Dark matter searches with liquid xenon

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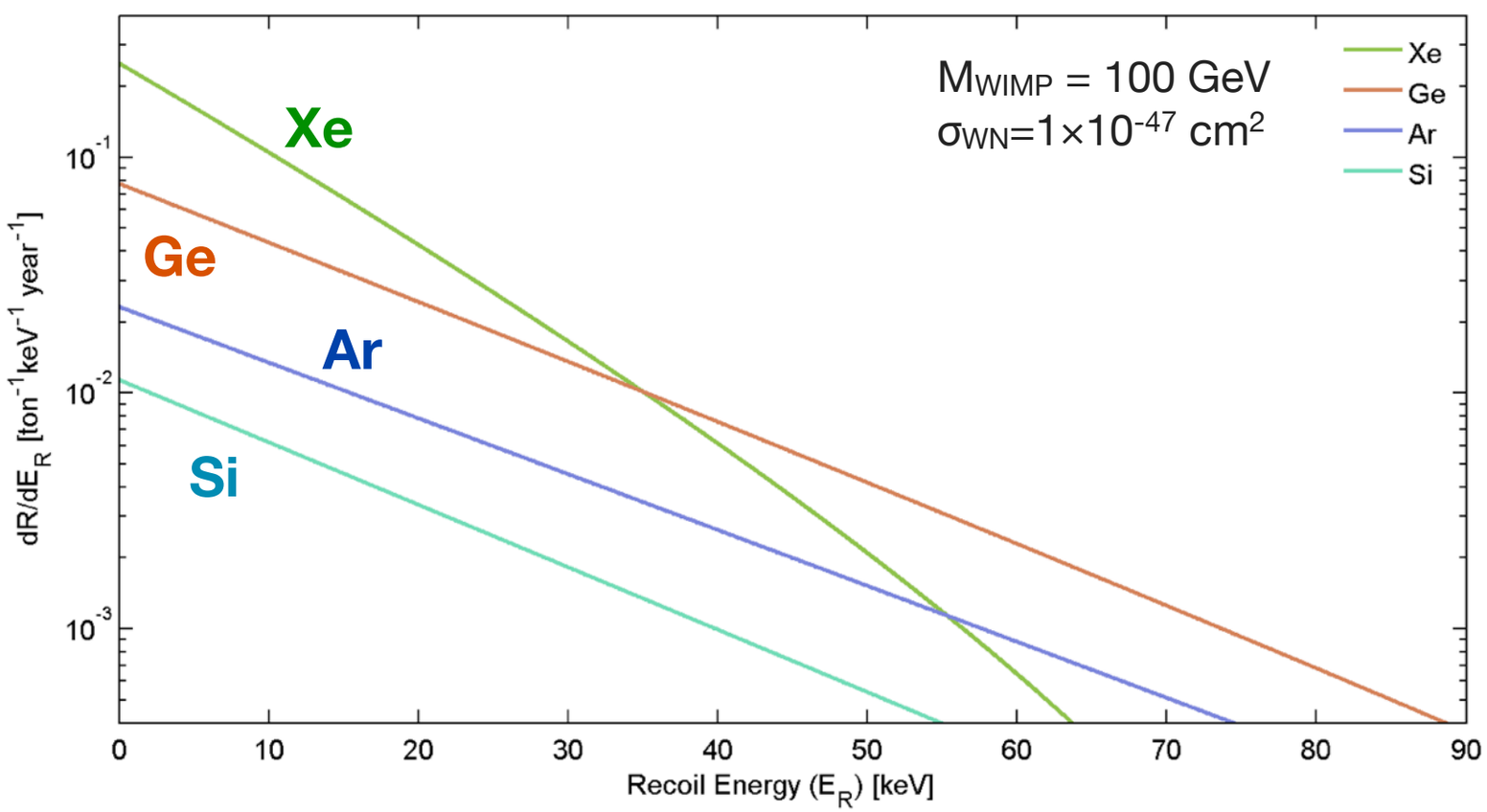
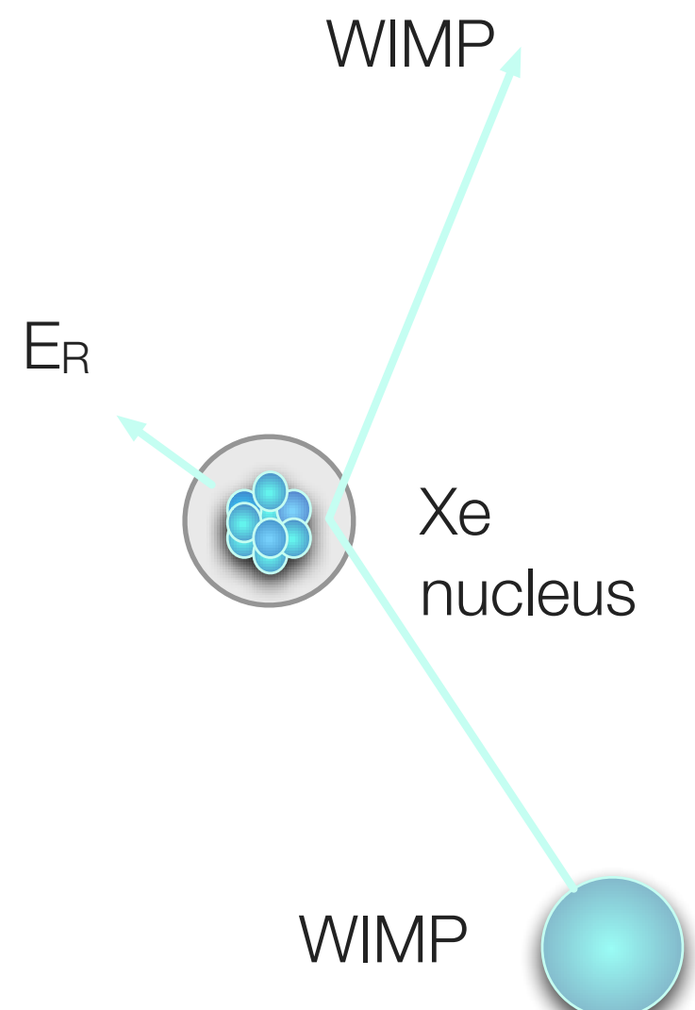
Physics aim of liquid xenon dark matter experiments

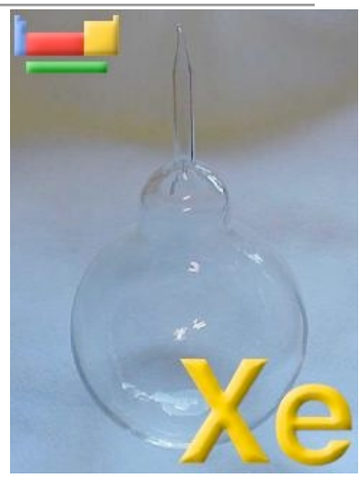
- Observe WIMP dark matter via elastic scattering off xenon nuclei
- The expected rate is:

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





Why xenon for direct dark matter detection?



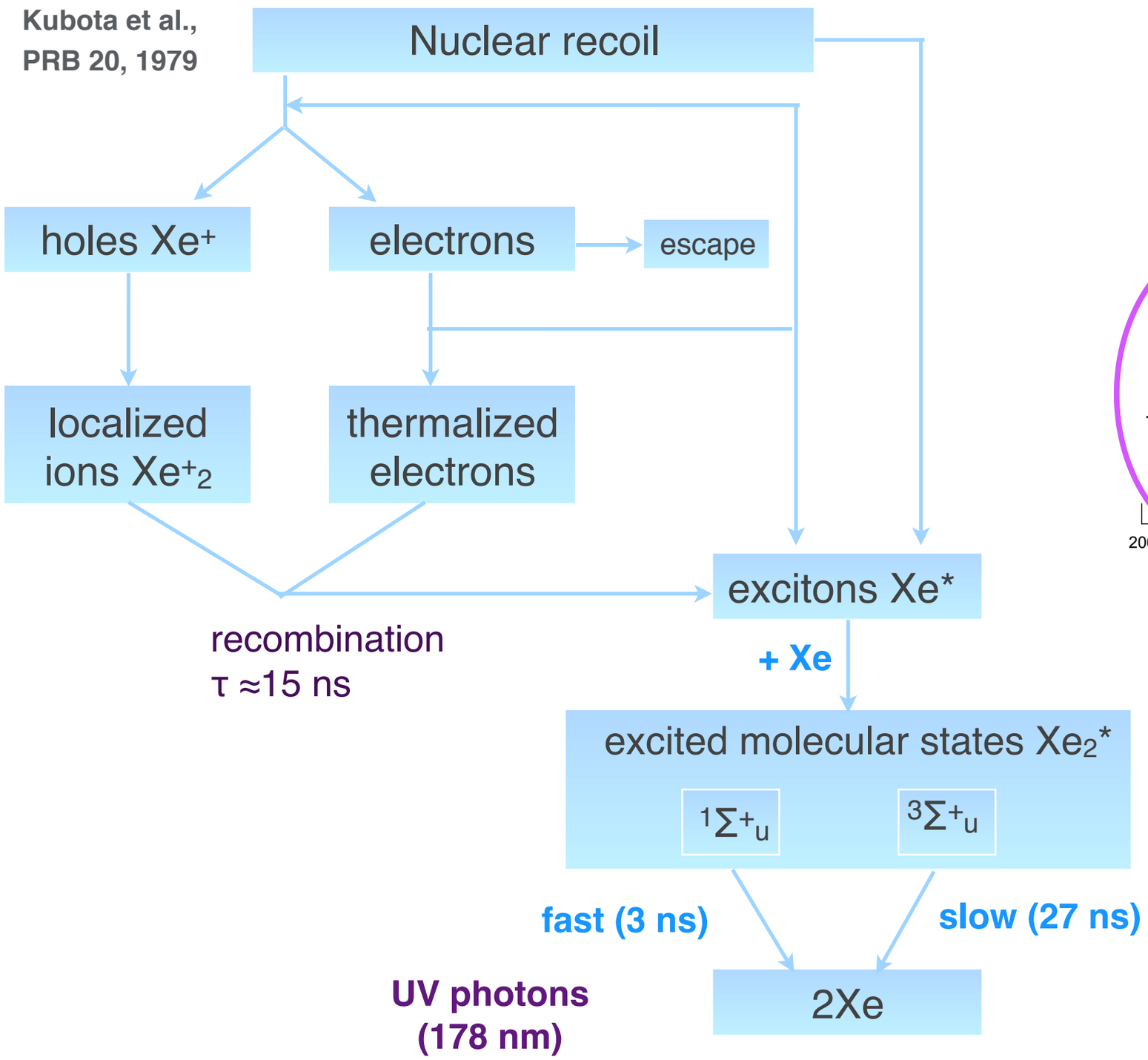
- Large mass number (A=131) => large rate for SI-interactions (sigma ~ A^2)
- Odd isotopes (^{129}Xe, spin-1/2, 26.4%; ^{131}Xe, spin-3/2, 21.2%) for SD-interactions
- High stopping power (Z = 54), active volume is self-shielding
- Efficient (~5×10^4 photons/MeV), fast scintillator and good ionizer in response to the passage of radiation
- Inert, not flammable, good dielectric, easy to purify
- Scalable to large, homogeneous detector masses

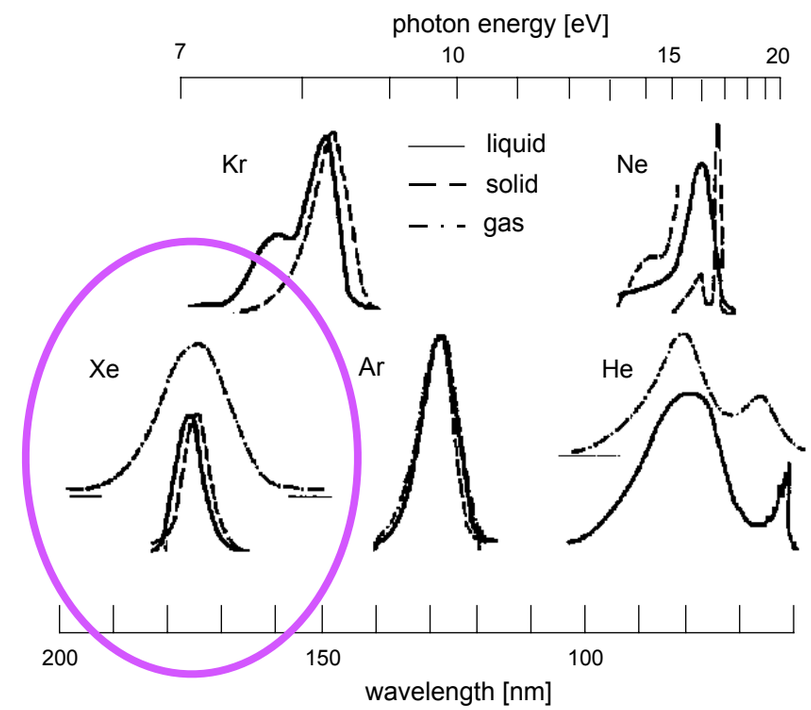
Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6 ± 0.3[b]	18.4 ± 0.3[c]	15.6 ± 0.3[d]

- W-value = average energy required to produce an electron-ion pair

Charge and light in liquid xenon

Kubota et al., PRB 20, 1979





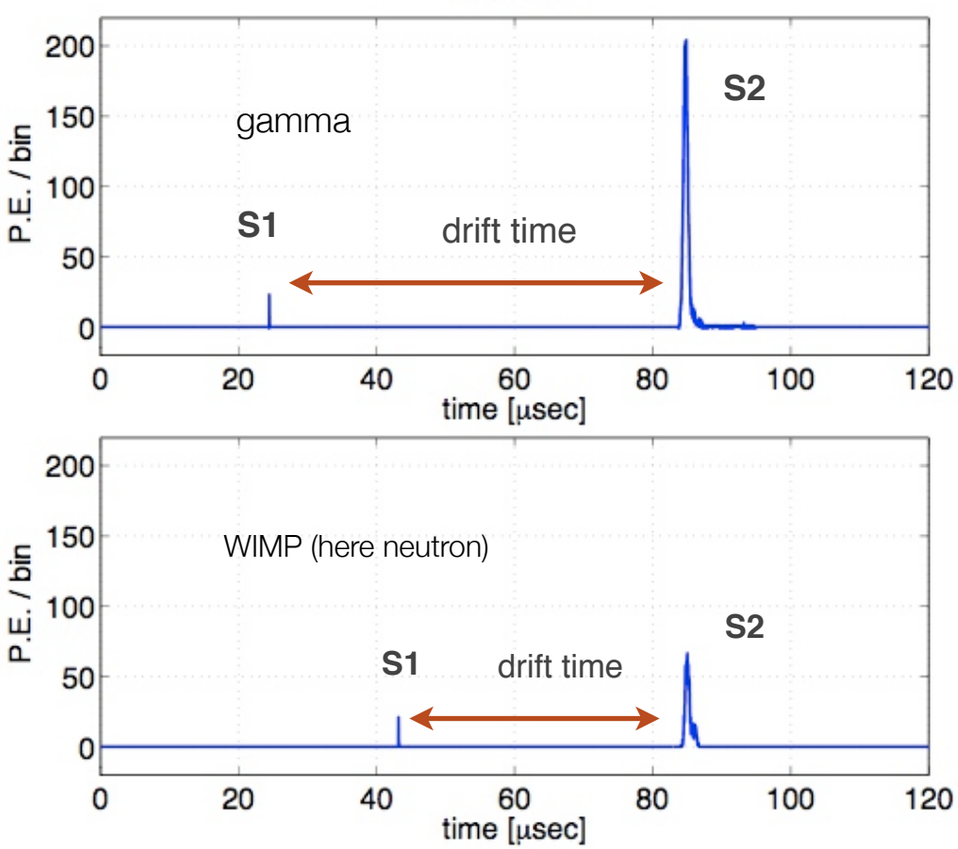
A liquid xenon time projection chamber

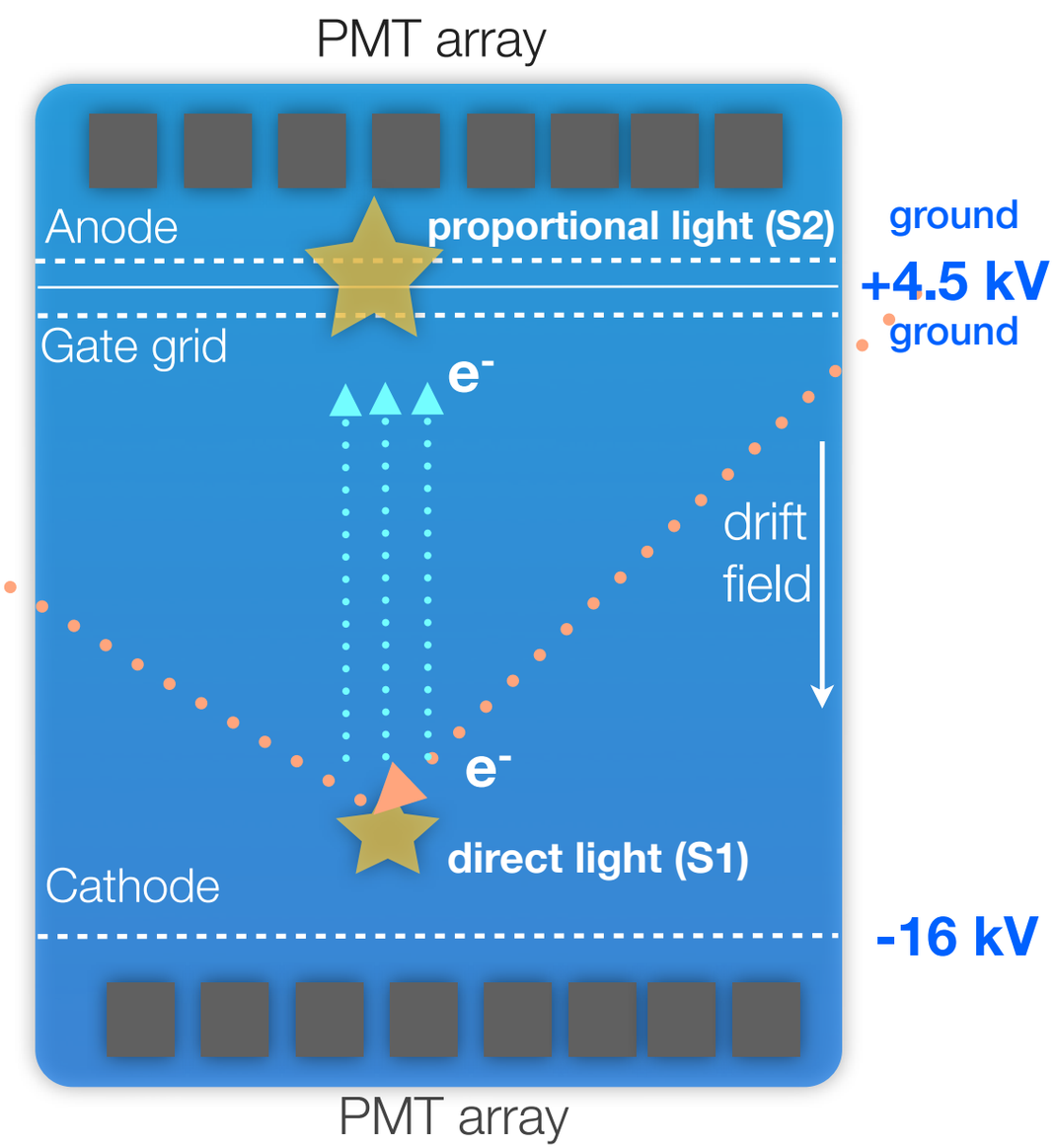
- Particle interaction in the active volume produces *prompt scintillation light (S1)* and ionization electrons
- Electrons drift to interface (E= 0.53 kV/cm) where they are extracted and amplified in the gas. Detected as *proportional scintillation light (S2)*
  - $(S2/S1)_{WIMP} << (S2/S1)_{Gamma}$
  - 3-D position sensitive detector with particle ID

Xe (A=131); λ = 178 nm

position resolution:

<3mm in x-y; < 0.3 mm in z





Overview: existing and future projects

- Single-phase: e^--ion recombination occurs; only scintillation signal is detected
- Double-phase: ionization and scintillation; e- are drifted in E-field, ~ 1kV/cm

LXe detectors	Current	Future
Single phase	XMASS	XMASS (5t)
Double phase	LUX, XENON100, Panda-X	LZ (7t), Panda-X (1t), XENON1T (3t), DARWIN (20 t)

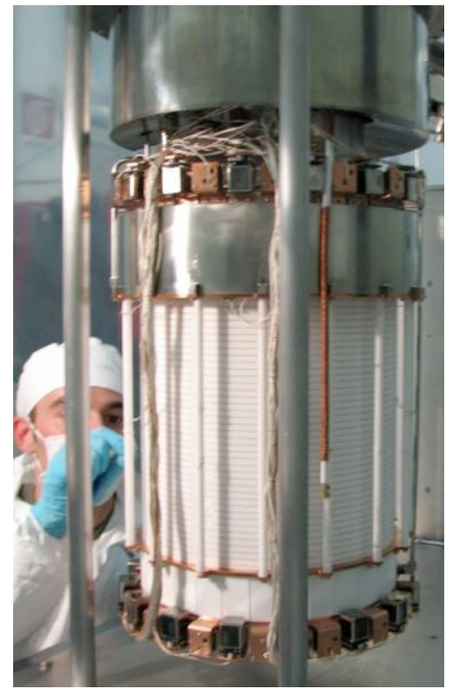
Overview: existing projects

XMASS: in water Cherenkov shield at Kamioka:

835 kg LXe (100 kg fiducial), single-phase, 642 PMTs taking science data

LUX: In water Cherenkov shield at SURF:

350 kg LXe (100 kg fiducial), dual-phase, 122 PMTs, commissioning, run to start in early 2013



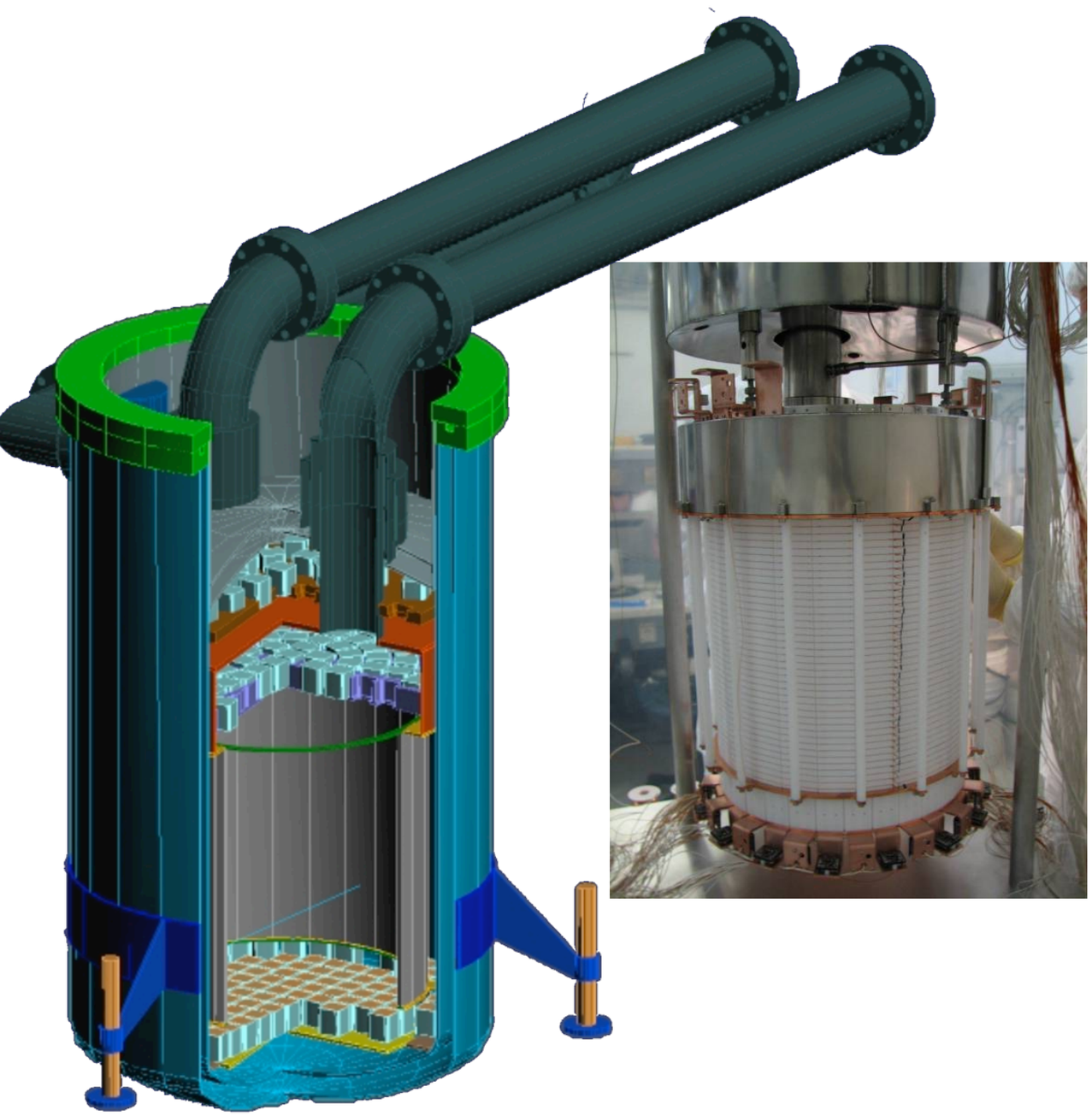
XENON100 in conventional shield at LNGS:

161 kg LXe (~50 kg fiducial), dual-phase, 242 PMTs taking science data

PandaX in conventional shield at CJPL:

stage I: 123 kg LXe (25 kg fiducial), dual-phase, 180 PMTs
starts in 2013

Design of the XENON100 detector



Instrument described in: Astroparticle Physics 35, 573-590, 2012

TPC with 30 cm drift x 30 cm diameter

161 kg ultra pure LXe (62 kg as target)

1” square PMTs with ~1 mBq (U/Th)

Requirements:

100 x less background than XENON10

10 x more fiducial mass than XENON10

Solutions:

Cryocooler and FTs outside shield

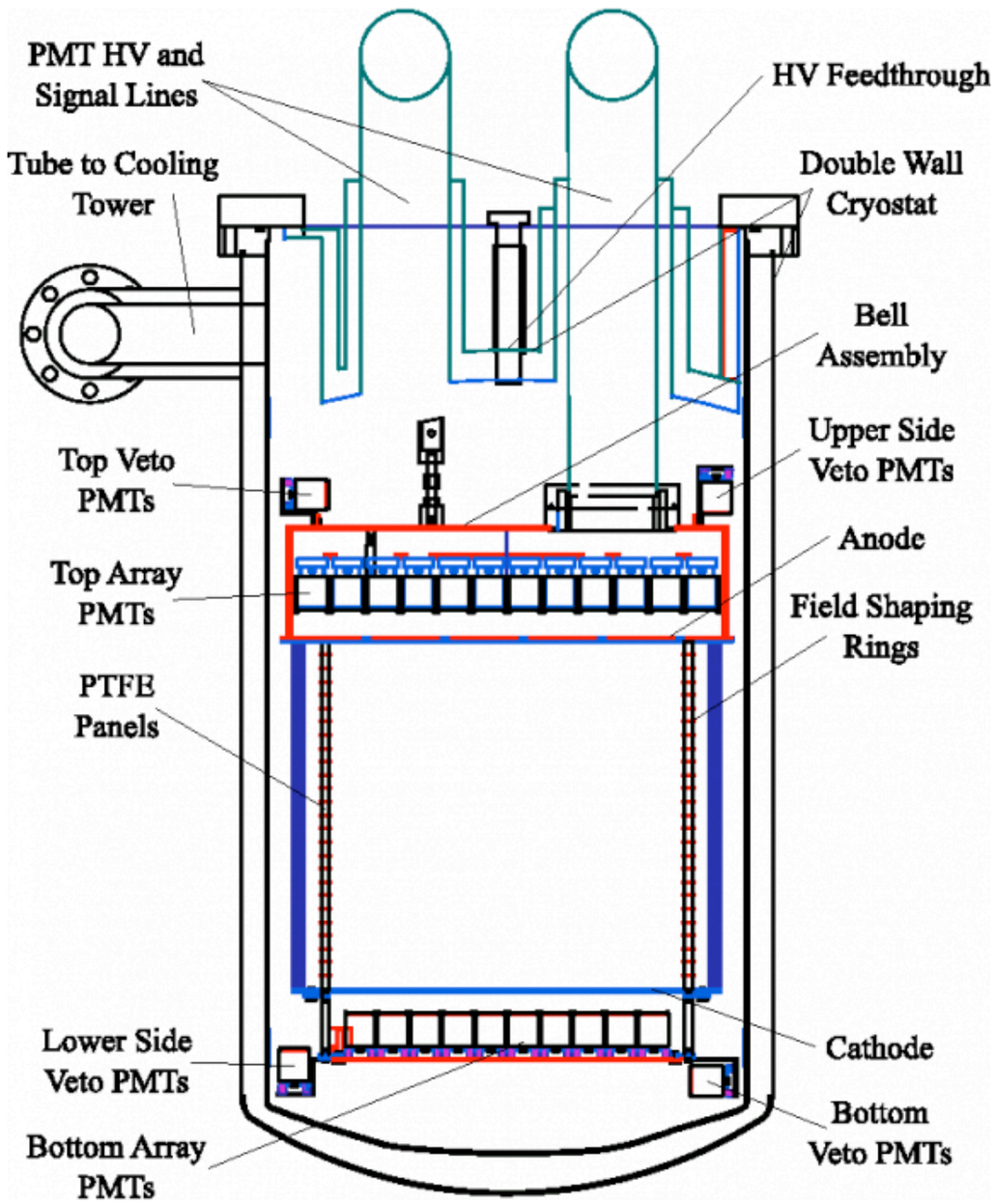
Materials screened for low radioactivity

LXe scintillator active veto system

Improved passive shield system

Dedicated Kr distillation column

XENON100 design

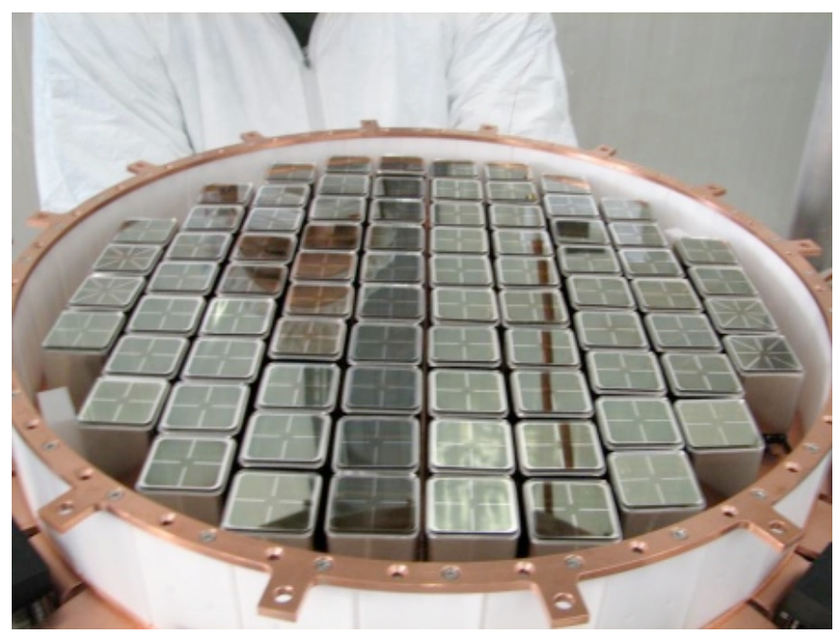


- TPC with 30.6 cm height, 15.3 cm radius, made of 24 interlocking teflon panels
- Drift field (0.53 kV/cm) generated between cathode on bottom (-16 kV) and grounded gate grid on top
- Anode at +4.5 kV between two grounded grids: extraction field of ≈ 12 kV
- Field shaping rings (40) for homogeneous drift field inside the TPC
- Liquid xenon shield (99 kg), 4 cm thick, optically separated from the TPC
- 242 PMTs: 98 on top, 80 on bottom, 64 in the liquid xenon shield
- Because of the 1.69 refractive index of LXe, about 80% of the S1 signal is seen by the bottom PMT array

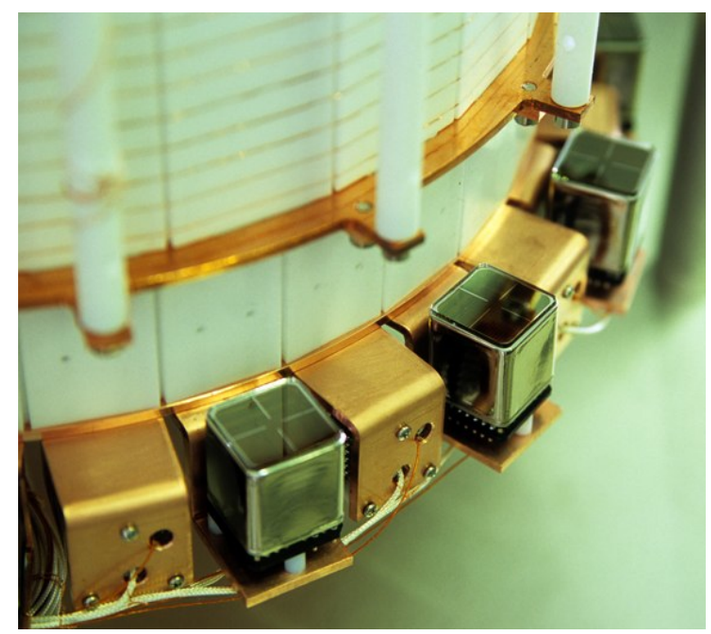
The photosensors

- 1-inch square R8520 Hamamatsu PMTs, optimized to work at LXe T and P, and of low-radioactivity (< 1 mBq/PMT in $^{238}U/^{232}Th$)
- Top array: 98 PMTs (23% quantum efficiency) in concentric circles to improve radial event position reconstruction, teflon holder
- Bottom array: 80 PMTs, closely packed, and of higher quantum efficiency (~ 33% at 178 nm), for efficient S1 light collection
- Liquid xenon veto: 64 PMTs, 23% quantum efficiency

top array



bottom array



veto PMTs

Screening results in Astroparticle Physics 35, 43-49, 2011

Location and shield

- Gran Sasso Laboratory: shield against cosmic rays: 1.4 km of mountain
- Passive shield:

  ➡ 5 cm (2 tons) of Cu, 20 cm (1.6 tons) of PE, 20 cm (33 tons) of Pb, plus 20 cm water shield

- Detector housing is continuously purged with boil-off N_2, to maintain a radon level < 0.5 Bq/m^3
- All materials were screened with HPGe detectors at LNGS JINST 6 P08010, 2011

Screening results in Astroparticle Physics 35, 43-49, 2011

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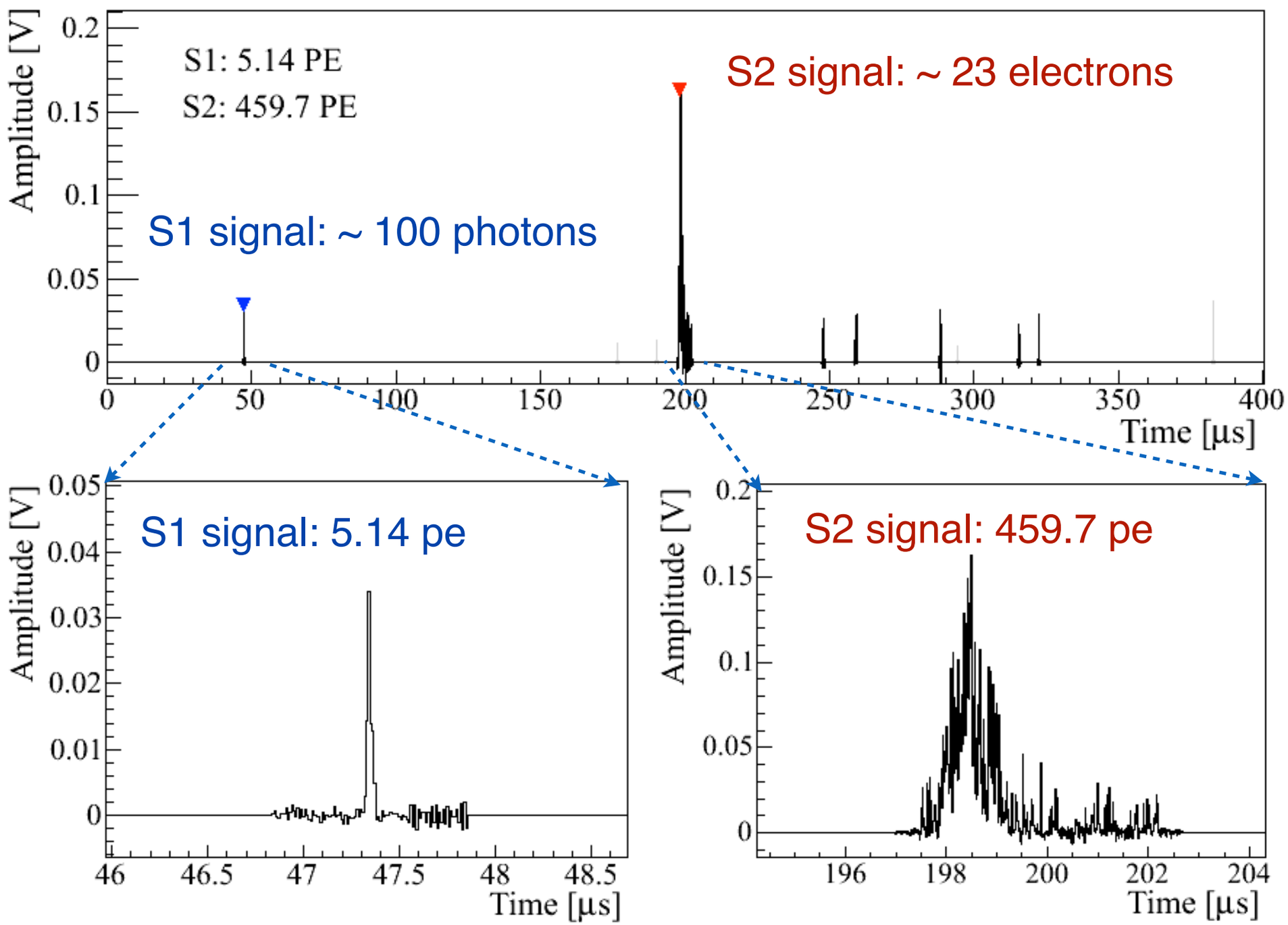
The XENON collaboration

Columbia Rice UCLA Zurich Coimbra LNGS Shanghai Subatech

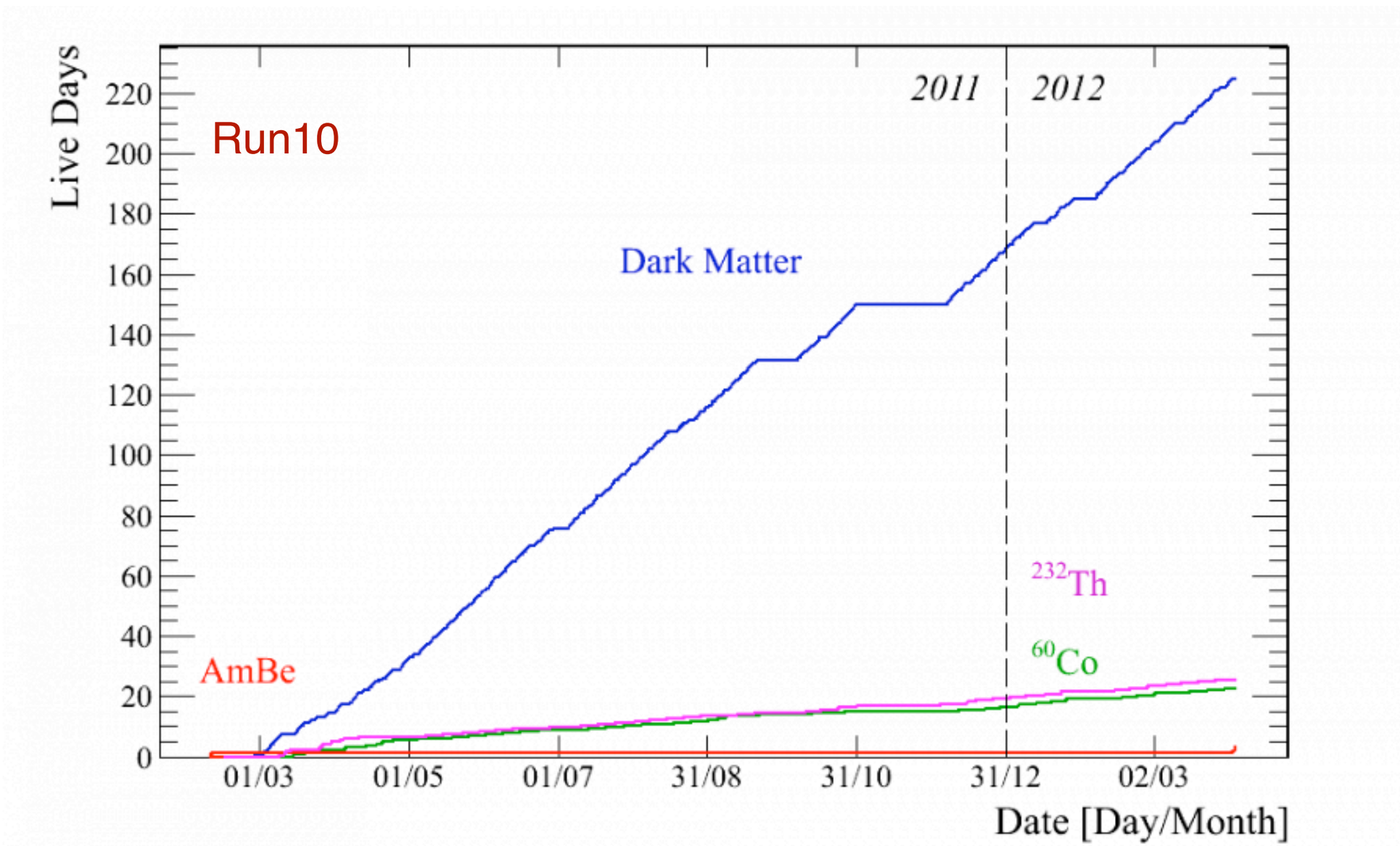
Mainz Bologna Münster Heidelberg Purdue NIKHEF Weizman

Example of a low-energy event



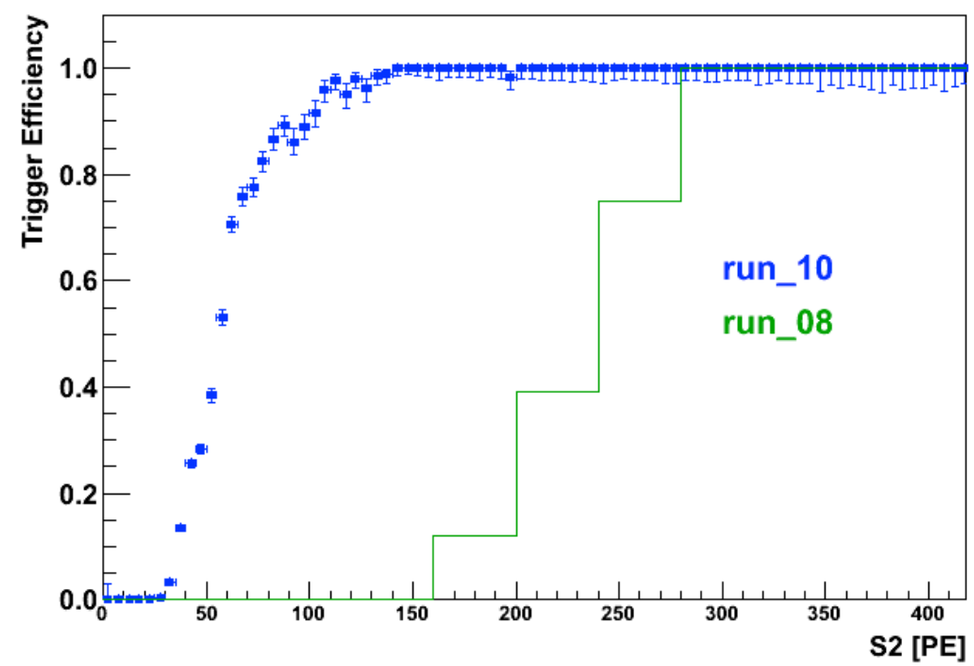
XENON100's most recent run: 2011-2012

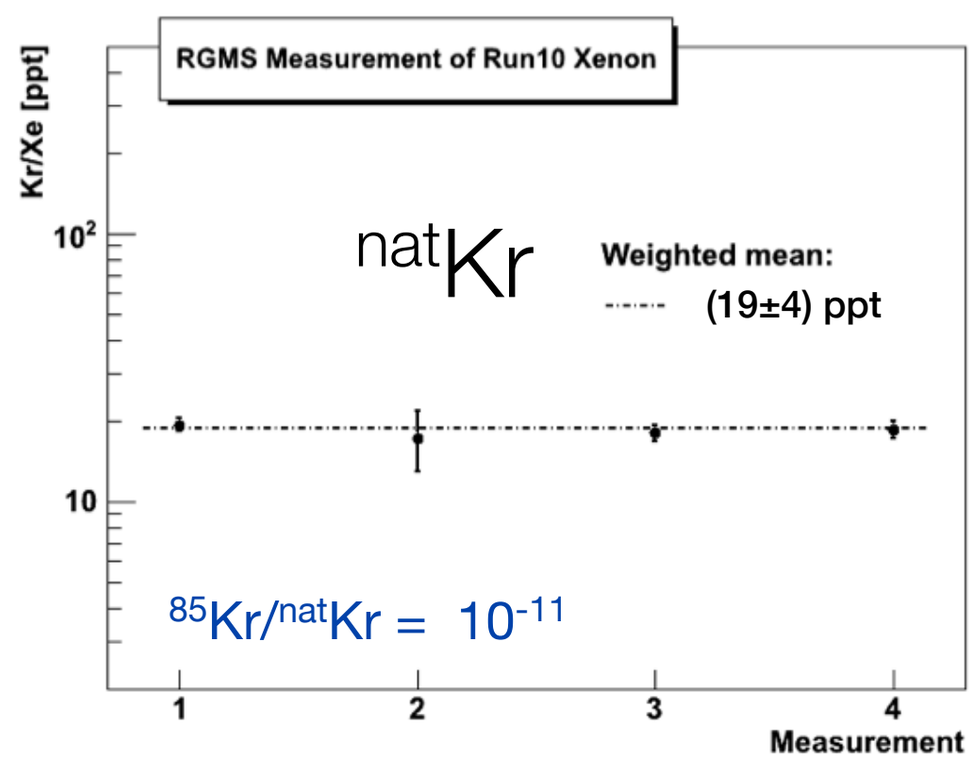
- Data from February 2011 - March 2012, with three maintenance interruptions
- A total of 224.6 live days of dark matter data; region of interest "blind"



Progress compared to previous runs

- Lower trigger efficiency in S2
- Lower ^{nat}Kr concentration by a factor of 20, now at (19±4) ppt
- Doubled exposure
- Improved noise conditions
- Higher statistics calibration data (35 x science data in region of interest)
- Higher liquid xenon purity (e^- mean lifetime from 375 μs to 611 μs during this run)





The gamma background in Run10

- Reached background level before S2/S1-discrimination: 5.3 x 10^{-3} events/(kg day keV)

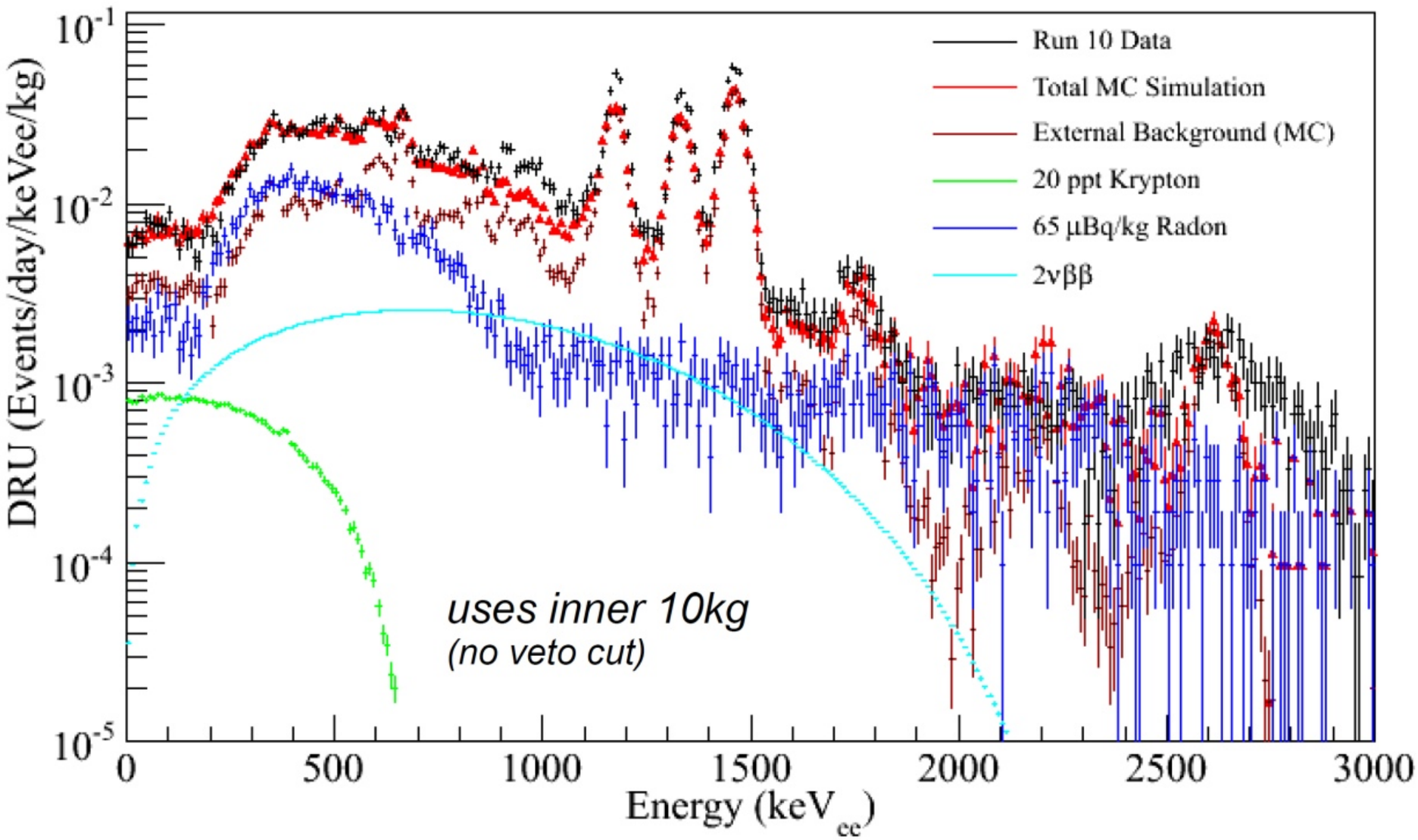
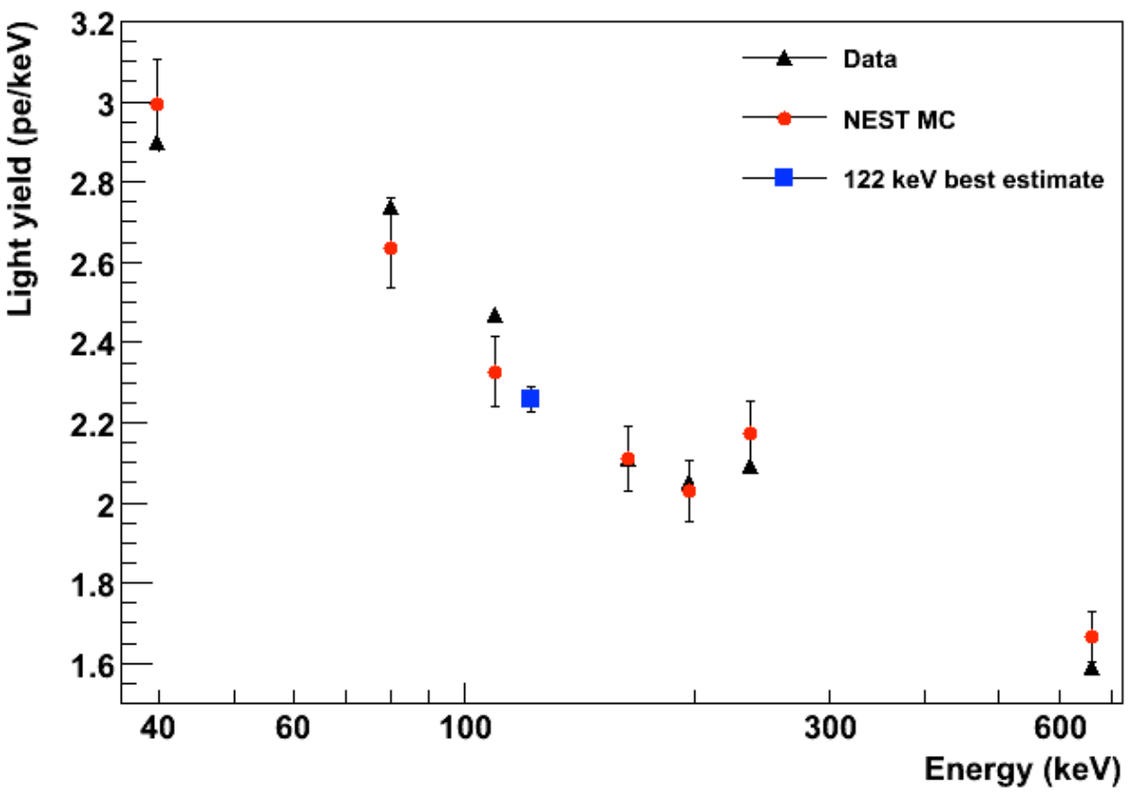


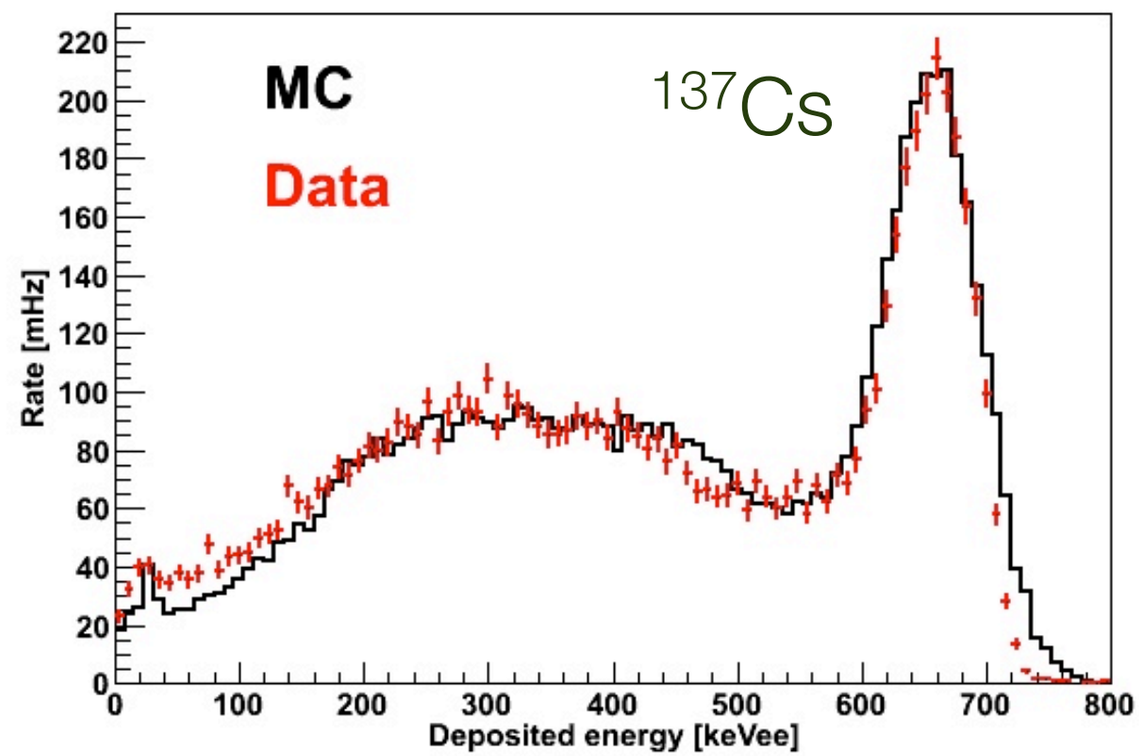
Figure: 10 kg inner detector region; before applying LXe veto cut

See also PRD 83, 082001 (2011) for a detailed background description

Calibration

- ^{137}Cs data to determine and monitor the charge & light yields in the TPC

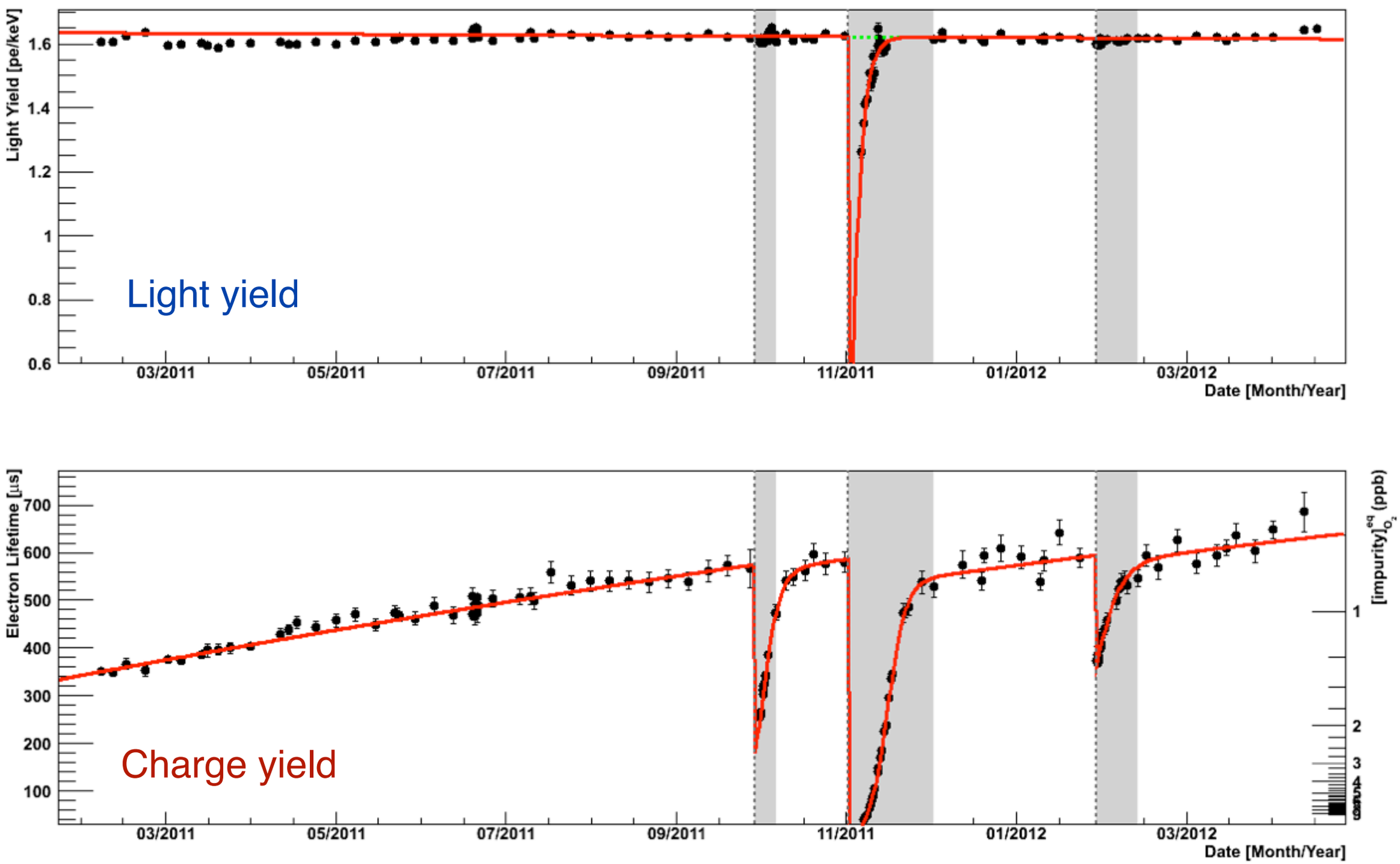




- Light yield at 122 keV is interpolated using NEST model and measurements at lower/higher energies with conservative 5% uncertainty

- For Run10 the LY_{122keV} = (2.28 ± 0.04) PE/keV)

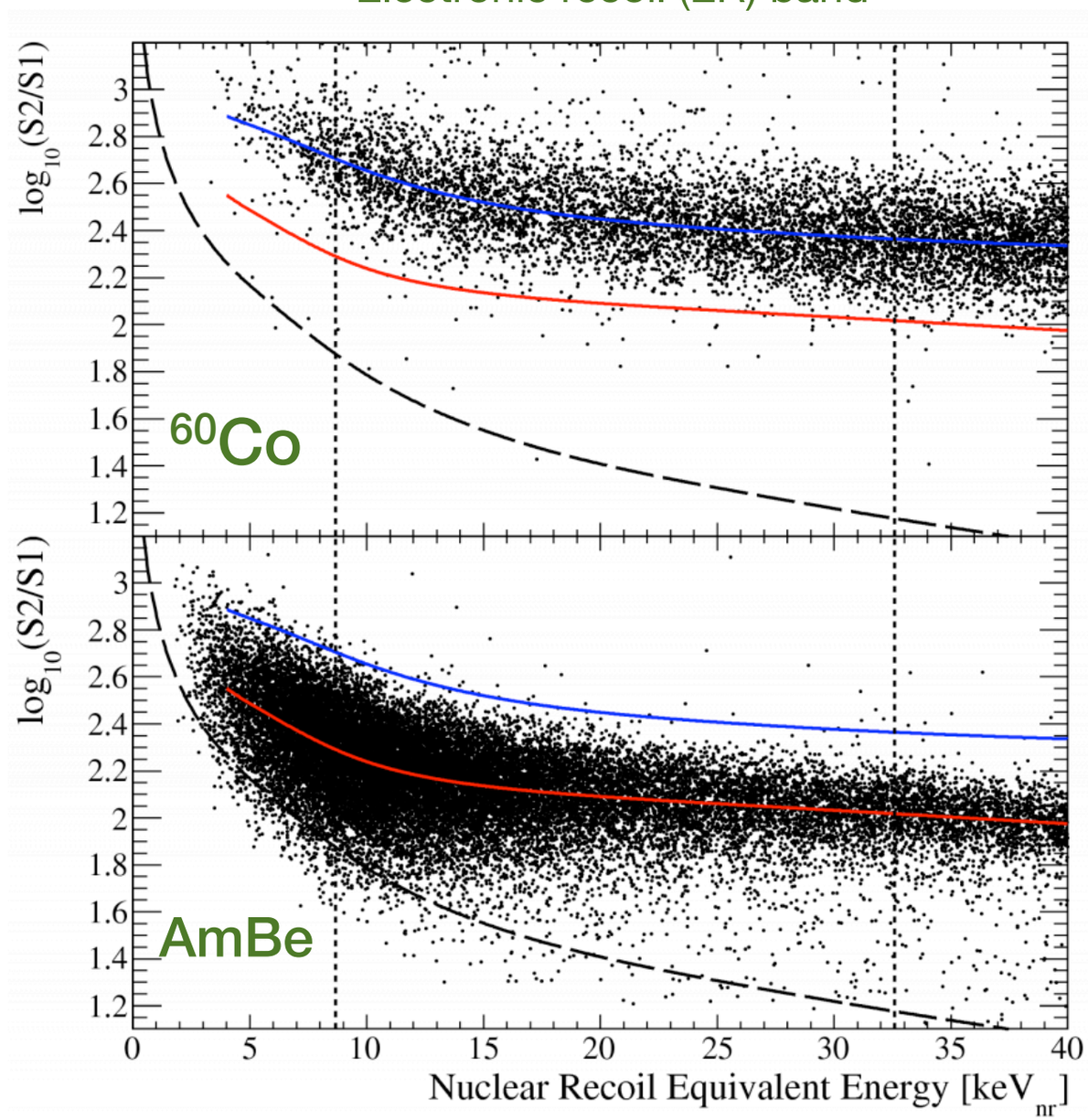
Calibration: light and charge yield versus time



Calibration of ER and NR bands

- The electronic recoil (ER) band is calibrated with high energy gammas from ^{60}Co and ^{232}Th sources
- This data is also used to determine the background in the signal region due to low-energy Compton scatters
- The nuclear recoils band (NR) is calibrated with an AmBe neutron source
- Single scatters from elastic neutron-xenon collisions are used to define the expected WIMP signal region

Electronic recoil (ER) band



Nuclear recoil (NR) band

Nuclear recoil energy scale

- Nuclear recoil energy scale is set using the S1 signal

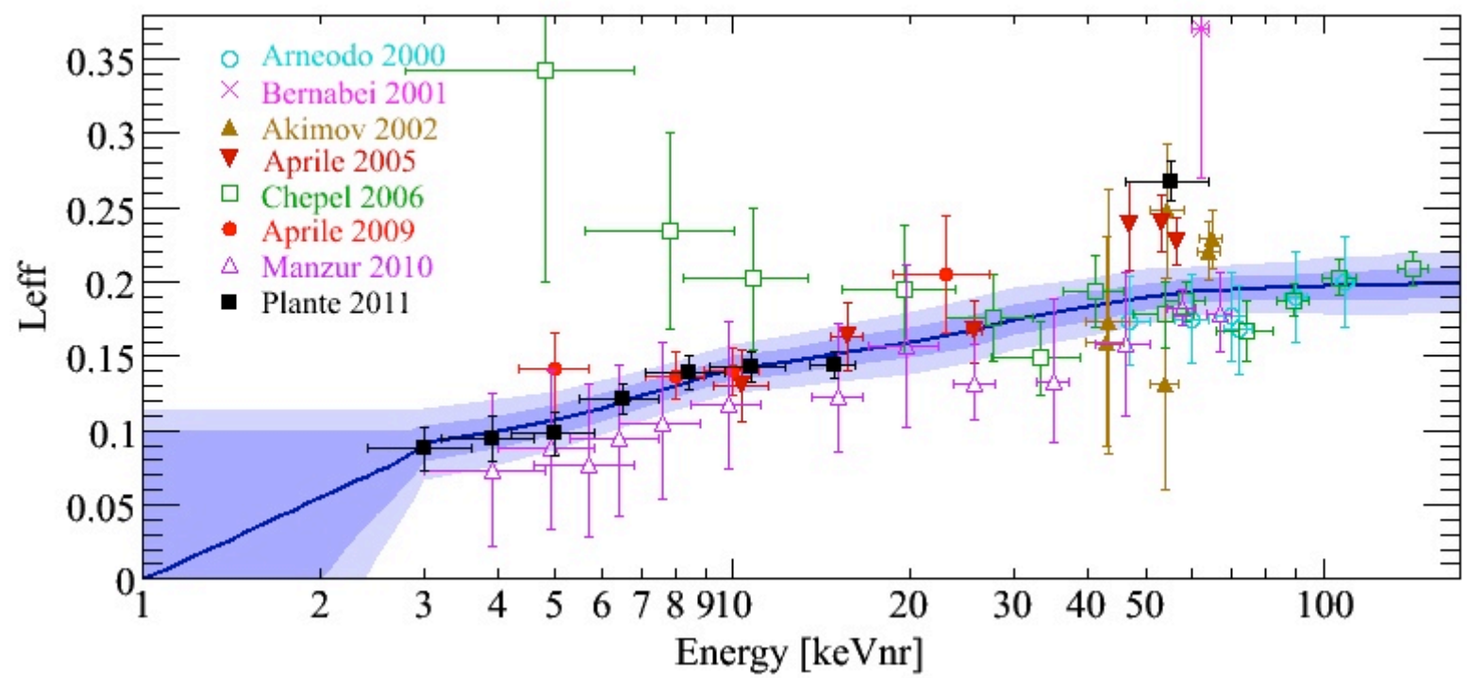
$$E_{\mathrm{nr}} = \frac{S1}{L_y} \frac{1}{\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}})} \frac{S_{\mathrm{ee}}}{S_{\mathrm{nr}}}$$

- L_y =2.3 pe/keV the light yield for electron recoils of 122 keVee

- S_{ee}=0.58 and S_{nr} = 0.95 represent quenching factors due to the drift fie

- Relative scintillation efficiency (measured in dedicated experiment) given as:

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

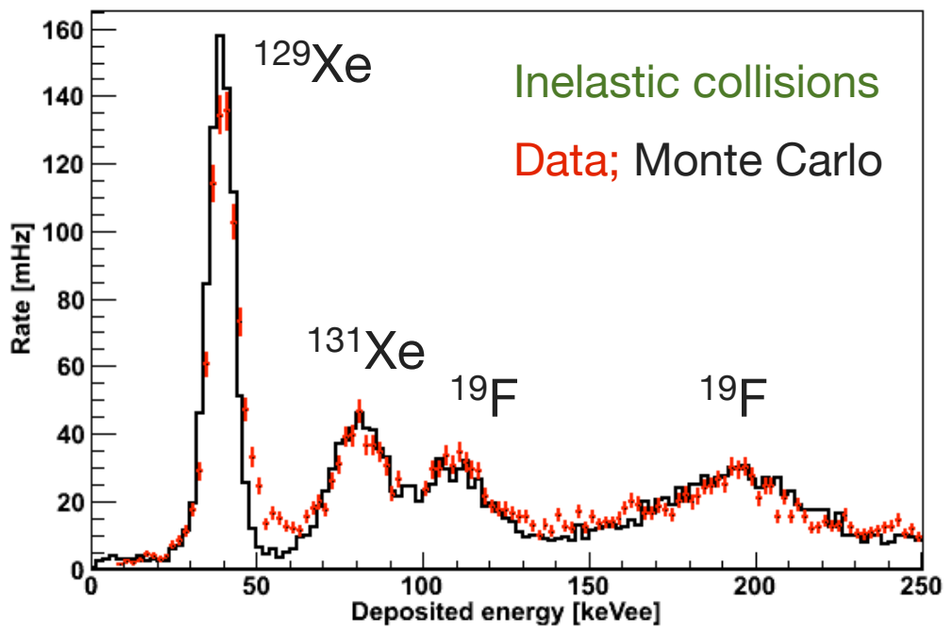


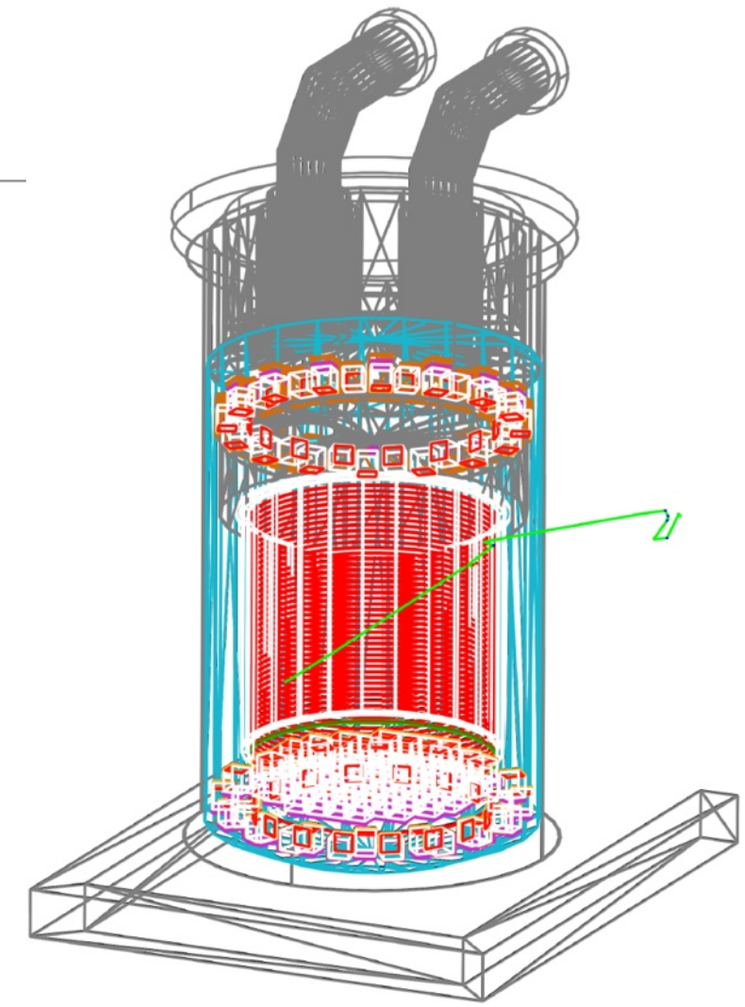
mean (solid) and 1-, 2-sigma uncertainties (blue bands)

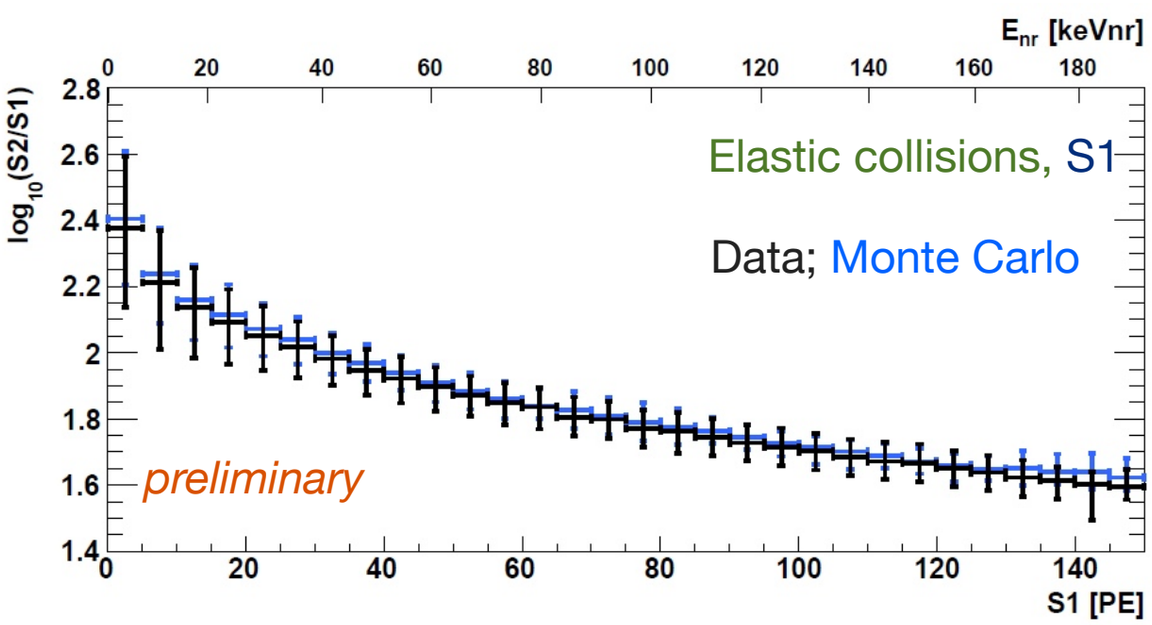
$$\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}}) = \frac{L_{y,er}(E_{\mathrm{nr}})}{L_{y,er}(E_{\mathrm{ee}} = 122\,\mathrm{keV})}$$

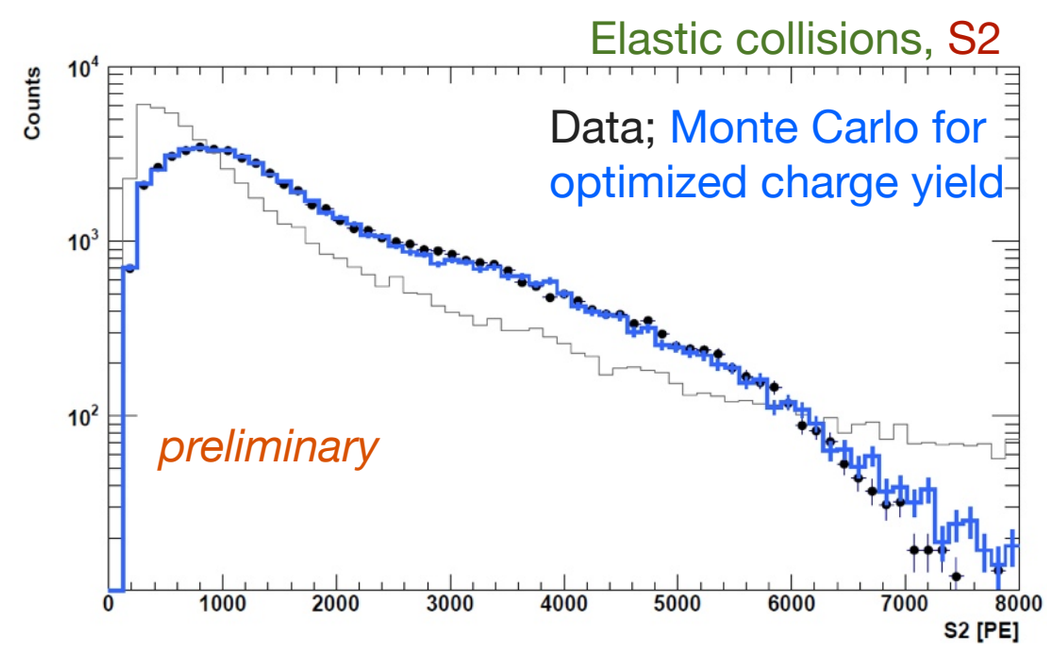
Nuclear recoils: data and MC

- Matching the AmBe data with MC simulations





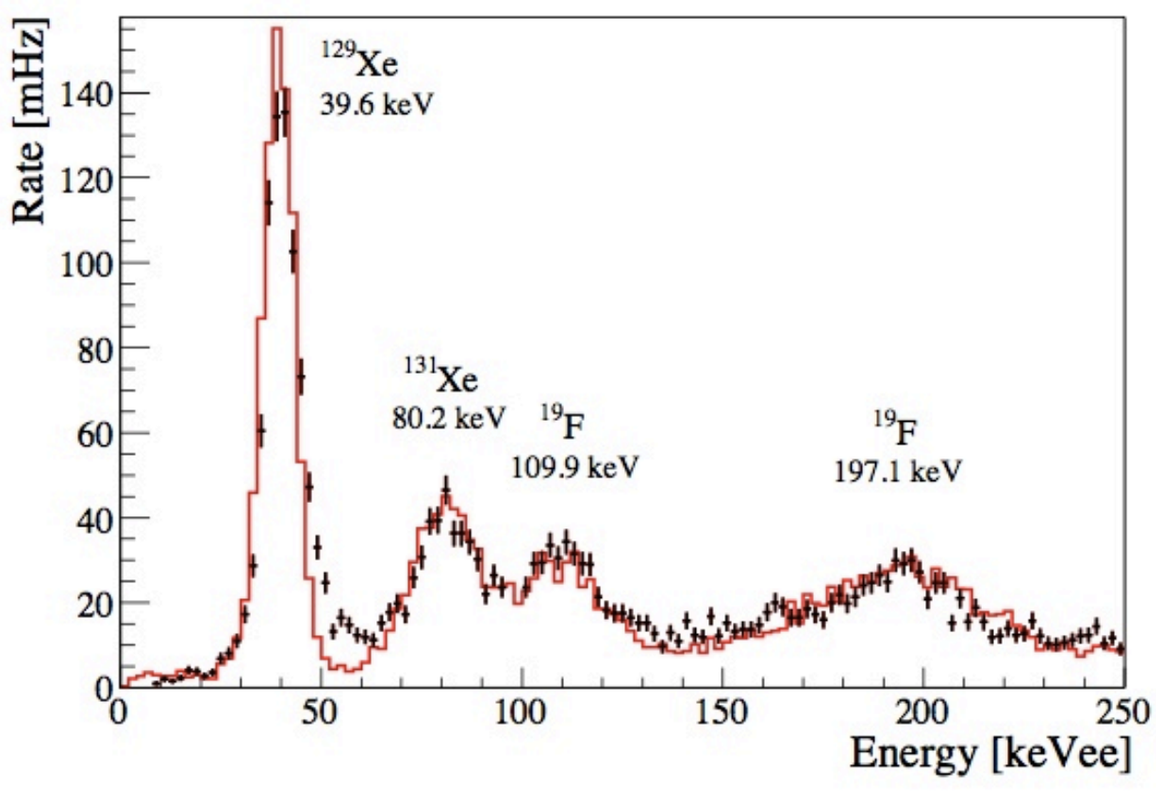


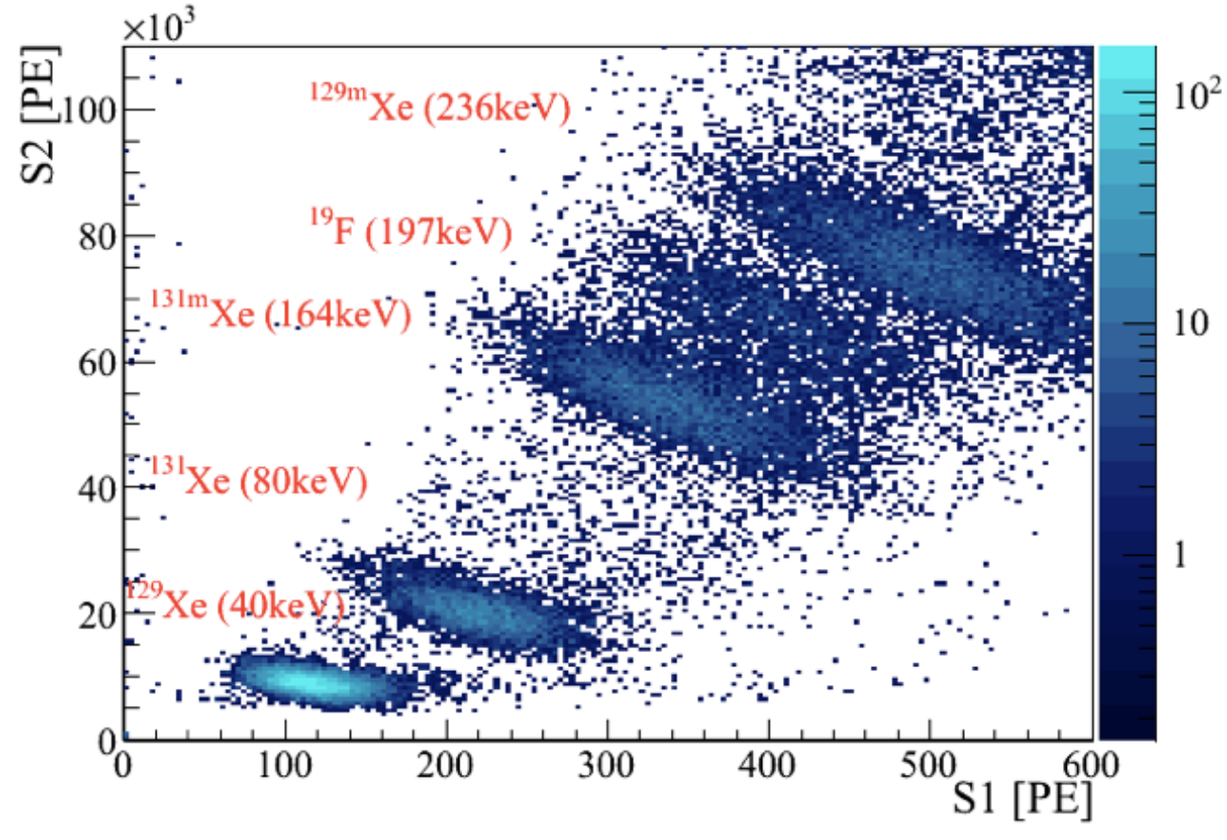


Manuscript in preparation: XENON collaboration

Gammas from neutron calibrations

- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}Xe + n \rightarrow {}^{129,131}Xe + n + \gamma$ (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): $^{19}F + n \rightarrow {}^{19}F + n + \gamma$ (110 keV, 197 keV)
- Also Xe activation lines: ^{129m}Xe (236 keV) and ^{131m}Xe (164 keV)

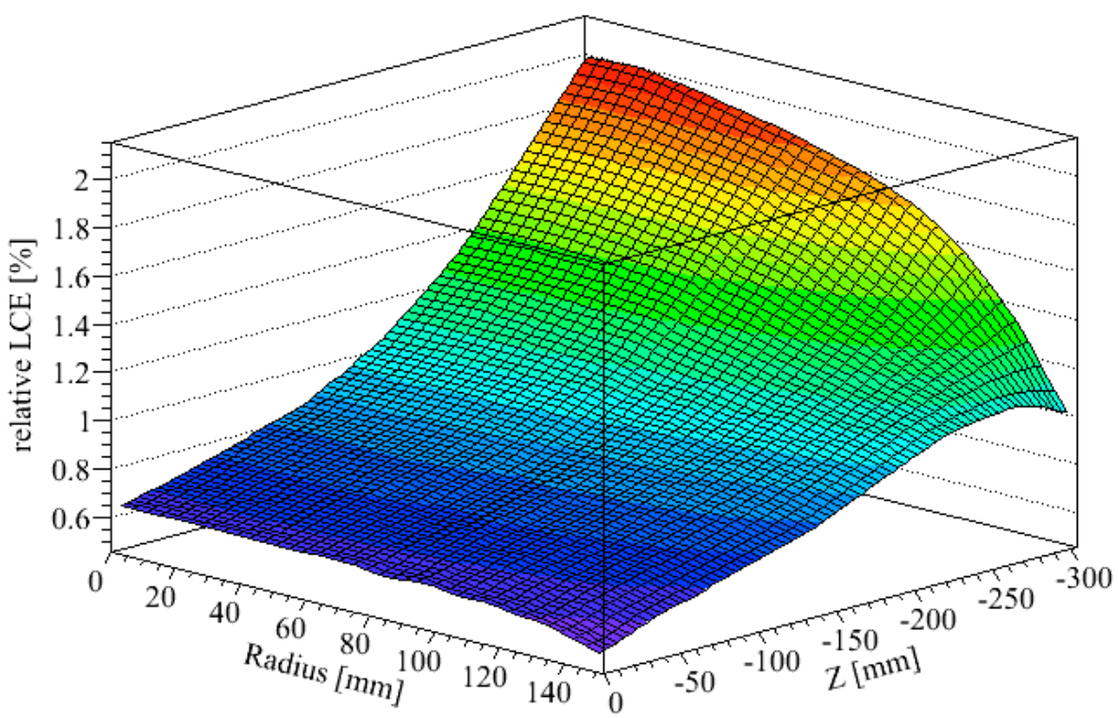




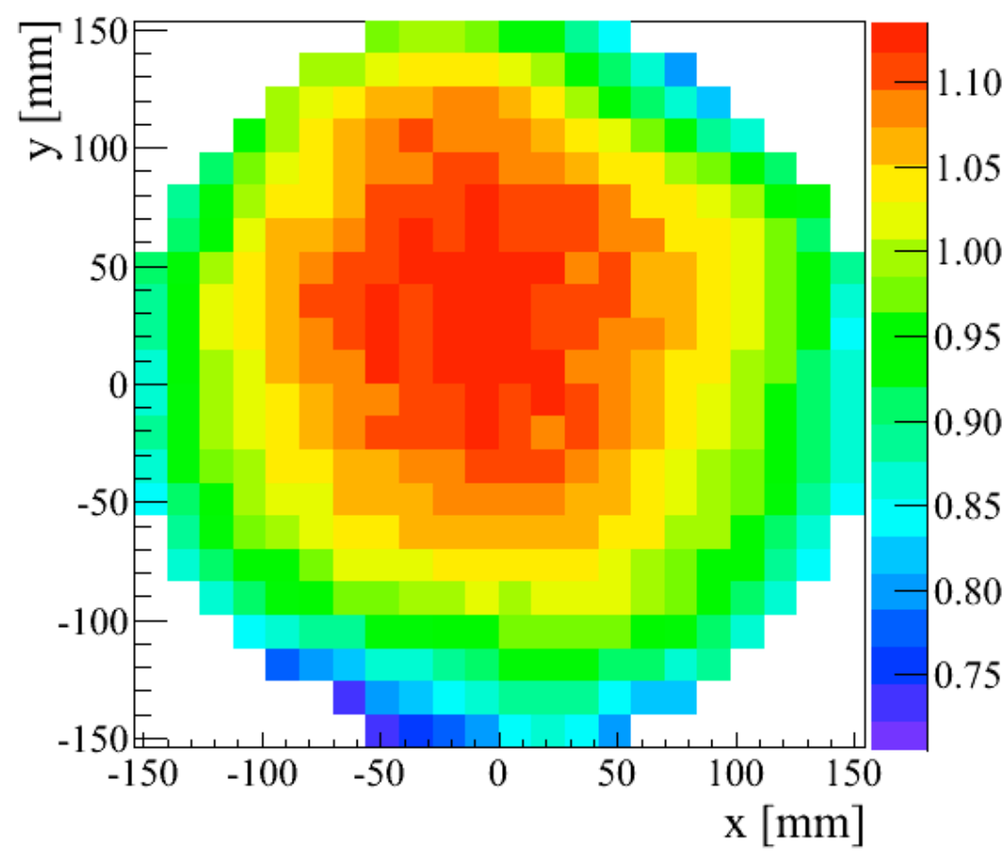
All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV

Position-dependent signal correction

- S1 light collection depends on the event position in the TPC: a 3D map of the light collection efficiency (LCE) is inferred from irradiation with ^{137}Cs (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated ^{131m}Xe (all agree within 3%)
- S2 response measured with the 40 keV gamma line
- Shown are relative changes compared to the mean



S1 signal

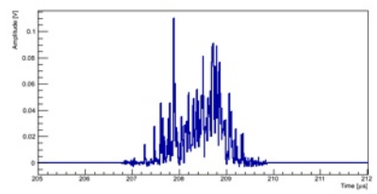


S2 signal

From raw data to results

Majority trigger, efficiency > 99% for S2>150 pe

Data acquisition: sample PMT traces @ 100 MS/s in windows around signals > 0.35 pe



PMT waveforms

Raw data processing, baseline and noise measurement; S1, S2 signal recognition; signal integration; position reconstruction; signal correction (gain, spatial)

root trees

Event selection, remove "bad" events:
- noise
- S1/S2 not matching

Select single interaction events

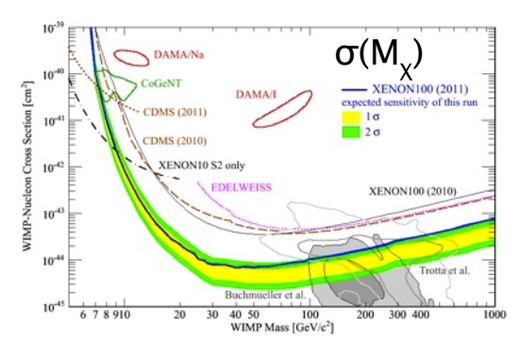
Acceptances!

reduced data

Physics analysis input: astrophysics, nuclear physics, DM data sidebands, NR and ER calibration => response, background

profile likelihood

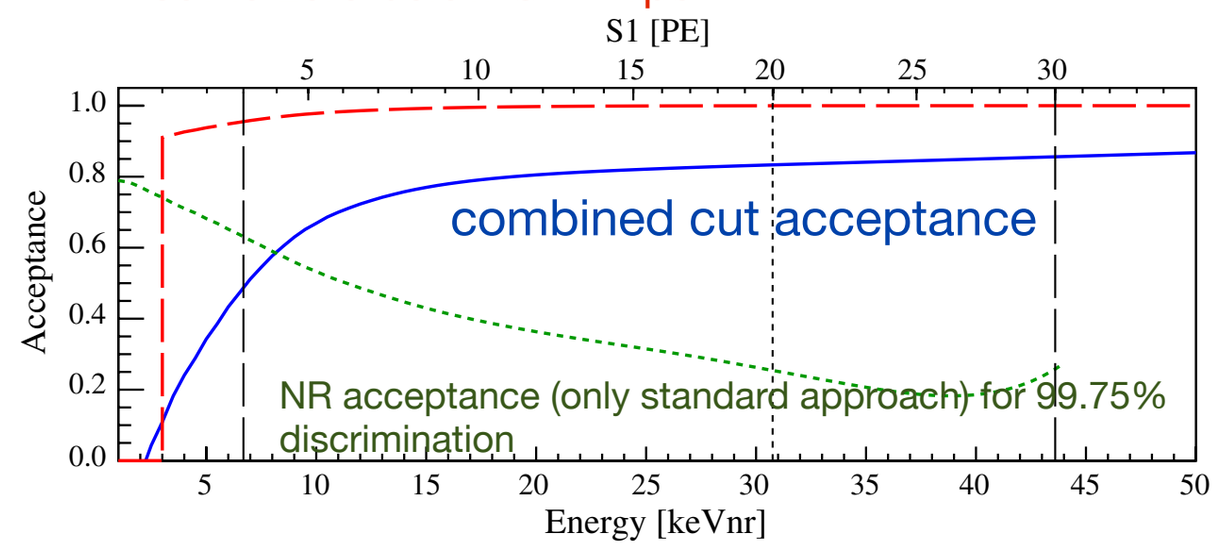
results

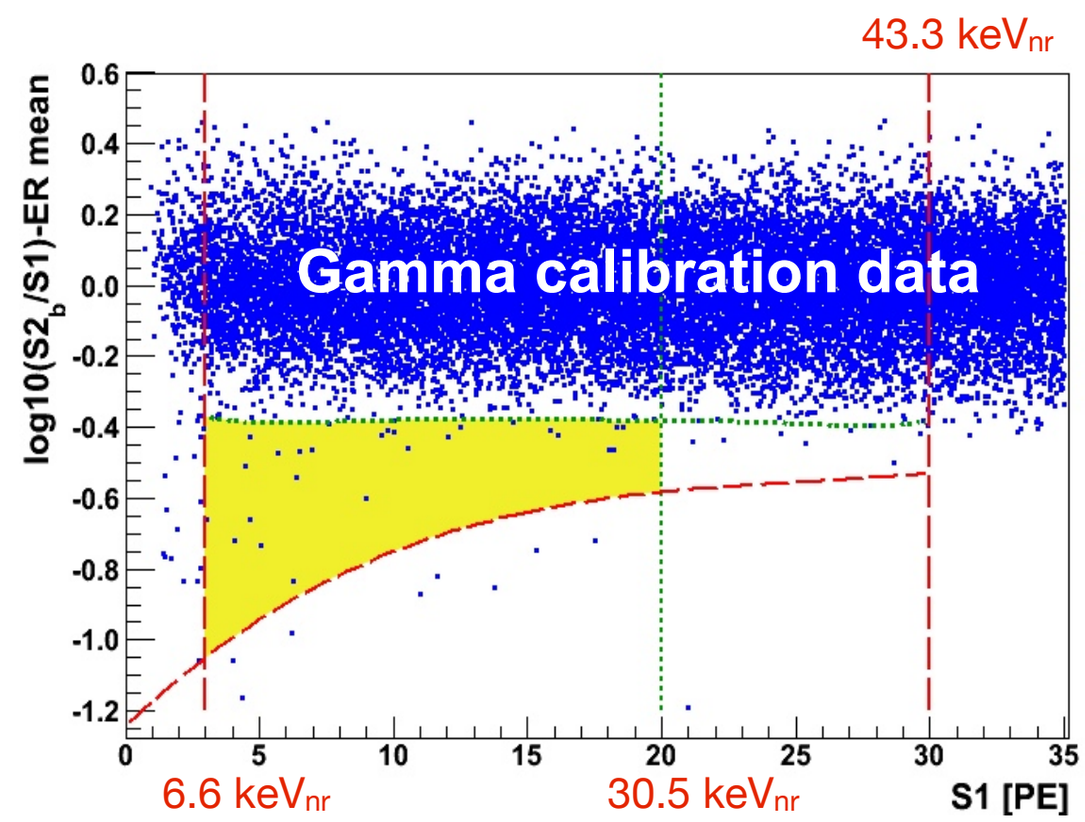


Nuclear recoil acceptance

- Data quality cuts acceptance estimated from AmBe and ^{60}Co calibration data, MC simulations and ERs outside the WIMP search energy range
- A priori decision to use profile likelihood (PL) approach and test both background only and signal + background hypotheses
- The PL approach does not use an *"S2/S1-based rejection cut"*
- A cross check based on the standard approach, where a *"benchmark WIMP region"* is defined:
  - 3 - 20 photoelectrons in S1
  - 99.75% ER rejection line
  - 150 pe S2 threshold
  - 97% NR band quantile

S2 threshold (> 150 pe) acceptance:
set to zero below S1 = 1pe





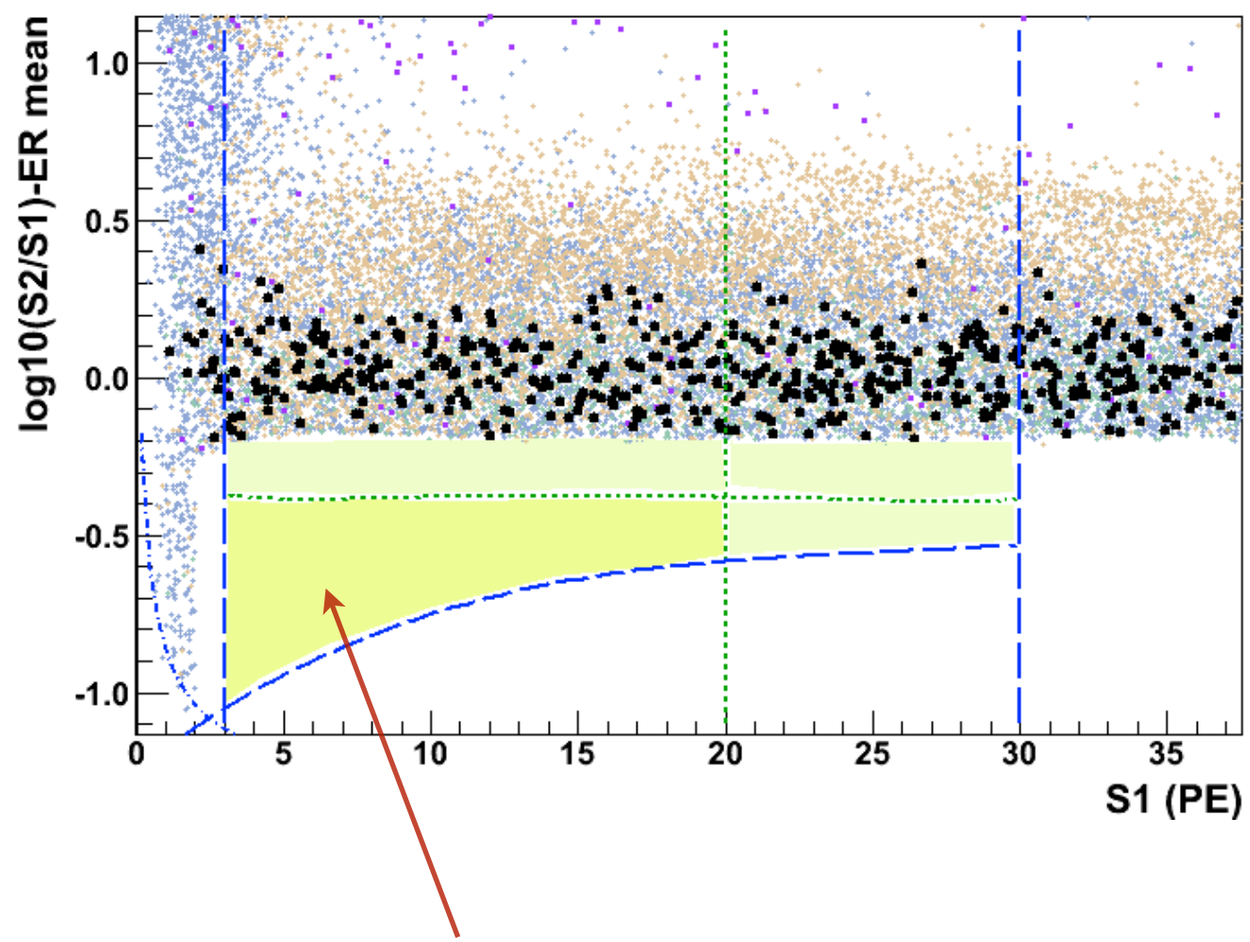
Background prediction for Run10

- Expected background in: 34 kg inner region, 224.6 live days, 99.75% rejection of electronic recoils

- Electronic recoil background:
  - 0.79±0.16 events
  - from ER calibration data, scaled to non-blinded ER band background data

- Nuclear recoil background
  - 0.17+0.12-0.07 events
  - from cosmogenic and radiogenic neutrons

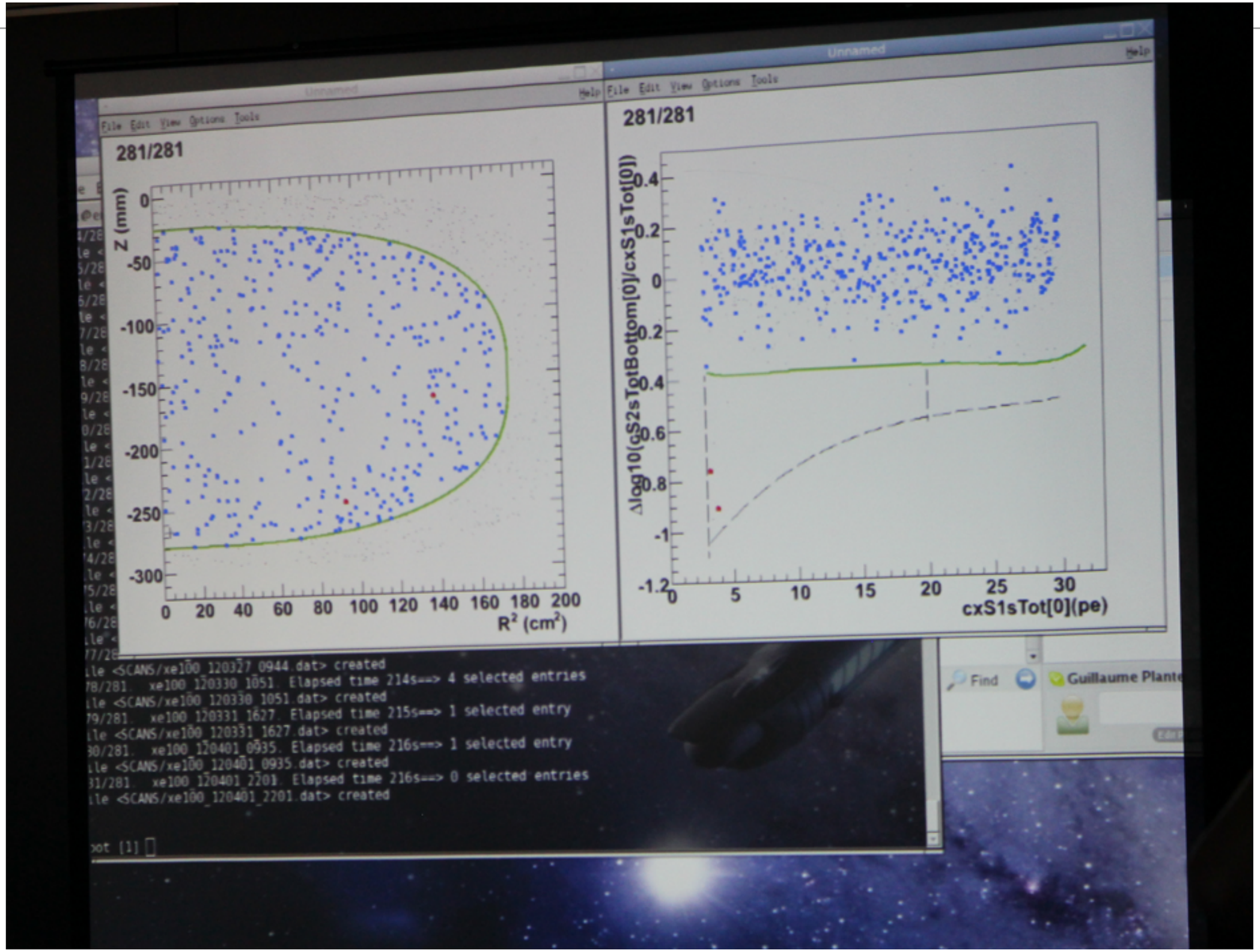
- Total: 1.0±0.2 events



- *benchmark WIMP region (not used in PL analysis)*

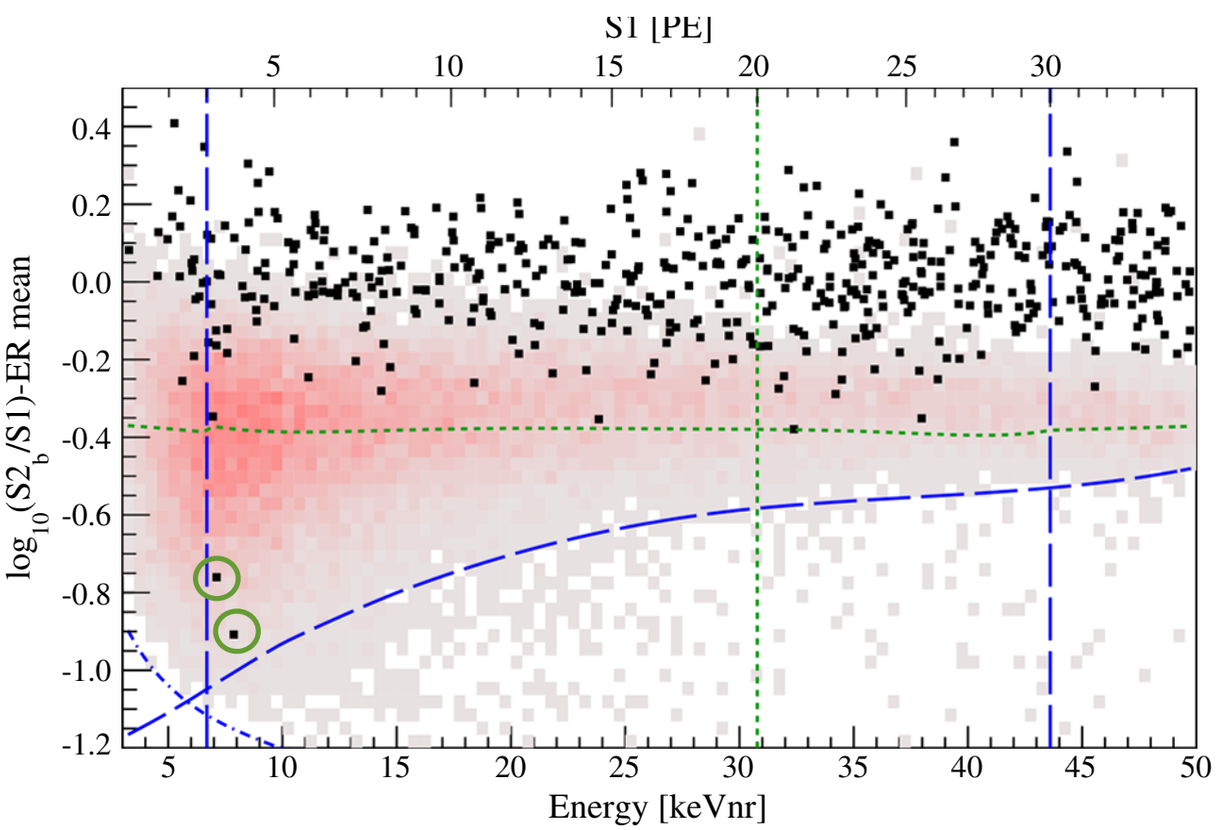
Before/after unblinding

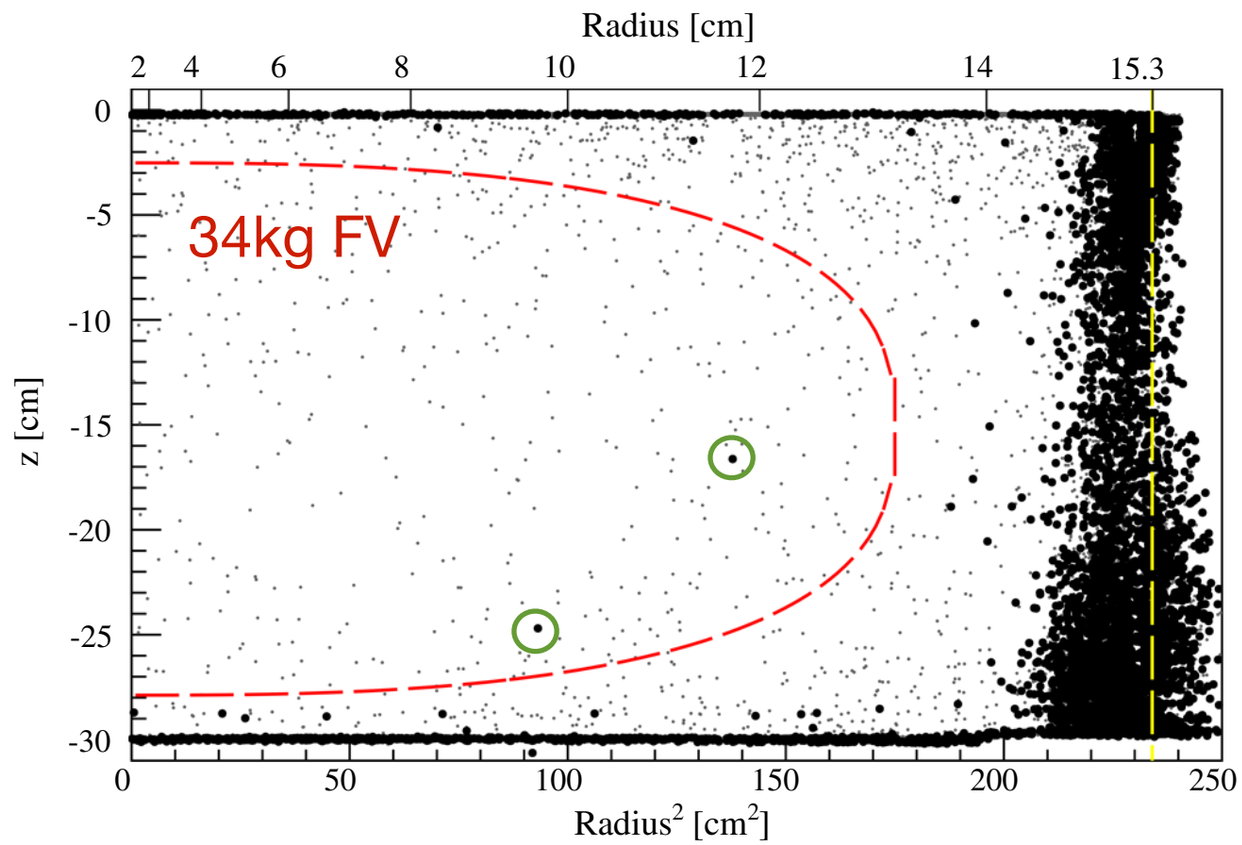
After unblinding



After unblinding

- Two events observed in signal region (there is a 26.4 % chance for upward fluctuation): at 7.1 keV_{nr} (3.3 pe) and at 7.8 keV_{nr} (3.8 pe)
- Both events at low S2/S1 with respect to NR calibration data
- Visual inspection: waveforms of high quality

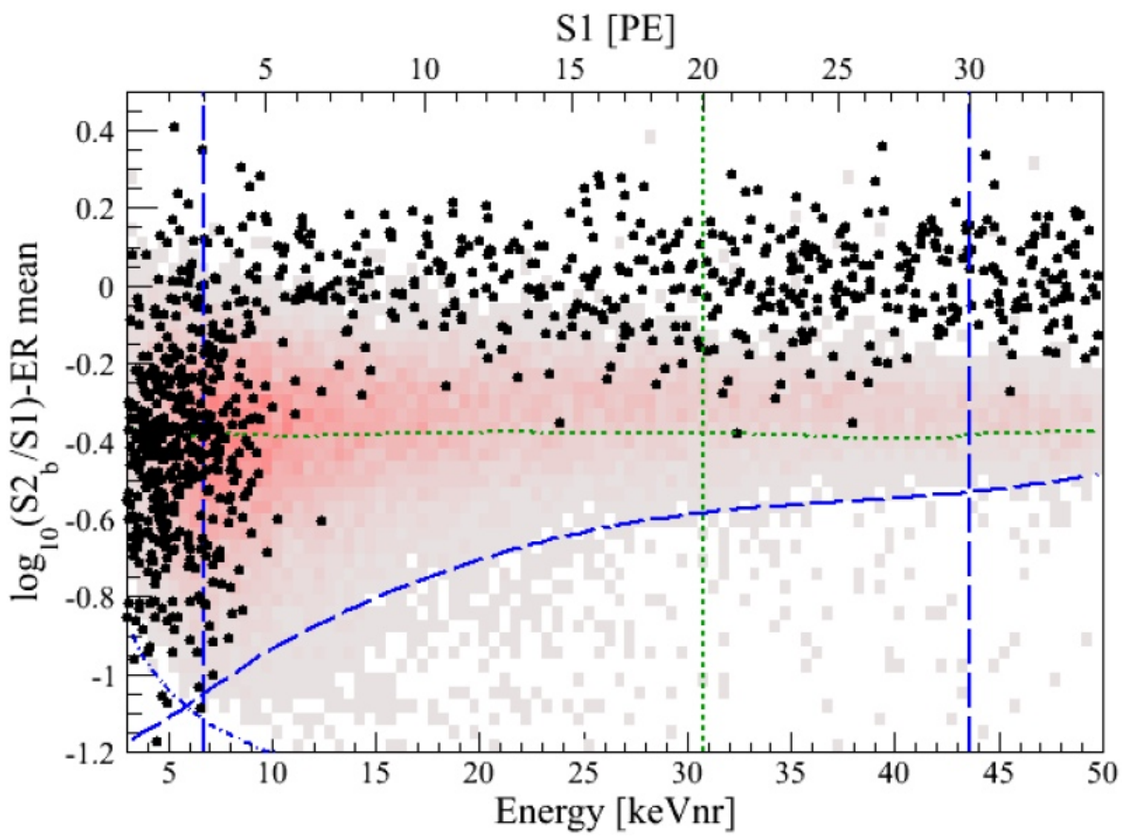




What if?

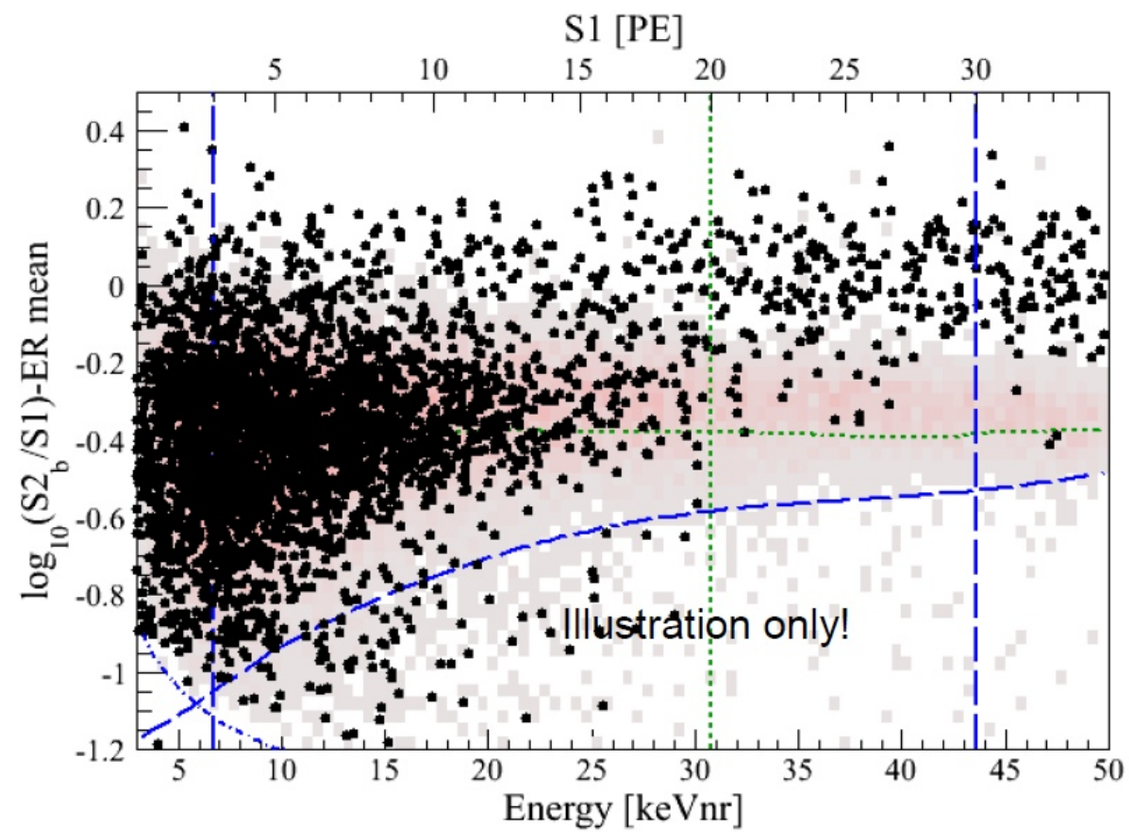
- How would signal claims of other experiments look like in XENON100's Run10 data?

Light WIMP: m_W = 8 GeV



WIMP-nucleon cross section : 3 x 10^{-41} cm^2

CRESST-like WIMP; m_W = 25 GeV



WIMP-nucleon cross section : 1.6 x 10^{-40} cm^2

Run10 SI Results

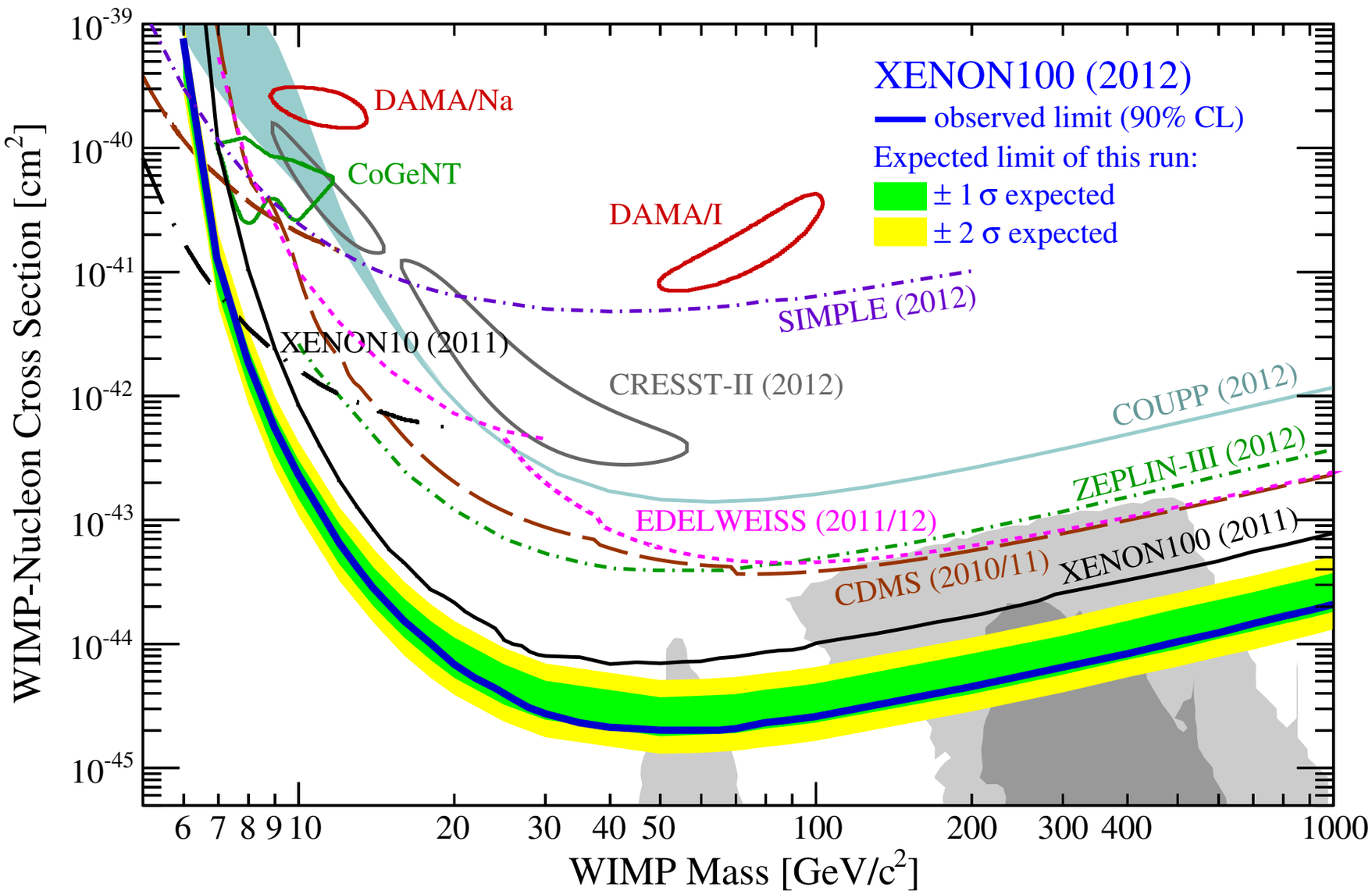
PRL **109,** 181301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Dark Matter Results from 225 Live Days of XENON100 Data

E. Aprile,[1] M. Alfonsi,[2] K. Arisaka,[3] F. Arneodo,[4] C. Balan,[5] L. Baudis,[6] B. Bauermeister,[7] A. Behrens,[6] P. Beltrame,[3] K. Bokeloh,[8] E. Brown,[8] G. Bruno,[4] R. Budnik,[1] J. M. R. Cardoso,[5] W.-T. Chen,[9] B. Choi,[1] D. Cline,[3] A. P. Colijn,[2] H. Contreras,[1] J. P. Cussonneau,[9] M. P. Decowski,[2] E. Duchovni,[10] S. Fattori,[7] A. D. Ferella,[6] W. Fulgione,[11] F. Gao,[12] M. Garbini,[13] C. Ghag,[3] K.-L. Giboni,[1] L. W. Goetzke,[1] C. Grignon,[7] E. Gross,[10] W. Hampel,[14] F. Kaether,[14] A. Kish,[6] J. Lamblin,[9] H. Landsman,[10] R. F. Lang,[15,1] M. Le Calloch,[9] C. Levy,[8] K. E. Lim,[1] Q. Lin,[12] S. Lindemann,[14] M. Lindner,[14] J. A. M. Lopes,[5] K. Lung,[3] T. Marrodán Undagoitia,[6] F. V. Massoli,[13] A. J. Melgarejo Fernandez,[1,*] Y. Meng,[3] A. Molinario,[11] E. Nativ,[10] K. Ni,[12] U. Oberlack,[7,16] S. E. A. Orrigo,[5] E. Pantic,[3] R. Persiani,[13] G. Plante,[1] N. Priel,[10] A. Rizzo,[1] S. Rosendahl,[8] J. M. F. dos Santos,[5] G. Sartorelli,[13] J. Schreiner,[14] M. Schumann,[6,†] L. Scotto Lavina,[9] P. R. Scovell,[3] M. Selvi,[13] P. Shagin,[16] H. Simgen,[14] A. Teymourian,[3] D. Thers,[9] O. Vitells,[10] H. Wang,[3] M. Weber,[14] and C. Weinheimer[8]

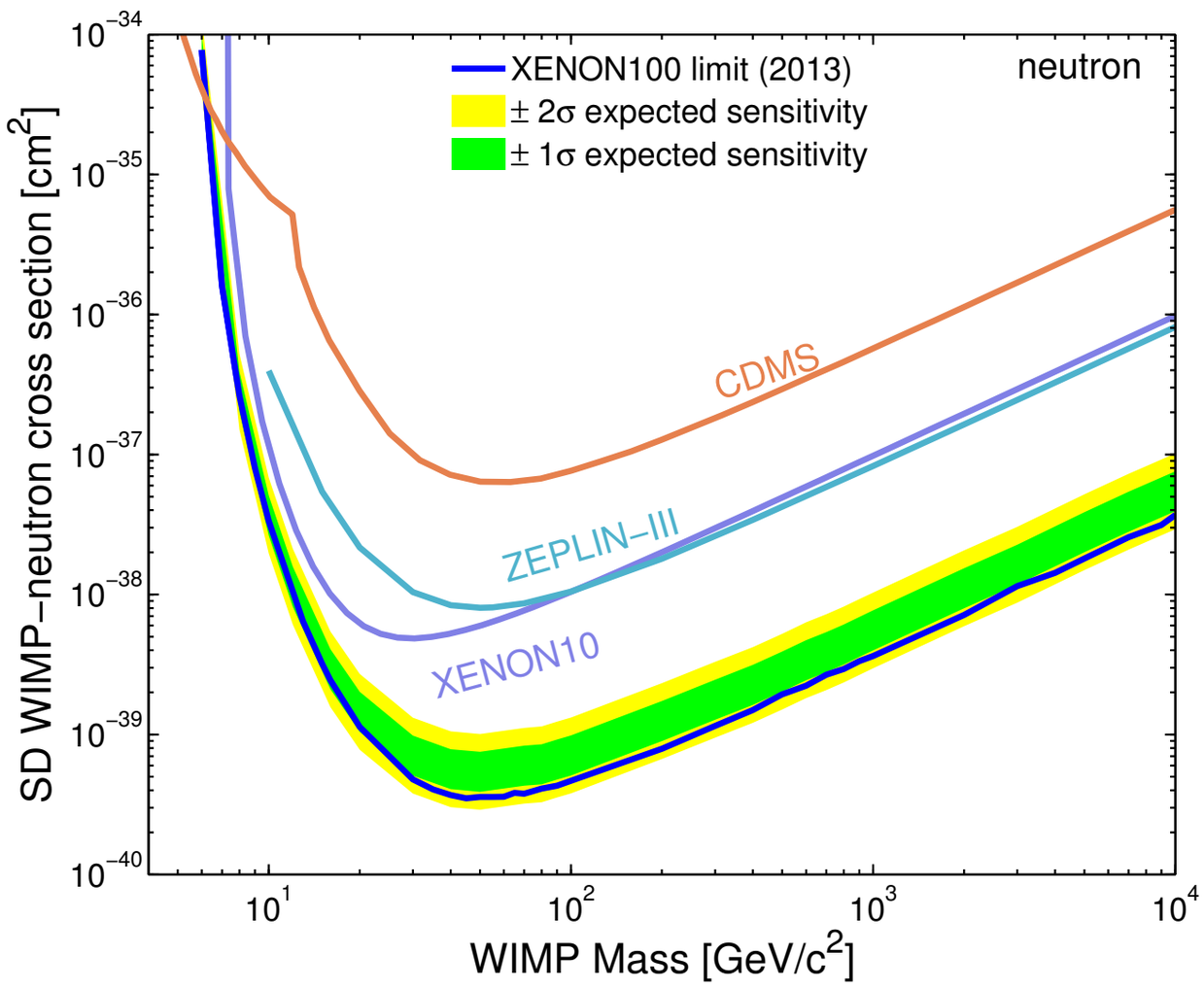
(XENON100 Collaboration)

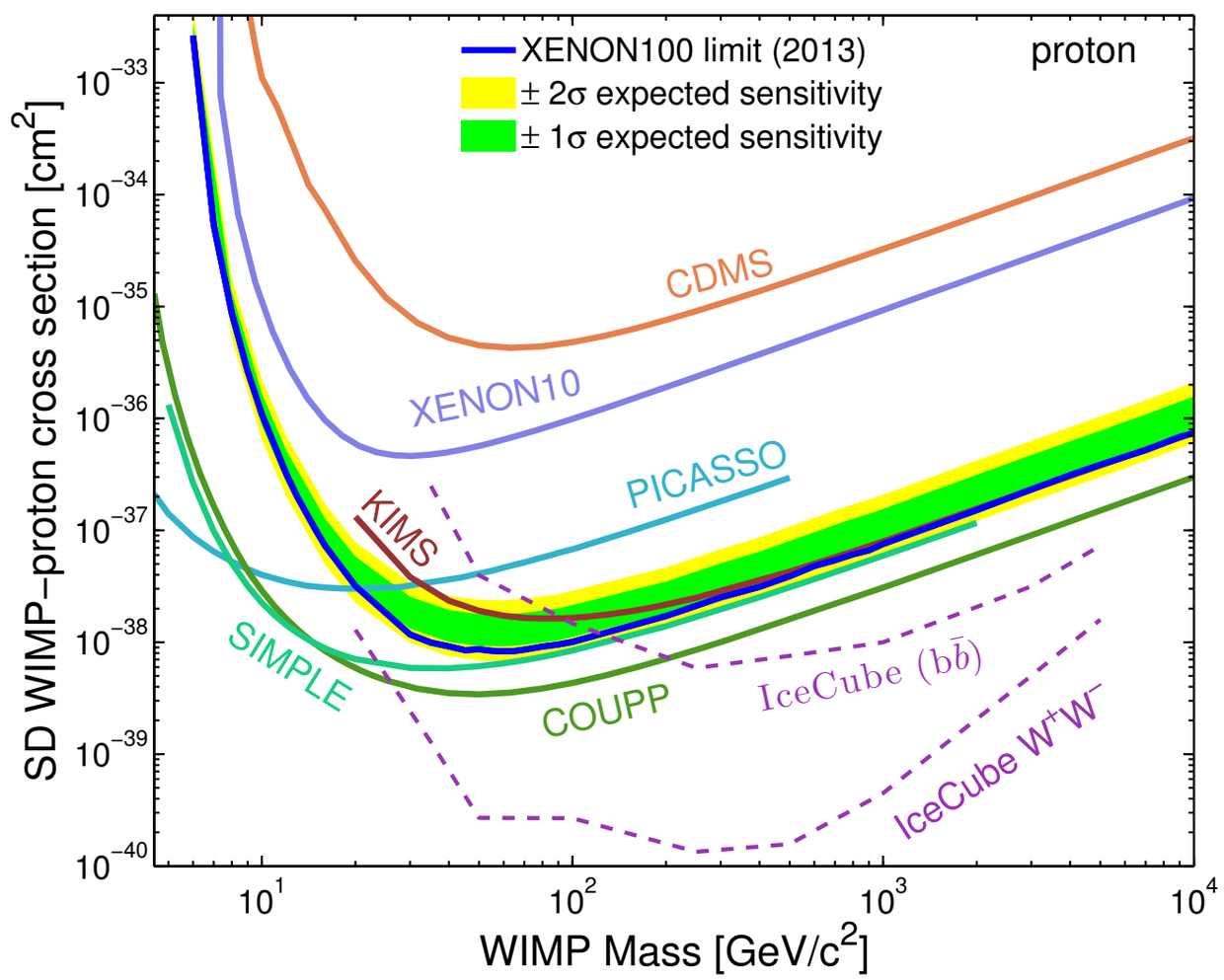
- No evidence for WIMPs
- Upper limit on SI WIMP-nucleon cross section is 2×10^{-45} cm^2 at M_W = 55 GeV



Run10 SD results

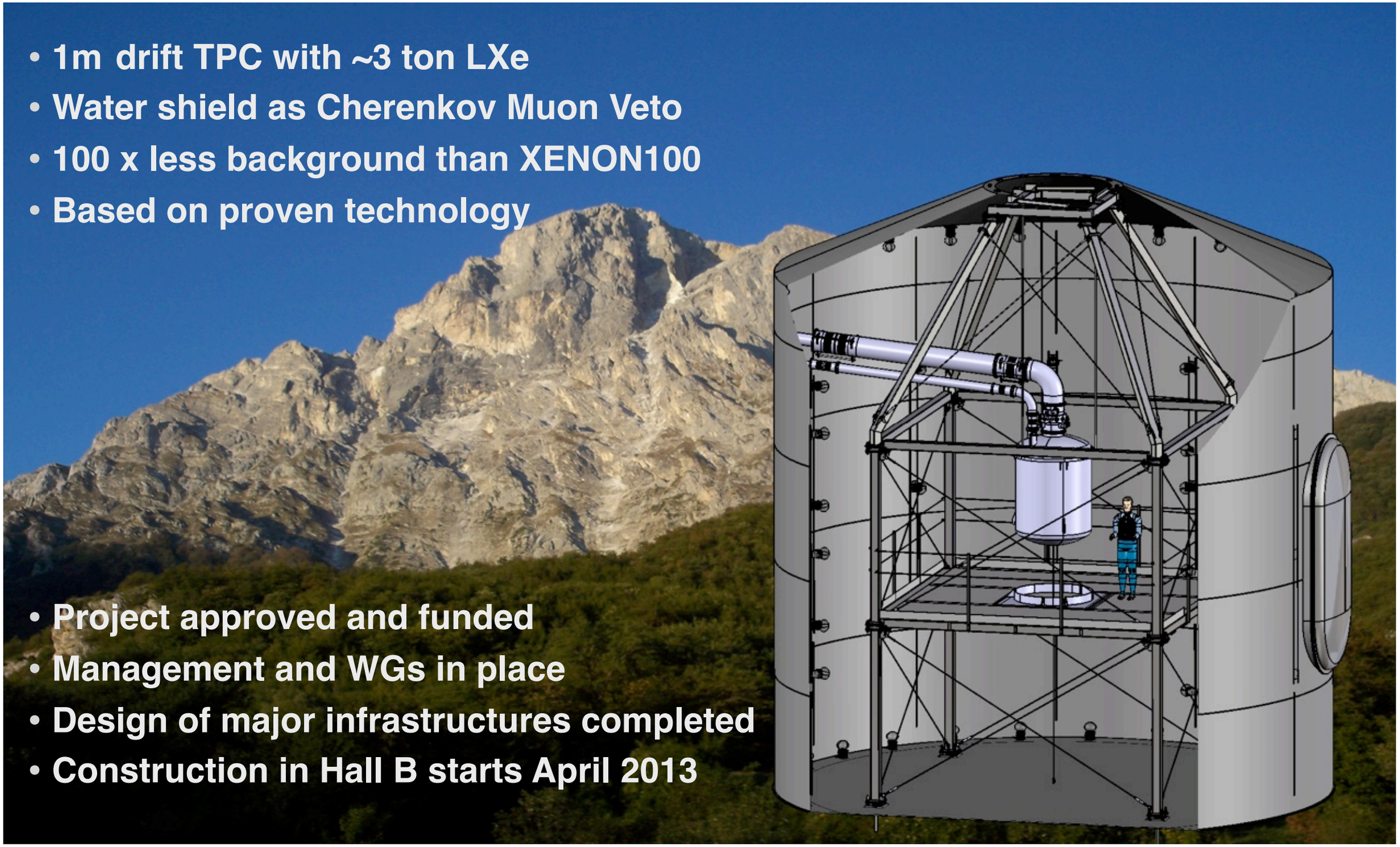
- ^{129}Xe (spin-1/2) and ^{131}Xe (spin-3/2), two isotopes with J ≠ 0 and abundance of 26.2% and 21.8% in XENON100



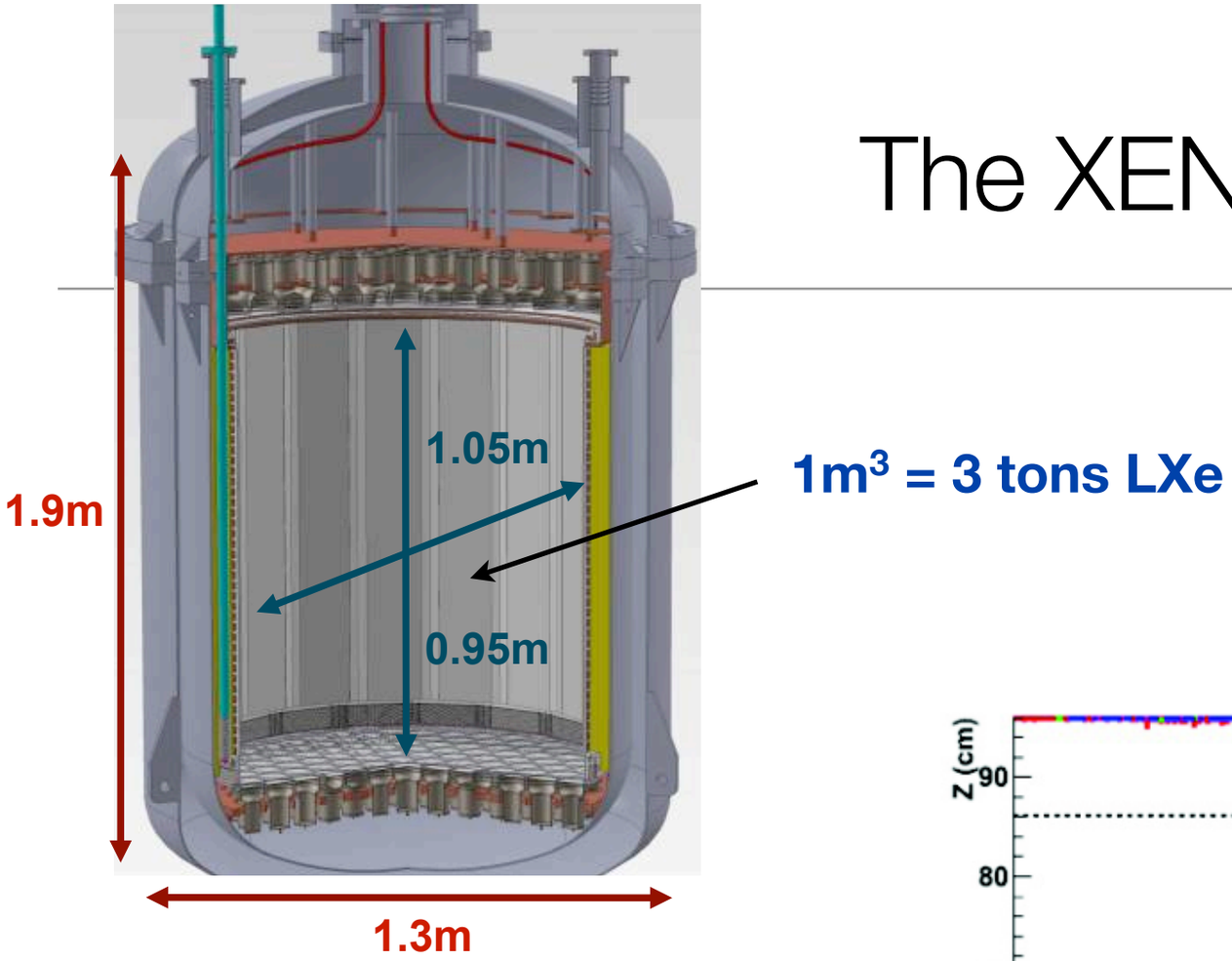


arXiv:1301.6620v2 [astro-ph.CO]

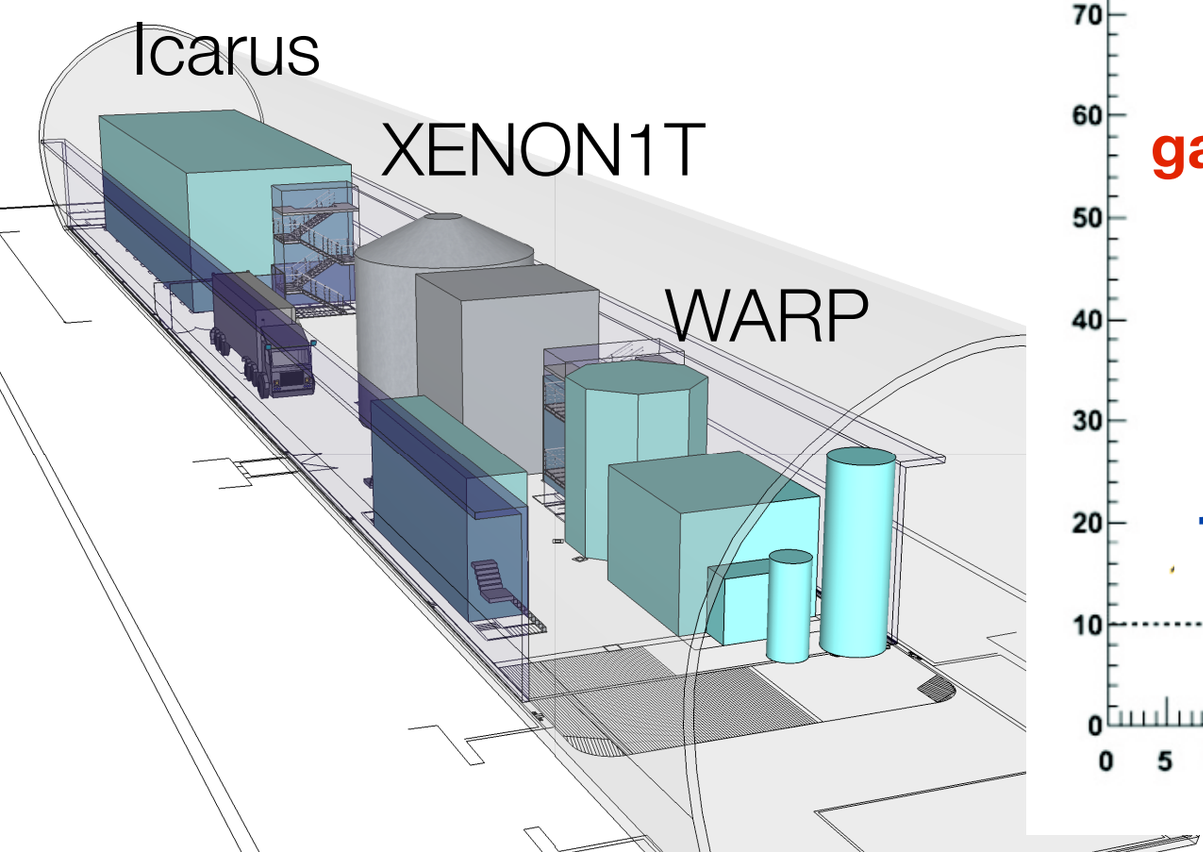
The near future: XENON1T at Gran Sasso

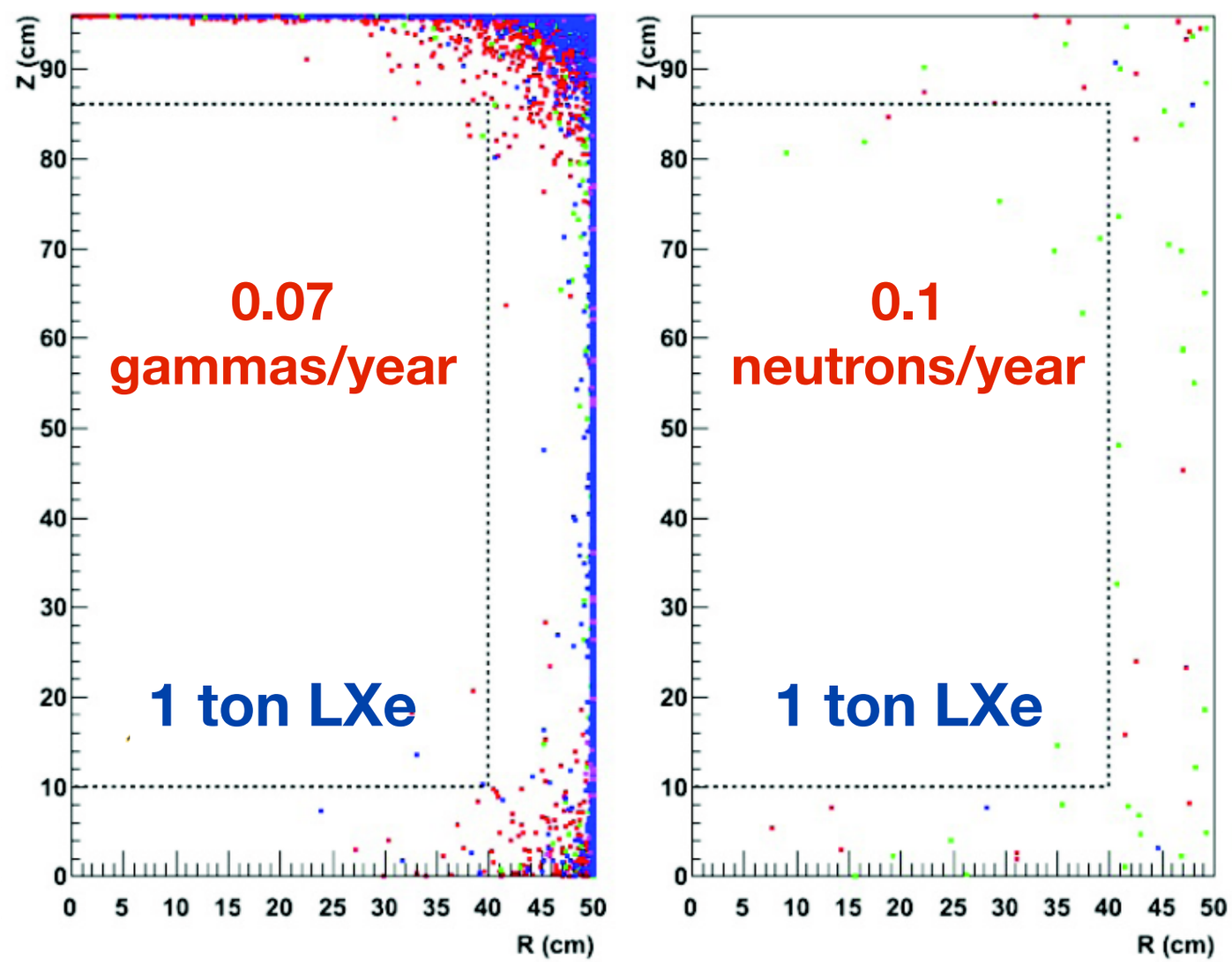


The XENON1T detector at LNGS



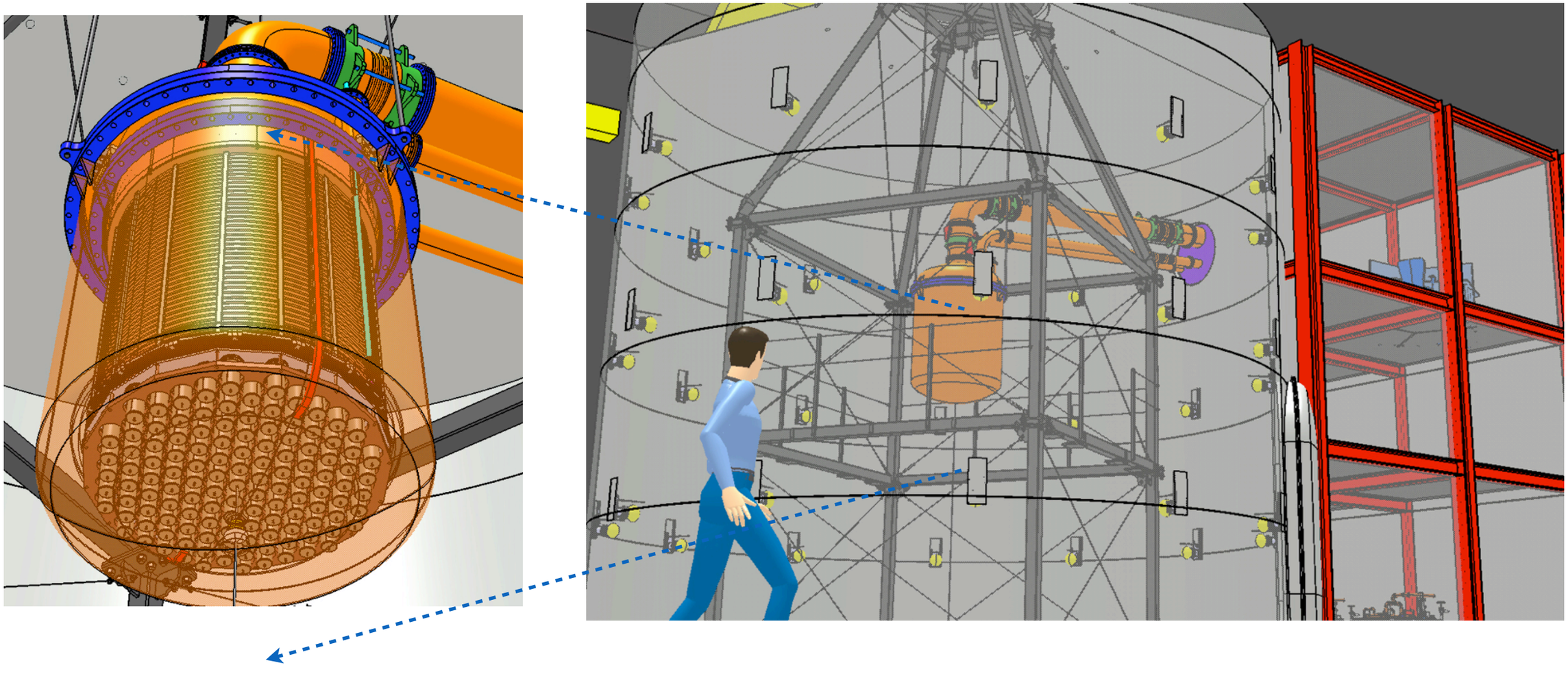
Dual phase time projection chamber
~ 3 ton liquid xenon; 1 ton fiducial mass
100 x lower background than XENON100





XENON1T schedule

- Commissioning and start of physics run in 2015
- Goal: ~2×10^{-47} cm^2 SI cross section after 2 years of data



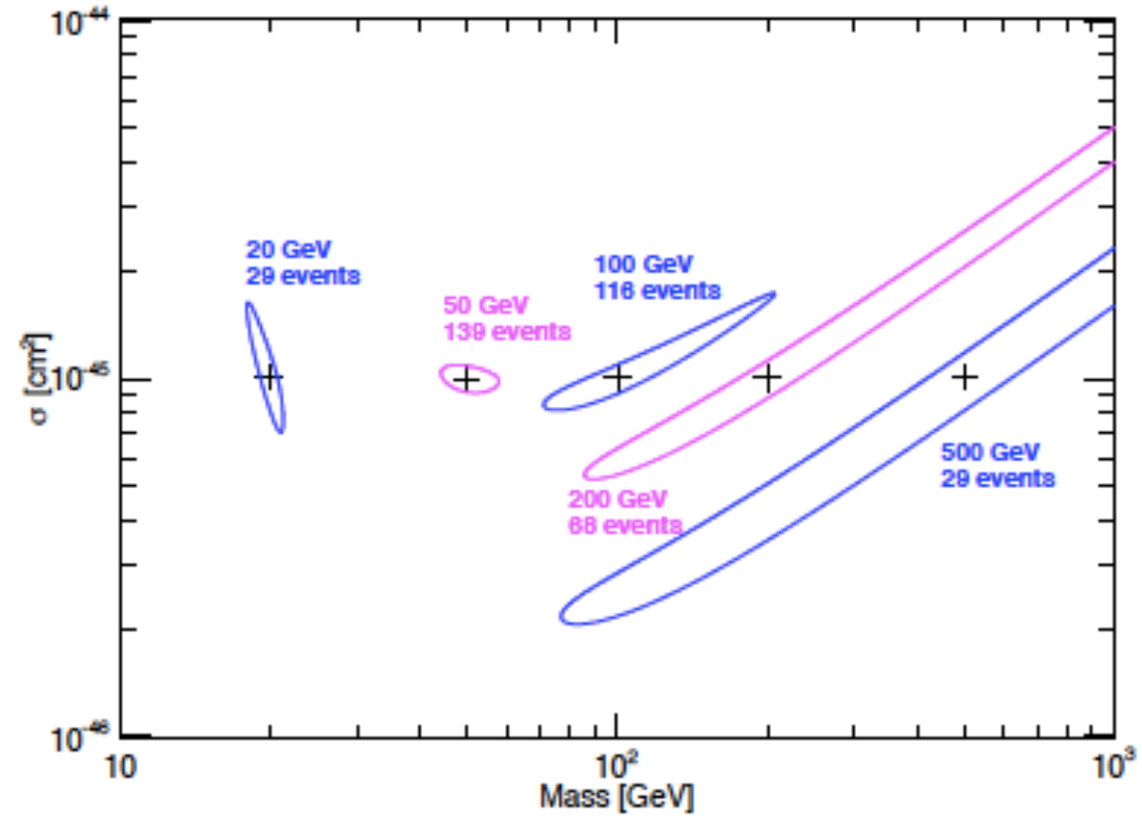
XENON1T: 3 tons LXe

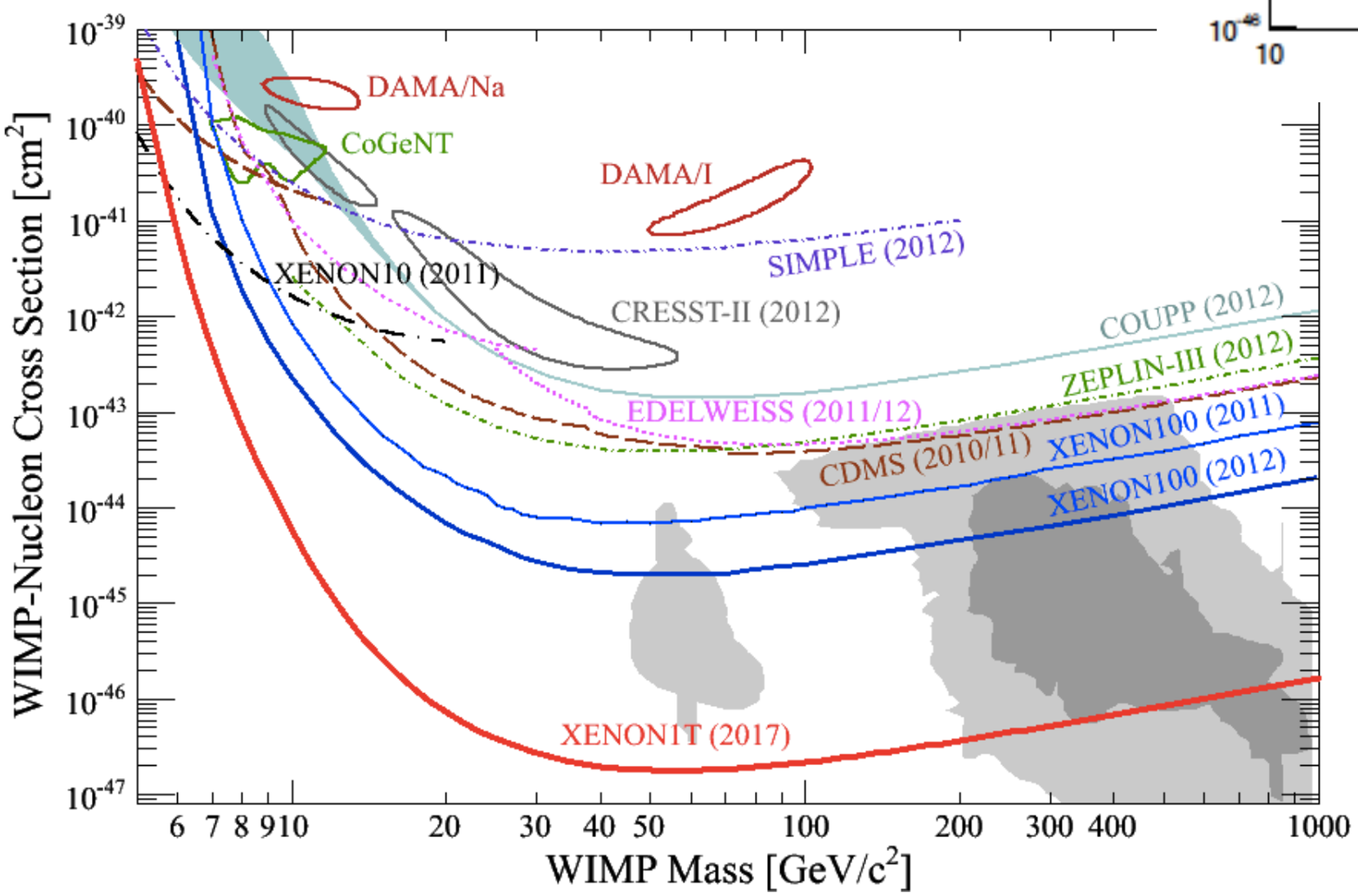
In a ~10 m x 10 m water Cherenkov shield

XENON1T goal

A statistically significant WIMP signal after 2 ton-years of data:

~100 events if cross section at 10^{-45} cm^2





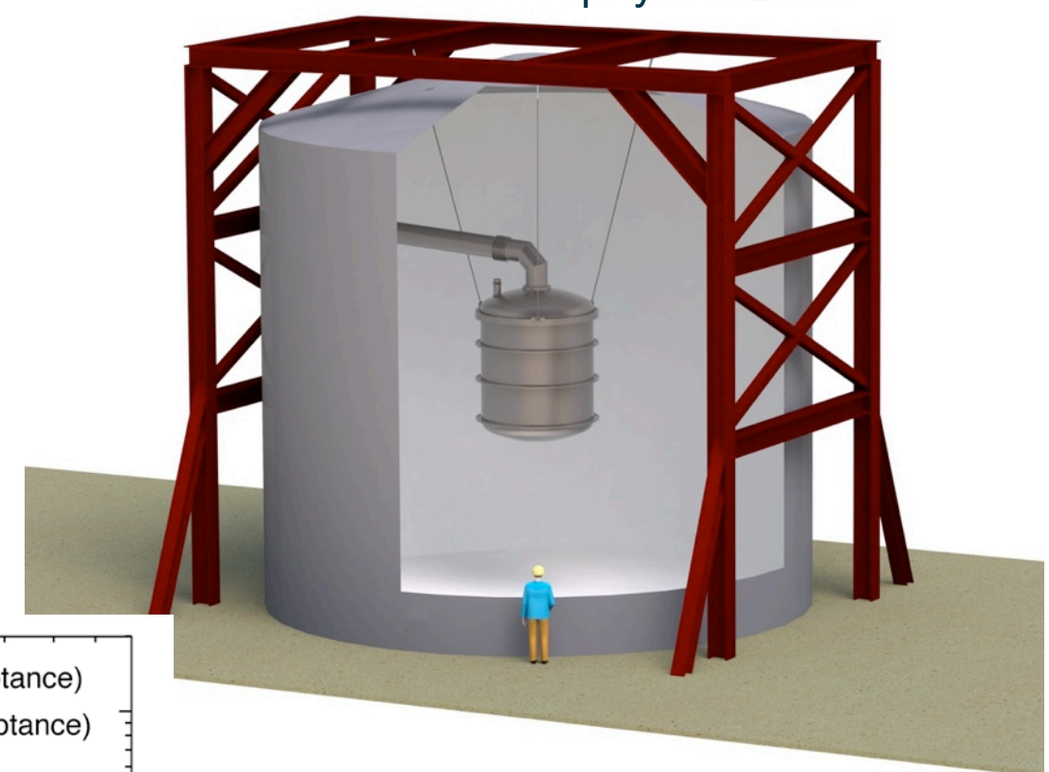
2×10^{-47} cm^2 for 50 GeV WIMP in 2 ton-year

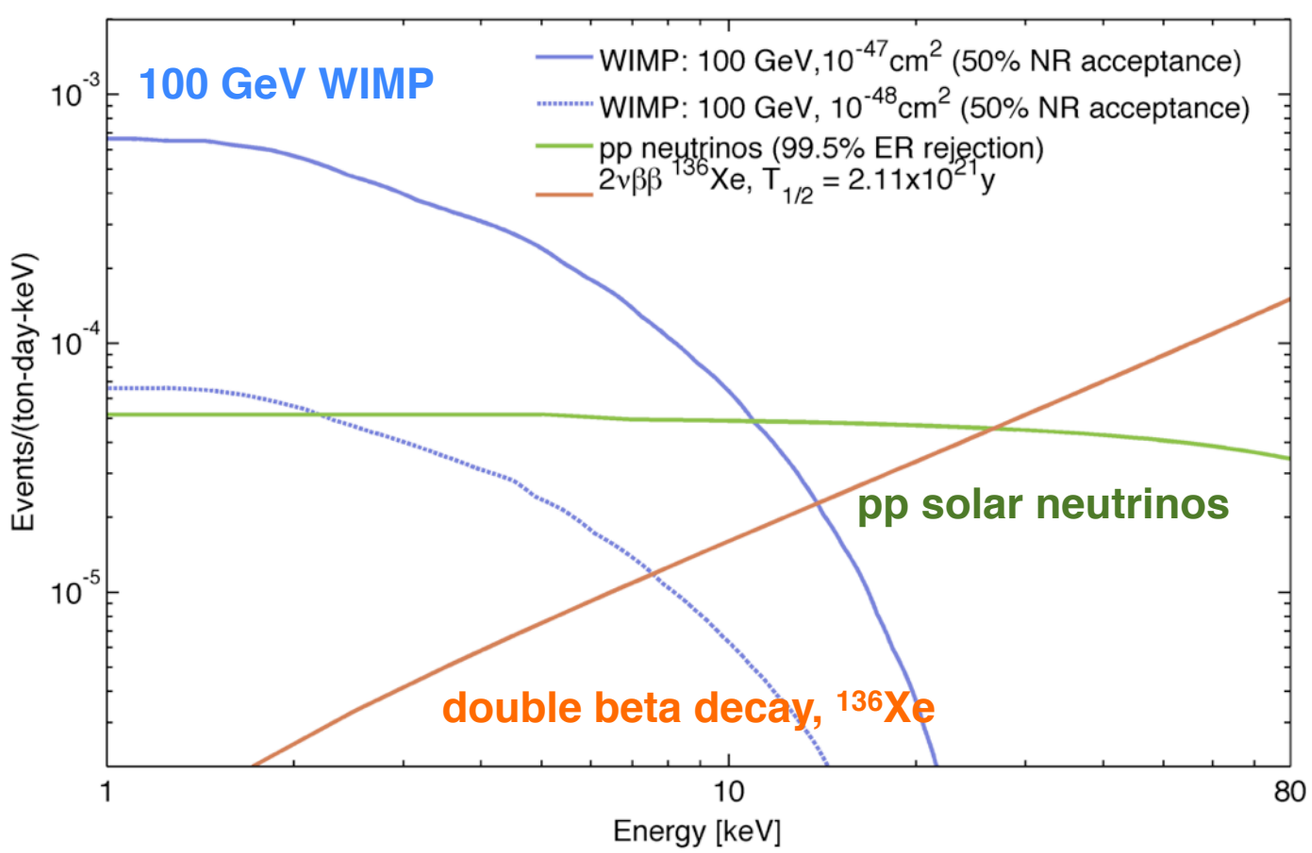
Two orders of magnitude improvement in SI cross-section sensitivity w/r to XENON100

The far future

- DARWIN: dark matter search with noble liquids
- Physics channels of 20t LXe detector:
  - dark matter searches
  - real-time detection of solar pp-neutrinos:
  - search for neutrinoless double beta decay in ^{136}Xe

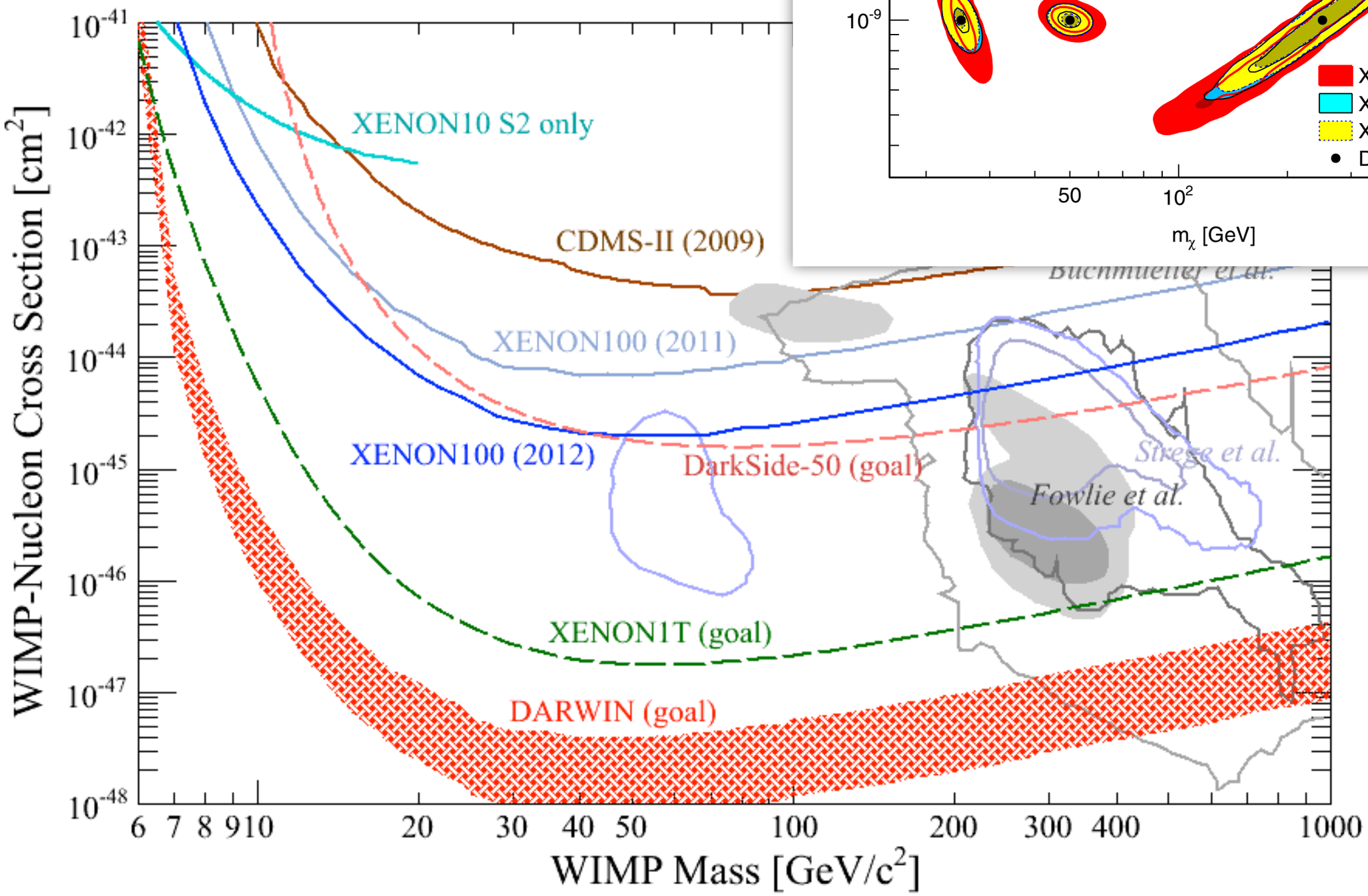
darwin.physik.uzh.ch

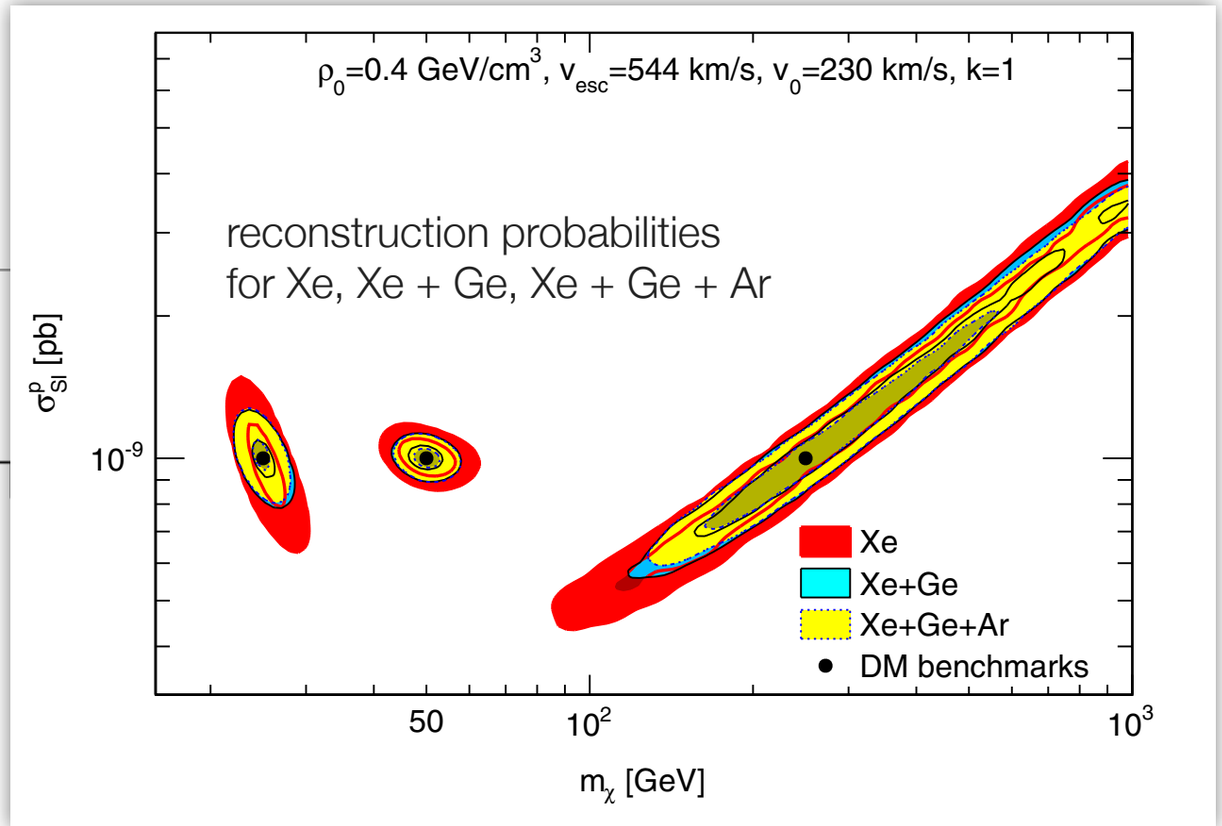




L. Baudis, Physics of the Dark Universe 1, 94 (2012)

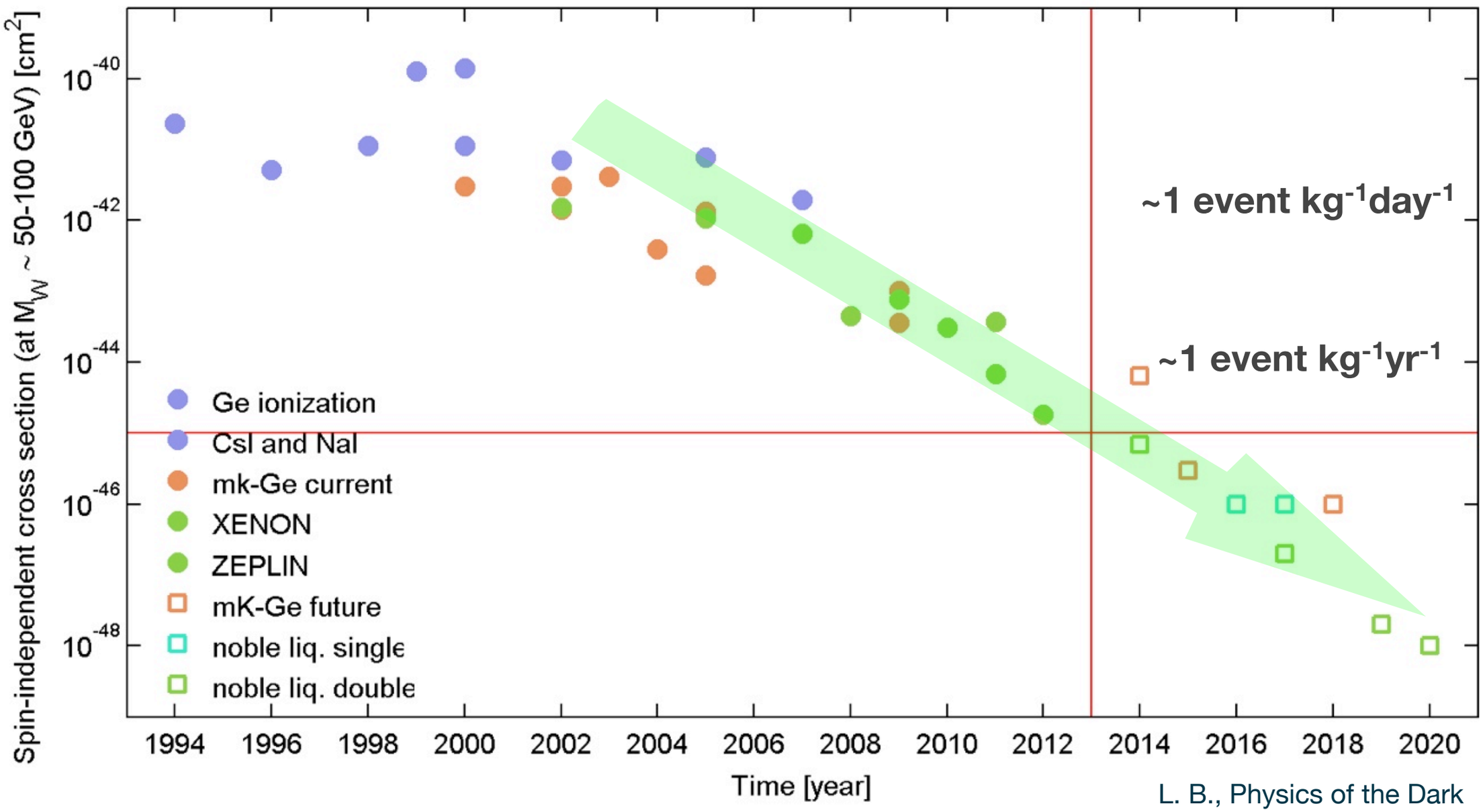
DARWIN goal


WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
XENON10 S2 only
CDMS-II (2009)
XENON100 (2011)
XENON100 (2012)
DarkSide-50 (goal)
XENON1T (goal)
DARWIN (goal)
Buchmueller et al.
Strege et al.
Fowlie et al.


ρ_0=0.4 GeV/cm^3, v_{esc}=544 km/s, v_0=230 km/s, k=1
reconstruction probabilities
for Xe, Xe + Ge, Xe + Ge + Ar
σ^p_{SI} [pb]
m_χ [GeV]
Xe
Xe+Ge
Xe+Ge+Ar
DM benchmarks

Direct detection: sensitivity versus time

Factor ~ 10 every two years!



L. B., Physics of the Dark Universe 1, 94 (2012)