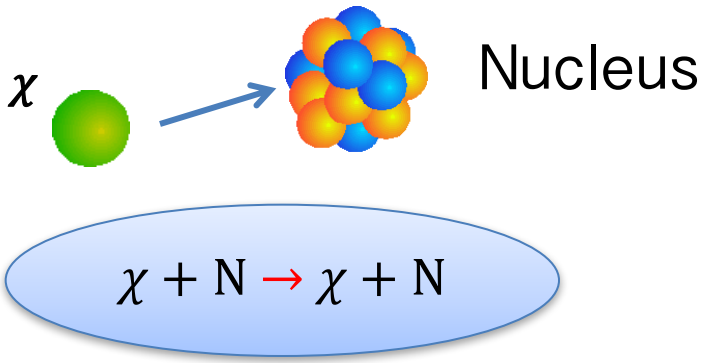
Dark Matter
Direct Detection Experiments with Xenon in Dual Phase

Julien Masbou
Subatech – Université de Nantes

52nd Rencontres de Moriond
Electroweak Interactions and Unified Theories

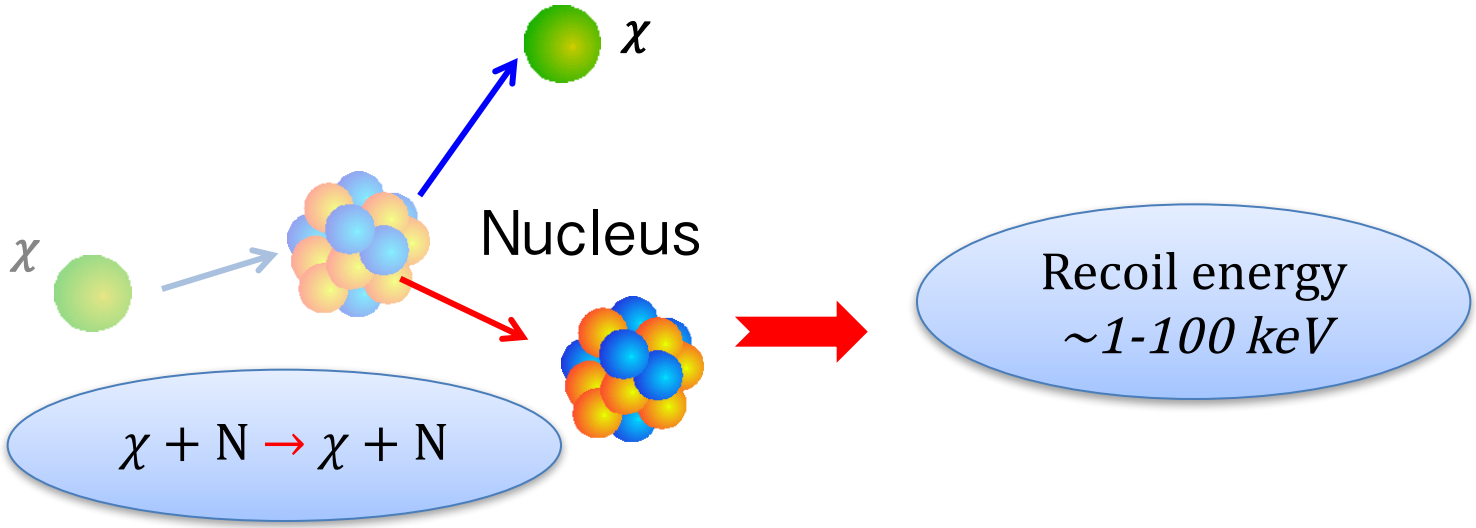
Direct dark matter detection principle

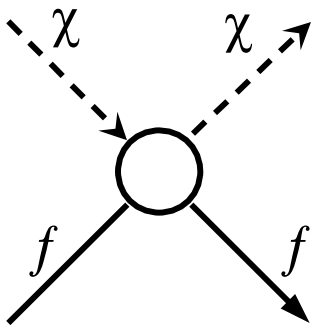
Nuclear Recoil (NR)



Direct dark matter detection principle

Nuclear Recoil (NR)





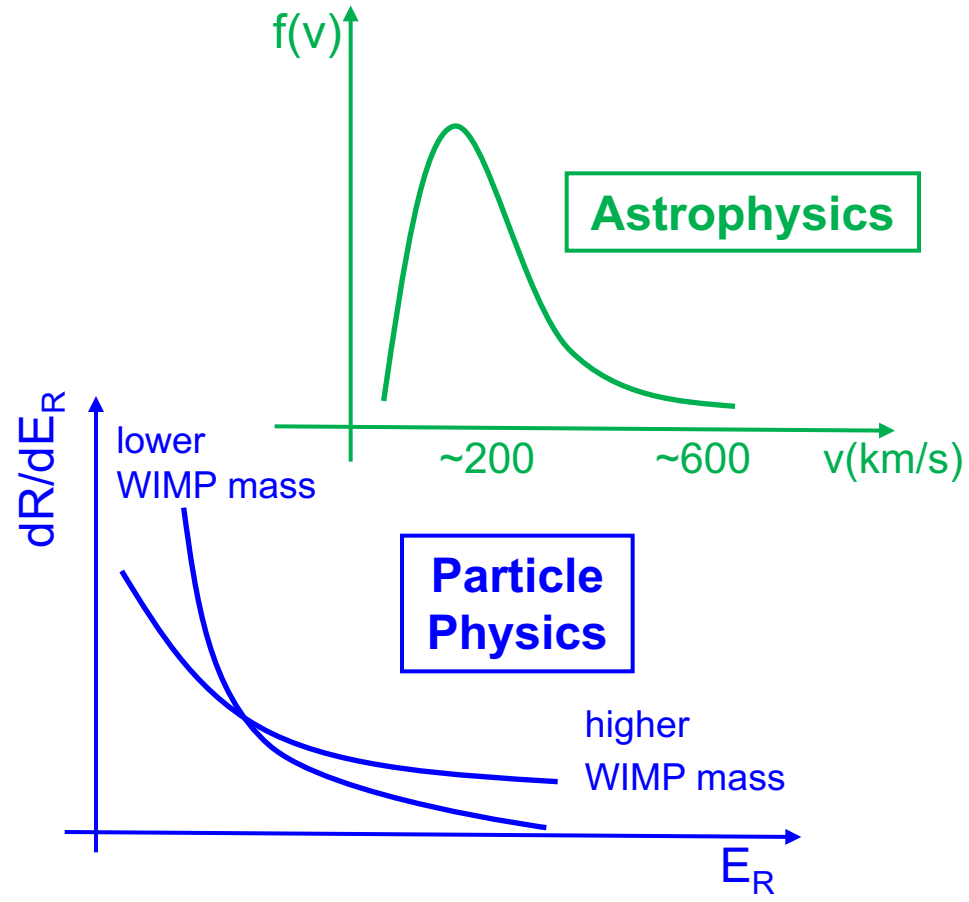
Electronic Recoil (ER)

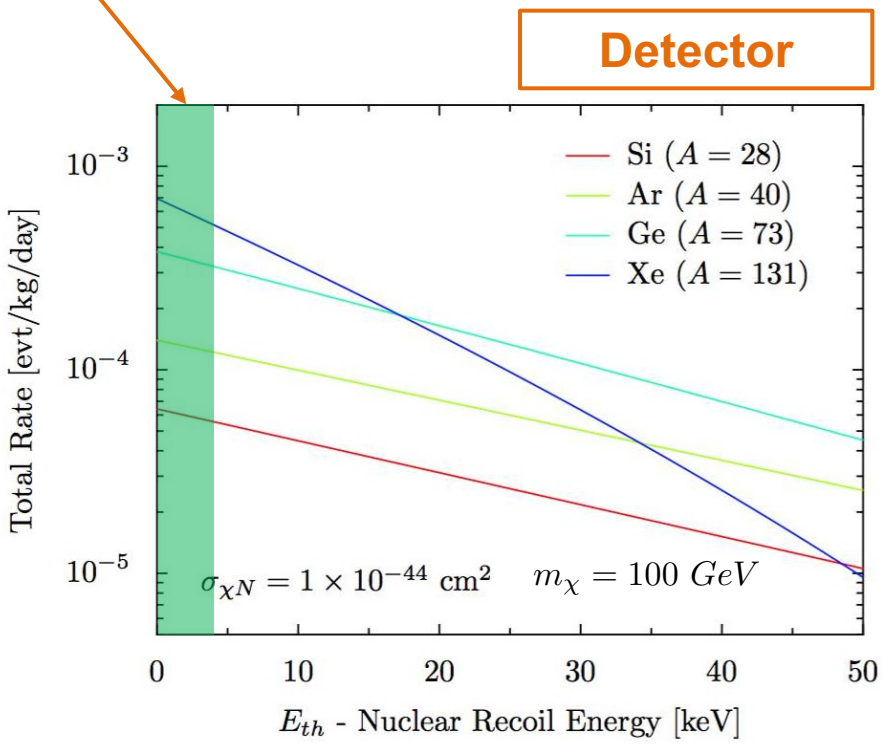
γ and β particles
interact with the atomic electrons
→ background

Expected rate for terrestrial detector

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

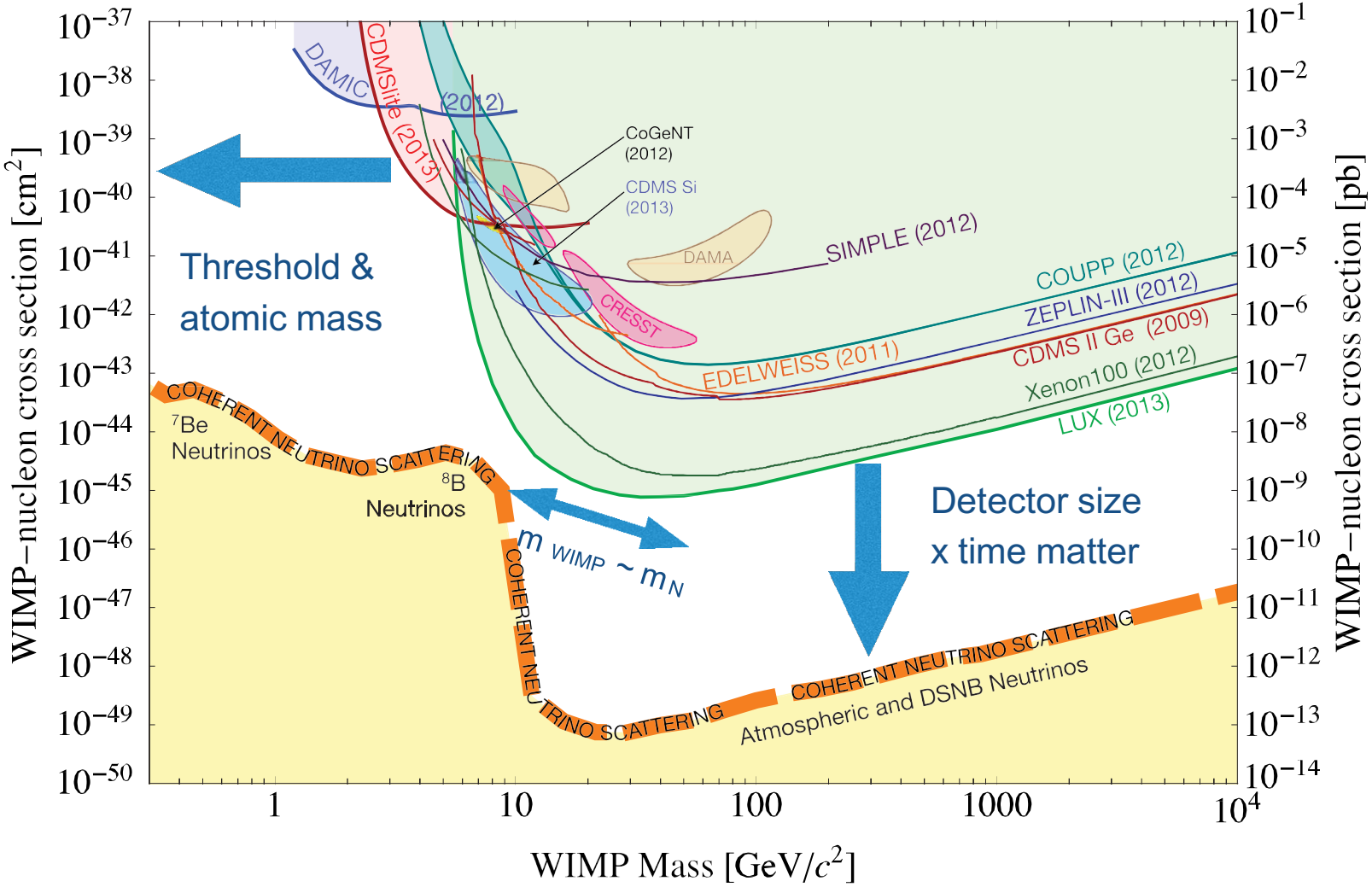
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu}}$$



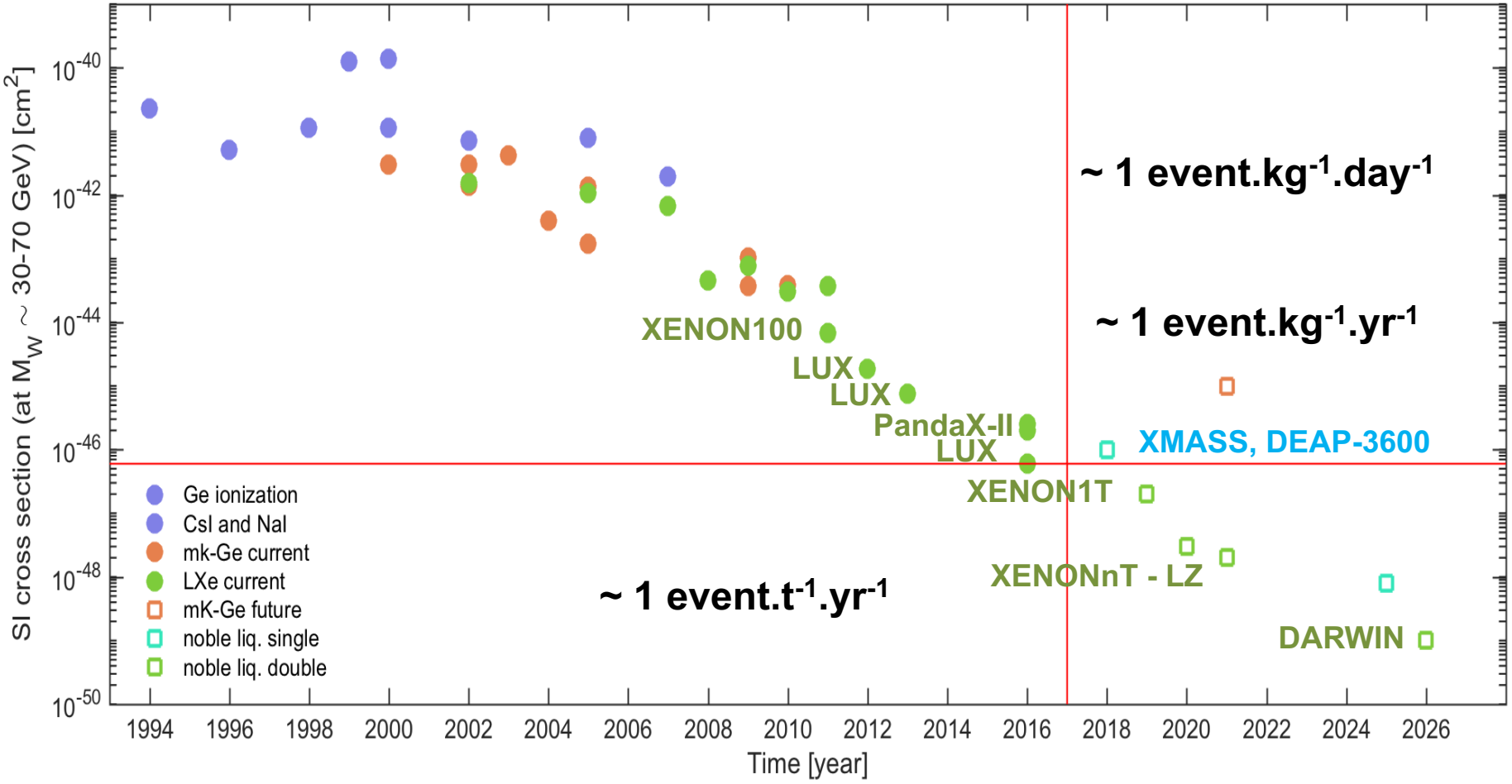


How is evolving the field of Direct Detection ?

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



Direct detection : progress over time



The fight against the background

- **Use WIMP properties**

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

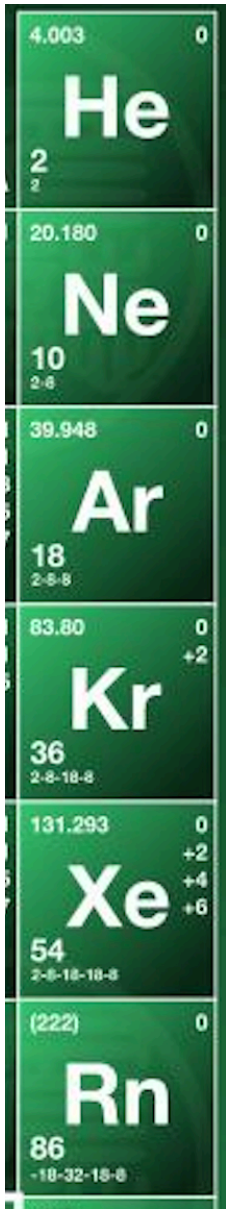
- **Avoid background**

- **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 : ββ decay, long lifetime ($T_{1/2}$ = 2.2x10^{21} years)

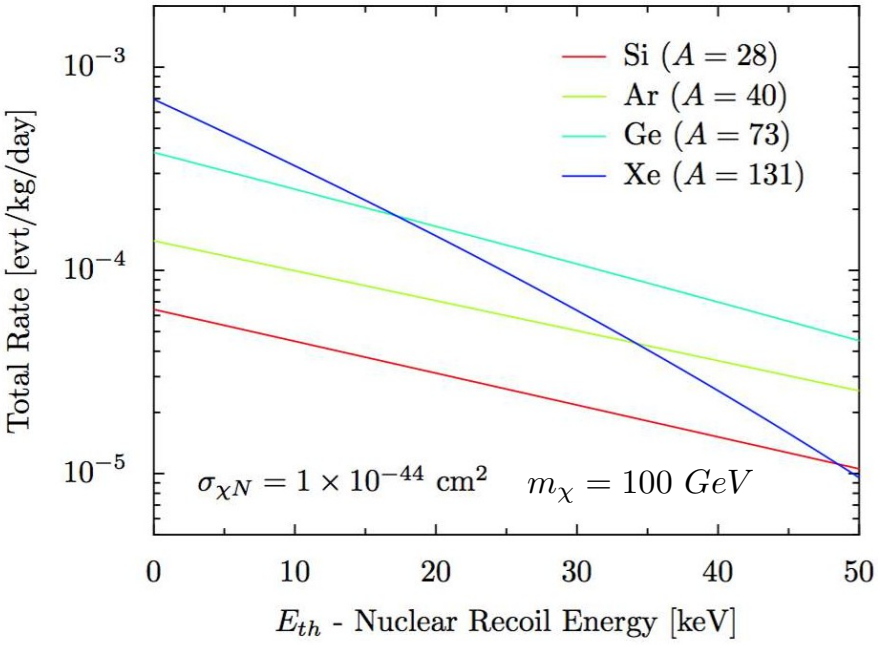
Noble gases



	Neon	Argon	Krypton	Xenon
Atomic Number	10	18	36	54
Density	1.2	1.4	2.4	3
Scintillation (γ/keV)	30	40	25	42
Wavelength (nm)	85	128	150	178
Decay Time (ns)	15400	6.3, 1500	2, 91	2.2, 27, 45
Ionization (e-/keV)	46	42	49	64
Boiling Point (K)	27.1	87.3	119.8	165.0
Radioactivity	No	^{39}Ar 1Bq/kg (1mBq/kg)	Yes	^{136}Xe / Kr can be removed to ppt level
Price	$$	$ ($$$)	$$$	$$$$

Why Xenon ?

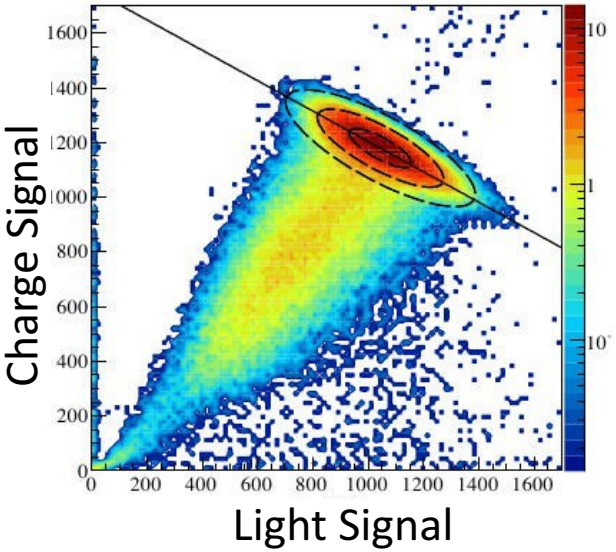
- Large mass number A (131) (Interaction cross section $\propto A^2$)
- 50% odd isotopes (^{129}Xe, ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization

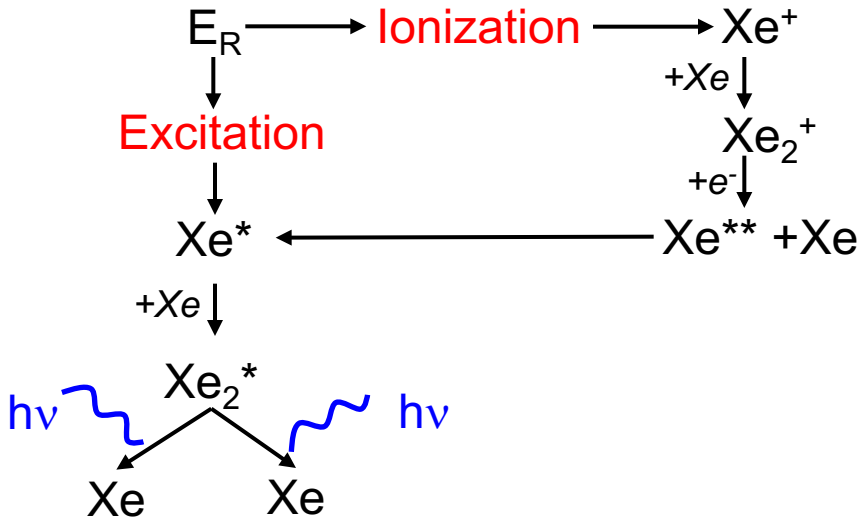


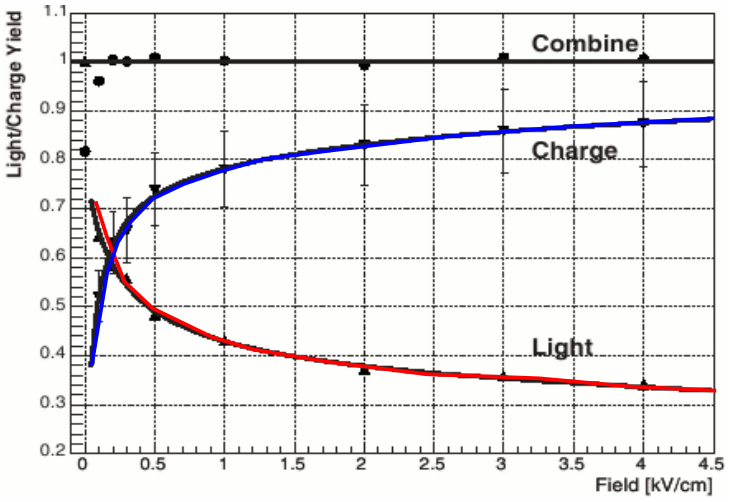
Scintillation and ionization in noble liquids

- Energy deposit produce both:
  - Electron-ion pair
  - Excited atom states

- Anti-correlation between charge and light
  → Improve energy resolution
- Excitation depends on dE/dx
  → Discrimination capabilities

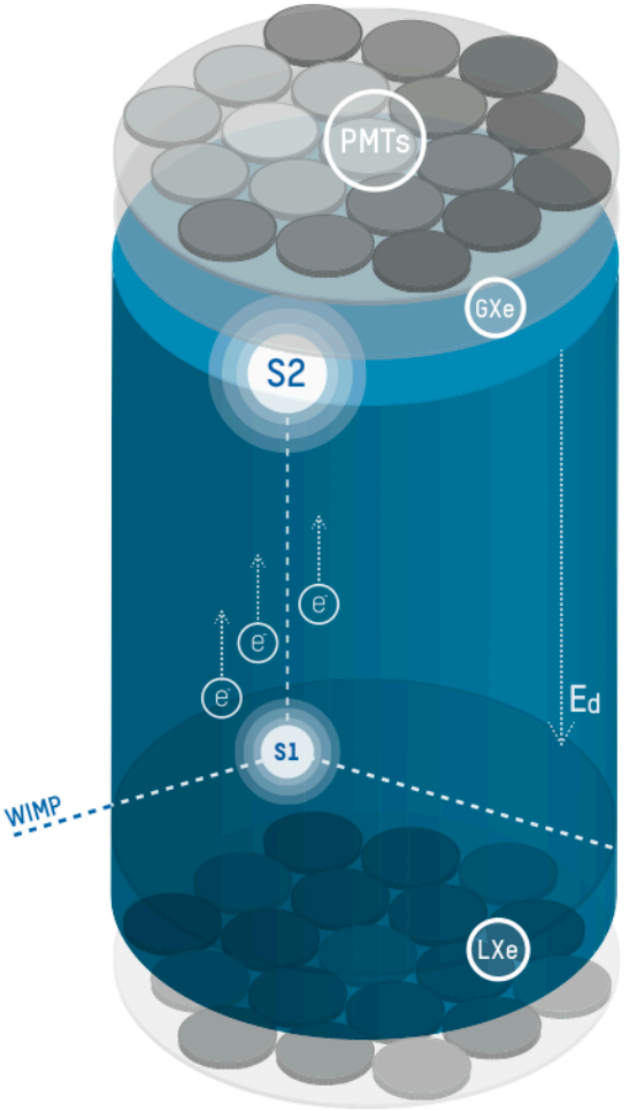






Dual phase TPC: principle

TPC = Time Projection Chamber



S1:

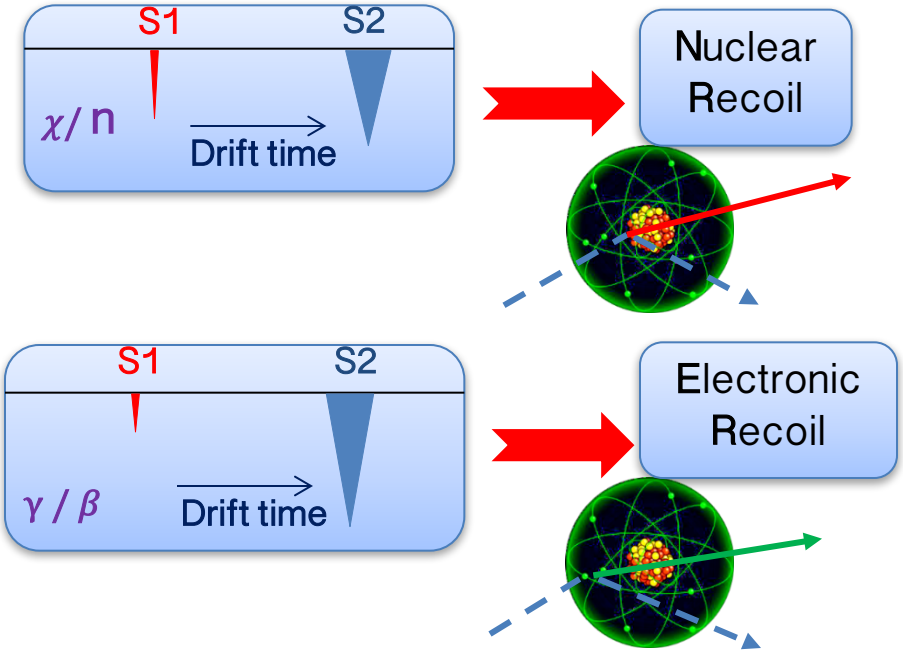
→ Photon (λ = 178 nm) from Scintillation process → Dectected by PMTs (mainly botton array)

S2:

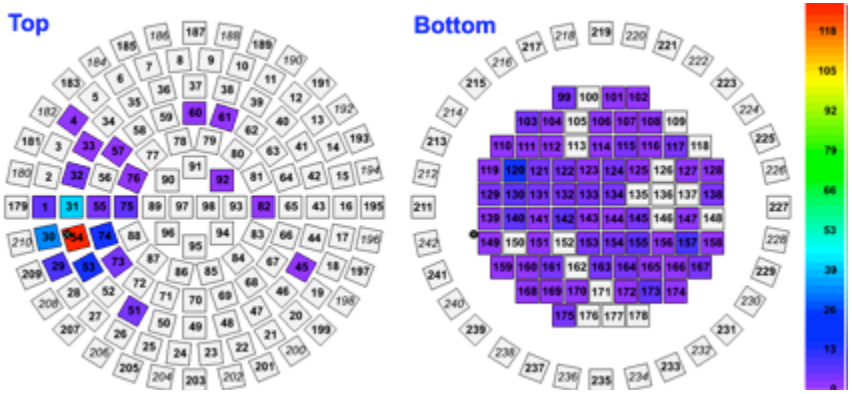
→ Electrons drift
→ Extraction in gaseous phase
→ Proportional scintillation light

3D reconstruction :

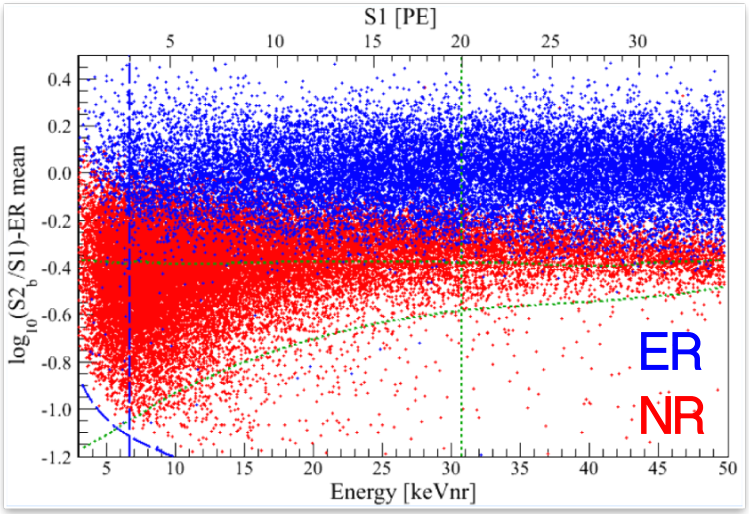
→ X,Y from top array
→ Z from Drift time

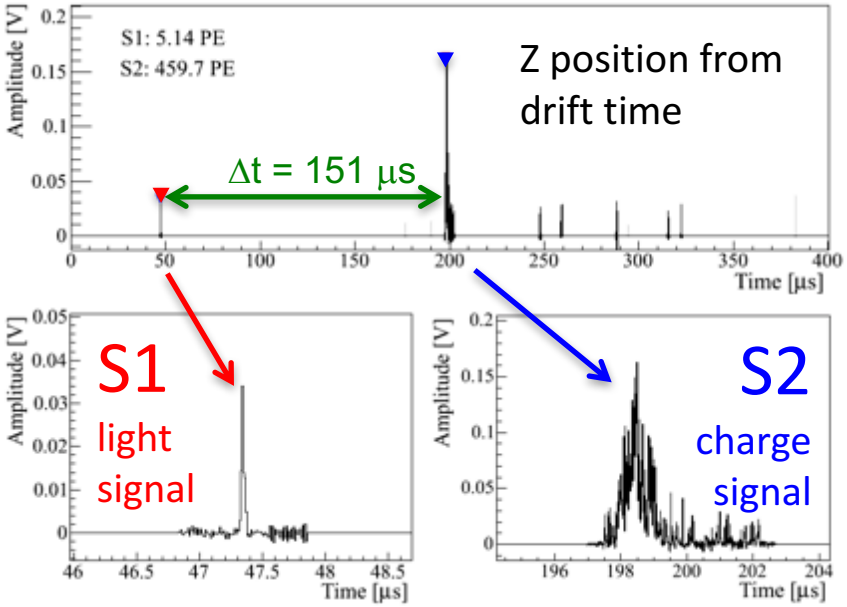


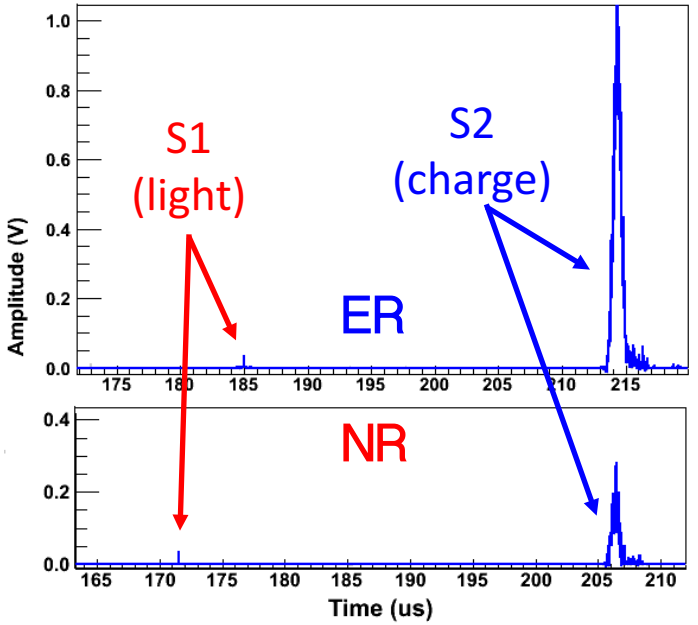
Dual phase TPC: real life



X and Y position from S2 hit pattern on the top PMTs

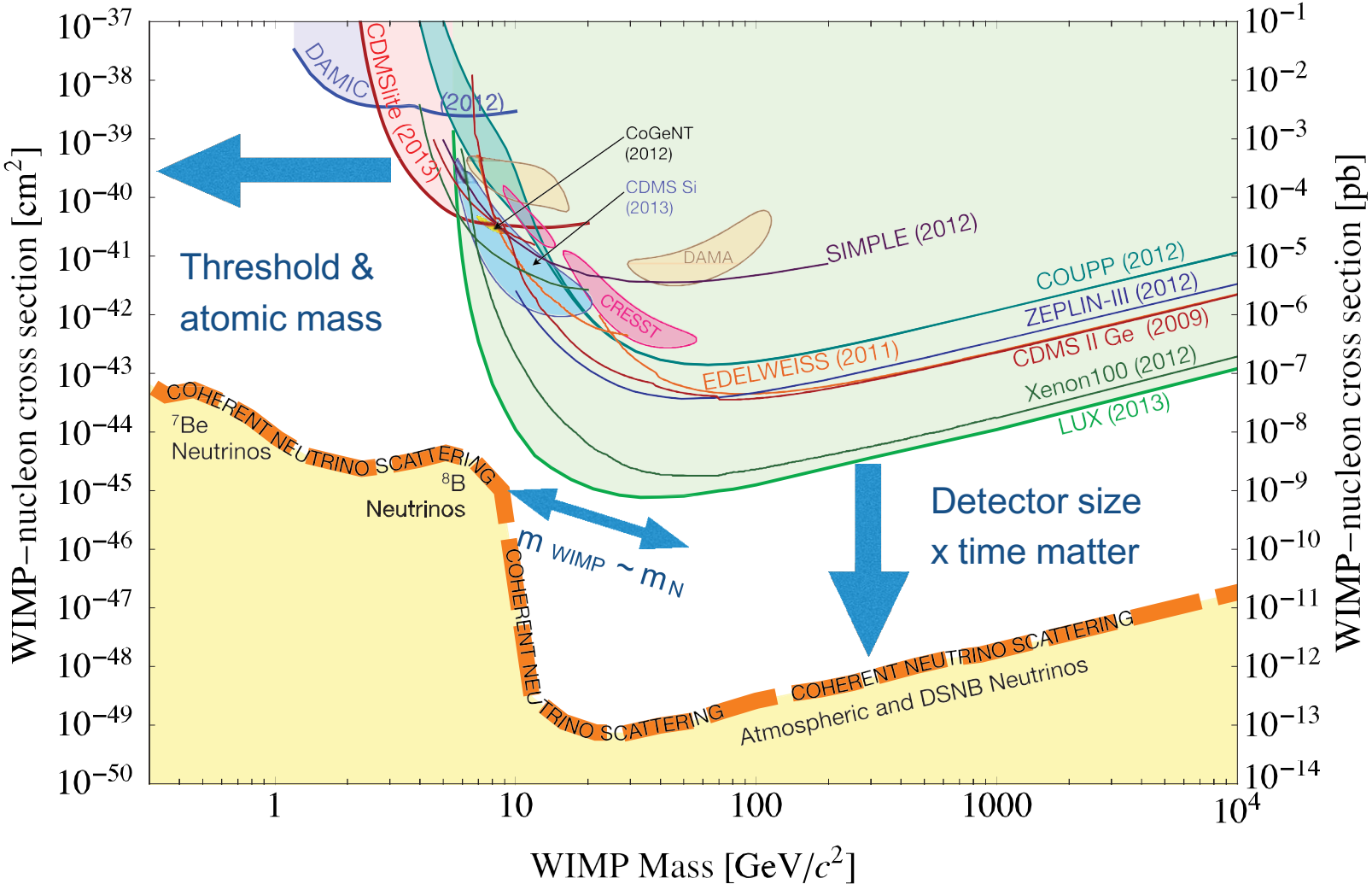




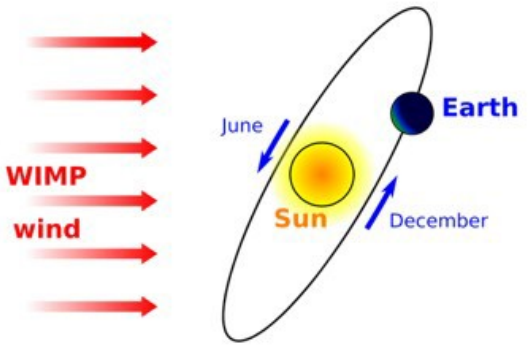


How is evolving the field of Direct Detection ?

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



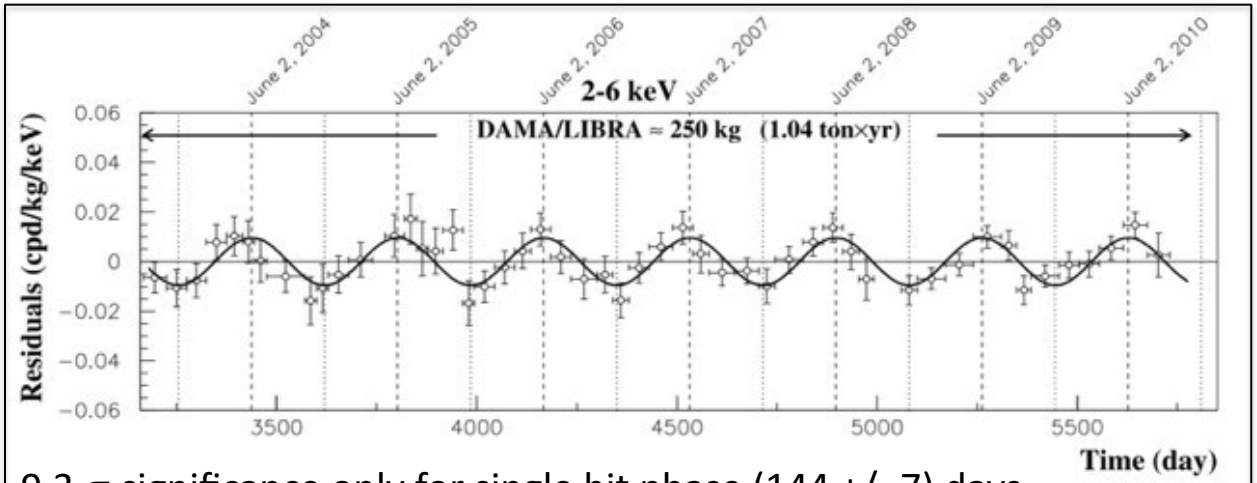
Probing the DAMA/LIBRA Anomaly with XENON100



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

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

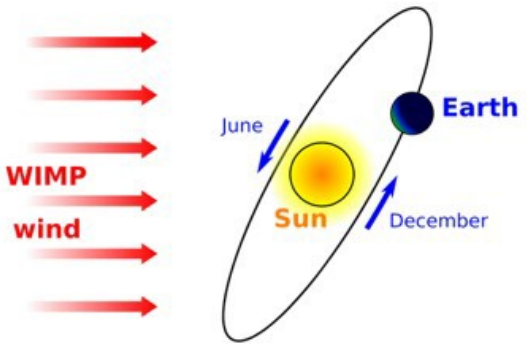
Bernabei et al., Eur. Phys. J. C 73, 12 (2013)



9.3 σ significance only for single hit phase (144 +/- 7) days
No signal above 6 keV, No ER/NR discrimination

Seems to be convincing evidence, HOWEVER…

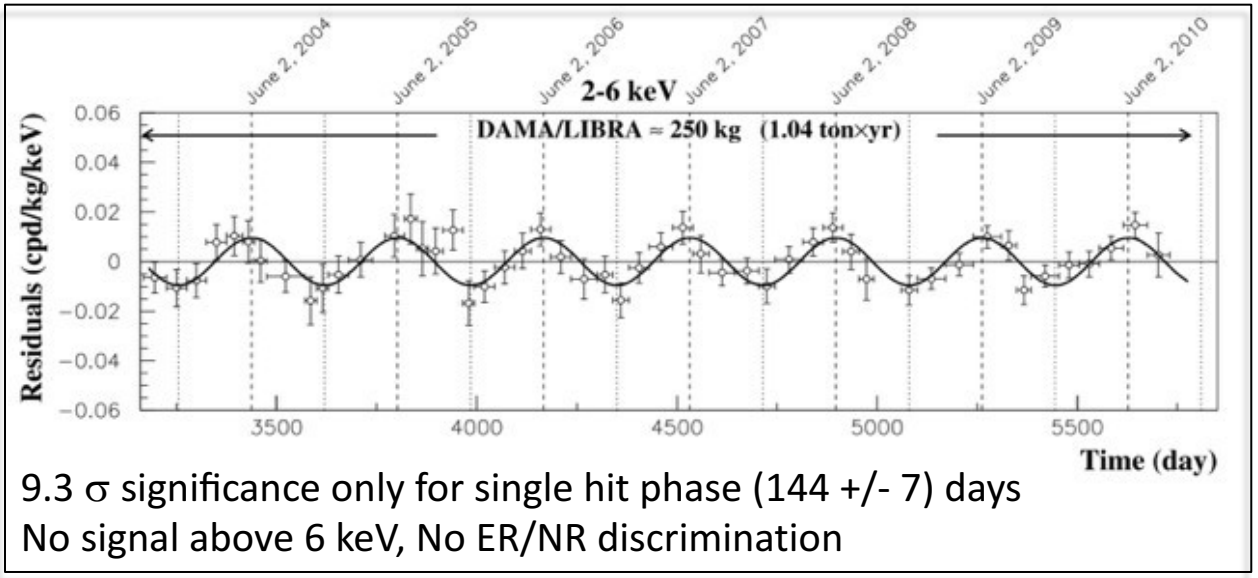
Probing the DAMA/LIBRA Anomaly with XENON100



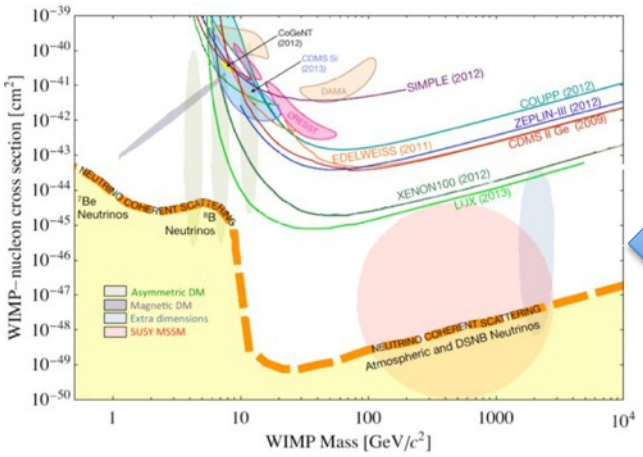
Freese et al., Rev. Mod. Phys. 85, 1561 (2013)

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

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



9.3 σ significance only for single hit phase (144 +/- 7) days
No signal above 6 keV, No ER/NR discrimination



Seems to be convincing evidence, HOWEVER…

… *Null results* from many experiments *more sensitive* than DAMA/LIBRA

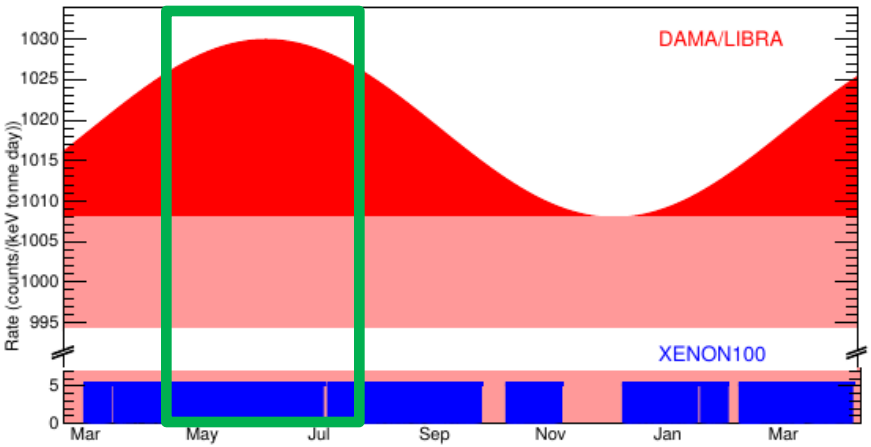
➔ Reconcile DAMA/LIBRA with the null-results from other experiments assuming leptophilic dark matter?

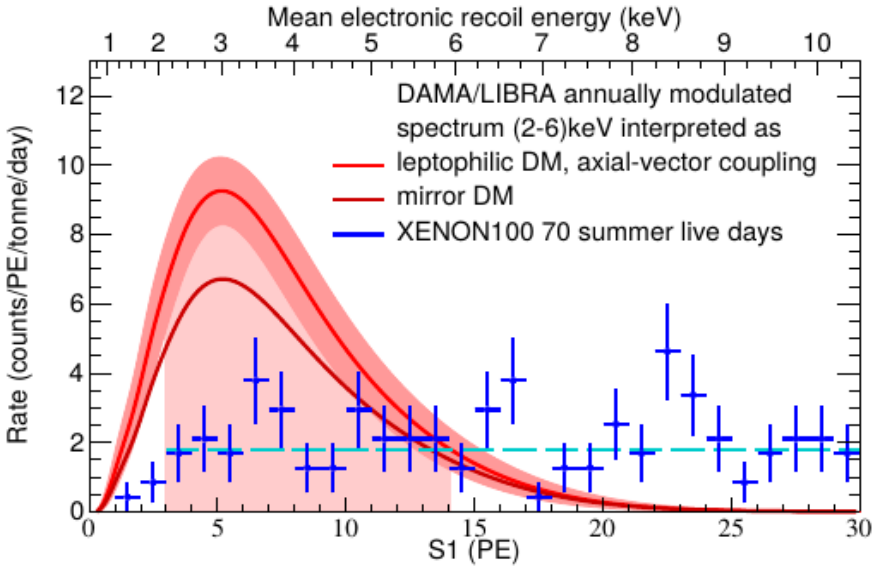
➔ DAMA/LIBRA might see electronic recoils ?

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



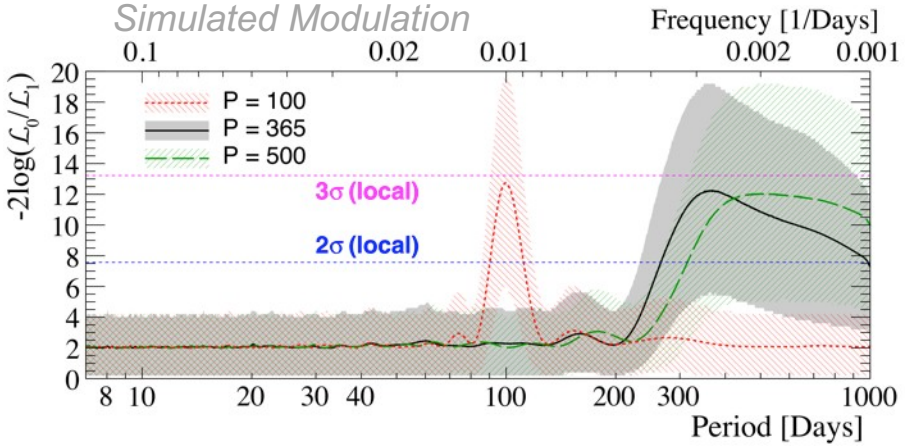


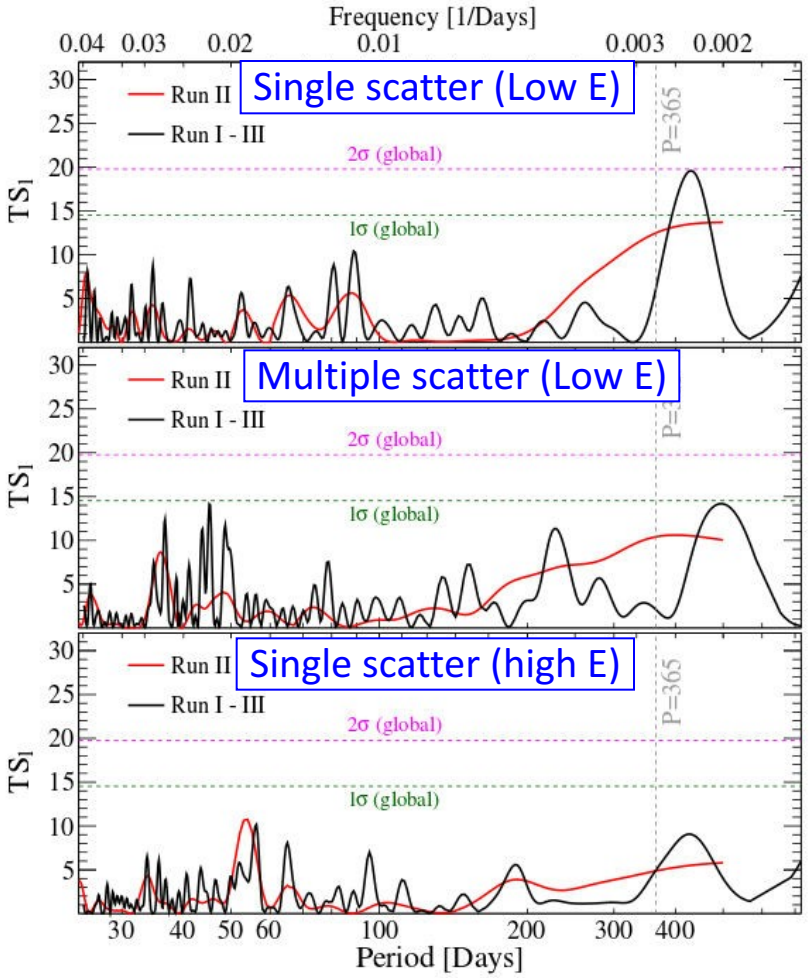
XENON100: Science 349, 851 (2015)
Confirmed by XMASS: PLB 759 272 (2016)

Search for Event Rate Modulation

- Time span : 4 years (477 live-days)
- Temporal evolution of relevant detector parameters studied
  → no significant correlation with event rate observed
- No evident peak crossing the 1σ global significance threshold!

Discovery potential:

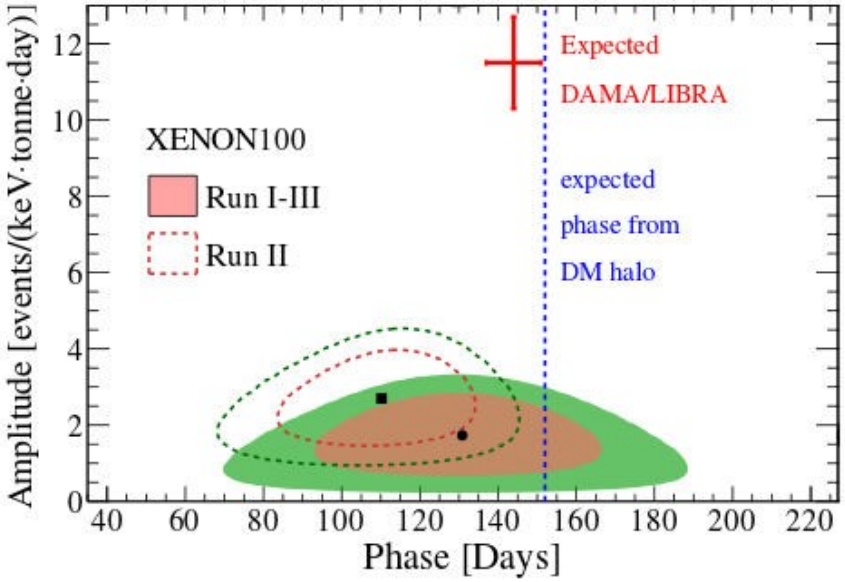




Phys. Rev. Let. 118, 101101 (2017), arXiv: 1701.00769

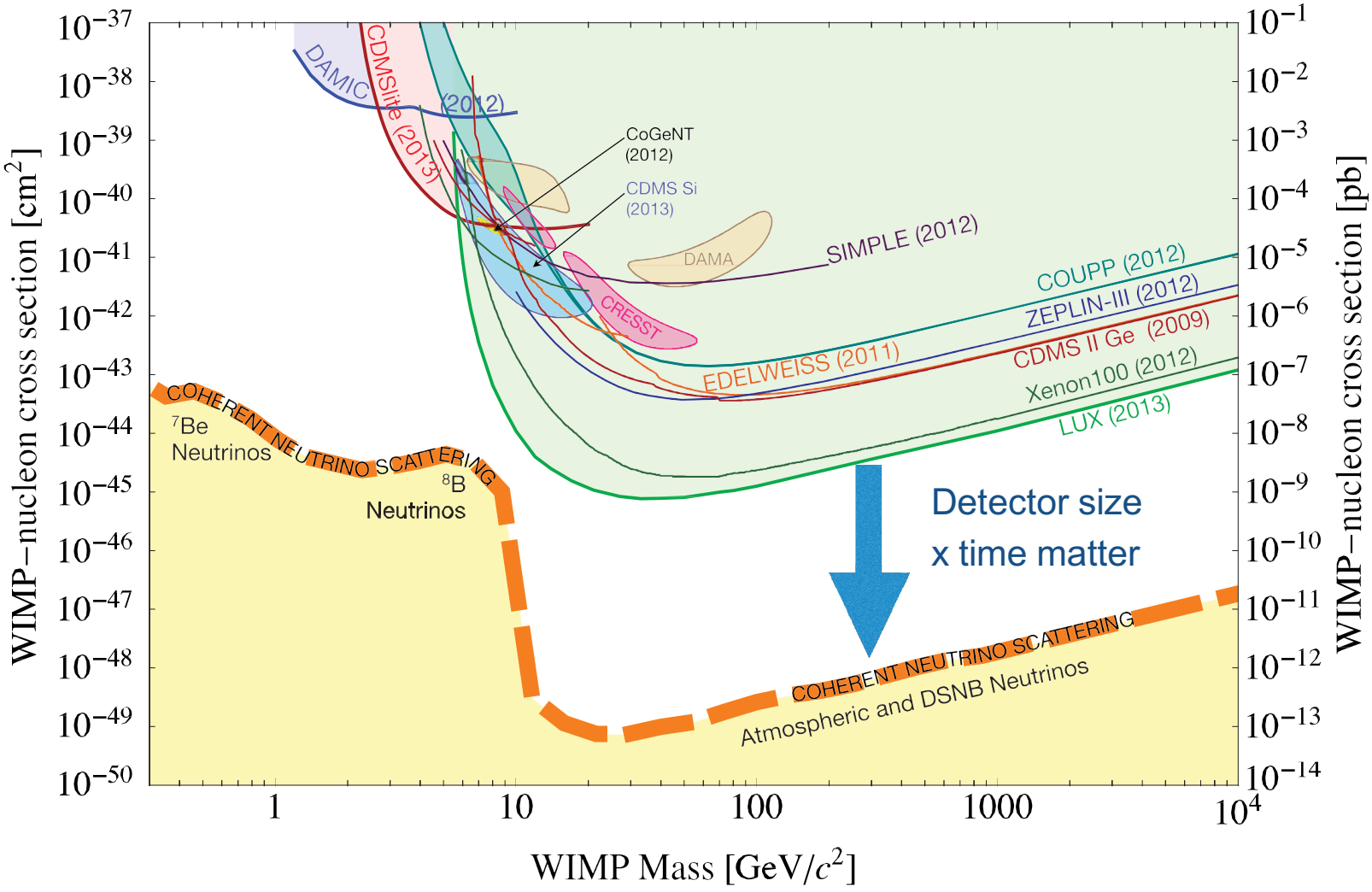
Search for Event Rate Modulation

- The amplitude of is also too small compared with the expected DAMA/LIBRA modulation signal in XENON100.
- The DM interpretation of DAMA/LIBRA annual modulation as being due to WIMPs electron scattering through axial vector coupling is disfavored at 5.7 σ from a PL analysis



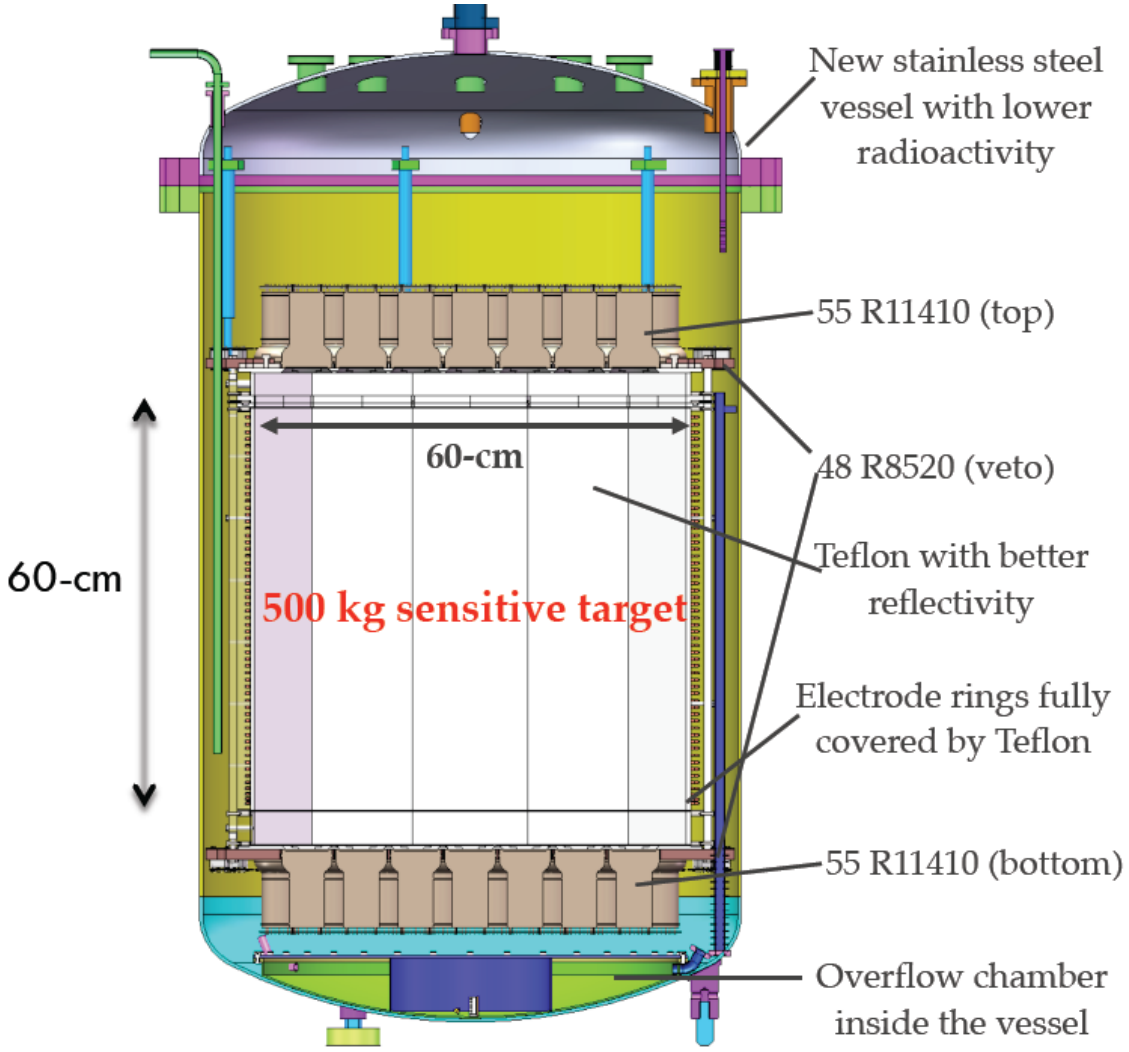
Phys. Rev. Let. 118, 101101 (2017), arXiv: 1701.00769

How is evolving the field of Direct Detection ?



PANDA X

Particle and Astrophysical Xenon Experiments



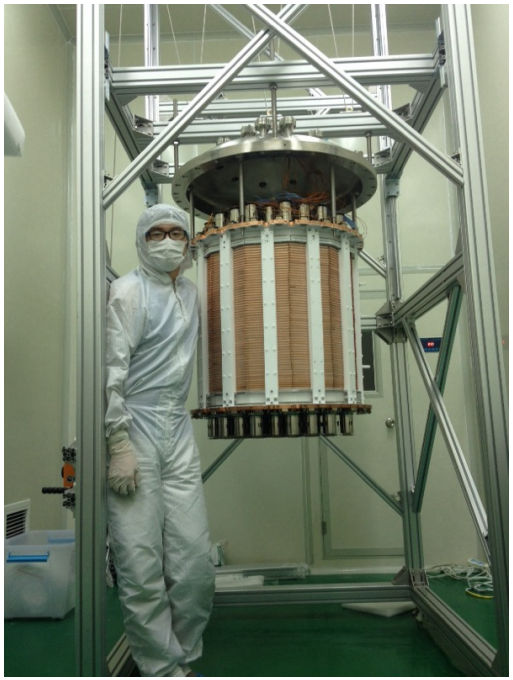
Mar. 9-Jun 30 2016, in total 79.6 live-day of under slightly different conditions (optimization of drift and extraction fields).

Condition	live time (day)	E_{drift} (V/cm)	E_{extract} (kV/cm)
1	7.76	397.3	4.56
2	6.82	394.3	4.86
3	1.17	391.9	5.01
4	63.85	399.3	4.56

PandaX II new results SI limits

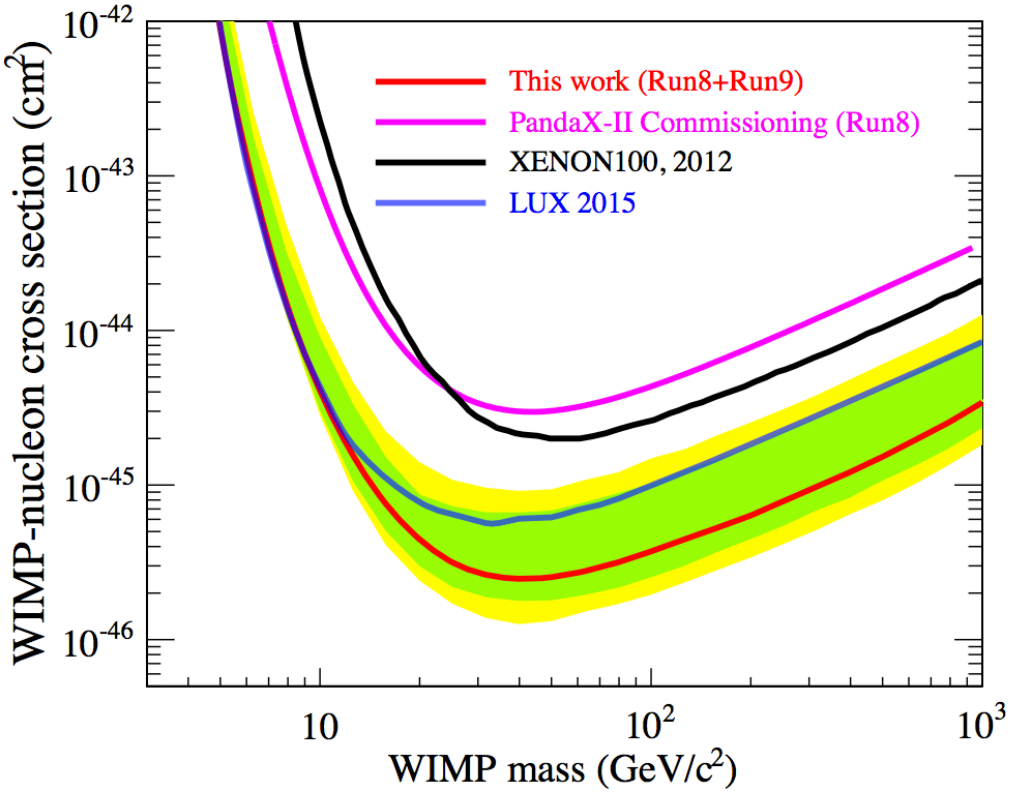
PandaX-II
@ CJPL (China)

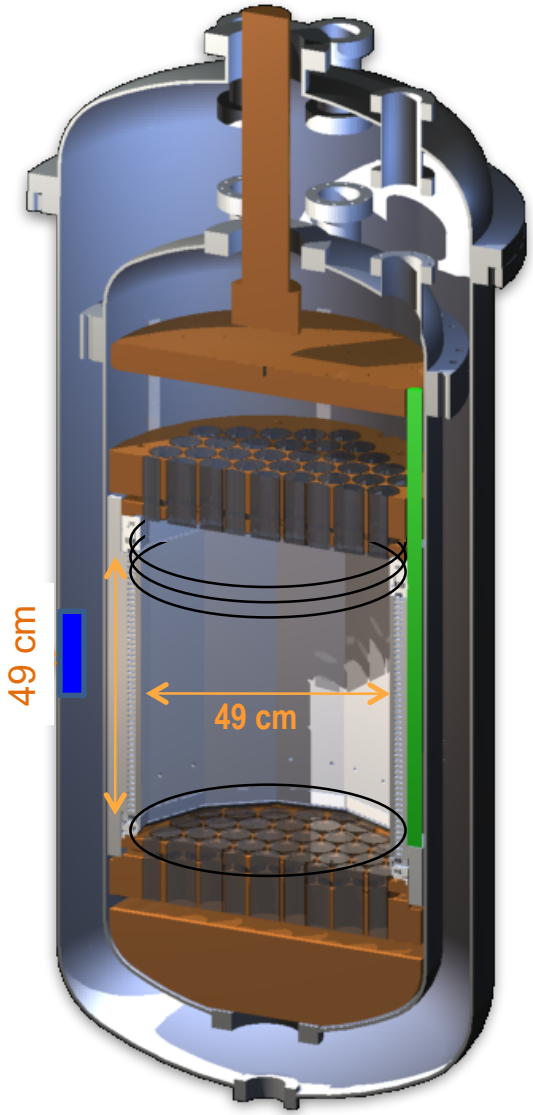
- 60 cm x 60 cm, ~400 kg fiducial
- 2nd largest operating LXe TPC
- 3.3 x 10^4 kg.day = 0.1 t.year
- No excess
- Data tacking for the 2 next years



Particle and Astrophysical Xenon Experiments

Phys. Rev. Lett. 117, 121303 (2016)
arXiv:1607.07400

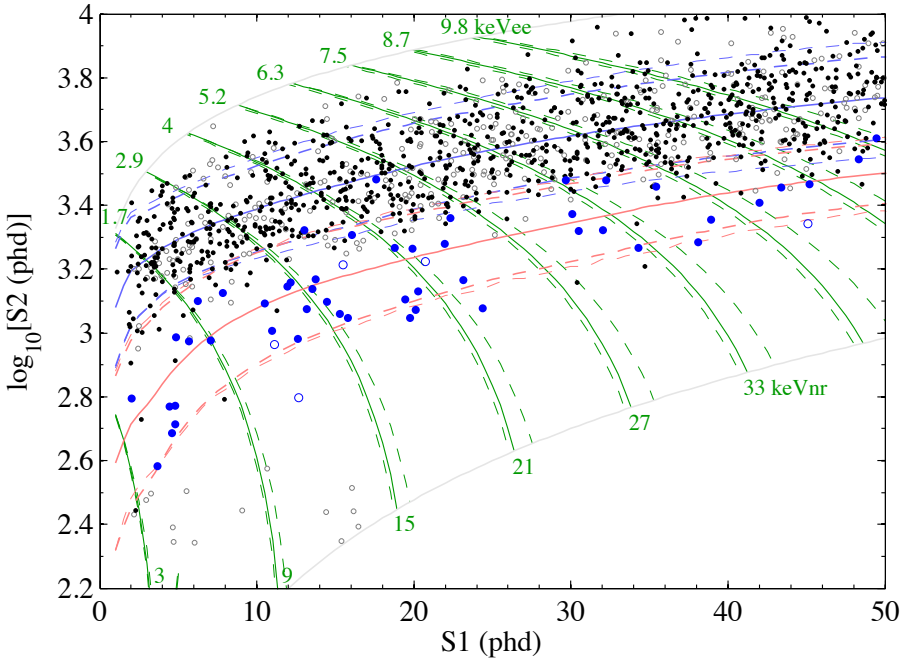




370 kg

A common approach is to blind oneself to events in the signal regions but it often blinds us to rare backgrounds and pathologies

Large Underground Xenon experiment

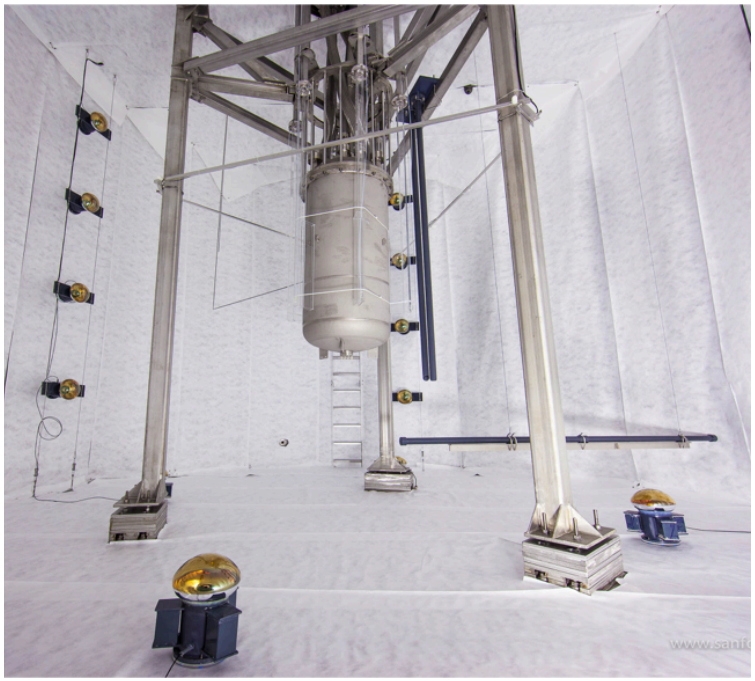


Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIMULATION!!

LUX new results SI limits

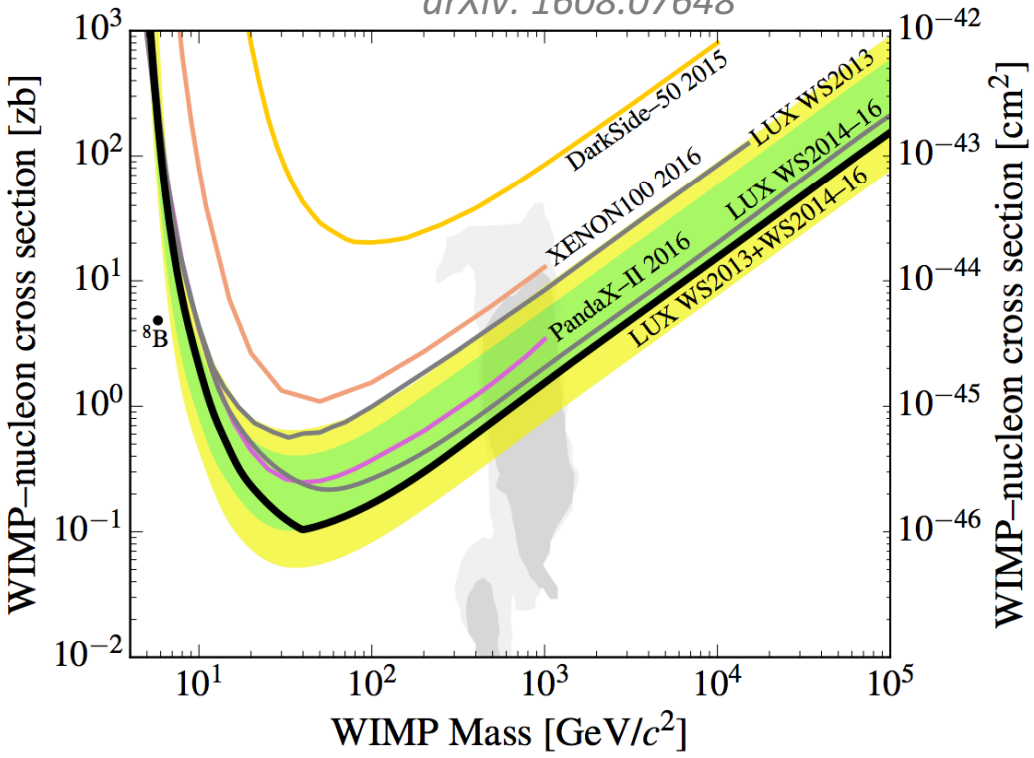
LUX
@ SURF (USA)

- 49 cm x 49 cm, ~100kg fiducial
- 332 live-days
- 3.4 x 10^4 kg.day = 0.1 t.year
- No excess
- Stopped



Large Underground Xenon experiment

PRL, 116, 161301 (2016)
arXiv: 1608.07648



LUX new results SD limits

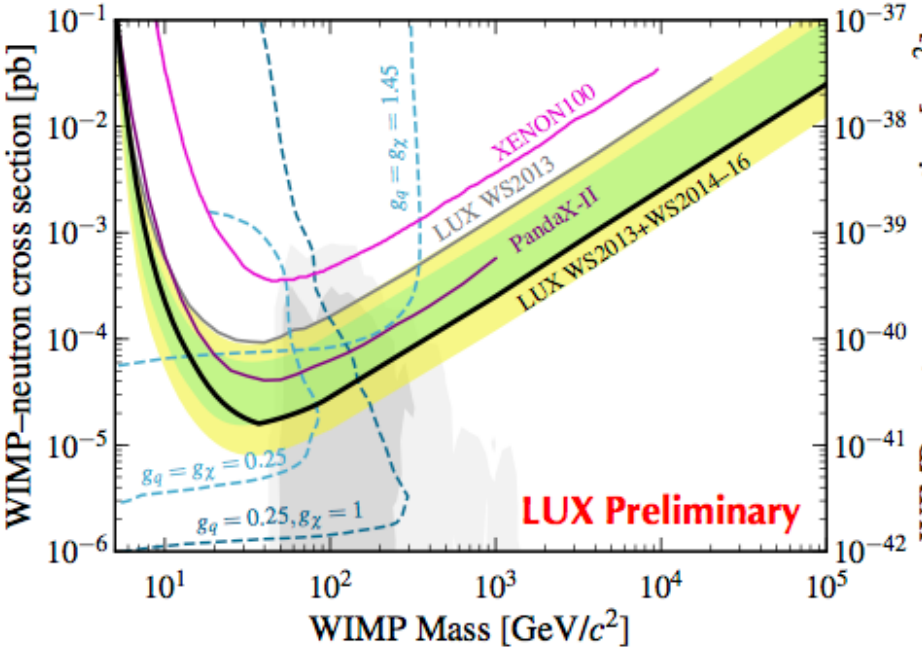
- 48 cm x 48 cm, ~100kg fiducial
- 332 live-days
- 3.4 x 10^4 kg.day = 0.1 t.year
- No excess

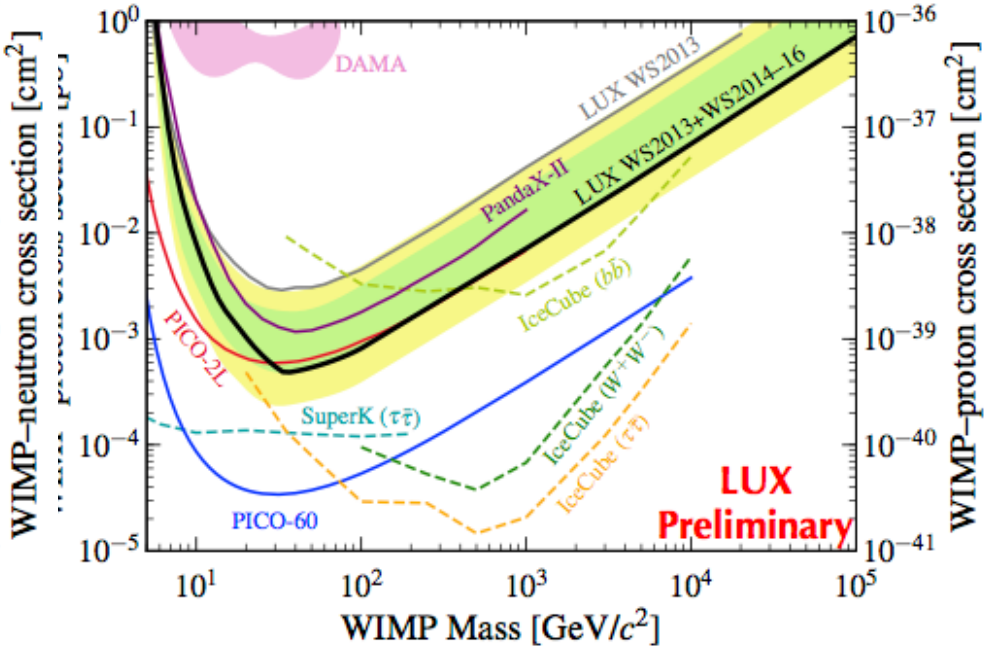
Results shown 3 days ago @ Moriond VHEPU

Large Underground Xenon experiment

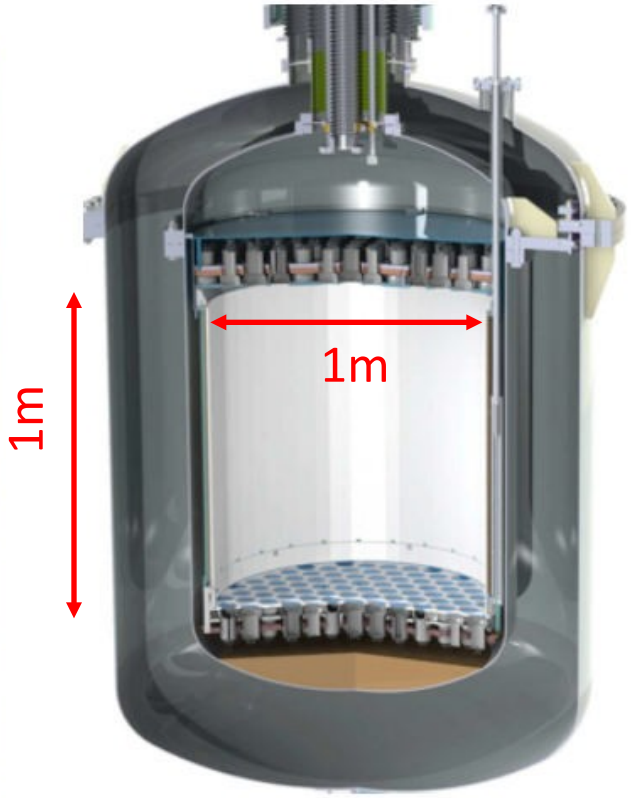
Improvement of a factor of six compared with the results from the first science run – 95 days (PRL, 116, 161302 (2016))

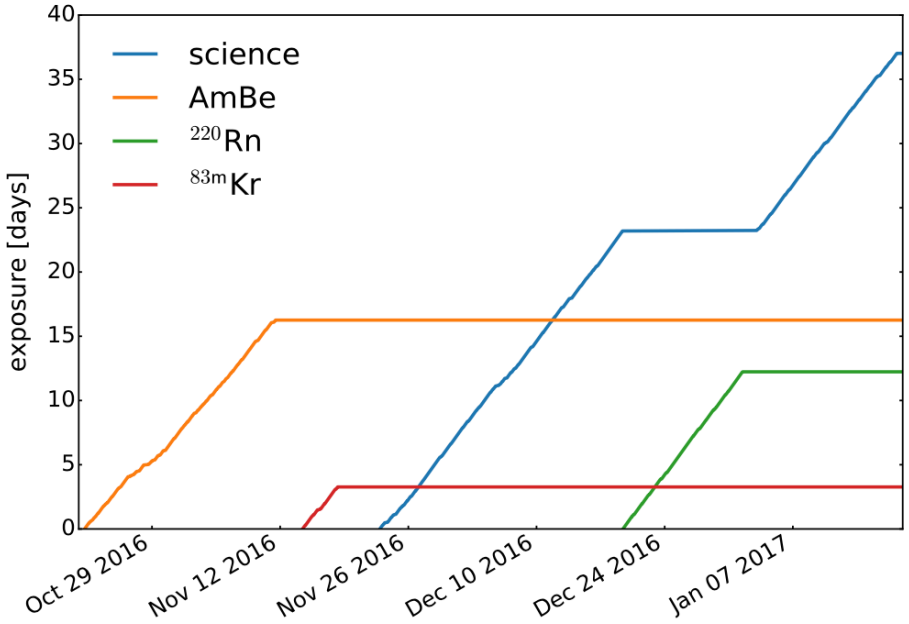
(pictures with the courtesy of Cláudio Silva - LUX Collaboration)





XENON1T : the near future





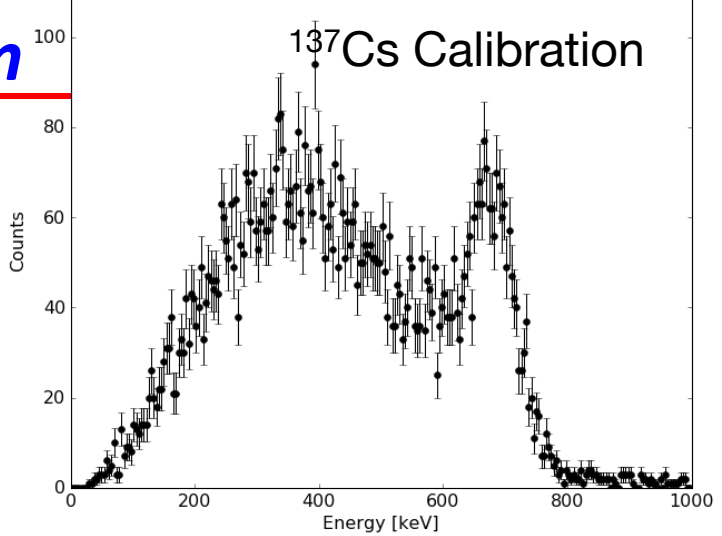
- **Science data** acquired until the earthquake (Jan. 18th) being analyzed
- Electronic recoil band determined from **Rn220 calibration**
- Nuclear recoil (signal region) data from **AmBe neutron source**
- Data corrections and processor performance tested on **^{83m}Kr data**

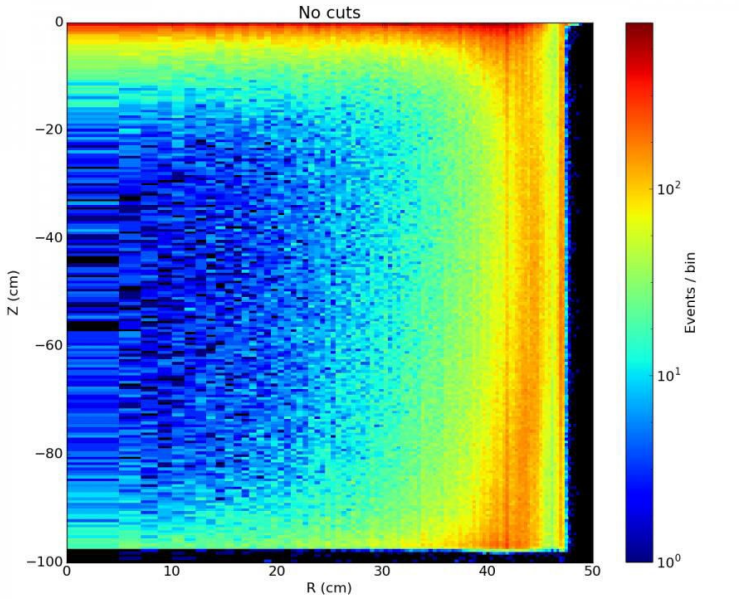
XENON1T: Commissioning & First Run

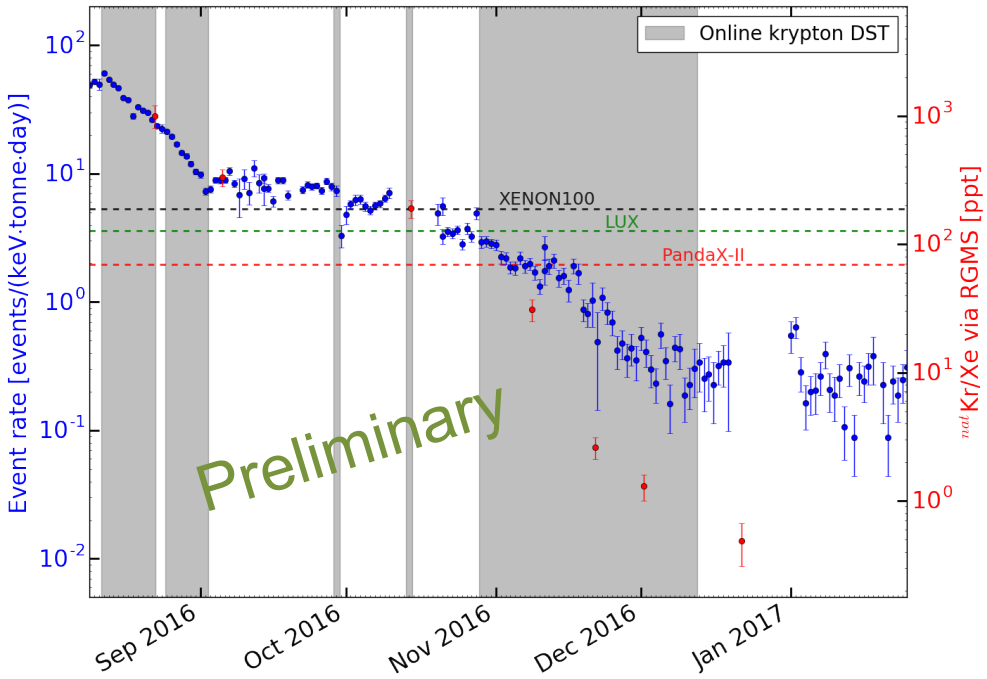
- Started commissioning in April 2016 with first fill
  Other subsystems came online
- First Calibration with ^{137}Cs γ source

- Purity have increase – Full TPC visible

- Lowest background level of all LXe experiments



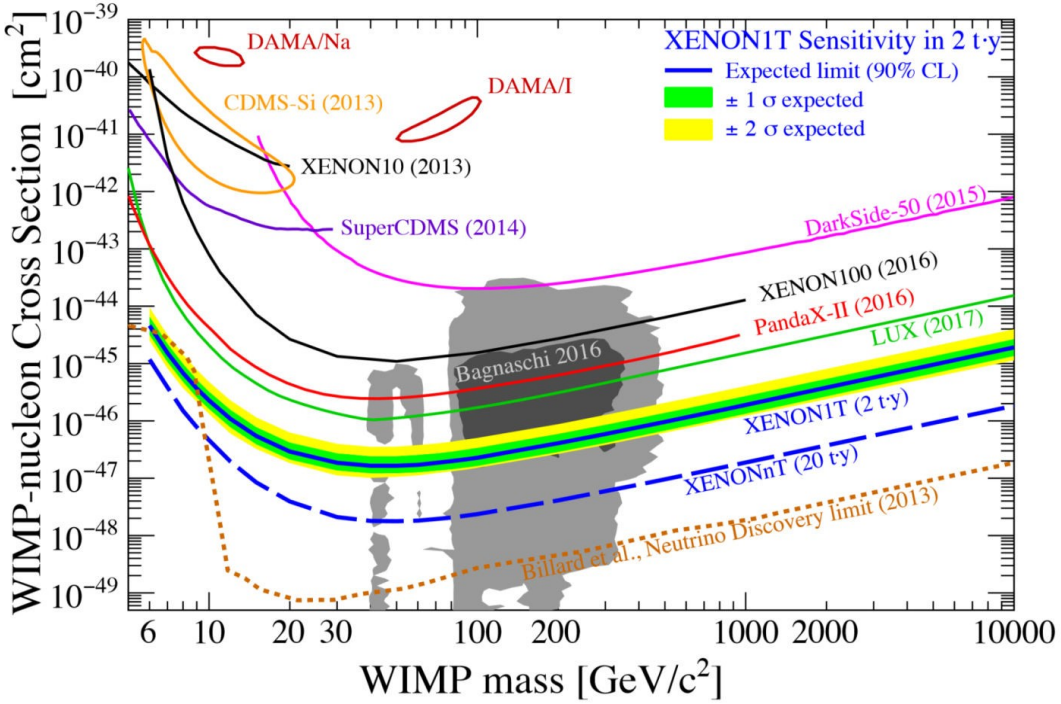


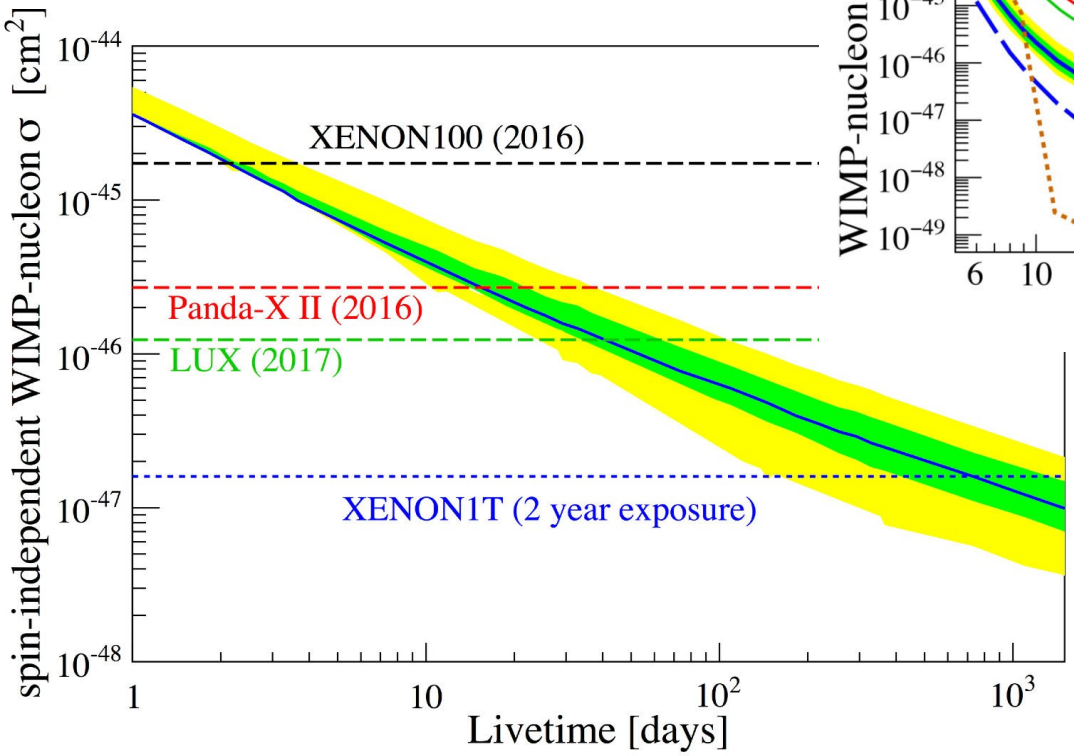


XENON1T: Expected sensitivity

JCAP04(2016)027

based on background predictions
2 t × y exposure

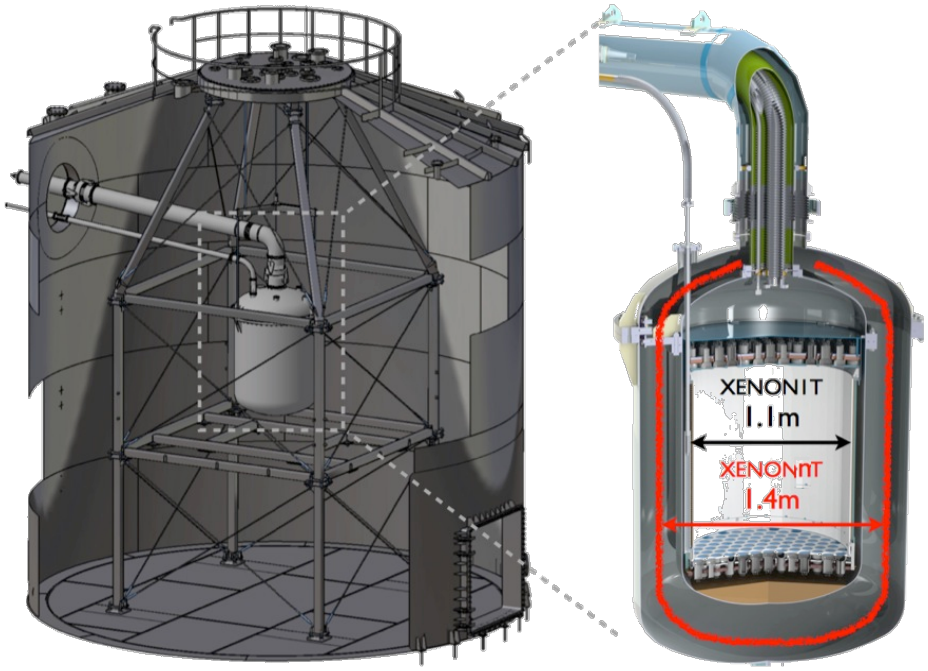




assumptions: S1 interval: 3 – 70 PE

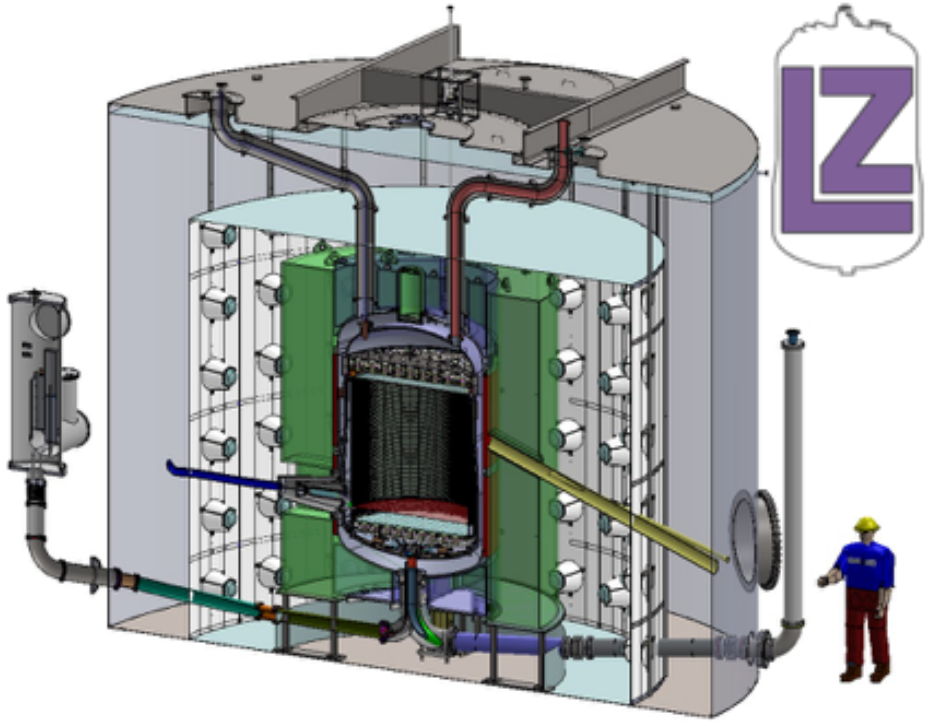
ER rejection 99.5% @ 50% NR acceptance
→ measured LY is ~2x higher than in XENON100!

Future: LZ & XENONnT



LZ = LUX + ZEPLIN

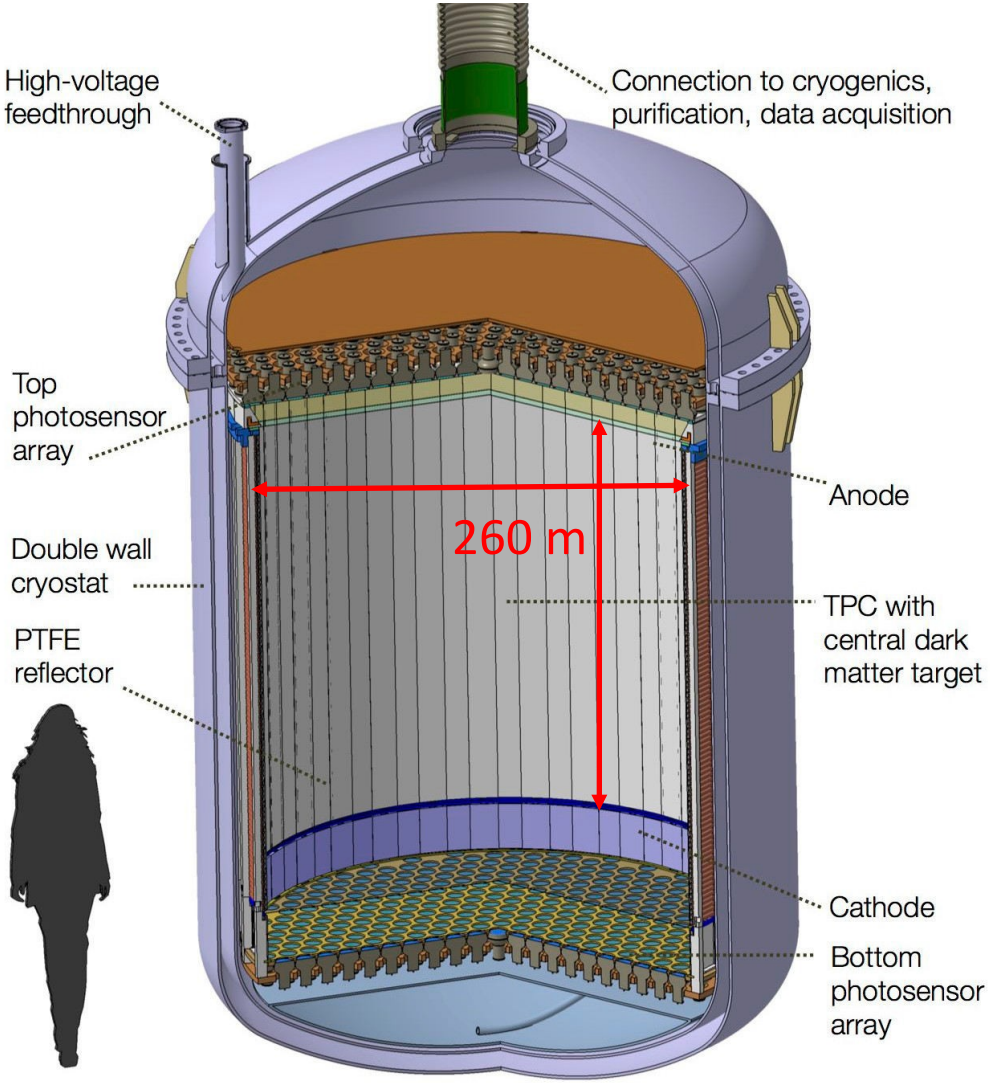
- Same location than LUX
- Turning on by 2020 with 1 000 initial live-days
- 10 tons total, 7 tons active,



XENONnT:

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018
- 8 tons total, 6 tons active

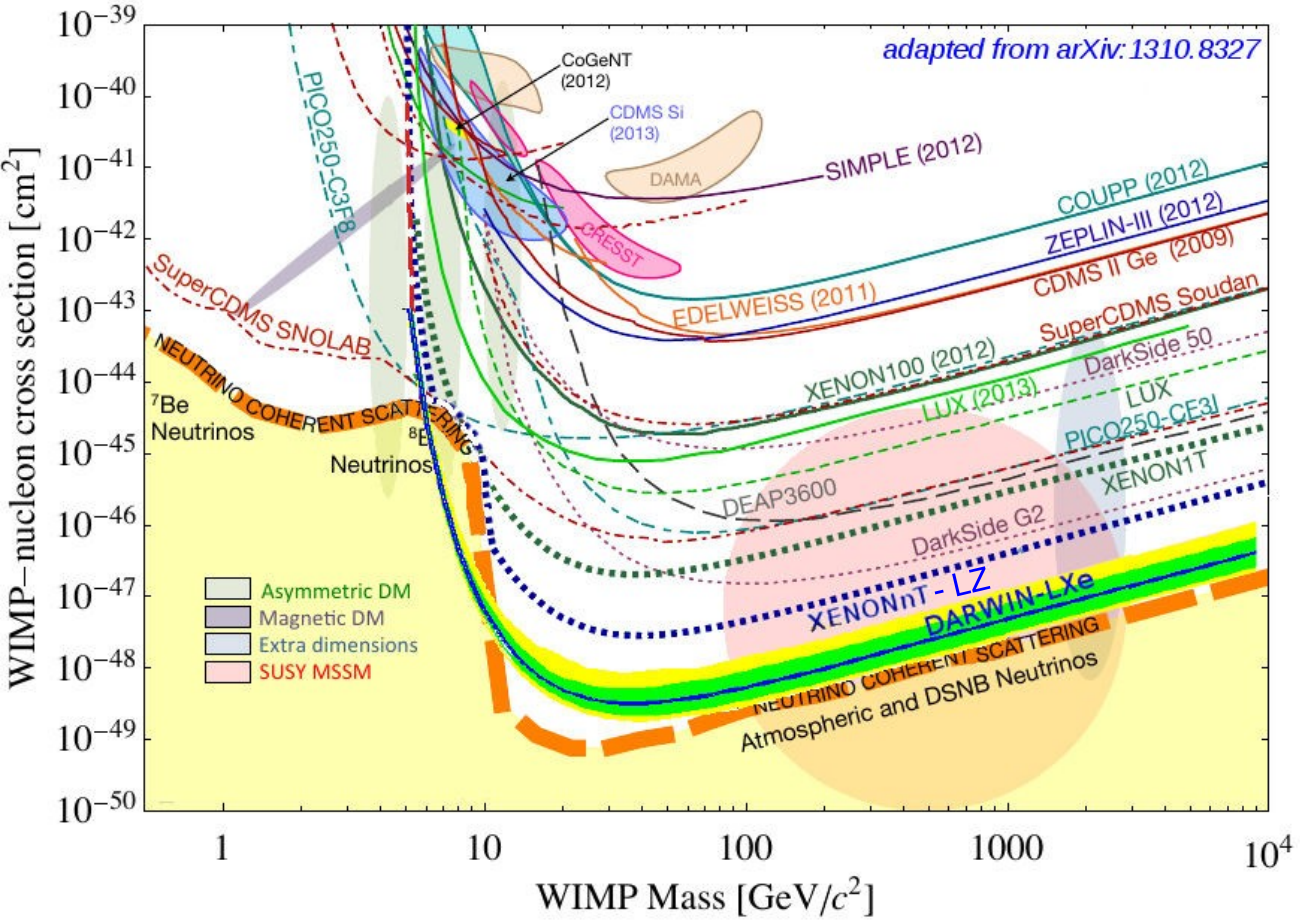
Far future: DARWIN the ultimate detector



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

- Aim at sensitivity of a few 10^{-49} cm², limited by irreducible ν-backgrounds
- R&D started
- 50 tons total LXe
  40 tons TPC
  30 tons fiducial

Perspectives



And other analysis already published or to come:

- Axions / ALP
- 2ν double electron capture on ^{124}Xe
- Low mass
- Effective field theories
- Calibration
- …
- Stay tuned !

PandaX-II continue data taking with ~400kg

XENON1T is analyzing Science Run 0 !

XENONnT & LZ construction is starting…