Status and perspectives of Direct Dark Matter searches

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cnrs

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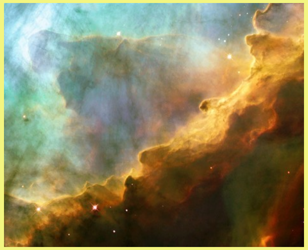
The known and the unknown



Free Hydrogen and Helium : 4 %

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Stars : 0.5 %

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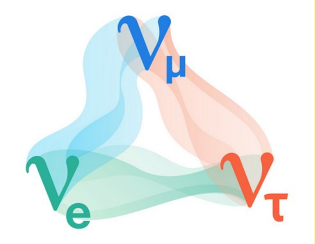

Active neutrinos : 0.3 %

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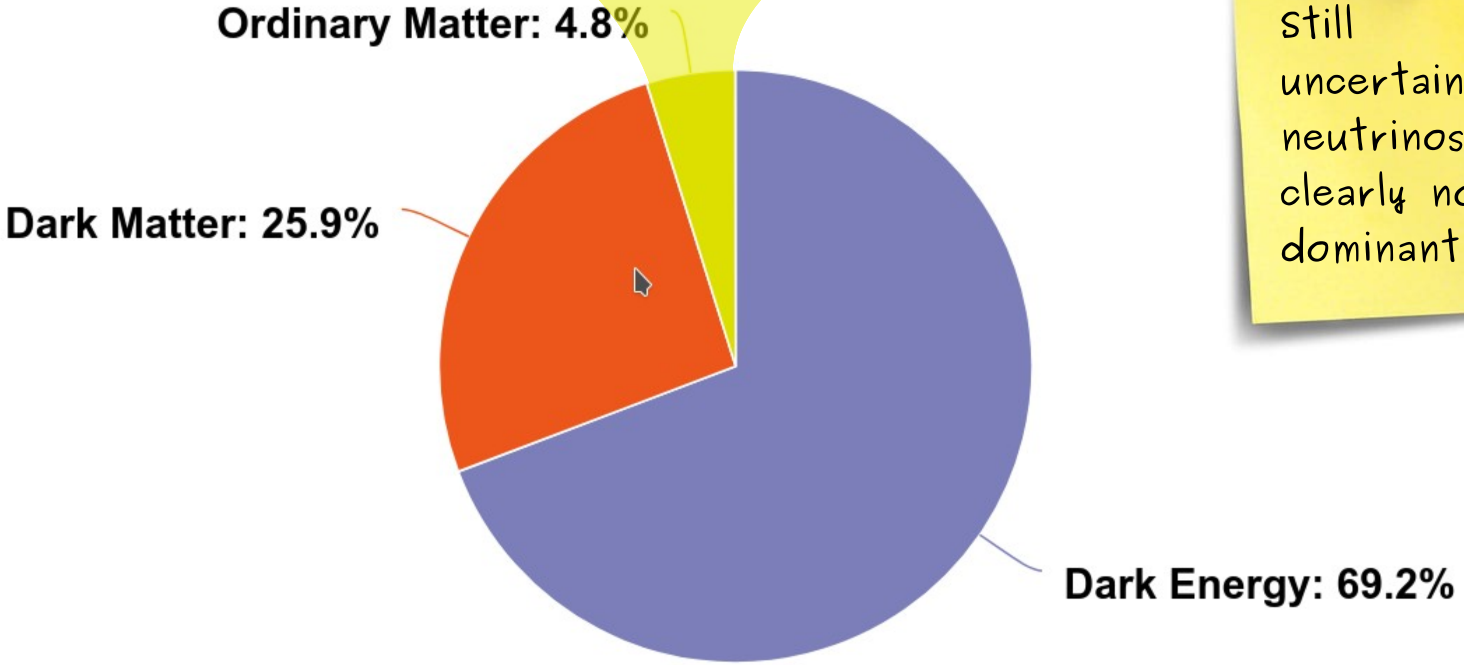
Heavy elements : 0.03 %



Still uncertainty on neutrinos, but clearly not the dominant one

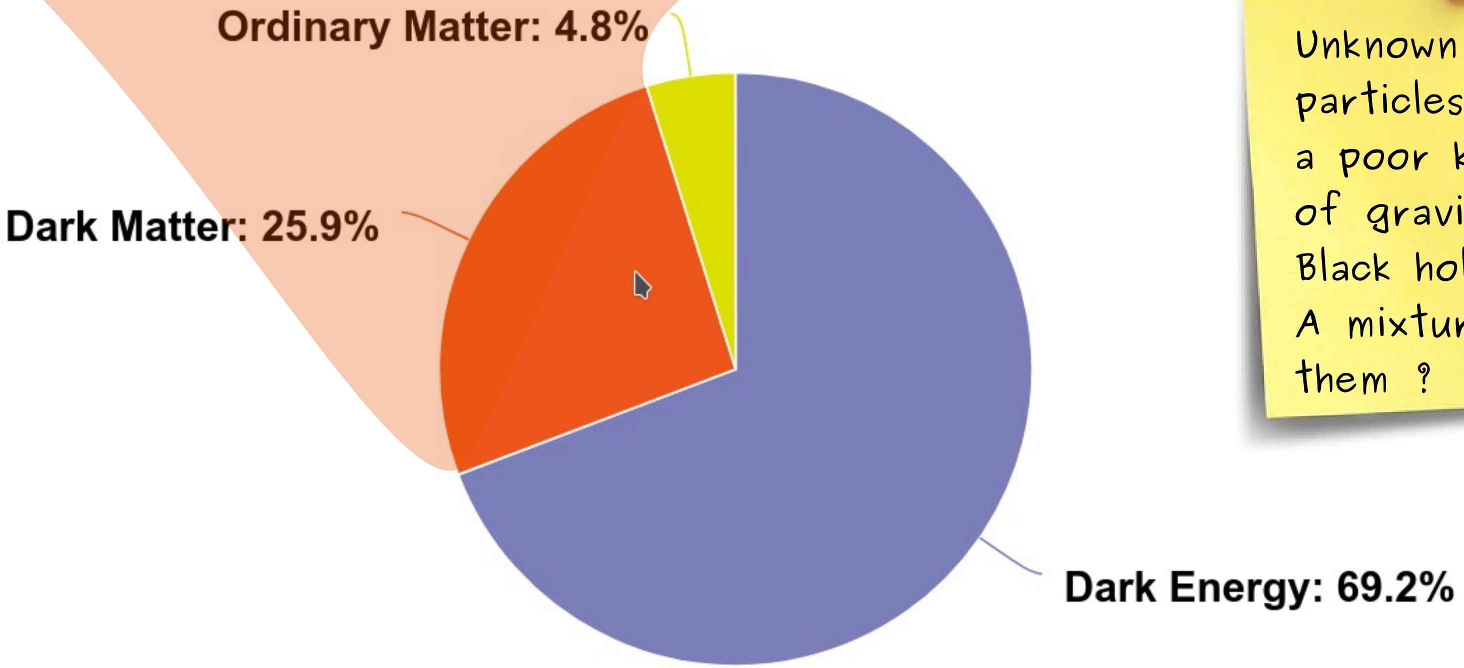
The known and the unknown

Particle candidates :

- Weakly Interacting Massive Particles (WIMPs) (WIMP miracle, SUSY, …)
- Axions (QCD axions and Axion-Like Particles)
- Sterile neutrinos (~keV → "warm" DM)
- A dark sector ?

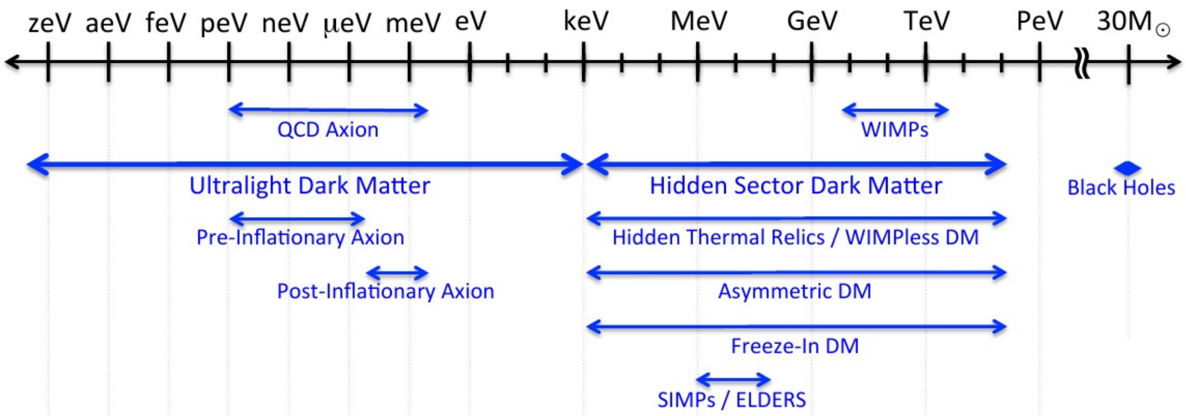
Alternatives :

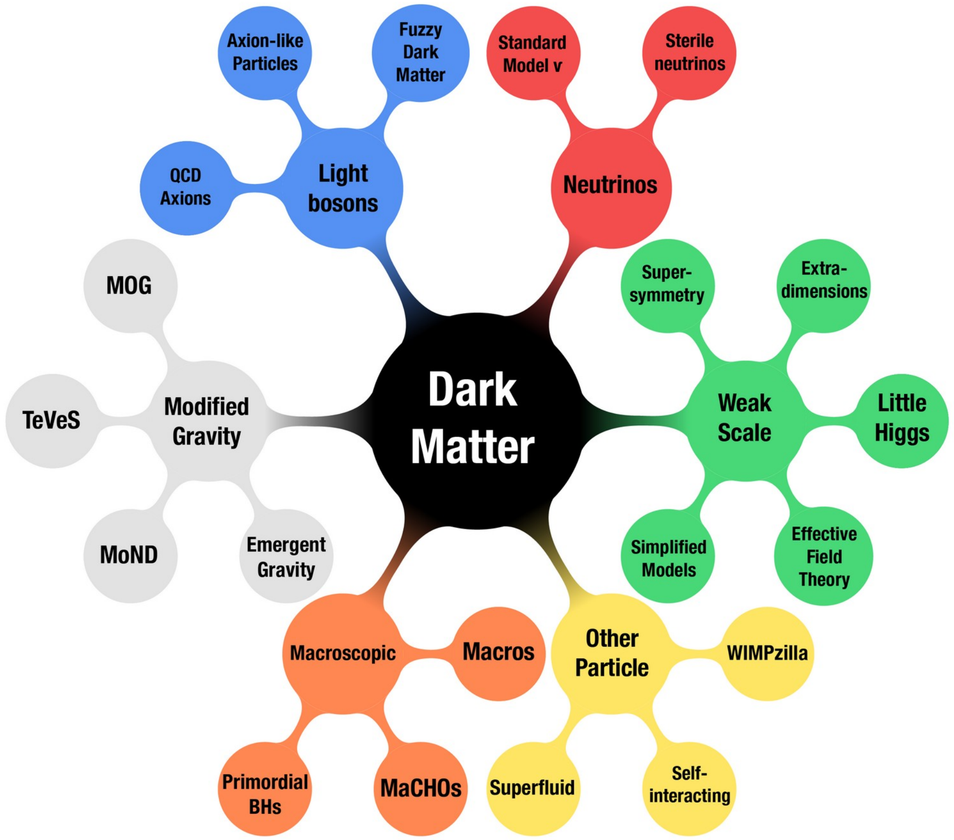
- Primordial black holes
- MACHOs
- Modifications of gravity



Unknown particles ? Or just a poor knowledge of gravity laws ?
Black holes ?
A mixture of them ?

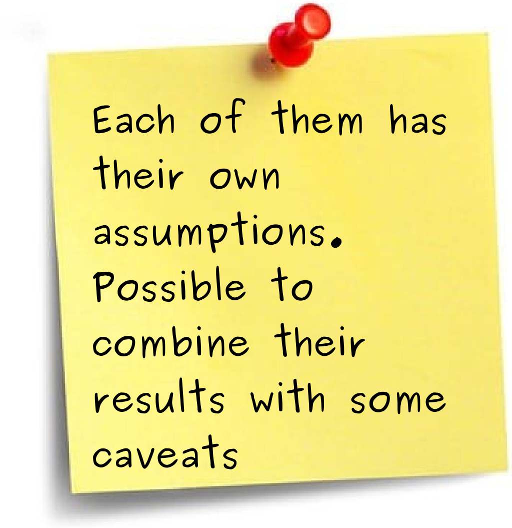
Fantastic Beasts and Where to Find Them



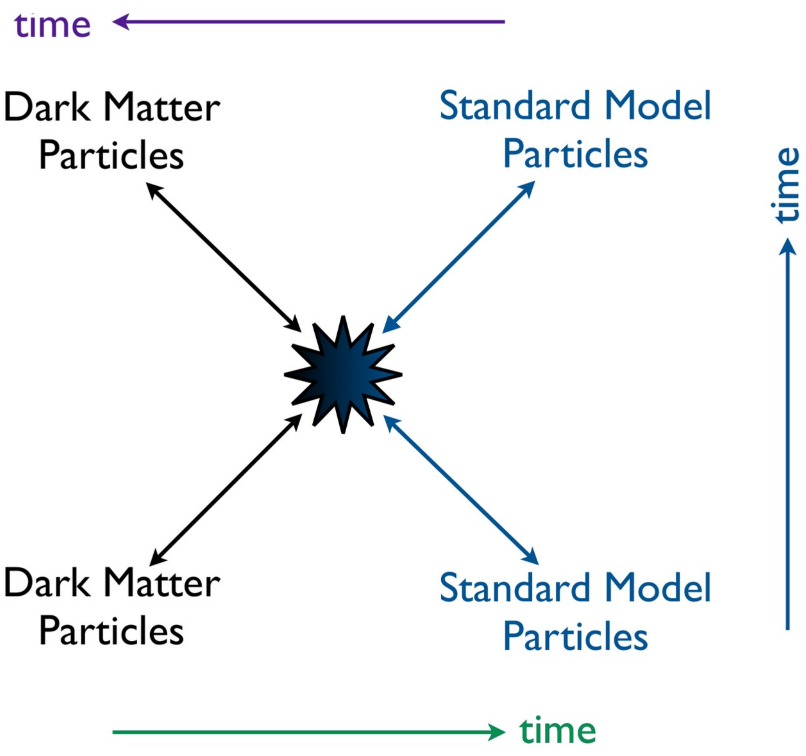


Hunting WIMPs

Make ! → "Detection" with colliders : measuring missing P_T
(CMS, ATLAS @ LHC)



Each of them has their own assumptions. Possible to combine their results with some caveats



Shake ! → Direct detection of galactic DM :

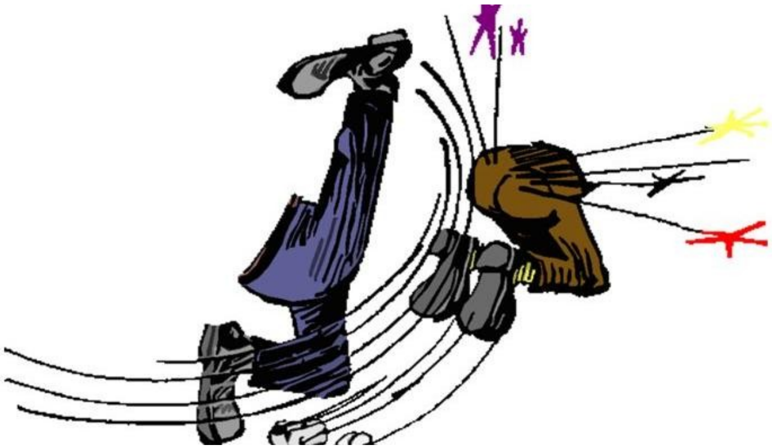
on earth scattering off a detector nuclei

(Xe, Ar, Ge, NaI, Si, ...)

Break ! → Indirect detection of cosmic DM : annihilation
(AMS, PAMELA, CTA, IceCube, ...)

Direct detection in one phrase (and one picture)

WIMP elastically scatters off nuclei

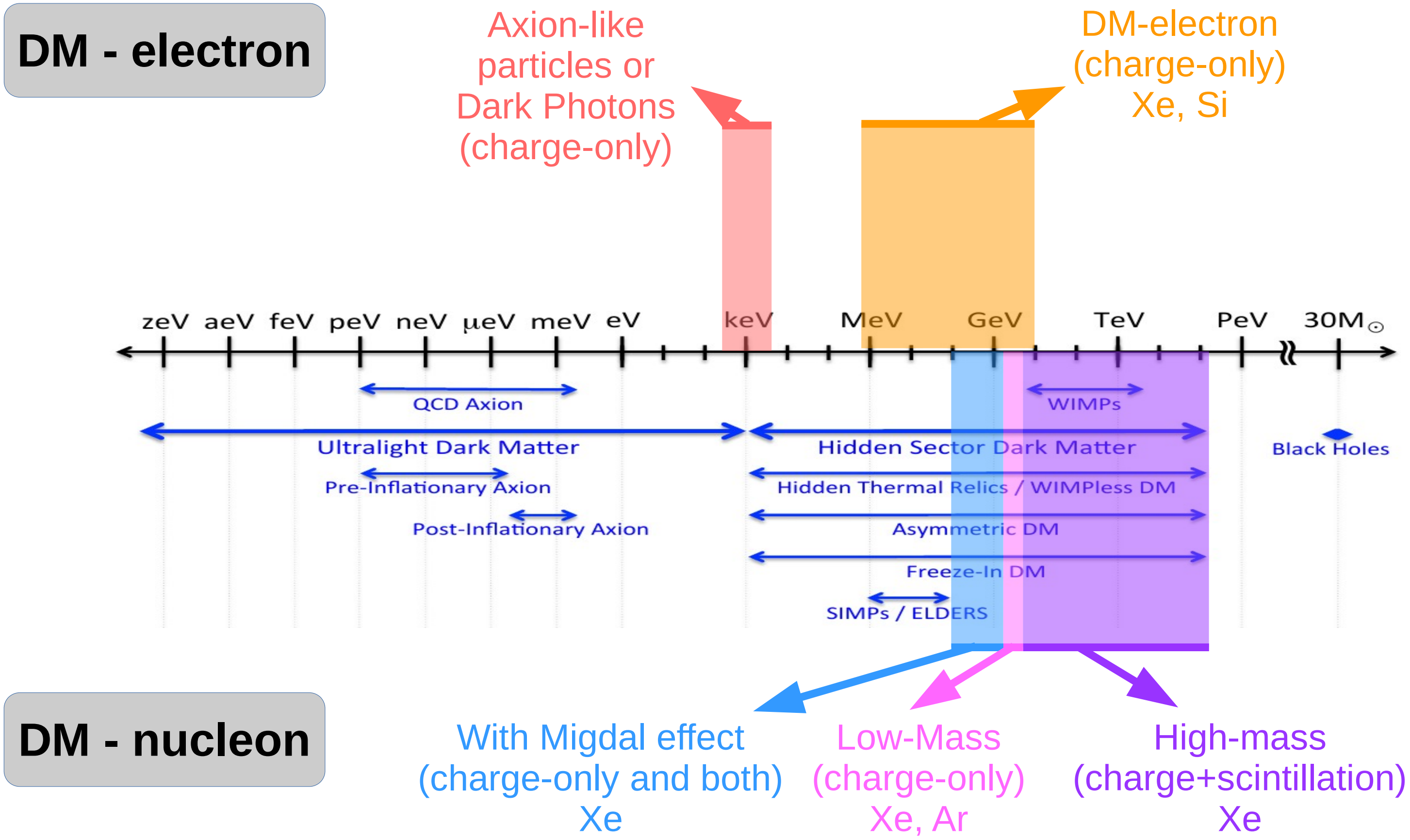


Direct detection in one phrase, but…

WIMP elastically scatters off nuclei

? ? ?

The scoped energy domains



DM - electron

Axion-like particles or Dark Photons (charge-only)

DM-electron (charge-only) Xe, Si

DM - nucleon

With Migdal effect (charge-only and both) Xe

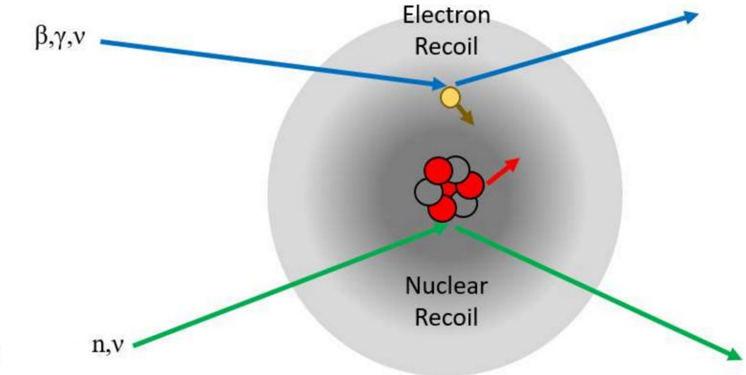
Low-Mass (charge-only) Xe, Ar

High-mass (charge+scintillation) Xe

Direct detection in one slide

WIMP elastically scatters off nuclei → nuclear recoils

χ + N → χ + N



$$E = \frac{\mu^2 v^2}{m_N}(1 - cos\theta) \lesssim 100 keV$$

$$\frac{dR}{dE} = \frac{\rho_\chi}{m_\chi}\frac{\sigma |F(E)|^2}{2\mu_p^2}\int_{v_{min(E)}}^{v_{esc}} d^3v \frac{f_\oplus(\vec{v},t)}{v}$$

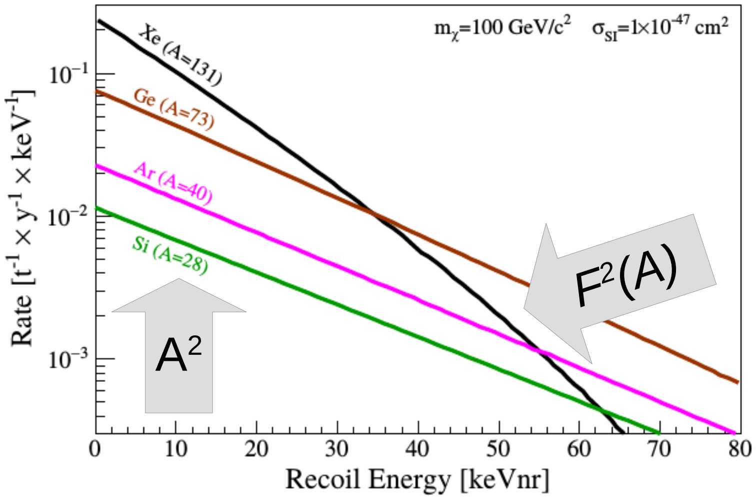
$$v \sim 230\ km/s$$

$$m_\chi = 10 - 10^4\ GeV/c^2$$

$$\rho_\chi \sim 0.3\ GeV/c^2/cm^3$$

Spin Independent : χ scatters coherently off of the **entire nucleus** A: σ ~ A^2

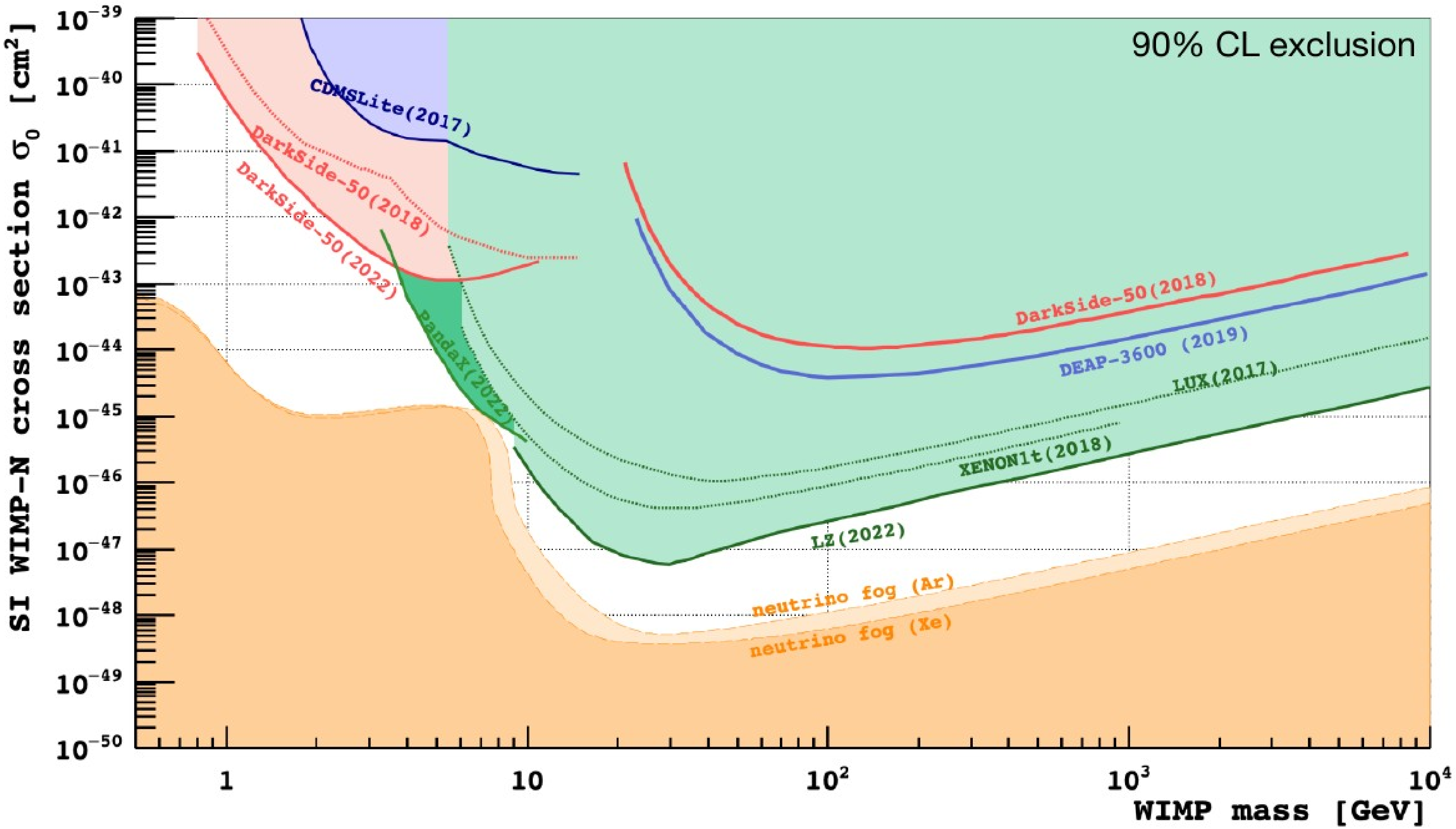
Spin Dependent : mainly **unpaired nucleons** contribute to scattering amplitude: σ ~ J(J+1)



Experimental challenge :

- low energy thresholds : O(1) keV
- very low backgrounds

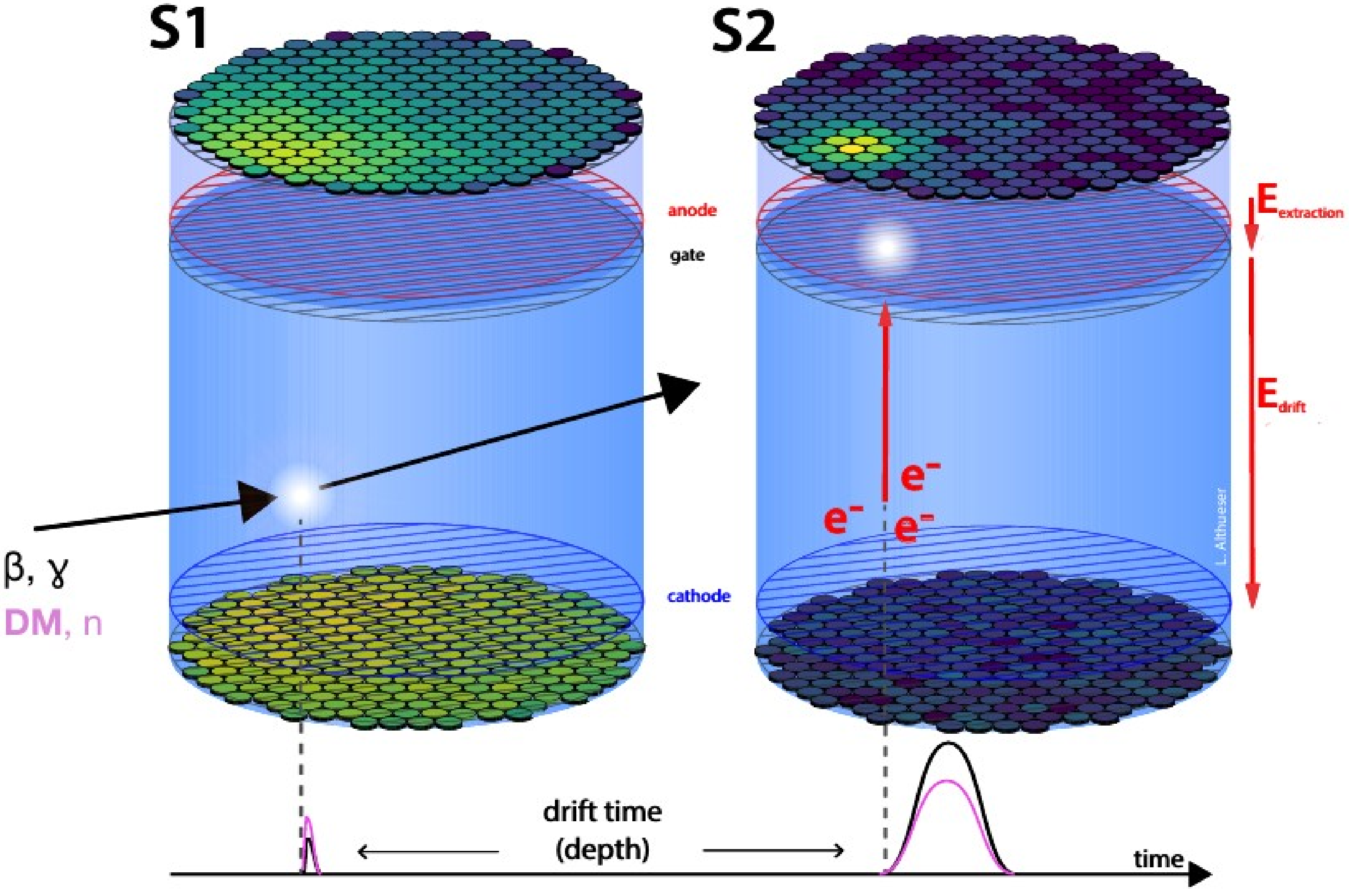
Current status of Dark Matter hunt



Liquid Xenon leads from ~3 GeV (WIMPs dominated)

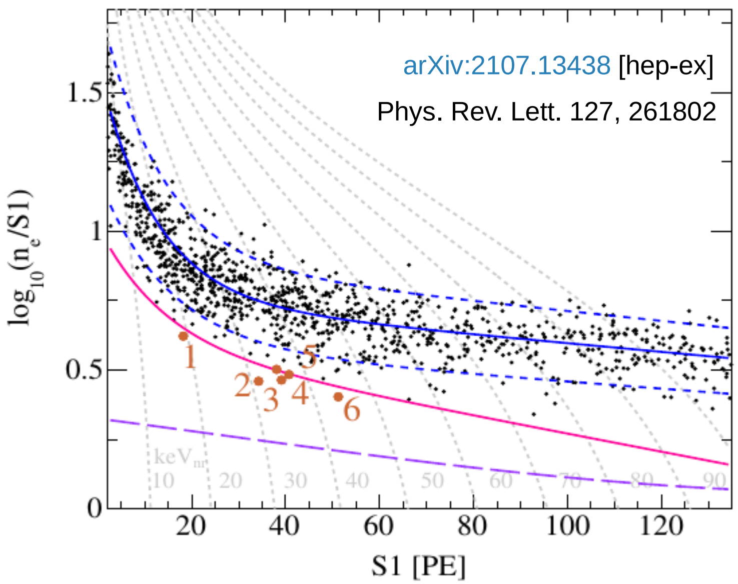
LAr leads
(and needed)
for low masses

Double phase noble targets TPCs



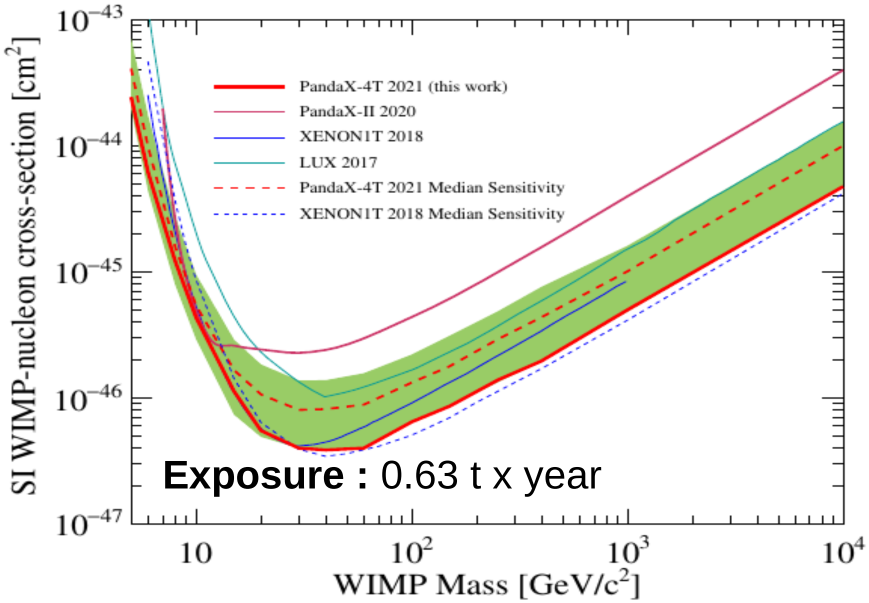
ER / NR recoil discrimination: $\left.\frac{S2}{S1}\right._{NR} < \left.\frac{S2}{S1}\right._{ER}$

High masses: PandaX-4T (2021), then LZ (2022)

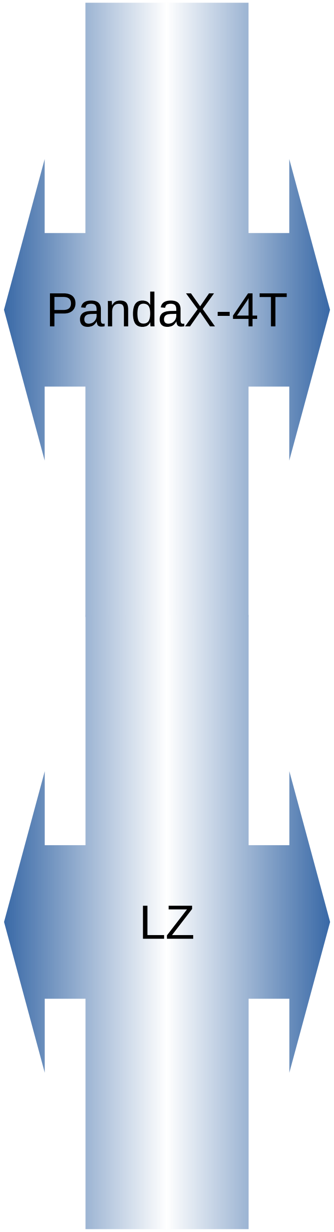


arXiv:2107.13438 [hep-ex]

Phys. Rev. Lett. 127, 261802

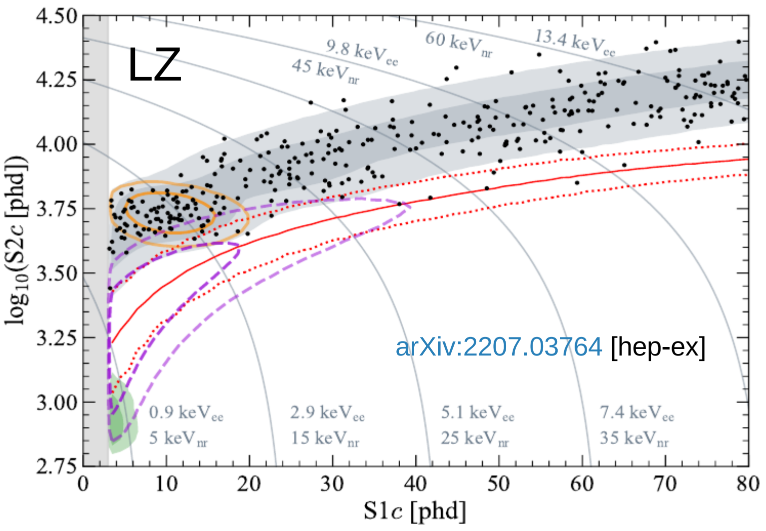


Exposure : 0.63 t x year

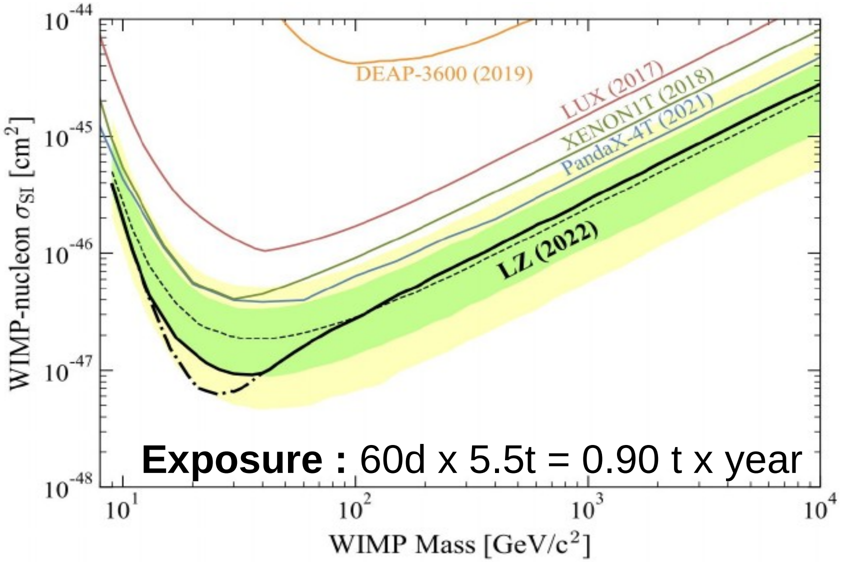


PandaX-4T

LZ

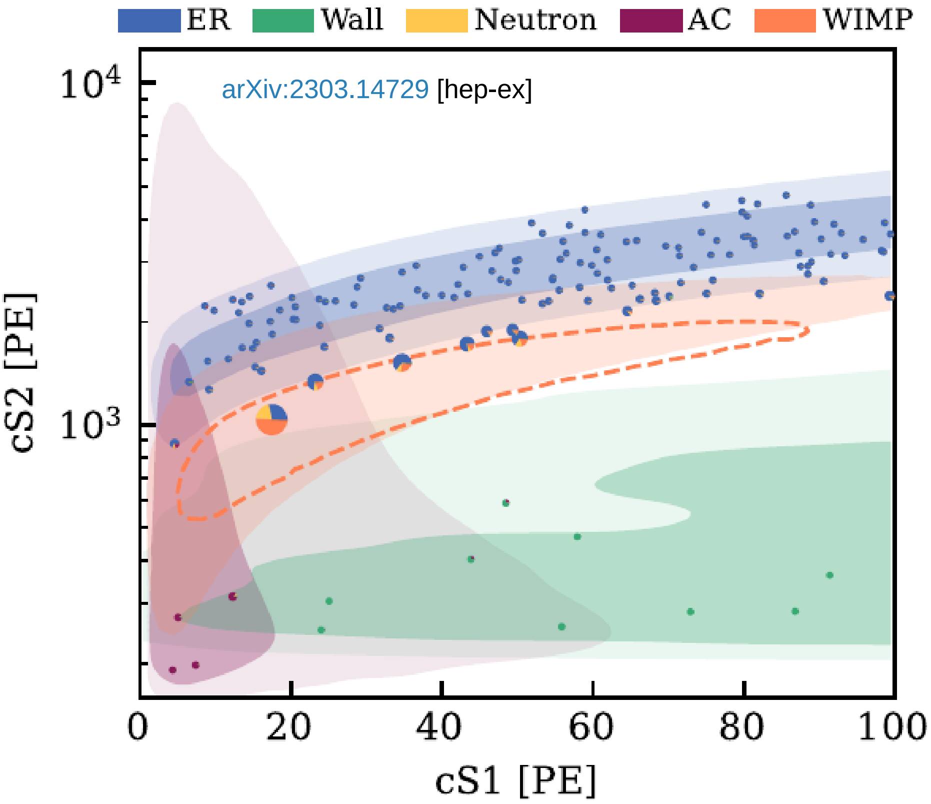


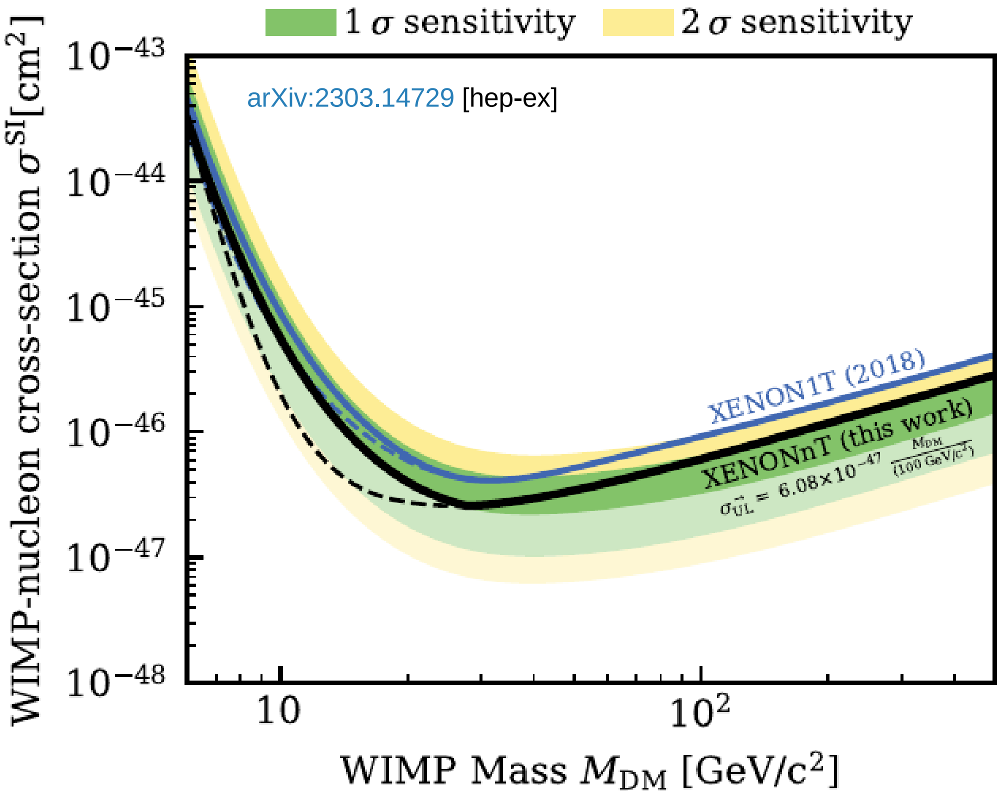
arXiv:2207.03764 [hep-ex]



Exposure : 60d x 5.5t = 0.90 t x year

High masses: XENONnT (2023)





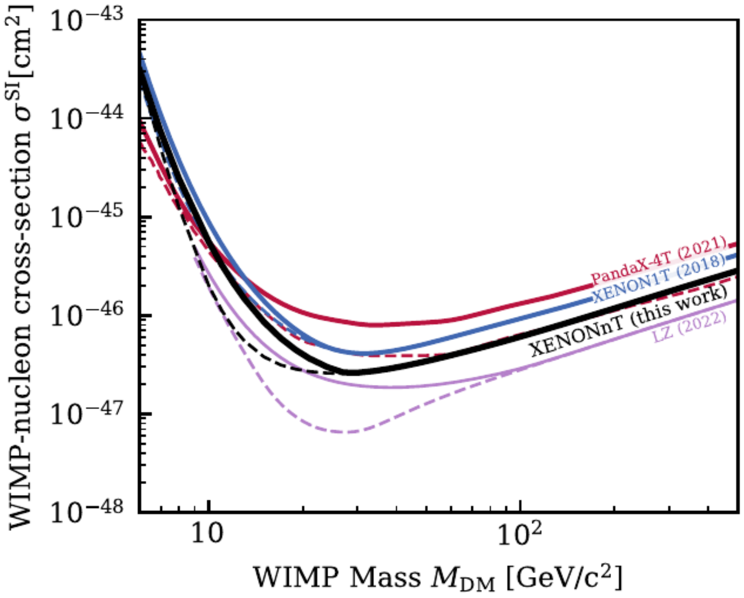
Exposure : 1.1 t x year

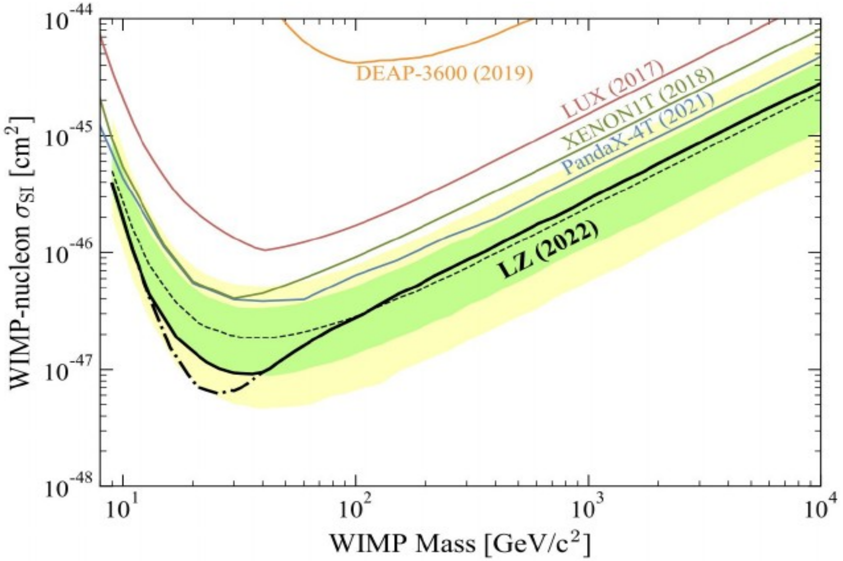
Electronic recoil background rate : $(15.8 \pm 1.3)\ \text{events}/(\text{t}\cdot\text{y}\cdot\text{keV})$

See the **talk of Ko Abe** (Tokyo University) for an overview of **XENONnT analyses** (Wednesday morning parallel session)

Constraining large downwards fluctuations

- Set of conventions to estabilish a **standard on statistical treatment of data** on the field : arXiv:2105.00599
- To **constrain large downwards fluctuations**, the limit should be subjected to a power-constraint : arXiv:1105.3166
- However, the above reccommandations defined the sensitivity in terms of *discovery power*, while it should rather be in terms of *rejection power*





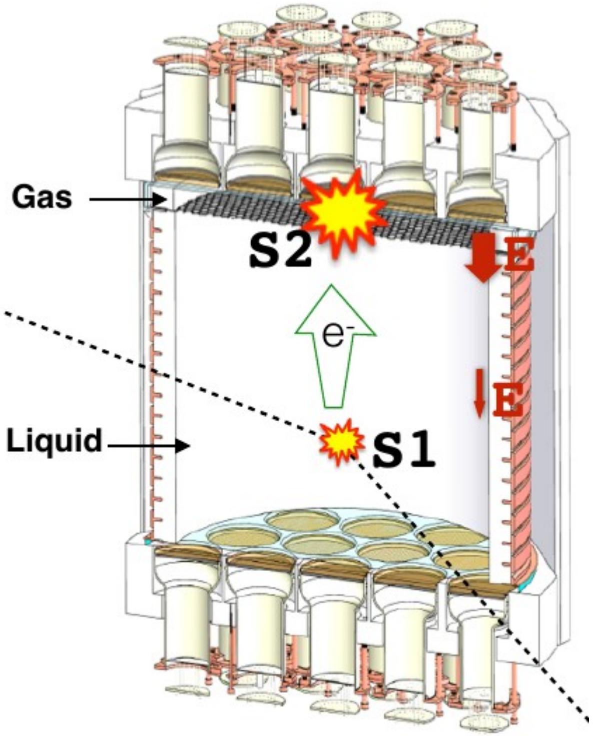
XENON applied the same **very conservative** power-constraint on itself and re-did it on the other recent LXe experiments

- Full curve : 90% C.L. limit with a power-constraint to restrict it at or above the median unconstrained upper limit (→ 0.5).
- Dashed curve : no power contraint applied

LZ applied a power constraint using a −1 σ quantile

Careful on comparing results using different conventions !

Low masses : DarkSide-50



S1 and S2 Yields:

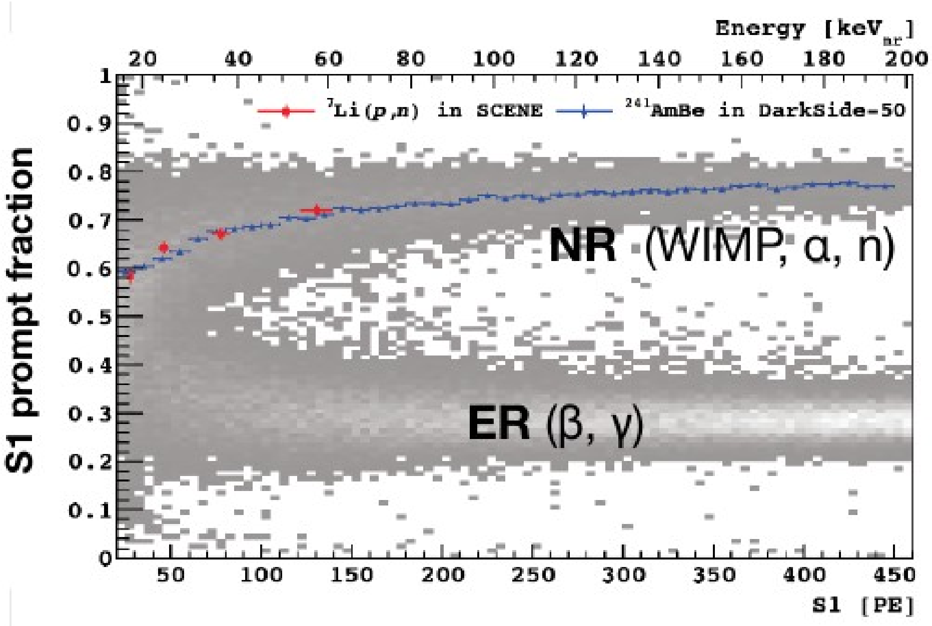
- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm
- S2 yield **~23 pe / e-**

Electron lifetime > 5 ms

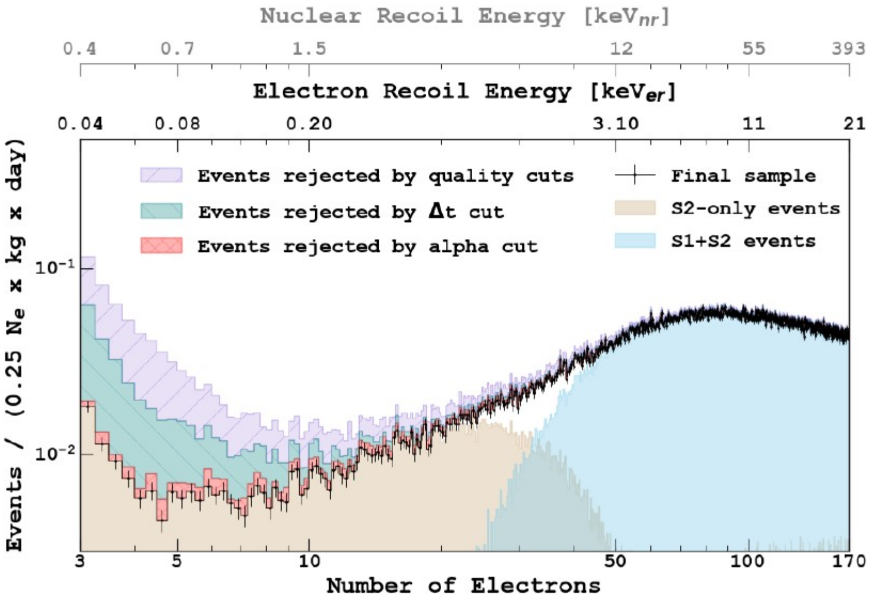
Maximum drift time: 376 μs

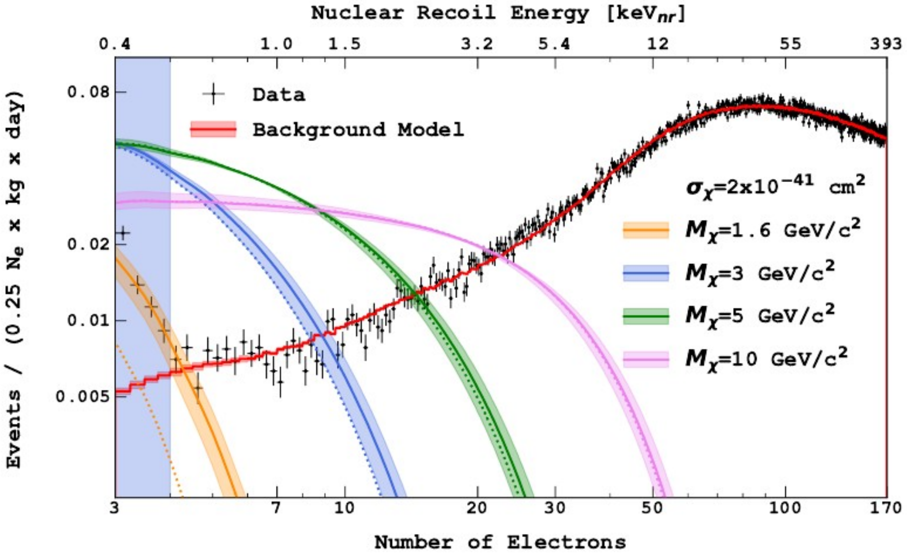
ER and NR excite fast and slow in different proportions in noble liquids.

In Argon, great **ER discrimination** factor: ~ 10^8



Low masses : DarkSide-50





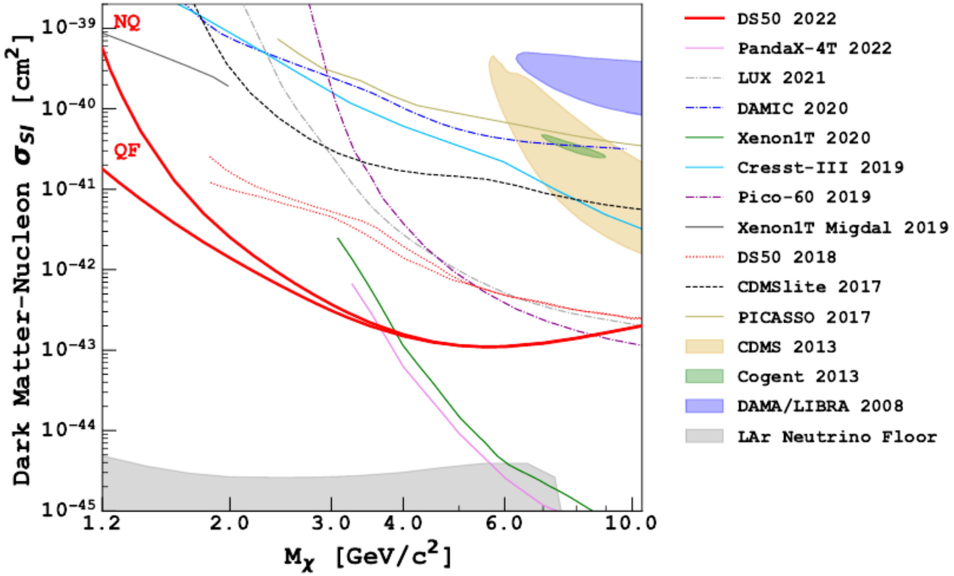
Look at the **ionization only** spectrum
(W_{ion} = 23.5 eV, gain in the gas: 23 PE/e^-)
Below 3 keV_{ee}: give up the scintillation signal (too small to trigger the detector), and thus

- **minimal fiducialization** (only radial)
- **no PSD**

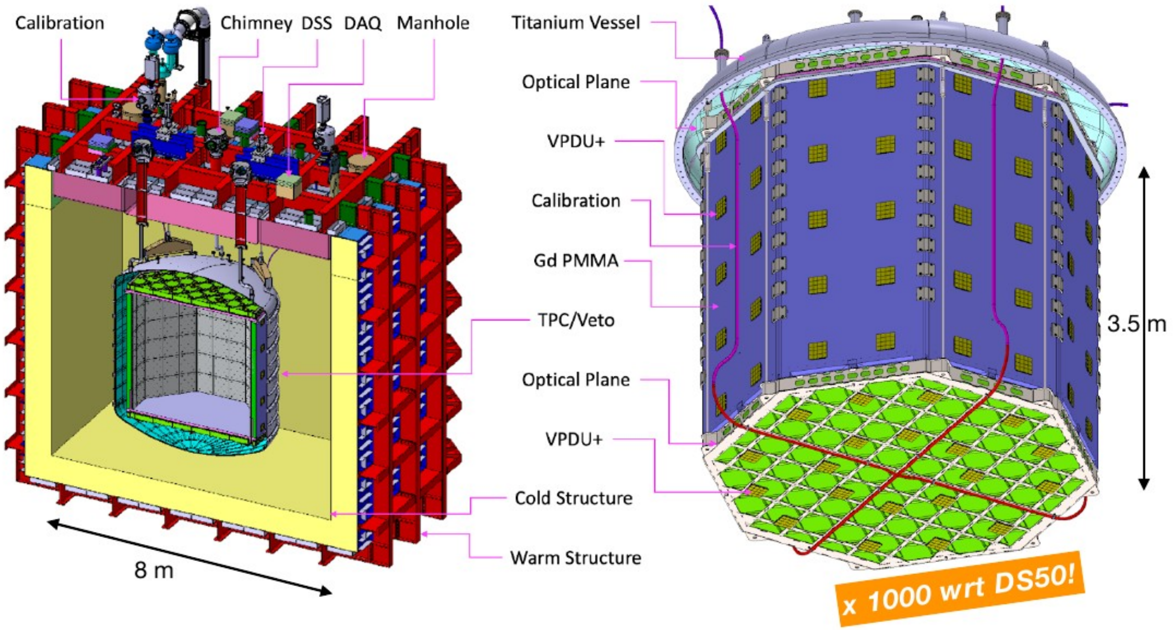
arXiv:2207.11966 [hep-ex]

Quenching fluctuations, two approaches :

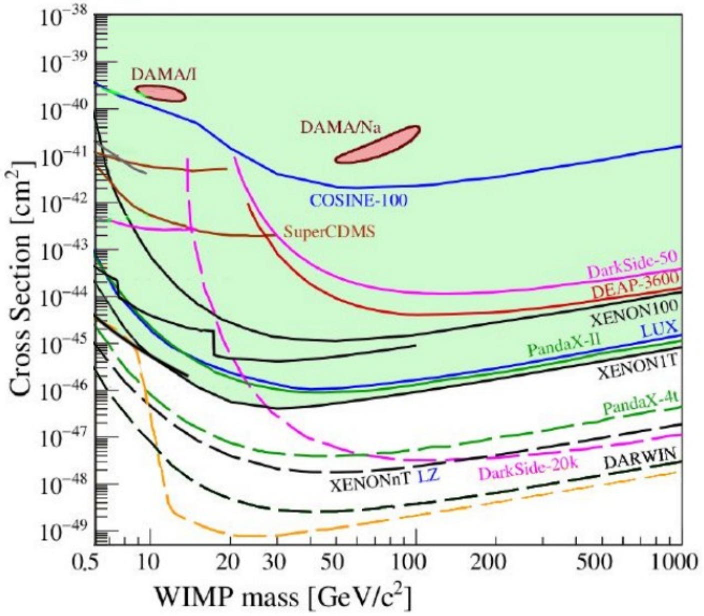
- No Quenching (unphysical but conservative)
- Binomial quenching



Forthcoming years : DarkSide-20k



x 1000 wrt DS50!



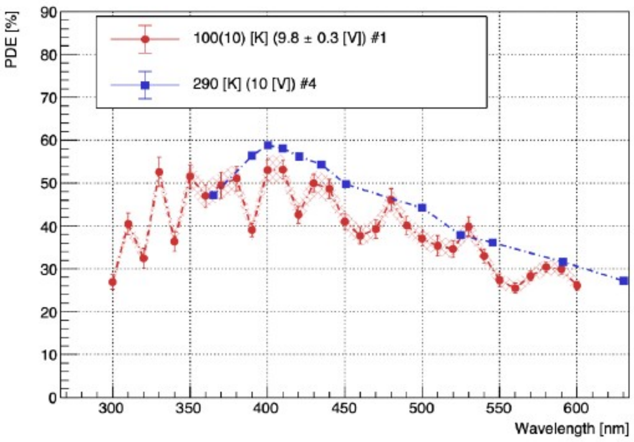
100 y·t

- To be installed in Hall C at LNGS
- Hosted inside a 700 t AAr LAr bath, in a cryostat *à la* ProtoDUNE
- **Target: 50 t UAr as WIMP target**
- **Veto: 35 t UAr + custom developed Gd-PMMA,** optimized for radiogenic neutrons
- **Novel readout** system for the **scintillation light**, based on **grouped SiPM arrays (> 25 m²)**

Underground Argon procurement ongoing

Collaboration targets data taking for 2026

DarkSide-20k : SiPM arrays

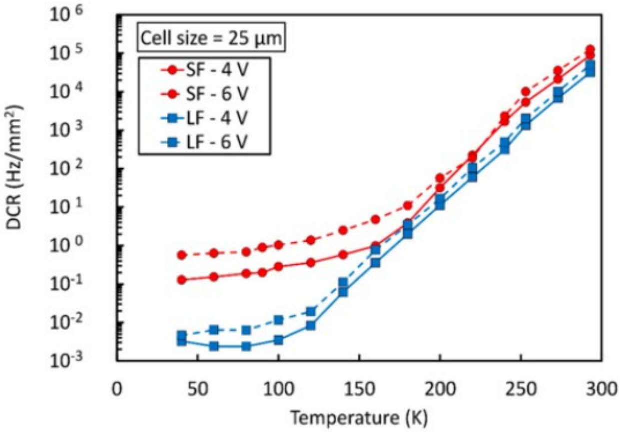


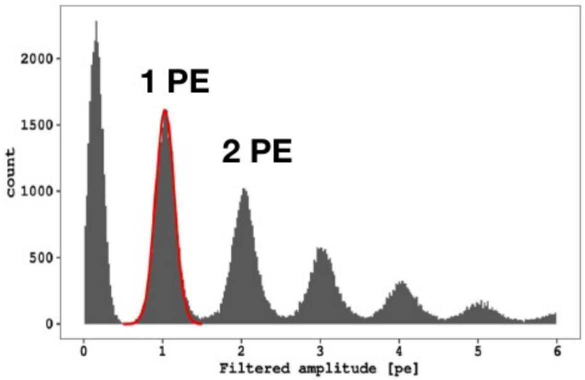
PROS

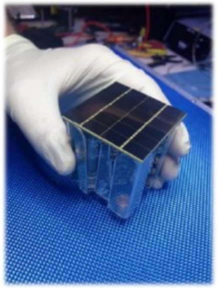
- Cryogenic temp stability
- Better single photon resolution
- **Higher photo-detection efficiency**
- Low voltage operation
- **Lower background** (Si intrinsically radiopure)
- Lower cost

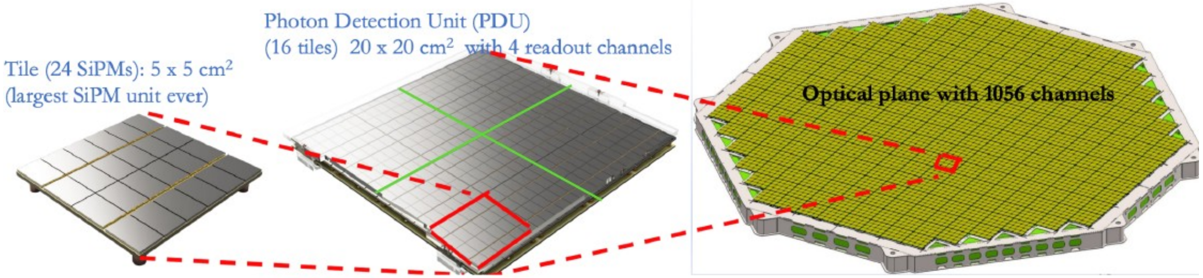
CONS

- Small area ≈ cm2 (group them)
- High dark rate (solved, + operated at 87K)
- High output capacitance for large devices (~0.5 us recharge)





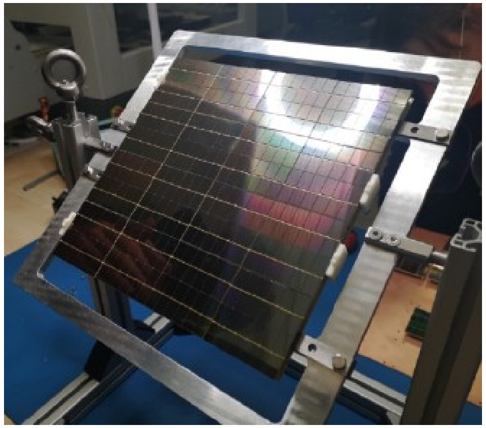




Tile (24 SiPMs): 5 x 5 cm²
(largest SiPM unit ever)

Photon Detection Unit (PDU)
(16 tiles) 20 x 20 cm² with 4 readout channels

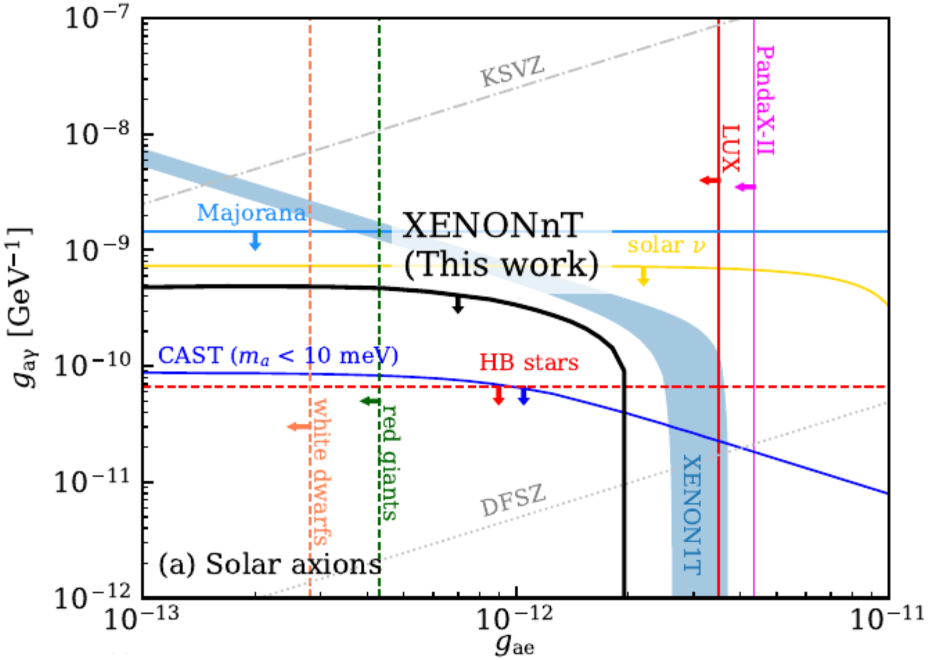
Optical plane with 1056 channels



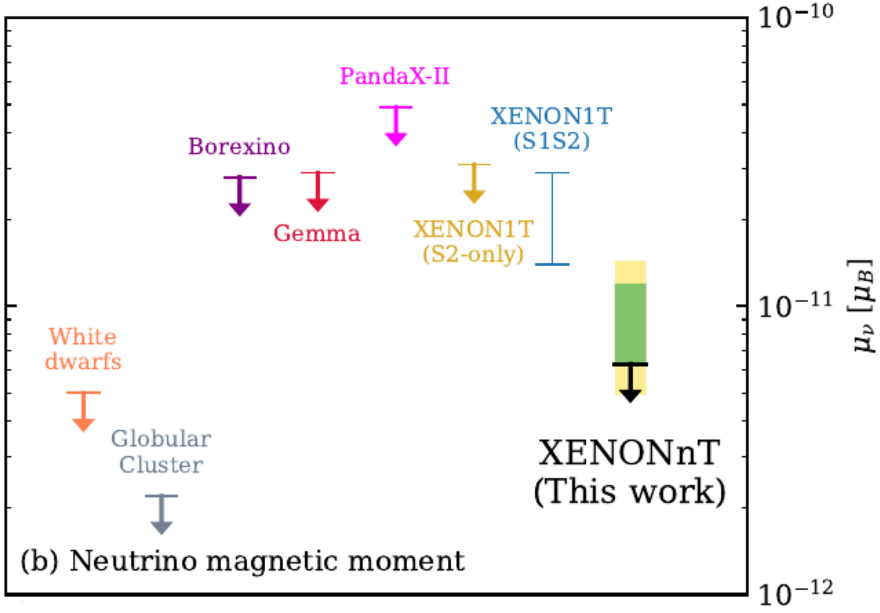
Other physics

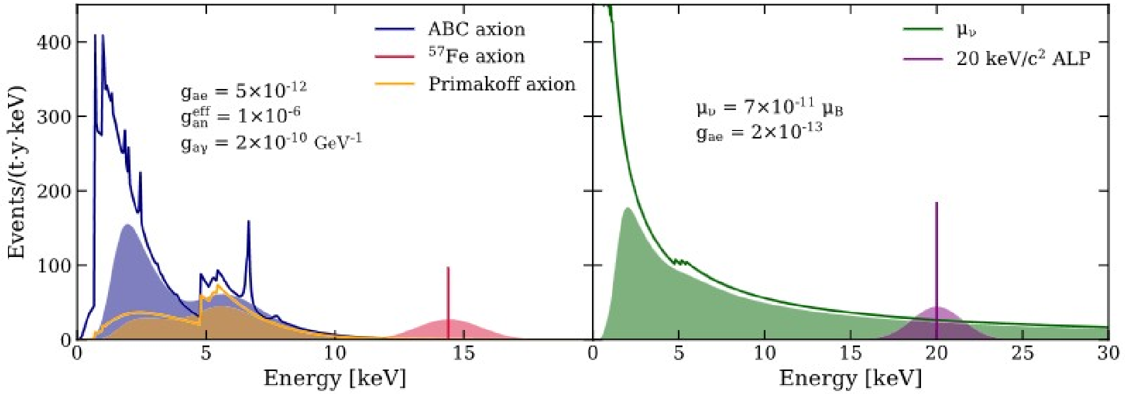
XENONnT (2022) : Phys. Rev. Lett. 129, (2022) 161805

Solar axions



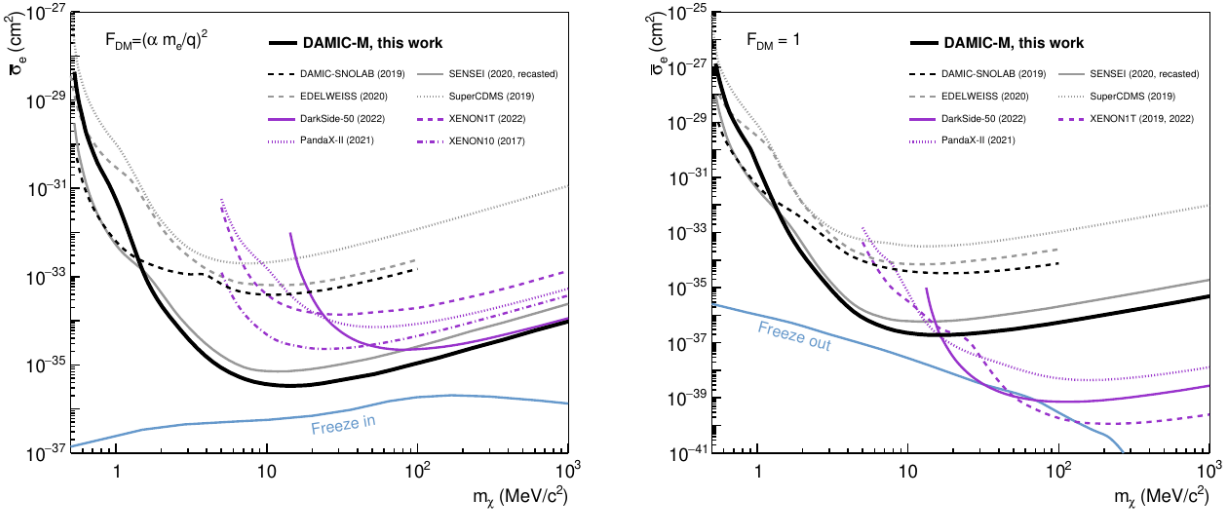
Neutrino magnetic moment





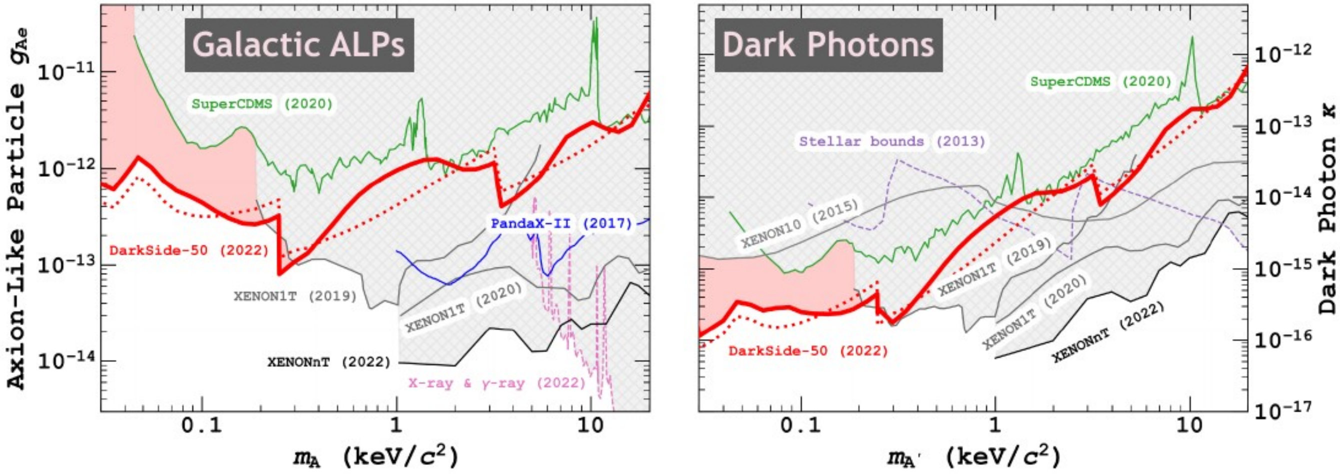
Leptophilic dark matter

DM-electron scattering



Leading results :

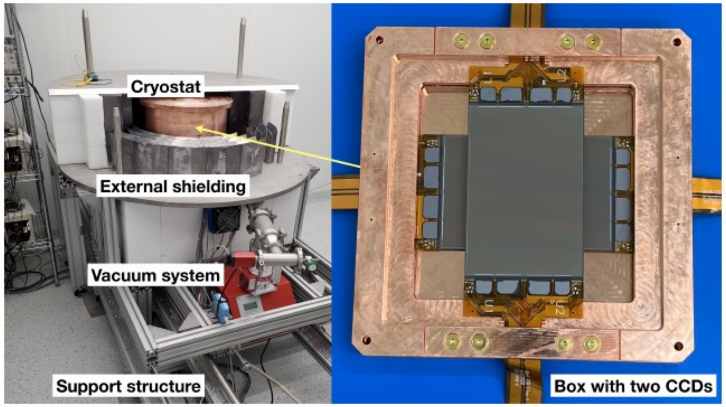
DAMIC@SNOWLAB (2019) :
Phys. Rev. Lett. 123, (2019) 181802
SENSEI (2020) :
Phys. Rev. Lett. 125, (2020) 171802
DAMIC-M (2023) :
arXiv:2302.02372 [hep-ex]
DarkSide-50 (2022) :
Phys. Rev. Lett. 130, (2023) 101002
XENON1T (2019) :
Phys. Rev. Lett. 123, (2019) 251801
XENONnT (2022) :
Phys. Rev. Lett. 129, (2022) 161805



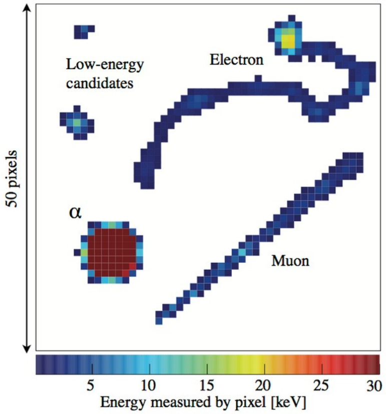
Dark Matter with Skipper-CCDs

Main idea : ultralow-noise electronics in combination with repetitive, nondestructive readout of a thick, fully depleted charge-coupled device (CCD)

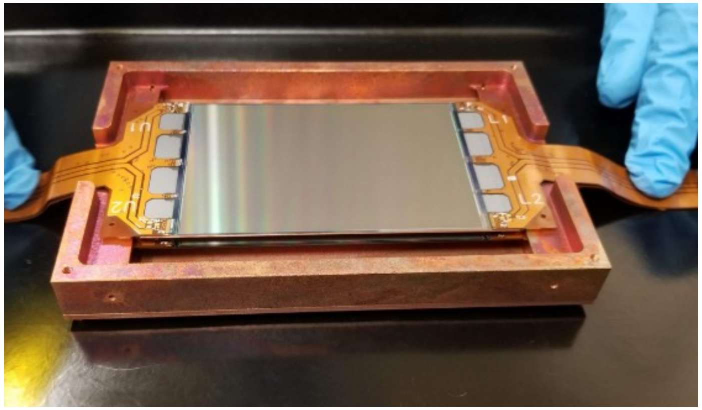
Three detectors : SENSEI, DAMIC @ SNOWLAB, DAMIC-M



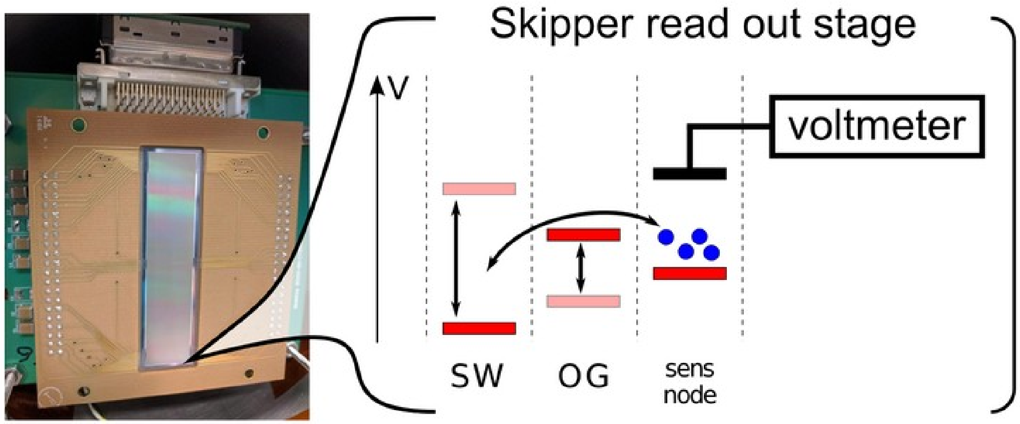
DAMIC-M



Particle ID

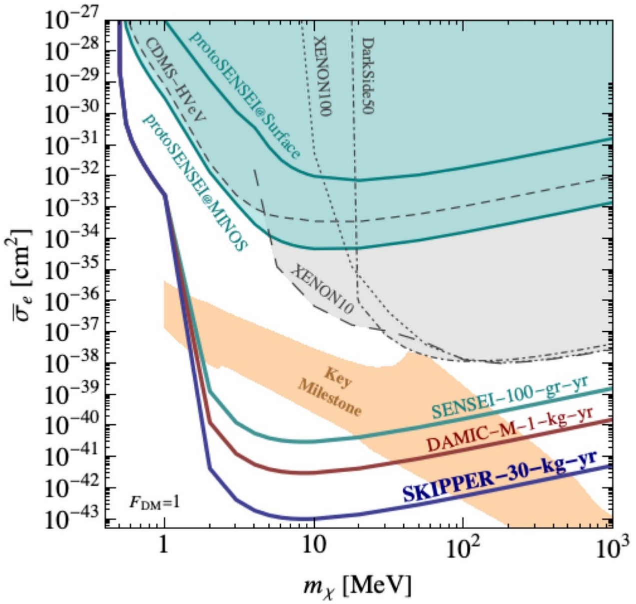


DAMIC @ SNOWLAB



SENSEI

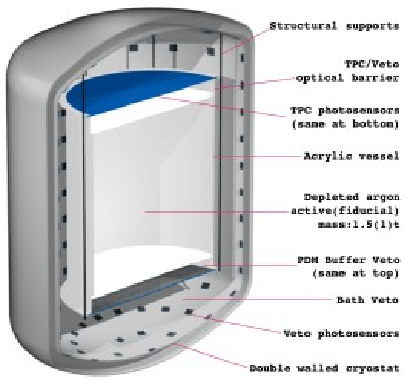
Next generation experiments : low thresholds

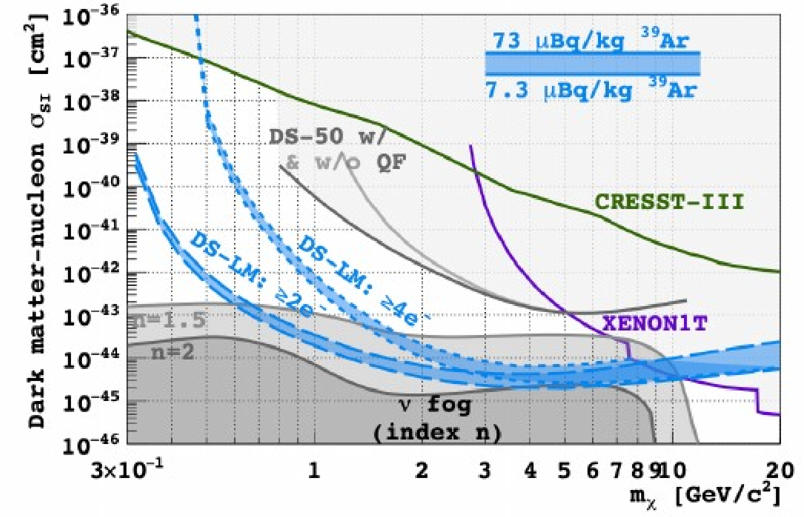


Skipper-CCD is now a well estabilished technology

To gain sensitivity it needs to increase target mass :

- Silicium thickness
- High number of devices
- Improved background





Argon enough light and easily shielded to be competitive at low masses if a dedicated detector is built : **DS-LM**
Challenge of single electrons background

Next generation experiments : high mass

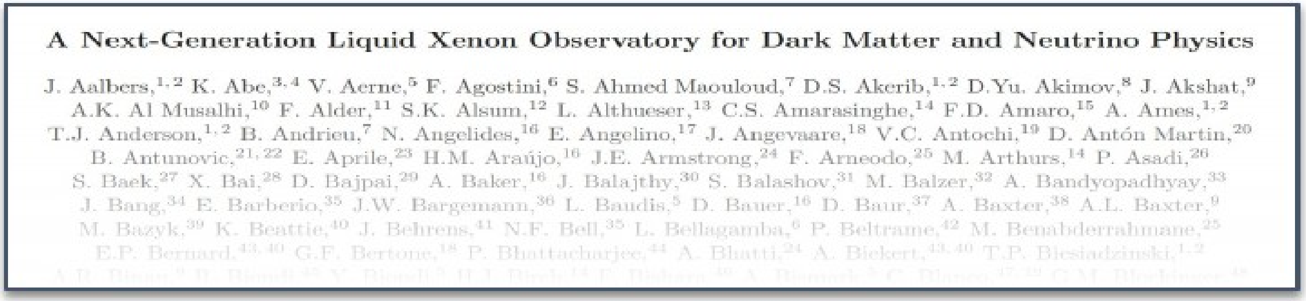
The xenon community is uniting into the XLZD Consortium to build the ultimate xenon rare event observatory

- White paper: arXiv:2203.02309

- Baseline : Outcome of DARWIN R&D

- xlzd.org

Leading Xenon Researchers unite to build next-generation Dark Matter Detector



A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

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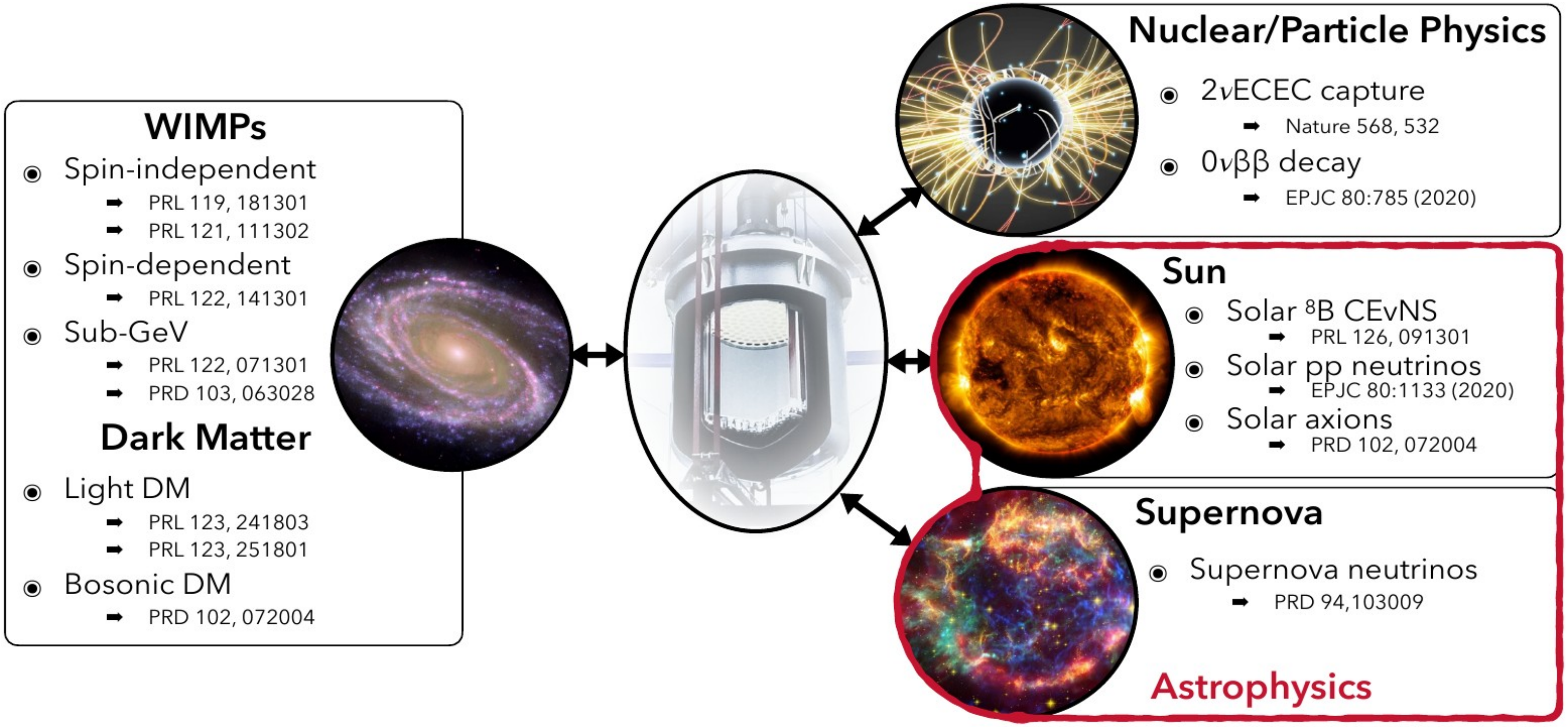
E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert,[43,40] T.P. Biesiadzinski,[1,2]

DARWIN : Dark matter detector ?
No, astroparticle observatory



WIMPs

- Spin-independent
  - ➡ PRL 119, 181301
  - ➡ PRL 121, 111302
- Spin-dependent
  - ➡ PRL 122, 141301
- Sub-GeV
  - ➡ PRL 122, 071301
  - ➡ PRD 103, 063028

Dark Matter

- Light DM
  - ➡ PRL 123, 241803
  - ➡ PRL 123, 251801
- Bosonic DM
  - ➡ PRD 102, 072004

Nuclear/Particle Physics

- 2νECEC capture
  - ➡ Nature 568, 532
- 0νββ decay
  - ➡ EPJC 80:785 (2020)

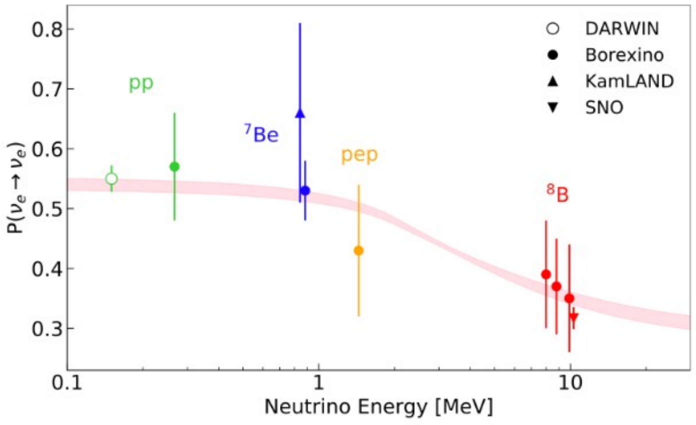
Sun

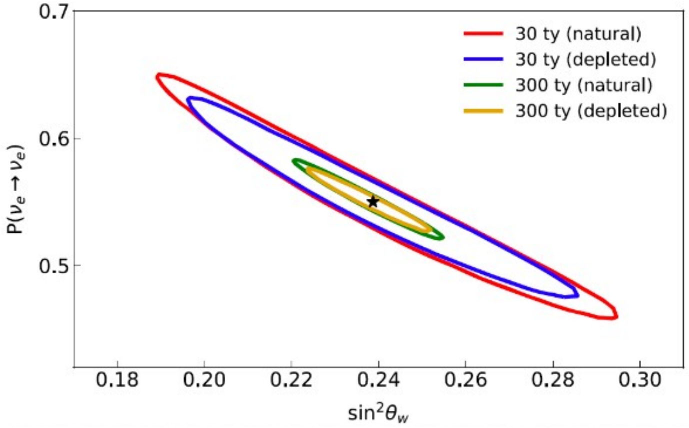
- Solar ^{8}B CEvNS
  - ➡ PRL 126, 091301
- Solar pp neutrinos
  - ➡ EPJC 80:1133 (2020)
- Solar axions
  - ➡ PRD 102, 072004

Supernova

- Supernova neutrinos
  - ➡ PRD 94,103009

Astrophysics



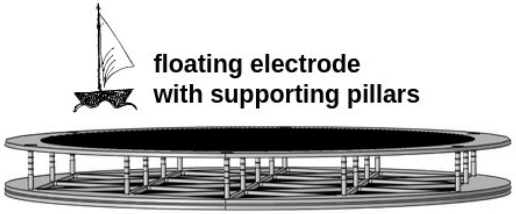


Elastic electron-neutrino scattering

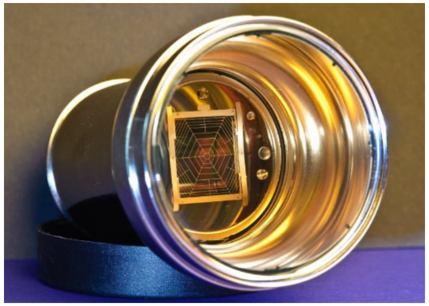
- 0.15% precision in the pp flux measurement with 300 ty exposure
- Measurement of electron neutrino survival probability and weak mixing angle
- 7.2 events/day in 30 t for the energy range E = (2 − 30) keVee (pp-neutrinos)

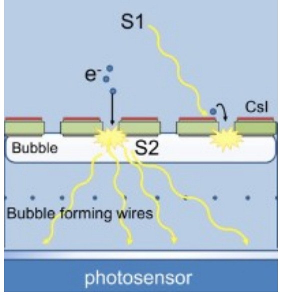
Challenges for DARWIN

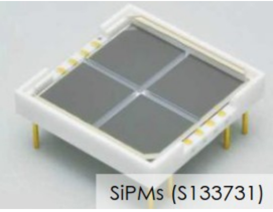
- Efficient amplification of the **ionization signal** (improved structure of electrodes, floating electrodes ?, single phase ?)
- **Radon** reduction (online distillation, material reduction, acrilic vessel?)
- High **purification** rates (liquid phase purification)
- Muons / **neutrons veto** tagging
- Noble liquid handling (**storage**, recovery,…)
- Photosensors



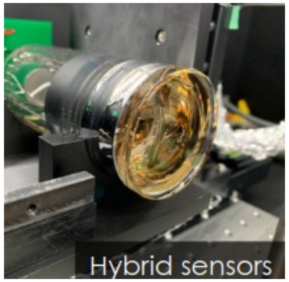
Baseline option
3” PMTs R11410 (XENONnT, LZ)





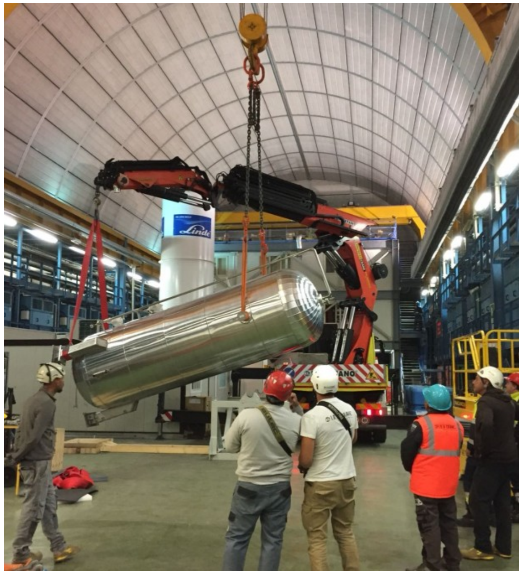


Alternatives

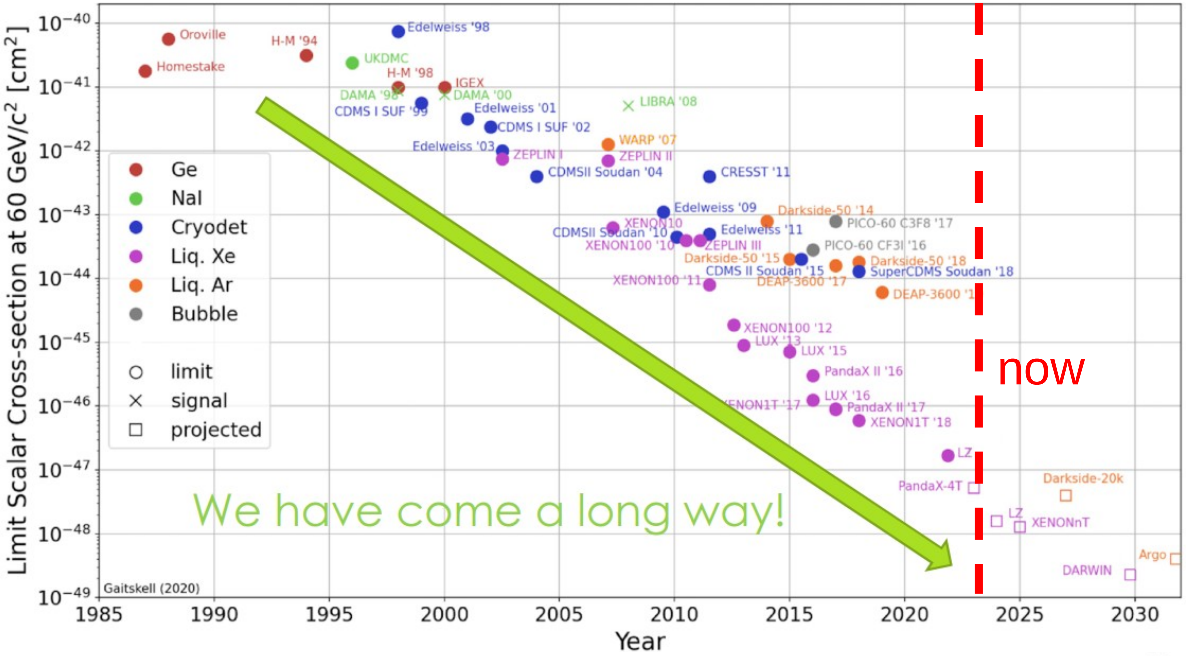


XENONnT online distillation
< 1 µBq/kg (arXiv:2205.11492)

XENONnT storage and recovery



Past, present and future



Liquid xenon sensitivity running at a speed of 1 order of magnitude on cross section every 4 years

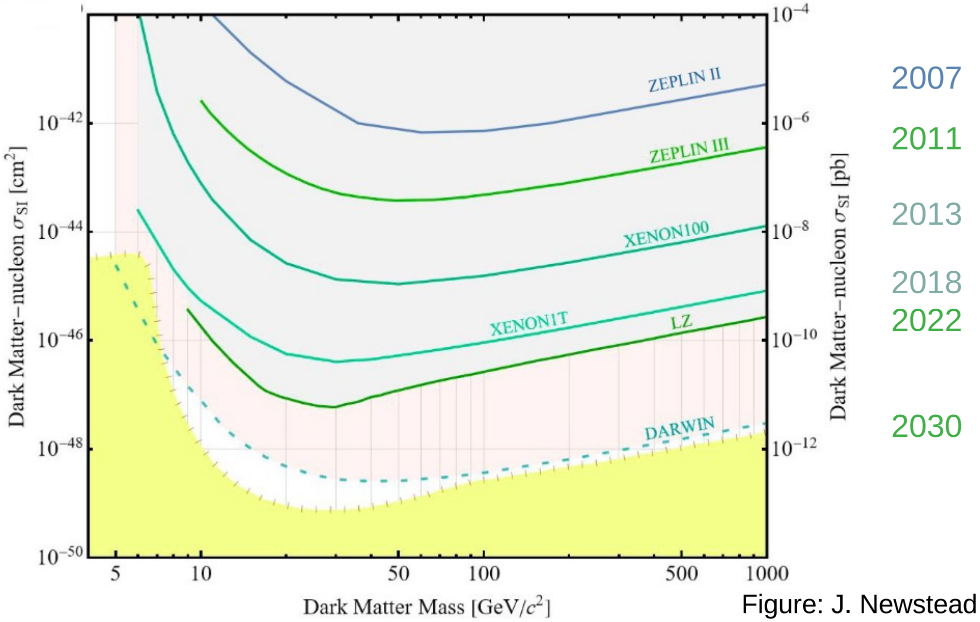
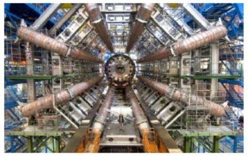


Figure: J. Newstead

Thank you

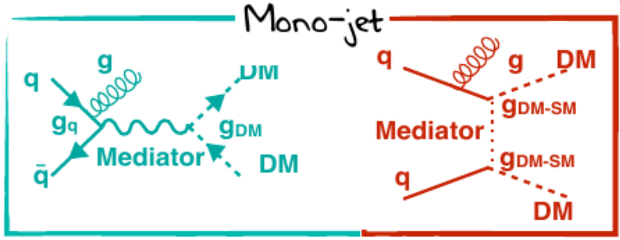
Dark Matter searches by accelerators

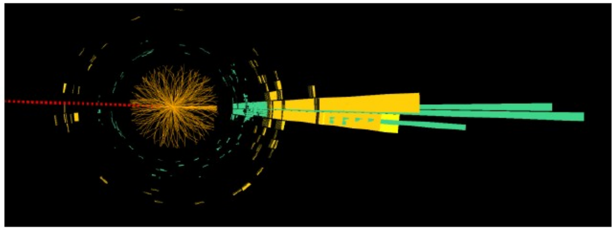
CMS

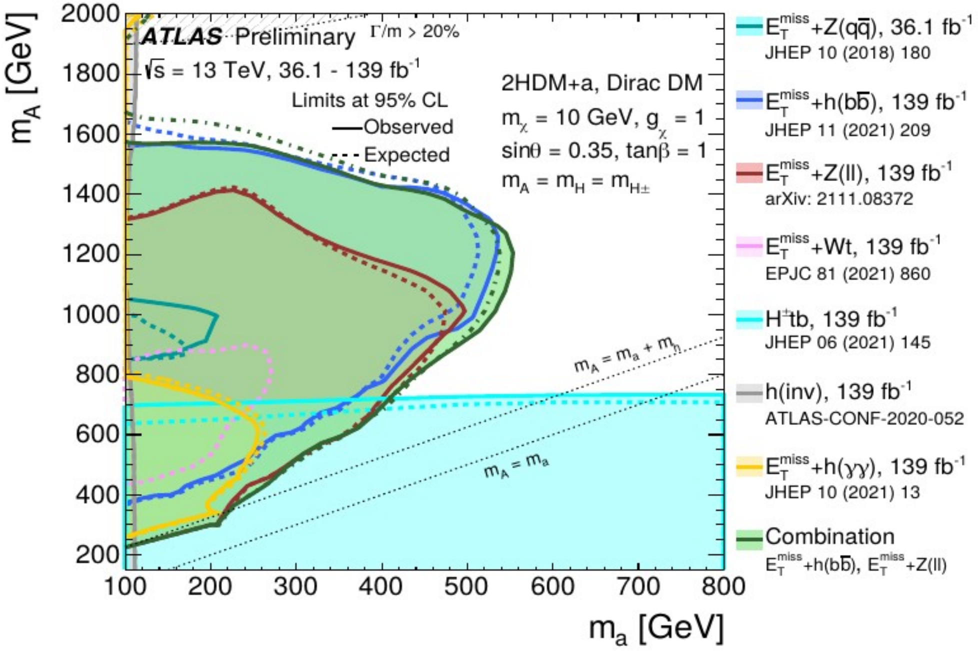


ATLAS

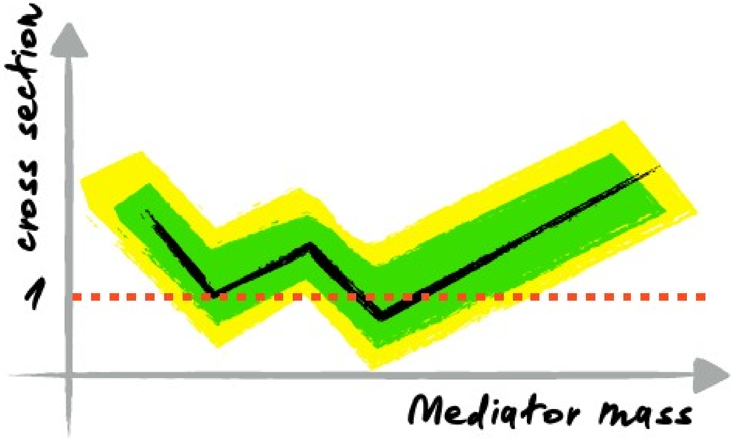
Example : monojet with P_T missing





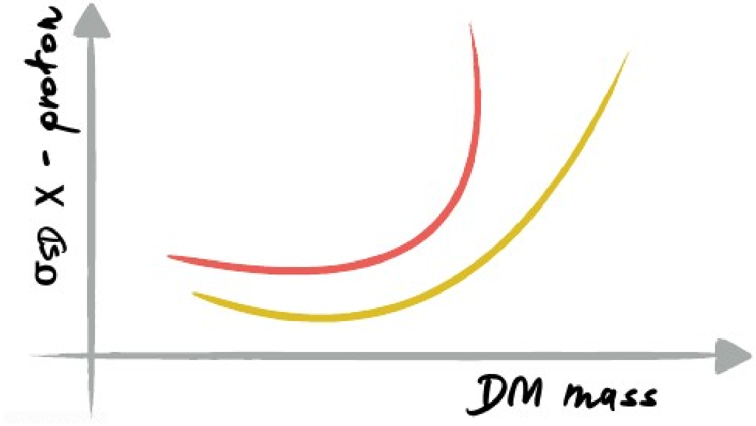


How to represent the results



Mediator mass

- Fix couplings
- Fix DM mass
- #% C.L. on production cross section ratio of mediators



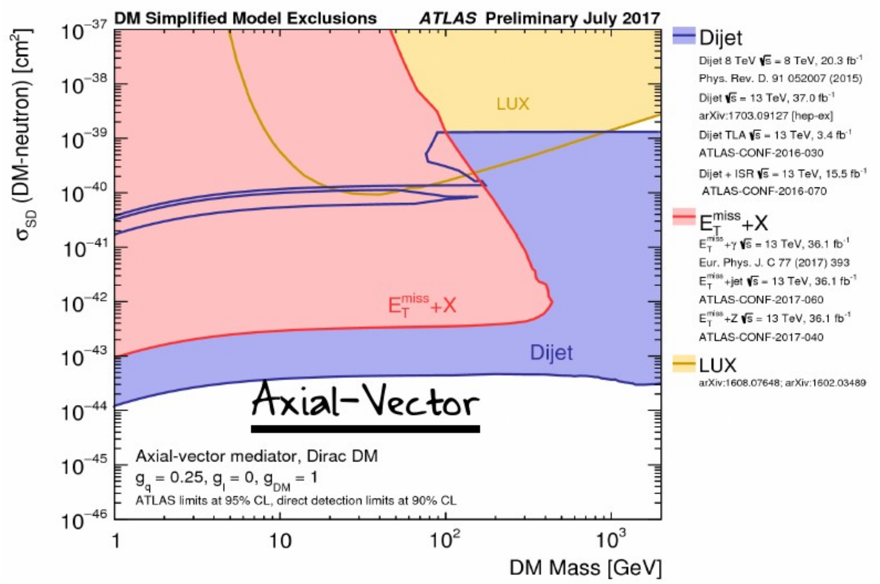
DM mass

- Fix couplings
- Limits on spin χ-nucleon cross sections at # % C.L.
- Allow to compare collider searches with other experiments

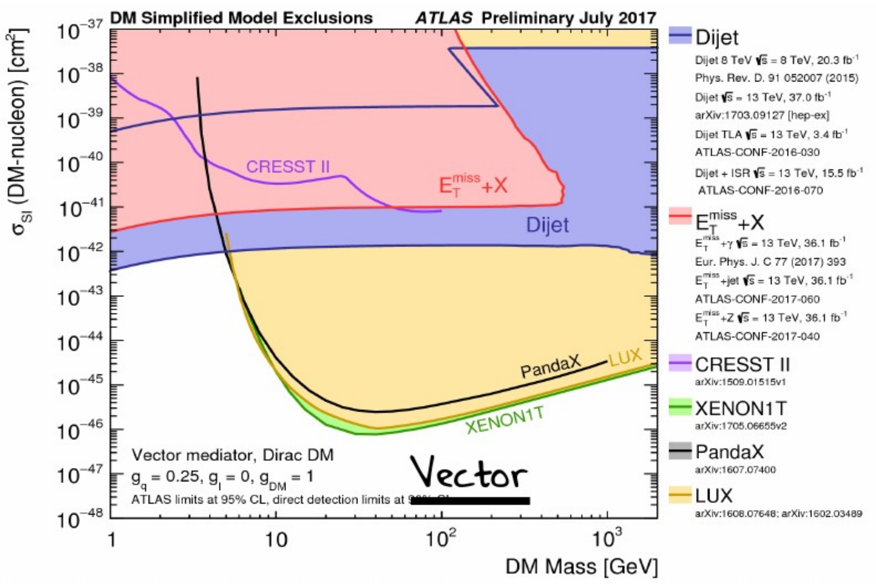
Credits : F. Cirotto, Dark matter searches with the ATLAS detector

Towards the cross-section vs Dark Matter mass

Spin dependent DM-neutron interaction



Spin independent DM-nucleon interaction



Just to show the concept.
Old data :

- ATLAS 2017
- Latest XENON1T results missing

Complementarity between accelerators and direct search at low mass only, and in any case based on coupling assumptions

Hunting axions

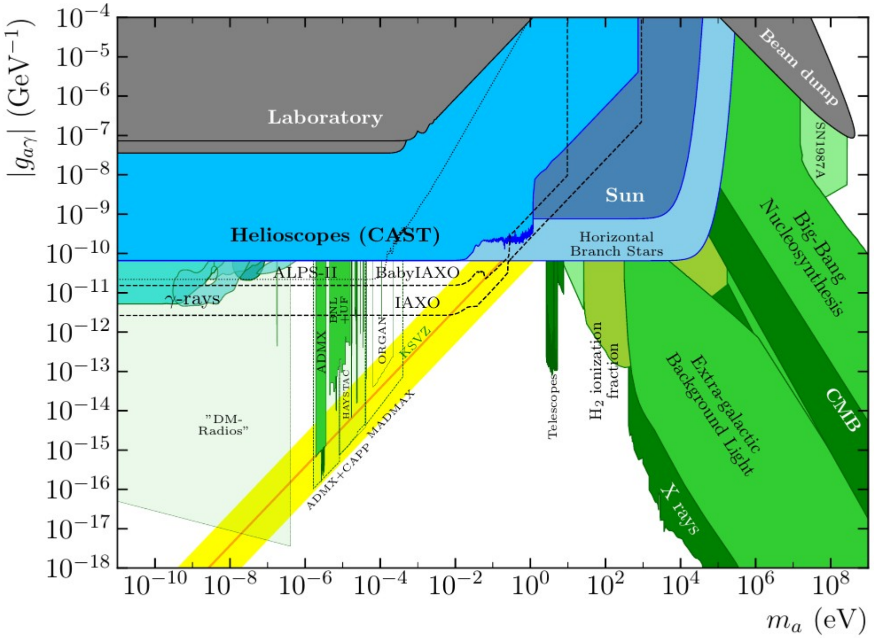
Models :

- Strong CP problem → "Peccei-Quinn" mechanism PQWW (Peccei-Quinn-Weinberg-Wilczek)
- Axion-photon coupling : $\mathcal{L}_{A\gamma} = -\frac{g_{A\gamma}}{4} A F_{\mu\nu}\widetilde{F}^{\mu\nu}$ $\quad g_{A\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{A\gamma}}{f_A}$
- Now ruled out and replaced by two new benchmarch models : KSVZ and DFSZ

Many experiments fully dedicated on them :

Solar axions (helioscopes) :
- CAST, ...

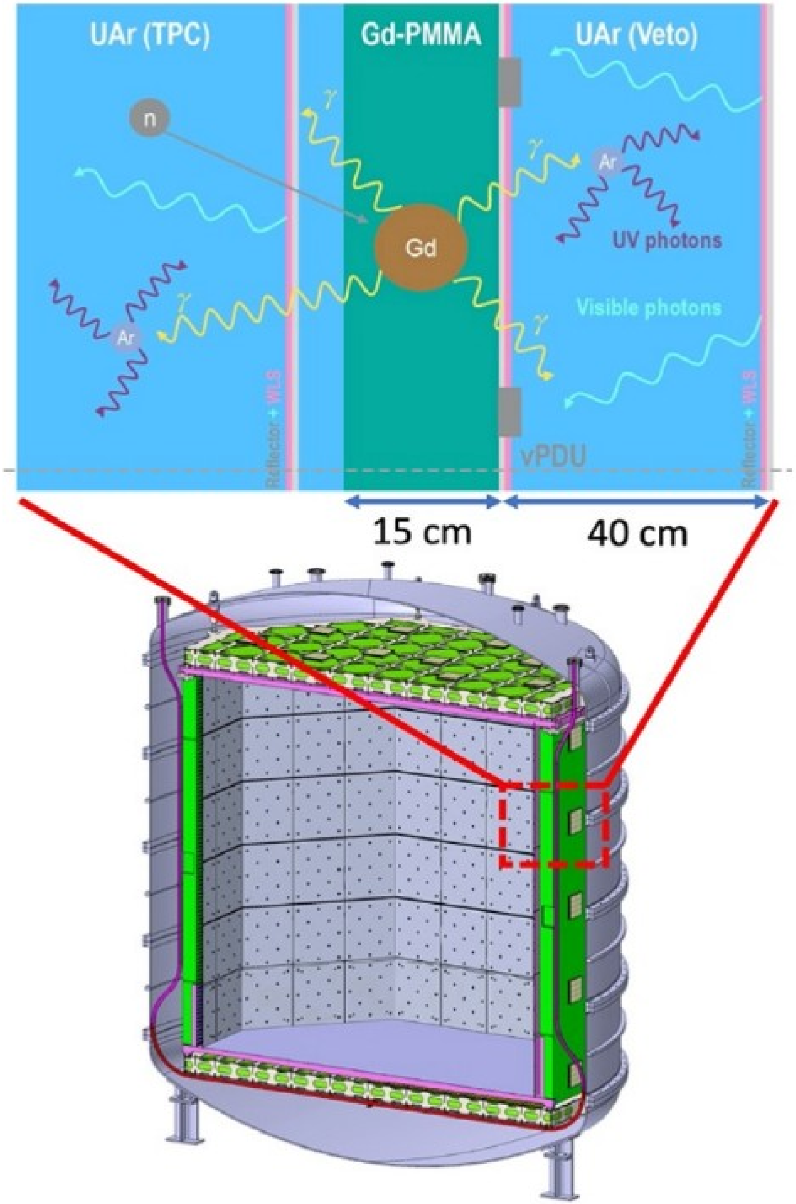
Haloscopes :
- ADMX, ORGAN, ...



Very wide mass (frequency) range. Each project aiming to reach the benchmarch models

DarkSide-20k : radiogenic neutron veto

- TPC surrounded by a single phase (S1 only) detector in UAr (35 tonne)
- Neutrons are captured by the Gd-loaded acrylic
- From the capture gamma ray shower up to 8 MeV
- Scintillation light is shifted by PEN wls and detected by SiPMs (400 channels) in both buffer and TPC
- **~90% tagging efficiency from simulation**, acceptable accidental lifetime loss



Gd(MAA)$_3$ doped acrylic sheet