Overview of dark matter searches

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Outline

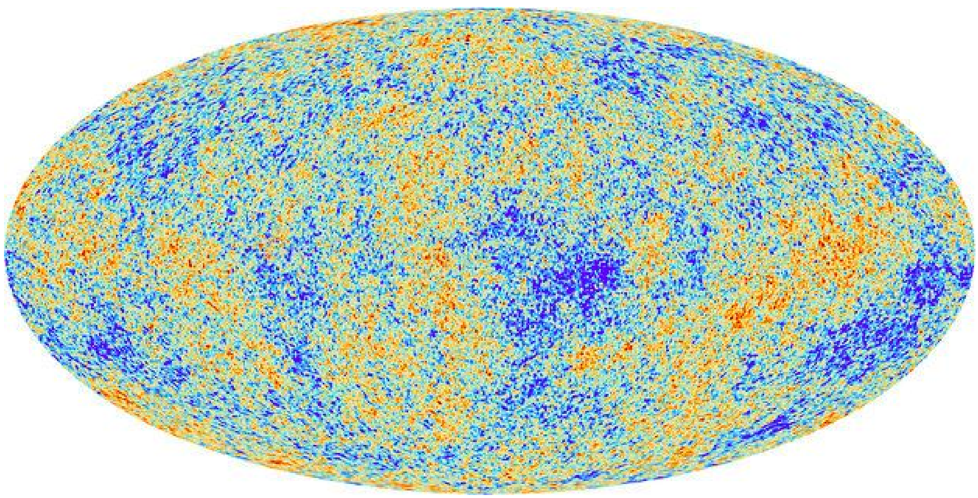
- Motivation and main candidates
  - Primordial black holes
  - Axions
  - WIMPs
- WIMP search methodology
- Indirect searches
- Direct searches
    - Spin-independent
    - Spin-dependent
    - Other channels
- Noble liquid based programs
- Target complementarity
- Main challenges moving forward
- Summary

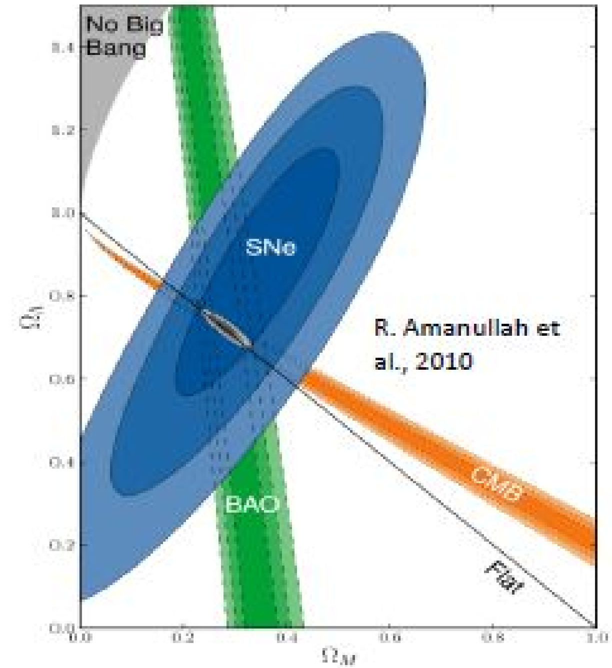
Very rich field

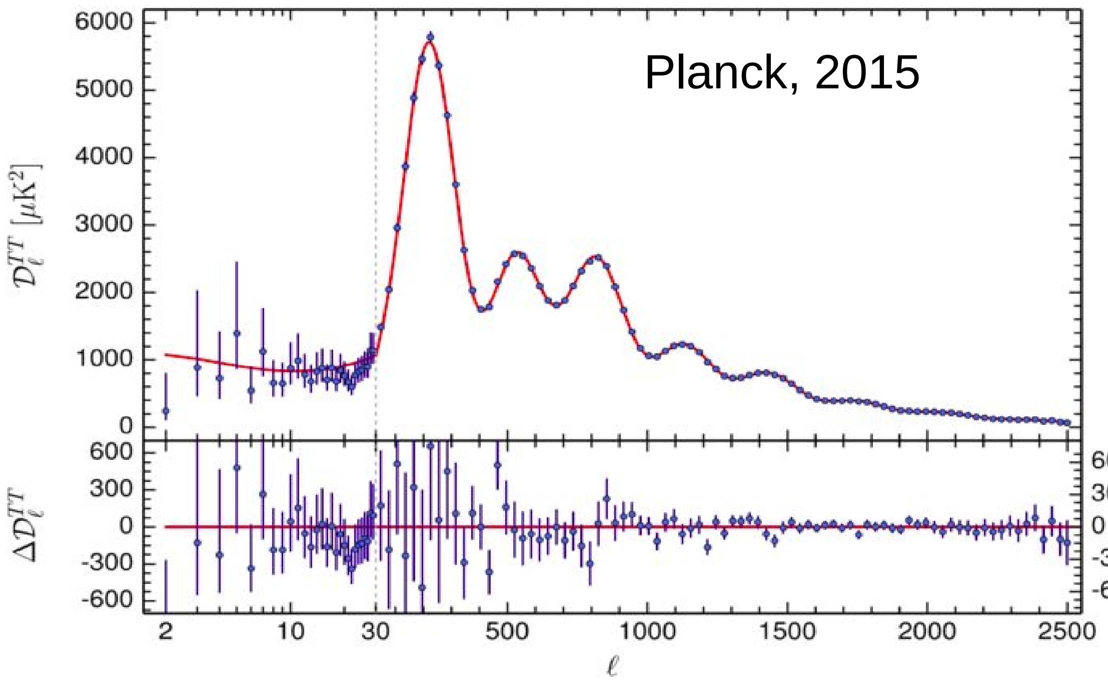
Limited and biased selection of topics in this talk

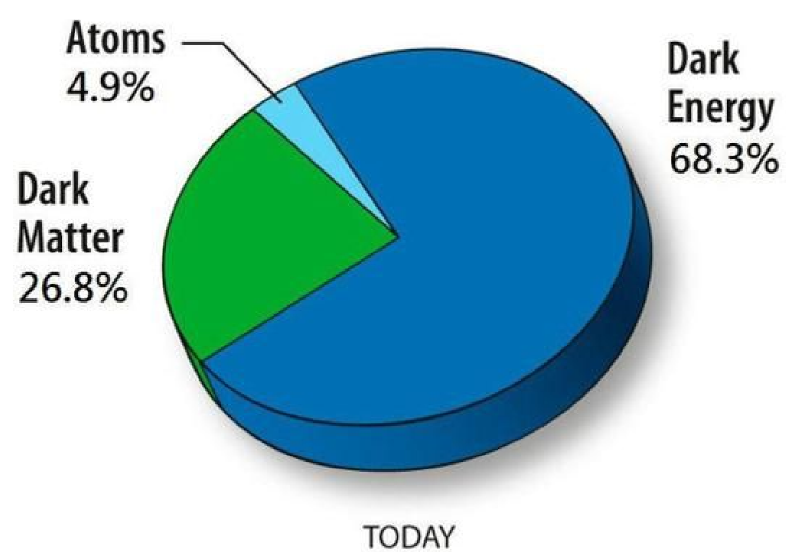
Evidence for Dark Matter

- Cosmic microwave background (CMB) observations, resulting in precise estimates (WMAP, Planck) supporting ΛCDM model



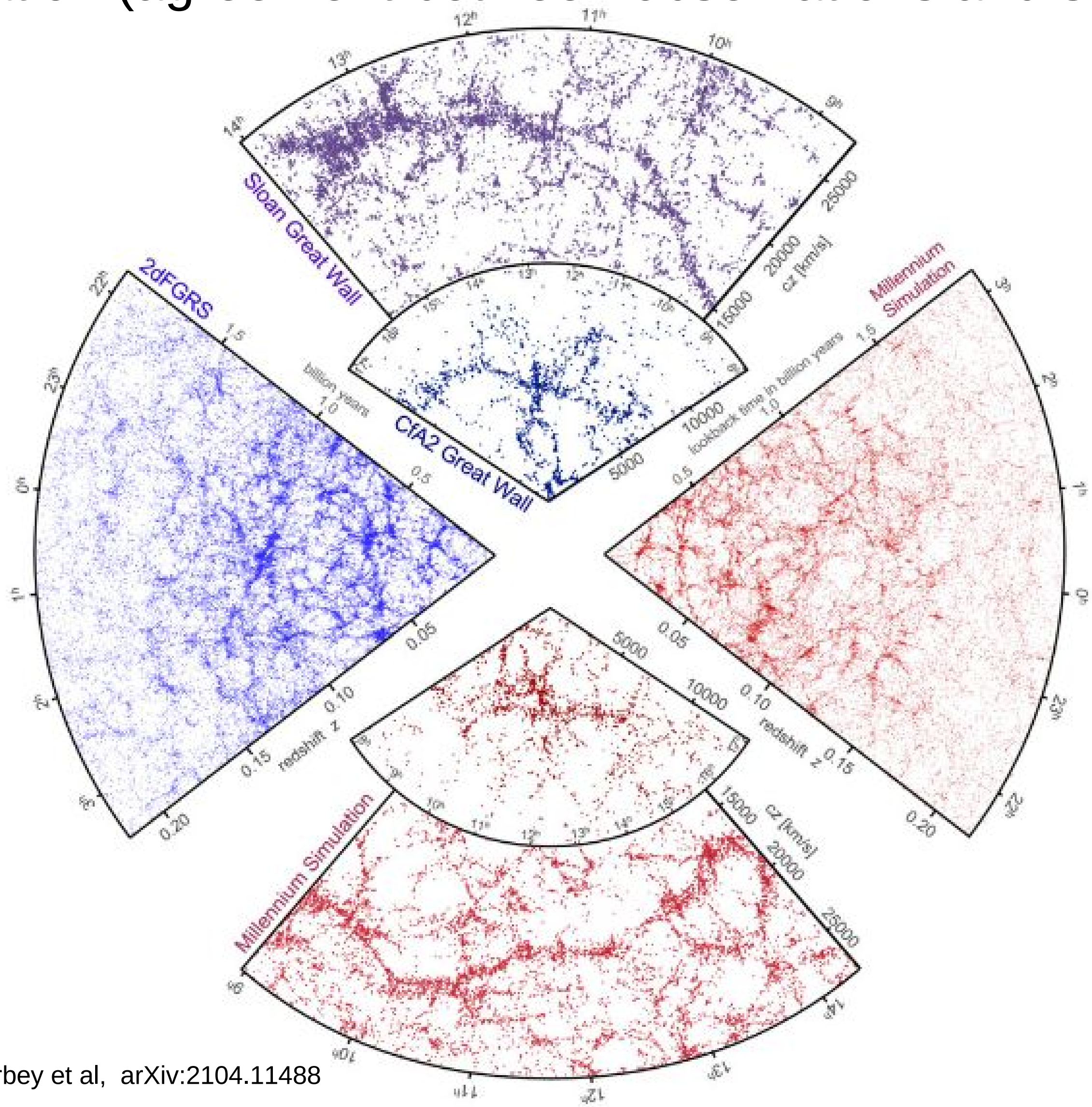






More evidence for Dark Matter

- Large scale formation (agreement between observations and simulation)

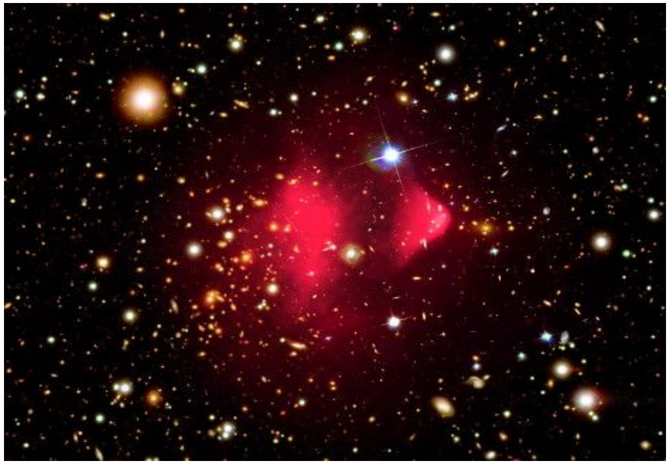


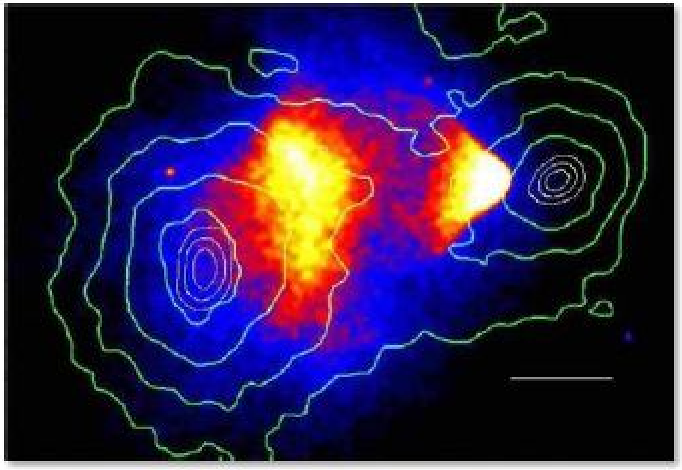
A. Arbey et al, arXiv:2104.11488

Figure 6: Simulated distribution of structures from the Millenium simulation (in red) to be compared to the observed distributions by CfA2 [16], 2dFGRS [17] and SDSS [18]. From [19].

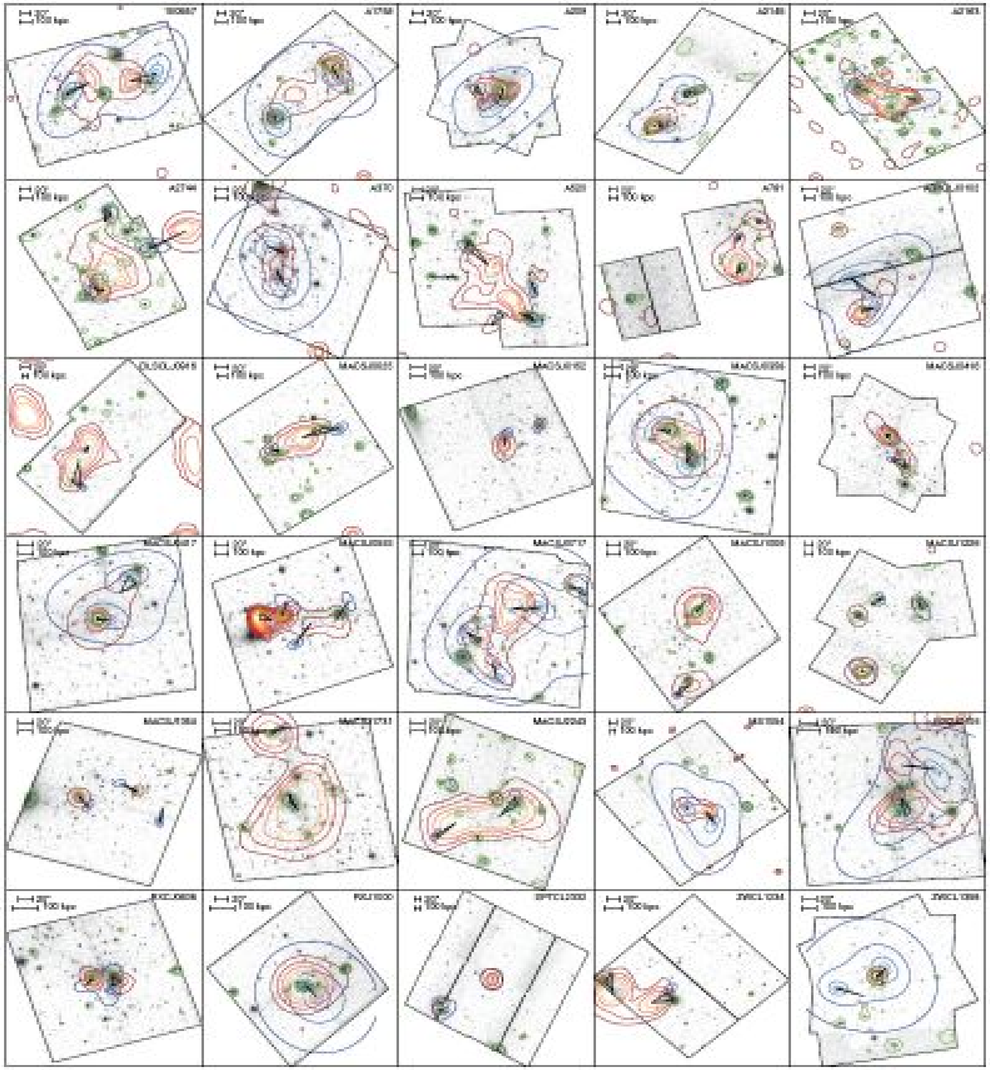
More evidence for Dark Matter

- Gravitational lensing observations (Bullet Cluster, ...)





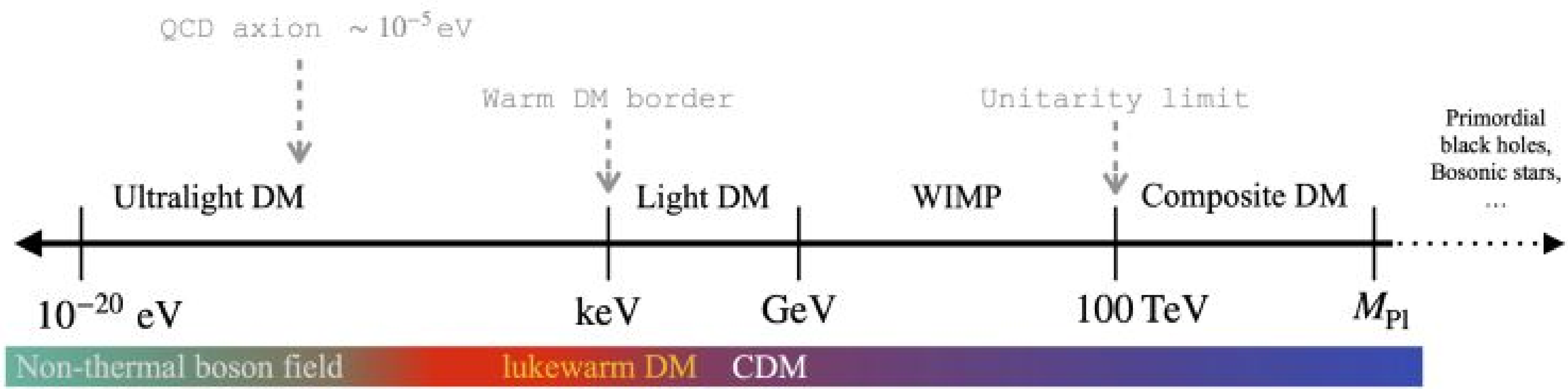
The bullet cluster, D. Clowe et al., 2006



D. Harvey & al., Science, March 27, 2015.
72 new colliding systems! (Also gives bounds on self-interacting DM.)

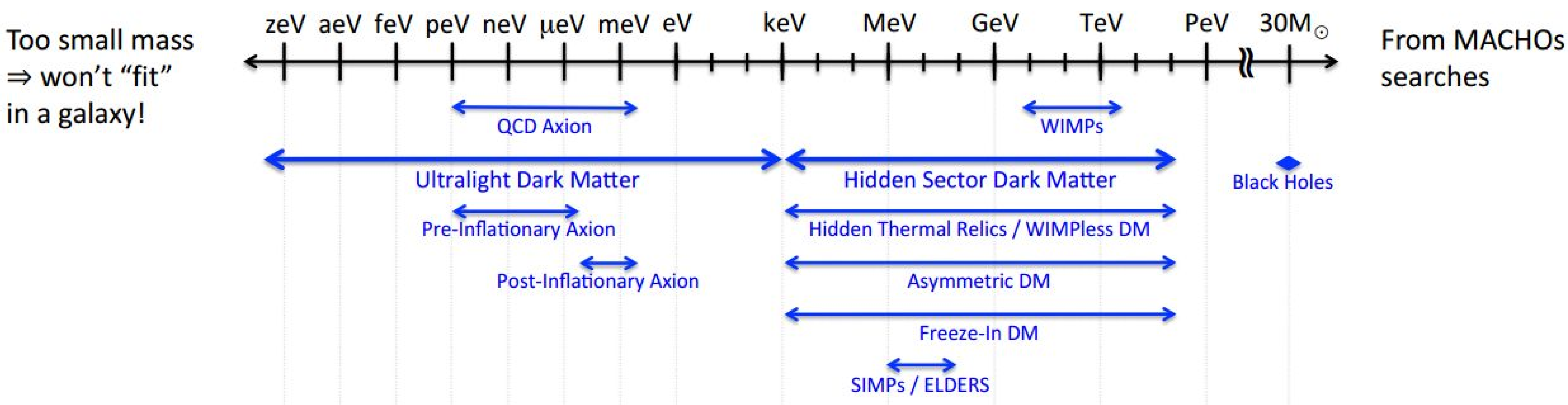
What is Dark Matter?

- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- New Particles. Options include:
  - Axions
  - Weakly Interacting Massive Particles (WIMPs)
  - ...

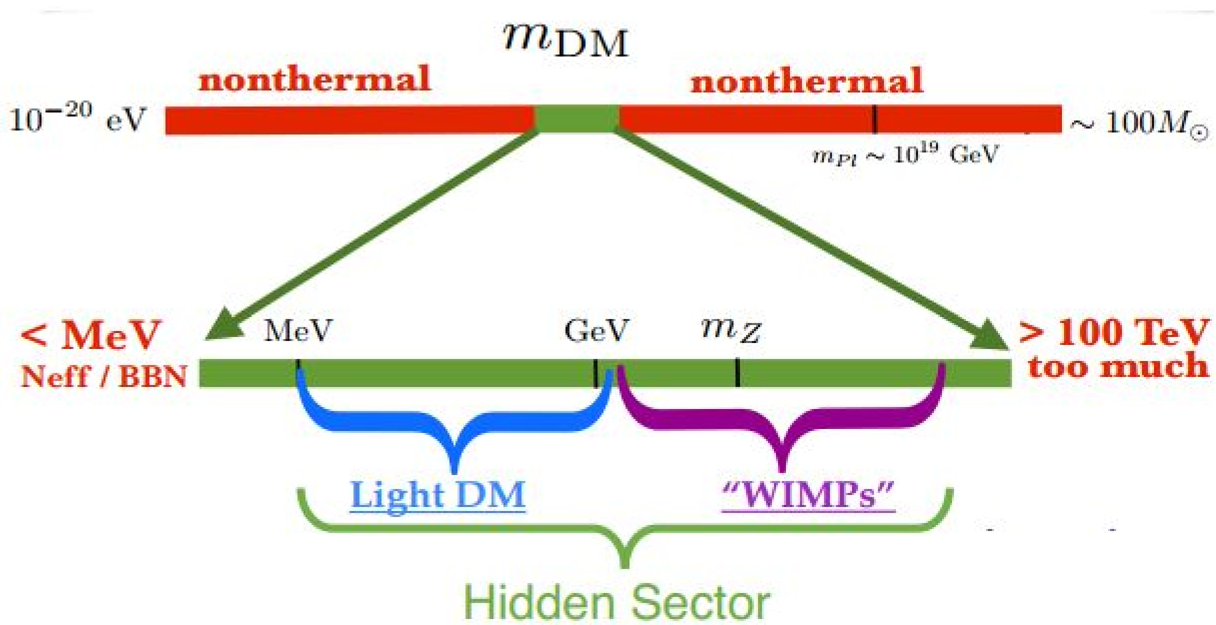


K. Tuominen, Symmetry 2021, 13, 1945

Mass scale

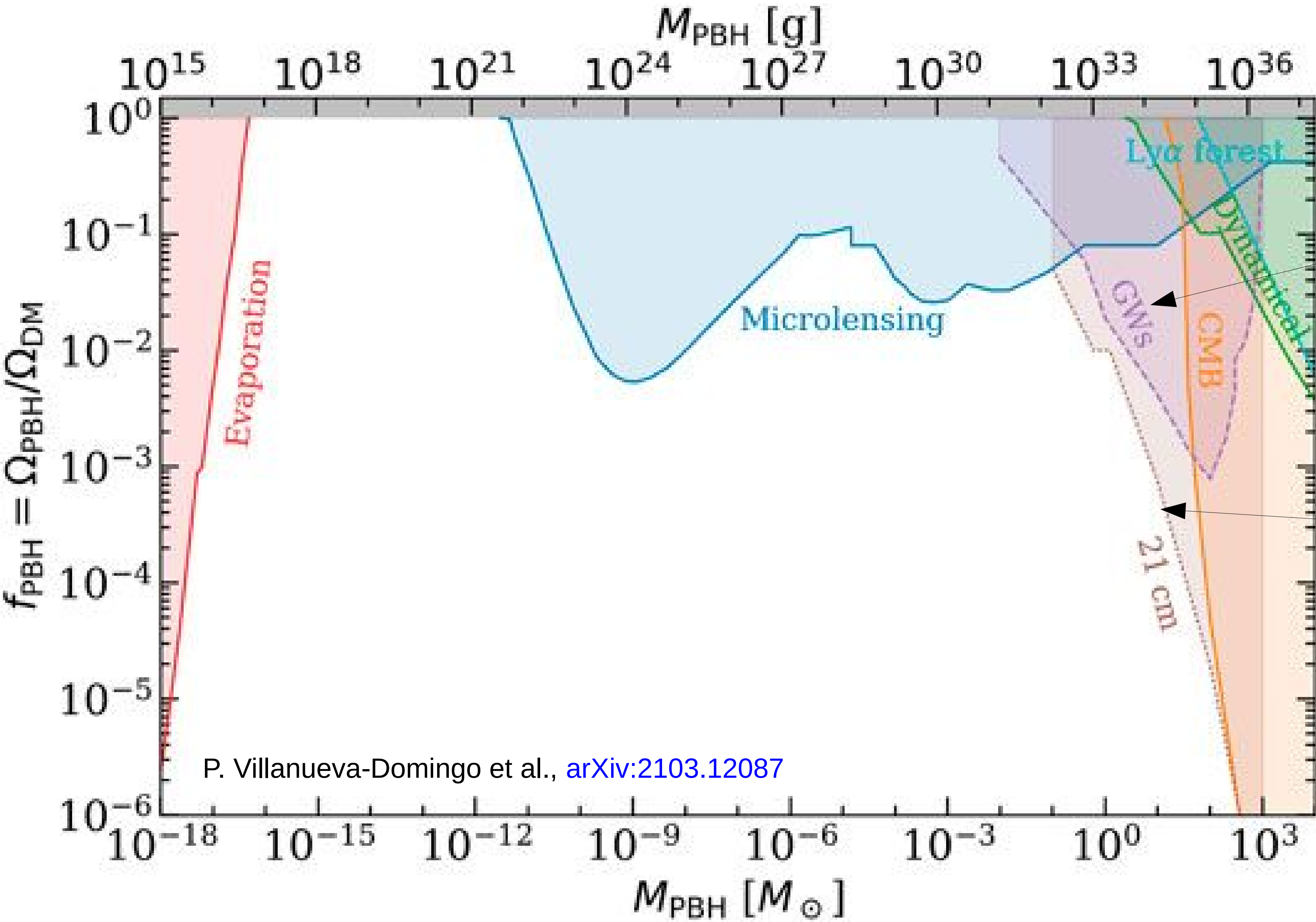


Thermal Equilibrium in early Universe narrows the viable mass range



(M. Carena, ESPPU 2019 Dark Sectors Summary Talk)

Primordial black holes



B. Kavanagh et al., Phys. Rev. D 98, 023536 (2021)

debated

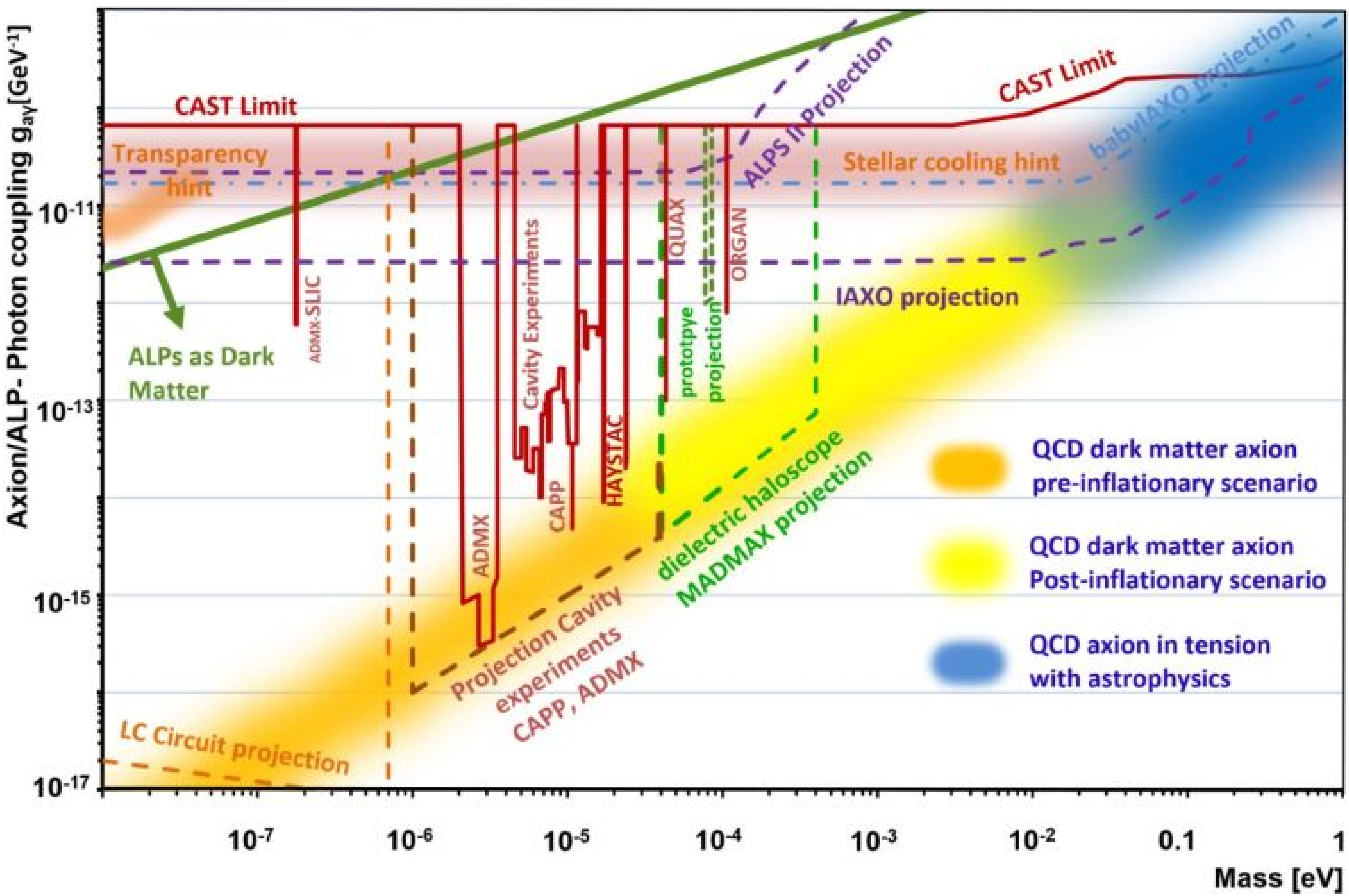
C. Bœhm et al JCAP03(2021)078

projected future sensitivity (SKA)

O. Mena et al., Phys. Rev. D 100, 043540 (2019)

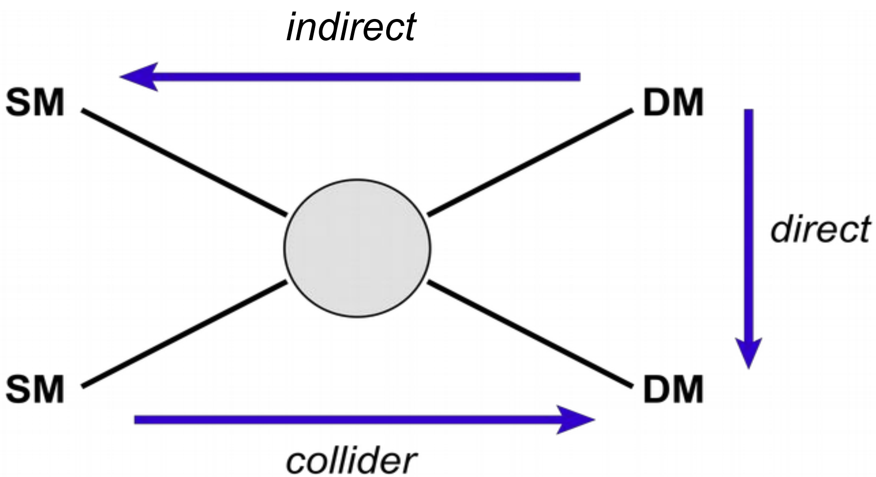
Heavily constrained as a primary DM component. But some room still exists...

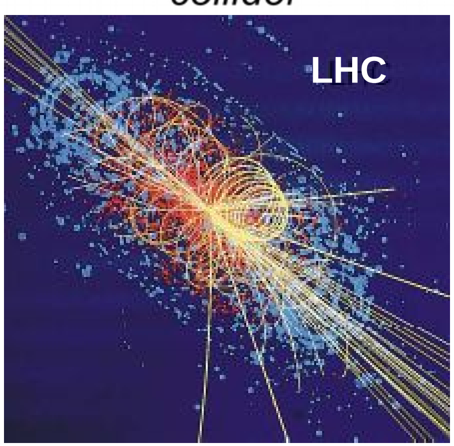
Axions and axion-like particles (ALPs)



J. Billard et al., APPEC Committee Report, arXiv:2104.07634

Ways to look for Dark Matter particles

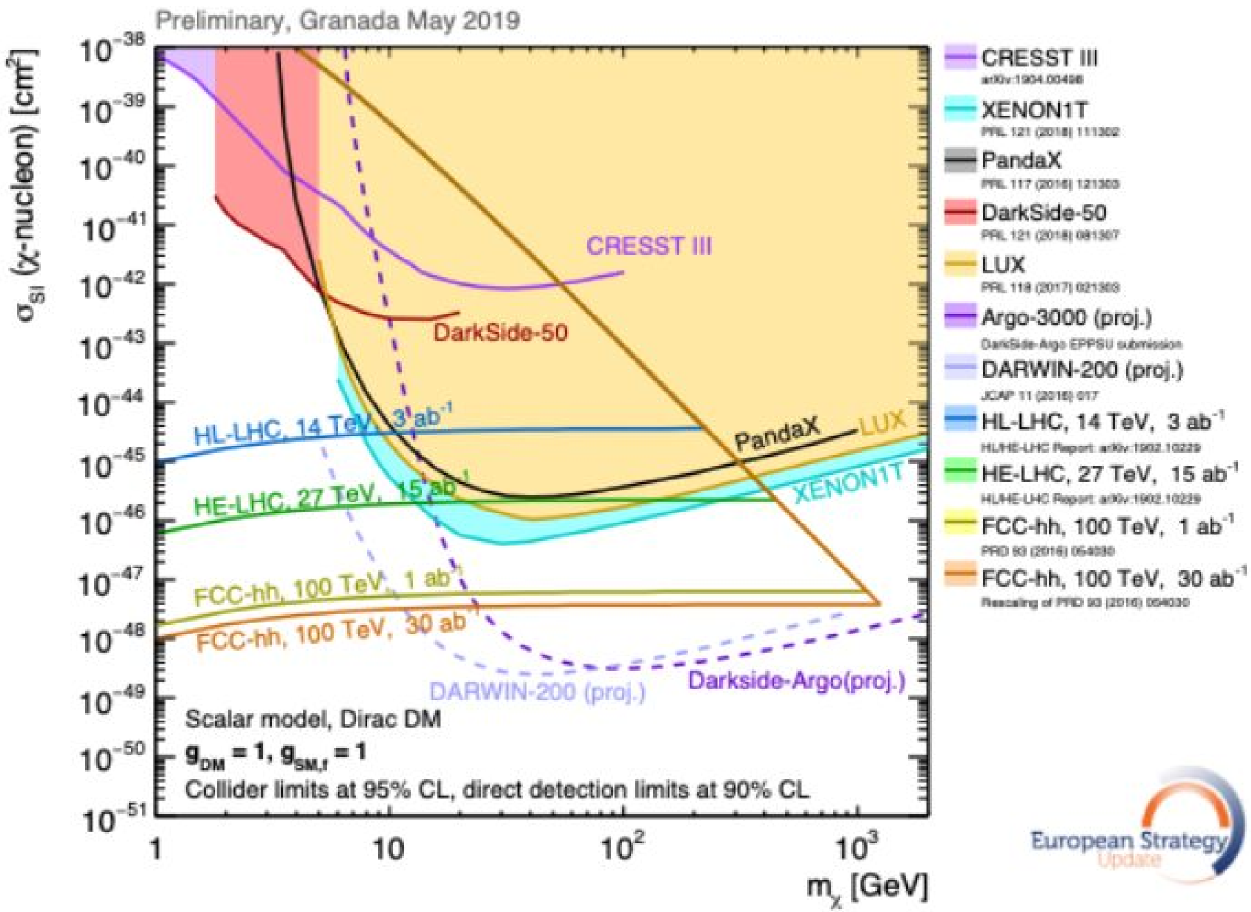




- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares)
  - Positrons, antiprotons (AMS)
  - γ-rays (Fermi-LAT, CTA)
- <u>**Direct detection**</u>
- By producing them at accelerators (LHC, beam dump experiments)

Colider/direct detection complementarity

Example of Complementary reach for future colliders and future DD for benchmarks considered (this case: scalar mediator)

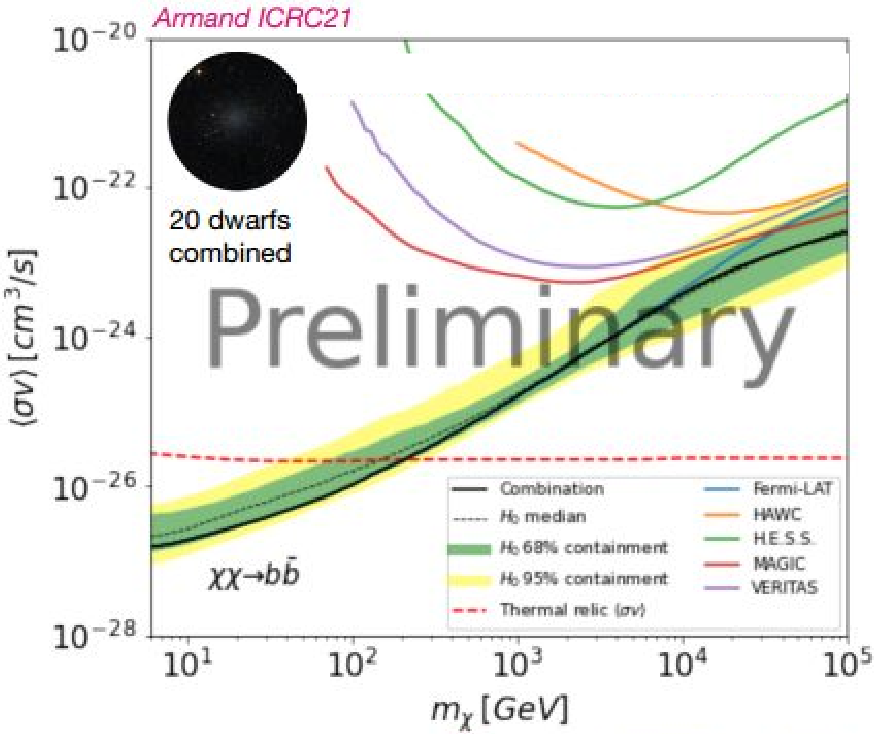


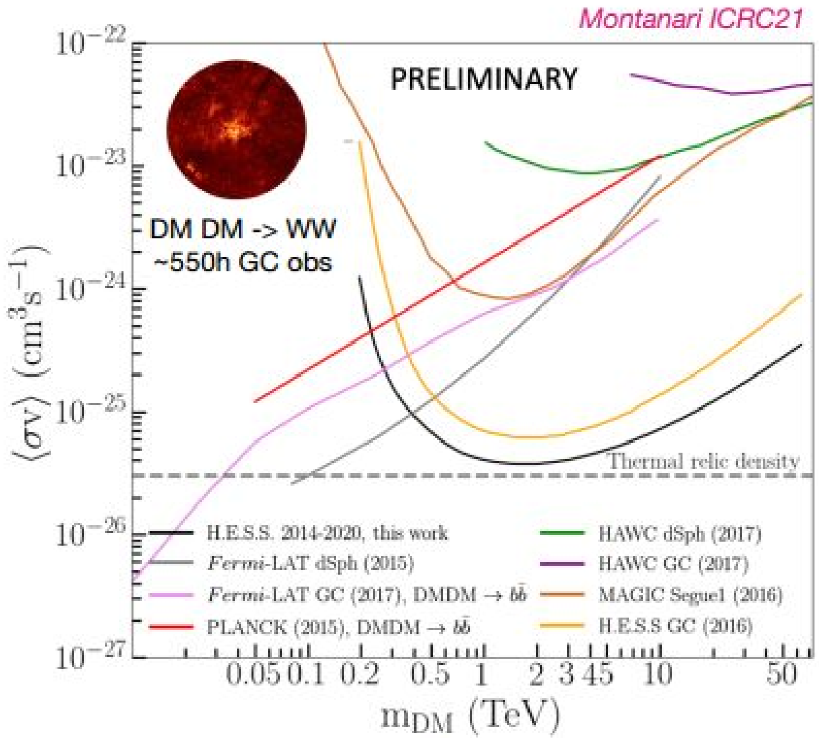
- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

(M. Carena, ESPPU 2019 Dark Sectors Summary Talk)

Indirect searches

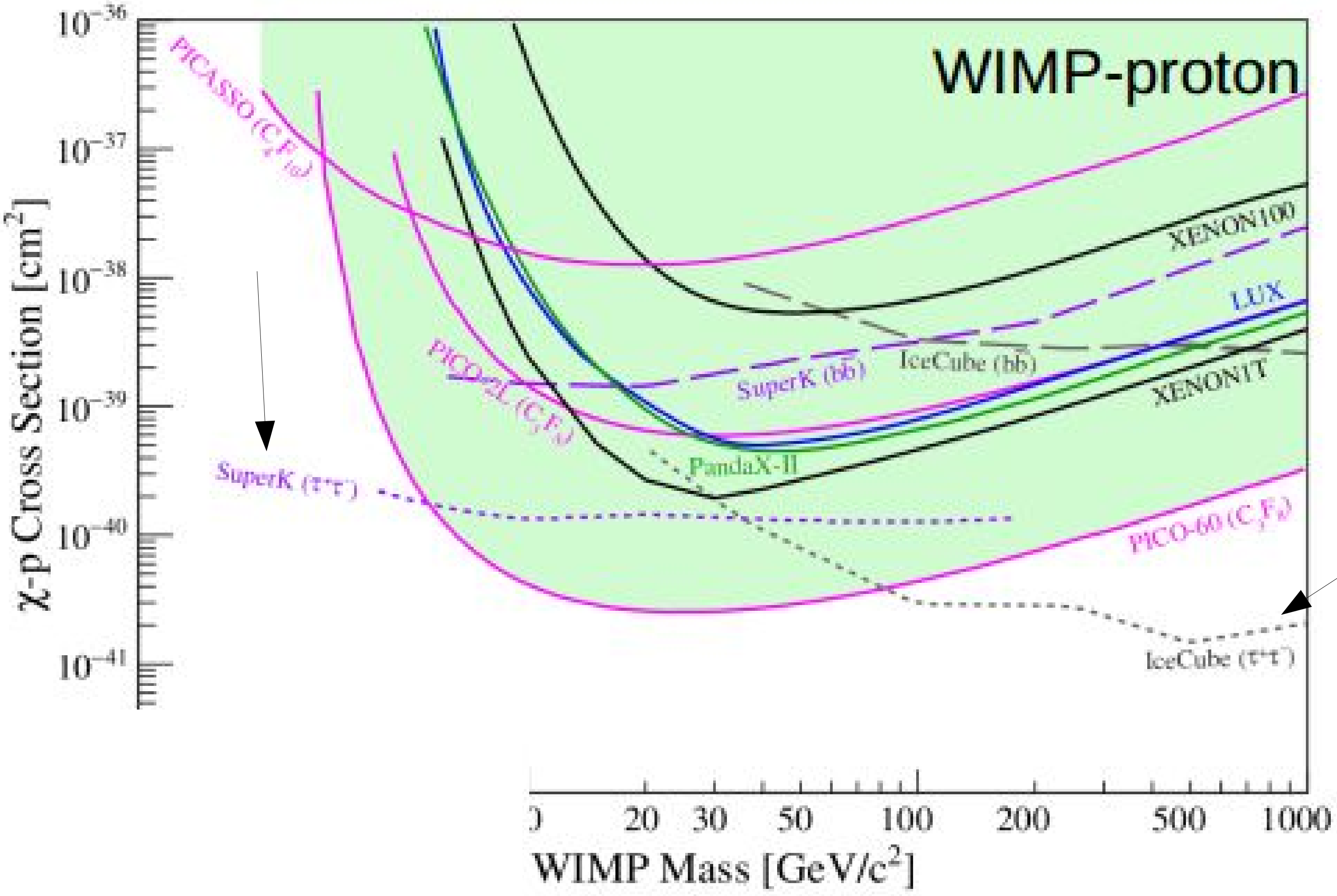
- Gamma ray limits on annihilating WIMPs





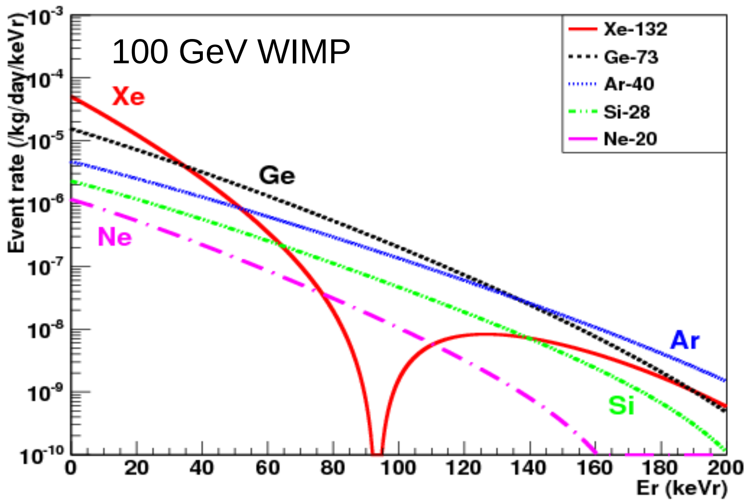
Indirect searches

- Neutrino limits on annihilating WIMPs: SuperK, IceCube



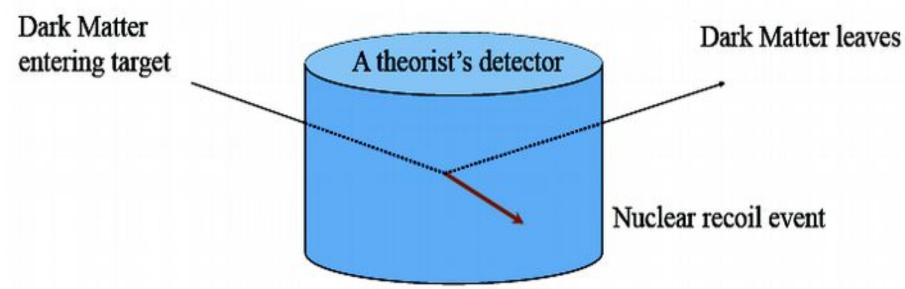
DM direct detection signature

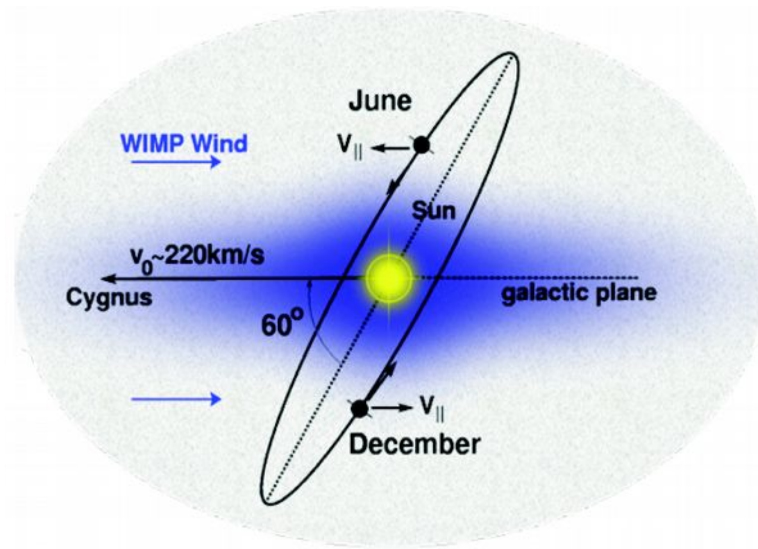
- Only through rare interactions with ordinary matter
- After the interaction, recoiling nucleus deposits energy (**heat, light, electric charge, ...**) in the detector



Nuclear recoil spectrum

- featureless, ~exponential
- lower threshold =>more sensitivity
- natural radioactivity is a background





Annual modulations in the event rate should be present!

Directionality
=> annual modulation of the signal

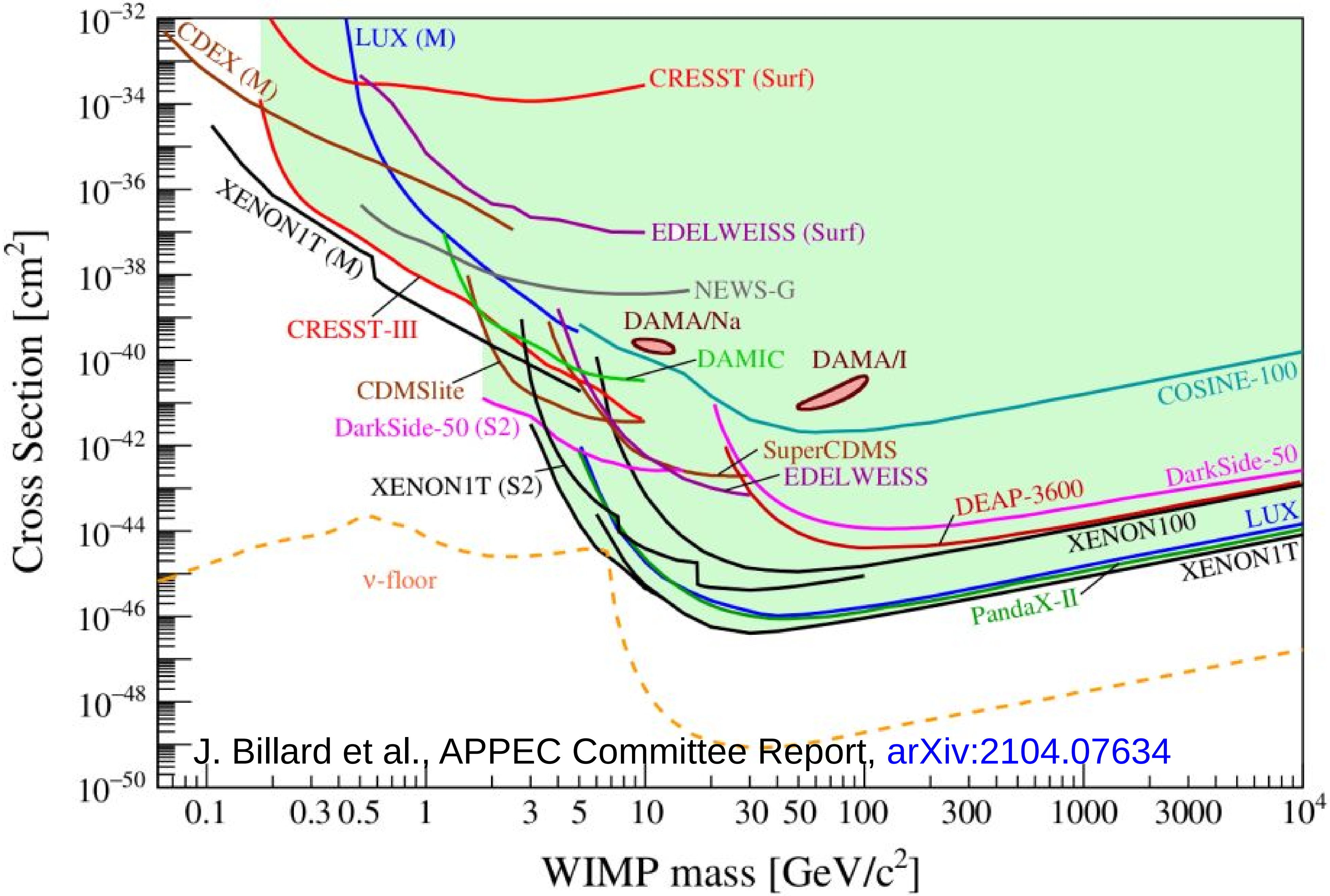
astrophysics

$$\frac{dR}{dE_R} = N_T \int_{v_{min}}^{\infty} dv\, v\, \Phi(v, v_E) \frac{d\sigma}{dE_R} \varepsilon(E_R)$$

detector response

particle/nuclear physics

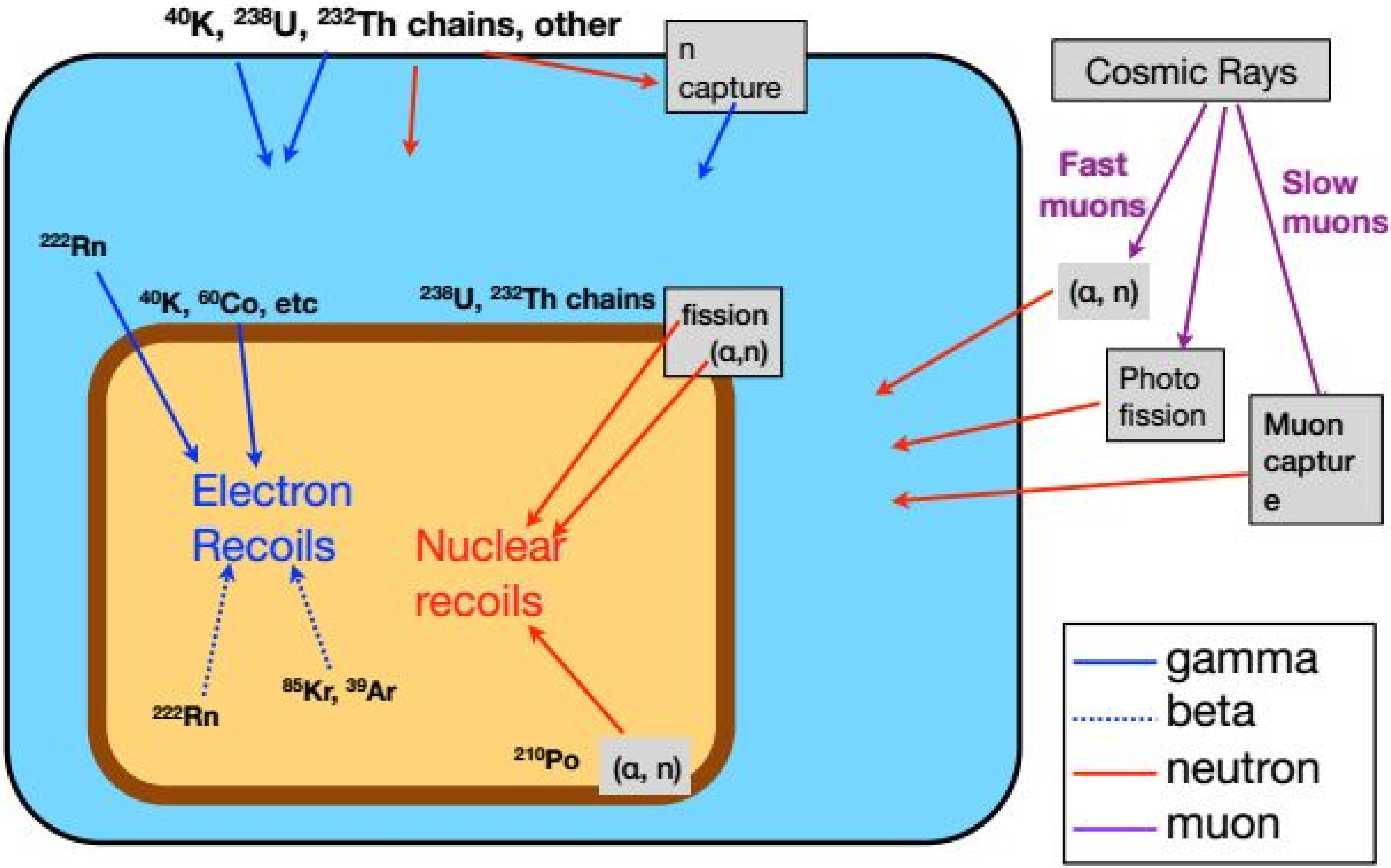
Direct detection: current landscape



J. Billard et al., APPEC Committee Report, arXiv:2104.07634

Spin-independent, with the usual assumptions: Standard Halo Model, isospin parity

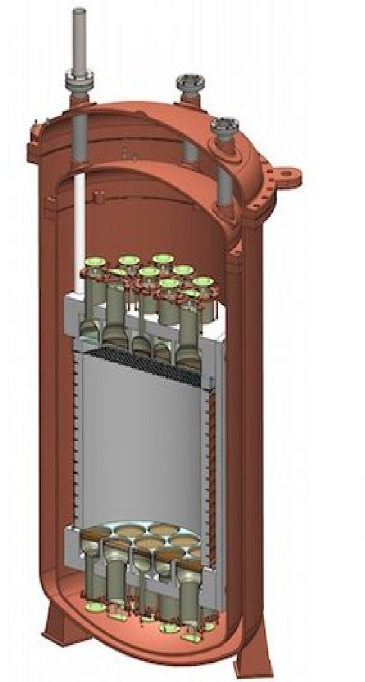
Backgrounds



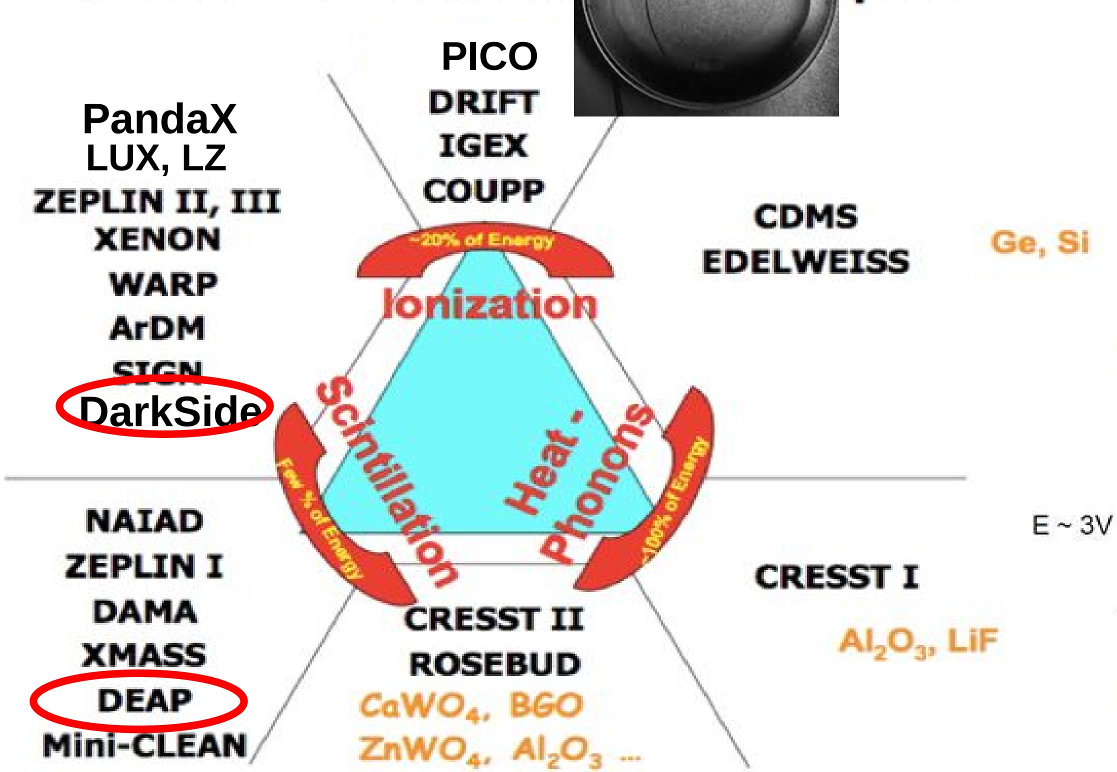
Ambient backgrounds: 10^{11} time DM rate

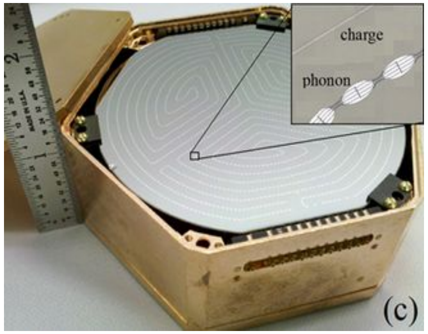
T. Shutt -LIDINE, Sept 22, 2017

Detection techniques

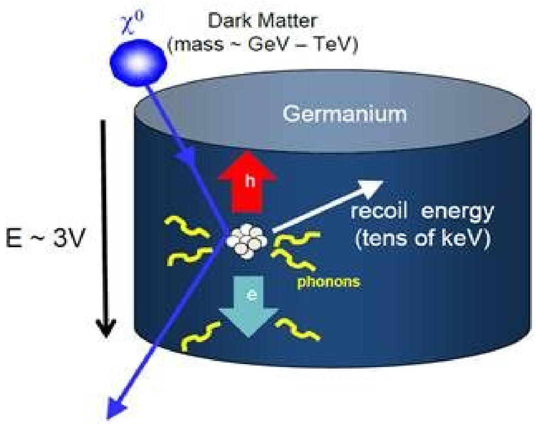


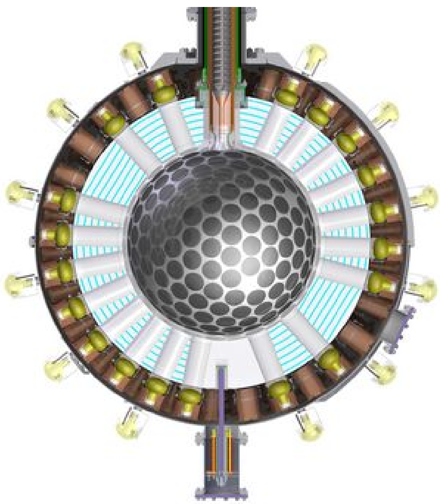
PICO



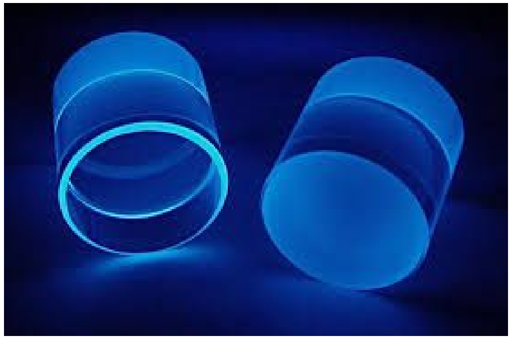


CDMS



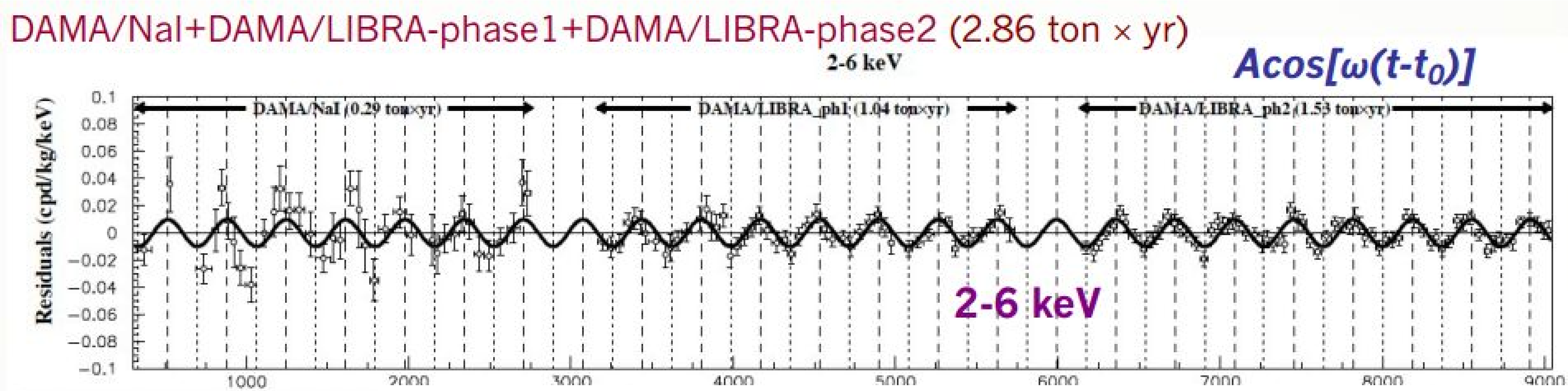


P. Salati "Indirect and direct dark matter detection"

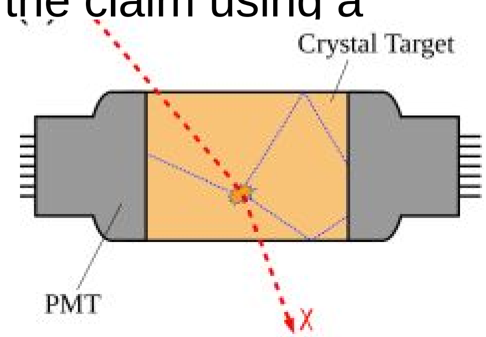


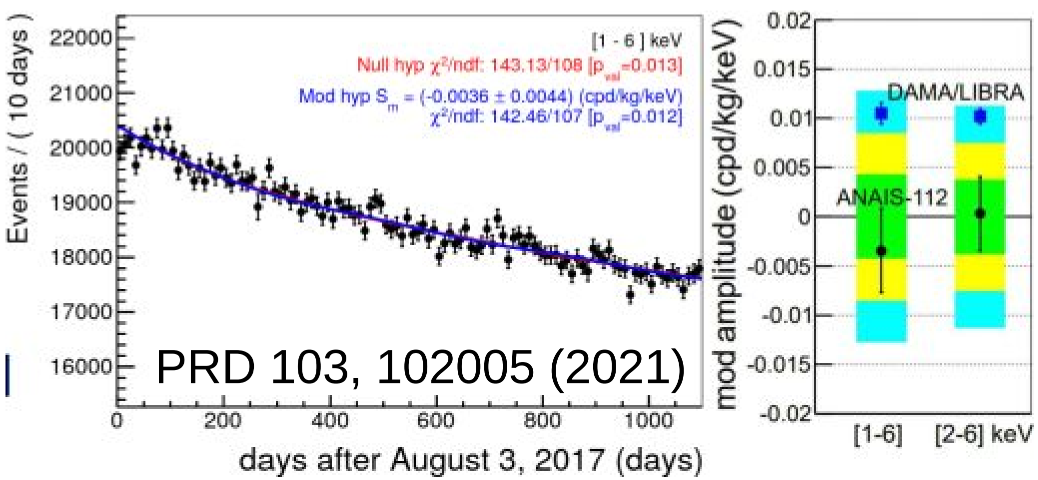
CRESST

DAMA and ANAIS-112



- Annual modulation can be a signature of DM (or a tricky background)
- DAMA/LIBRA signal in tension with experiments using other target materials
- Several groups attempt to independently verify the claim using a similar NaI(Tl) scintillator technology

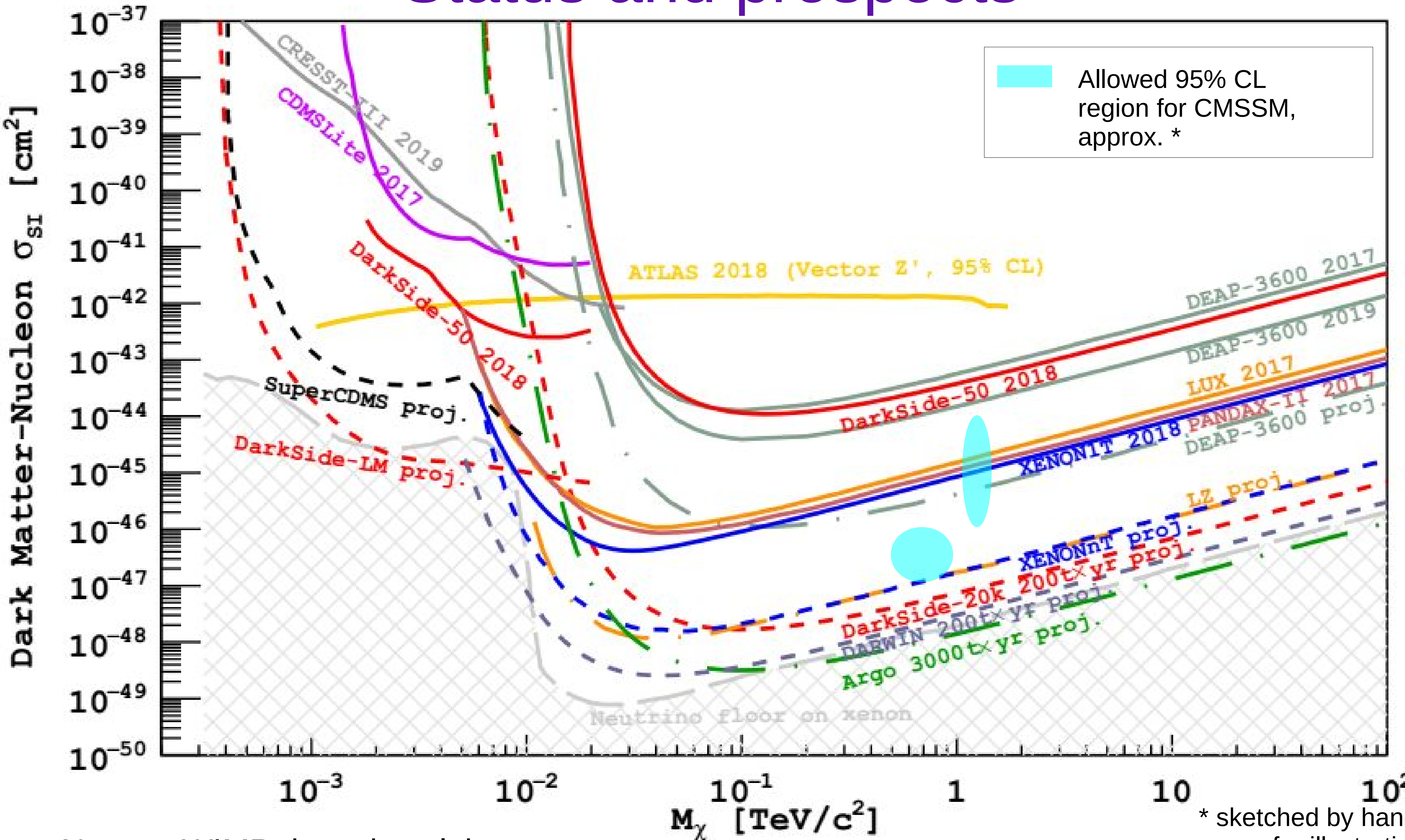




ANAIS-112:

- First independent result with the same methodology
- Data incompatible with DAMA at 3.3σ, consistent with no modulation
- Expecting future higher sensitivity from this and other experiments

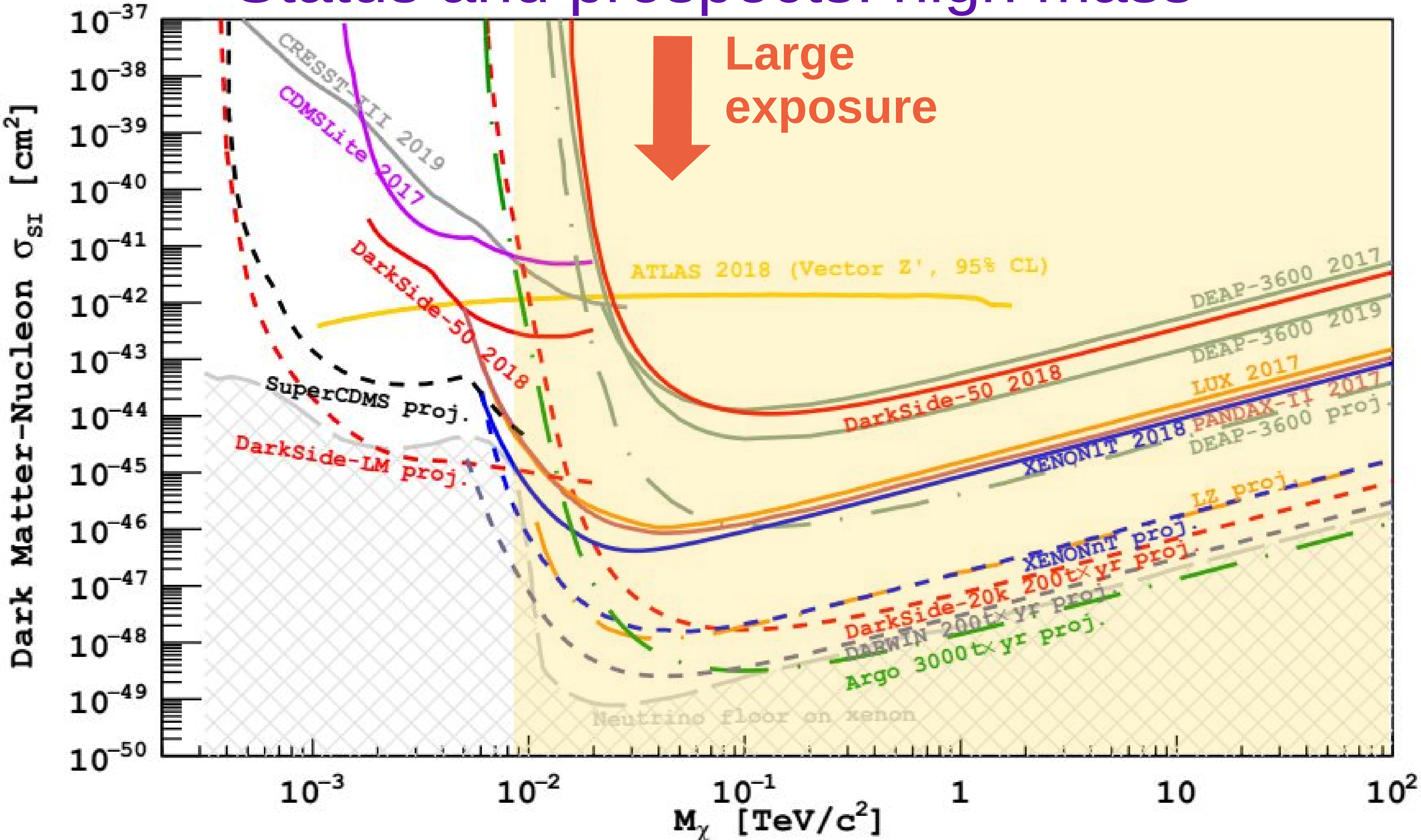
Status and prospects



* sketched by hand, for illustration

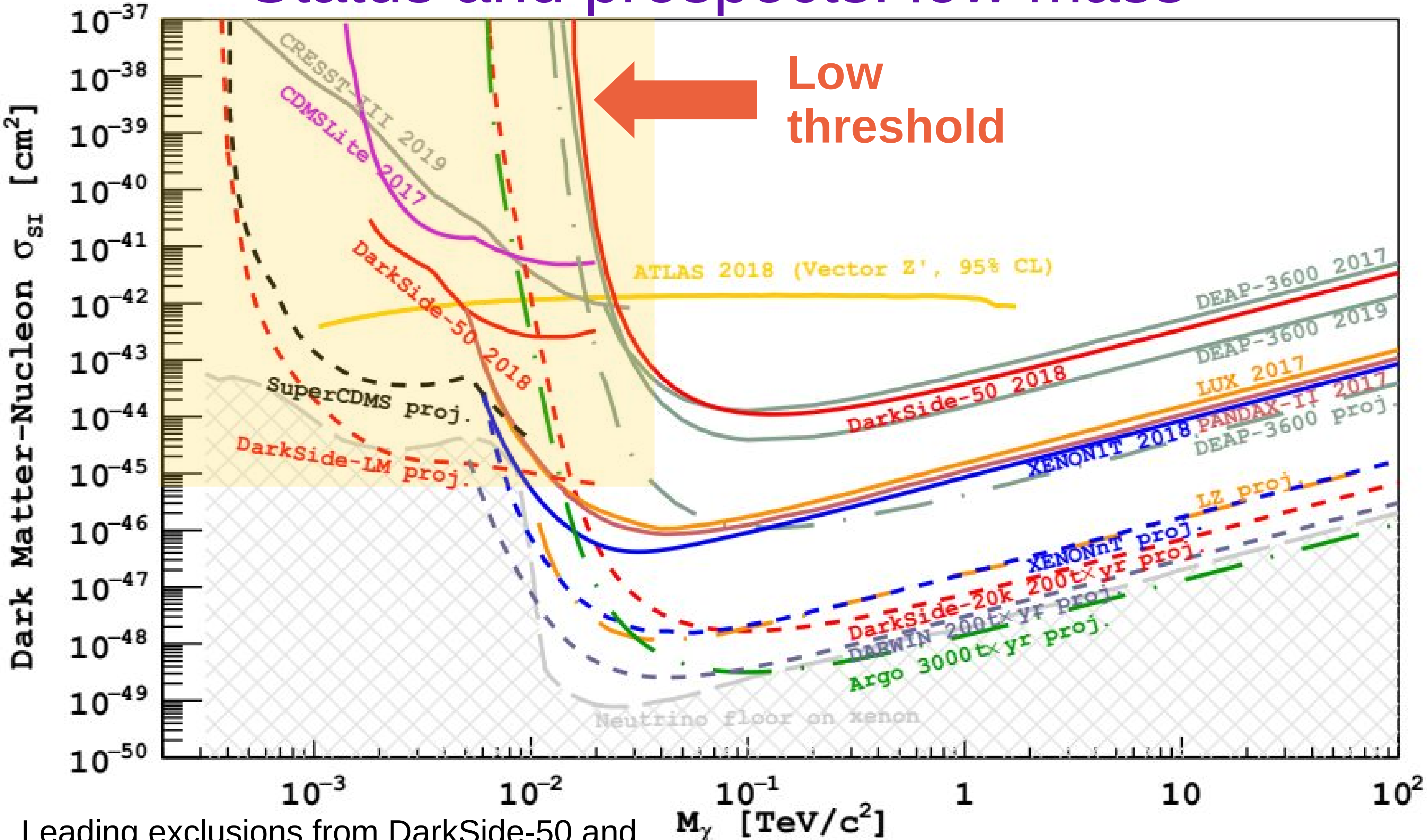
- No new WIMP detection claims
- LAr and LXe dominate searches in the spin-independent sector >~2 GeV/c2
- Continued search towards the neutrino floor still very well motivated
  - see e.g. Roszkowski et al., Rept.Prog.Phys. 81 (2018), 066201

Status and prospects: high mass



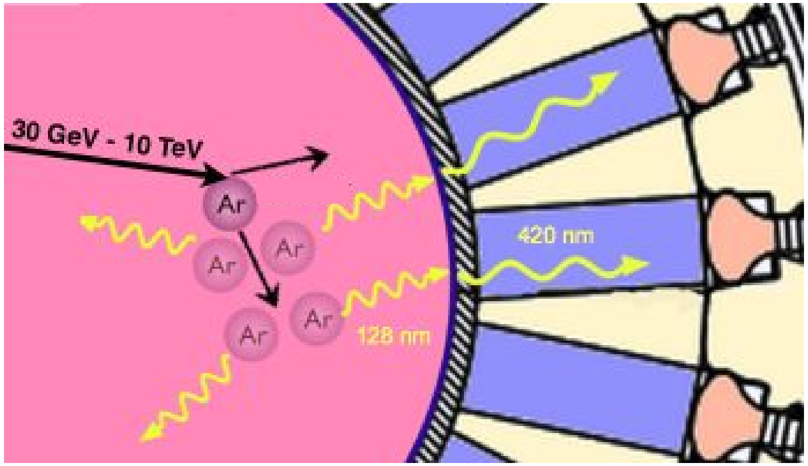
- New limits published ~twice a year
- Beautiful results from LUX, XENON and PandaX
- Multiple new results from LAr detectors, reducing the sensitivity gap
- Roadmap in place for reaching the neutrino floor
- **Scale-up requires global consolidation of efforts and R&D**

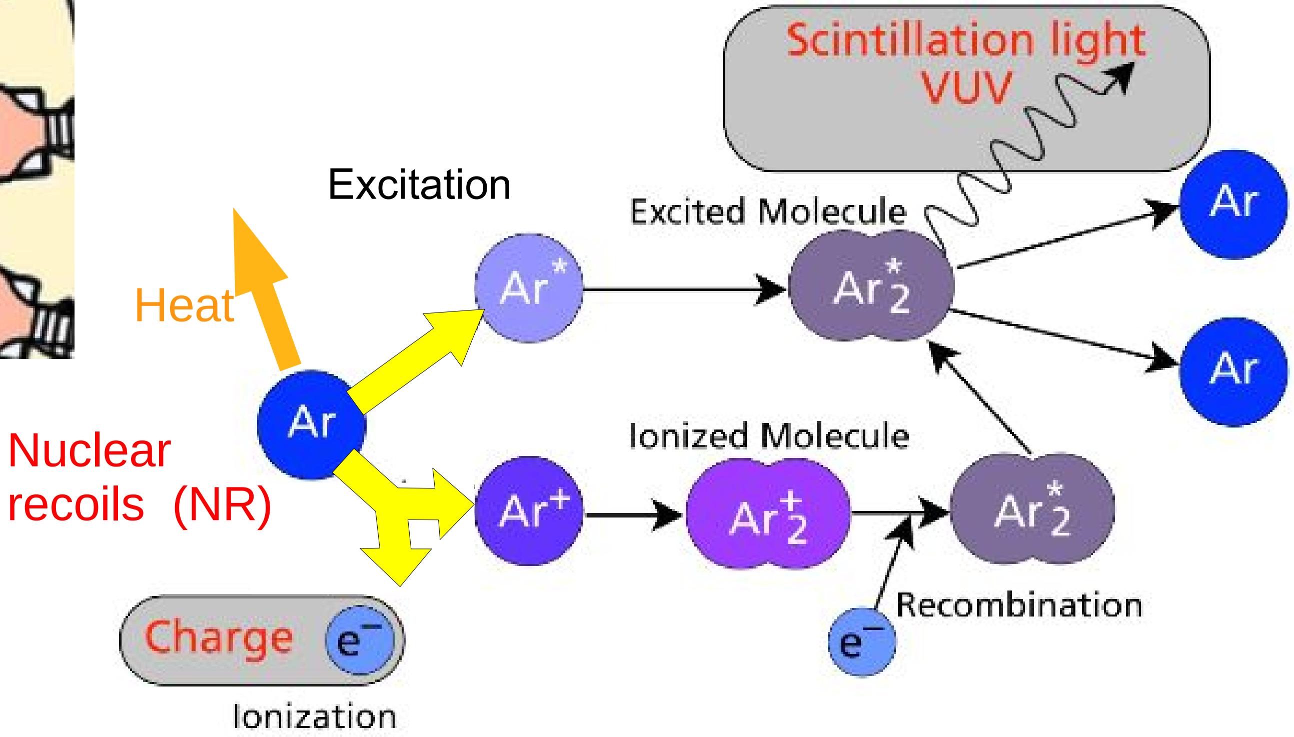
Status and prospects: low mass



- Leading exclusions from DarkSide-50 and XENON1T (both S2-only)
- Multiple noble liquid-based and other technologies still in play in different parts of the mass spectrum (SuperCDMS, CRESST, NEWS-G, DAMIC)
- The neutrino floor soon within reach
- Still much work on low-energy calibration and backgrounds
- **Room for exciting R&D and new ideas!**

Liquid noble detectors





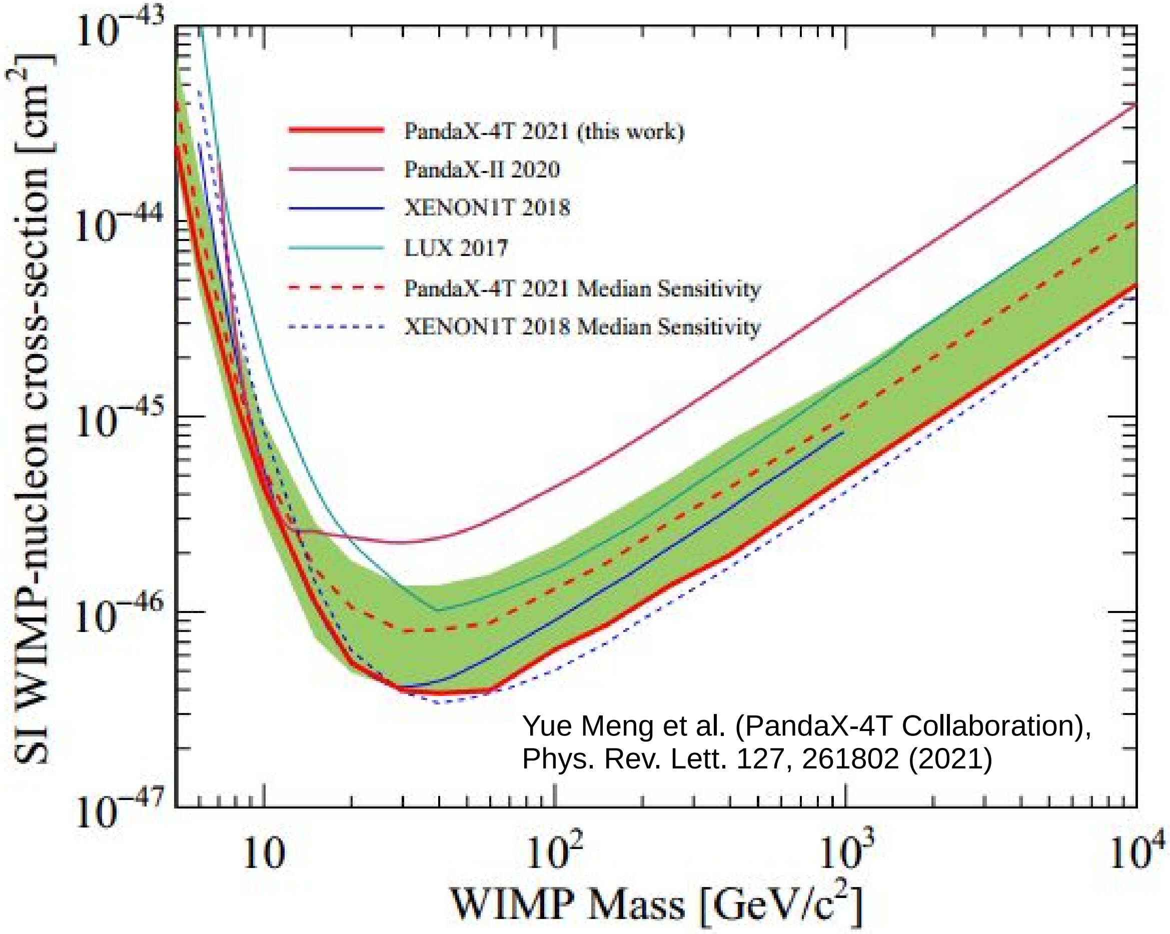
Ar and Xe are used for WIMP detection.

- Ar inexpensive and advantageous for purification and background rejection

Why noble elements?

- High light yield, transparent to their own scintillation
- Easy to purify and scalable to very high masses
- (At least) two available detection channels: scintillation and ionization

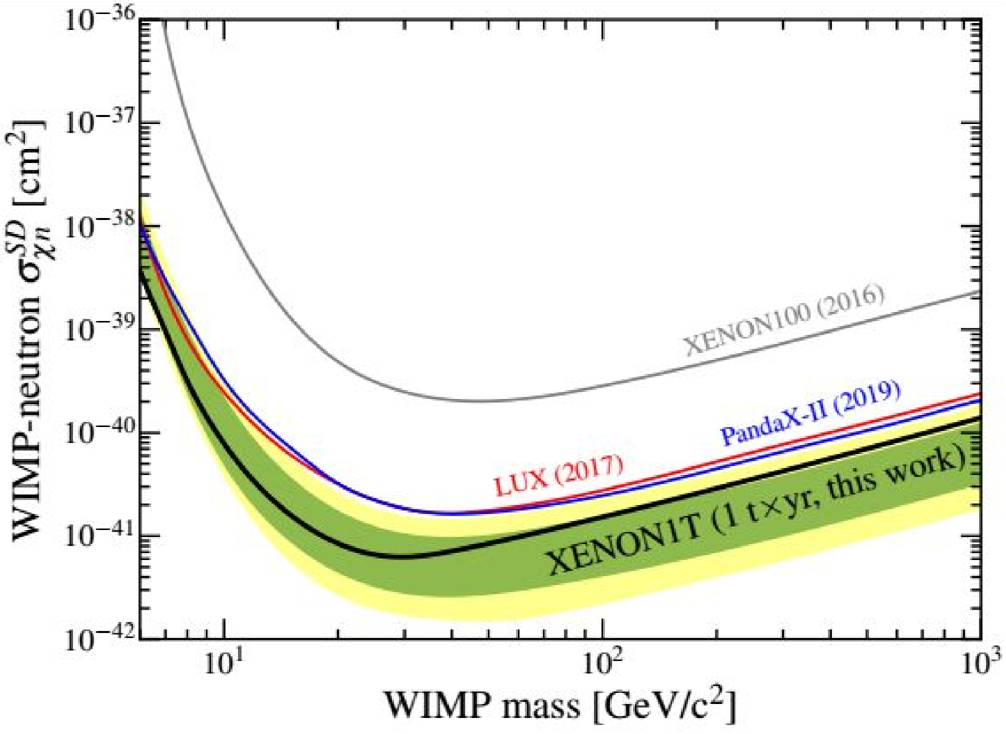
Spin-independent limit: PandaX-4t



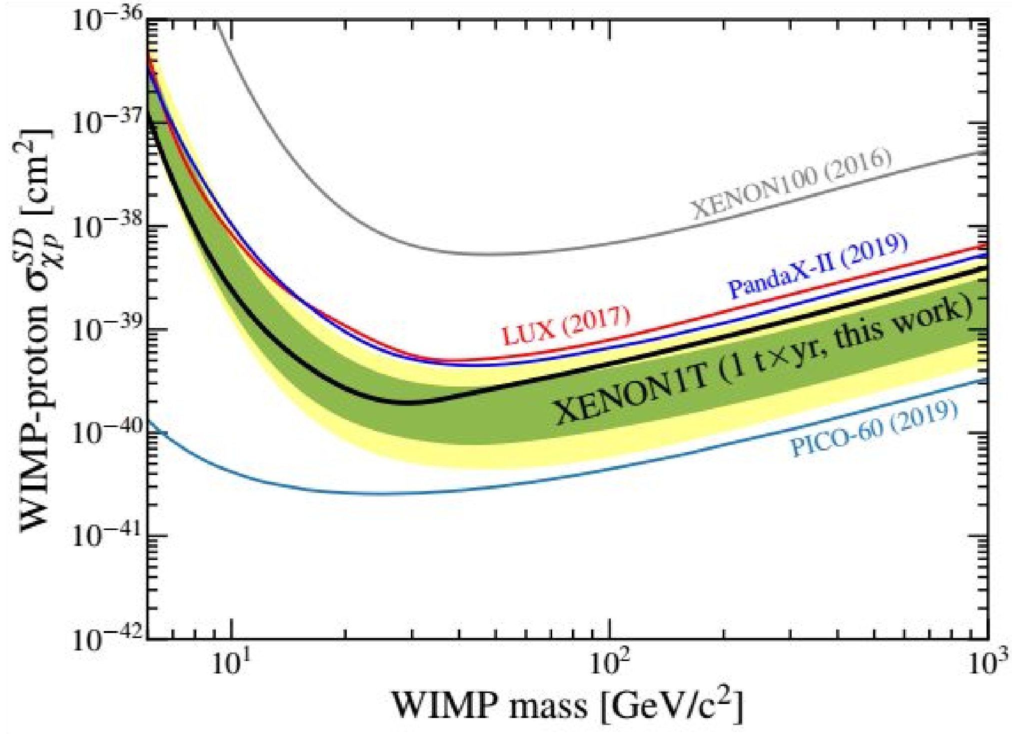
- 3.7t active LXe target, the largest DM detector with published results
- 0.63 t x y exposure from the commissioning run
- background level ~XENON1T, mainly 3H and Rn (~4.2 µBq/kg)
- non-blind analysis: downward fluctuation of signal compared to background expectation

Spin-dependent limits

XENON1T, Phys. Rev. Lett. 122, 141301 (2019)



PICO-60, Phys. Rev. D 100, 022001 (2019)

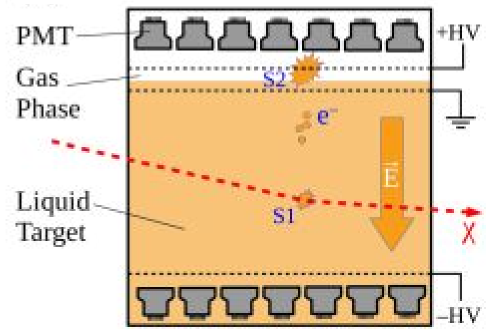


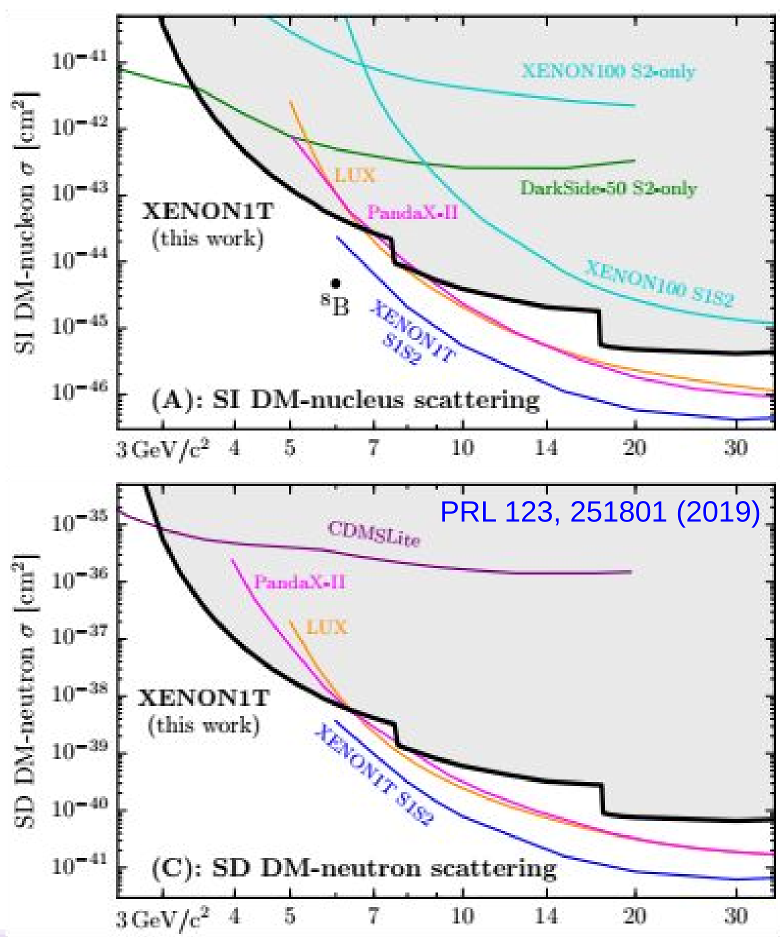
- Coupling of WIMP to unpaired nucleon spins
- Fluorine based target (PICO-60) remain on the lead for WIMP-proton cross-section
- LXe detectors dominate the WIMP-neutron sector
- Same parameter space explored by indirect and collider searches

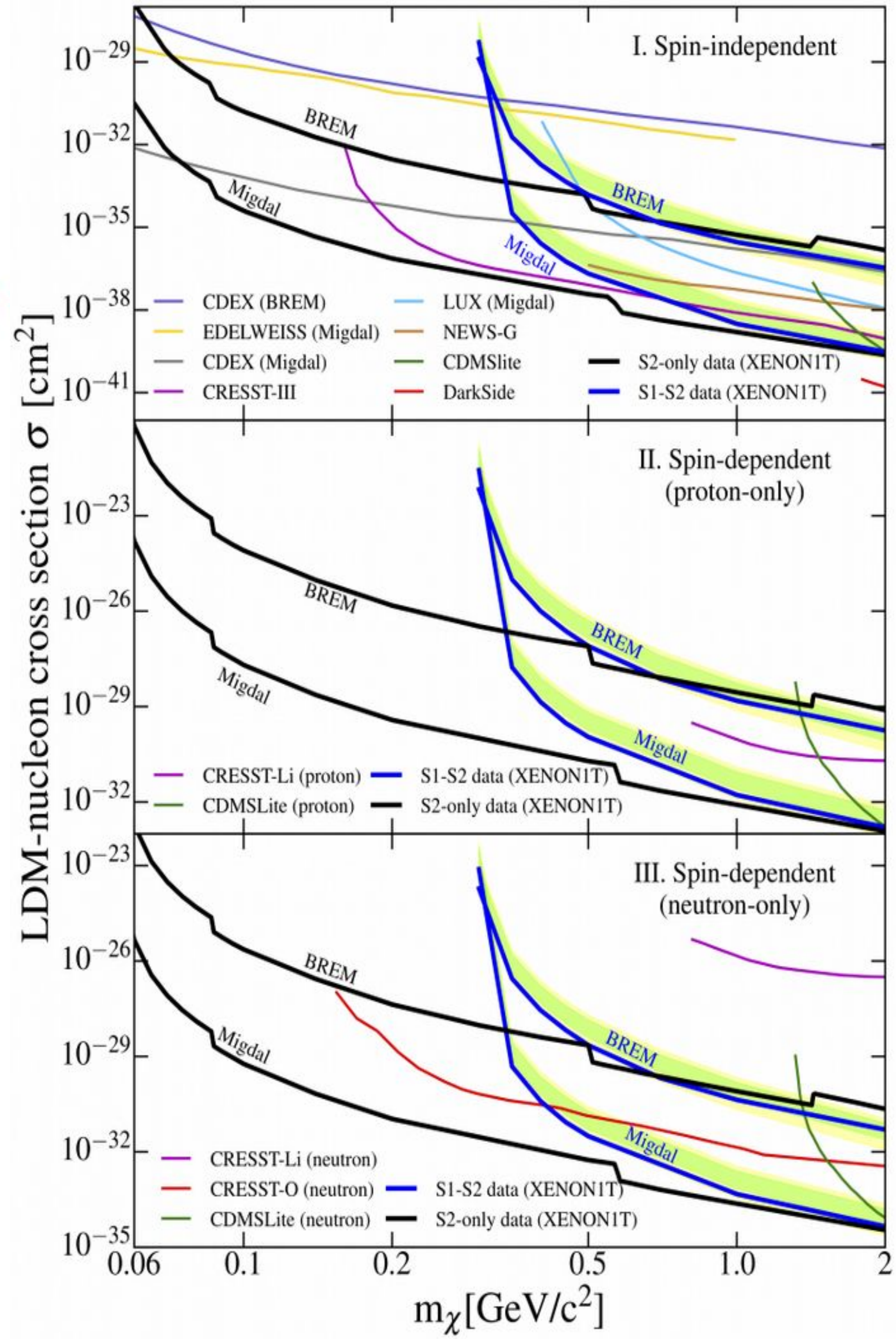
New low-mass and SD results from LXe

XENON1T

- Migdal effect based analysis
- S2-only (ionisation-only) analysis
  - 258 days livetime
  - 30% used to inform cuts

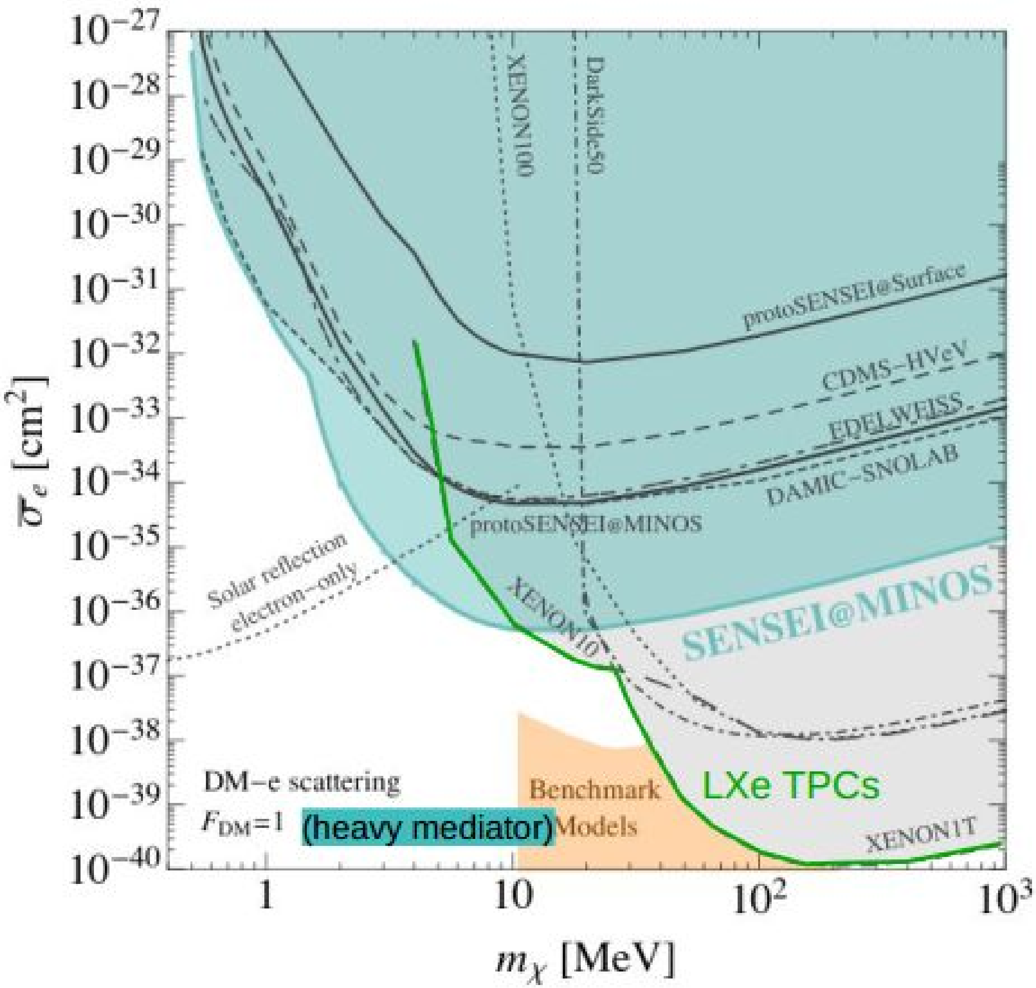


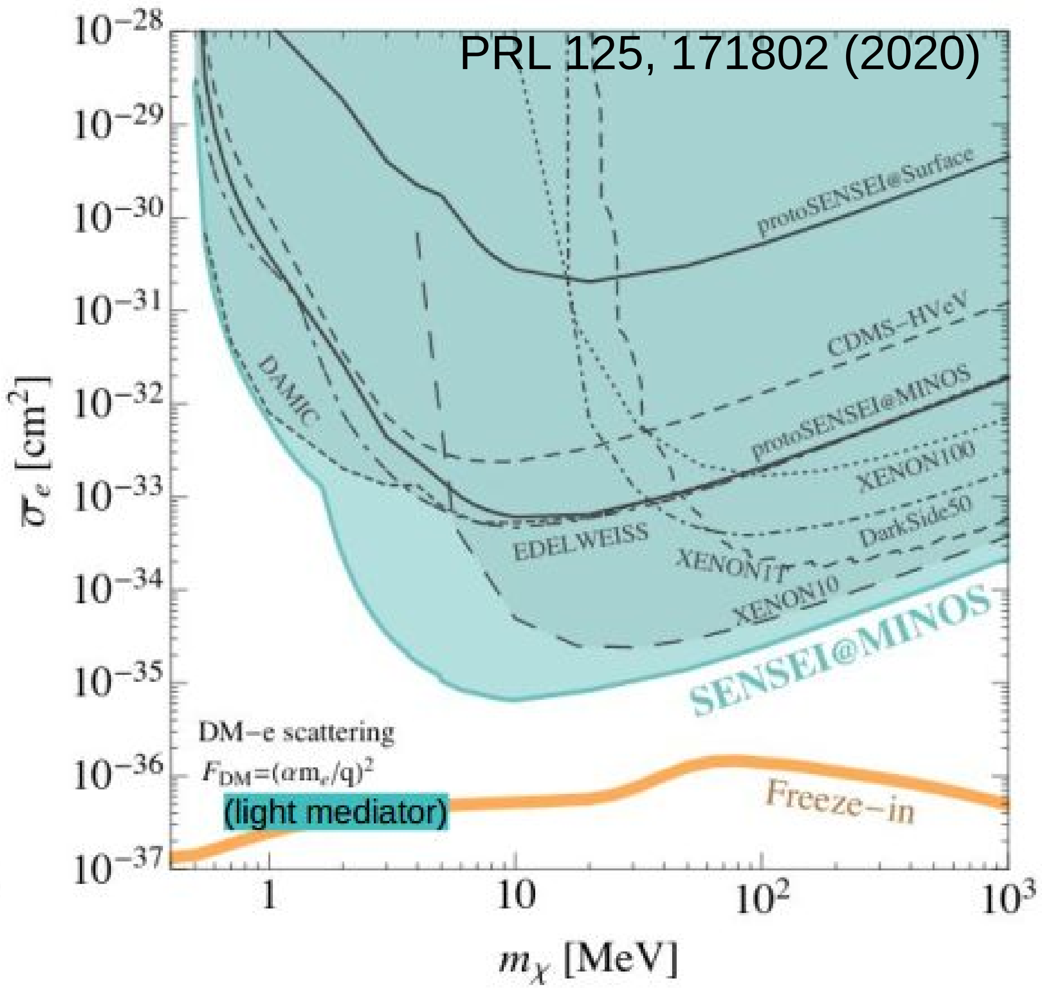




PRL 123, 241803 (2019)

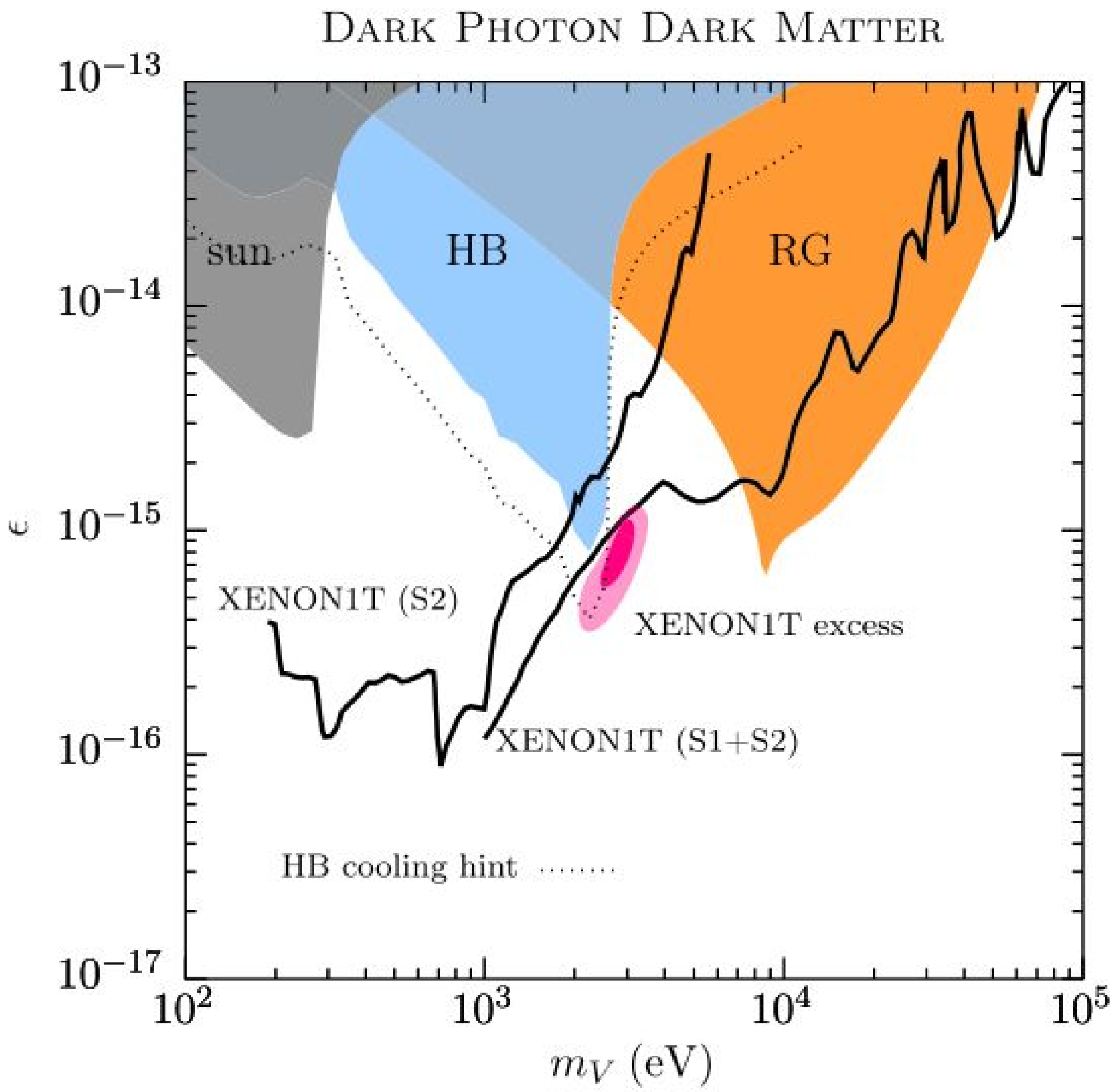
Other channels: WIMP-electron





- Detectors with single-e– sensitivity required
- Noble liquid TPCs or Si-CCDs on the lead
- SENSEI: ~2g Si-CCD with best limit >500 keV/c²

Other channels: dark photon DM



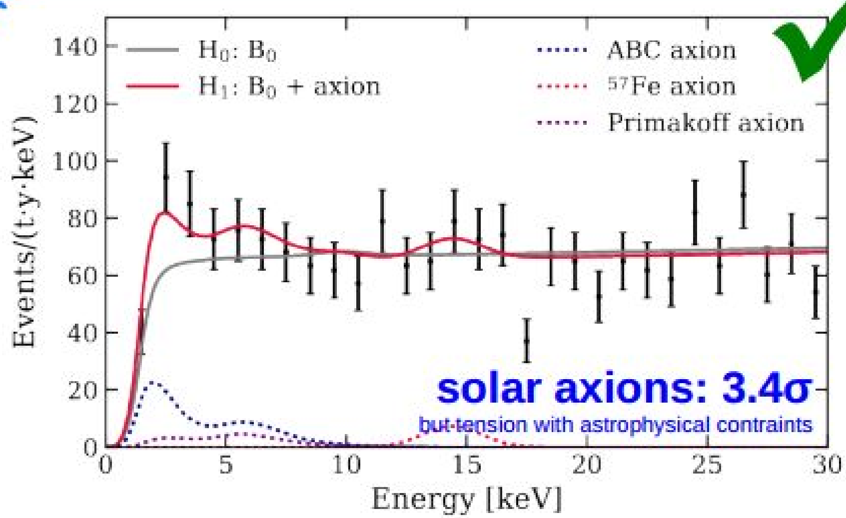
H. An et al., PRD 102, 115022 (2020)

XENON1T excess

Possible Explanations

NEW!

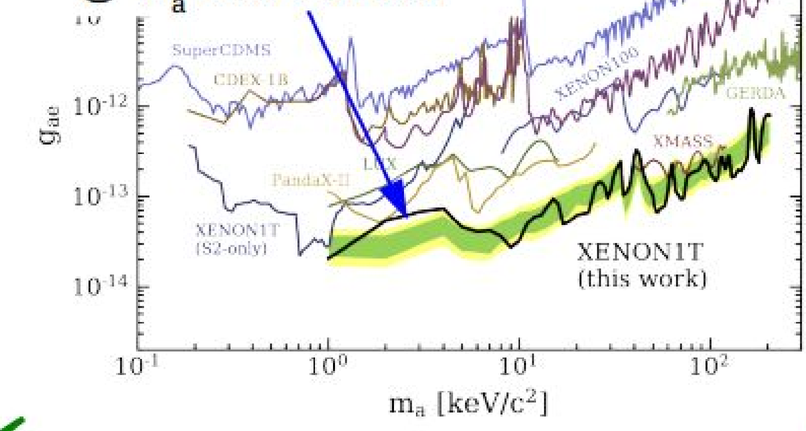
PRD 102, 072004 (2020)

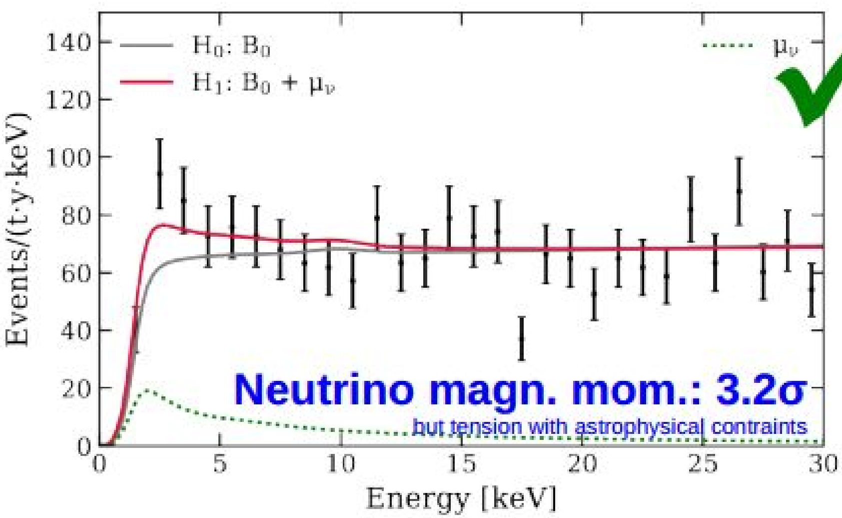


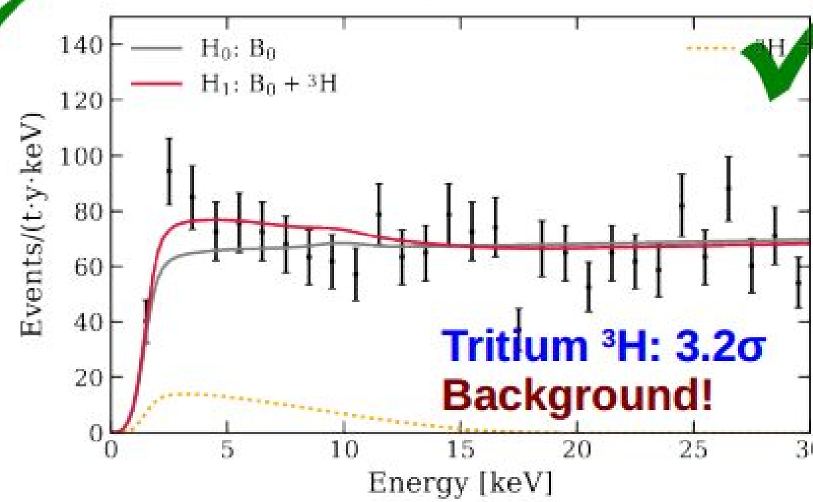
Bosonic ALPs

3.0σ global (4.0σ local)

@ m_a=2.3±0.2 keV







… and many others since XENON made result public.

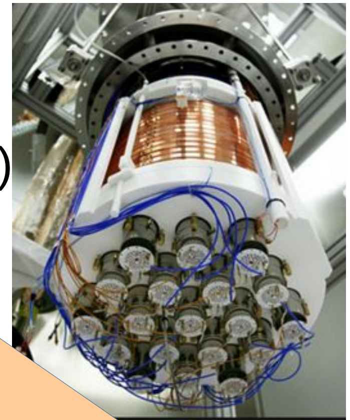
(TAUP2021)

LAr detectors

2010

10 kg

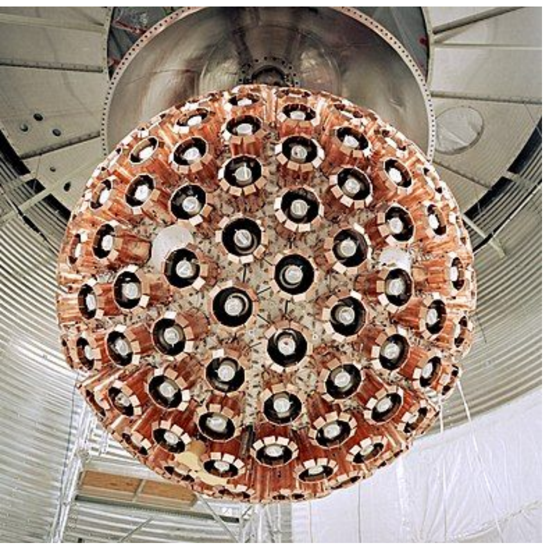
DarkSide-50
(50 kg, LNGS)



- More than 300 scientists from 15 countries and 60 institutions
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

100 kg

ArDM (1t, LSC)

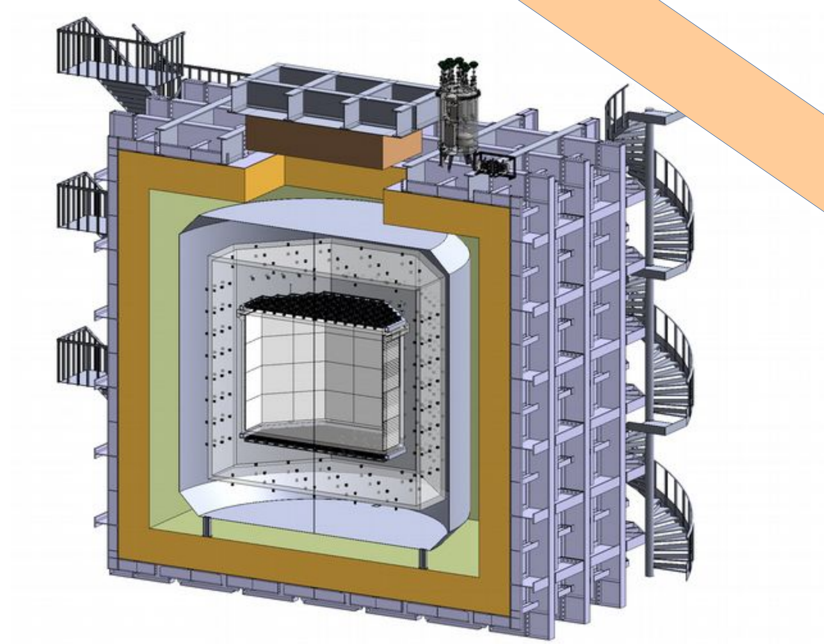


1000 kg

2015

DEAP-3600 (3.3t, SNOLAB)

Global Argon Dark Matter Collaboration formed



2020

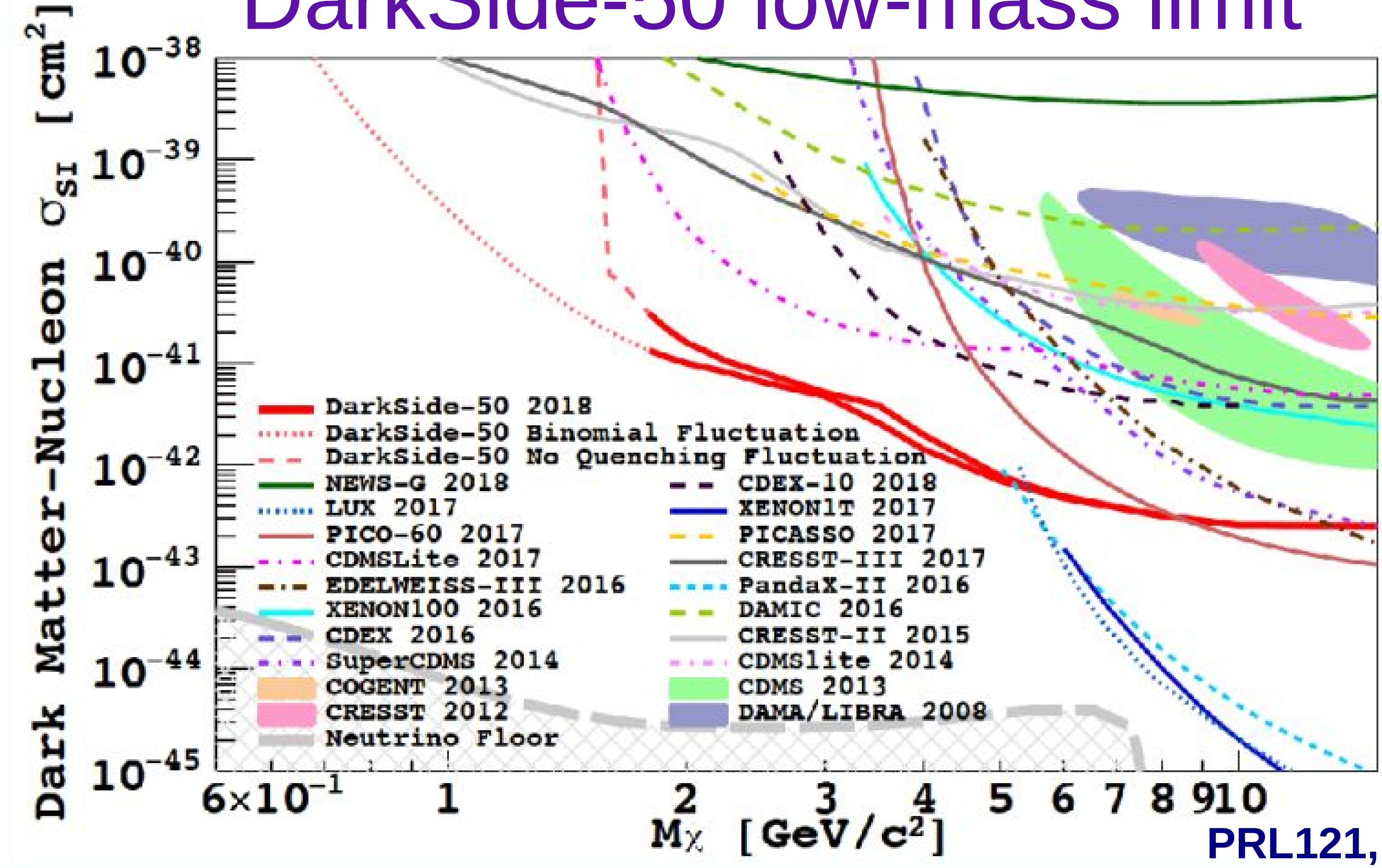
DarkSide-20k
(50t, LNGS)

100000 kg

Argo: 400 t

Slide courtesy J. Monroe

DarkSide-50 low-mass limit



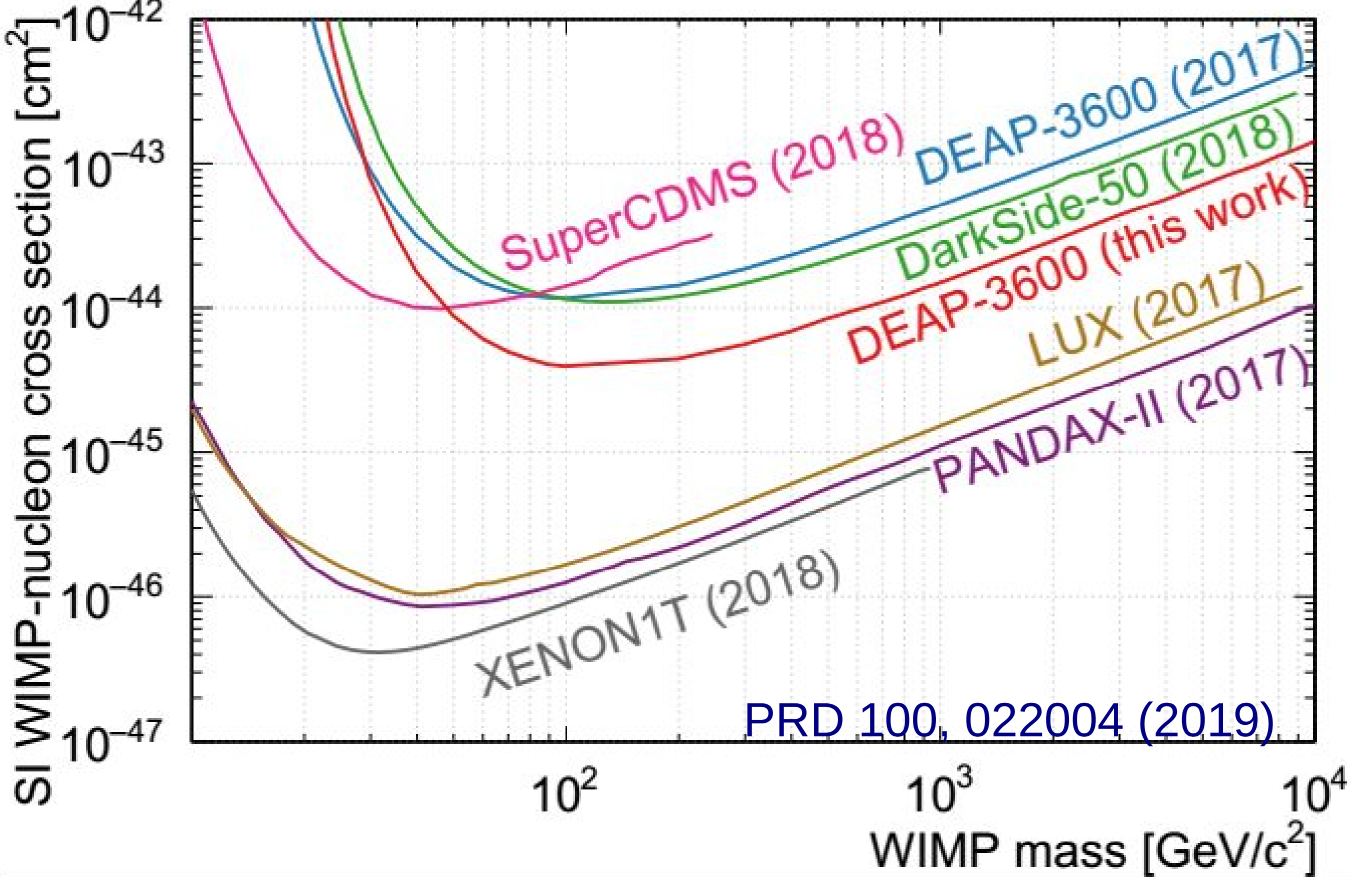
PRL121, 081307 (2018)

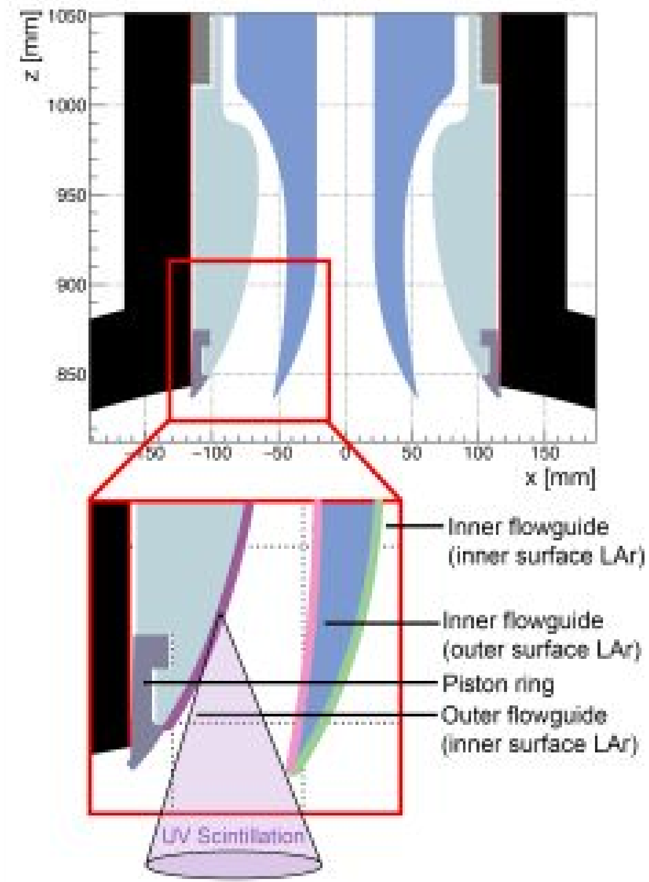
S2-only analysis. Ionization-only signal allows sensitive searches for low mass WIMPs:

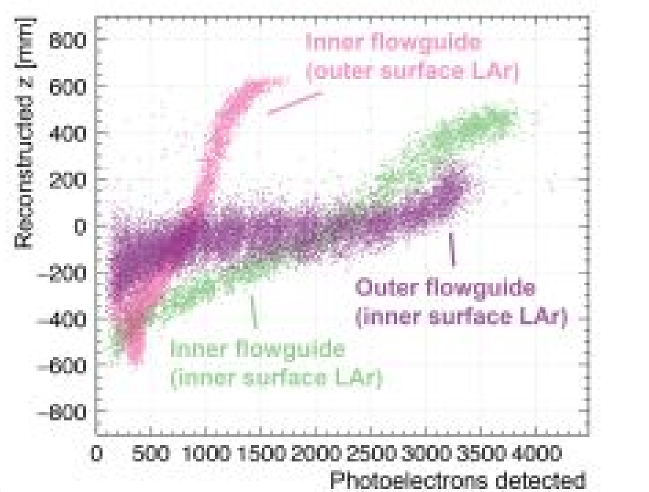
- Two cases: no quenching fluctuations and binomially distributed fluctuations
- Background measured at higher energy is extrapolated to low energy

Future improvements require reduction of quenching fluctuation systematic and further background reduction

DEAP-3600 result and plans



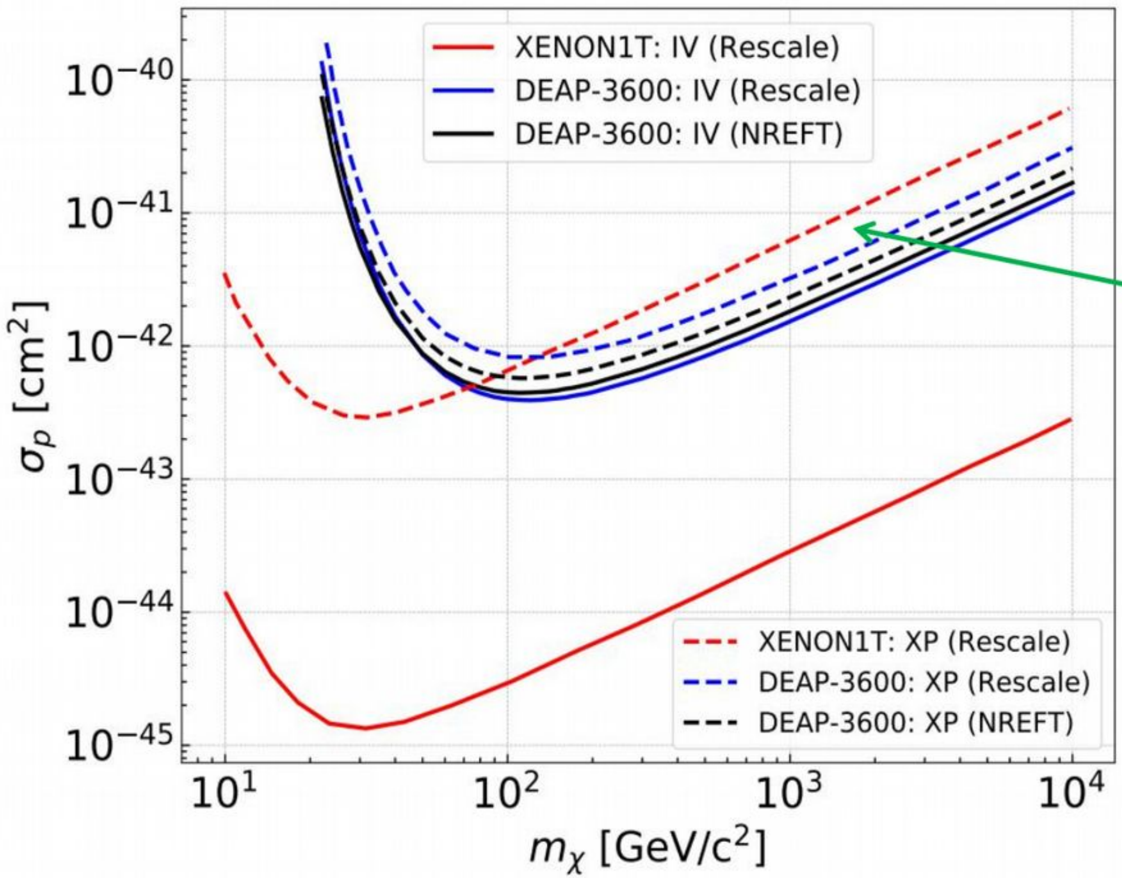




- Leading WIMP exclusion in Ar
- Acceptance reduced due to cuts against events induced by alpha activity in the neck
  - Ongoing development of multivariate analysis expected to recover much of acceptance lost due to neck event cuts
  - Ongoing hardware mitigation of the background problem
- Other physics papers in preparation

Effects of isospin parity breaking

P. Adhikari et al. (DEAP-3600 Collaboration), Phys. Rev. D **102**, 082001 (2020)



Region where DEAP-3600 sets stronger limits than XENON1T by considering the XP scenario.

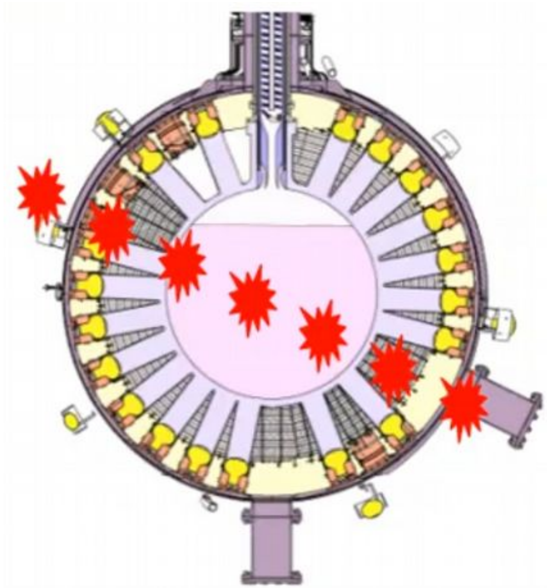
Using NREFT + XP (black dash line), the region increases. While the Helm form factor doesn't change assuming $c_n \neq c_p$, in the NREFT formalism the form factor does.

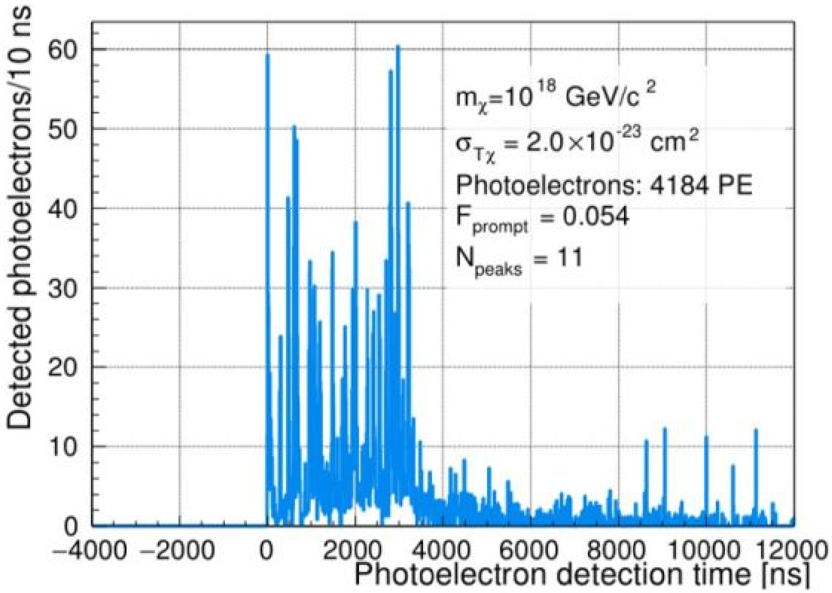
Planck-scale mass multi-scattering dark matter

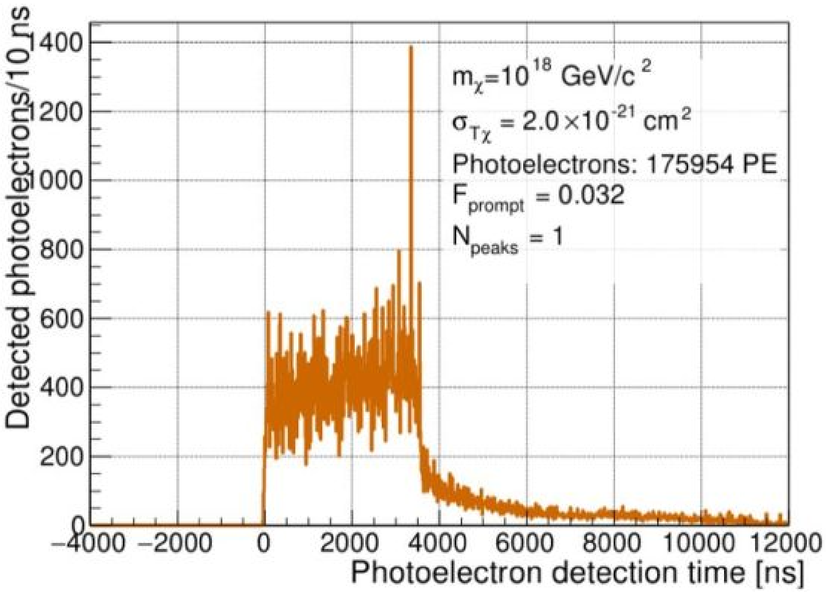
- a.k.a multiply-interacting massive particles (MIMPs)

- DM candidates above $\sigma_{\chi\text{-}n} \cong 10^{-25}$ cm^2 and $m_\chi \gtrsim 10^{12}$ GeV lose a negligible amount of energy in the scatterings with the Earth nuclei and can reach underground detectors designed for WIMP search.

- Event signature:
  - Contains multiple nuclear recoil scatters
  - Apparent low Fprompt (electronic recoil-like event)

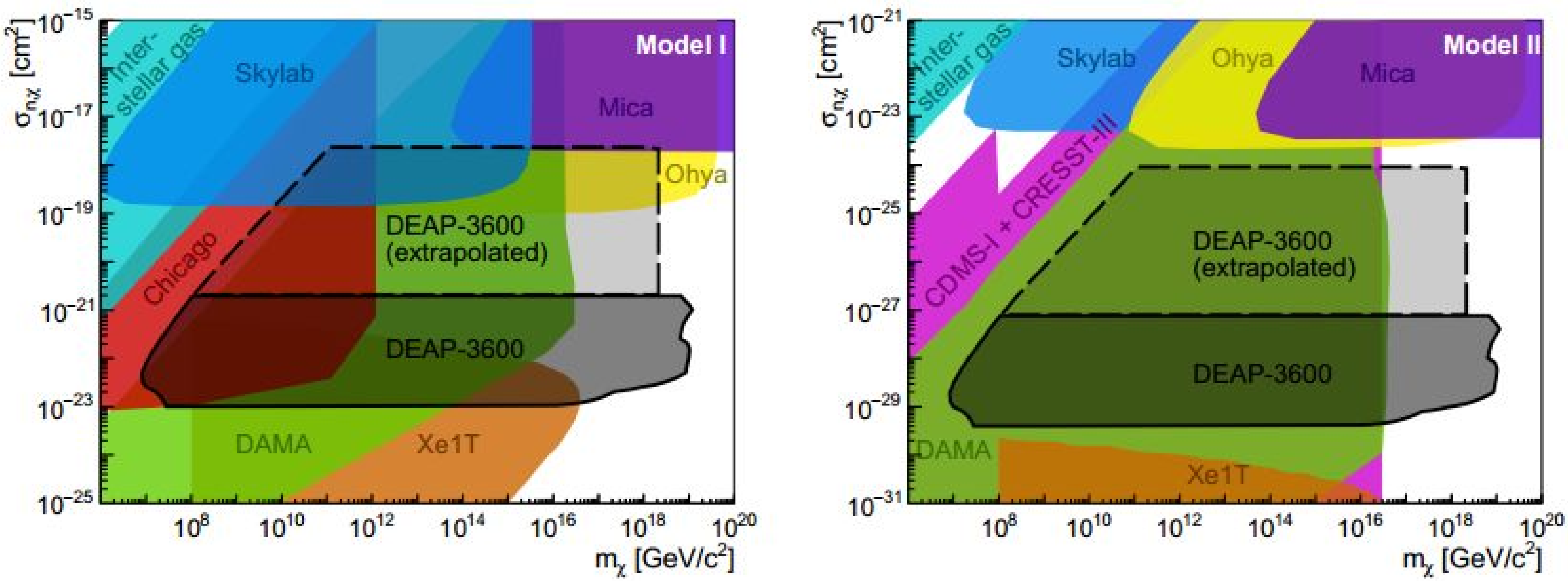






Planck-scale mass DM exclusion

- P. Adhikari et al. (DEAP Collaboration), Phys. Rev. Lett. 128, 011801 (2022)
- 813 live-days, blind analysis
- New exclusion for candidates at Planck-scale masses



$$\sigma_{T\chi} = \sigma_{n\chi}|F_T(q)|^2$$

(relevant for composite DM models)

$$\sigma_{T\chi} \simeq \sigma_{n\chi}A^4|F_T(q)|^2$$

LXe detectors

2010

XENON10 (LNGS)

ZEPLIN II (Boulby)

ZEPLIN III (Boulby)

10 kg

100 kg

XENON100 (LNGS)

LUX (250 kg, SURF)

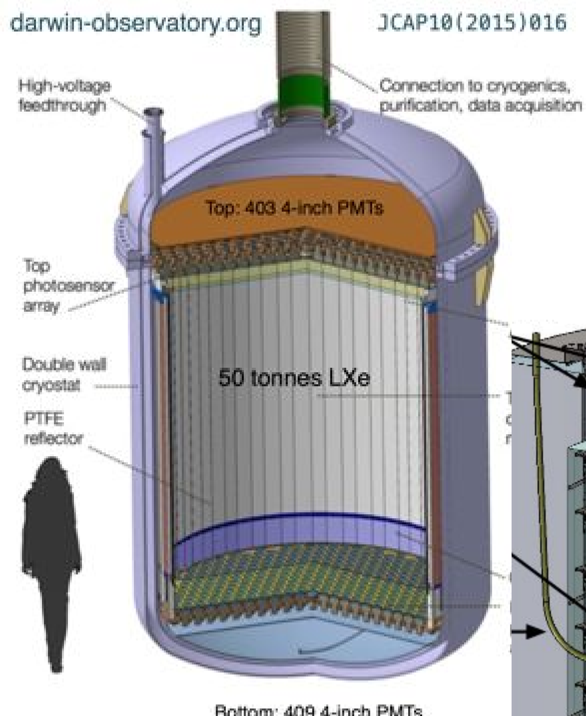
PandaX (500 kg, CJPL)

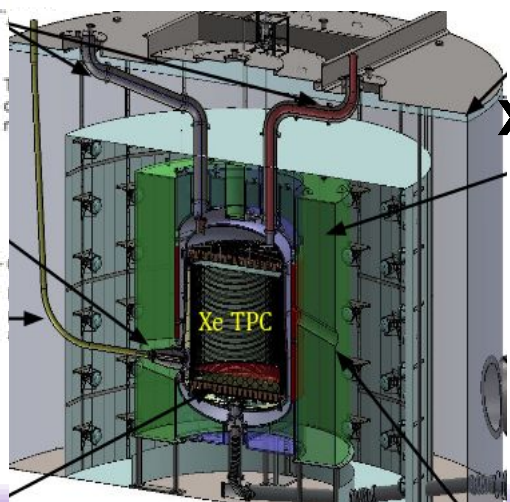
2015

XMASS (0.8t, Kamioka)

1000 kg

XENON1T (1t, LNGS)





2020

PandaX-4 (4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

10000 kg

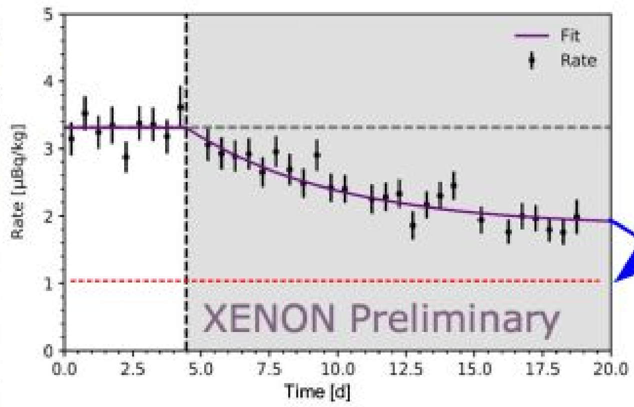
DARWIN: 50 t

Slide courtesy J. Monroe

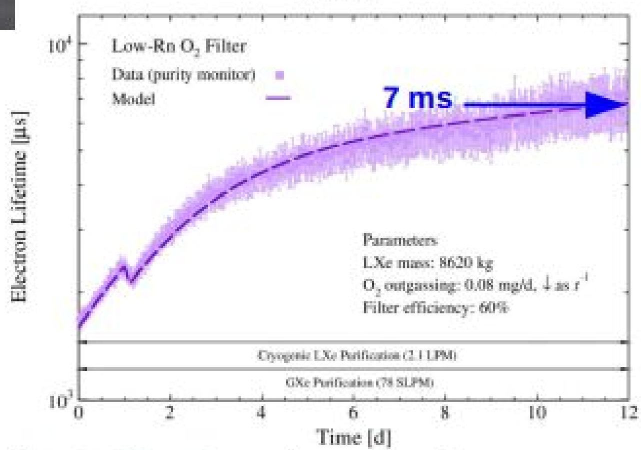
Upcoming: XENONnT and LZ

A. Kopec, J. Pienaar @ TAUP 2021

XENONnT @ LNGS
- 5.9 t LXe target
- Rn activity (goal): 1 µBq/kg
- in data taking phase



LXe cleaning yields factor ~2



B. Penning @ EPS-HEP 2021

LZ @ SURF
- 7.0 t LXe target
- Rn activity (goal): 2 µBq/kg
- in commissioning phase
- expect first data later this year


Assembled TPC (July 2019)


OD installed, Summer 2021

M. Schumann (Freiburg): Direct Detection – Experiments 29

Ar-Xe complementarity

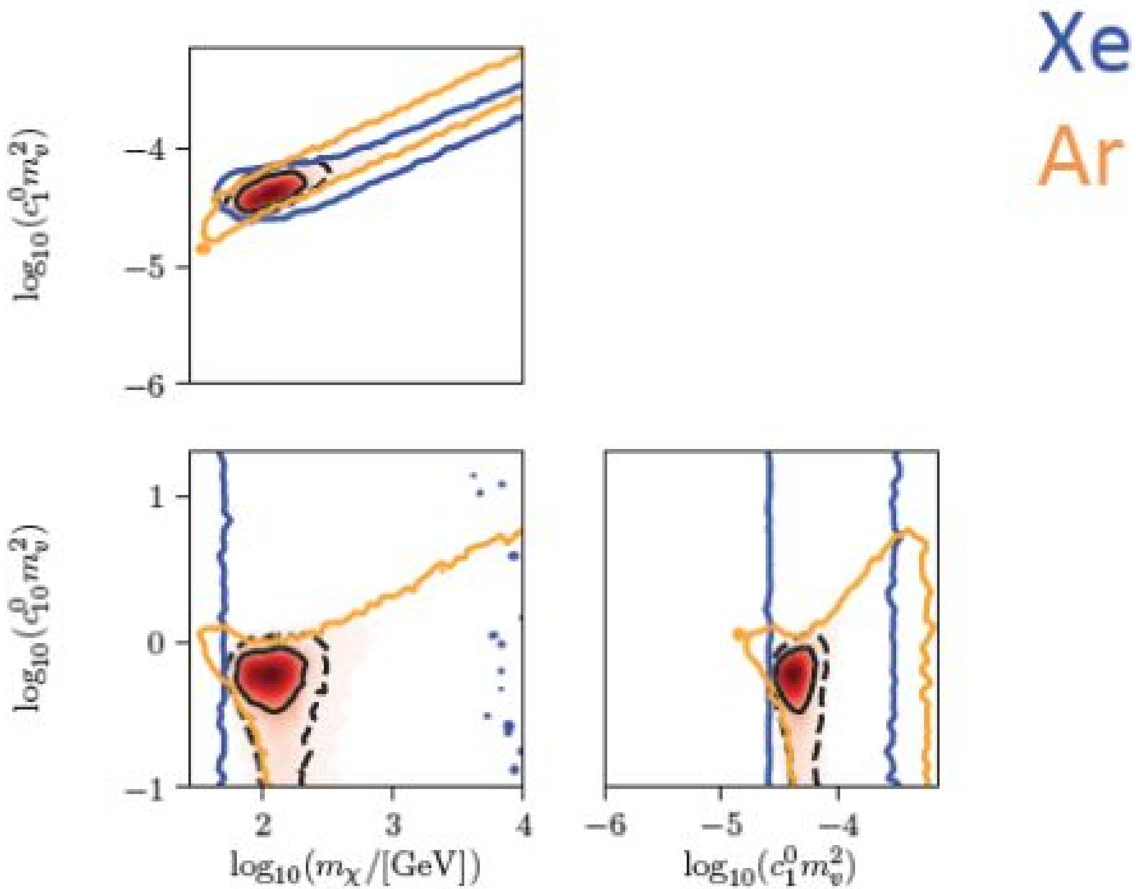
Example: Scalar DM – Scalar Mediator
m = 100 GeV

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

A single target cannot determine the DM mass and couplings

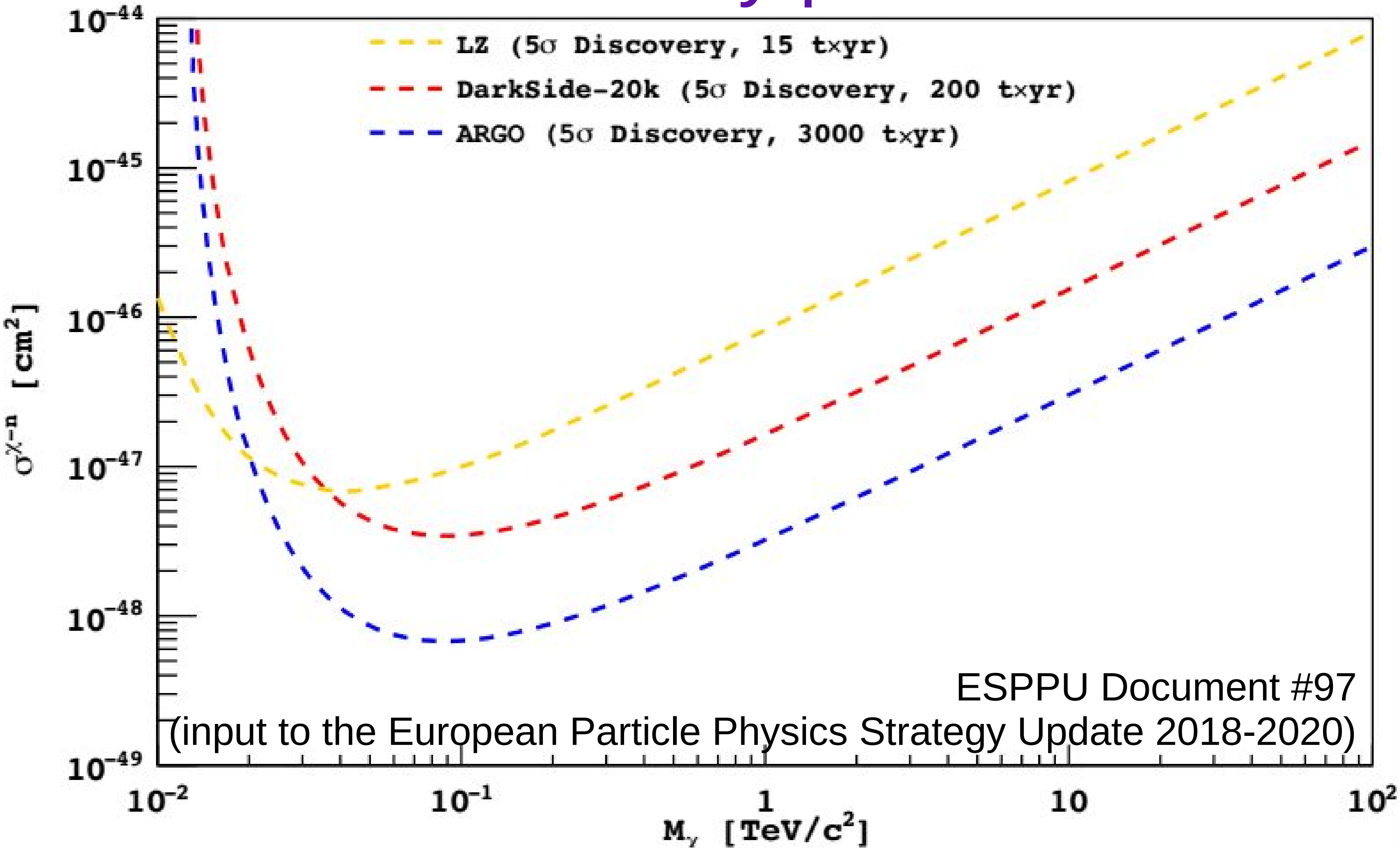
The experimental response is very sensitive to the target

Combining data some degeneracies can be removed



D. Cerdeno, IPPP April 2018

Discovery potential



- Superior ER rejection in LAr (with PSD) allows to suppress background from elastic scattering of solar neutrinos on electrons
- Zero background paradigm results translates to better 5-sigma discovery sensitivity
- **Need for both programs recognized by APPEC, P5, and under consideration for the European Long Range strategy**

Other notable ideas

- 1 TeV WIMPs
  - Paleodetectors
- Low-mass WIMPs
  - Exploiting the Migdal effect in limit setting
  - Scintillating LAr bubble chamber
- Light DM
  - Diverse program of beam dump experiments
  - Much activity, with proposed detectors based on: DNA, graphene, qubits, quasiparticles, ...
  - Exploiting effects of light DM up-scattering by astrophysical sources

Summary

- No discovery, however...
- Many interesting new results and ideas over the last few years
  - Low-mass region (1-10 GeV/c2) increasingly competitive (LXe S2 only, LAr S2 only, LAr SBC, SuperCDMS)
  - Much activity and novel R&D on the light DM front
  - Huge progress in interpretation of results with EFT
- General paradigm change: leave no stone unturned
- Larger detectors still the best strategy for high-mass WIMP searches towards to neutrino floor
  - LAr:
    - Global consolidation of efforts towards DarkSide-20k and the ultimate detector, Argo
    - Fruitful synergy with ProtoDUNE/DUNE
    - Novel materials to facilitate scale-up
    - Rapid growth of the SiPM technology
  - LXe:
    - XMASS contribution of Gd-veto to the XENONnT program
    - Successful progression of 2 phase LXe TPCs
    - Ongoing R&D for DARWIN

See upcoming talk on DarkSide-20k!

Backup

Main challenges moving beyond LZ/XENONnT/DS-20k

LXe

- Securing enough Xenon
- Rn mitigation
- ER rejection
- HV scalability/stability
- Other backgrounds

LAr

- Very large, highly efficient, photosensitive surface area
- UAr extraction/storage
- Scalable and robust wavelength shifter/light collection approach
- Backgrounds

Paleodetectors

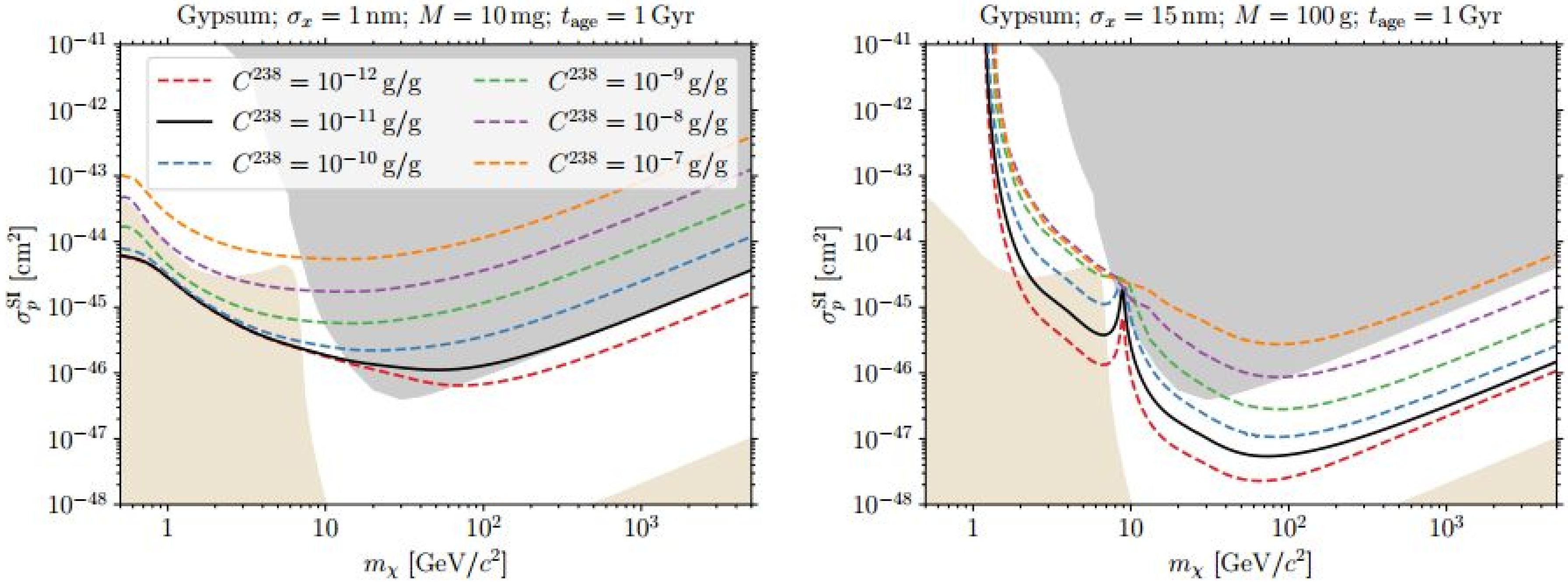
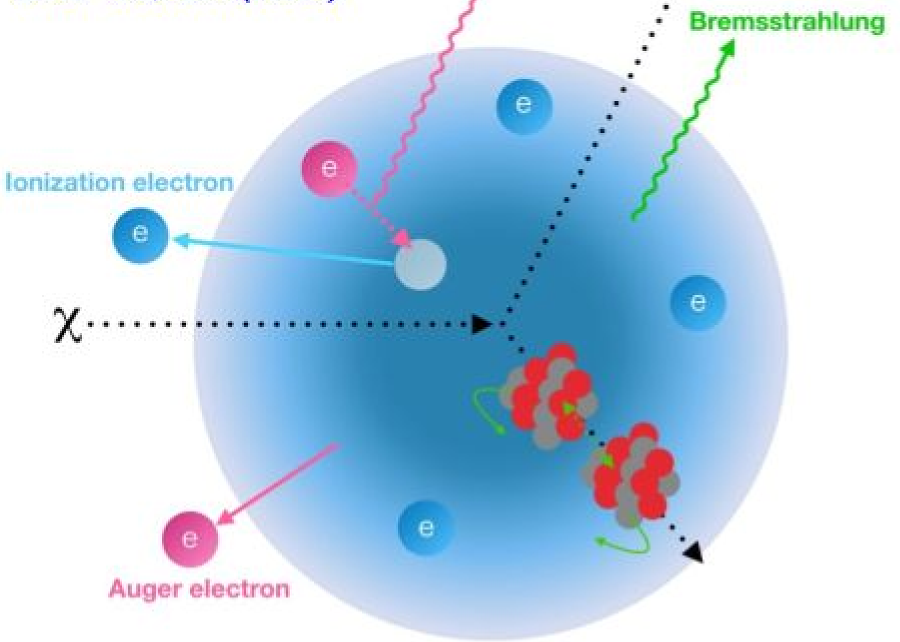


Figure 5. Projected 90 % confidence level exclusion limits in a gypsum [$Ca(SO_4)\cdot 2(H_2O)$] paleo-detector in the high-resolution (left) and high-exposure (right) readout scenarios for different assumptions on the ^{238}U concentration C^{238} controlling the radiogenic backgrounds. The solid black line shows the sensitivity with our fiducial value for marine evaporites, $C^{238} = 10^{-11}$ g/g, while the differently colored dashed lines show the projected upper limit for both larger and smaller C^{238}. The gray and sand-colored shaded areas indicate current upper limits and the conventional neutrino floor in a Xe-based direct detection experiment, respectively, see Figure 3. Colors and linestyles are the same in both panels.

S. Baum et al., Instruments 2021, 5(2), 21

Migdal Effect

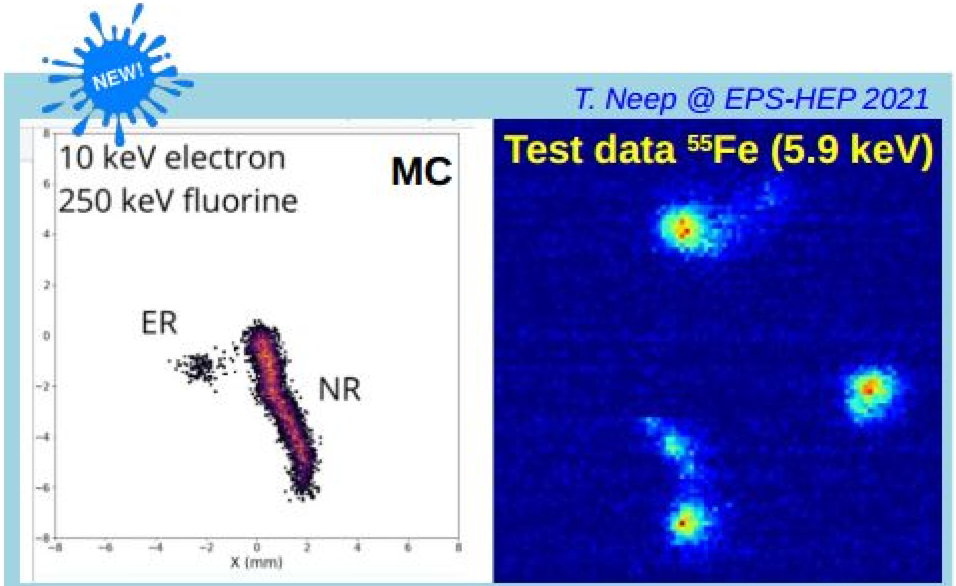
PRL 121, 101801 (2018)
JHEP 03, 194 (2018)



– exploit expected effects after nuclear recoil
→ very low threshold

– caveat: effect not yet observed in calibration

T. Neep @ EPS-HEP 2021



Experiments to detect Migdal effect from n-scattering are being prepared, e.g., **MIGDAL collaboration** (UK)
– optical TPC filled with gas
– initially CF_4, later mixed with Xe and Ar
– track details for signal/background discr.

(TAUP2021)