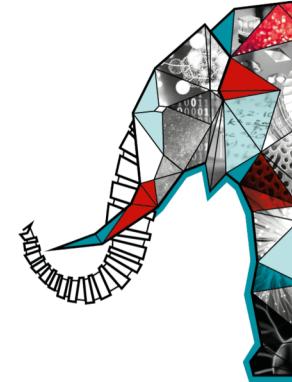


Le xénon liquide : une avancée majeure pour la recherche directe de matière noire

Julien Masbou

Subatech – Université de Nantes

**25^e Congrès Général
de la Société Française
de Physique** 



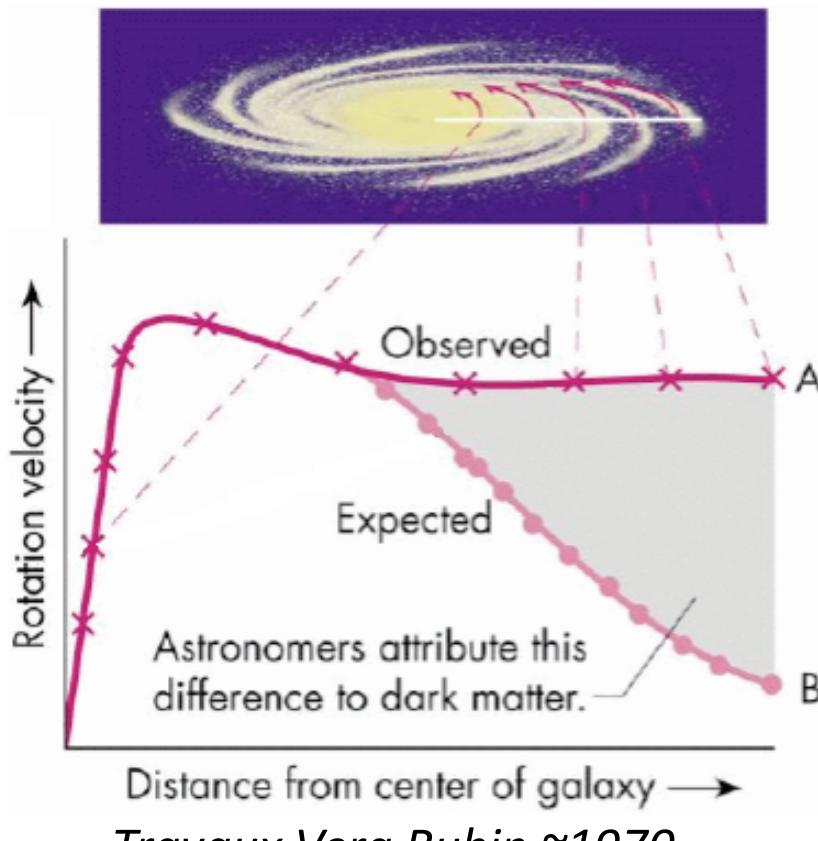
What Dark Matter it not



→ Barnard 68 : cold molecular cloud ~ 500 ly.
Transparent in infrared

Definition

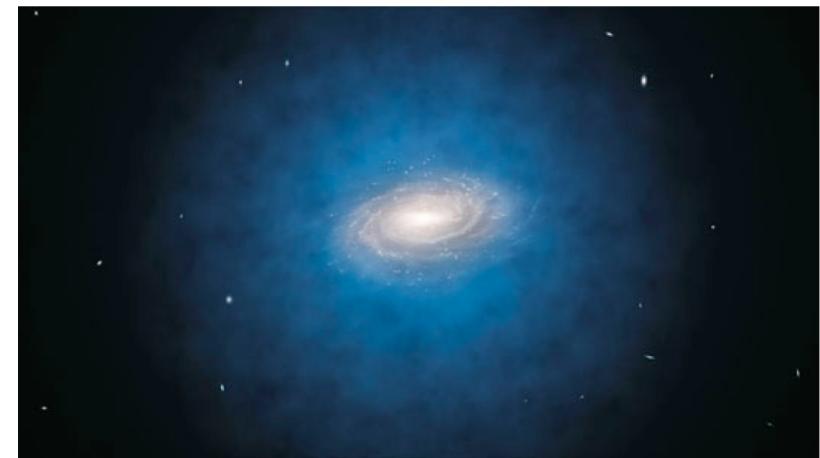
By « Dark Matter » we mean non-luminous matter :
no associated emission of light (visible, UV, IR, radio, etc...)
... But we assume its existence by its gravitational effect.



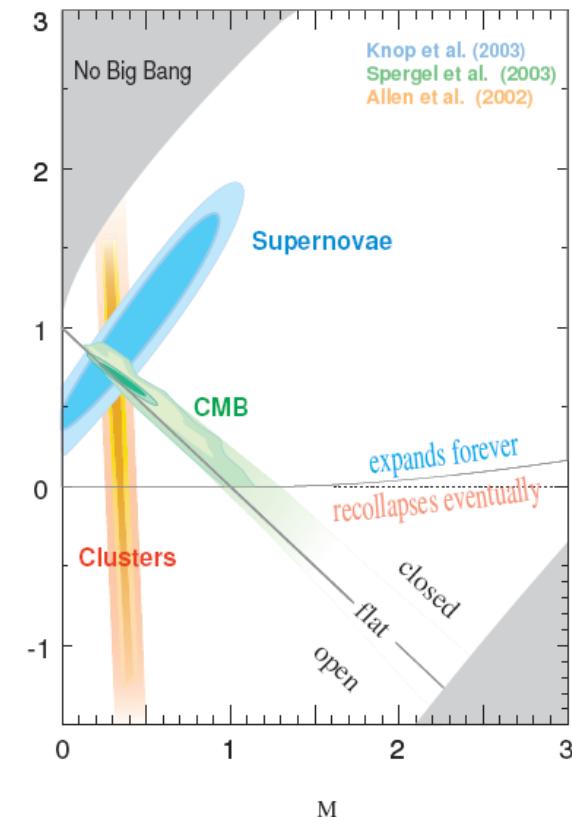
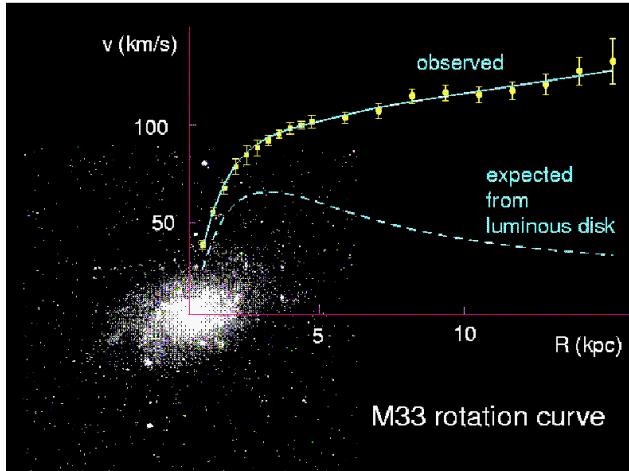
Distance from center of galaxy →

Travaux Vera Rubin ~1970

→ Presence of a halo of invisible matter, 5-10 times heavier than standard matter



Dark Matter at all scales



Hints for Dark Matter :

- Galaxies
- Cluster of galaxies
- Cosmological Measurements

Unknown matter
~ 80 % of the matter is non baryonic

Nature of Dark Matter

We are looking for particles:

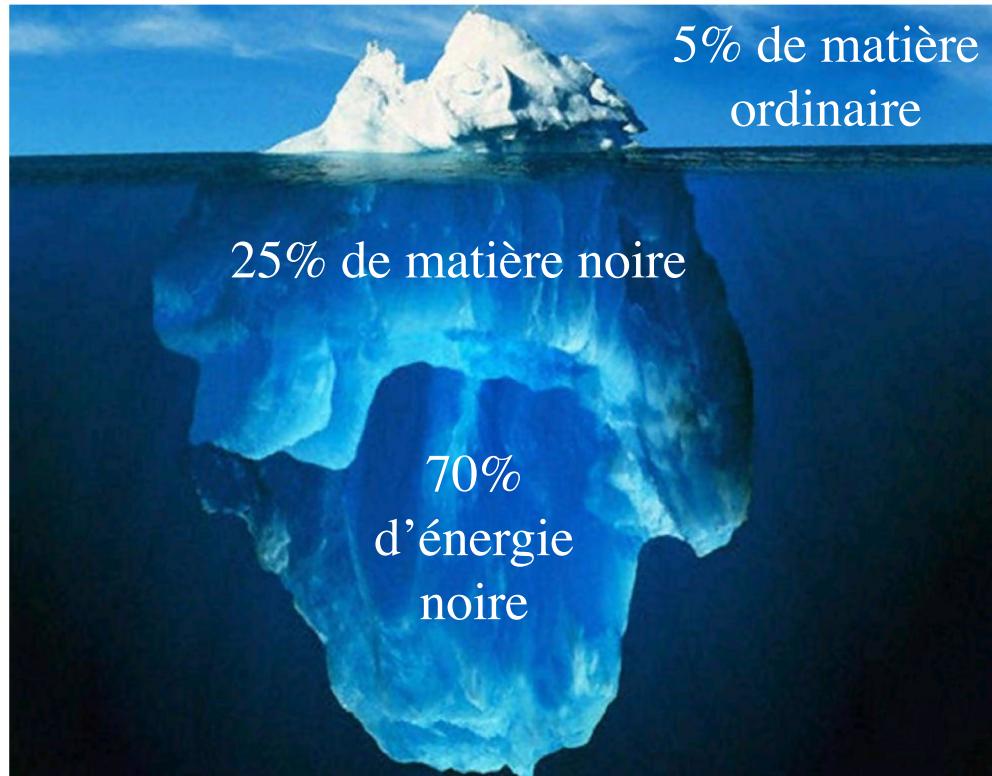
- Non relativistic
- Neutral
- Weakly interacting $\langle\sigma v\rangle$

WIMP:

Weakly Interacting Massive Particle

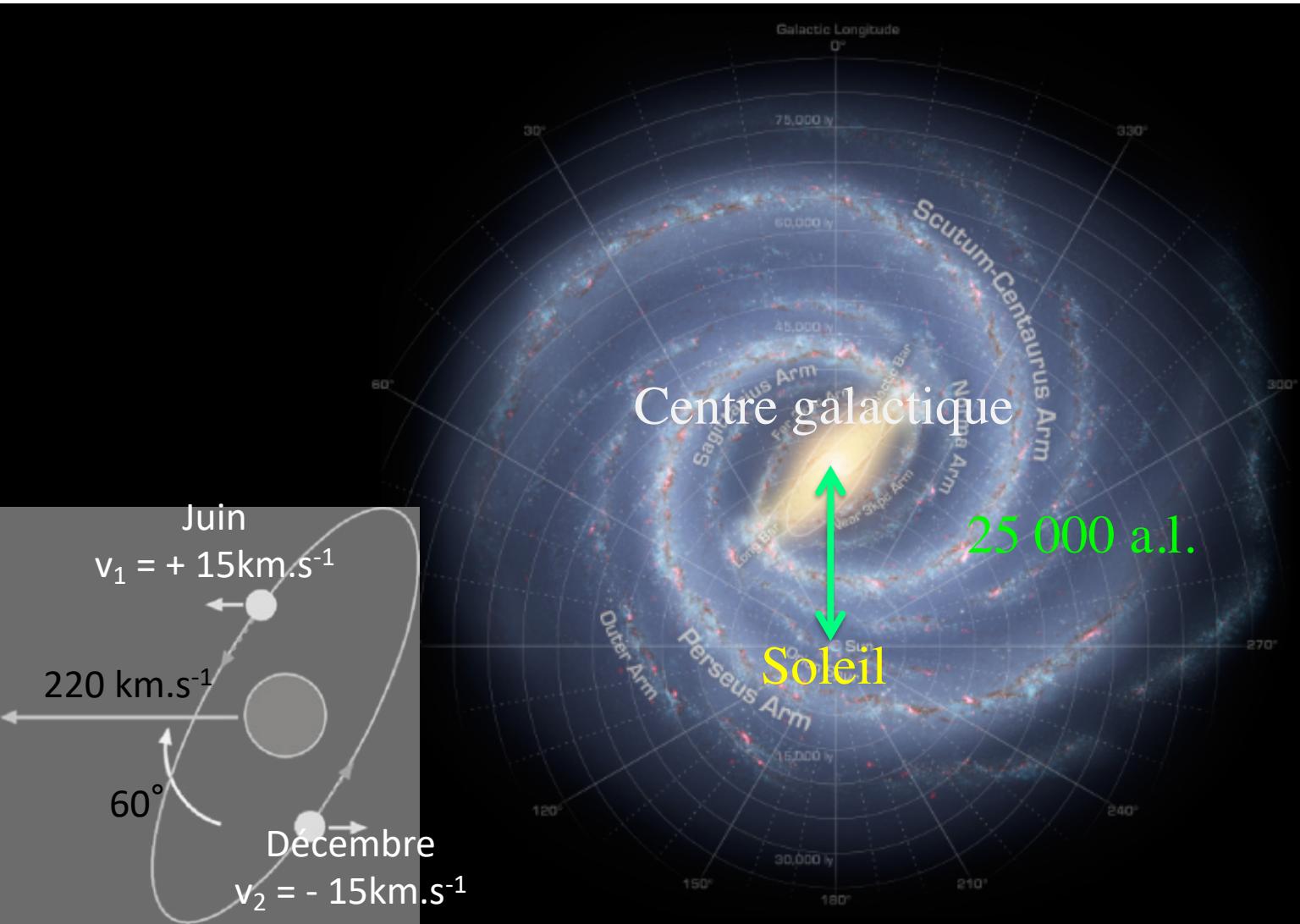
Candidats :

- Extension supersymétrique (SUSY) du Modèle Standard
- Modèles à dimensions supplémentaires universelles (UED)
→ $\text{GeV} < m_{\text{DM}} < \text{TeV}$



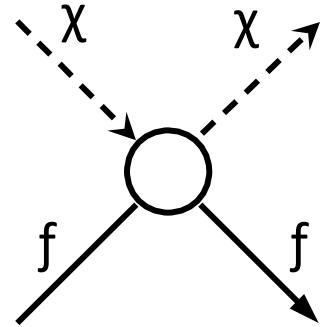
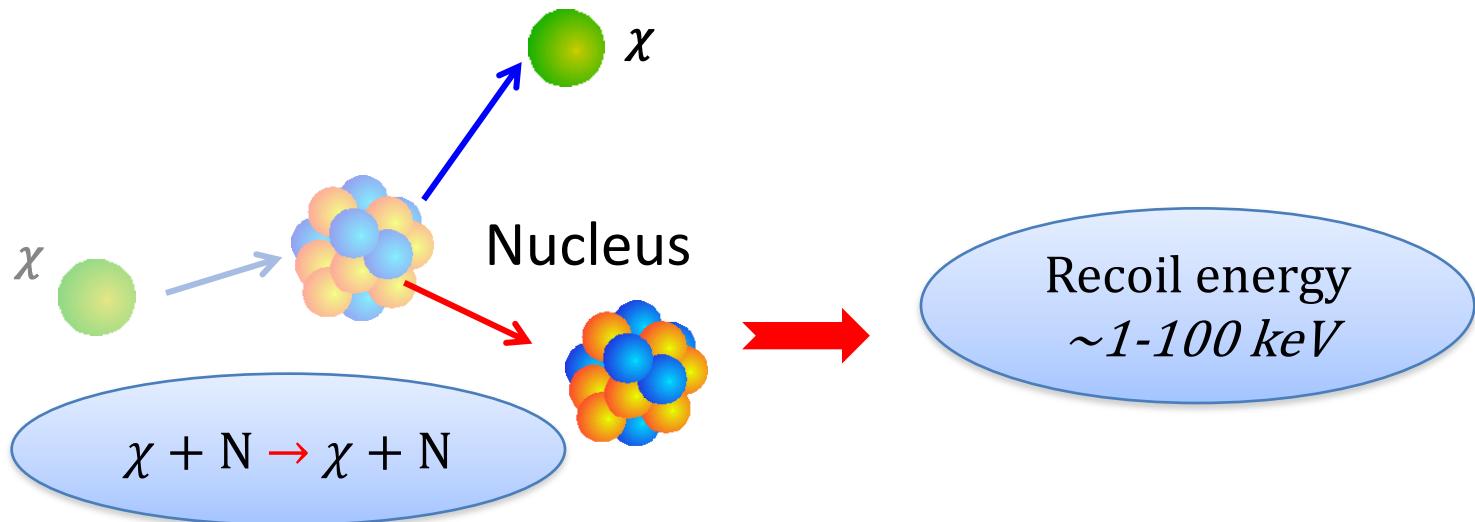
Main characteristic of Dark Matter particle

- Weakly interactive
- Stable
- Non baryonic matter
- Non relativistic



Direct dark matter detection principle

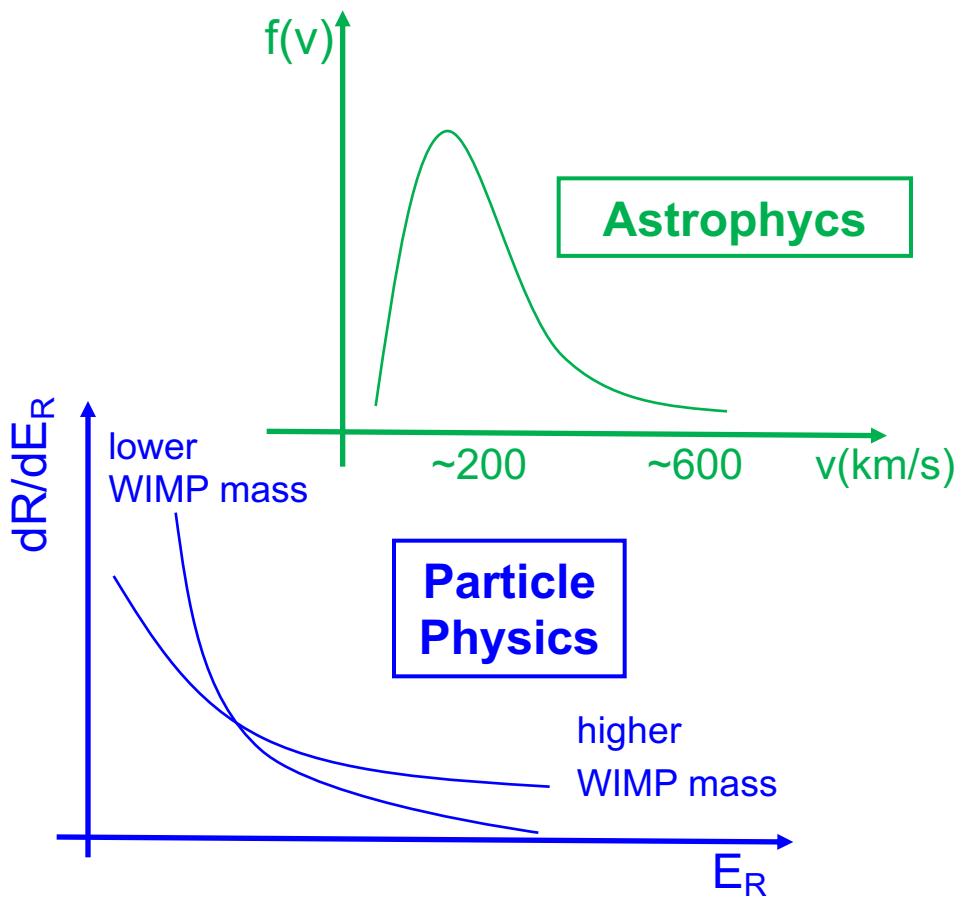
Nuclear
Recoil
(NR)



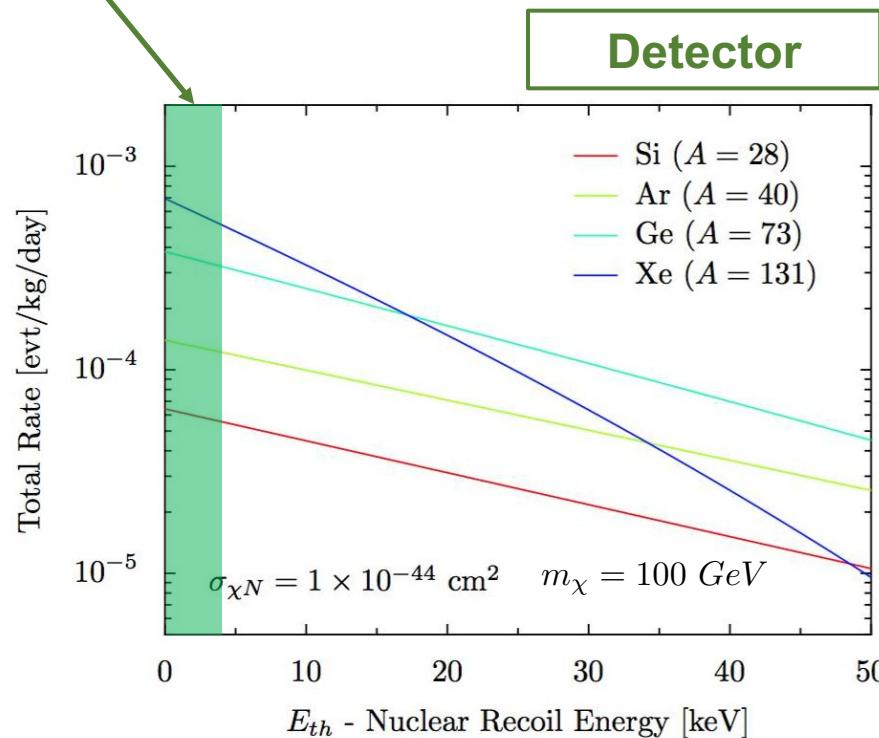
Electronic
Recoil
(ER)
 γ and β particles
interact with the atomic electrons
 \rightarrow background

Expected rate for terrestrial detector

$$\frac{dR}{dE_R} = N_N \frac{\rho_\odot}{m_\chi} \int_{v_{min}}^{v_{max}} f(v) v \frac{d\sigma}{dE_R} dv$$

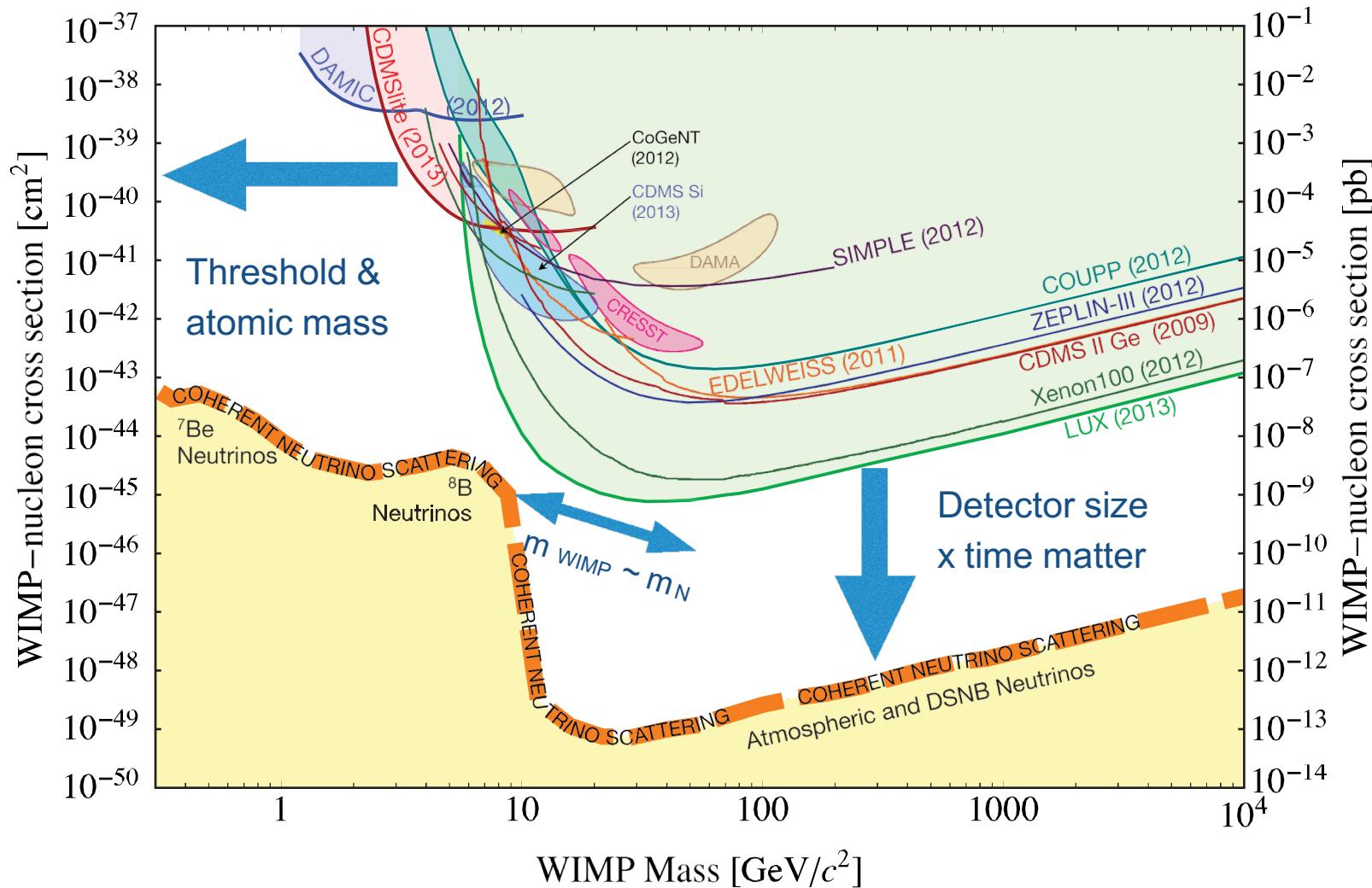


$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu}}$$

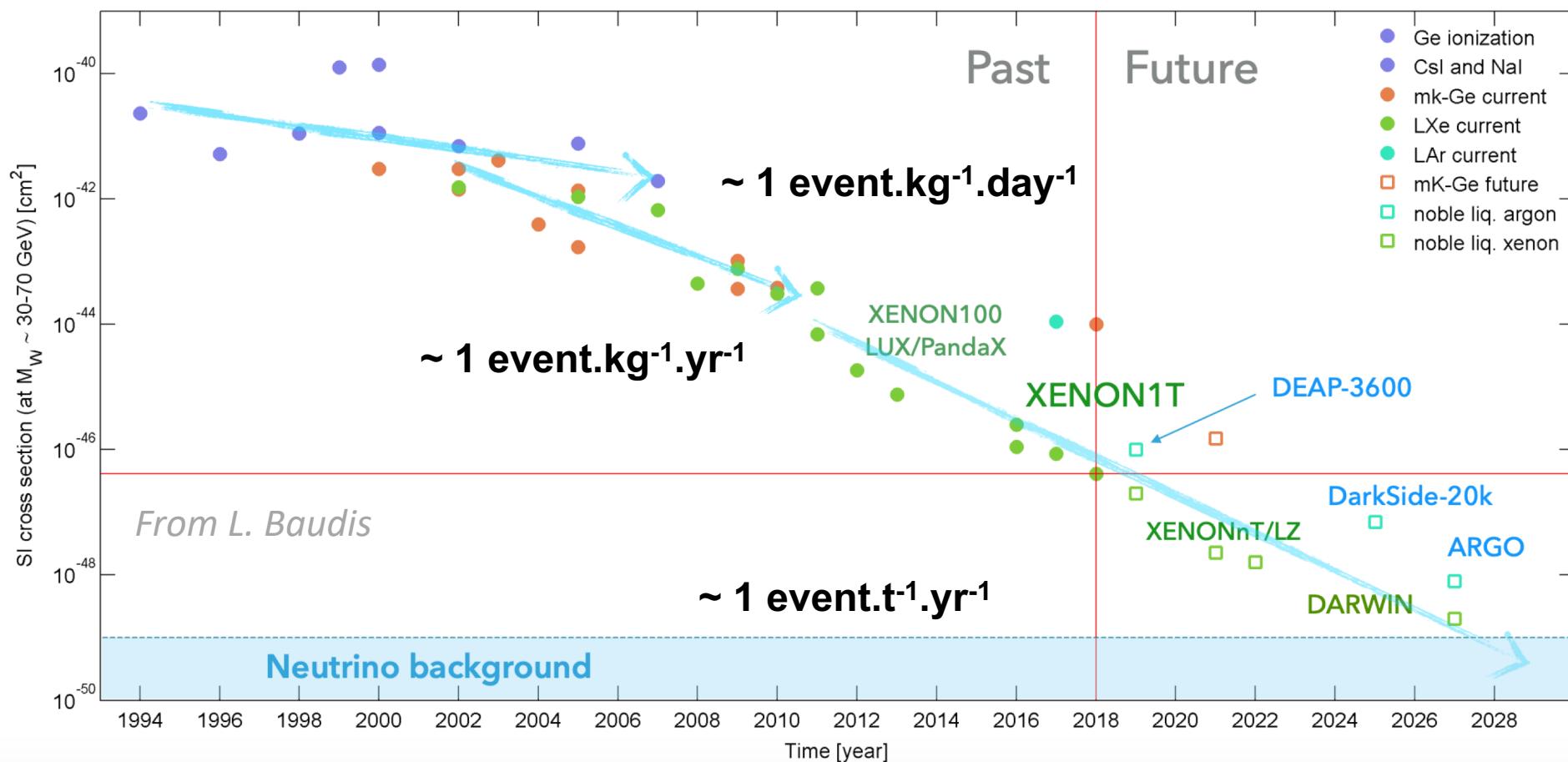


How is evolving the field of Direct Detection ?

$$R \sim 0.13 \frac{\text{events}}{\text{kg} \cdot \text{year}} \left[\frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km.s}^{-1}} \times \frac{\rho_{\odot}}{0.3 \text{ GeV.cm}^{-3}} \right]$$



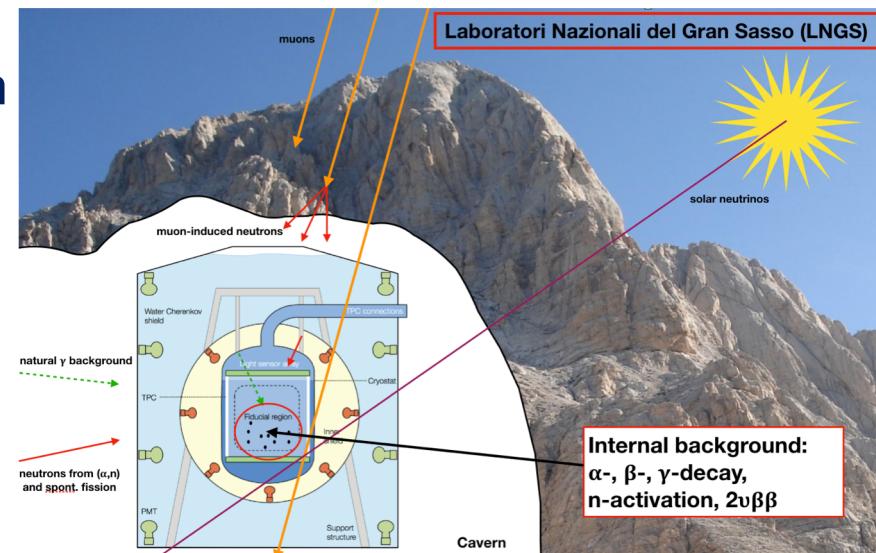
Direct detection : progress over time



The fight against the background

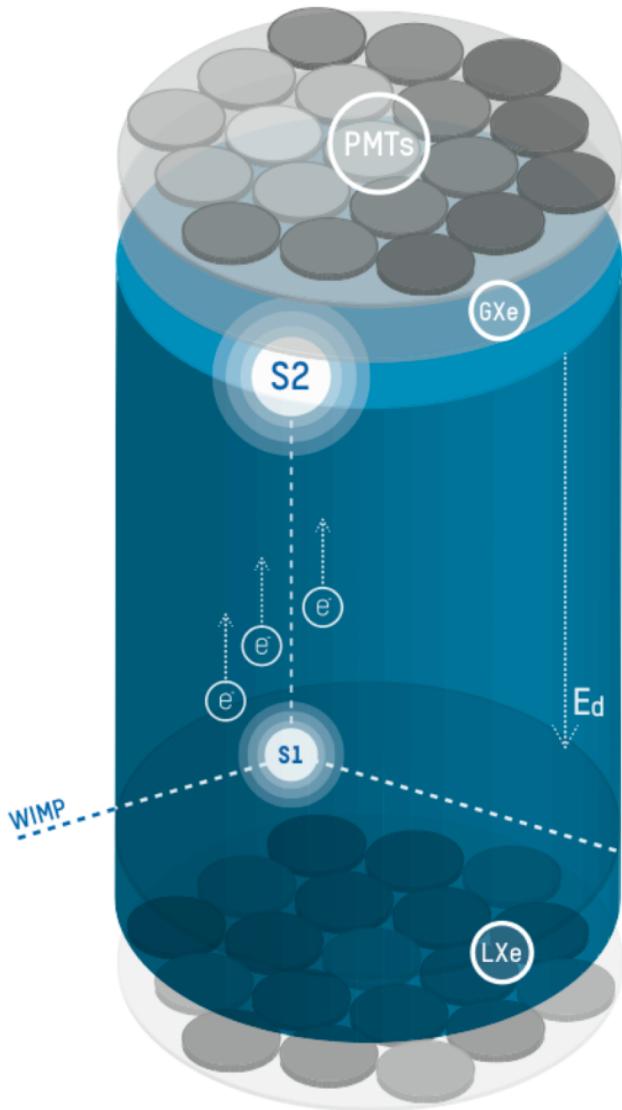
- **Avoid background**
- **External γ 's** from natural radioactivity
 - Material screening
 - Self shielding (fiducialization)
- **External neutrons**
 - muon-induced (α, n) and fission reaction
 - Material screening (low U and Th)
 - Underground experiments
 - Shield & active veto
- **Internal contamination**
 - ^{85}Kr : removed by cryogenic distillation
 - ^{222}Rn : removed by cryogenic distillation
 - ^{136}Xe : $\beta\beta$ decay, long lifetime ($T_{1/2} = 2.2 \times 10^{21}$ years)

- **Use WIMP properties**
 - No double scatter
 - Homogeneously distributed
→ *Position reconstruction*
 - Nuclear recoils
→ *ER/NR Discrimination*



Dual phase TPC: principle

TPC = Time Projection Chamber



S1:

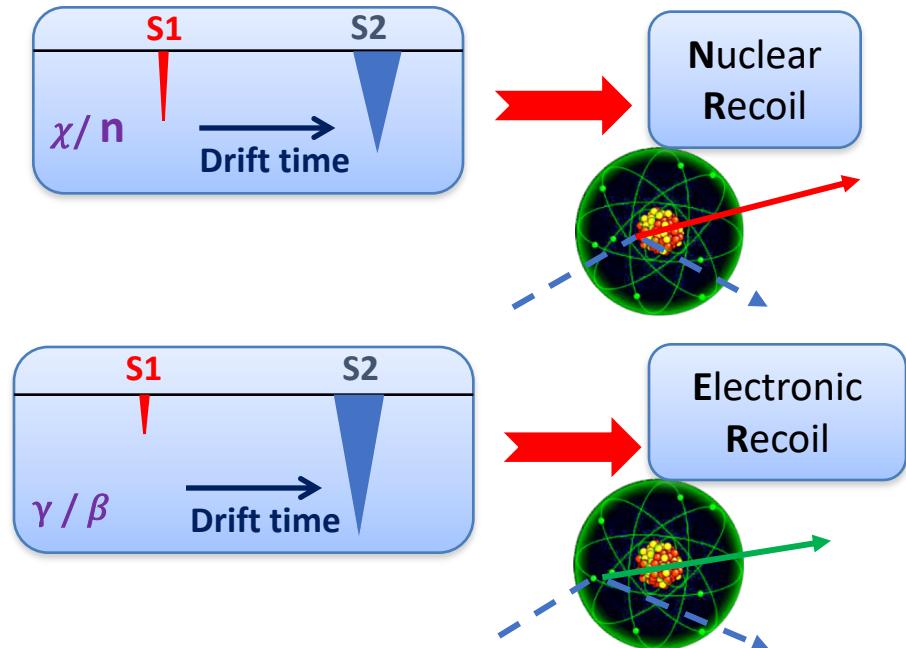
→ Photon ($\lambda = 178$ nm)
from Scintillation process → Detected by PMTs
(mainly bottom array)

S2:

→ Electrons drift
→ Extraction in gaseous phase
→ Proportional scintillation light

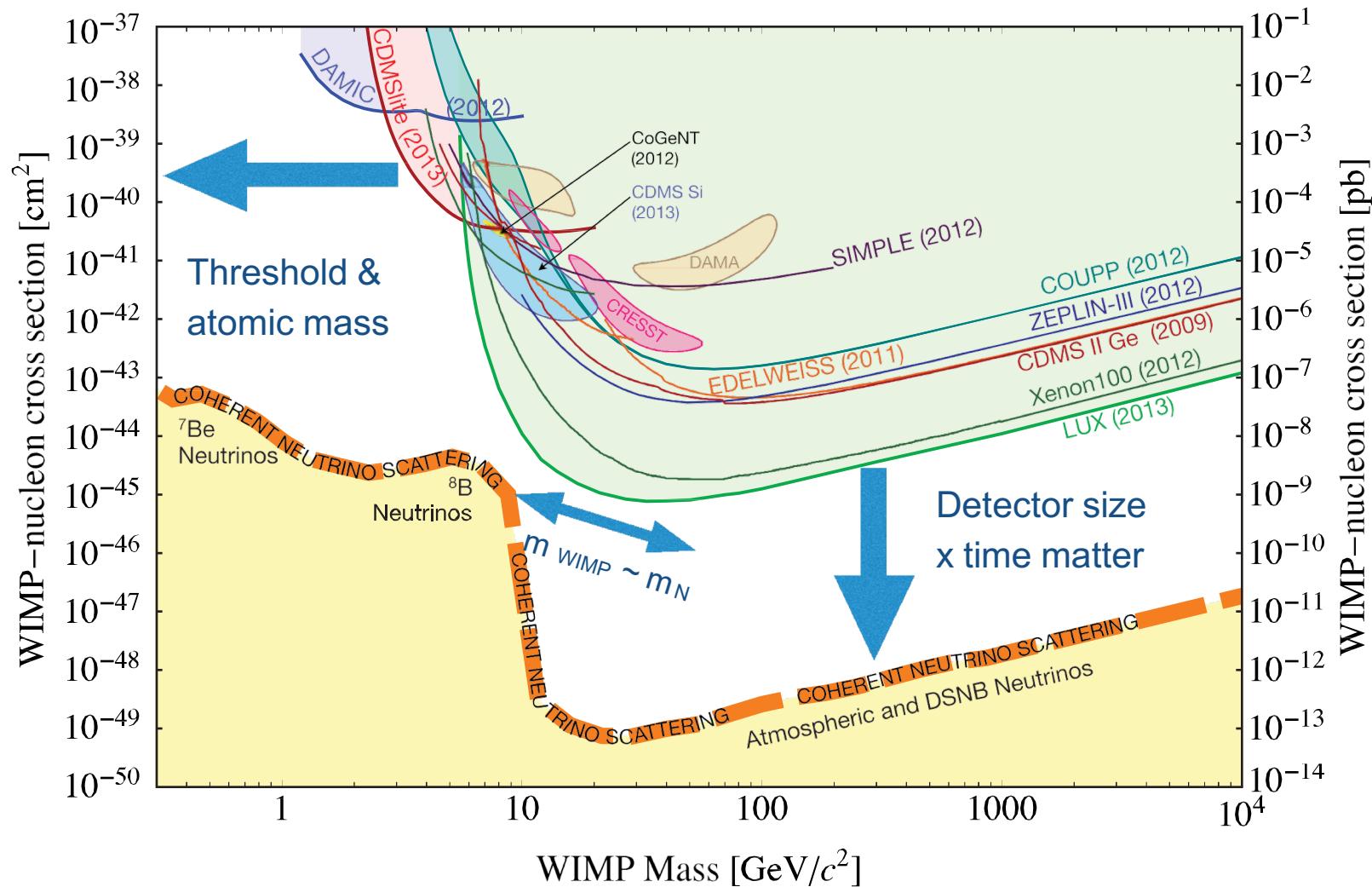
3D reconstruction :

→ X,Y from top array
→ Z from Drift time



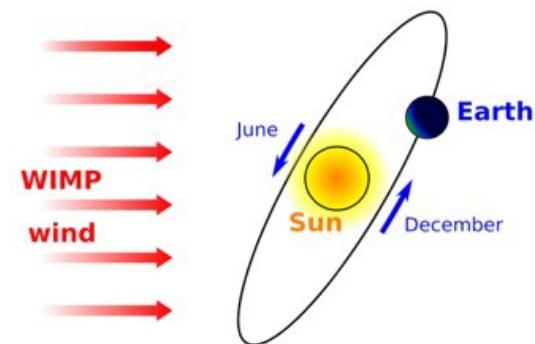
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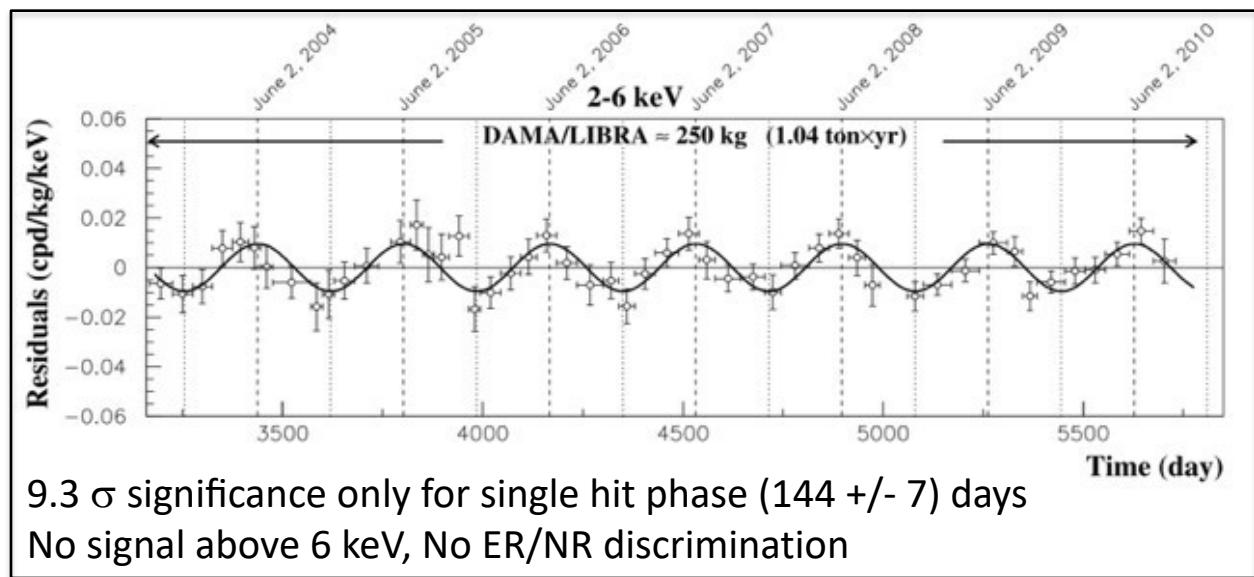
Probing the DAMA/LIBRA Anomaly with XENON100

Bernabei et al., Eur. Phys. J. C 73, 12 (2013)



Freese et al., Rev. Mod. Phys. 85, 1561 (2013)

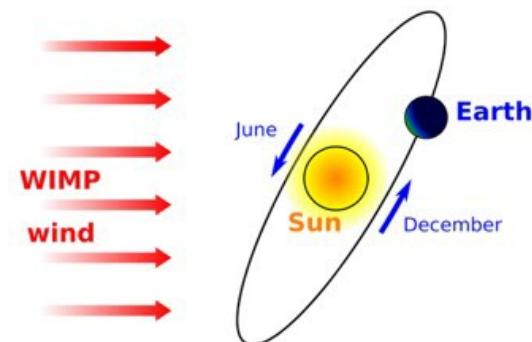
DM signal rate is expected to be
annually modulating
Peak phase 152 days (June 1)



Seems to be convincing evidence, HOWEVER...

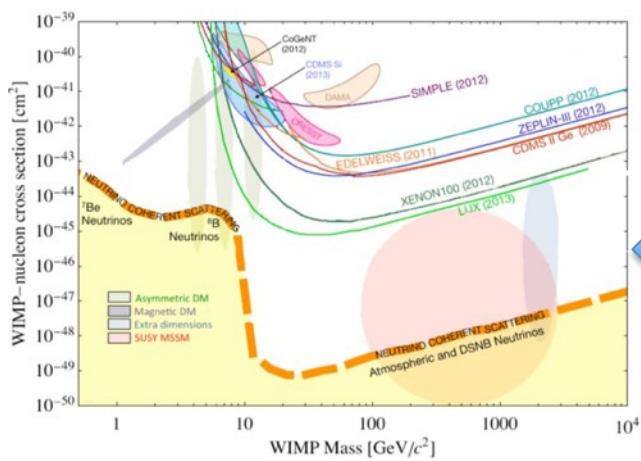
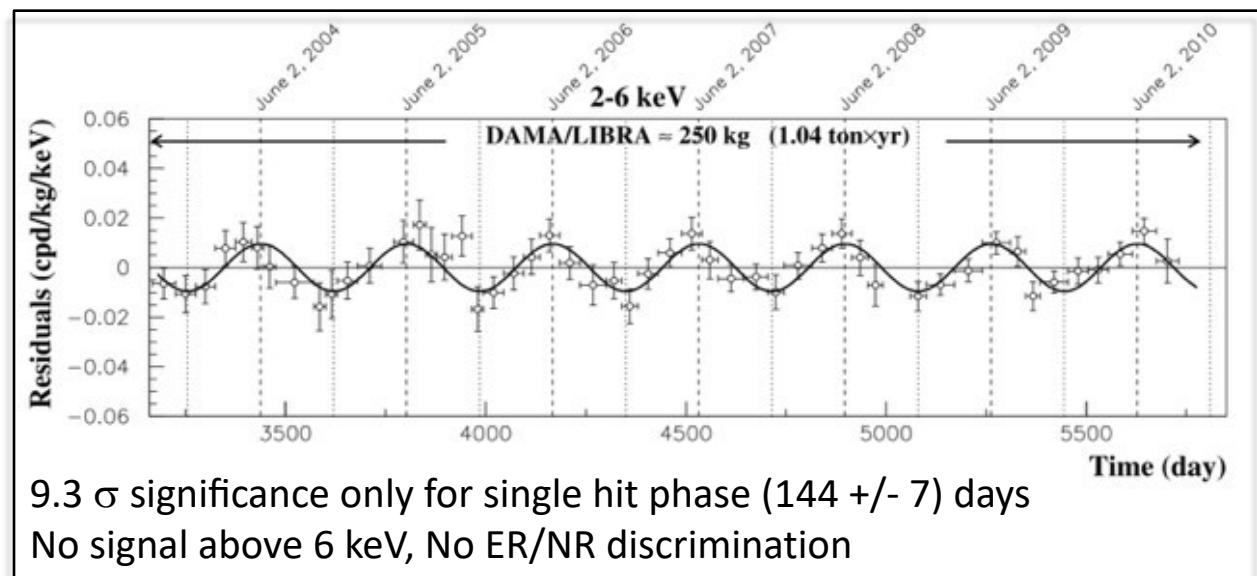
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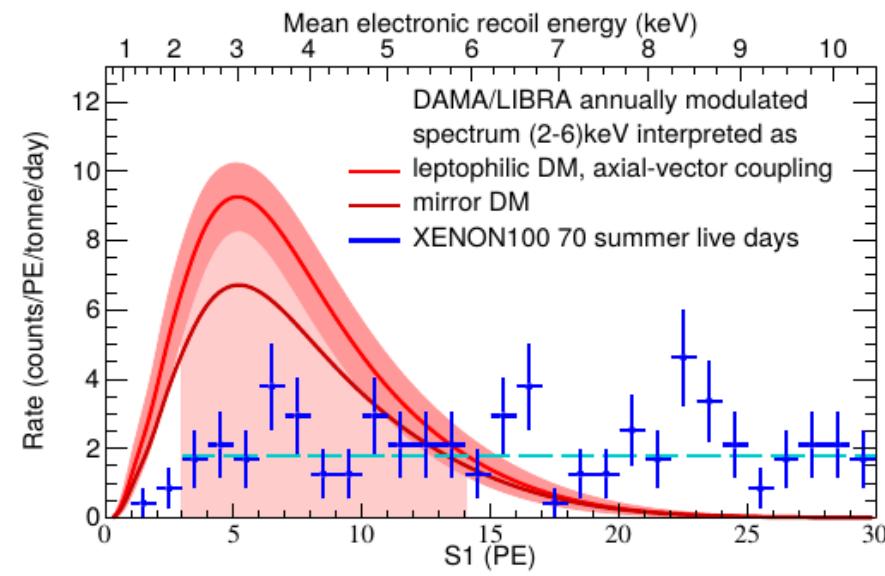
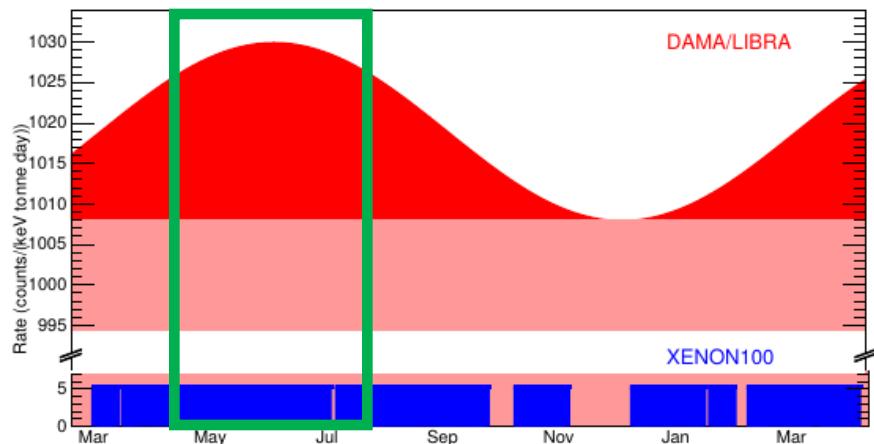
Seems to be convincing evidence, HOWEVER...
... Null results from many experiments more sensitive than DAMA/LIBRA

→ Reconcile DAMA/LIBRA with the null-results from other experiments assuming leptophilic dark matter?
→ DAMA/LIBRA might see electronic recoils ?

Exclusion of leptophilic Dark Matter

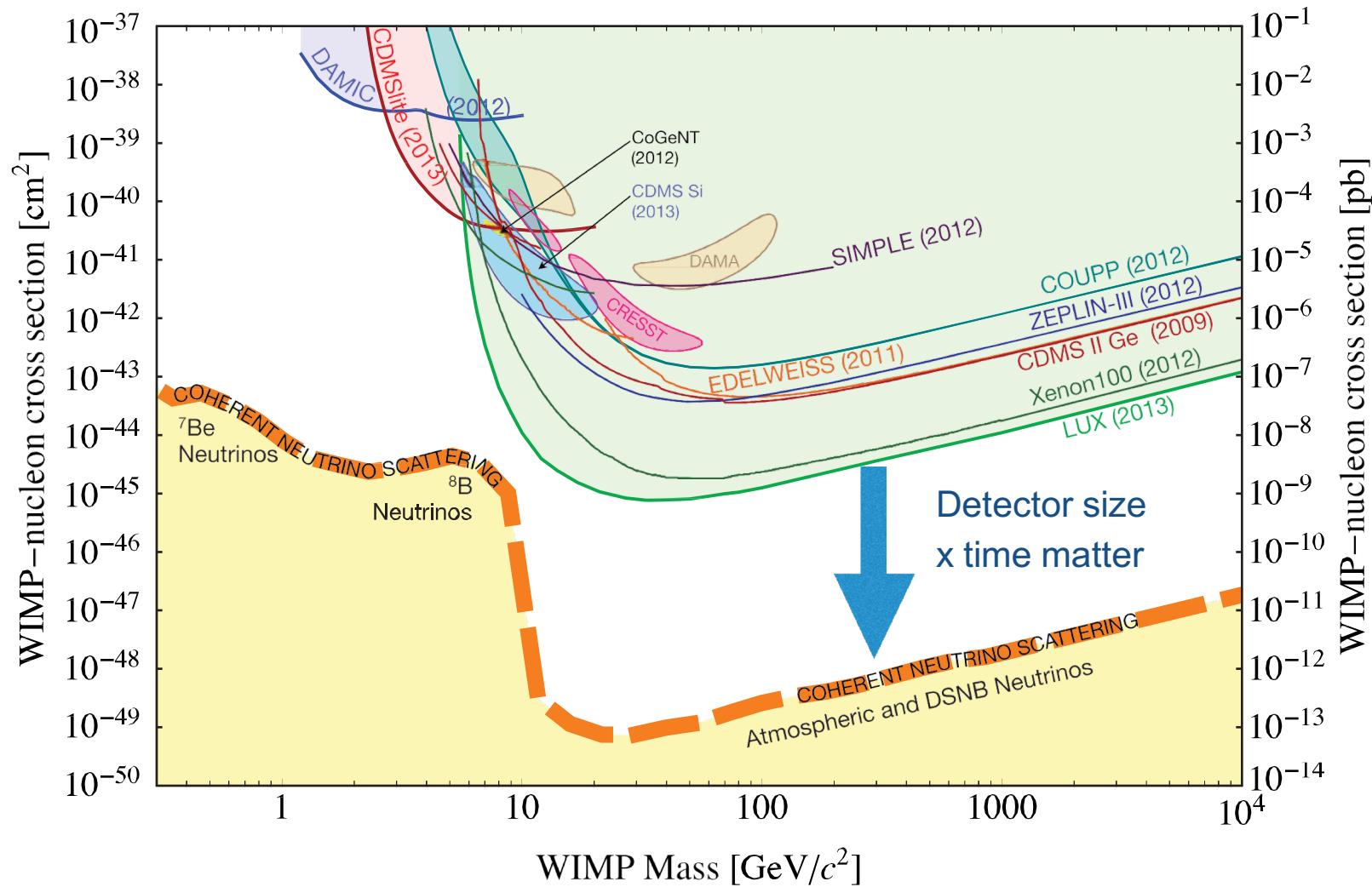
- DAMA/LIBRA experiment observes annual modulation interpretable with leptophilic DM
- Selection of 70 live days of electronic recoil XENON100 data, where DAMA signal is highest
- Assume some model of WIMP coupling to e⁻ to estimate expected signal in XENON100
- XENON100 steady background level lower than DAMA modulation signal
- **Exclusion of several types of DM models as the cause of the annual modulation**

Kinematically mixed Mirror DM: 3.6σ Exclusion
Luminous DM: 4.6σ Exclusion
Axial-vector coupling: 4.4σ Exclusion



*XENON100: Science 349, 851 (2015)
Confirmed by XMASS: PLB 759 272 (2016)*

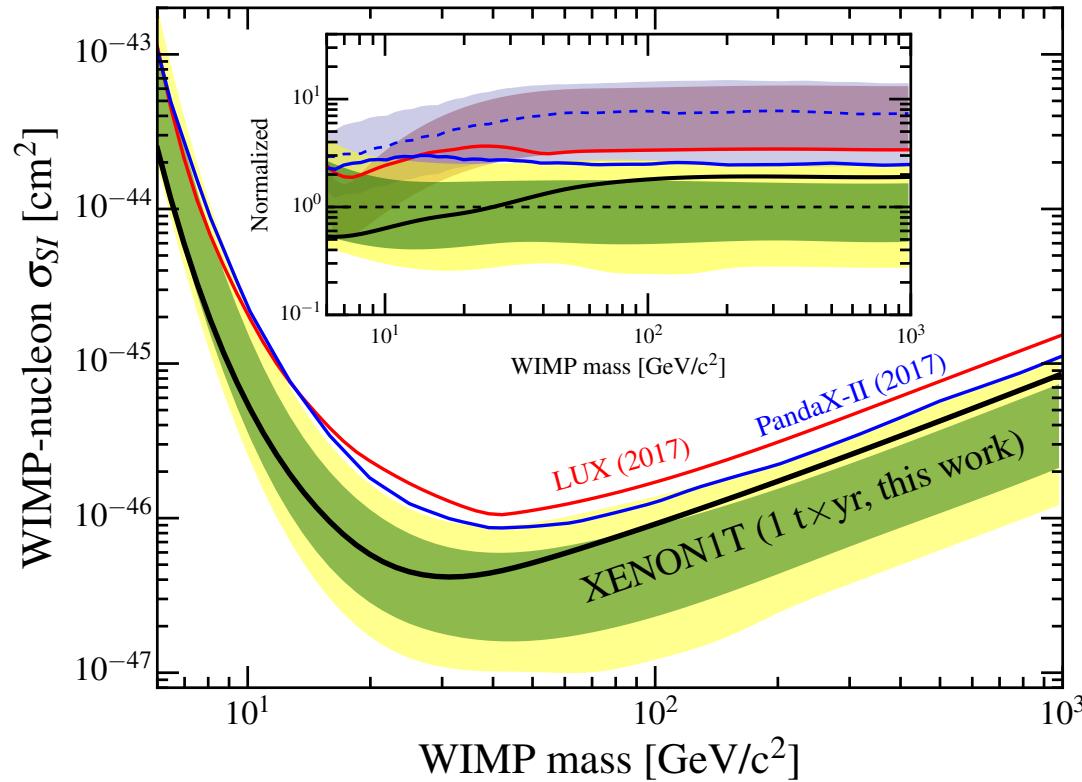
How is evolving the field of Direct Detection ?



XENON1T Results

- **Spin-independent WIMP-nucleon cross section**

Strongest exclusion limits (at 90% CL) on WIMPs $> 6 \text{ GeV}/c^2$.

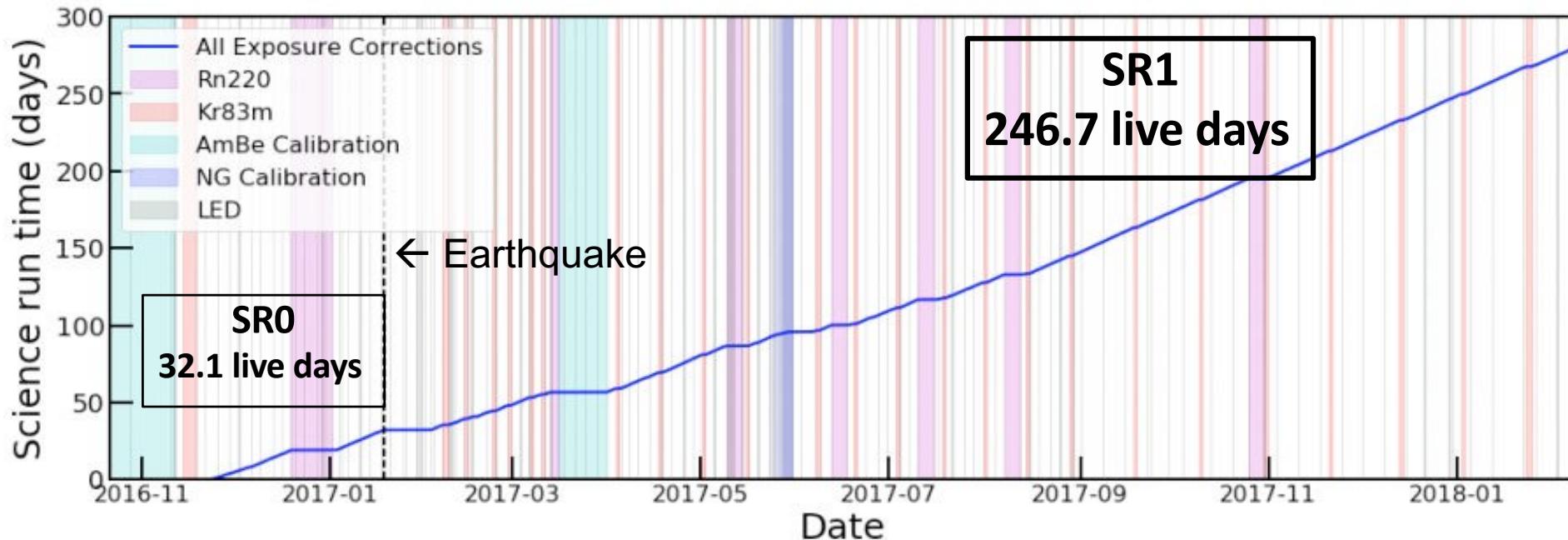


- **1 sigma upper fluctuation at higher WIMP masses**

No significant excess (> 3 sigma) is observed.

Phys. Rev. Lett. 121, 111302 (2018)

XENON1T Data Taking



- DM total exposure SR0+SR1: 278.8 Live days
→ Largest exposure reported to-date with this type of detector
- Calibration Data:
 - 83mKr → Spacial Response (electron lifetime,...)
 - 220Rn → ER-Band
 - 241AmBe & NG → NR-Band
 - LED → PMT gain monitoring

XENON1T facility

Water shield: deionized water as passive radiation shield

Muon veto: Active muon veto against muon induced neutrons (84 PMTs)

Cryogenics: Stable conditions(3.2t LXe)

Purification: LXe flow through getters, remove impurities

DAQ: Each channel has its own threshold, Flexible software algorithms

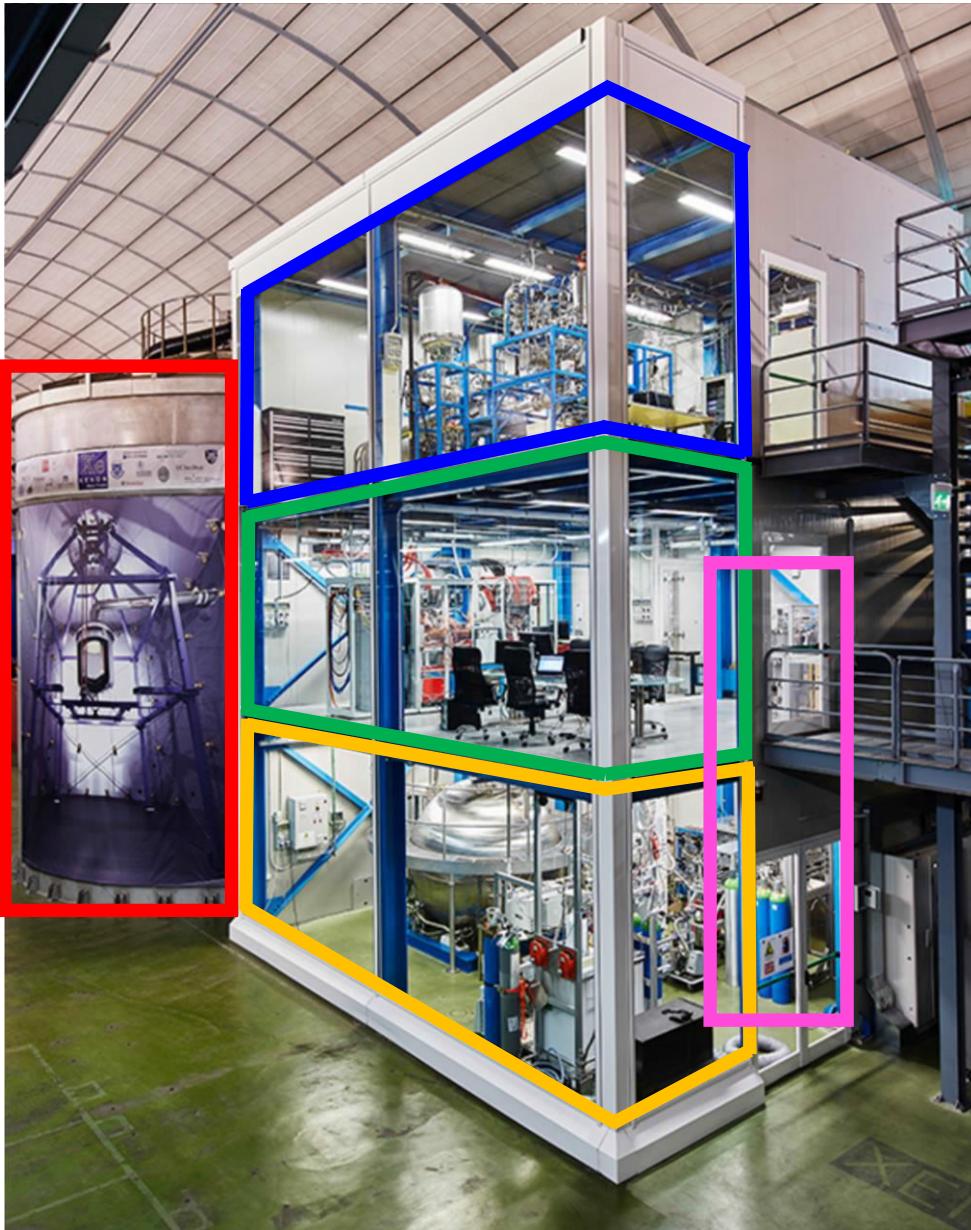
Readout: Up to 300MB/s for high rate calibrations

ReStoX: Emergency recovery up to 7.6 tons of LXe

Passive: No active cooling required to keep Xe contained

Kr Distillation: Remove Kr from system during fill or online

Rn Distillation: Initial tests show promising reduction for Rn



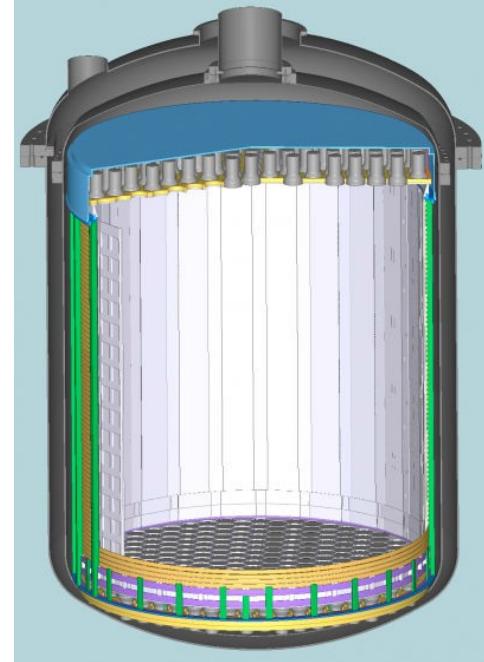
XENON World

27 Institutions
11 Countries
165 Scientists

Experiment
@LNGS (Italy)
- 3600 mwe
underground



Phases of the XENON Program



XENON10

2005 – 2007

15 cm drift TPC

Total: 25 kg

Target: **14** kg

Fiducial: 5.4 kg

Achieved (2007)

$$\sigma_{\text{SI}} = 8.8 \cdot 10^{-44} \text{ cm}^2$$

@ 100 GeV/c²

XENON100

2008 – 2016

30 cm drift TPC

Total: 161 kg

Target: **62** kg

Fiducial: 34/48 kg

Achieved (2016)

$$\sigma_{\text{SI}} = 1.1 \cdot 10^{-45} \text{ cm}^2$$

@ 55 GeV/c²

XENON1T

2011 – 2018

100 cm drift TPC

Total: 3 200 kg

Target: **2 000** kg

Fiducial: 1 300 kg

Achieved (2018)

$$\sigma_{\text{SI}} = 4.1 \cdot 10^{-47} \text{ cm}^2$$

@ 30 GeV/c²

XENONnT

2019 – 2023

150 cm drift TPC

Total: 8 000 kg

Target: **6 000** kg

Fiducial: 4 500 kg

Projected (2022)

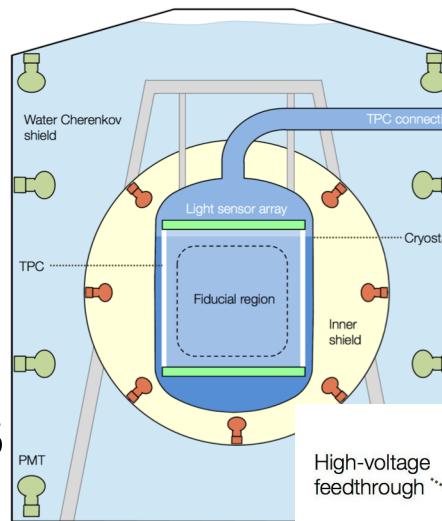
$$\sigma_{\text{SI}} = 1.6 \times 10^{-48} \text{ cm}^2$$

@ 50 GeV/c²

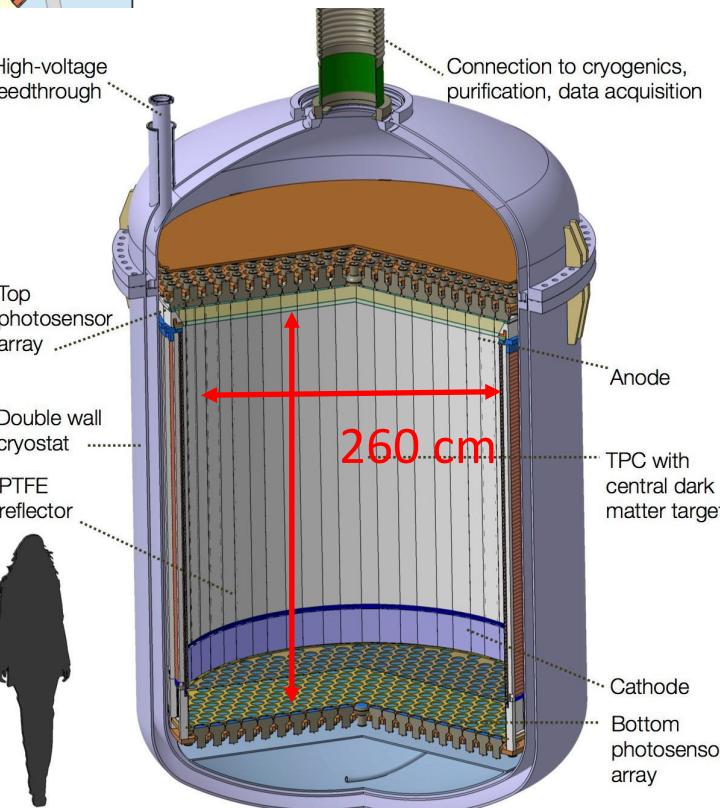
DARWIN the ultimate detector



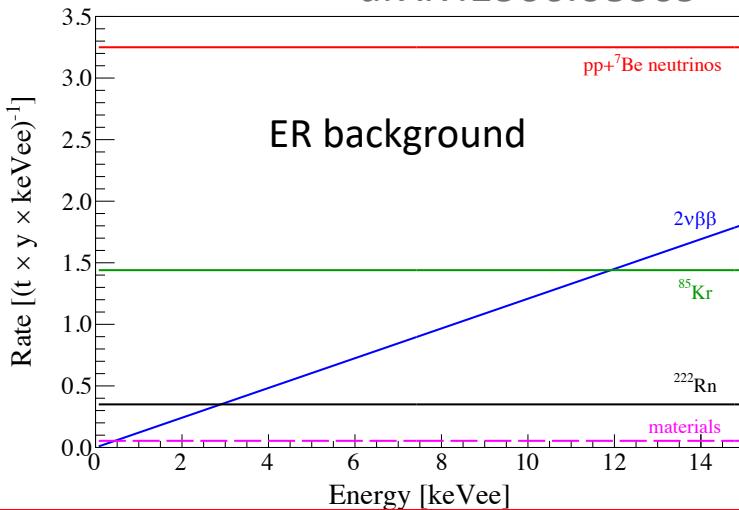
- Based on proved technologies
- Aim at sensitivity of a few 10^{-49} cm^2 , limited by irreducible ν -backgrounds (200 t y)
- R&D started – data taking in 2026
- 50 tons total LXe
40 tons TPC
30 tons fiducial



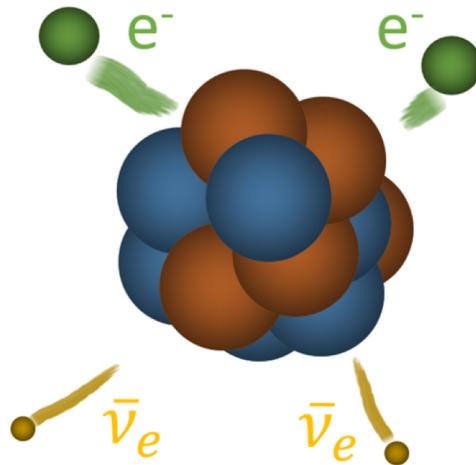
JCAP 1611 (2016) no.11, 017
arXiv:1606.07001



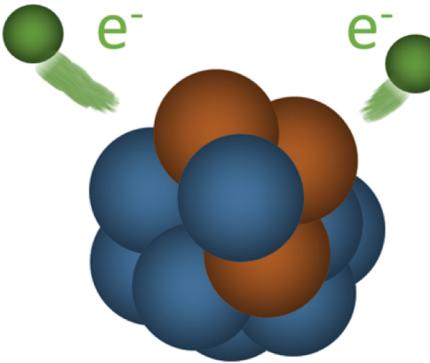
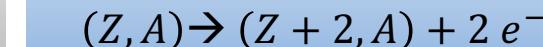
arXiv:1506.08309



Double β decay with and without neutrinos



Rare process :
 $T^{1/2} = 21 \times 10^{20}$ yr
 $T^{1/2} = 10^{11} * T^{\text{Univers}}$
Observed
(EXO & NEXT)



Rare process :
 $T^{1/2} > 1.07 \times 10^{26}$ yr
 $T^{1/2} > 10^{16} * T^{\text{Univers}}$
X Observed
(Limit by KamLandZen)

Why searching at it ?

- Neutrino = Majorana particle ?
- Lepton number violation
- Absolute mass of neutrino
 - Number of events is related to the effective majorana neutrino mass ($m_{\beta\beta}$)

$$N = \log 2 \frac{\epsilon m_{Xe} N_a}{M_{Xe}} \frac{t}{T_{1/2}^{0\nu}}$$

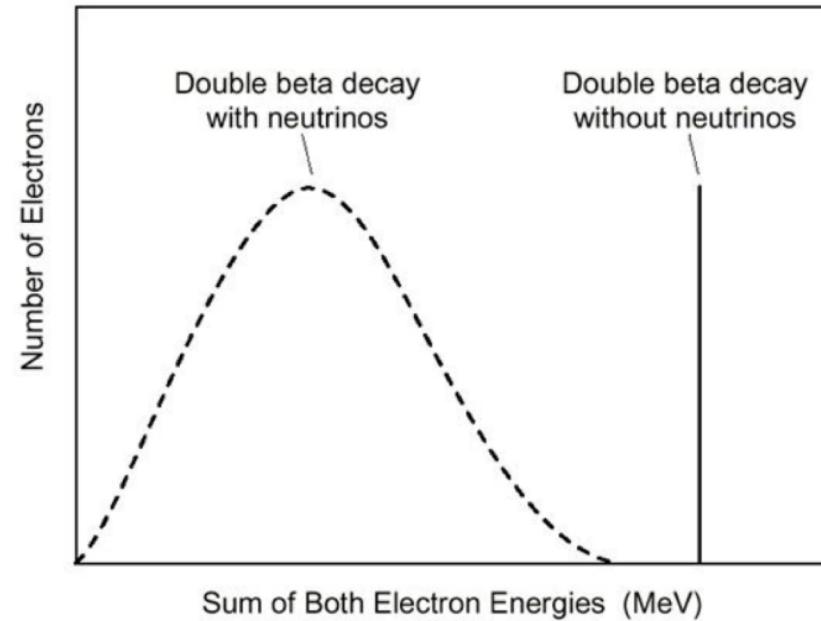
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

Rare event = Need a low background experiment

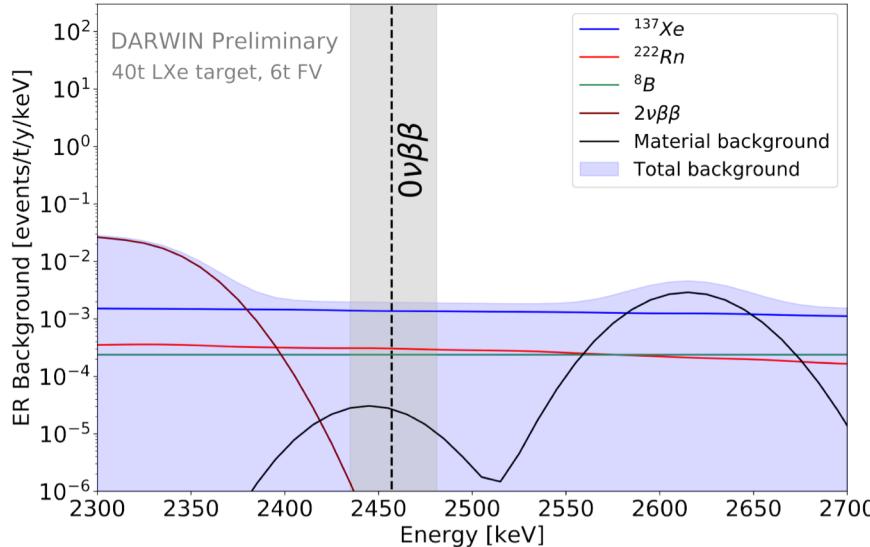
Double β decay with and without neutrinos

^{136}Xe isotope

- Double β emitter
- Naturally present in XENON1T (abundance of 8.49%)
- **Detection of electrons \Leftrightarrow Electronic Recoil**
- Peak @ 2.457 MeV
- High stopping power of LXe \Leftrightarrow Single Scatter
 - Need a good discrimination between **Single Scatter** and **Multiple Scatter**
 - **Multiple Scatter :**
 - More abundant at high energy: background γ -lines \Leftrightarrow Compton scattering



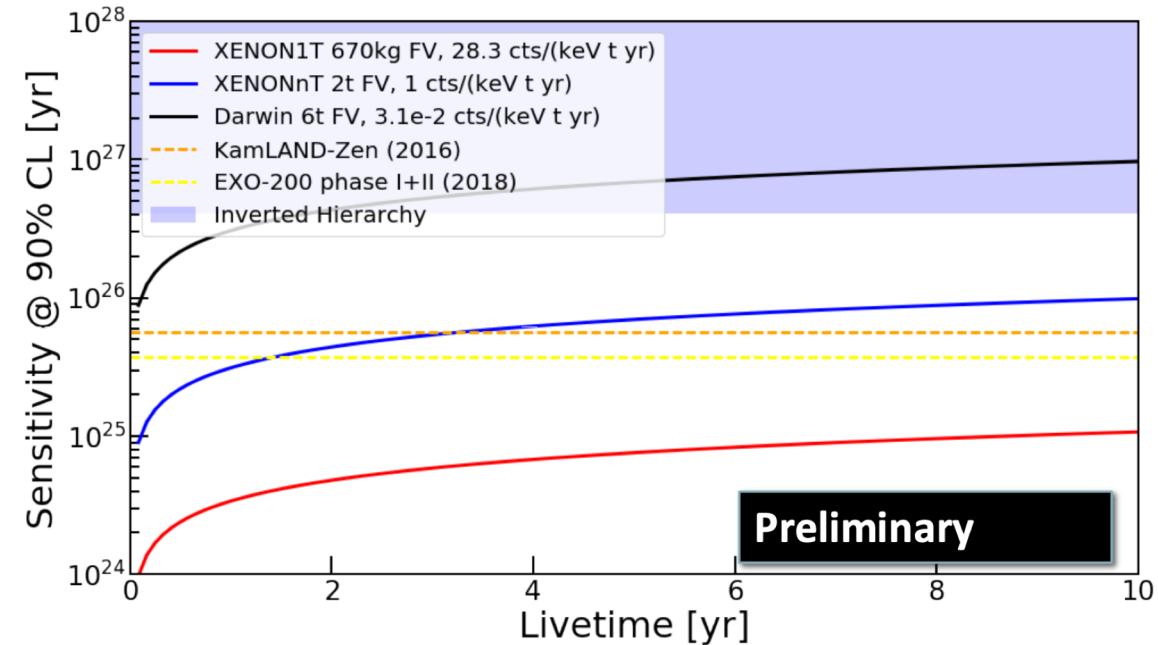
Double β decay with and without neutrinos



Preliminary background estimation for :

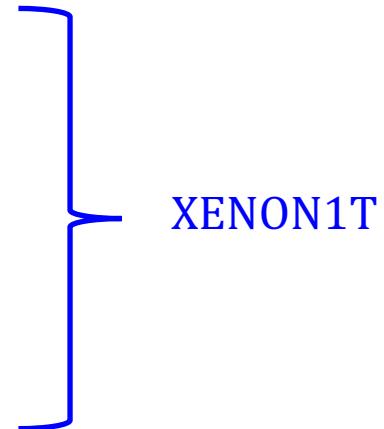
- Dark matter
- $0\nu\beta\beta$

Expected sensitivity according to the baseline design

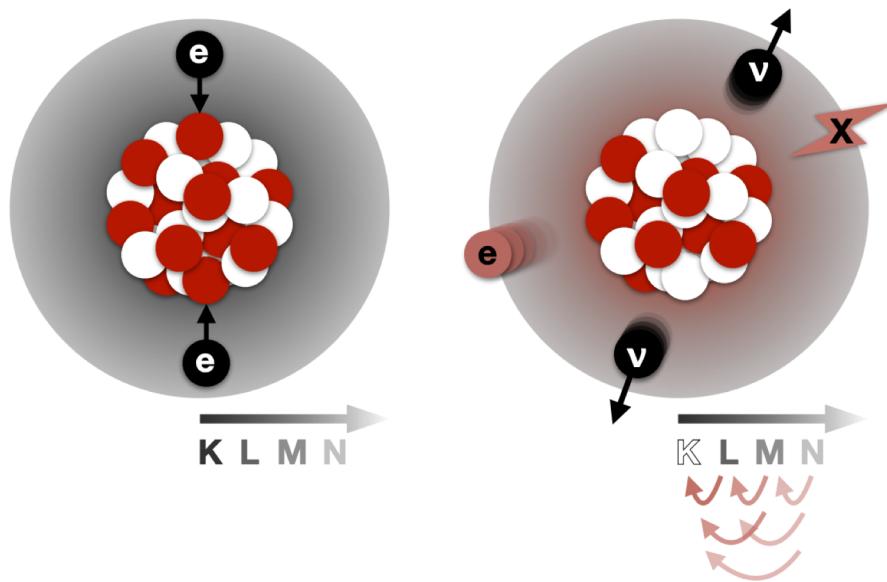


Double electron capture (DEC) with ^{124}Xe

- $^{124}\text{Xe} + 2\text{e}^- \rightarrow ^{124}\text{Te} + 2\nu_e$
- Vacancies on the K shell : Detectable cascade of X-rays and Auger electrons in the keV-range (64.3 keV)
- Large half-lives : $> 10^{12} \cdot T_{\text{univers}}$
- Needs very low background experiment



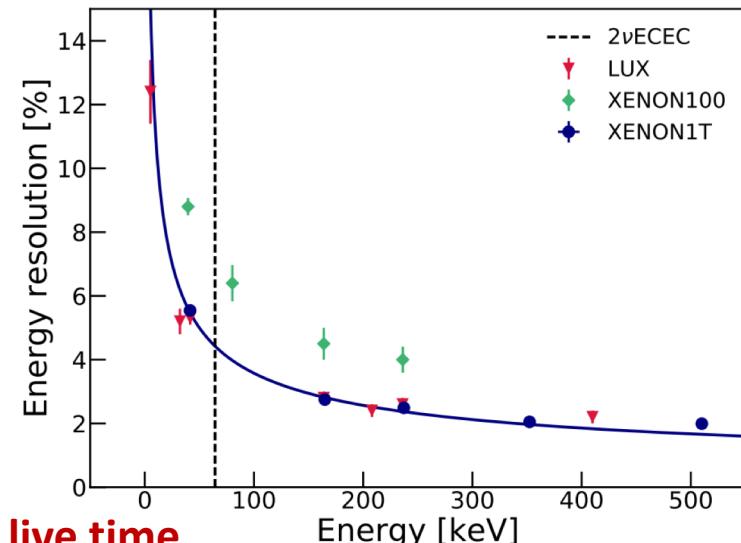
$^{124}\text{Xe} \sim 1 \text{ kg / t}$



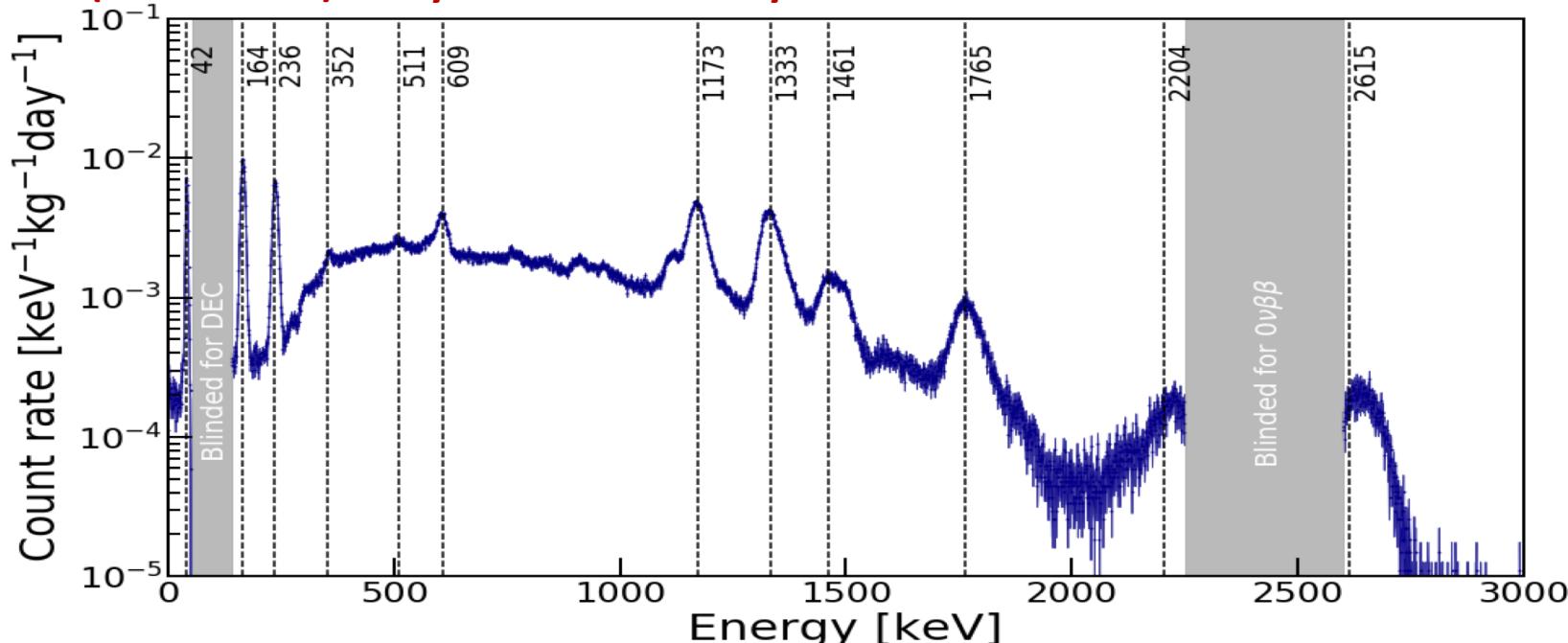
Double electron capture (DEC) with XENON1T

$^{124}\text{Xe} \Leftrightarrow$ Double K-shell capture :
X-rays and Auger electrons
Single peak @64.3 keV

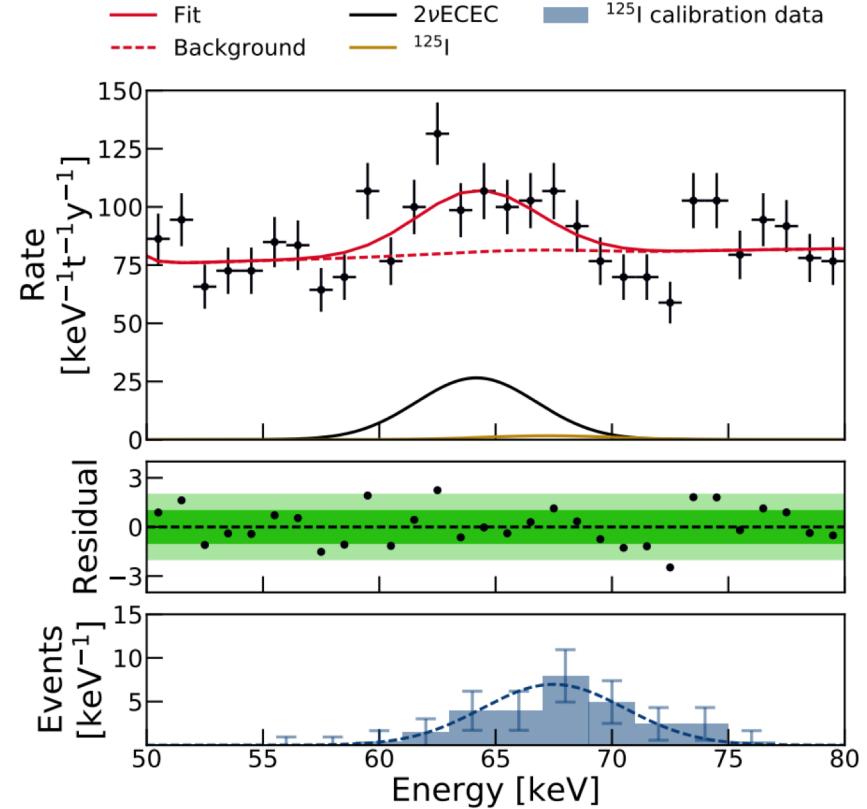
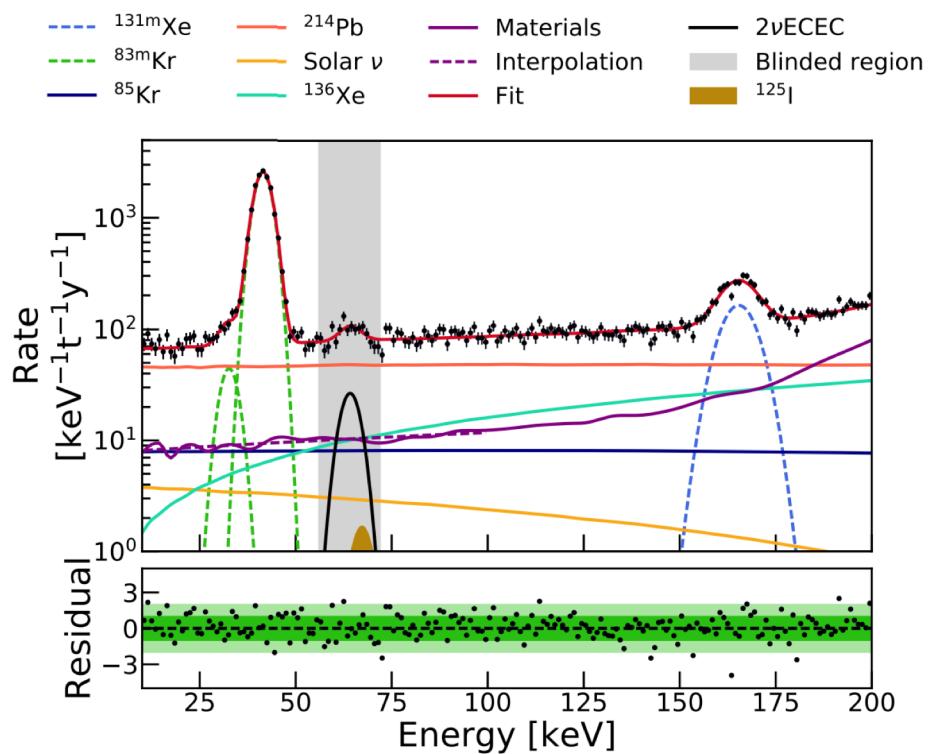
Energy resolution @64.3 keV:
 $\frac{|\sigma|}{\mu} = (4.1 \pm 0.4) \%$



Blinded (56 – 72 keV) analysis with 177.7 days of live time



Double electron capture (DEC) Results

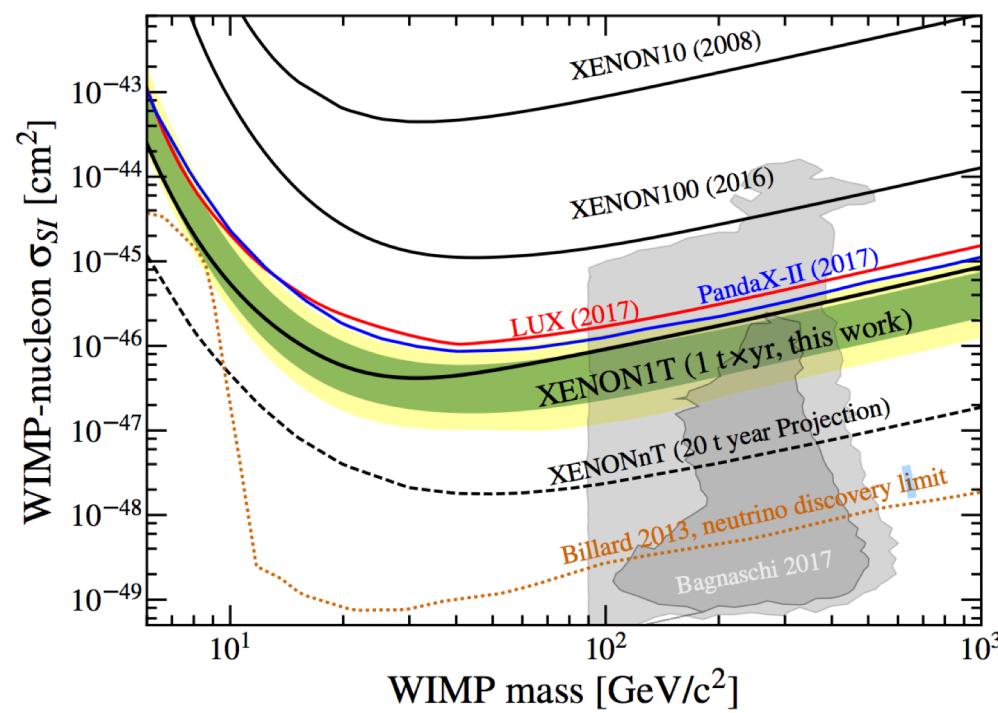


- Blinded region from 56 keV to 72 keV
- Ellipsoidal 1.5 t inner fiducial volume
- Peak at $E = (64.2 \pm 0.5)$ keV and $\sigma = (2.6 \pm 0.3)$ keV
- Significance 4.4σ

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

Conclusions

- Liquid Xenon is the world leading technique of DM searches
- First multi-ton scale LXe-TPC successfully operated for more than 1 year
- Strongest limit on WIMP-nucleon SI cross-section above 6 GeV/c²: minimum at $4.1 \cdot 10^{-47} \text{ cm}^2$ for a WIMP of 30 GeV/c²
- Double Electron Capture detection : longest half-life ever measured directly
- Proof that xenon-based Dark Mater search experiments are sensitive for rare event searches



Other XENON1T analysis:

- S2 only analysis channel
- Annual modulation
- Migdal effect
- Light dark matter searches
- 0νββ of ¹³⁶Xe

Stay Tuned!