Review on
Future liquid noble gas detectors

Julien Masbou Subatech – Université de Nantes

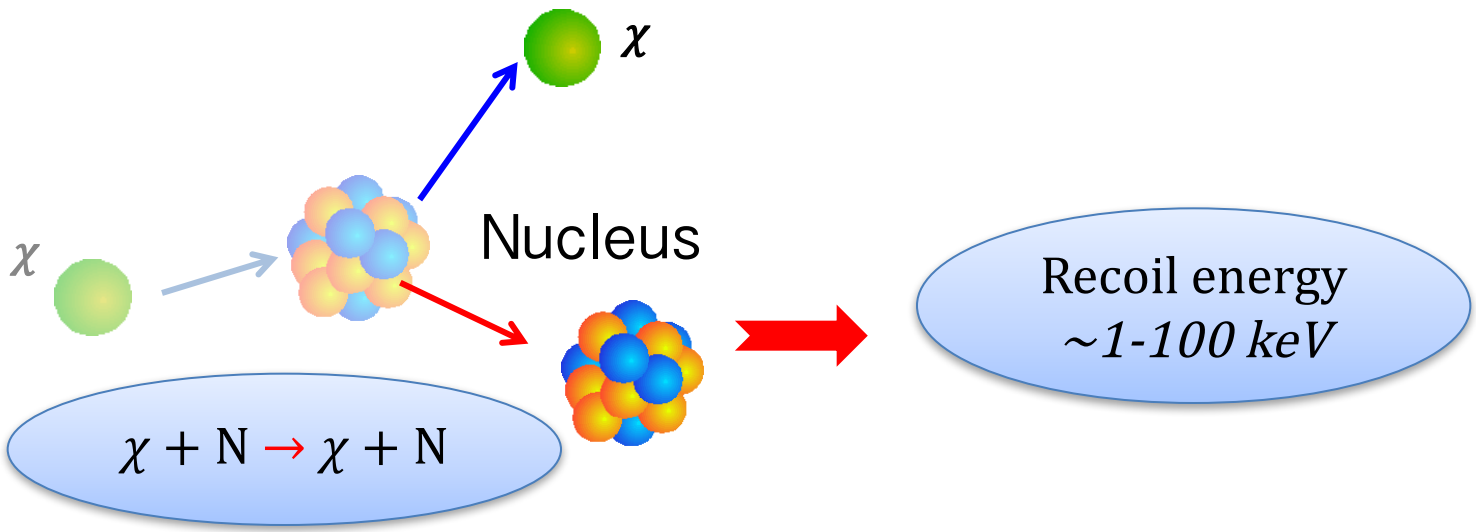
13th Rencontres du Vietnam July 23-29

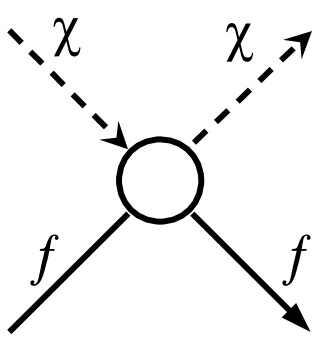
ICISE

Exploring the Dark Universe 2017

Direct dark matter detection principle

Nuclear Recoil (NR)



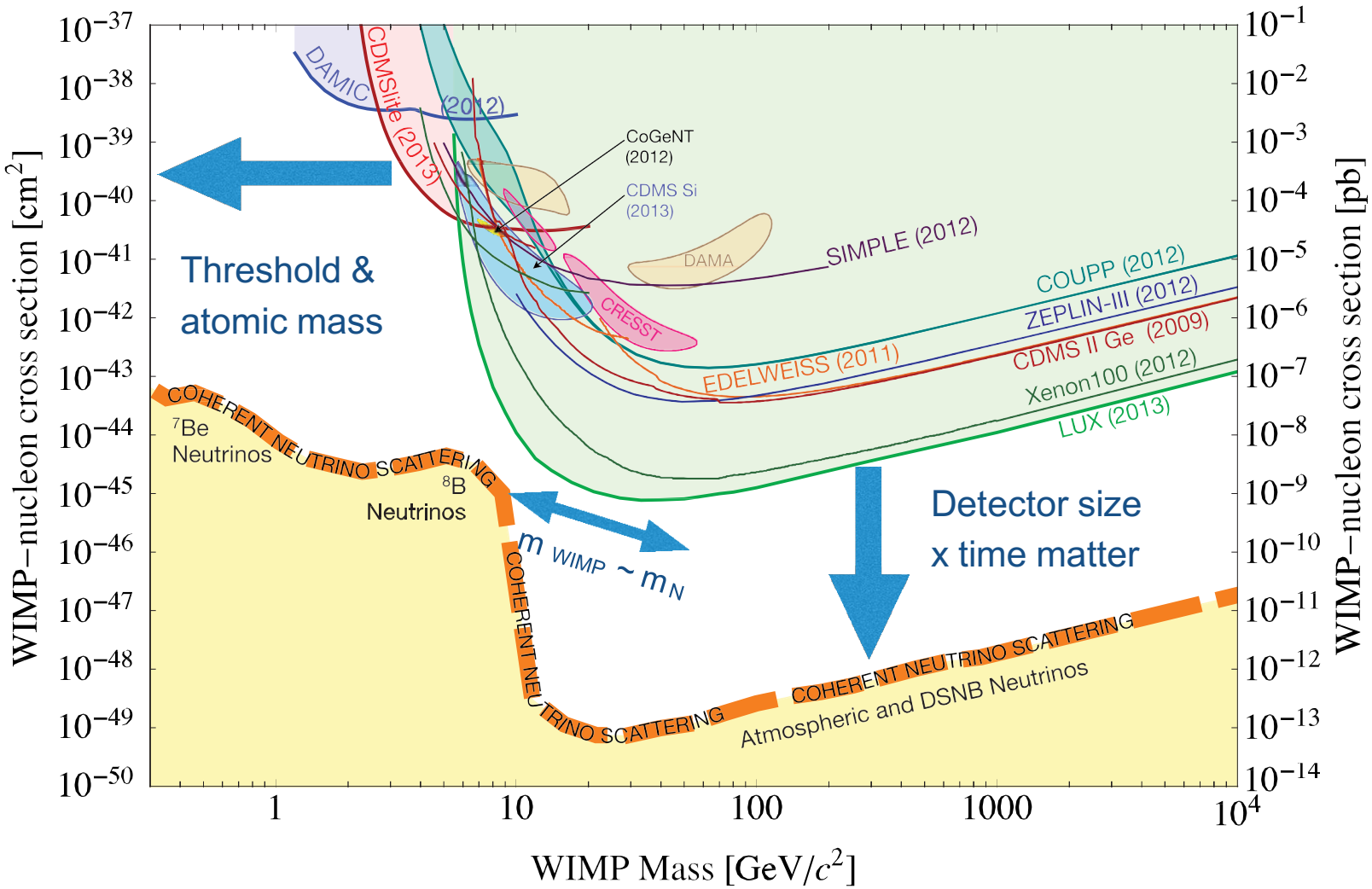


Electronic Recoil (ER)

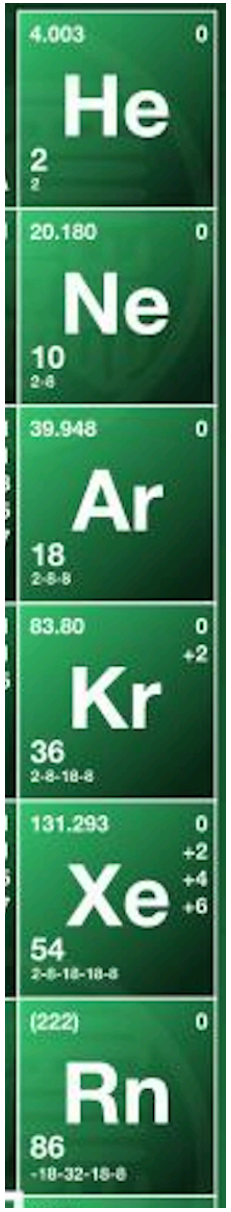
γ and β particles
interact with the atomic electrons
→ background

How is evolving the field of Direct Detection ?

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



Noble gases



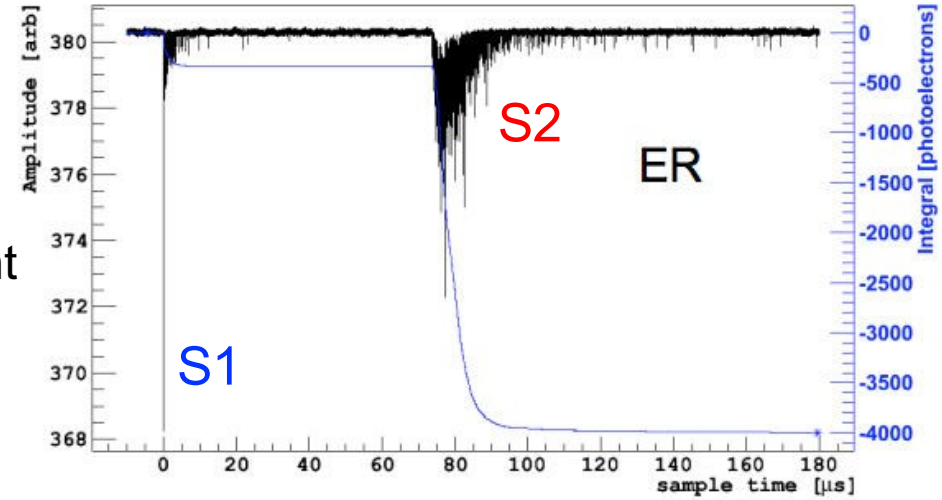
	Neon	Argon	Krypton	Xenon
Atomic Number	10	18	36	54
Density	1.2	1.4	2.4	3
Scintillation (γ/keV)	30	40	25	42
Wavelength (nm)	85	128	150	178
Decay Time (ns)	15400	6.3, 1500	2, 91	2.2, 27, 45
Ionization (e-/keV)	46	42	49	64
Boiling Point (K)	27.1	87.3	119.8	165.0
Radioactivity	No	^{39}Ar 1Bq/kg (1mBq/kg)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

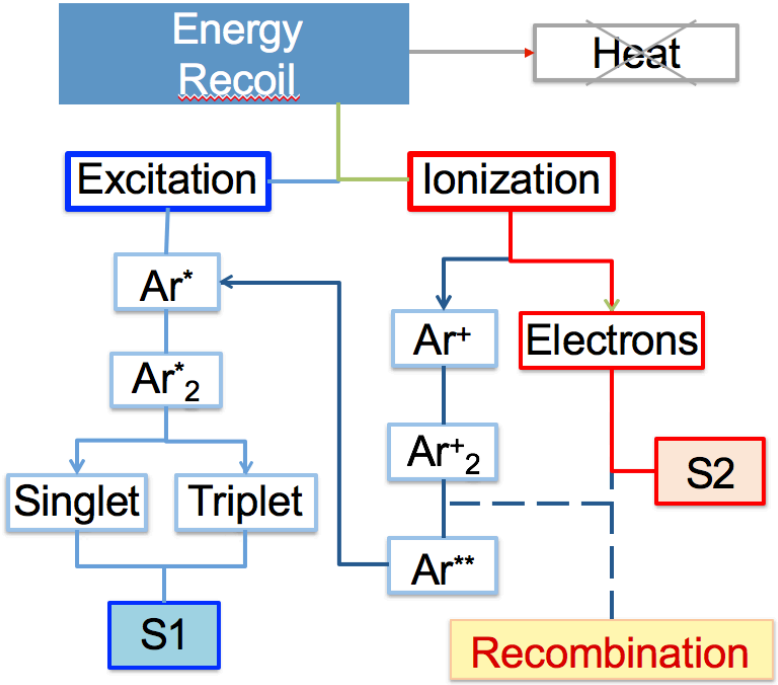
Scintillation and ionization in noble liquids

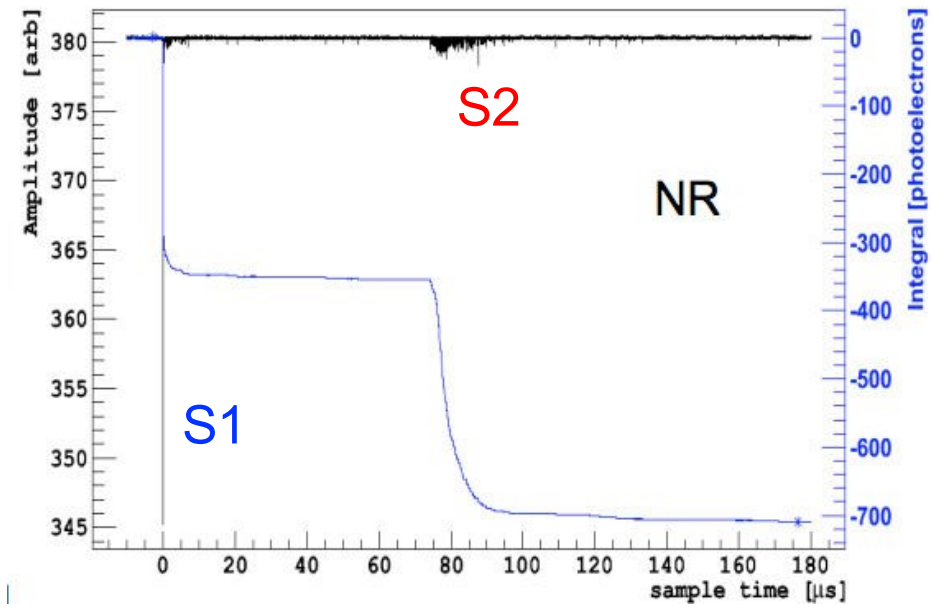
- Energy deposit produce both:
  - Electron-ion pair
  - Excited atom states

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

Examples from DarkSide50







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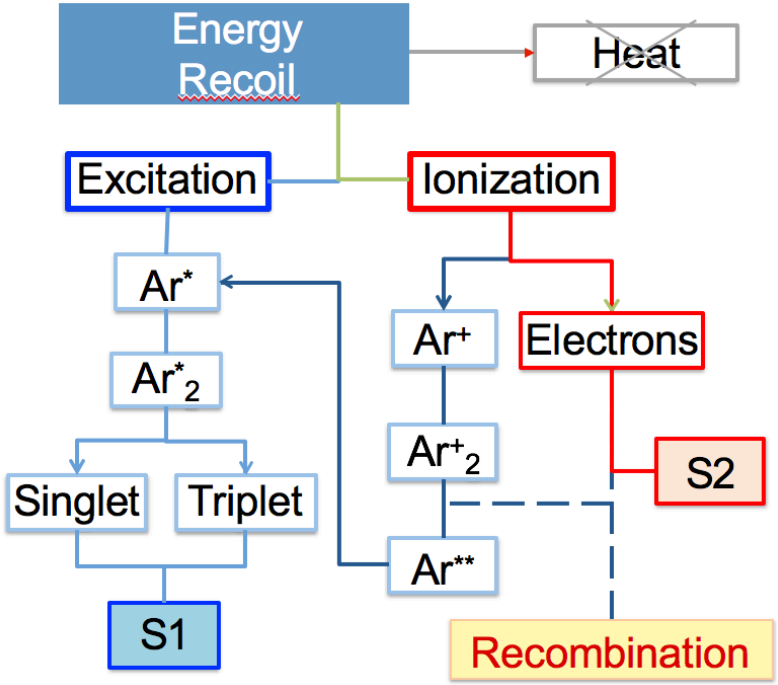
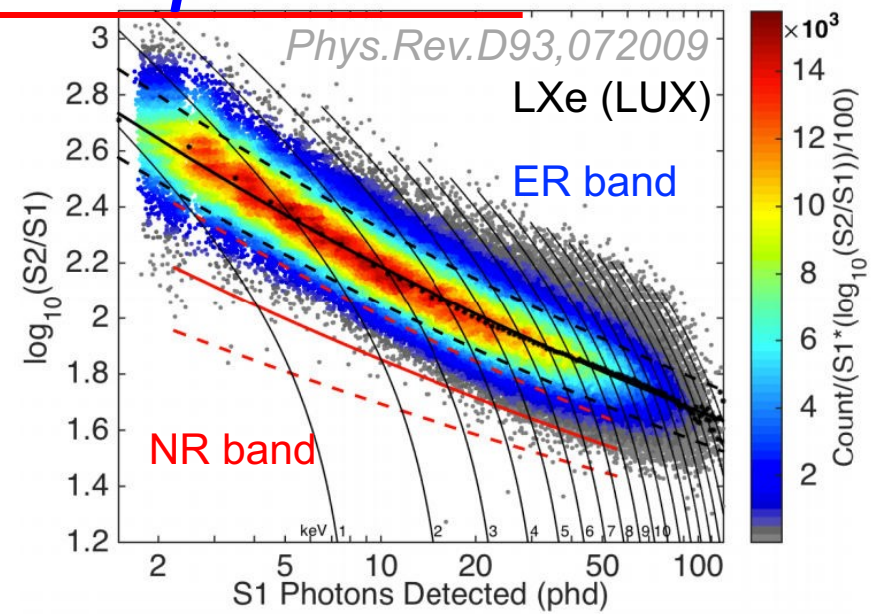
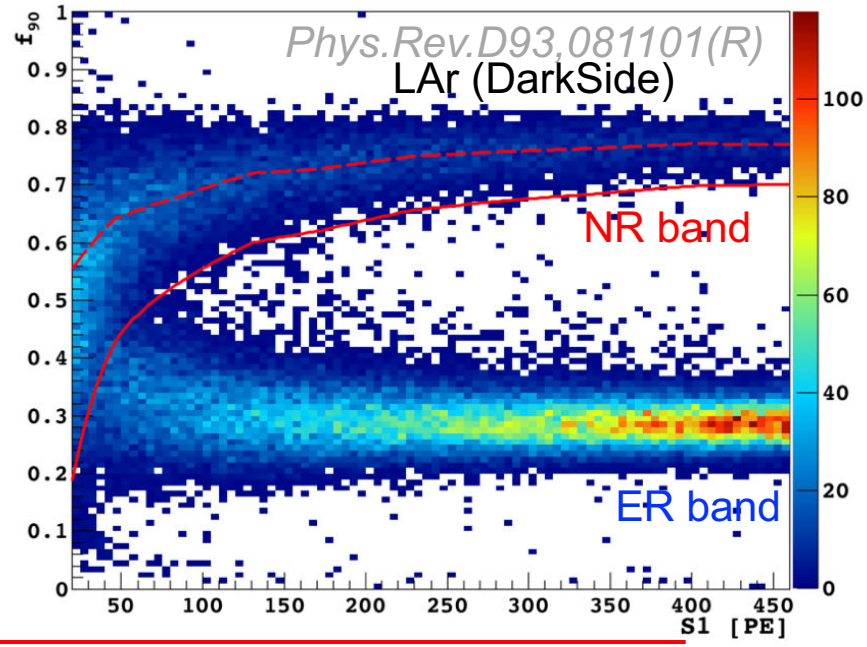
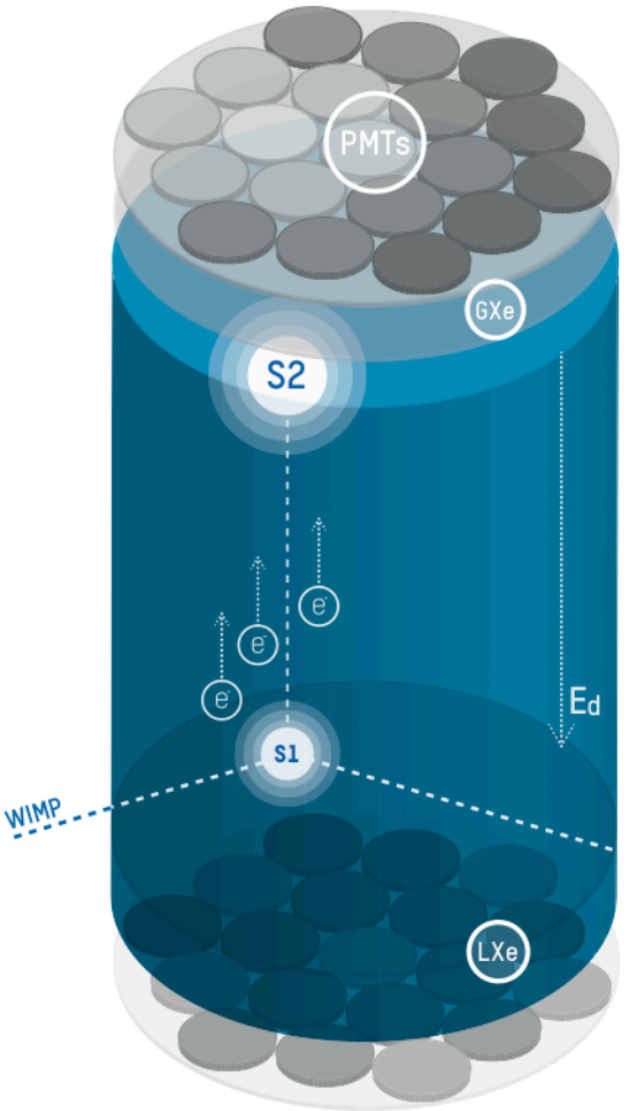






Dual phase TPC: principle

TPC = Time Projection Chamber



S1:

→ Photon (λ = 178 nm) from Scintillation process

→ Dectected by PMTs (mainly botton array)

S2:

→ Electrons drift

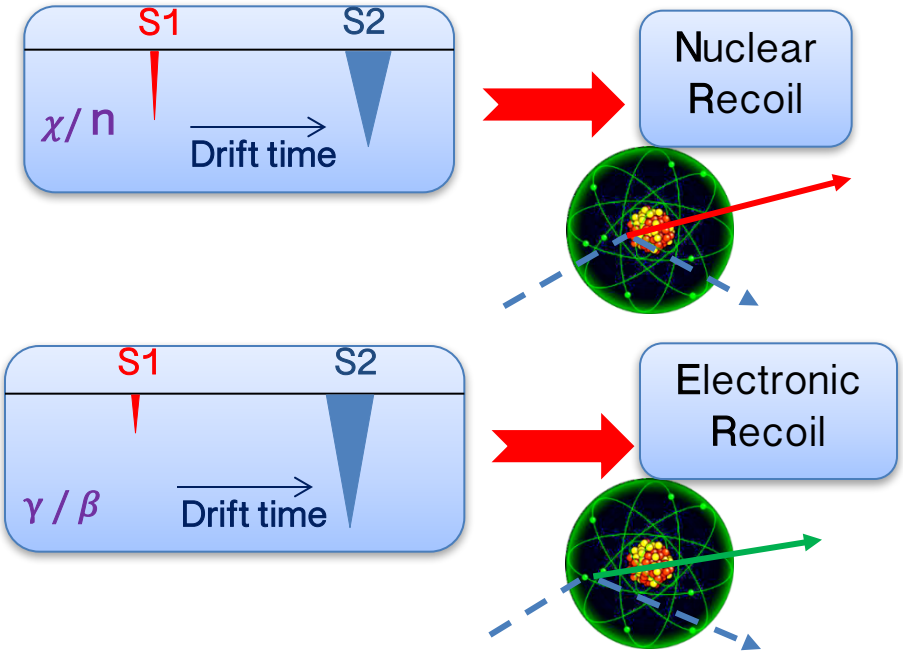
→ Extraction in gaseous phase

→ Proportional scintillation light

3D reconstruction :

→ X,Y from top array

→ Z from Drift time



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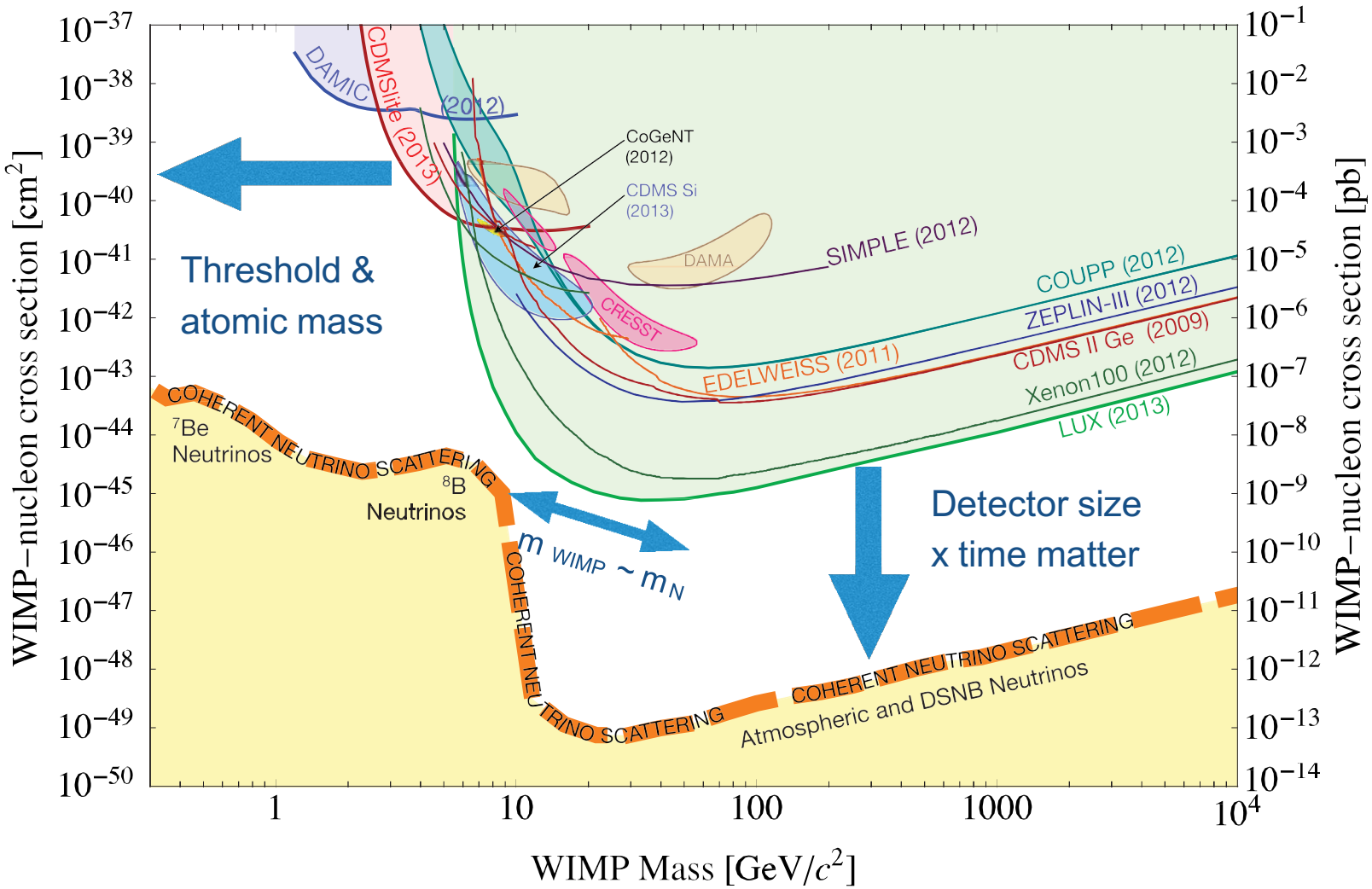
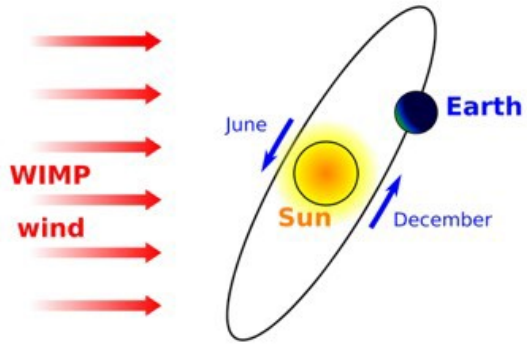


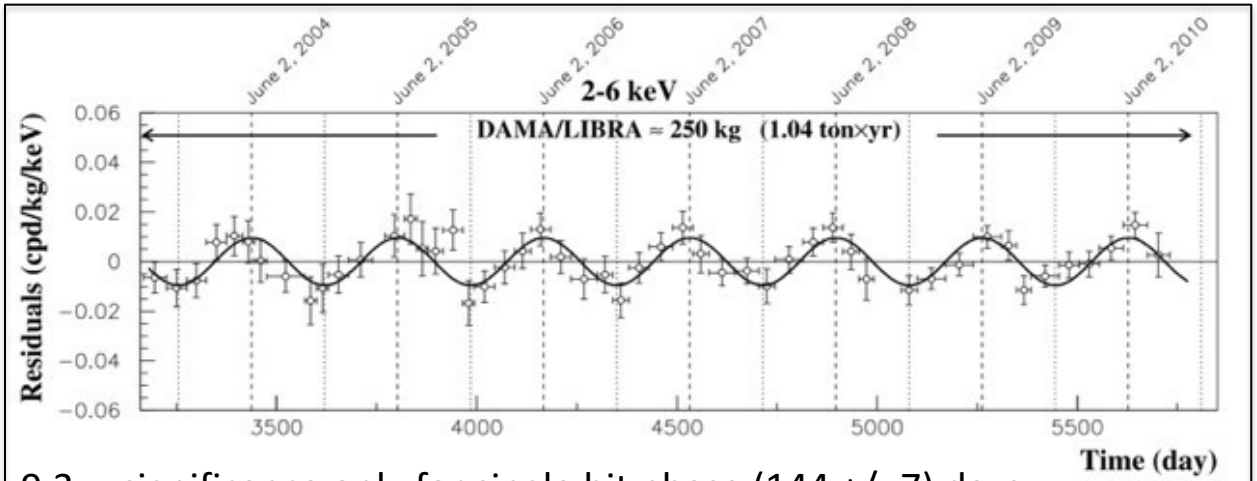
Probing the DAMA/LIBRA Anomaly with XENON100



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…

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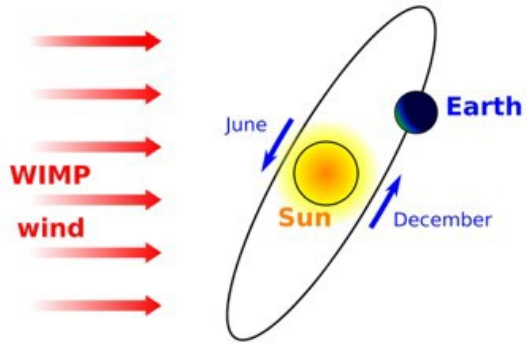

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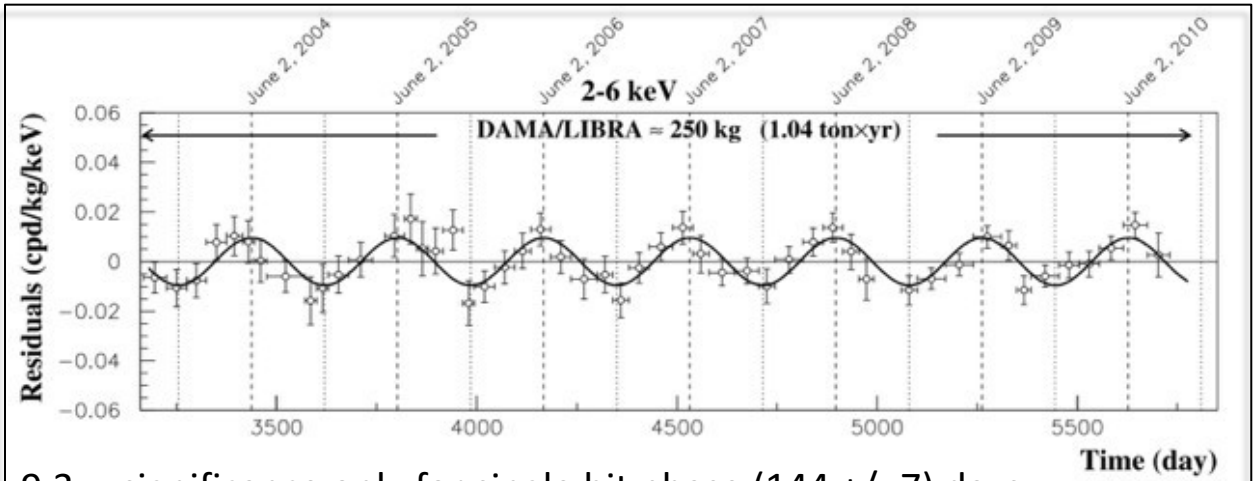

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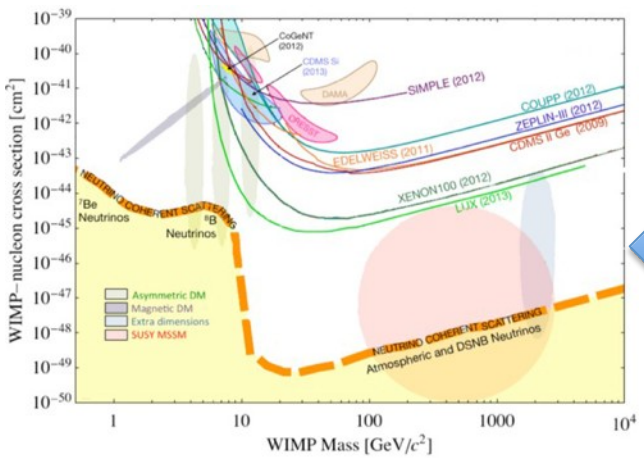


Seems to be convincing evidence, HOWEVER…

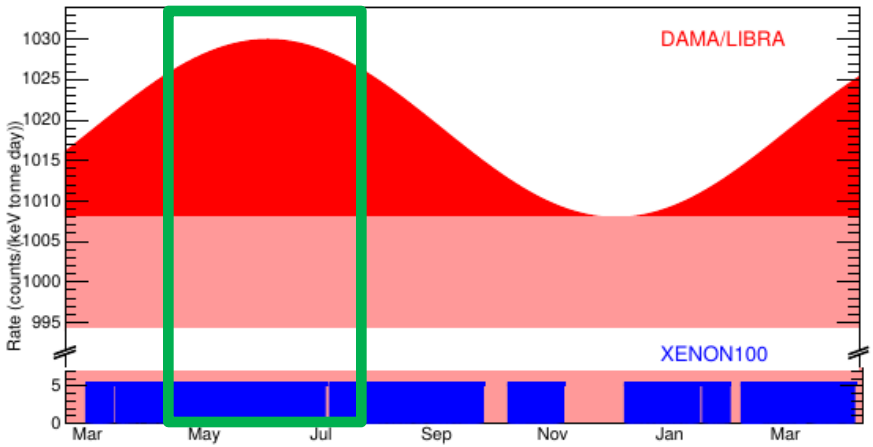
… *Null results* from many experiments *more sensitive* than DAMA/LIBRA

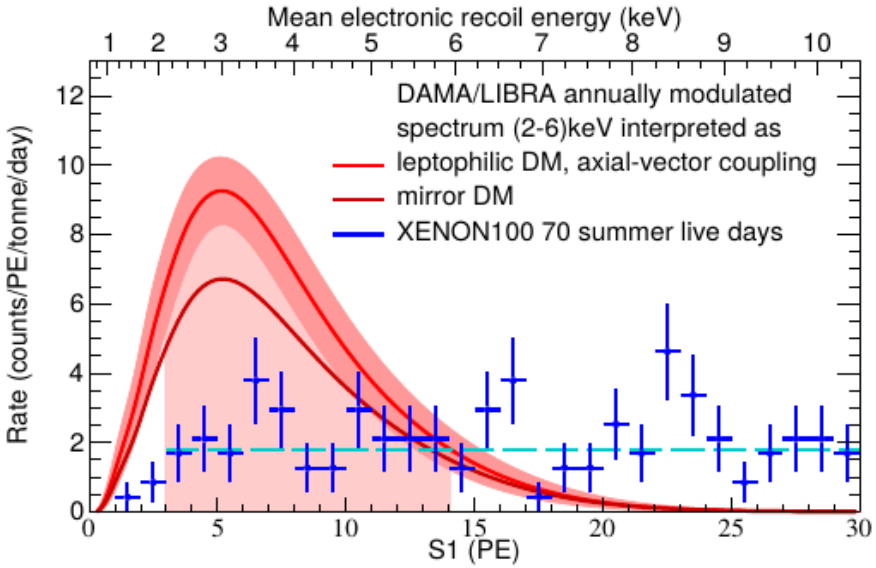
➔ Reconcile DAMA/LIBRA with the null-results from other experiments assuming leptophilic dark matter?
➔ DAMA/LIBRA might see electronic recoils ?

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

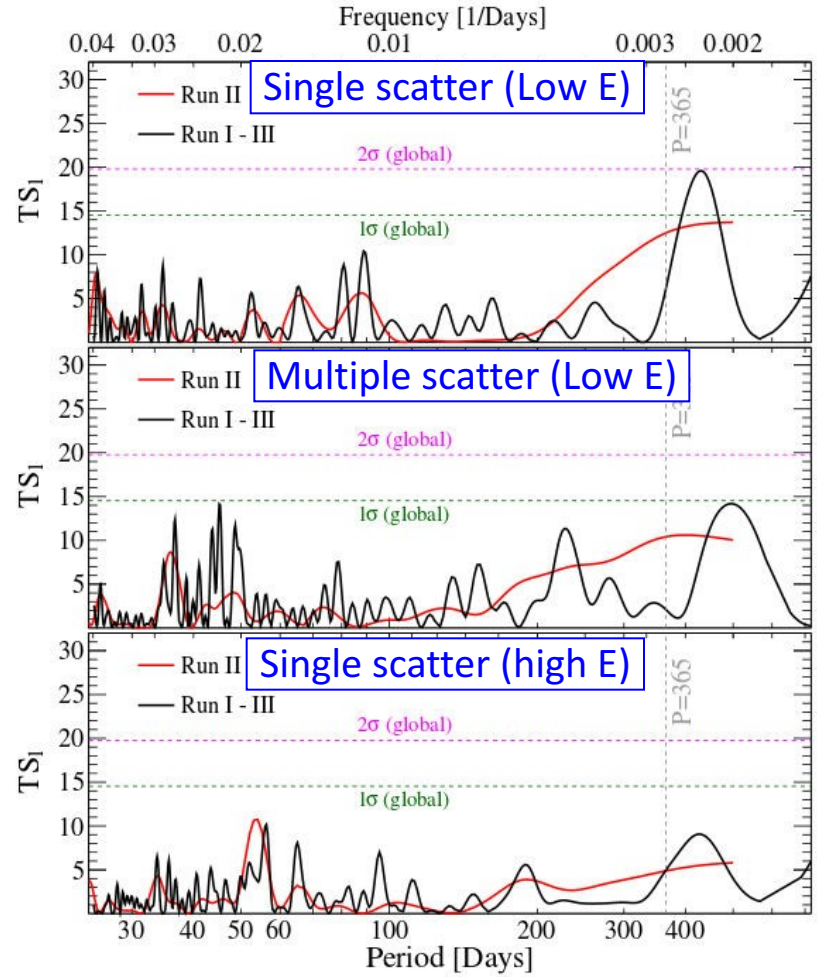




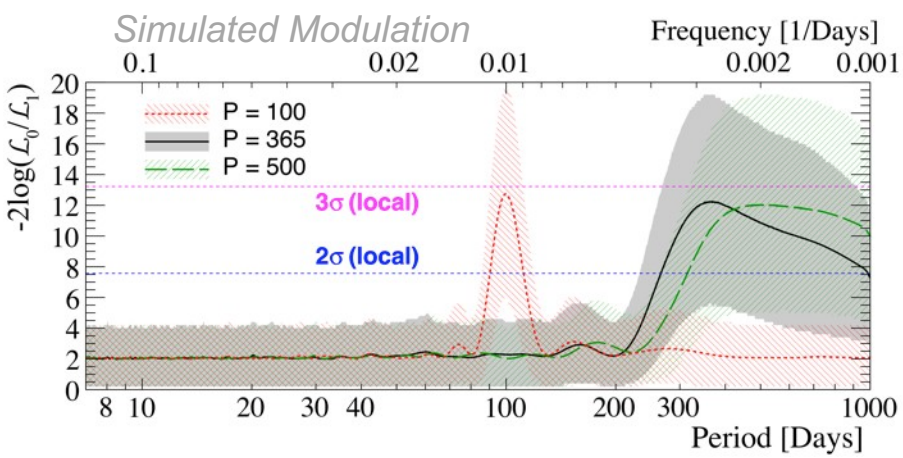
XENON100: Science 349, 851 (2015)
Confirmed by XMASS: PLB 759 272 (2016)

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!



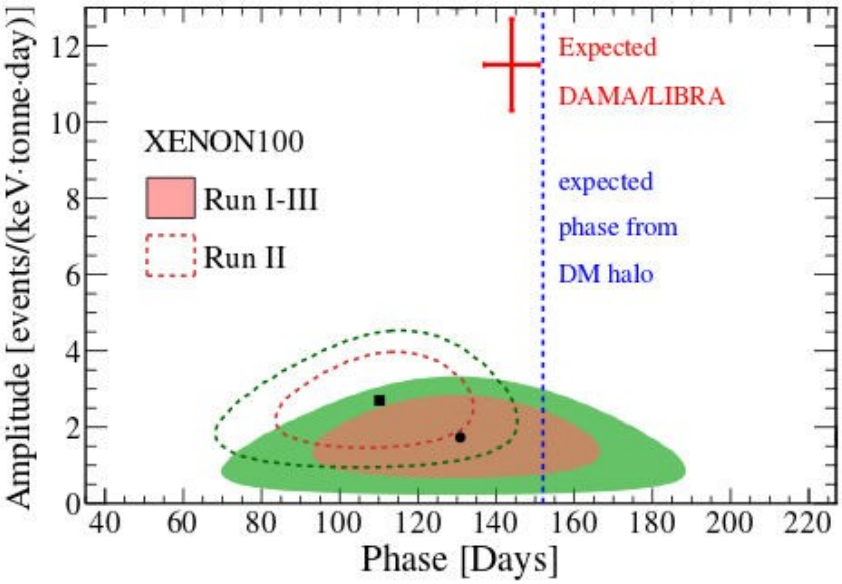
Discovery potential:



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



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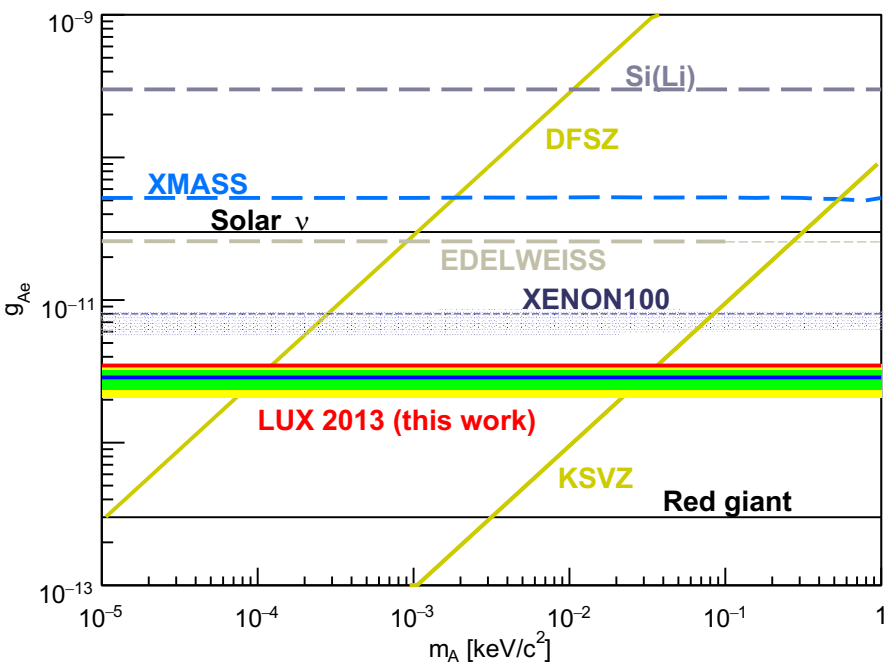
Axions and Axion Like Particles (ALPs)

LUX world leading

arXiv:1704.02297

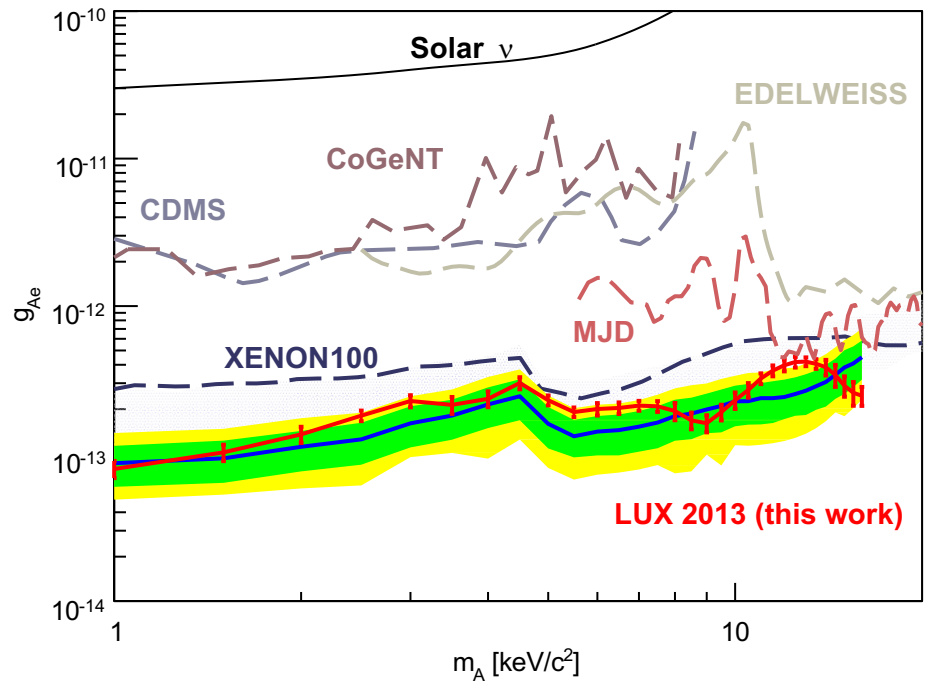
Solar Axions



LUX 2013 excludes $g_{AE} > 3.5\times10^{-12}$ (90% CL)

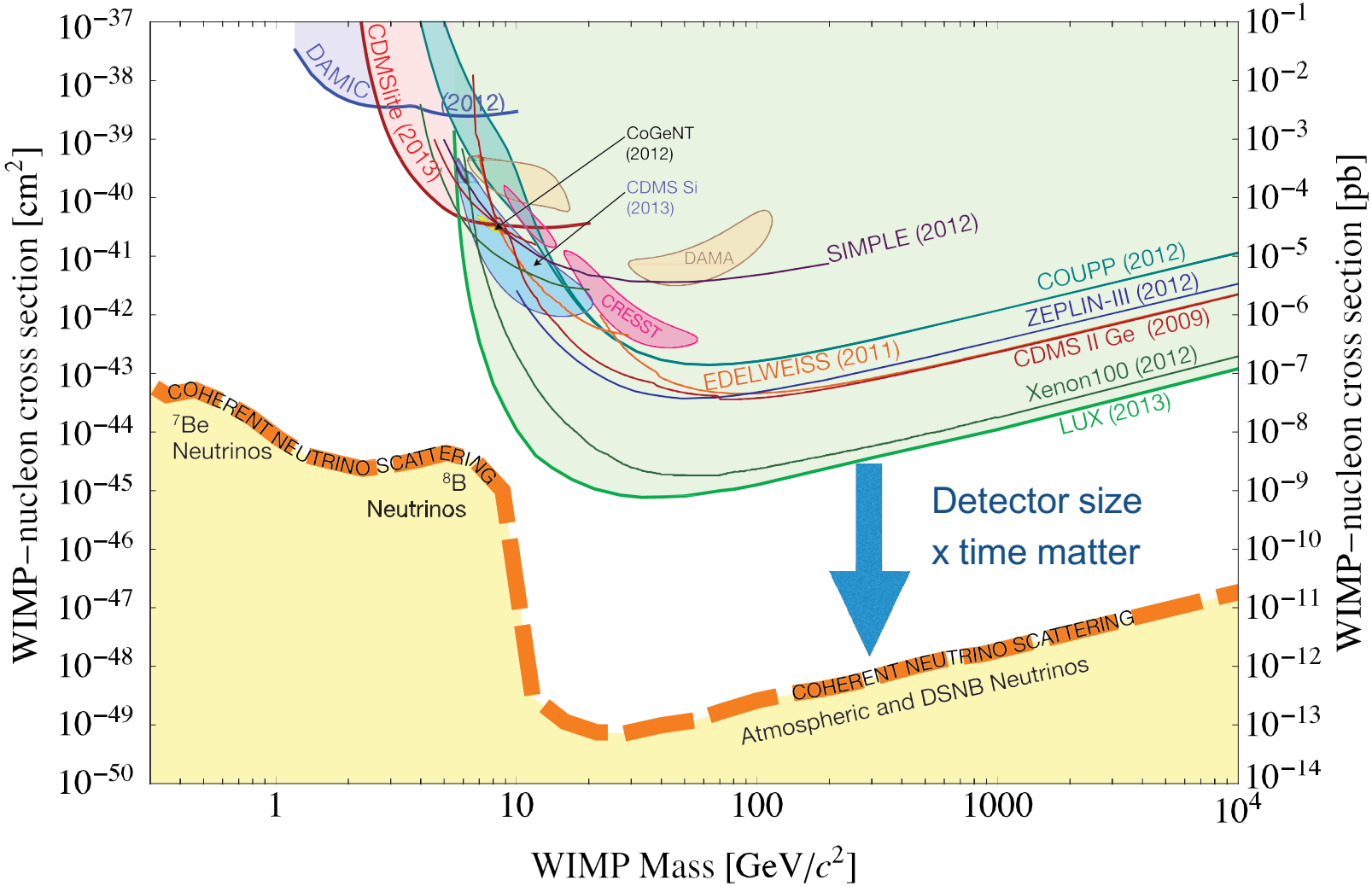
- $m_A > 0.12$ eV/c^2 (DFSZ model)
- $m_A > 36.6$ eV/c^2 (KSVZ model)

Galactic ALPs



LUX 2013 excludes $g_{AE} > 4.2\times10^{-13}$ (90% CL) across the range 1-16 keV/c^2 in ALP mass

How is evolving the field of Direct Detection ?



The fight against the background

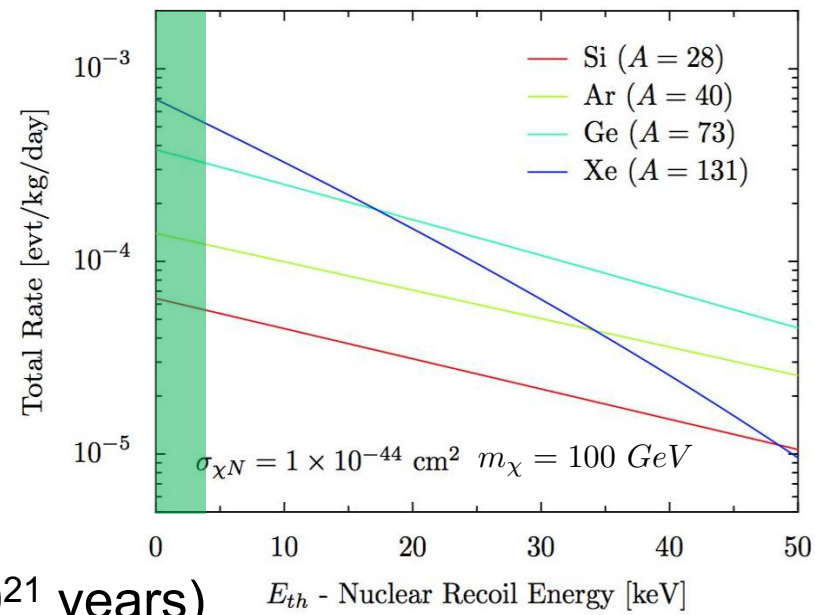
- **Use WIMP properties**

  - No double scatter
  - Exponential spectrum
  - 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)
- ^{39}Ar : β^- decay, 1Bq/kg ($T_{1/2}$ = 269 years)

Direct detection with noble liquids (2013)

DarkSide goals

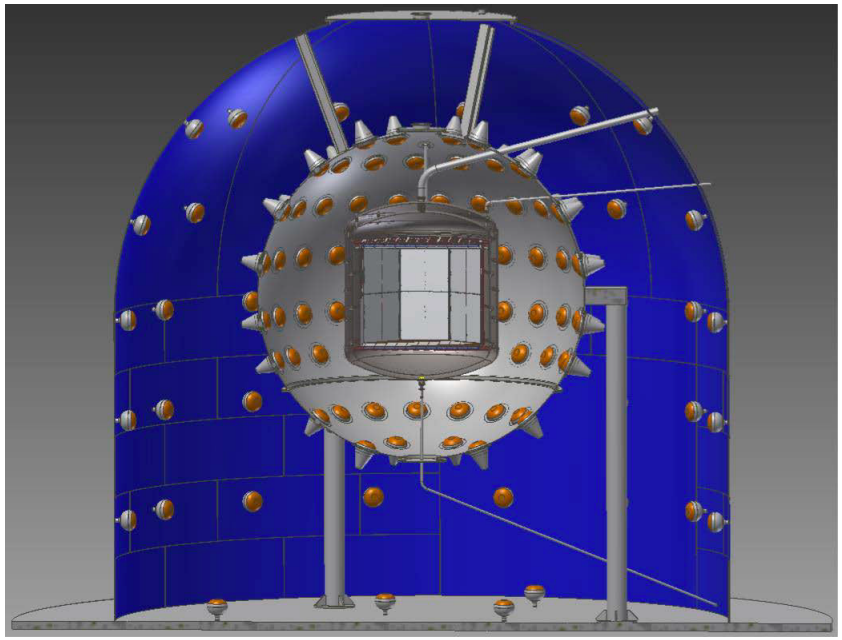
from M. Boulay

(New) Argon Collaboration

Researches from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

→ DS-20K → multi-100-T (Argo/DEAP-nT)



DS-20k: Two-phase argon TPC

- 20 T of low-radioactivity Ar: Underground and isotopic depletion
- TPC scaled-up from DS-50
- First large-scale use of SiPMs for light readout

More info about future of DarkSide ~20 min ago (C. Savarese)

DarkSide program

from P. Agnes

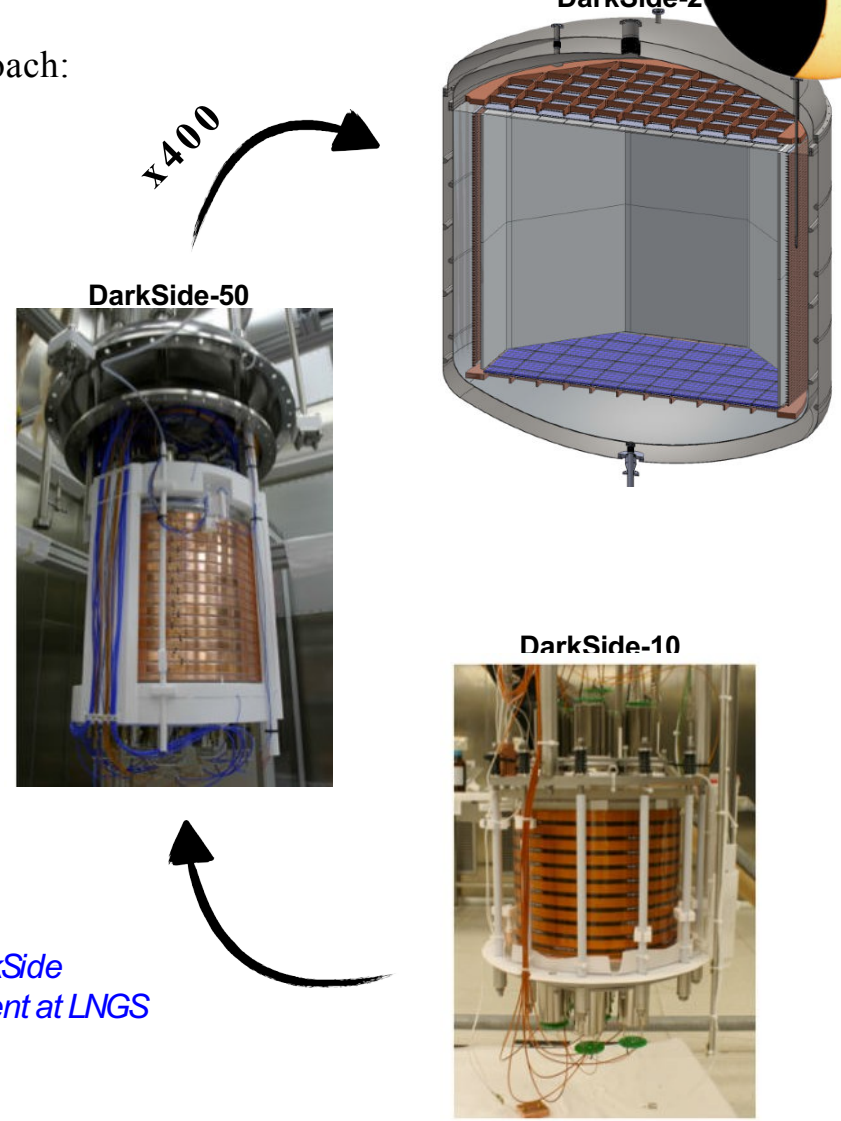
Dual phase liquid argon TPC, through a **staged** approach:

Main goal: a bg-free experiment
ER background: βs and γs
NR background: neutrons

Background suppression
- Ultra-low background materials
- **Depleted Liquid Argon**
- Low background photo-detectors
- Low background material components

Background identification
- **Pulse Shape Discrimination** (PSD)
- Ionization/scintillation ratio
- Position reconstruction (surface events)
- **Multiple scatters within the TPC**

Active Shielding
- **Liquid Scintillator Veto** (LSV)
- Water Cherenkov against muons (WCD)

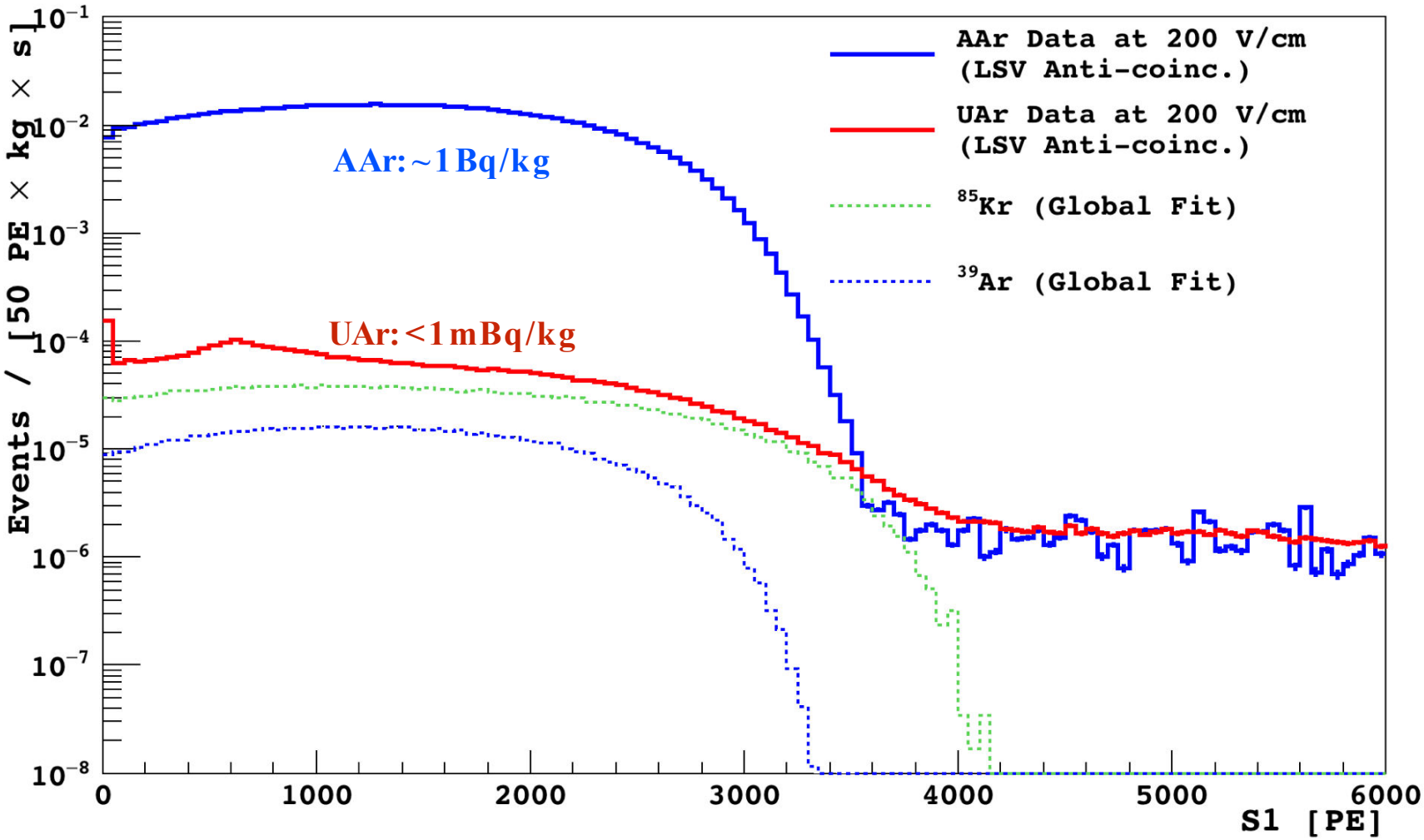


The DarkSide experiment at LNGS

Underground Argon

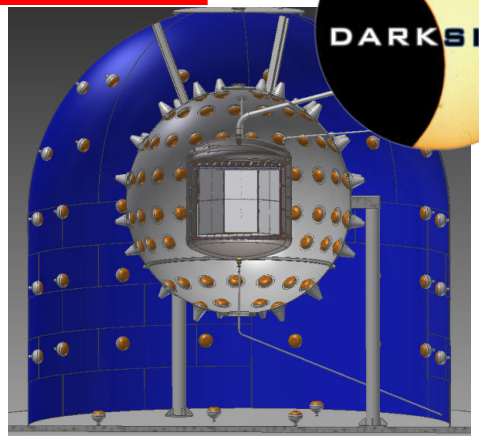
from P. Agnes

^{39}Ar, **cosmic ray produced,** first forbidden βdecay: endpoint at 565 keV, $t_{1/2}$ = 269 years
Pile up in large TPC (drift time: acquisition window of the order of 1 ms)
~150 kg successfully extracted from a **CO_2 well in Colorado**, detector **filled in April 2015**



DarkSide 20k

from P. Agnes



Goals:

bg-free search with **exposure of 100 t.y** (possibly 200 t.y)

start taking data by 2021

Same detector concept:

Larger TPC (**20 t fiducial**)

Larger LSV (8 m diameter)

Larger WT (14 m diameter)

x400 wrt DS50

High LY required

Different readout system

14 m^2 SiPM array (grouped)

Same need for low-background

Fiducialization

Radiopurity

UAr procurement

URANIA (Colorado) goal: 100 kg/day

x1400

ARIA (>300 m distillation column for even larger detector)

Intense calibration and prototyping

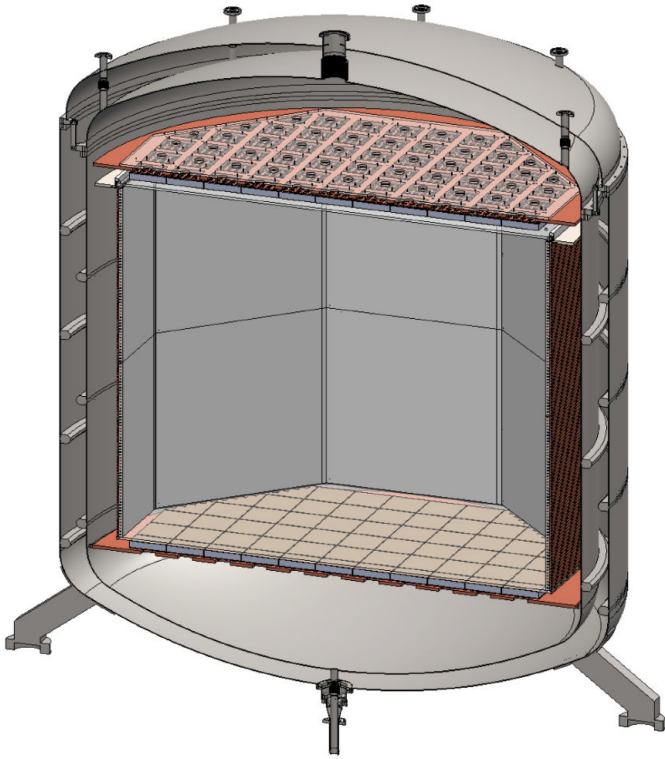
chemical purification

DSProto: 1 m^3 TPC to test SiPM

Neutron calibrations:

ARIS (pulsed neutron beam, single phase)

ReD (dual-phase TPC, directionality)



DarkSide 20k projected

from P. Agnes

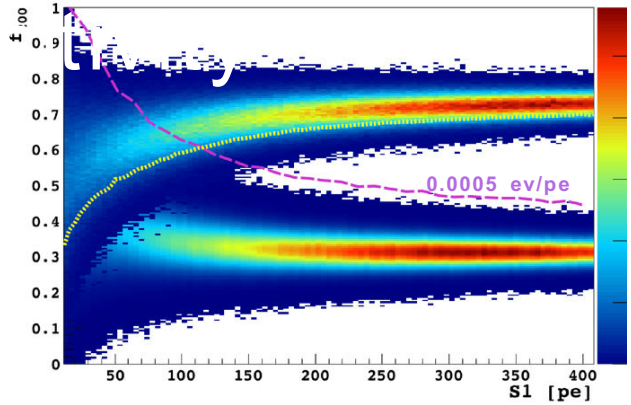
Simulation of several millions of events (ER and NR) to determine **the acceptance to WIMPs,** assuming NR + ER background < 0.1 events.

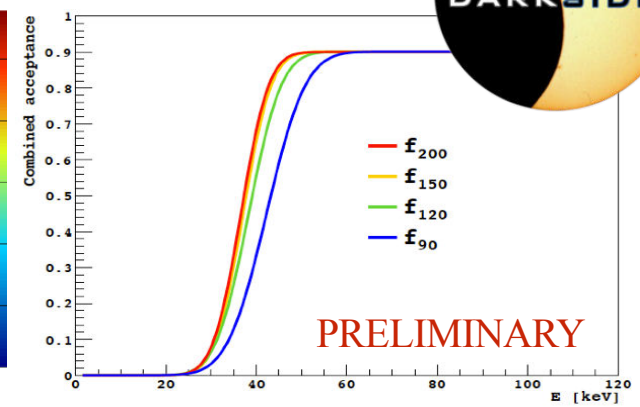
+ Nuclear recoil quenching from DS50

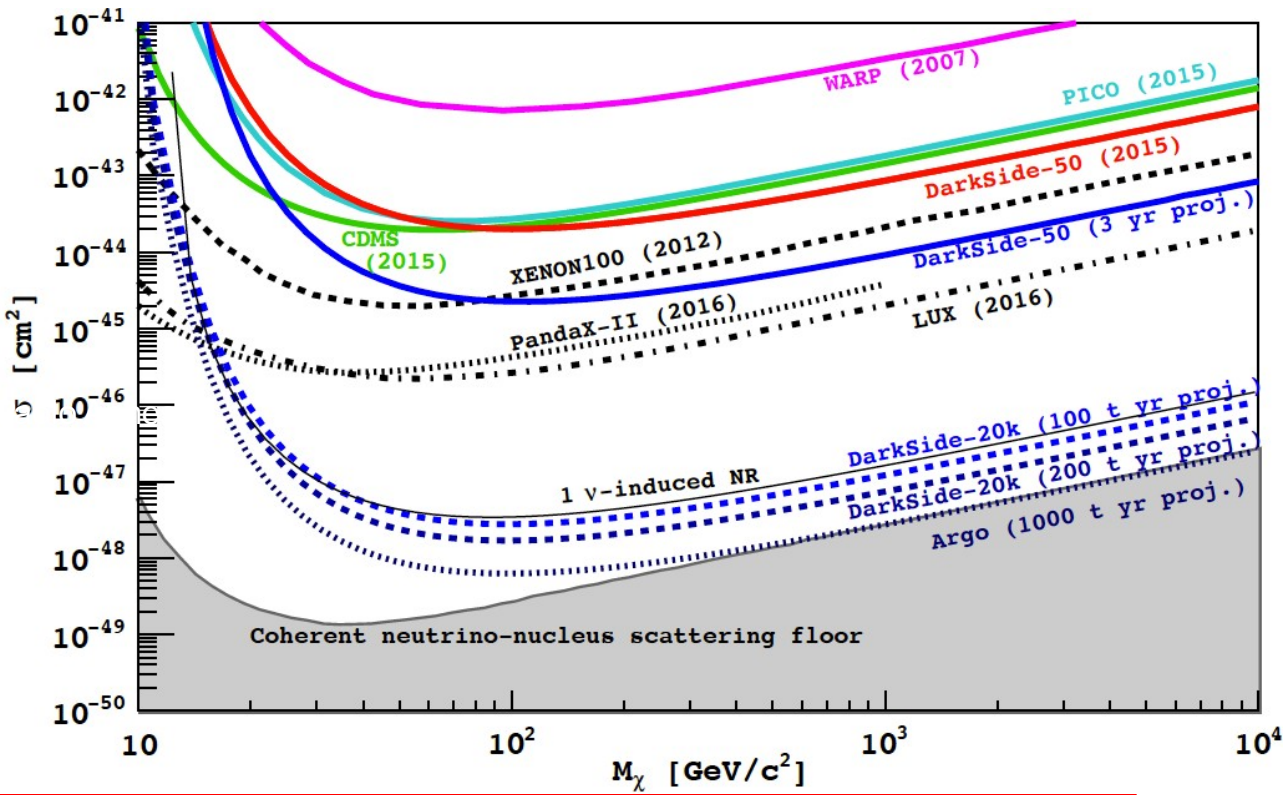
Optimization of PSD parameter for the best sensitivity.

Expected **>200x10⁶** events (1400 depletion) from ^{39}Ar only in [0,50] keV. A simulation of the **full statistics** is ongoing.

1.6 CNNS events expected, likelihood approach in progress.







DEAP-3600 First results

from M. Boulay

LAr experiment
Single phase

3600 kg argon
in sealed ultraclean Acrylic
Vessel (1.7 m ID)

Vessel is "resurfaced" in-situ to
remove deposited Rn daughters
after construction

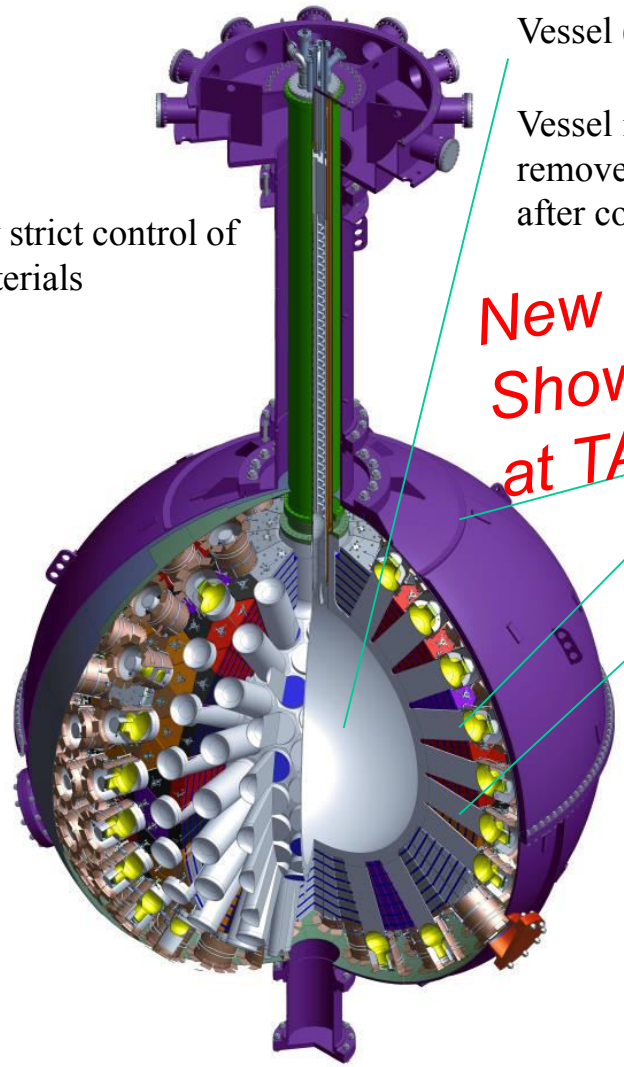
255 Hamamatsu
R5912 HQE PMTs 8-inch
(Light Sensors)

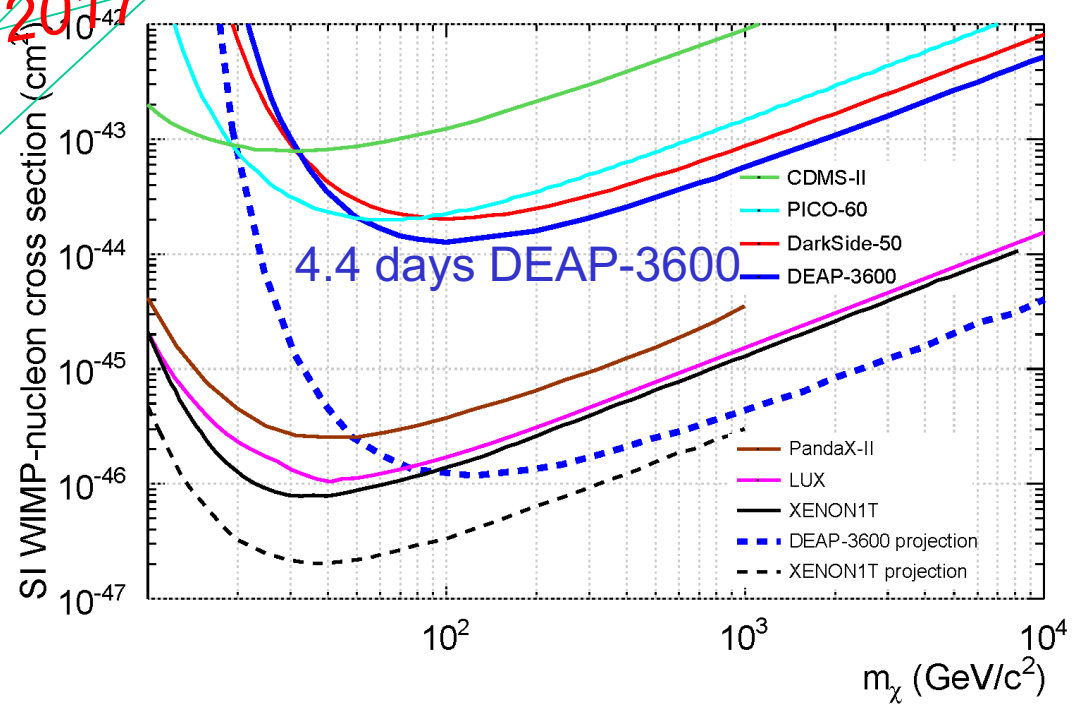
50 cm light guides + PE shielding
provide neutron moderation

Steel Shell immersed in 8 m water shield
at SNOLAB

very strict control of
materials

New results
Shown this week
at TAUP 2017





PandaX program

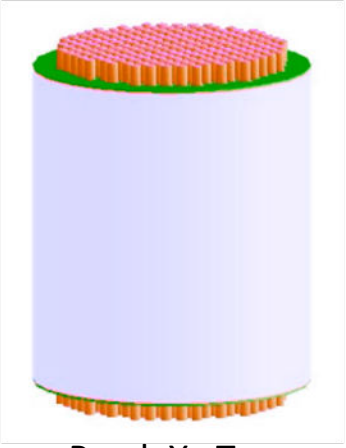
From N. Zhou

PANDA X

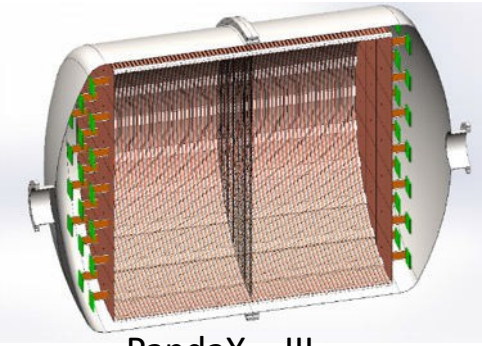
- **P**article **and A**strophysical **X**enon Experiments
  - Formed in 2009, ~50 people
- PandaX-II 500kg results published at PRL
  - World-leading sensitivity in 2016
- **Plan to build a 4-ton Xenon detector**
  - to push the DM SI sensitivity down to 10^{-47} cm^2

Phase I
120 kg DM
2009-2014

Phase II
500 kg DM
2014-2017



PandaX-xT
Multi ton DM
2016 -

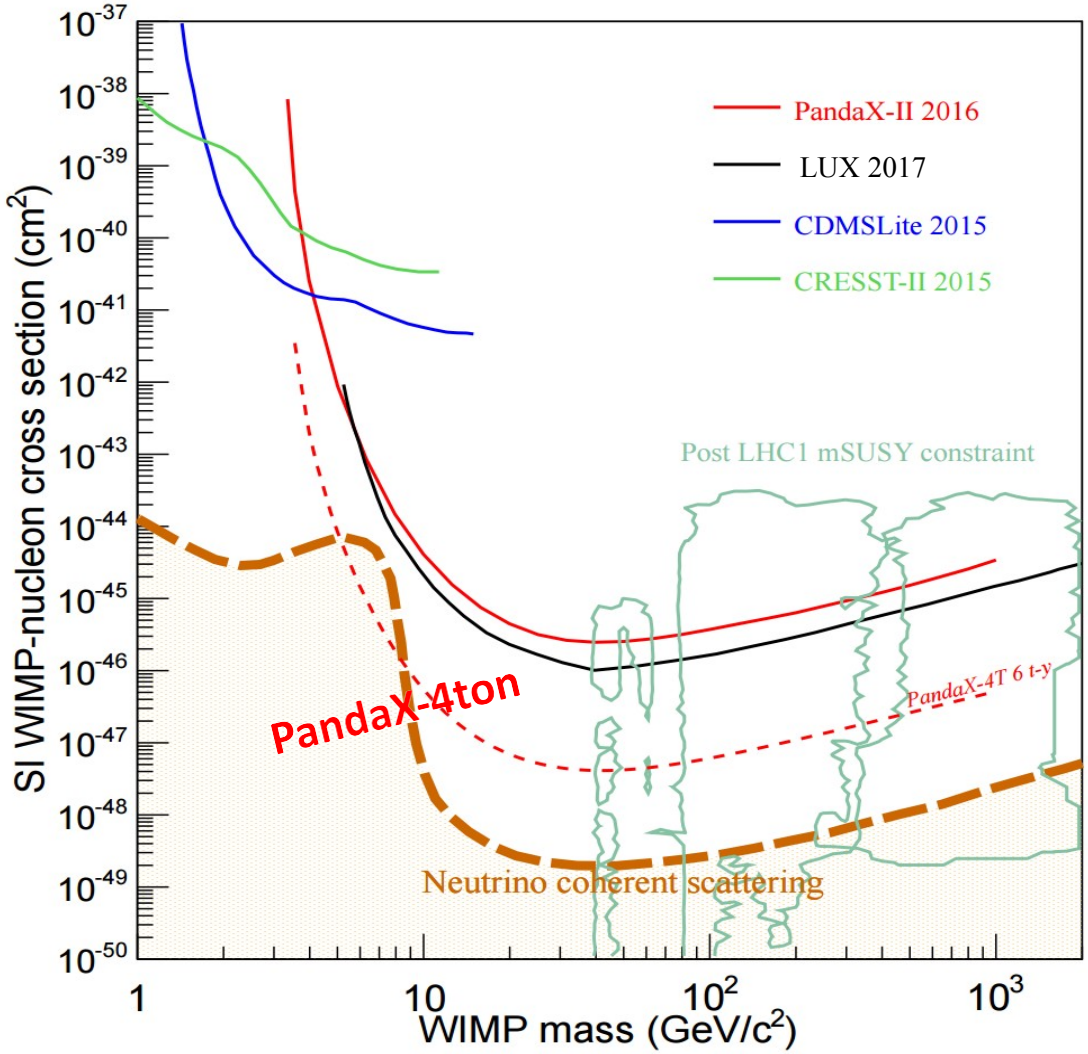


PandaX – III
200kg to 1 ton
136Xe 0vDBD
2016 -

Expected Sensitivity

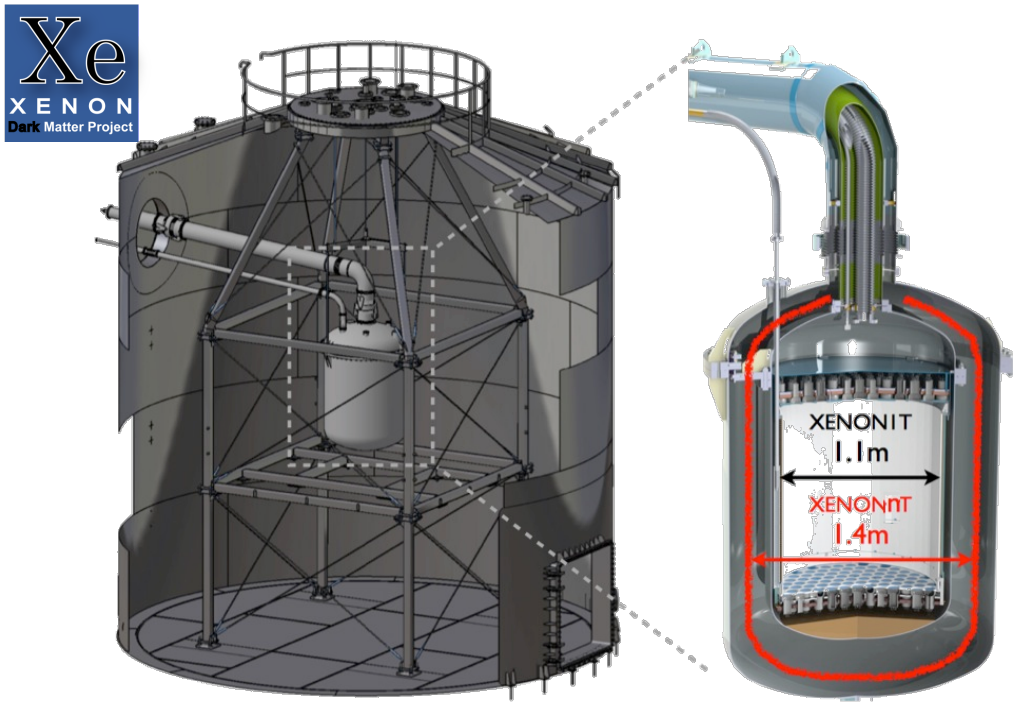
From N. Zhou

- With exposure reaching 6 ton-year
- DM SI sensitivity could reach ~10^{-47}c



More info about future of CJPL in ~20 min (H. Wong)

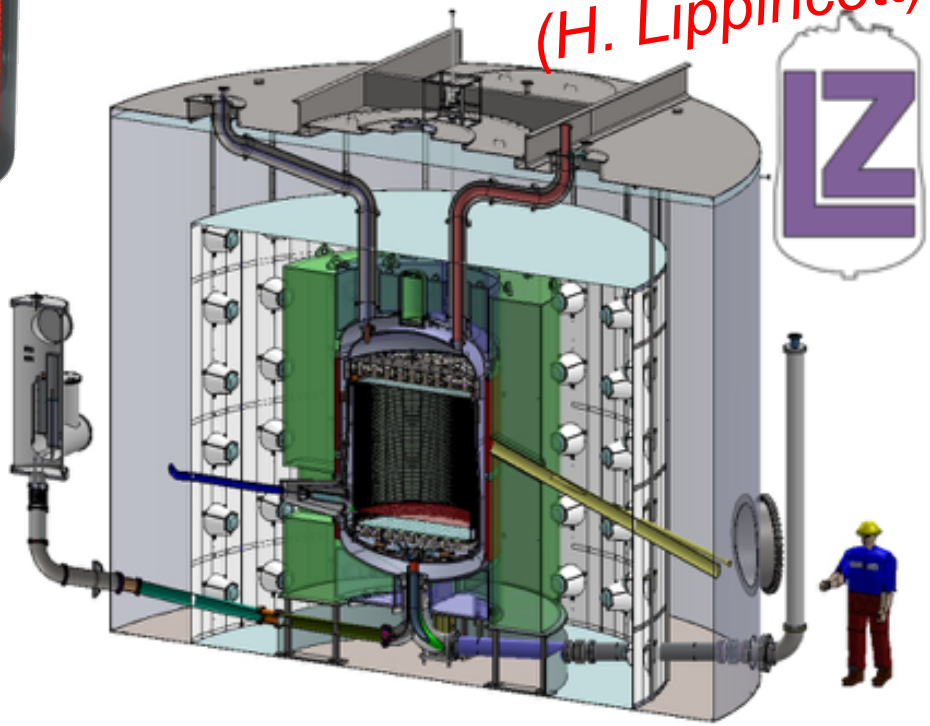
Future: LZ & XENONnT



LZ = LUX + ZEPLIN

- Same location than LUX
- Turning on by 2020 with 1 000 initial live-days
- 10 tons total, 7 tons active, 5.6t fiducial

More info about LZ last Tuesday (H. Lippincott)

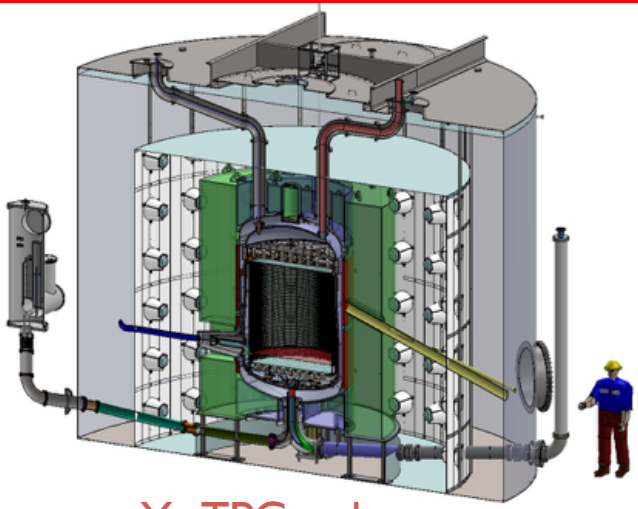


XENONnT:

- 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, 4.5 t fiducial

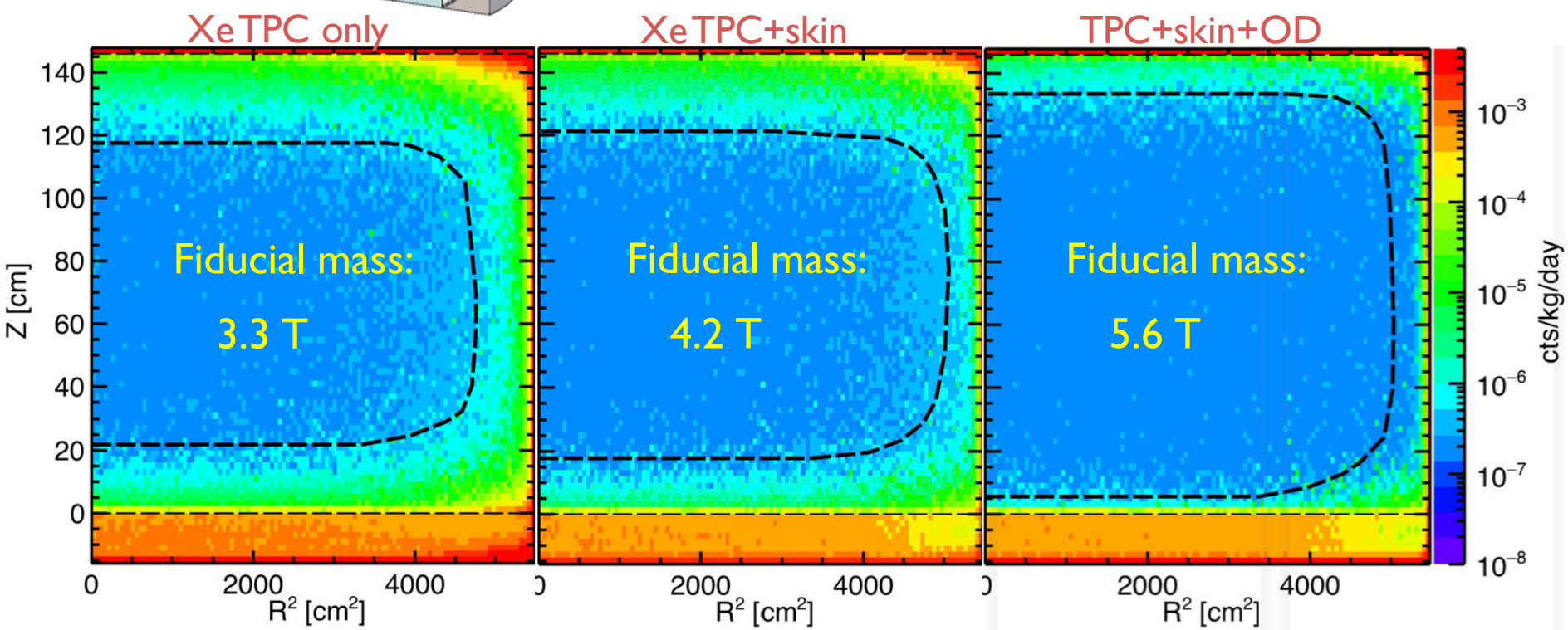
Background suppresion by veto

Adapted from H. Lippincott



Two component outer detector:

- Gd-loaded liquid scintillator
- instrumented skin

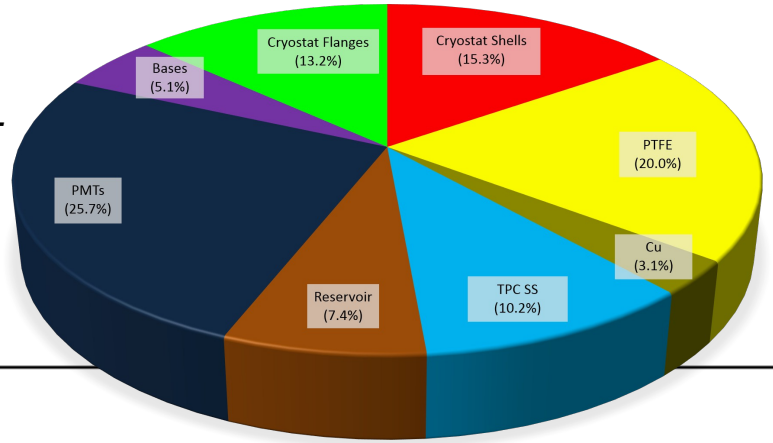


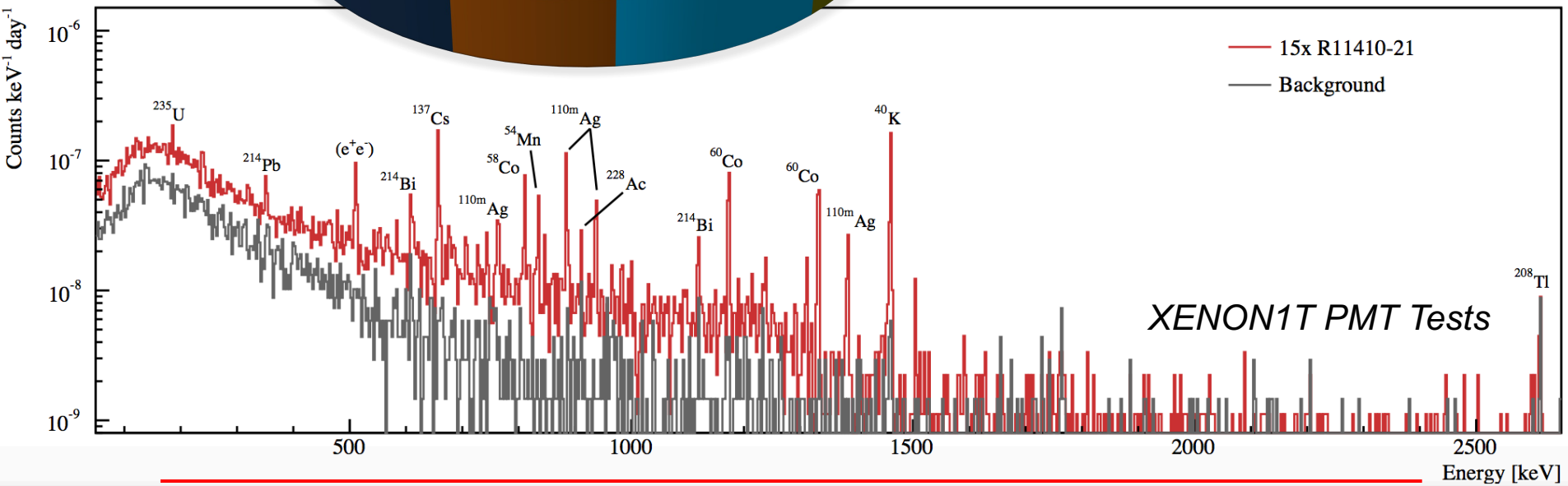
Screening & Cleaning Every materials

2 ways to avoid contamination:
- Use clean materials
- Continuously clean liquid

LZ Test in clean room

XENON1T NR origins





Materials Screening

From C. Ignarra

arxiv:1703.09144

- Dedicated gamma counting facilities

– Primary gamma emitting isotopes: ^{40}K, ^{137}Cs, ^{60}Co, ^{238}U, ^{235}U, ^{232}Th, (U and Th chains also responsible for neutron production)

- Intrinsic radioactivity goals for fixed contamination in detector components: single scatter rate less than 0.4 NR counts and less than 37 x 10^{-6} events/keV/kg/d (37 μdru).
- Direct measurements of radon emanation from construction materials

– Maximum tolerable activity is 10 mBq throughout LXe, 1 mBq goal for emanation

— ^{210}Pb activity on surfaces < 10 mBq/m^2, 0.5 for inner TPC surfaces

- Screening programs for cryostat titanium, detector PTFE, PMT bases & components, etc
- Robust cleanliness protocols during assembly

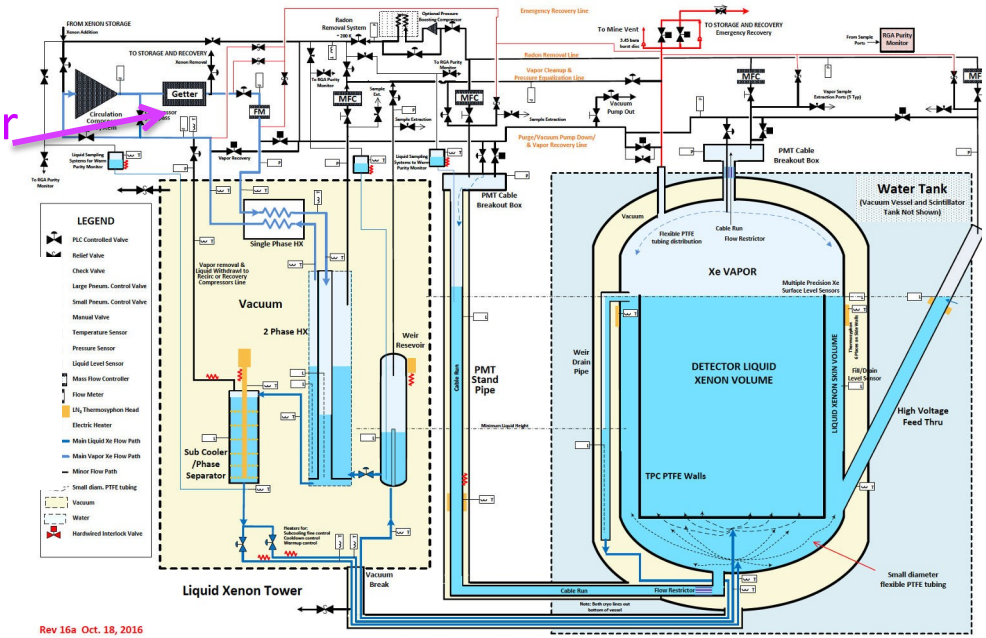
Reactive Background

From C. Ignarra

- Mostly outgassing from detector materials
- Constant gas phase circulation/purification to maintain free electron lifetime
  - Requirement: 670 μs, already achieved with LUX
- Heated zirconium getter (commercial) removes non-noble impurities

Getter

LZ Online Circulation System



^{85}Kr

From C. Ignarra

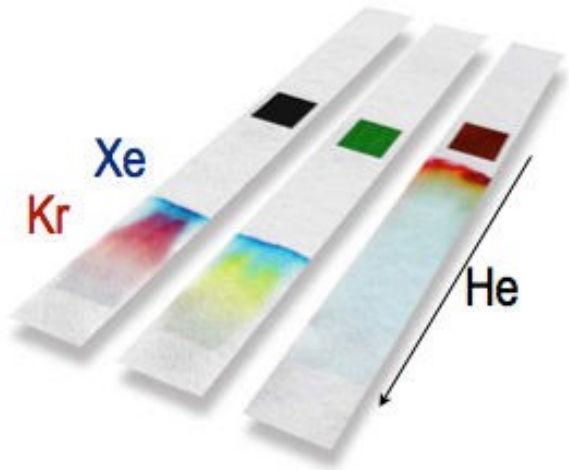
- Kr-85 is an ER-like background (beta emitter)
  - Present in the atmosphere, half life of 10 years

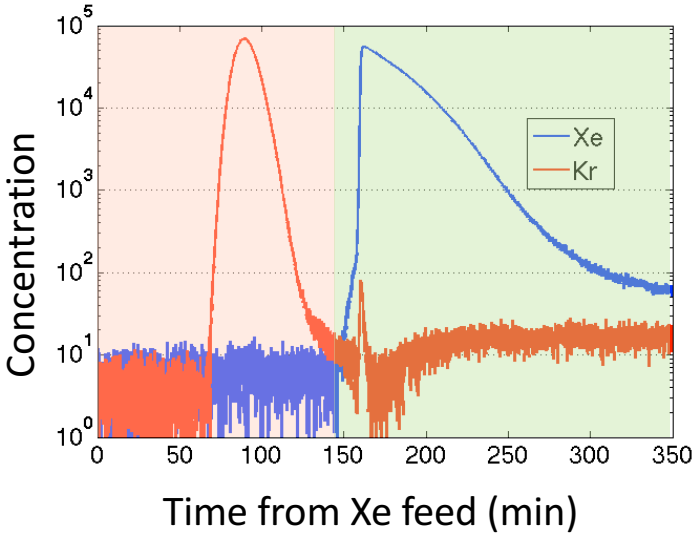
~10,000 ppt → 3 ppt → 0.015 ppt (0.300 ppt)

Commercial Xe LUX LZ Goal (LZ requirement)

- 0.015 ppt corresponds to only a shotglass of air in 10 tons of xenon
- Remove via gas charcoal chromatography (with helium carrier gas)

– Kr has a faster flow rate through activated charcoal than Xe

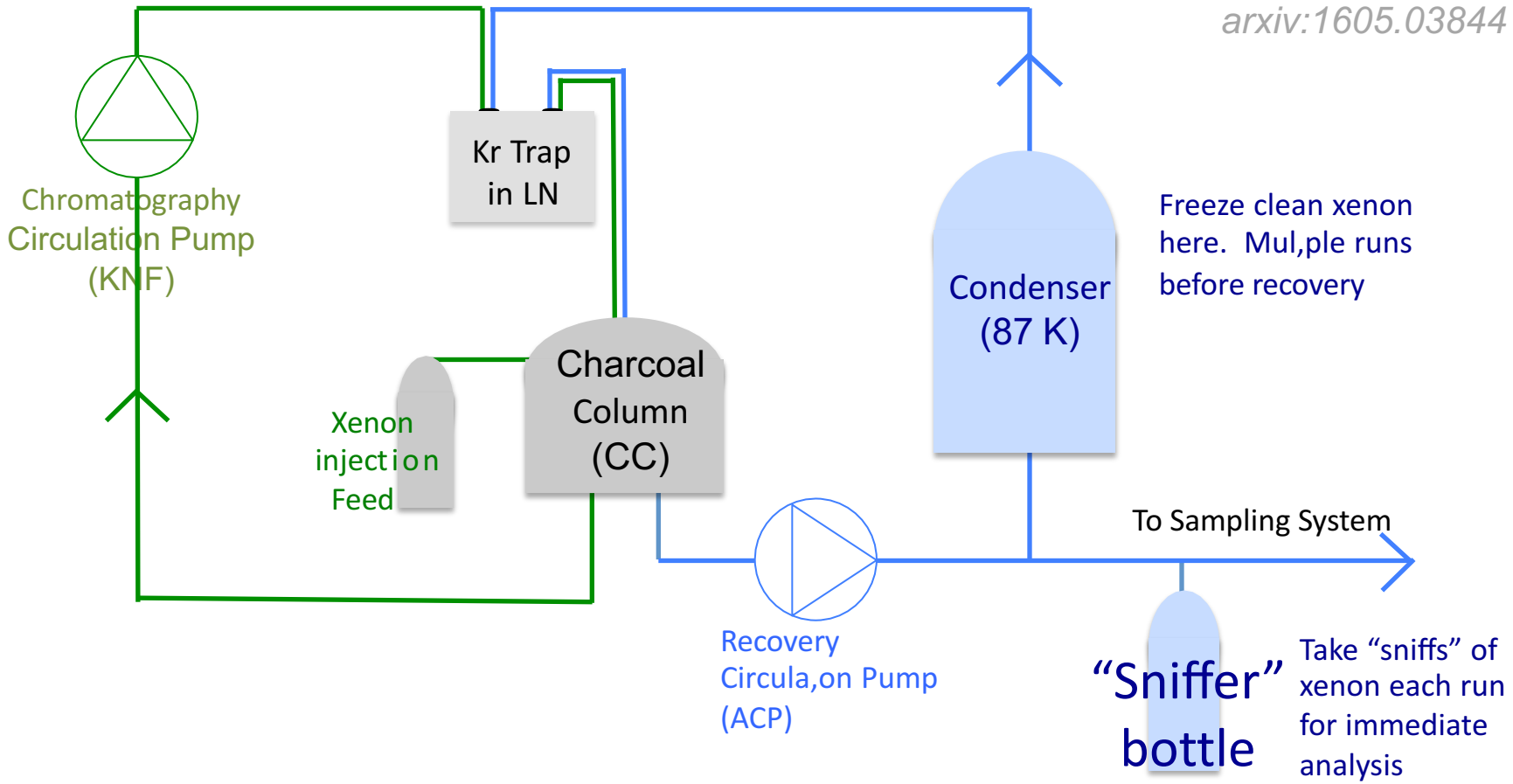




Kr Removal R&D System at SLAC

From C. Ignarra

- Upgraded version of LUX Kr removal system
- Run through **Chromatography Loop** to trap Kr
- Then switch to **Recovery Loop** to recover purified xenon into condenser

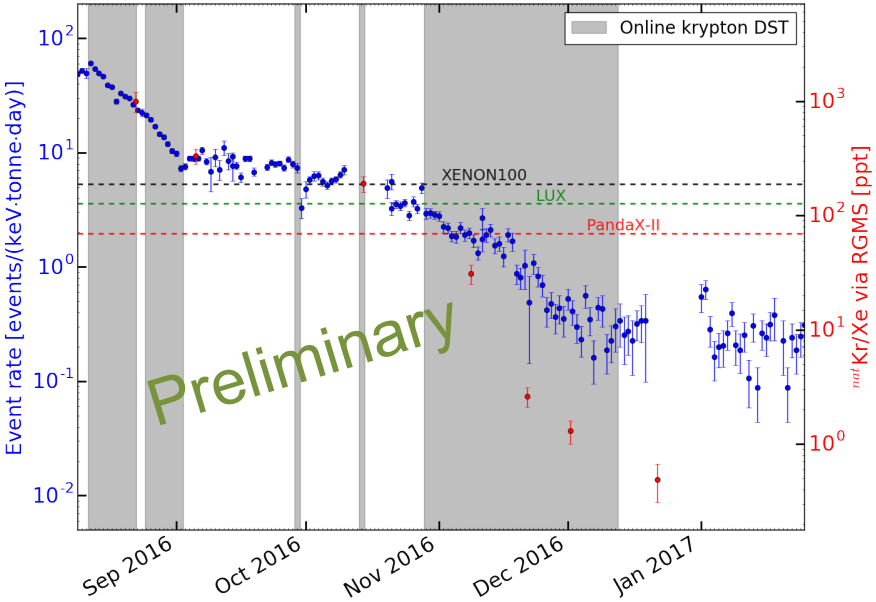


Background Reduction: ^{85}Kr

- Commercial Xe contains ~ ppb of Kr
- Column principle : remove Kr from Xe by means of cryogenic distillation (gases have different boiling points)
- >6.4×10^5 separation, output concentration < 0.048 ppt
- 5.5 m column, 6.5 kg/hr,

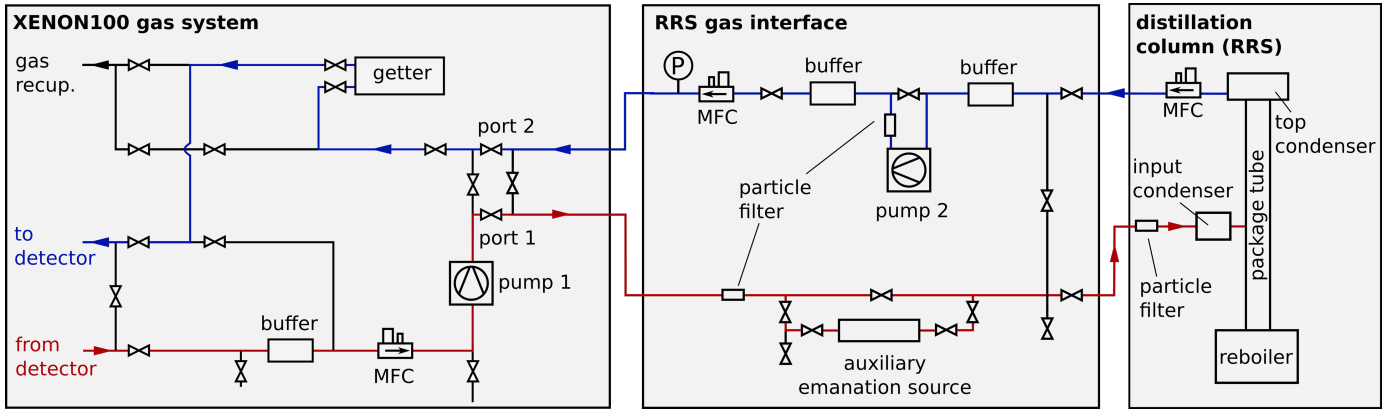
- New approach: Online Distillation
- Successfully reduced Kr to (0.62 +- 0.13) ppt measured by RGMS

- Background is now radon dominated



arXiv:1612.04284
EPJC 74, 2746 (2014)

Background Reduction: ^{222}Rn

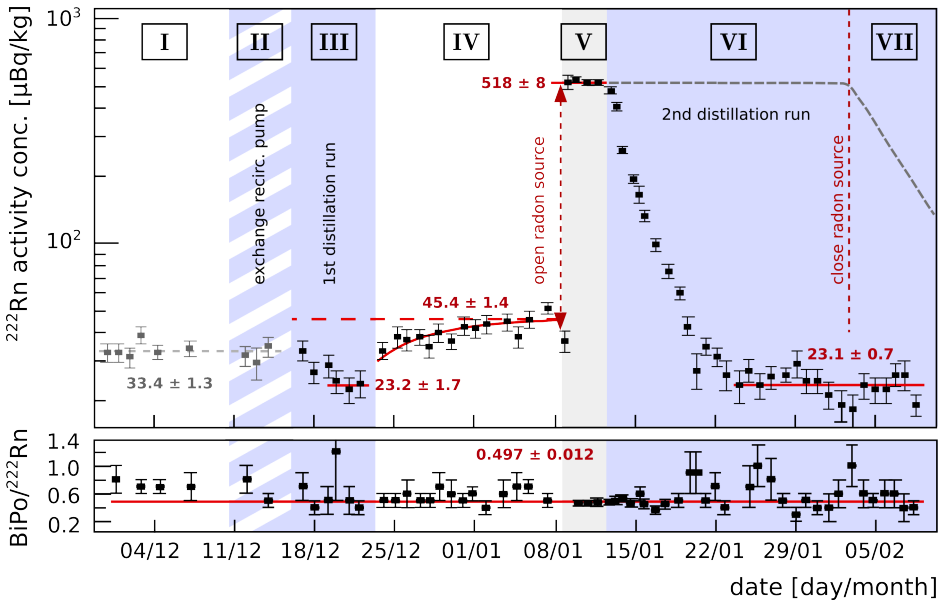


- Successful demonstration of radon removal by cryogenic distillation at XENON100
- Reduction factor of R > 27 (95% C.L.)

XENON1T:

- Minimize leakage into purification system at Xe1T (i.e., hermetically sealed pumps)
- Low radon emanation components
- Dedicated radon emanation measurements

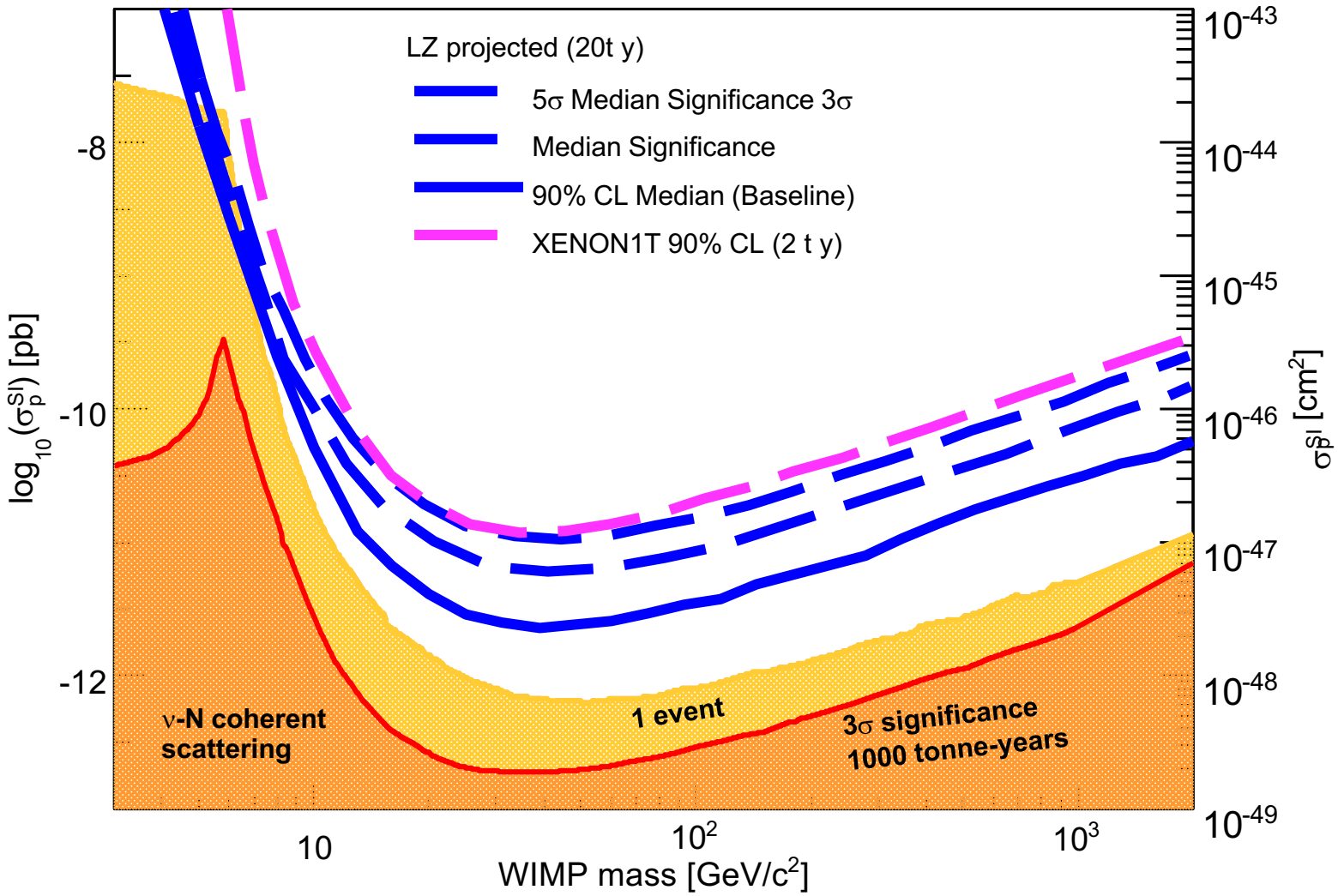
arXiv:1702.06942



Sensitivity projections

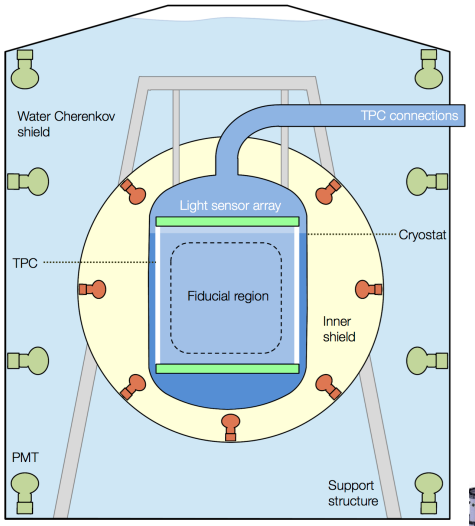
Adapted from H. Lippincott

DM Detection can be around the corner!



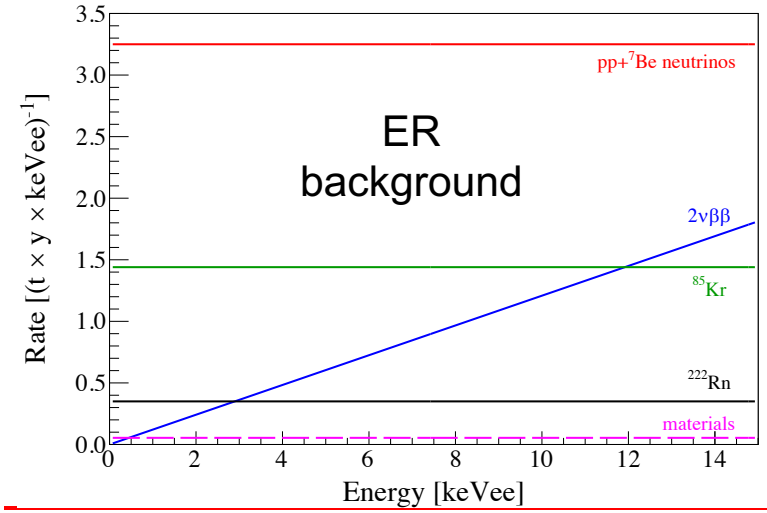
Far future: DARWIN the ultimate detector

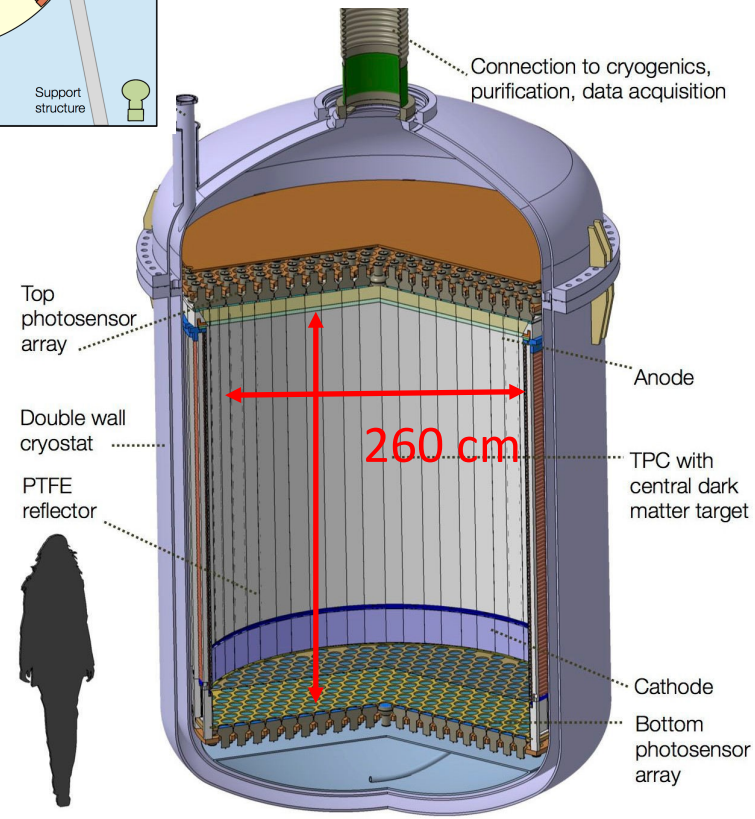
- Based on proved technologies
- Aim at sensitivity of a few 10^{-49} cm², limited by irreducible ν-backgrounds (200 t y)
- R&D started
- 50 tons total LXe
  40 tons TPC
  30 tons fiducial



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

arXiv:1506.08309

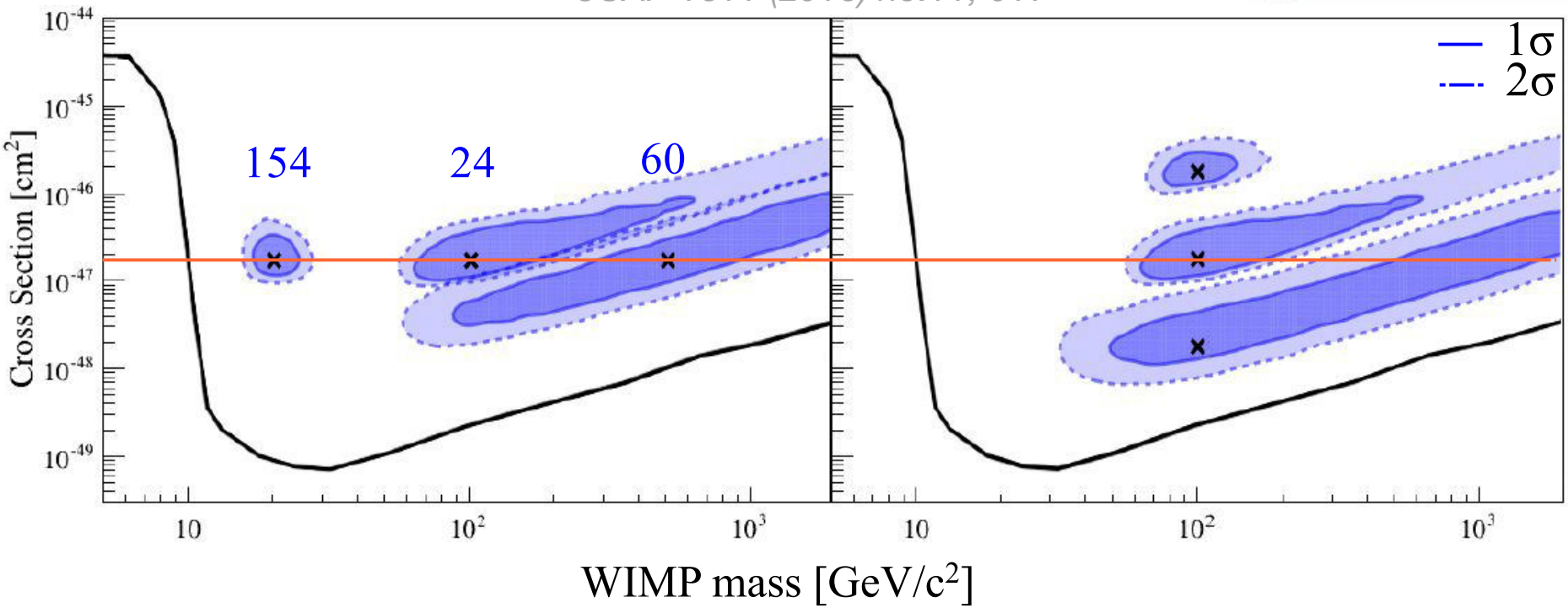




WIMP spectroscopy

Adapted from L. Scotto-Lavina

JCAP 1611 (2016) no.11, 017



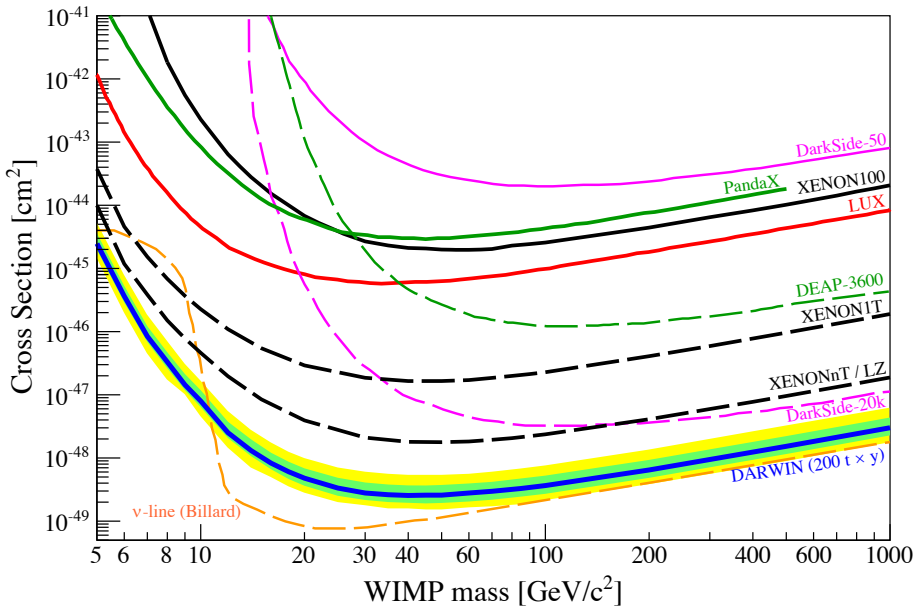
200t·y exposure
v_{esc}=544 ±40 km/s
v_0 =220±20 km/s
ρ_χ=0.3±0.1GeV/cm^3

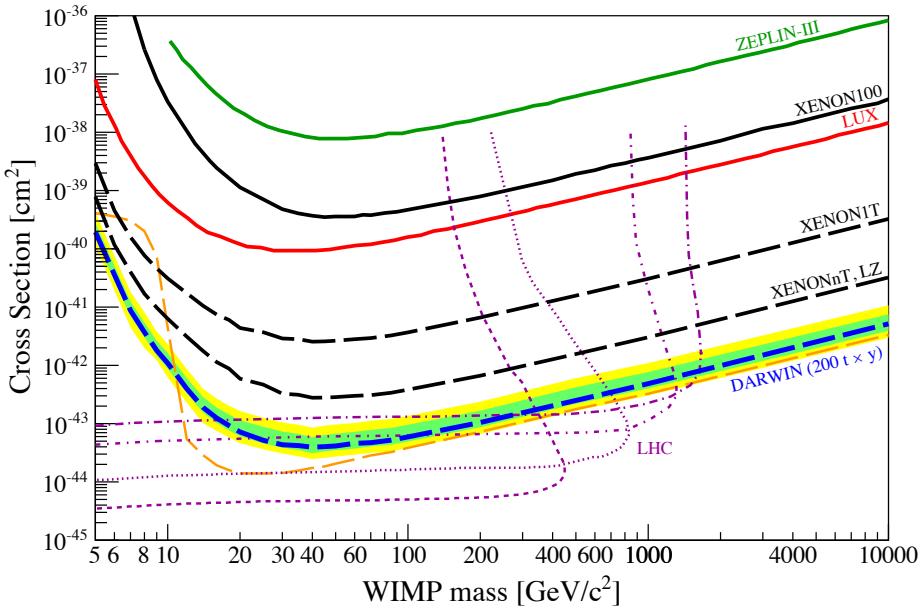
Capability on reconstructing the WIMP mass and cross section for various masses (20, 100 ,500 GeV/c^2) and cross sections
(reference line: XENON1T sensitivity (20ty))

Science goal : SI and SD limits

Adapted from L. Scotto-Lavina

JCAP 1611 (2016) no.11, 017





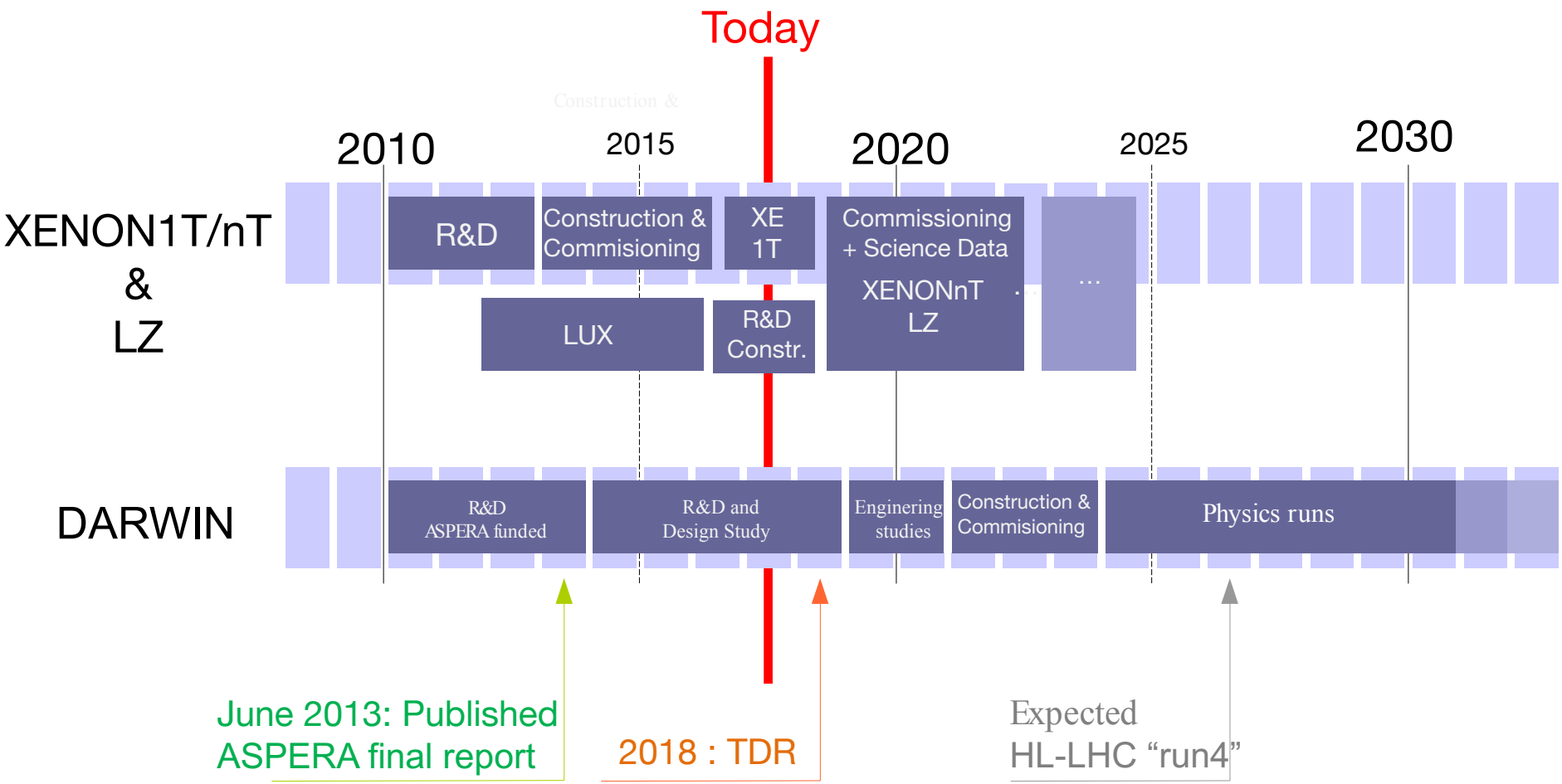
200 t·y exposure
E=4-50 keV$_{nr}$
30% NR aceptance
99.98% ERrejection
LY=8PE/keV @ 122 keV

Complementarity with the LHC:
Minimal simplified Model with Dirac fermion
Interacting with an axial-vector mediator $g \equiv g_q = g_{DM}$

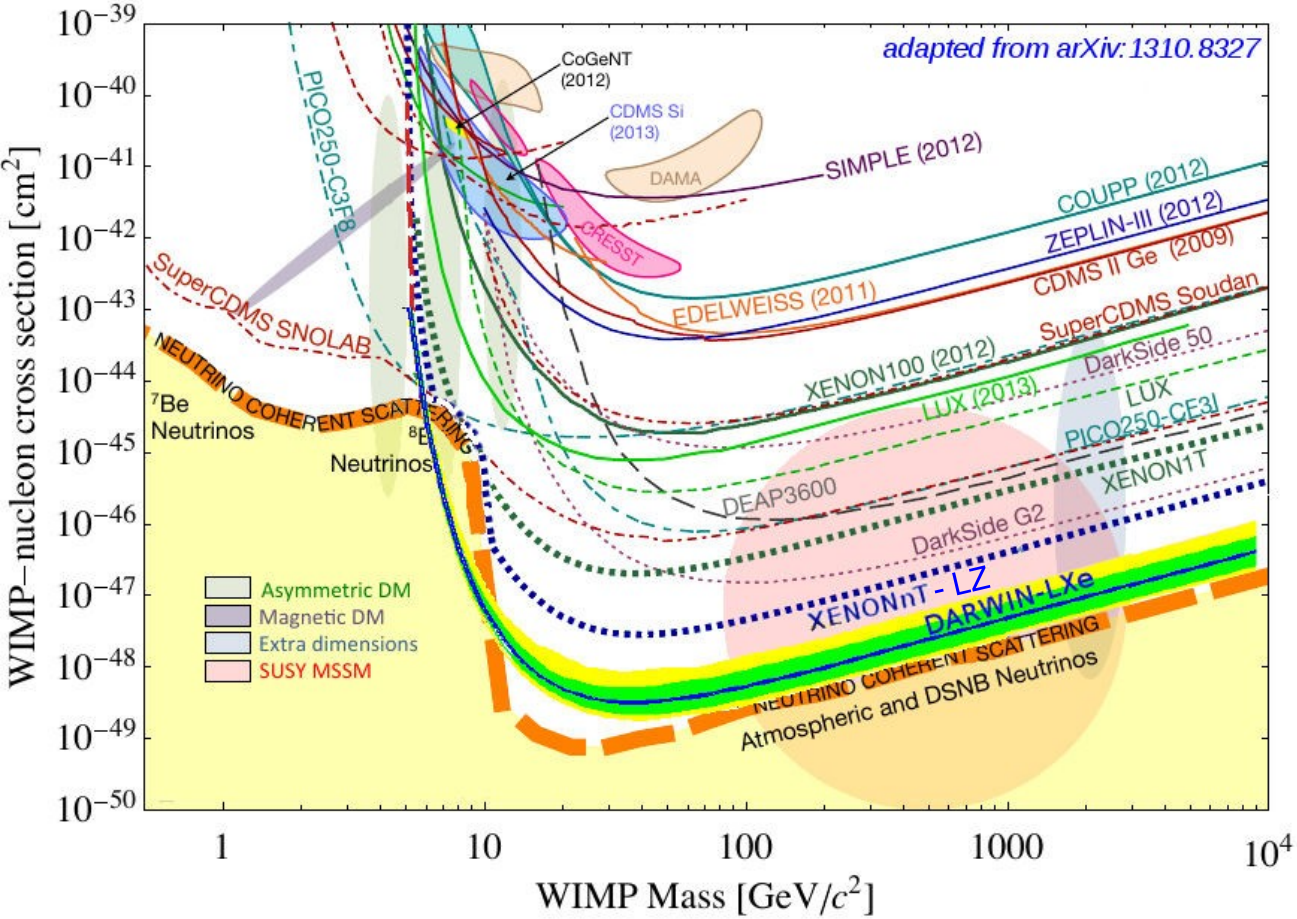
S.A.Maliketal.,Phys.DarkUniv.9-10(2015)51

Estimated Timescale

Adapted from L. Scotto-Lavina



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

XENONnT & LZ construction is about to start…

XENON1T has analyzed it first result and data taking continue

DARWIN is in design study phase