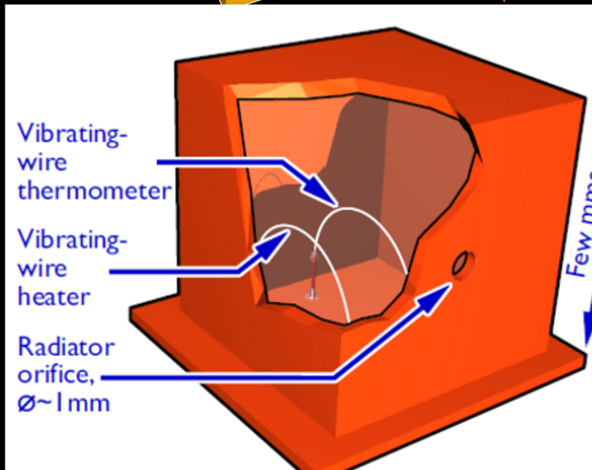
- Quasiparticles generated by a scattering event propagate until they are detected by a nano-electromechanical resonator (NEMS)
- NEMs coupled to SQUID readout reaching quantum-limited displacement measurement
- Operation at 80 uK in U. Lancs platform

Ionisation partition measurement

- Detect scintillation in TES
- TES with 3.5 eV resolution demonstrated by HeRALD

UK Quantum Technologies for Fundamental Physics project, builds on European Microkelvin Platform ULTIMA





Conclusions & Outlook

Direct detection searches are rapidly expanding physics reach:

to lower cross sections, probing new parameter space,
to lower masses, testing new models,
to higher masses, complementary with the LHC,
to new particle candidates (axions, ALPS, ...)

Many new ideas for non-standard searches in direct detection!

Experiments running now or under construction will improve sensitivity reach by 1-2 orders of magnitude in next few years, aiming to continue to beat Moore's Law by 2x.

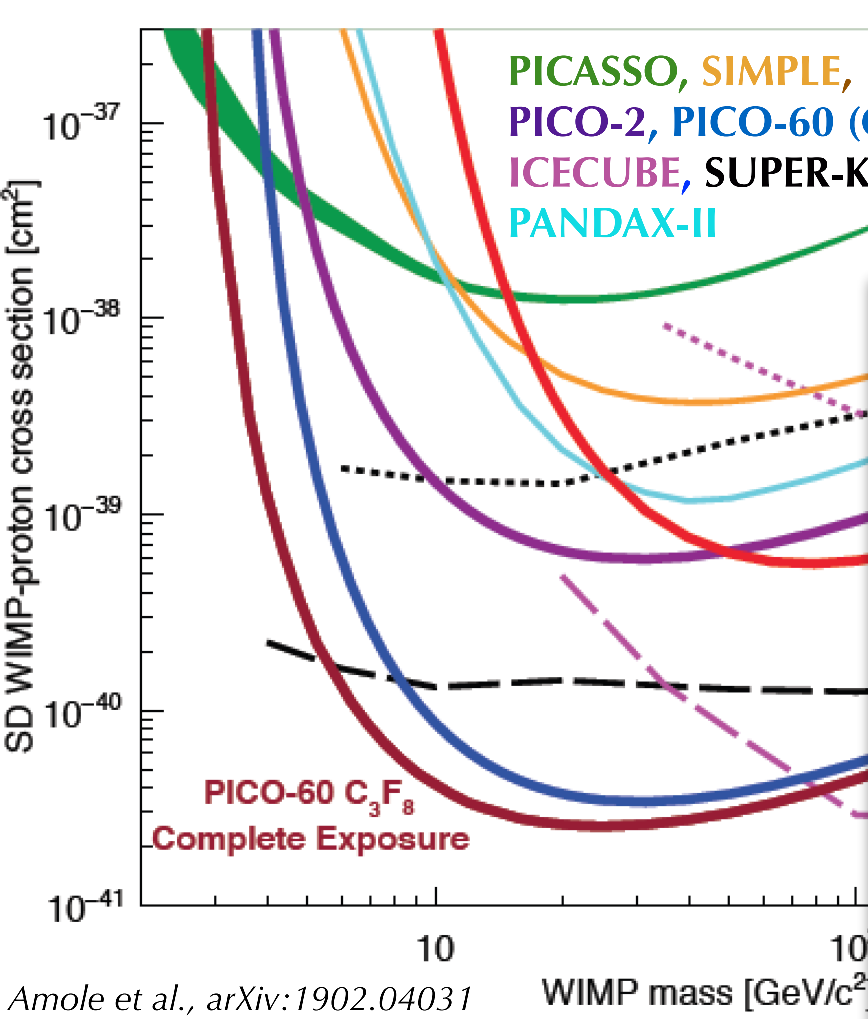
… and today's background may be tomorrow's signal. *(T. Kajita, 2015)*

more slides

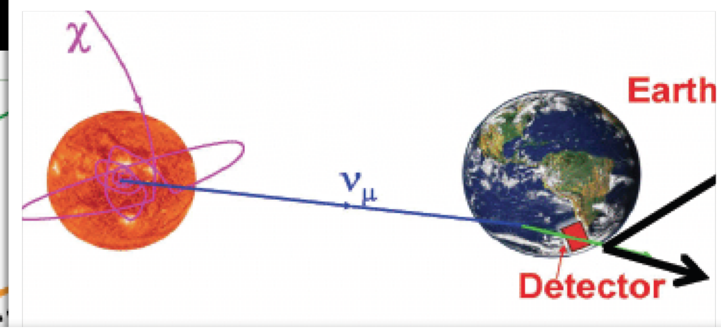
Complementarity (3): Indirect Detection

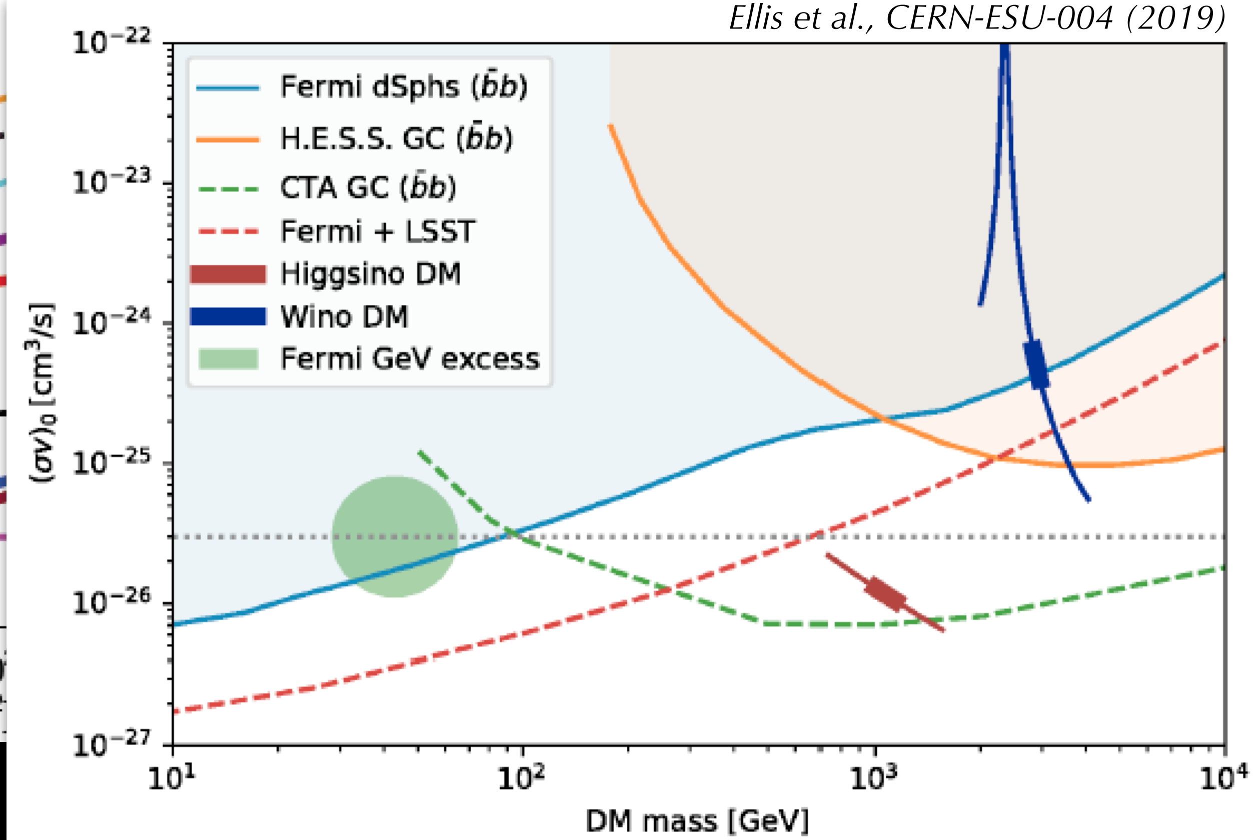
Direct Detection: leading WIMP-p constraints at low mass from PICO-60 kg. Best WIMP-n limits at high mass from Xenon-1T, at low mass from collider searches (for specific operators)

Indirect Detection: leading WIMP-p limit at high mass from neutrino telescopes, via WIMP scattering on p, +capture in the sun, leading to annihilation signatures.



Amole et al., arXiv:1902.04031

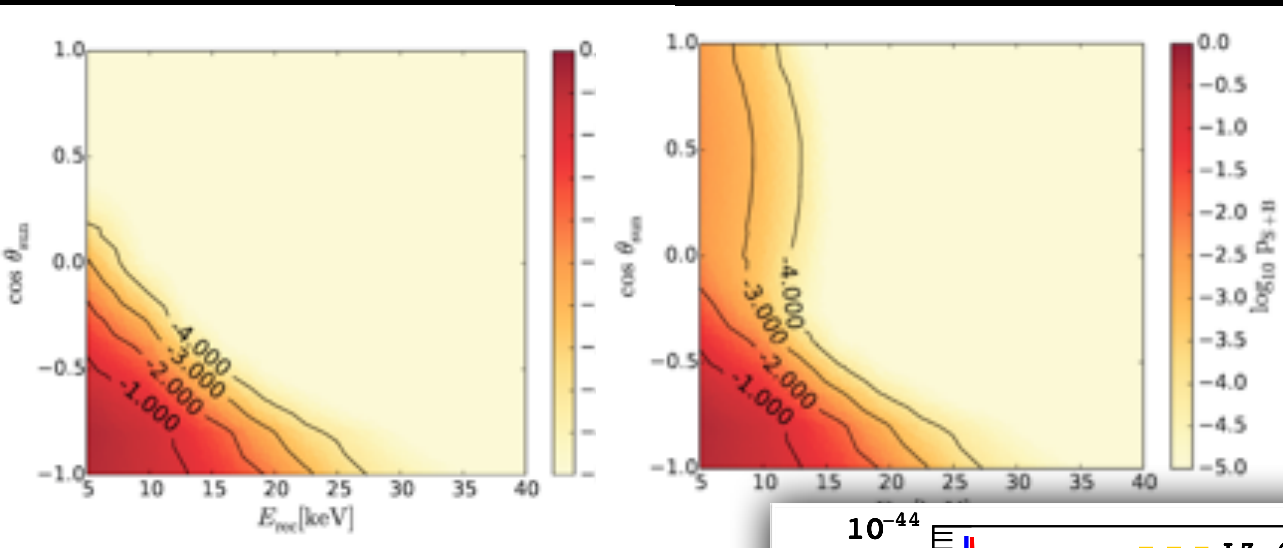




Ellis et al., CERN-ESU-004 (2019)

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.