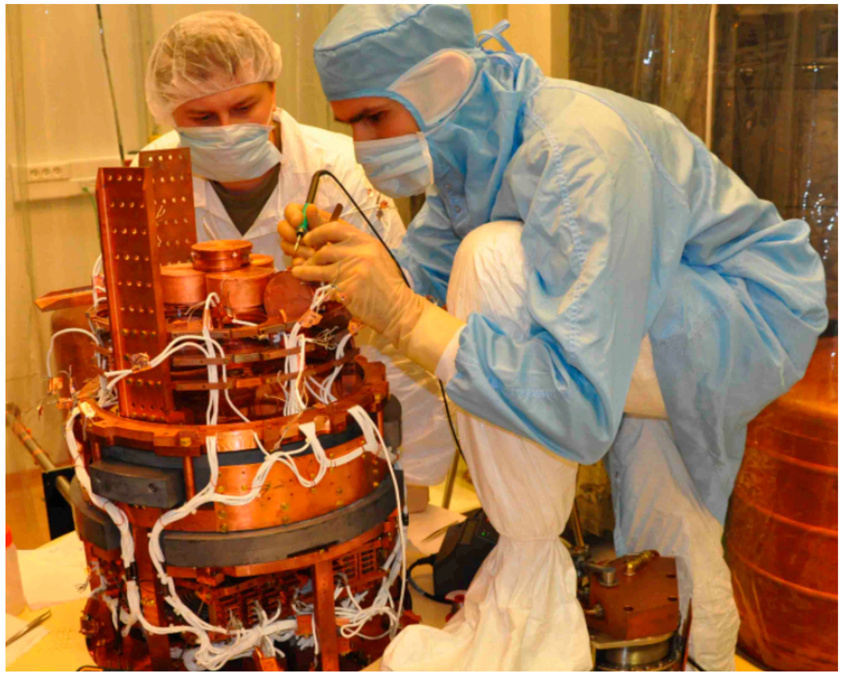
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Lecture 2
Dark Matter Direct Detection Experiments : part 1

December 2, 2017

XIV ICFA School on
Instrumentation in Elementary
Particle Physics
La Havana,Cuba



Elena Aprile
Columbia University

Outline of Lecture 2 & 3

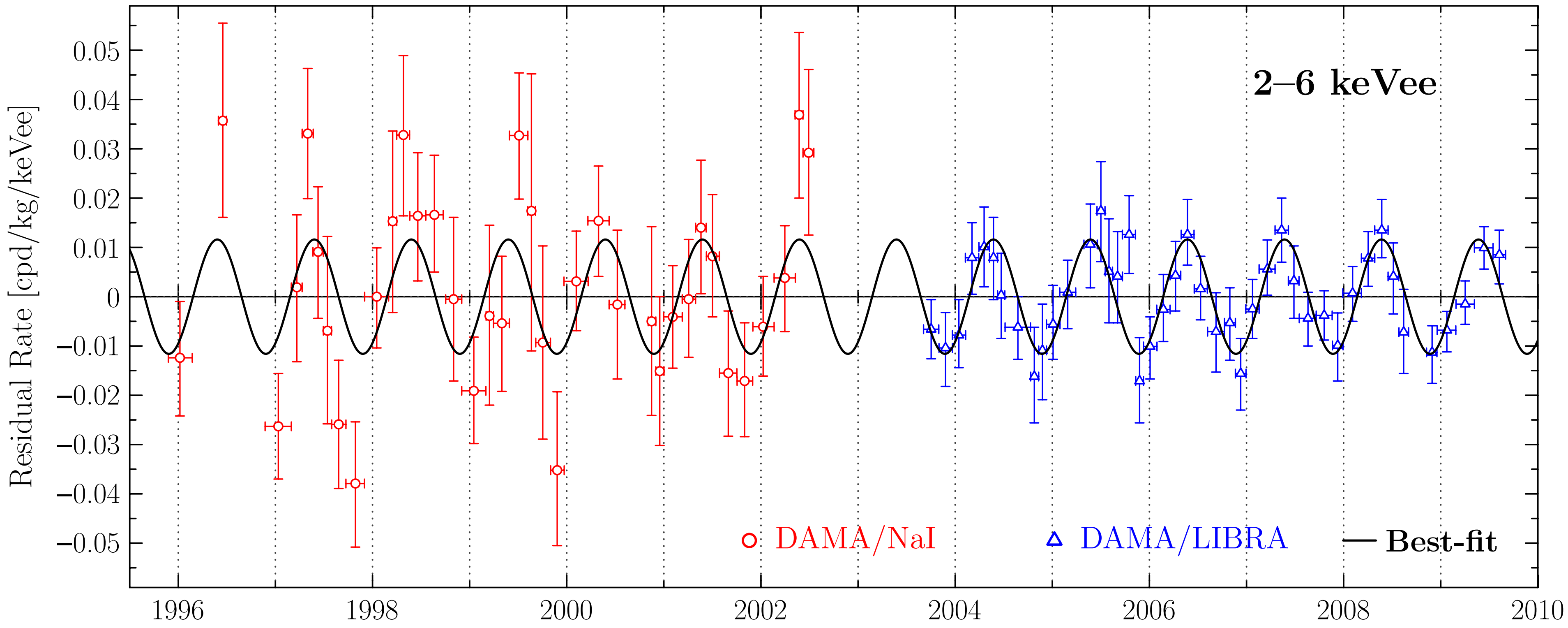
- Crystal Scintillator Detectors (**DAMA/LIBRA, ANAIS, COSINE, SABRE**)
- mK Detectors (**CDMS,EDELWEISS,CRESST**)
- Bubble Chambers (**PICO**)
- Noble Liquid Detectors (**DEAP, XMASS, DarkSide, LZ, XENON**)

Room Temperature Scintillation Experiments

- Inorganic alkali halide crystals (NaI (Tl), CsI (Tl) : high density, high light output
- can be produced with high purity in large mass at affordable cost (annual modulation study)
- Sensitive to both SD and SI WIMP interactions
- PSD (better for CsI) but no discrimination between electron and nuclear recoils on an event-by-event basis
- Experiments: DAMA-LIBRA/Italy, KIMS/Korea

Annual modulation

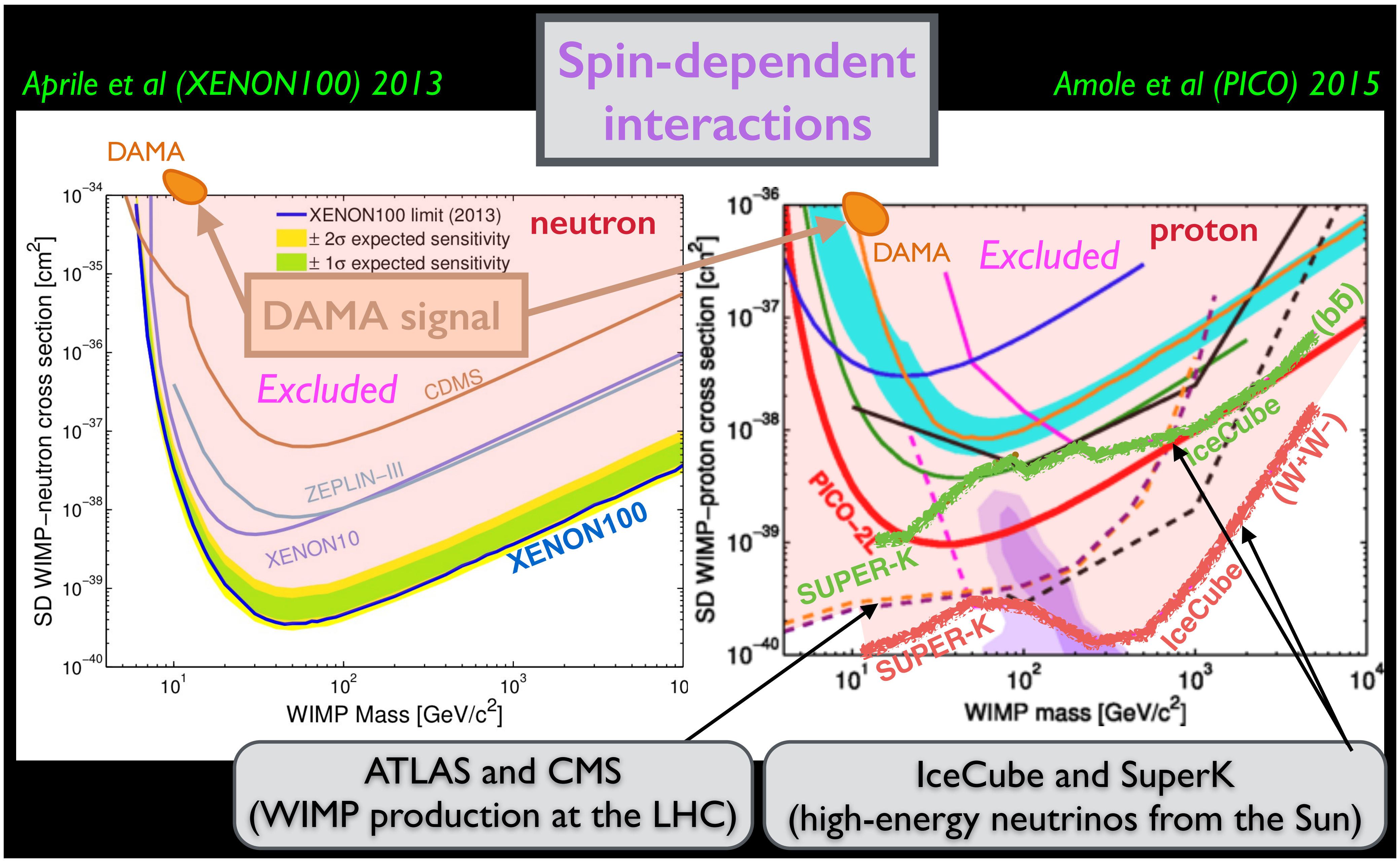
- Observed in the DAMA/LIBRA experiment (8.9-sigma; 250 kg NaI, 0.82 tons-year)
- Origin remains unclear



Amplitude: ~ (0.0116 ± 0.0013) events/(kg keV d)

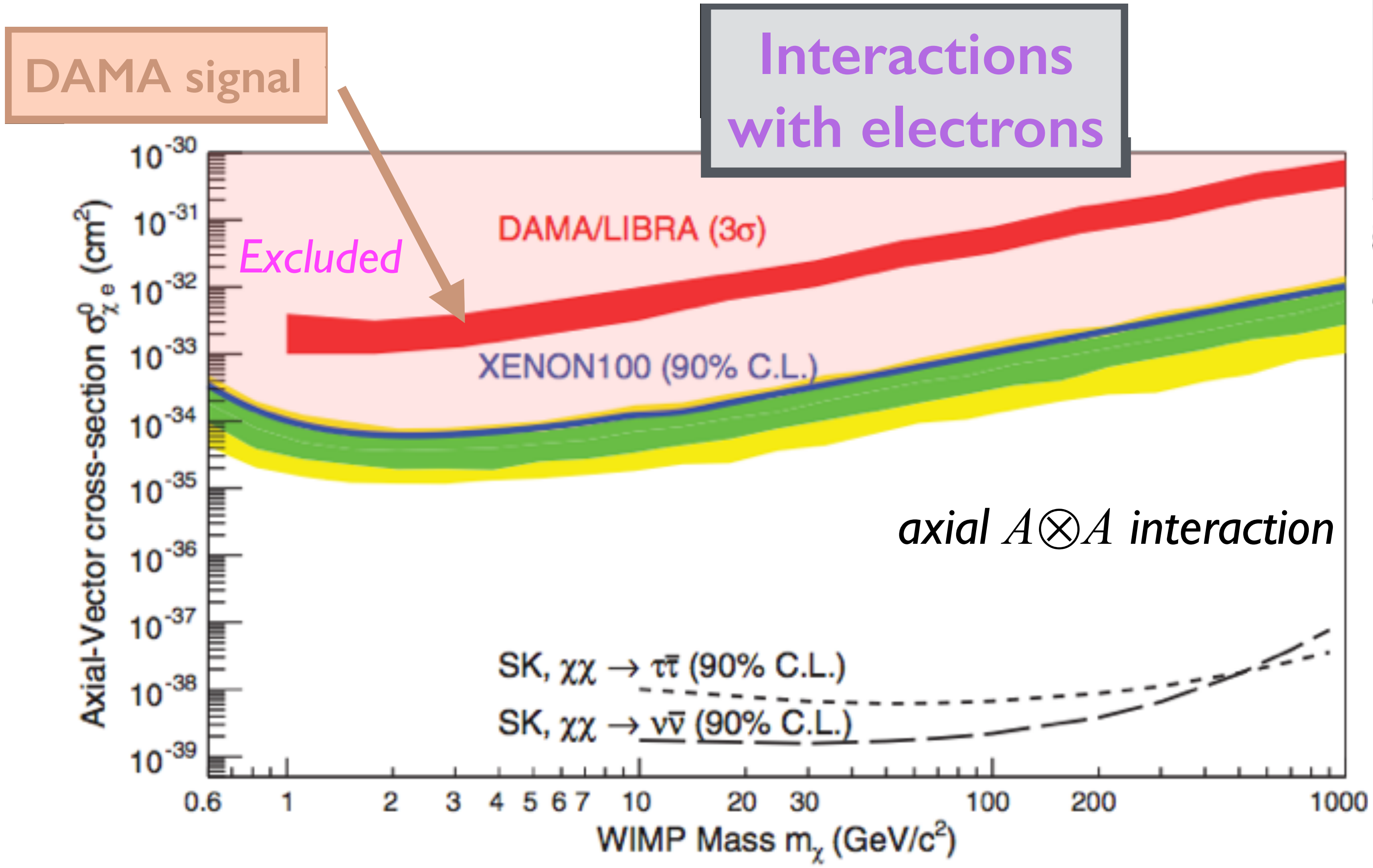
T = 0.999 ± 0.001 yr, t_0 = 0.400 ± 0.019 (May 26±7 days)

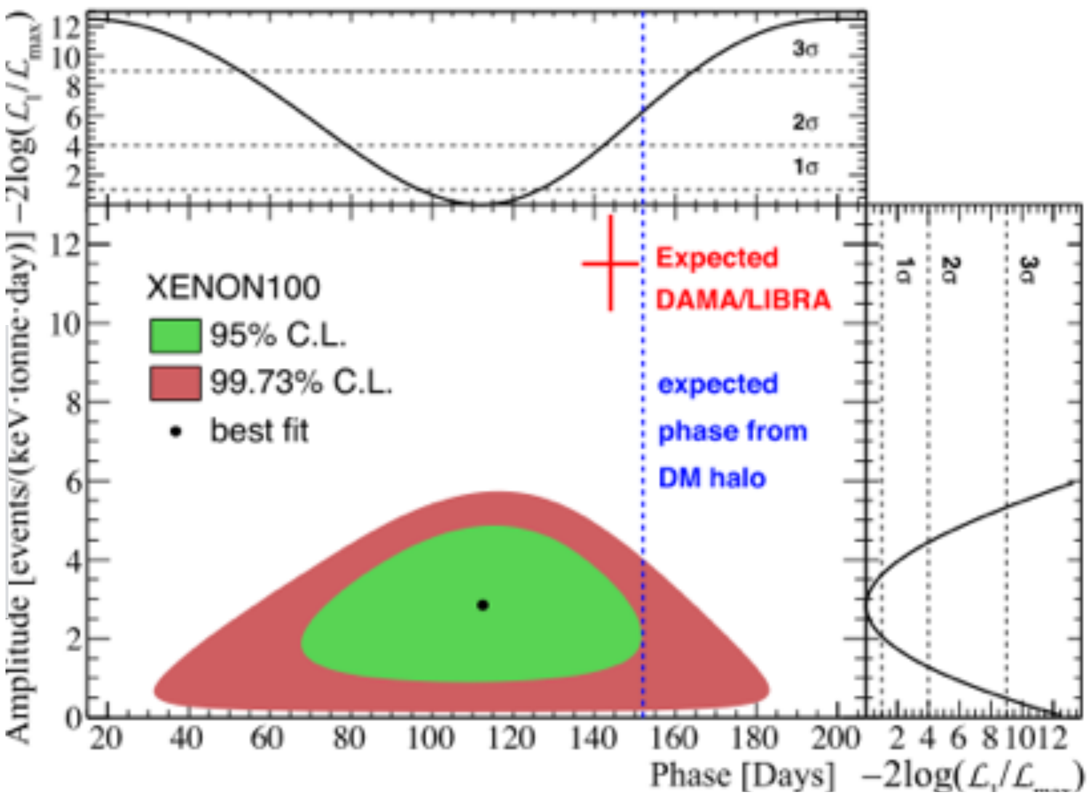
DAMA Incompatible with Other Experiments



Gondolo, IDM 2016

DAMA Incompatible with Other Experiments



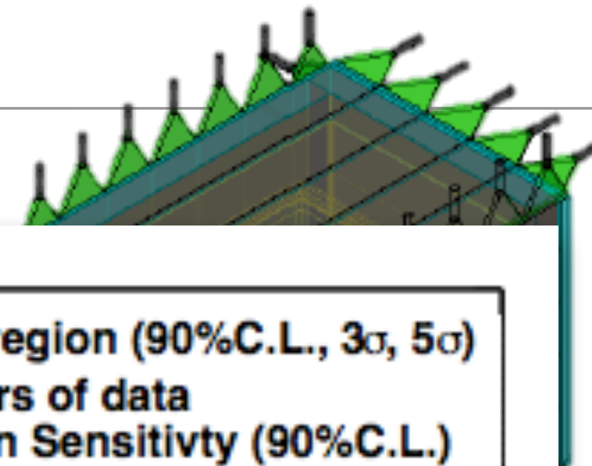


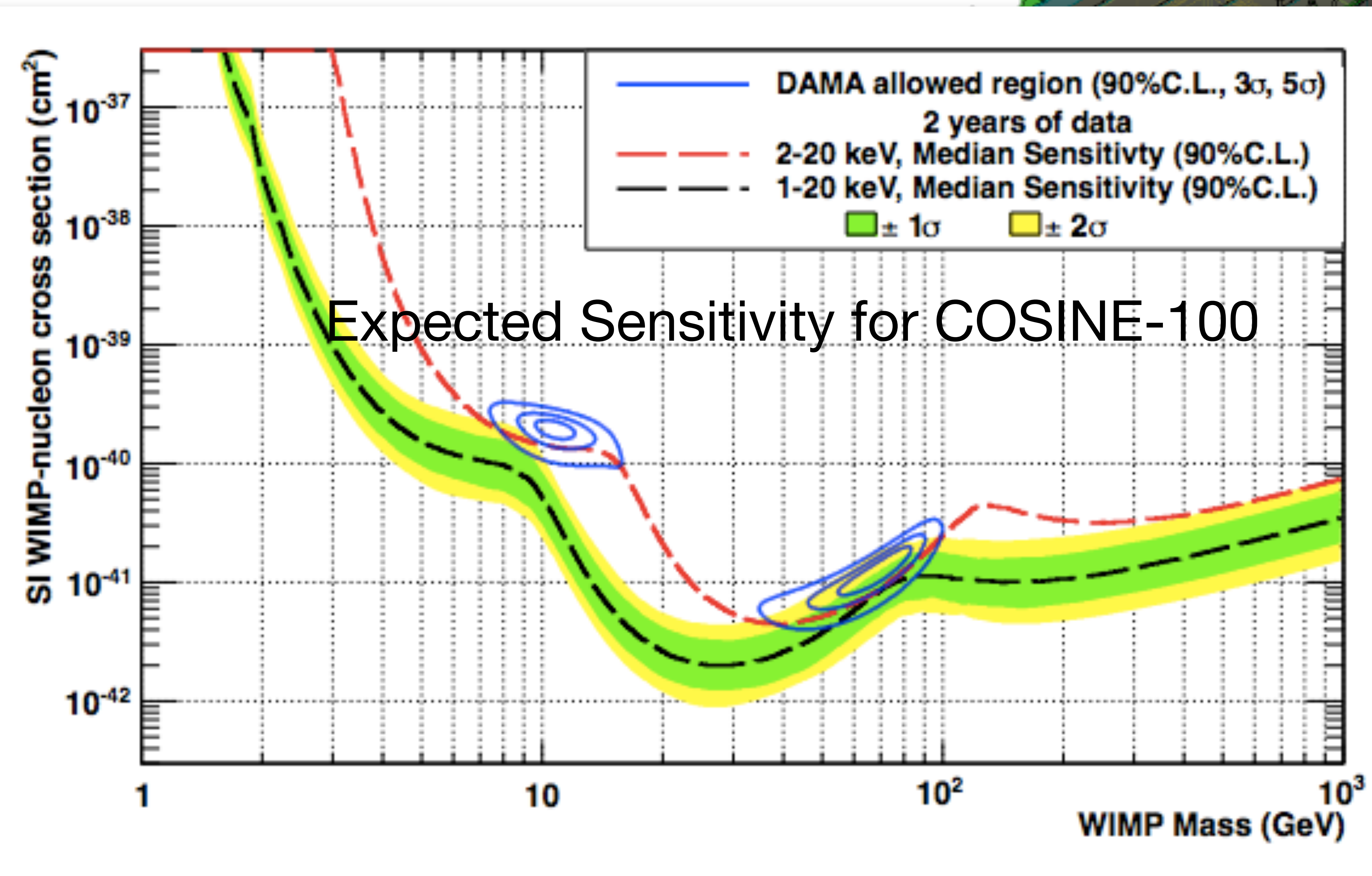
No dark matter-induced modulation observed by XENON

XENON Coll., Science 349 no. 6250 pp. 851-854 (2015)

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

Upcoming NaI Projects to directly test DAMA

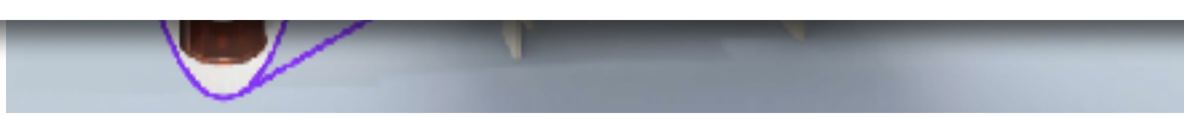




MS) **@Yangyang**

e

hield - commissioning



start data taking by June 2016

→ background 2-3x DAMA (no veto)

Cryogenic Experiments at mK Temperatures

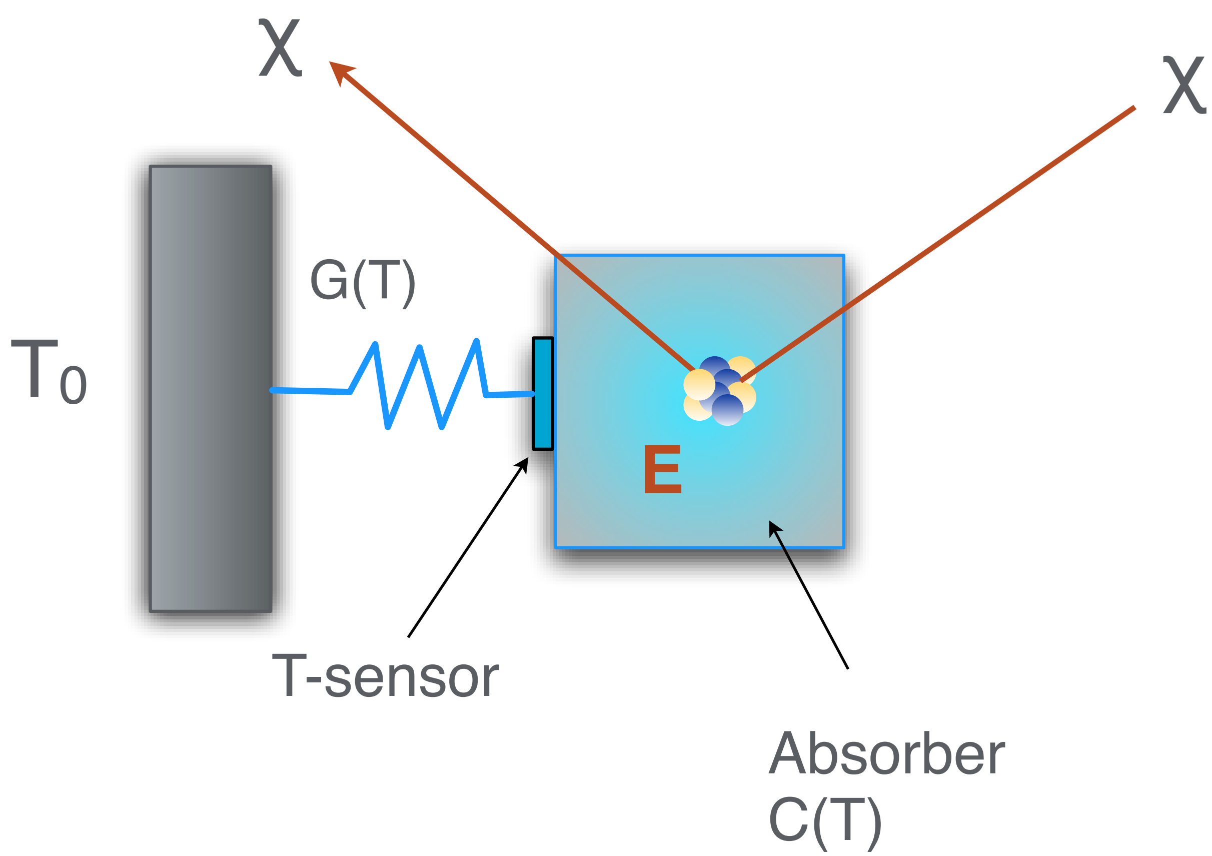
- Principle: phonon (quanta of lattice vibrations) mediated detectors
- **Motivation:** increase the energy resolution + detect smaller energy depositions (lower the threshold); use a variety of absorber materials (not only Ge and Si)
- The energy resolution (W = FWHM) of a semiconductor detector (N = nr. of e^--h excitations)

$$W_{stat} = 2.35\sqrt{F\epsilon E} \qquad \frac{\sigma(E)}{E} = \sqrt{\frac{F}{N}} = \sqrt{\frac{F\epsilon}{E}} \qquad W_{stat} = 2.35\,\sigma(E)$$

- E = deposited energy; F = Fano factor (the energy loss in a collision is not purely statistical; F=0.13 in Ge; 0.11 in Si); N = E/ε; in Si: ε = 3.6 eV/e^--h pair
- Maximum phonon energy in Si: 60 meV
  - ➡ **many more phonons are created than e^--h pairs!**
- For dark matter searches:
  - ➡ **thermal phonon detectors (measure an increase in temperature)**
  - ➡ **athermal phonon detectors (detect fast, non-equilibrium phonons)**

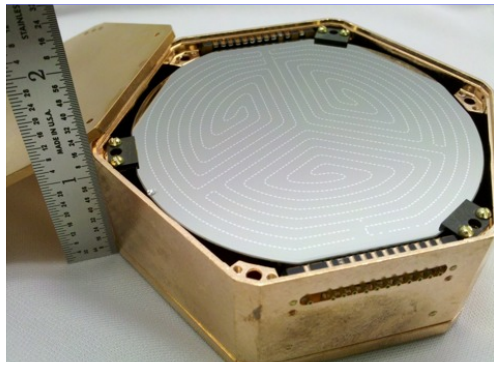
Cryogenic detectors at T ~ mK

- Detect a temperature increase after a particle interacts in an absorber

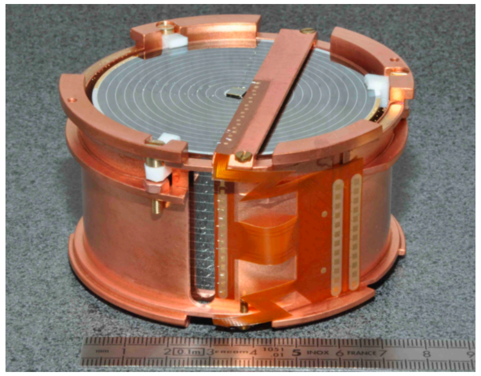


$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

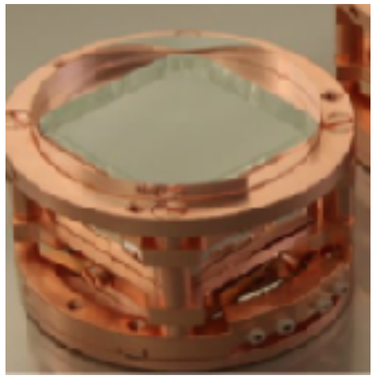
$$\tau = \frac{C(T)}{G(T)}$$



SuperCDMS: Ge, Si



EDELWEISS-III (Ge)



CRESST ($CaWO_4$)

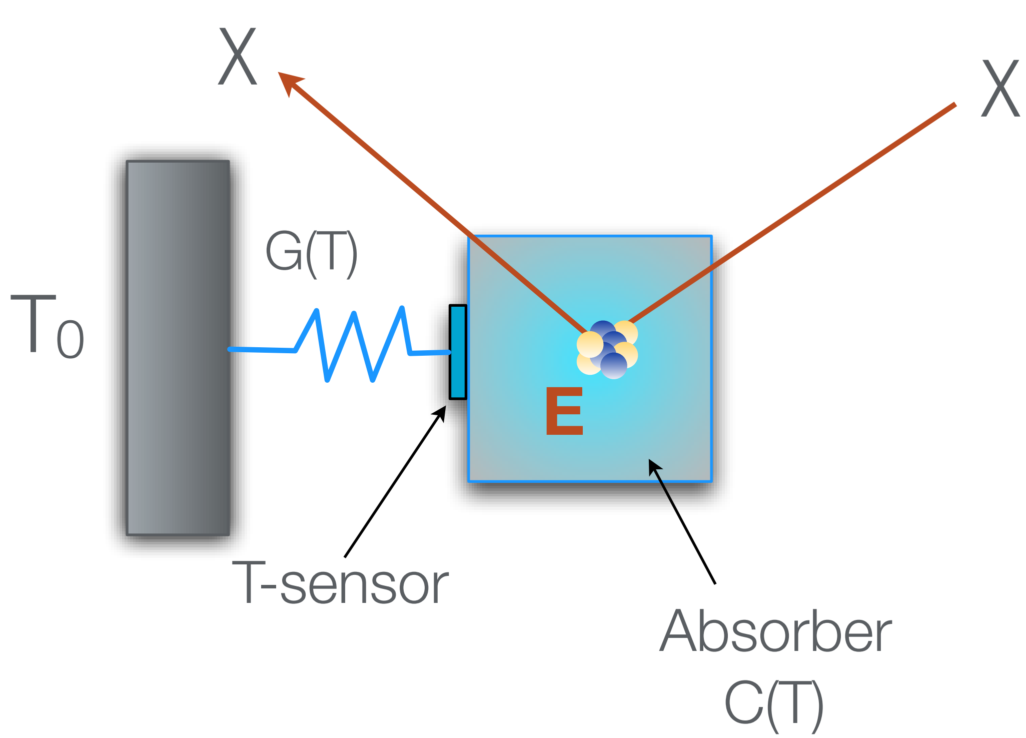
Basic Principles of mK Cryogenic Detectors

- A deposited energy E (ER or NR) will produce a temperature rise ΔT given by:

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}} \qquad \tau = \frac{C(T)}{G(T)}$$

C(T) = heat capacity of absorber

G(T) = thermal conductance of the link between the absorber and the reservoir at temperature T_0



Normal metals: the electronic part of C(T) ~ T, and dominates the heat capacity at low temperatures

Superconductors: the electronic part is proportional to exp(-T_c/T)
(T_c = superconducting transition temperature)
and is negligible compared to lattice contributions for $T \ll T_c$

Basic Principles of mK Cryogenic Detectors

- For pure dielectric crystals and superconductors at $T << T_c$, the heat capacity is given by:

$$C(T) \sim \frac{m}{M} \left(\frac{T}{\theta_D} \right)^3 \mathrm{J\,K^{-1}}$$

m = absorber mass

M = molecular weight of absorber

Θ_D = Debye temperature (at which the highest frequency gets excited) $\theta_D = \frac{h\nu_m}{k}$

➡ the lower the T, the larger the ΔT per unit of absorbed energy

➡ in thermal detectors E is measured as the temperature rise ΔT

- **Example:** at T = 10 mK, a 1 keV energy deposition in a 100 g detector increases the temperature by:

$$\Delta T \approx 1\,\mu K$$

- this can be measured!

Thermal Detectors

- Ideal case of a perfect calorimeter: all the energy is converted into heat and the resulting T-rise is measured
- For a superconductor as absorber: a fraction of the energy goes into breaking of Cooper pairs creating electronic excitations called *quasiparticles*, which will not all recombine on the timescale to be measured as a thermal pulse (also, the phonons are far from equilibrium and must first decay to lower energy phonons and become thermalized, before ΔT can be measured)
- For a finite thermalization time τ_{th}, the time behavior of the thermal pulse is given by:

$$T(t) = T_0 + \frac{E}{C(T)} \frac{\tau}{\tau - \tau_{th}} \left[e^{-t/\tau} - e^{-t/\tau_{th}} \right] \qquad \tau = \frac{C(T)}{G(T)}$$

- Rise time of the pulse: in general at least 1 μs (limited by detector physics)
- Decay time: several ms ⇒ < few Hz counting rates for thermal detectors

Thermal Detectors

- The intrinsic energy resolution (as FWHM) of such a calorimeter is given by (k_B is the Boltzmann constant):

$$W = 2.35\xi\sqrt{k_B T^2 C(T)}$$

$$\frac{C(T)}{k_B} = \text{ number of phonon modes}$$

$$k_B T = \text{ mean energy per mode}$$

$$\xi = 1.5 - 2$$

Info about the sensor. the thermal link and the T-dependance of C(T)

- Example for the theoretical expectation of the intrinsic energy resolution:
  - ➡ a 1 kg Ge crystal operated at 10 mK could achieve an energy resolution of about 10 eV => two orders of magnitude better than Ge ionization detectors
  - ➡ a 1 mg of Si at 50 mK could achieve an energy resolution of 1 eV => two orders of magnitude better than conventional Si detectors

Temperature Sensors

- Semiconductor thermistor: a highly doped semiconductor such that the resistance R is a strong function of temperature (NTD = neutron-transmutation-doped Ge - uniformly dope the crystal by neutron irradiation)
- Superconducting (SC) transition edge sensor (TES): thin film of superconductor biased near the middle of its normal/SC transition

- For both NTDs and TESs, an energy deposition produces a change in the electrical resistance R(T). The response can be expressed in terms of the logarithmic sensitivity:

$$\alpha \equiv \frac{d\log(R(T))}{d\log(T)}$$

Typical values:

α = -10 to -1 for semiconductor thermistors

$\alpha \sim +10^3$ for TES devices

→ the sensitivity of TESs can be extremely high (depending on the width of the SC/normal transition)

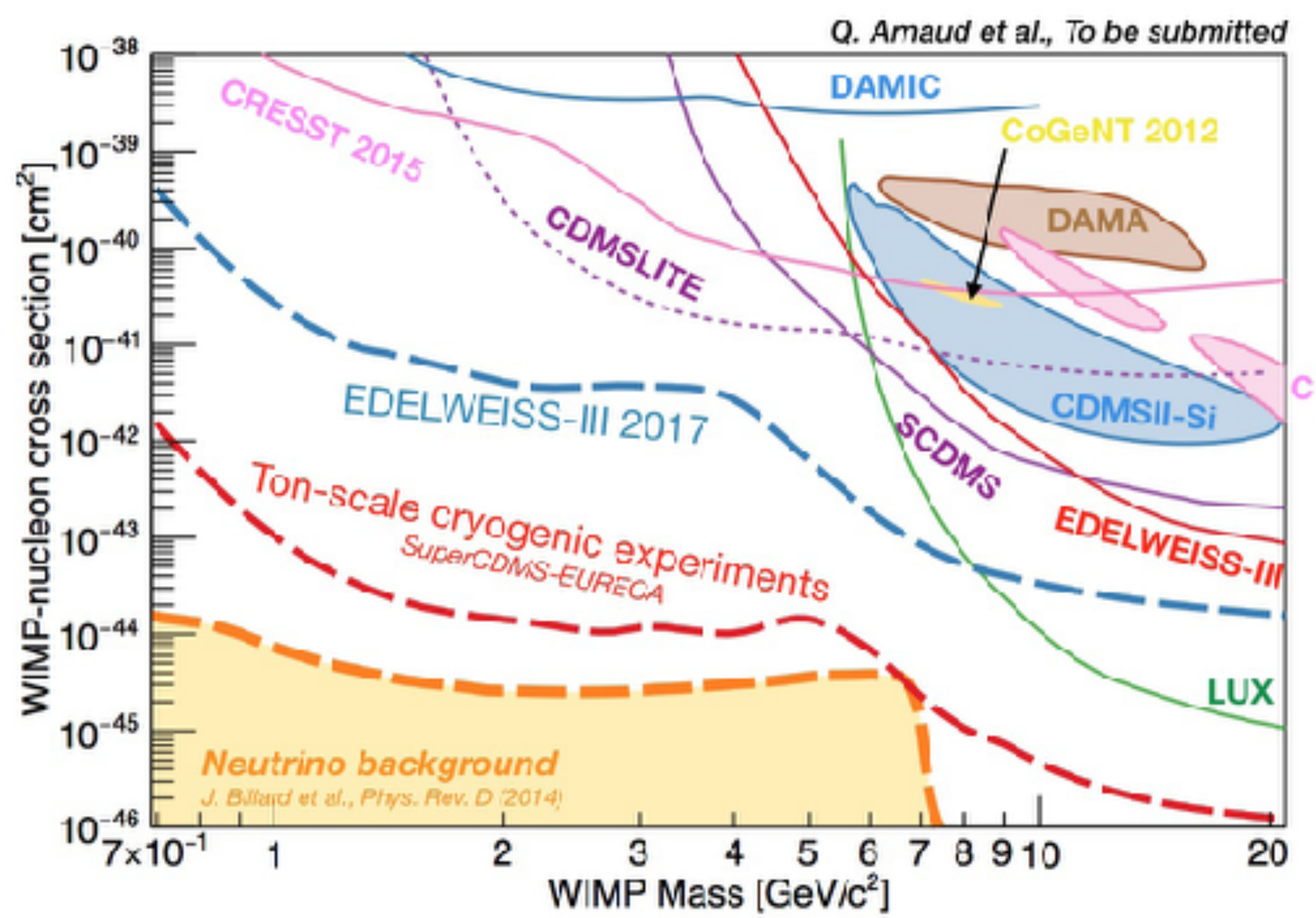
→ however, the temperature of the detector system must be kept very stable

EDELWEISS - SuperCDMS - CRESST: the race for the low WIMP mass region

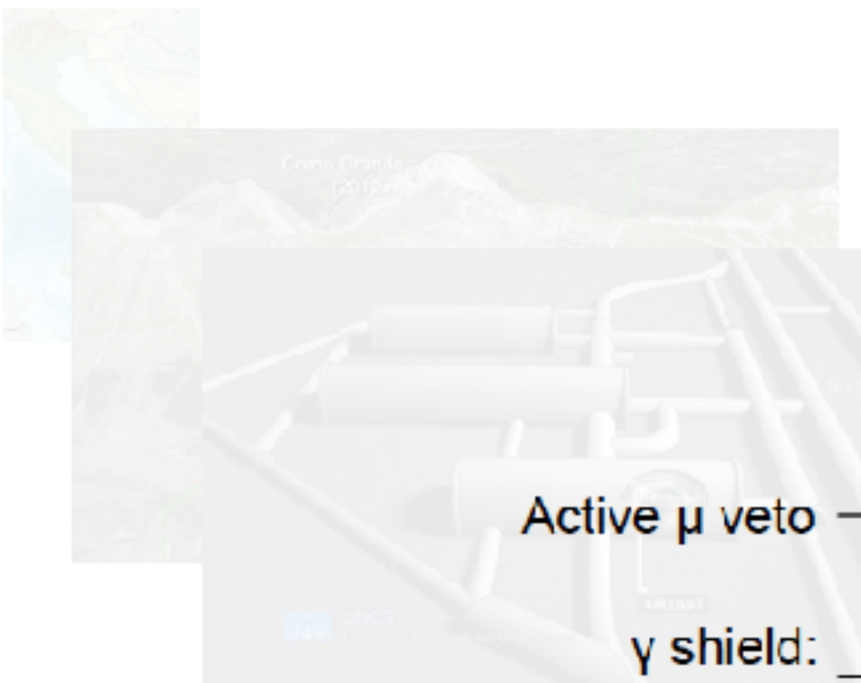
SuperCDMS @SNOLAB
•aim for 50 kg-scale experiment (cryostat can accomodate 400 kg)
low threshold → focus on 1-10 GeV/c² mass range
• Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
• 100 x 33.3 mm IZPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established
2018-20: construction
2020: begin data taking

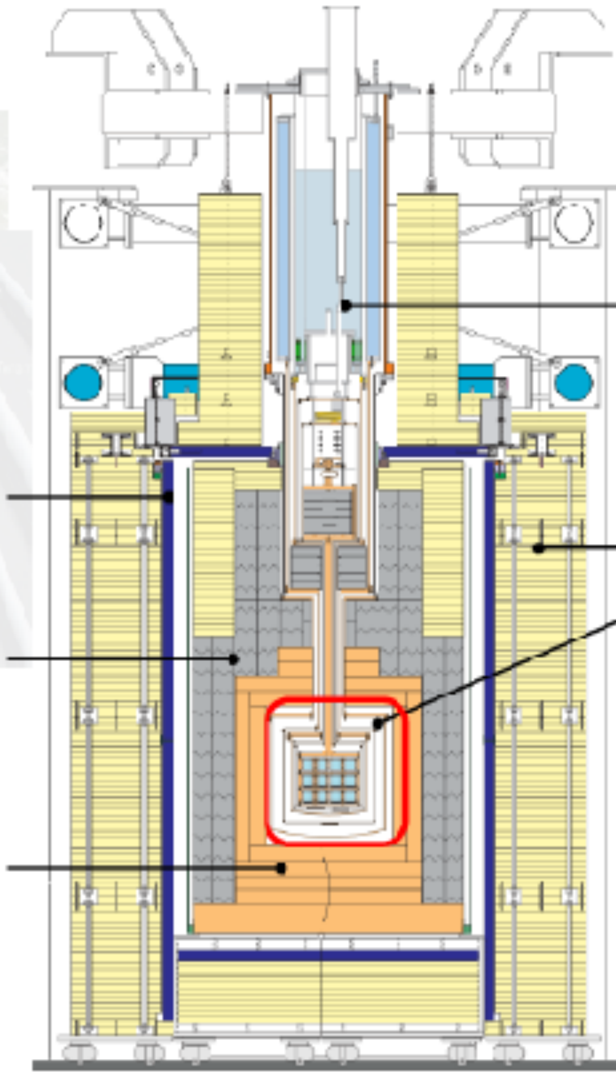
EDELWEISS @ LSM : arXiv:1603.05120
2016: largest (20 kg) Ge array in operation
2017: 350 kg×d in HV mode to optimize 1-10 GeV
Future: ton scale together with CDMS (EURECA)

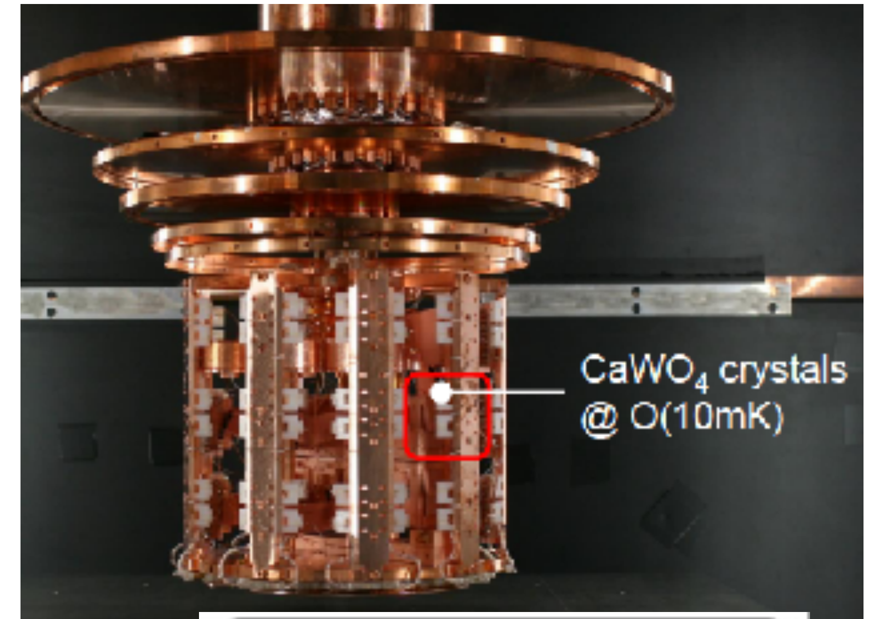
CRESST II @ LNGS: *EPJ C, 76, 25 (2016)*
read phonons and scintillation light from $CaWO_4$
successful background reduction;
data taking 2013-2015, 52 kg×d
2016: lowest thresh 300 eVnr
Record sensitivity below 1.7 GeV

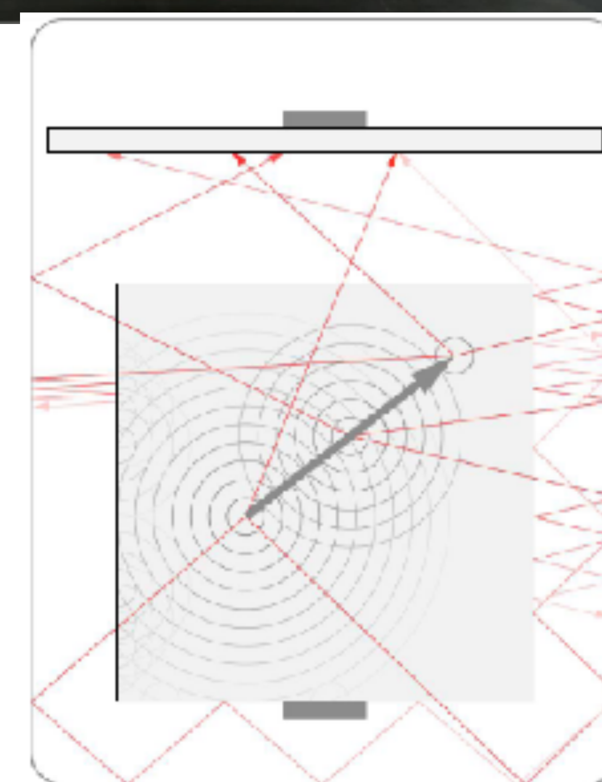


The CRESST experiment





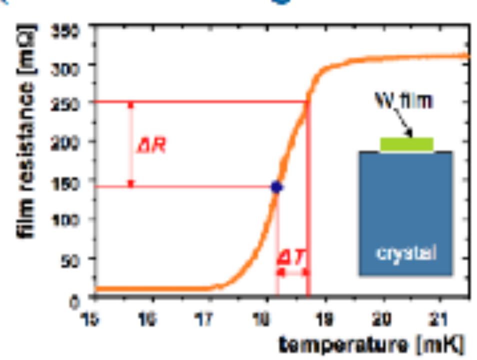




- Phonon signal: measurement of recoil energy

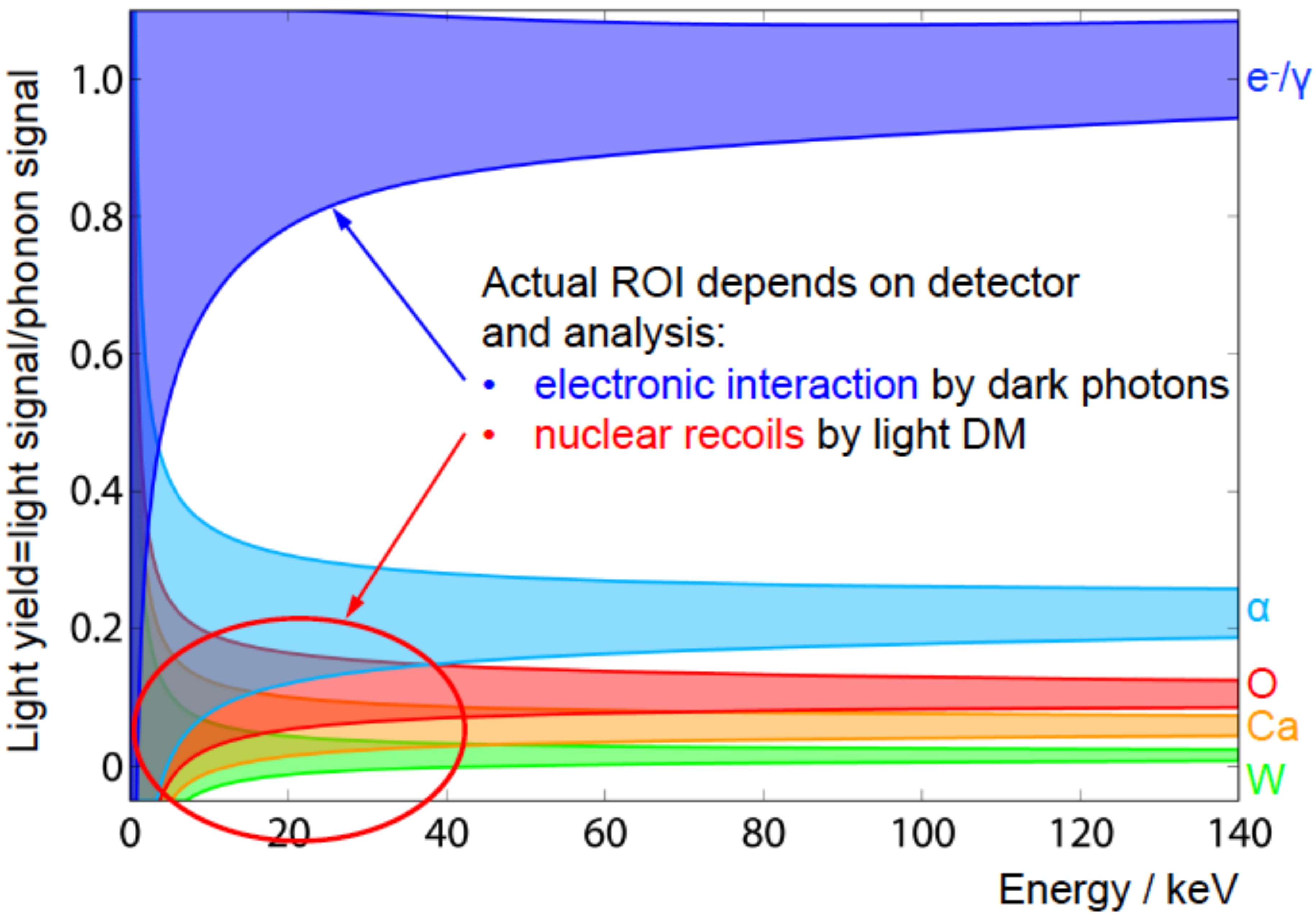
  $\Delta E/C = \Delta T$
  1keV ~ 1μK

- Read-out by a TES (transition edge sensor)



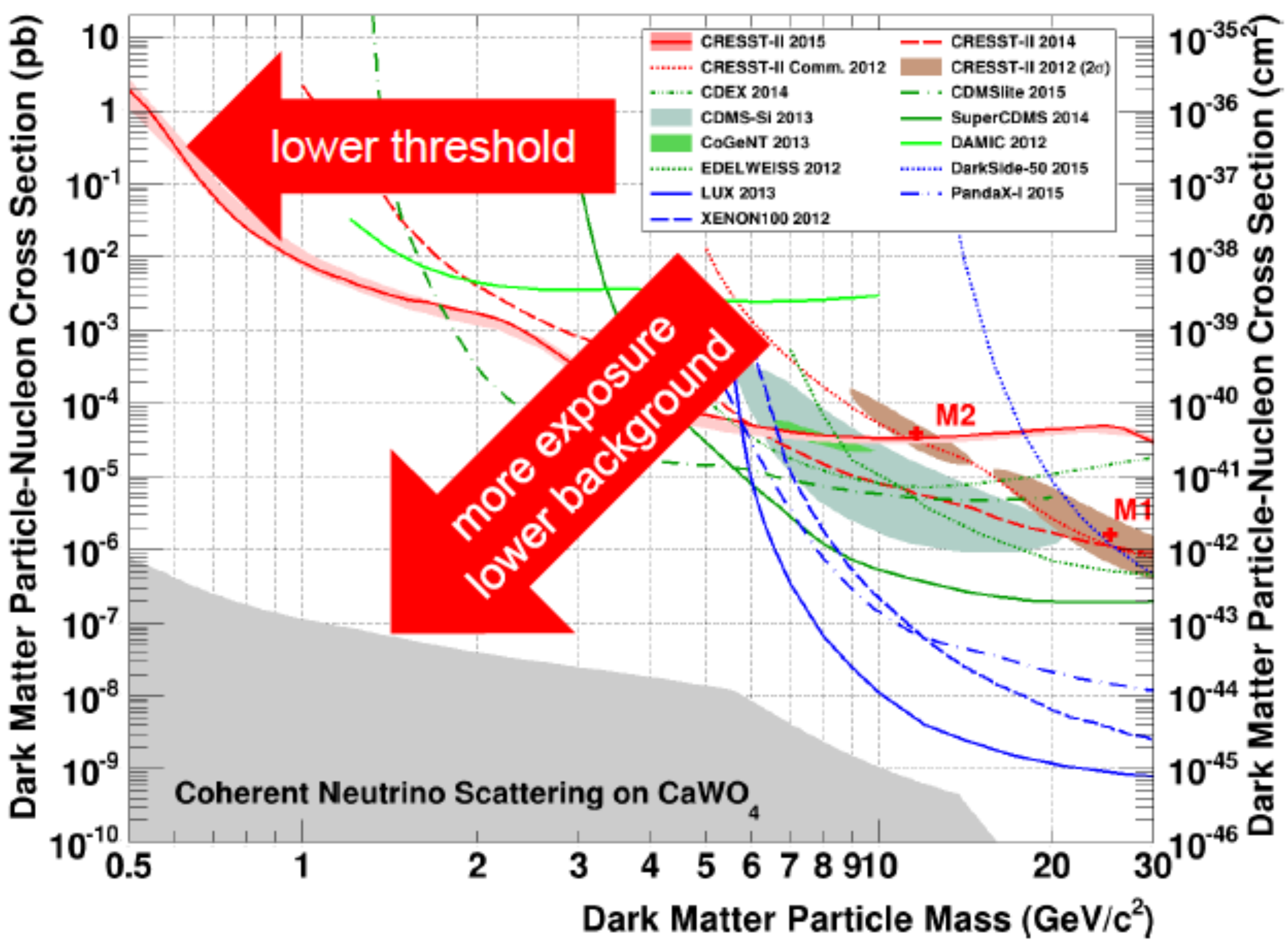
- Scintillation light signal: dedicated detector inside a reflective & scintillating housing, particle dependent

The CRESST experiment



Low Mass Record!

Results of CRESST-II phase 2

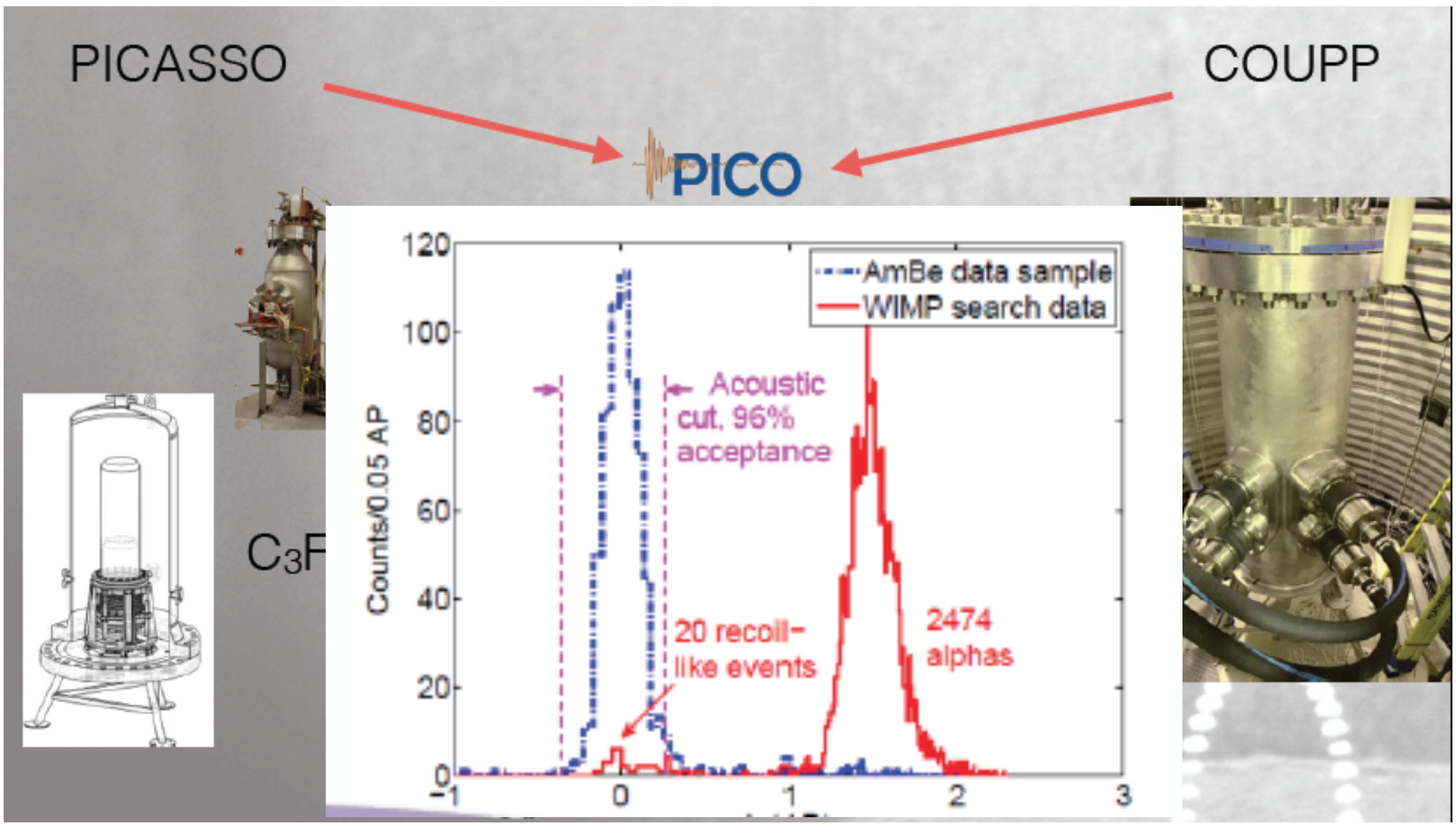


- TUM40: successfull reduced intrinsic background
- Low-mass search
  → low threshold
  Lise: 307eV
- ➔combine both in CRESST-III

Eur. Phys. J-C 76, 2016

PICO Bubble Chambers @ SNOLAB

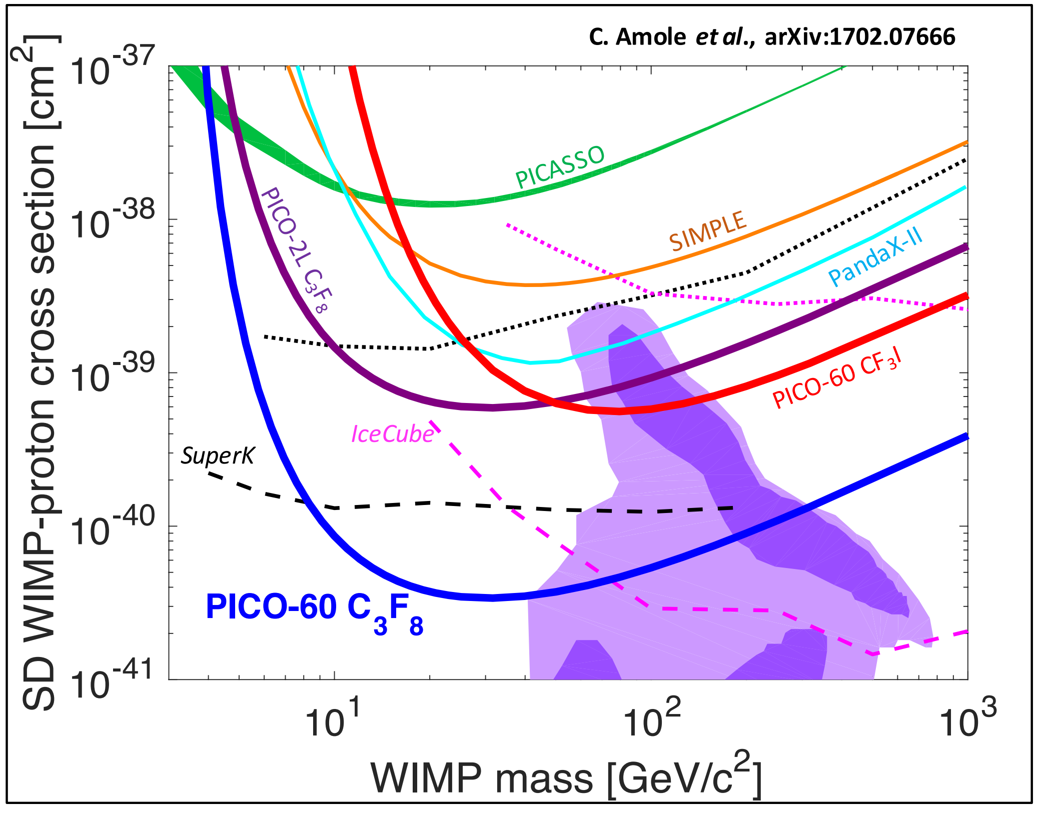
- chamber filled with a superheated fluid in metastable state
- Detect expanding bubble when particle deposits energy > Eth in radius < r0
- Acoustic Discrimination: alpha deposits energy over tens of microns; NRs deposit energy over tens of nanometer
-



PICO 60 (now) and PICO 500 (future ~2018)

- the largest (36.8 kg target of CF3I) in operation (SNOLAB), made with radio pure synthetic quartz. Run I: world leading SD proton sensitivity for WIMP> 25GeV
- Anomalous background correlated with time of expansion has been identified as bubble nucleation by surface tension
- Run II of PICO 60: new 45 L target with lower threshold (C3F8); new water system, new vessel and geometry; new online filtration system

C. Amole, *et al.*, Phys. Rev. D 93, 052014 (2016)



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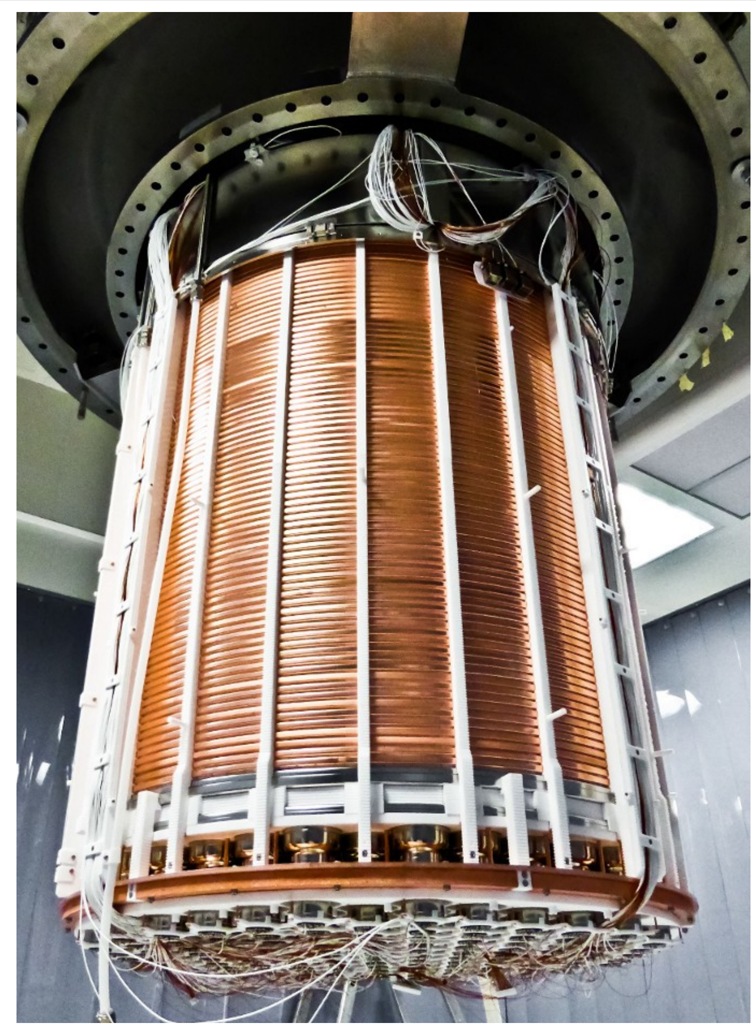
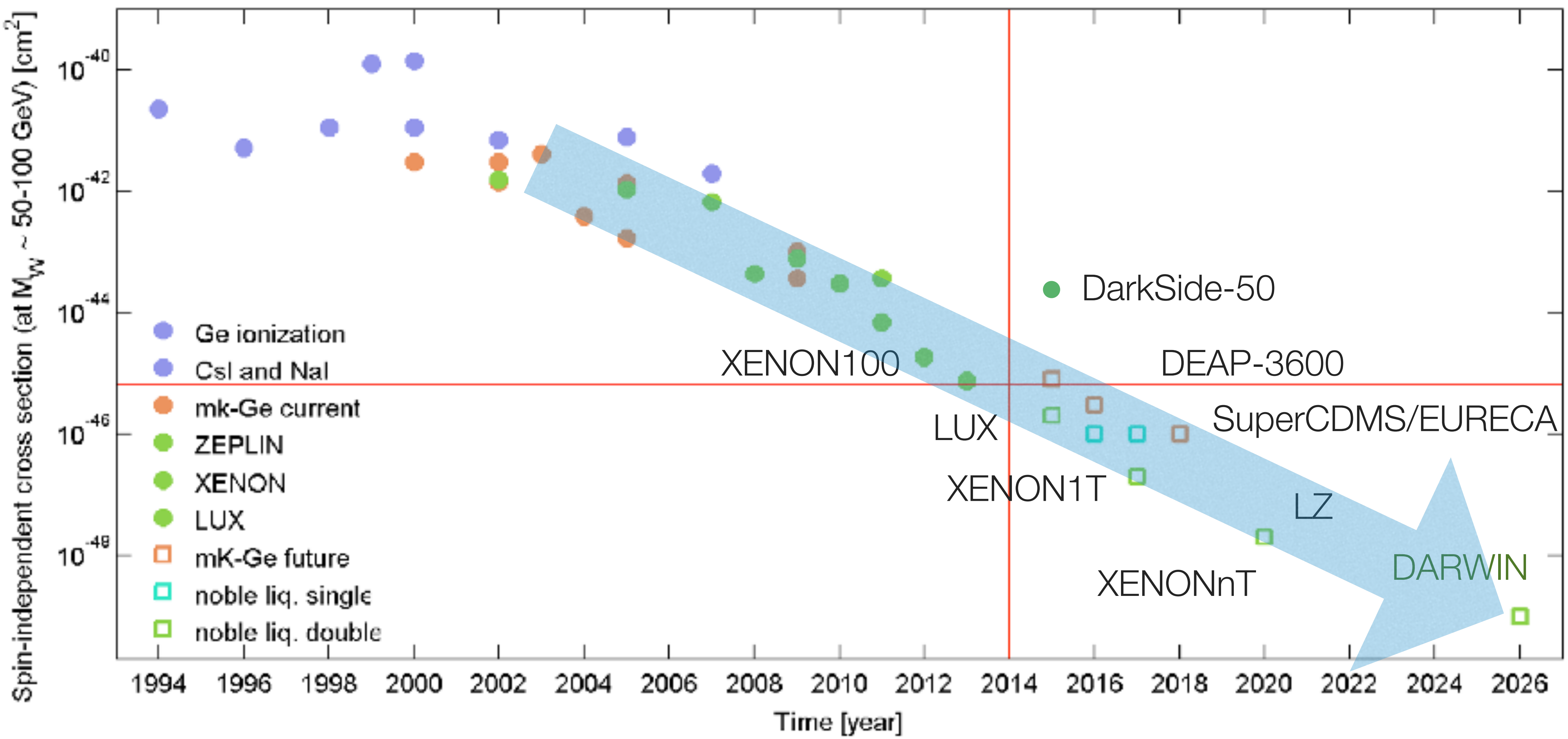


Worldwide WIMP Searches

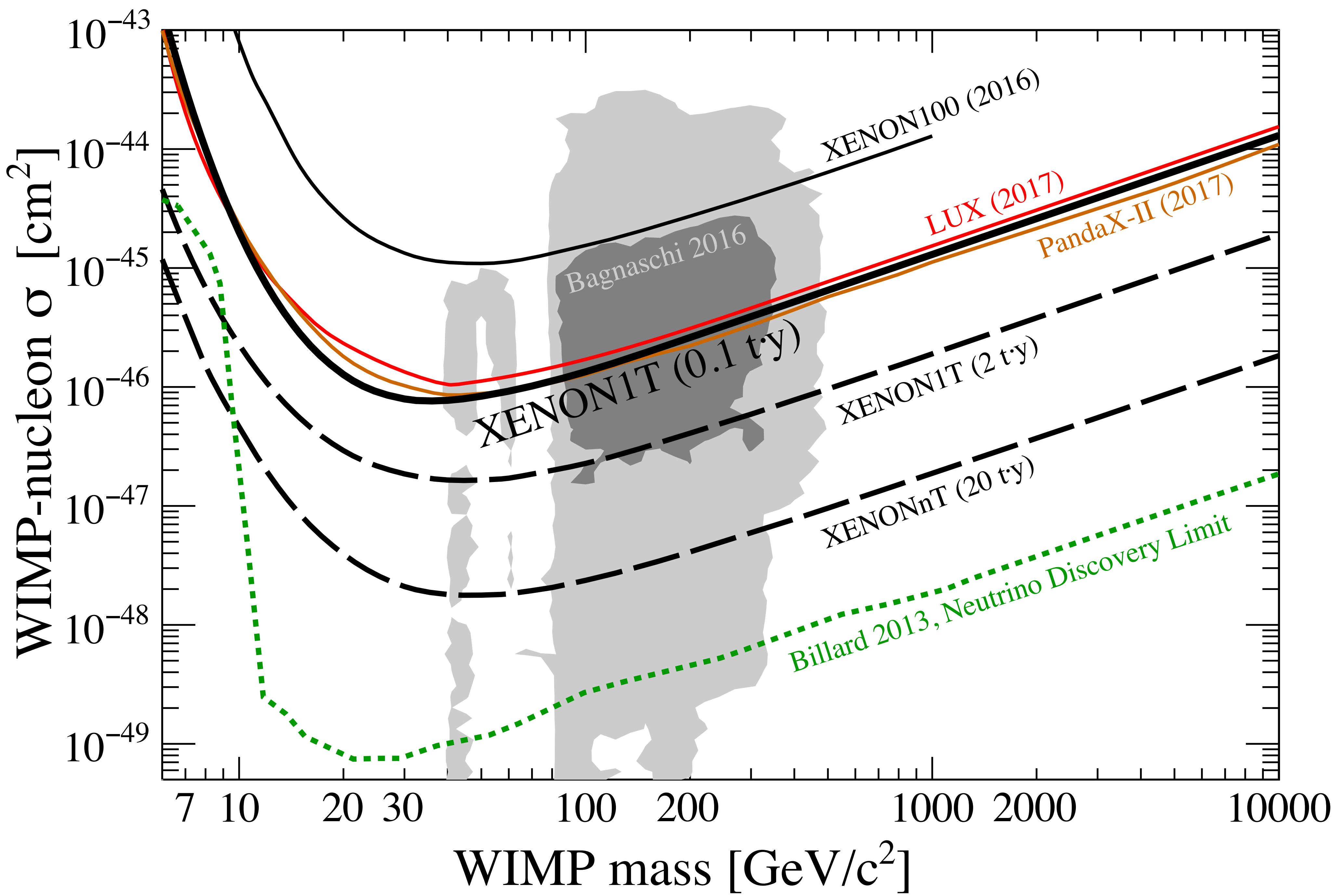
WIMP-nucleon cross section versus time

- About a factor of 10 increase every ~ 2 years
- Progress led by searches using LXe



LB, Physics of the Dark Universe 4, 2014

the state-of-the-art: driven by experiments using LXe



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

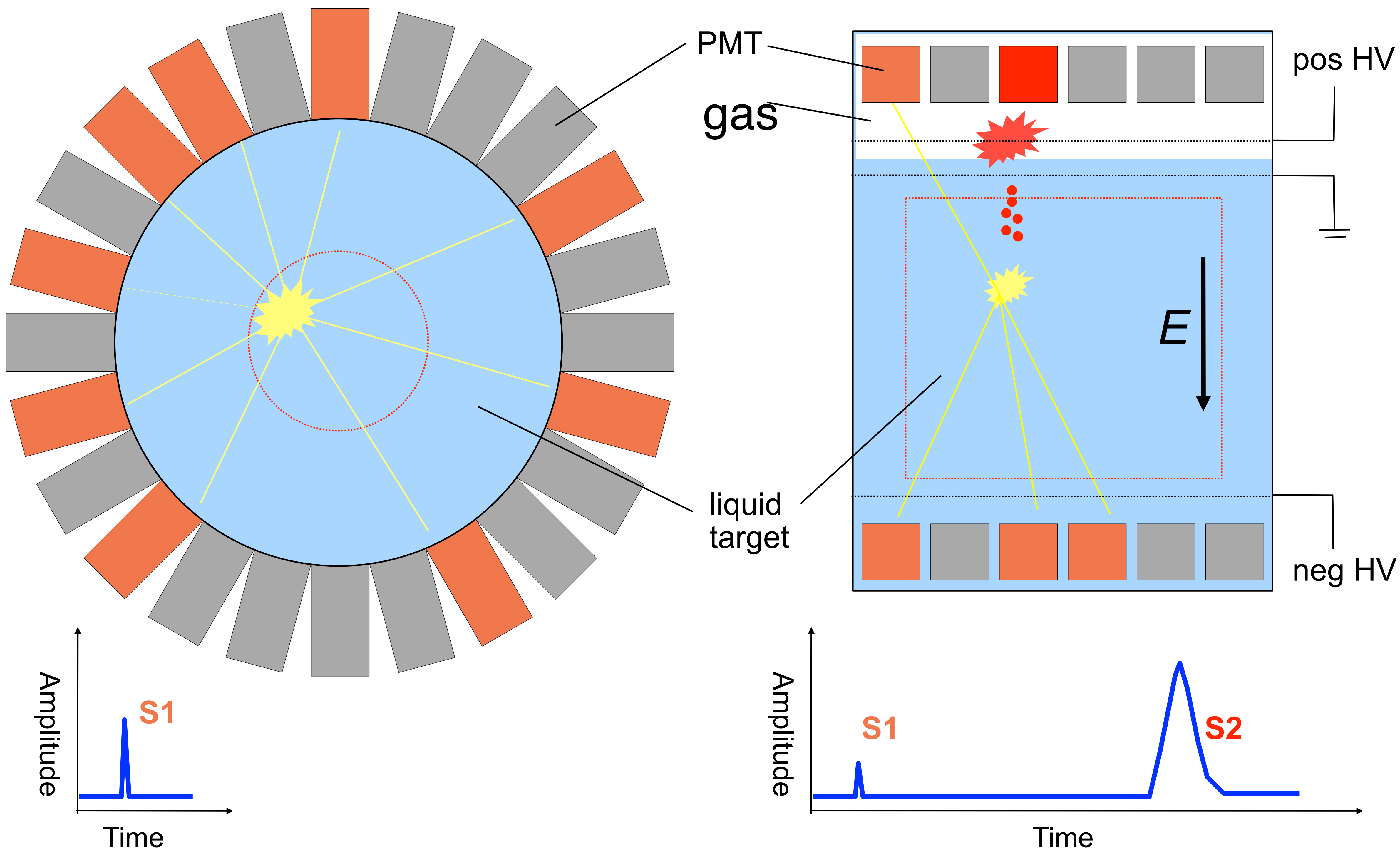
Why Noble Liquids for Dark Matter Detection

- ✦ *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

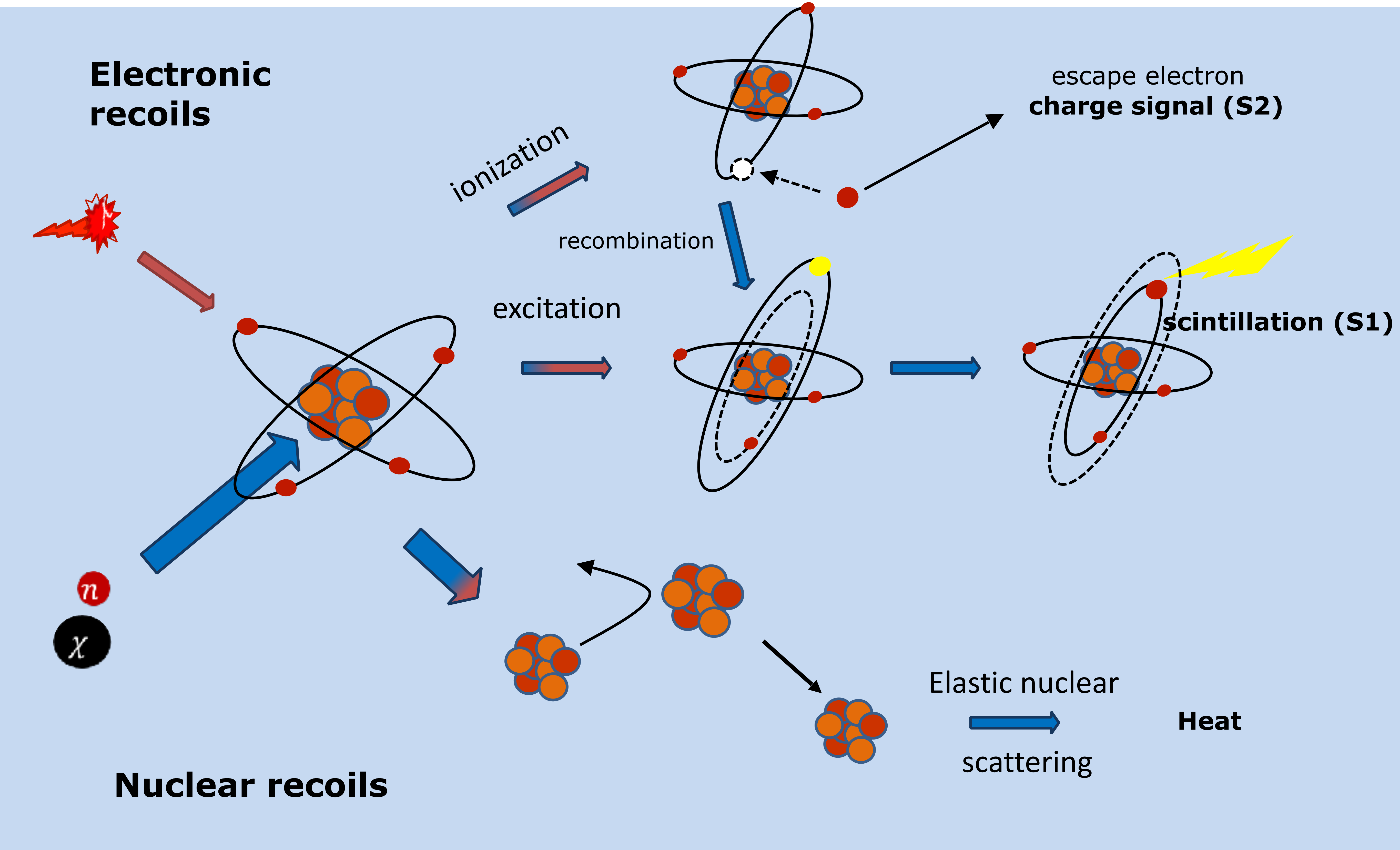
Single Phase Detector

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

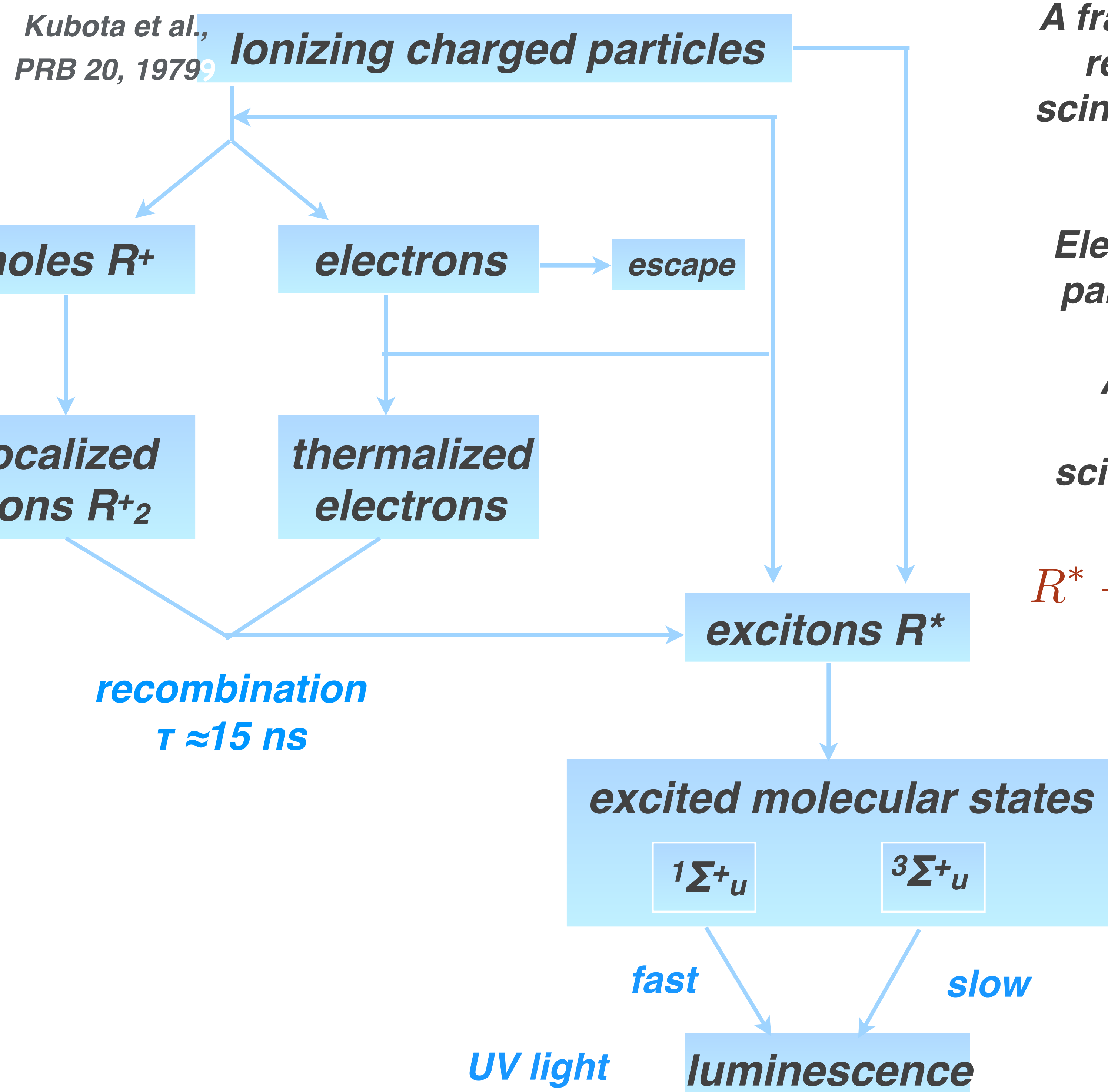
Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6 ± 0.3[b]	18.4 ± 0.3[c]	15.6 ± 0.3[d]

- 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



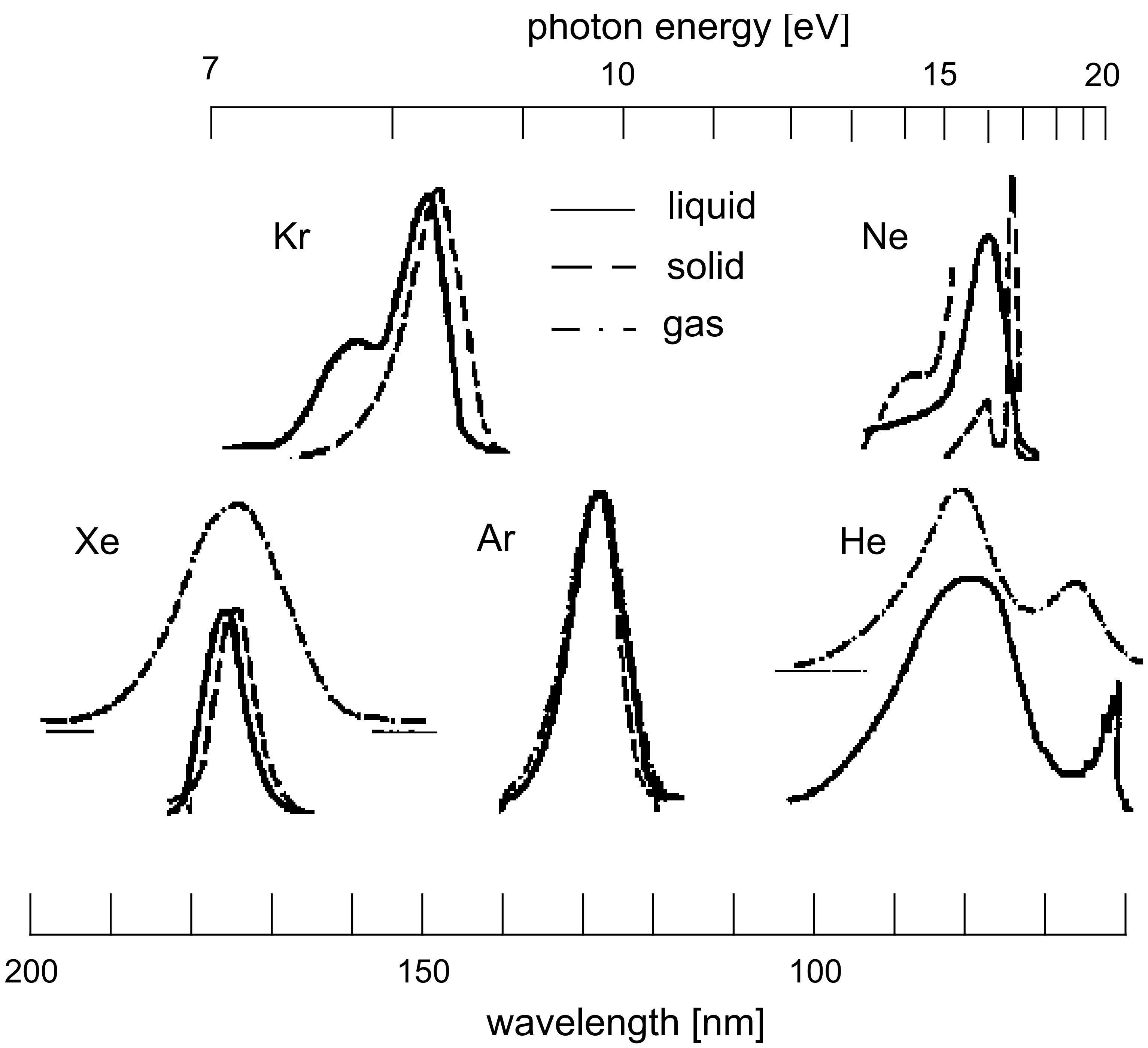
A fraction of the ionization electrons will recombine with ions and produce a scintillation photon in the process called recombination

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



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

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

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

Scintillation Pulse Shape

- The scintillation light from pure noble liquids has *two decay components* due to the de-excitation of the singlet and triplet states of the excited dimer:

$$R_2^* \longrightarrow 2R + h\nu$$

- Figure:
    - ➡ Alphas and fission fragments: the shorter decay time comes from the de-excitation of singlet states, the longer from triplet states
    - ➡ Relativistic electrons: only one decay component
- Difference in pulse shape between different type of particle interactions is used to discriminate among the various particles via PSD

time constants:
Ne: few ns versus15.4 µs
Ar: 10 ns versus 1.5 µs
Xe: 4 ns versus 27 ns Xe

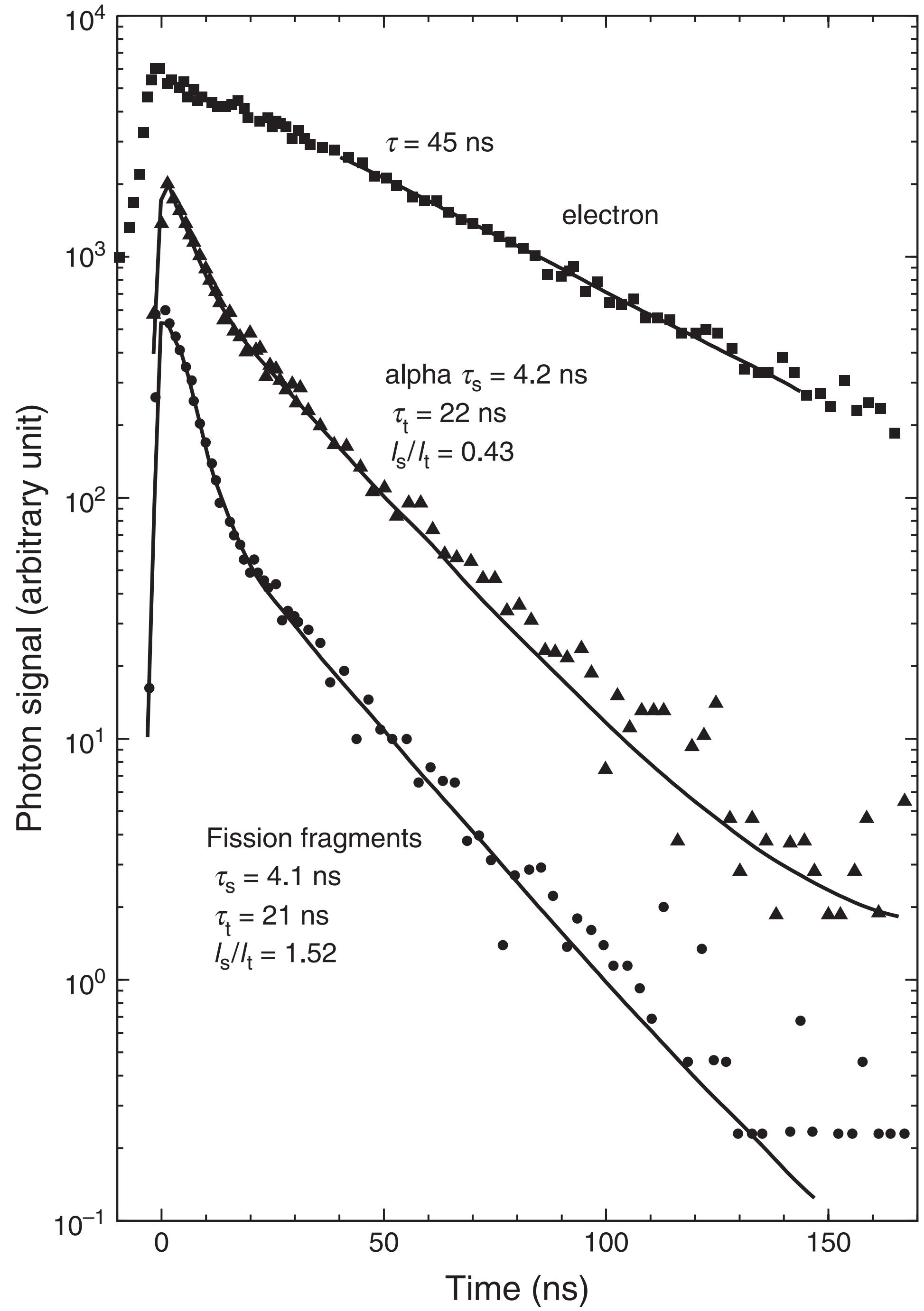


Fig. 21.1. Decay curves of luminescence from liquid xenon excited by electrons, α-particles and fission fragments, without an external electric field [1109; 1283].

Scintillation Yield

- An energetic particle looses energy through:
  - ➡ inelastic interactions with electrons in the medium *(electronic stopping)*
  - ➡ elastic collisions with nuclei *(nuclear stopping)*
- Electrons, gamma rays and fast ions loose most of their energy through electronic stopping
- Nuclear recoils loose a considerable fraction of their energy through nuclear stopping (nuclear quenching, q_{nc})

L_{eff} : Relative scintillation efficiency of NRs

- the scintillation light yield of nuclear recoils in noble liquids is different than the one produced by electron recoils of the same energy
- The ratio of the two = *relative scintillation efficiency (L_{eff})* is important for the determination of the sensitivity of noble liquids as dark matter detection media
- Experimentally this quantity is defined as the *zero-field value of light yield of nuclear recoils* (generated with n-sources) and *electronic recoils* (generated with γ-sources):

$$\mathcal{L}_{eff} = \frac{L_{y,nr}}{L_{y,er}} = \frac{E_{er}}{n_{\gamma,er}} \frac{n_{\gamma,nr}}{E_{nr}} = \frac{1}{L_y} \frac{n_{pe,nr}}{E_{nr}} = \frac{E_{ee}}{E_{nr}}$$

$n_{\gamma,er}$ = nr. of primary photons from electronic recoils
$n_{\gamma,nr}$ = nr of primary photons from nuclear recoils
$n_{pe,nr}$ = nr of primary photoelectrons from nuclear recoils

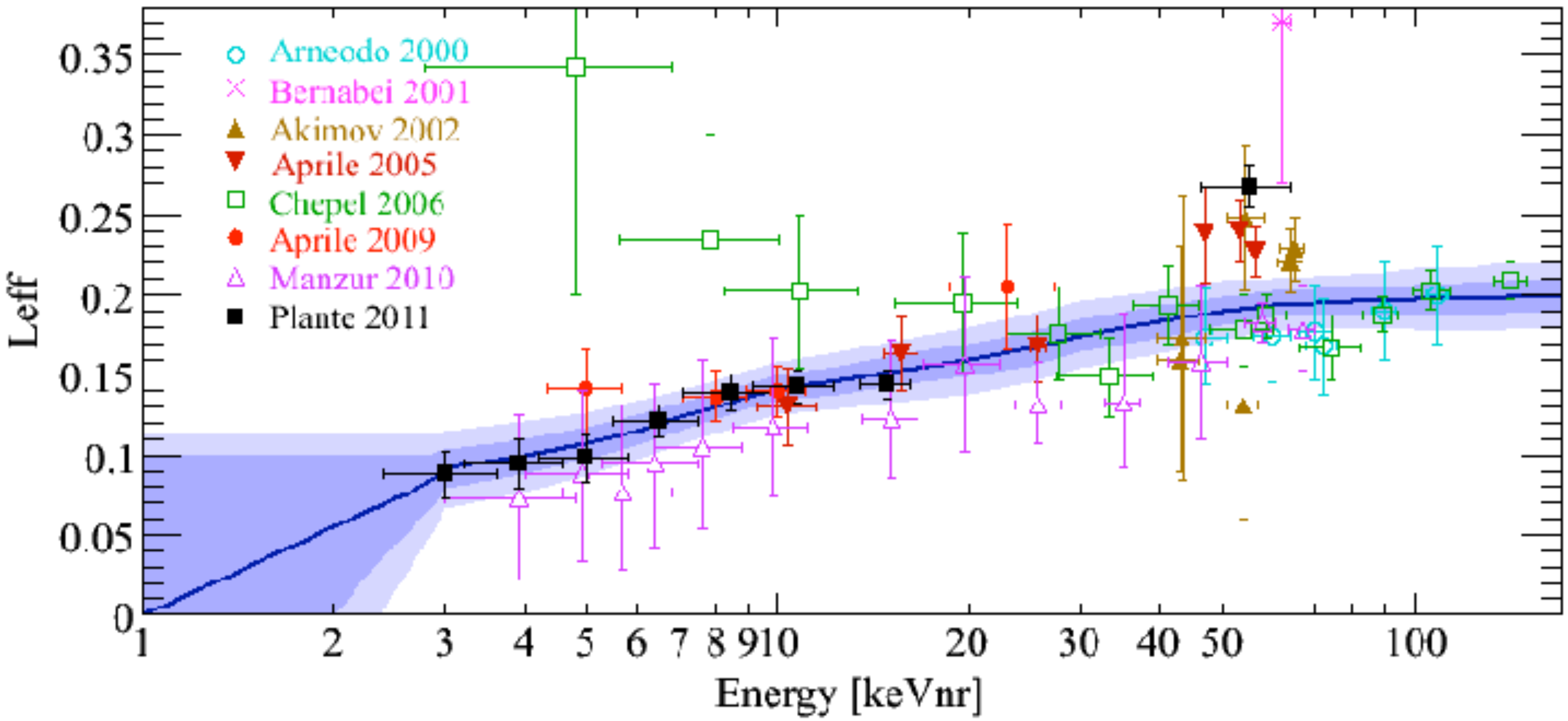
E_{ee} = "electron-equivalent" energy
L_y = the light yield of 122 keV gamma rays (^{57}Co source) as "standard calibration candle"

L_{eff} in Liquid Xenon

- In general, two methods are used:
  - ➡ a direct method using mono-energetic neutrons scatters which are tagged with a n-detector
  - ➡ an indirect method by comparing measured energy spectra in LXe from n-sources (AmBe) with Monte Carlo predictions

Direct method

Plante *et al.*, Phys. Rev. C **84**, 045805, 2011



mean (solid) and 1-, 2-sigma uncertainties (blue bands)

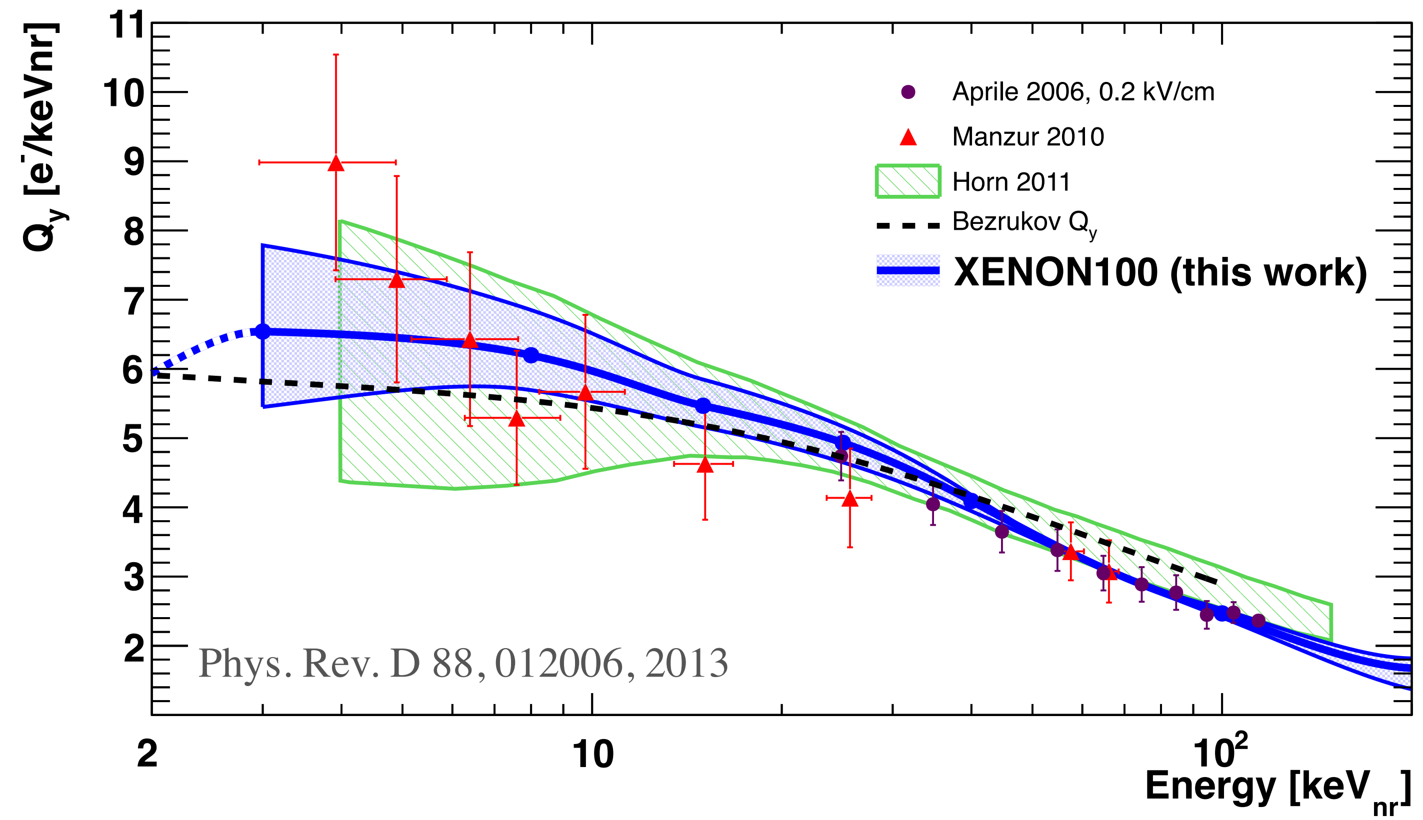
Ionization Yield of NRs in LXe

- Nuclear recoils have denser tracks, and are assumed to have *larger electron-ion recombination than electronic recoils*

  ➡ consequently, the collection of ionization electrons becomes more difficult for nuclear than electronic recoils

- The ionization yield of nuclear recoils is defined as the number of observed electrons per unit recoil energy:

$$Q_{y,nr} = \frac{n_{e,nr}}{E_{nr}}$$



blue: indirect measurement, by data/MC comparison of AmBe neutron calibration data

- It has been measured mostly in LXe, with two-phase detectors

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

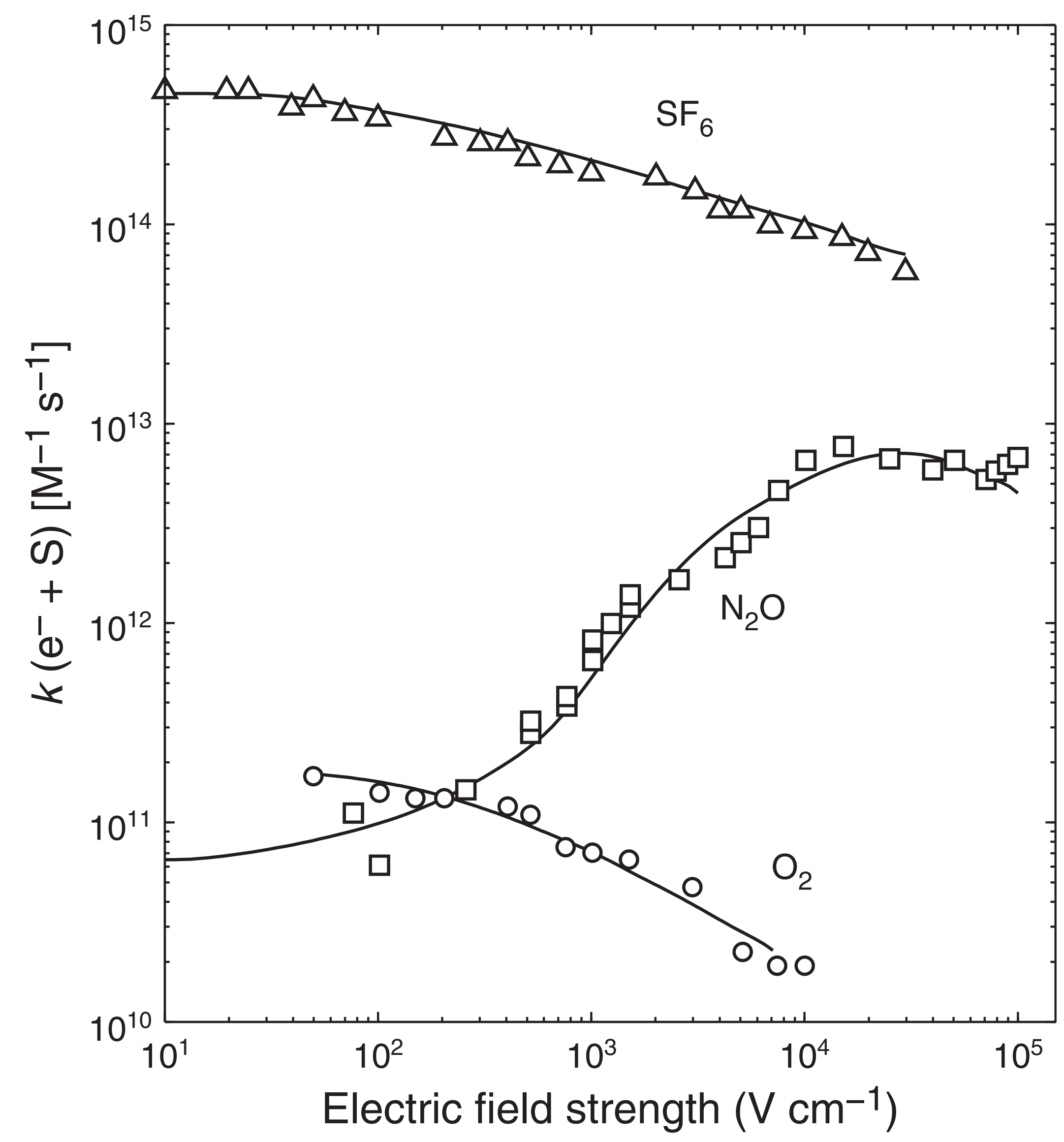


Fig. 21.4. Rate constant for the attachment of electrons in liquid xenon (T = 167 °K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2 [174].

Cryogenic Noble Liquids: 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

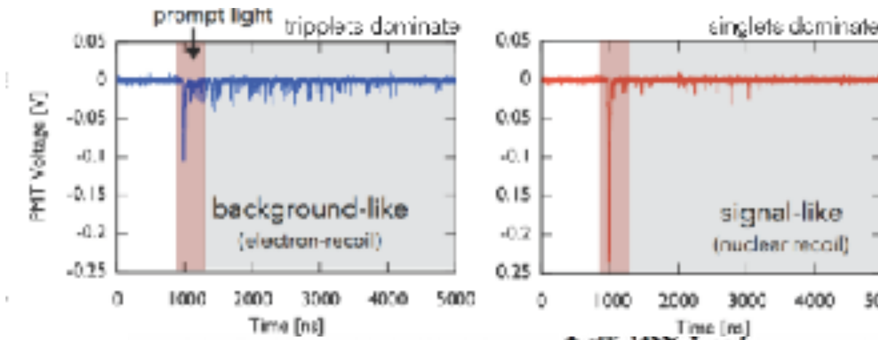
- **Light detection:**
  - ➡ efficient VUV PMTs, directly coupled to liquid (low T and high P capability, high purity), effective UV reflectors (also solid state Si devices are under study)
  - ➡ light can be absorbed by H_2O and O_2: continuous recirculation and purification
- **Charge detection:**
  - ➡ 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

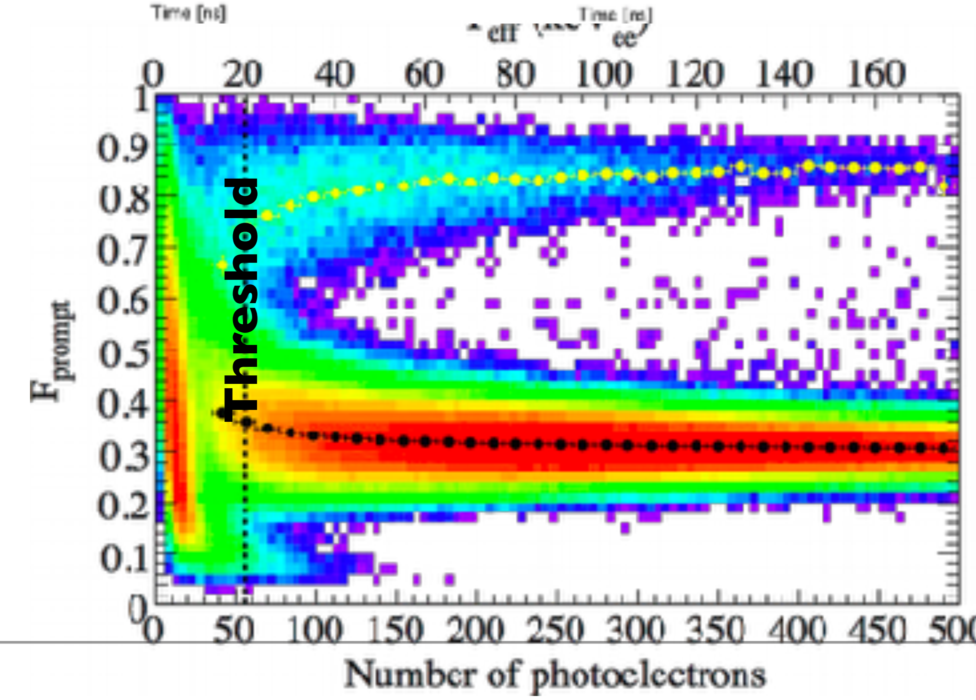
DEAP-3600 @ SNOLAB

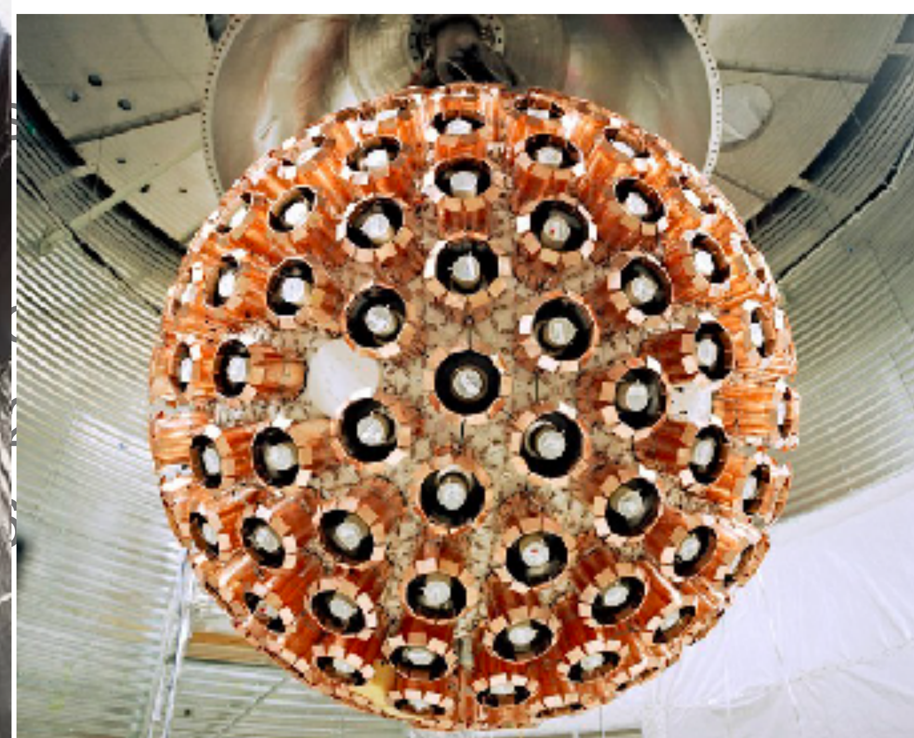
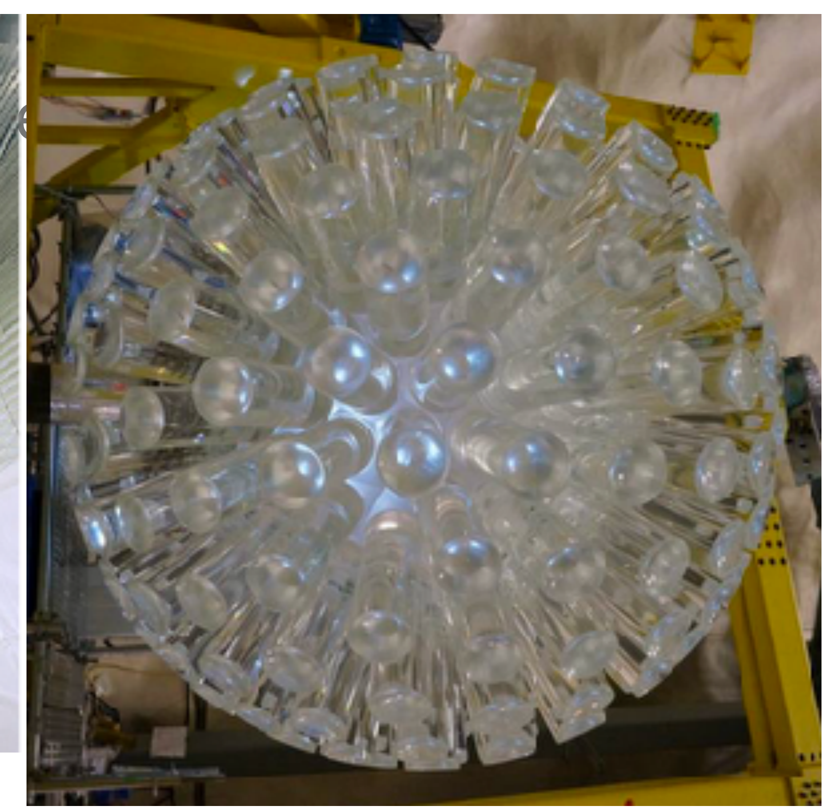
Single-phase liquid argon (no E-field)

- 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

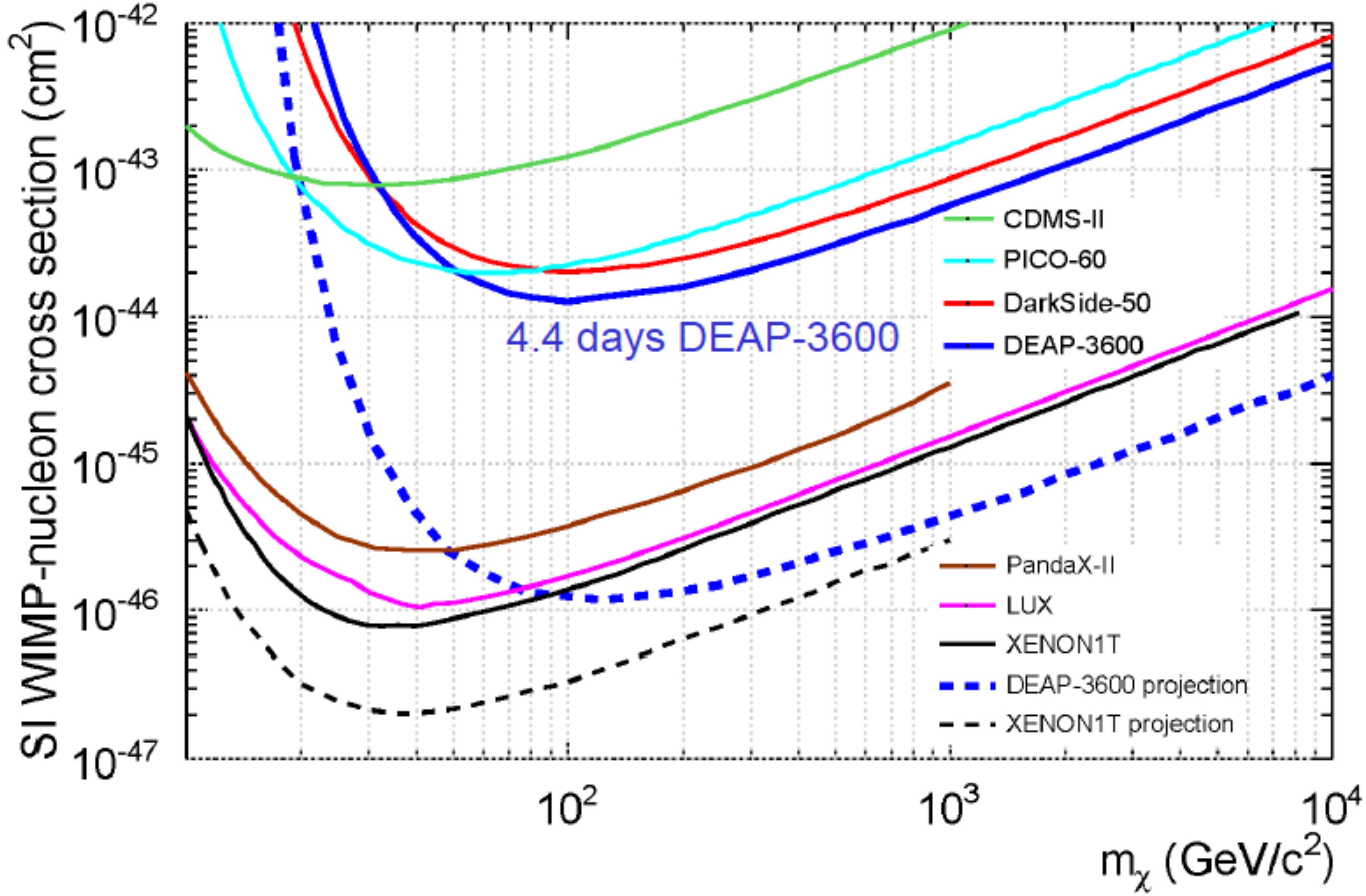


Pulse shape discrimination (PSD) parameter
fprompt = prompt light (150 ns) / total light (10000 ns)



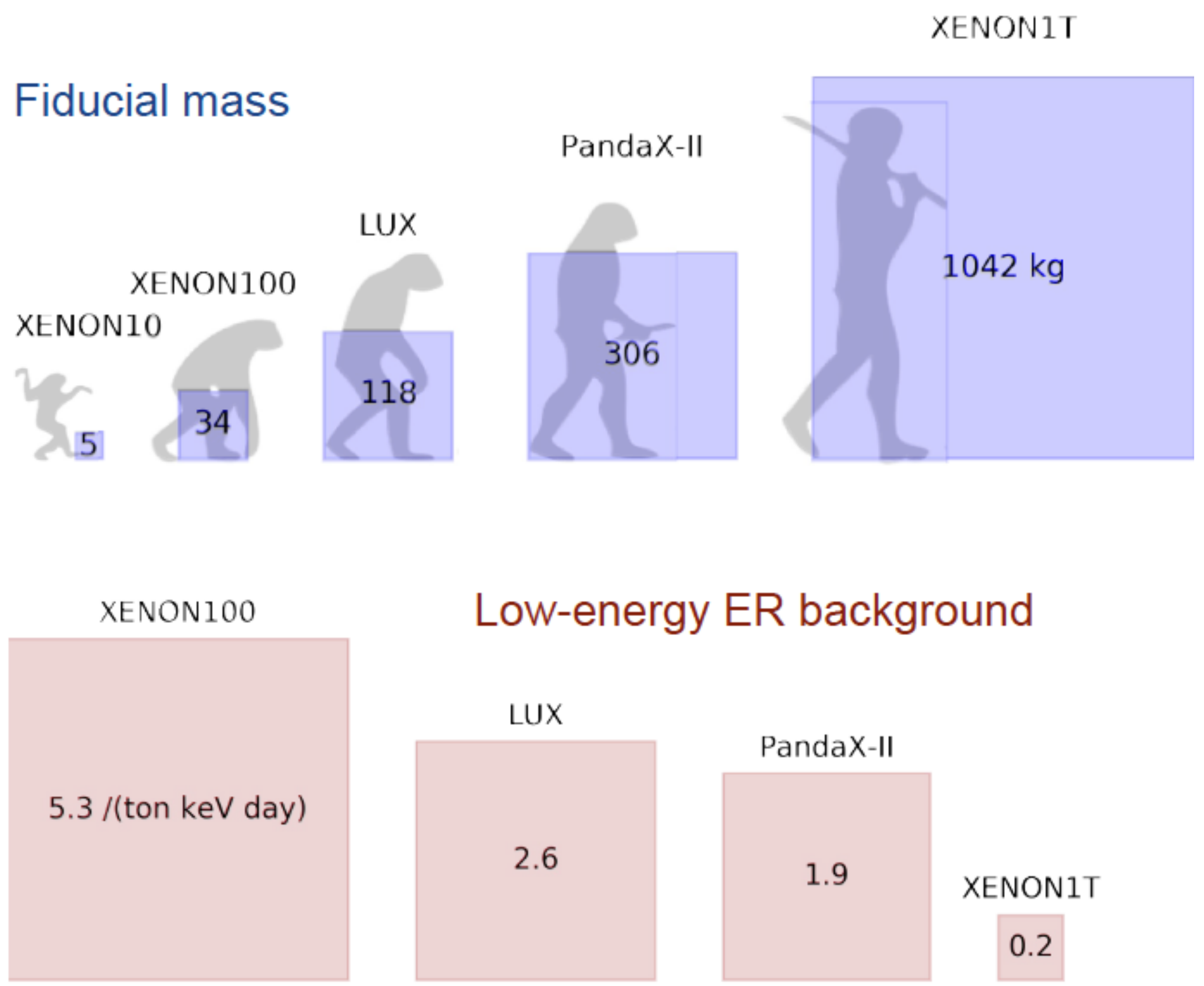
WIMP exclusion with DEAP-3600



Mark Boulay

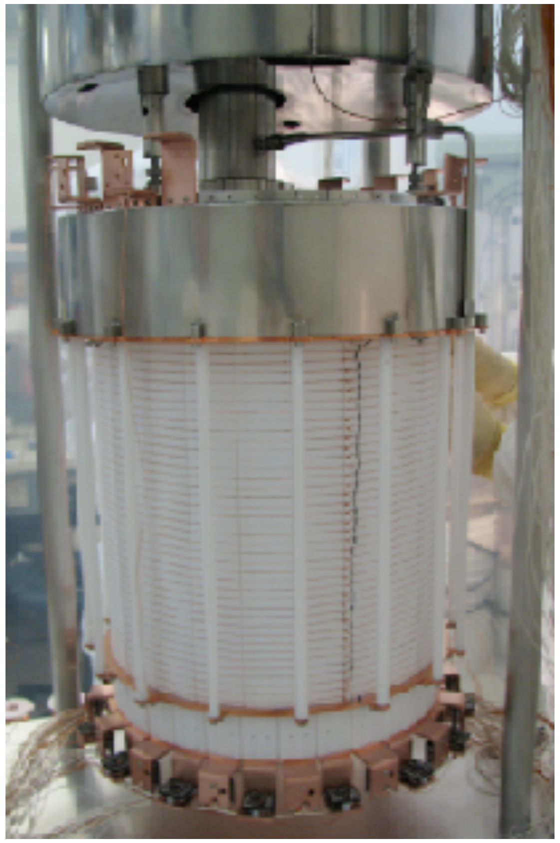
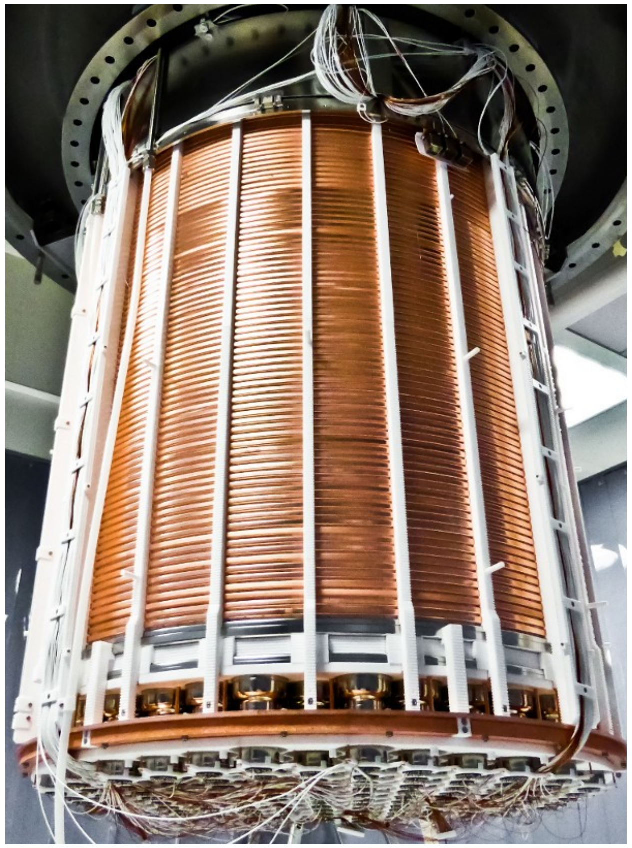
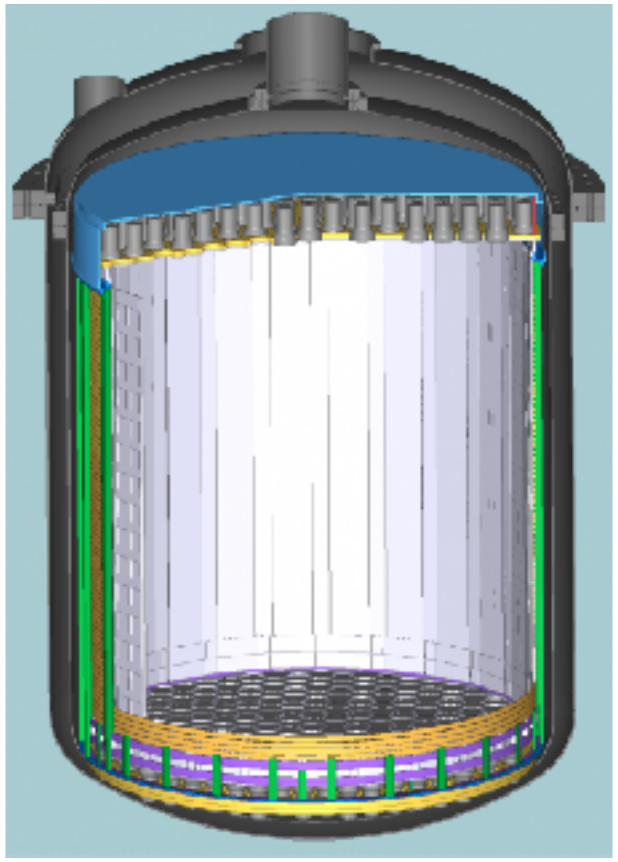
State-of-the-art in LXe Experiments: XENON1T

XENON1T: the next step in evolution



from Jelle Aalbers

The phases of the XENON Program

XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2018	2019-2023
25 kg- 15cm drift	161 kg- 30 cm drift	3200 kg- 100 cm	8000 kg-150 cm
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

The XENON collaboration

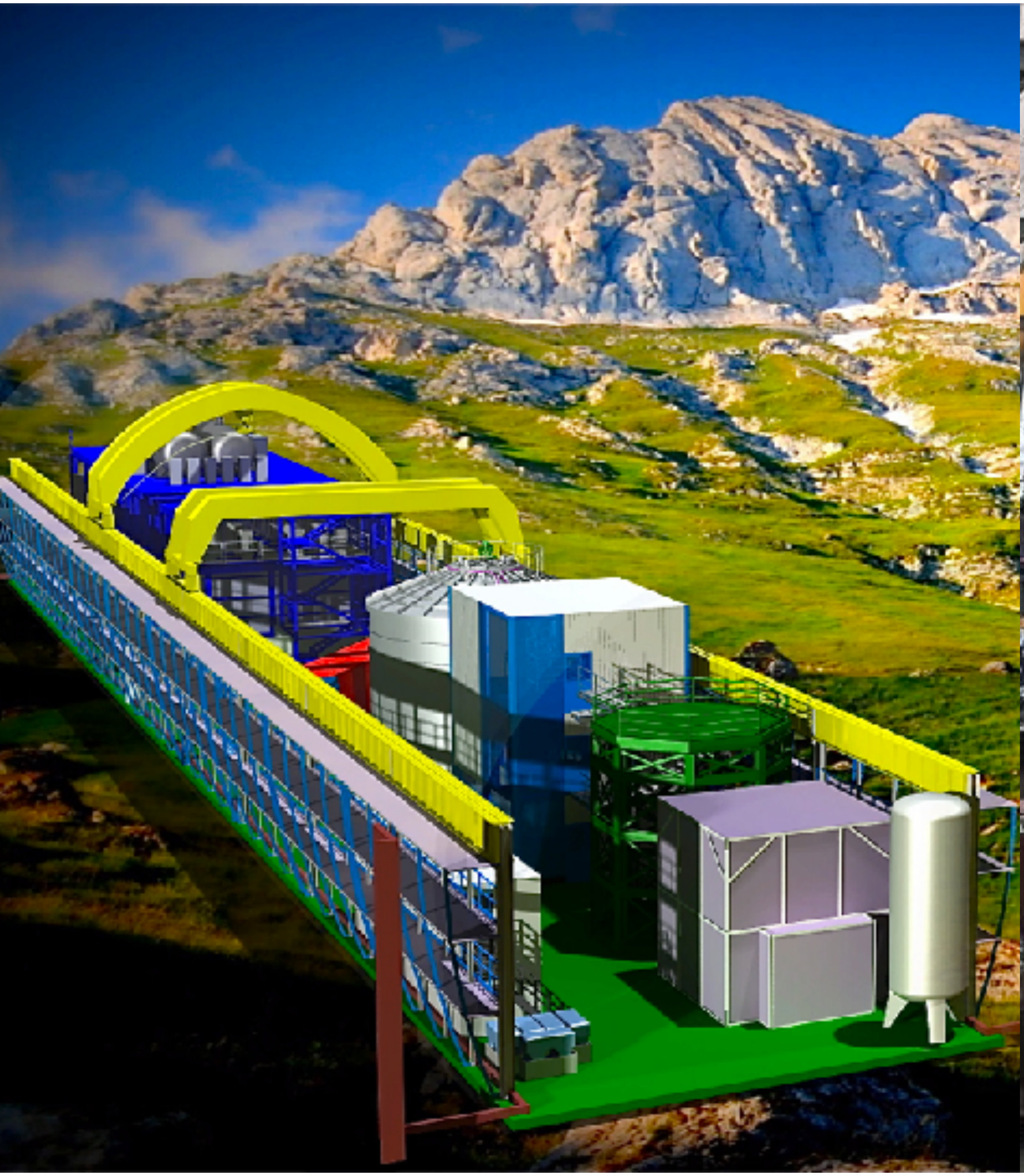
144 scientists

25 institutions

10 countries

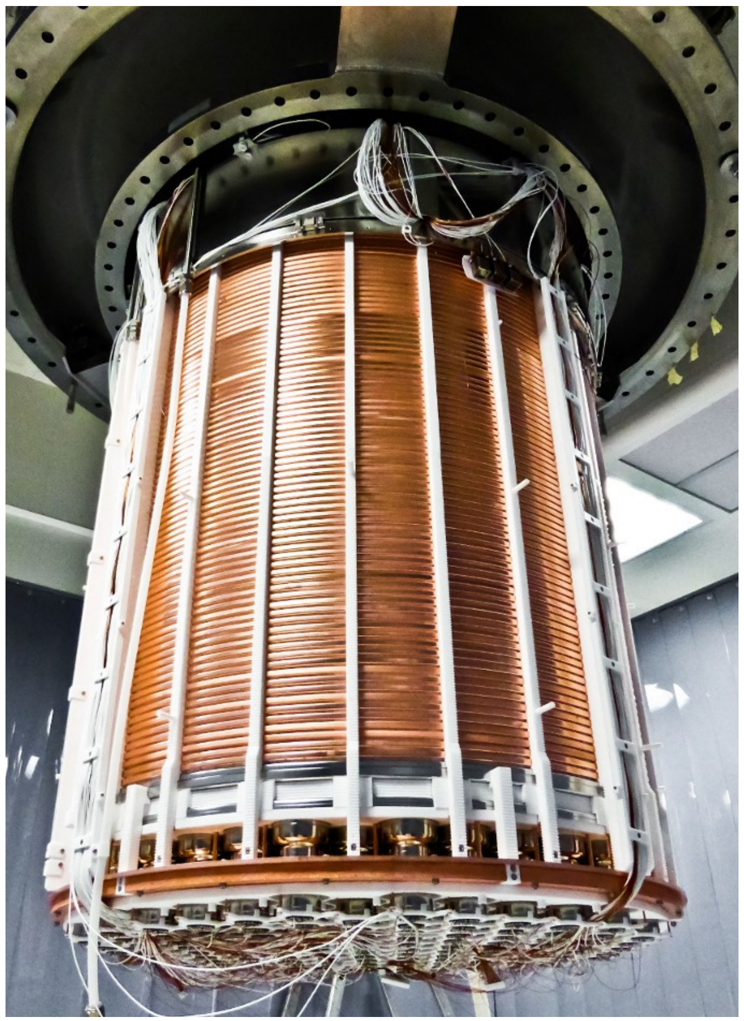
Where is XENON1T ?

The XENON1T Experiment
www.xenon1t.org



The XENON1T Time Projection Chamber

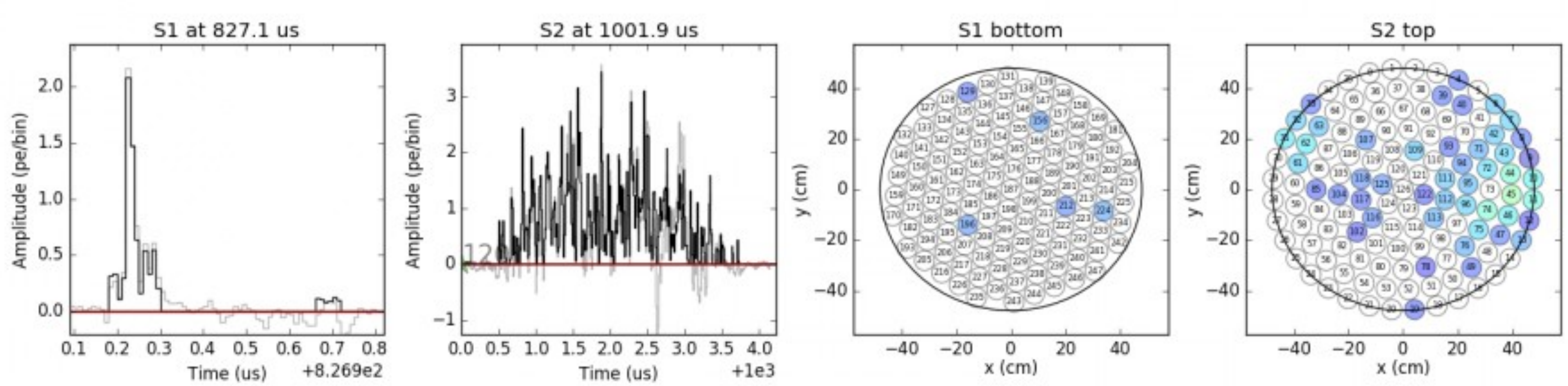
- 248 3-inch, low-radioactivity PMTs arranged in two arrays EPJC 75 (2015) 11, 546

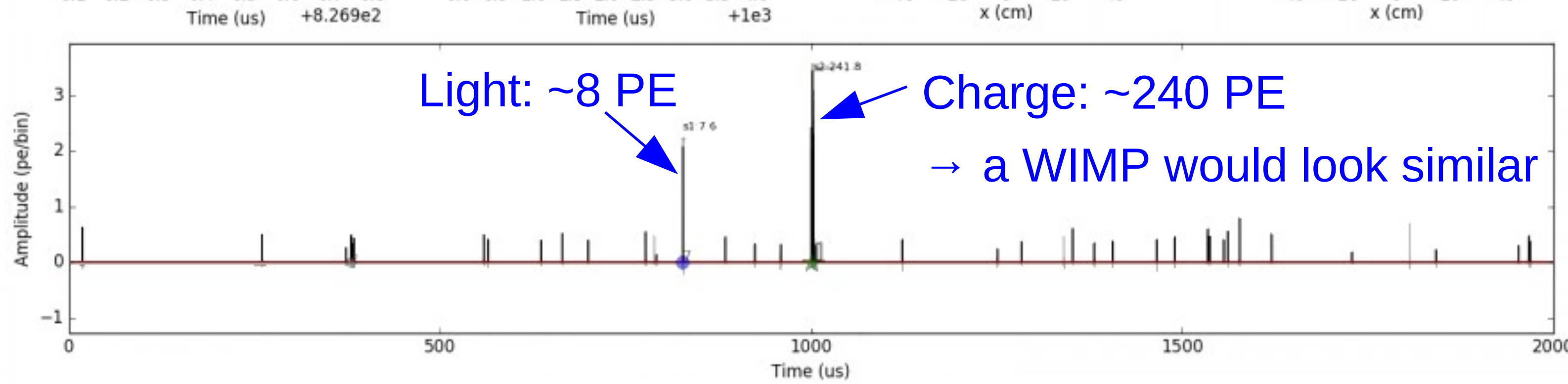


3.2 t LXe @180 K
~1 meter drift length
~1 meter diameter

127 PMTs in the top array

121 PMTs in the bottom array



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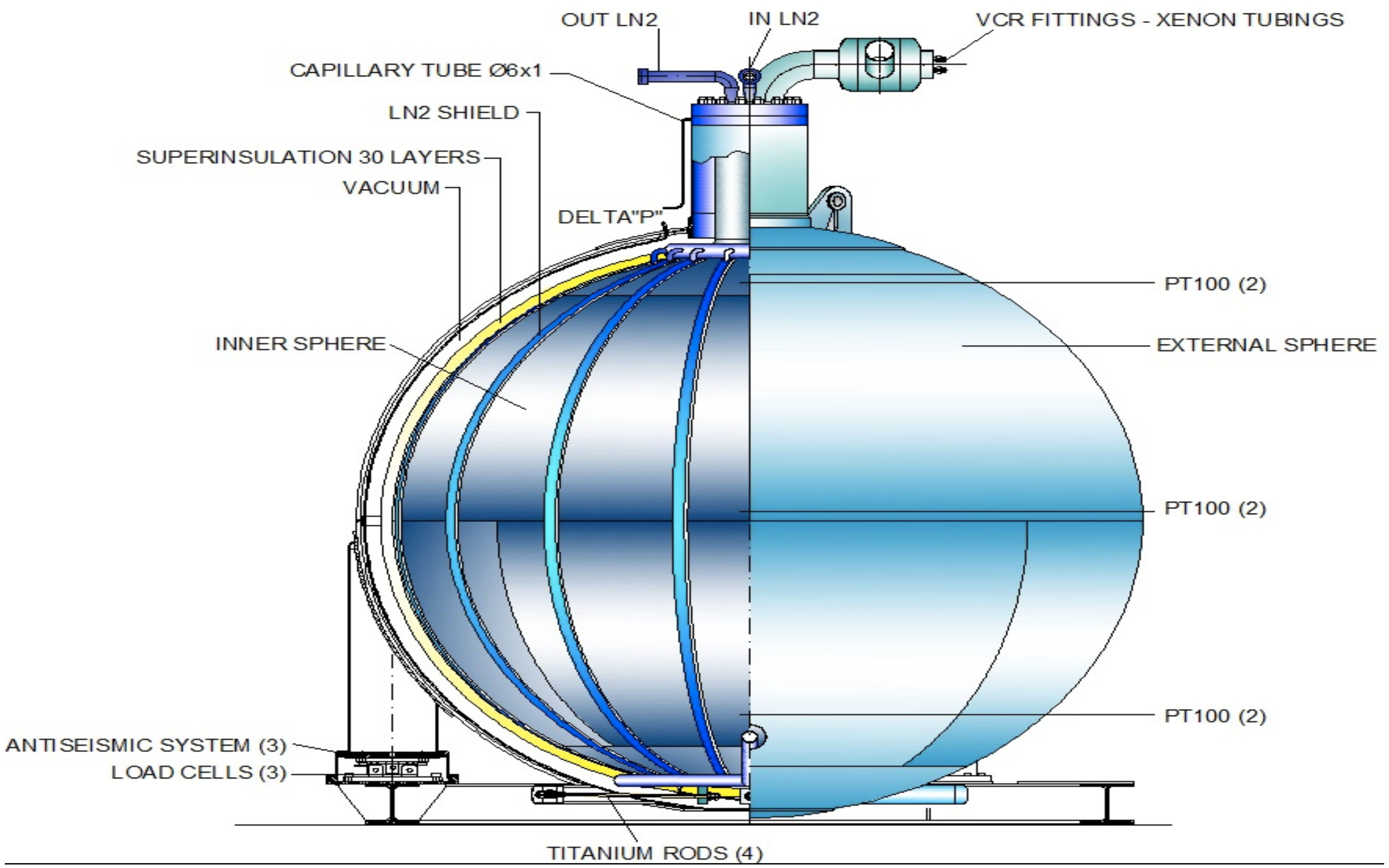
and the systems to handle/condense/purify/ keep cold and clean the Xe in the detector

It takes ~600,000 liters of Xe gas to fill the detector with 3500 kg of LXe

The Xe Recovery & Storage System

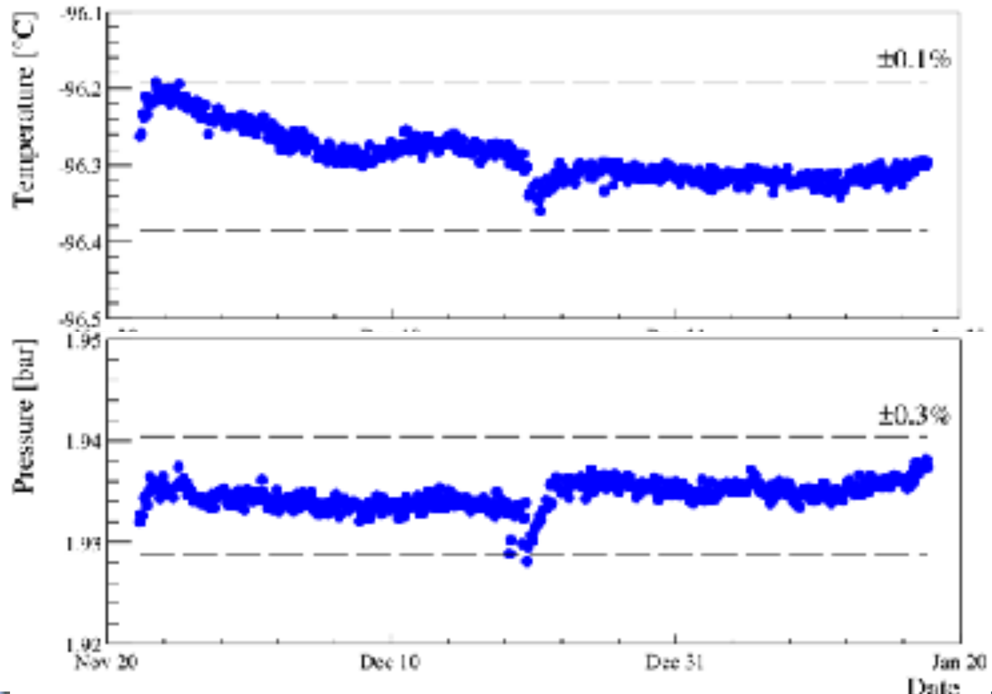
- Double-walled, high pressure (70 atm), vacuum-insulated, LN_2 cooled
- Can store up to 10t of xenon in gas or liquid/solid phase in high-purity conditions
- Fast recovery (few hours) in case of emergency

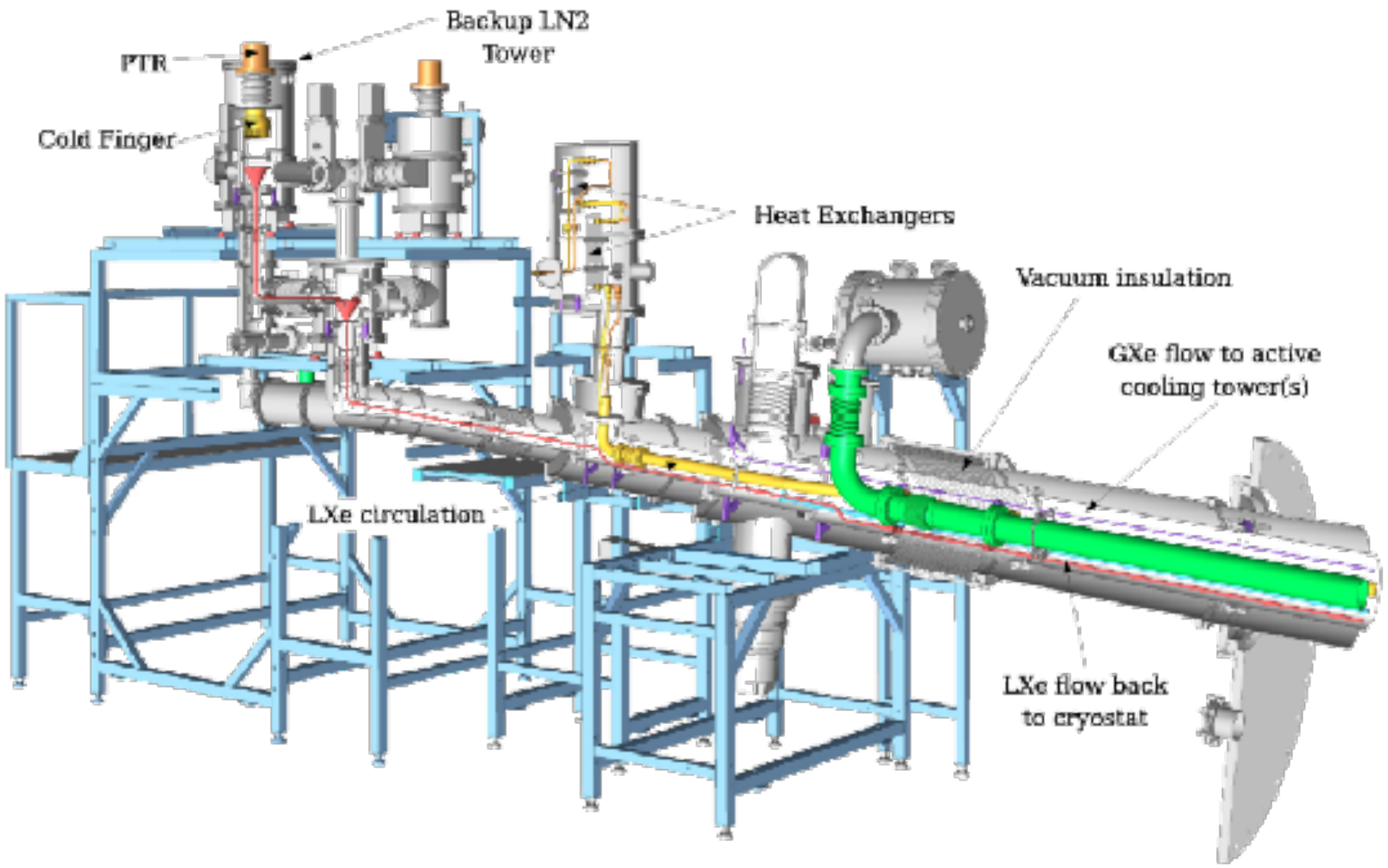


The Cryogenic System

- 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



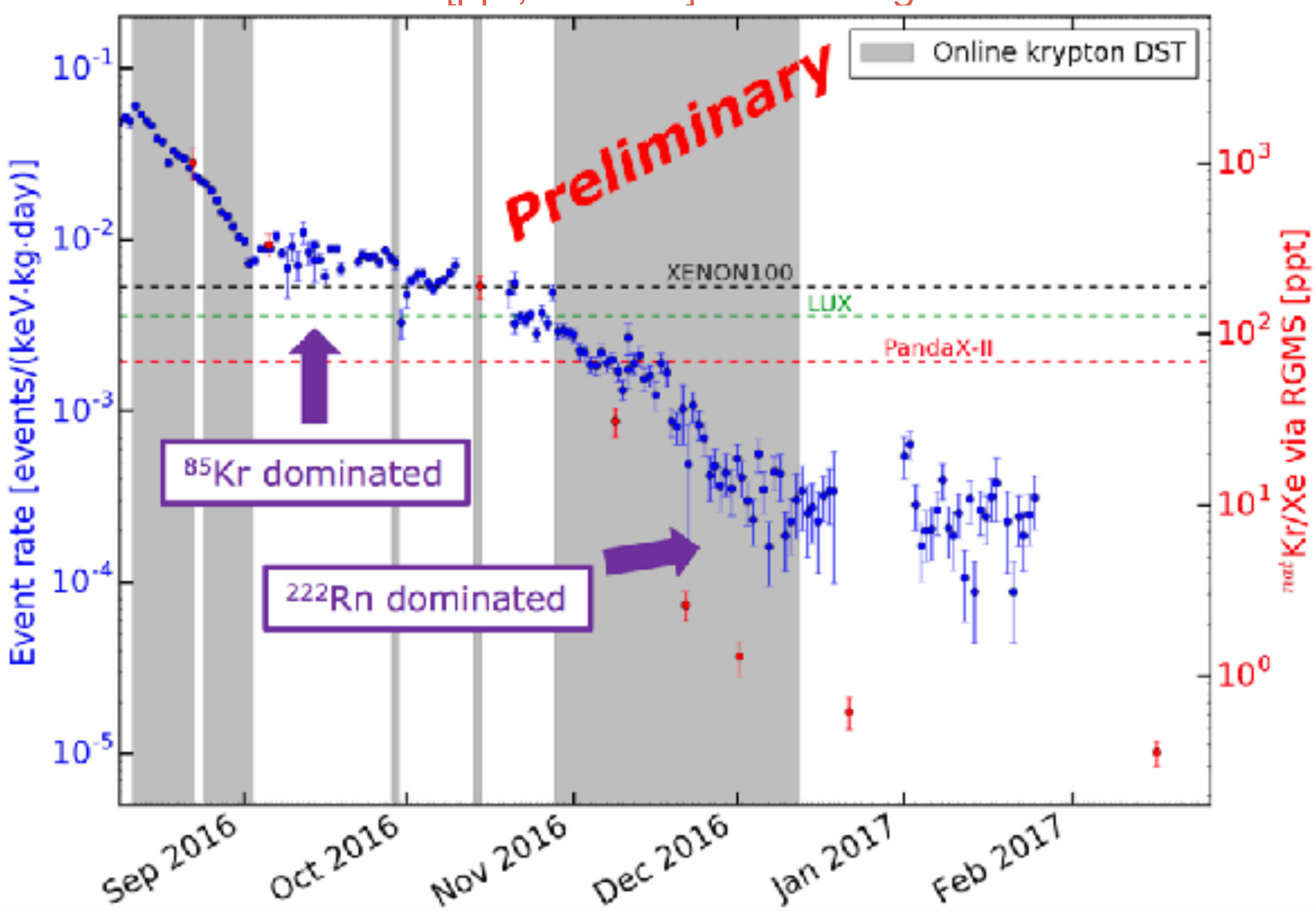


The Distillation Column

- 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 $>6.4\times10^5$ separation, output concentration < 48 ppq (RGMS)

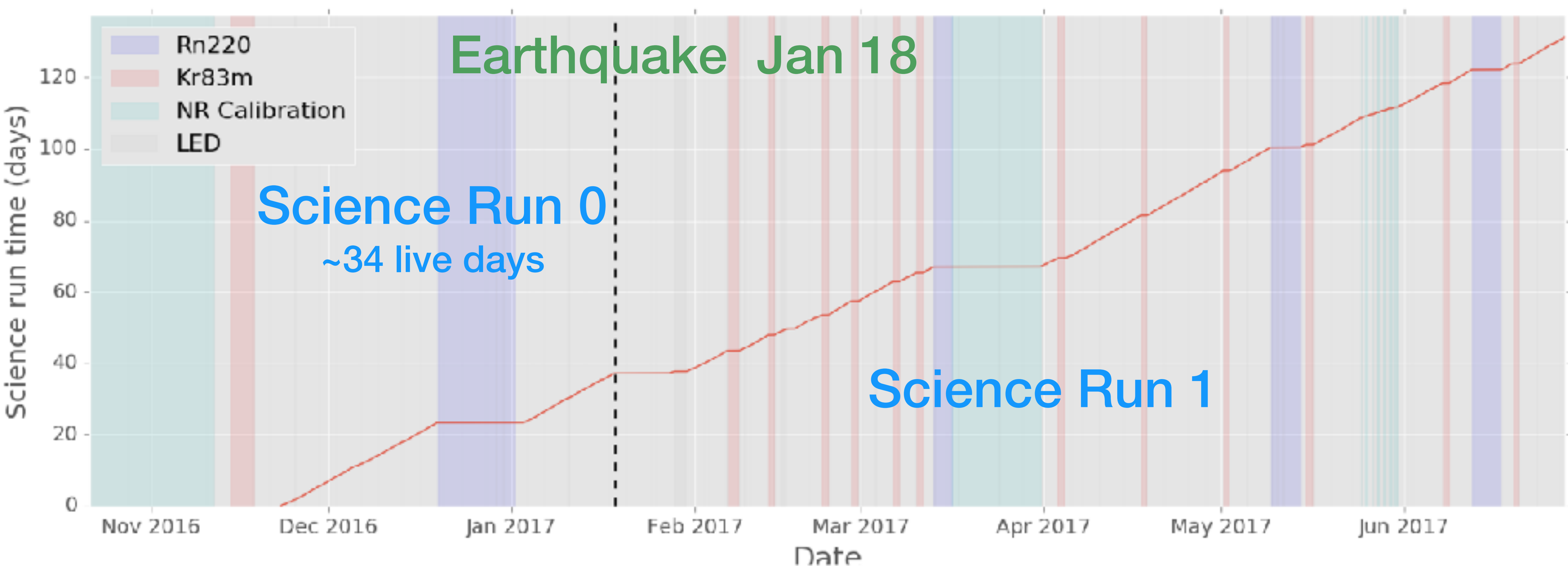
XENON collaboration arXiv:1612.0428, & EPJ-C74, 2014

Evolution of Kr/Xe [ppt, mol/mol] level during online distillation

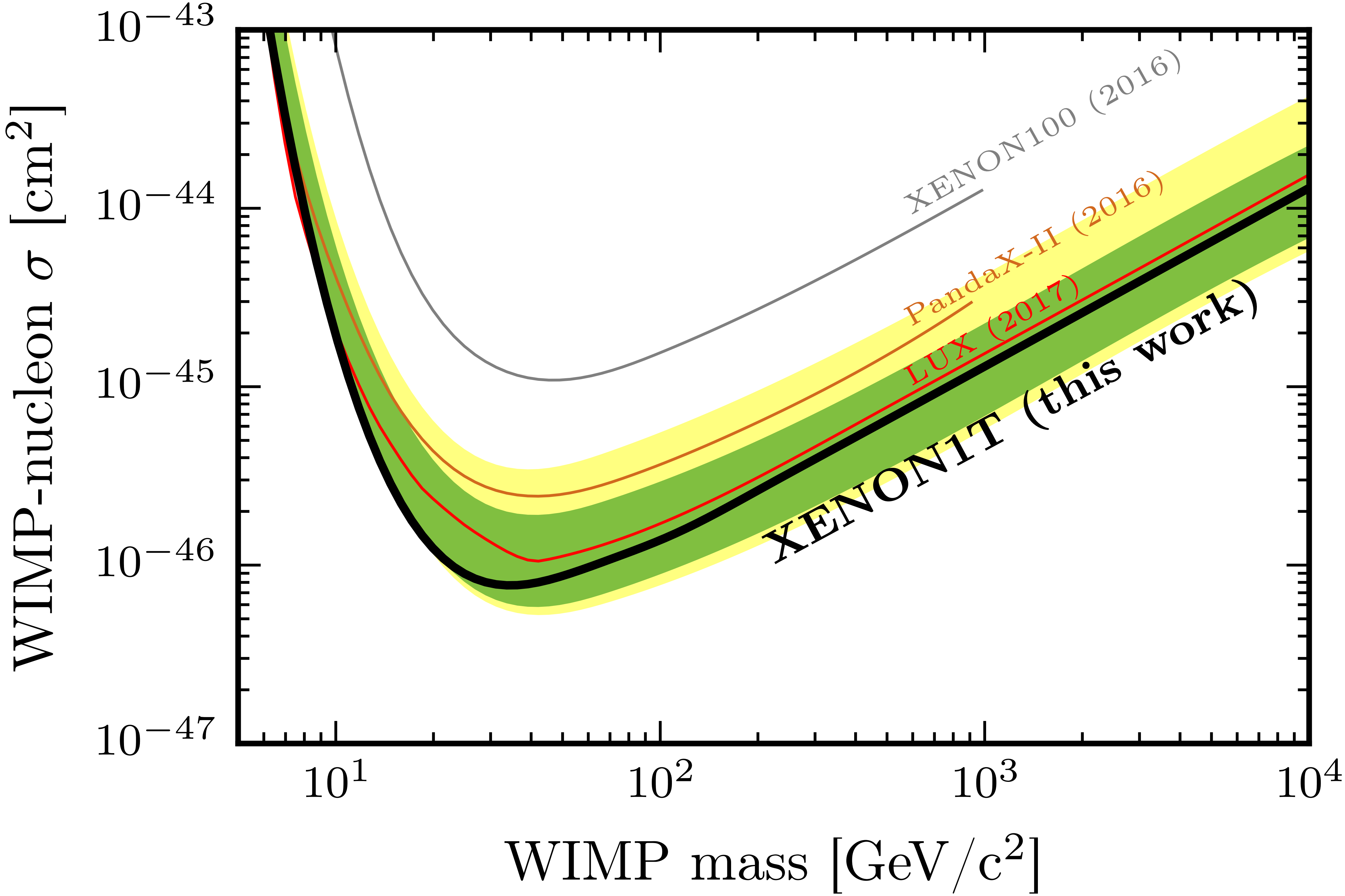


Science and calibration data

- First science run: Nov 22, 2016 - Jan 18, 2017 - Blind Analysis completed May '17
- Second science run ongoing: significant additional (blinded) exposure accumulated



SR0 Dark Matter Search



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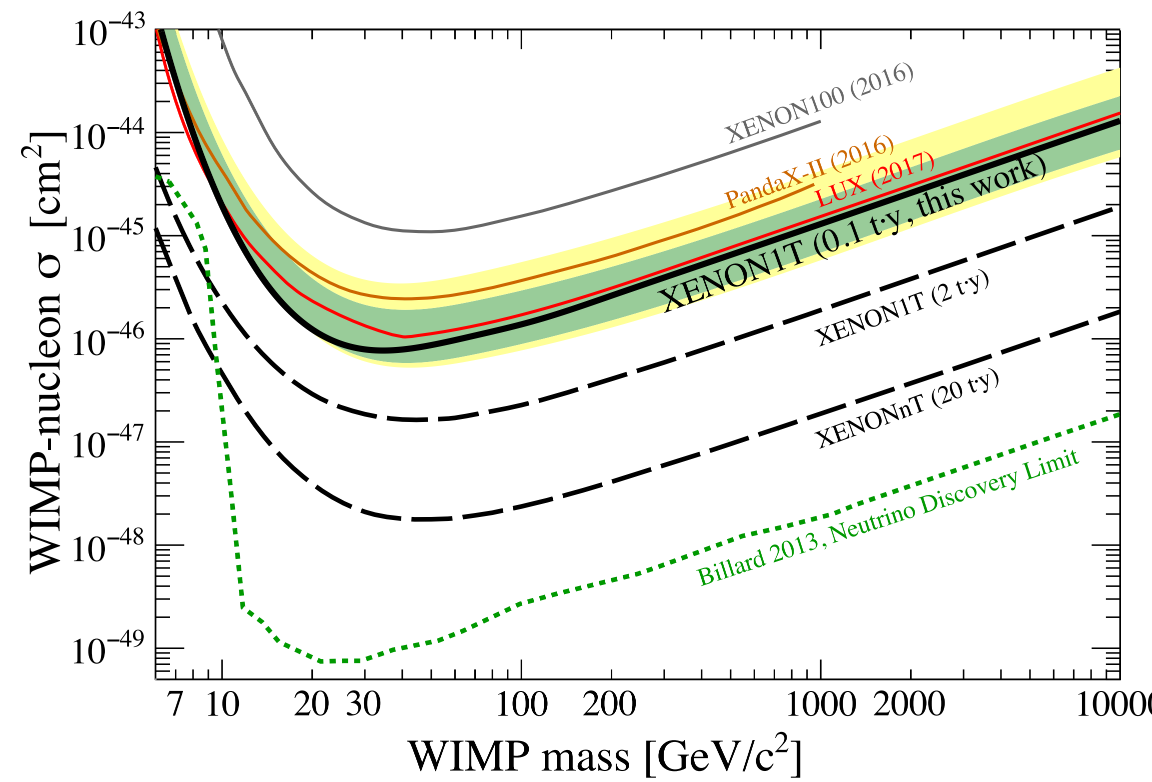
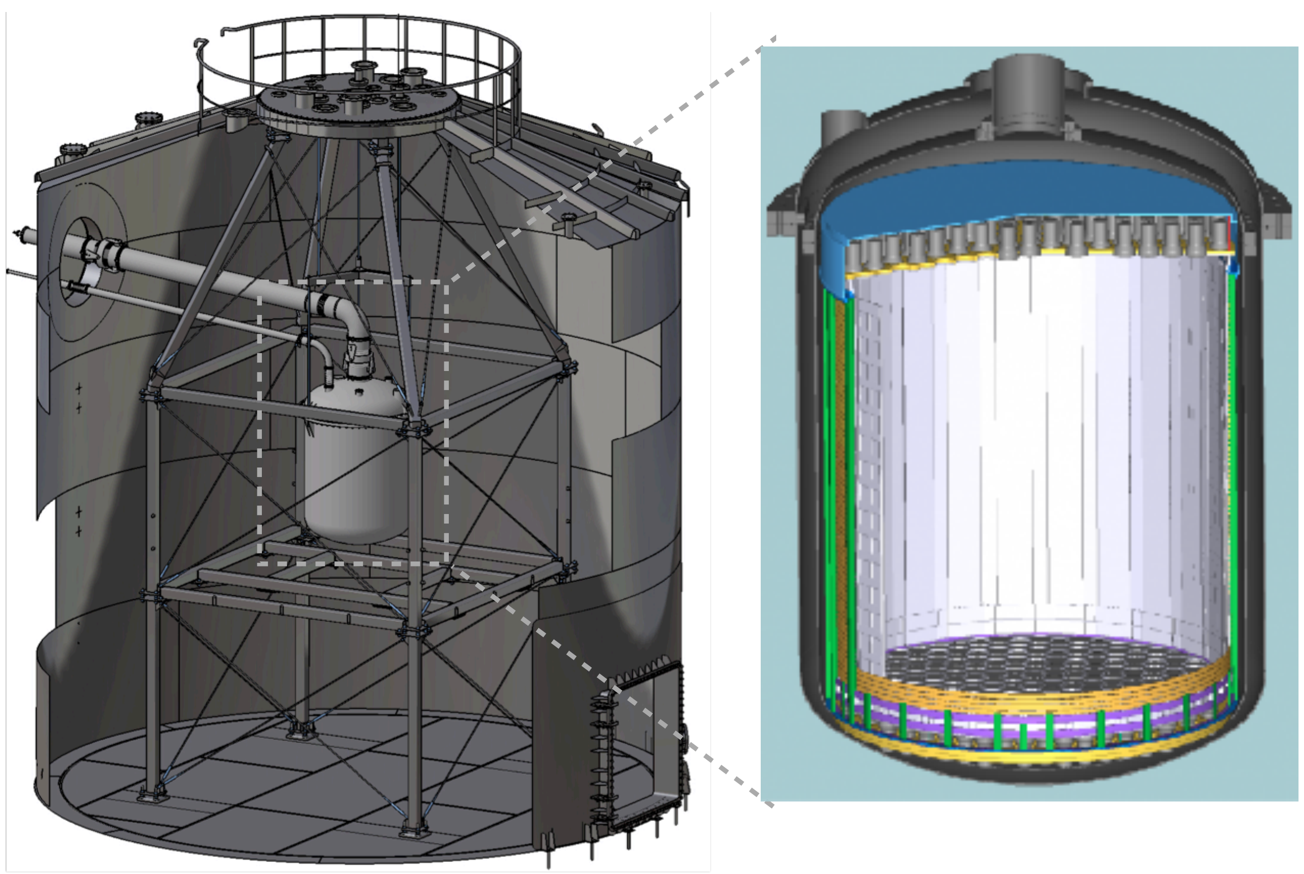
XENON1T Summary

- Largest LXeTPC - First ton-scale target for DM
- Lowest-ever low-energy background: ~2mdru
- Currently the most sensitive DD search worldwide
- Significant additional exposure > 150 live-days





- The upgrade to XENON1T, with a TPC x 3 larger(8 t total LXe mass, 6 t active) has started
- Will rely mostly on systems already built/tested with XENON1T for a fast deployment (early 2019)