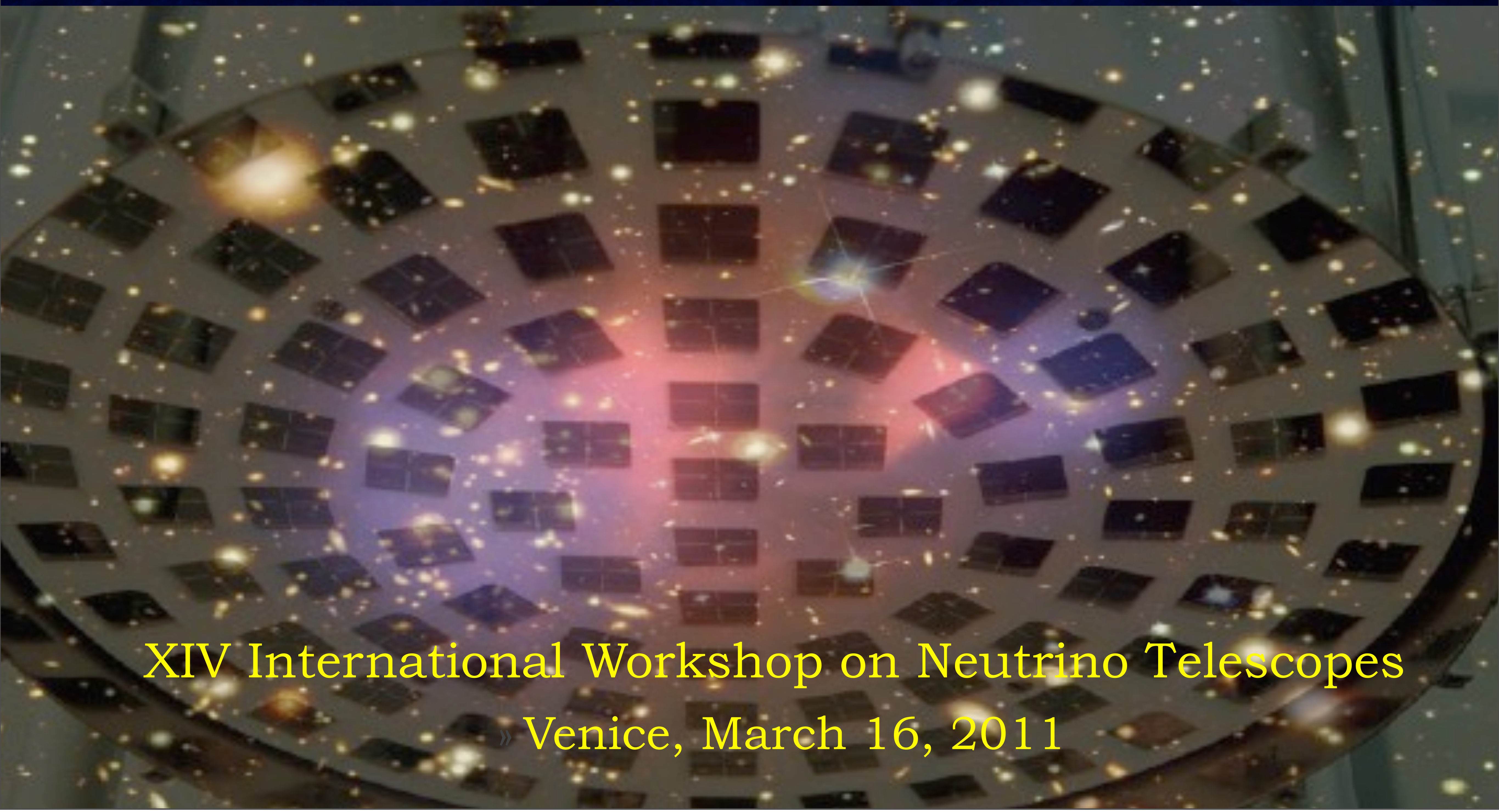
Results from the XENON100 Experiment

Elena Aprile, Columbia University
on behalf of the Collaboration



XIV International Workshop on Neutrino Telescopes

Venice, March 16, 2011

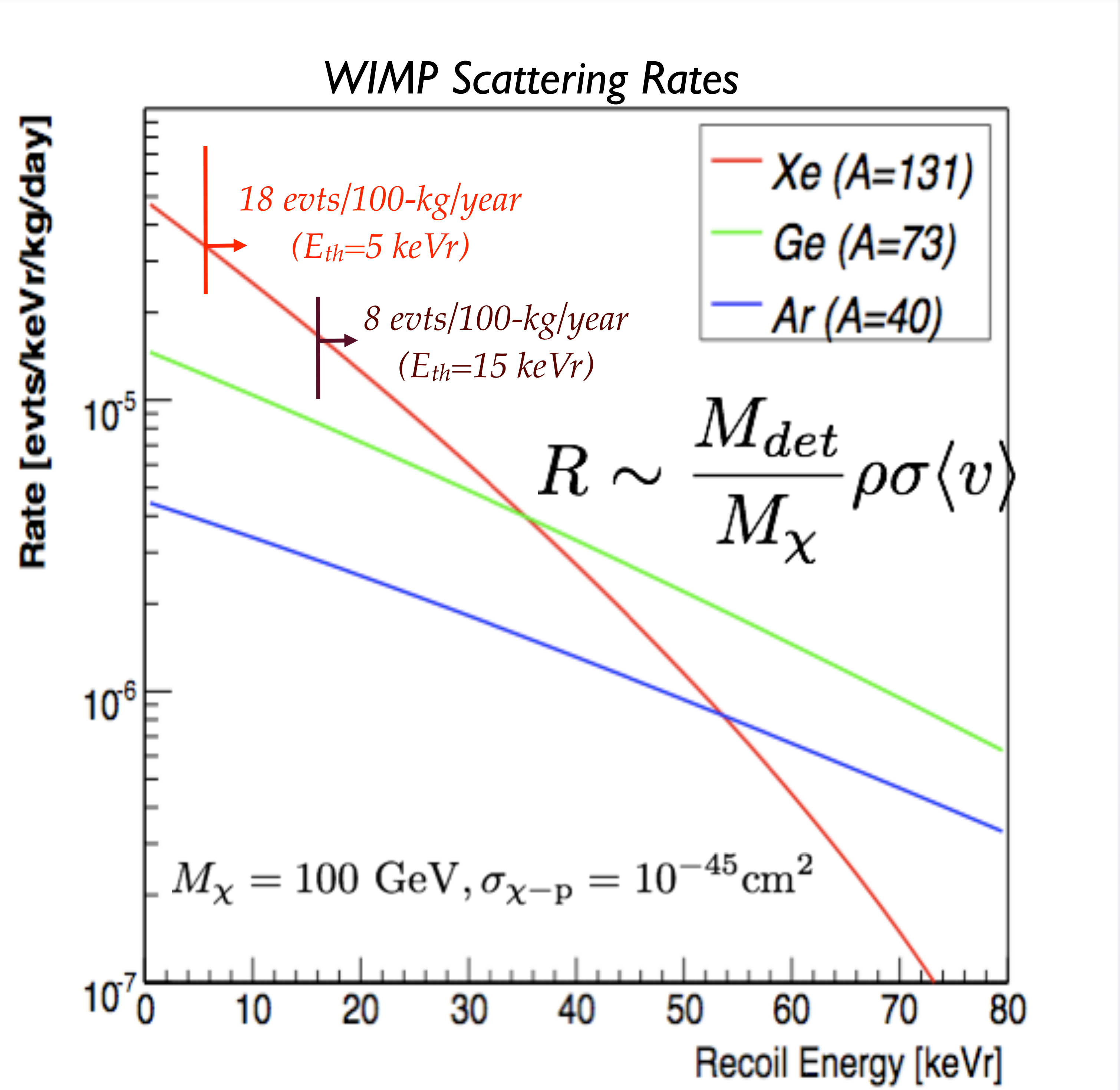
The XENON Collaboration

~60 scientists from 15 institutions:

Columbia University New York
University of California Los Angeles
Rice University Houston
Universidade de Coimbra
Subatech Nantes
NIKHEF Amsterdam
Weizmann Institute of Science Israel
Willhelms Universität Münster
Max-Planck-Institut Heidelberg
Johannes Gutenberg-Universitat Mainz
Johannes Gutenberg-Universität Mainz
Universität Zürich
Laboratori Nazionali del Gran Sasso
INFN e Università di Bologna
Jiao Tong University Shanghai

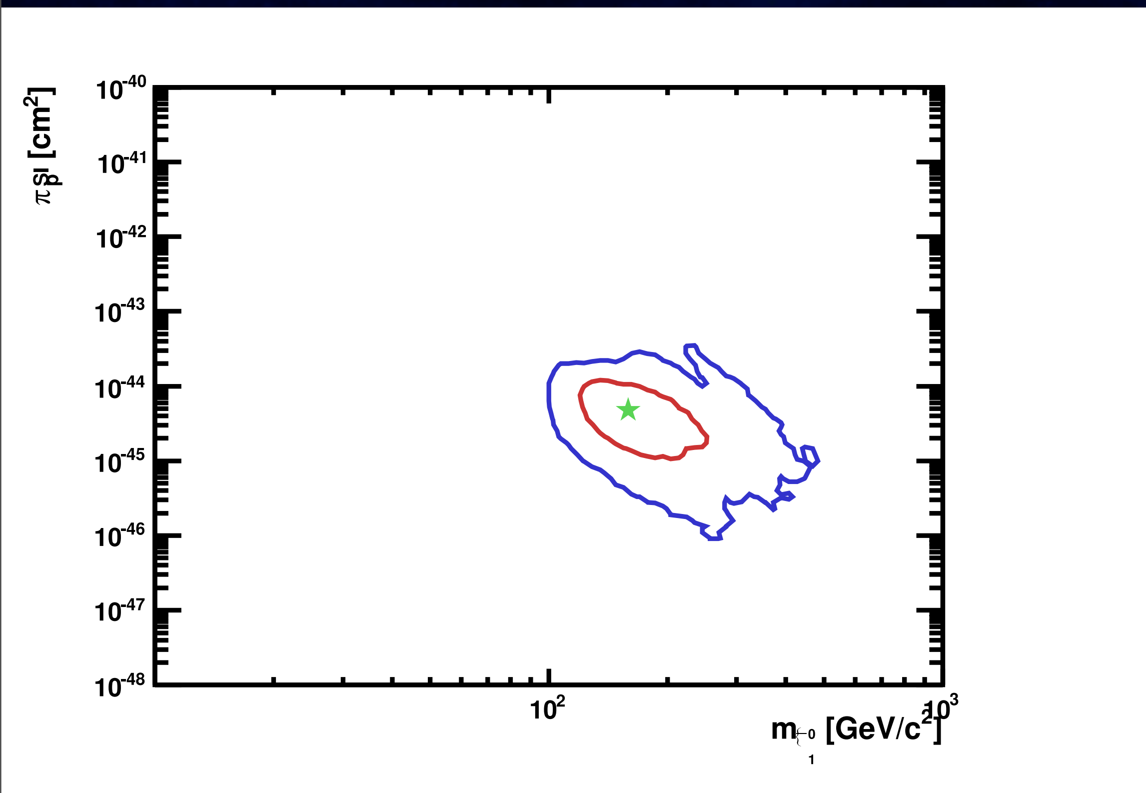
Liquid Xe as WIMPs Target & Detector

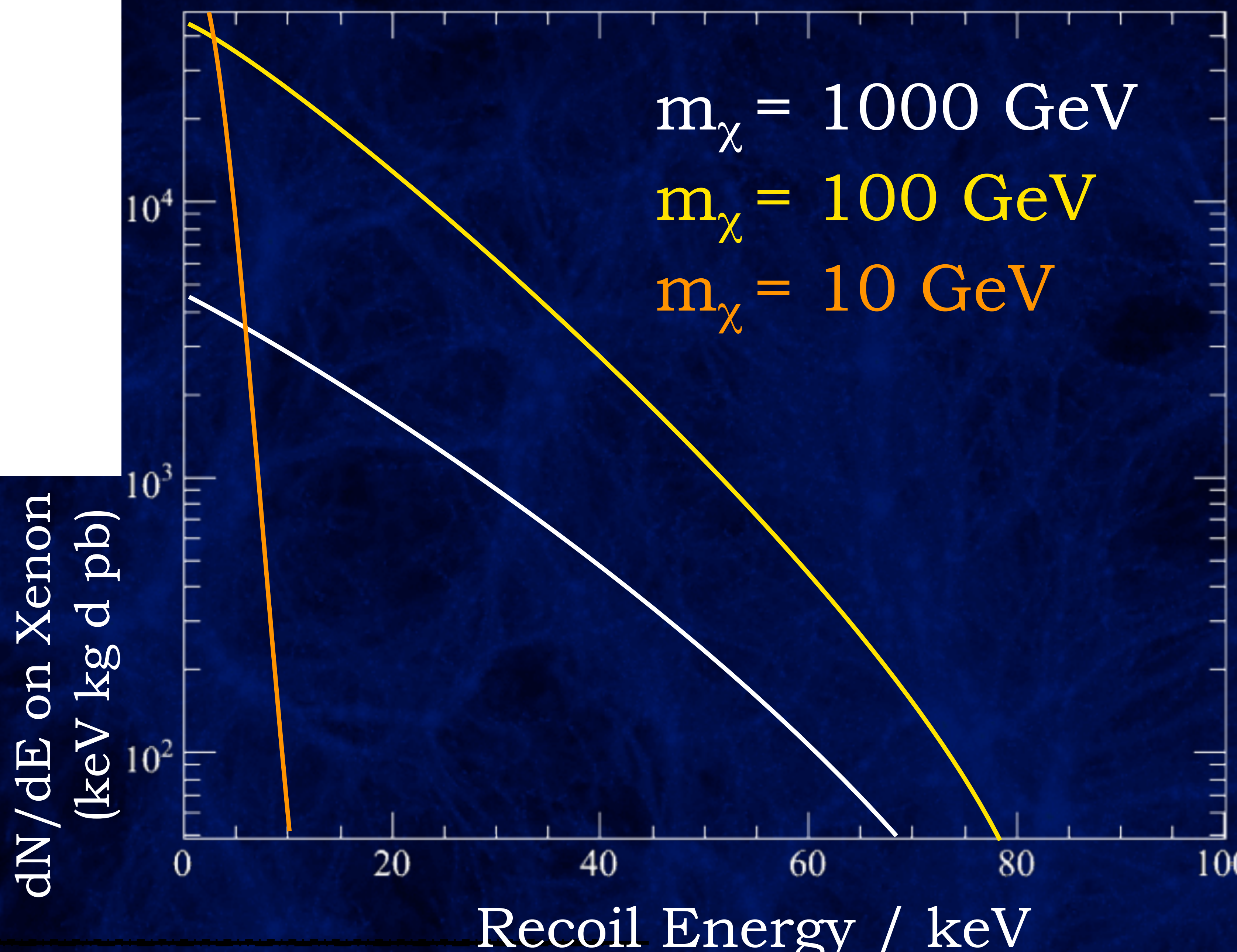
- ★ *scalability:* *relatively inexpensive for very large detector (today ~$700 /kg with <10 ppb Kr/Xe)*
- ★ *big nucleus (A~131):* *good for SI plus SD sensitivity (~50% odd isotopes)*
- ★ *Charge & Light:* *highest yield among noble liquids and best self-shielding*
- ★ *Low energy threshold:* *photosensors within liquid for efficient light detection*
- ★ *Background reduction:* *by charge-to-light ratio, 3D-event imaging, LXe active veto*
- ★ *Intrinsically pure:* *no long-lived radioactive isotopes; Kr/Xe reduction to ppt level with established methods*
- ★ *DM sensitivity:* *the best to-date*



Xe especially promising if WIMP mass is in the 100 GeV range..as hinted by initial LHC searches for SUSY

Buchmueller et al. arXiv:1102.4585



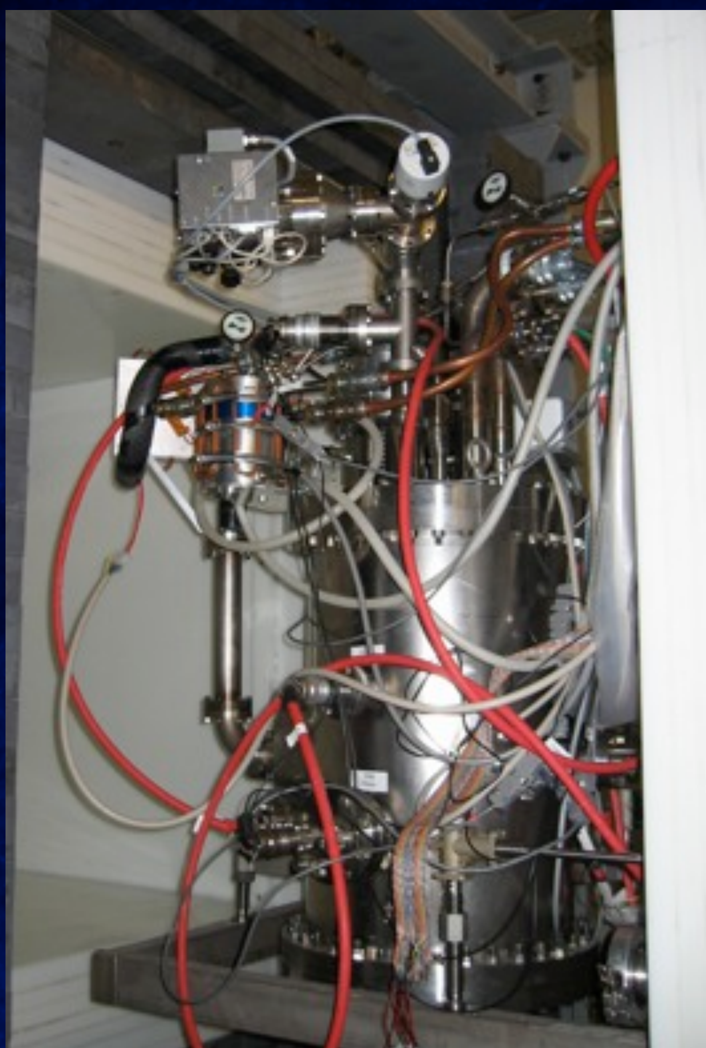


The CMSSM 68% and 95% CL contours in (m_χ, s_{SI}) and the best fit point (green star) with CMS and ATLAS constraints

The XENON Dark Matter Phases

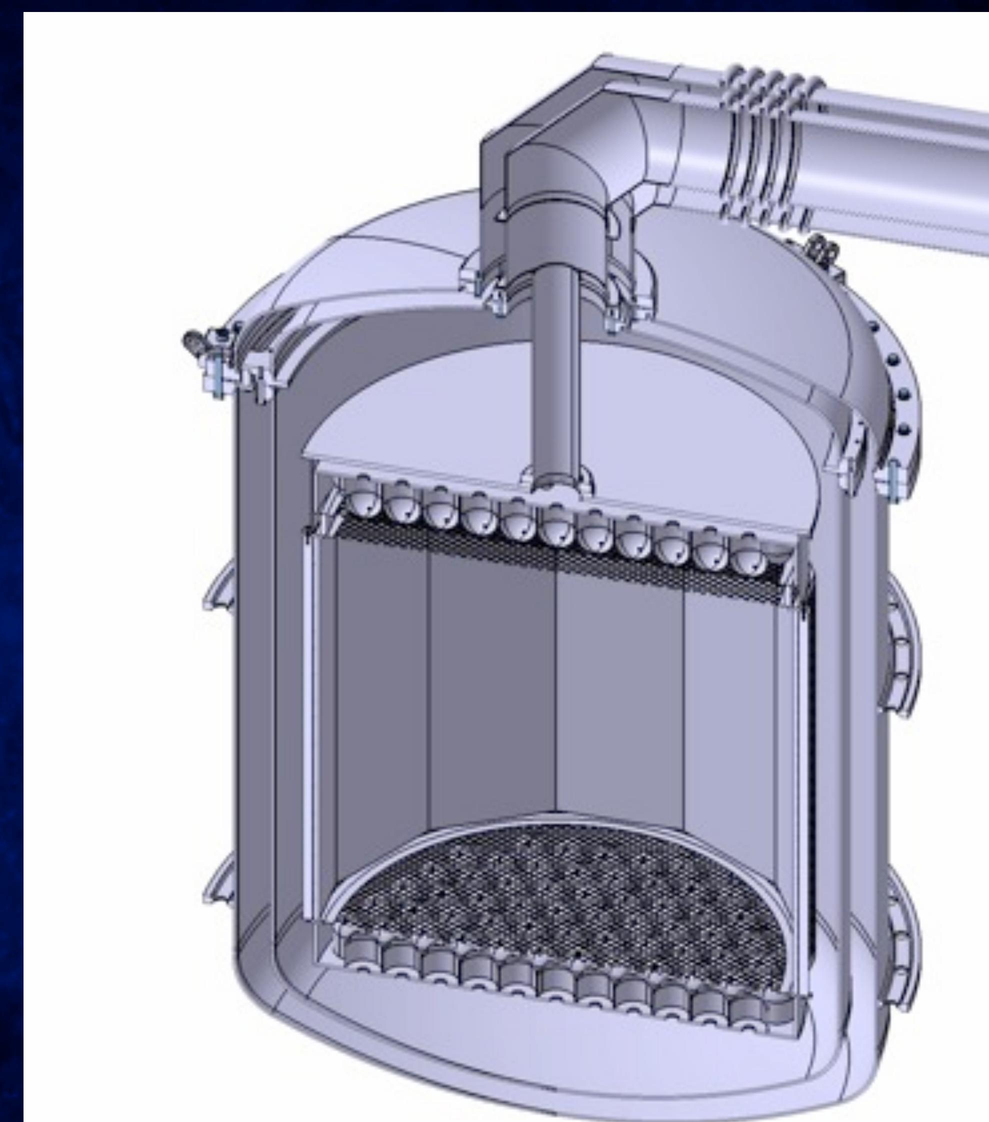
Xe XENON Dark Matter Project

2005 - 2007 | *2008-2011* | *2011- 2015*



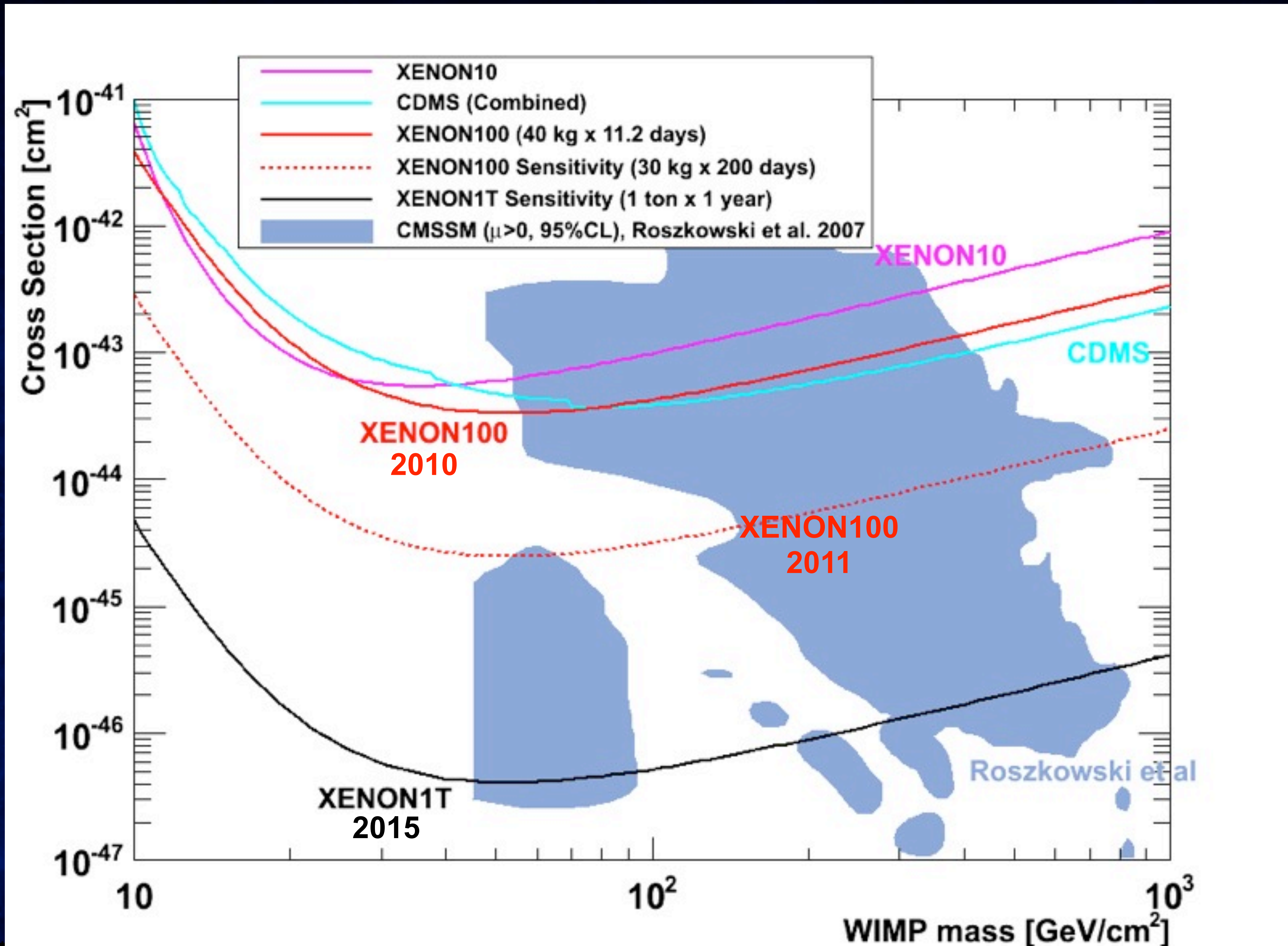
XENON10

XENON100



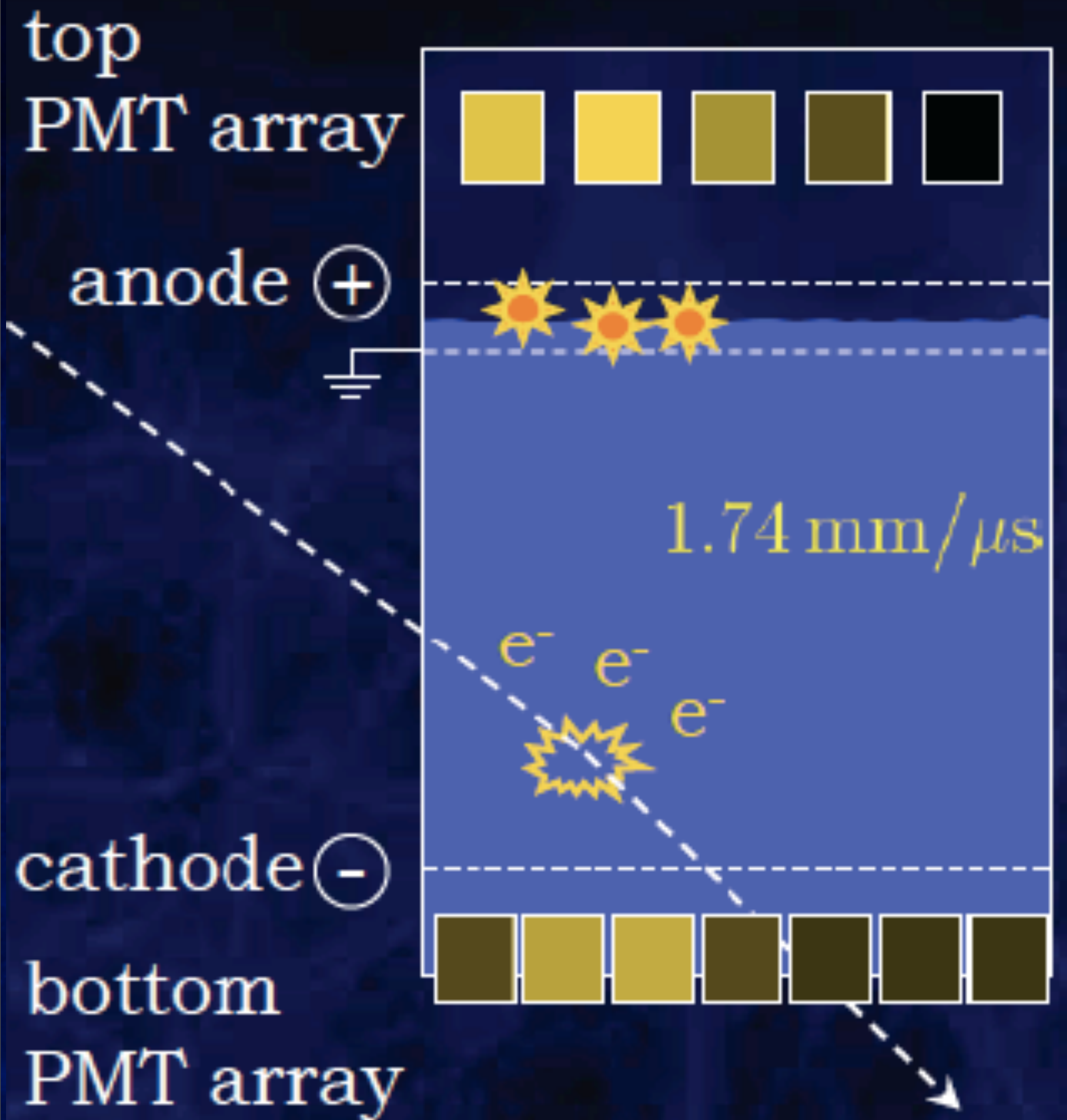
XENON1T

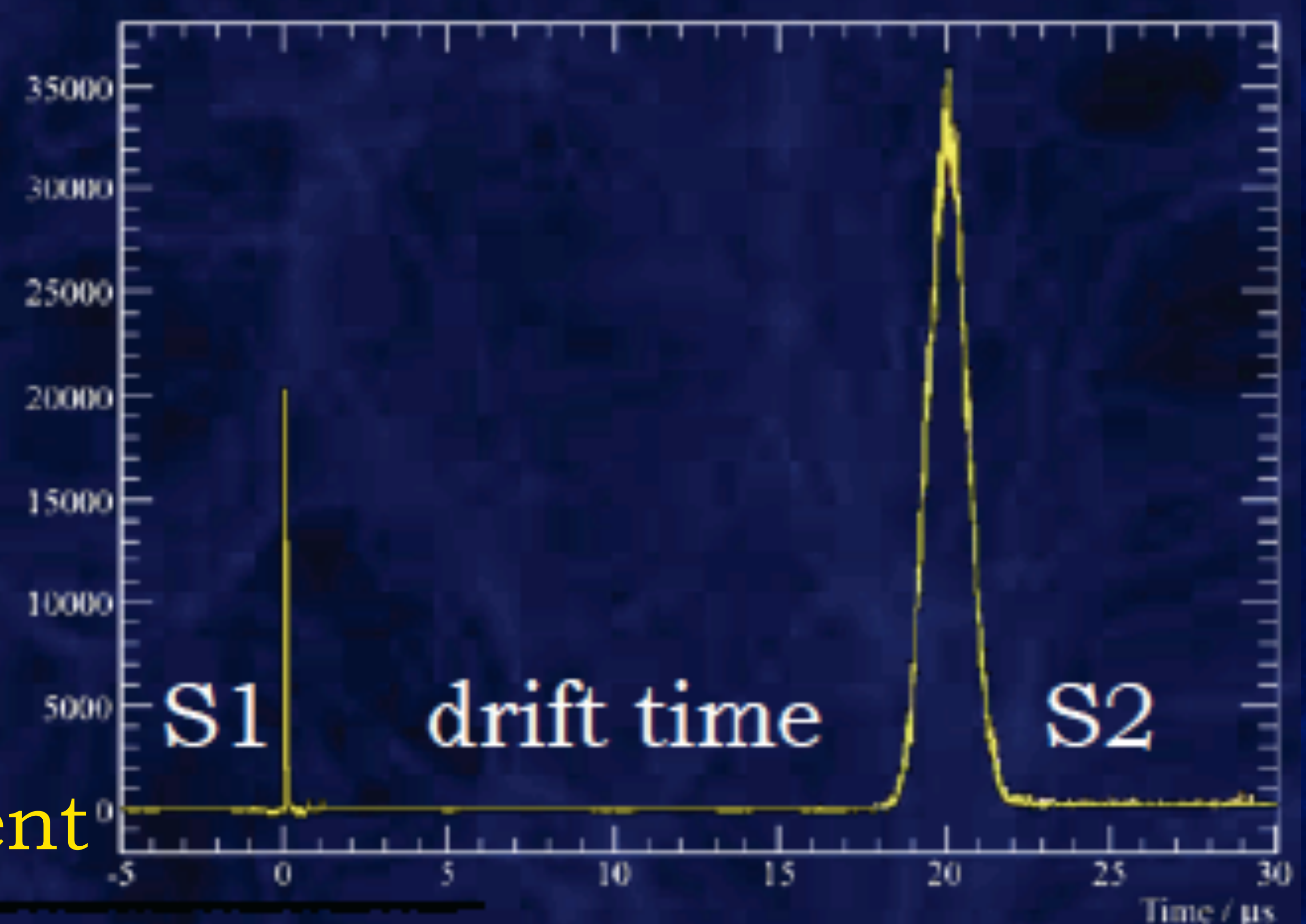
XENON Sensitivity Goal



The XENON Detector Concept

3D position information
S2 hit pattern: $\Delta r < 3\,\mathrm{mm}$
drift time: $\Delta z < 2\,\mathrm{mm}$

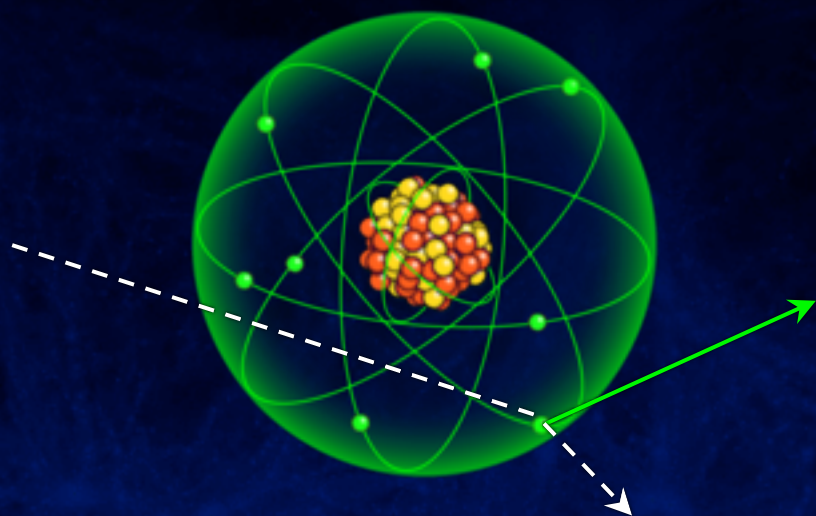


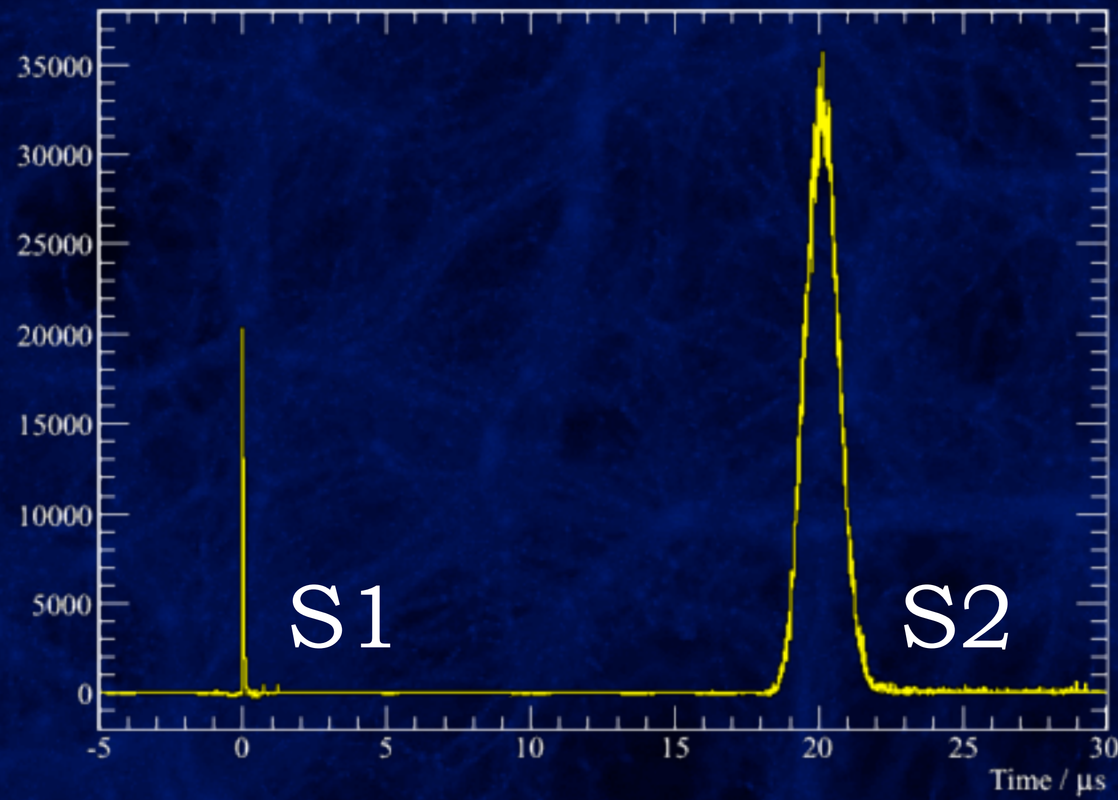


→ lots of information for each event

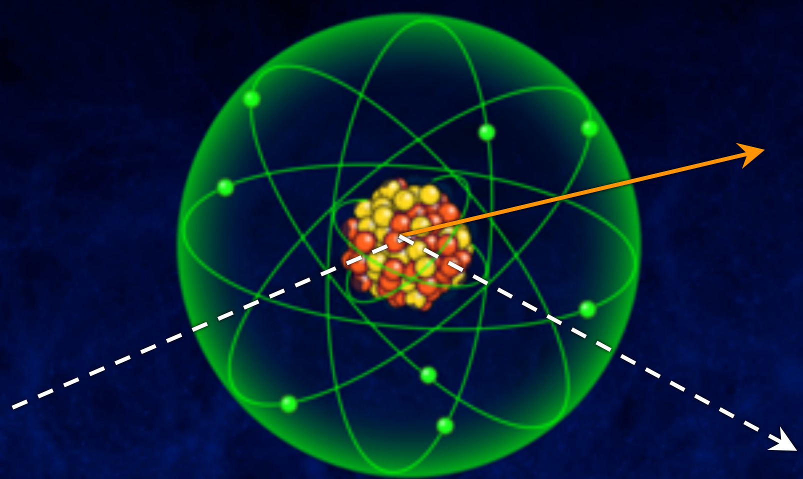
Particle Discrimination

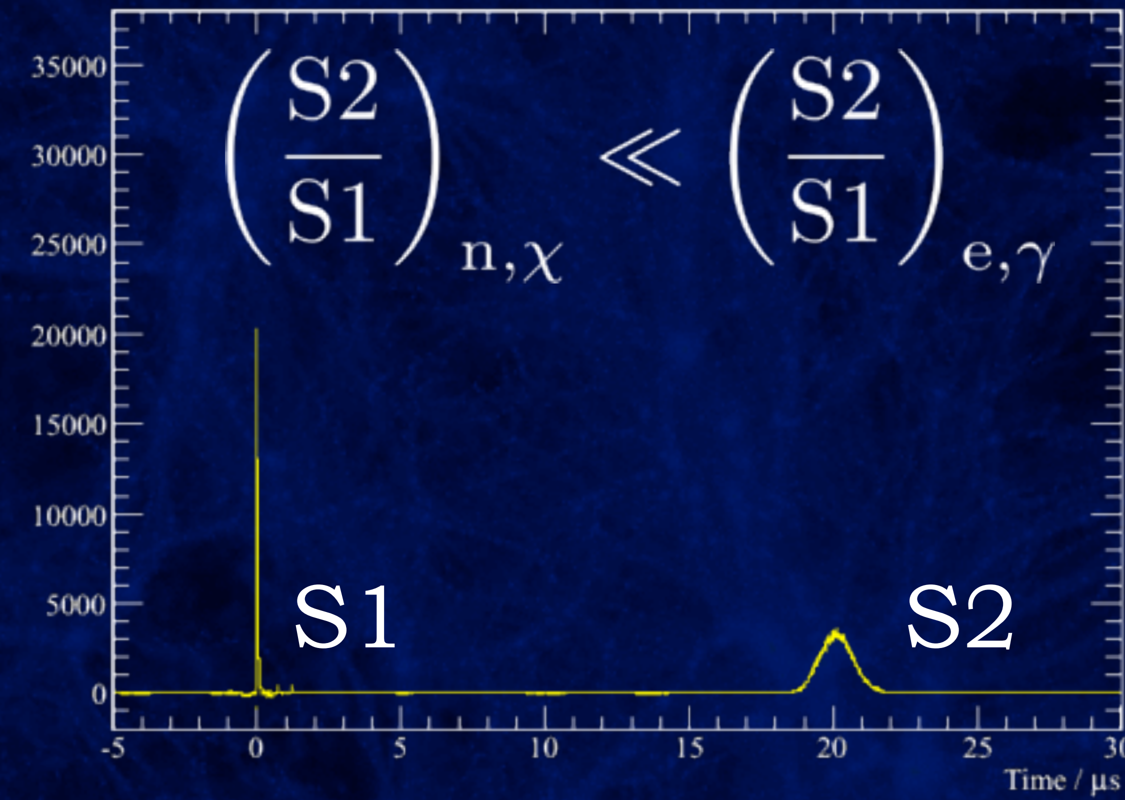
e^-/γ: electronic recoil





n/WIMPs: nuclear recoil

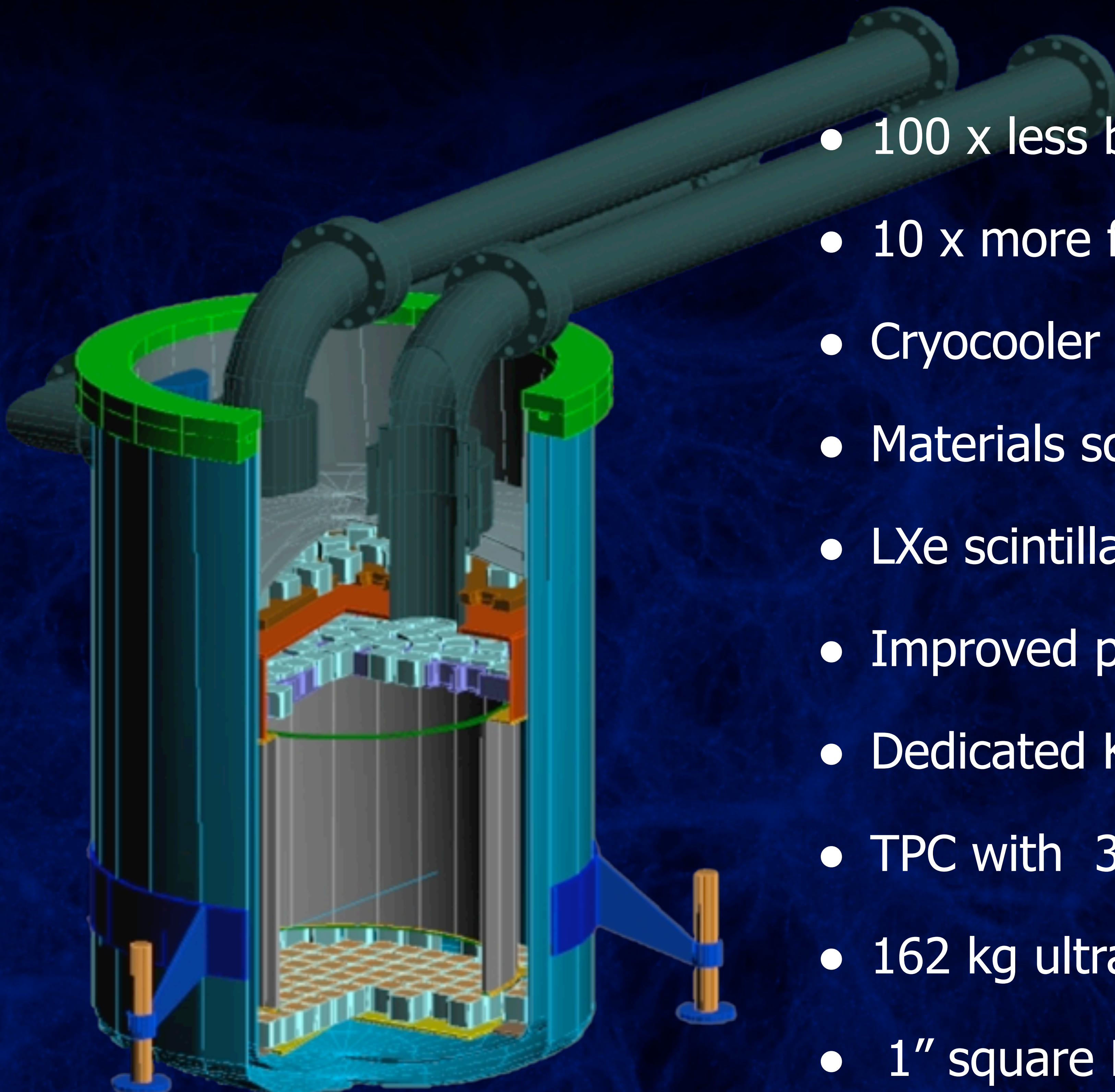




$$\left(\frac{S2}{S1}\right)_{n,\chi} \ll \left(\frac{S2}{S1}\right)_{e,\gamma}$$

(illustration)

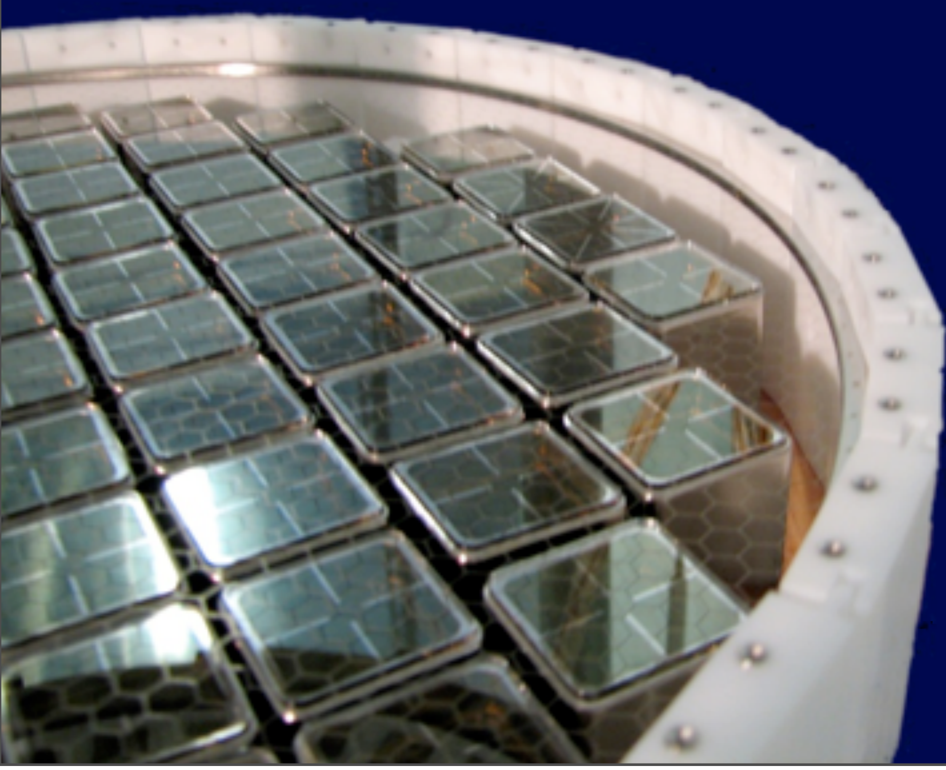
The XENON100 Phase



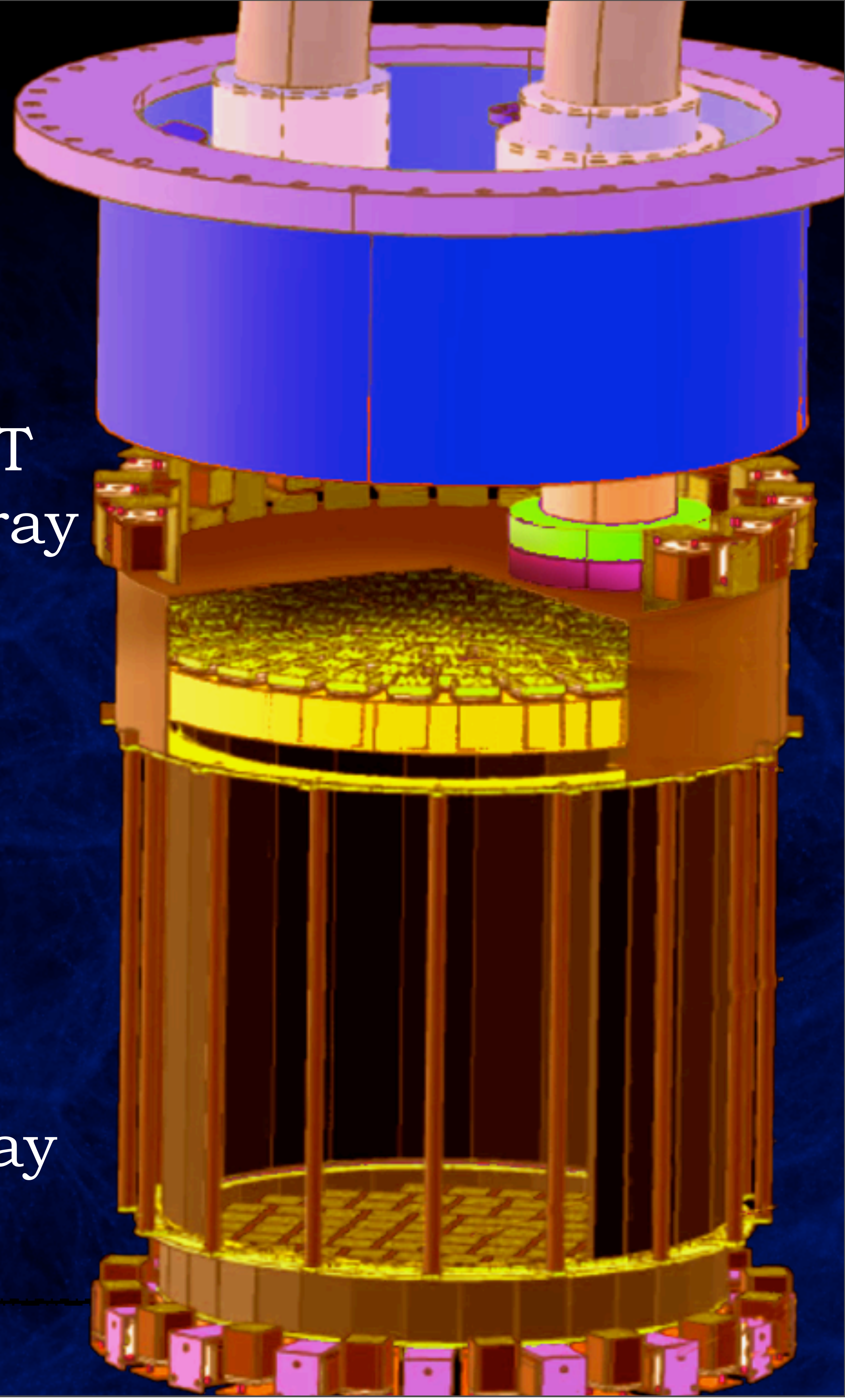
- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr Distillation Column
- TPC with 30 cm drift x 30 cm diameter
- 162 kg ultra pure LXe - 62 kg as target
- 1″ square PMTs with ~1 mBq (U/Th)

XENON100 TPC

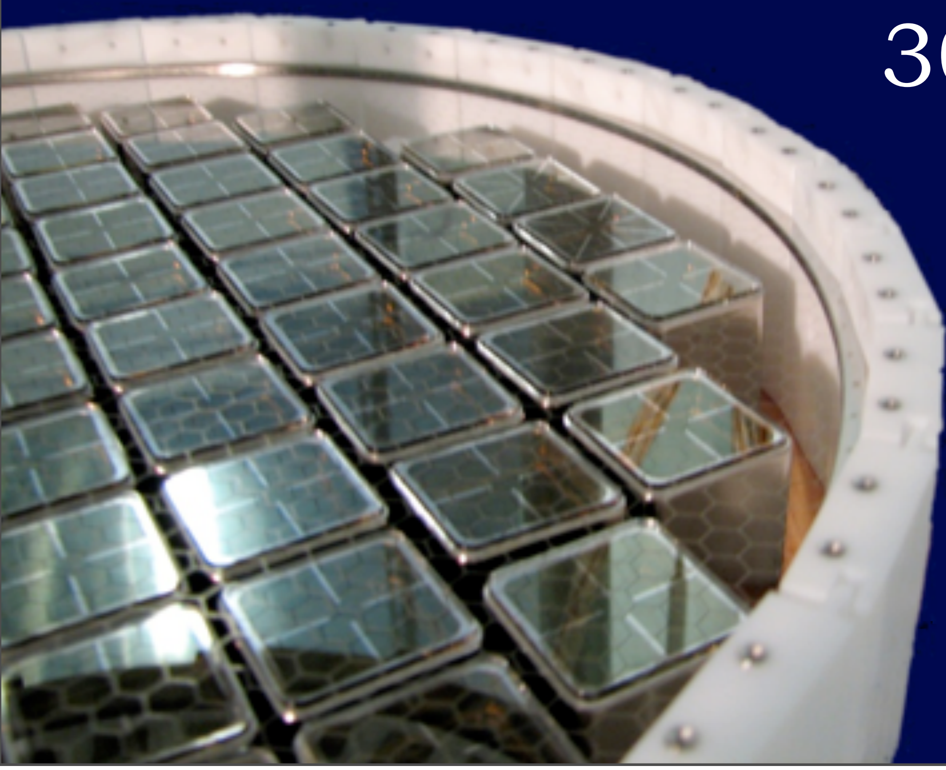
98 PMT
top array

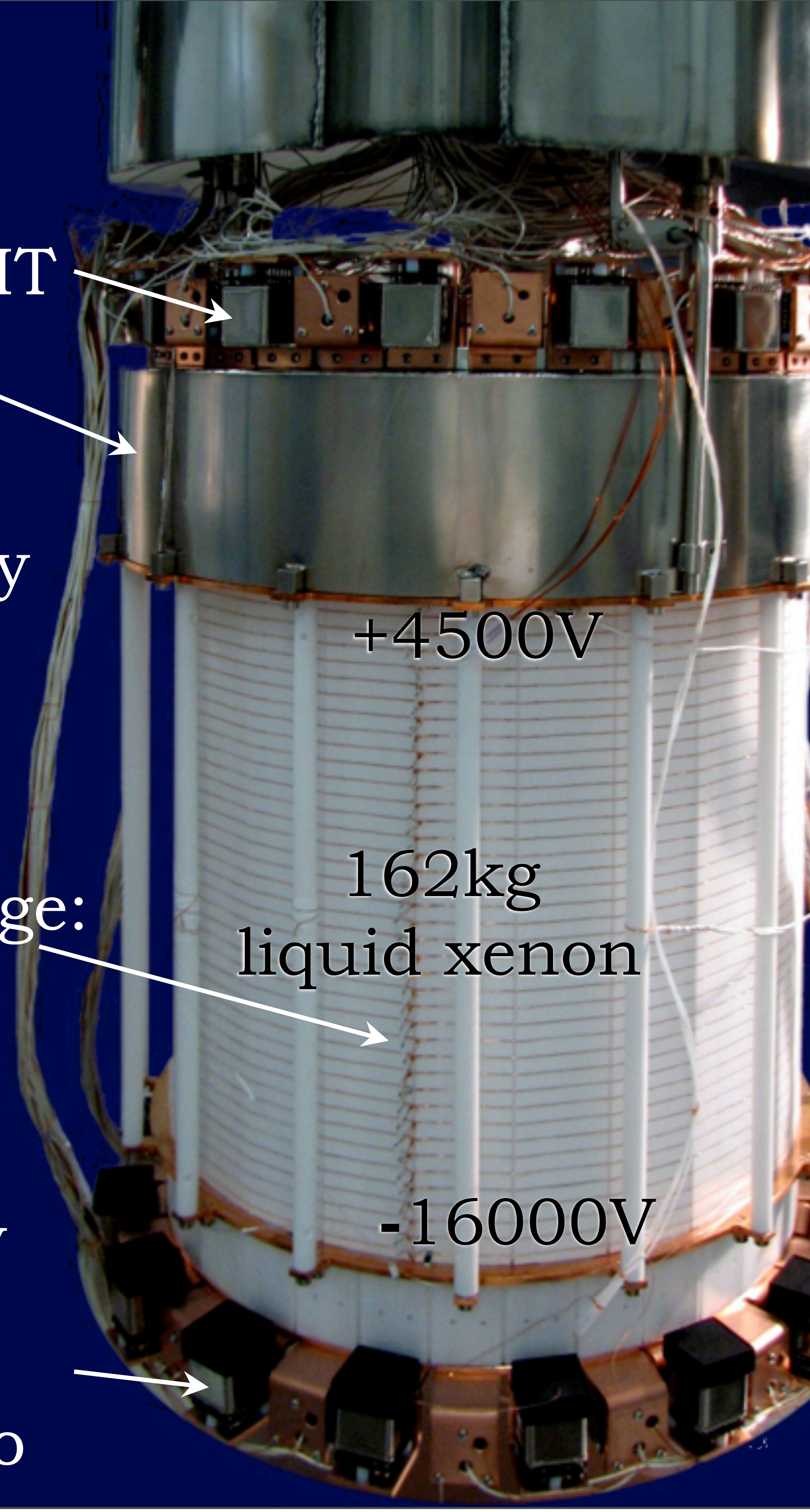


80 PMT
bottom array

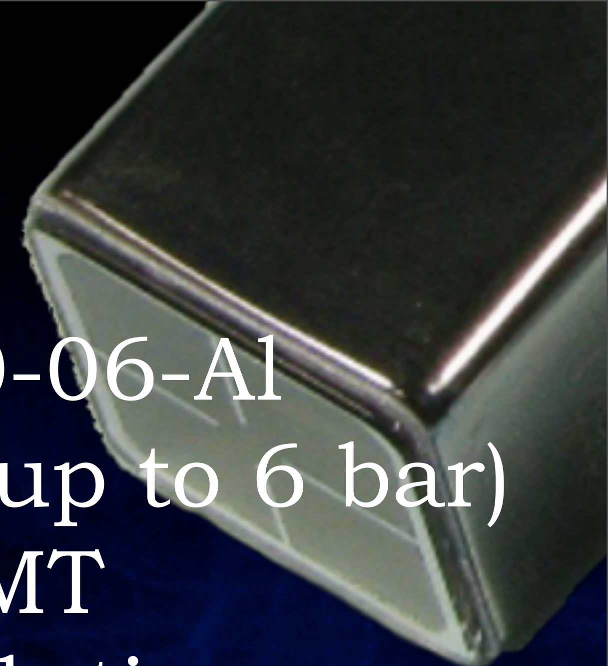


XENON100 TPC

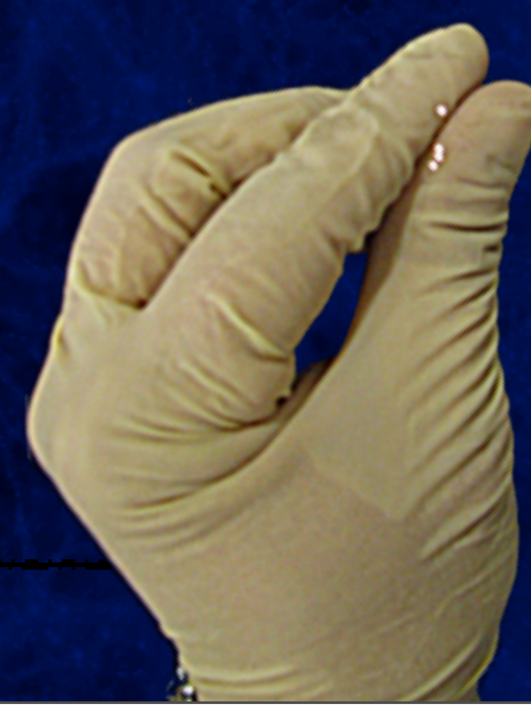


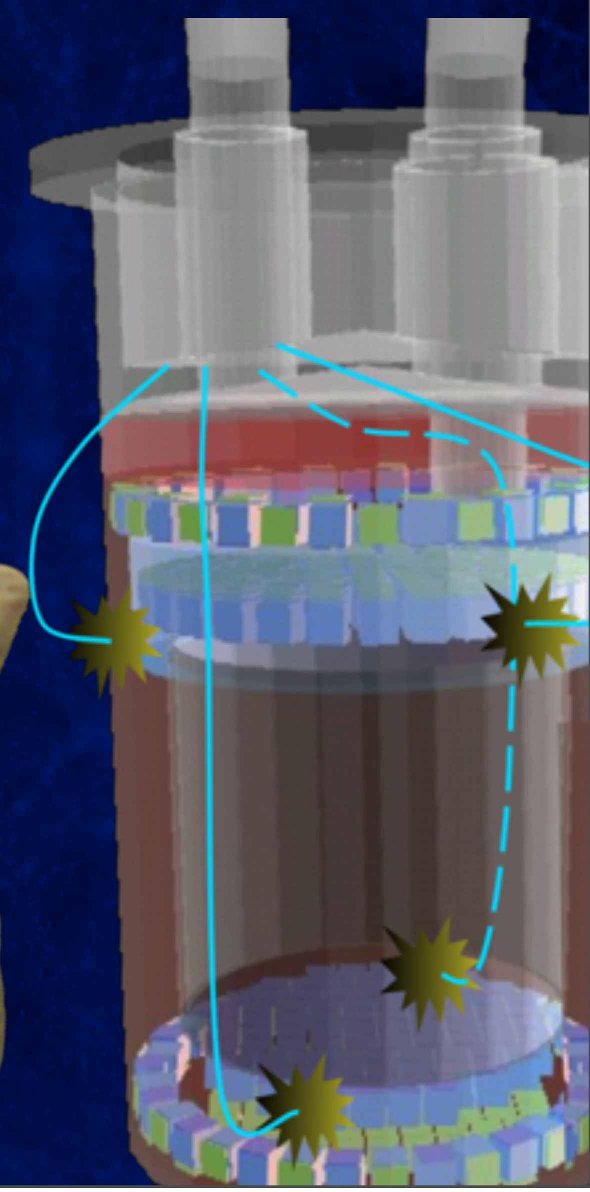


XENON100 PMTs

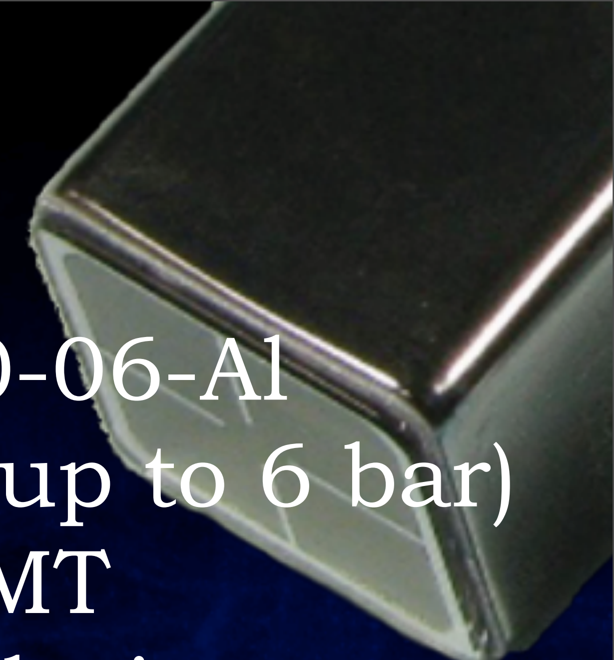


- 1” square metal-channel Hamamatsu R8520-06-Al
- optimized for 178nm, low T (-110C), high P (up to 6 bar)
- low radioactivity <1mBq in $^{238}U/^{232}Th$ per PMT
- 98 top PMTs, optimized for good spatial resolution
- 80 bottom PMTs, optimized for filling factor, QE ~33%
- 64 in LXe veto looking up, down and inward
- regular gain monitoring





XENON100 PMTs



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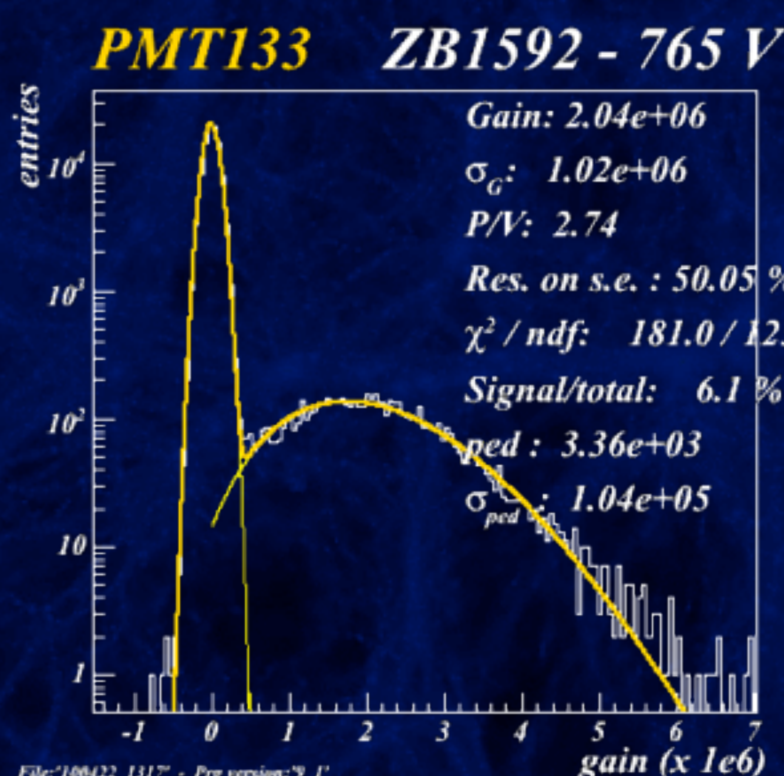
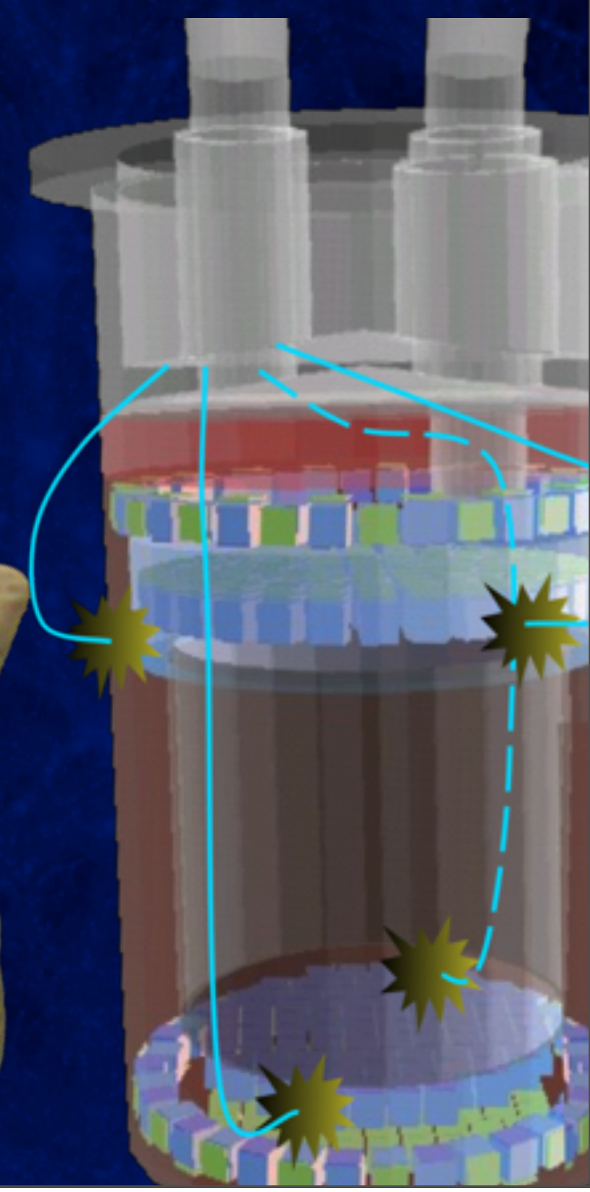
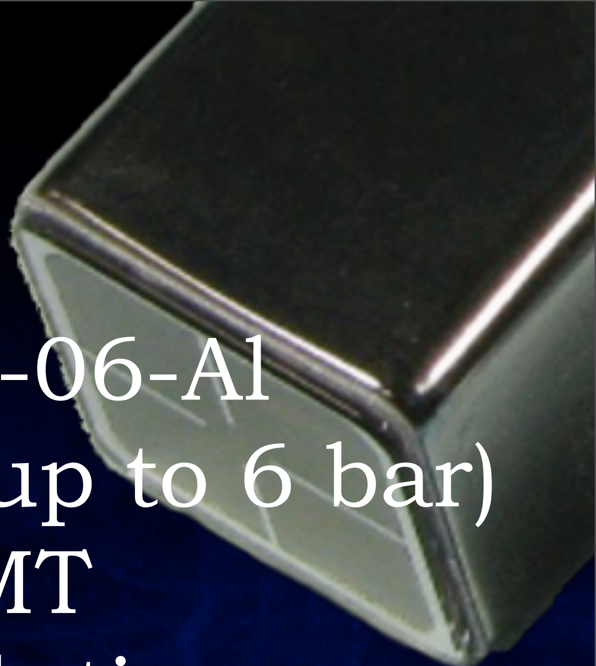




XENON100 PMTs



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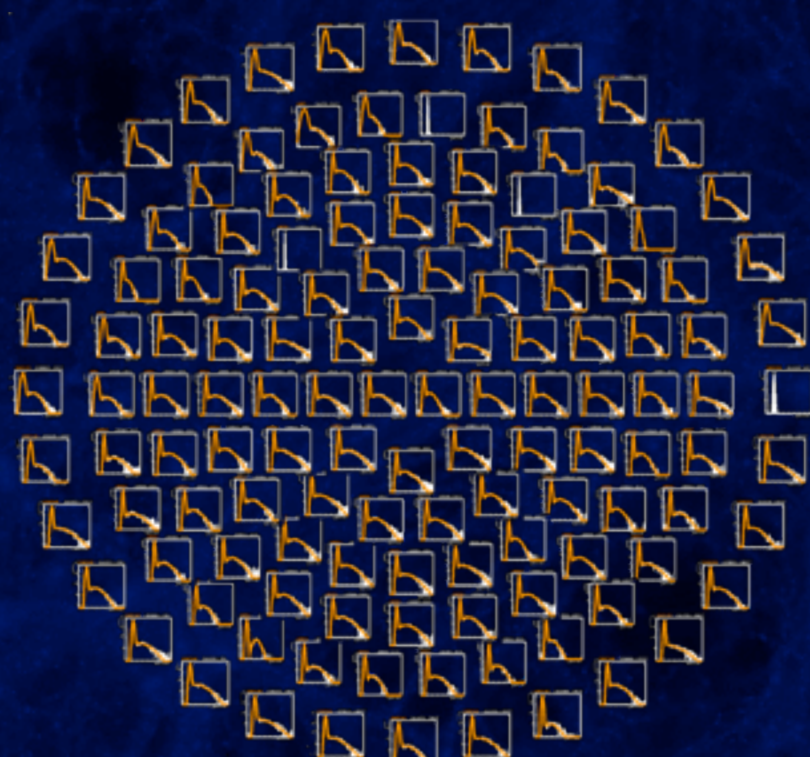
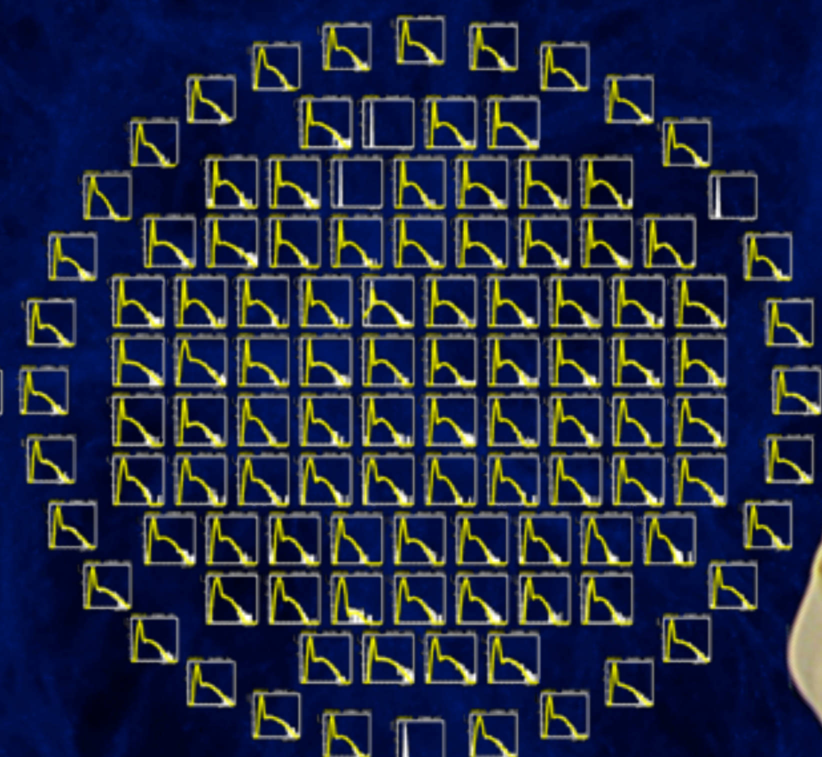
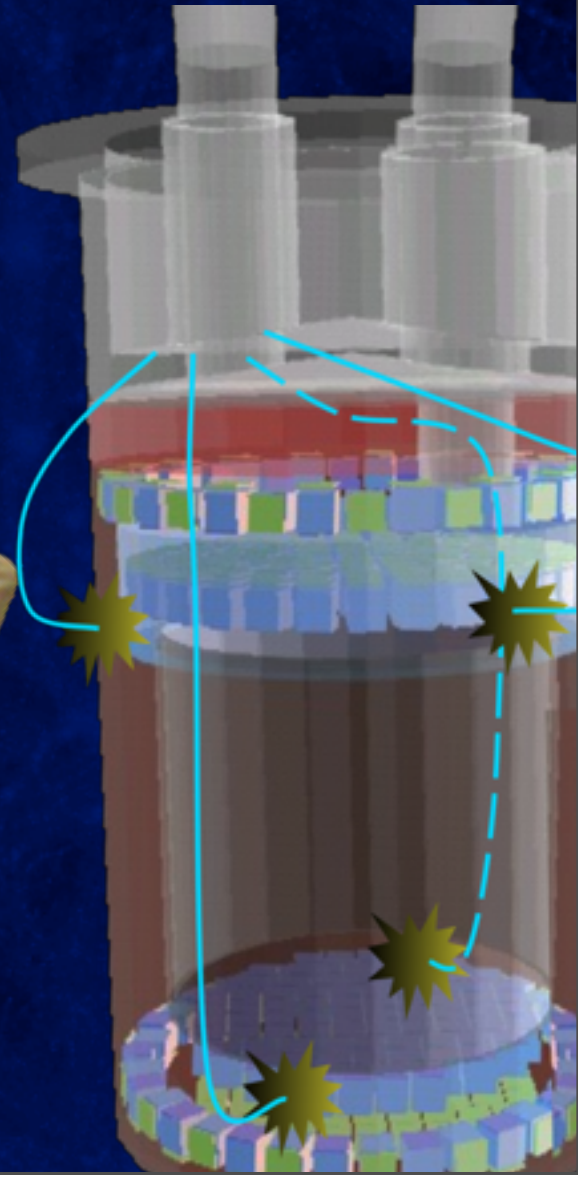
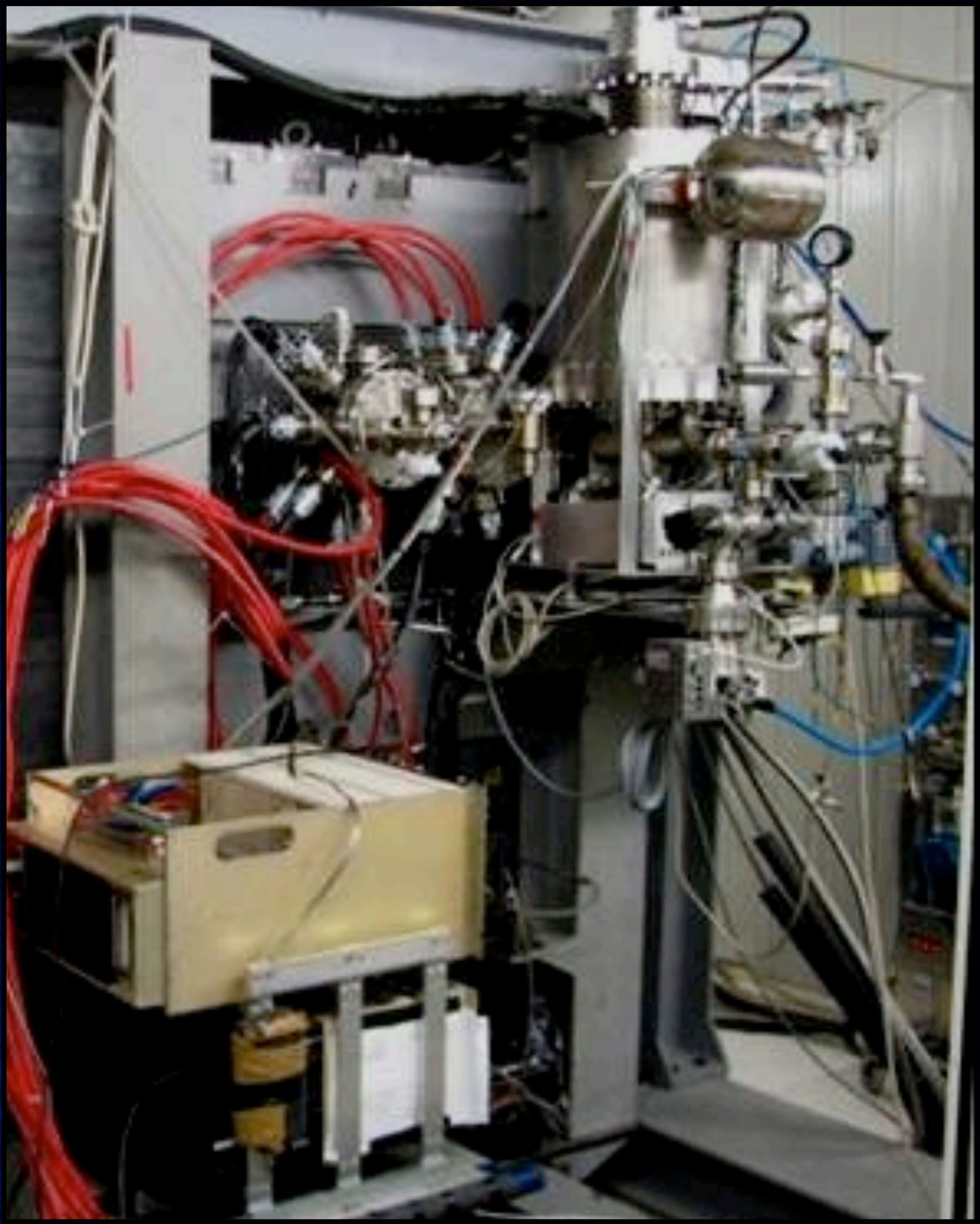




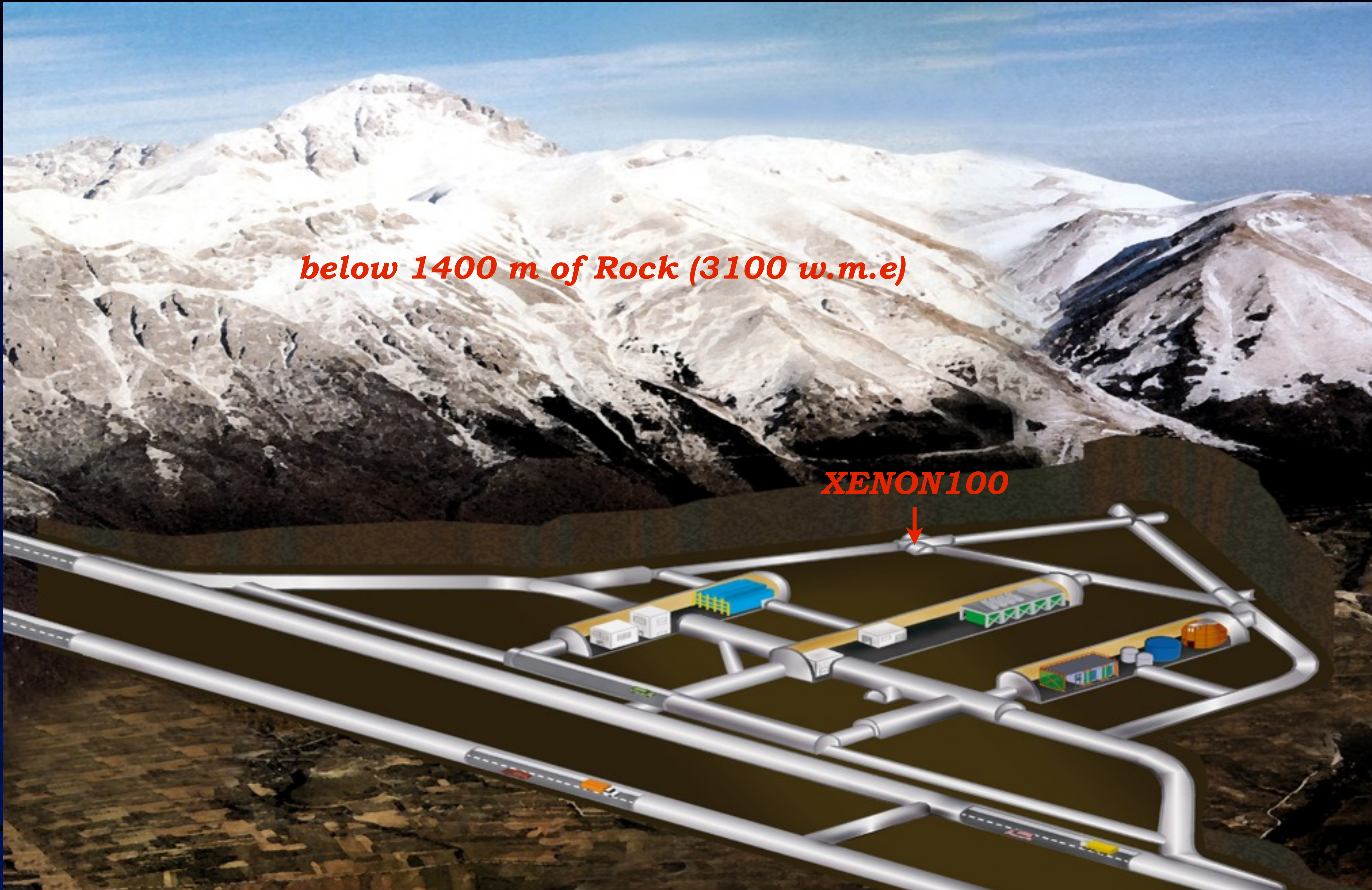


XENON100 Shield



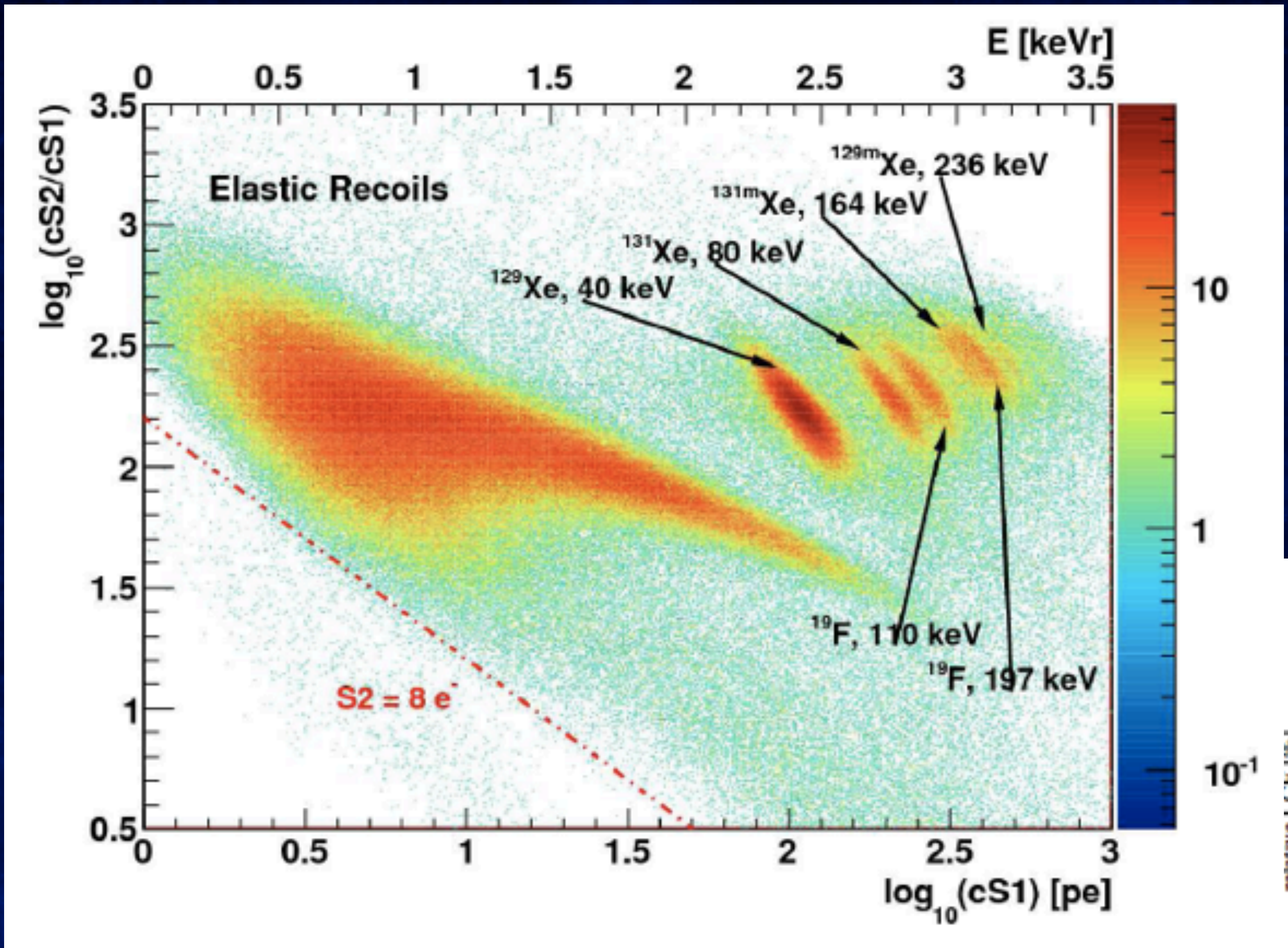
20cm H_2O, 15cm (high activity) Pb, 5cm (low activity) Pb, 20cm PE, 5cm Cu

XENON100 @ Gran Sasso Underground Lab

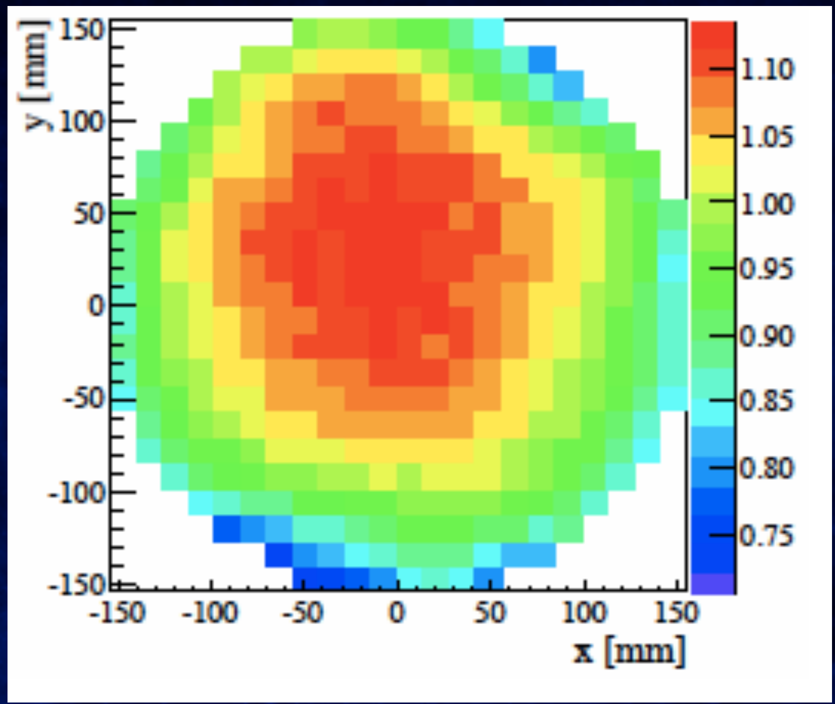


XENON100 Light & Charge

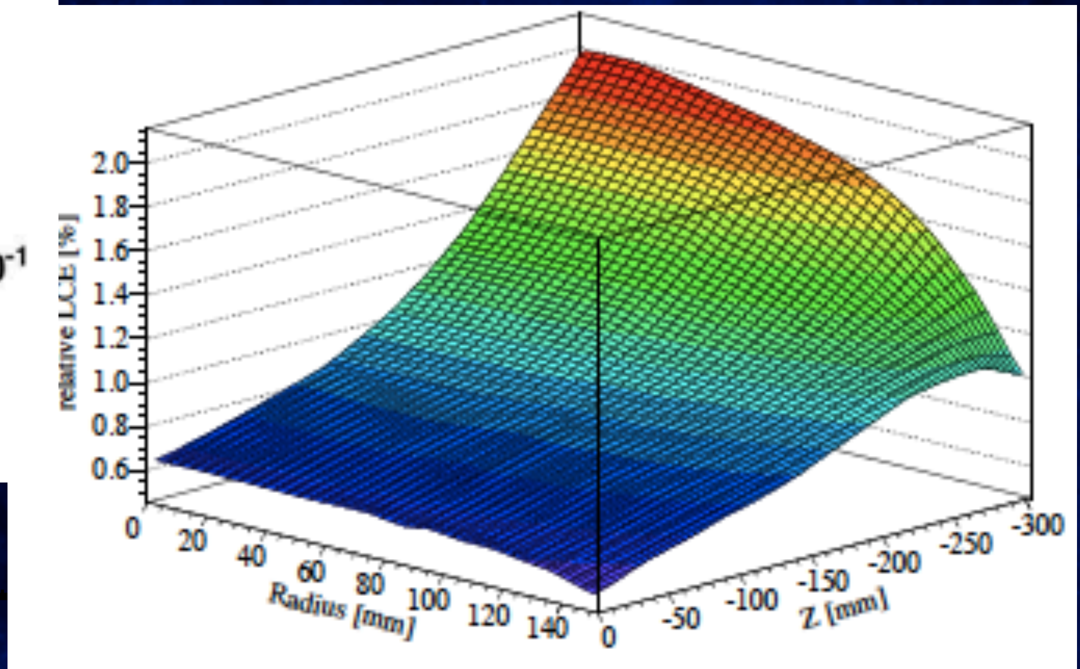
AmBe Calibration Data:
more than just n-recoils



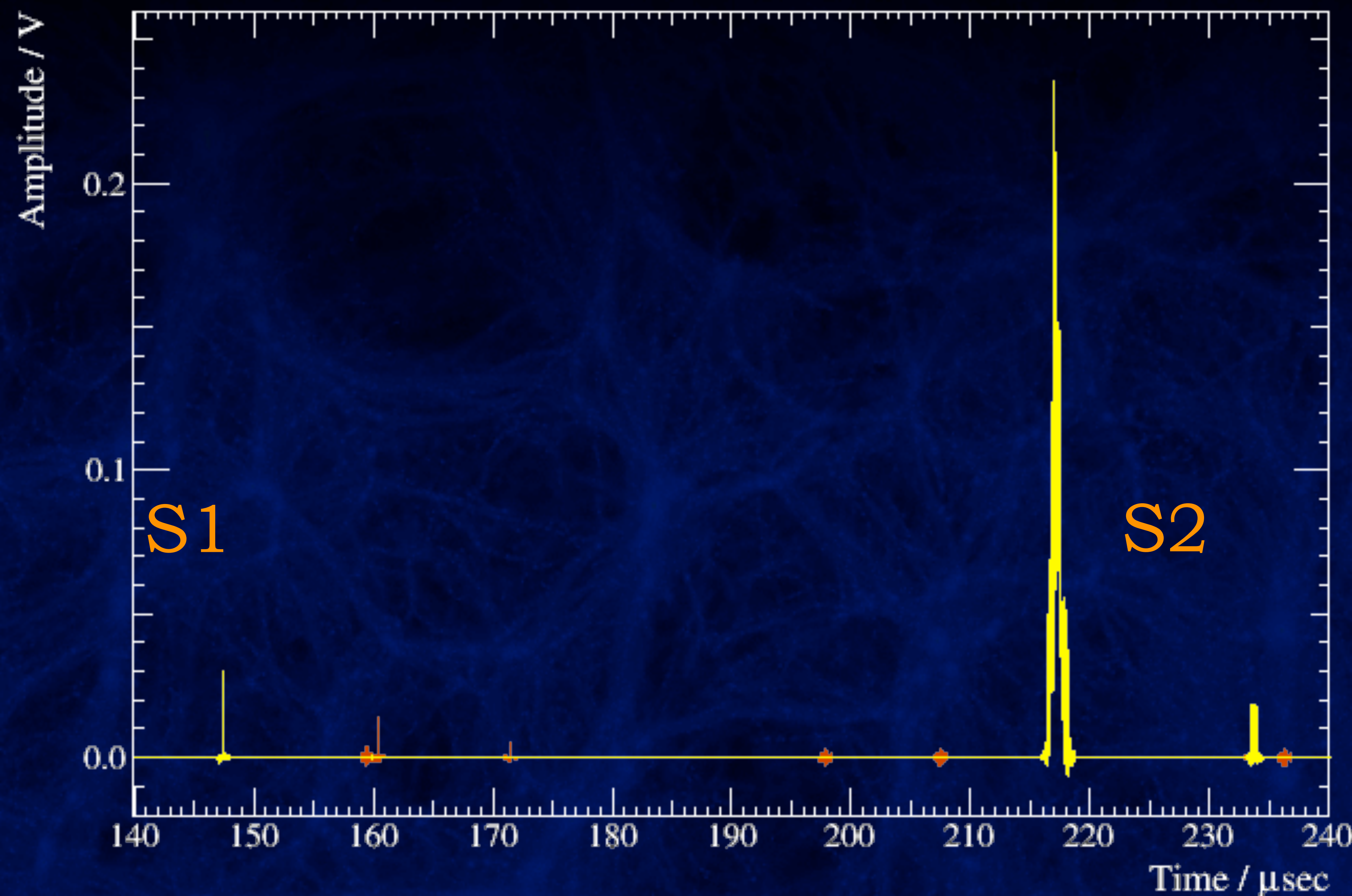
S2 x-y dependence



S1 light collection

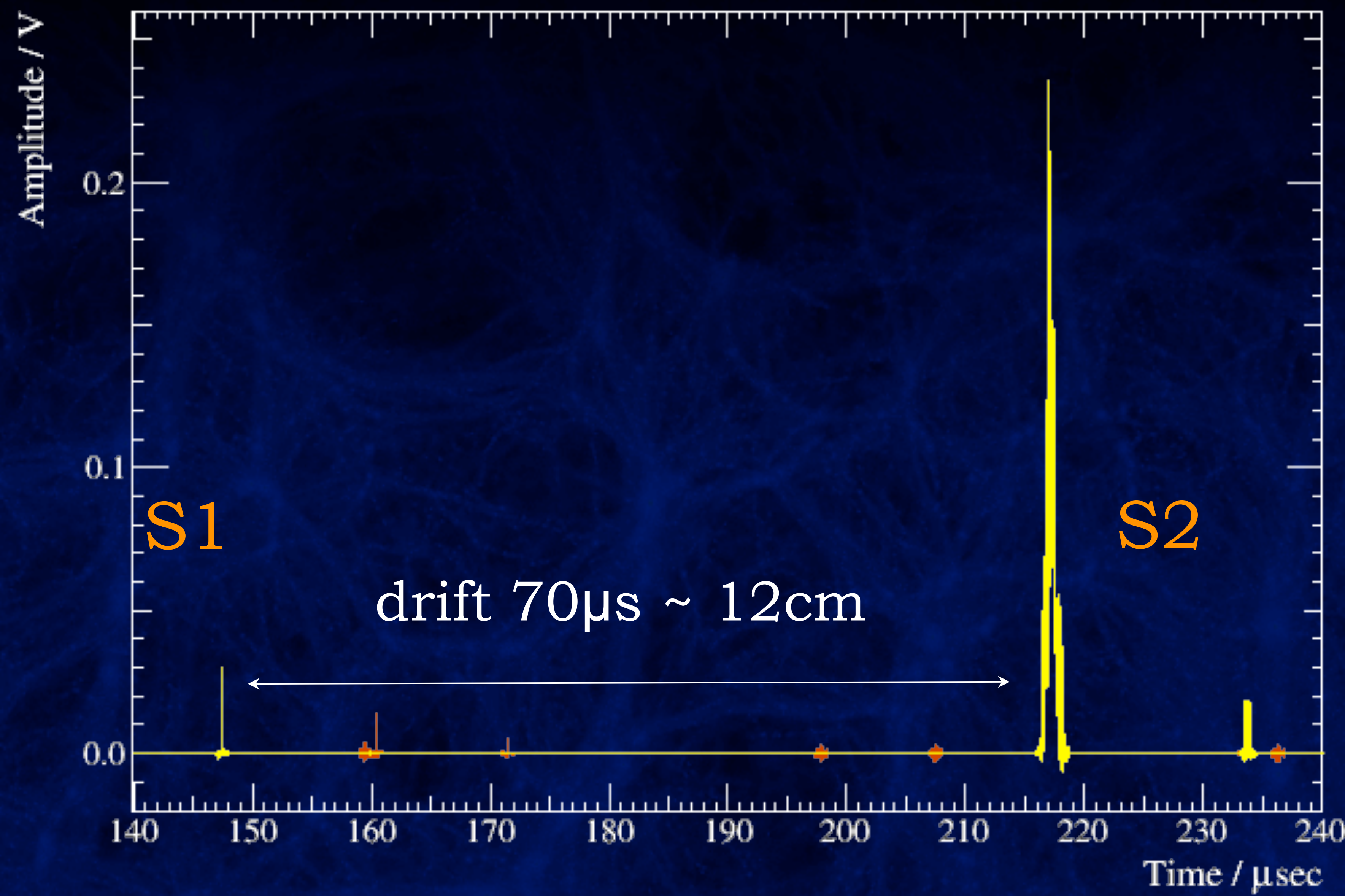


Example: 9keV$_{nr}$ Nuclear Recoil



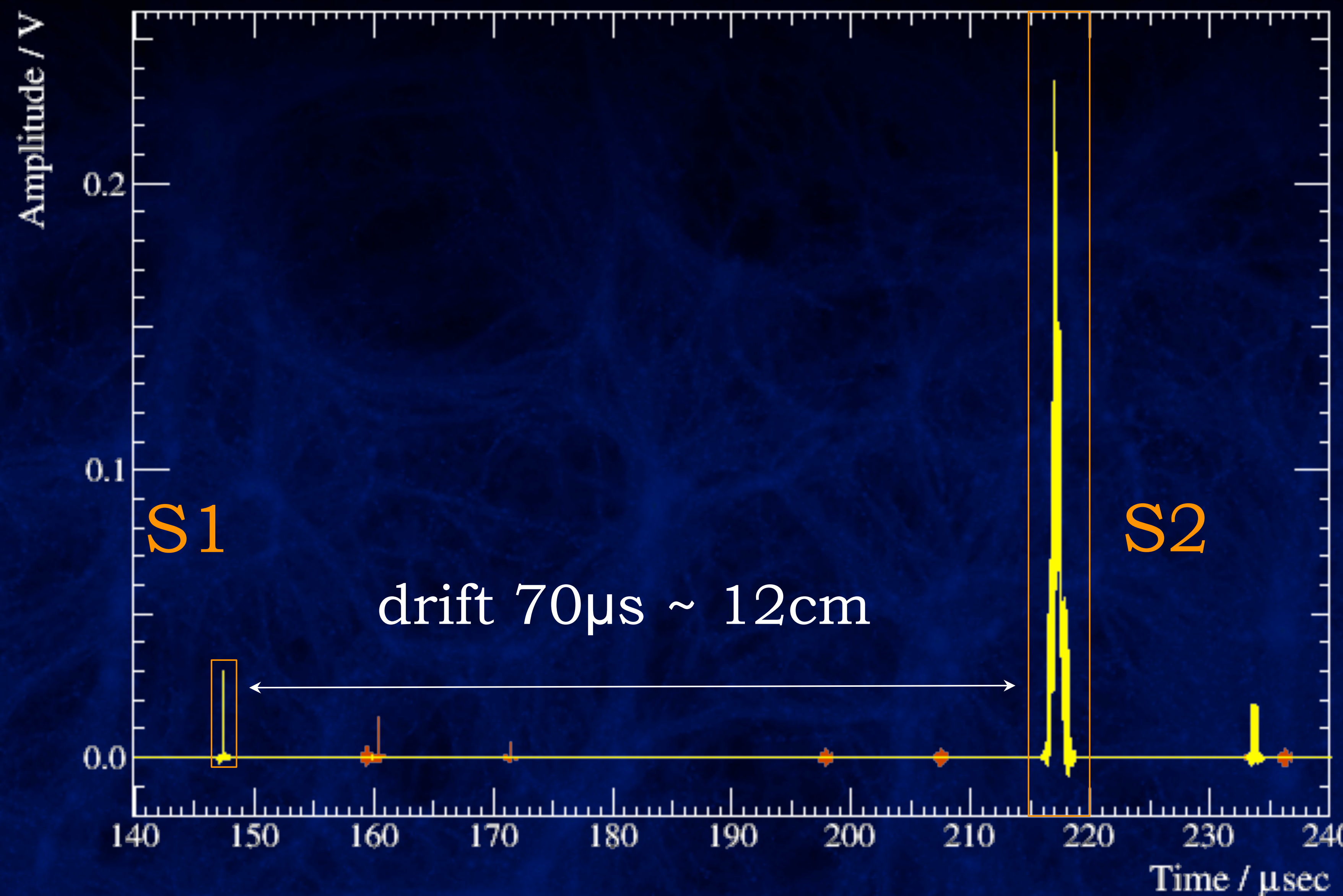
xe100_091215_1039_000030-830

Example: 9keV$_{nr}$ Nuclear Recoil



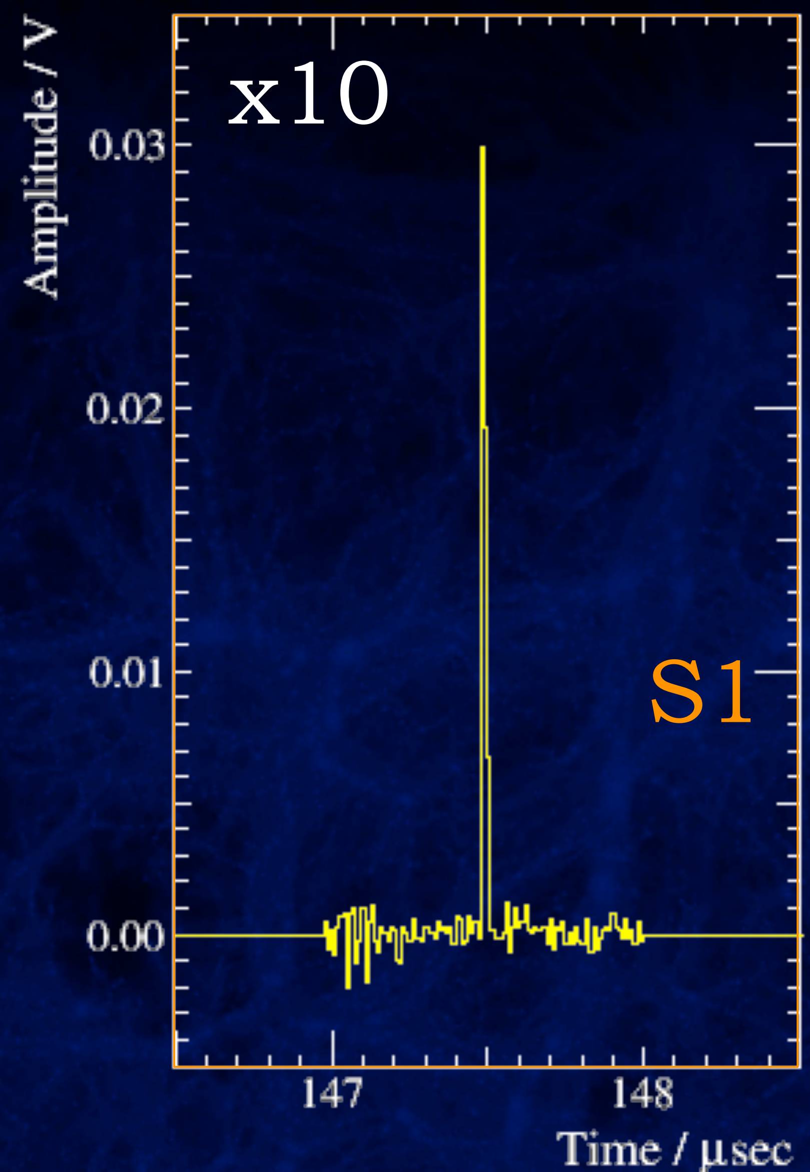
xe100_091215_1039_000030-830

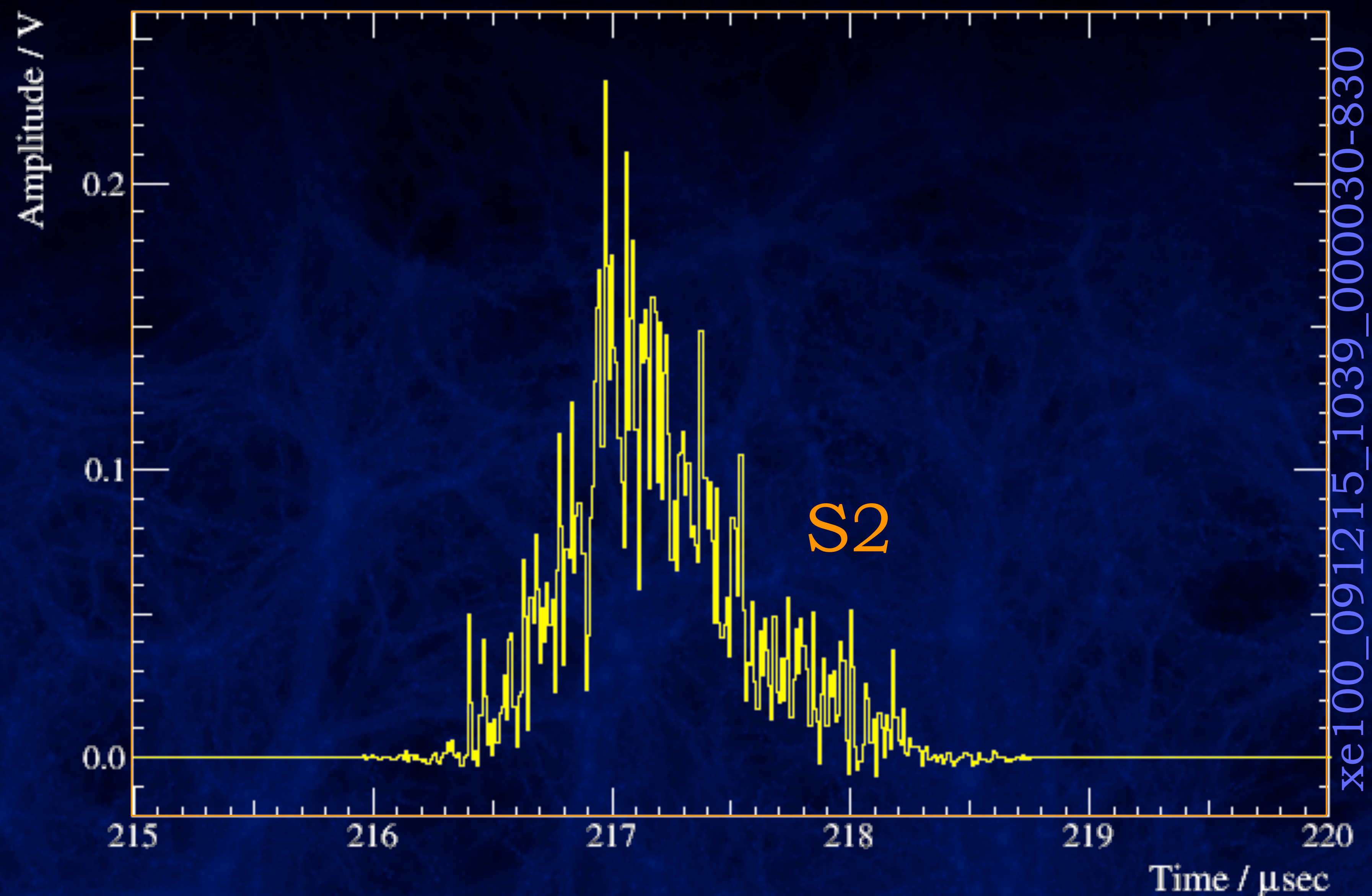
Example: 9keV$_{nr}$ Nuclear Recoil



xe100_091215_1039_000030-830

Example: 9keV$_{nr}$ Nuclear Recoil

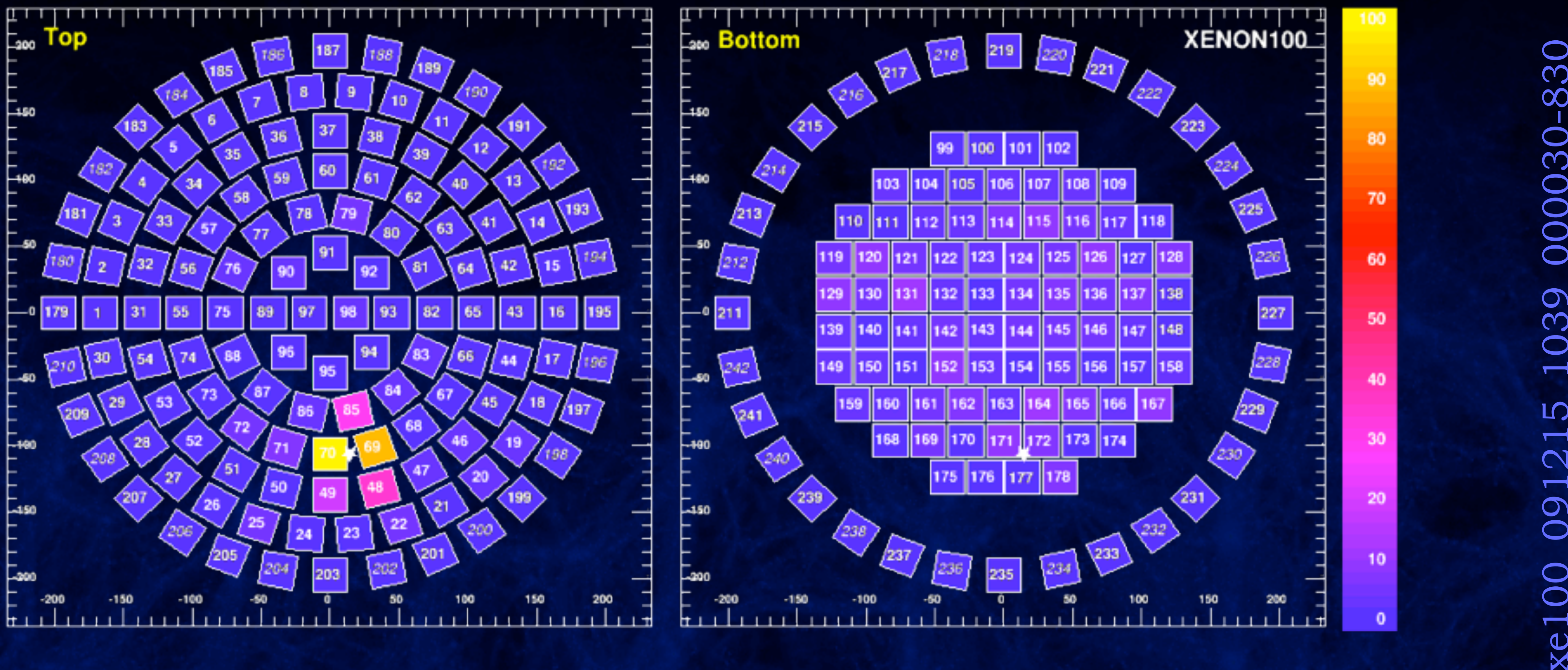




3.6 PE detected
(from ~100 S1 photons)

645 PE detected
(from 32 ionization electrons which generated ~3000 S2 photons)

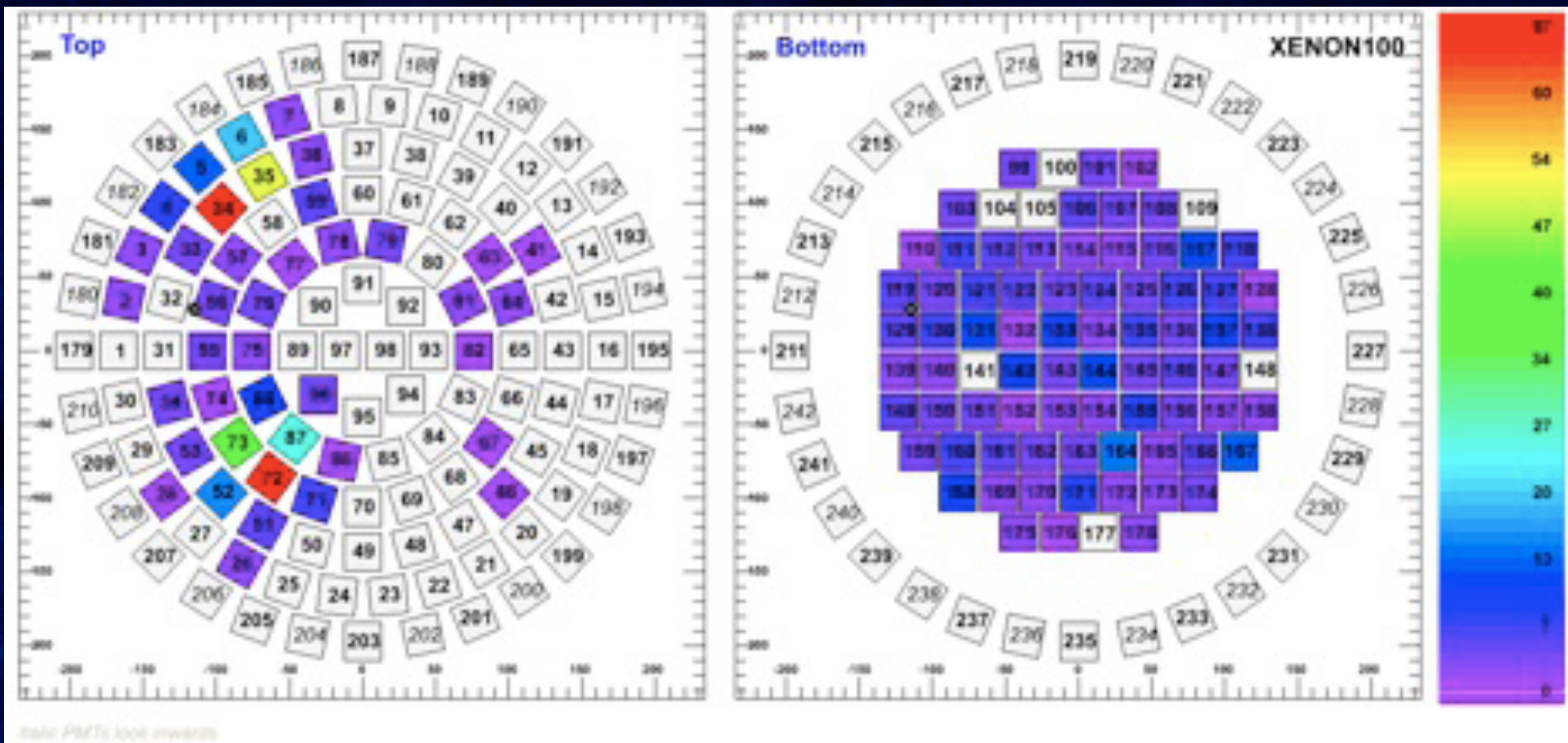
Example: 9keV$_{nr}$ Nuclear Recoil



position reconstruction based on top S2 hit pattern

$\Delta r < 3\,\mathrm{mm};\;\; \Delta z < 2\,\mathrm{mm}$

Typical Double Scatter AmBe Event



Nuclear Recoil Equivalent Energy

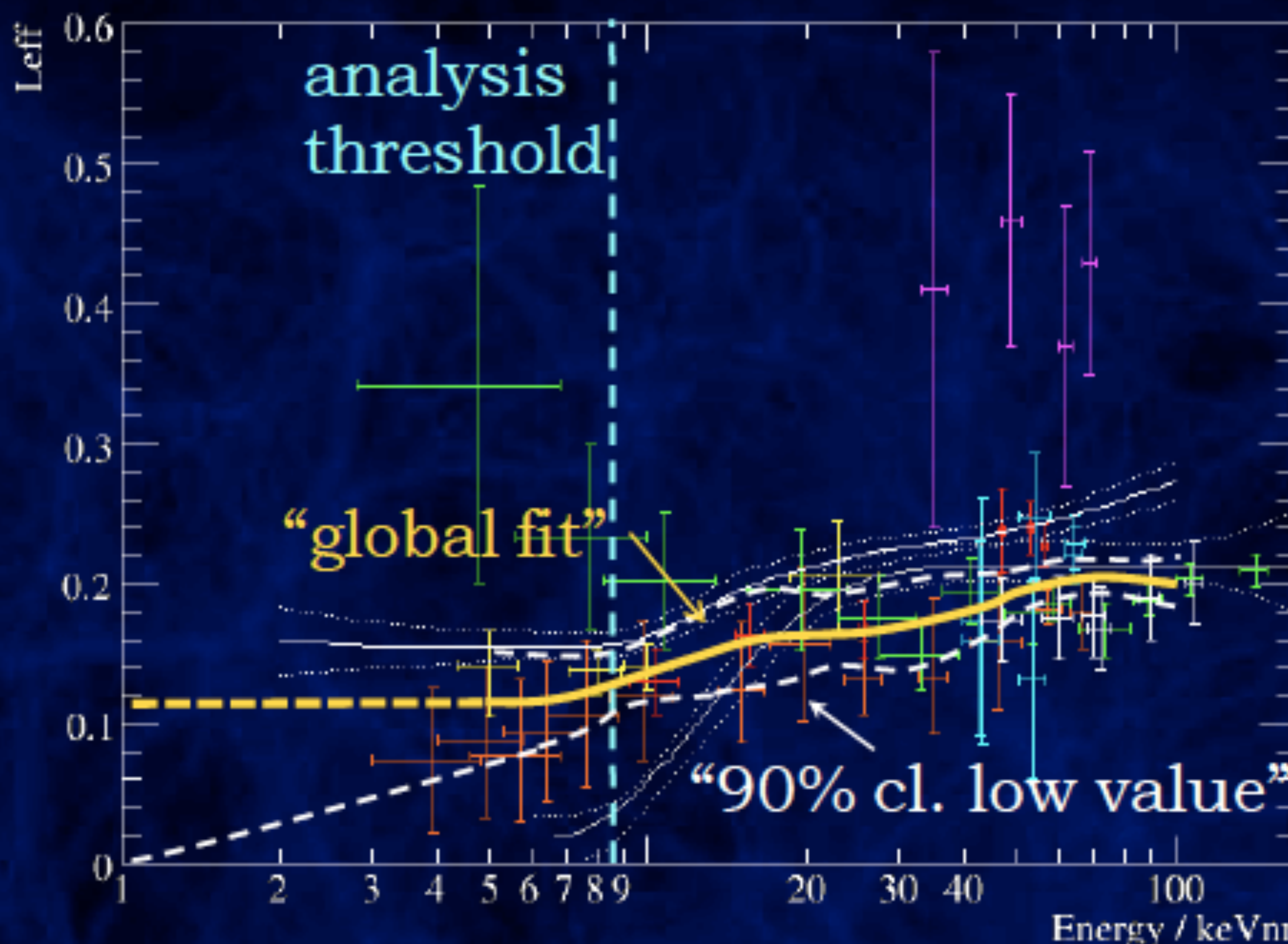
Nuclear Recoil Energy: $E_{\mathrm{nr}} = \frac{S1}{L_y} \cdot \frac{S_{\mathrm{ee}}}{S_{\mathrm{nr}}} \cdot \frac{1}{\mathcal{L}_{\mathrm{eff}}}$

$L_y(122\,\mathrm{keV_{ee}}) = (2.2 \pm 0.1)\,\frac{\mathrm{PE}}{\mathrm{keV_{ee}}}$

$S_{ee} = 0.58$

$S_{nr} = 0.95$

XENON10 2009
ZEPLIN3 2009
Manzur et al. 2010
Aprile et al. 2009
Chepel et al. 2006
Aprile et al. 2005
Akimov et al. 2002
Bernabei et al. 2001
Arneodo et al. 2000



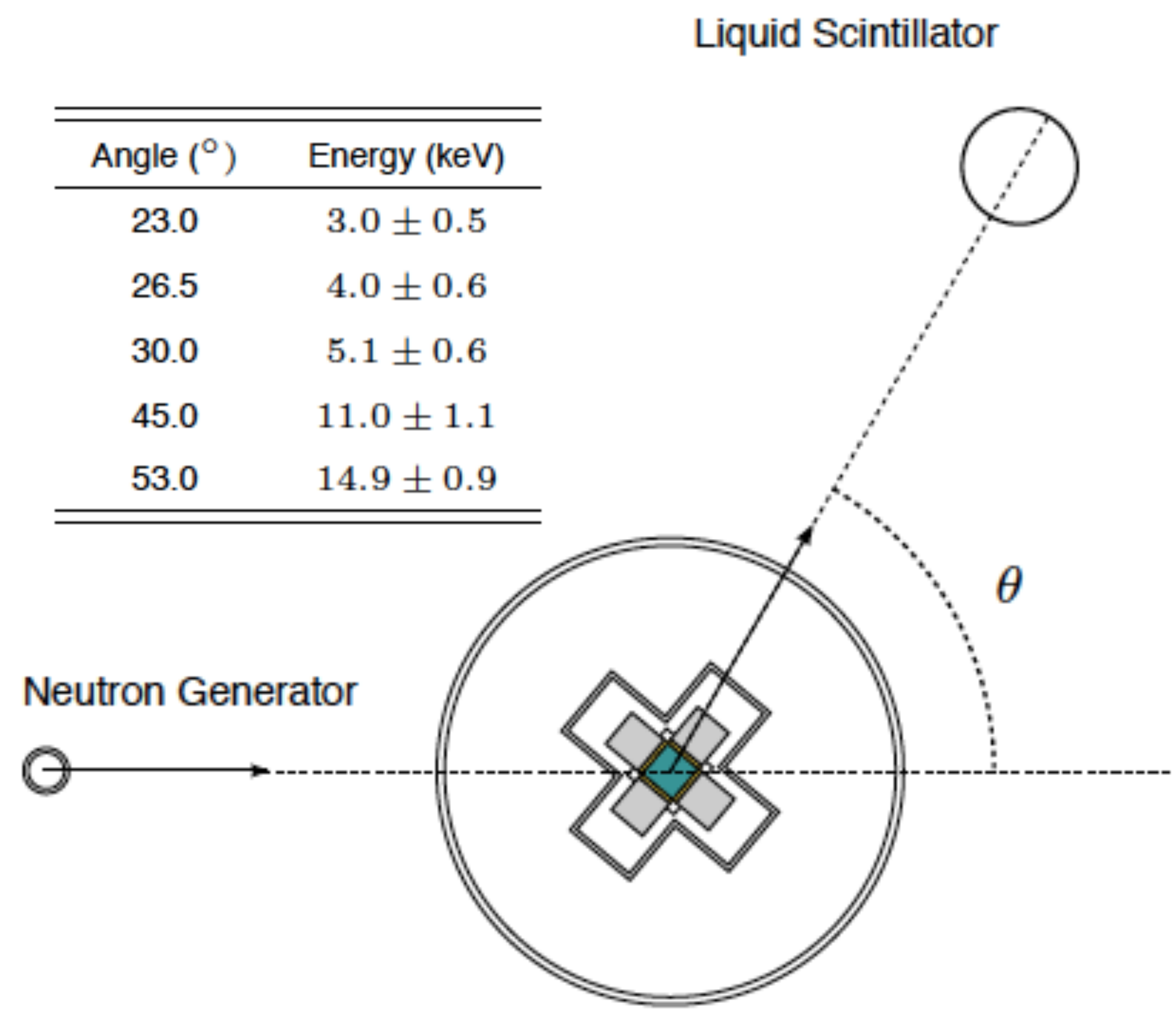
New Leff Measurement at Columbia

- More precise measurements of L_{eff} are essential for the interpretation of results from LXe WIMP searches especially at low WIMP masses

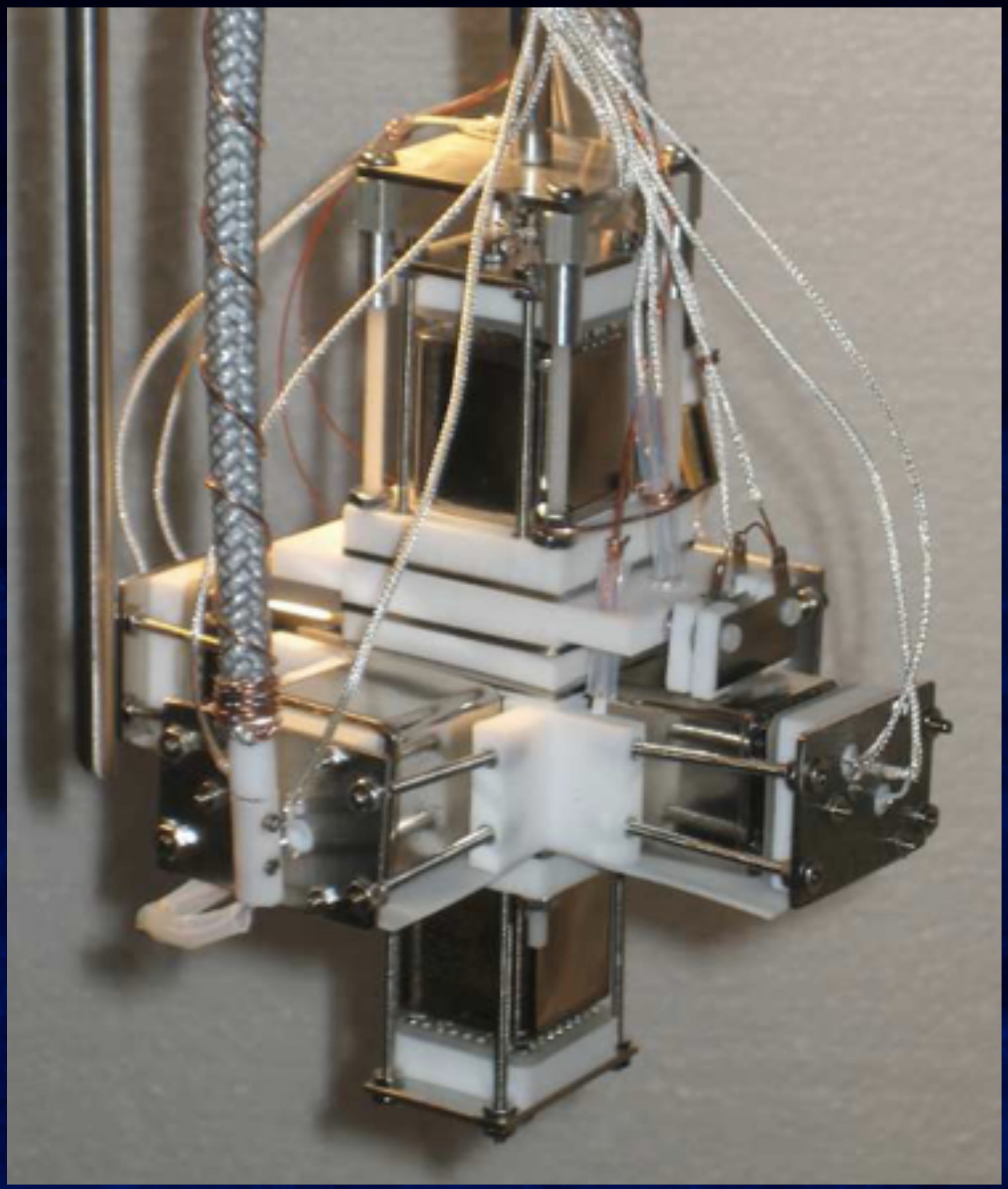
- At Columbia we have therefore embarked in a new experiment to measure this quantity again, with the best control of systematics to-date

- We have measured L_{eff} for Xe recoils between 3 keVr - 14.9 keVr. Data analysis is completed. Paper will be submitted shortly (before XENON100 data "unblinding"

Angle ($^\circ$)	Energy (keV)
23.0	3.0 ± 0.5
26.5	4.0 ± 0.6
30.0	5.1 ± 0.6
45.0	11.0 ± 1.1
53.0	14.9 ± 0.9



Design of the Leff Detector System



★Maximize the scintillation light detection efficiency. Measured 25 pe/keV is about 10 times that of XENON100

★Minimize background from multiple scattered neutrons with a vessel design which reduces non-active materials near sensitive LXe volume.

25 pe/keV

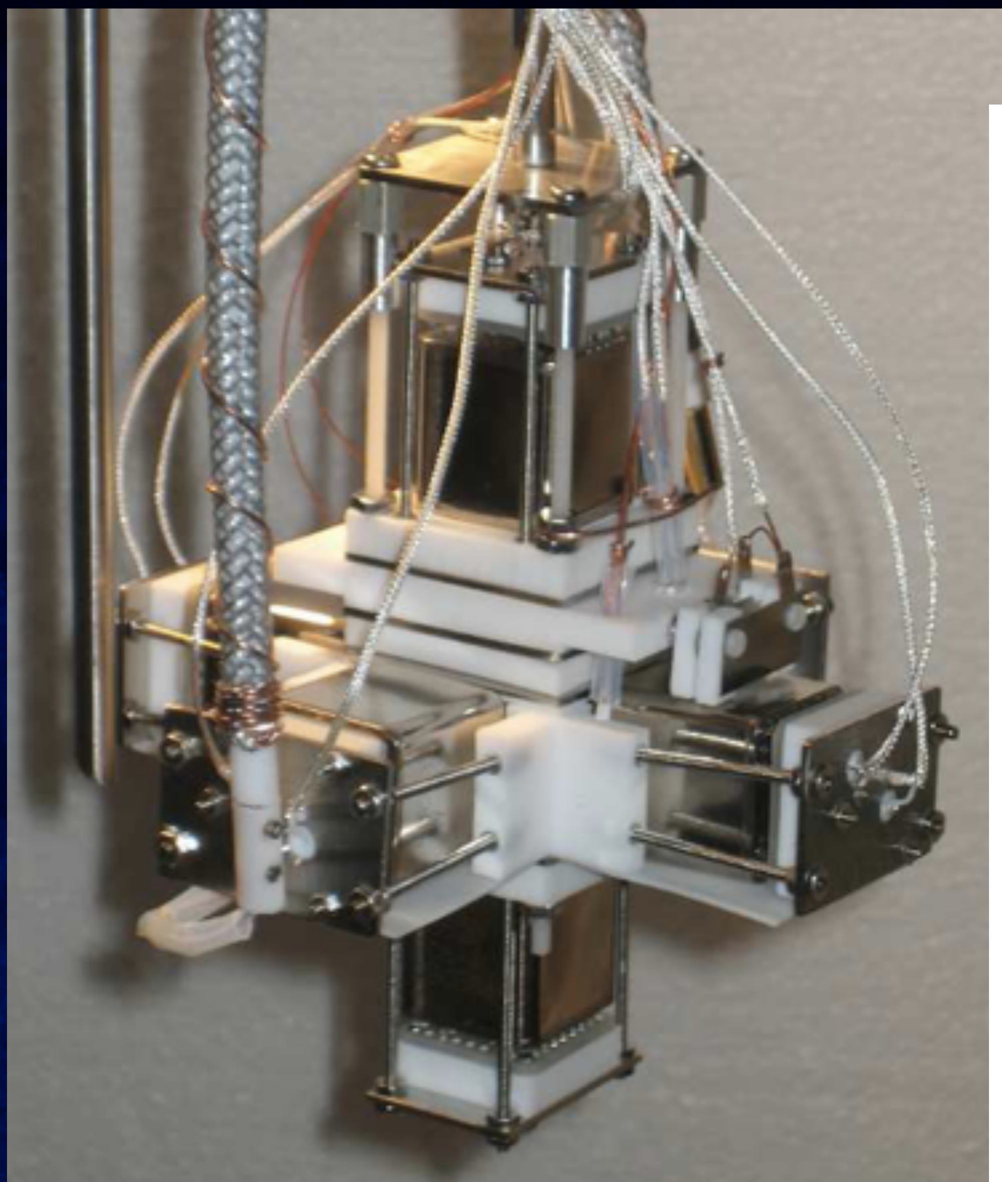
★Cubic LXe sensitive volume with six 2.5 x 2.5 cm Hamamatsu R8520-406 SEL High QE PMTs

★2-fold coincidence trigger on LXe PMTs with single channel thresholds at 0.3 pe for very low trigger threshold

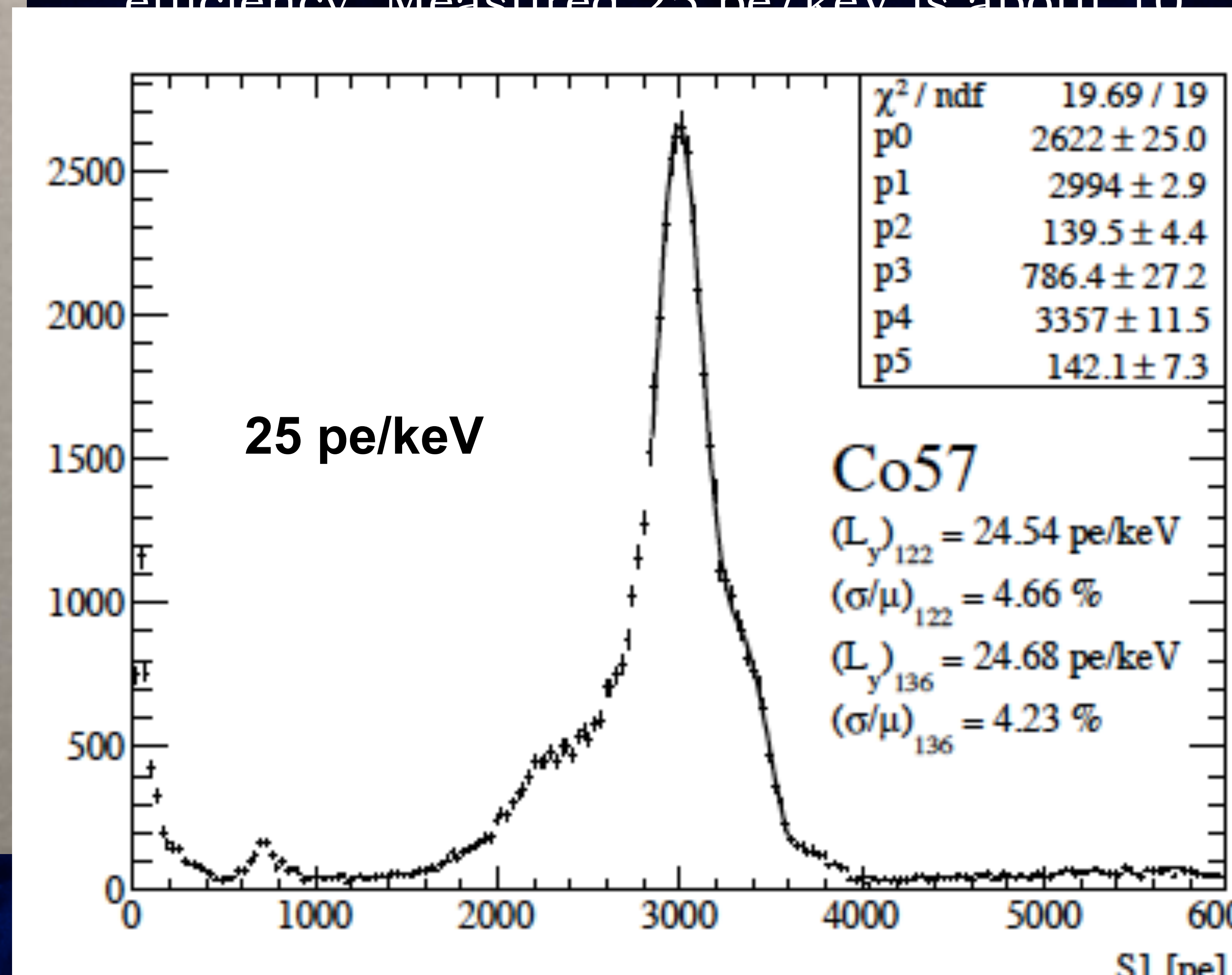
★Cooling with a Pulse Tube Refrigerator for reliable long time operation

★2.5 MeV neutrons from a miniature DD generator (Schlumberger Minitron)

Design of the Leff Detector System



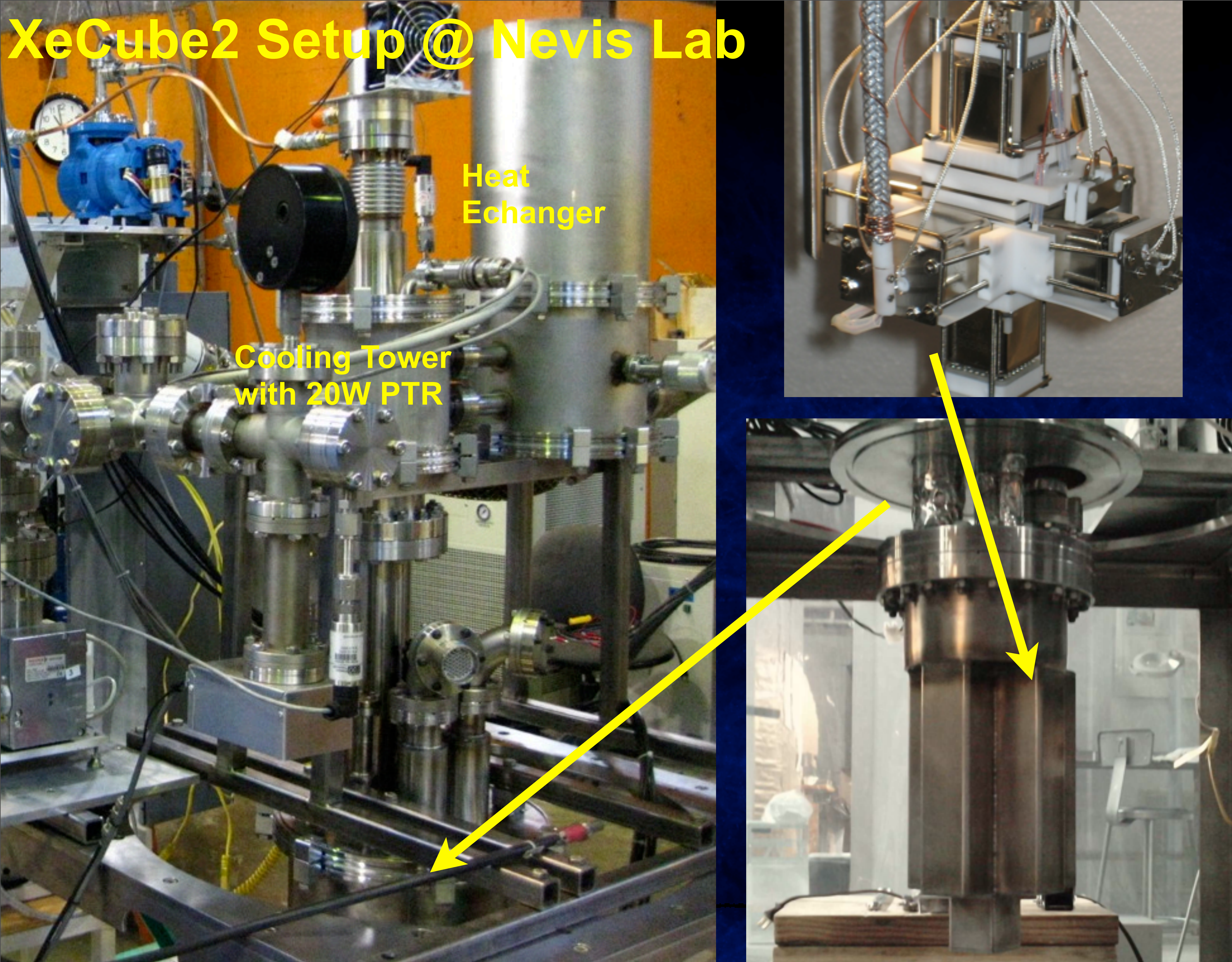
★Maximize the scintillation light detection efficiency. Measured 25 pe/keV is about 10



reliable long time operation

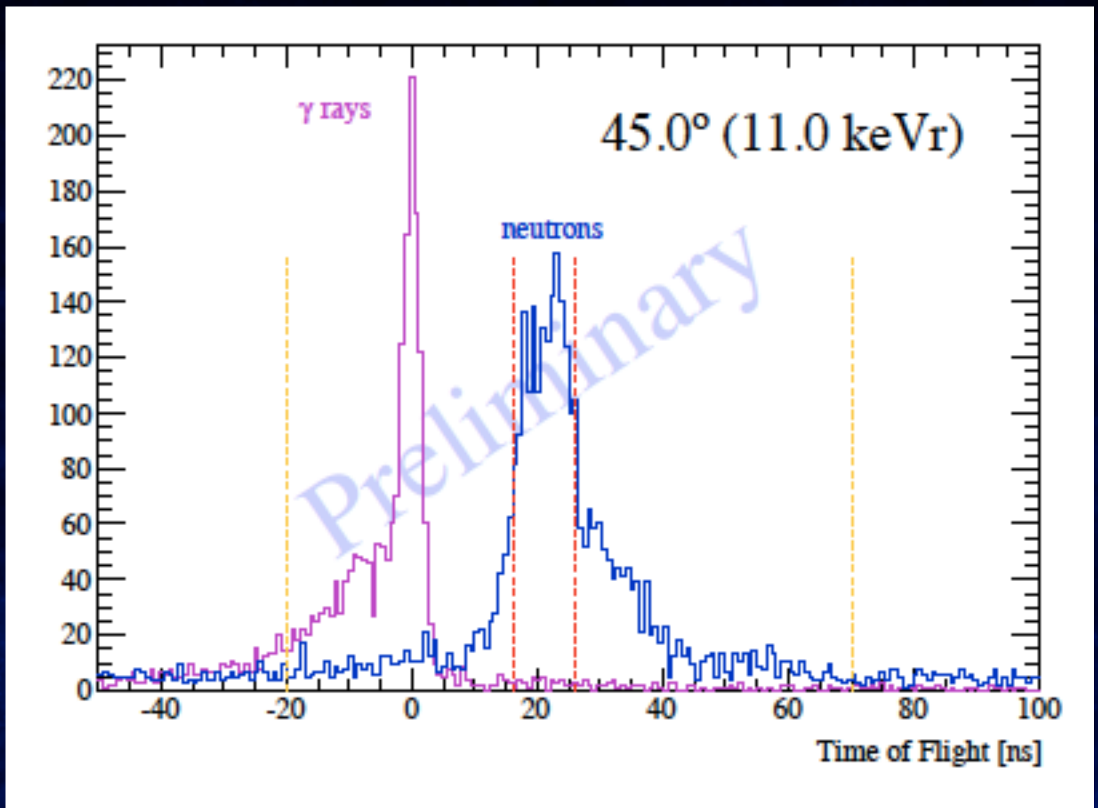
★2.5 MeV neutrons from a miniature DD generator (Schlumberger Minitron)

XeCube2 Setup @ Nevis Lab



XeCube2 Leff Measurement @ 11 keV

$$\mathcal{L}_{\text{eff}}(11.0\,\text{keVr}) = 0.141 \pm 0.017$$



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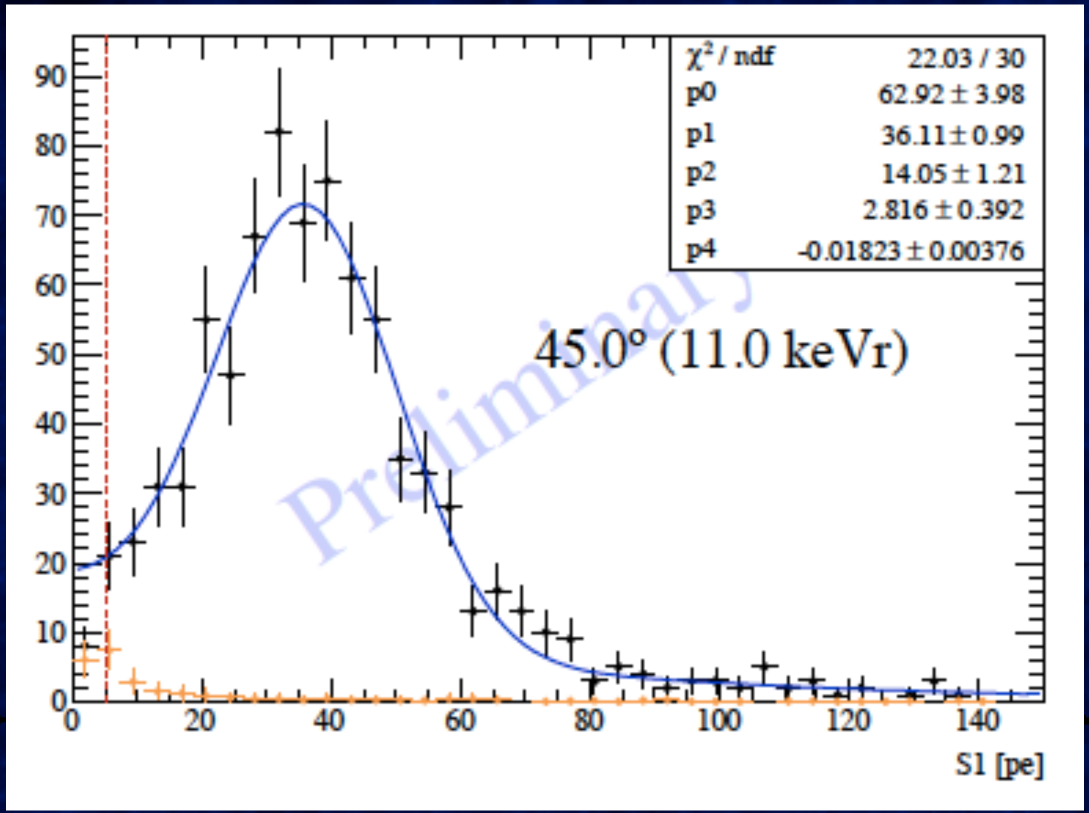
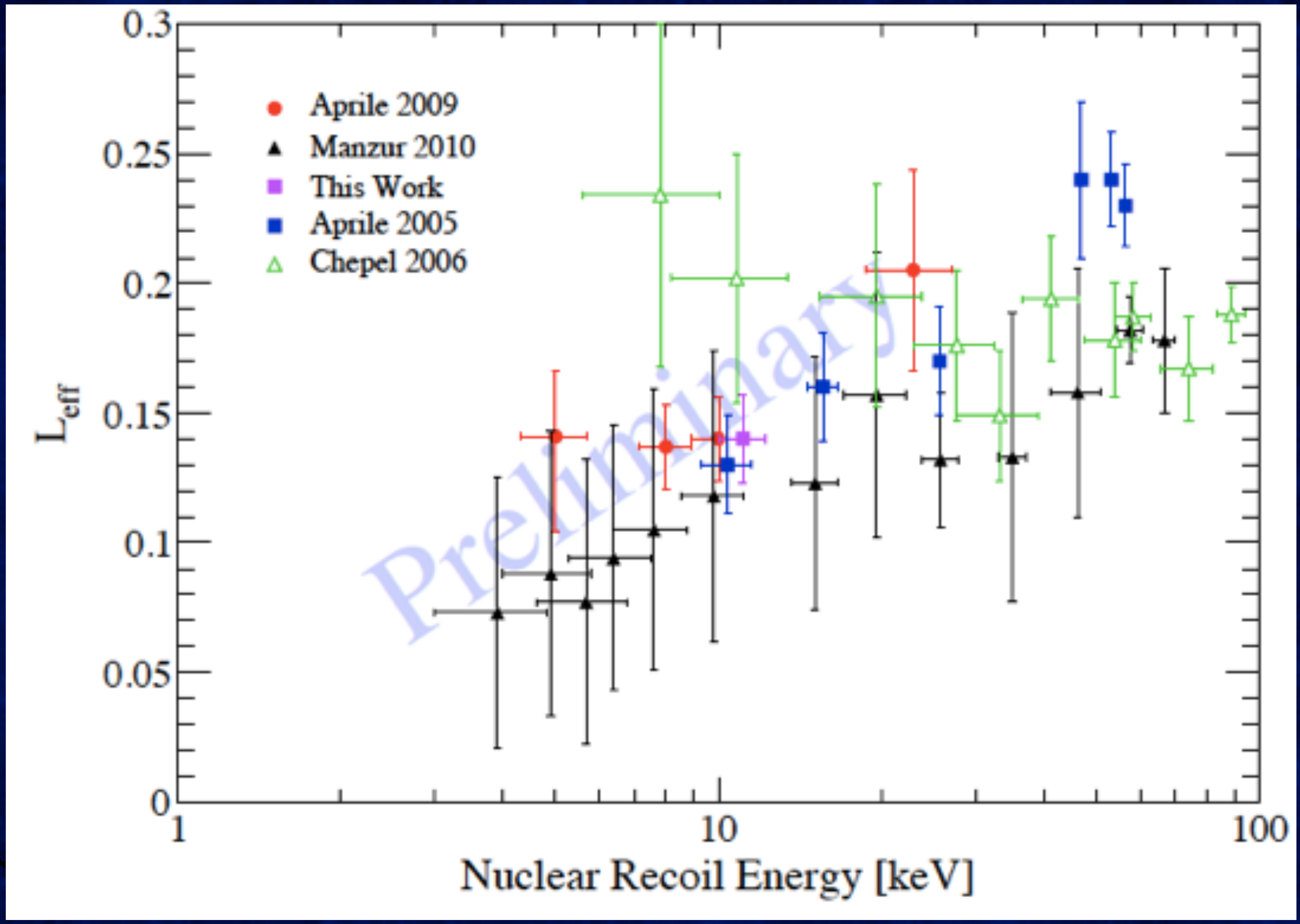




Light & Charge Anticorrelation

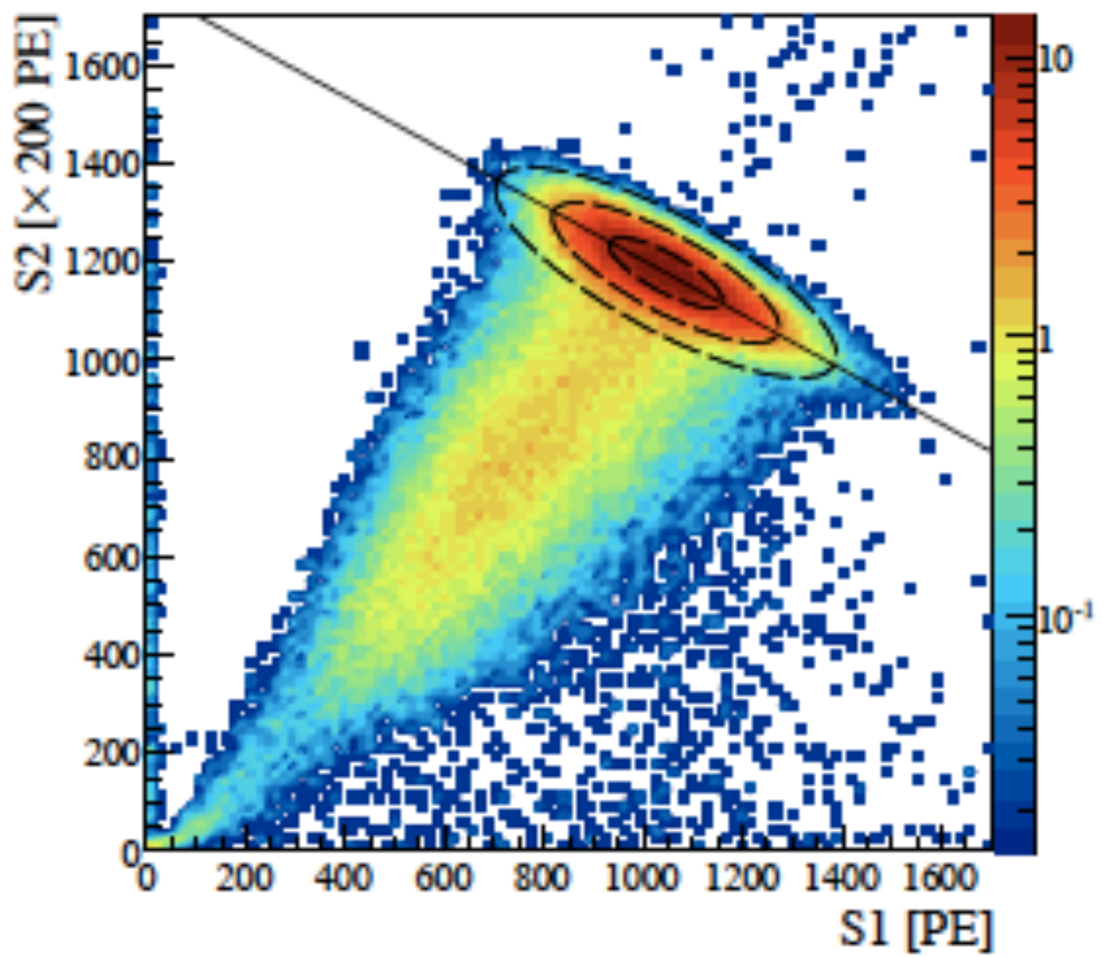


Figure 15: ^{137}Cs calibration data in position-corrected S2-S1 parameter space. The signals are anti-correlated and a projection along the rotation angle θ of the anti-correlation ellipse leads to an improved energy resolution.

measured in XENON100: 2.3% at 662 keV energy resolution in the 62 kg LXeTPC

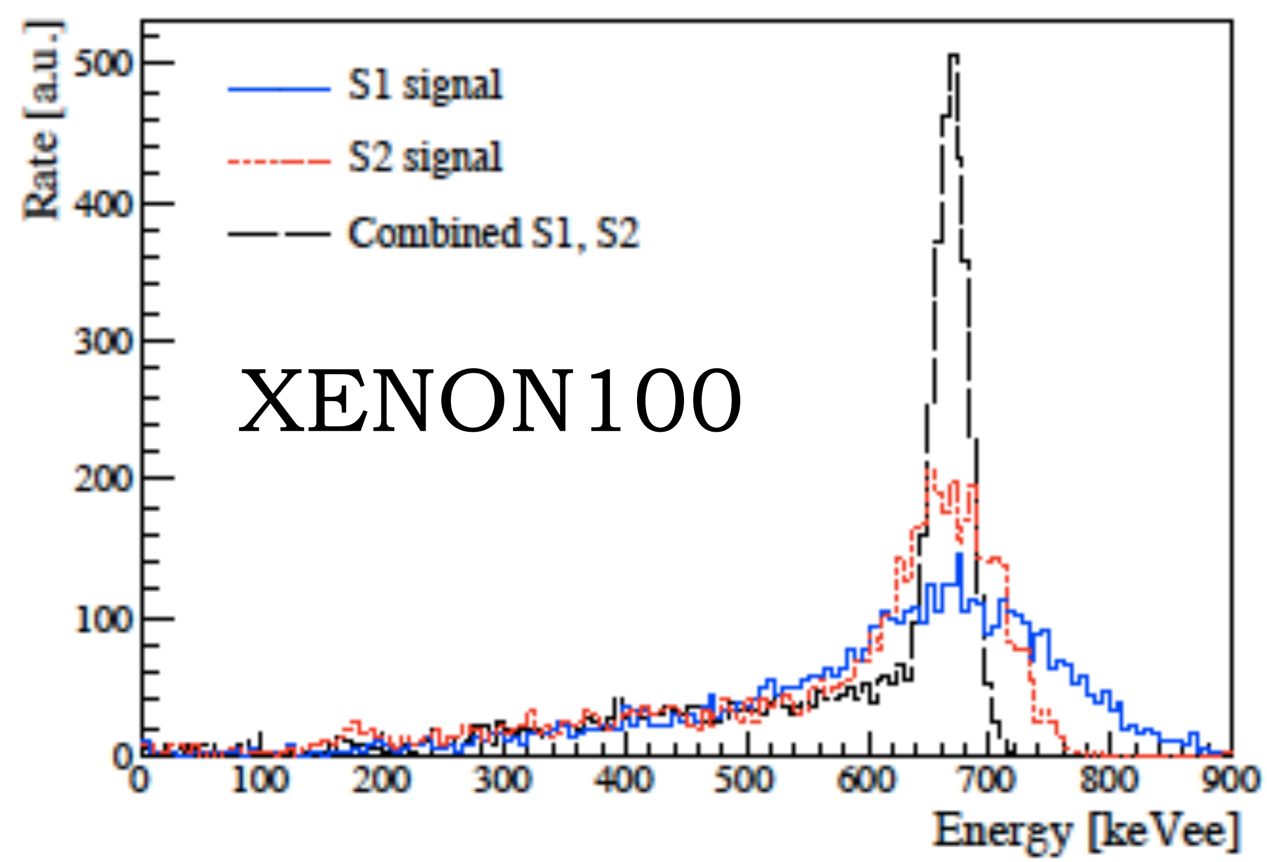
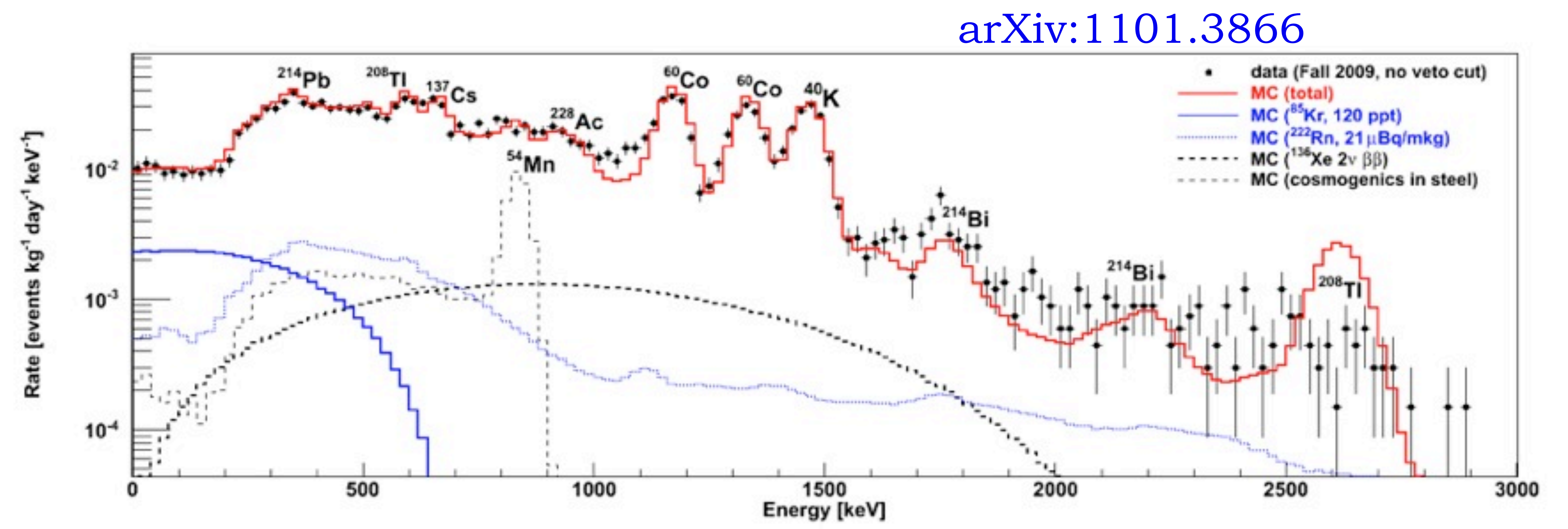
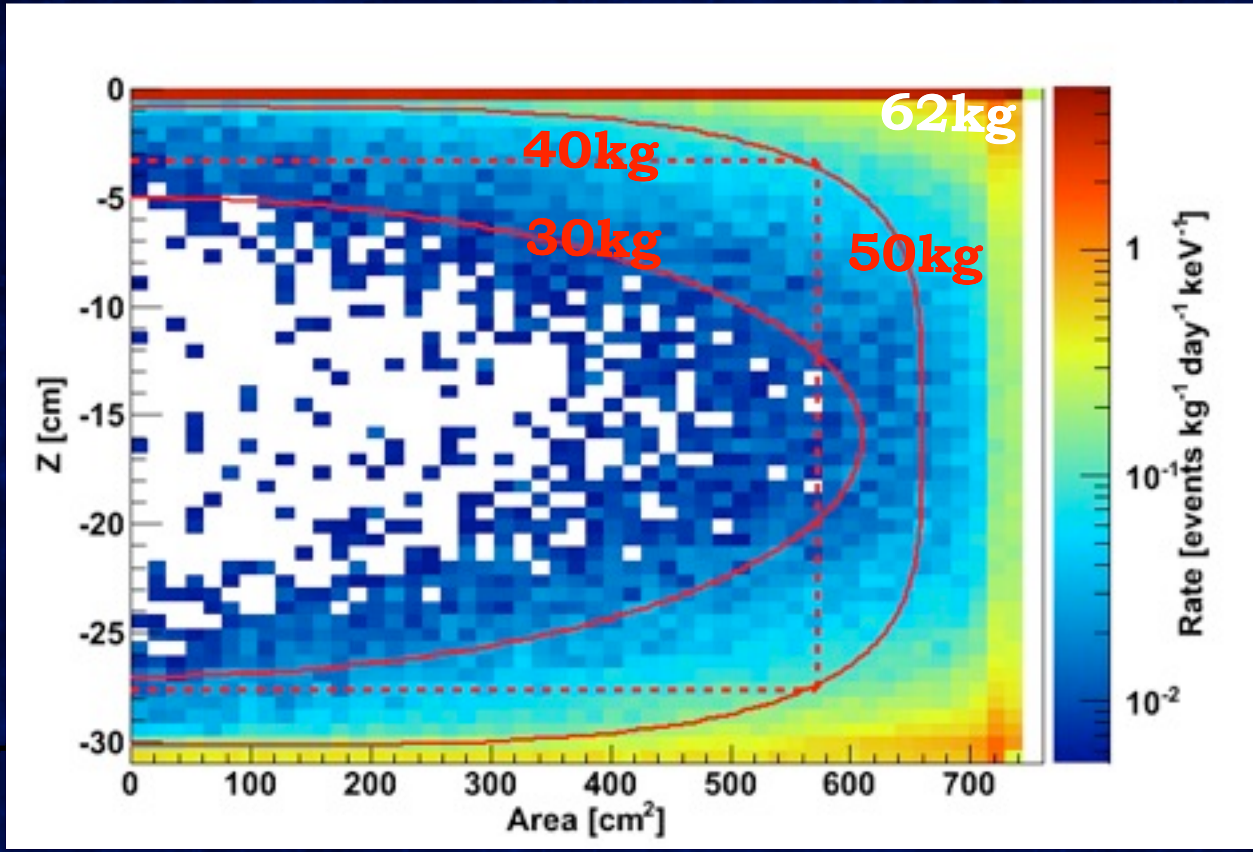


Figure 17: Spectrum of ^{137}Cs in three different energy scales: The resolution is 12.5% for the S1 scale, 6.5% for the S2 scale, and 2.3% for the combined energy scale where the anti-correlation between charge and light signal is exploited.

XENON100 Gamma Background

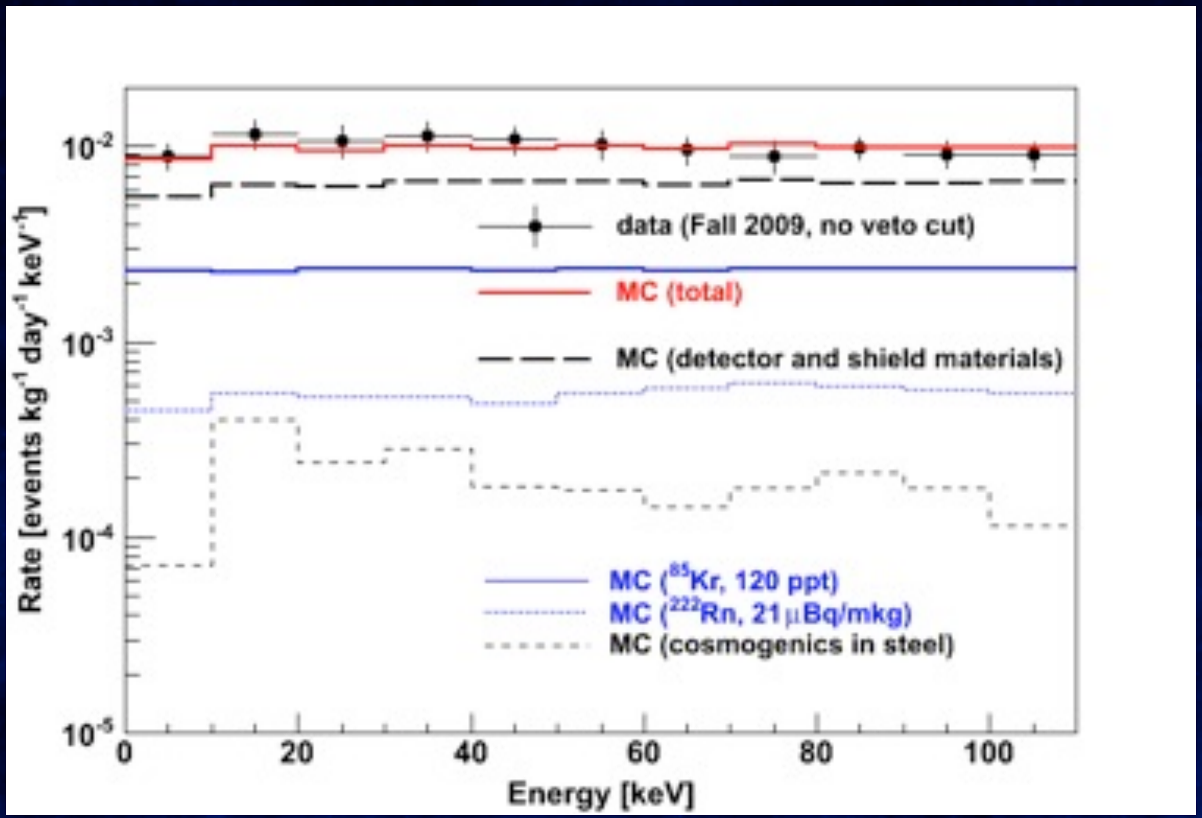


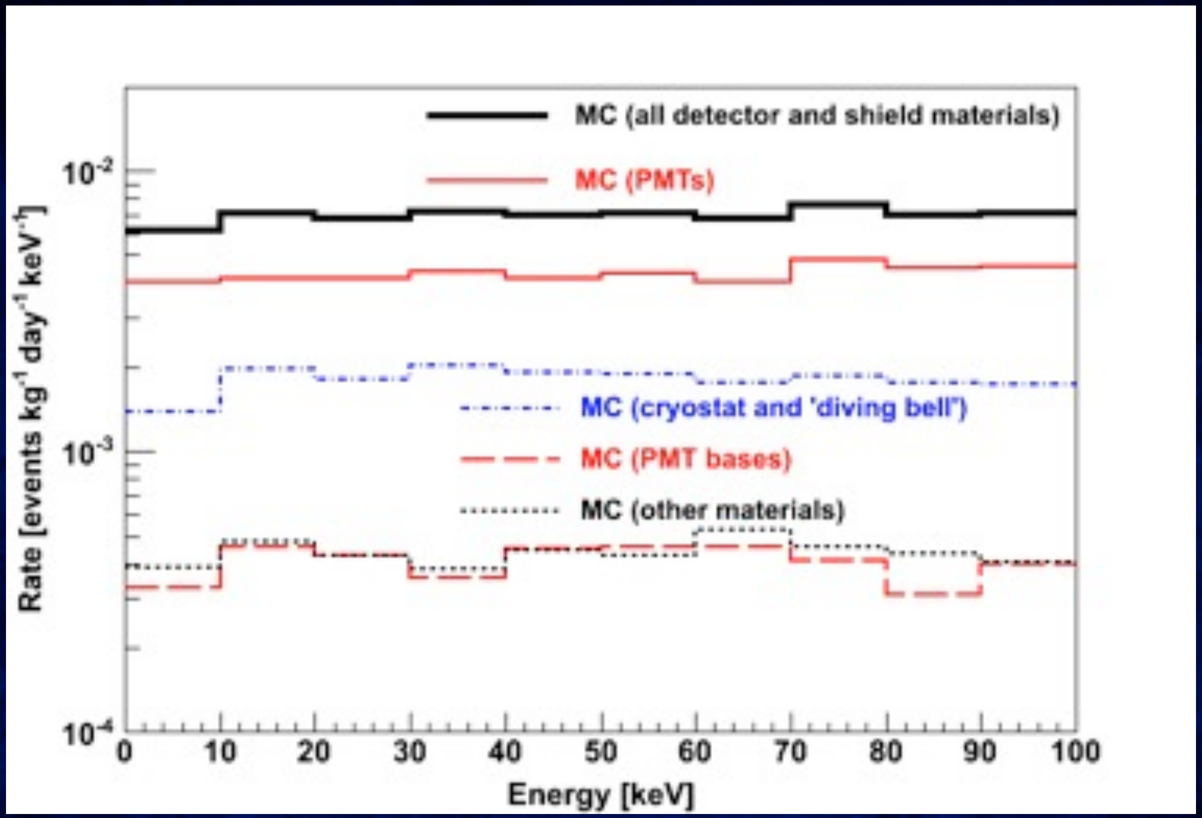
- Monte Carlo simulations of XENON100 EM background in very good agreement with measured data
- Background is well understood in the full energy range
- Fiducial volume cuts optimized on MC prediction for high rejection efficiency and high target mass



XENON100 Gamma Background

The background in a 30kg fiducial volume in the WIMP-search energy region is ~10 mdru even before the LXe veto cut

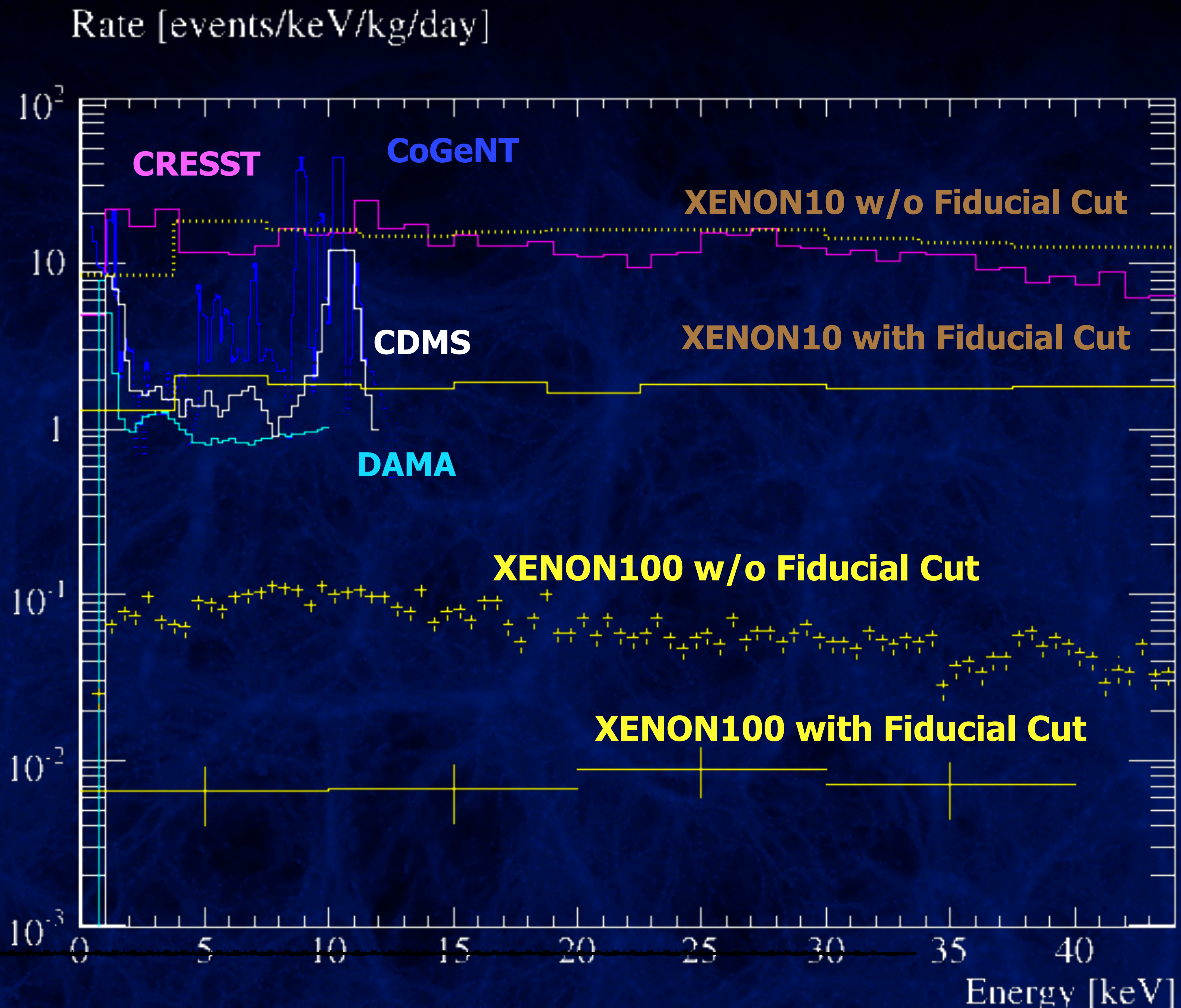




The LXe veto with 100 keVee average threshold reduces the background rate down to the level of ~5 mdru, where ^{85}Kr in LXe starts to dominate

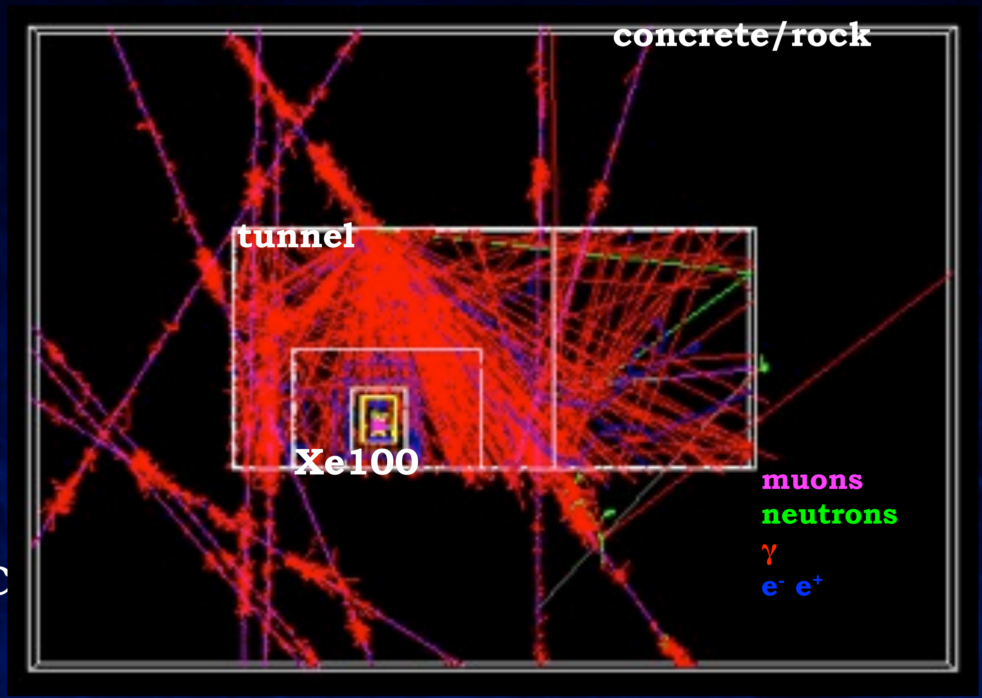
	Predicted rate [$\times 10^{-3}$ events$\cdot$kg$^{-1}\cdot$day$^{-1}\cdot$keV^{-1}]					
Volume	62 kg target		40 kg fiducial		30 kg fiducial	
Veto cut	none	active	none	active	none	active
Detector and shield materials	134.39	73.66	12.24	3.29	6.85	1.92
^{222}Rn in the shield (1 Bq/m^3)	5.95	1.72	0.92	0.16	0.16	0.02
^{85}Kr in LXe (120 ppt of ^{nat}Kr)	2.35	2.35	2.35	2.35	2.35	2.35
^{222}Rn in LXe (21 μBq/kg)	1.04	0.51	0.56	0.38	0.53	0.37
All sources	143.73	78.24	16.07	6.18	9.89	4.66

XENON100 background compared to other DM searches



XENON100 Neutron Background

Generate/propagate Neutrons from (α,n) , spontaneous fission and muon-induced. Take into account trigger efficiency and single scatter cut



Predicted NR background:

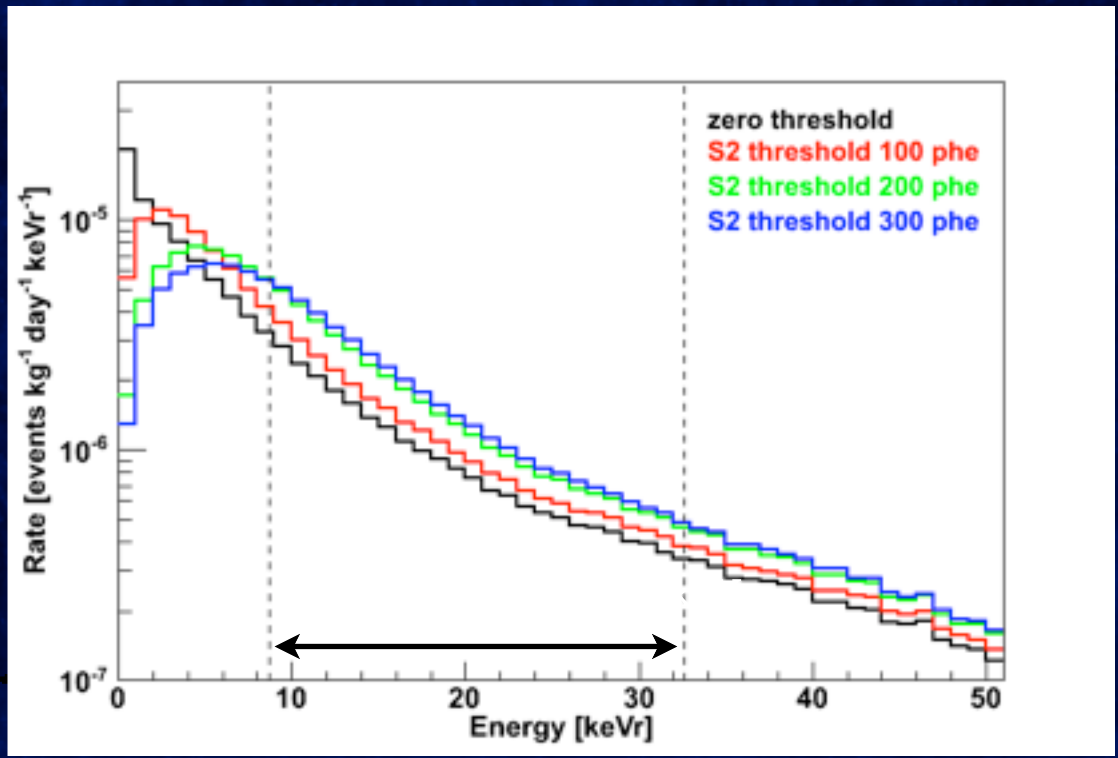
entire target (62 kg of LXe)	< (1.66 +1.22 -0.62) n/year
40 kg fiducial volume	< (0.81 +0.60 -0.31) n/year
30 kg fiducial volume	< (0.58 +0.43 -0.22) n/year

Predictions for Run 08 (100 live days, 50% NR acceptanc

entire target (62 kg of LXe)	< (0.23 +0.17 -0.04) events
40 kg fiducial volume	< (0.11 +0.08 -0.04) events
30 kg fiducial volume	< (0.08 +0.06 -0.03) events

Background from muon-induced neutrons is ~5 times higher than from natural radioactivity in the detector and shield.

Total predicted NR background is negligible with respect to statistical leakage from ER band.

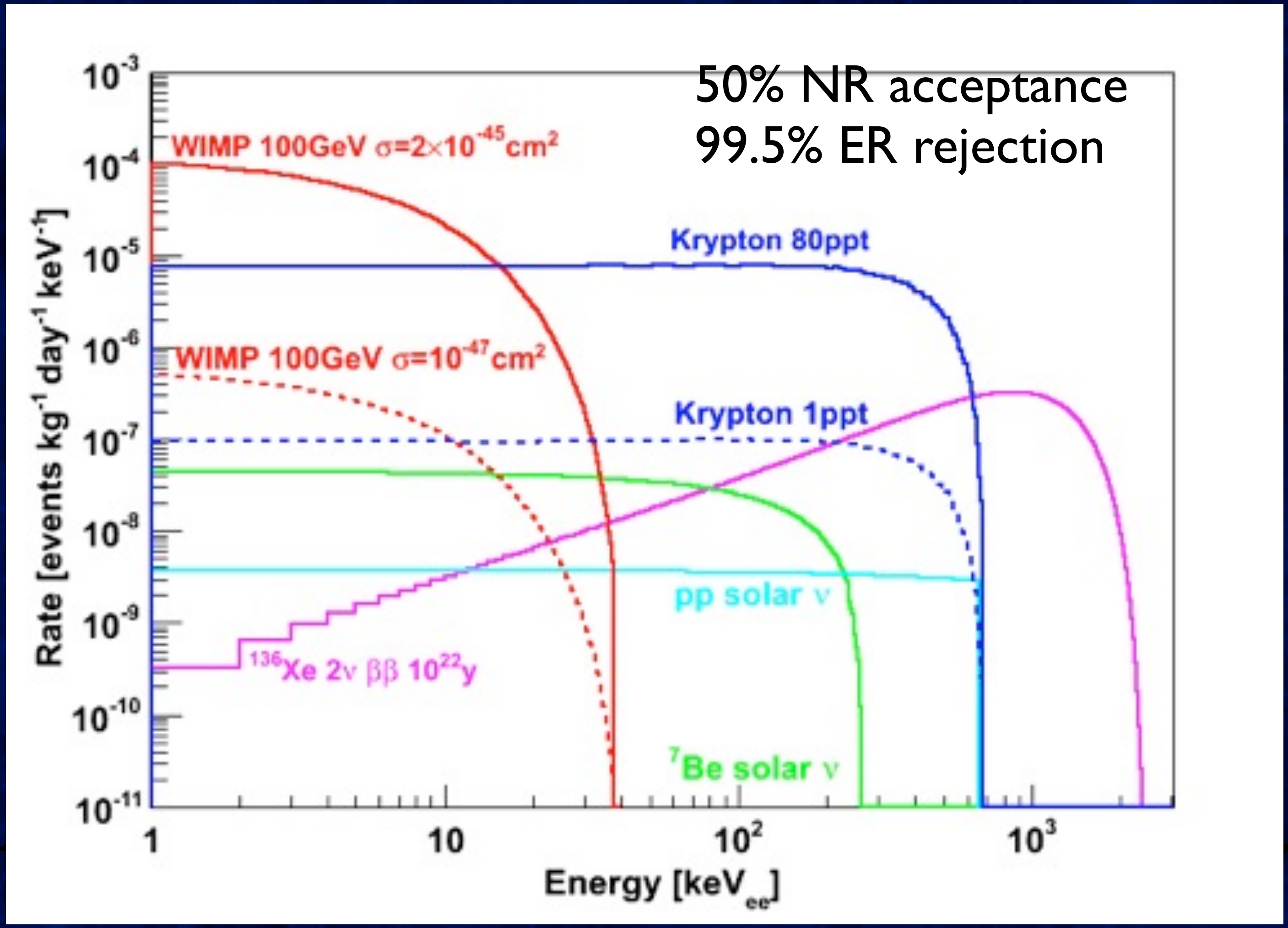


XENON100 Krypton Background

Trace amounts of radioactive Kr85 (Emax = 687 keV, t ~11 yr) in Xe gas contribute an irriducible background in XENON100.

The Kr level in in commercial Xe gas is at the ppm- ppb level and **^{85}Kr/Kr ~2 x 10^{-11}**

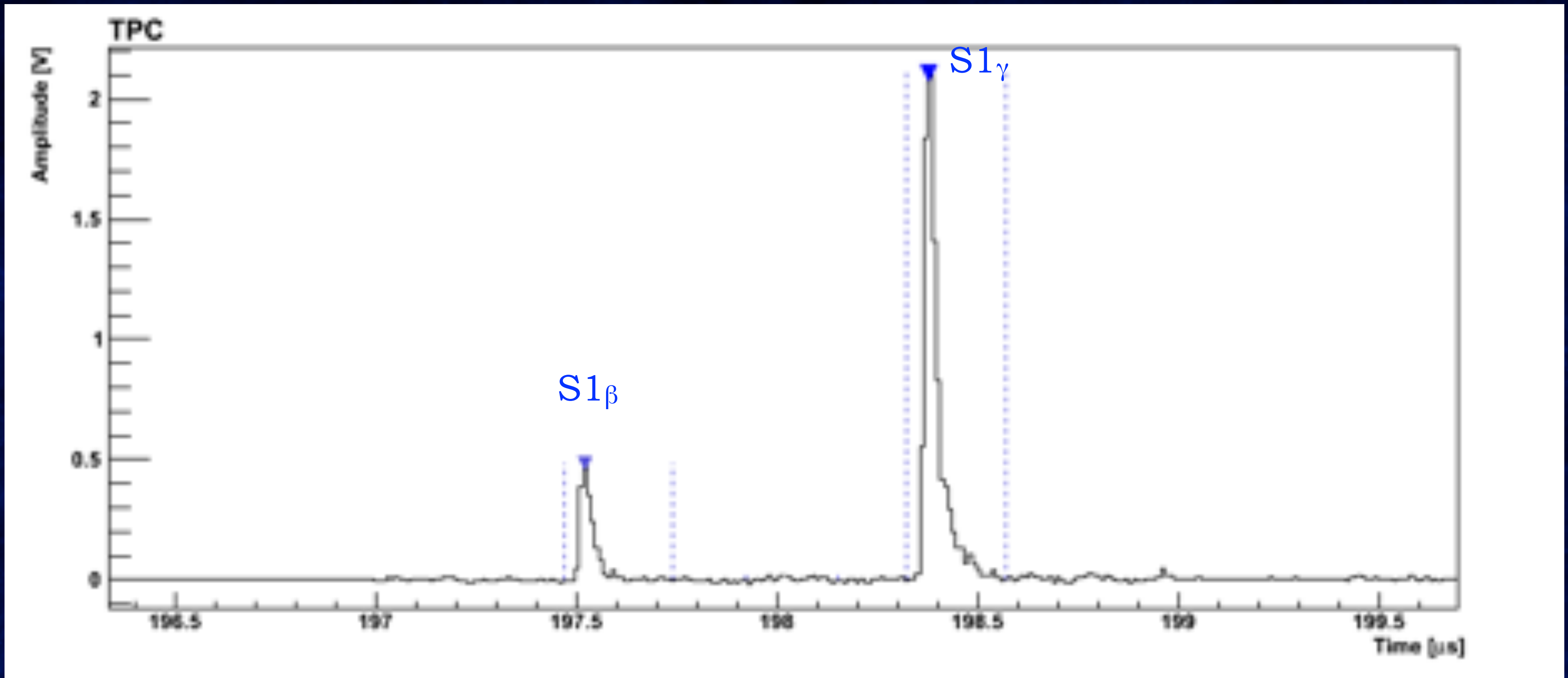
To reduce the Kr in Xe we use a cryogenic distillation column designed for a **10^3** reduction. Column is part of the XENON100 underground installation at LNGS.



Delayed Coincidence Analysis

The Kr/Xe concentration in the 162 kg of Xe filled in XENON100 is measured with a delayed coincidence analysis

^{85}Kr
β, 173.4 keV
↓
^{85m}Rb
γ, 514.6 keV
τ = 1.46 μs
↓
^{85}Rb



Analysis of 2009 data gives a value of (178 +76 -59) ppt of ^{nat}Kr at 90% C.L. consistent with the value inferred from a comparison of measured and Monte Carlo energy spectra (120 ppt) and with another independent analysis (143 +130 -90 ppt)

Following the most recent purification, the Kr level in XENON100 has been measured as (82 +62 -41) ppt at 90% C.L.

An Atom Trap Trace Analysis for XENON

Delayed coincidence analysis (BR = 0.43%) has limited accuracy

We are developing an Atom Trap Trace Analysis (ATTA) system to measure **^{84}Kr/Xe ≤ 10^{-12} = ppt** or **^{85}Kr/Xe < 10^{-23}**

ATTA Capability especially relevant for XENON1T

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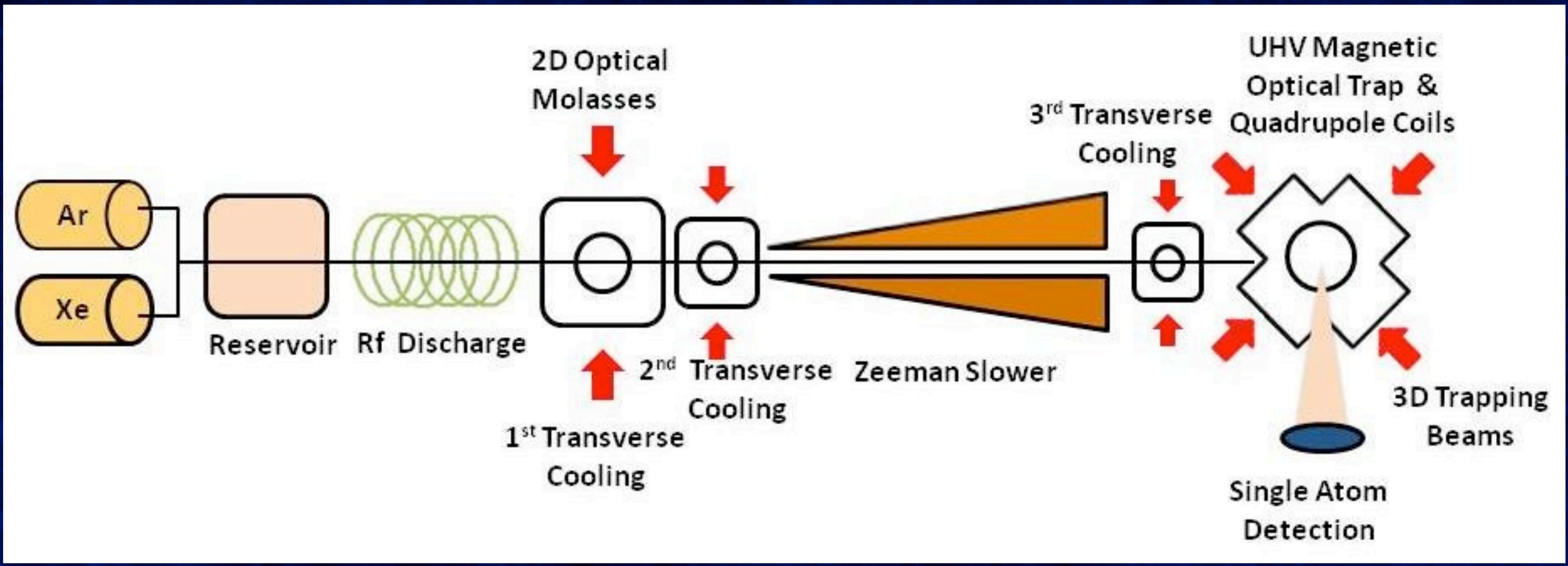

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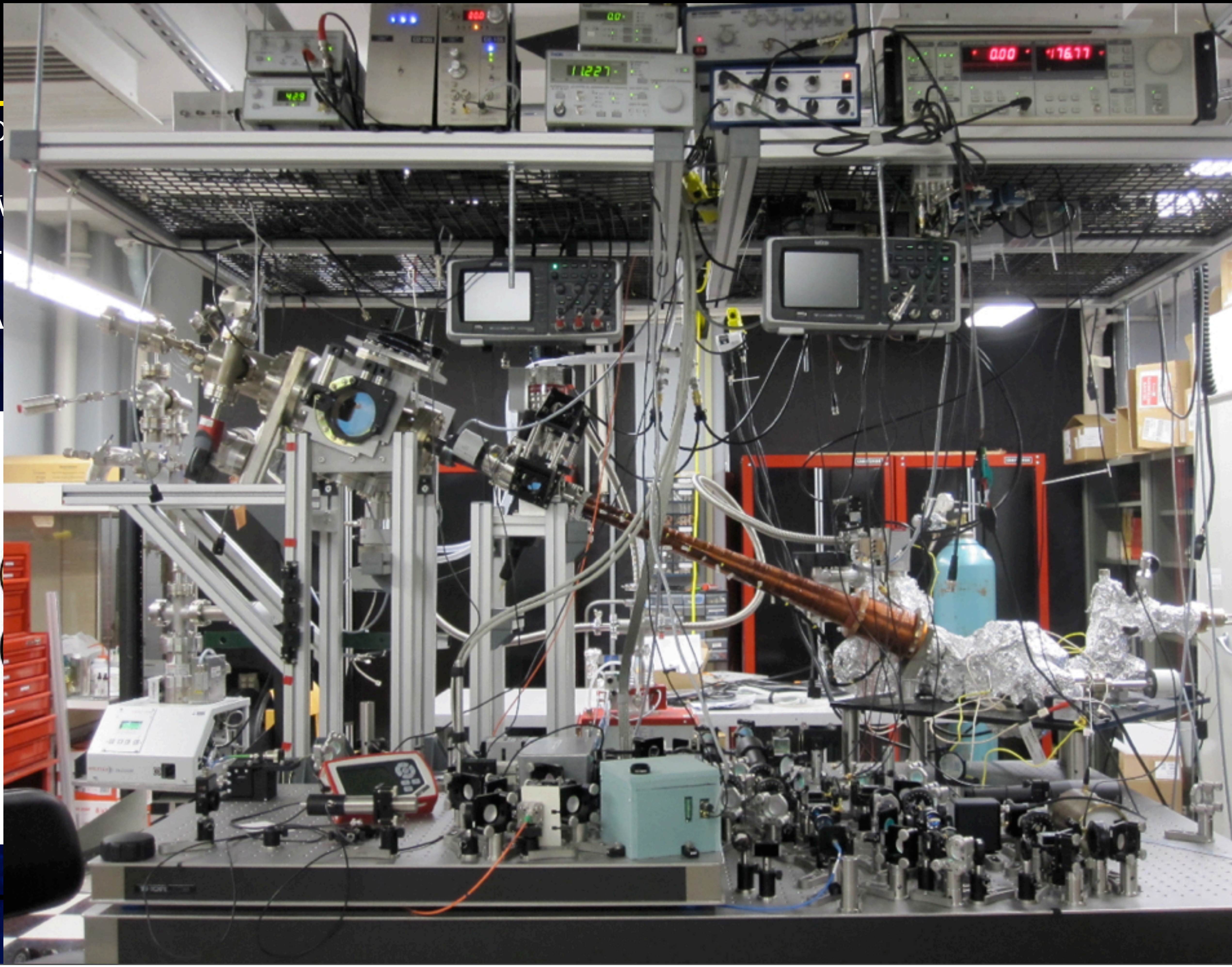
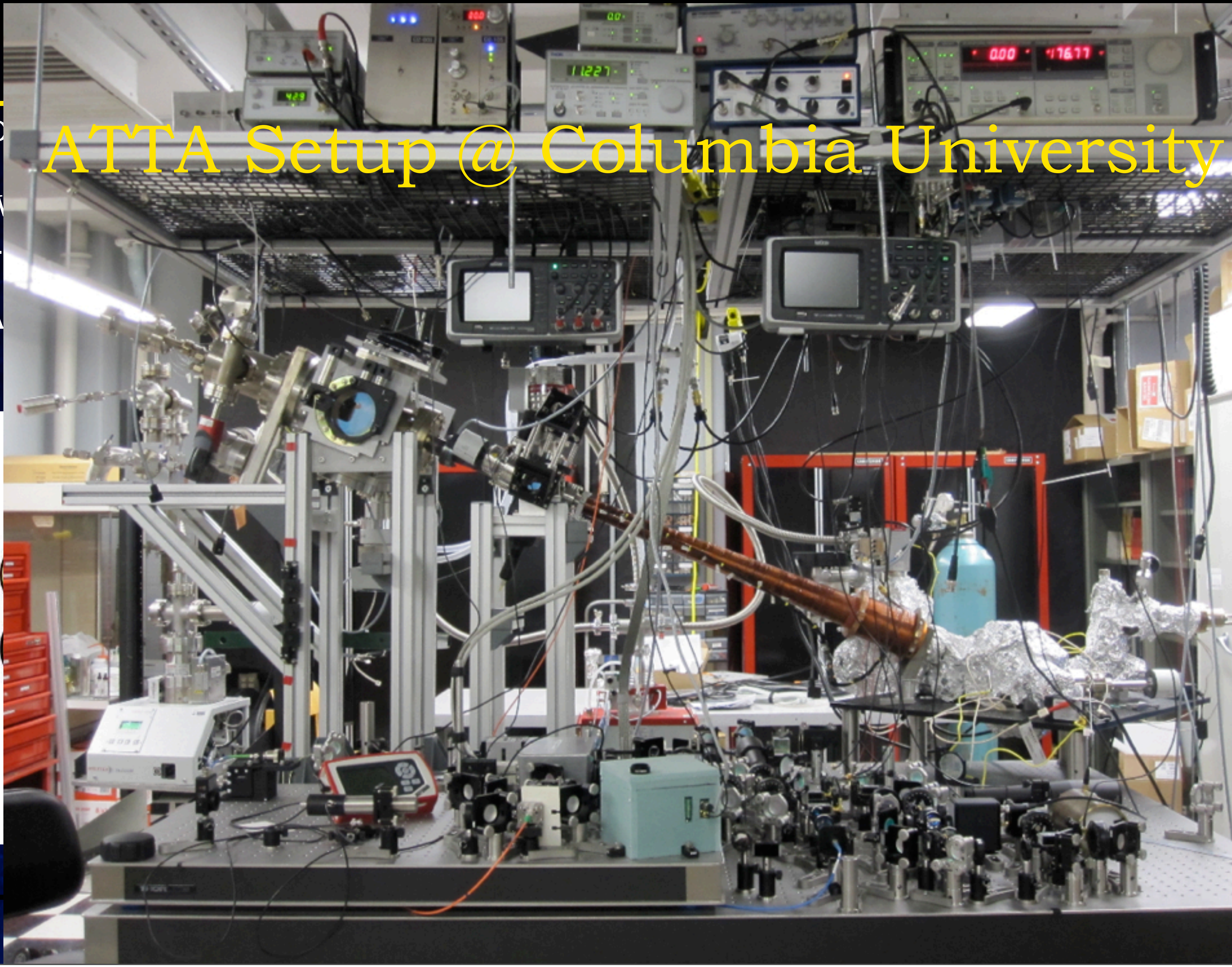
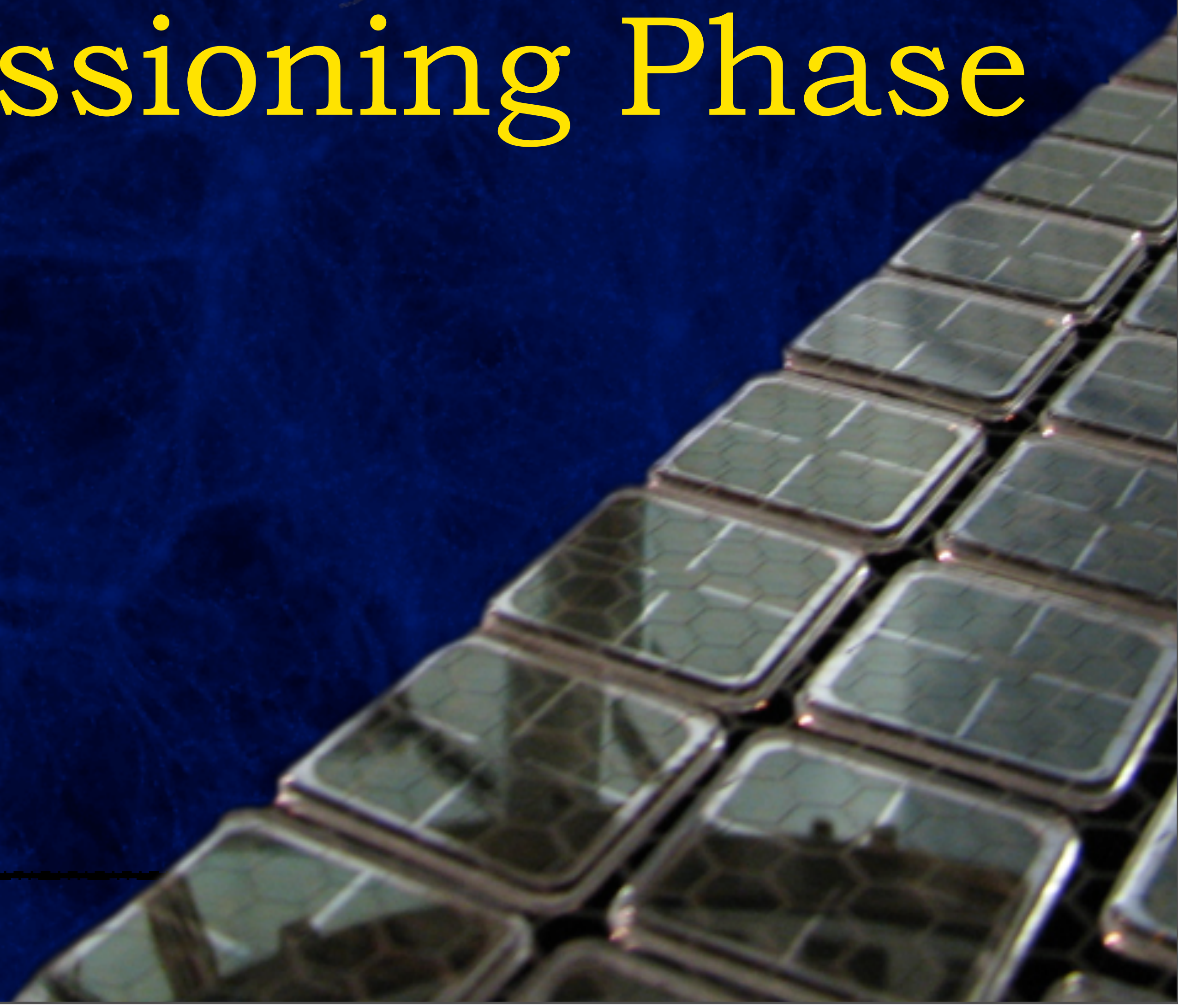


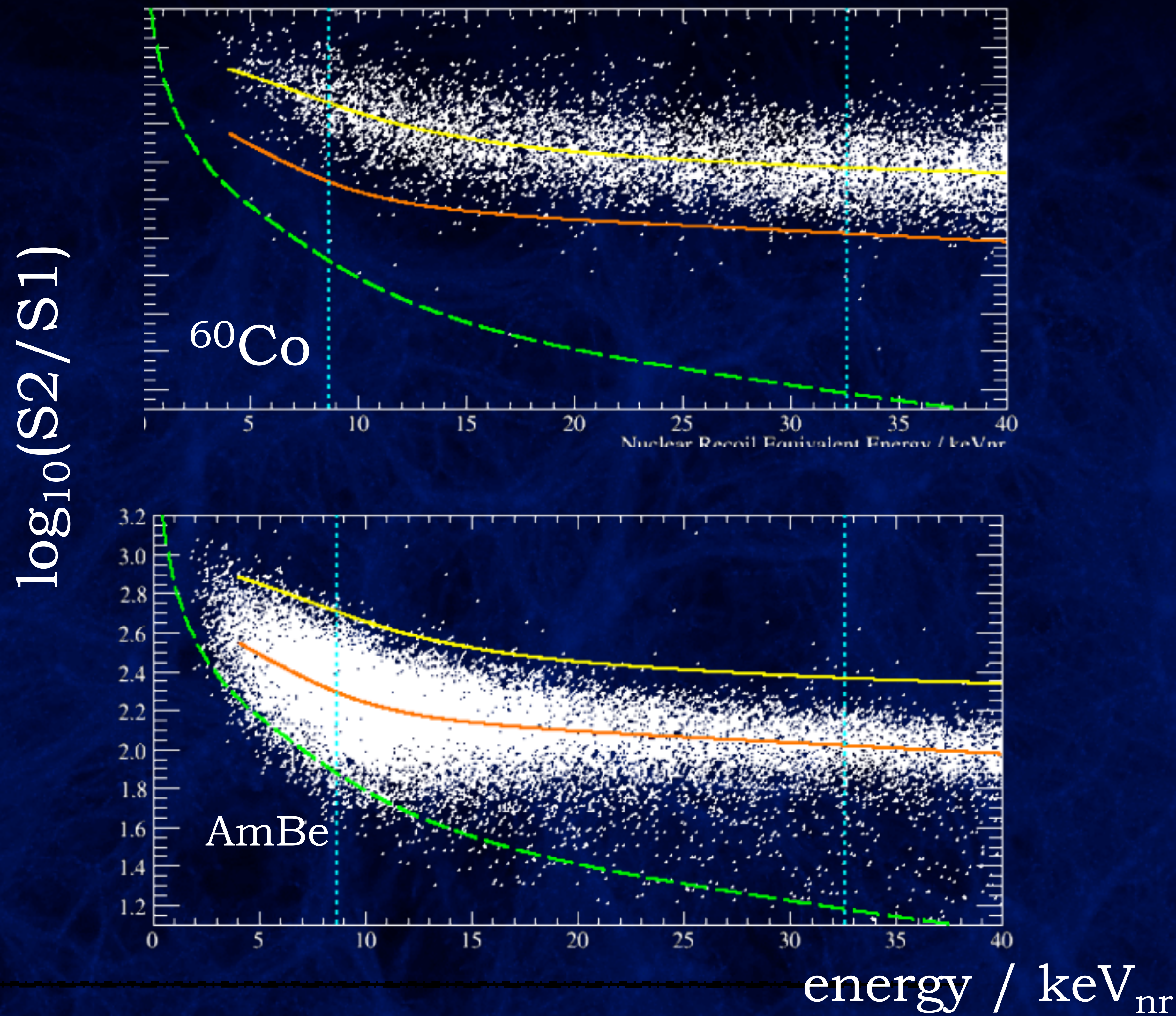
ATTA Setup @ Columbia University



XENON100 Dark Matter Search Results from 11 days of data during the Commissioning Phase

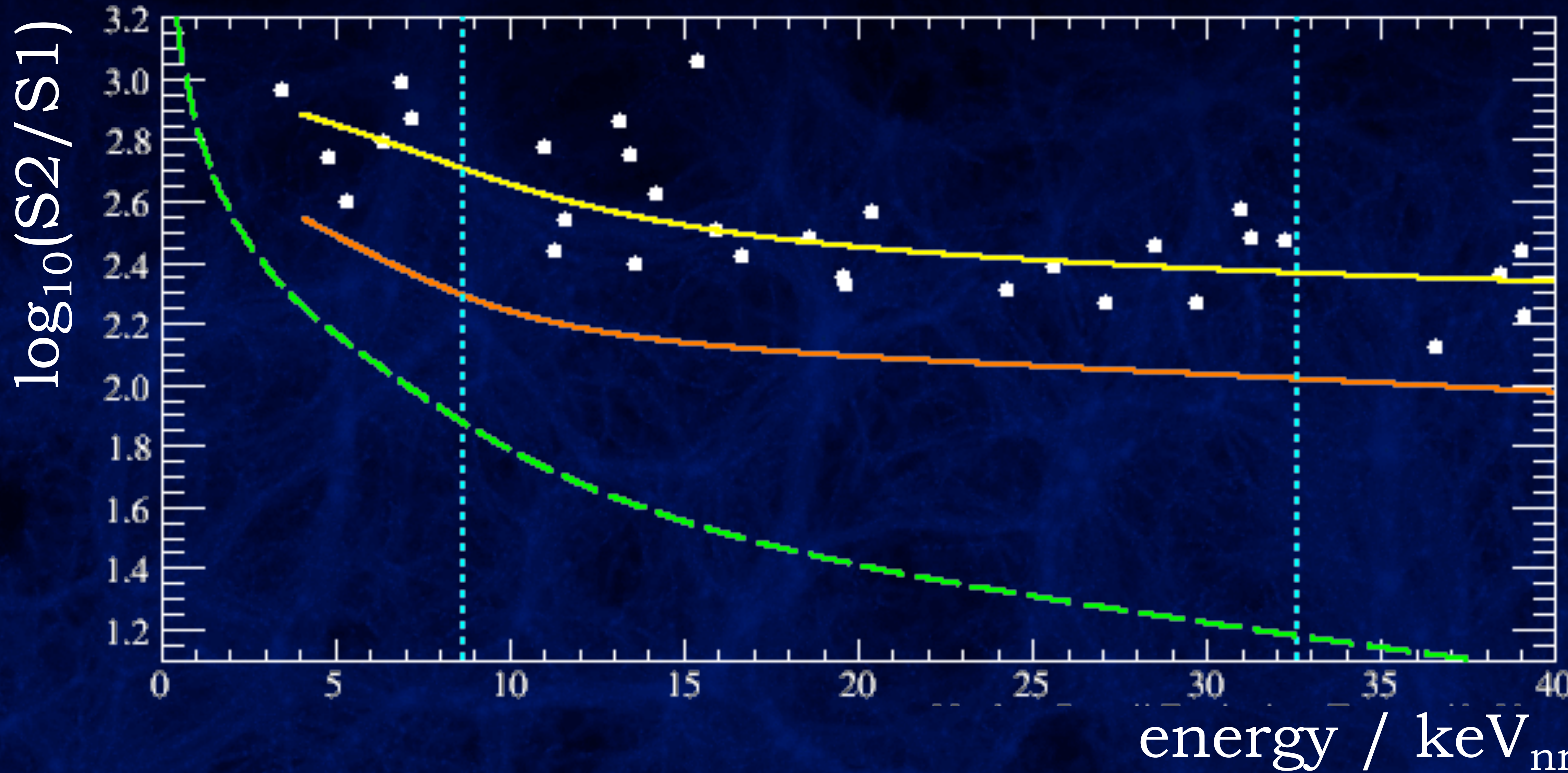


Electron & Nuclear Recoil Bands



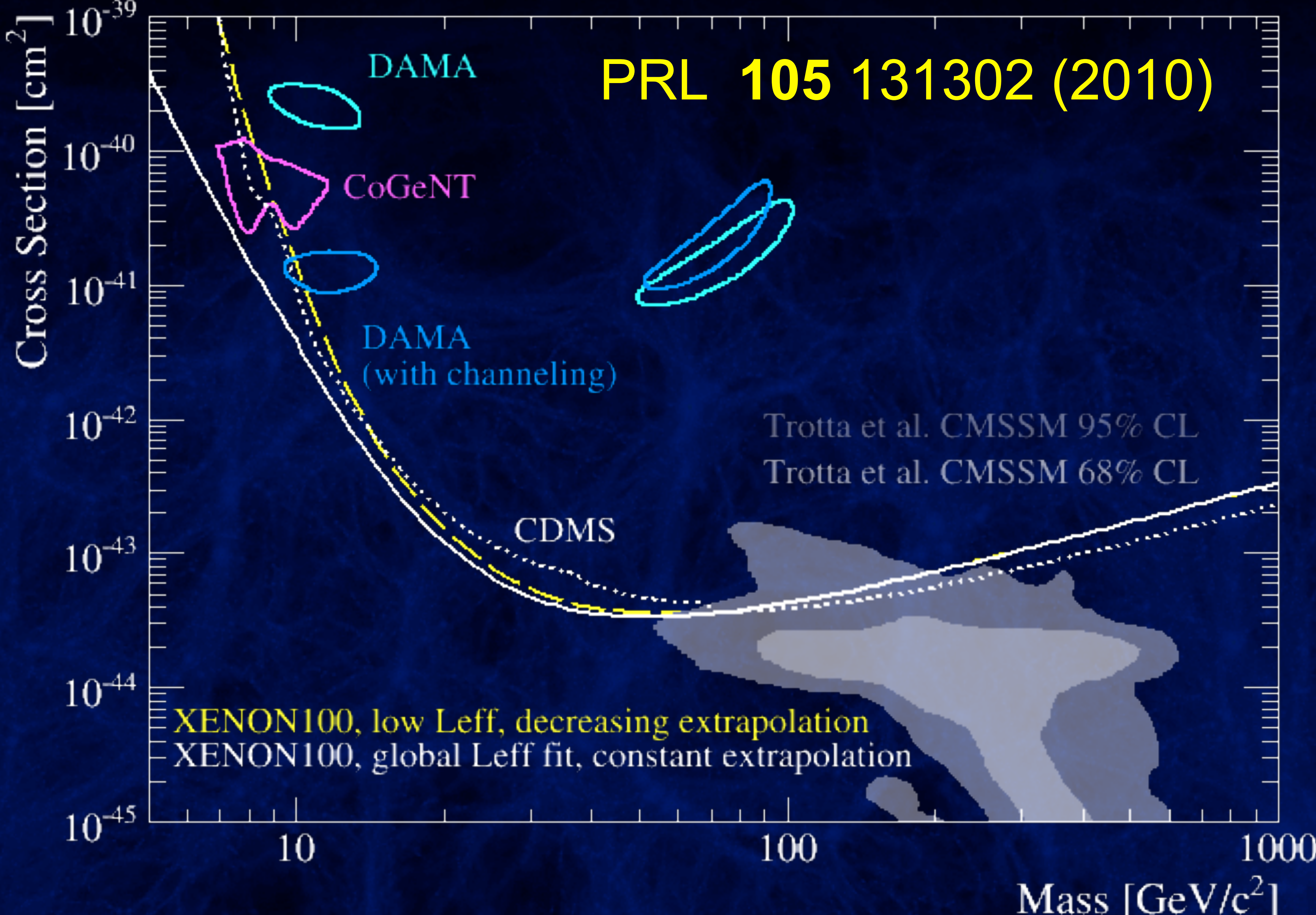
Discrimination

Exposure: 11.2 days x 40kg x 0.76 x 0.50 (50 % NR acceptance)



no events close to or below the nuclear recoil median

XENON100 1st Dark Matter Result



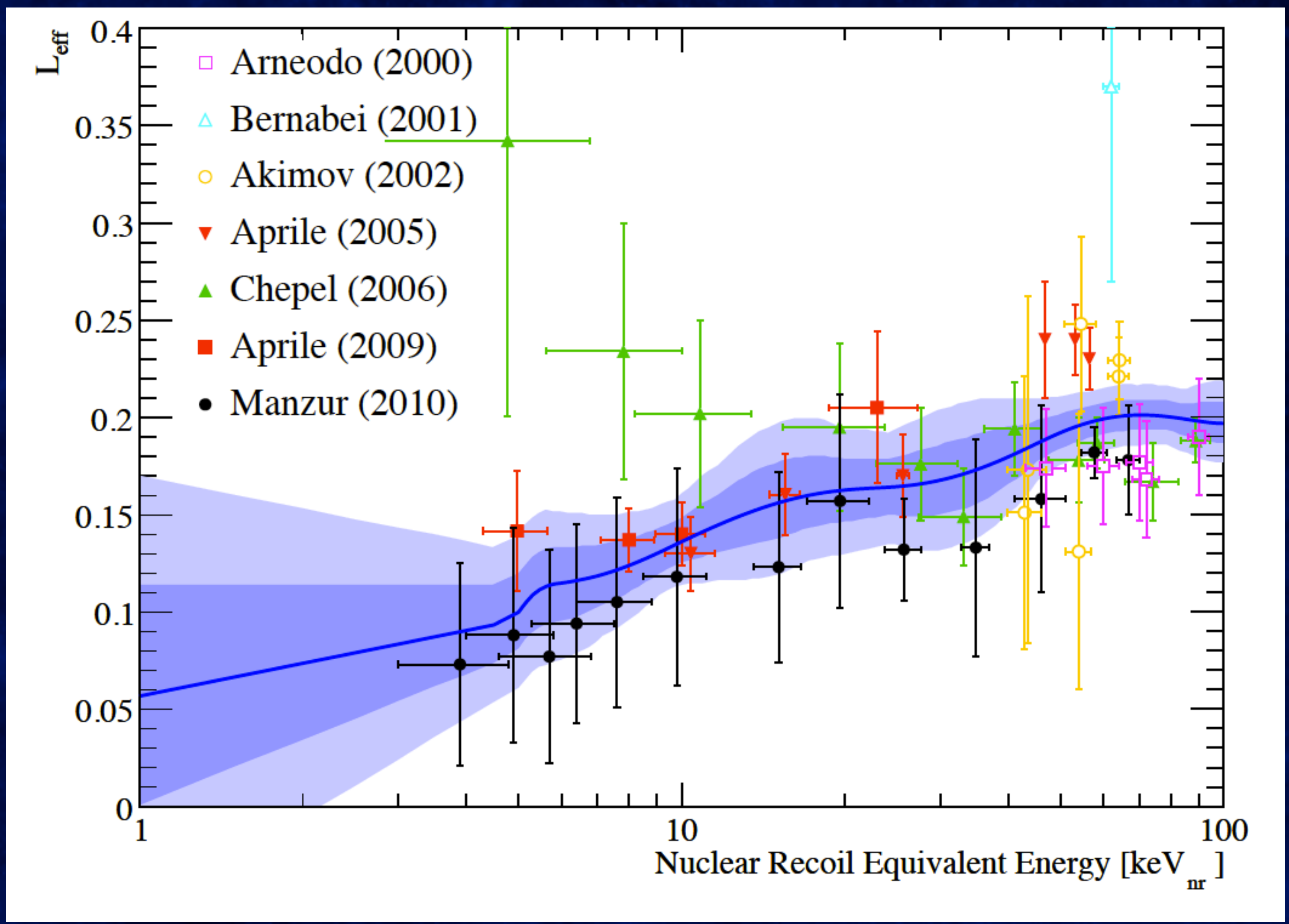
At 55 GeV WIMP mass limit on SI WIMP-nucleon cross section is 3.4×10^{-44} cm^2 (90 % CL)

arXiv:1103.0303v1

Likelihood Approach to the First Dark Matter Results from XENON100

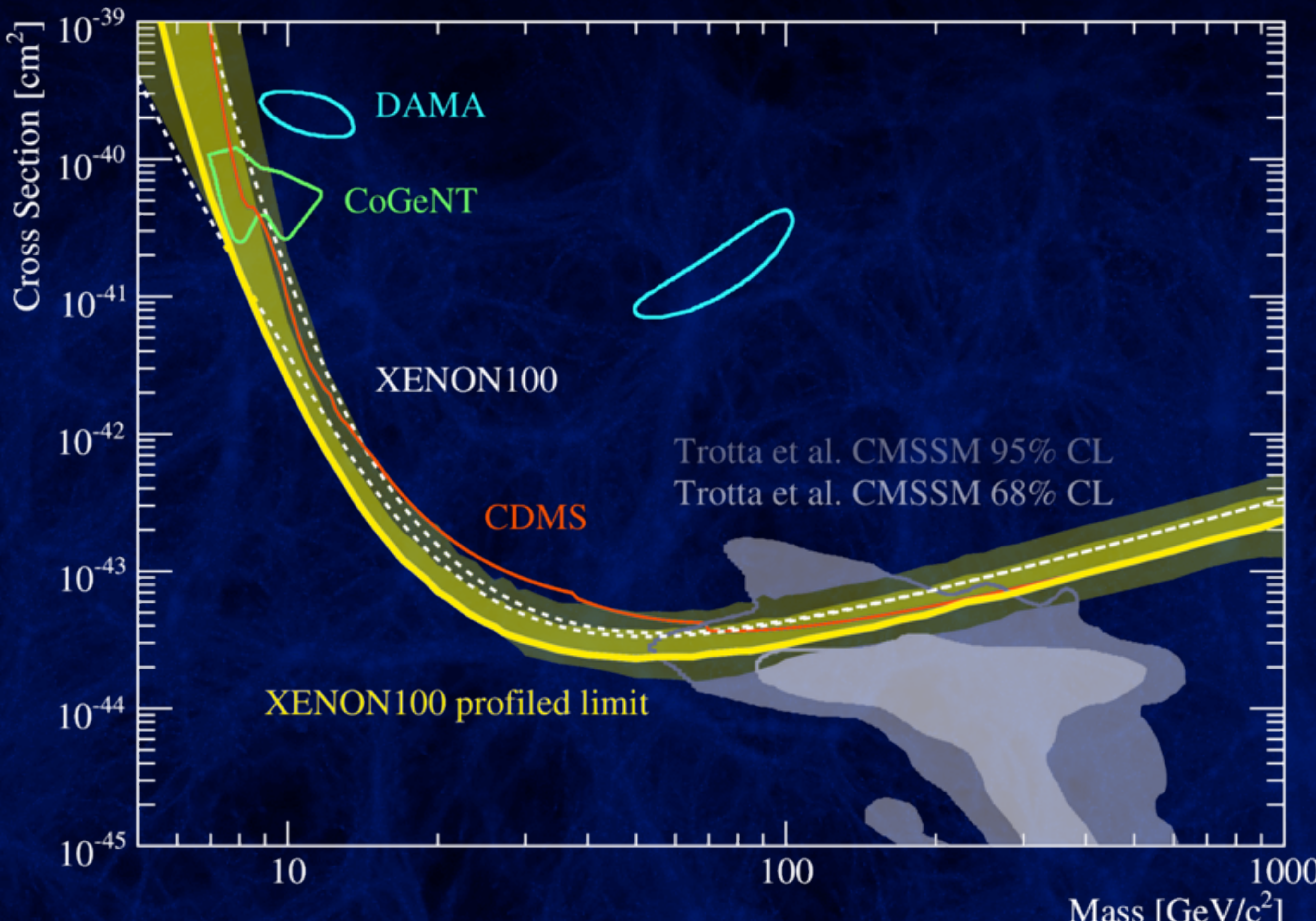
E. Aprile,[1] K. Arisaka,[2] F. Arneodo,[3] A. Askin,[4] L. Baudis,[4] A. Behrens,[4] K. Bokeloh,[5] E. Brown,[2] T. Bruch,[4] J. M. R. Cardoso,[6] B. Choi,[1] D. Cline,[2] E. Duchovni,[7] S. Fattori,[3] A. D. Ferella,[4] K.-L. Giboni,[1] E. Gross,[7] A. Kish,[4] C. W. Lam,[2] J. Lamblin,[8] R. F. Lang,[1] K. E. Lim,[1] S. Lindemann,[9] M. Lindner,[9] J. A. M. Lopes,[6] T. Marrodán Undagoitia,[4] Y. Mei,[10] A. J. Melgarejo Fernandez,[1] K. Ni,[1,11] U. Oberlack,[12,10] S. E. A. Orrigo,[6] E. Pantic,[2] G. Plante,[1] A. C. C. Ribeiro,[6] R. Santorelli,[1,4] J. M. F. dos Santos,[6] M. Schumann,[4,10] P. Shagin,[10] A. Teymourian,[2] D. Thers,[8] E. Tziaferi,[4] O. Vitells,[7] H. Wang,[2] M. Weber,[9] and C. Weinheimer[5]
(The XENON100 Collaboration)

- Developed a statistical model taking the Profile Likelihood ratio as a test statistic in a frequentist approach.
- Data from calibrations is taken as control measurements
- Uncertainties in the energy scale due to L_{eff} as well as systematic uncertainties in astrophysical parameters are built into the model in a natural way.



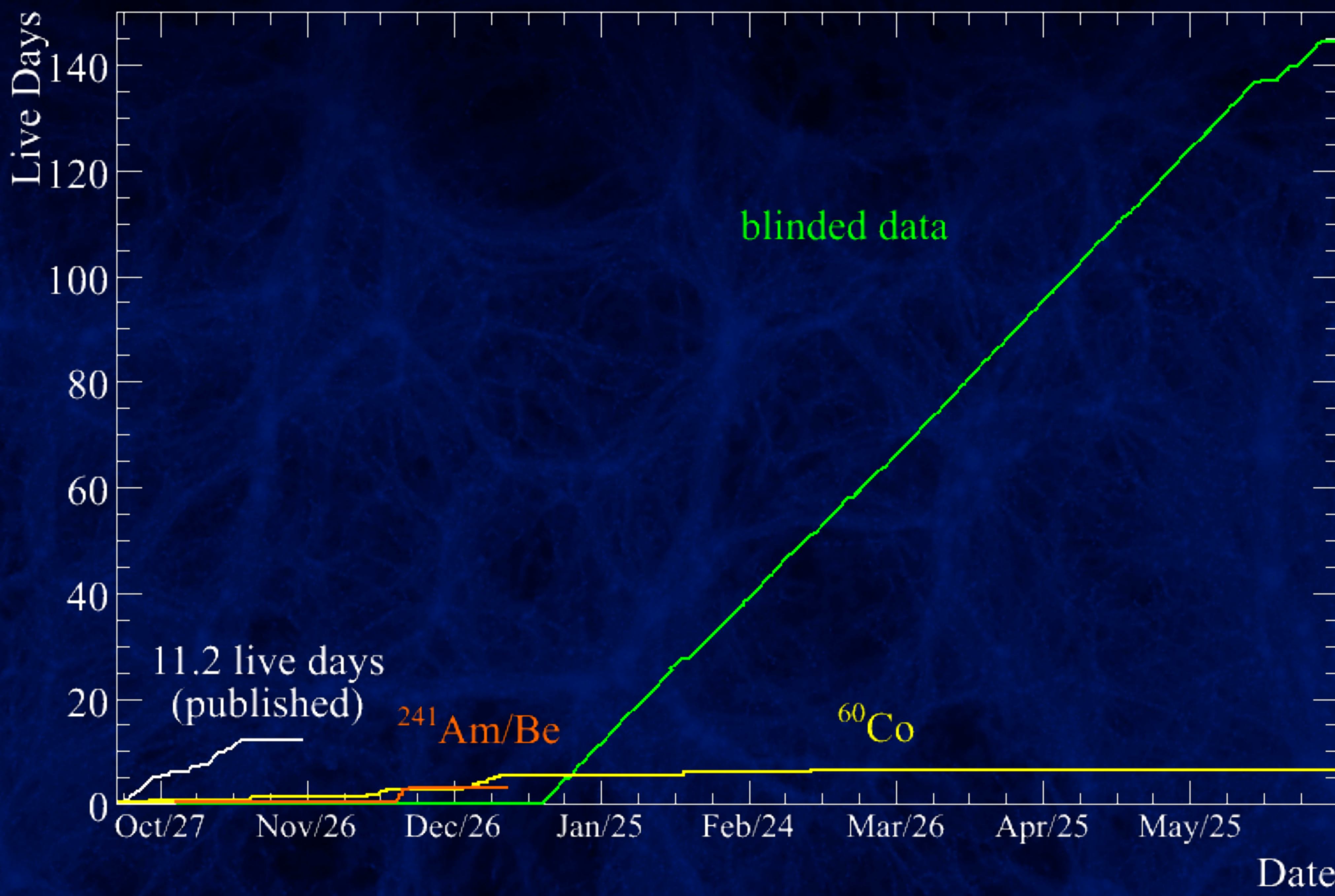
New XENON100 SI Limit arXiv:1103.0303v1

The Profile Likelihood analysis has led to the strongest limit to date over a wide range of WIMP masses. CoGeNT result highly disfavored



Minimum at 2.4 x 10^{-44} cm^2 for a 50 GeV WIMP

XENON100 New Dark Matter Data



Progress towards "Unblinding"

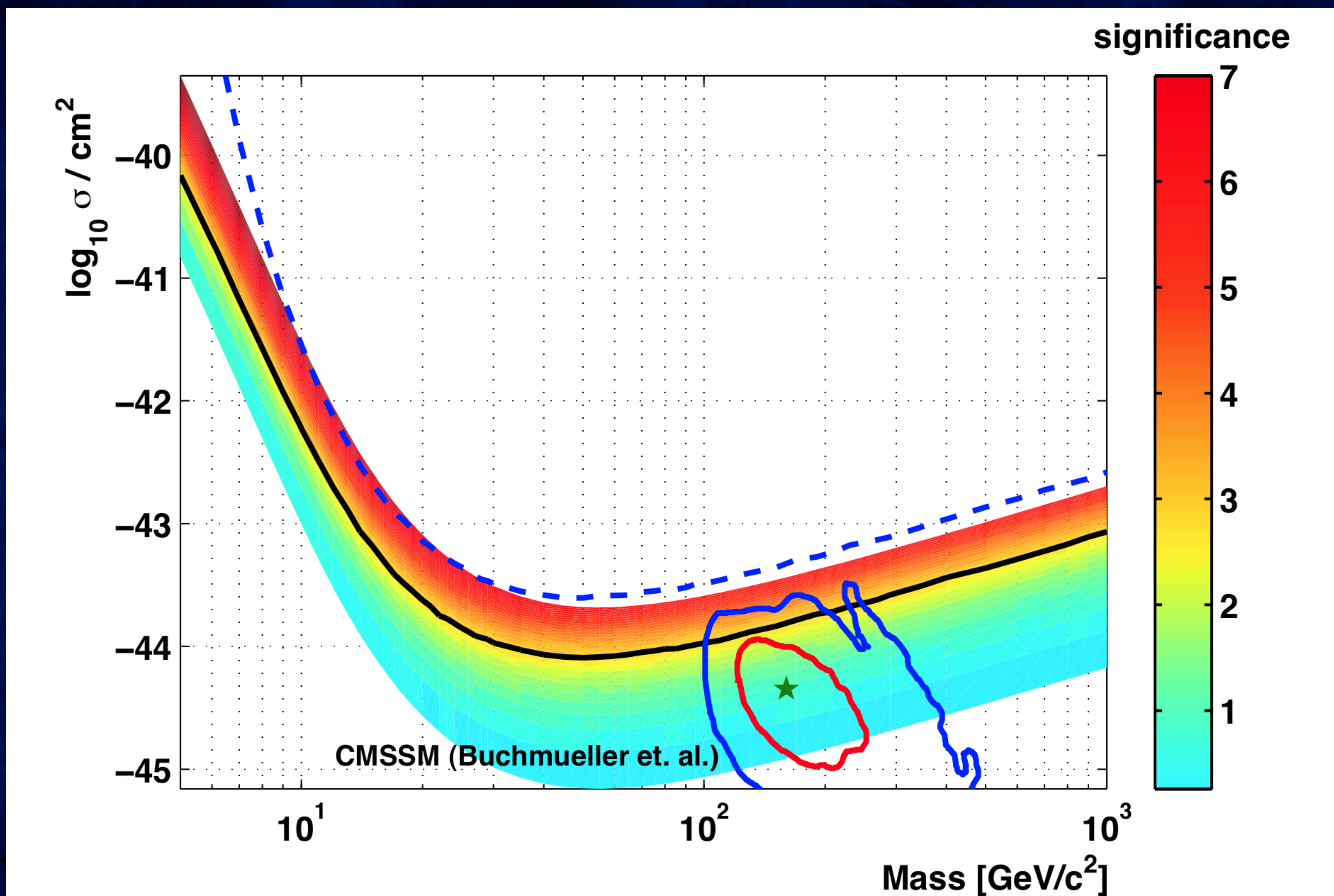
- improved raw data processing and single /multiple scatter selection
- improved corrections for field non-uniformity and acceptance of quality cuts
- improved correction maps for S1 and S2 signal spatial dependence
- improved position reconstruction and chosen Neural Network algorithm
- improved Monte Carlo simulations for more accurate background predictions
- improved understanding of the background in the detector and its spatial distribution has led to an optimized fiducial volume
- implemented new statistical methods to calculate exclusion and discovery regions with proper treatment of systematic uncertainties
- optimized our cuts for best discovery potential
- "unblinding procedure" in final stage of internal review

Projected WIMP Discovery Sensitivity

- Median significance from toy experiments with signal injected into Background
- Based on exposure and background of Blinded data
- Black line is the 3 sigma sensitivity line. Dashed line is 11 days PL limit

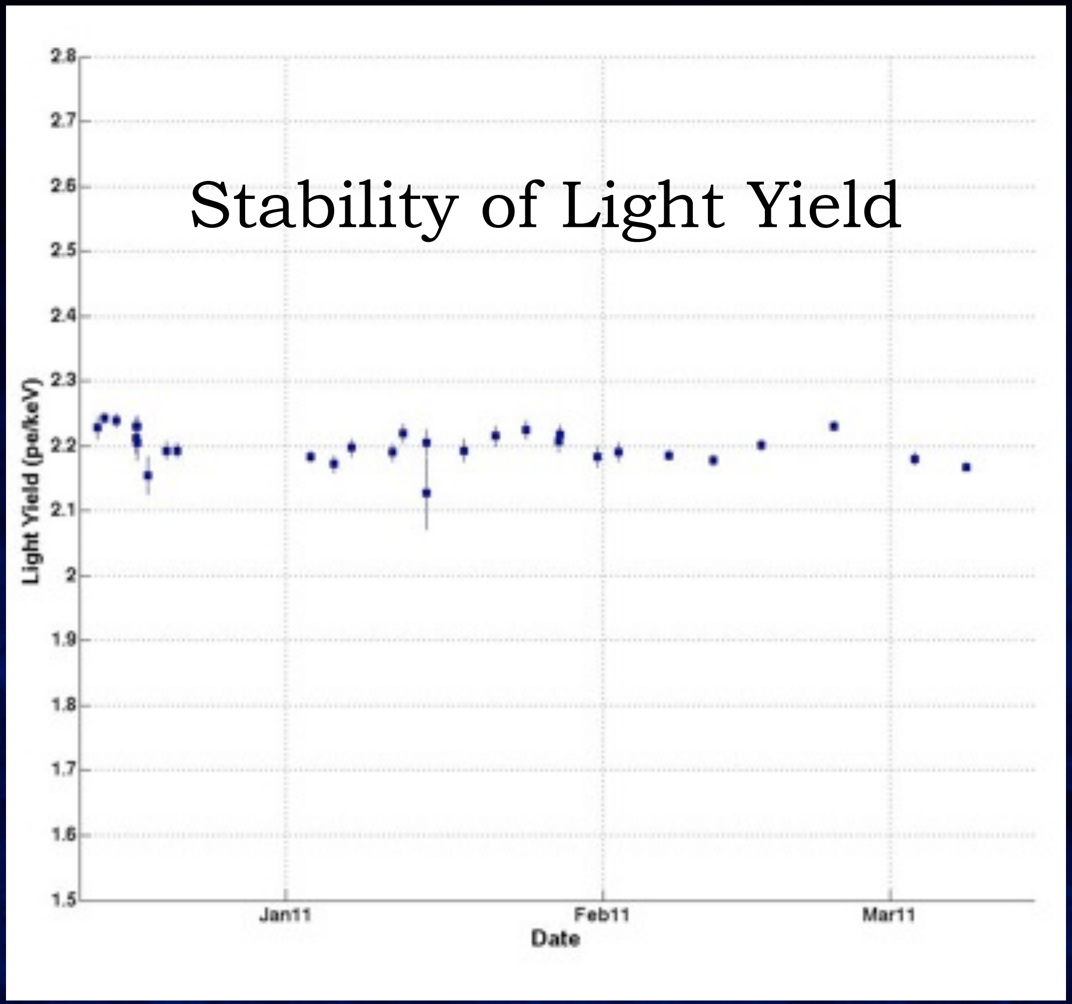
le Likelihood limit

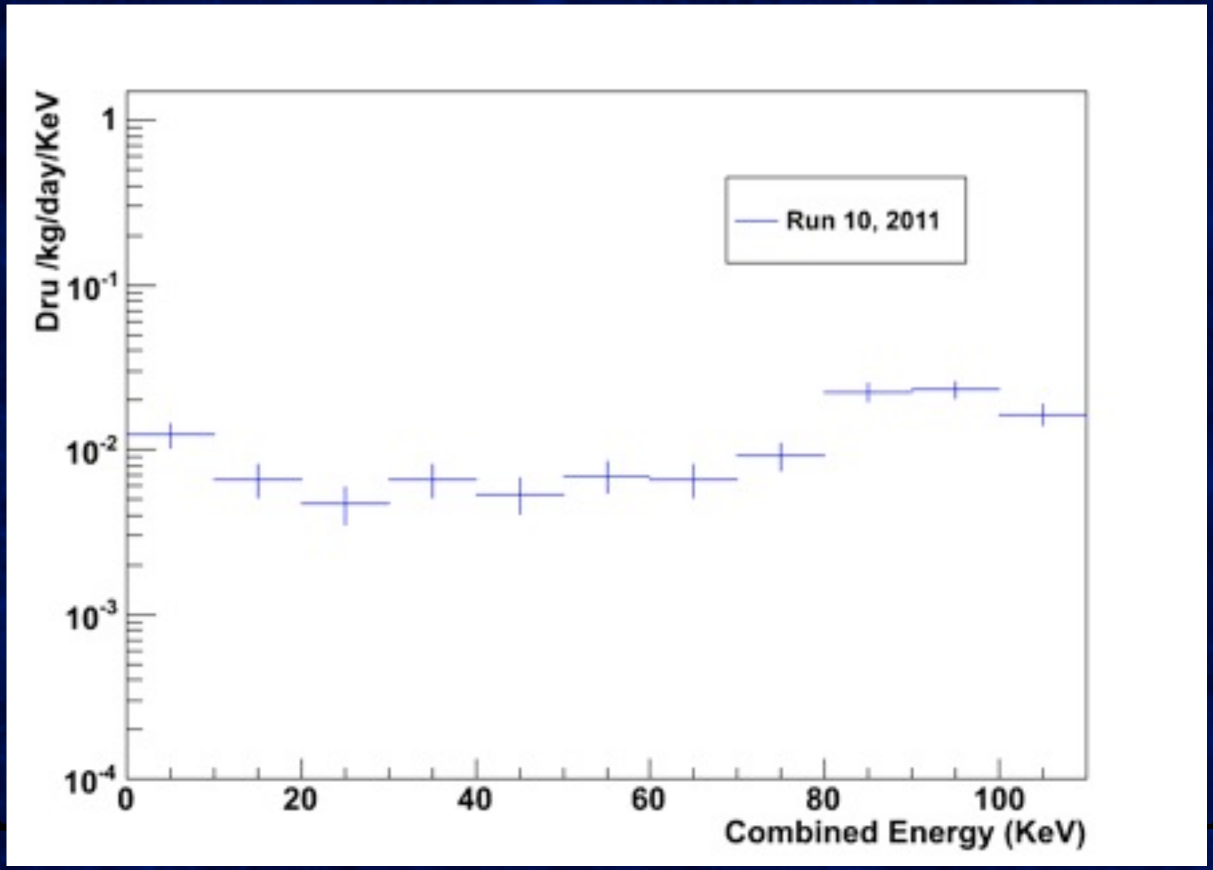
- SUSY contours from latest LHC results   arXiv:1102.4585

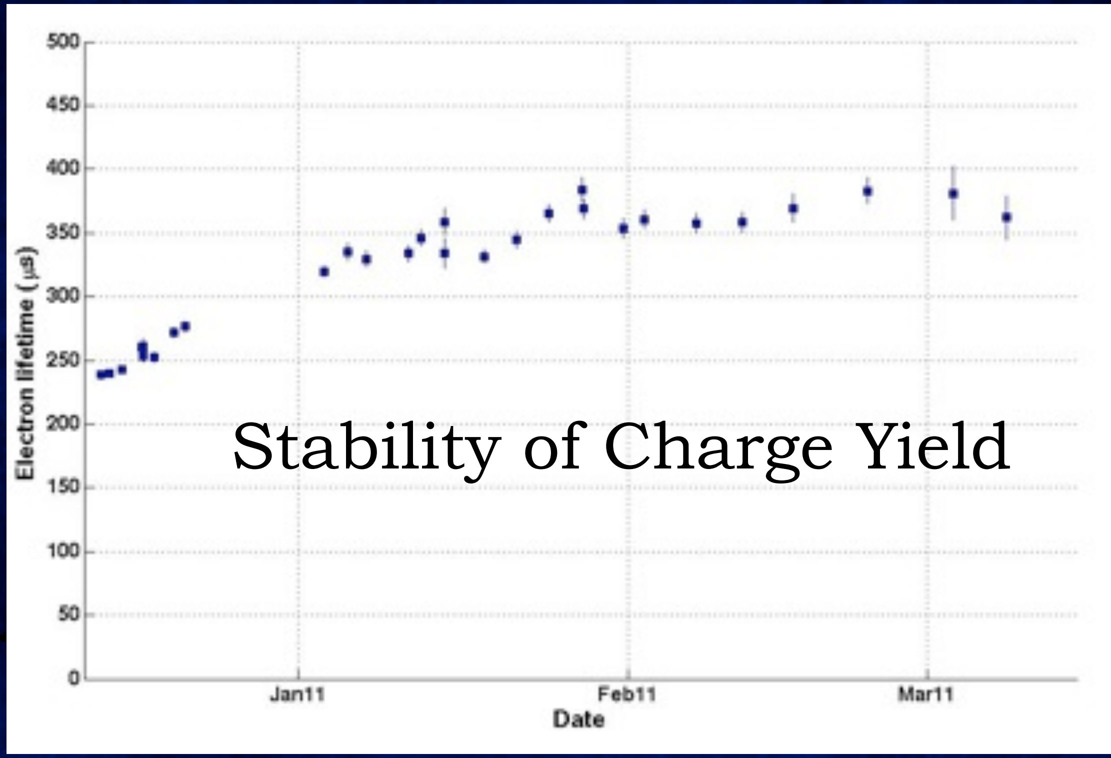


XENON100 Status and Outlook

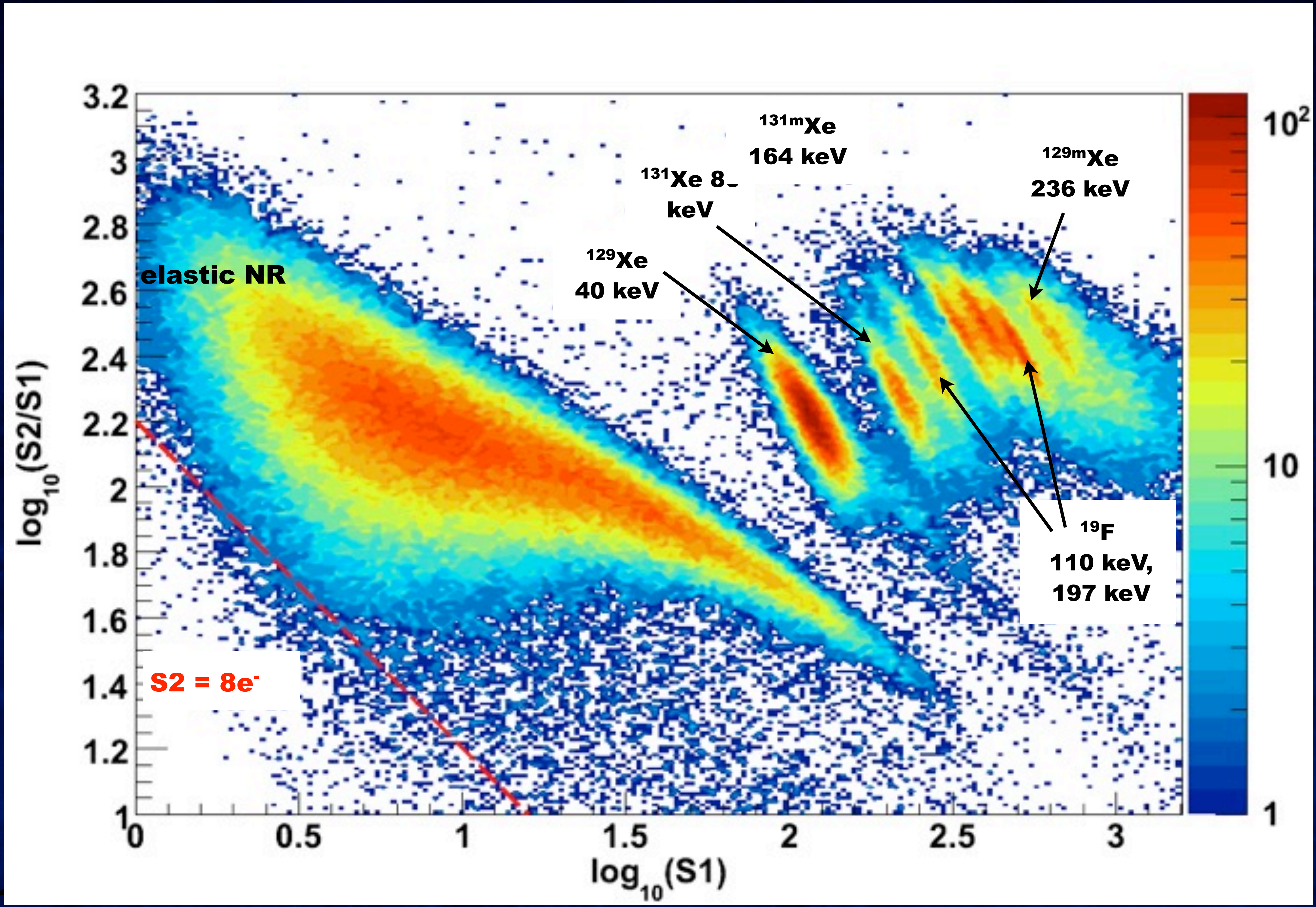
- Serviced Cryogenic System
- Run Kr distillation column
- Lowered S2 Trigger Threshold
- Completed new AmBe Calibration
- Taking Co60 data for ER band
- Charge and Light yield are at max
- Background rate very low
- factor 2 less Kr



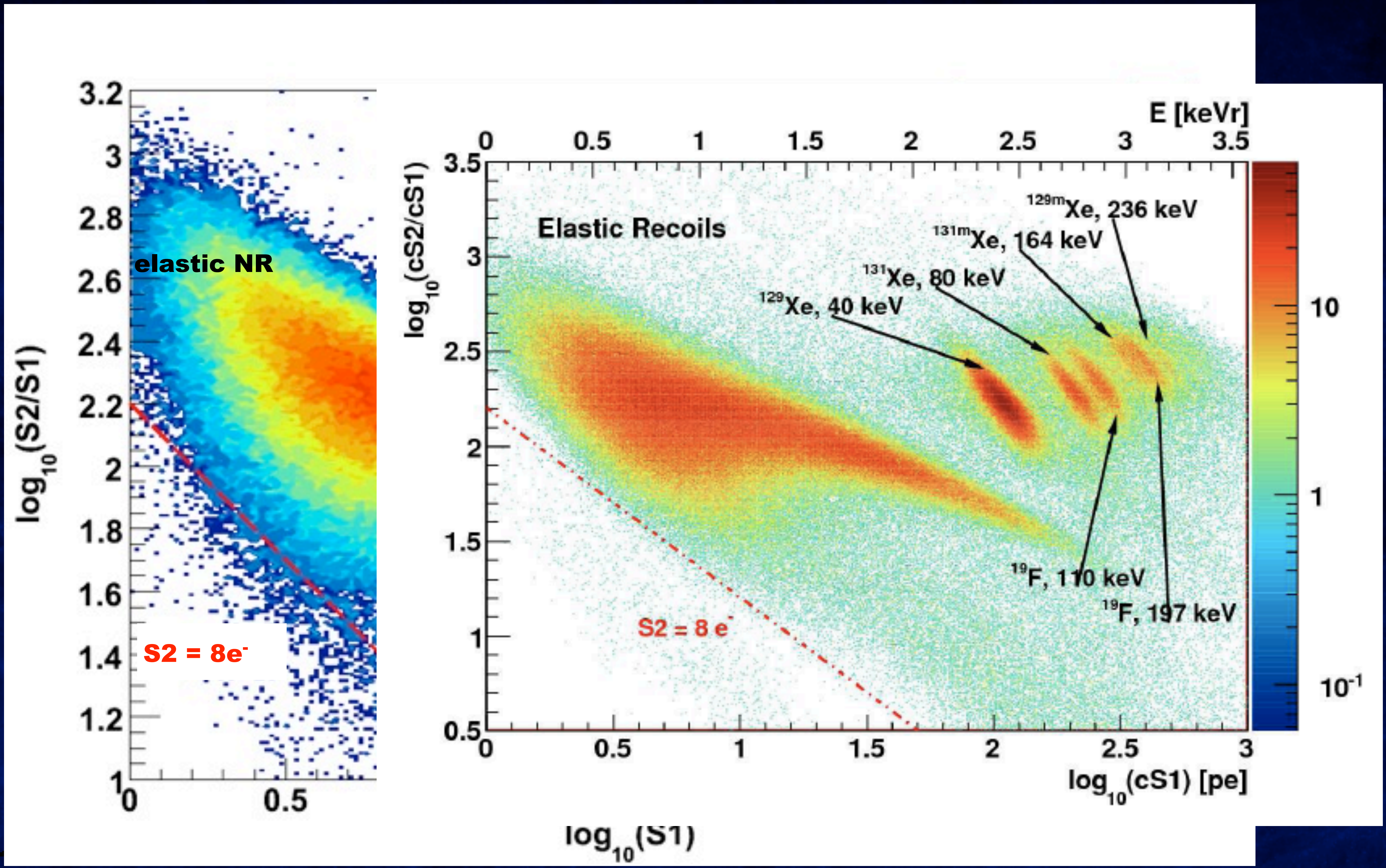




XENON100 AmBe Data- Jan 2011



XENON100 AmBe Data- Jan 2011



Summary

- XENON100 is to-date the largest mass and lowest background Dark Matter experiment in operation underground
- Data from 11 days have yielded the most stringent limit on SI WIMP-nucleon cross section. Minimum at 2.4×10^{-44} cm^2 & 50 GeV WIMP
- A "blind" analysis of ~10 times more data is near completion. Results expected within weeks. Non negligible discovery potential
- Experiment continues at LNGS and detector performance is better than last year. Will reach sensitivity goal of 2×10^{-45} cm^2 in 2011.
- Proposal and TDR for the XENON1T phase submitted to the LNGS Scientific Committee in 2010
- Large fraction of funds and detailed work plan in place to start construction in Fall 2011. Collaboration awaiting INFN decision