LIQUID XENON DETECTORS
LECTURE 3

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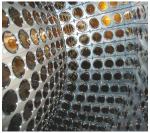
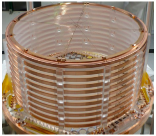
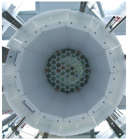
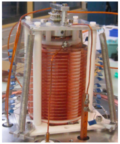
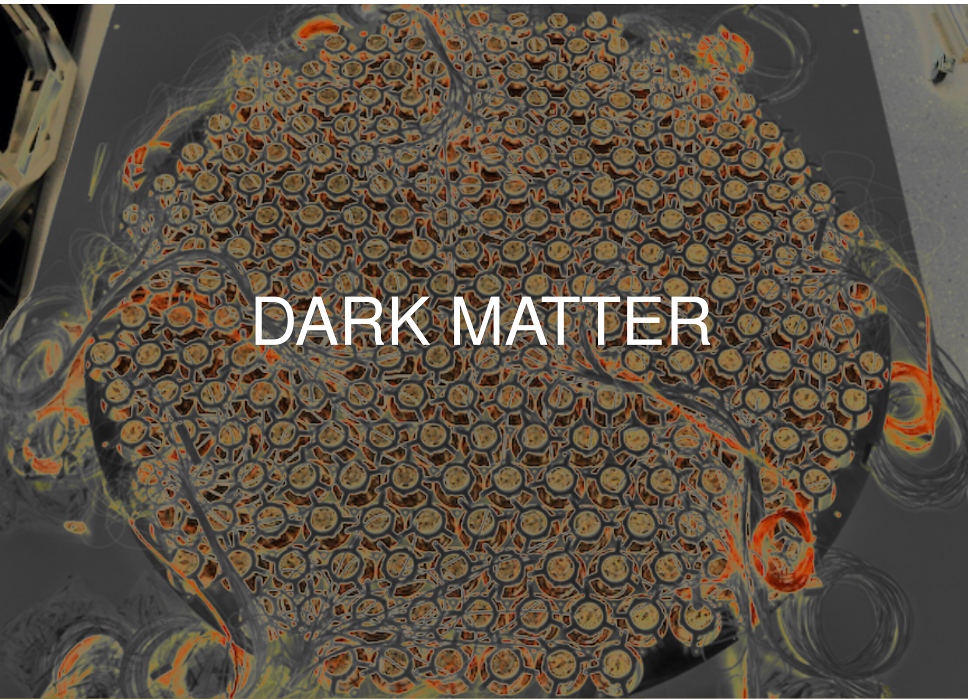
Liquid xenon as detector

- Direct search for dark matter via elastic scattering
- Measurement of coherent neutrino-nucleus scattering
- Measurement of supernova and solar neutrinos
- Search for neutrinoless double-beta decay
- Particle physics calorimeter
- Applications in medical physics



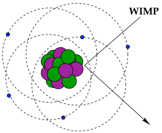







DARK MATTER

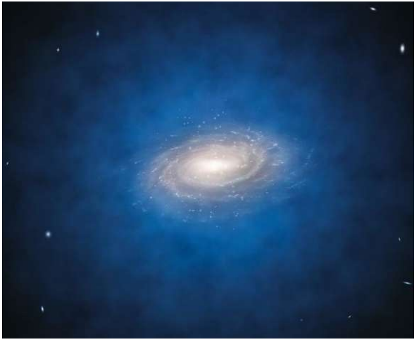
Direct detection of dark matter



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

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

Credit: ESO/L. Calçada



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, $\langle v \rangle \sim 220\,\mathrm{km/s}$

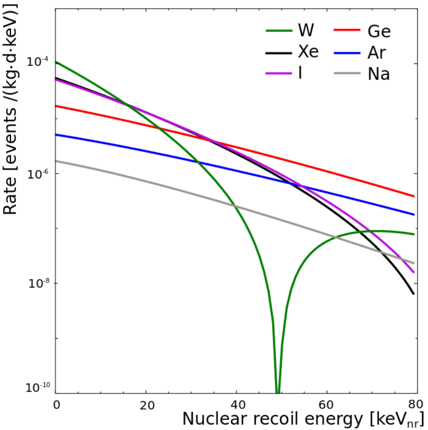
Parameters of interest:

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

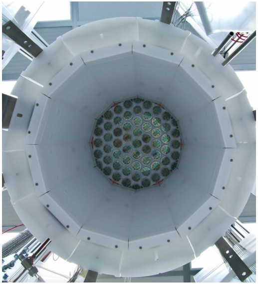
Why is xenon ideal for dark matter searches?

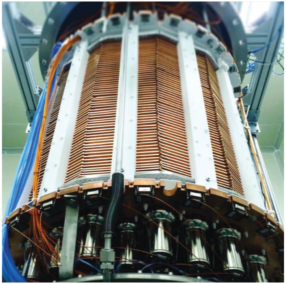
- Large masses and homogeneous targets
- Low energy threshold at $\sim$ a few keV
- Very low intrinsic background
- 3D position reconstruction $\rightarrow$ fiducialization
- Heavy nucleus $\rightarrow$ high SI rate at low energies

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



The last years liquid-xenon TPC competition





LUX:

- 100 kg fiducial mass (370 kg total)
- 33.5 ton·day exposure

PANDAX-II:

- 580 kg fiducial mass (1.2 t total)
- 54 ton·day exposure

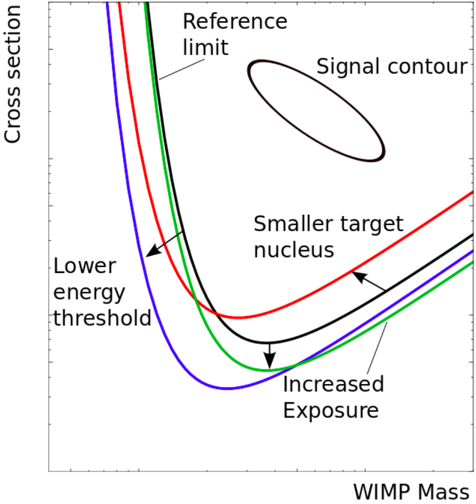
XENON1T:

- 1.3 t LXe fiducial mass (3.2 t total)
- 365 ton·day exposure

Result of a direct detection experiment

→ Statistical significance of signal over expected background?

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



- Positive signal **Q**
  - 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

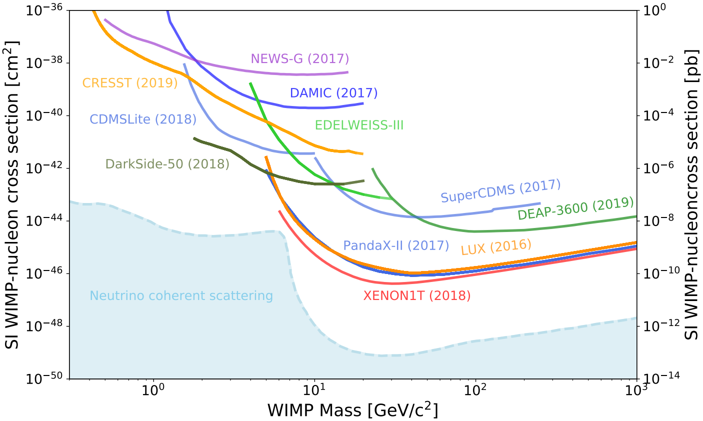
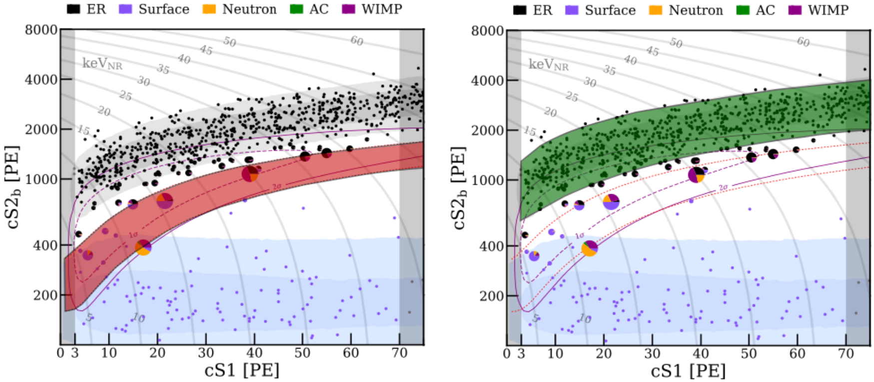


Figure from P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

- Best upper limits on WIMP-nucleon coupling for WIMP masses above $\sim 6\,\mathrm{GeV}/c^2$ by liquid xenon detectors
- Charge-only (S2-only) searches lower further the threshold

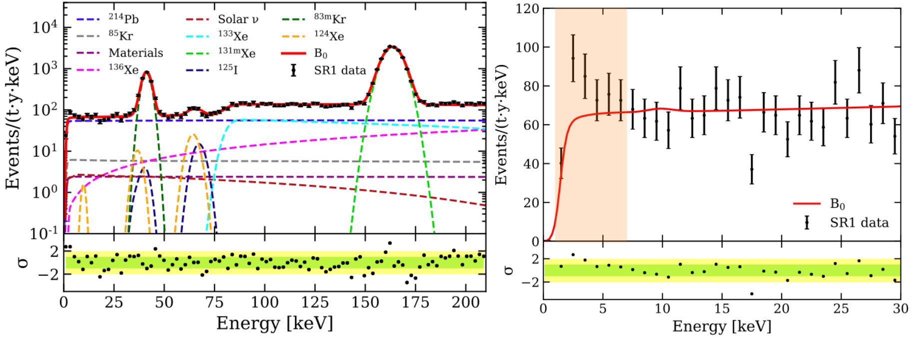
Focussing recently on electronic recoils



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 in XENON1T

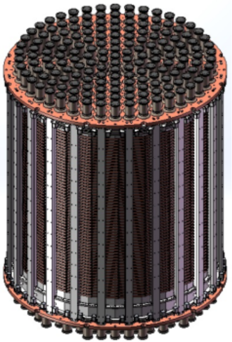


XENON1T, arXiv: 2006.09721 (2020), accepted for publication in PRD

Excess between (1-7) keV Q

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

The race



LZ:

- 7 T target mass
- Assembly and commissioning

PANDAX-4T:

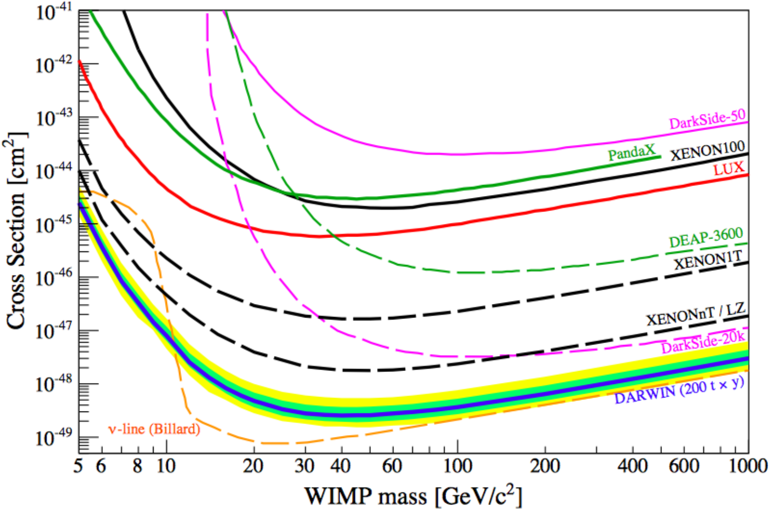
- 4 T target mass
- Assembly and commissioning?

XENONnT:

- 6 T target mass
- Commissioning

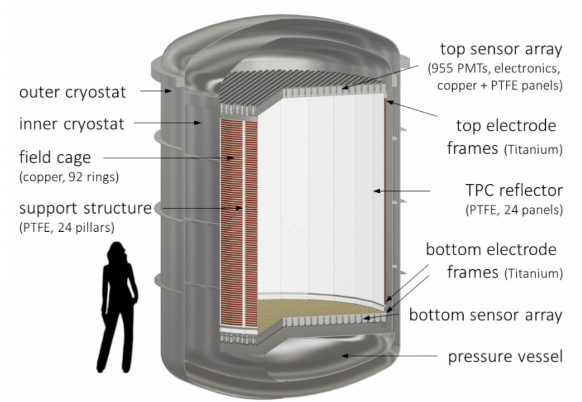
$\rightarrow$ A race to measure WIMPs down to $\sigma \sim 10^{-48}\,\text{cm}^2$

Sensitivity of upcoming liquid xenon detectors



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

DARWIN: the ultimate WIMP detector

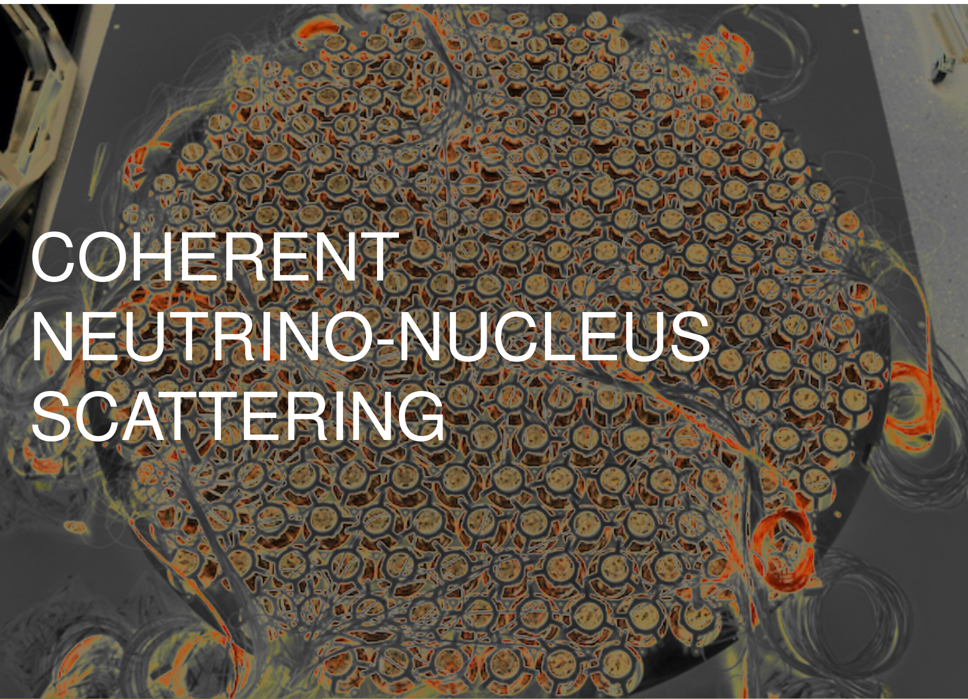


http://darwin-observatory.org/

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

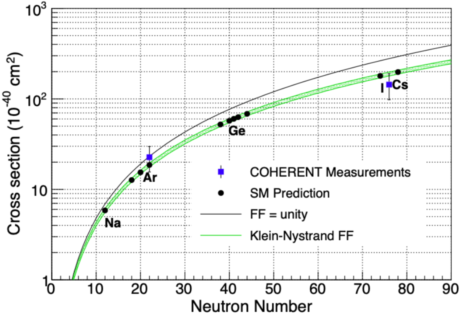
DARWIN, JCAP 1611 (2016) 017

- Large observatory for astroparticle physics:
- Neutrinoless double-beta decay, solar/SN neutrinos, rare processes ...



COHERENT NEUTRINO-NUCLEUS SCATTERING

Coherent ν scattering: why interesting?



COHERENT collaboration, (2000) arXiv:2003.10630

What's it good for?

- To look for signatures of new physics
- To understand nuclear physics
- To characterize it as background for DM searches
- To understand astrophysical processes

- COHERENT experiment has measured the process:

  @ the Spallation Neutron Source at Oak Ridge National Laboratory

  $\rightarrow$ with a 14.6 kg cesium iodine (CsI[Na]) in 2017

  $\rightarrow$ with single-phase 24kg liquid argon in 2020

RED-100 experiment

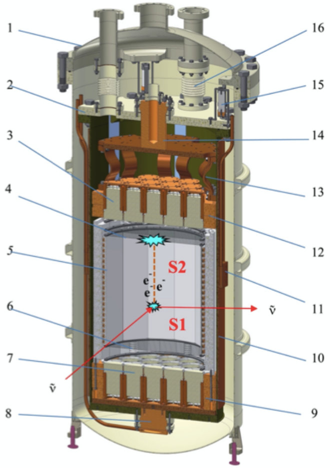


Figure 2. Schematic view of the RED-100 detector: 1 – external vessel of the cryostat, 2 – internal vessel of the cryostat, 3 – top array of 19 Hamamatsu R11410-20 photomultipliers, 4 – gridded anode and electron shutter, 5 – drift cage with Teflon reflecting walls, 6 – gridded cathode, 7 – bottom array of 19 Hamamatsu R11410-20 photomultipliers, 8 – cold head of the bottom thermosyphon, 9 – copper housing of the bottom PMT array, 10 – Copper screen of the internal vessel of the cryostat, 11 – cold head of the side thermosyphon, 12 – copper housing of the top PMT array, 13 – flexible heat bridge, 14 – top cold head for xenon condensation, 15 – Vespel made stand supporting cold vessel inside the external vessel of the cryostat, 16 – connection for cable channel; S1 – scintillation flash, S2 – electroluminescent flash.

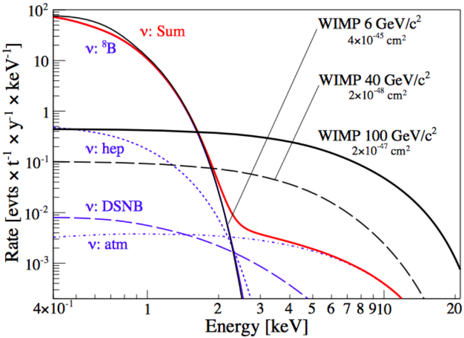
Dedicated experiment to measure CEνNS

- 200 kg liquid-xenon TPC assembled and operating
- Neutrinos from an industrial nuclear reactor at the Kalinin nuclear power plant

RED-100 Collaboration, JINST 15 (2020) 02, P02020 & arXiv:1910.06190

Coherent ν scattering in DM detectors

Precise measurement vs Background for WIMPs



L. Baudis *et al.*, JCAP01 (2014) 044

$$\nu + Xe \rightarrow \nu + Xe$$

- Low threshold in DM detectors

$\rightarrow$ access to coherent ν scattering from solar neutrinos

- DARWIN: 90 events/t/y ^{8}B-ν's above $\sim$ 1 keV$_{ee}$
  - $\rightarrow$ 18 000 events in 200 t·y
  - $\rightarrow$ High statistics measurement of the spectral shape

Limits the sensitivity to WIMP masses below few GeV/c^2

^{8}B signal in the S2/S1 space

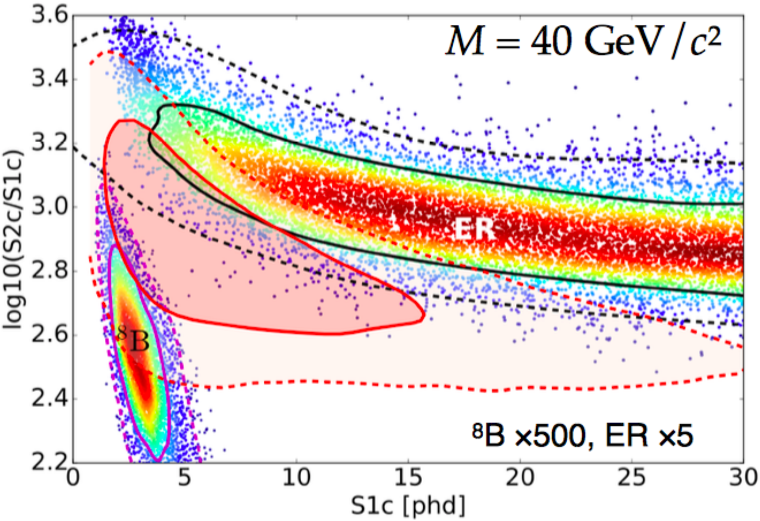
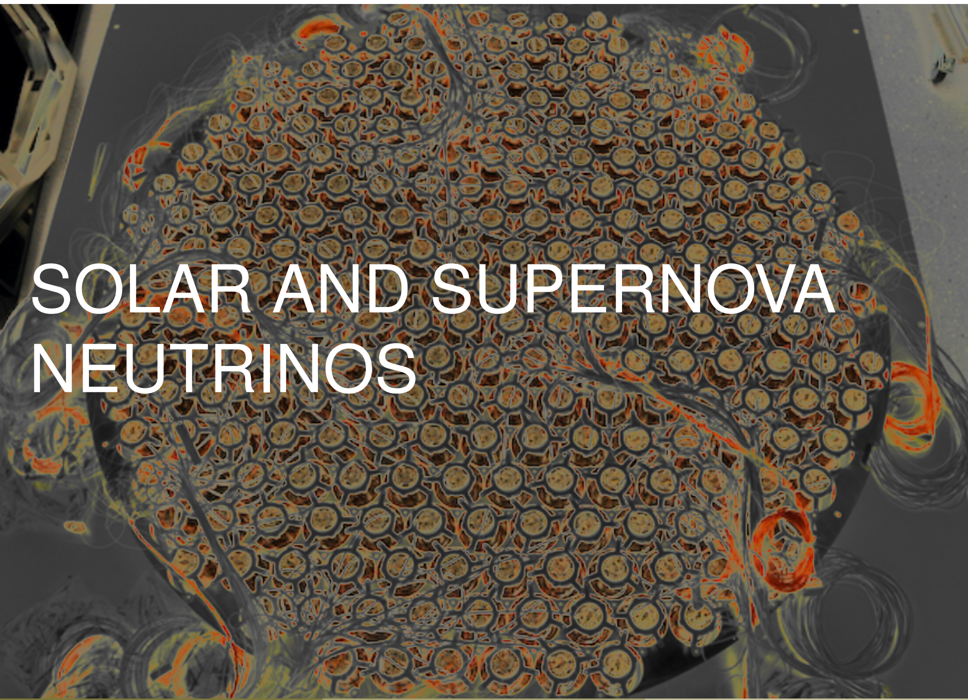
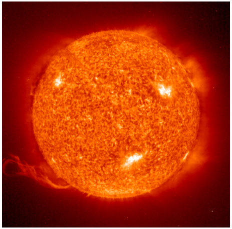


Figure from the LZ collaboration, see also arXiv:1802.06039

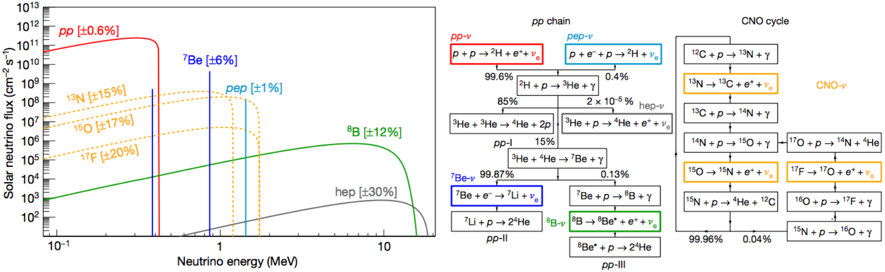


SOLAR AND SUPERNOVA NEUTRINOS

Measuring solar neutrinos at lowest energies

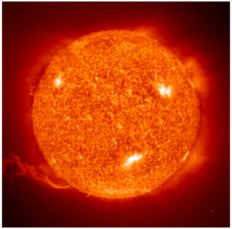


- *pp* - and ^{7}Be-ν's make 98% of solar neutrino flux
- Borexino measures *pp*-flux with 9.5% precision
- ν-electron elastic scattering $\nu + e^- \rightarrow \nu + e^-$
- The recoiling electron is recorded in the LXe detector

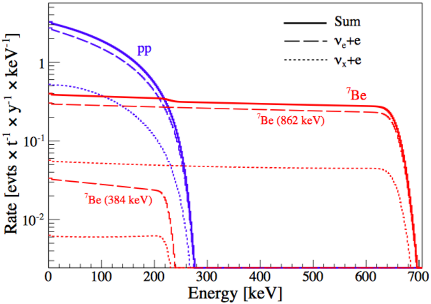


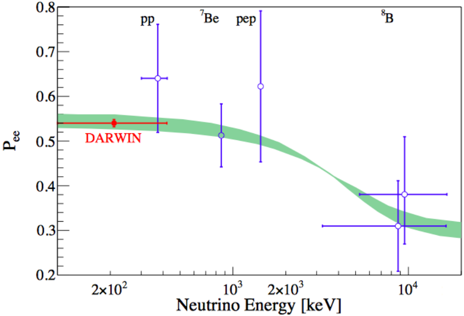
Borexino Collaboration, Nature 562 (2018) 505

Solar neutrinos in DARWIN



- DARWIN: 7.2 ev/day in 30 t
  in the energy range $E = (2 - 30)\,\mathrm{keV}_{ee}$
- Precision $< 1\%$ $\rightarrow$ test non-standard ν-interactions

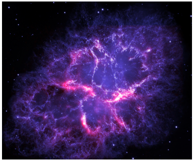


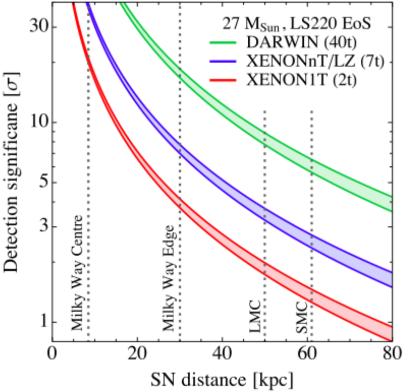


DARWIN, JCAP 1611 (2016) no.11, 017

Supernova neutrinos

- Core-collapse supernova
- 99% of the energy is released in νs
- S2-only signal method above a threshold of S2 $=$ 60 PE





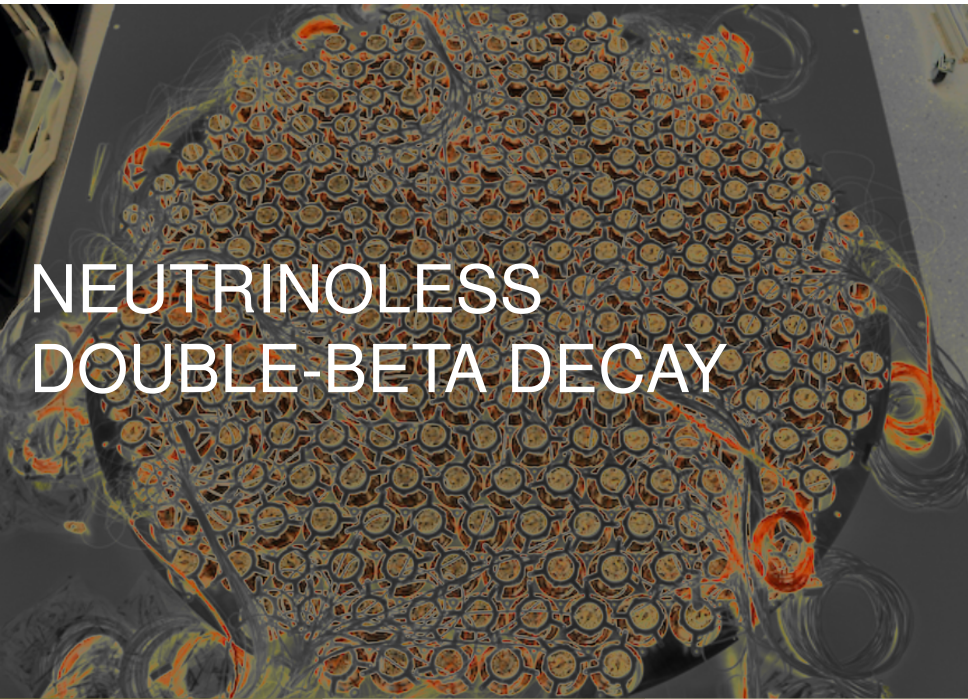
Lang *et al.*, Phys. Rev. D 94, 103009 (2016)

- For a 27 $M_\odot$ SN at a distance of 10 kpc from the Earth

  $\rightarrow$ 123/704 events in XENONnT/DARWIN, respectively

- For a detector like DARWIN: $>$ 3 σ significance even for a SN as far as the small Magellanic cloud

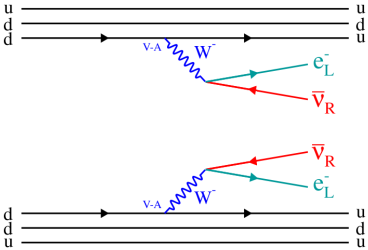
NEUTRINOLESS DOUBLE-BETA DECAY



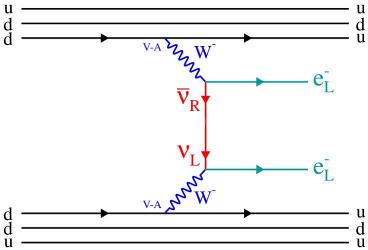
Neutrinoless double beta decay

Process to test lepton flavour conservation

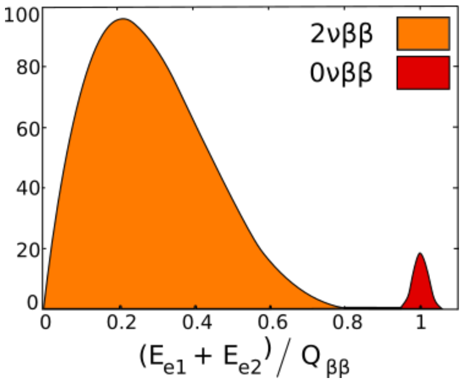
The standard model process



The new phenomenon



Signal signature

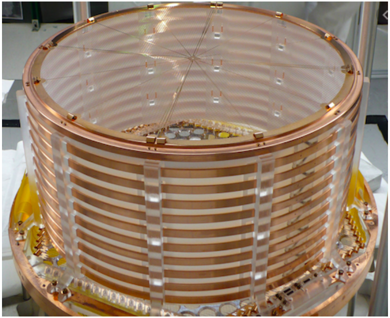


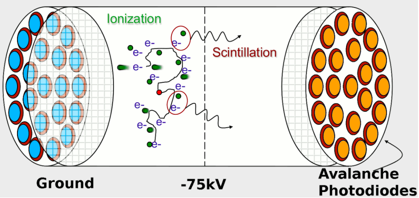
- ^{136}Xe is a $0\nu\beta\beta$ candidate with 8.9% natural abundance (α)
- $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e^{-} (+2\overline{\nu})$
- Peak at the spectrum endpoint $Q_{\beta\beta}(^{136}\text{Xe}) = 2.458\,\text{MeV}$

Sensitivity: $$S_{0\nu} \propto \epsilon \cdot \frac{\alpha}{A} \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot b}}$$

ϵ: detection eff., A: atomic mass, ΔE: energy resolution & b: background level

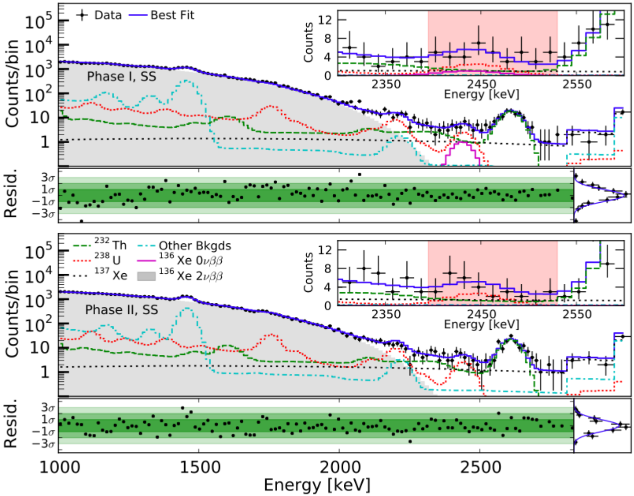
EXO-200 detector





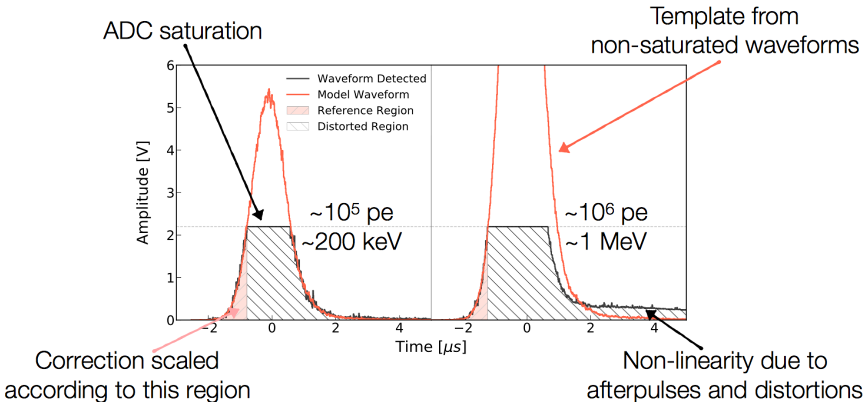
- EXO-200 operated at an underground mine (WIPP)
- 200 kg of liquid xenon enriched to 80% in ^{136}Xe
- Drifted electrons detected with wire grids
- Scintillation collected with avalanche photodiodes (APDs)

EXO-200 results



- No statistically significant evidence for $0\nu\beta\beta$ is observed
- Lower limit on the ^{136}Xe $0\nu\beta\beta$ half-life is $T_{1/2} > 3.5 \cdot 10^{25}$ y

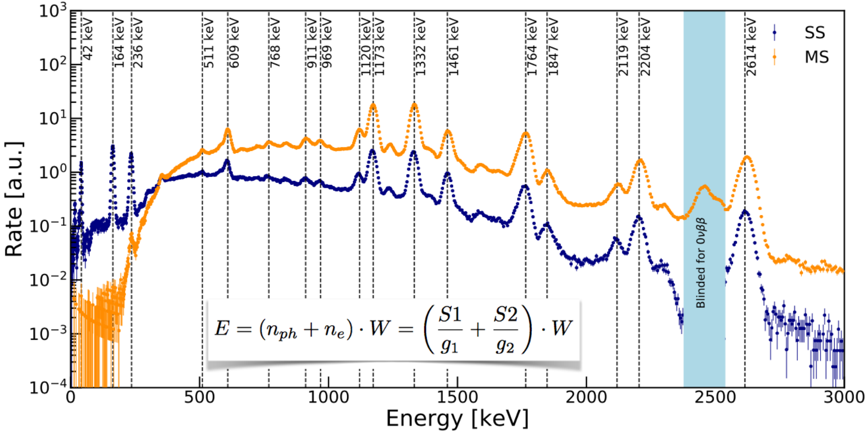
Extending from keV to MeV energies in XENON1T



XENON1T, method described in Eur. Phys. J. C 80 (2020) 785

- Correction of pulse saturation
- Improvements on the the identification of single/multiple scattering

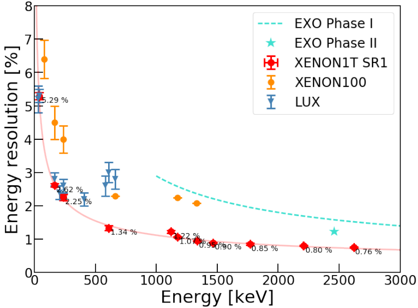
XENON1T high energy spectrum



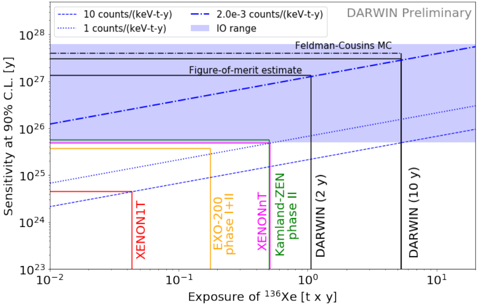
XENON1T, Eur. Phys. J. C 80 (2020) 785

- Energy scale employs both charge and light signals
- Search for $0\nu\beta\beta$ currently on-going

XENON1T energy resolution

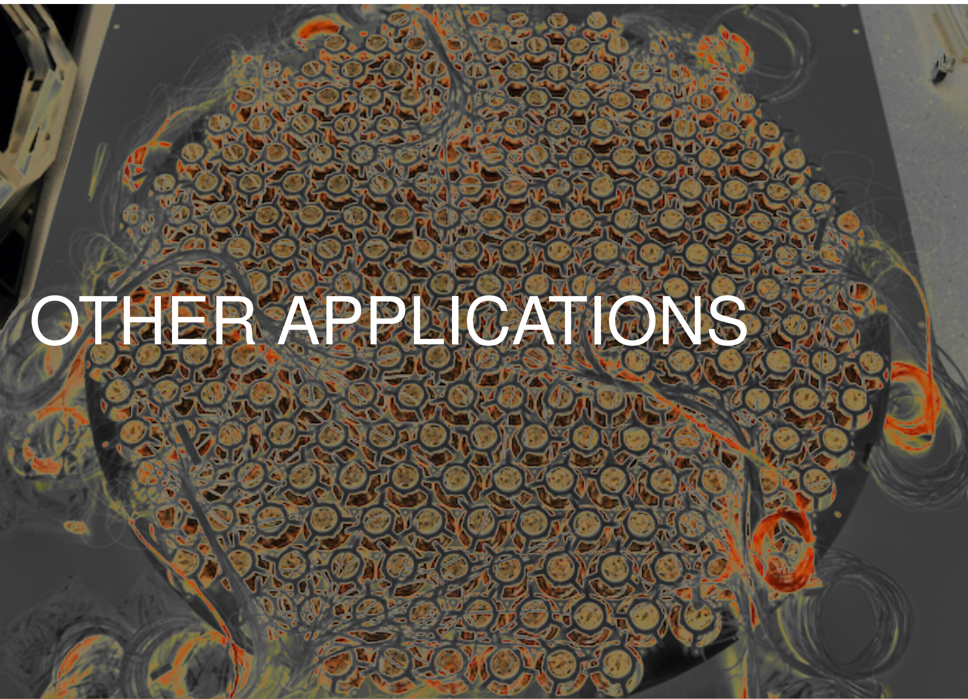


XENON1T Eur. Phys. J. C 80 (2020) 785



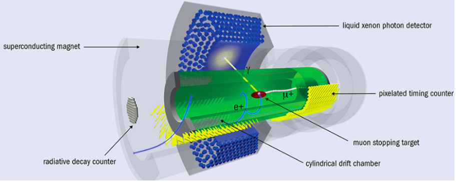
DARWIN preliminary

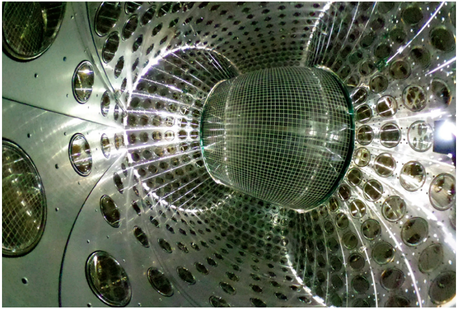
- Energy resolution optimized $\rightarrow$ $\sigma/E = 0.8\%$ at 2.45 MeV
- Improved towards dedicated $0\nu\beta\beta$ experiments



OTHER APPLICATIONS

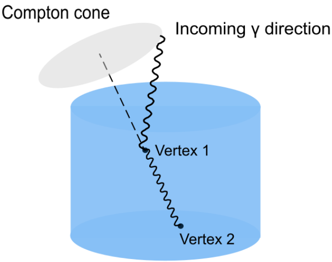
MEG experiment



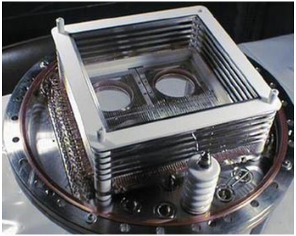


- MEG experiment @ PSI (Switzerland)
- Searching for the process $\mu^+ \rightarrow e^+ + \gamma$ (52.8 MeV) testing lepton flavour conservation
- C-shaped 900 ℓ liquid xenon detector
- Scintillation-only detector
- $\sim$ 600 2-inch PMTs and 4092 newly developed VUV-sensitive MPPCs

Compton telescopes



Working principle of a Compton telescope



LXeGRIT gamma-ray detector

- Gamma-ray telescopes provide information on astrophysical isotopes

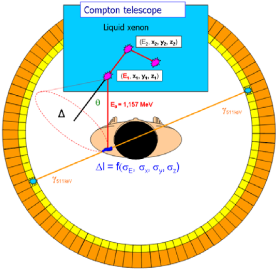
  $\rightarrow$ supernova explosions or winds from massive stars

- Compton telescope image γ-interactions

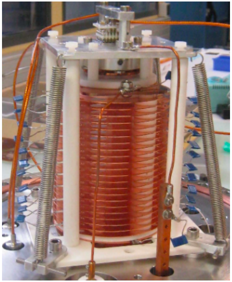
  $\rightarrow$ reconstruction of γ-direction via Compton kinematics

- LXeGRIT: balloon flights in 1999 and 2000

Applications in medicine



Principle of 3 γ medical imaging. Figure from arXiv:1109.3300



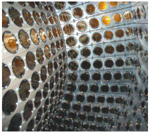
XEMIS detector

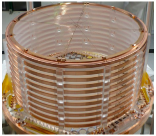
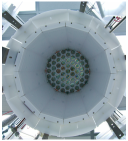
- Application for positron emission tomography: PET scanners
  - Employed for the precise identification of the tumours position and extend
- XENON detectors are superior due to fast timing & good energy and spatial resolution
  - Good time/position resolution would allow to monitor the radioisotope uptake
- Adding Compton imaging
  $\rightarrow$ improved position determination
  $+$ less dose to patient necessary

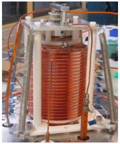
Summary

Great technology with a wide variety of applications

- Direct search for dark matter via elastic scattering
- Measurement of coherent neutrino-nucleus scattering
- Measurement of supernova and solar neutrinos
- Search for neutrinoless double-beta decay
- Particle physics calorimeter
- Applications in medical physics





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.

XENON1T data from SR1

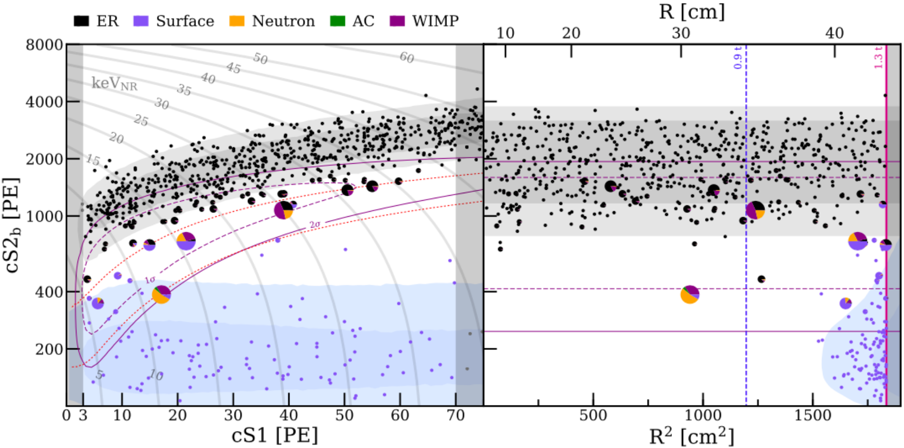


Figure from XENON1T, arXiv:1805.12562