Enlightening the dark
Direct dark matter searches with XENON

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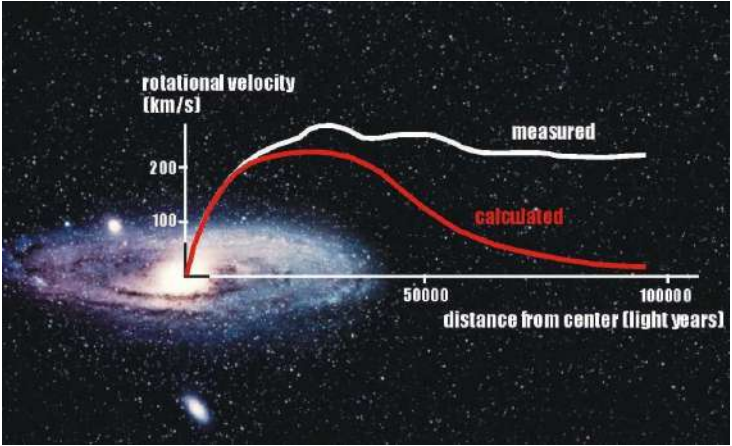
Looking at our Universe ...

... dynamics do not behave as expected

Vera Rubin, undergraduate at Vassar 1940s (brainpickings.org)

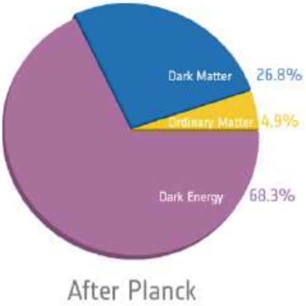
Looking at our Universe ...

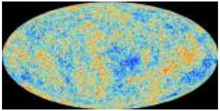
... dynamics do not behave as expected

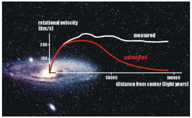


Cosmological and astronomical hints

- Cosmic microwave background
- Large scale structure-formation
- Velocity dispersion of galaxies in clusters (F. Zwicky 1933)
- Rotation velocities of stars in galaxies (V. Rubin 1978)
- Gravitational lensing (A. Einstein 1936)
- Collisions of galaxy clusters (Bullet cluster, Abell 520 and few others)







What is dark matter?

Early solutions to the missing mass problem:

- Modified gravitational theories e.g. MOND (Milgrom 1983)
  → fail/need unrealistic parameters for some observables (e.g. CMB)

- Massive astrophysical compact halo objects: MACHOS
  → not enough such objects found (MACHO Coll. 2001)
  → Disfavoured by Big Bang nucleosynthesis
  Primordial black holes as an option

A new elementary particle?

- Massive → explain gravitational effects
- Neutral → no EM interaction & Weakly interacting at most
- Stable or long-lived → not to have decayed by now
- Cold (moving non-relativistically) or warm → structure formation

Millenium simulation

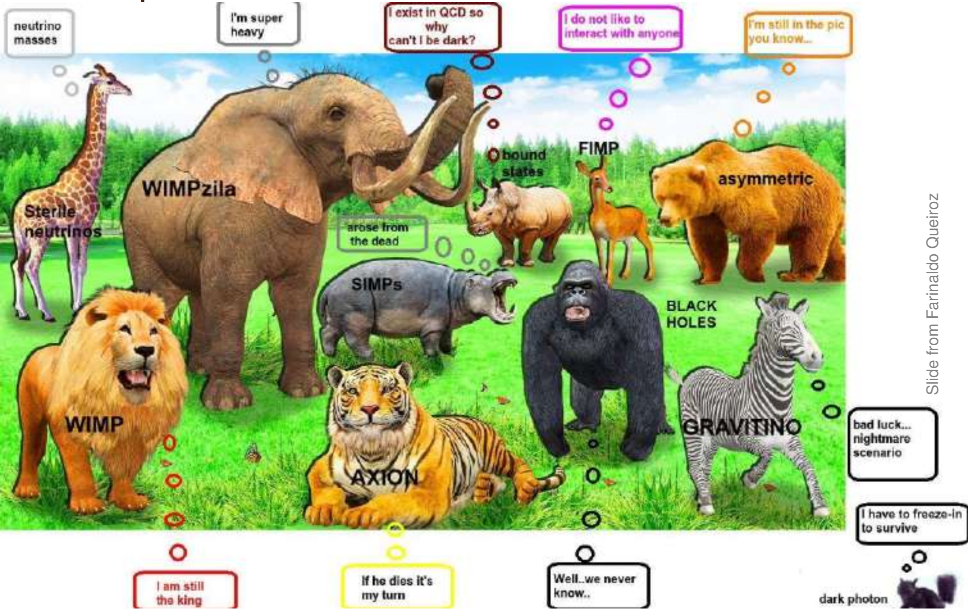
In the standard model of particle physics:
Neutrino fulfil most
but it is a hot dark matter candidate

Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

A new particle?

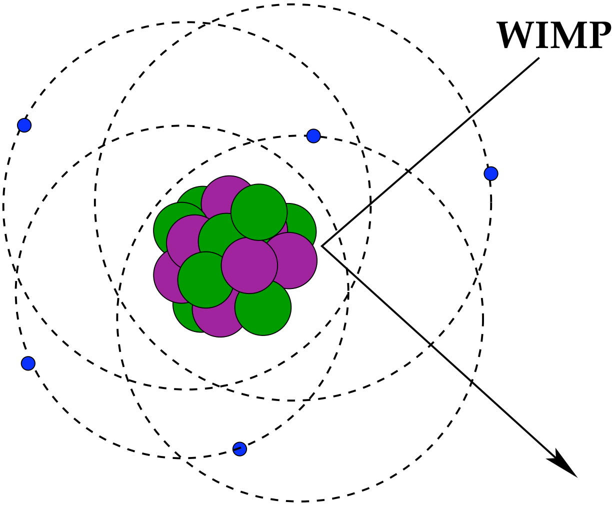


Slide from Farinaldo Queiroz

How can we look for dark matter?

Indirect detection	Direct detection	Production at LHC
		
$\chi\overline{\chi} \rightarrow \gamma\gamma, q\overline{q}, ...$	χ N $\rightarrow \chi$ N	p + p $\rightarrow \chi\overline{\chi}$ + X

Direct dark matter detection



$E_{\mathrm{R}} \sim \mathcal{O}(10\,\mathrm{keV})$

Expected interaction rates in a detector

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Astrophysical parameters:

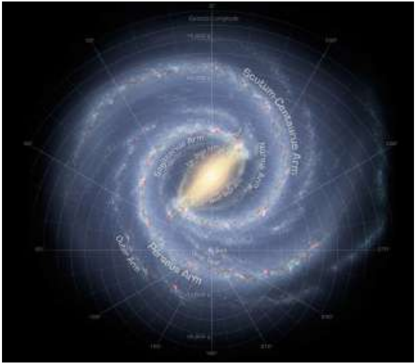
- ρ_0 = local density of the dark matter in the Milky Way

  'Standard' value: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- $f(\mathbf{v},t)$ = WIMP velocity distribution, $\langle v \rangle \sim 220\,\mathrm{km/s}$

Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

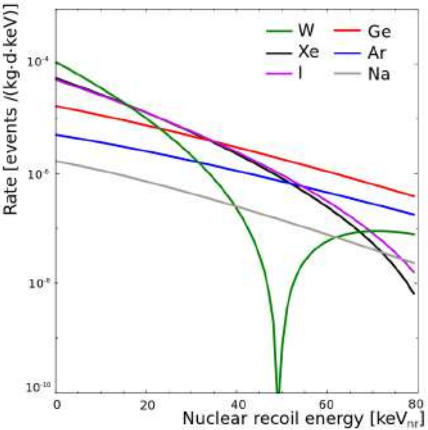
Figure from NASA



Detector requirements

J. Phys. G: 43 (2016) 1, & arXiv:1509.08767

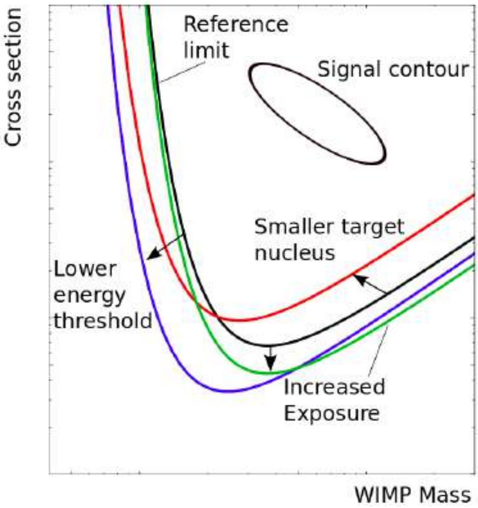
- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold $\sim$ few keV's
  - Very low background
  - Technology or analysis tools to discriminate signal and background



Result of a direct detection experiment

→ Statistical significance of signal over expected background?

J. Phys. G: 43 (2016) 1 & arXiv:1509.08767



- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

o Low WIMP masses: detector threshold matters

o Minimum of the curve: depends on target nuclei

o High WIMP masses: exposure matters $\epsilon = m \times t$

Overview spin-independent results

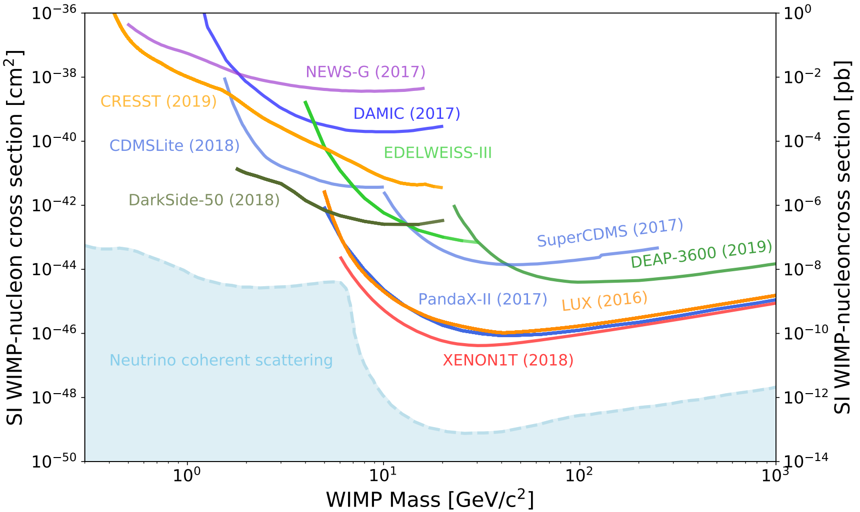
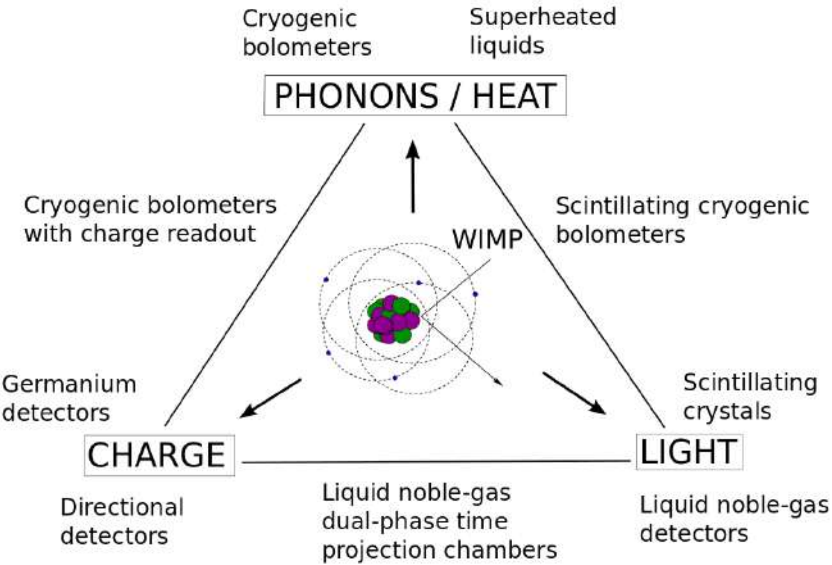


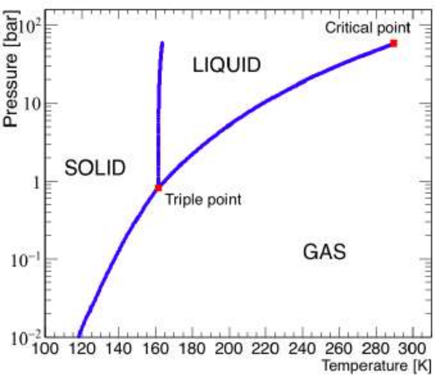
Figure from P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020 (2020) 083C01

Direct detection experiments

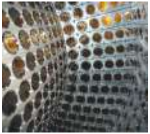


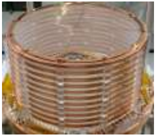
J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

Liquid xenon as detector

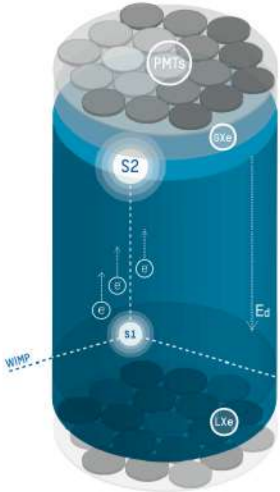


- Cryogenic liquid typically operated at 2 bar and −100°C
- High density: 3 g/cm^3
- High scintillation and ionization yields
- Employed in particle-, neutrino-, dark matter- and medical physics





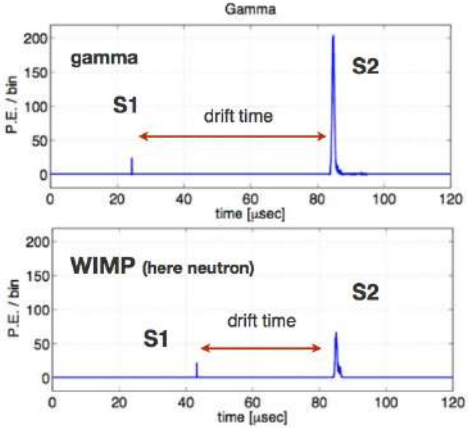

Two phase noble-gas TPC



Position resolution to define the innermost radiopure volume for analysis

- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

→ Electron- /nuclear recoil discrimination



Particle identification based on S1 & S2

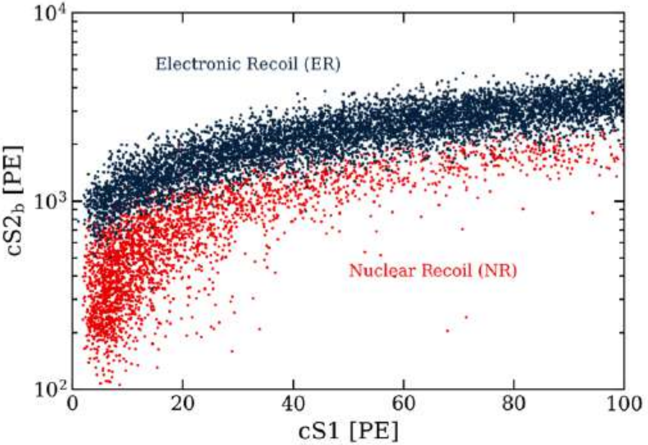


Figure from XENON1T data

- ER: calibrated using a ^{220}Rn source (β-decays of ^{212}Pb)
- NR: calibrated using a neutron generator / AmBe-neutron source

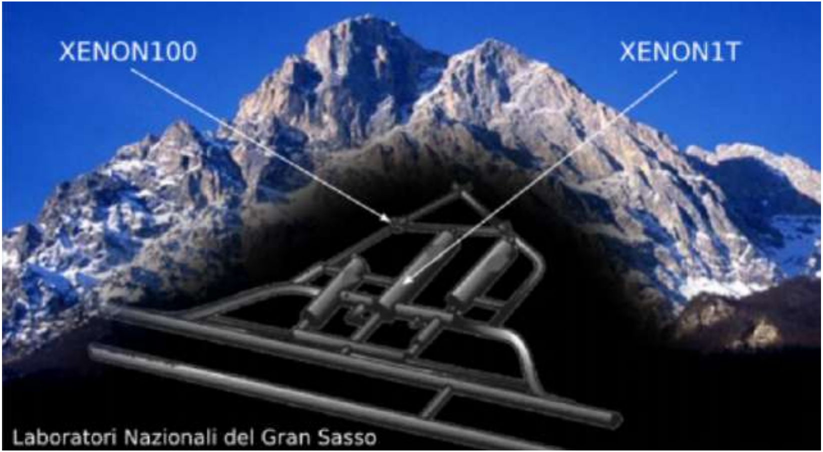
THE XENON EXPERIMENT

XENON collaboration

Experiment operated by ~ 160 scientists worldwide

XENONnT technical meeting with ZOOM

XENON experiment



@ Laboratori Nazionali del Gran Sasso (Italy)
below 3 650 m.w.e. shielding

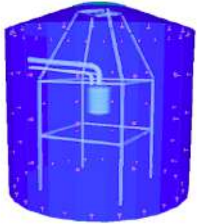
XENON underground

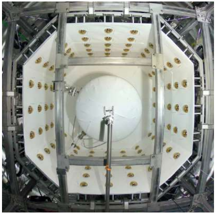
XENON water tank and building @LNGS, location underground

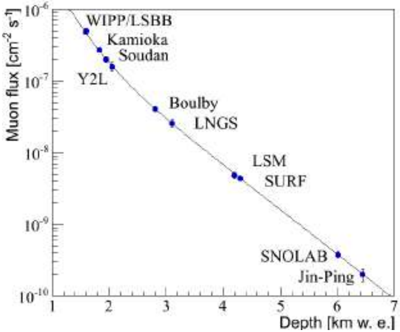
The XENON program

XENON10	XENON100	XENON1T	XENONnT
			
(2005-2007)	(2008-2016)	(2015-2018)	(2019-20xx)
Target: 25 kg	Target: 62 kg	Target: 2 ton	Target: 5.9 ton
$\sigma \sim 10^{-43}$ cm^2	$\sigma \sim 10^{-45}$ cm^2	$\sigma \sim 10^{-47}$ cm^2	$\sigma \sim 10^{-48}$ cm^2

Shielding against radiation





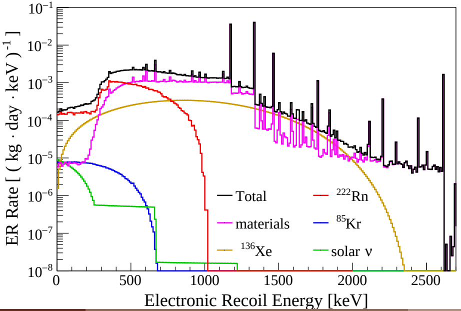


J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

- Underground location to shield from cosmic particles
- Active water-Cherenkov muon shield
- Neutron veto for XENONnT
- Veto system instrumented with photosensors (PMTs)

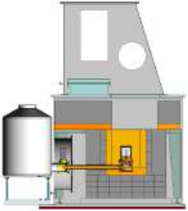
Backgrounds

- **External backgrounds**: from natural radioactivity:
  - γ-activity and neutrons
- **Neutrinos** from the Sun:
  - Elastic neutrino-electron scattering of ν
  - Coherent elastic neutrino-nucleus scattering (CEνNS)
- **Internal contamination**:
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.3 \times 10^{21}$ y)
  - ^{85}Kr: from ^{nat}Kr in Xe in the xenon inventory
  - Rn: dominant contribution to the background

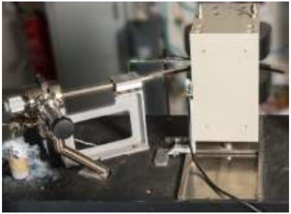


XENON1T, JCAP04 (2016) 027

Background reduction @MPIK


Scheme GeMPI detector


Giove @ MPIK


RGMS for Kr measurements


Radon measuring system

- High sensitive HPGe spectrometers
  - GeMPIs detectors at LGNS (Italy) with ~ 10 μBq/kg sensitivity in U & Th
  - 3 additional spectrometers at MPIK shallow lab
- Measurement of Kr concentration with a rare-gas mass spectrometer
  - Sensitivity of 6 ppq   Lindemann & Simgen, Eur. Phys. J. C 74 (2014) 2746
- Radon emanation and radon measuring systems
  - Automatized emanation setup

XENON1T WIMP searches

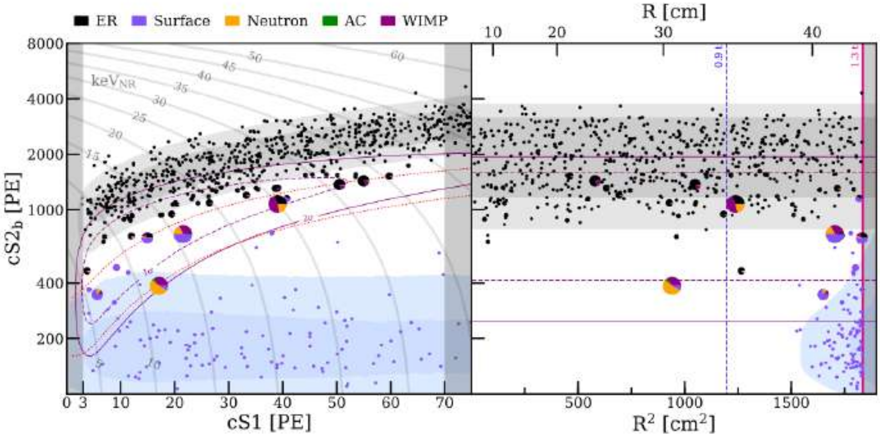
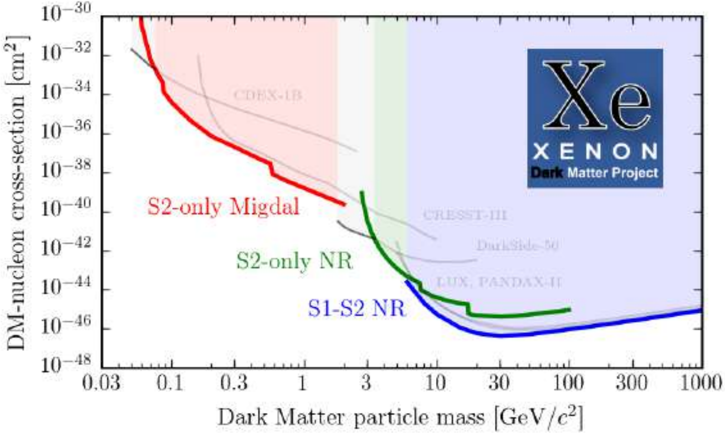


Figure from XENON1T, PRL 121, 111302 (2018) & arXiv:1805.12562

Science run 1 data from XENON1T

no significant signal → exclusion limit derived

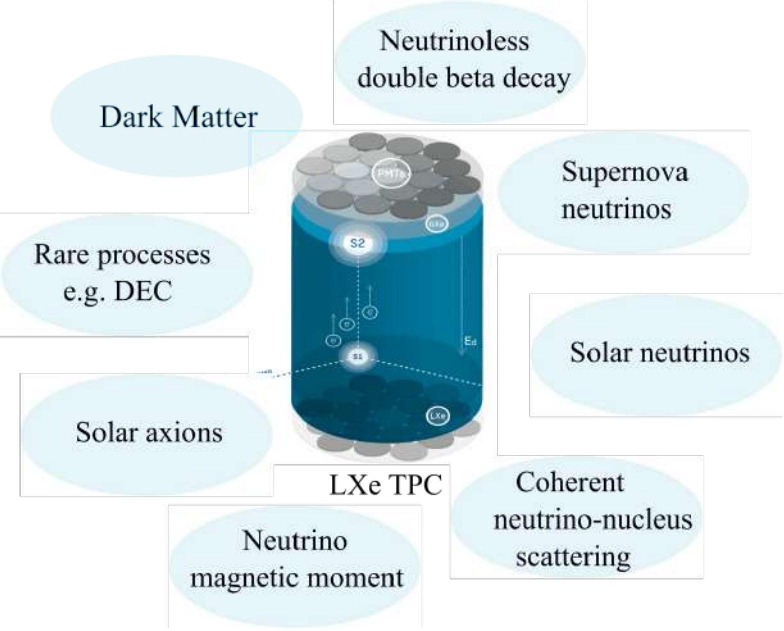
Latest dark matter results



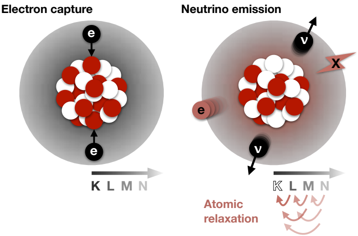
XENON1T, PRL 121 (2018) 111302, PRL 123 (2019) 251801 & PRL 123 (2019) 241803

BEYOND WIMP SEARCHES

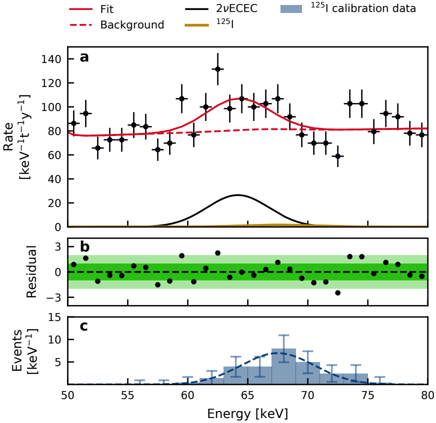
Multi-physics goals in large liquid xenon detectors



^{124}Xe double-electron capture



From XENON1T, Nature 568 (2019) 7753, 532

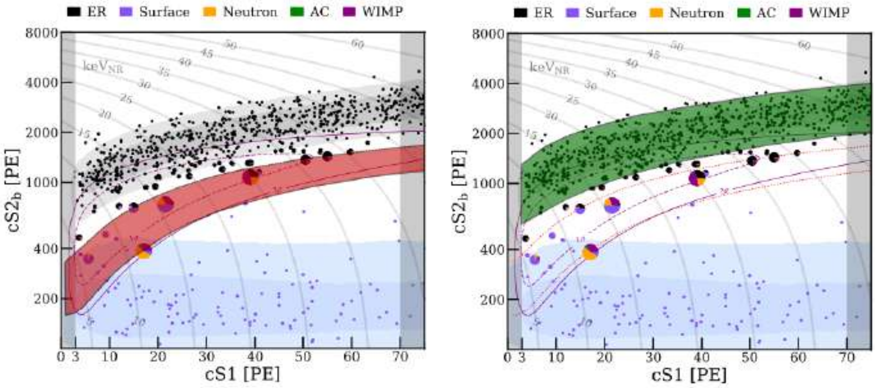


Measured half-life:

$$T_{1/2}^{2\nu\text{ECEC}} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{y}$$

→ longest directly measured half-life

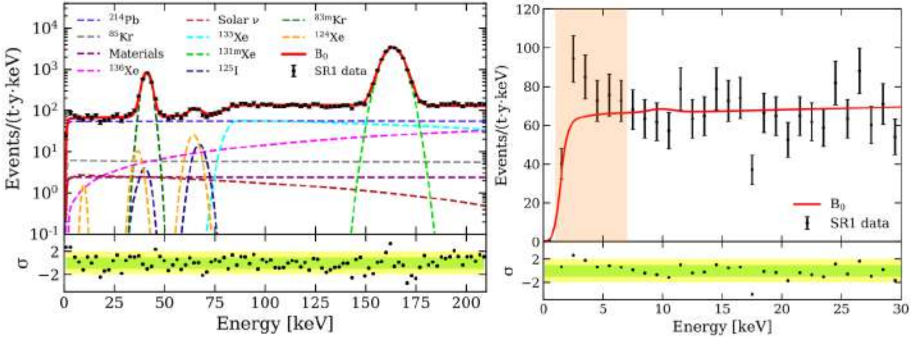
Focussing on electronic recoils



Data from XENON1T, Phys. Rev. Lett. 121 (2018) 111302 & arXiv:1805.12562

- WIMP search: in the NR region with almost zero background
- ER searches: excess events above a known background level

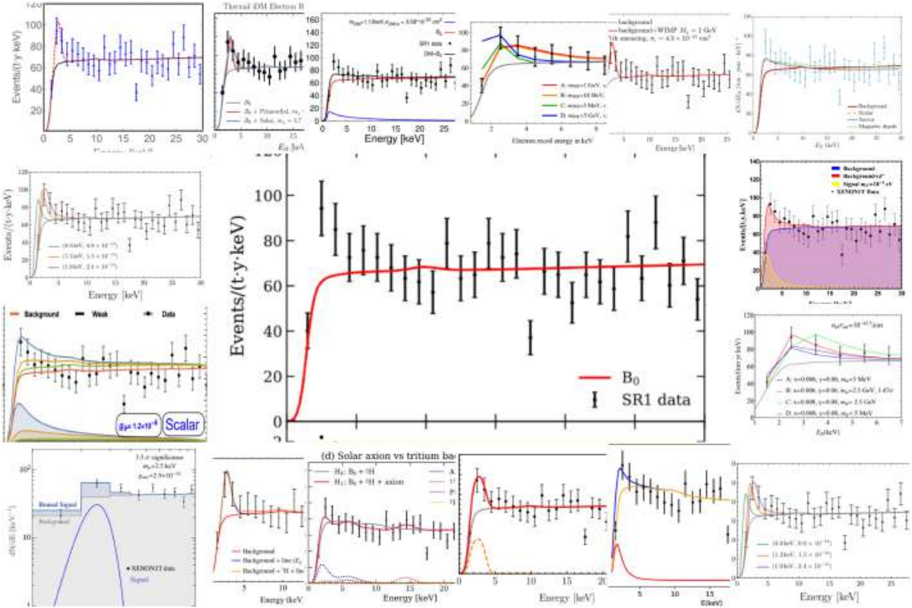
Low energy excess



XENON1T, Phys. Rev. D 102 (2020) 072004 & arXiv: 2006.09721

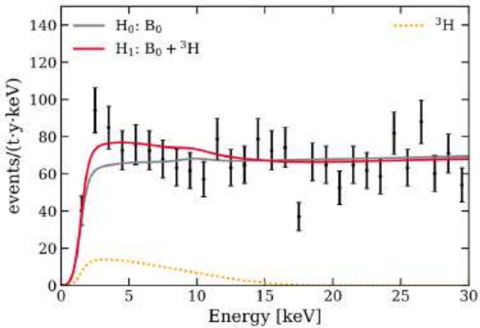
Excess between (1-7) keV

- 285 events observed vs. 232 events expected from best-fit
- 3.3 σ fluctuation → naive estimation (we actually use a likelihood)
- Great resonance in the community (> 140 citations since June)

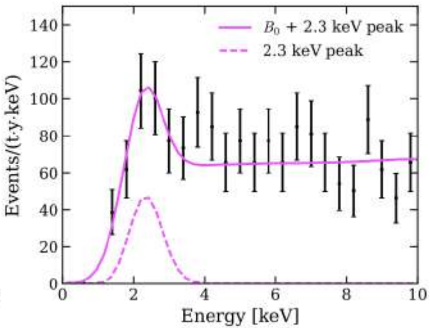


Collage of different models trying to explain the excess by ParticleBites

A new background?



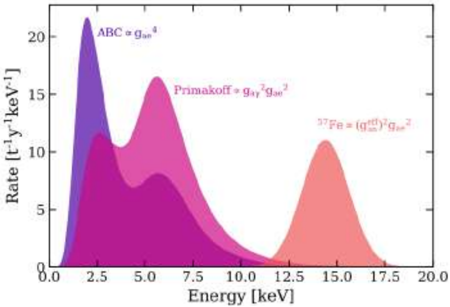
Test of the tritium hypothesis



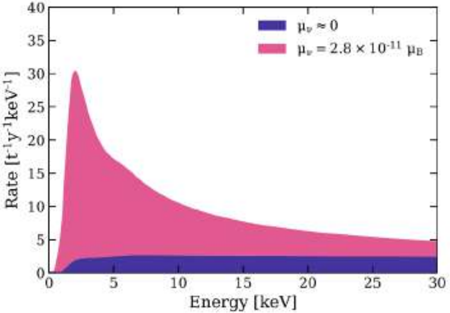
Test of monoenergetic signal hypothesis

- Tritium favoured over background-only at **3.2** σ
  - Tiny concentration ($<$ 3 atoms per kg of xenon)
  - Unclear origin → cosmogenic activation and from natural abundance unlikely
- ^{37}Ar: argon in xenon is strongly reduced by cryogenic distillation
  - Leak hypothesis or in-situ production ruled out

A signal of new physics?



Solar axion signal



Neutrino magnetic moment signature

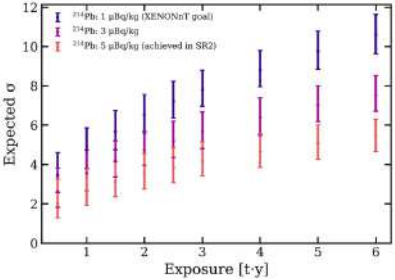
- Solar axion hypothesis favoured over background-only at **3.4** σ
  - In strong tension with astrophysical constrains from stellar cooling
    (see for instance arXiv:2003.01100)

- Neutrino magnetic moment favoured at **3.2** σ
  - Magnetic moment: $\mu_\nu \in (1.4, 2.9) \times 10^{-11} \mu_B$ at 90% CL
  - In tension with astrophysical constraints (arXiv:1910.10568 & arXiv:1907.00115)

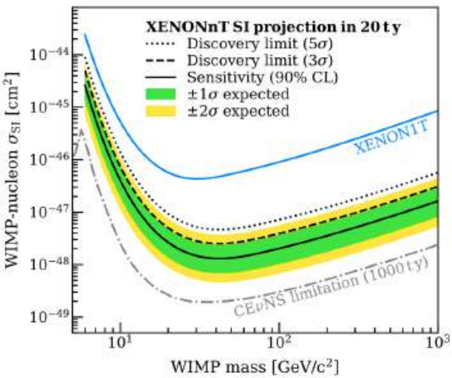
XENONnT

TPC installed underground

- XENONnT is coming soon!!!
- Able to discriminate axions from tritium with ~ few months of data



XENONnT

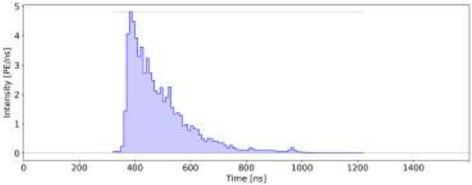


- Aim to measure WIMPs soon ☺

  → Figure from XENON1T, (2020) arXiv:2007.08796

- Commissioning of subsystems being finalized

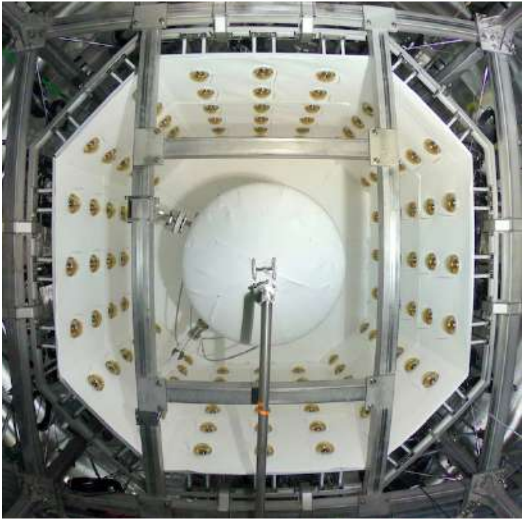
- Expecting to start data taking this year



PRELIMINARY: XENONnT S1 waveform in xenon gas

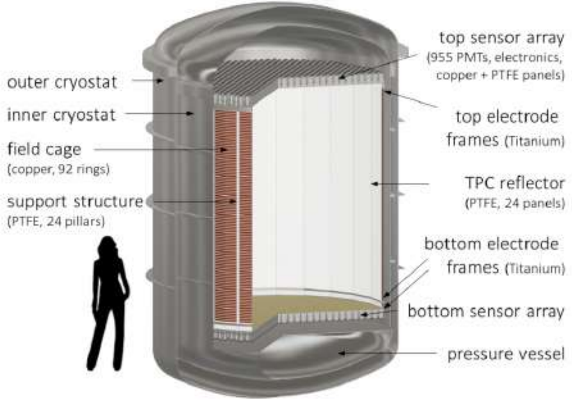
XENONnT impressions

XENONnT impressions



DARWIN: the ultimate WIMP detector

http://darwin-observatory.org/



- R&D and design study for a large liquid xenon dark matter detector
- TPC of ~2.6 m ⌀ & 2.6 m drift length
- 50 t LXe total (40 t in the TPC)

DARWIN, JCAP 1611 (2016) 017

- Vertical and horizontal demonstrators at UZH and U Freiburg, respectively
- Various R&D activities on alternative photosensors ongoing
- MPIK: developing radon reduction measures

Sensitivity of upcoming liquid xenon detectors

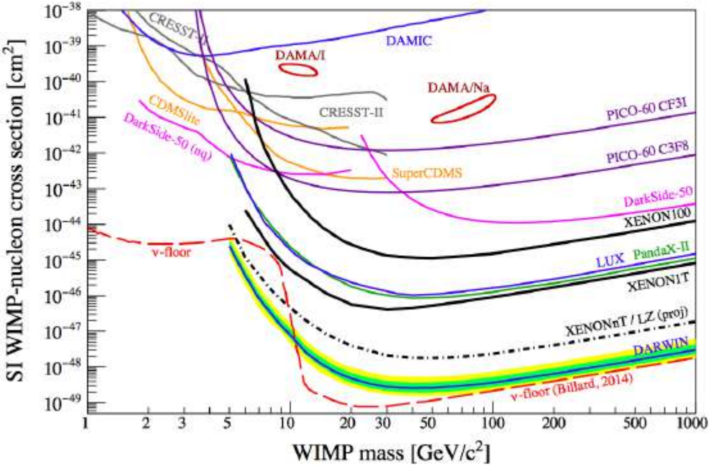


Figure updated from JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

DARWIN: a large observatory for astroparticle physics:

→ Neutrinoless double-beta decay, solar/SN neutrinos, rare processes ...

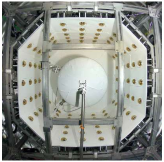
Summary

Sensitivity for dark matter searches has progressed rapidly

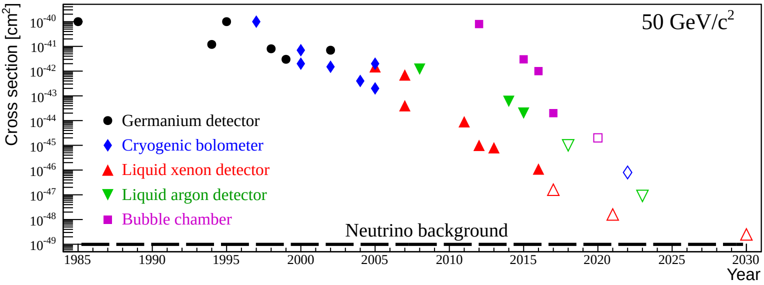
- XENON1T: largest detector with lowest background rate to date
  → Best sensitivities for WIMP searches reached
- Excess of ER events at lowest energies:
  New background? New signal?
- XENONnT is being commissioned!
- XENONnT and DARWIN are the future devices to investigate the dark matter properties and a wide variety of neutrino physics

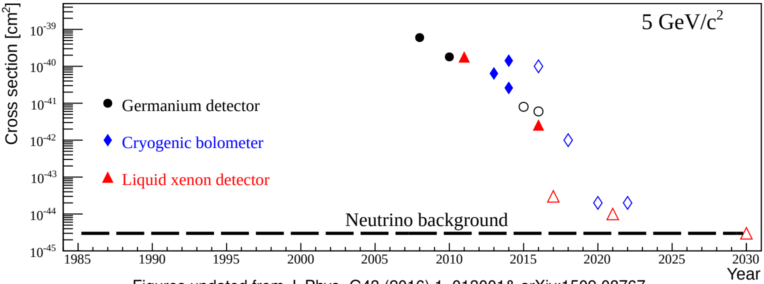







Sensitivity evolution and prospects

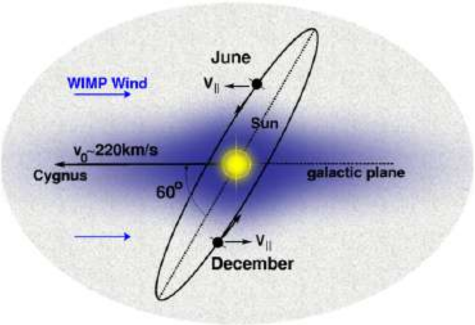


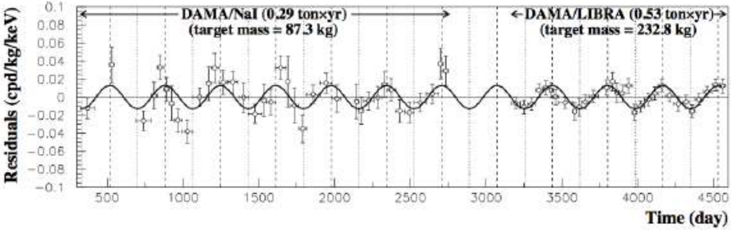


Figures updated from J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Other signatures of dark matter

- Annual modulation of the detector rate
- Directional dependance of the signal





DAMA experiment, R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi+m_N)^2} \cdot [Z \cdot f_p + (A-Z) \cdot f_n]^2$$

$f_{p,n}$: effective couplings to p and n.

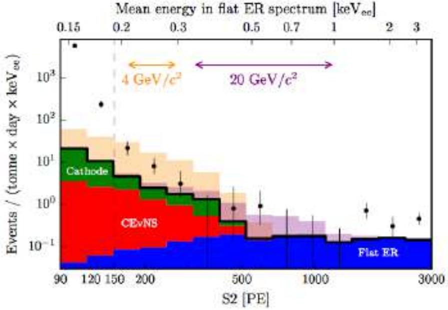
- Spin-dependent interactions: coupling to nuclear spin

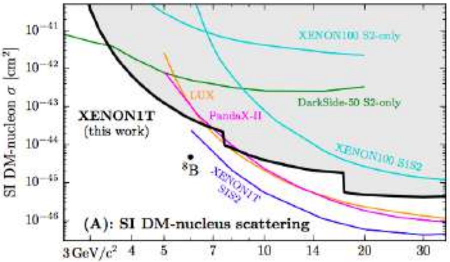
$$\sigma_{SD} = \frac{32}{\pi} \cdot G_F \cdot \frac{m_\chi^2 m_N^2}{(m_\chi+m_N)^2} \cdot \frac{J_N+1}{J_N} \cdot [a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

$\langle S_{p,n}\rangle$: expectation of the spin content of the p, n in the target nuclei

$a_{p,n}$: effective couplings to p and n.

Lowering the energy threshold: charge-only results





From XENON1T, Phys. Rev. Lett. 123 (2019) 251801

- Sensitivity loss below ~ 6 GeV/c^2 DM mass
  due to S1 (light) threshold
- S2 has a larger yield
  + it is amplified

→ lower energy threshold

BUT loss of z-position
(without S1, no S1-S2 time)
→ additional background

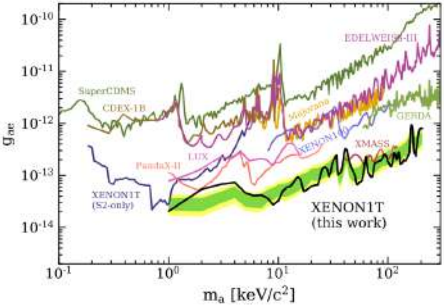
- Sensitivity extended down to ~ 3 GeV/c^2

Examples of peak searches

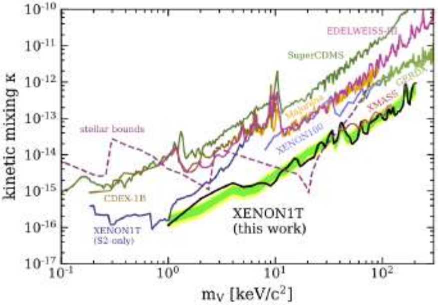
No global significance over 3 σ under the BG model B_0

- Axion-like particles (ALPs) are viable DM candidates
- ALPs would be absorbed in XENON1T via axio-electric effect
- Best exclusion limits for bosonic dark matter

Figures from XENON1T, Phys. Rev. D 102 (2020) 072004 & arXiv: 2006.09721



Axion-like particles



Dark photons