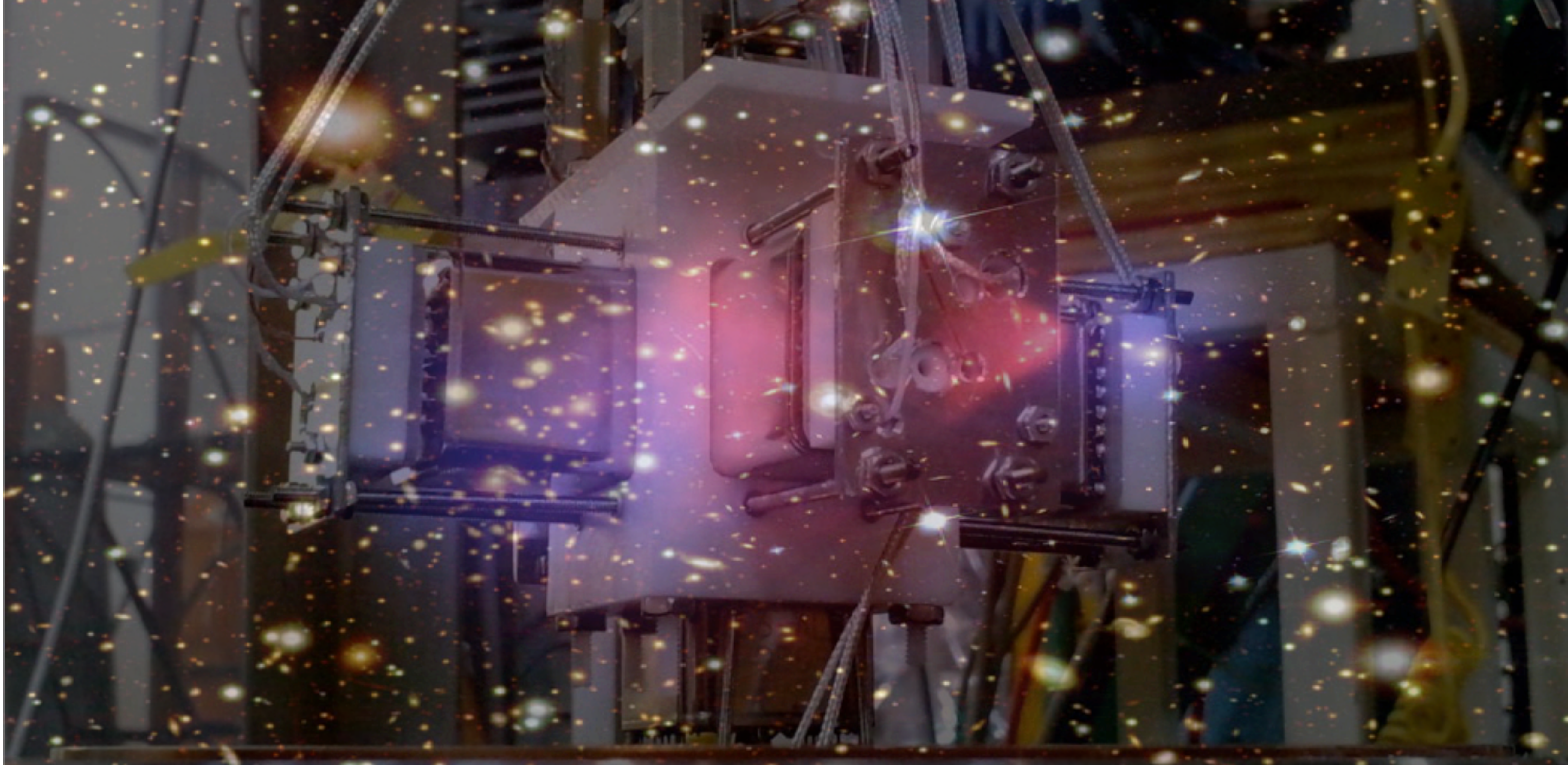


Dark Matter Results from XENON100 and Scintillation Response of LXe to Low Energy Particles

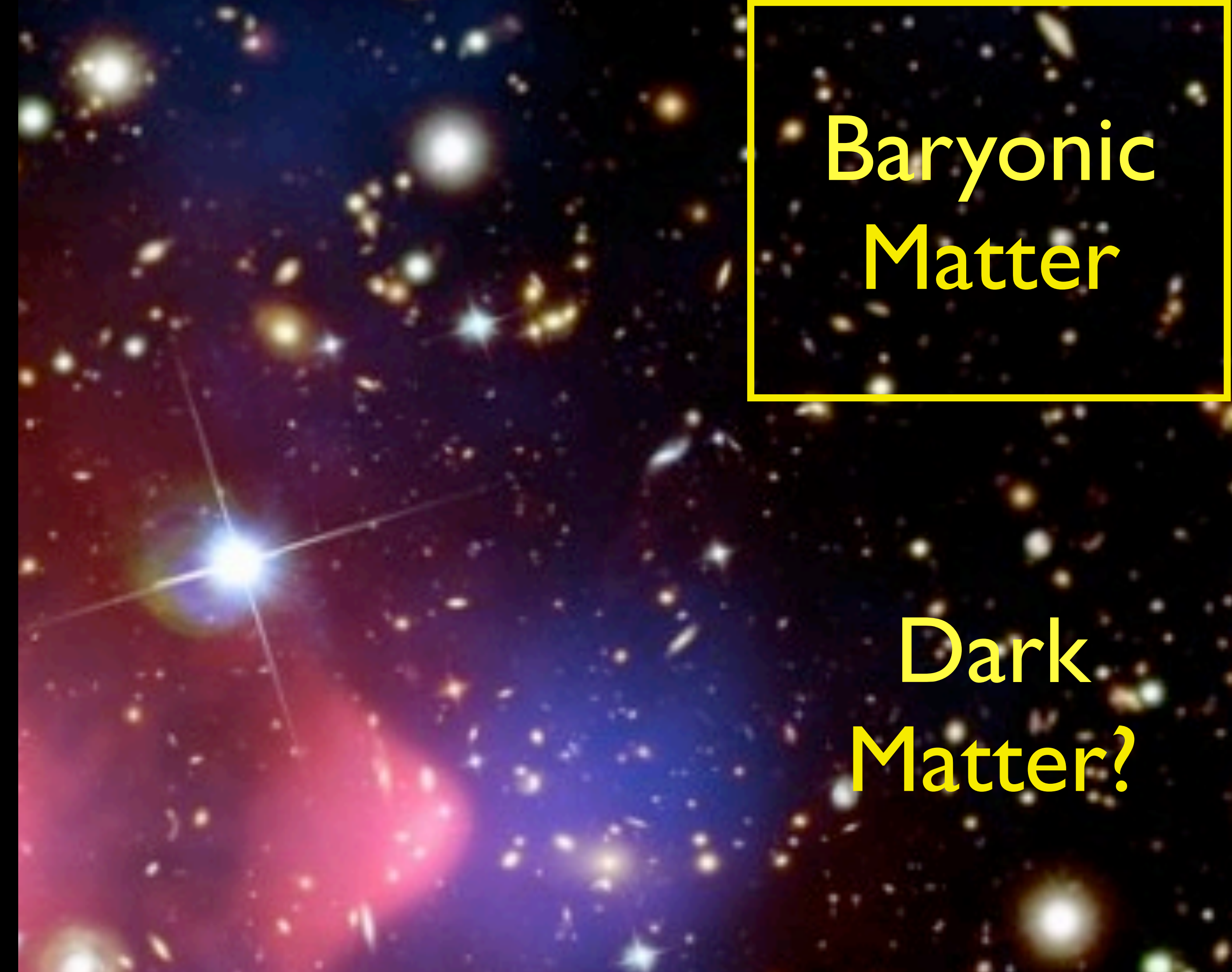
Kyungeun E. Lim (on behalf of the XENON collaboration)

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

XENON Dark Matter Project

Oct. 30th, 2012 SLAC National Accelerator Laboratory, Menlo Park, CA

95% of the Universe is Dark!

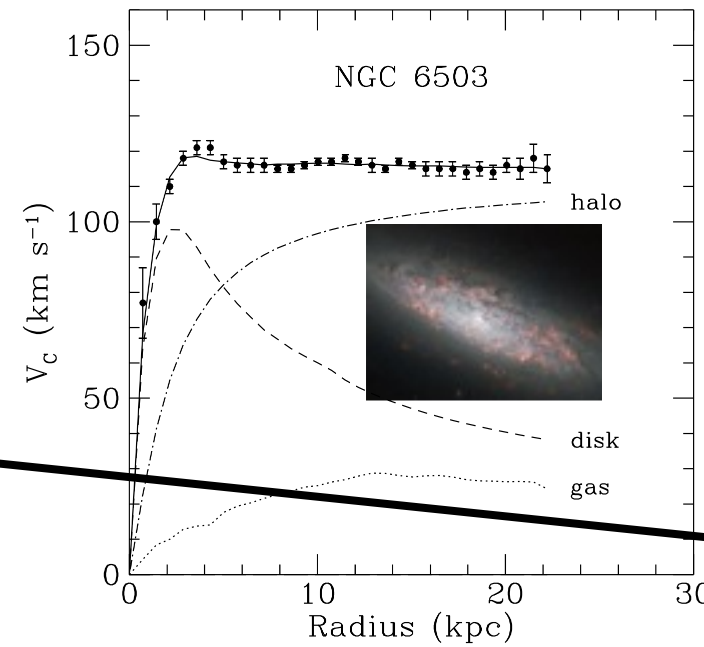


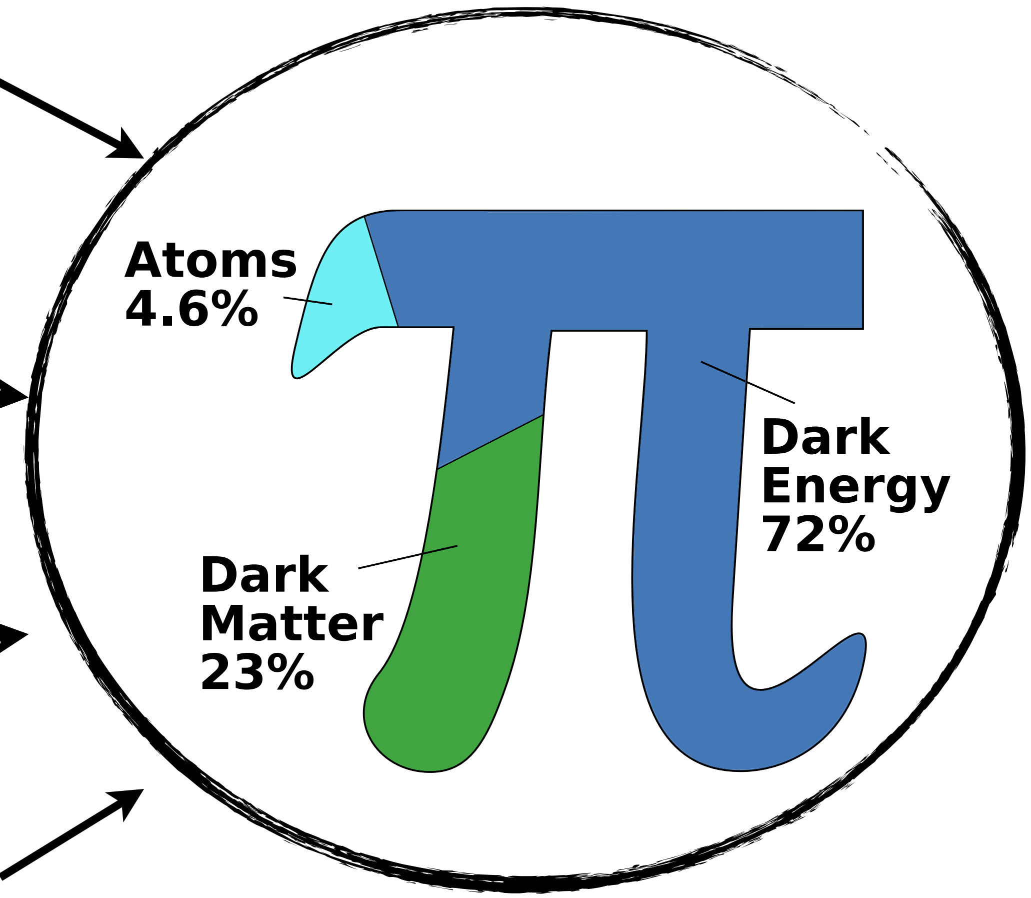
Dark
Energy??

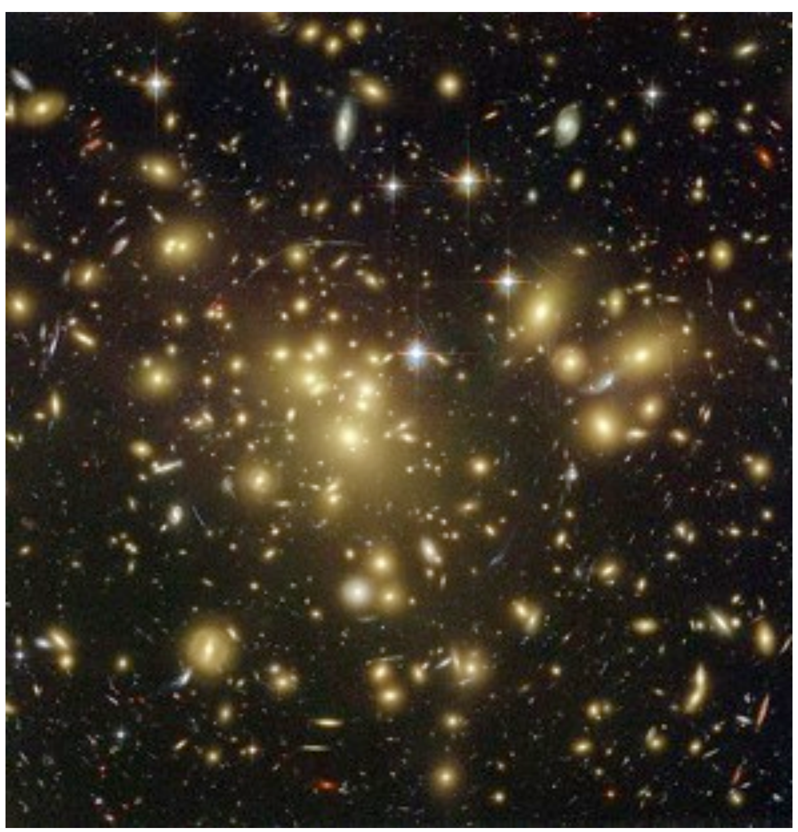
Outline

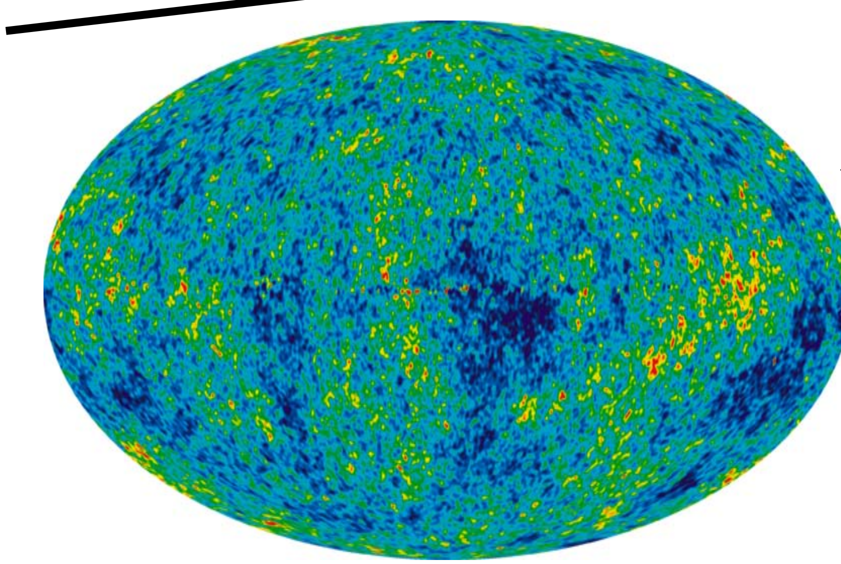
- Introduction
- XENON100 as a LXe TPC
- Measuring the scintillation response of LXe
- New results from XENON100
- Summary

Dark Matter: Evidences and Candidates





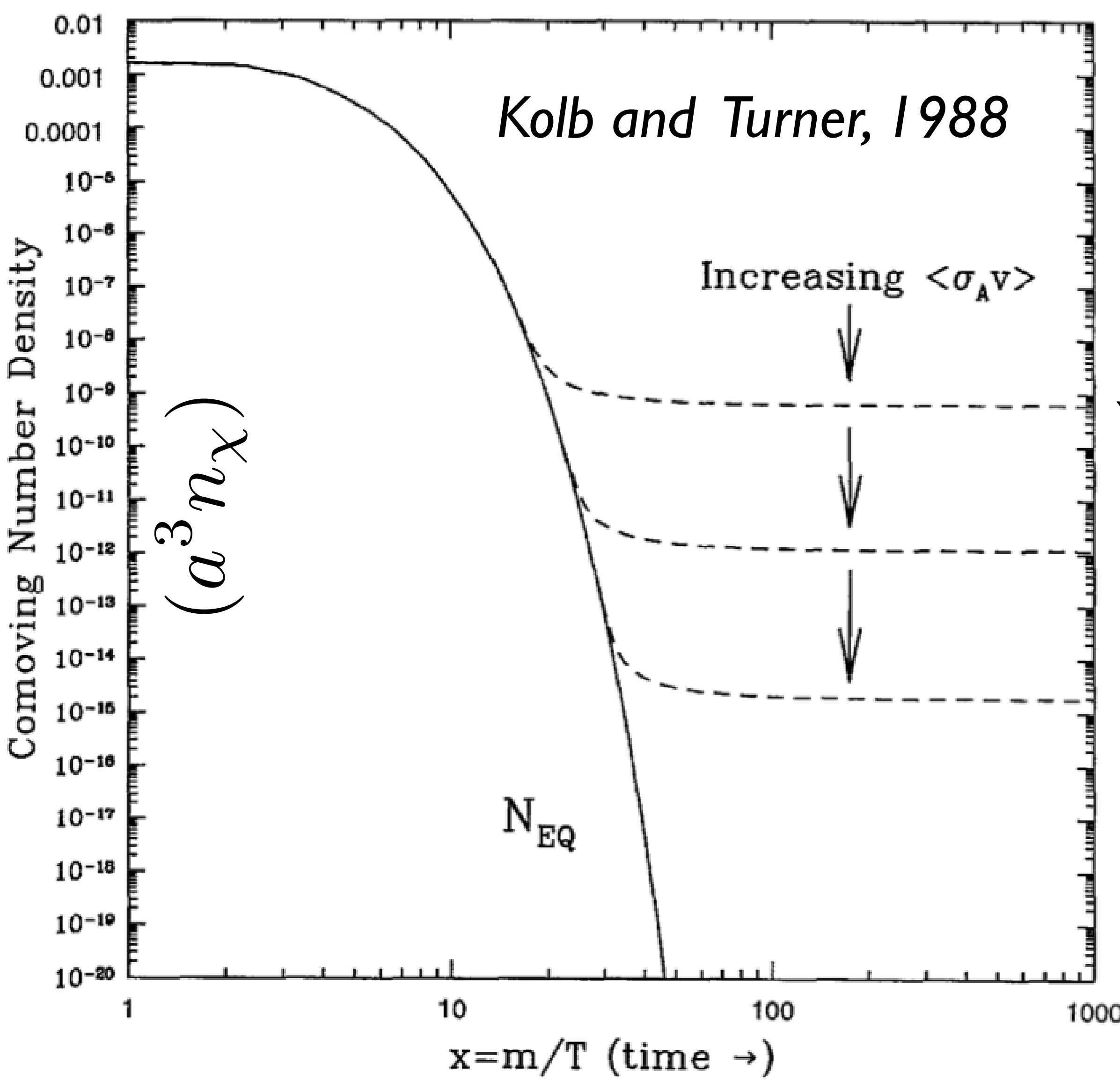




Axions, WIMPs, ...

WIMP Miracle

- Time evolution of the number density of WIMPs is given by



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle [(n_\chi)^2 - (n_\chi{}^{eq})^2]$$

depletion creation

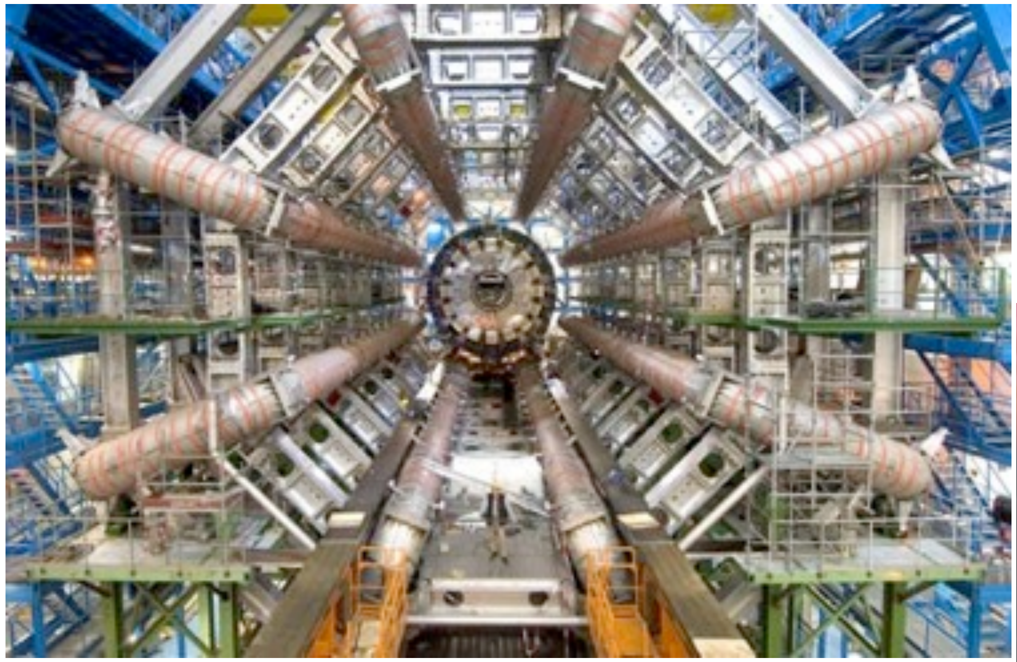
$\langle \sigma_A v \rangle$: $\chi\tilde{\chi} \to \mathrm{SM\ SM}$ (thermal average)

Freeze out when annihilation rate falls below expansion rate *H*

for weak-scale interaction of ~ 100 GeV ptl

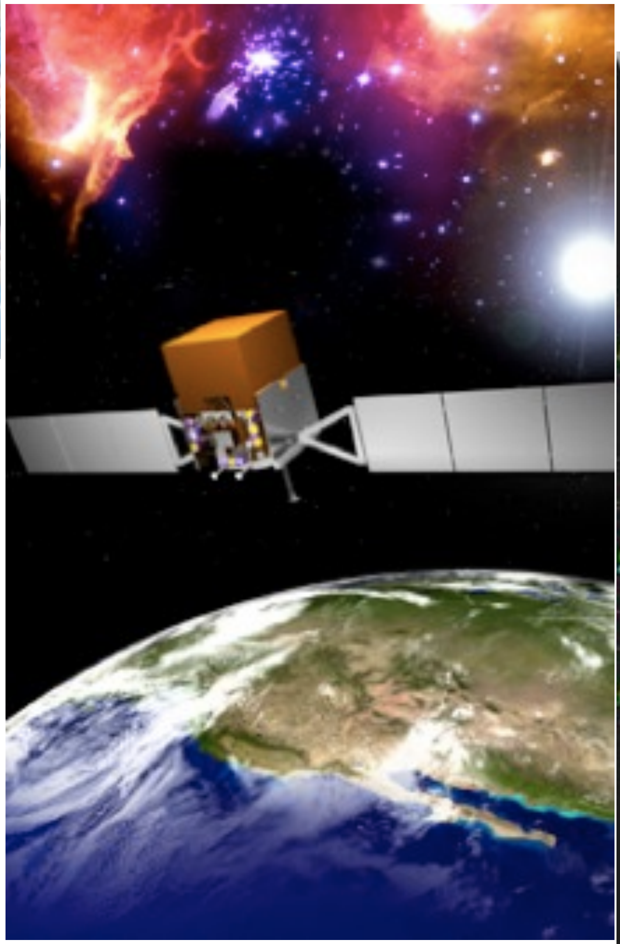
- Relic density of WIMPs Today: $\Omega_\chi h^2 \sim \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle} \sim \mathcal{O}(0.1)$

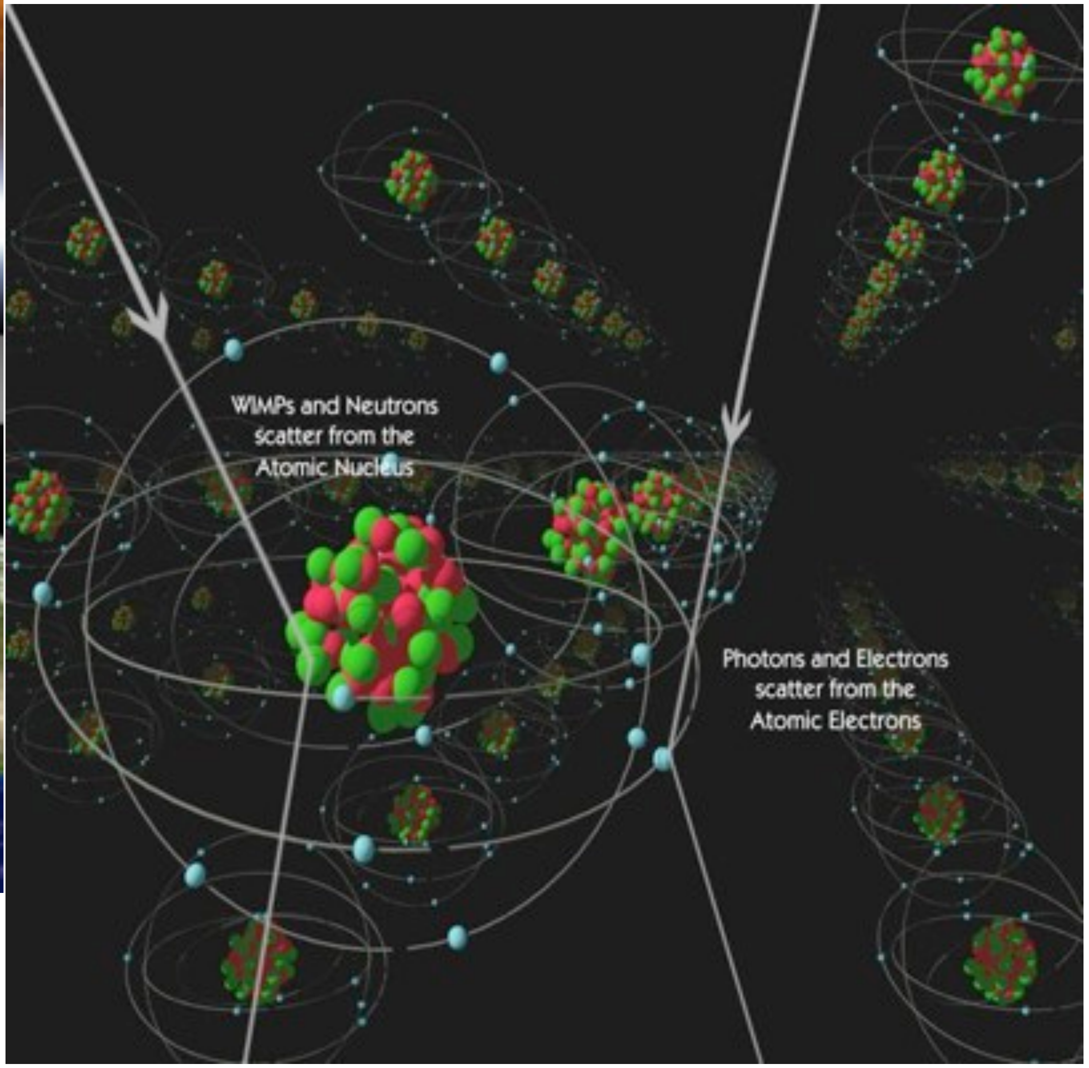
Strategies for WIMP Detection



PARTICLE COLLIDERS
: Produce and Detect WIMPs

INDIRECT DETECTION: *measure secondary particles from WIMP annihilation or decays in GC, in Sun, in MW (such as neutrinos, positrons, etc).*





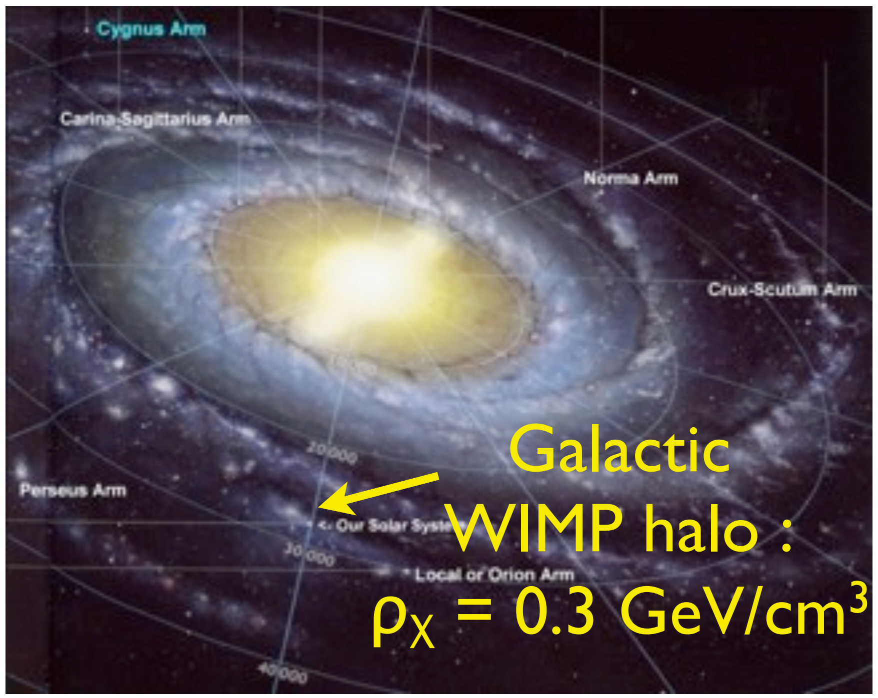
DIRECT DETECTION: *measure WIMP scattering off targets in detectors on Earth*

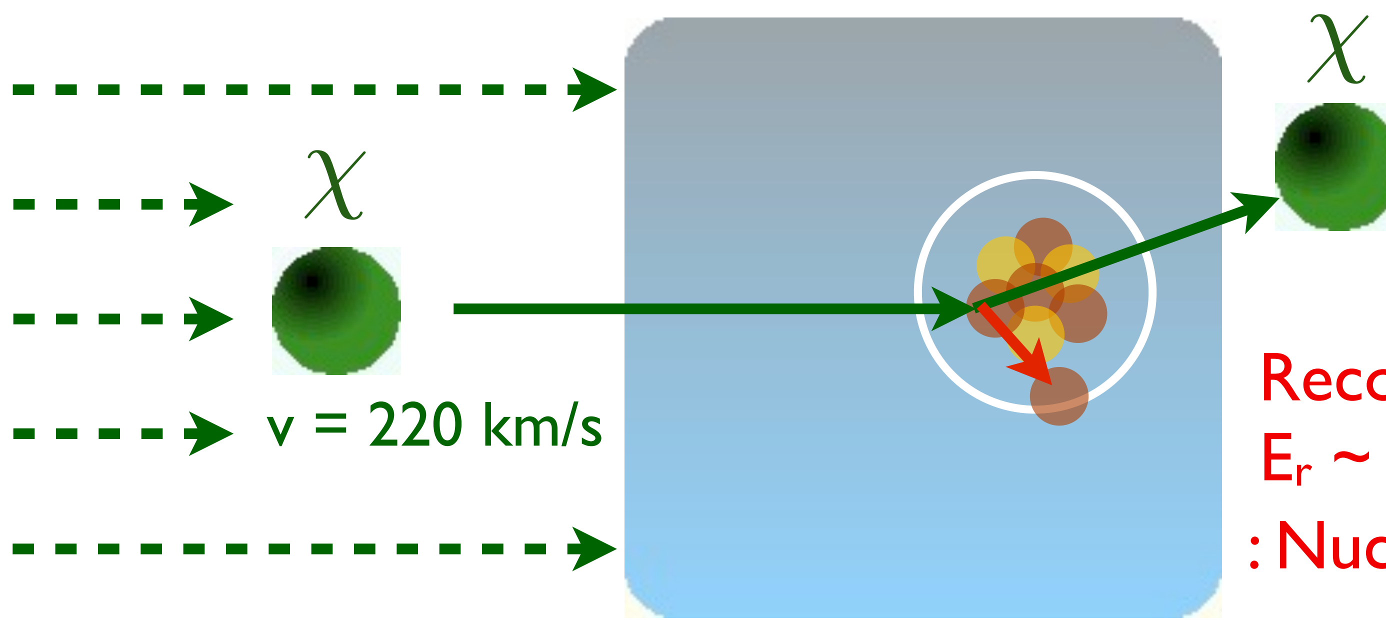
Potential for Breakthrough in coming decade:
WIMP models will be stringently probed by one or more methods

Principle of Direct Detection

Xe XENON Dark Matter Project

Goodman and Witten: Elastic Scattering of WIMPs off Target Nuclei (1985)





Recoil Nucleus
$E_r \sim \mathcal{O}$ (10 keV)
: Nuclear Recoil

Recoil Energy : $E_\mathrm{r} = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$

Expected Rate : $R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$

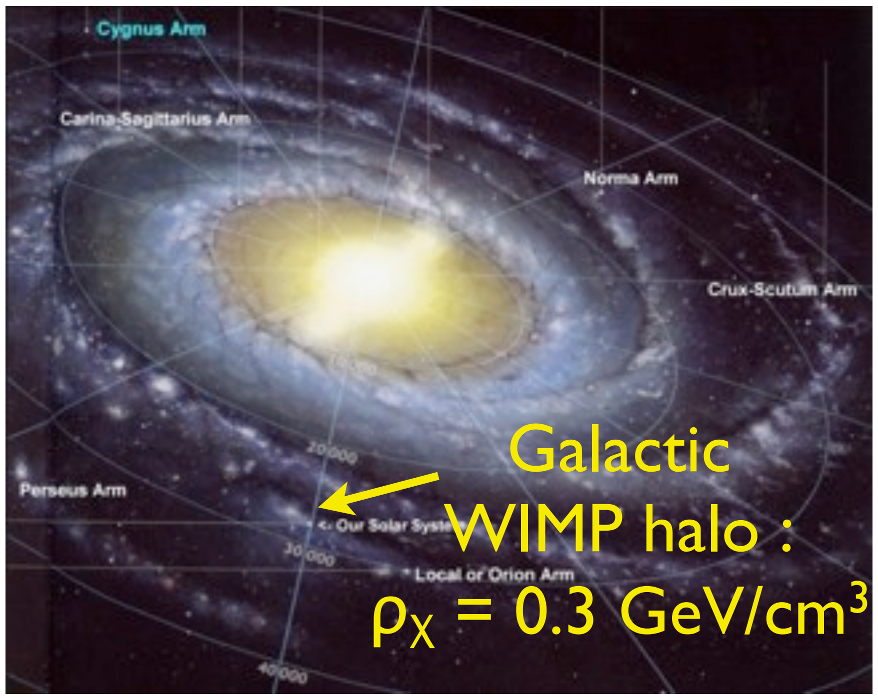
Astrophysics Input
(the local DM density at our position in galaxy)
(average WIMP velocity in the lab frame)

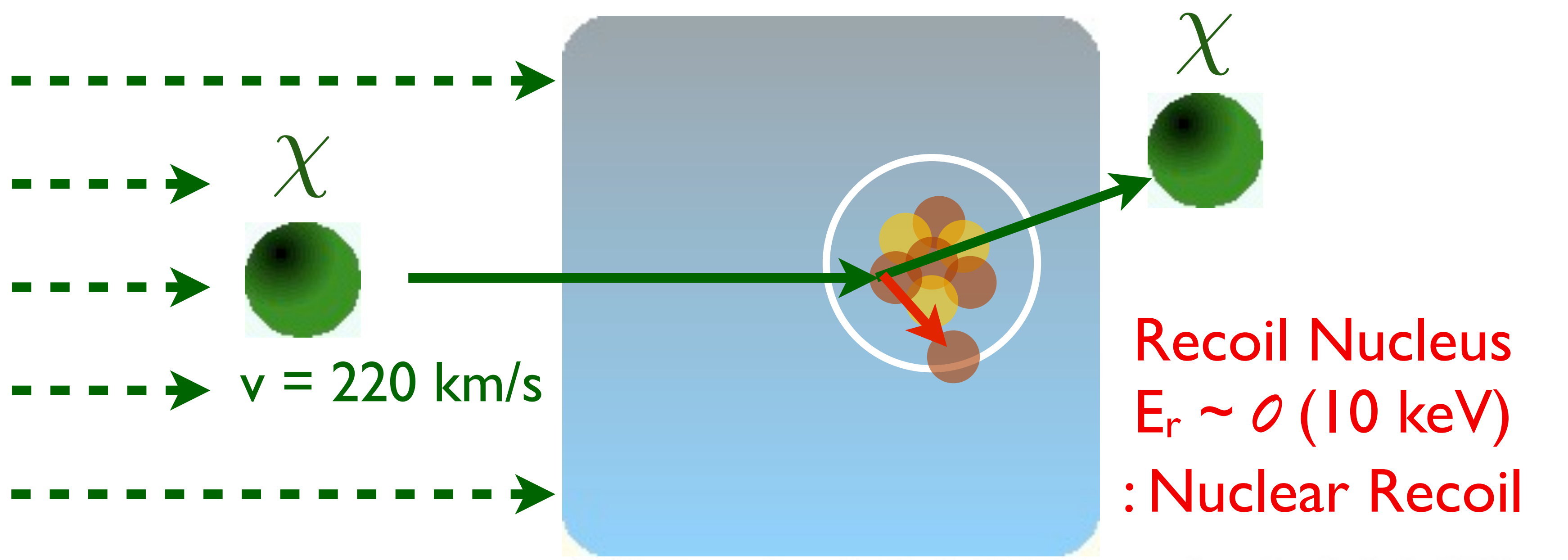
Detector Physics Input
(number of nuclei in target)

Particle Physics Input
(WIMP-nucleus elastic scattering cross section)
(WIMP mass)

Principle of Direct Detection

Goodman and Witten: Elastic Scattering of WIMPs off Target Nuclei (1985)

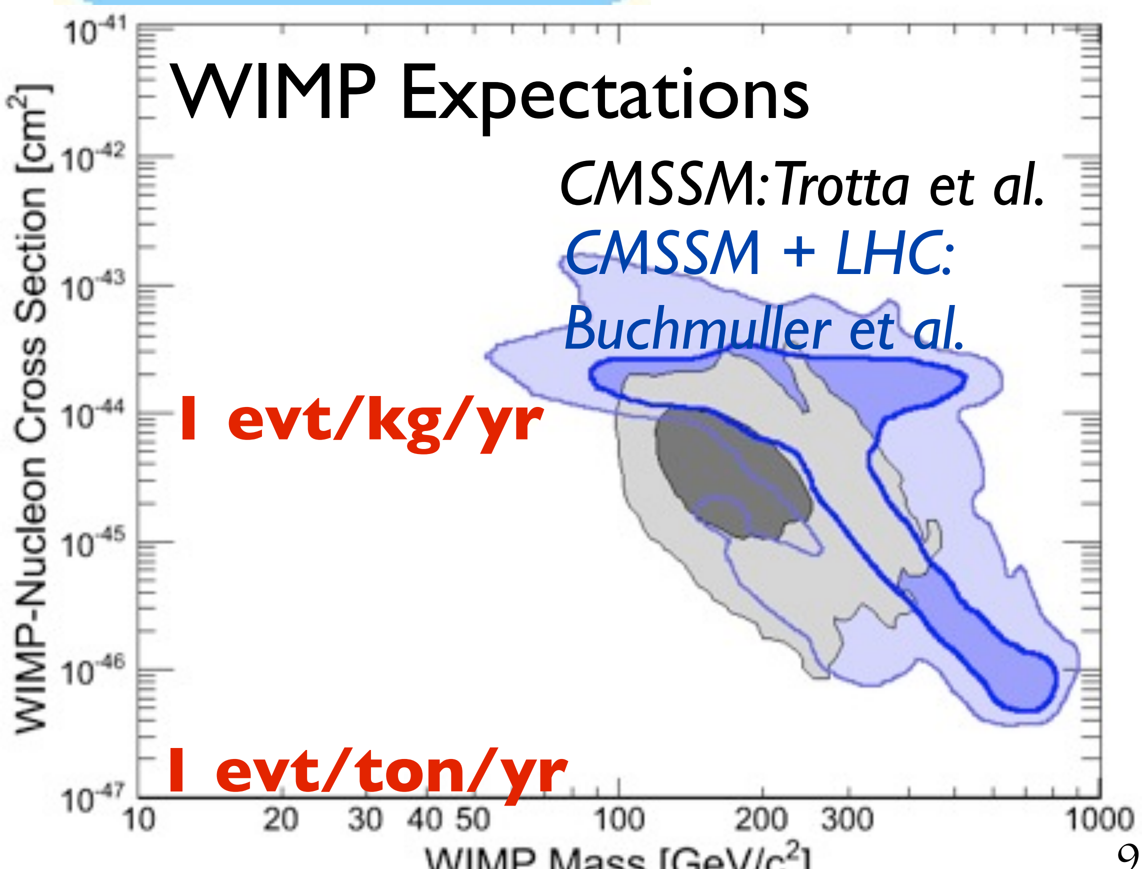




Recoil Energy : $E_{\rm r} \sim \mathcal{O}(10 \text{ keV})$

Expected Rate : $R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$

Tiny Rate!



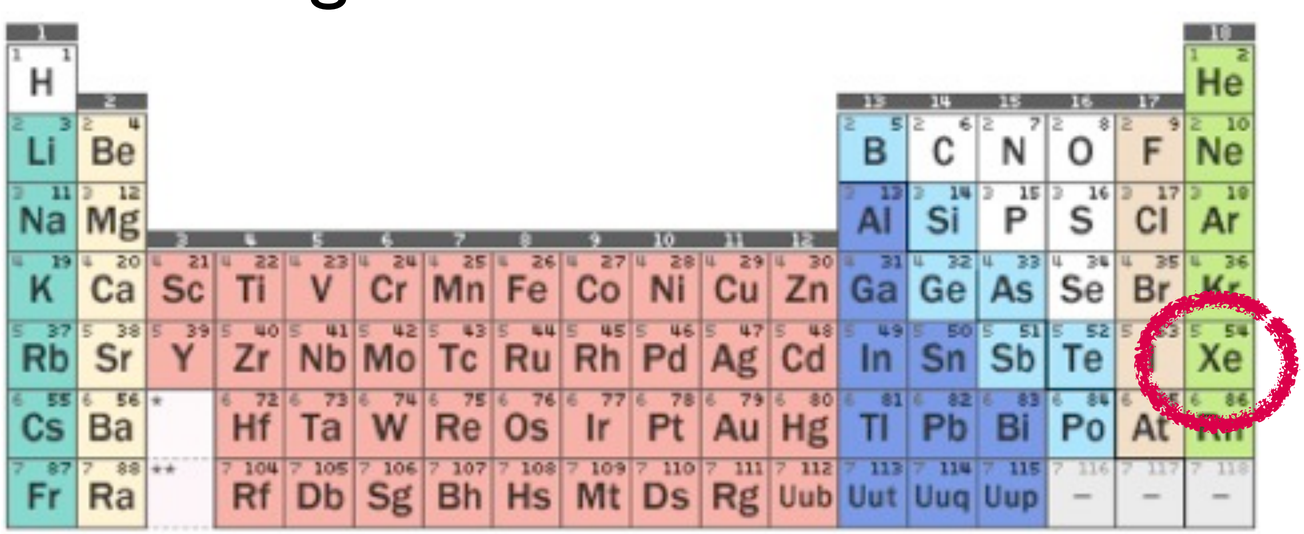
Principle of Direct Detection

Xe XENON Dark Matter Project

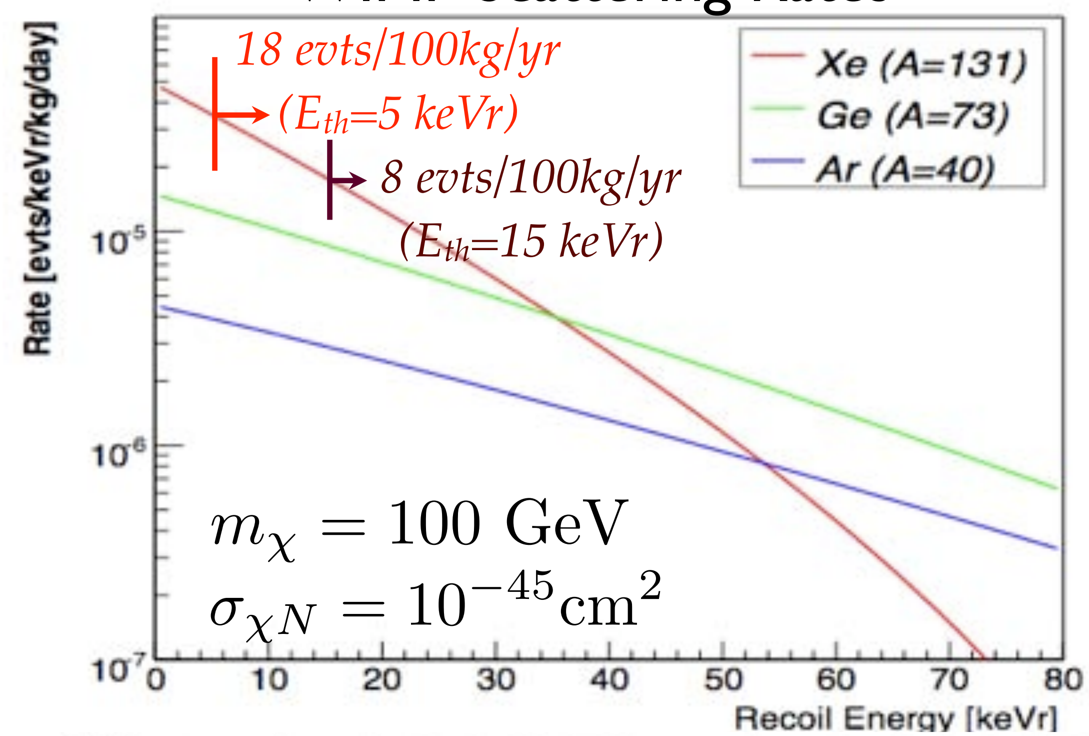
Summary:
Exponentially Falling
Tiny Rates

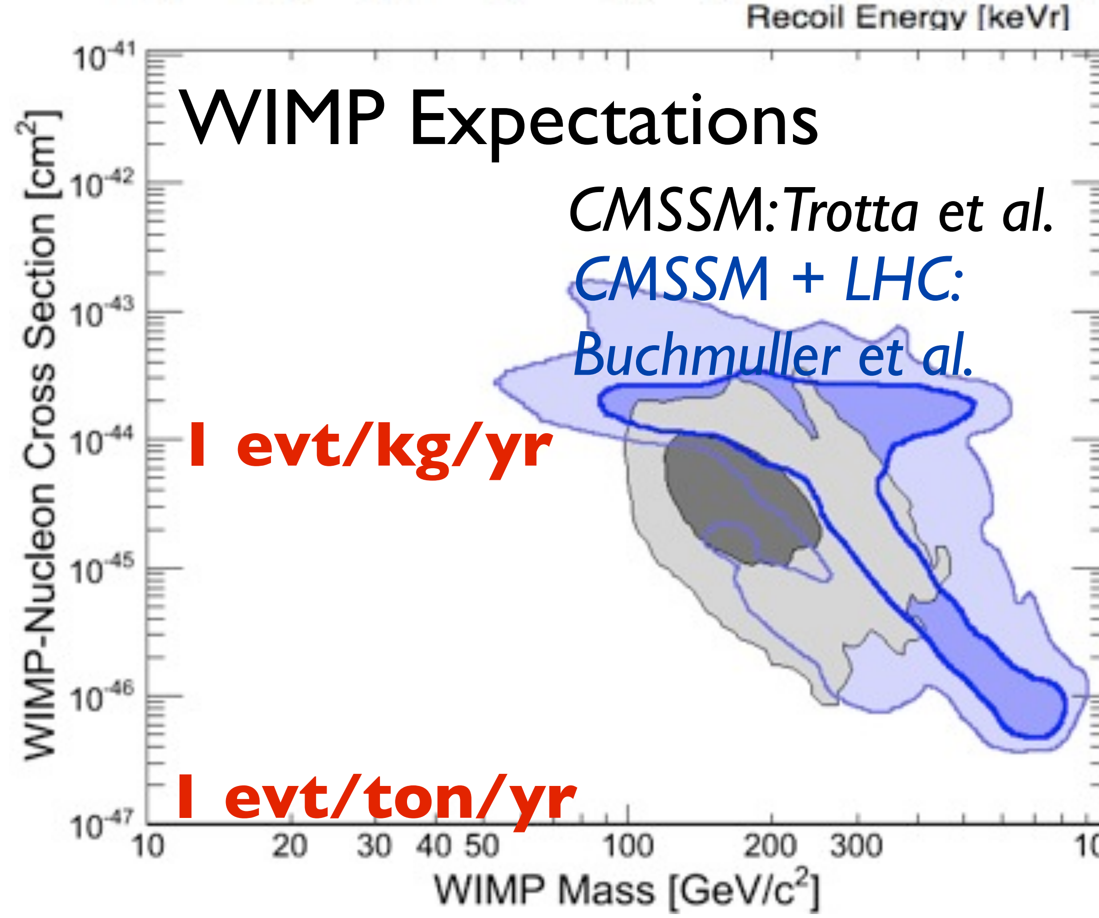
Detector Building Strategies

- Large total mass
- Low energy threshold
- Ultra-low background
- Background discrimination



WIMP Scattering Rates





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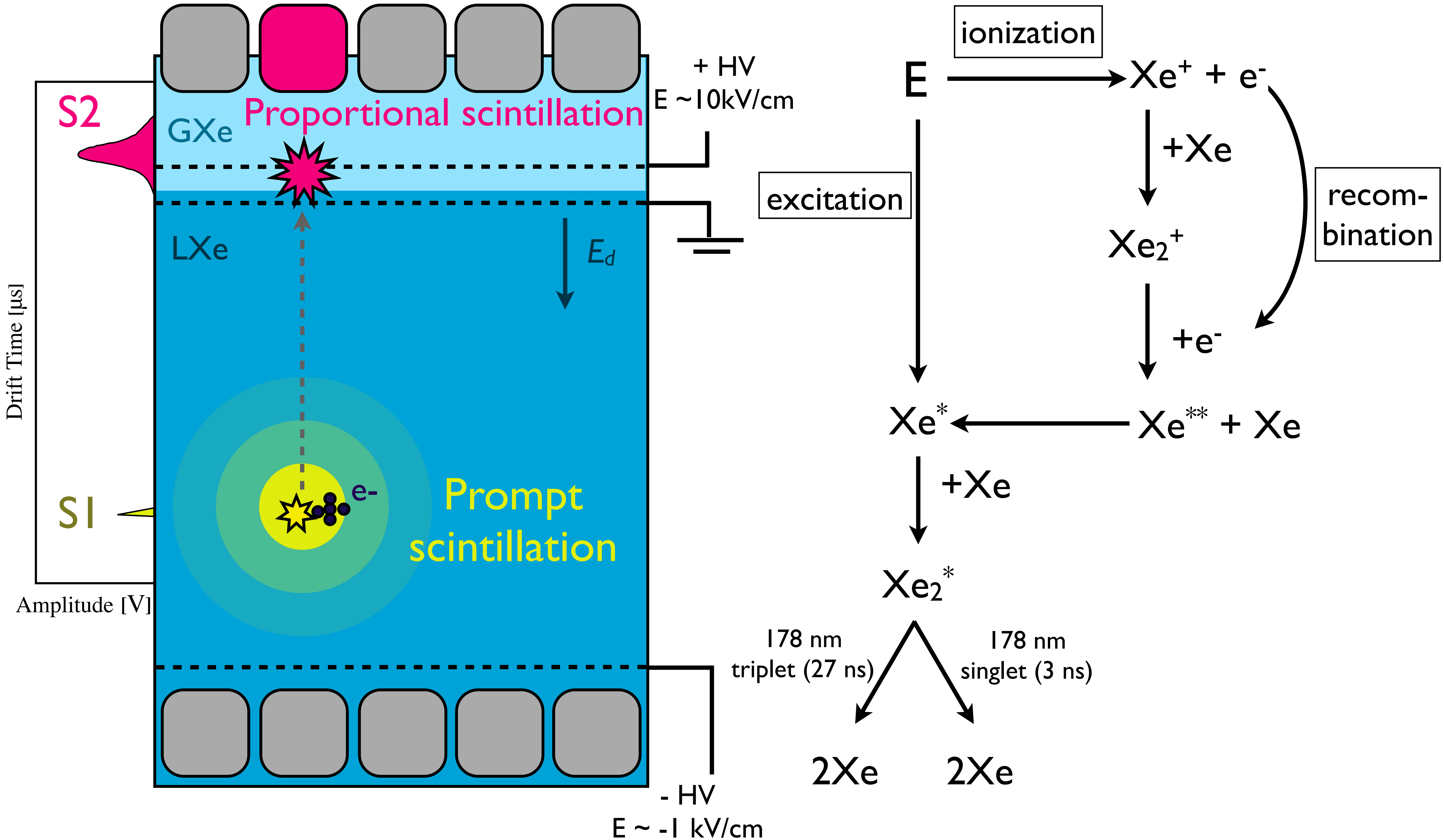
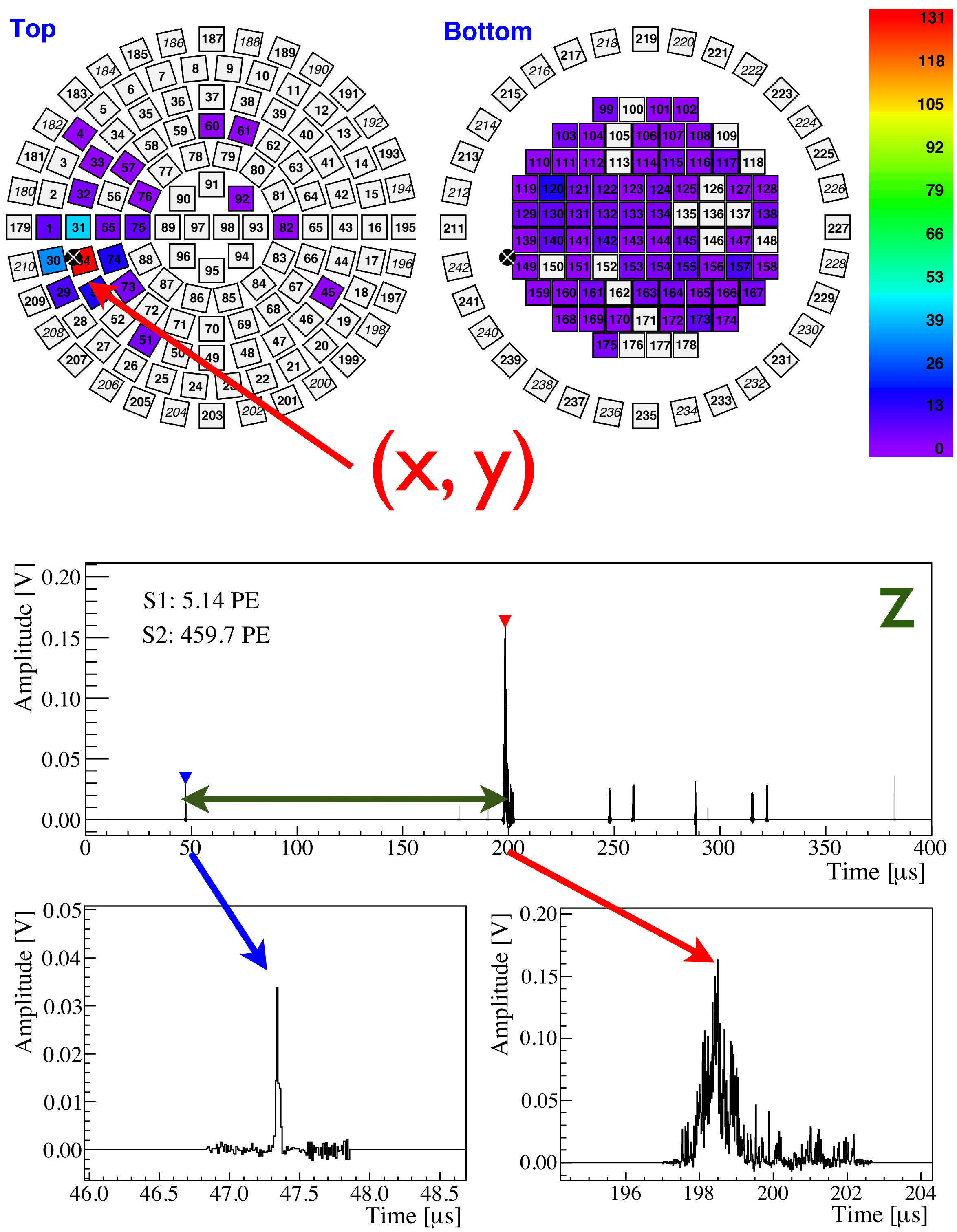
Dual-phase (Liquid-gas) LXe TPC



Proportional Scintillation (S2)

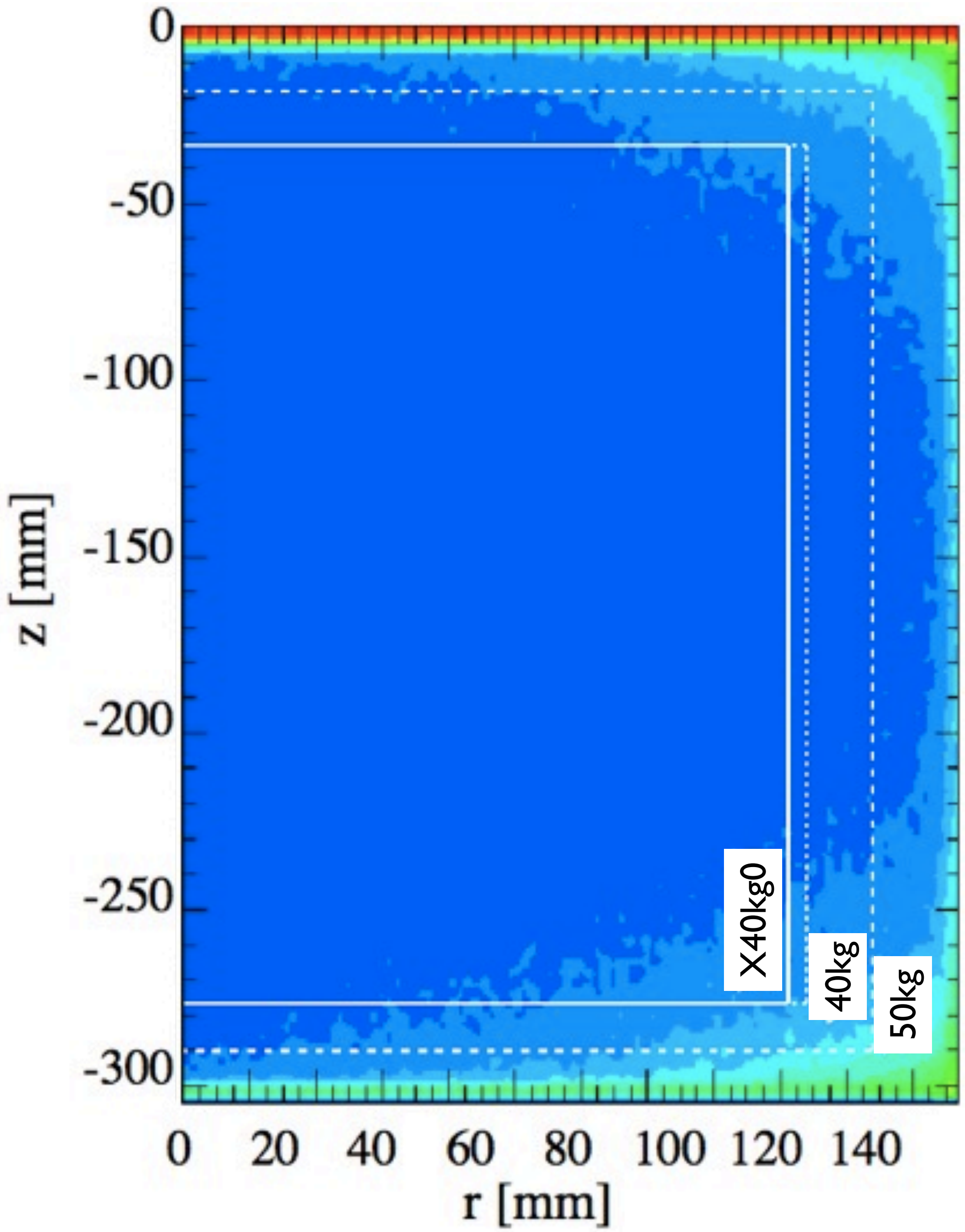


- Drifted electrons from ionization are amplified in the gas gap btw gate grid and anode, and produce proportional scintillation (S2).
- Due to the amplification, S2 signal size is much larger than prompt scintillation (S1), lower energy threshold than S1.
- Simultaneous measurements of both S2 and S1 provides z position of the particle interaction.
- S2 pmt hit pattern is used to (x,y) position reconstruction.

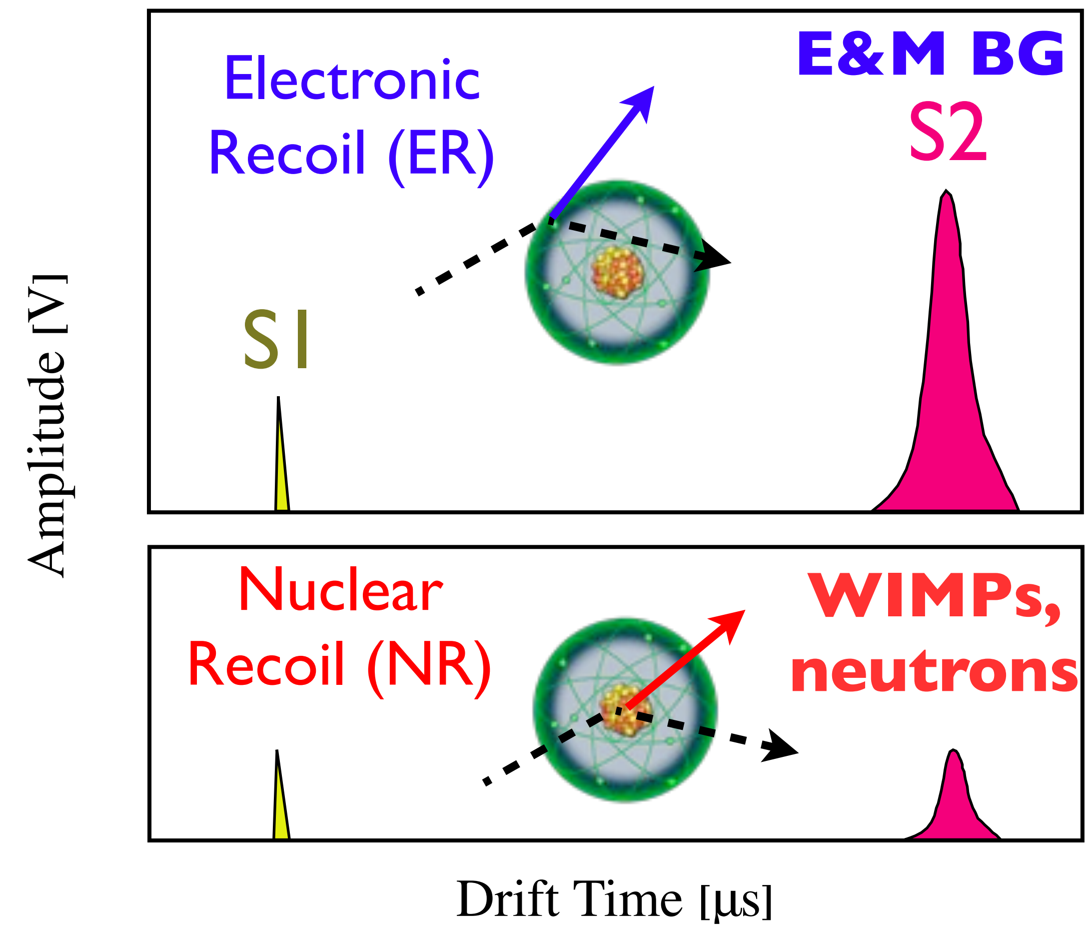
3D vertex reconstruction

Background Suppression in the LXe TPC

Fiducialization



S/B Discrimination



$(S2/S1)_{WIMPs,\,n} \ll (S2/S1)_{\gamma,\beta}$

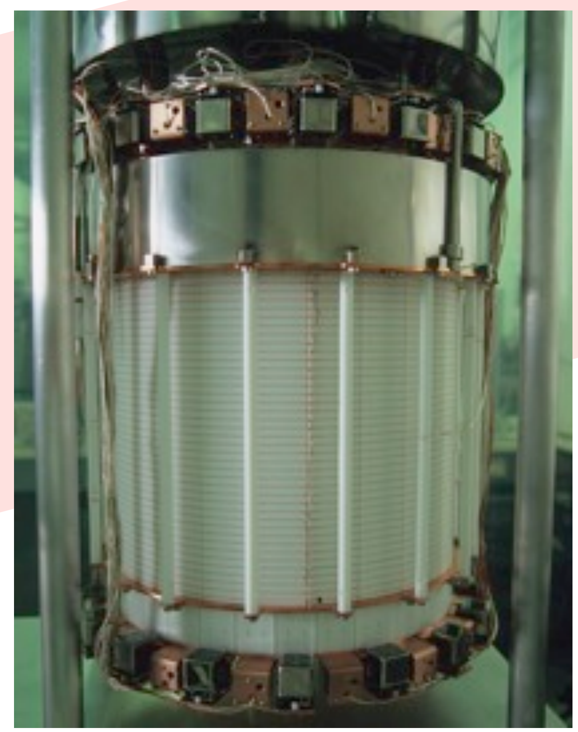
The XENON Dark Matter Search

XENON:
A phased WIMP search program

XENON10
(2005-2007)

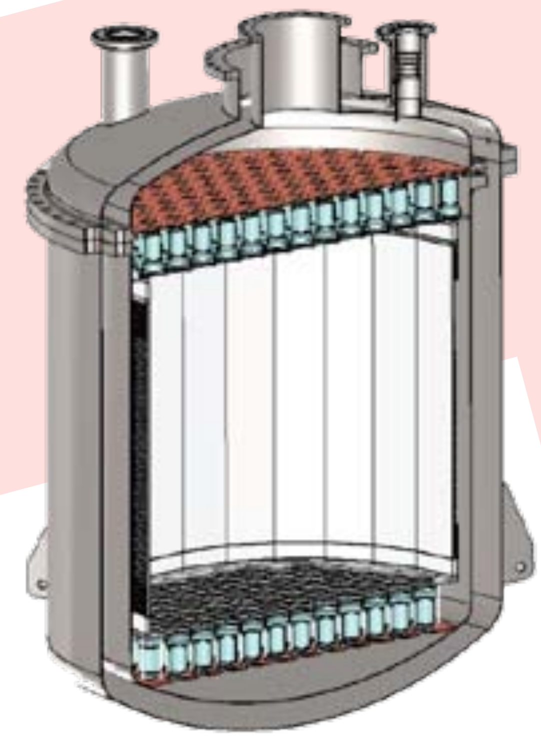
Achieved (2007)
$\sigma_{SI} = 8.8 \times 10^{-44}\ \mathrm{cm}^2$

XENON100
(2008-2013)



Achieved (2012)
$\sigma_{SI} = 2.0 \times 10^{-45}\mathrm{cm}^2$

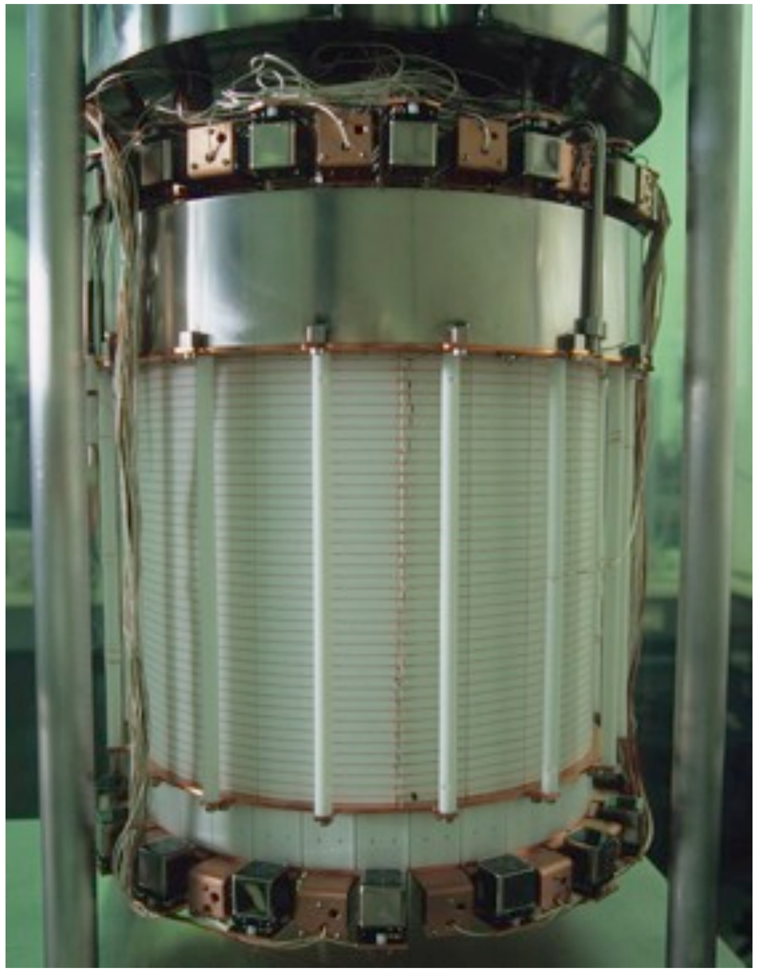
XENON1T
(2012-2017)



Projected (2015)
$\sigma_{SI} < 10^{-47}\ \mathrm{cm}^2$

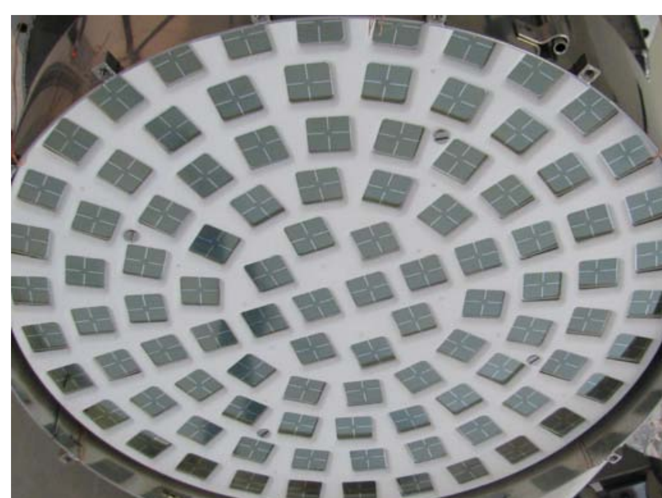
The XENON Collaboration

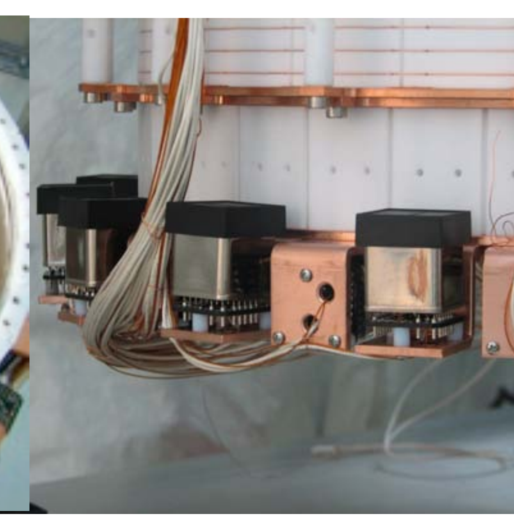
The XENON100 Detector



- Designed to be x100 less background and x10 fiducial target compared to XENON10
- Cryocooler and FTs outside shield
- Materials screened for low activity
- 30 cm drift x 30 cm diameter TPC
- 162 kg ultra-pure LXe (target+veto)
- Multilayer passive shield
- For details, see Aprile *et al*., Astropart. Phys. 35, 573, 2012

- Active veto all around the target
- 242 PMTs: 1 mBq (U/Th) w/ 30% QE





XENON100 at LNGS

Outline

- Introduction
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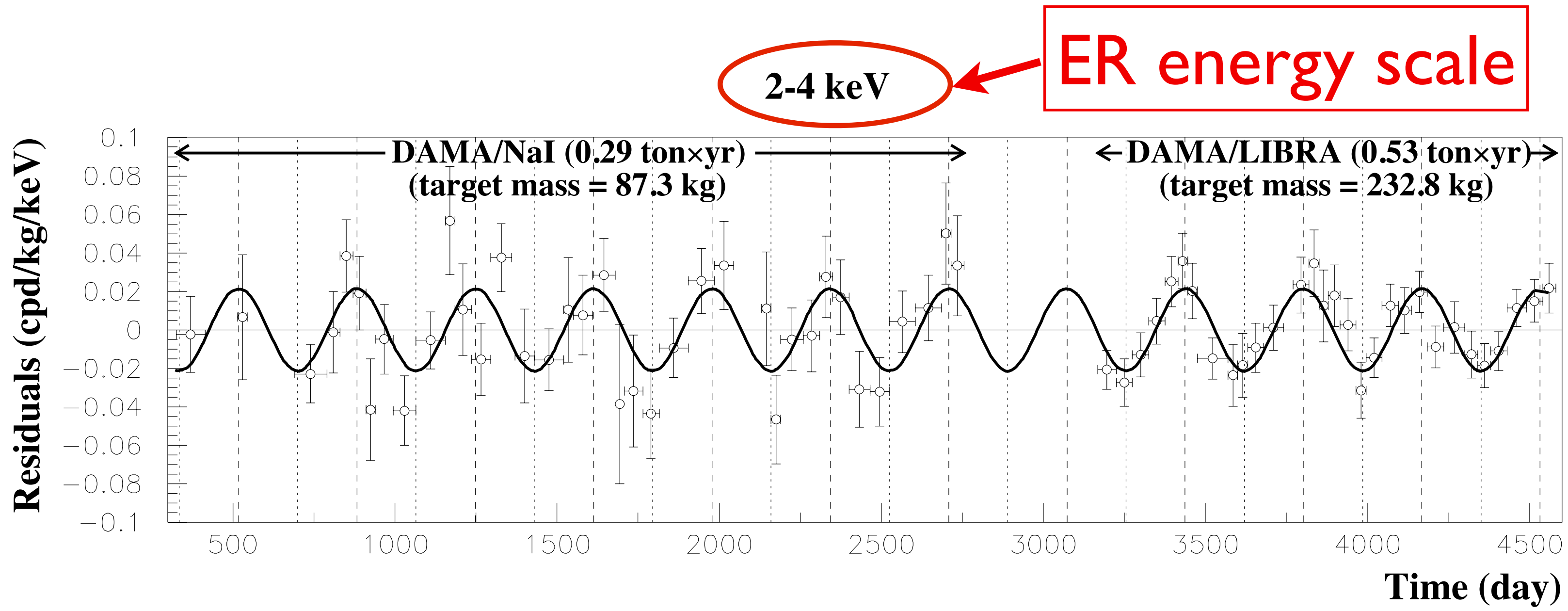
Energy Calibration of XENON100

- Scintillation/ionization response of LXe depends on the electronic stopping power for the recoil type, its energy, and the strength of electric field (NR energy scale is different from ER energy scale).
- Understanding the behavior of single elastic NRs in LXe is essential since WIMPs are expected to elastically scatter off of Xe nuclei.
- Understanding the ER response in LXe is important for the interpretation of the dark matter results such as annual modulation and the estimation of ER background contribution.



Bernabei *et al.*, Eur. Phys. J. C56, 333, 2008

Nuclear Recoil Equivalent Energy

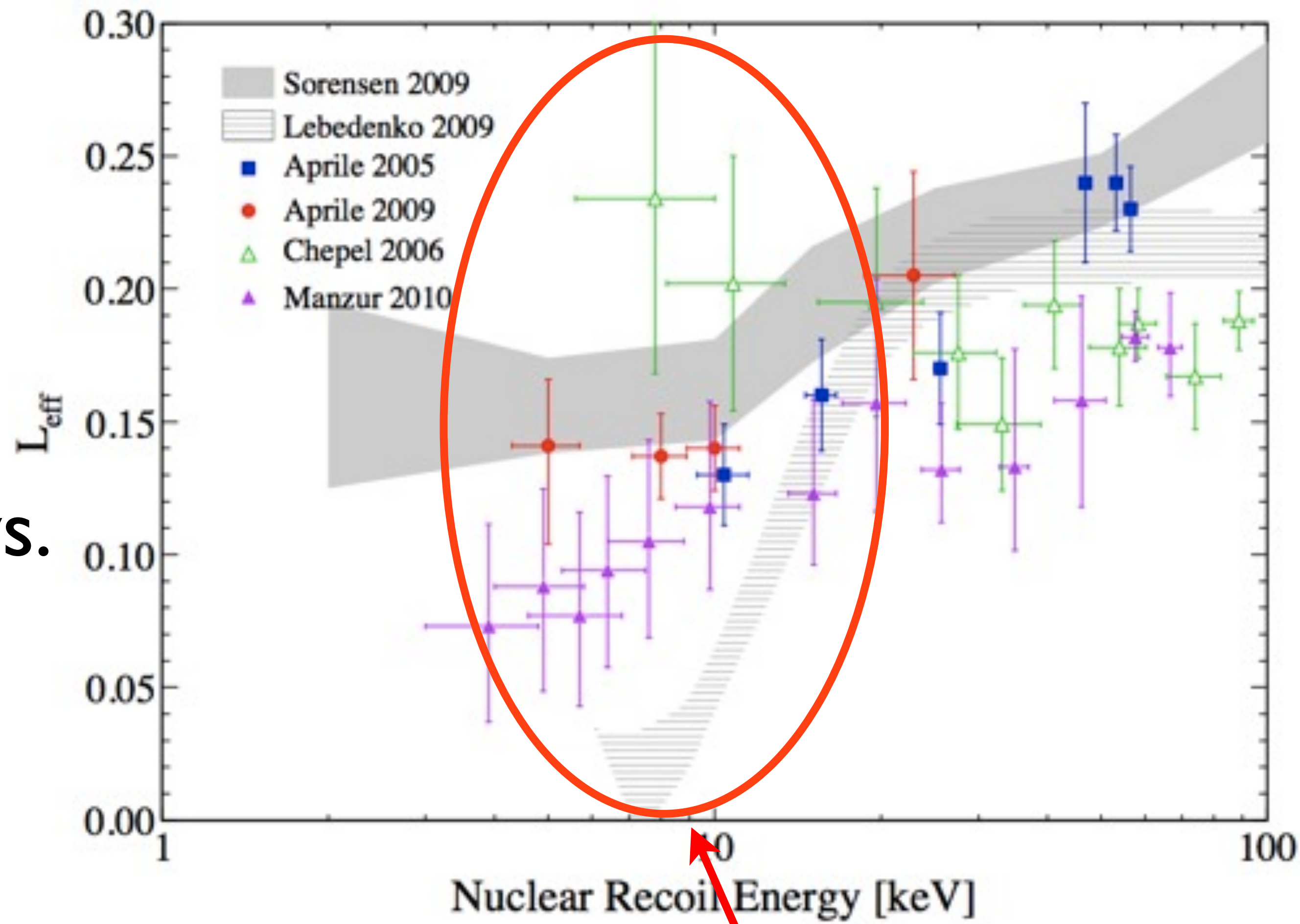
- Nuclear recoil equivalent energy (E_{nr}) is obtained from S1 signal.

$$E_{\rm nr} = \frac{S1}{L_y}\frac{1}{\mathcal{L}_{\rm eff}}\frac{S_e}{S_r}$$

- L_y is light yield of electronic recoils from 122 keV photo-absorbed γ rays.
- S_e, S_r, Scintillation light quenching due to drift field.
- $\mathcal{L}_{\rm eff}$, Relative Scintillation Efficiency

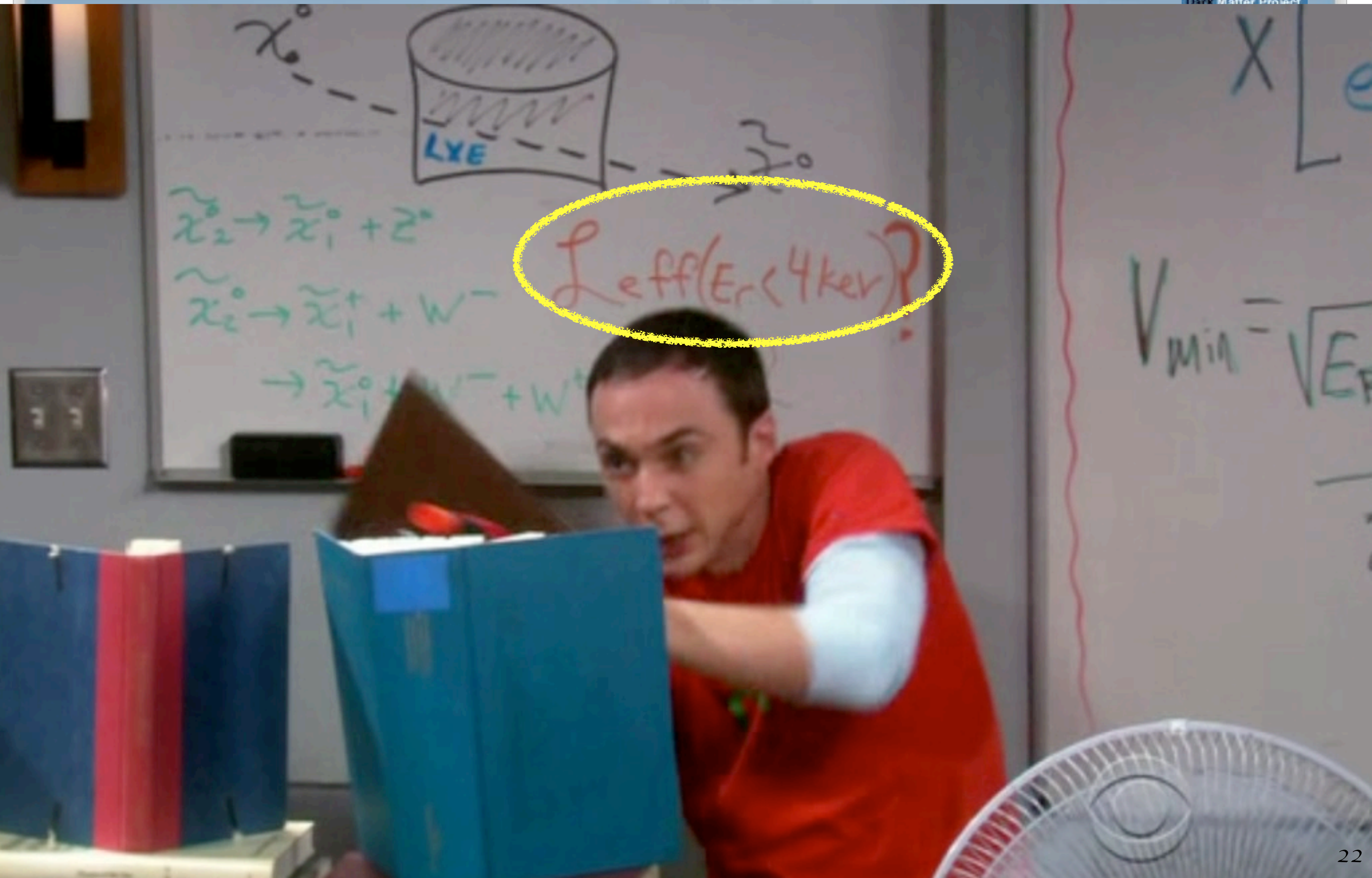
$$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{L_{y,\rm nr}(E_{\rm nr})}{L_{y,\rm er}(E_{\rm ee} = 122\ \rm keV)}$$

$\mathcal{L}_{\rm eff}$ status in **2010**



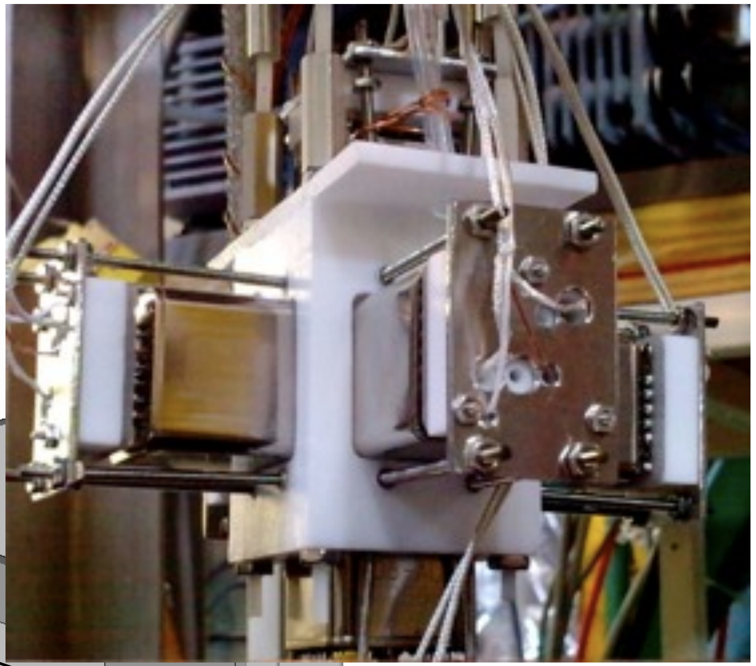
Measurements at low energies were inconsistent!

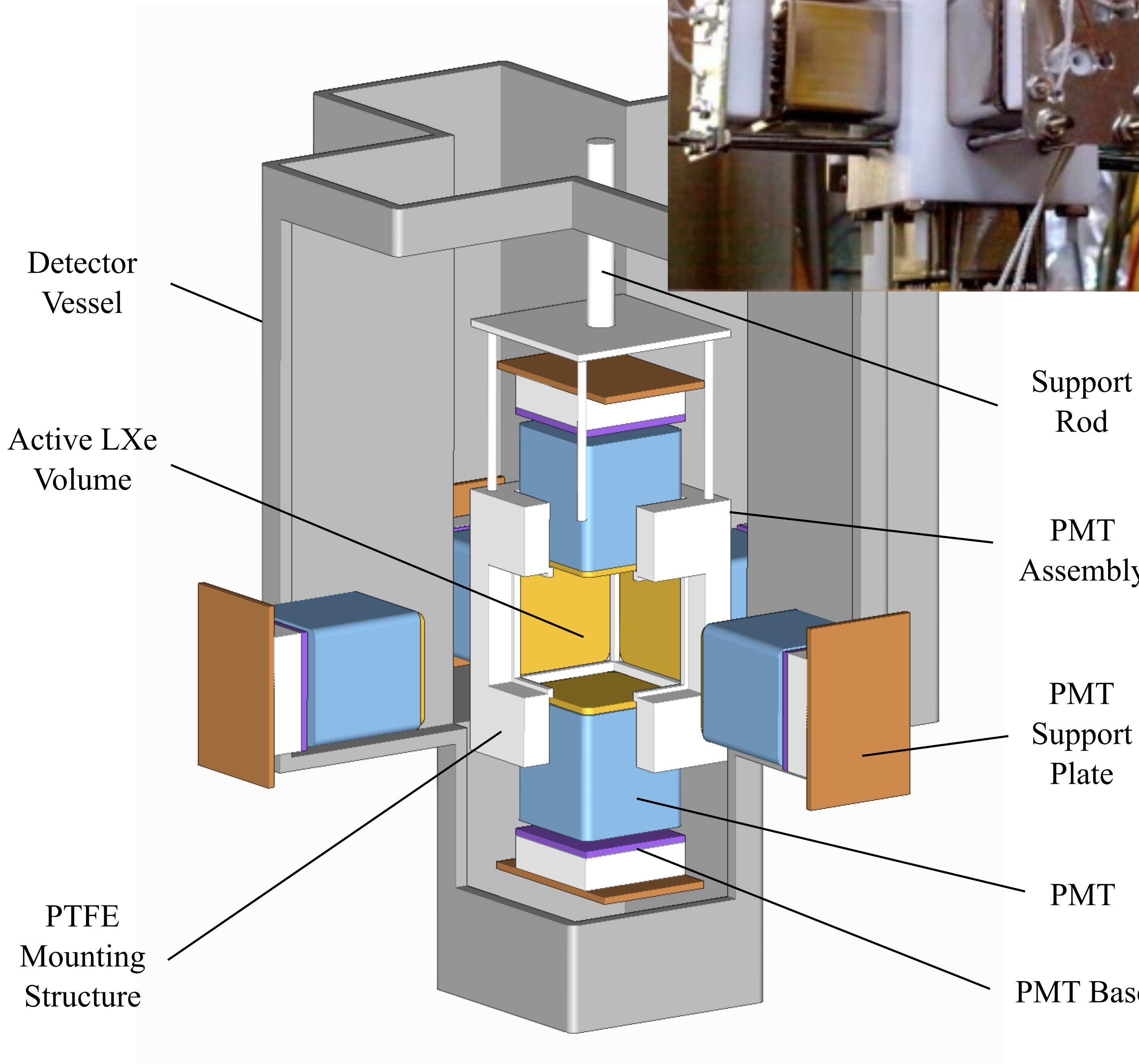
Sheldon was also curious about $\mathcal{L}_{eff}$



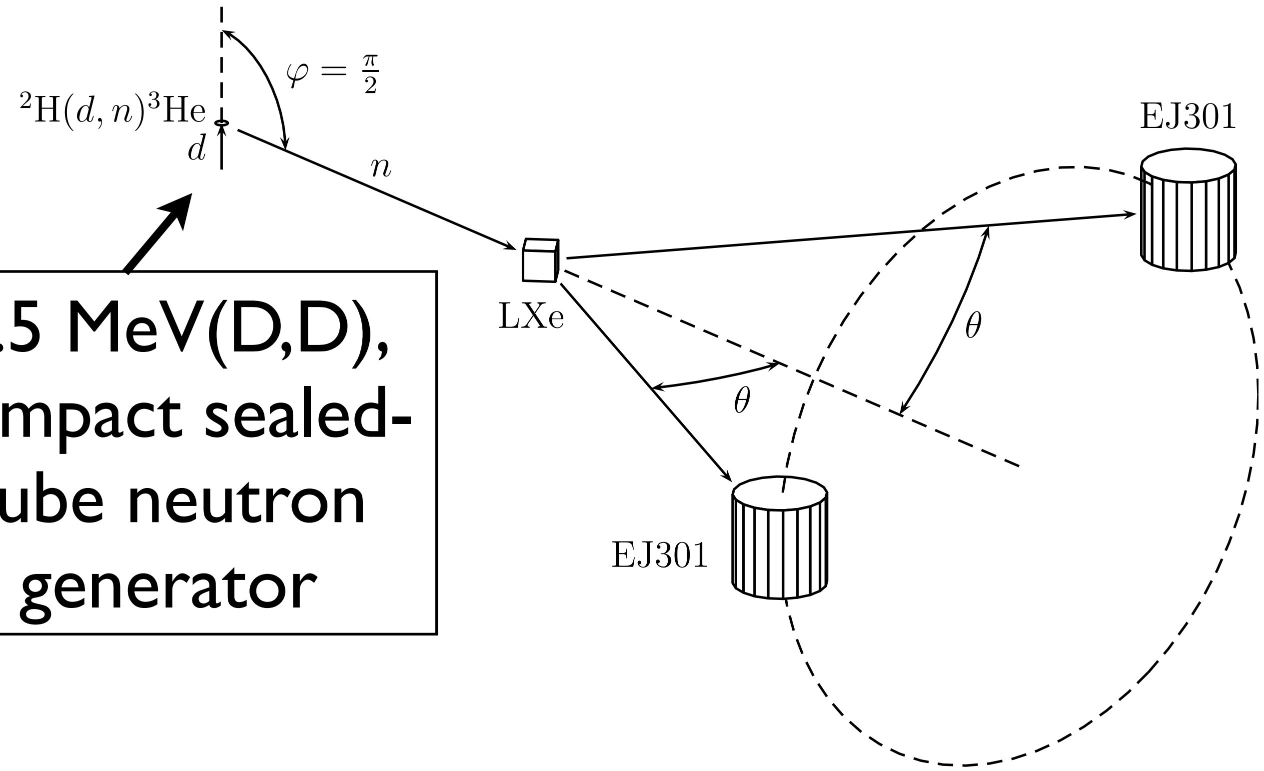
LXe Detector for Low Energy Particles

- Six 2.5 x 2.5 cm Hamamatsu R8520-406 SEL High QE PMTs (~ 30%)
- Maximize light collection efficiency by covering the target volume with PMTs: low energy threshold
- Minimize adjacent materials to suppress background from multiple scatters.

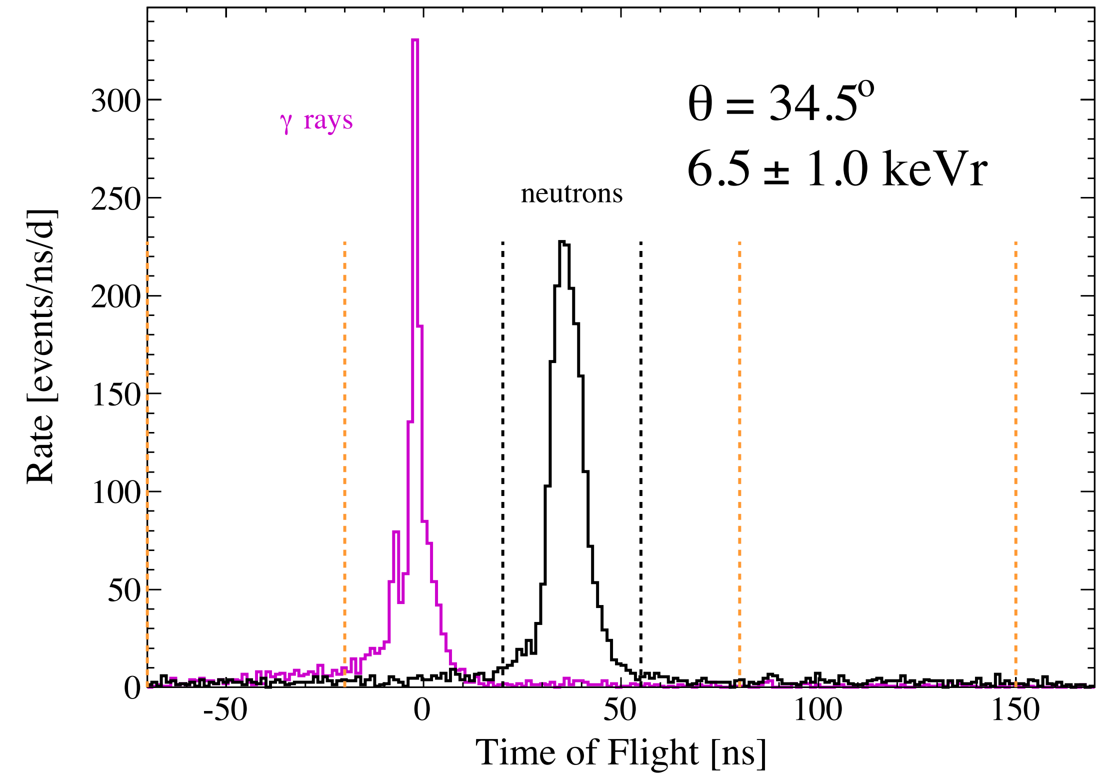




New Measurement of $\mathcal{L}_{\mathrm{eff}}$: Setup



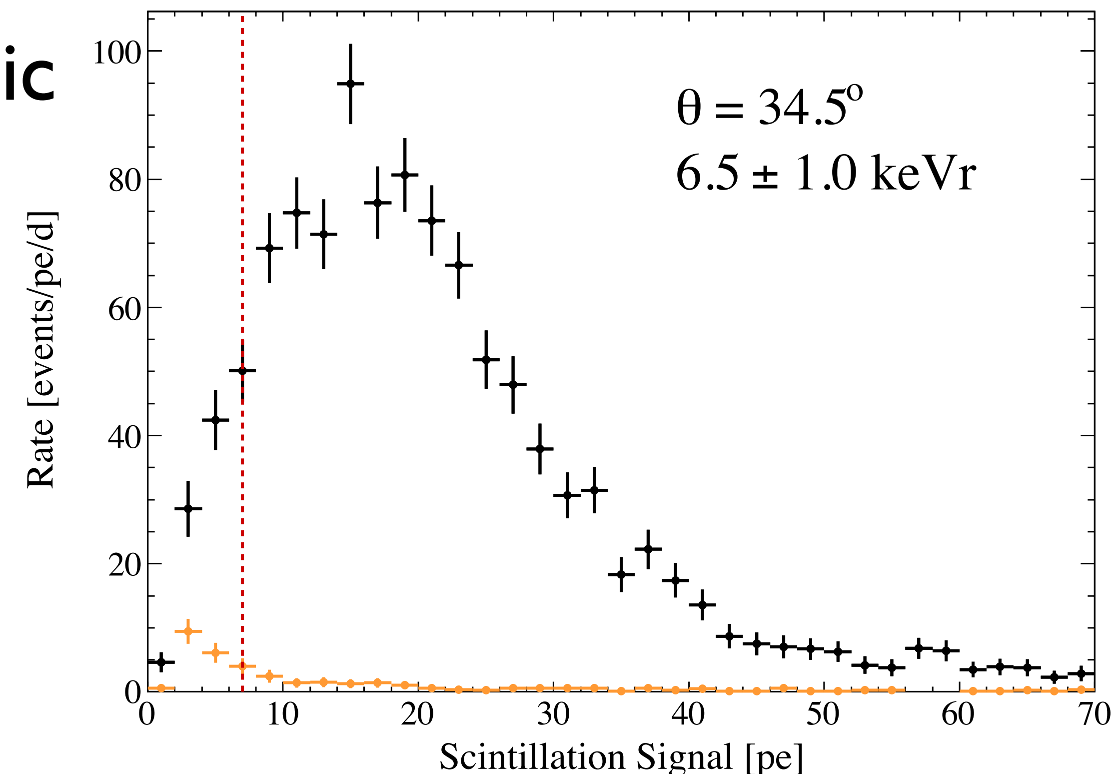
2.5 MeV(D,D), compact sealed-tube neutron generator



- Record fixed-angle elastic scatters of mono-energetic neutrons tagged by organic liquid scintillators with n/γ discrimination.

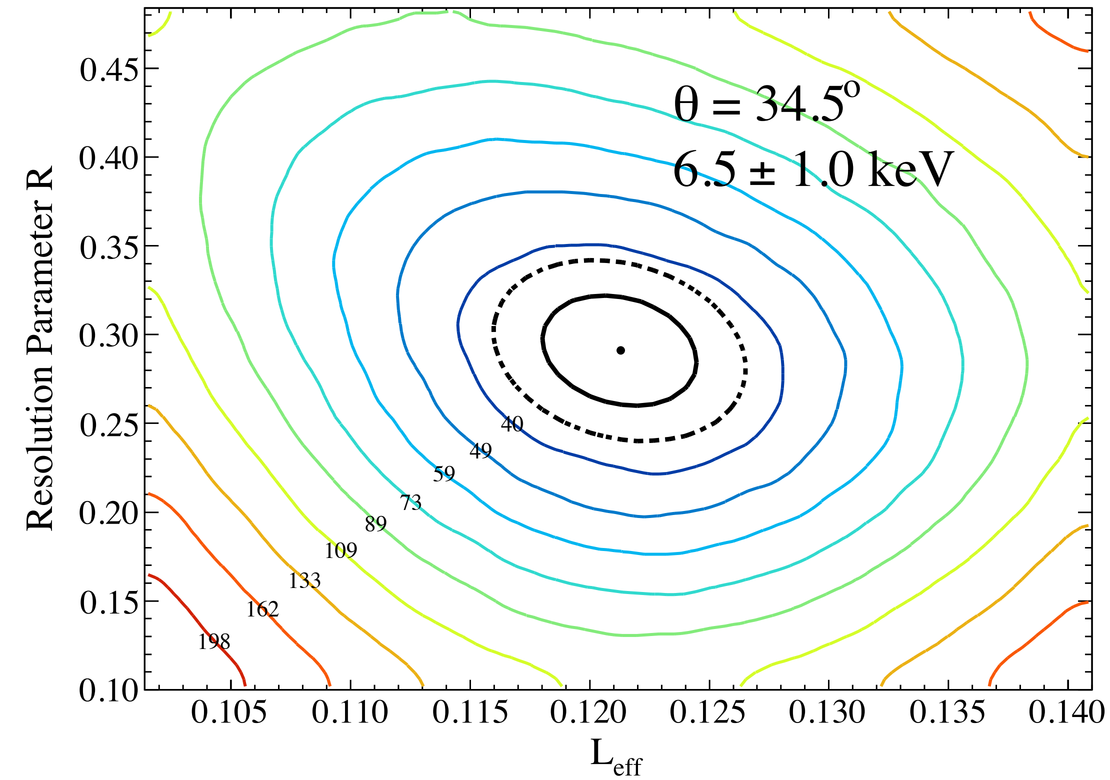
- Recoil Energy is fixed by kinematics

$$E_{\mathrm{r}} \approx 2E_n \frac{m_n M_{\mathrm{Xe}}}{(m_n + M_{\mathrm{Xe}})^2}(1 - \cos\theta)$$



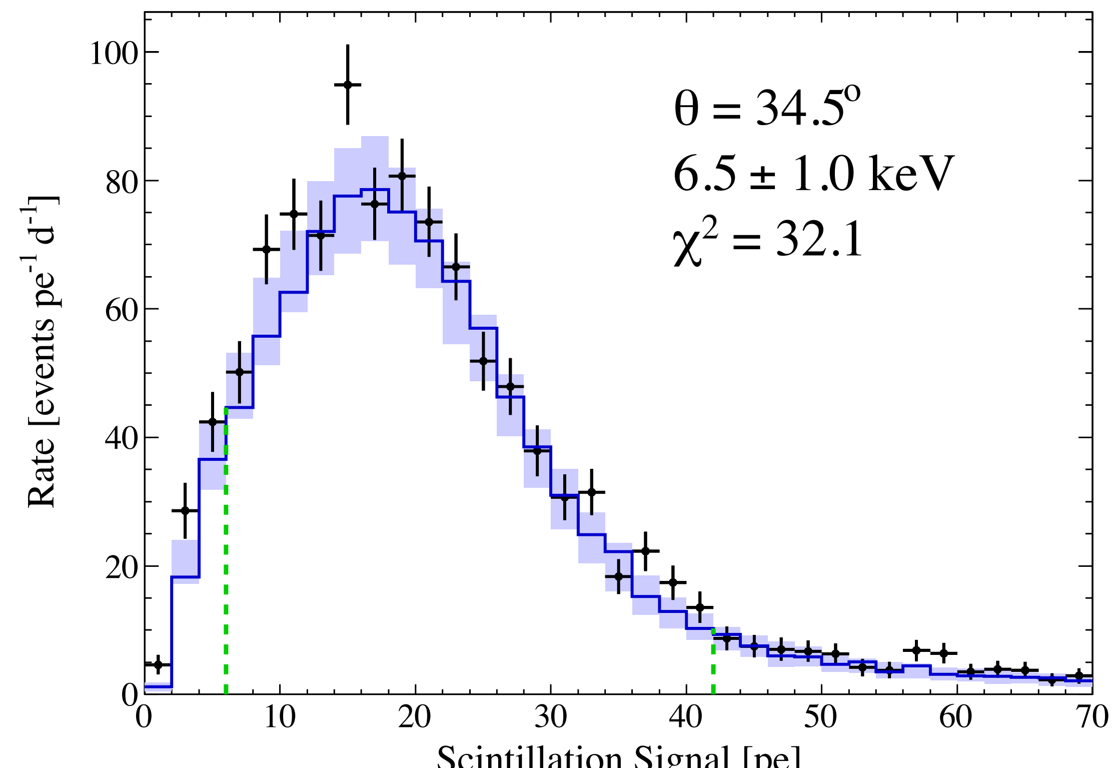
New Measurement of $\mathcal{L}_{eff}$: Extracting $\mathcal{L}_{eff}$

- Transform the MC recoil spectrum into a simulated spectrum *g* using $S1 = L_y \cdot \mathcal{L}_{\mathrm{eff},j} \cdot E_{\mathrm{r}}$, with gaussian energy resolution $\sigma = R\sqrt{E_{\mathrm{r}}}$, PMT gain fluctuations and applying trigger efficiency.

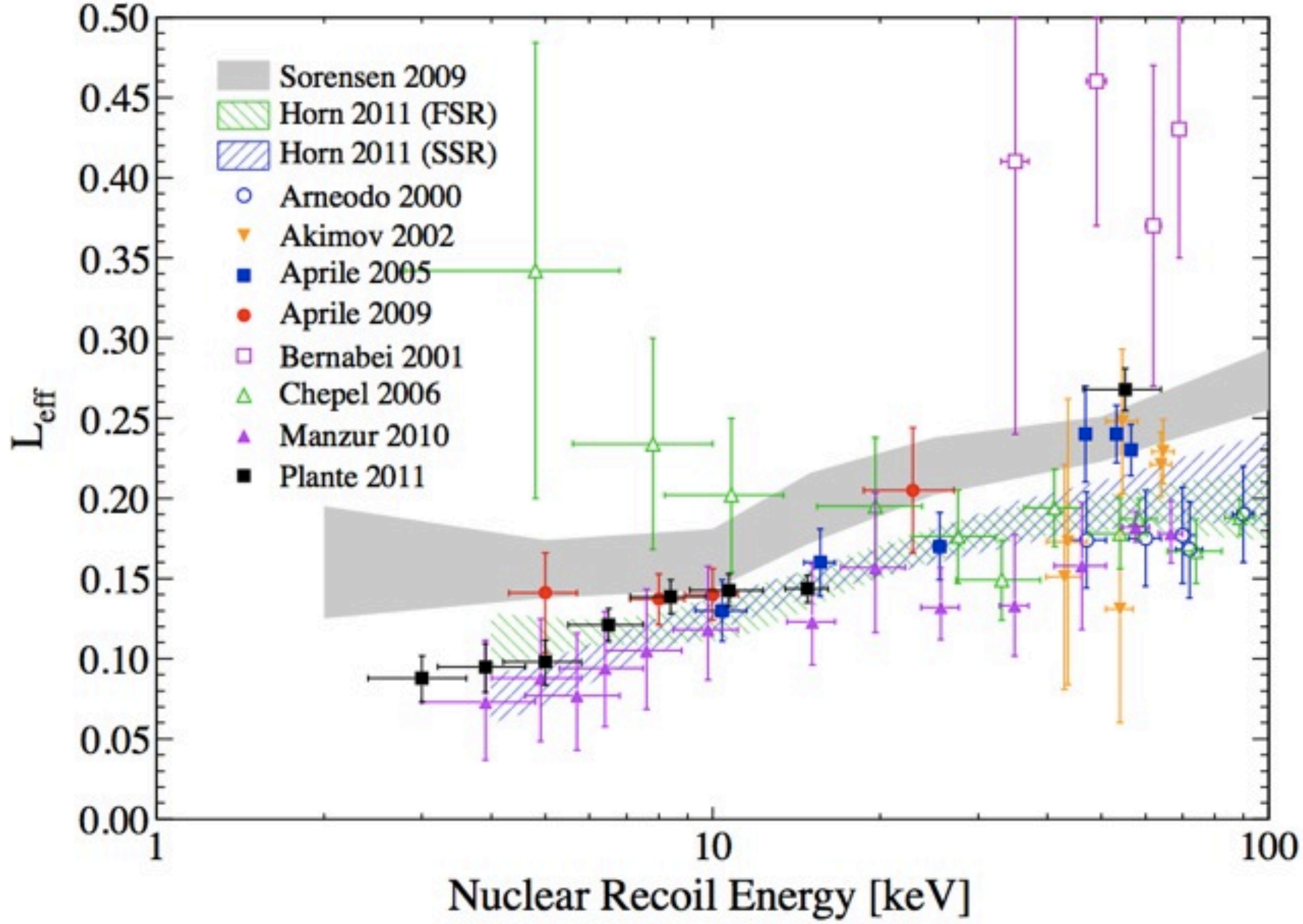


- Extract the energy dependence of $\mathcal{L}_{eff}$ by minimizing the χ^2 btw the measured and simulated spectra, *h*, *g*

$$\chi^2(\mathcal{L}_{\mathrm{eff},j}, R_j) = \sum_{i=0}^{N} \frac{\left[h_i - g_i(\mathcal{L}_{\mathrm{eff},j}, R_j)\right]^2}{\sigma_{h,i}^2 + \sigma_{g,i}^2(\mathcal{L}_{\mathrm{eff},j}, R_j)}$$



New Measurement of $\mathcal{L}_{eff}$: Results



- Lowest energy (3 keV) and most precise $\mathcal{L}_{eff}$ direct measurement achieved to date.
- For details, see Plante *et al.*, Phys. Rev. C 84, 045805, 2011

Scintillation Yield of Low-E Electrons: Setup

- Compton coincidence technique allows measurements of a single electron response, instead of the response of multiple electrons produced as a result of photo-absorbed γ rays.

$$E_{\mathrm{er}} = E_{\gamma} - E_{\gamma'}$$

$$E_{\mathrm{er}} = E_{\gamma} - \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e c^2}(1 - \cos\theta)}$$

Recoil Energy in LXe (E_{er})

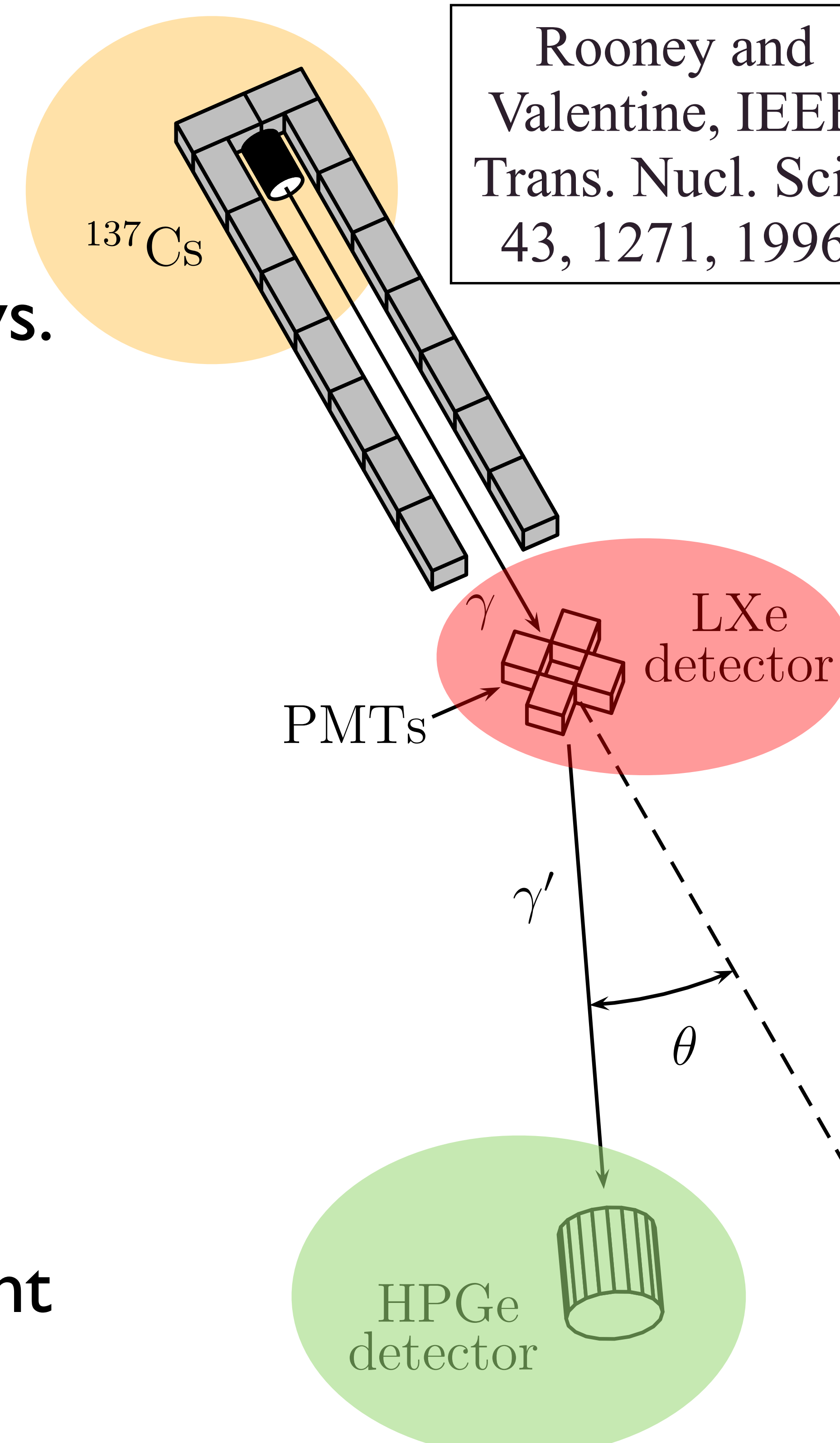
γ energy from the Source (E_{γ})

Electron Mass (m_e)

Compton-scattered γ energy

Scattering Angle (θ)

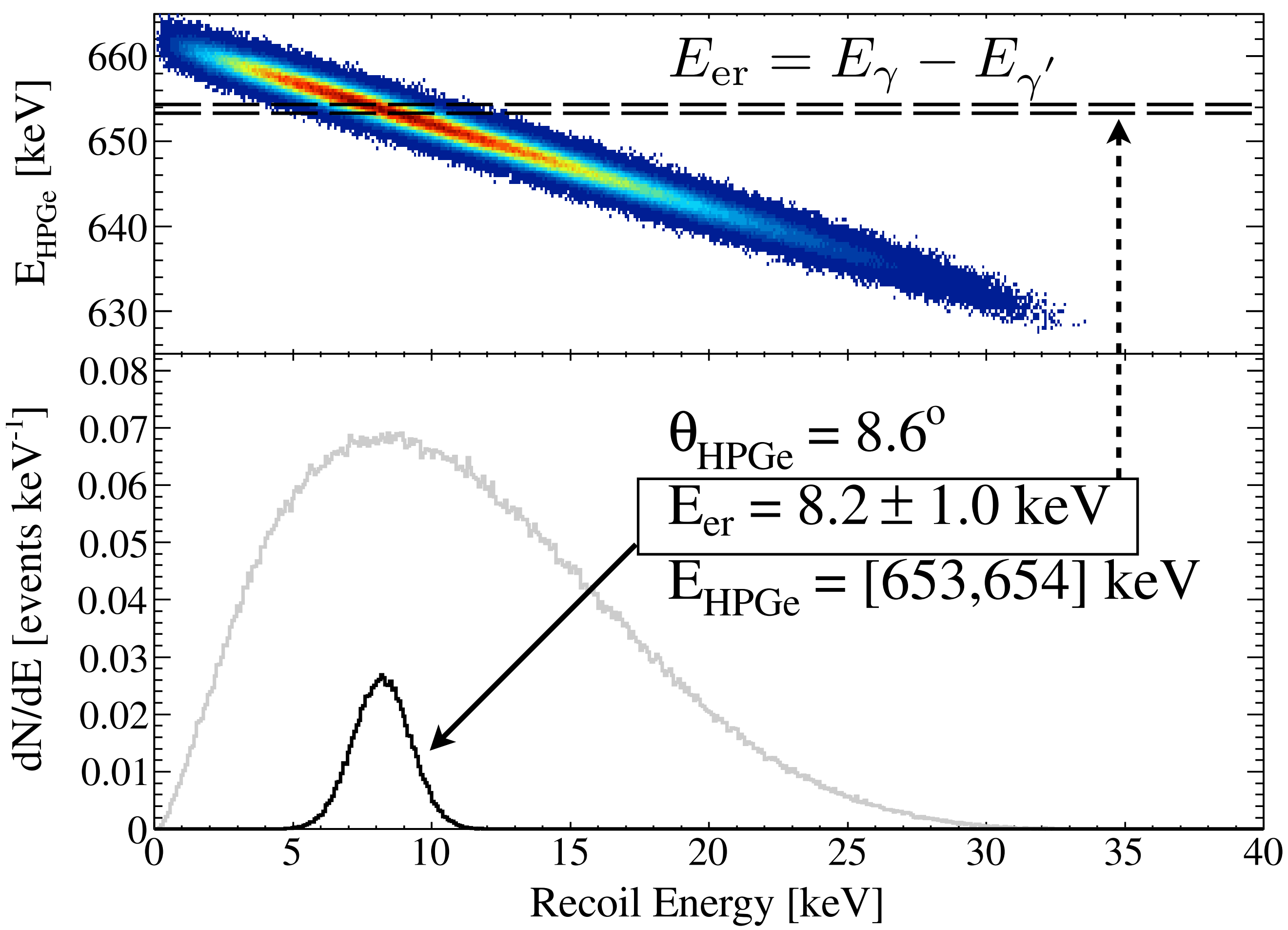
Rooney and Valentine, IEEE Trans. Nucl. Sci., 43, 1271, 1996



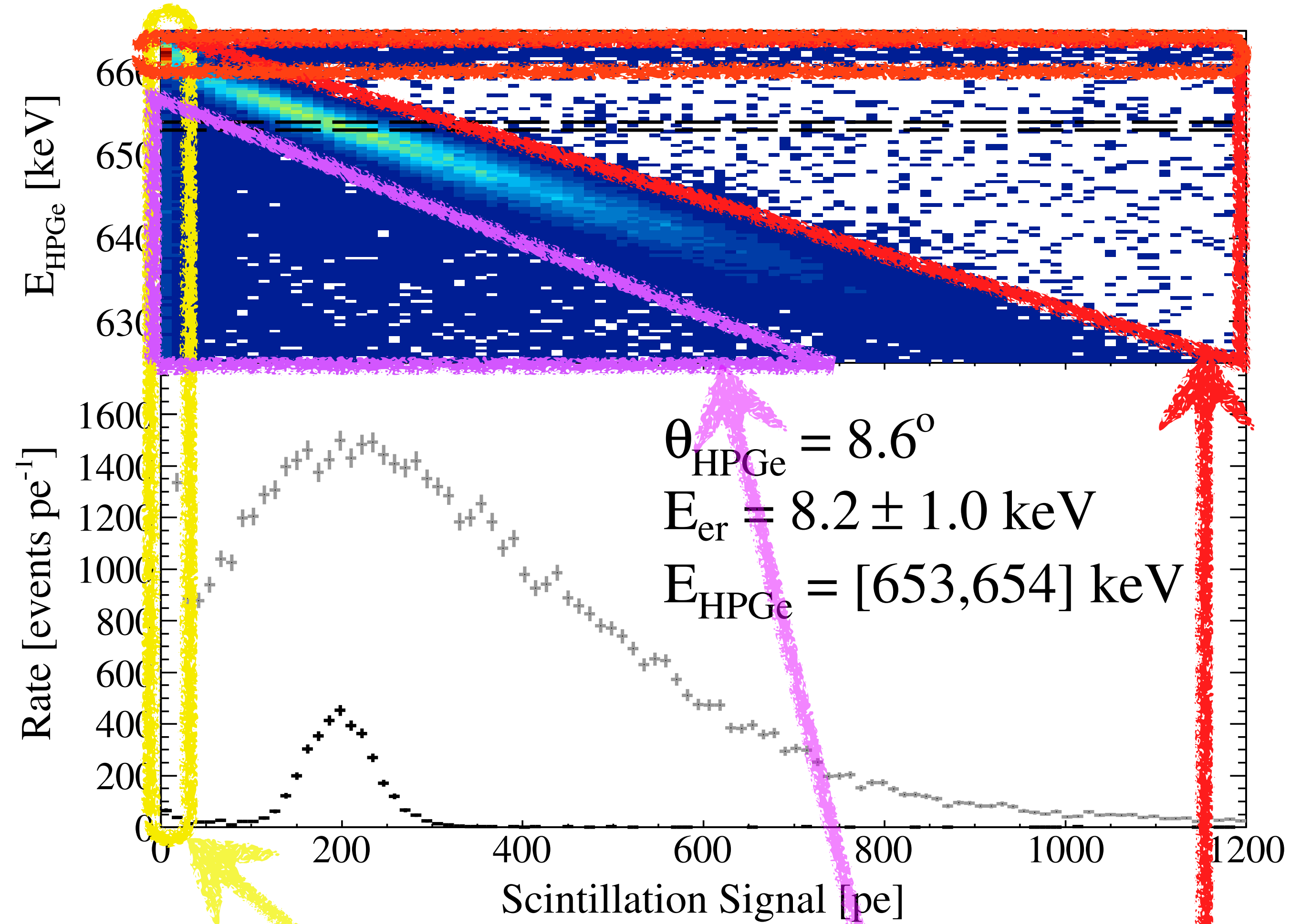
- The low-energy ER background is induced by Compton-scattered high energy γ rays present in the detector materials and environment.

Recoil Energy Selection

Monte Carlo Simulation



Data



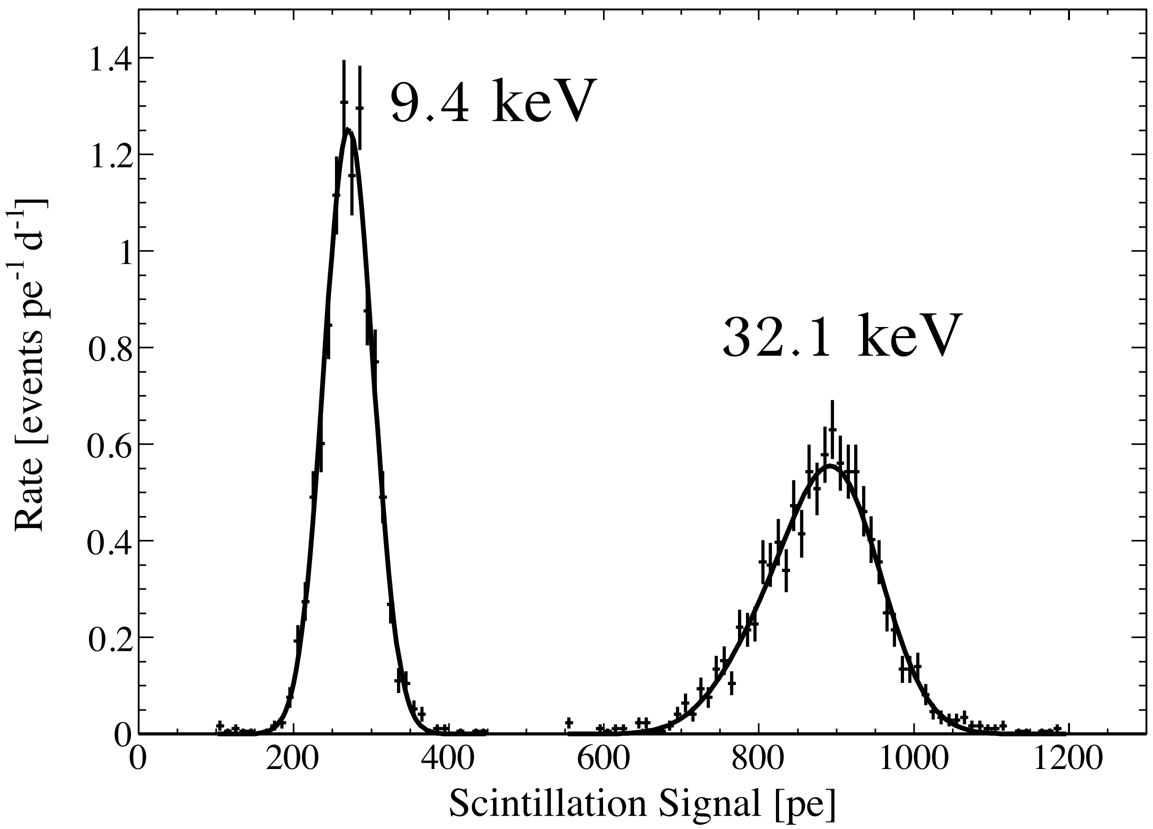
Most likely due to poor light collection efficiency outside of target volume

Accidental Coincidences

1. Accidental Coincidences
2. Partial energy deposit in HPGe

- Excellent resolution of HPGe detector provides precise energy selection w/ small energy spread (easy to measure continuous energy response).

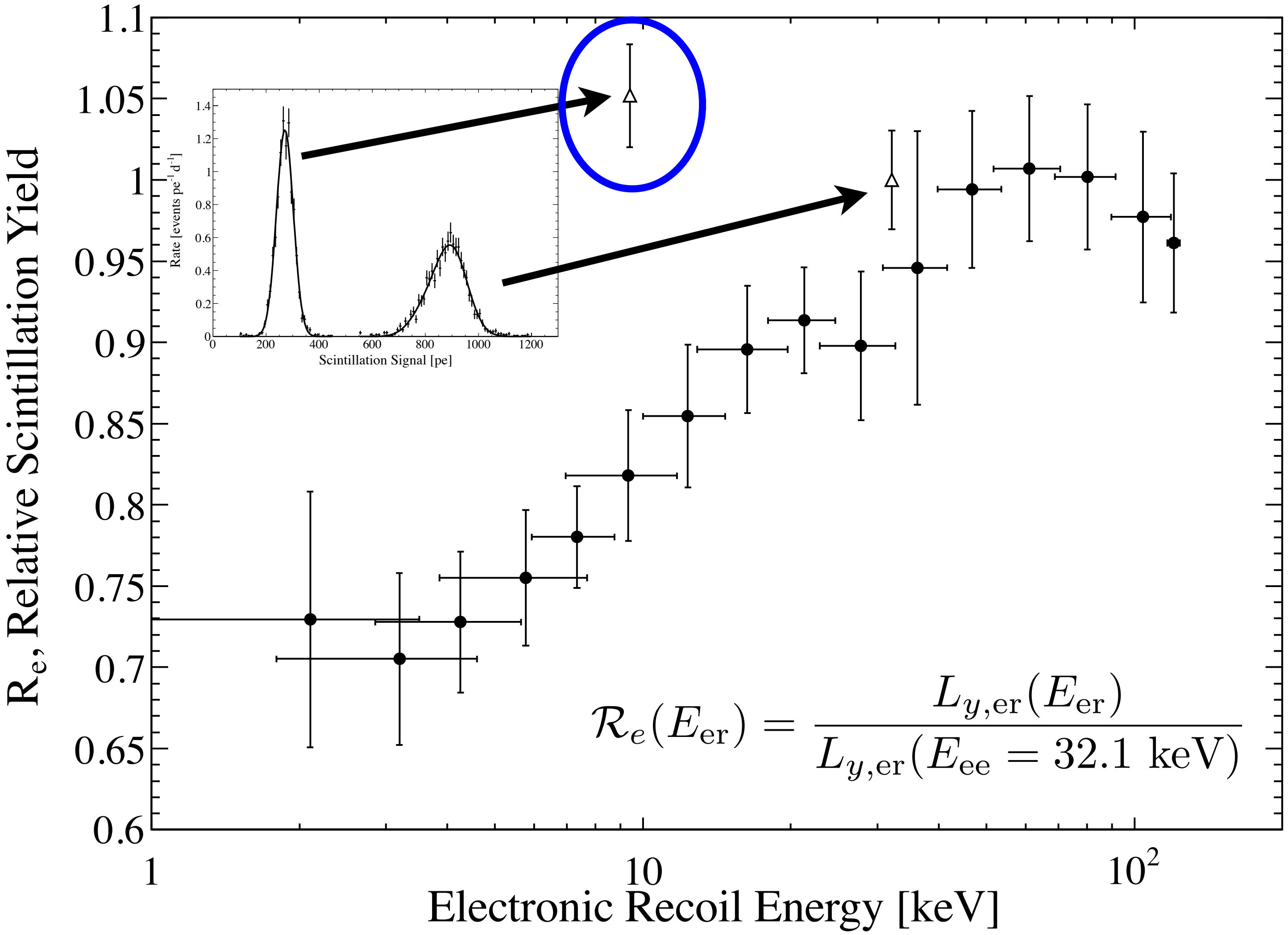
^{83m}Kr Measurement



Transition Energy	Decay Mode	Branching Ratio [%]
32.1 keV	$CE_{M,N}(32)$	11.5
	$CE_L(30.4) + A(1.6)$	63.8
	$CE_K(17.8) + X_{K\alpha}(12.6) + A(1.6)$	15.3
	$CE_K(17.8) + A(10.8) + 2A(1.6)$	9.4
	γ	< 0.1
9.4 keV	$CE_L(7.5) + A(1.6)$	81.1
	$CE_M(9.1)$	13.1
	γ	5.8

- ^{83m}Kr (gas) is a good reference source since the uncertainty on light collection efficiency due to the position dependence is removed.
  (V. Hannen *et al.*, Phys. JINST 6, P10013, 2011)
- For both decays, the energy is mostly transferred via conversion electrons with similar energy, comparison with Compton coincidence measurement is possible.

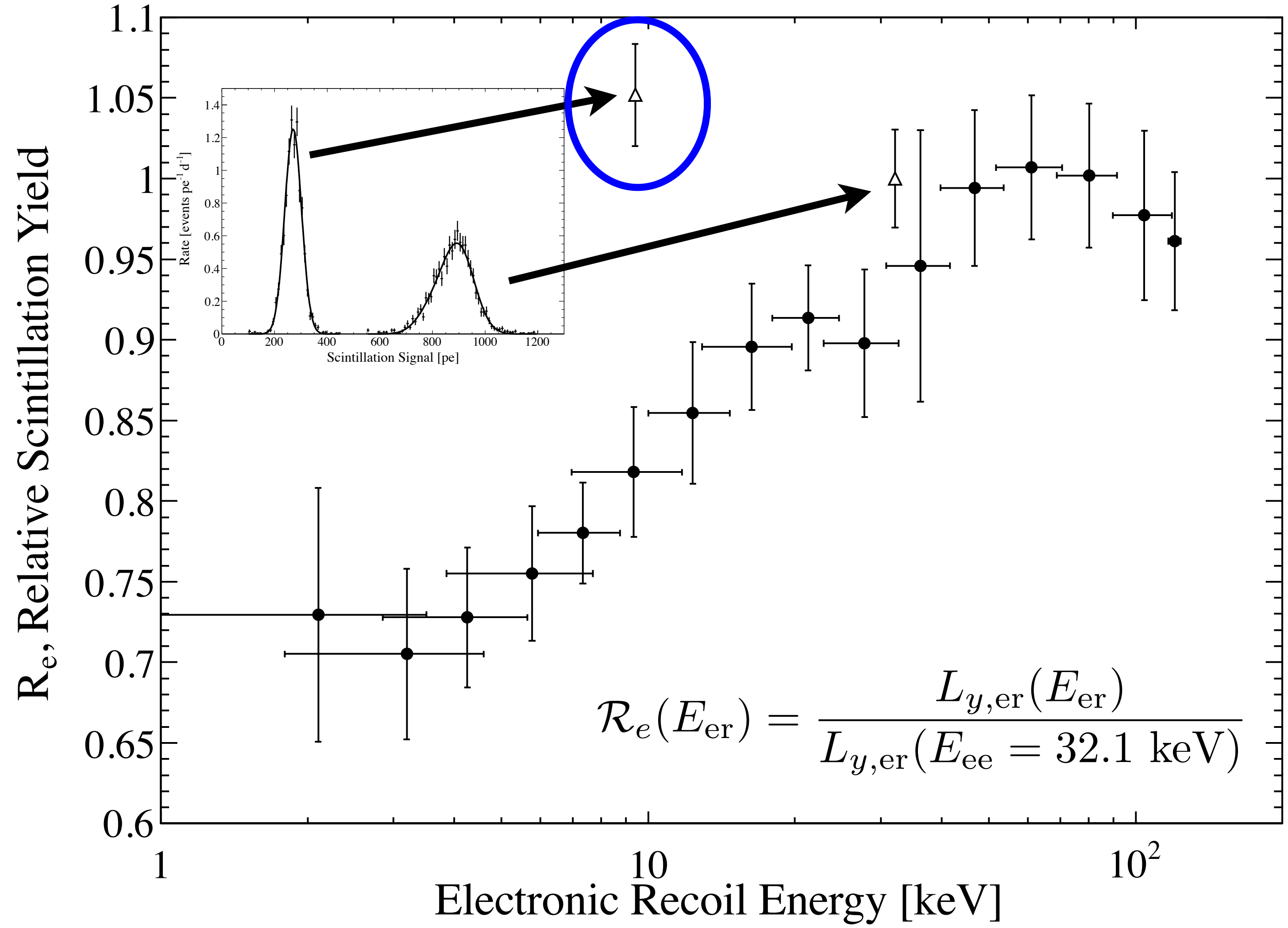
Scintillation Yield of Low-E Electrons: Results



- @ 2 keV, $\mathcal{R}_e$ is ~ 70%.
- $\mathcal{R}_e$ is maximum @ 60 keV.
- Large scintillation yield for 9.4 keV decays of ^{83m}Kr is due to the enhanced recombination rate in the presence of Xe ions left from 32.1 keV decay.

- This is the first measurement with such a wide range of electron energies extending as low as 2 keV.
- For details, see Aprile *et al*. arXiv:1209.3658, Submitted to PRD

Scintillation Yield of Low-E Electrons: Results



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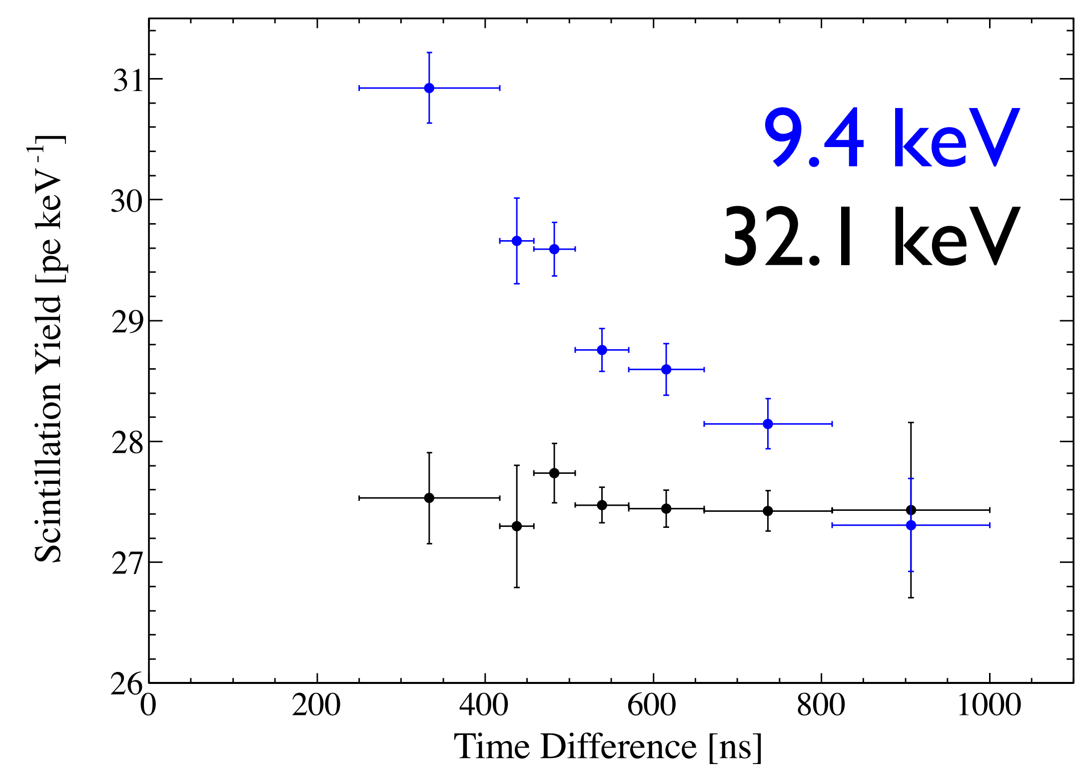

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- Measuring properties of LXe
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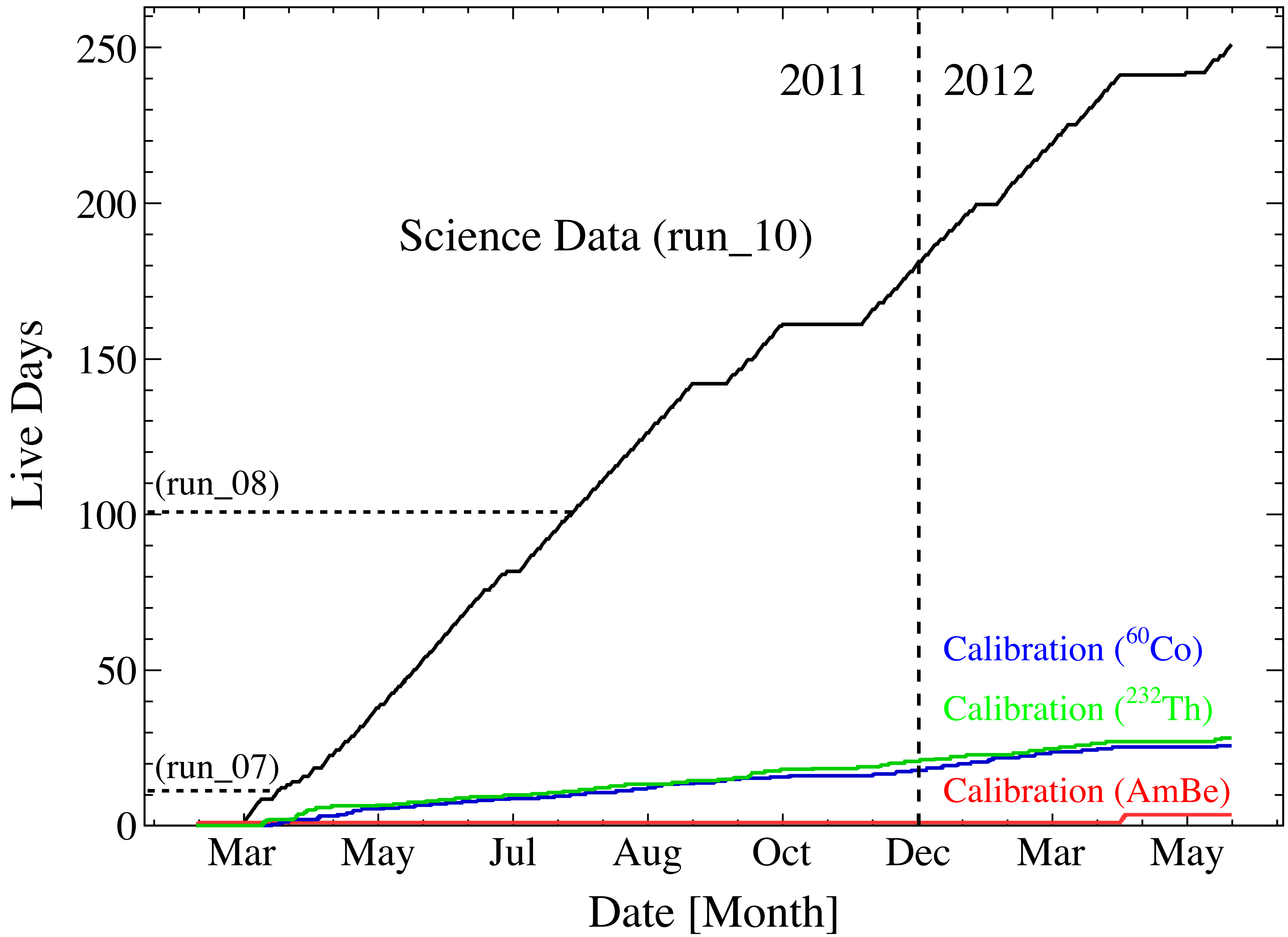
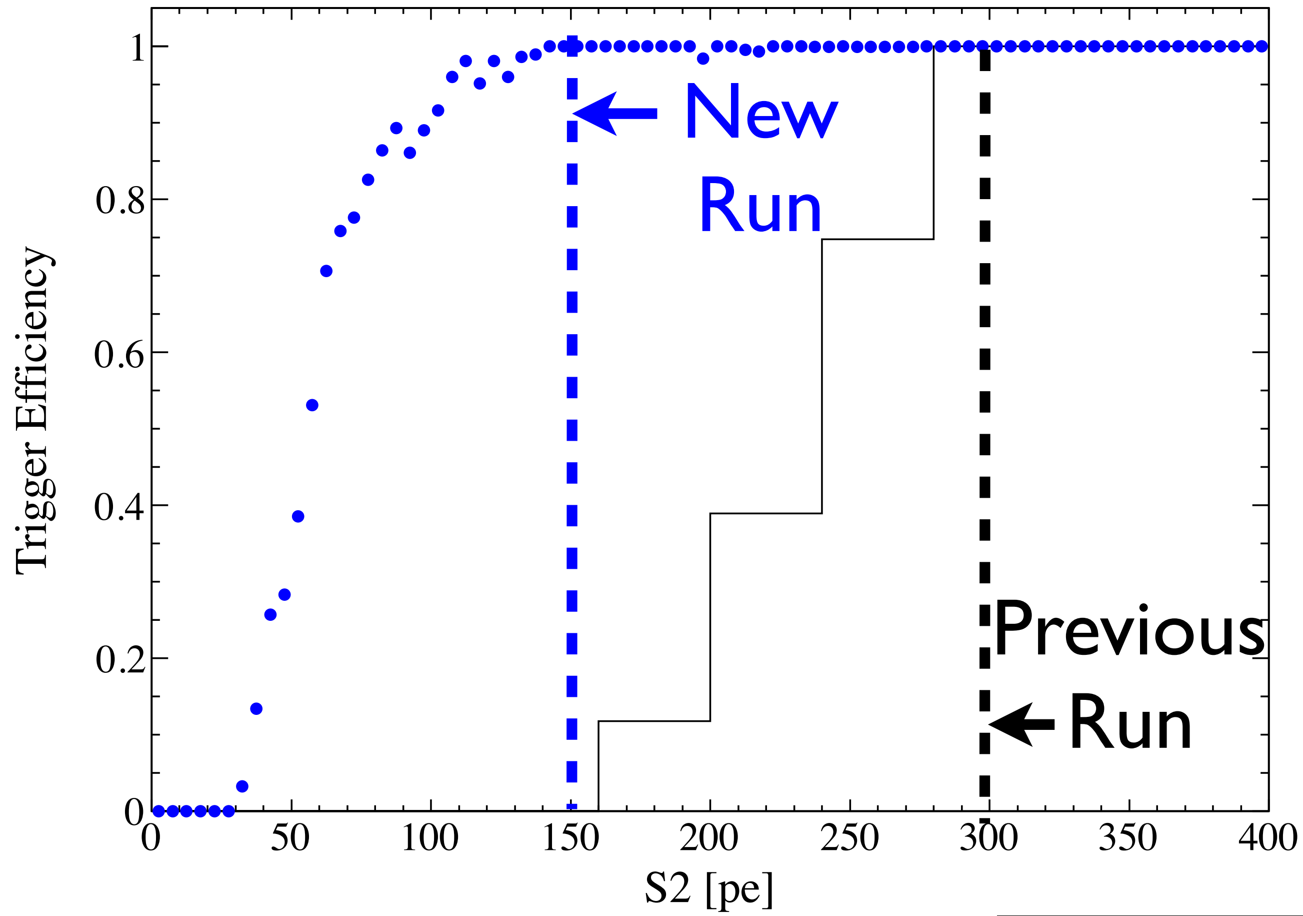
New Results of 2012: Data Taking



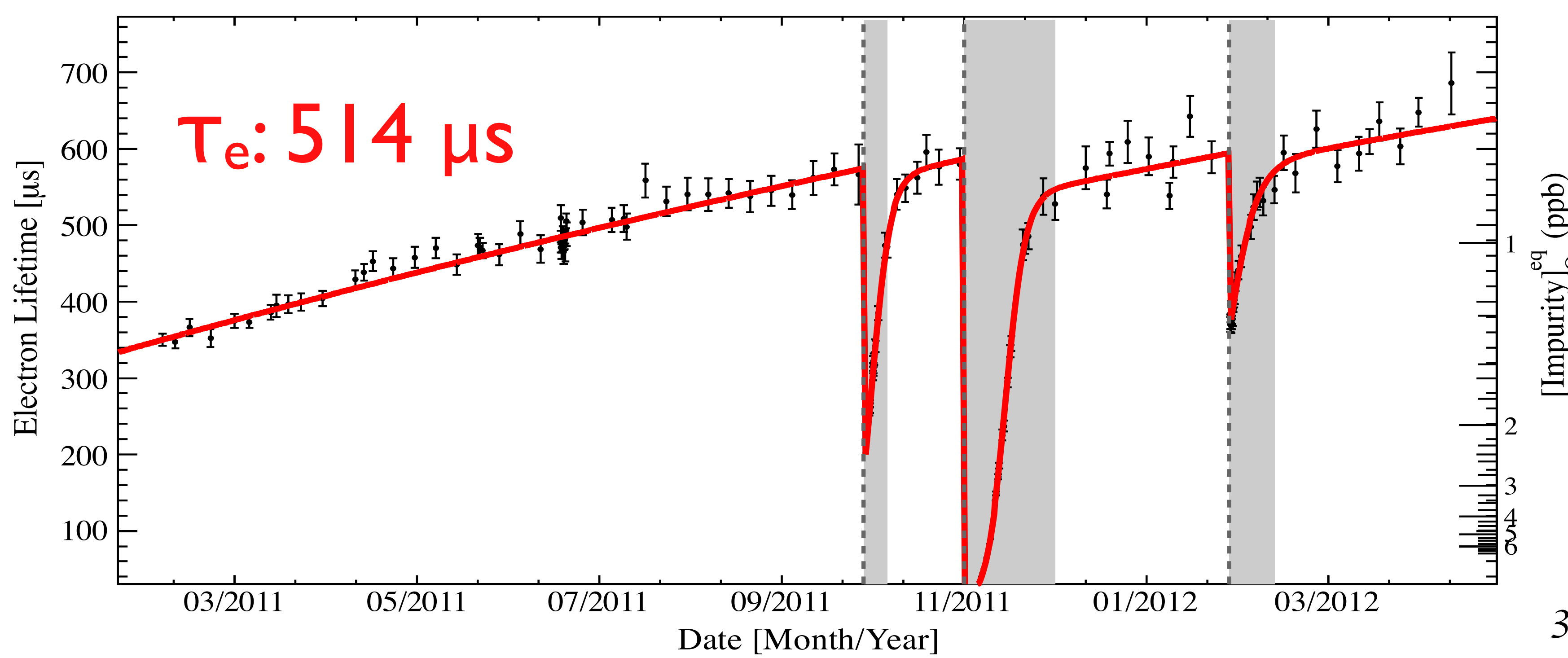
Data taking over 13 months: full annual cycle (224.6 live days)

Improvements

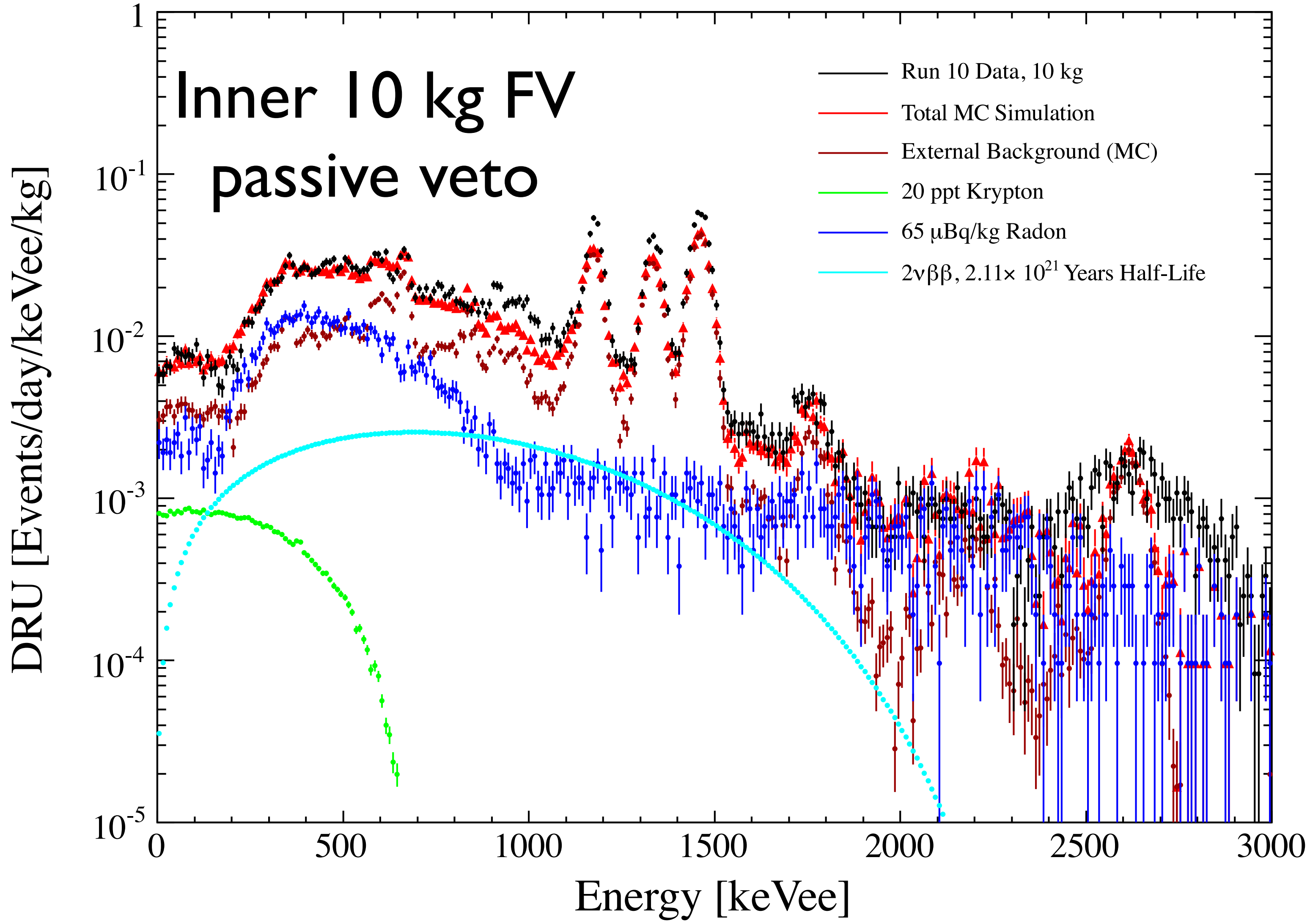


- > x2 exposure
- Lower energy threshold: > 99% (S2 >150 pe, 10 e⁻), S1 > 3 pe (6.6 keV_{nr})
- Reduced Kr contamination: by a factor of 20
- More calibration data: x35 ER, x2 NR

- Larger electron lifetime: smaller S2 correction



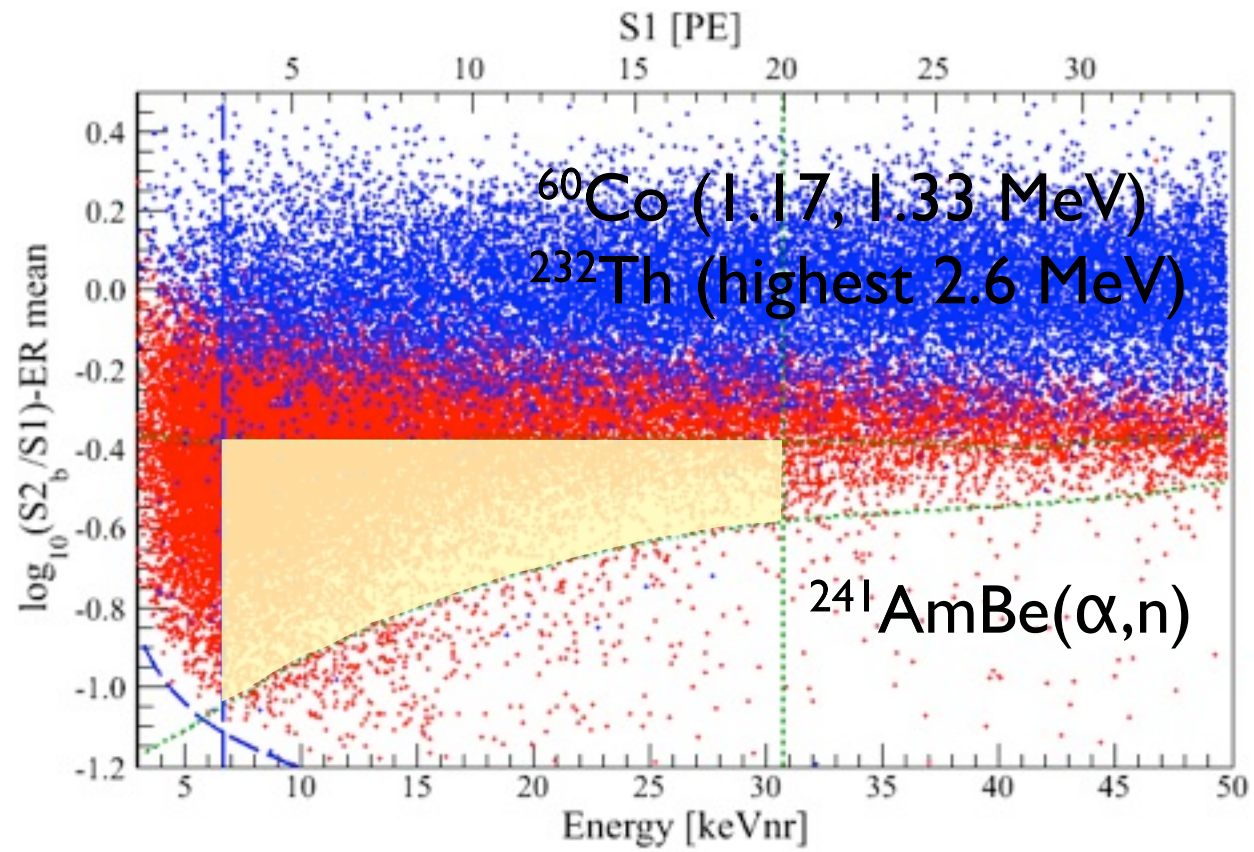
Total Electronic Recoil Background



- Use EXO-200 2νββ results as ^{136}Xe contribution input.
- Good agreement btw MC and Data (no tuning).
- (5.3 ± 0.6) x 10^{-3} evts/keV/kg/day w/ active veto before discrimination.
- For details of ER MC, see Aprile *et al*. Phys. Rev. D 83, 082001, 2011

Discrimination

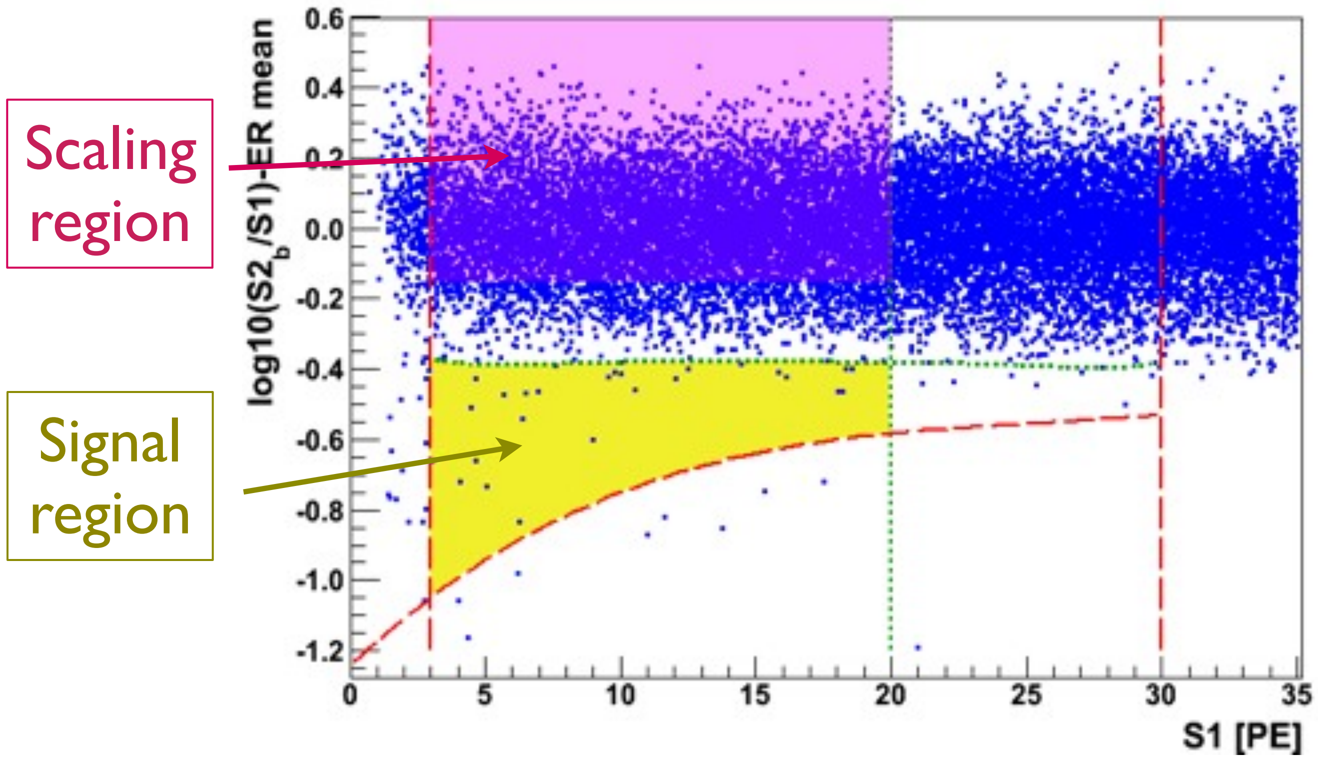
- Electronic recoil (ER) band calibration is performed w/ high energy γ rays from ^{60}Co and ^{232}Th.
- Background in the region of interest is due to low energy Compton scatters from high energy γ rays or β decays.



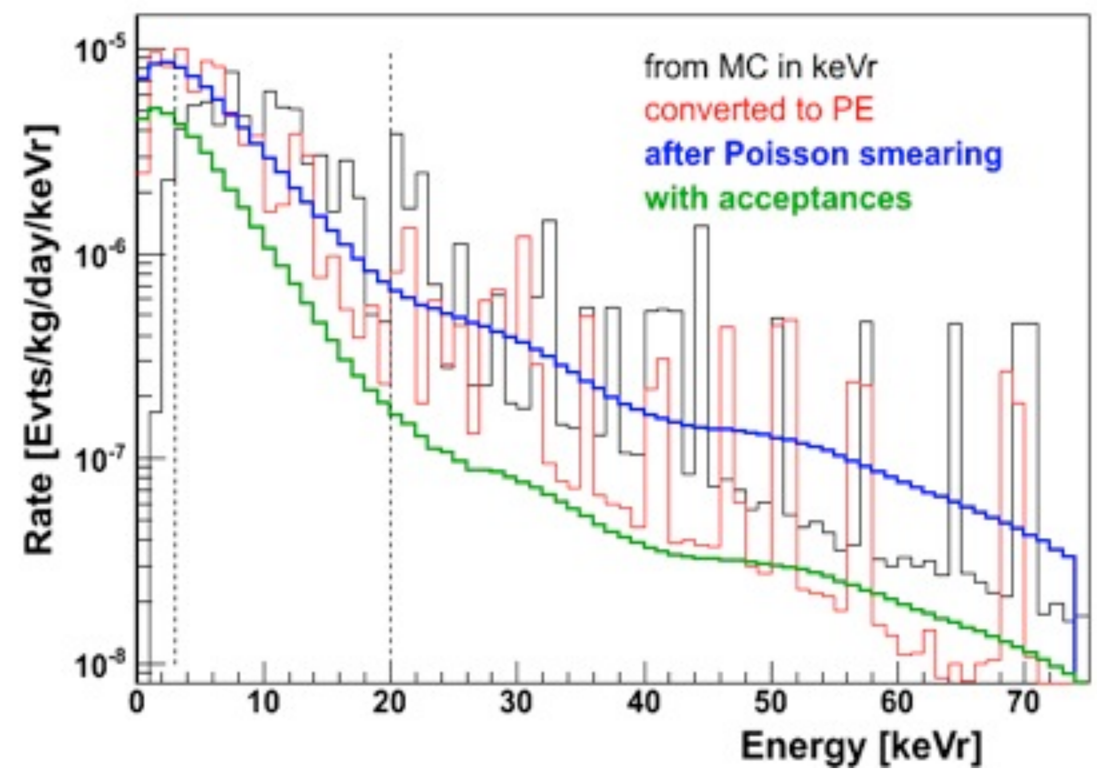
- Nuclear recoil (NR) band calibration is performed w/ ~ 200 n/s ^{241}AmBe neutron source.
- Benchmark signal region for the cut-based analysis was chosen 99.75% of ER band rejection and S1 btw 3 pe and 20 pe.
- The FV and the benchmark signal region are adjusted simultaneously to maximize the sensitivity (34 kg was chosen).

Background Prediction: Cut-based Analysis

ER Background Prediction



NR Background Prediction



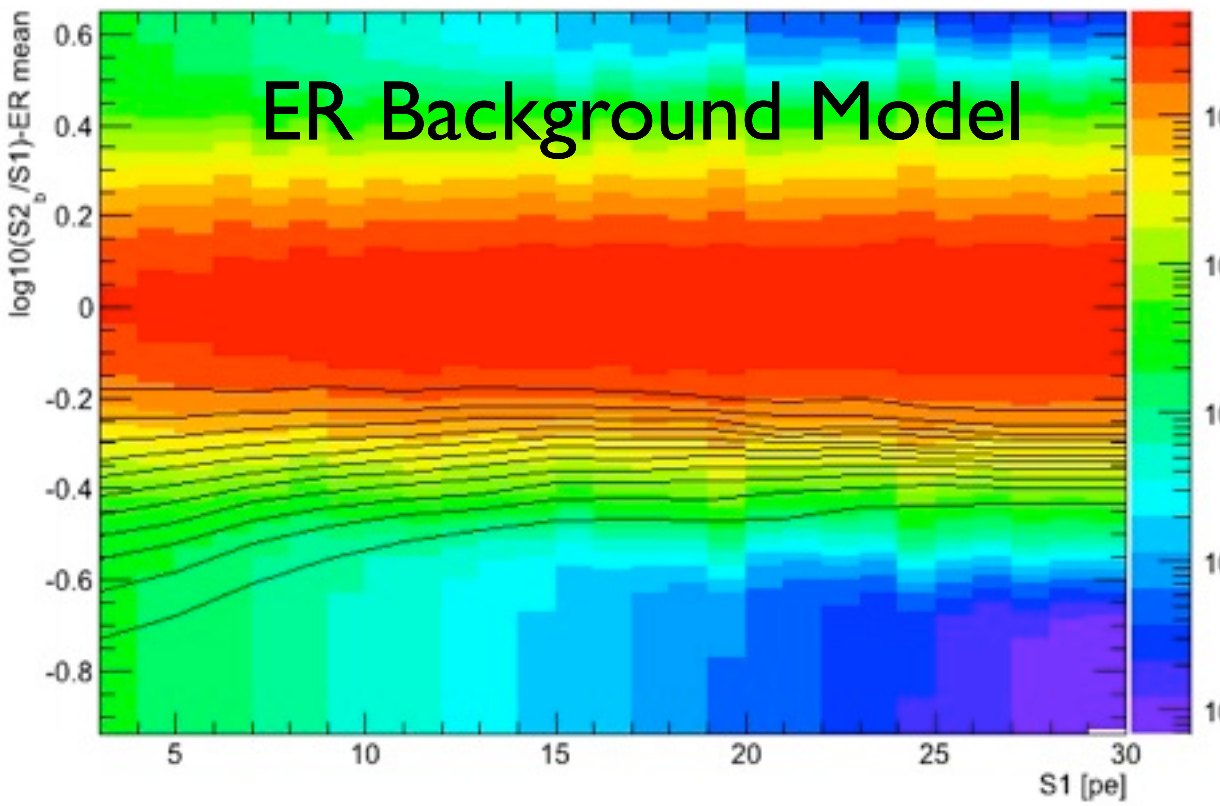
- ER BG expectation is obtained from calibration data.
- ER BG in the signal region is computed by the ratio of the number of events in the signal region over the number of events in the scaling region.
- NR BG expectation is obtained from the MC (muon-induced fast neutrons, neutrons from (α,n) reactions and spontaneous fission).
- Total BG prediction: 1.0 ± 0.2 evts (0.79 ± 0.16 ER, 0.17 + 0.12/-0.07 NR)

Background Prediction: Profile Likelihood (PL)

- Instead of applying hard cut, take into account of the background distribution in Log_{10}(S2/S1) vs S1.
- Test both discovery and exclusion at the same time w/o flip-flop.
- Systematic uncertainties are incorporated in a consistent manner.
- Construct the likelihood function

$$\mathcal{L} = \mathcal{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\text{eff}}; m_\chi)$$
$$\times \mathcal{L}_2(\epsilon_s) \times \mathcal{L}_3(\epsilon_b) \times \mathcal{L}_4(\mathcal{L}_{\text{eff}})$$

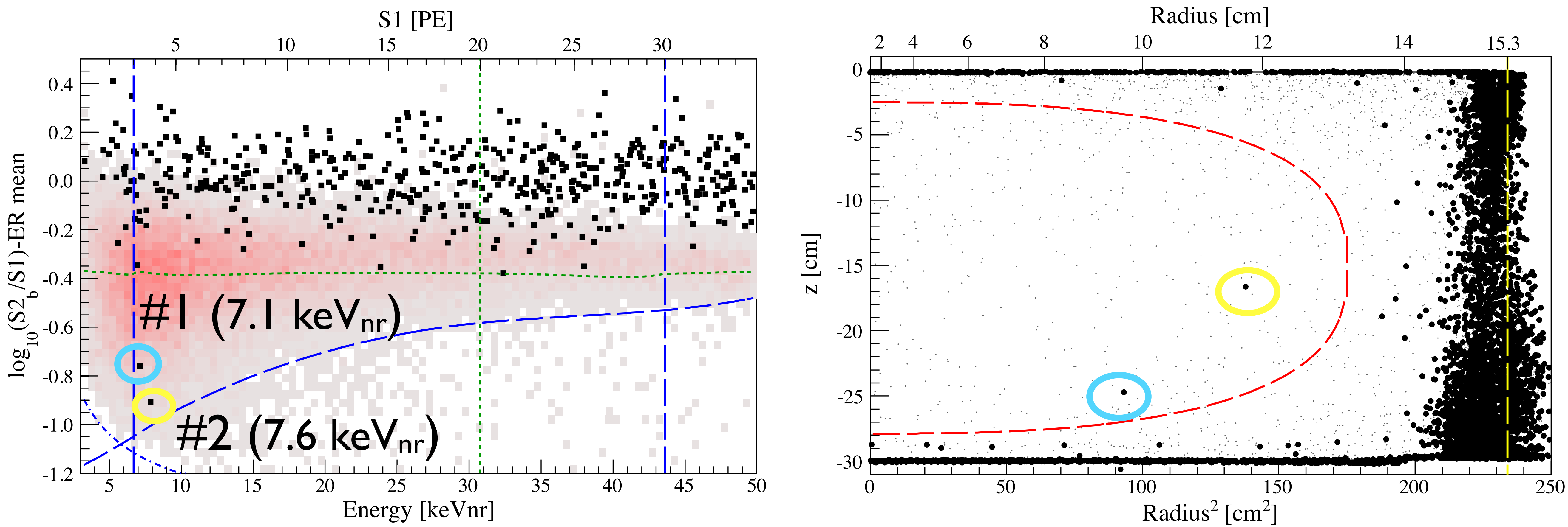
- Main term contains only one parameter of interest, σ, other parameters are nuisance parameters and profiled out.



- Use the same data input as cut based analysis.
- PL method was used to report the dark matter results.
- For the details, see Aprile *et al.*, Phys. Rev. D 84, 052003, 2011

Unblinding

Unblinding Results

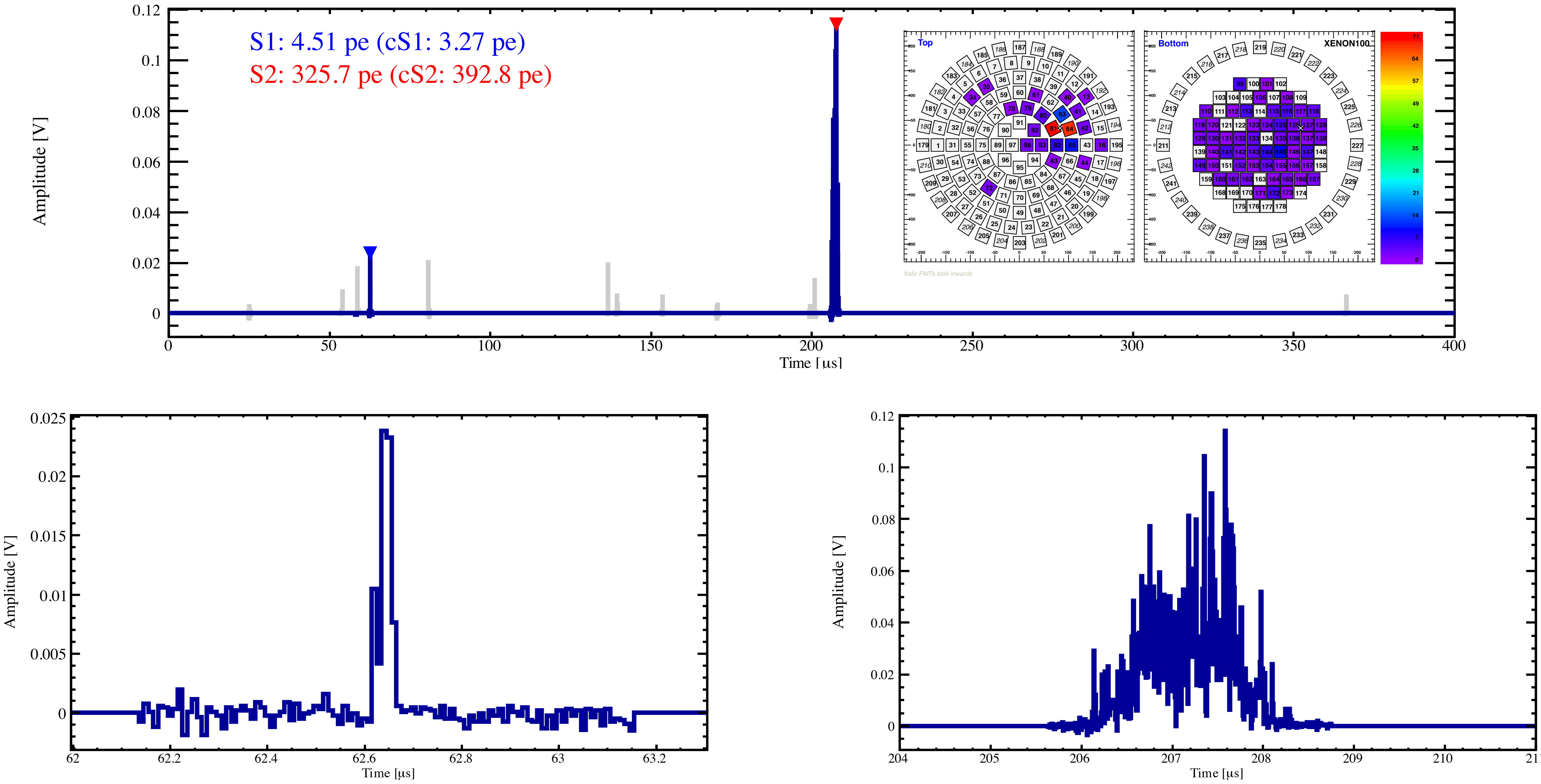


- Profile Likelihood analysis cannot reject the background-only hypothesis (p-value: > 0.05 for all WIMP masses).
- 2 evts observed w/ 1 evt of background prediction from cut-based analysis (26.4% probability that background fluctuates > 1 evt)

No significant excess due to a signal seen in XENON100 data.

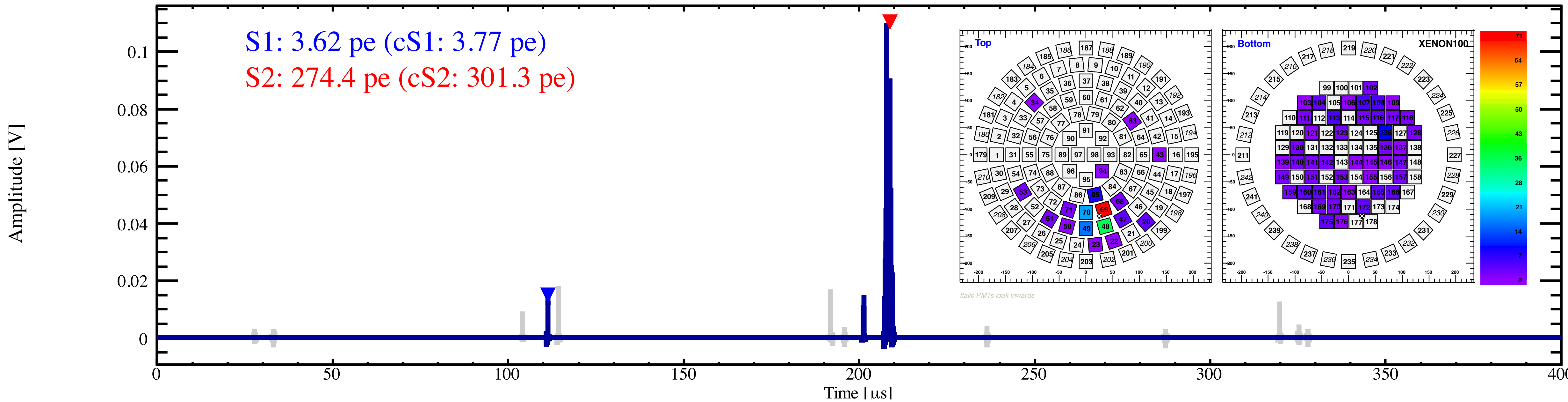
Candidate Event #1

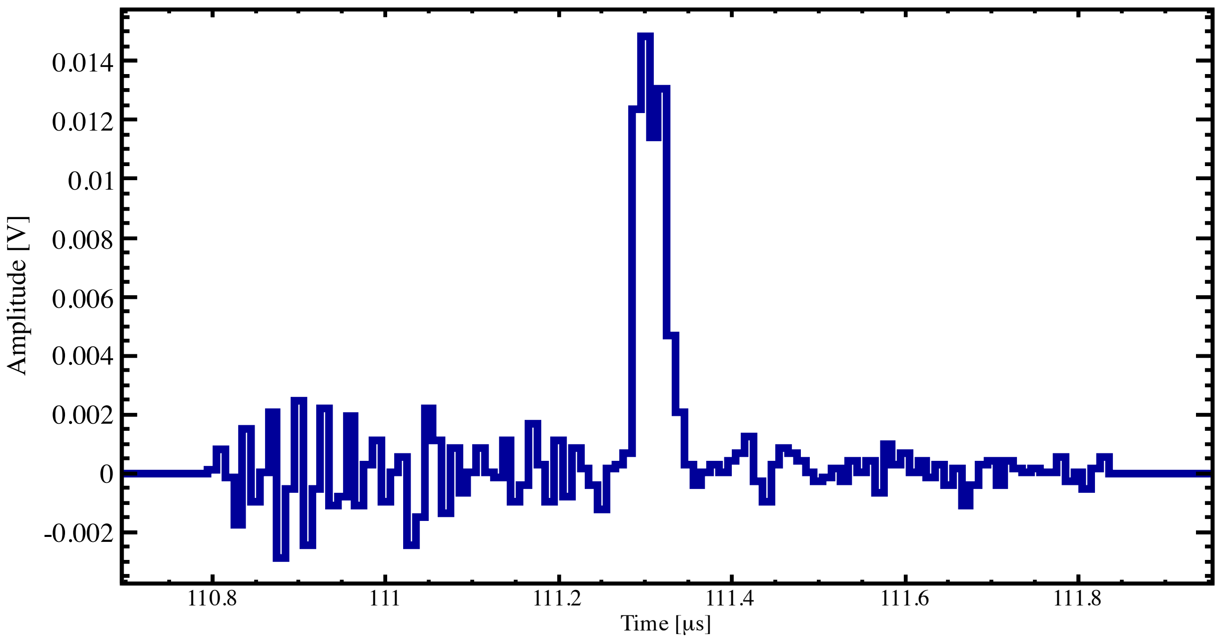
Event_1 (xe100_111023_1101_000023-859)

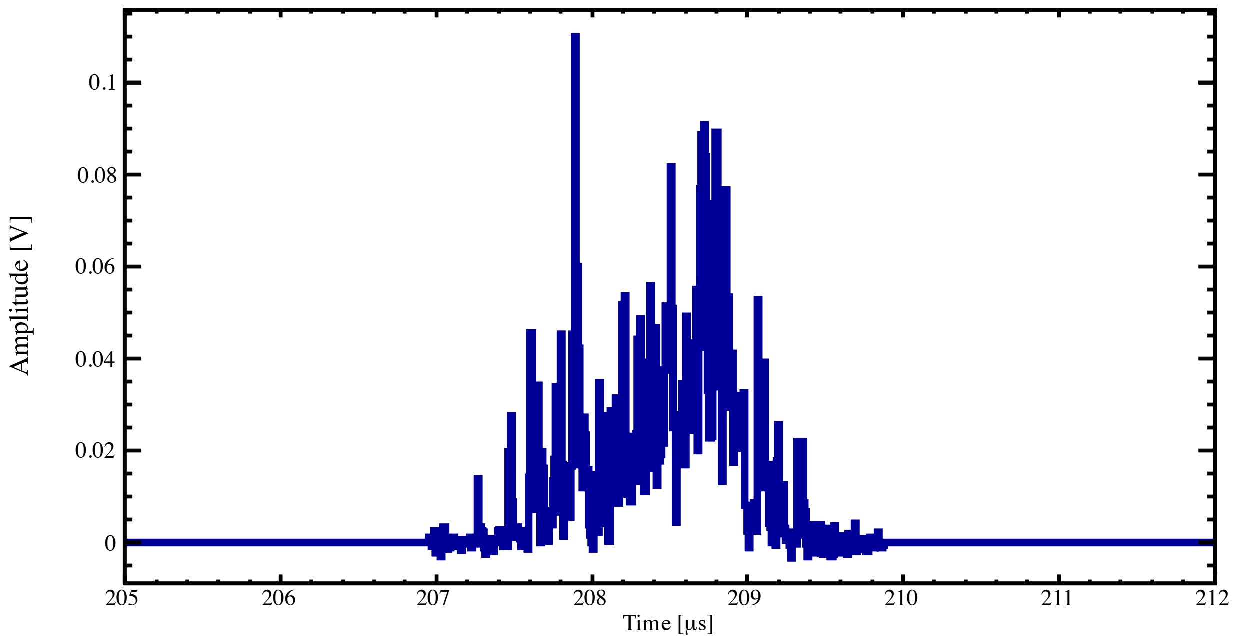


Candidate Event #2

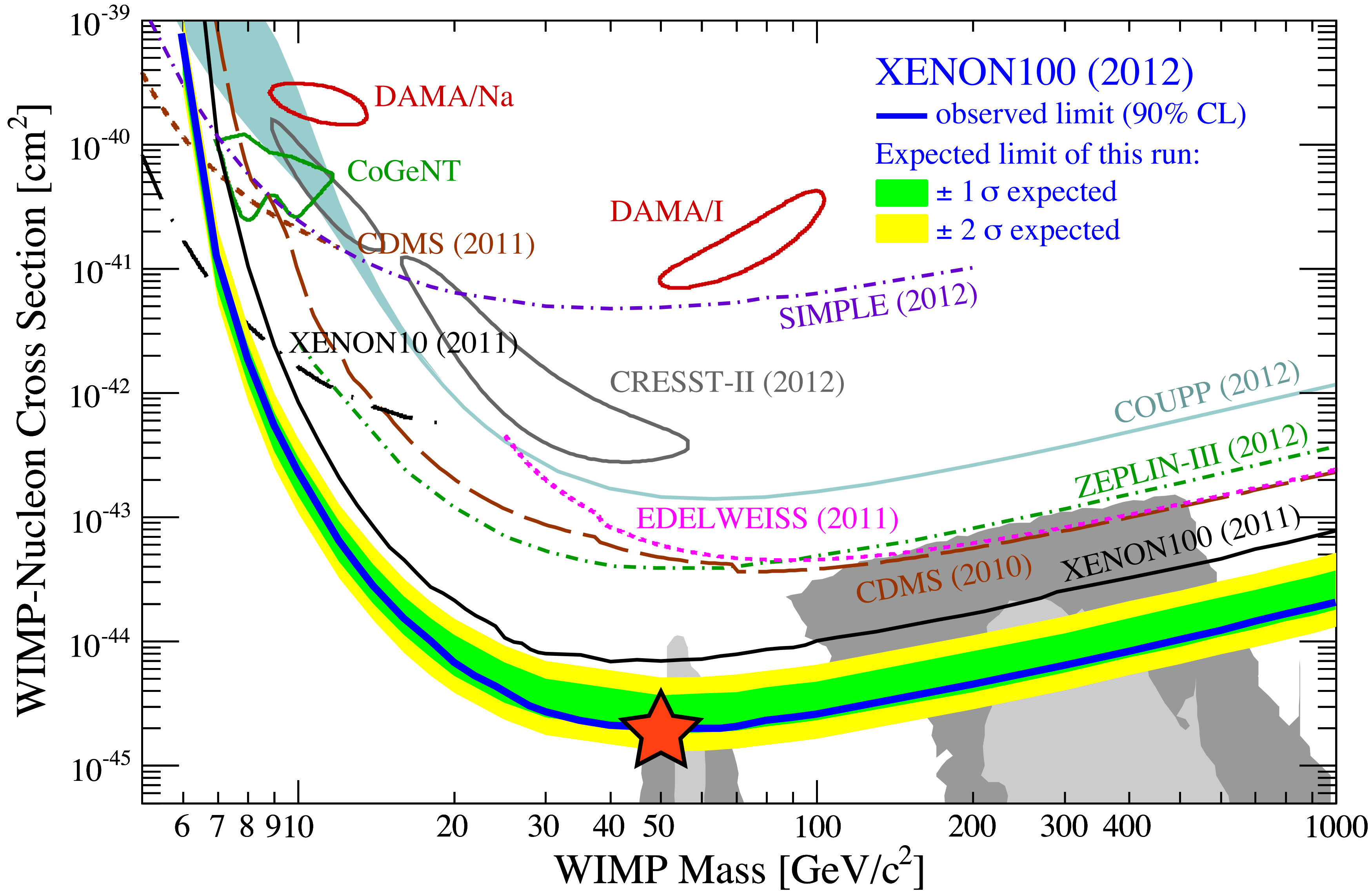
Event_2 (xe100_120111_1920_000040-253)





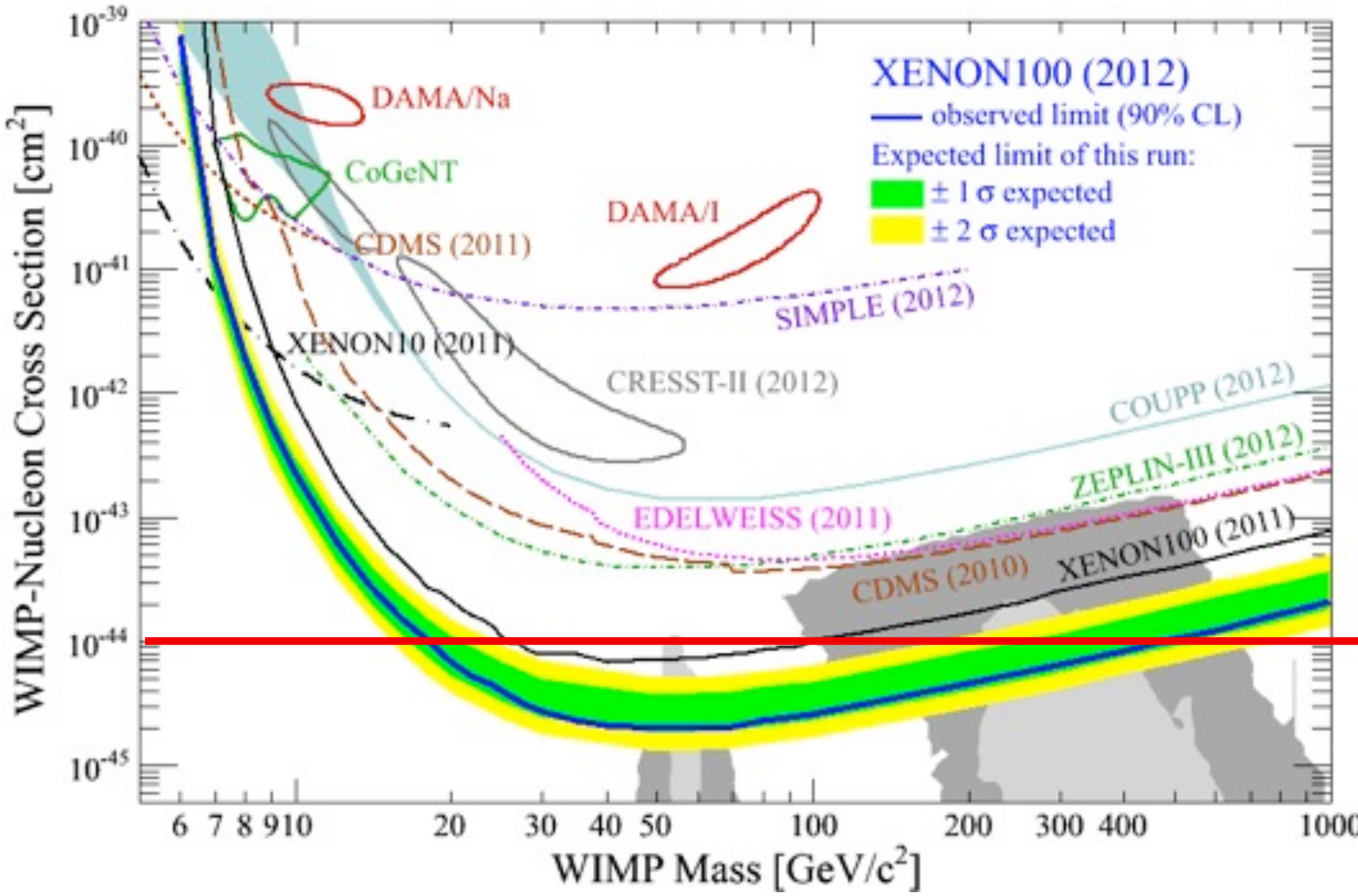


The New XENON100 Limit

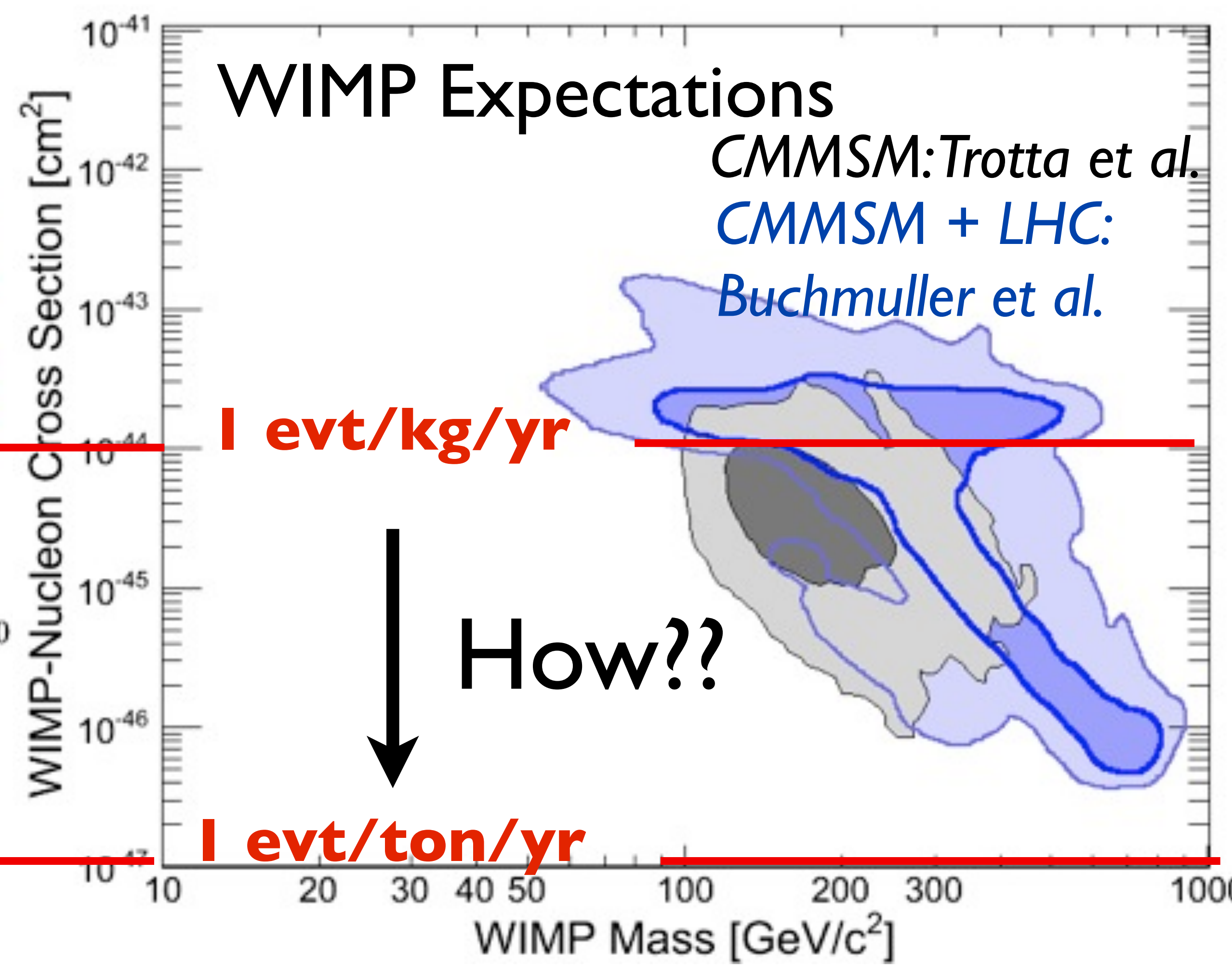


- Strongest limit to date over a large WIMP mass range (2×10^{-45} cm^2 @ 50 GeV), keep challenging the interpretation of CoGeNT and DAMA signals being due to low mass WIMPs.
- Results recently accepted in PRL (Aprile *et al.*, arXiv:1207.5988).

What Next?



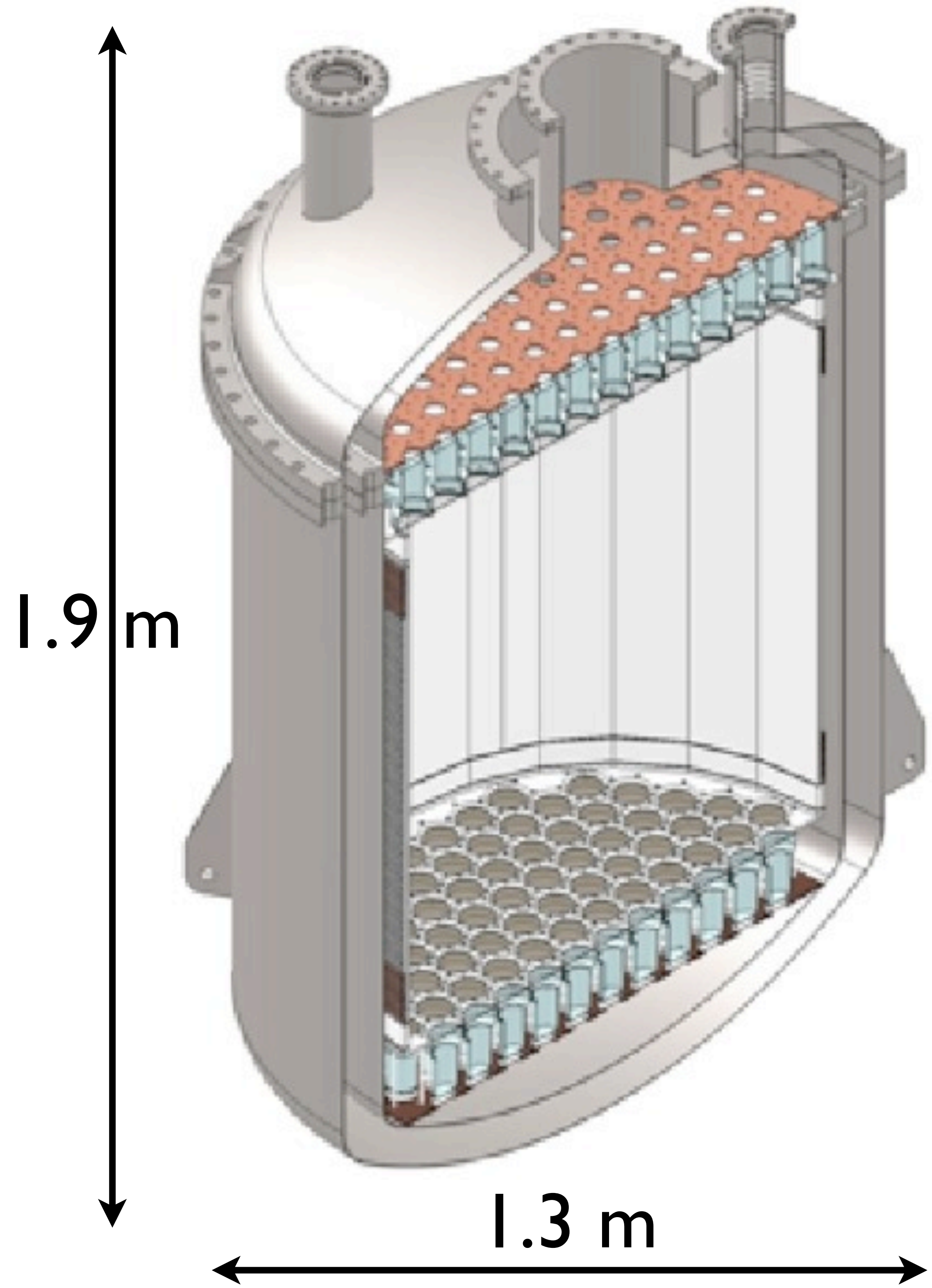
XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS (2010)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]

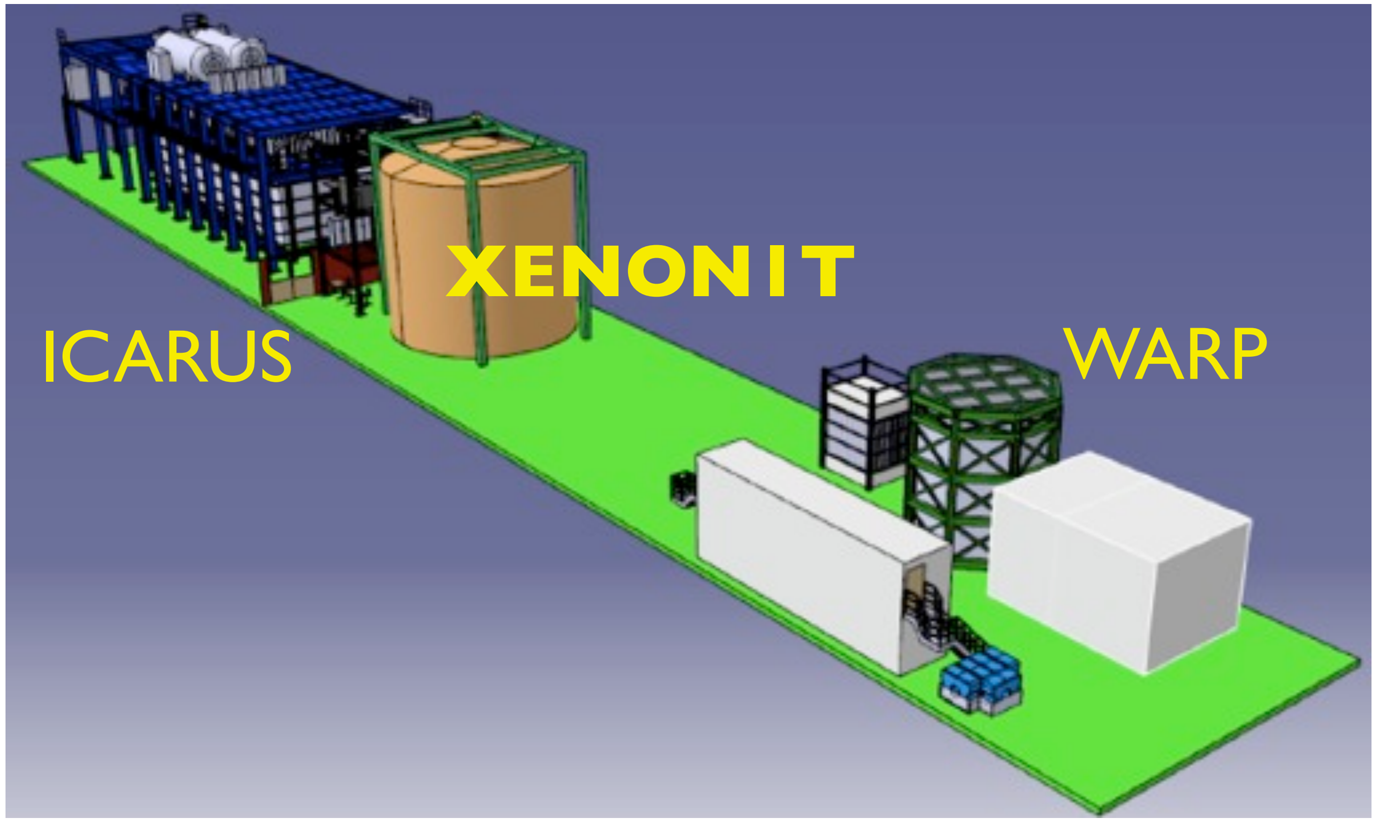


WIMP Expectations
CMMSM:Trotta et al.
CMMSM + LHC:
Buchmuller et al.
1 evt/kg/yr
How??
1 evt/ton/yr
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]

XENON1T: Future

- 1m^3 TPC, 3t LXe, 1t fiducial mass
- x100 less BG compared to XENON100
- Low radioactivity photosensors
- 9.6 m diameter water shield
- Approved for construction in HallB at LNGS (start in 2012)





Summary

- The XENON100 direct WIMP search detector has been operated since 2008, using LXe as a target/detection medium.
- Scintillation response of LXe to both NR/ERs at zero field was measured with a high light detection efficiency LXe detector at Columbia as an effort to set up the energy scales of LXe dark matter detector.
- The new dark matter results from 225 live days of XENON100 data show no significant signal excess due to WIMPs.
- Set the most stringent limit on the WIMP-nucleon spin-independent cross section above 8 GeV/c^2 WIMP masses (2×10^{-45} cm^2 @ 50 GeV).
- Currently XENON100 is in the commissioning of the new run.