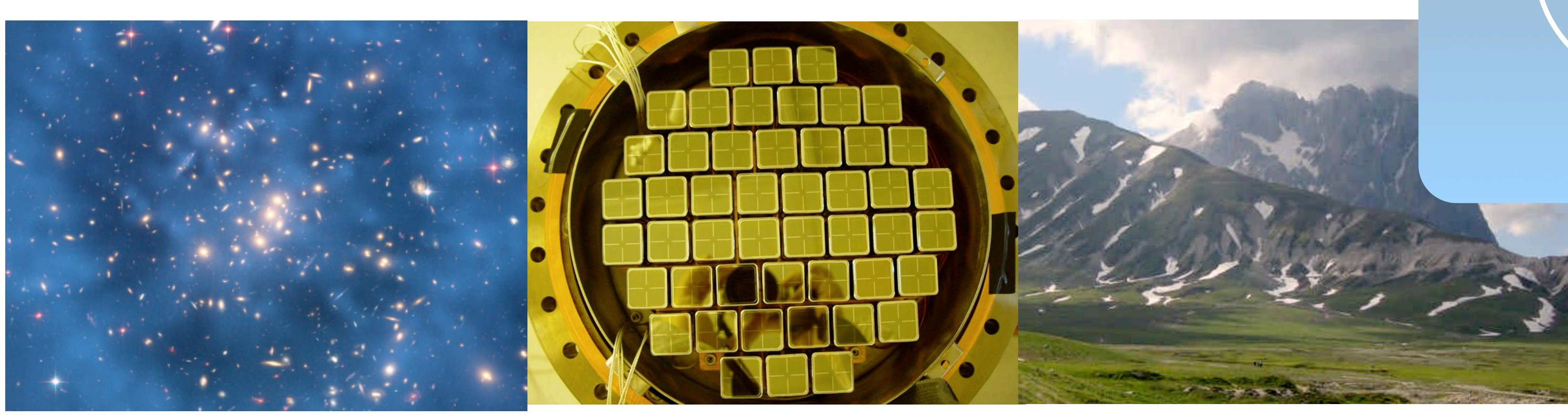
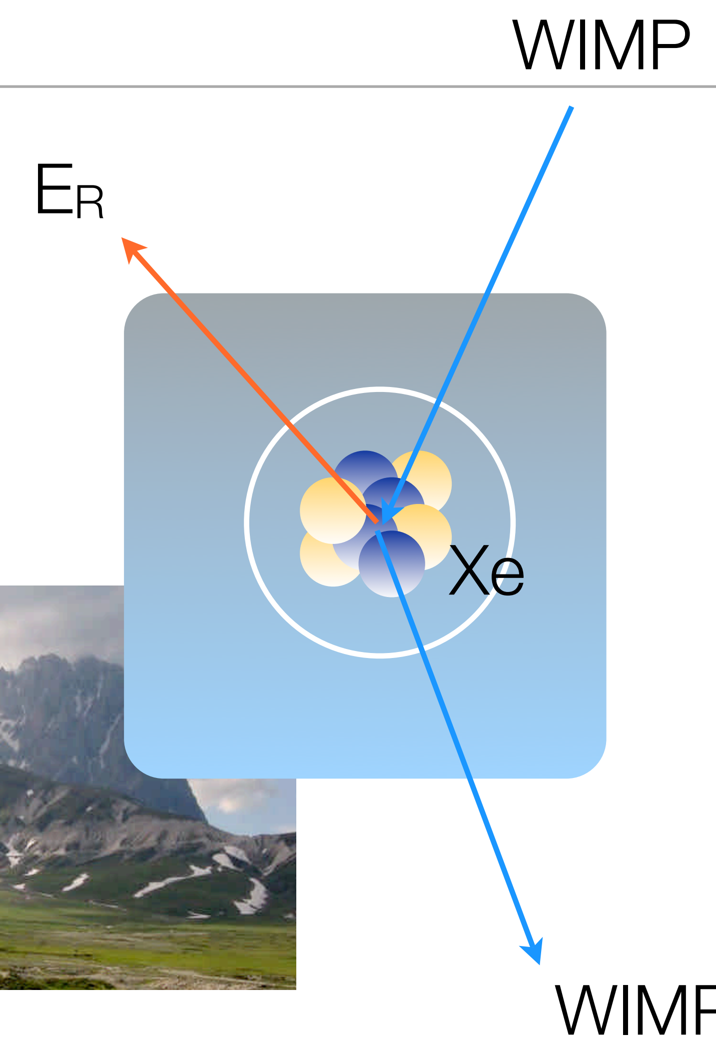
Results from the XENON10 Experiment and Status of XENON100

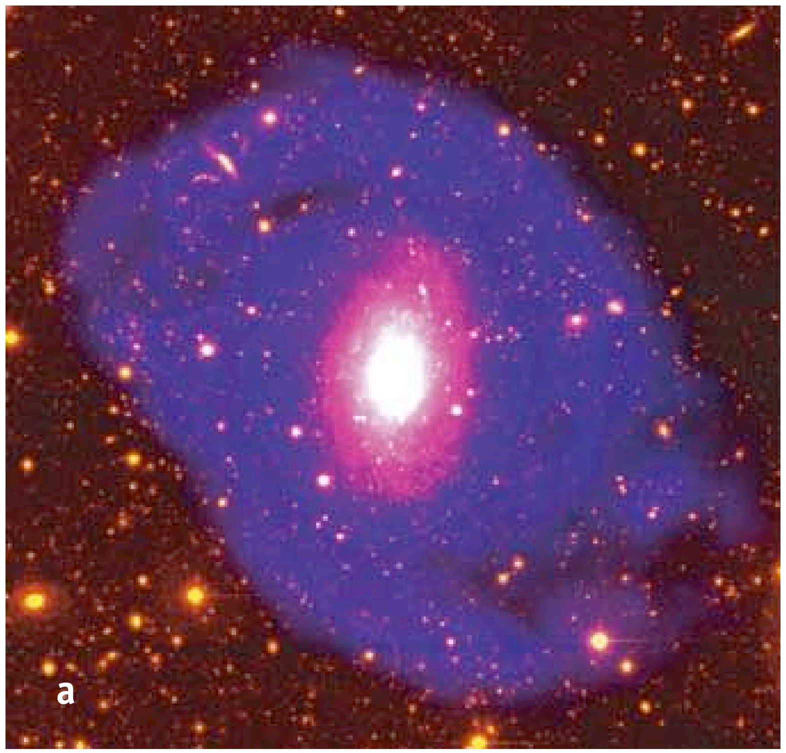
SPP, Saclay, November 12, 2007

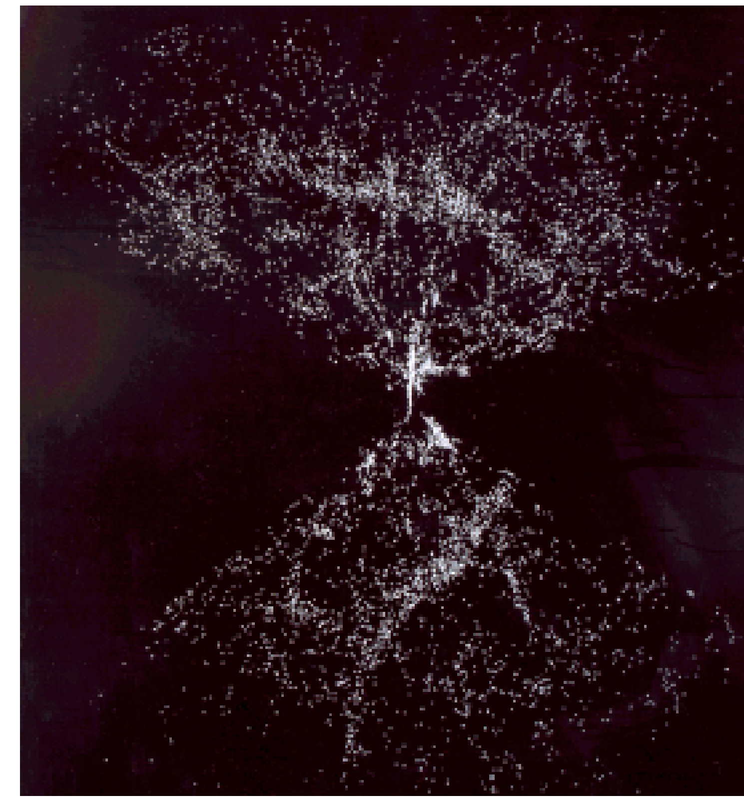
Laura Baudis, University of Zürich

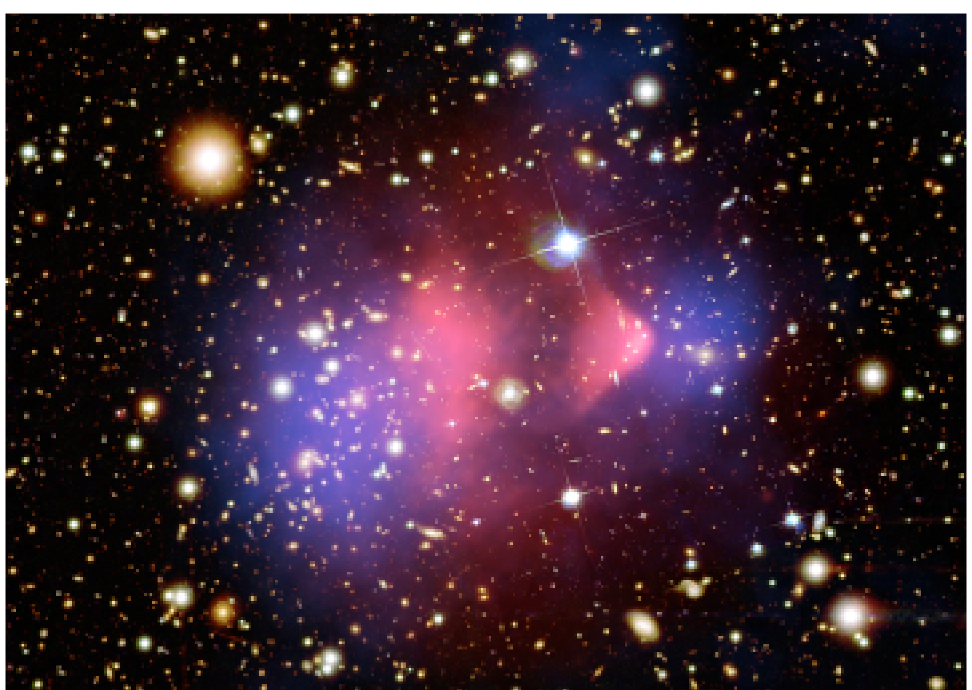


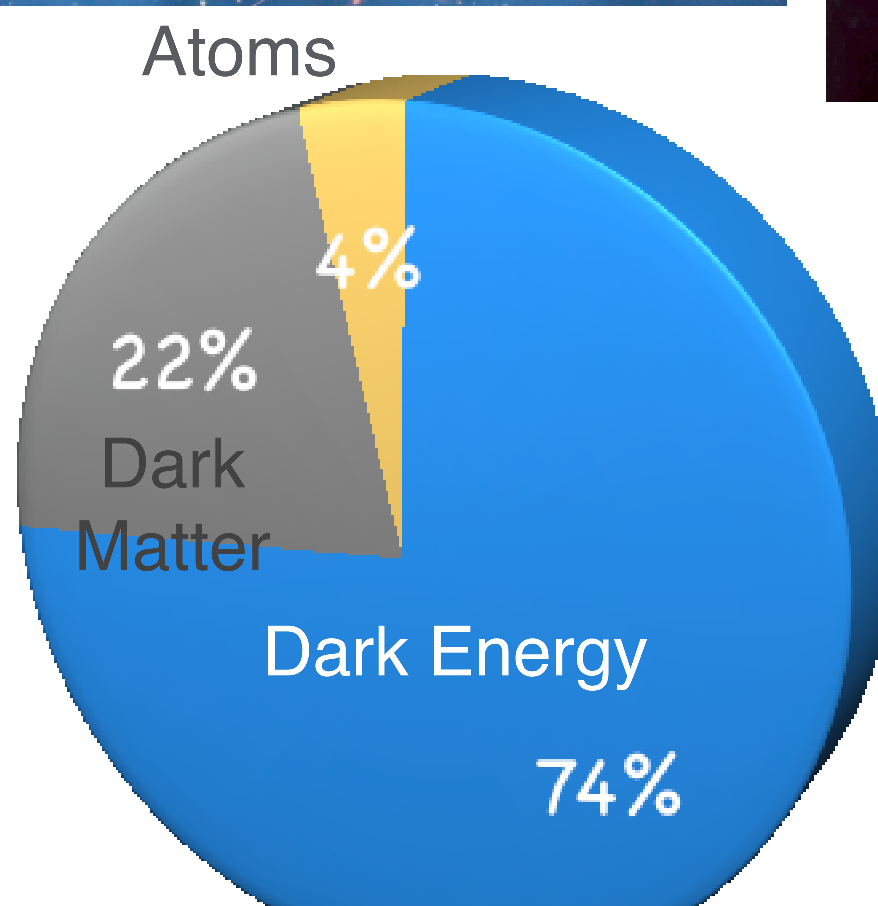


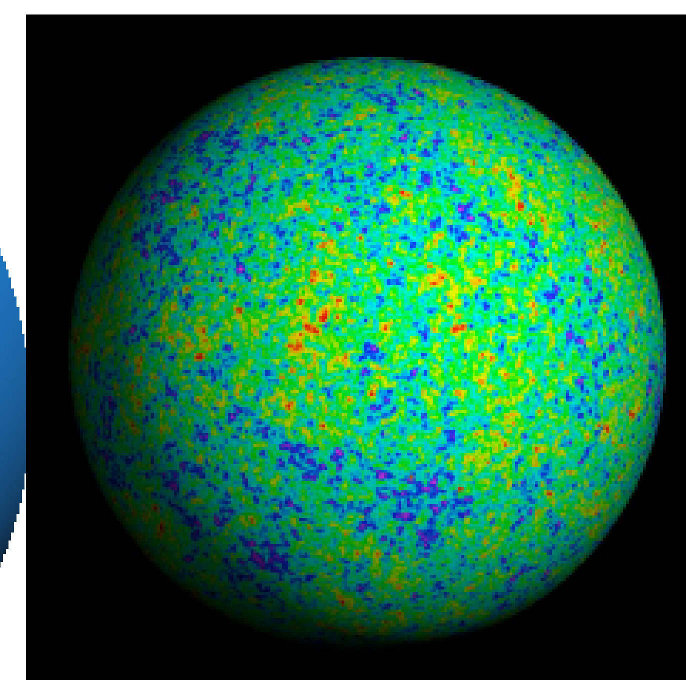
Dark Matter in the Universe



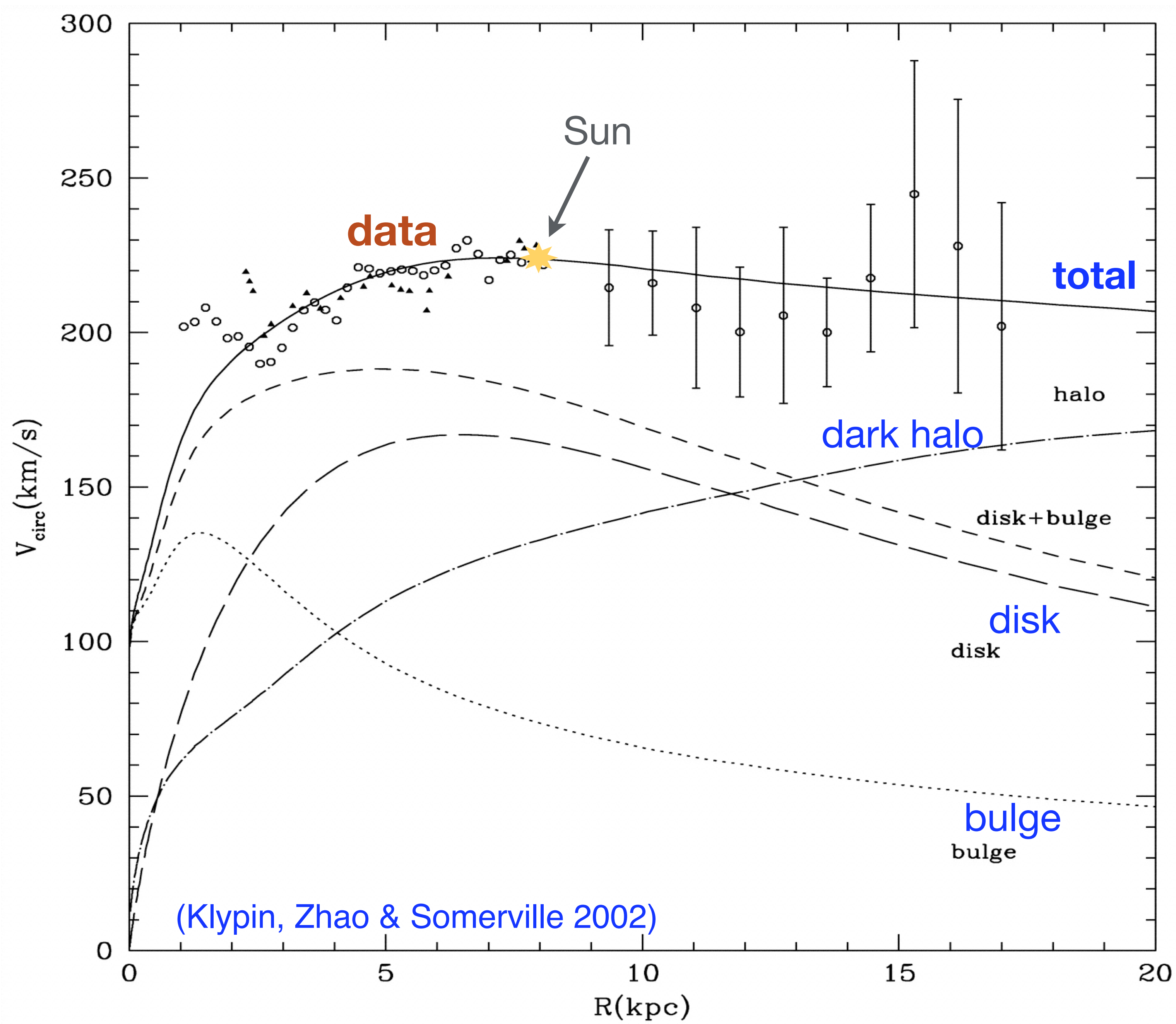








Dark Matter in the Milky Way



$$M_{tot,lum} \approx 9 \times 10^{10} M_{\odot}$$

$$M_{virial} \approx 1...2 \times 10^{12} M_{\odot}$$

$$\rho_{dark} \simeq 0.3 - 0.6\ GeV \cdot cm^{-3}$$

Cold Thermal Relics and the Weak Scale

- if a **massive, weakly interacting particle** (WIMP) existed in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

- it was in equilibrium as long as the **reaction rate** was larger than the **expansion rate**

$$\Gamma \gg H$$

- after Γ drops below H ⇒ “freeze-out”, we are left with a **relic density**

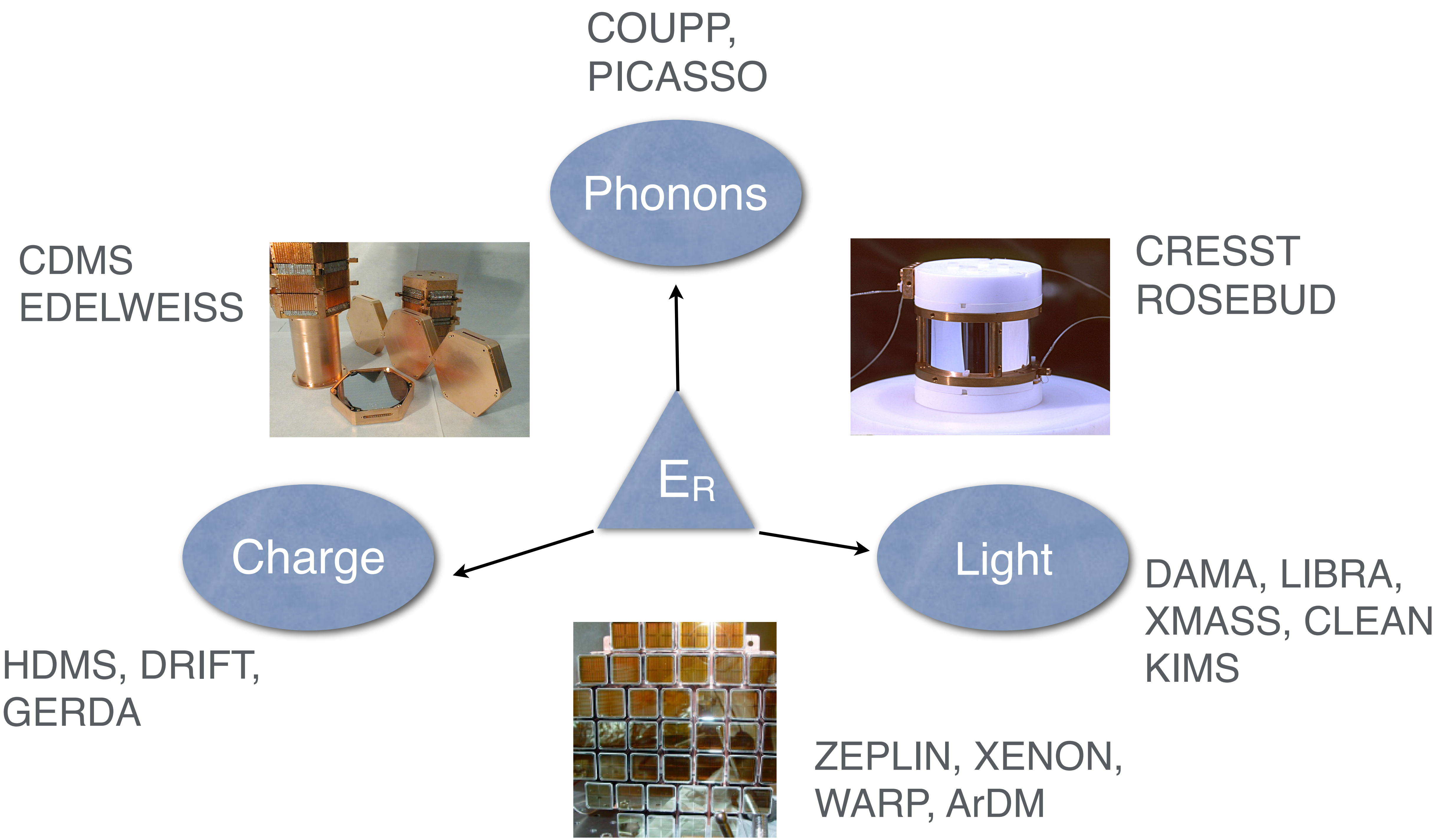
$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{\langle \sigma_A \mathrm{v} \rangle}$$

$$\Omega_\chi \sim 0.2 \Rightarrow \langle \sigma_A v \rangle \sim 1 \text{ pb}$$

$$\sigma_\mathrm{A} \sim \frac{\alpha^2}{m^2} \Rightarrow m \sim 100 \text{ GeV}$$

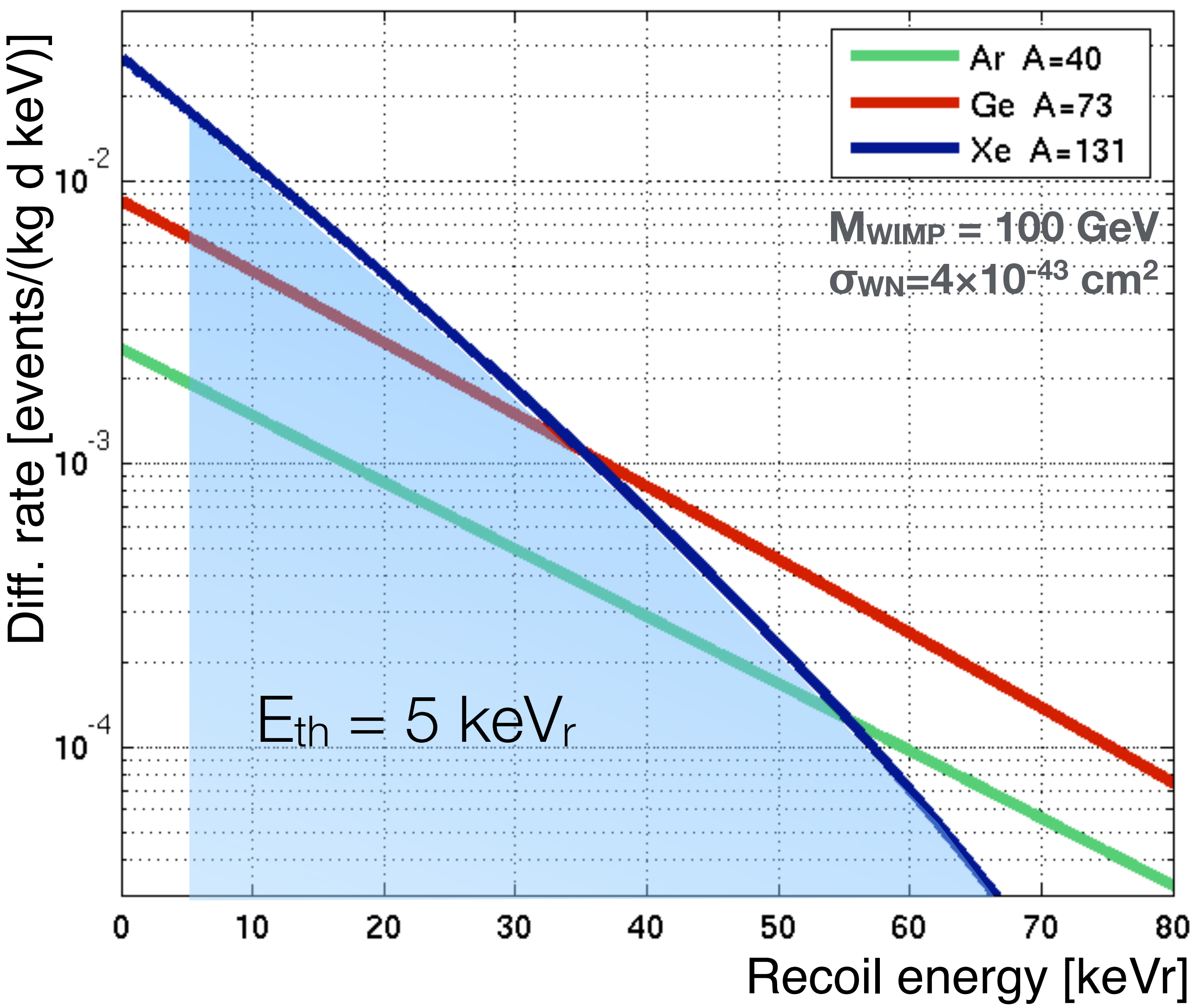
⇒ the relic density and mass point to the **weak scale**
⇒ the new physics responsible for EWSB likely gives rise to a **dark matter candidate**
⇒ examples: LSP (neutralino), LKP (KK-partner of photon, or KK-partner of Z-boson)

Direct WIMP Detection Experiments



Liquid Xenon for Direct Dark Matter Detection

- XENON goal: detect galactic WIMPs by their **elastic collision with Xe nuclei**:
  - ➡Achieve sub-10 keV recoil energy threshold
  - ➡Achieve a WIMP-nucleon σ sensitivity of ~ **2×10^{-44} to 2×10^{-45} cm^2**



Large A (~131) good for SI σ but need low E_{th}

^{129}Xe (26.4%) and ^{131}Xe (21.2%) for SD σ

No radioactive isotopes (^{85}Kr to ppt levels)

LXe high stopping power (Z=54, ρ=3g/cm^3) for compact, self-shielding geometry

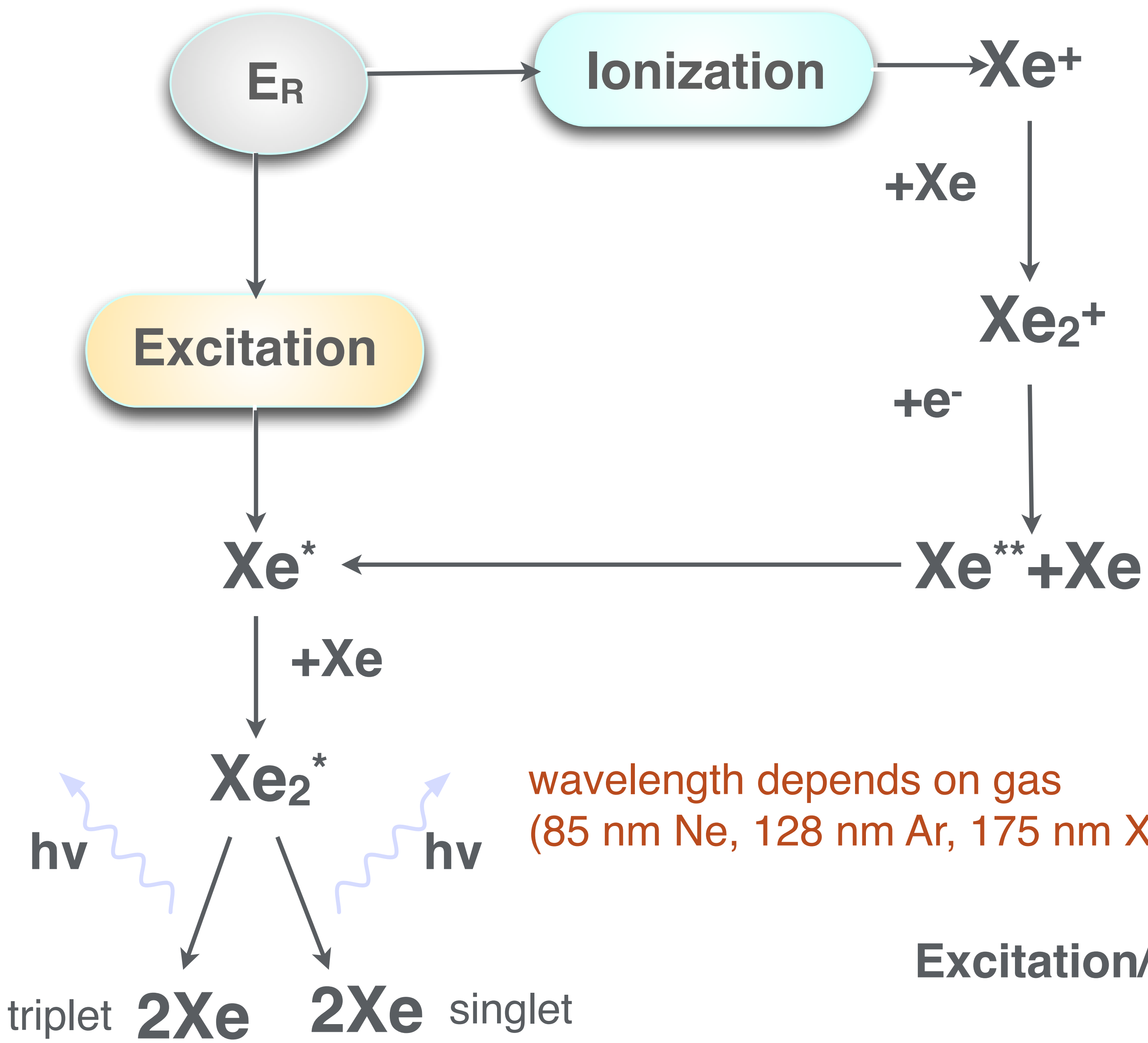
LXe: efficient and fast scintillator (yield ~ 80%NaI); good ionization yield (W=15.6 eV)

Modest quenching factor for NRs (~0.2)

'Easy' cryogenics at ~ 165 K

BG rejection: > 99.5% by simultaneous light and charge detection, plus 3D event localization and Lxe shelf-shielding

Charge and Light in Noble Liquids



wavelength depends on gas
(85 nm Ne, 128 nm Ar, 175 nm Xe)

time constants depend on gas
(few ns/15.4µs Ne, 10ns/1.5µs Ar, 3/27 ns Xe)

$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

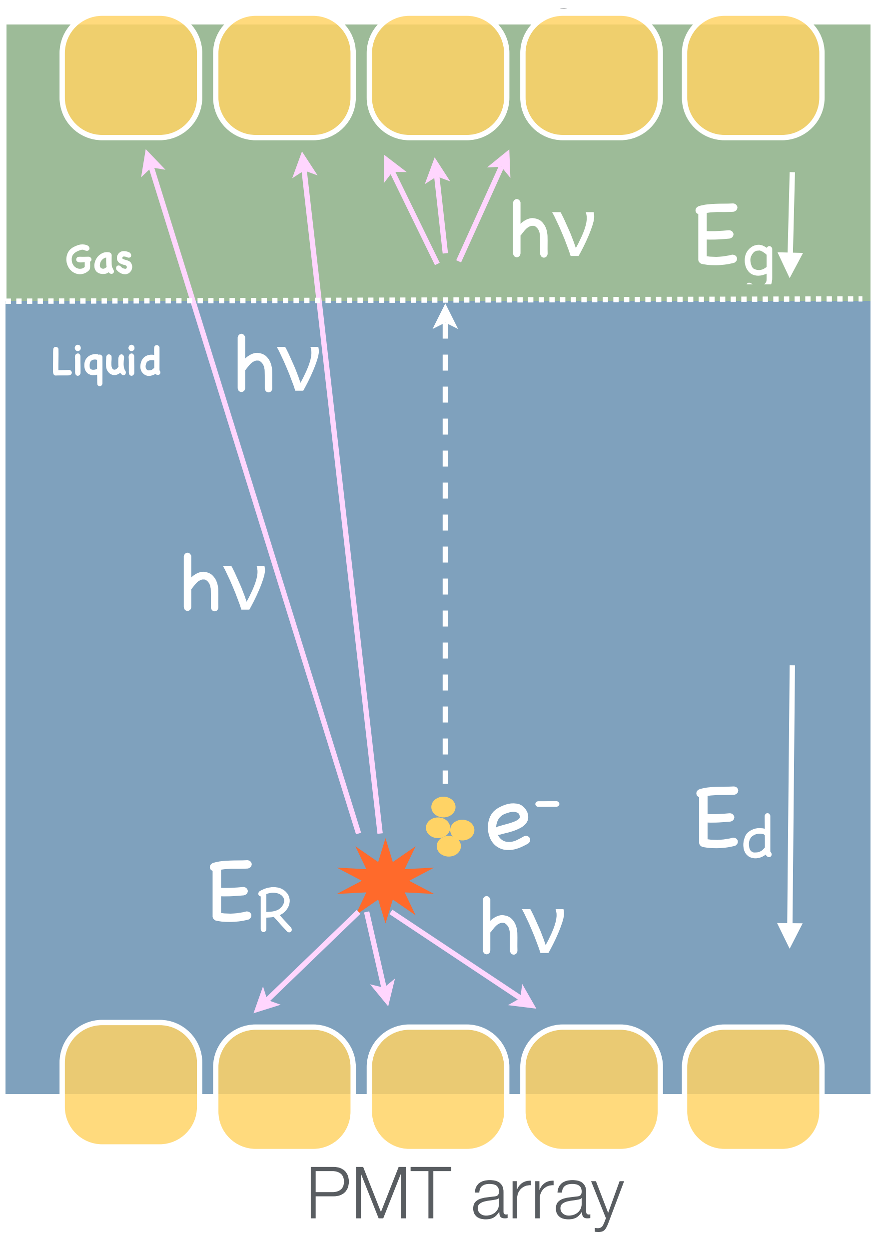
$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$$
$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}$$
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat}$$
$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

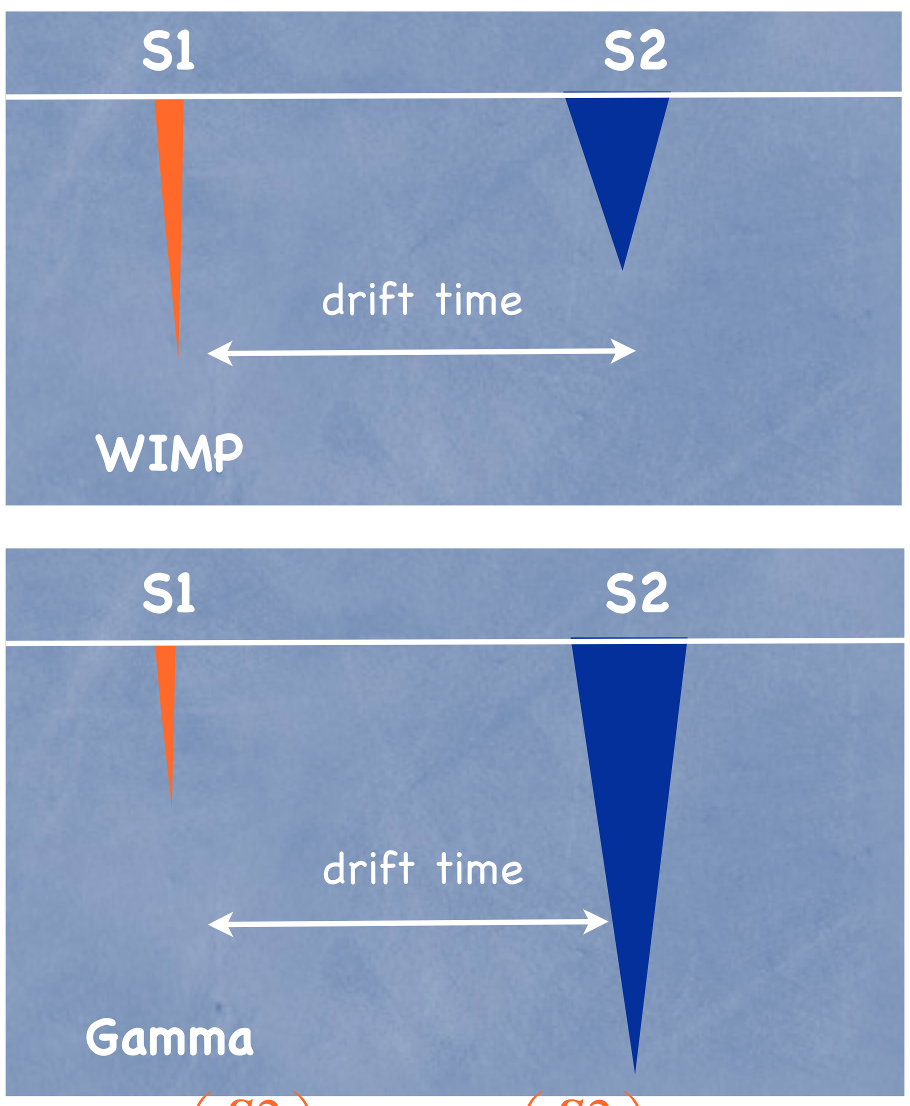
Excitation/Ionization depends on dE/dx!

=> discrimination of signal (**WIMPs=>NR**)
and (most of the) background (**gammas=>ER**)!

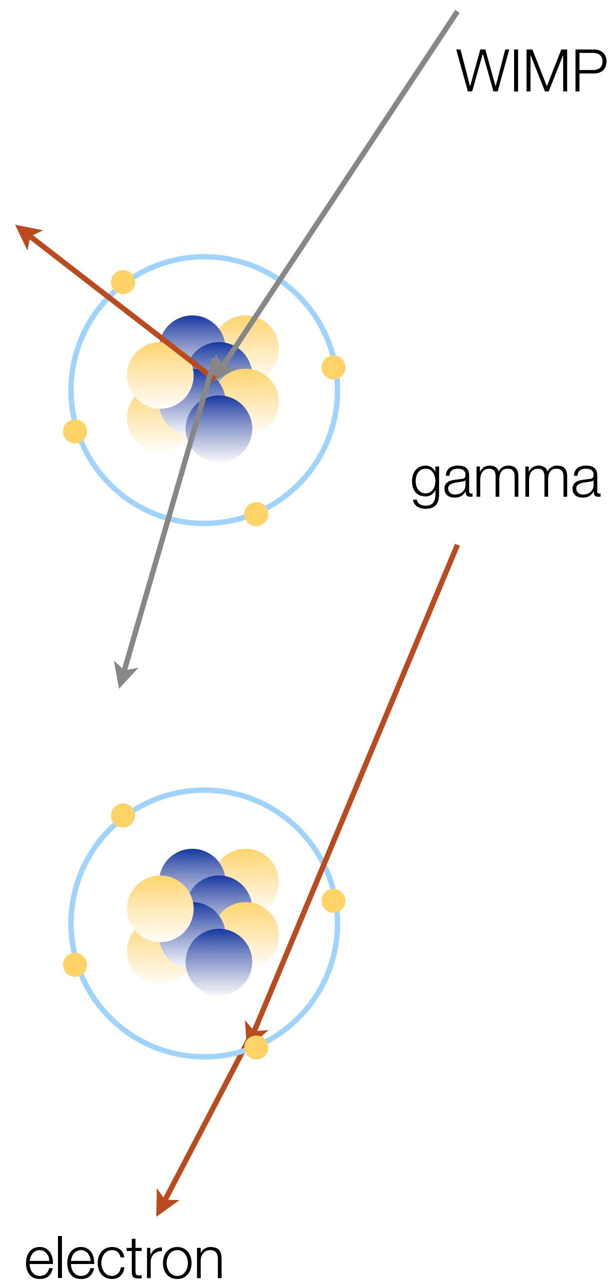
The XENON10 Detector Concept

- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e$^-$





$$\left(\frac{S2}{S1}\right)_{WIMP} \ll \left(\frac{S2}{S1}\right)_{gamma}$$



The XENON10 Detector

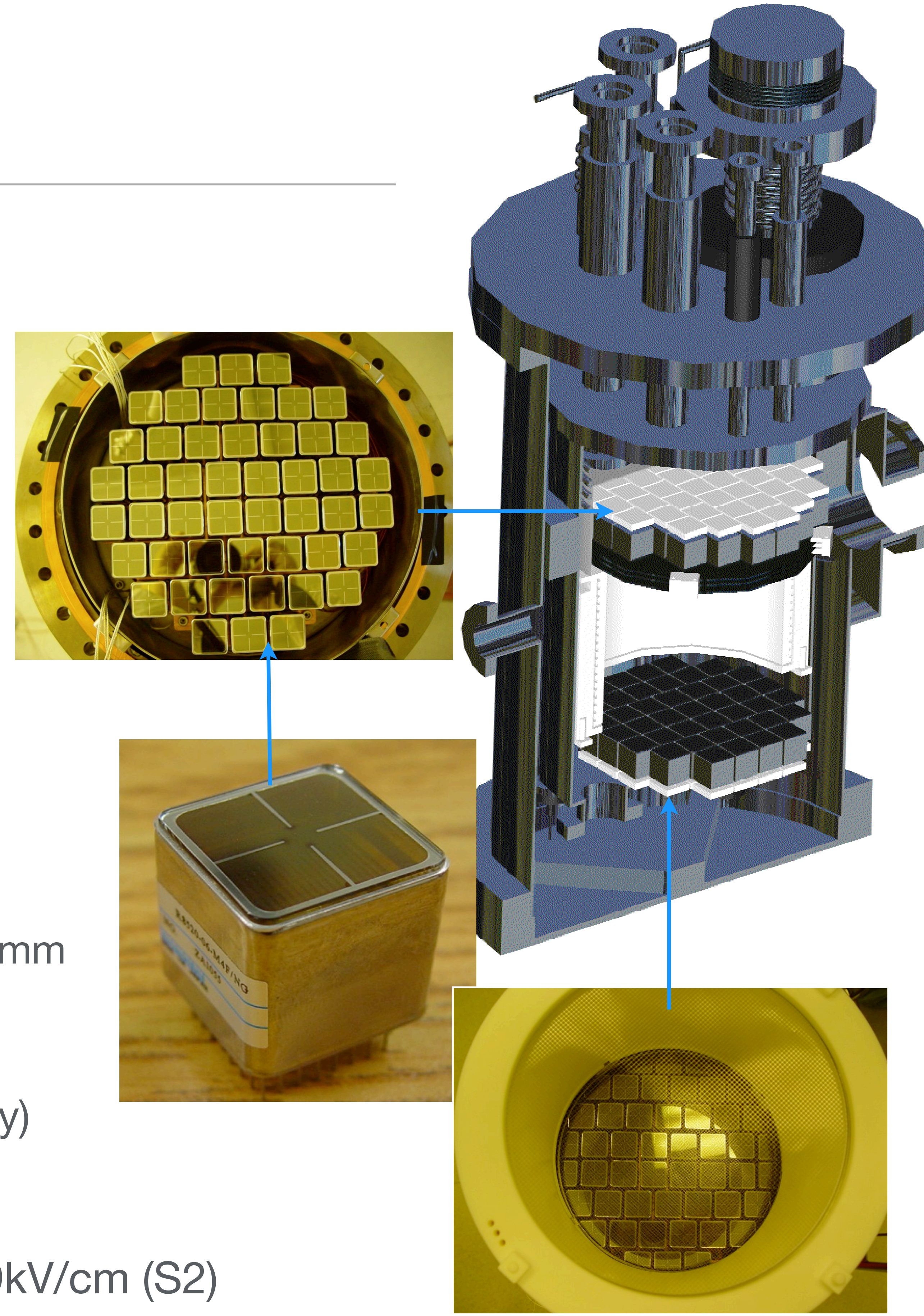
- **22 kg of liquid xenon**
  - ➡ 15 kg active volume
  - ➡ 20 cm diameter, 15 cm drift
- **Hamamatsu R8520 1”×3.5 cm PMTs**

  bialkali-photocathode Rb-Cs-Sb,

  Quartz window; ok at -100°C and 5 bar

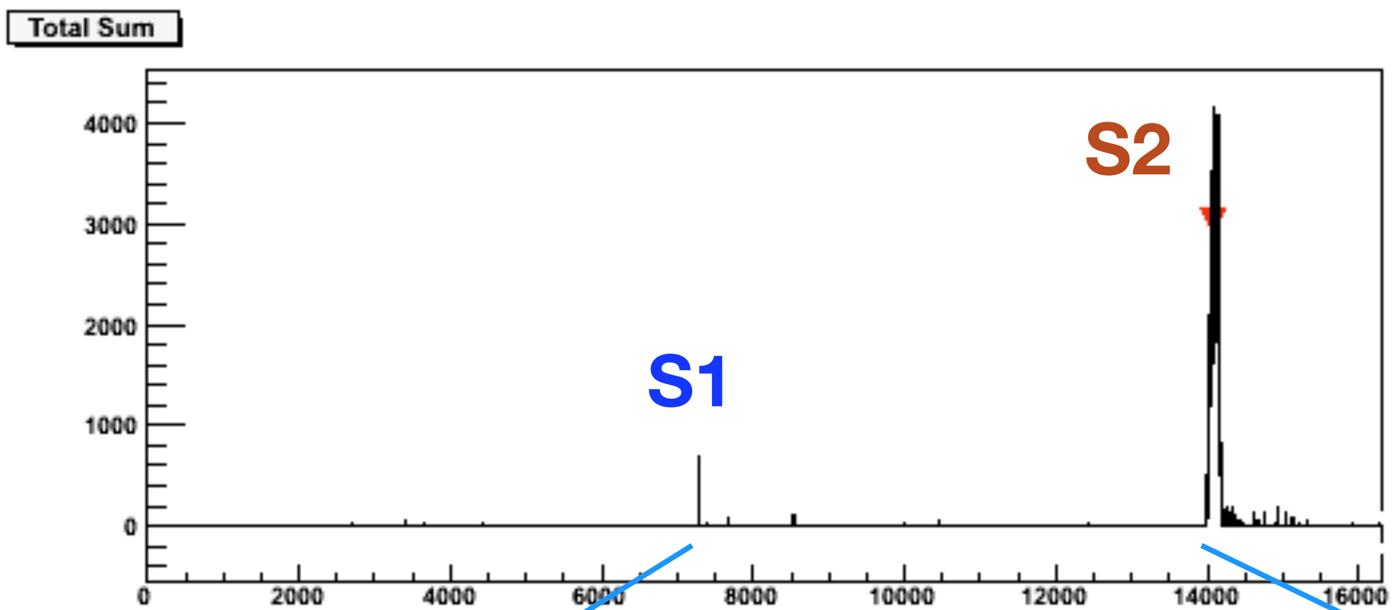
  Quantum efficiency > 20% @ 178 nm
- **48 PMTs top, 41 PMTs bottom array**
  - ➡ x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx$ 1 mm
  - ➡ z-position from Δt_{drift} ($v_{d,e^-} \approx$ 2mm/μs), $\sigma_Z \approx$0.3 mm
- **Cooling: Pulse Tube Refrigerator (PTR),**

  90W, coupled via cold finger (LN_2 for emergency)
  - ➡ LXe maintained at T = 180 K and P=2.2 atm
- **12 kV cathode:** E_d=0.73 kV/cm (drift), E_{gas}=9kV/cm (S2)

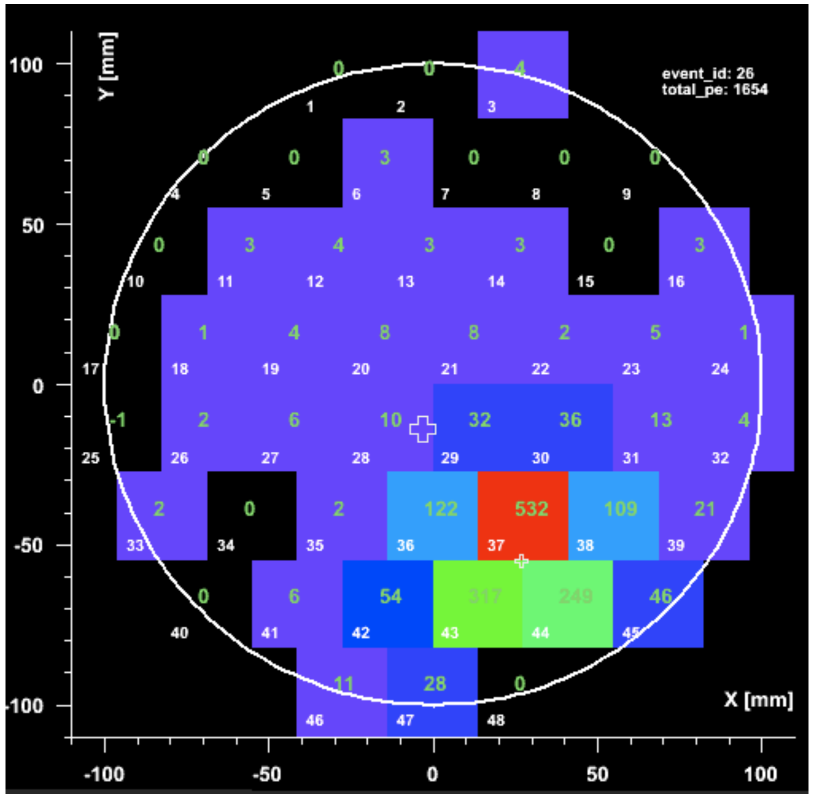


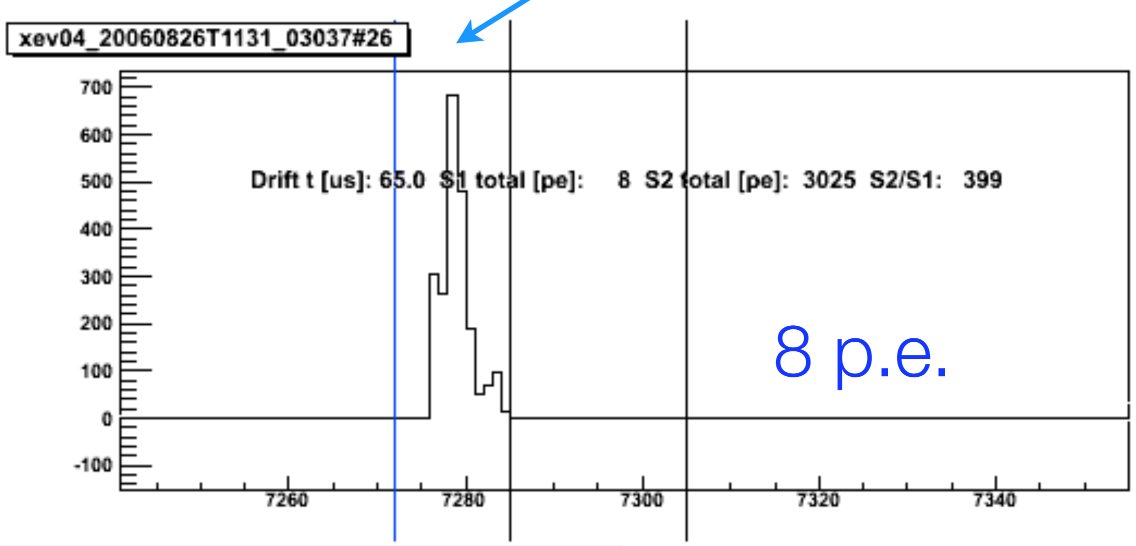
Typical XENON10 Low-Energy Event

- 4 keV_{ee} event; **S1: 8 p.e => 2 p.e./keV**

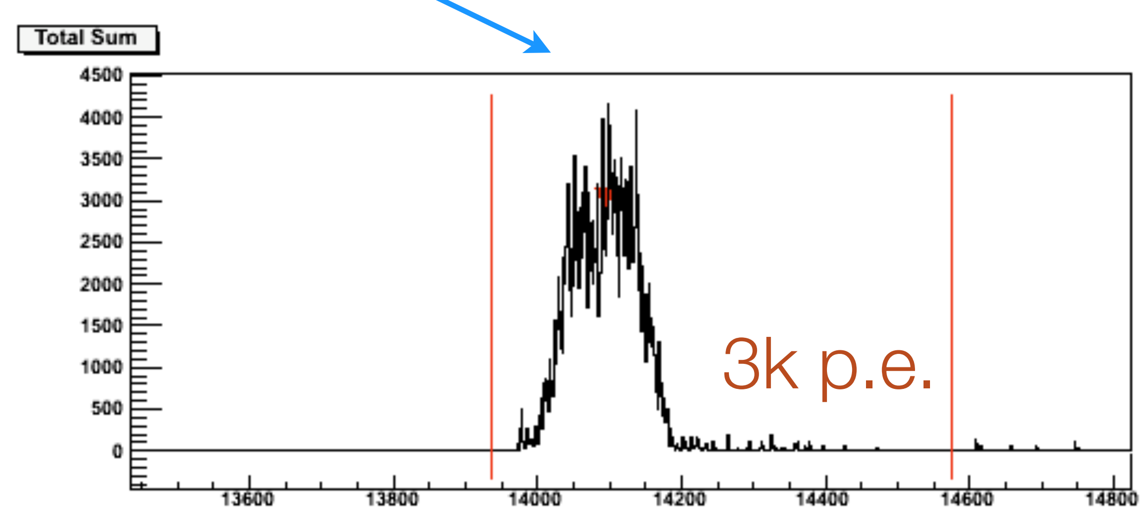


Hit pattern of top PMTs





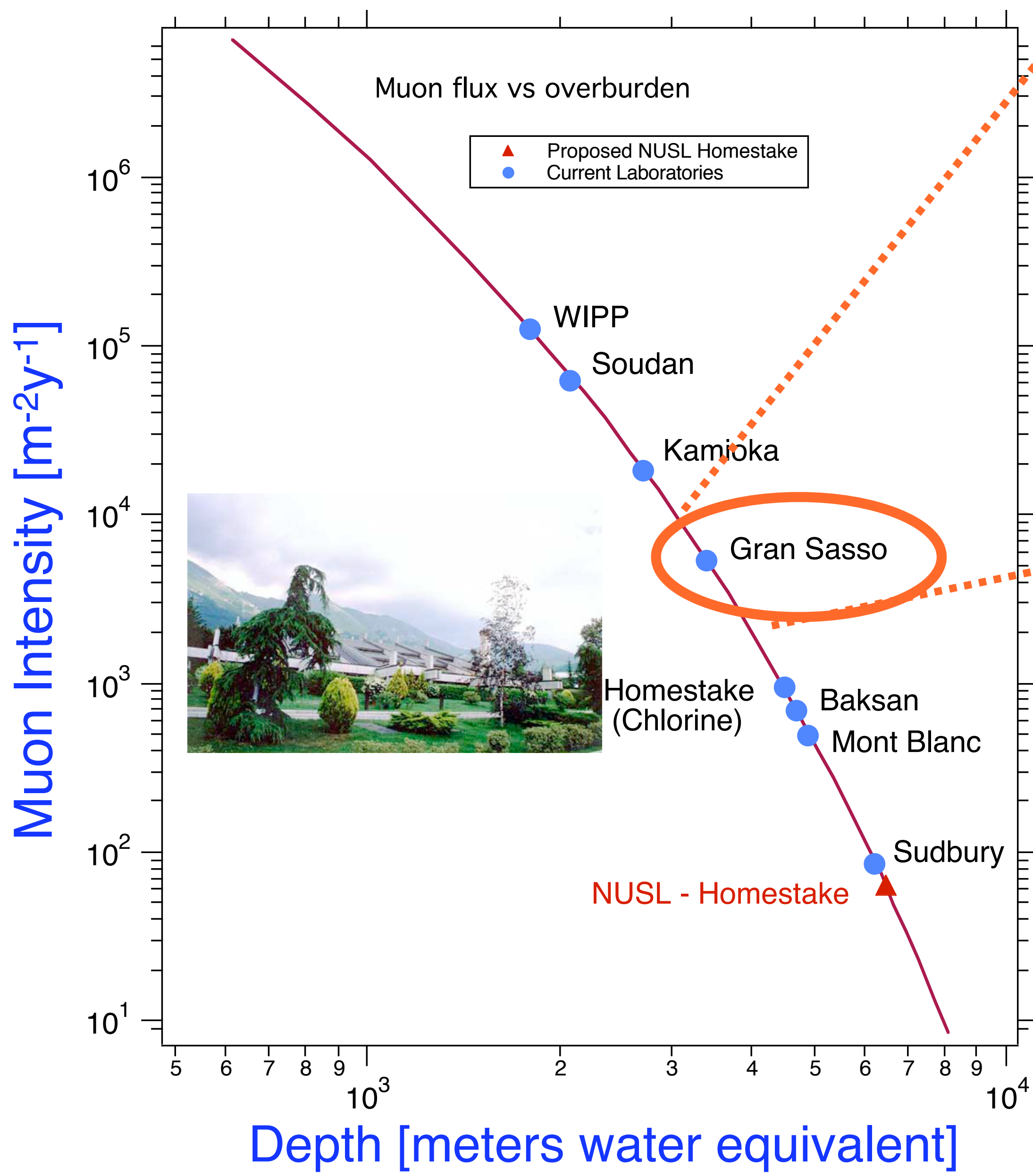
S1

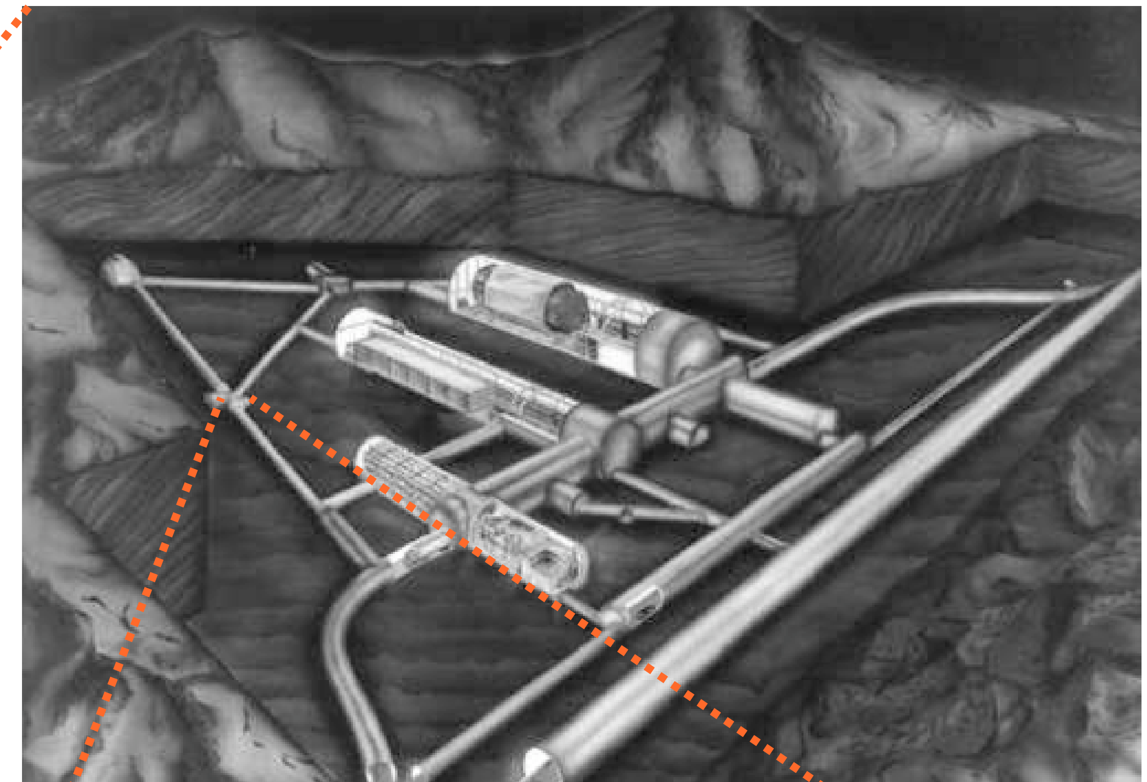


S2

XENON10 at the Gran Sasso Laboratory

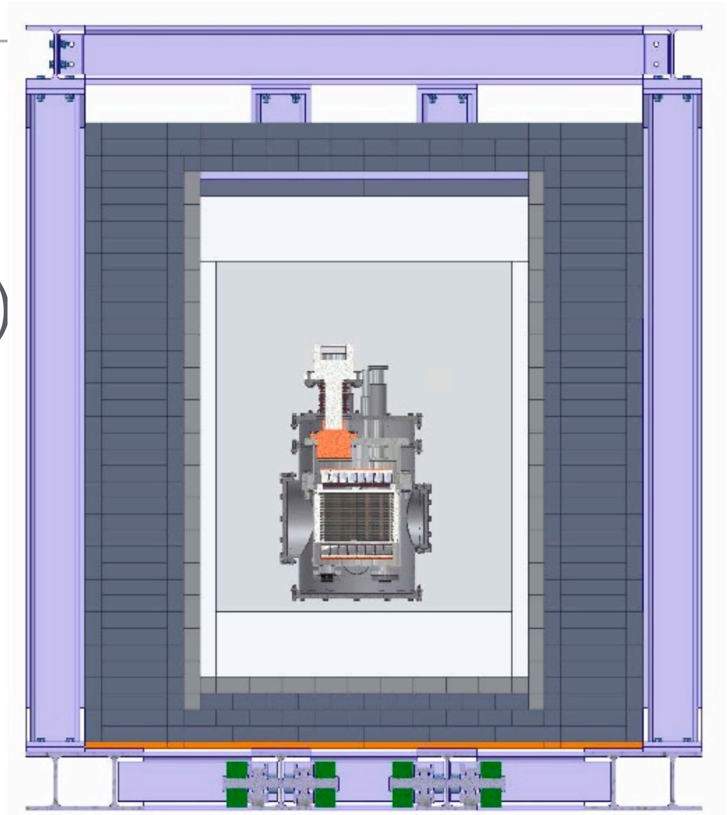
- ~3100 m.w.e; muon flux ≈ 1 m^{-2} h^{-1}

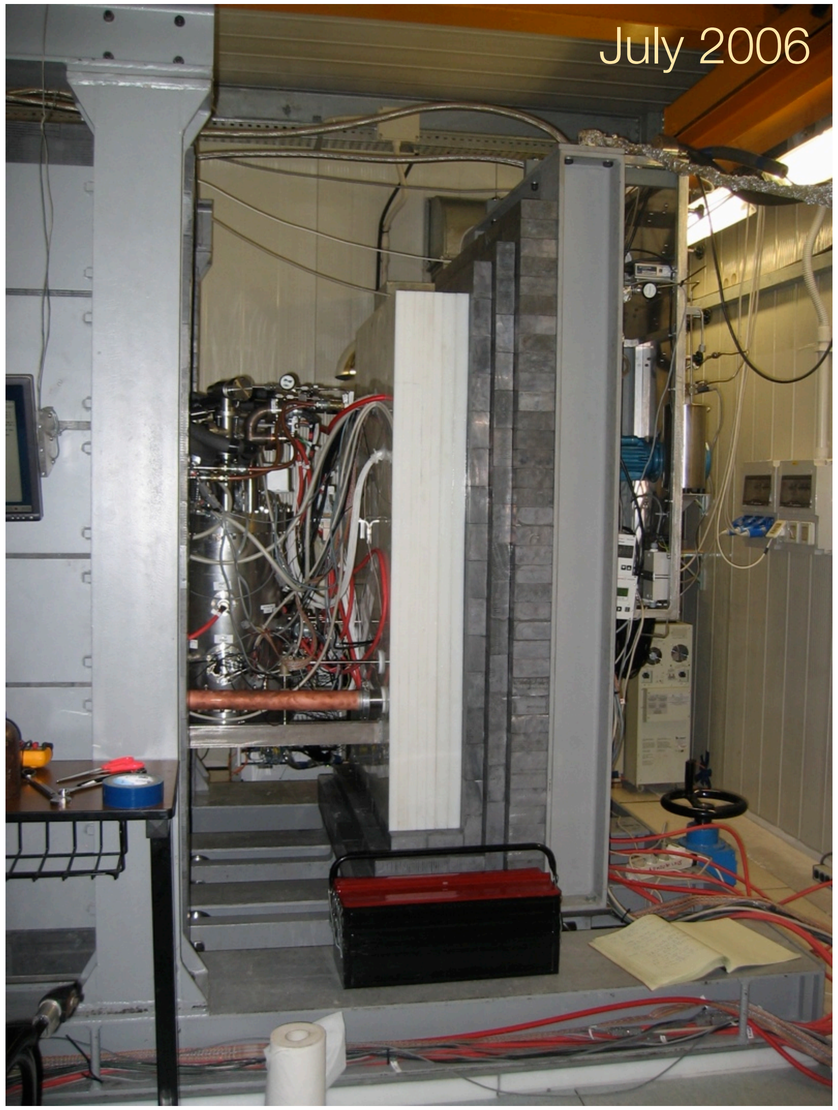




XENON10 at the Gran Sasso Laboratory

- **March 06:** detector first installed/tested outside the shield
- **July 06:** inserted into shield (20 cm Pb, 20 cm HDPE, Rn purge)
- **August 24, 06 - February 14, 07: first WIMP search run**





The XENON10 Collaboration

Columbia University Elena Aprile, Bin Choi, Karl-Ludwig Giboni, Sharmila Kamat, Yun Lin, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli and Masaki Yamashita

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Lawrence Livermore National Laboratory Adam Bernstein, Chris Hagmann, Norm Madden and Celeste Winant

Case Western Reserve University Tom Shutt, Peter Brusov, Eric Dahl, John Kwong and Alexander Bolozdynya

Rice University Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

Yale University Daniel McKinsey, Louis Kastens, Angel Manzur and Kaixuan Ni

LNGS Francesco Arneodo and Serena Fattori

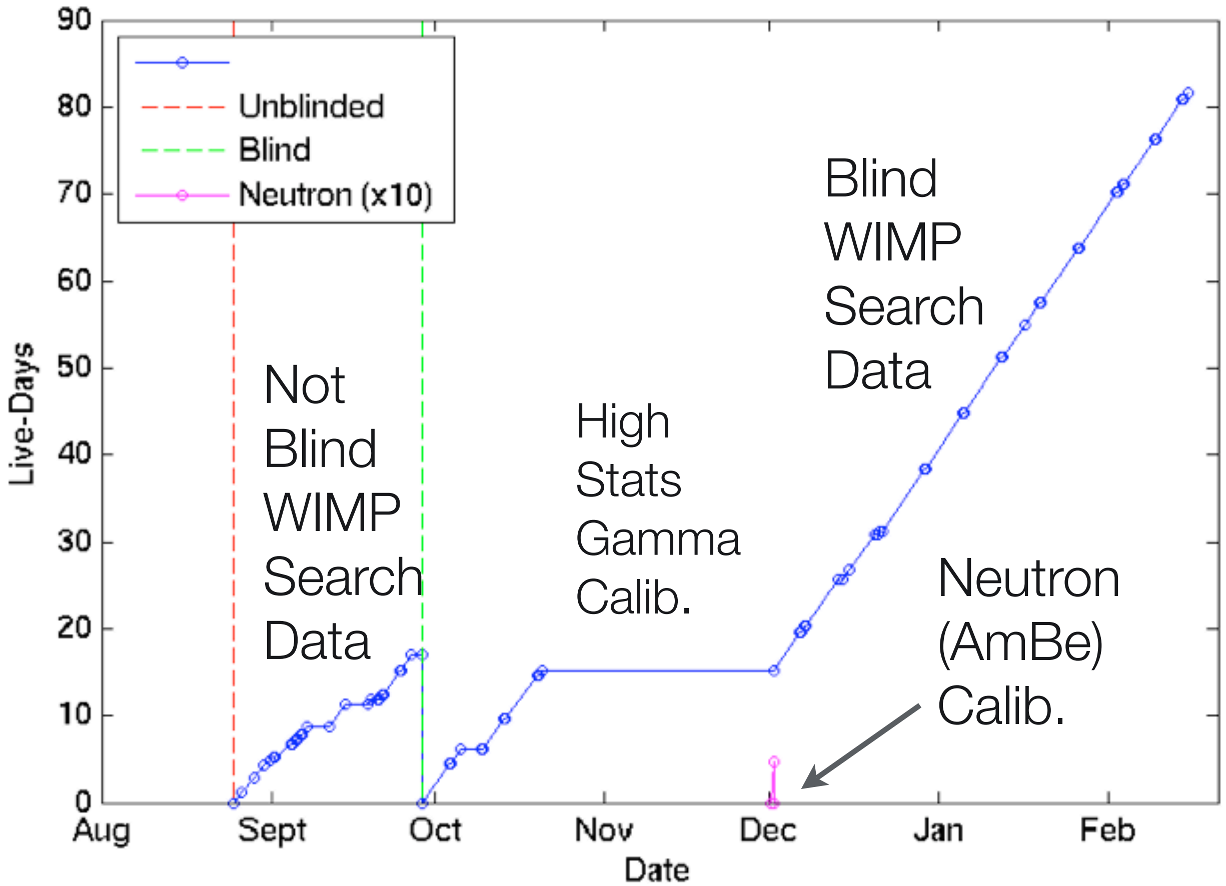
Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

The XENON10 Collaboration

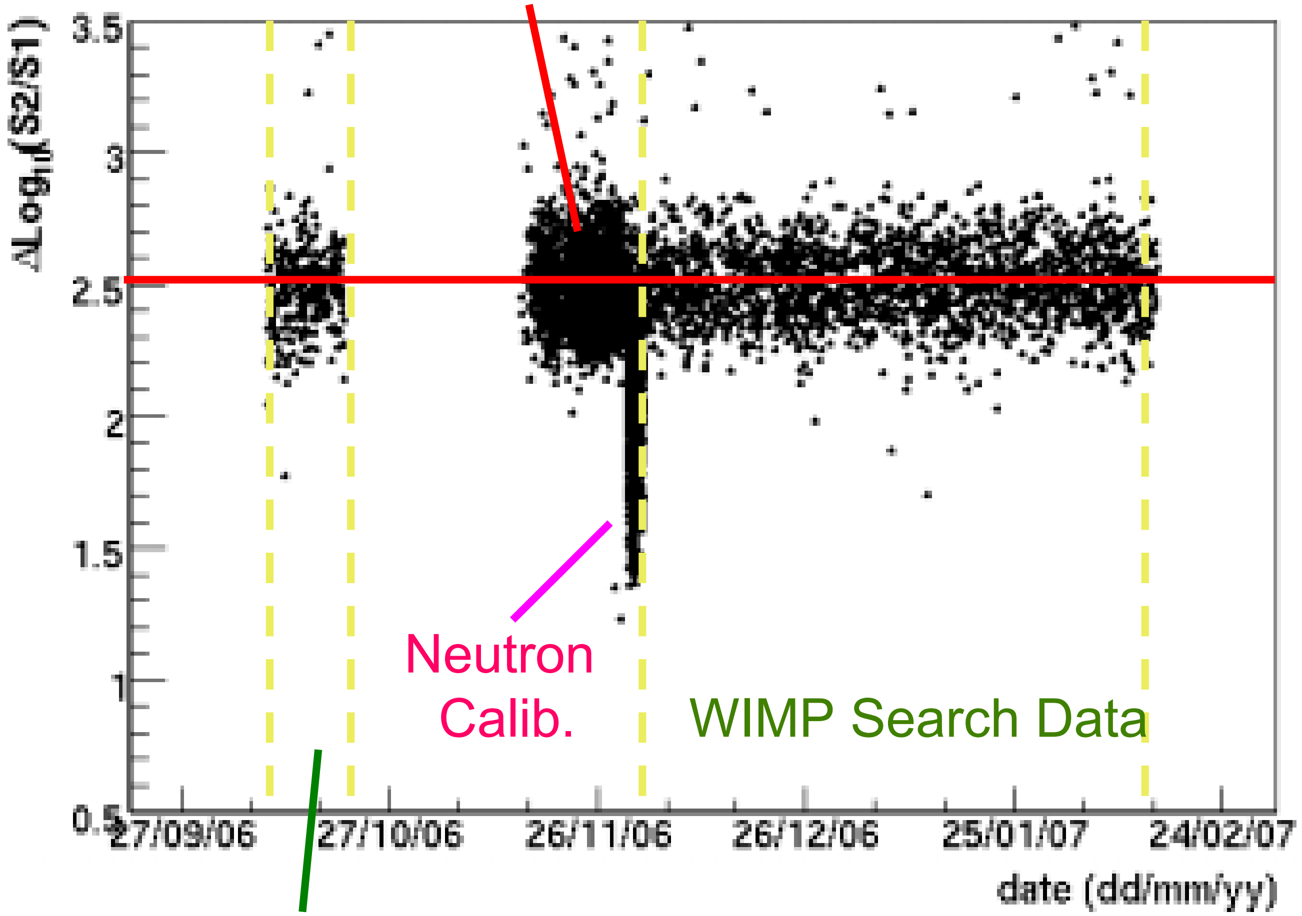
10 young postdocs, 13 graduate students, many at LNGS

Gran Sasso Lab, May 2006 (not all members in this picture)

XENON10 Live-Time and Run Stability

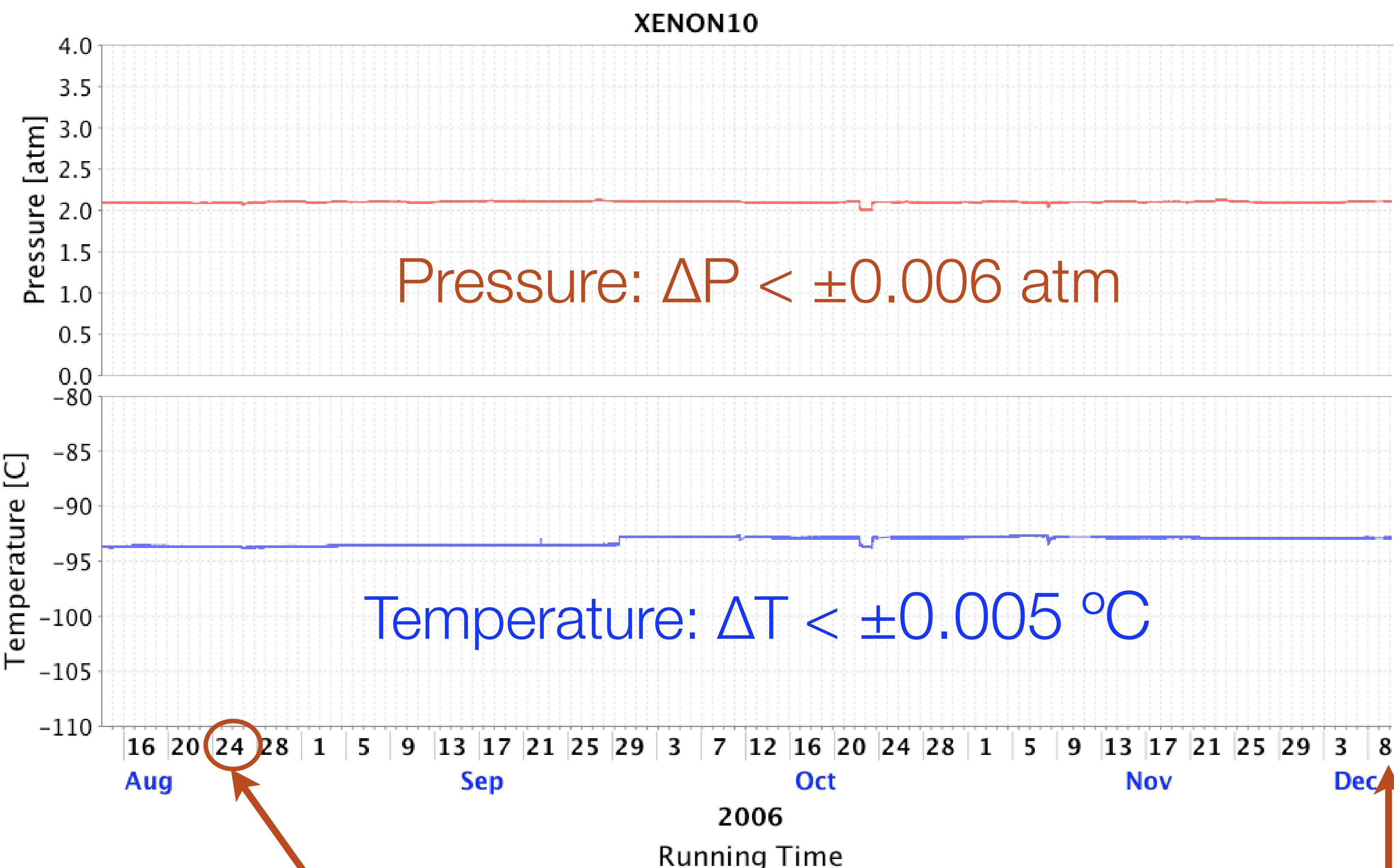


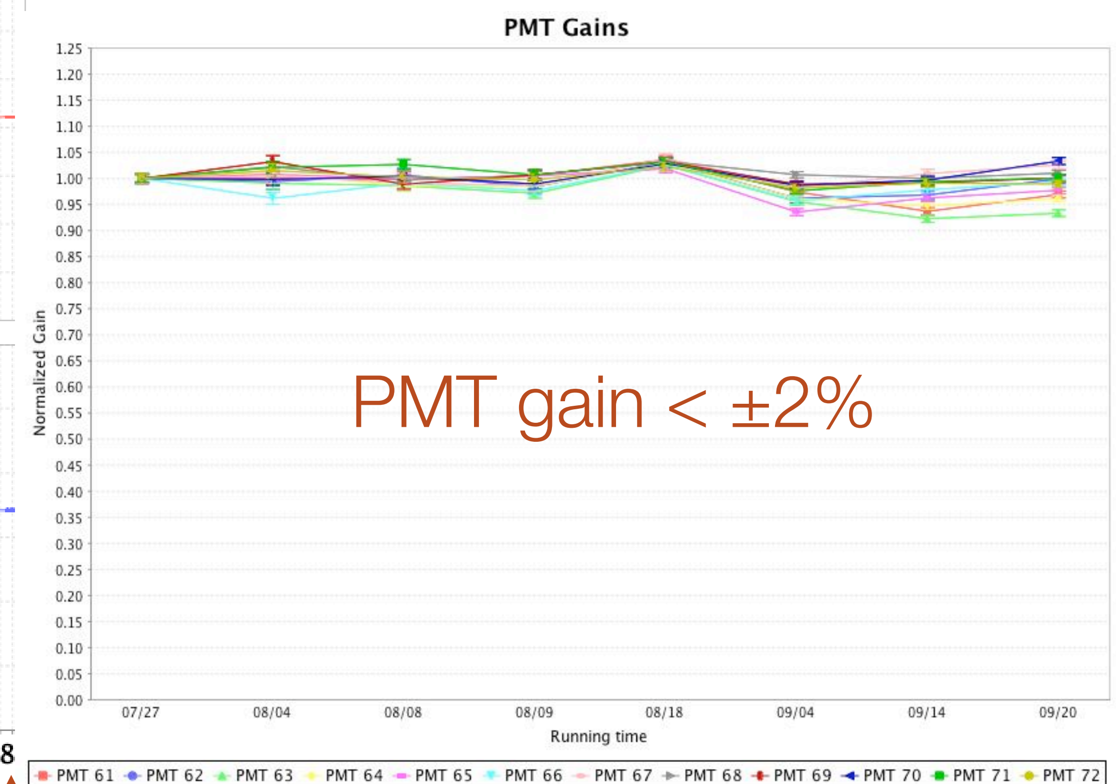
Calibration + WIMP Search Data



XENON10 Performance at LNGS

- Stable pressure, temperature, PMT gain, liquid level, cryostat vacuum, HV...
  ➡over many months (continuously monitored with ‘slow control system’)





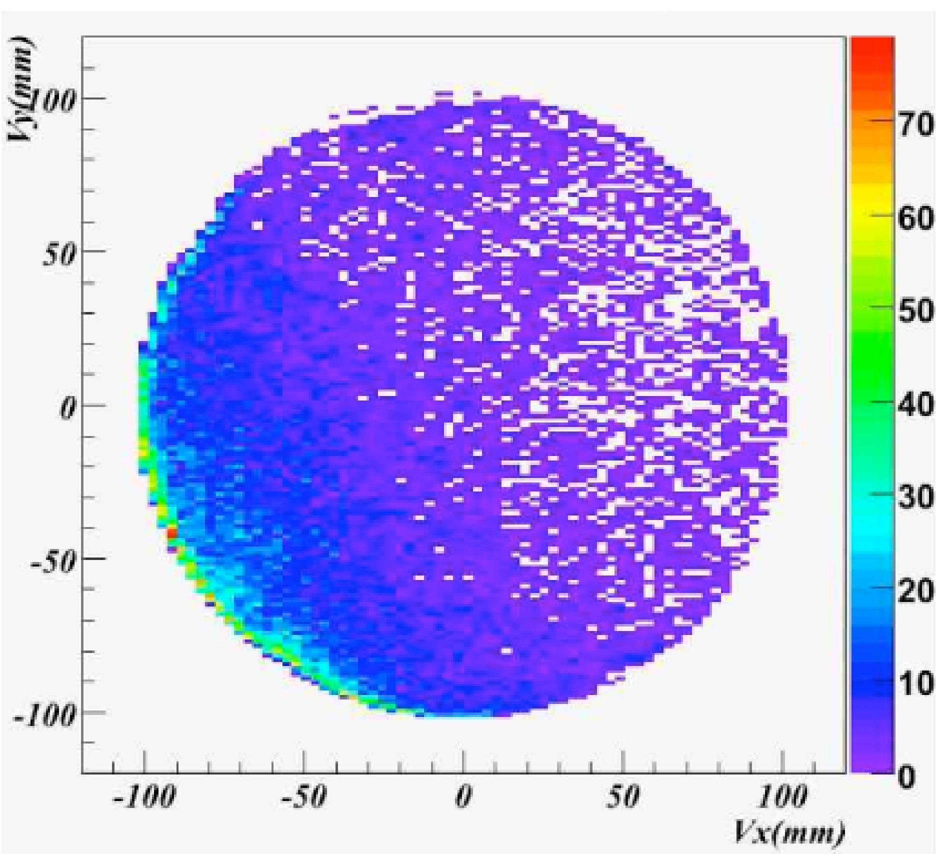
Start of WIMP Search Run

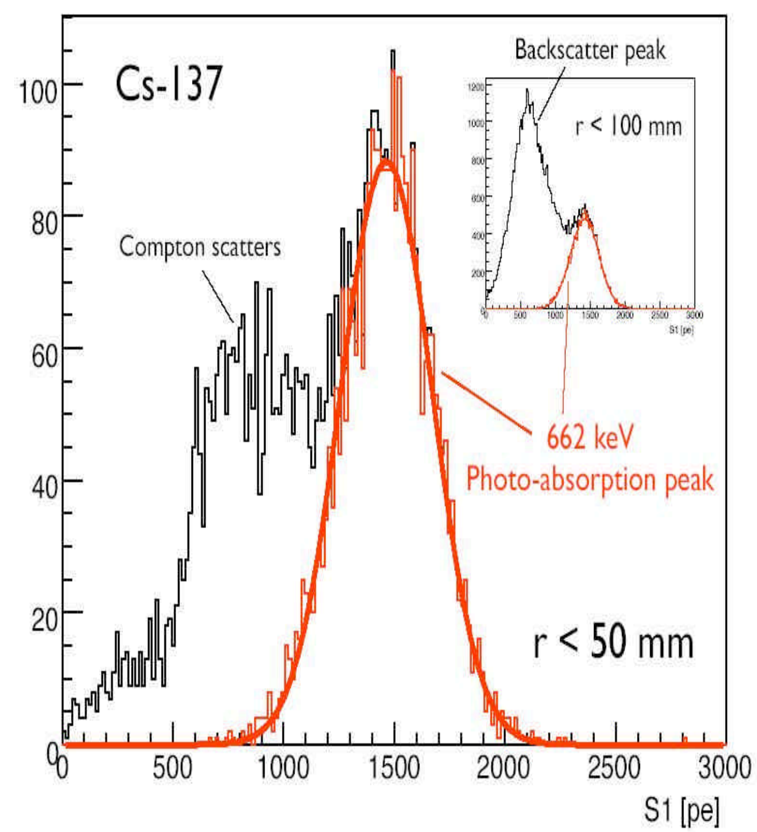
December 8, 06

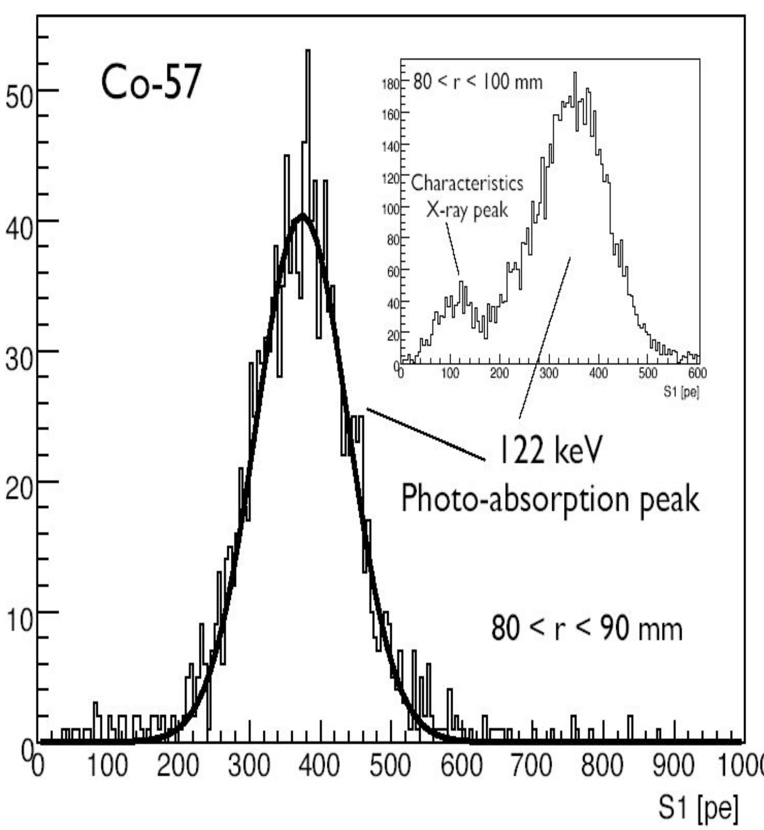
XENON10 Gamma Calibrations

- **Gamma Sources**: ^{57}Co, ^{137}Cs; determine energy scale and resolution; position reconstruction; uniformity of detector response, position of gamma band, electron lifetime: (1.8±0.4) ms => << 1 ppb (O_2 equiv.) purity

energy scale (S1 in p.e)





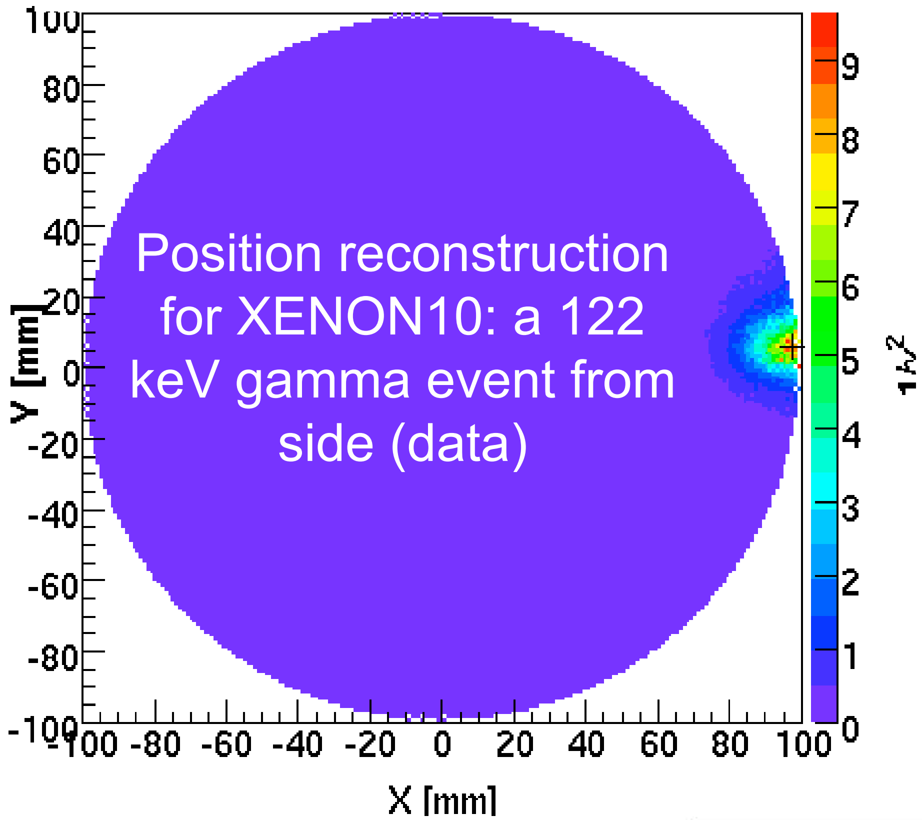


reconstructed source position (^{137}Cs)

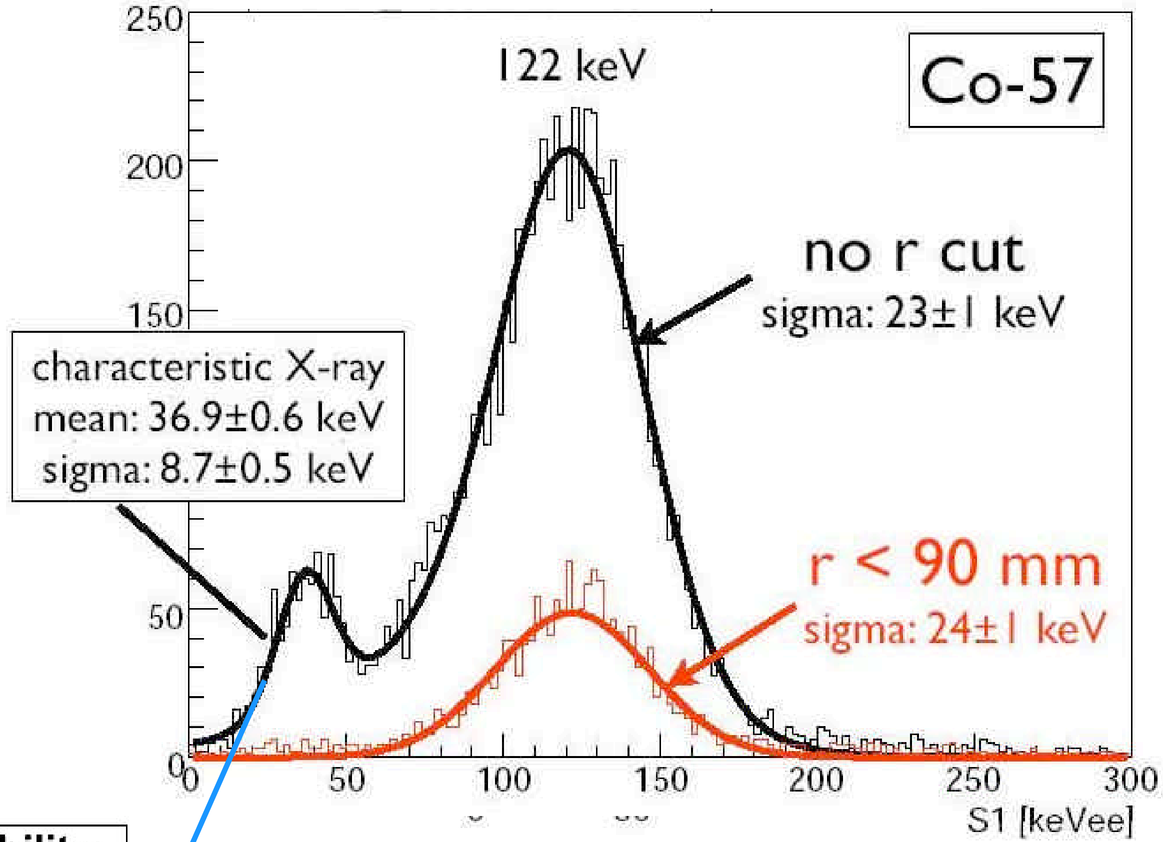
light yield from ^{137}Cs: 2.25 p.e./keV

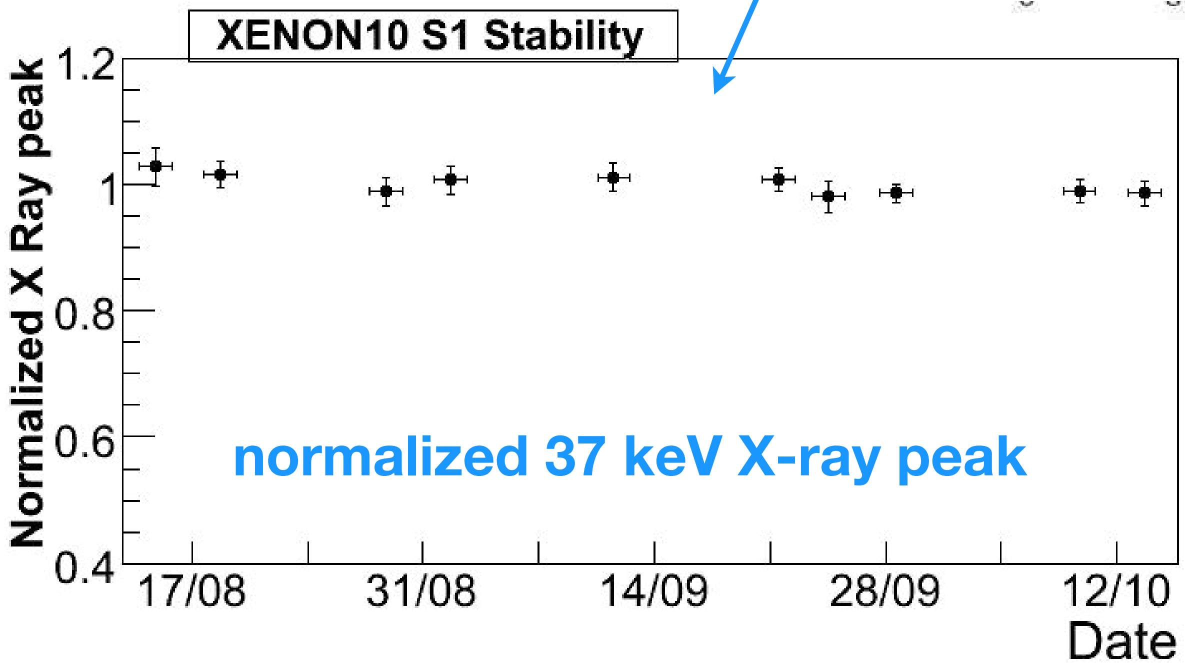
XENON10 Gamma Calibrations

reconstructed source position (^{57}Co)



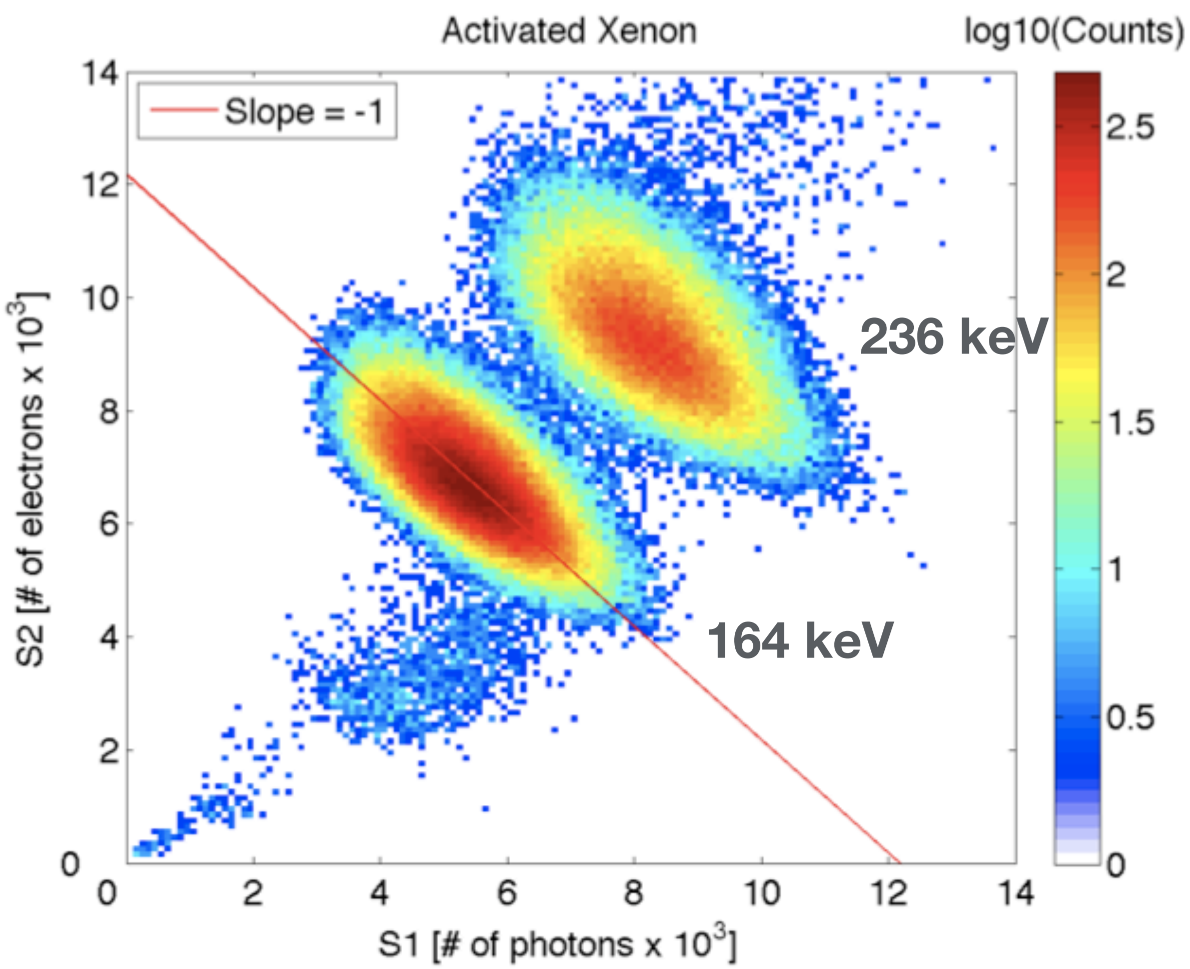
detector stability test: the 37 keV X-ray



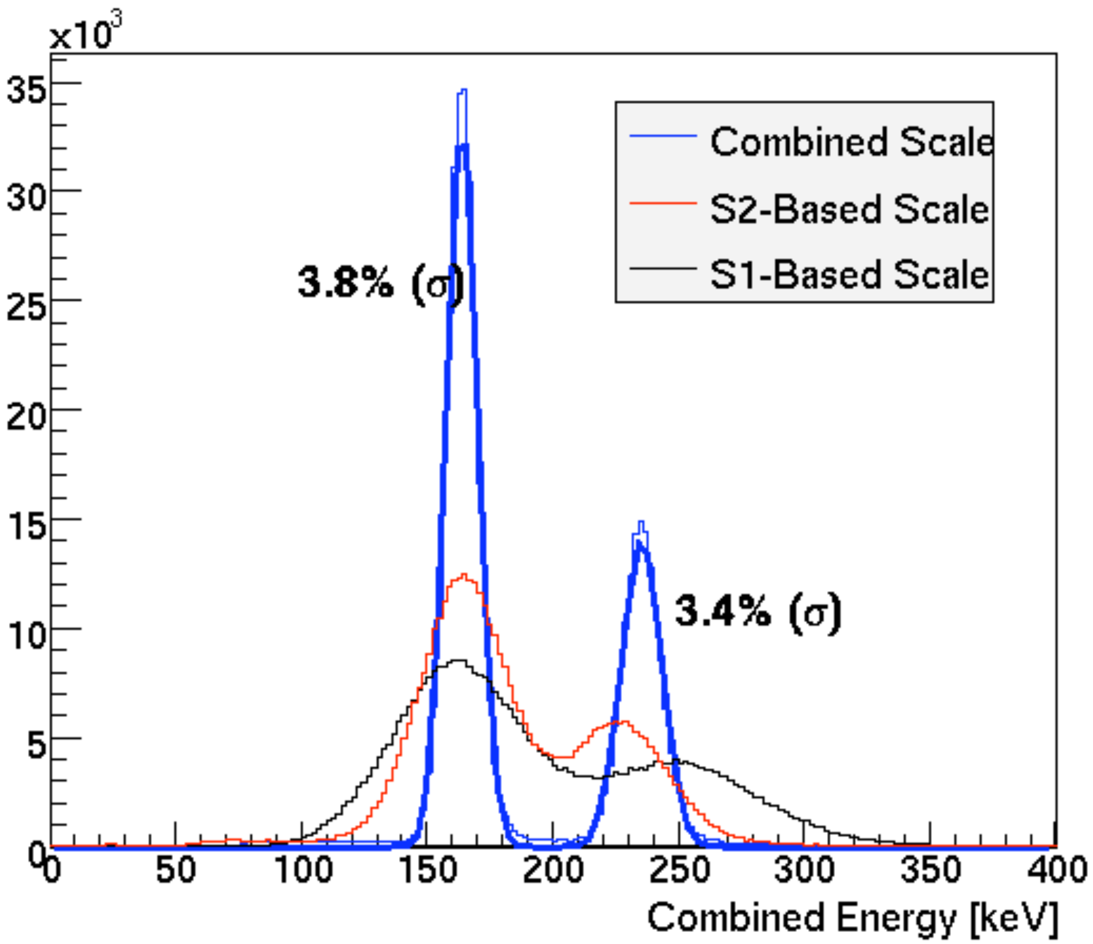


XENON10 Calibration with Activated Xenon

- **Neutron activated Xenon** => 2 meta-stable states, ^{131m}**Xe** (164 keV gamma, $T_{1/2}$=11.8 d), ^{129m}**Xe** (236 keV gamma, $T_{1/2}$ = 8.9 d)
- Uniform position and energy calibration of detector => validate position reconstruction of events in full volume



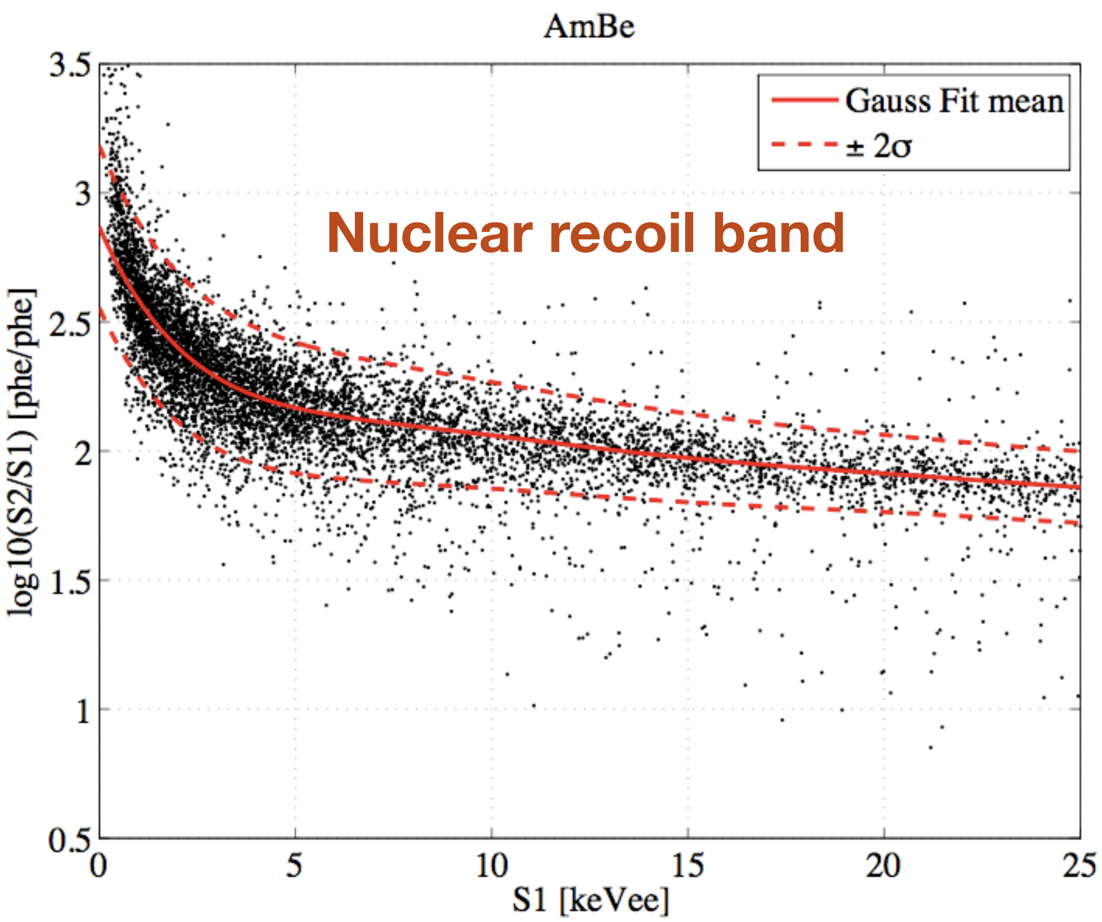
Anti-correlation of charge/light signals

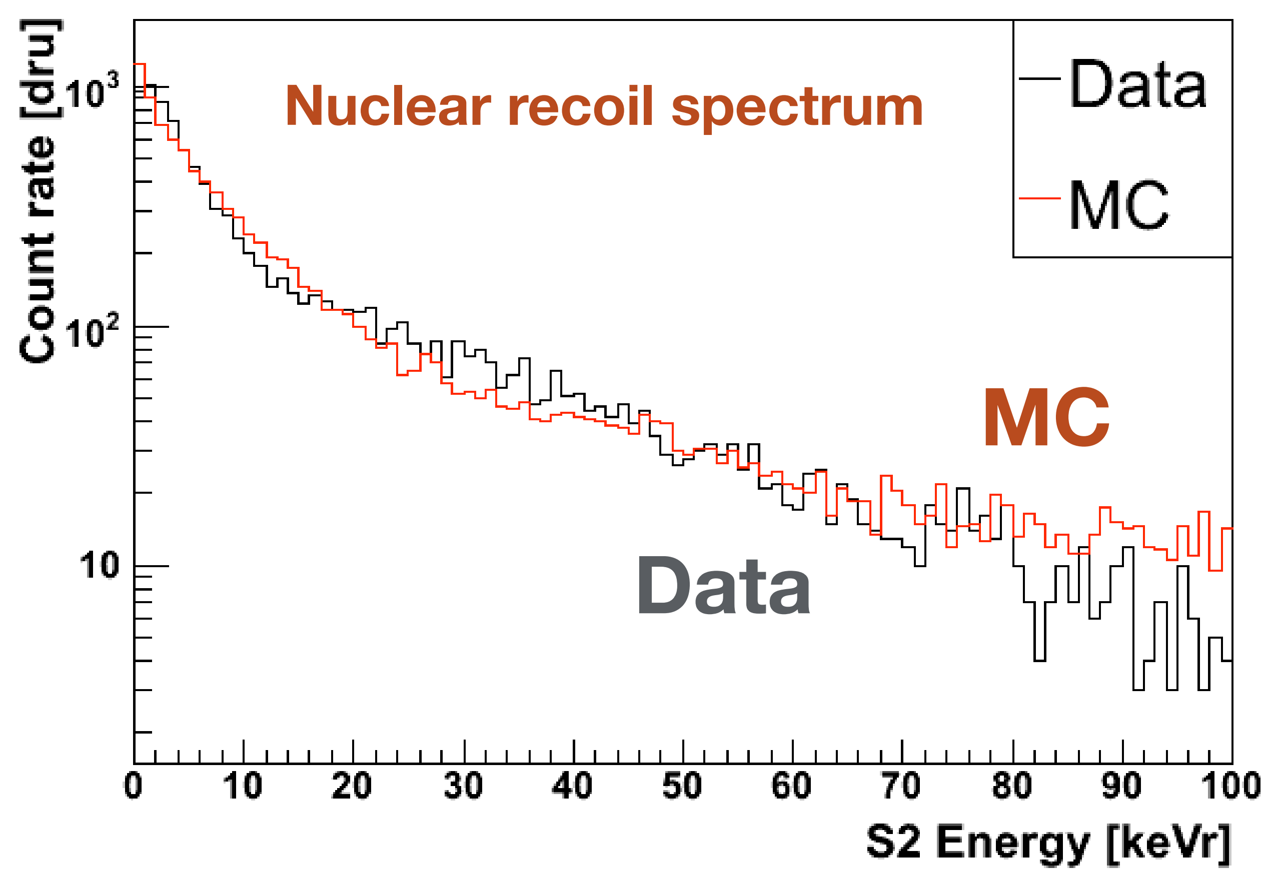


Combined energy spectrum

XENON10 Neutron Calibration

- (Encapsulated) neutron source: **AmBe** (E_{max} ≈ 10 MeV), ~ 3.7 MBq (220 n/s) in shield
- In situ calibration: December 1, 06 => determination of the nuclear recoil band





Data and Monte Carlo agree well:

⇒ NR response at low energies well understood

XENON10 Neutron Calibration

Energy of nuclear recoils (NRs)

Measured signal in nr. of p.e.

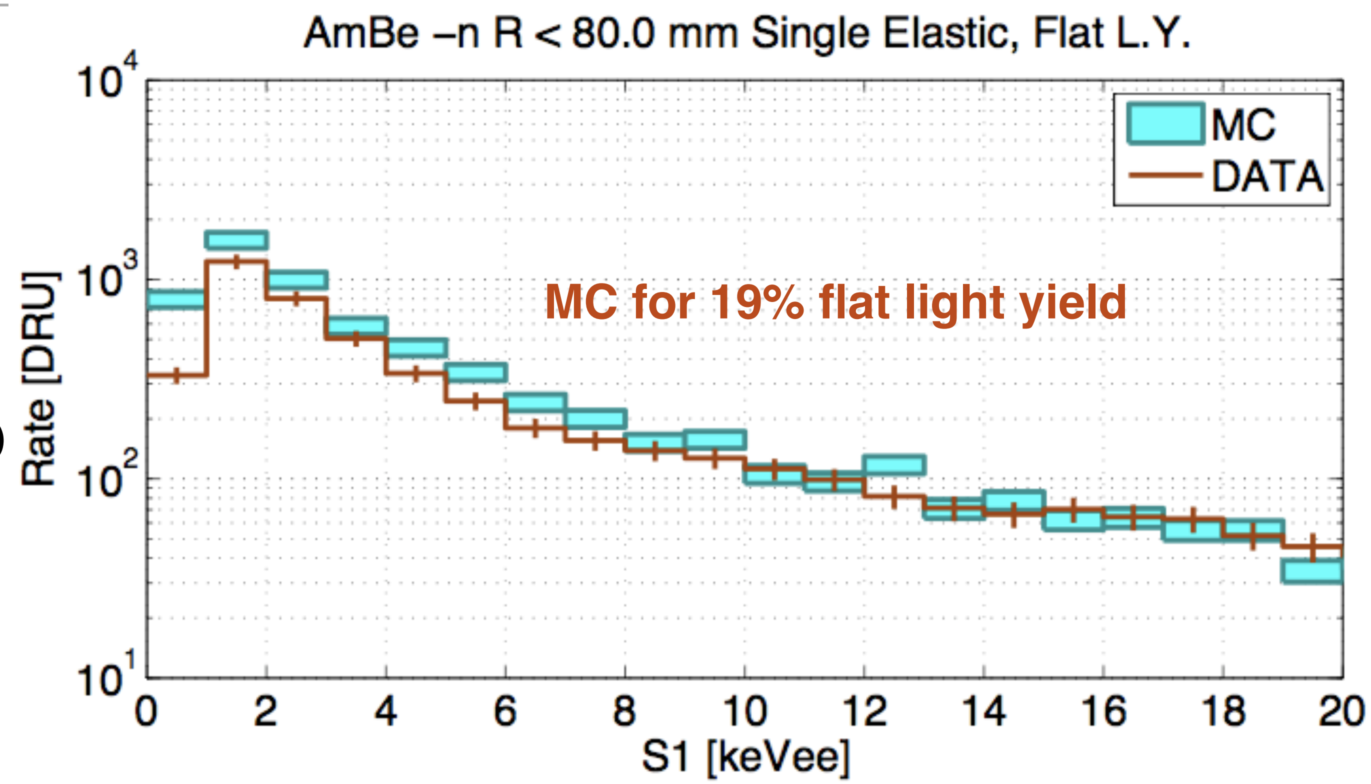
Quenching of scintillation yield for 122 keV γ's due to field (0.54 at 0.73 kV/cm)

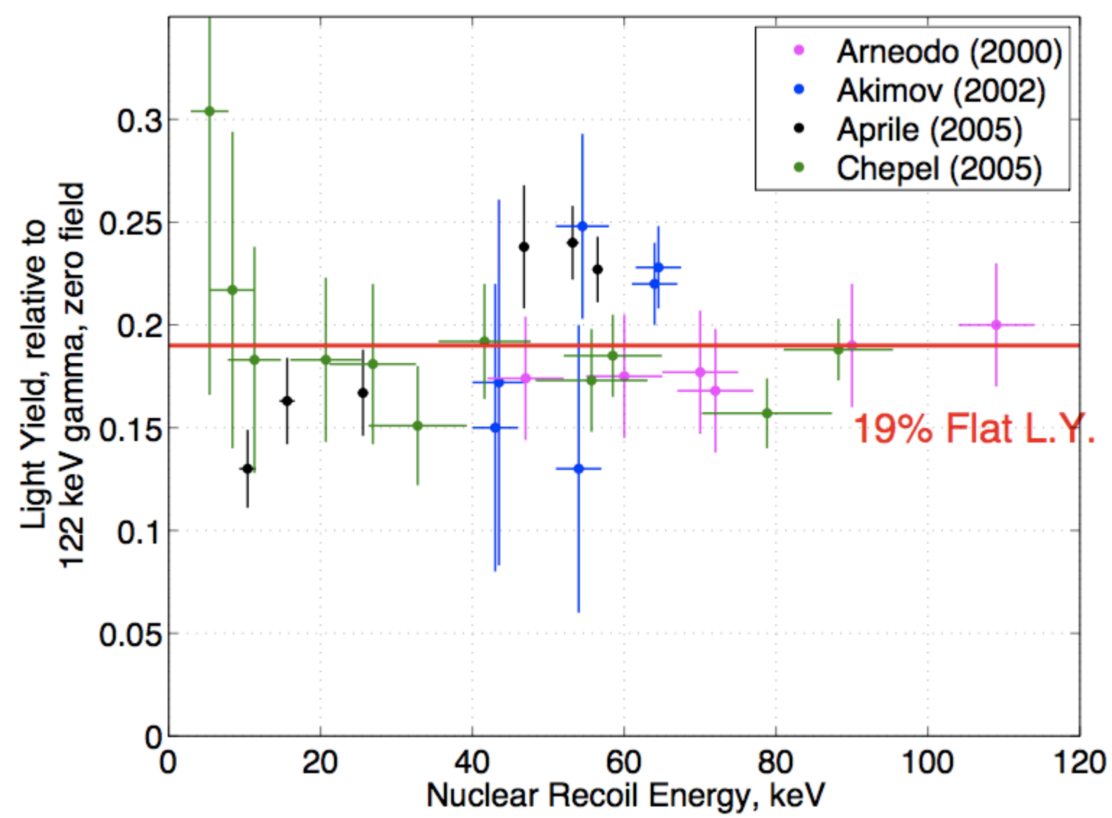
$$E_{nr} = \frac{S1}{L_y \cdot \mathcal{L}_{eff}} \times \frac{S_{er}}{S_{nr}}$$

Light yield for 122 keV γ in p.e. (3.00 p.e./keV)

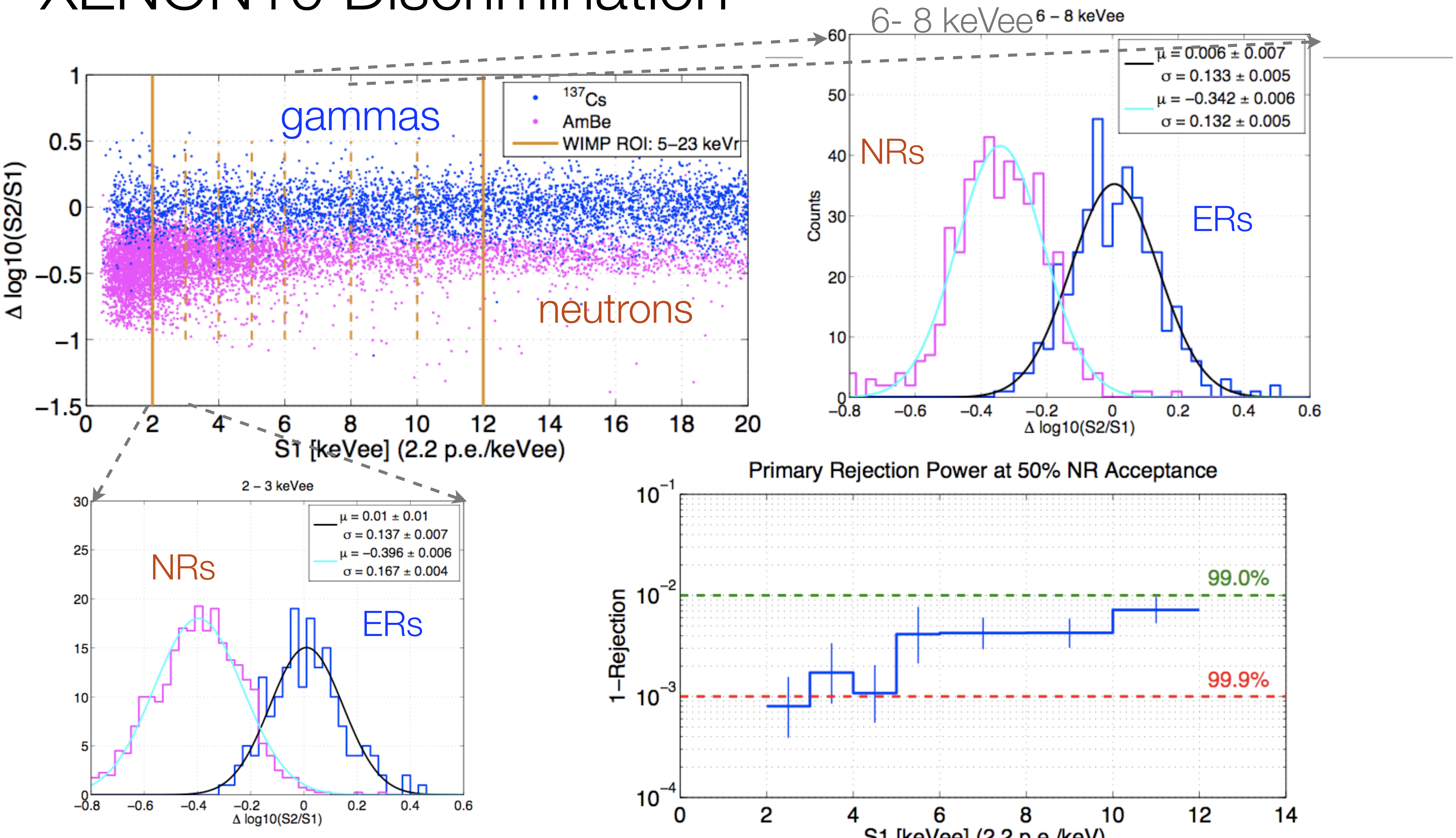
Relative scintillation efficiency of NRs to 122 keV γ's at zero field (flat value: 0.19)

Quenching of scintillation yield for NRs due to field (0.93 at 0.73 kV/cm)





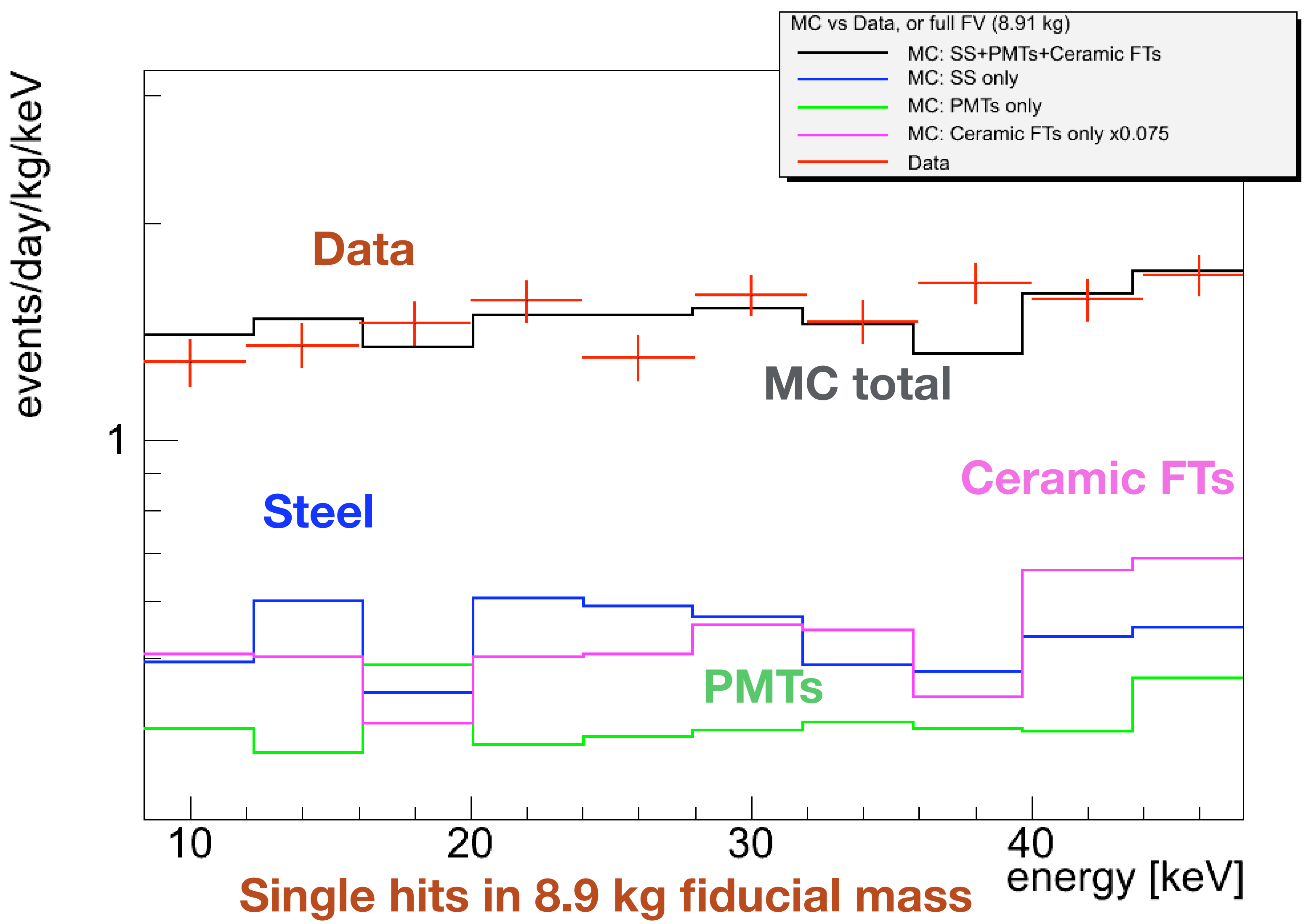
XENON10 Discrimination

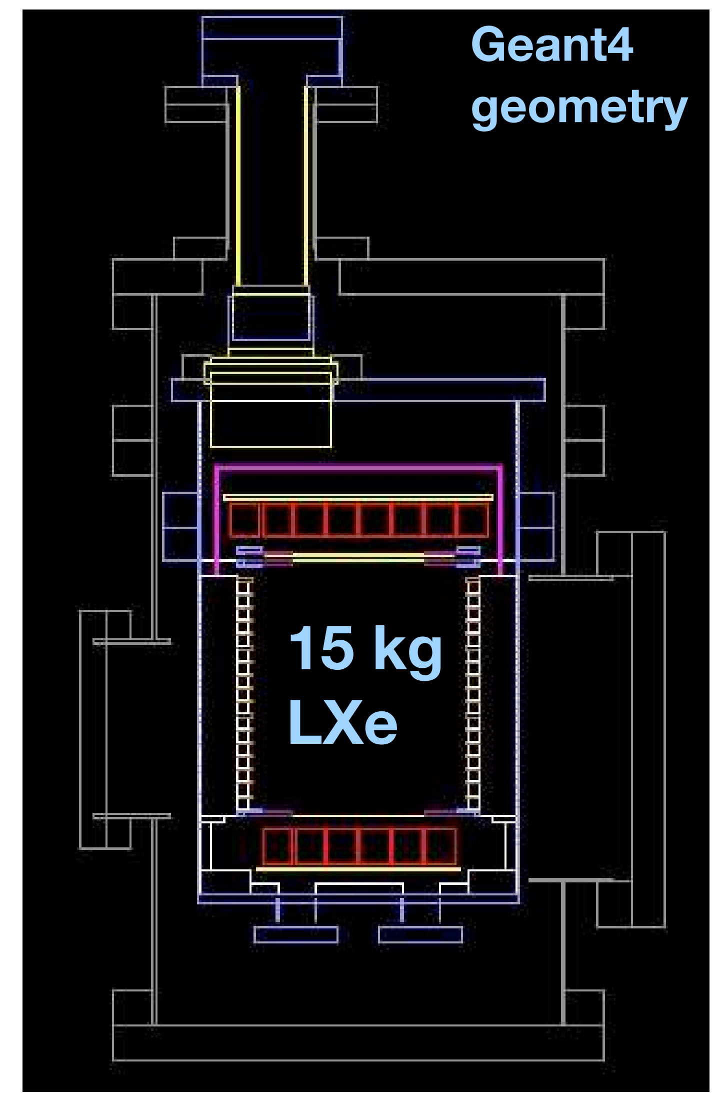


- **Rejection is > 99.6% for 50% Nuclear Recoil acceptance**
  - ➡ **Cuts:** fiducial volume (remove events at teflon edge where poor charge collection)
  - ➡ Multiple scatters (more than one S2 pulse)

XENON10 Backgrounds: Data and MC Simulations

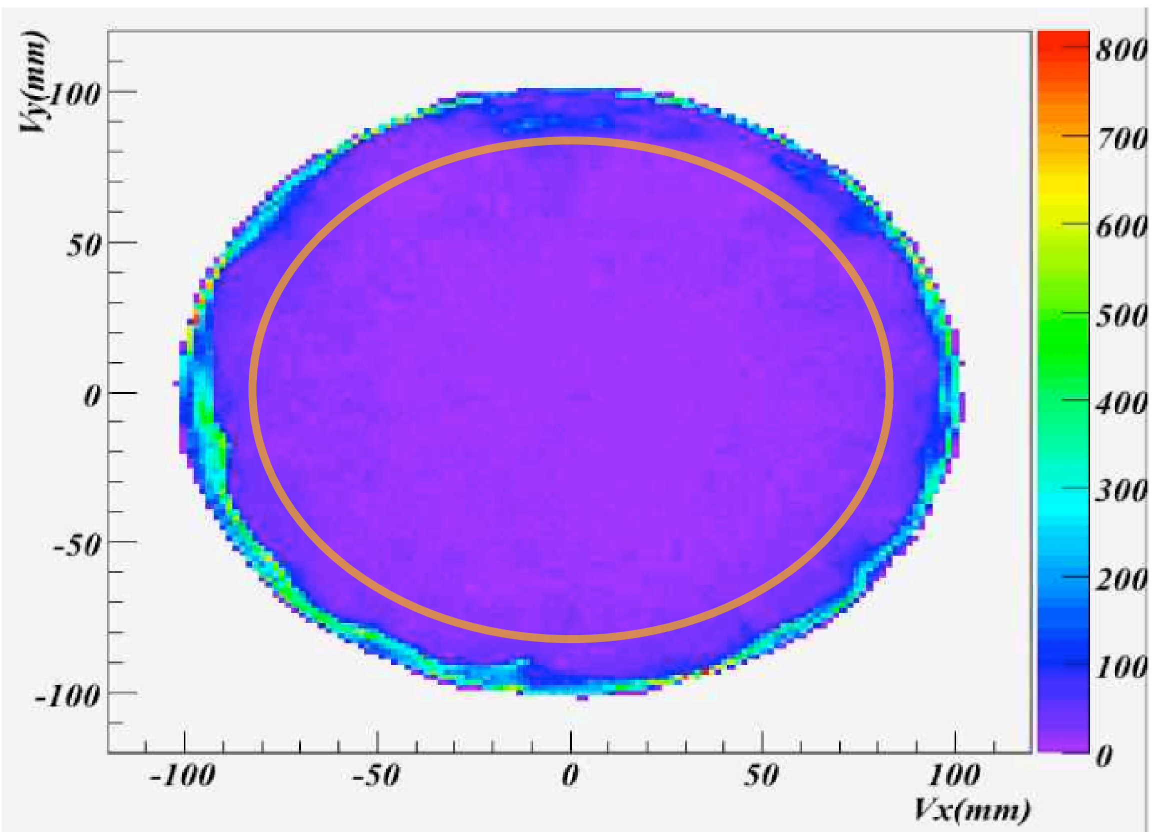
- **Gamma BG**: dominated by steel (inner vessel and cryostat = 180 kg), ceramic FTs, PMTs
- **Neutron BG**: subdominant for XENON10 sensitivity goal (MC: < 1 event/year from (α,n) in materials and < 5 events/year from μ-induced n's)
- **Red crosses**: data; **Black curve**: sum of background contributions from MC
  - ➡ ~ 1event/(kg d keV) (1 dru) (for r < 8 cm fiducial volume cut -> 8.9 kg)

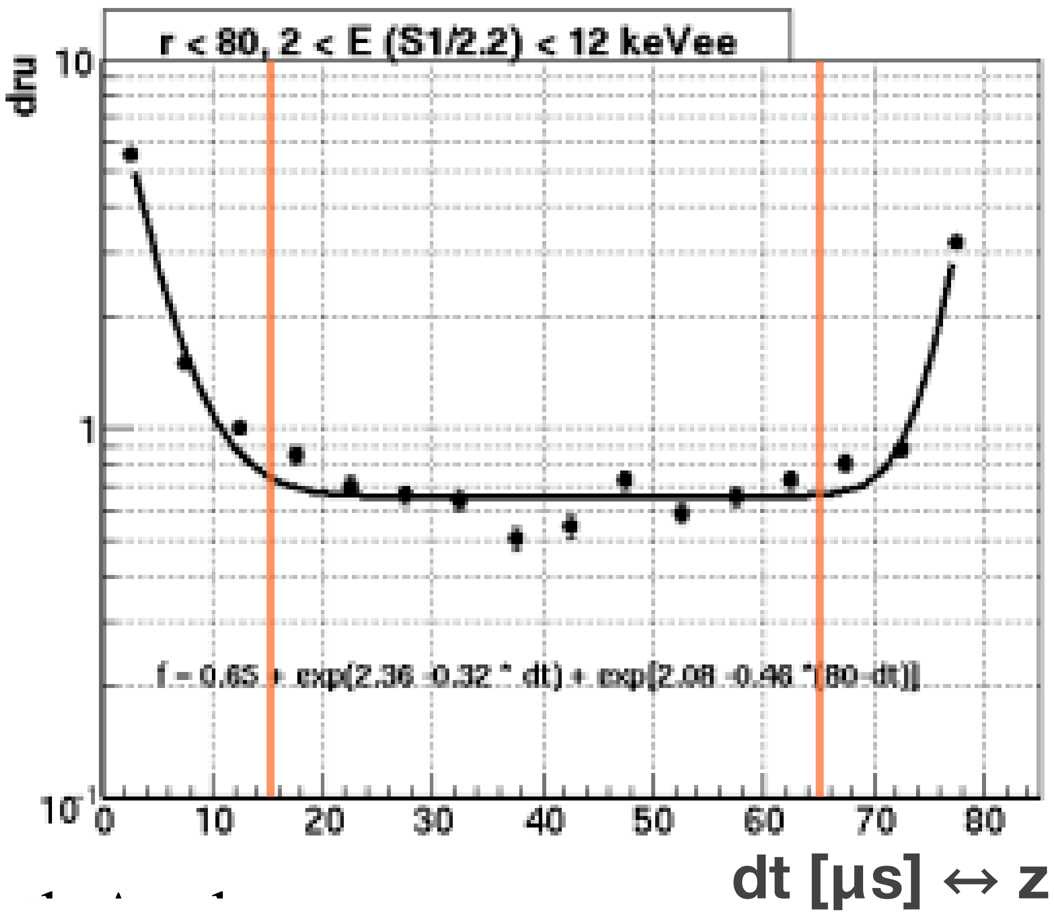




XENON10 Blind WIMP Analysis Cuts

- Energy window: 2 - 12 keVee -> based on 2.2 p.e./keVee
  - ➡Basic Quality Cuts (QC0): remove noisy and uninteresting (no S1, multiples, etc) events
  - ➡Fiducial Volume Cuts (QC1): capitalize on LXe self-shielding
  - ➡High Level Cuts (QC2): remove anomalous events (S1 light pattern)

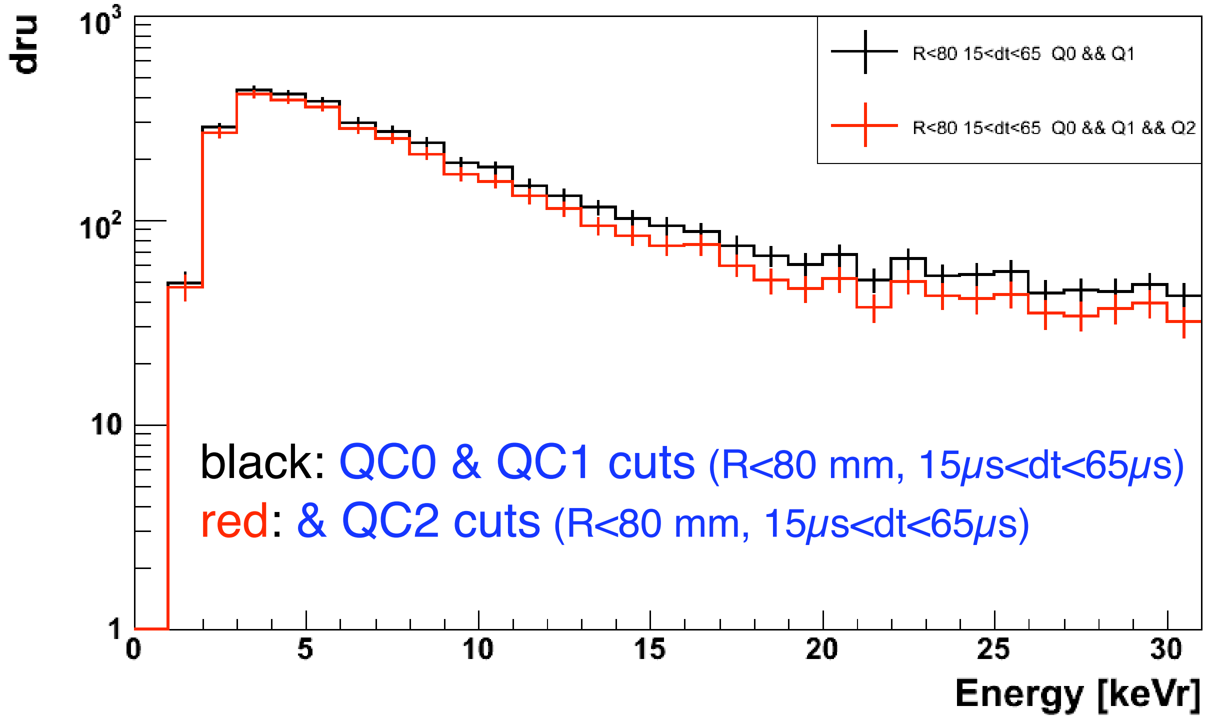


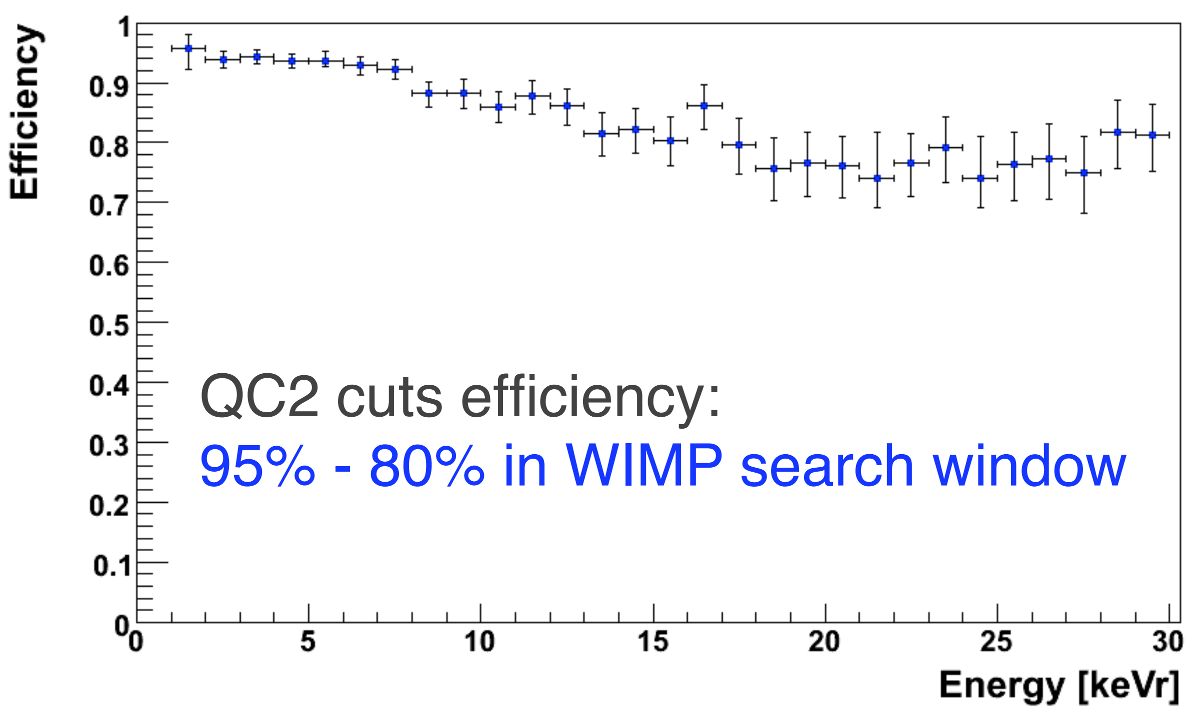


- **Fiducial Volume Cut: 15 μs < dt < 65 μs, r < 80 mm => fiducial mass = 5.4 kg**
- **Overall Background** in Fiducial Volume: ~ **0.6 events/(kg · day · keVee)**

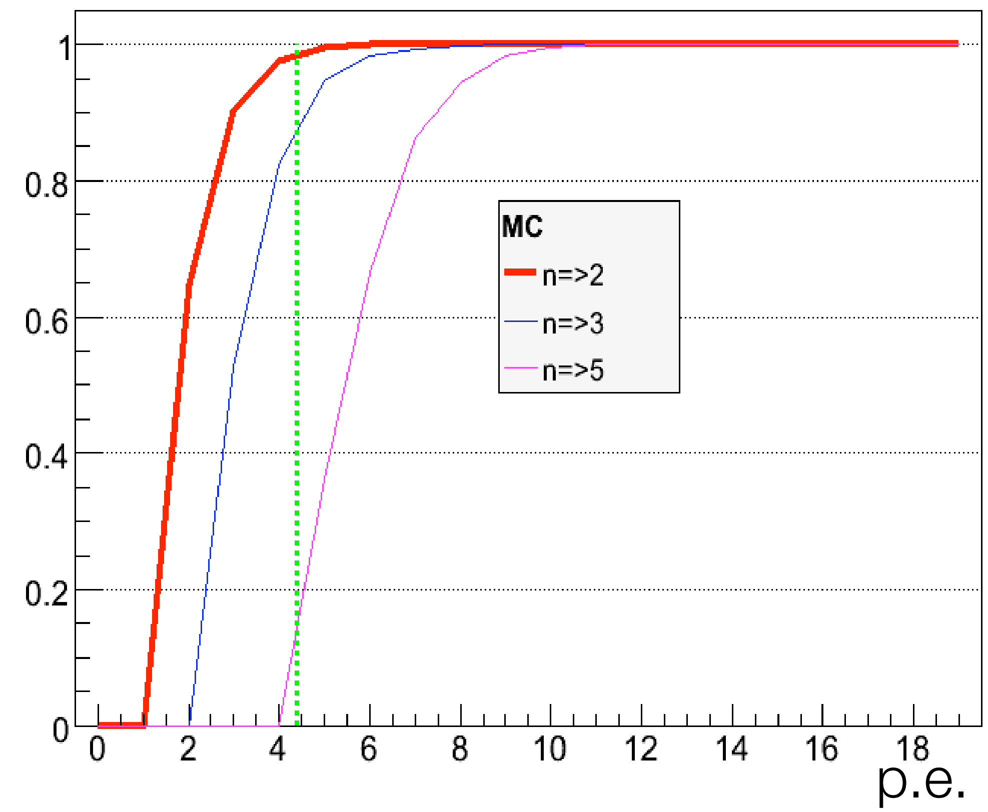
Analysis Cut Efficiencies

neutron data





S1 efficiency

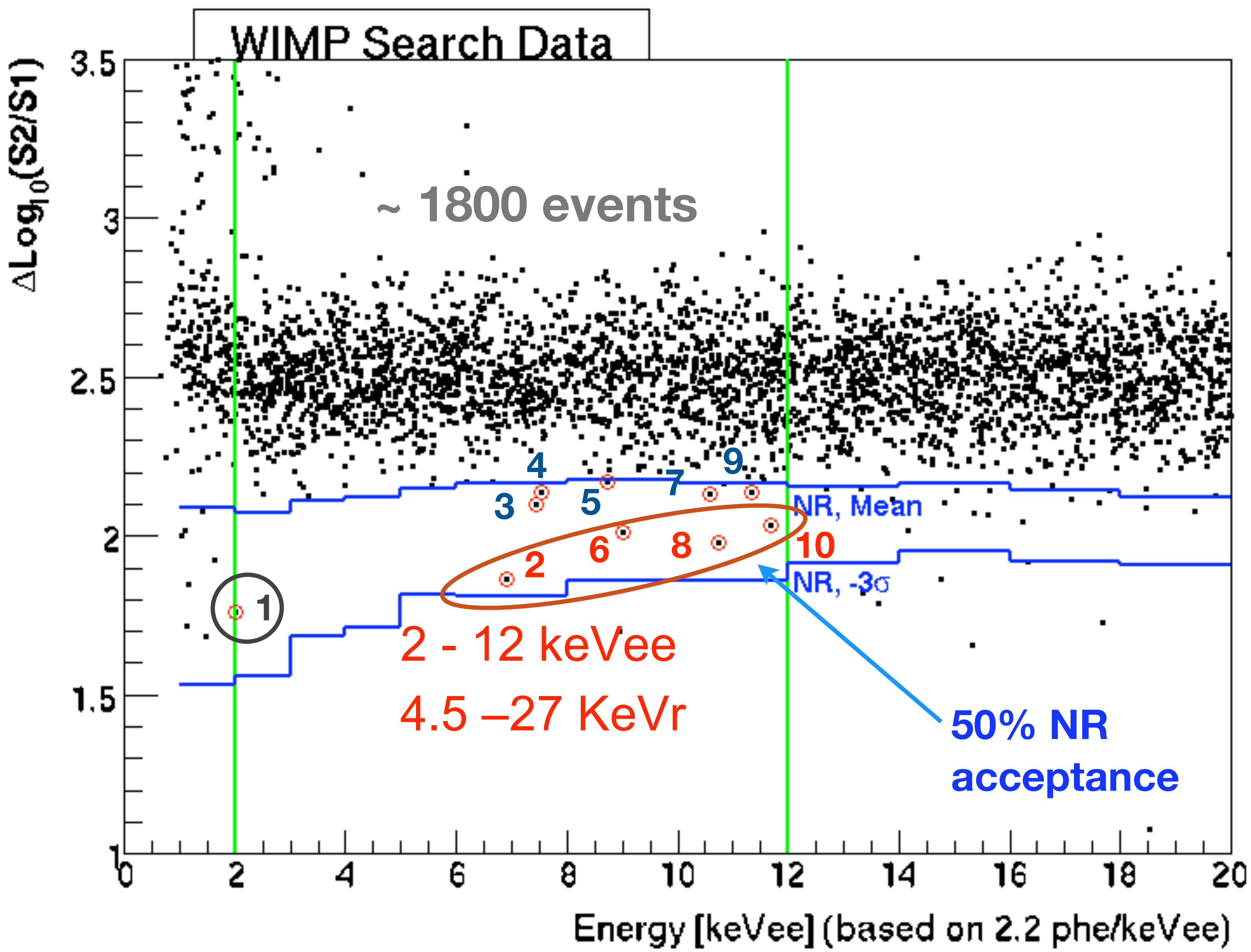


Trigger: S2 sum signal from top PMTs
S2 threshold: 300 p.e. (~ 20 e^-)
(gas gain of a few 100s allows 100% S2 trigger efficiency)

S1 signal associated with S2: searched for in offline analysis -> coincidence of 2 PMT hits
S1 energy threshold is set to 4.4 p.e. (efficiency is 100% at 2 keVee)

XENON10 WIMP Search Data

- WIMP search run Aug. 24. 2006 - Feb. 14, 2007: ~ **60 (blind) live days**
- **136 kg-days exposure** = 58.6 live days × 5.4 kg × 0.86 (ε) × 0.50 (50% NR acceptance)



4.5 keVr **27 keVr**

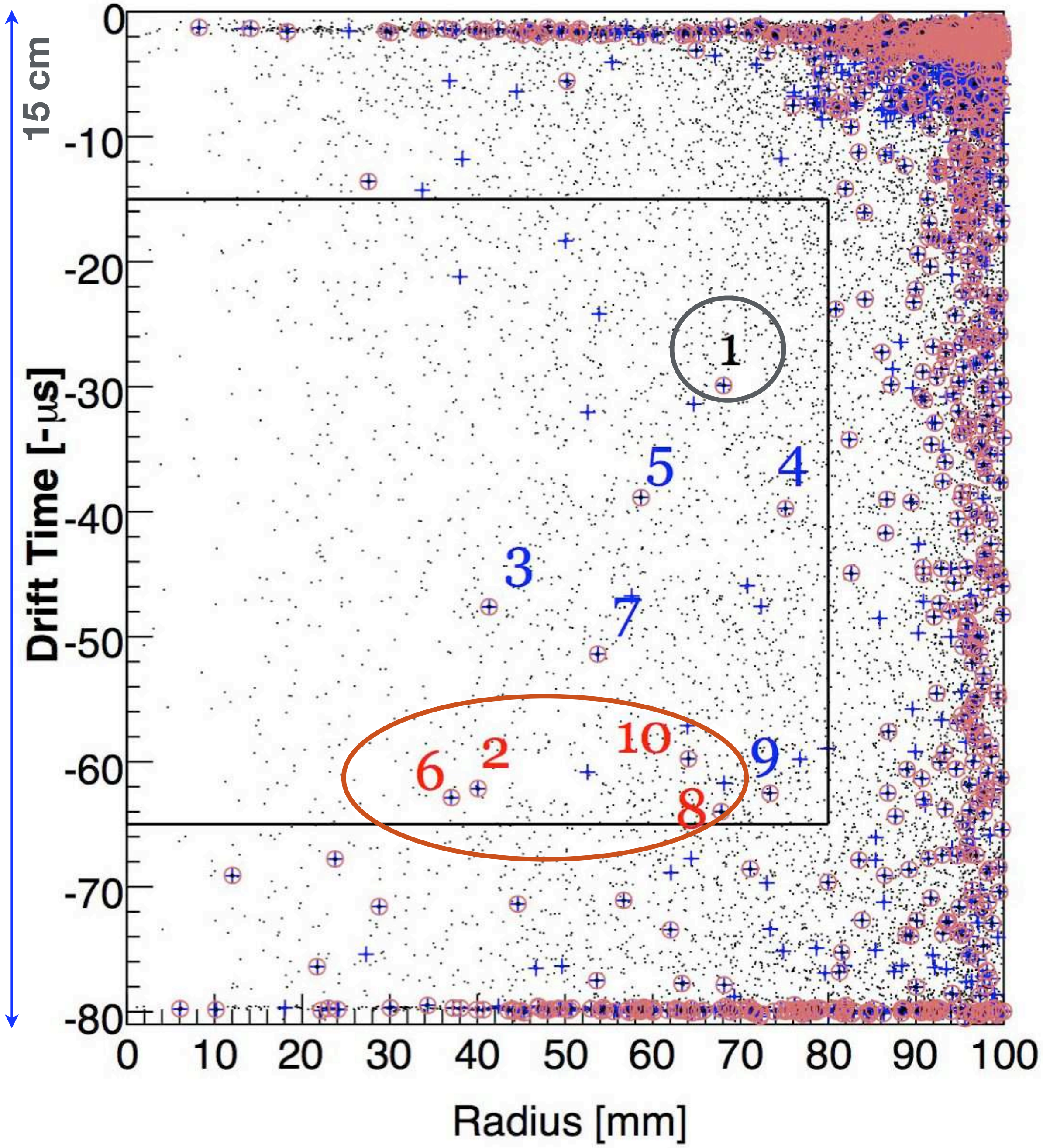
WIMP 'Box' defined at

50% acceptance of NRs (blue lines): [Mean,-3σ]

10 events in 'box' after all cuts
7.0 ($^{+1.4}_{-1.0}$) statistical leakage expected from the gamma (ER) band

NR energy scale based on constant 19% QF

Spatial Distribution of Events



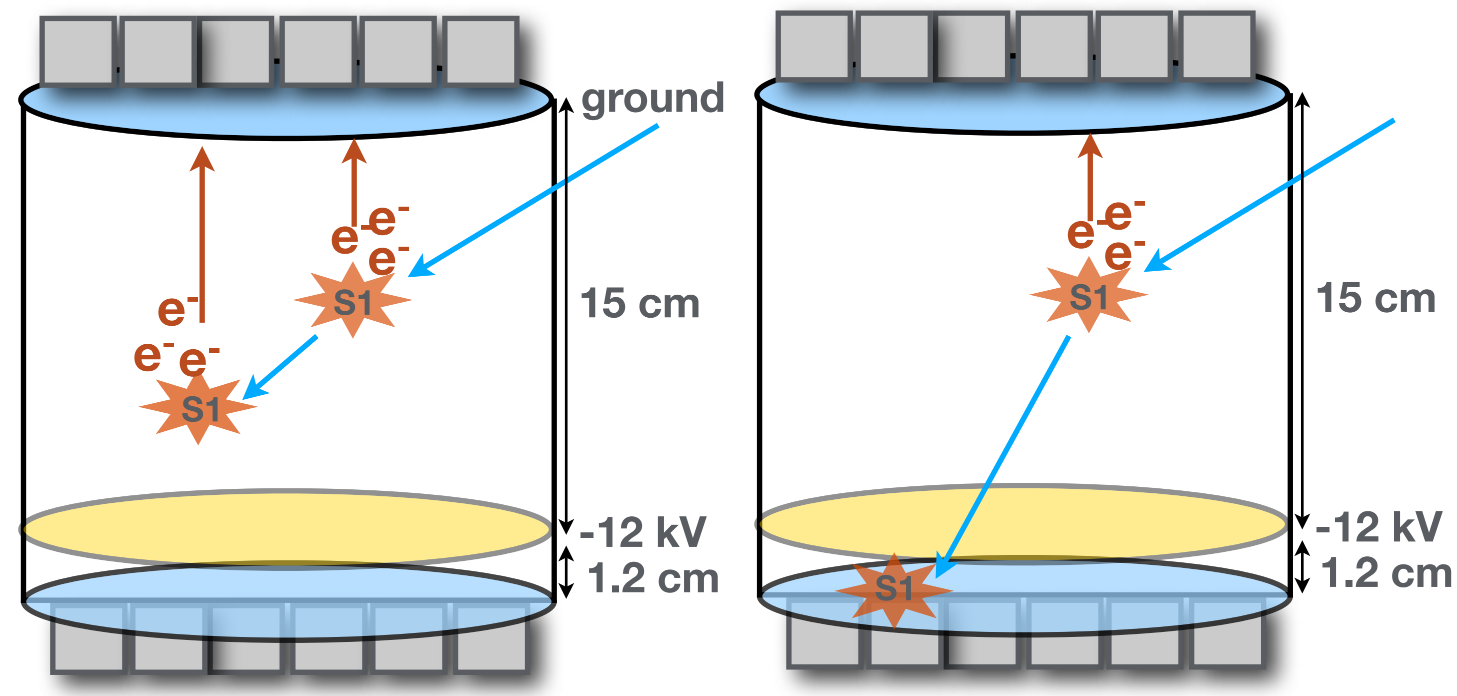
'Gaussian events': nr. 3, 4, 5, 7,9

'Non-Gaussian events': nr: 1, 2, 6, 8, 10

Ev. nr. 1: S1 due to noise glitch (a posteriori)

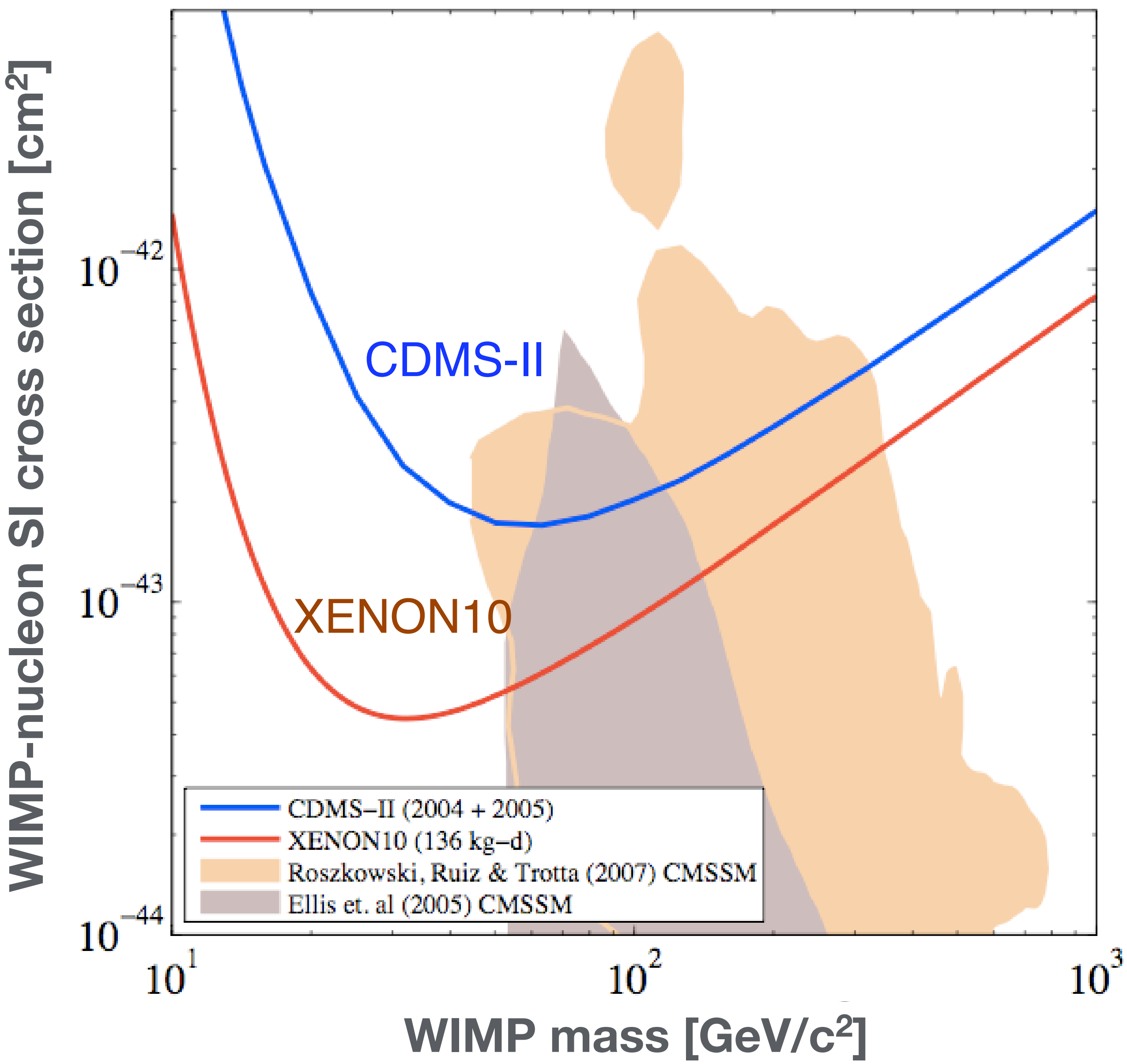
Ev. 2, 6, 8, 9 -> not WIMPs!

Likely explanation: reduced S2/S1-events due to double scatters with one scatter in a 'dead' LXe region => no S2 for 2nd scatter



XENON10 WIMP Search Results for SI Interactions

- To set limits: all 10 events considered, thus no background subtraction performed
- Probe the elastic, SI WIMP-nucleon σ down to ≈ **4×10^{-44} cm²** (at M_{WIMP} = 30 GeV)



Upper limits in WIMP-nucleon cross section derived with Yellin Maximal Gap Method [PRD 66 (2002)]

At 100 GeV WIMP mass

9.0×10^{-44} cm² (no background subtraction, red curve)

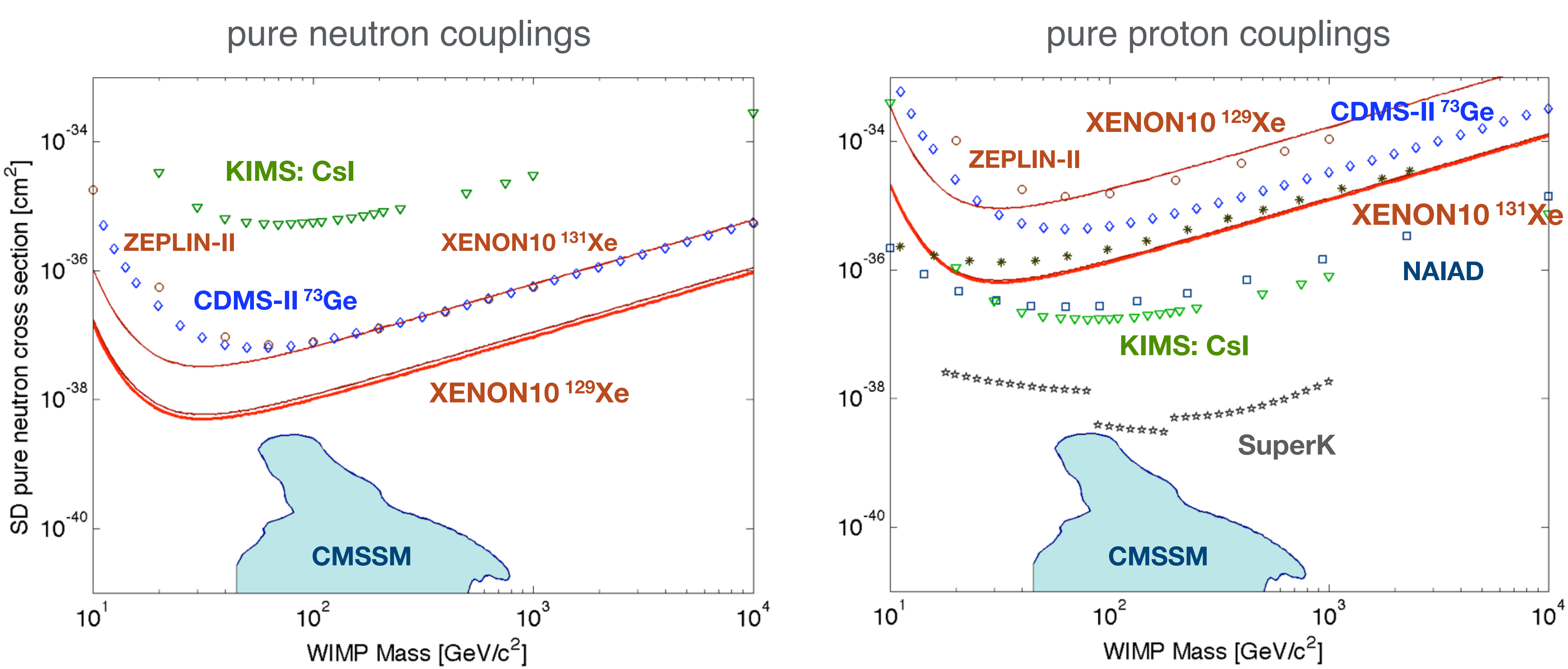
5.5×10^{-44} cm² (known background subtracted, not shown)

Factor 6 below previous best limit

Results submitted to PRL
arXiv:0706.0039 (XENON collaboration)

XENON10 WIMP Search Results for SD Interactions

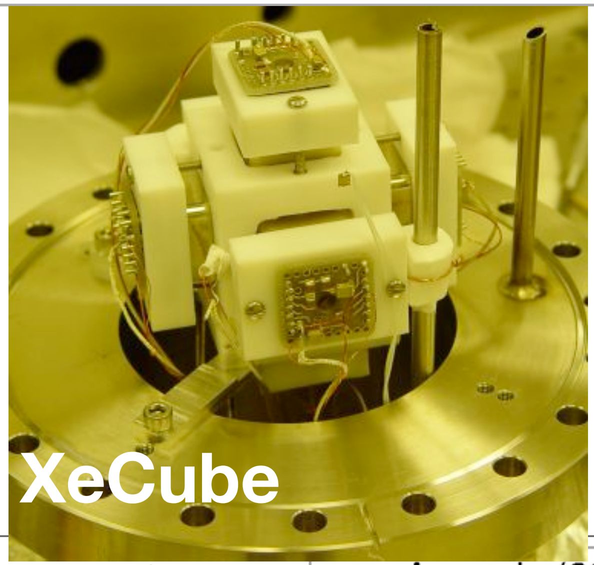
- natural Xe: ^{129}Xe, 26.4 %, spin 1/2, ^{131}Xe, 21.2%, spin 3/2
- use shell-model calculations by Ressel and Dean [PRC 56, 1997] for <S_n>, <S_p>
- upper limits: Yellin Maximal Gap method, **no background subtraction** (paper in preparation)

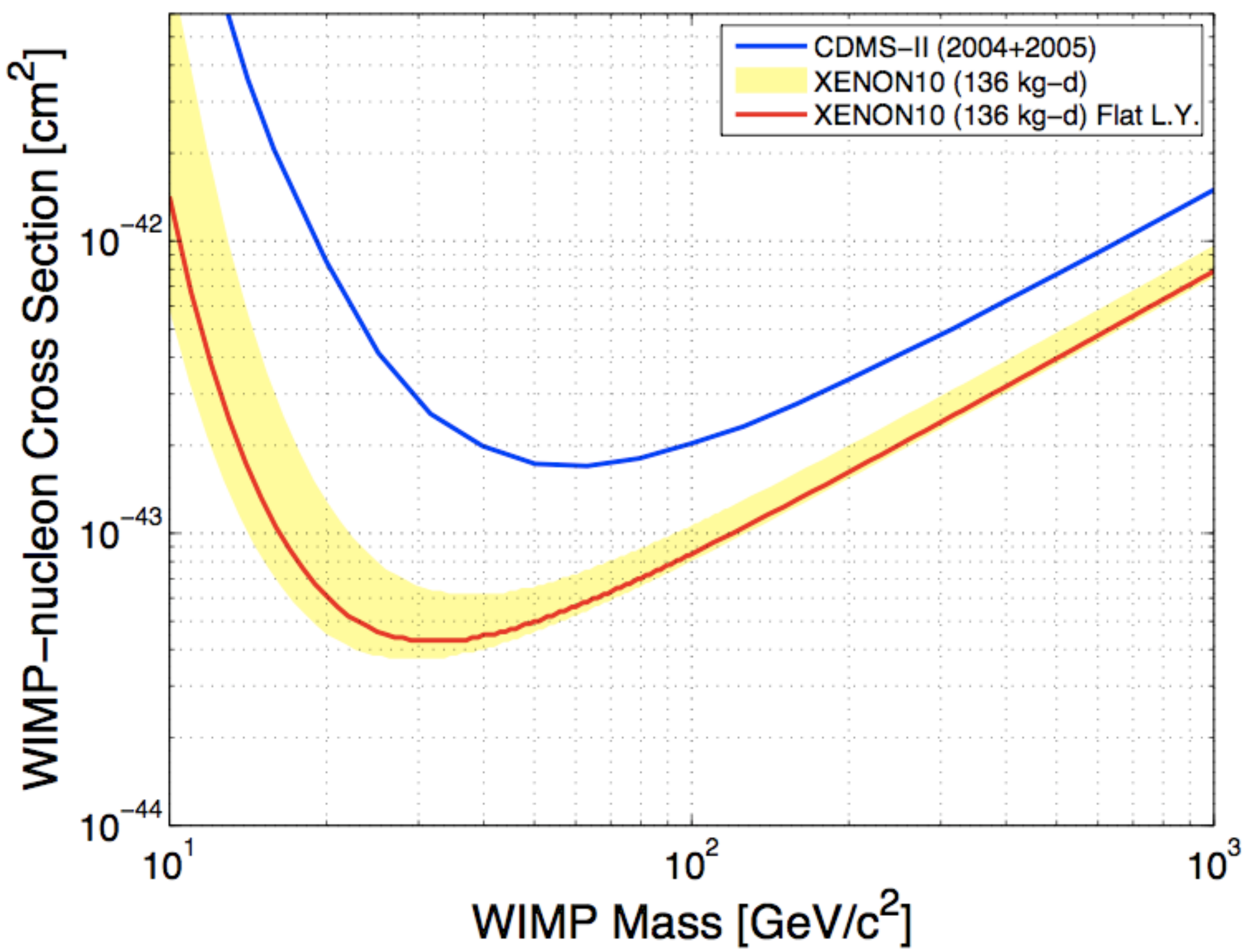


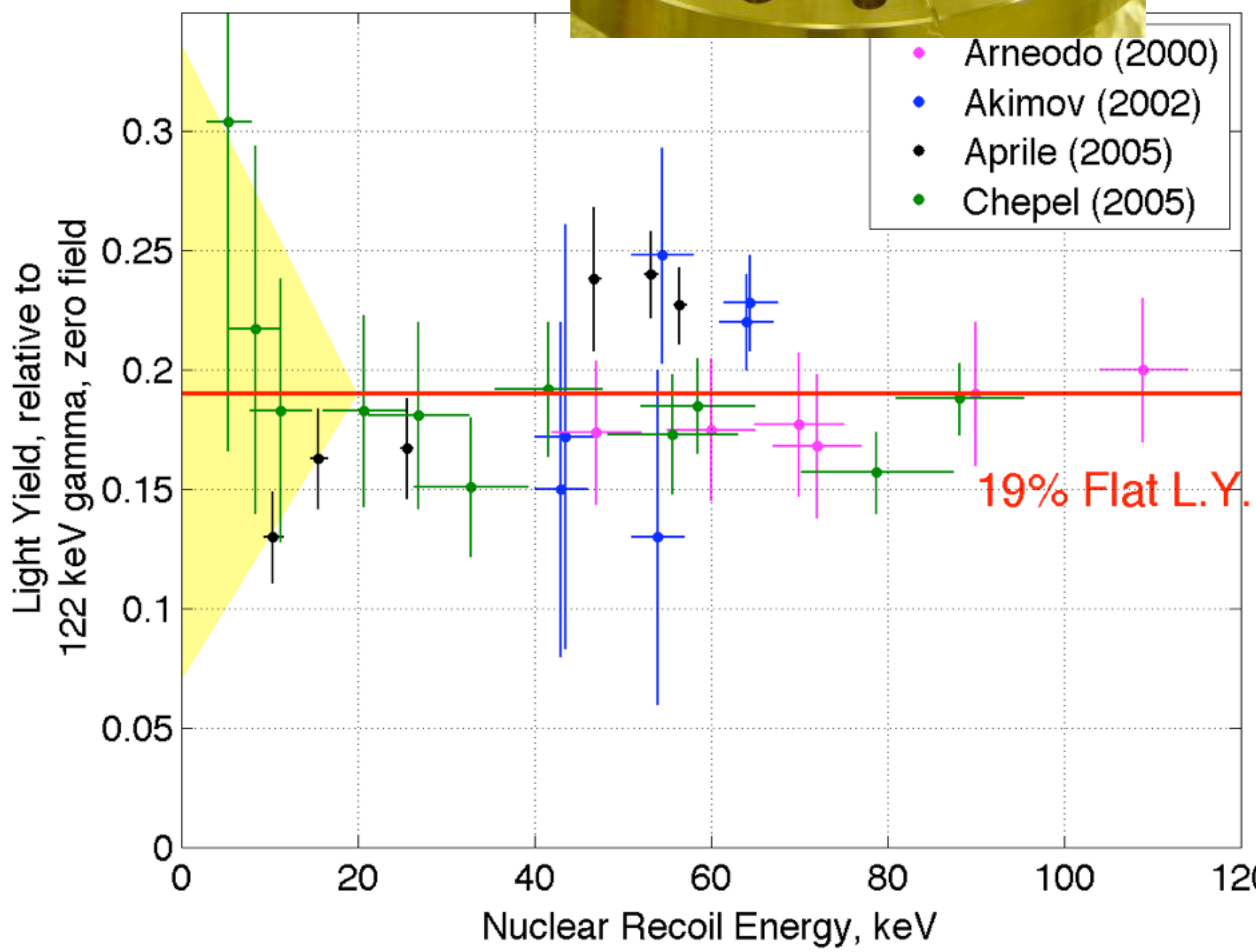
XENON10 Results: Effect of Light Yield Uncertainty

- 19% yield gives good agreement with the AmBe calibration data
- however: new data (4-40 keVr) with n-beam at Nevis (XeCube)

- data analysis ongoing; results to be published soon

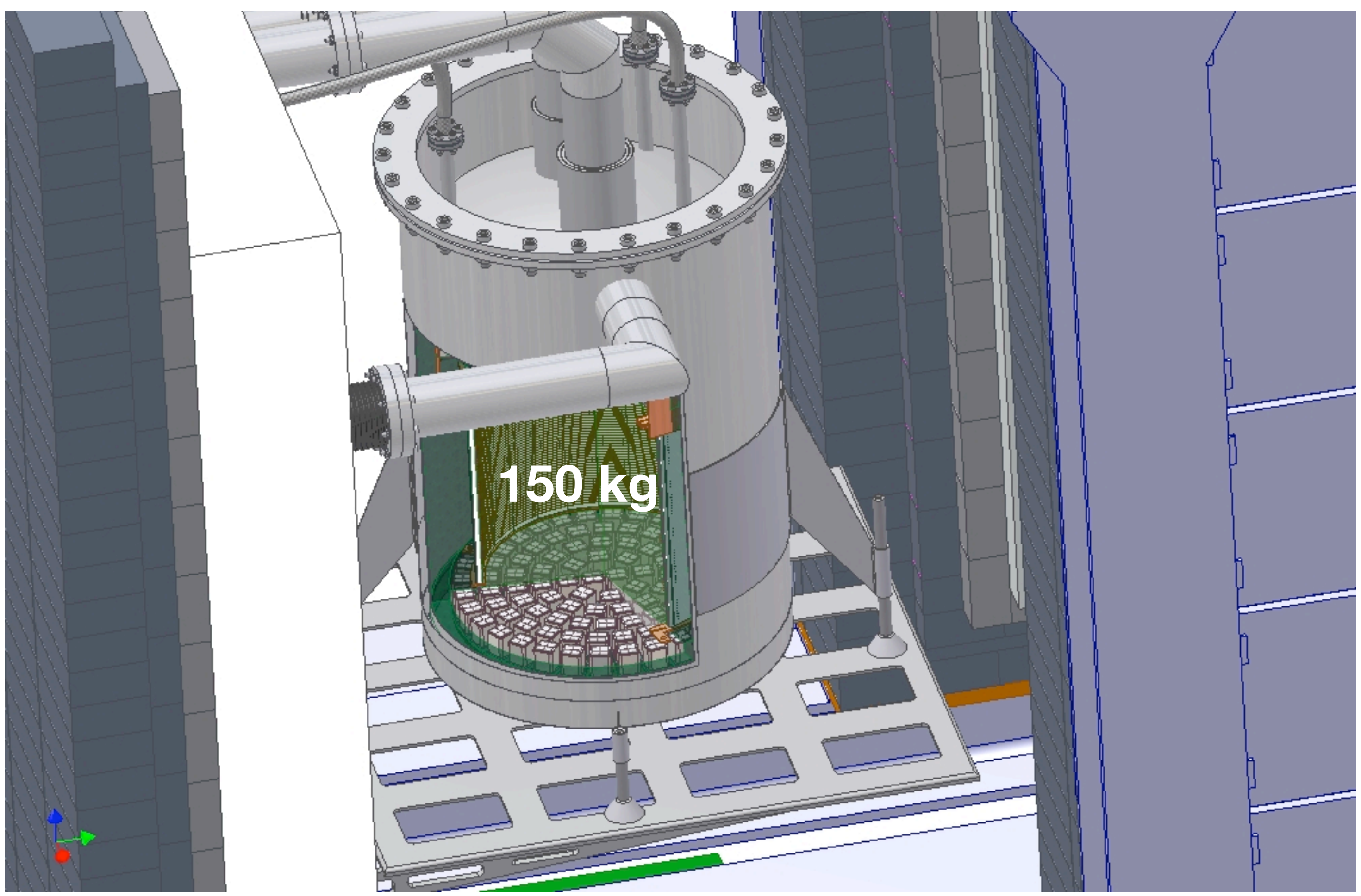


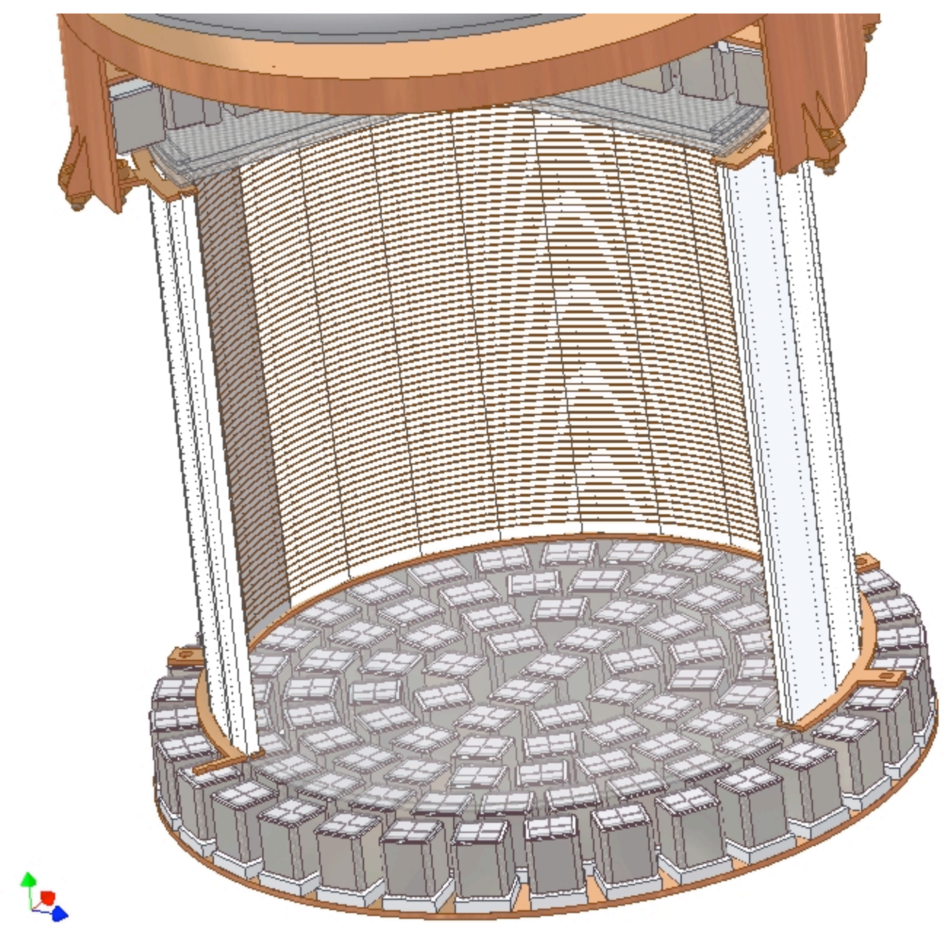




XENON Program 2007-2008

- **New collaboration:** Columbia, Coimbra, LNGS, Rice, Zurich
- **New detector in current shield at LNGS** is under construction:
  - ➡ 150 kg LXe (70 kg target), active LXe veto (factor 3-4 BG reduction vs. passive LXe)
  - ➡ 250 low-activity 1 inch R8520 PMTs, stainless steel cryostat; cryocooler (170 W) and feed-throughs outside the shield
- **New dedicated material screening facility at LNGS**

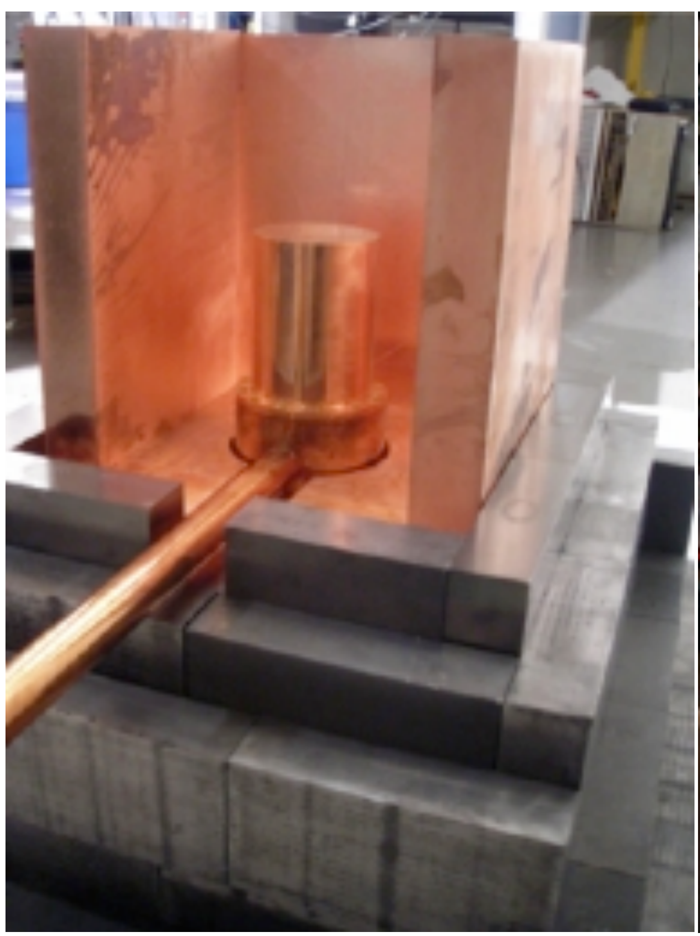


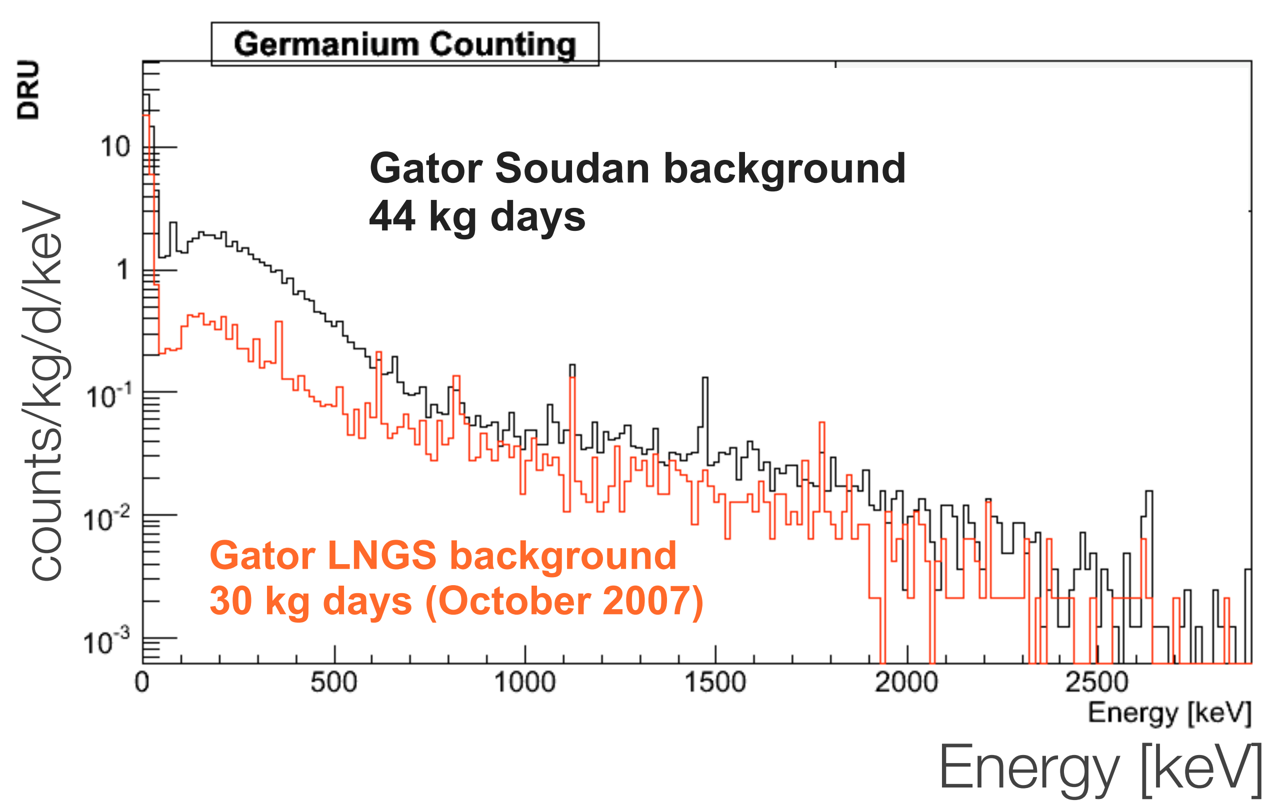


~ 15 cm radius, 30 cm drift (150 μs)

New XENON100 material screening facility

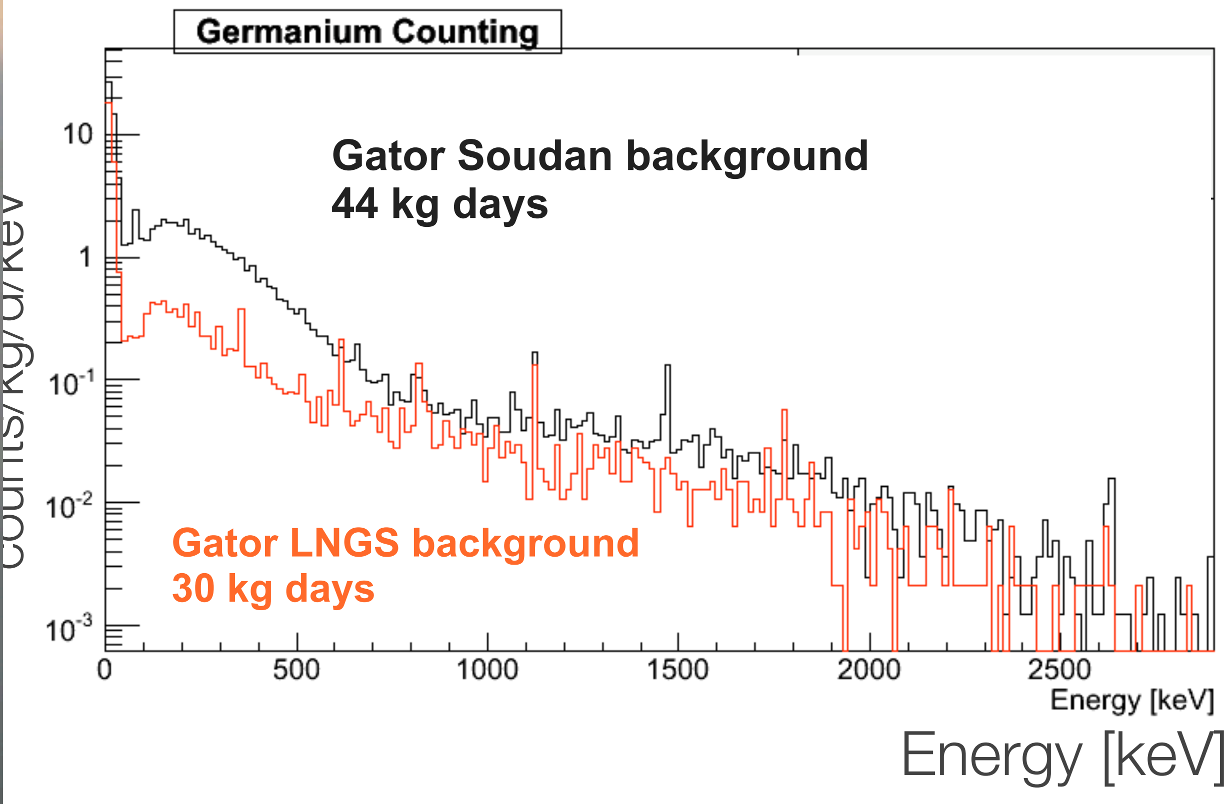
- Ultra-low background, 100 % efficient (2 kg) HPGe-spectrometer
- Shield: 5 cm of OFRP Cu (Norddeutsche Affinerie); 20 cm Plombum Pb (inner 5 cm: 3 Bq/kg 210Pb), air-lock system and Nitrogen purge against Rn
- **First background spectrum: < 1 event/kg d keV above 40 keV**
- Goal: screen all XENON100 detector/shield components for a complete BG model





New XENON100 material screening facility

- Ultra-low background, 100 % efficient (2 kg) HPGe-spectrometer
- Shield: 5 cm of OFHC Cu; 20 cm Plombum Pb (inner 5 cm: 3 Bq/kg 210Pb), air-lock system and Nitrogen purge against Rn
- **First background spectrum: < 1 event/kg d keV above 40 keV**
- Goal: screen all XENON100 detector/shield components for a complete BG model



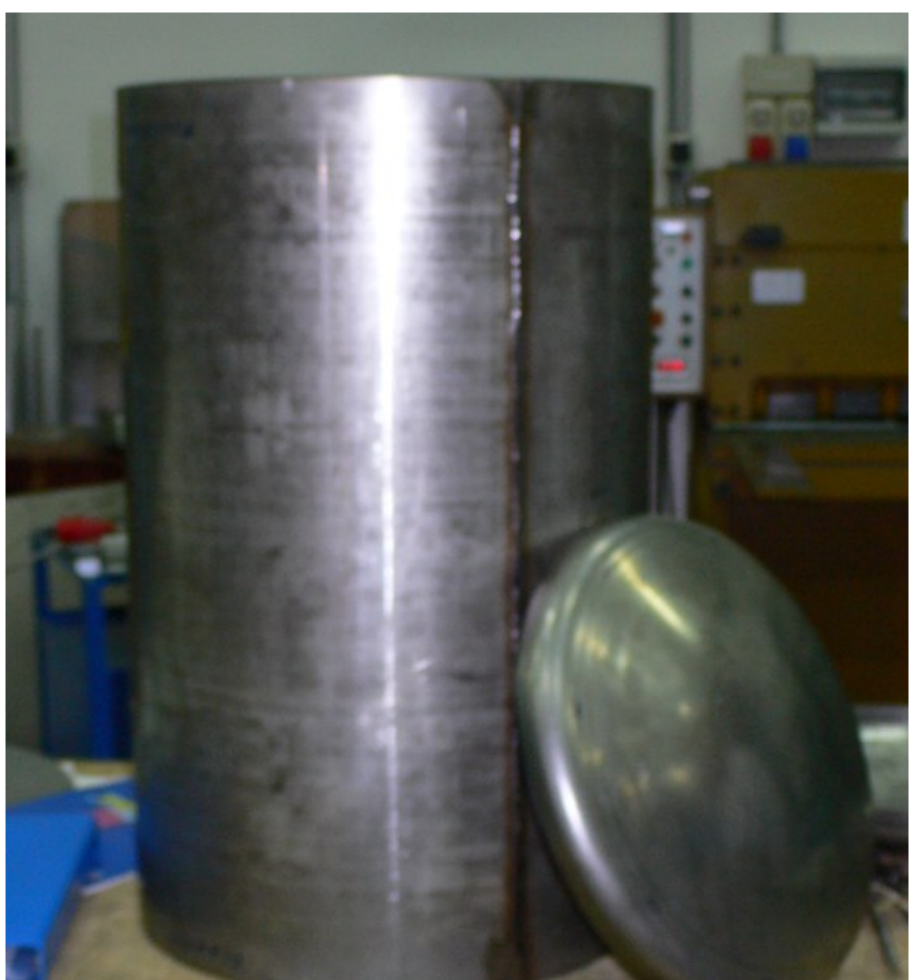
XENON100 Materials Screened at LNGS Facility

Material*	^{238}U	^{232}Th	^{40}K	^{60}Co
Stainless Steel 1.5mm (316Ti, Nironit)	<2 mBq/kg	<2 mBq/kg	10.5 mBq/kg	8.5 mBq/kg
Stainless Steel 25mm (316Ti, Nironit)	<1.3 mBq/kg	<0.9 mBq/kg	<7.1 mBq/kg	1.4 mBq/kg
PMTs (R8520-AL)	0.25 mBq/PMT	0.19 mBq/PMT	7.0 mBq/PMT	0.67 mBq/PMT
PMT Bases	0.16 mBq/pc	0.10 mBq/pc	<0.16 mBq/pc	<0.01 mBq/pc

*: a selection, thanks to Matthias Laubenstein, LNGS

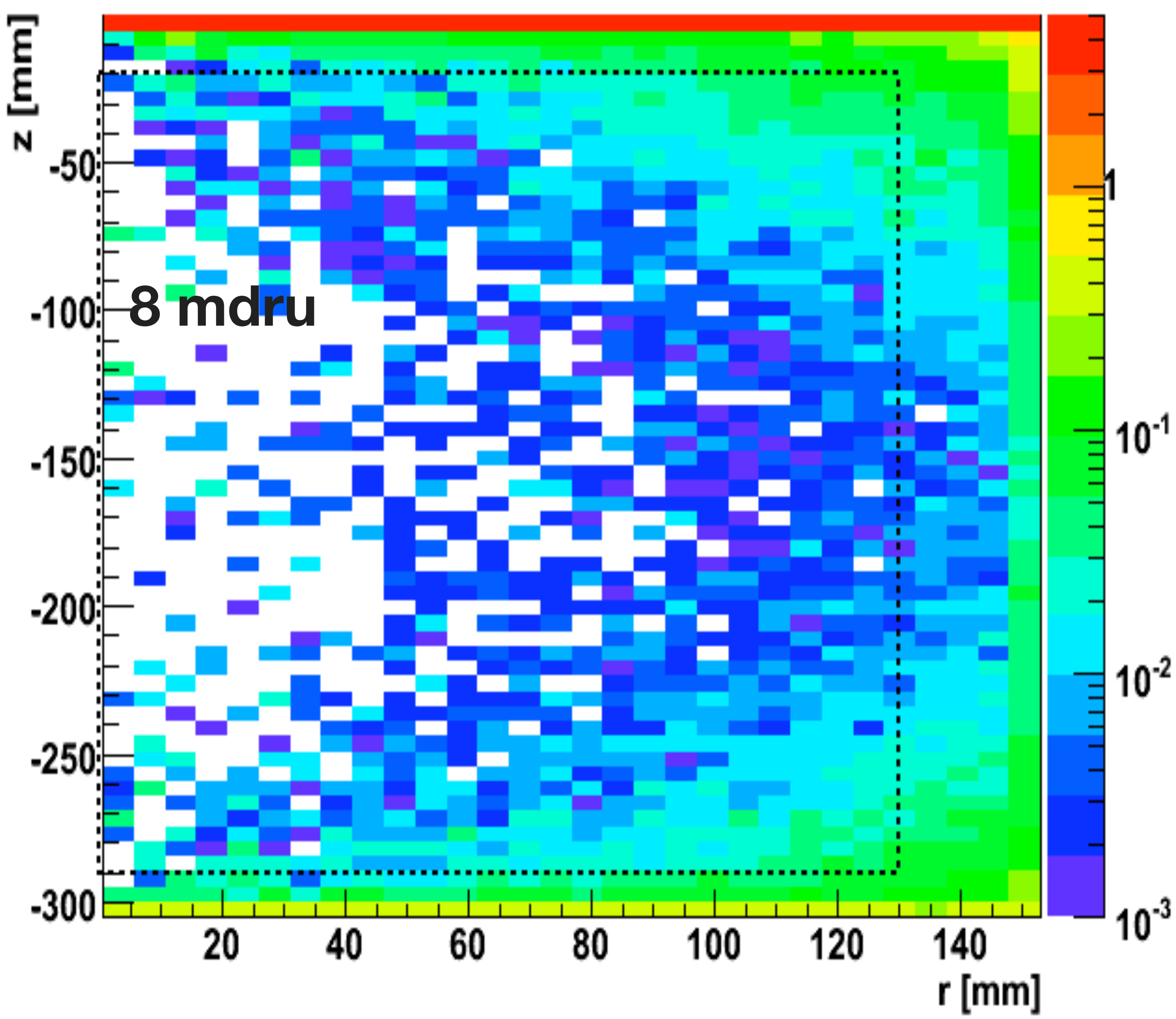
Status of XENON100

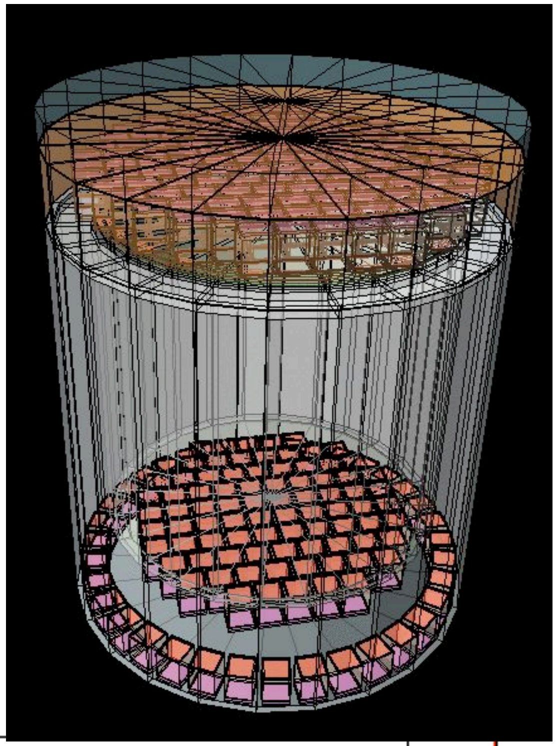
- high-purity, double walled stainless steel cryostat being assembled at LNGS
- PMT production and screening is on schedule (bottom array > 33% QE)
- PTFE inner TPC (custom mold); OFRP NA Cu for bell + inner PMT holder
- 150 kg Xe purchased and being purified to ppt ^{85}Kr-levels ($T_{1/2}$ = 10.7 y, β^- 678 keV)
- commission early 2008 expect to test cross sections $\lesssim 9 \times 10^{-45}$ cm^2 (at 100 GeV WIMP)

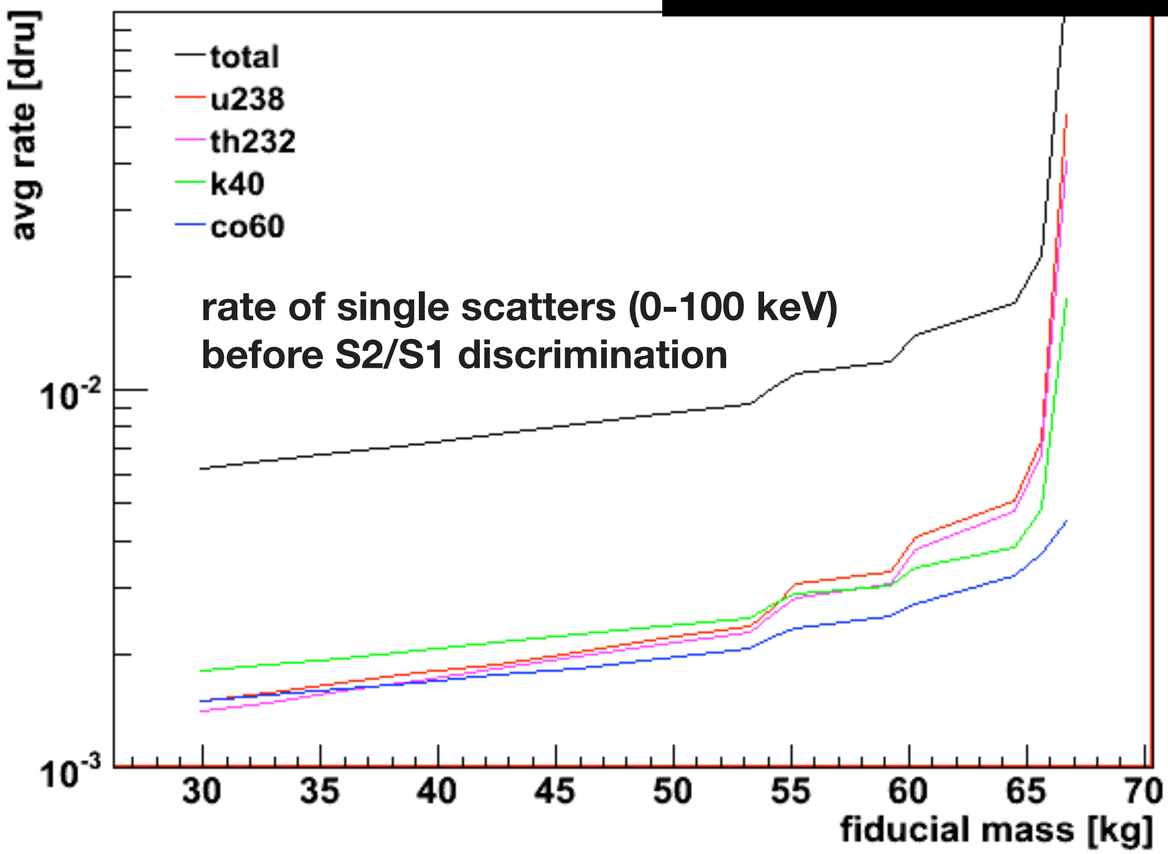


XENON100: expected Gamma Background

- background from U/Th/K/Co in stainless steel cryostat & PMTs
- active LXe veto shield on sides, and top/bottom of target mass
- assume E_{th} = 50 keV for active veto







XENON100 Collaboration

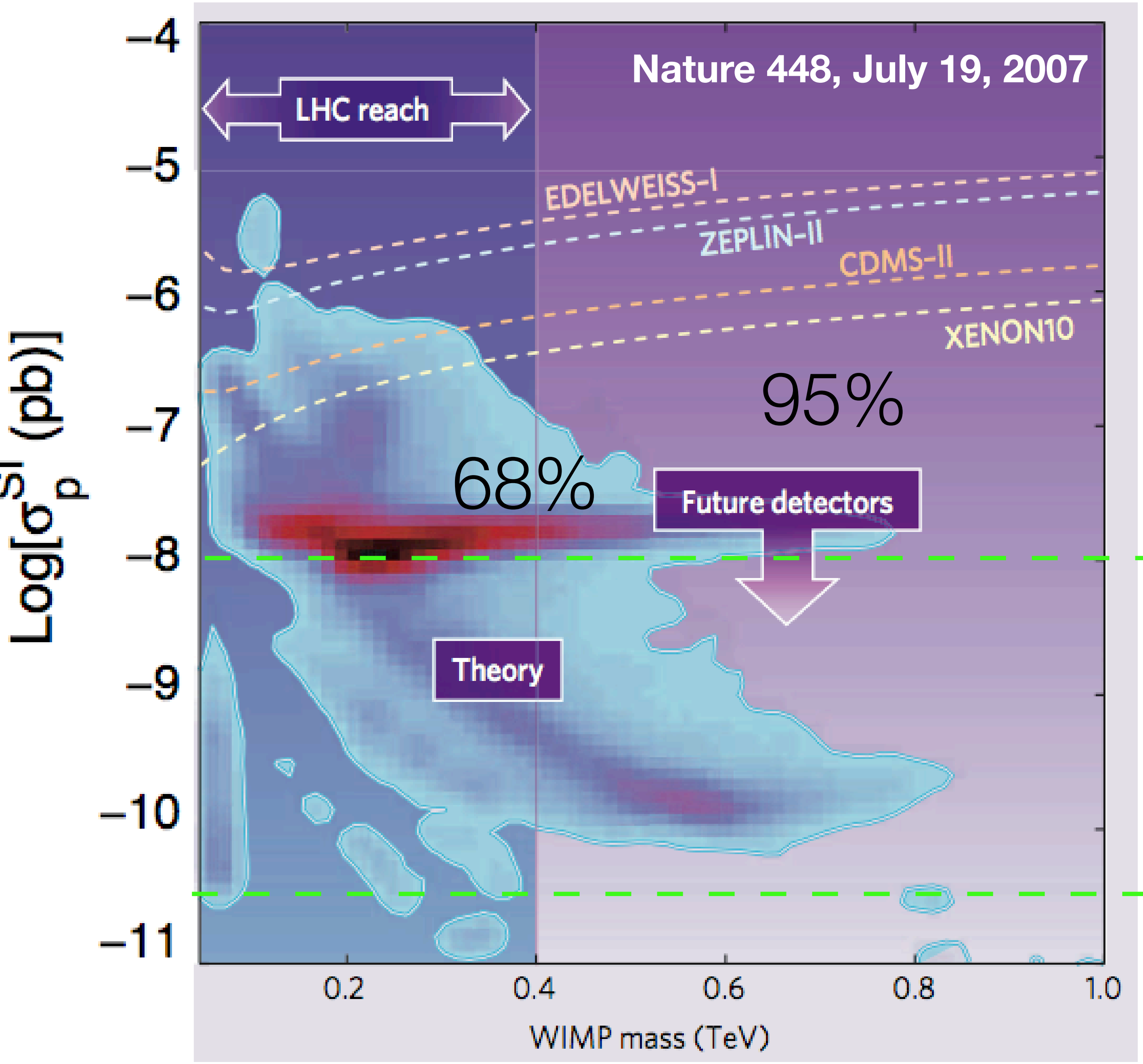
- LNGS, October 2007

Summary

LXe technique: well suited for dark matter searches

XENON10: most stringent limit on WIMP-nucleon cross section; current: WS data with upgraded detector

XENON100: in construction, expect science data by 2008



Theory example: CMSSM (Roszkowski, Ruiz, Trotta)

1 event/kg/yr

CDMS-II, XENON100, COUPP,
CRESST-II, EDELWEISS-II, ZEPLIN-III,...

1 event/t/yr

SuperCDMS1t, WARP1t, ArDM
XENON1t, EURECA, ELIXIR, XMASS, ...