DIRECT DARK MATTER DETECTION

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University College London

HEP Seminar
30th November 2012

1. Very Brief Intro to Dark Matter and Direct Detection

2. The LXeTPC & XENON100

3. Latest Results

4. The Next Generation (Tonne scale) Detectors

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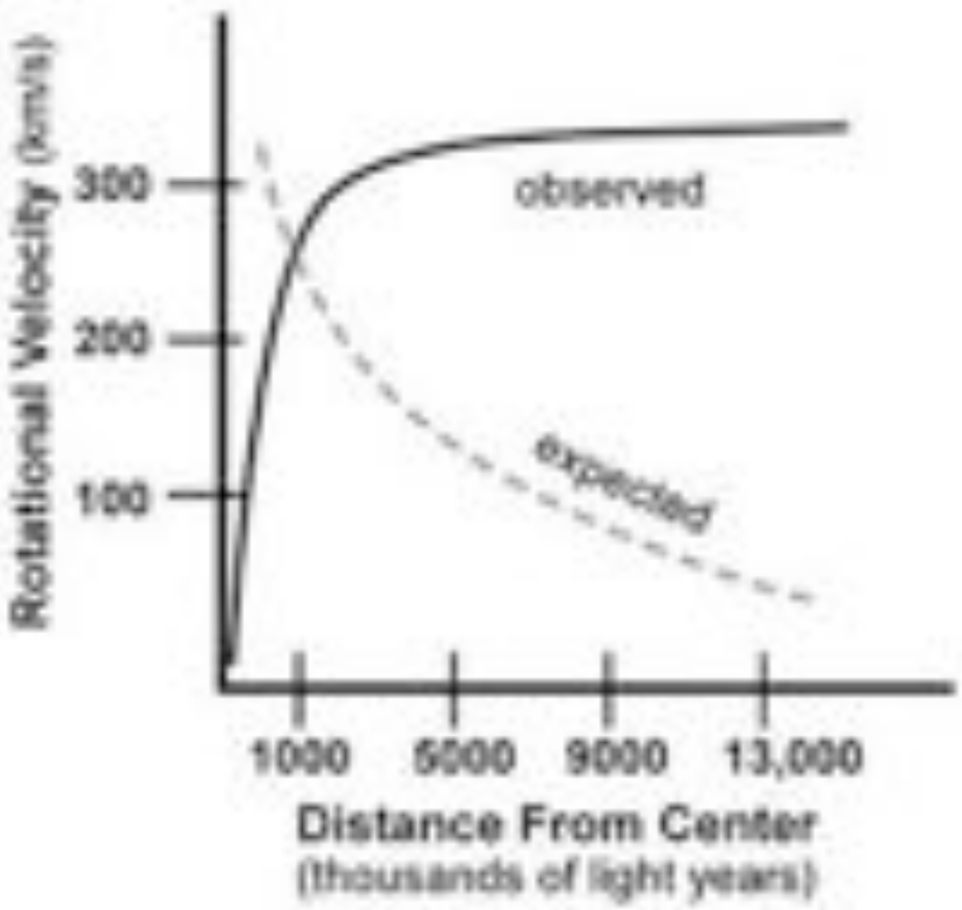
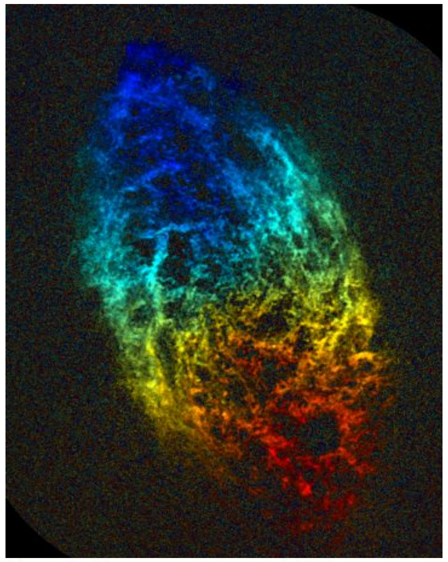
Early evidence for Dark Matter

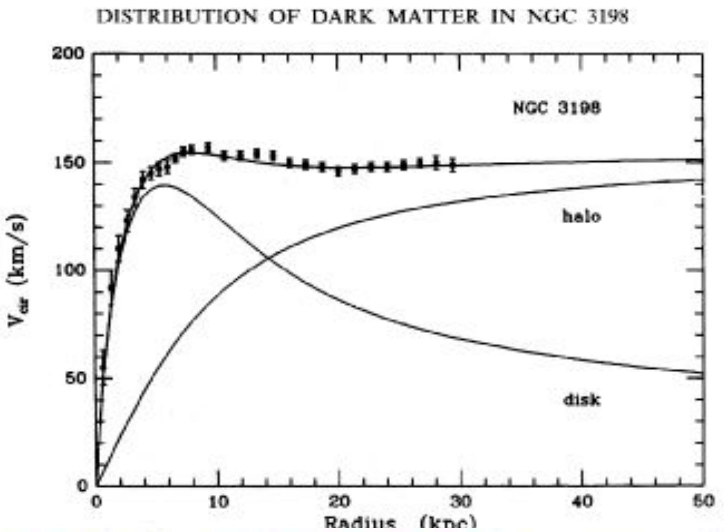
1930's - Fritz Zwicky
1970's - Vera Ruben
Measured rotational velocity of galaxies and observed flat curves rather than expected Keplerian fall-off with distance from galactic centre

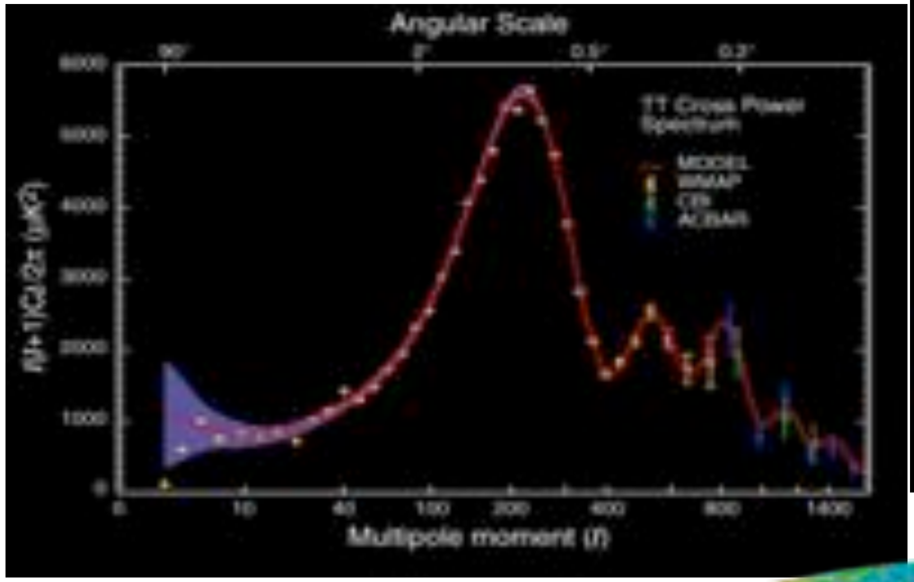
GALAXIES ARE ROTATING TOO FAST!

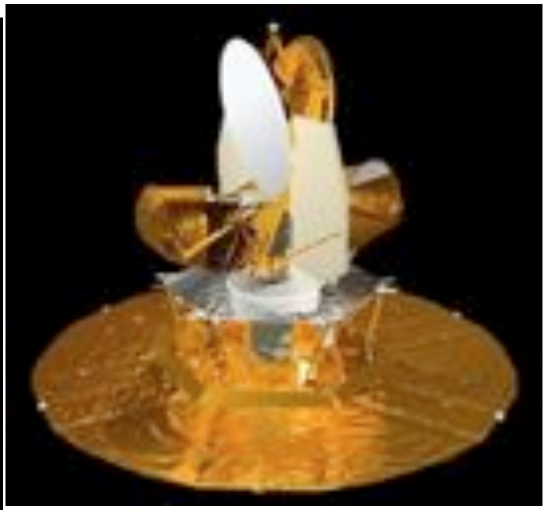


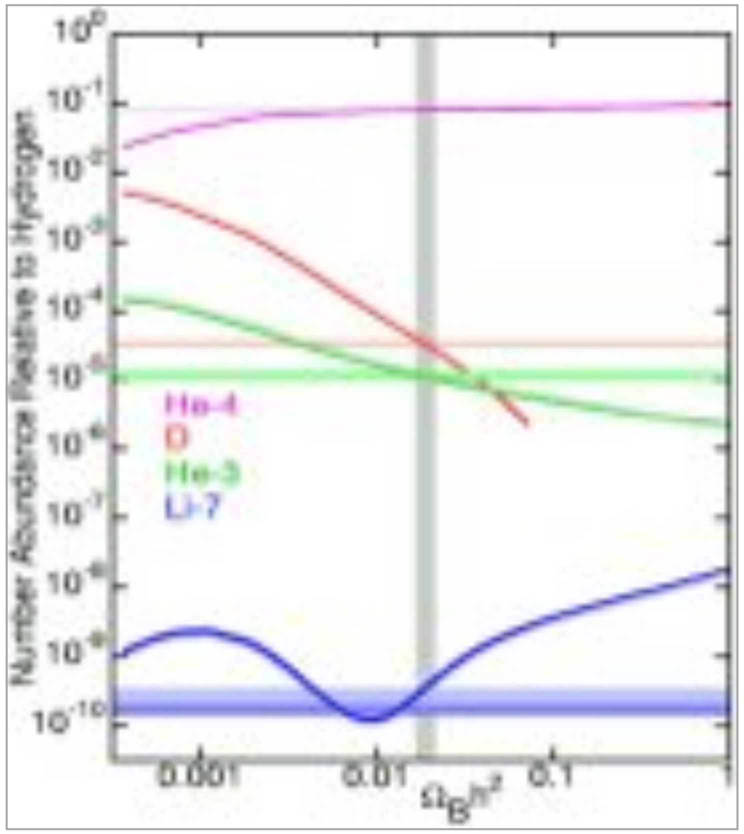
Lots more evidence since then...

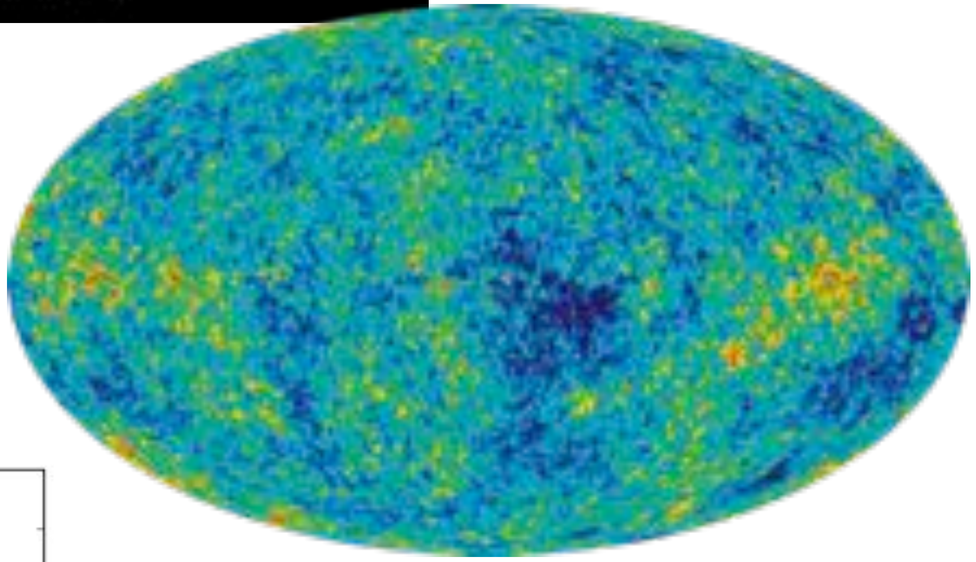


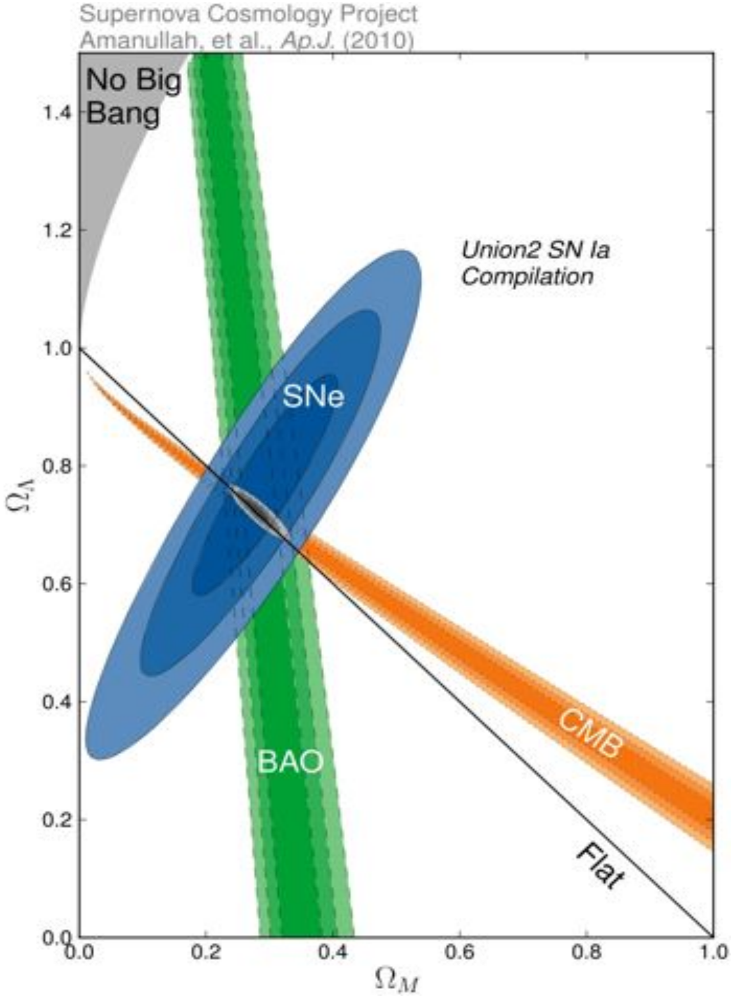

DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50


Angular Scale
Multipole moment (l)

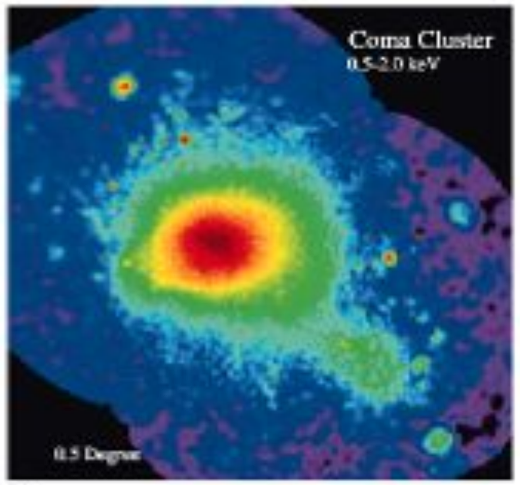


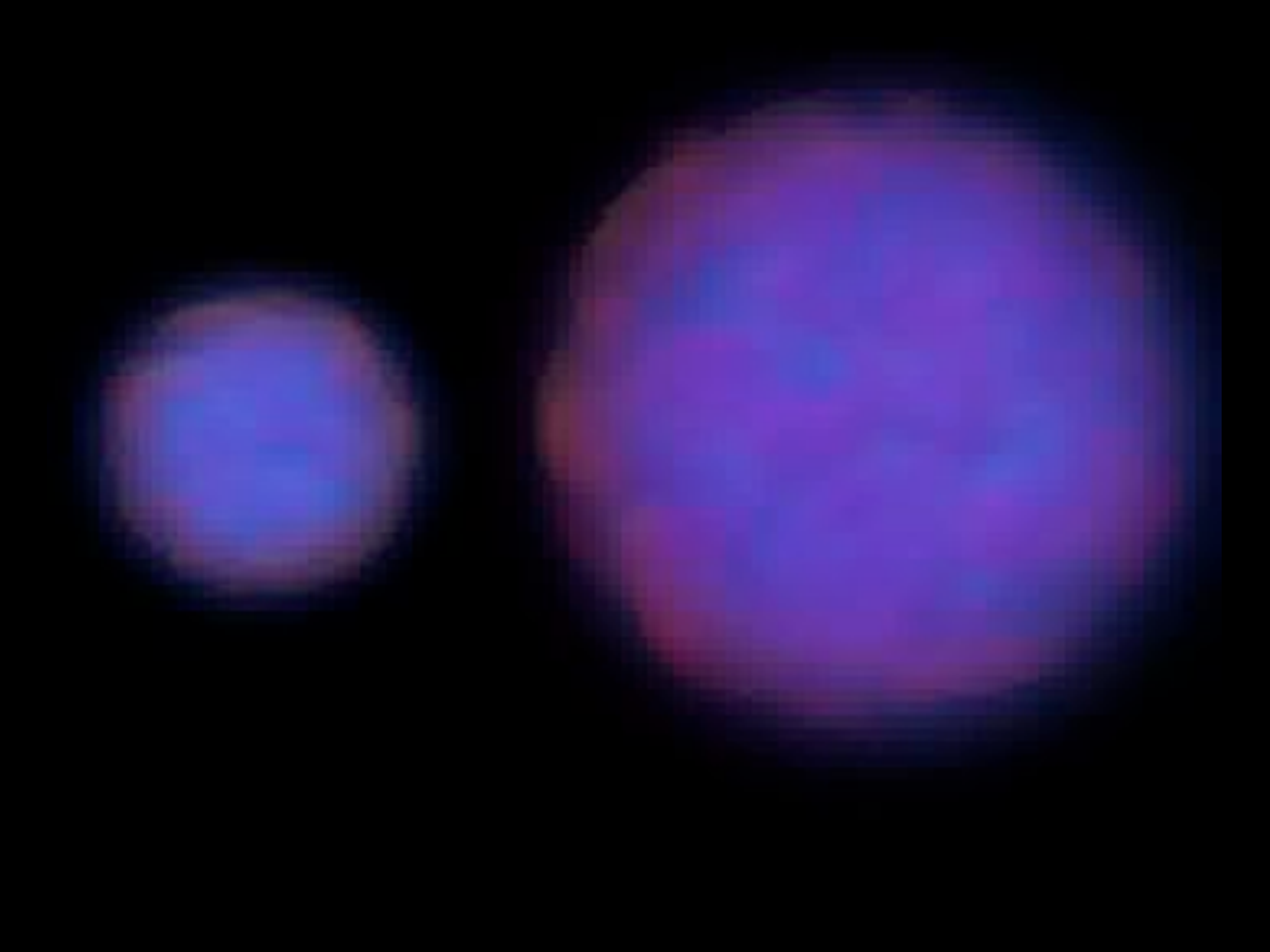

He-4
D
He-3
Li-7
Number Abundance Relative to Hydrogen
$\Omega_B h^2$
0.001
0.01
0.1
1

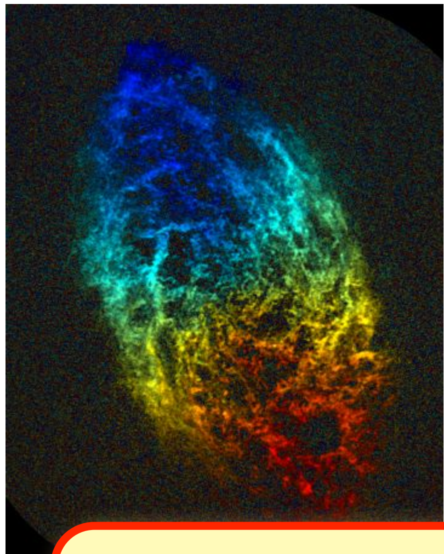


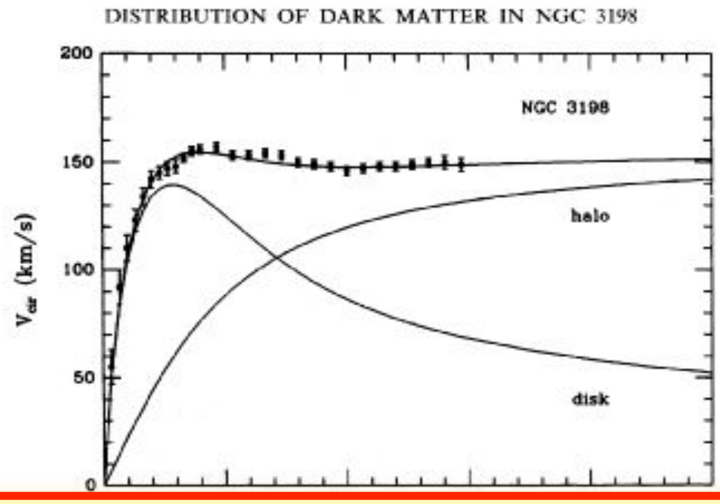

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

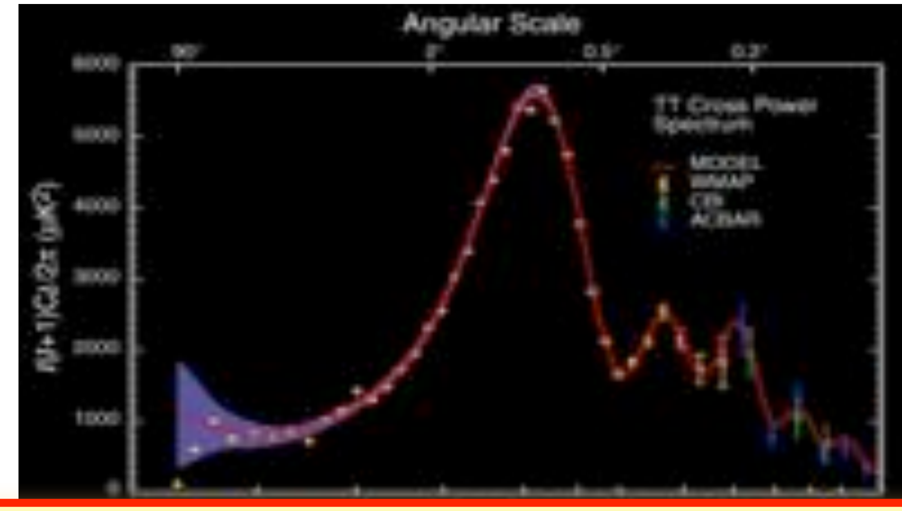

(a)

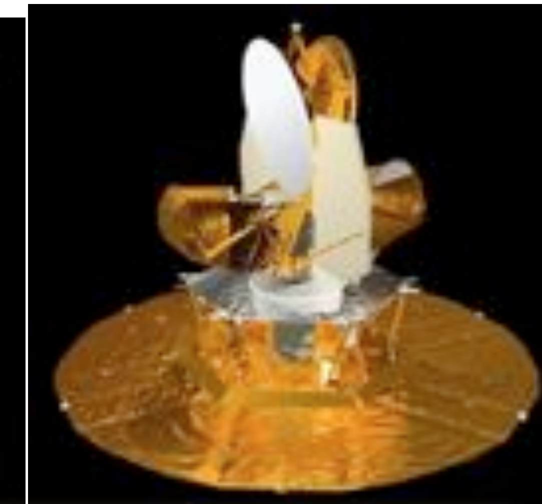

Coma Cluster
0.5-2.0 keV
0.5 Degree
(b)









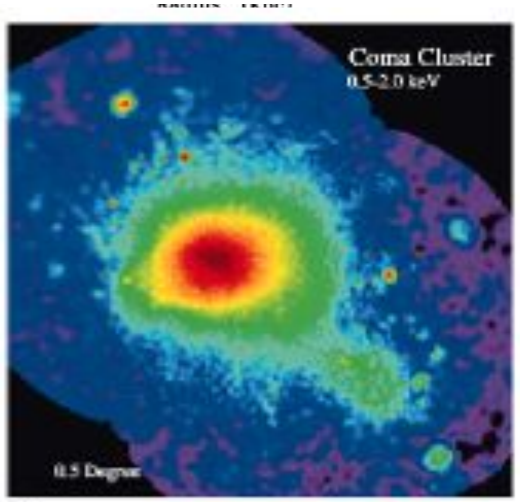


We have a 'Missing Mass' Problem!

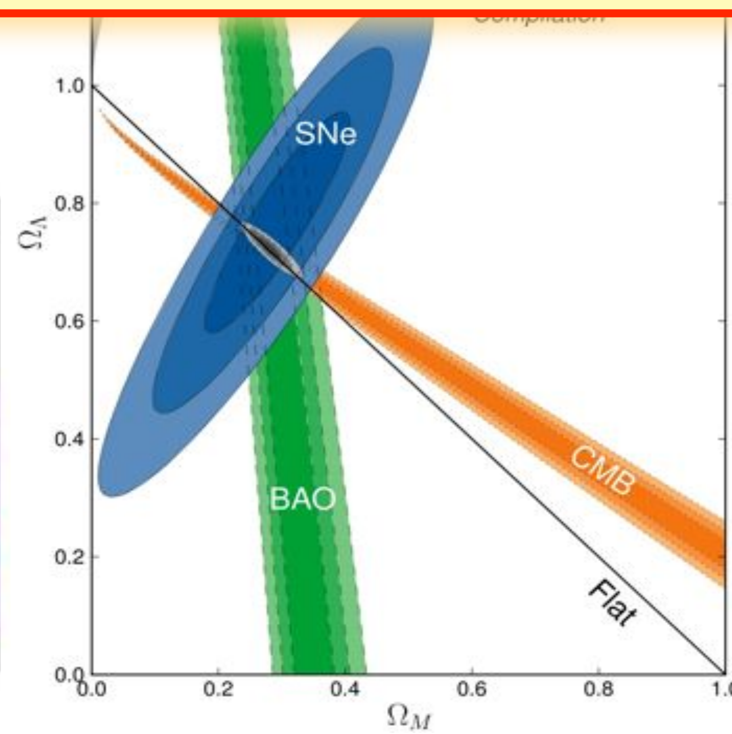
85% of the mass of the Universe is **DARK!**


(a)

Copyright © Addison Wesley.



(b)



Dark Matter Detection

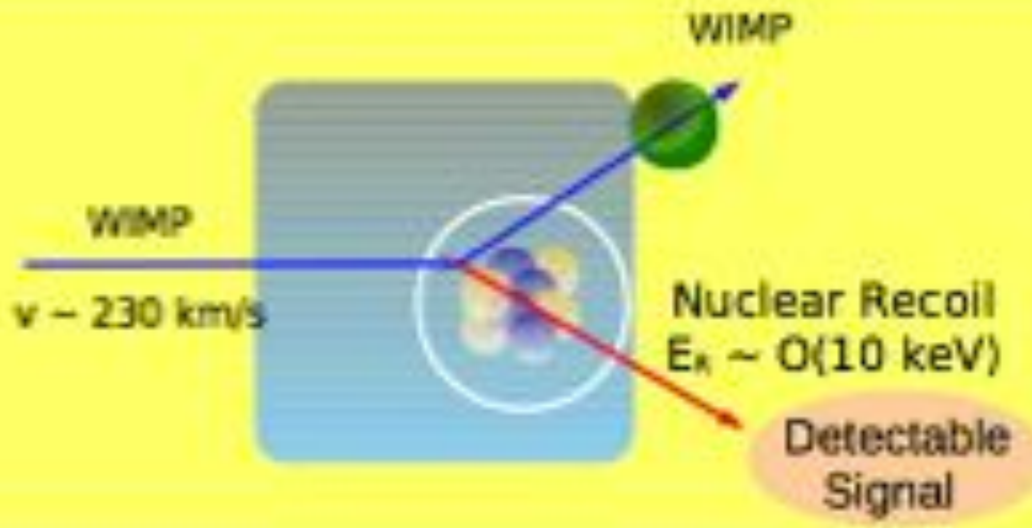
Favoured candidates are Weakly Interacting Massive Particles (WIMPs)

- Indirect - observe annihilation products
- Accelerator - produce WIMPs
- **Direct** - interact with galactic WIMPs (*our* Dark Matter!) in unltra-low background terrestrial detectors

Direct detection is internationally recognised as one of THE highest priorities in science!

Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei
➡ nuclear recoil



Recoil Energy: $E_r \sim \mathcal{O}(10 \text{ keV})$

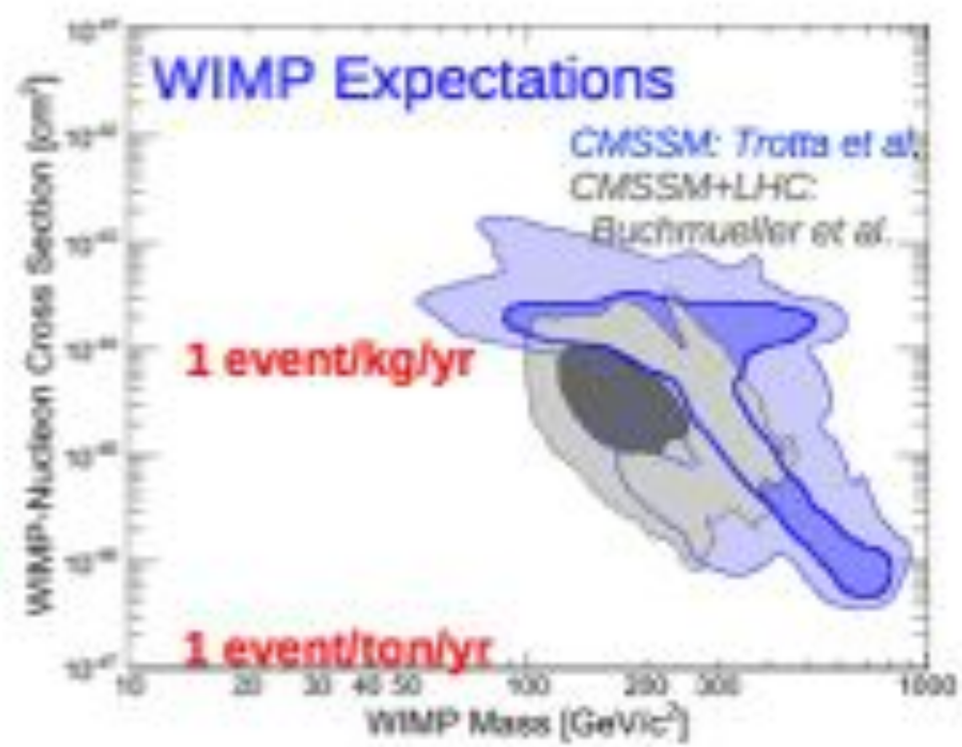
Event Rate: $R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$

Detector

Local DM Density

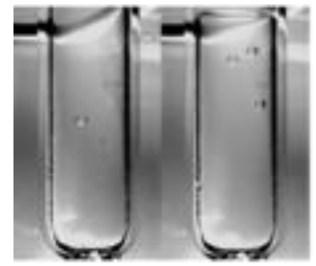
ρ_χ~0.3 GeV/c²

Physics



WIMP Detection Techniques

Heat and ionisation bolometers:
CDMS
EDELWEISS



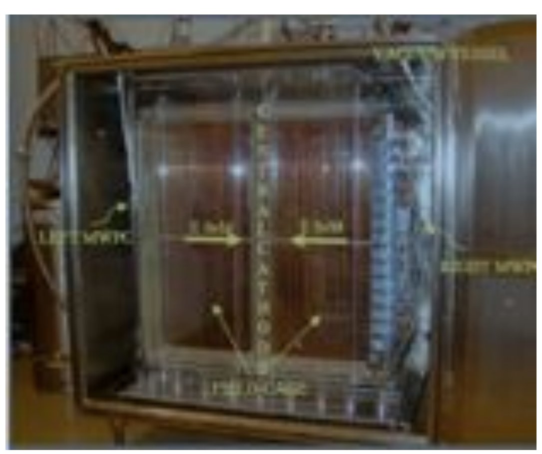
Bubbles and Droplets:
CUOPP
PICASSO

Light and heat Bolometers:
CRESST
ROSEBUD

Phonons

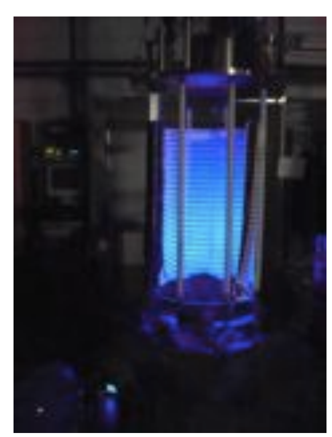
Charge

Light



Ionisation detectors:
DRIFT, DMTPC, GENIUS, NEWAGE,
HDMS, IGEX

Scintillation and ionisation charge detectors:
XENON
DarkSide
ZEPLIN
LUX



Scintillators:
DAMA
LIBRA
XMASS
CLEAN
DEAP
ANAIS
KIMS

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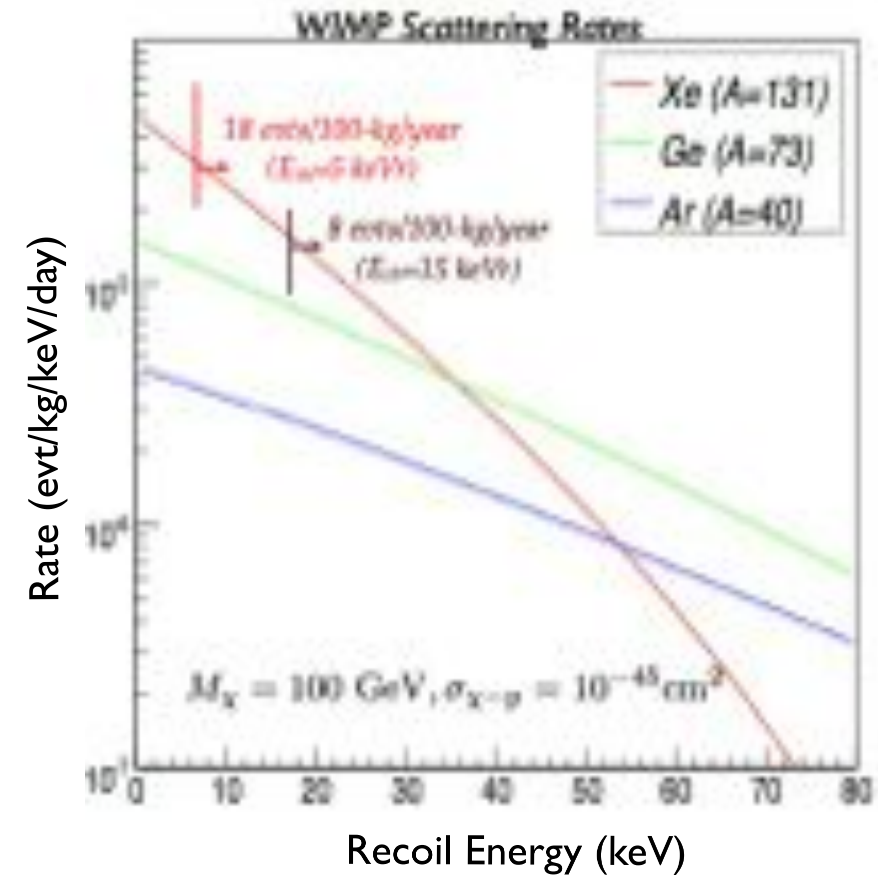
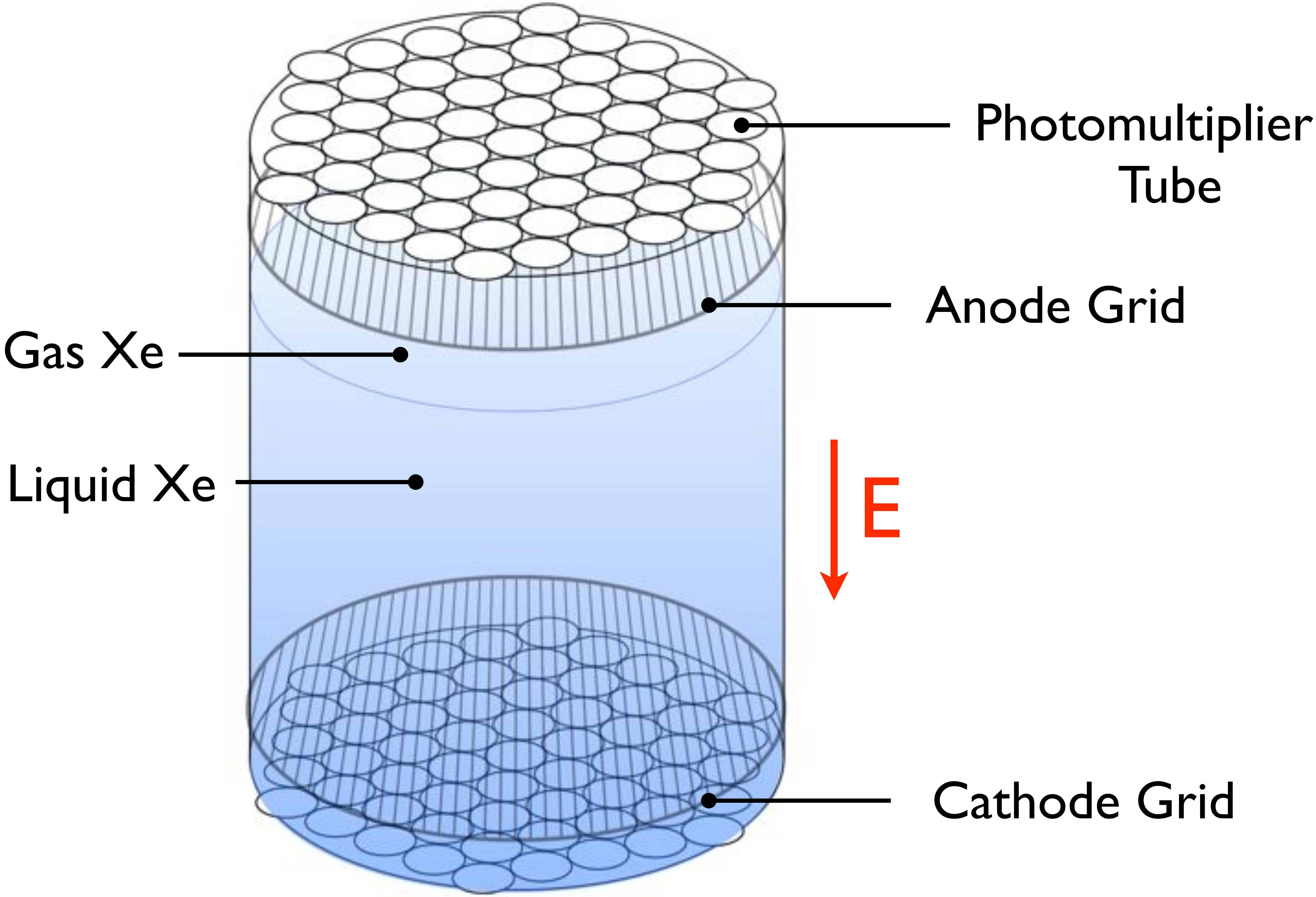
Liquid Xenon Time Projection Chambers

- **S1: LXe is an excellent scintillator**
  - Density: 3 g/cm^3
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~5-8 keV**

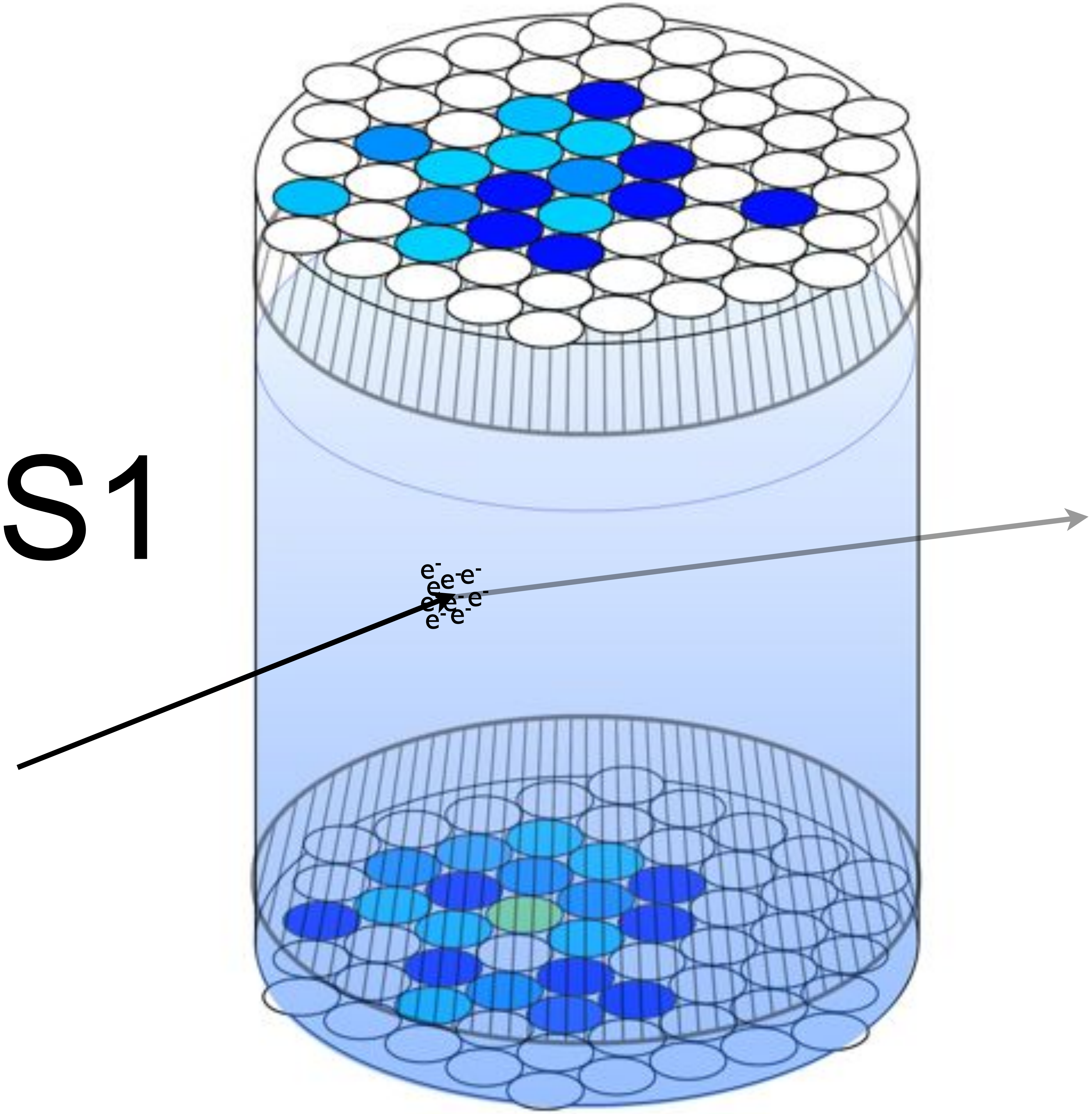


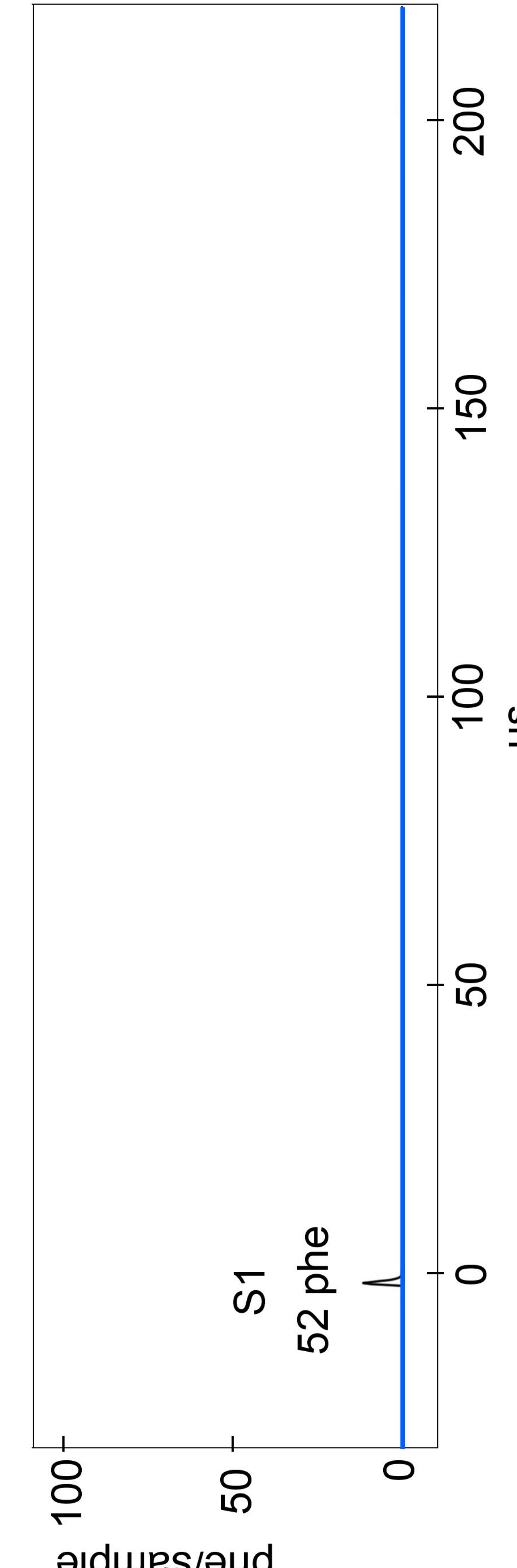
- **S2: Even better ionisation detector**
  - S1+S2 allows mm vertex reconstruction
  - Sensitive to single ionisation electrons
  - **Nuclear recoil threshold ~1 keV**

- **And a great WIMP target too**
  - Scalar WIMP-nucleon scattering rate dR/dE~A^2
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity
  - Excellent ionisation threshold: ‘light WIMP’ searches using S2 only
  - No intrinsic backgrounds (^{85}Kr can be removed, low rate from ^{136}Xe $2\nu\beta\beta$)
  - Easily scaled with no loss of performance (actually improves!)


Photomultiplier Tube
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

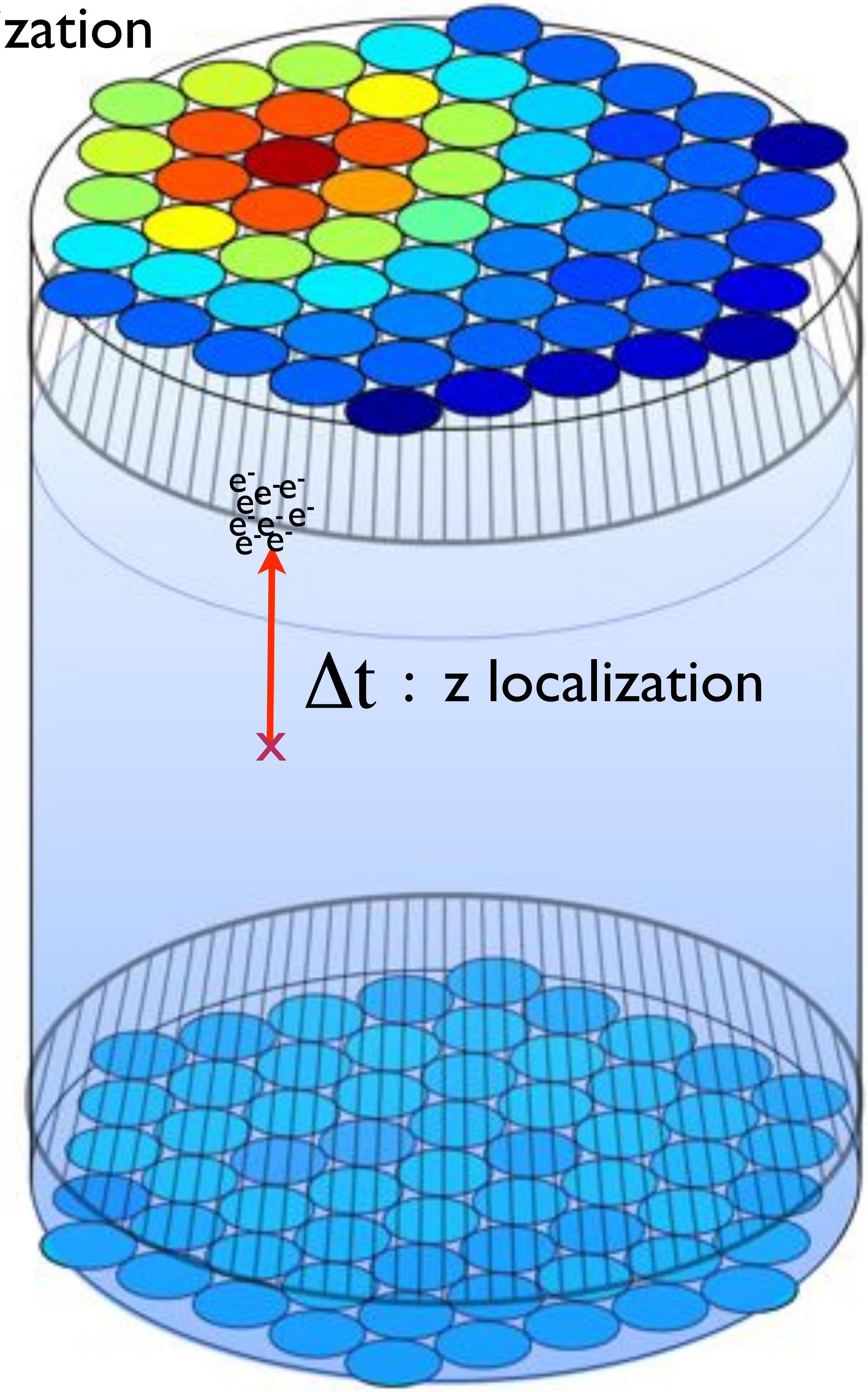
S1

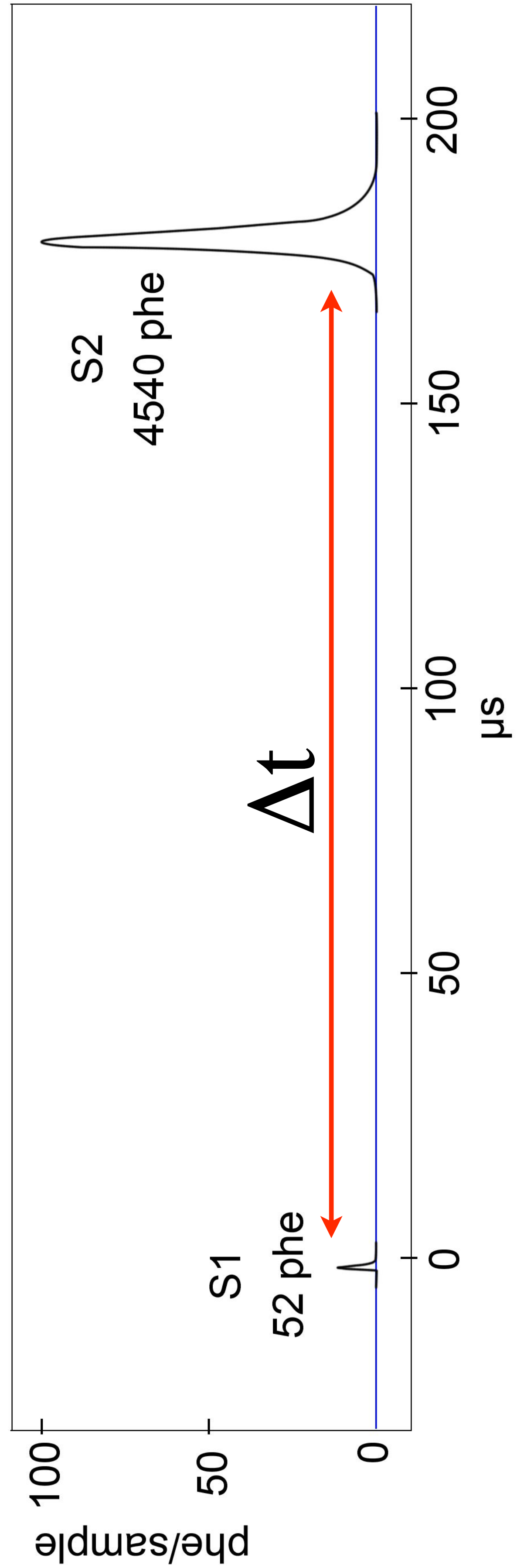


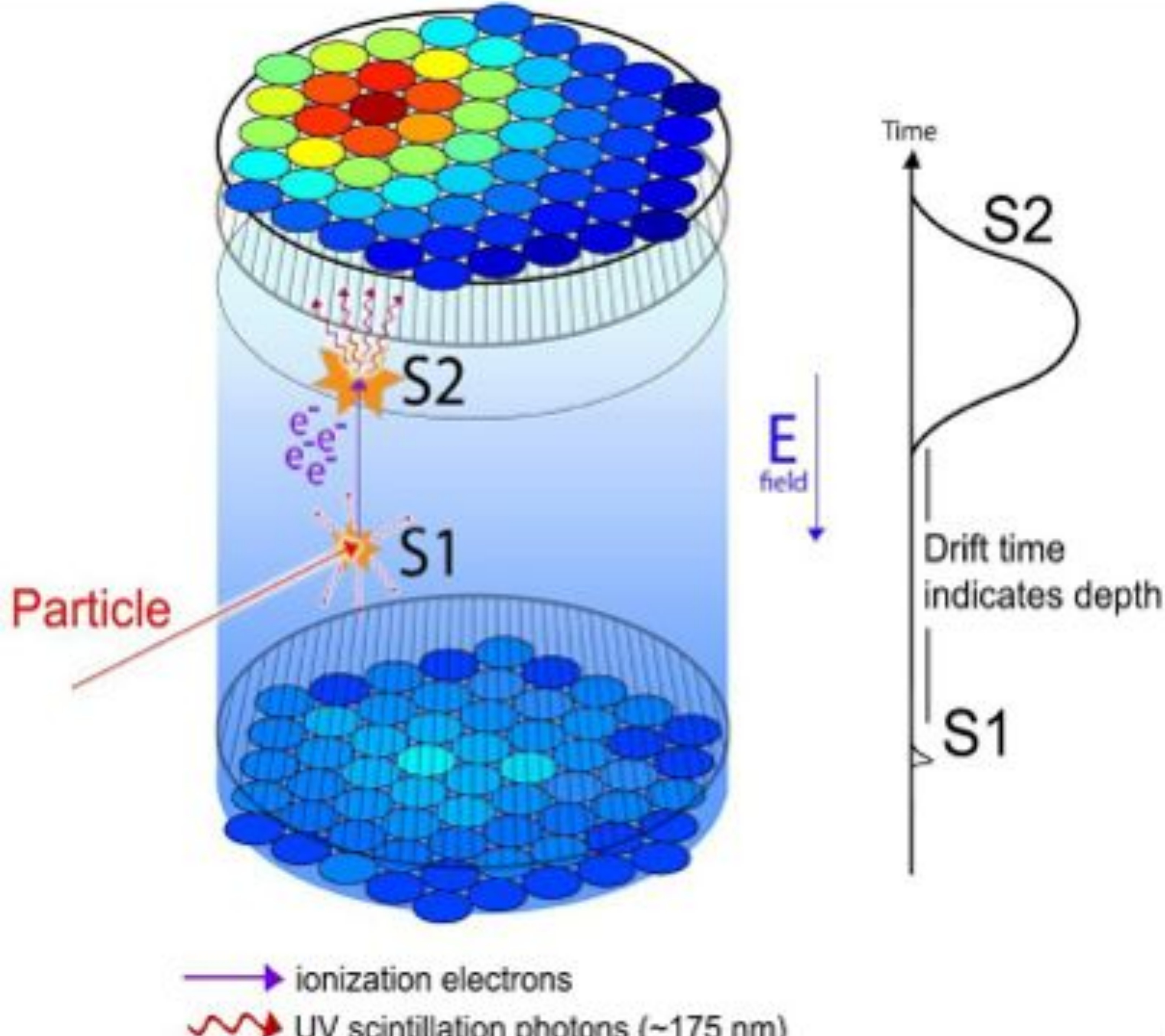


top hit pattern:
x-y localization

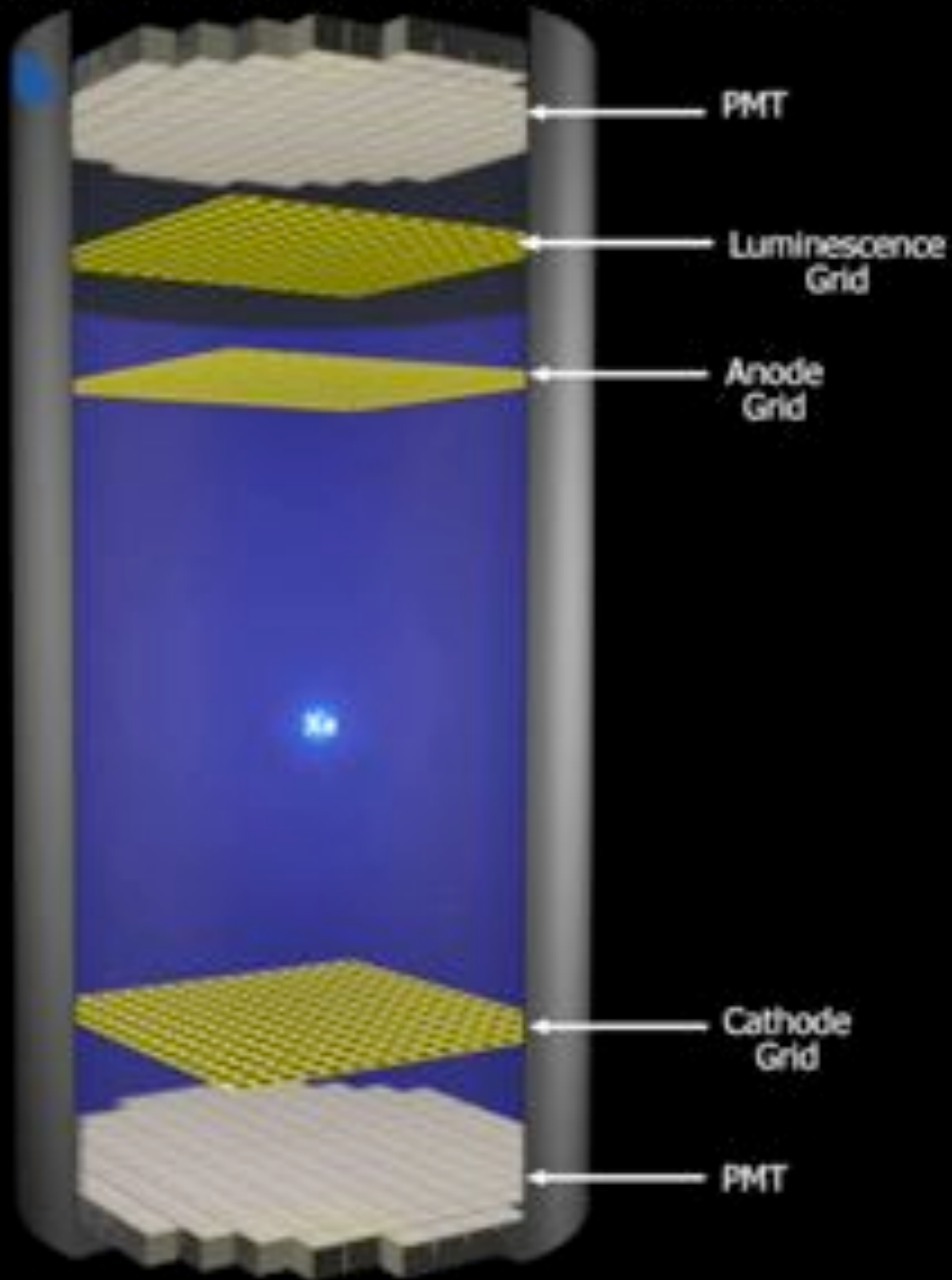
S2



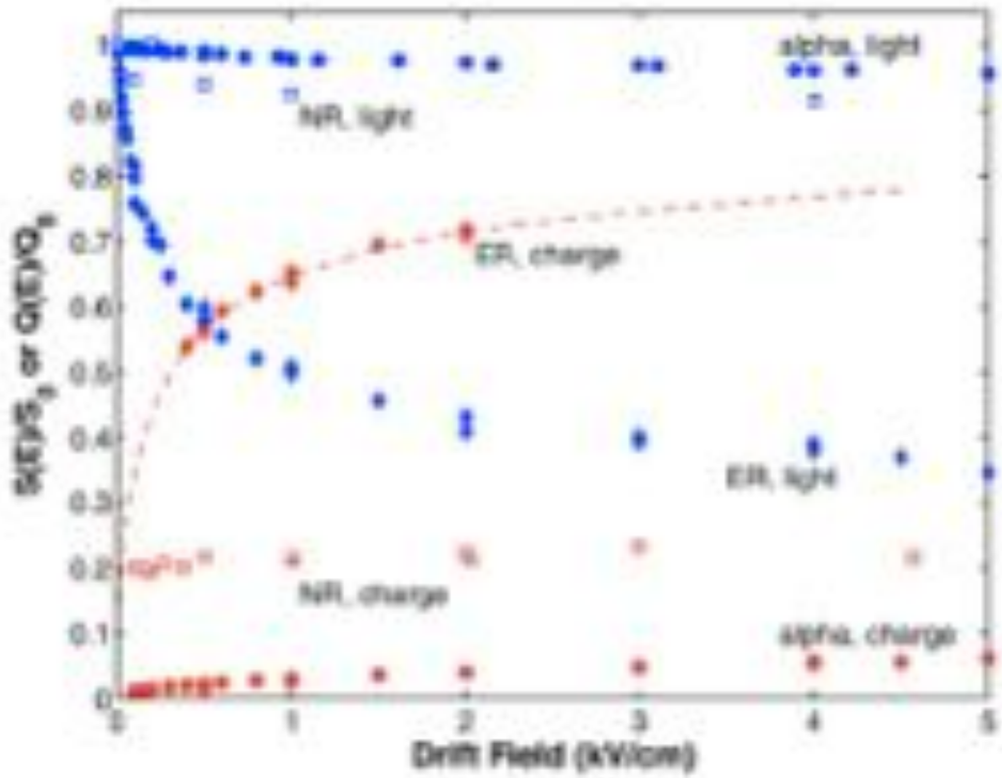



Time
S2
S2
e⁻ e⁻ e⁻ e⁻
E
field
S1
Particle
Drift time
indicates depth
S1
ionization electrons
UV scintillation photons (~175 nm)

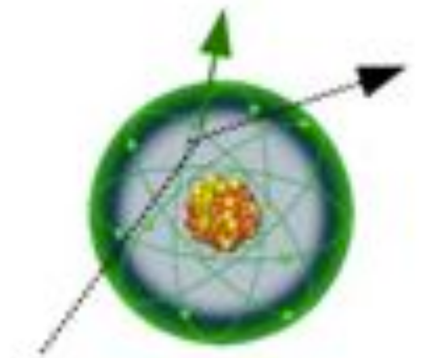
WIMP Signals in a Dual-Phase Xenon Detector



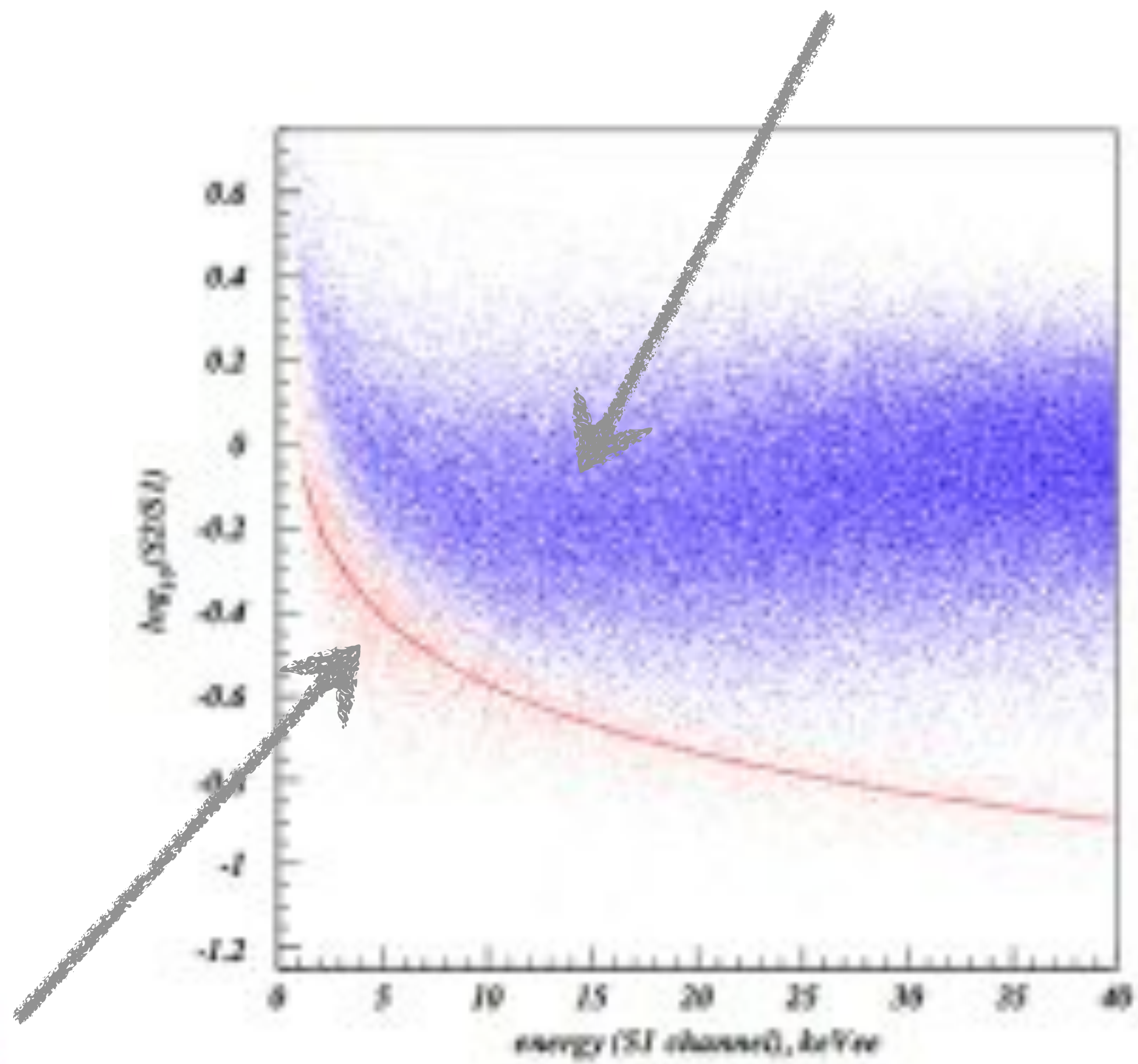
Particle Discrimination

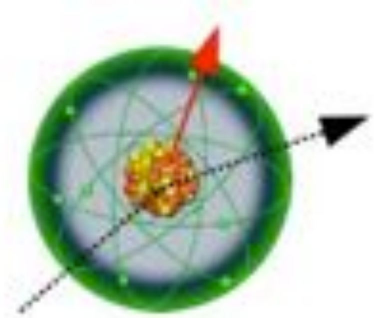


Light (S1) and charge (S2)
depend on recoil dE/dx



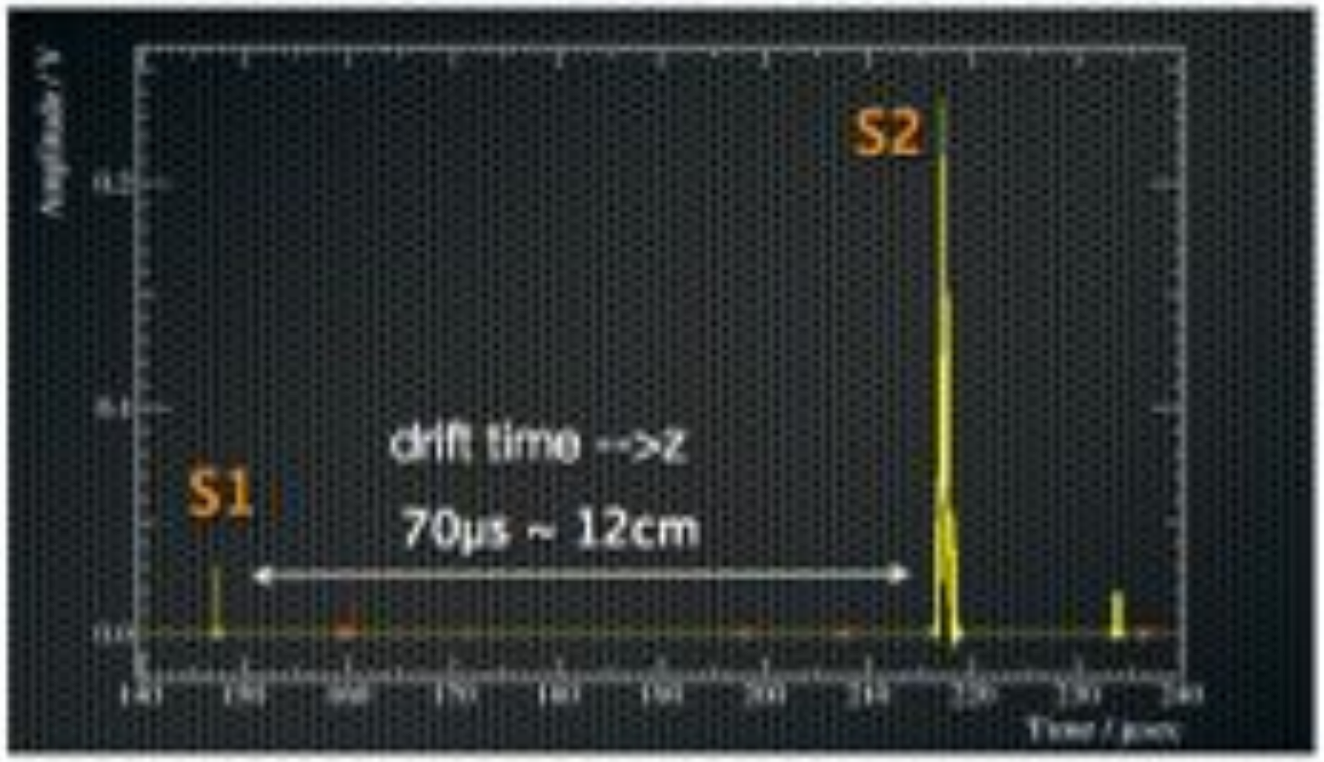
Electronic Recoils
(gamma, beta)

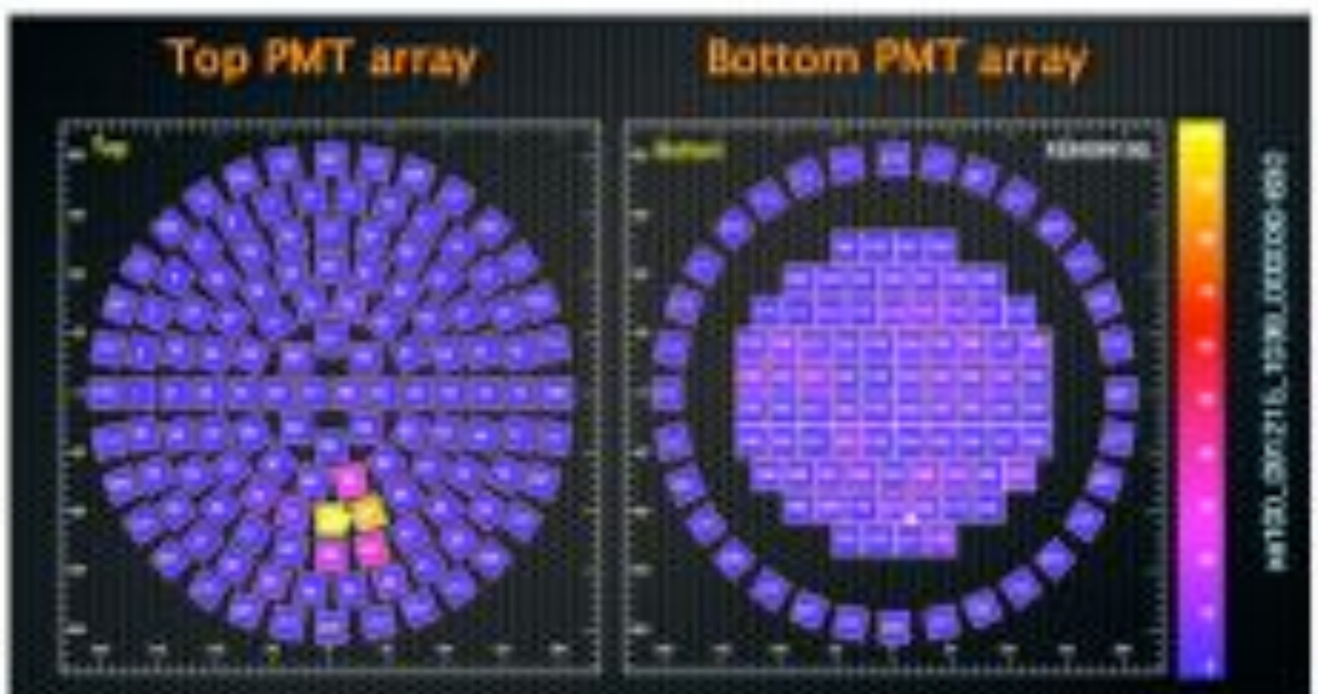




Nuclear Recoils
(neutron, WIMPs)

Event Position Reconstruction





Example of a low energy (9 keVnr)

4 photoelectrons detected from about 100 S1 photons

645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Event Z-position from measured drift time t(S2) - t(S1) and known e- velocity. dZ< 0.3 mm

event X-Y position from measured S2-hit-pattern. dR < 3mm

The XENON Roadmap

XENON10

2005-2007

PRL100
PRL101
PRL 107
PRD 80
NIM A 601

XENON100

2007-2013

first results:
PRL105, PRL107, PRD84

XENON1T

2012-2017

approved at LNGS, Hall B
construction starts in fall 2012

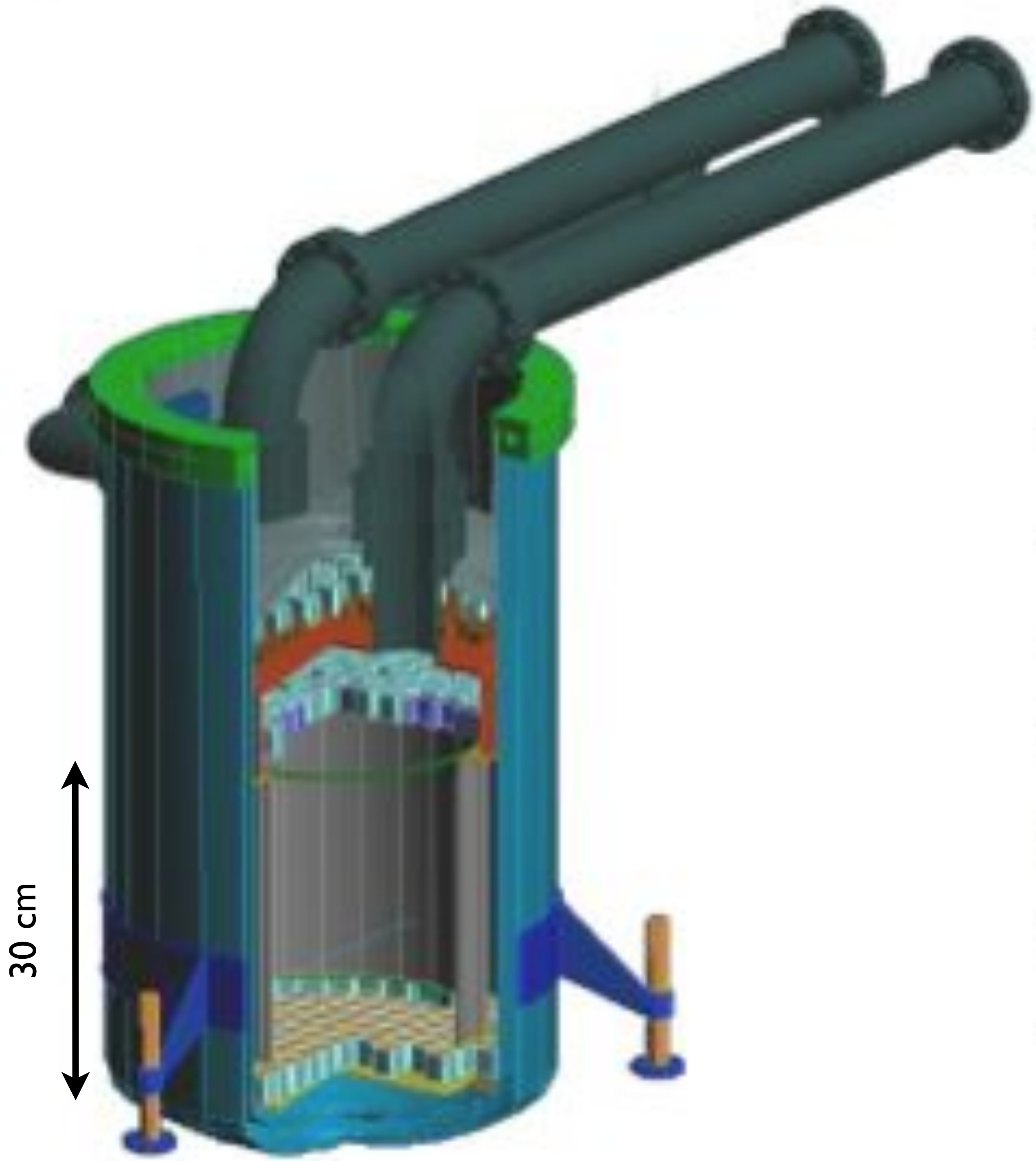
- Gradually increasing the WIMP target mass while decreasing the background level

The XENON Collaboration

Columbia Rice UCLA Zürich Coimbra LNGS SJTU

Mainz Bologna Subatech Münster Nikhef Heidelberg Weizman Purdue

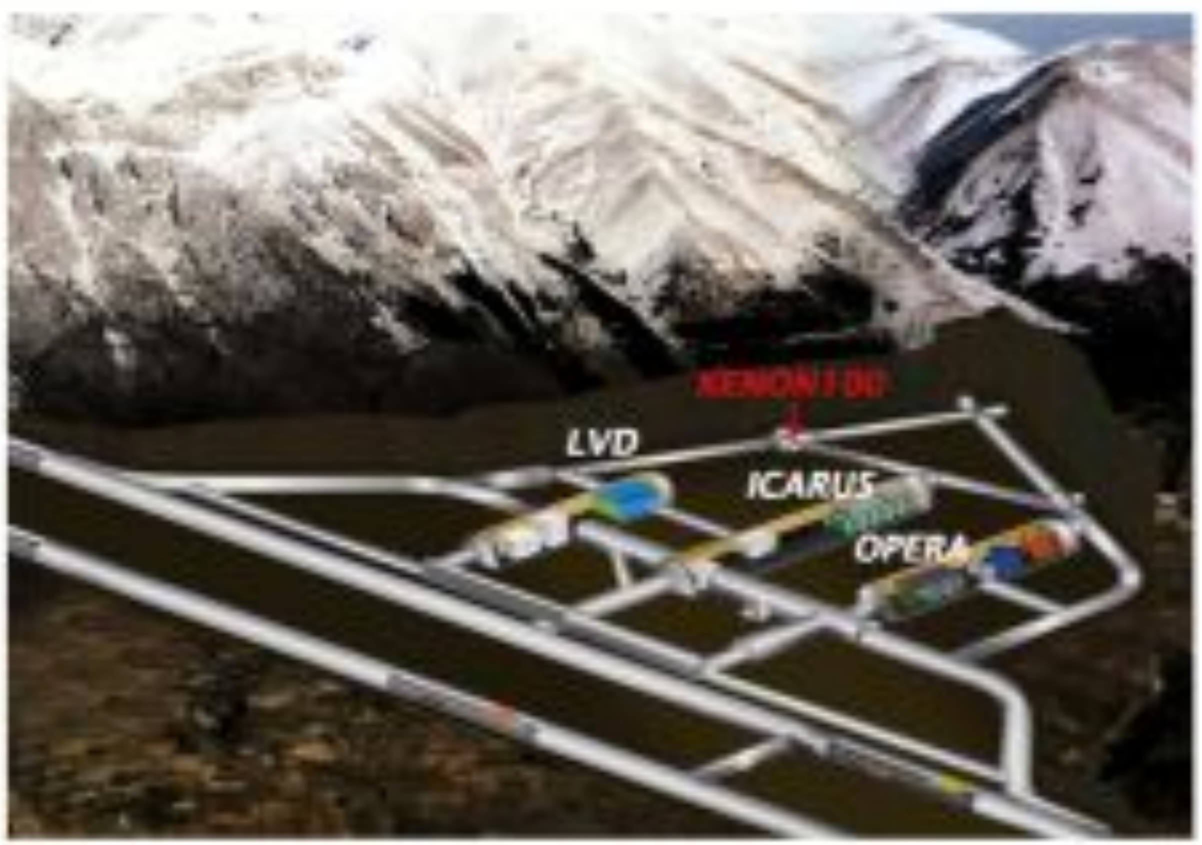
The XENON100 detector overview



- 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
- 161 kg ultra pure LXe - 62 kg as target
- 1" square PMTs with ~1 mBq (U/Th)

XENON100 Location and Shield

- LNGS provides the shield against cosmic rays: 1.4 km of mountain
- Passive shield:
  - ➡ 5 cm (2 tons) of Cu, 20 cm (1.6 tons) of PE, 20 cm (33 tons) of Pb, plus 20 cm water shield
- Detector housing is continuously purged with boil-off N_2, to maintain a radon level < 0.5 Bq/m^3
- All materials screened with HPGe detectors at LNGS



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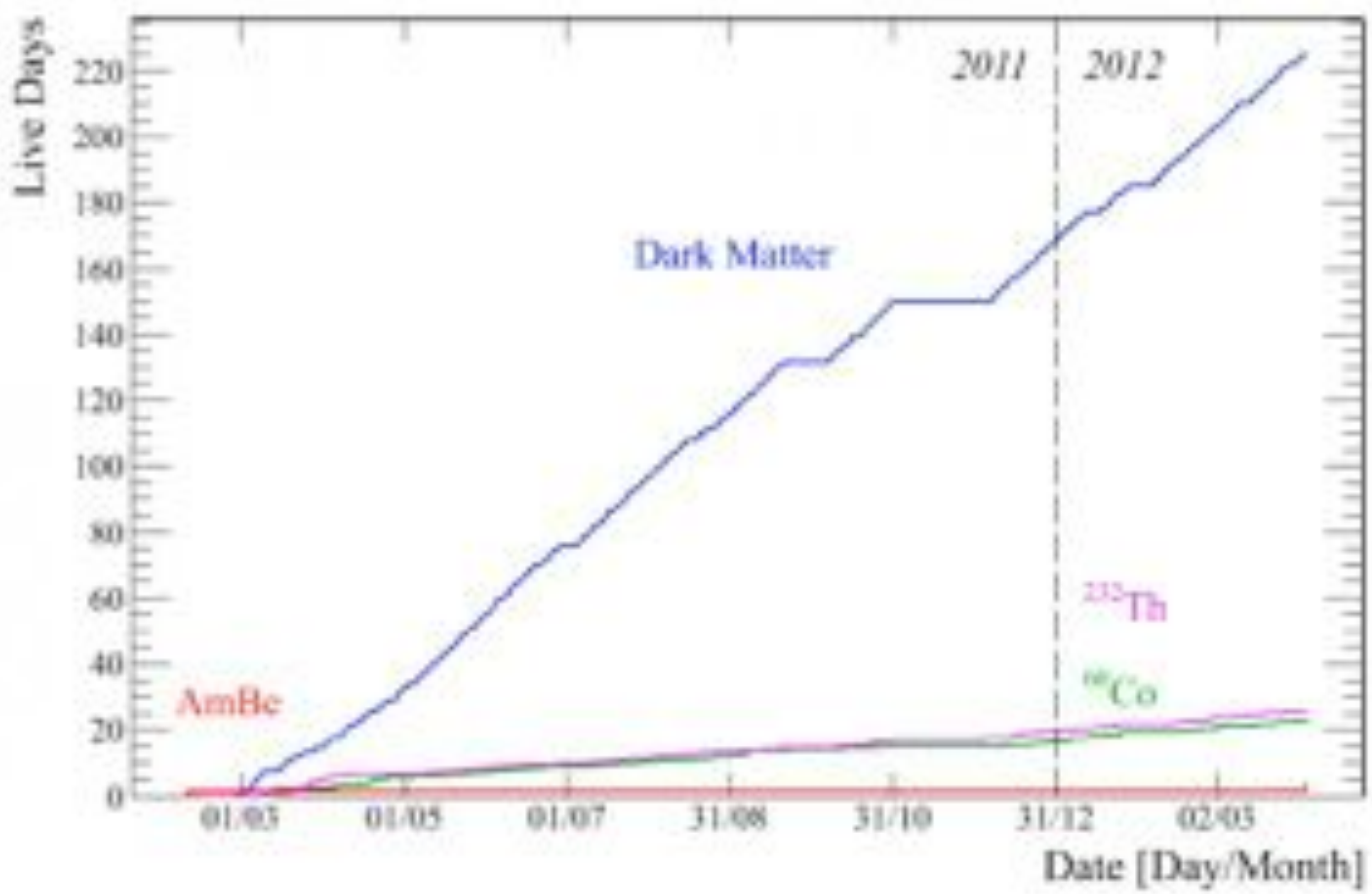
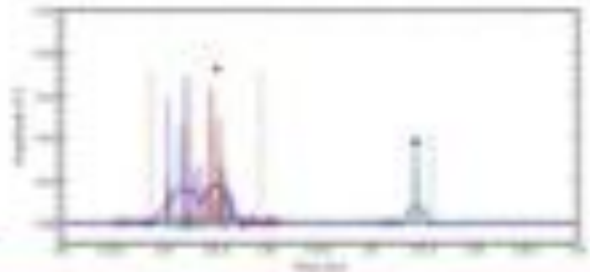
New XENON100 Dark Matter Search: Run10

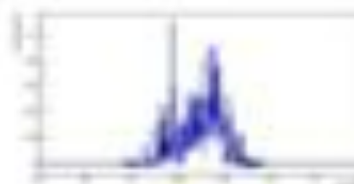
- Data taking period: February 2011 - March 2012
- 224.56 live days of dark matter data
- 48 live days of ^{60}Co and ^{228}Th calibration data; 2 AmBe runs (beginning/end of science run)



From raw waveforms to results



Majority trigger, efficiency > 99% for S2>150 pe



Data acquisition: sample PMT traces @ 100 MS/s in windows around signals > 0.35 pe

PMT waveforms

Raw data processing, baseline and noise measurement; S1, S2 signal recognition; signal integration; position reconstruction; signal correction (gain, spatial)

root trees

Event selection, remove bad events:

- noise
- S1/S2 not matching

Select single interaction events

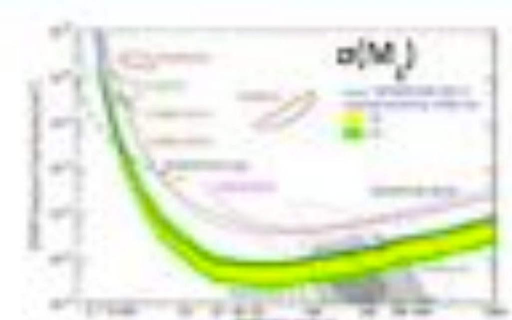
Acceptances!

reduced data

Physics analysis input: astrophysics, nuclear physics, DM data sidebands, NR and ER calibration => response, background estimate

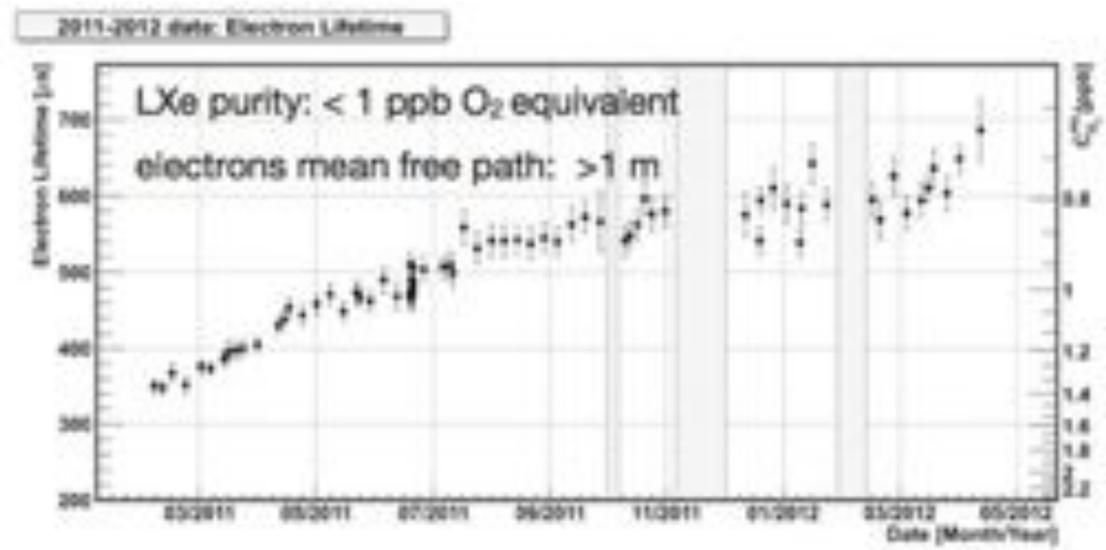
profile likelihood

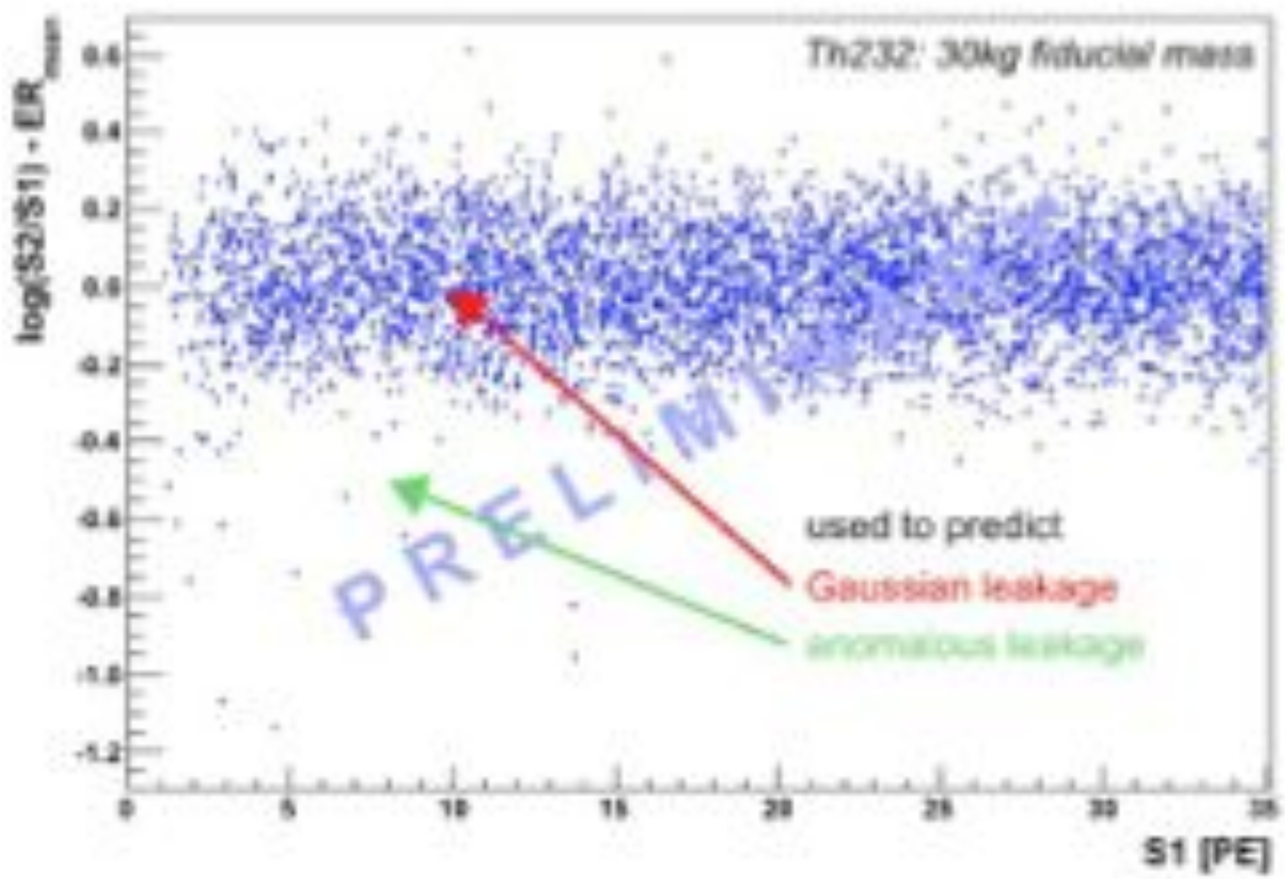
results

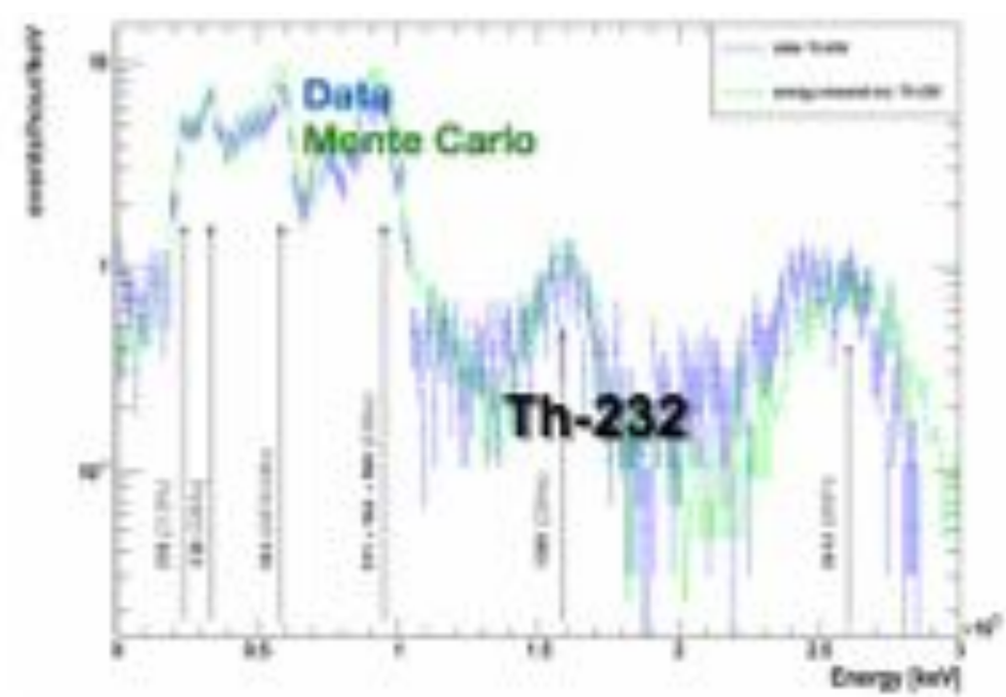


XENON100 gamma calibrations

- ^{137}Cs data to monitor the charge & light yields
- ^{60}Co and ^{232}Th data used to map the electron recoil band and predict EM background (irradiate at three points around TPC)
- ^{232}Th data also used to understand spectrum up to high energies

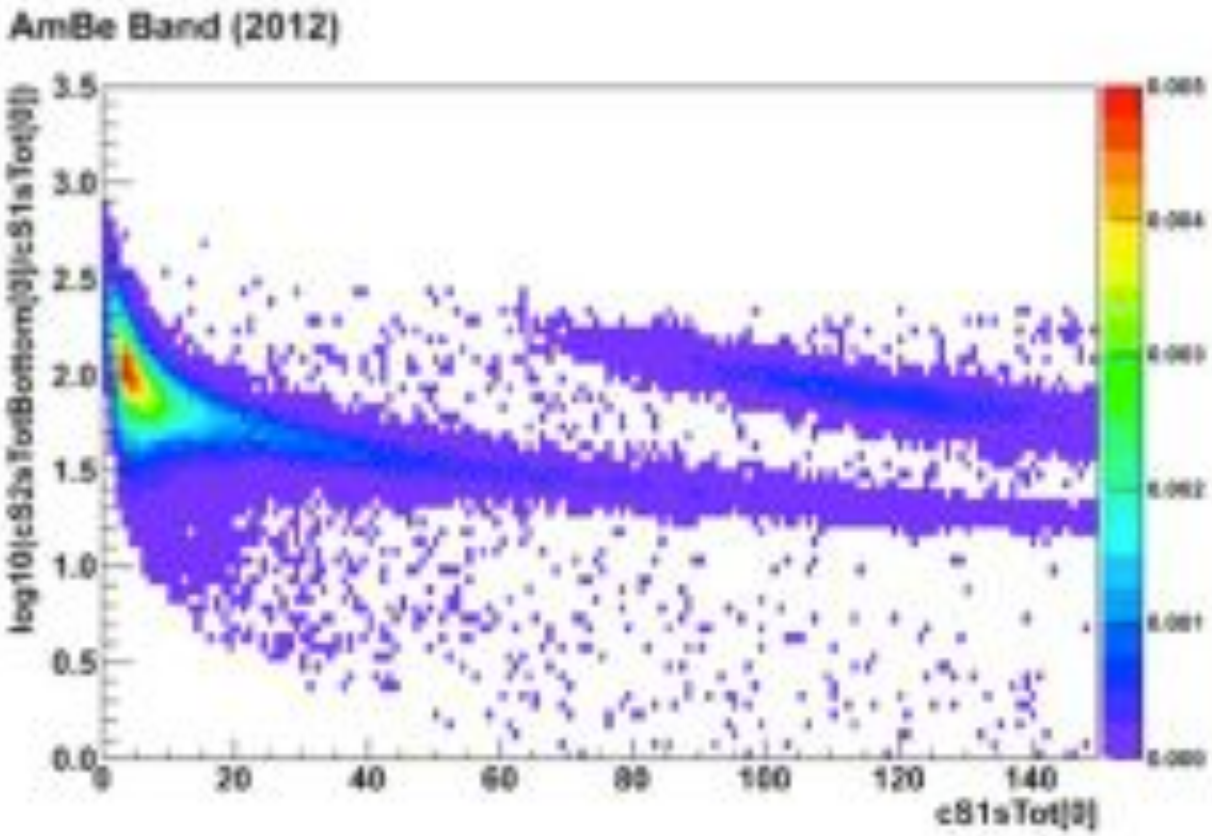


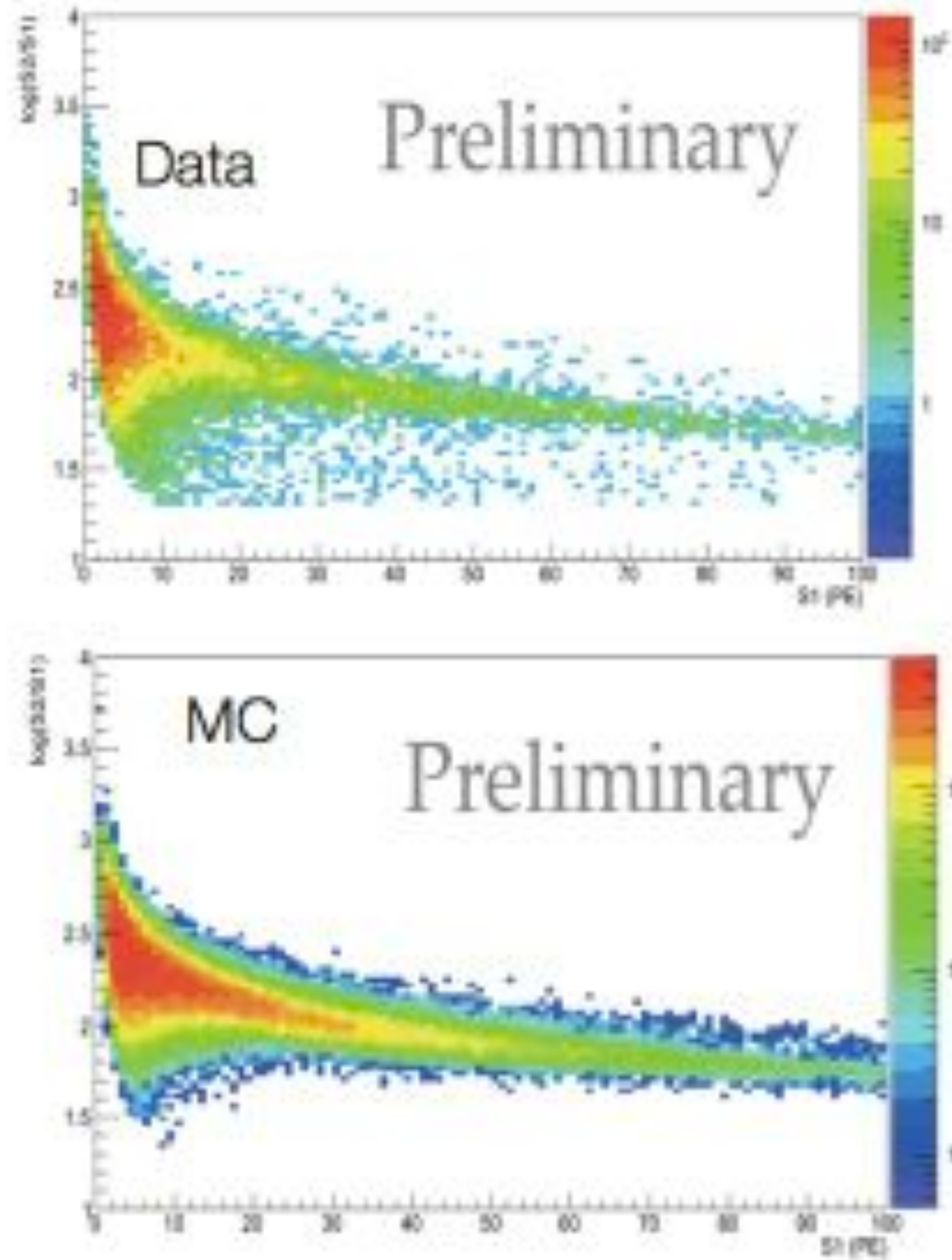




XENON100 neutron calibration

- Nuclear Recoil band calibration performed with a 220 n/s AmBe neutron source

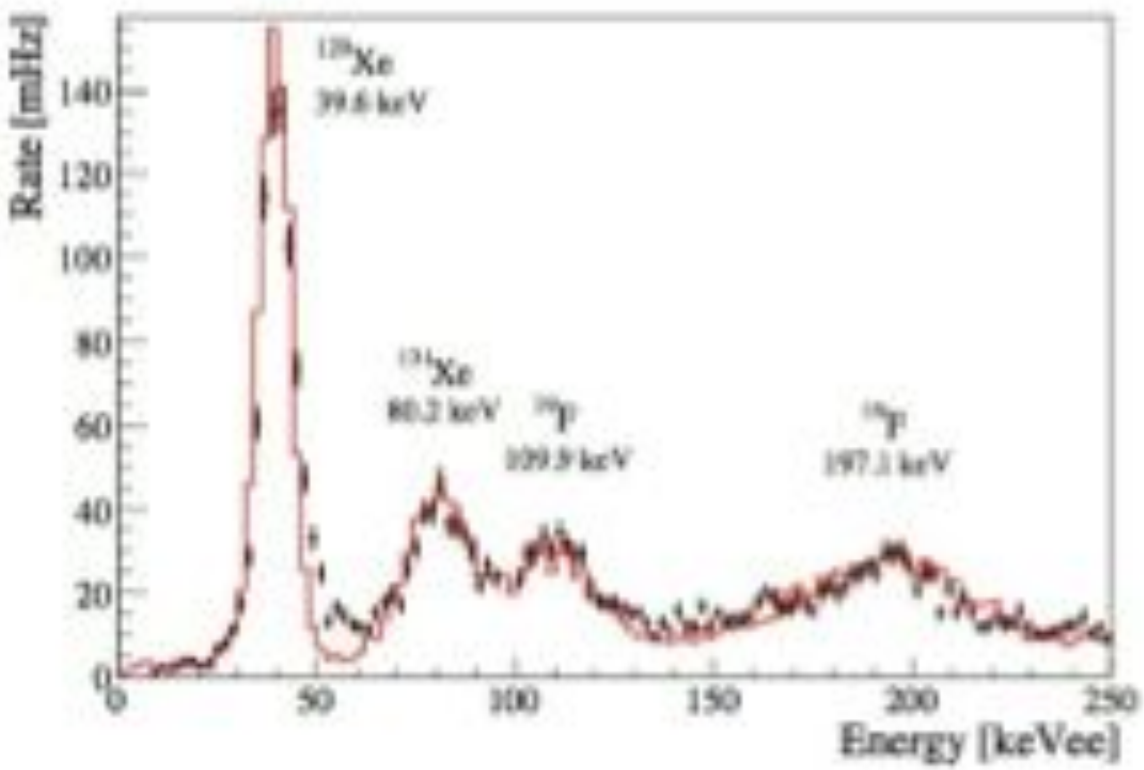


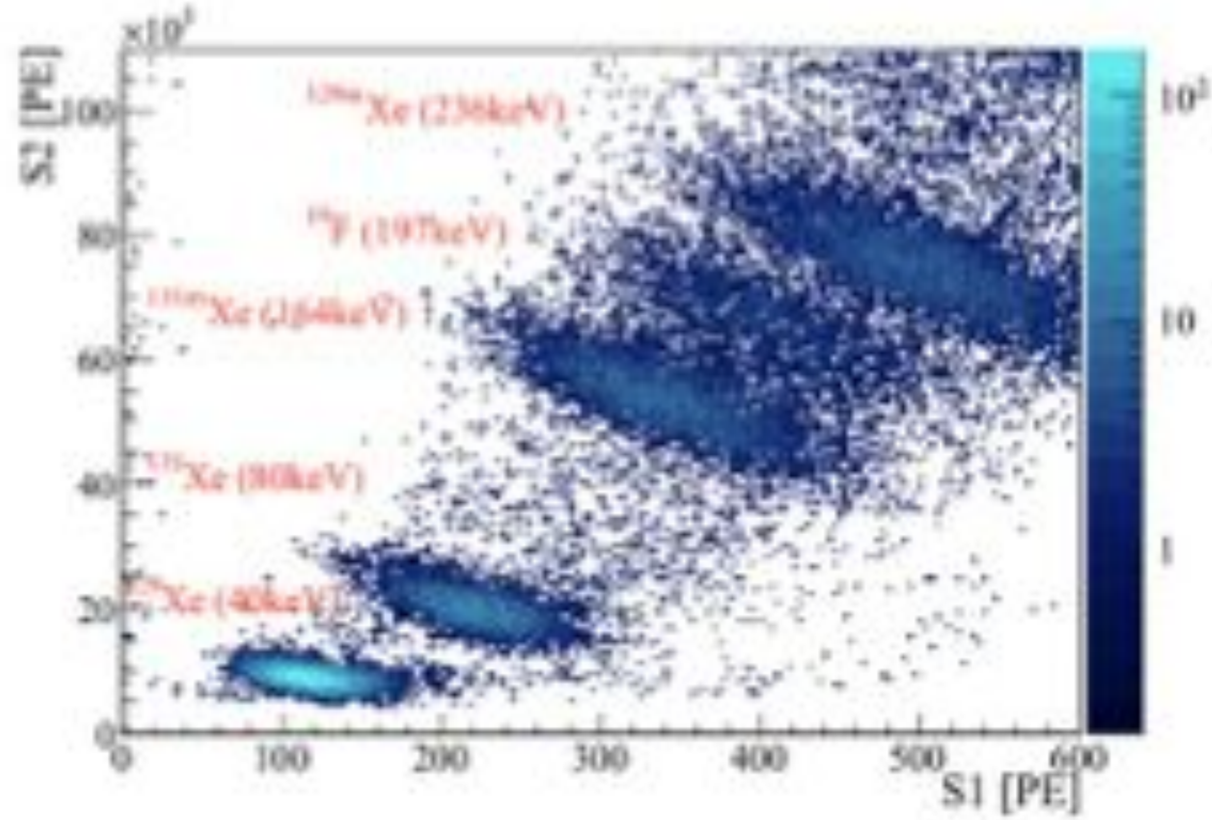


Absolute matching (rate(pos, E)) demanded!

Gammas from neutron calibrations

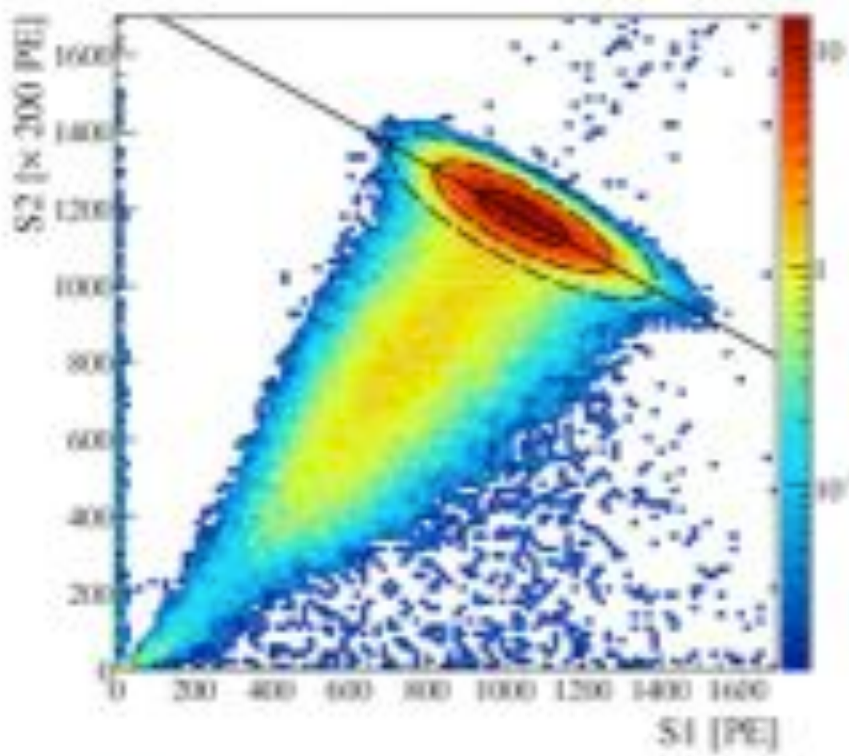
- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}Xe + n \rightarrow ^{129,131}Xe + n + \gamma$ (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): $^{19}F + n \rightarrow ^{19}F + n + \gamma$ (110 keV, 197 keV)
- Also Xe activation lines: ^{129m}Xe (236 keV) and ^{131m}Xe (164 keV)

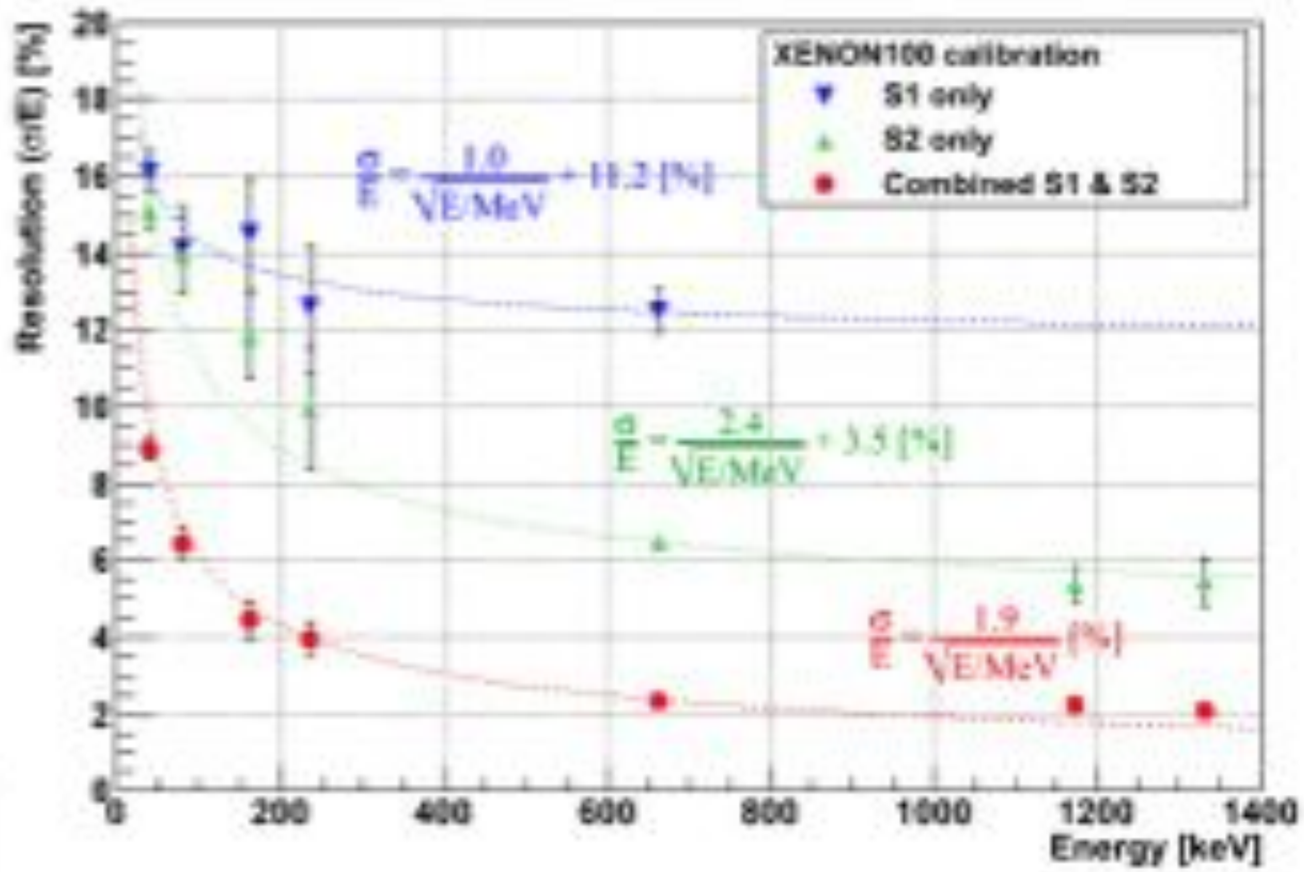


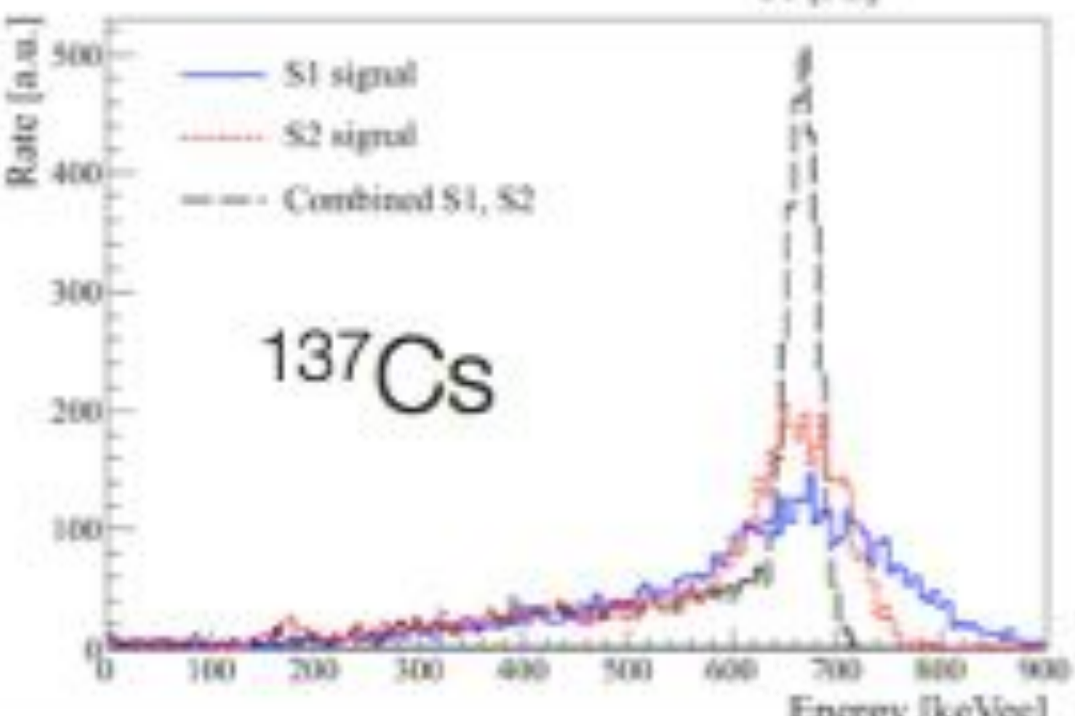


All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV

XENON100 energy resolution



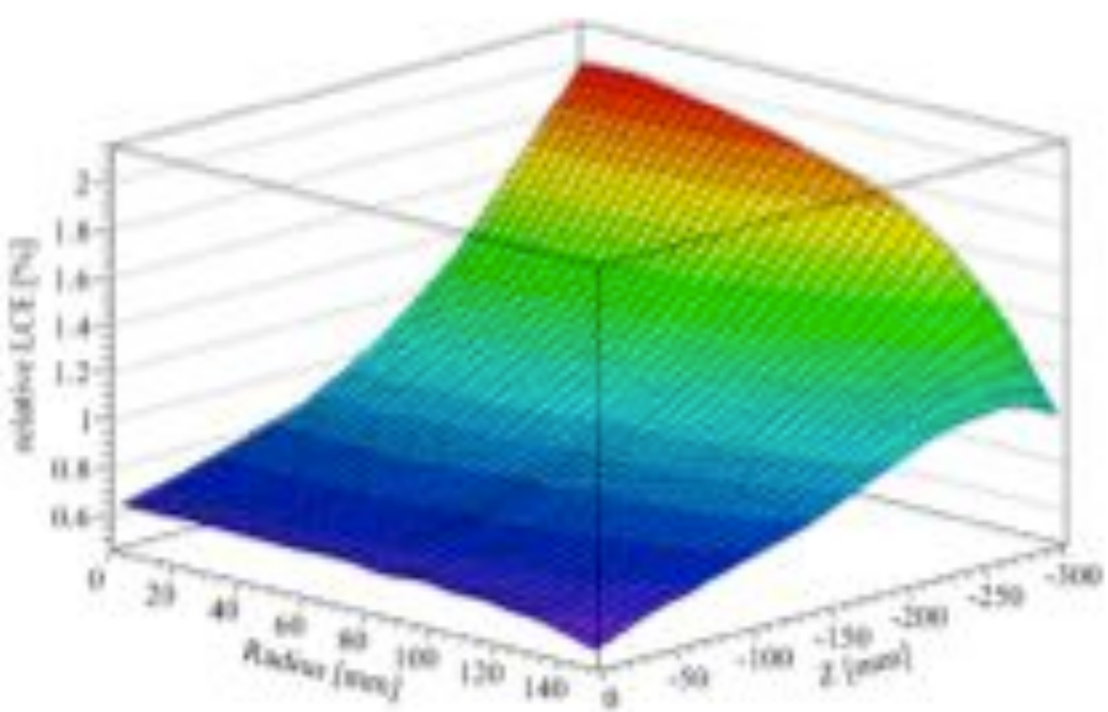




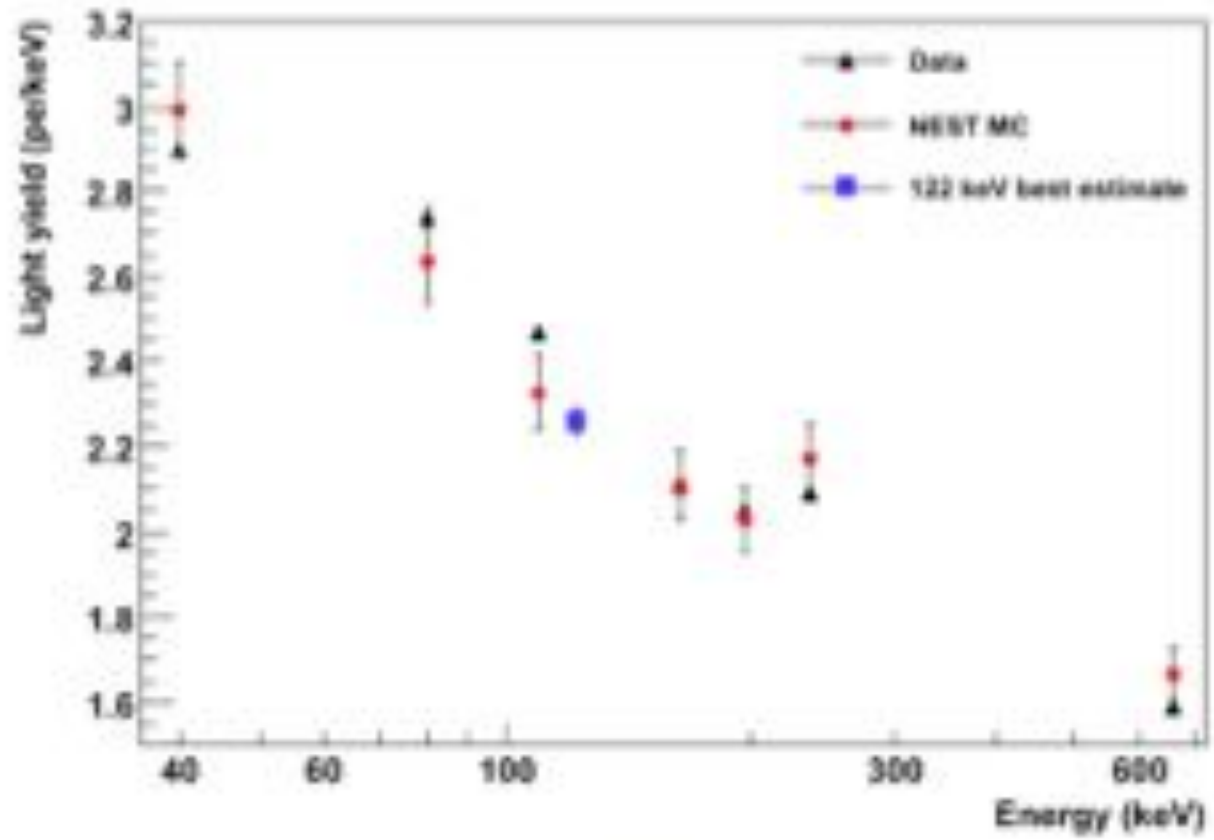
- Energy dependent energy resolution
- In S1, in S2 and in the "combined energy scale"
- Because of the anti-correlation of the S1 and S2 signals, the resolution is much improved when using both

S1 Signal Corrections

- S1 light collection depends on the event position in the TPC: a 3D map of the light collection efficiency (LCE) is inferred from irradiation with ^{137}Cs (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated ^{131m}Xe (all agree within 3%)
- Light yield at 122 keV is interpolated using NEST model and measurements at lower/higher energies with conservative 5% uncertainty. For Run10 the LY_{122keV} = (2.28 ± 0.04) PE/keV)

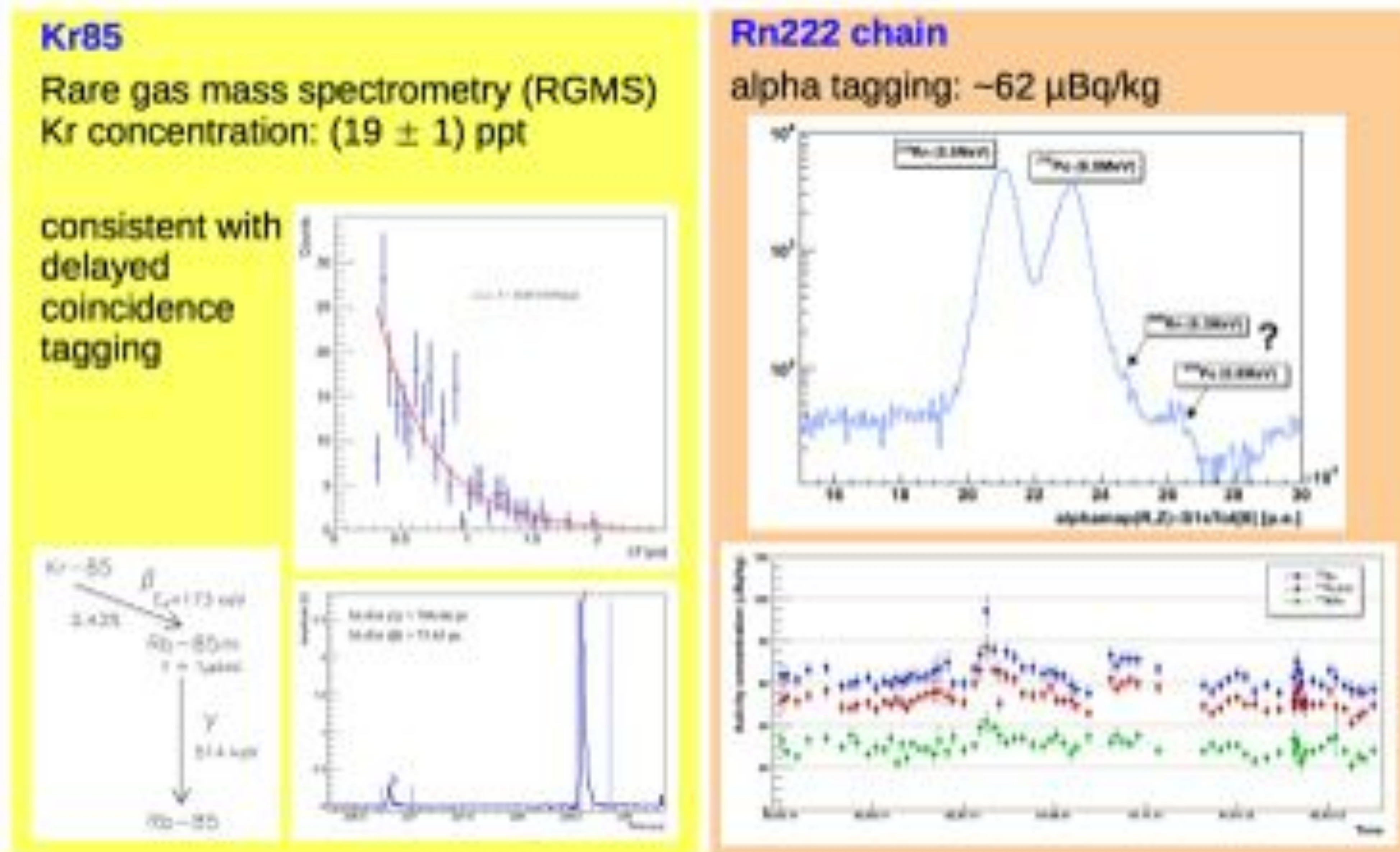


LCE correction map using the 40 keV line



Light yield for different gamma lines

Intrinsic backgrounds

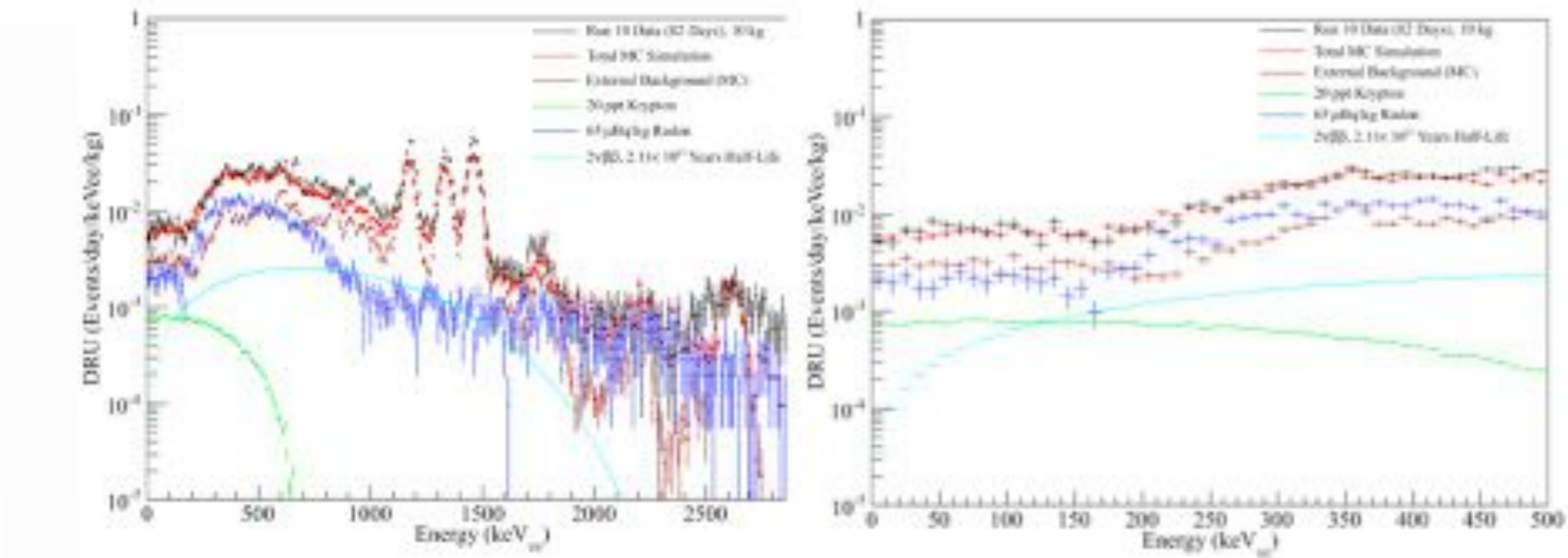


LXeTPCs easily identify surface backgrounds, alphas and delayed coincidences with 3D vertex and energy reconstruction

Measured Background Level in Run10

- Reached background level before S2/S1-discrimination: 5.3 x 10^{-3} events/(kg day keV)
- Same level as in 1st XENON100 results (E.Aprile *et al.*, Phys. Rev. Lett. **105,** 131302, 2010)
- **see also** PRD 83, 082001 (2011)

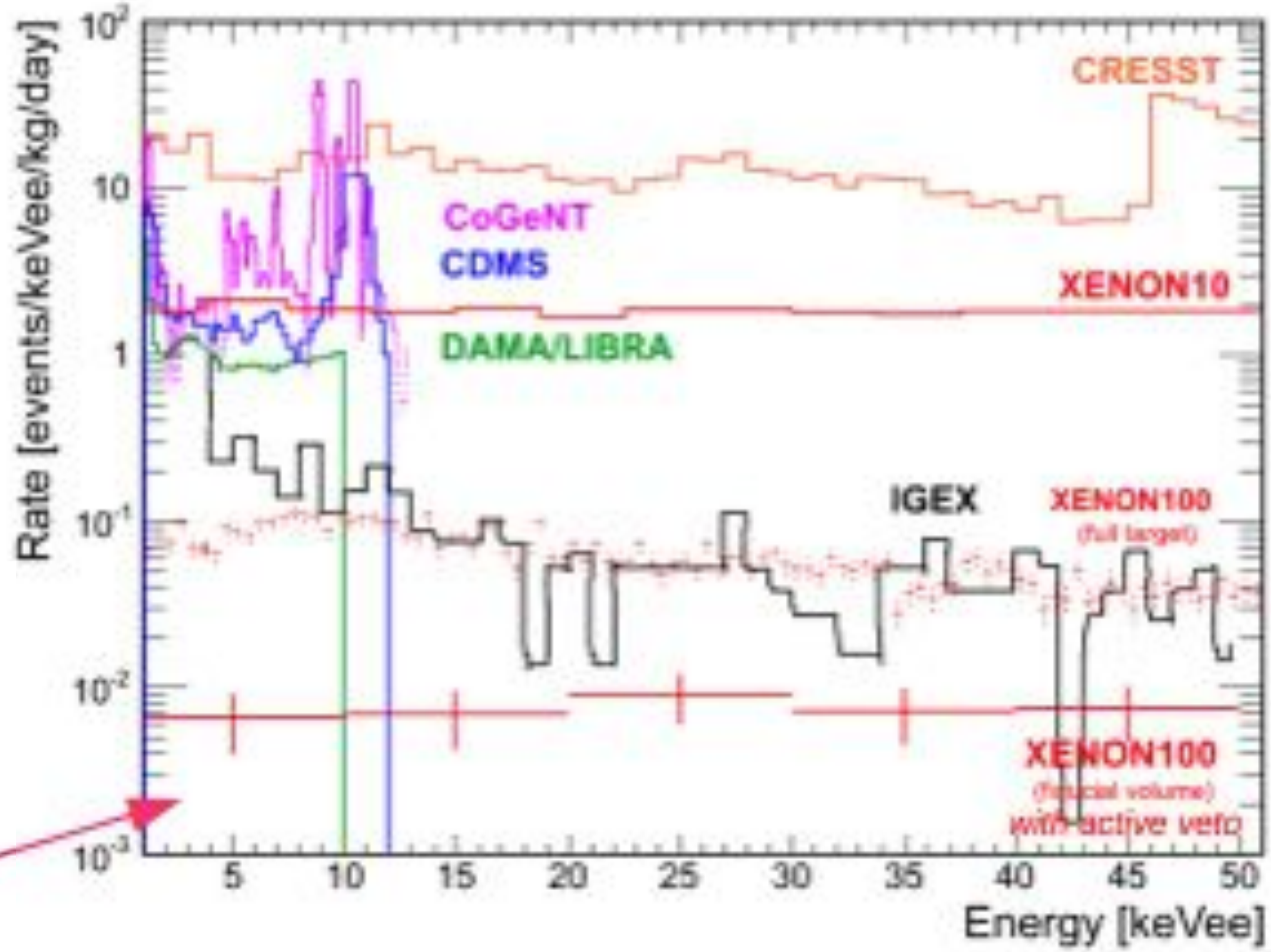
Before applying LXe veto cut



Background tracked as a function of (r, z) through TPC

Measured Background in good agreement with MC prediction.

At low energies: Lowest background ever achieved in a Dark Matter Experiment!

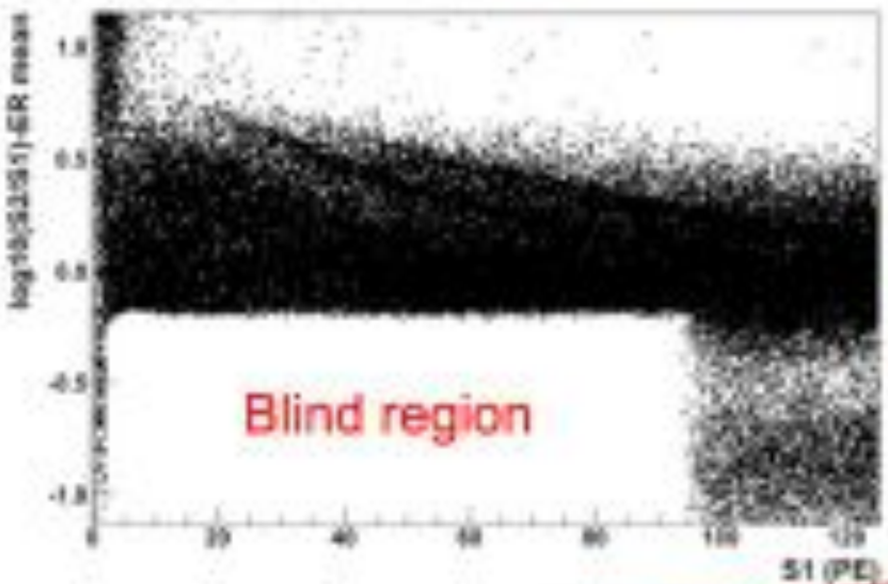


Xenon keVee-Scale not precisely known below 9 keVee

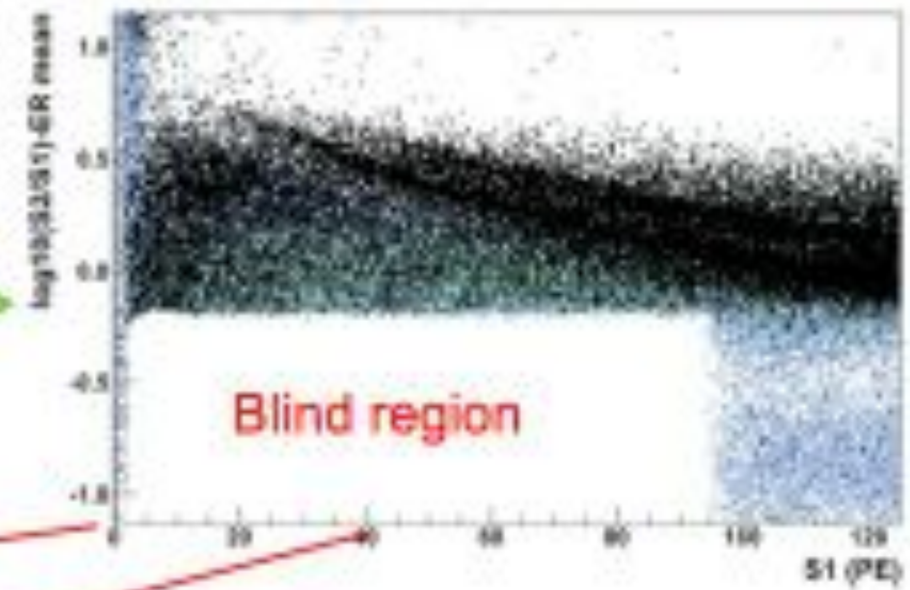
Analysis sequence for the 225 live days of data

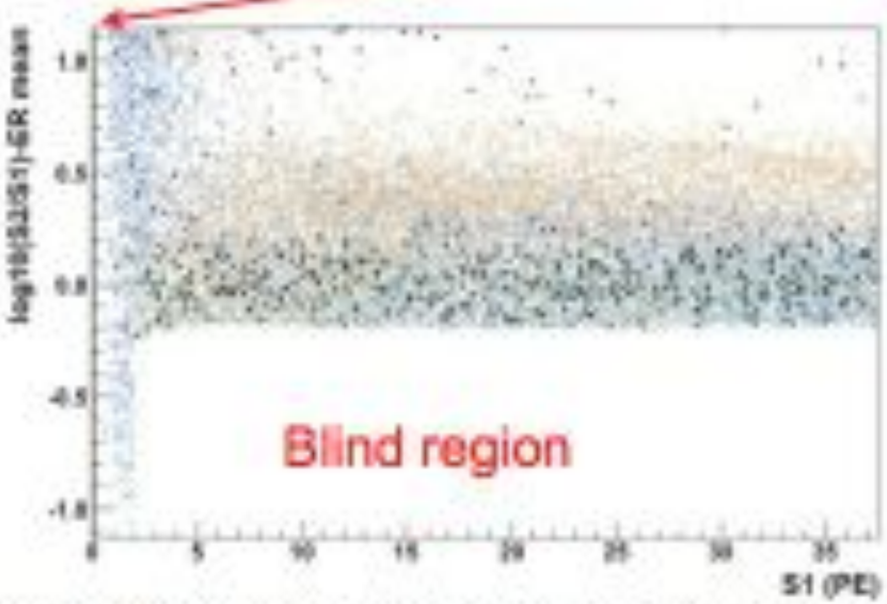
(Different colors represent the events removed with the successive cuts)

(1) Start from all non-blind data in 48kg FV

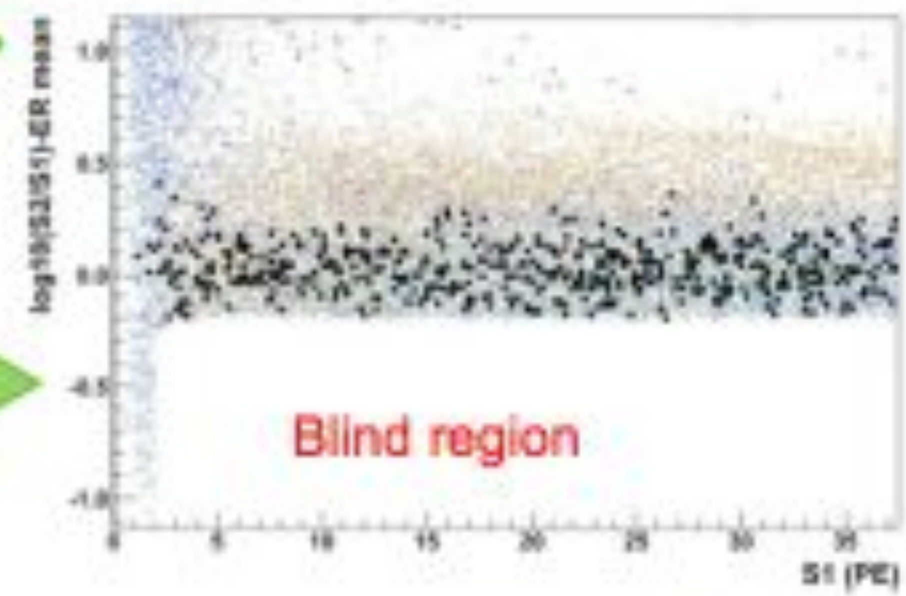


(2) Apply basic quality cuts and single scatter



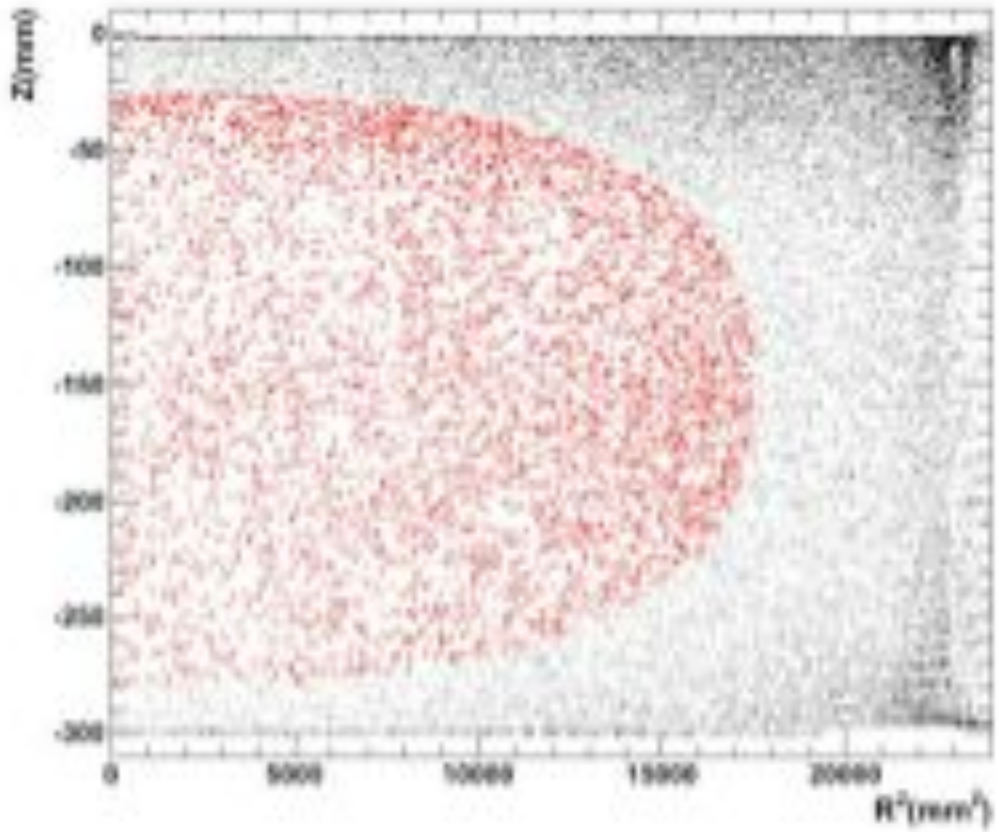


(3) Set low energy threshold, restrict to low energies and apply FV cut



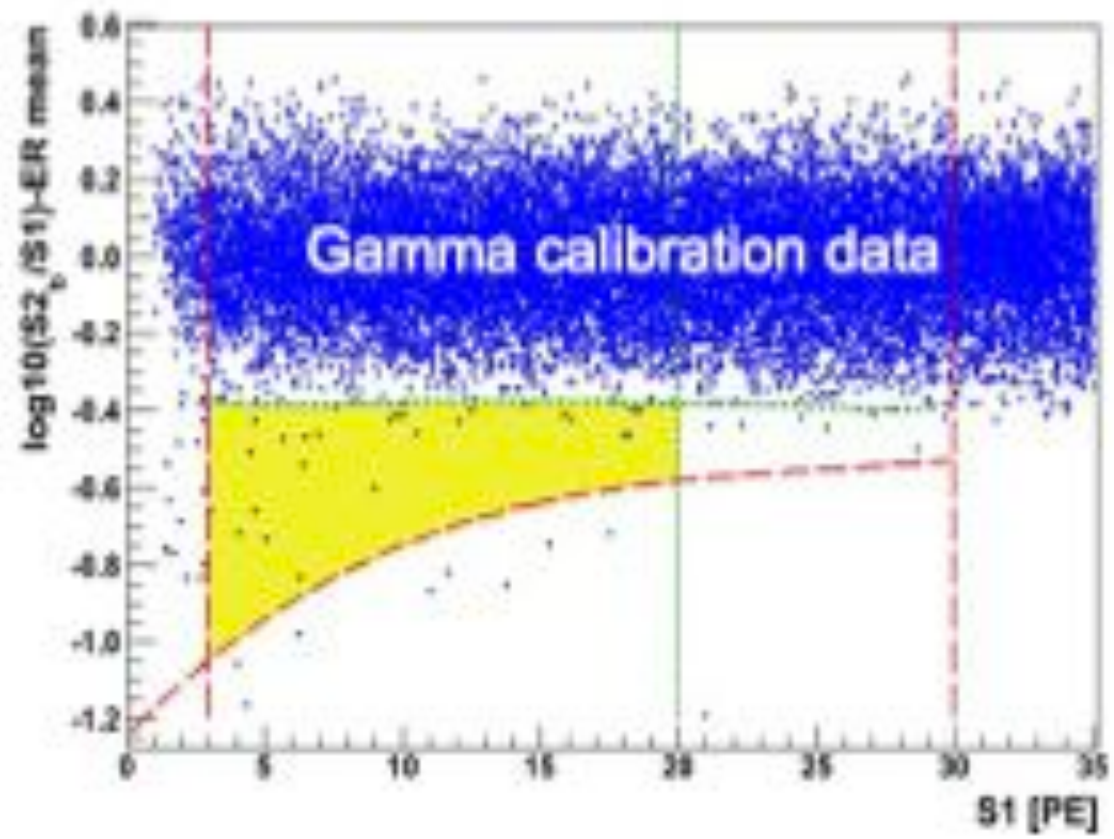
(4) Add consistency cuts for the remaining events

Optimization of the fiducial volume and signal region

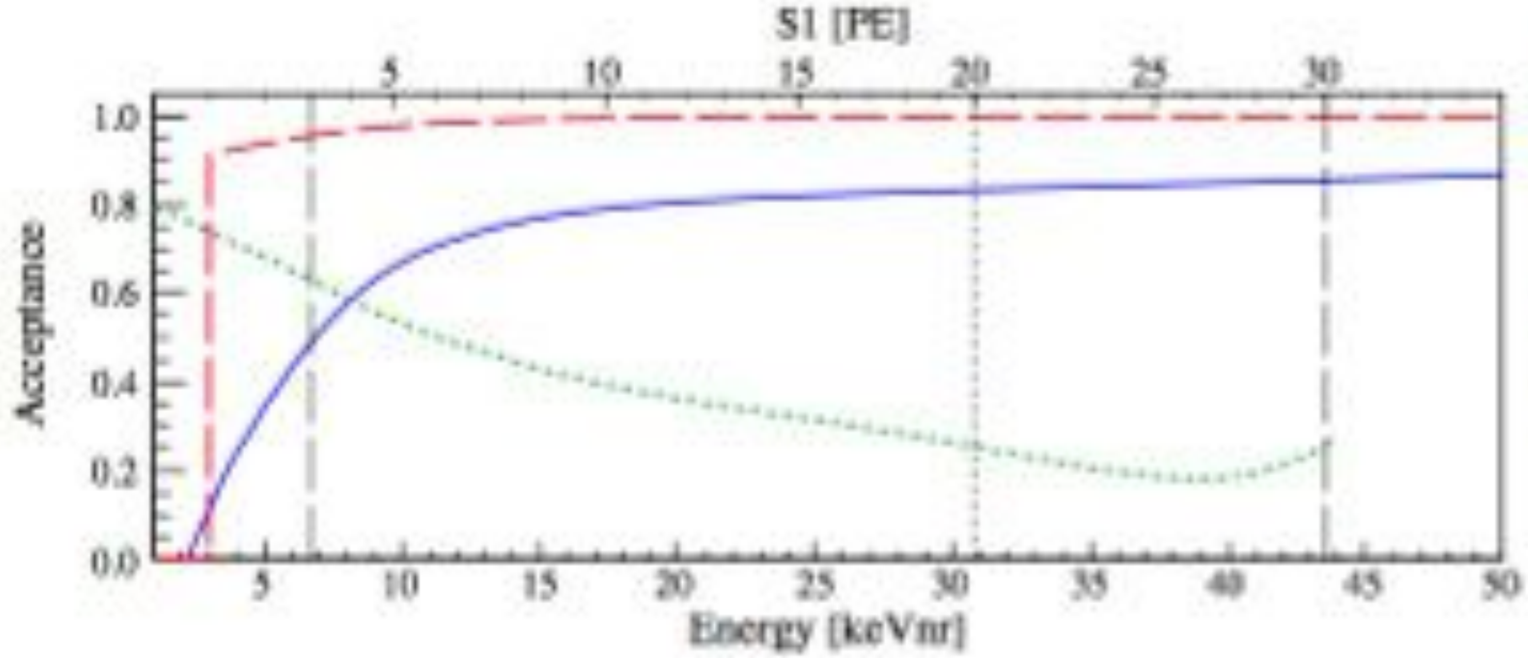


- The fiducial volume and signal region are simultaneously adjusted to maximize sensitivity
- Given the lower beta background in this run, we choose a smaller FV (34 kg) to profit from LXe self-shielding

- The signal region is chosen below the 99.75% constant rejection line for ER
- The signal region for the Maximum-Gap based analysis is set between 3 and 20 PE



Cuts acceptance and L_{eff} parameterization

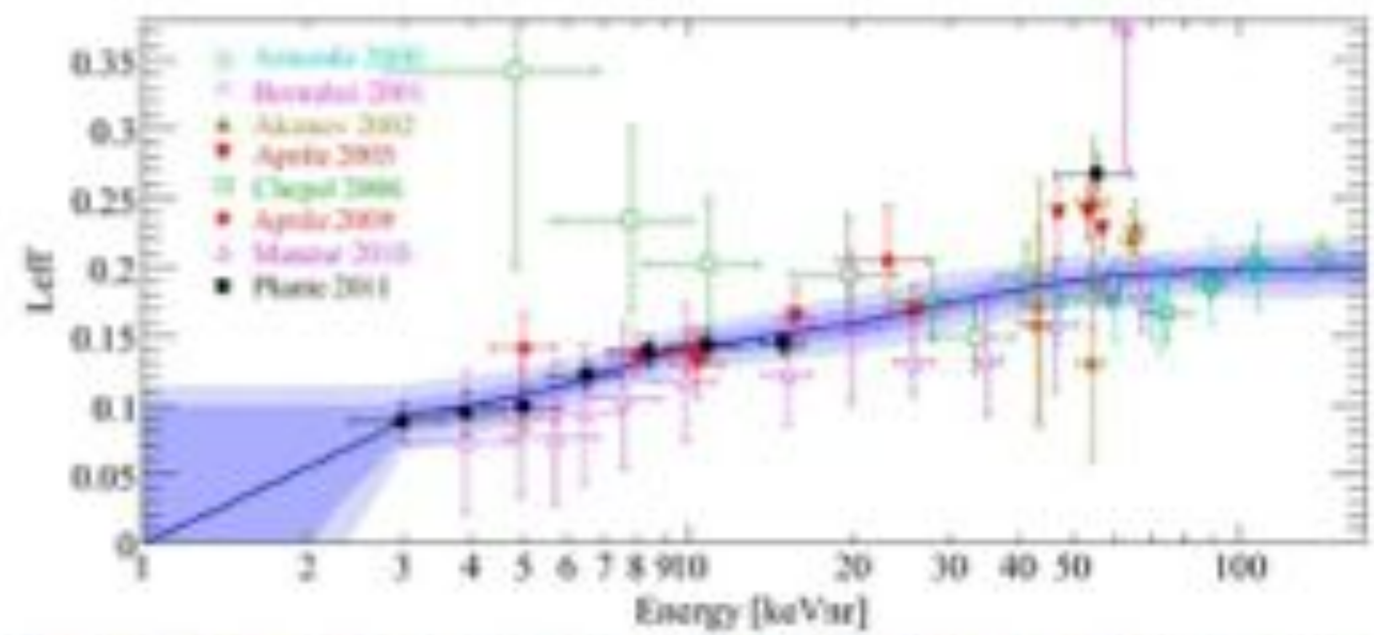


S2 threshold cut (S2 > 150 PE)

Combined acceptance

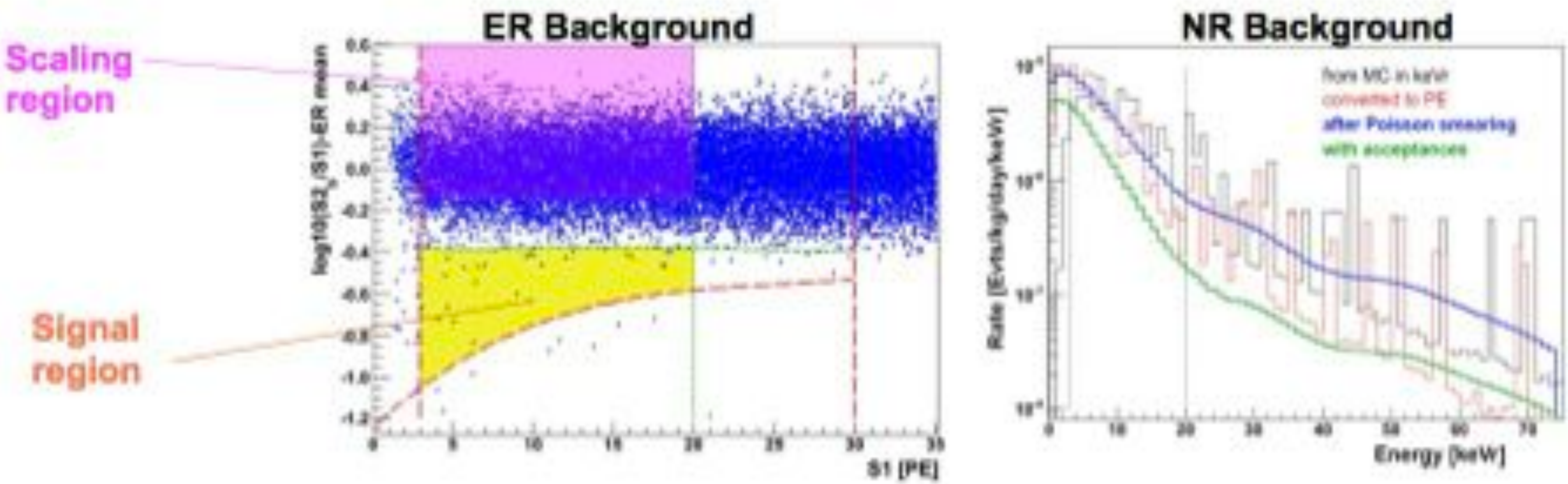
NR acceptance for a 99.75% ER rejection (Maximum Gap analysis only)

$$E_{nr} = \frac{S1}{L_{eff} \cdot L_y}$$



mean (solid) and 1- 2-sigma uncertainties (blue bands) of L_{eff} direct measurements

Background expectation

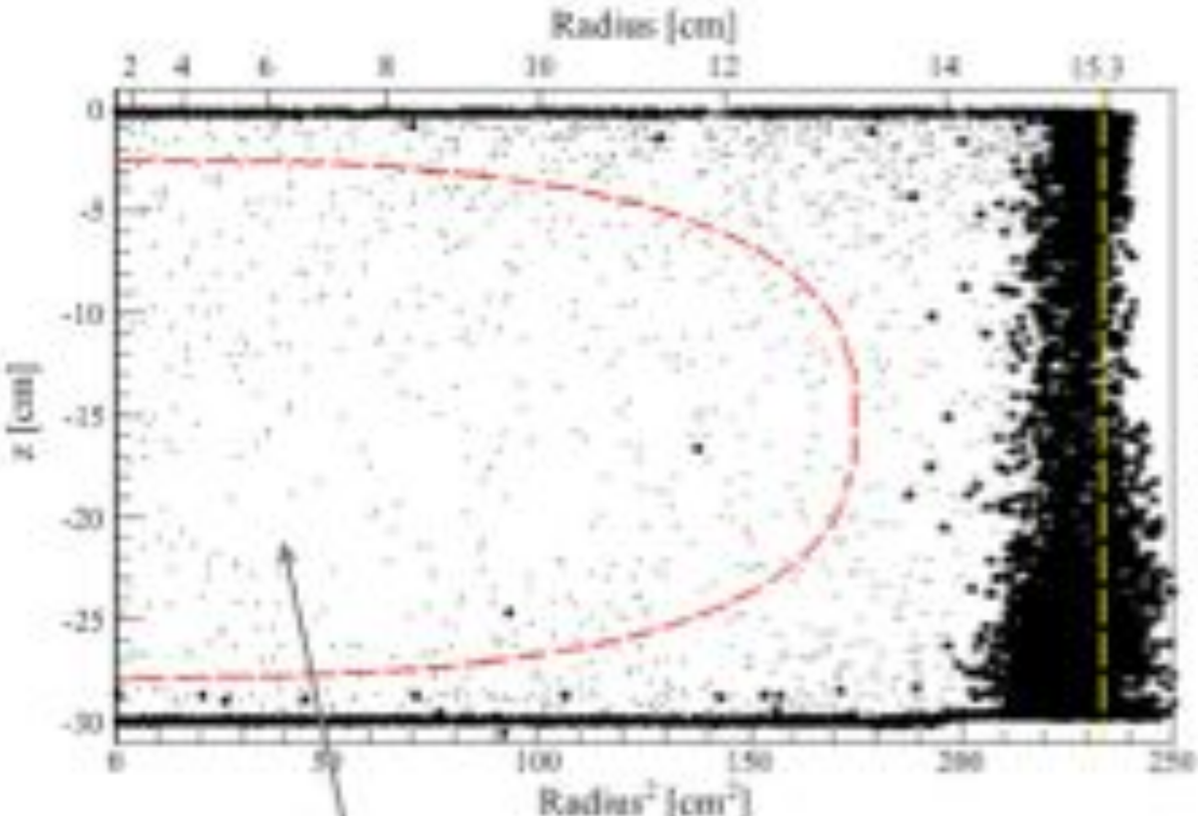


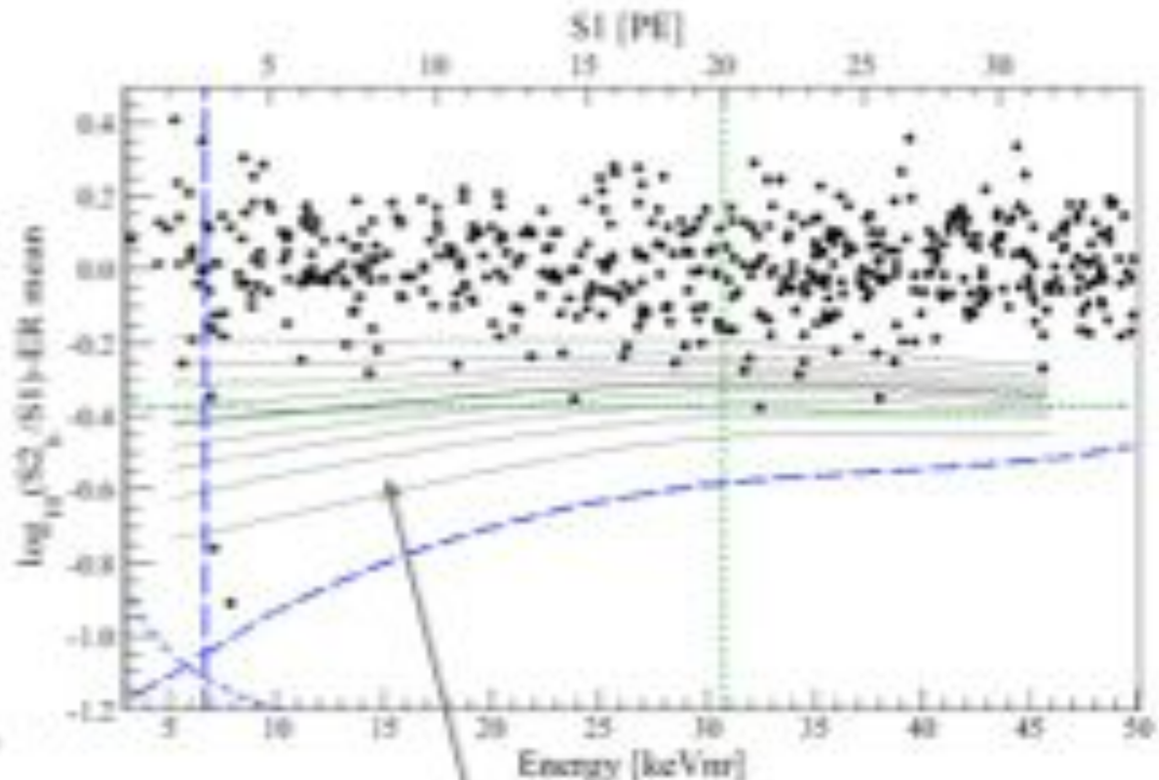
- The background expectation is computed from the calibration data
- The number of events in the signal region from ER calibration data is counted
- That number is scaled to the number of events in the non-blinded region
- An additional contribution from neutrons from the materials is added to the final number and scaled to the total exposure
- Background expectation: 1.0 ± 0.2 events (0.79± 0.16 from gammas, 0.17+0.12-0.07 from neutrons)

And the result.....

Unblinding: Distribution of events in the TPC

Exposure: 225 days x 34 kg fiducial mass

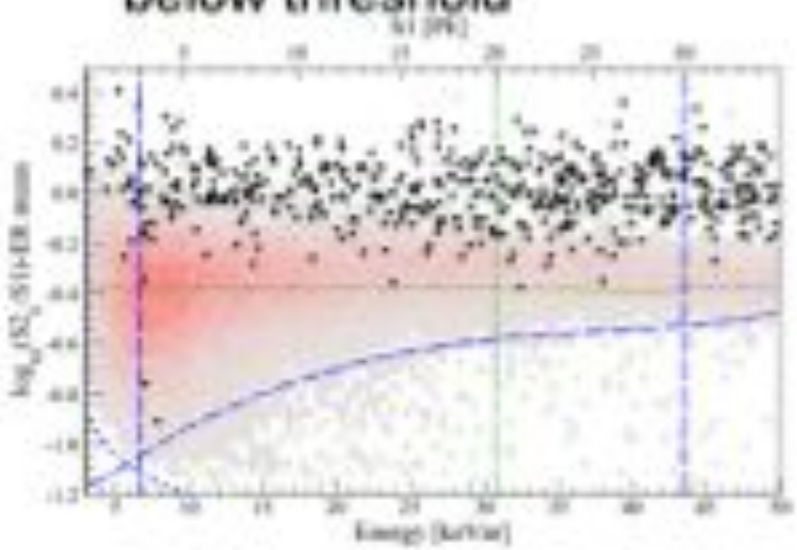


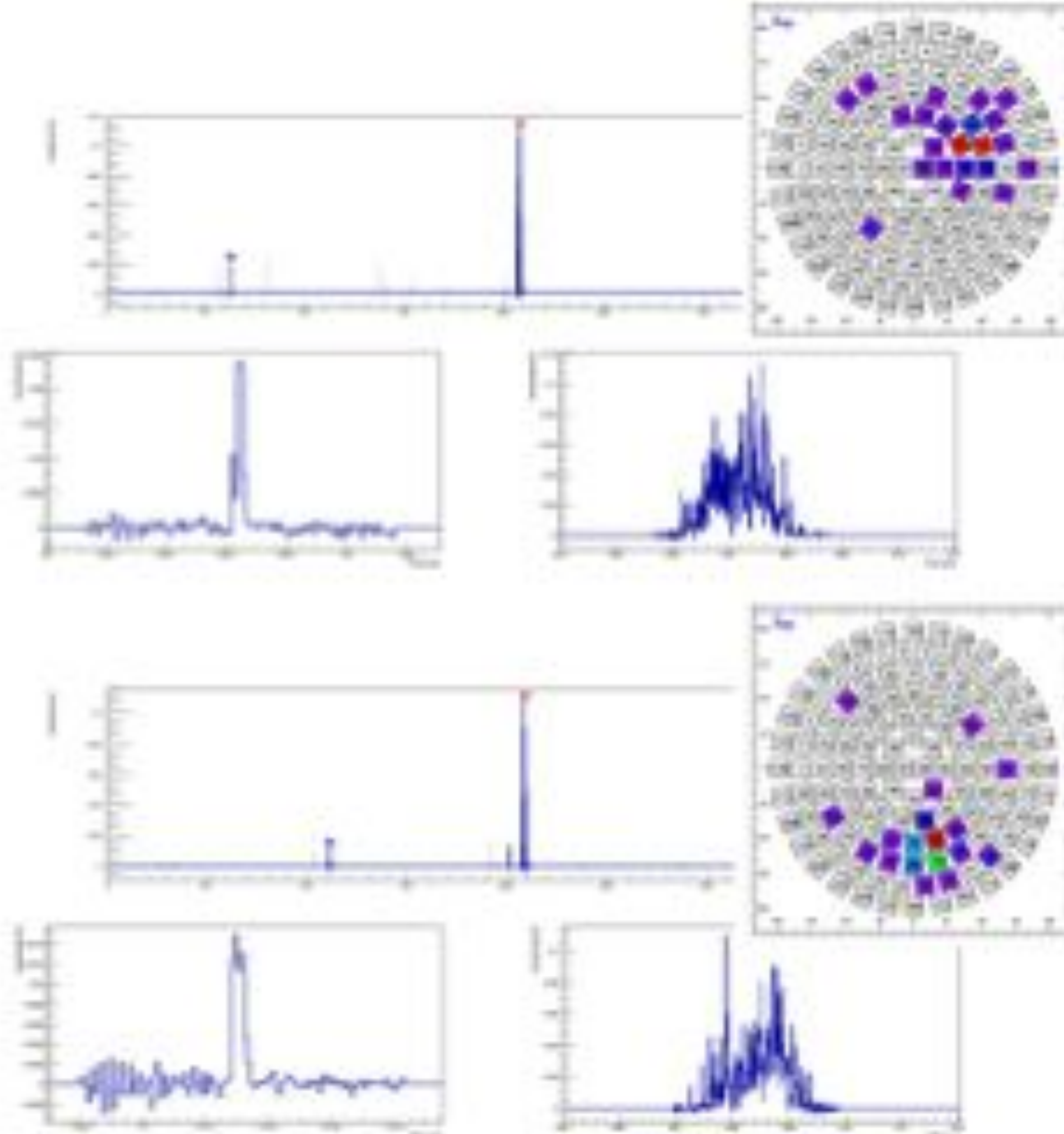


Fiducial mass region:
34 kg of liquid xenon
406 events in total

Signal region:
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected

- visual inspection: valid waveforms
- at 7.1 keVr and 7.8 keVr both events between 3 and 4 PE
- rather low wrt the NR calibration data
- no low S2/S2-events below threshold





(1.0 ± 0.2) events expected

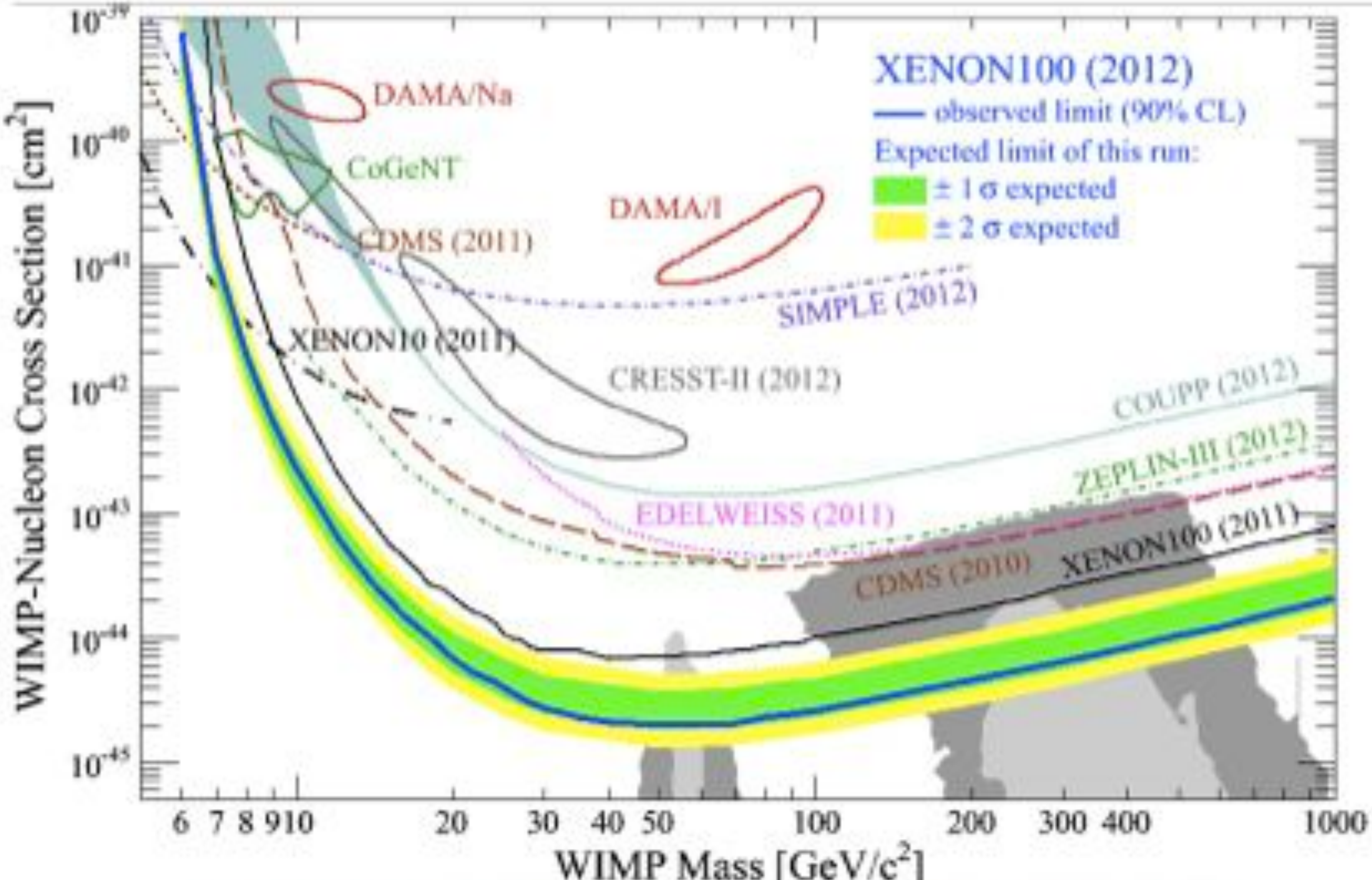
2 events observed

→ 26.4% probability that background fluctuated to 2 events

→ PL analysis cannot reject the background only hypothesis

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

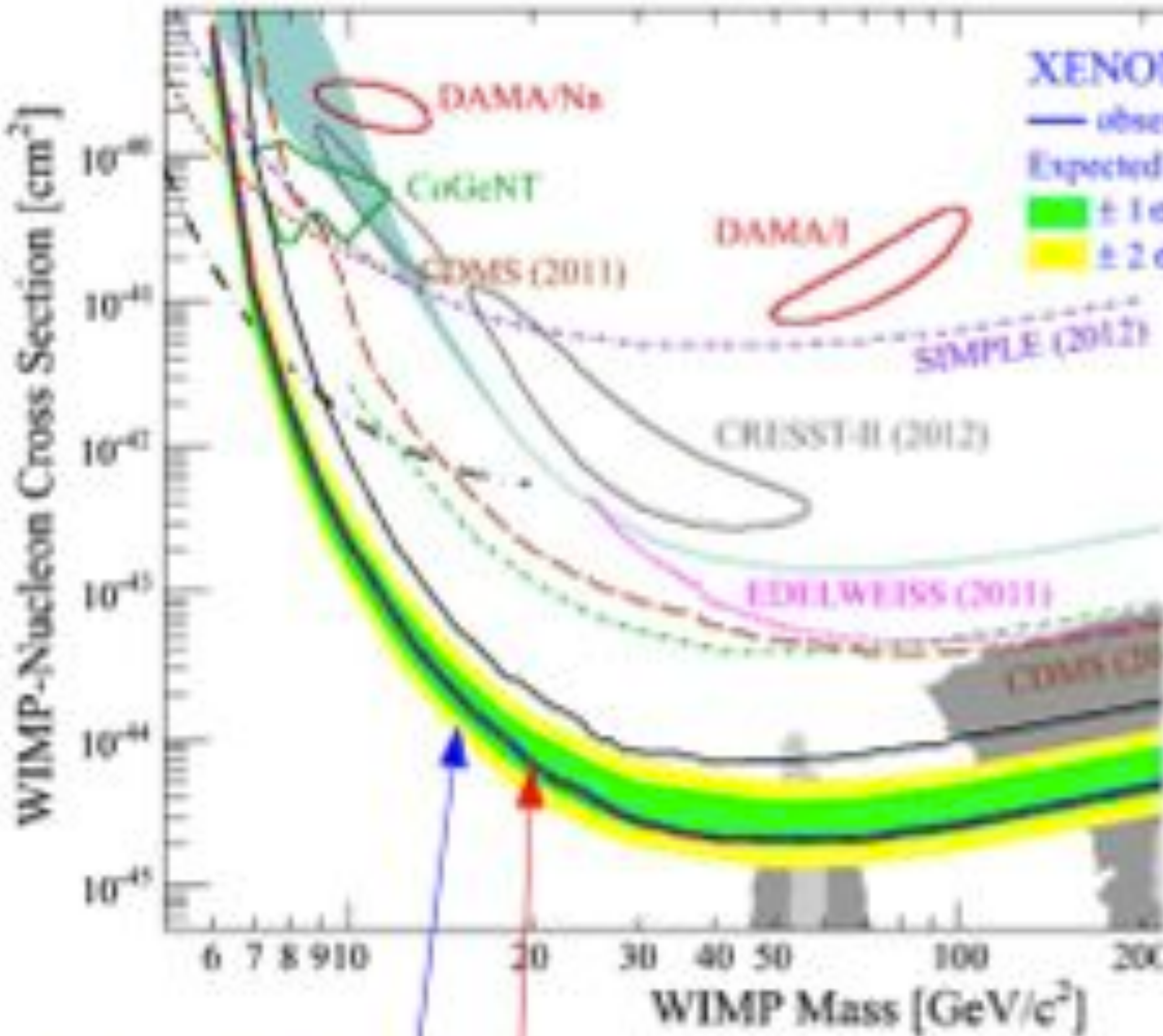
XENON100: New Spin-Independent Results

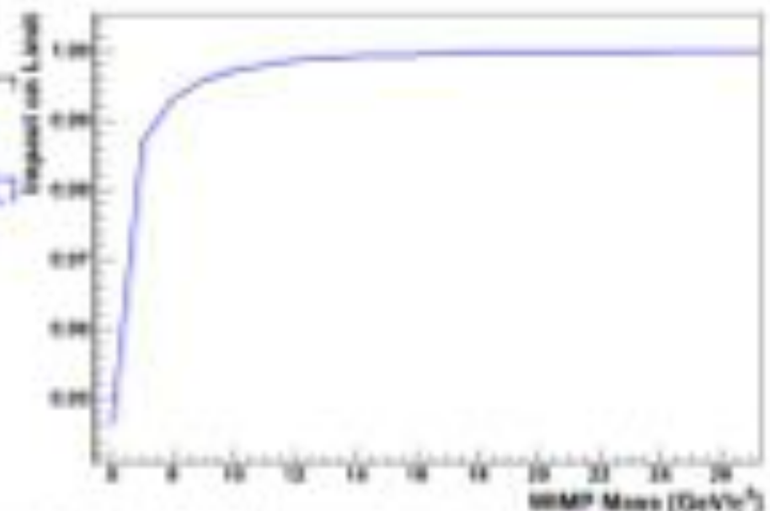


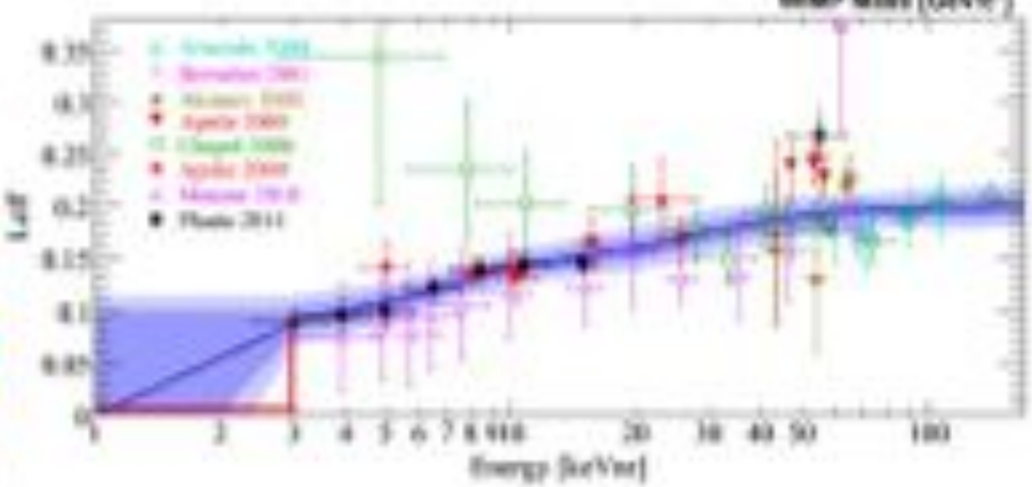
Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

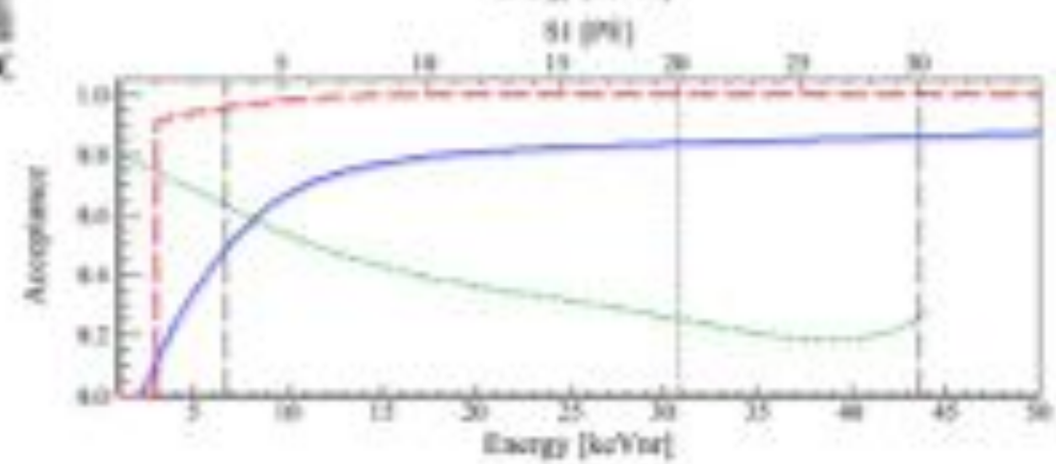
Physical Review Letters 109 (2012) 181301

No Impact of L_{eff} below 3 keVr





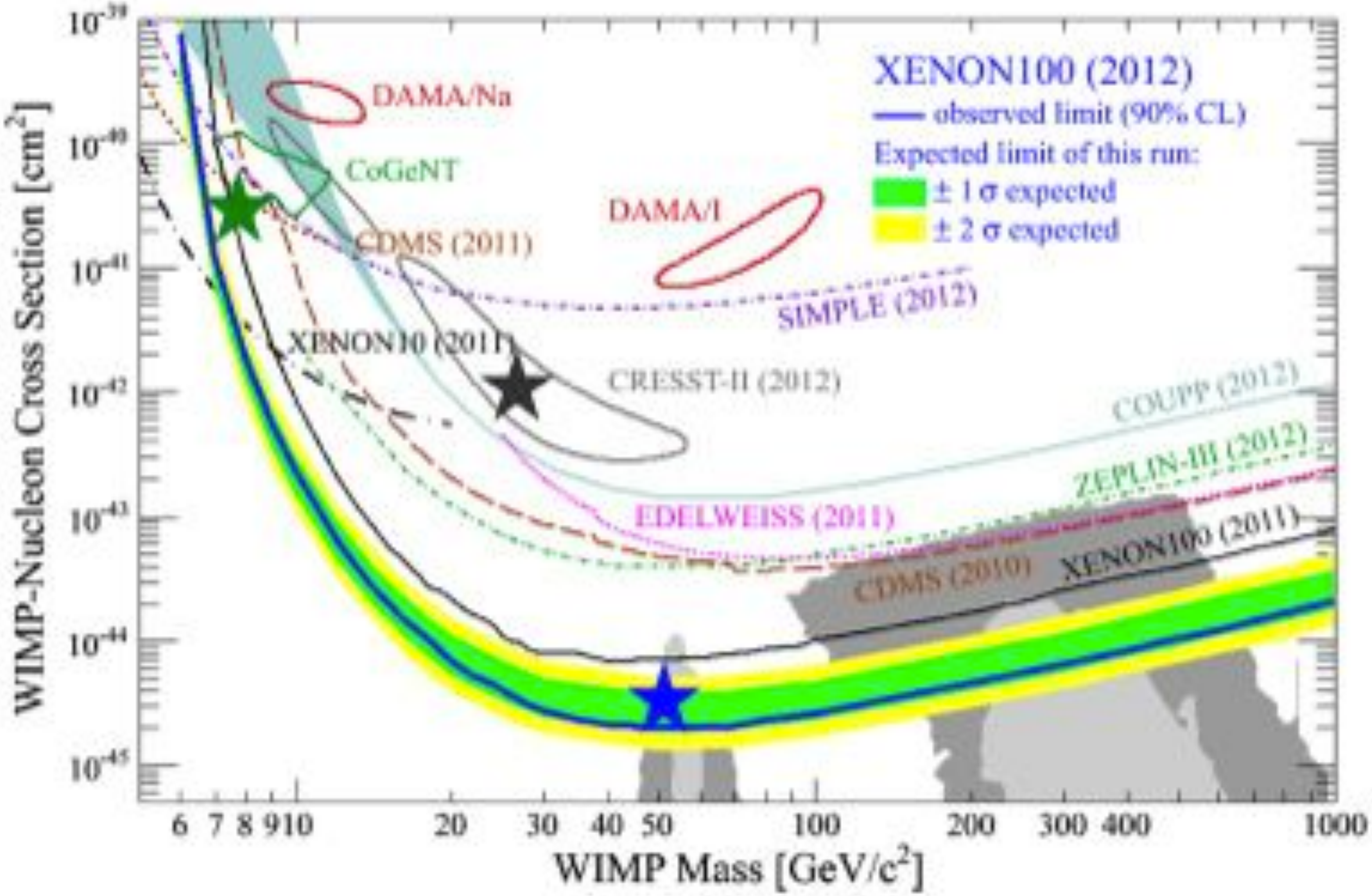




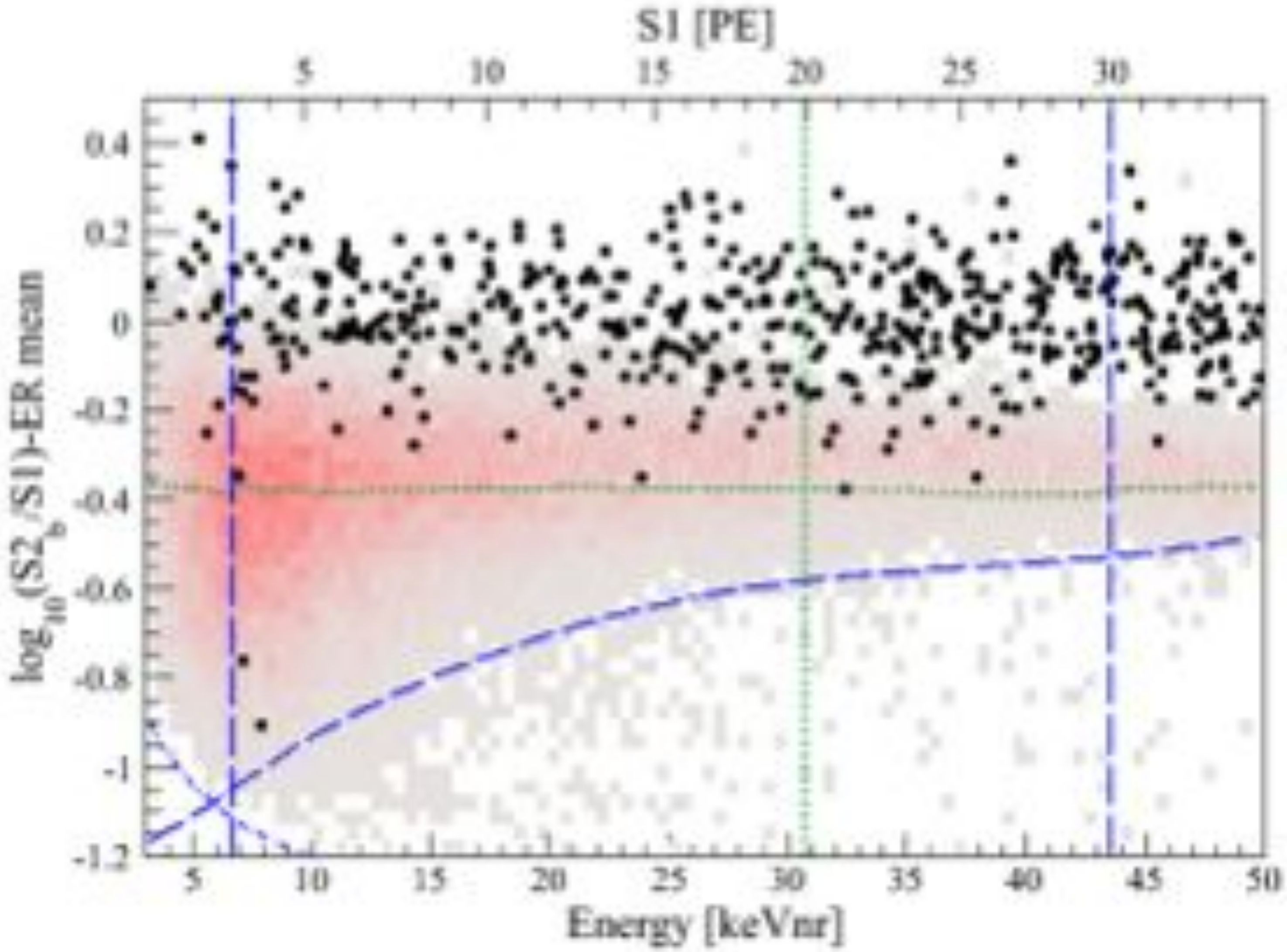
„standard“ Leff

L_{eff}=0 below 3 keVnr

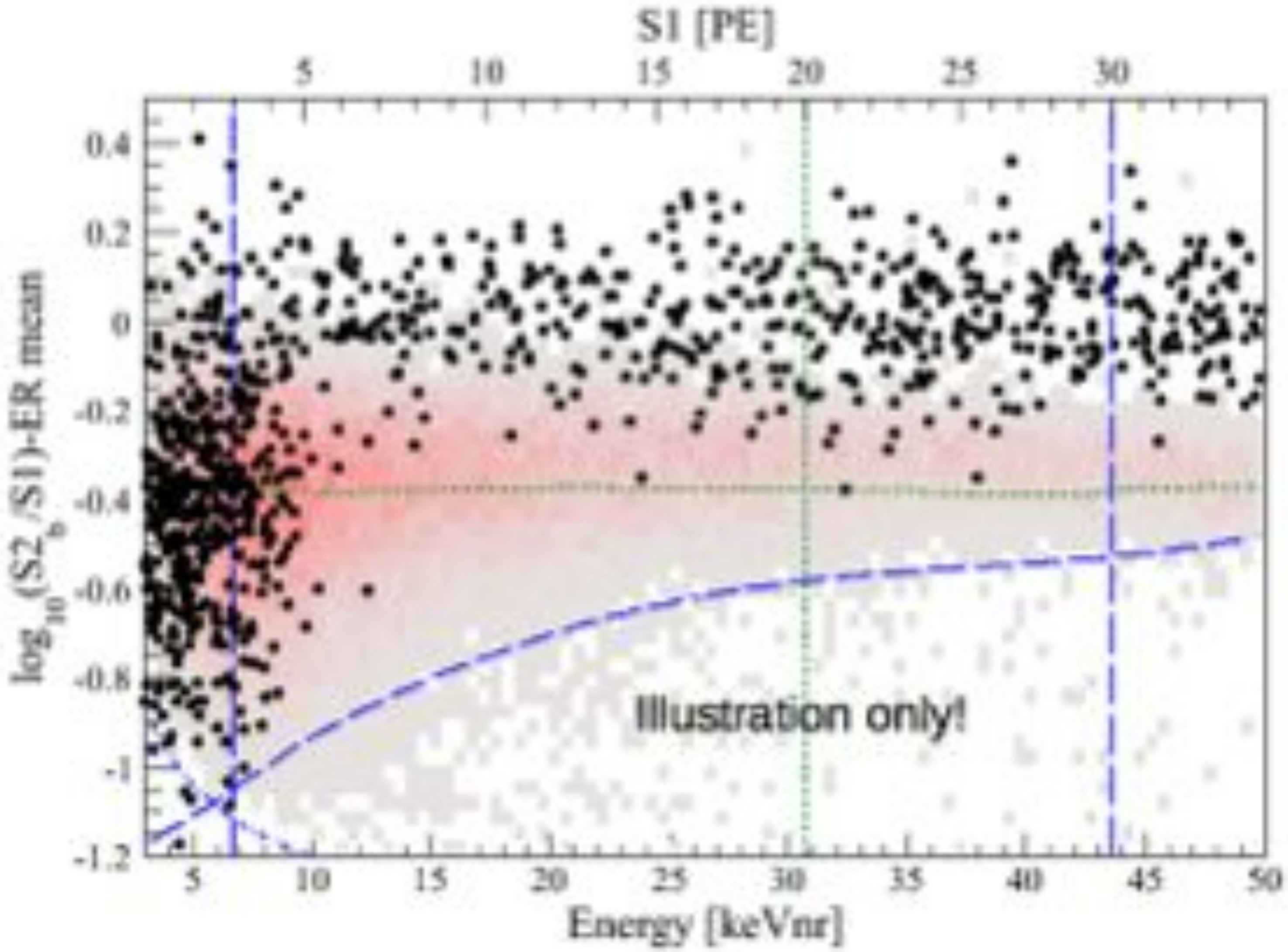
The new XENON100 Limit



What XENON100 sees...

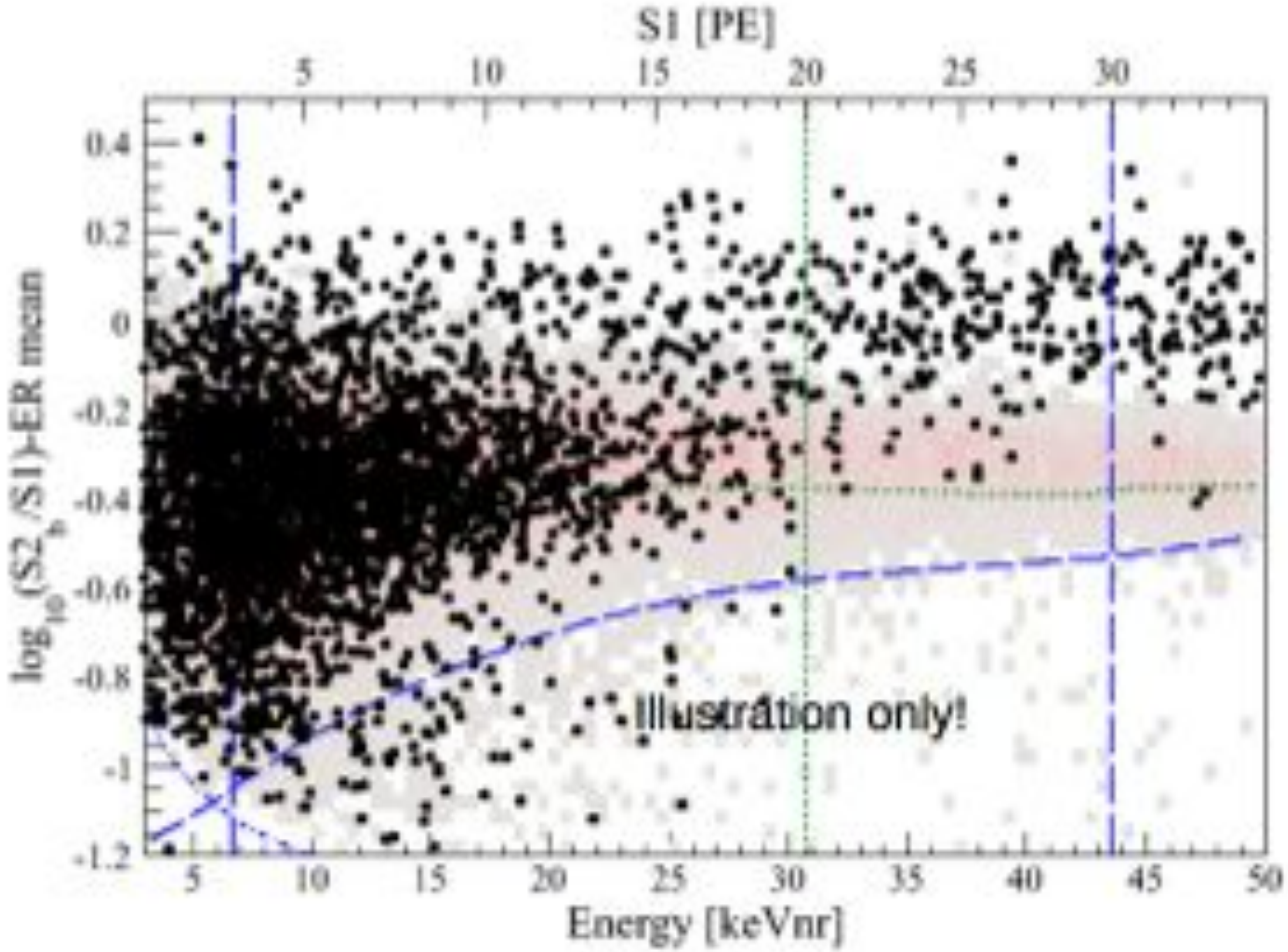


A light mass WIMP...



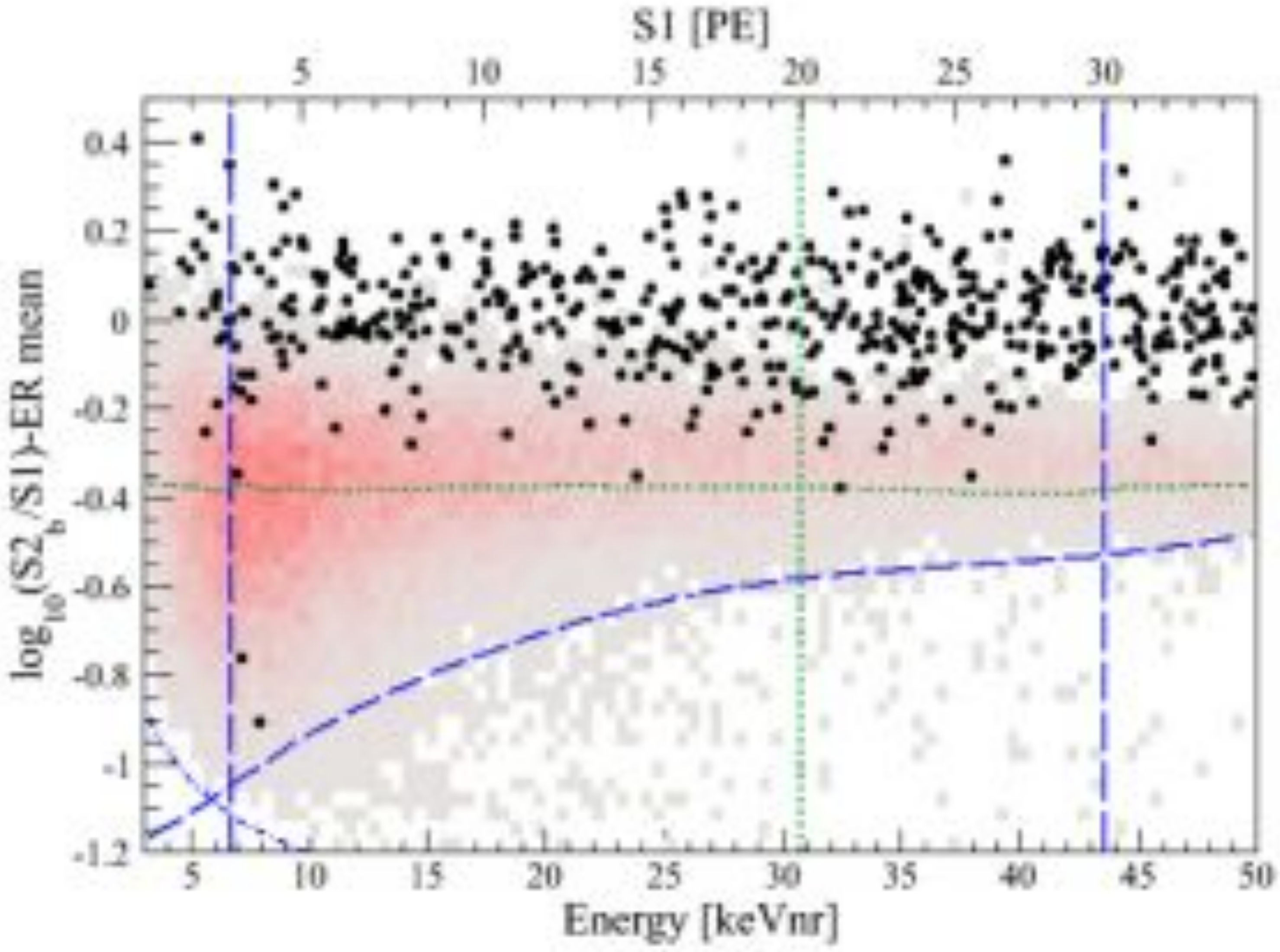
m_χ= 8 GeV/c² σ=1.0x10⁻⁴⁰cm²

A CRESST-like signal...

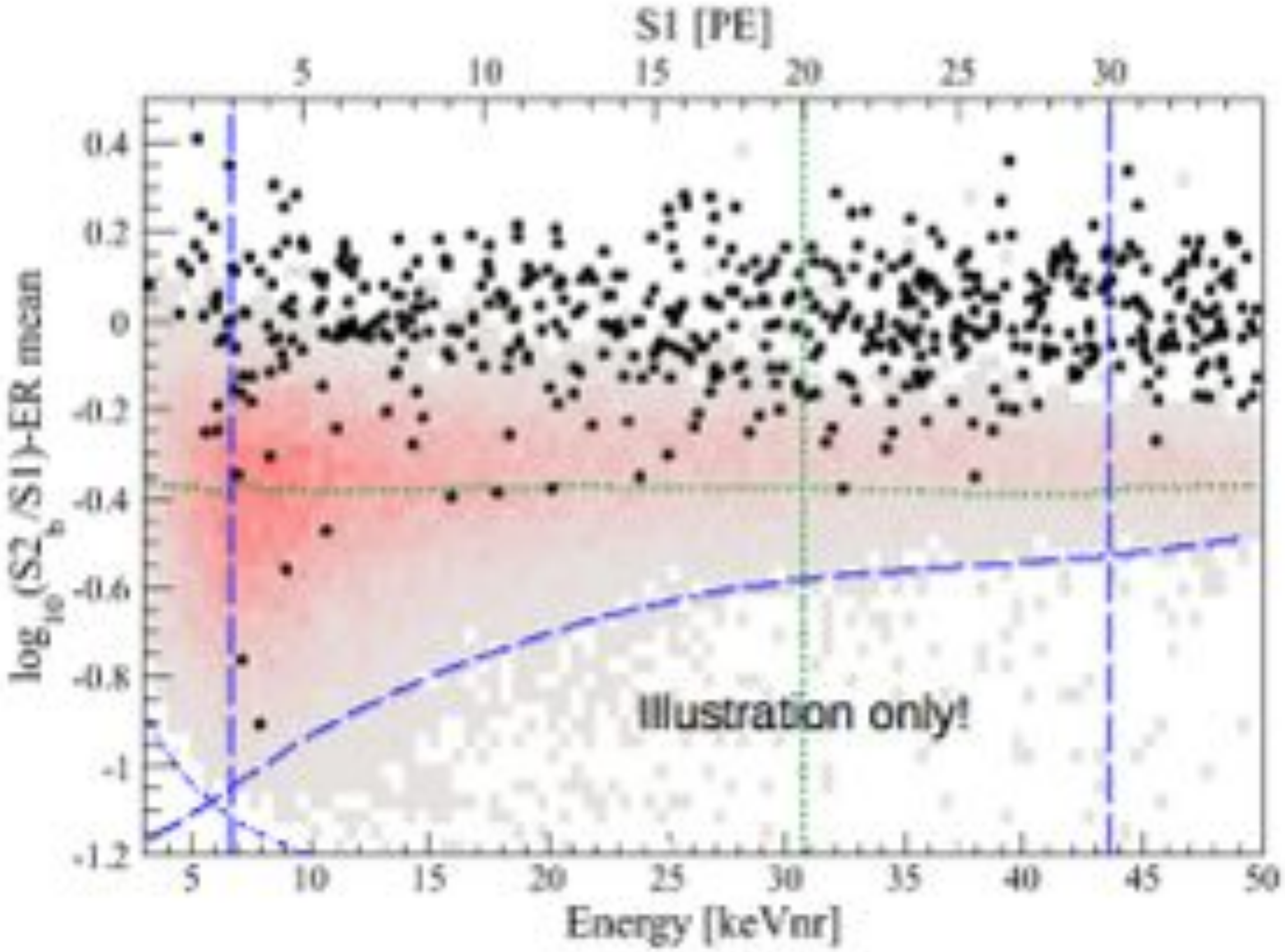


m_χ= 25 GeV/c² σ=1.6 x10^{-40} cm²

What XENON100 sees...

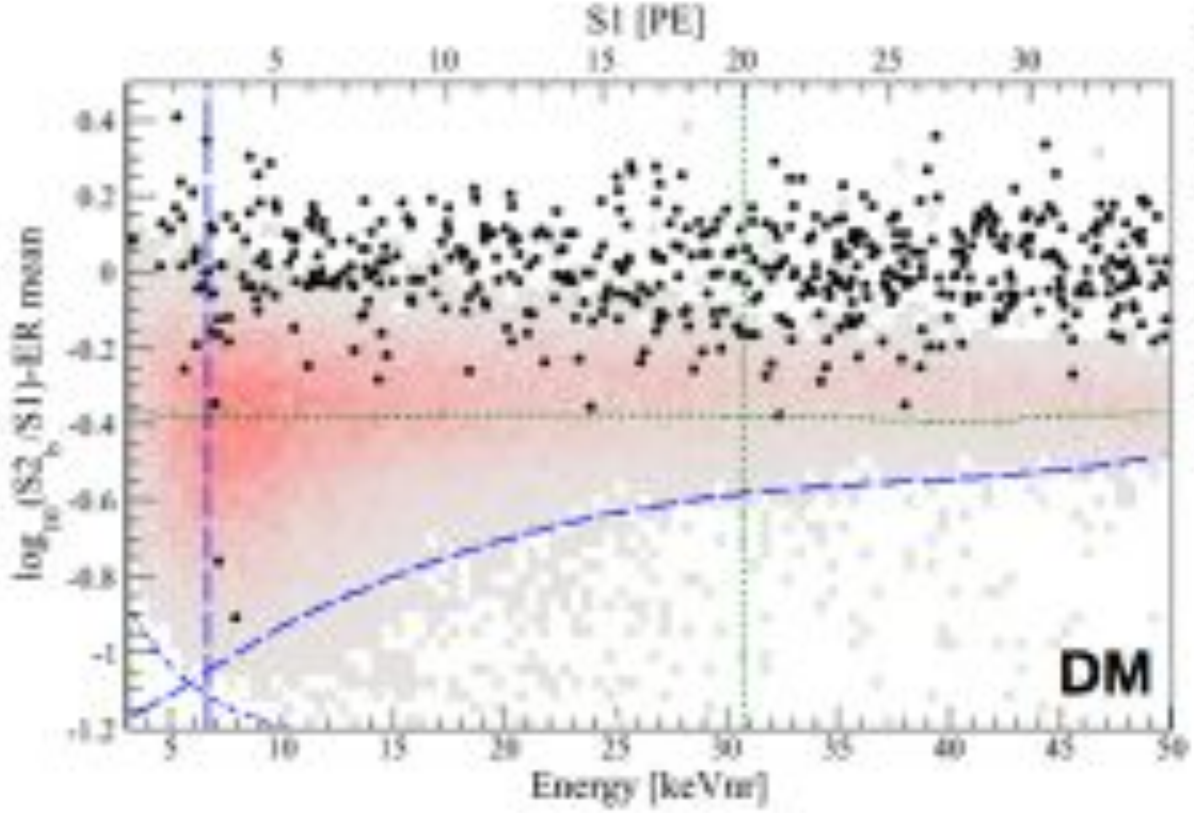


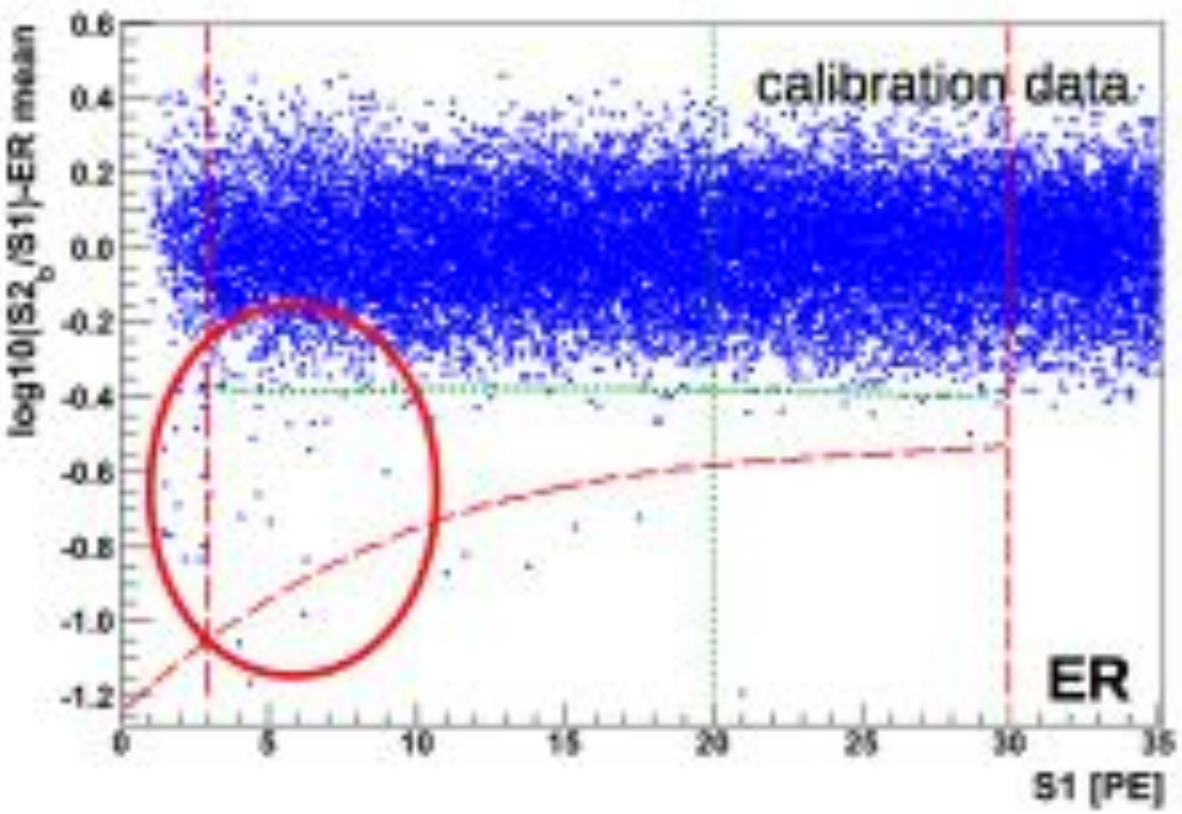
What XENON100 excludes...



m_χ= 50 GeV/c² σ=3.0 x10⁻⁴⁵ cm²

What could the Events be?



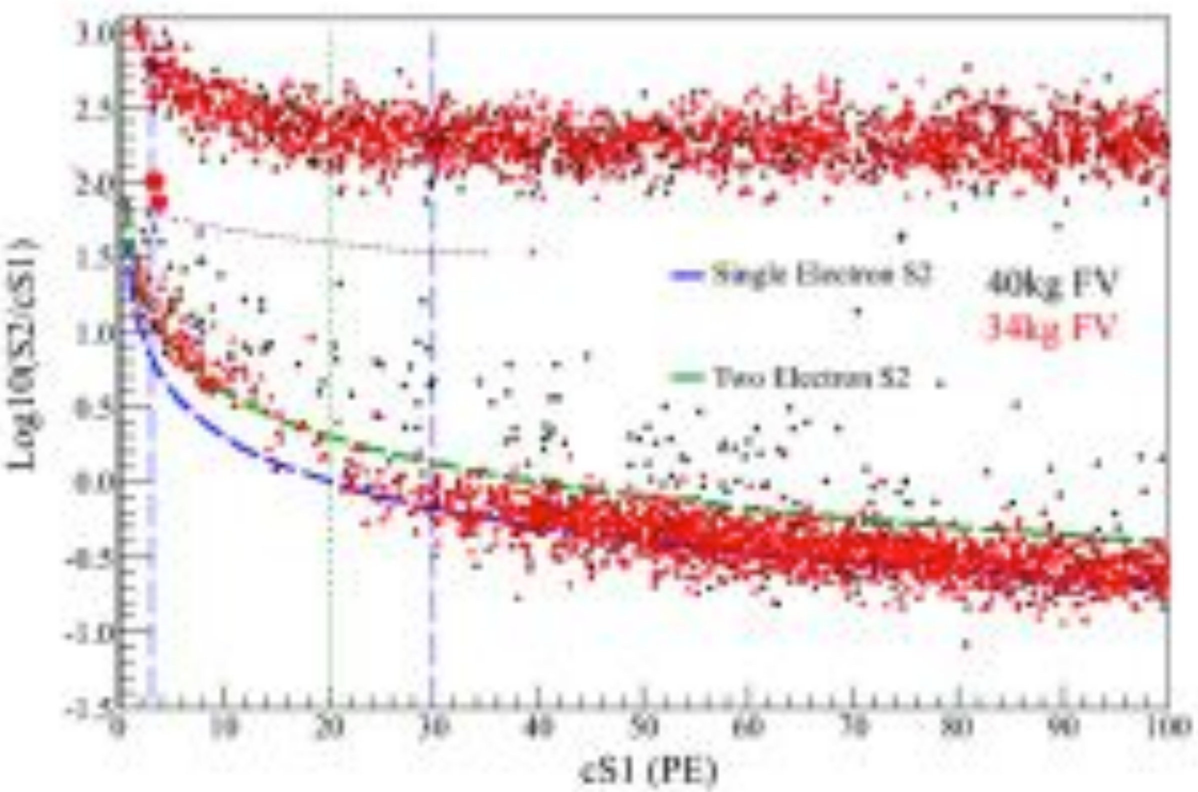


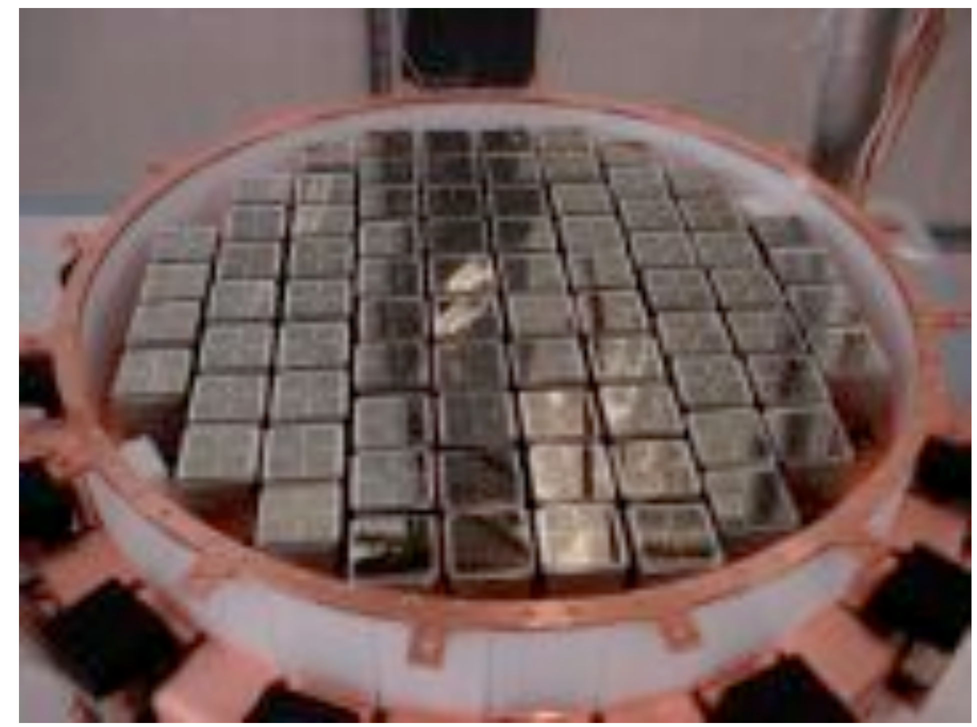
Reminder:

Background is modeled using ER calibration data from Co60 and Th232
This data shows an increased probability for anomalous leakage below ~8 PE

Background prediction depends on the information which is put into the model

Sensitivity to single electrons



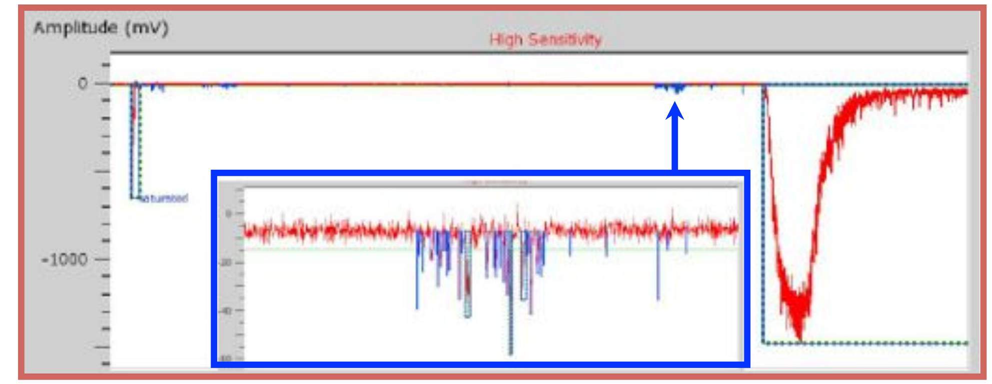


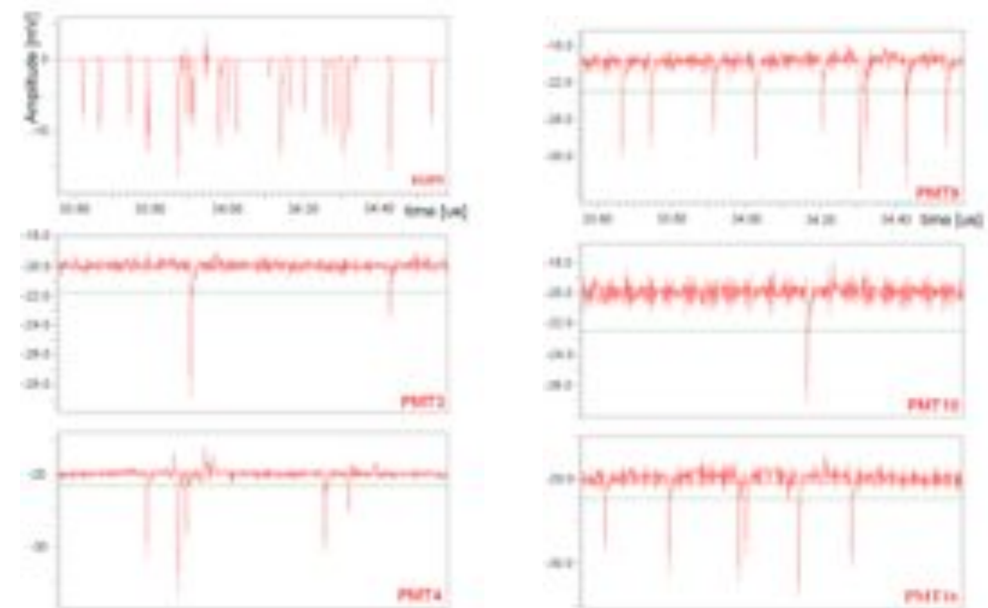
Relaxing the S2 threshold condition (S2>150 PE)
leads to a band of events at very low S2/S1(below signal range)

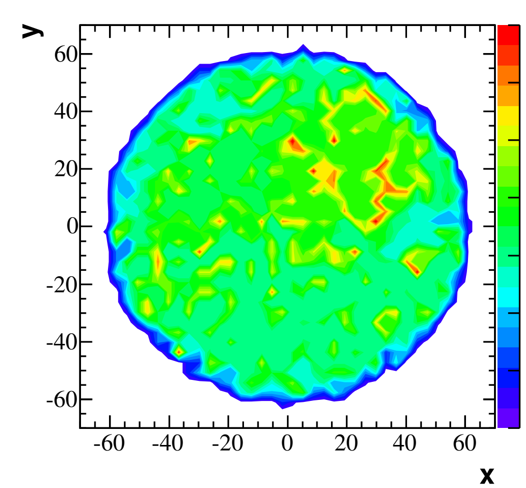
→ can the 2 events be in the tail of this band???
→ further studies are required
→ aim: quantify and put into background model for the next run

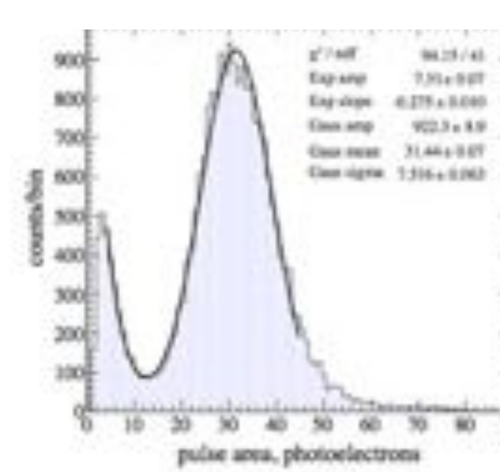
(Further) Exploiting the Ionisation Channel

- Resolution of primary scintillation is dominated by photon generation and photoelectron collection statistics
- Single electron detection demonstrated in LXe TPCs
- Origin:
  - ✤ Photon-induced (post S1): photoionisation and emission from cathode
  - ✤ Spontaneous emission: background related
- Application:
  - ★ Electron lifetime measurement (extremely useful for ton and greater scale detectors)
  - ★ Lower thresholds (~1 keV) and superior resolution
  - ★ Neutrino physics
  - ★ **Low mass WIMP searches**

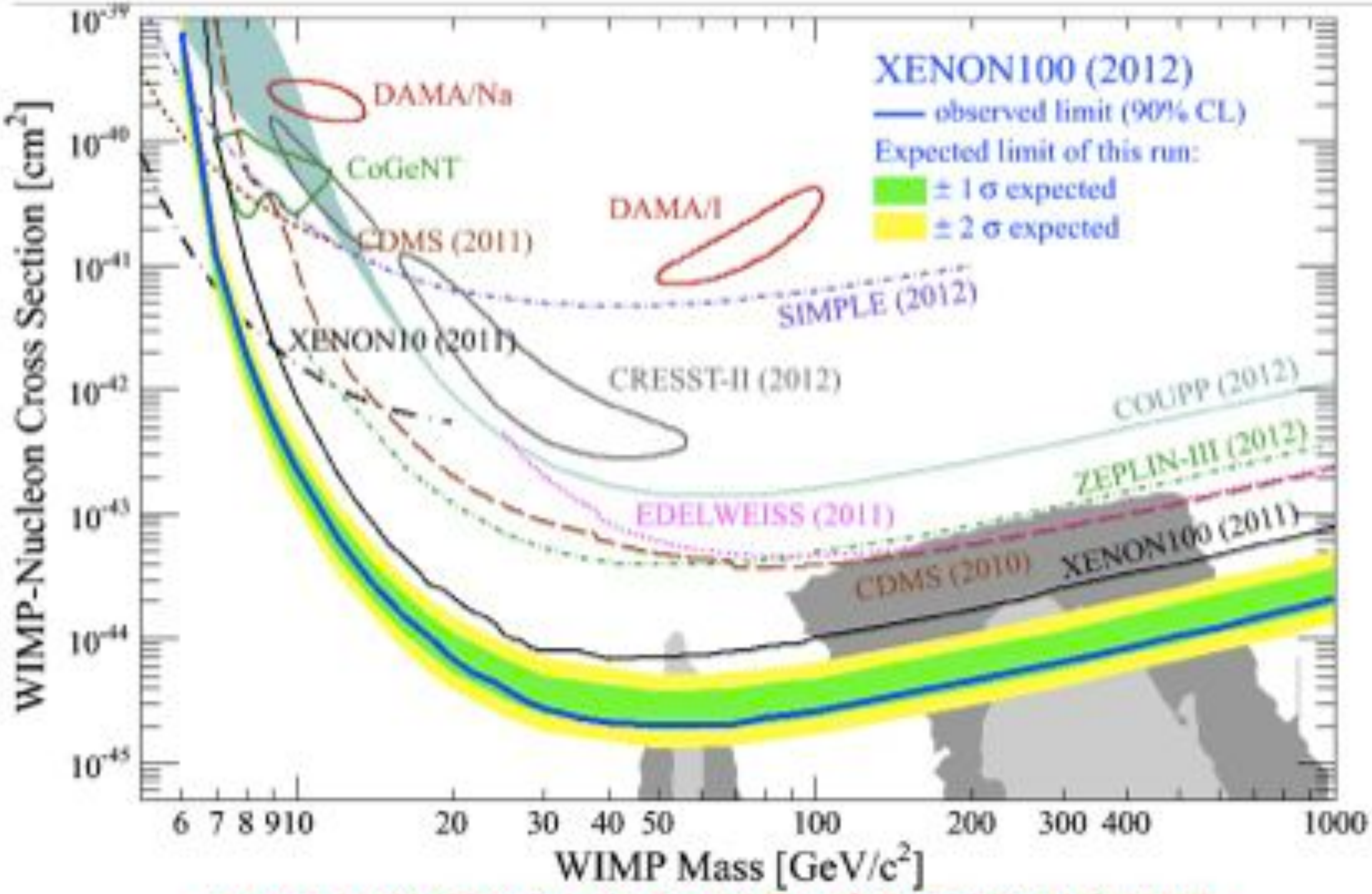






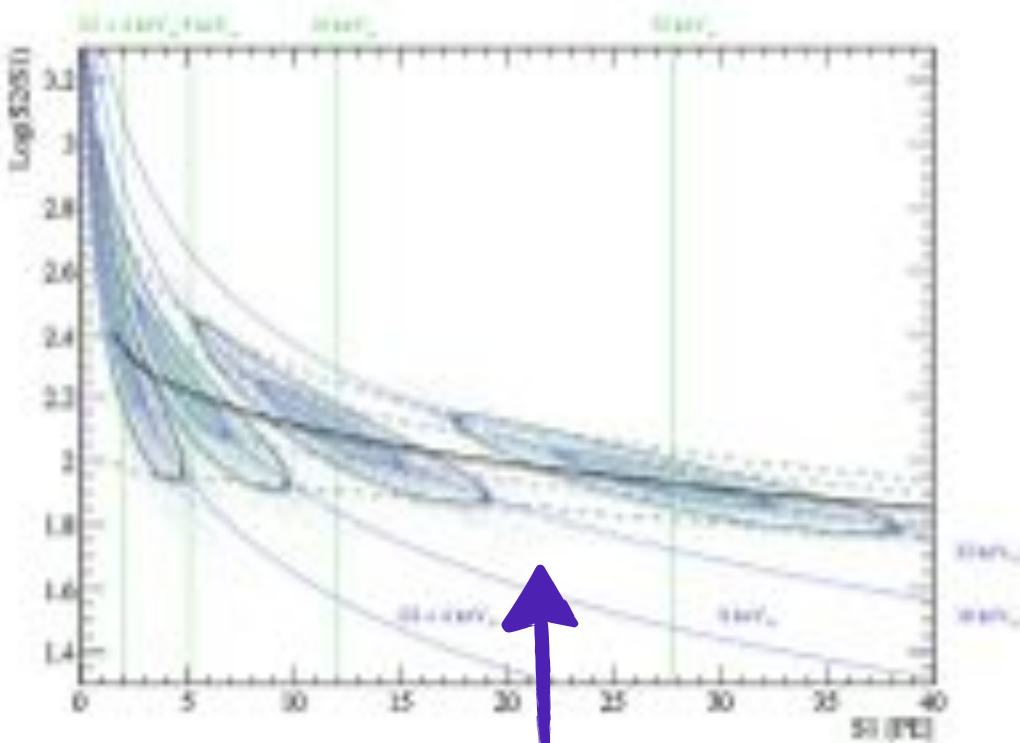


XENON100: New Spin-Independent Results

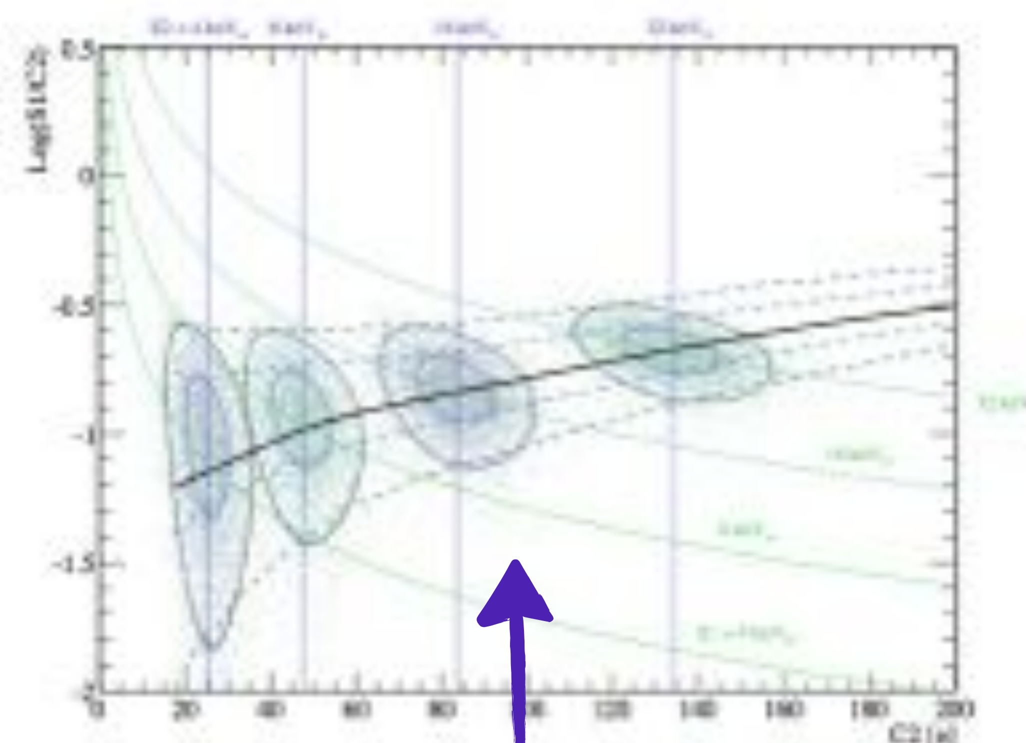


Upper Limit (90% C.L.) is 2×10^{-45} cm^2 for 55 GeV/c^2 WIMP

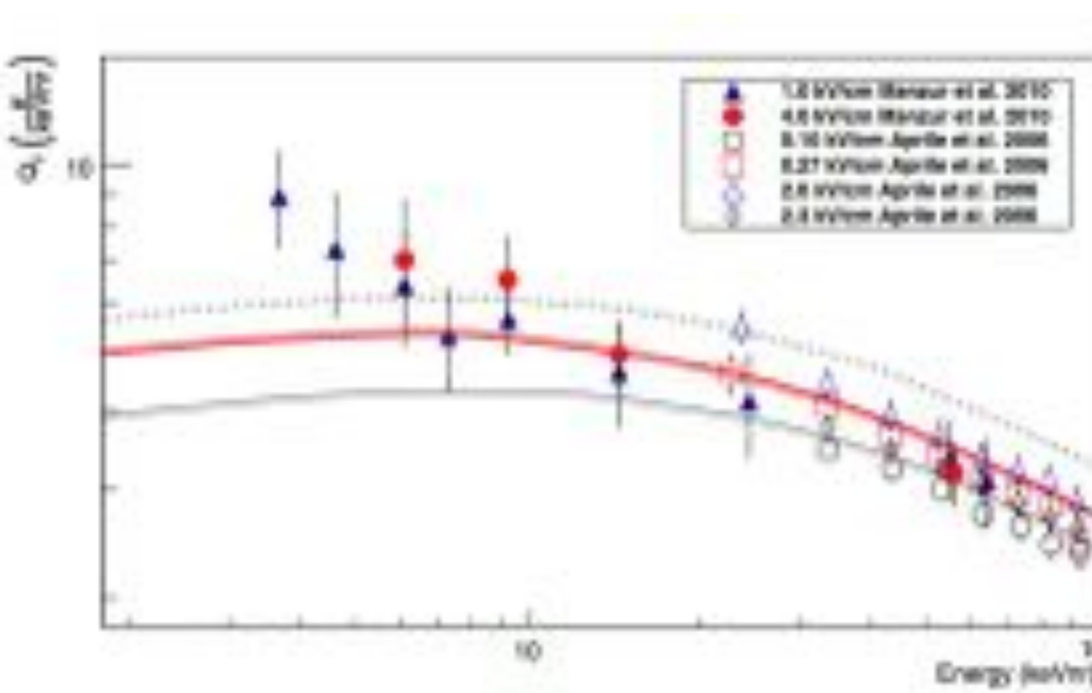
(Further) Exploiting the Ionisation Channel



To go from this...



to this...



...we need this!

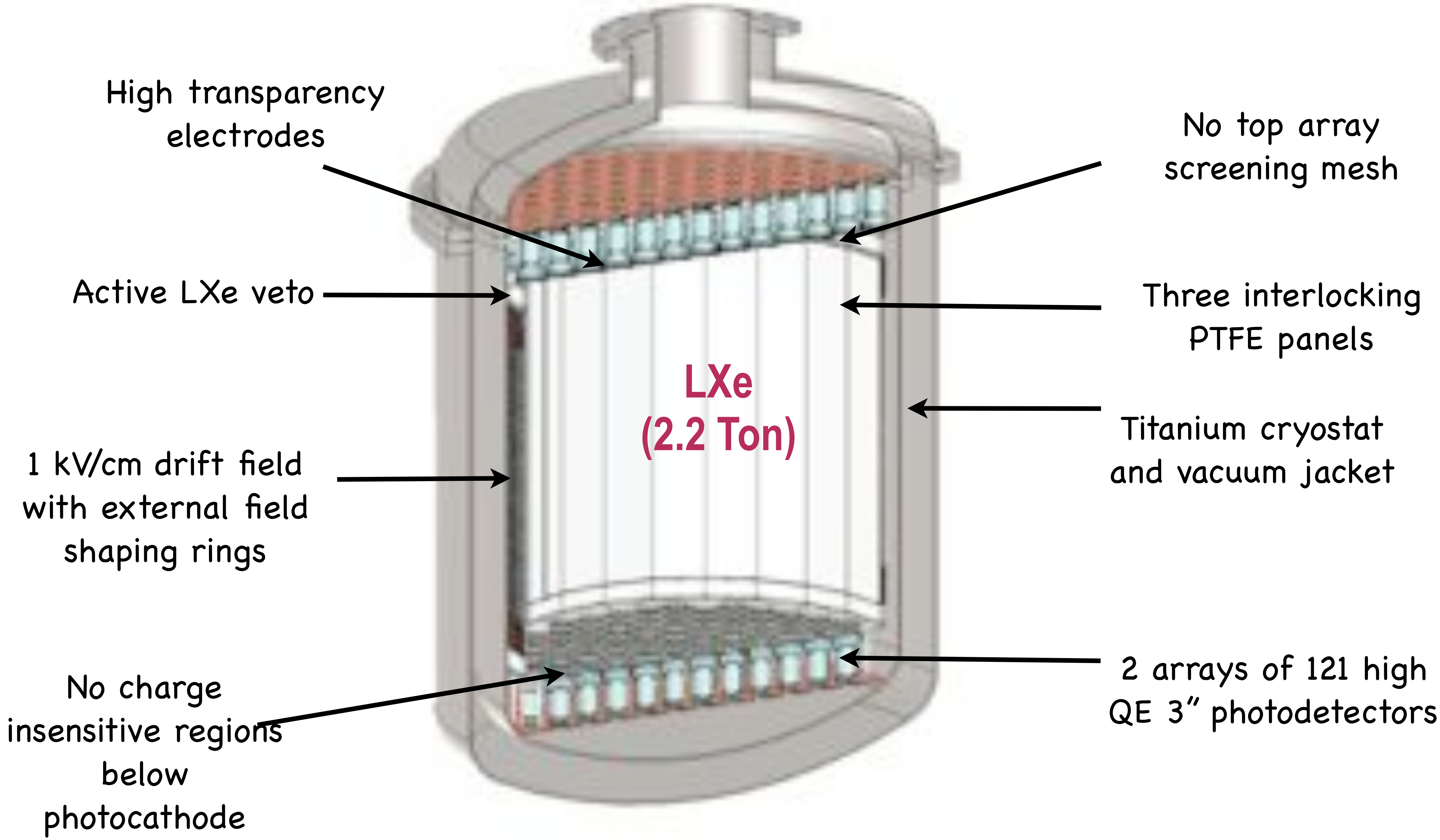
1. Very Brief Intro to Dark Matter and Direct Detection

2. The LXeTPC & XENON100

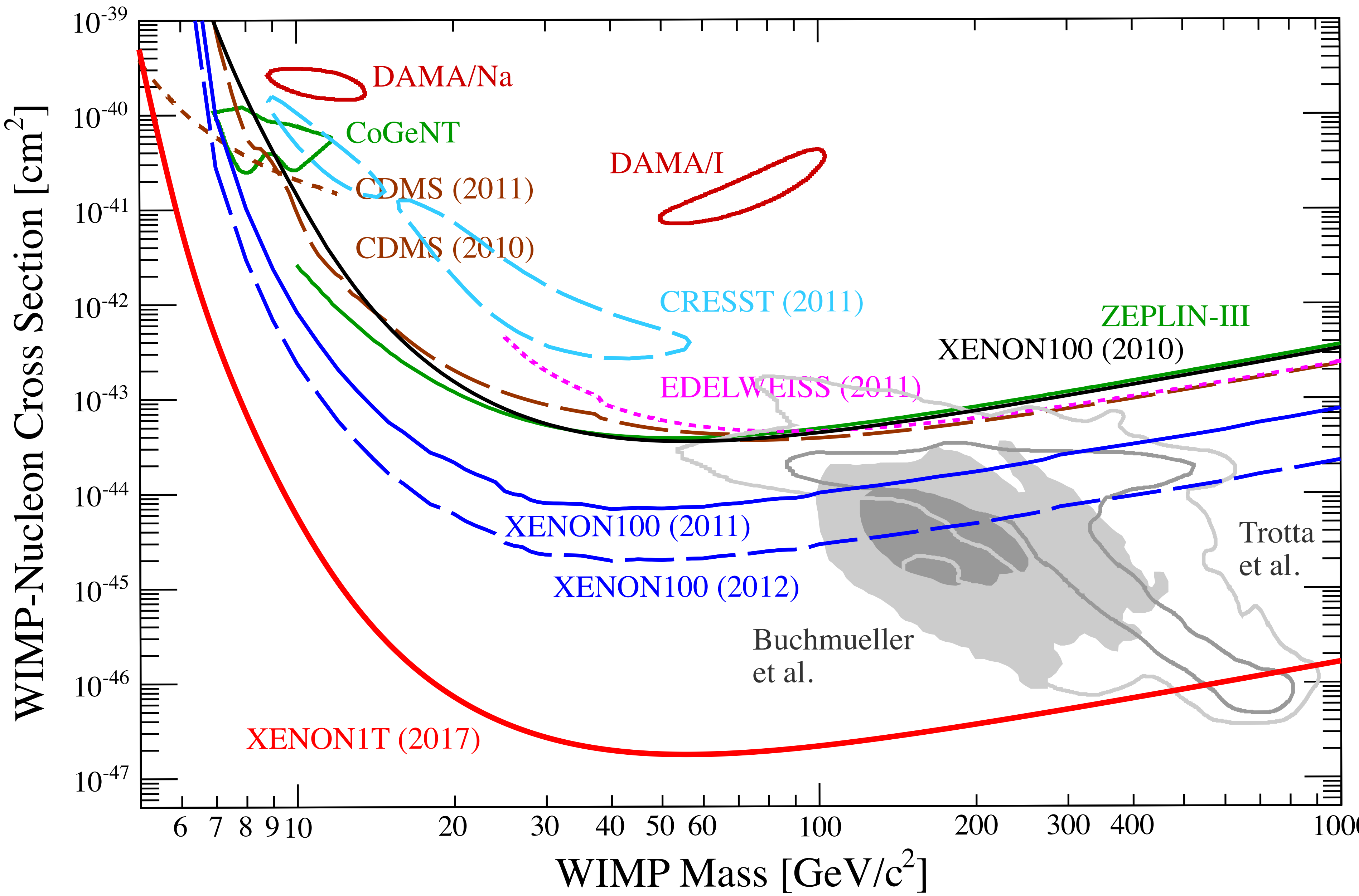
3. Latest Results

4. The Next Generation (Tonne scale) Detectors

The Next Step: XENON1T



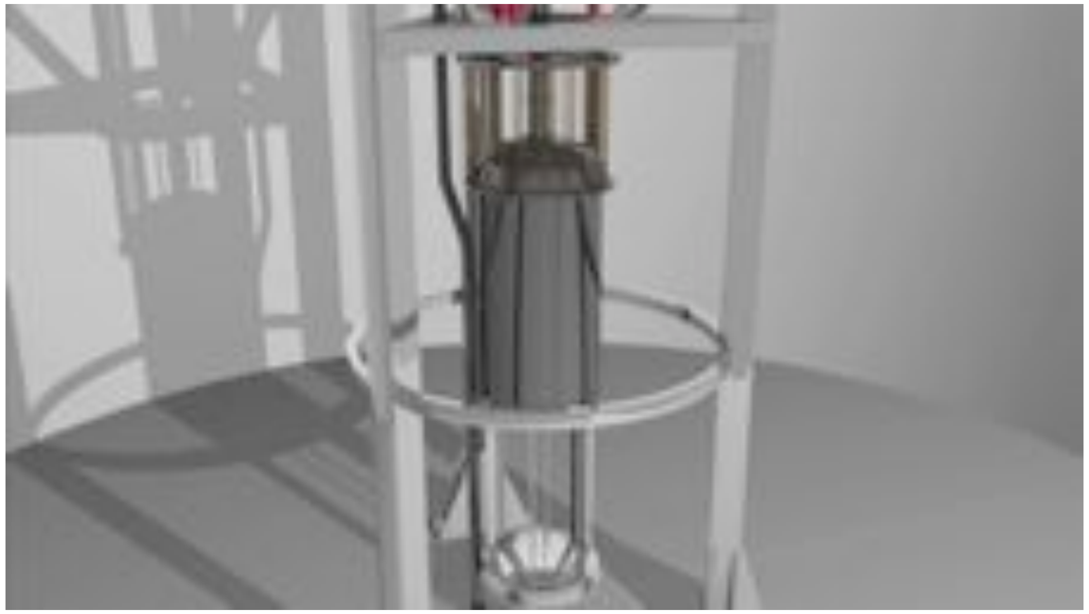
Scaleability has been demonstrated repeatedly - gets easier (no performance loss) as we get bigger!



1 Tonne Fiducial Mass
2 Year Exposure (~2017)

Homestake mine
South Dakota

Davis Cavern (5th May 2011)
4850 ft depth



Dec 2011

World leader in 2013

Sept 5th 2012
Water Shield and lab ready for LUX!

Now submerged in water tank - cool-down imminent!

The ZEPLIN Programme at Boulby

ZEPLIN I
Single phase, 3 PMTs, 5/3.1 kg
Run 2001-04
*Limit: 1.1*10^{-6} pb*

Single-phase

ZEPLIN II
Double phase, 7 PMTs,
moderate E field, 31/7.2 kg
Run 2005-06
*Limit: 6.6*10^{-7} pb*

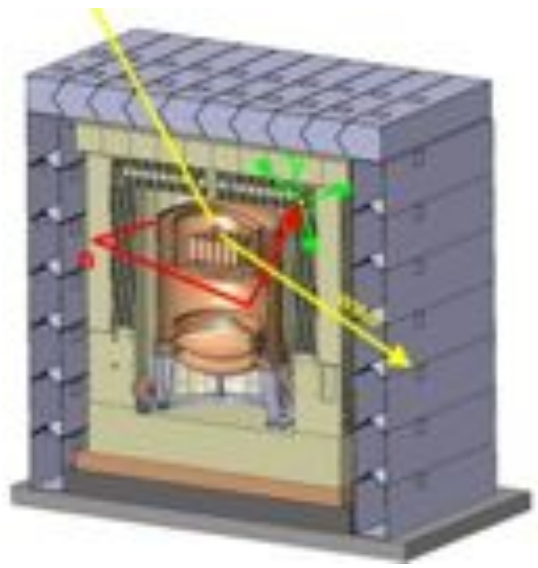
The first 2-phase LXe Dark Matter detector!

ZEPLIN III
Double phase, 31 PMTs,
high E field, 10/6.4 kg
Run 2009-11
*Limit: 3.9*10^{-8} pb*

Europe's most sensitive SI
World's best WIMP-neutron SD

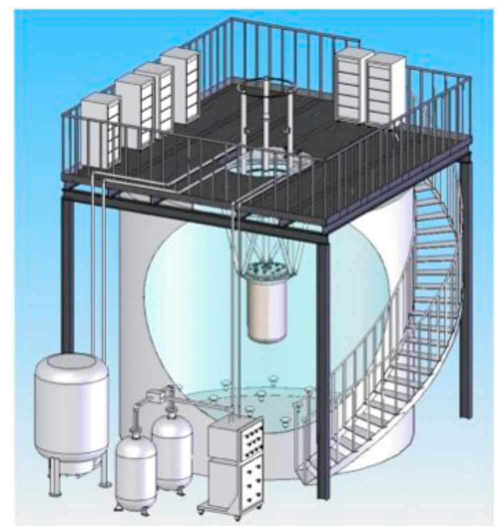
LUX-ZEPLIN (LZ)

ZEPLIN-III



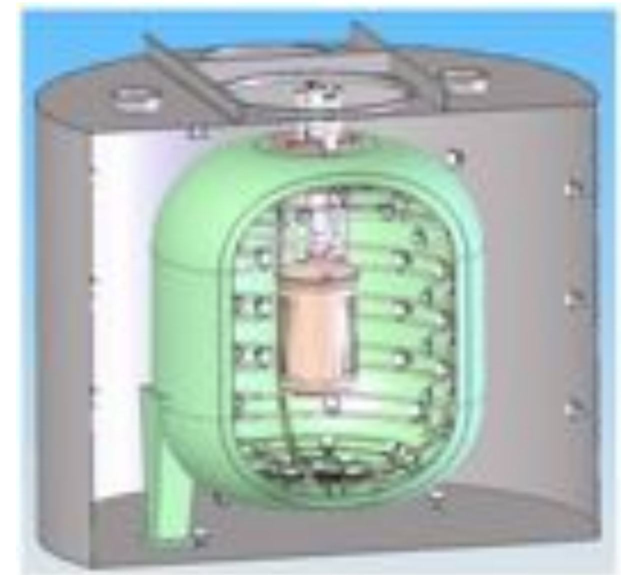
6 kg LXe

LUX



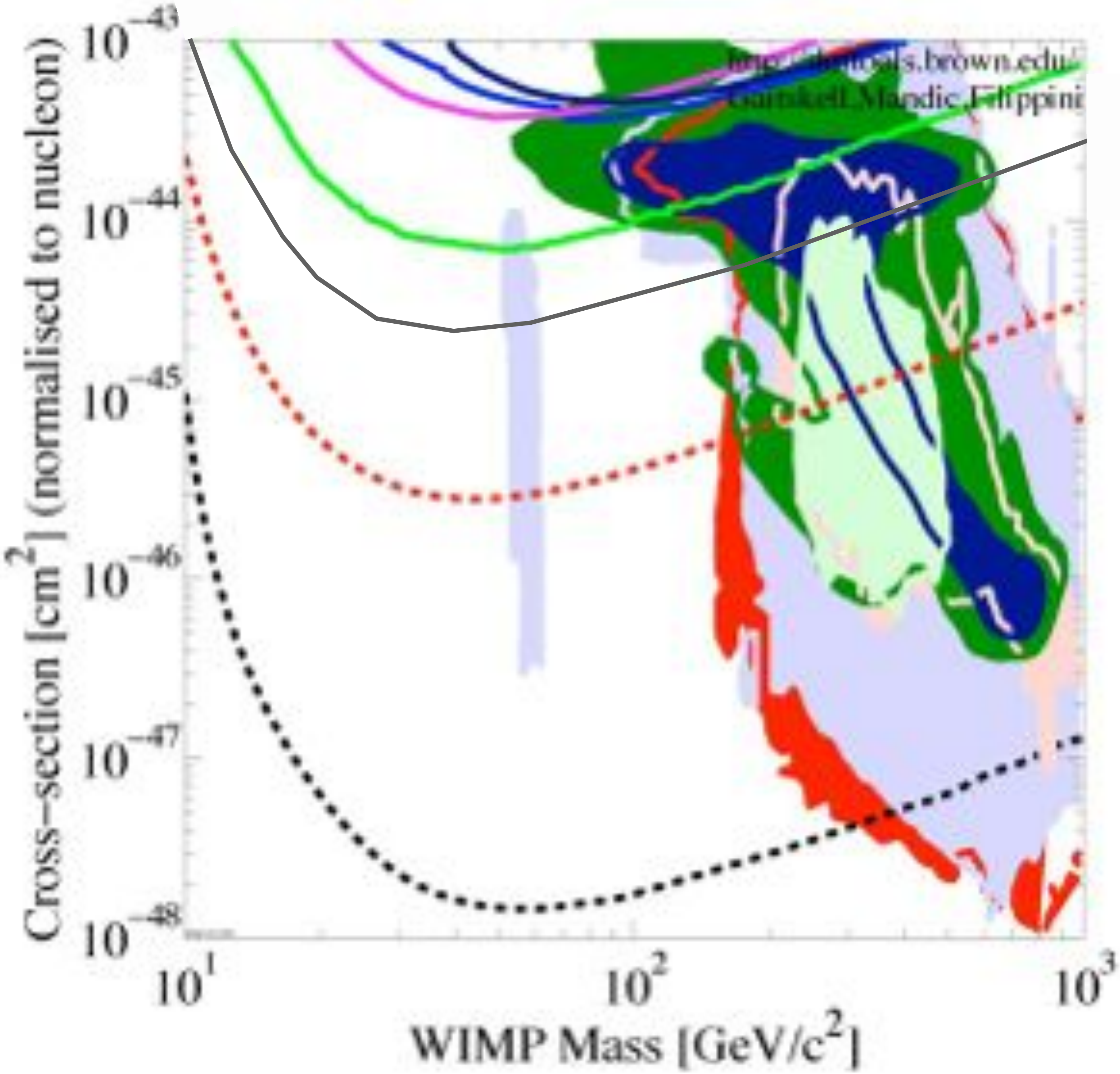
100 kg

LZ



5,000 kg

- Merger of the UK-led ZEPLIN and LUX progressive programmes
- SI WIMP-nucleon cross-section sensitivity to $\sim 10^{-48}$ cm^2
- UK leading roles in 3/10 of WPs for LZ
    - Backgrounds/screening/analytics (UCL)
    - Inner detector/TPC (IC)
    - Ti vessels (RAL)



Elastic scattering SI cross-section

Results

ZEPLIN-III 2011 (magenta)

XENON100 2011 (green)

XENON100 2012 (grey)

EDELWEISS II 2011 (dark blue)

CDMS-II 2010 (blue)

Projections

LUX (red dash)

100 kg fiducial x 300 live days

LUX-ZEPLIN (black dash)

5-tonne fiducial x 1,000 live days

LZ will be >10x more sensitive than XENON1T (>1000x more than XENON100) and will sweep virtually all of the favoured electroweak parameter space!

Summary

- LXeTPCs, pioneered by the ZEPLIN and XENON collaborations have rapidly accelerated the race for WIMPs, excluding **3 orders of magnitude** in WIMP-nucleon cross-section over the past decade

- Scaling detectors **lowers background**, but does not harm threshold, discrimination, or event vertex reconstruction

- XENON100 achieved sensitivity an **order of magnitude** better than any competing experiment - but no WIMPs!

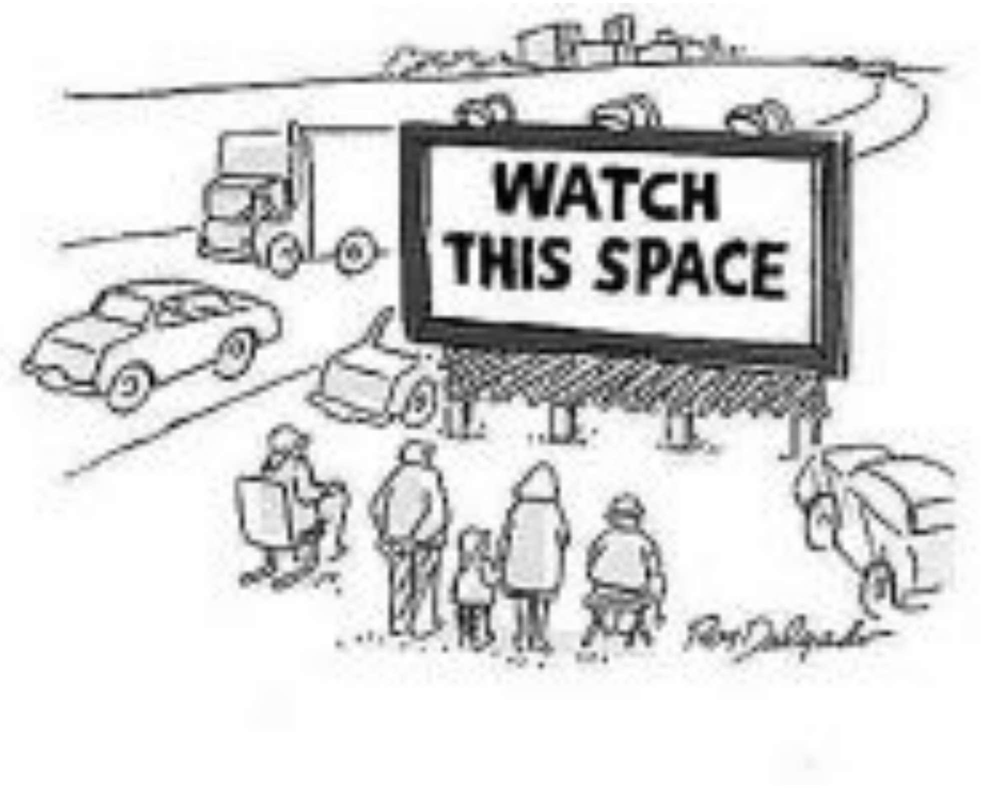
- Exploiting the ionisation channel lowers threshold from existing 6-7 keV down to **1 keV**
  LXeTPCs perform broadband Dark Matter searches

- Next up is LUX, to become the **world leader in 2013**

- The tonne scale ‘G2’ Experiments, XENON1T (1.1T) and LUX-ZEPLIN (5T), will build on the LXeTPC track-record to deliver sensitivity for a robust and statistically significant **first discovery**!

- DarkSide uses the same technology with LAr - multiple targets needed for confirmation!

Exciting times ahead....



Thank you all for listening!