First results on WIMP-nucleon interactions from the XENON10 Experiment at the Gran Sasso Underground Laboratory

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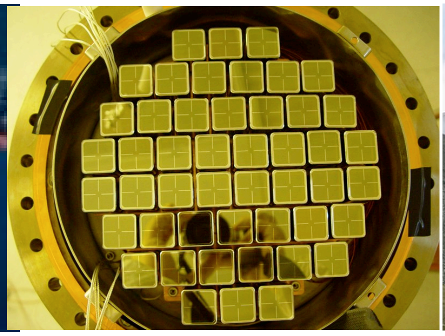
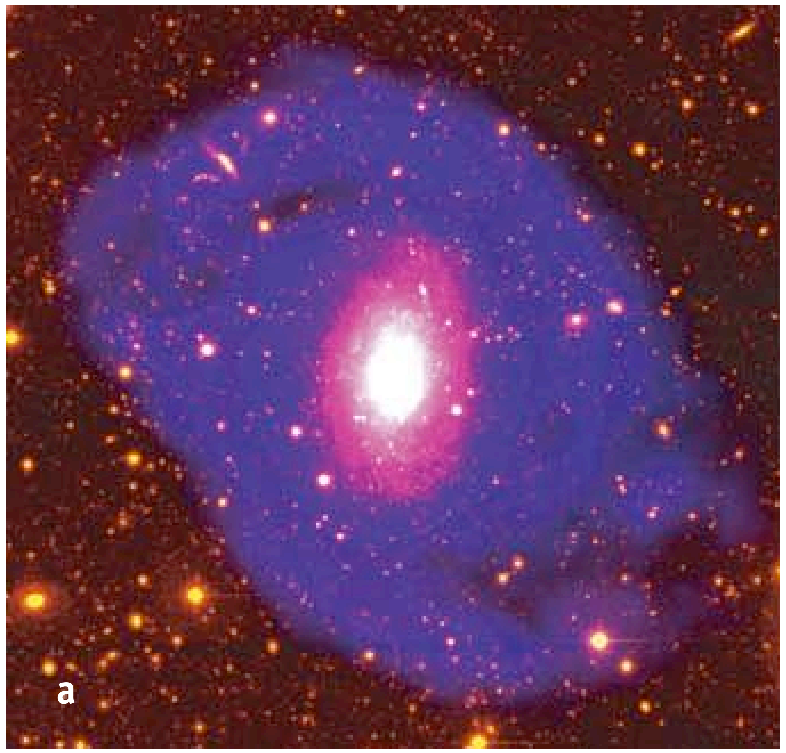
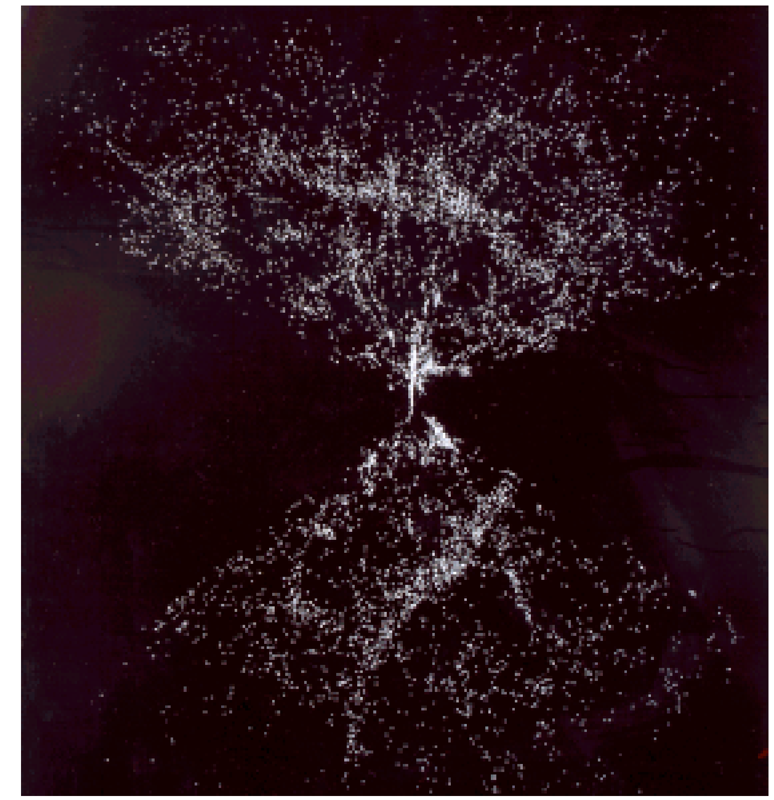
for the XENON Collaboration

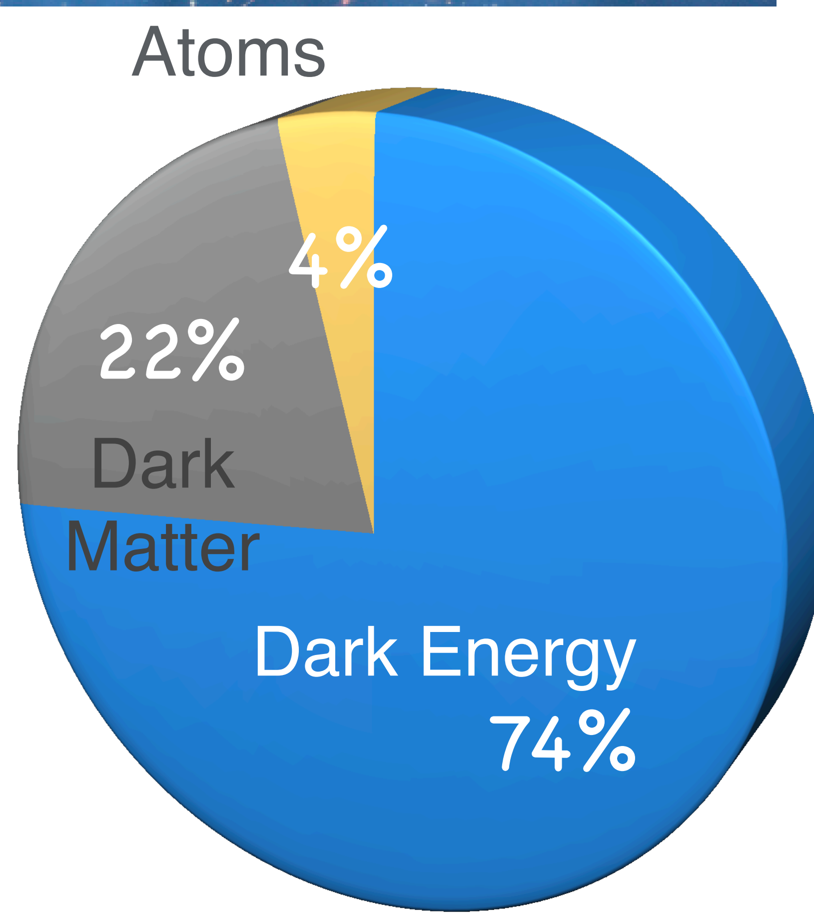
3rd Joint ILIAS-CERN-DESY Axion-WIMPs Training Workshop
University of Patras, Greece, June 19-25, 2007

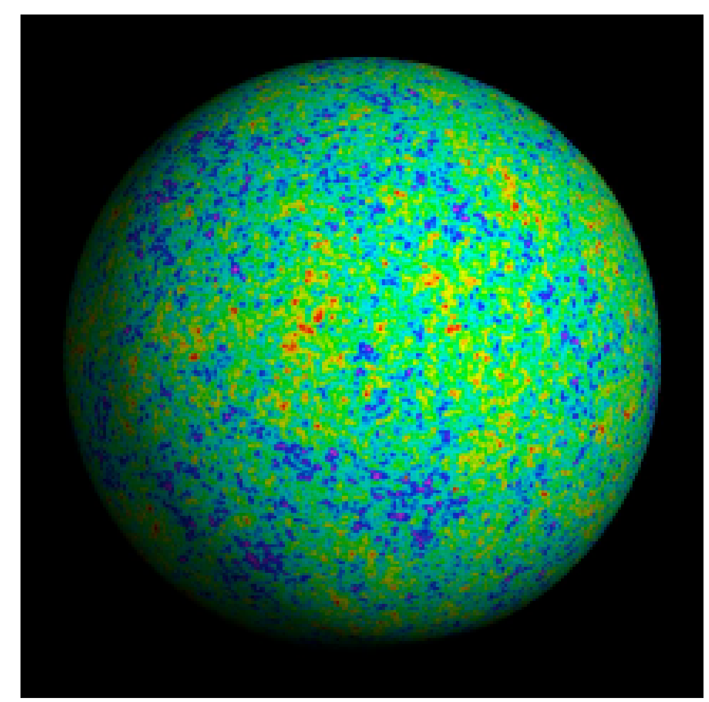



Dark Matter in the Universe

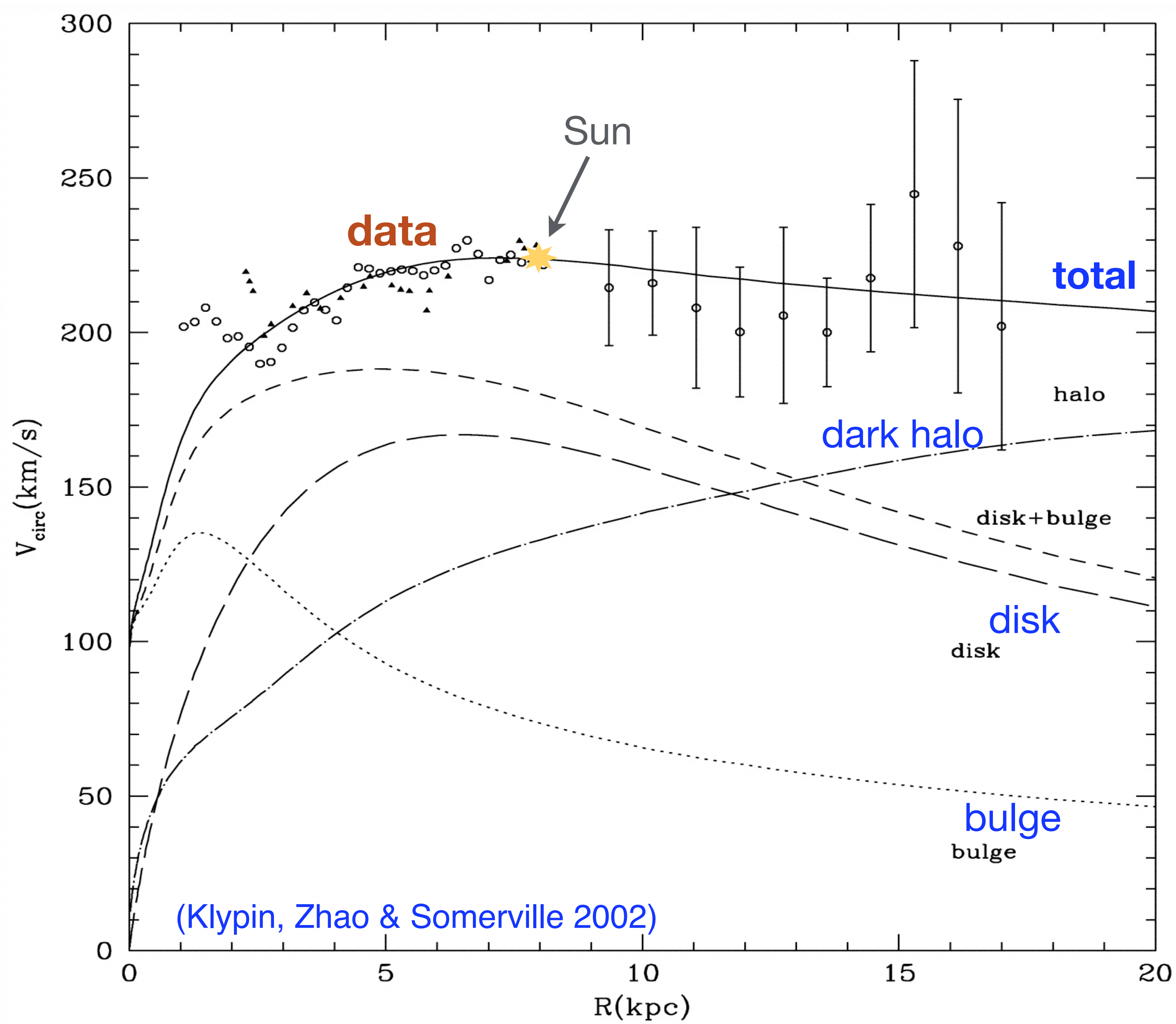








Dark Matter in the Milky Way



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

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

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

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**

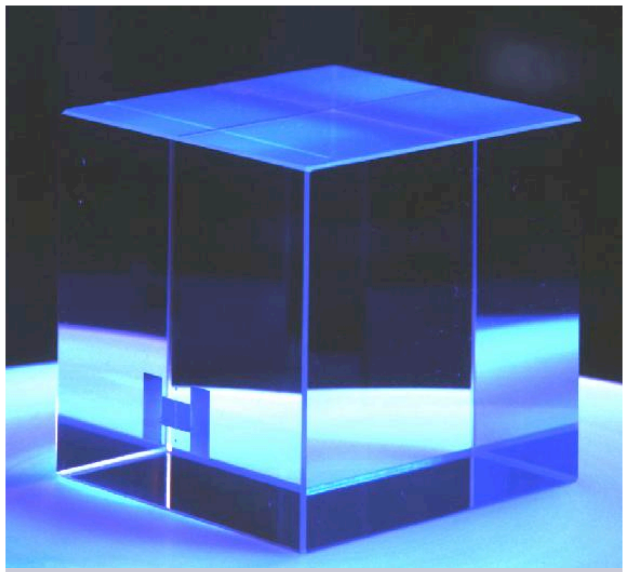
$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27}\, cm^3 s^{-1}}{\langle \sigma_A \mathrm{v} \rangle}$$

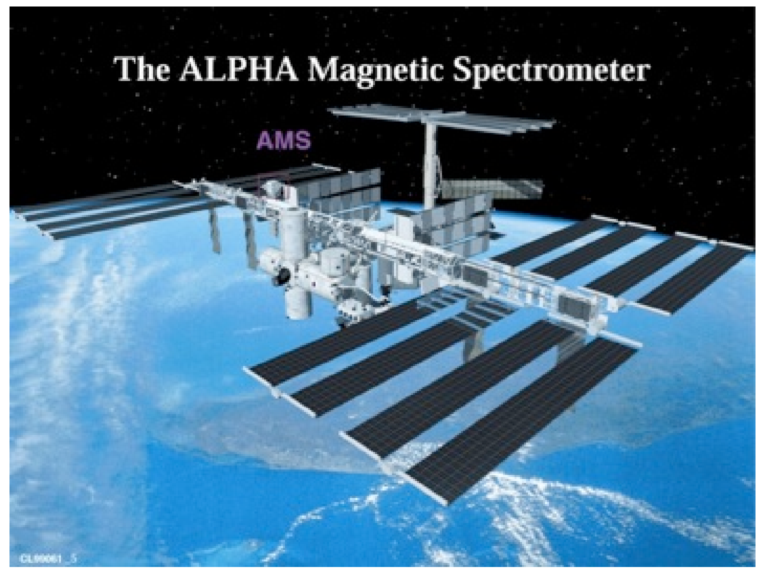
$$\Omega_\chi \sim 0.2 \Rightarrow \langle \sigma_A v \rangle \sim 1\ \mathrm{pb}$$

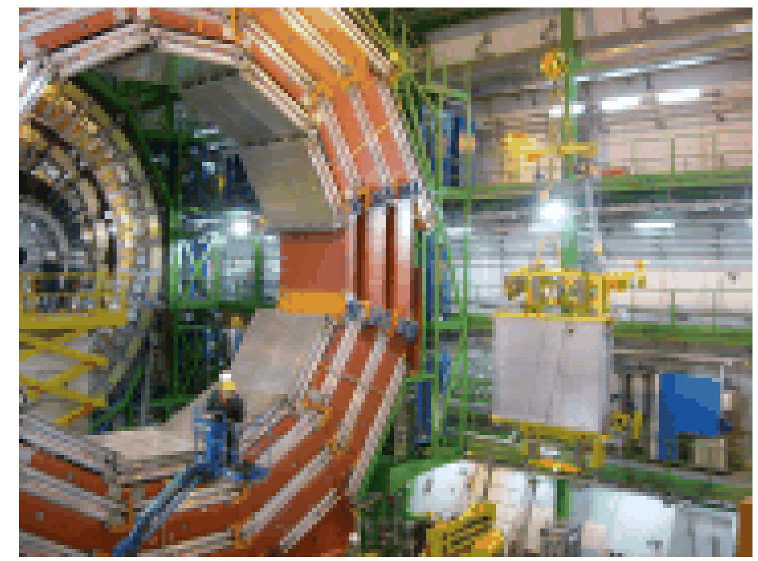
$$\sigma_\mathrm{A} \sim \frac{\alpha^2}{m^2} \Rightarrow m \sim 100\ \mathrm{GeV}$$

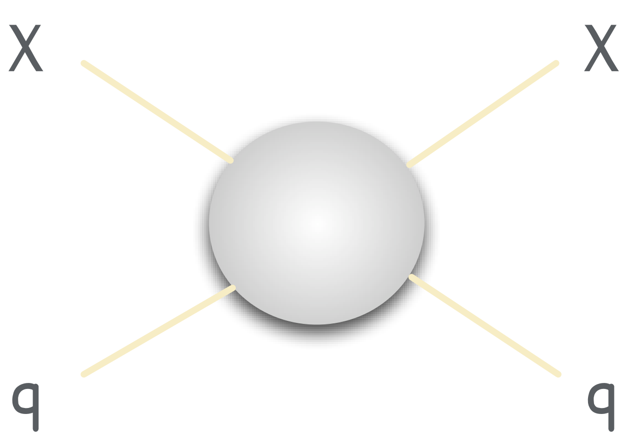
⇒ the relic density and mass point to the **weak scale**
⇒ the new physics responsible for EWSB likely gives rise to a **dark matter candidate**
⇒ examples: LSP (neutralino), LKP (KK-partner of photon, or KK-partner of Z-boson)

Approaches to WIMP Dark Matter Detection

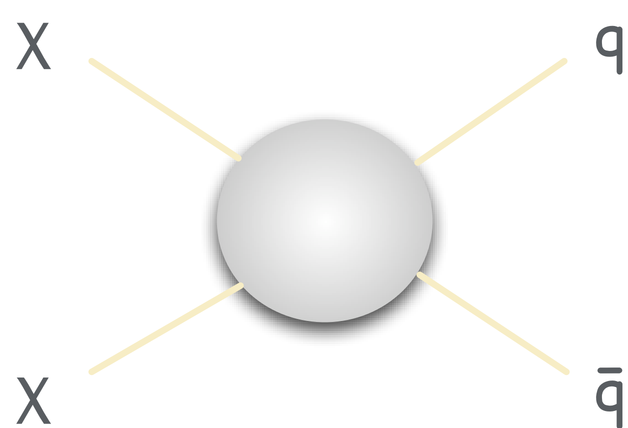




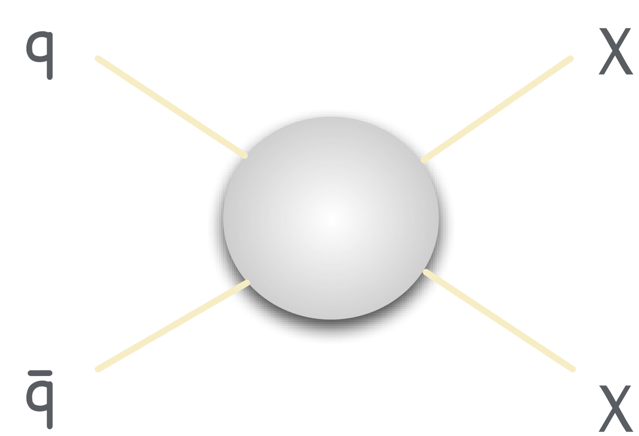




Direct



Indirect



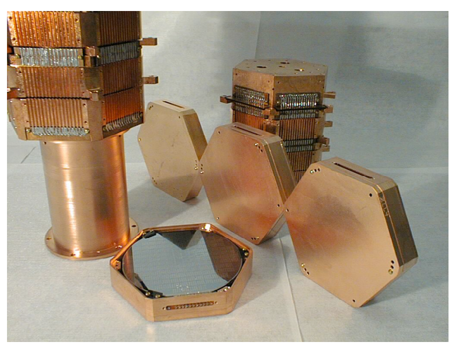
Colliders

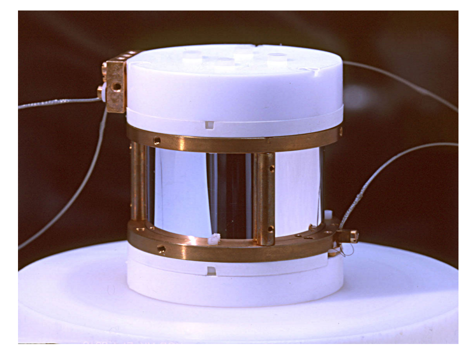
Direct WIMP Detection Experiments

COUPP,
PICASSO

Phonons

CDMS
EDELWEISS





CRESST
ROSEBUD

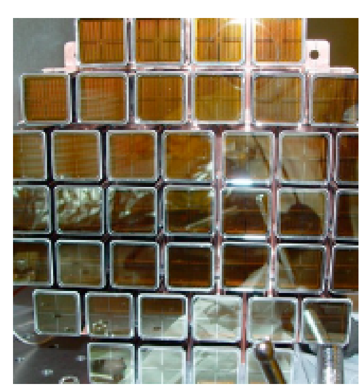
E_R

Charge

Light

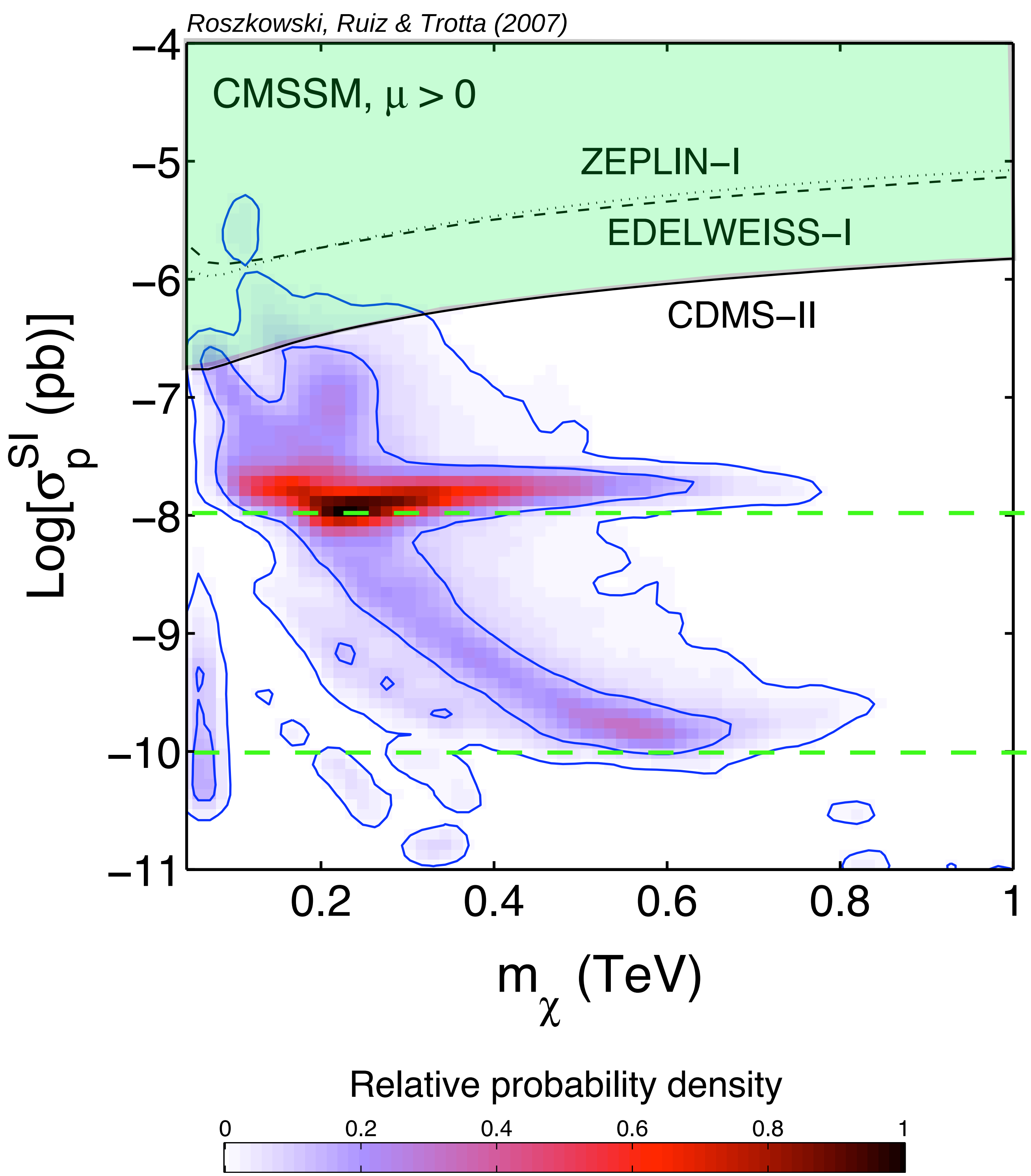
DAMA, LIBRA,
XMASS, CLEAN,
KIMS

HDMS, DRIFT,
GERDA



ZEPLIN, XENON,
WARP, ArDM

Experiments and SUSY Predictions



excluded by CDMS-II
(situation before 2007)

1 event/kg/yr

CDMS-II, XENON10, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

1 event/t/yr

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

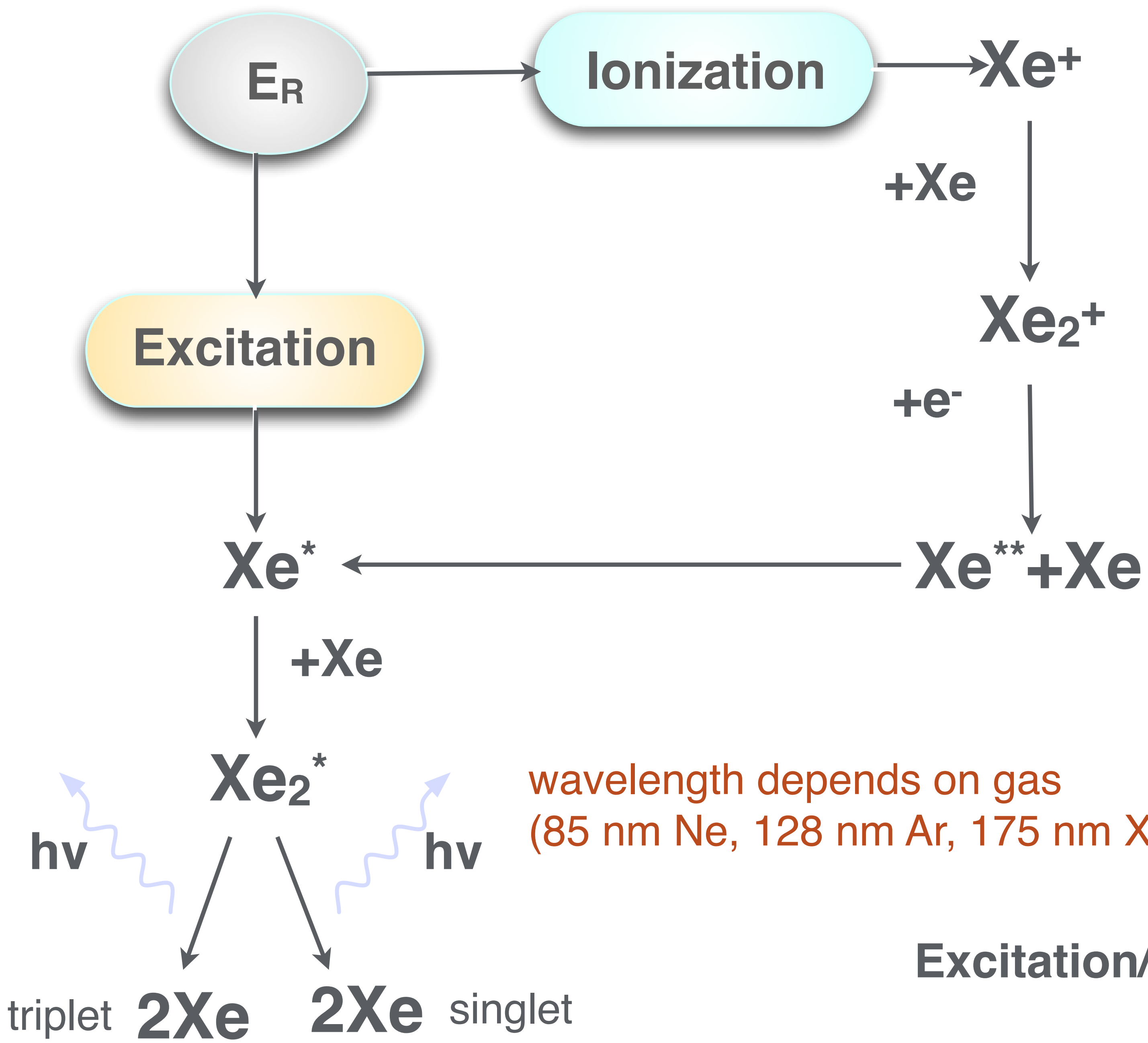
CMSSM in 2007
http://xxx.lanl.gov/abs/0705.2012

The XENON10 Experiment at the Gran Sasso Lab

Noble Liquid Element Detectors

- **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**

Charge and Light in Noble Liquids



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

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

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

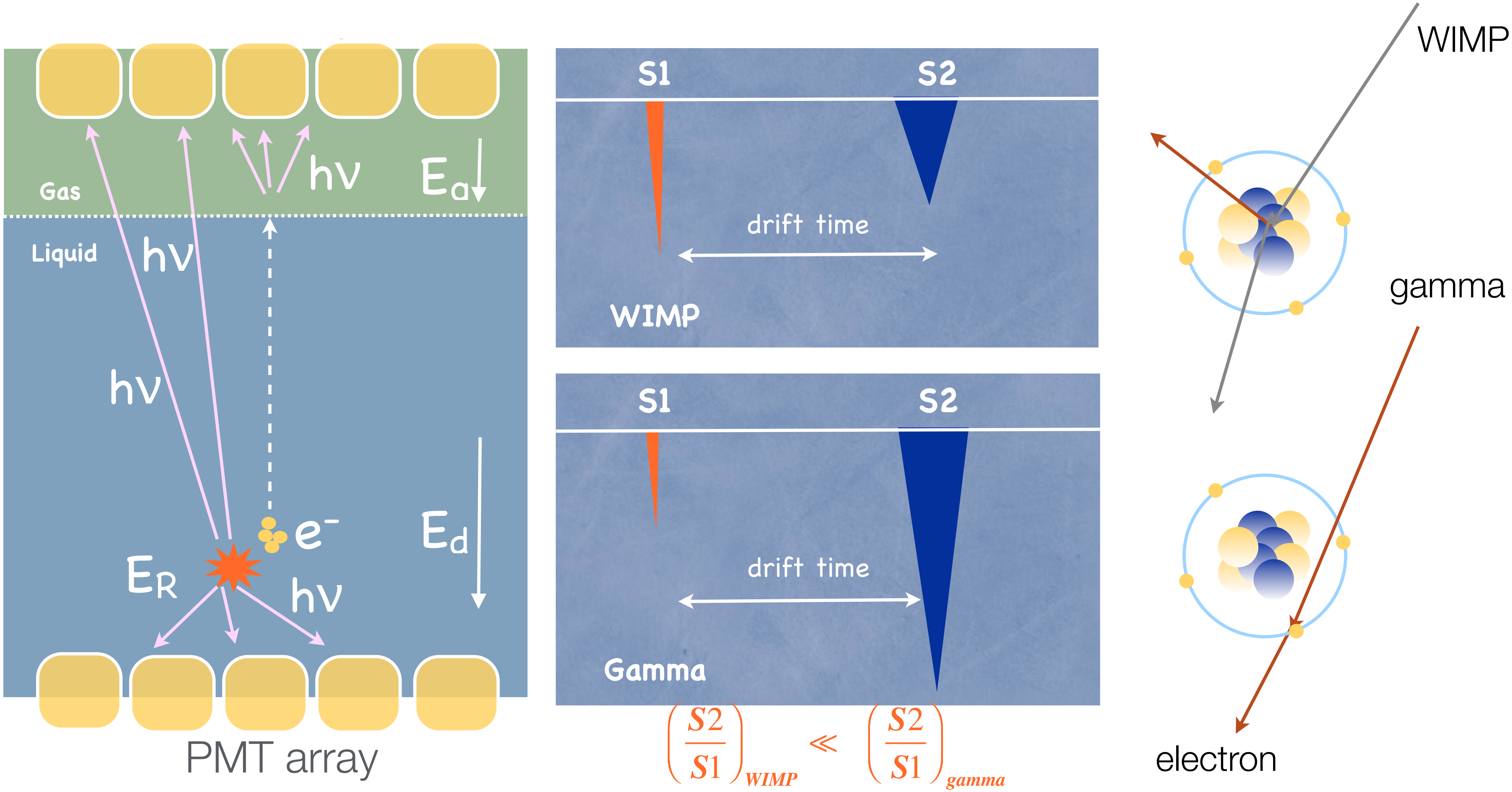
time constants depend on gas
(few ns/15.4µs Ne, 10ns/1.5µs Ar, 3/27 ns Xe)

Excitation/Ionization depends on dE/dx!

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

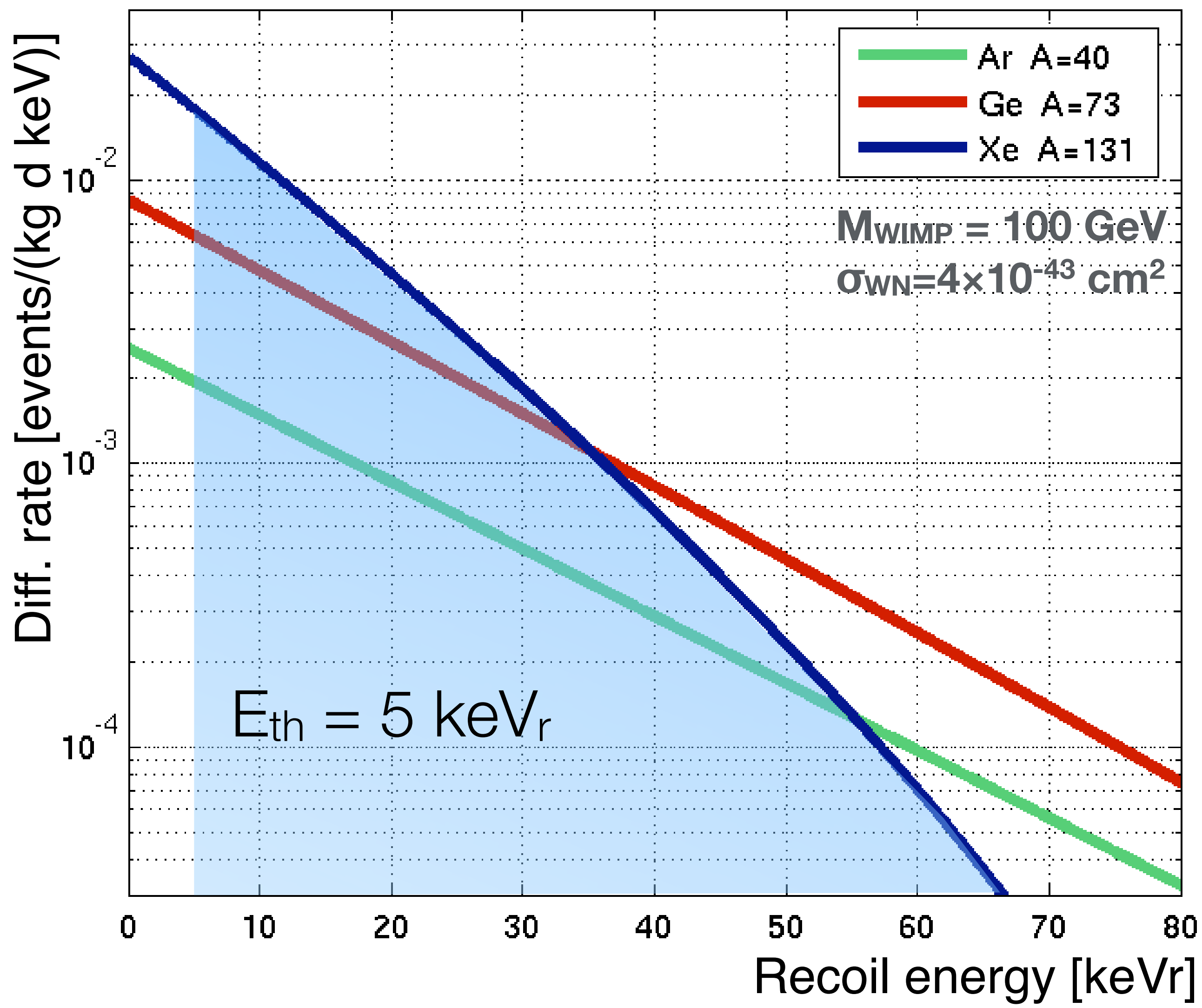
Two-Phase (Liquid/Gas) Detection Principle

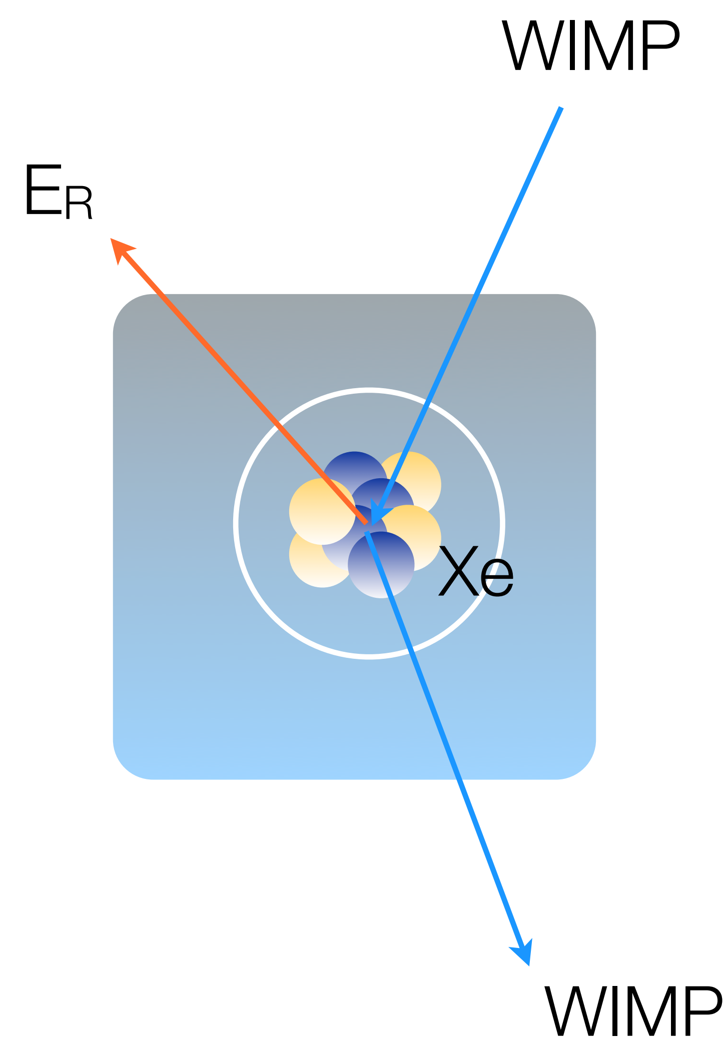
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected **directly**, or as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-



XENON10 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





Timeline of XENON10 (past - present)

- **December 05 - February 06**: detector was built and assembled at the Nevis Laboratory/Columbia University
- **March 2006**: equipment was shipped to LNGS; first tests underground (in preliminary XENON box in interferometer tunnel); at the same time electrical work in LUNA1 box assigned for XENON10
- **April-July 2006**: tests and calibration measurements with gamma sources, optimization of detector response
- **December 05 - July 06**: shield was designed and commissioned at LNGS
- **July-August 2006**: XENON10 was moved into the shield in LUNA1 box, all lines for subsystems (cryogenics, gas, electrical, emergency LN, radon purge, etc) were installed
- **August 24, 2006 - February 14, 2007**: WIMP search run
- **December 1, 2006**: calibration with AmBe neutron source
- **May 2007 - present**: Background and Calibration data with upgraded detector

The XENON10 Detector

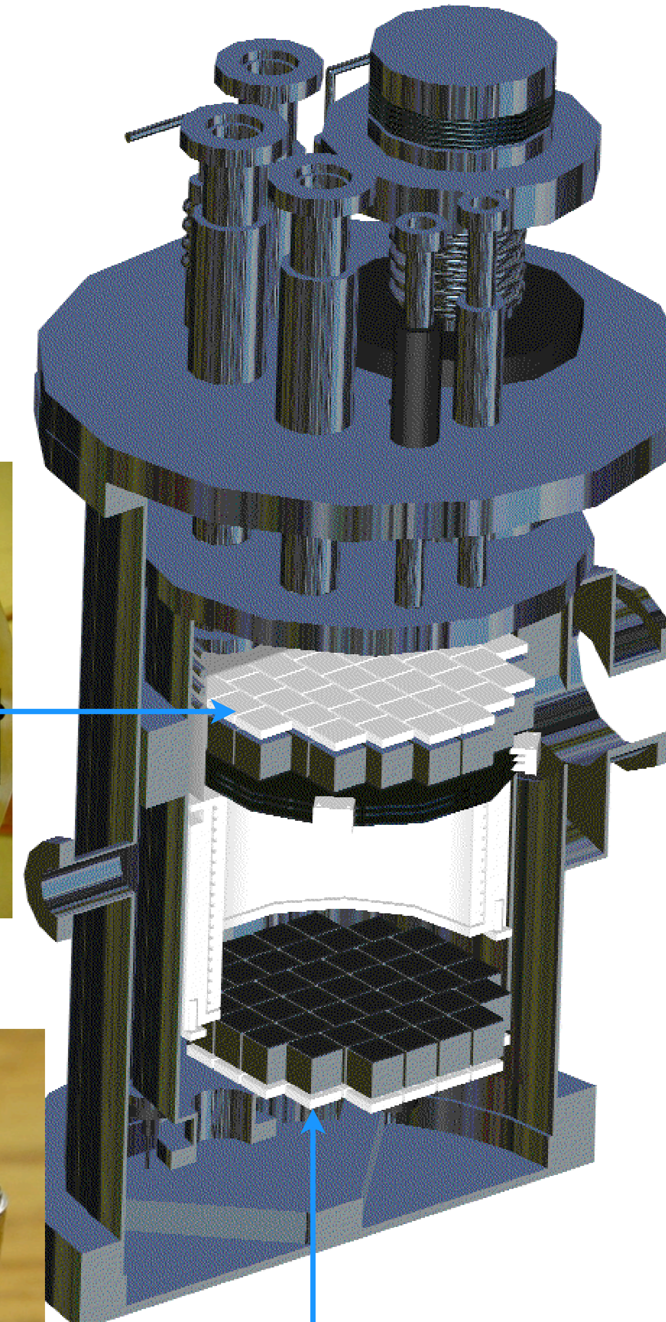
- **22 kg of liquid xenon**
  - ➡ 15 kg active volume
  - ➡ 20 cm diameter, 15 cm drift
- **Hamamatsu R8520 1”×3.5 cm PMTs**

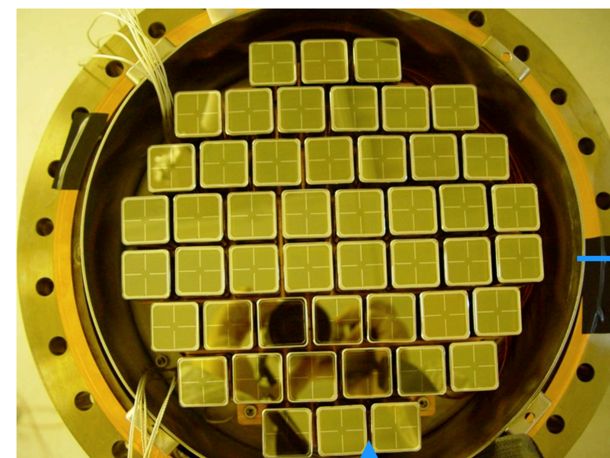
  bialkali-photocathode Rb-Cs-Sb,

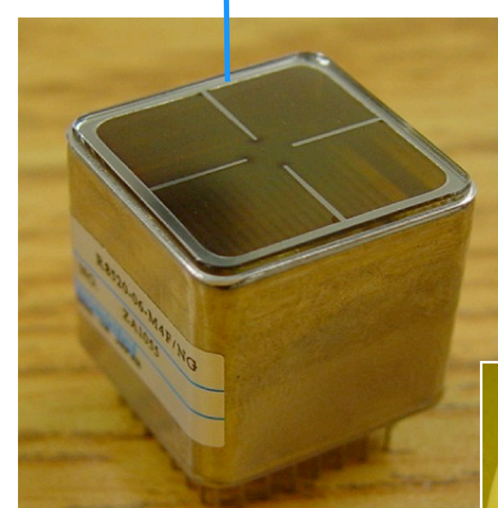
  Quartz window; ok at -100ºC and 5 bar

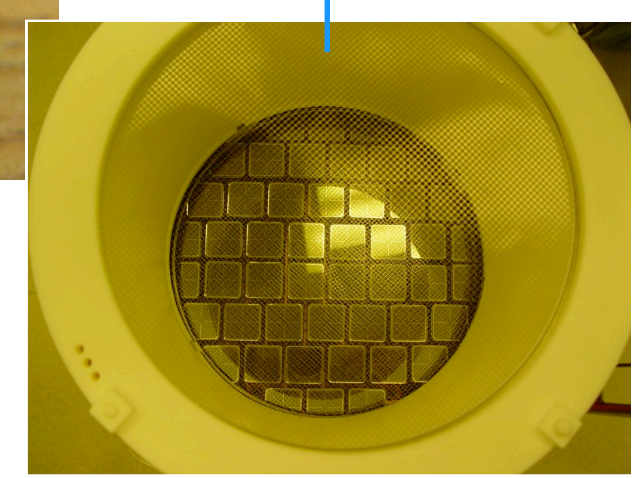
  Quantum efficiency > 20% @ 178 nm
- **48 PMTs top, 41 PMTs bottom array**
  - ➡ x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx 1$ mm
  - ➡ z-position from Δt_{drift} ($v_{d,e^-} \approx 2$ mm/μs), $\sigma_Z \approx 0.3$ mm
- **Cooling: Pulse Tube Refrigerator (PTR),**

  90W, coupled via cold finger (LN_2 for emergency)
  - ➡ 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)



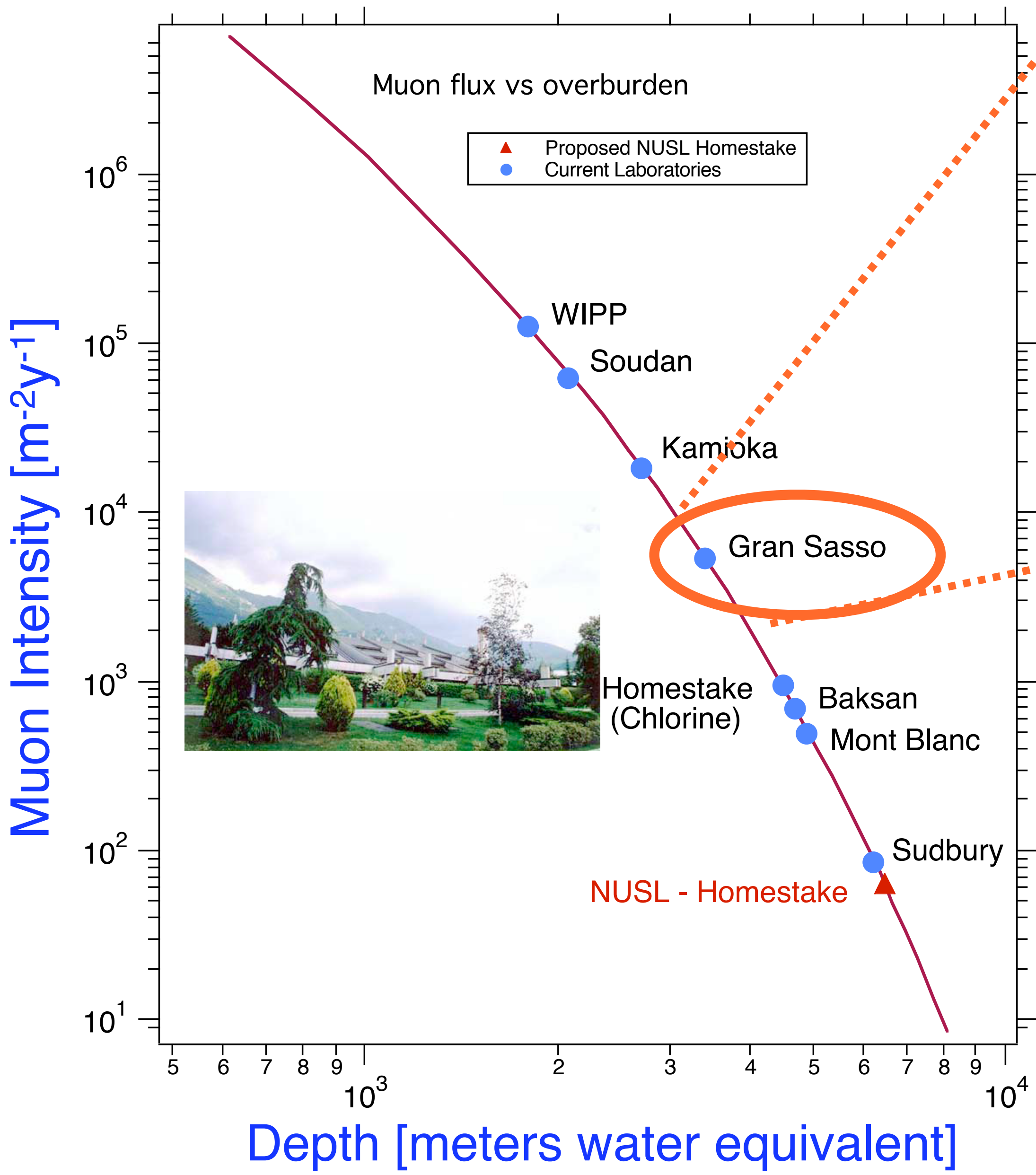


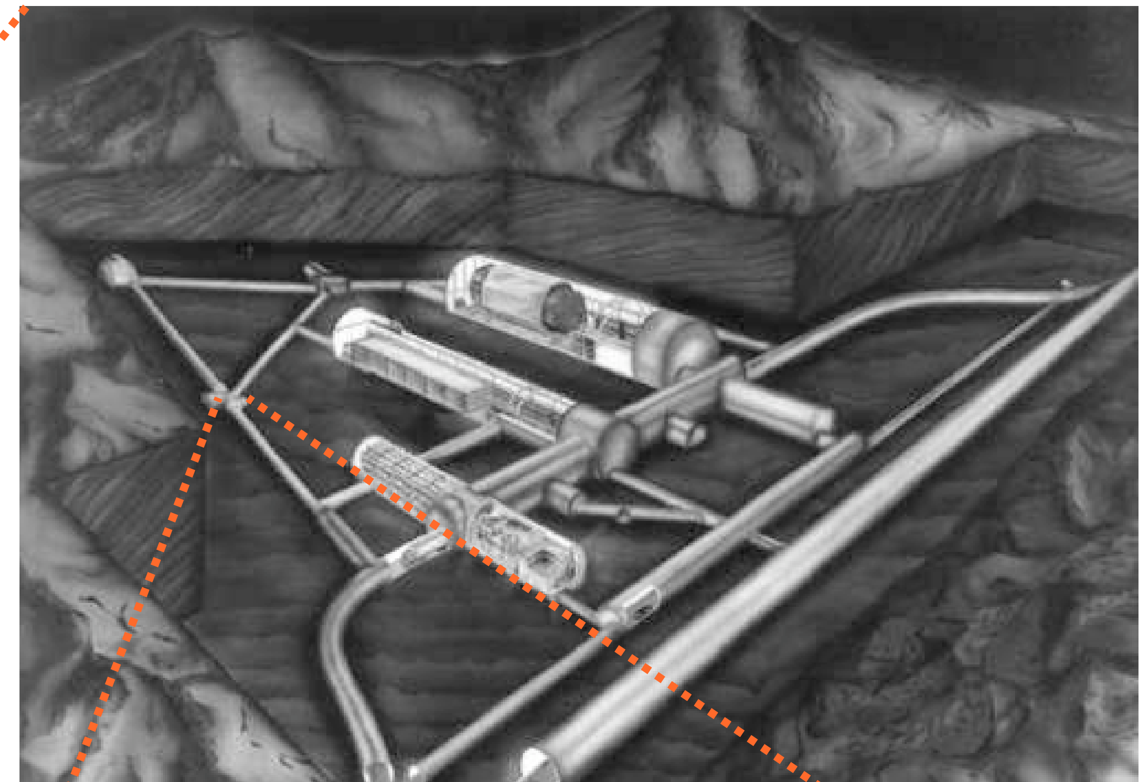




XENON10 at the Gran Sasso Laboratory

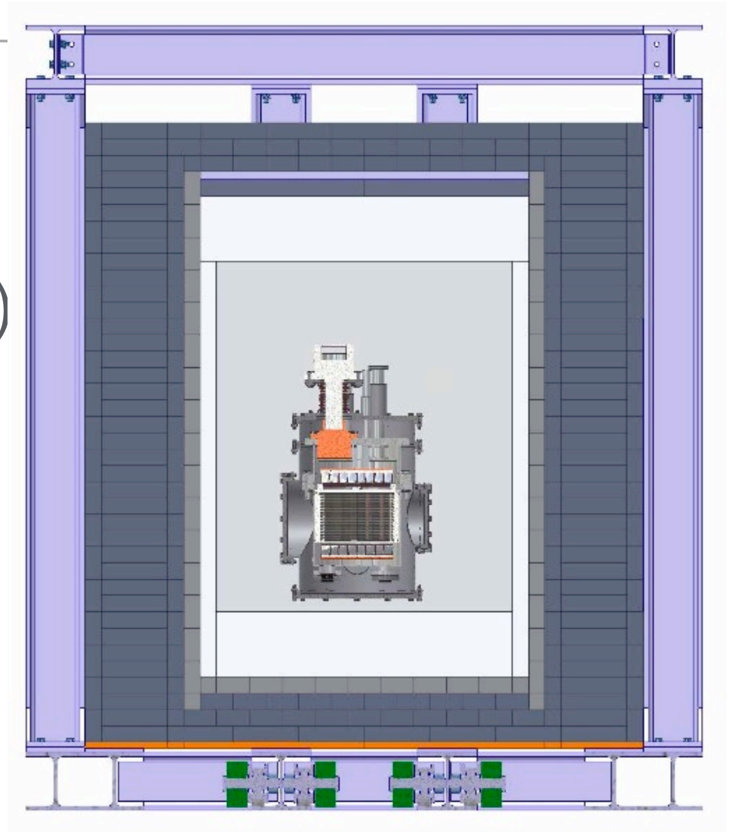
- since March 2006, in ex-LUNA box
- ~3100 m.w.e; muon flux $\approx$ 1 m^{-2} h^{-1}

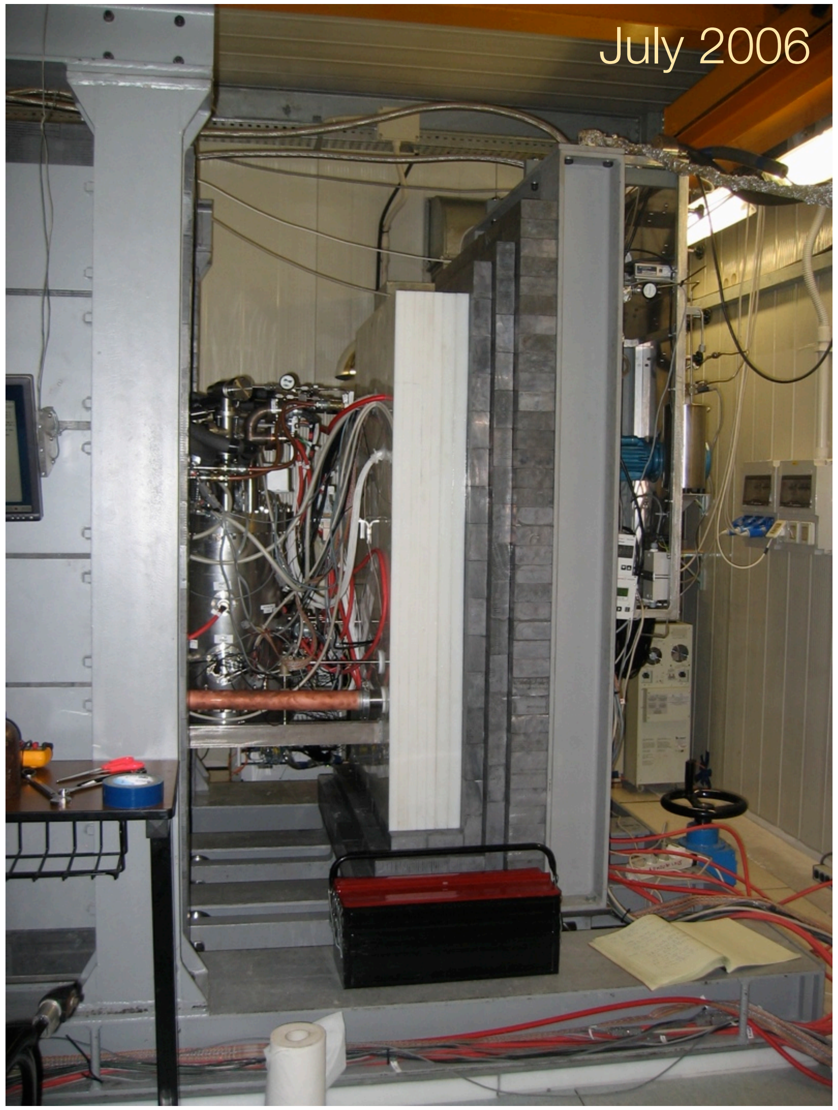




XENON10 at the Gran Sasso Laboratory

- **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: start 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

Brown University Richard Gaitskell, Simon Fiorucci, Peter Sorensen and Luiz DeViveiros

RWTH Aachen University Laura Baudis, Jesse Angle, Ali Askin, Martin Bissok, Alfredo Ferella, Marijke Haffke, Alexander Kish, Aaron Manalaysay, Stephan Schulte, Eirini Tziaferi

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

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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

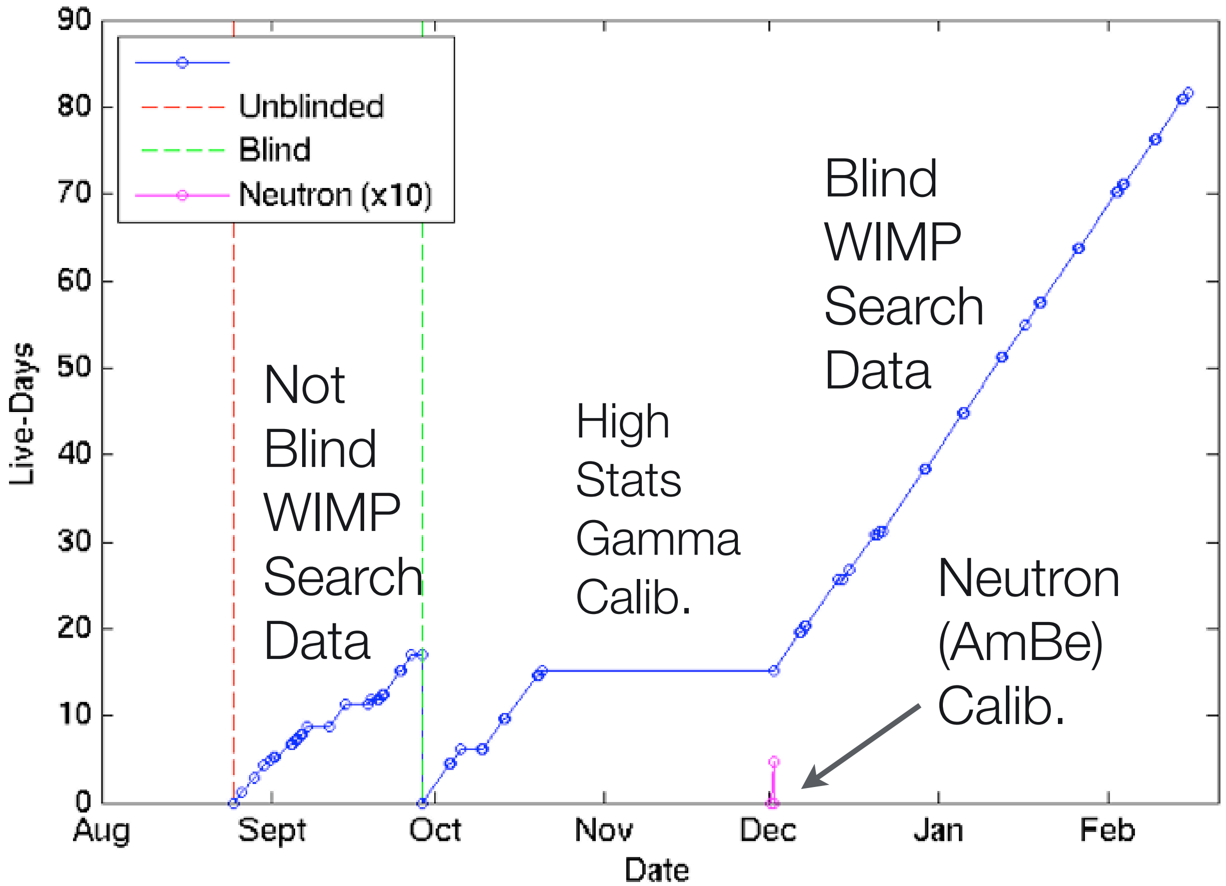
Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

The XENON10 Collaboration

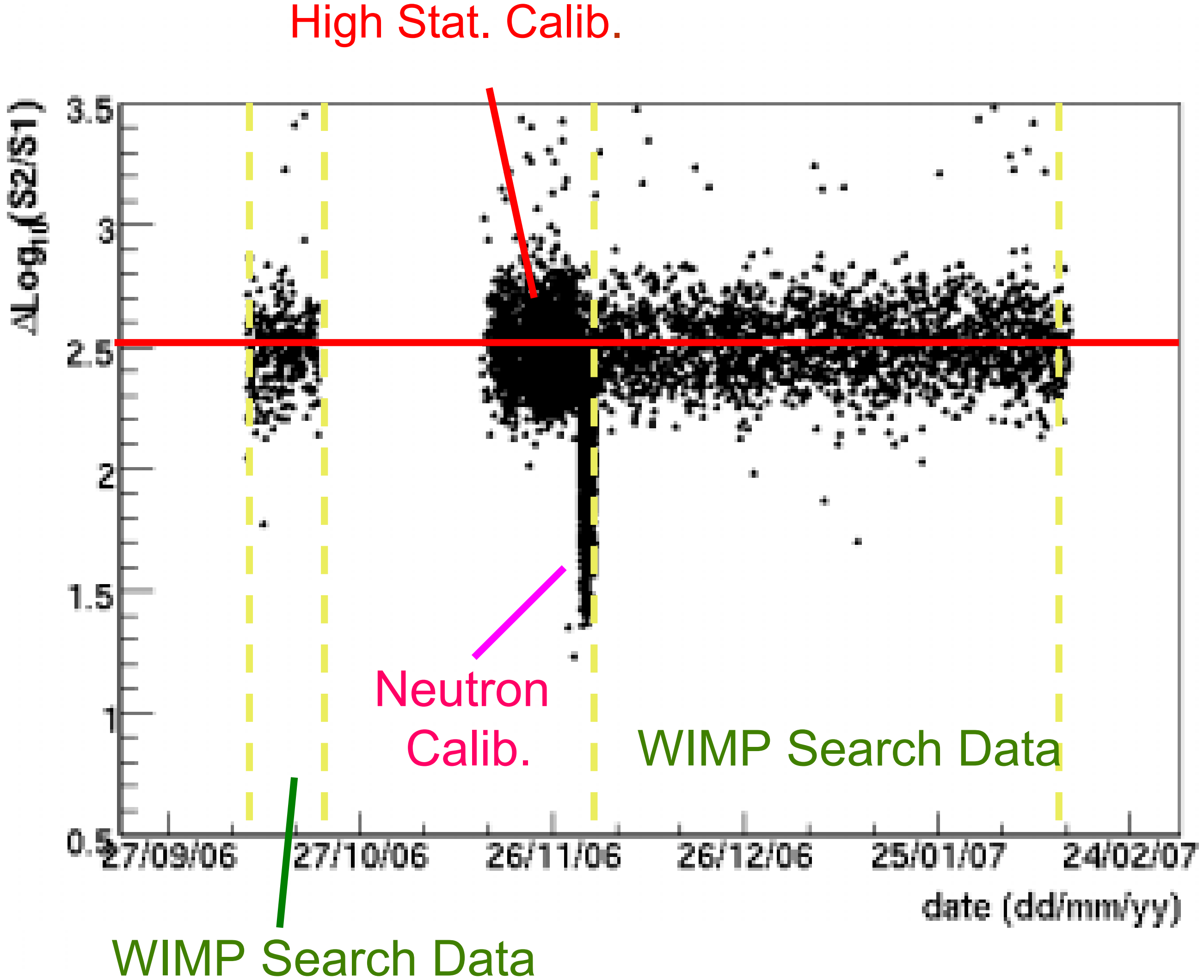
10 young postdocs, 13 graduate students, many at LNGS

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

XENON10 Live-Time and Run Stability

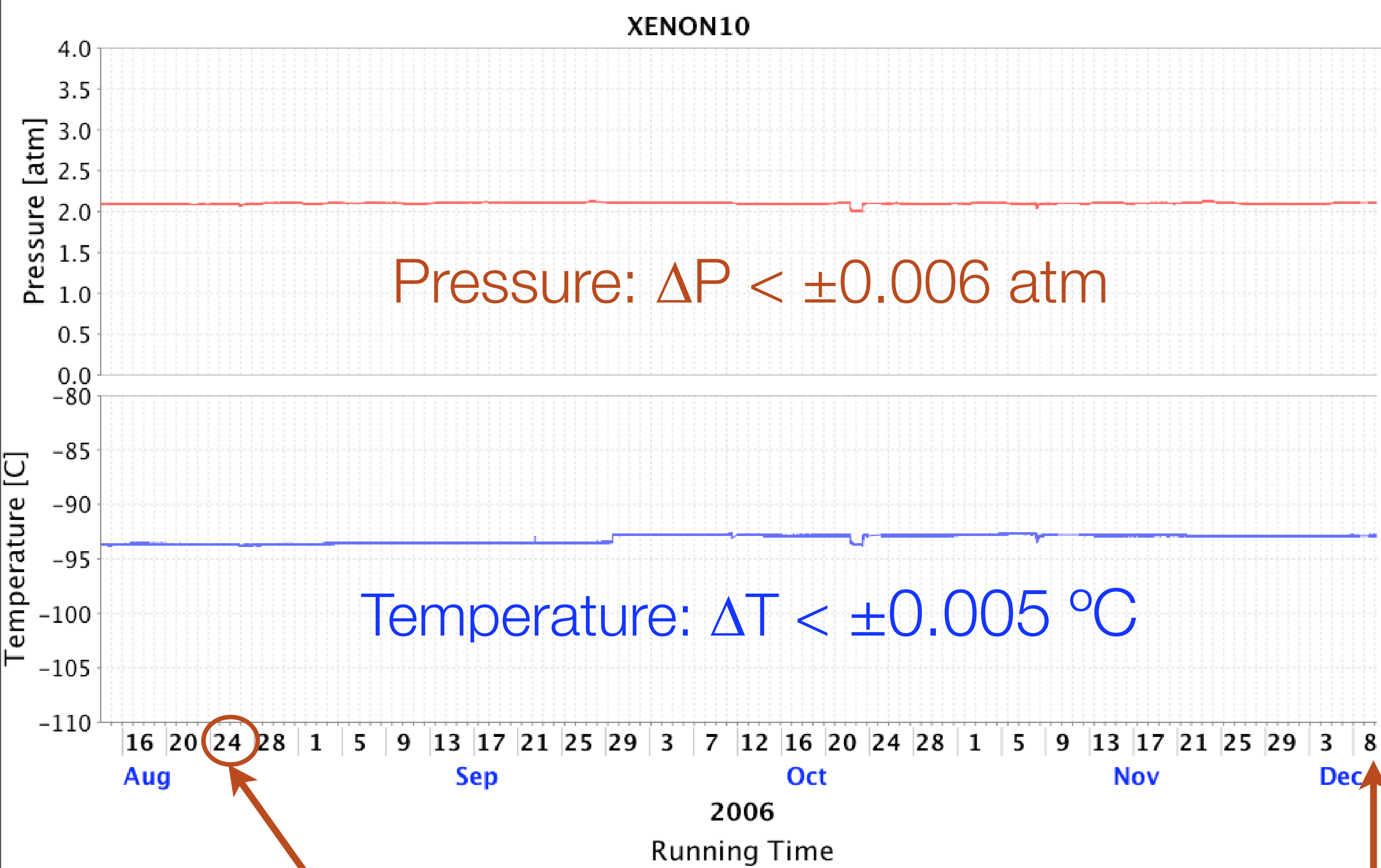


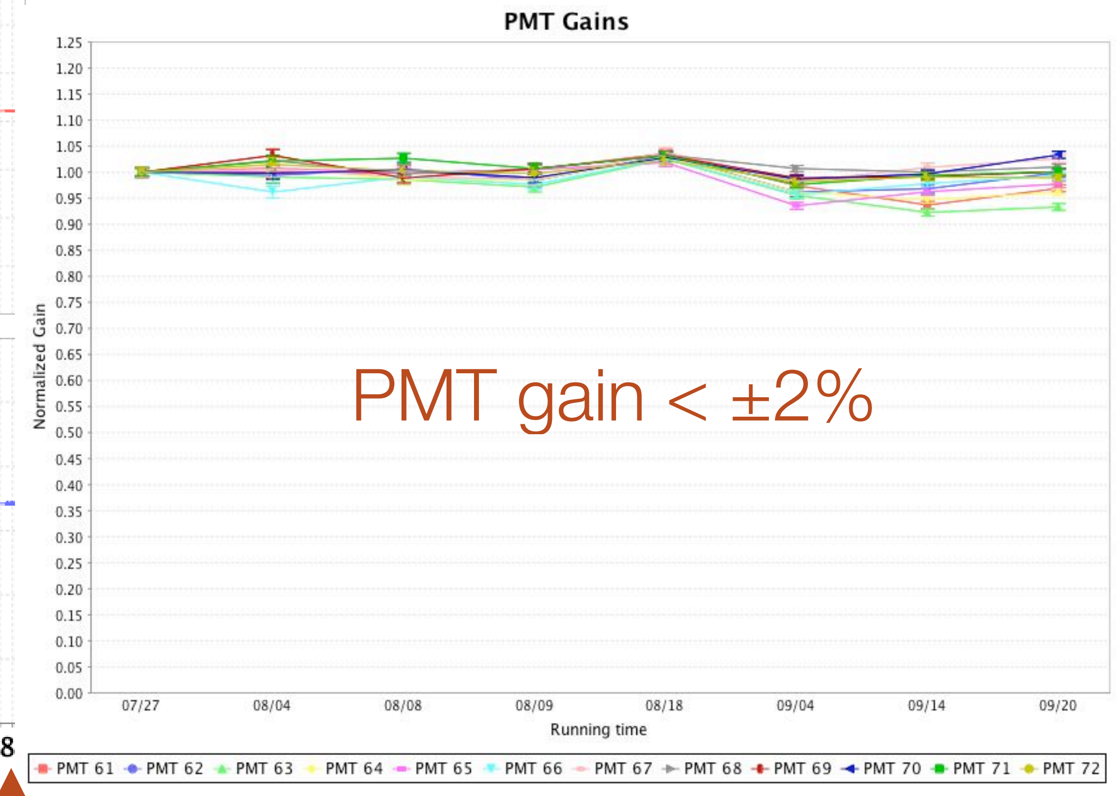
Calibration + WIMP Search Data



XENON10 Performance at LNGS

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



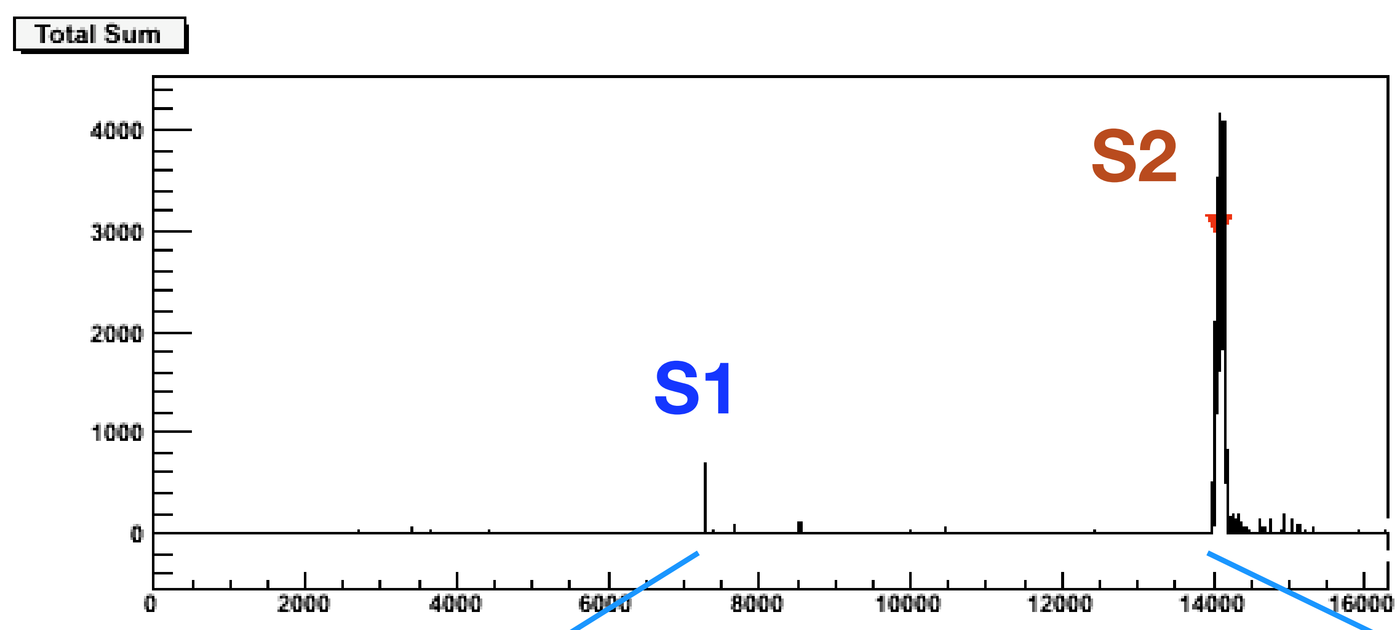


Start of WIMP Search Run

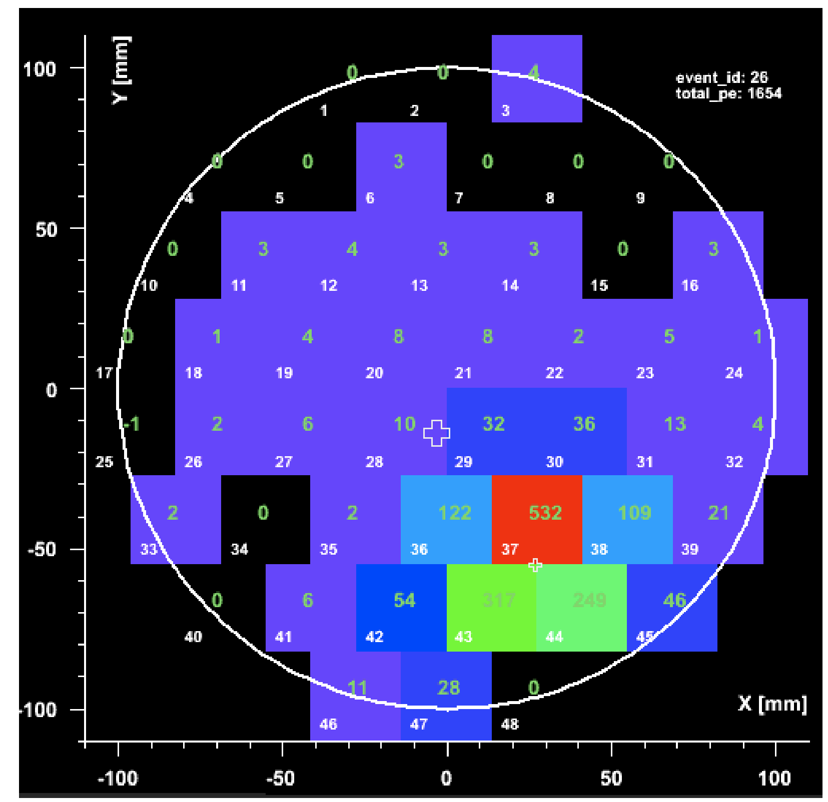
December 8, 06

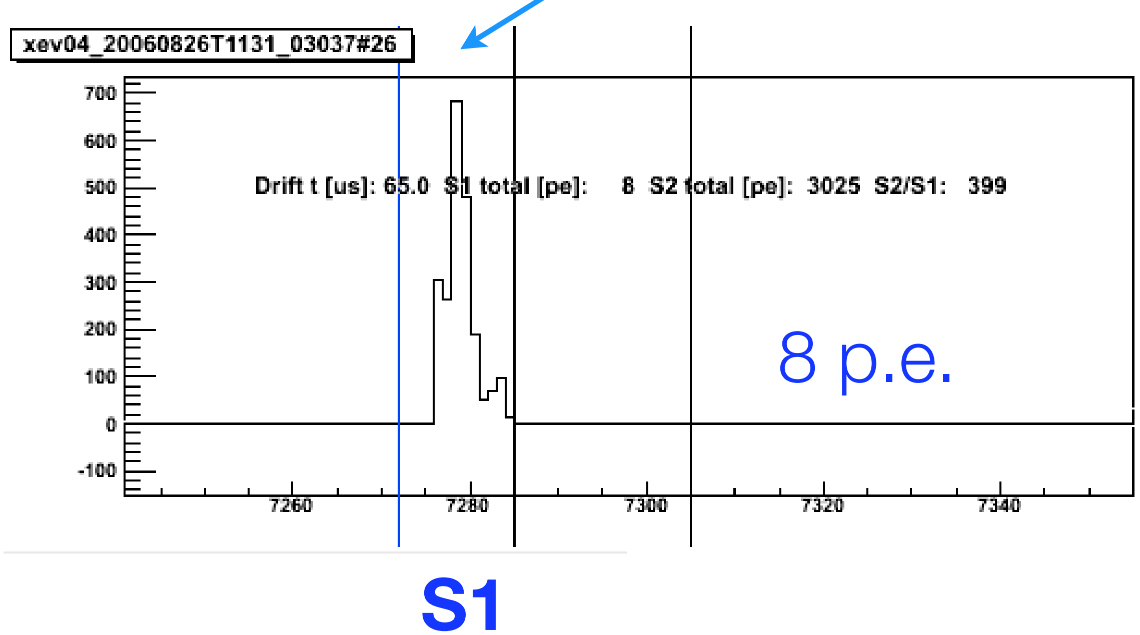
Typical XENON10 Low-Energy Event

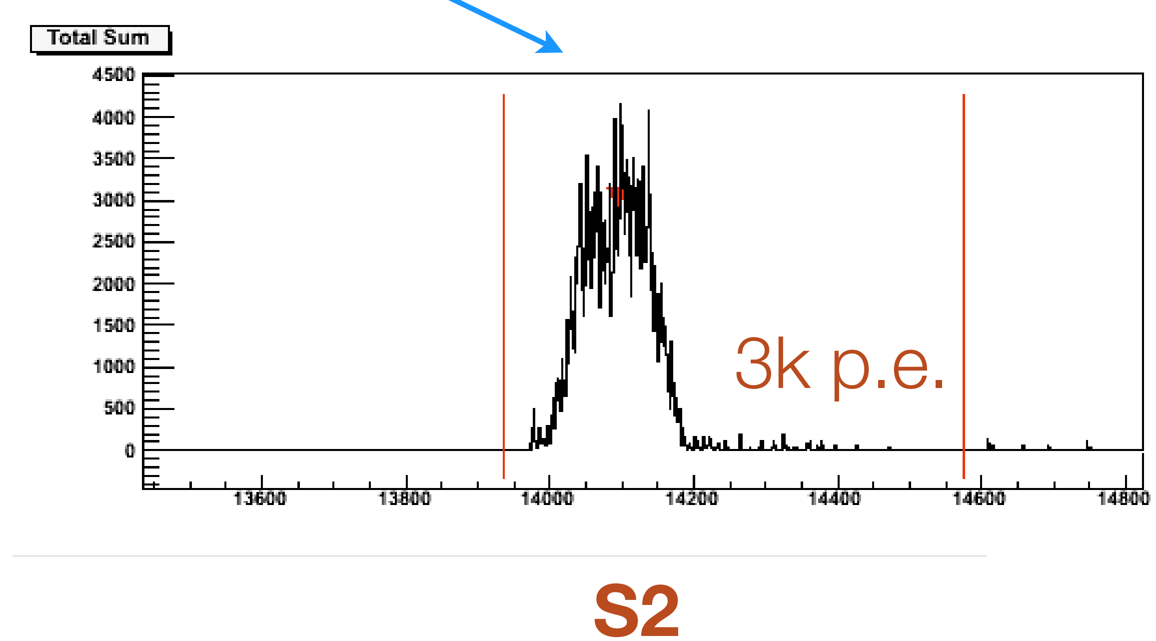
- 4 keV_{ee} event; **S1: 8 p.e => 2 p.e./keV**



Hit pattern of top PMTs



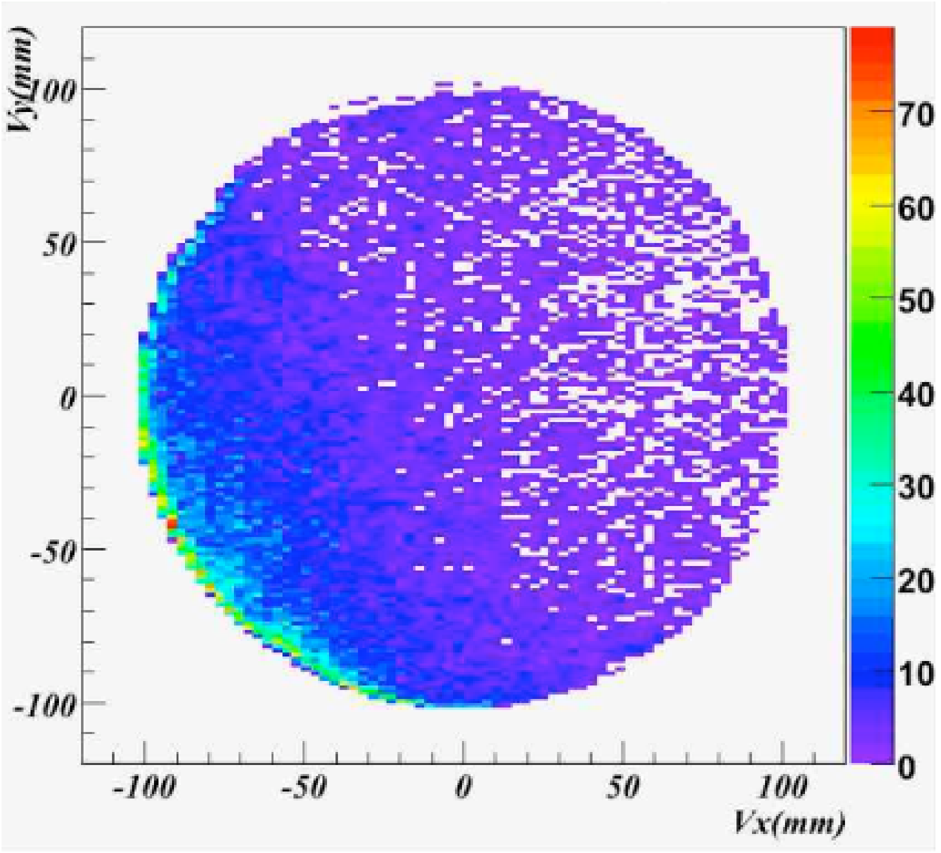


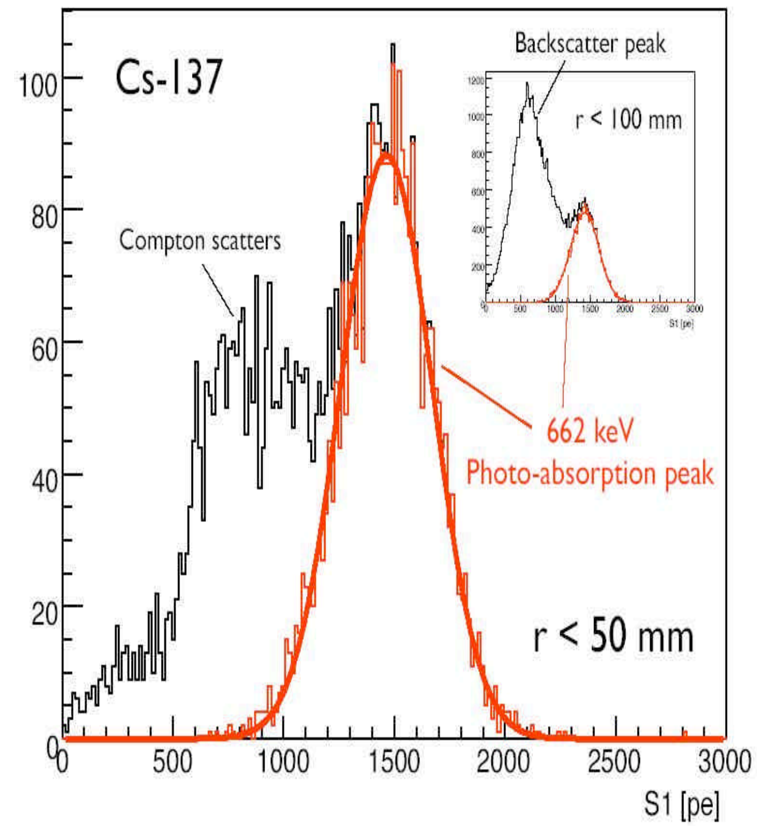


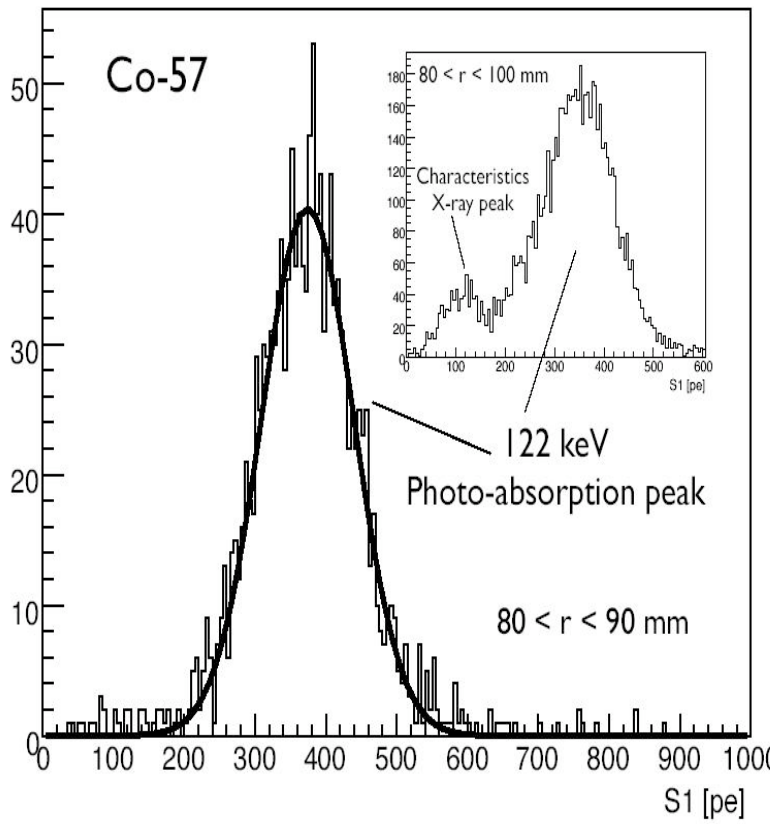
XENON10 Gamma Calibrations

- 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)





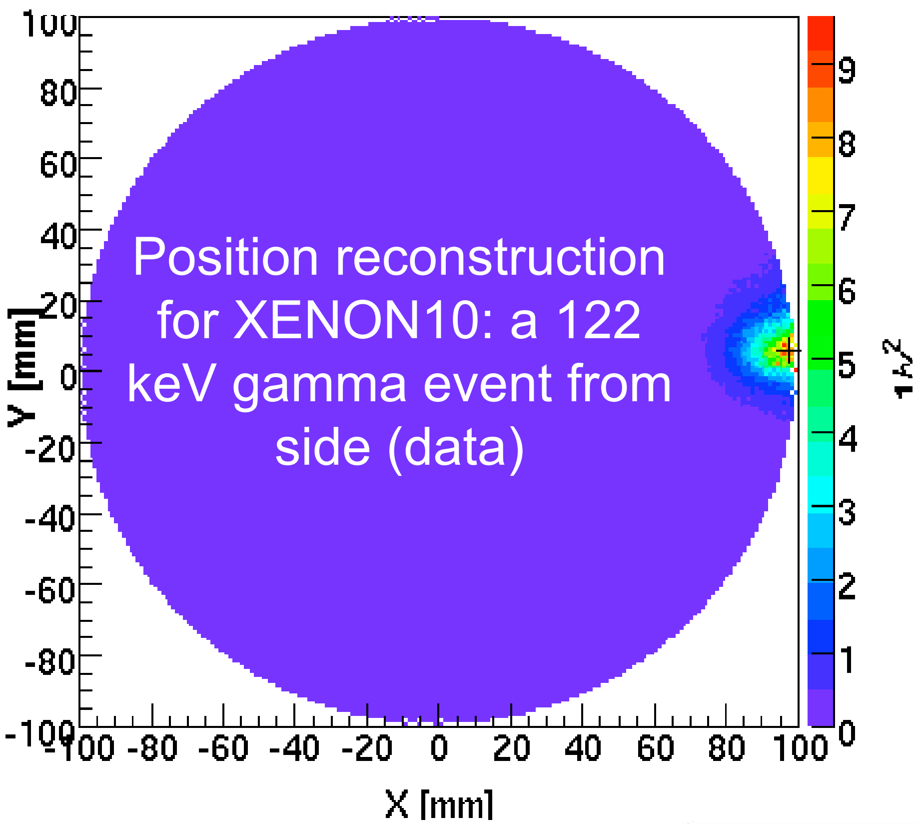


reconstructed source position (^{137}Cs)

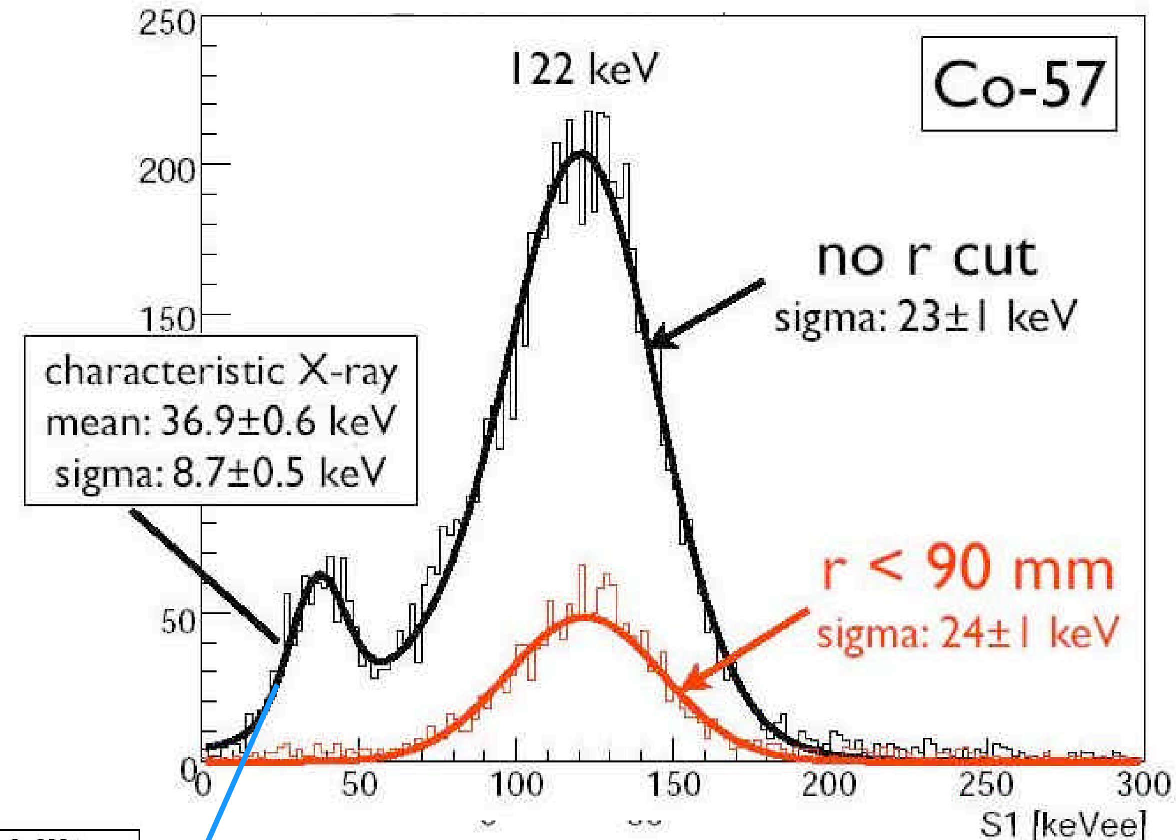
light yield from 137Cs: 2.25 p.e./keV

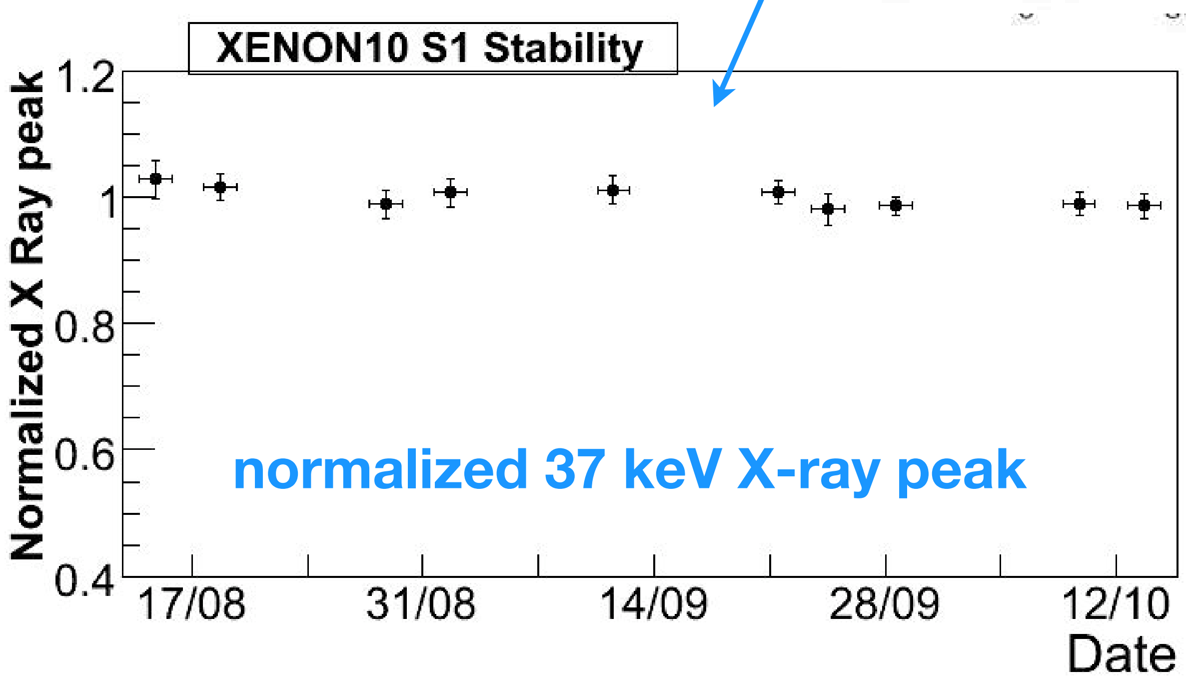
XENON10 Gamma Calibrations

reconstructed source position (^{57}Co)



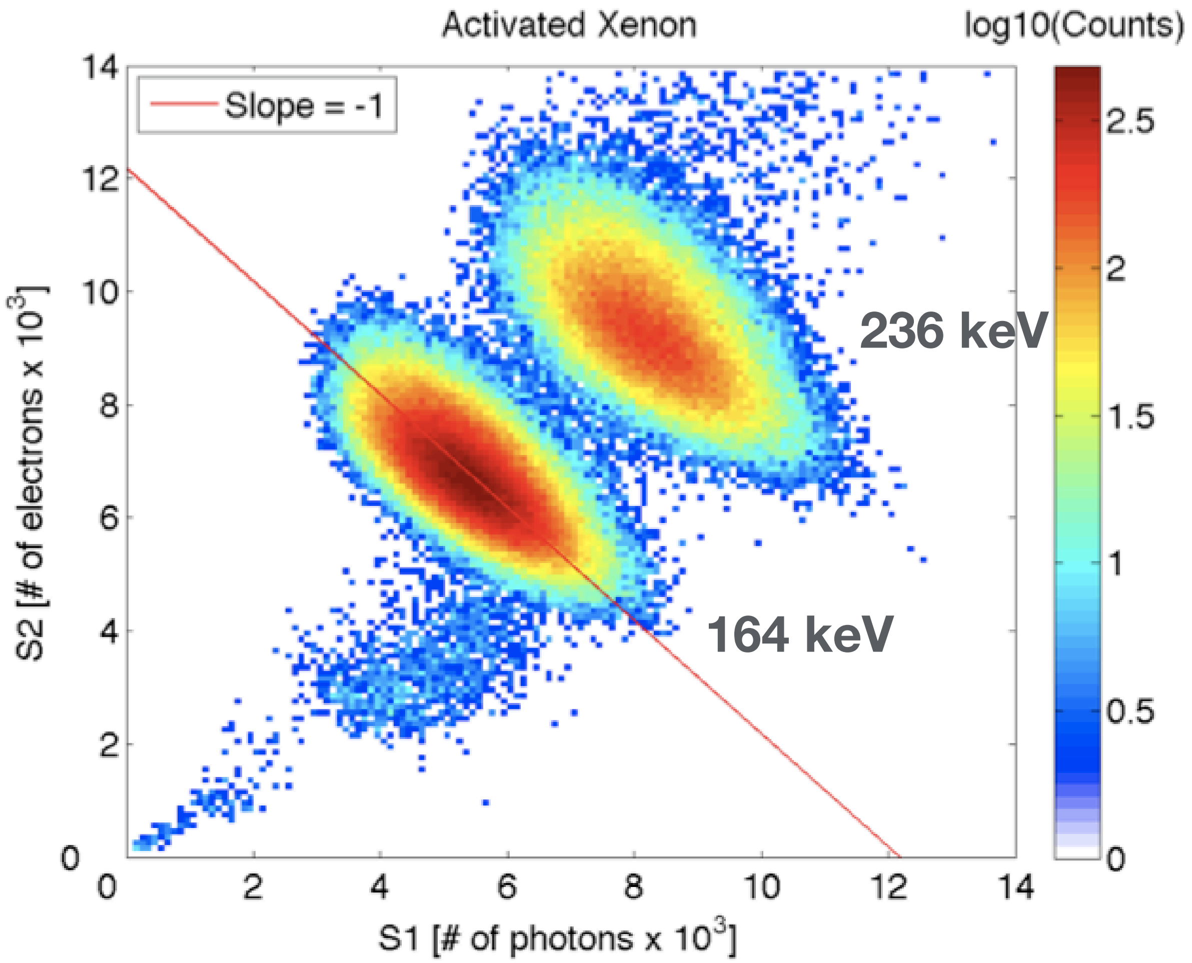
detector stability test: the 37 keV X-ray



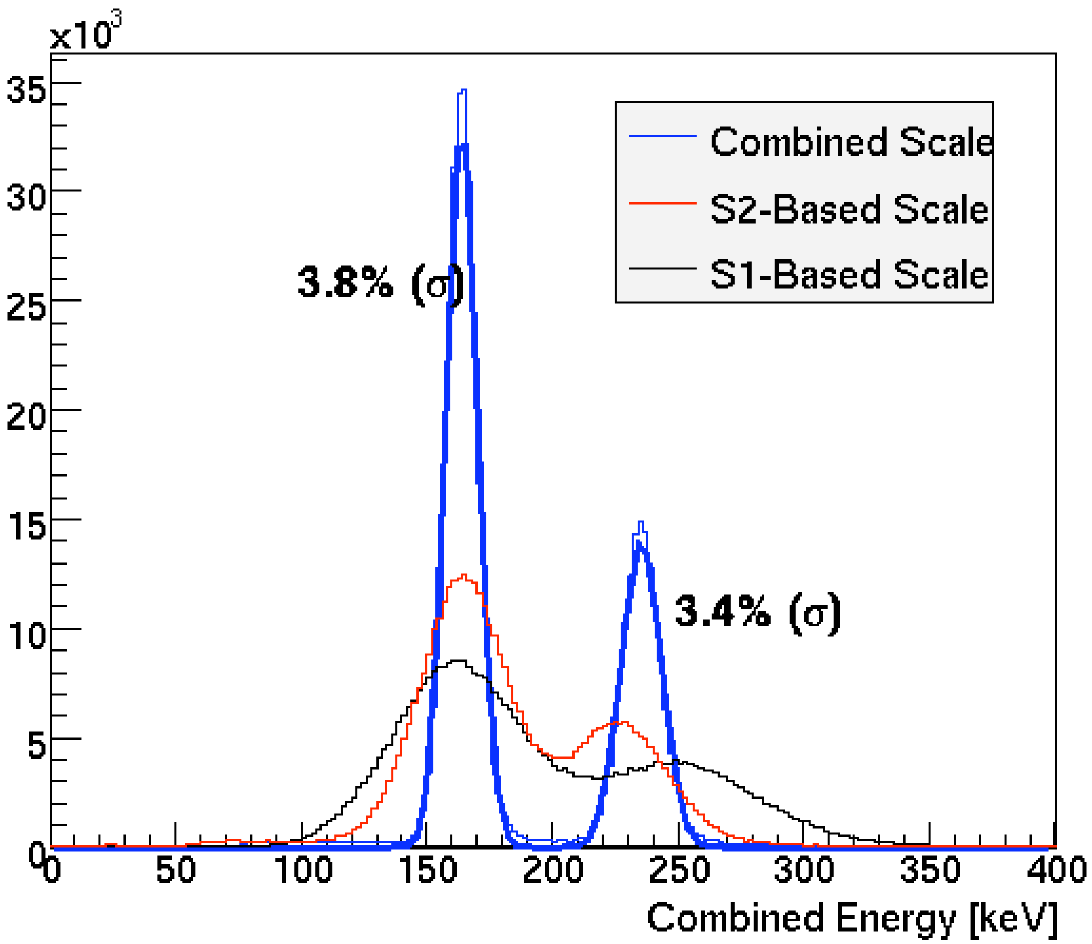


XENON10 Calibration with Activated Xenon

- 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



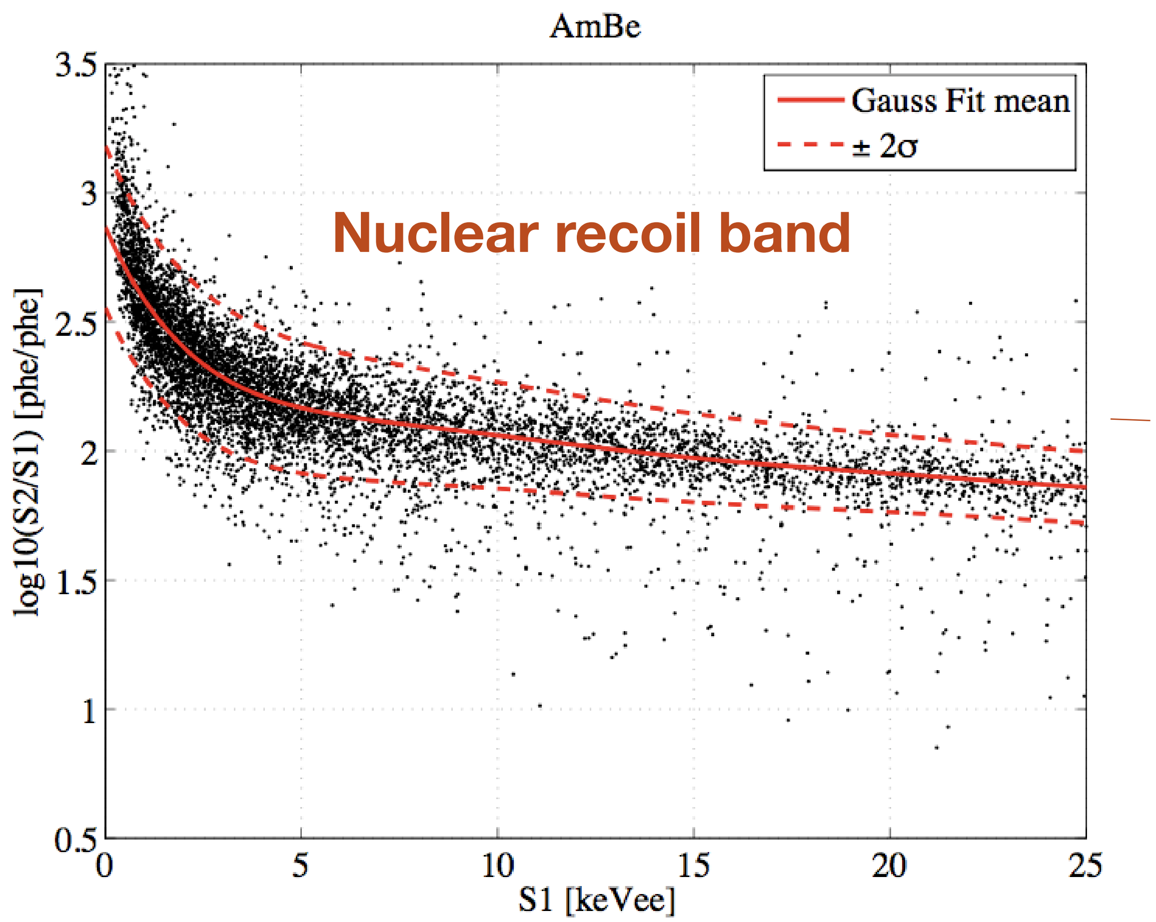
Anti-correlation of charge/light signals

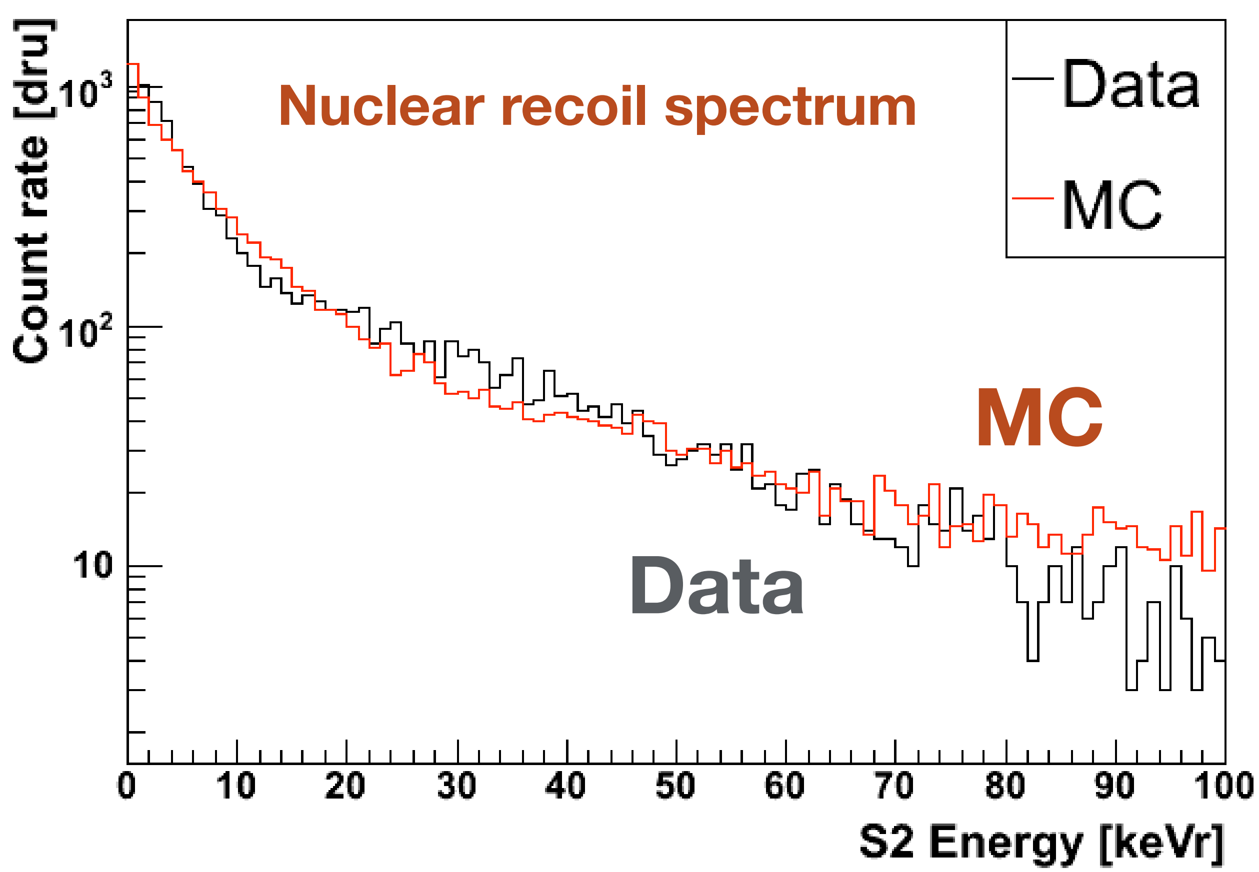


Combined energy spectrum

XENON10 Neutron Calibration

- (Encapsulated) neutron source: AmBe ($E_{max} \approx$ 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.

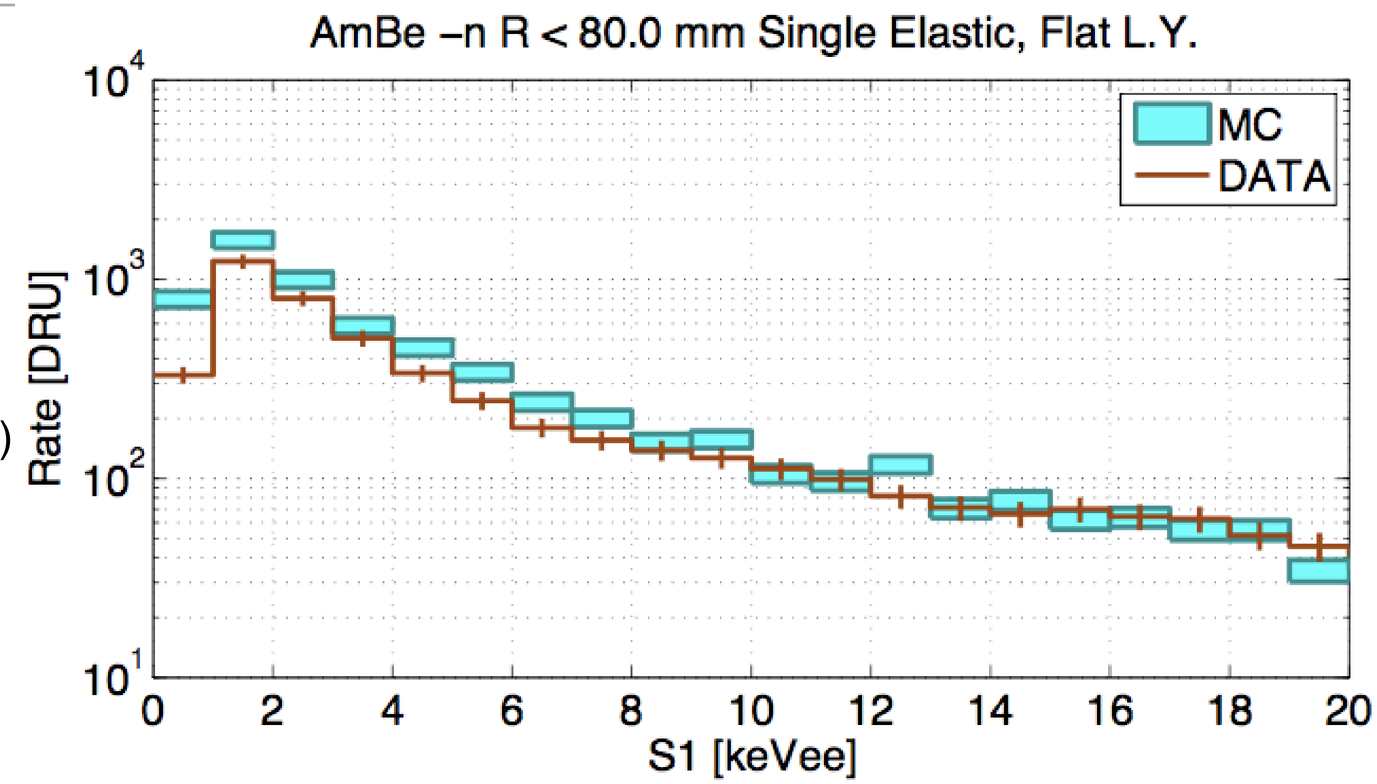
Quenching of scintillation yield for 122 keV γ's due to field (0.54 at 0.73 kV/cm)

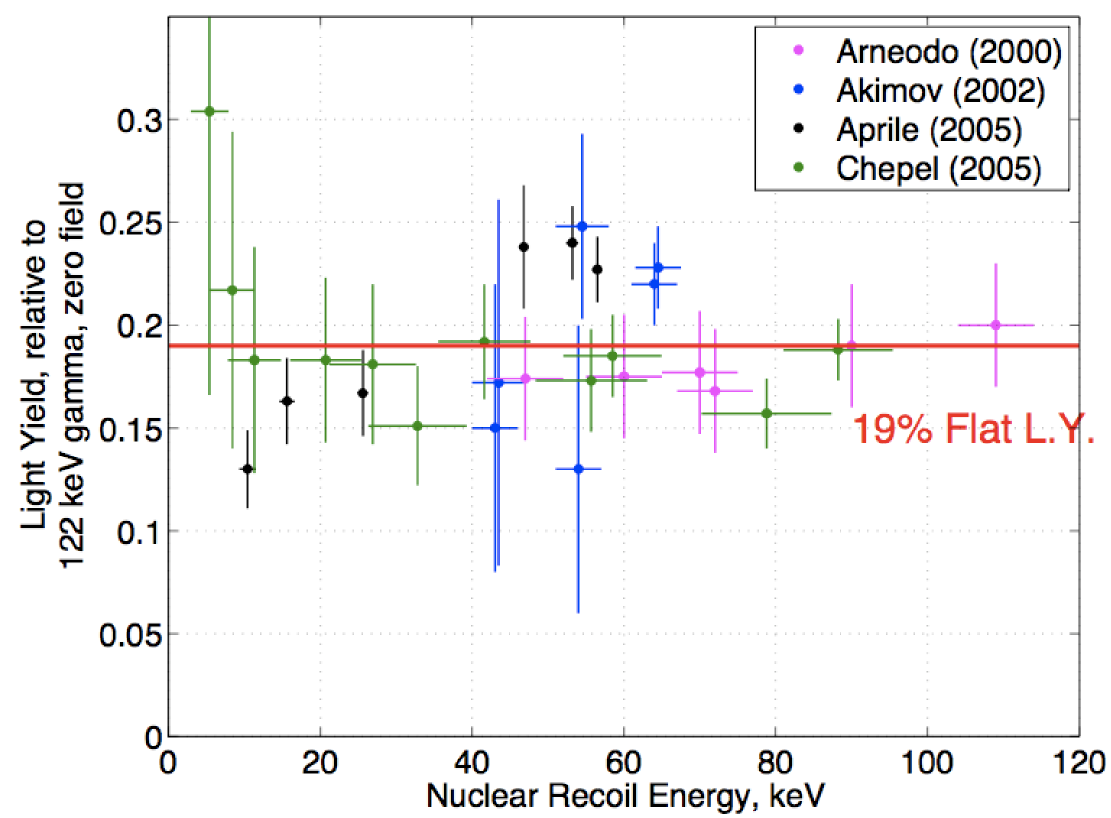
$$E_{nr} = \frac{S1}{L_y \cdot \mathcal{L}_{eff}} \times \frac{S_{er}}{S_{nr}}$$

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

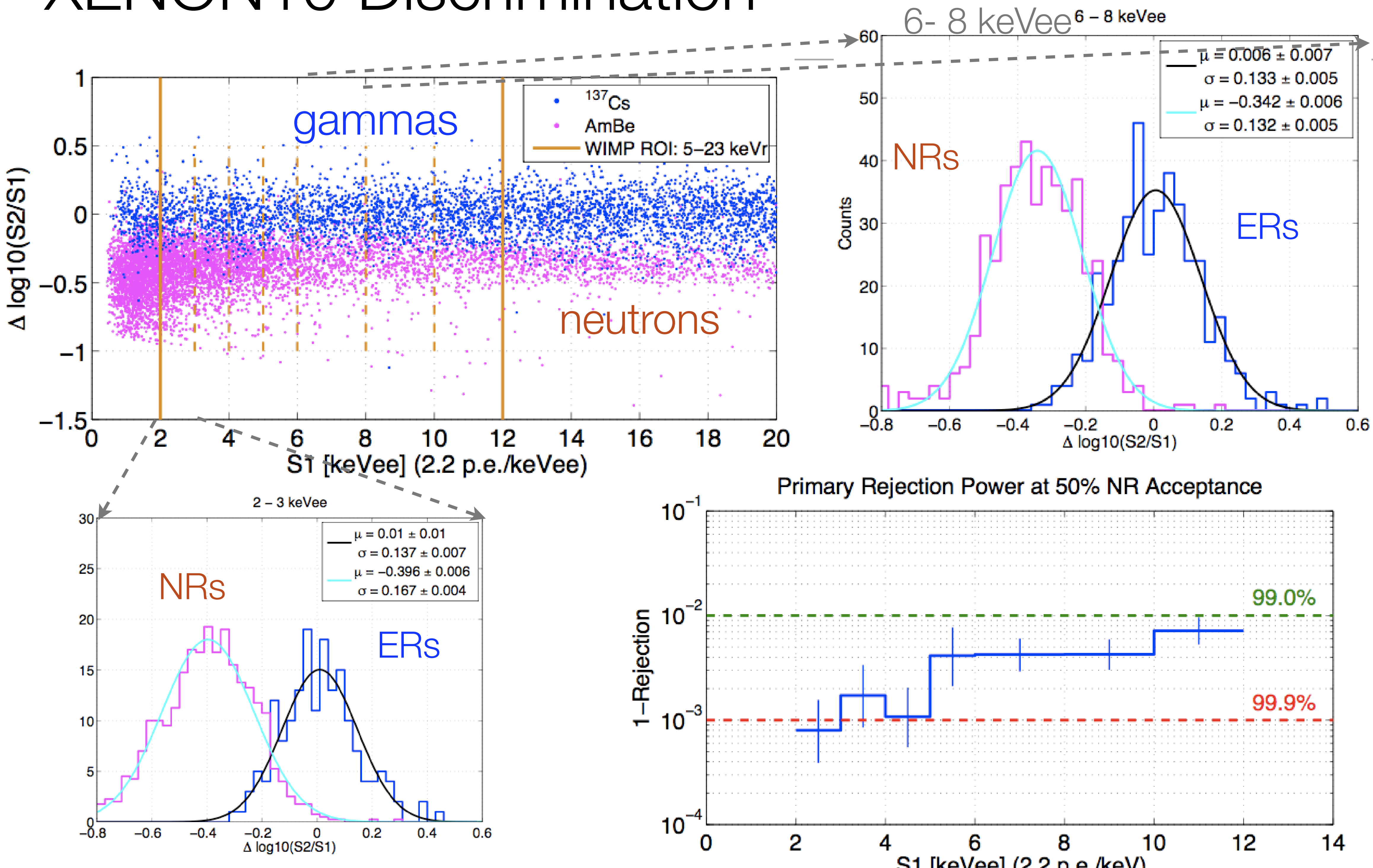
Relative scintillation efficiency of NRs to 122 keV γ's at zero field (flat value: 0.19)

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: Material Screening

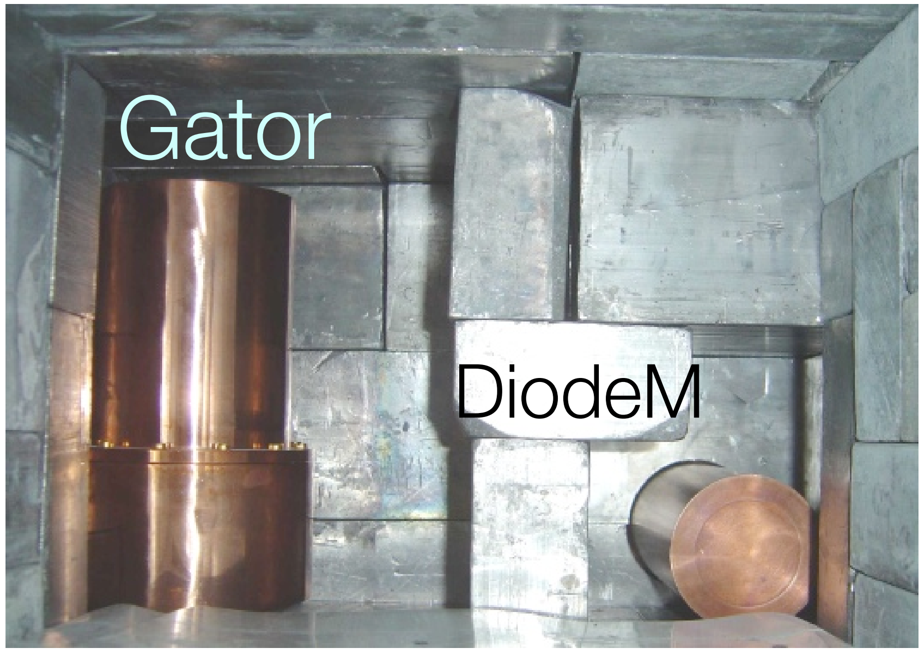
- we have screened the XENON10 detector+shield components with 2 HPGe detectors at SOLO/Soudan and a HPGe detector at LNGS

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 (4 PMTs)**	**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**

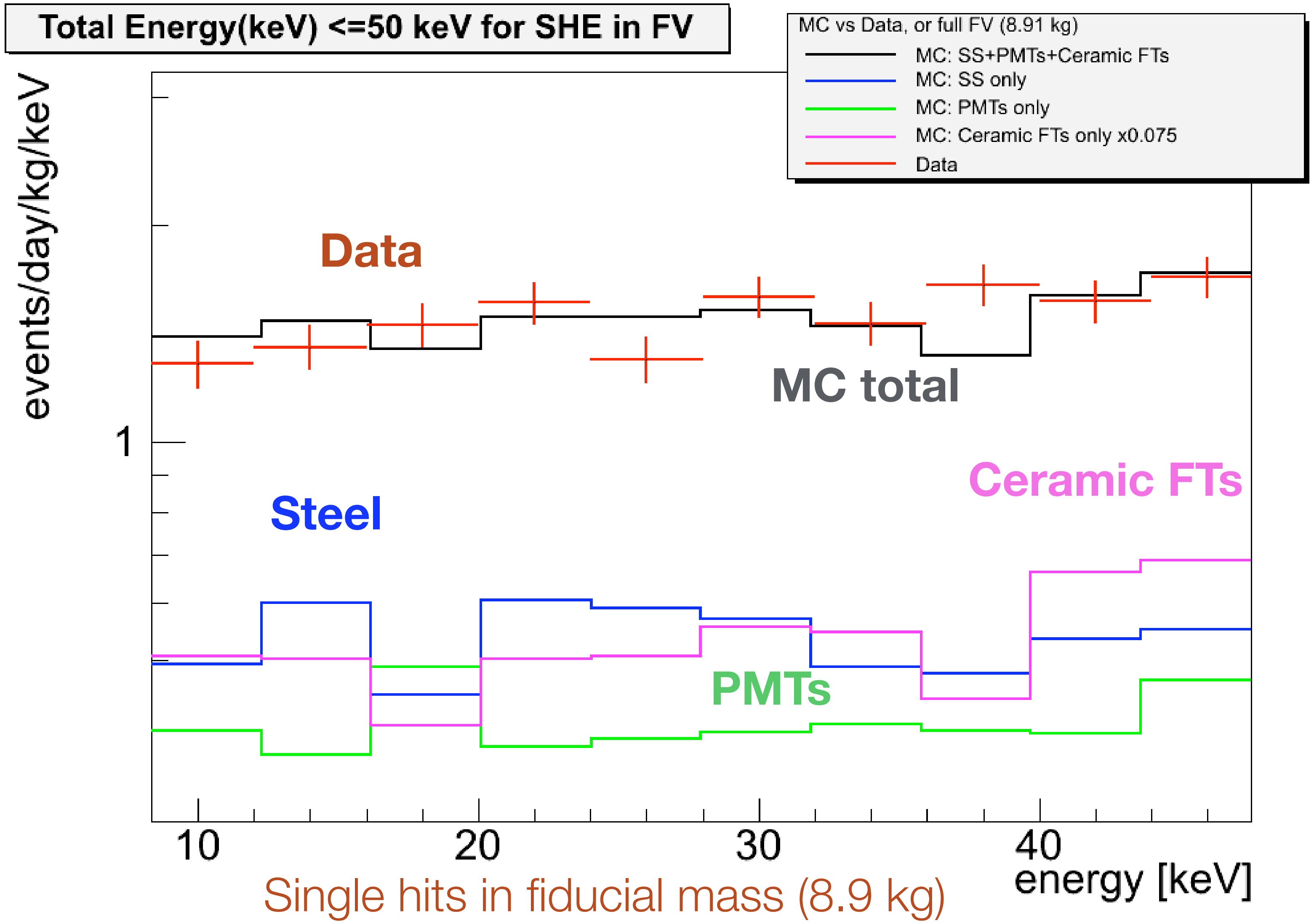
→ **XENON10 upgrade:** we replaced known 'hot' components (FTs) in May 2007

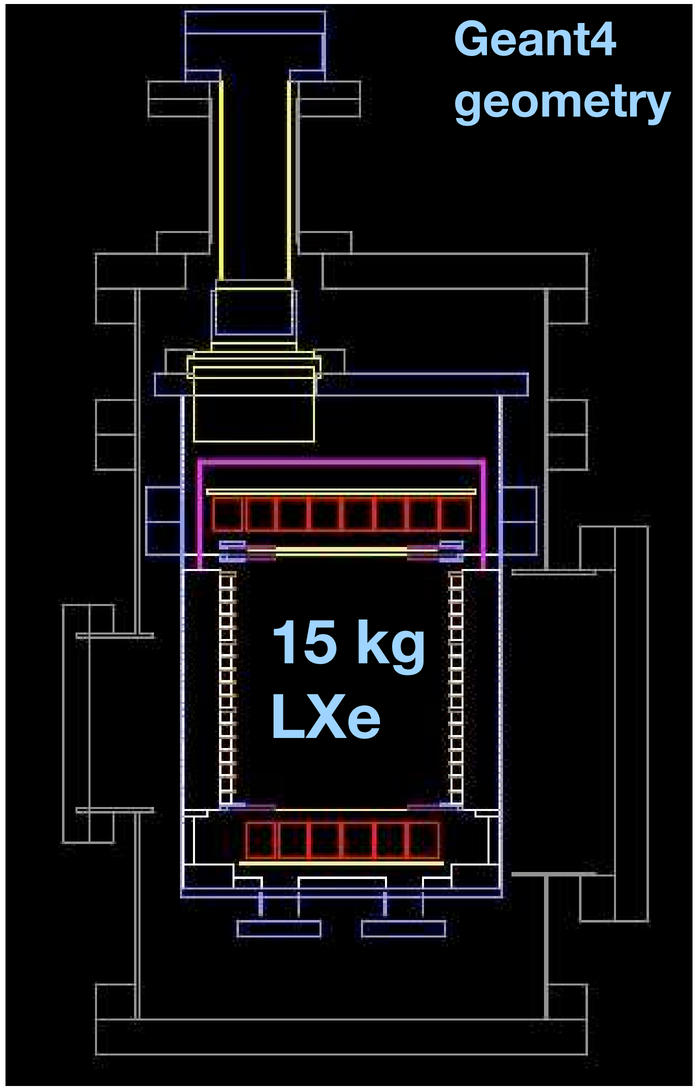
→ we are increasing Gator's sensitivity by building new shield at LNGS with 5 cm inner OFHC Cu lining and low activity Pb (3 Bq/kg ^{210}Pb) shield



XENON10 Backgrounds: Data and MC Simulations

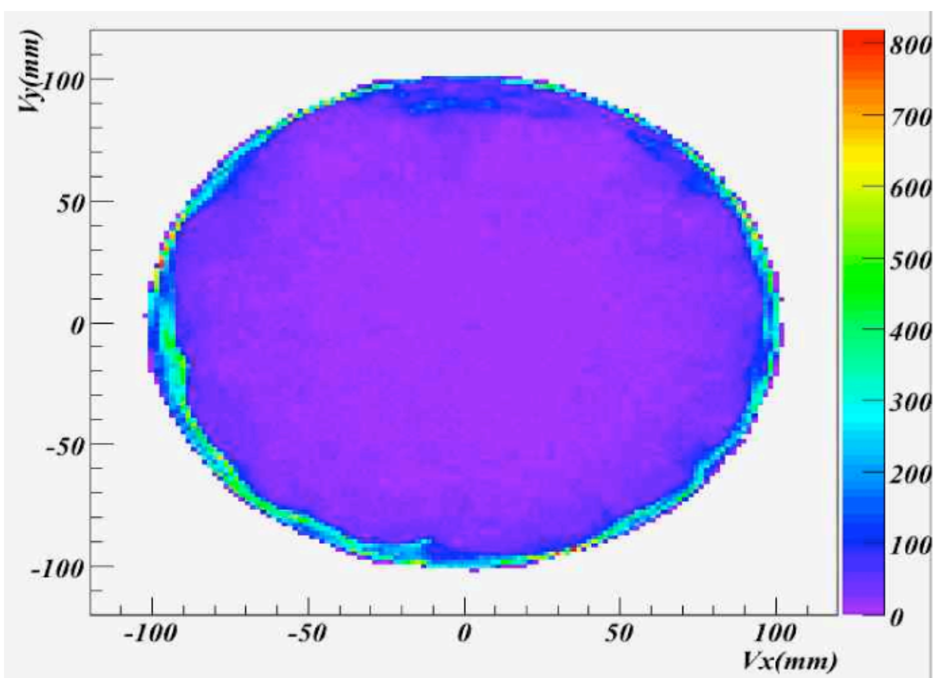
- **Gamma BG**: dominated by steel (inner vessel and cryostat) and ceramic FTs
- **Neutron BG**: subdominant for XENON10 sensitivity goal (MC: < 1 event/year from (α,n) in materials and < 5 events/year from μ-induced n's)
- **Red crosses**: data; **Black curve**: sum of background contributions from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

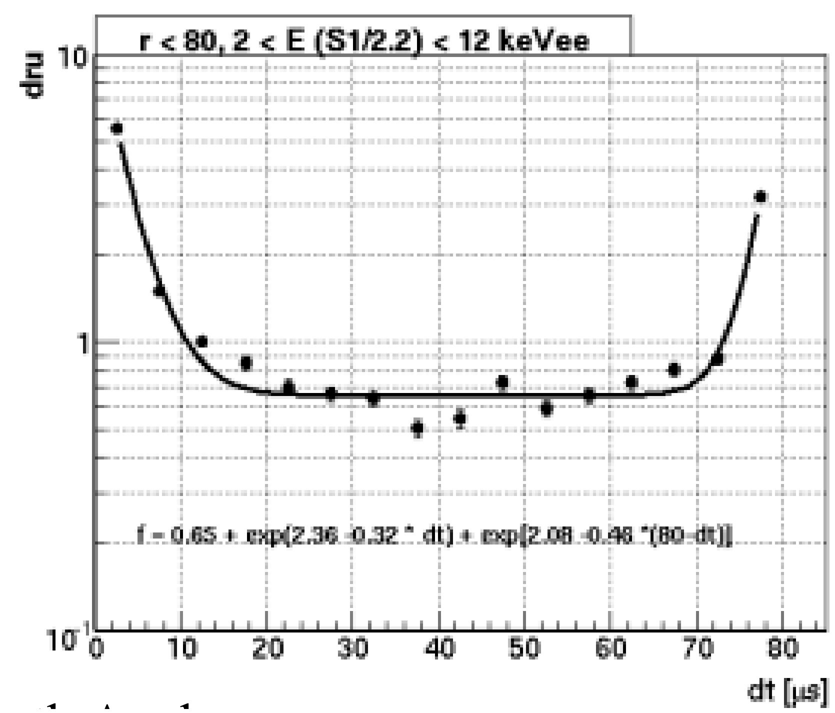




XENON10 Blind WIMP Analysis Cuts

- 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)

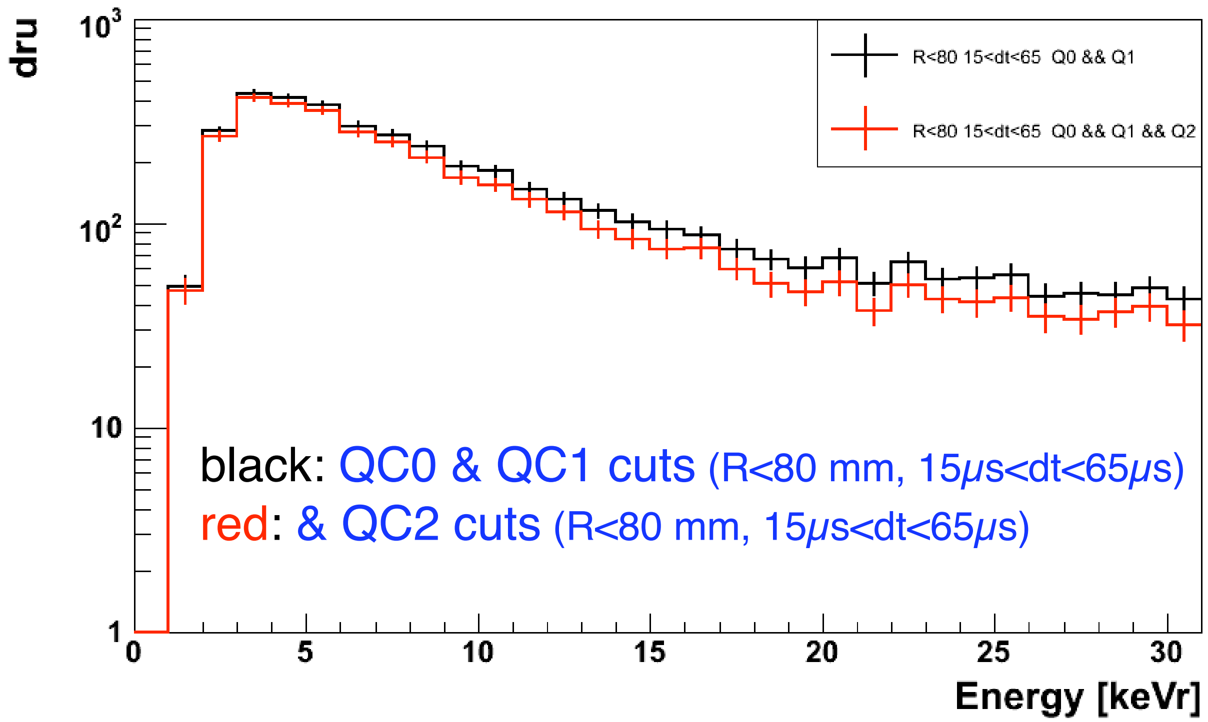


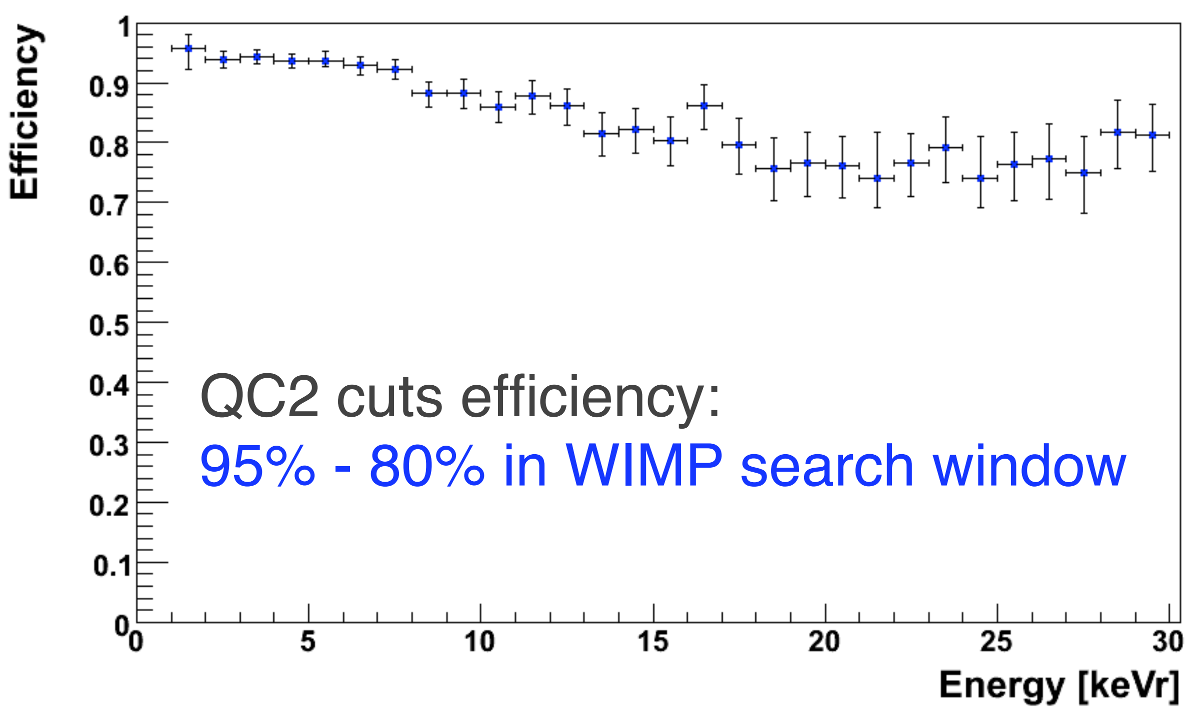


- **Fiducial Volume Cut**: 15 μs < dt < 65 μs, r < 80 mm => fiducial mass = 5.4 kg
- **Overall Background** in Fiducial Volume: ~ 0.6 events/(kg · day · keVee)

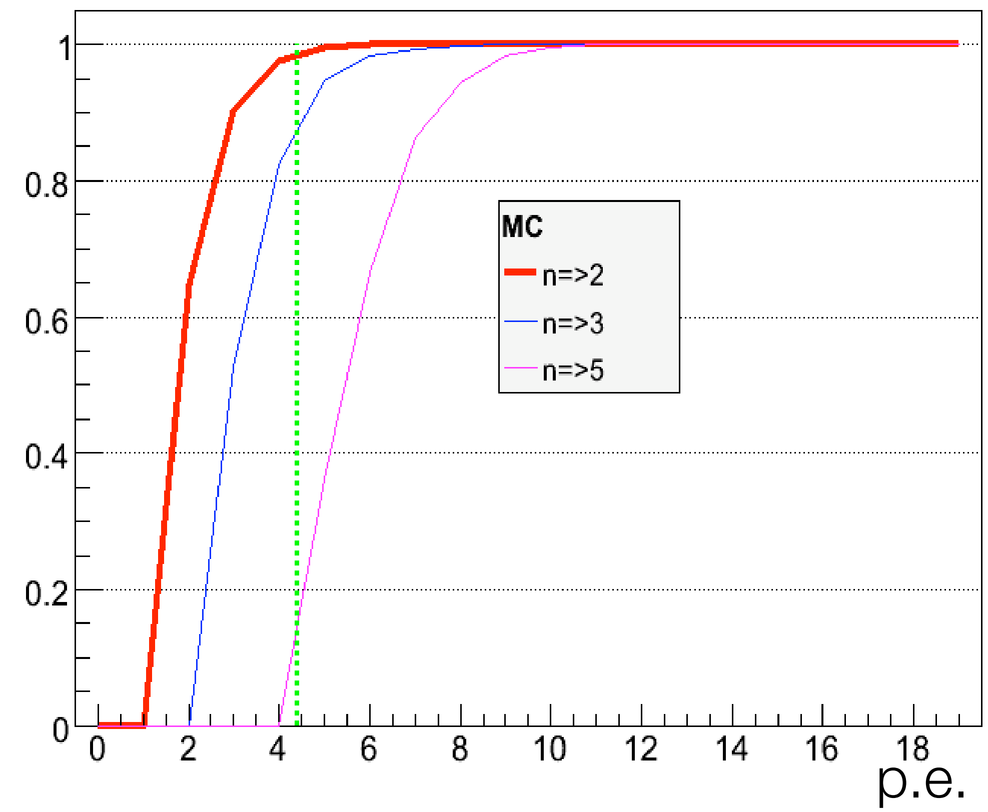
Analysis Cut Efficiencies

neutron data





S1 efficiency

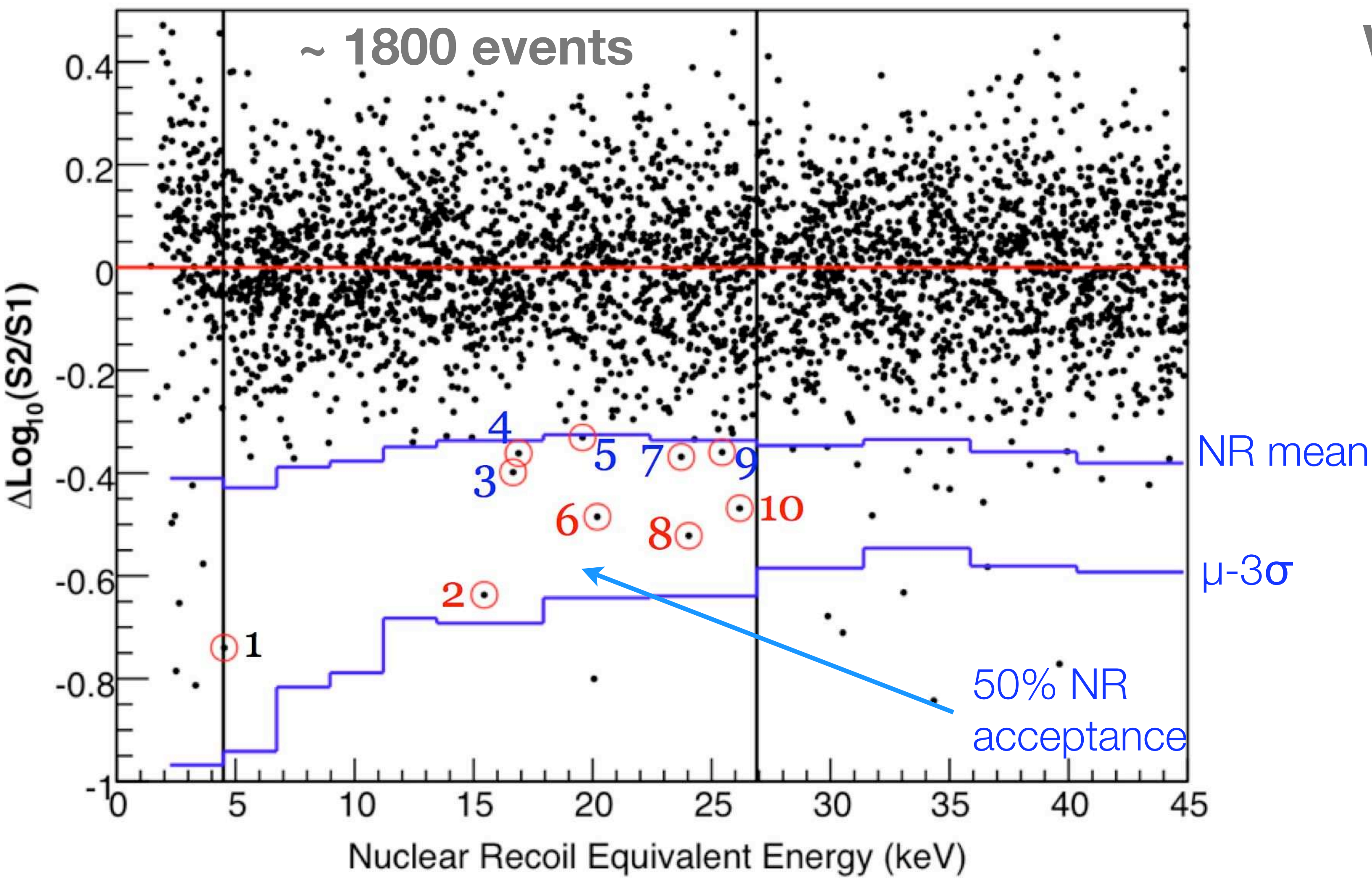


Trigger: S2 sum signal from top PMTs
S2 threshold: 300 p.e. (~ 20 e-)
(gas gain of a few 100s allows 100% S2 trigger efficiency)

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 - February 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
(2.0 keVee)

27 keVr
(12 keVee)

WIMP 'Box' defined at

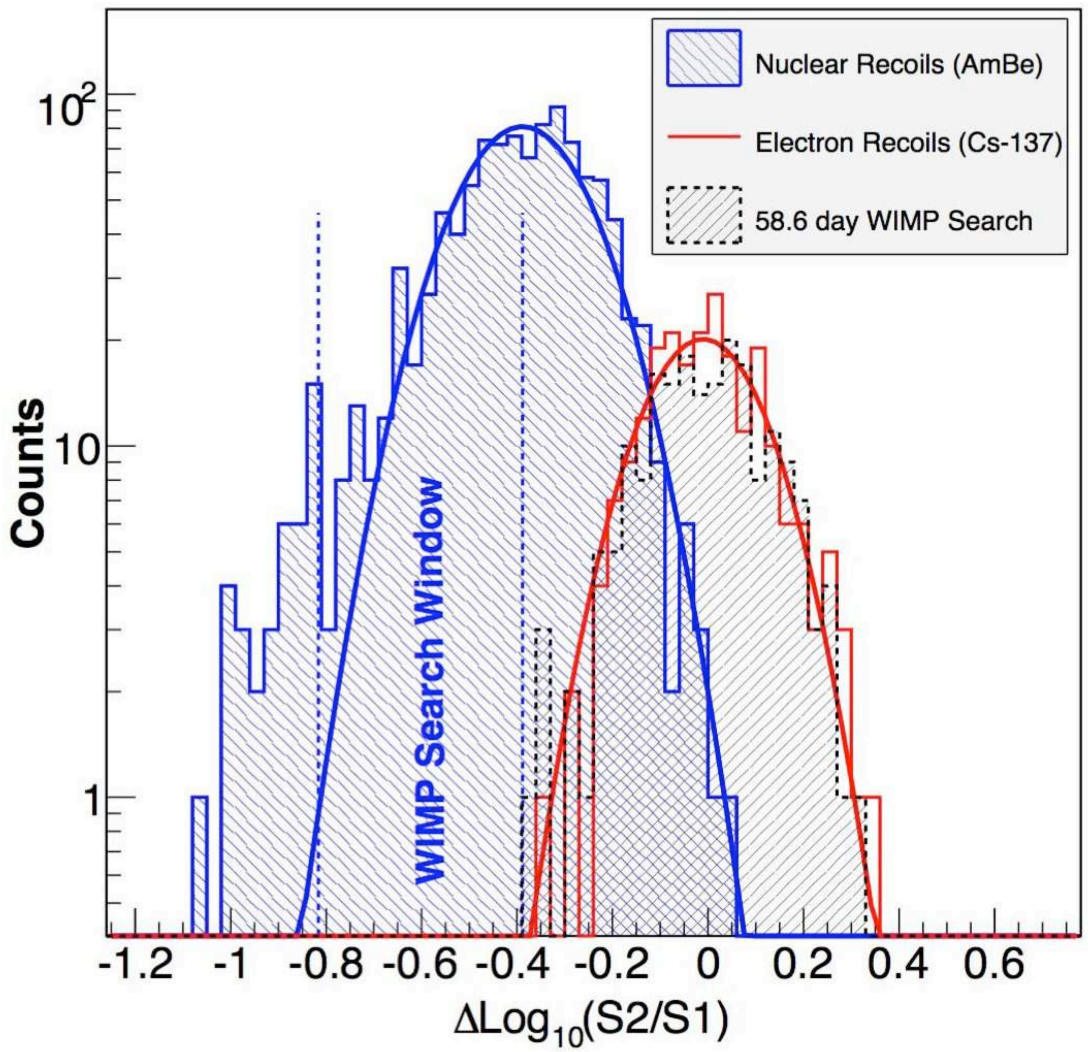
50% acceptance of NRs (blue lines): [Mean,-3σ]

10 events in 'box' after all cuts
7.0 ($^{+2.1}_{-1.0}$) statistical leakage expected from the gamma (ER) band

Other 5 events not consistent with Gaussian leakage

NR energy scale based on constant 19% QF

Event Distribution and Predicted Leakage



$\Delta Log_{10}(S2/S1)$ distribution in the 6.7-9.0 keVr energy bin

The distribution for ERs is fit by a Gaussian
-> the parameters are used to predict the number of stat. leakage events

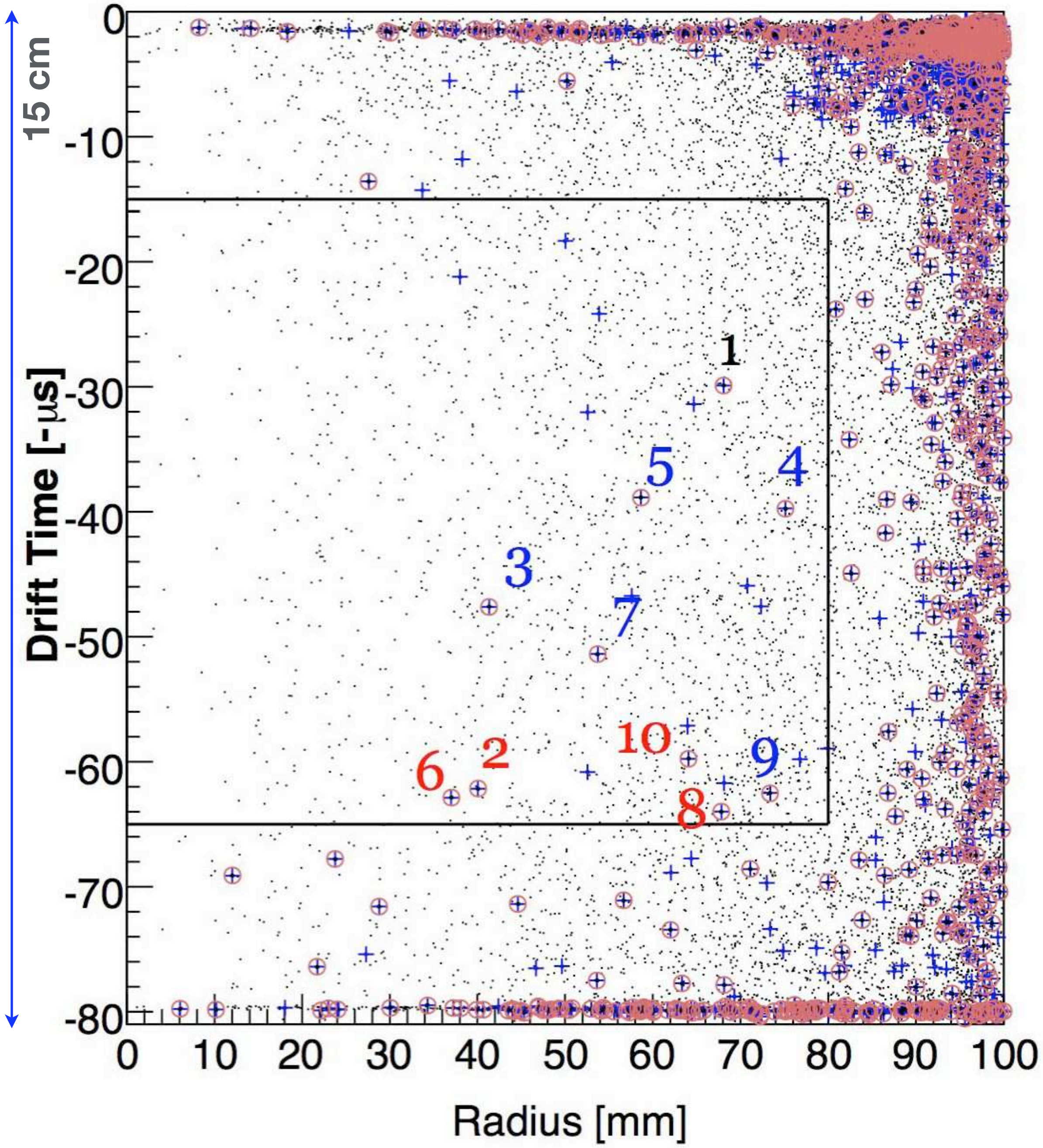
Total cut efficiency on NRs → ε_c; Acceptance of NRs → A_{nr}; 1 - ER rejection efficiency → $1 - R_{er}$

E_{nr} (keV)	ε_c	A_{nr}	$1 - R_{er}$ (10^{-3})	N_{evt}	N_{leak}
4.5 - 6.7	0.943	0.446	$0.8^{+0.7}_{-0.4}$	213	$0.2^{+0.2}_{-0.1}$
6.7 - 9.0	0.902	0.458	$1.7^{+1.6}_{-0.9}$	195	$0.3^{+0.3}_{-0.2}$
9.0 - 11.2	0.894	0.457	$1.1^{+0.9}_{-0.5}$	183	$0.2^{+0.2}_{-0.1}$
11.2 - 13.4	0.854	0.442	$4.1^{+3.6}_{-2.0}$	190	$0.8^{+0.7}_{-0.4}$
13.4 - 17.9	0.827	0.493	$4.2^{+1.8}_{-1.3}$	332	$1.4^{+0.6}_{-0.4}$
17.9 - 22.4	0.797	0.466	$4.3^{+1.7}_{-1.2}$	328	$1.4^{+0.5}_{-0.4}$
22.4 - 26.9	0.766	0.446	$7.2^{+2.4}_{-1.9}$	374	$2.7^{+0.9}_{-0.7}$
Total				1815	$7.0^{+1.4}_{-1.0}$

Total nr. of events in 4.5-26.9 keVe → N_{evt}

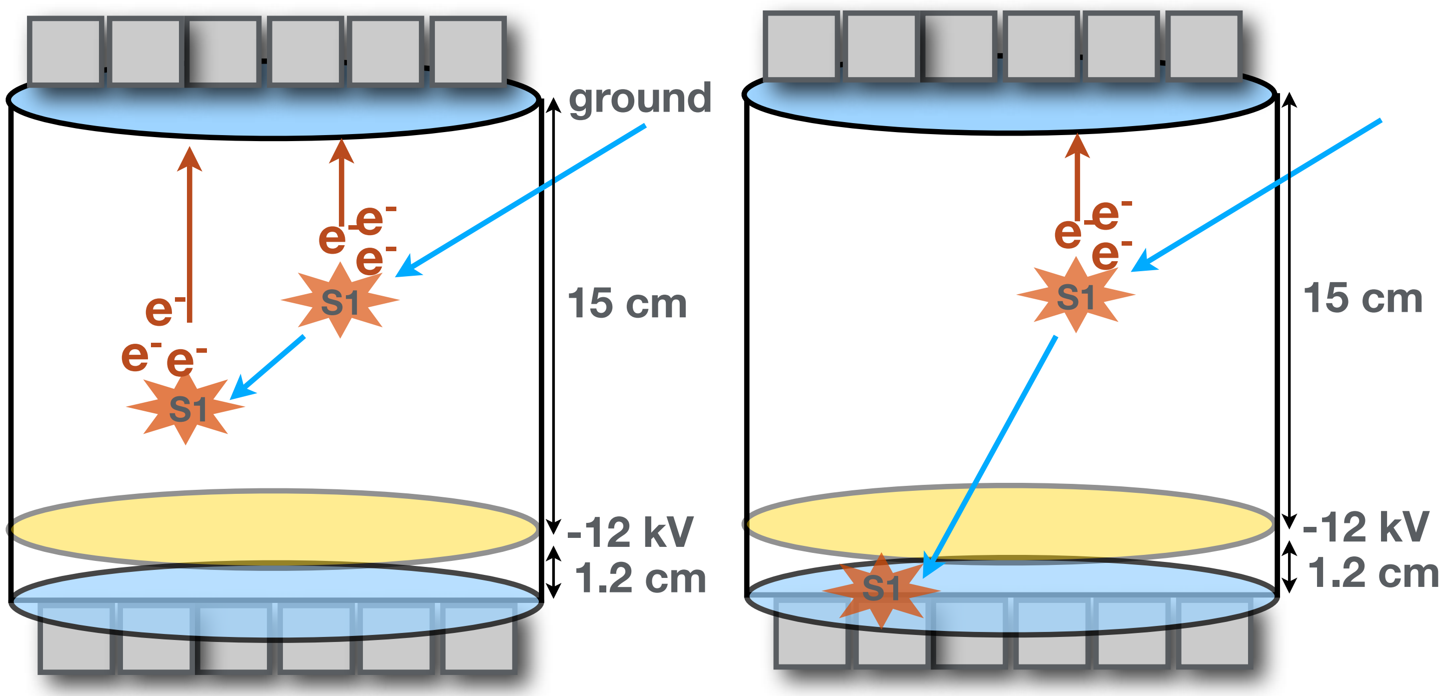
Predicted nr. of stat. leakage → N_{leak}

Spatial Distribution of Events



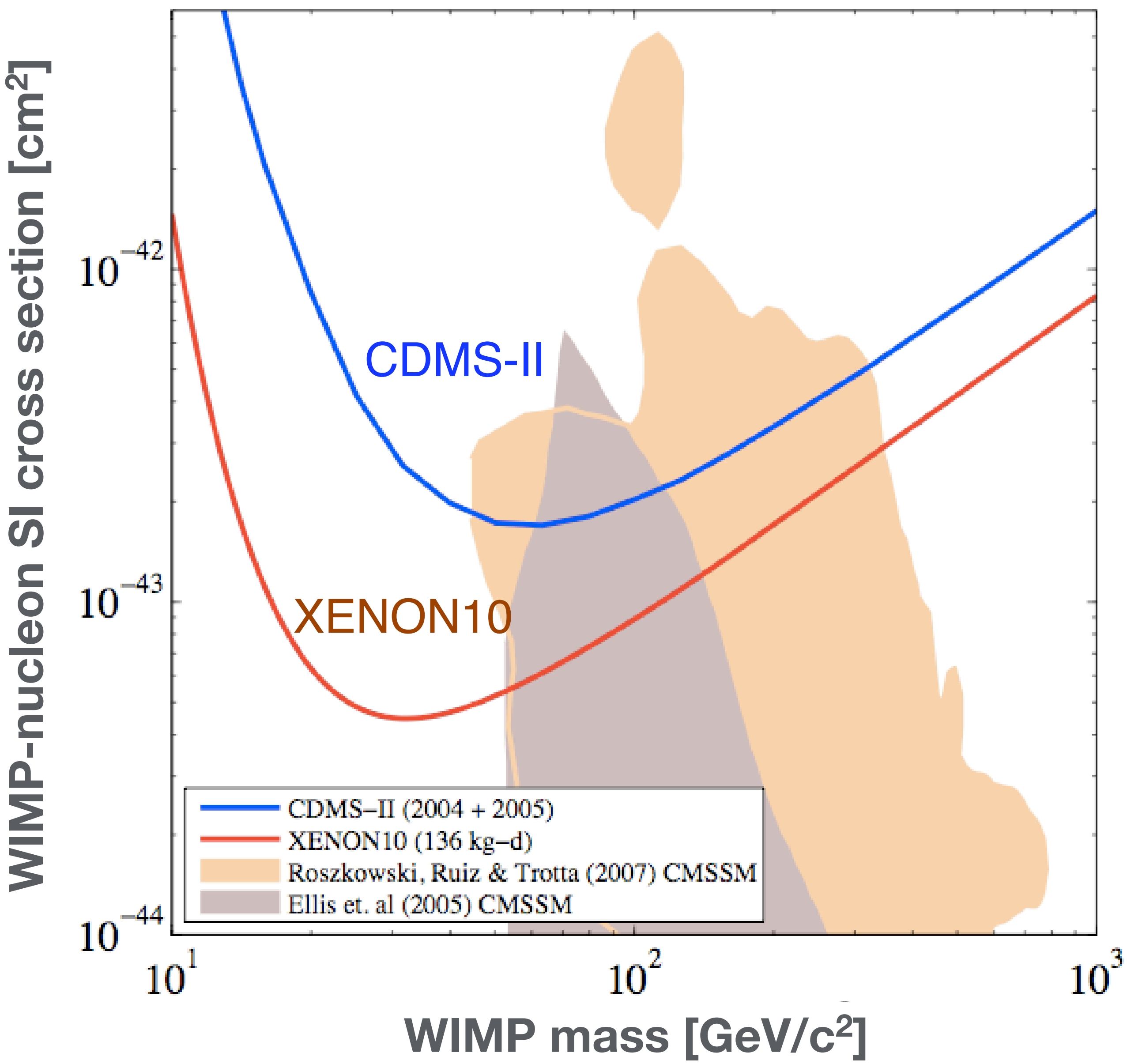
‘Gaussian events’: nr. 3, 4, 5, 7,9
‘Non-Gaussian events’: nr: 1, 2, 6, 8, 10

- 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

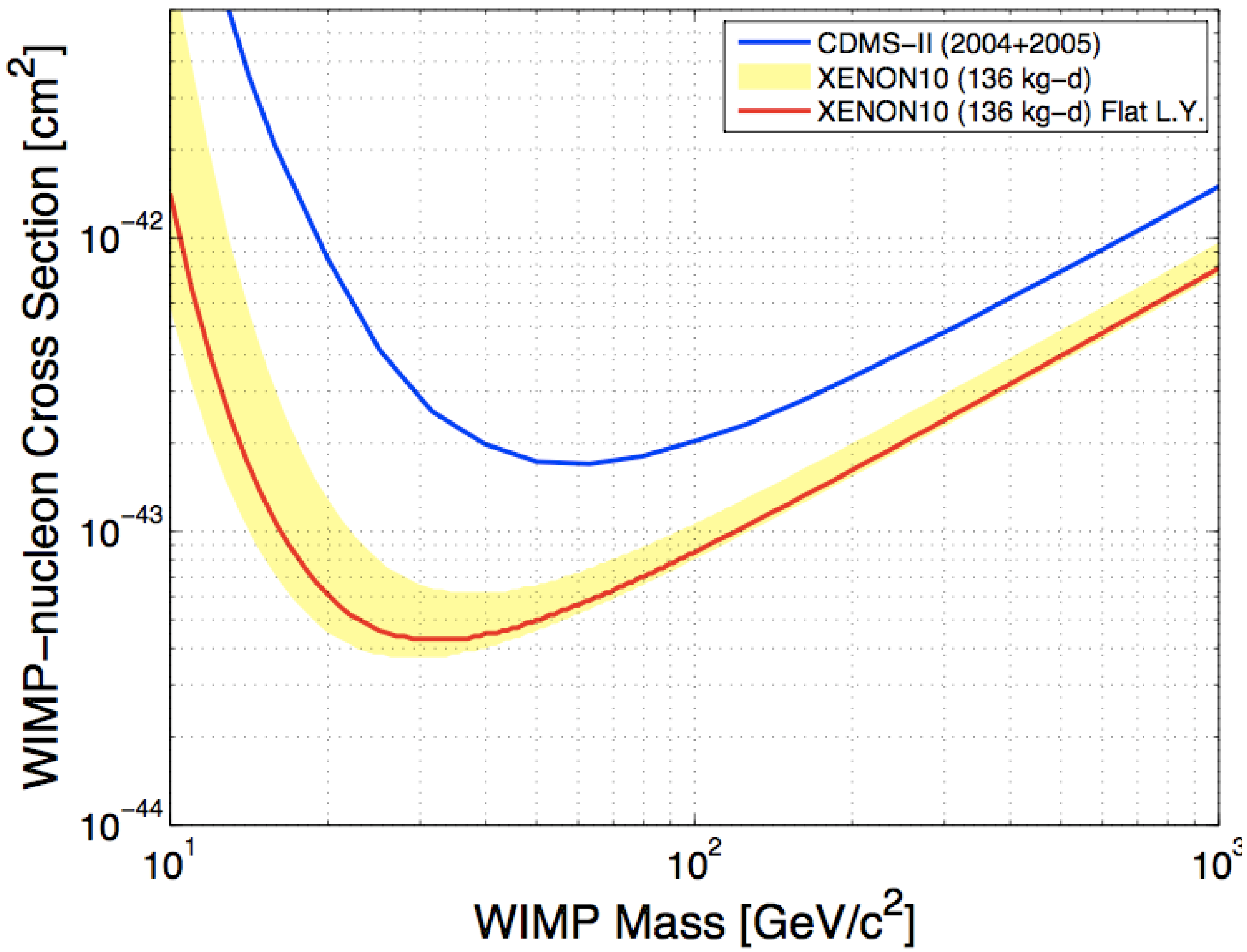
9.0×10^{-44} cm² (no background subtraction, red curve)

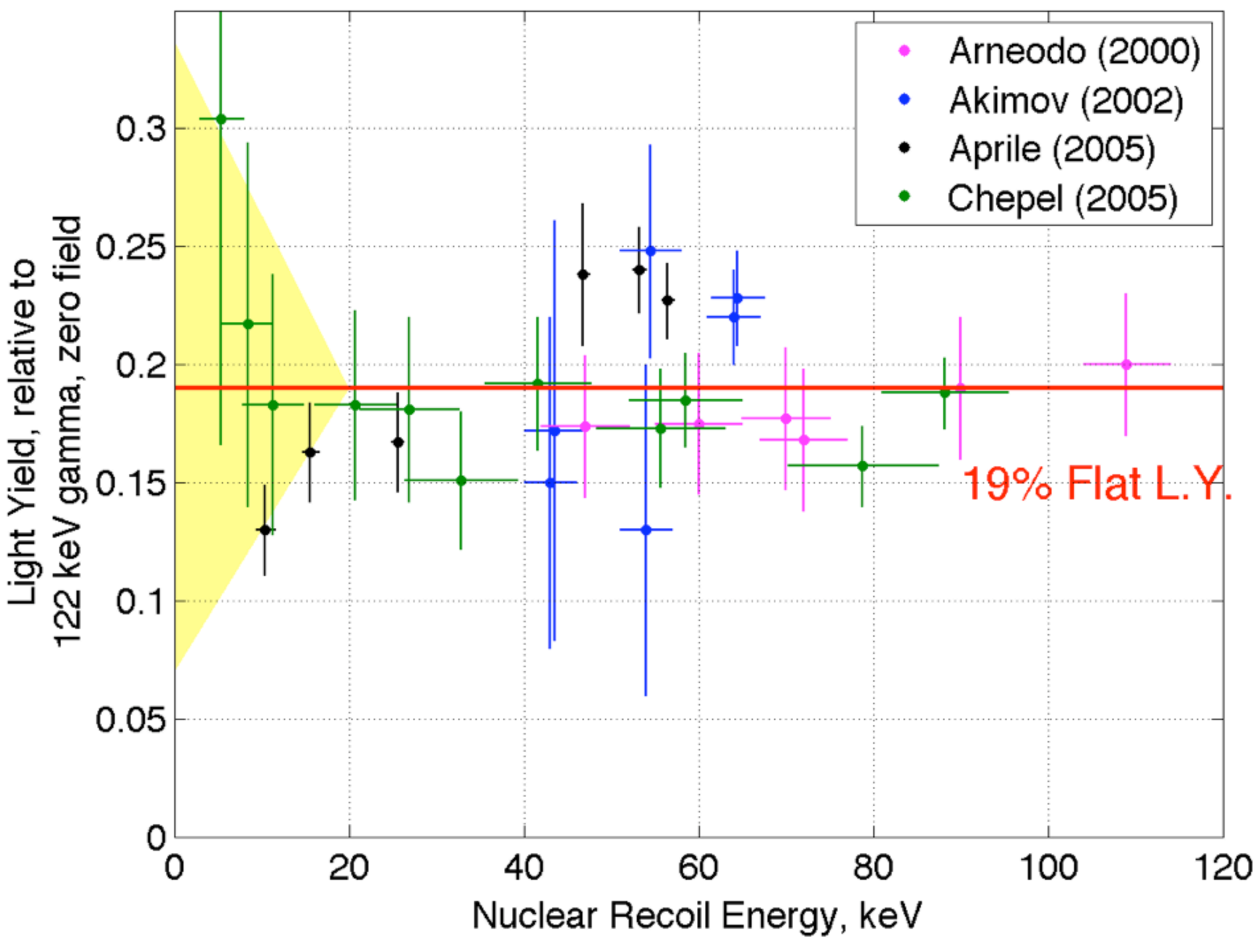
5.5×10^{-44} cm² (known background subtracted, not shown)

Factor 6 below previous best limit

Results submitted to PRL arXiv:0706.0039

XENON10 Results: Effect of Light Yield Uncertainty

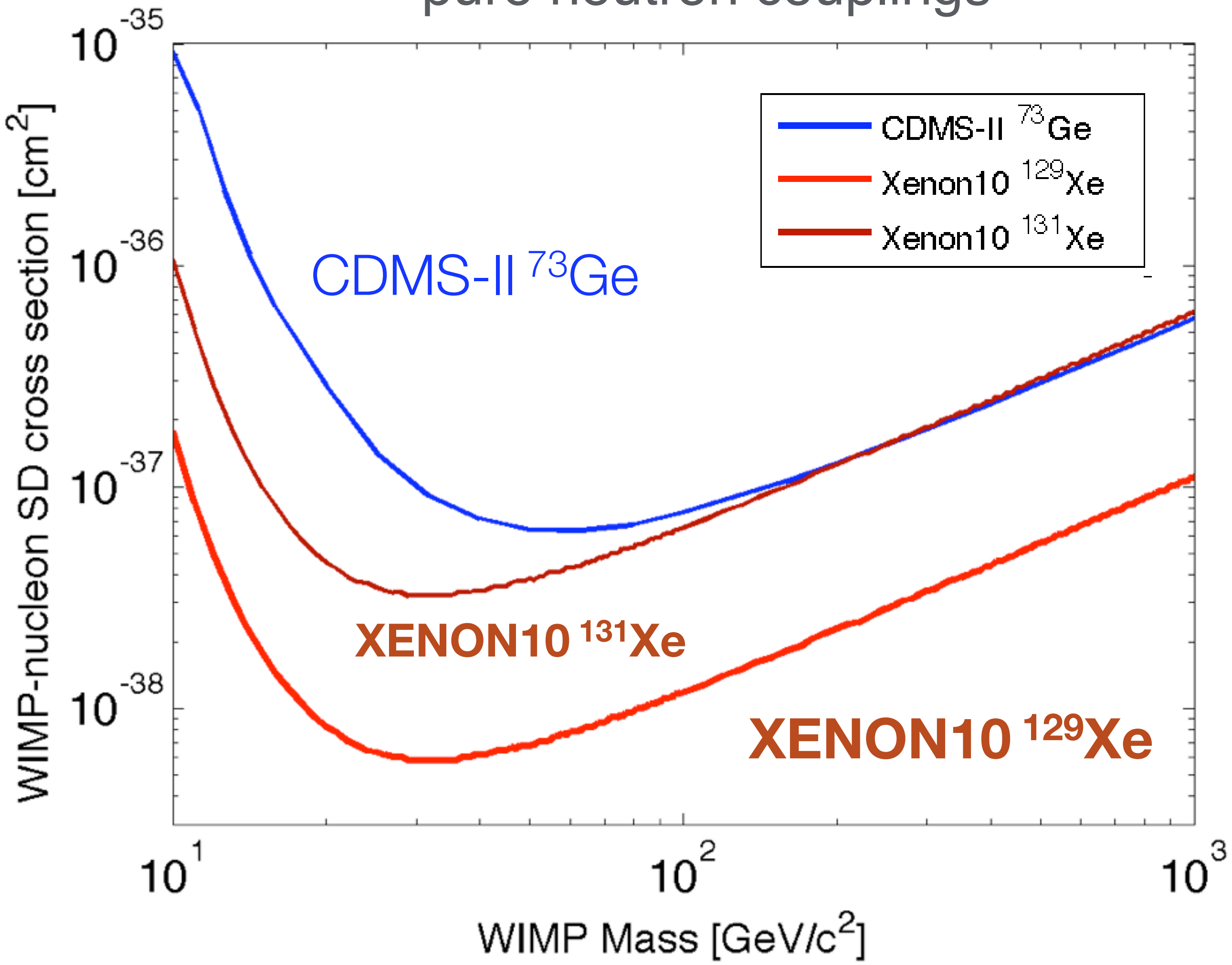




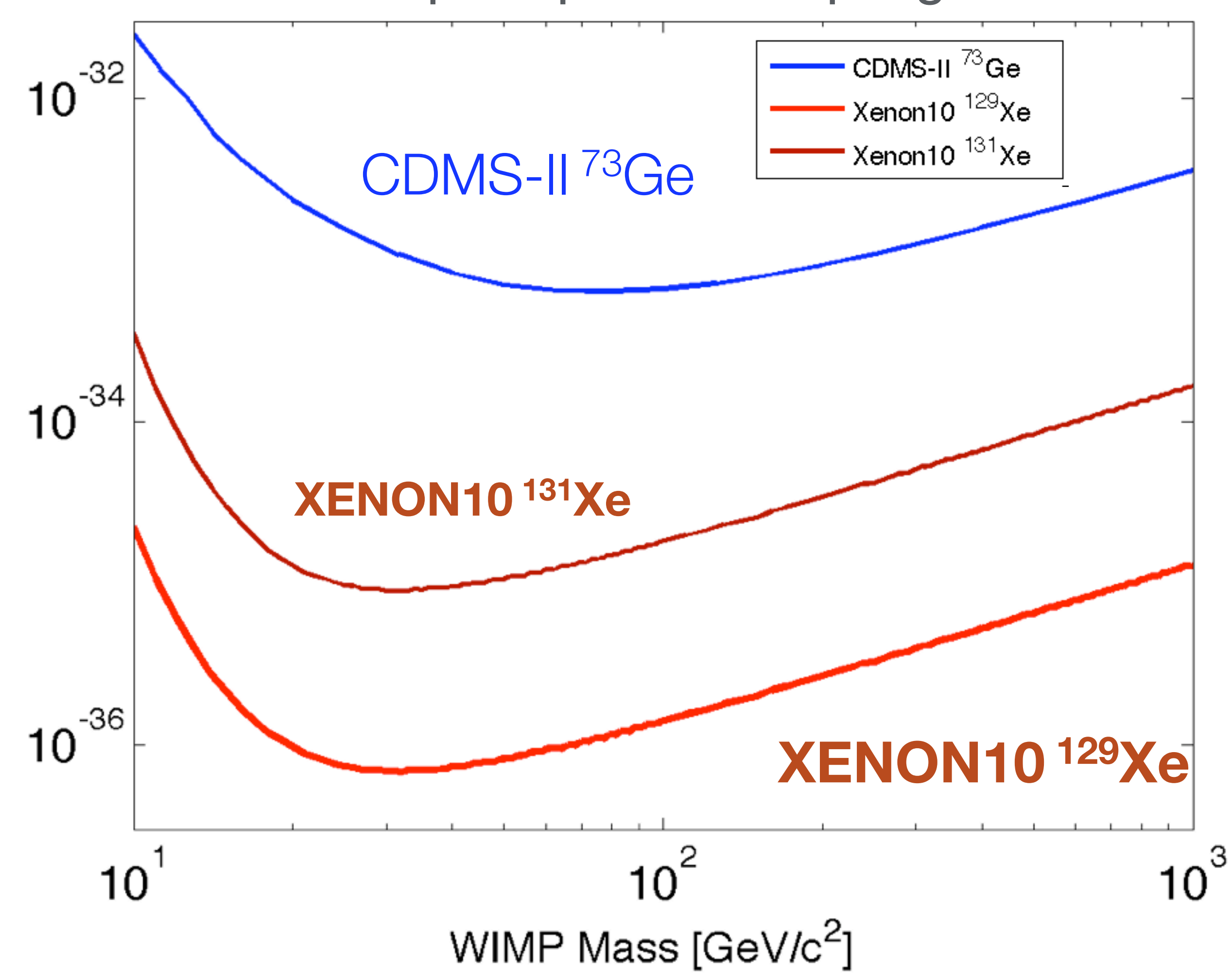
XENON10 WIMP Search Results for SD Interactions

- 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**

pure neutron couplings

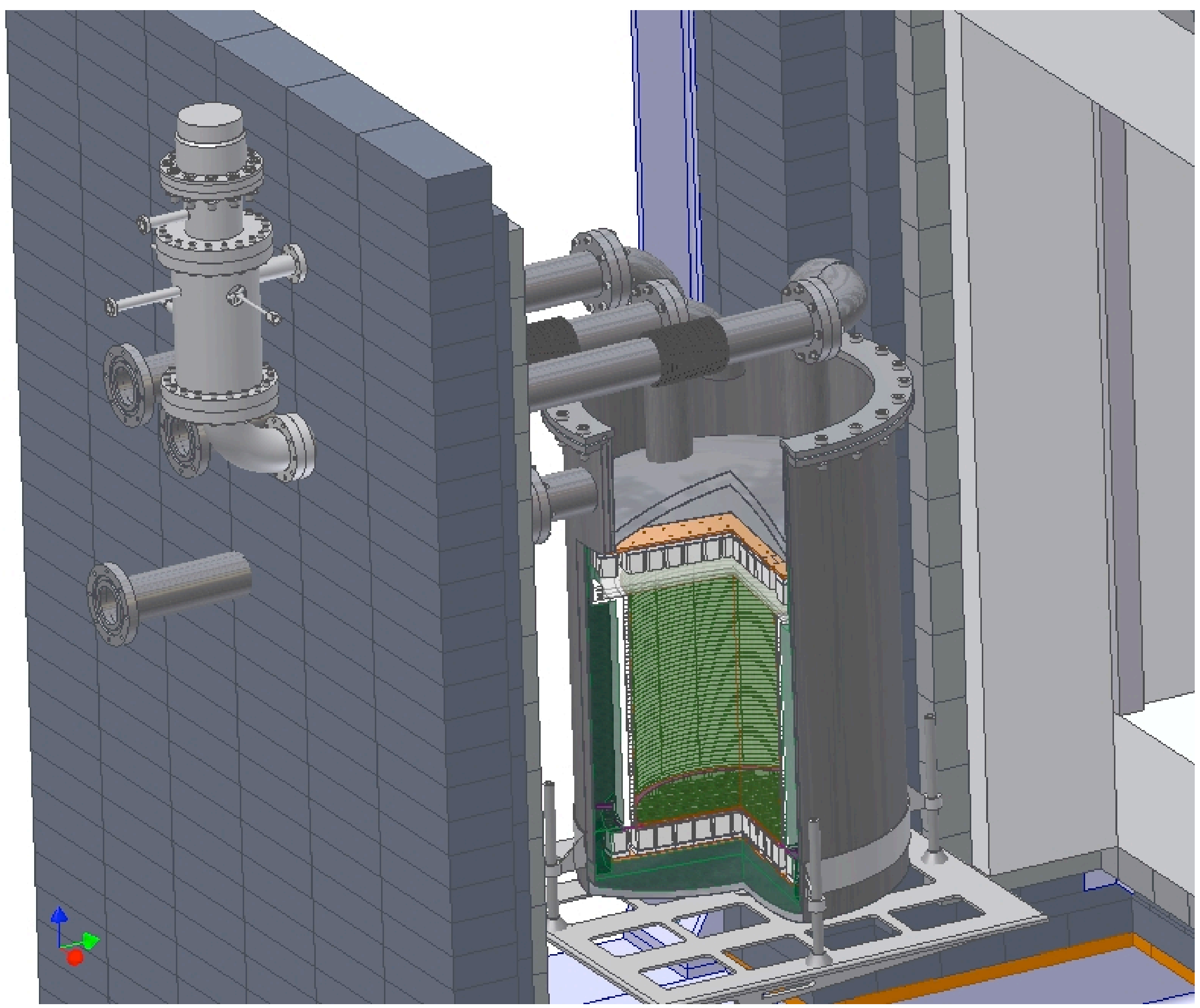


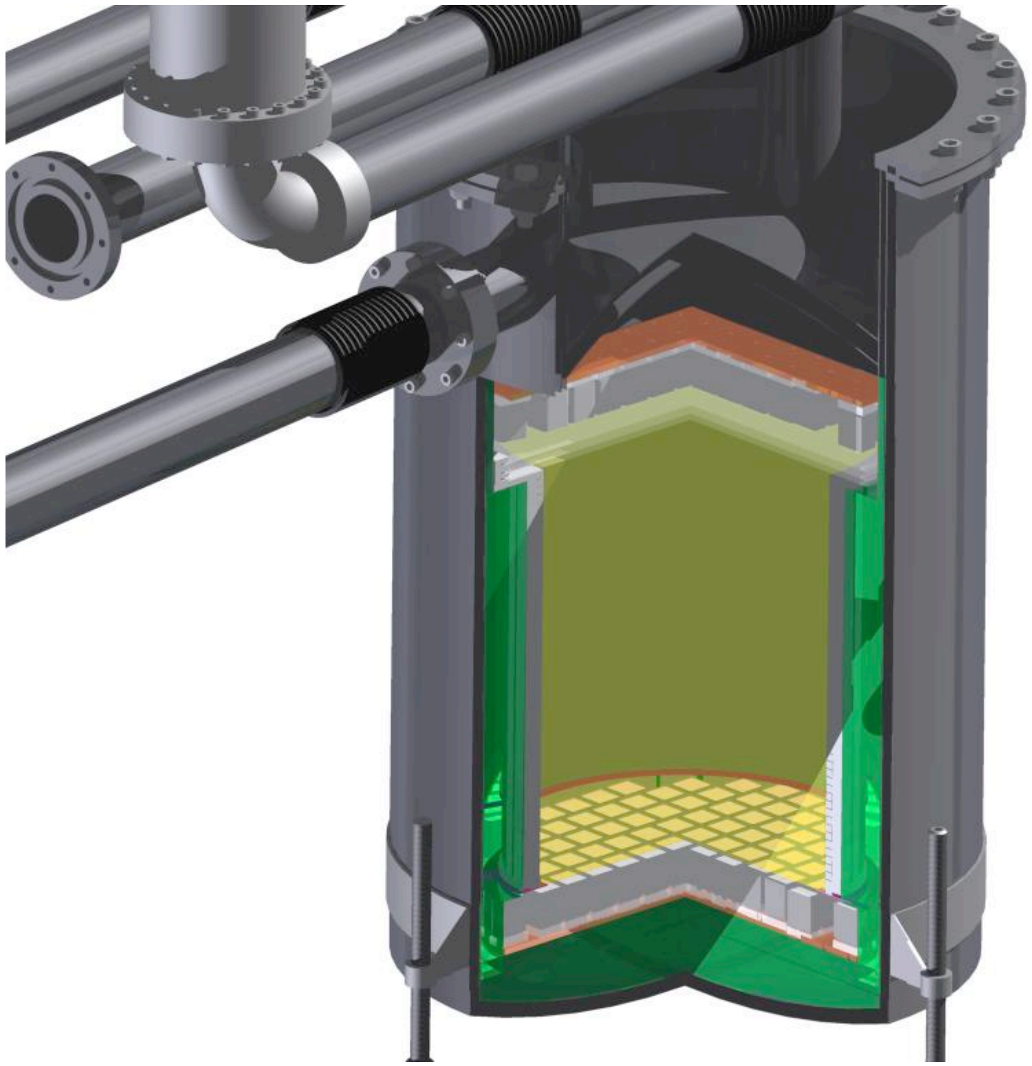
pure proton couplings



The XENON10+ Experiment at Gran Sasso

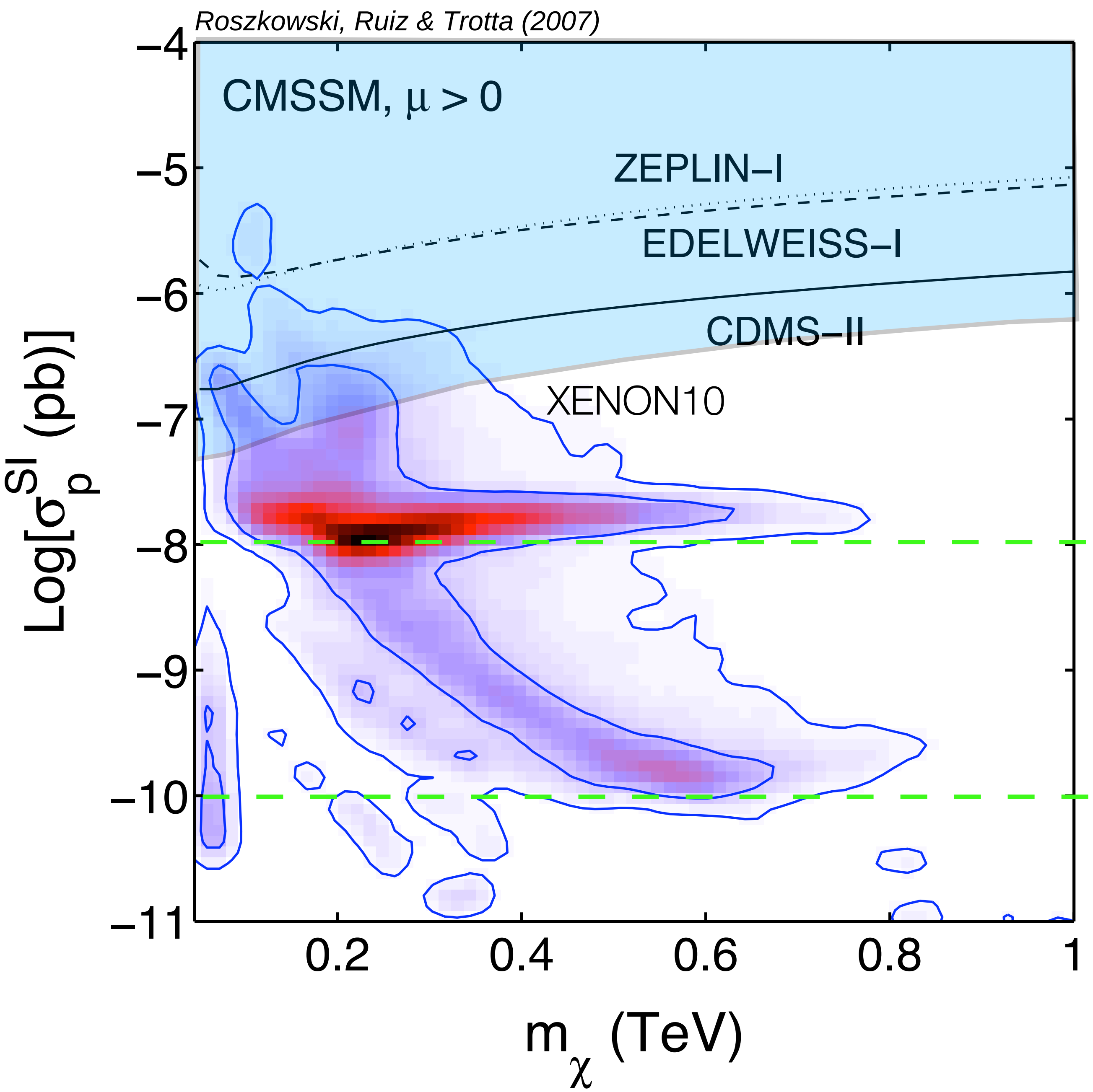
- low-background cryostat; cryogenics and FTs outside passive shield
- larger number of PMTs, larger target mass, active LXe veto
- design in progress; results expected by 2008 (aim factor 10 in sensitivity)





Summary

- Many techniques are being employed to search for dark matter particles
- Sensitivities are now approaching the theoretically most interesting regions!
- LXe-TPC: a mature technology; XENON10 first results in 2007, ready to go to larger scales



excluded by XENON10
(2007)

1 event/kg/yr

CDMS-II, XENON10+, COUPP,
CRESST-II, EDELWEISS-II, ZEPLIN-III,...

1 event/t/yr

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

CMSSM in 2007
http://xxx.lanl.gov/abs/0705.2012

Expected sensitivity of Xenon10+