COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Dark Matter Direct Detection: the state-of-the-art

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xenon1t.org

Outline of Lecture

- **Evidence for Dark Matter and Candidates**
  - Rotation curves
  - gravitational lensing
- **WIMP direct detection**
  - kinematics of the elastic WIMP-nucleus scattering
  - cross sections, differential rates, expected rates in a detector
- **WIMP signatures and Backgrounds**
  - time dependance of the rate, directional dependance
  - background sources, background discrimination
- **State-of-the-art in direct detection**
  - noble liquid properties
  - the XENON project

References and Additional Readings

- *Rate/Signal Definition*

J. D. Lewin and P. F. Smith, Astropart. Phys. 6, (1996) 87.

F. Donato, N. Fornengo, and S. Scopel, Astropart. Phys. 9,(1998) 247.

- *Backgrounds and more*

G. Heusser, Ann. Rev. Nucl. Part. Sci., 45, (1995) 543.

R. J. Gaiskell, Ann. Rev. Nucl. Part. Sci., 54, (2004) 315.

- *Detectors and experimental methods*

W. R. Leo, *Techniques for nuclear and particle physics experiments*, Springer, (1994)

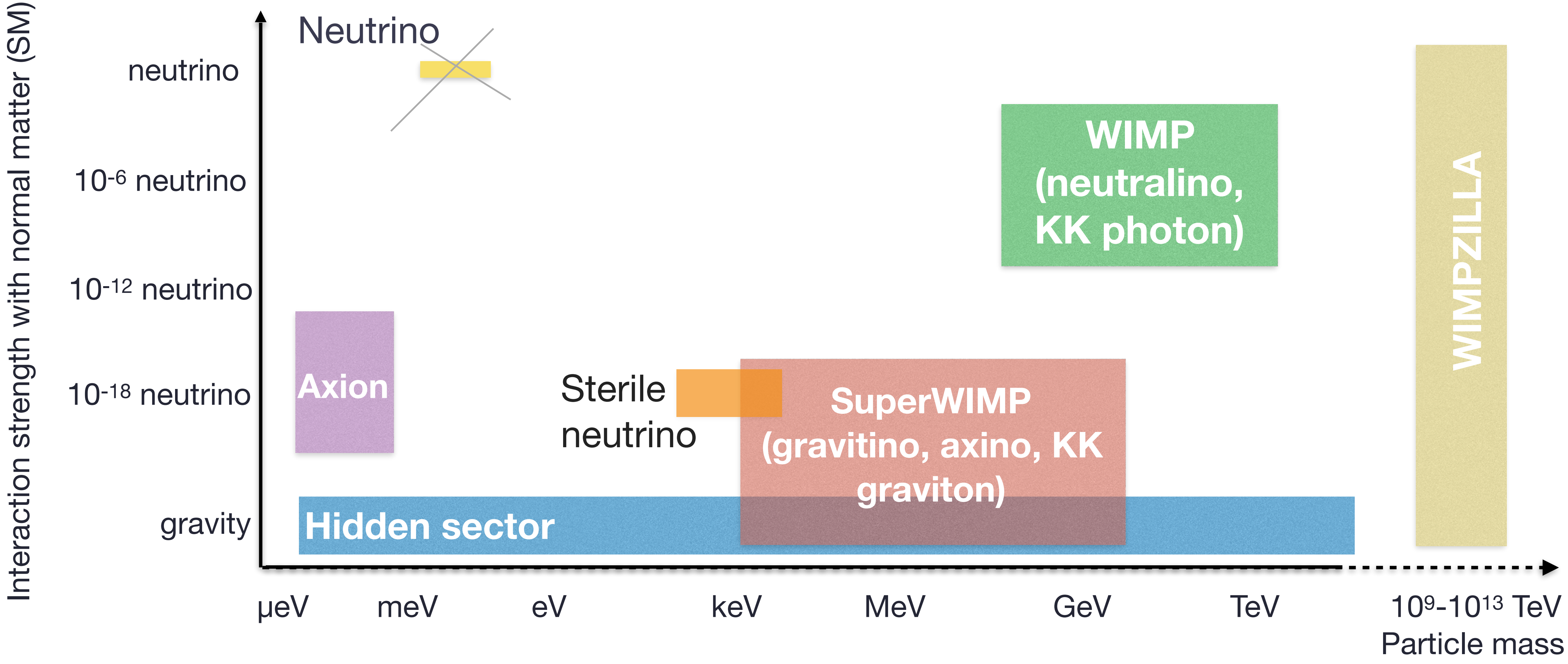
G. F. Knoll, *Radiation Detection and Measurement*, Wiley, (2000).

- *LXe Detectors and Applications*

E. Aprile and T. Doke, Review of Modern Physics (2010).

Dark Matter Candidates

- **Attractive idea: a new particle produced in an early phase of our Universe**
- Predicted masses and cross sections span many orders of magnitude
- Most experiments optimized to search for WIMPs, but also searches for axions, SuperWimps,..



How to detect Weakly Interacting Massive Particles

Direct detection

nuclear recoils from elastic scattering

dependance on A, J; annual modulation, directionality

local density and v-distribution

Indirect detection

high-energy neutrinos, gammas, charged CRs

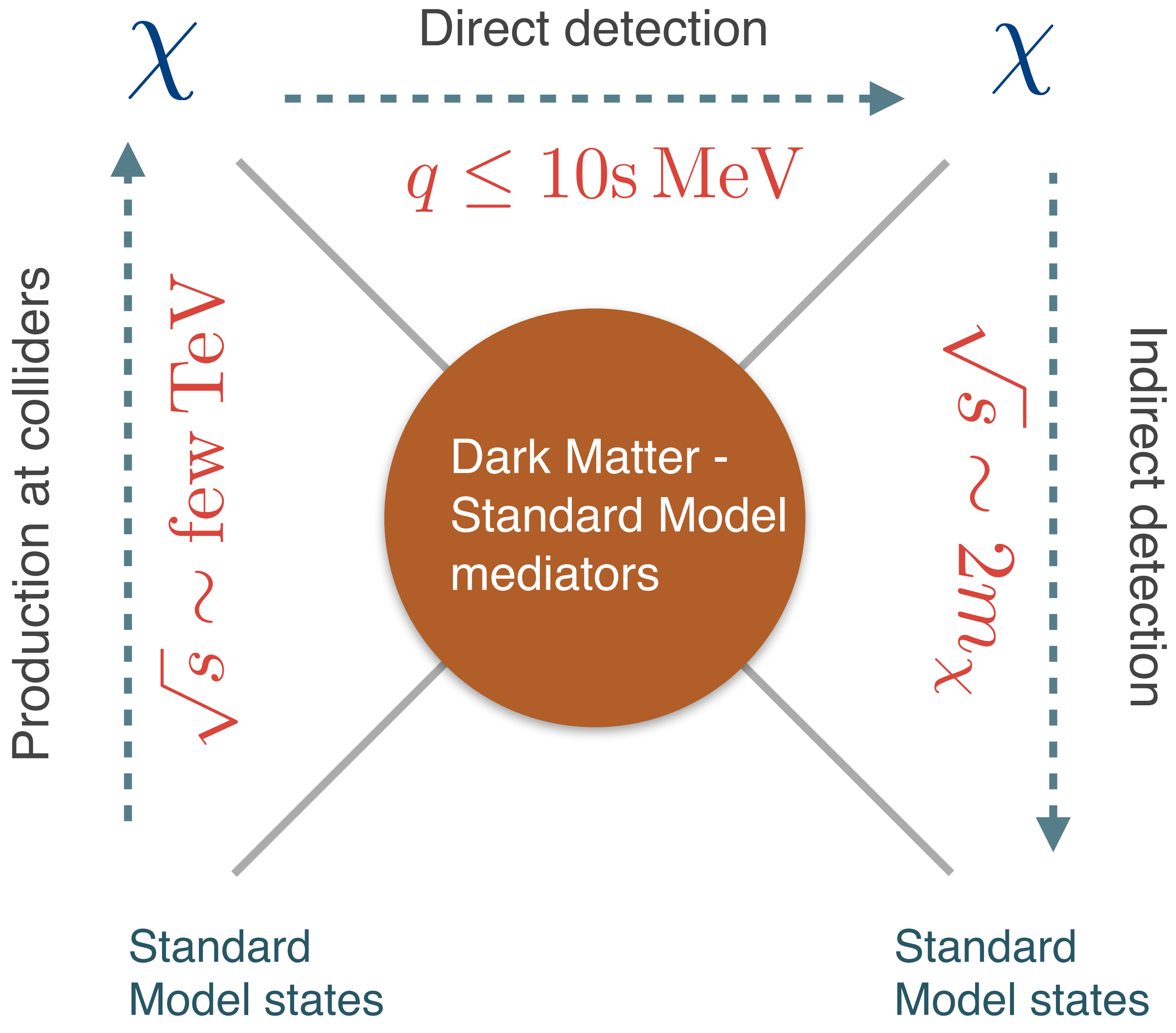
look at over-dense regions in the sky

astrophysics backgrounds difficult

Accelerator searches

missing E_T, mono-‘objects’, etc

can it establish that the new particle is the DM?



χ

Direct detection

χ

$q \leq 10\mathrm{s\,MeV}$

Production at colliders

$\sqrt{s} \sim \mathrm{few\,TeV}$

Dark Matter - Standard Model mediators

$\sqrt{s} \sim 2m_\chi$

Indirect detection

Standard Model states

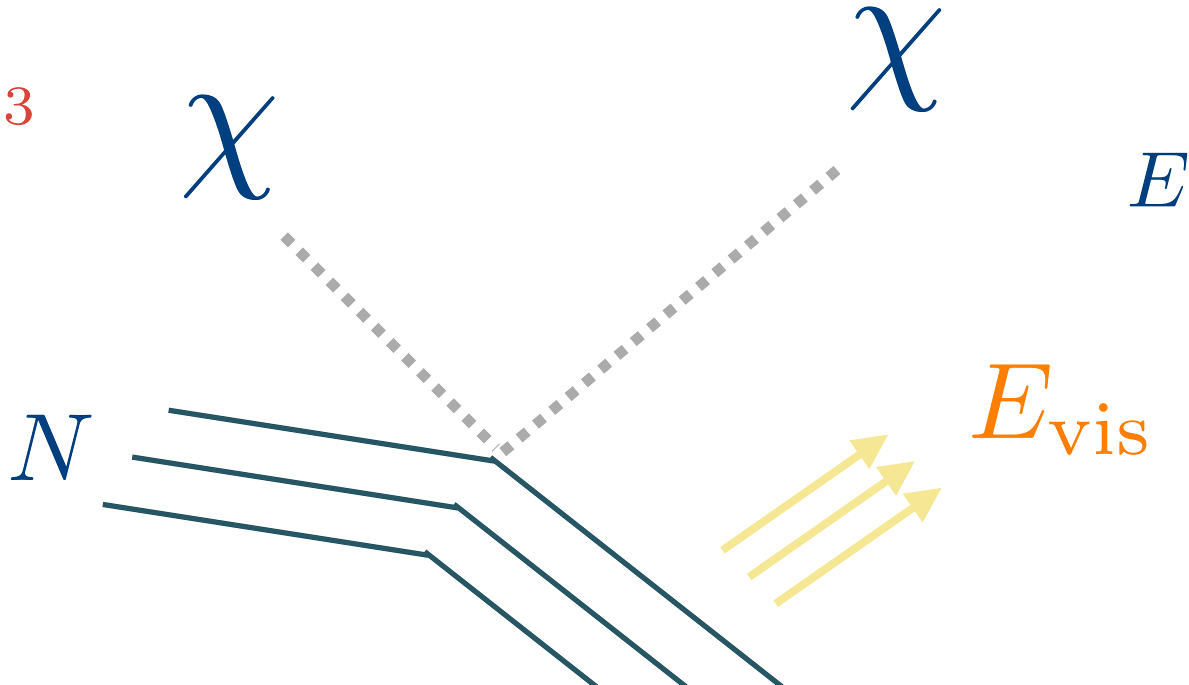
Standard Model states

Direct detection

Collisions of invisibles particles with atomic nuclei

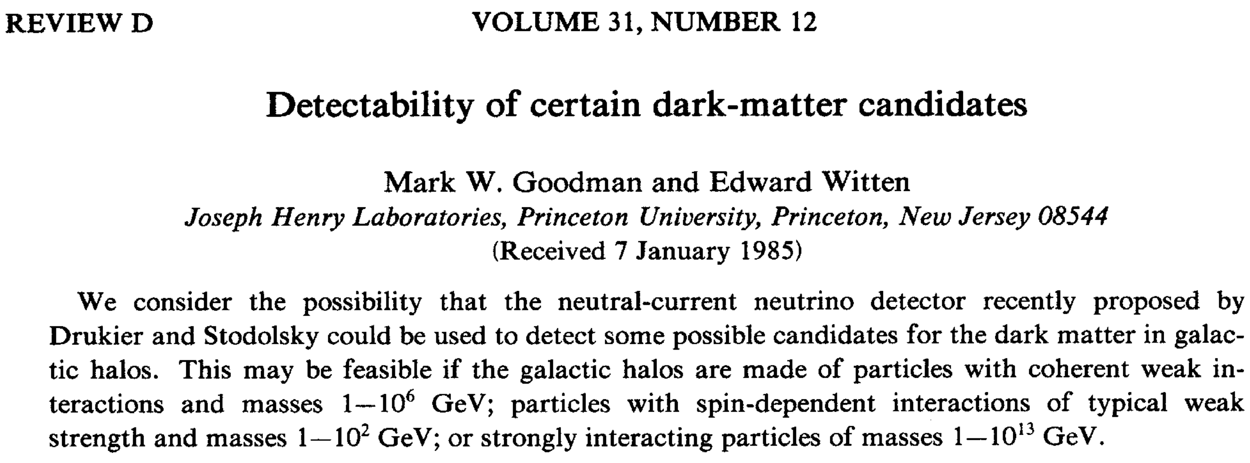
=> E_{vis} (q ~ tens of MeV):

$$v/c \sim 0.75 \times 10^{-3}$$



$$E_R = \frac{q^2}{2m_N} < 30\,\text{keV}$$

Observable: kinetic energy of the recoiling nucleus


REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Expected Rates in a Detector

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}$$

Detector physics

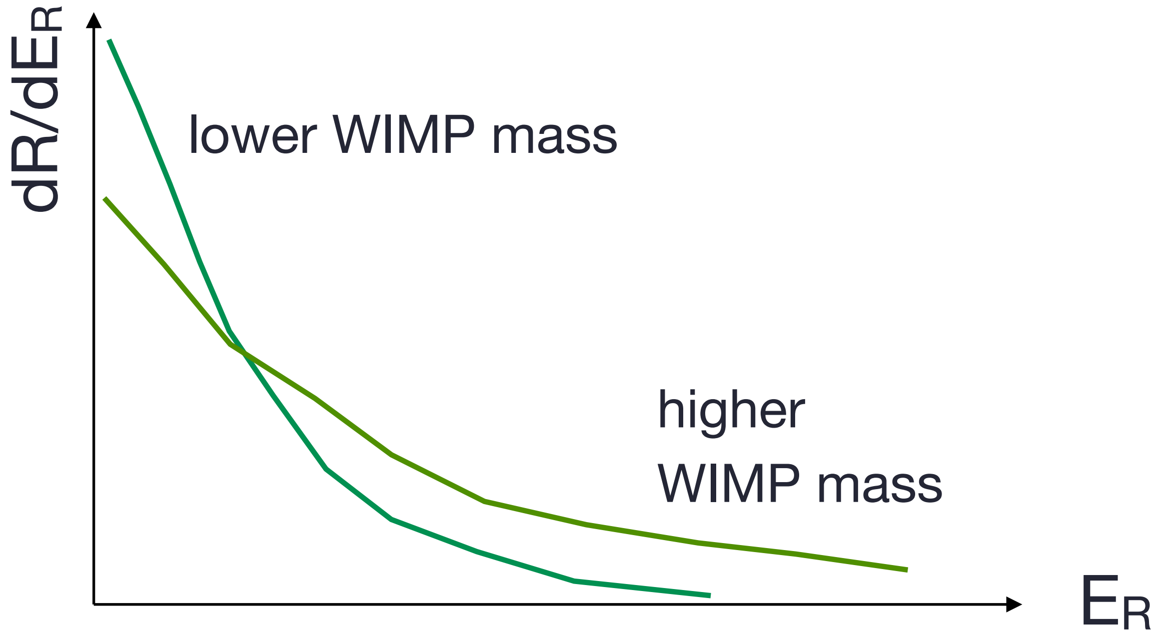
N_N, E_{th}

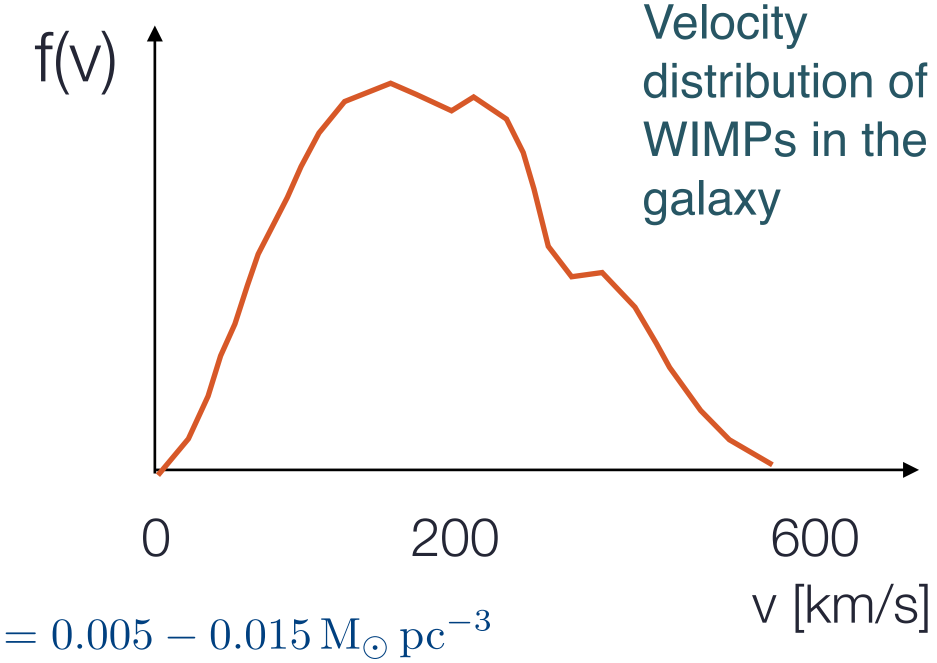
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$





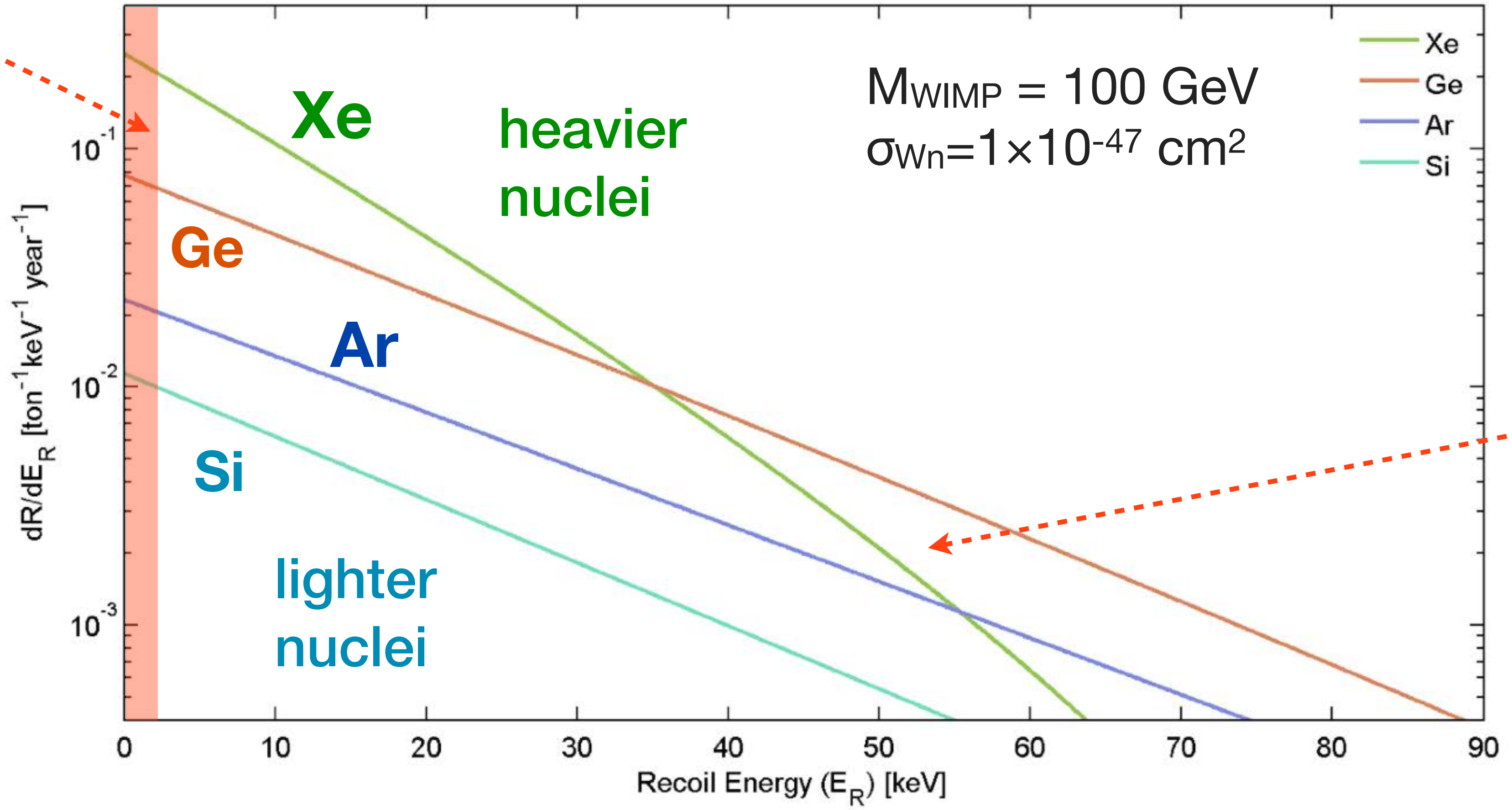
Velocity distribution of WIMPs in the galaxy

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

Expected interaction rates

$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}}\left[\frac{A}{100}\times\frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2}\times\frac{\langle v\rangle}{220\,\text{km}\,\text{s}^{-1}}\times\frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}}\right]$$

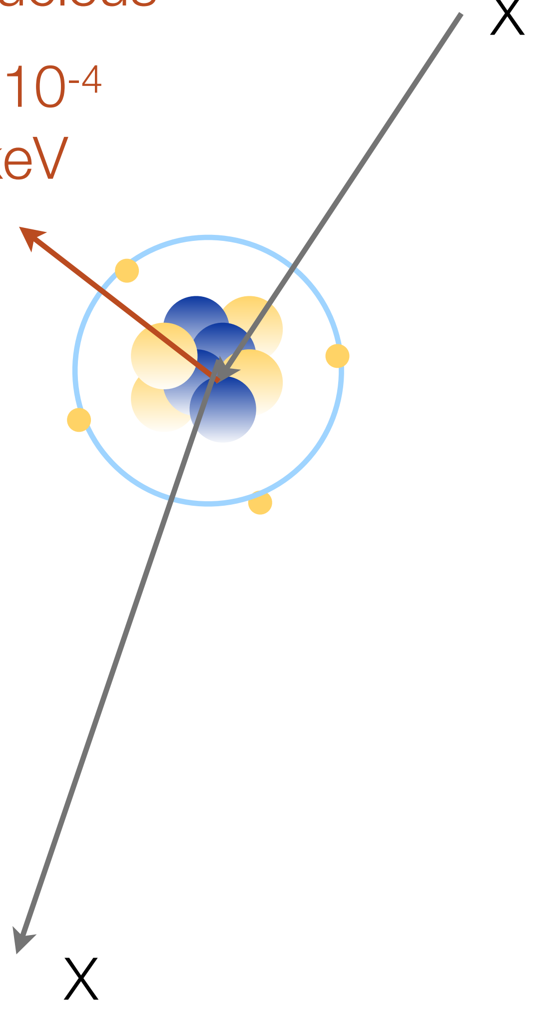
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$



$F^2(E_R)$

Detection of WIMPs: Signal and Backgrounds

Signal (WIMPs)



Recoiling nucleus

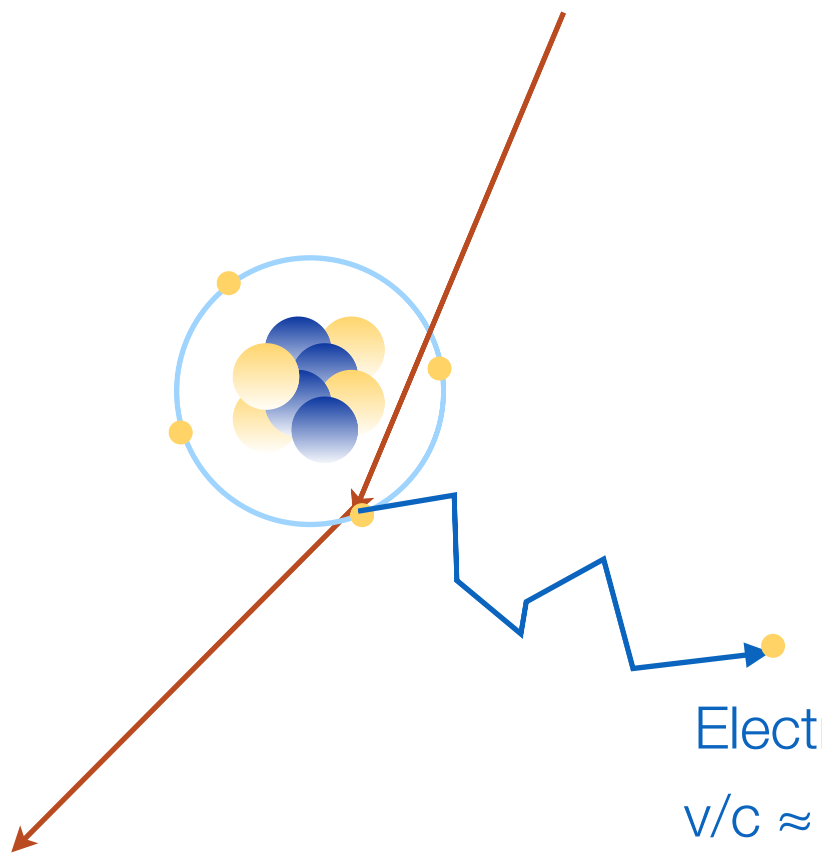
$v/c \approx 7 \text{ x } 10^{-4}$

$E_R \approx 10$ keV

X

X

Background (gamma-, beta-radiation)



gamma

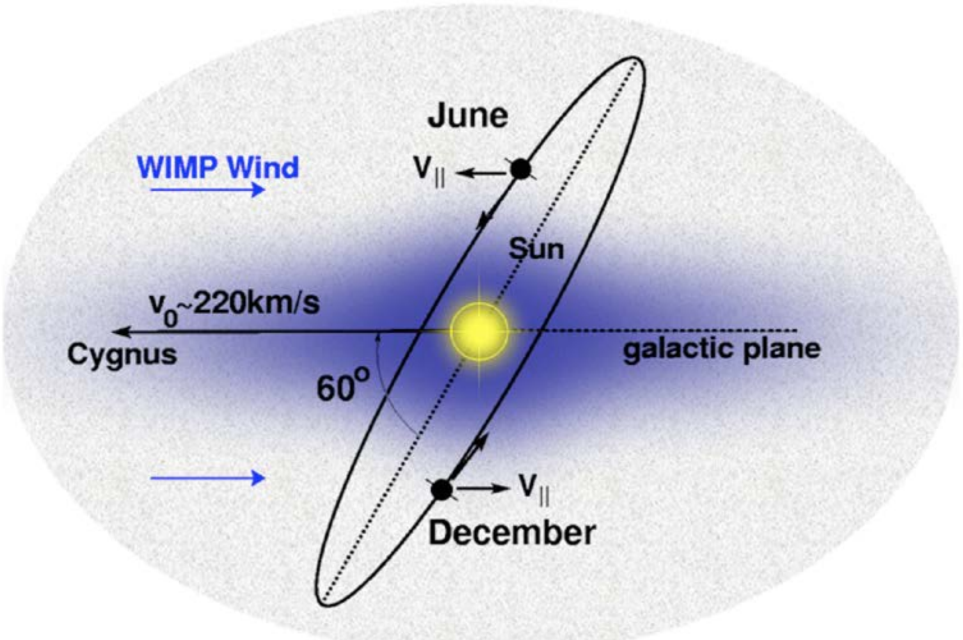
Electron

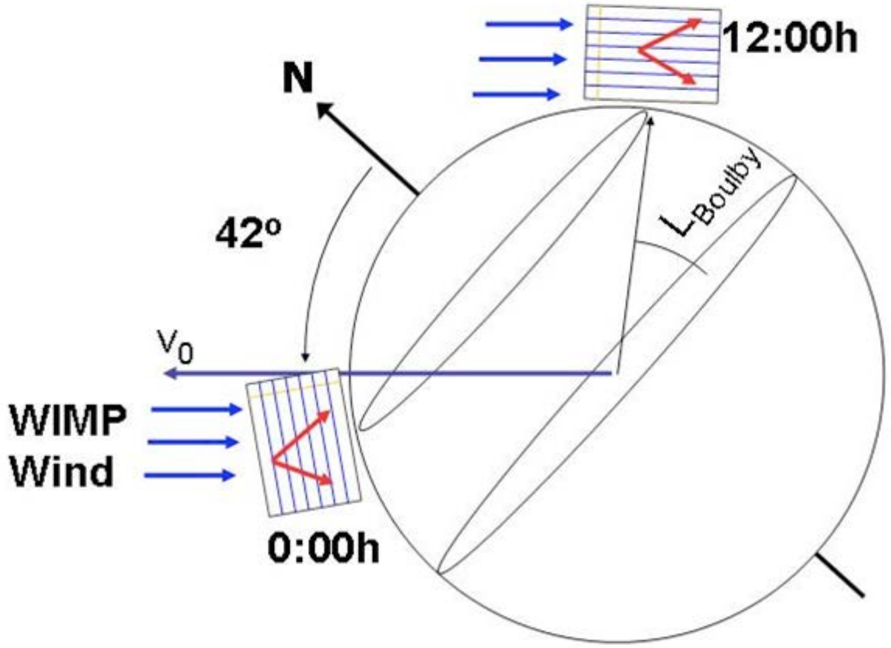
$v/c \approx 0.3$

gamma

WIMP Signatures

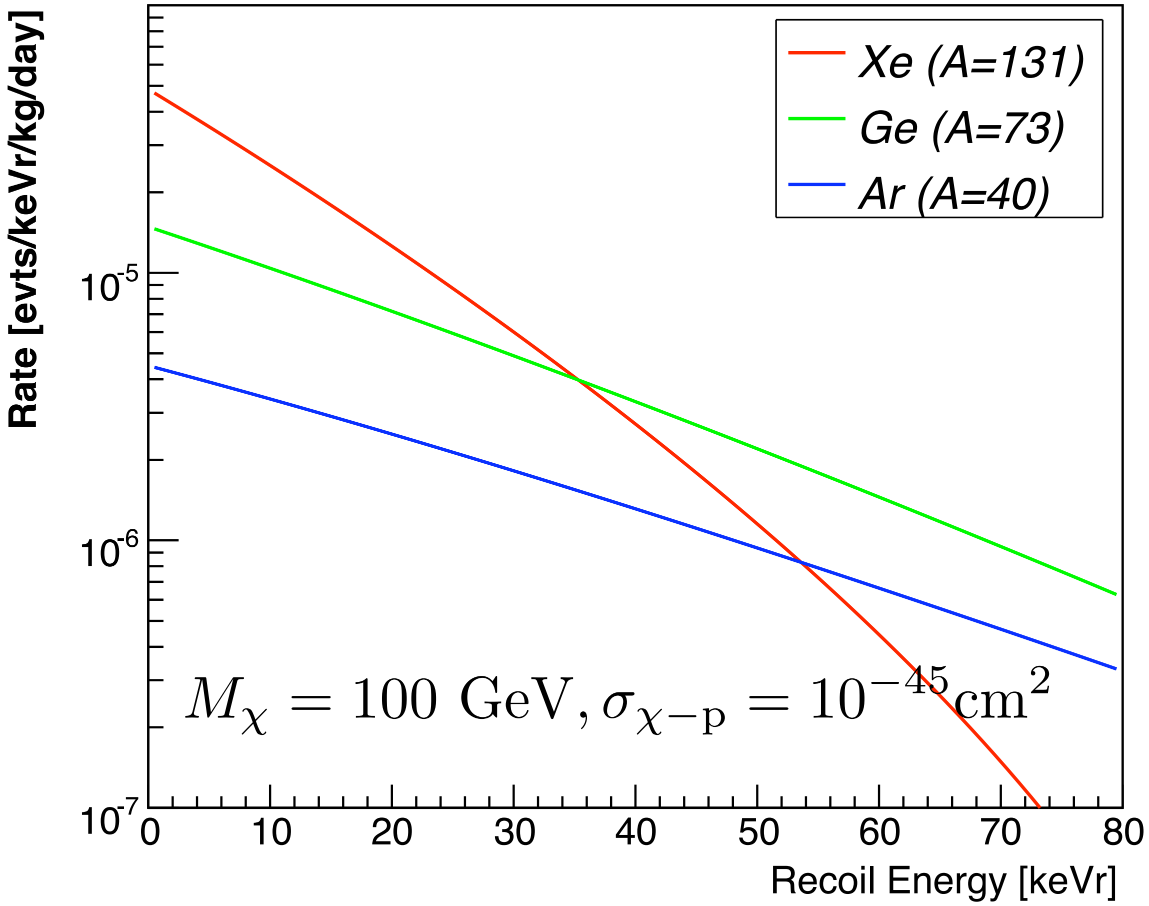
- Nuclear recoils: single scatters with uniform distribution in target volume
- A^2 & $F^2(Q)$ Dependence: we have seen that recoil rate is energy dependent due to kinematics and WIMP velocity distribution. Hence we can test consistency of signal with different targets (SI and SD)
- Annual Modulation: Earth annual rotation around Sun: orbital velocity has a component that is anti-parallel to WIMP wind in summer and parallel to it in winter. So apparent WIMP velocity (and hence the rate) will increase (decrease) with season: rate modulation with a period of 1 year and phase ~2 June; small effect (few %) among other effects which also have seasonal dependence
- Diurnal Direction Modulation: Earth rotation about its axis, oriented at angle w/respect to WIMP "wind" , change the signal direction by 90 degree every 12 hrs. ~30% effect.

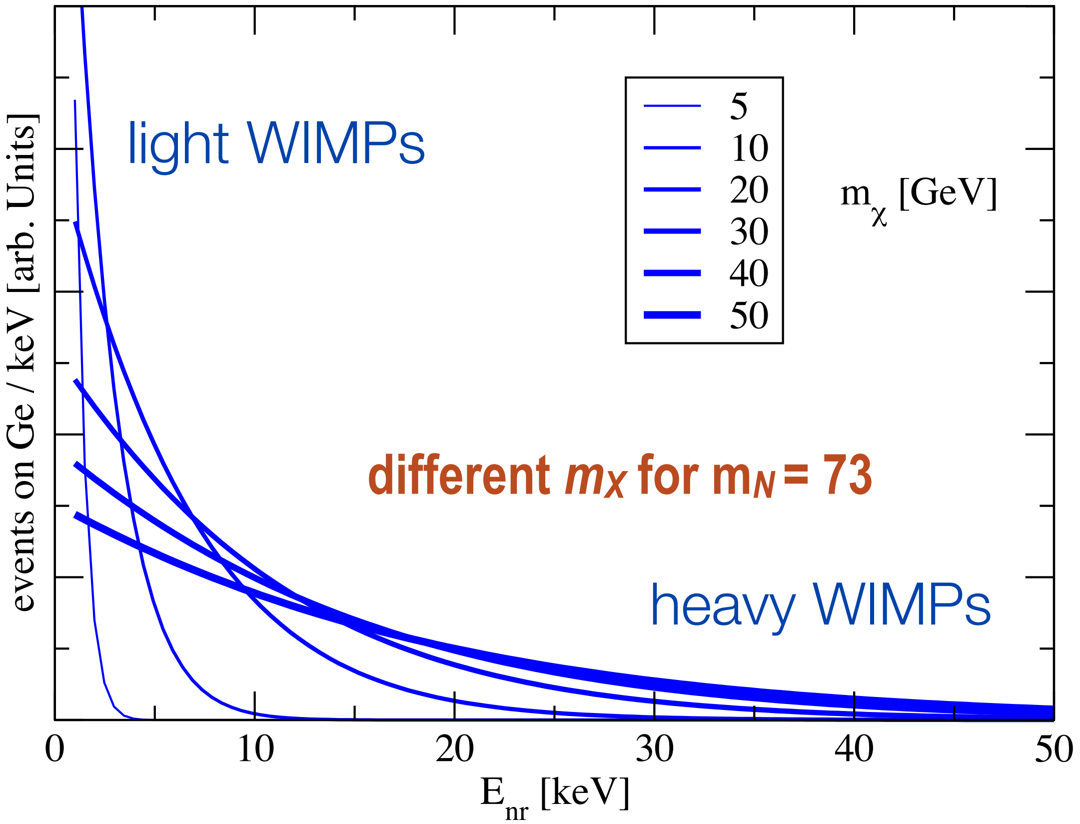




Summary: Signal Characteristics of a WIMP

- A^2 - dependence of rates
- coherence loss (for q~μv ~ $1/r_n$ ~ 200 MeV)
- relative rates, for instance in Ge/Si, Ar/Xe,...
- dependance on WIMP mass
- time dependence of the signal (annual, diurnal)





Backgrounds in Dark Matter Detectors

Electromagnetic radiation

- natural radioactivity in detector and shield materials
- airborne radon (^{222}Rn)
- cosmic activation of materials during storage/transport

Neutrons

- slow/low energy neutrons from materials radioactivity: (α,n) and fission reactions. Can be reduced by shielding
- fast/energetic neutrons from spallation of nuclei in materials by cosmic muons. Cannot be shielded. Detectors must operate deep underground to reduce muon flux

Alpha particles

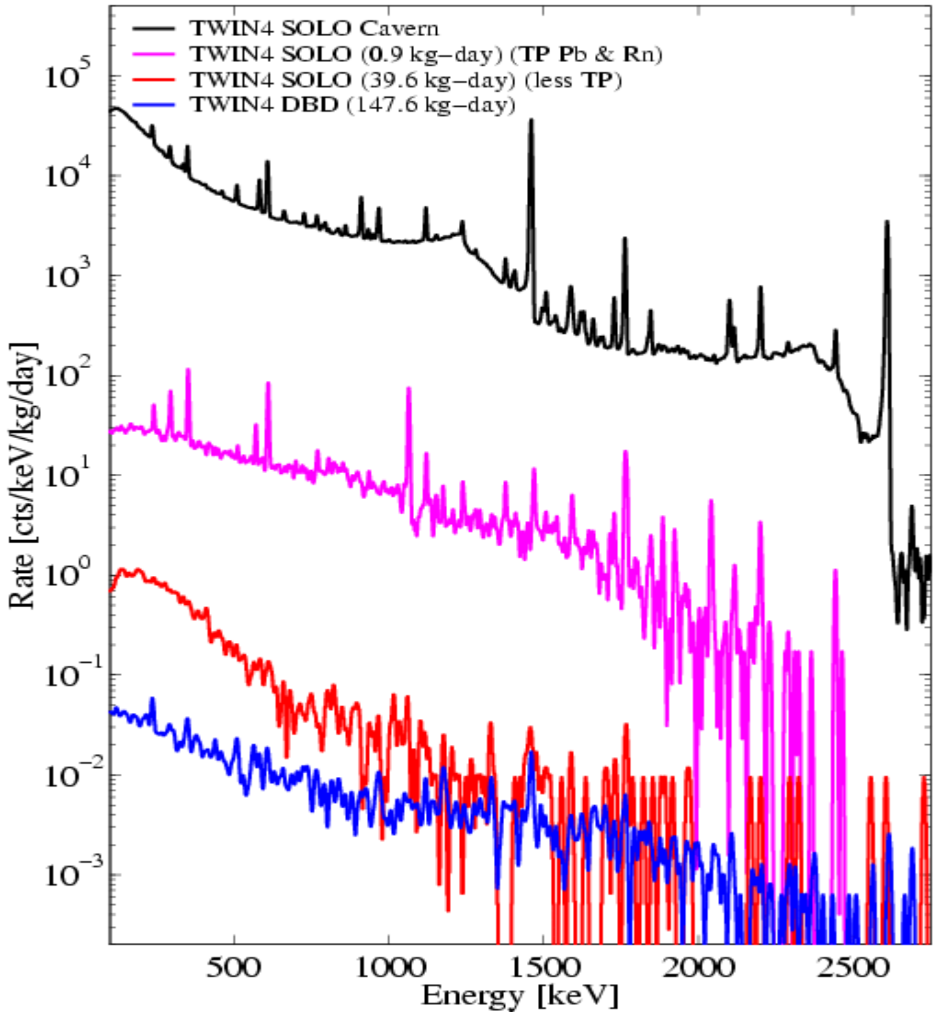
- ^{210}Pb decays at the detector surfaces
- nuclear recoils from the Rn daughters

Neutrinos

- scattering on electrons give ERs which can “leak” into ROI. Rate is however still very low
- coherent neutrino-nucleus scattering give nuclear recoils-undistinguishable from WIMPs-the ultimate background for direct searches. Of course exciting signal per se

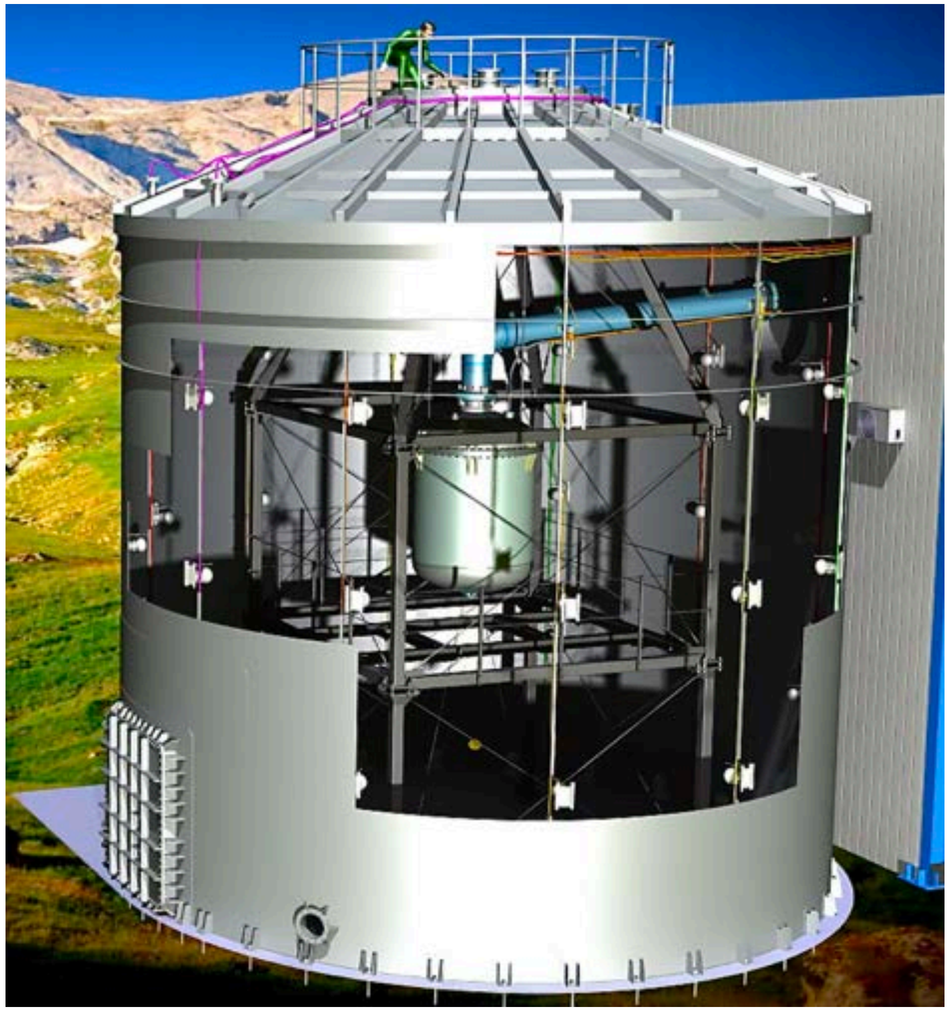
Backgrounds in Dark Matter Detectors

- **External, natural radioactivity:** ^{238}U, ^{238}Th, ^{40}K decays in rock and concrete walls of the laboratory => mostly gammas and neutrons from (α,n) and fission reactions
- Radon decays in air
  - ➡ passive shields: Pb against the gammas, polyethylene/water against neutrons
  - ➡ active shields: large water Cherenkov detectors or scintillators for gammas and neutrons



Ge detector underground, no shield

Ge detector underground, Pb shield and purge for Rn



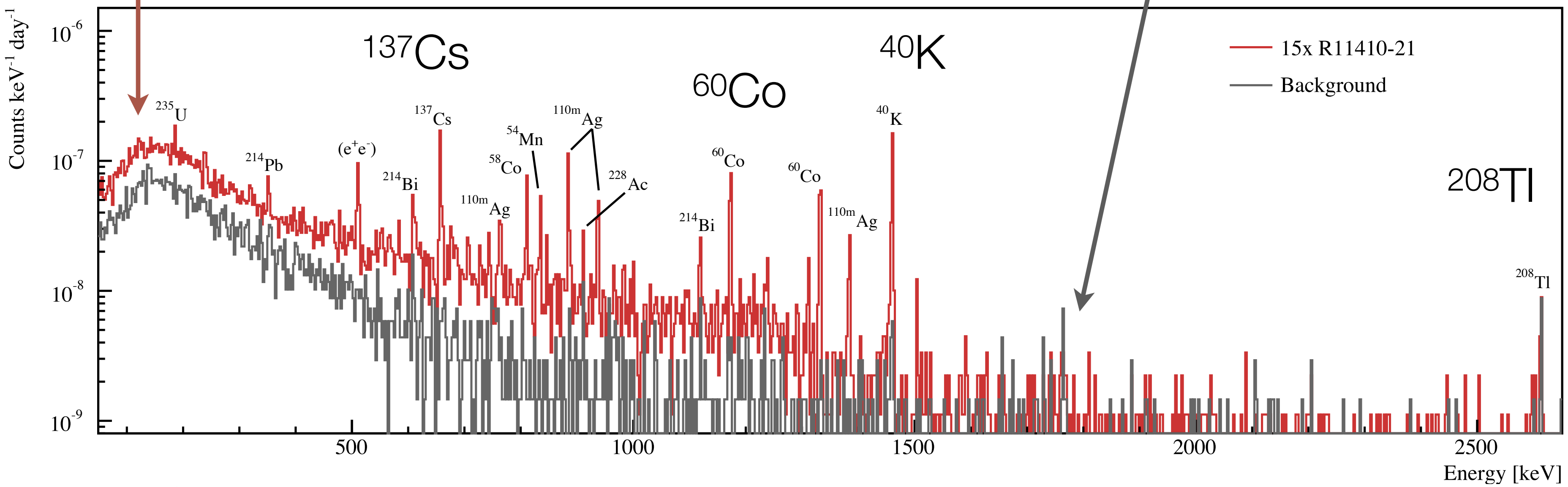
Backgrounds in Dark Matter Detectors

- **Internal radioactivity:**
- ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector materials, target medium and shields
- Ultra-pure Ge spectrometers (as well as other methods) are used to screen the materials before using them in a detector, down to parts-per-billion (ppb) (or lower) levels

PMT sample

^{226}Ra/^{228}Th:
~1 mBq/PMT

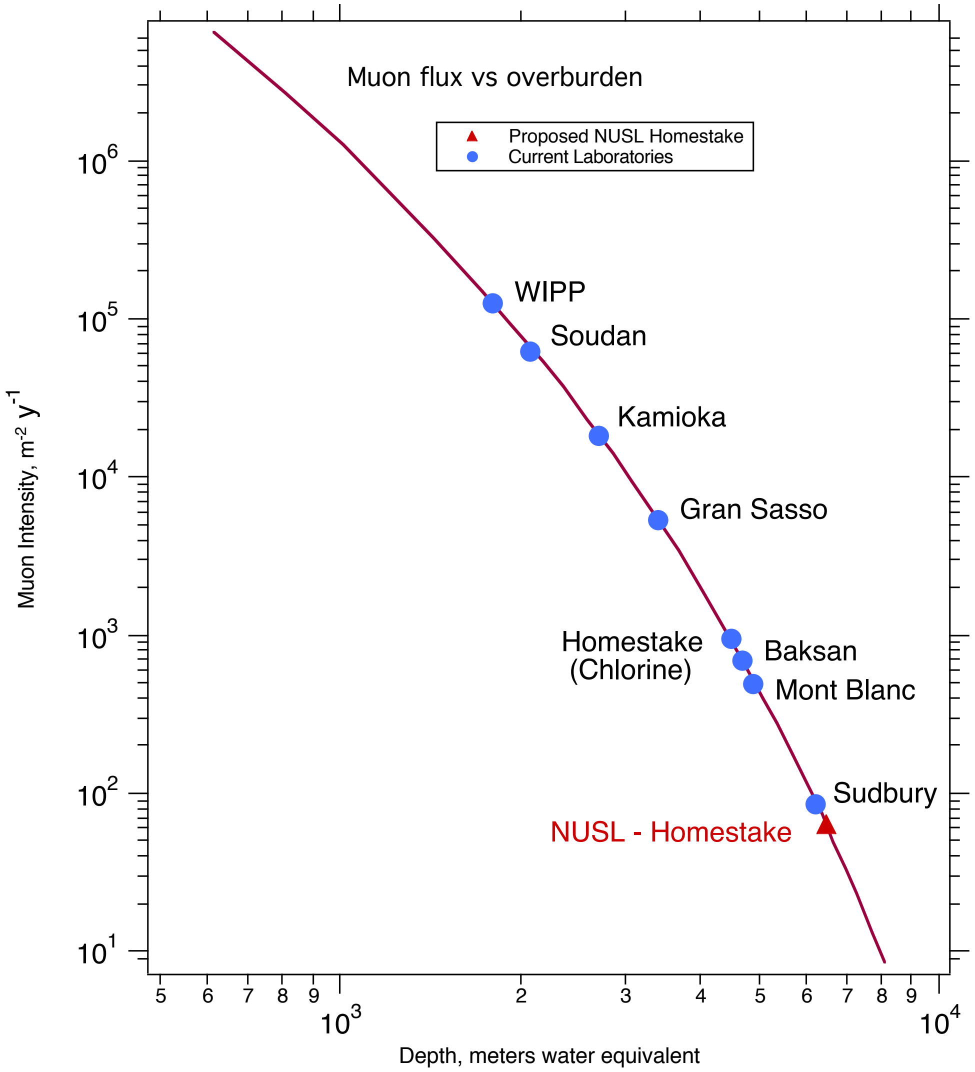
HPGe detector
background



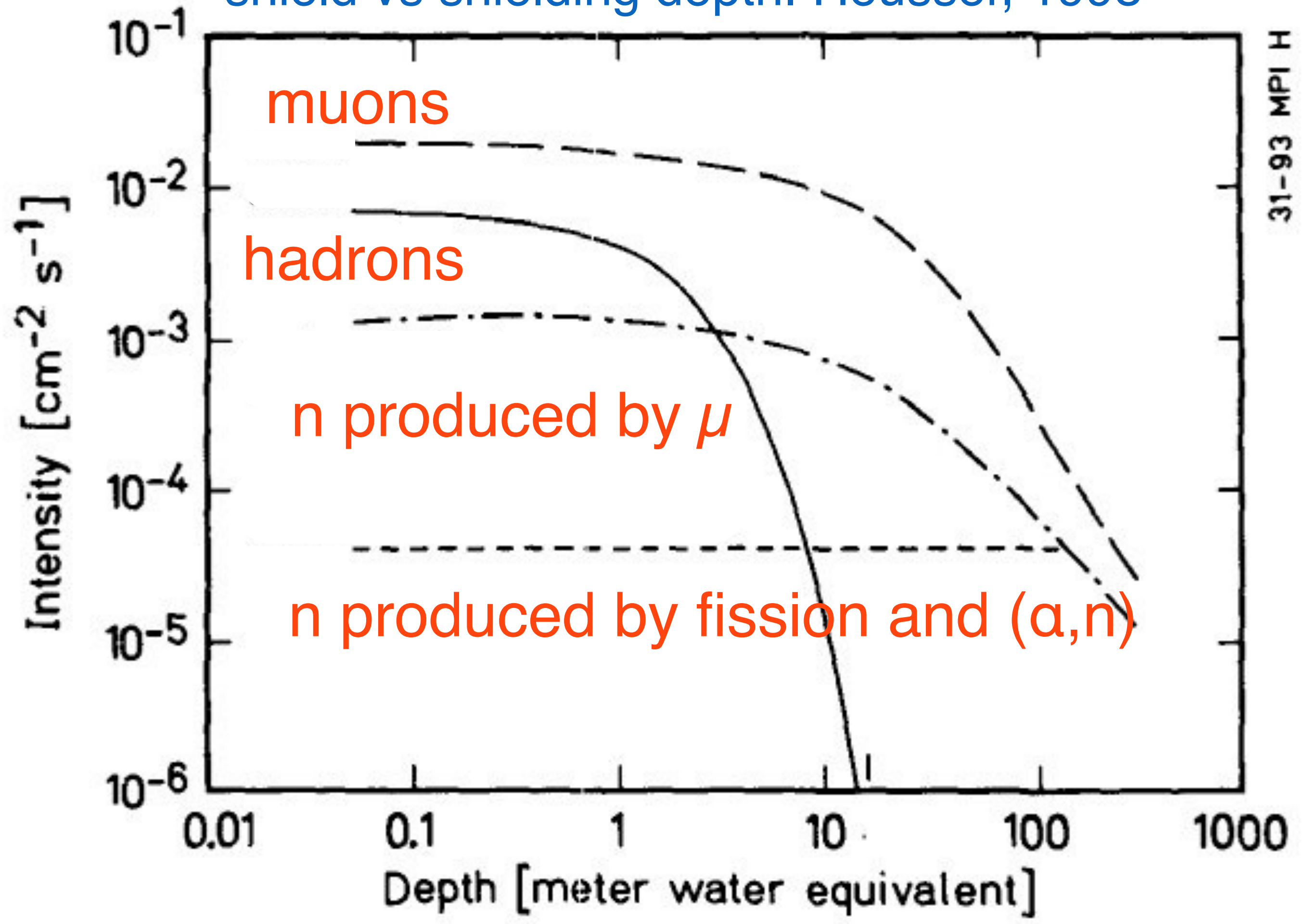
XENON collaboration, arXiv:1503.07698v1

Backgrounds in Dark Matter Detectors

- **Cosmic rays and secondary/tertiary particles:** **deep underground** laboratories
- **Hadronic component (n, p)**: reduced by few meter water equivalent (m w. e.)
- **Most problematic:** muons and muon induced neutrons. MeV neutrons can mimic WIMPs



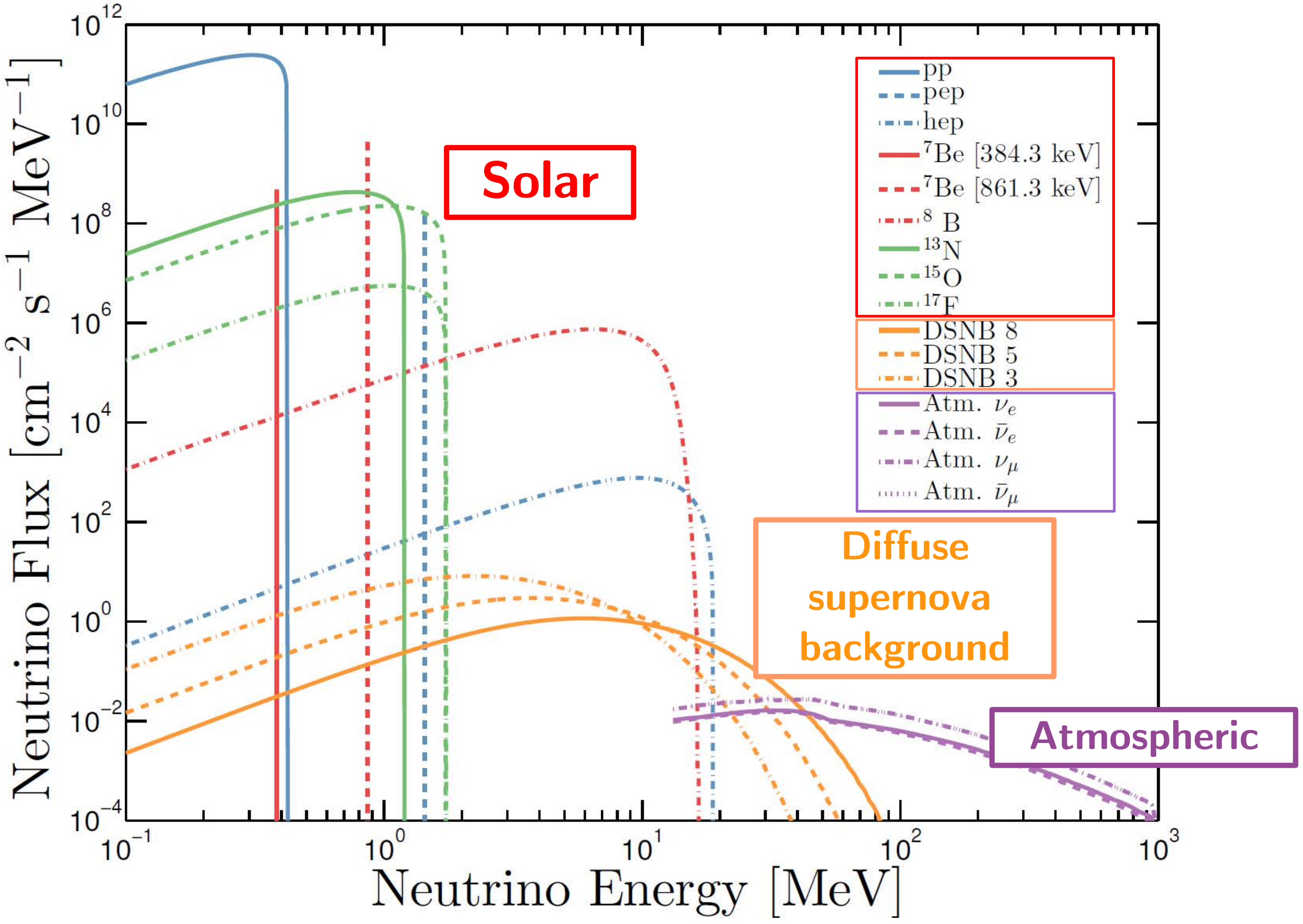
Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Heusser, 1995

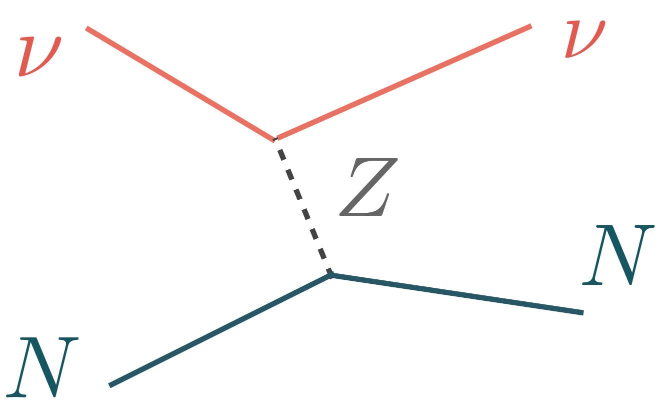


Neutrino backgrounds

- Neutrino-electron and neutrino-nucleus scatters

$$\nu + e^- \longrightarrow \nu + e^-$$





$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

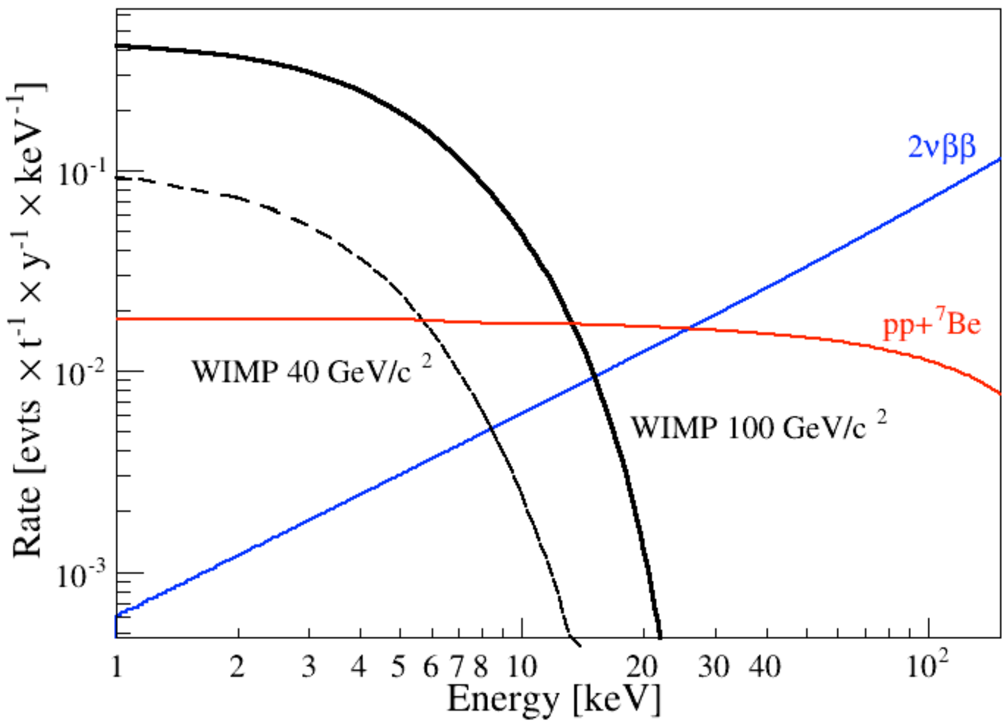
$$Q_\omega = N - (1 - 4\sin^2\theta_\omega)Z$$

F. Ruppin et al., 1408.3581, PRD 90, 2015

Neutrino-electron scatters

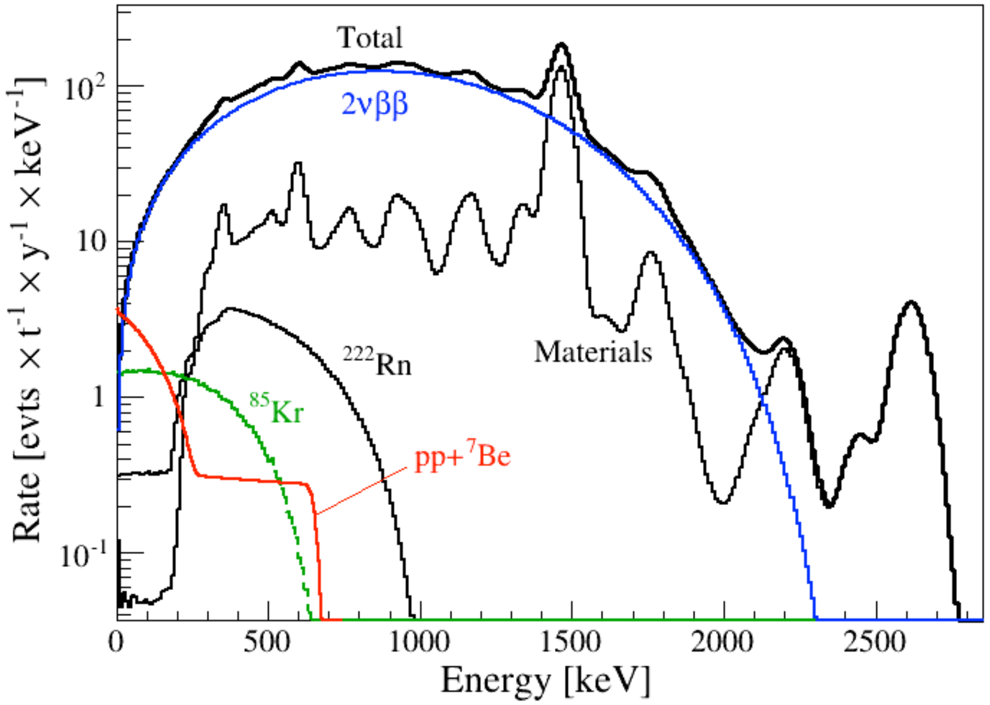
- Will generate electron recoils, uniformly distributed in the detector
- In spite of various background discrimination techniques, such events can potentially “leak” into the signal region
- Example (in liquid xenon) for spectra expected from WIMPs and solar neutrinos

After discrimination (99.5%)



$$\nu + e^- \rightarrow \nu + e^-$$

Before discrimination

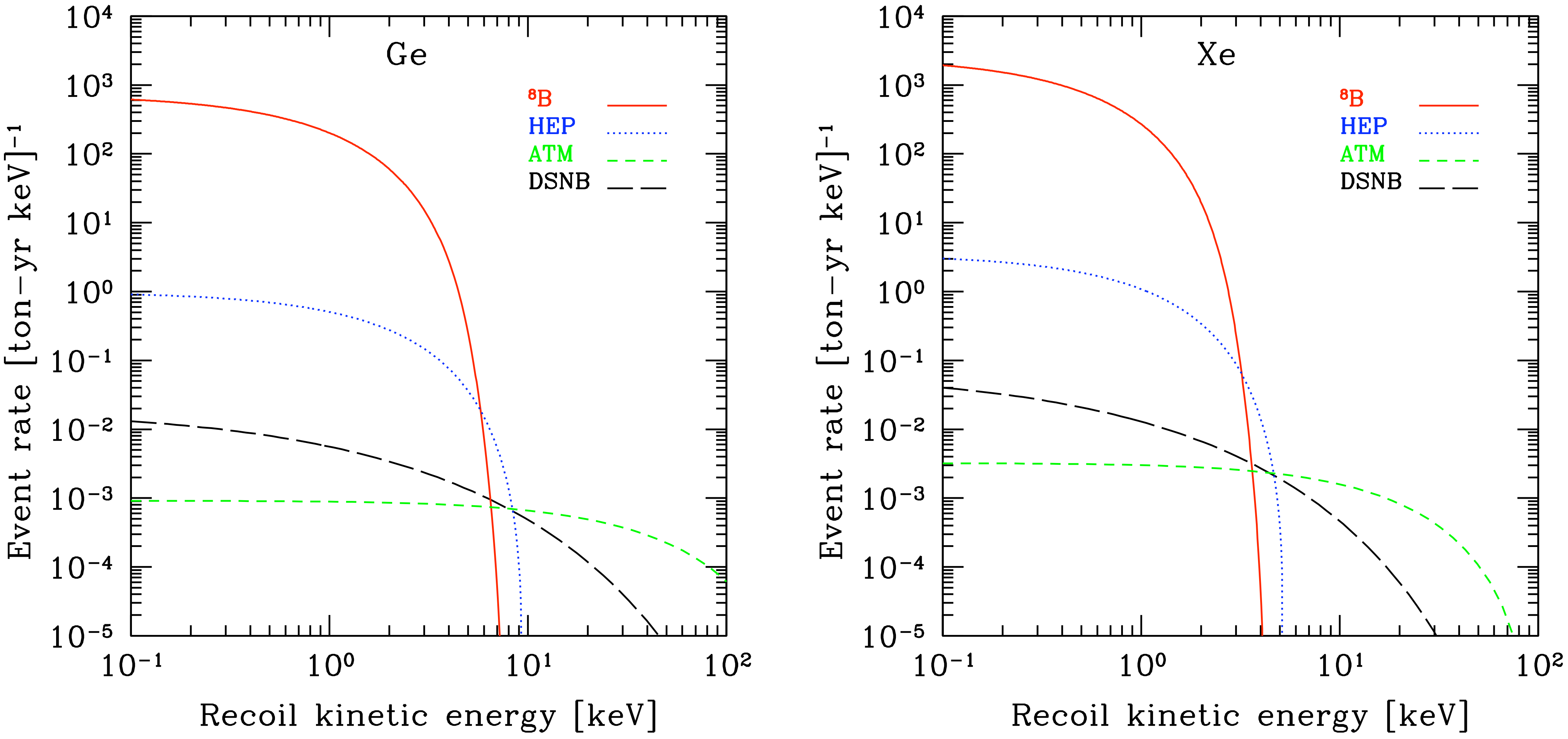


LB et al., JCAP01 (2014) 044

Neutrino-nucleus scatters

- ^{8}B neutrinos dominate: serious background if the WIMP-nucleon cross section < 10^{-10} pb
- But: energy of nuclear recoils: <4 keV (heavy targets, Xe, I etc) to <30 keV in light targets (F, C)
- Non-^{8}B neutrinos: impact on WIMP detectors at much lower WIMP-nucleon cross sections

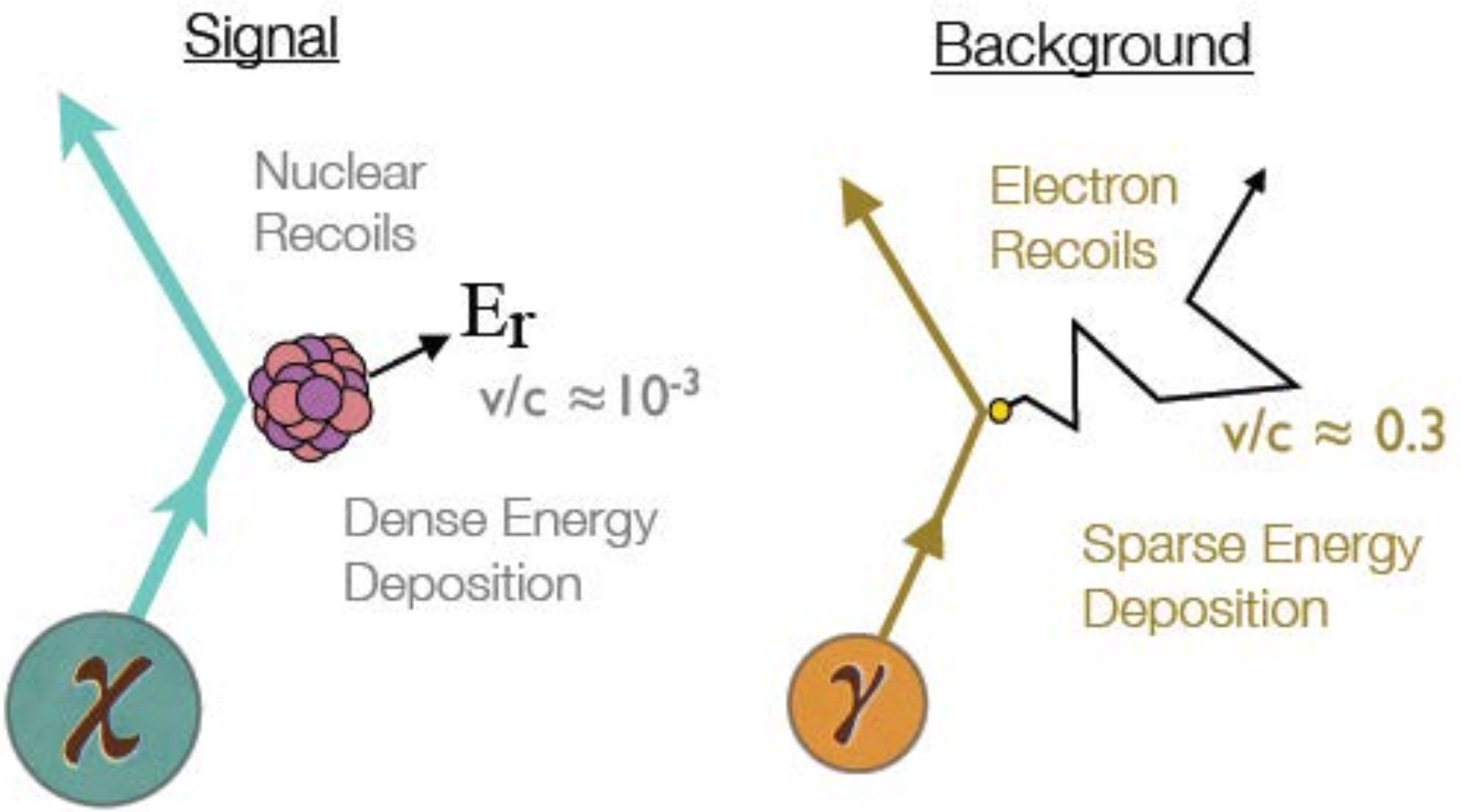
L. E. Strigari, New J. Phys. 11 (2009) 105011



Germanium

Xenon

Discriminating Signal from Background



- given that background from radioactivity and environment cannot be eliminated completely, despite effort in materials selection, shielding and underground location, detectors must have effective S/N discrimination
- scattering from an atomic nucleus leads to different response in most materials than scattering from an electron
- Detectors which can measure this difference can effectively reduce the dominant EM background
- Neutrons however scatter also off nuclei but unlike WIMPs they scatter in multiple sites hence can be recognized with position sensitive detectors large enough compared to the typical mean free path of order 10 cm

Detector strategies

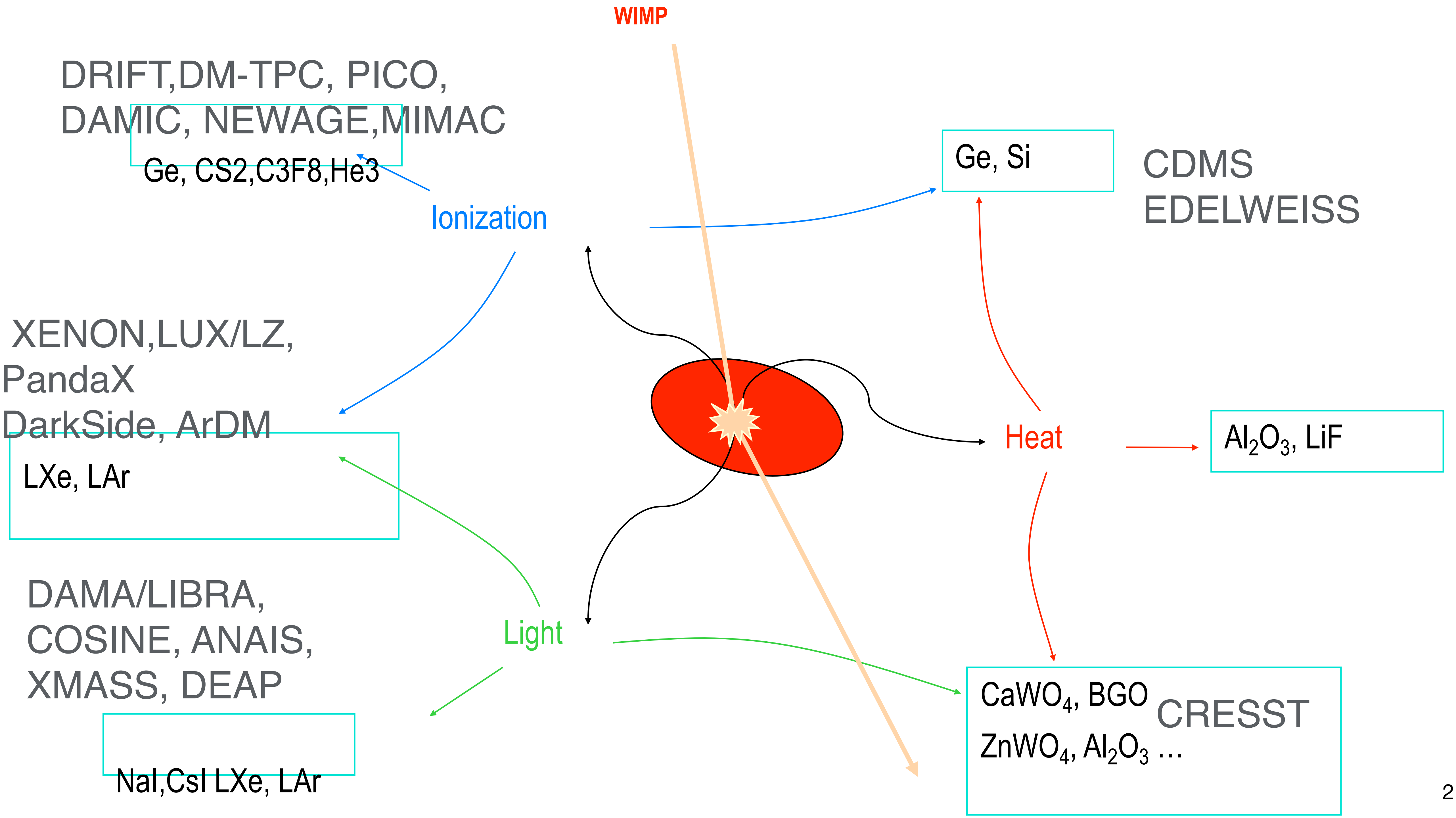
Aggressively reduce the absolute background & pulse shape analysis	Background reduction by pulse shape analysis and/or self-shielding	Background rejection based on simultaneous detection of two signals	Other detector strategies
State of the art: (primary goal is 0νββ decay): Past experiments: Heidelberg-Moscow HDMS IGEX Current and near-future projects: GERDA MAJORANA	Large mass, simple detectors: NaI (DAMA/LIBRA, COSINE, ANAIS, SABRE) Large liquid noble gas detectors: XMASS, DEAP-3600	**Charge/phonon** (CDMS, EDELWEISS, SuperCDMS) **Light/phonon** (CRESST) **Charge/light** (XENON, LUX-LZ, PandaX DarkSide)	Large bubble chambers - insensitive to electromagnetic background: COUPP, PICASSO, SIMPLE, PICO Low-pressure gas detectors, sensitive to the direction of the nuclear recoil: DRIFT, DMTPC, NEWAGE, MIMAC,DAMIC

In addition:

→ reject multiple scattered events and events close to detector boundaries

→ look for an annual and a diurnal modulation in the event rate

Direct Detection Experiments



WIMP

DRIFT,DM-TPC, PICO,
DAMIC, NEWAGE,MIMAC

Ge, CS2,C3F8,He3

Ionization

Ge, Si

CDMS
EDELWEISS

XENON,LUX/LZ,
PandaX
DarkSide, ArDM

LXe, LAr

Heat

Al_2O_3, LiF

DAMA/LIBRA,
COSINE, ANAIS,
XMASS, DEAP

Light

NaI,CsI LXe, LAr

$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 …

CRESST

Worldwide WIMP Searches

~50% use Noble Liquids

SNOLab
DEAPCLEAN
PiCO
DAMIC

Boulby
DRIFT

YangYang
KIMS,COSINE

Kamioka
XMASS
Newage

Homestake
LUX-LZ

Modane
EDELWEISS
MIMAC

Soudan
SuperCDMS
CoGeNT

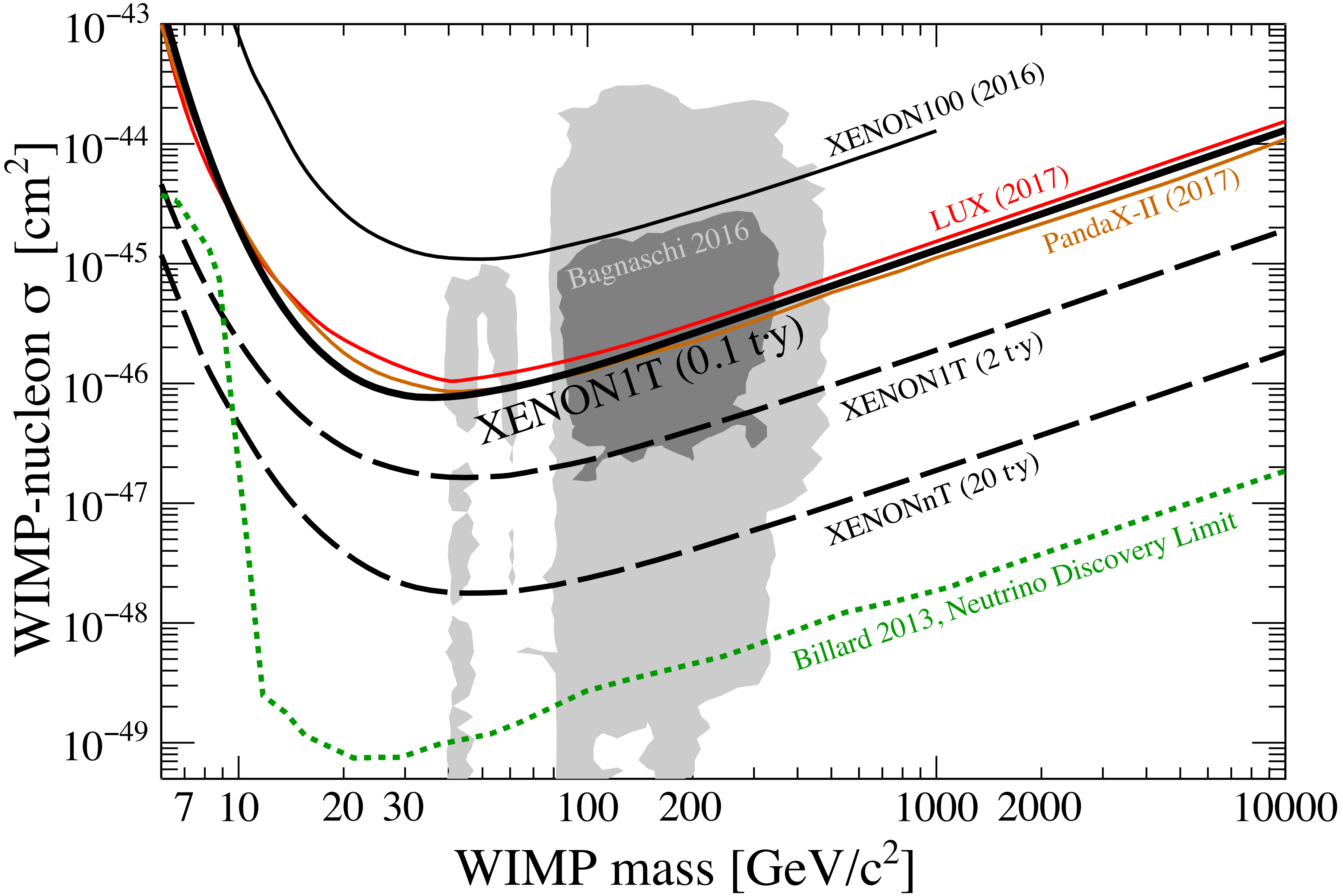
Canfranc
ArDM
Rosebud
ANAIS

Gran Sasso
XENON
CRESST
DAMA/LIBRA
DarkSide

Jinping
Panda-X
CDEX

South Pole
DM Ice

the state-of-the-art: driven by LXeTPC experiments



$$\sigma_{\text{min}} = 7.7 \times 10^{-47}\,\text{cm}^2 \text{ at } 35\,\text{GeV}/\text{c}^2$$

The impressive evolution of LXeTPCs as WIMP detectors

	Fiducial mass [kg]	Low-energy ER background [events / (tonne keV day)]
XENON10	5	1000
XENON100	34	5.3
LUX	118	2.6
PandaX	306	0.8
XENON1T	1000-1300	0.2

Cryogenic Noble Liquids: some properties

- Suitable materials for detection of ionizing tracks:
  - ➡ dense, homogeneous target and also detectors (scintillation and ionization)
  - ➡ do not attach electrons; inert not flammable, very good dielectrics
  - ➡ commercially easy to obtain and purify
- Large detector masses are feasible (at modest costs compared to semiconductors)
- Self-shielding + good position resolution in time projection chamber mode

Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e^-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.4	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165	3.06	64	46

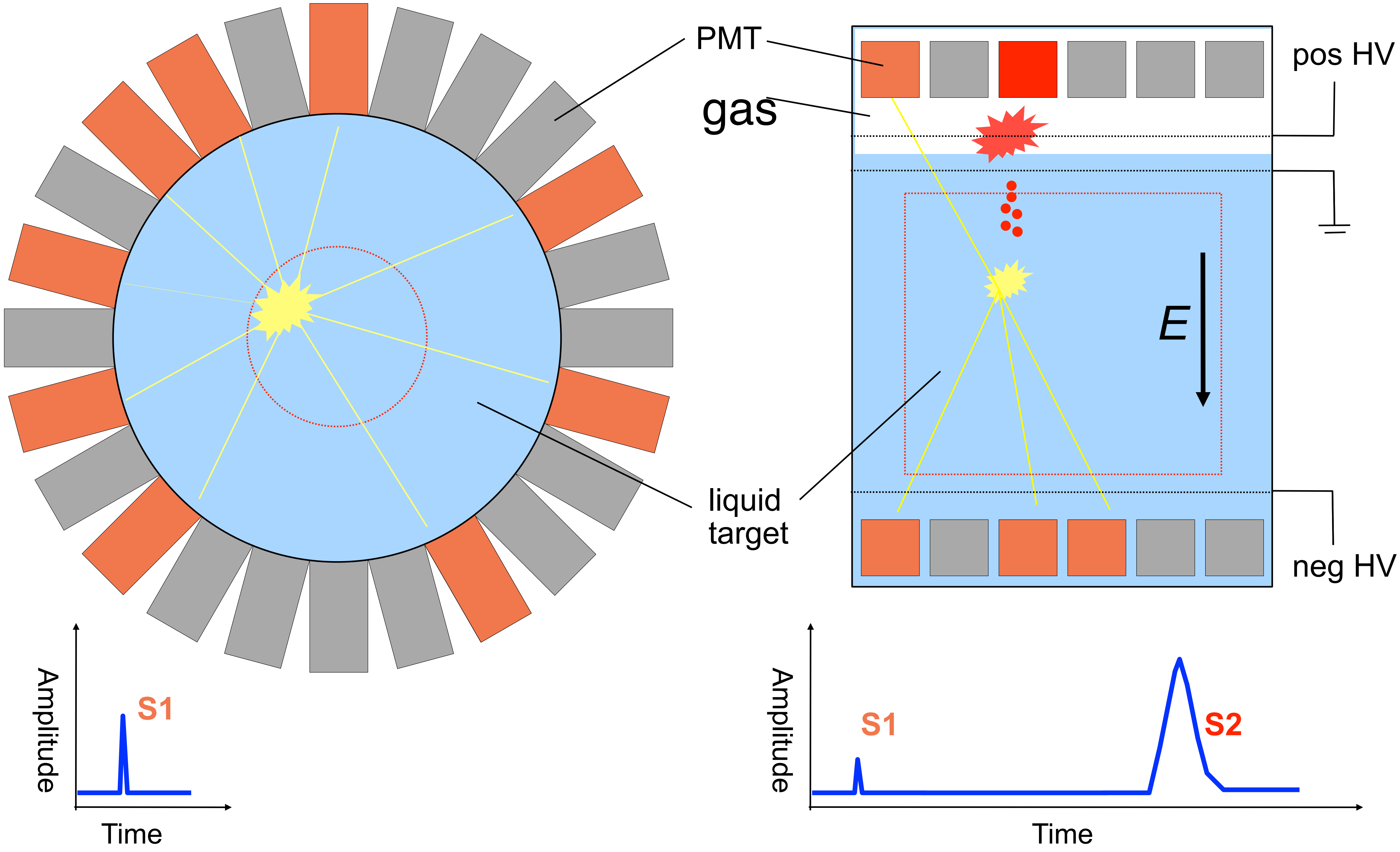
Why Noble Liquids for Dark Matter Detection

- ✦ *scalability : relatively inexpensive for large scale (multi-ton) detectors*
- ✦ *easy cryogenics : 170 K (LXe), 87 K (LAr)*
- ✦ *self-shielding : very effective (especially for LXe case) for external background reduction*
- ✦ *low threshold : high scintillation yield (similar to NaI(Tl) but much faster timing)*
- ✦ *n-recoil discrimination: by charge-to-light ratio and pulse shape discrimination*
- ✦ *Xe nucleus (A~131) : good for SI plus SD sensitivity (~50% odd isotopes)*
- ✦ *For Xe: no long-lived radioactive isotopes (Kr-85 can be removed)*
- ✦ *For Ar: radioactive Ar-39 is an issue but there are ways to overcome it*

Noble Liquid Detector Concepts

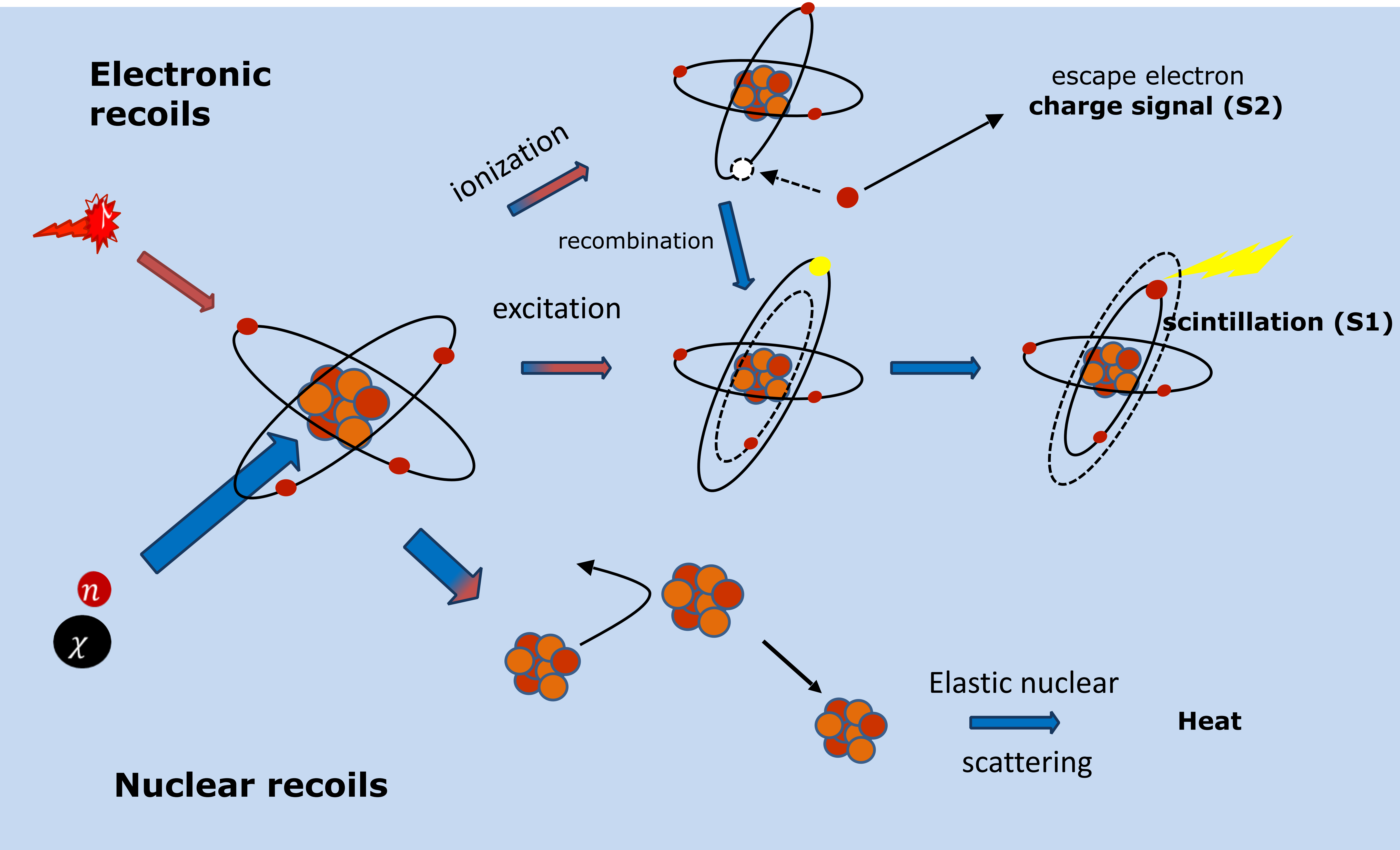
Single Phase Detector

Dual Phase Detector



Signals in Noble Liquids

- Detect either light only or simultaneously light and charge signals produced by a particle interaction in the sensitive liquid target



Ionization in Noble Liquids

- The energy loss of an incident particle in noble liquids is shared between excitation, ionization and sub-excitation electrons liberated in the ionization process
- The average energy loss in ionization is slightly larger than the ionization potential or the gap energy, because it includes multiple ionization processes
- as a result, the ratio of the W-value (= average energy required to produce an electron-ion pair) to the ionization potential or gap energy = 1.6 - 1.7

Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

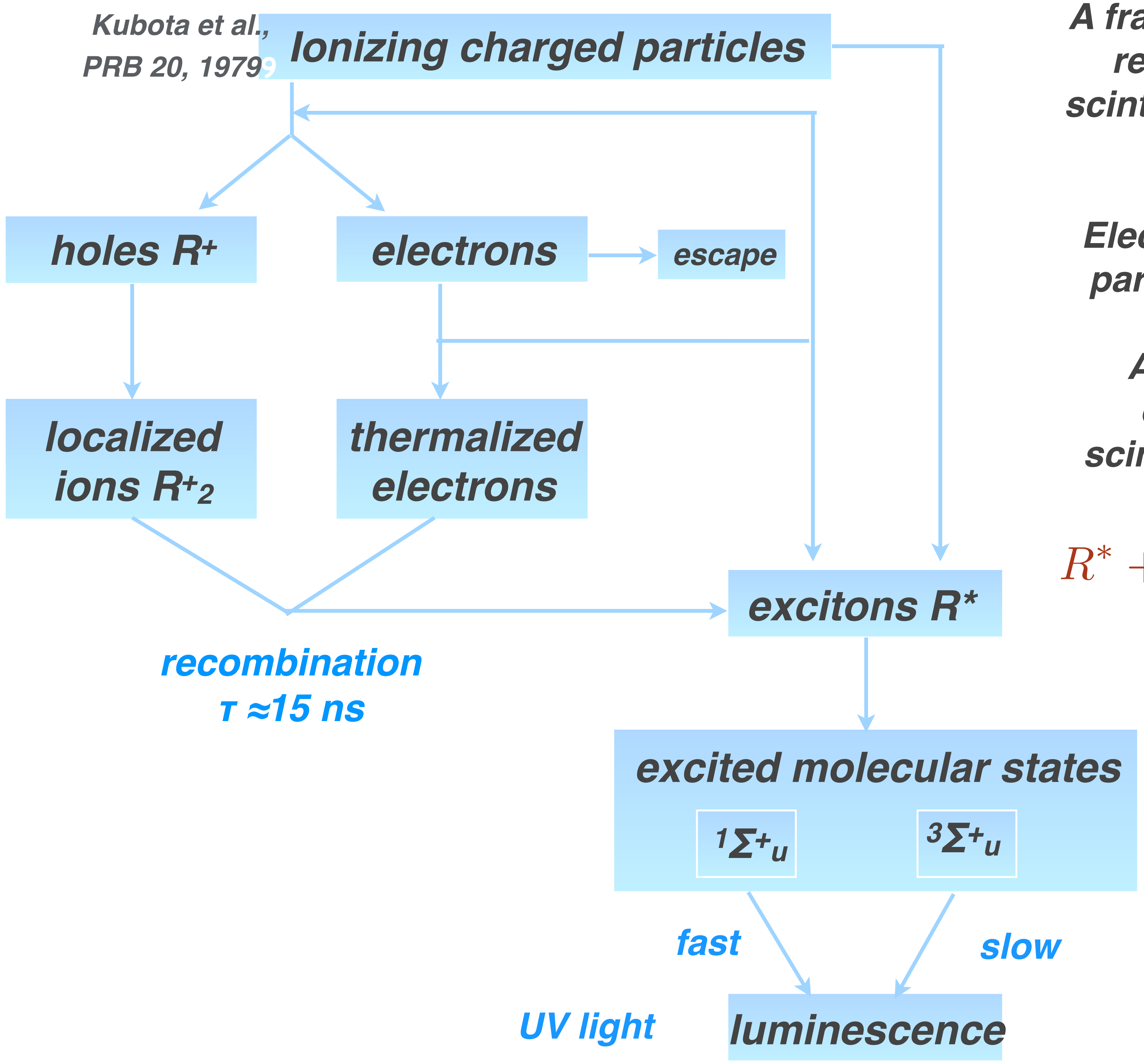
- the W-value in the liquid phase is smaller than in the gaseous phase

- the W-value in xenon is smaller than the one in liquid argon, and krypton (and neon)

=> the ionization yield is highest in liquid xenon (of all noble liquids)

Scintillation in Noble Liquids

Kubota et al.,
PRB 20, 1979


Ionizing charged particles

holes R^+

electrons

escape

localized ions R^+_2

thermalized electrons

recombination
τ ≈15 ns

excitons R^*

excited molecular states

$^1\Sigma^+_u$

$^3\Sigma^+_u$

fast

slow

UV light

luminescence

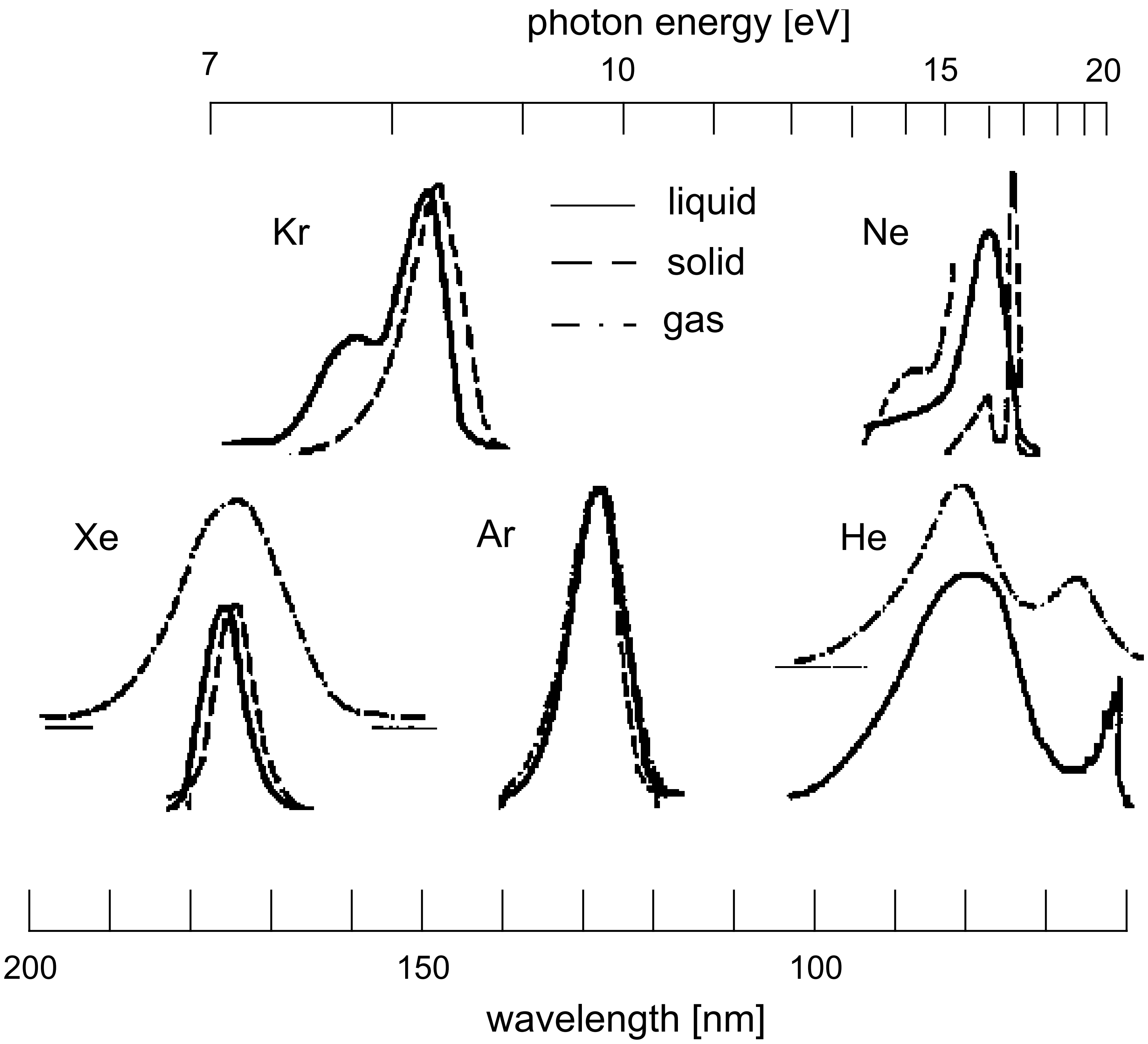
A fraction of the ionization electrons will recombine with ions and produce a scintillation photon in the process called recombination

Electrons that thermalize far from their parent ion may escape recombination

A mechanism called “bi-excitonic quenching” can also reduce the scintillation yield in very dense tracks:

$$R^* + R^* \longrightarrow R_2^{**} \longrightarrow R + R^+ + e^-$$

Energy of the Scintillation Photons



$$\lambda_{LNe} \sim 78nm$$

$$\lambda_{LAr} \sim 128nm$$

$$\lambda_{LXe} \sim 178nm$$

Electron Attachment and Light Absorption

- To achieve a high collection efficiency for both ionization and scintillation signals, the concentration of impurities in the liquid has to be reduced and maintained to a level *below 1 part per 10^9 (part per billion, ppb) oxygen equivalent*
- The scintillation light is strongly reduced by the presence of water vapour
- The ionization signal requires both high liquid purity (in terms of substances with electronegative affinity, SF_6, N_2O, O_2, etc) and a high field (typically ~ kV/cm)
- Attenuation lengths of ~1 m for electrons and photons were already achieved > 1m and are necessary for ton-scale experiments

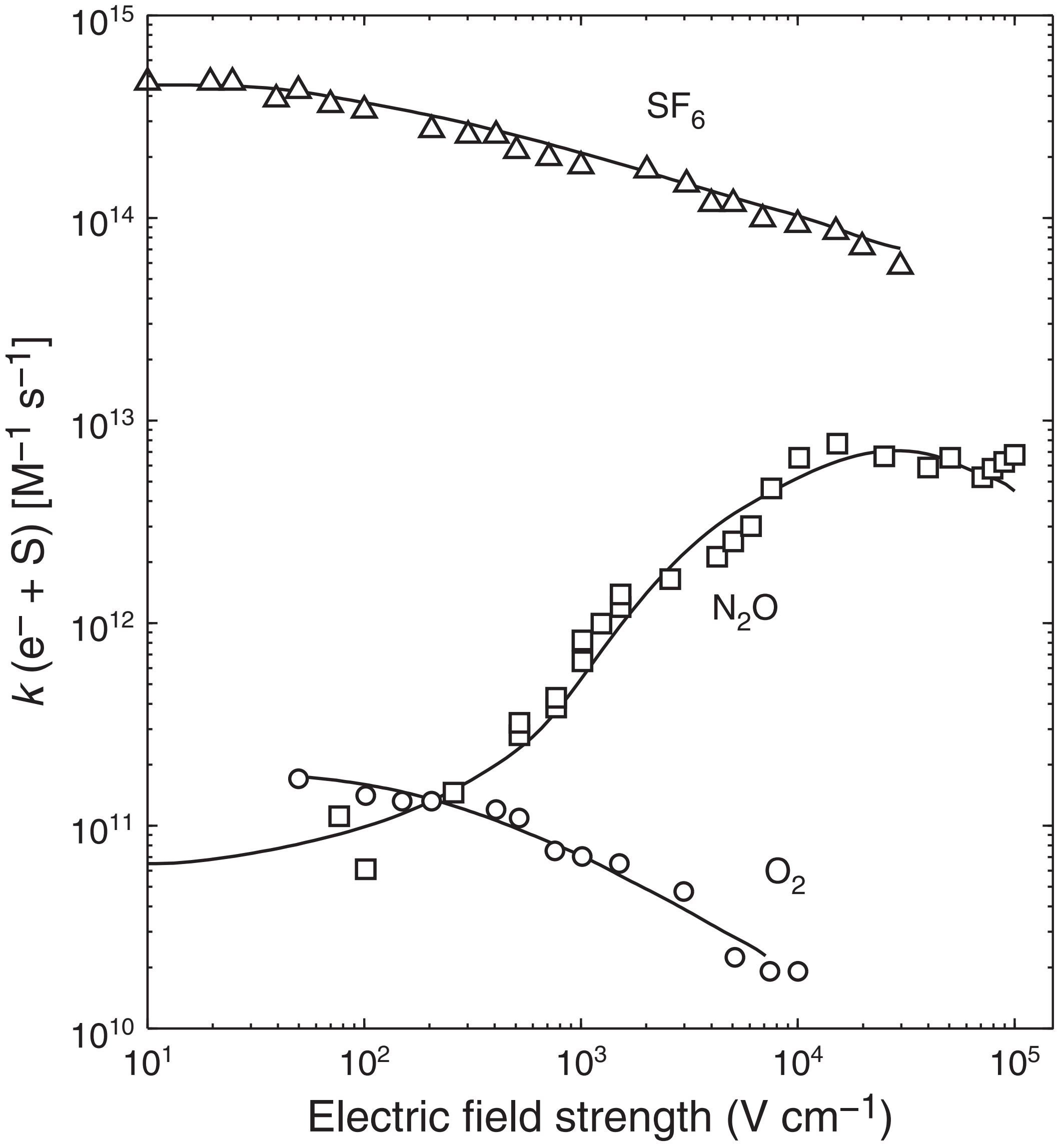


Fig. 21.4. Rate constant for the attachment of electrons in liquid xenon (T = 167 °K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2 [174].

Noble Liquid Detectors: some challenges

- Cryogenics: efficient, reliable and cost effective cooling systems
- Detector materials: compatible with low-radioactivity and purity requirements
- Intrinsic radioactivity: ^{39}Ar and ^{42}Ar in LAr, ^{85}Kr in LXe, radon emanation/diffusion

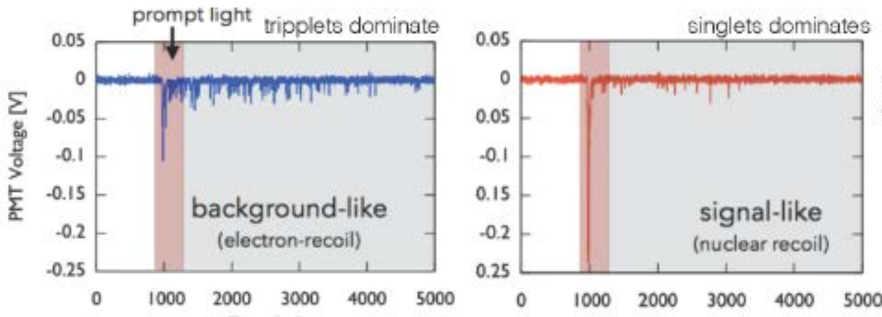
- **Light detection:**
  - ➡ efficient VUV PMTs, directly coupled to liquid (low T and high P capability, high purity), effective UV reflectors (also solid state Si devices are under study)
  - ➡ light can be absorbed by H_2O and O_2: continuous recirculation and purification
- **Charge detection:**
  - ➡ requires << 1ppb (O_2 equivalent) for e^--lifetime > 1 ms (commercial purifiers and continuous circulation)
  - ➡ electric fields ≥ 1 kV/cm required for maximum yield for MIPs; for alphas and NRs the field dependence is much weaker, challenge to detect a small charge in presence of HV

State-of-the-art in LAr Experiments:DEAP3600

DEAP-3600 @ SNOLAB

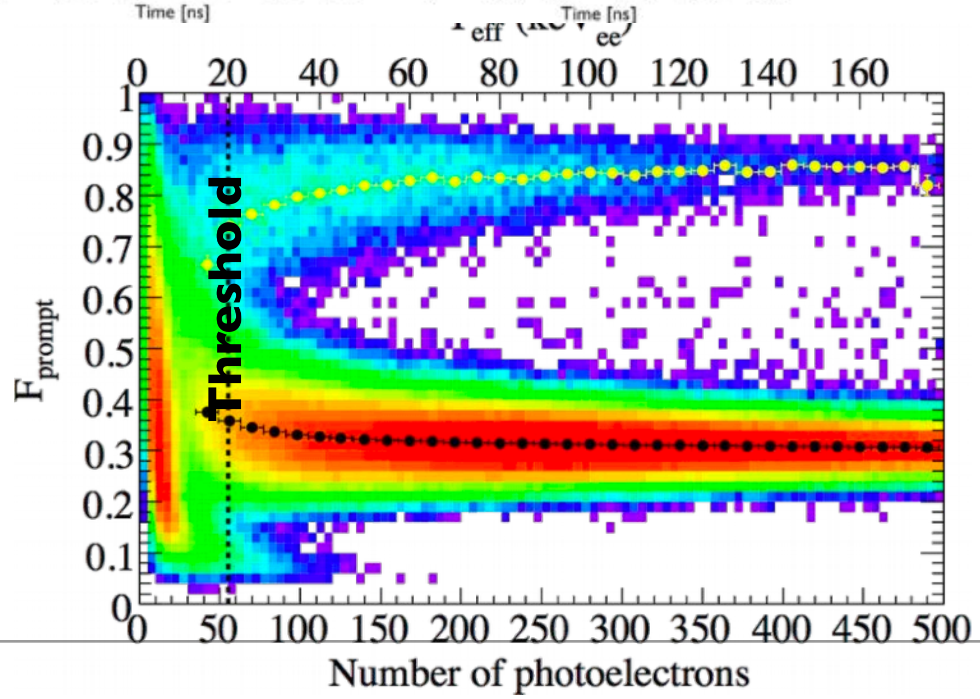
Single-phase liquid argon (no E-field)

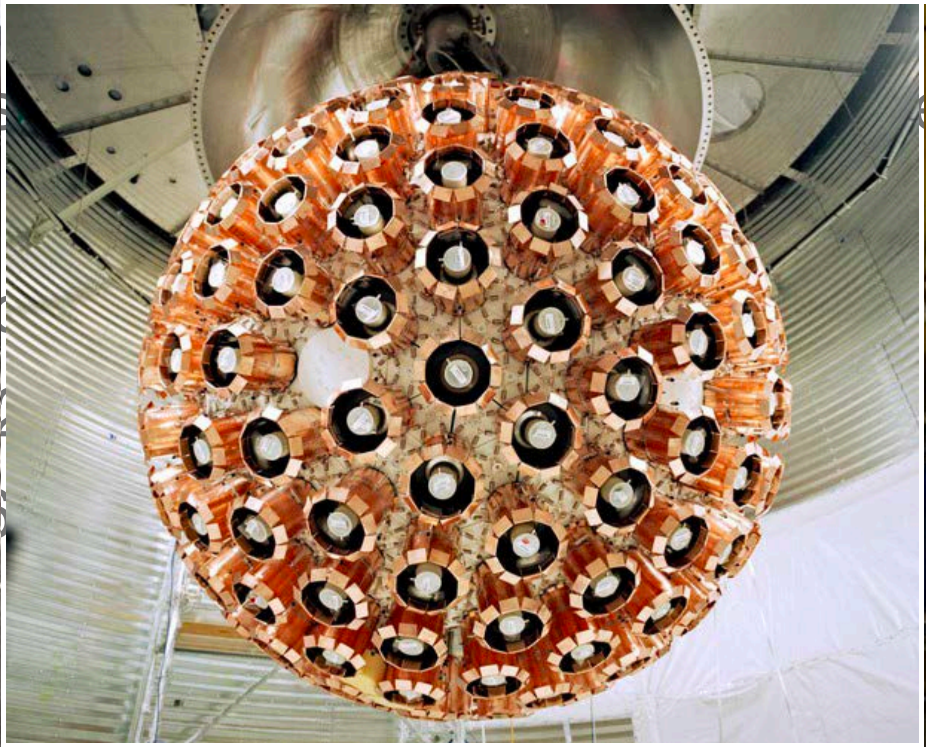
- 3.6 T of LAr, ~1 T fiducial
- High ^{39}Ar background when using ^{nat}Ar (~1 Bq/kg)
- Excellent discrimination using pulse shape. Prediction: ~10^{10} ER suppression
- Higher energy threshold compared with Xe detectors
- Collecting data since late 2016
- Projected sensitivity 10^{-46} cm2 @ 100 GeV/c^2



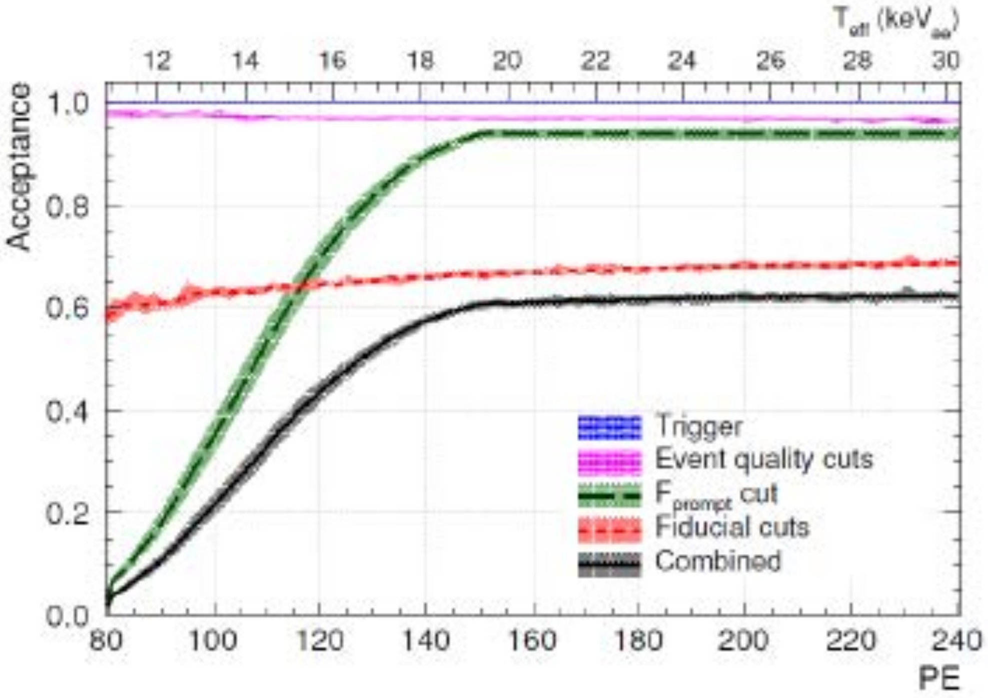
Pulse shape discrimination (PSD) parameter:

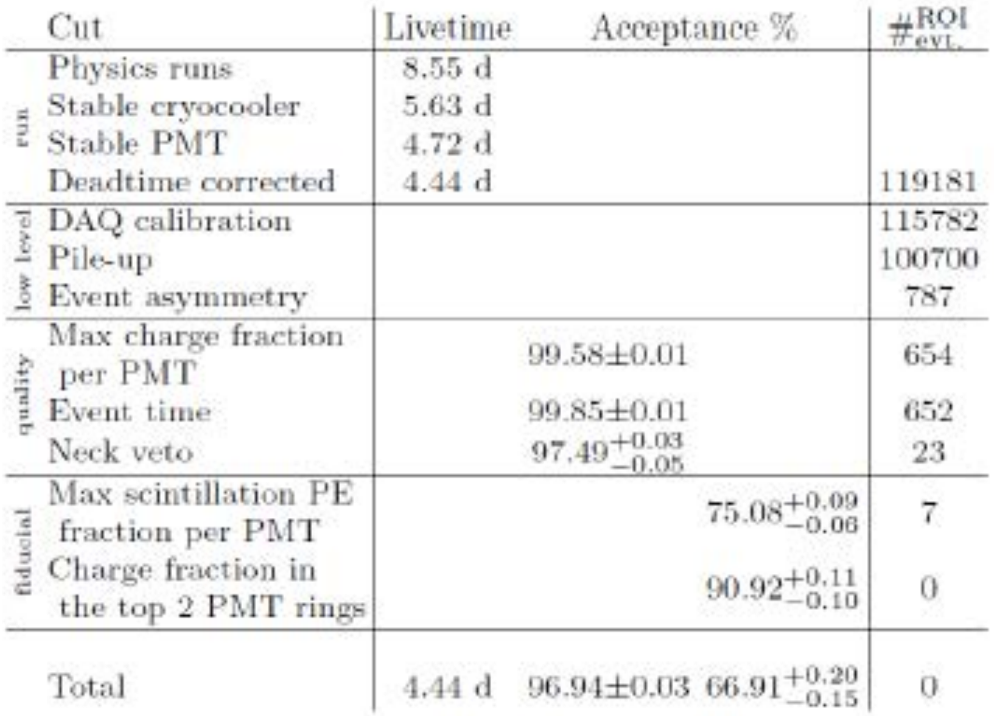
$$\text{fprompt} = \frac{\text{prompt light (150 ns)}}{\text{total light (10000 ns)}}$$



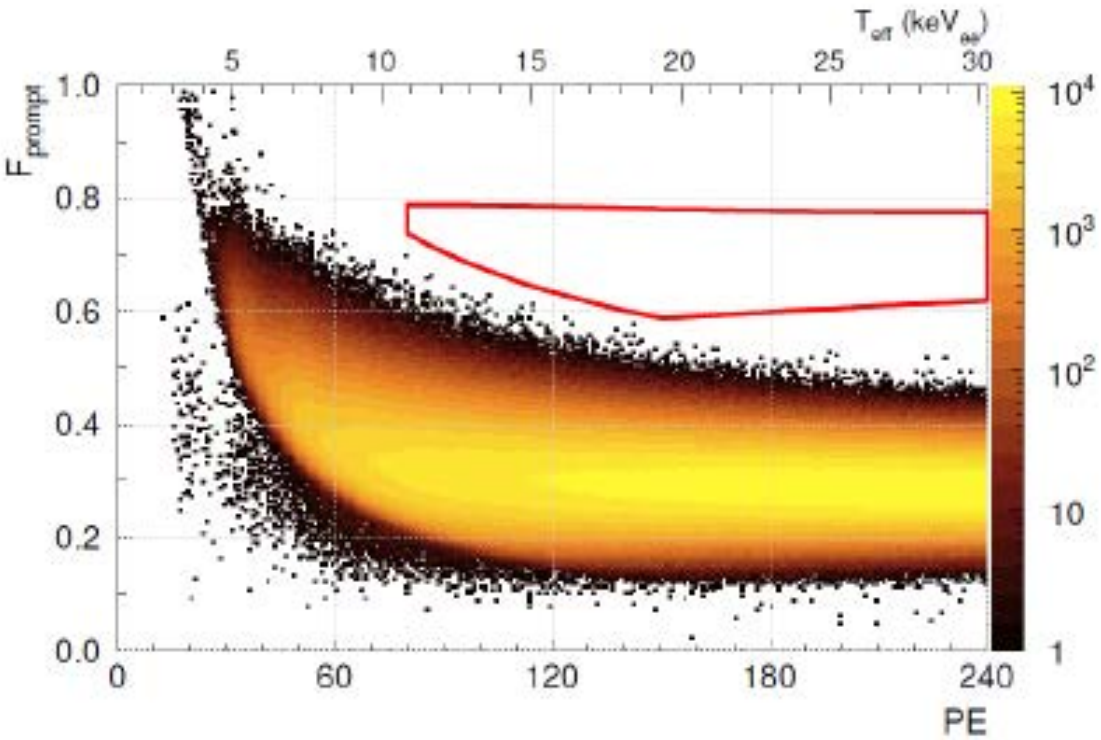


First Dark Matter Search with DEAP-3600 – 9,870 kg-days





	Cut	Livetime	Acceptance %		$\#^{\rm ROI}_{\rm evt.}$
run	Physics runs	8.55 d			
	Stable cryocooler	5.63 d			
	Stable PMT	4.72 d			
	Deadtime corrected	4.44 d			119181
low level	DAQ calibration				115782
	Pile-up				100700
	Event asymmetry				787
quality	Max charge fraction per PMT		99.58±0.01		654
	Event time		99.85±0.01		652
	Neck veto		$97.49^{+0.03}_{-0.05}$		23
fiducial	Max scintillation PE fraction per PMT			$75.08^{+0.09}_{-0.06}$	7
	Charge fraction in the top 2 PMT rings			$90.92^{+0.11}_{-0.10}$	0
	Total	4.44 d	96.94±0.03	$66.91^{+0.20}_{-0.15}$	0



4.44 live days

Selected ROI for < 0.2 leakage from β's

Developed prelim. cuts for instrumental and external-source events

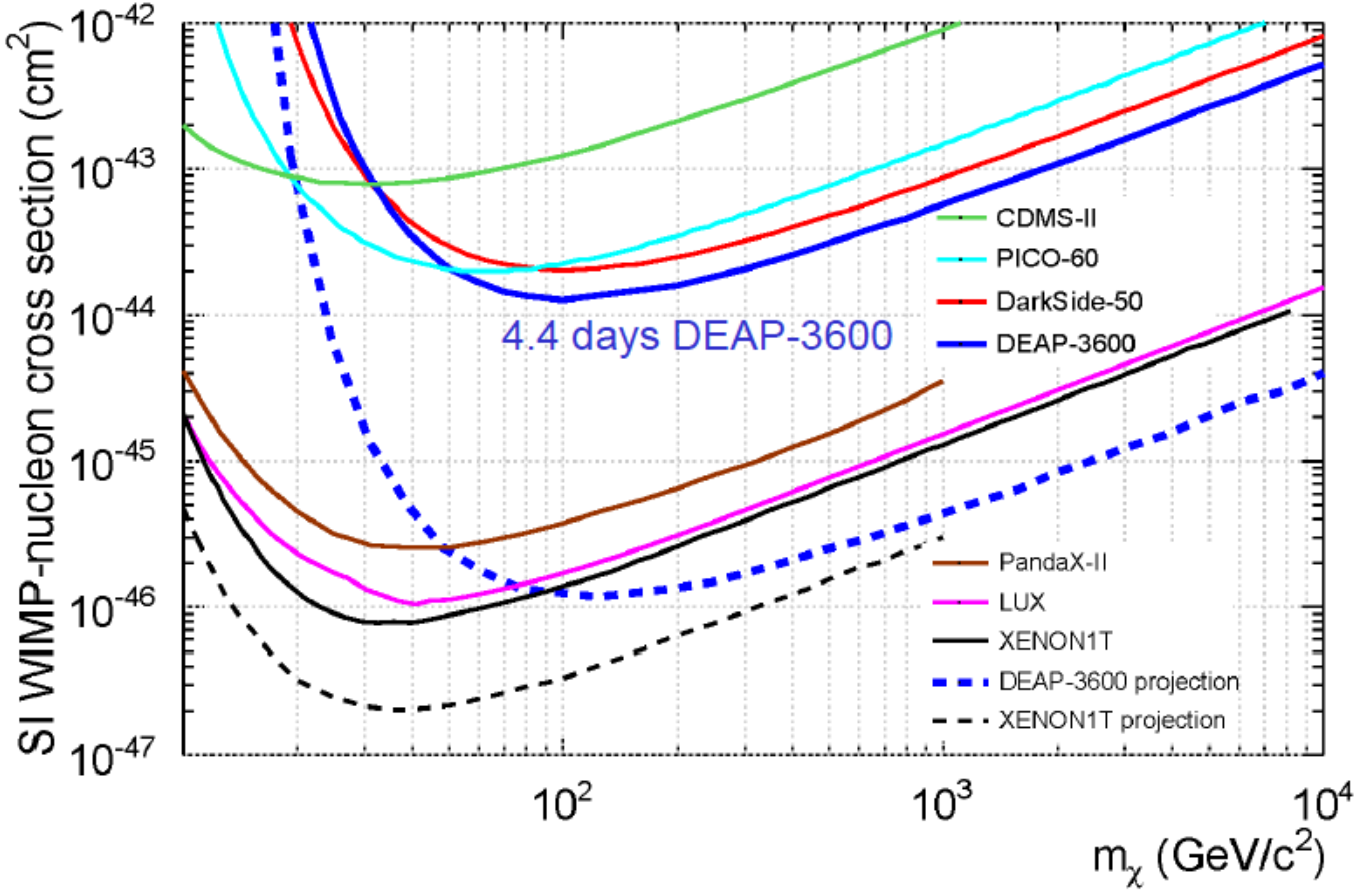
2223 kg fiducial mass

9,870 kg-day exposure

No events observed in ROI

Mark Boulay

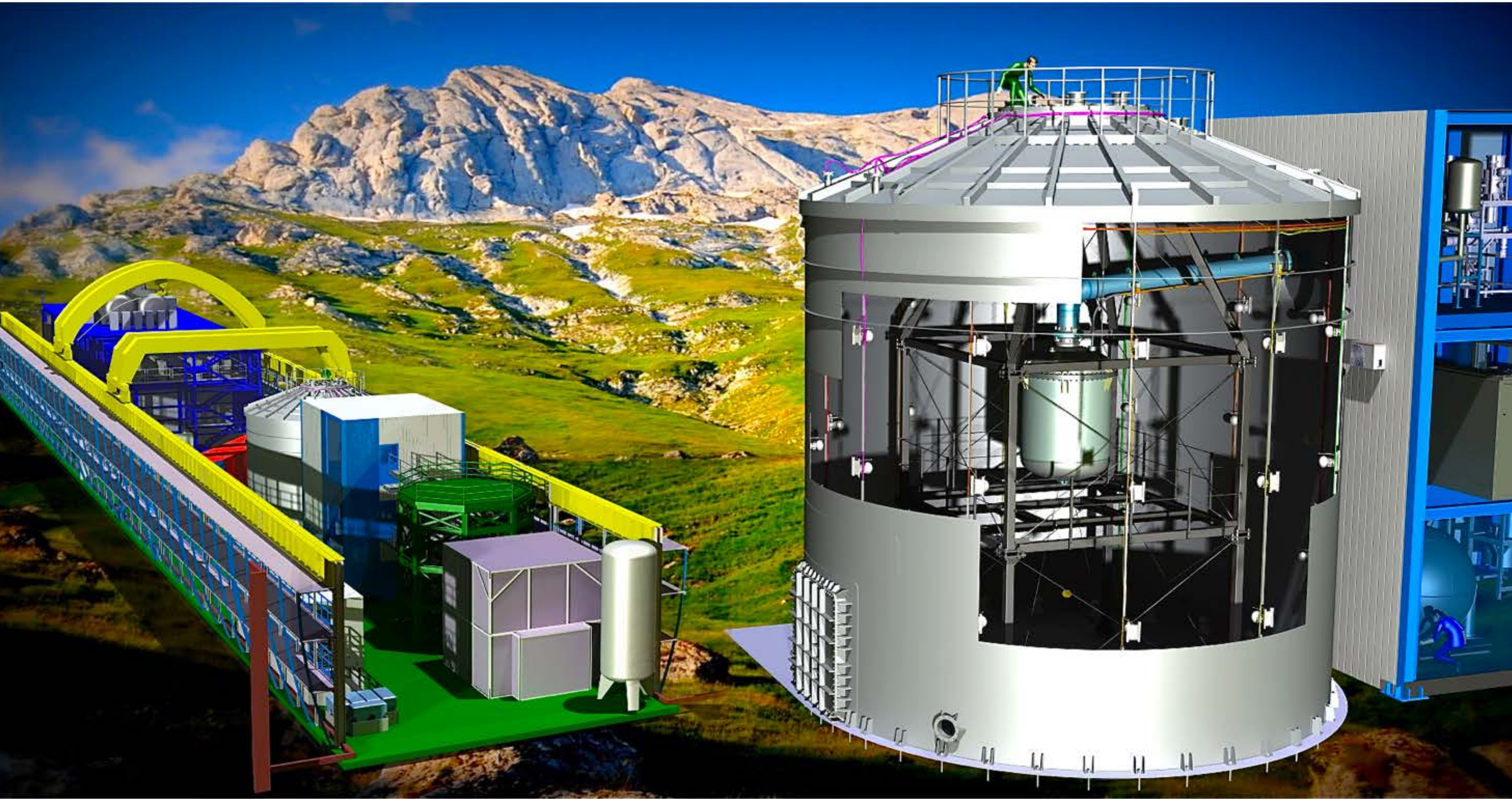
WIMP exclusion with DEAP-3600



State-of-the-art in LXe Experiments: XENON1T

The XENON1T Experiment

www.xenon1t.org



The XENON Collaboration: 160 scientists

Columbia

RPI

Nikhef

Muenster

Stockholm

Mainz

MPIK

Freiburg

Zurich

Chicago

UCLA

UCSD

Rice

Tokyo

Nagoya

Kobe

PURDUE UNIVERSITY

Subatech

LPNHE PARIS

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

INFN

WEIZMANN INSTITUTE OF SCIENCE

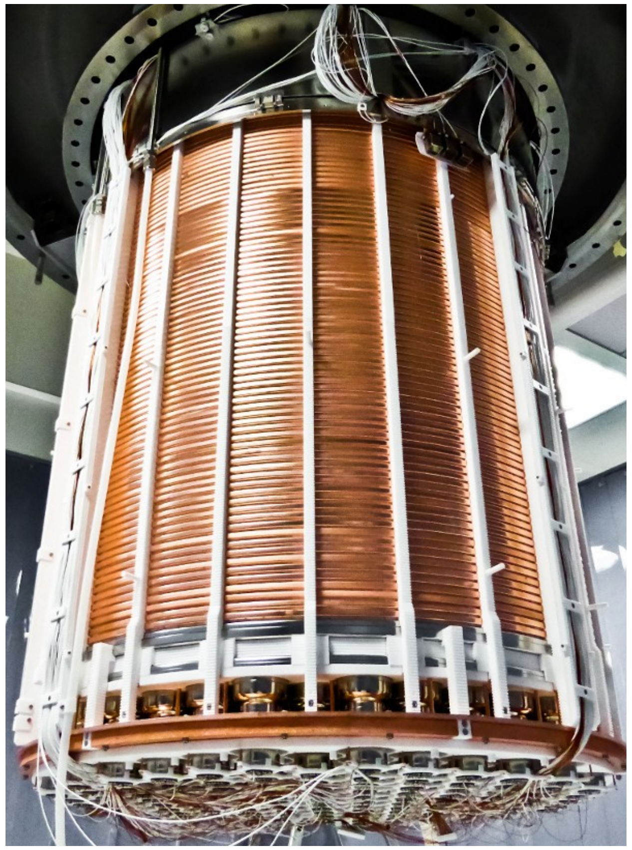
NYU ABU DHABI

The phases of XENON

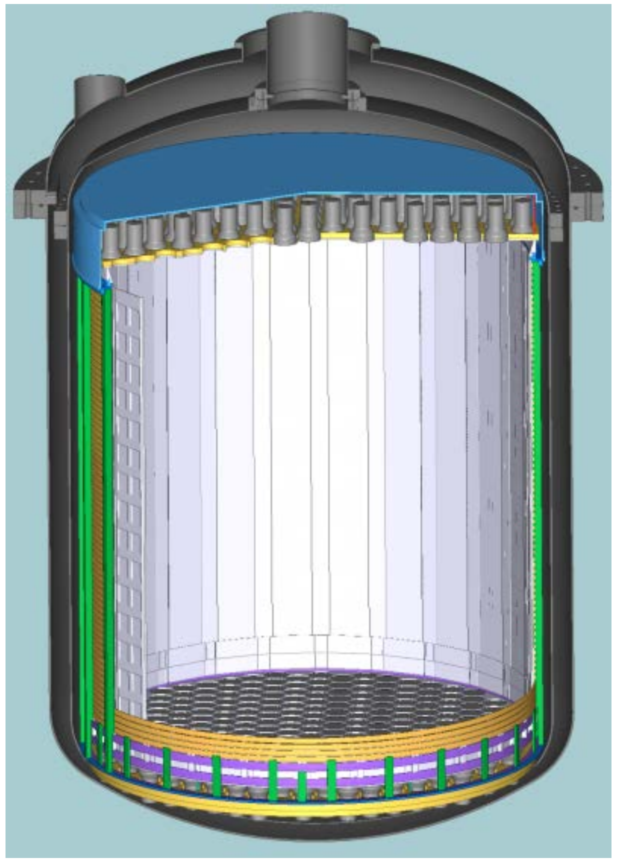
XENON10

XENON100

XENON1T



XENONnT



2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

XENON1T Overview

EPJ C 77, 881 (2017)

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

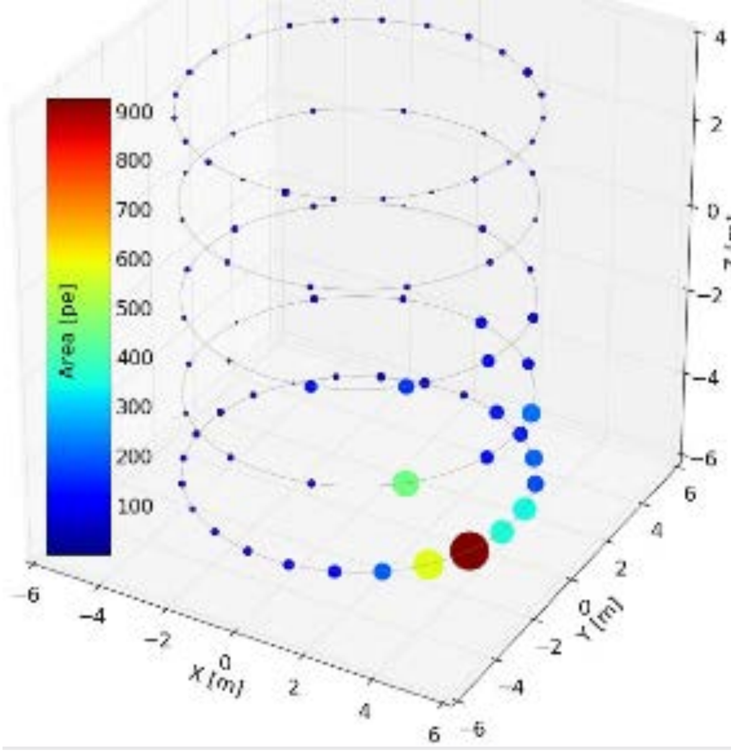
Umbilical pipe (cables, xenon)

Cryogenics and purification

Data acquisition and slow control

Xenon storage, handling and distillation column

The XENON1T Water Cherenkov Muon Veto



- 84 x 8 “ PMTs (R5912) with high QE and gain
- Taking data with a stable configuration: R = 0.45 Hz

SR	Coverage (%)	μ-Tag. Eff. (%)	Shower Tag. Eff. (%)
0	96	99.5	43
1	99	99.5	43

Muon-induced nuclear recoil background rate in SR1
1.2 10^{-2} (events/year) in 1 ton fiducial volume

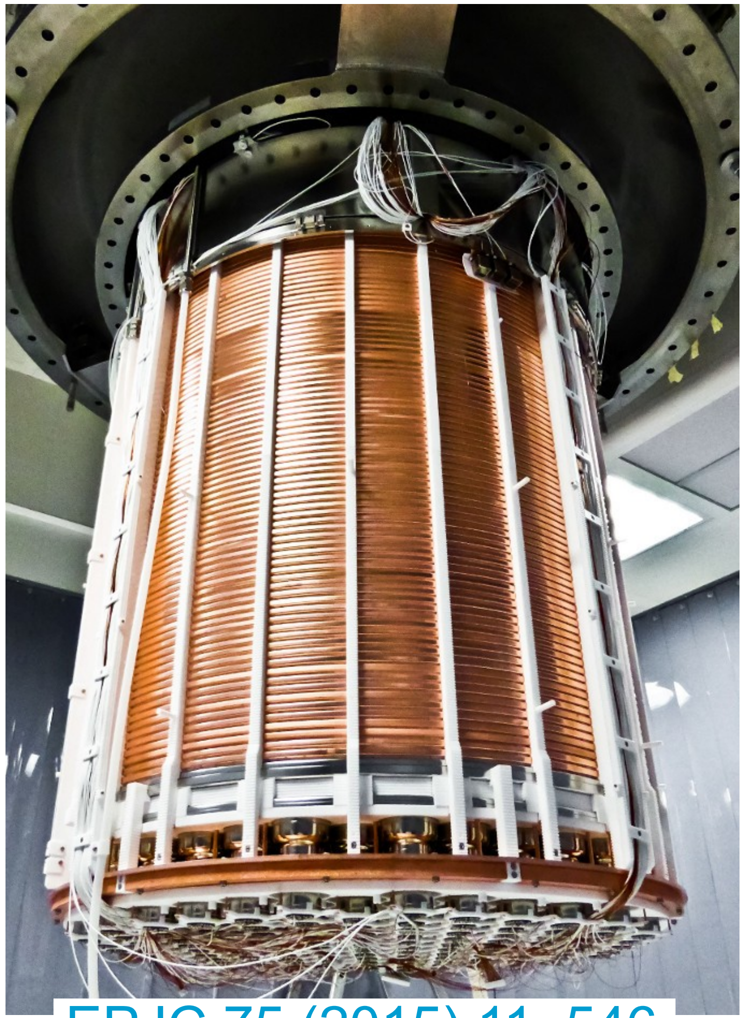
The XENON1T Time Projection Chamber

3.2 t LXe @180 K
2.0 t active target
~1 meter drift length
~1 meter diameter

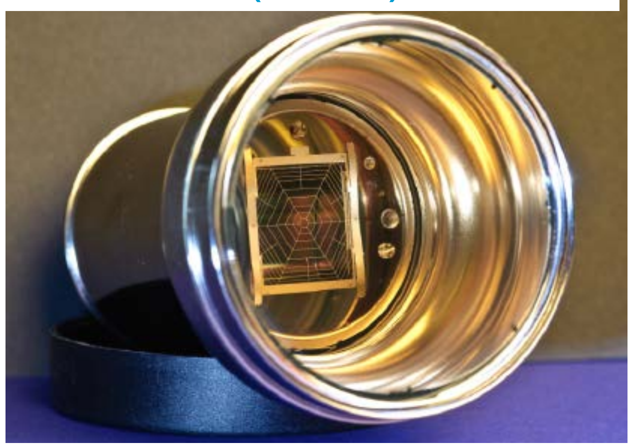

13.08.2014 04:34

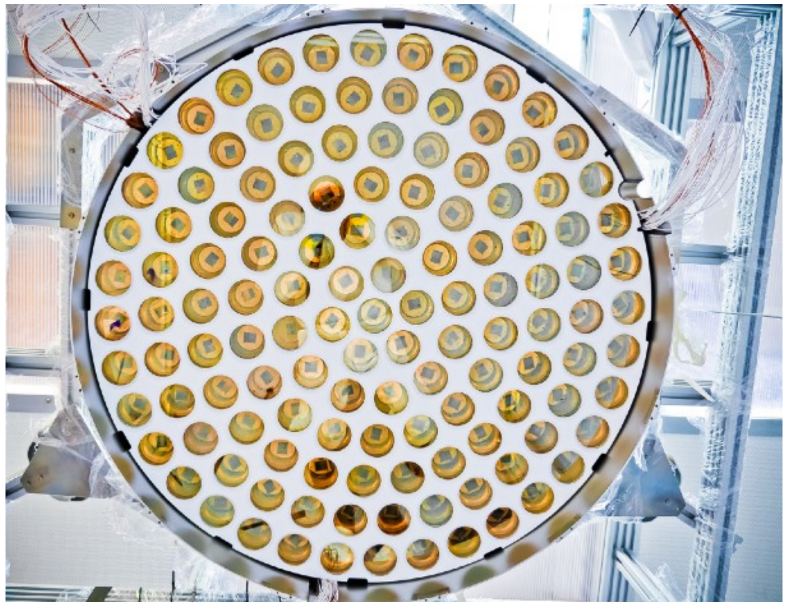
XENON1T Photomultipliers

- 248 3-inch, low-radioactivity R11410-21 PMTs with 34.5 % average QE at 178 nm

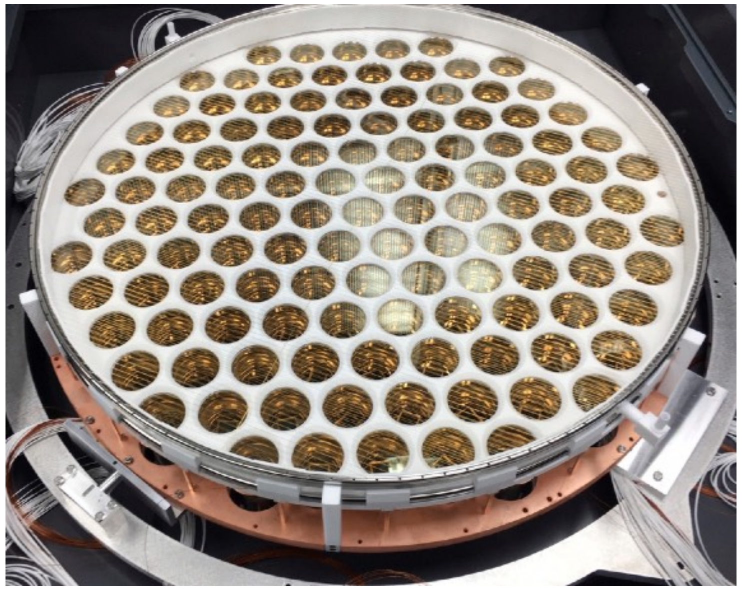


EPJC 75 (2015) 11, 546

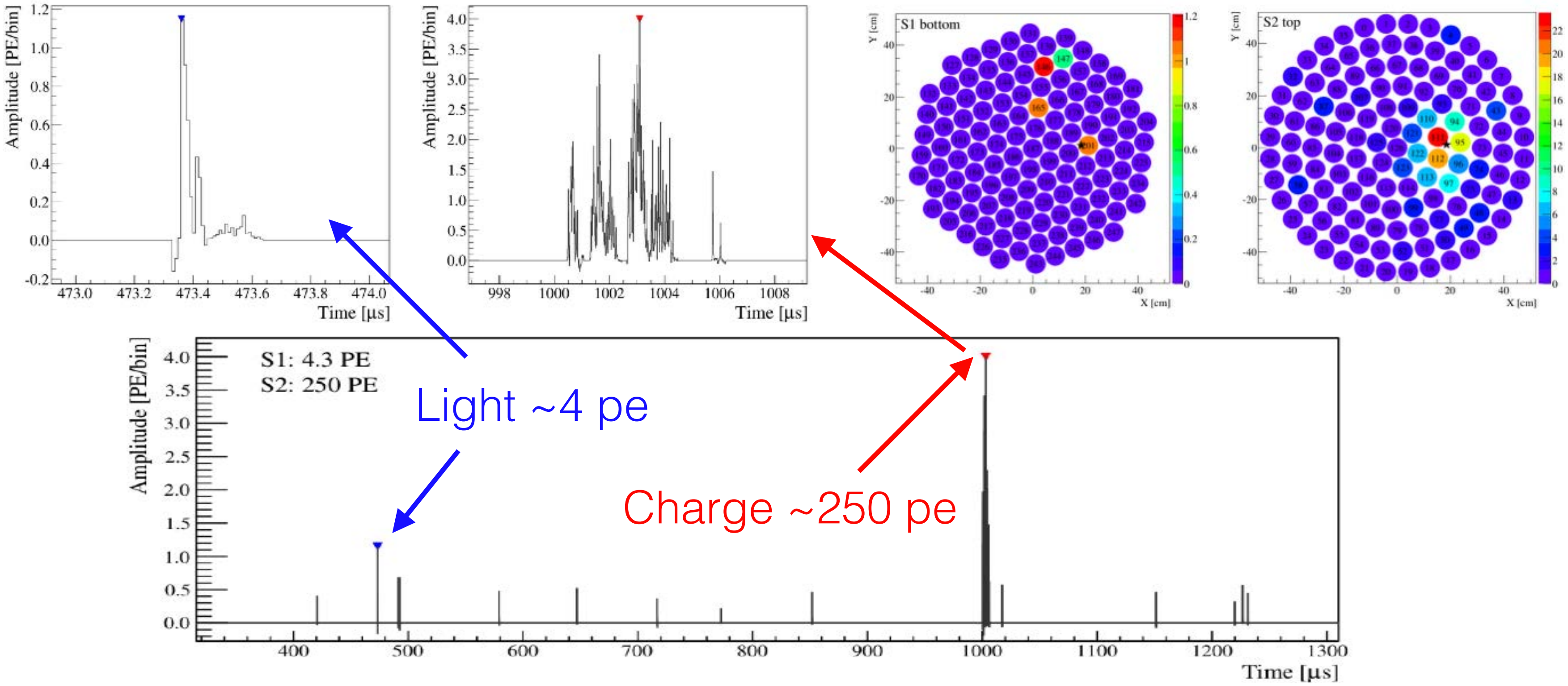




127 PMTs in the top array

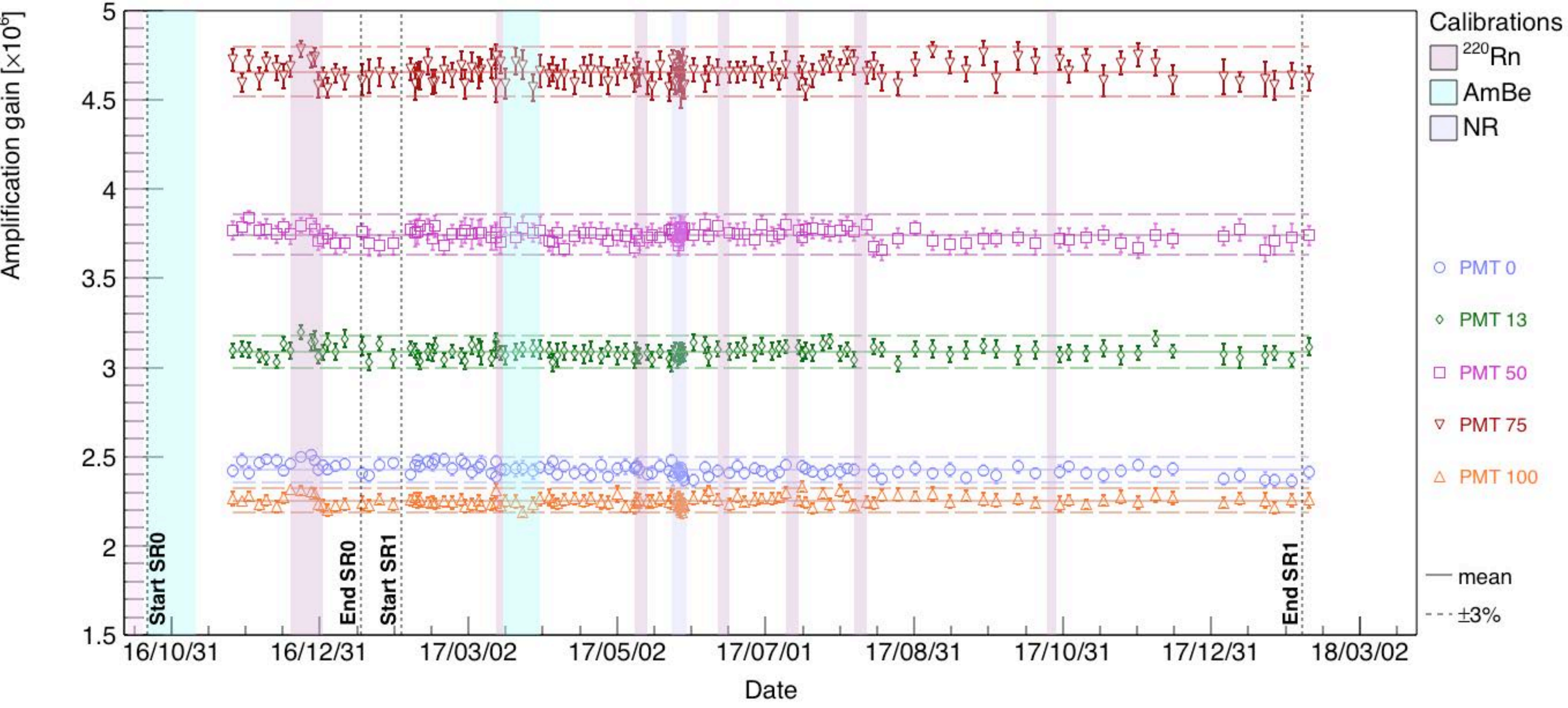


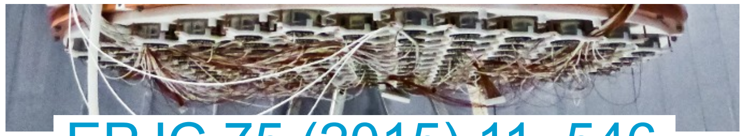
121 PMTs in the bottom array



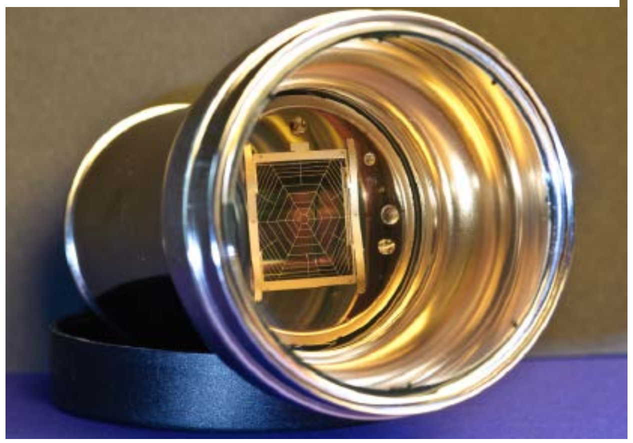
Light ~4 pe

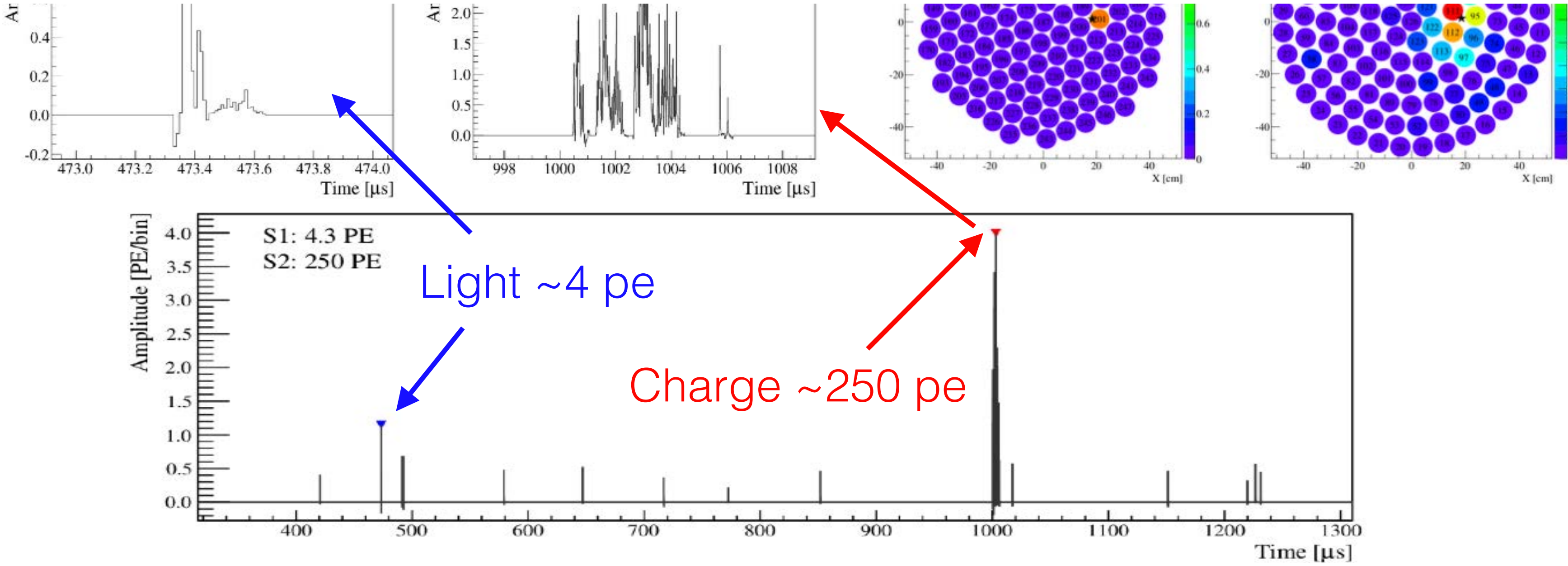
Charge ~250 pe





EPJC 75 (2015) 11, 546



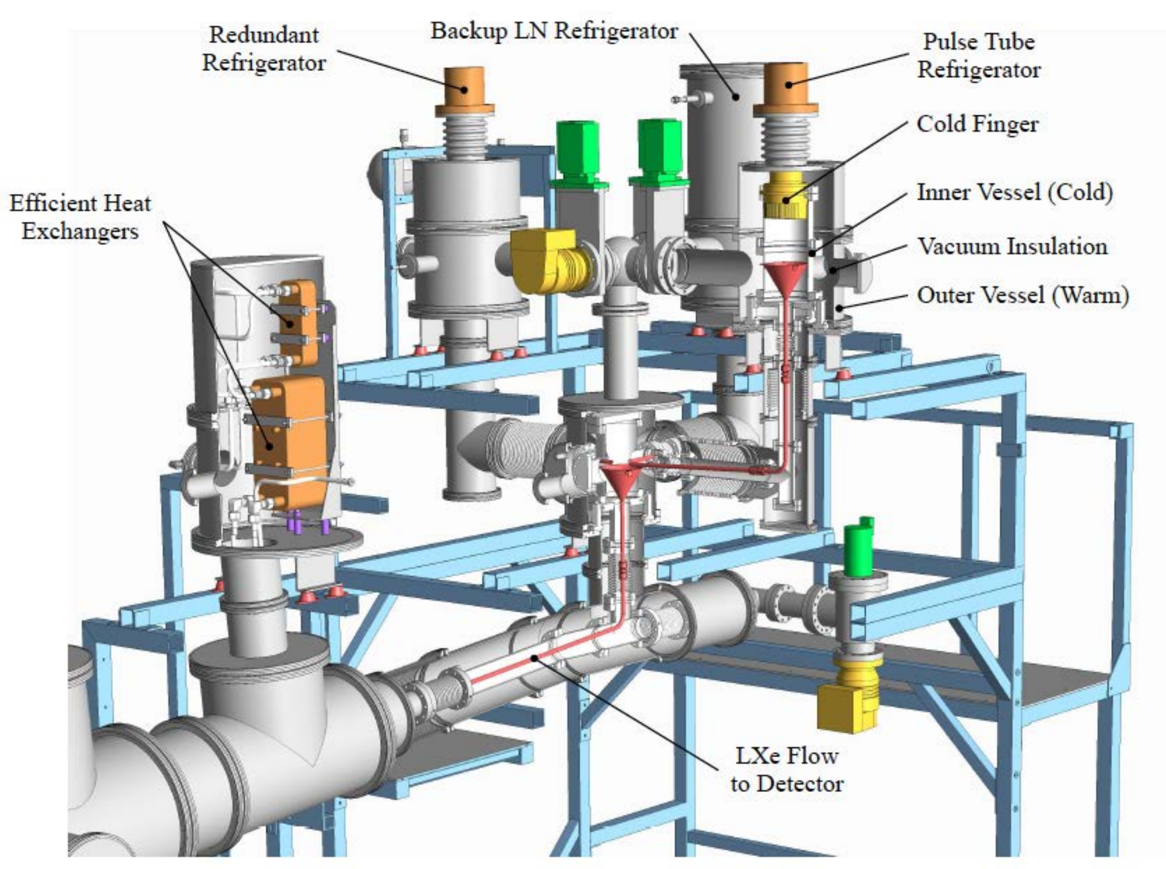


Light ~4 pe

Charge ~250 pe

It takes ~600,000 liters of Xe gas to fill the detector with 3200 kg of LXe

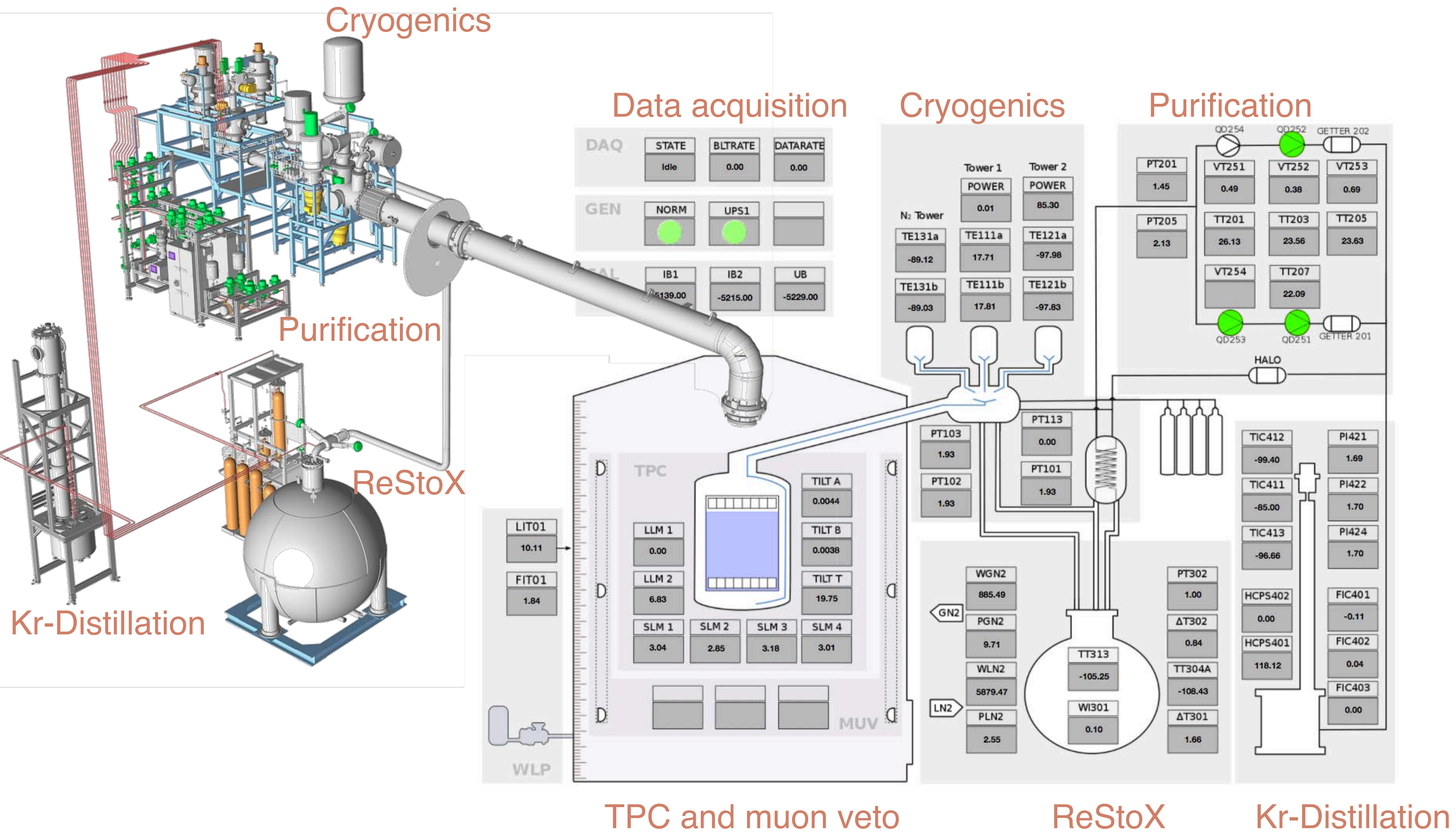
and several systems to handle/condense/purify/keep cold and clean the Xe in the detector



and several systems to handle/condense/purify/keep cold and clean the Xe in the detector

and several systems to handle/condense/purify/keep cold and clean the Xe in the detector

XENON1T Cryogenic Plants



DAQ
STATE Idle
BLTRATE 0.00
DATARATE 0.00

GEN
NORM ●
UPS1 ●

IB1 5139.00
IB2 -5215.00
UB -5229.00

LIT01 10.11
FIT01 1.84

TPC
LLM 1 0.00
LLM 2 6.83
TILT A 0.0044
TILT B 0.0038
TILT T 19.75
SLM 1 3.04
SLM 2 2.85
SLM 3 3.18
SLM 4 3.01

N₂ Tower
TE131a -89.12
TE131b -89.03

Tower 1
POWER 0.01
TE111a 17.71
TE111b 17.81

Tower 2
POWER 85.30
TE121a -97.98
TE121b -97.83

PT103 1.93
PT102 1.93
PT113 0.00
PT101 1.93

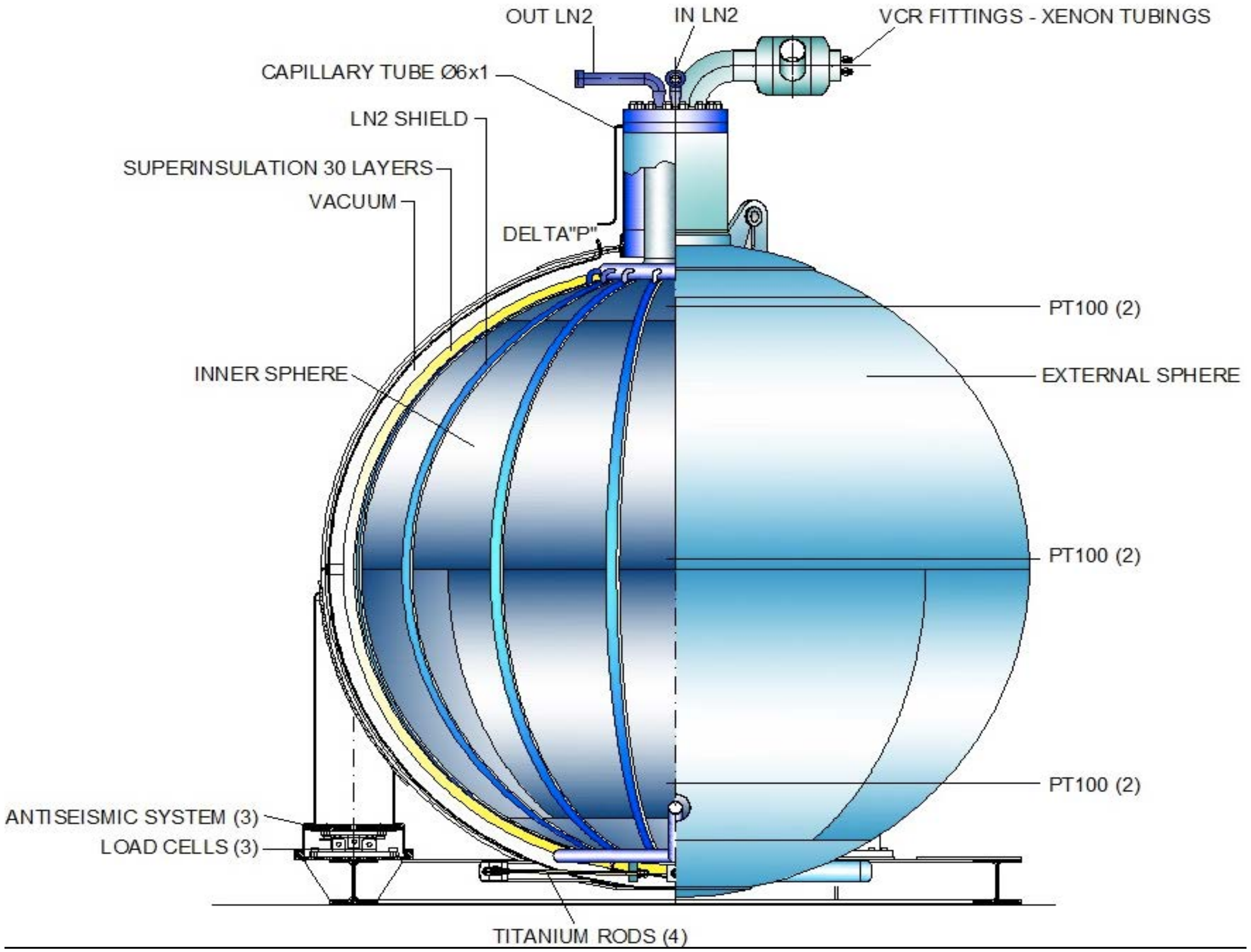
PT201 1.45
PT205 2.13
VT251 0.49
VT252 0.38
VT253 0.69
TT201 26.13
TT203 23.56
TT205 23.63
VT254
TT207 22.09

WGN2 885.49
PGN2 9.71
WLN2 5879.47
PLN2 2.55
TT313 -105.25
WI301 0.10
PT302 1.00
ΔT302 0.84
TT304A -108.43
ΔT301 1.66

TIC412 -99.40
TIC411 -85.00
TIC413 -96.66
HCPS402 0.00
HCPS401 118.12
PI421 1.69
PI422 1.70
PI424 1.70
FIC401 -0.11
FIC402 0.04
FIC403 0.00

The Xe Recovery & Storage System

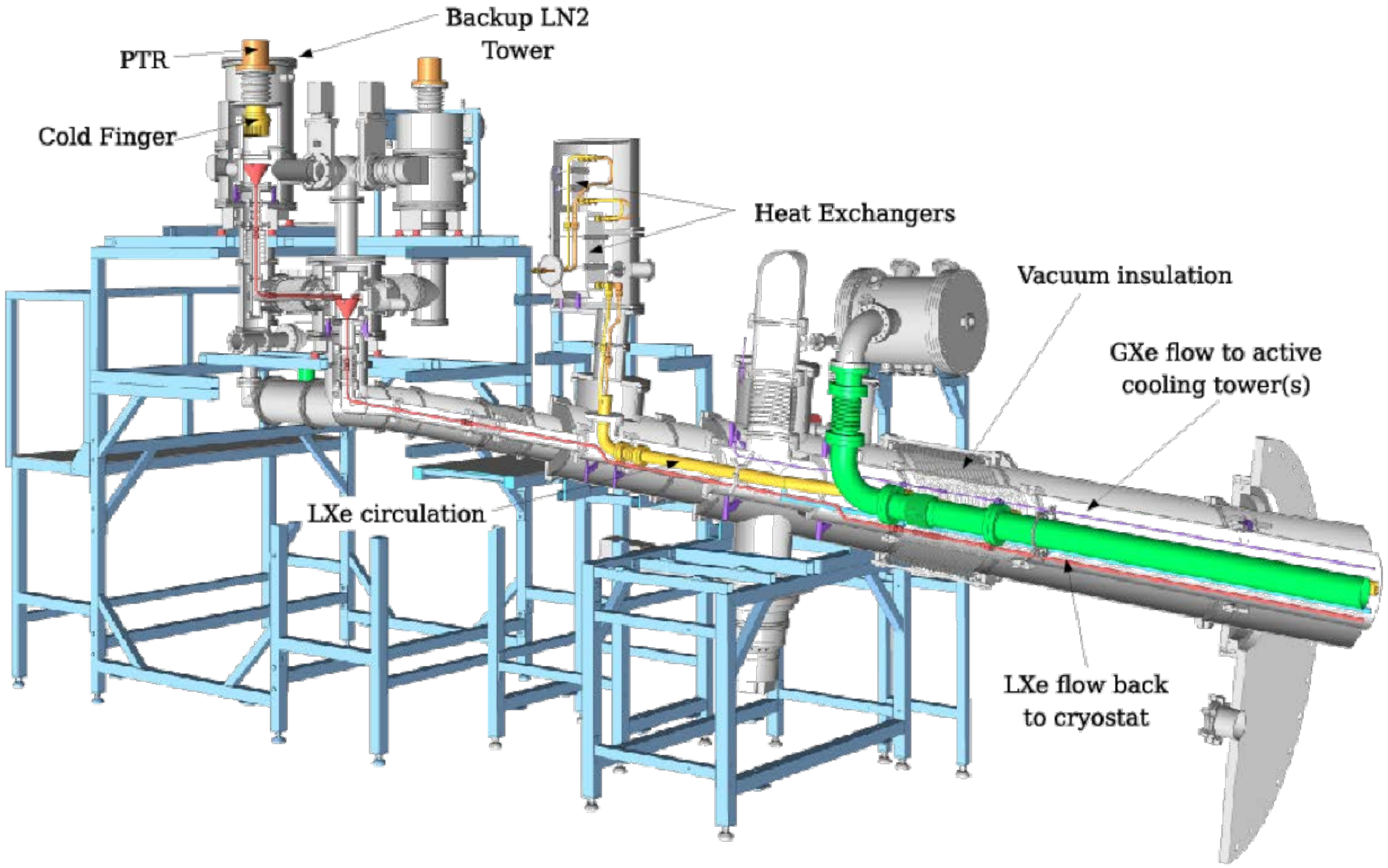
- Double-walled, high pressure (70 atm), vacuum-insulated, LN_2 cooled sphere
- Can store up to 10t of xenon in gas or liquid/solid phase in high-purity conditions



The Cryogenic System

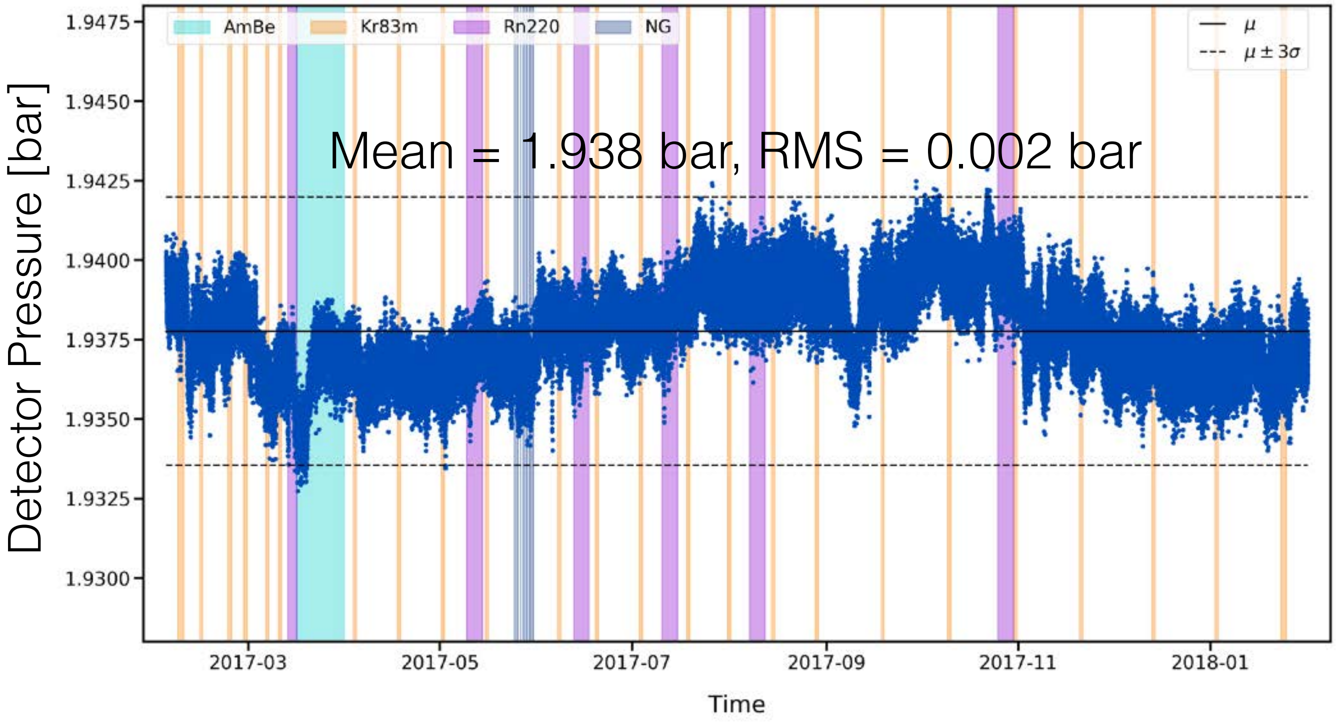
- Liquefies and maintains xenon in liquid state, provides stable conditions for data taking

- Two redundant PTR cooling systems and one LN_2 cooling tower backup
- Efficient two-phase heat exchangers
- Detector cold with stable pressure/ temperature since Fall 2016!

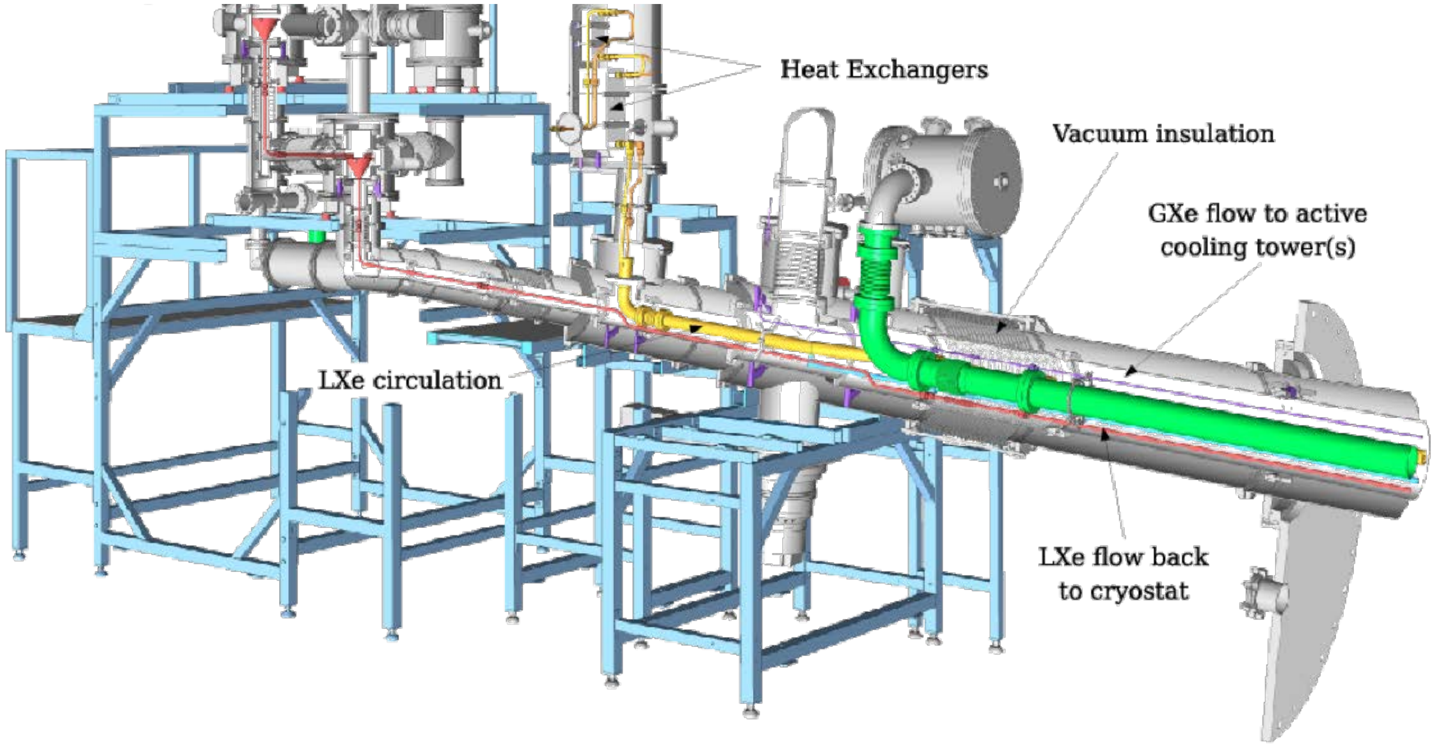


The Cryogenic System

te, provides stable conditions for data taking

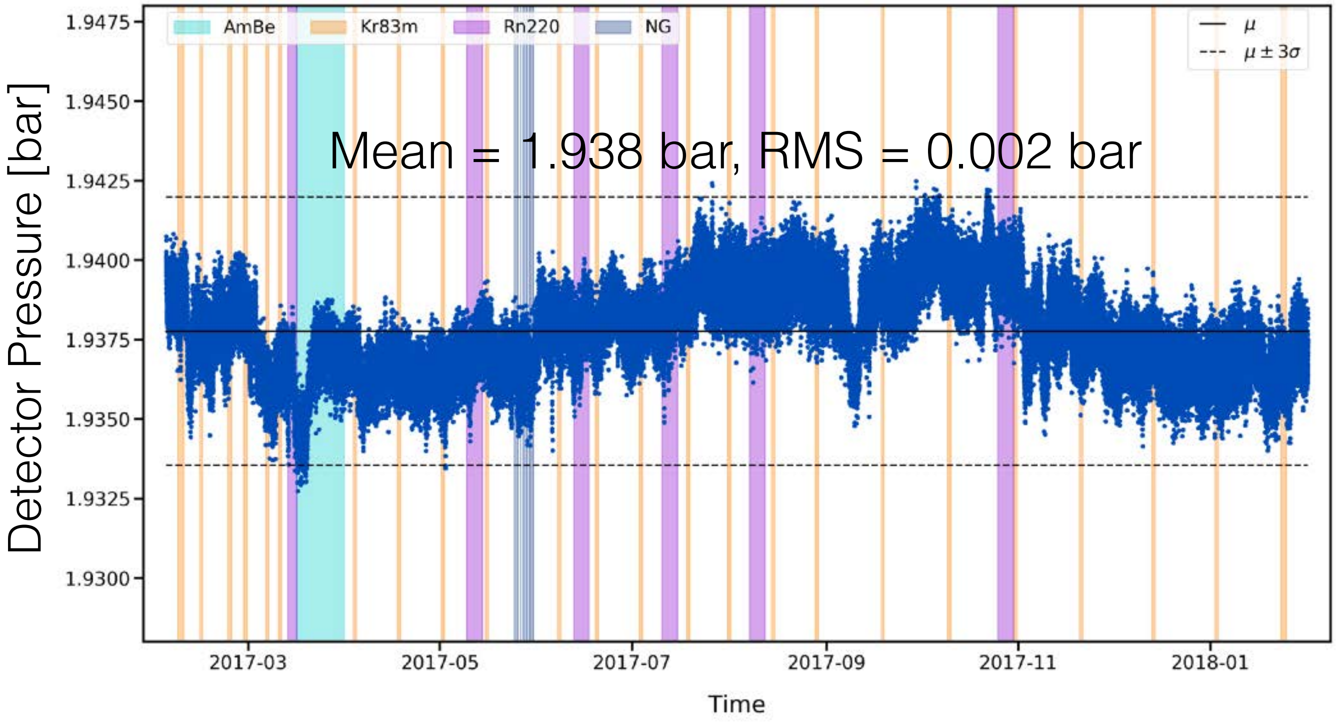


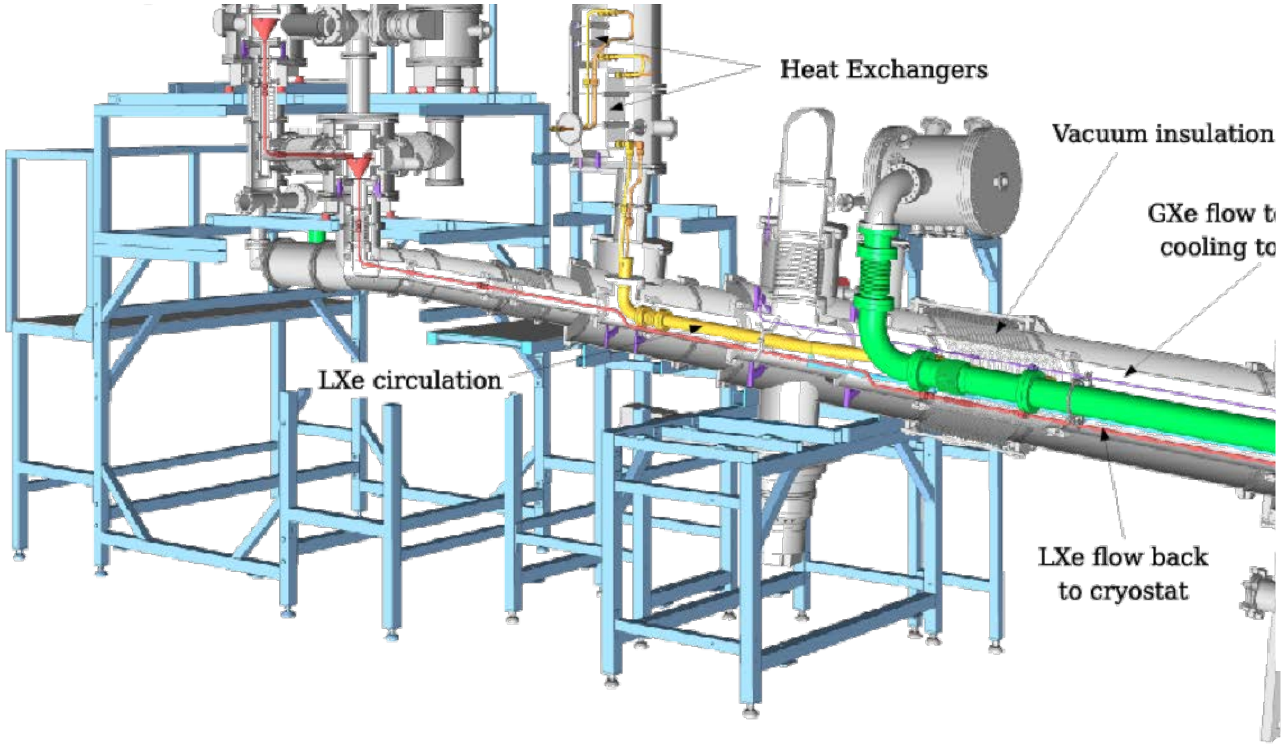
Mean = 1.938 bar, RMS = 0.002 bar

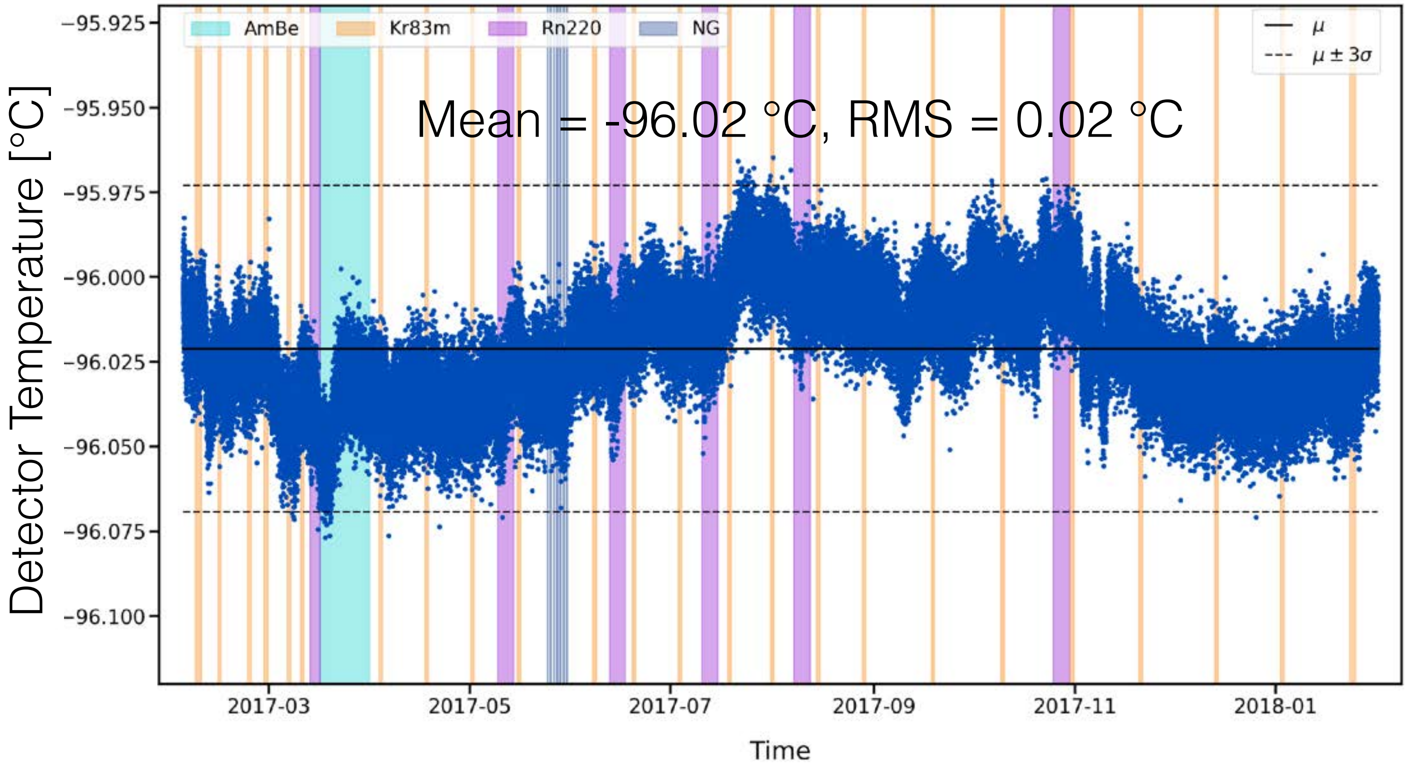


The Cryogenic System

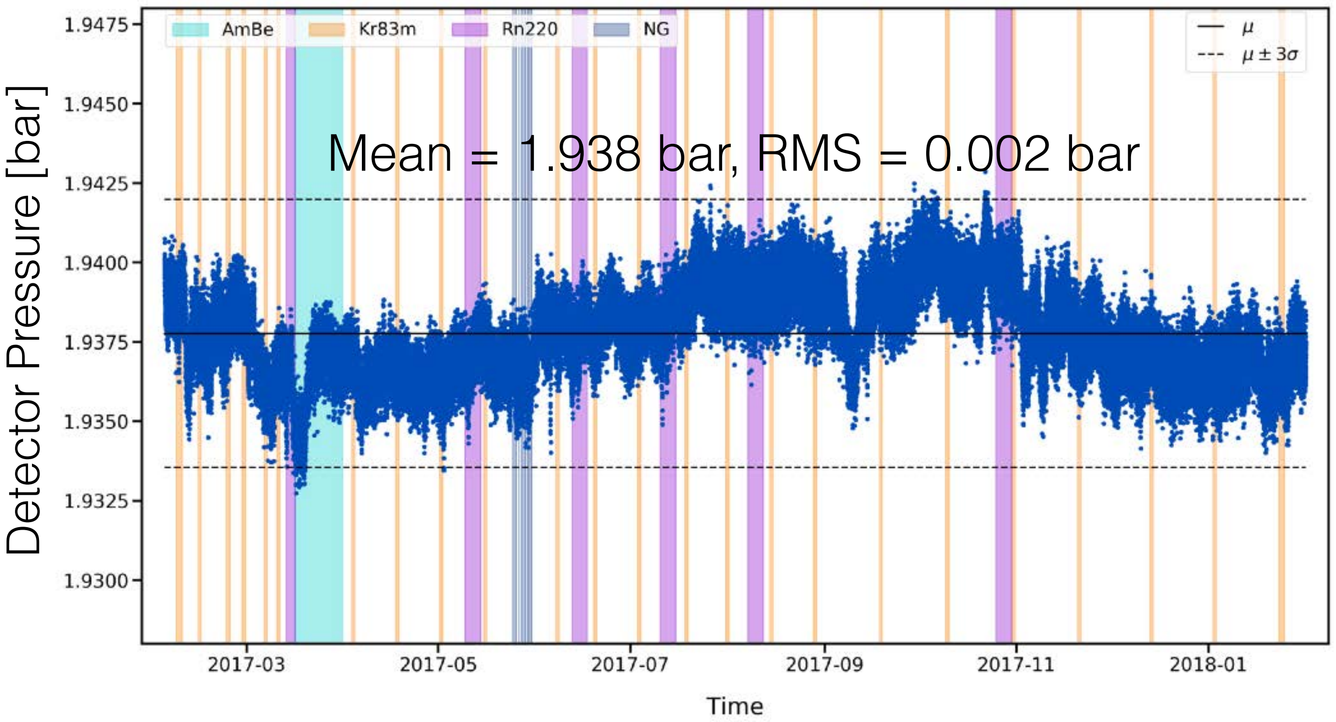
te, provides stable conditions for data taking



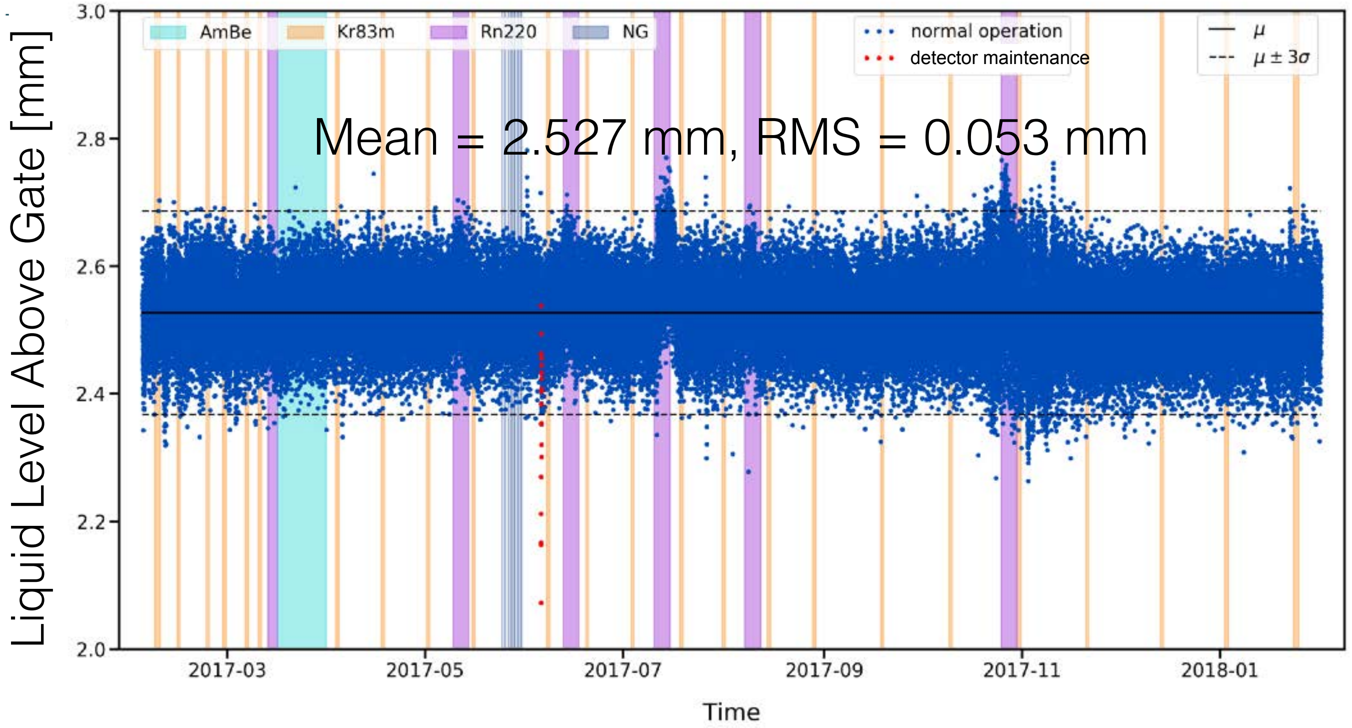




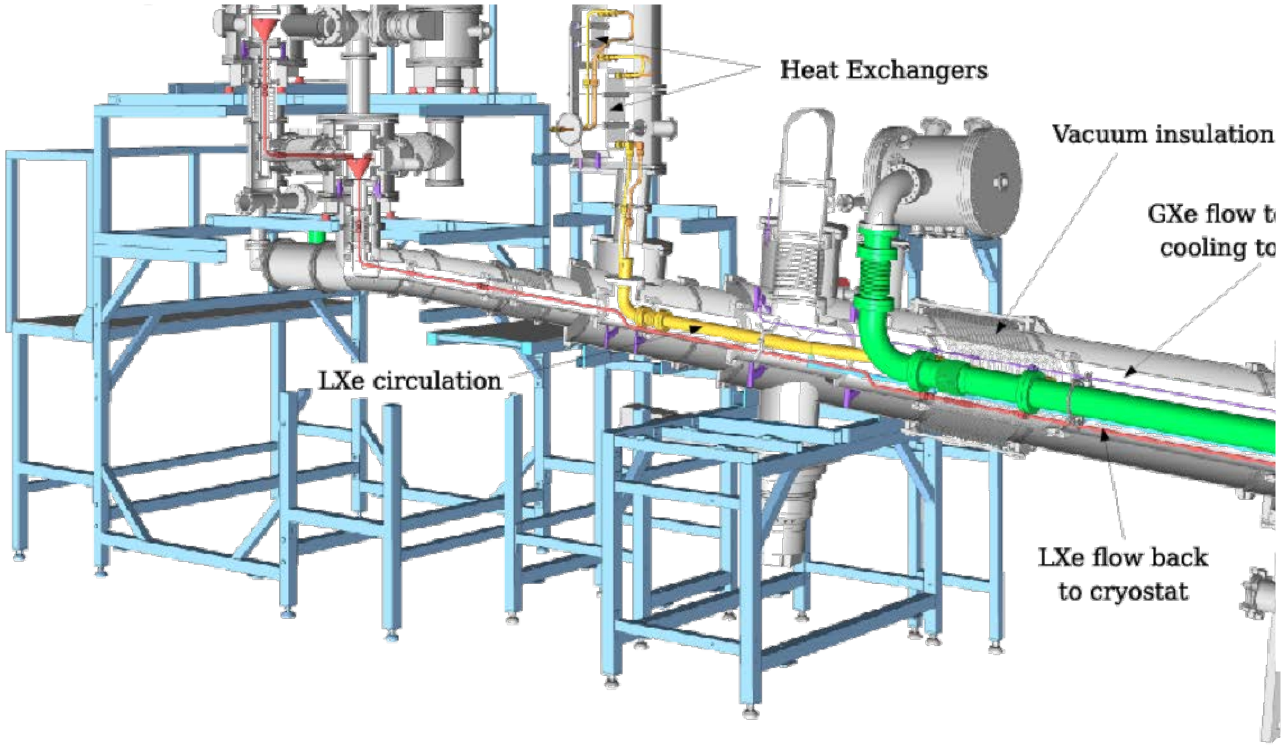
The Cryogenic System

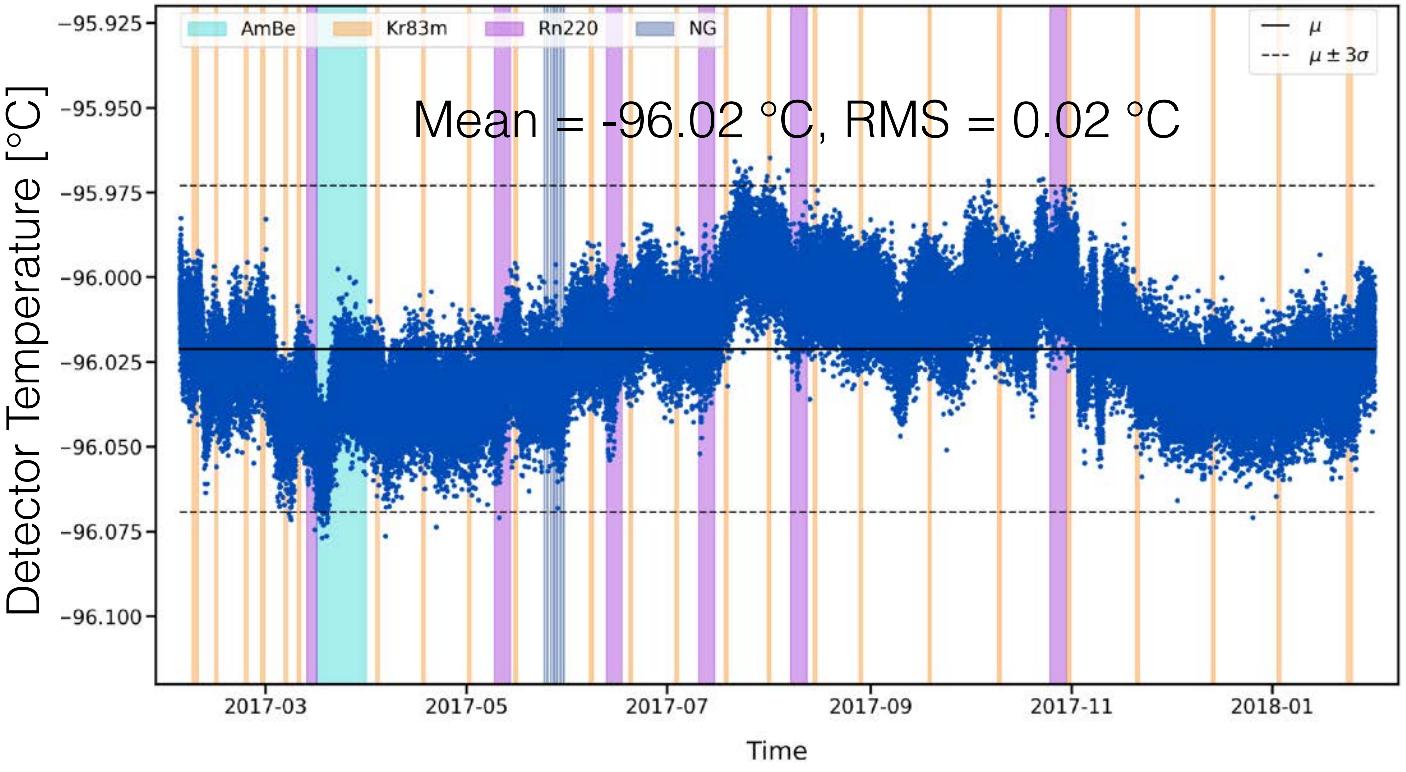


Mean = 1.938 bar, RMS = 0.002 bar



Mean = 2.527 mm, RMS = 0.053 mm



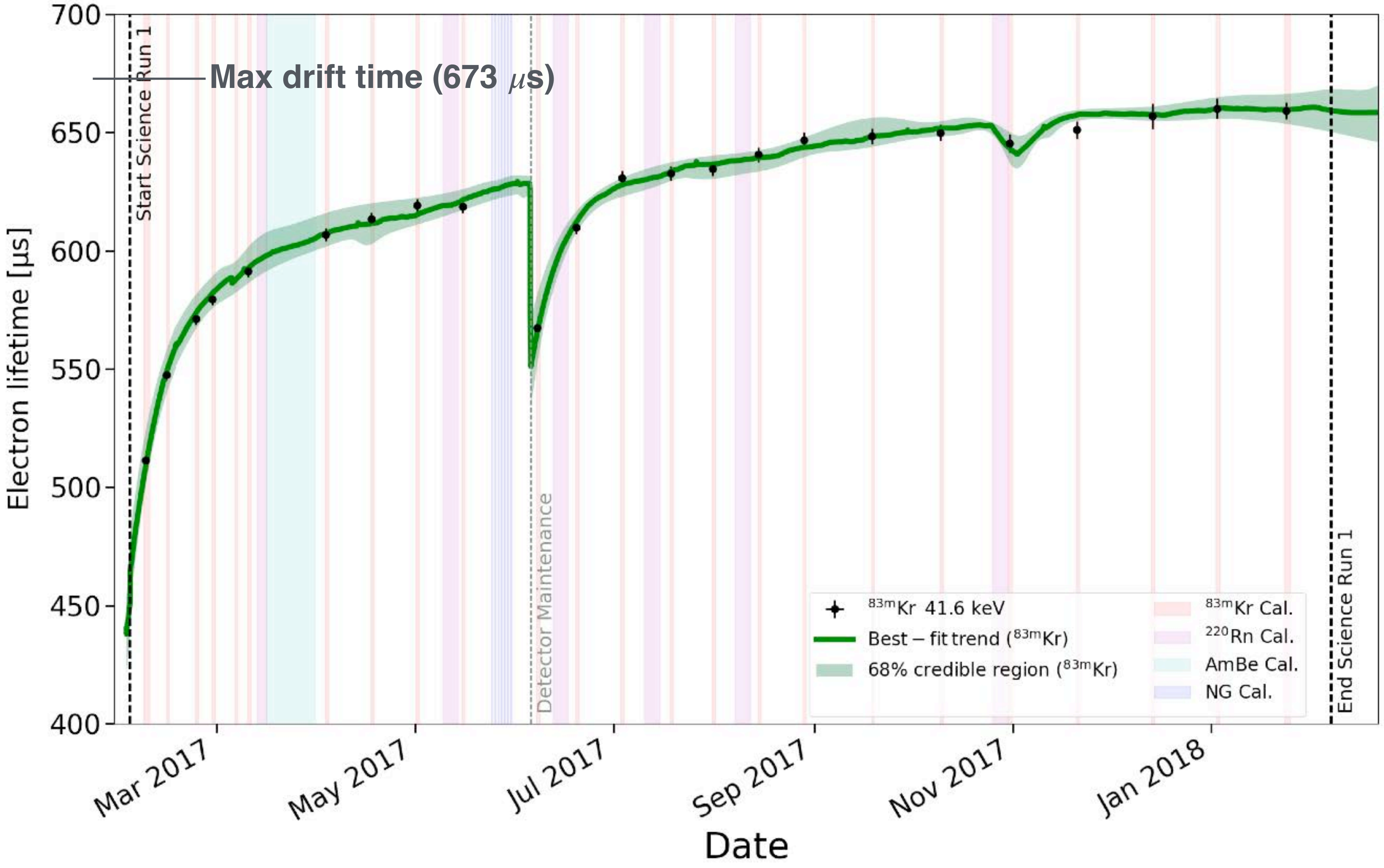


Mean = -96.02 °C, RMS = 0.02 °C

The Gas Purification System

- Continuous gas purification through heated getters
- Charge loss by impurities corrected with e-lifetime measured from ^{83m}Kr calibration and Rn222 alphas

$$S_2(t) = S_2(t_0)e^{(-t/\tau_e)}$$

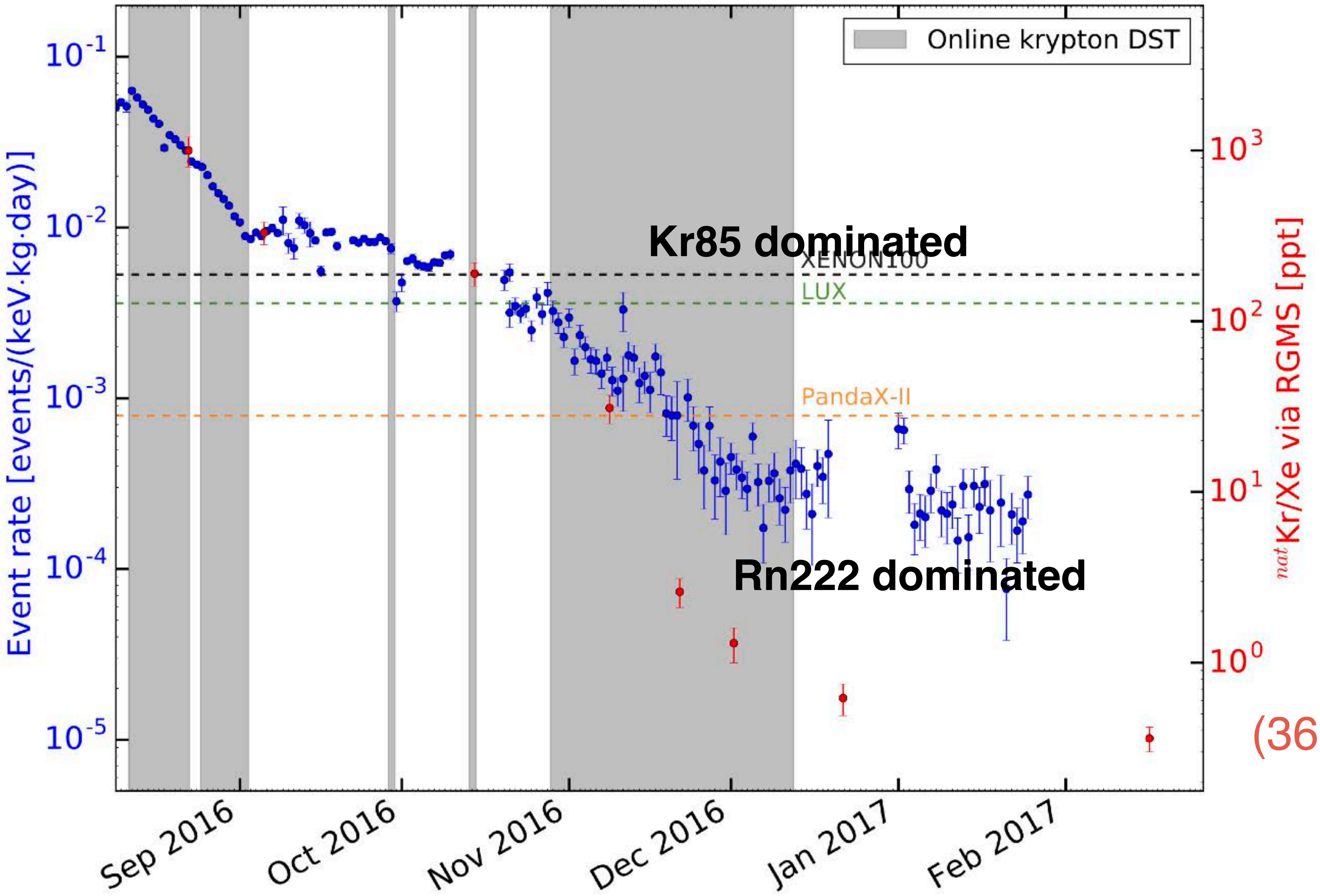


- Model accounts for the different impurity concentrations and outgassing in GXe and LXe, flow rate and other detector conditions
- Maximum electron lifetime achievable is limited by the outgassing of materials and the maximum purification flow rate, itself limited mostly by the circulation pumps

The Distillation Column

- Commercial Xe: 1 ppm - 10 ppb of Kr
- XENON1T sensitivity demands: 0.2 ppt
- Solution: 5.5 m distillation column, 6.5 kg/h throughput
  >6.4×10^5 separation, output concentration < 26 ppq (RGMS)
- on-line distillation used to reduce Kr/Xe while taking data
- Regular samples from TPC measured with a RGMS

EPJ-C74, 2014



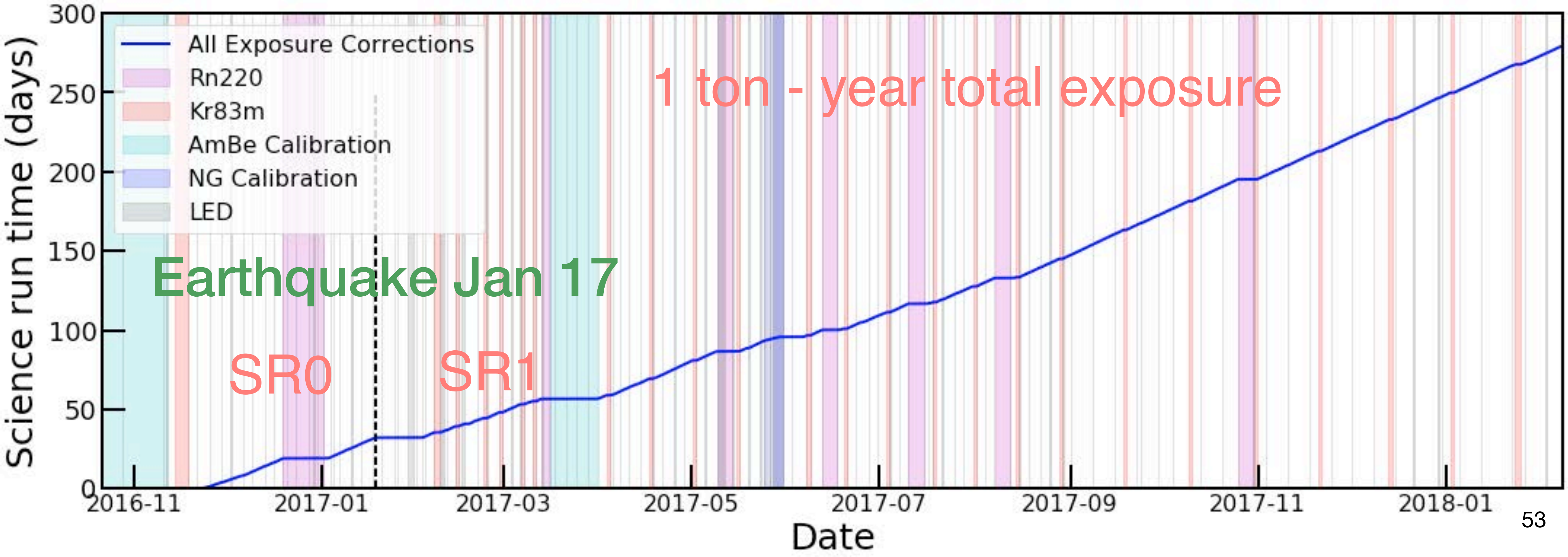
Kr85 dominated

Rn222 dominated

(360 ± 60) ppq

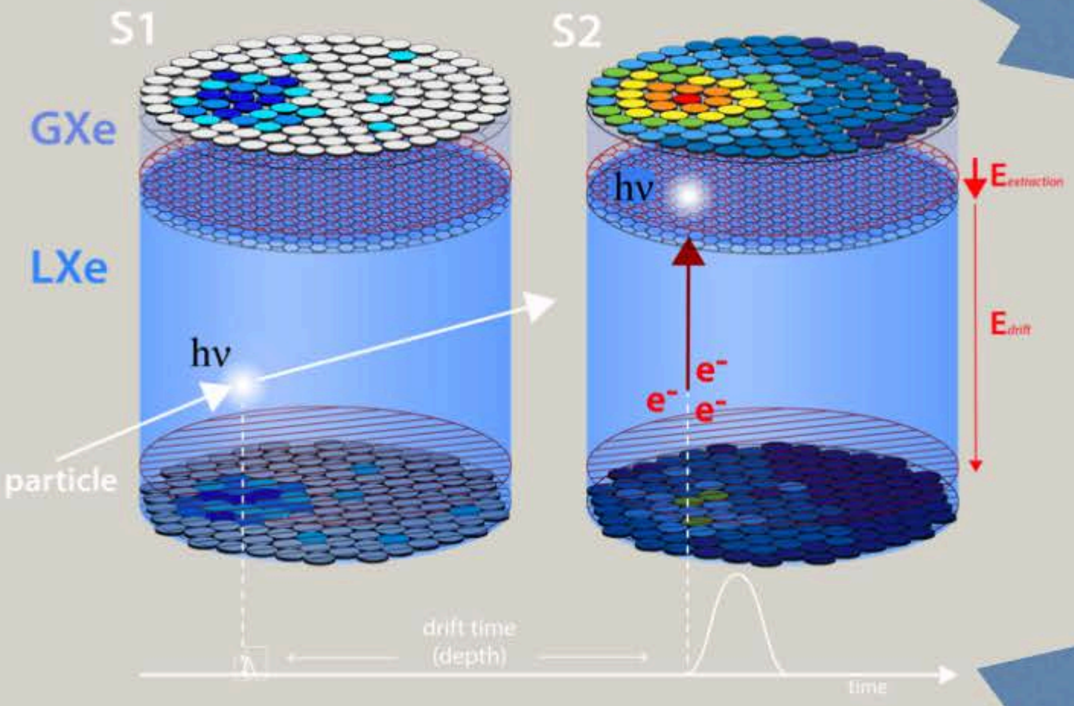
XENON1T Data overview: science and calibration

- Detector still running smoothly and taking data with high efficiency
- SR0 (34.2 days): best SI limit 7.7 x 10^{-47} cm^2 at 35 GeV/cm^2 (PRL 119, 2017)
- SR1 (246.7 days): improved detector stability - calibration statistics - refined analysis
- Total Exposure: 1 ton-year for the estimated 1.3 ton fiducial mass!



XENON1T data analysis

XENON1T
(real waveforms)



Geant4
+waveform
simulation

Raw data
Processor (PAX)

- pulse-finding
- pos reconstruction
- S1, S2
- etc.

Calibration
analysis

Background
analysis

Statistical
interpretation

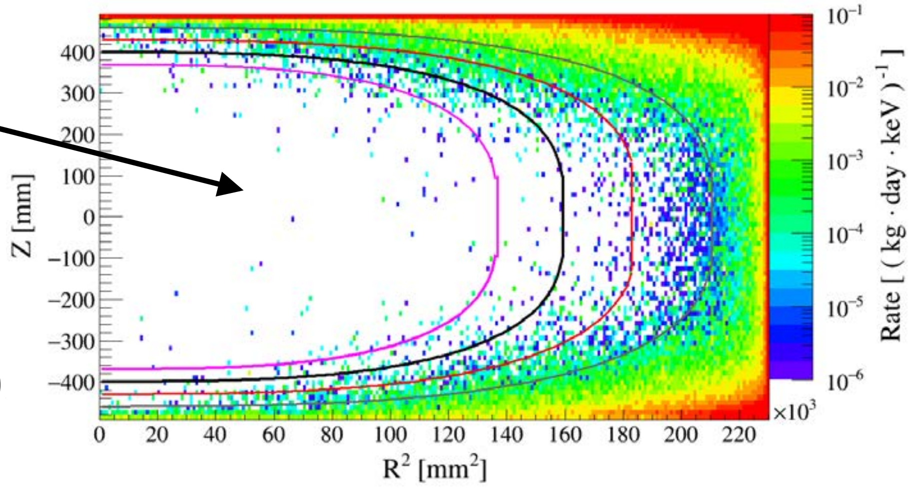
Physics Results

ER Background: Monte Carlo

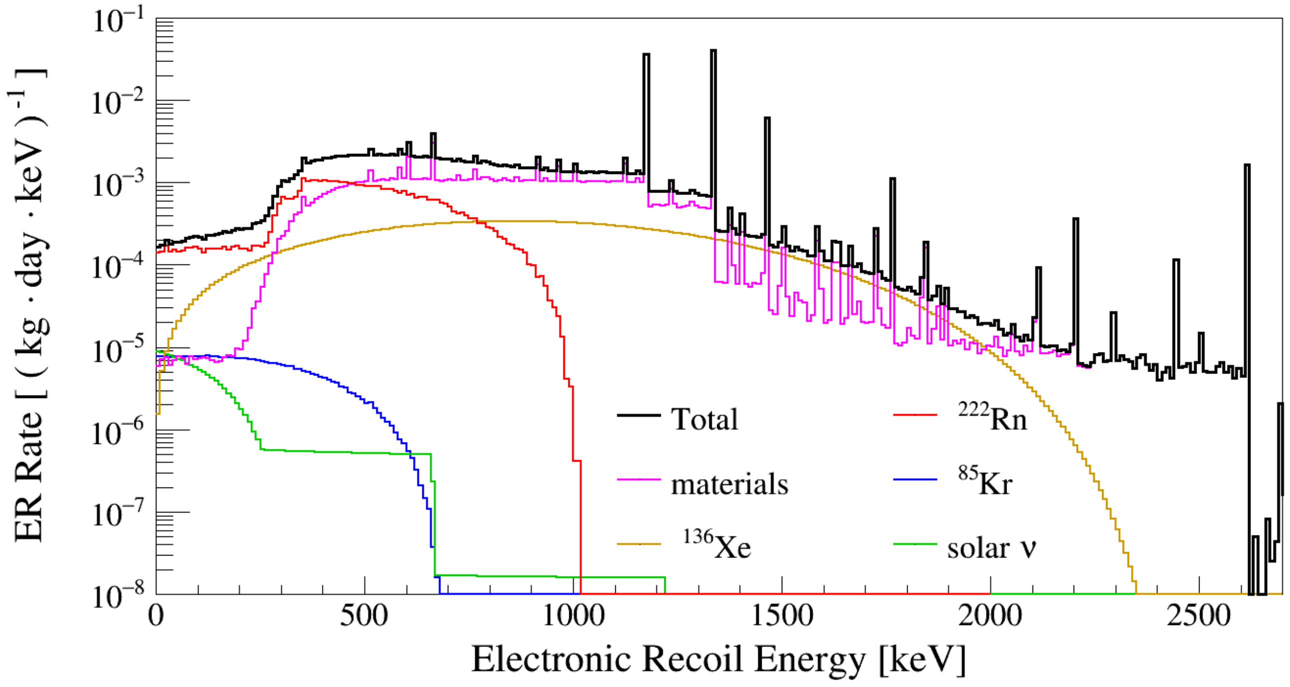
Predictions from MC simulations: ER background from materials is negligible in the 1t FV.

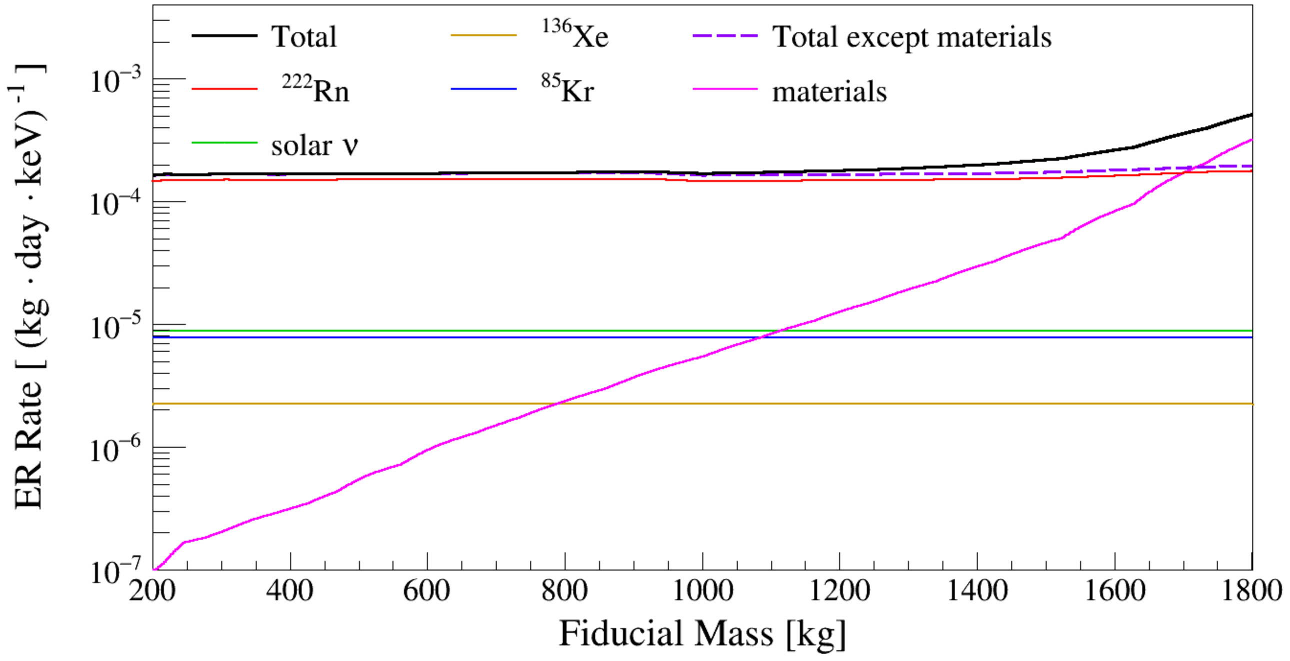
MC assumptions on the intrinsic backgrounds:

- 0.2 ppt of ^{nat}Kr (achieved in XENON1T distillation column tests),
- 10 μBq/kg of ^{222}Rn (estimation based on Rn emanation measurements)



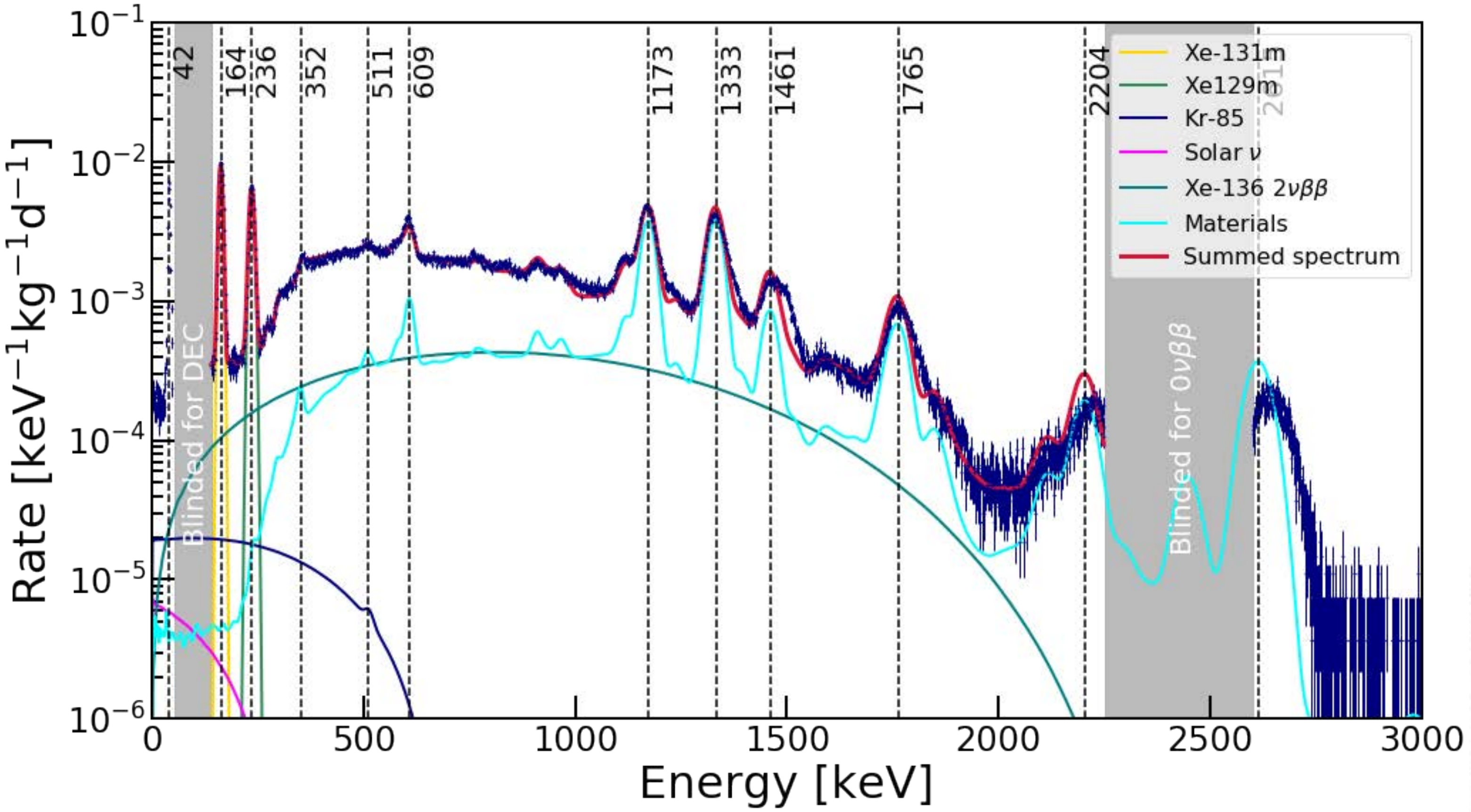
Eur. Phys. J. C77 (2017) no.5, 275 & arXiv:1702.06942





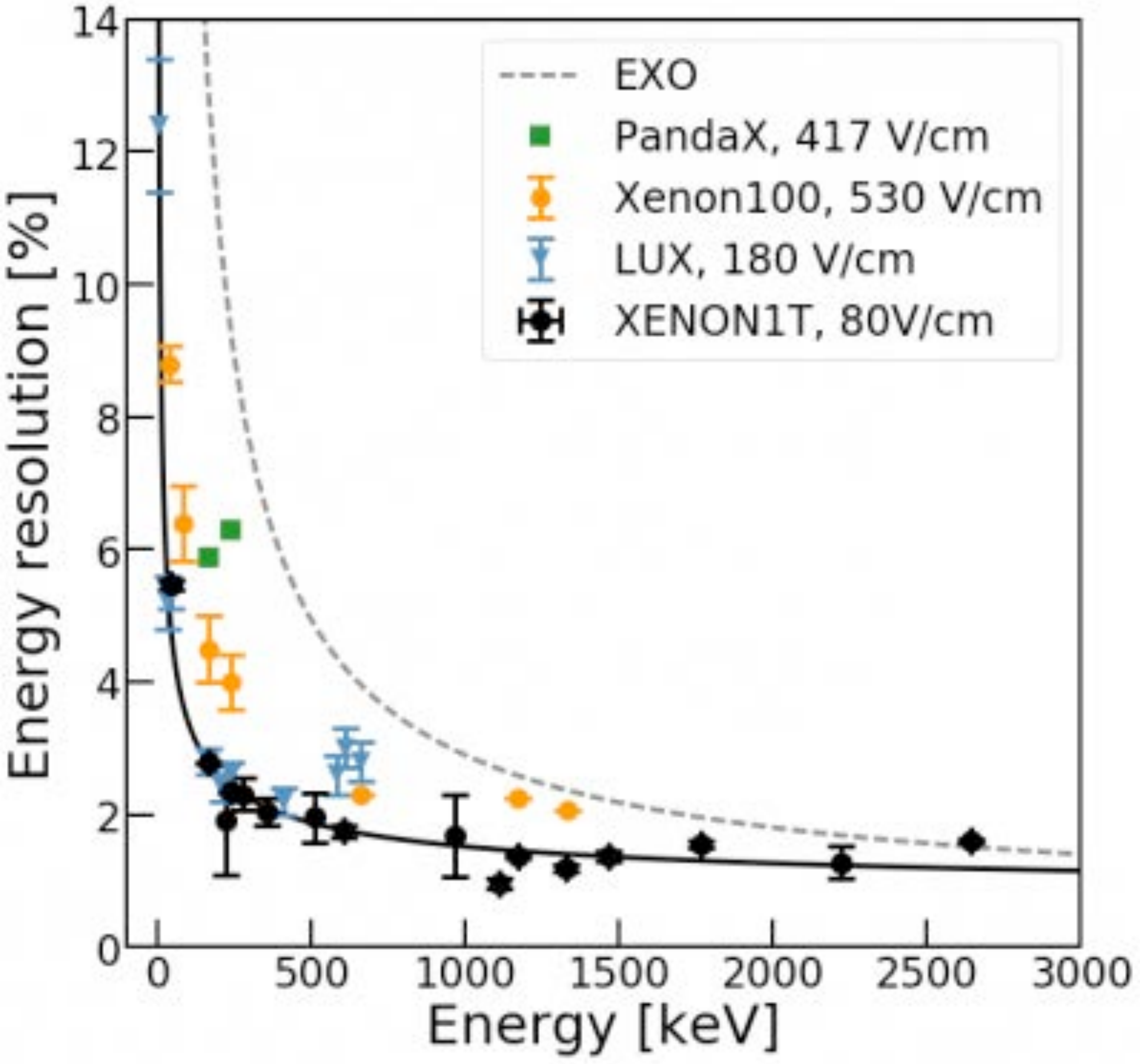
^{222}Rn (mainly from ^{214}Pb β-decay) is the most relevant source of ER background in most of the TPC.

Background Data: Energy Spectrum and Energy Resolution



- Good agreement between predicted and measured background spectrum
- Kr: ~0.45 ppt; Pb214: ~ 10 uBq/kg
- Gammas based on screening measurements

- Excellent energy resolution measured with a large LXeTPC
- Background



Exciting time ahead!

A blind analysis is the only way to perform this type of rare event search

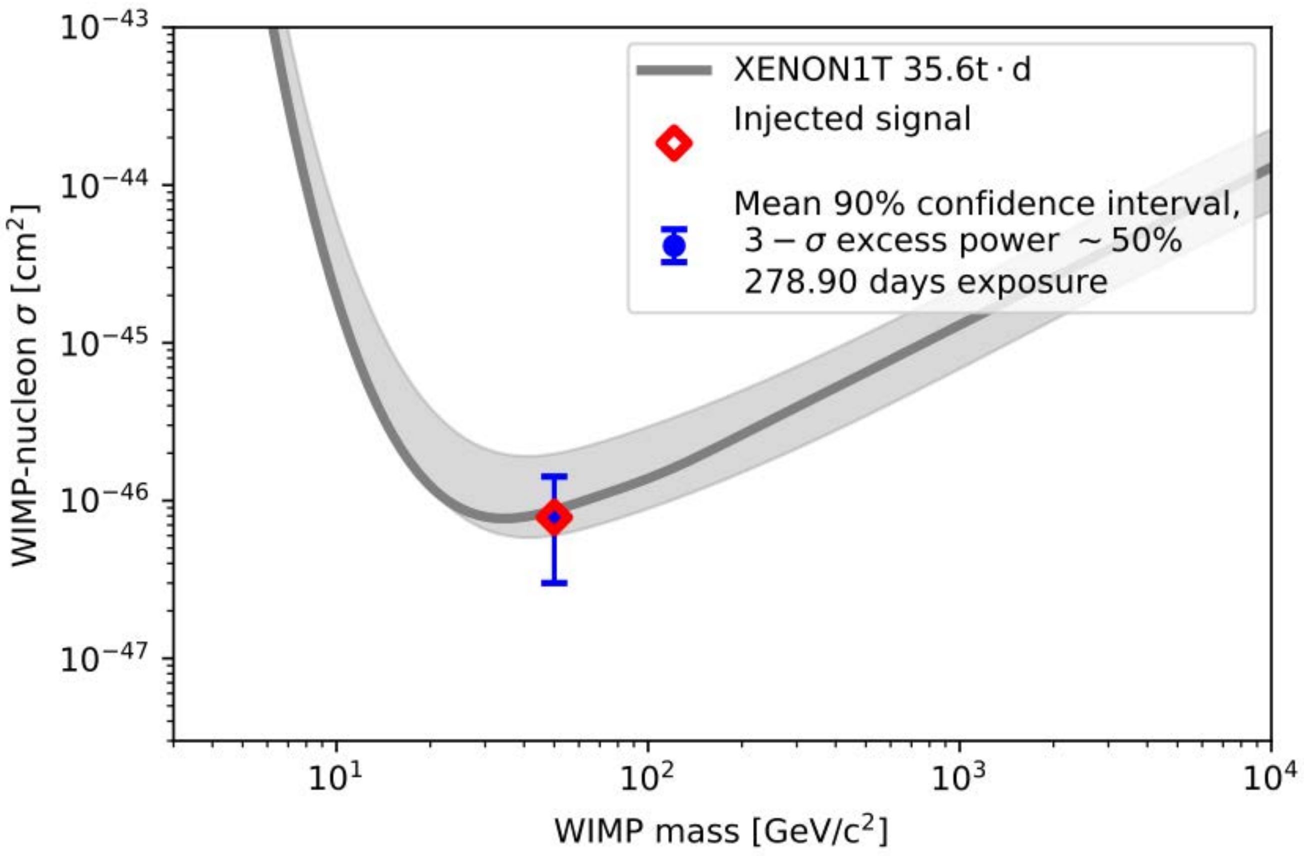
- Signal region inaccessible to analysts until analysis fixed
- Prevents human bias

The data is also 'salted'

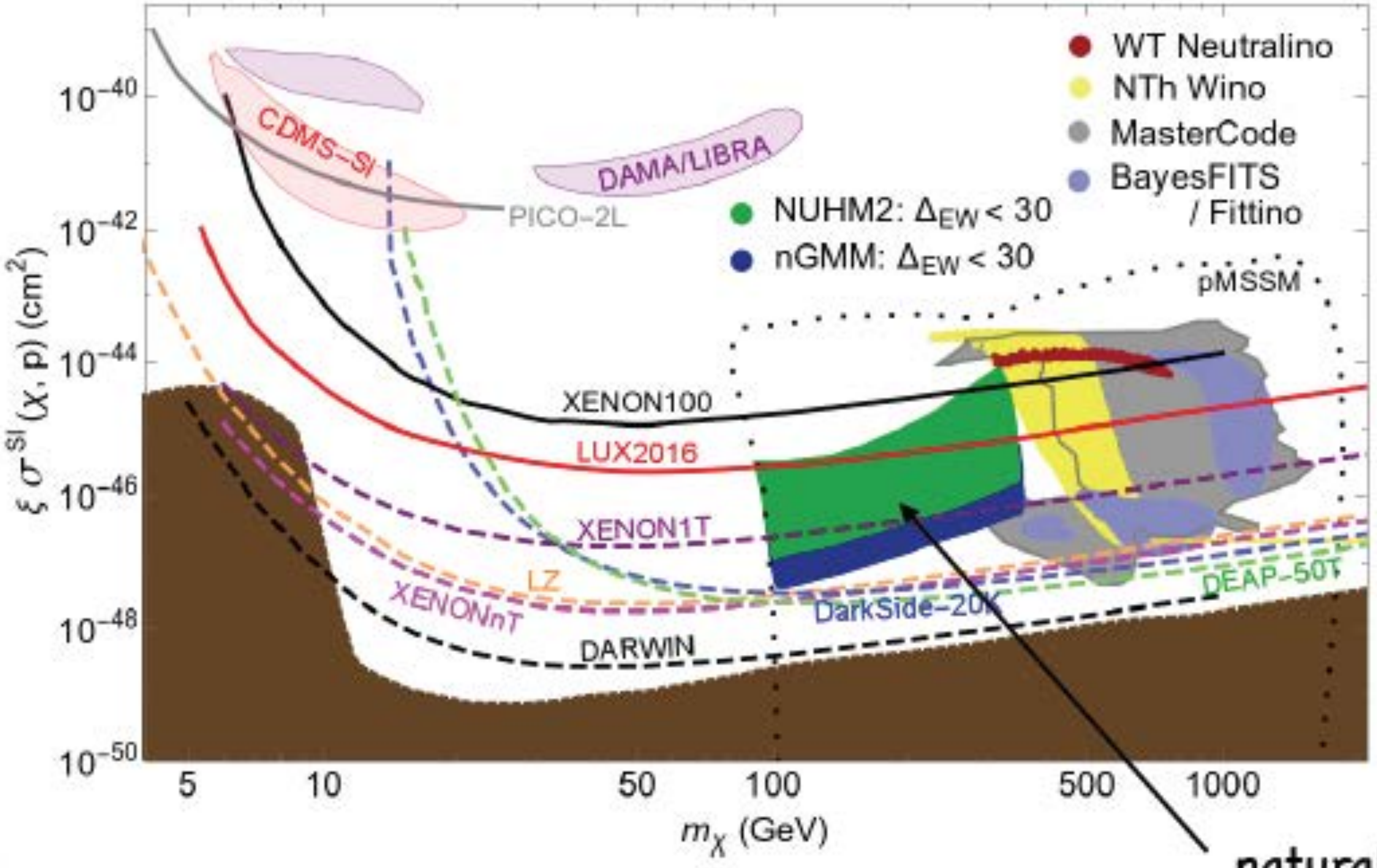
- Fake signal events may or may not inhabit signal region
- Additional protection against bias in post-unblinding scrutinization of events

We're unblinding this data very soon!

- For a WIMP-nucleon cross-section at the current best limit, this exposure has >50% chance at a 3-sigma excess



Direct higgsino detection rescaled for minimal local abundance $\xi \equiv \Omega_\chi^{TP} h^2/0.12$



natural SUSY

Bae, HB, Barger,Savoy,Serce

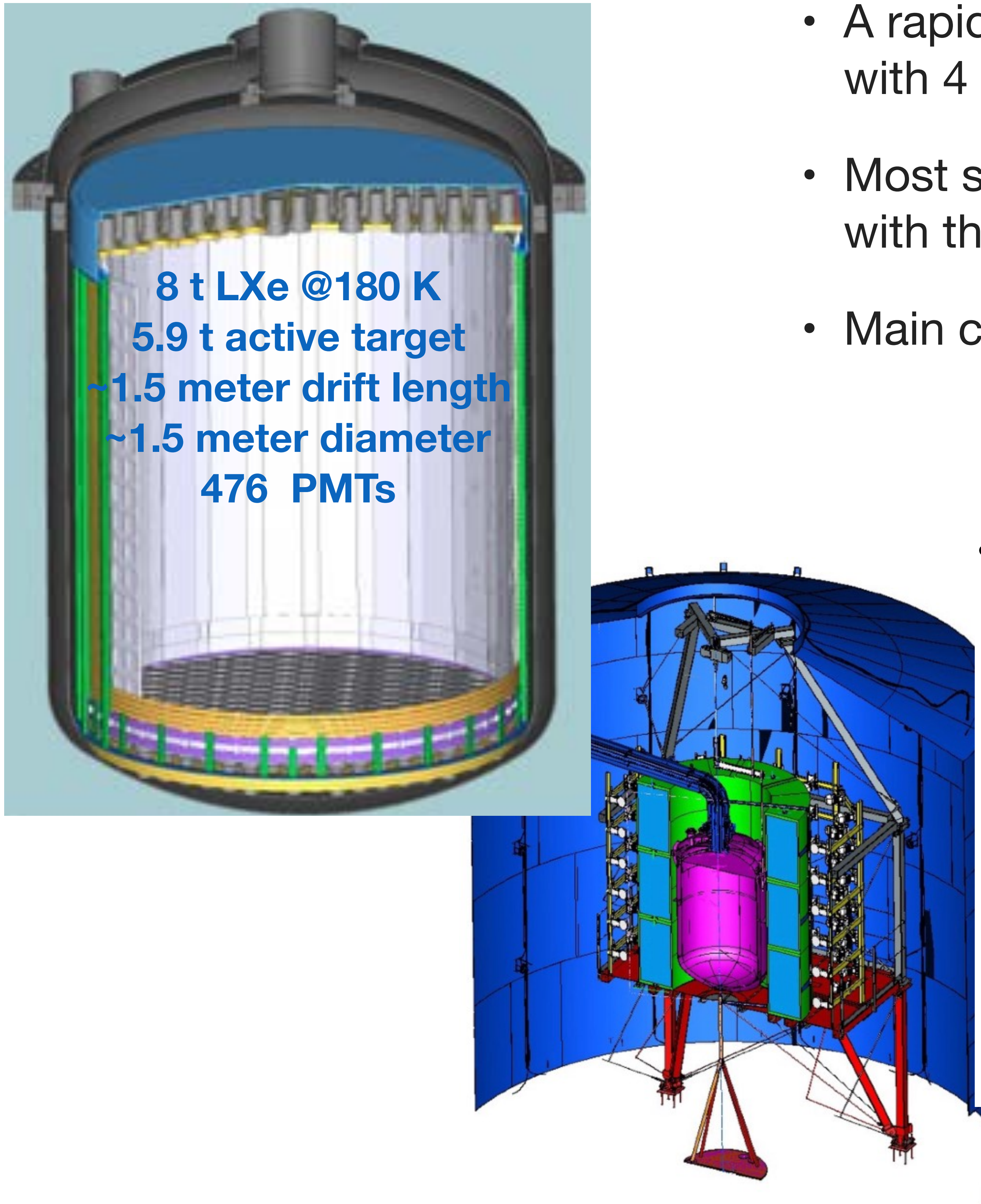
$$\mathcal{L} \ni -X_{11}^h \overline{\tilde{Z}}_1 \tilde{Z}_1 h$$

$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

Xe-1-ton
now operating!

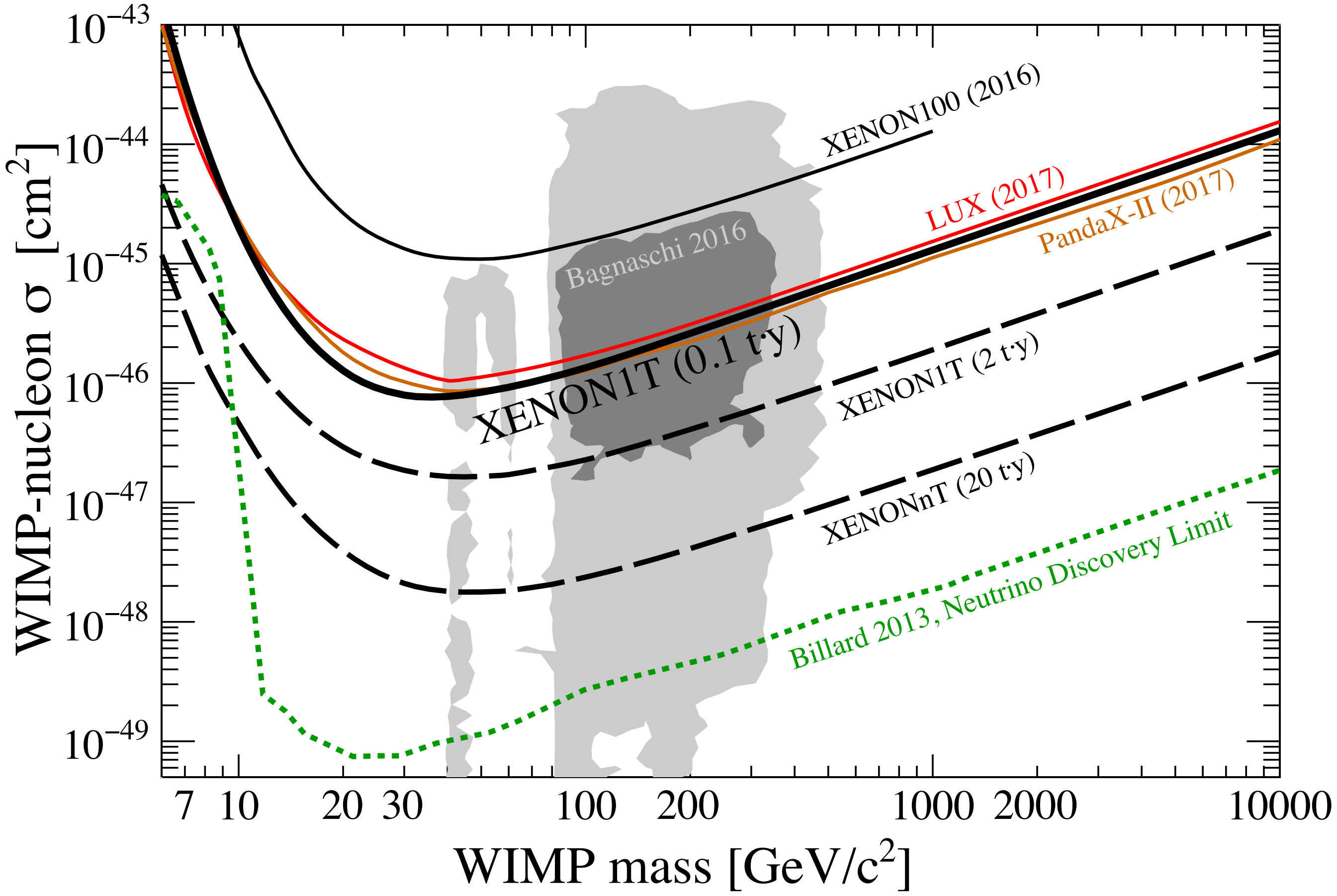
Can test completely with ton scale detector or equivalent (subject to minor caveats)

Next step: XENONnT to start in 2019

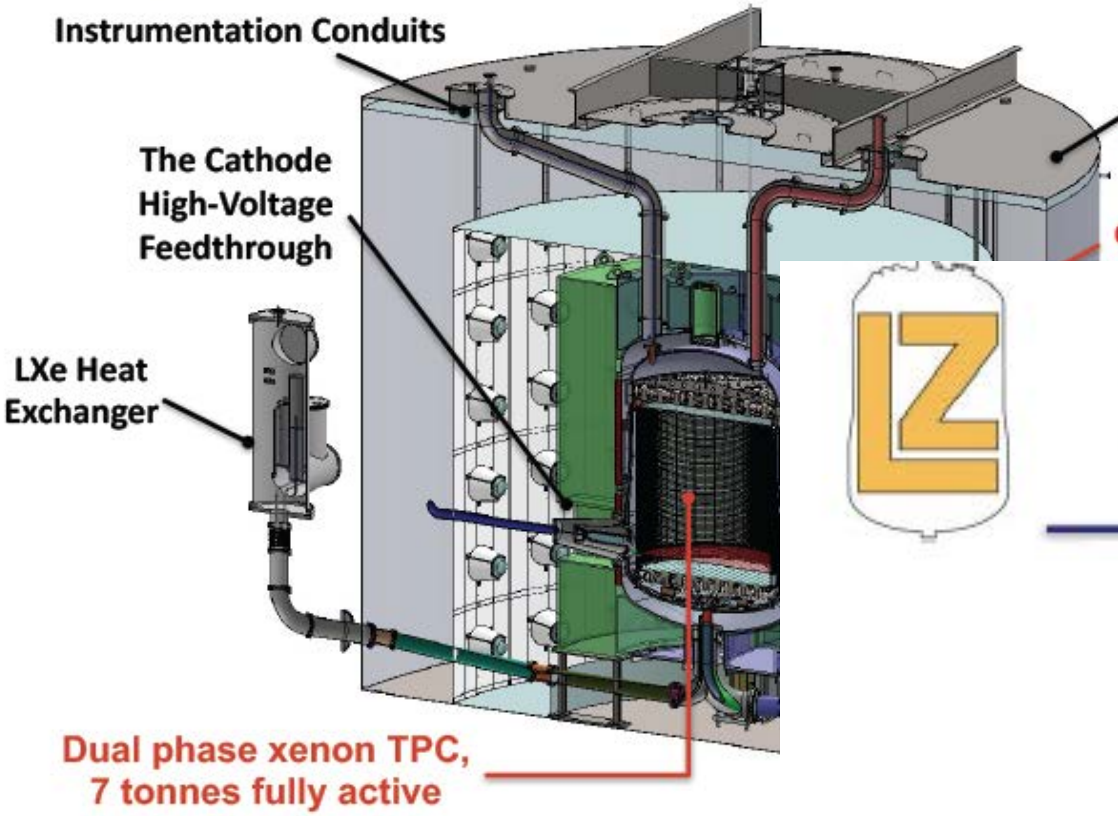


8 t LXe @180 K
5.9 t active target
~1.5 meter drift length
~1.5 meter diameter
476 PMTs

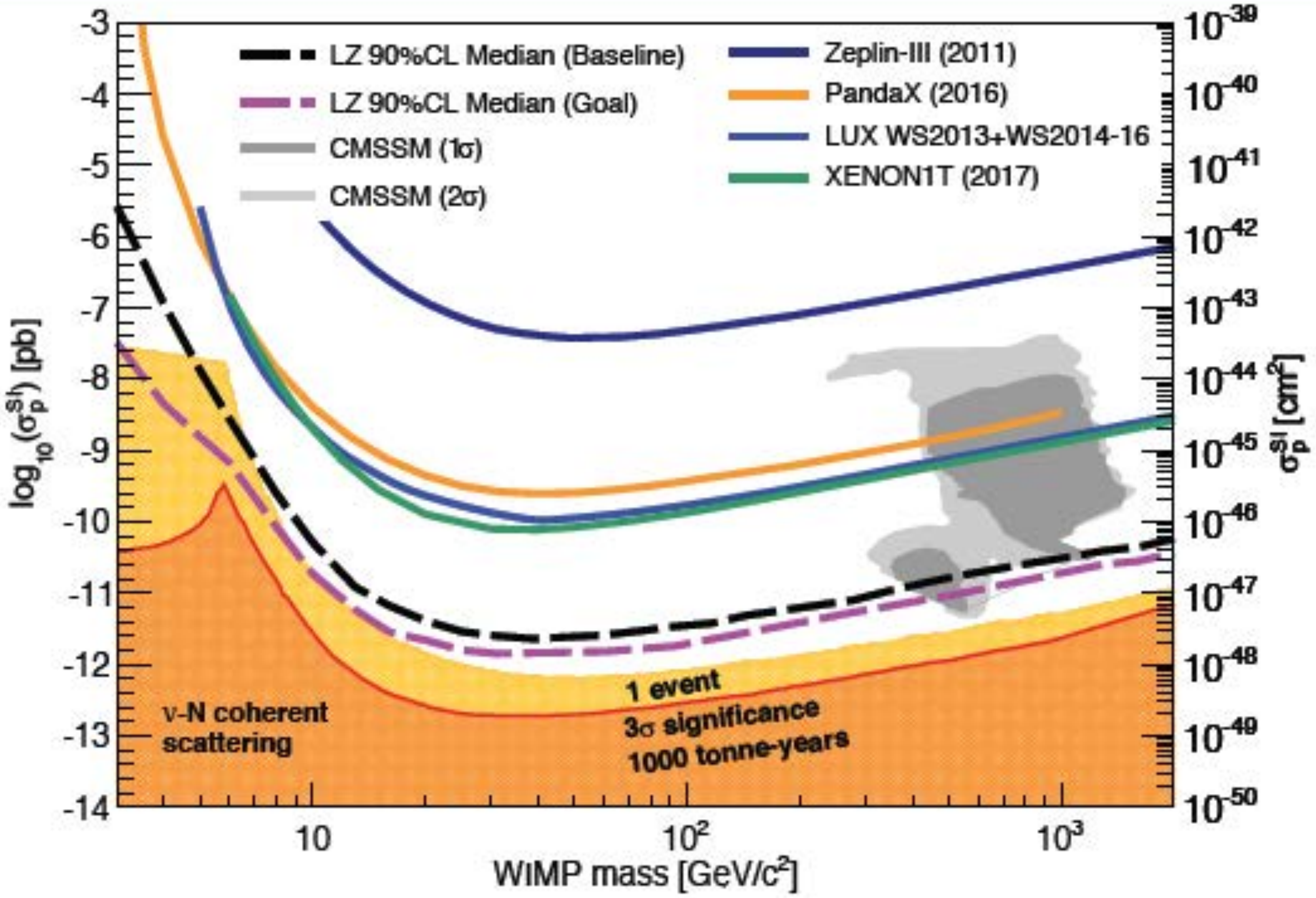
- A rapid upgrade to XENON1T, with a new TPC with 4 x target mass than XENON1T
- Most sub-systems, already operative, designed with this upgrade in mind
- Main challenge: reduce Radon by x 10



The LUX-ZEPLIN detector



LZ Spin-Independent WIMP Sensitivity



- Baseline WIMP sensitivity is 2.3 x 10^{-48} cm^2 @ 40 GeV/c^2 (arXiv:1703.0914).
- 1000 days, 5.6 tonne fiducial mass.
- Begin on-site assembly spring 2018, install underground 2019, first data spring 2020.

Summary

- XENON1T is the first LXeTPC dark matter at the multi-ton scale in operation.
- First result with 34 live days yielded the most stringent limit on SI WIMP cross section.
- Detector has continued to work incredibly well after the break forced by an earthquake.
- Demonstrated > 1 year operation with 3.2 t of LXe: a milestone for this technology.
- Achieved the lowest background ever measured in a DM detector: 0.2 events/ (t keV d)
- Collected ~ 1 ton x year dark matter data and large calibration statistics.
  - Data still blinded. Expect world-leading result in March 2018.
  - > 50% chance for a 3 sigma signal if WIMP cross-section at current limit!
- XENON1T continues to take data until we upgrade it to XENONnT. Installation of the new TPC (~6 t Xe target) before end of 2018.