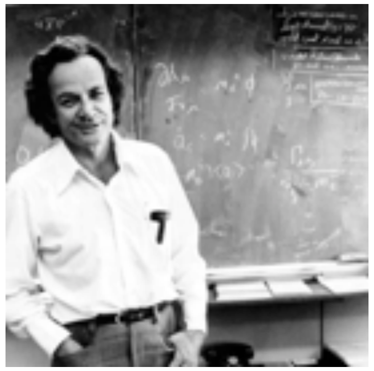
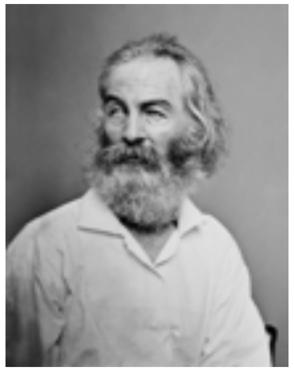
Peter Sorensen
LLNL

9 April 2013

When I heard the learn'd astronomer,
When the proofs, the figures, were ranged in columns before me,
When I was shown the charts and diagrams, to add, divide, and measure them,
When I sitting heard the astronomer where he lectured with much applause in the lecture-room,
How soon unaccountable I became tired, and sick,
Till rising and gliding out I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

Walt Whitman, 1865



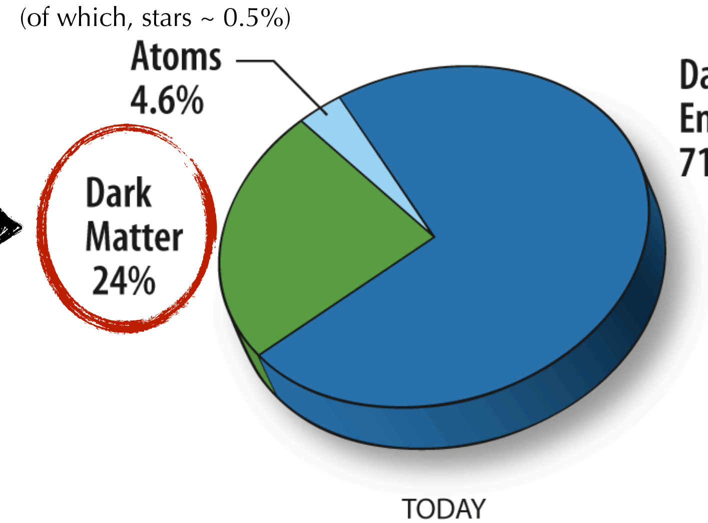


Poets say science takes away from the beauty of the stars - mere globs of gas atoms.
I too can see the stars on a desert night, and feel them. But do I see less or more? ...
It does not do harm to the mystery to know a little about it.

Richard Feynman, circa 1960

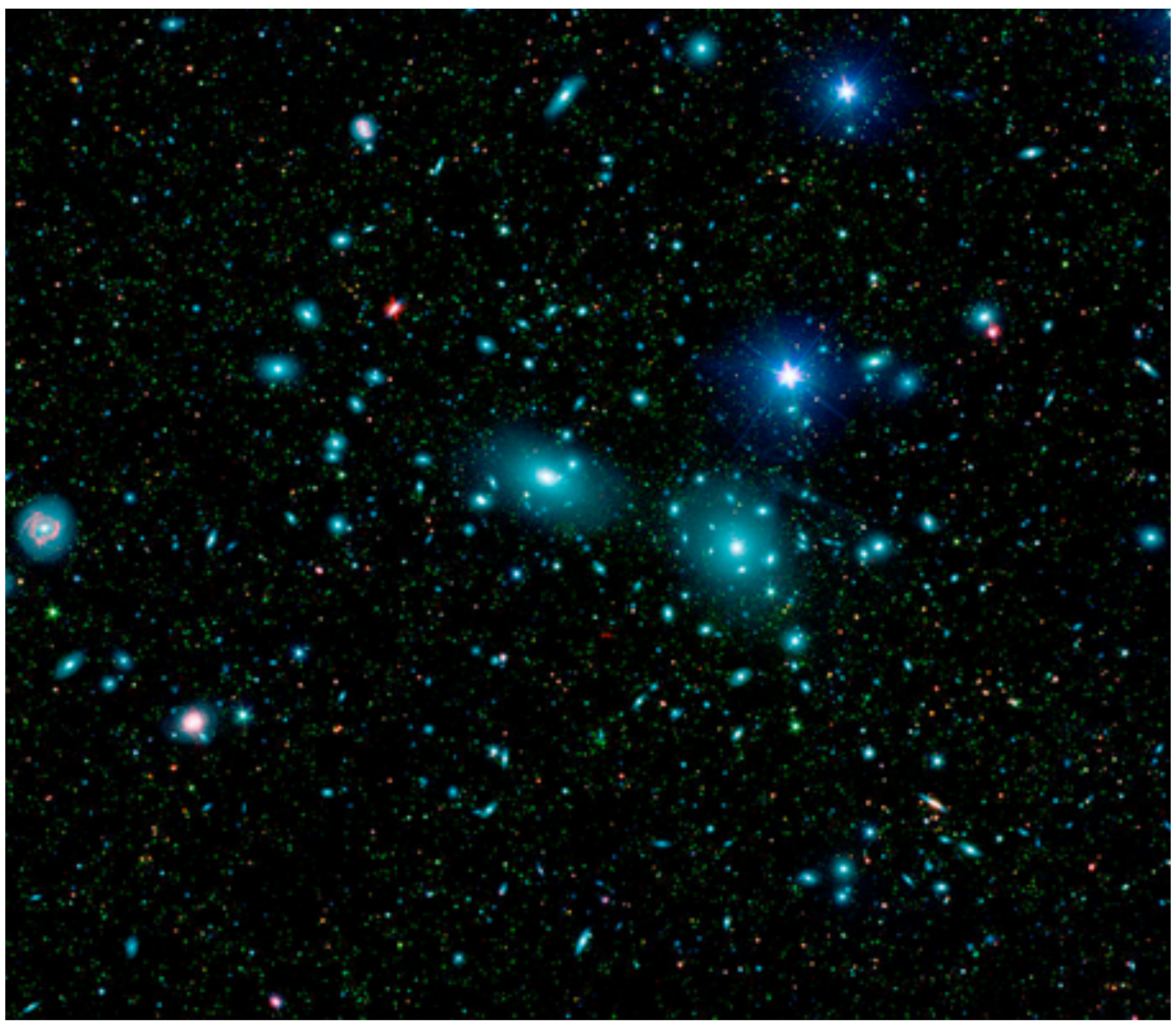
Most of the mass in the universe is dark

focus of this seminar



The matter budget of the universe (WMAP)

NASA/JPL-Caltech/GSFC/SDSS



from velocity dispersion measurements of the Coma Cluster, c. 1933, F. Zwicky concluded that stars account for <1% of the mass..!

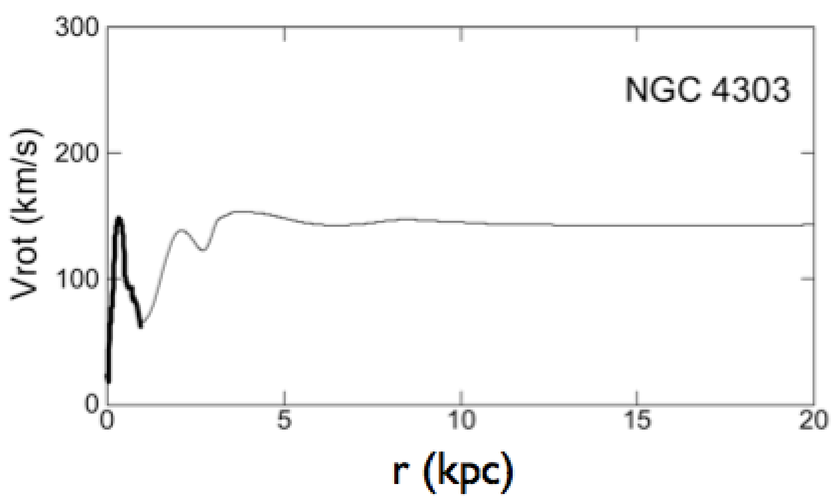
he suggested we should *"throw some light on the problem of the density of internebular matter in clusters."*

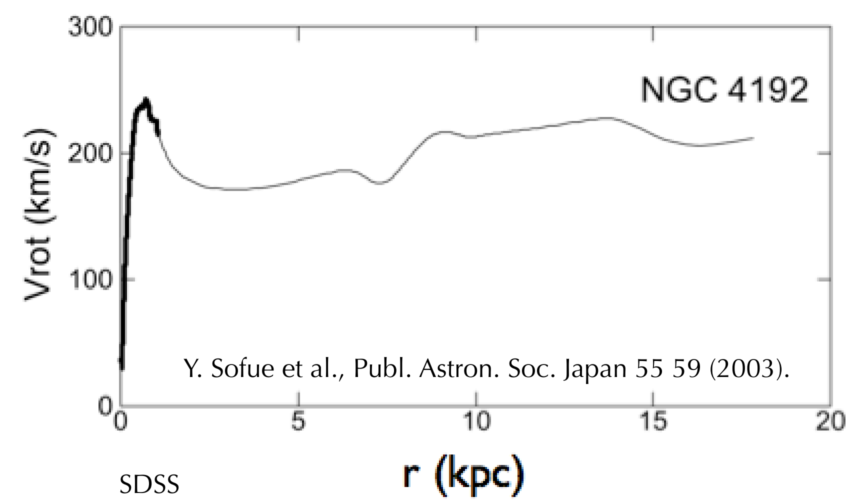
he suggested using gravitational lensing.

Radioastronomy weighed in first, on a galactic scale: rotation curves

from classical dynamics, one expects: $v_{rot}(r) = \sqrt{\frac{GM(r)}{r}}$

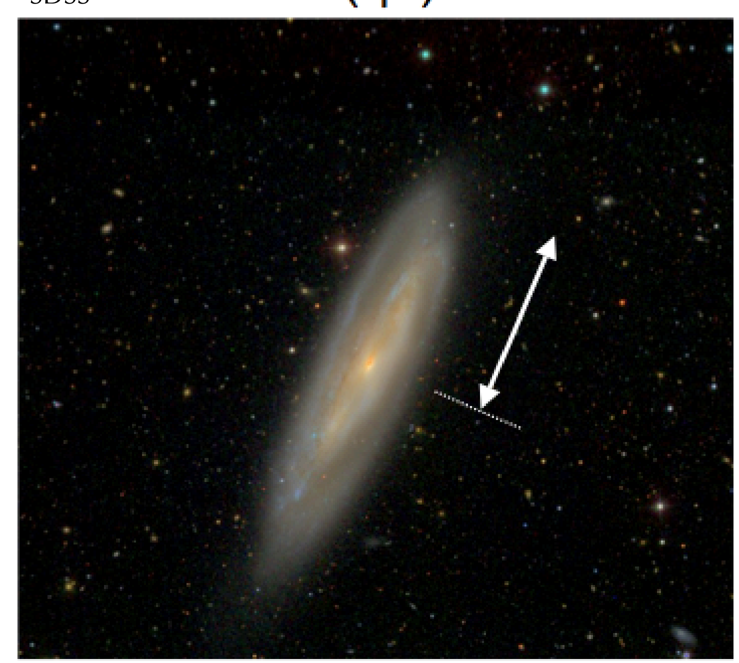
it seems M(r) ~ r
implying $\rho(r) \sim 1/r^2$





Y. Sofue et al., Publ. Astron. Soc. Japan 55 59 (2003).

SDSS

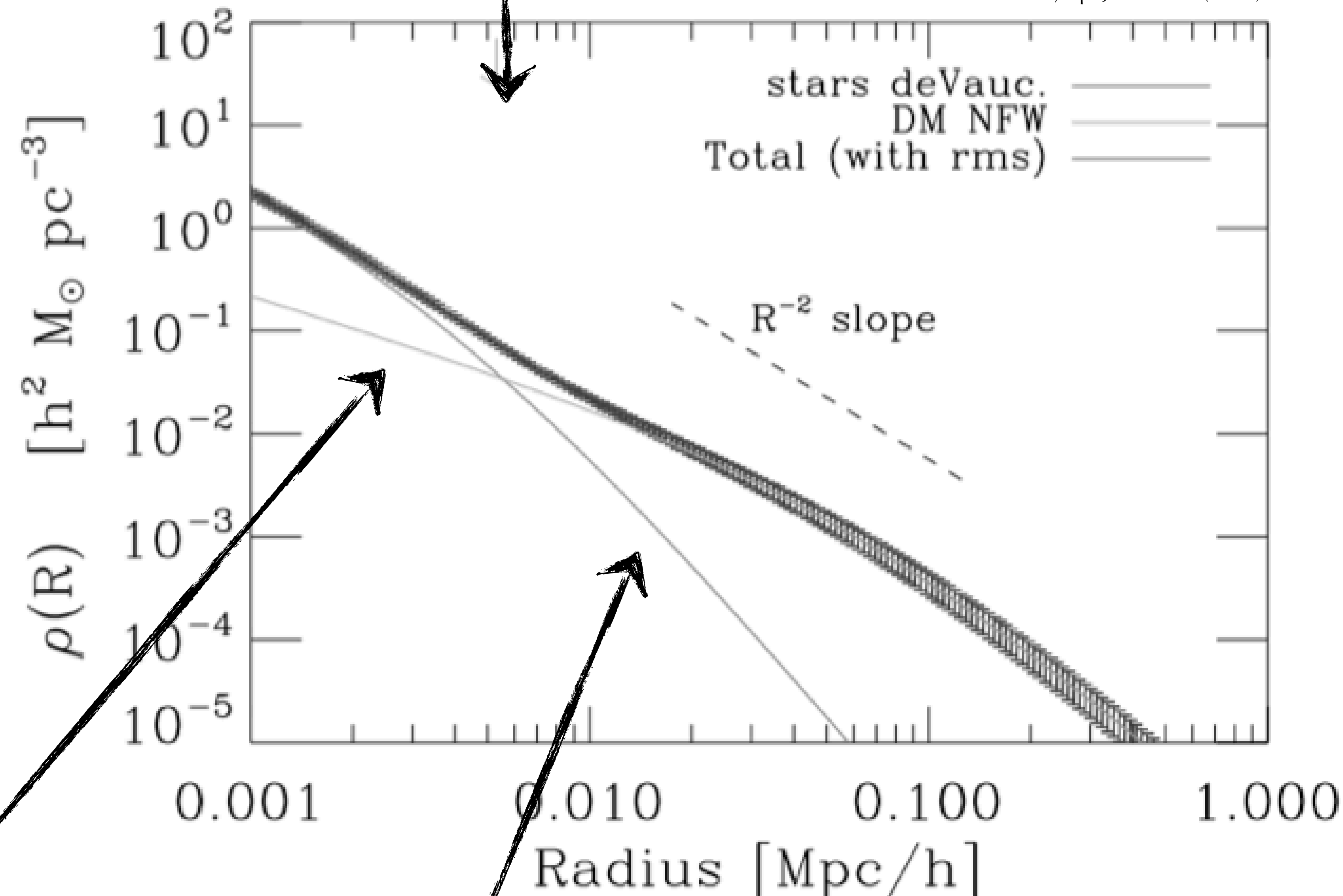


arrows indicate a span of ~20 kpc

Gravitational lensing (weak + strong) of galaxies suggests a dark halo

our approximate position
in the Milky Way

R. Gavazzi et al., Ap. J. 667 176 (2007)

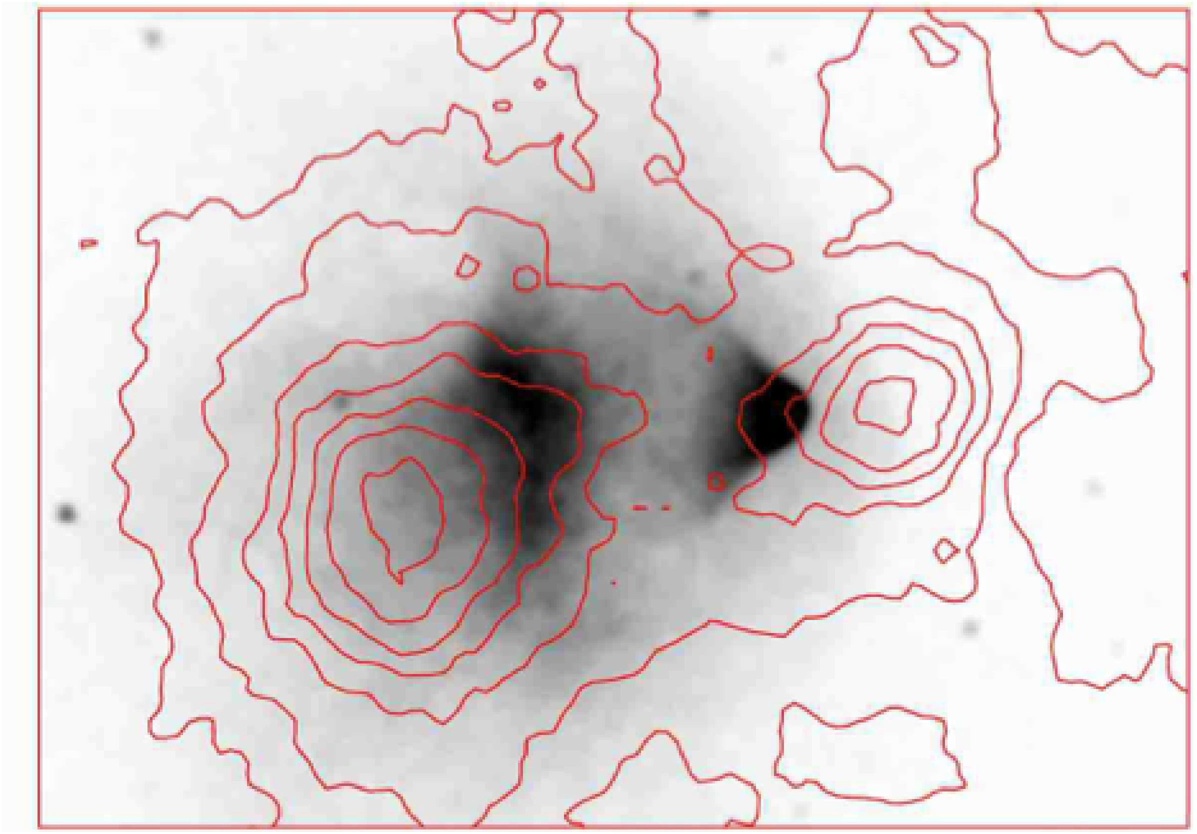


distribution of dark matter

distribution of visible matter

Merging clusters: evidence for dark matter on cluster scales

Clowe et al. Nucl. Phys. B **173** 28 (2007)

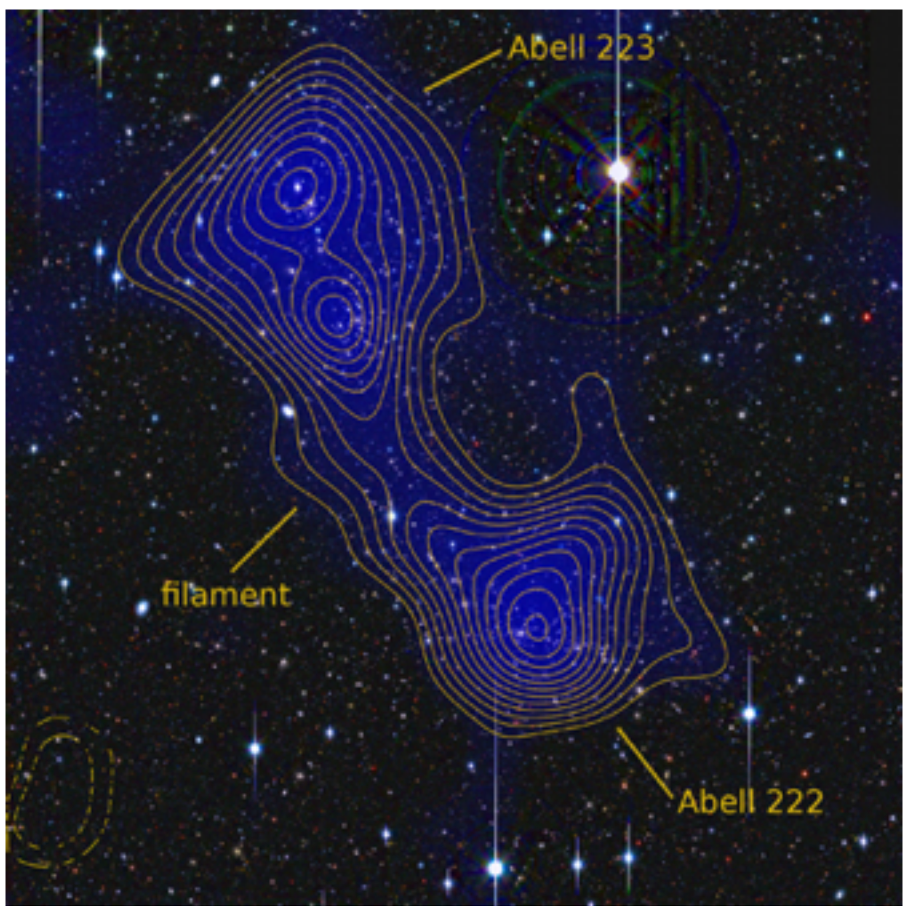


This outcome is expected for ~collisionless stars,
and especially for *collisionless* dark matter

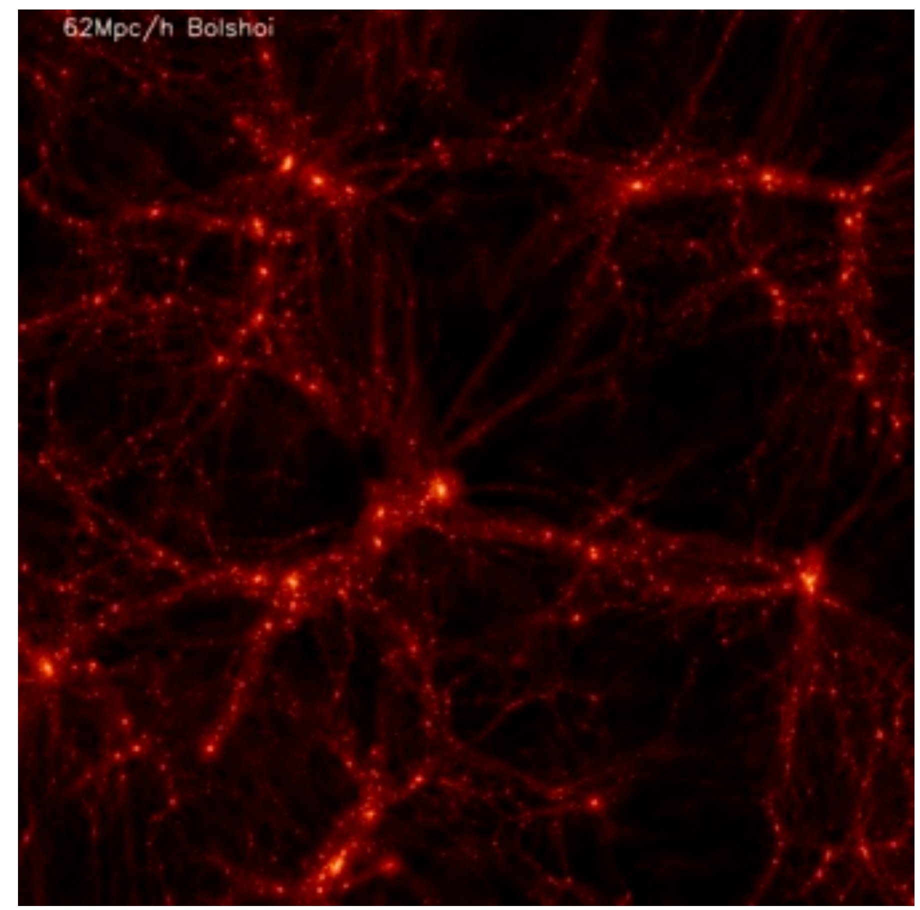
Cosmic web of dark matter: predicted, recently observed!

weak-lensing mass reconstruction of a filament stretching between two clusters, separated by ~15 Mpc/h

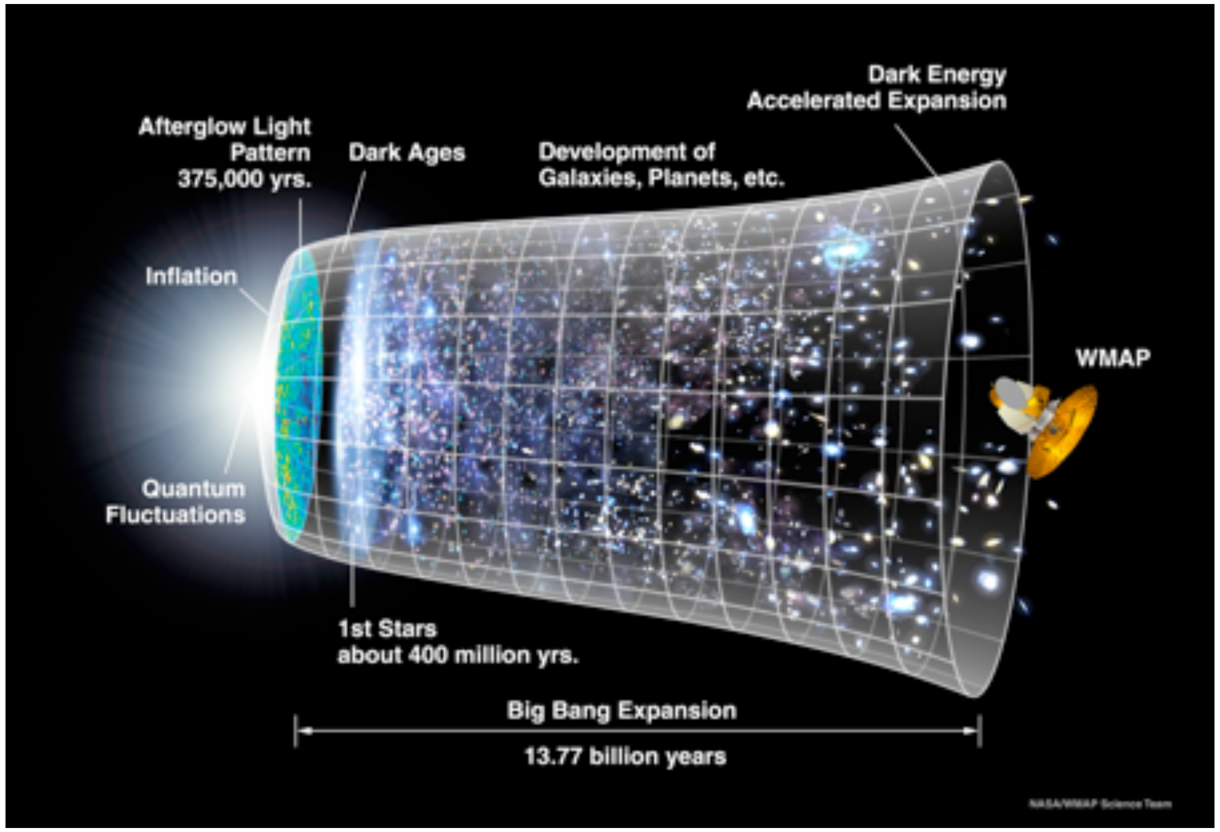
Dietrich et al, Nature **487** 202 (2012)

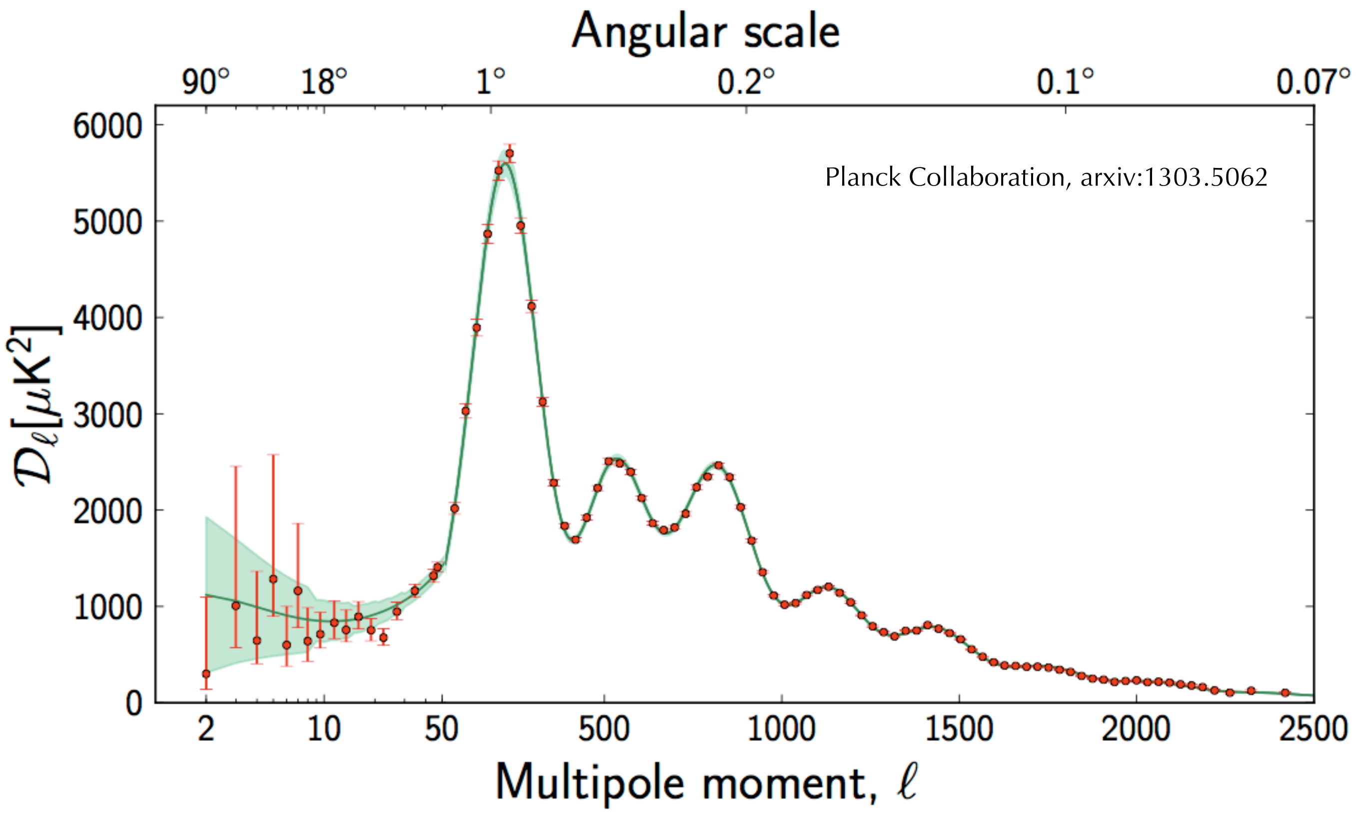


large-scale DM structure filaments in the Bolshoi simulation



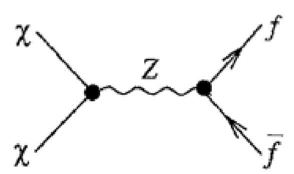
Very brief history of the universe



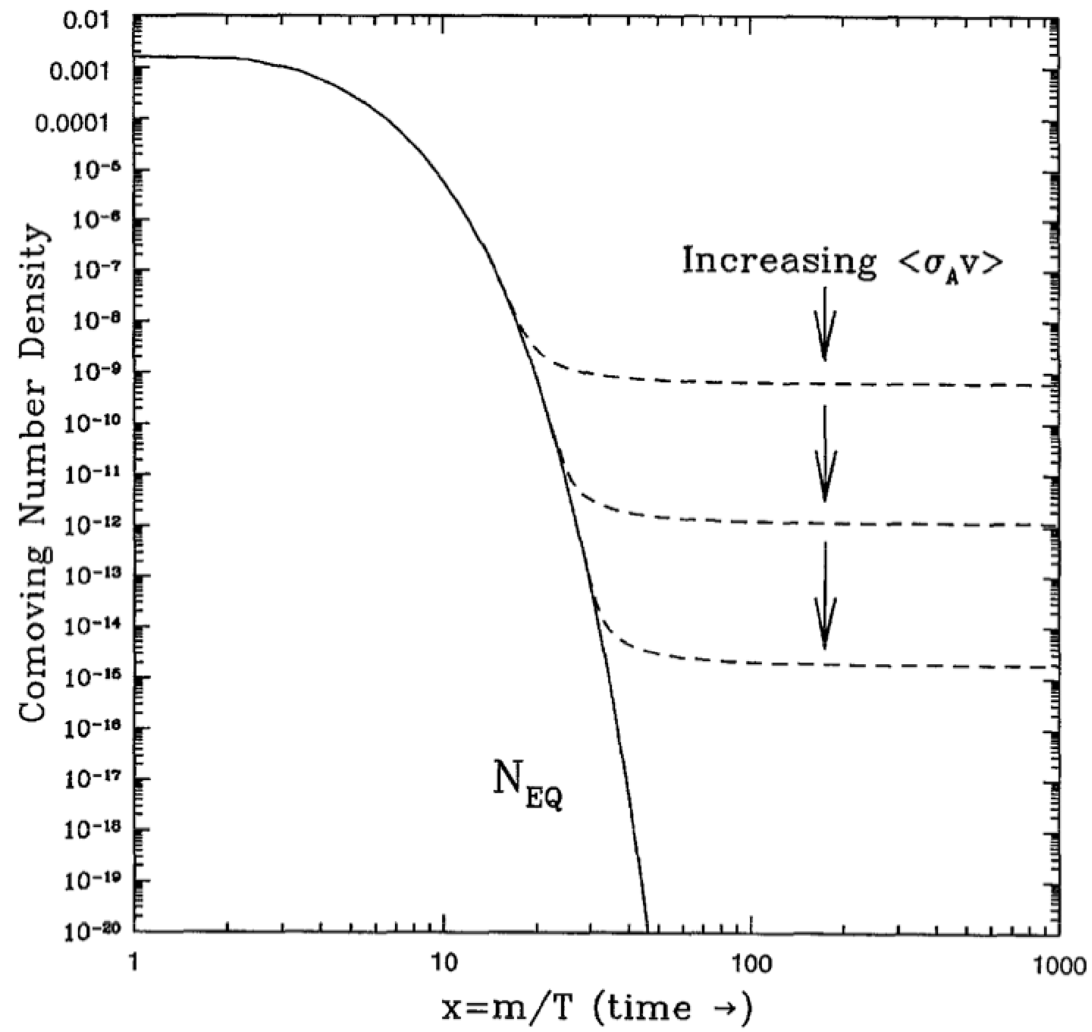


The "WIMP miracle" explanation

e.g.

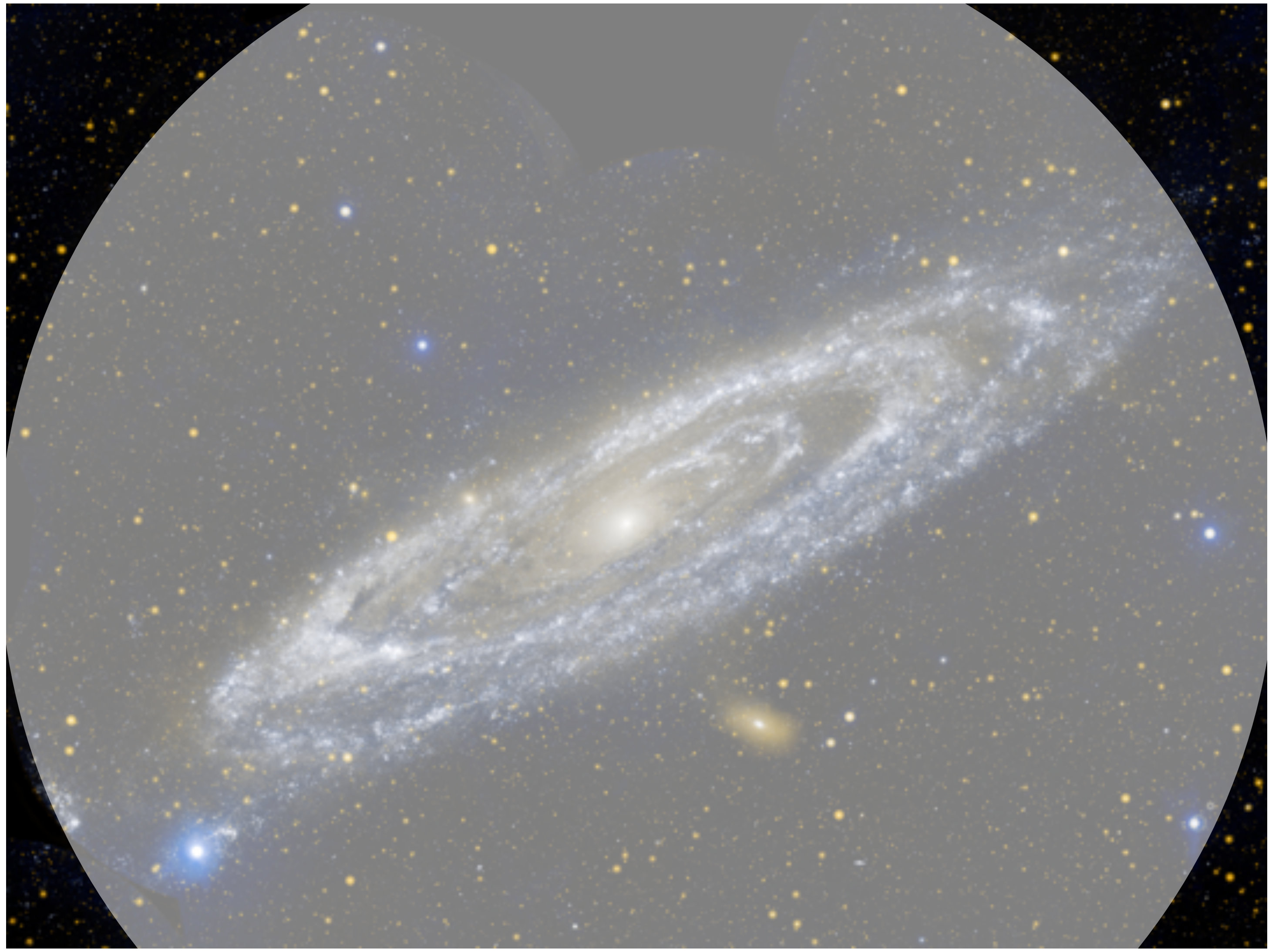


Jungman et al Phys. Rep. **267** 195 (1996)



$$\Omega_\chi h^2 = m_\chi n_\chi/\rho_c \simeq (3\times10^{-27}\,\mathrm{cm^3\,s^{-1}}/\langle\sigma_A v\rangle)$$

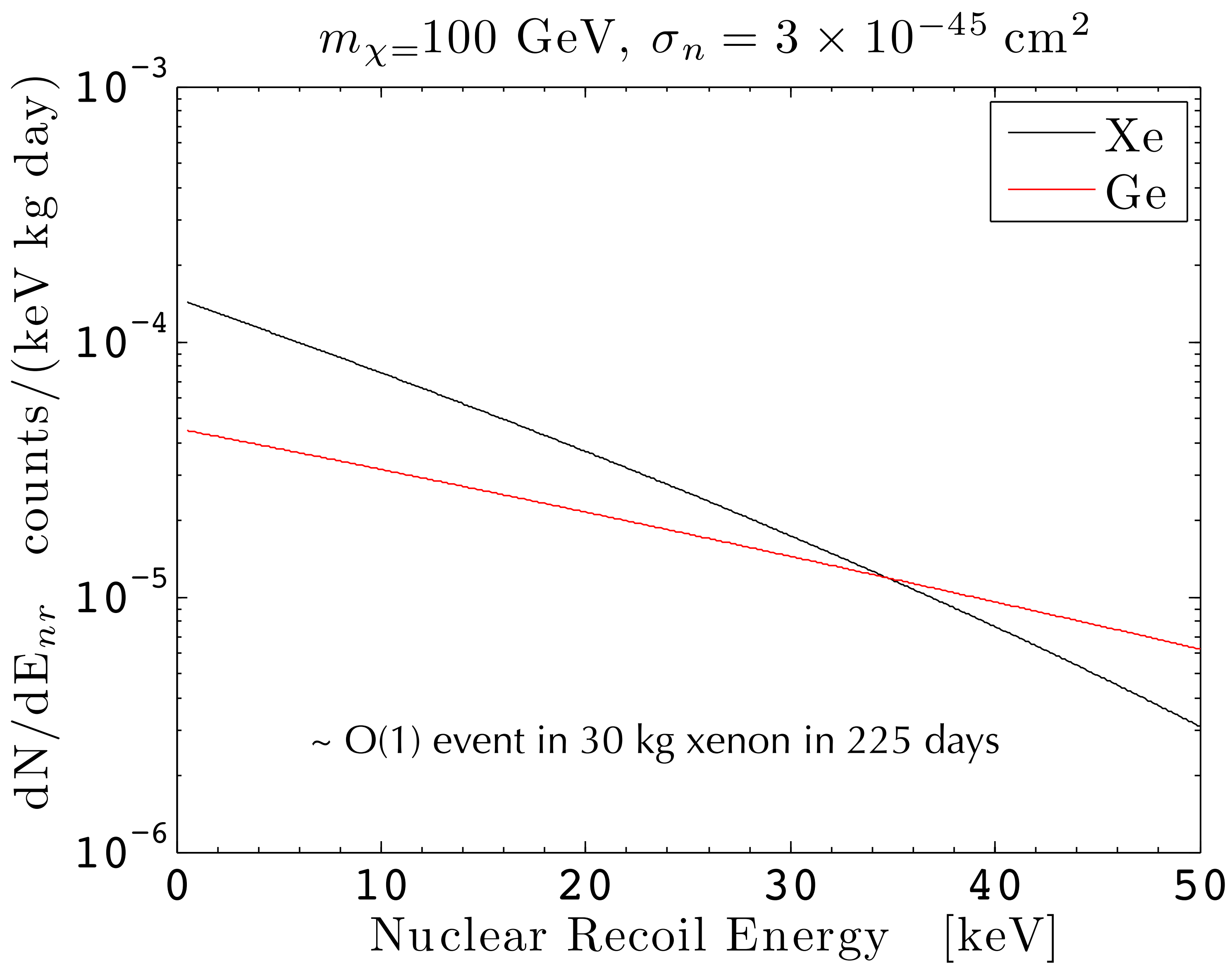
weak scale



$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

Expected energy spectrum for spin-independent elastic scattering

(spin-dependent coupling also generally expected, but less sensitive than SI)



rare event search!

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

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[e] *Applied Research Corp., 8201 Corporate Dr , Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

Quoting from page 3:

eters. The detector is located in the Homestake mine at a depth equivalent to 4000 m of water to eliminate the cosmic ray induced background. The detector cryostat is constructed from high-purity copper and is surrounded by 11 tons of lead, sheet cadmium and neutron moderator, to eliminate the radioactive background and neutrons from the rock. The inner shield was made from high purity copper, when the 14 d of data used in this work were taken. These data were selected because they correspond to a period of decreased level of mining operations in the vicinity of the detector. This resulted in fewer microphonic

(1) go underground

(2) build a castle

(3) avoid miners

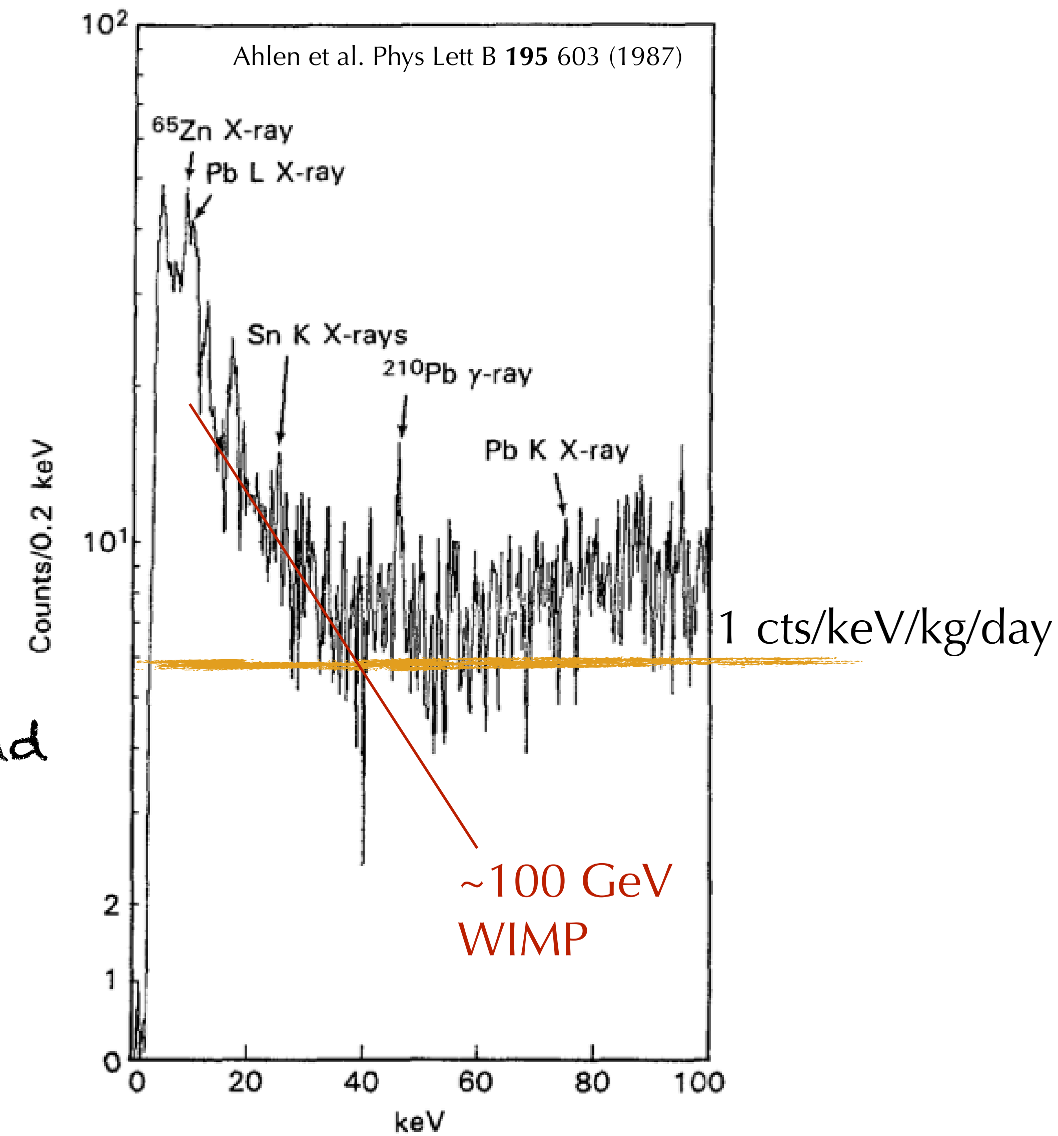


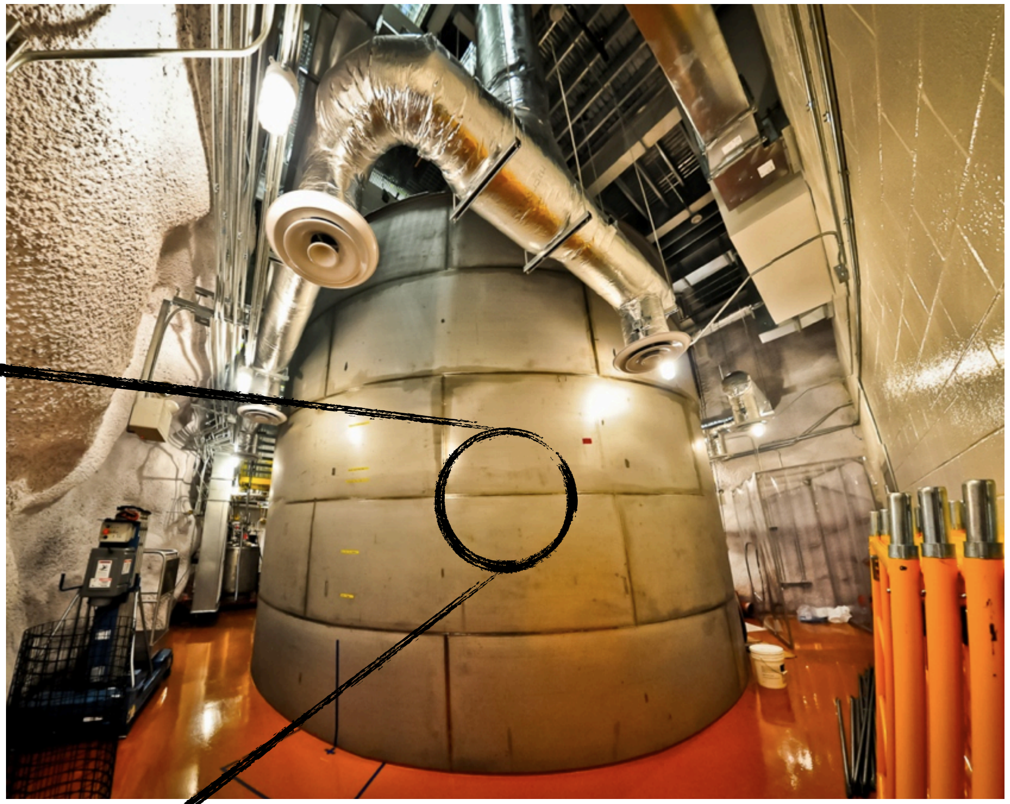
Fig. 2. 1000 h of data from the Ge spectrometer are shown The width of each channel is 0.2 keV. The identified peaks result from the decay products of radioactivity in the exposed solder.

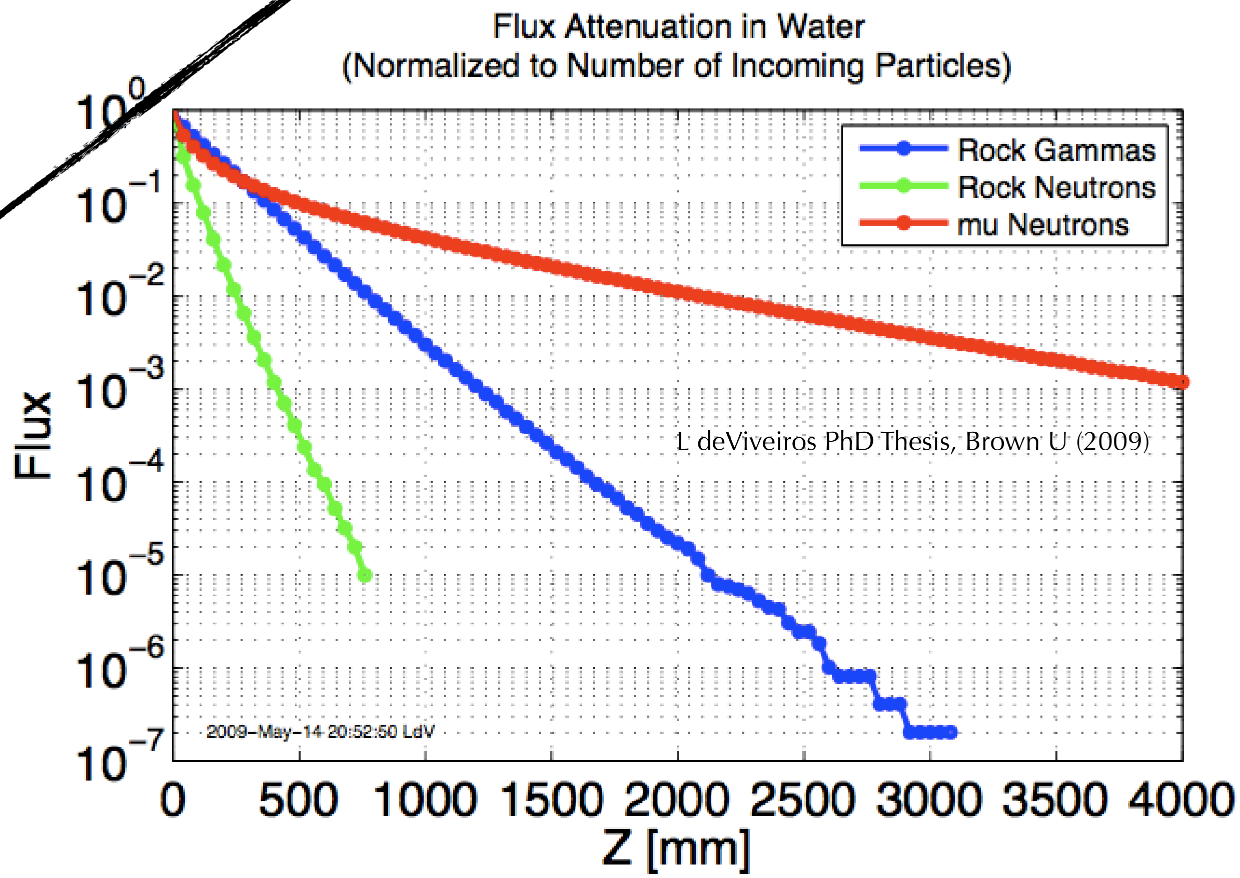
The basic tricks haven't changed

LUX is installed 1.5 km below the surface
- the muon rate is reduced from ~50 Hz to <1/day
- 8 meter ∅ water shield renders ambient radioactivity irrelevant

(below) LUX inside its water tank

(below) view of the LUX water tank

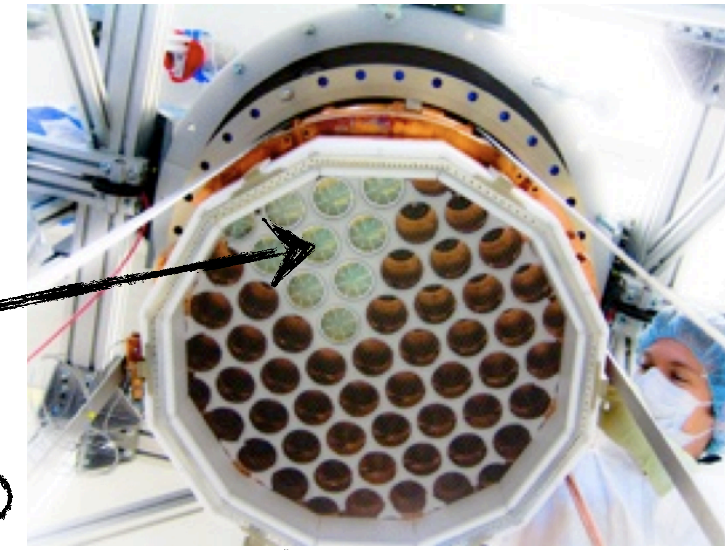




remaining challenge:
radioactivity from the **detector itself**

...if mildy esoteric

arxiv:1112.1376 Radio-assay of Titanium samples for the LUX Experiment
arxiv:1205.2272 An Ultra-Low Background PMT for Liquid Xenon Detectors


LUX during construction

bottom line:

all internal materials sub-dominant to long-lived isotopes in PMTs
10 mBq U / 2 mBq Th / 65 mBq K per PMT

! reference: a banana, ~x4 in mass, has ~15 Bq ^{40}K (x60 activity)

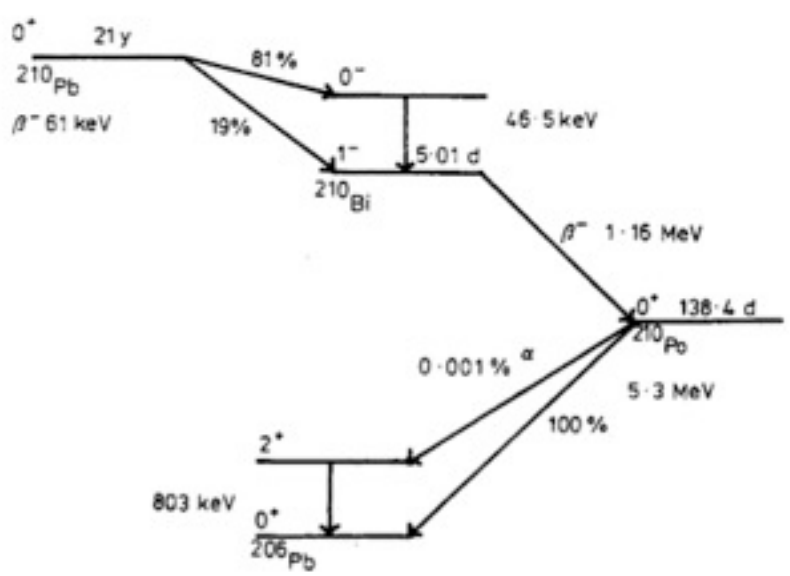
xenon is radiopure, but other noble gases are not:

^{85}Kr ($\tau_{1/2}$ ~ 11.7 y), present at ~10^{-12} in ^{nat}Kr.
^{nat}Kr present at ~ O(10) ppb + in commerical Xe
=> dedicated chromatographic separation system reduces this to ~5 ppt

! reference: XENON100 results from 2011 (700 ppt) and 2012 (20 ppt)

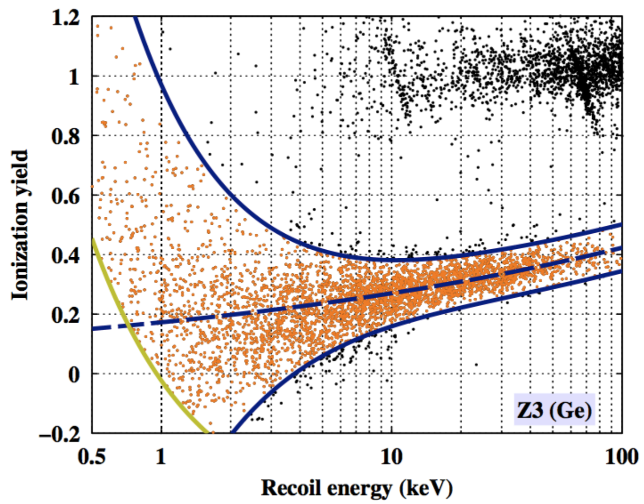
^{222}Rn ($\tau_{1/2}$ ~ 3.8 d): quickly decays to ^{210}Pb ($\tau_{1/2}$ ~ 22.3 y).
scary enough to have DAMA working in N_2 atmosphere

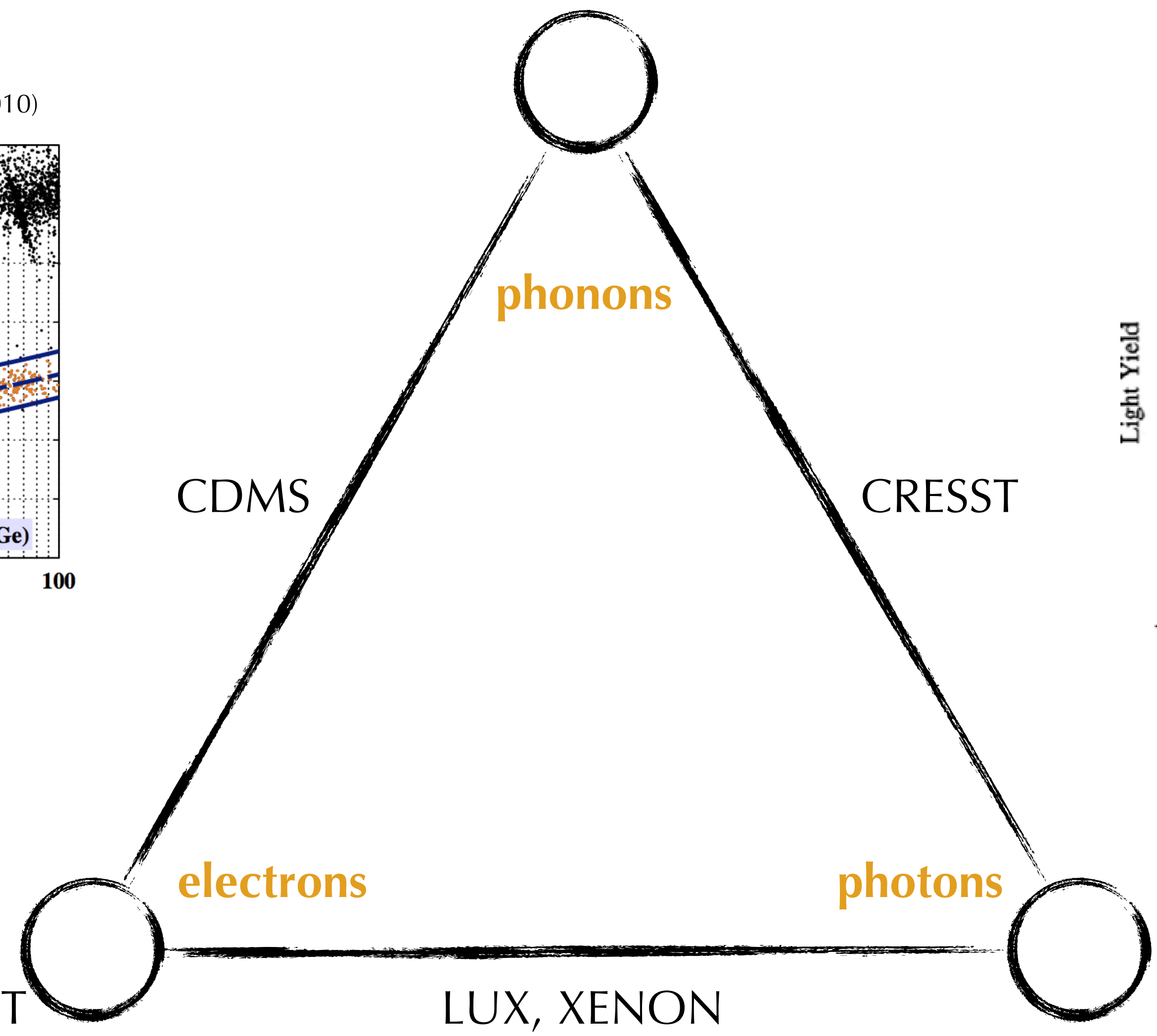
Bernabei et al, Nucl. Instr. Meth. A **592** 297 (2008)



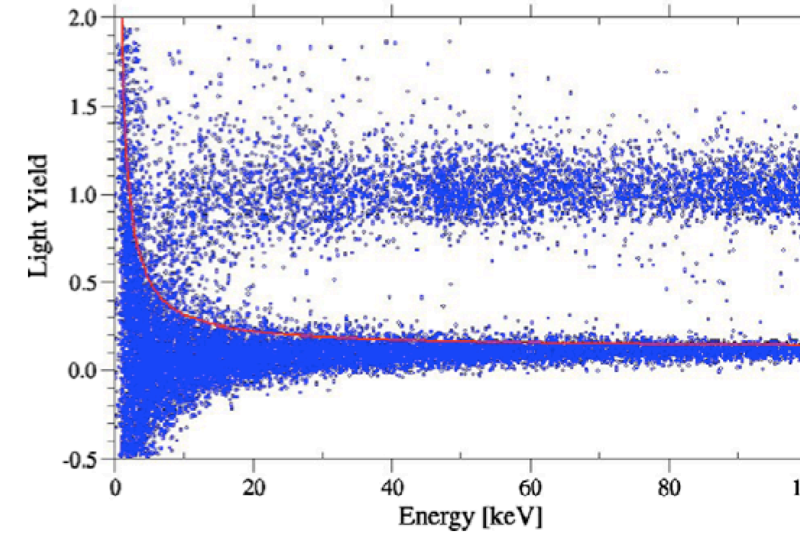
Available signal, and example experiments

CDMS, Phys Rev D **82** 122004 (2010)

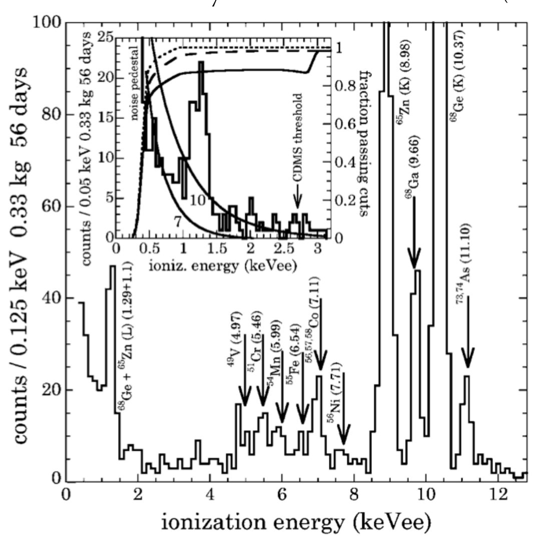




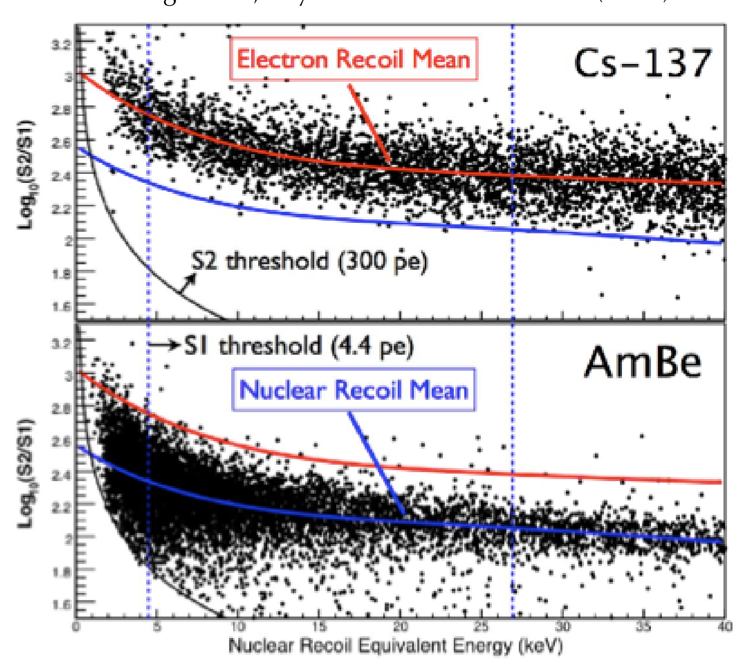
Angloher et al, Astropart. Phys. **31** 270 (2009)

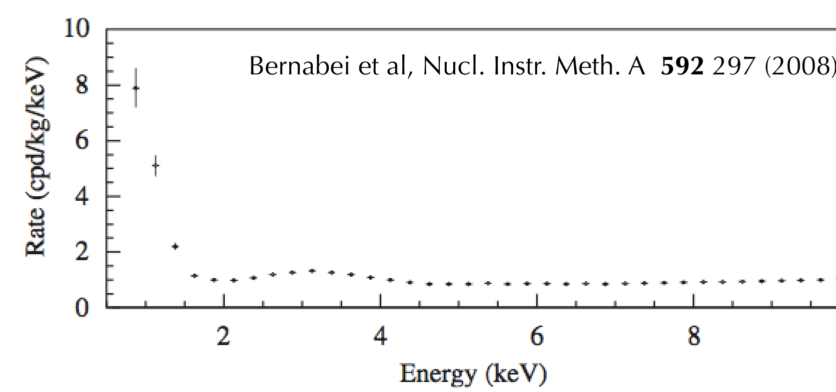


C. Aalseth et al Phys Rev. Lett. **106** 131301 (2011)



Angle et al, Phys. Rev. Lett. **100** 021303 (2008)



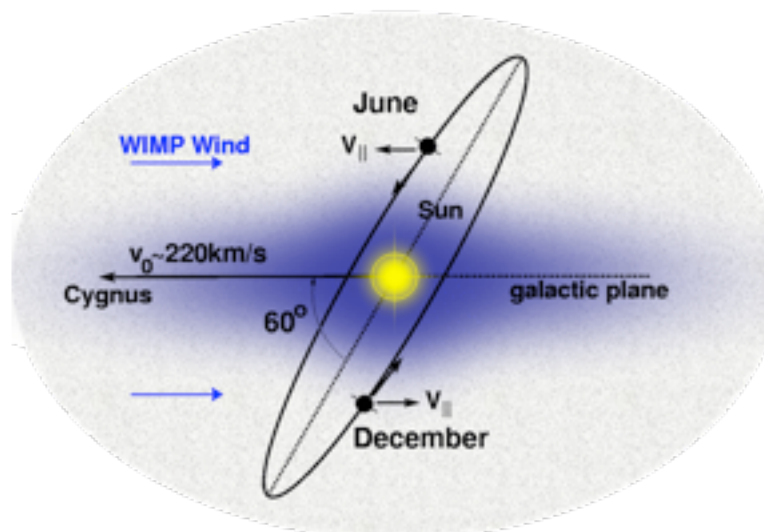


Bernabei et al, Nucl. Instr. Meth. A **592** 297 (2008)

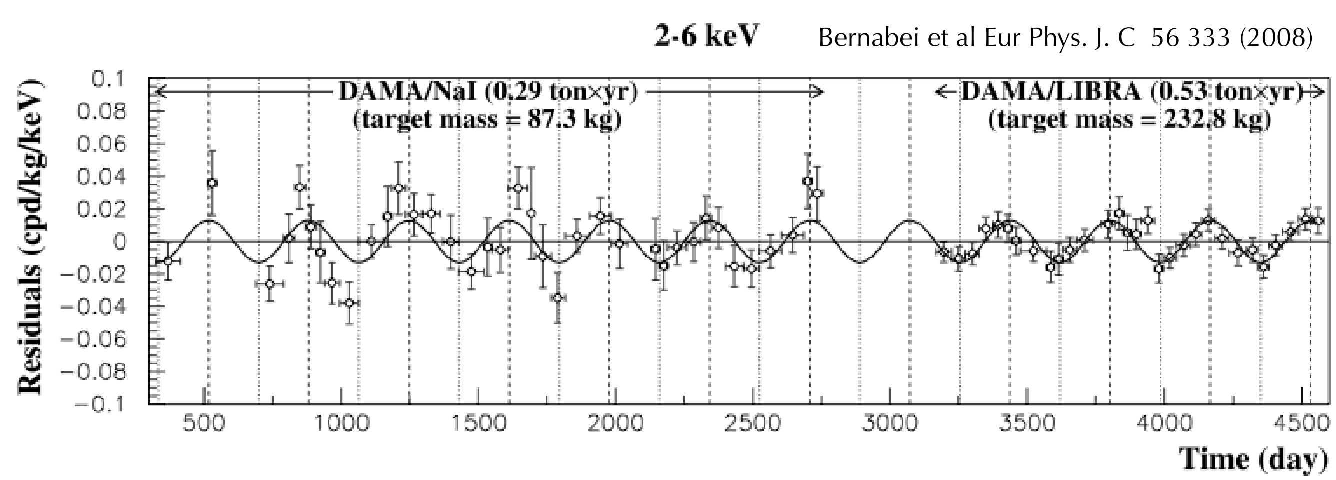
Modulation would be a nice extra discriminant

minor prerequisite: direct detection of dark matter

annual modulation



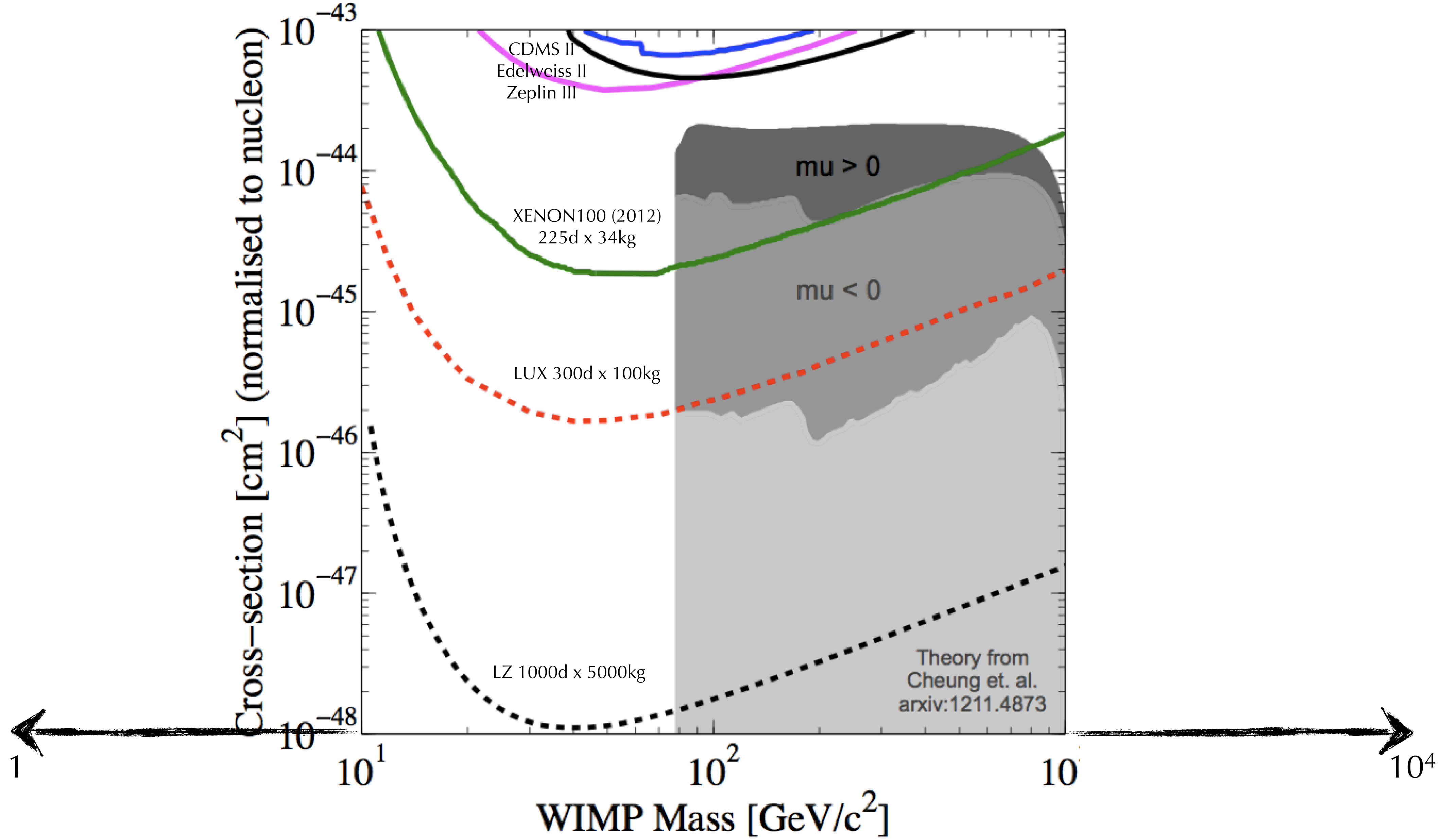
http://www.hep.shef.ac.uk/research/dm/intro.php



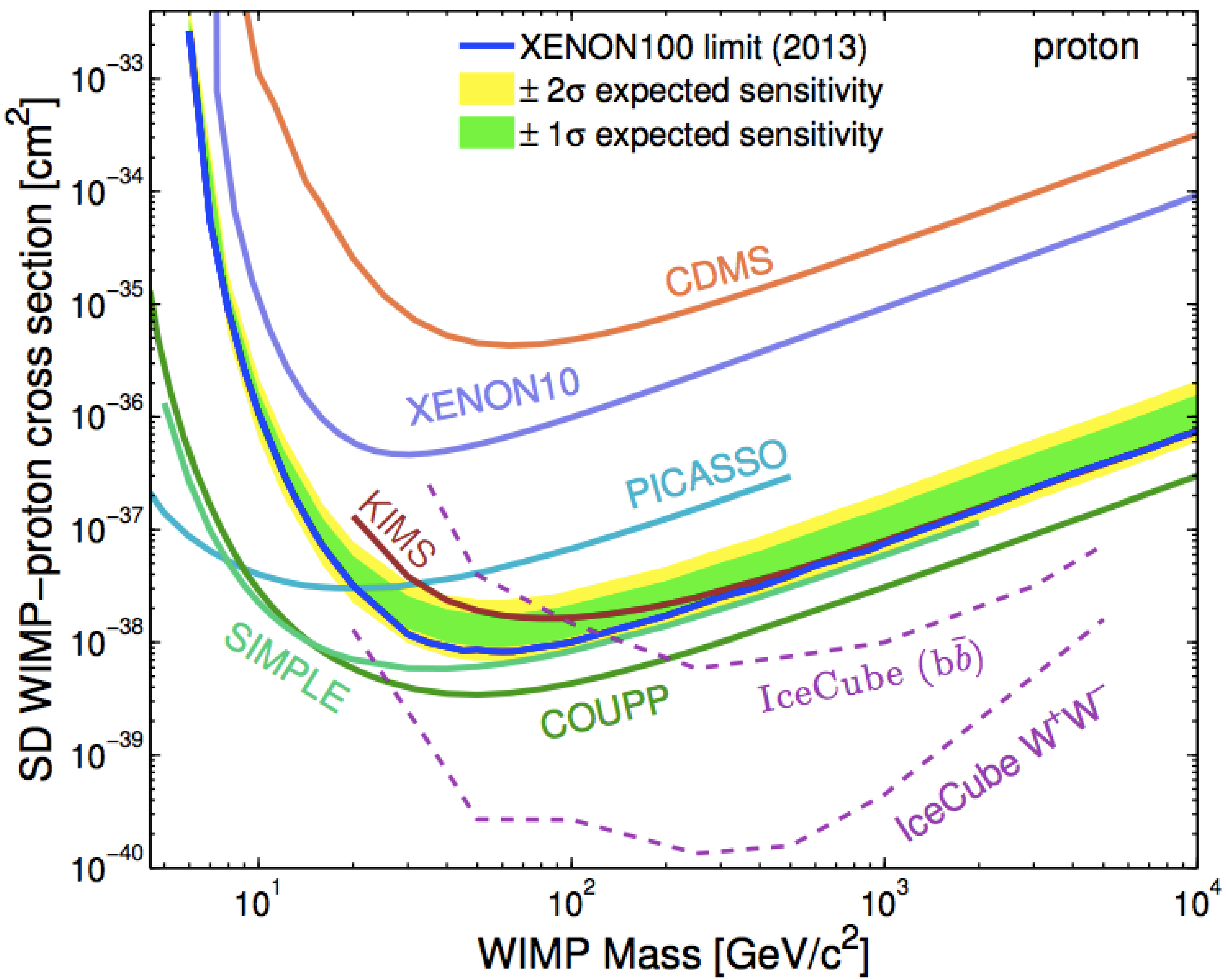
Bernabei et al Eur Phys. J. C 56 333 (2008)

but see e.g. Nygren, arXiv:1102.0815

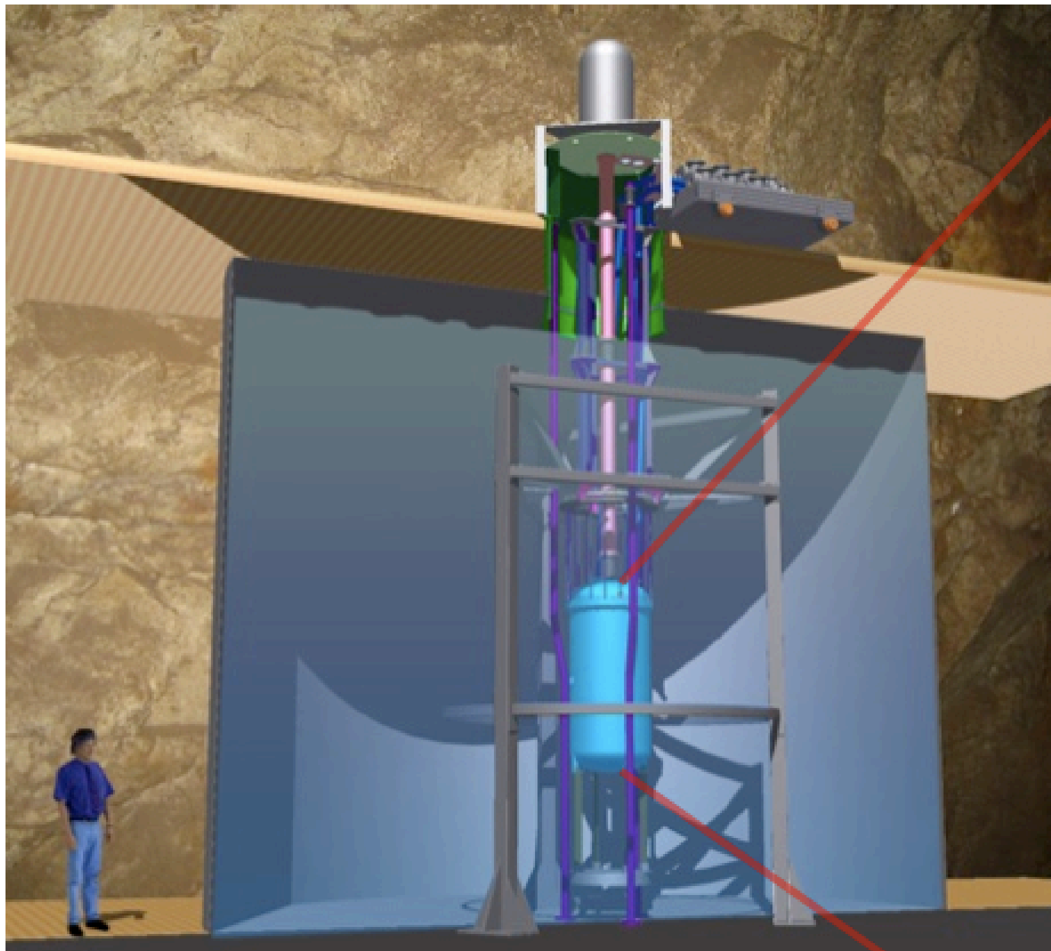
experimental sensitivity assuming spin-independent interactions

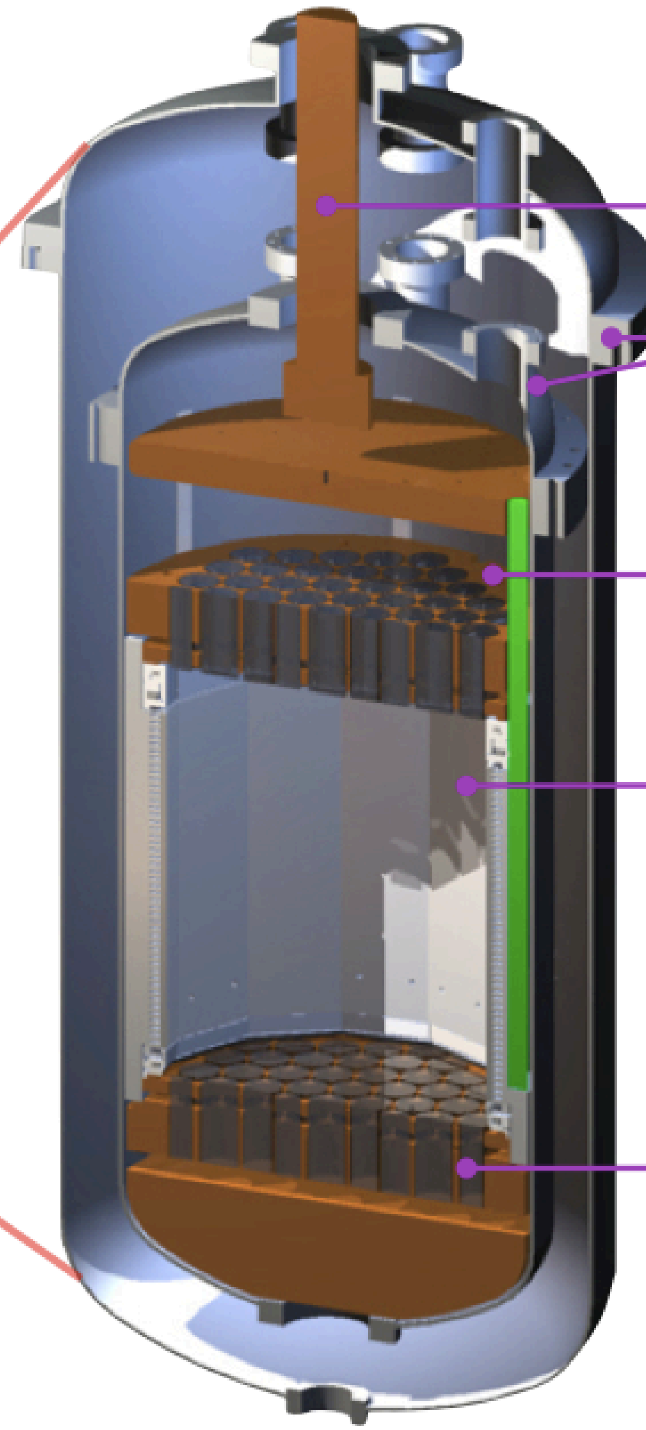


arxiv:1301.6620



(actually, this would be the view from -4850′)



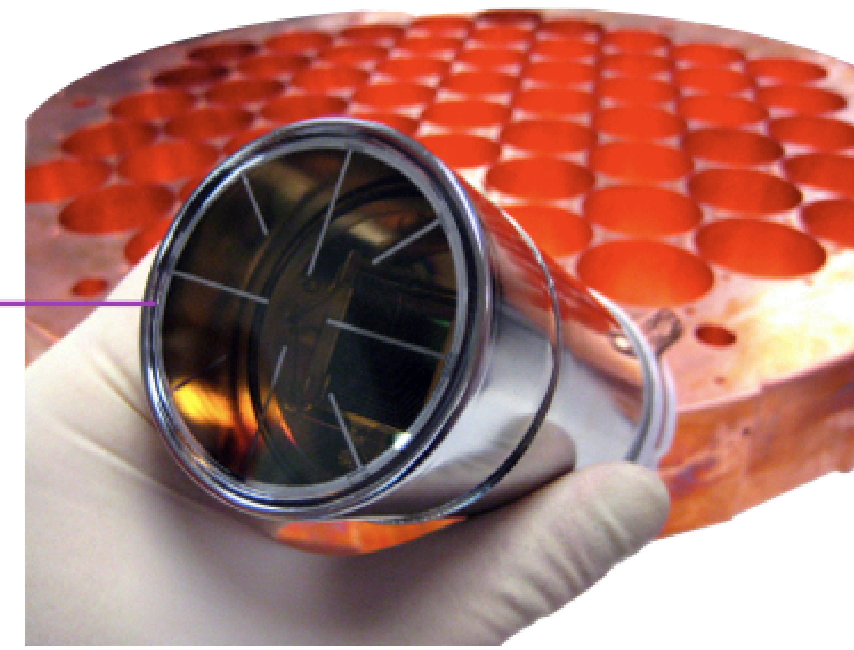


Thermosyphon

Titanium Vessels

PMT Holder Copper Plates

Dodecagonal field cage
+ PTFE reflector panels



2” Hamamatsu R8778
Photomultiplier Tubes (PMTs)

- 370 kg (300 kg active) LXe
- 122 PMTs (2” round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)

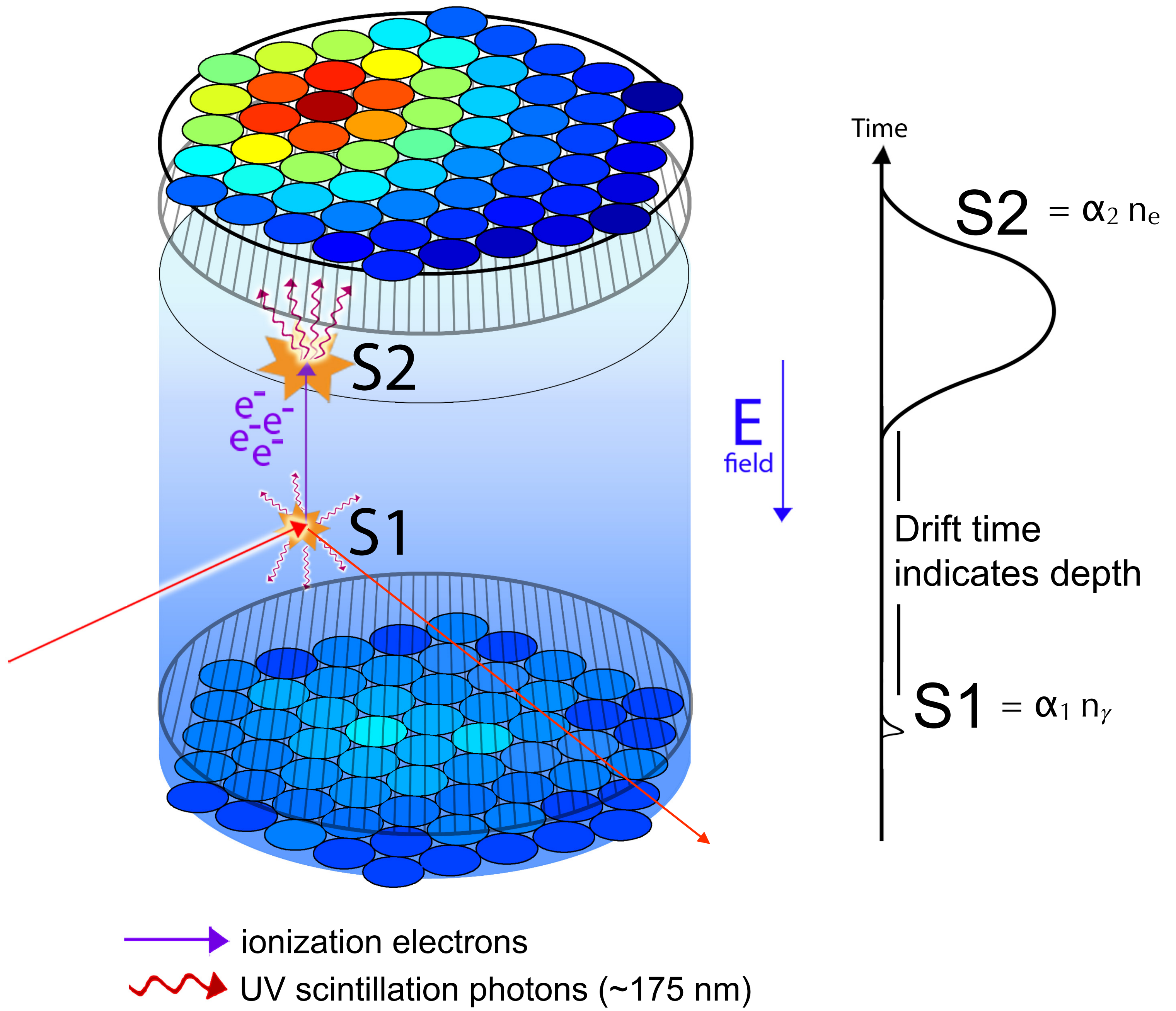
what: a monolithic, “wall-less,” radiopure, ~350 kg xenon target viewed by 122 Photomultiplier Tubes

- 3D vertex reconstruction => no edge effects!
- target is self-shielding

how: detect scintillation photons and ionized electrons

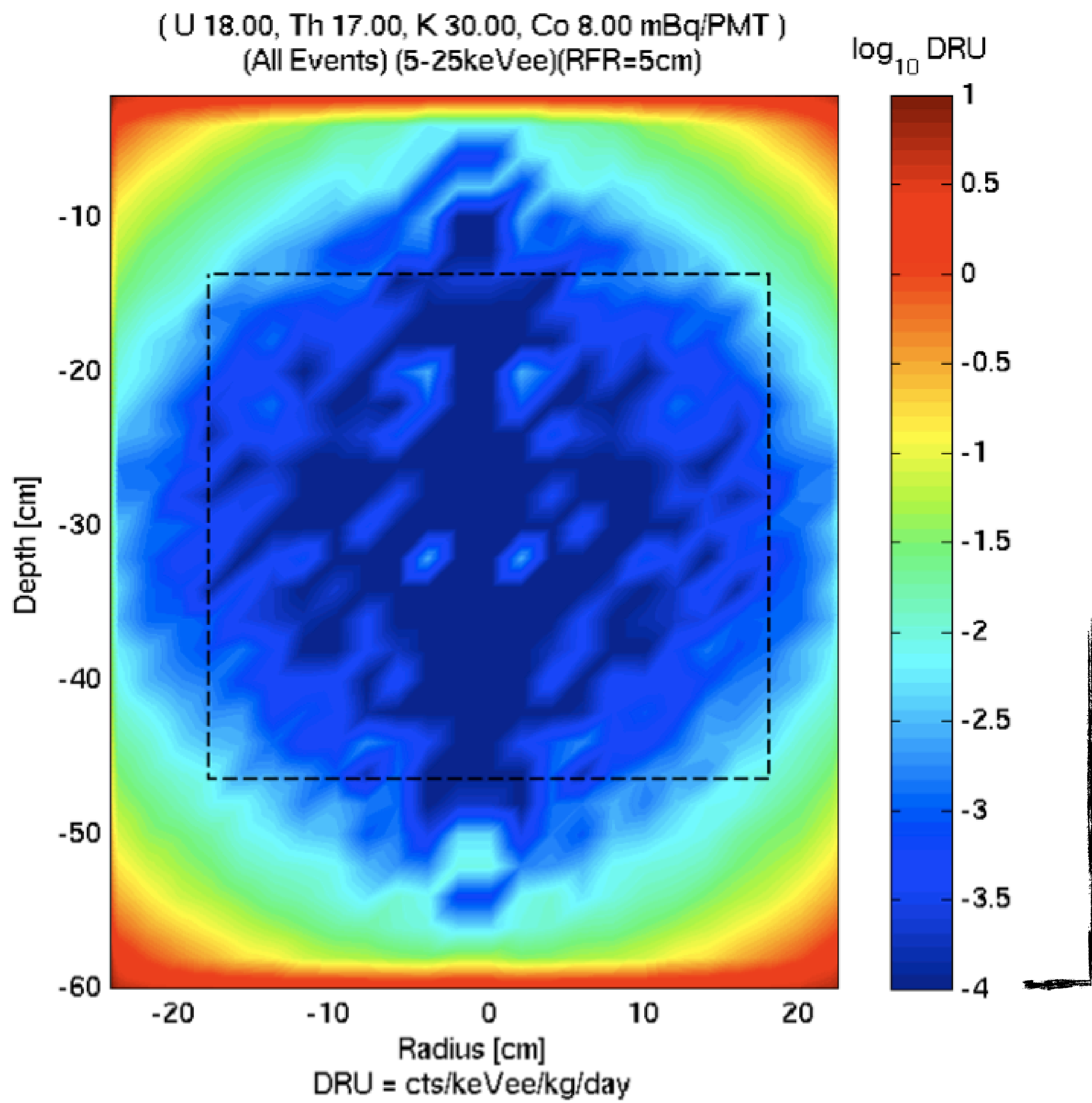
- n_γ and n_e are the fundamental measured quantities you want to know
- α_1 ~ O(0.10) and α_2 ~ O(10) are the probabilities for detection of each quanta
- α_1 is often quoted as “photoelectrons per keV,” which can be confusing (even to “experts”).
- examples:
  - LUX α_1 ~ 0.15
  - XENON100 α_1 ~ 0.06

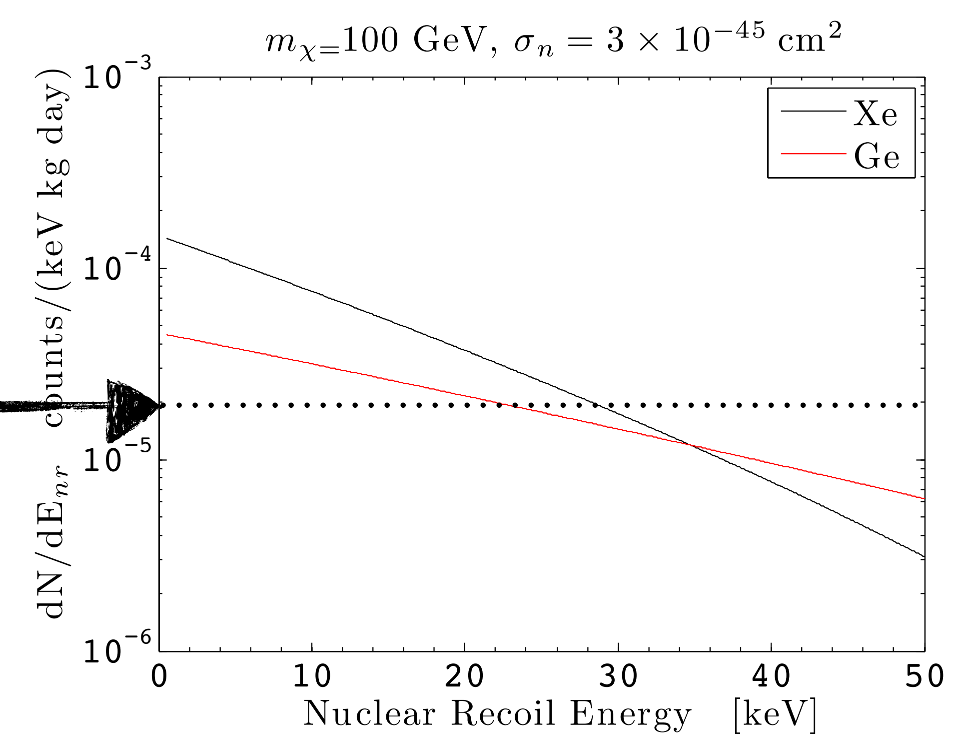
LUX, Nucl. Instr. Meth. A 668 1 (2012)



The beauty of self-shielding

Simulation of 5-25 keV depositions due to gamma activity from the PMTs
background neutrons also range out or multiply scatter (easy to tag)

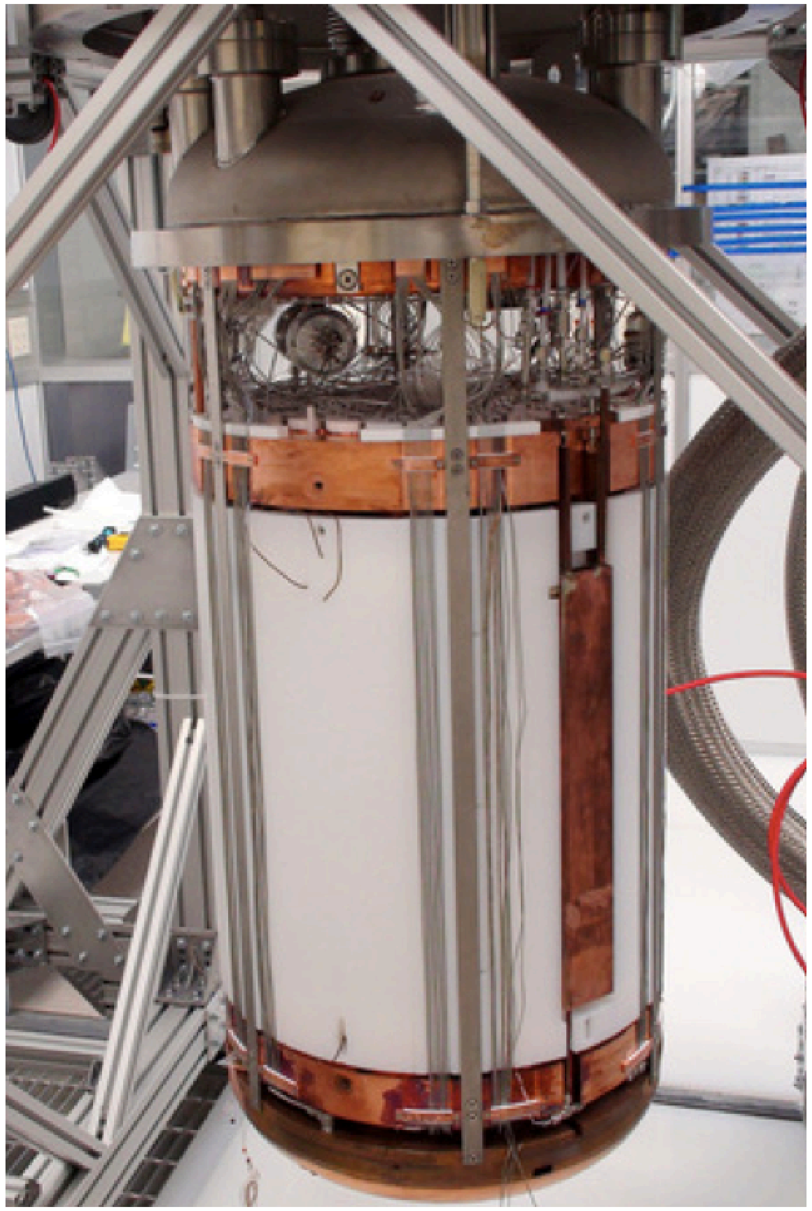


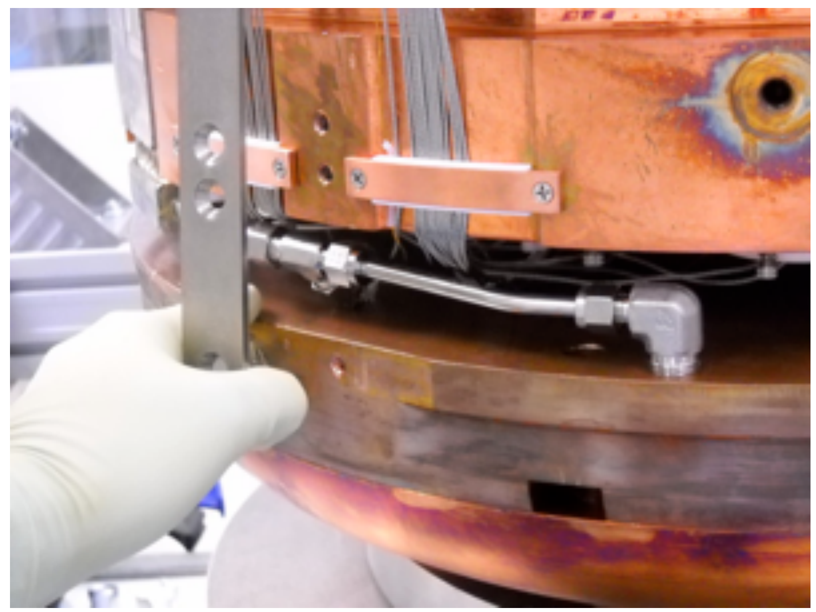


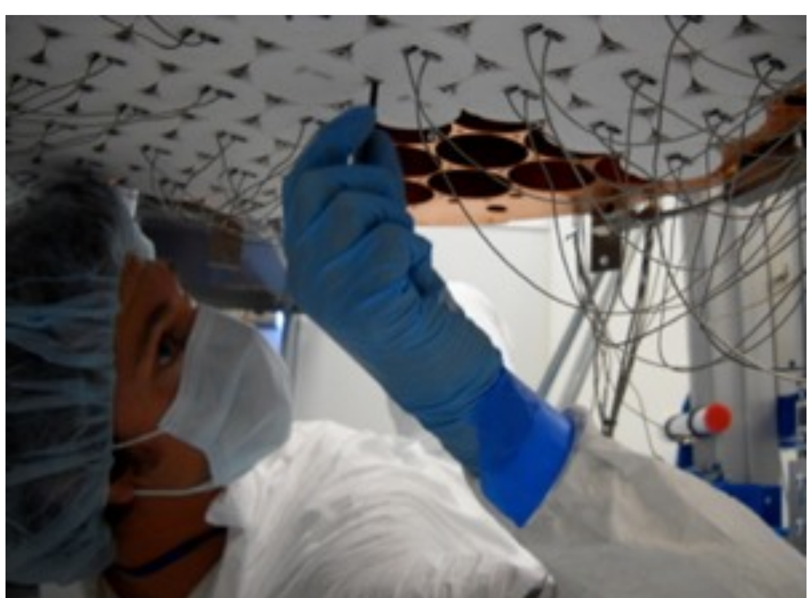
1e-4 => 0.2e-4 due to nuclear recoil quenching factor ~ x0.2

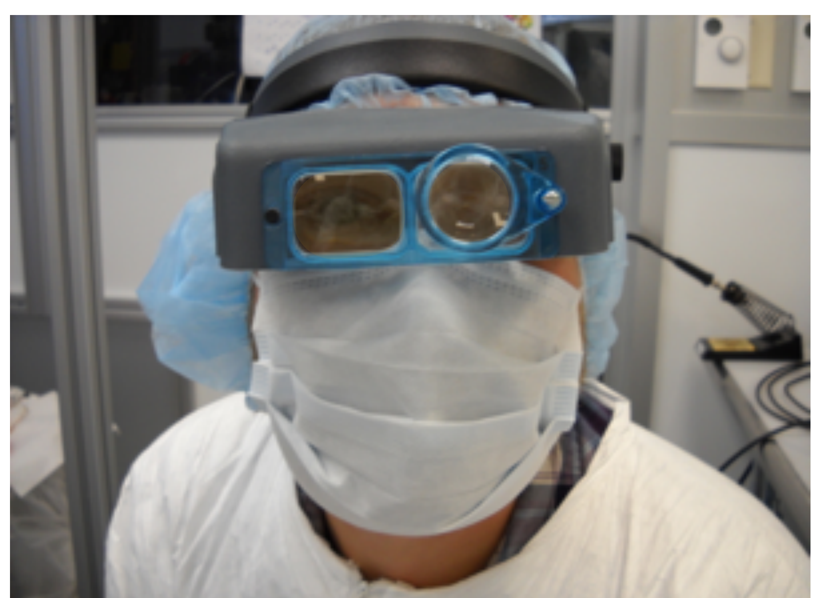
this is before the factor ~x200 discrimination from S2/S1 ~ n_e/n_γ

2010-2011: we built LUX in the surface lab at SURF, SD ...

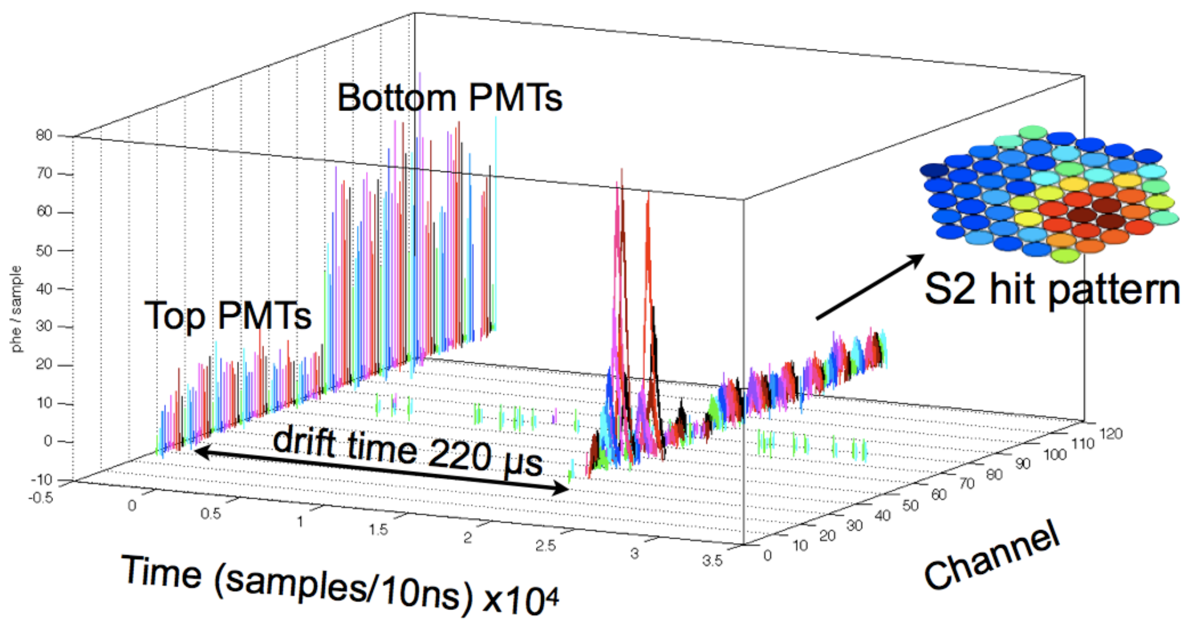








sealed it up, and sent it underground

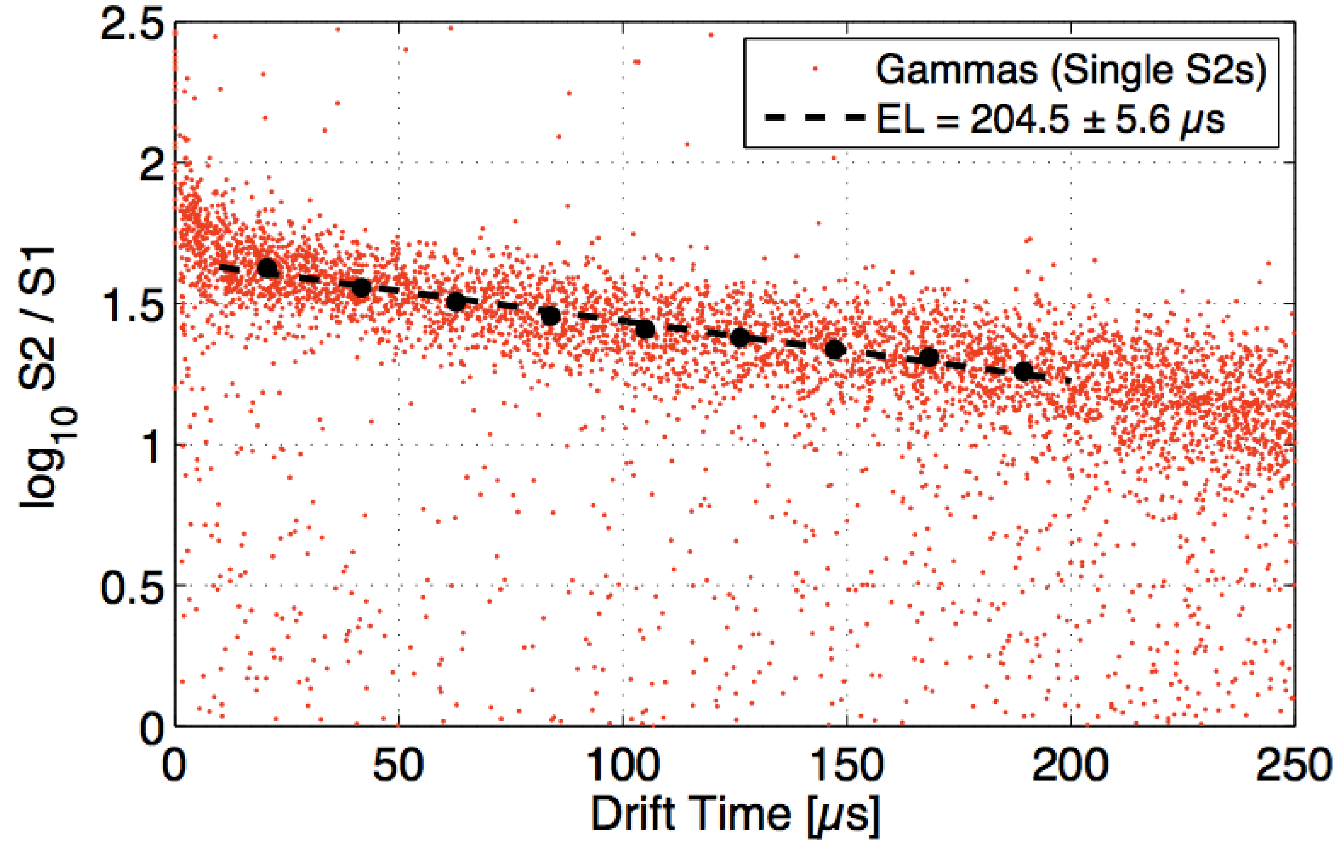


200 μs lifetime achieved in 2012 during surface operation,
despite broken plumbing connection

- in the liquid noble gas detector business, we obsess over purity:
- electronegative impurities capture electrons
- manifests itself as a free electron lifetime

- XENON10, τ = 2000 μs, max t_{drift} = 80 μs (up to 4% e- loss)
- XENON100, τ = 514 μs, max t_{drift} = 160 μs (up to 26% e- loss)

LUX, arxiv:1210.4569

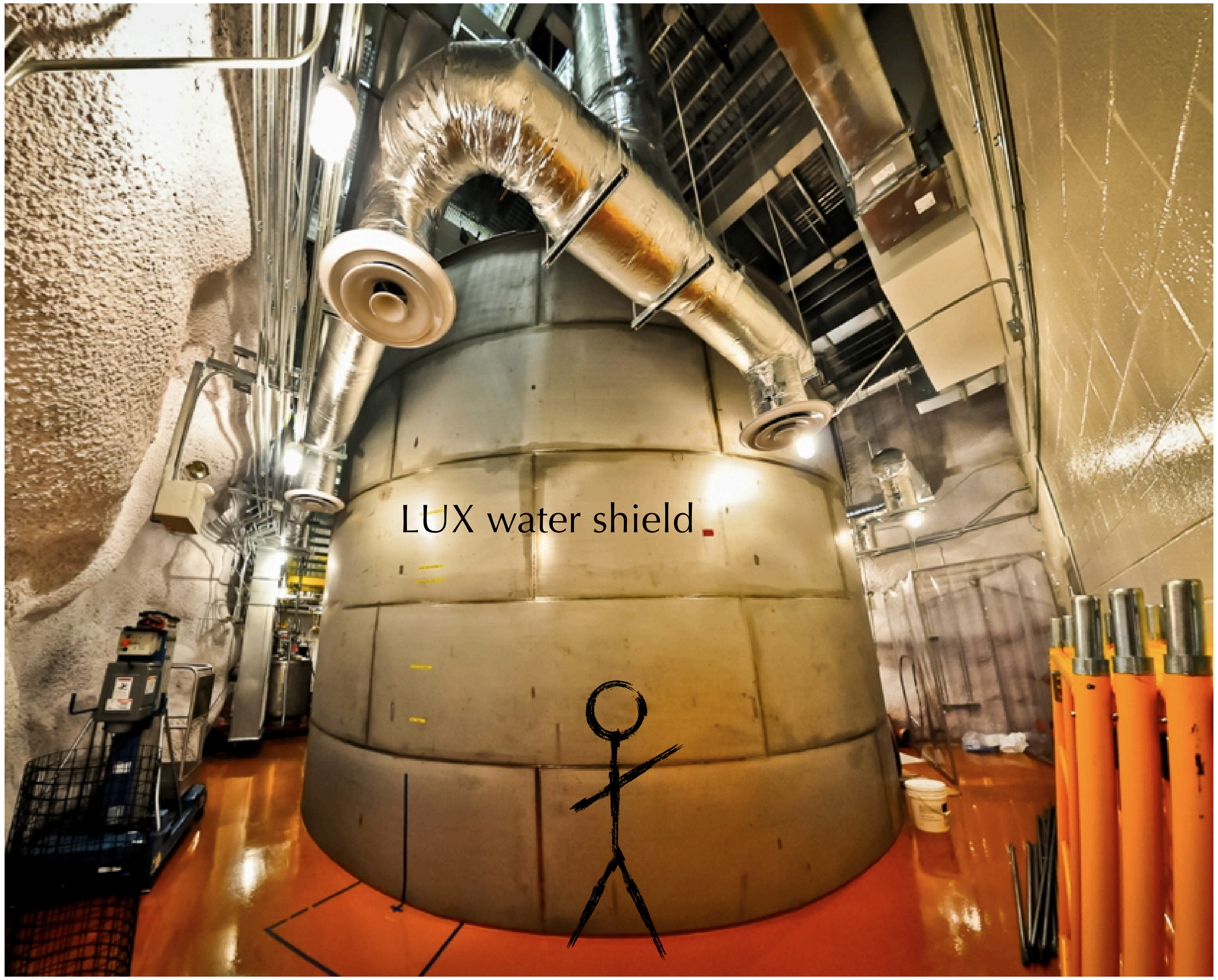


Summer of 2012: underground in the Davis Cavern at SURF!

perspective:
Ray Davis swimming in his water shield, 1971

Assembling all the ancillary support systems

Unfortunately, swimming in a *"confined space"* is strictly forbidden

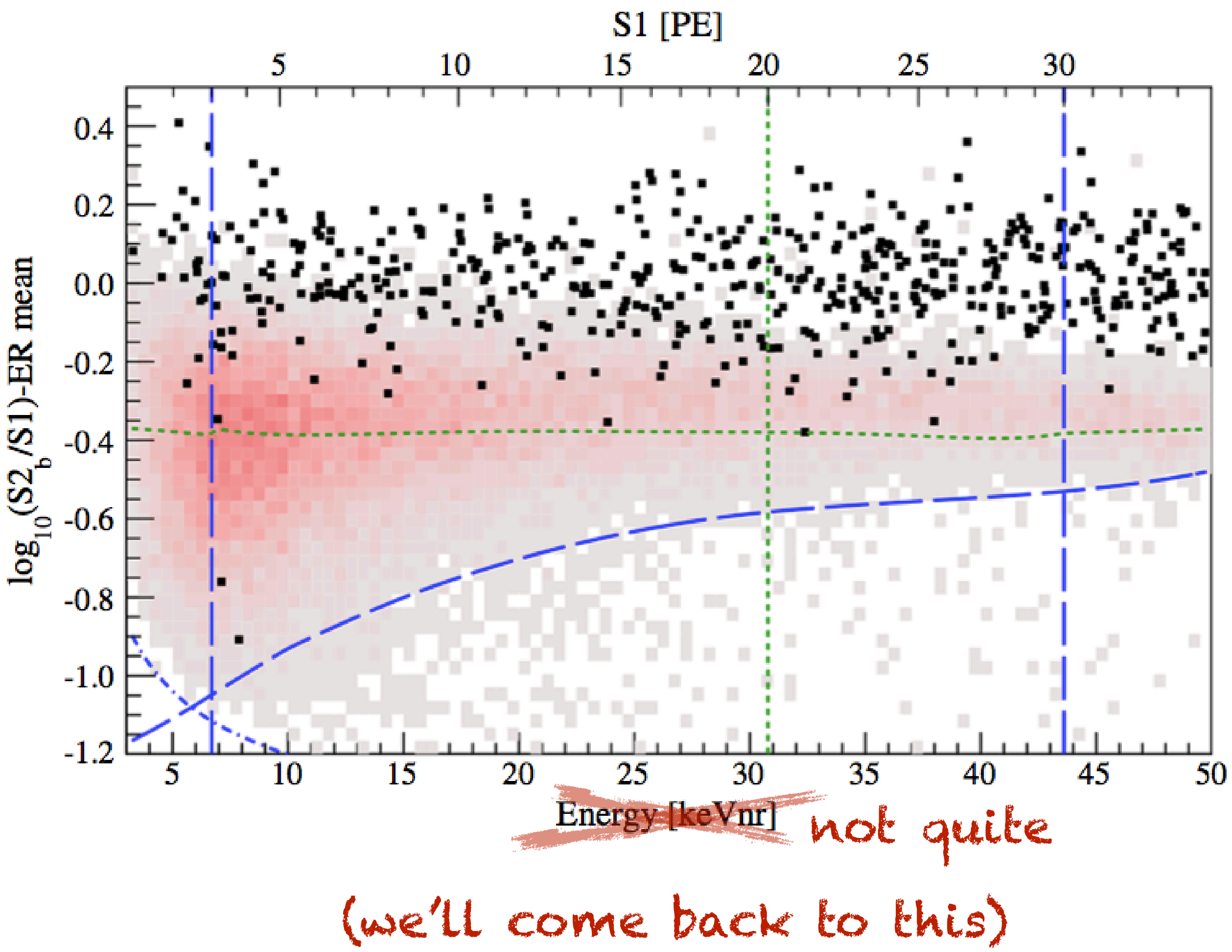


Now (finally!)

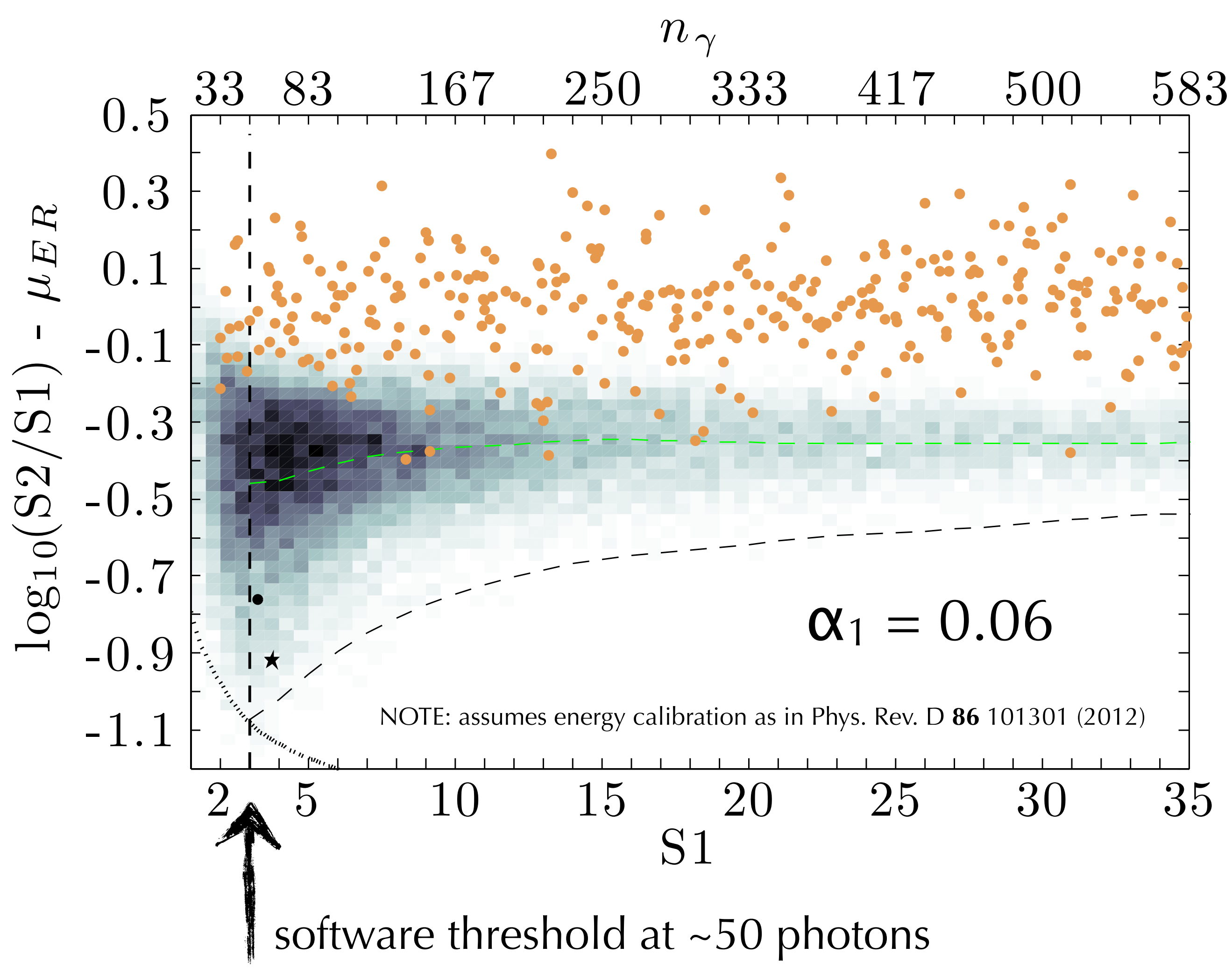
LUX is nearly ready for dark matter search

!!

let's first review the recent XENON100 results

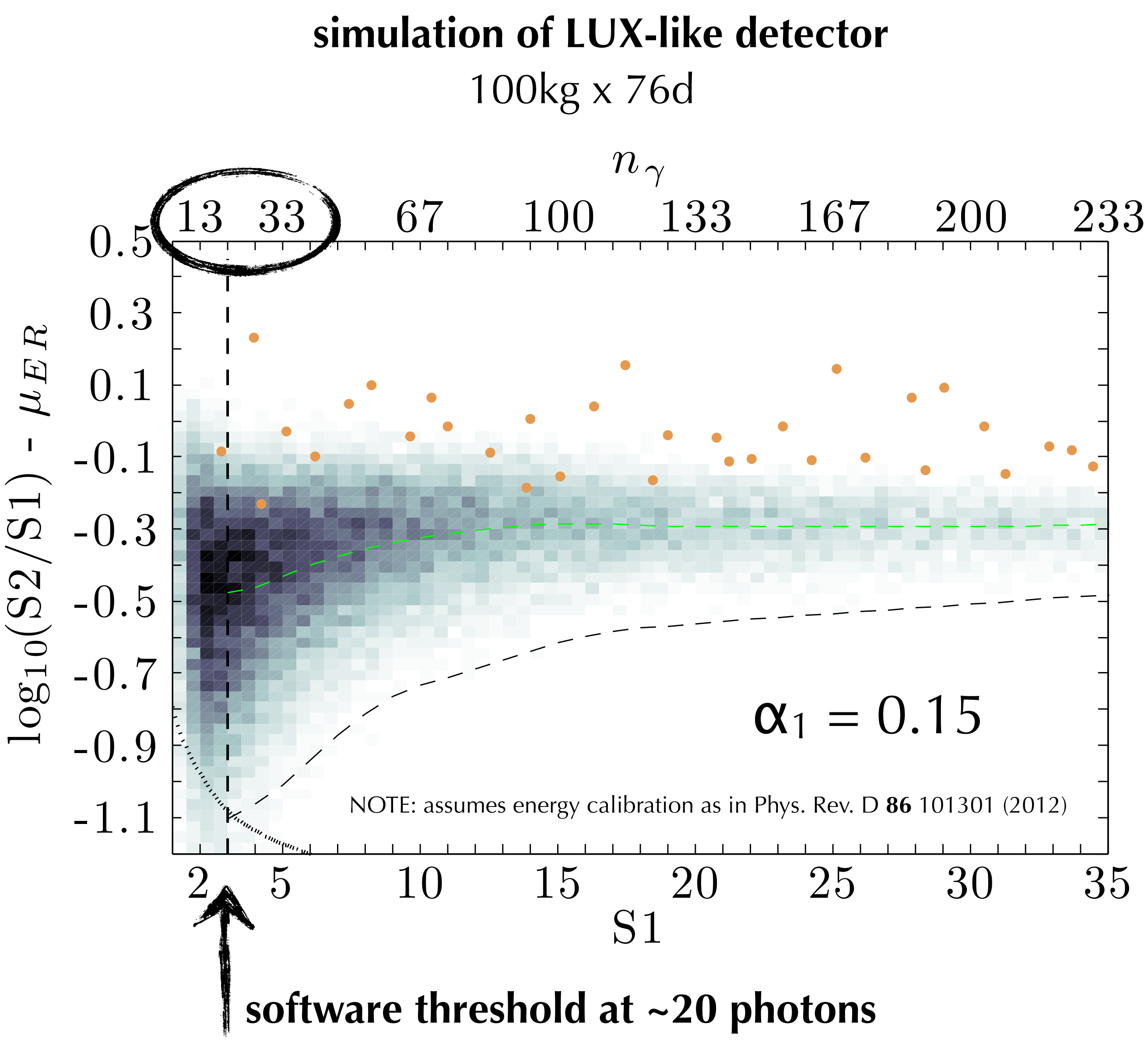


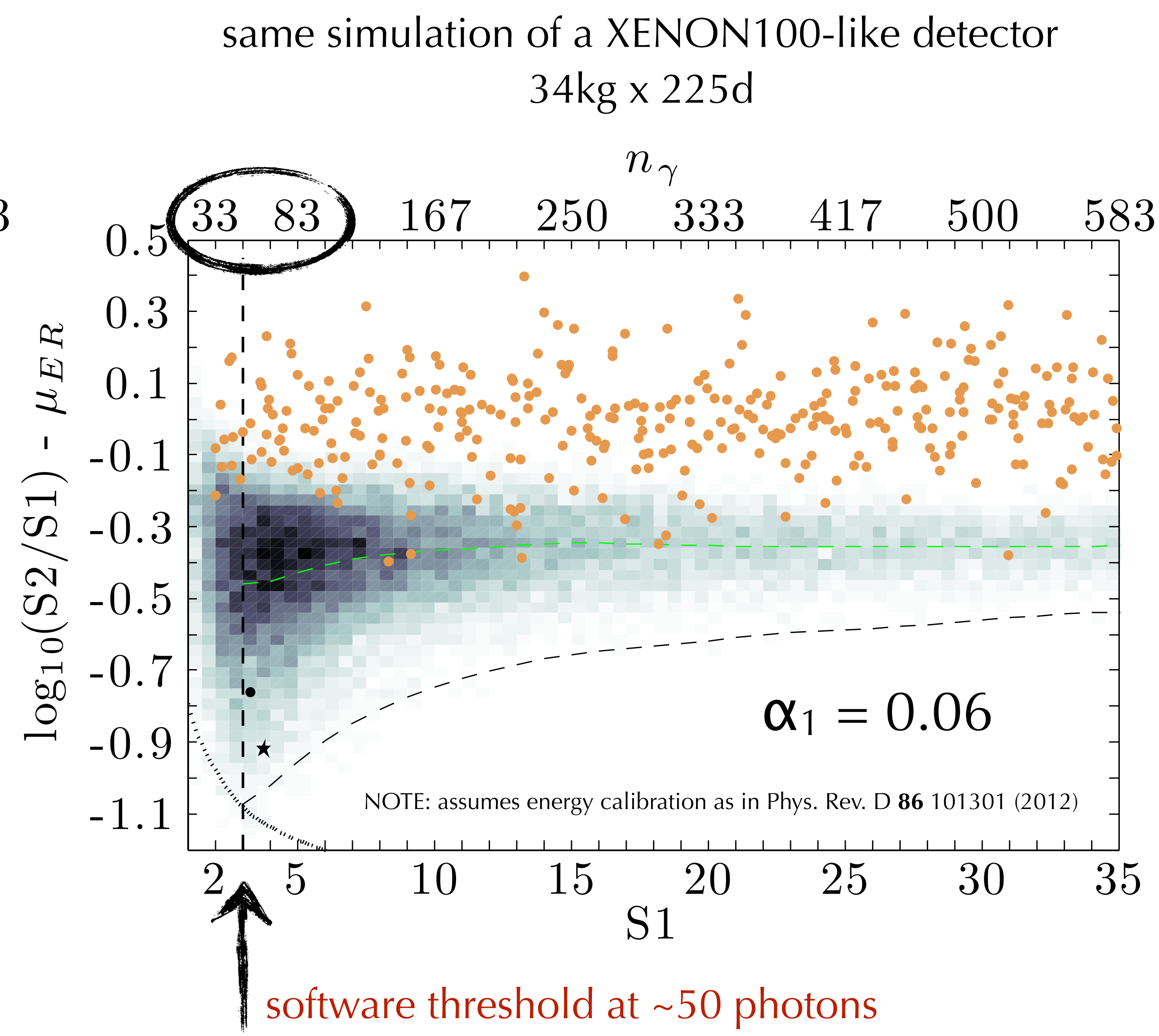
and compare a simulation of a XENON100-like detector



NB: apparent difference in band width is a binning artifact -- the lower dashed line is -3σ in both plots

LUX discovery potential



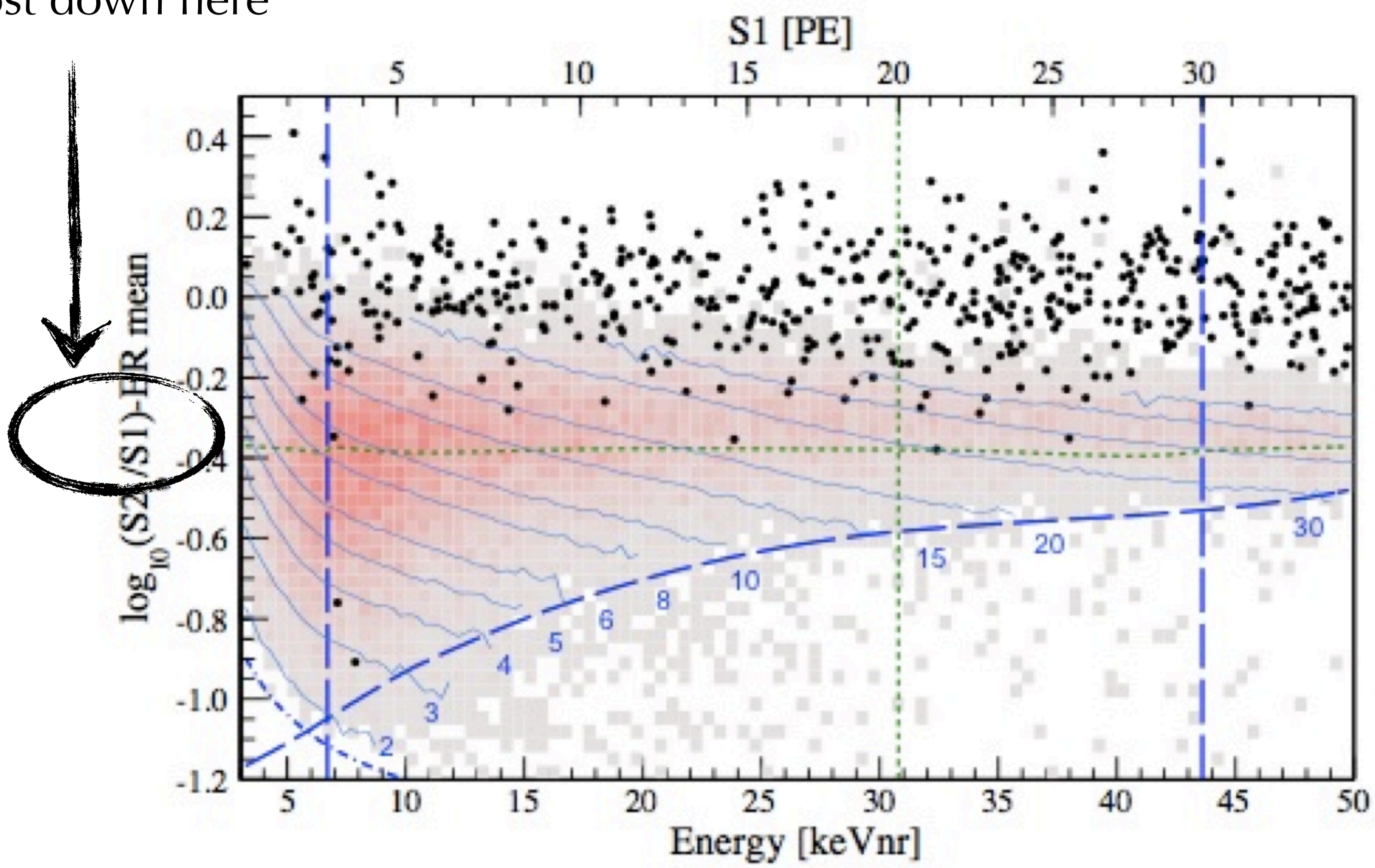


- LUX is bigger, self-shielding benefit increases exponentially with linear dimension
  - lower background rate => **increased discovery potential**
- LUX will have a factor ~x2.5 lower photon detection threshold, period.
  - n_γ does not depend on energy calibration (L_{eff}, Q_y)
  - probably leads to 1-2 keV in energy

Nuclear recoil energy scale in liquid xenon

"Confusion now hath made his masterpiece" - Macduff, in Macbeth Act II Scene III

most of the 2 keV signal is lost down here

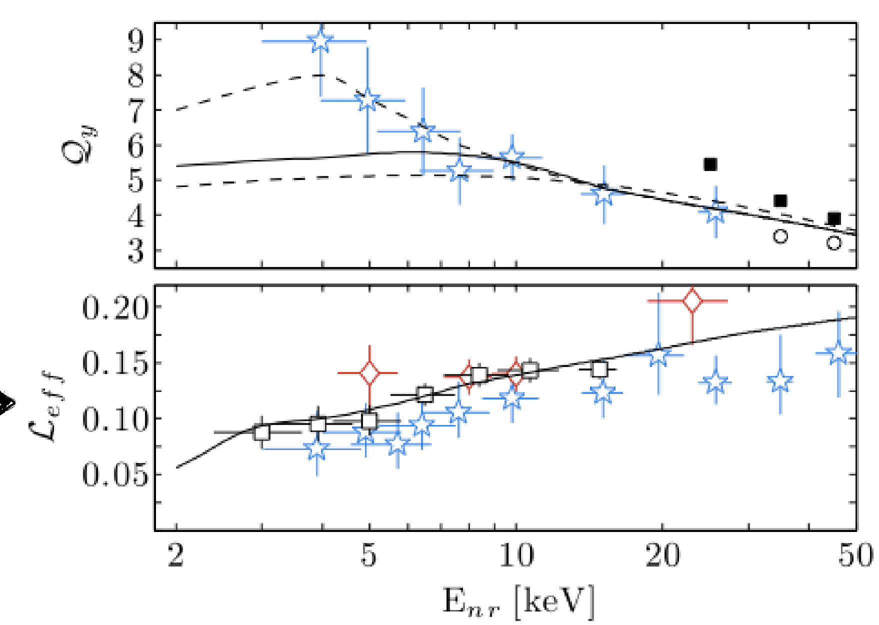


measured quantity

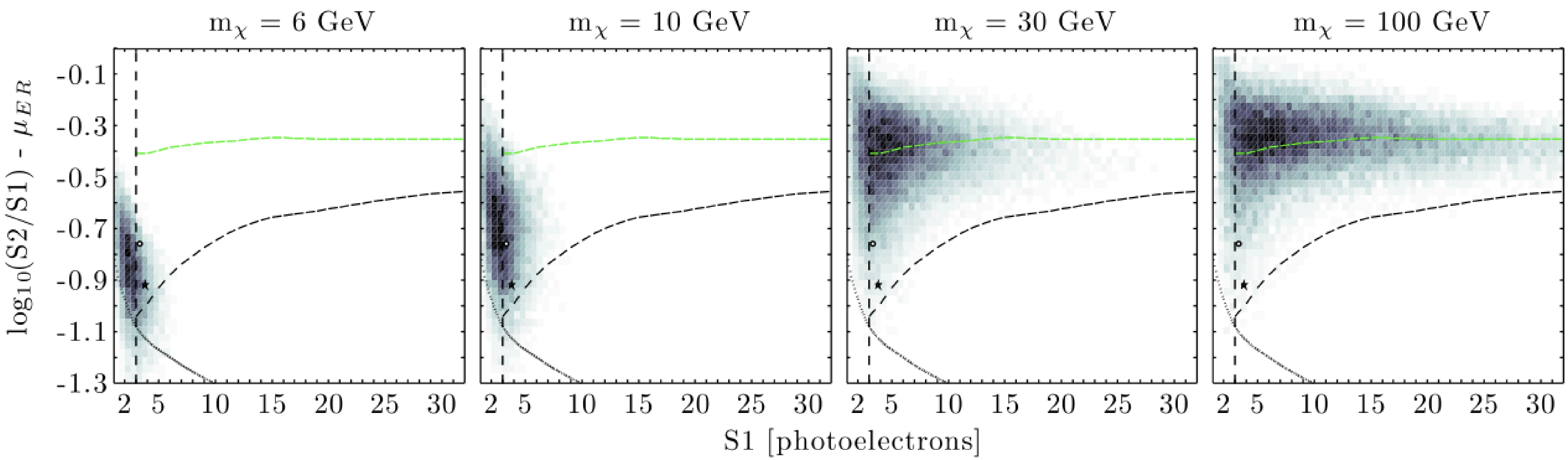
correctly derived quantity

incorrectly derived quantity, except close to the centroid of NR distribution

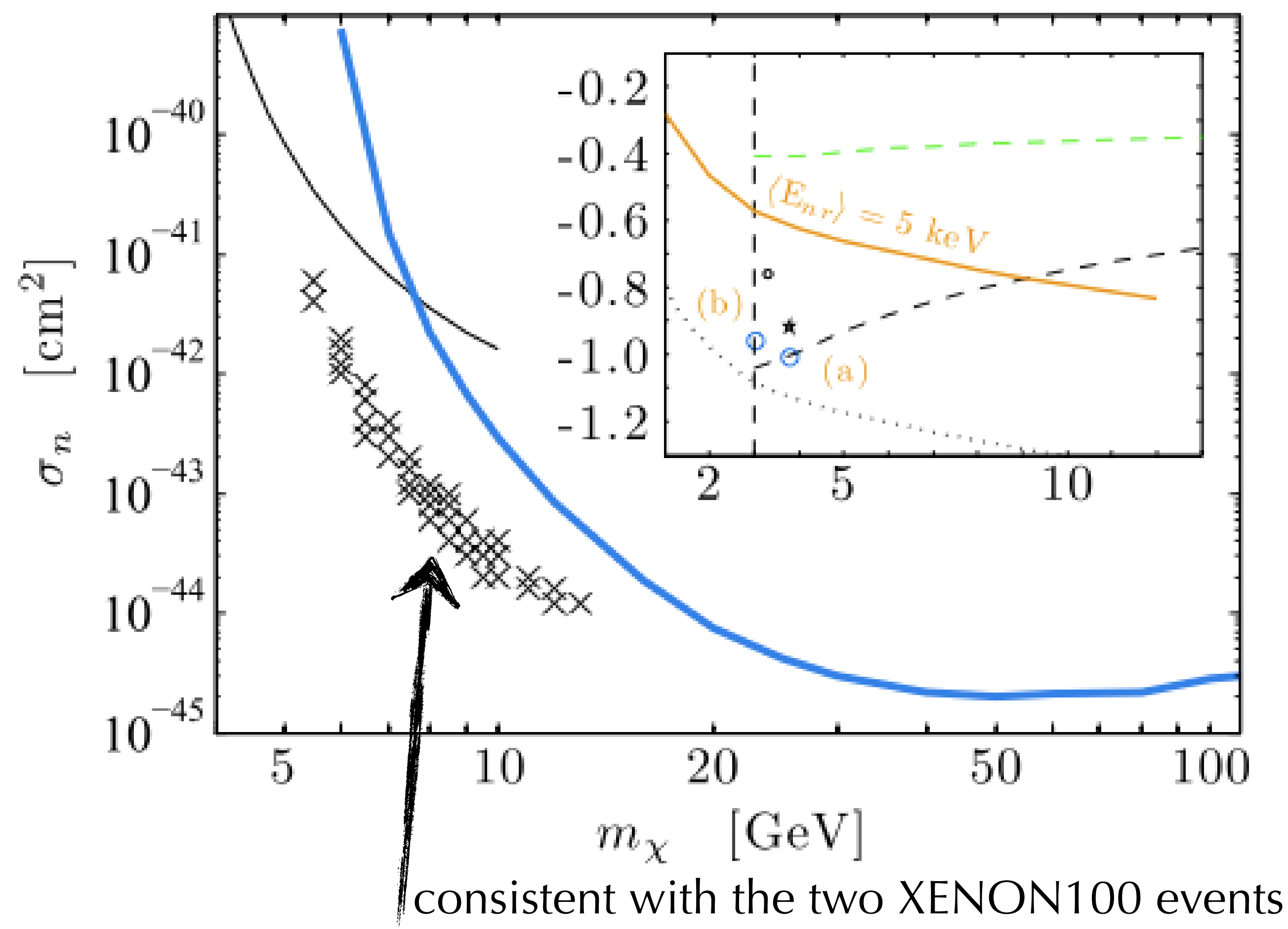
XENON100, Phys. Rev. Lett. **109** 181301 (2012)
with energy scale overlaid from
PS, Phys. Rev. D **86** 101301 (2012)



both derived quantities assume the same "L_{eff}" curve!
(L_{eff} is the energy calibration for scintillation)



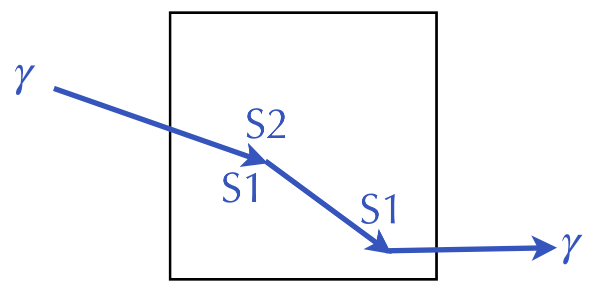
PS, Phys. Rev. D **86** 101301 (2012)



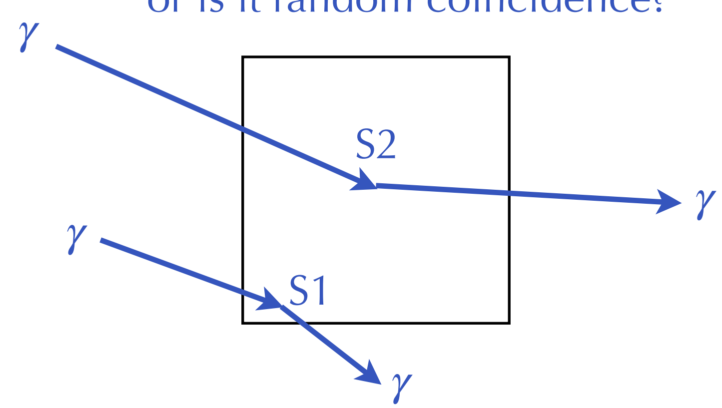
- based on a consistent treatment of low-energy fluctuations
- light DM signal first appears at -3σ from calibration centroid
- I don't really think these two events are DM

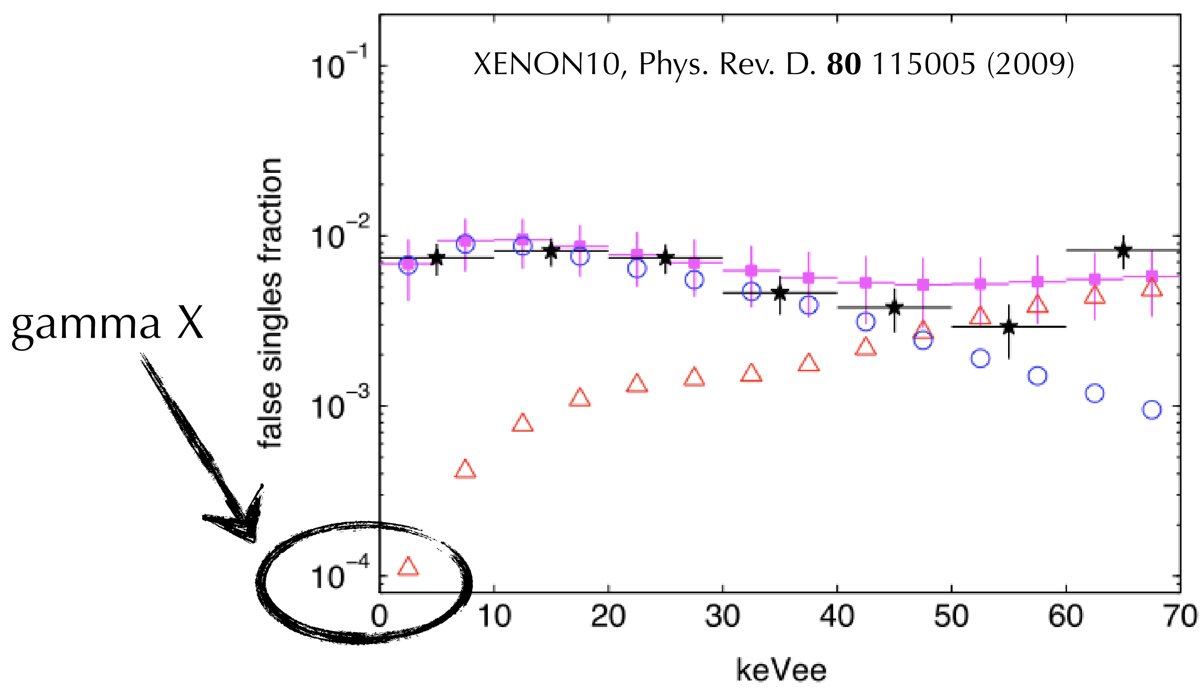
what is the mechanism behind the XENON100 background events?

XENON100: its "gamma X"



or is it random coincidence?





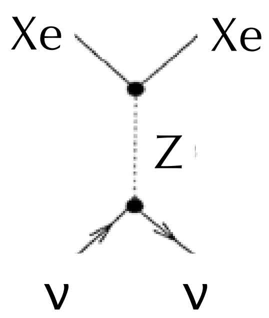
gamma X (red triangles) should preferentially populate higher-energy region

in principle, random coincidence rate can be calculated, based on measured S1-only rate

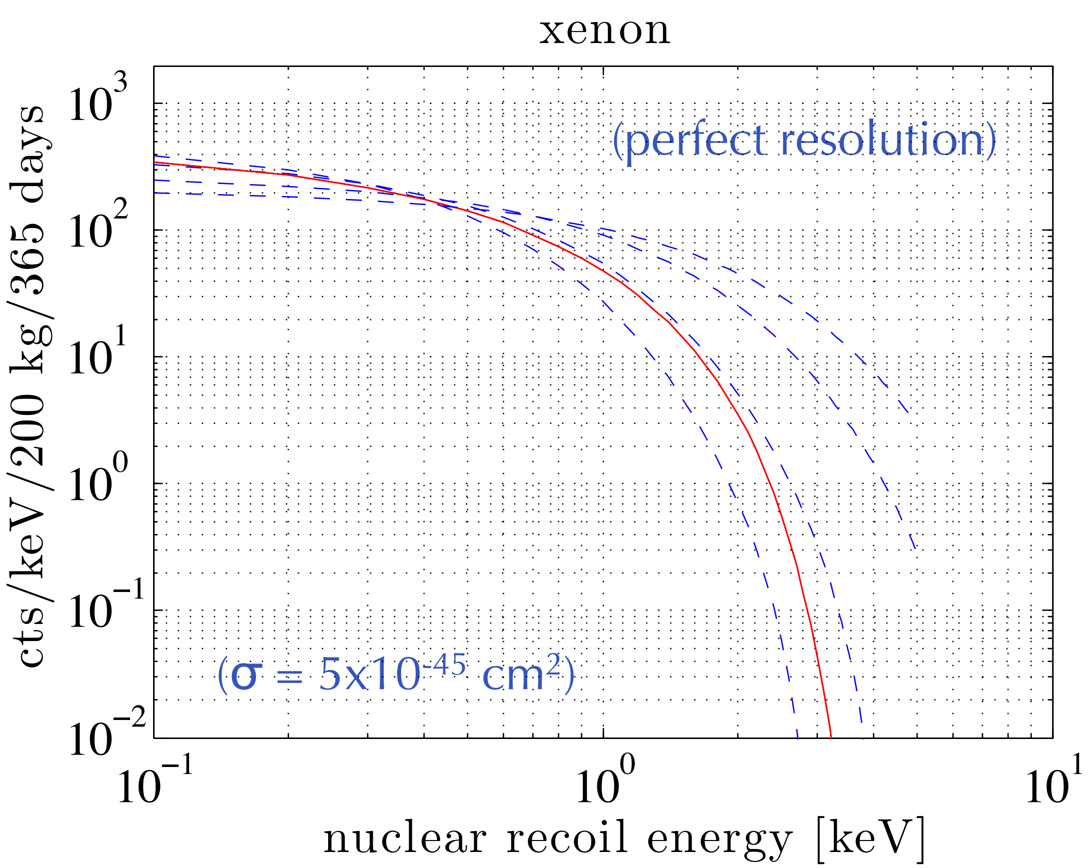
(minimizing that rate would mitigate the background for light dark matter search..)

bottom line: need a comprehensive understanding of background pathologies

Other "backgrounds": coherent neutrino nucleus scattering



- calculable, never-observed interaction
- ^{8}B neutrino end point ~ 15 MeV
- predicted energy spectrum in xenon (below, red)

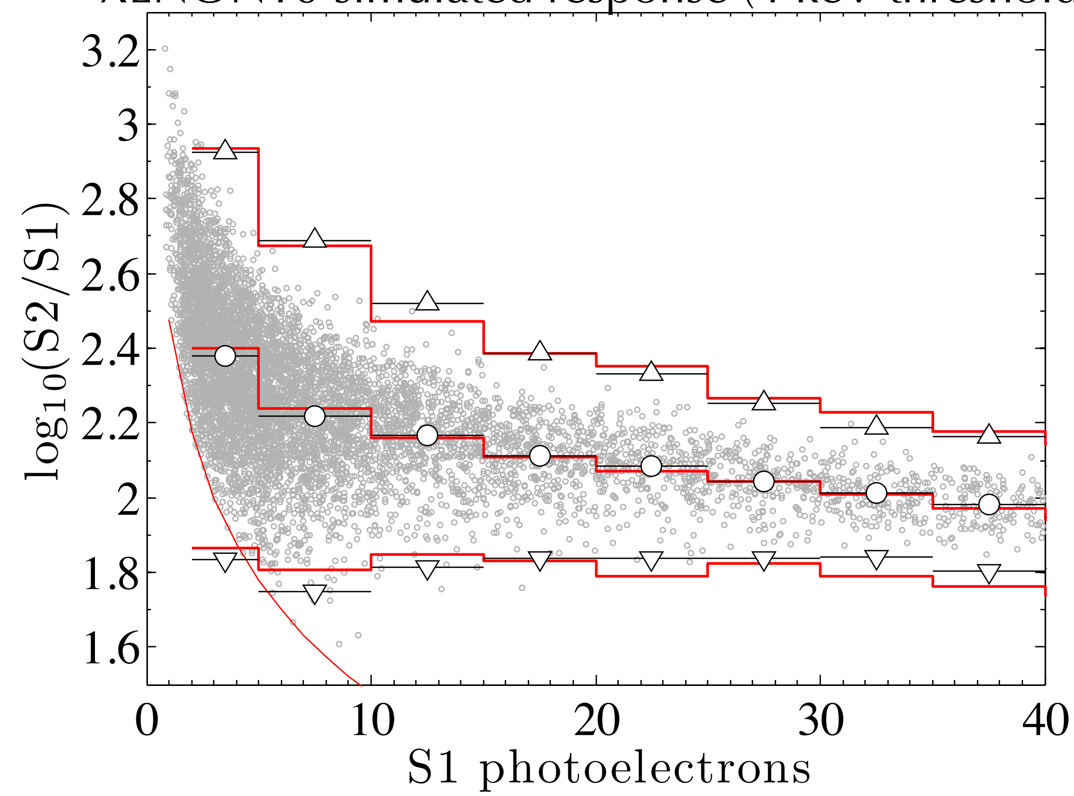


dashed: DM masses 5, 6, 8 and 10 GeV
solid: ^{8}B coherent neutrinos

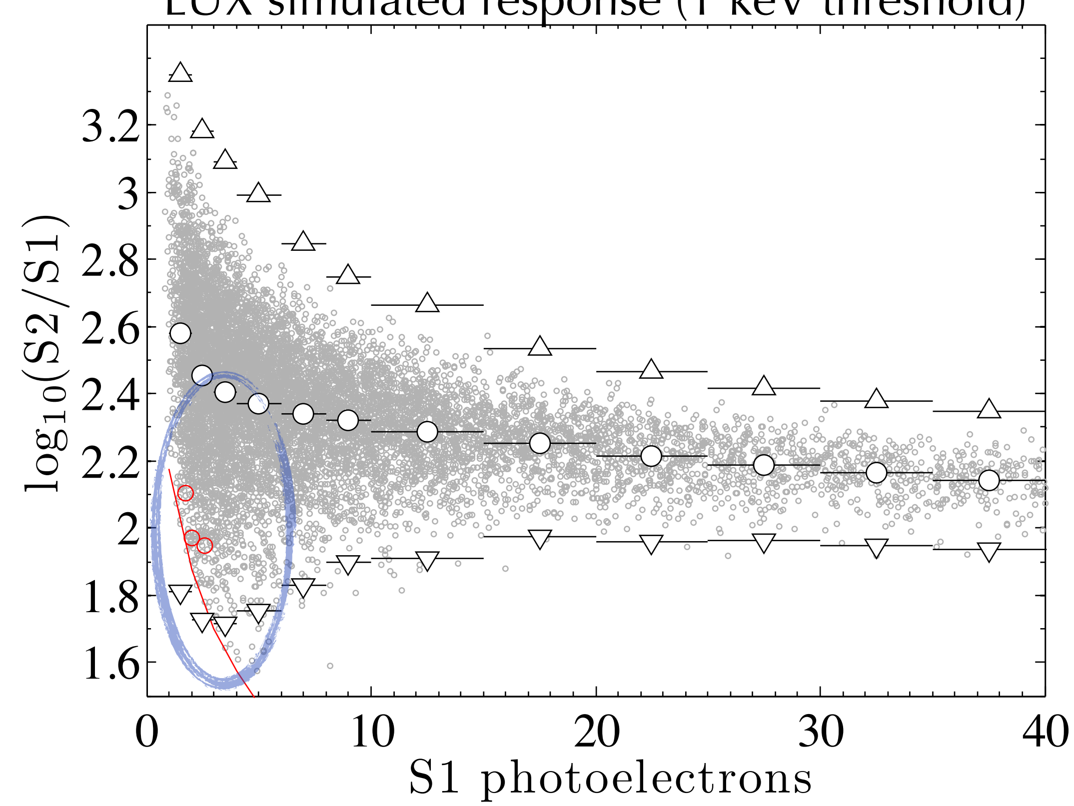
- detection in LUX is dependent on actual energy threshold: 1 keV is speculative

recent literature: Strigari, New J. Phys. 11 (2009) 105011
Anderson et al, Phys Rev D **84** 013008 (2011)

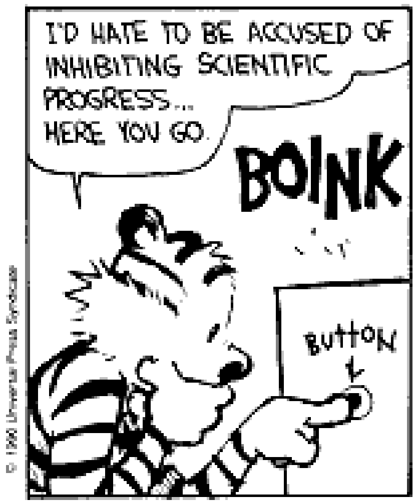
XENON10 simulated response (4 keV threshold)



LUX simulated response (1 keV threshold)



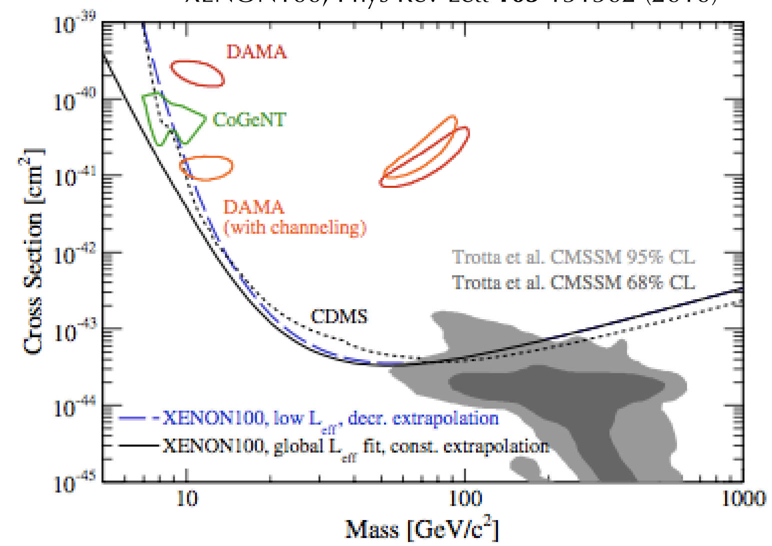
Scientific progress looks like what?



(it looks mostly like pusuit of WIMPs)

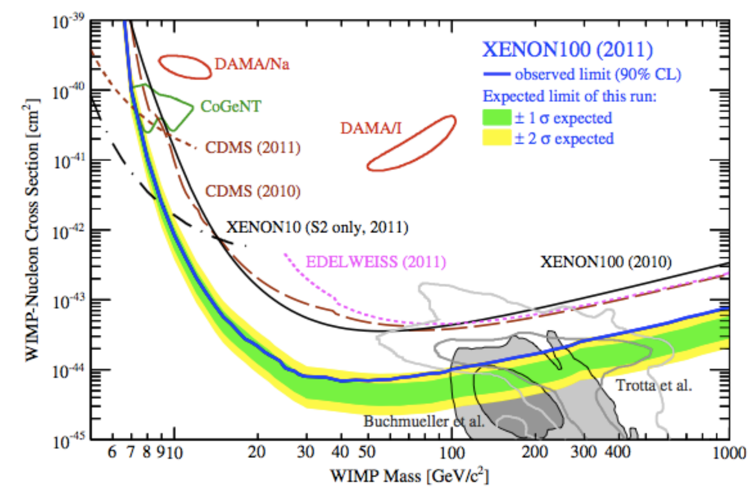
2010: σ ~ 4x10^{-44} cm^2

XENON100, Phys Rev Lett **105** 131302 (2010)



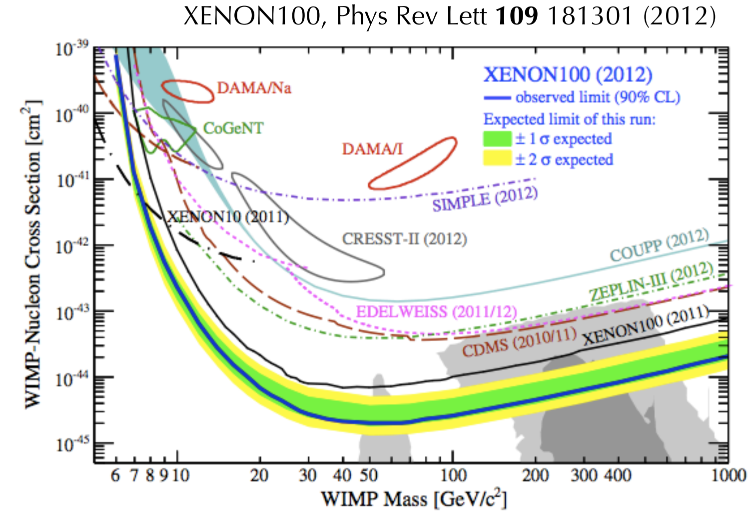
2011: σ ~ 7x10^{-45} cm^2

XENON100, Phys Rev Lett **107** 131302 (2011)

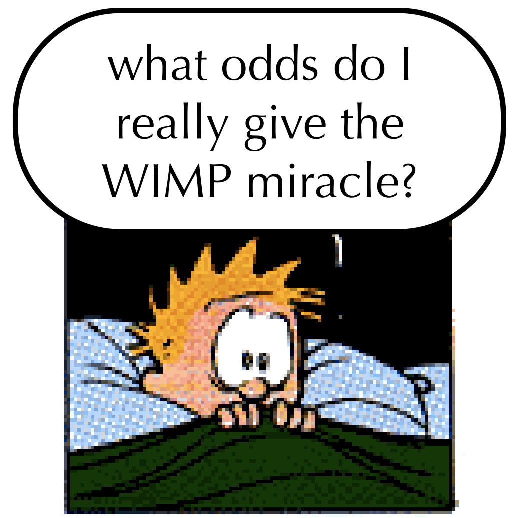


2012: σ ~ 2x10^{-45} cm^2

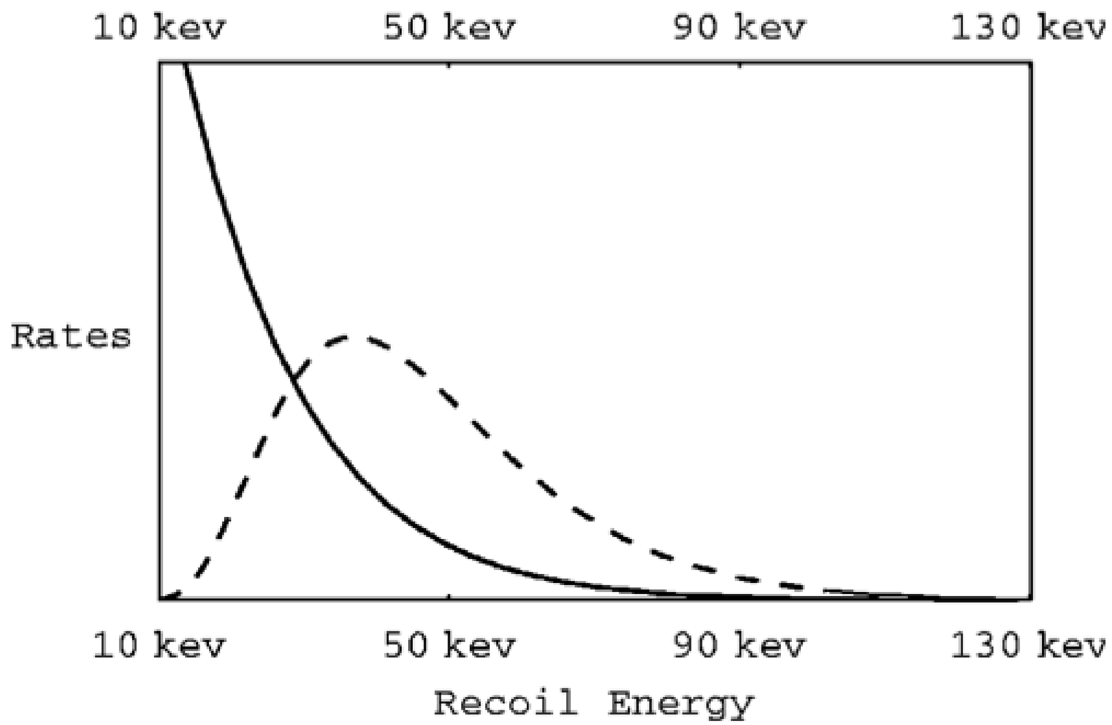
XENON100, Phys Rev Lett **109** 181301 (2012)



standard WIMP hypothesis is “well-motivated” but not the only possibility

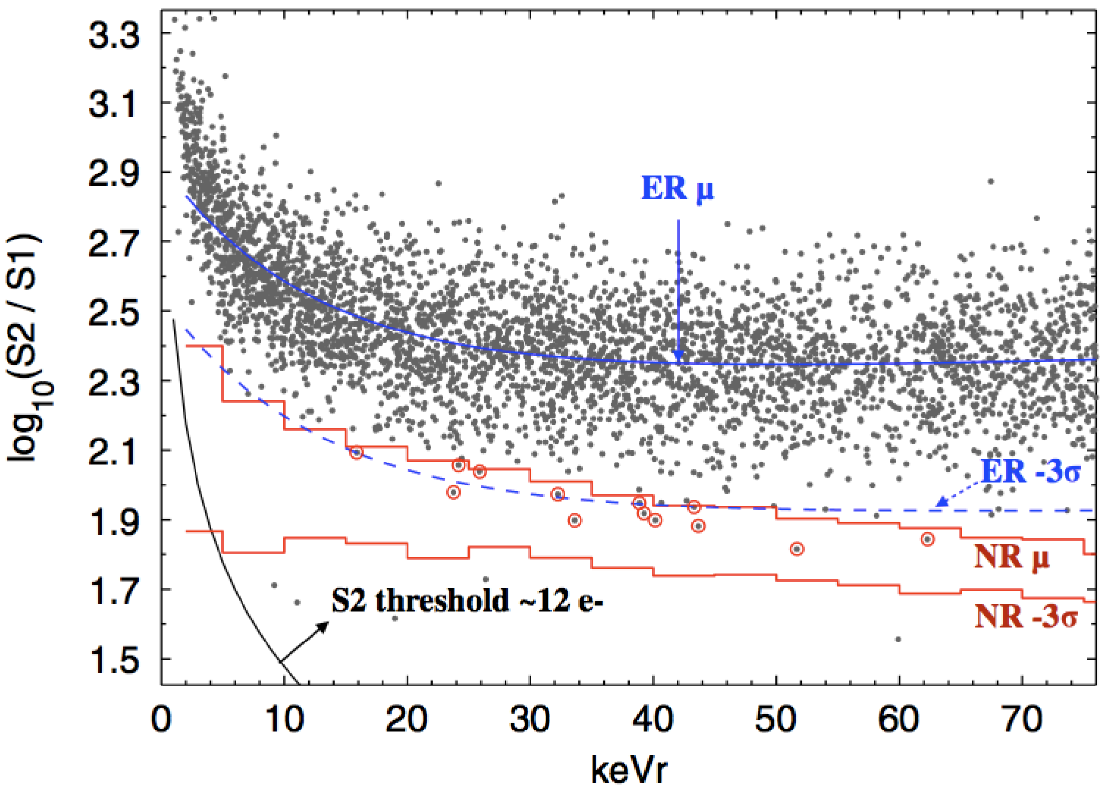


Smith and Weiner, Phys Rev D 64 043502 (2001)



- postulate that DM upscatters to a heavier state (~100 keV splitting)
- leads to peaked spectrum rather than exponential
- postulated to reconcile DAMA and CDMS

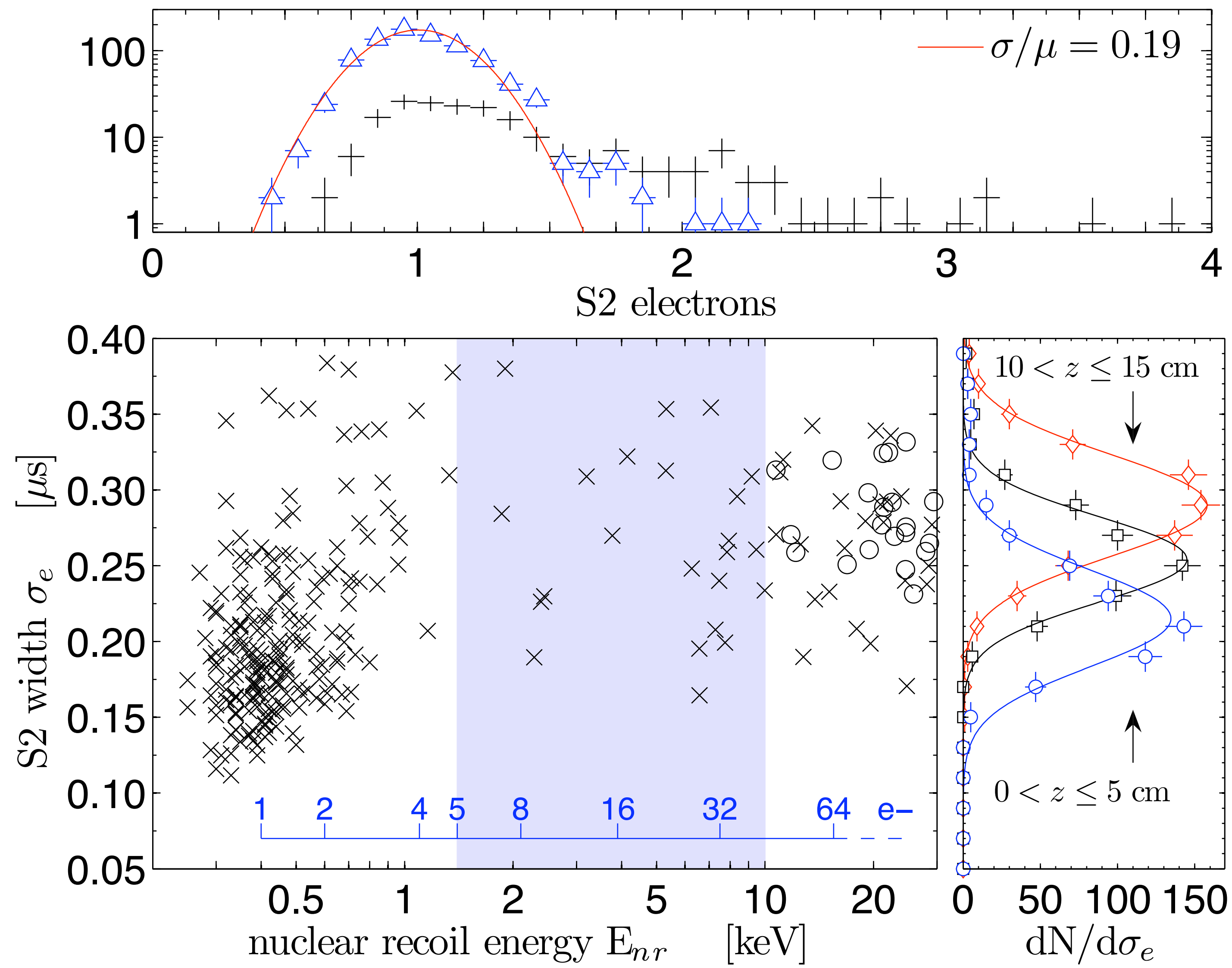
XENON10, Phys Rev D **80** 115005 (2009)

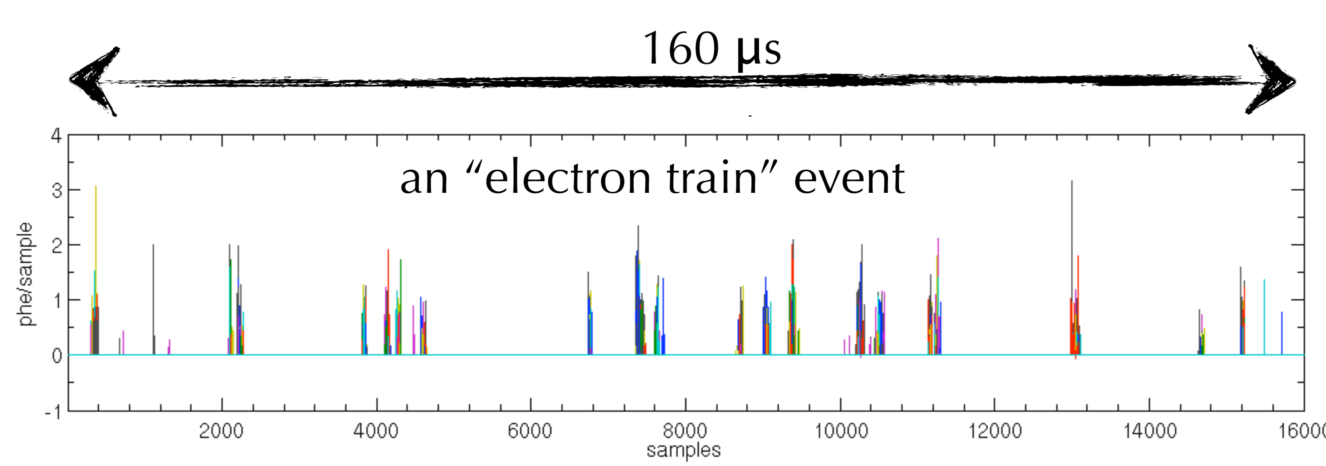


- (right) re-analysis of XENON10 data, across full range of interest to inelastic hypothesis.
- found energy-localized background (!?)
- seems to be present in XENON100 data, too

2010/2011: searching for O(10) GeV dark matter in XENON10

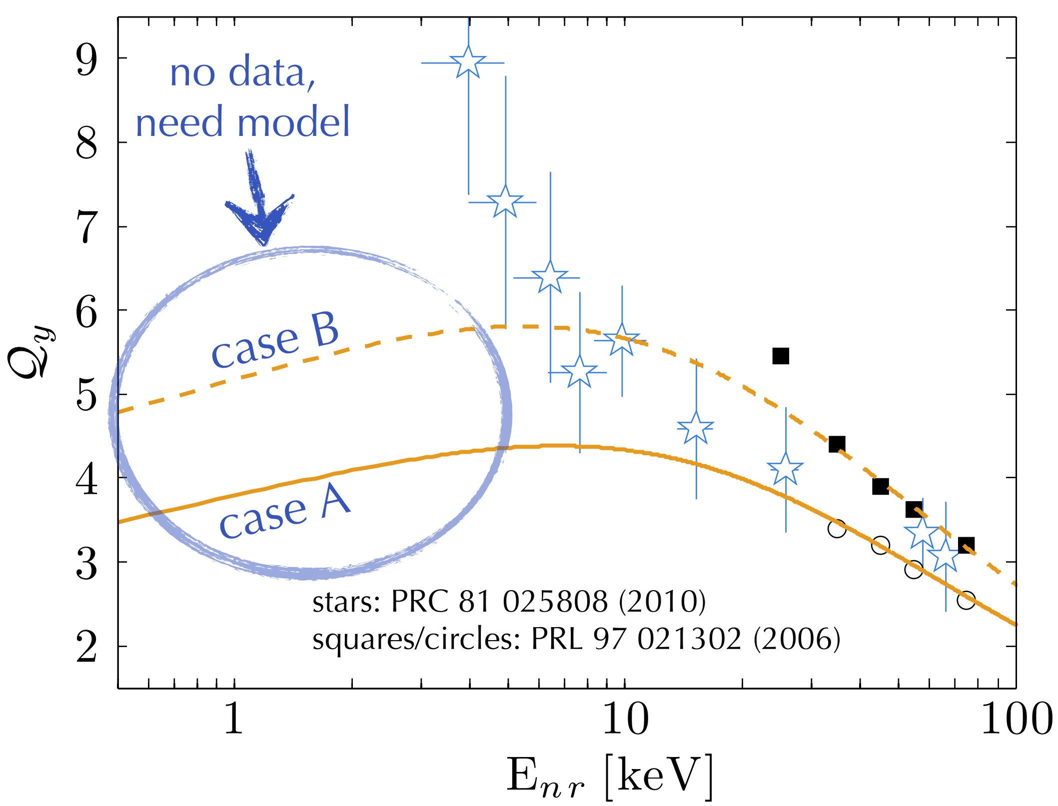
XENON10, Phys. Rev. Lett. 107 051301 (2011)



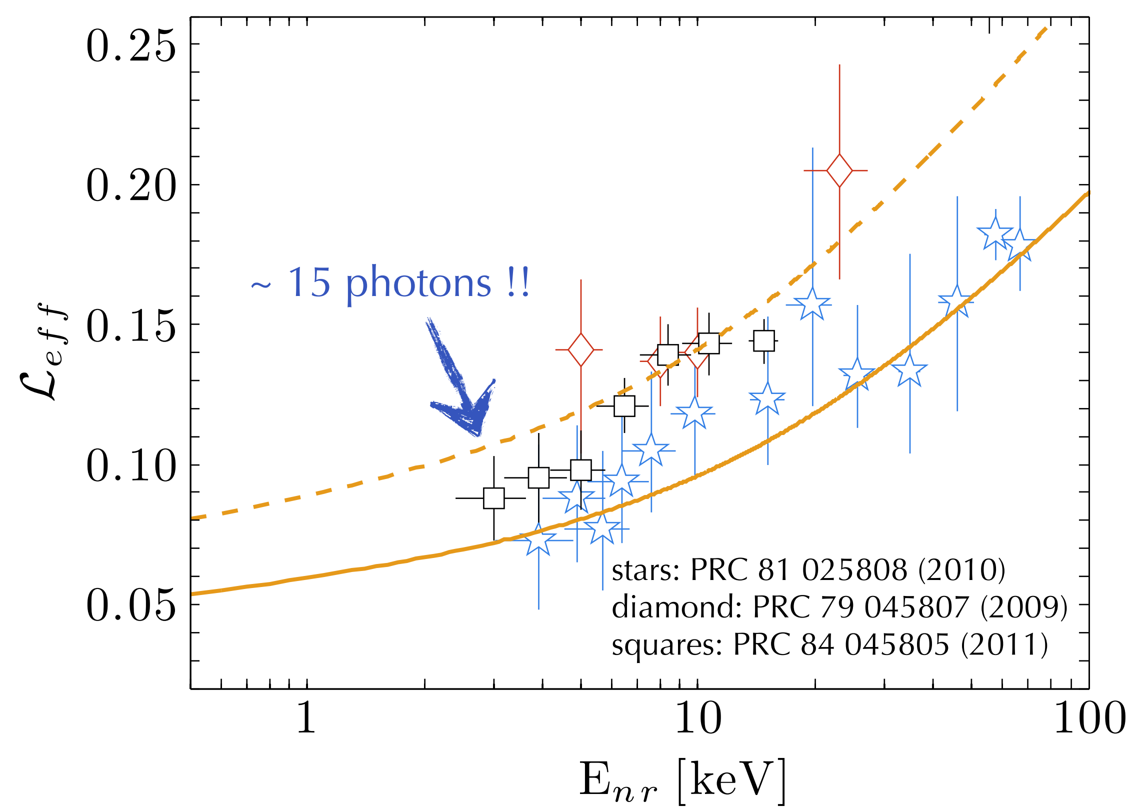


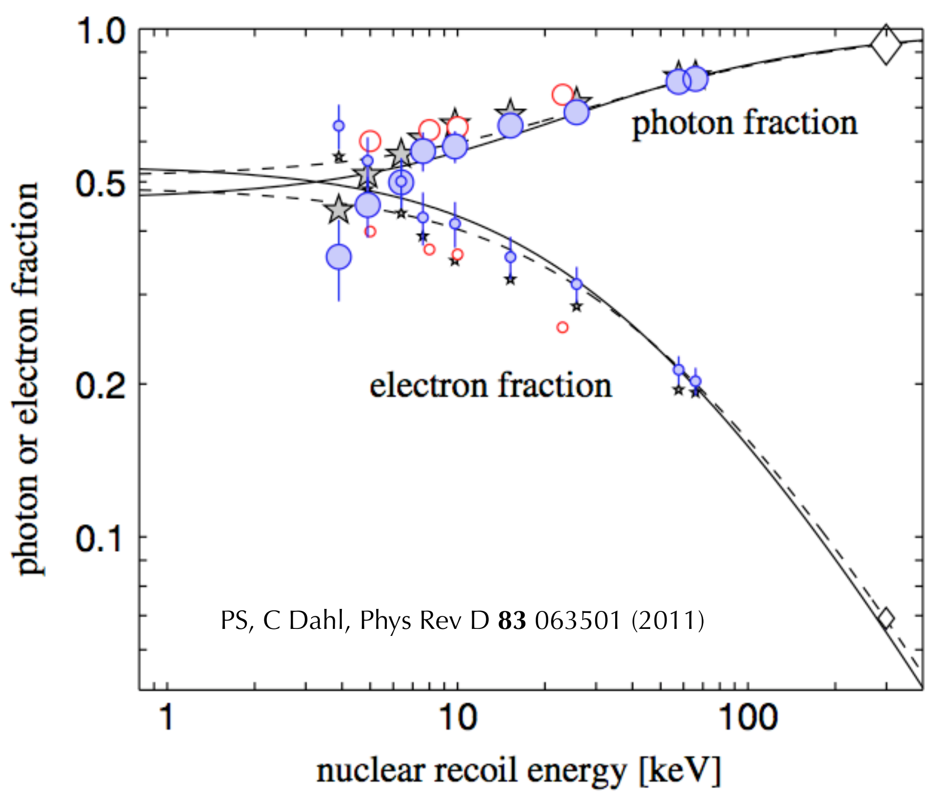
2010: sidetracked by atomic physics of xenon nuclear recoil energy scale

electrons / keV



photons / keV * 0.015



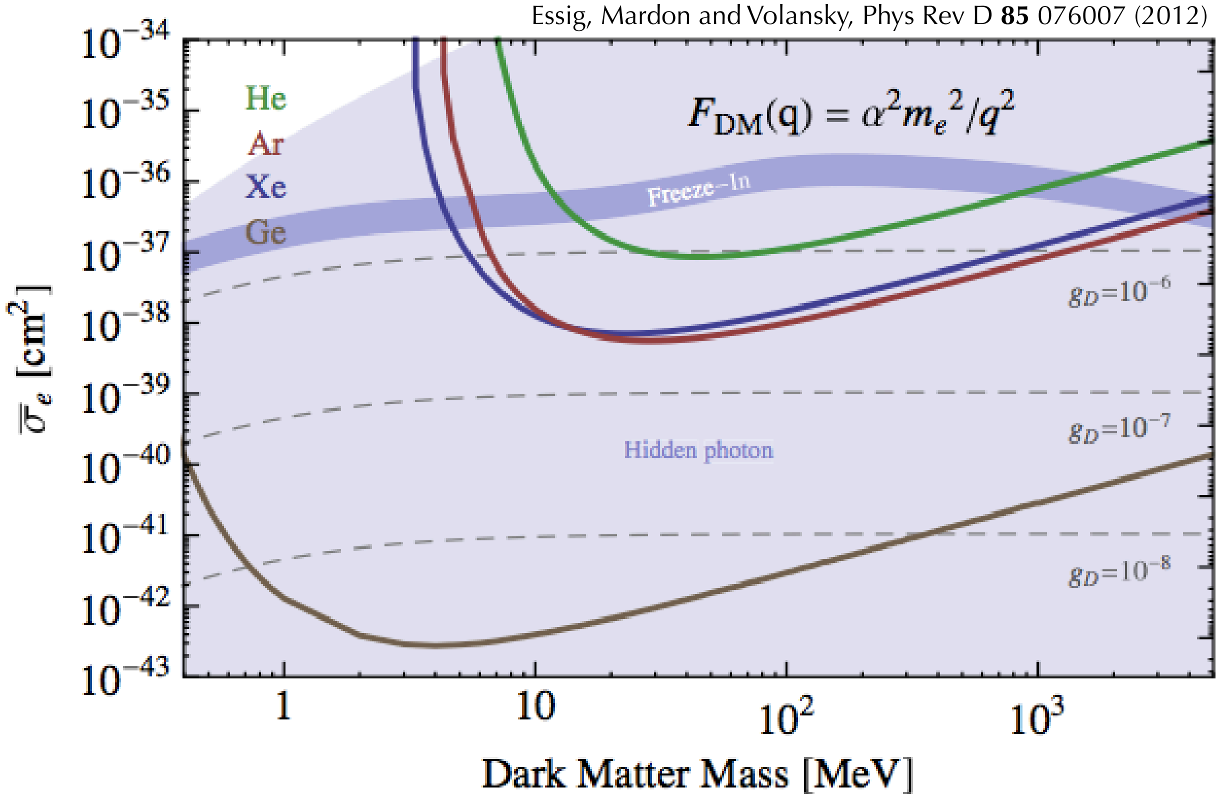


- what you really want to know is how many electrons and photons result from a nuclear recoil
- problem — DM experiments have sensitivity below the lowest energy calibration data points
- problem — dedicated (neutron scattering) calibration data shows systematic disagreement
- step in the right direction — model (solid and dashed curves) predicts general trend but not absolute value

- sub-GeV DM-nucleus scattering generally does not result in measurable signal (simple kinematics)
- so, look for DM-electron scattering!

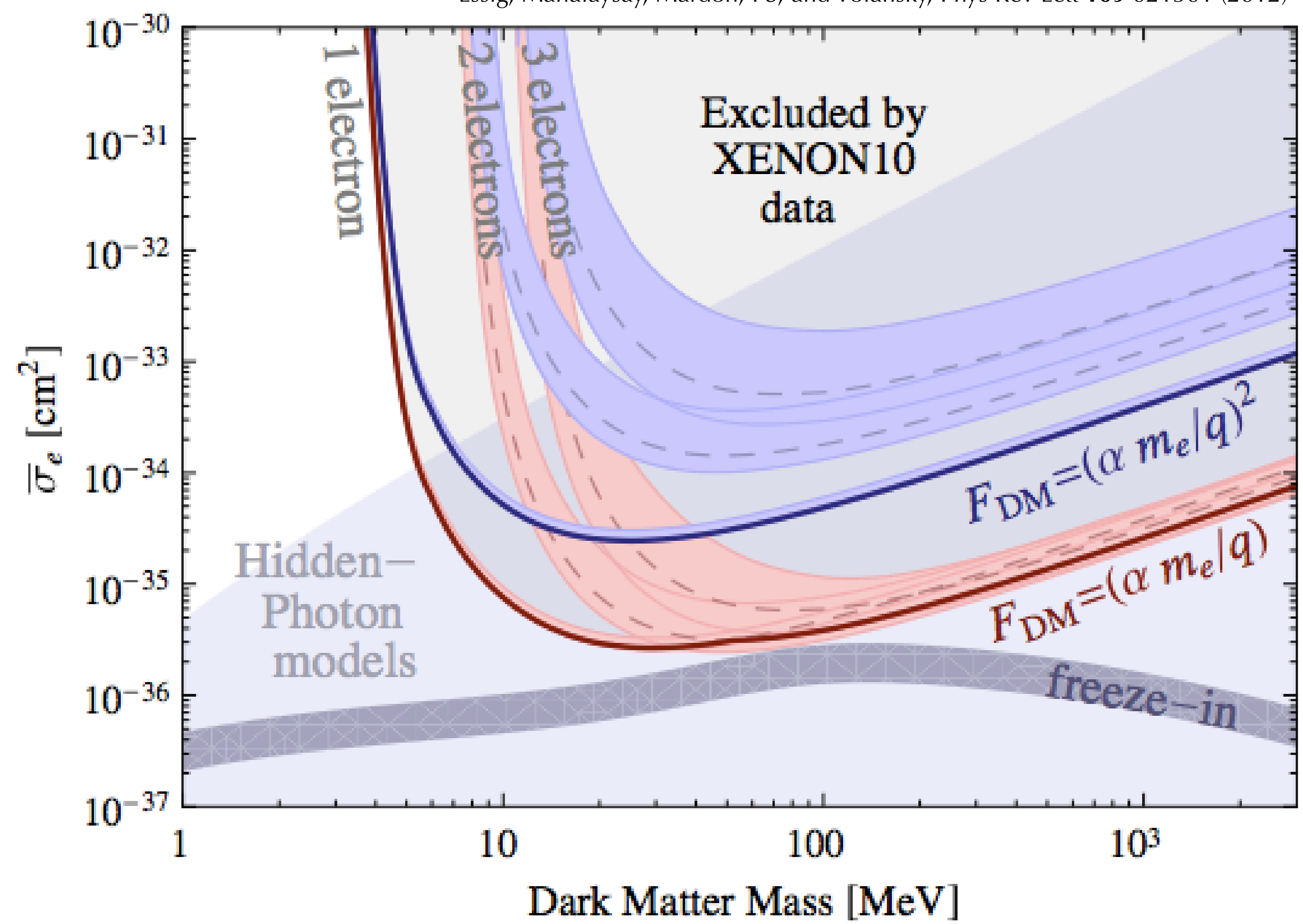
predicted 365 kg day sensitivity (only neutrino bkg)

Essig, Mardon and Volansky, Phys Rev D **85** 076007 (2012)



obtained 15 kg day sensitivity (bkg not optional)

Essig, Manalaysay, Mardon, PS, and Volansky, Phys Rev Lett **109** 021301 (2012)

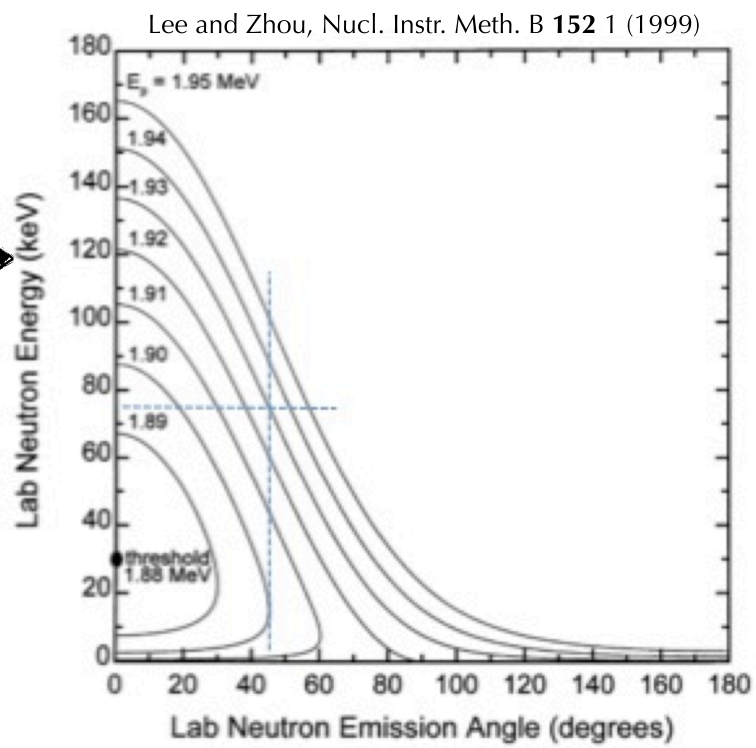


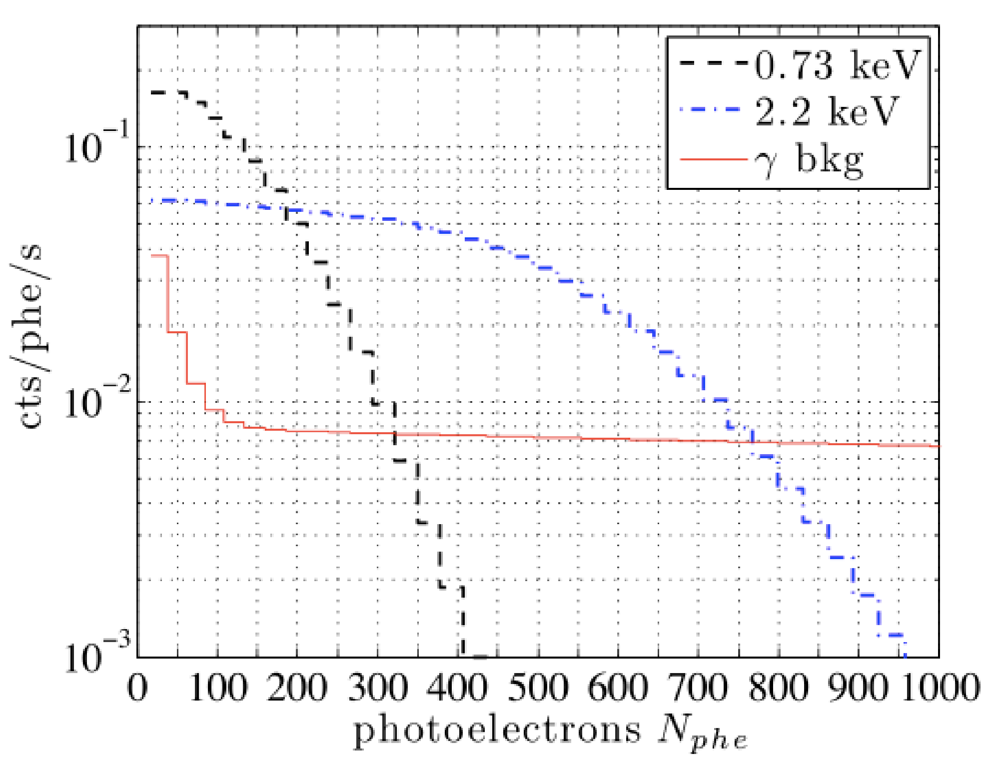
2013+: Sorting out the nuclear recoil energy scale in xenon

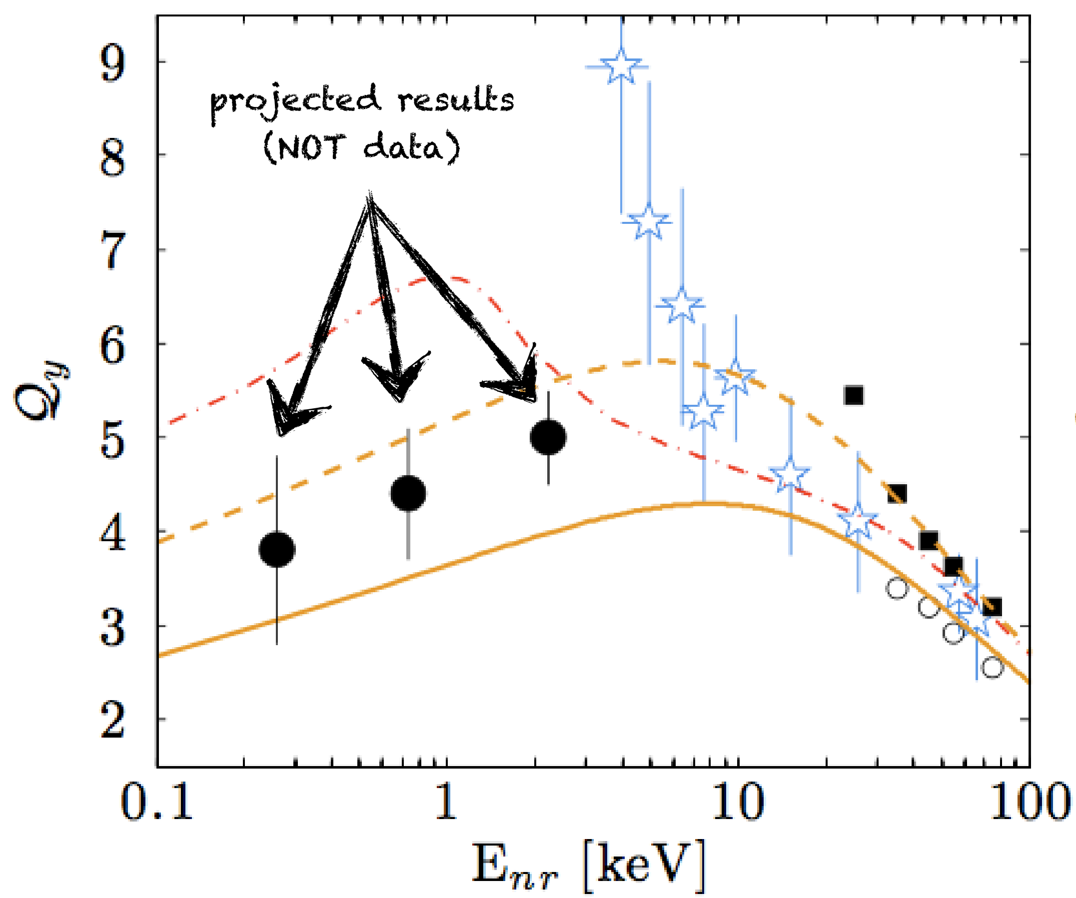
problem
- previous measurements use 2.5 MeV DD neutrons.. need to tag low angle scatters (and detectors subtend several degrees)

- use ^{7}Li(p,n)^{7}Be reaction
- ...along with ^{56}Fe transmission resonances
- obtain a beam of mono-energetic neutrons at 24 keV and 73 keV

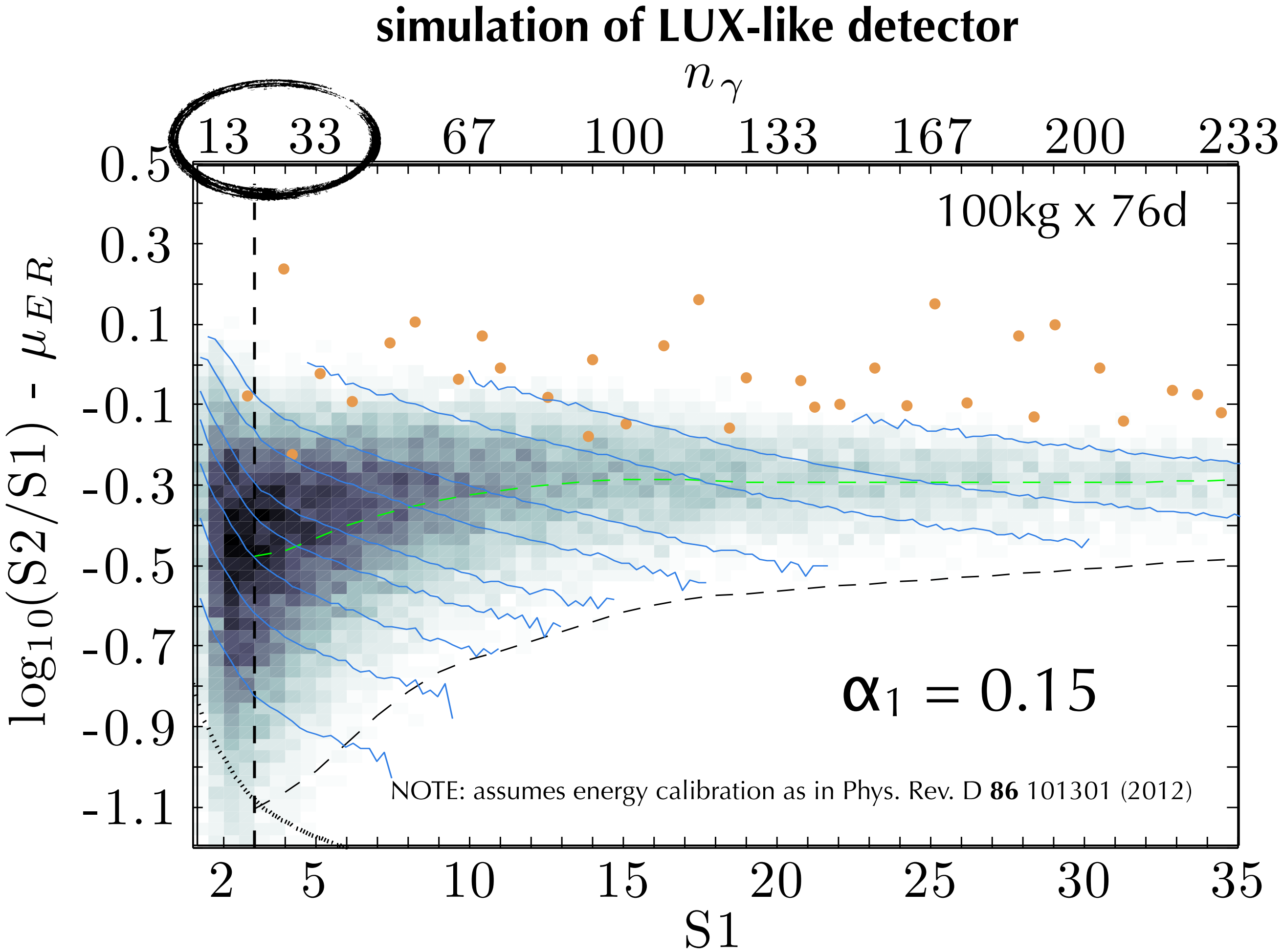
lower sysematics!
- measure endpoint nuclear recoil energy

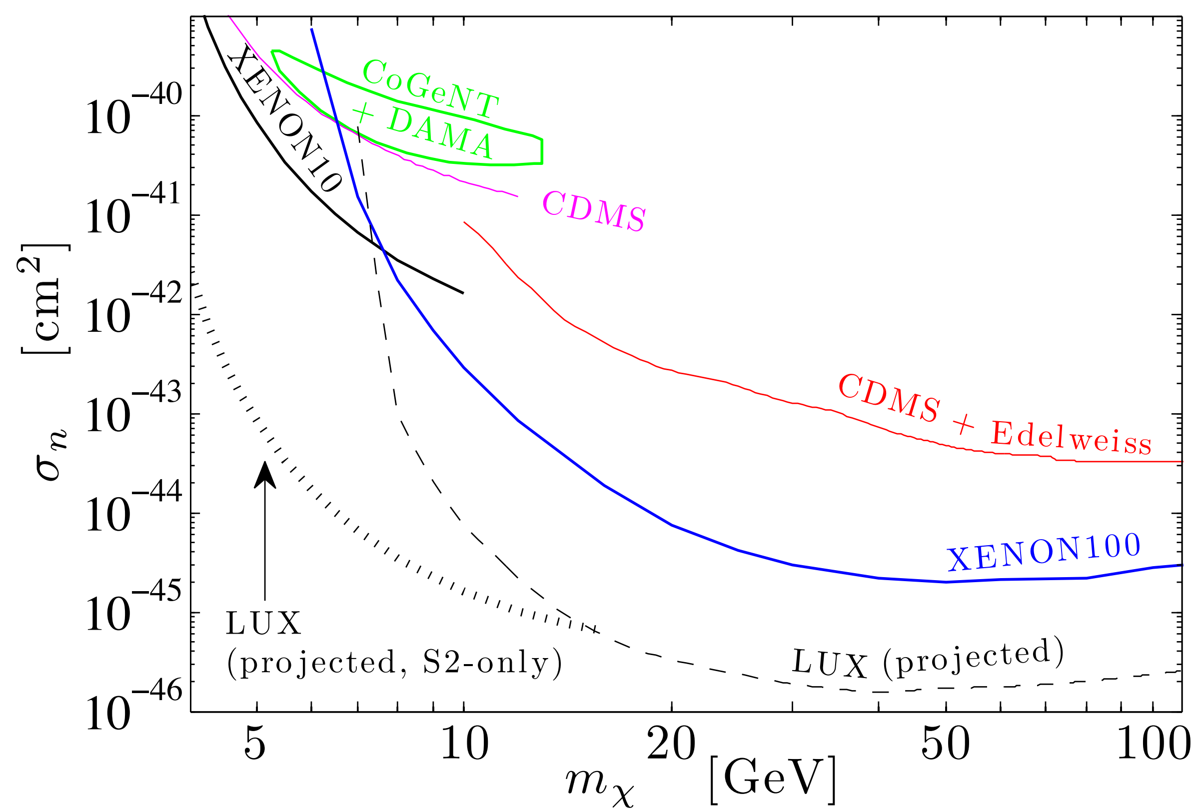




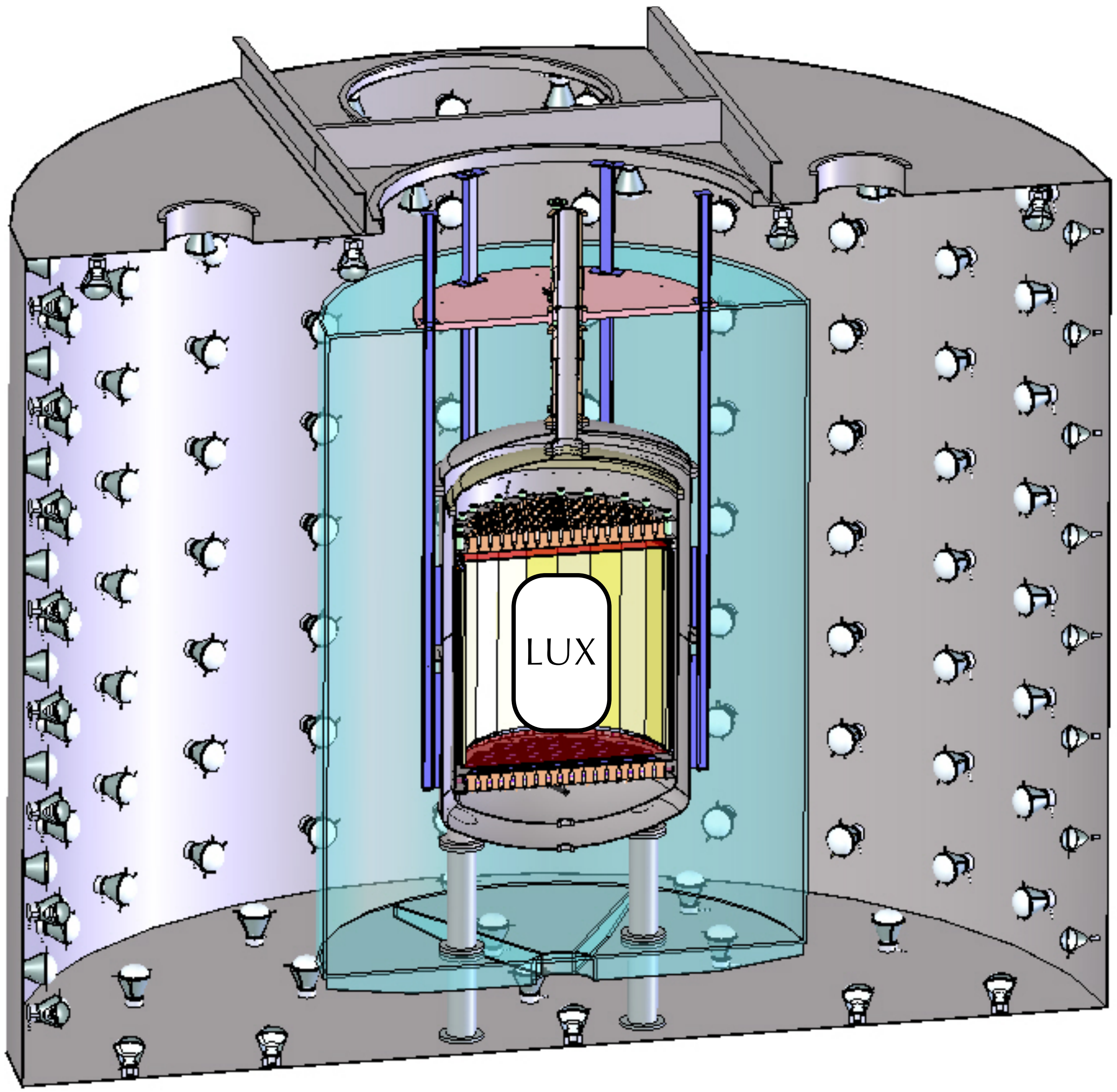


in 2013, LUX will (probably) first and foremost address garden variety WIMPs

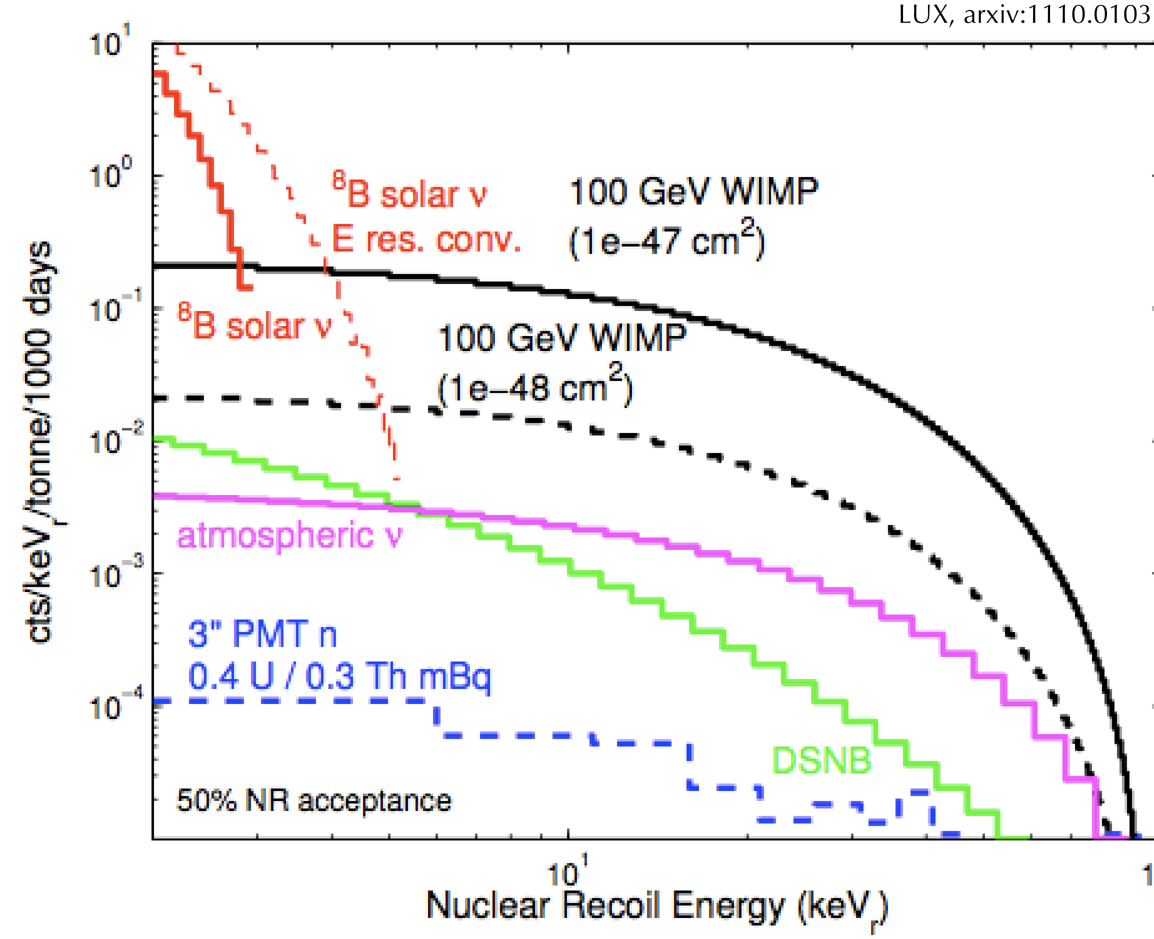




LUX is about to generate an awesome, unprecedented, low-background data set
exciting to think about new possible DM signals/searches



LUX, arxiv:1110.0103



- LZ: 7000 kg liquid xenon target
- 350 kg LUX shown inset for comparison
- LZ expected sensitivity: $\sigma \sim 10^{-48}$ cm^2
- The “ultimate” xenon detector, limited by neutrino backgrounds

Thanks!

Extra slides follow

LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
Carlos Hernandez Faham	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student
Samuel Chang	Graduate Student
Dongqing Huang	Graduate Student

Case Western Reserve

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Dan Akerib	PI, Professor
Mike Dragowsky	Research Associate Professor
Tom Coffey	Research Associate
Carmen Carmona	Postdoc
Karen Gibson	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student
Tim Ivancic	Graduate Student

Imperial College London

Henrique Araujo	PI, Senior Lecturer
Tim Sumner	Professor
Alastair Currie	Postdoc

Lawrence Berkeley + UC Berkeley

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Victor Gehman	Scientist
David Taylor	Engineer
Mia ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors
Dennis Carr	Mechanical Technician
Kareem Kazkaz	Staff Physicist
Peter Sorensen	Staff Physicist
John Bower	Engineer

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Luiz de Viveiros	Postdoc
Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

SD School of Mines

Xinhua Bai	PI, Professor

Texas A&M

James White	PI, Professor
Robert Webb	Professor
Rachel Mannino	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Robert Svoboda	Professor
Richard Lander	Professor
Britt Hollbrook	Senior Engineer
John Thomson	Senior Machinist
Matthew Szydagis	Postdoc
Richard Ott	Postdoc
Jeremy Mock	Graduate Student
James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Dean White	Engineer
Susanne Kyre	Engineer
Curt Nehrkorn	Graduate Student

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Alex Murphy	PI, Reader
James Dobson	Postdoc
Lea Reichhart	Graduate student

University of Maryland

Carter Hall	PI, Professor
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Richard Knoche	Graduate Student

University of Rochester

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Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Mongkol Moongweluwan	Graduate Student

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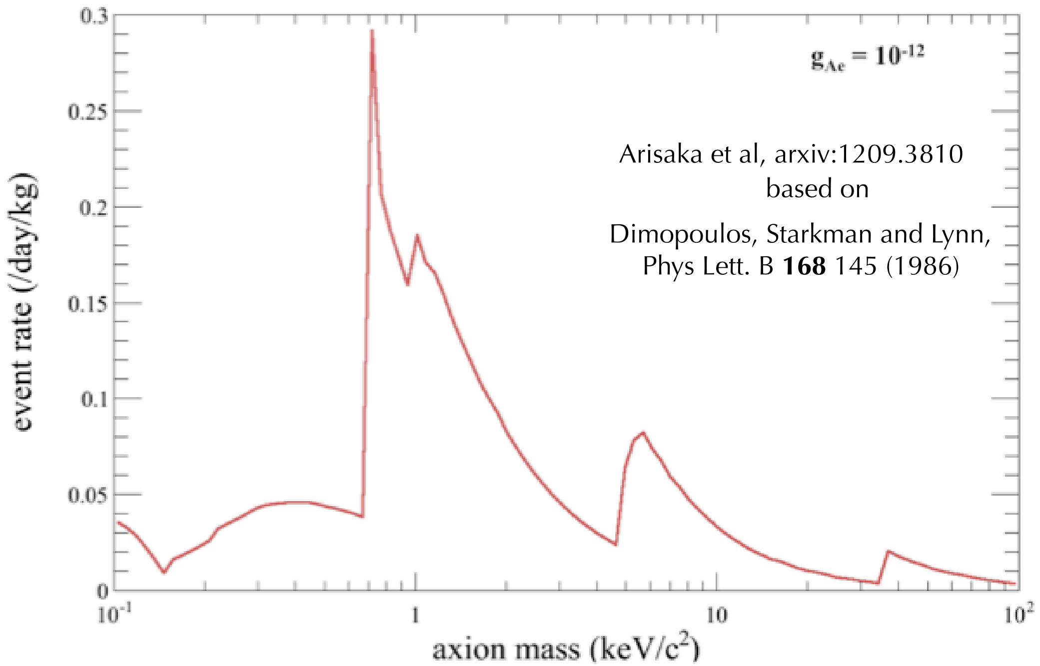
Dana Byram	Graduate Student
Chris Chiller	Graduate Student
Angela Chiller	Graduate Student

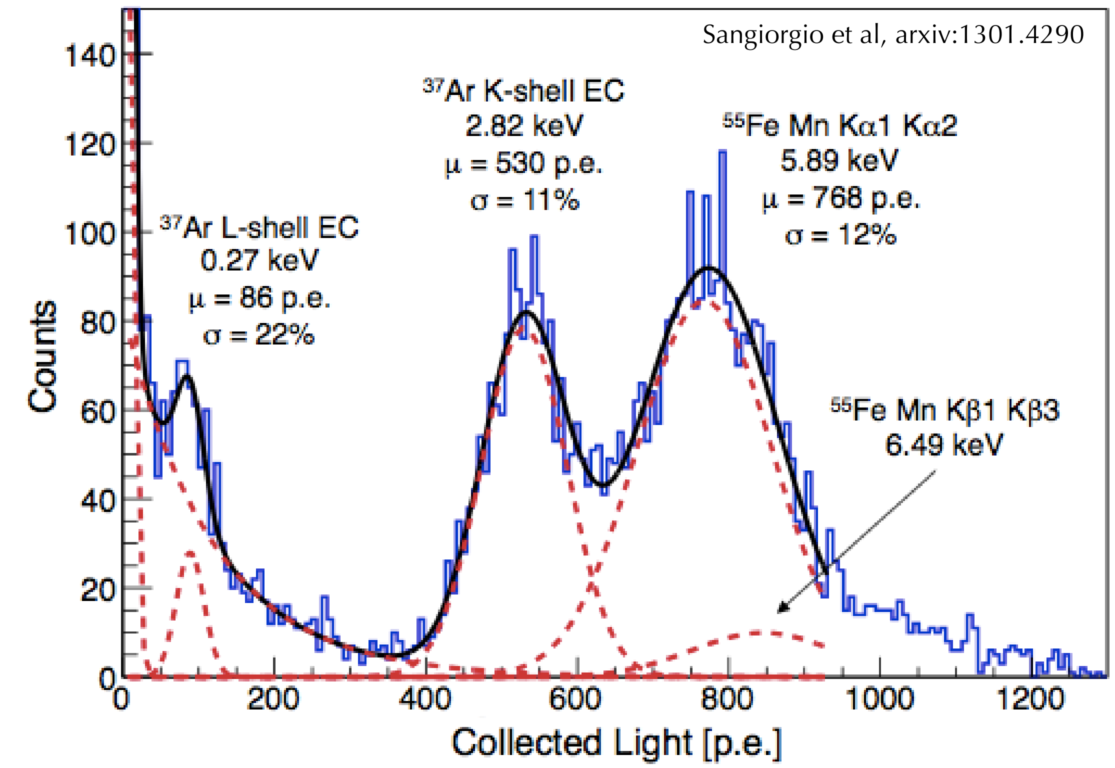
Yale

Daniel McKinsey	PI, Professor
Peter Parker	Professor
James Nikkel	Research Scientist
Sidney Cahn	Lecturer/Research Scientist
Alexey Lyashenko	Postdoc
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student

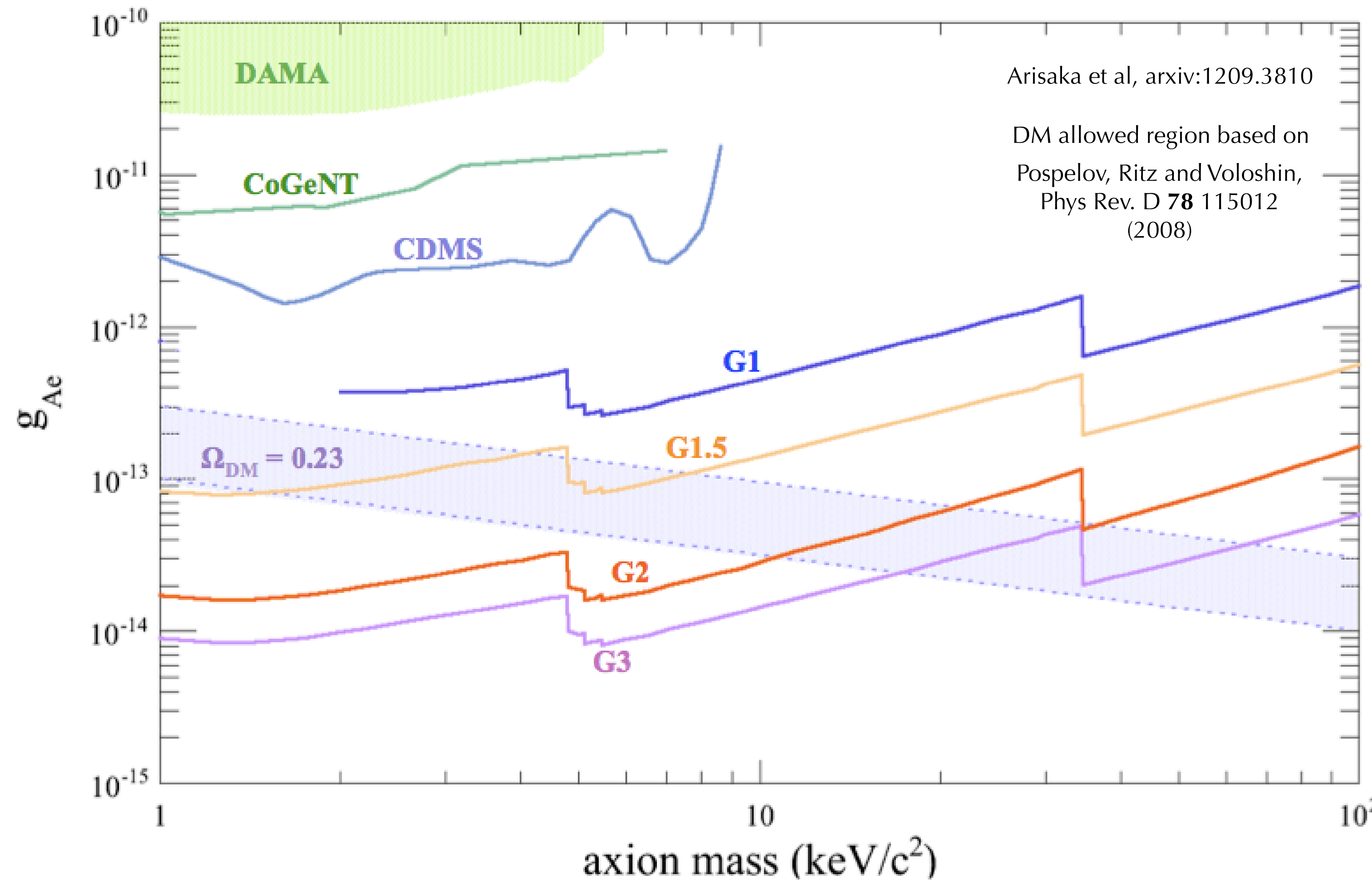
Collaboration was formed in 2007 and fully funded by DOE and NSF in 2008.

2013+: non-WIMP searches: e.g. axions (solar and/or galactic)?



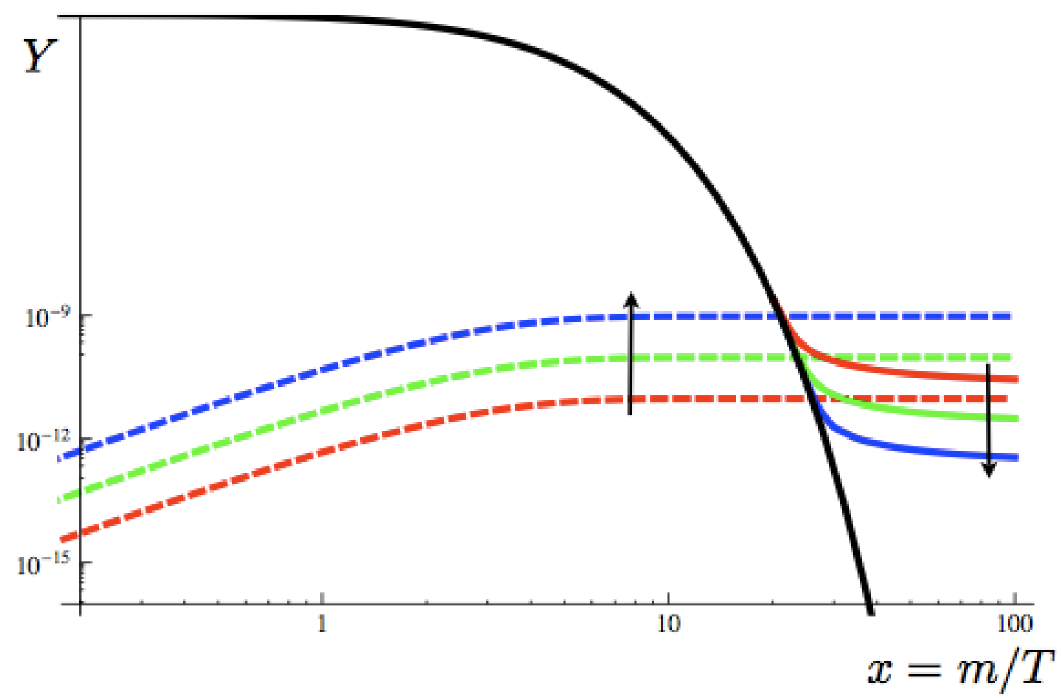


- (above) calculated event rate for axio-electric conversion in xenon
- (top right) **first sub-keV energy calibration of liquid argon detector.. we plan to apply this technique to liquid xenon detectors**
- (right) predicted sensitivity (LUX roughly represented by G1.5 curve)
- other DM models could give electromagnetic line signal, e.g. Luminous DM Phys Rev D **82** 075019 (2010)



There are other dark matter relic production mechanisms (and particle candidates)

Hall et al JHEP 03 (2010) 080



- e.g. “freeze-in”

- Another possibility: relic density determined by baryon asymmetry (“asymmetric dark matter”)

- A completely different possibility: relic density of pseudo-Nambu-Goldstone bosons, e.g. the axion

Electronic signal from nuclear recoils is quenched: Lindhard theory

Electromagnetic interactions

$$E_{\rm er} = \epsilon(n_\gamma + n_e)$$

Neutral particle interactions

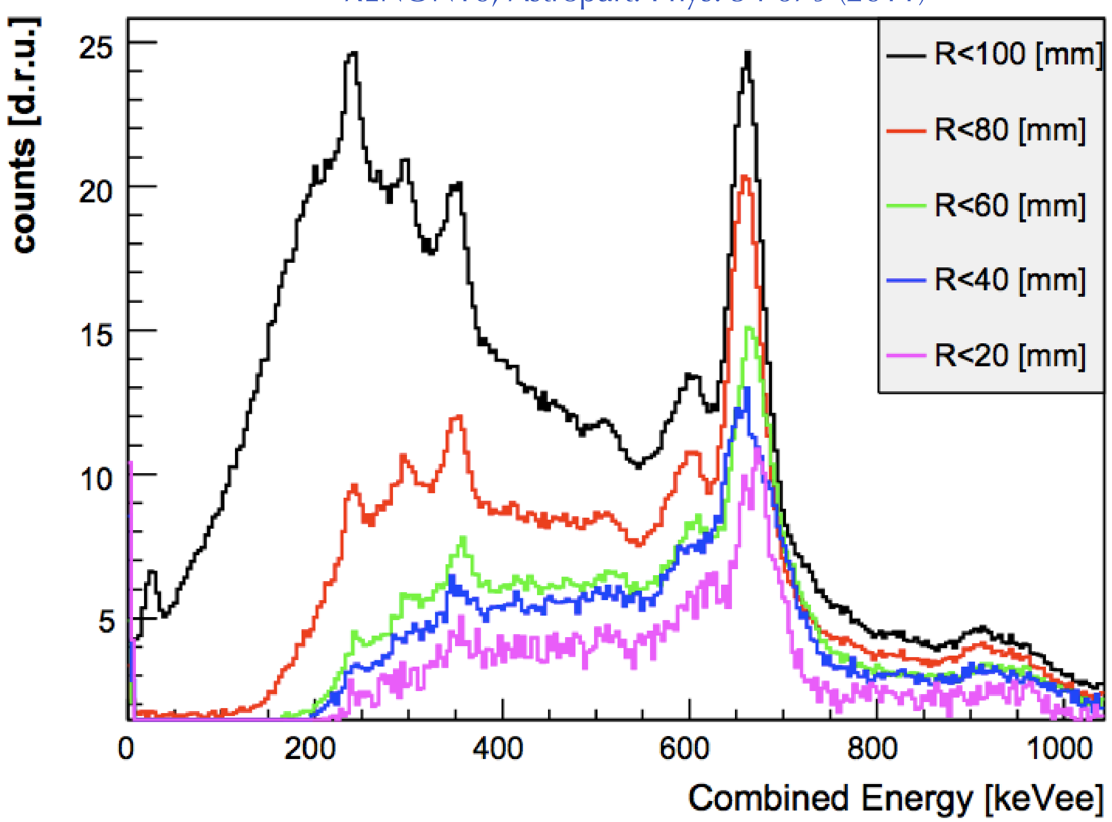
$$E_{\rm nr} = \epsilon(n_\gamma + n_e)/f_n$$

ϵ = 13.8 eV, the average energy to create a single quanta (e or γ)

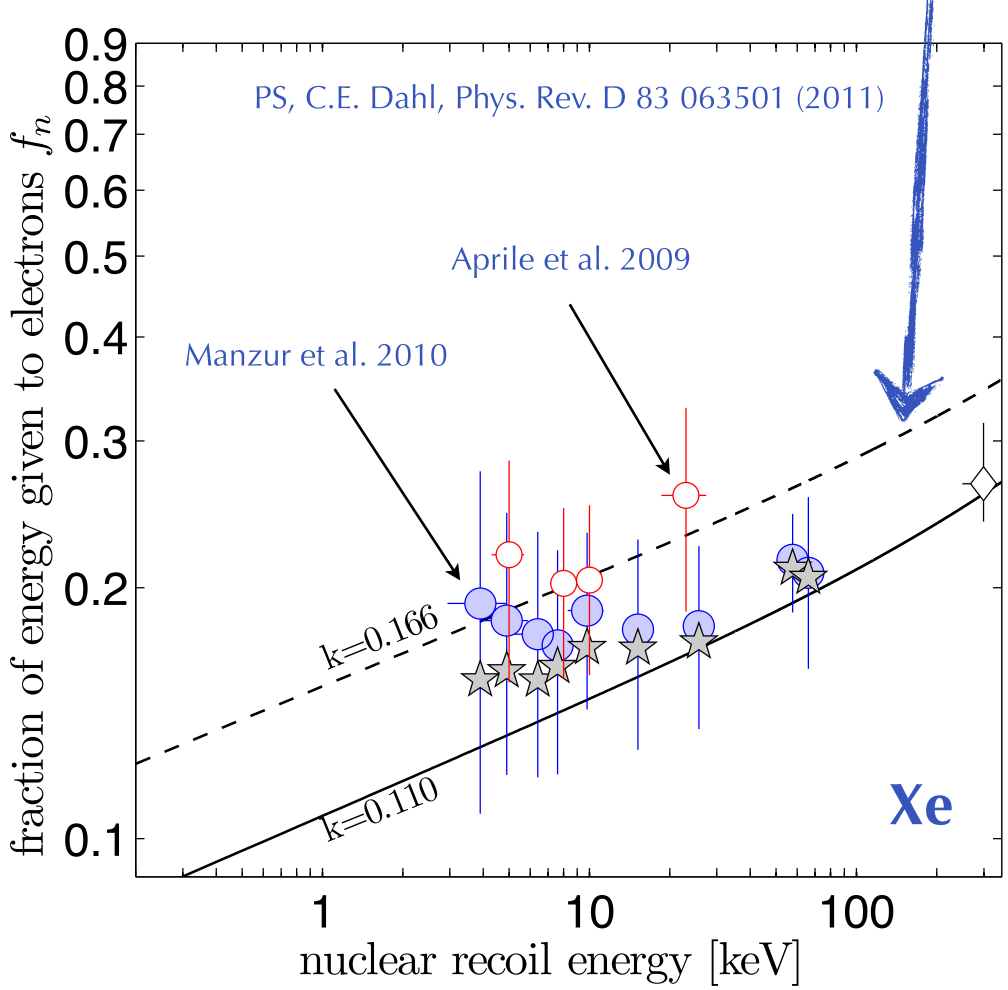
$\boldsymbol{f_n}$ = energy dependent Lindhard prediction for signal quenching

well-known that combined energy gives the best resolution

XENON10, Astropart. Phys. 34 679 (2011)



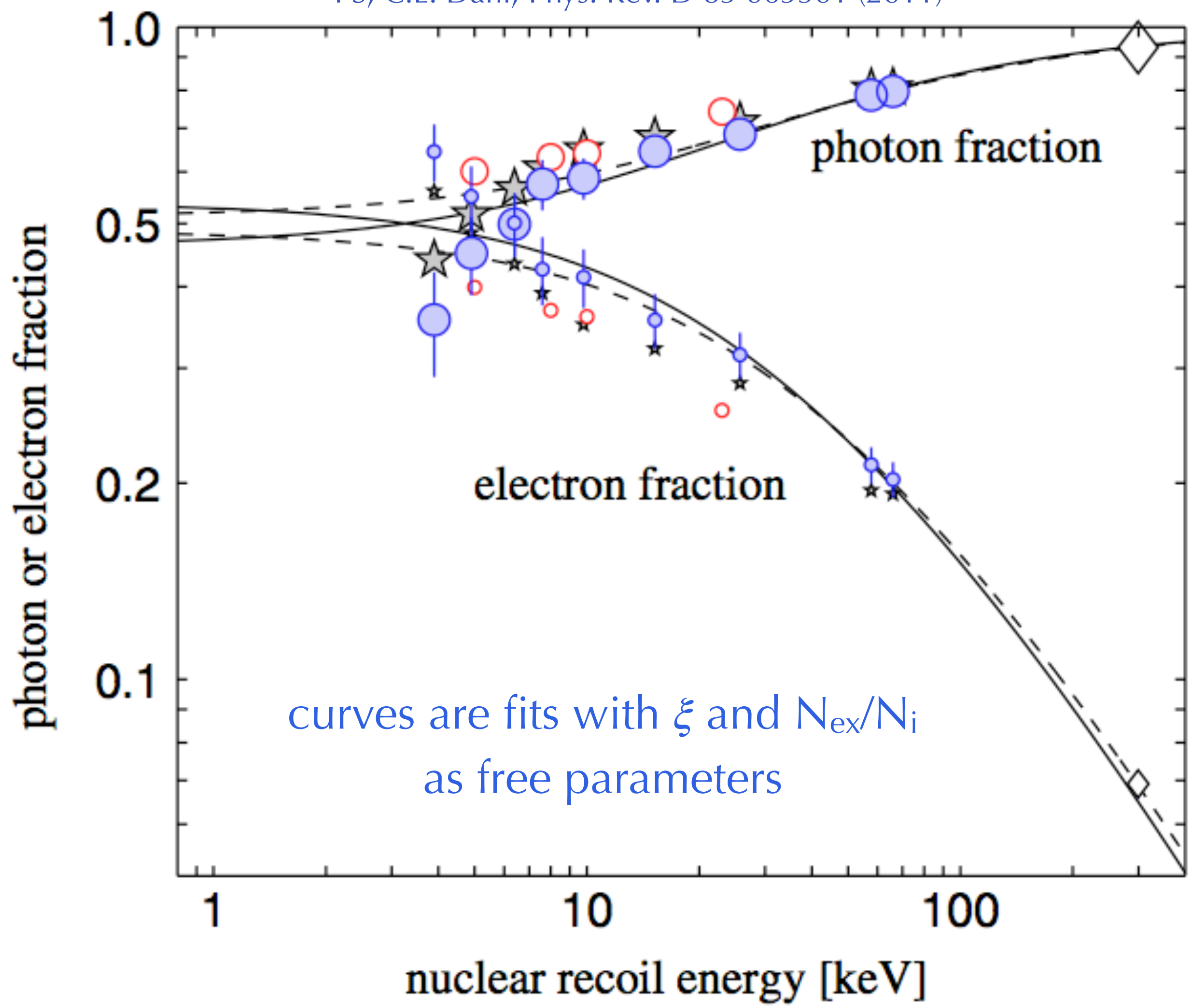
Lindhard prediction for $\boldsymbol{f_n}$
(parameterized by the electronic stopping power k)



In liquid xenon, E_{nr} partions into photons and electrons

this has caused a lot of confusion concerning measured versus expected liquid xenon scintillation response (L_{eff}, the "effective" Lindhard factor)

PS, C.E. Dahl, Phys. Rev. D 83 063501 (2011)



Two-step model:
(1) Lindhard model gives quenching, f_n
(2) Thomas-Imel model gives partioning

electron fraction: $$\mathcal{F}_e = \frac{\ln(1+\xi)}{\xi(1+N_{ex}/N_i)}$$

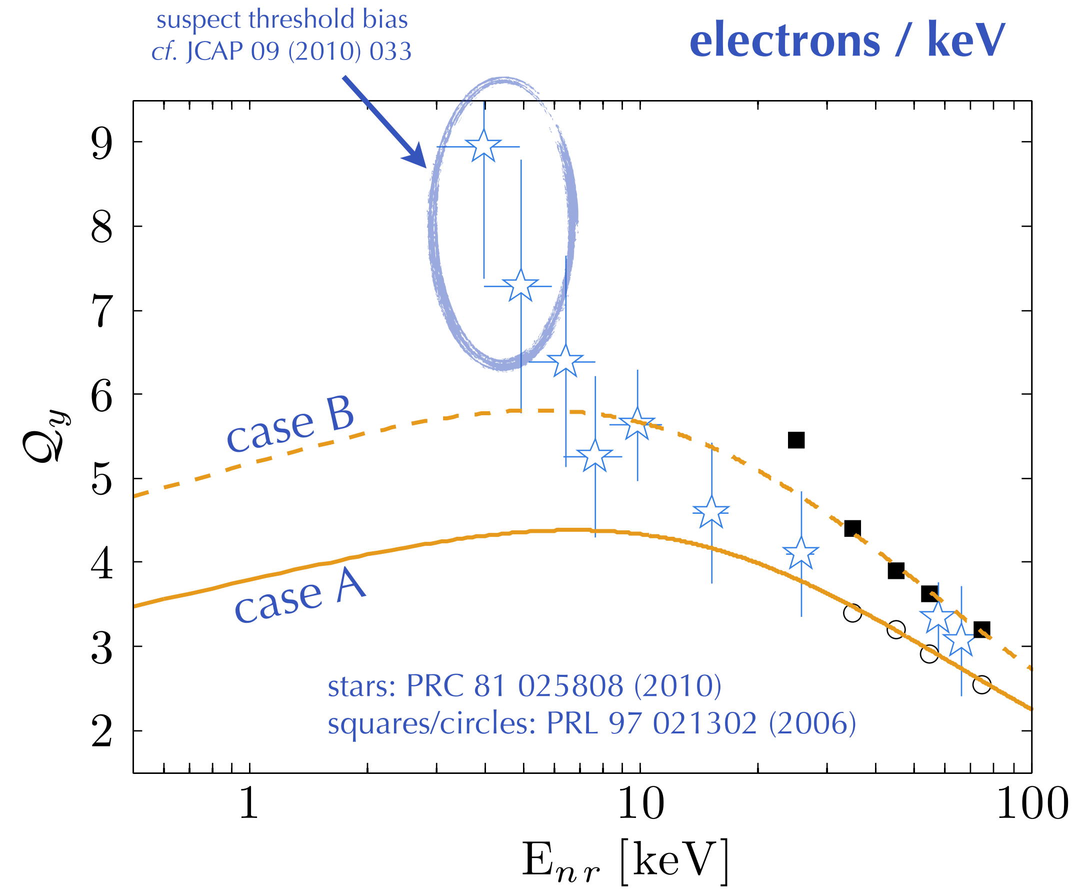
electron yield: $$\mathcal{Q}_y = \frac{\mathcal{F}_e f_n}{\epsilon}$$ $= S2/(\alpha_2 E_{nr})$

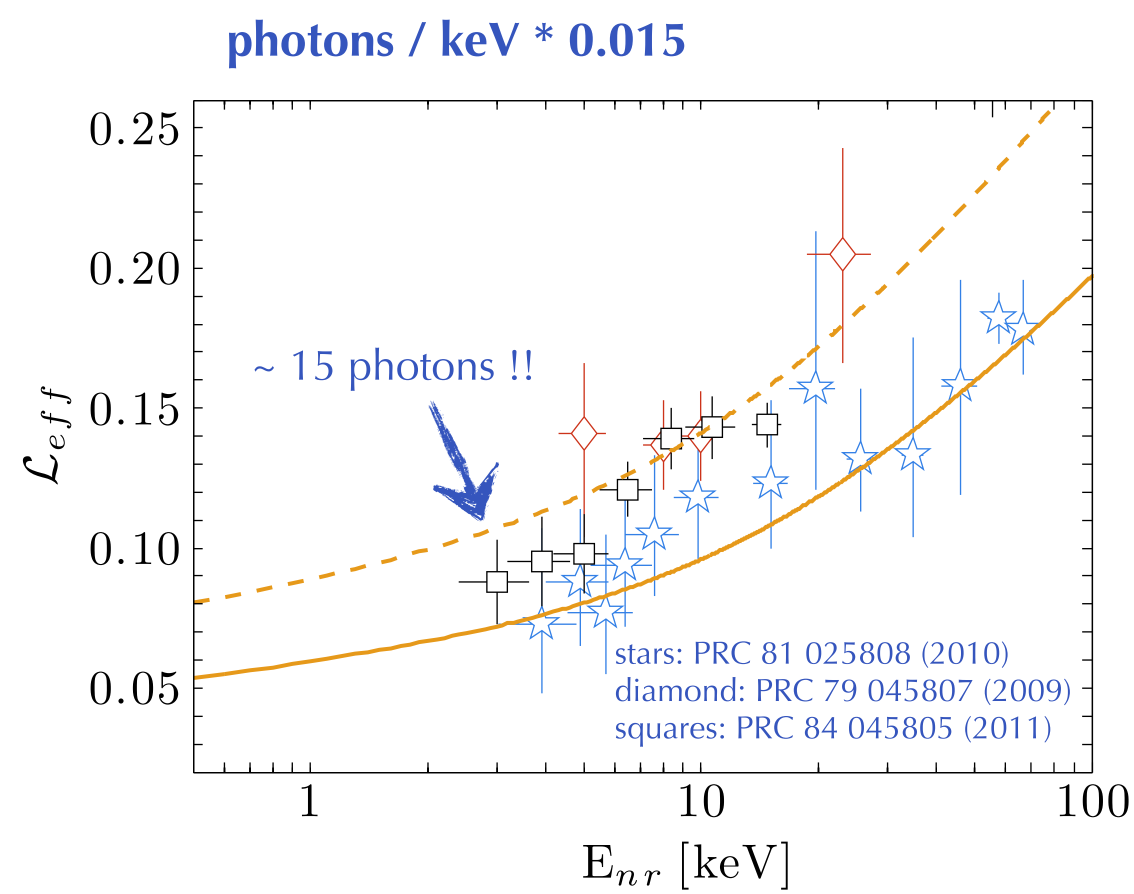
"effective" photon yield: $$\mathcal{L}_{eff} = \frac{(1-\mathcal{F}_e)f_n}{\epsilon}\frac{\alpha_1 S_e}{L_y S_n}$$

this is the "effective" bit, an ad-hoc constant with a value of ~0.015

reminder:
1. origin of ionization: Xe+
2. origin of scintillation: Xe* and Xe+

Model compared with neutron scattering data





curves: model prediction

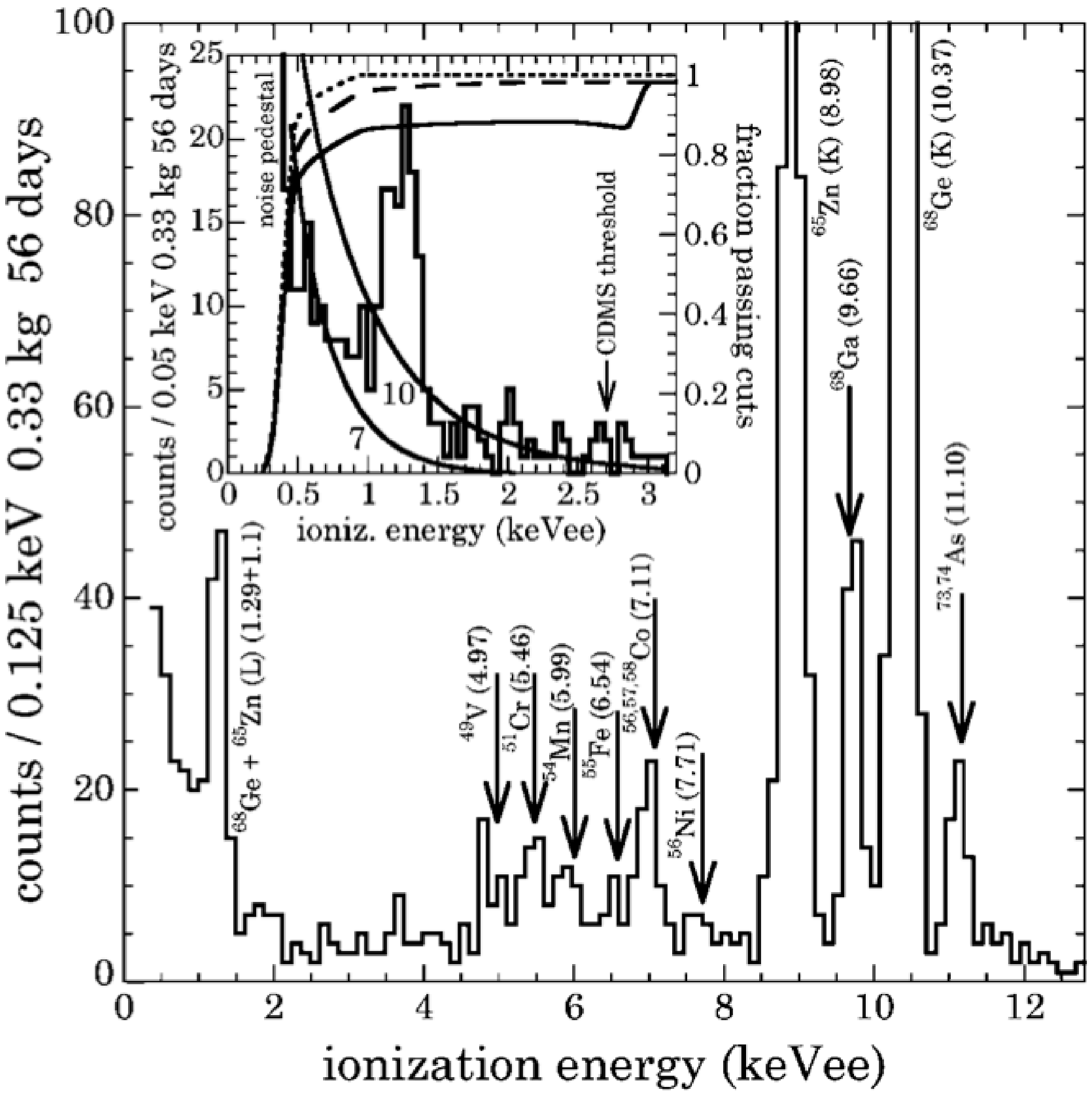
case A:

- k = 0.110
- $4\xi/N_i = 0.037$
- $N_{ex}/N_i = 1.00$

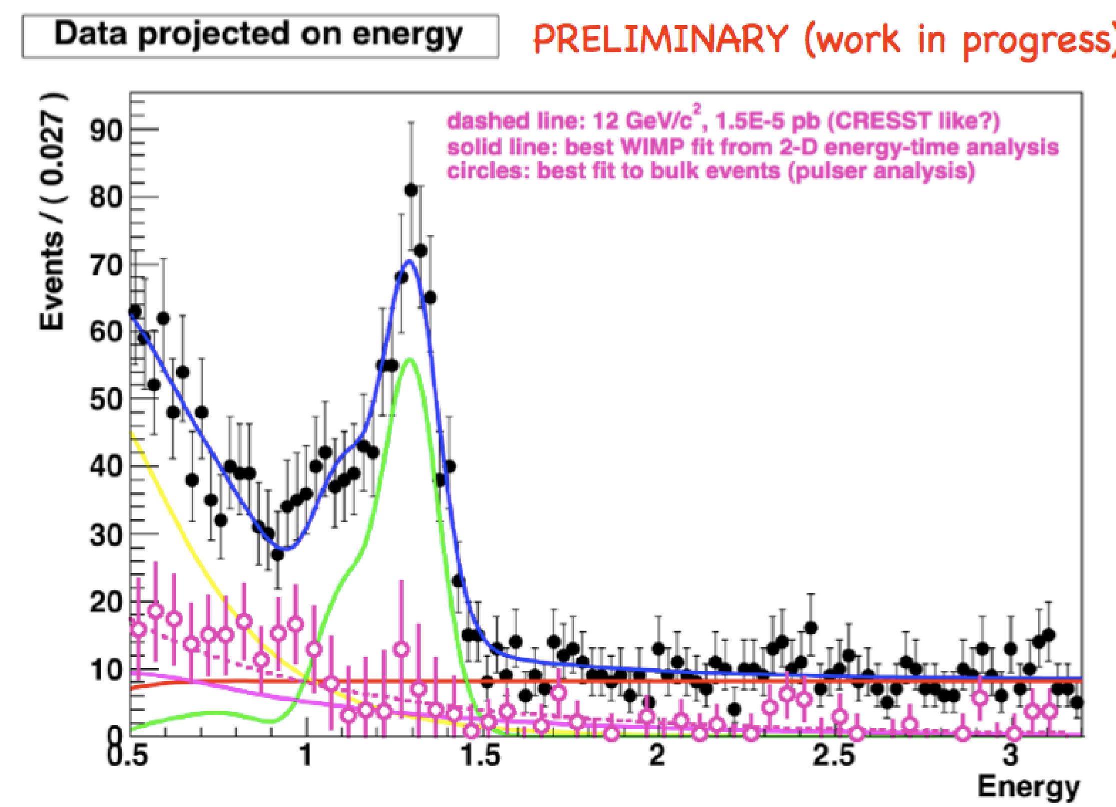
case B:

- k = 0.166
- $4\xi/N_i = 0.032$
- $N_{ex}/N_i = 1.09$

C. Aalseth et al Phys Rev. Lett. **106** 131301 (2011)

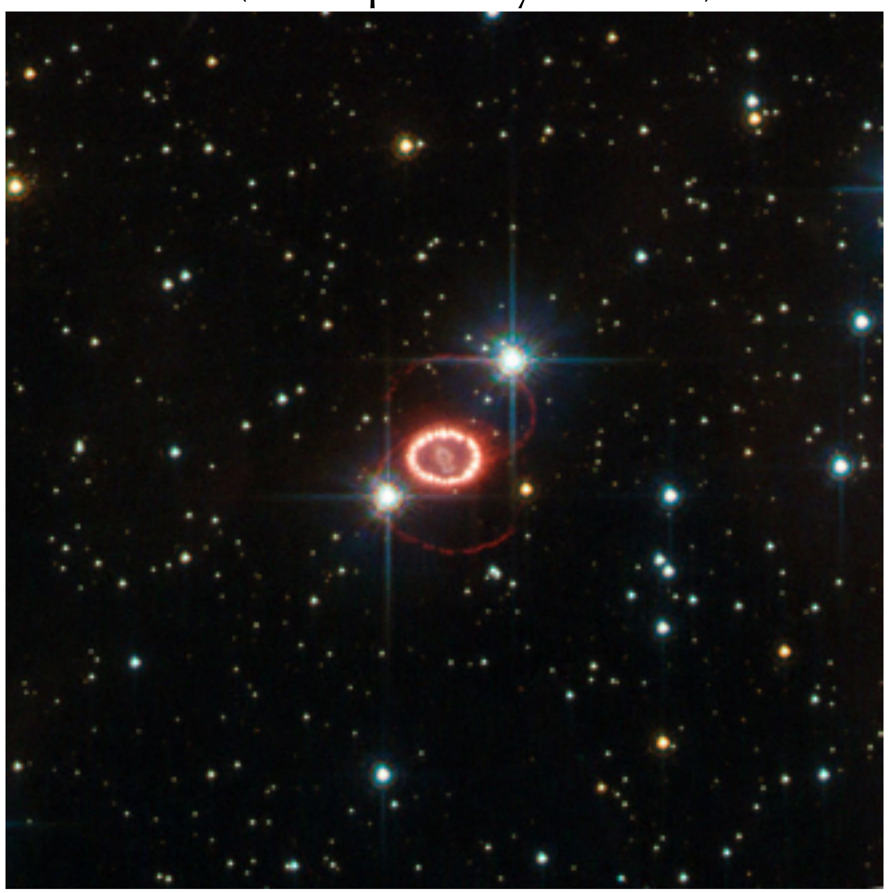


J. Collar at TAUP 2011



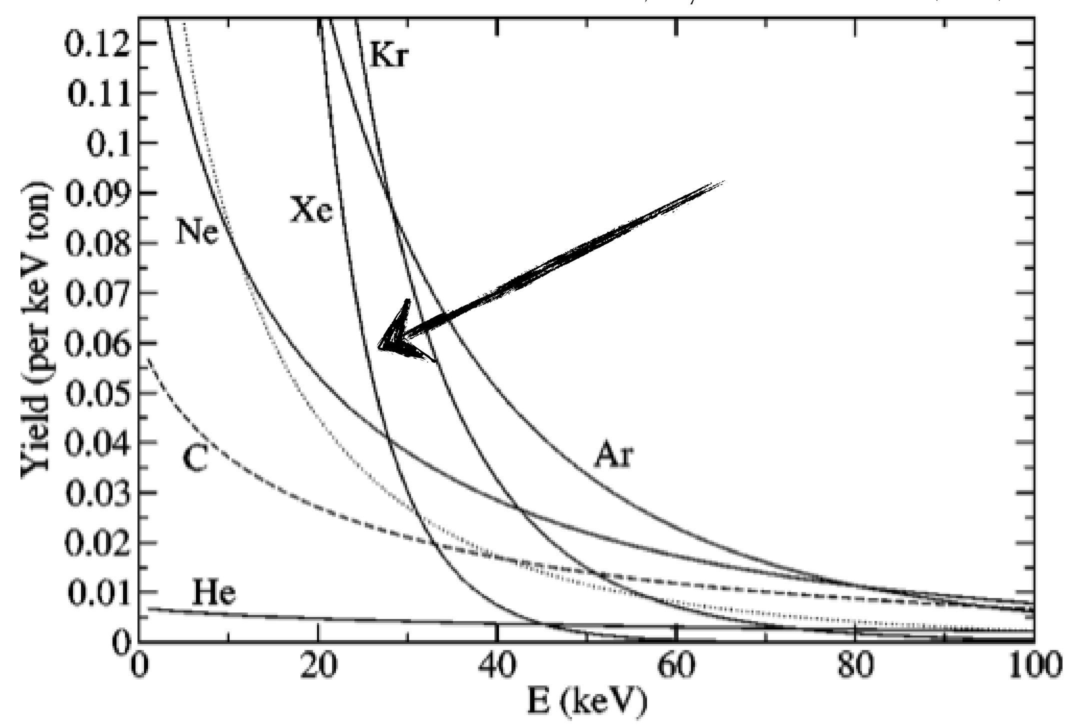
Detecting neutrinos from a supernova in our galaxy?

2011 HST image of SN1987a
(~51 kpc away in LMC)



SN1987a antineutrinos detected by
Kamiokande (11), IMB (8) and Baksan (5)

Horowitz et al, Phys Rev D **68** 023005 (2003)



~10 coherent neutrino scatters above 5 keV in xenon, for SN at 10 kpc

- sitting around waiting for SN sounds silly; but,
- next generation DM experiments will have large target masses and long exposure times, and
- coherent interaction is flavor blind (x6), and
- signal is a burst, easily identifiable, and
- we have lots to learn about both SN and neutrinos

MOND, TeVeS, f(R) models
basic premise of MOND: postulate that for very small accelerations,

$a_N \to a_N \mu(a/a_0)$, where the function $\mu \sim 1$ for $a \gg a_0$, and $\mu \sim a/a_0$ for $a \ll a_0$

MOND explains rotation curves, and to a degree, merging clusters.
But it still requires dark matter

TeVeS appears to be largely ruled out by weak lensing + galaxy velocity observations
Reyes et al Nature **464** 256 (2010)