Probing Light WIMPs with Liquid Xenon

Universität Zürich[UZH]

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7th Patras workshop on axions, WIMPs and WISPs

Mykonos, Greece

30 June, 2011

Overview

- Light WIMPs: the evidence FOR (DAMA/CoGeNT/CRESST)
- Light WIMPs: the evidence AGAINST (XENON100, CDMS, XENON10)
- Examining the critique of XENON10
- Examining the evidence for light WIMPs

Light* WIMPs: the evidence FOR

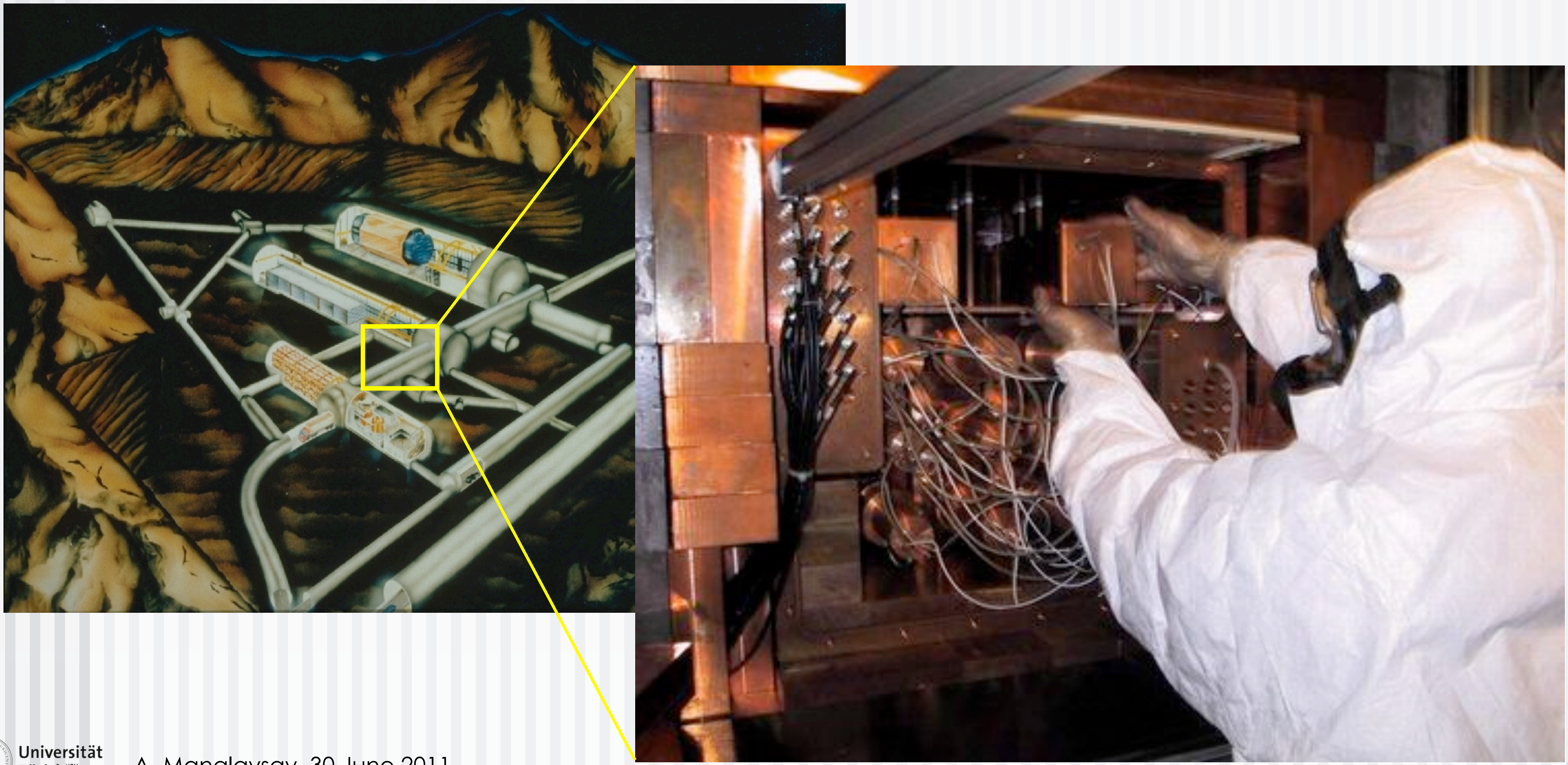
- DAMA/NaI and DAMA/LIBRA
- CoGeNT
- CRESST

See talk by Raimund Strauß

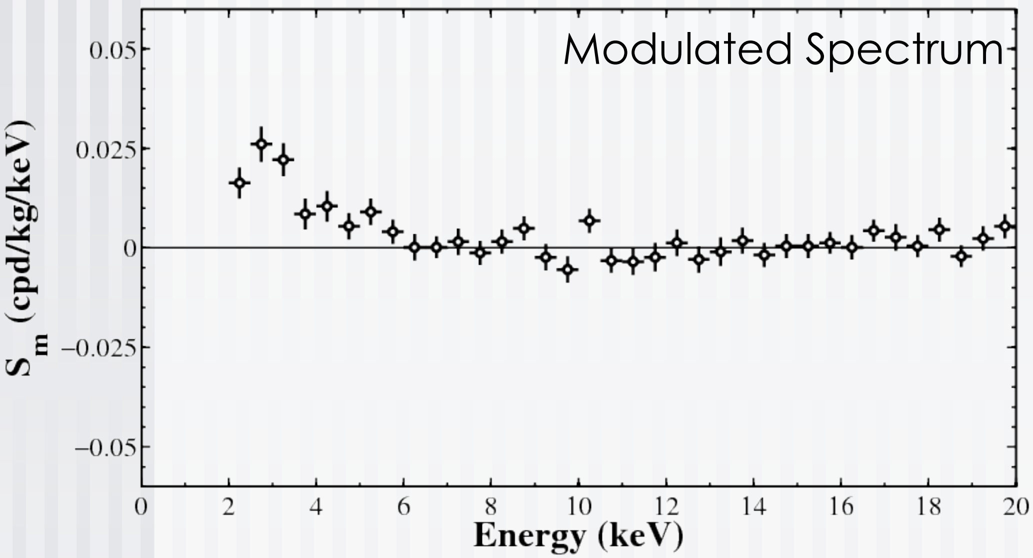
* ~10 GeV/c²

DAMA/NaI and DAMA/LIBRA

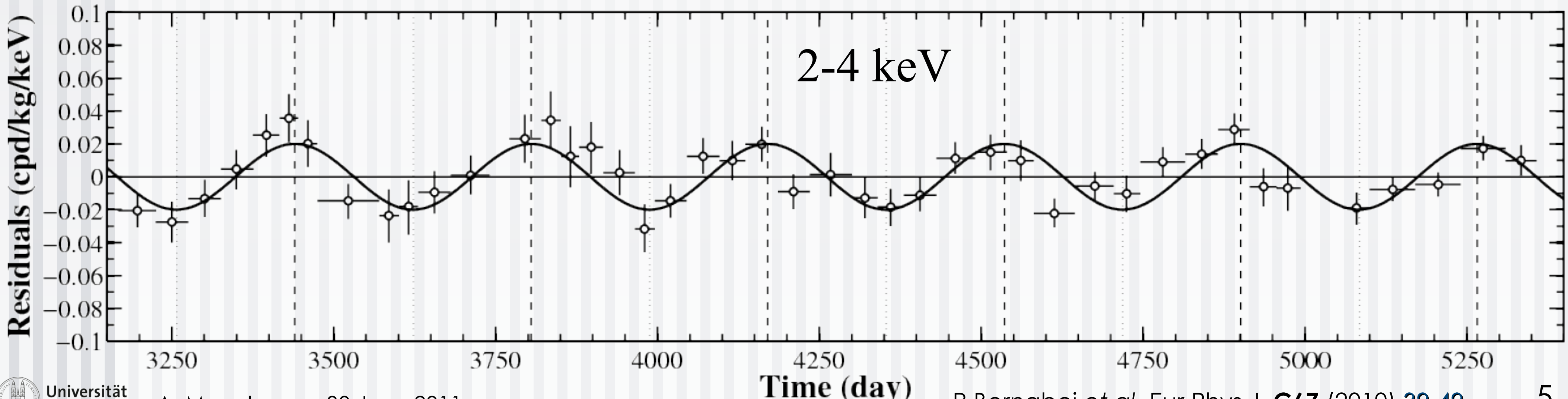
Operating 242 kg of low-radioactivity NaI(Tl) at the Laboratori Nazionali del Gran Sasso



DAMA/NaI and DAMA/LIBRA

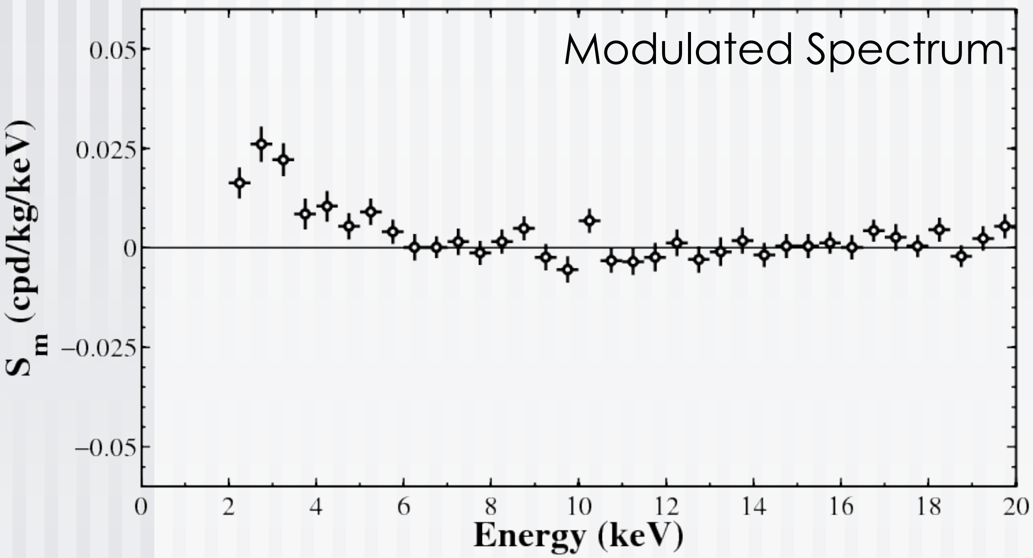


DAMA uses low-background NaI crystals, operated at LNGS. They observe a modulation in the rate of background events with roughly 1-year period and a maximum near the early summer. Such a modulation is predicted as a result of the Earth's changing velocity through the DM halo throughout the year.



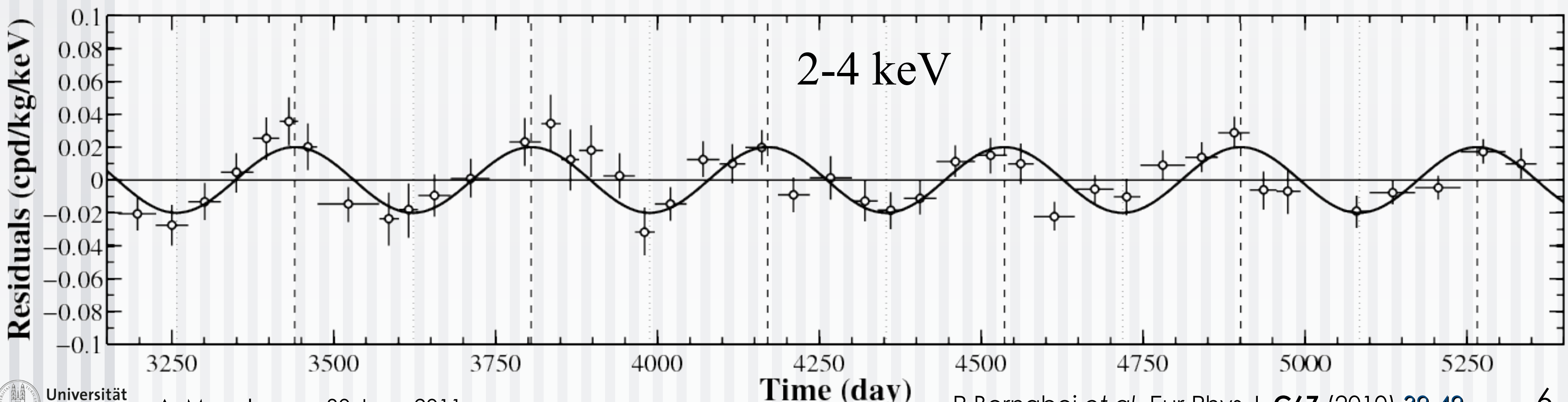
R.Bernabei *et al*, Eur.Phys.J. **C67** (2010) 39-49

DAMA/NaI and DAMA/LIBRA



But what are they seeing? It's difficult to obtain a specific conclusion, because not much is known on a per-event basis. The essential facts:

- Modulation observed with correct phase and period
- Modulation observed in lowest energy bins
- No modulation observed in multi-hit events



DAMA/NaI and DAMA/LIBRA

Some possible dark matter explanations:

- Recoils from iodine nuclei
- Recoils from sodium nuclei
- Axio-electric absorption

DAMA/NaI and DAMA/LIBRA

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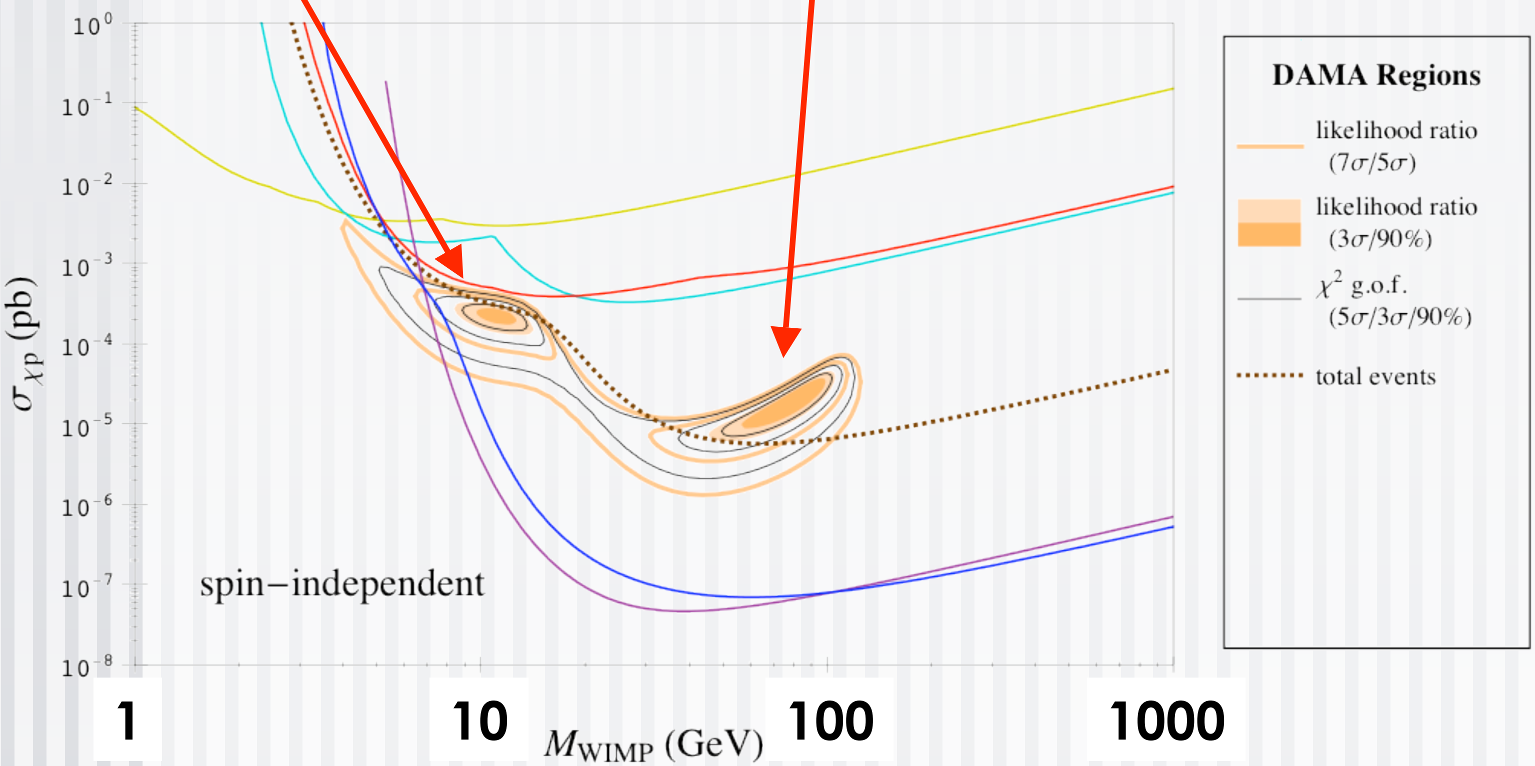
Let's ignore this one for this talk…

DAMA/NaI and DAMA/LIBRA

Sodium recoils

Iodine recoils

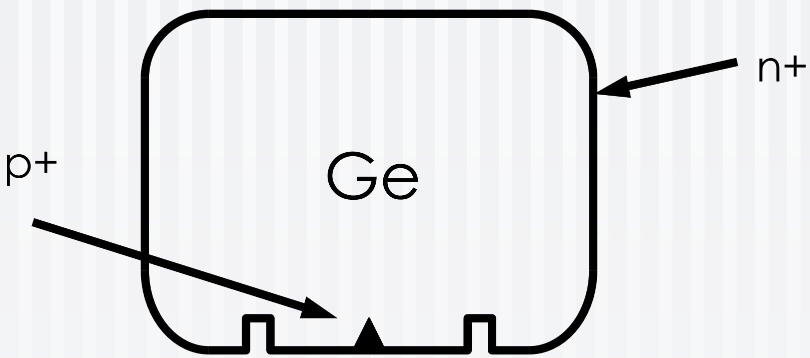
(this interpretation excluded by many experiments, even DAMA/LIBRA)

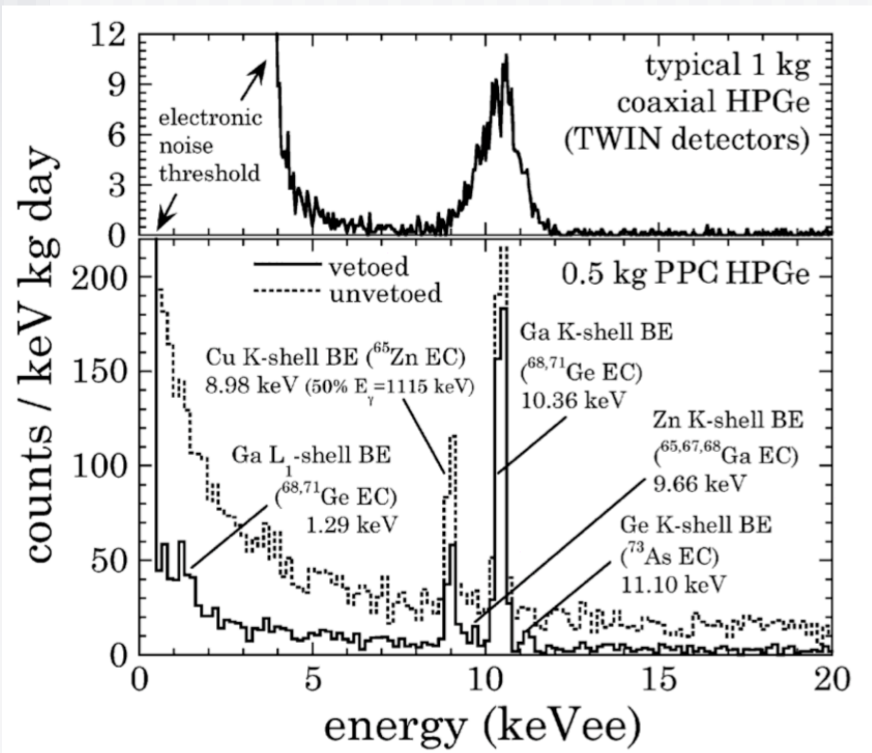


C.Savage *et al.*, JCAP04 (2009) 010

This plot shows these interpretations assuming pure spin-independent coupling, no ion channeling. Channeling is not favored anymore, but one can play games with SI vs. SD couplings, and proton/neutron couplings. But the result is the same: we are looking at an interpretation involving ~10 GeV WIMPs recoiling with sodium nuclei

CoGeNT





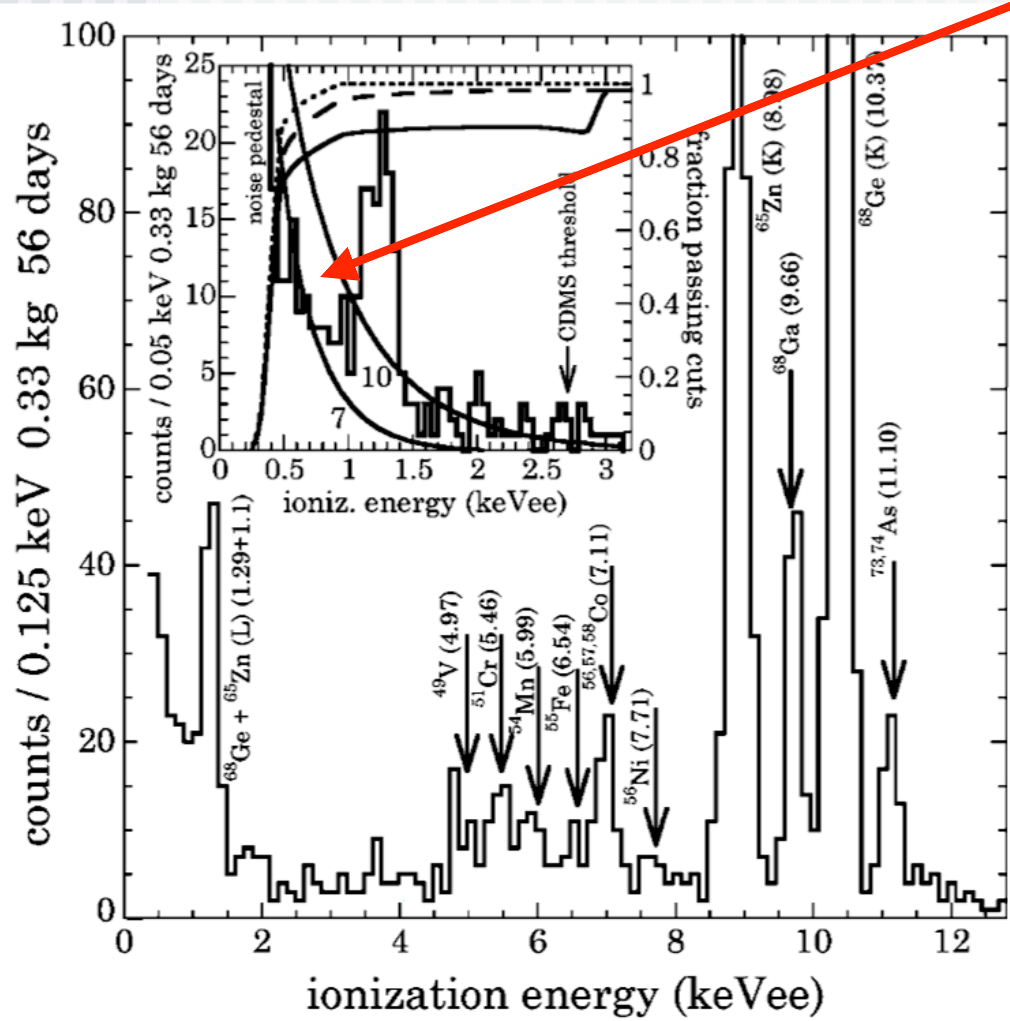
C.E.Aalseth *et al.*, PRL **101**, 251301 (2008)

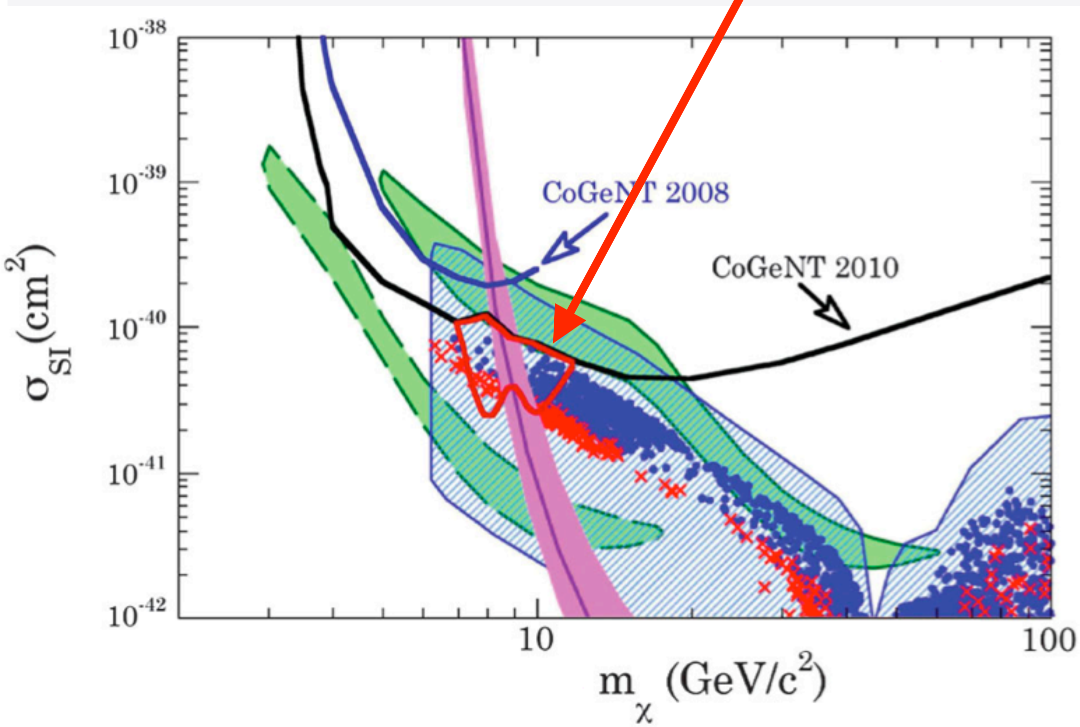
p-type point-contact high purity germanium detector (PPC HPGe). Features superior timing precision, improved resolution, and lower threshold, compared with traditional coaxial or planar Ge detectors.

Originally designed to detect coherent neutrino scattering, these were re-targeted to probe light WIMPs due to the low threshold. First operated shallow at U. Chicago, then at Soudan in Minnesota.

CoGeNT

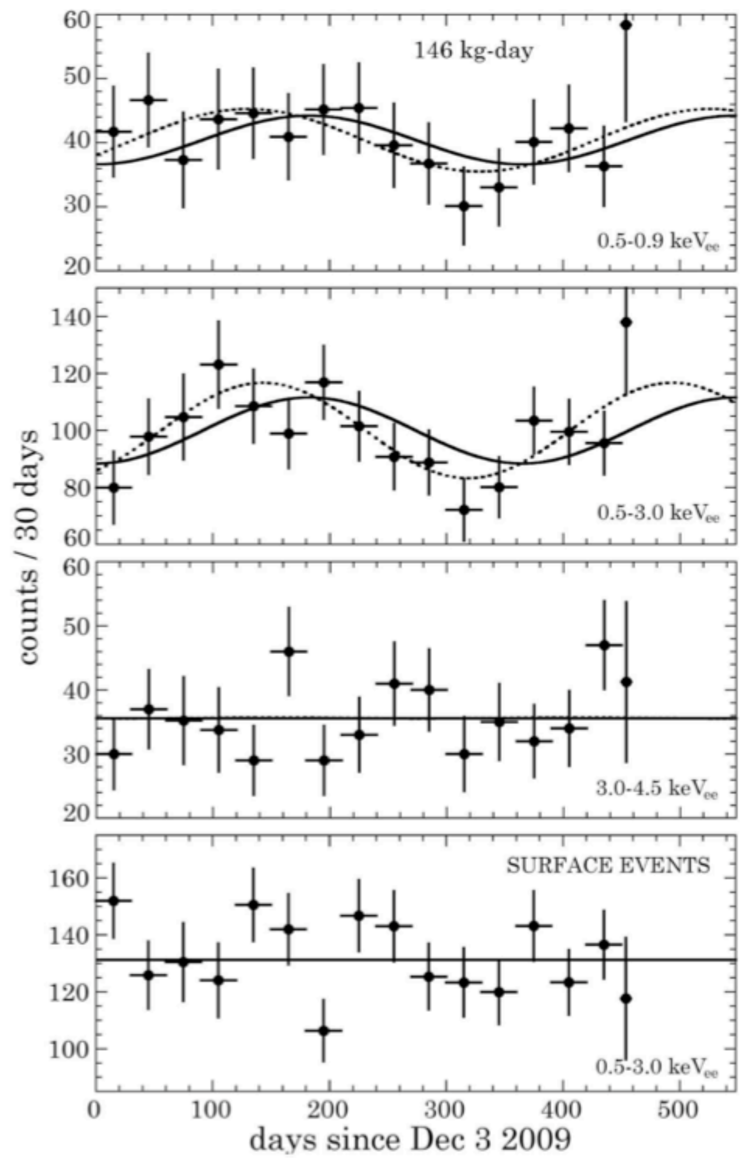
In the first run at Soudan, an exponentially-decaying diff. energy spectrum observed in the lowest energy bins (≲ 1 keVee, or ≲ 4 keVr). The origin is uncertain, but they are able to fit the expected signal from a low-mass WIMP, enclosing a region of parameter space.





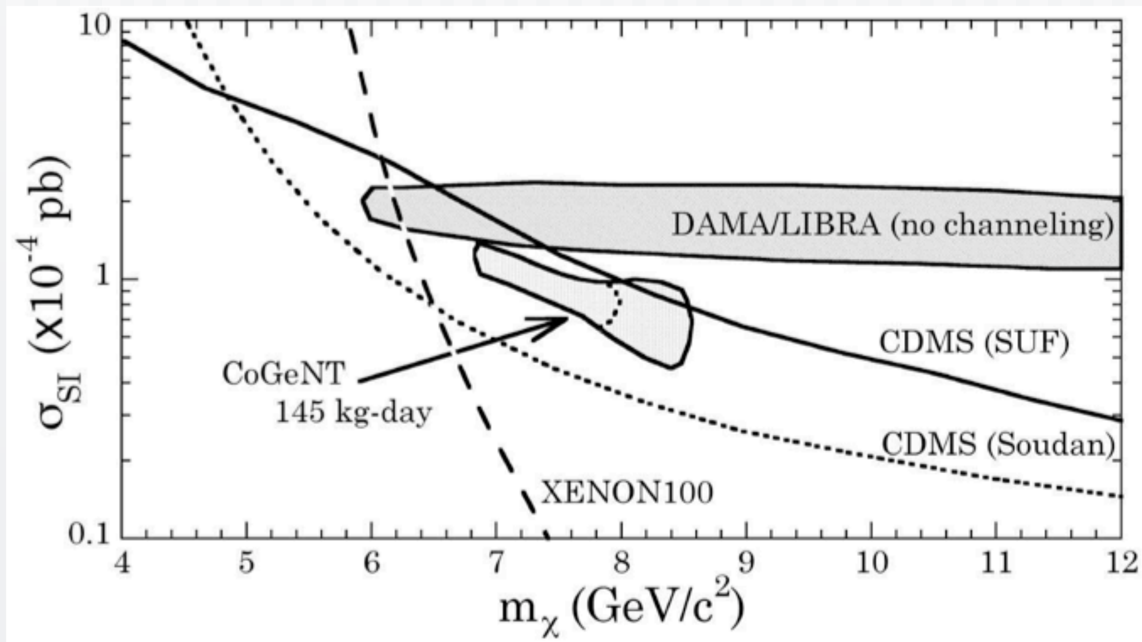
C.E.Aalseth *et al.*, PRL **106**, 131301 (2011)

CoGeNT

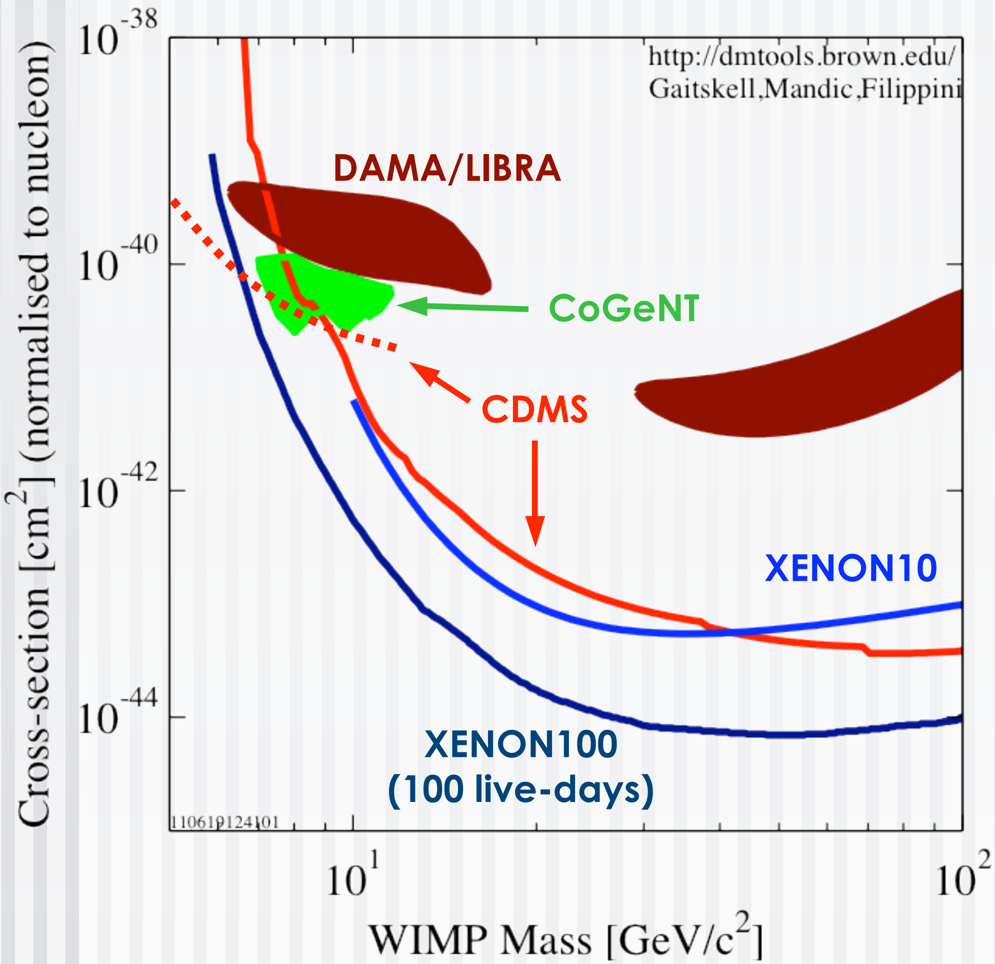


C.E.Aalseth *et al.*, arXiv:1106.0650 [astro-ph.CO]

Recently, they have reported a modulation in the low-energy spectrum, with a phase and period (dashed lines) consistent with those expected by a WIMP signal (solid lines). This leads to a similar signal region as in the last slide:

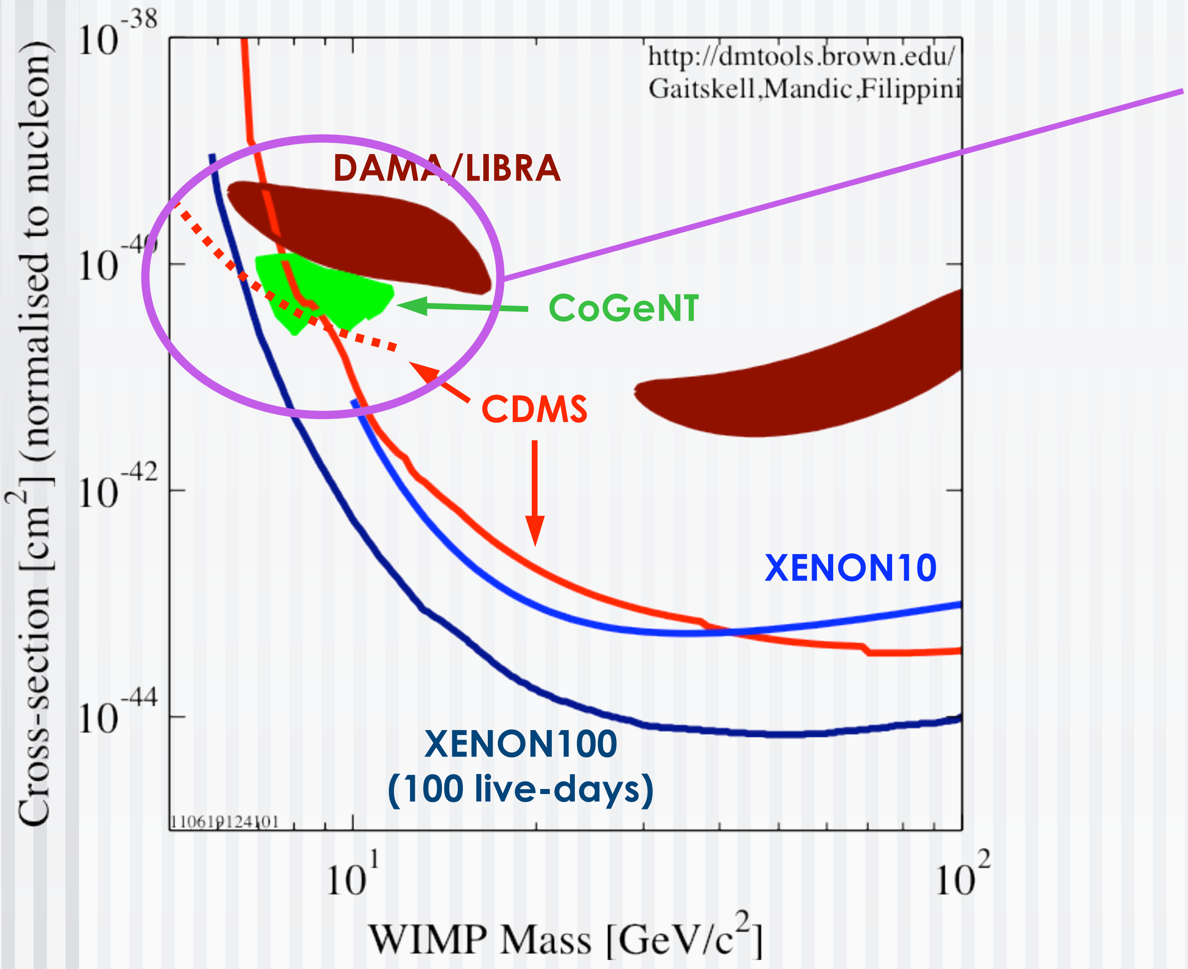


Signals and Limits…



There is a region of this plot that appears to contain quite a bit of activity (also see the CRESST talk and CDMS talk).

Signals and Limits…



There is a region of this plot that appears to contain quite a bit of activity (also see the CRESST talk and CDMS talk).

Not everyone agrees on the robustness of the CDMS and the XENON10/100 limits.

…and not everyone agrees on the credibility of the purported signal detections

…but why did I bother putting XENON10 on this plot??

Isn't XENON10 dead?

(shame on you if you don't get this movie reference)

XENON10 Collaboration

Brown University

Rick Gaitskell, Peter Sorensen, Luiz DeViveiros, Simon Fiorucci

Laboratori Nazionali del Gran Sasso

Francesco Arneodo, Serena Fattori

Case Western Reserve University

Tom Shutt, Alexander Bolozdynya, Pavel Brusov, Eric Dahl, John Kwong

Lawrence Livermore National Laboratory

Adam Bernstein, Norm Madden, Celeste Winant, Chris Hagmann

Rice University

Uwe Oberlack, Roman Gomez, Peter Shagin

Universidade de Coimbra

Jose Matias, Luis Coelho, Luis Fernandes, Joaquim dos Santos, J. Lopes

Yale University

Dan McKinsey, Rick Hasty, Kaixuan Ni , Louis Kastens, Angel Manzur

Columbia University

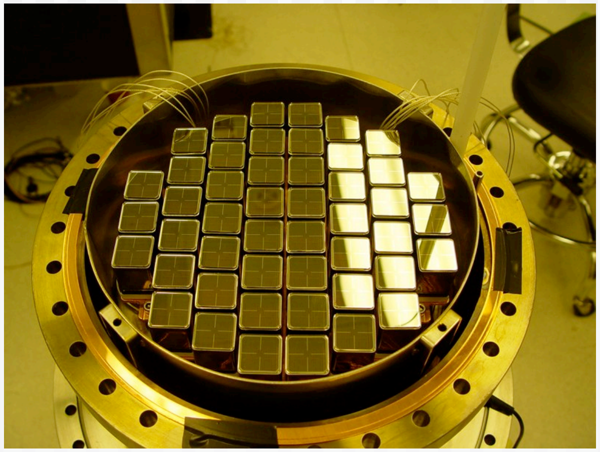
Elena Aprile (P.I.), Karl Giboni, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli, Masaki Yamashita

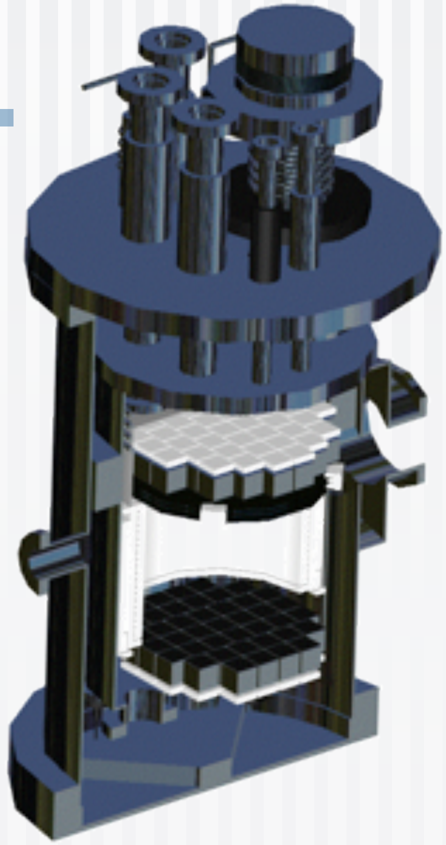
Universität Zürich

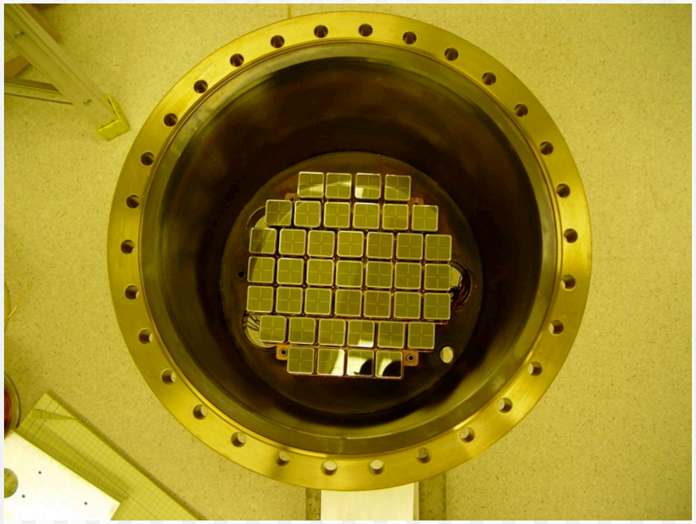
Laura Baudis, Alfredo Ferella, Jesse Angle, Aaron Manalaysay, Joerg Orboeck, Stephan Schulte

XENON10 Detector

- **Dimensions**
  - 22 kg LXe , 15 kg active, 5.4 kg fiducial
  - Cylinder, r = 10 cm, z = 15 cm
- **PMTs**
  - Hamamatsu R8520 Al, 1" x 3.5 cm
  - Bialkali-photocathode Rb-Cs-Sb,
  - Quantum efficiency > 20% for 178 nm
- **Detector Readout**
  - 48 PMTs top, 41 PMTs bottom
  - x-y position from top PMT hit pattern. $\sigma_{x\text{-}y}$ ~ 1 mm
  - z - position from electron drift time. σ_z ~ 0.3 mm
- **Cryogenics**
  - 90W Pulse Tube Refrigerator (PTR) (LN_2 backup for emergencies)
  - Extremely stable T = 180 K at P = 2.2 bar
- **Electric Fields**
  - Drift Field = 730 V/cm (drift), Extraction Field = 12 kV/cm

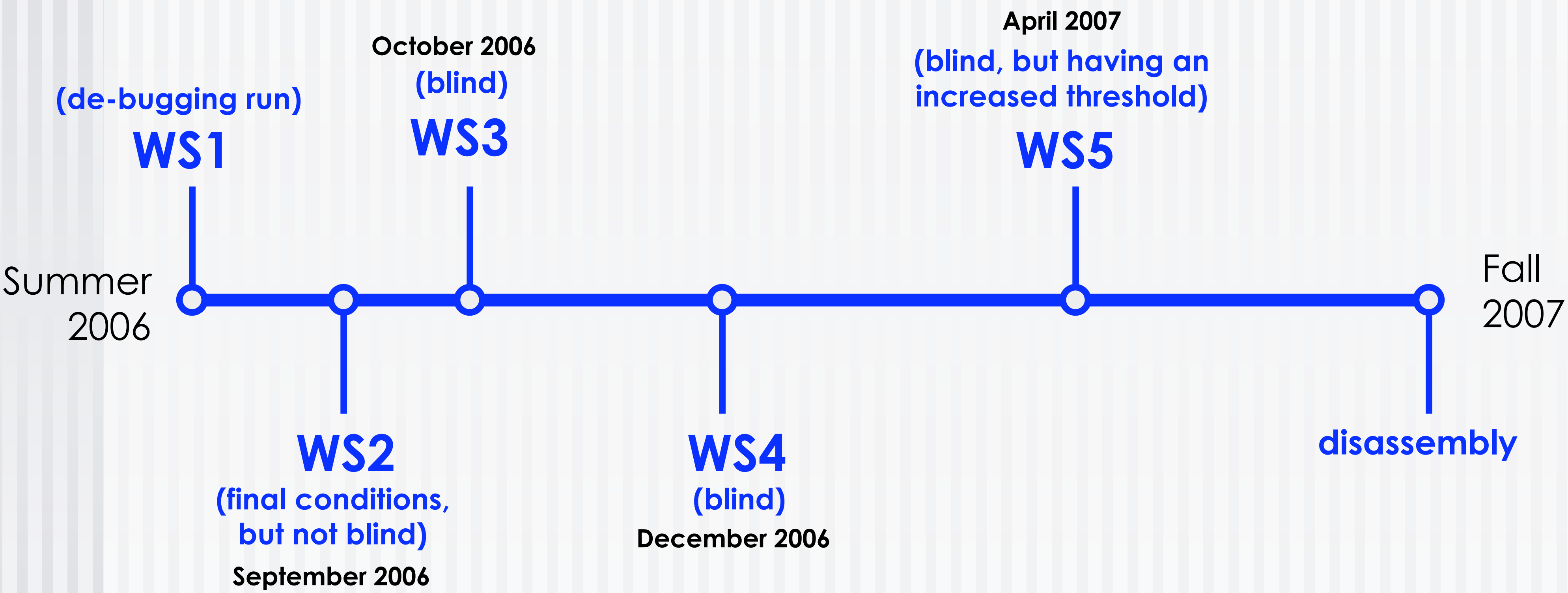




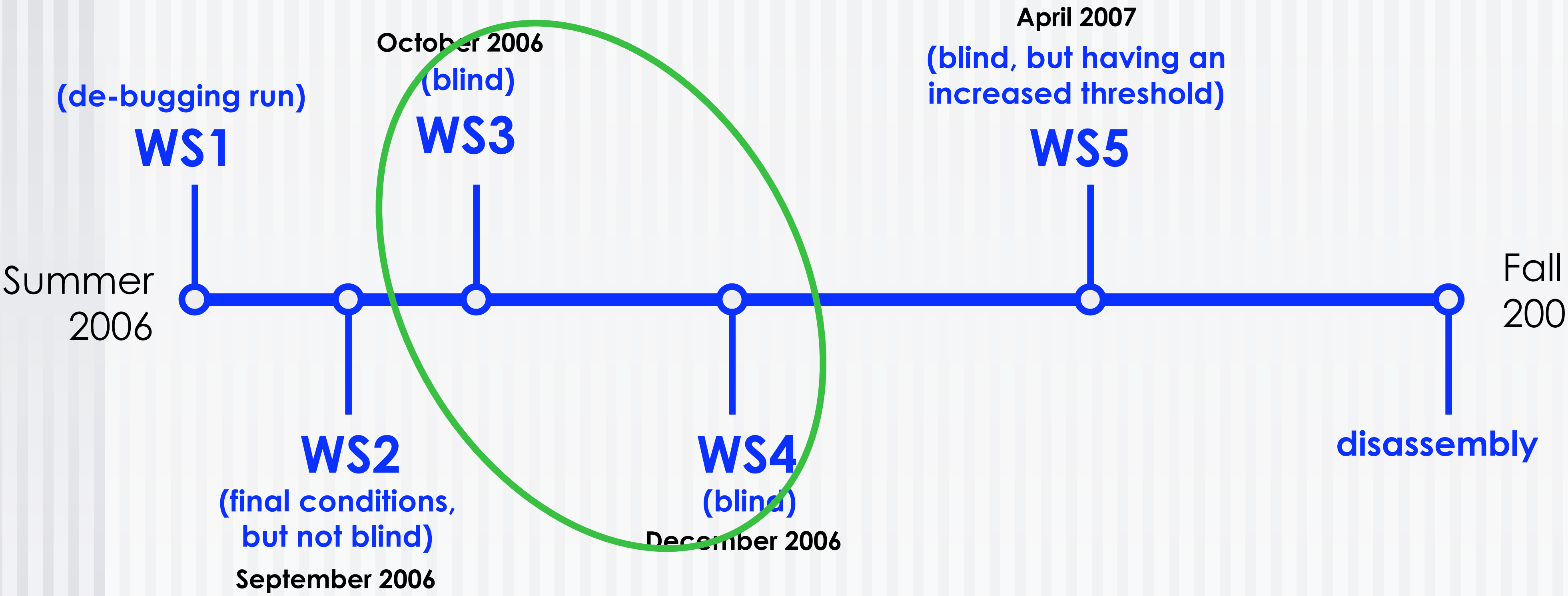


[E.Aprile *et al.*, Astro. Part. Phys. **34** (2011) 679]

Xe10 WIMP search (WS) runs:



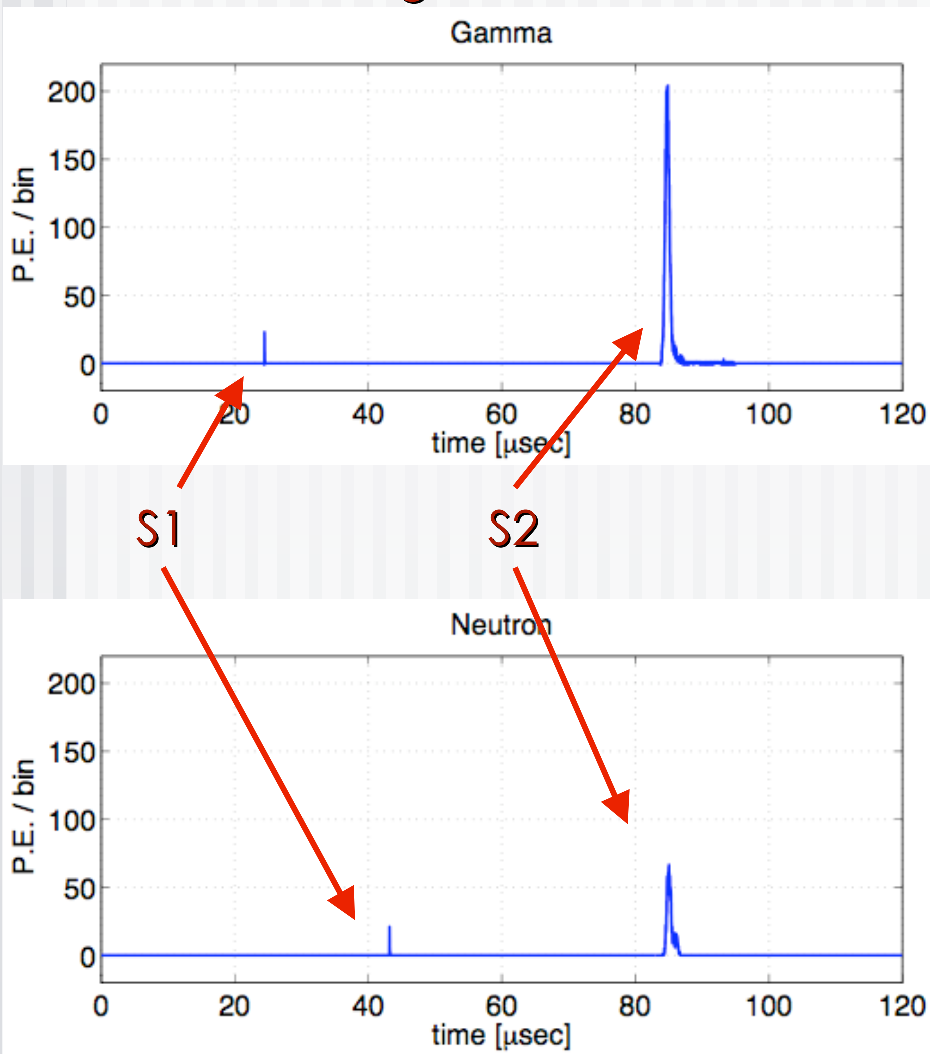
Xe10 WIMP search (WS) runs:

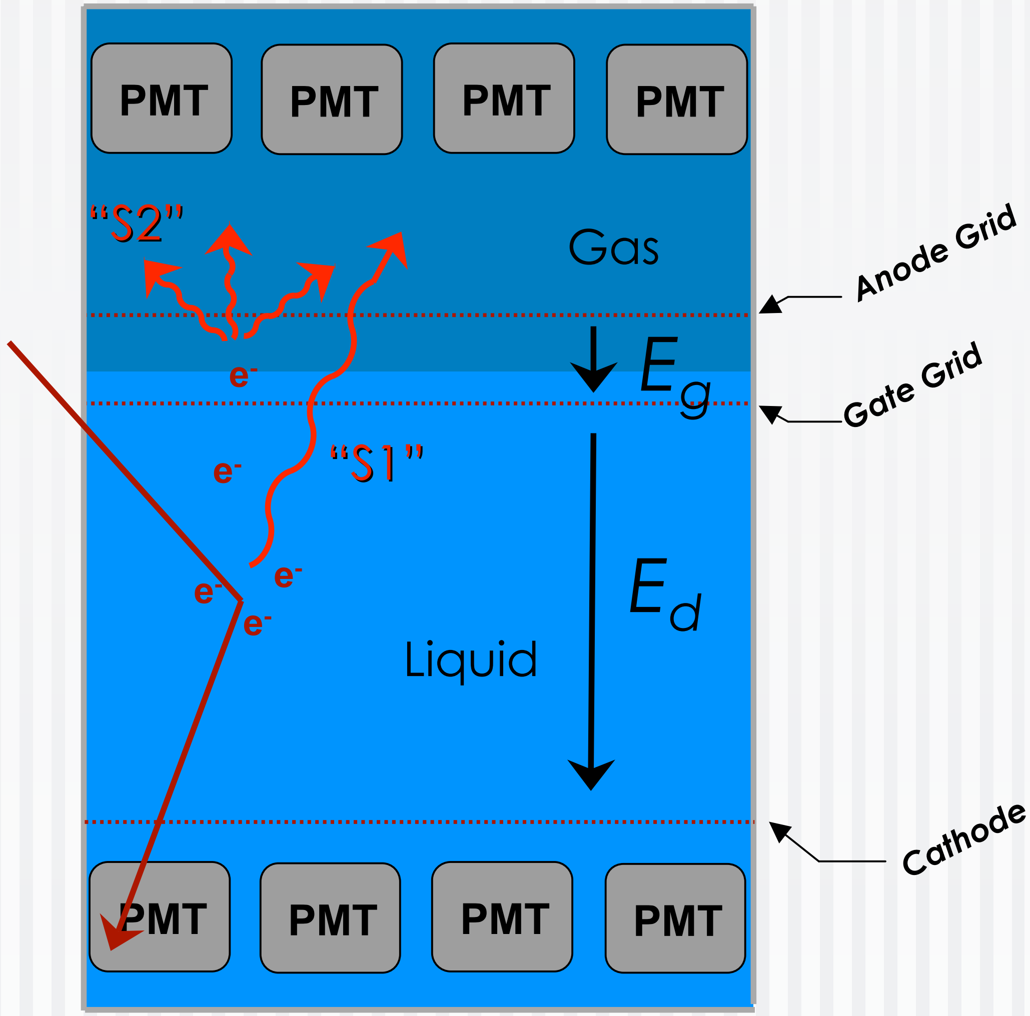


Used in all XENON10 DM publications so far

Detection with a LXe TPC

- "S1" = primary scintillation
- "S2" = ionization signal





Conventional energy reconstruction

This discrepancy causes some tension in the field...

energy of nuclear recoil (NR)

measured signal in p.e.

quenching of scintillation yield for 122 keV γ due to drift field

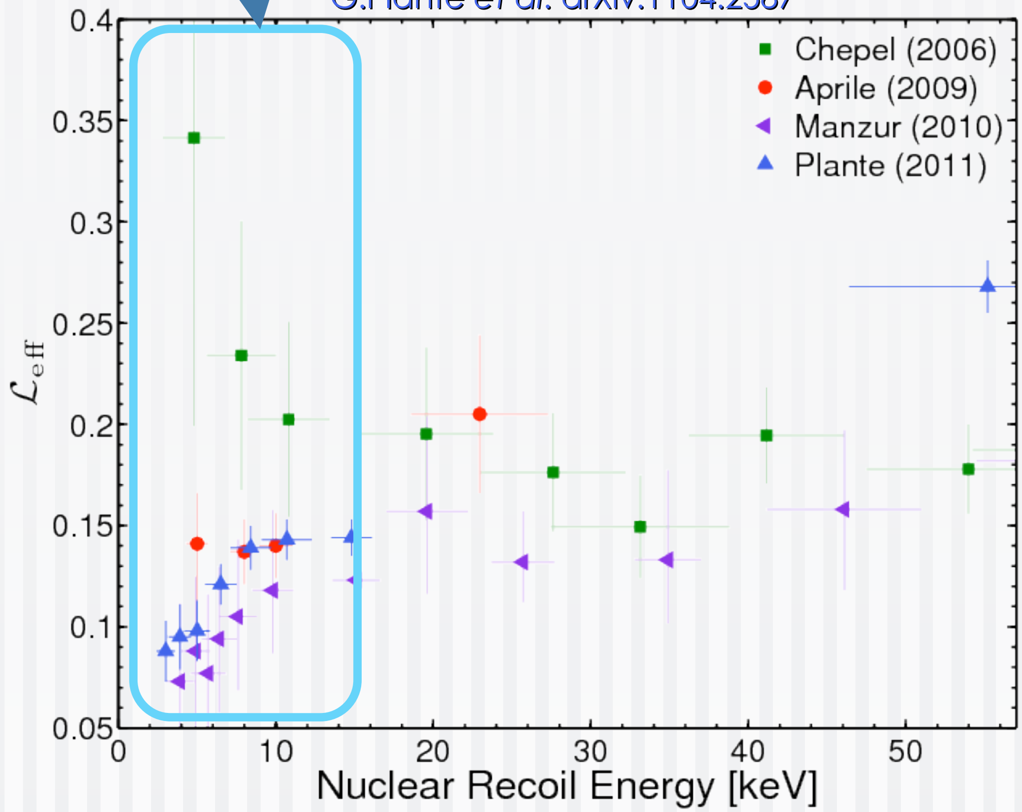
$$E_{\mathrm{nr}} = \frac{S1}{L_y \mathcal{L}_{\mathrm{eff}}} \times \frac{S_{\mathrm{e}}}{S_{\mathrm{nr}}}$$

light yield for 122 keV γ in p.e./keV

relative scintillation efficiency of NR to 122 keV γ at zero field

quenching of scintillation yield for NR due to drift field

V.Chepel *et al*, Astropart.Phys. **26** (2006) 58
E.Aprile *et al*, Phys.Rev.C **79** (2009) 045807
A.Manzur *et al*, Phys.Rev.C **81** (2010) 025808
G.Plante *et al*. arXiv:1104.2587



$\mathcal{L}_{\mathrm{eff}}$ quantifies the nonlinear relationship between the energy of a nuclear recoil and the average number of scintillation photons it produces.

see A.Manalaysay, arXiv:1007.3746 [astro-ph.IM]

What if we want to avoid the debate over $\mathcal{L}_{eff}$?

Another energy reconstruction

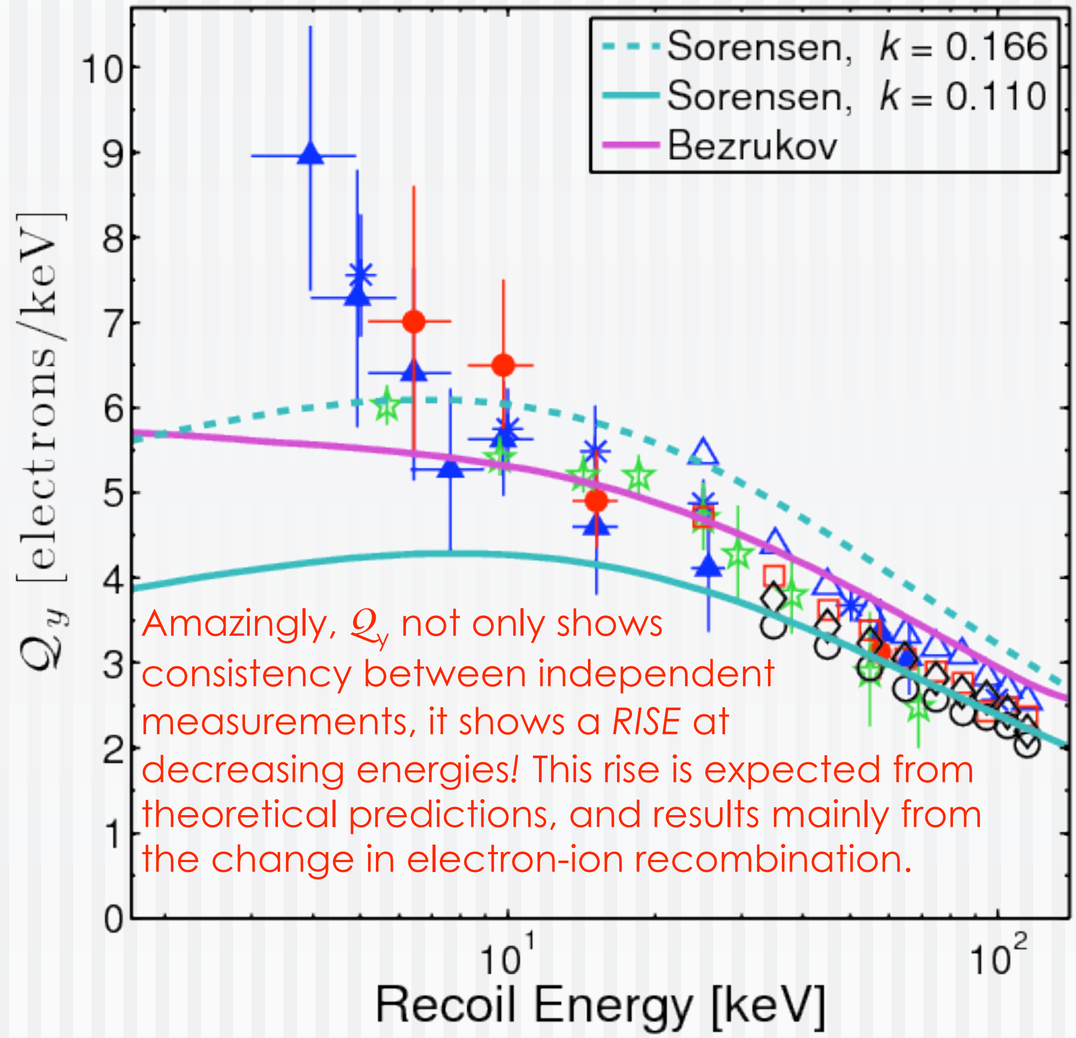
charge signal, in PE

energy of nuclear recoil (NR)

$$E_{\mathrm{nr}} = \frac{S2}{G_g \, \mathcal{Q}_y}$$

gas gain, in PE/e⁻

LXe NR charge yield, in e⁻/keV
(field and energy dependent)



The conversions for S1 and S2 are roughly:

- ~0.1 *S1* PE per scintillation photon
- ~27 *S2* PE per ionization electron

See IDM2010 proceedings by P.Sorensen:
PoS (IDM2010)017 (2010), arXiv:1011.6439

P.Sorensen and C.E.Dahl, Phys.Rev.**D83** (2011) 063501
(Lindhard, Thomas-Fermi, Thomas-Imel)

F.Bezrukov *et al.*, arXiv:1011.3990 (acc. to Astro.Part.Phys)
(Lindhard, Ziegler, Thomas-Imel)

Consequences of using S2 only

For very low recoil energies, we often observe no S1, so we have to give up this handle.

Giving up on S1, we lose:

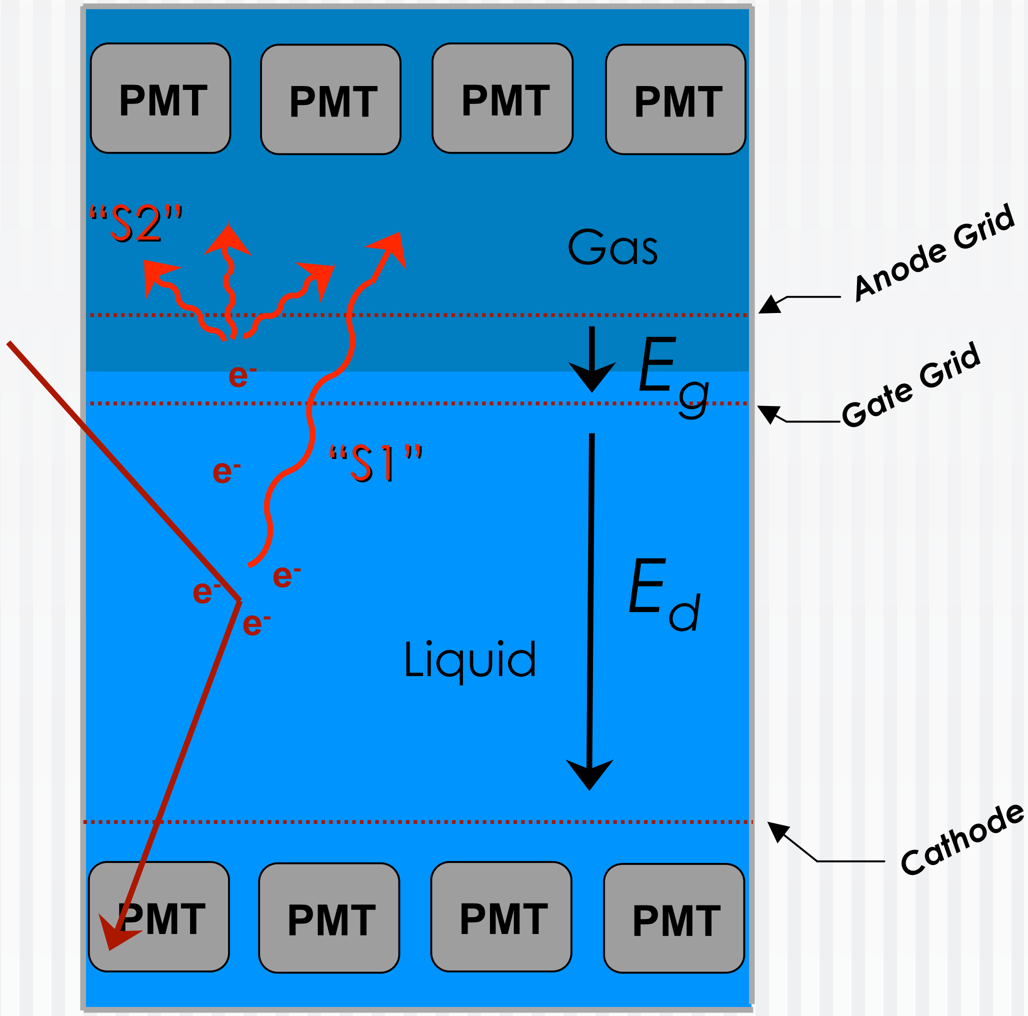
- z-position*
- n-γ discrimination

But we still have:

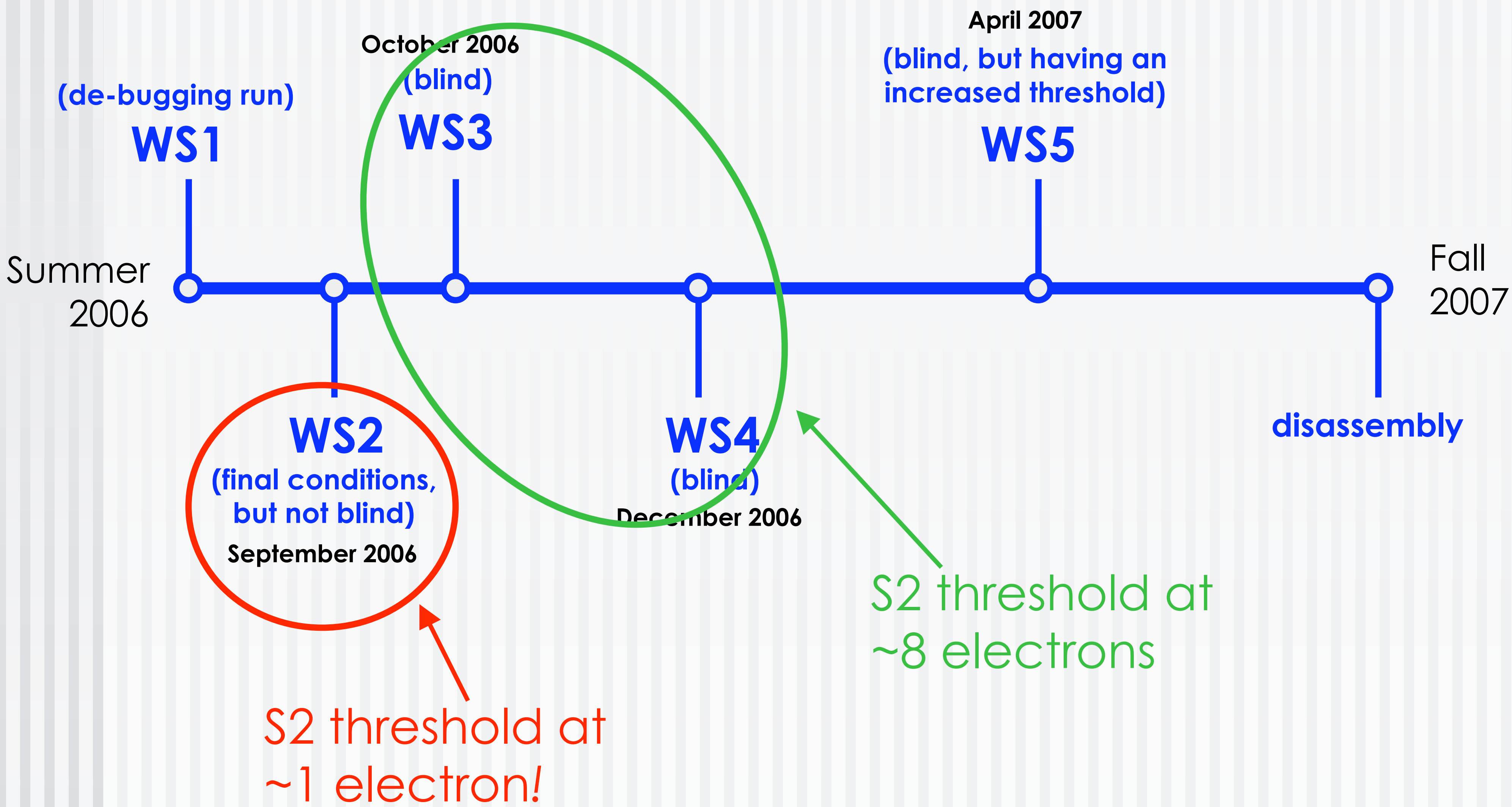
- x,y - position

So we make a very tight (r < 3 cm) fiducial cut.

But we can get some z-pos from the S2 width

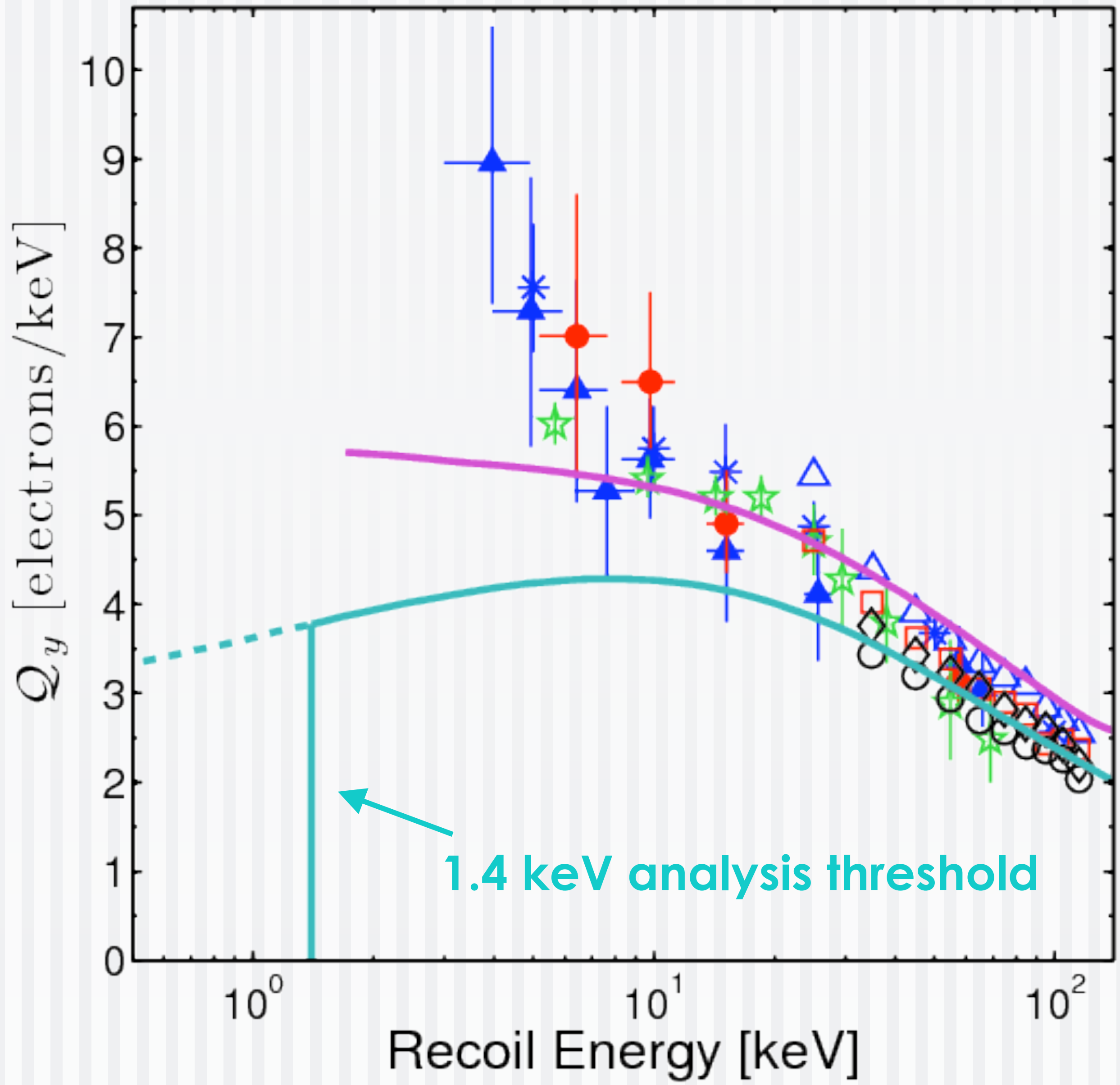


Trigger thresholds



Energy scale

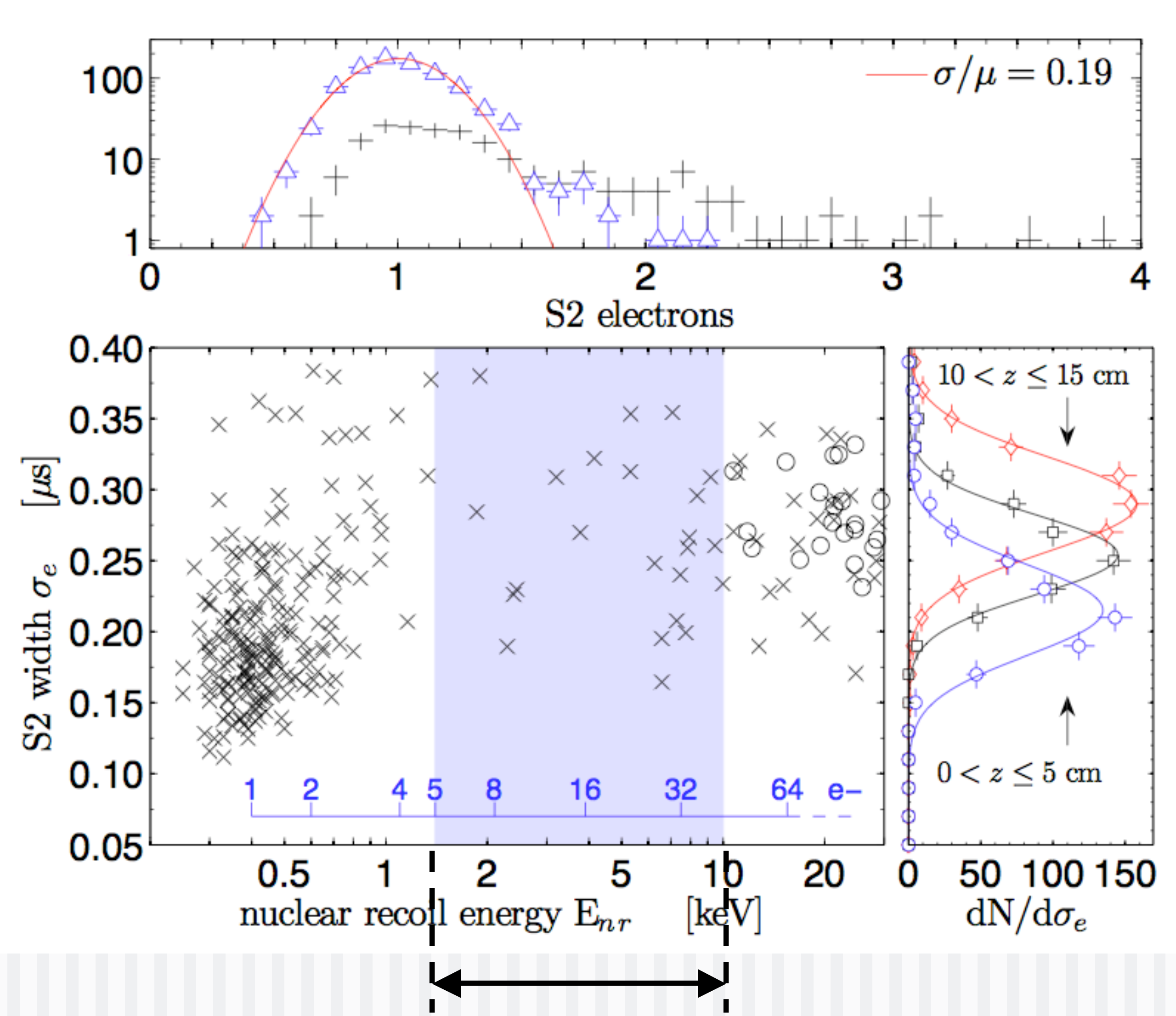
The Lindhard quenching model, combined with Thomas-Imel recombination, gives a set of theoretical predictions with a free parameter *k*. We choose a conservative *k* = 0.110, which just barely matches the measurements. Additionally we impose an artificial cutoff at 1.4 keV, which is our analysis threshold. This conservative (and unphysical) choice prevents events from below threshold to fluctuate upwards into our signal region.



WS2 results

- 1.2 kg fiducial (full z-active region, r<3cm
- 12.5 live days
- 1.4 keV threshold (5 electrons)

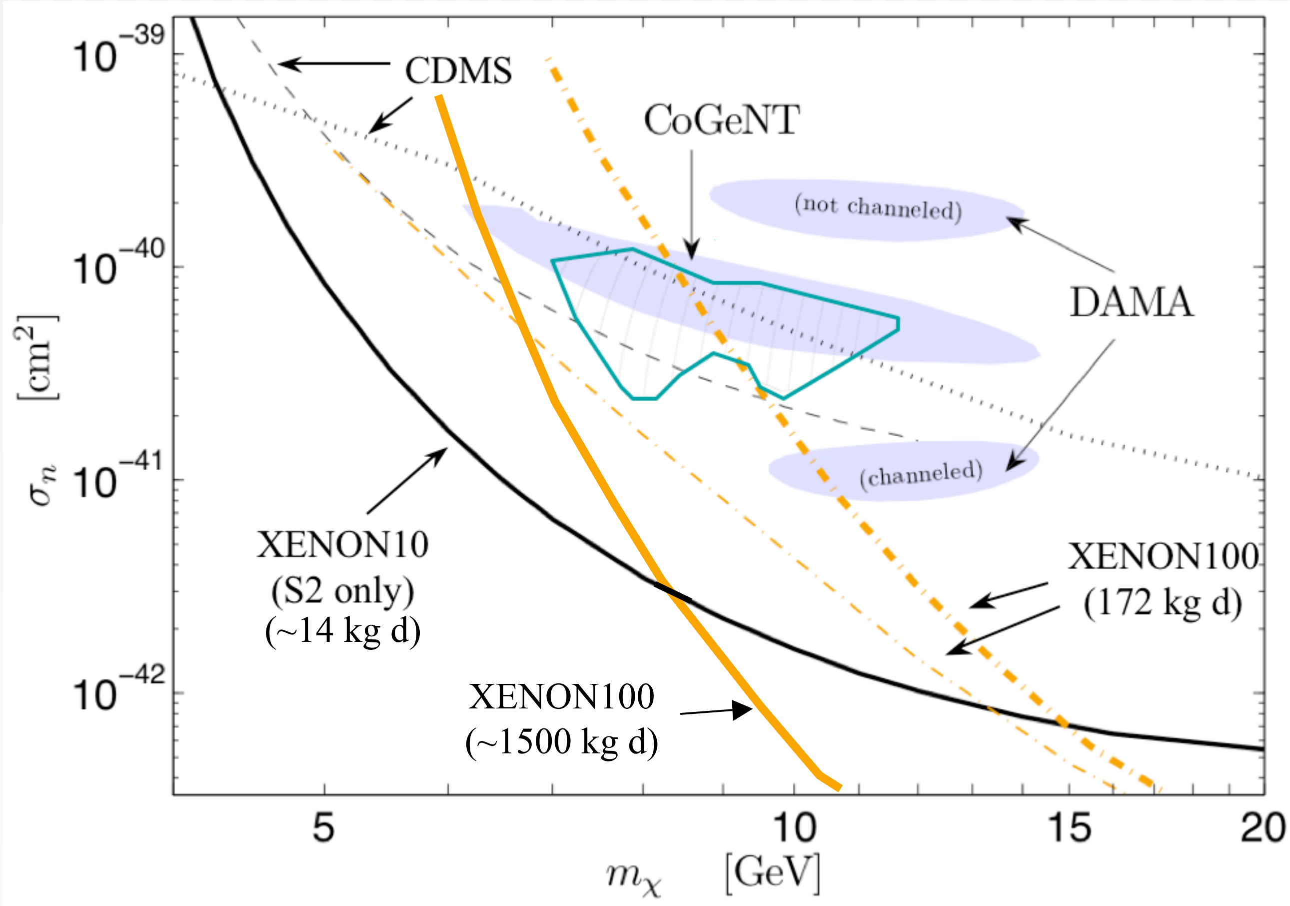
J.Angle *et al.*, arXiv:1104.3088 (accepted to PRL)



Signal window (1.4 -10 keVr)

WS2 results

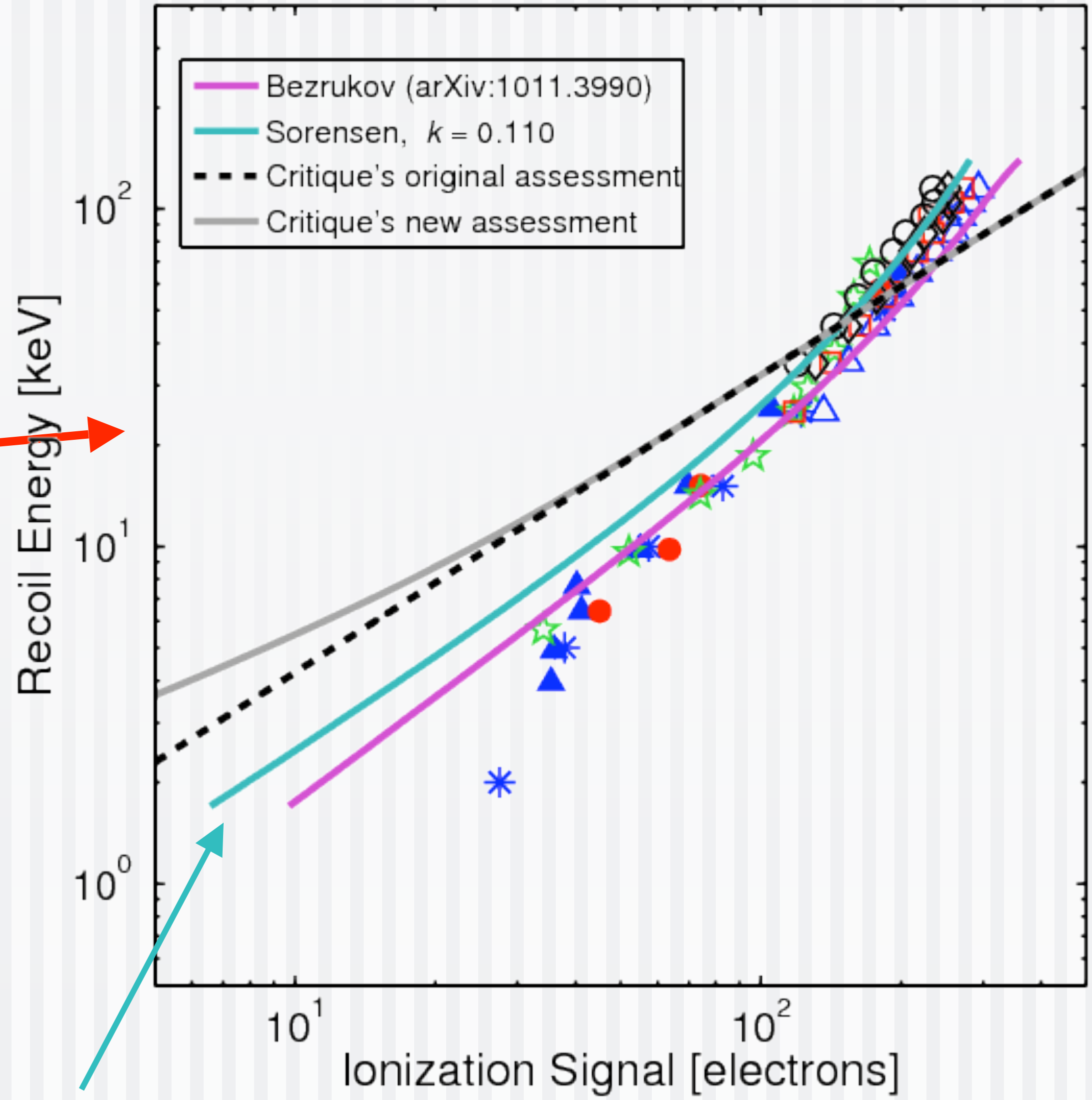
Using the optimum interval method from Yellin, we robustly exclude the CoGeNT region by more than an order of magnitude, with no dependence on $\mathcal{L}_{\mathrm{eff}}$. Is competitive to 1.5 tonne-days of Xe100 exposure using the traditional energy reconstruction.



J.Angle *et al.*, arXiv:1104.3088 (accepted to PRL)

Criticism of this limit…

The only way to get around the robustness of this limit is to play with $\mathcal{L}_y$, which has been done in arXiv:1010.5187 and arXiv:1106.0653. In these critiques, the charge-to-energy relationship is shown in this manner:



But this is a bit awkward and zoomed-out. How do these suggested alternative scales look like in the more conventional parameter space of $\mathcal{L}_y$ vs Energy?

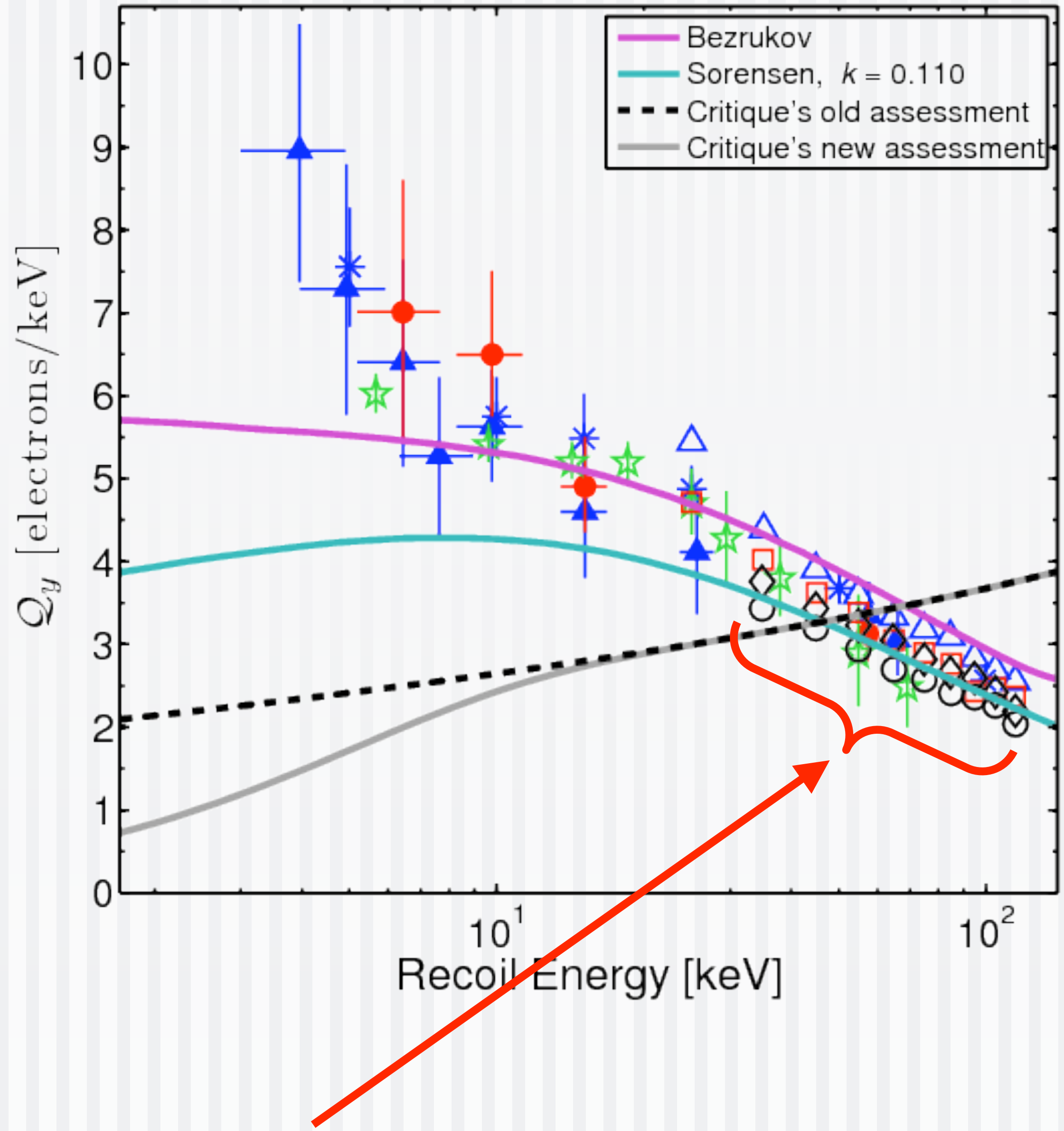
We used:

Criticism of this limit…

… i.e. nowhere near the data. The author of these criticisms says that these expectations are based on "the formalism of [1]". But the data points from [1] are the open markers in the facing plot.

It turns out that this critiquer made a mistake in his calculation by using only Lindhard, and forgetting to include two quantities that change with energy:

- Electron-ion recombination fraction
- Exciton-to-ion ratio

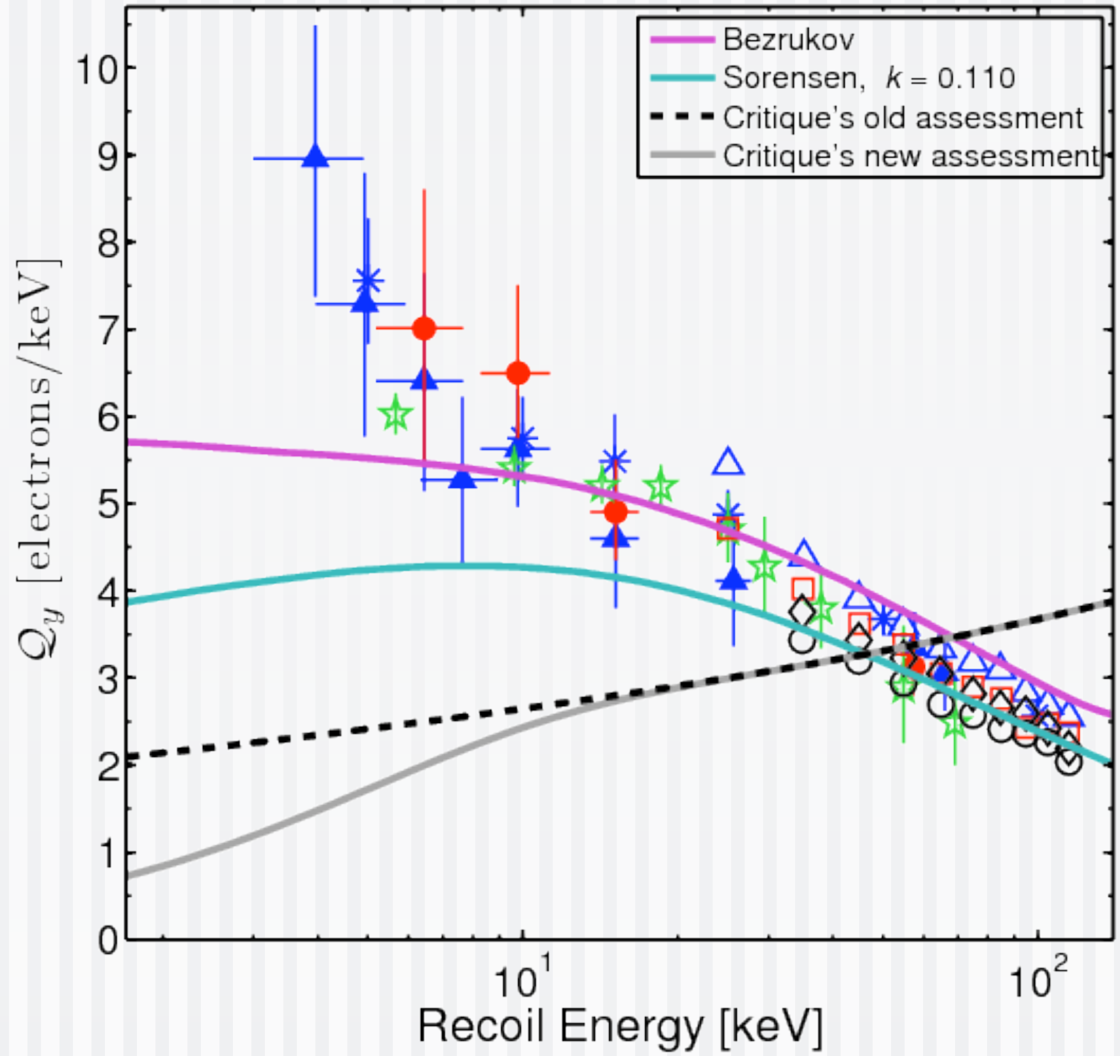


[1] E.Aprile *et al.*, PRL **97**, 081302 (2006)

Criticism of this limit…

In other words, the exclusion of the CoGeNT signal can only be avoided by adopting a $\mathcal{Q}_y$ that is completely contradictory to all measurements and theoretical expectations. So we can be quite certain that this limit is robust.

Therefore, given the combined exclusion limits of CDMS, XENON100, and especially this new XENON10 result, it becomes difficult to understand the CoGeNT and DAMA signals as being due to nuclear recoils from low-mass WIMPs.



So what *IS* behind the DAMA and CoGeNT observations?

Should we not first exhaust possible mundane explanations before invoking new physics?

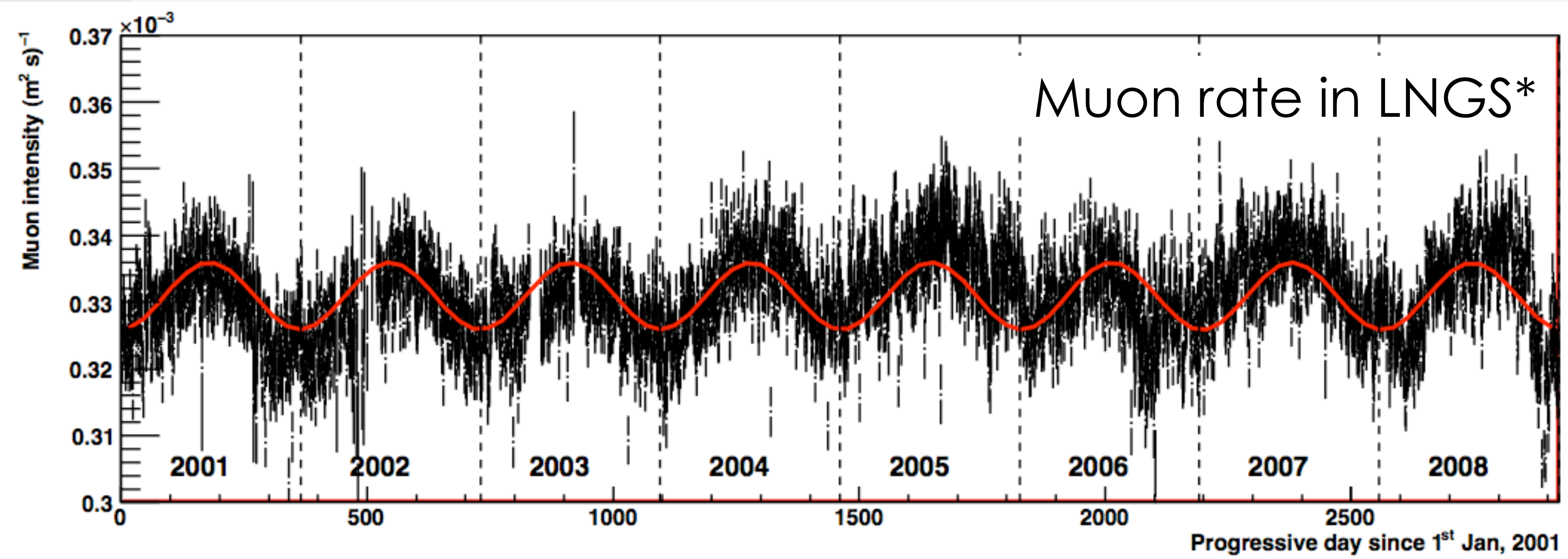
So what *IS* behind the DAMA and CoGeNT observations?

Should we not first exhaust possible mundane explanations before invoking new physics?

> Enticing as it is to contemplate cosmological implications from unexpected low-energy spectral features, our focus must remain on finding less exotic explanations. One

DAMA

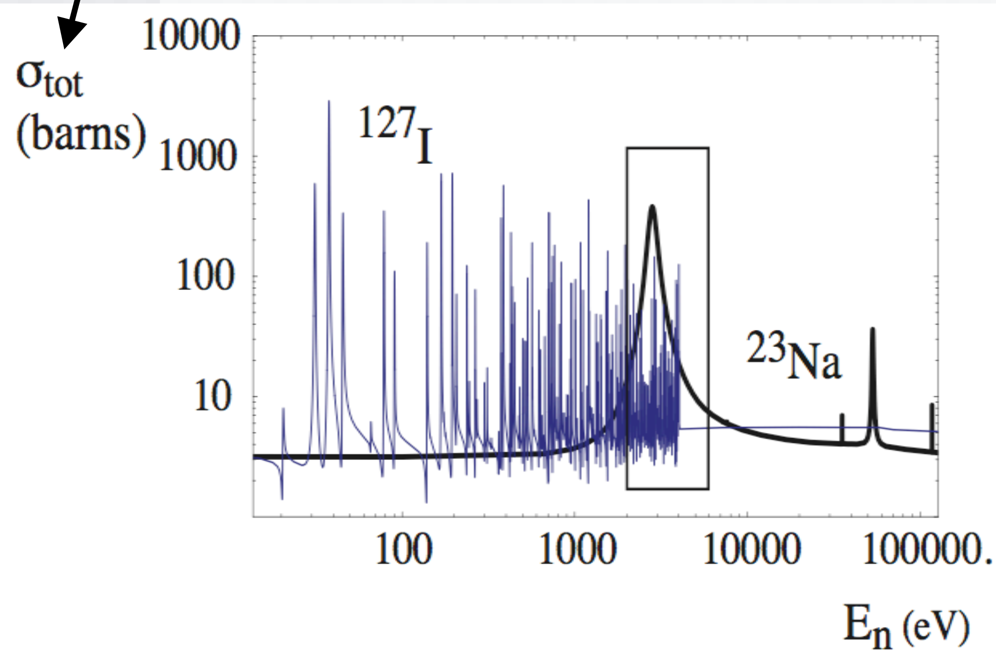
David Nygren has pointed out [arXiv:1102.0815] that the muon rate measured at LNGS fluctuates annually (same period and phase as DAMA), and provides an explanation on how muons can produce delayed low-energy scintillation pulses, possibly mimicking a WIMP signal.

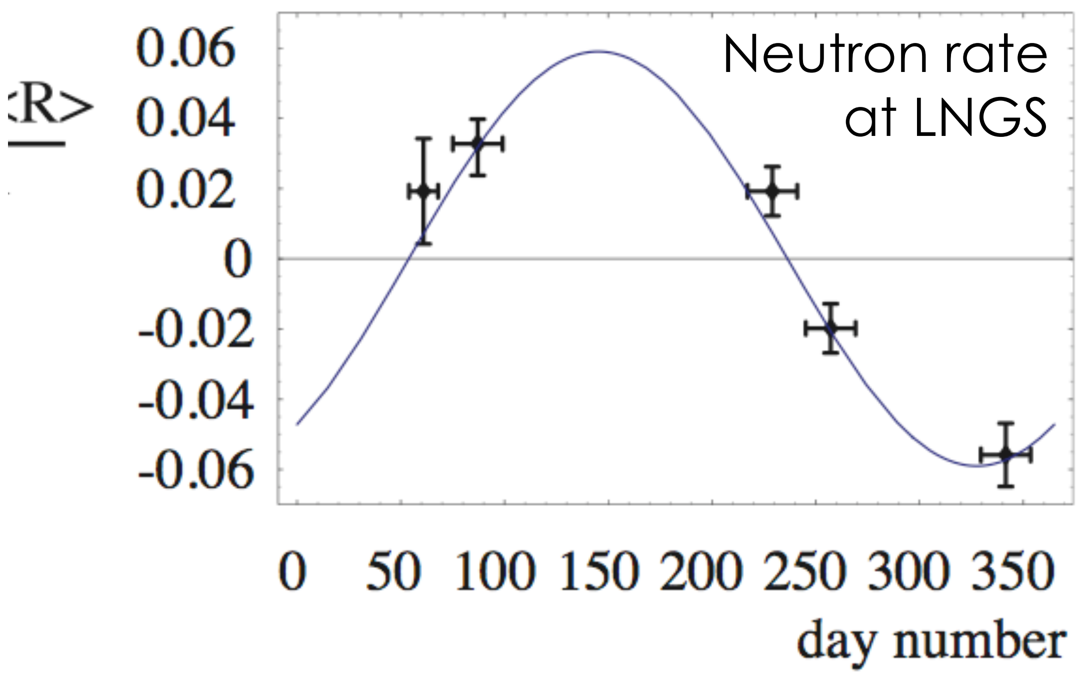


* M.Selvi et al., Proc. 31st ICRC, **ŁÓDŹ** 2009

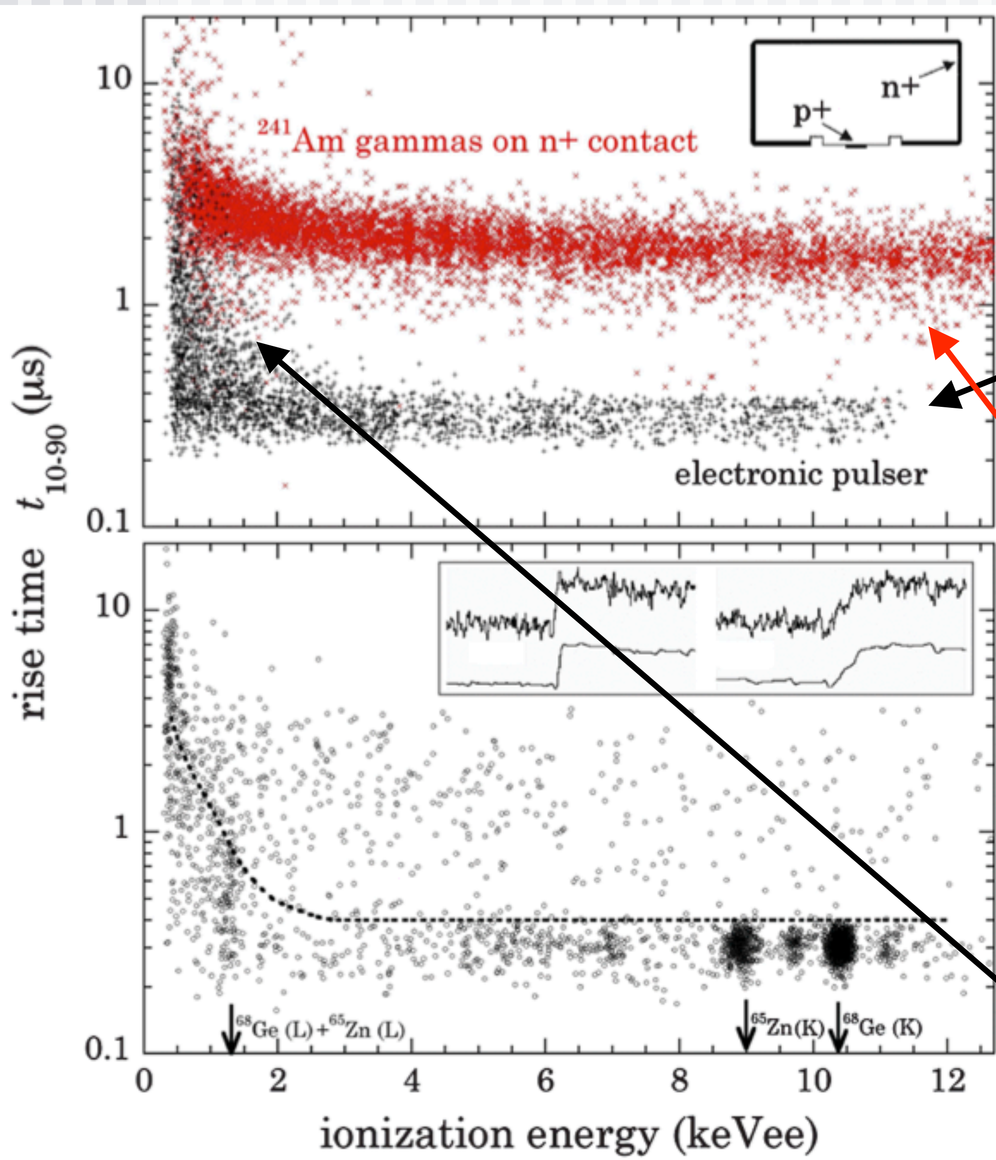
DAMA

John Ralston has pointed out [arXiv:1006.5255] that the *resonant* neutron cross section in sodium has a peak at the exact same energy as the DAMA signal, and indeed the neutron rate in LNGS has been measured (by ICARUS) to modulate with the correct period and phase.





CoGeNT



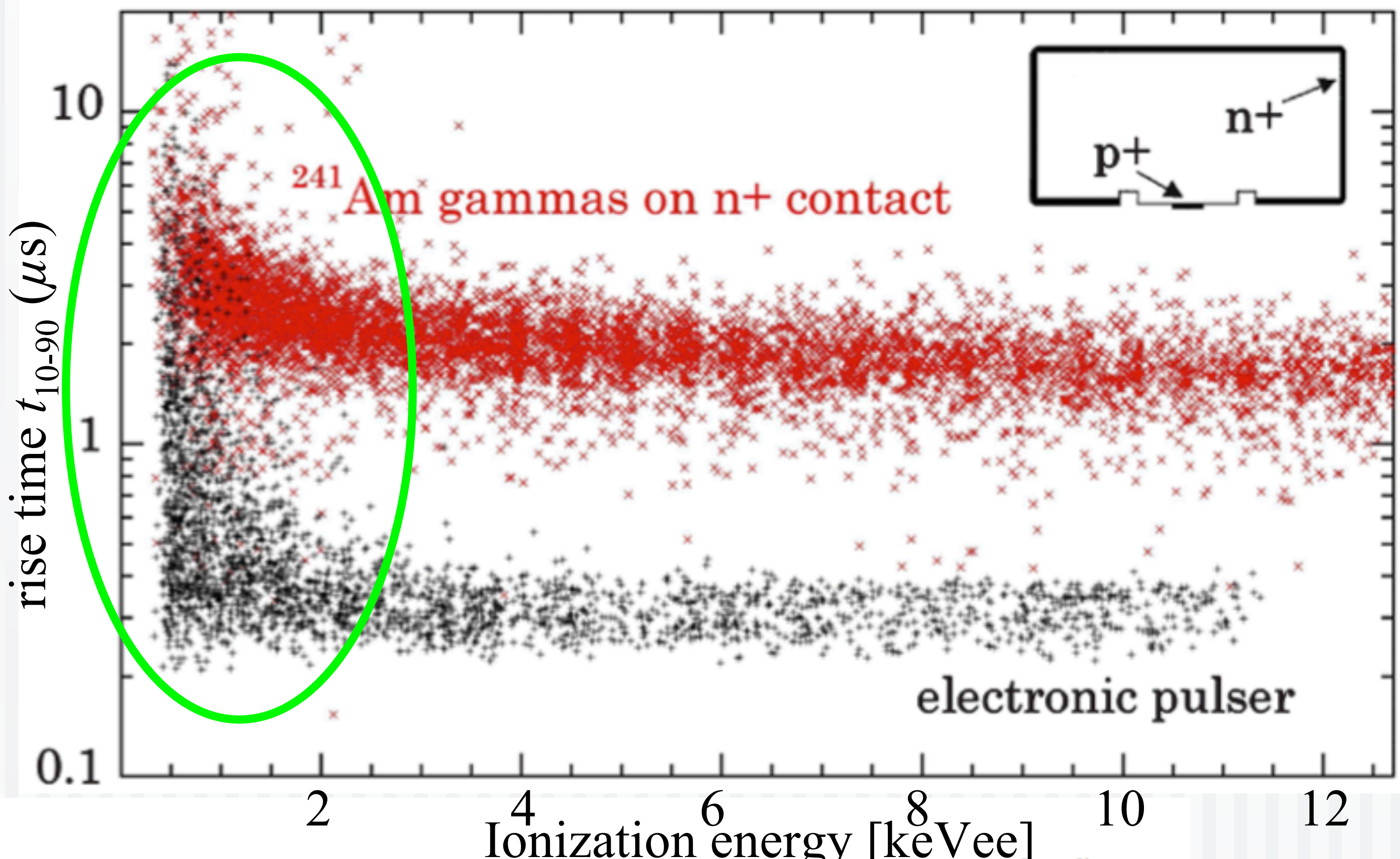
C.E.Aalseth *et al.*, PRL **106**, 131301 (2011)

Some important things to keep in mind regarding the experimental details:

- Signal acceptance region defined on electronic pulser data (not on physical data).
- Surface background calibration run with ^{241}Am performed with a different detector (from a different factory even) than the one used in the WIMP search.
- Bands overlap for energies below ~1.5 keVee

What happens with surface events at low energies?

The band of surface events appears to leak into the signal region gradually below ~2 or ~1.5 keVee



PRL 106, 131301 (2011) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2011

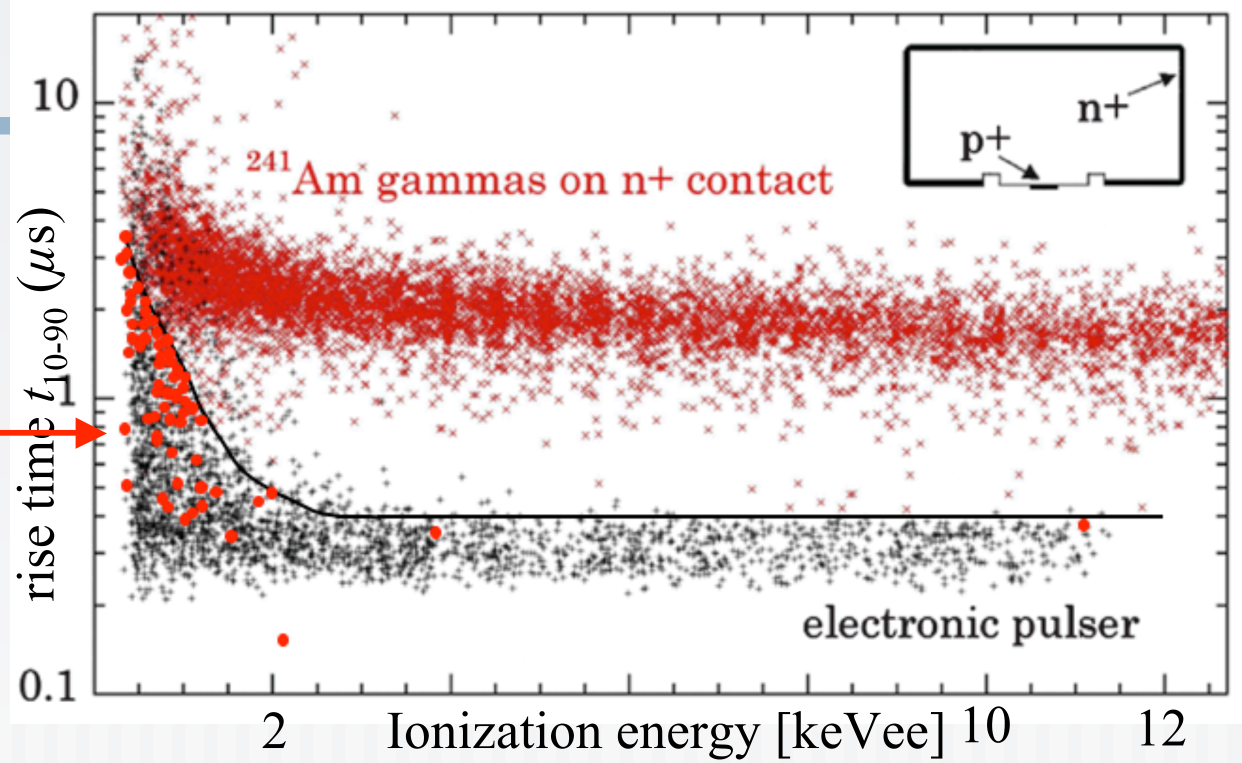
events closer to threshold. A comparison with the distribution of ^{241}Am surface events [Fig. 2] indicates that any such contamination should be modest.

2–3 reduction in background. This residual spectrum is dominated by events in the bulk of the crystal, like those

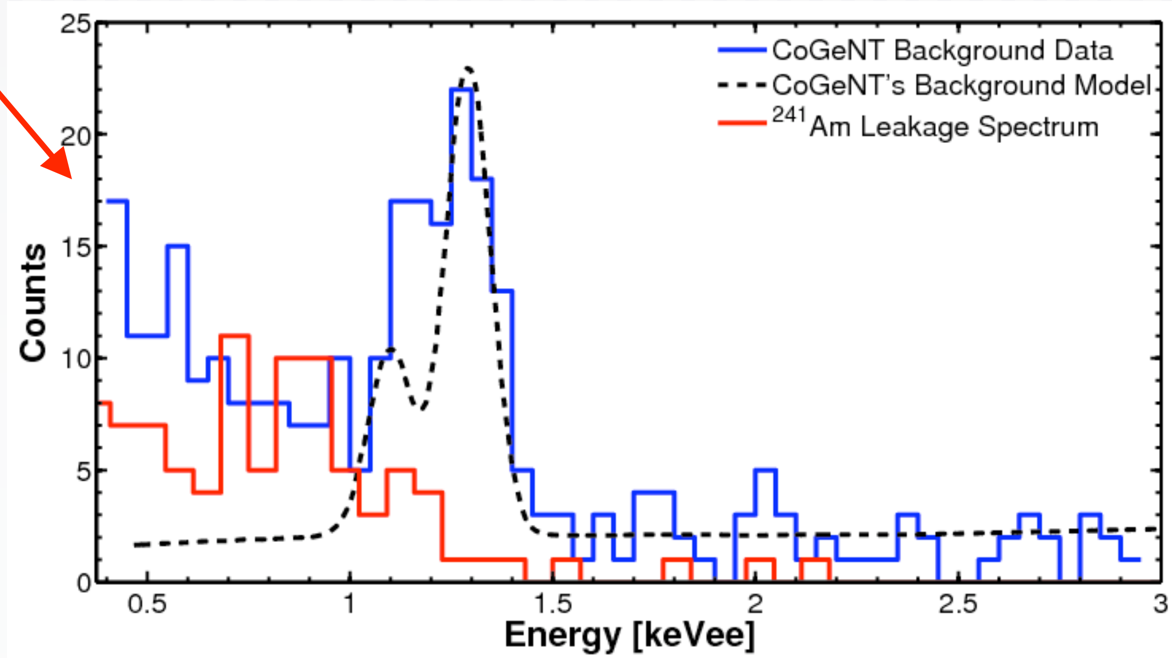
...ility of some residual ...on towards threshold ... background possibly ...ities from cosmogen- ...xpected to contribute <10% of the 0.5–0.9 keVee rate (their L-shell to K-shell EC ratio is ~11% [4]). Another possibility, discussed

CoGeNT

As an exercise, I have zoomed in with a magnifying glass and put a red dot over every ^{241}Am event that is leaking below the signal acceptance line.



The spectrum of these leaking events is in red, and doesn't seem to support their background model.



Keep in mind, I have picked out these data points by eye, so this spectrum is **only a qualitative assessment**, but it indicates an increasing degradation of surface rejection starting at ~1.3 keV and below.

Summary

- DAMA, CoGeNT, CRESST have observed anomalous signals that can be interpreted as nuclear recoils from low-mass galactic WIMPs.
- These interpretations have been excluded by a number of experiments, most robustly by a new XENON10 analysis using the charge signal only.
- There remain a number of possible mundane explanations for the DAMA and CoGeNT observations. Our priority as a community should be to focus on these possibilities before we invoke new physics, regardless of how tempting it is to jump beyond the Standard Model.

Thanks for your attention!

Fin.