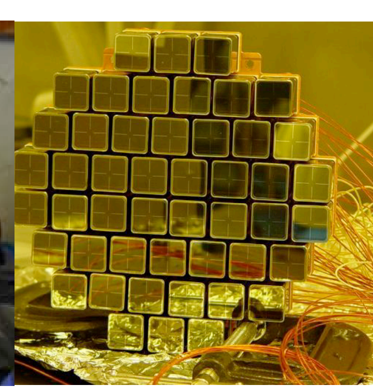
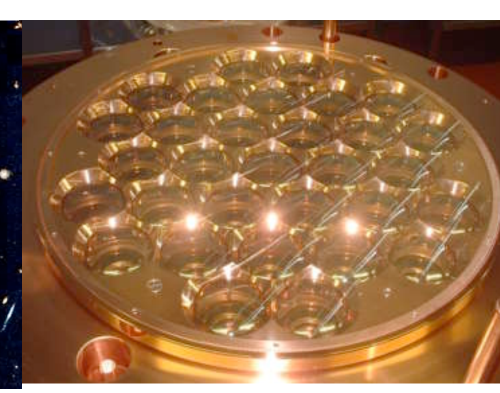
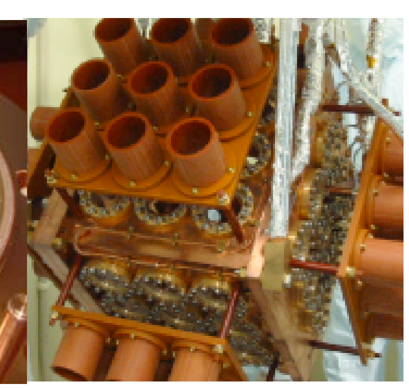
Dark Matter Experiments with Noble Gases

Laura Baudis, RTWH Aachen University

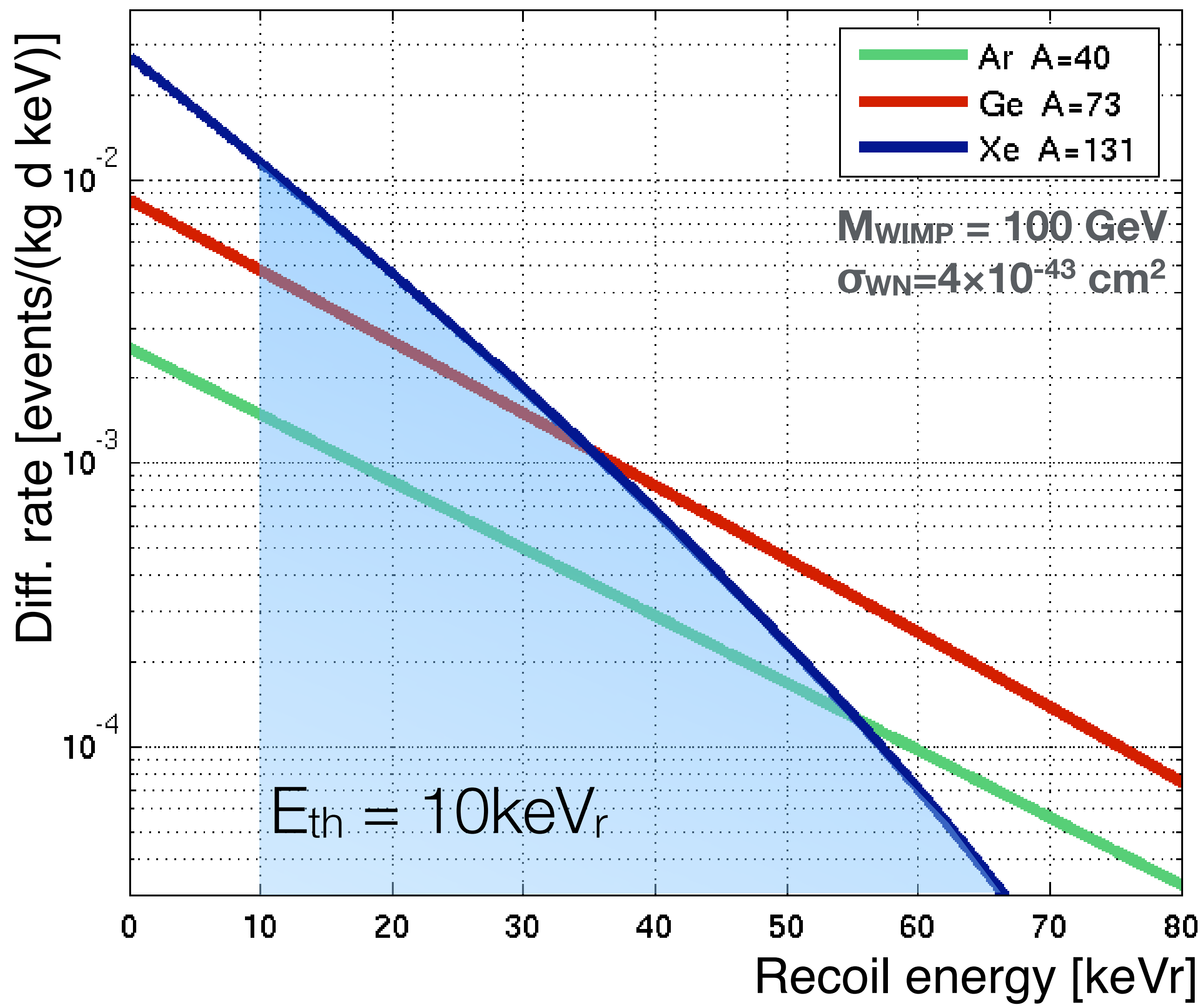
LAUNCH Workshop, Heidelberg, March 21, 2007

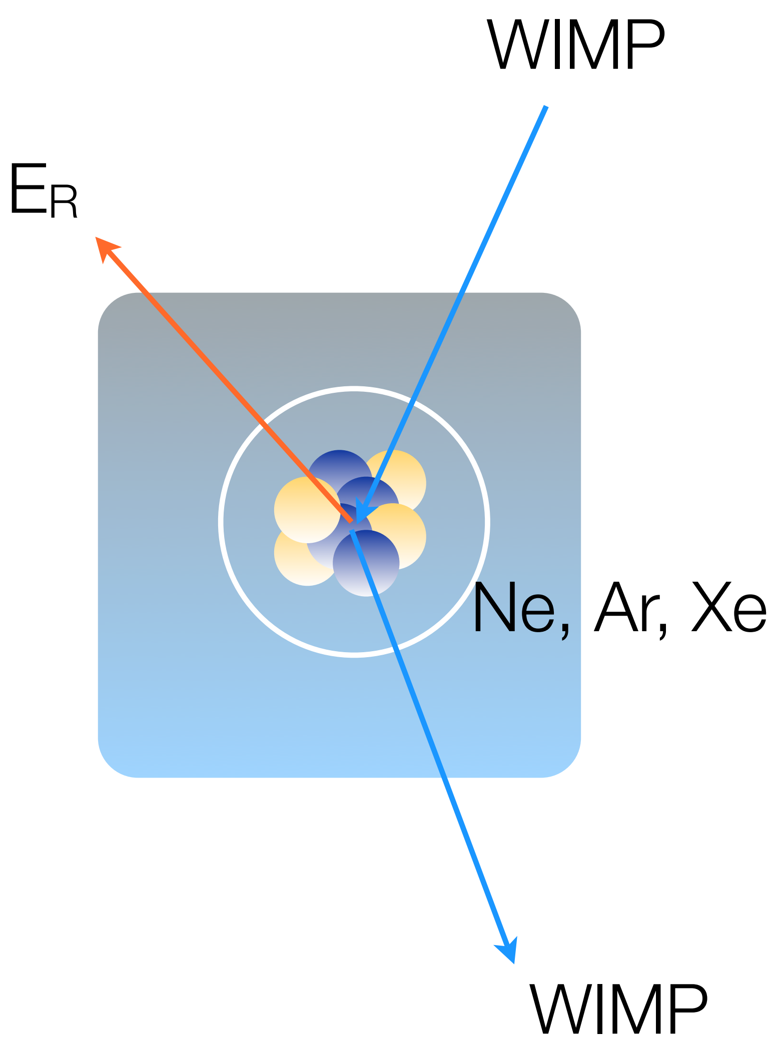



Dark Matter Goals

- Detect galactic WIMPs by their **elastic collision with Ne, Ar, Xe nuclei**:
  - ➡Achieve low (~10 keVr in LXe) recoil energy thresholds
  - ➡Achieve WIMP-nucleon σ sensitivity of ~ 1×10^{-9} pb in 2008-2009





Why Noble Liquids?

- **Good Nuclear versus Electron Recoil discrimination**
  - pulse shape of scintillation signal
  - ratio of ionization to scintillation signals
- **High Scintillation Light Yields; transparent to their own light**
  - low energy thresholds can be achieved
- **Large Detector Masses are feasible**
  - self-shielding => low-activity of inner fiducial volumes
  - good position-resolution in TPC operation mode (use ionization signal)
- **Ionization Drift >> 1 m achieved**
  - corresponding to << ppm electronegative impurities
- **Competitive Costs and Practicality of large instruments**

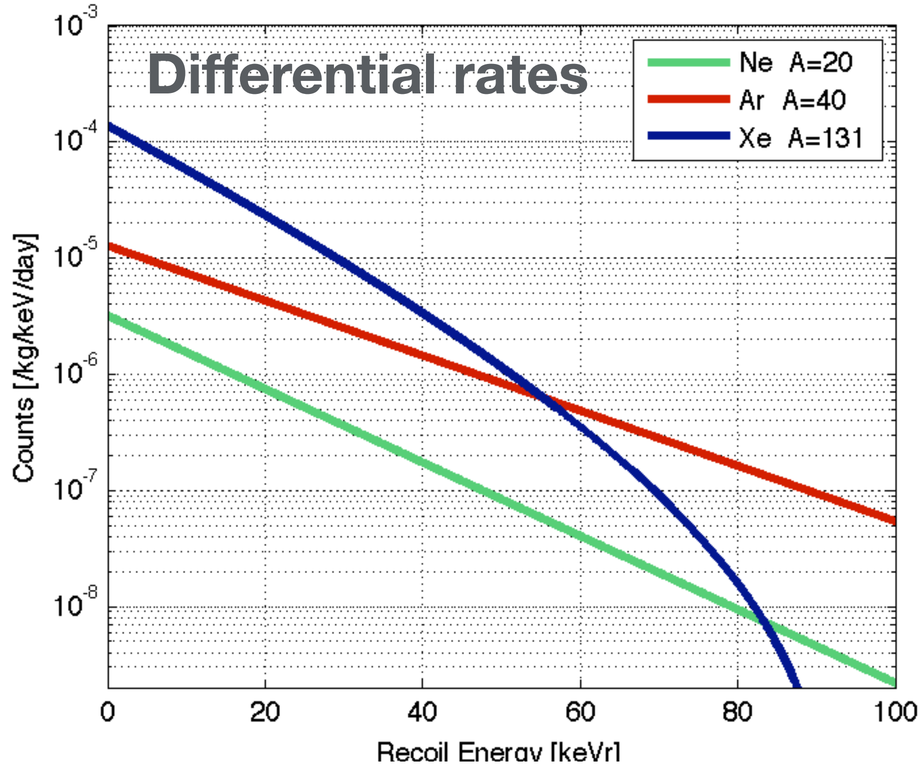
Noble Liquids as Detector Media

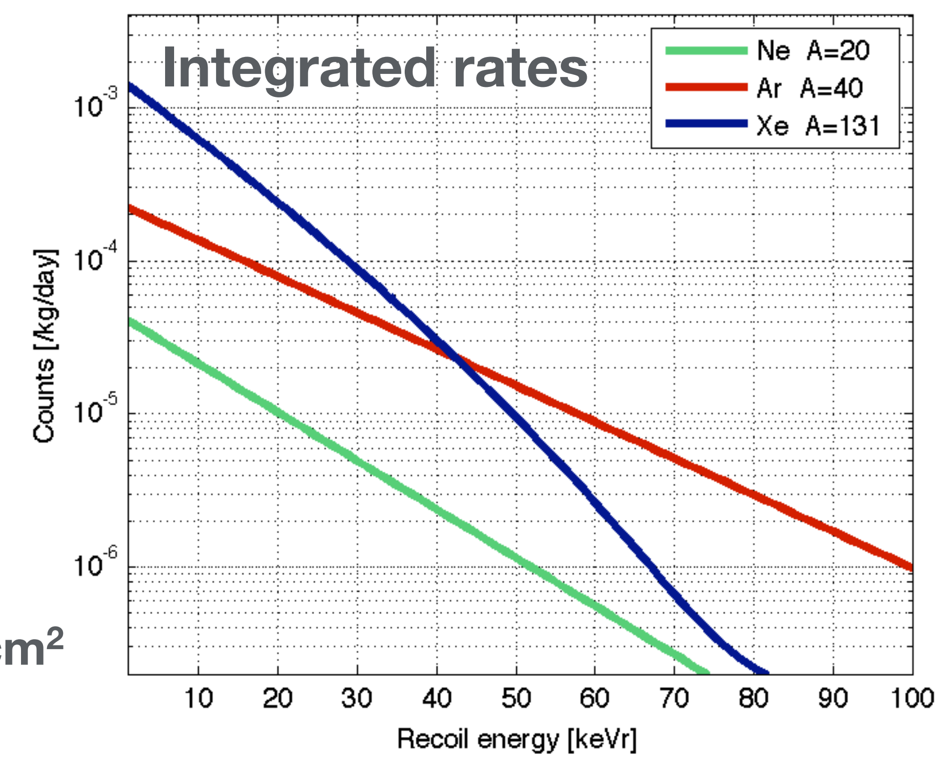
	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

- Liquid noble gases yield both charge and light
- Scintillation is decreased (~ factor 2) when drift field to extract charge is applied

Noble Liquids as Dark Matter Detectors

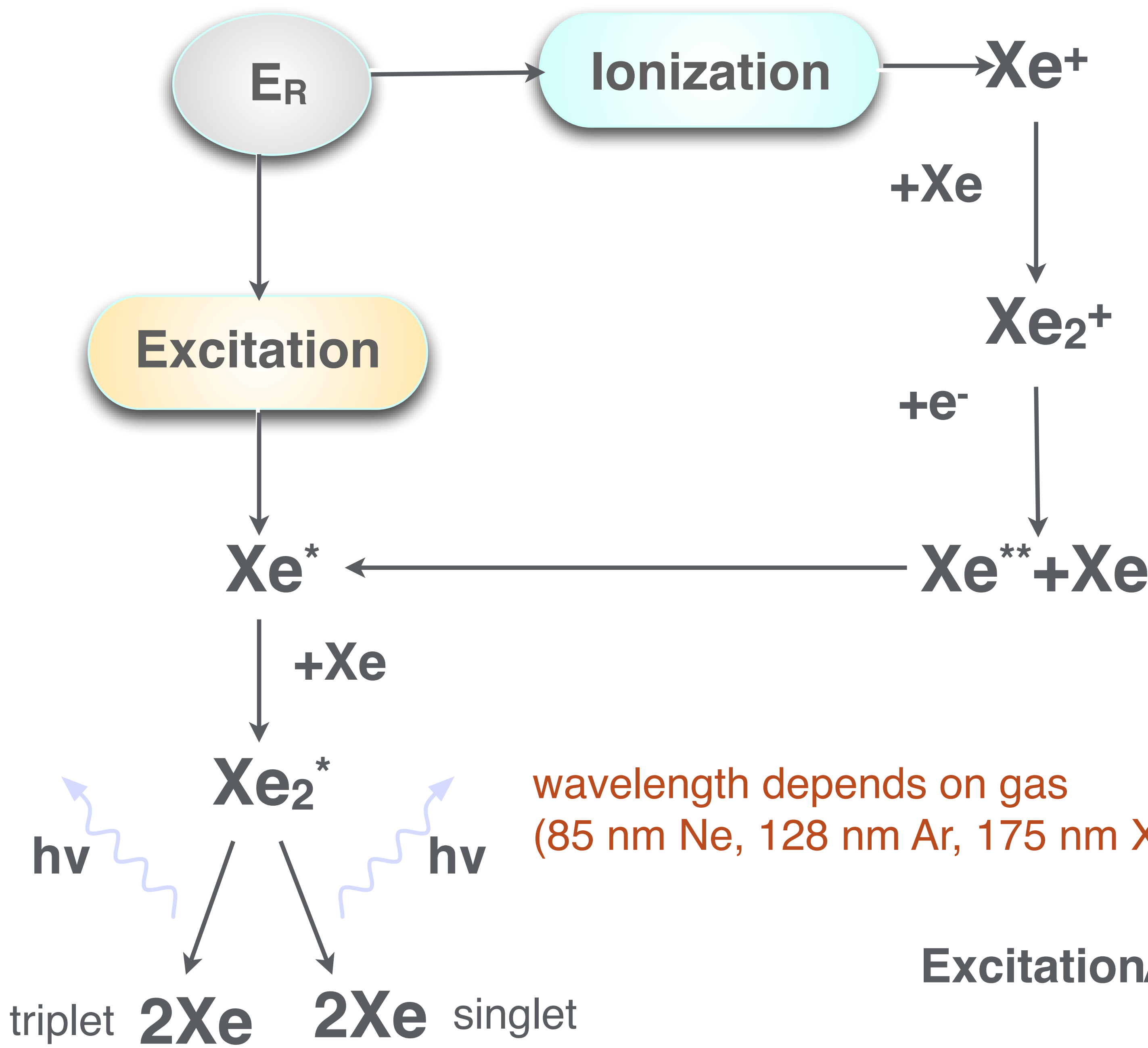
	Scintillation Light	Intrinsic Backgrounds
Ne (A=20) $60/kg 100% even-even nucleus	**85 nm** requires wavelength shifter	Low BP (20 K), all impurities frozen out No radioactive isotopes
Ar (A=40) $2/kg 100% even-even nucleus	**128 nm** requires wavelength shifter	Natural Ar contains ^{39}Ar at 1Bq/kg, corresp. to ~150 ev/kg/day/keV at low energies
Xe (A=131) $800/kg 50% odd nuclei ($^{129}Xe$, ^{131}Xe)	**175 nm** UV quartz PMT window	No long lived isotopes ^{85}Kr can be removed by active charcoal filter or distillation





M_{WIMP} = 100 GeV
$\sigma_{WIMP-N}=4\times10^{-43}$ cm²

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)

$$\begin{aligned} Xe^* + Xe &\rightarrow Xe_2^* \\ Xe_2^* &\rightarrow 2Xe + h\nu \end{aligned}$$

$$\begin{aligned} Xe^+ + Xe &\rightarrow Xe_2^+ \\ Xe_2^+ + e^- &\rightarrow Xe^{**} + Xe \\ Xe^{**} &\rightarrow Xe^* + \text{heat} \\ Xe^* + Xe &\rightarrow Xe_2^* \\ Xe_2^* &\rightarrow 2Xe + h\nu \end{aligned}$$

Excitation/Ionization depends on dE/dx!

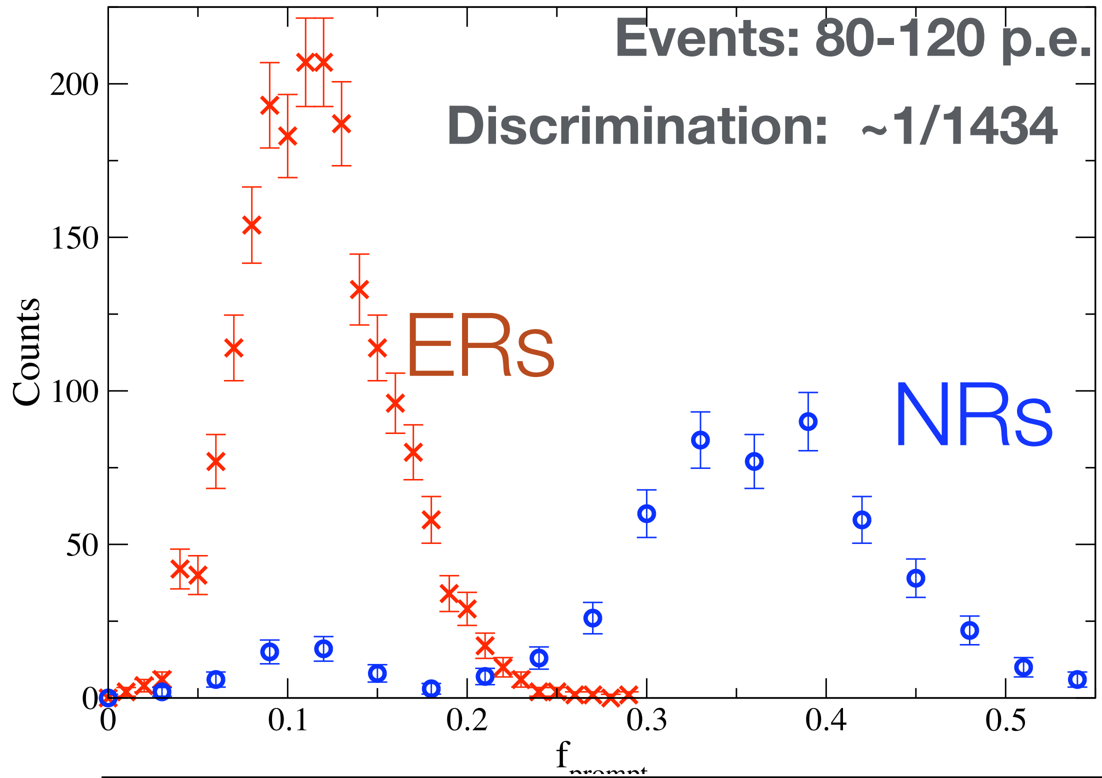
=> discrimination of signal (**WIMPs=>NR**)
and (most of the) background (**gammas=>ER**)!

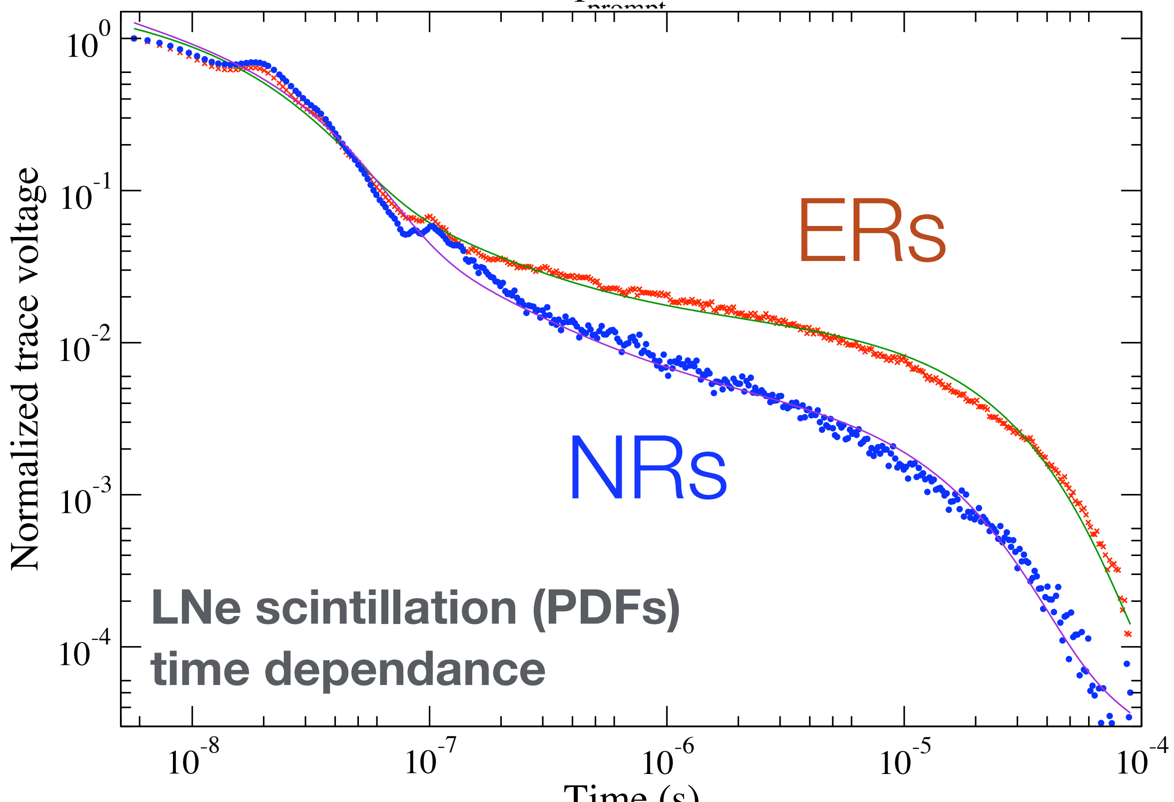
Noble Liquid Detectors: Existing Experiments and Proposed Projects

	Single Phase (liquid only) PSD	**Double Phase (liquid and gas) PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	--
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	ArDM (1 ton) WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) XENON10, XENON100 LUX (300 kg), ELIXIR (1t)

- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field

Scintillation in LNe from Electronic and Nuclear Recoils

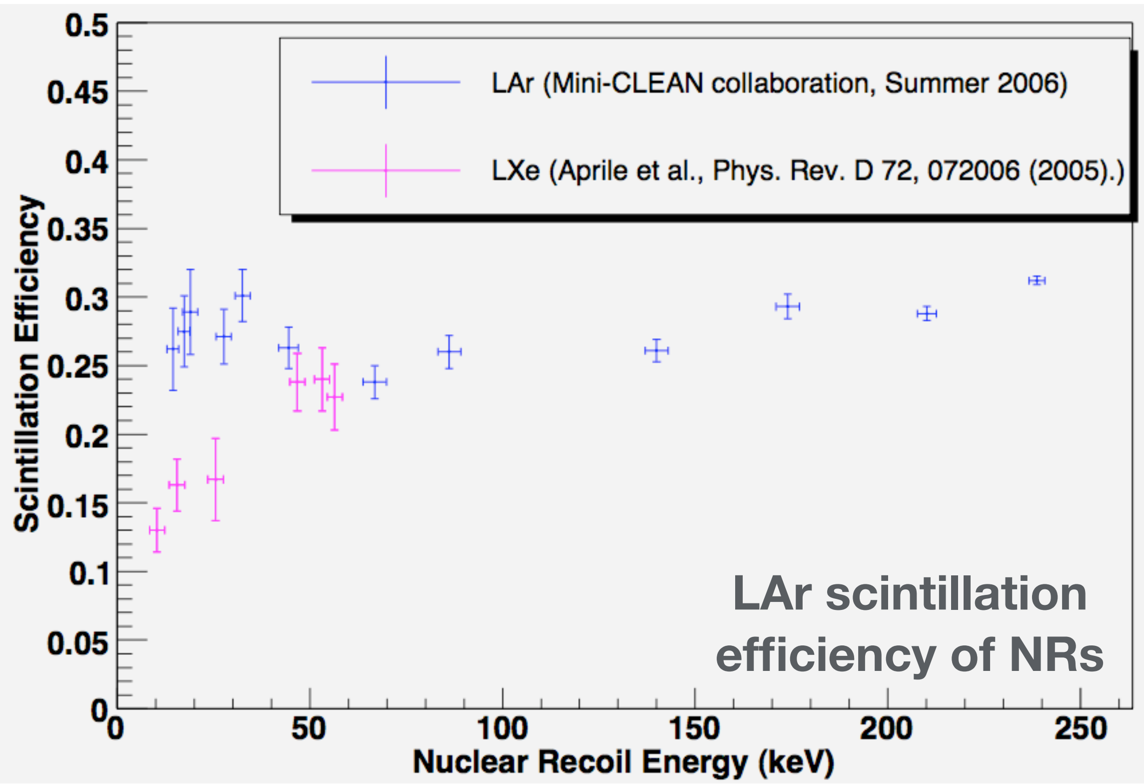


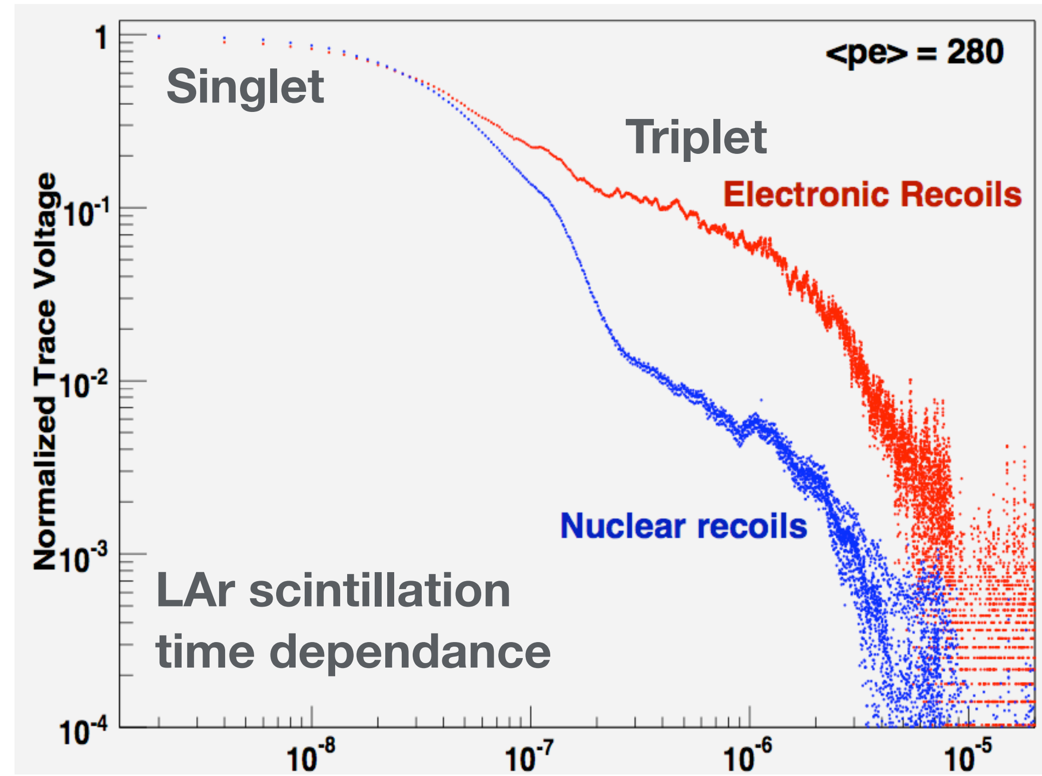


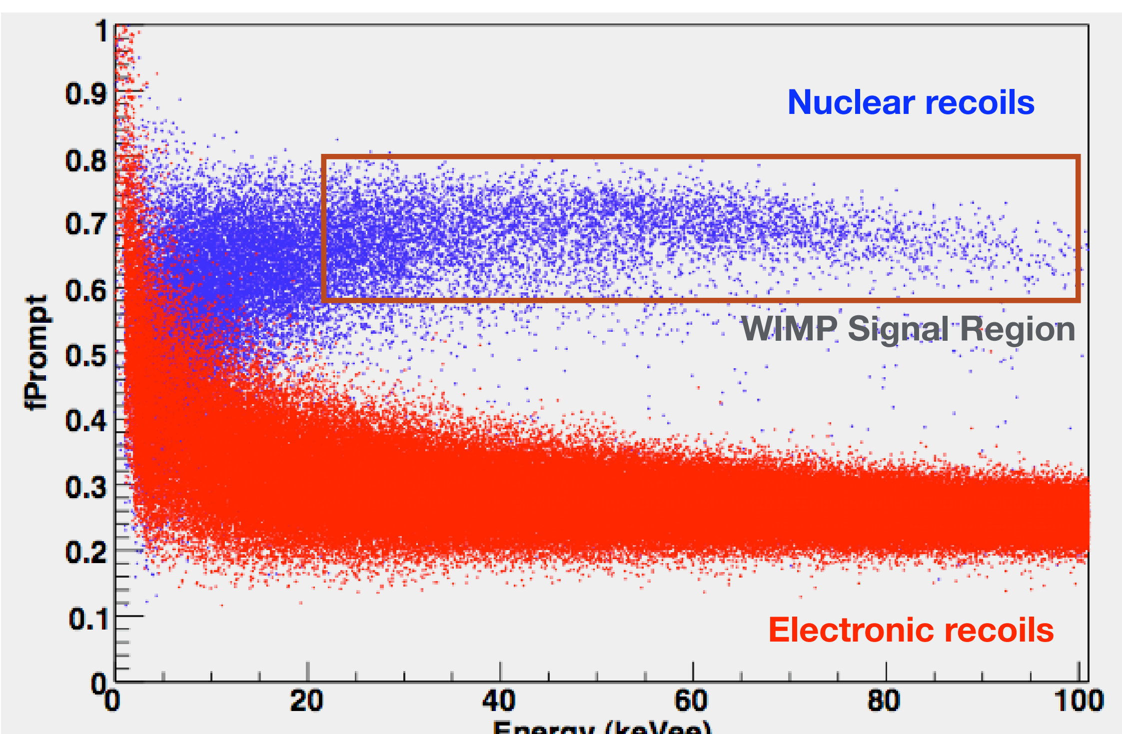
Pico-CLEAN (200g LNe)

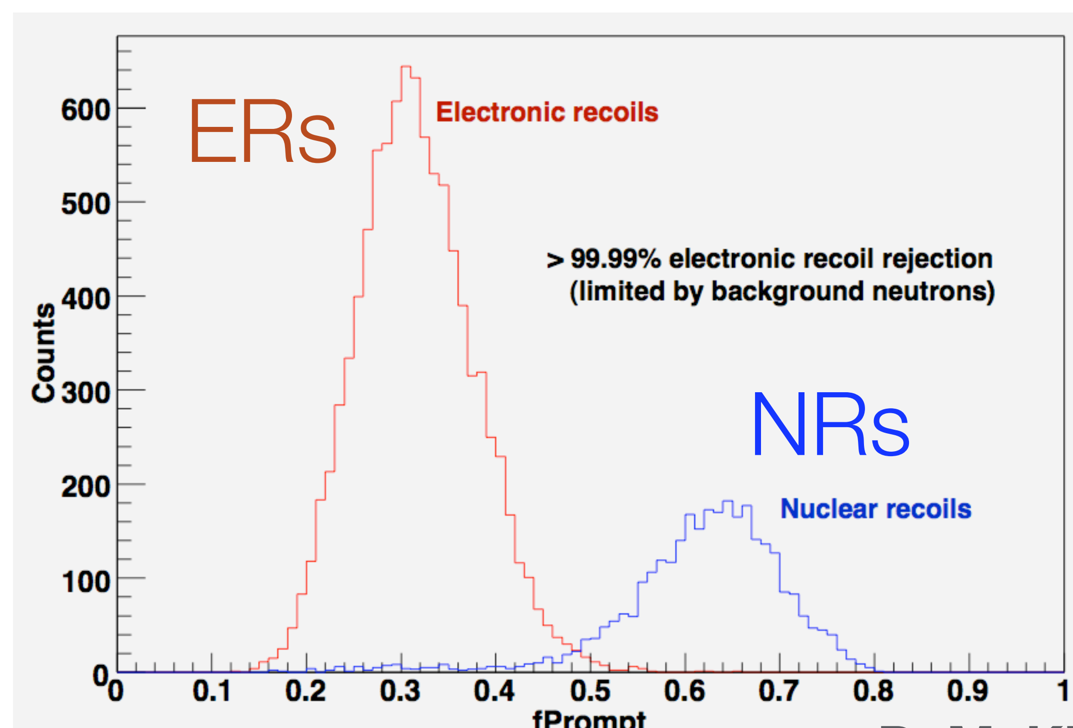
D. McKinsey et al, Yale

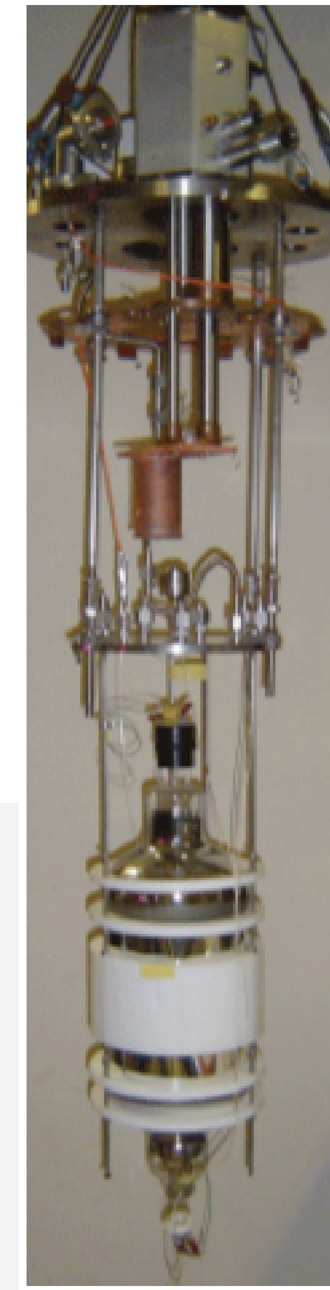
Scintillation in LAr from Electronic and Nuclear Recoils









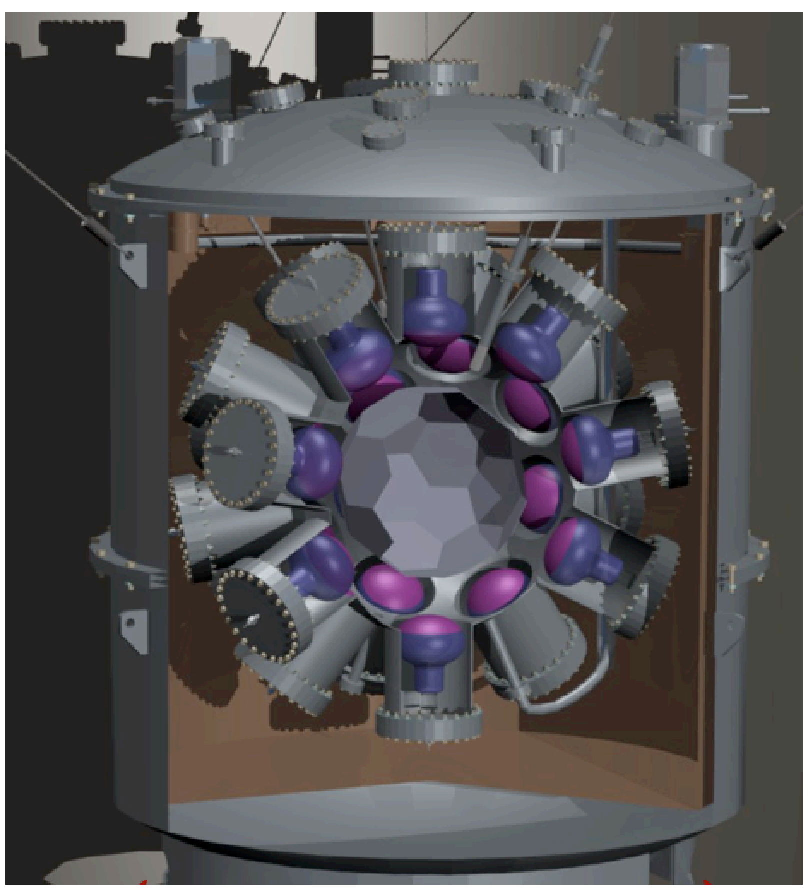


Micro-CLEAN
(4 kg LAr)

D. McKinsey et al, Yale

Mini-CLEAN/CLEAN: Proposed Projects

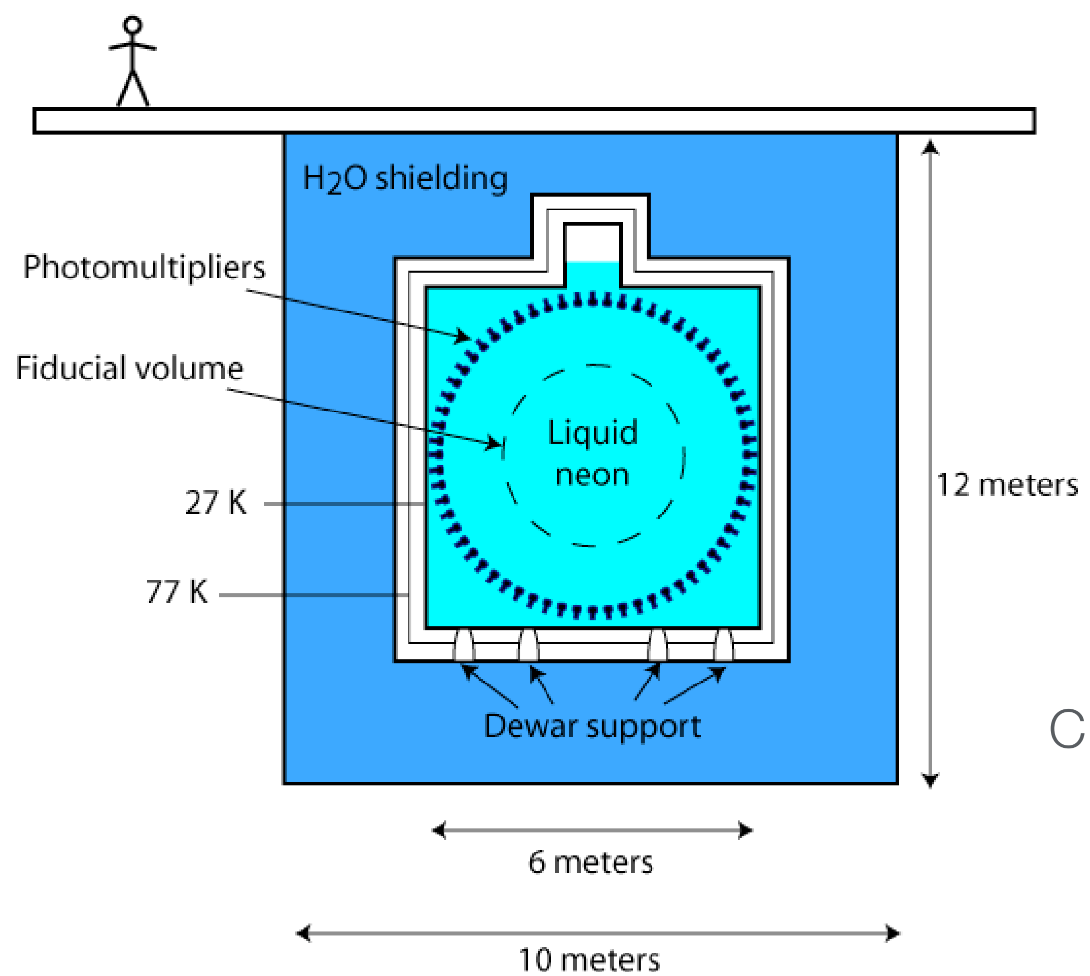
- Mini-CLEAN (2007): 100 kg of LNe or LAr, WIMP goal: 5×10^{-9} pb, 10 events/year
- Backgrounds: gammas from PMTs (require > 10^{-8} rejection of ER at 50keVr; currently demonstrated rejection of 10^{-5} limited by n-BG in lab), neutrons from PMTs (not expected to be a problem in large target), position reconstruction
- CLEAN (2011): 10-100 tons of LNe (maybe LAr), pp-neutrinos, WIMPs



2 m

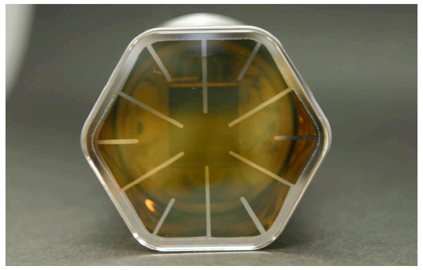
2 m

Mini-CLEAN



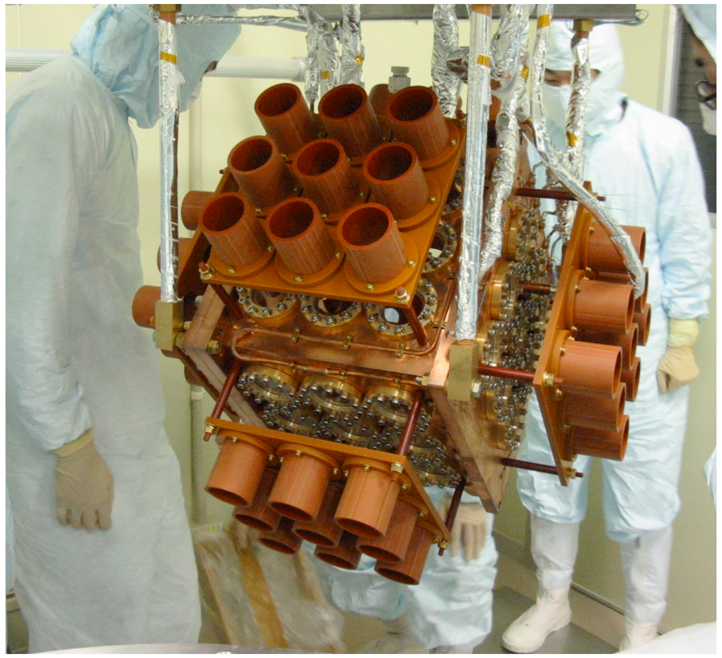
CLEAN

XMASS

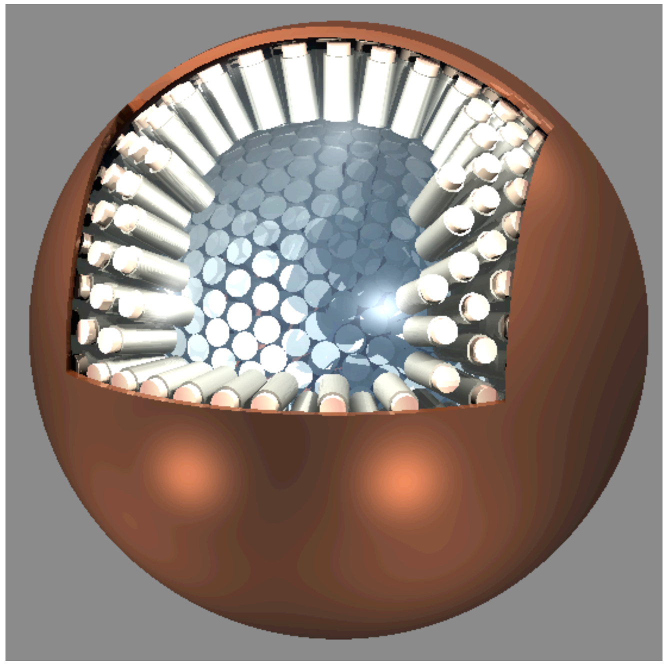


- 100 kg (3 kg fiducial mass) prototype operated (52 2” Hamamatsu R8778 PMTs)
  - the PMT coverage was limited, thus also the position reconstruction of edge events
- next step: 800 kg with 812 PMTs (67% photo coverage)
  - basic performance confirmed with prototype
  - vertex reconstruction, self-shielding, BG level studied with MCs
- detector is being designed, excavations will start soon

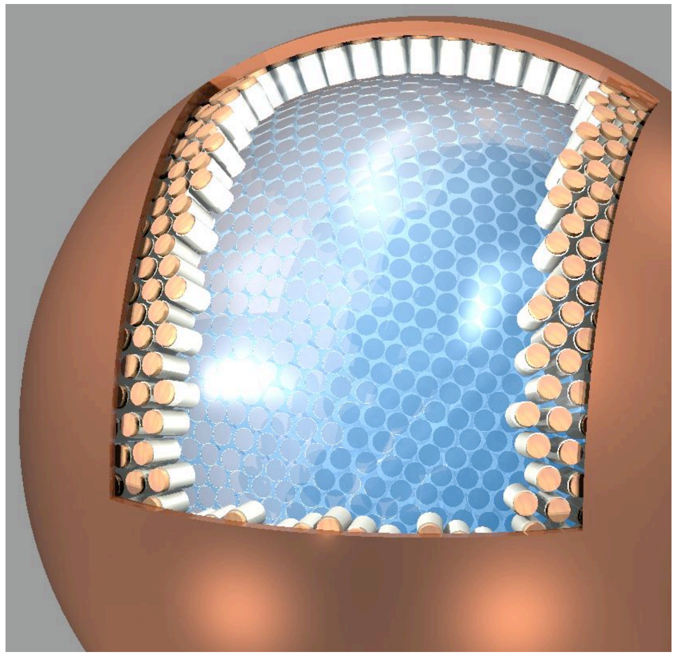
S. Moriyama, KEKPH07, March 07



100 kg (3 kg fiducial)



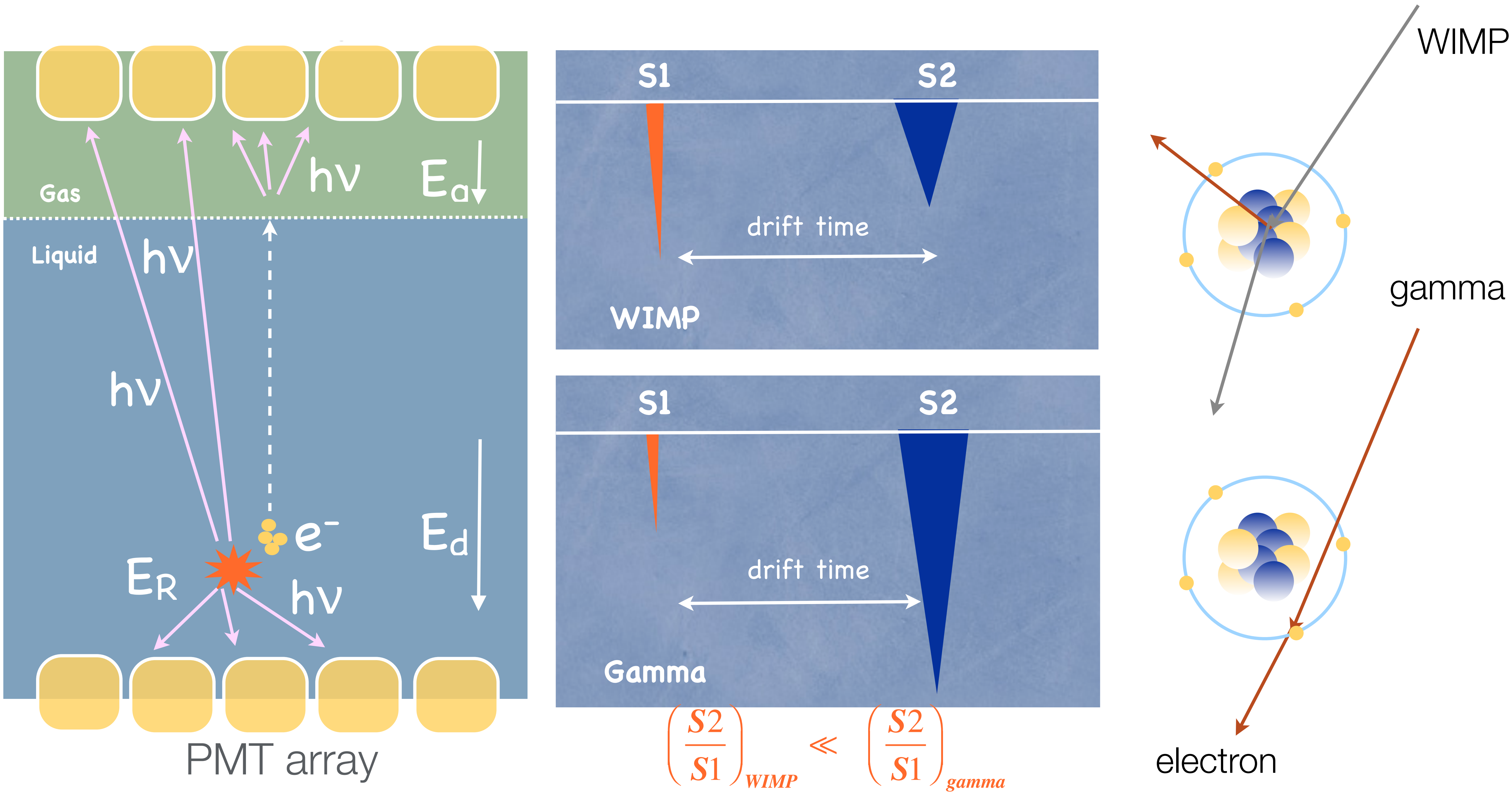
800 kg (100 kg fiducial)



23 t (10 t fiducial)

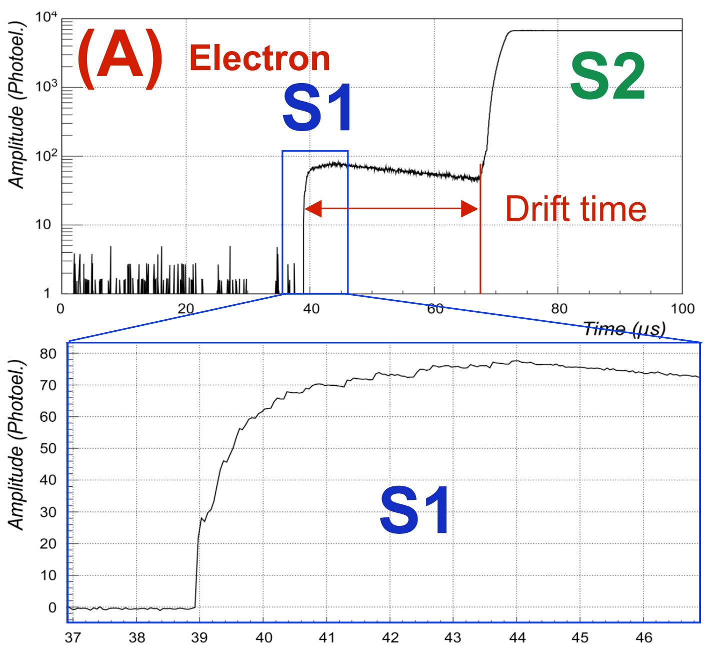
Two-Phase (Liquid/Gas) Detection Principle

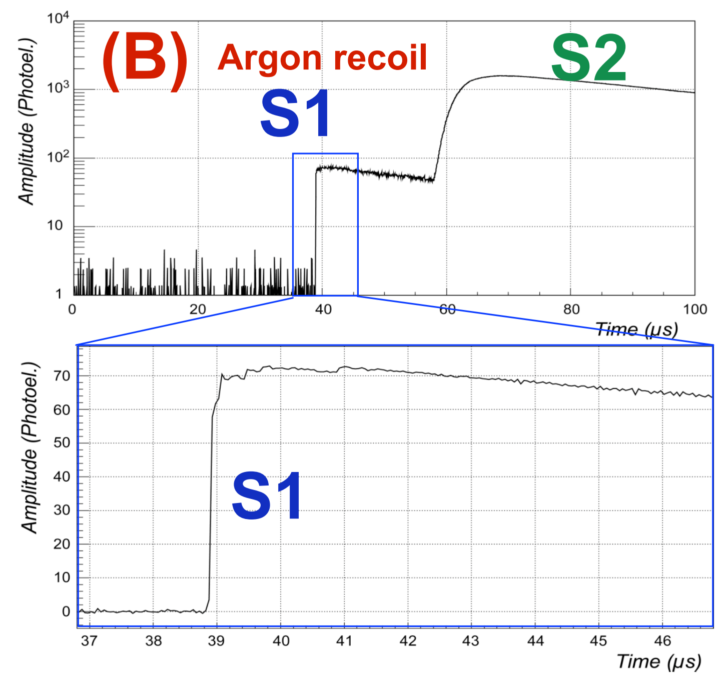
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected **directly**, or as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-

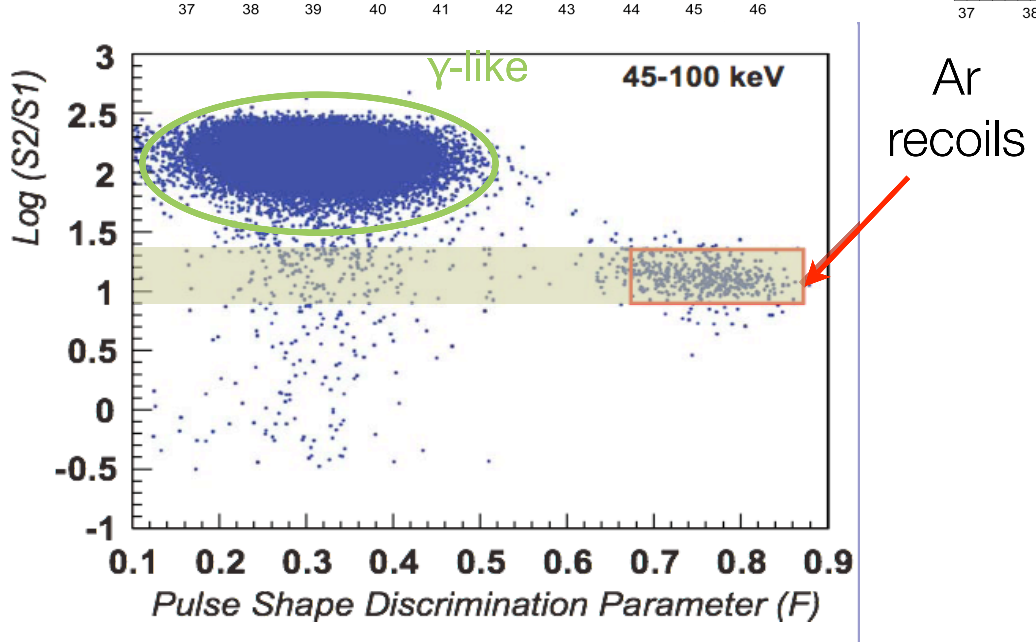


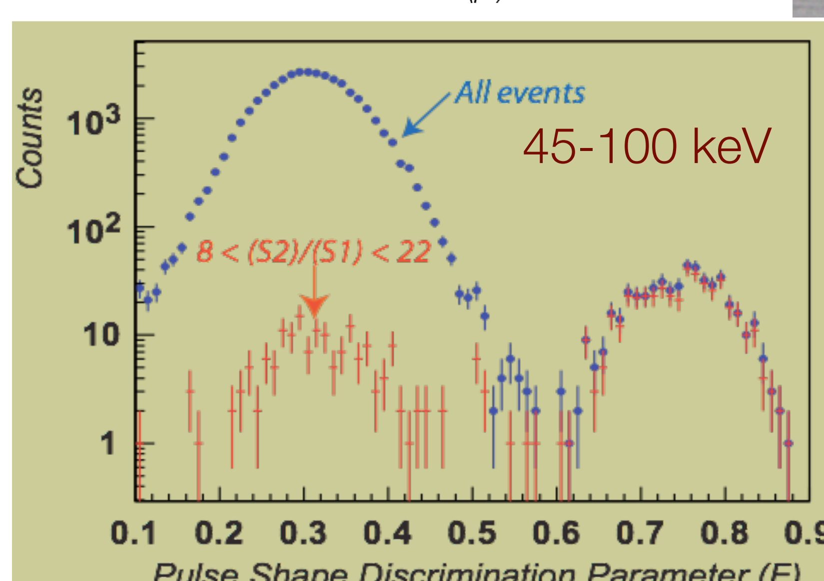
Two-Phase Ar: WARP

- 3.2 kg detector is running at LNGS (first installation in 2004)
- WARP discrimination: PSD and S2/S1









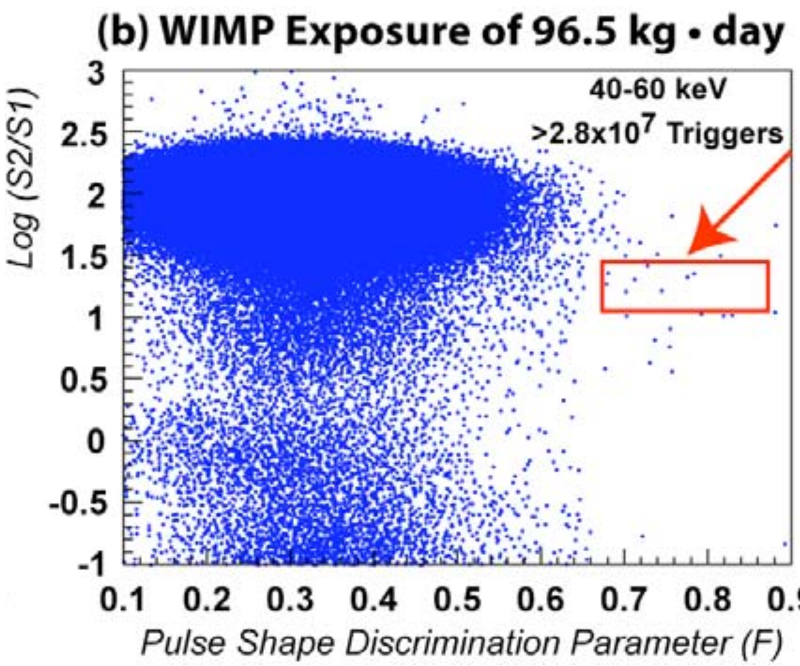
n-calibration data

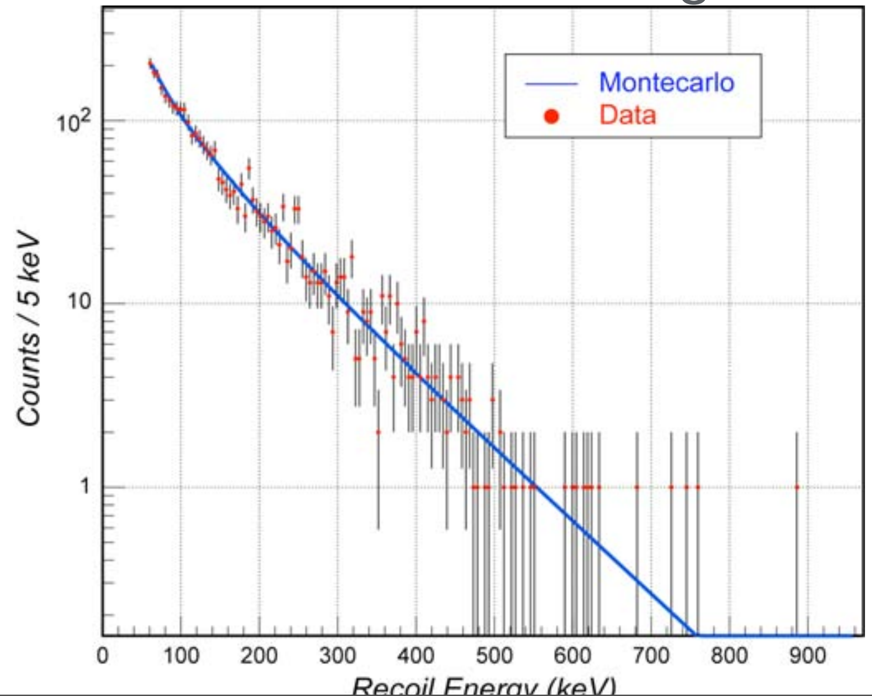
effect of S2/S1 ratio cut

=> depletes the gamma-like population (F < 0.6)

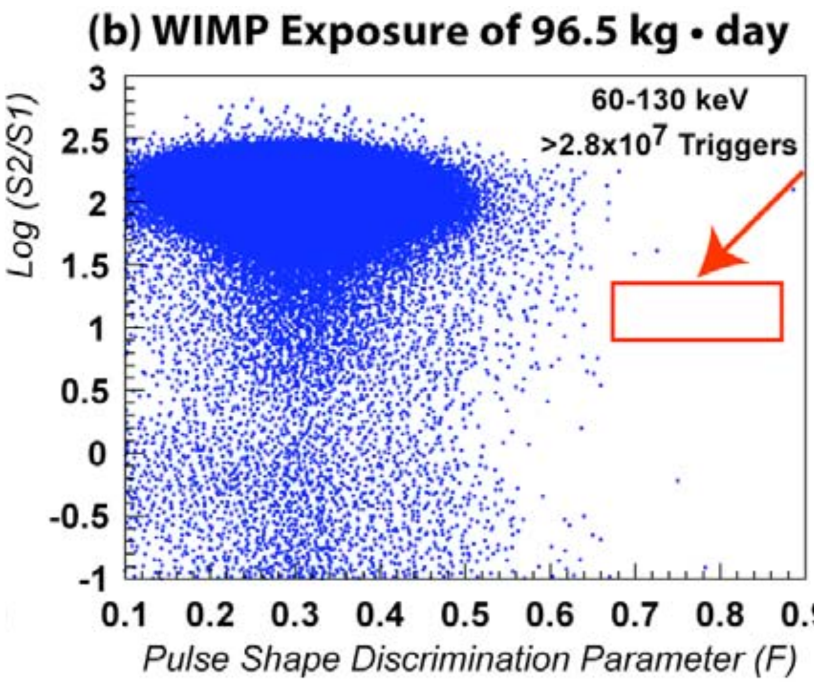
WARP Recent Results

- WARP reported results from ~ **3 months of WIMP search data at LNGS**
- Analysis based on **zero events > 55 keV**
- The reported limit is ~ **5 times above CDMS result**
- New data (50 kg days) in hand, improved electronics
  - ➡Results soon; **140 kg detector in preparation**
- WARP energy calibration: n-calibration
  - ➡fitted with MC over the range 60 - 700 keVr



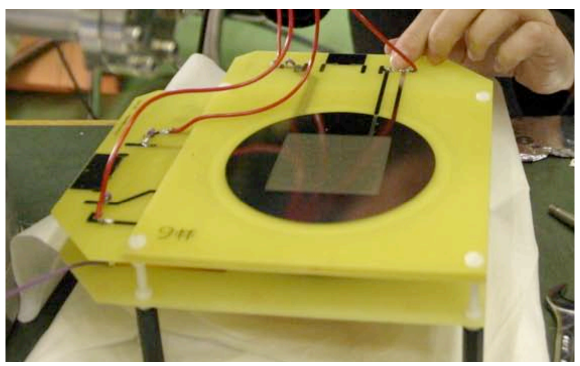
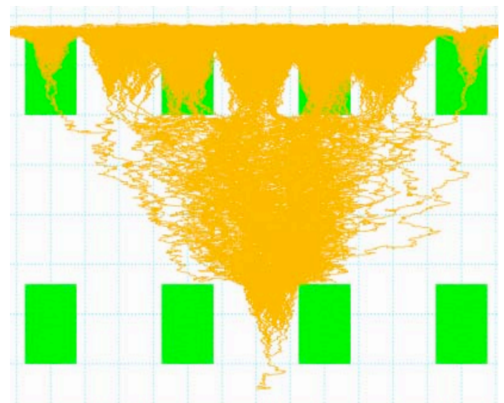
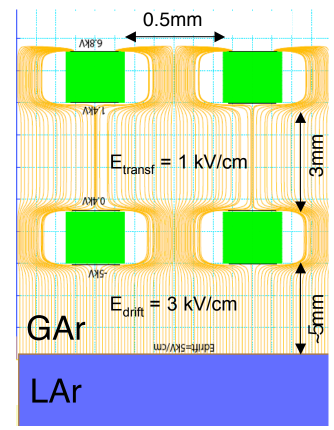


P. Benetti et al., astro-ph/0701286

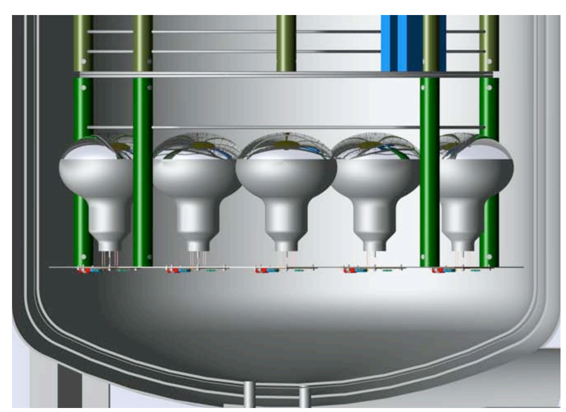


Two-Phase Ar: ArDM

- 1 ton prototype under construction at CERN
- Direct charge readout with 2 stage, thick LEM (macroscopic GEM, gain up to 10^4)

- Photon readout: 85 tetra-phenyl-butadiene coated PMTs: shift λ 128 nm -> 430 nm (20%QE)

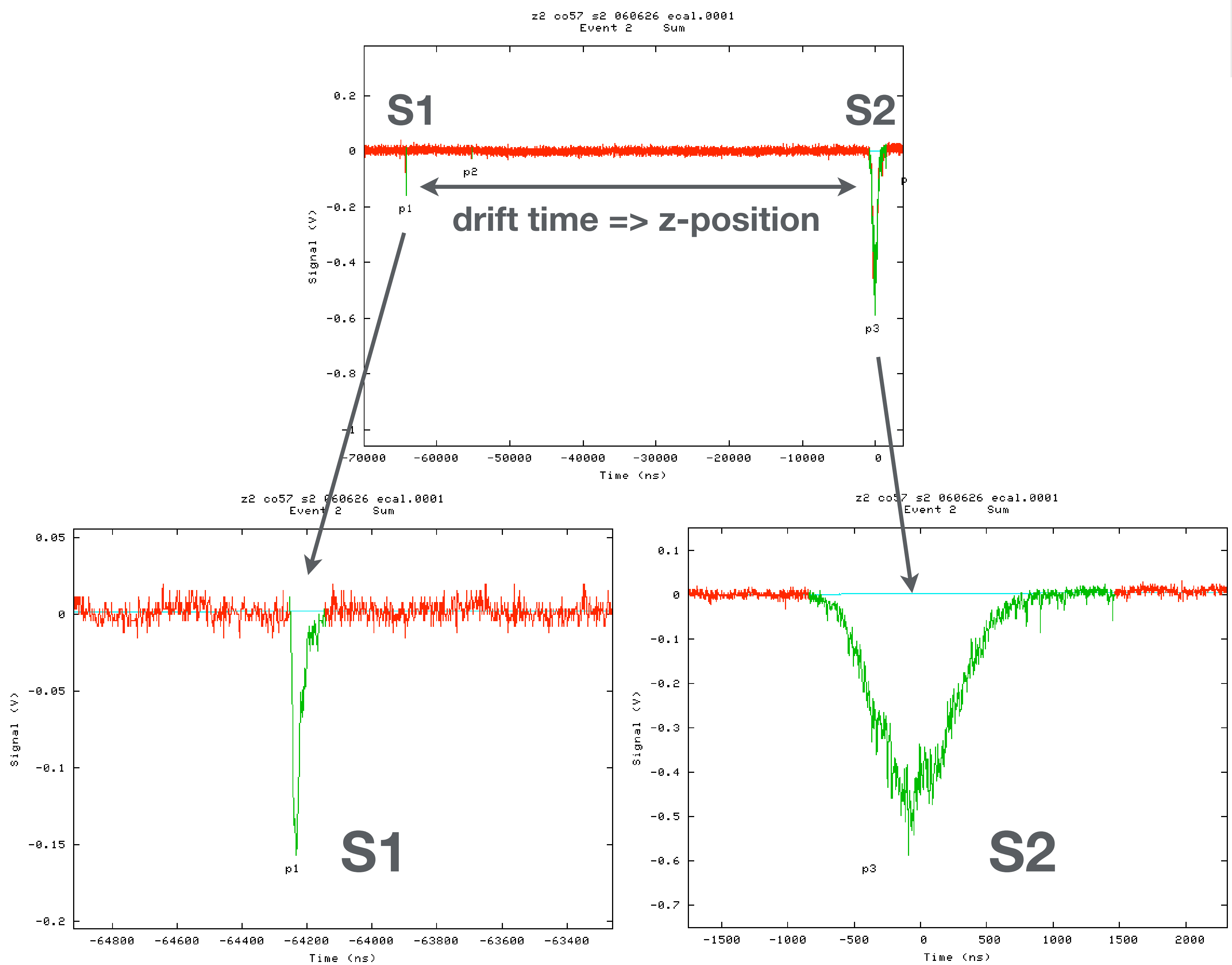



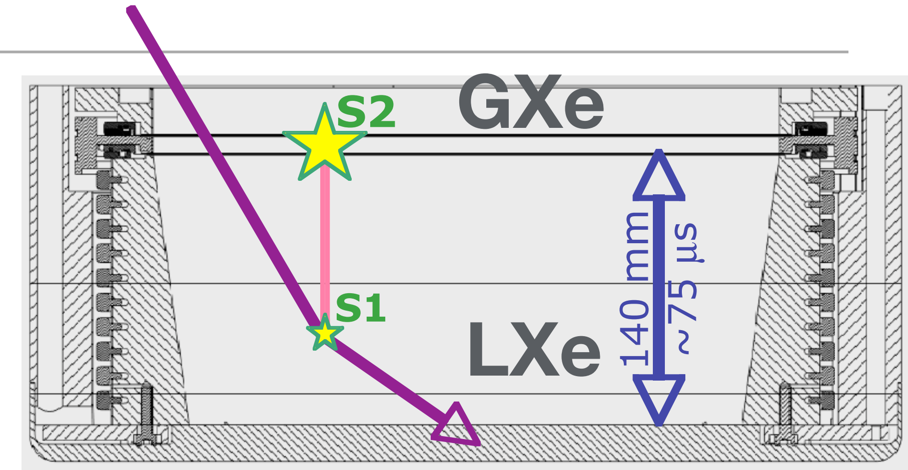
- Field: Greinacher Chain + field shapers
- Goal: test at CERN (2007), then move to Canfranc (07-08)

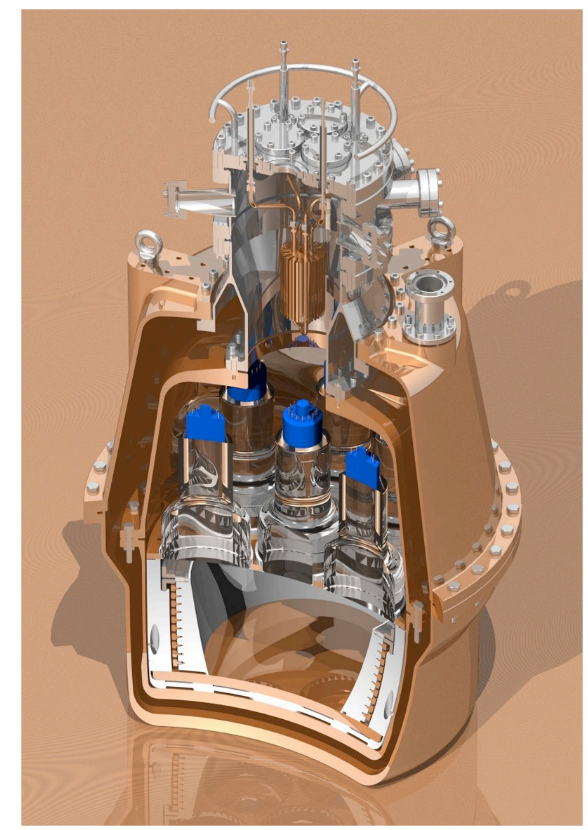
M. Laffranchi et al., astro-ph/0702080

Two-Phase Xenon: ZEPLIN-II

- 5 months continuous operation at the Boulby Lab
- 1.0 t *day raw Wimp Search data





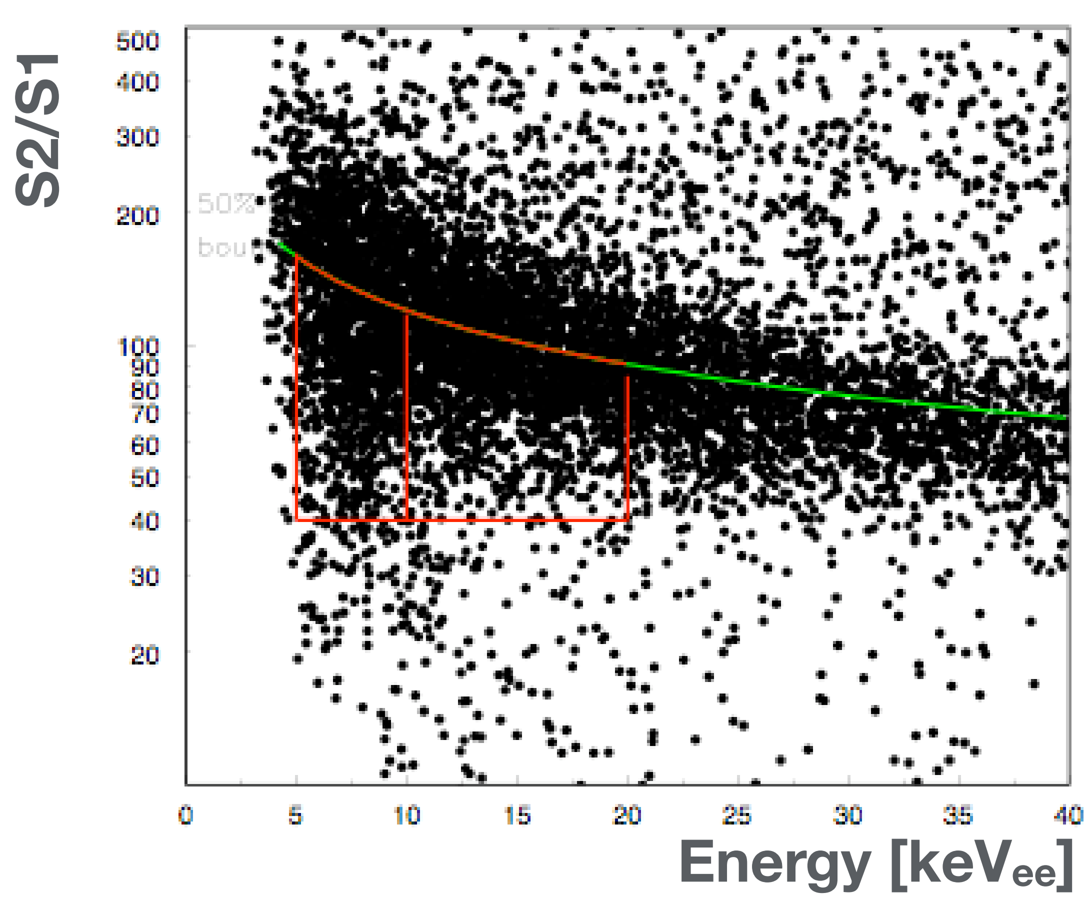


31 kg LXe (7.2 kg fiducial)
7 x 13 cm ø ETL-PMTs
1 cm spatial resolution
0.55 pe/keV_{ee} (^{57}Co, w. field)

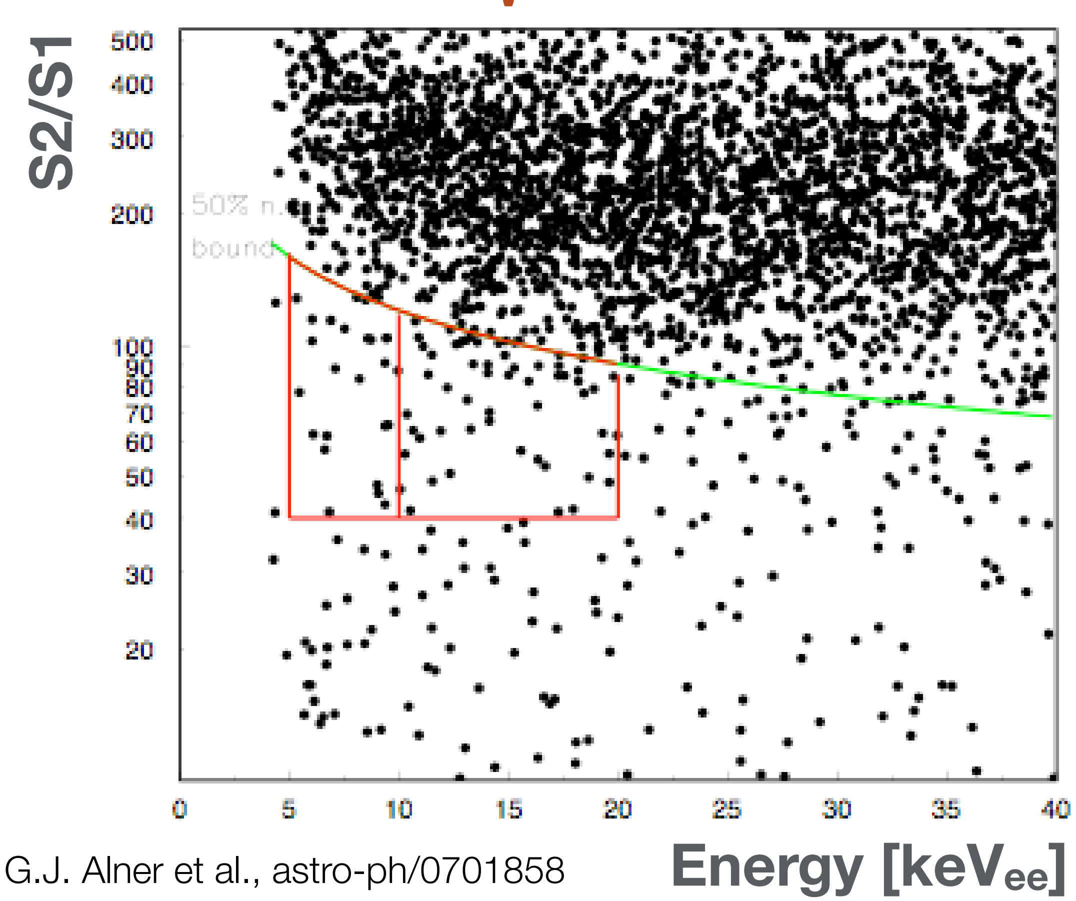
ZEPLIN-II Discrimination

- Calibration data is used to define NR acceptance window (50% NR acceptance shown)
- Lower S2/S1 = 40 bound is fixed
- Red box defined 5-20 keVee
- Uniform population across plots: high rate calibrations, coincidences between events and 'dead-region' events
- **98.5 γ discrimination at 50% NR acceptance**

AmBe n-calibration



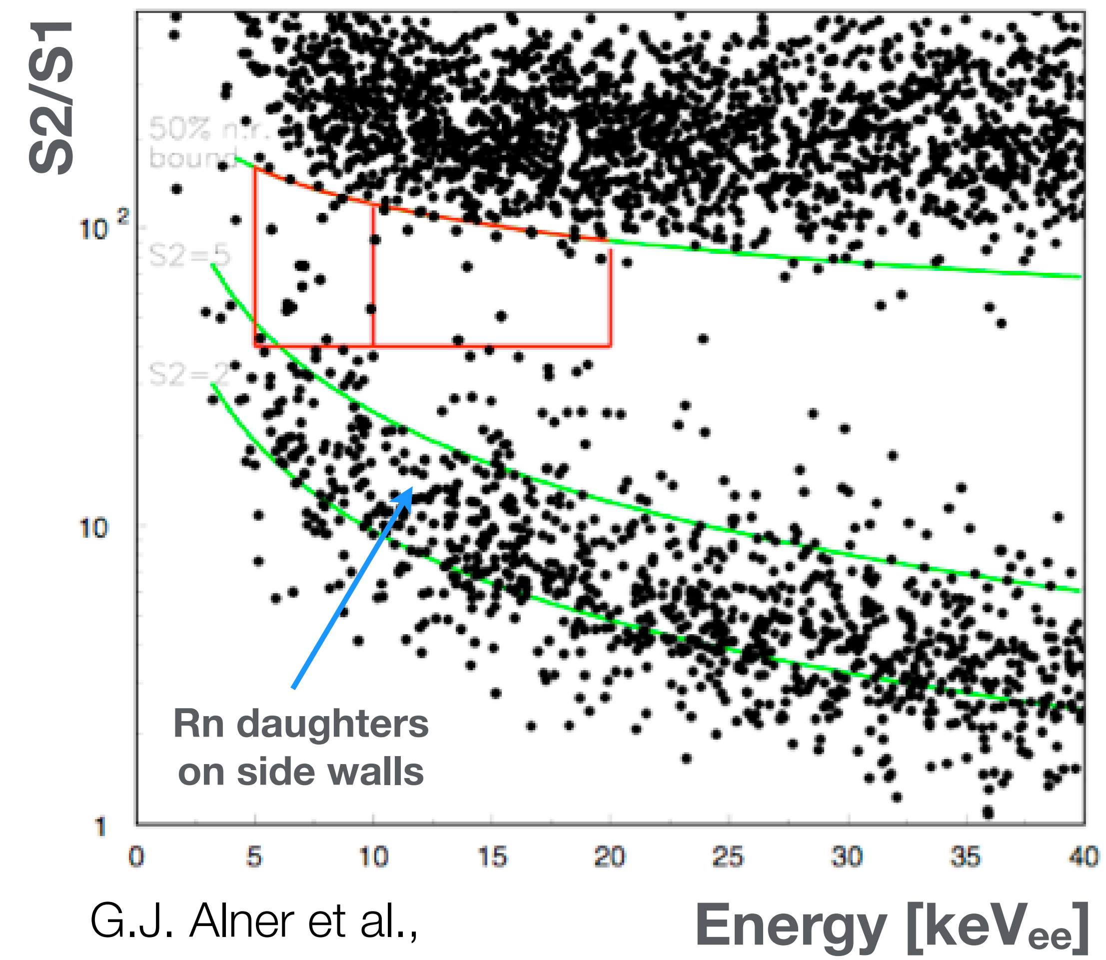
^{60}Co γ-calibration



G.J. Alner et al., astro-ph/0701858

ZEPLIN-II Wimp Search Data and Results

- **31 live days running, 225 kg d exposure**
  - ➡Red box: 5-20 keVee, 50% NR acceptance based on neutron calibration
  - ➡**29 candidate events seen**
  - ➡50% from ER leakage from upper band
  - ➡50% from lower band (Rn daughter recoils on PTFE side walls)



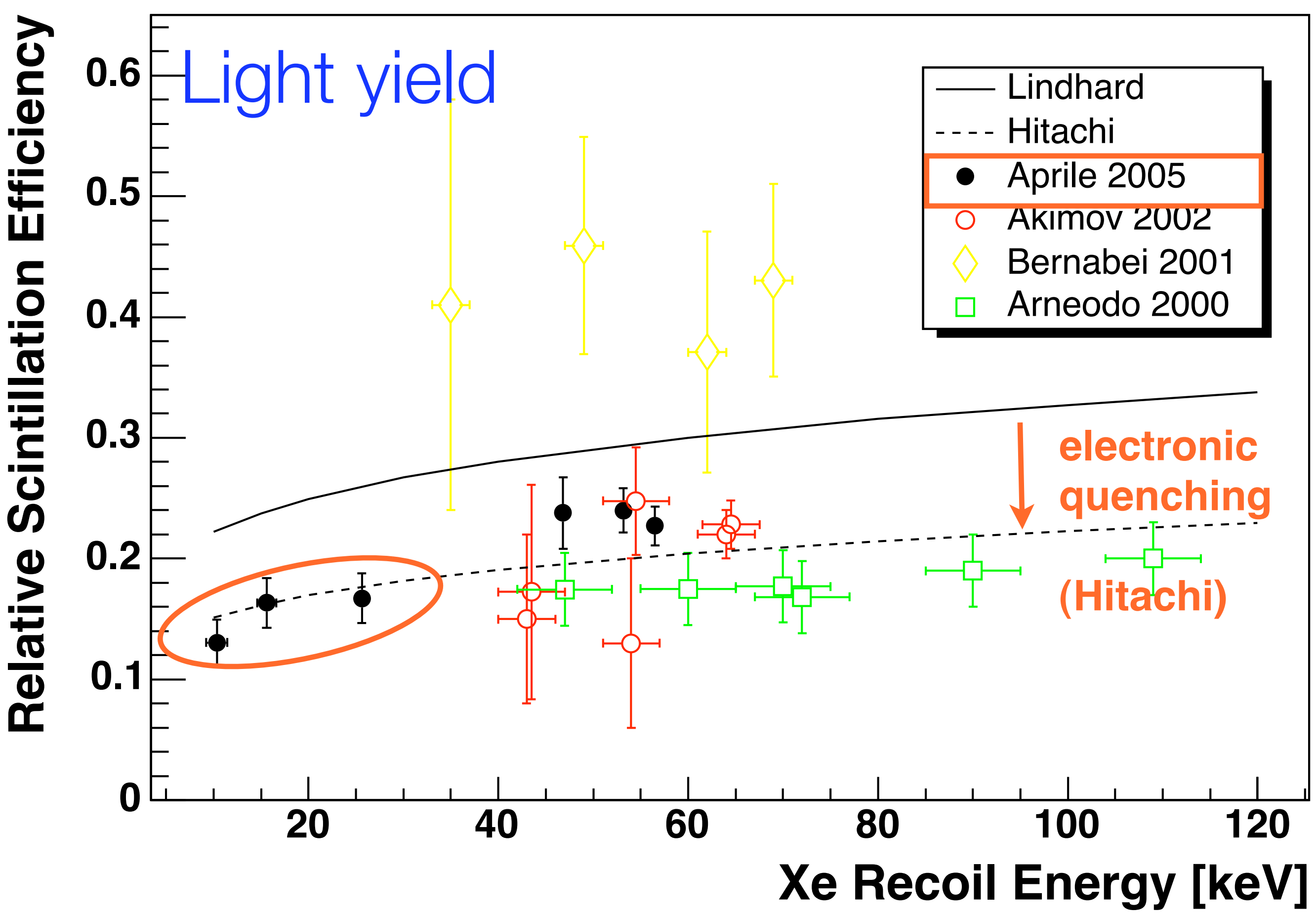
G.J. Alner et al., astro-ph/0701858

- Both populations have been modeled and background subtraction performed
- With **29 events observed**, and **28.6±4.3 predicted**, the final results is < 10.4 events (90% CL) => translates to a min. upper limit ~ **6.6 x 10^{-7} pb at 65 GeV WIMP mass**
- New run with low Rn-levels (high T getter) in preparation; **ZEPLIN-III** (kg fiducial mass, 31 low-background PMTs in liquid, 3.5 cm drift) being deployed at Boulby

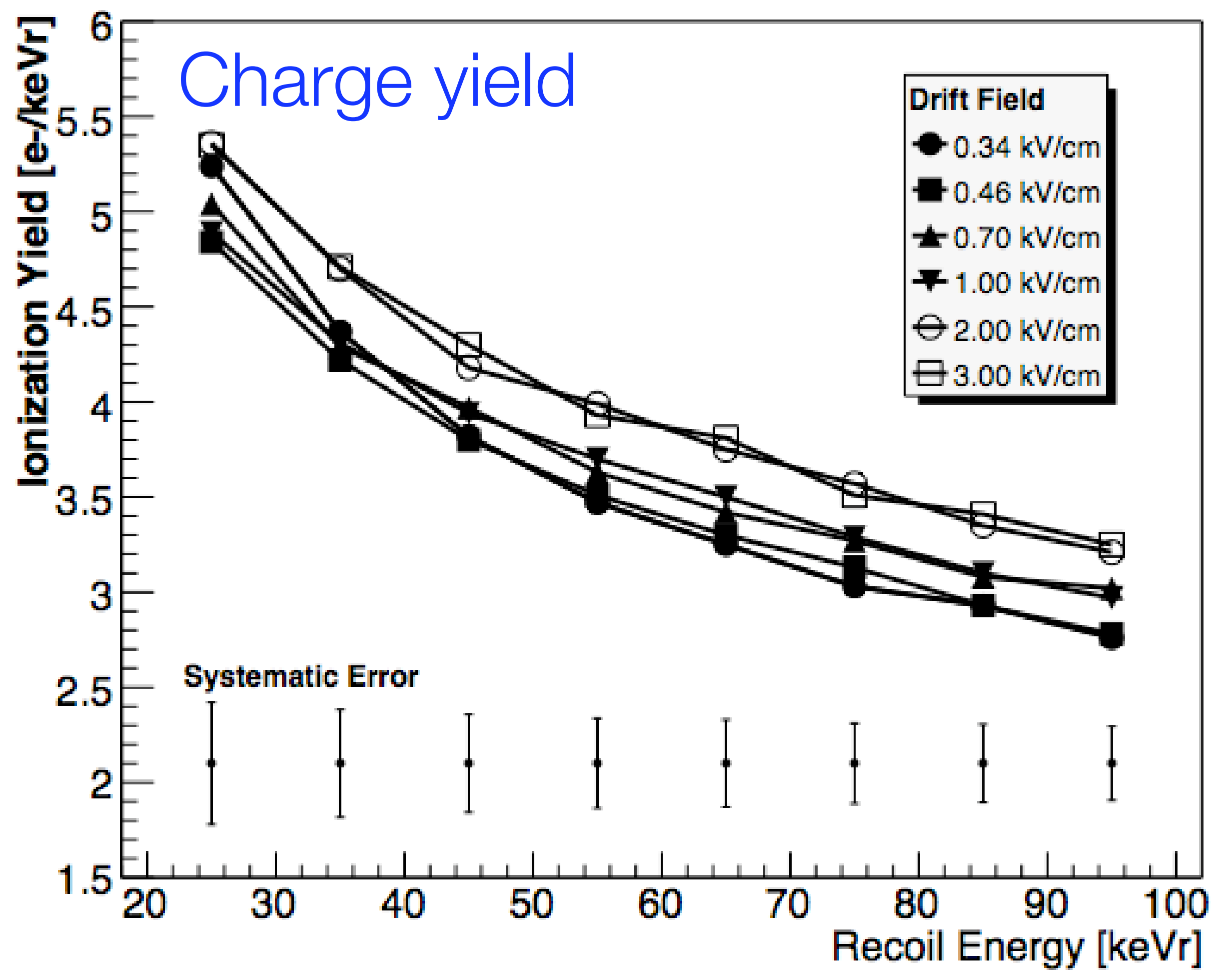
Two-Phase Xenon: XENON10

Liquid Xenon for Dark Matter Searches

- light and charge yield measured at **low nuclear recoil energies** for the first time



Data down to 10 keVr; yield: 13% - 20% from 10 keVr to 60 keVr. Good agreement with prediction by Hitachi (Astrop. Phys. 24, 2005) at low recoil energies



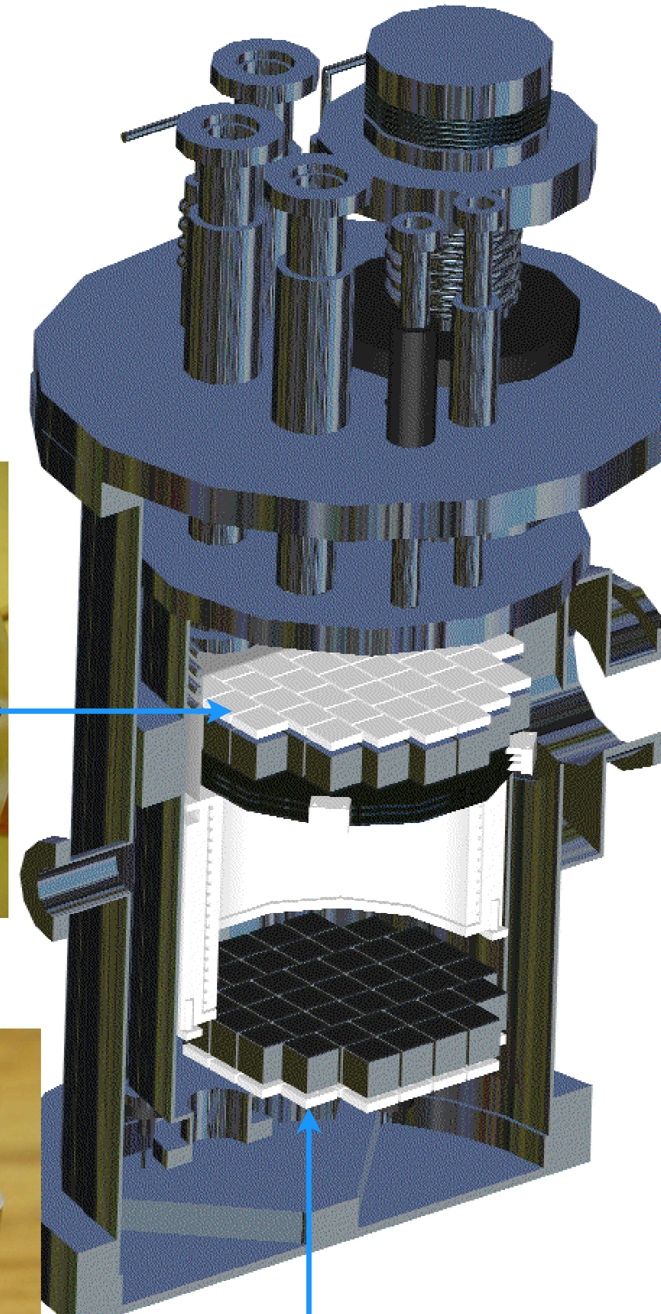
Weak dependence on electric field
Yield increases at low recoil energies

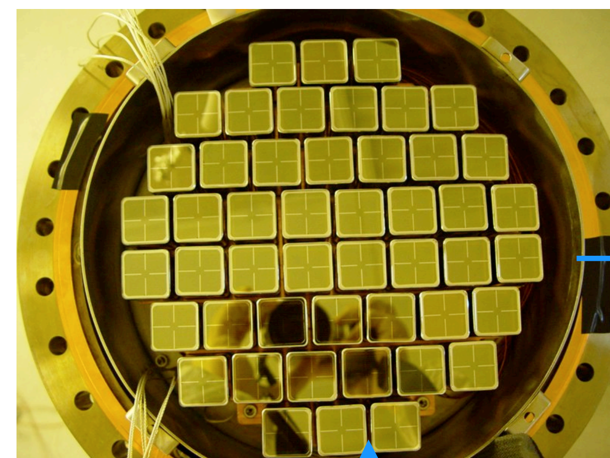
Aprile et al., Phys. Rev. D. 72 (2005)

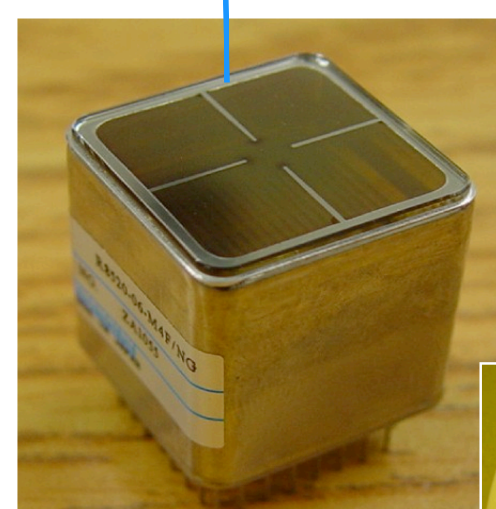
Aprile et al., Phys. Rev. Lett. 97 (2006)

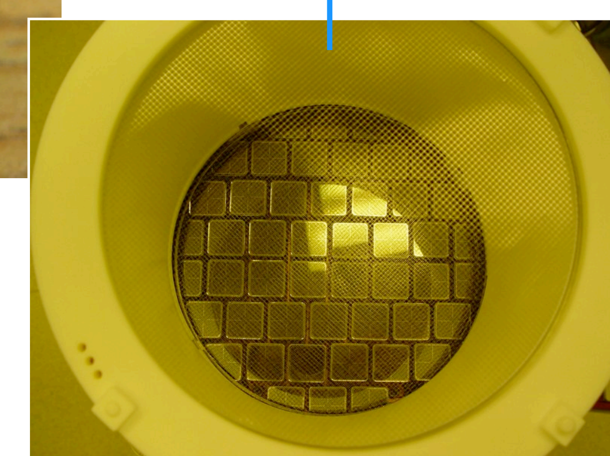
The XENON10 Detector

- **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 -100ºC 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} ($v_{d,e-} \approx 2$mm/µs), $\sigma_Z \approx 0.3$ mm
- **Cooling: Pulse Tube Refrigerator (PTR),**
  90W, coupled via cold finger (LN_2 for emergency)



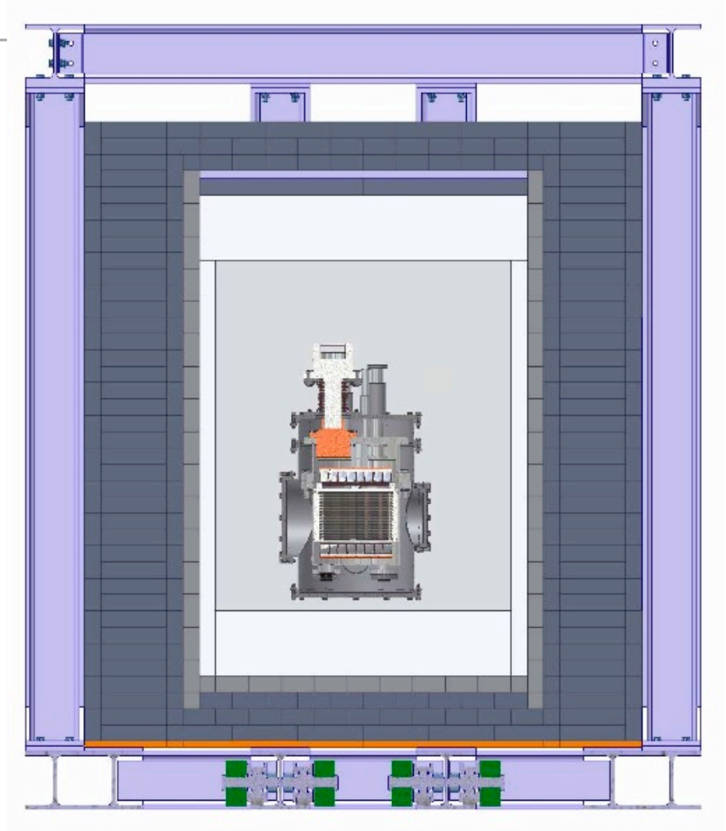


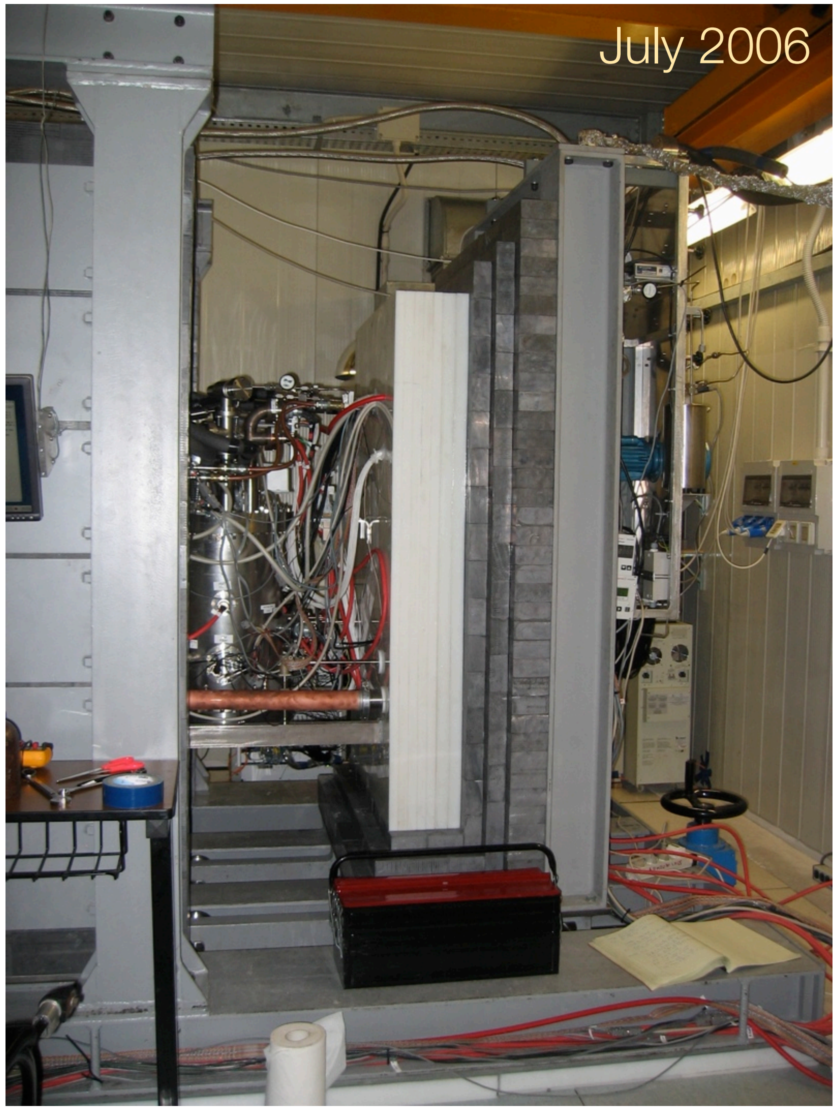




XENON10 at the Gran Sasso Laboratory

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

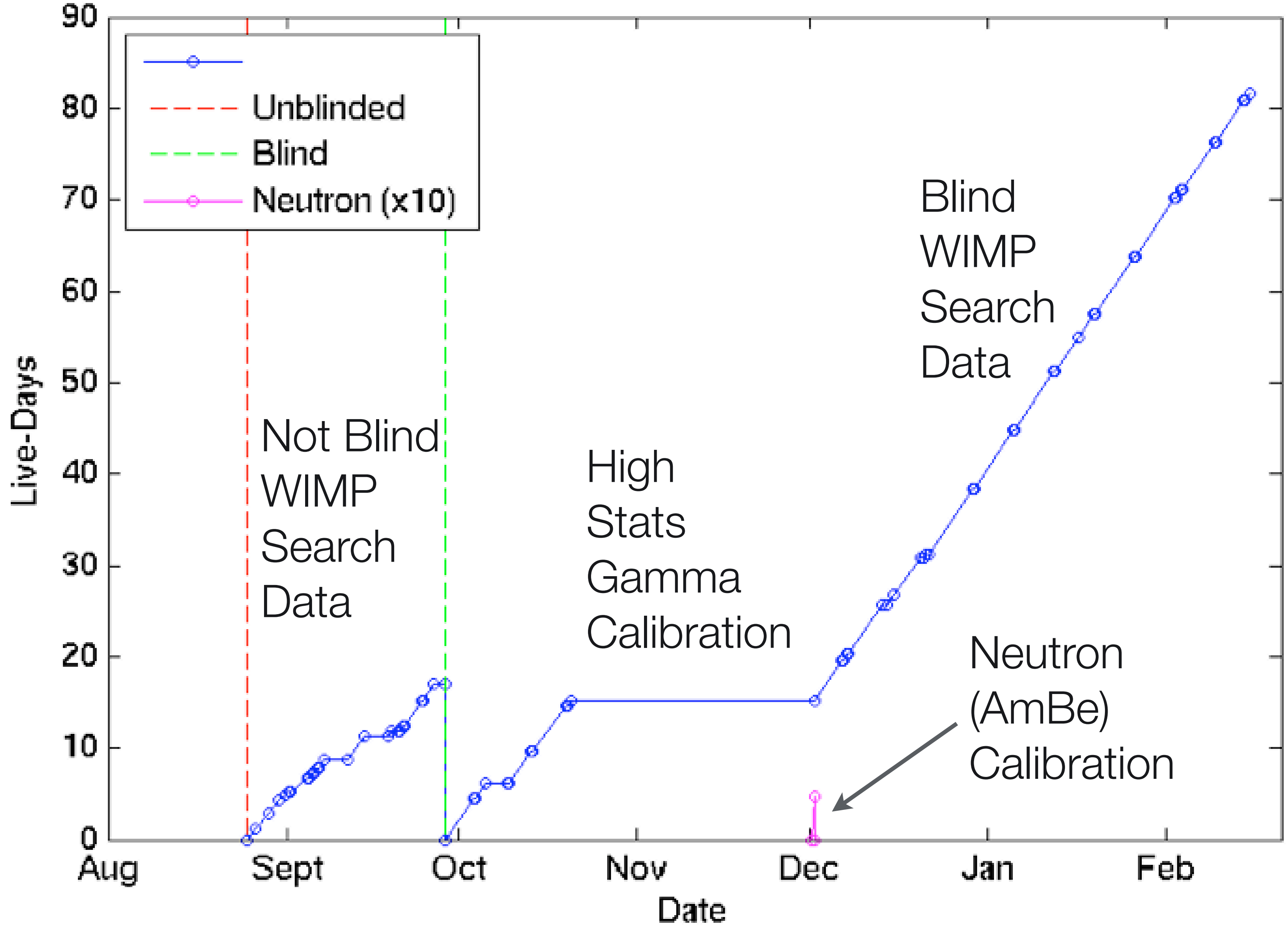




The XENON10 Collaboration

Columbia University Elena Aprile, Karl-Ludwig Giboni, Sharmila Kamat, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli and Masaki Yamashita
Brown University Richard Gaitskell, Simon Fiorucci, Peter Sorensen and Luiz DeViveiros
RWTH Aachen University Laura Baudis, Jesse Angle, Ali Askin, Martin Bissok, Alfredo Ferella, Alexander Kish, Aaron Manalaysay and Stephan Schulte
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, Serena Fattori
Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

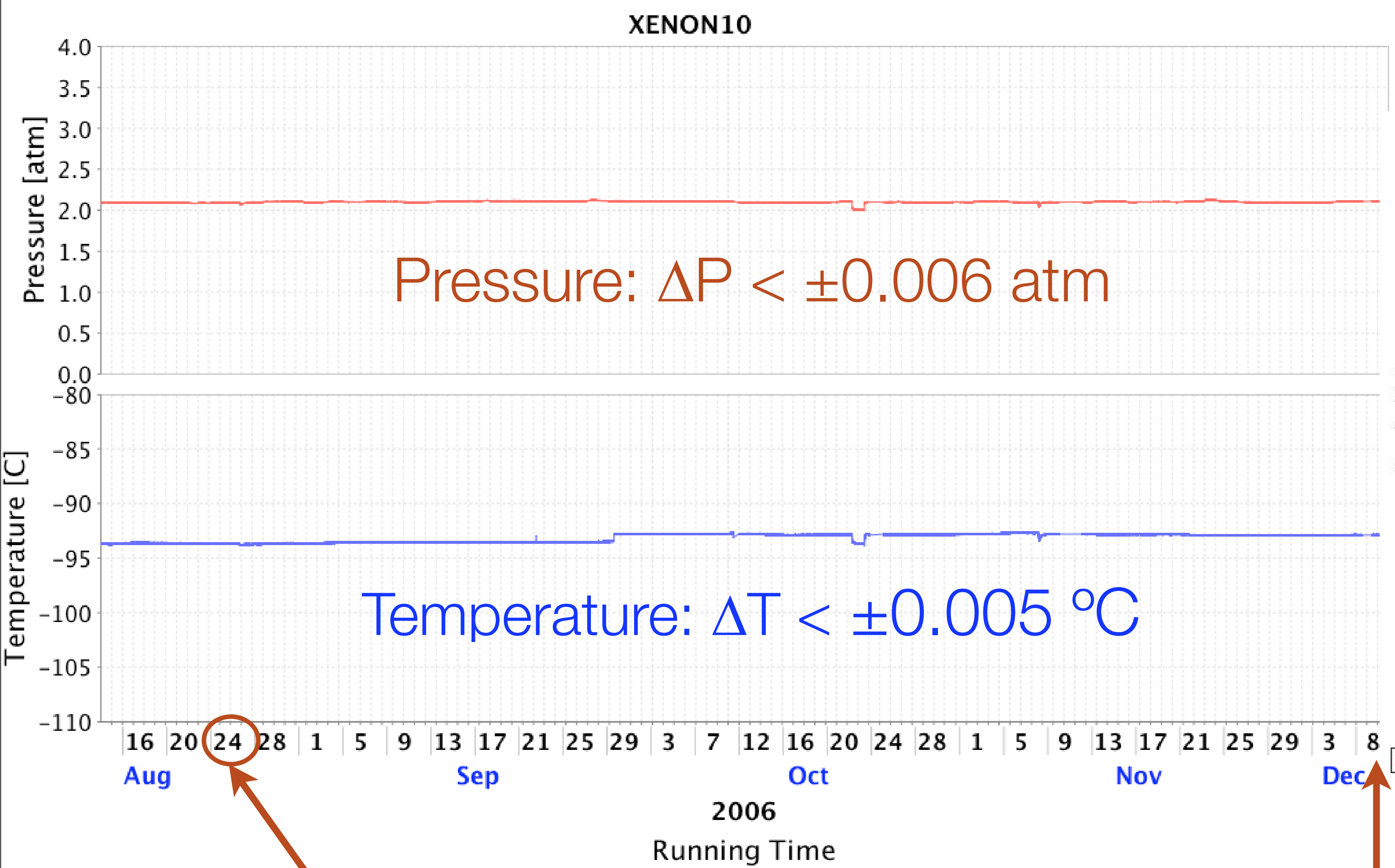
XENON10 Live Time at Gran Sasso

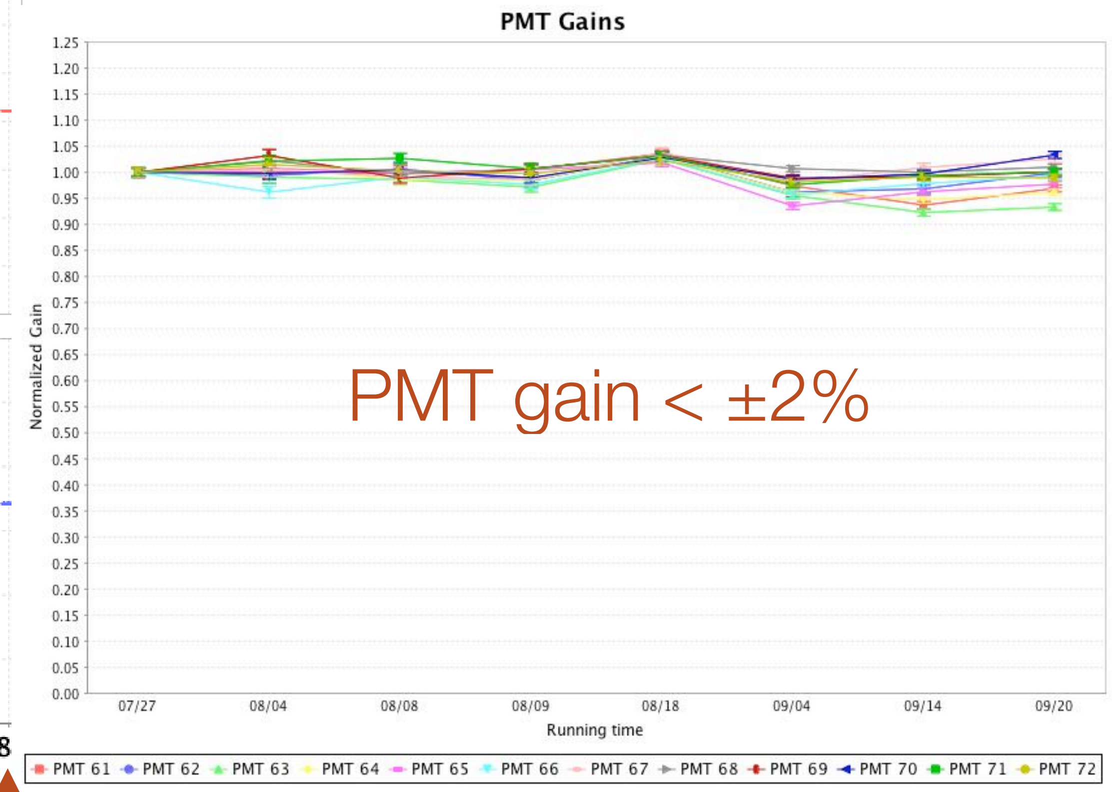


- **Discuss data from:** Gamma, Neutron Calibration + Not Blind WS data (~ 20 live days)
- **WIMP Search Results (~ 80 live days):** to be announced Mid April 07 (APS meeting)

XENON10 Performance at LNGS

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



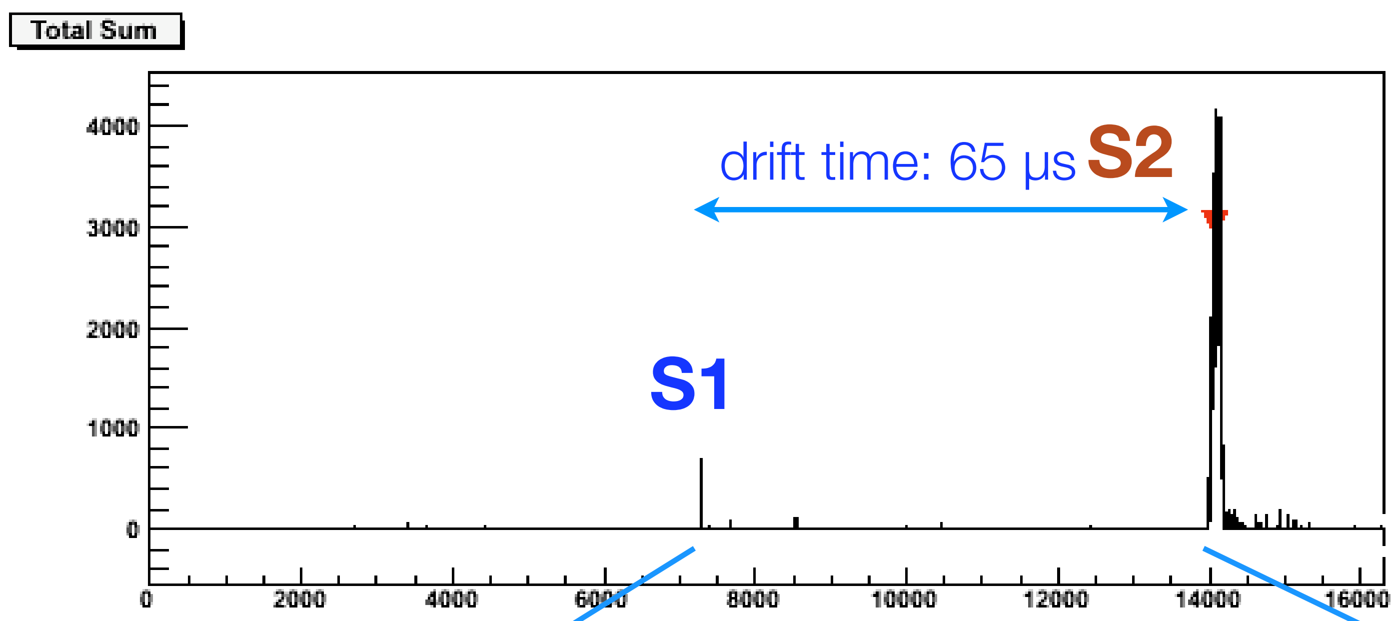


Start of WIMP Search Run

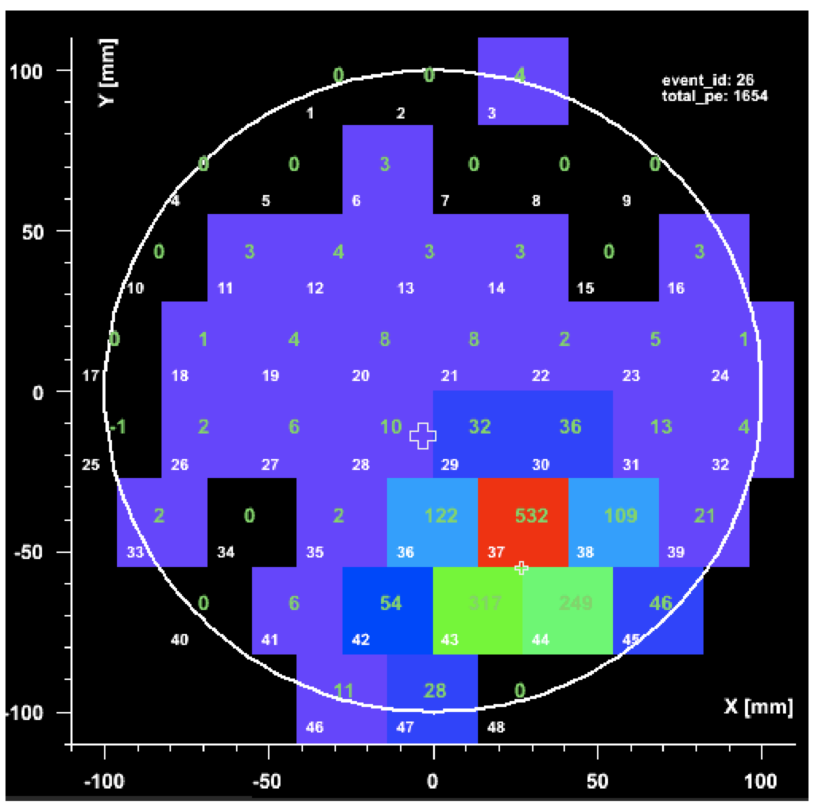
December 8, 06

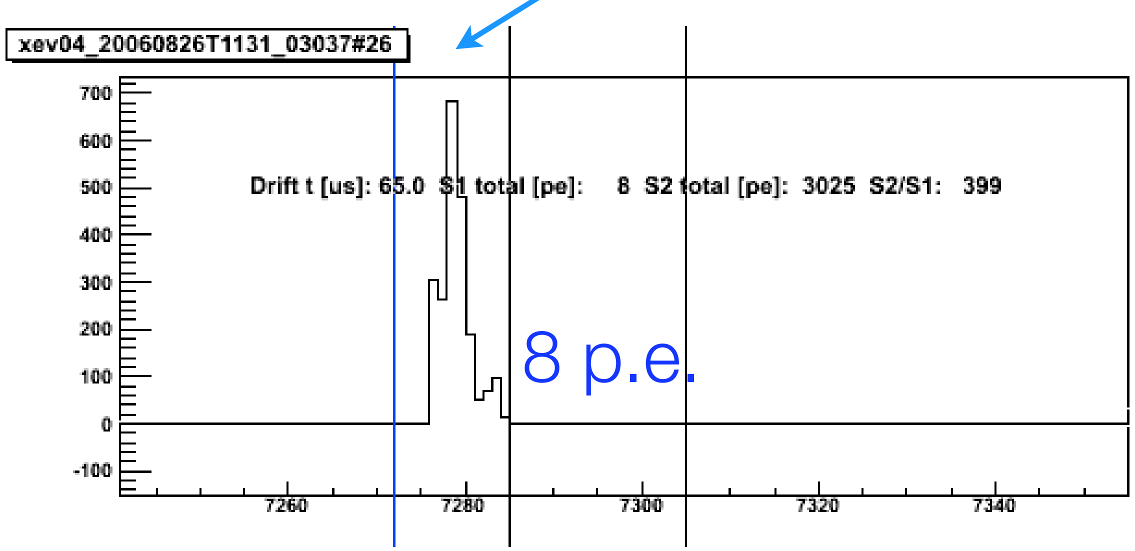
Typical XENON10 Low-Energy Event

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

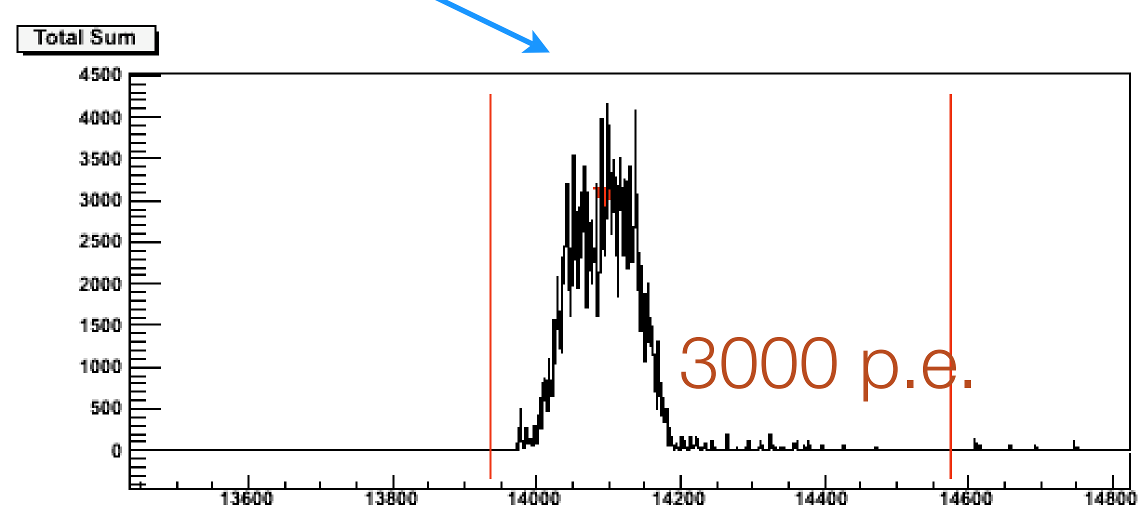


Hit pattern of top PMTs





S1

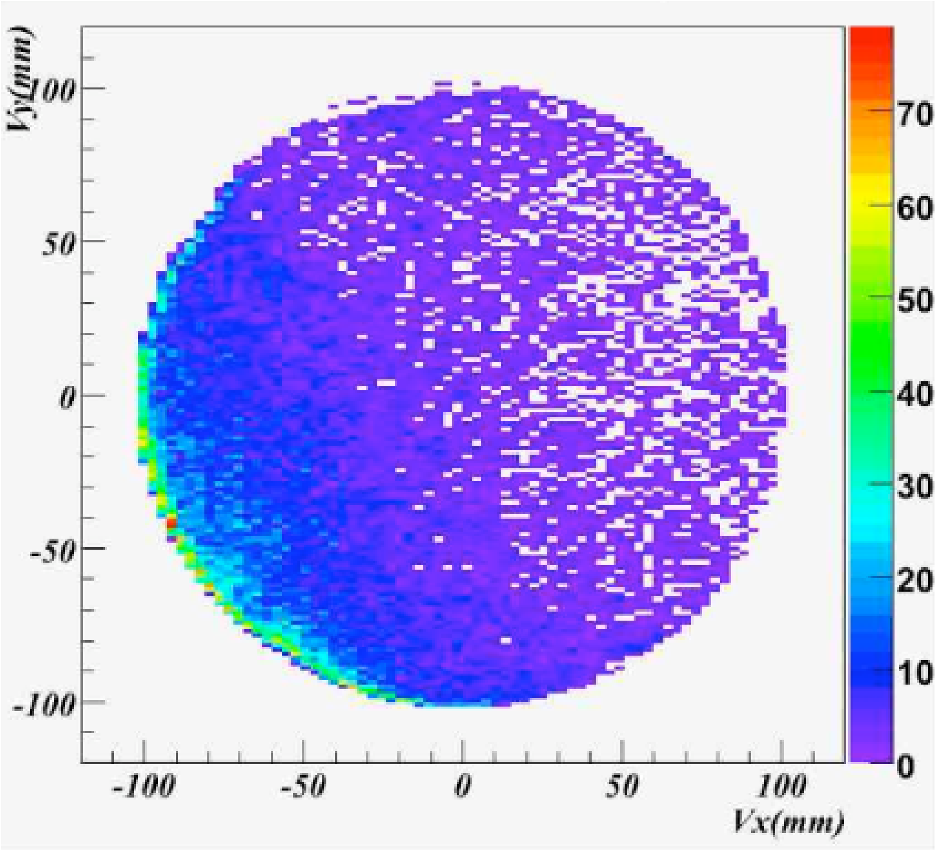


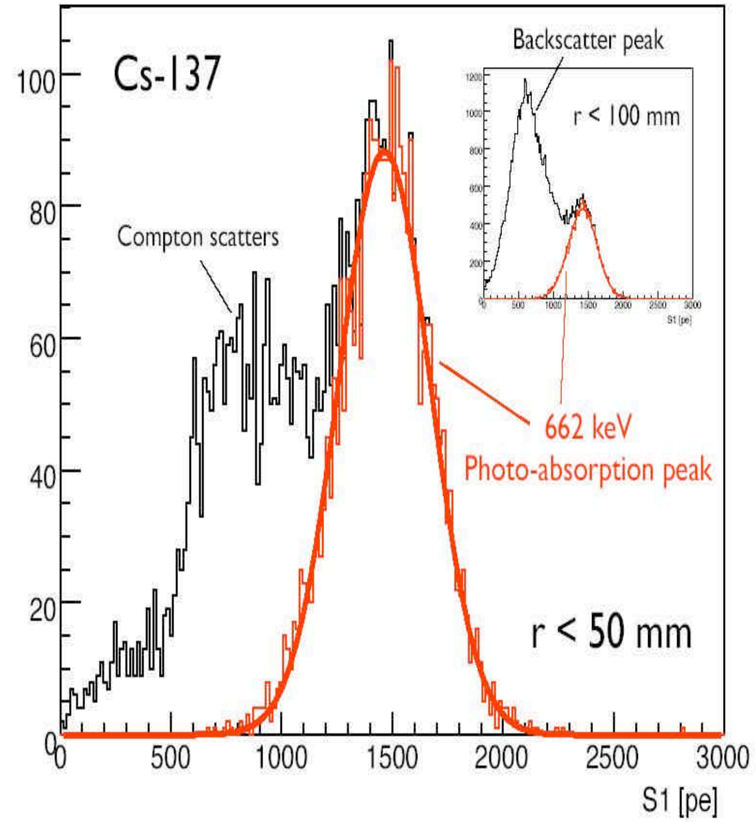
S2

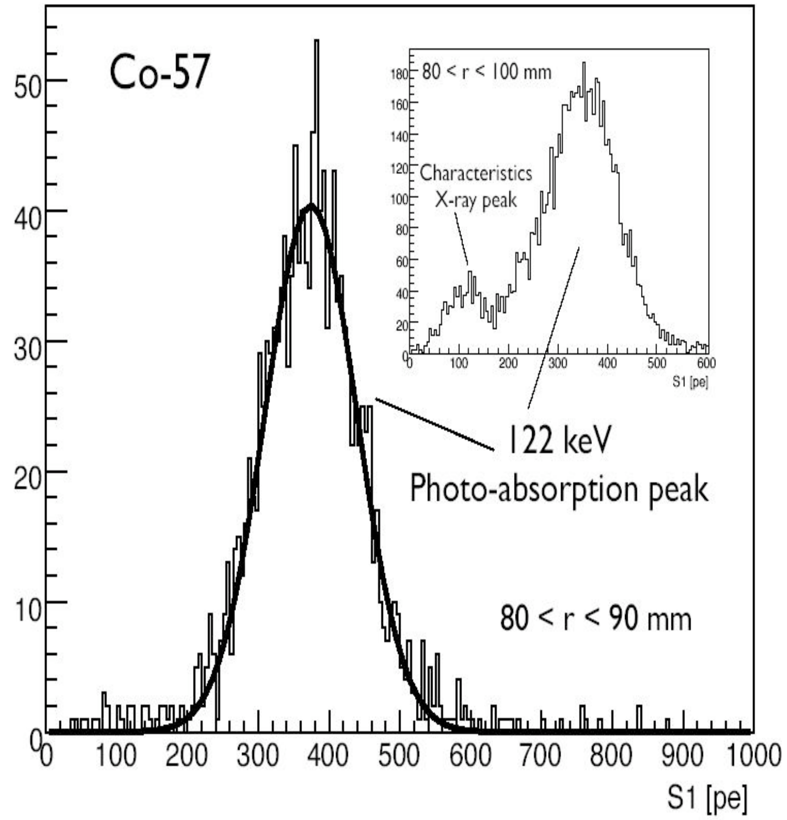
XENON10 Gamma Calibrations

- 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 => << 1ppb (O_2 equiv.) purity

energy scale (S1 in p.e)





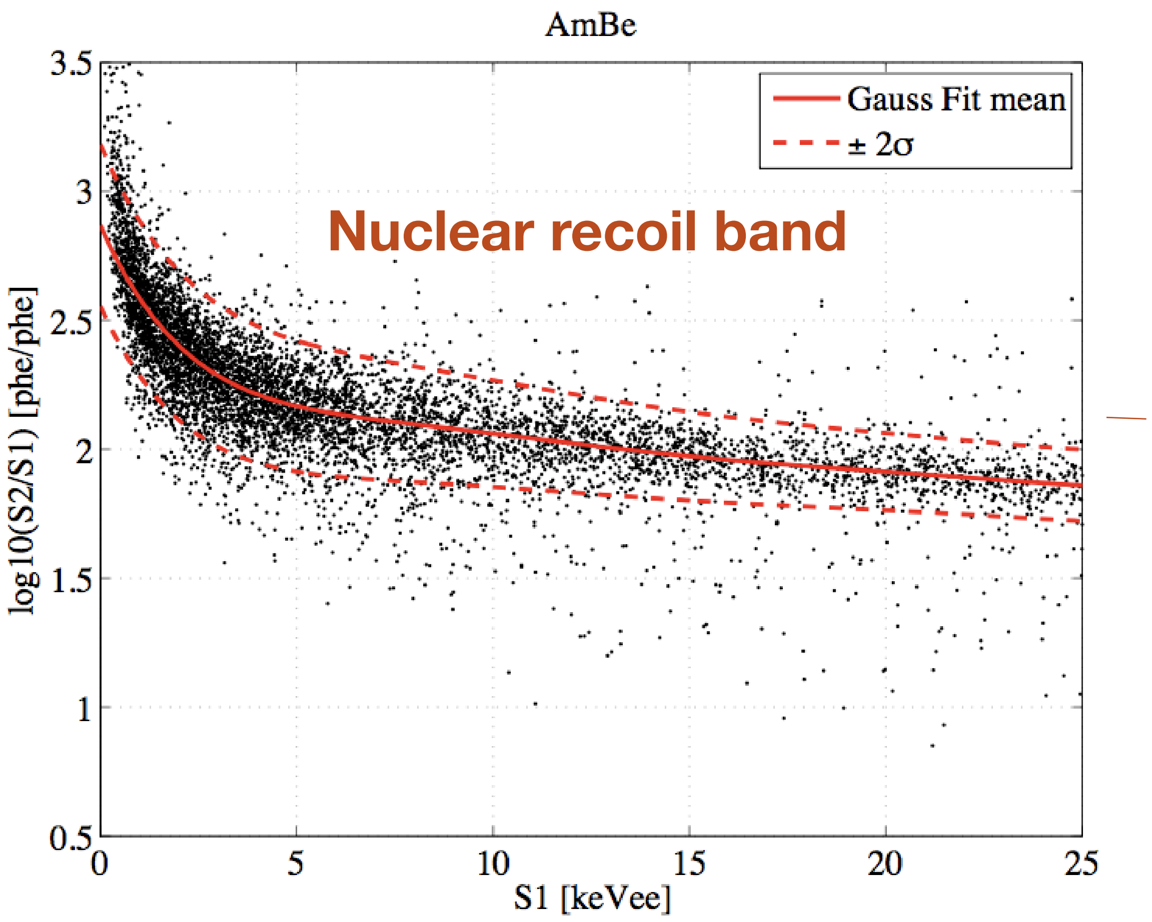


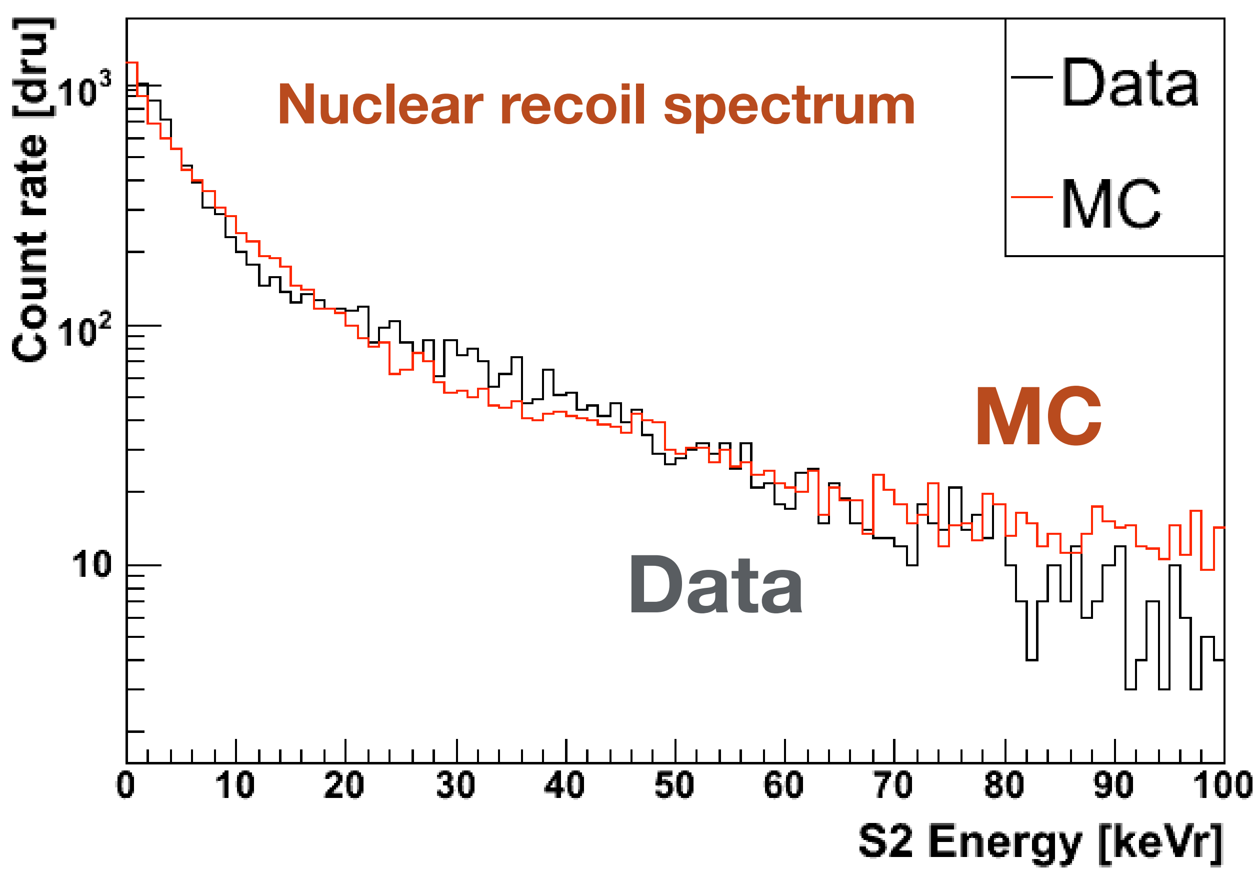
reconstructed source position (^{137}Cs)

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

XENON10 Neutron Calibration

- Neutron source: AmBe ($E_{max} \approx 10$ MeV)
- In situ calibration: December 1, 06 => determination of the nuclear recoil band

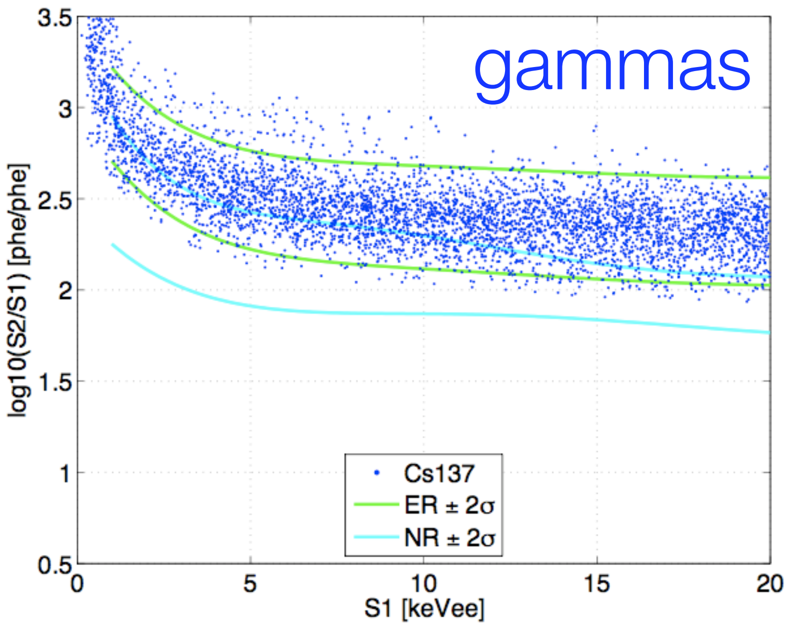


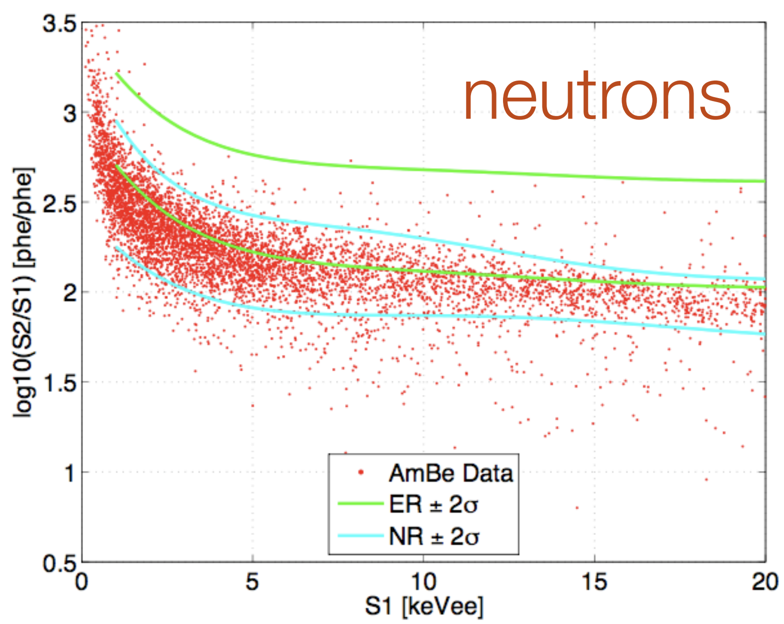


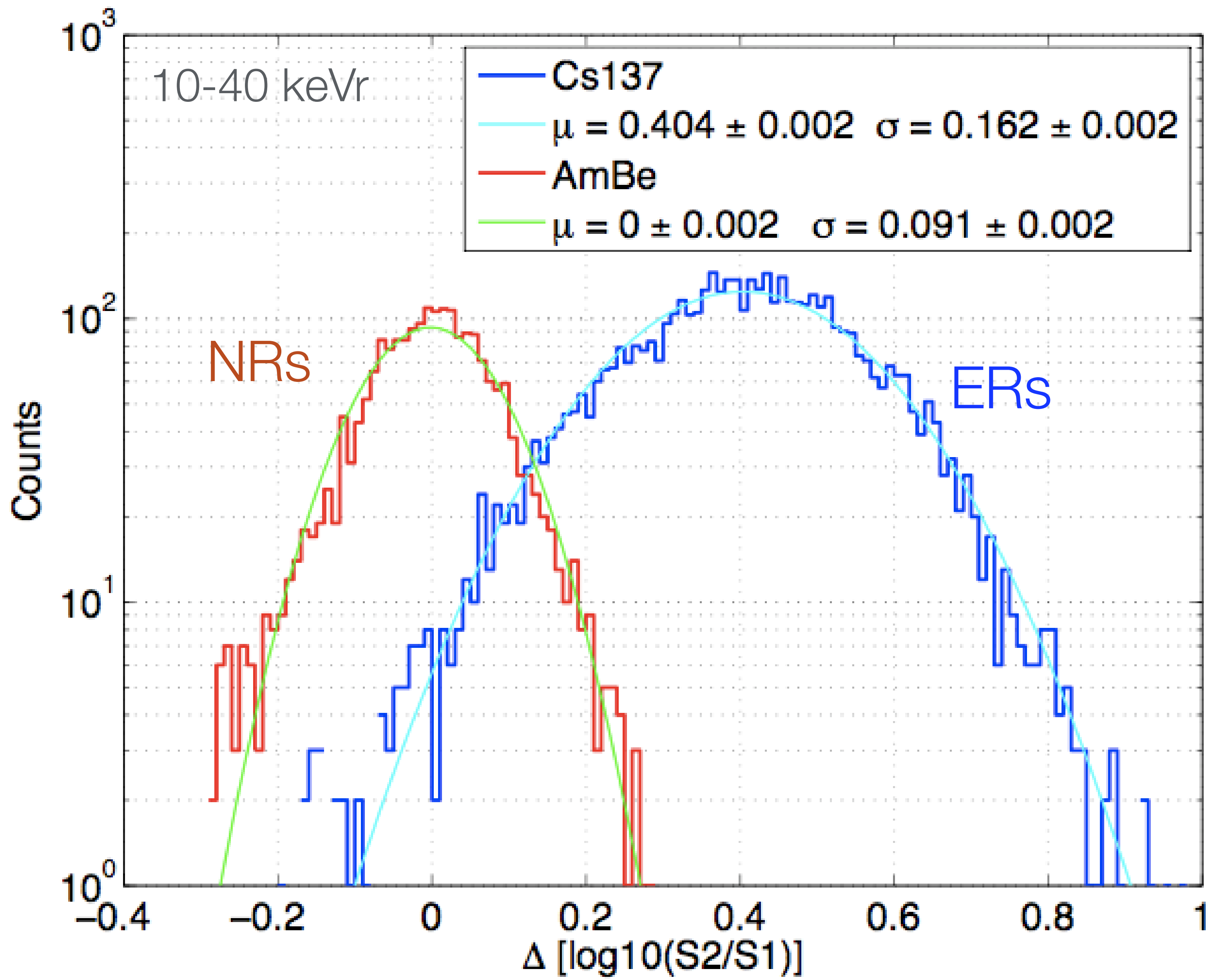
Data and Monte Carlo agree well:

⇒ NR response at low energies well understood

XENON10 Discrimination



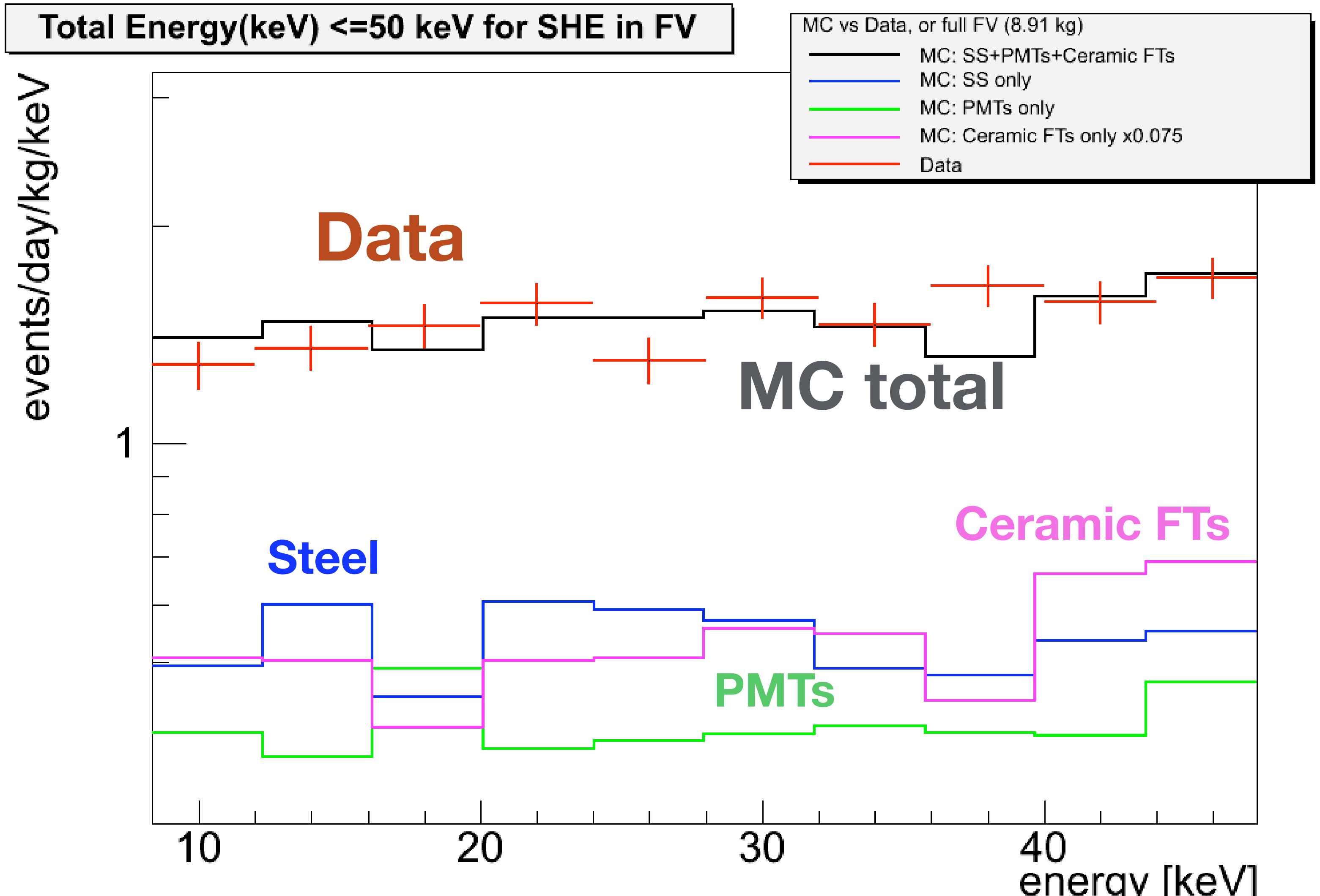




- **Rejection is > 99% for 50% Nuclear Recoil acceptance**
  - ➡ **Cuts:** fiducial volume (remove events at teflon edge where poor charge collection)
  - ➡ Multiple scatters (more than one S2 pulse)

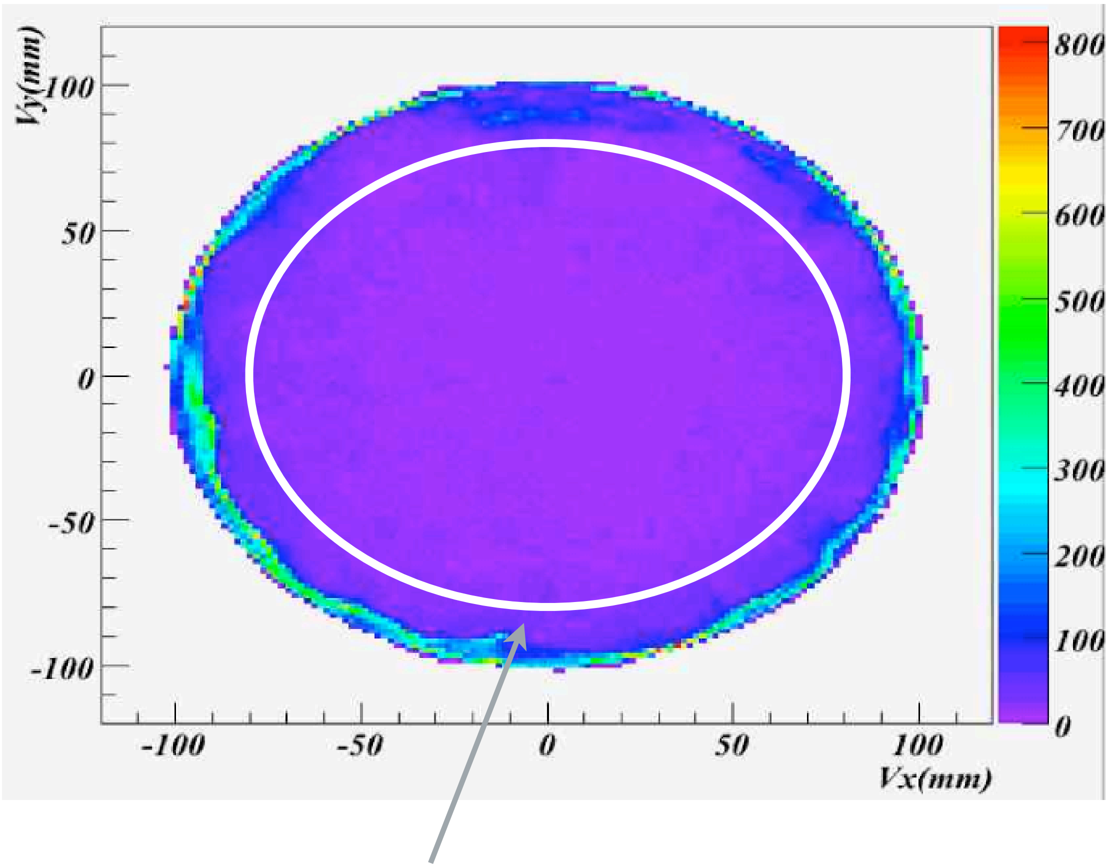
XENON10 Backgrounds

- **Red crosses**: data; **Black curve**: sum of background contributions from MC
  - ➡ < 1event/(kg d keV) (< 1 dru) (for r < 8 cm fiducial volume cut)



Single hits in fiducial mass (8.9 kg)

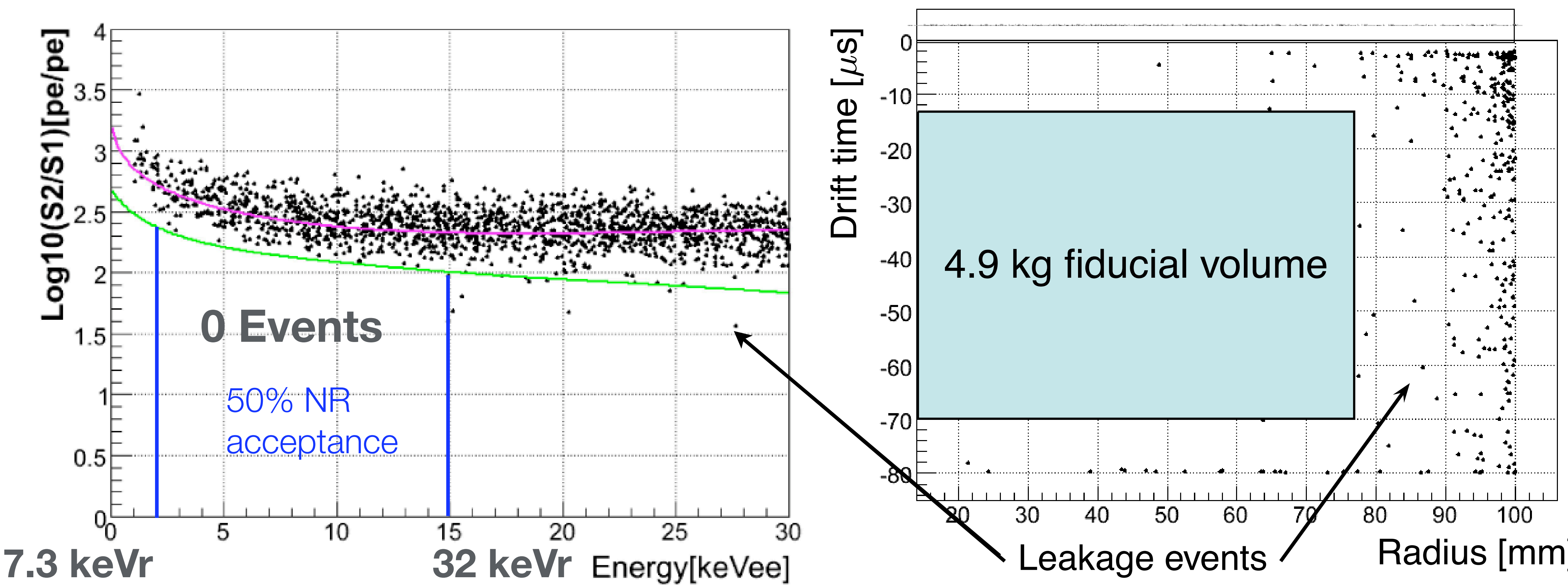
x-y position of WS data



r < 8 cm fiducial volume cut

XENON10 Preliminary WIMP Search Data

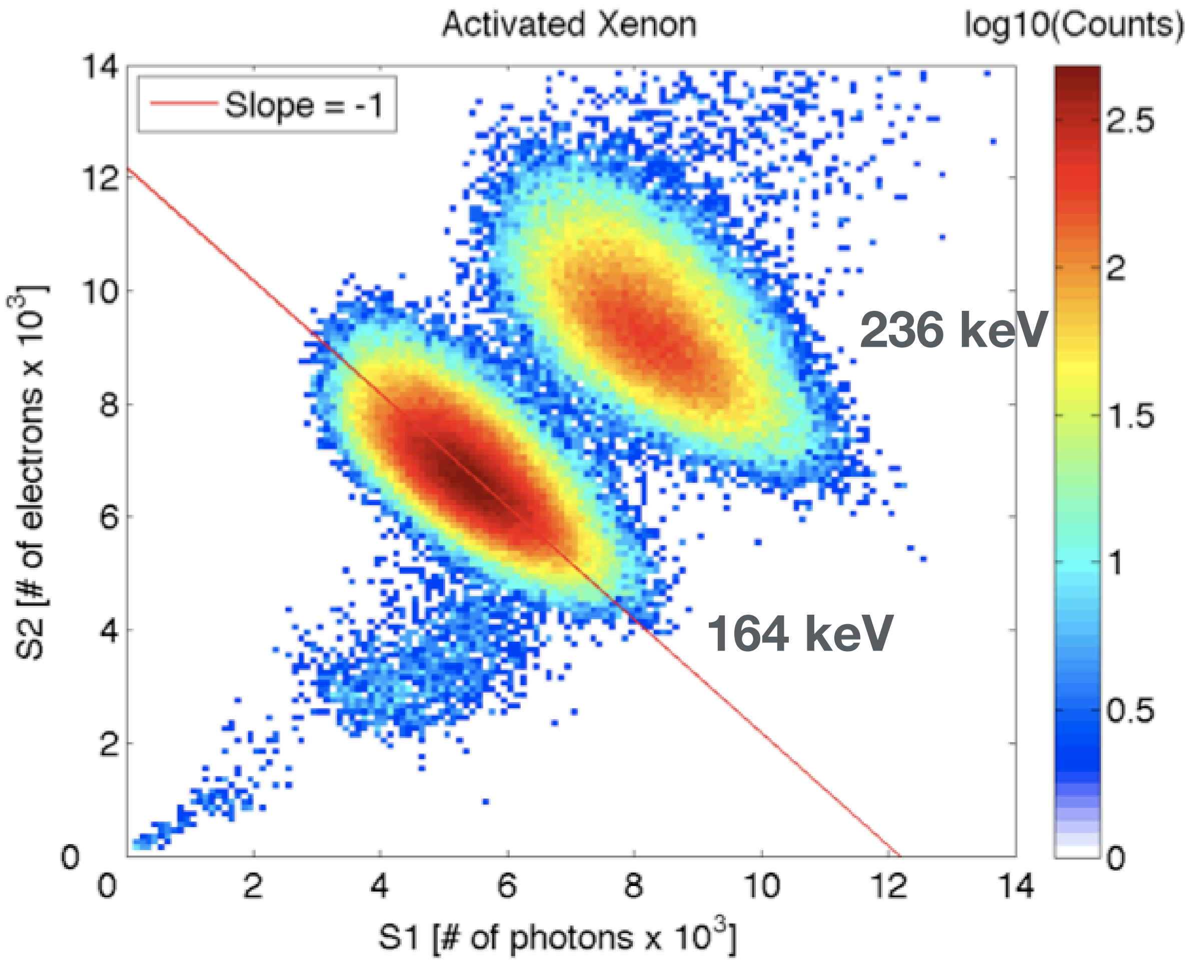
- WIMP search run started Aug. 24. 2006: ~ **80 (blind) live days**
- 2 independent analysis groups (root and matlab based)
- Example: **preliminary data from ~ 17 live days**



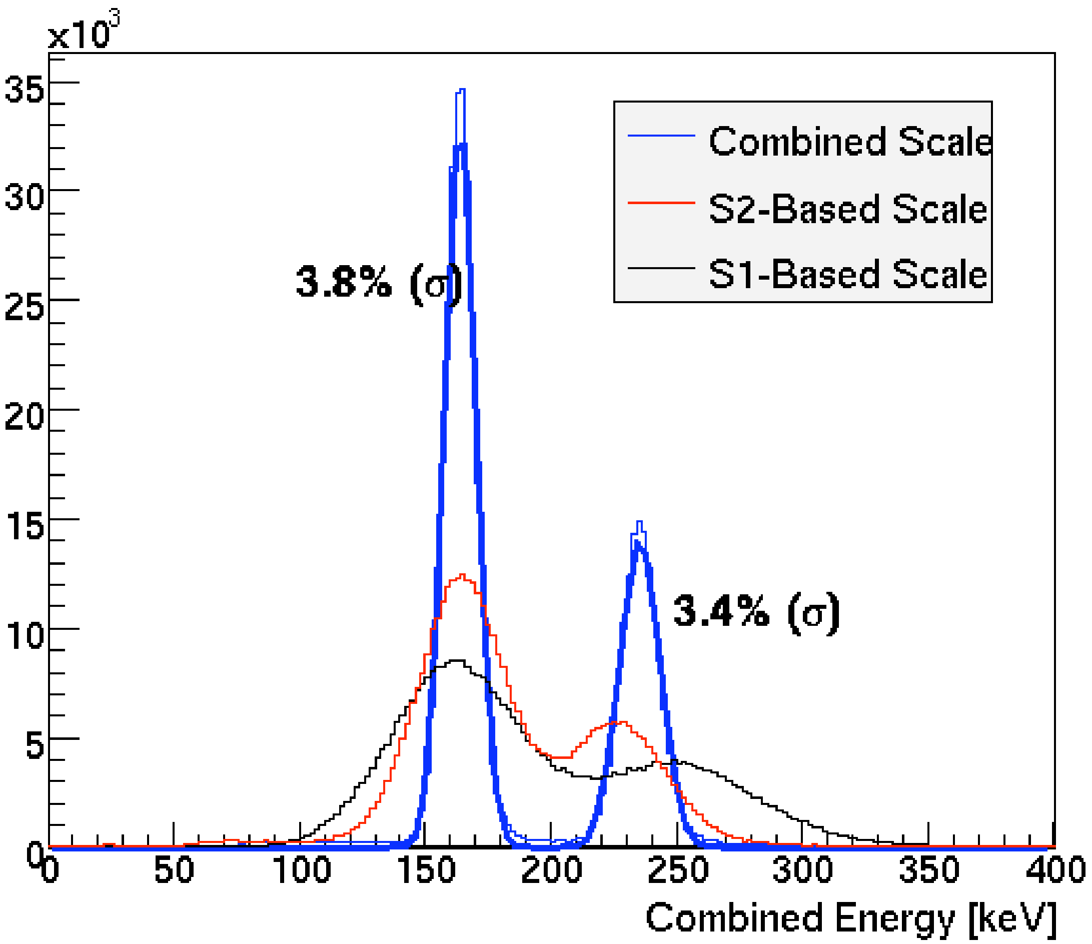
- **Full analysis in progress**: understand source of leakage events; set cuts and calculate efficiencies based on γ- and n-calibration data, ...

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



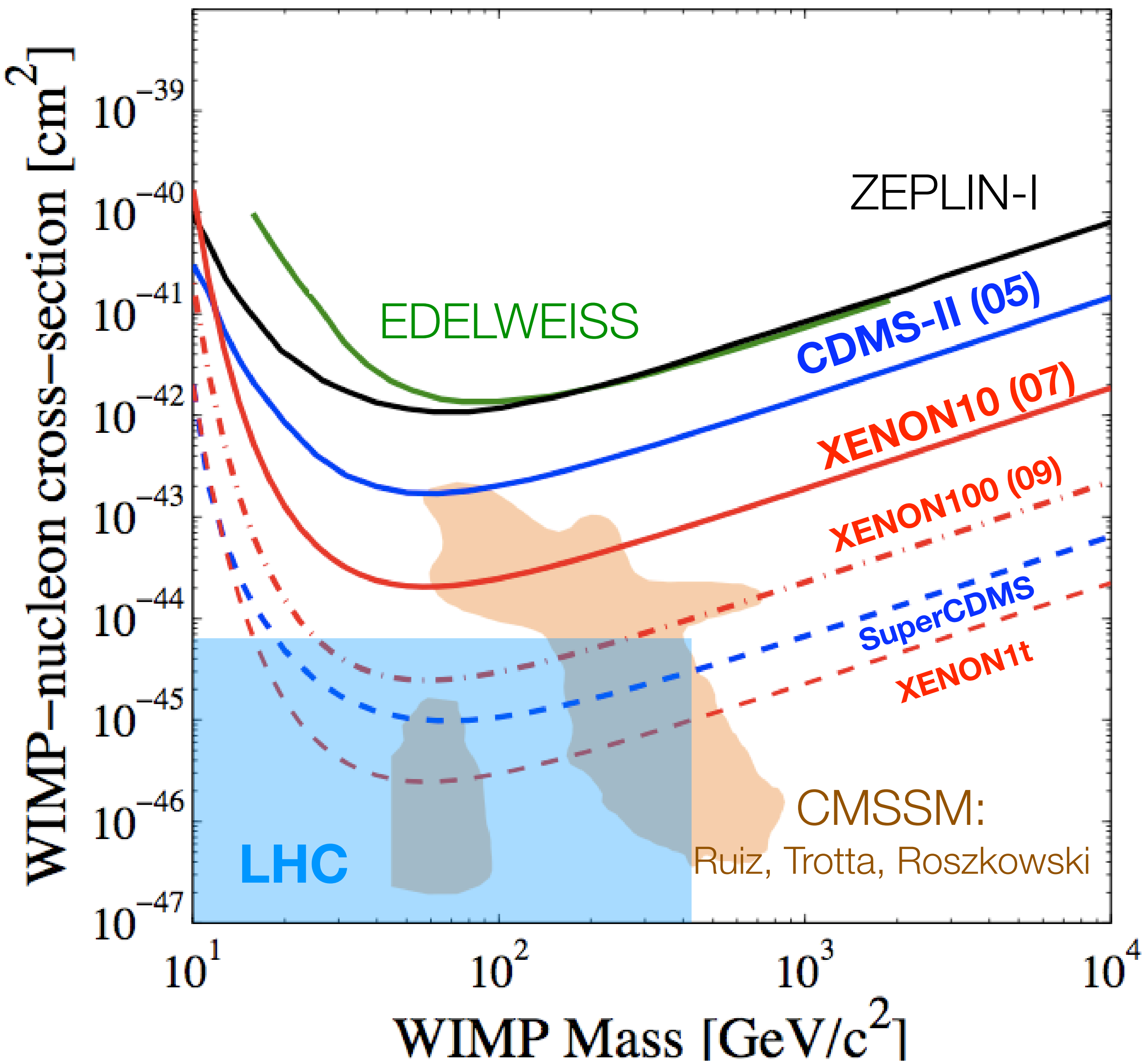
Anti-correlation of charge/light signals



Combined energy spectrum

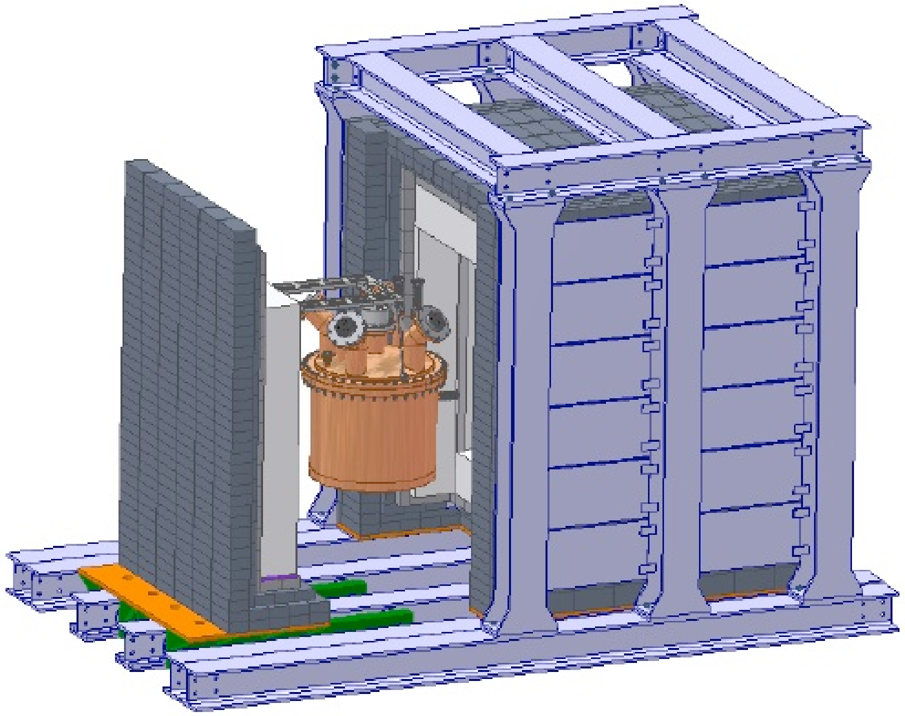
XENON10 WIMP Search Goals

- Test the elastic, SI WIMP-nucleon σ down to $\approx 2 \times 10^{-44}$ cm^2 in 2007 (red curve)

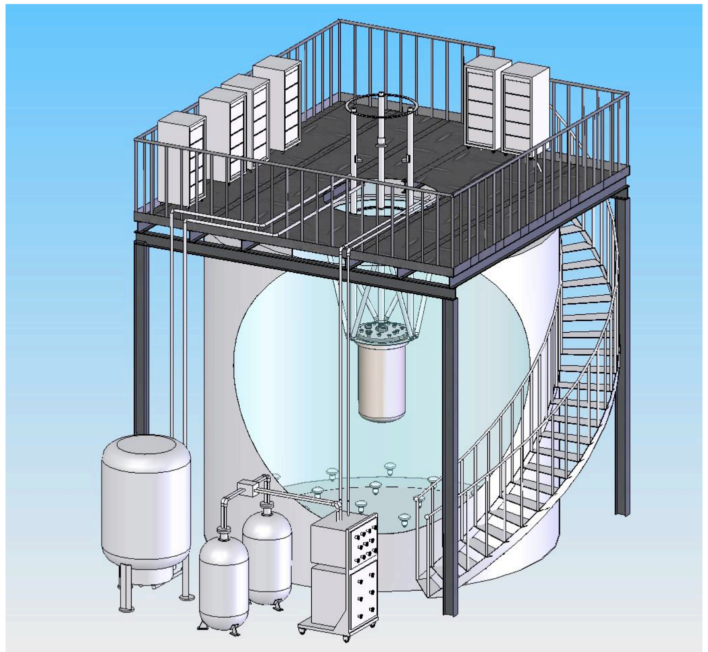


Dual-Phase Xenon: Future Projects (Proposals/ Design Studies)

- **XENON100:** US/EU Collaboration to build 100 kg (fiducial) LXe detector in (conventional: Pb, PE) XENON10 shield at LNGS (NSF/DoE/SNF/FCT proposal)
- **LUX** (Large Underground LXe detector): US Collaboration to build a 300 kg (100 kg fiducial mass) LXe detector at DUSEL in large (6 m ø water shield) (NSF/DoE proposal)
- **ELIXIR** (European Liquid Xenon Identifier of Recoils): Large European design study for ton-scale LXe detector; Construction after completion of ZEPLIN-III, XENON100 (FP7 Proposal)



XENON100 experiment

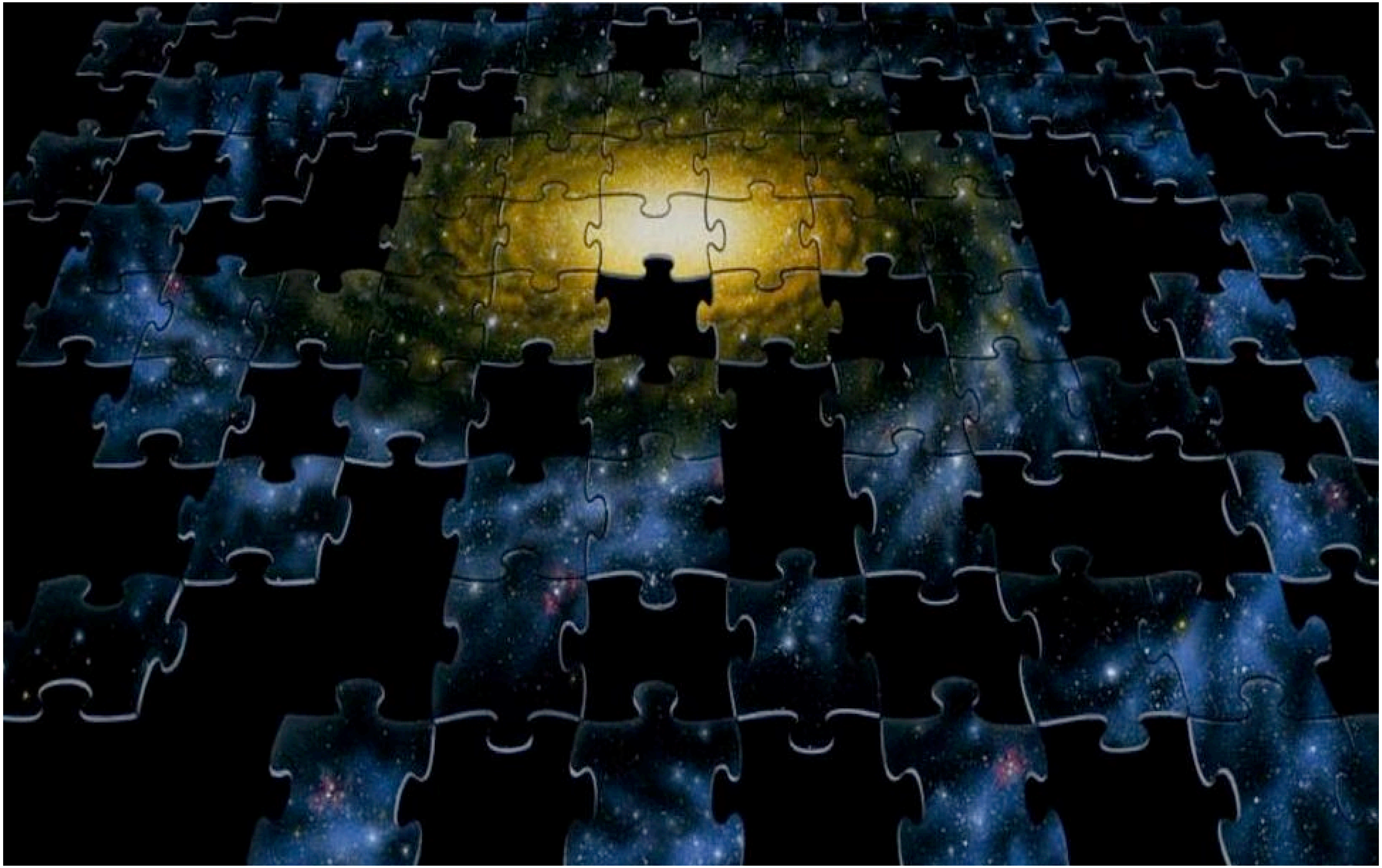


LUX experiment

Summary

- WIMPs: still excellent candidates for Cold Dark Matter
- Liquid Noble Elements: very promising WIMP detectors
  - ➡large, homogeneous detectors; self-shielding; position resolution; NR/ER discrimination (light/charge and/or pulse timing); affordable costs
- first results: from LAr (WARP) and LXe (ZEPLIN-II) (at the 6.7 - 10 x 10^{-7}pb level)
- XENON10: results from 80 live days public in mid April (~ 2 x 10^{-7}pb level)
- Many near-term projects, proposals and design studies:
  - ➡ZEPLIN-III, XENON100, MiniCLEAN, DEAP-1, ArDM, XMASS800, WARP140, LUX, ELIXIR...
  - ➡Test the WIMP-nucleon cross section parameter space down to $\approx 10^{-7}$ pb -10^{-9} pb.
- Optimistic scenario: discovery of new particle, in conjunction with signals from indirect search experiments and new physics at colliders
- But: we are open for surprises!

Noble Liquids: Solving the Dark Matter Puzzle?



Direct Detection of WIMPs

- **In the extreme NR limit ($v_{WIMP} \approx 10^{-3}$ c)**

  ⇒ axial-vector interaction (coupling to the nuclear spin)

  ⇒ scalar interaction (coupling to the nuclear mass)

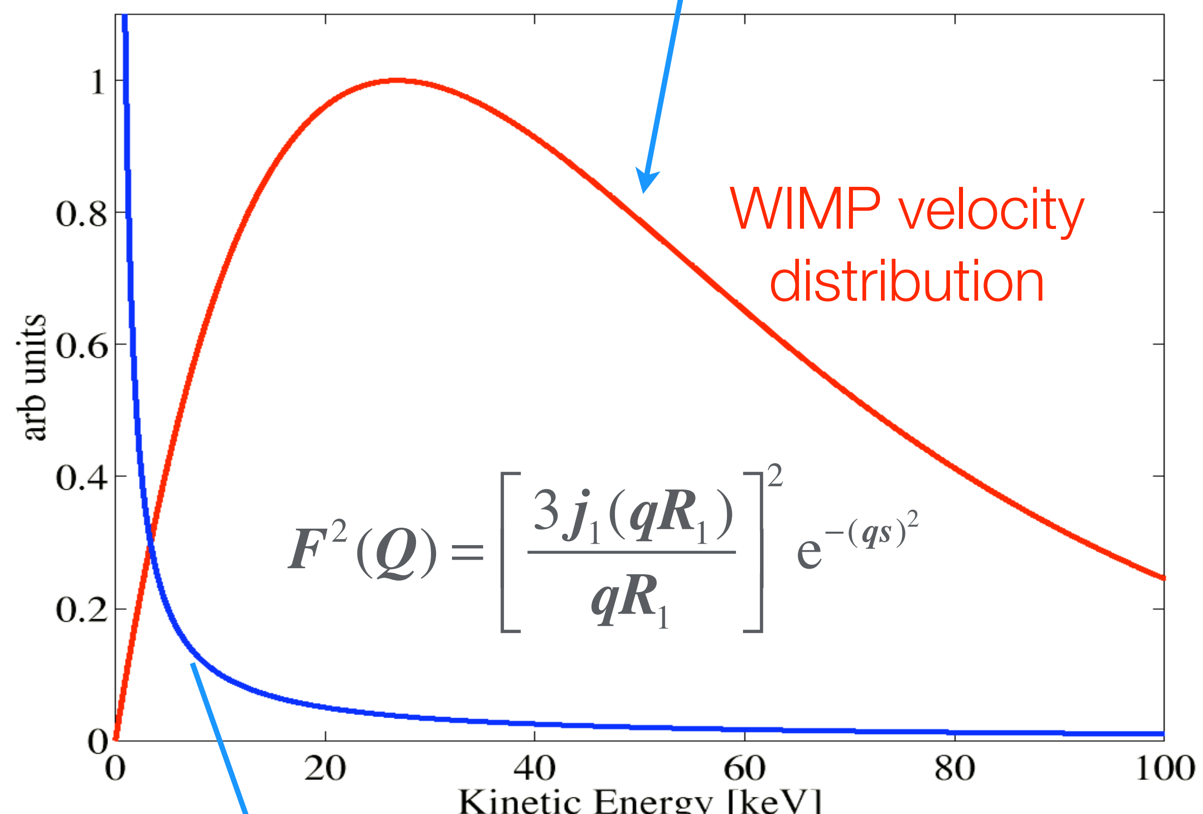
- Event rate:

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi \mu^2} \exp\left(-\frac{Q m_N}{2 \mu^2 v_0^2} \right) F^2(Q)$$

- Recoil energy

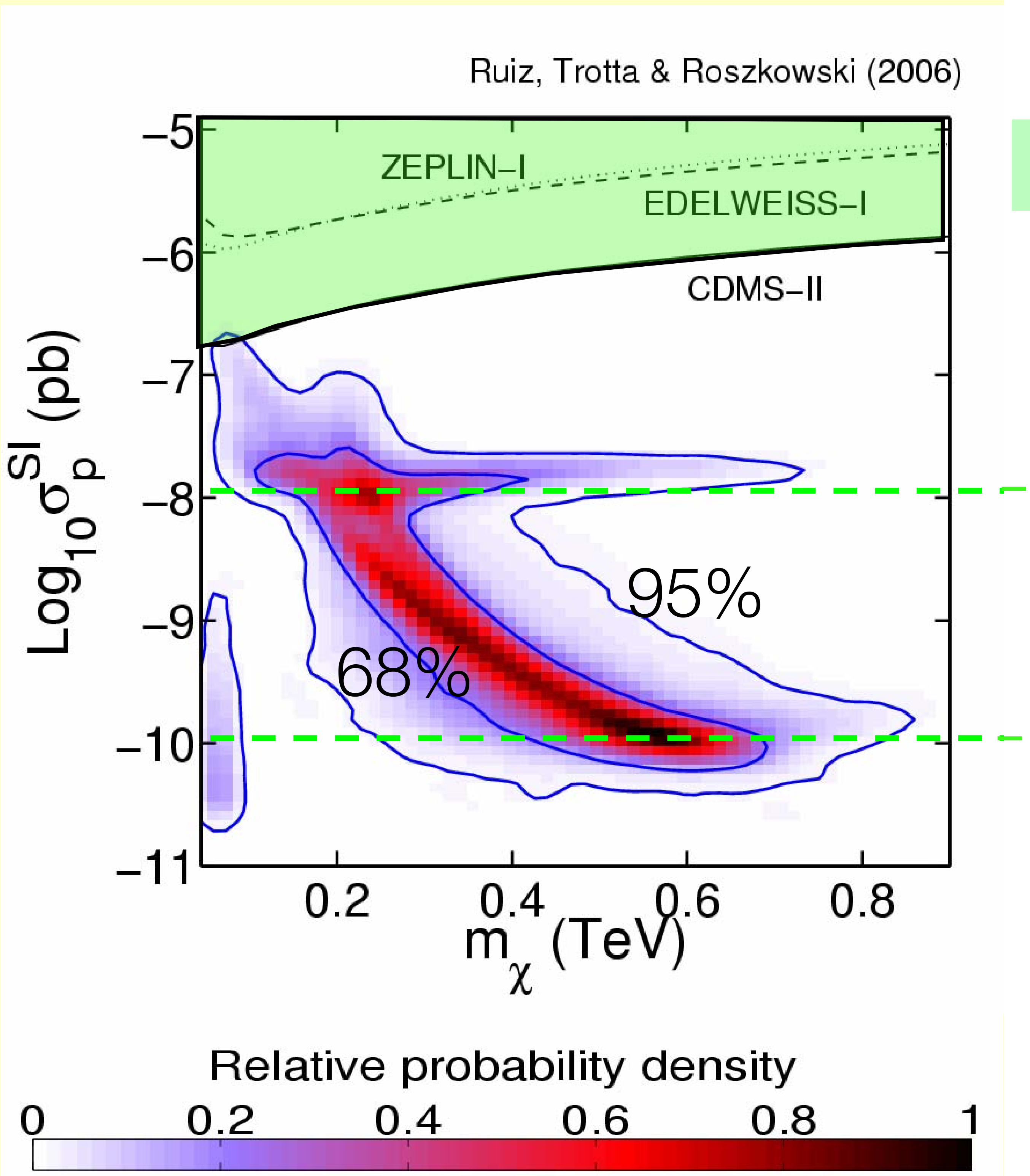
$$Q = \frac{|\vec{q}|^2}{2 m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) < 100 keV$$

$$f(v)dv = \frac{4 v^2}{v_0^3 \sqrt{\pi}} e^{-v^2/v_0^2} d^3 v$$



$\frac{dR}{dQ}$ nucleus recoil spectrum

Experiments and SUSY Predictions



excluded by CDMS-II

1 event/kg/yr

CDMS-II, XENON10

CRESST-II, EDELWEISS-II

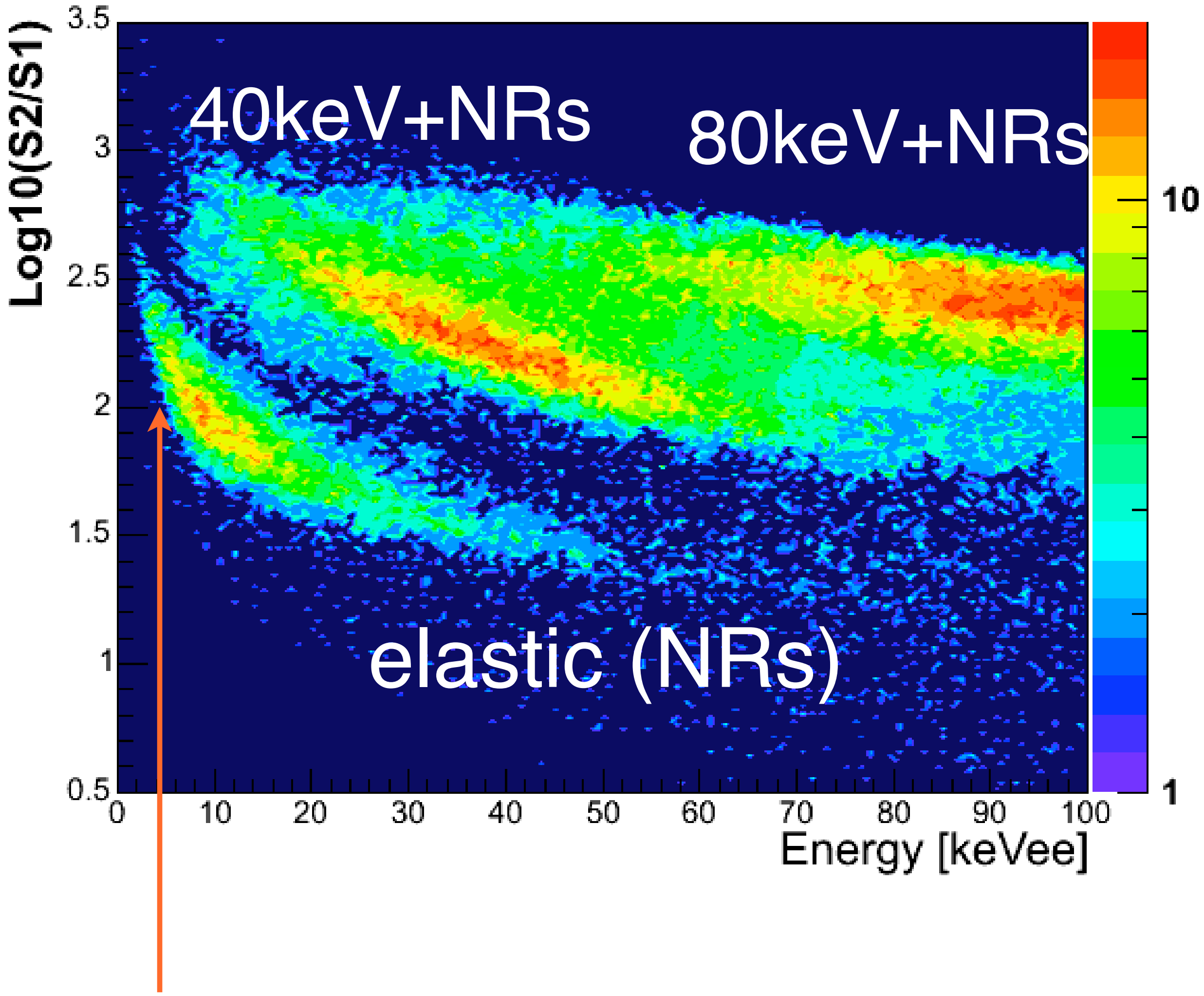
1 event/t/yr

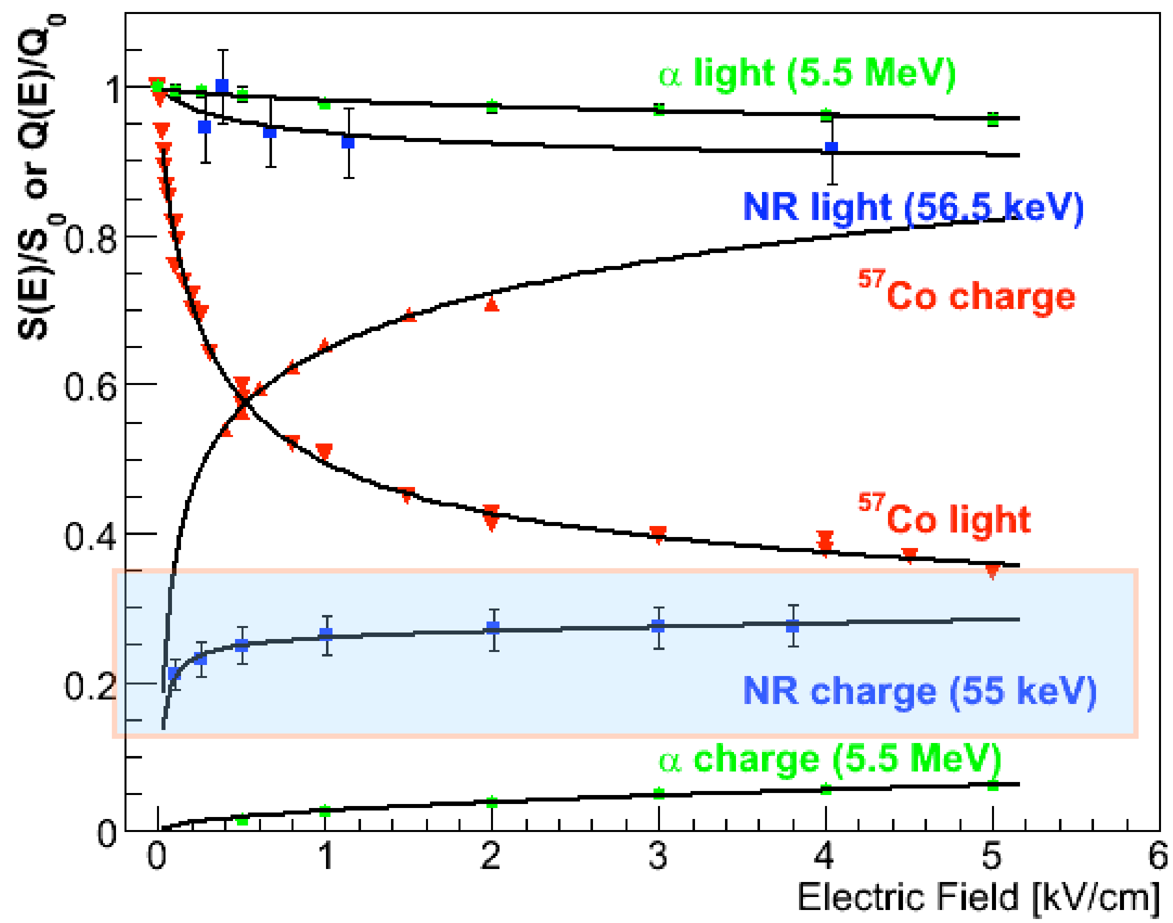
SuperCDMS1t

XENON1t, EURECA

Ionization Yield and Discrimination in Liquid Xenon

AmBe n-source





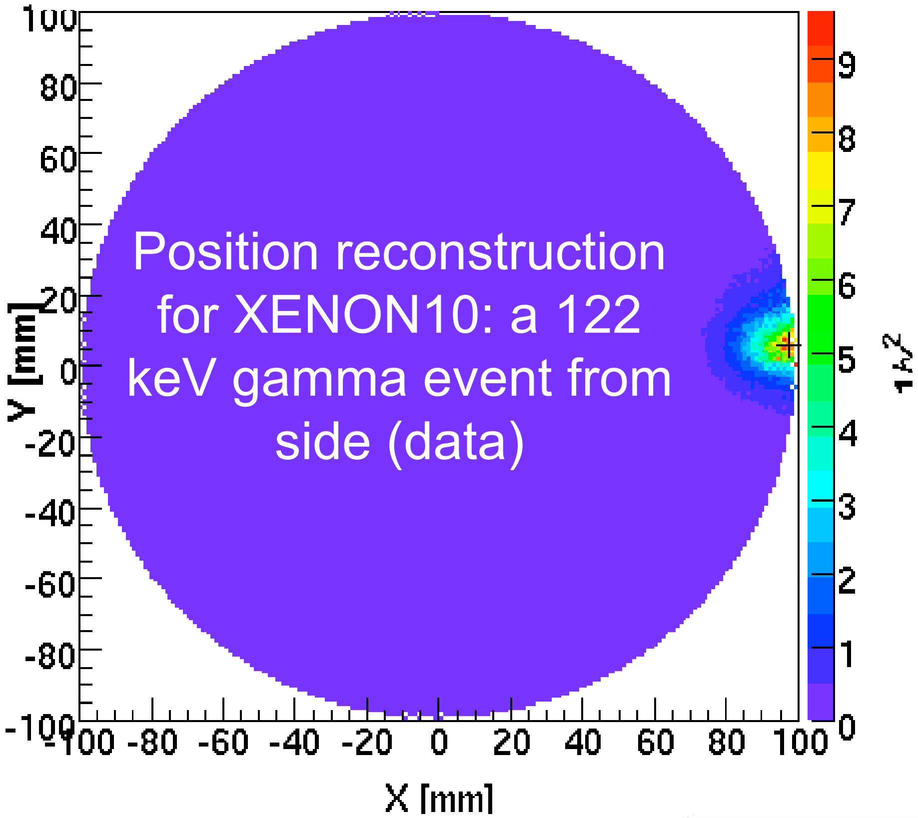
Electric Field [kV/cm]

5 keVee energy threshold = 10 keVr
good discrimination (>99%) between NR und ER

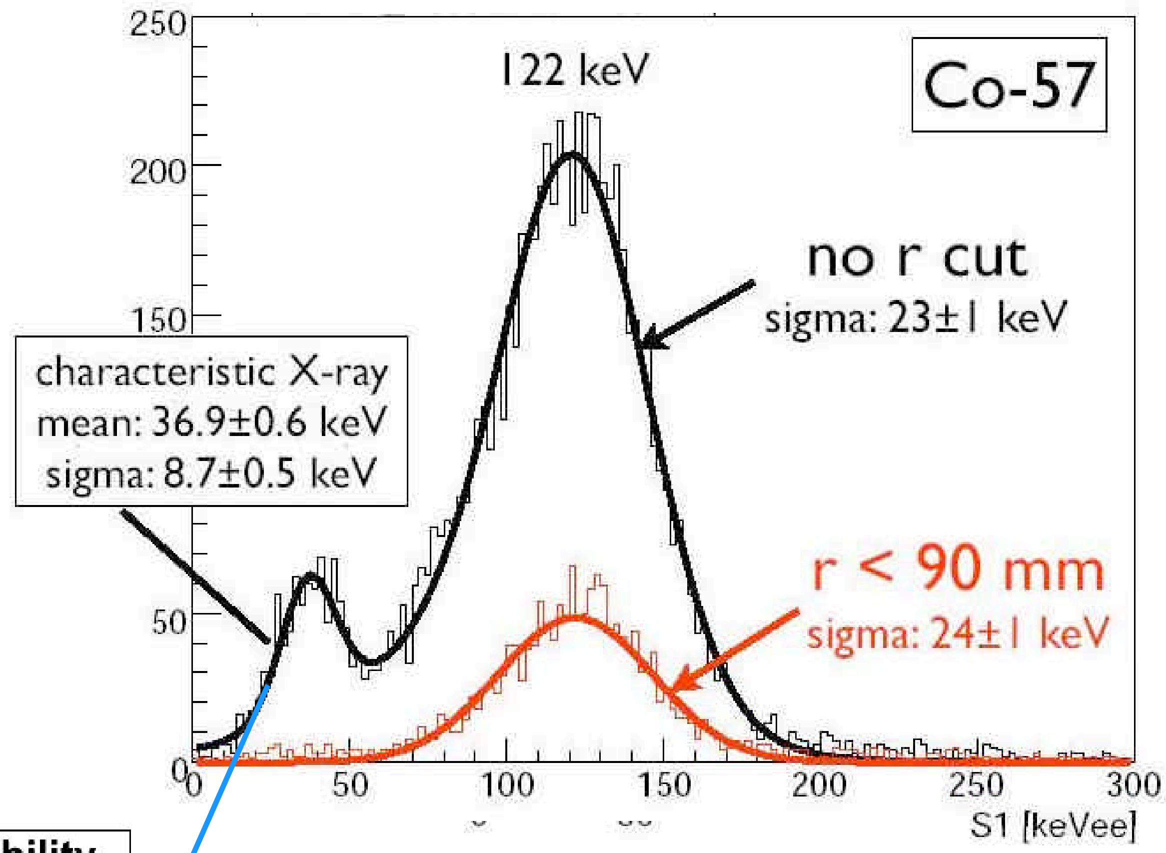
Aprile et al., Phys. Rev. Lett. 97 (2006)

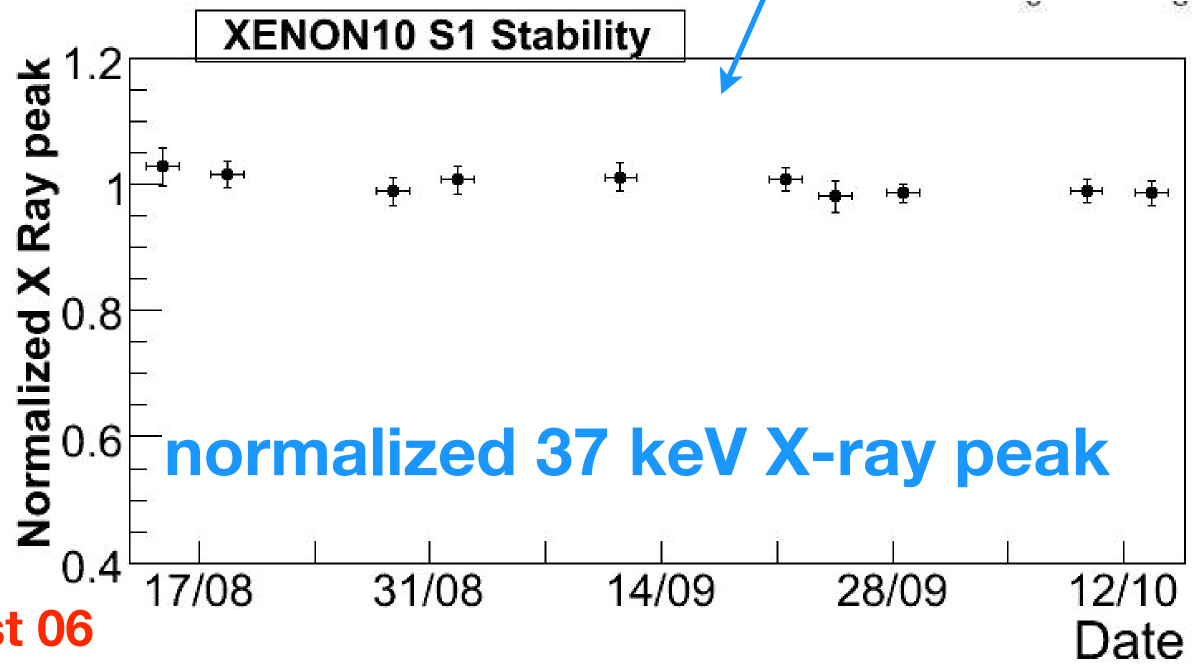
XENON10 Gamma Calibrations

reconstructed source position (^{57}Co)



detector stability test: the 37 keV X-ray





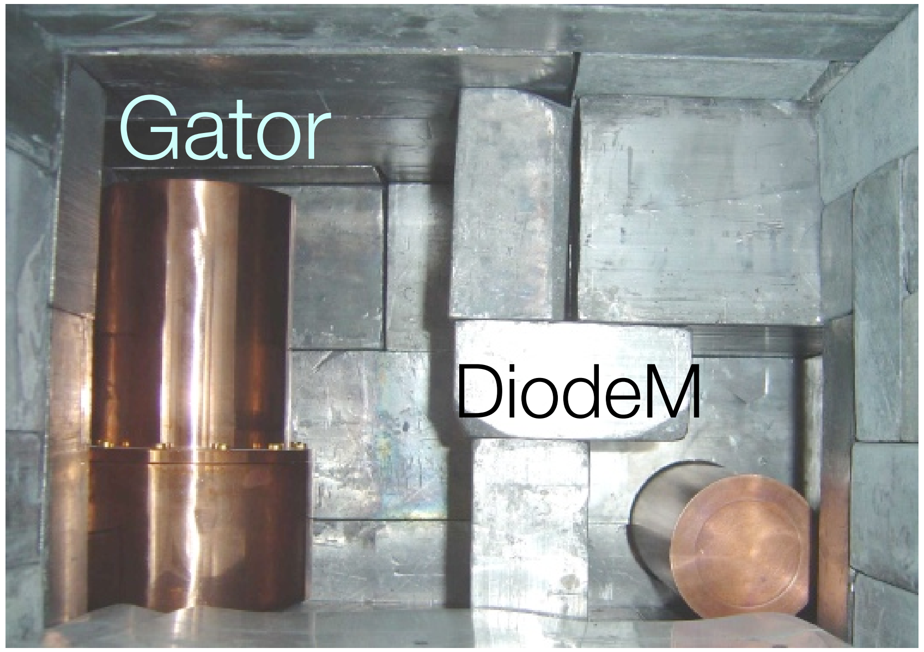
XENON10 Backgrounds: Material Screening

- we have screened the XENON10 detector+shield components with 2 HPGe detectors at SOLO/Soudan and a HPGe detector at LNGS (M. Laubenstein)

Sample	R8520 PMTs [mBq/PMT]	Kyocera FTs [Bq/kg]	Ceramaseal FTs [Bq/kg]	SS inner vessel [mBq/kg]	Teflon [mBq/kg]	PMT bases [mBq/base]	PE shield [mBq/kg]
Activity	**15.6/<6.4/110/0.08 (4PMTs)**	**937/58/3**	4.8/0.5/2.1	<21/<61/12/101	<4.8/<7.9/61	1.2/<2.9/6.7/0.09	26.7/2.9/49
	0.17/0.2/10/0.56 (14 PMTs)	**0.5/0.2/0.1**					

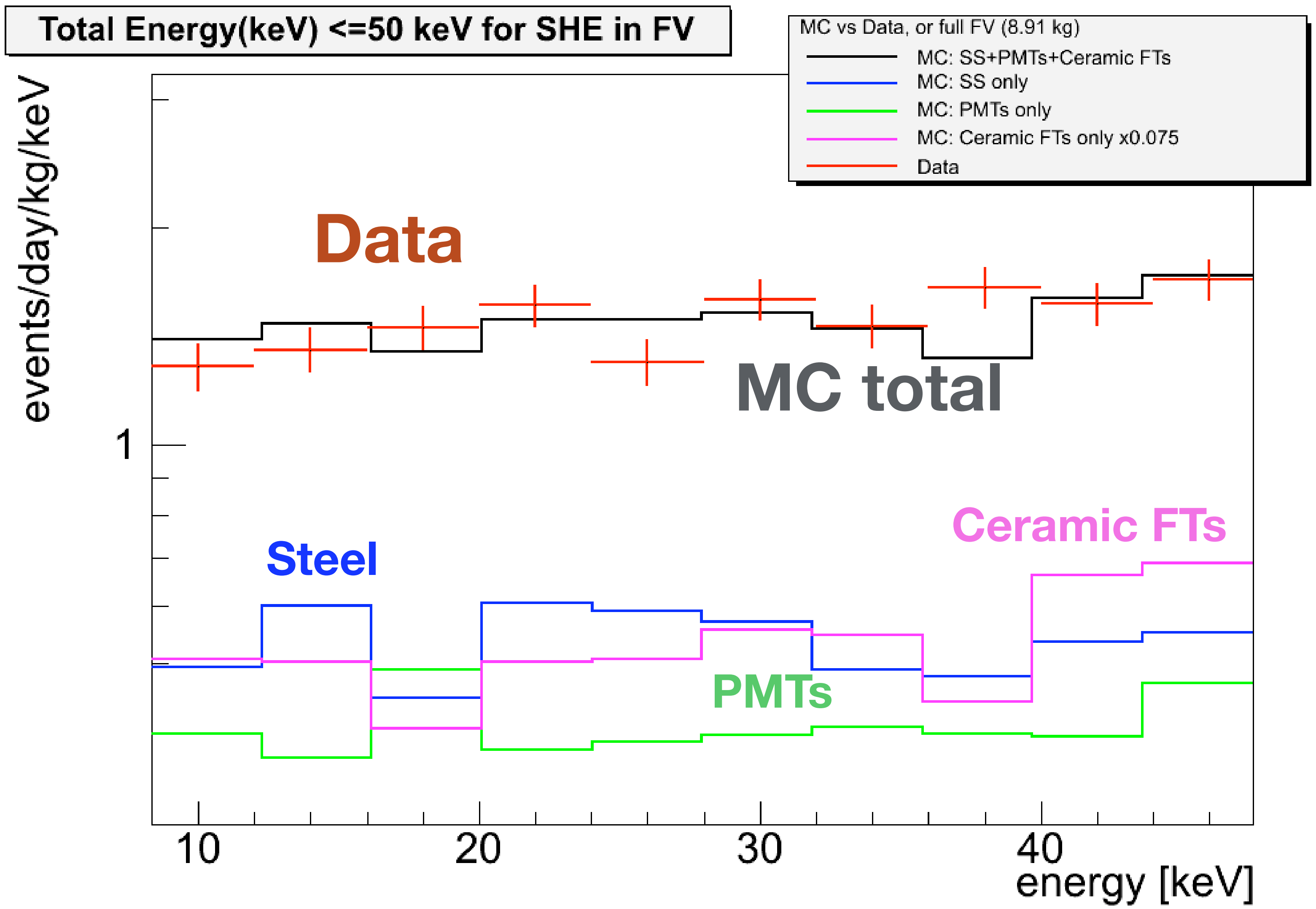
→ **results => Monte Carlo background model**
→ **XENON10 upgrade: replace known 'hot' components**

→ increase Gator's sensitivity by building new shield at LNGS with 5 cm inner OFHC Cu lining and low activity Pb (3 Bq/kg ^{210}Pb) shield

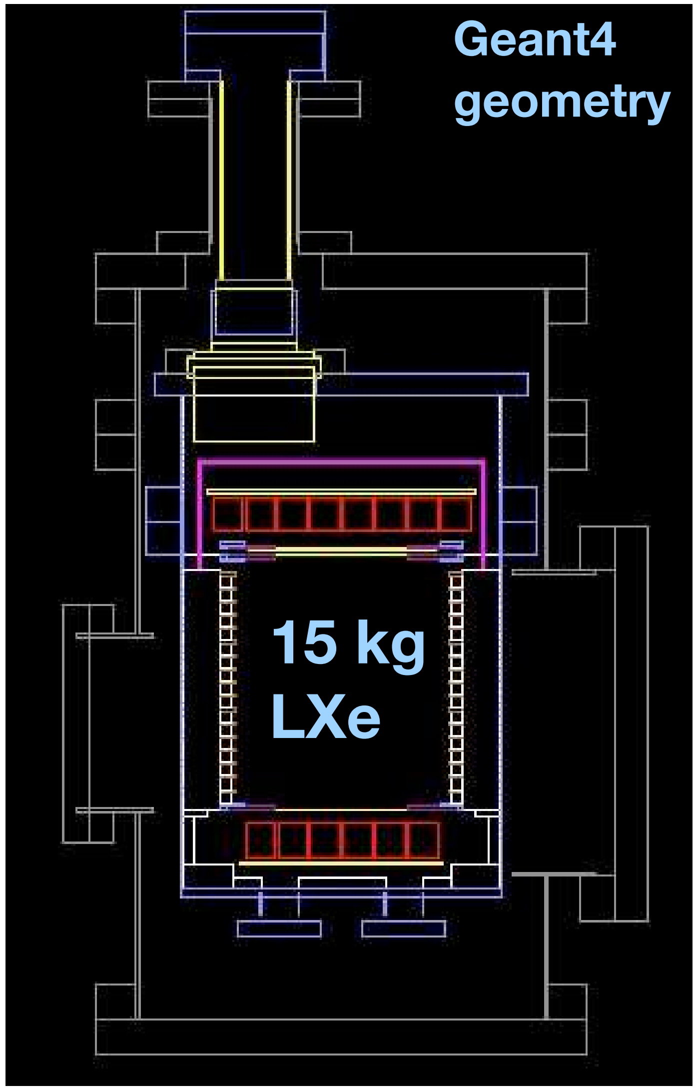


XENON10 Backgrounds: Data and MC Simulations

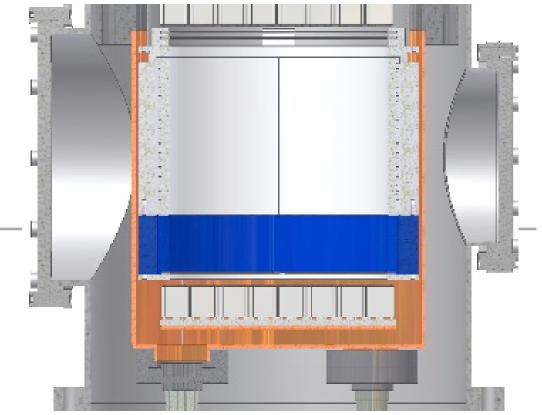
- **Gamma BG**: dominated by steel (inner vessel and cryostat) and ceramic FTs
- **Neutron BG**: subdominant for XENON10 sensitivity goal (MC: < 1 event/year from (α,n) in materials and < 5 events/year from μ-induced n's)



Single hits in fiducial mass (8.9 kg)



XENON10 Near Future Plans



- **Finish current WIMP search run (WS04)**
- Calibrate detector with n-activated Xenon: ^{131m}Xe ($T_{1/2}$=11.8 d), ^{129m}Xe ($T_{1/2}$=8.9 d), E_{γ}=164 keV, 236 keV => uniform position and energy calibration across the LXe vol.
- **Upgrade in February 2007:**
  - ➡ replace hot components (FTs), select low- radioactivity PMTs
  - ➡ **BG goal: 140 mdru**
  - ➡ to better understand leakage events: optically shield the regions outside the active volume
  - ➡ possibly enlarge drift length to increase mass and reduce Compton BG