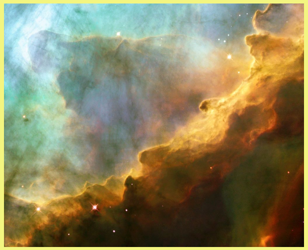
18th RENCONTRES DU VIETNAM

The rentless hunt for Dark Matter

Luca Scotto Lavina, LPNHE, Paris
With many thanks to the speakers of this conference

ICISE, Quy Nhon, Vietnam, July 22nd, 2022

The known and the unknown



Free Hydrogen and Helium : 4 %

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Stars : 0.5 %

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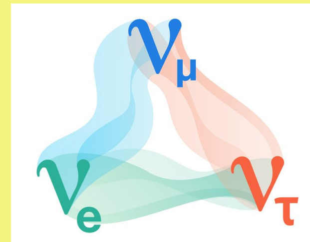

Active neutrinos : 0.3 %

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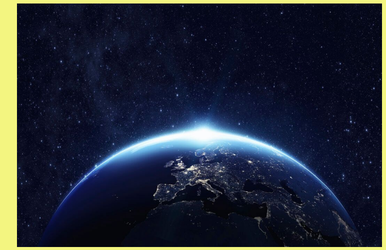
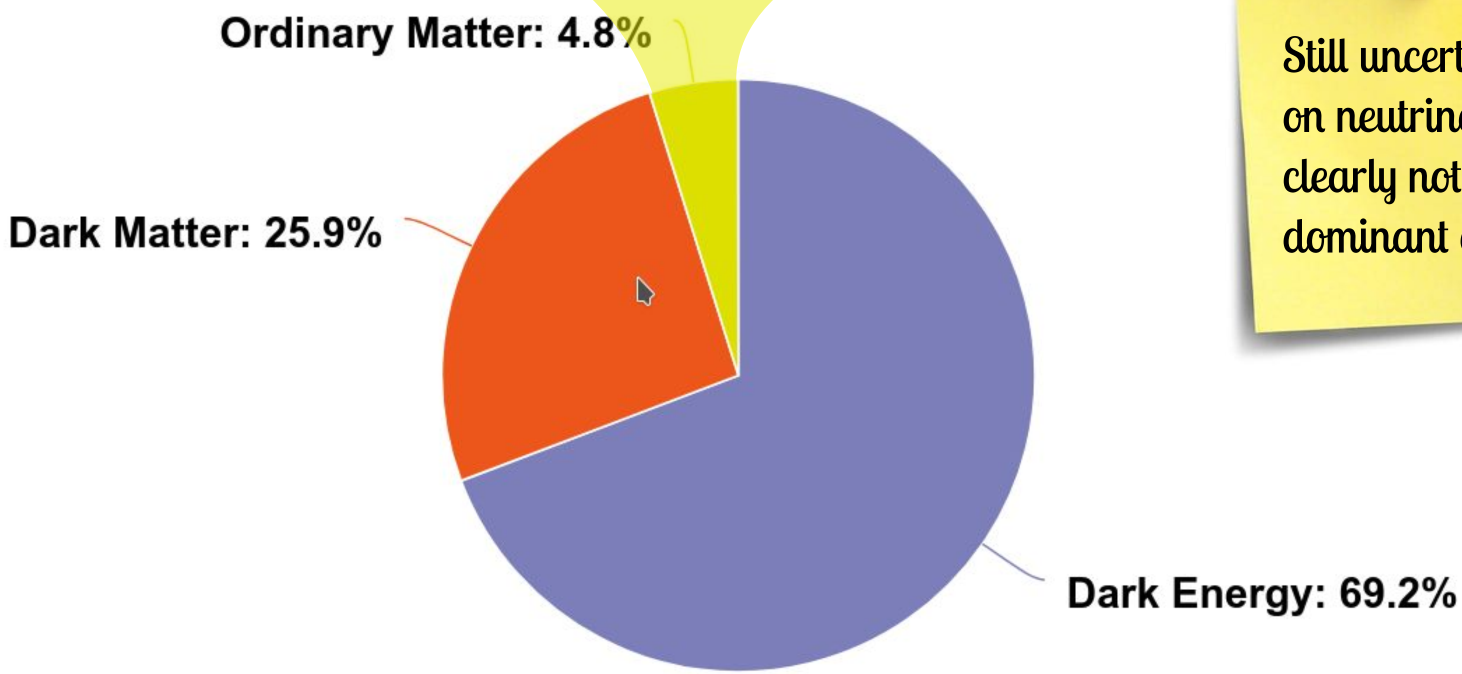


Heavy elements : 0.03 %



Still uncertainty on neutrinos, but clearly not the dominant one

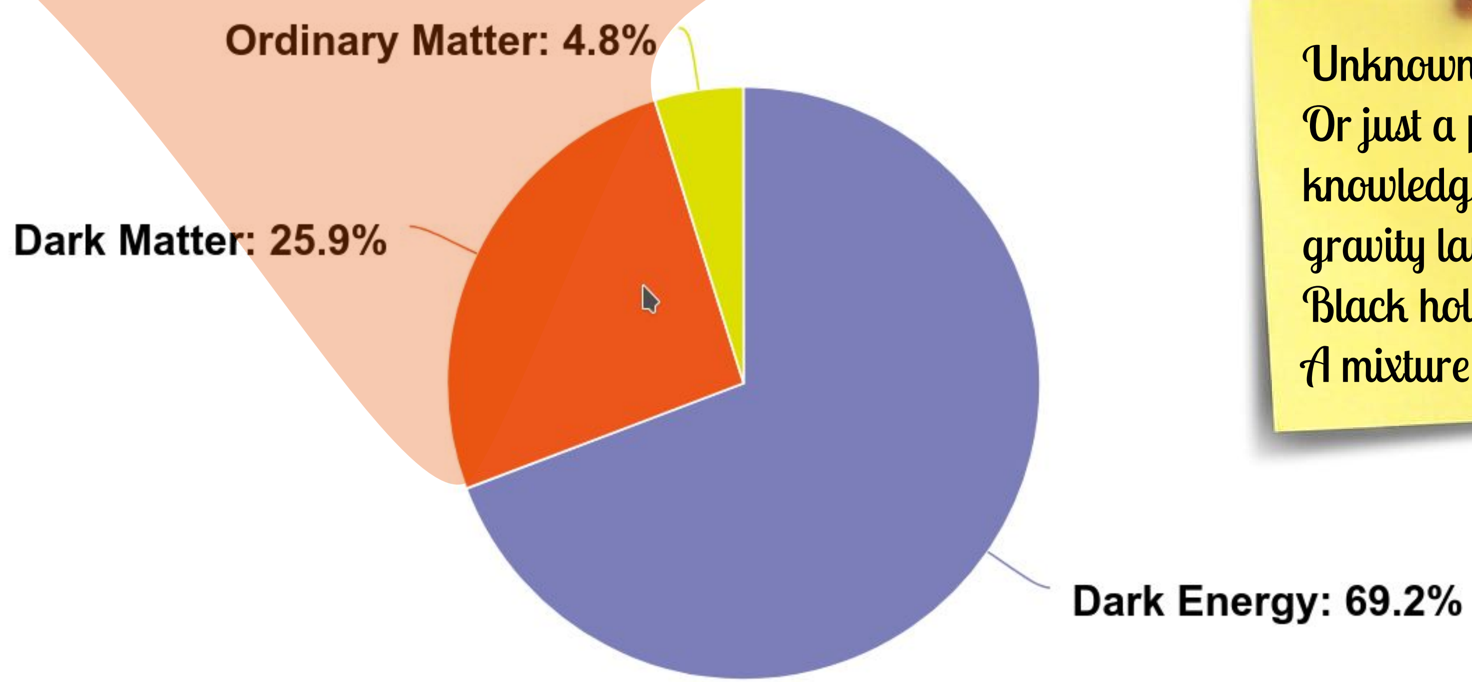
The known and the unknown

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 ?

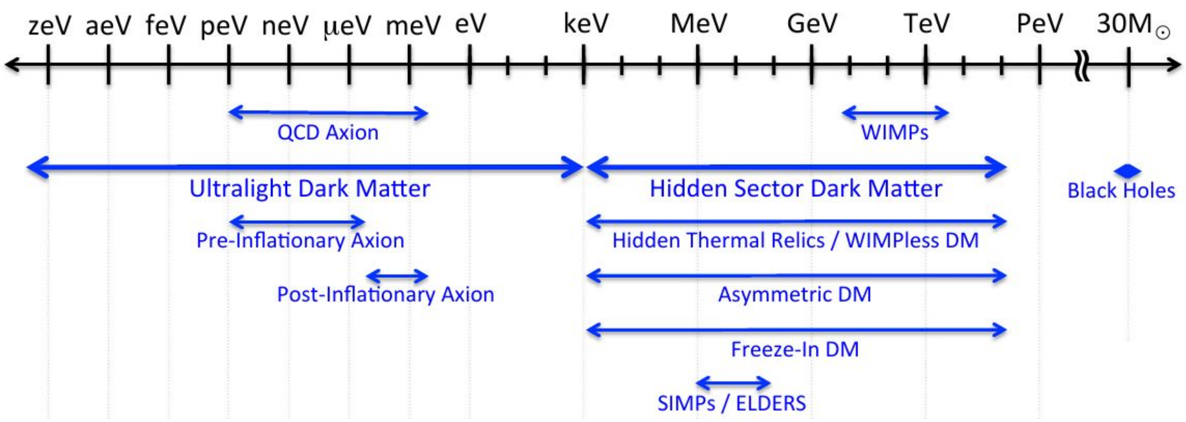
Alternatives :

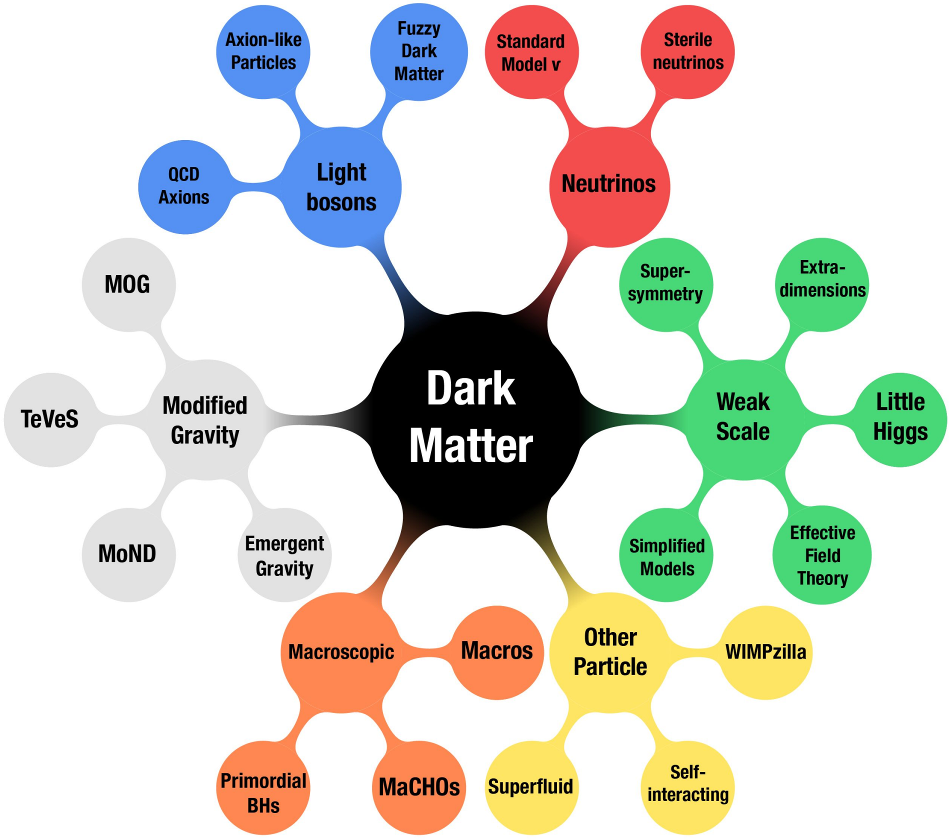
- Primordial black holes
- MACHOs
- Modifications of gravity



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

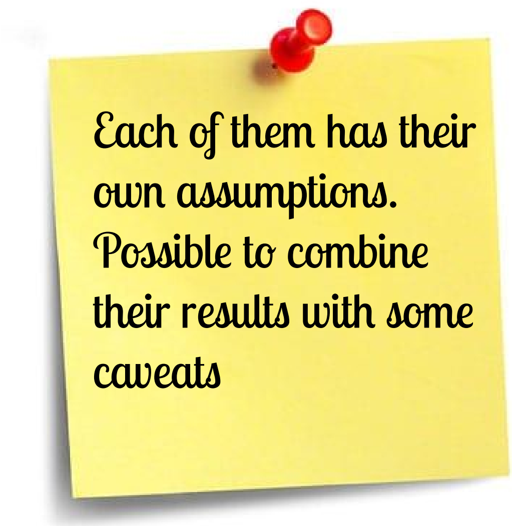
Fantastic Beasts and Where to Find Them

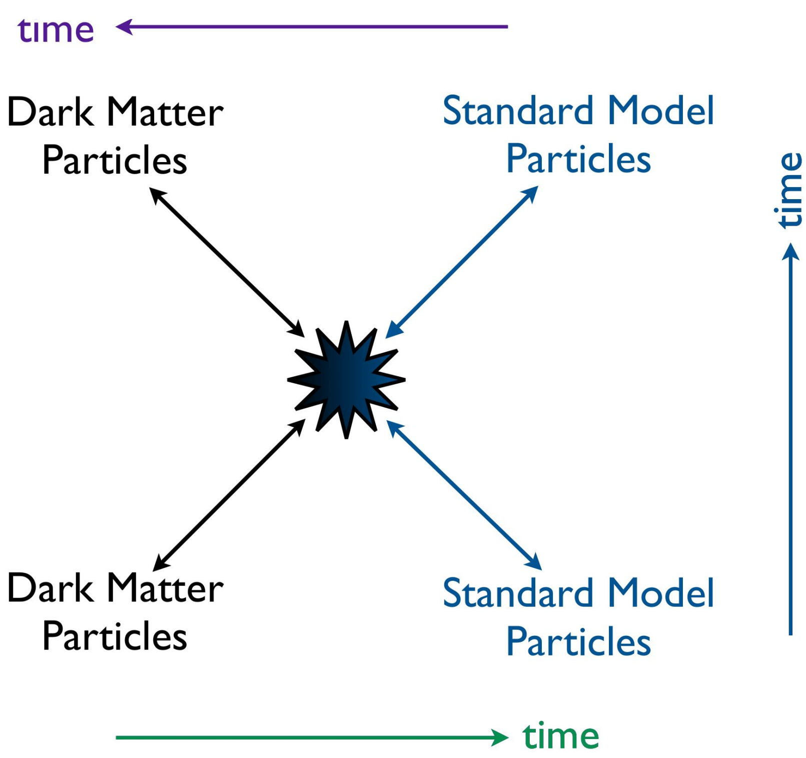




Hunting WIMPs

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





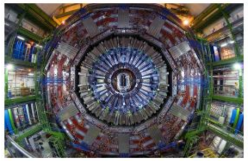
Shake ! → Direct detection of galactic DM :

on earth scattering off a detector nuclei

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

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

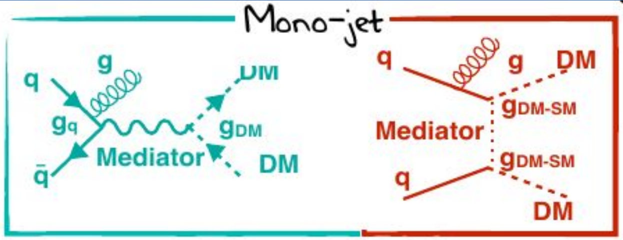
Dark Matter searches by accelerators

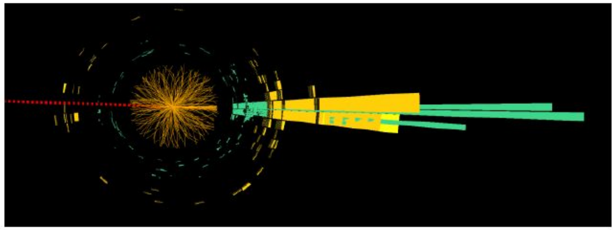


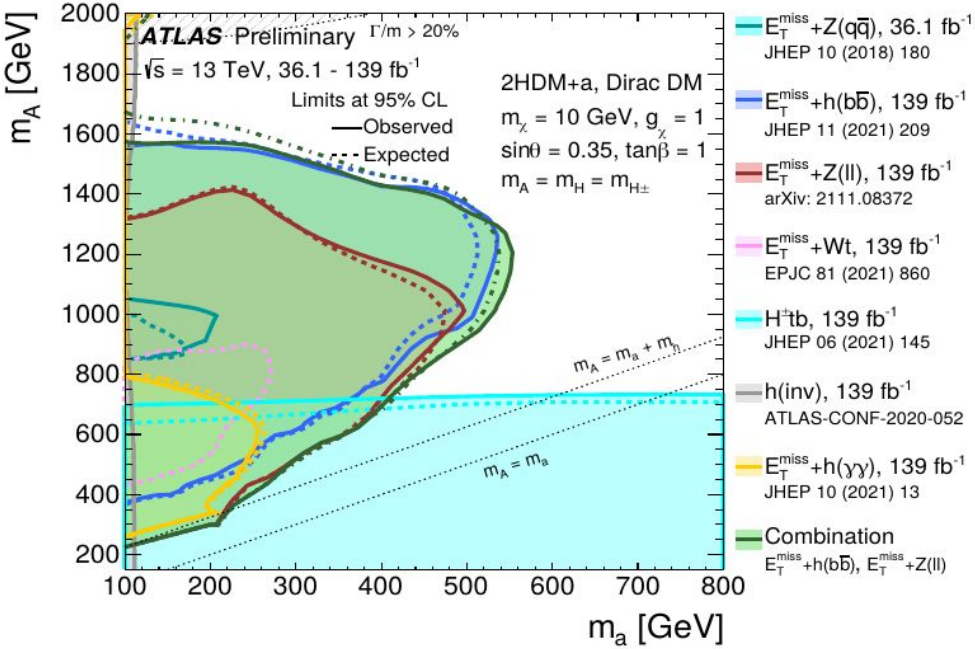
CMS

ATLAS

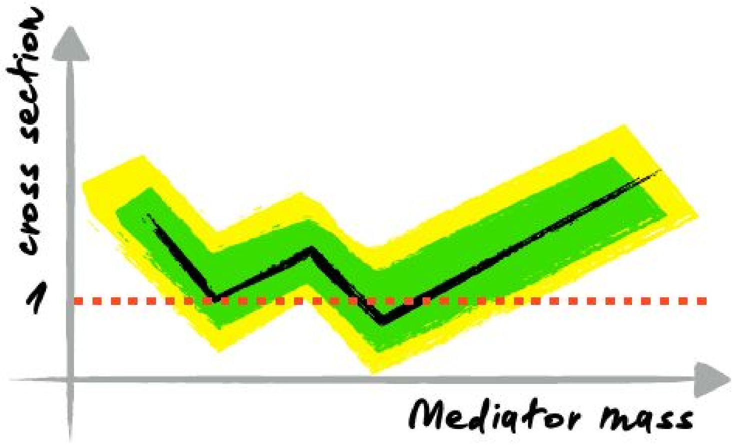
Example : monojet with P_T missing





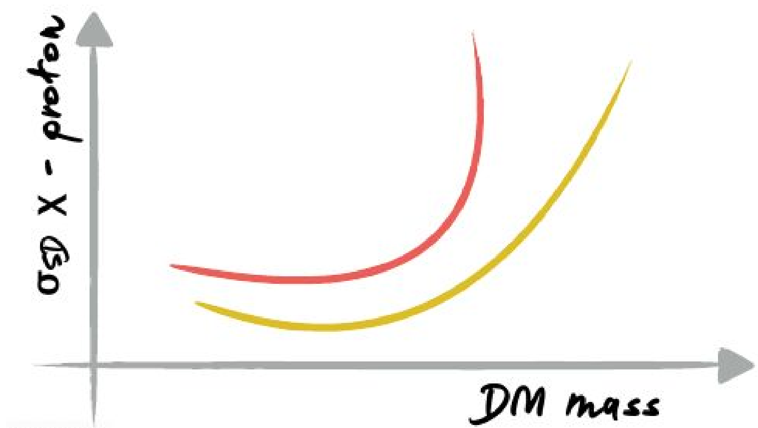


How to represent the results



Mediator mass

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



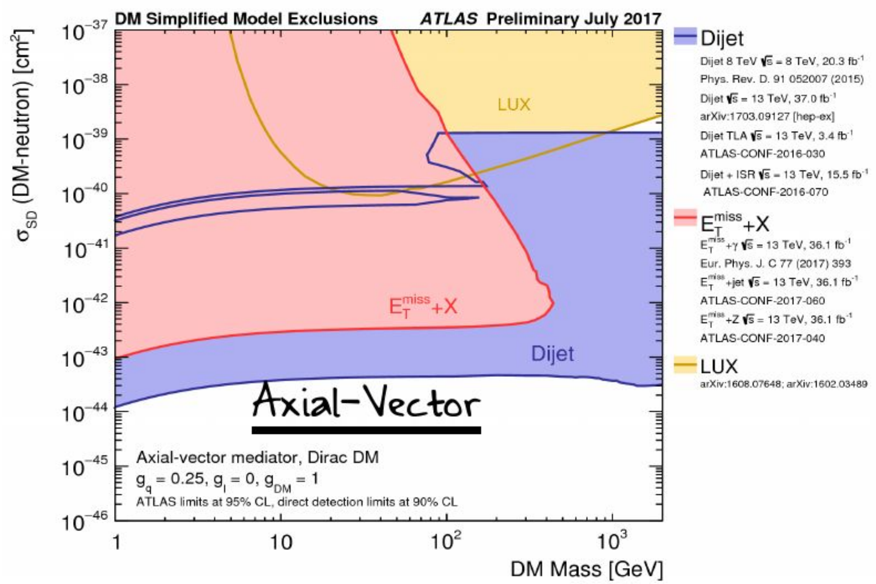
DM mass

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

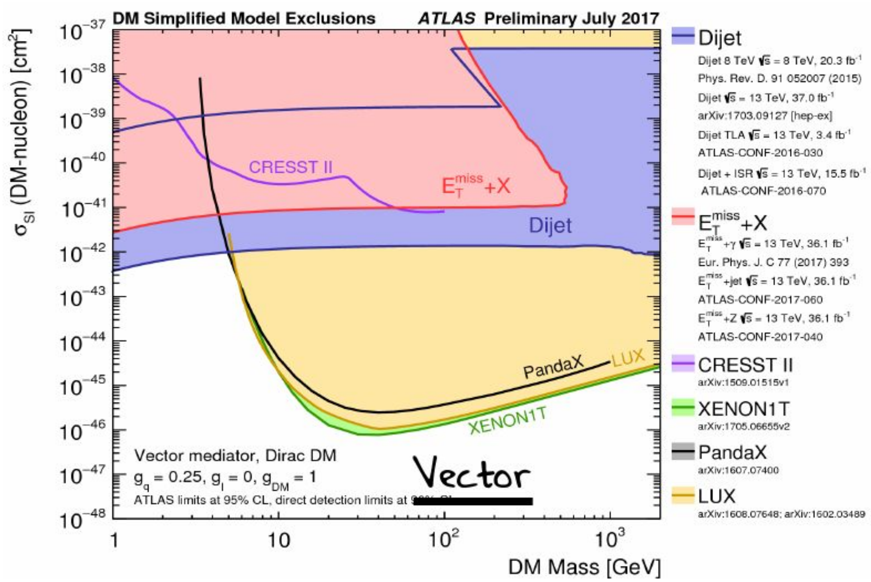
Credits : F. Cirotto, Dark matter searches with the ATLAS detector

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

Hunting axions

Models :

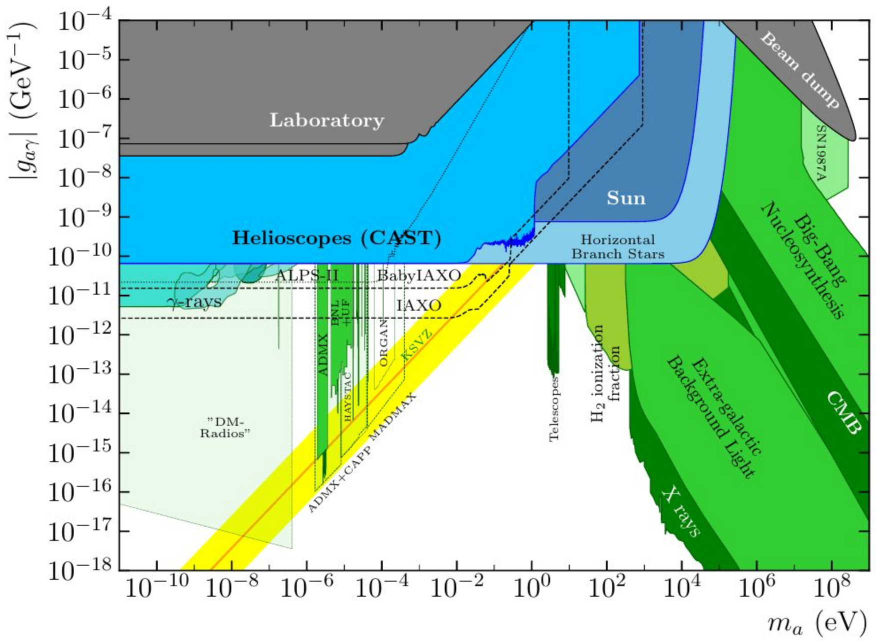
- Strong CP problem → "Peccei-Quinn" mechanism PQWW (Peccei-Quinn-Weinberg-Wilczek)
- Axion-photon coupling : $\mathcal{L}_{A\gamma} \;=\; -\frac{g_{A\gamma}}{4} A F_{\mu\nu} \widetilde{F}^{\mu\nu}$ $\quad g_{A\gamma} \equiv \frac{\alpha}{2\pi} \frac{C_{A\gamma}}{f_A}$
- Now ruled out and replaced by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

Many experiments fully dedicated on them :

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

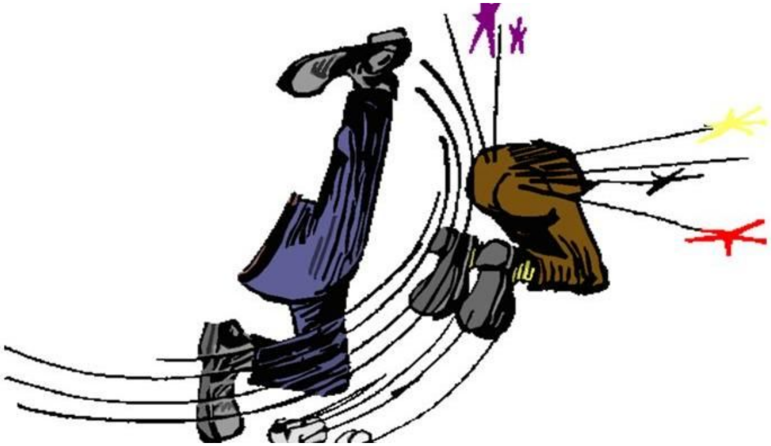
Haloscopes :
- ADMX, ORGAN, ...

See talk from Michael Tobar on ADMX



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

WIMP elastically scatters off nuclei



Direct detection in one phrase, but…

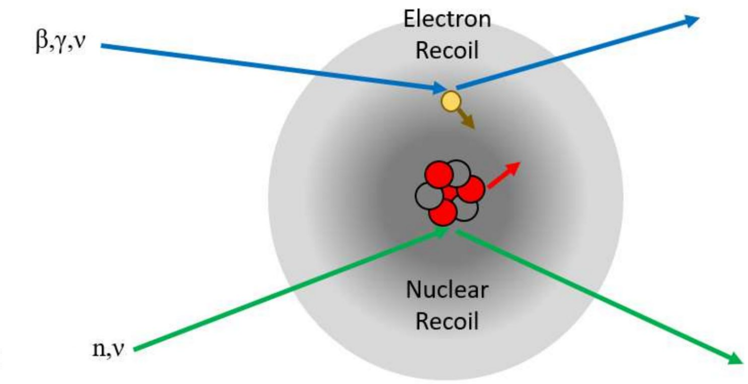
WIMP elastically scatters off nuclei

? ? ?

Direct detection in one slide

WIMP elastically scatters off nuclei → nuclear recoils

$$\chi + N \rightarrow \chi + N$$



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

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

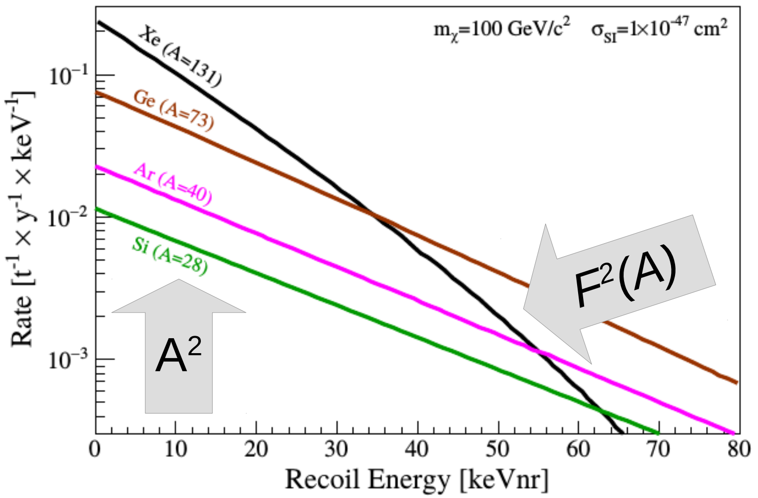
$$m_\chi = 10 - 10^4\ GeV/c^2$$

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

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

Spin Independent : χ scatters coherently off of the **entire nucleus** A: $\sigma \sim A^2$

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

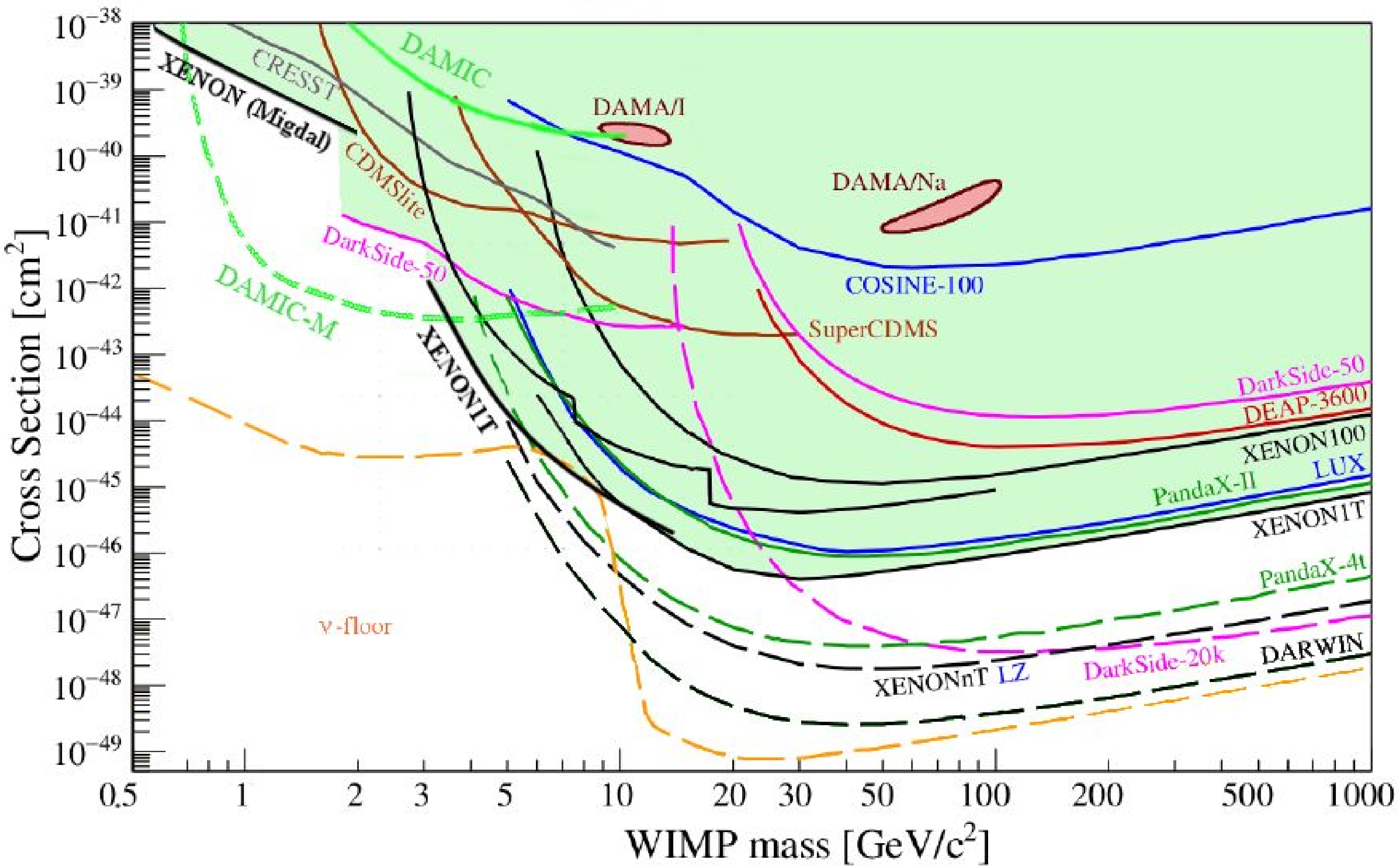


Experimental challenge :

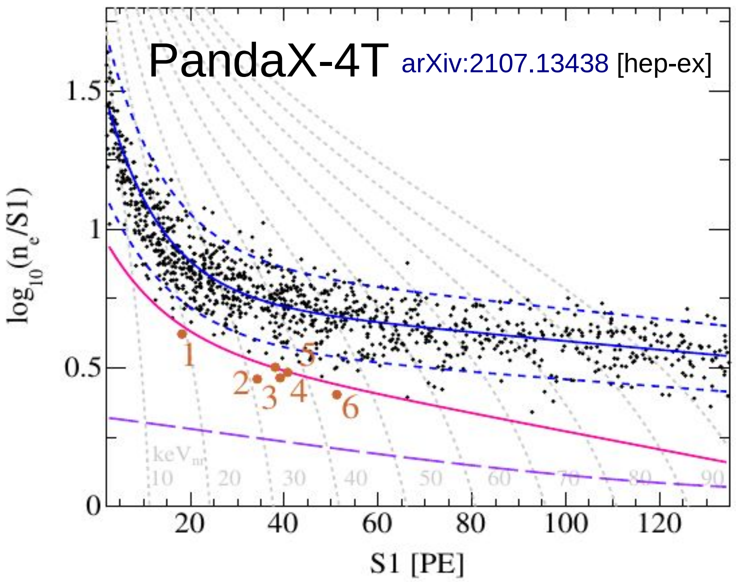
- low energy thresholds : O(1) keV

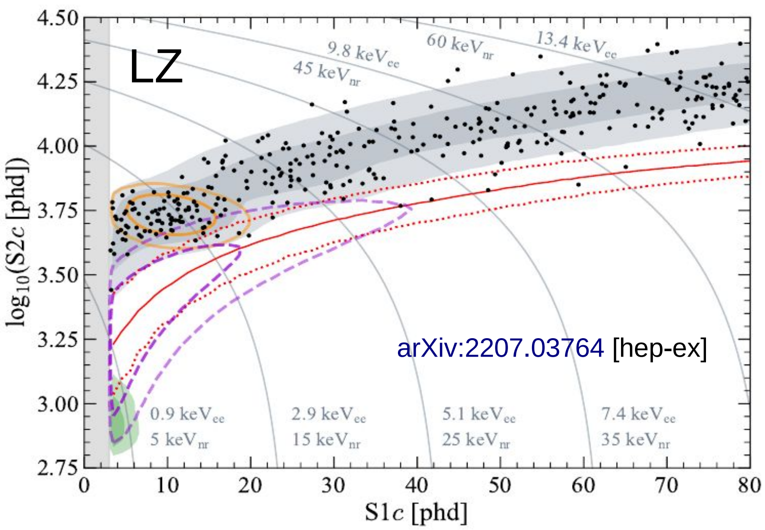
- very low backgrounds

Past, present and future



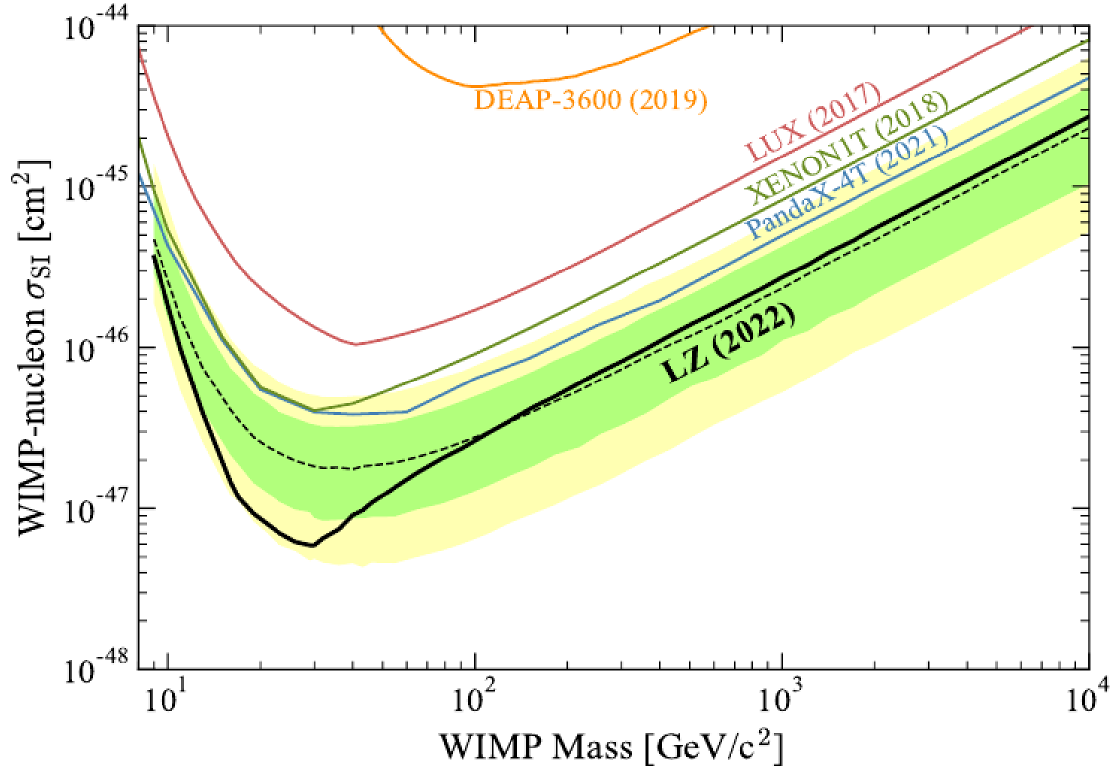
Latest news : PandaX-4T (2021), then LZ (2022)





Exposure :

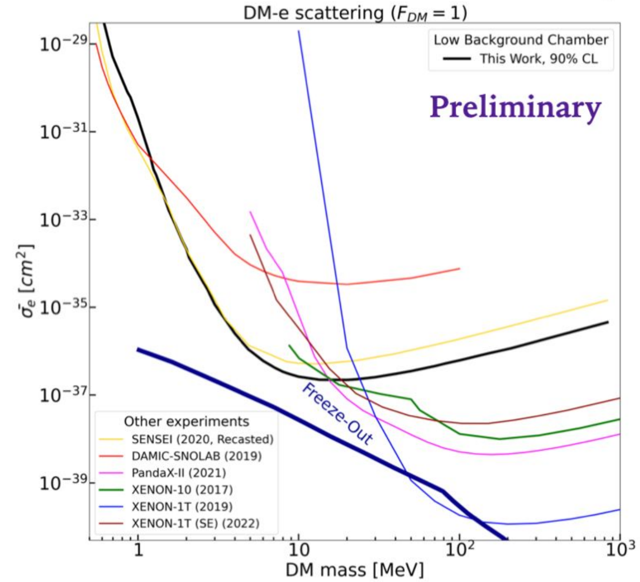
- PandaX-4T : 0.63 tons x year
- LZ : 60d x 5.5t = 0.90 tons x year

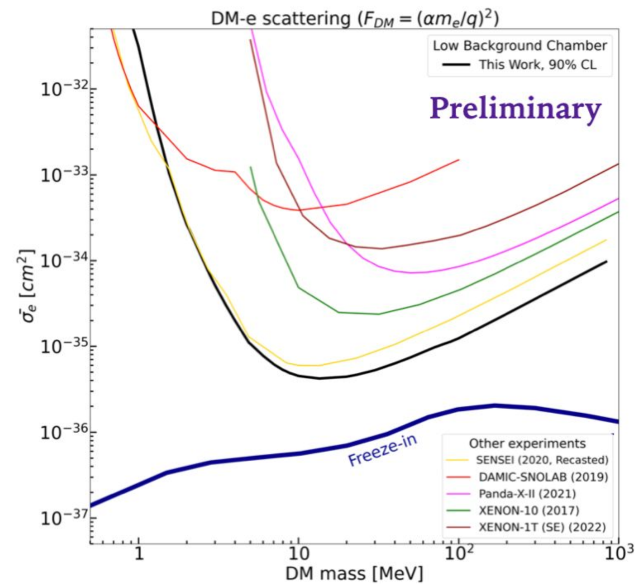


Both of them did a non-blinded analysis for their first scientific run

Scoping many other models

DAMIC-M : World class sensitivity !!!

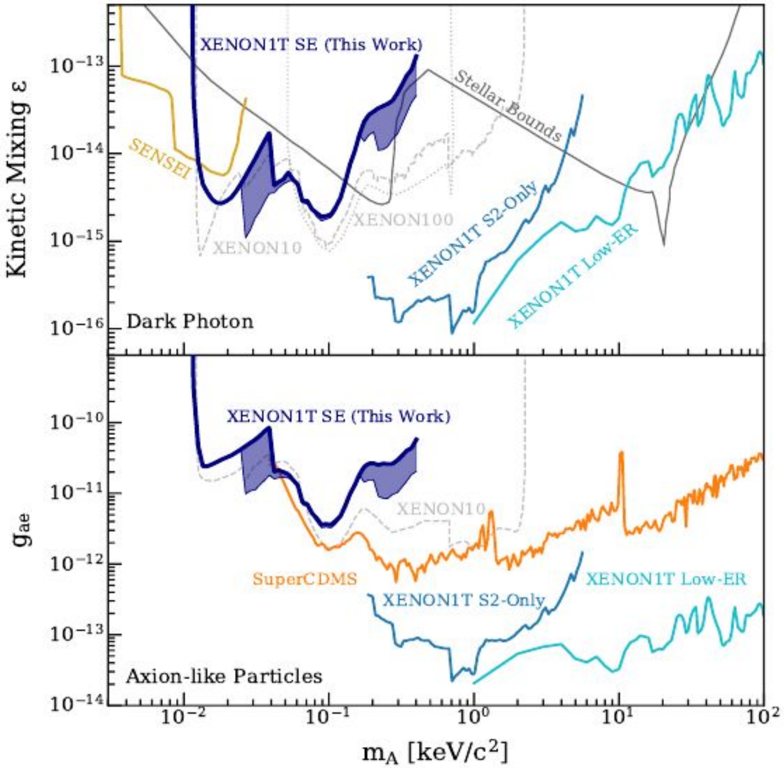




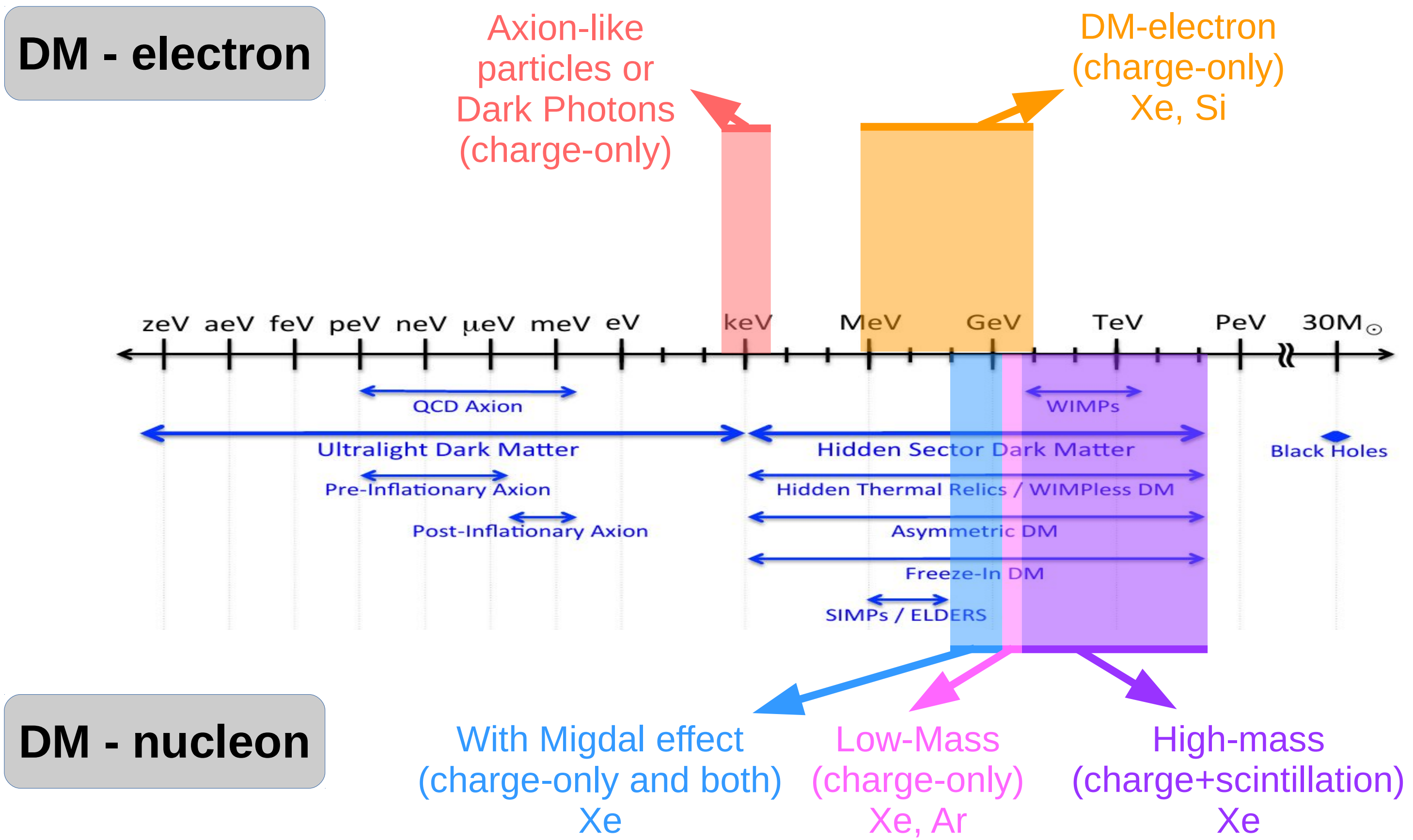
Stay tuned with XENONnT !!! (IDM2022)

Vector-boson
dark matter:
relic dark photon

Pseudo-scalar
dark matter : axion-like
particles (ALPs)



The scoped energy domains



Dark Matter and neutrinos

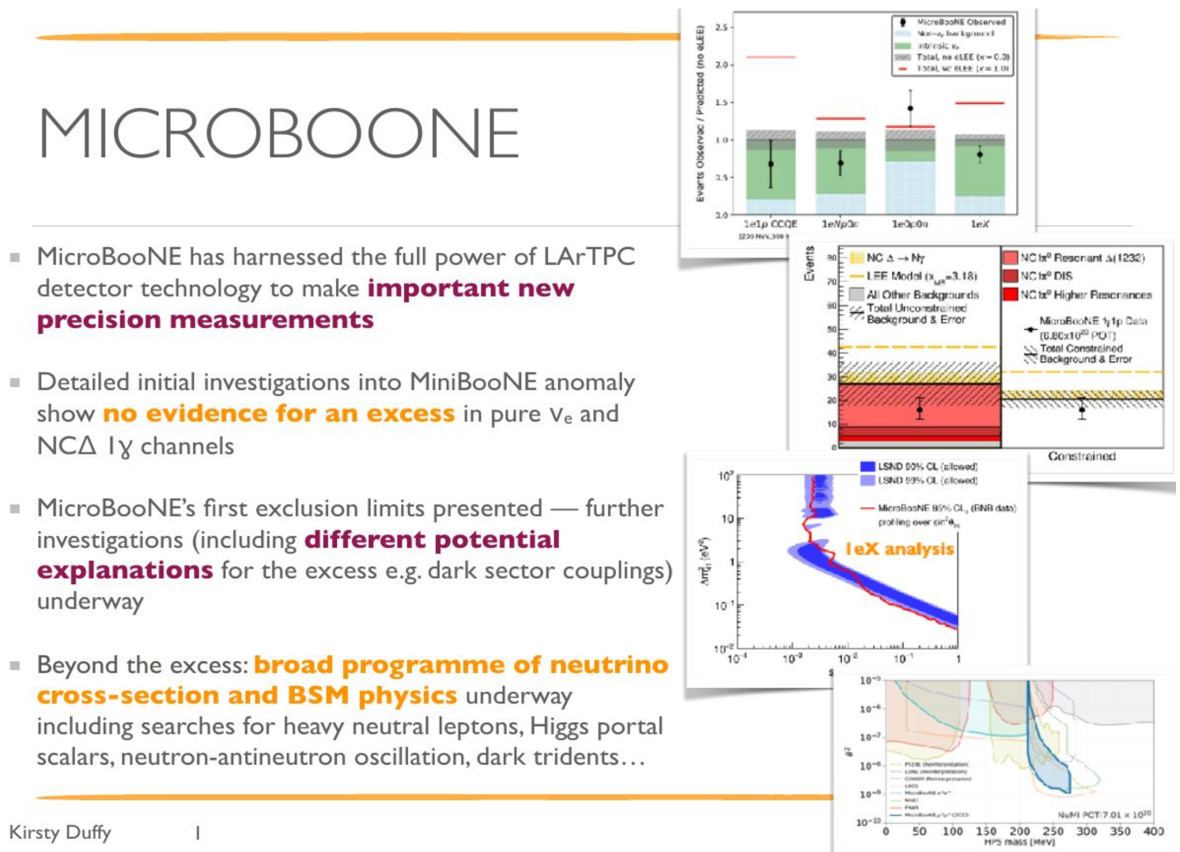
- Neutrinos as component of Dark Matter. Ruled out ? No, simply it has been quantified (hot dark matter with a well precise density)

- Short baseline experiments : NOMAD and CHORUS (~1995-1998), neutrinos at high Δm^2 (1-100eV^2)

- LNSD anomaly (1995, 2001)
  Sterile neutrino ?

- MiniBooNE excluded (2007) then confirmed a similar anomaly (2010)

- MicroBooNE improved the exclusion

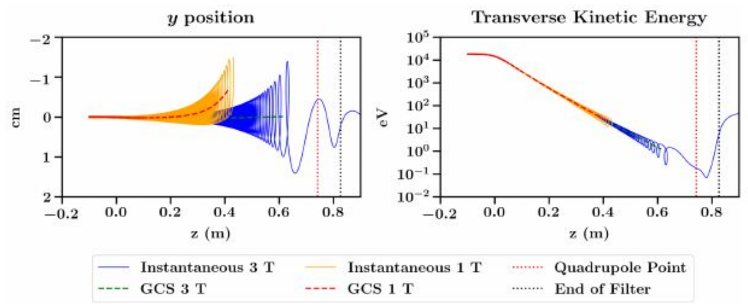


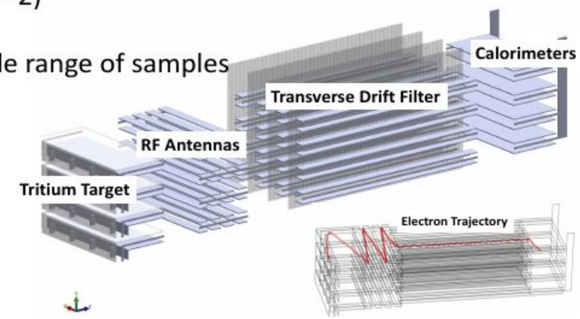
Cosmic Neutrino Background detection

PTOLEMY

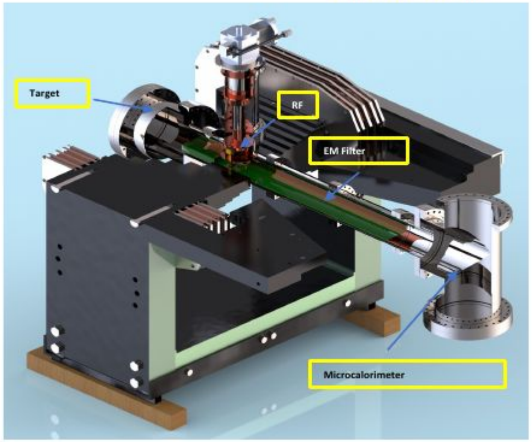
wonyongc@princeton.edu
https://ptolemy.lngs.infn.it

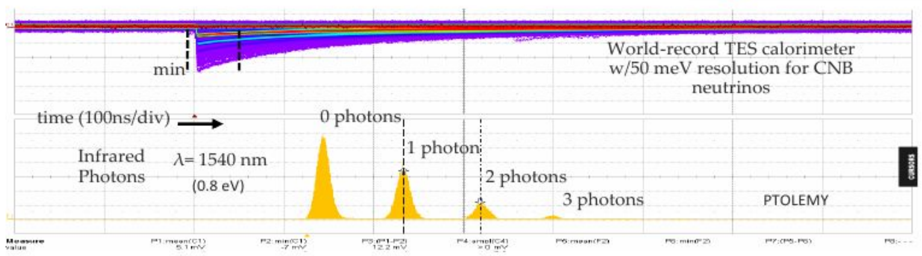
- Collection of cutting-edge technologies for CNB detection opens up interesting possibilities for other unknown DM searches
  - Configurable target
  - First-stage RF detection
  - Next-order compact EM filter (10^-4)
  - Next-next-order TES microcalorimeter (10^-2)
- Compact/highly-scalable size (~1m)
  - Suitable for precision spectroscopy for wide range of samples (<50meV resolution in ~10 eV steps)
  - Sterile keV neutrinos, directional DM
- Full-scale LNGS prototype 2022-2024



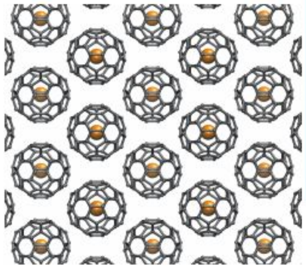


Andi Tan (Princeton)



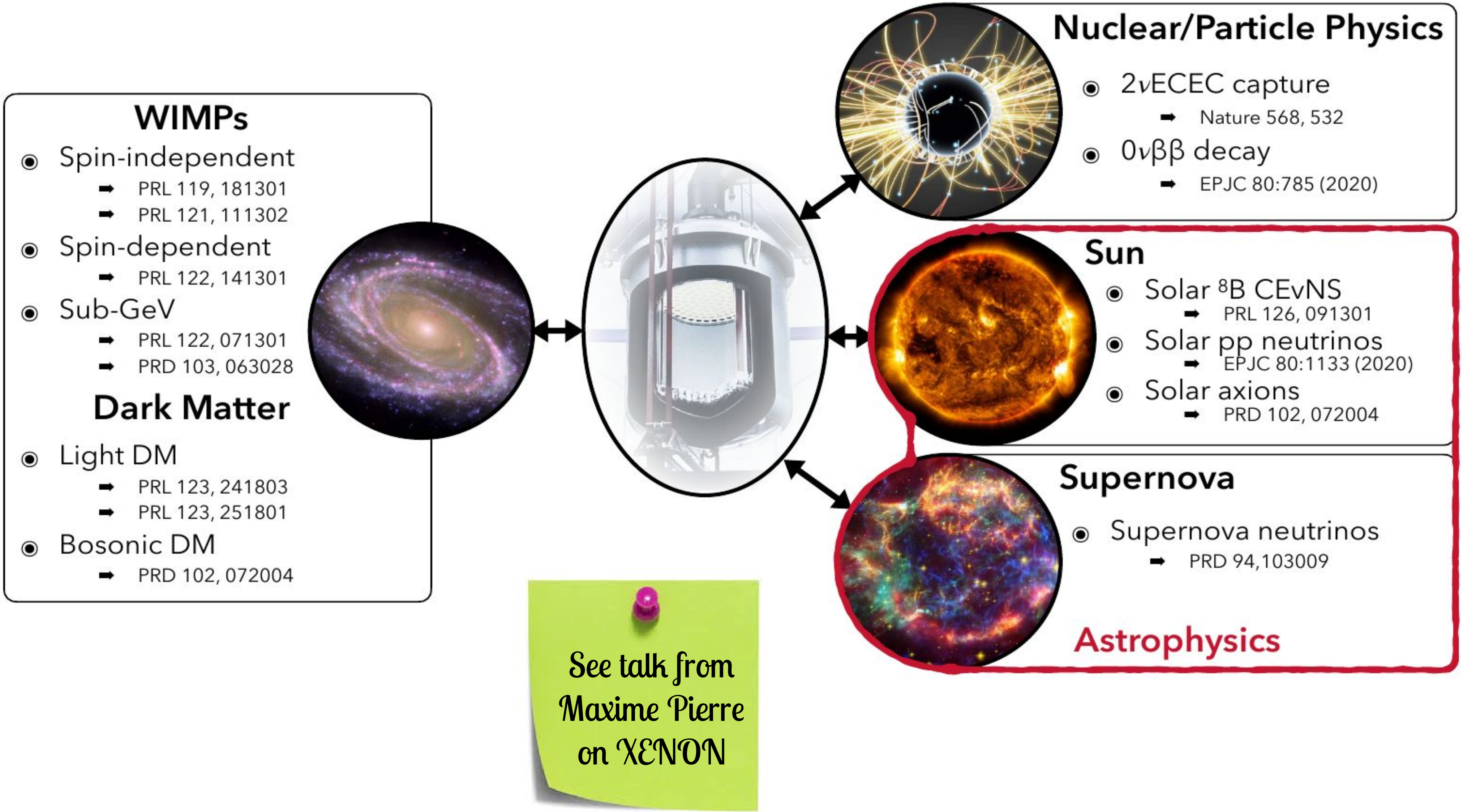


C. Pepe, E. Monticone, M. Rajteri



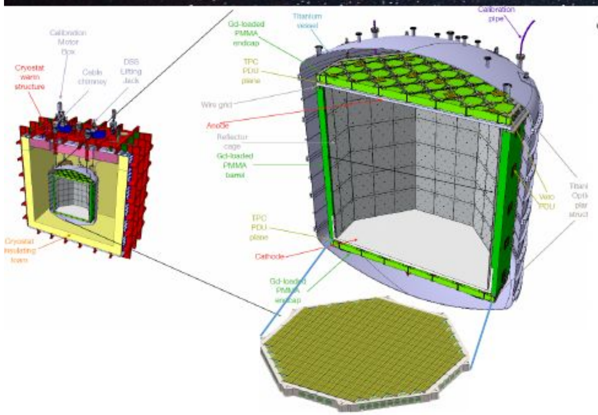
See talk from Wonyong Chung on PTOLEMY

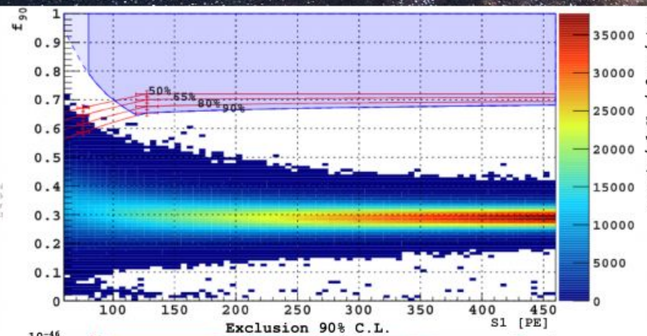
Dark matter detectors ?
No, astroparticle observatories

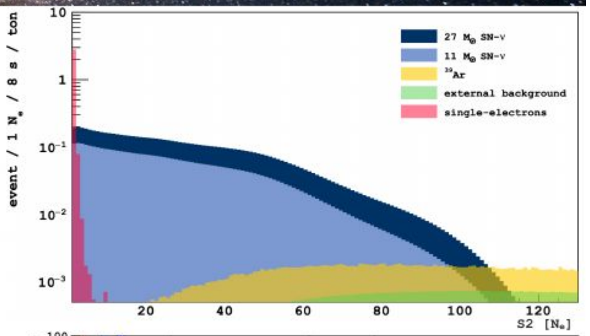


Dark matter detectors ?
No, astroparticle observatories

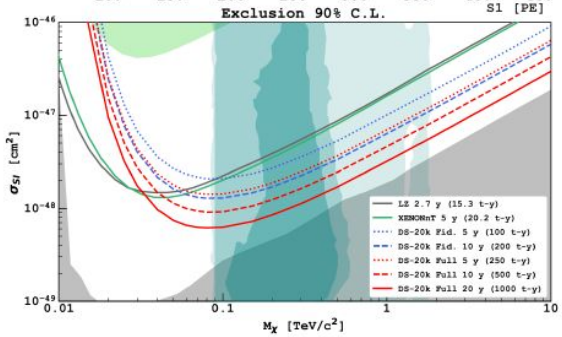
Dual phase LAr TPCs



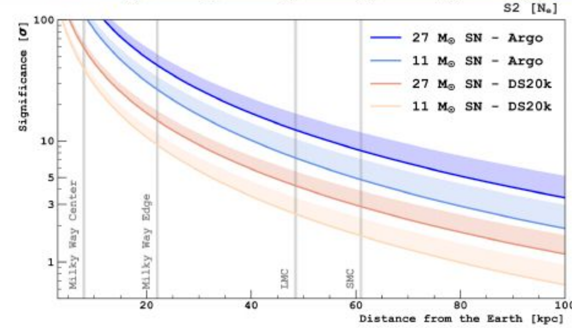




- Dual phase LAr TPCs are powerful tools to search for rare events thanks to:
  - Scalability to high target masses;
  - Event 3D position reconstruction;
  - ER vs NR discrimination.
- DarkSide-20k, under construction at LNGS, will have an active (fiducial) UAr target mass of 50 (20) tonnes.



- DarkSide-20k expects only 3.2 events of atmospheric neutrinos in the DM ROI for a 200 tonnexyr exposure.



- DarkSide-20k (Argo) will be able to detect and study core collapse Supernovae to the edge of the Milky Way (LMC).

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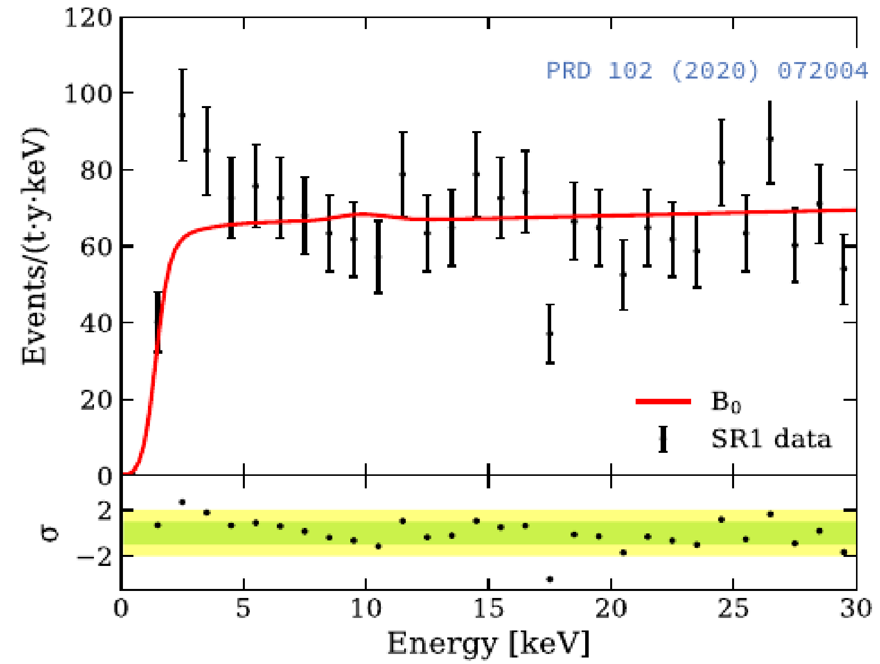
See talk from Claudio Savarese on DarkSide

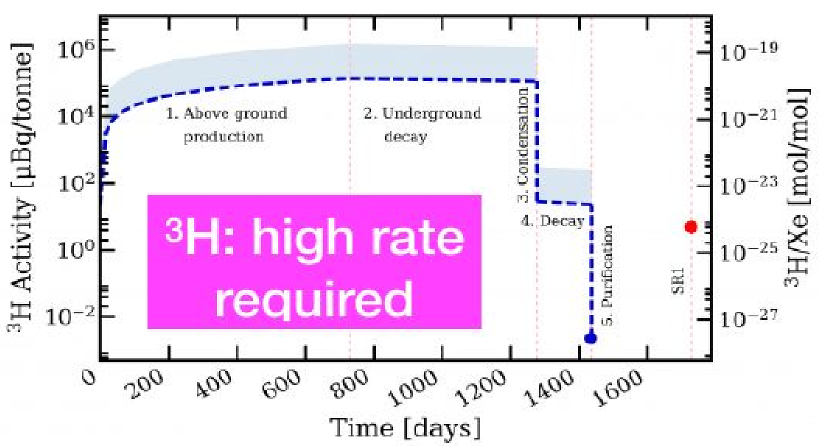
Looking for low-energy Electron Recoils



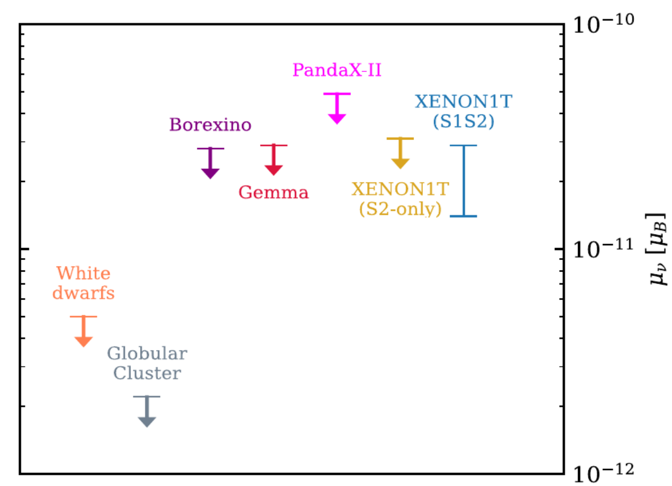
Excess found in 2020 by XENON1T on low-energy electron recoils :

- Tritium contamination ?
- Axion signal ?
- Effect of a non-null neutrino magnetic moment ?

$$\delta m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} = \frac{\mu_\nu}{10^{-18}\mu_B}\left(\frac{\Lambda}{1\ Tev}\right)^2 eV$$

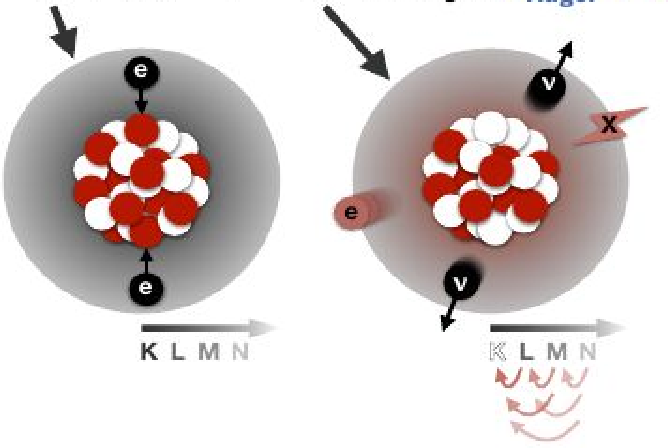


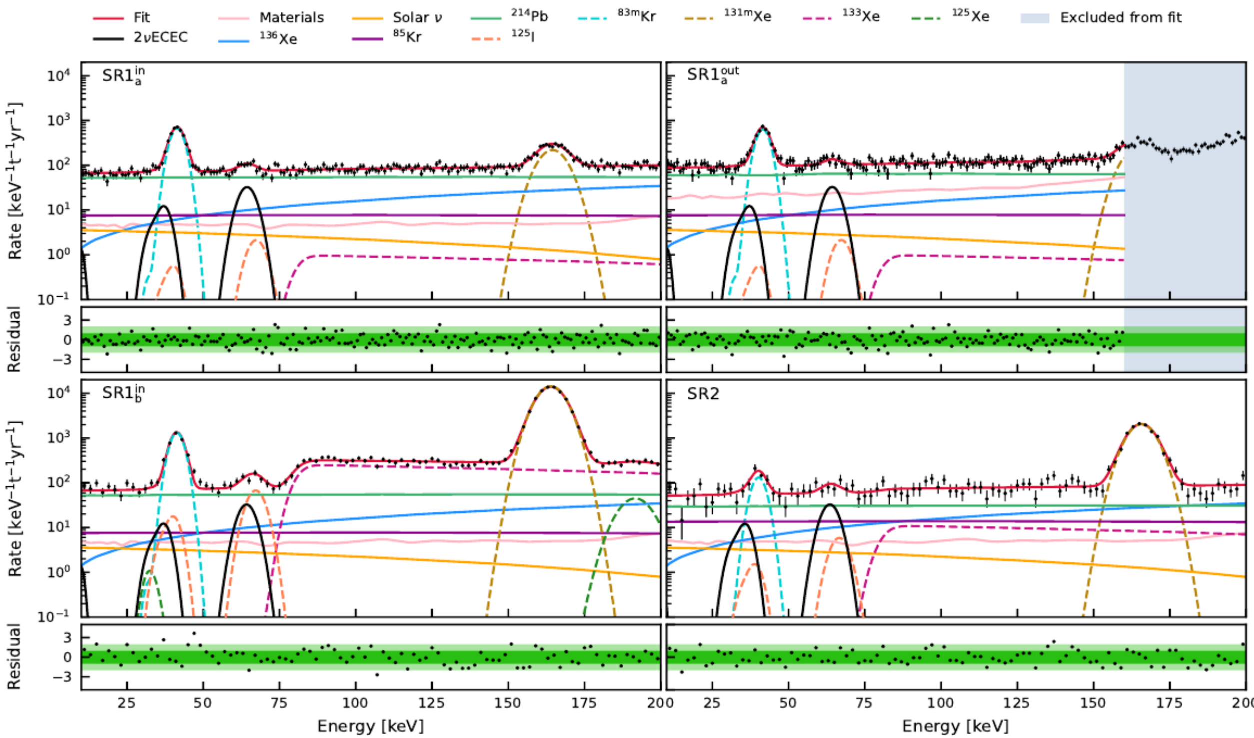
Limits on neutrino magnetic moment in the latest years



Double electron capture in ^{124}Xe

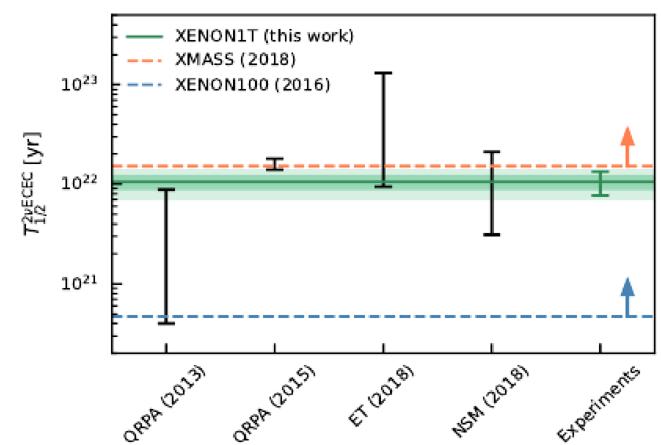
$$^{124}\mathrm{Xe} + 2\,e^- \rightarrow {}^{124}\mathrm{Te} + 2\,\nu_e + e_{Auger} + X$$





- Extremely rare process, never observed before
- K-shell electron capture → **X-rays and e_{Auger} (64.3 keV)**

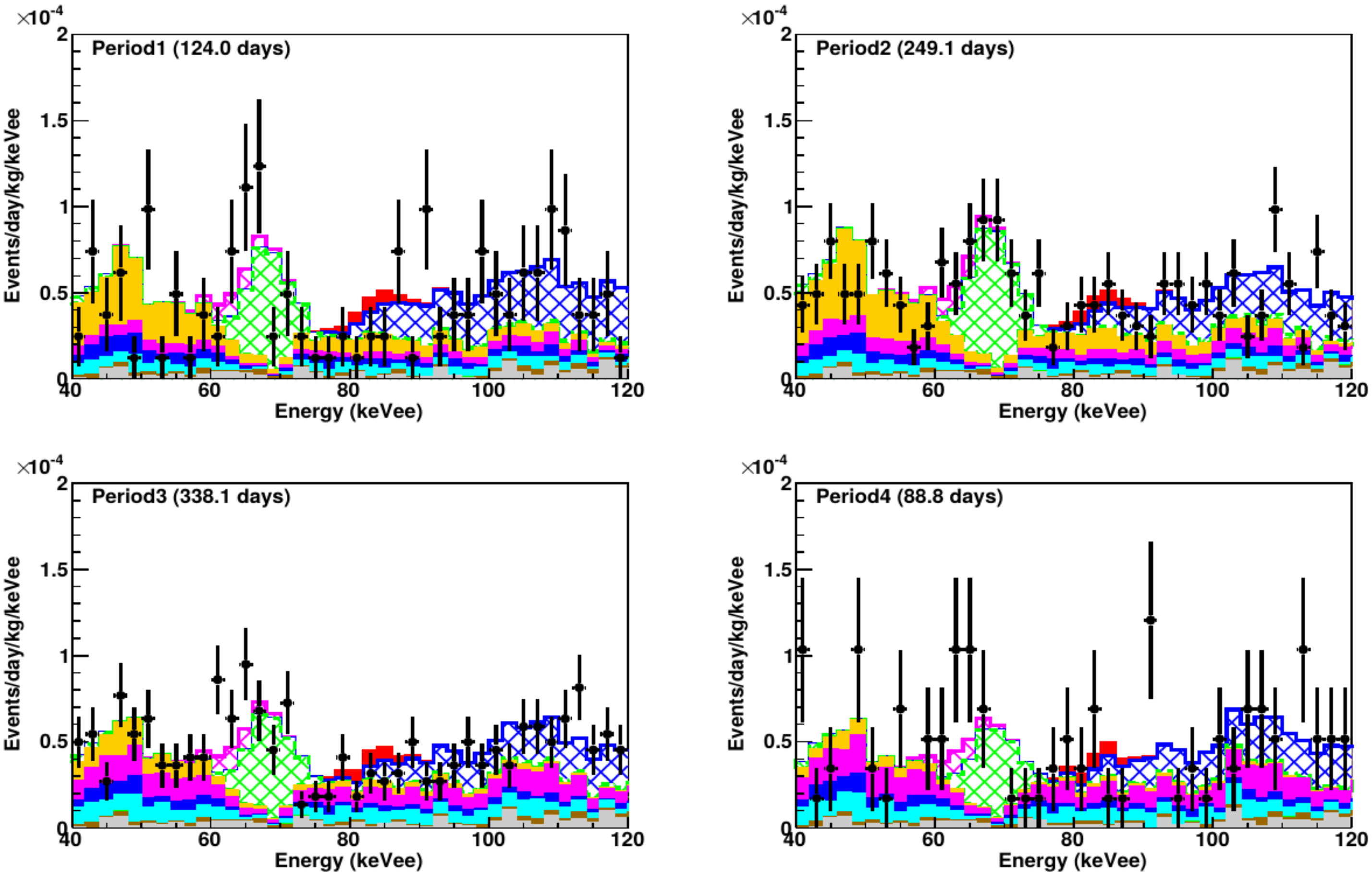
$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.1 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{sys}}) \times 10^{22}\ \mathrm{yr}$$



Nature volume 568, pages 532–535 (2019)

Then, recent paper with all XENON1T science runs (accepted in PRC) : arXiv:2205.04158 [hep-ex]

Neutrinoless quadruple decay of ^{136}Xe in XMASS-I



See talk from Kentaro Miuchi on XMASS

First experimental constraint on 0ν4β of ^{136}Xe. The longest half life limit

Exposure : 327kg x 800 days

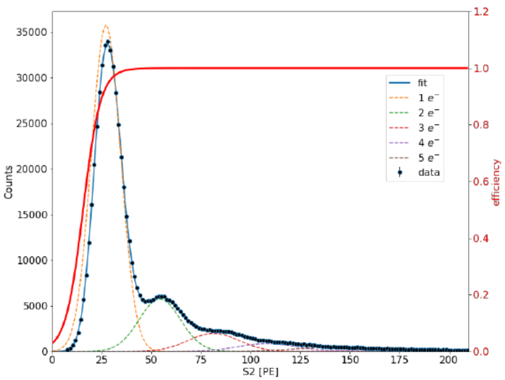
Looking for a peak >~ 79 keV

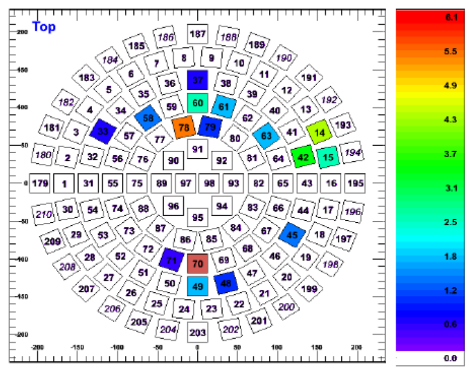
arXiv:2205.05231 [nucl-ex]

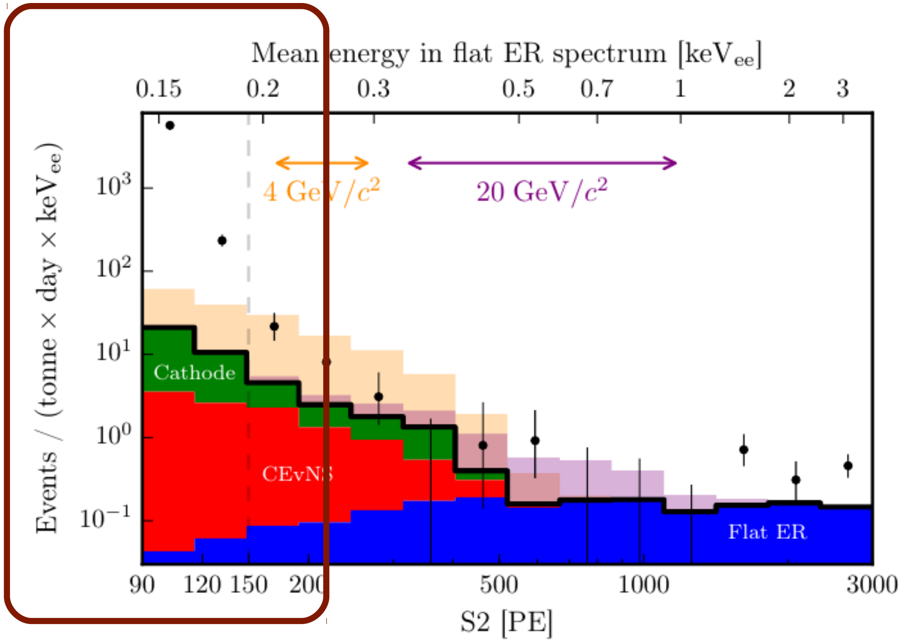
The calculated 90% CL upper limit is 3.7×10^{24} years.

Challenges for very low-mass DM search

Isolated electrons are the main background for this analysis and the mayor obstacle to go below 1GeV





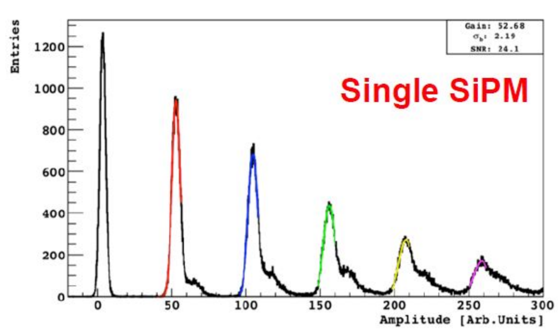


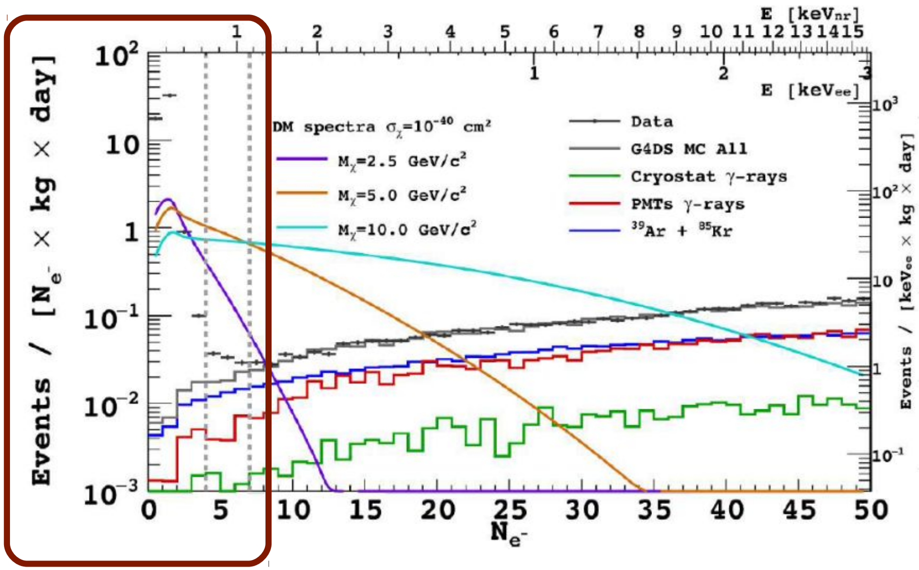
Possible reasons :

1) photo-dissociation of negatively charged impurities;
2) delayed extraction of trapped electrons at the liquid-gas interface
3) field emission from electrodes
4) neutralization of positive xenon ions at the cathode surface
5) long-lived bound states of excimers or weakly bound higher-energy states

Solutions to be investigated:

- Passivation of electrodes
- Optimization of electrodes geometry
- Minimization of metallic components
- Flushing electrons from surface
- Use of SiPM to improve resolution





A new physics case : neutrinos

Neutrino is background for Dark Matter search with noble liquids but it also offers a physics case of unvaluable richness !

Electronic Recoils (ER) from solar neutrinos

$\nu + e^- \rightarrow \nu + e^-$

Scoping neutrino and solar models !
ARGO : CNO neutrinos
JCAP 1608 (2016) 8, 017
DARWIN: ~ 2000 neutrino pp per year, 2% (1%) precision in 1 (5) years
JCAP 01, 044 (2014), arXiv:1309.7024

Nuclear Recoils (NR) from solar neutrinos

$\nu + N \rightarrow \nu + N$

DARWIN: 90 events/t/y @ E>1keVnr (~3000 CNNS events/year)
JCAP 01, 044 (2014), arXiv:1309.7024

Nuclear Recoils (NR) from supernova bursts

$\nu + N \rightarrow \nu + N$

ARGO and DARWIN
DARWIN: O(10) MeV ν's → O(1) keVnr
→ 5σ significance with a 27 $M_\odot$ progenitor far up to 65 kpc from Earth
→ 704 events @ 10 kpc
Phys.Rev. D94 (2016) no.10, 103009, arXiv:1606.09243

Double Electron Capture

$2\,(p + e^- \rightarrow n + \nu_e)$

Results from XENON1T with ^{124}Xe

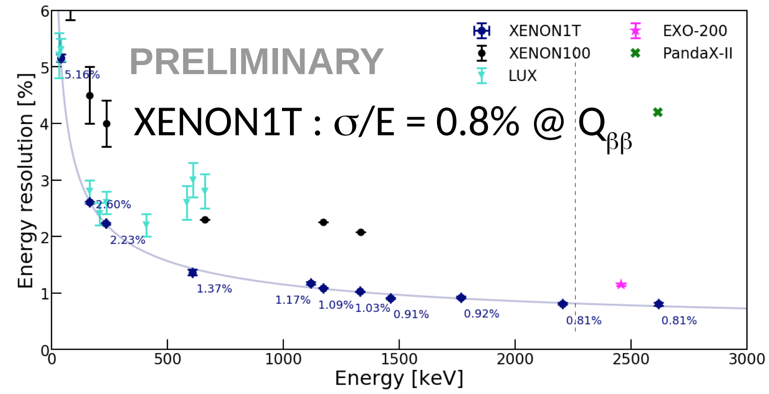
XENONnT will confirm the 2vECEC measurement and will also scope :

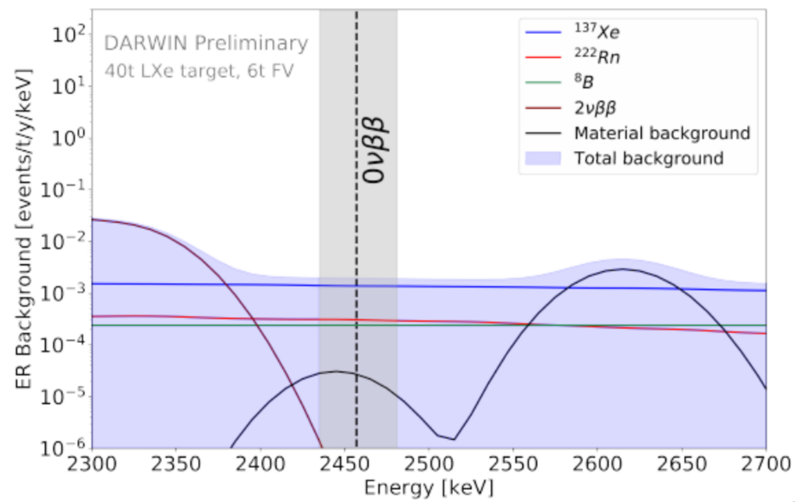
2v EC β+, 2v β+ β+,
0v EC β+, 0v β+ β+

Nature 568, 532–535 (2019), arXiv:1904.11002

Neutrinoless Double Beta Decay

^{136}Xe (8.9%): $Q_{\beta\beta}$ = 2458.7 ± 0.6 keV



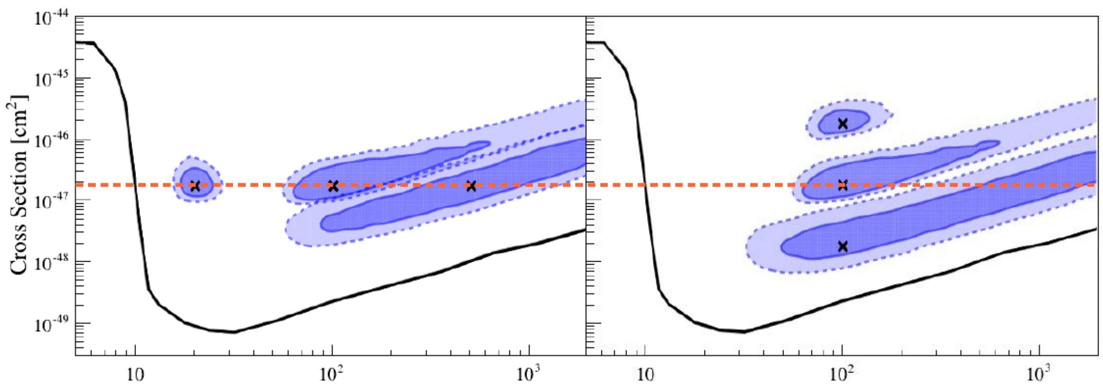


What if XENONnT (or LZ or PandaX) finds a signal ?

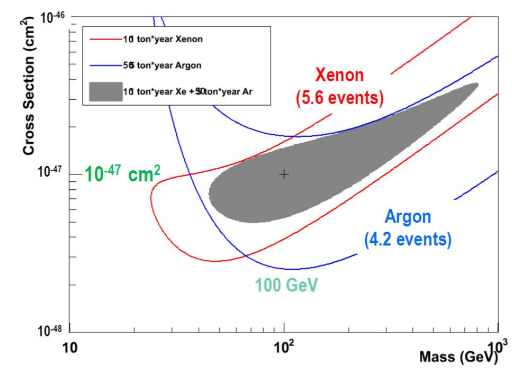
If the interaction is **Spin Independent**

It needs to be confirmed with larger detectors like DARWIN or DarkSide-20k

DARWIN and Argo could do spectroscopy :



Capability of DARWIN on reconstructing the WIMP mass and cross section for various masses (20, 100, 500 GeV/c2) and cross sections

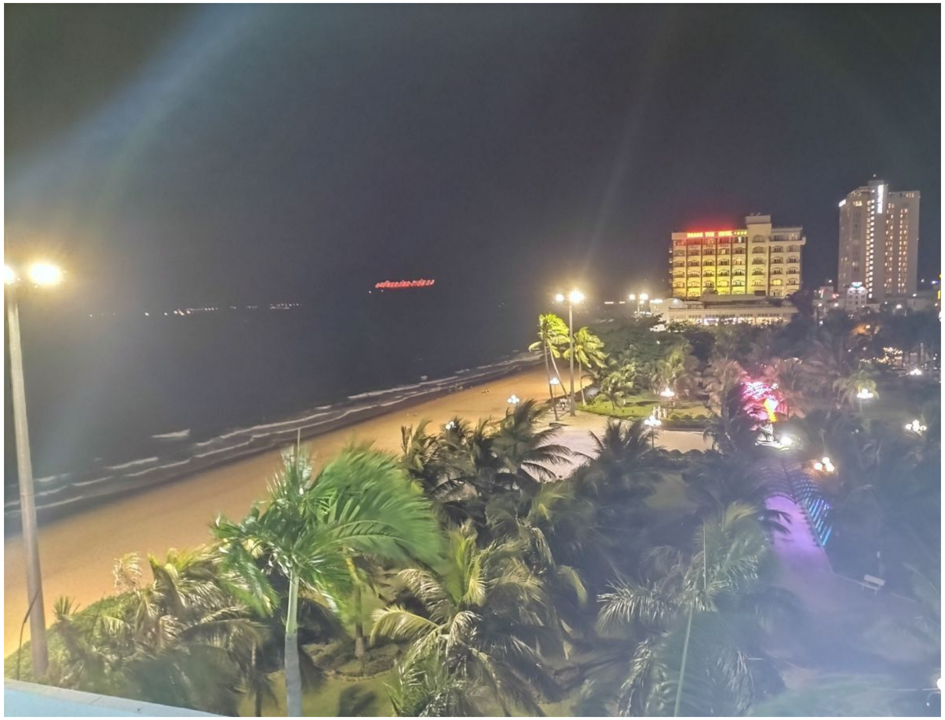


Crossing Argon and Xenon detectors can reduce the likelihood, but only for a WIMP at 100 GeV/c²

If the interaction is **Spin Dependent**

Argon or any pair target is useless. The only way is to re-run a xenon detector with different xenon isotopes (enrichment)

Continuing enlightening the Dark…



Thanks