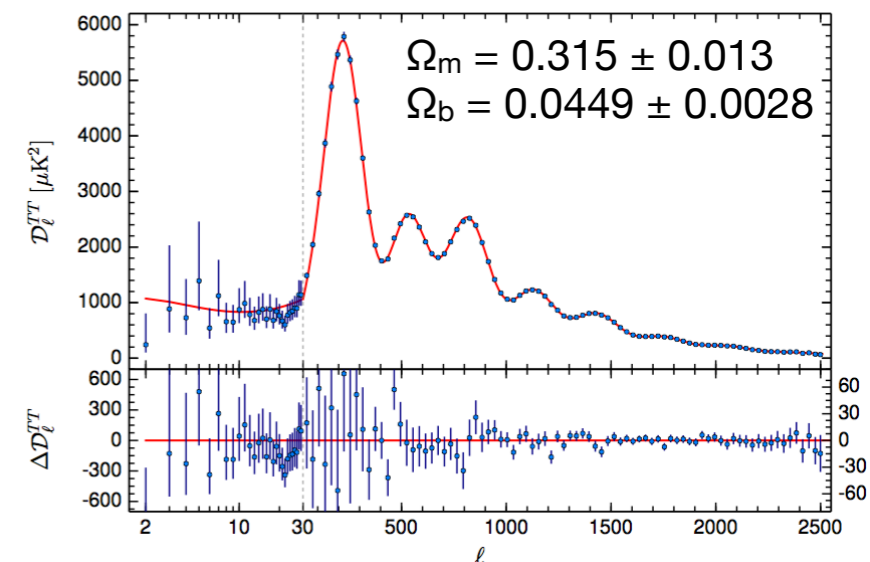
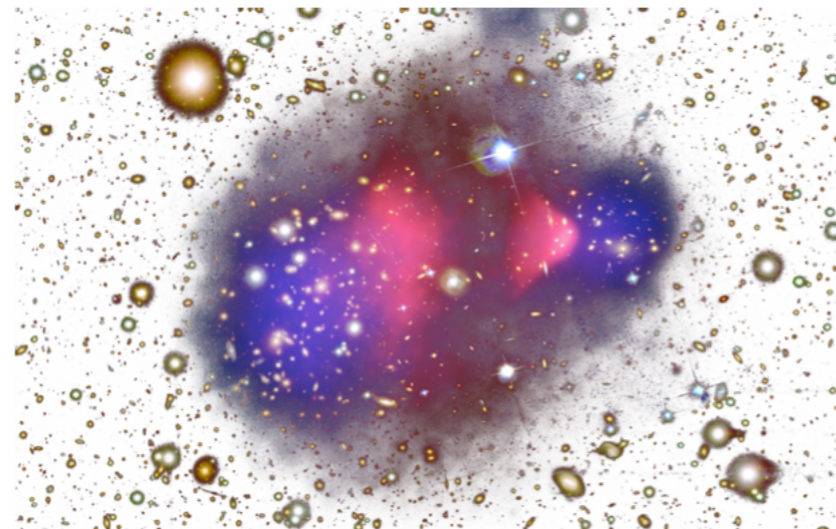
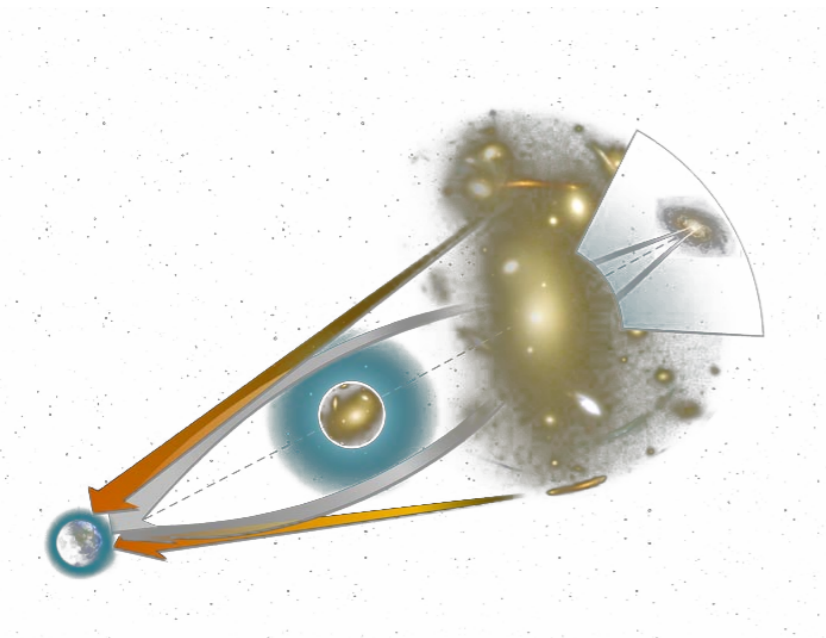
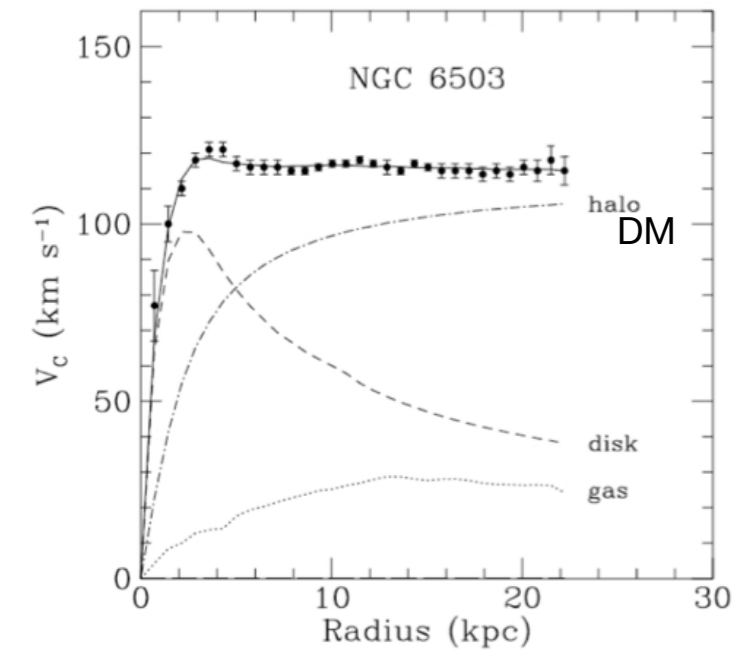
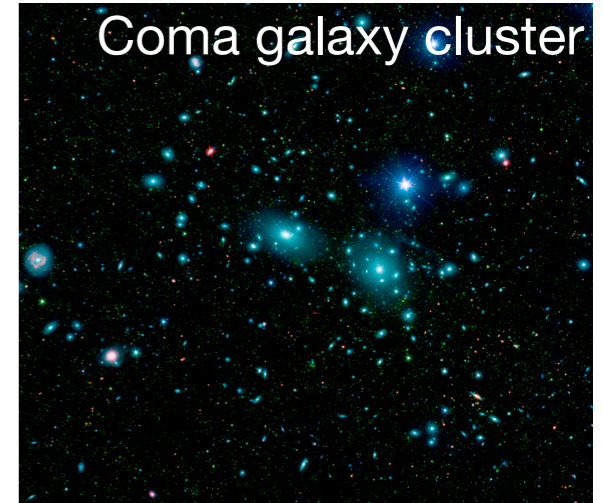


# XENON: Dual-phase TPCs for Dark Matter Detection



**Alexander Kish**  
Department of Physics, University of Zürich

- Redshift / velocity dispersion measurements in galaxy clusters  
(dark matter postulated 82 years ago by Fritz Zwicky) [Helv. Phys. Acta 6, 110-127 \(1933\)](#)
- Rotation curves of stars and gas in galaxies  
(pioneering work of Vera Rubin) [The Astrophys. J. 238, 471-487 \(1980\)](#)
- Temperature spectrum of Cosmic Microwave Background  
(energy density at the time of photon decoupling)
- Gravitational lensing  
(gravitational deflection of photons)

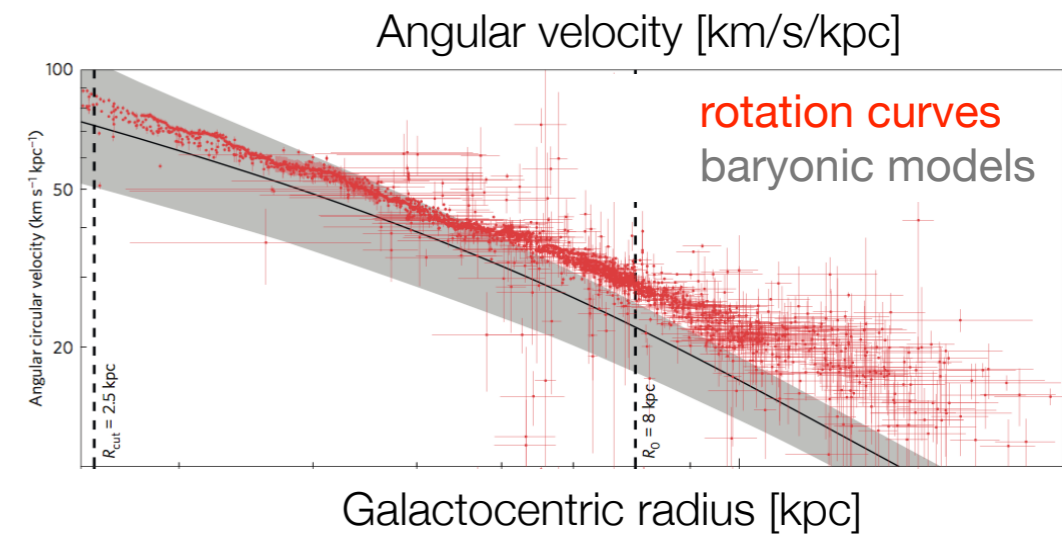
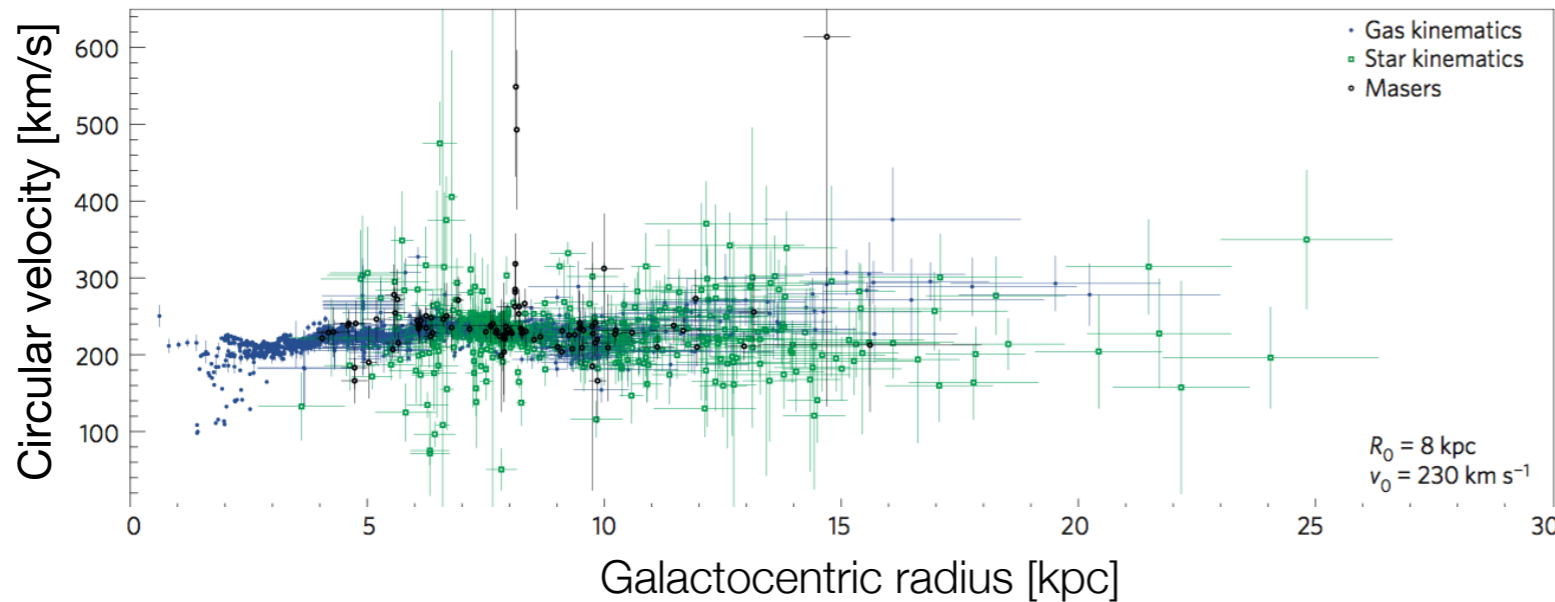




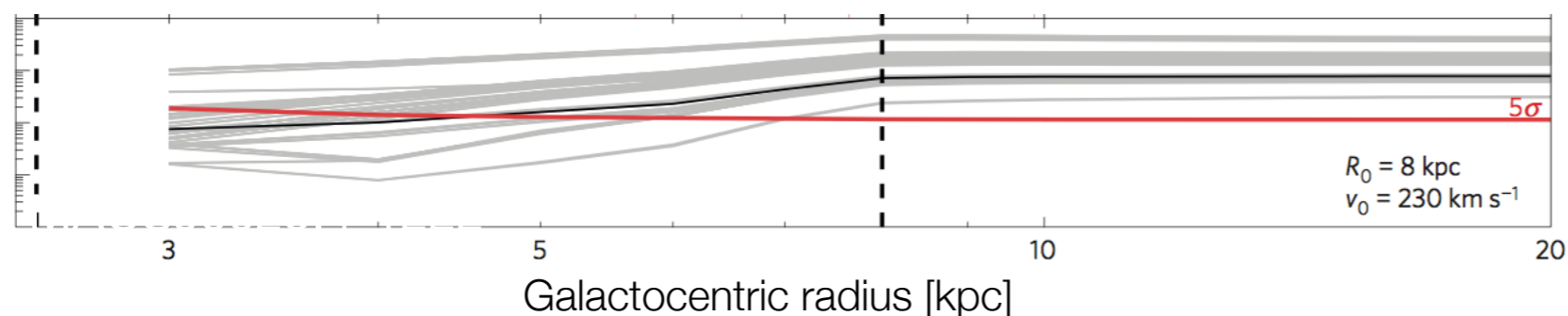
## Evidence for dark matter in the inner Milky Way

Fabio Iocco<sup>1,2\*</sup>, Miguel Pato<sup>3,4</sup> and Gianfranco Bertone<sup>5</sup>

- Compilation of rotation curve data (2780 measurements)

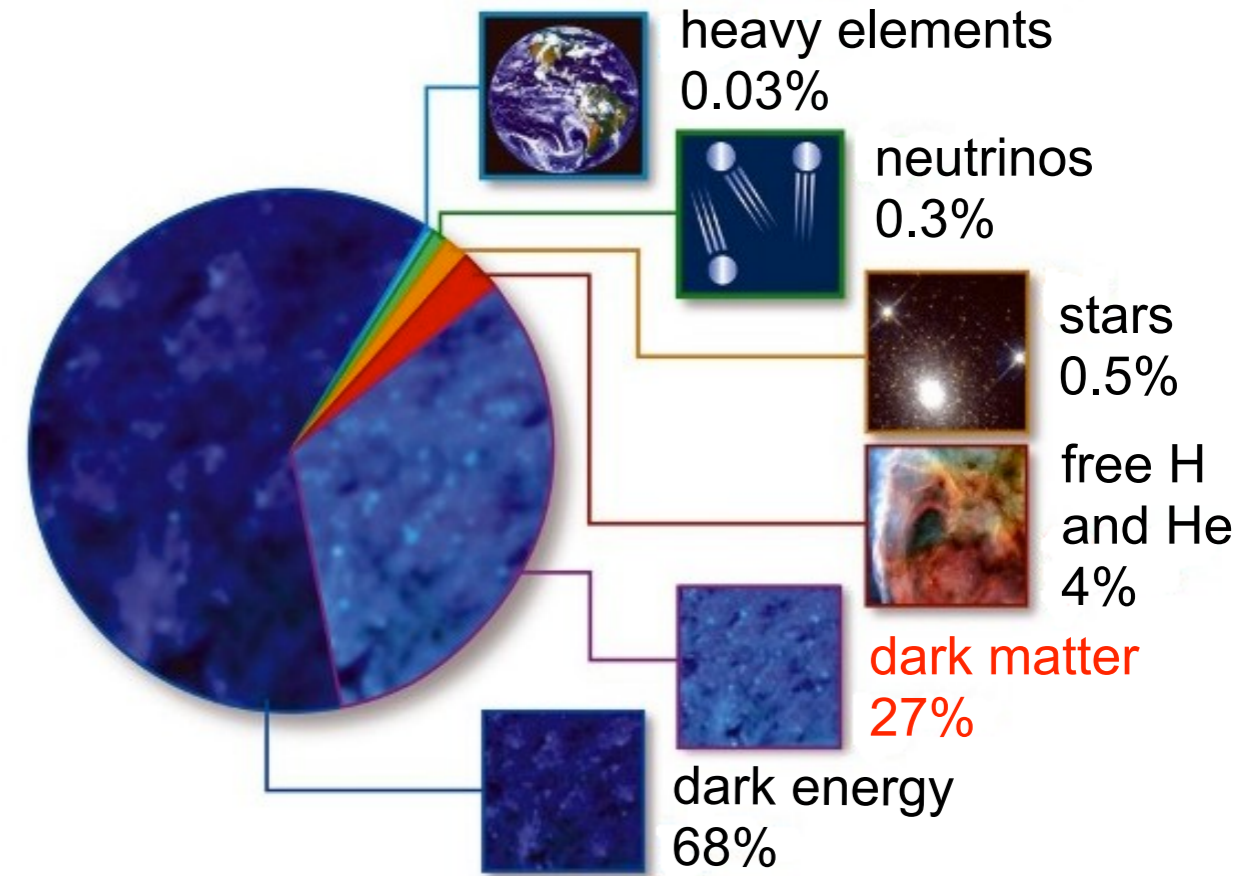


- Discrepancy between observations and expected contributions from baryonic models
- Evidence for dark component above  $5\sigma$



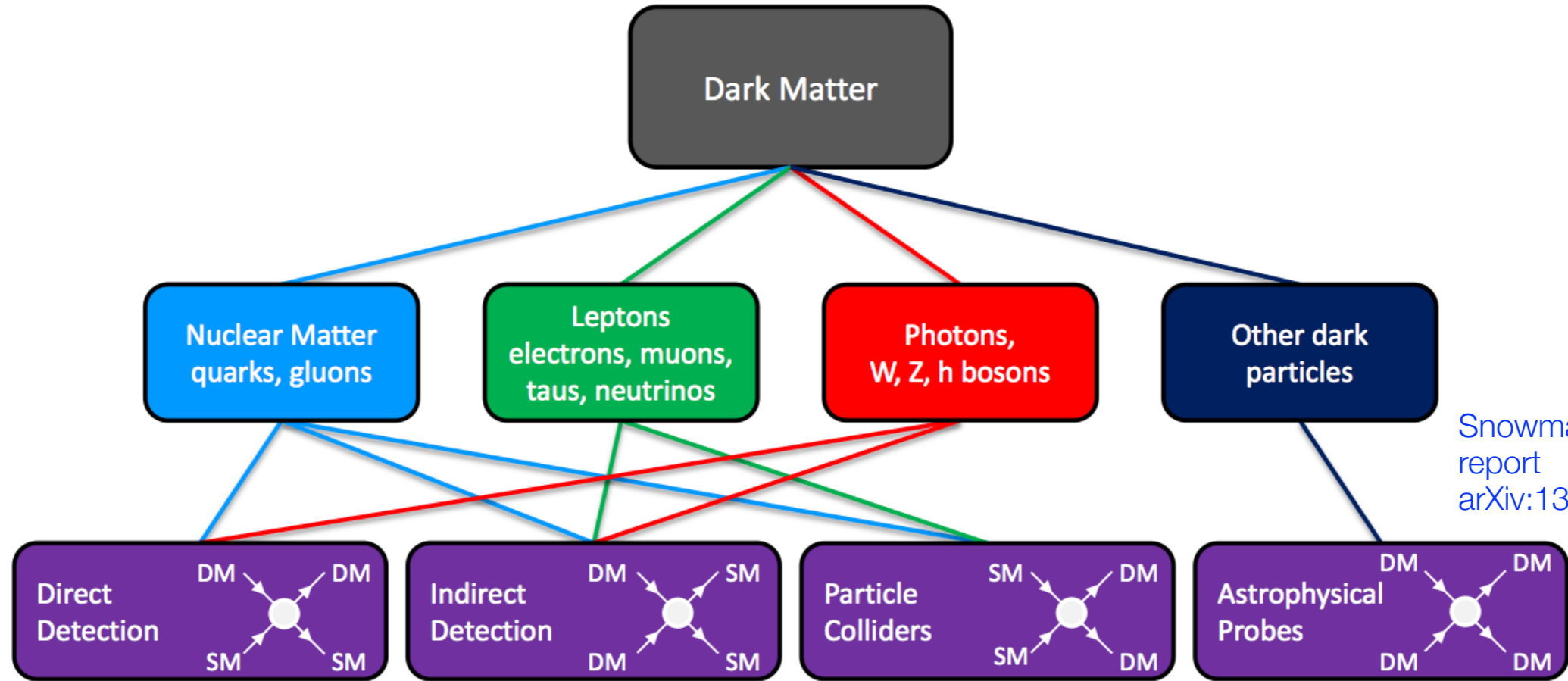
## Properties

- Leads to the formation of structure and galaxies in the universe
- In thermal equilibrium with the rest of the particles in the early universe
- 'Cold' (non-relativistic at the time of decoupling)
- No electric charge
- No color charge
- No strong self-interaction
- Not a Standard Model particle
- Weak interaction → heavy [few GeV to ~10 TeV]



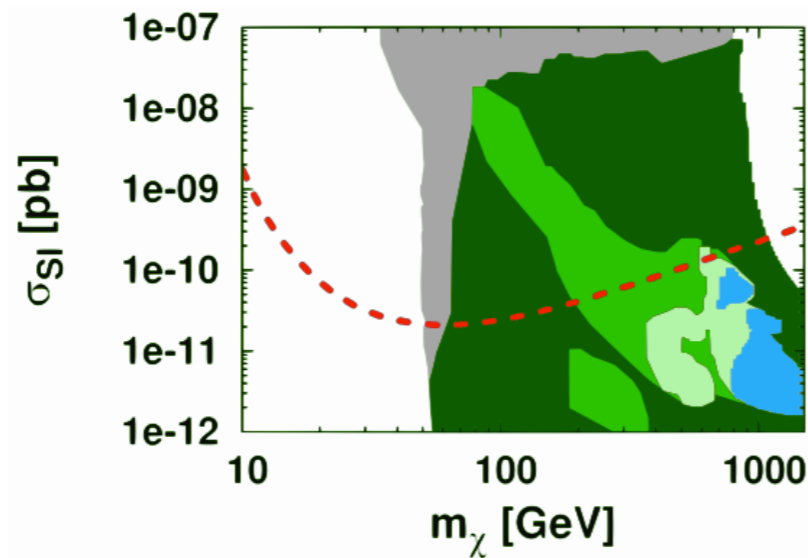
## Best candidate → Weakly Interacting Massive Particle (**WIMP**)

- Supersymmetry: lightest superpartner with R-parity conservation
- Universal extra dimensions: lightest Kaluza-Klein particle, first excitation of the hypercharge gauge boson



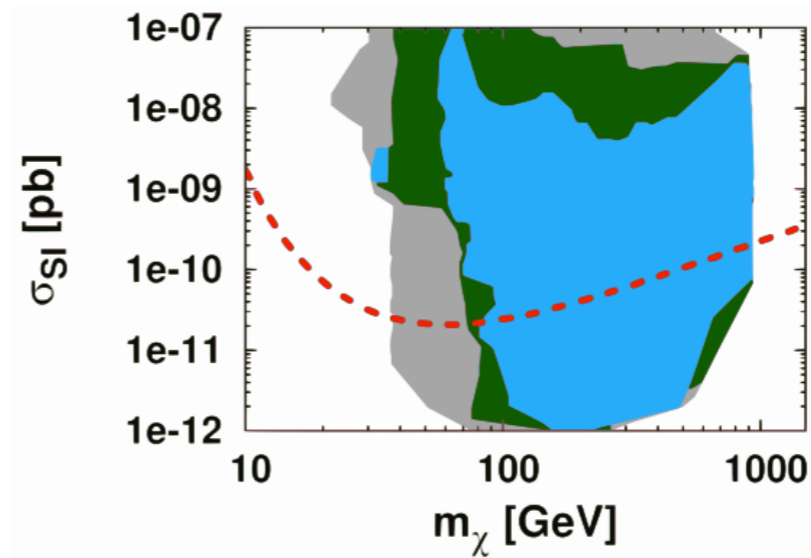
Snowmass CF1  
report  
arXiv:1310.8327

CMSSM



(a)

NMSSM



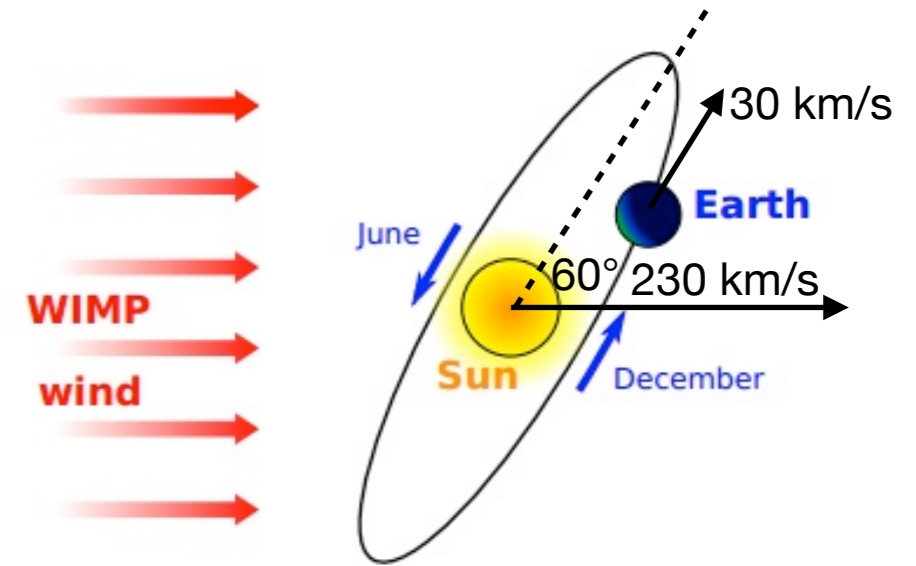
(b)

parameter space ■      Higgs +  $\Omega h^2$  ■      all con. + LHC14 ■  
Higgs = 126 GeV ■      all constraints ■      XENON1T - - -

Phys. Lett. B738,  
505–511 (2014)

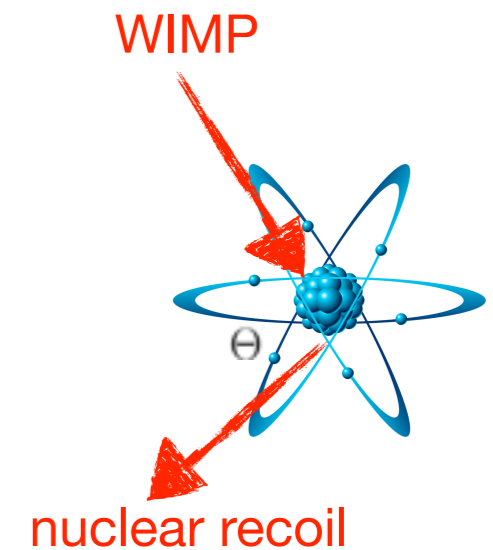
## Standard Halo Model

- Non-rotating isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution
- Local dark matter density (0.2–0.56) GeV/cm<sup>3</sup>  
→ average ~ 0.3 GeV/cm<sup>3</sup>
- WIMP (~100 GeV/c<sup>2</sup>) flux on Earth is ~ 10<sup>5</sup> cm<sup>-2</sup>s<sup>-1</sup>



## Direct Dark Matter Detection

- Search for collisions of 'invisible' particles with atomic nuclei
- Elastic scattering
- Expected energy of the recoiling nucleus with maximum of a few tens of keV



## Expected signatures

- Single scatter nuclear recoils
- ~Exponential shape of the energy spectrum
- Dependence on the target material (~A<sup>2</sup>)
- Annual flux modulation (~3% effect)

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos\Theta)$$

Scalar (**spin-independent**) interaction

- WIMP  $\chi$  couples to nucleus  $N$
- Cross-section increases with the mass  $m_N$

$$\sigma_{\text{SI}} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} [Z f_p + (A - Z f_n)]^2, \quad f_{p,n} - \text{effective couplings to p and n}$$

Axial-vector (**spin-dependent**) interaction

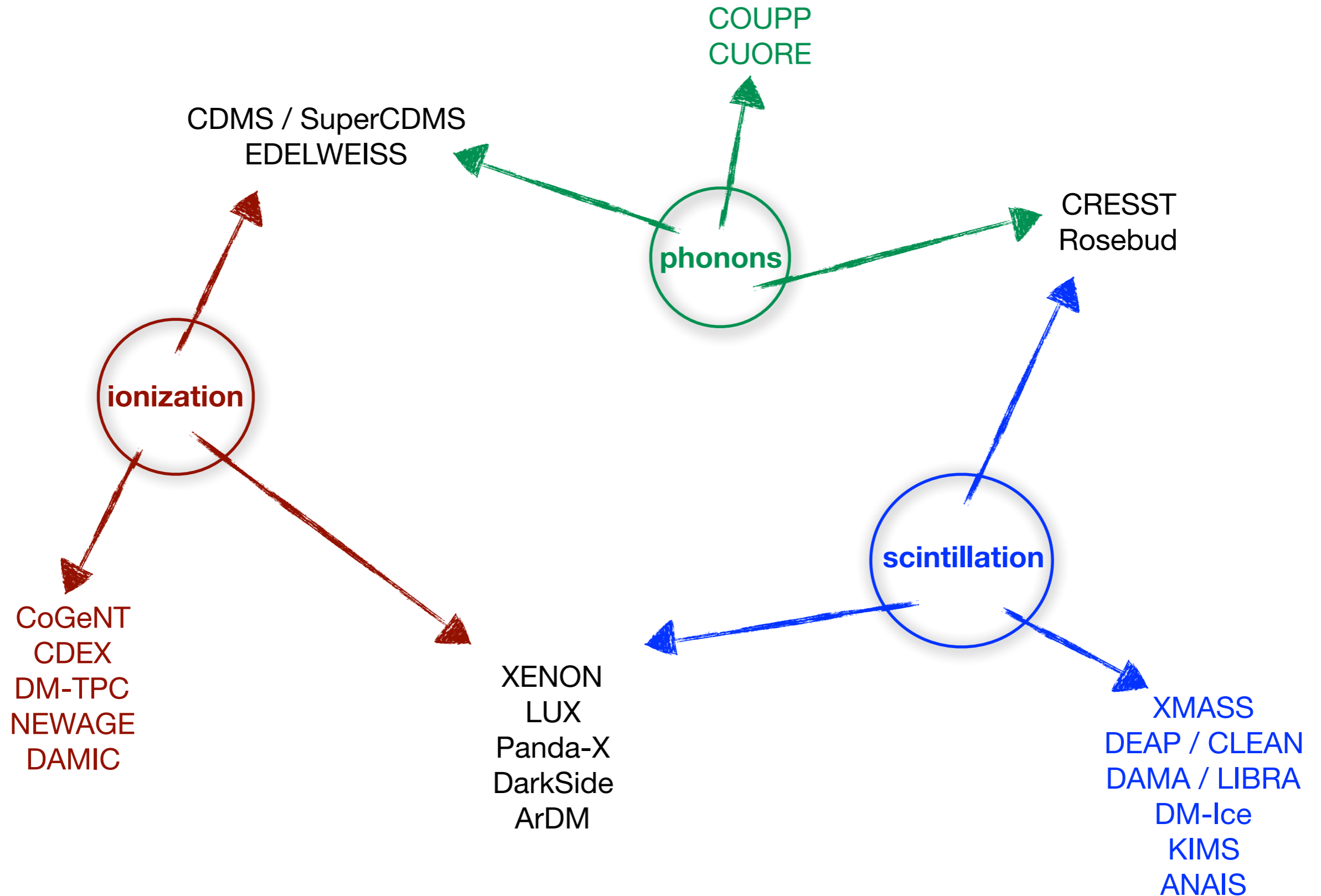
- Coupling to unpaired nuclear spin  $J_N$
- Cross-section is proportional to  $J \cdot (J+1)$  → to the number of odd-even or even-odd isotopes

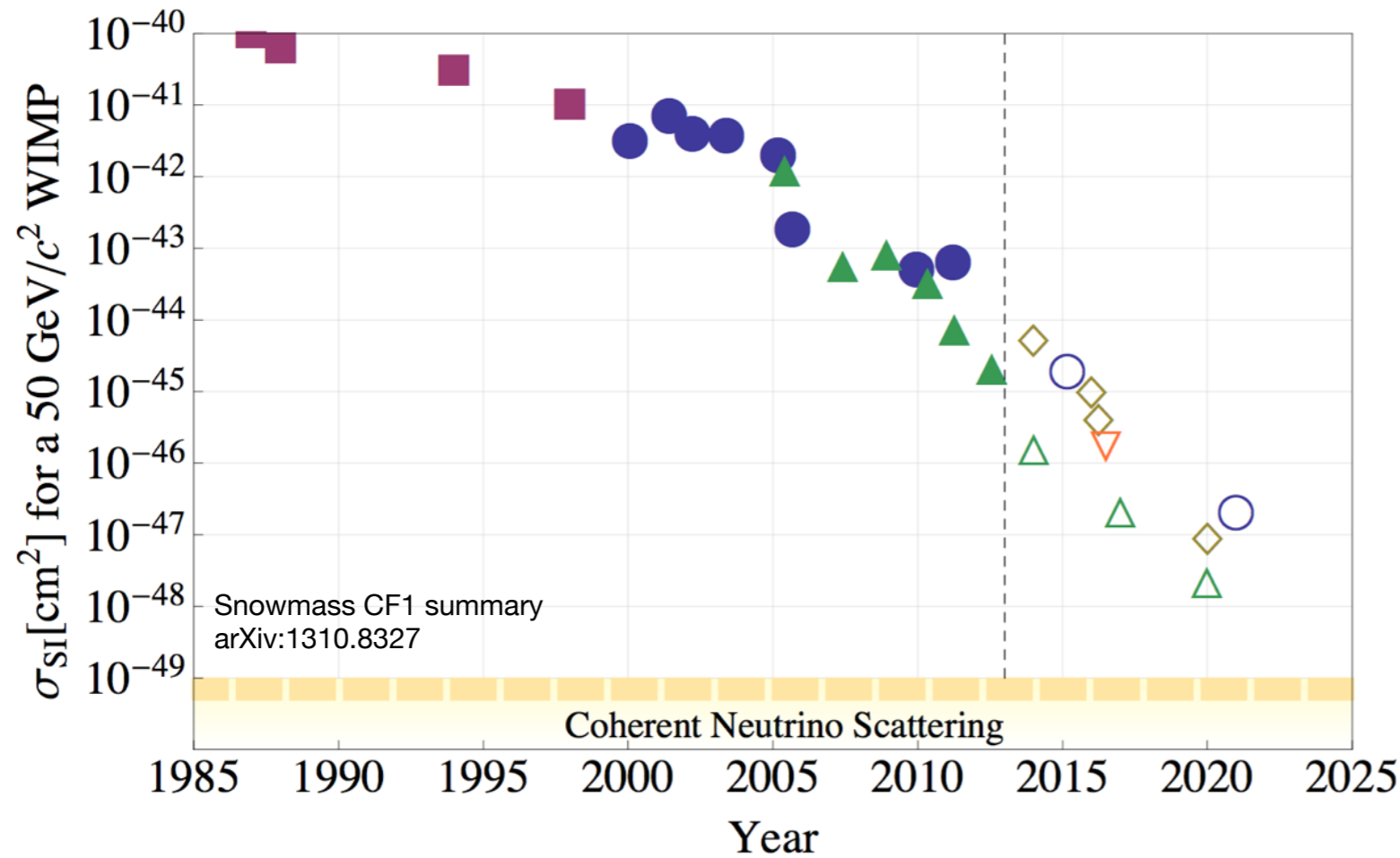
$$\sigma_{\text{SD}} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2, \quad S_{p,n} - \text{expectation values of the spin content of p and n in the target nucleus}$$

$a_{p,n}$  – effective couplings to p and n

- Variety of techniques and dedicated experiments







Requirements:

- heavy target
- low threshold
- detectable signal
- easy/cheap scalability

- Expected energy of the recoiling nucleus with maximum of a few tens of keV

→ low threshold requirement

- Differential recoil rate depends on the mass of a WIMP and target nucleus

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2m_\chi \mu^2} F^2 E_R \int_{v > \sqrt{m_N E_R / 2\mu^2}}^{v_{\max}} \frac{f(\vec{v}, t)}{v} d^3v$$

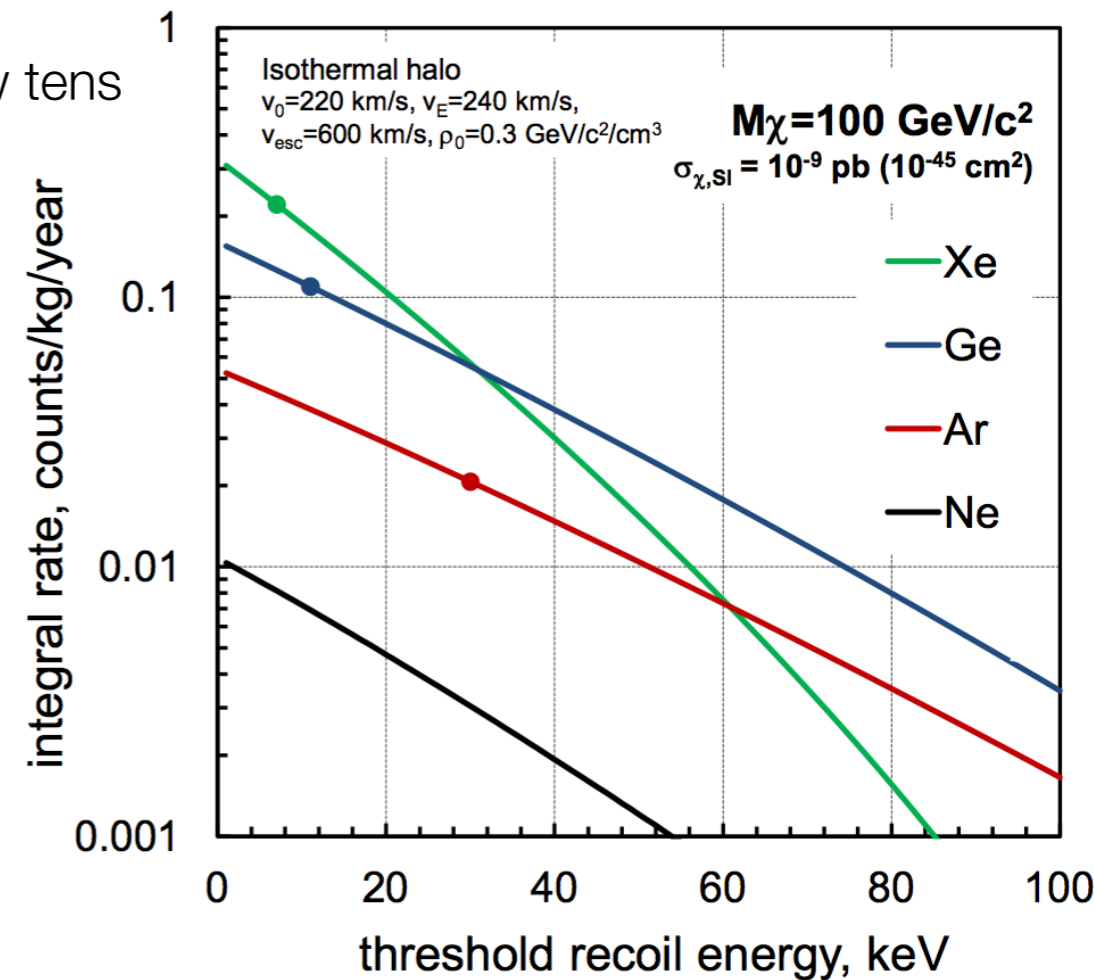
→ heavy target requirement



- High mass number → good for SI interactions
- Natural abundance:  
 $^{129}\text{Xe}$  spin 1/2 (26.4%),  $^{131}\text{Xe}$  spin 3/2 (21.2%) → good for SD interactions

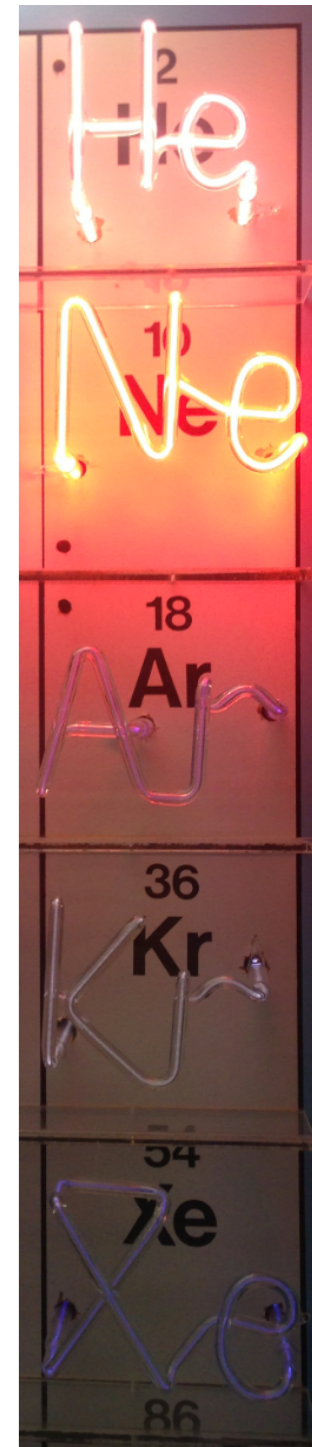
- No radioactive isotopes (except double-beta)
- High stopping power → self-shielding, compact geometry

- Fast and efficient scintillation
- Light can be detected directly (178nm), no need for wavelength-shifter
- Relatively high ionization yield
- ‘Simple’ cryogenics

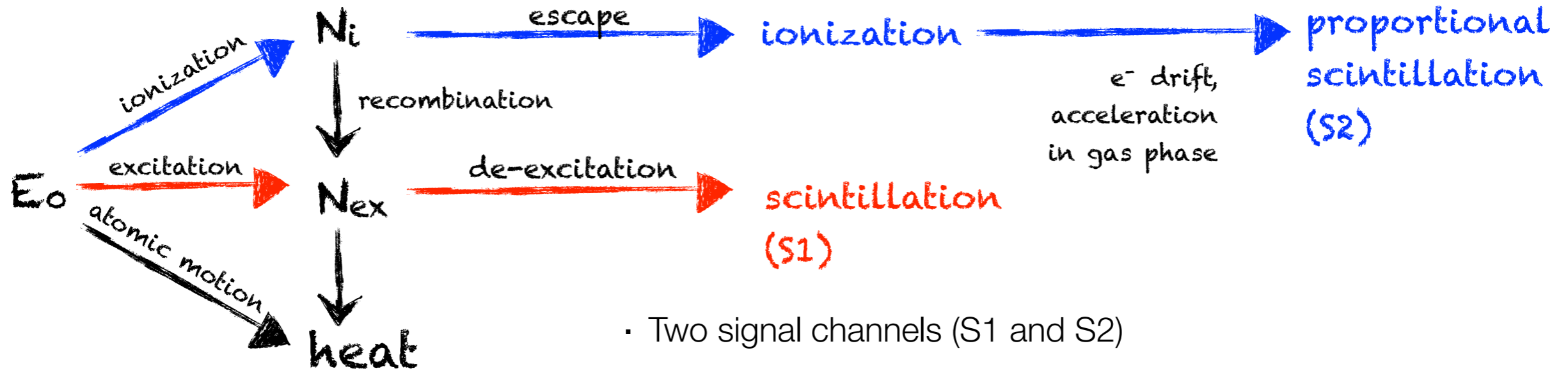


	Z / A	T <sub>b</sub> [K]	ρ [g/cc]	scint. [PE/keV]	ioniz. [e <sup>-</sup> /keV]	λ [nm]	decay time singl./tripl.
He	2 / 4	4.2	0.13	15	39		
Ne	10 / 20	27.1	1.21	7	46	77.5	few ns / 15.4 μs
Ar	18 / 40	87.3	1.4	40	42	128	10 ns / 1.5 μs
Kr	36 / 84	119.8	2.41	25	49		
<b>Xe</b>	<b>54 / 131</b>	<b>165</b>	<b>3.06</b>	<b>46</b>	<b>64</b>	<b>178</b>	<b>3 ns / 27 ns</b>

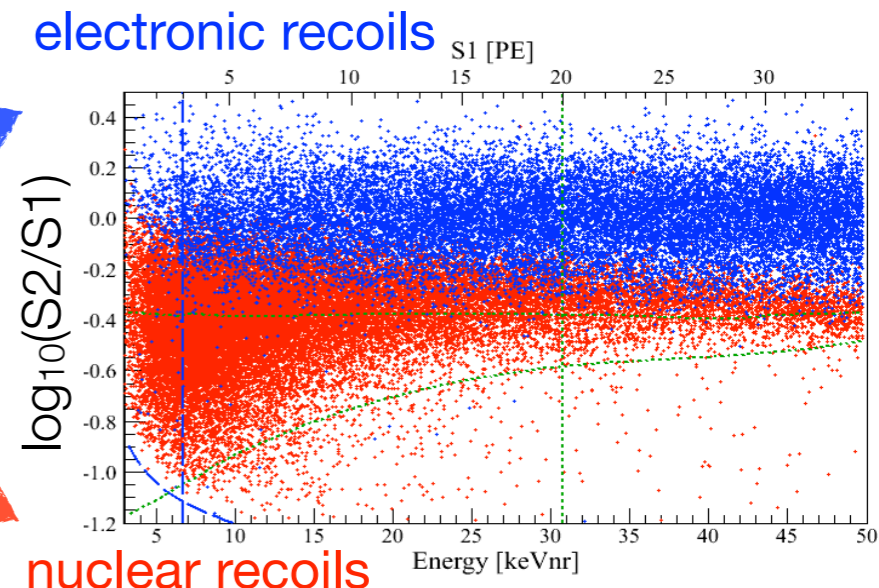
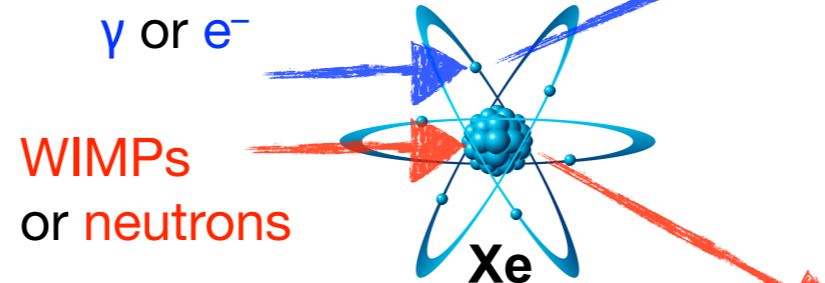
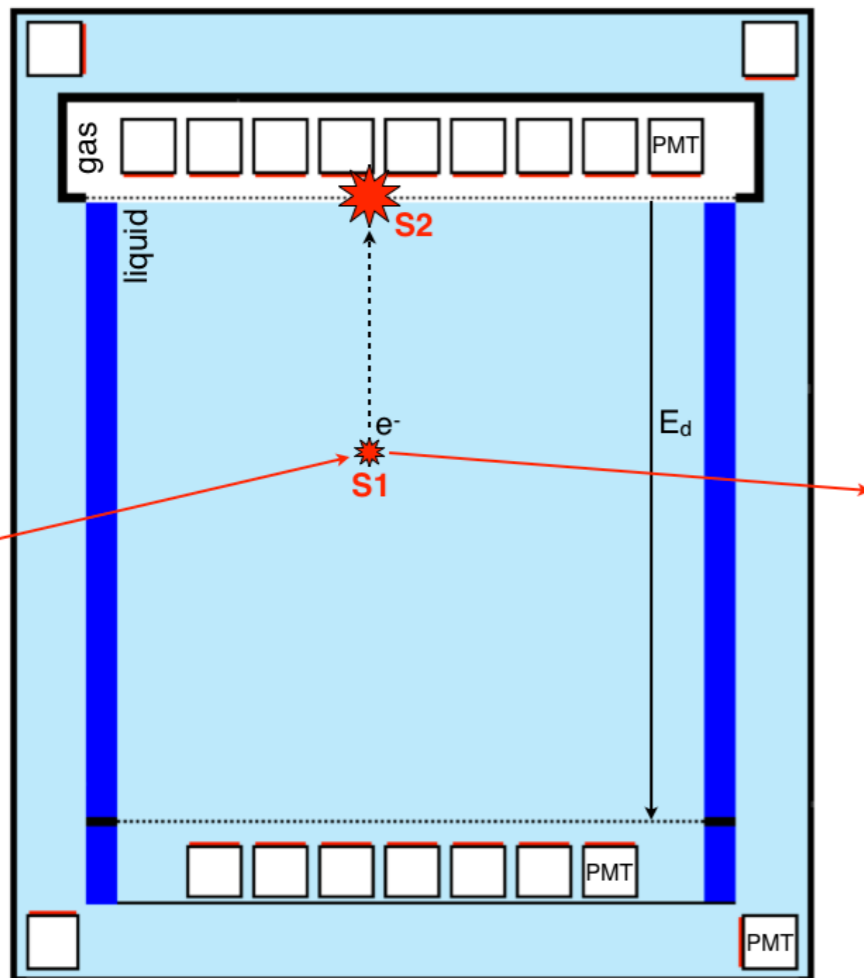
- High mass number → good for SI interactions
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- No radioactive isotopes (except double-beta)
- High stopping power → self-shielding, compact geometry
- Fast and efficient scintillation
- Light can be detected directly, no need for wavelength-shifter
- Relatively high ionization yield
- ‘Simple’ cryogenics



# Dual-phase Time-projection Chamber



- Two signal channels (S1 and S2)
- Ratio depends on  $dE/dx$ , different probability for electron-ion pairs recombination
- event vertex reconstruction in 3D (~mm precision)
- particle type discrimination:  $(S2/S1)_\gamma > (S2/S1)_{WIMP}$   
factor ~ 200 and higher efficiency



- ~130 researches from 20 institutions





## **XENON10** (2005 - 2007)

15 kg target  
total 22 kg of LXe  
89 1-inch PMTs

shield: lead + polyethylene

achieved sensitivity:  
 $\sigma_{SI} = 8.8 \times 10^{-44} \text{ cm}^2$  (2007)



## **XENON100** (2008 - 2015)

62 kg target  
total 161 kg of LXe  
242 1-inch PMTs  
active LXe veto

shield: lead, polyethylene,  
copper, water canisters

storage/recovery: GXe

achieved sensitivity:  
 $\sigma_{SI} = 7.0 \times 10^{-45} \text{ cm}^2$  (2011)  
 $\sigma_{SI} = 2.0 \times 10^{-45} \text{ cm}^2$  (2012)



## **XENON1T** (2012 - 2018)

2 t target  
total 3.5 t of LXe  
248 3-inch PMTs

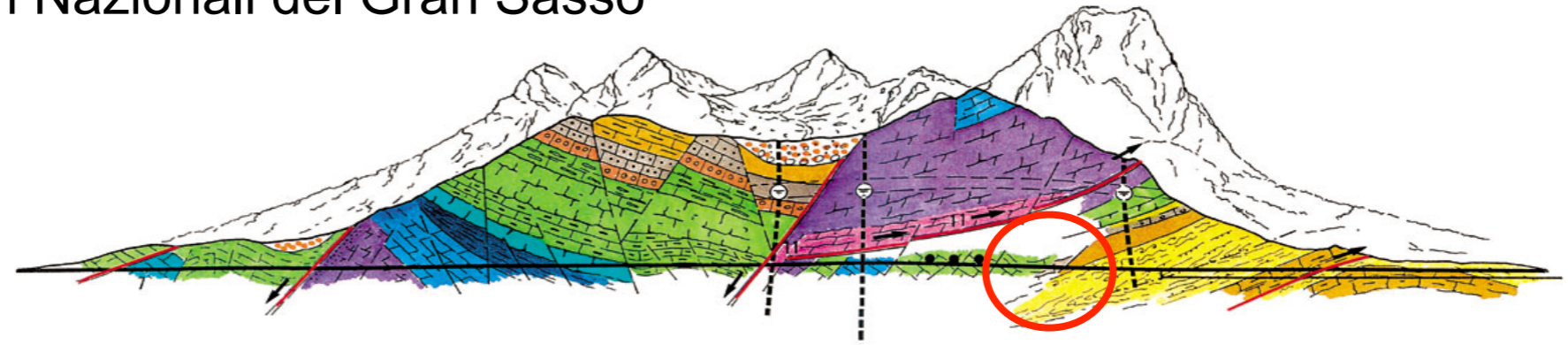
shield: water tank,  
Cherenkov veto

storage/recovery: LXe

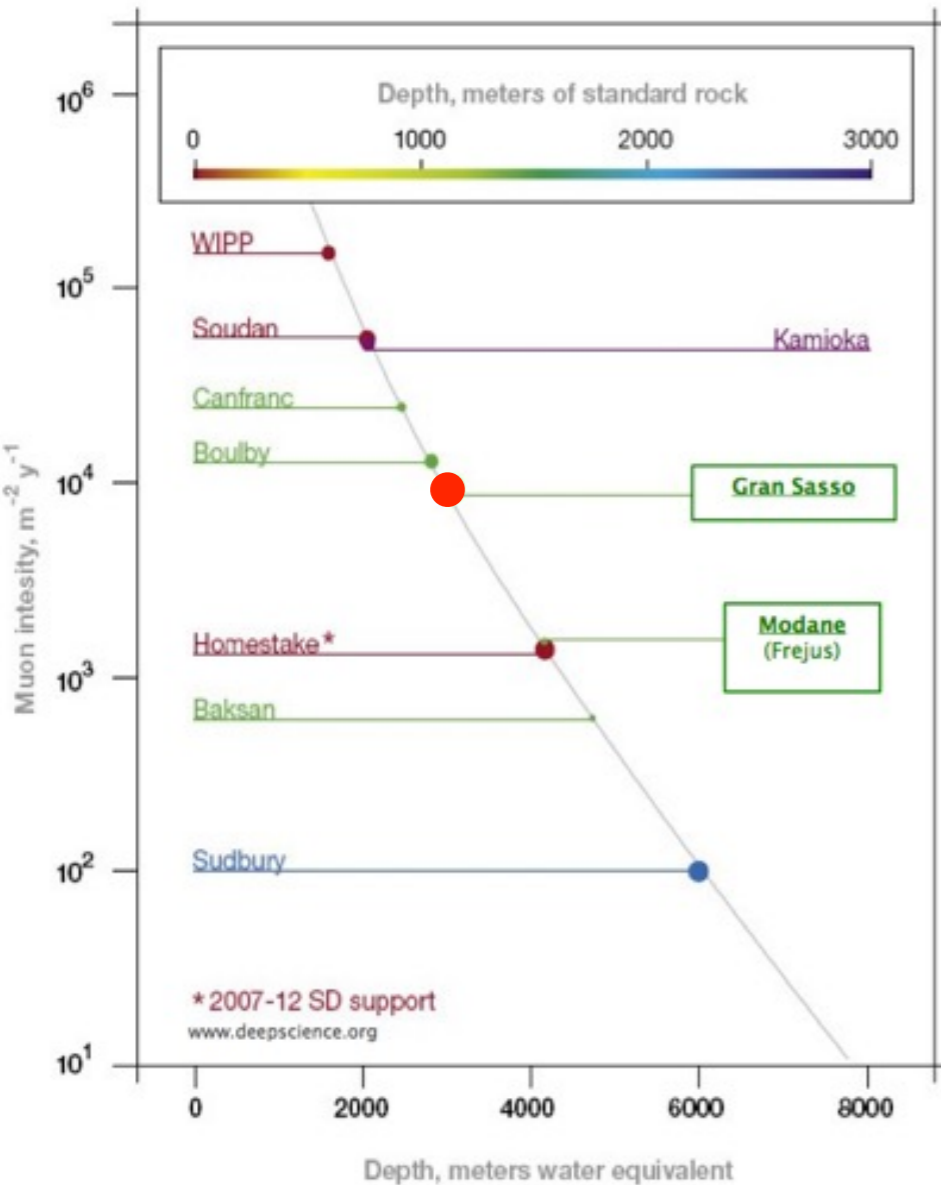
projected sensitivity:  
 $\sigma_{SI} = 2 \times 10^{-47} \text{ cm}^2$  (2018)

**XENONnT** twice larger target

- Laboratori Nazionali del Gran Sasso



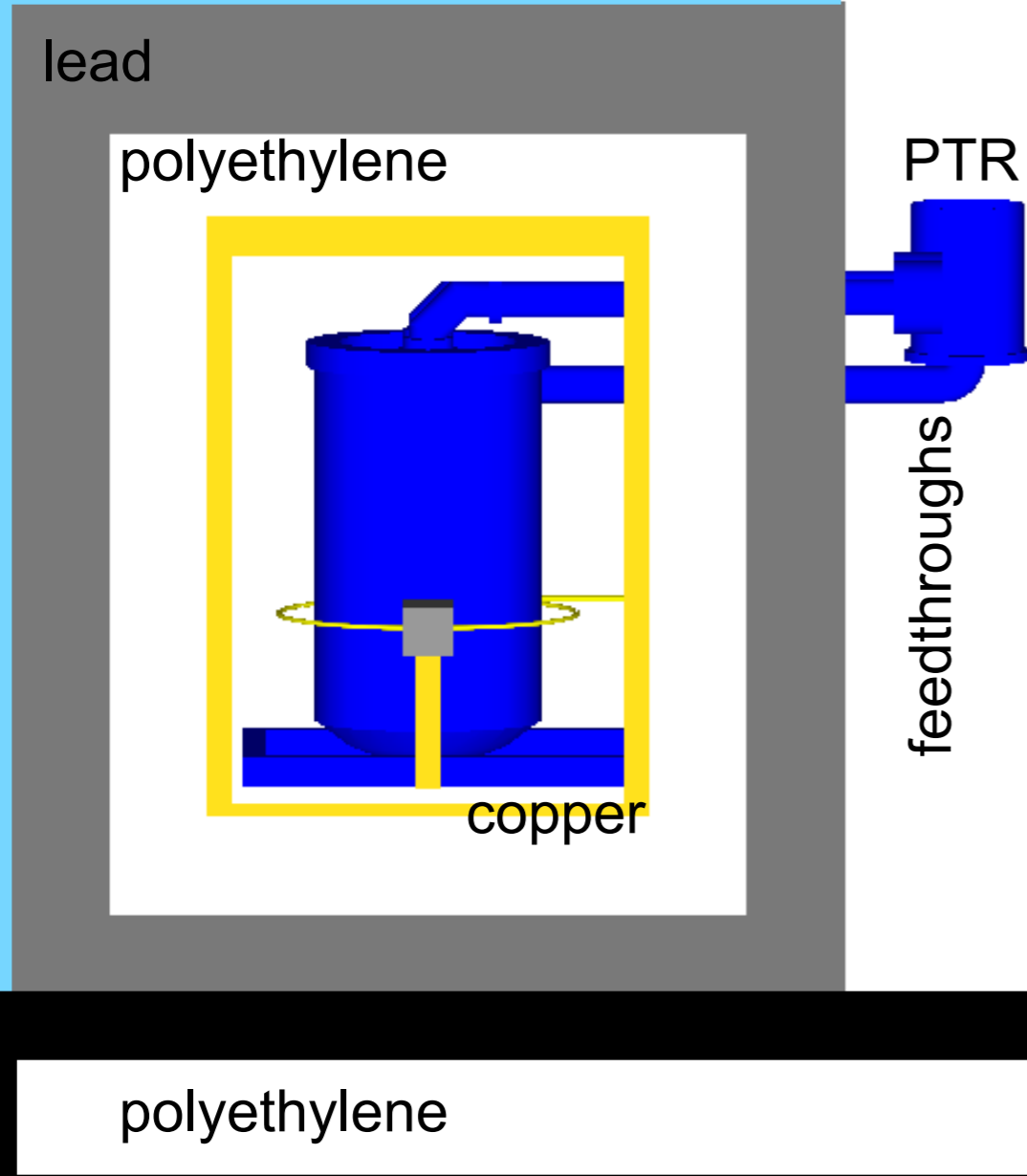
INFN  
Laboratori Nazionali del Gran Sasso



1.4 km rock  
 ↓  
 3.1 km water equivalent shielding from cosmic rays  
 ↓  
 factor 10<sup>6</sup> reduction of muon flux



plastic tanks with water



**γ-rays**

lead  
20 and 5 cm (low  $^{210}\text{Pb}$ ) layers, 33 t

copper  
5 cm, ~2 t



**neutrons**

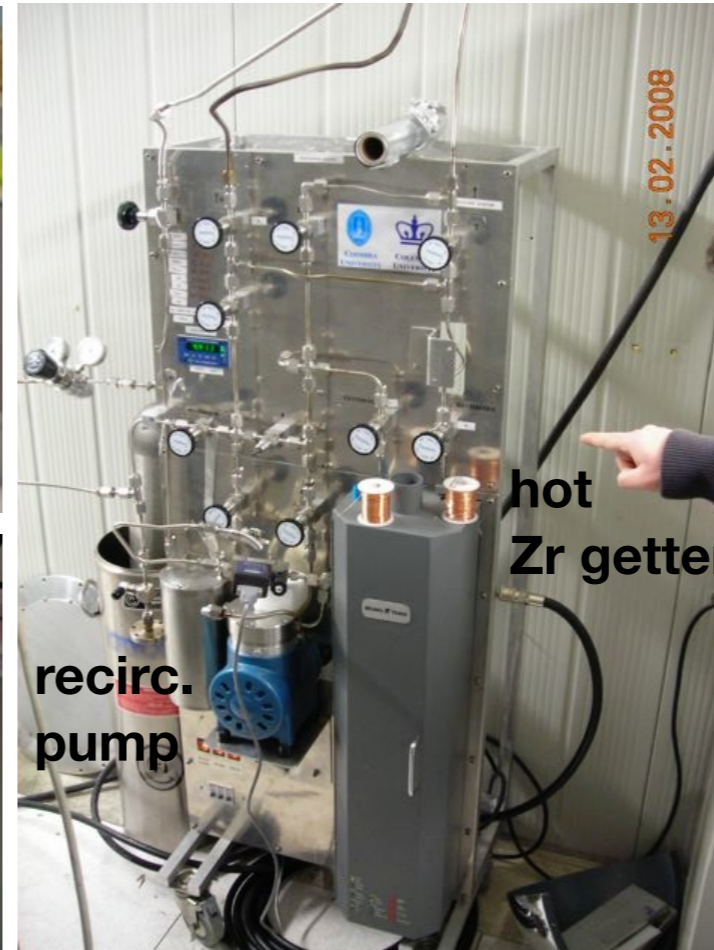
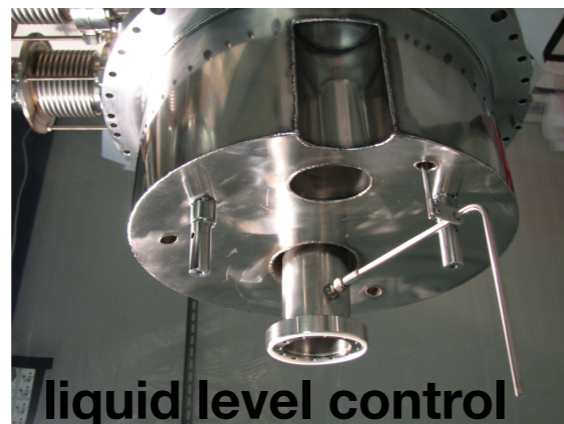
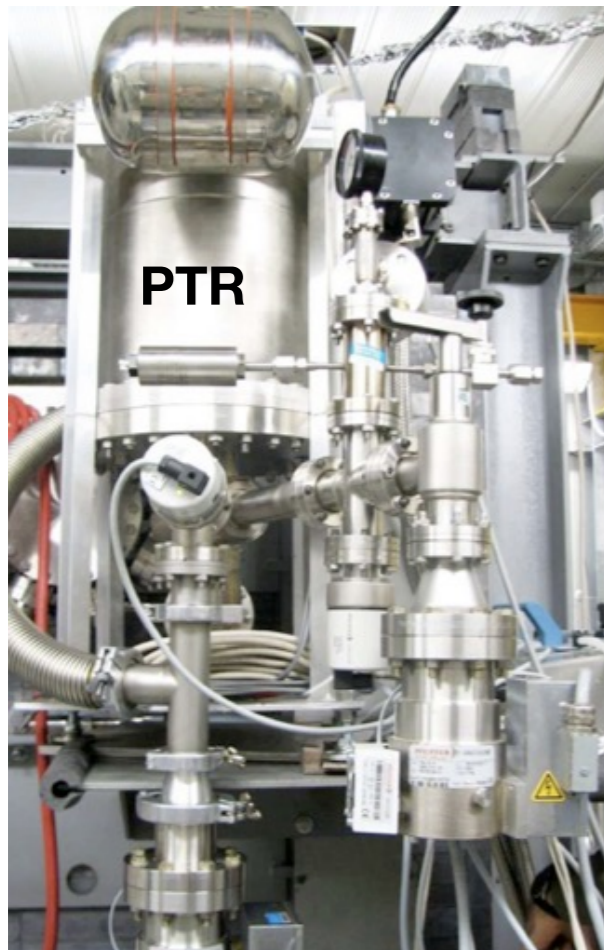
canisters with water (~20 cm)

polyethylene  
20 cm thick, 1.6 t

# XENON100: liquefaction and purification



- Xe liquefaction with the Pulse Tube Refrigerator (160W), which is placed outside the shield
- liquid Xe flows back into the main vessel from the cooling tower through a small pipe in the center of the double-walled vacuum insulated tube
- cooling system back up with the LN<sub>2</sub> emergency coil
- continuous recirculation through hot Zr getter → remove electronegative impurities



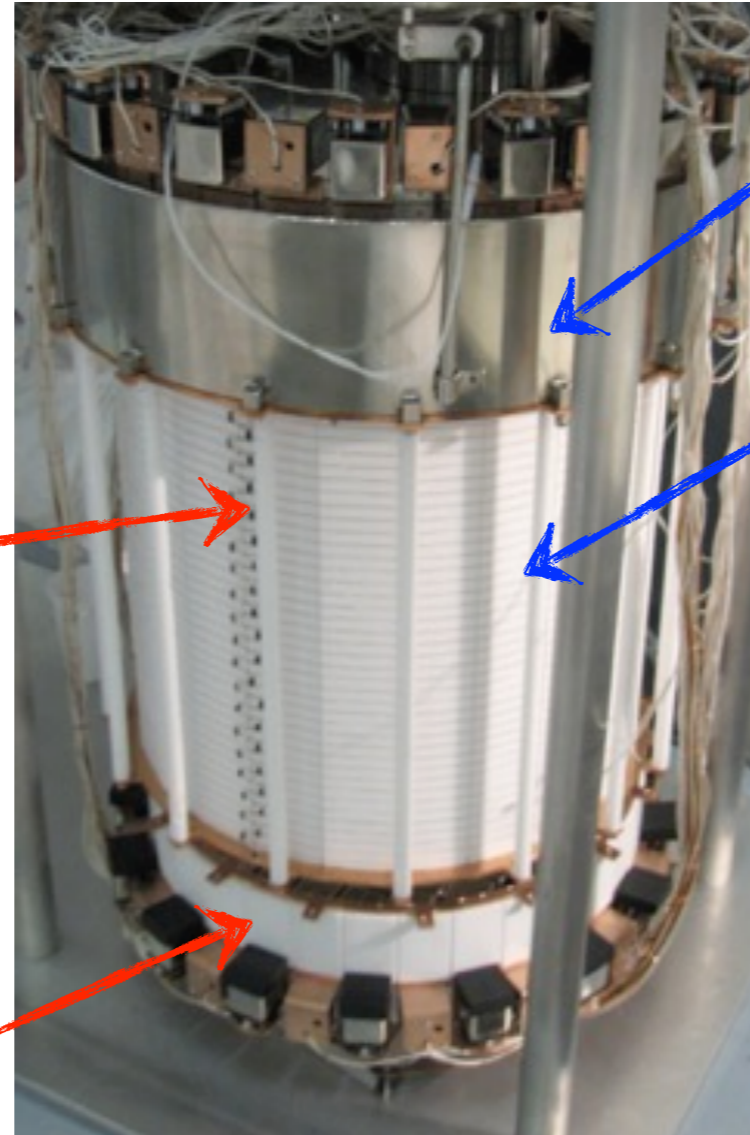
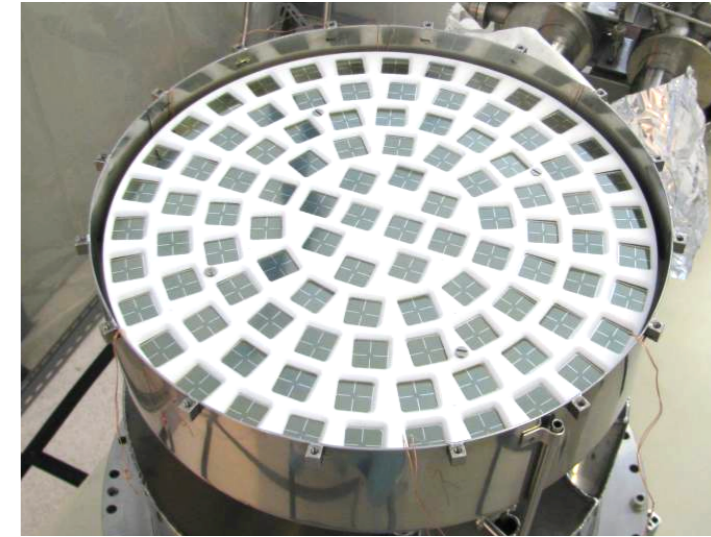


### Cryostat:

double walled (1.5 mm thick)  
low radioactivity stainless steel  
total weight 70 kg

### 'Diving bell' – liquid level control

stainless steel  
weight 3.6 kg



resistor chain  
for field shaping wires

### PTFE (Teflon) structure

24 interlocking panels  
total weight of teflon 12 kg  
enclose target volume  
support field shaping rings

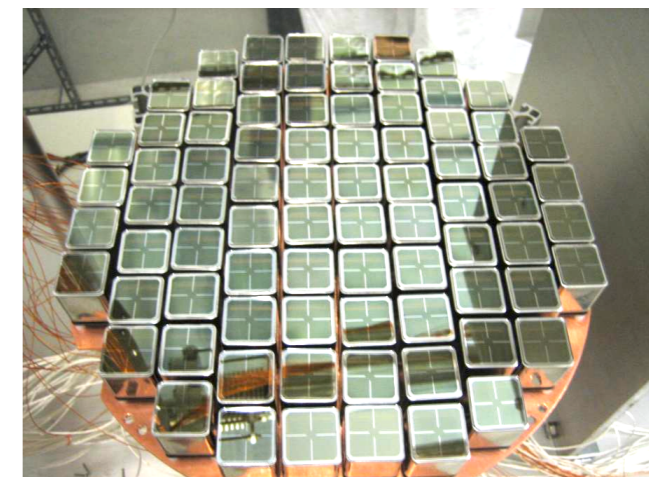
### LXe target

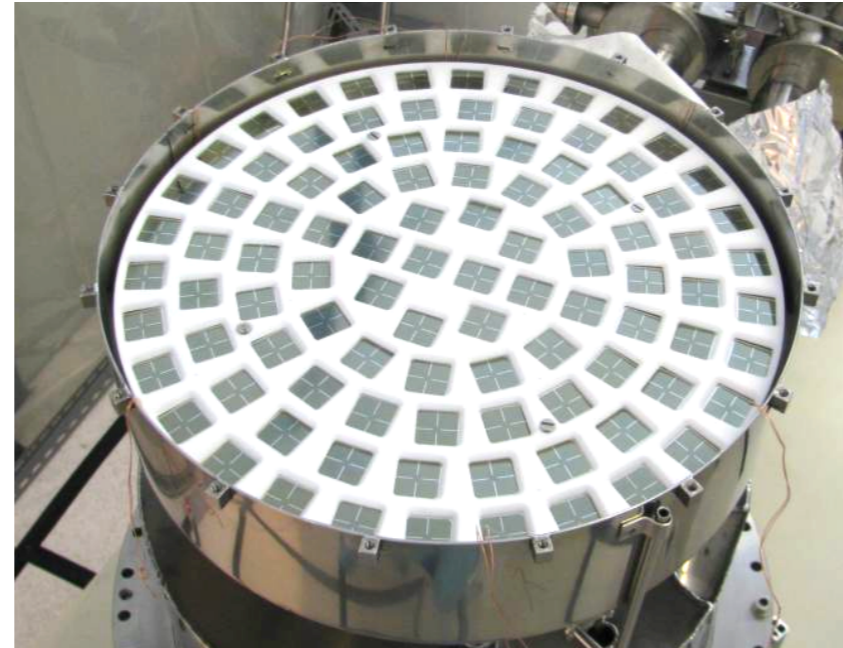
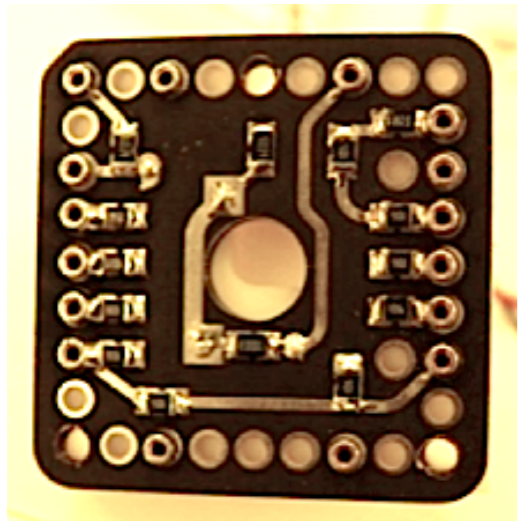
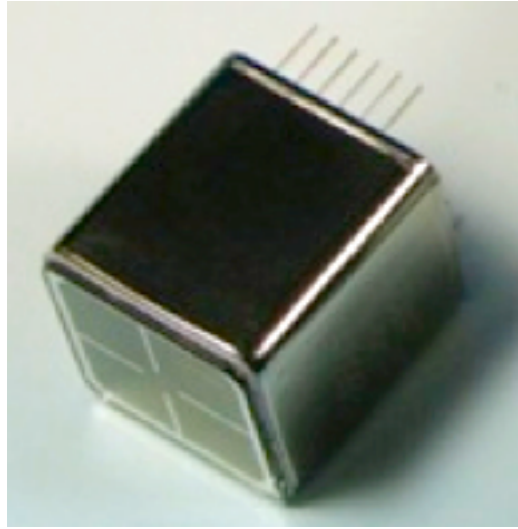
62 kg  
30 cm diameter  
30 cm height

### LXe Veto

109 kg  
~ 4 cm surrounding the target  
instrumented with 64 PMTs

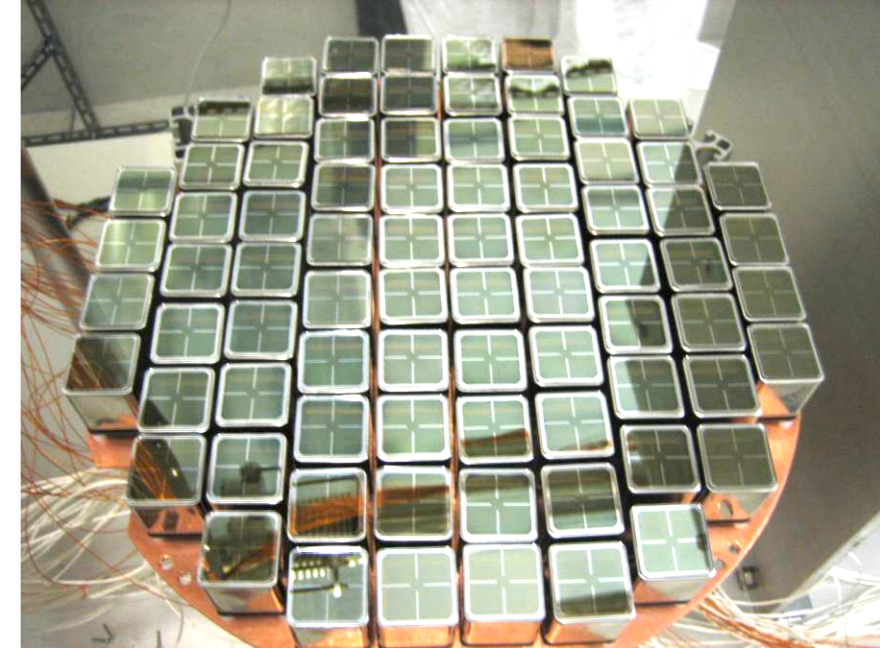
### VUV light reflector





top array

98 PMTs  
QE  $\approx$  25%

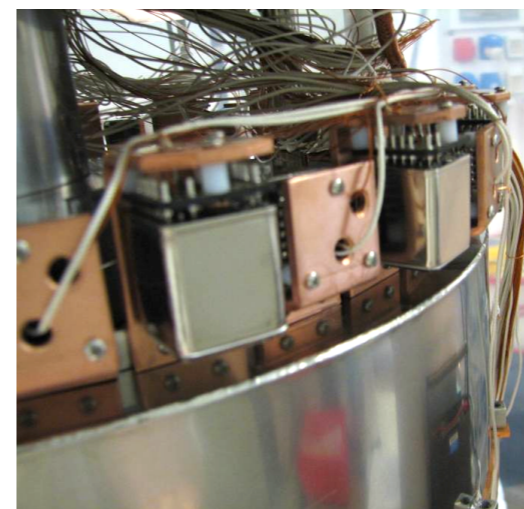


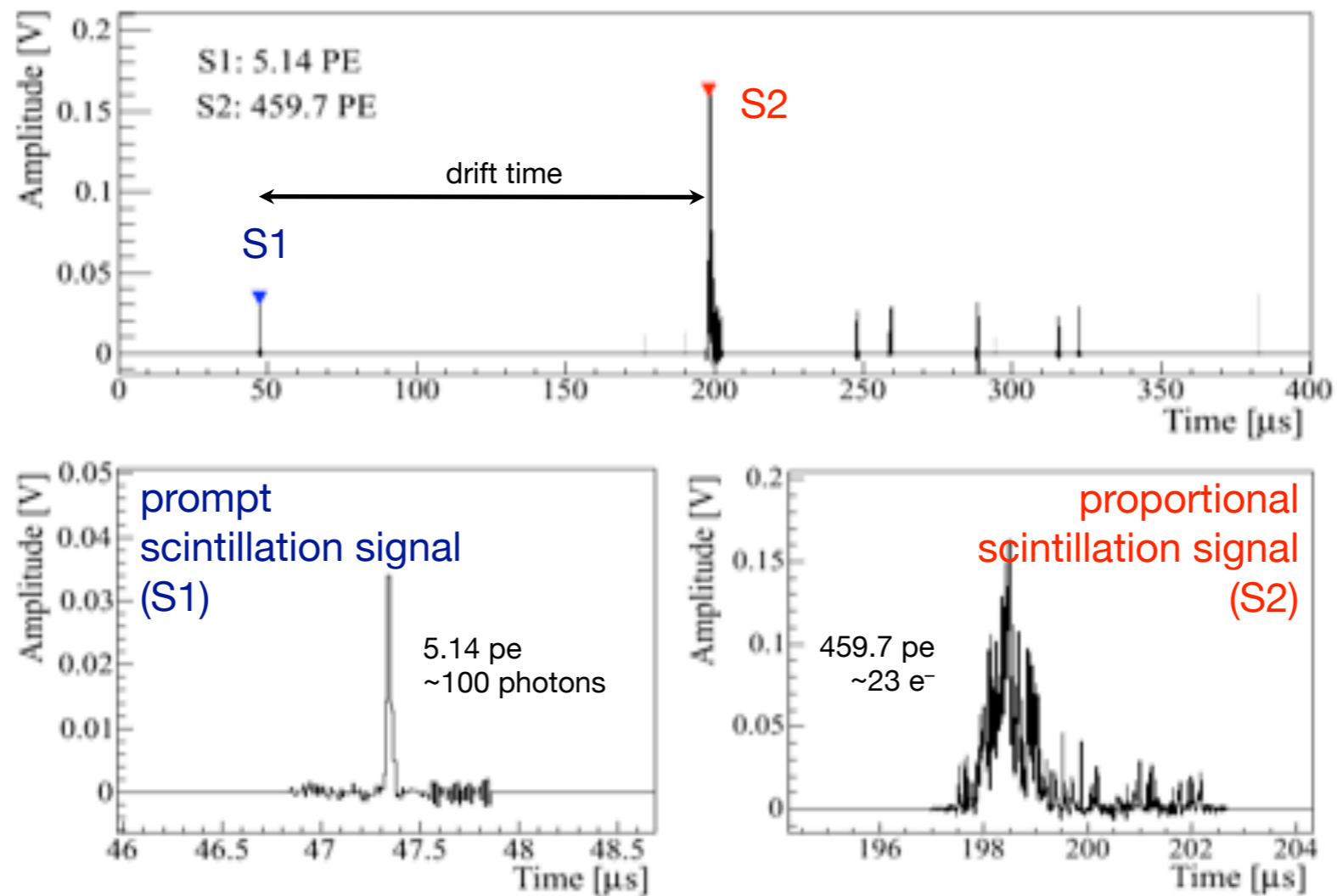
bottom array

80 PMTs  
QE  $\approx$  32%

- Hamamatsu R8520 PMT
- gain  $2 \times 10^6$
- voltage divider network on cirlex substrate
- low radioactivity
- low heat dissipation

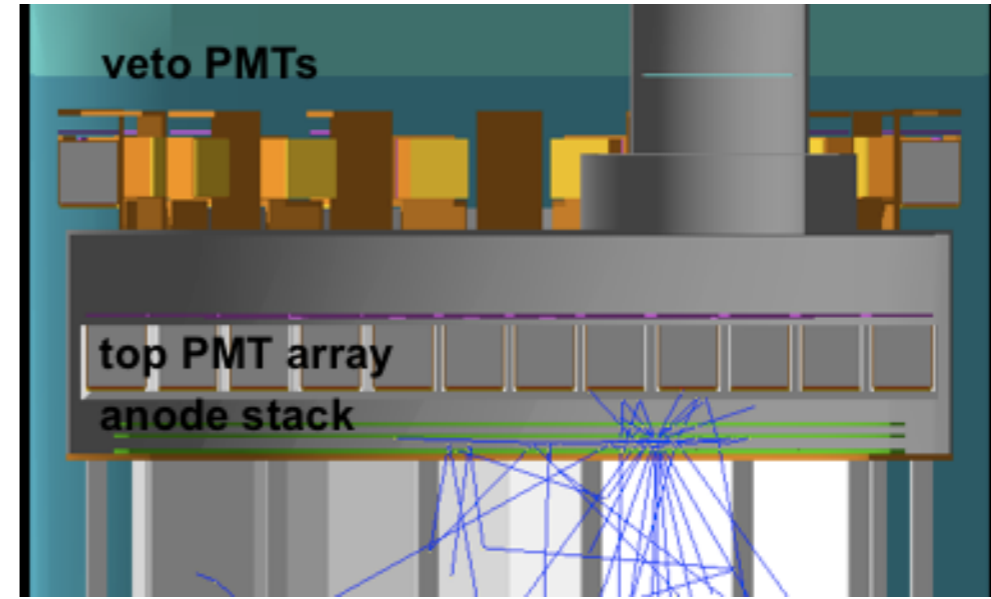
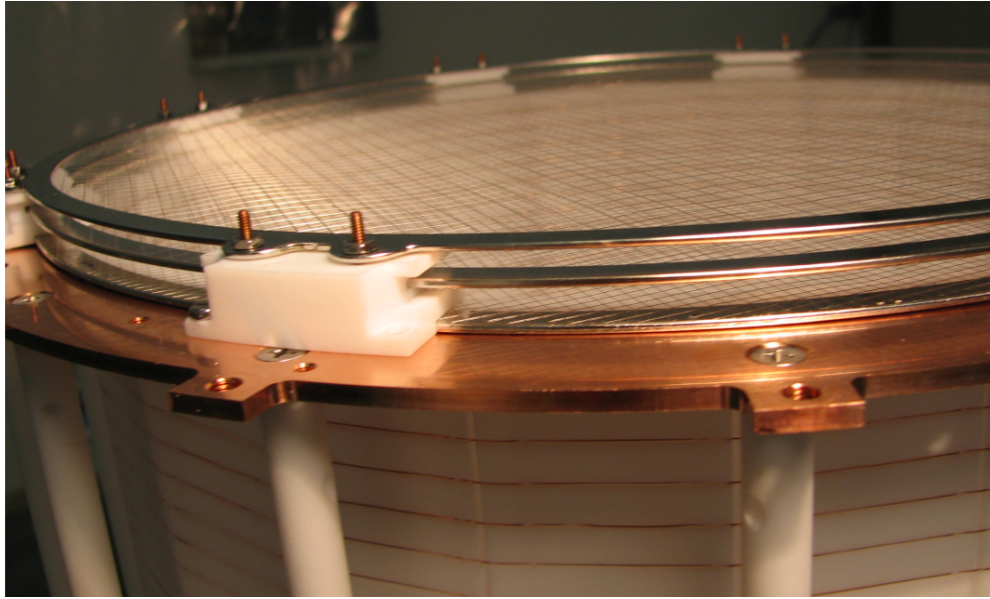
- 64 PMTs alternating direction in the LXe volume around the target



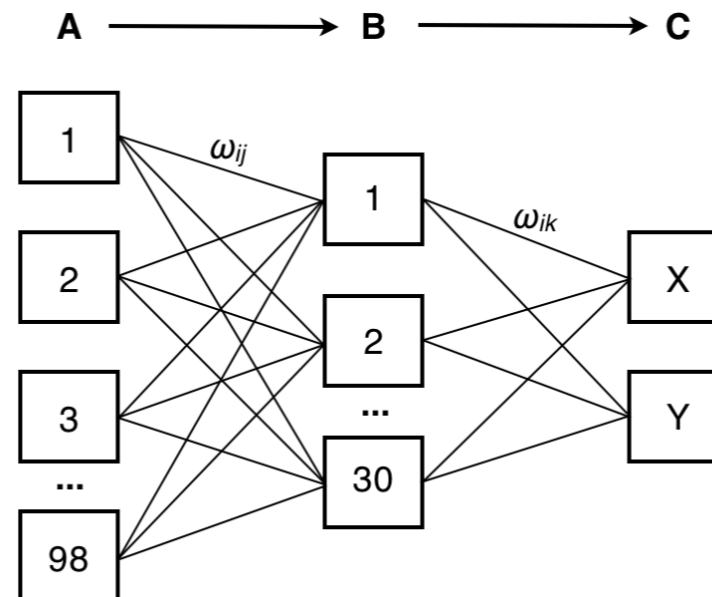


- Z-coordinate (interaction depth) is inferred from the delay time between S1 and S2 (resolution 0.3mm)
- Challenge: long  $e^-$  drift time in large detectors (XENON100: 30 cm drift = 176  $\mu\text{s}$  at 0.53 kV/cm)
- X and Y coordinates are reconstructed by hit pattern identification with Neural Networks, Support Vector Machines,  $\chi^2$ -minimization, etc. ( $\sim$ mm resolution)

- Monte Carlo simulation with GEANT4
  - generate isotropic optical photons in the S2 region (gas gap) at various XY positions
  - obtain PMT hit patterns, taking into account optical characteristics of all components

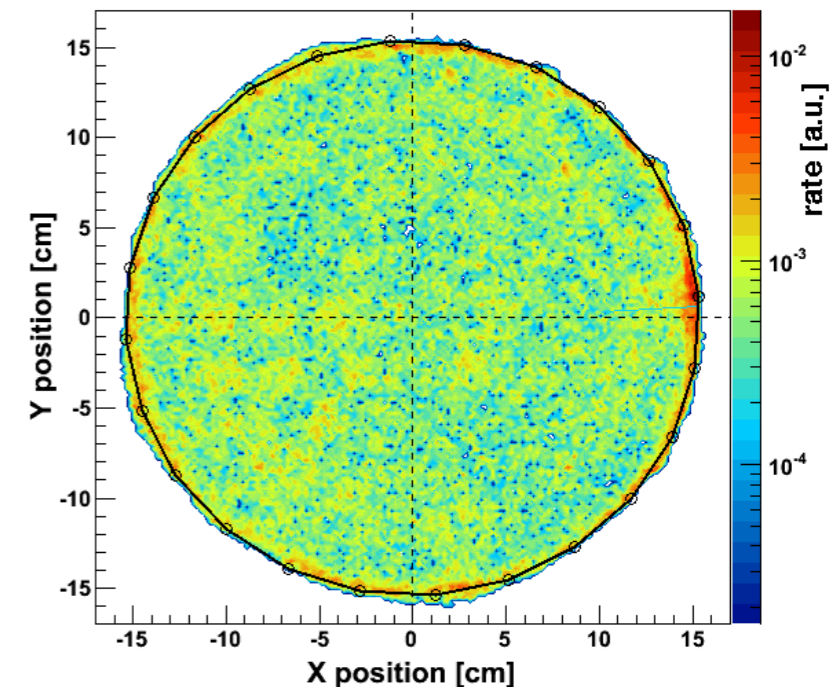


- Pattern identification with Neural Network (primary algorithm),  $\chi^2$ -minimization, Support Vector Machines
  - algorithm 'training' on MC hit patterns (take into account not working PMT channels)
  - application on real data, XY reconstruction



$$\text{input}_i = N_{\text{PE}}(\text{PMT}_i) / N_{\text{PE}}(\text{total})$$

→ mm resolution

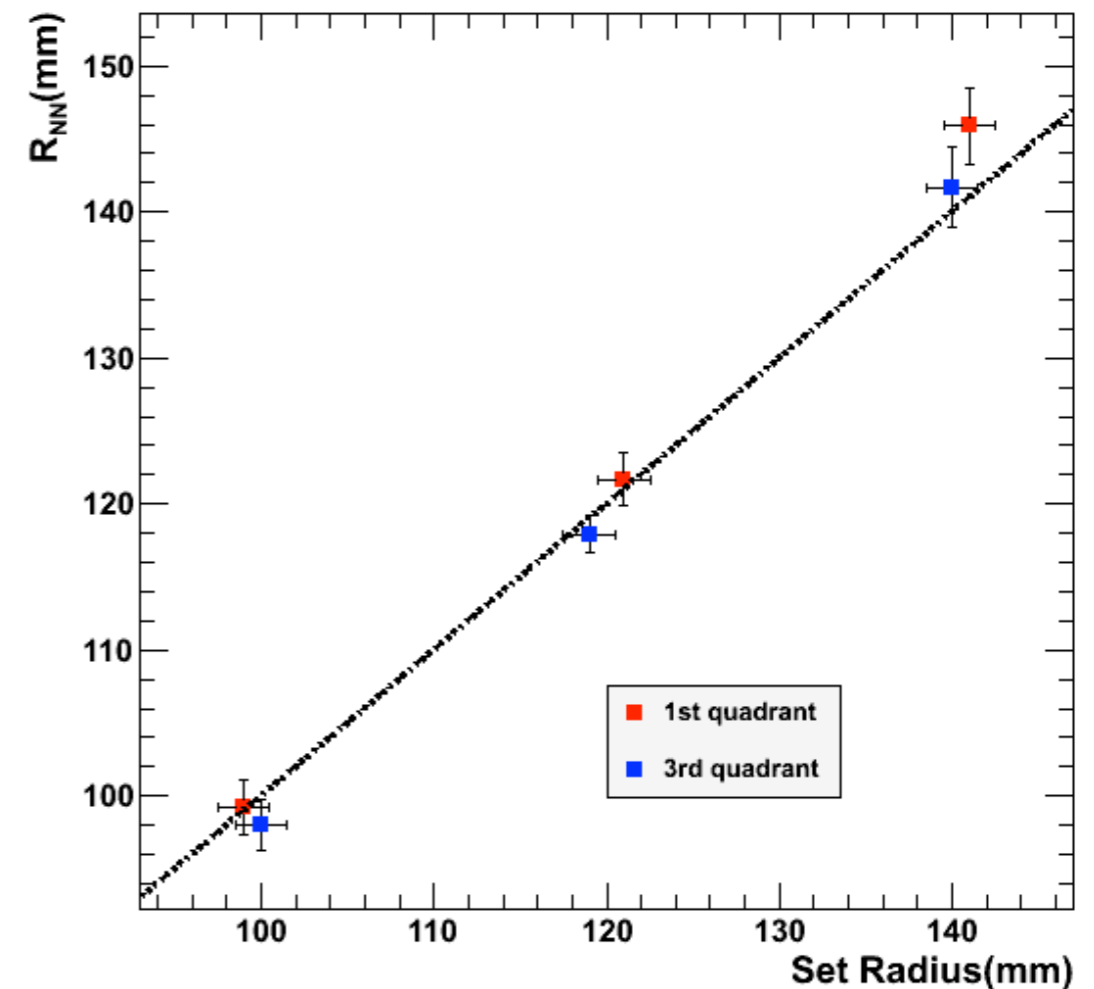
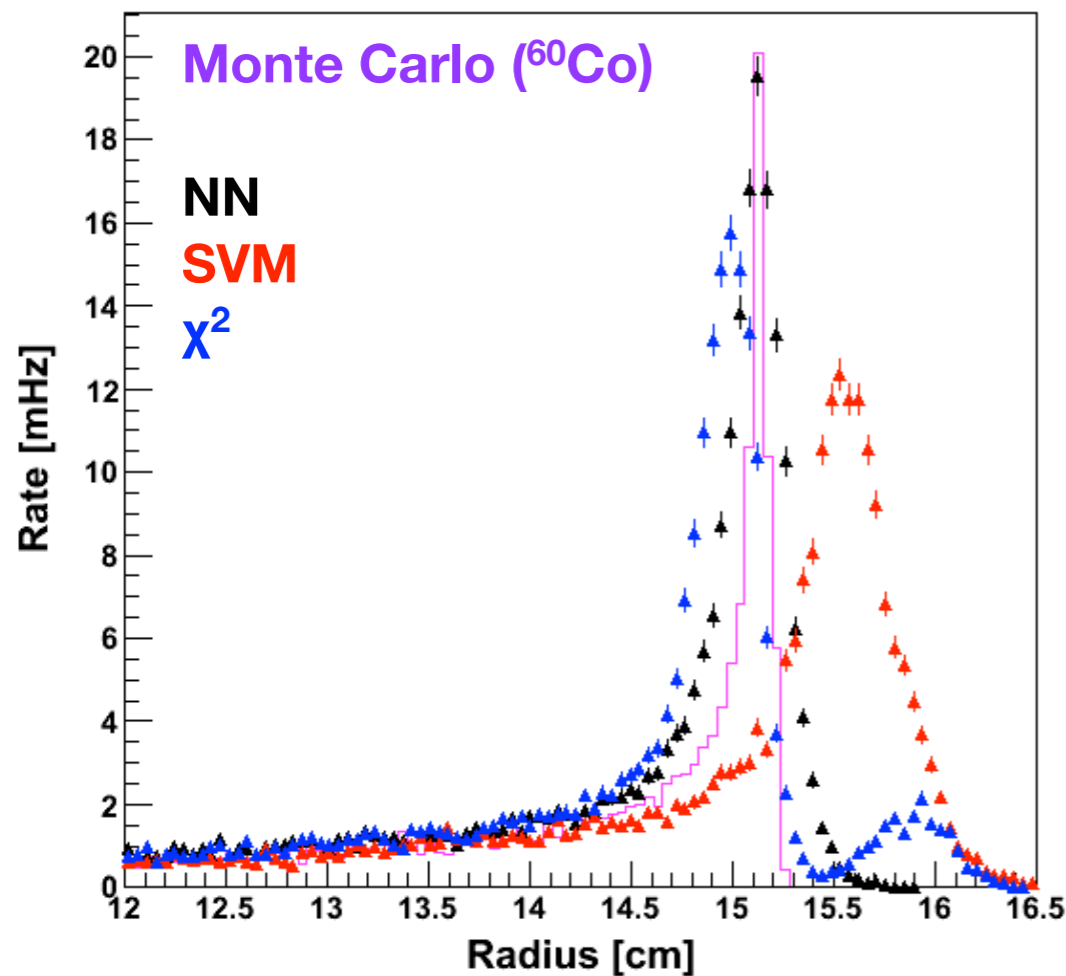


Validation of the reconstruction algorithms:

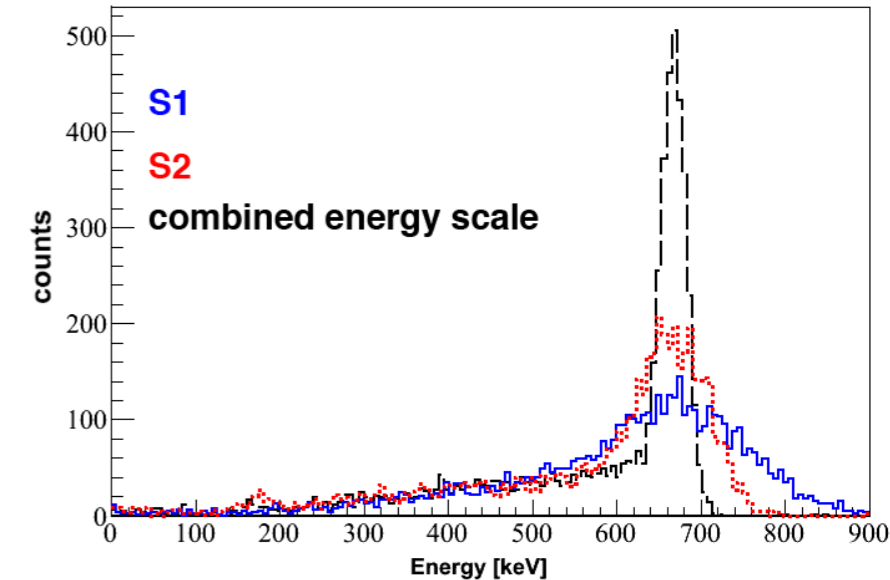
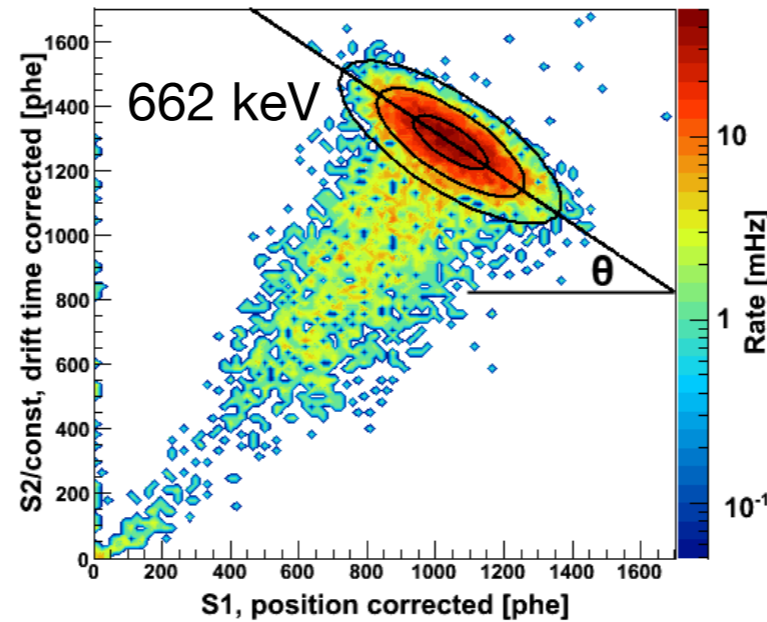
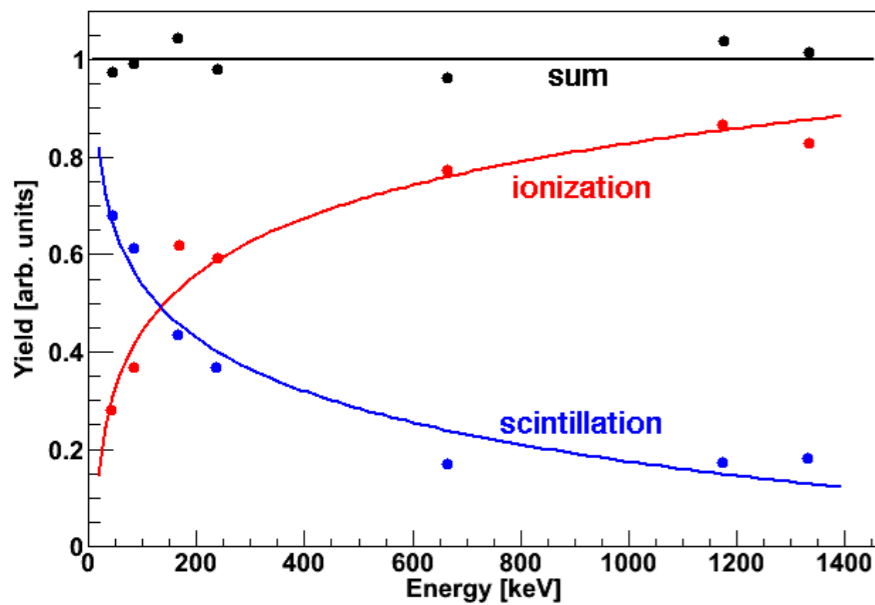
- measurements with a collimated  $^{137}\text{Cs}$  source
- comparison with MC for  $^{60}\text{Co}$  calibration

→ resolution better than 3 mm

→ Neural Network performs superior to  $\chi^2$ -minimization and Support Vector Machines, and is used since 2009 as the primary vertex reconstruction algorithm



- The proportion of light and charge is field- and energy-dependent
- energy scales using S1 or S2 signal alone are not linear
- The sum is constant
- both signals can be **combined** into a new **scale**, independent from the drift field and particle energy
- Fit S2-vs-S1 distribution for mono-energetic line with an elliptical Gaussian function
- compute anti-correlation angle  $\Theta$ , project along the major axis

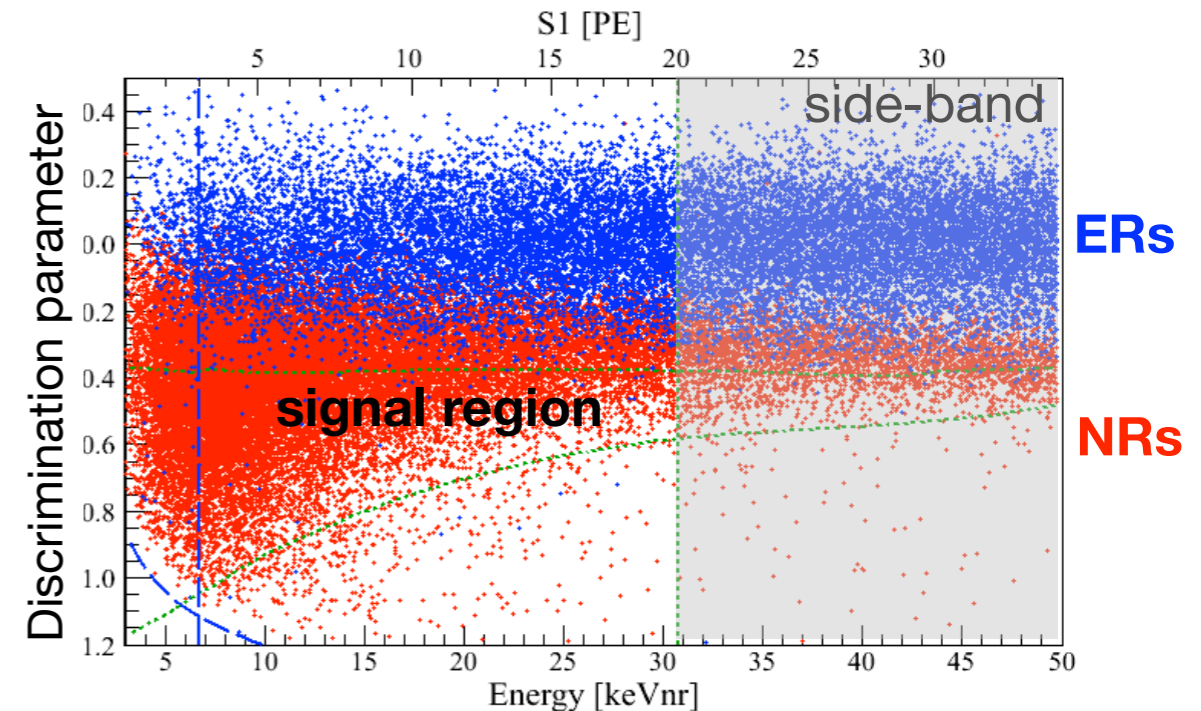


## Electronic recoil backgrounds

- radioactive contamination in detector components
- cosmogenic activation of detector components
- intrinsic LXe contamination (Rn, Kr)
- double beta decay (Xe)
- solar neutrino-electron scattering

discrimination with efficiency > 99.5%

→ can be measured on side band



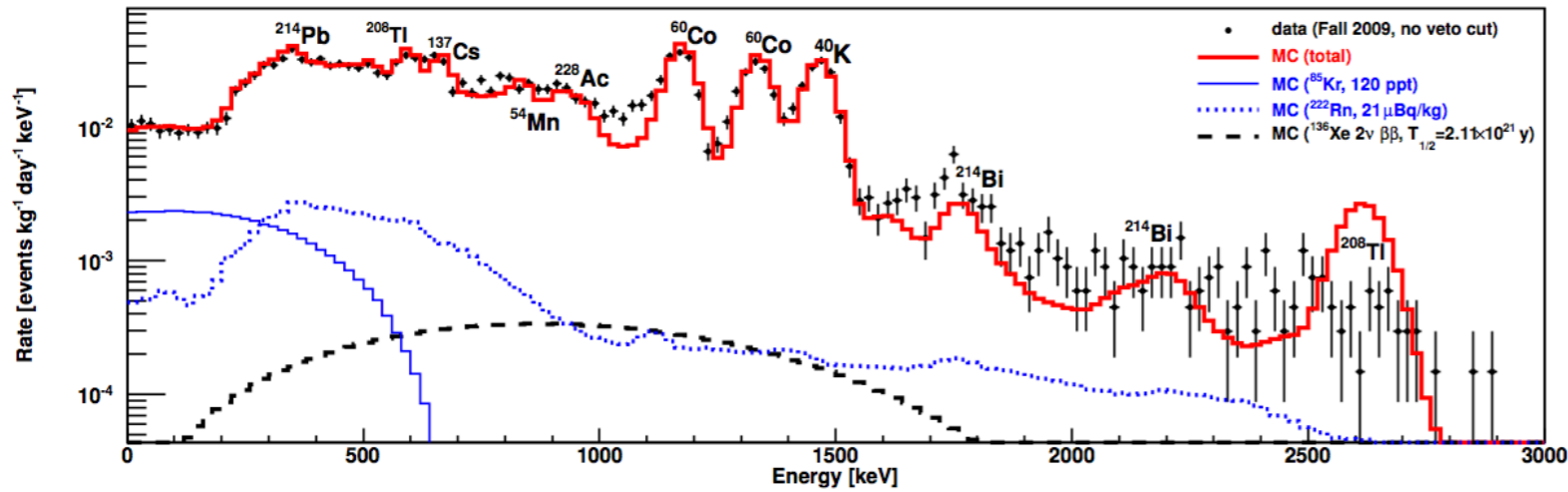
## Nuclear recoil backgrounds

- natural radioactivity in materials: neutron production in  $(\alpha, n)$  reactions and spontaneous fission
- cosmogenic (muon-induced) neutrons
- coherent solar neutrino scattering

→ rely on predictions with SOURCES-4A, MUSUN/MUSIC, GEANT4

no discrimination

- Monte Carlo simulations compared with the acquired background spectrum → very good agreement



commissioning run  
no MC tuning  
only measured contamination

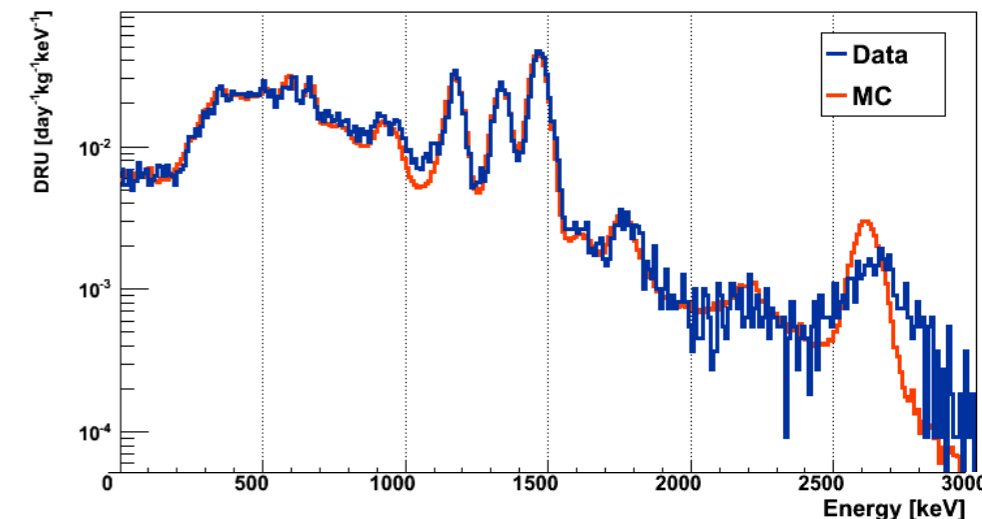
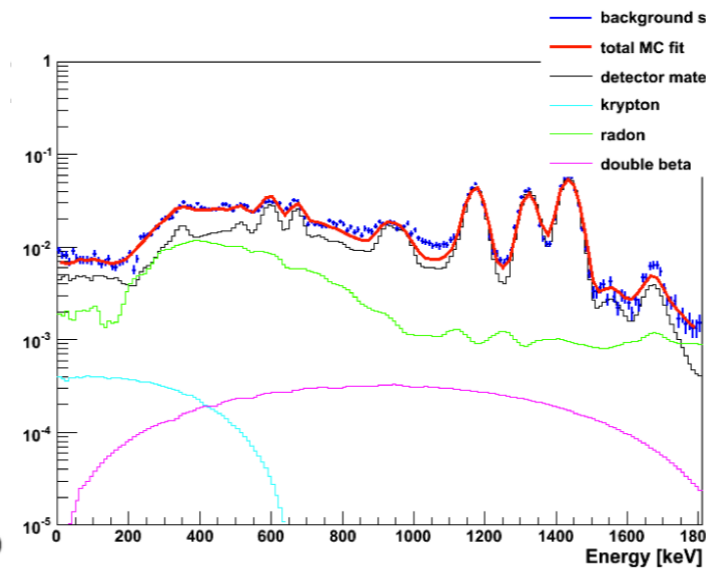
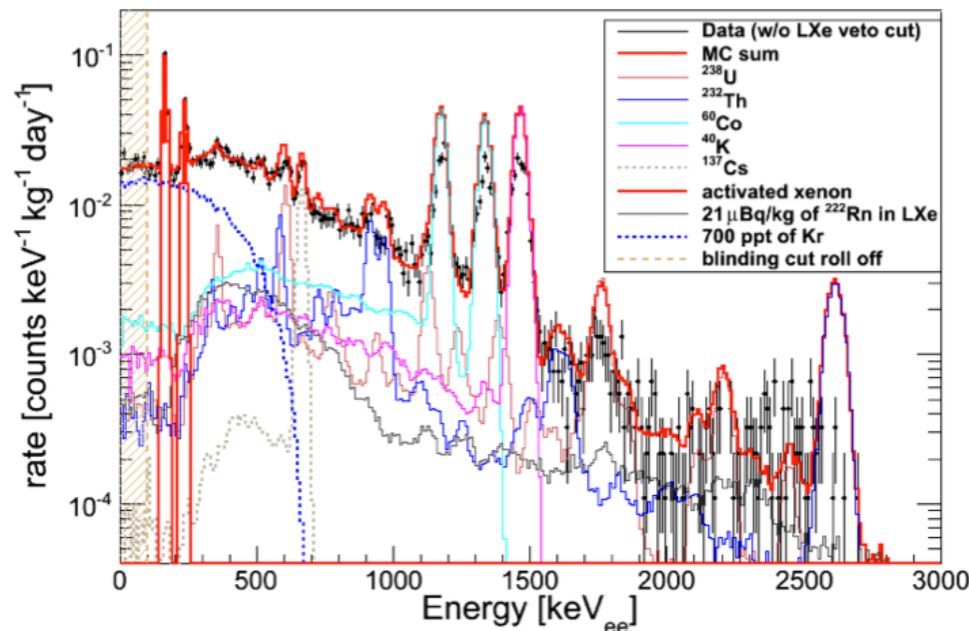
Phys. Rev. D. 83, 082001 (2011)  
Phys. Rev. D. 85, 029904 (2012)

- Generated data and developed analysis procedure are used for analysis of background in all DM-search runs and other studies

1st science run: 100 days

2nd science run: 225 days

3rd science run: 154 days



1. Apply data quality cuts and calculate acceptance

→ remove noise

→ remove anomalous events

(S2 pulse width, vertex reconstruction)

→ apply energy threshold

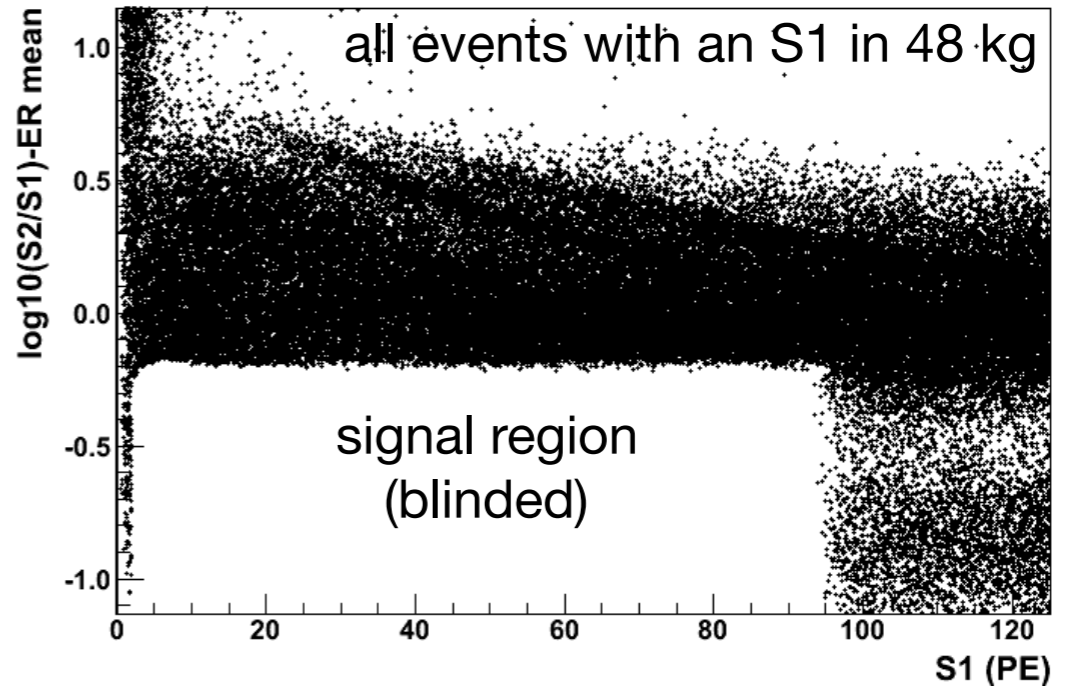
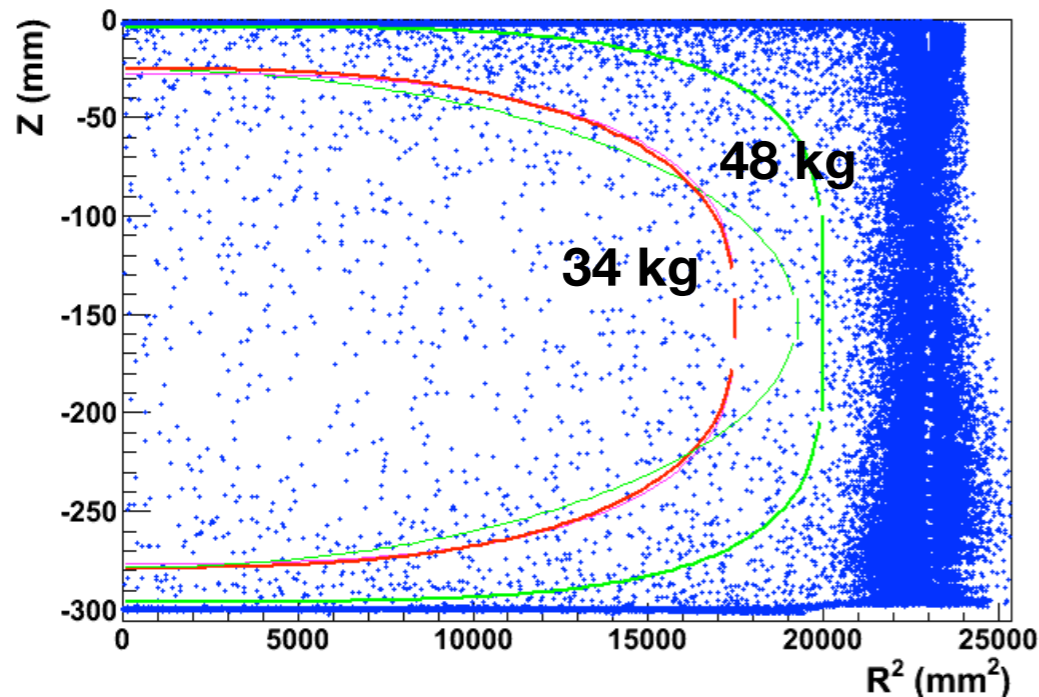
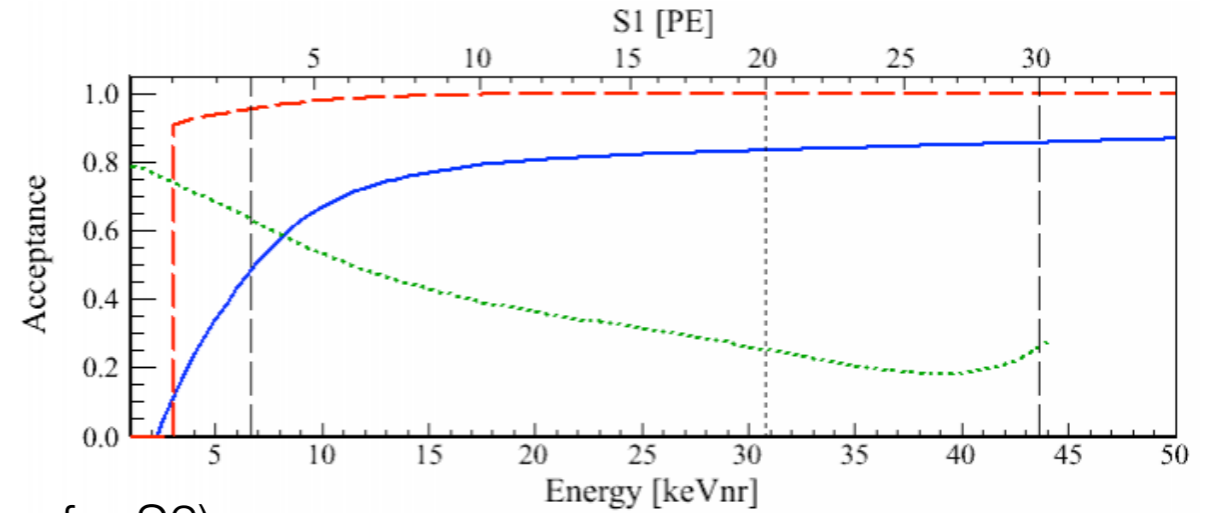
(2-fold PMT-coincidence for S1, ensure high trigger efficiency for S2)

→ LXe veto cut

→ select single scatters

2. Define fiducial volume based on background distribution

3. Define signal region in the discrimination parameter space (S2/S1 vs S1)



- Longest science run → Exposure 225 days × 34 kg fiducial liquid xenon mass

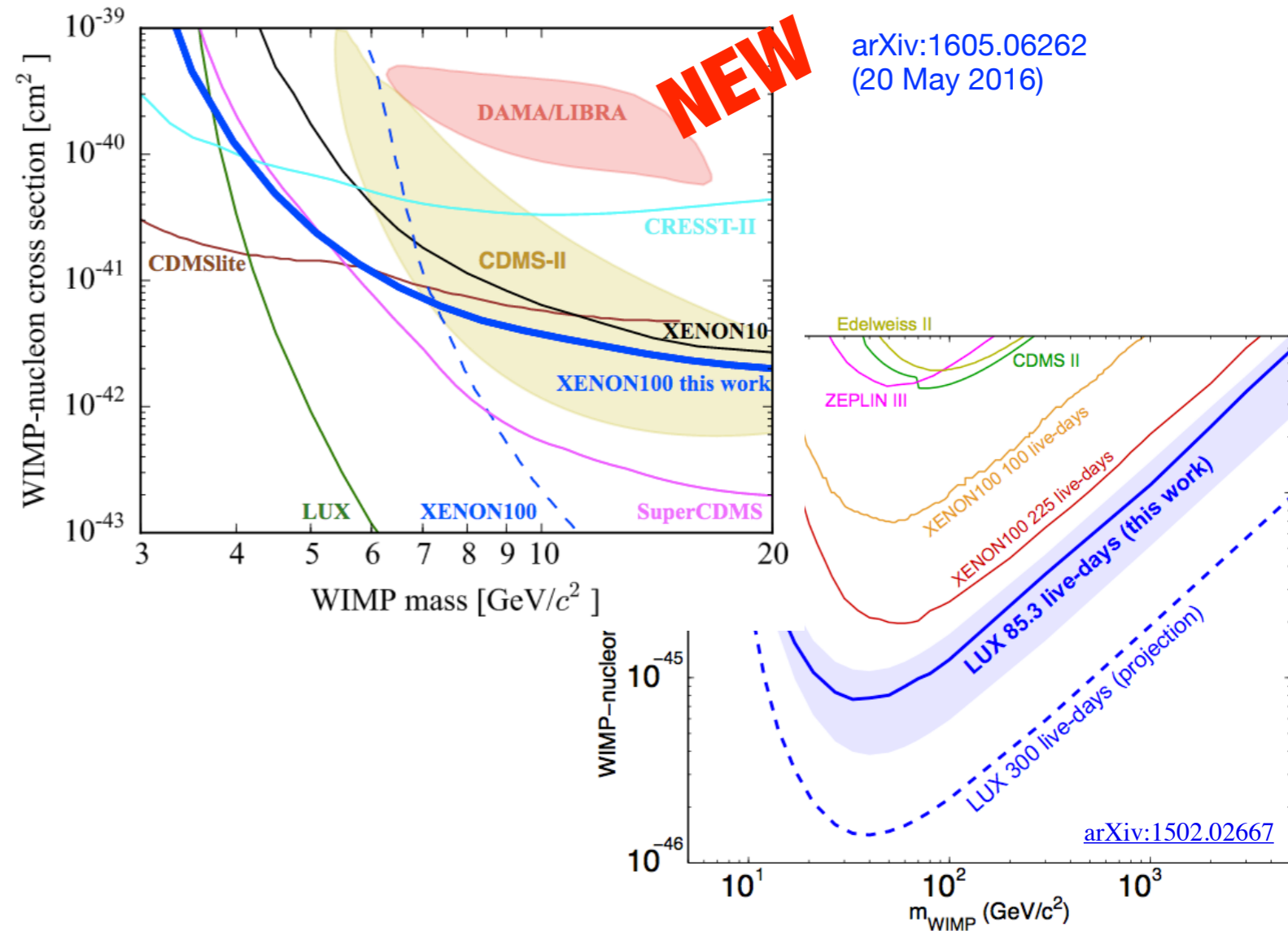
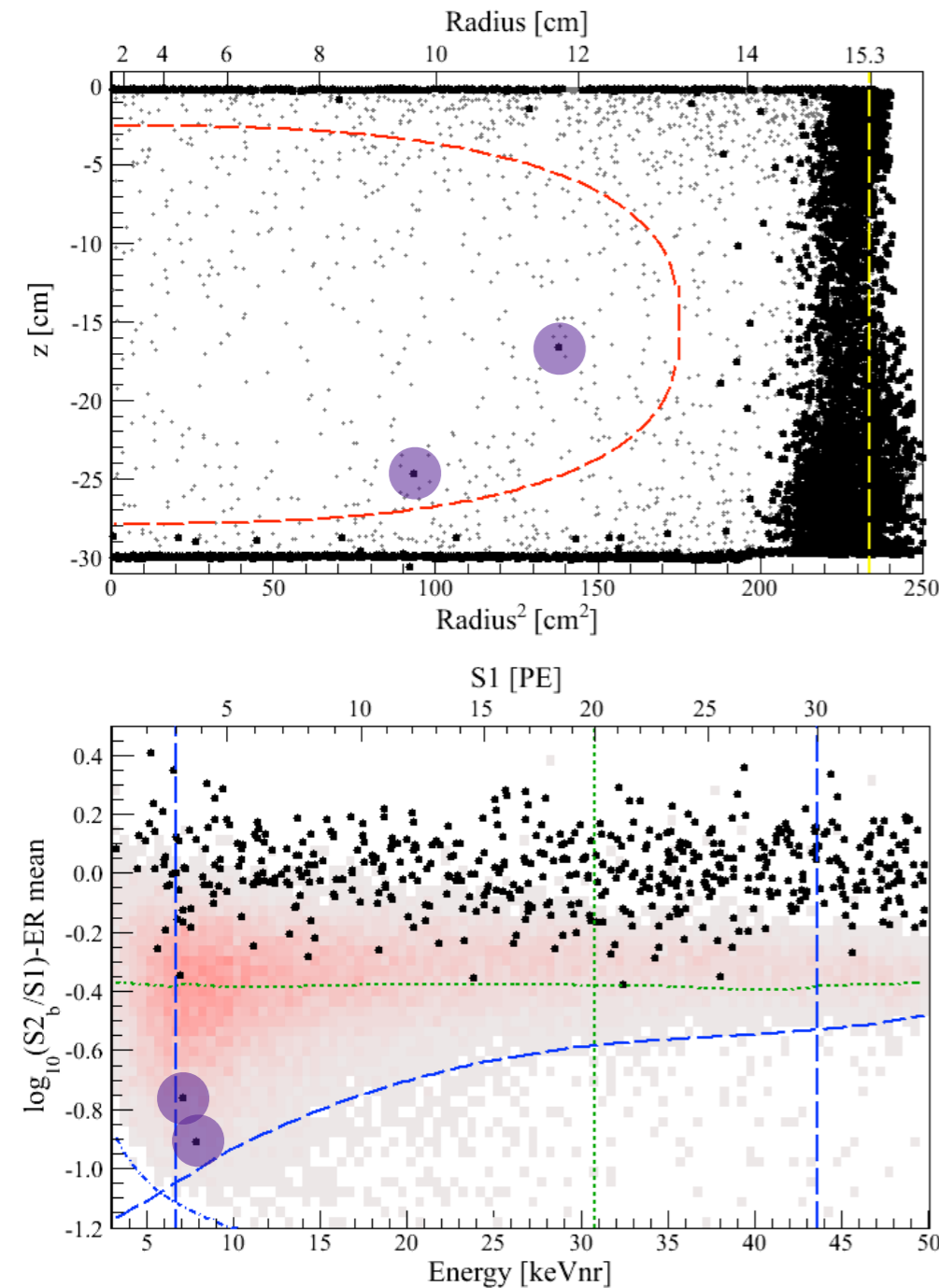
[Phys. Rev. Lett. 109, 181301 \(2012\)](#)

- No WIMP detection:
  - observed 2 events in the signal region

→ expectation from backgrounds:  
 $0.79 \pm 0.16$  from gamma leakage  
 $0.17 + 0.12 - 0.07$  predicted neutrons

[J. Phys. G: Nucl. part. Phys. 40, 115201 \(2013\)](#)

- Best limit at the time of publication
- Current best limit by the LUX experiment

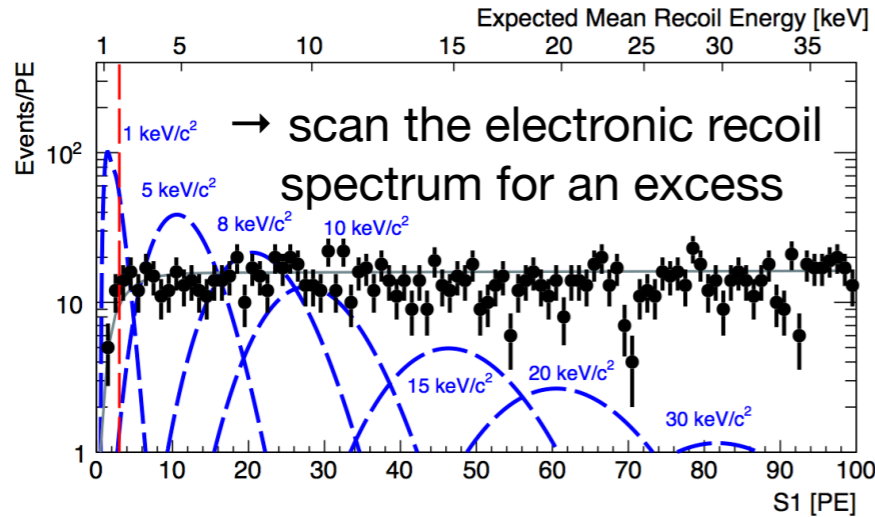


→ Combined analysis of the 3 runs (~500 live days) is ongoing

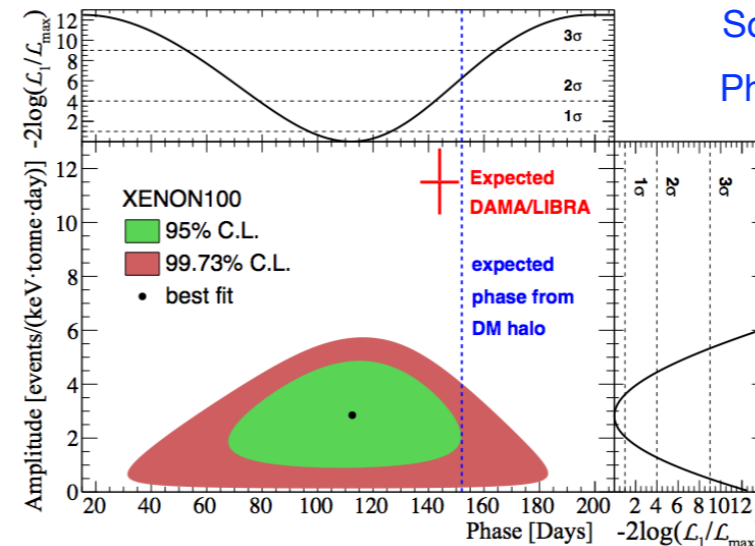
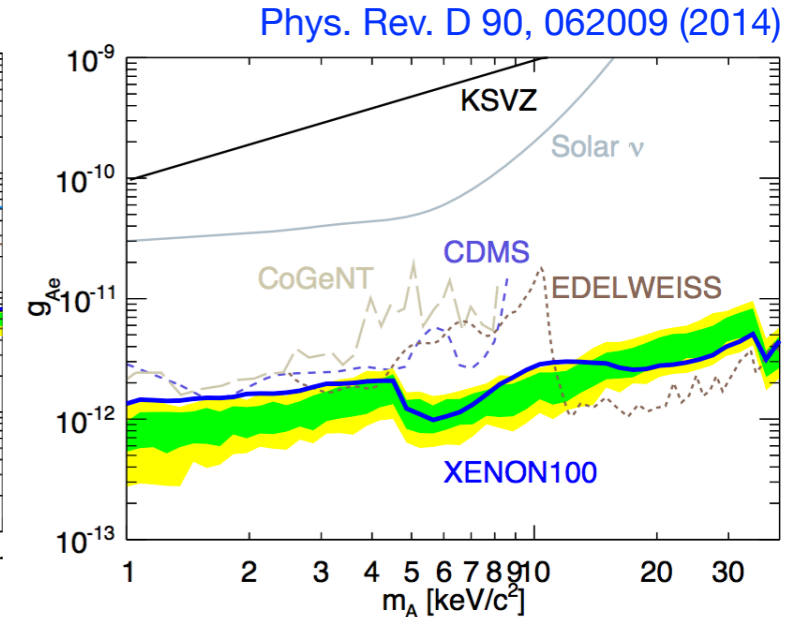
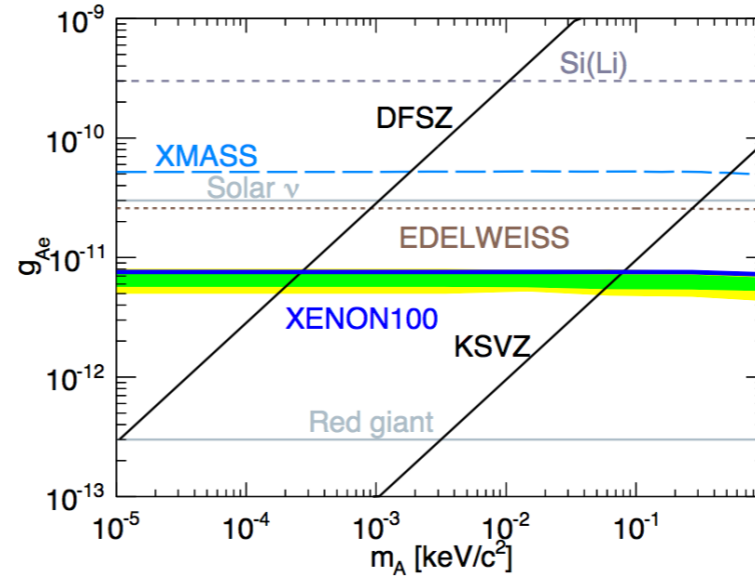
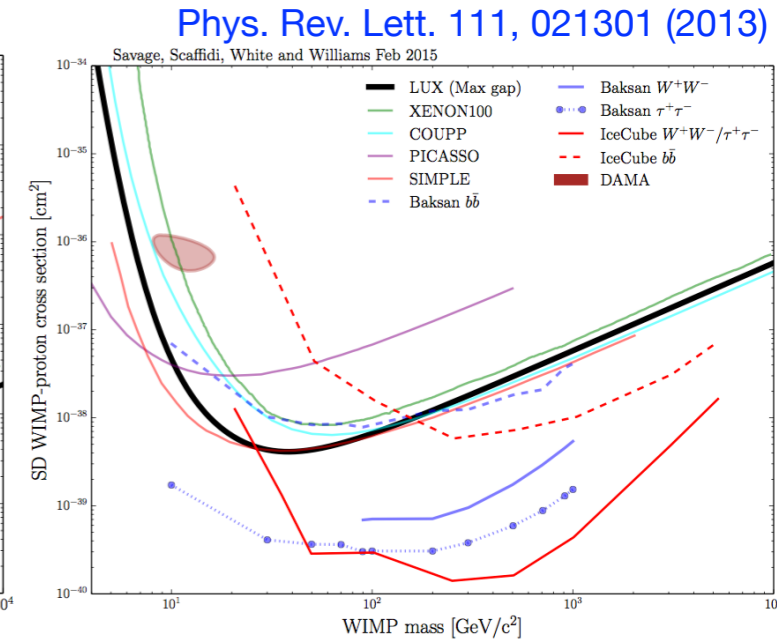
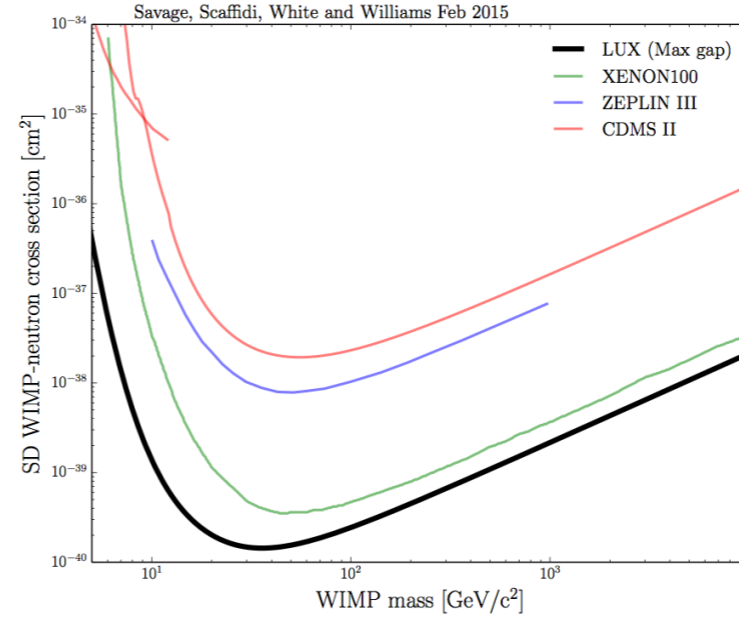
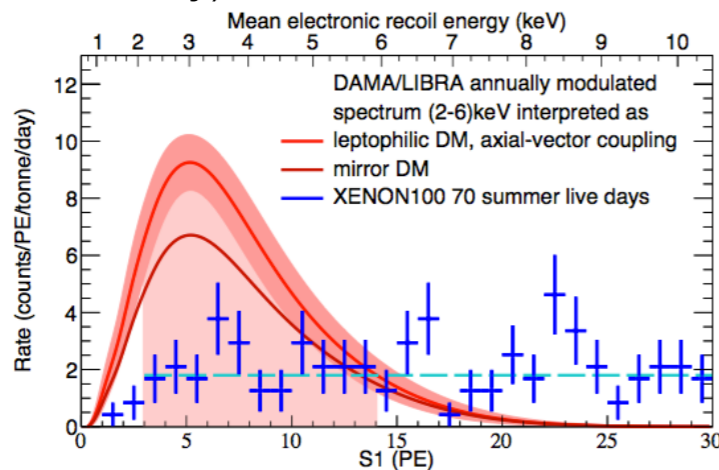
- Spin-dependent WIMP-nucleon interaction

→ Best sensitivity for neutron-coupling.  
Current best limit by the LUX experiment

- Searches for solar axions and axion-like particles

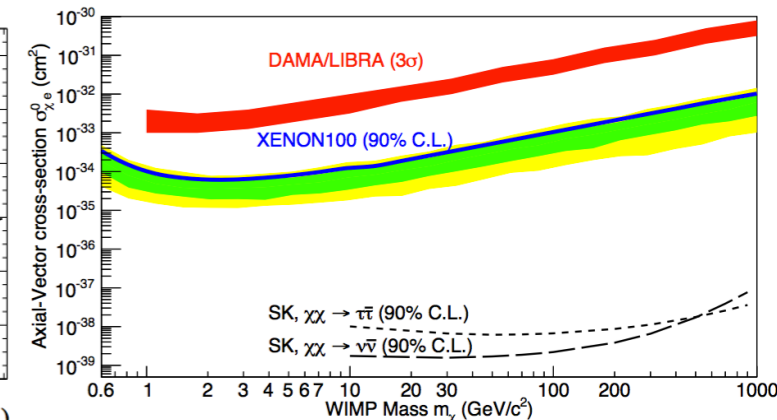


- Probing modulation signals (+DAMA/LIBRA anomaly)

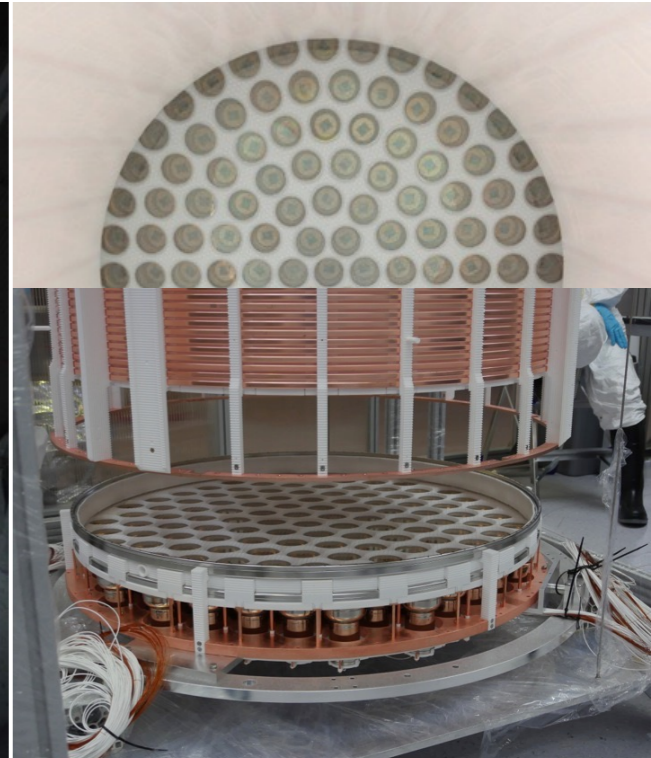
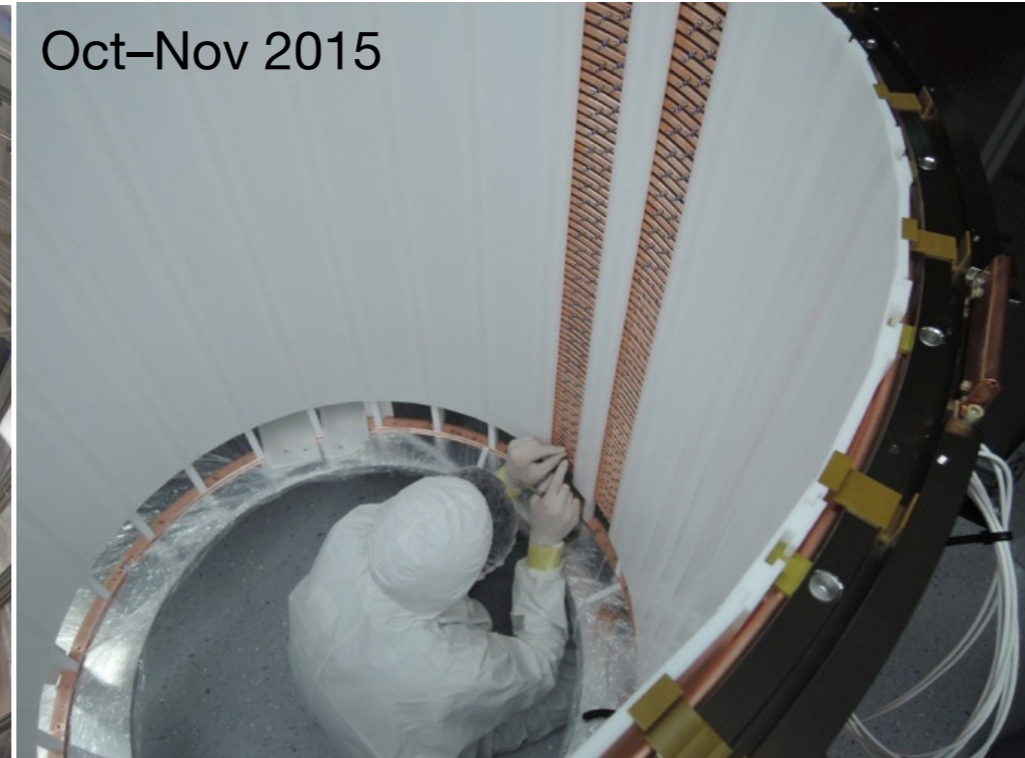


Science, Vol. 349, no. 6250, pp. 851-854 (2013)

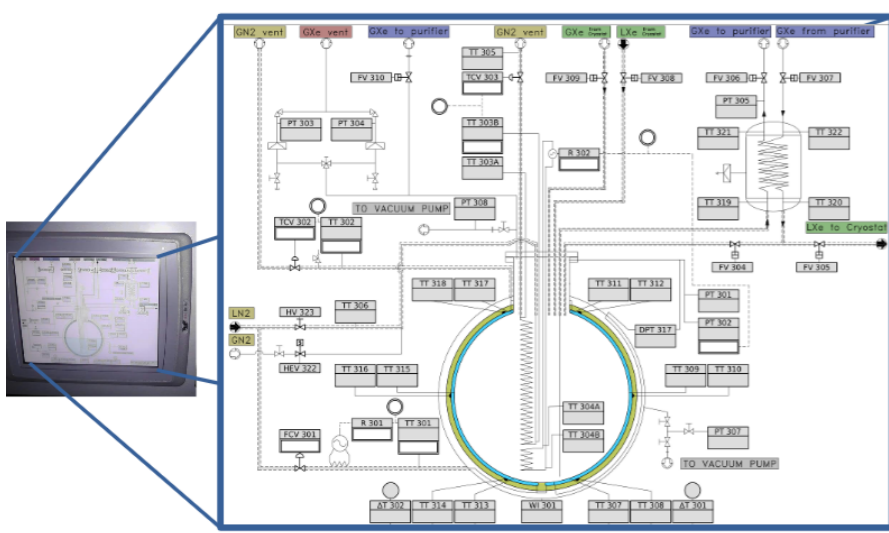
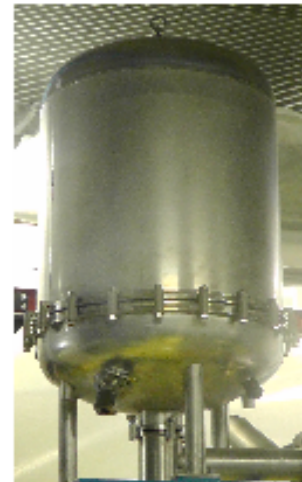
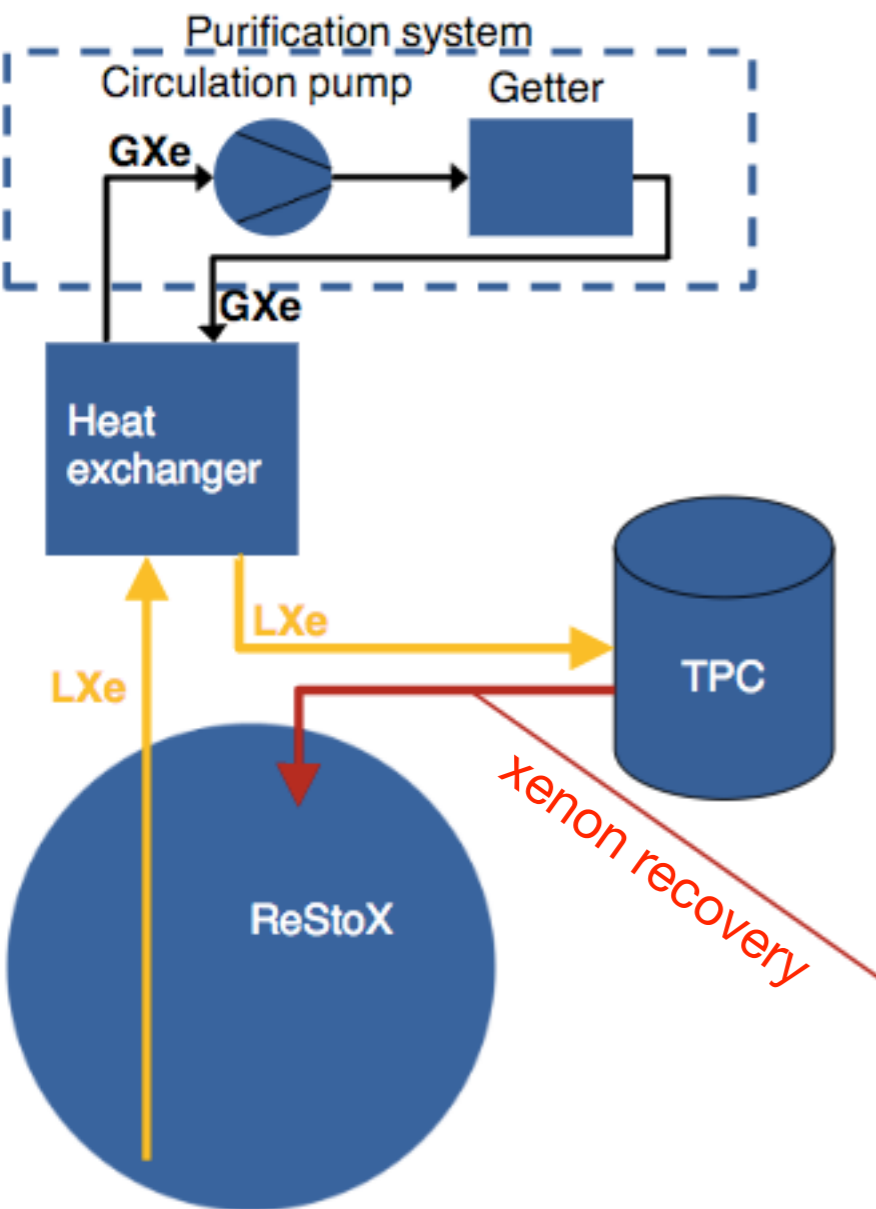
Phys. Rev. Lett. 115, 091302 (2015)



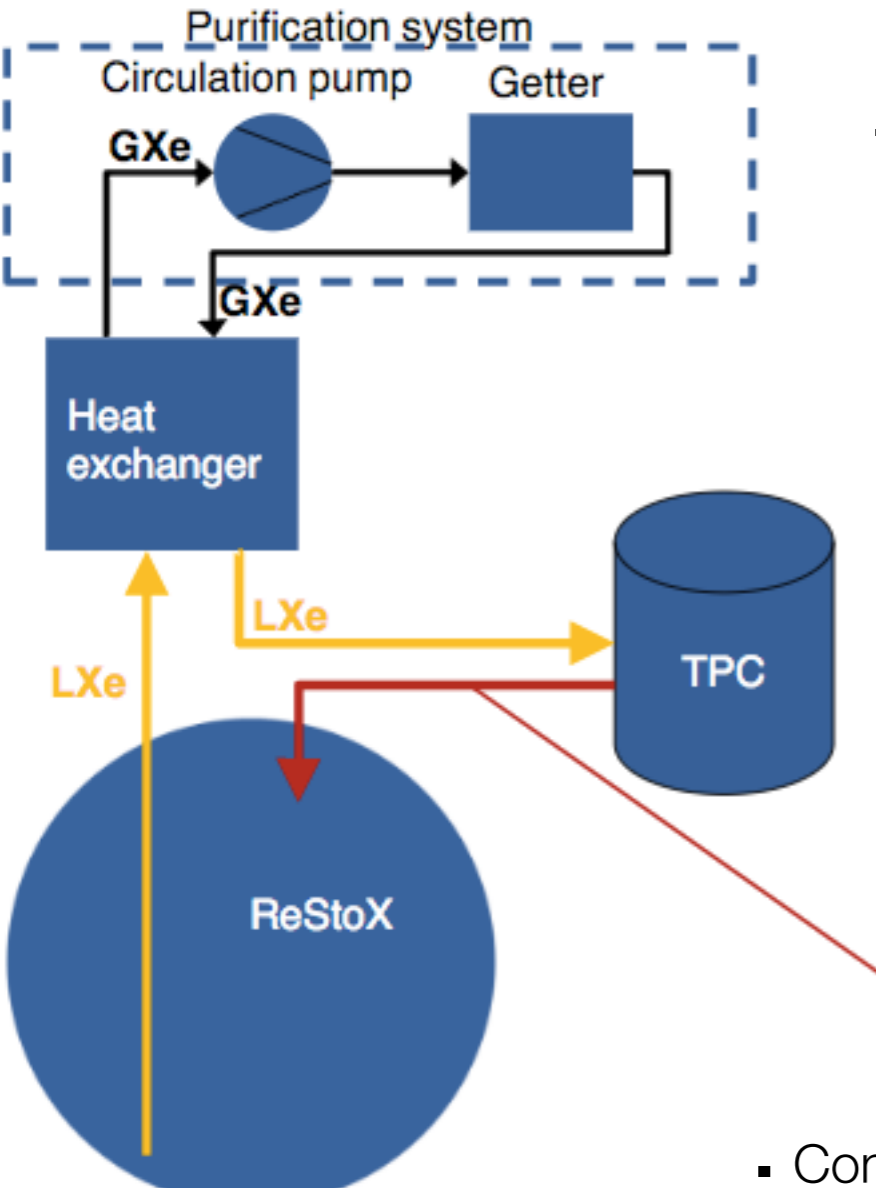
- Just started operations phase
- Design background level 2 orders of magnitude lower than in XENON100
- 3.3t of LXe total (~2.2t active, ~1t fiducial)
- 248 Hamamatsu R11410-21 PMTs (3-inch)
- 10m high and 9.6m diameter water tank (~700 m<sup>3</sup>). Cherenkov light is detected with 84 × 8" PMTs



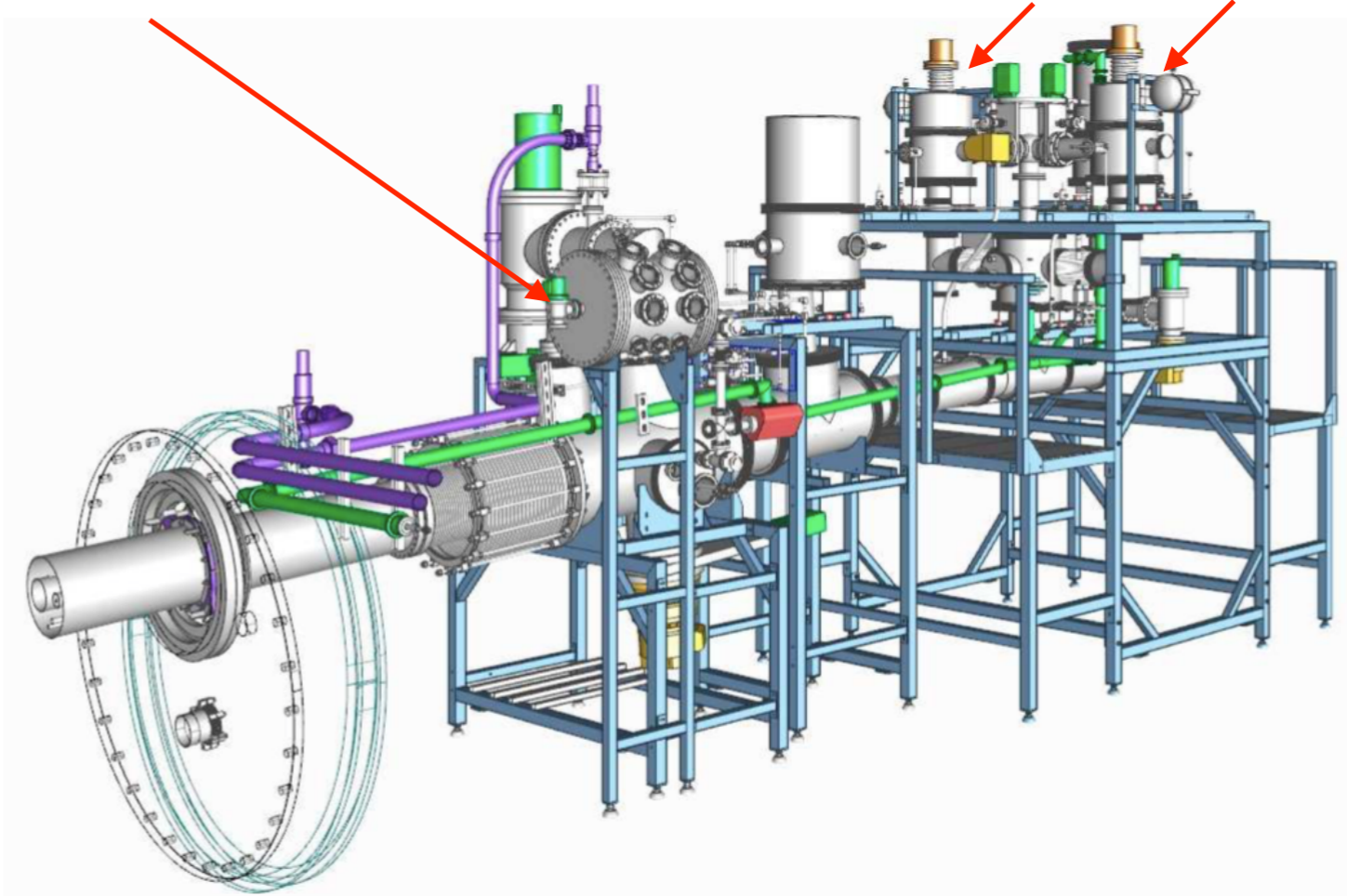
- Xe storage and fast recovery system (ResToX)
- Capable to store 7.6t of Xe either in gas or liquid phase under high purity conditions
- Double-walled, high pressure (70bar) sphere (stainless steel + copper)
- LN<sub>2</sub> based 3kW condenser, large surface area (~5m<sup>2</sup>) to minimize icing
- 1.5kW heater to melt Xe ice during TPC filling after emergency cooling



- Pulse Tube Refrigerator heads for xenon cooling and liquefaction



- 'Porcupine' with HV and signal FTs



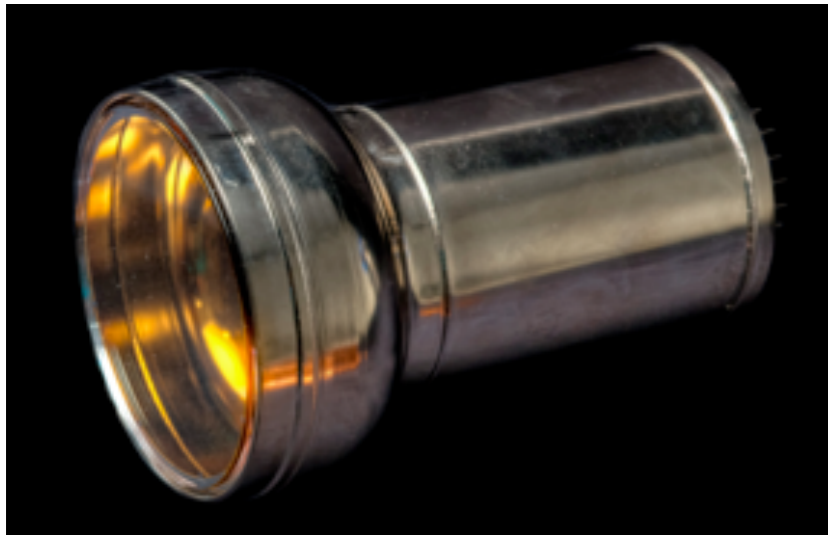
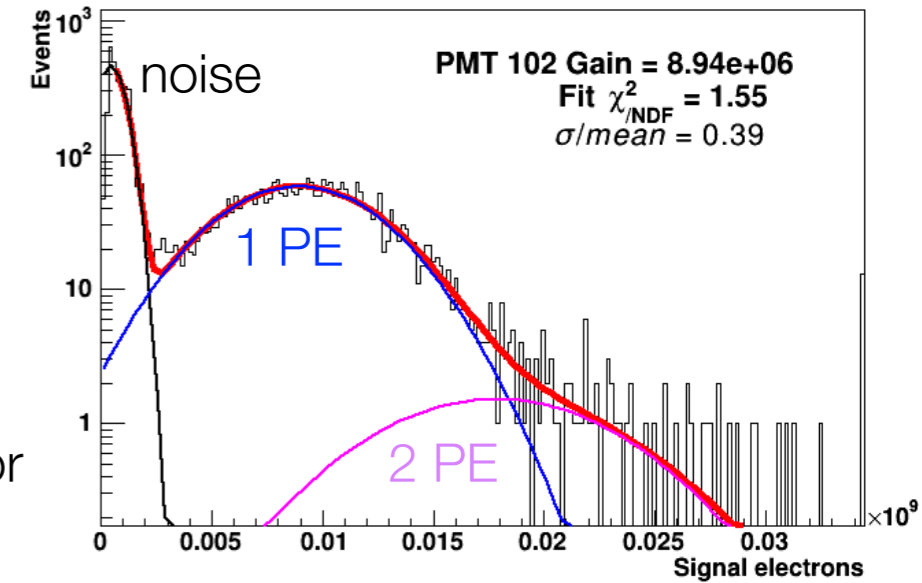
- Connection to 'umbilical' pipe (~10 m long)

- Hot-temperature Zr getters
- QDrive recirculation pumps

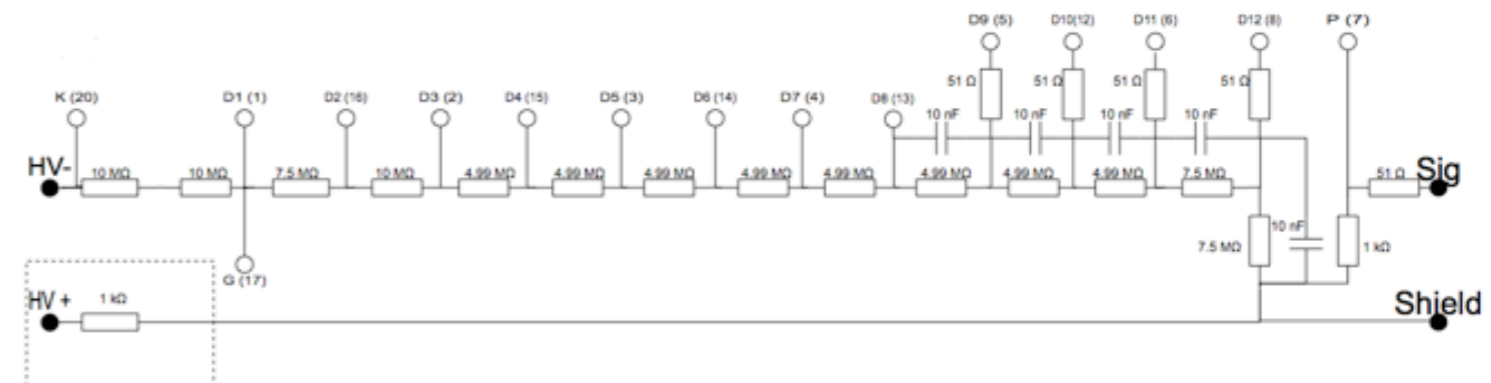


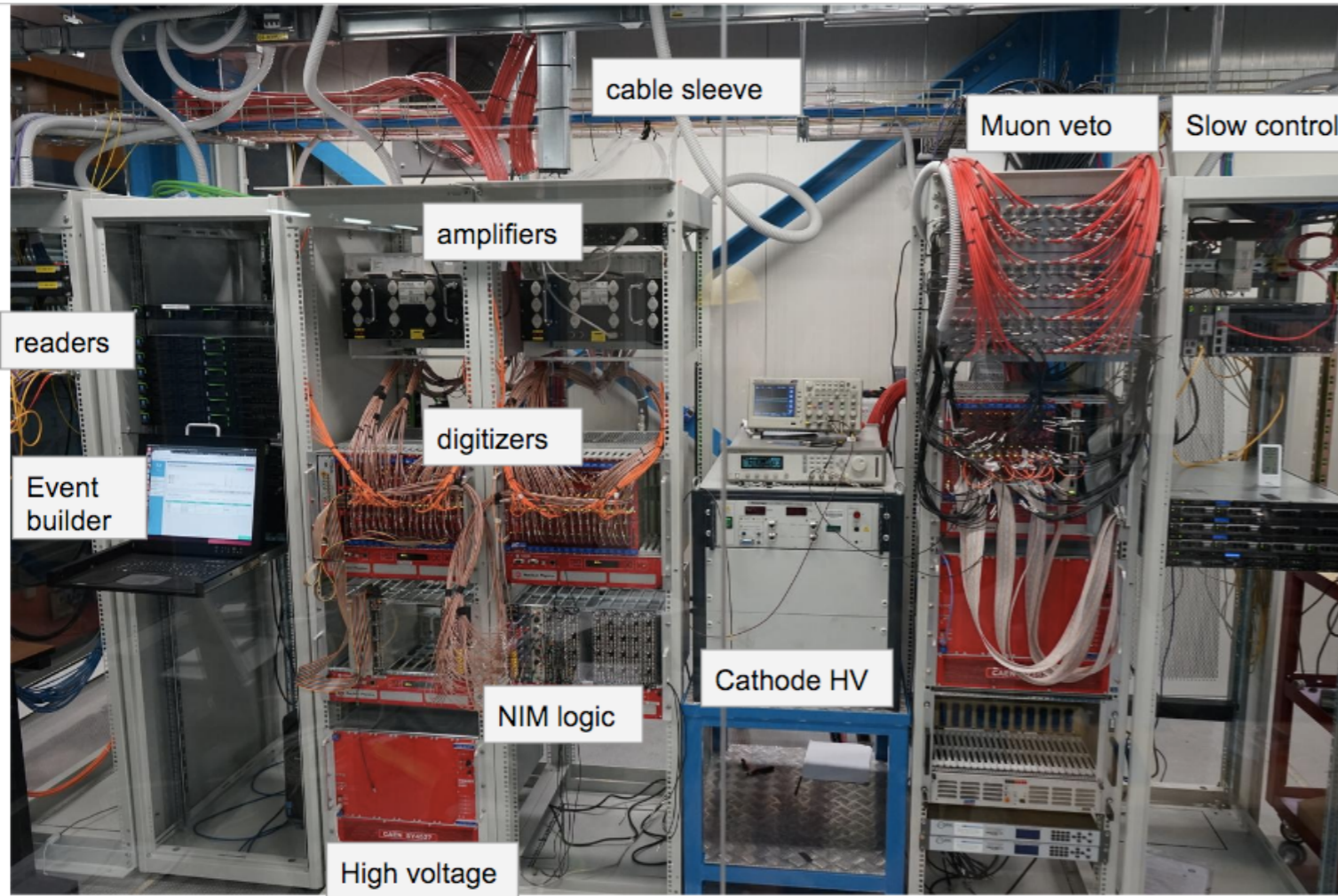
- 3-inch Hamamatsu R11410-21 PMTs
- Average quantum efficiency 36% (at  $\lambda=178\text{nm}$ ), gain  $2\div 5 \times 10^6$  at  $\sim 1.5\text{kV}$
- Optimized to operate in LXe conditions, minimized radioactive contamination  
[JINST 8, P04026, 2013](#)
- Radioactivity measurements by UZH group with the low-background Gator detector (high-purity Ge)
- Characterization in LXe chamber at UZH: gain stability, dark- and after-pulses, cooling cycles

XENON1T, 5 May 2016

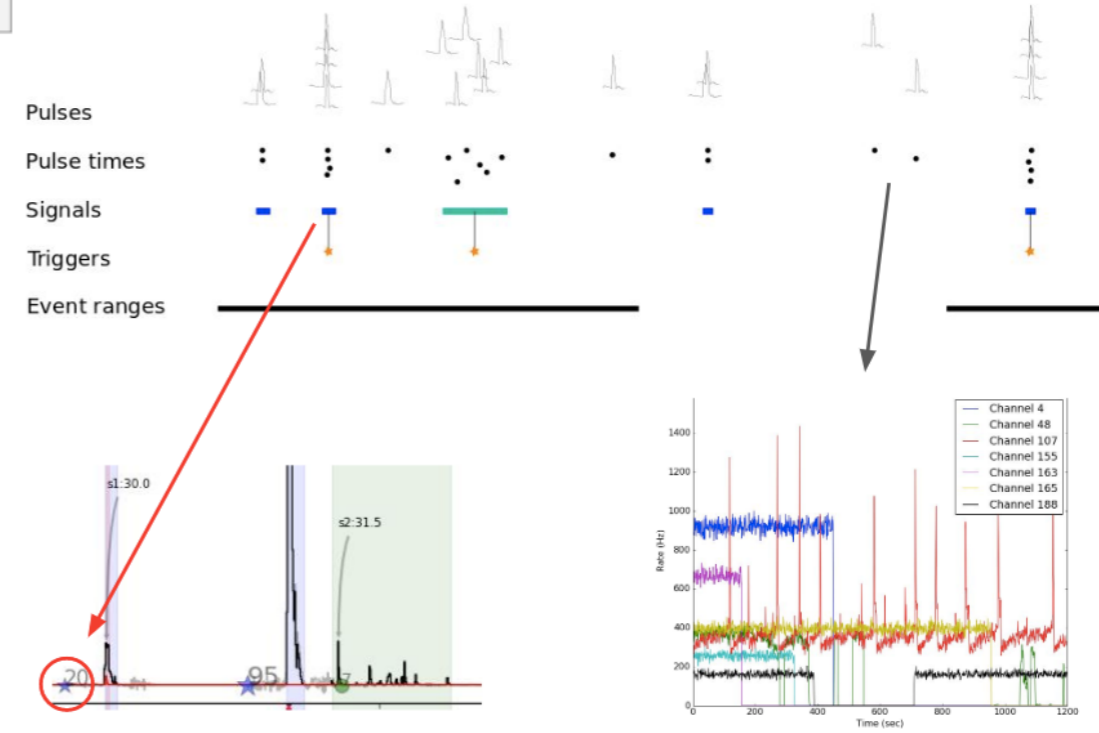


- Voltage divider network on Cirlex substrate
- High linearity and low power consumption/dissipation





## Trigger Design



XENON1T Data Acquisition | Connected | DAQ Status | Open Alerts | User: alexkish

Welcome back alexkish

Current DAQ Controller: mcfate

**Overview**

**Latest Data**

- TPC: mcfate started run 636 about 4 hours ago
- Muon Veto: grignon started run 160320\_1959 2 months ago

**Current shifters**

Shifter	Shifter	Run Coordinator
Qing Lin q2265@columbia.edu +1 646 256 9308	Yun Zhang yz2614@columbia.edu	Junji Naganoma junji@rice.edu +39 346 060 6374
mcfate	-	jnaganoma

**TPC DAQ uptime this month**

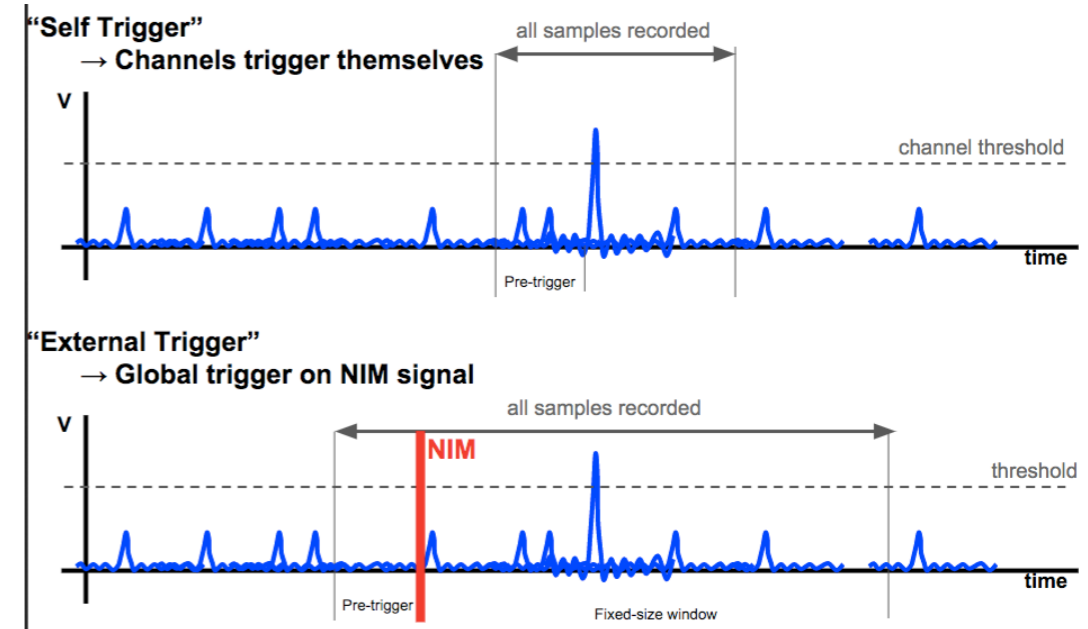
Idle: 0.18	LED: 0.02
PMT test: 0.00	none: 0.53
Cs137: 0.27	No source: 0.00

**My Activity**

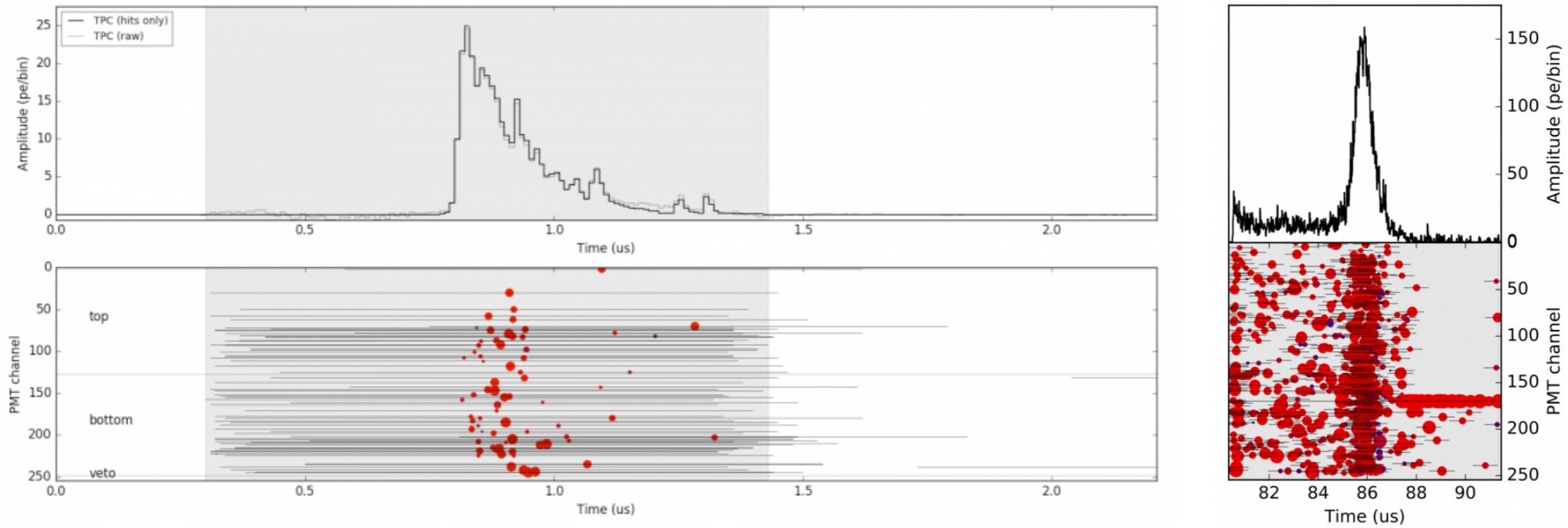
- Next shift: None scheduled
- Shift days (year): 0
- Shift days (all time): 0
- My Affiliation: Zurich

**Recent Log Entries**

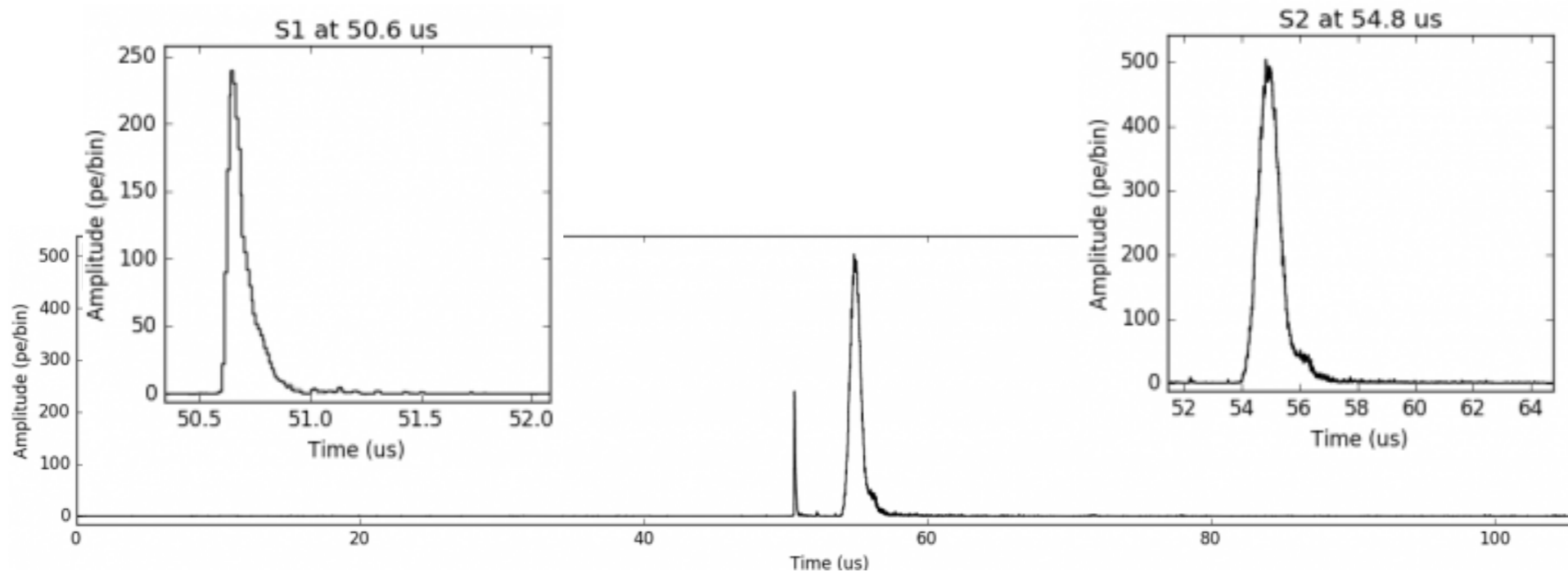
Time	User	Message
2016-05-25T10:07	tunnell	That was 7th from the top, left.
2016-05-25T10:07	tunnell	192 amp ID is 29563.



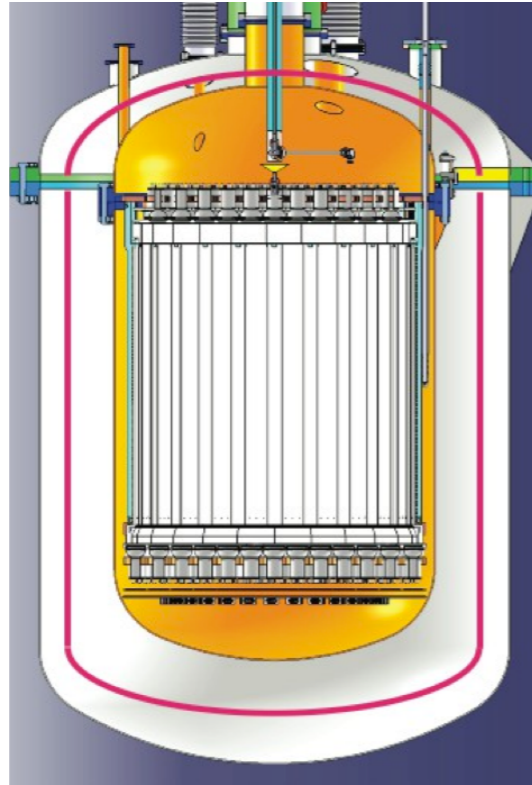
- March 17, 2016:  
First S1 in gas phase without field and first 'S2-like' signal from screening meshes



- June 18, 2016:  
First full trace (S1+S2 event) in dual-phase configuration (3.3t of LXe)



## • XENONnT



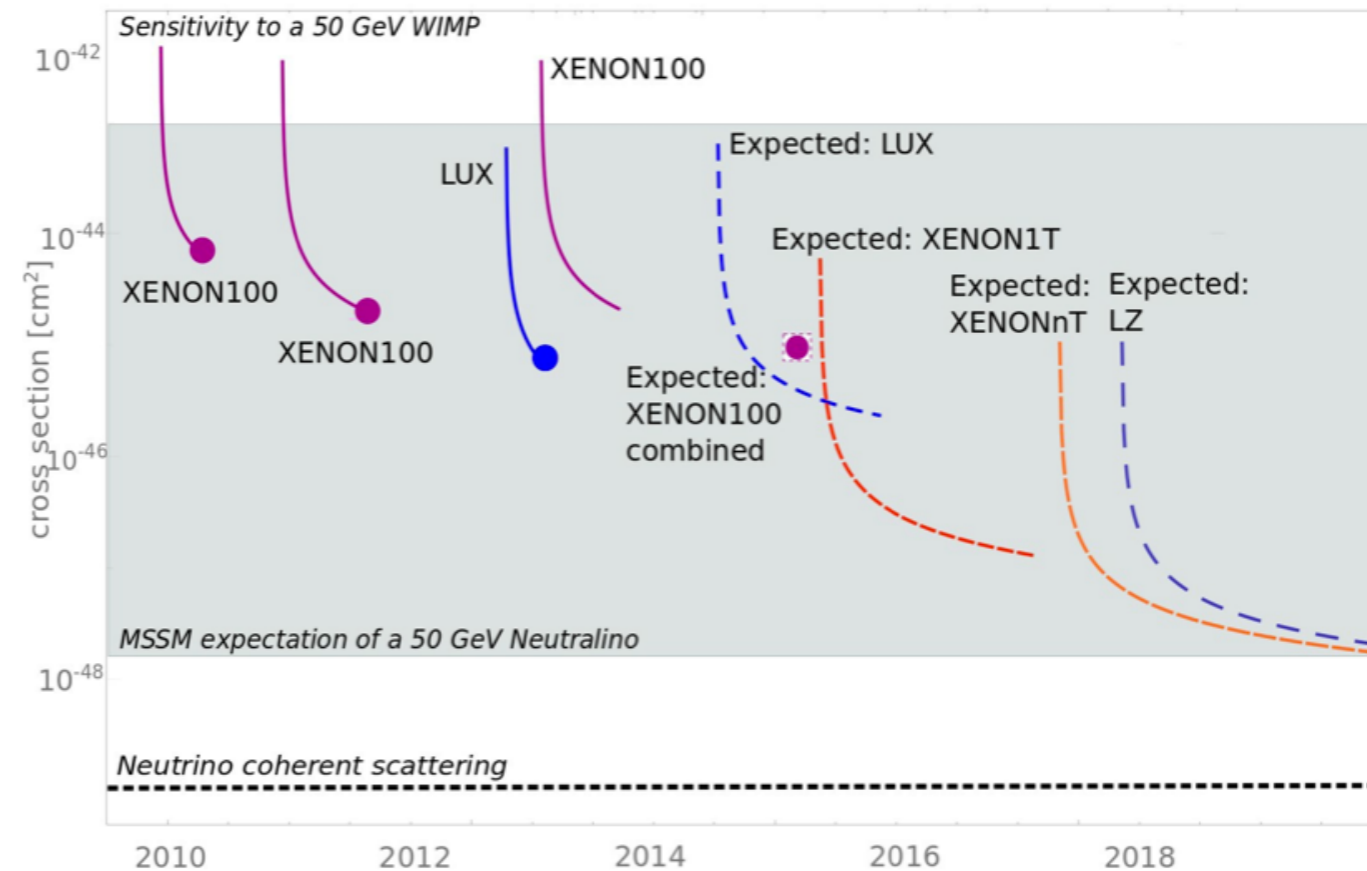
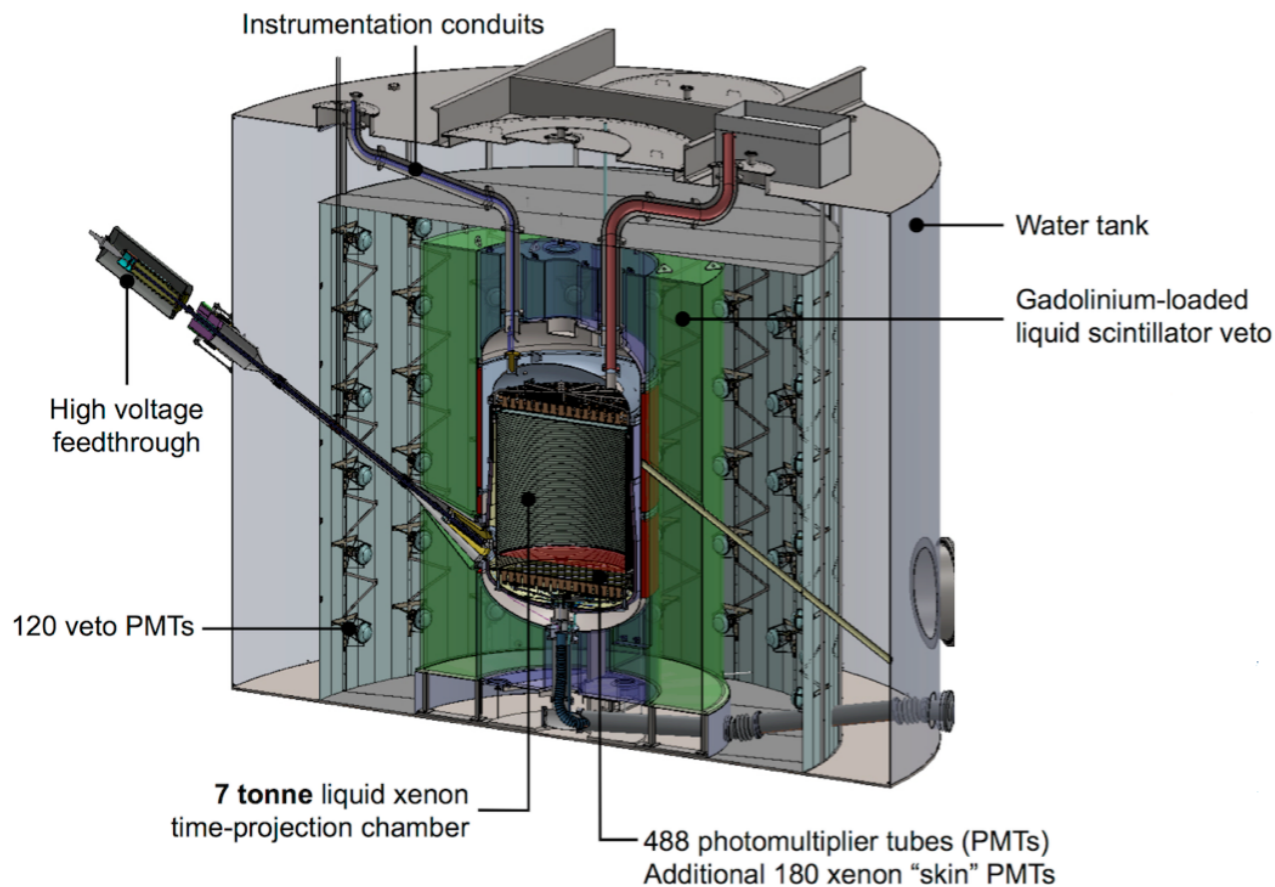
XENONnT = XENON1T facility + larger TPC and inner cryostat

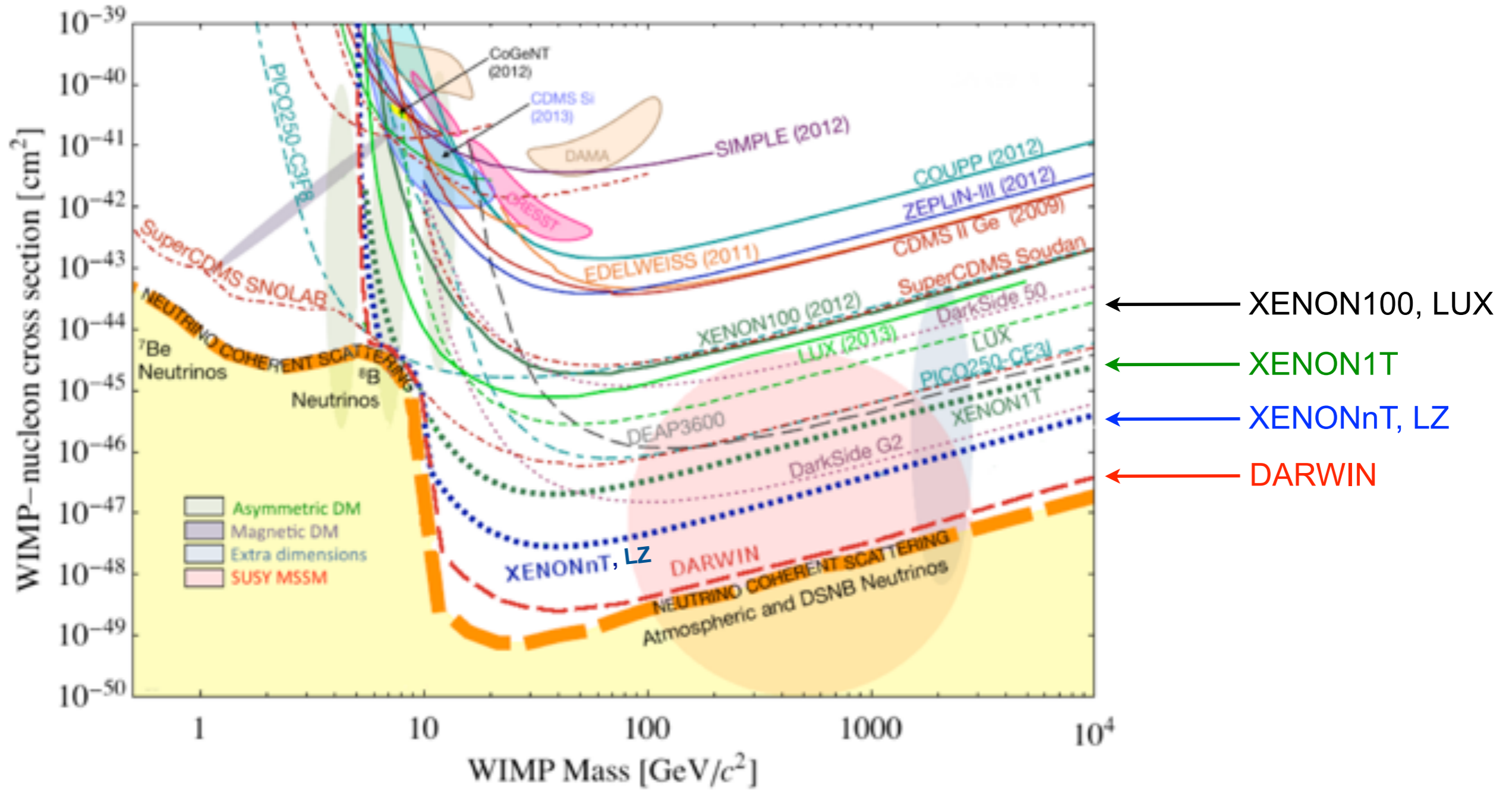
- everything from the cryostat out unchanged
- up to ~7.5t of LXe

Many subsystems already in place:

- water shield
- cooling and support systems,
- DAQ and cabling
- xenon storage and purification,
- distillation column
- outer cryostat

## • LZ (LUX-Zeplin)

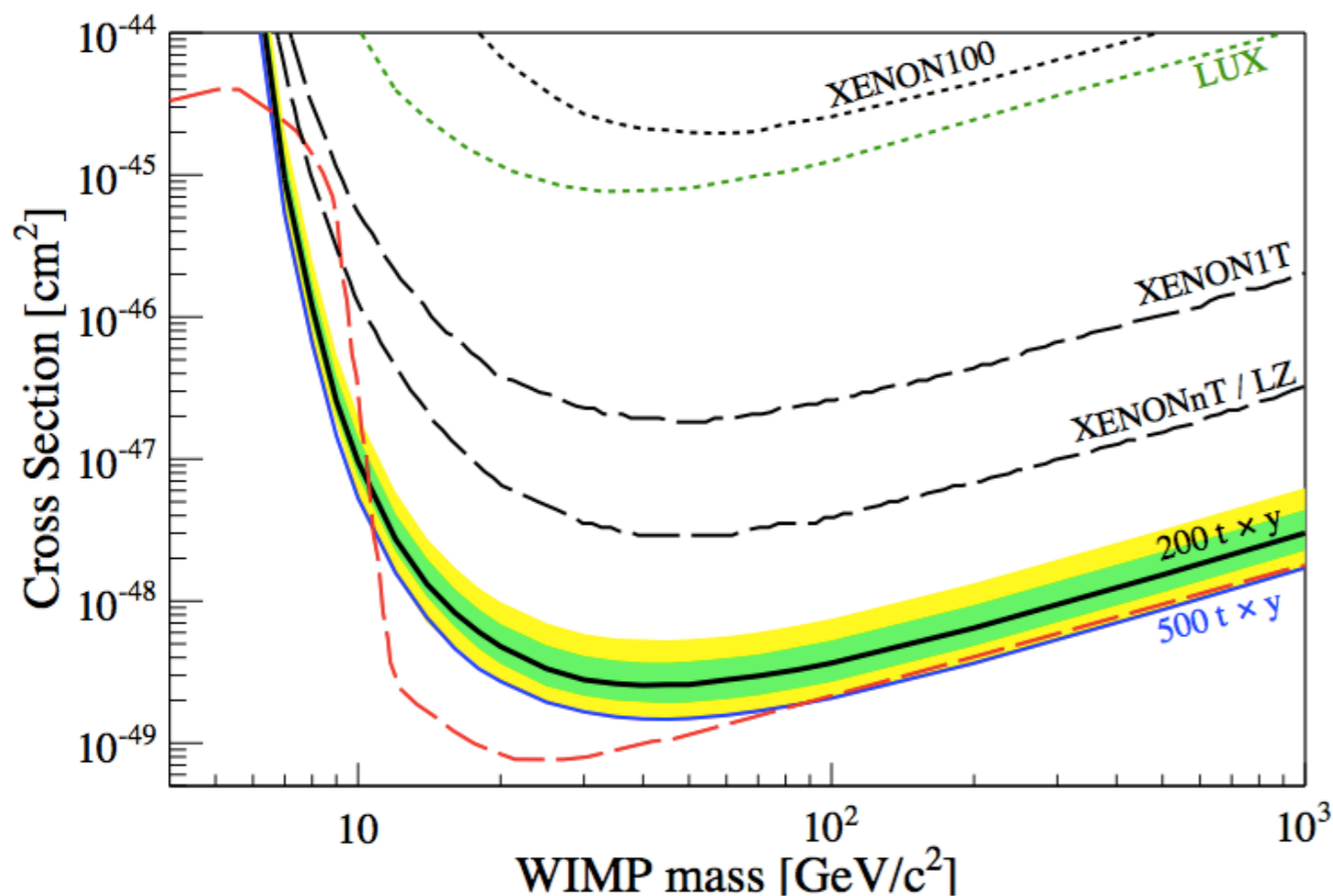




- DARWIN = DARK matter WImp search with Noble liquids

2010 – 2013	First R&D phase, Aspera funded
now	R&D and design
2018 – 2020	Engineering study
2020 – 2030	Construction, commissioning, science run

- Baseline design:  
20-30t scale, copper cryostat, teflon TPC, drift length ~2.1m
- Detailed MC and sensitivity studies performed for a LXe detector



Published January 28, 2014

## Neutrino physics with multi-ton scale liquid xenon detectors

L. Baudis,<sup>a,1</sup> A. Ferella,<sup>a,b</sup> A. Kish,<sup>a</sup> A. Manalaysay,<sup>a,e</sup>  
T. Marrodán Undagoitia<sup>a,c</sup> and M. Schumann<sup>a,d</sup>

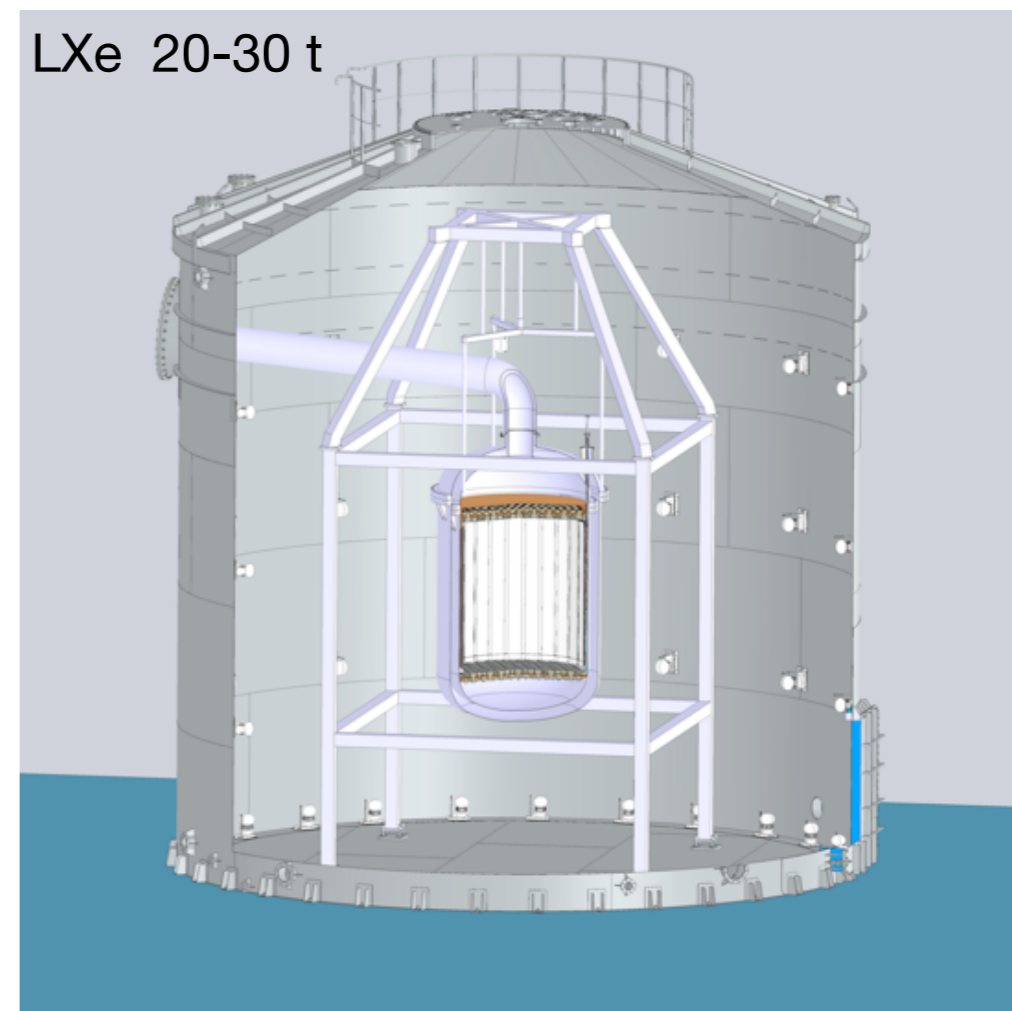
Journal of Cosmology and Astroparticle Physics

## Dark matter sensitivity of multi-ton liquid xenon detectors

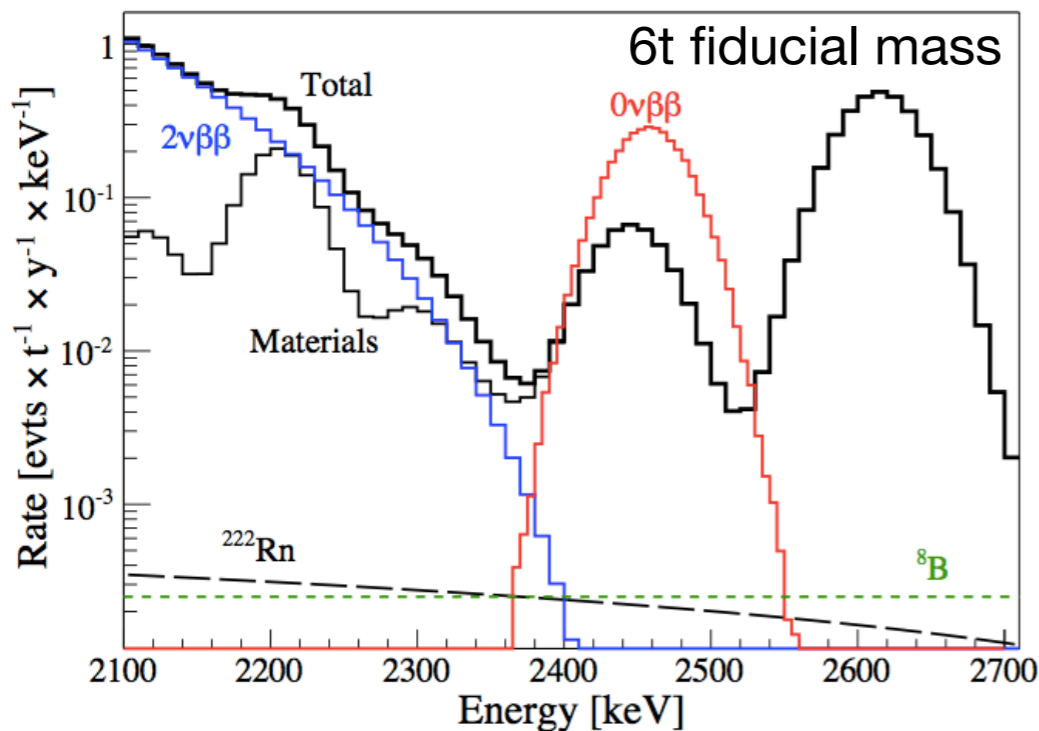
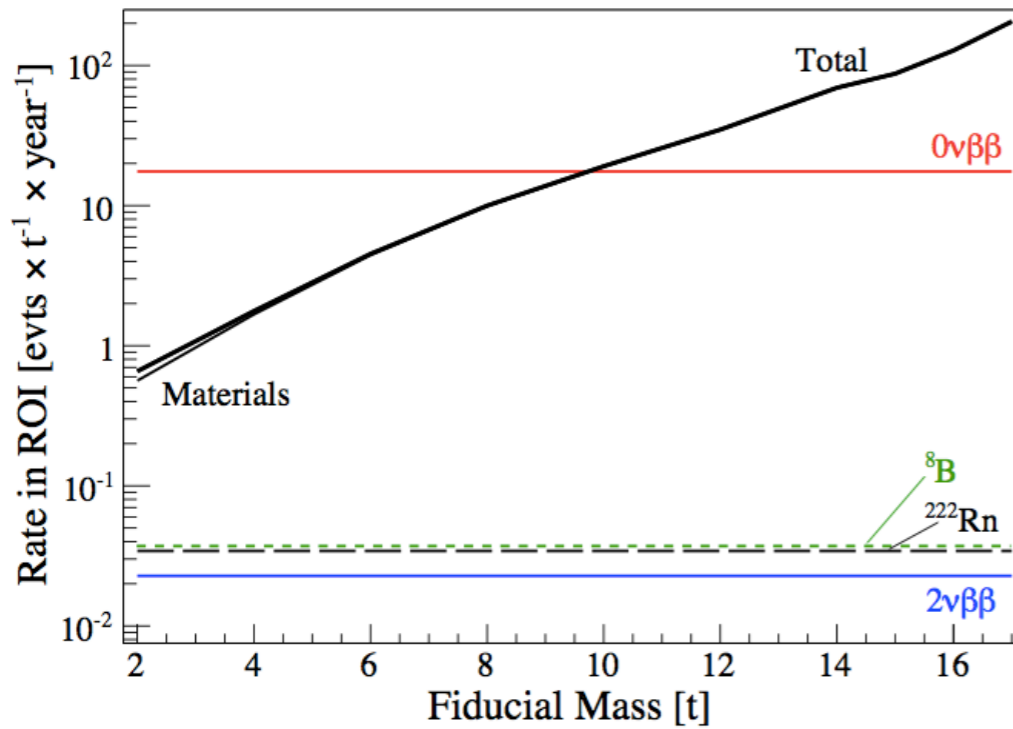
Marc Schumann<sup>a</sup>, Laura Baudis<sup>b</sup>, Lukas Büttikofer<sup>a</sup>, Alexander Kish<sup>b</sup> and Marco Selvi<sup>c</sup>

Published 8 October 2015 • © 2015 IOP Publishing Ltd and Sissa Medialab srl • Journal of Cosmology and Astroparticle Physics, Volume 2015, October 2015

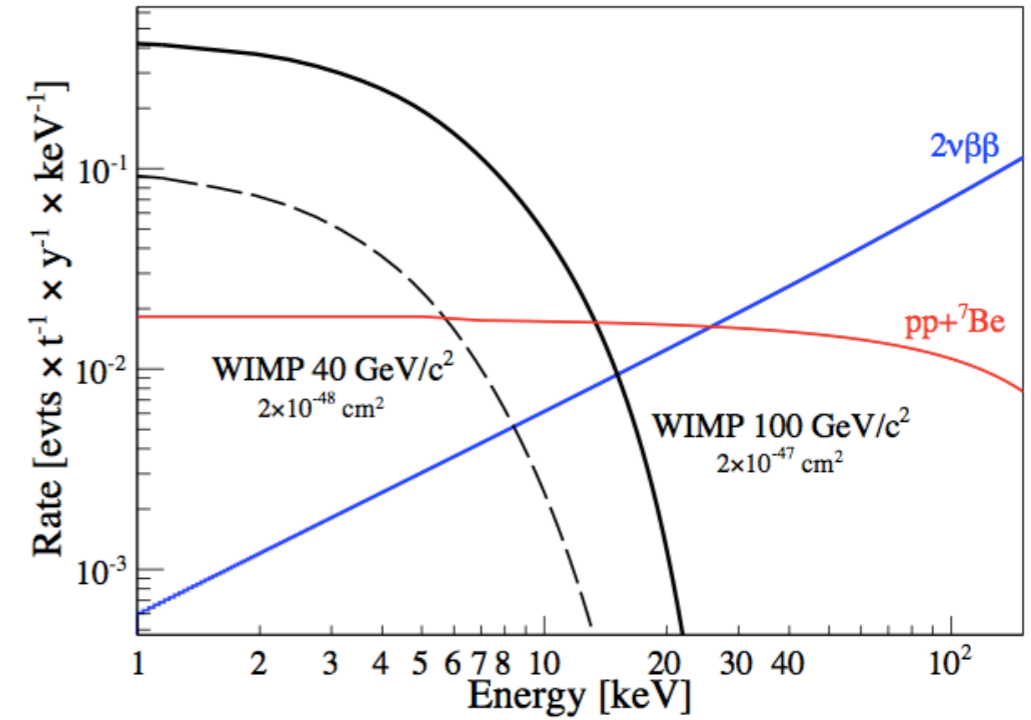
LXe 20-30 t



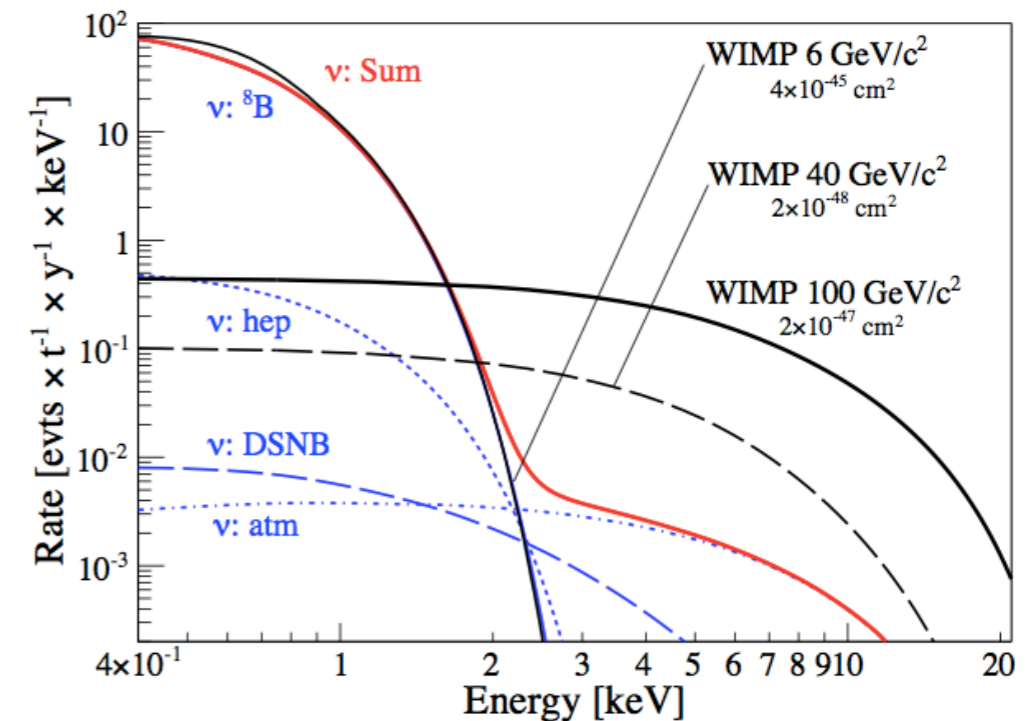
- $0\nu\beta\beta$  search in  $^{136}\text{Xe}$ 
  - find out if  $\nu$  has a Majorana mass component
  - lepton number conservation
  - constraint on the  $\nu$  mass hierarchy

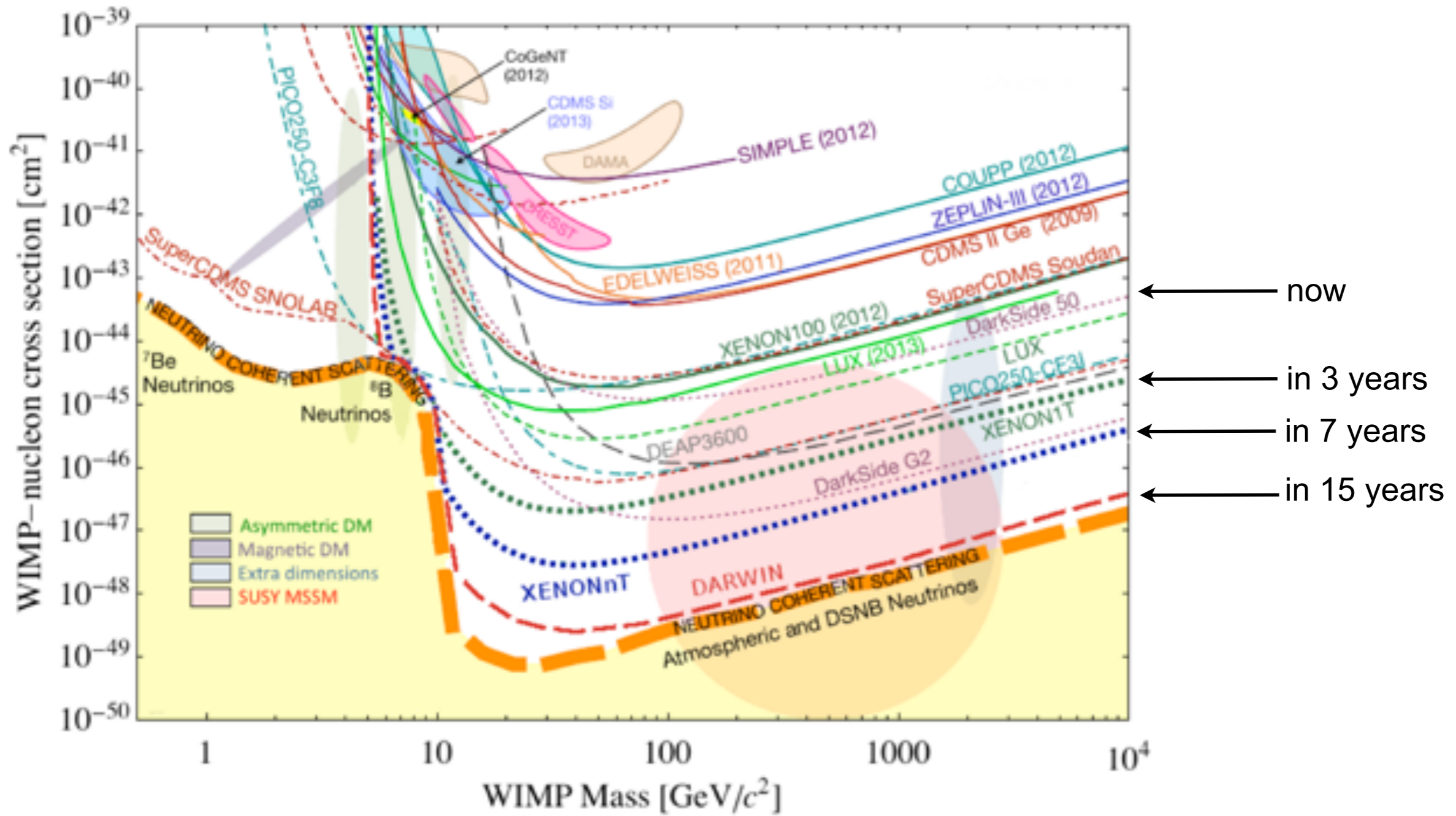


- Neutrino-electron scattering
  - constrain solar models



- Coherent neutrino-nucleus scattering (CNNS)
  - test SM predictions





alexkish@physik.uzh.ch  
alexkish@xenon1t.org