# Introduction to direct detection of dark matter

Peter Sorensen, LBL
UC Berkeley PH290E
Fall 2016

# Your guest lecturer

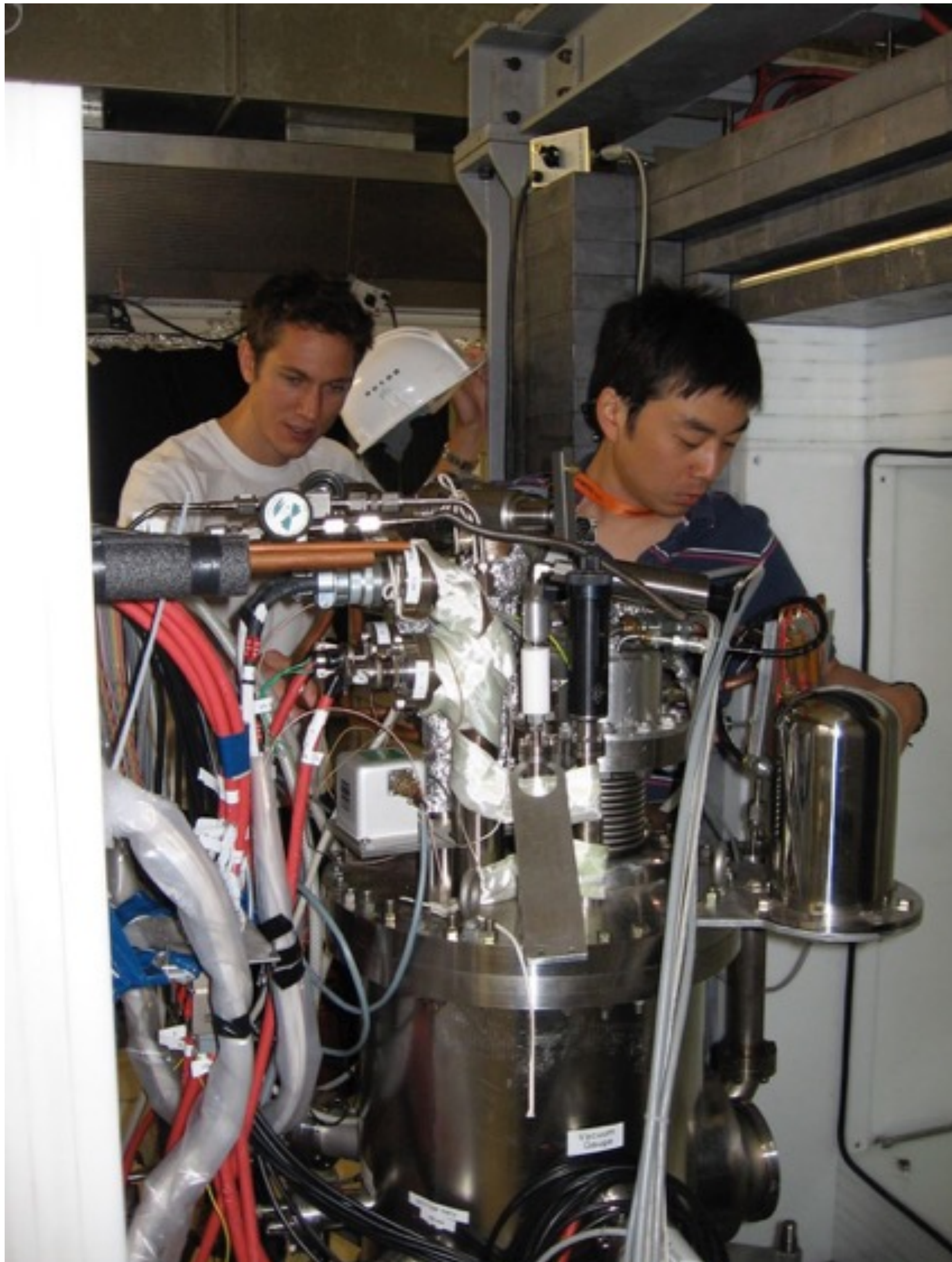
Grad school in Rhode Island
but mostly worked in NYC (Nevis Lab) and Italy
PhD in 2008
3 years of Postdoc at LLNL Rare Event Detection (RED) group
3 years as Staff Scientist at LLNL
Past 2 years as Divisional Fellow at LBL

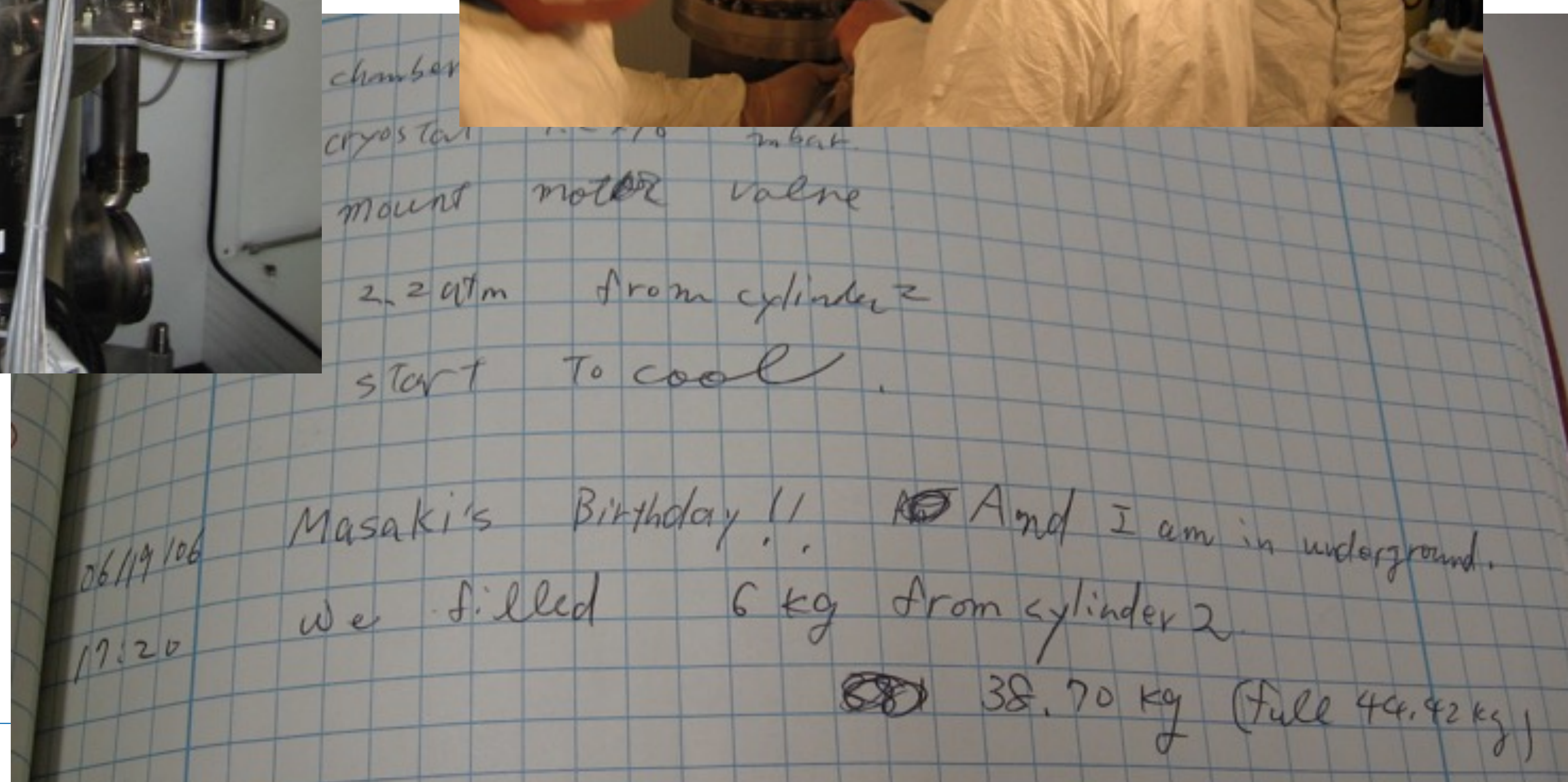
Dark matter searches are often classified as “astroparticle physics”
i.e. I am a terrible astrophysicist and a terrible particle physicist

A significant fraction of my work is actually detector development (including theoretical investigation and analysis (cf. articles in Phys Rev D/ Lett.)

# PhD work in Italy: life was good, above ground


We were never above ground!!

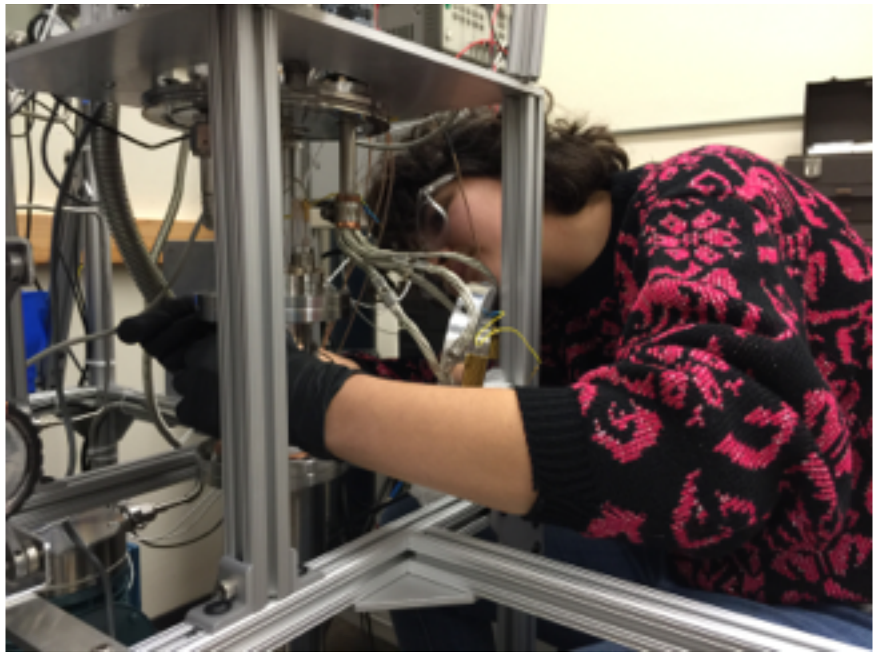




if you're interested in particles whose existence is unproven, come work on LUX/ LZ! The experiment is in South Dakota not Italy, but it has it's own charms and the underground has a swimming pool

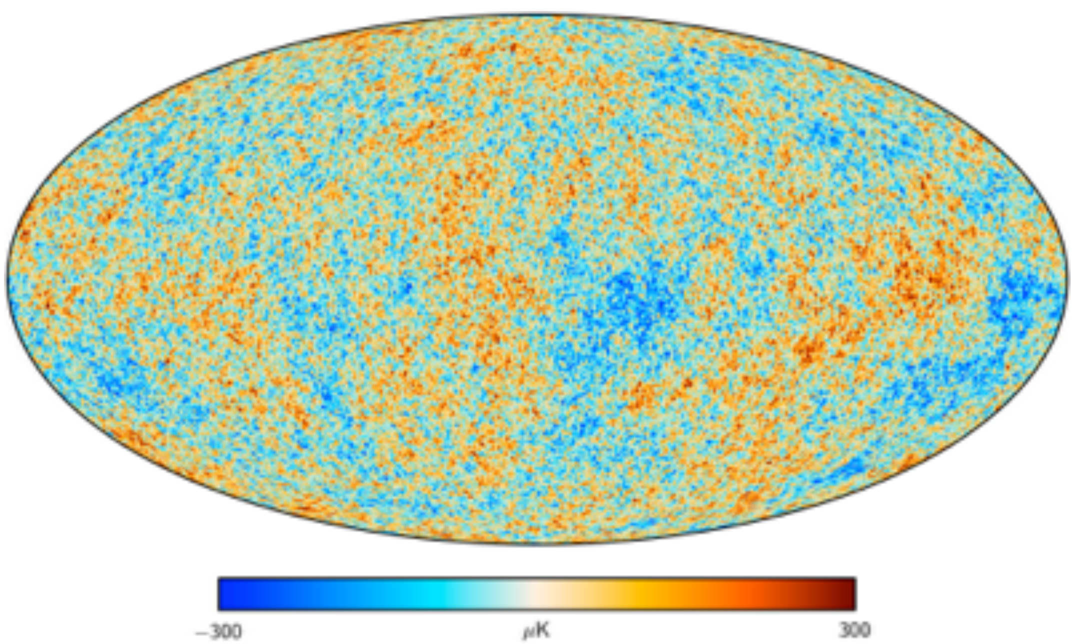
For research opportunities, check with
- Kevin Lesko (LBL senior scientist)
- Dan McKinsey (UCB professor)
- me

and also be sure to talk with our current students

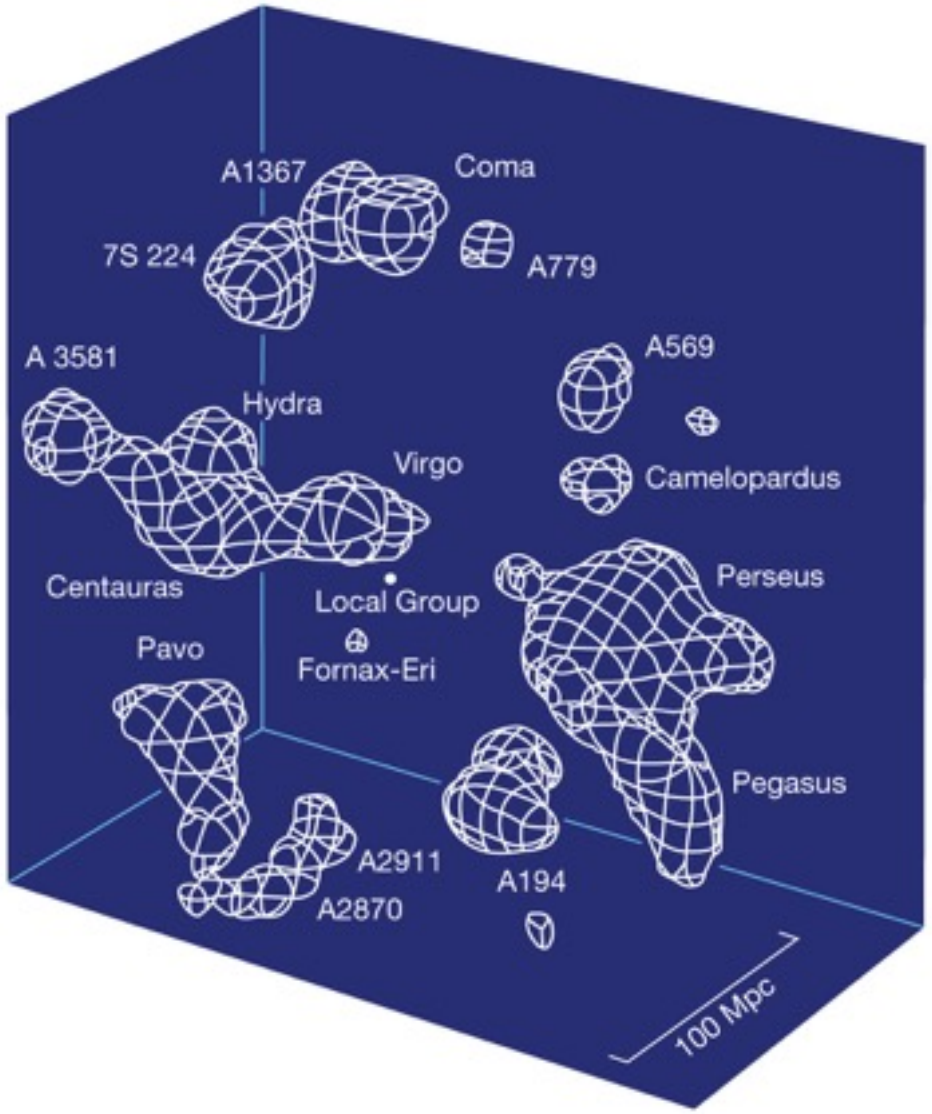


e.g. Kelsey, Kate (pictured), Vetri

ΔT




ΔM





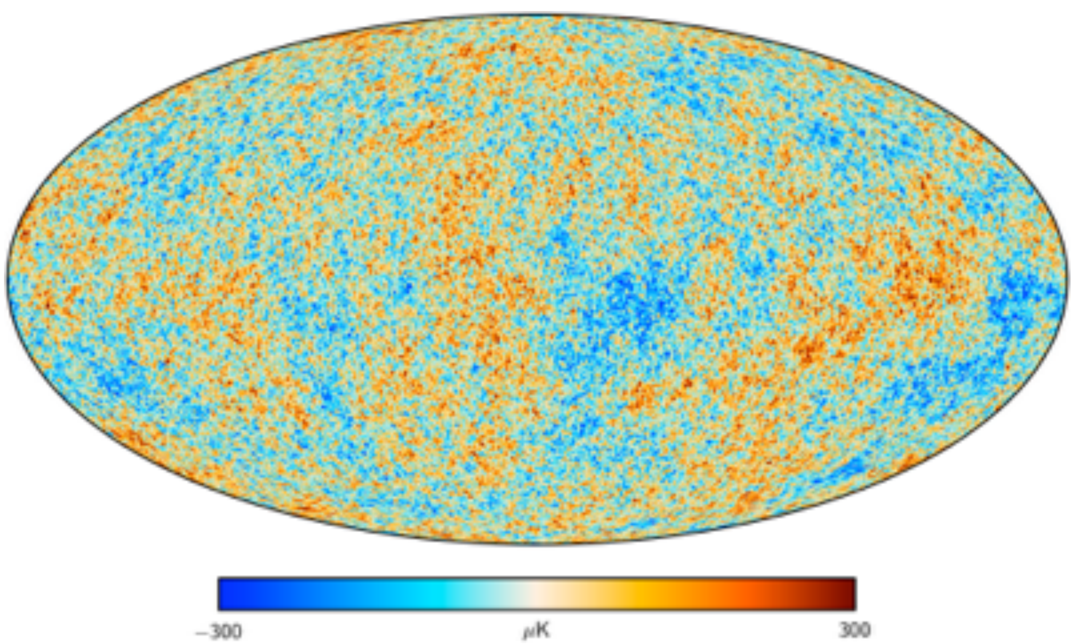

3/8 million years after big bang

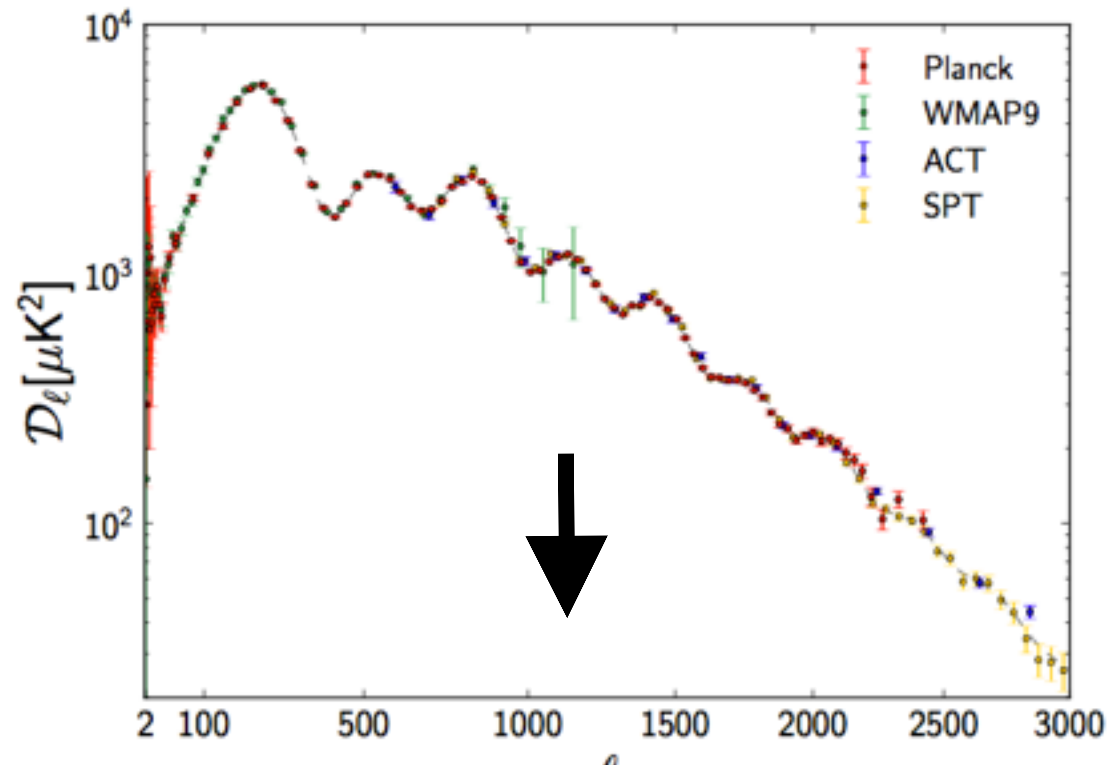
13700 million years after big bang

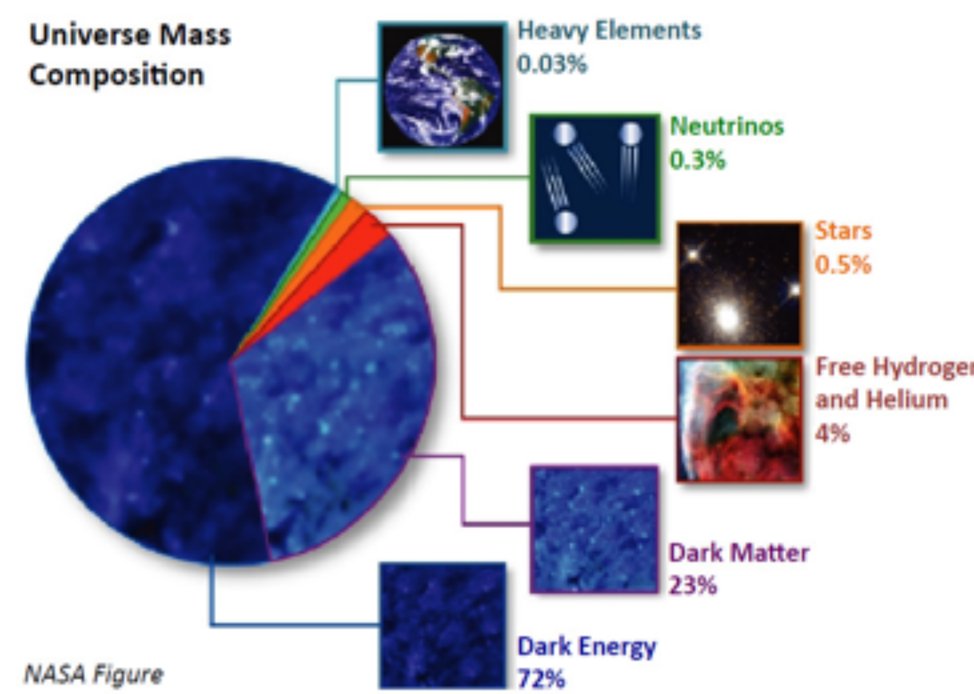
# CMB data interpreted in terms of the ΛCDM model:

we know:

- matter ~5%
- dark matter 23%
- dark energy 72%

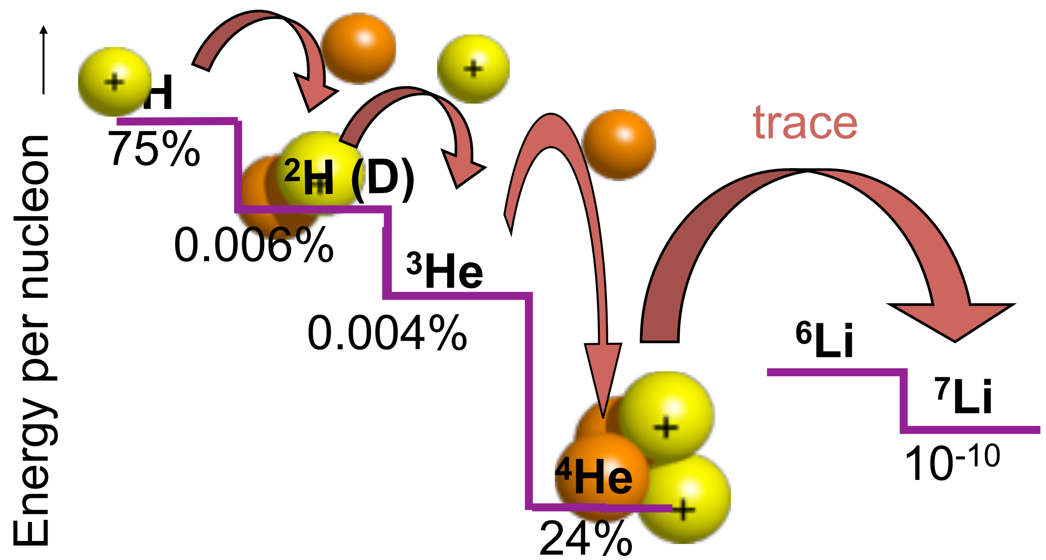


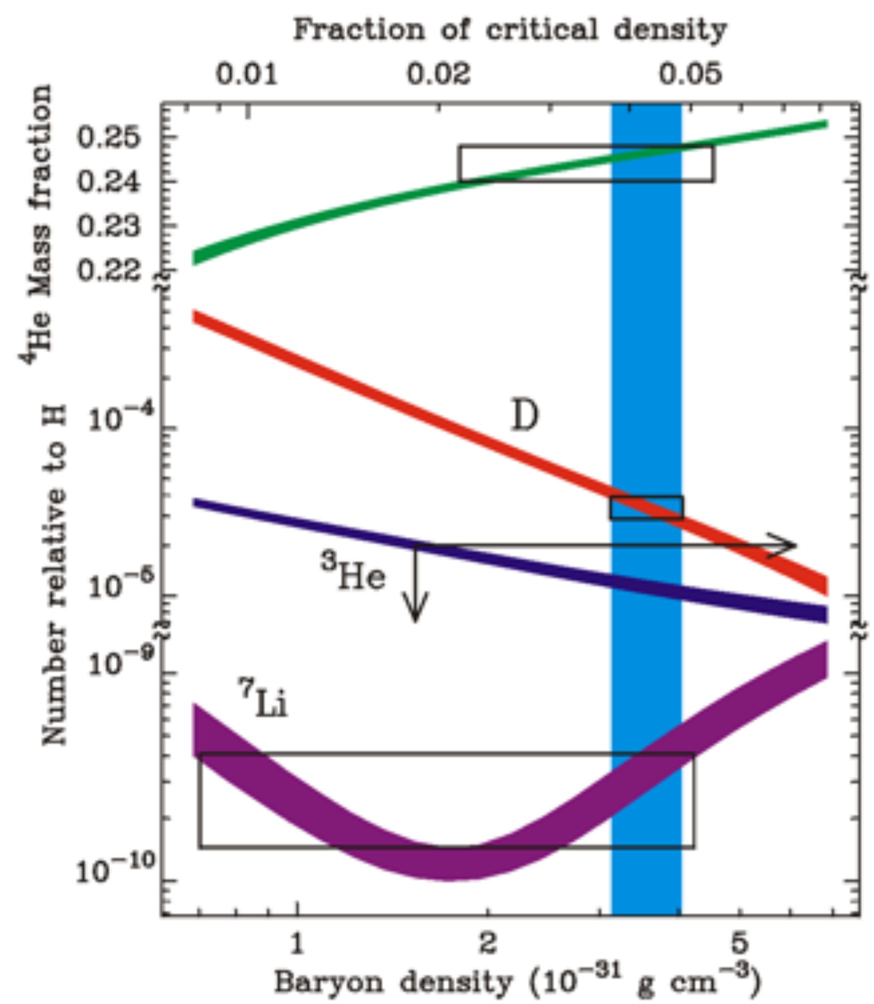




(you should make sure you catch a CMB talk by an actual CMB expert)

# Astrophysical observations + BBN give the baryon content of the universe:




$$\rho_c = \frac{3H^2}{8\pi G}$$

~5 protons/m$^3$

~5 keV/cm$^3$

∴ don't need to rely on ΛCDM, there appears to be a lot of non-baryonic stuff out there

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

# Alpha, Beta, Gamma...

## Letters to the Editor

*PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.*

### The Origin of Chemical Elements

R. A. ALPHER*
*Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland*

AND

H. BETHE
*Cornell University, Ithaca, New York*

AND

G. GAMOW
*The George Washington University, Washington, D. C.*
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by $\beta$-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where $n_i$ and $\sigma_i$ are the relative numbers and capture cross sections for the nuclei of atomic weight $i$, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to $5\times10^4$ g sec./cm$^3$.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time $t_0$, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \qquad (2)$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm$^3$. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value $2.5\times10^5$ g sec./cm$^3$ which can possibly be understood if we

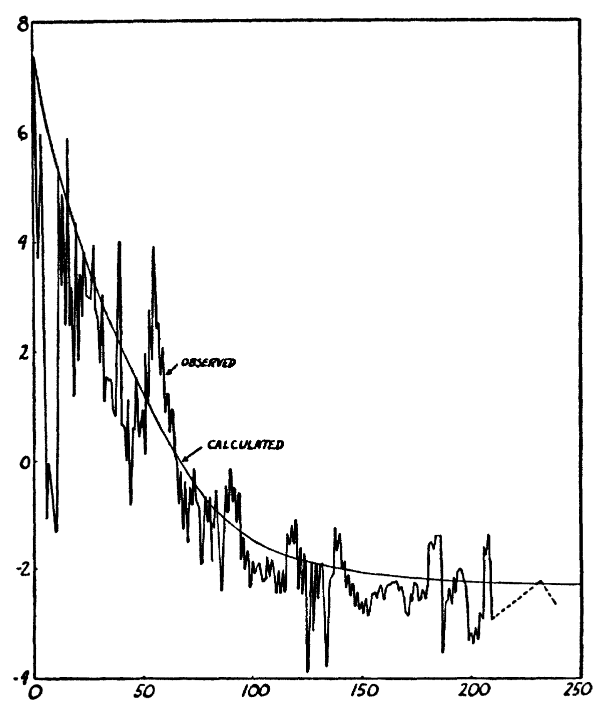
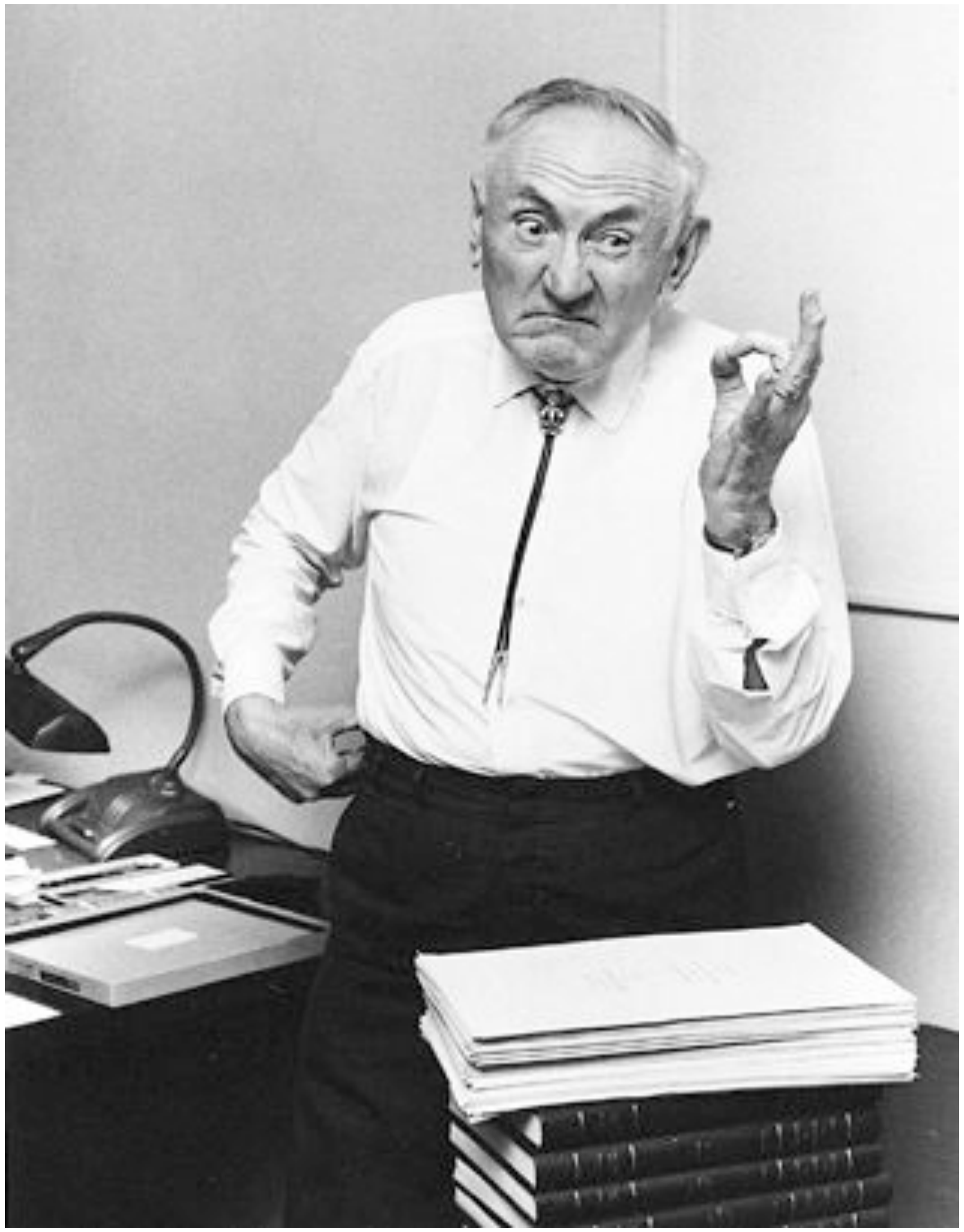



FIG. 1.
Log of relative abundance
Atomic weight



Ralph Alpher

# Fritz Zwicky circa 1933



- **stars account for <1% of the mass of Coma cluster**
- remains true for all observed clusters

"Tin tin et la stella misteriosa"


- suggested we *"throw some light on the problem of the density of internebular matter in clusters."*
- suggested gravitational lensing (it was not yet an established technique)

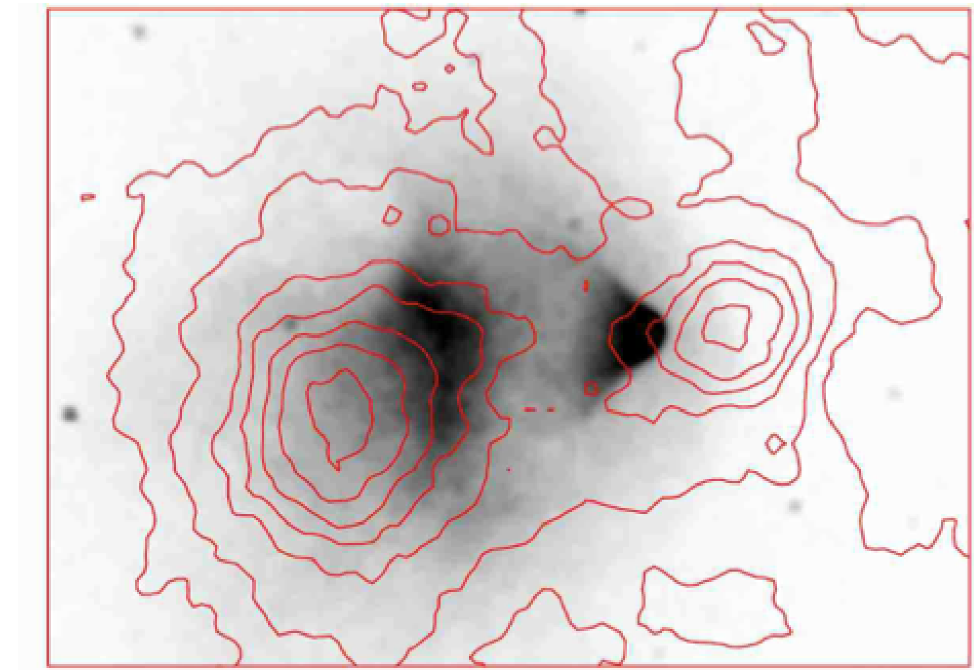
# Bullet cluster is a particularly sweet example

The "ooooh, ahhhh" view:

~95% of the mass (from gravitational lensing)

hot gas, 90% of the baryons (from x-ray obs.)

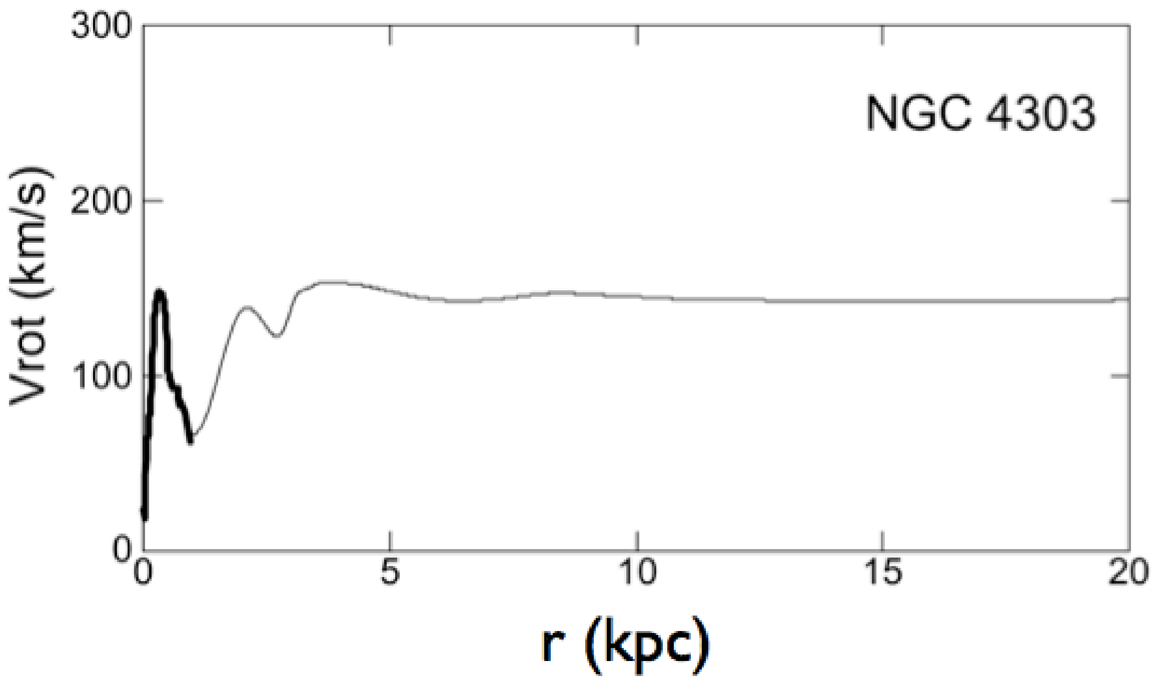
The physicist's view:

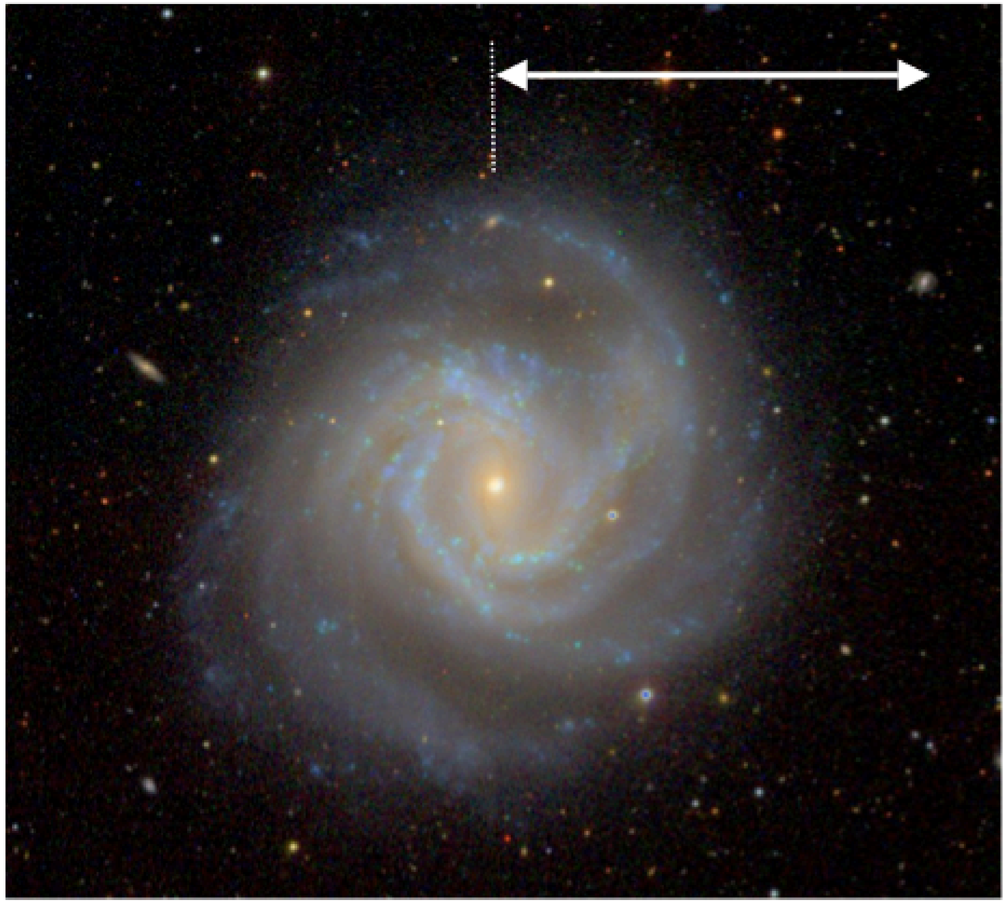


Clowe et al. Nucl. Phys. B **173** 28 (2007)

These data tell you something specific about dark matter (besides, it exists)…

# All the rage in the late 1970s (via a single example galaxy)



- The observed rotational velocity for (example galaxy) NGC 4303 as a function of radius from the galactic center

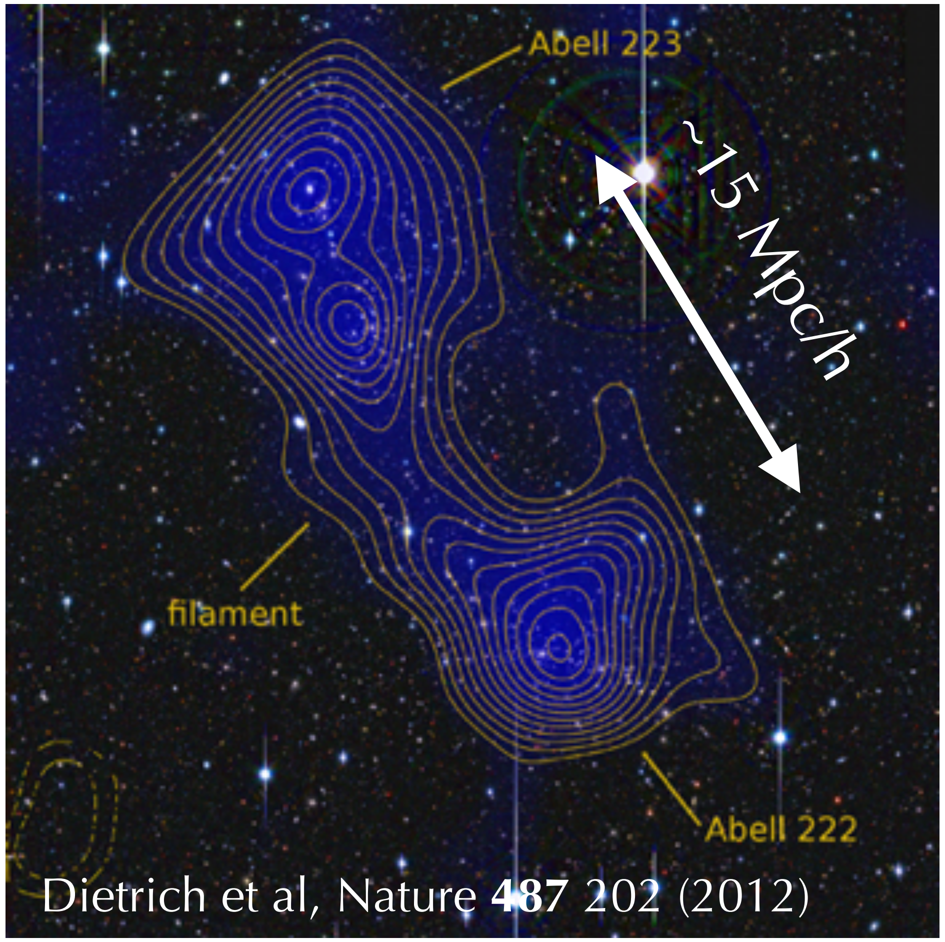
- we know: $$v_{rot}(r) = \sqrt{\frac{GM(r)}{r}}$$

- data require: $$M(r) \propto r$$

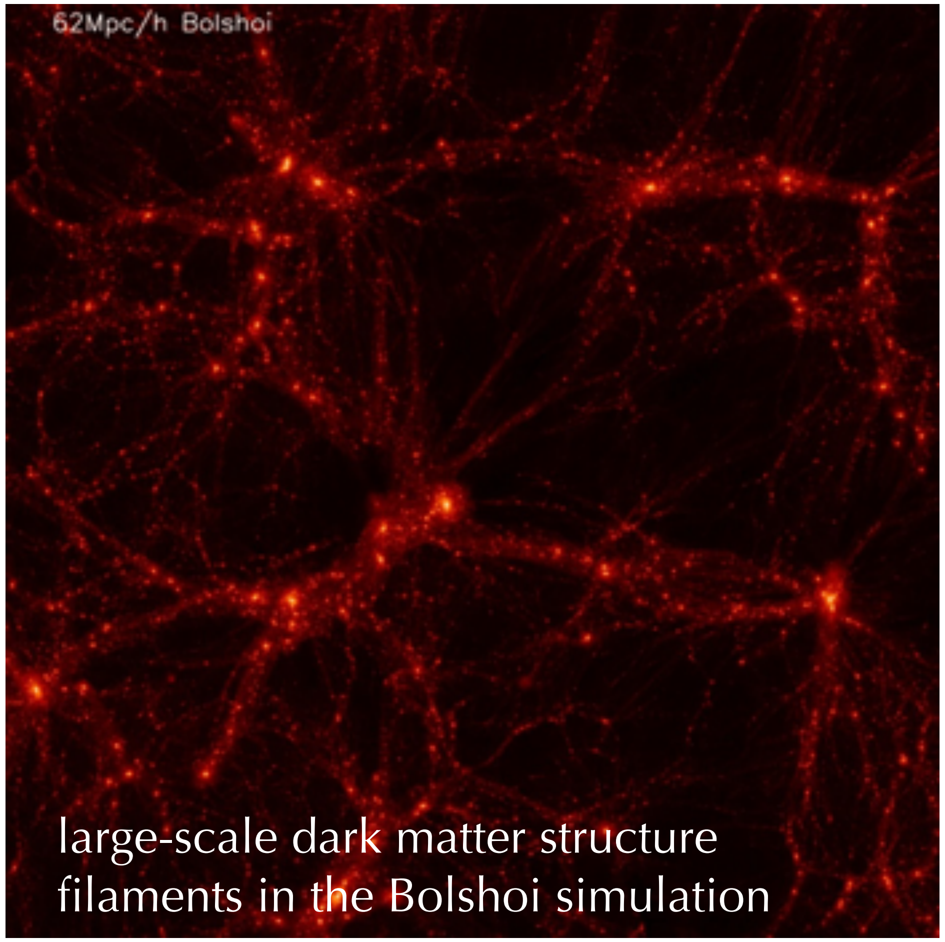
- which implies: $$\rho(r) \propto r^{-2}$$

- The simplest explanation is an isothermal halo of **non-interacting**, non-luminous, yet gravitating matter

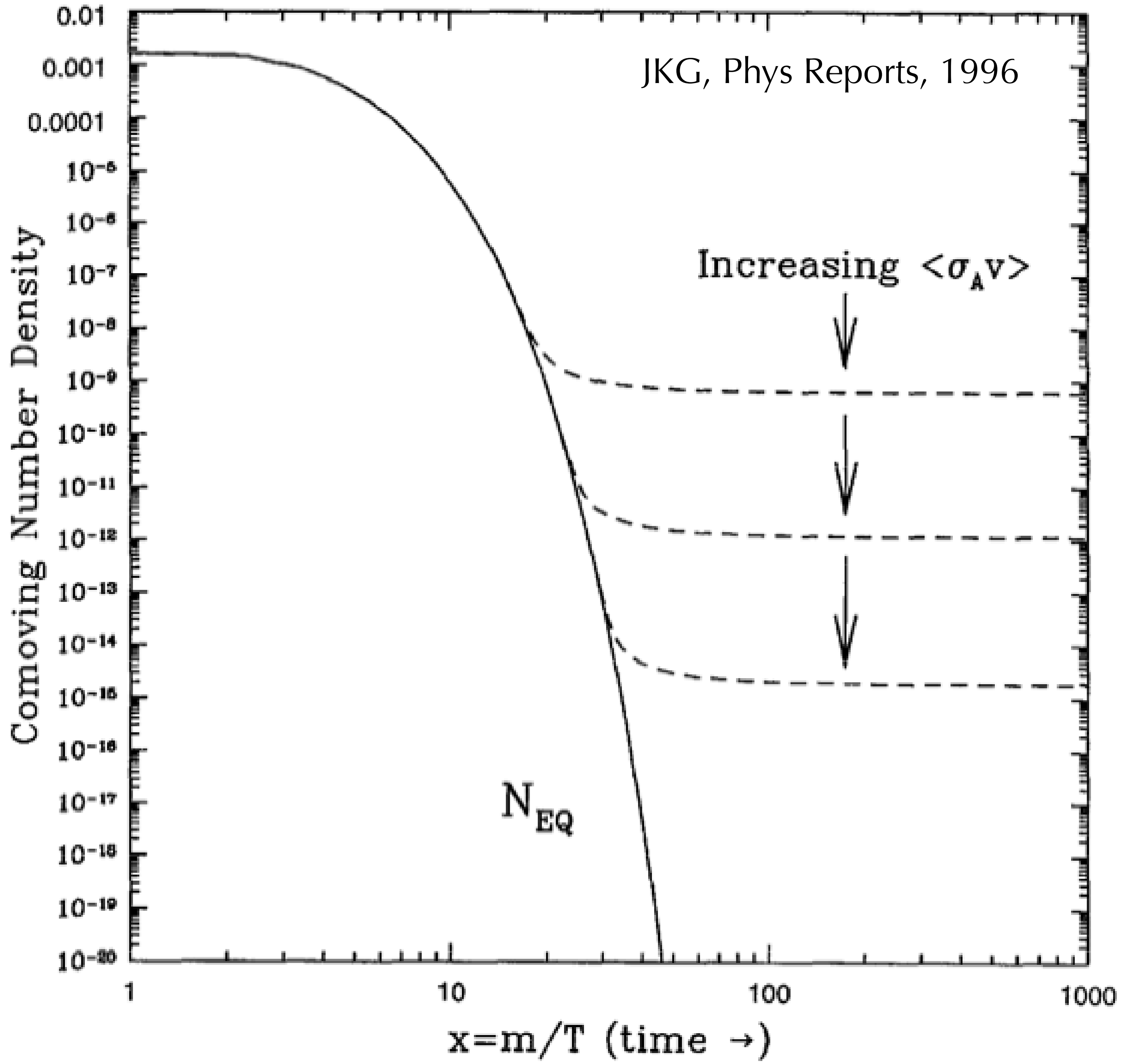
# Dark matter filaments between clusters (it all hangs together)



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

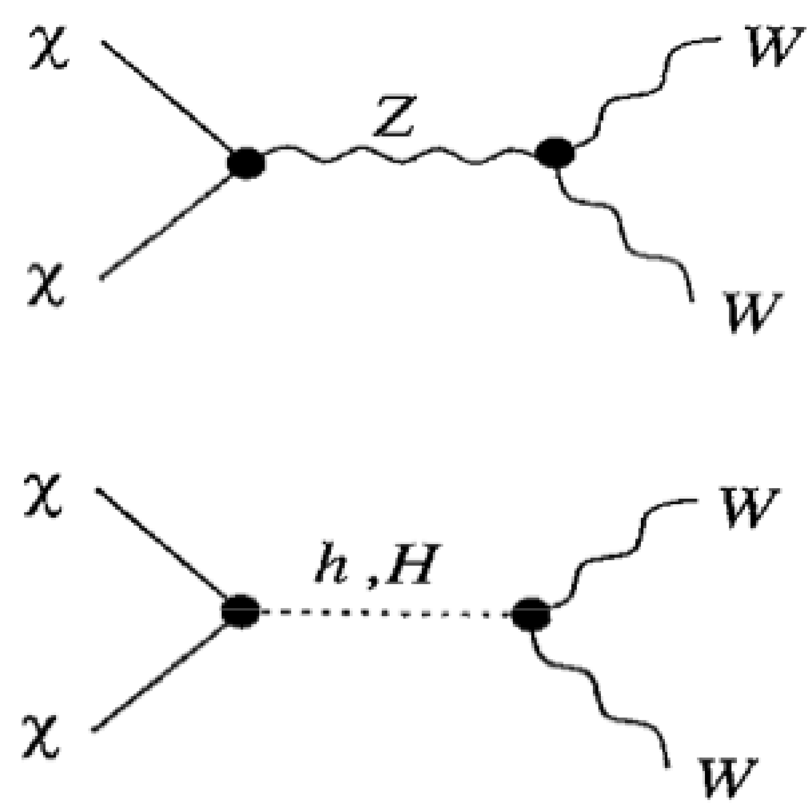


large-scale dark matter structure filaments in the Bolshoi simulation

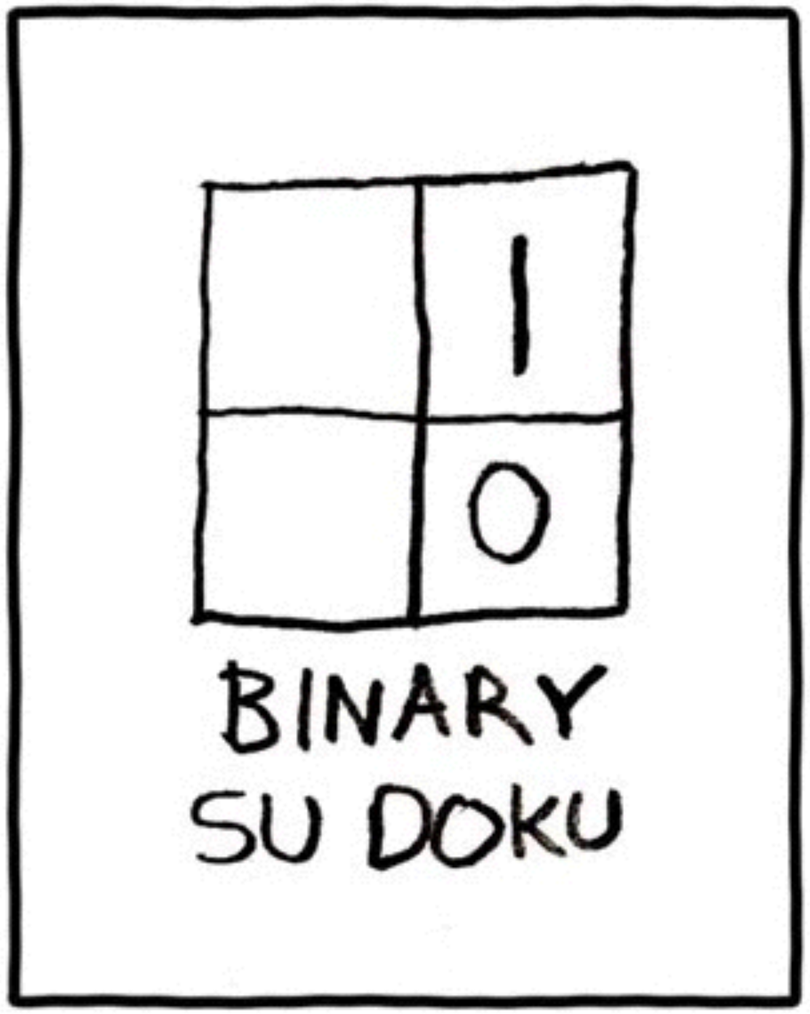



The WIMP miracle: It has always been there, it just fell out of thermal equilibrium

basic arguments lead to weak scale cross section

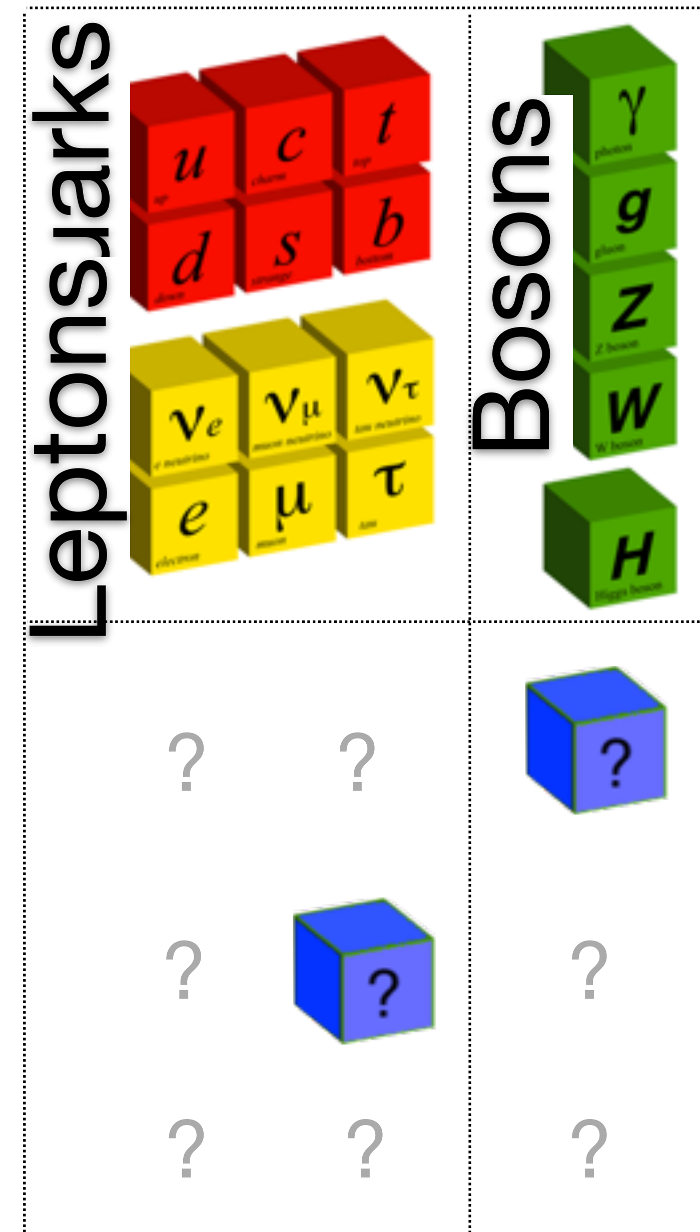


- A vanilla WIMP is the lightest, stable SUSY particle
- If WIMPs are the dark matter, we solve a cosmic riddle and the hierarchy problem at the same time!

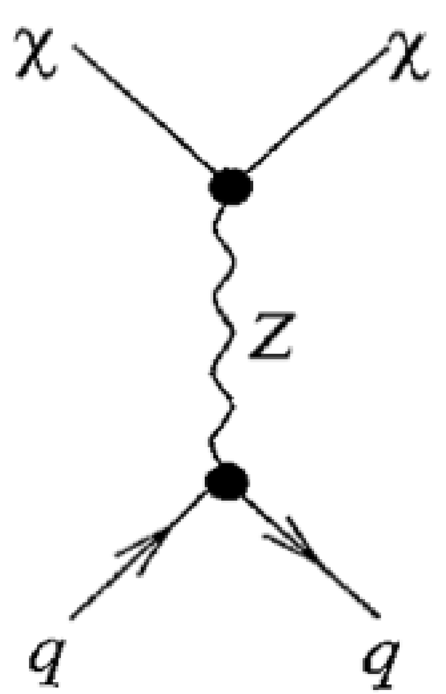



http://xkcd.com/74/

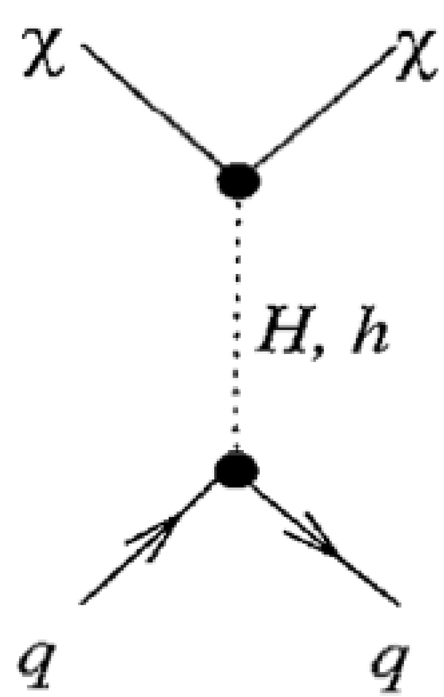
- A deep connection between dark matter, cosmology and particle physics
  - What are it's properties?
  - How does it interact?
  - What does it tell us about how the universe works?
- Direct detection (scattering) would be a unique probe of these questions



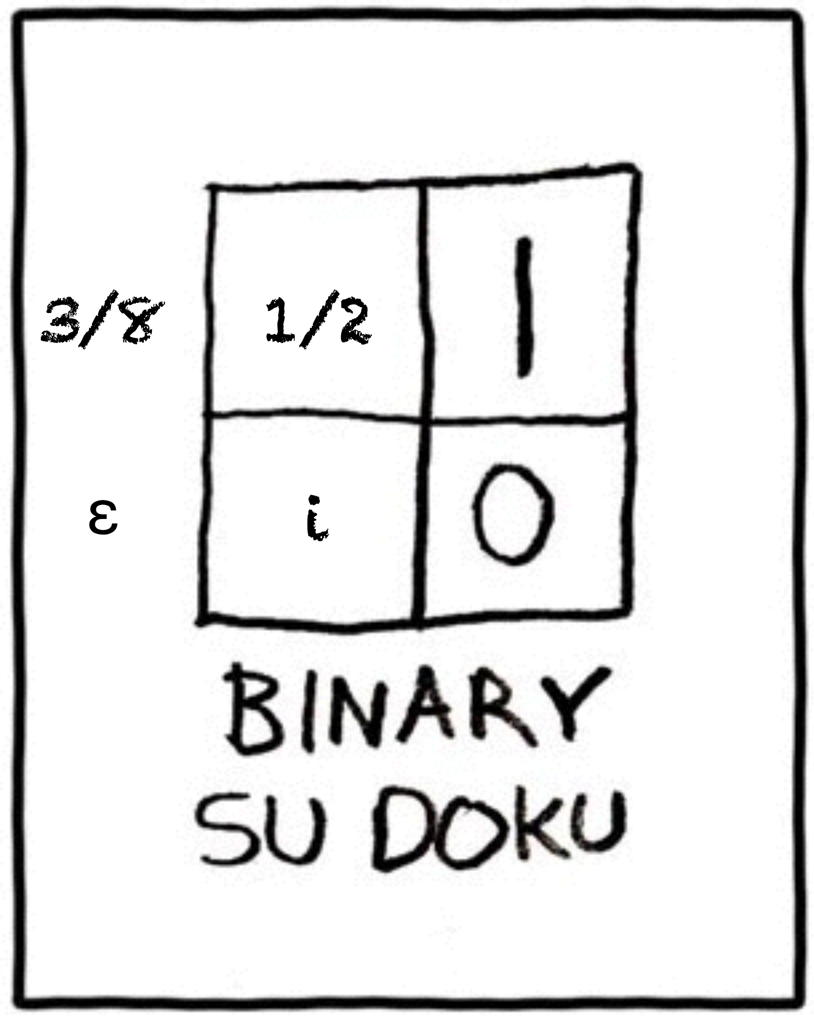

Classical WIMP




21st century WIMP

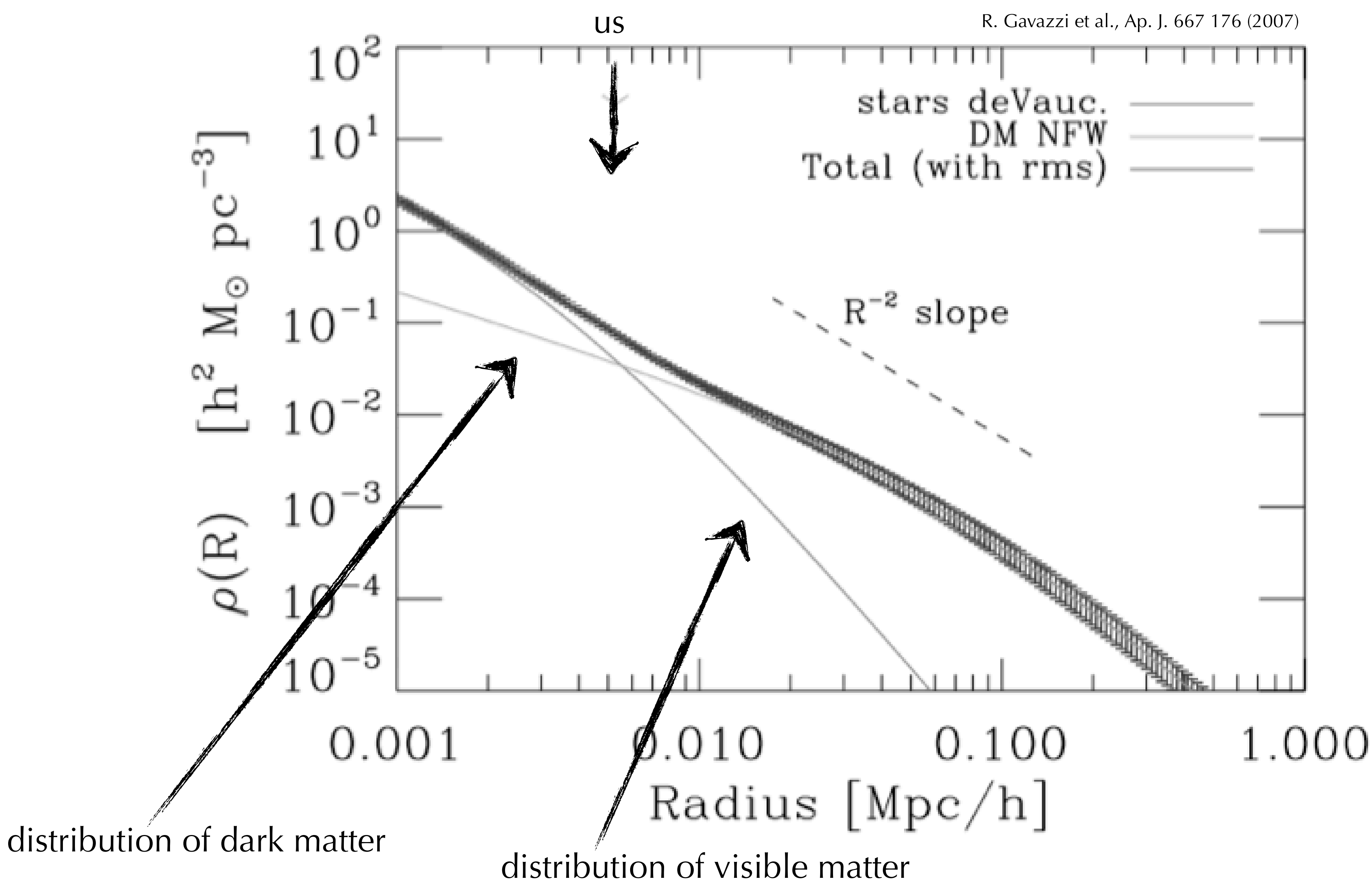


mirror DM, self-interacting DM, exothermic DM, inelastic DM, isospin-violating DM, sub-GeV DM, composite DM, accidental composite DM, Rayleigh DM, magnetic inelastic DM, millicharged DM, millicharged atomic DM, magnetic fluffy DM, higgsino DM, sneutrino DM, pure wino DM, asymmetric DM, leptophilic DM, too broke to pay attention DM, semi elastic DM, Q-ball DM, axino DM, Kaluza-Klein DM…




http://xkcd.com/74/

Lets be optimistic, though, and think about direct detection



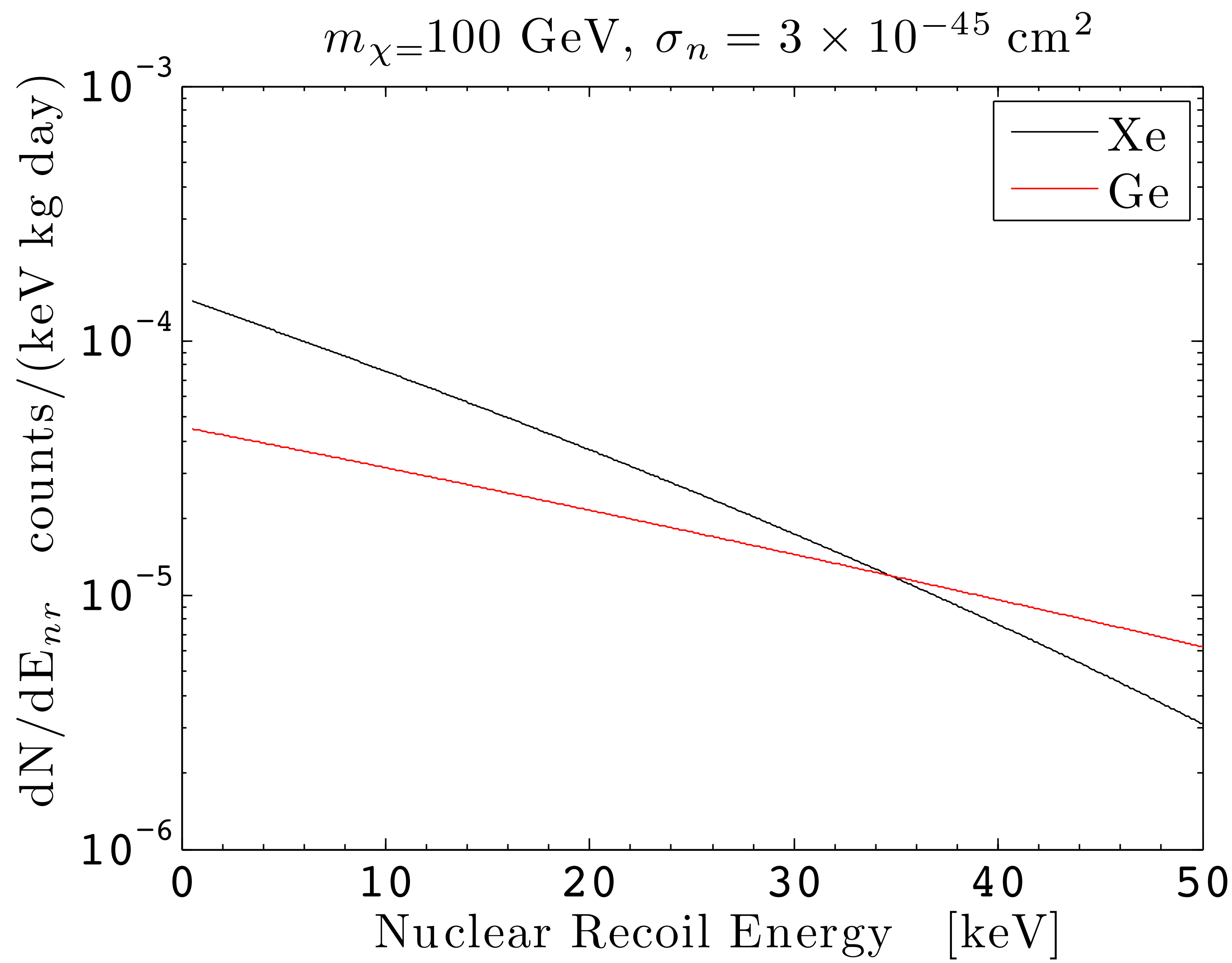

estimated DM density in our hood: ~0.3 GeV/cm$^3$ (x6e4 above critical)

Assume a spherical halo, and spherically symmetric scattering

PHYSICAL REVIEW D **72,** 063509 (2005)

$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi}{4 v_0 m_\chi} F^2(E_R) \frac{\sigma_n}{\mu_n^2} \frac{(f_p Z + f_n(A - Z))^2}{f_n^2} \times \left( \frac{\mathrm{erf}(x_{\mathrm{min}} + \eta) - \mathrm{erf}(x_{\mathrm{min}} - \eta)}{\eta} \right) \times \Theta(\beta_{\mathrm{esc}} - \beta_{\mathrm{min}}(E_R)). \quad (7)$$

$dR/dE_R$ : experimental rate



**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]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
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[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

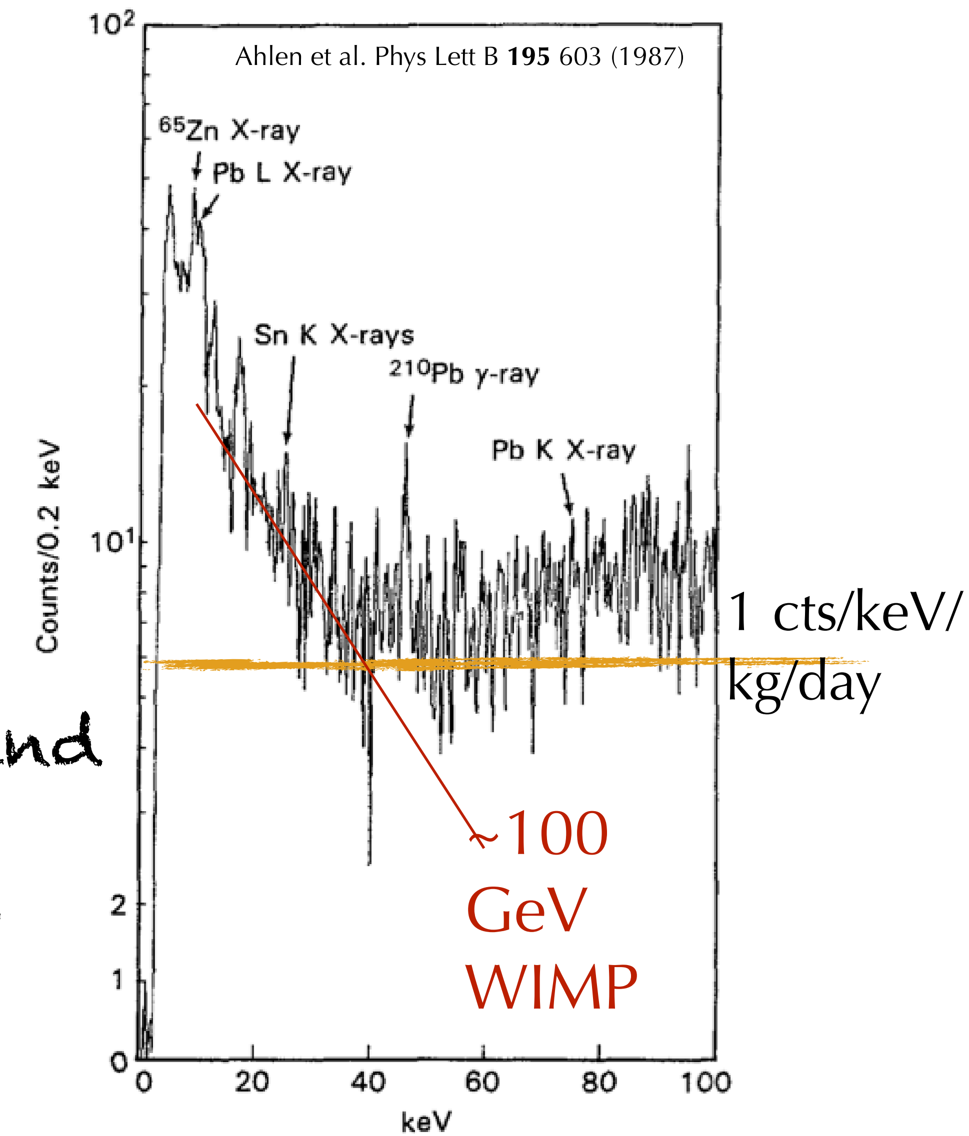



Fig. 2. 1000 h of data from the Ge spectrometer are shown The width of each channel is 0.2 keV. The identified peaks result from the decay products of radioactivity in the exposed solder.

## Basic recipe (p3):

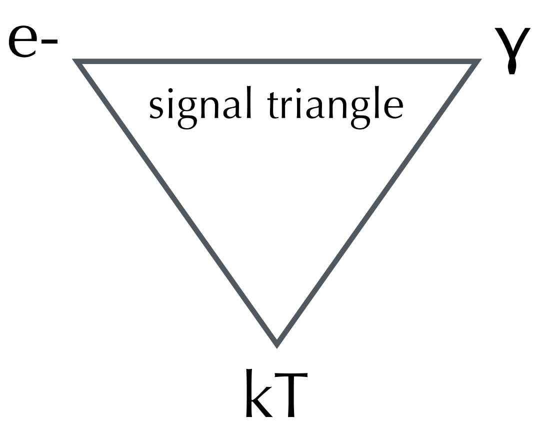
eters. The detector is located in the Homestake mine at a depth equivalent to 4000 m of water to eliminate the cosmic ray induced background. The detector cryostat is constructed from high-purity copper and is surrounded by 11 tons of lead, sheet cadmium and neutron moderator, to eliminate the radioactive 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

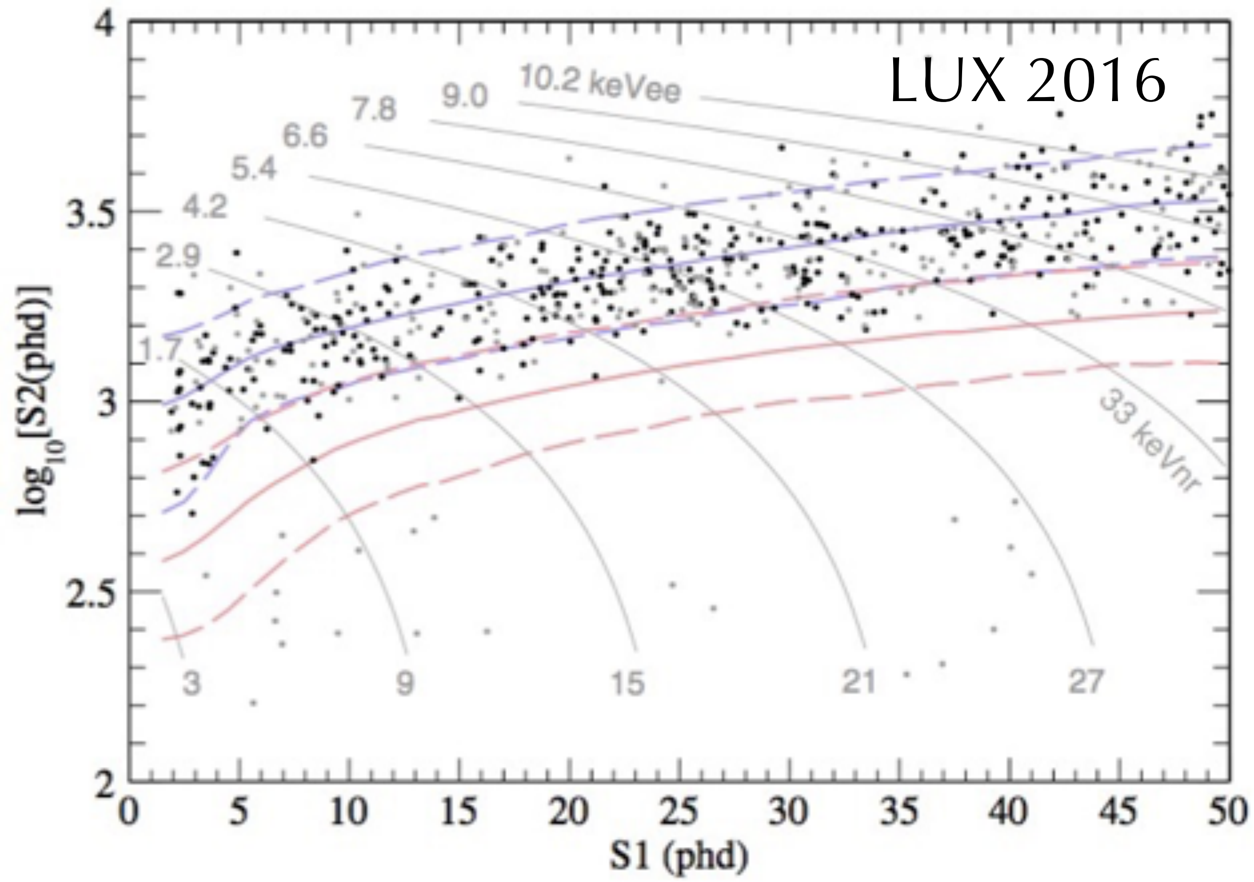
(1) go underground

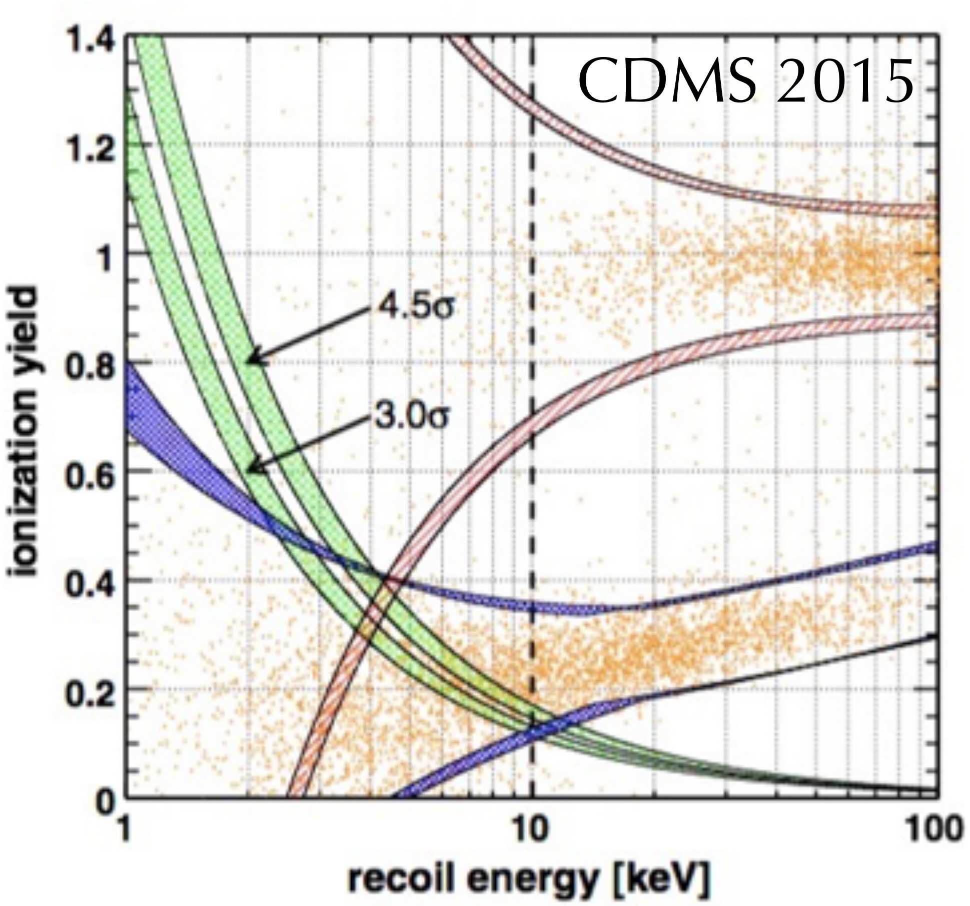
(2) build a castle

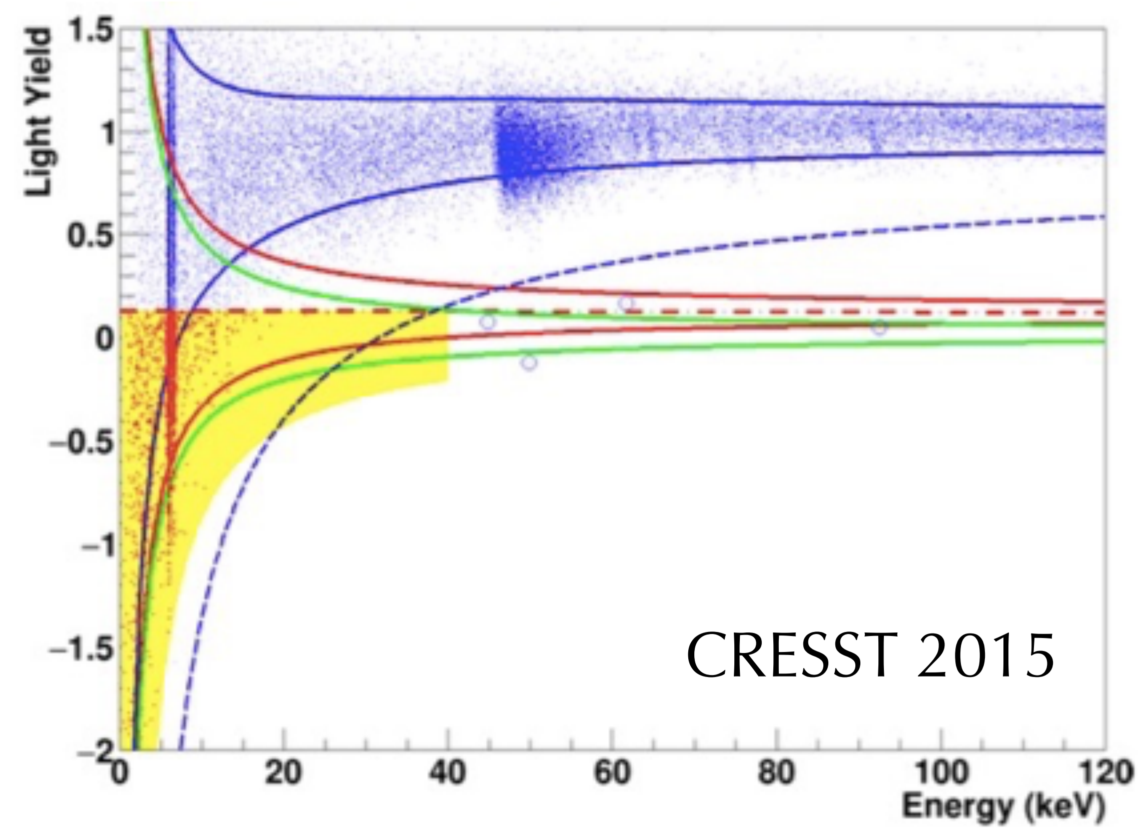
(3) avoid miners

# should add step: (4) be discriminating



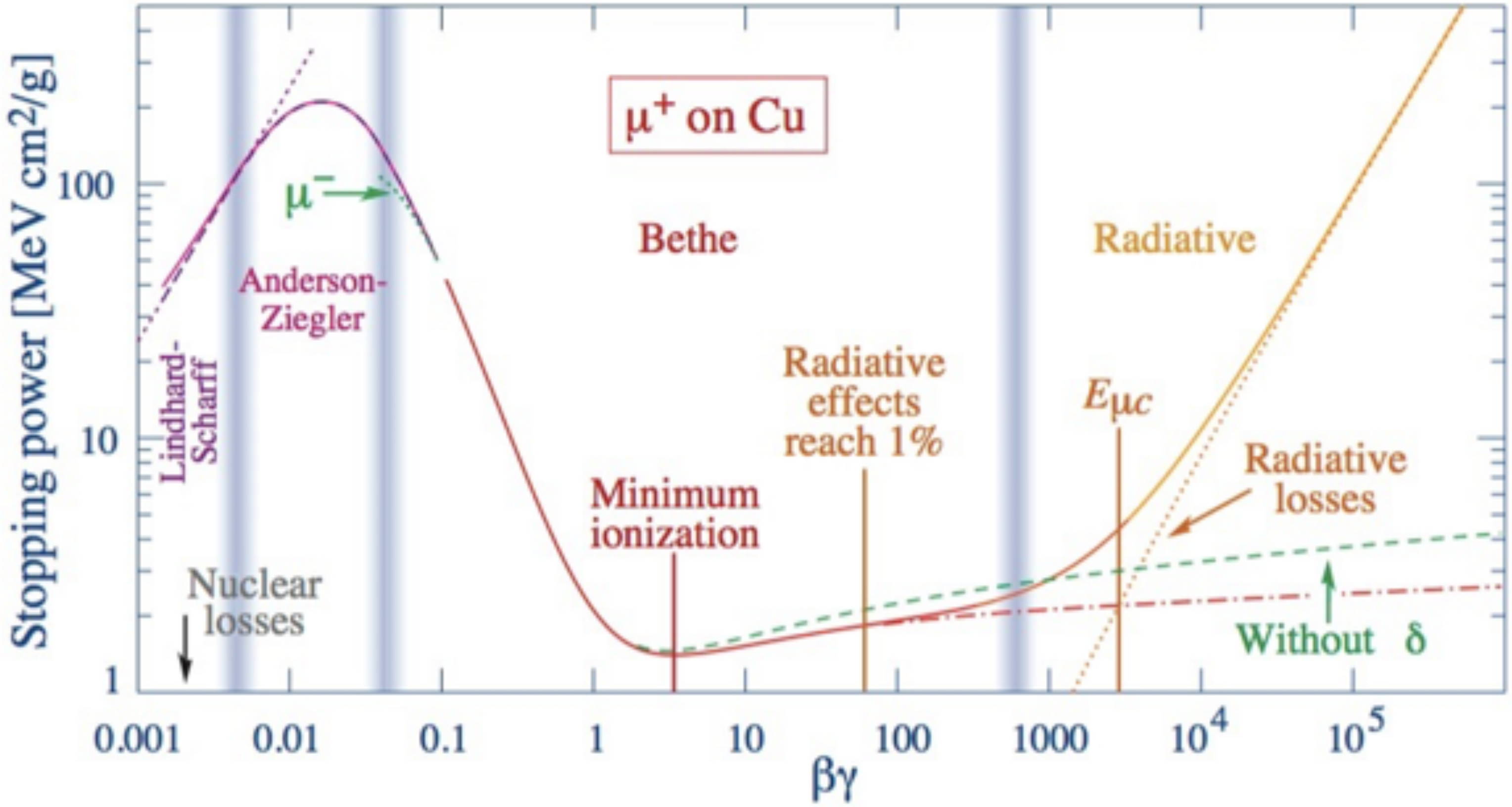



# particle discrimination! how does it work?

PDG plot for qualitative explanation



# The most critical form of discrimination is edge vs bulk

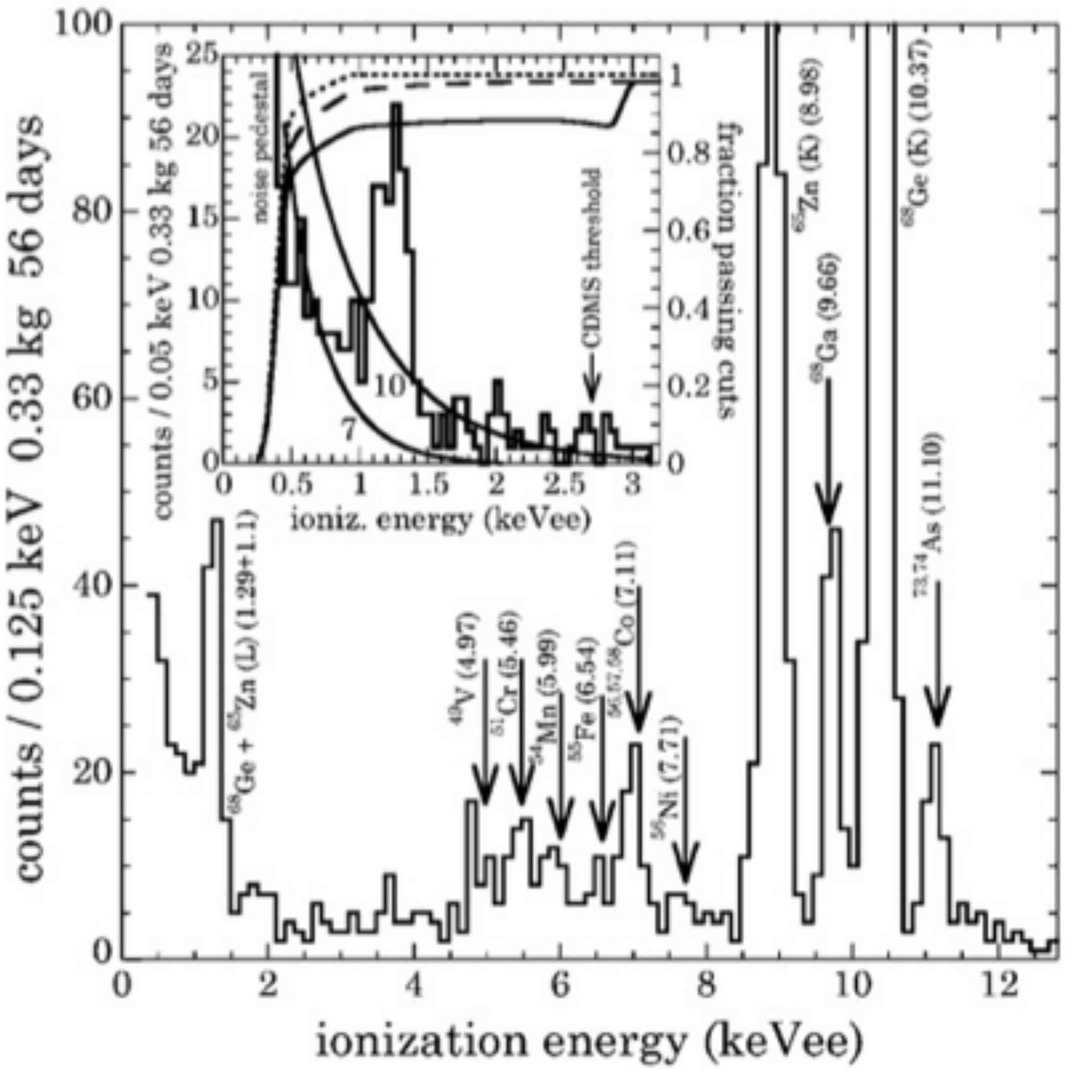



FIG. 3. Low-energy spectrum after all cuts, prior to efficiency

>500 citations

Results from a Search for Light-Mass Dark Matter with a p-Type Point Contact Germanium Detector
(CoGeNT Collaboration)
Phys. Rev. Lett. **106**, 131301 – Published 29 March 2011

>1400 citations

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory
(SNO Collaboration)
Phys. Rev. Lett. **89**, 011301 – Published 13 June 2002

NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1988

## Laboratory Limits on Galactic Cold Dark Matter

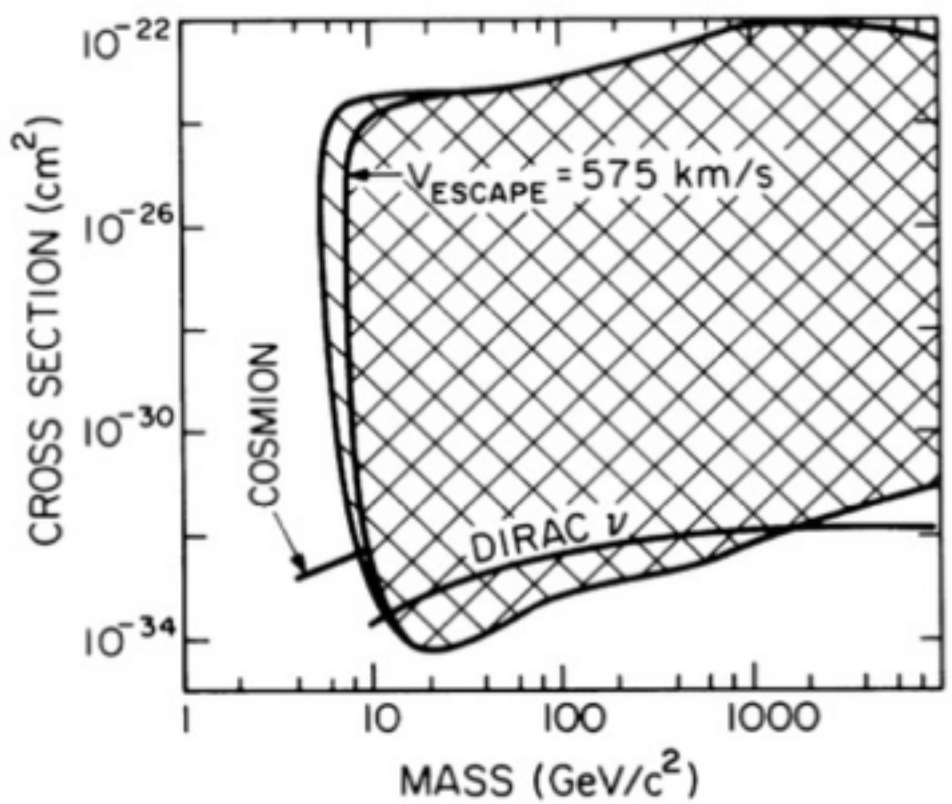
D. O. Caldwell, R. M. Eisberg, D. M. Grumm, and M. S. Witherell
*Department of Physics, University of California, Santa Barbara, California 93106*

B. Sadoulet
*Physics Department, University of California, Berkeley, California 94720*

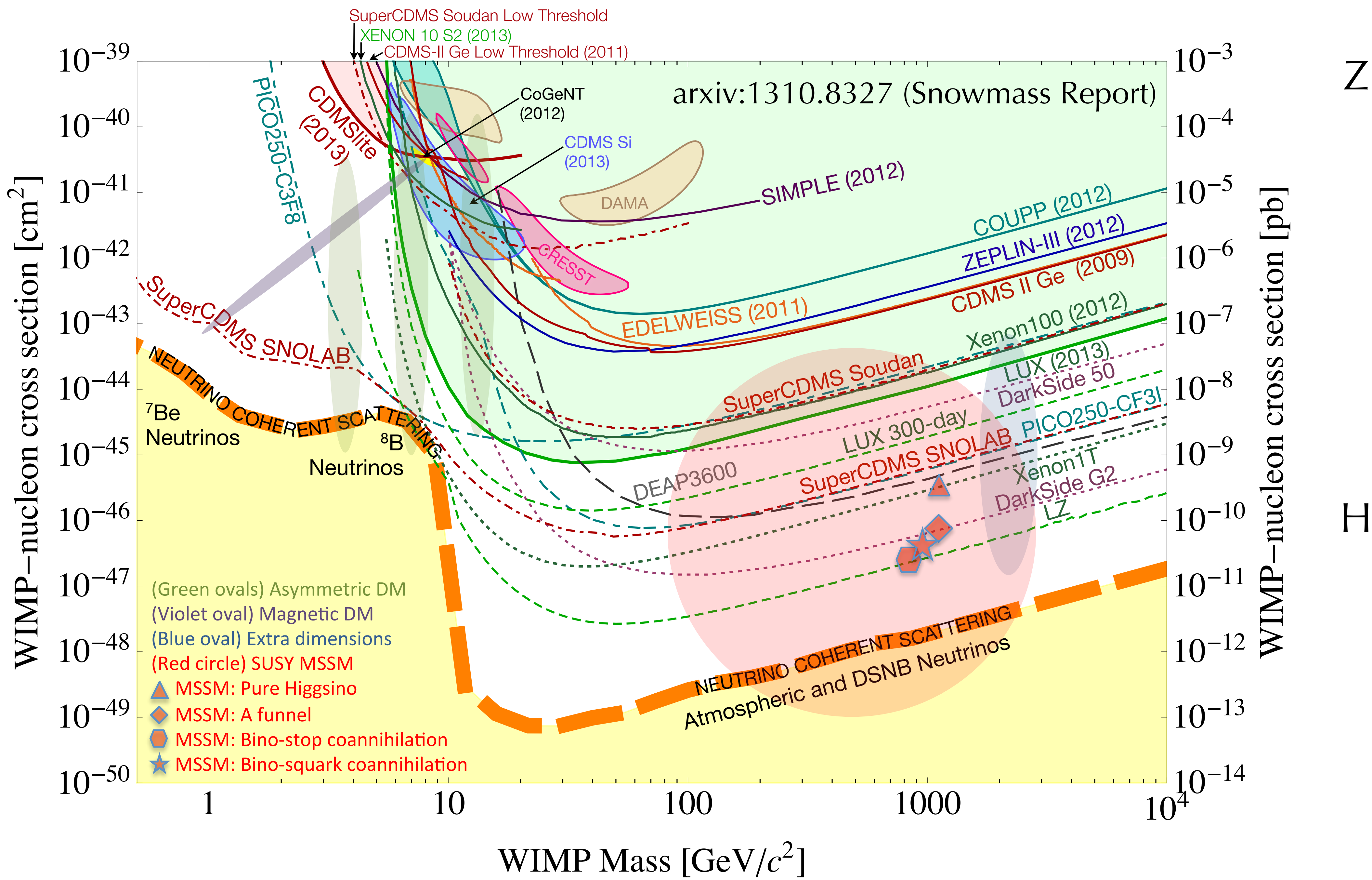
and

F. S. Goulding and A. R. Smith
*Lawrence Berkeley Laboratory, Berkeley, California 94720*
(Received 13 November 1987; revised manuscript received 16 May 1988)

Interesting limits are set on candidates for cold-dark-matter particles in the halo of our Galaxy from their interaction with a very-low-background Ge detector used to search for double-$\beta$ decay. Dirac neutrinos constituting all of dark matter are excluded for masses between 12 GeV/$c^2$ and 1.4 TeV/$c^2$. There are slightly better limits on magninos and cosmions, proposed massive particles which also explain the solar-neutrino problem but which interact more strongly with Ge. In addition, millicharged shadow matter is ruled out as the main form of dark matter.

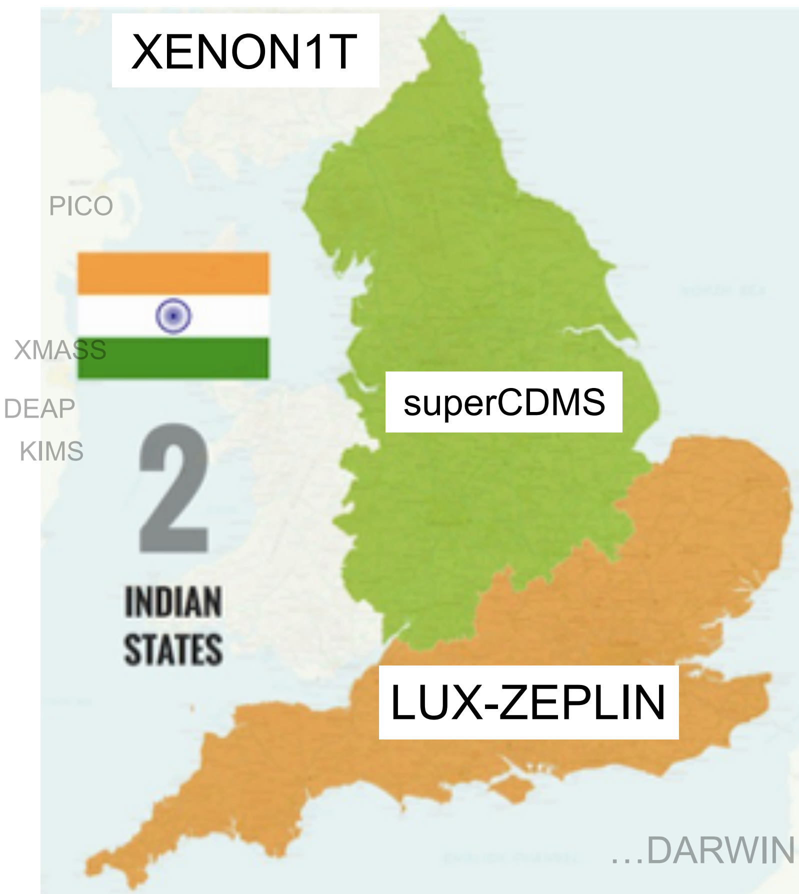


# exclusion limits: classical WIMPS ruled out



# Down-select

2012 => 2016


source: http://bigthink.com/strange-maps/xx-ways-to-carve-up-england

# Seminal paper:

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

## Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

$$R = \frac{1.1\ \text{events}}{\text{kg day}} \left[\frac{100\ \text{GeV}}{M_{\tilde{Q}}}\right]^4 \frac{4M_{\tilde{\gamma}} M_{\text{Nuc}}}{(M_{\tilde{\gamma}} + M_{\text{Nuc}})^2} \left[\frac{q}{\frac{2}{3}e}\right]^4 [\lambda^2 J(J+1)] \left[\frac{\rho}{10^{-24}\ \text{g/cm}^3}\right] \left[\frac{\langle v \rangle}{200\ \text{km/sec}}\right].$$

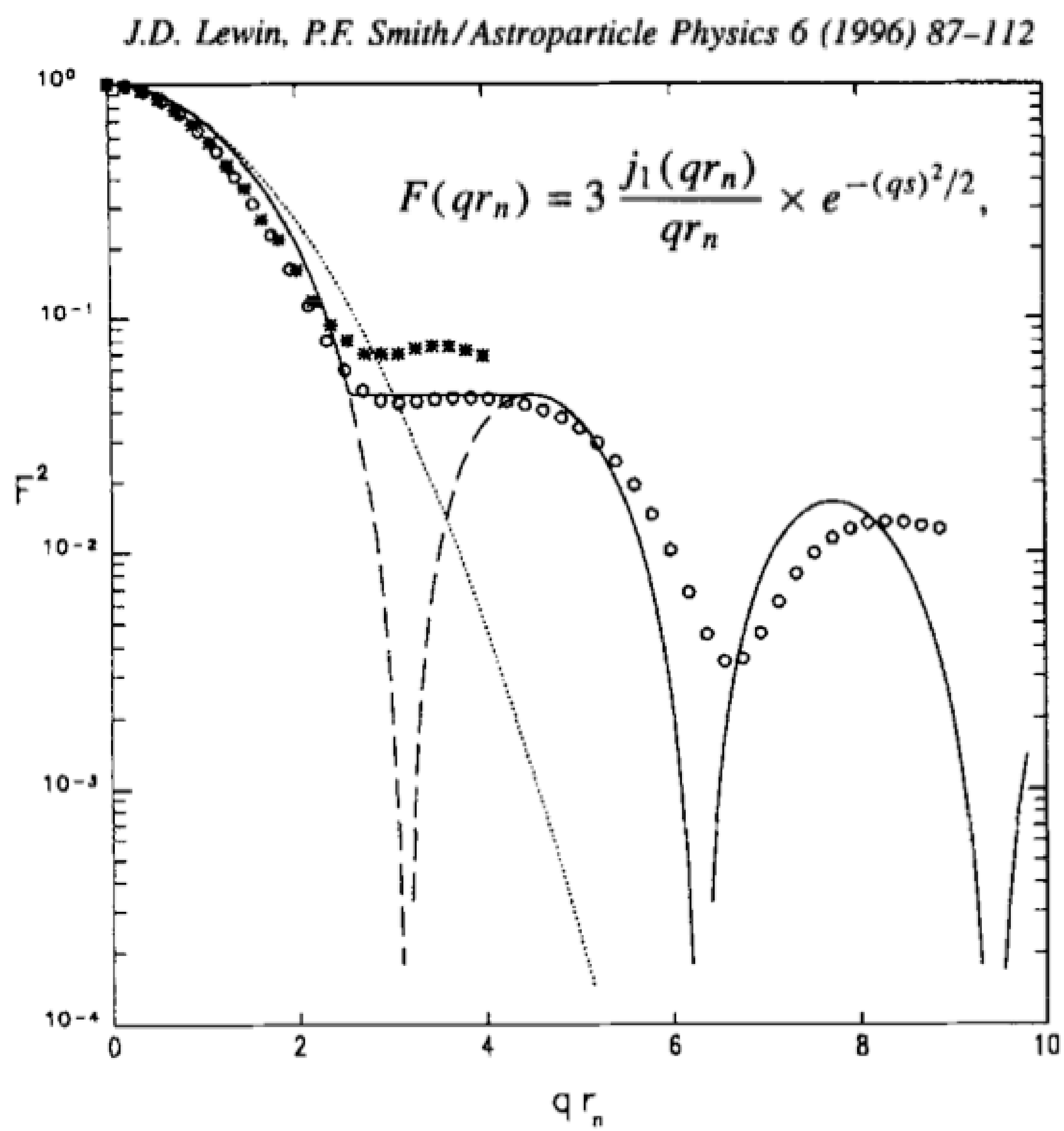
(note implicit Lee-Weinberg bound aka “the Tyranny of the WIMP” bound)

— Neal Weiner, NYU

Coherence! lets calculate the deBroglie wavelength of a 100 GeV WIMP in the halo

and compare it to the nuclear size

$h/q \sim r_A$



# 30 years later, still using Goodman+Witten framework…

PRL 116, 161302 (2016) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

**Results on the Spin-Dependent Scattering of Weakly Interacting Massive Particles on Nucleons from the Run 3 Data of the LUX Experiment**

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(LUX Collaboration)

=> spin independent

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(LUX Collaboration)

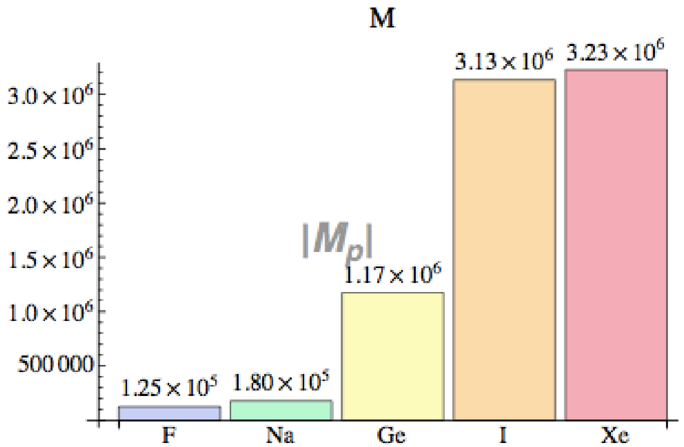
=> spin dependent

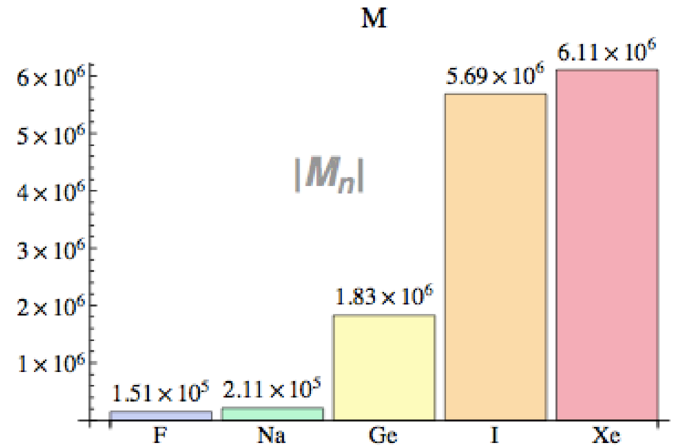
arxiv:1203.3542

| Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$ | Leading Multipole | Long-wavelength Limit | Response Type | |
|---|---|---|---|---|
| $\sum_{J=0,2,...}^{\infty} \lvert\langle J_i \lVert M_{JM} \rVert J_i\rangle\rvert^2$ | $M_{00}(q\vec{x}_i)$ | $\frac{1}{\sqrt{4\pi}} 1(i)$ | $M_{JM}$ : Charge | usual spin independent |
| $\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \lVert \Sigma''_{JM} \rVert J_i\rangle\rvert^2$ | $\Sigma''_{1M}(q\vec{x}_i)$ | $\frac{1}{2\sqrt{3\pi}} \sigma_{1M}(i)$ | $L^5_{JM}$ : Axial Longitudinal | spin dependent |
| $\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \lVert \Sigma'_{JM} \rVert J_i\rangle\rvert^2$ | $\Sigma'_{1M}(q\vec{x}_i)$ | $\frac{1}{\sqrt{6\pi}} \sigma_{1M}(i)$ | $T^{\mathrm{el5}}_{JM}$ : Axial Transverse Electric | spin dependent |
| $\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \Delta_{JM} \rVert J_i\rangle\rvert^2$ | $\frac{q}{m_N} \Delta_{1M}(q\vec{x}_i)$ | $-\frac{q}{2m_N\sqrt{6\pi}} \ell_{1M}(i)$ | $T^{\mathrm{mag}}_{JM}$ : Transverse Magnetic | nucleon angular momentum |
| $\sum_{J=0,2,...}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \Phi''_{JM} \rVert J_i\rangle\rvert^2$ | $\frac{q}{m_N} \Phi''_{00}(q\vec{x}_i)$ | $-\frac{q}{3m_N\sqrt{4\pi}} \vec{\sigma}(i) \cdot \vec{\ell}(i)$ | $L_{JM}$ : Longitudinal | nucleon spin and angular momentum (L dot S) |
| | $\frac{q}{m_N} \Phi''_{2M}(q\vec{x}_i)$ | $-\frac{q}{m_N\sqrt{30\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$ | | |
| $\sum_{J=2,4,...}^{\infty} \lvert\langle J_i \lVert \frac{q}{m_N} \tilde{\Phi}'_{JM} \rVert J_i\rangle\rvert^2$ | $\frac{q}{m_N} \tilde{\Phi}'_{2M}(q\vec{x}_i)$ | $-\frac{q}{m_N\sqrt{20\pi}} [x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$ | $T^{\mathrm{el}}_{JM}$ : Transverse Electric | |

Table 1: The response dark-matter nuclear response functions, their leading order behavior, and the response type. The notation $\otimes$ denotes a spherical tensor product, while $\times$ is the conventional cross product.

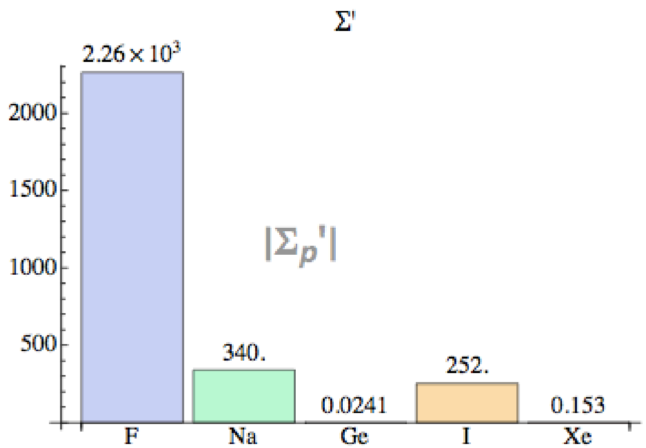
# Effect of effective field theory treatment

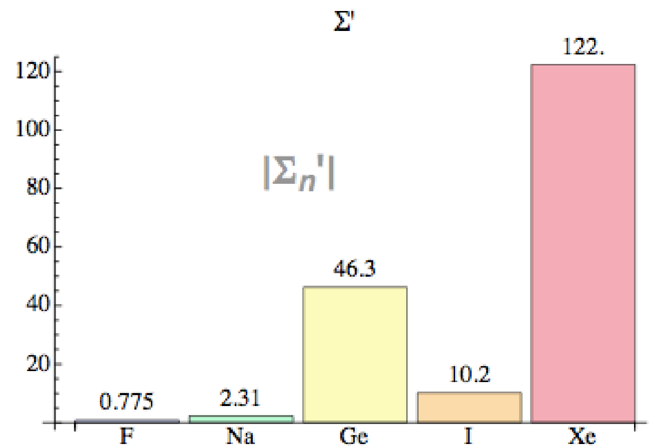


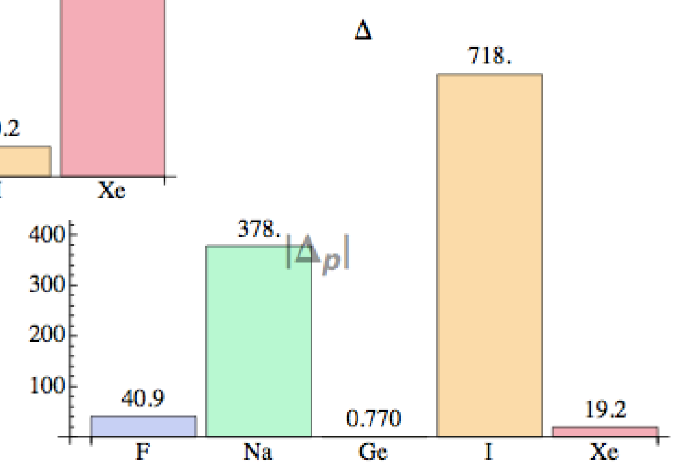



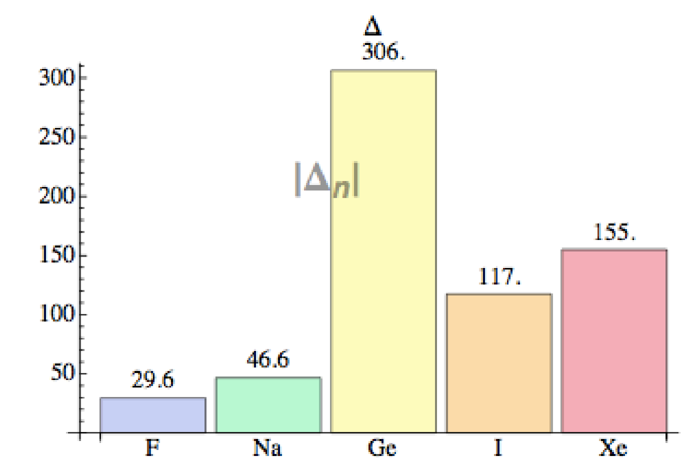

arxiv:1203.3542

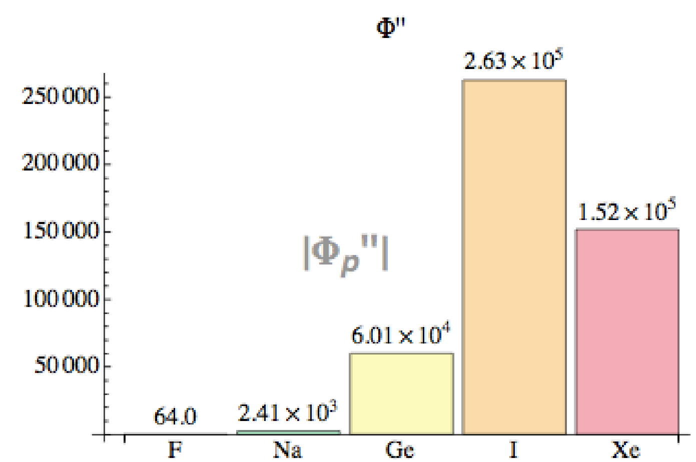
for 100 GeV dark matter

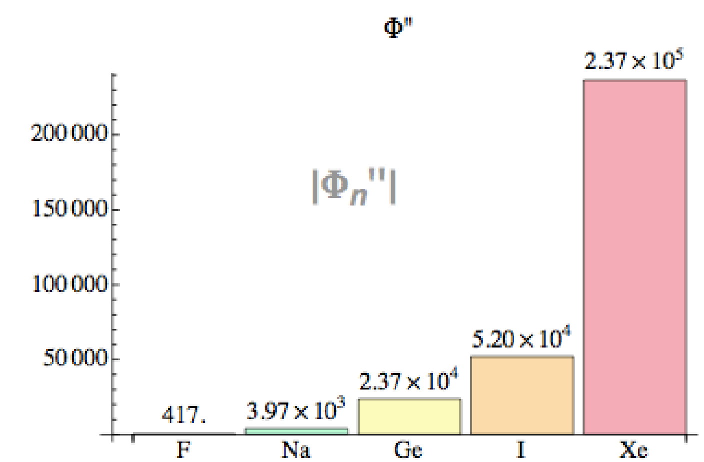


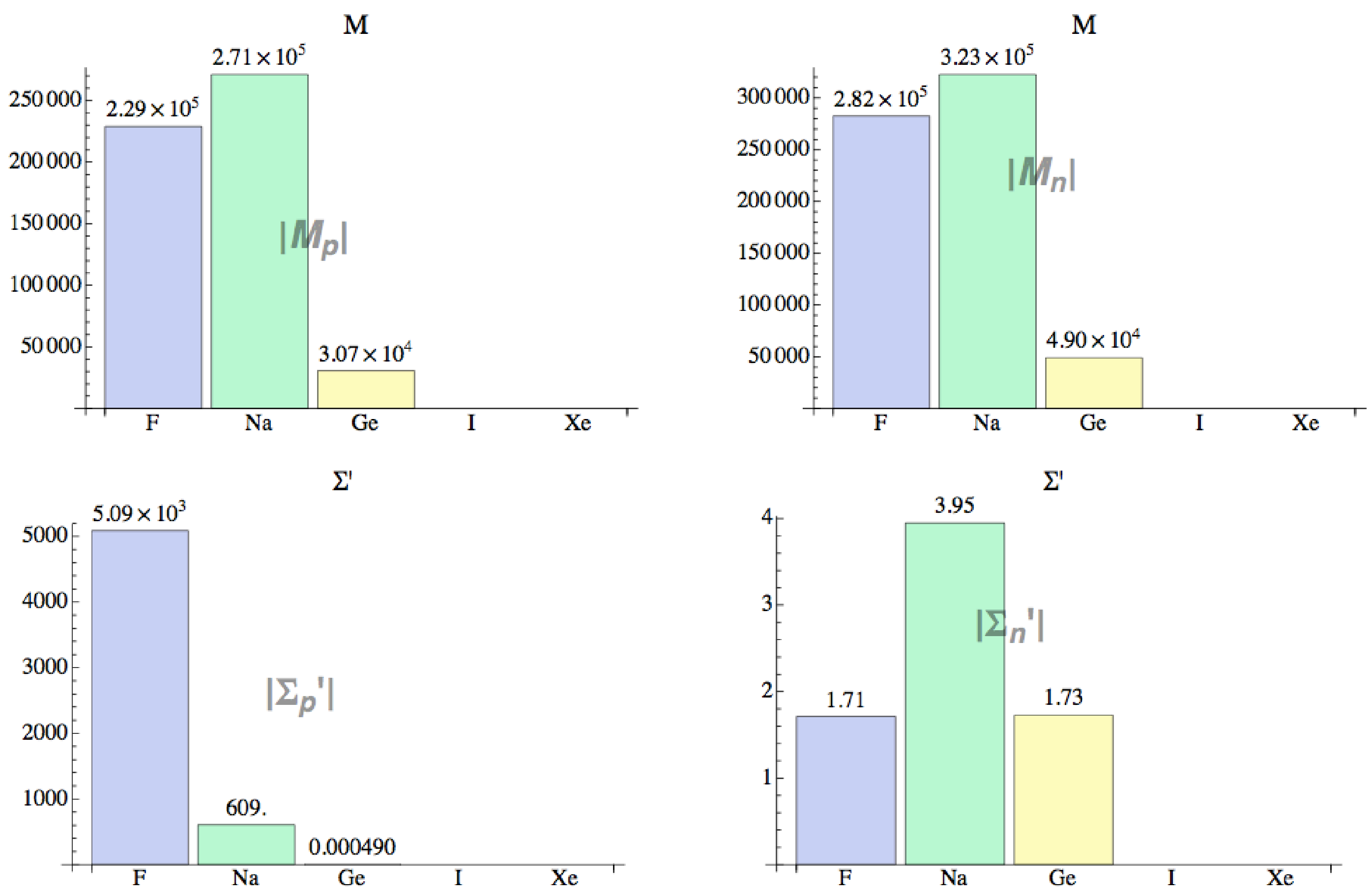



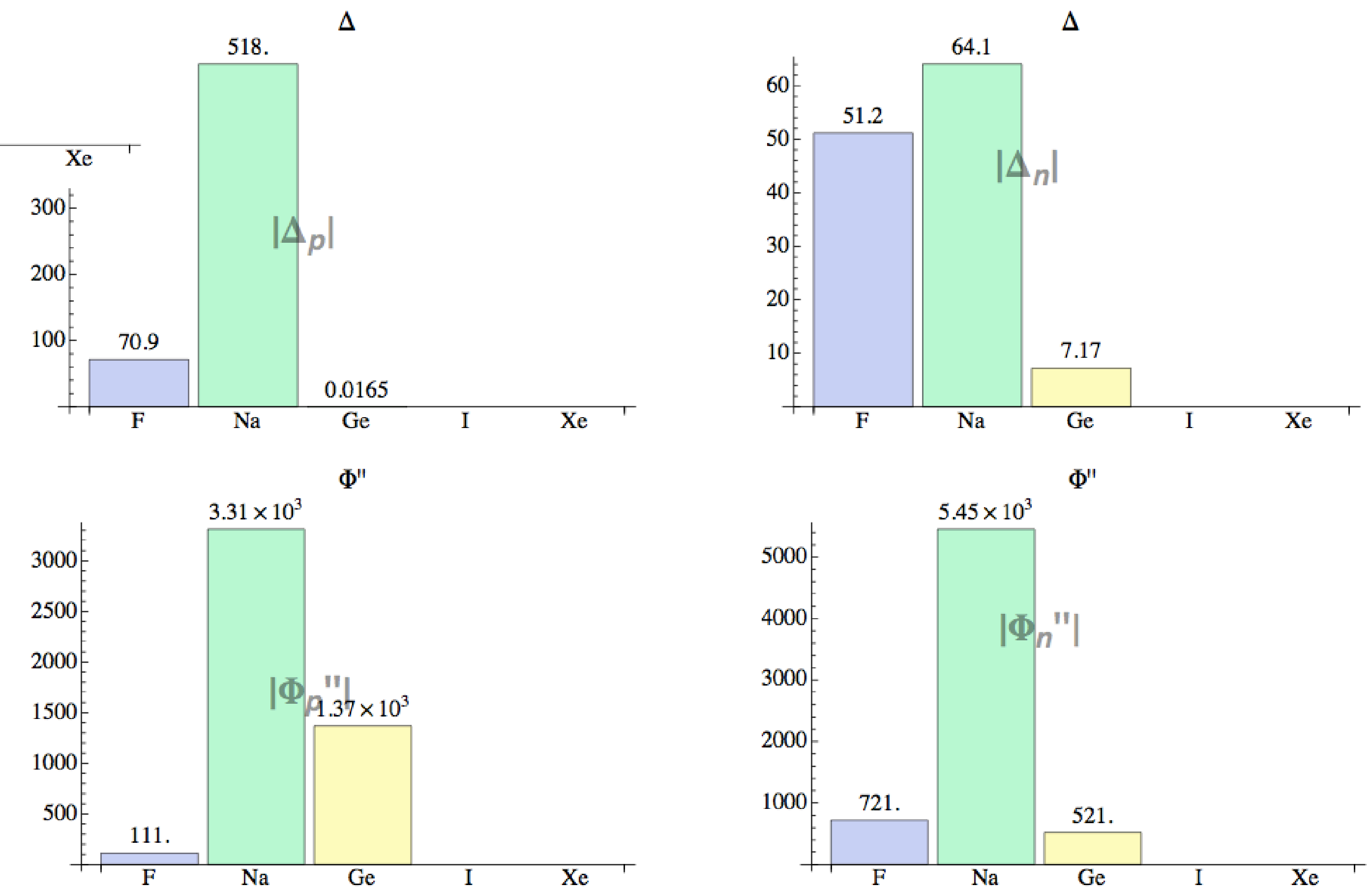



# Effect of effective field theory treatment

arxiv:1203.3542

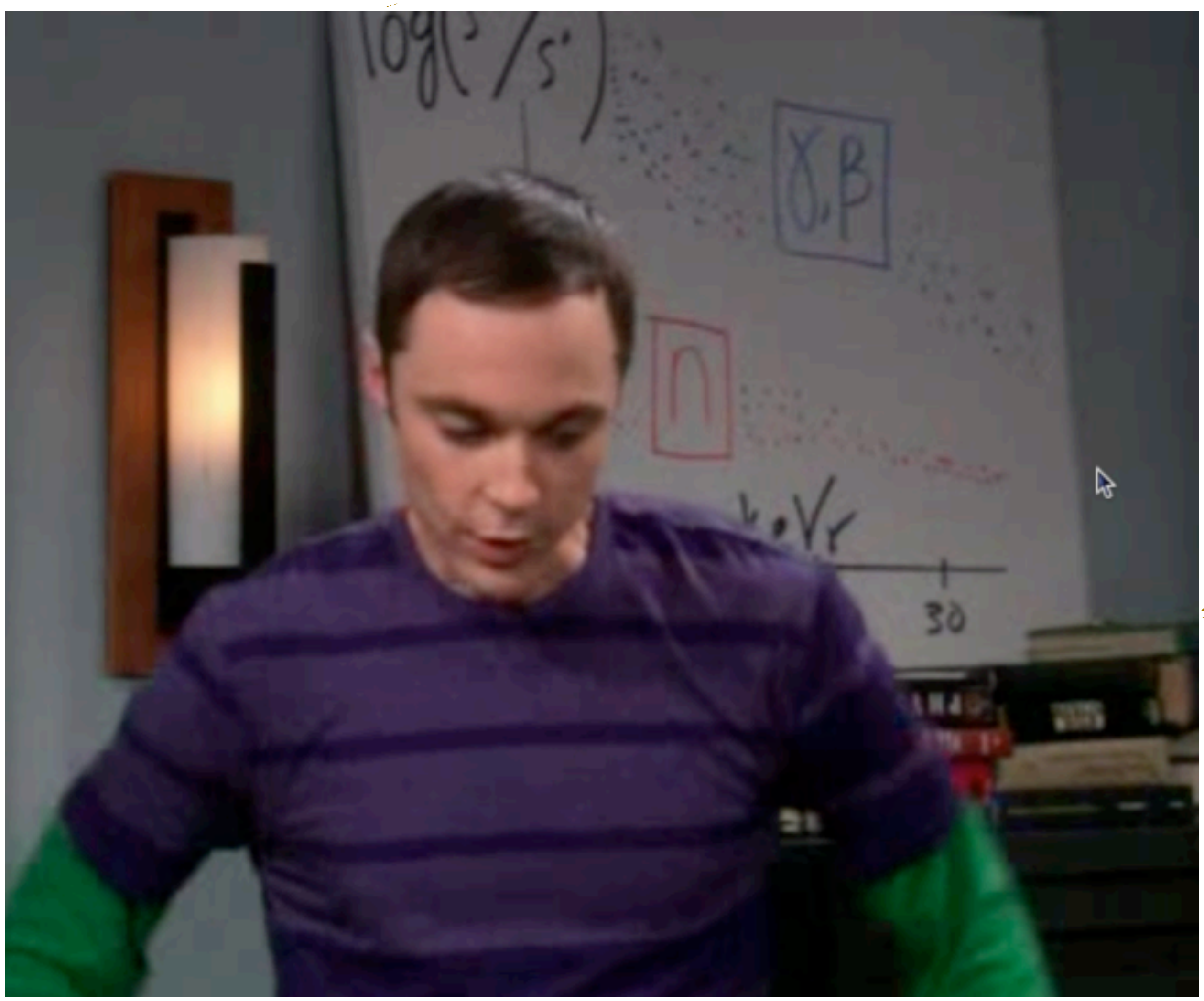
for 3 GeV dark matter



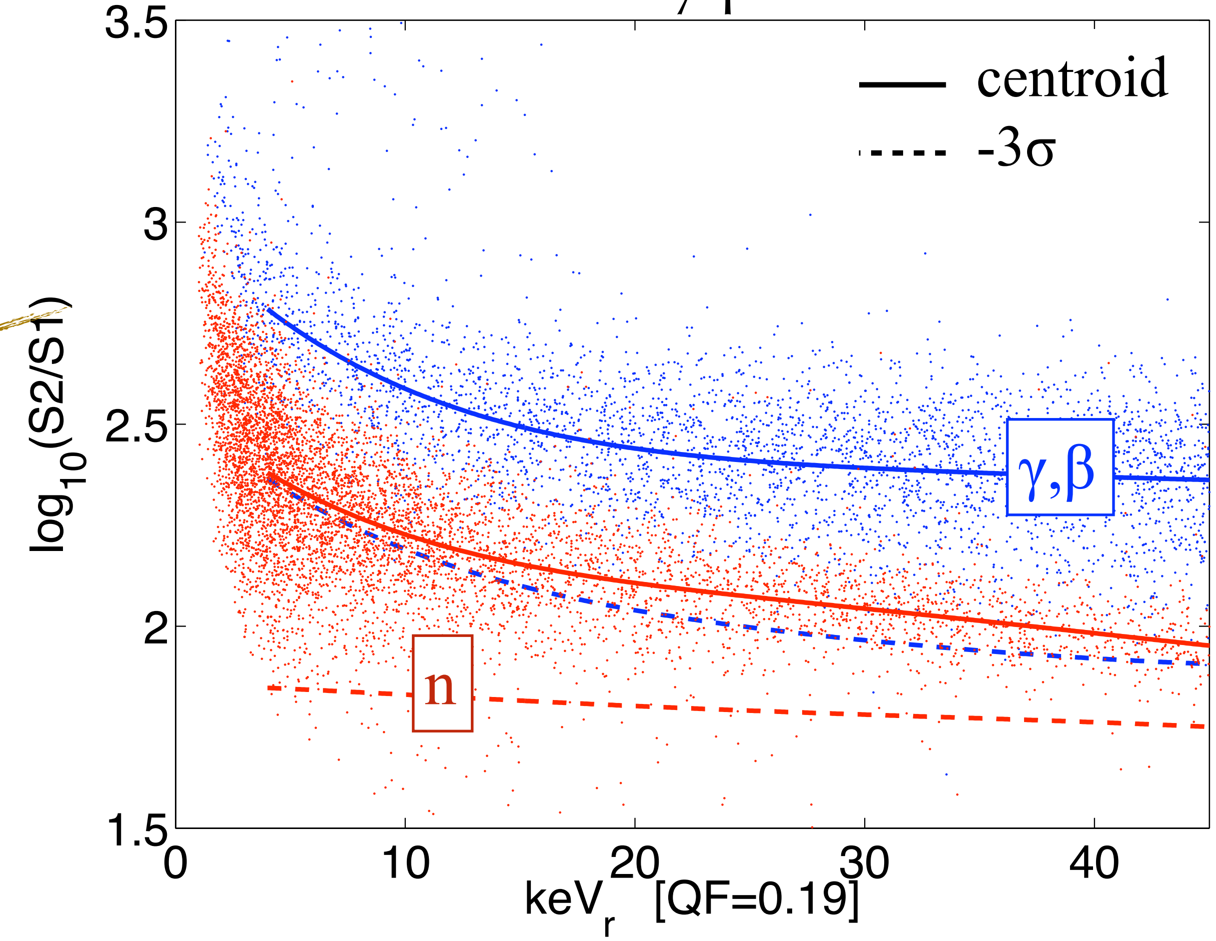



# Demonstrating ability to detect signal is CRITICAL when your primary results are null

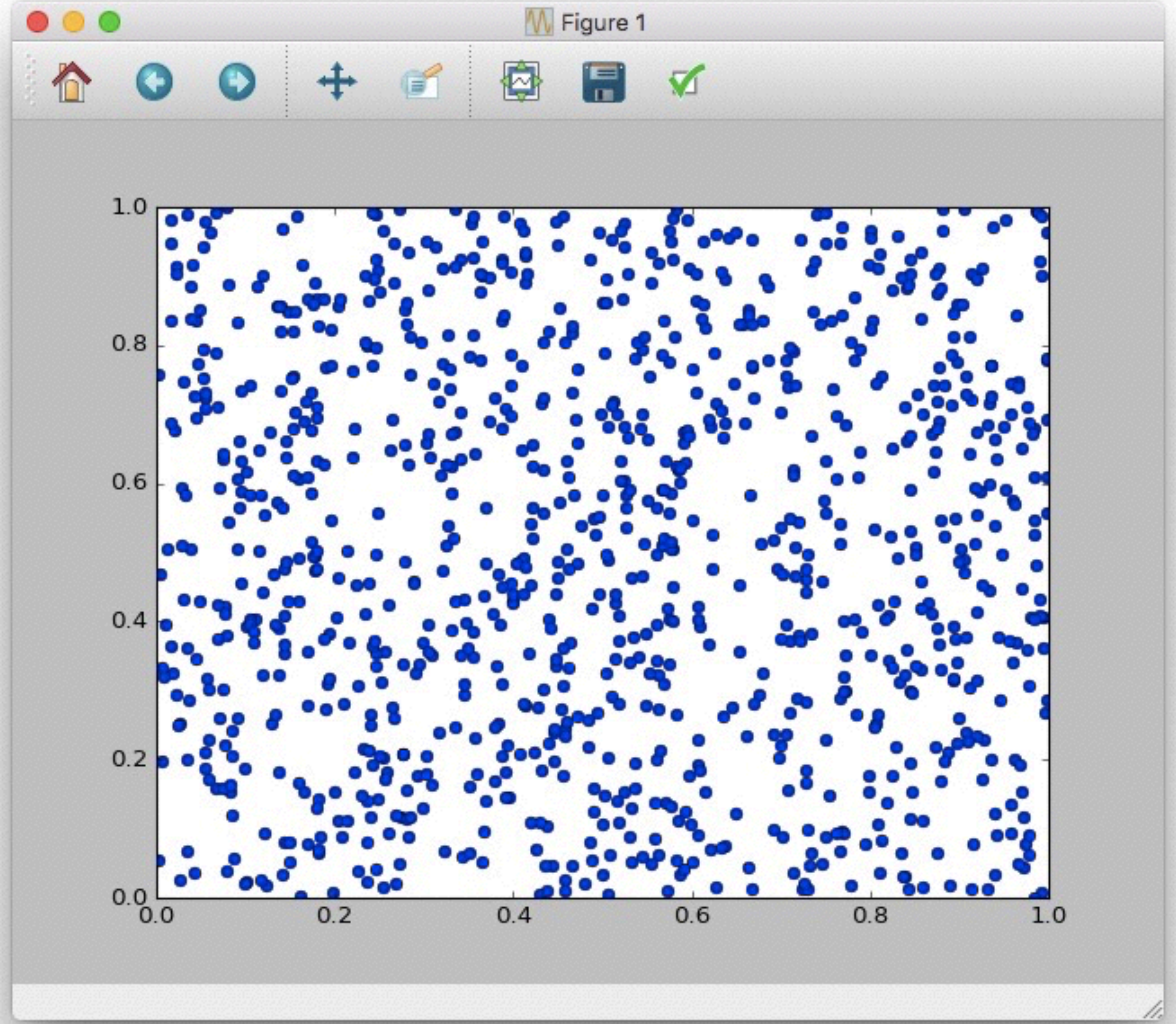
Sheldon on how to calibrate dark matter detectors



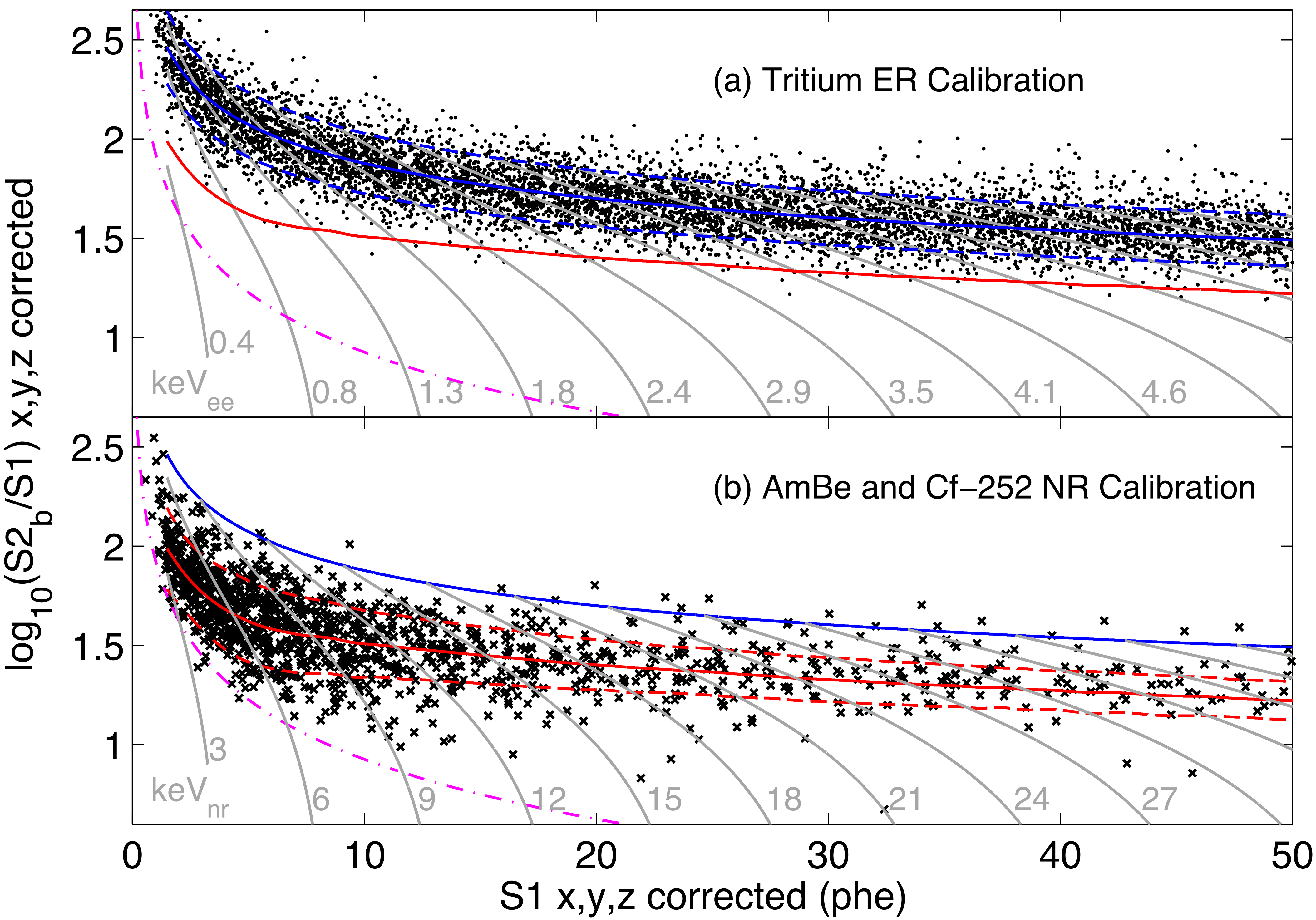
my plot!



# Calibrating: LUX data prior to (x,y,z) cut

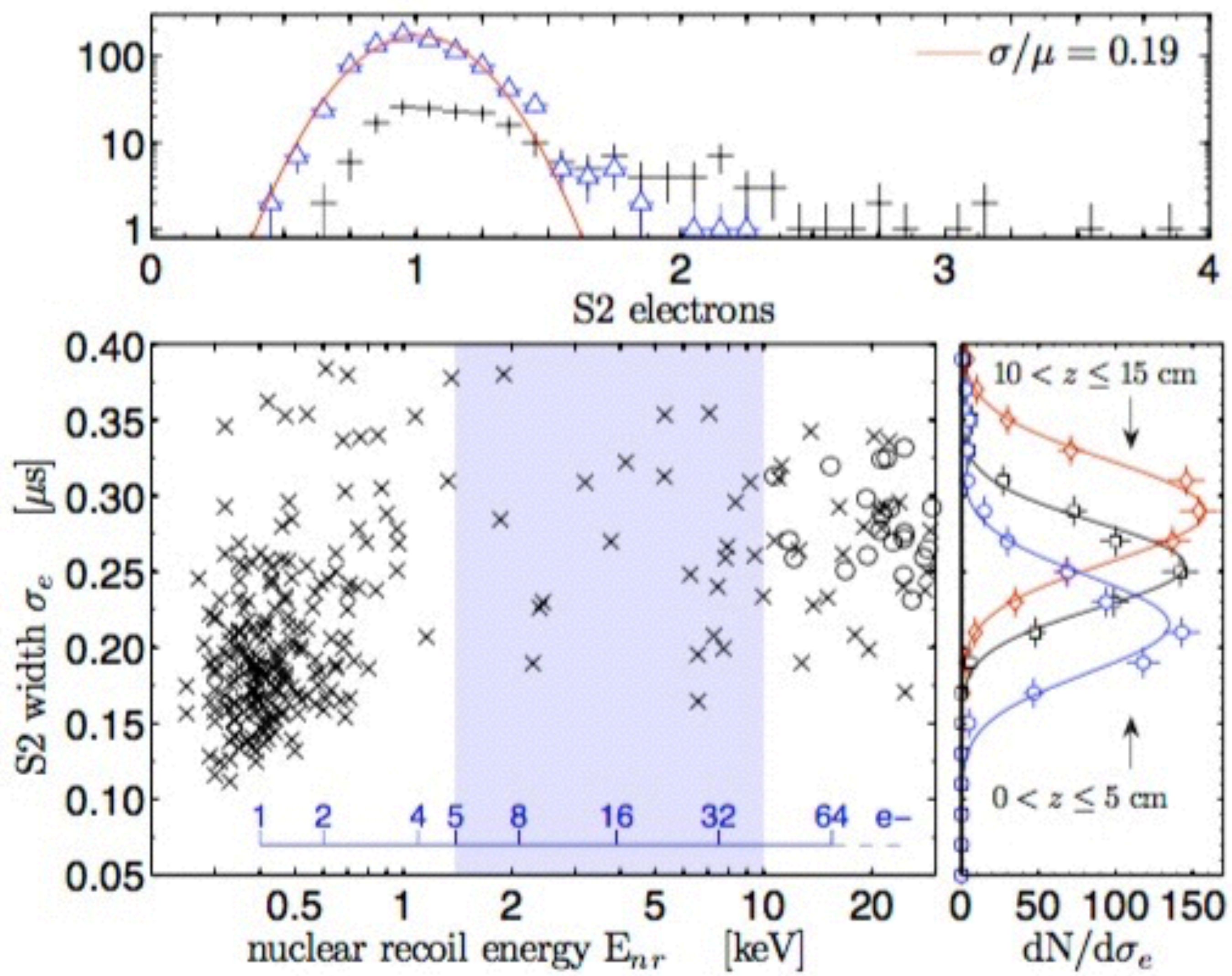


# Calibrating: LUX data after (x,y,z) cut



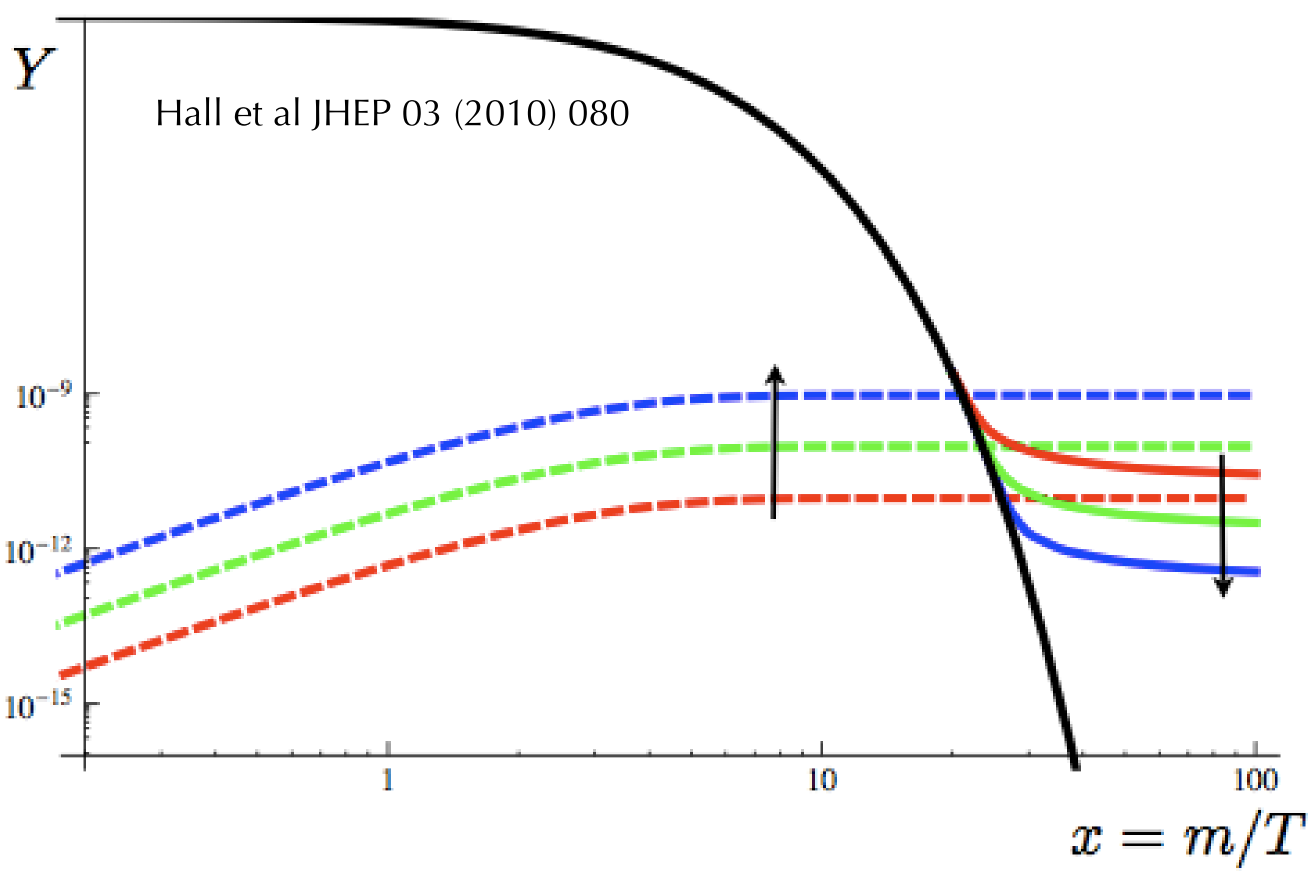
# Search for Light Dark Matter in XENON10 Data

J. Angle et al. (XENON10 Collaboration)
Phys. Rev. Lett. **107**, 051301 – Published 27 July 2011; Erratum Phys. Rev. Lett. **110**, 249901 (2013)



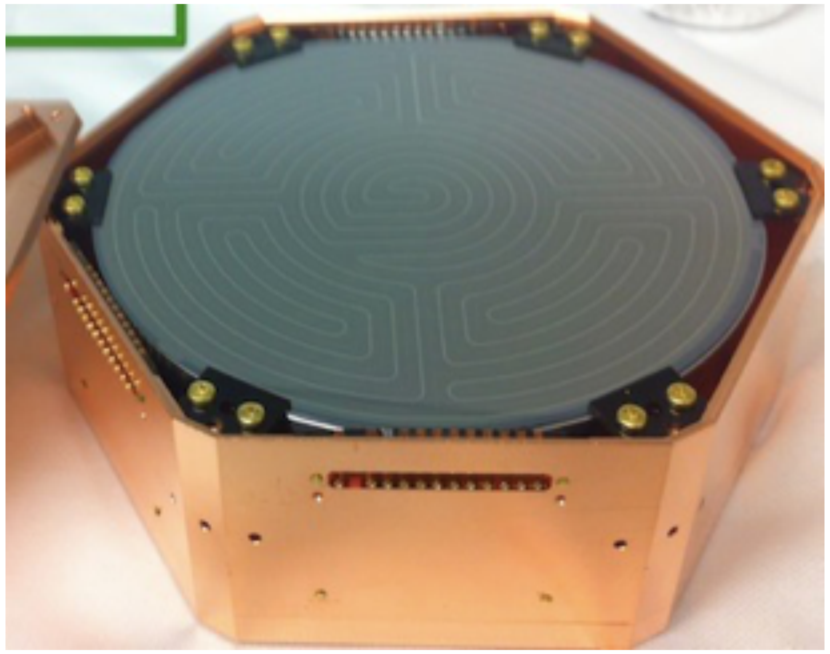

- motivated a search for sub-GeV dark matter
- conceptually similar to CDMSlite technology
- sub-GeV or "beyond WIMPs" is presently an active area of enquiry!

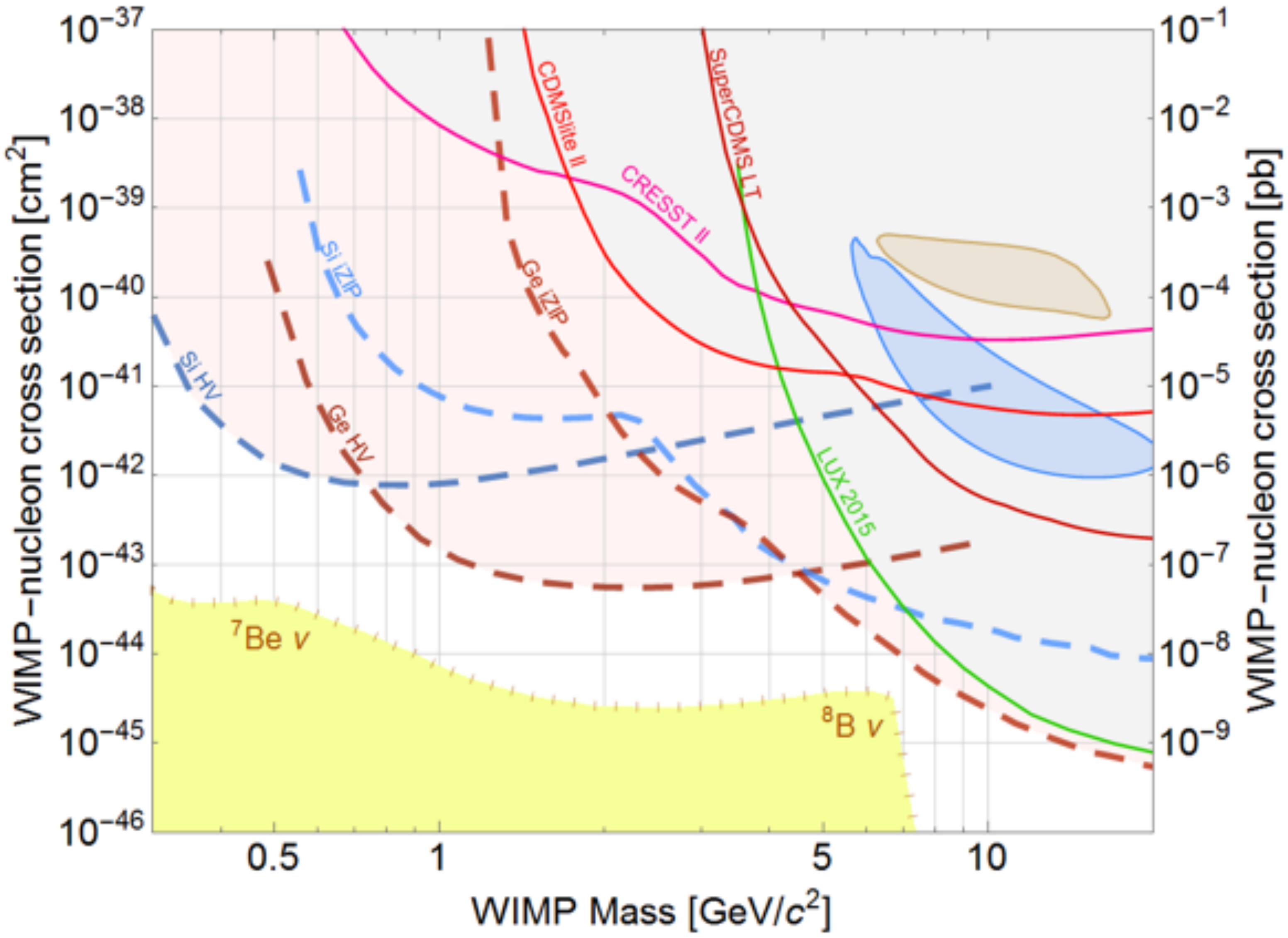
# non-WIMP mechanisms for populating the universe with DM




- There are compelling possibilities!
  - freeze-in (Hall et al 2012)
  - asymmetric dark matter," relic density determined by baryon asymmetry (Zurek et al 2009)
  - vector DM from inflation (Graham, Mardon and Rajendran 2015)
- Often coupled with postulation of a new vector boson, which evades the Lee-Weinberg bound by reducing the annihilation cross section of the DM

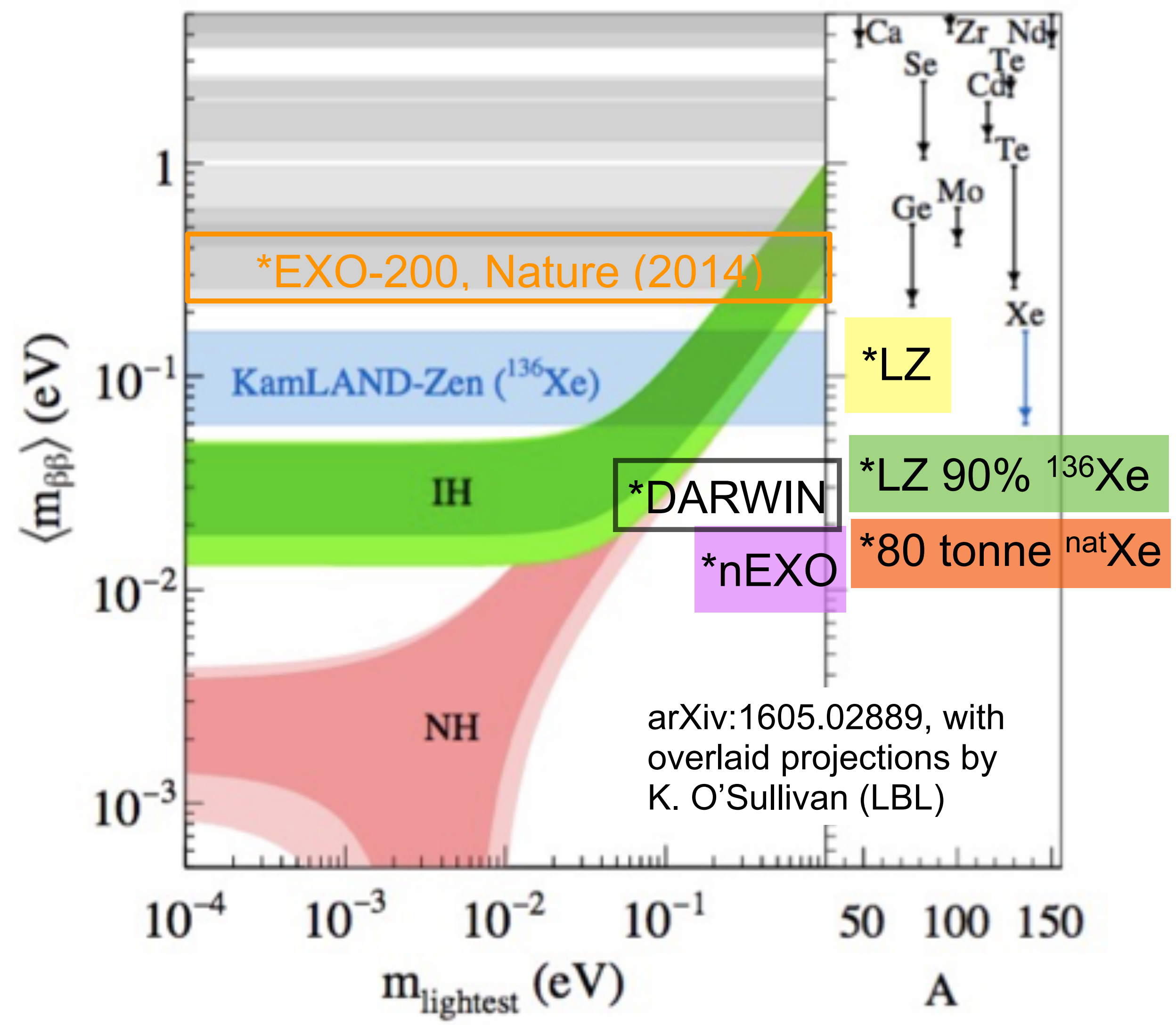
# Specialized technology for measuring such tiny energy depositions: superCDMS SNOLab



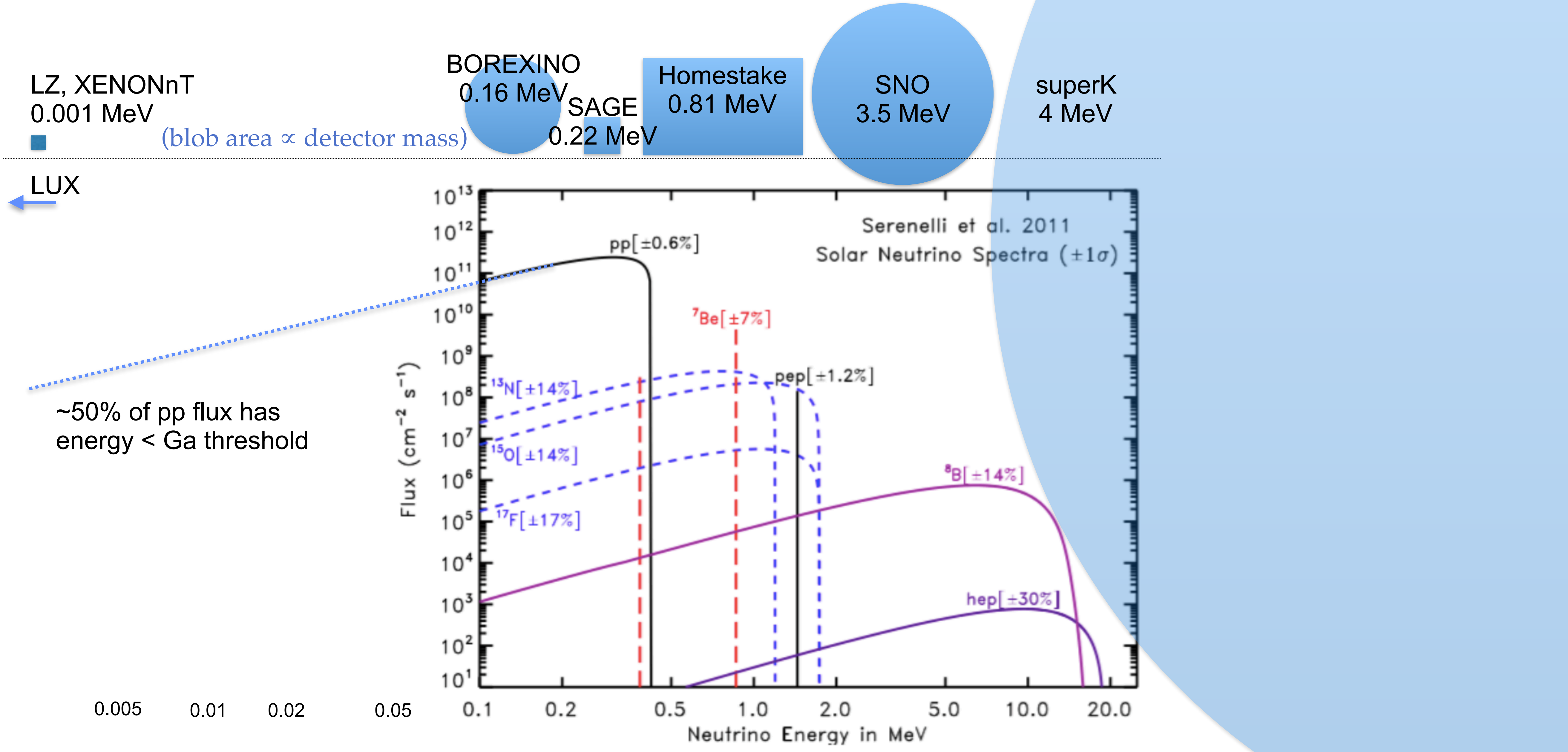


meaning, its up to nature if we will directly detect dark matter

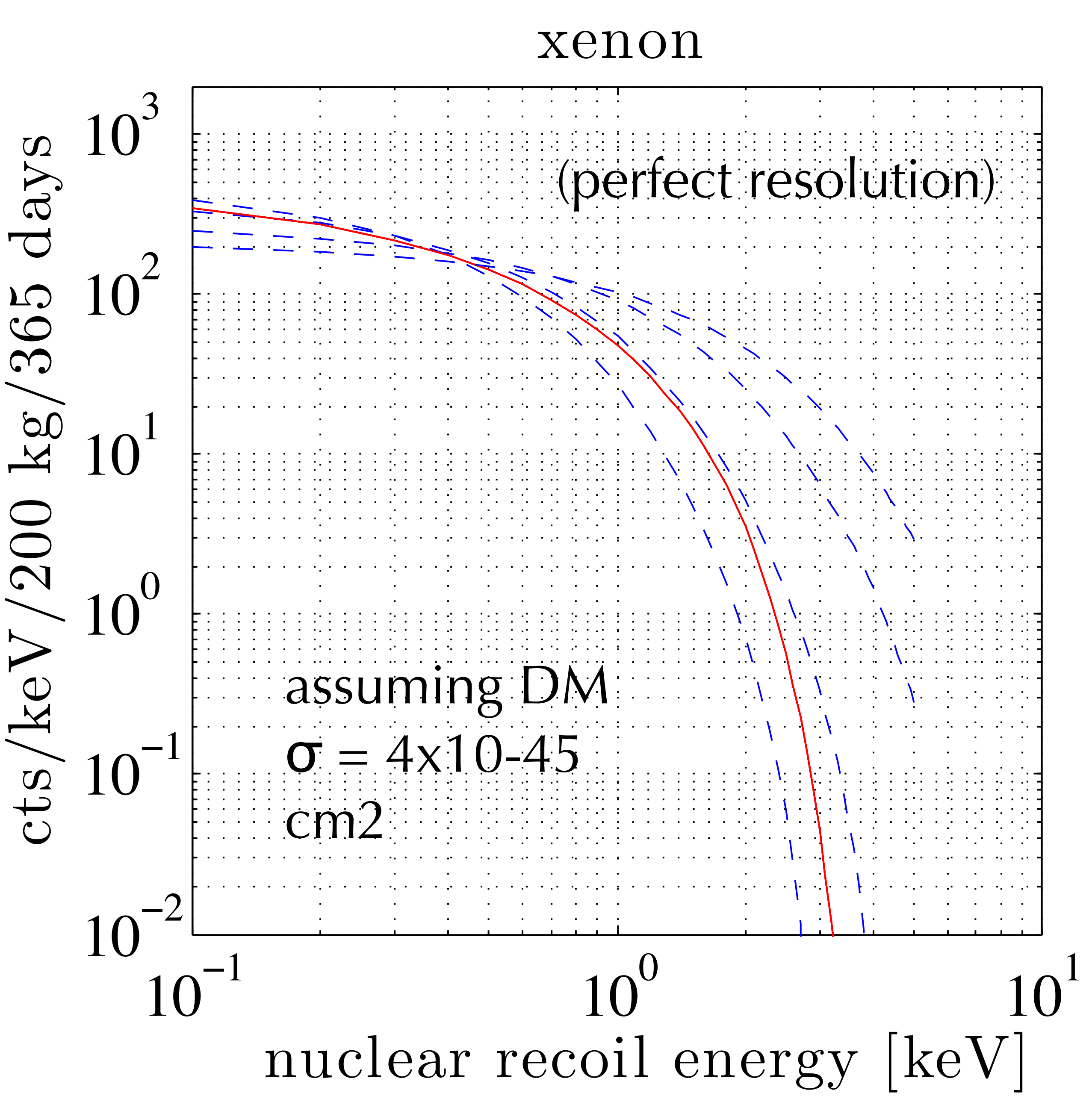
but its up to the funding agencies if we will detect low-energy solar neutrinos (and possibly zero-neutrino double beta decay, too)



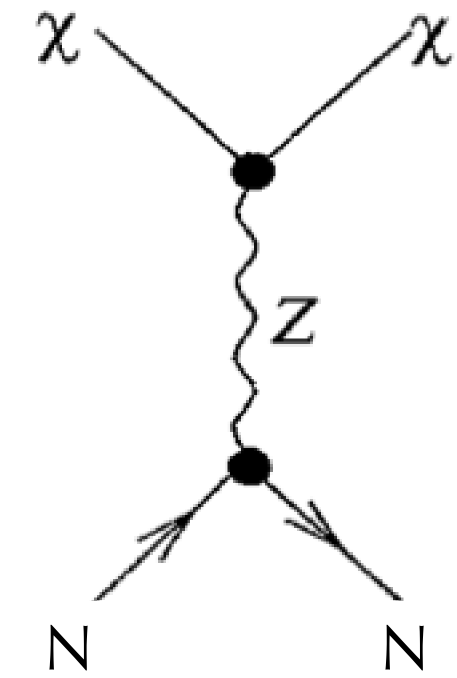
# Connection with solar neutrino experiments



# $^8$B coherent neutrino nucleus scattering




dashed: DM masses 5, 6, 7 and 10 GeV
solid: $^8$B coherent neutrino-nucleus scattering

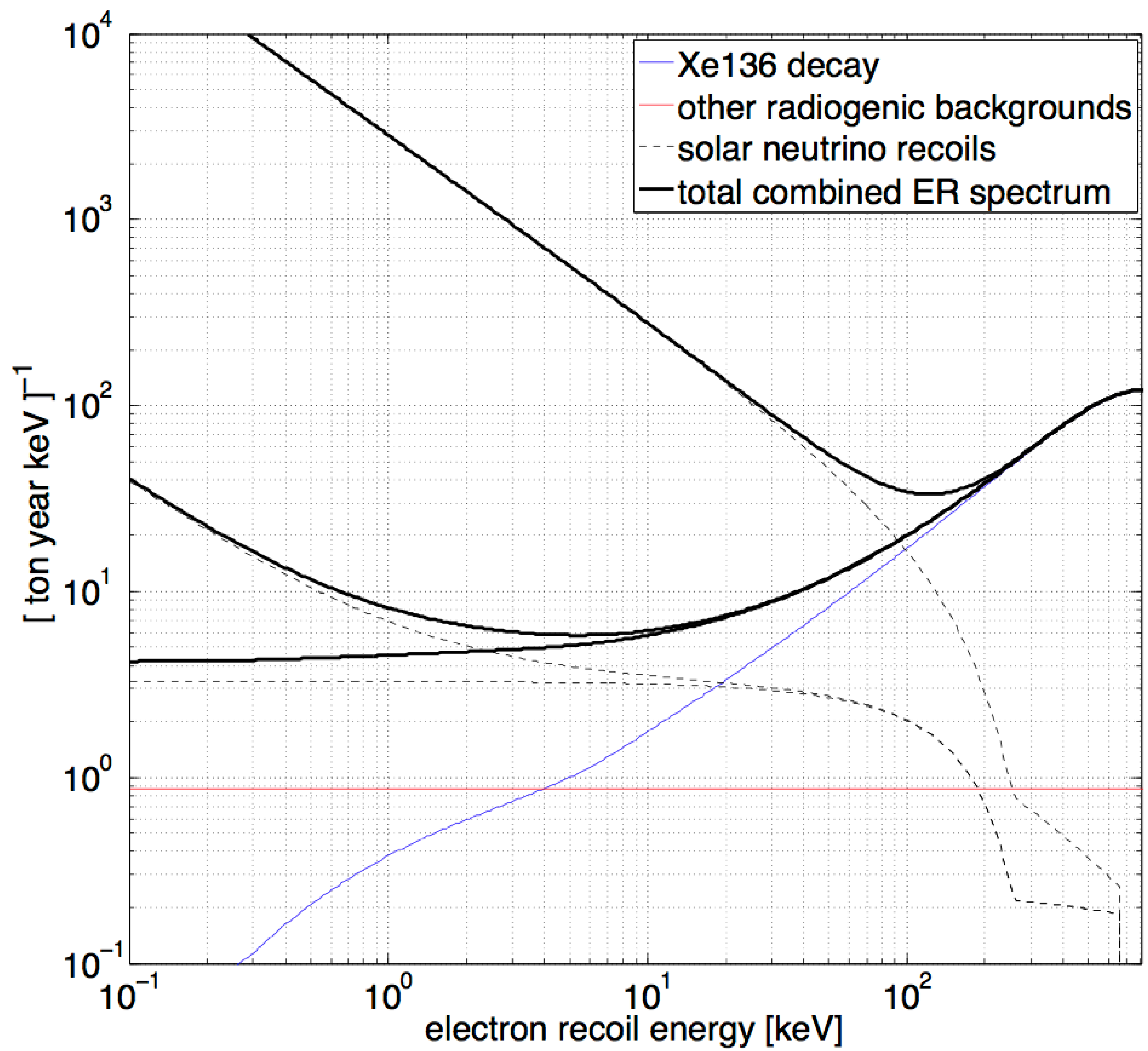


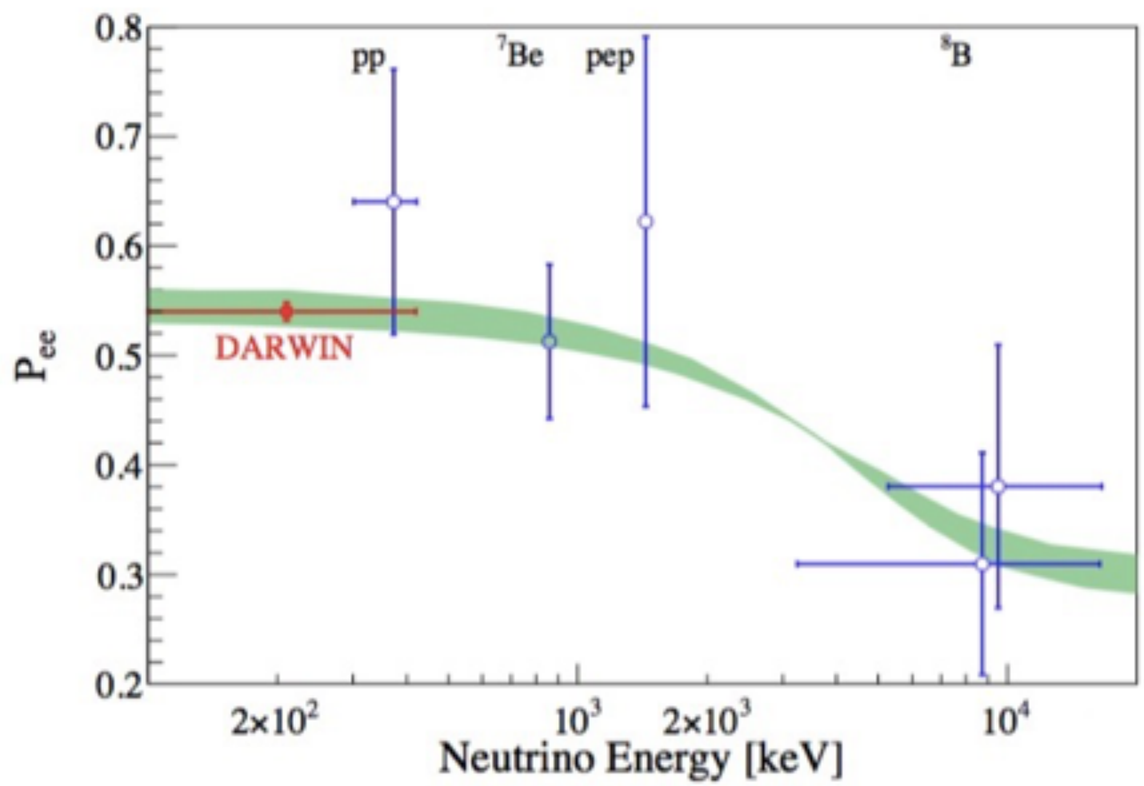

- Neat!
- extremely challenging to extract new physics due to sharply forward-scattered spectrum convolved with detector energy reconstruction uncertainty
- BUT! we come full circle… dark matter direct detection experiments (CDMS) evolved from efforts to bolometrically detect coherent neutrino nucleus scattering! PRL 55, 25 (1985)

$\mu_{\nu solar} = 8.4e\text{-}11\ \mu_B$ (the borexino limit) →

$\mu_{\nu solar} = 3e\text{-}12\ \mu_B$ (the astrophysical limit) →

$\mu_{\nu solar} = 0$ →



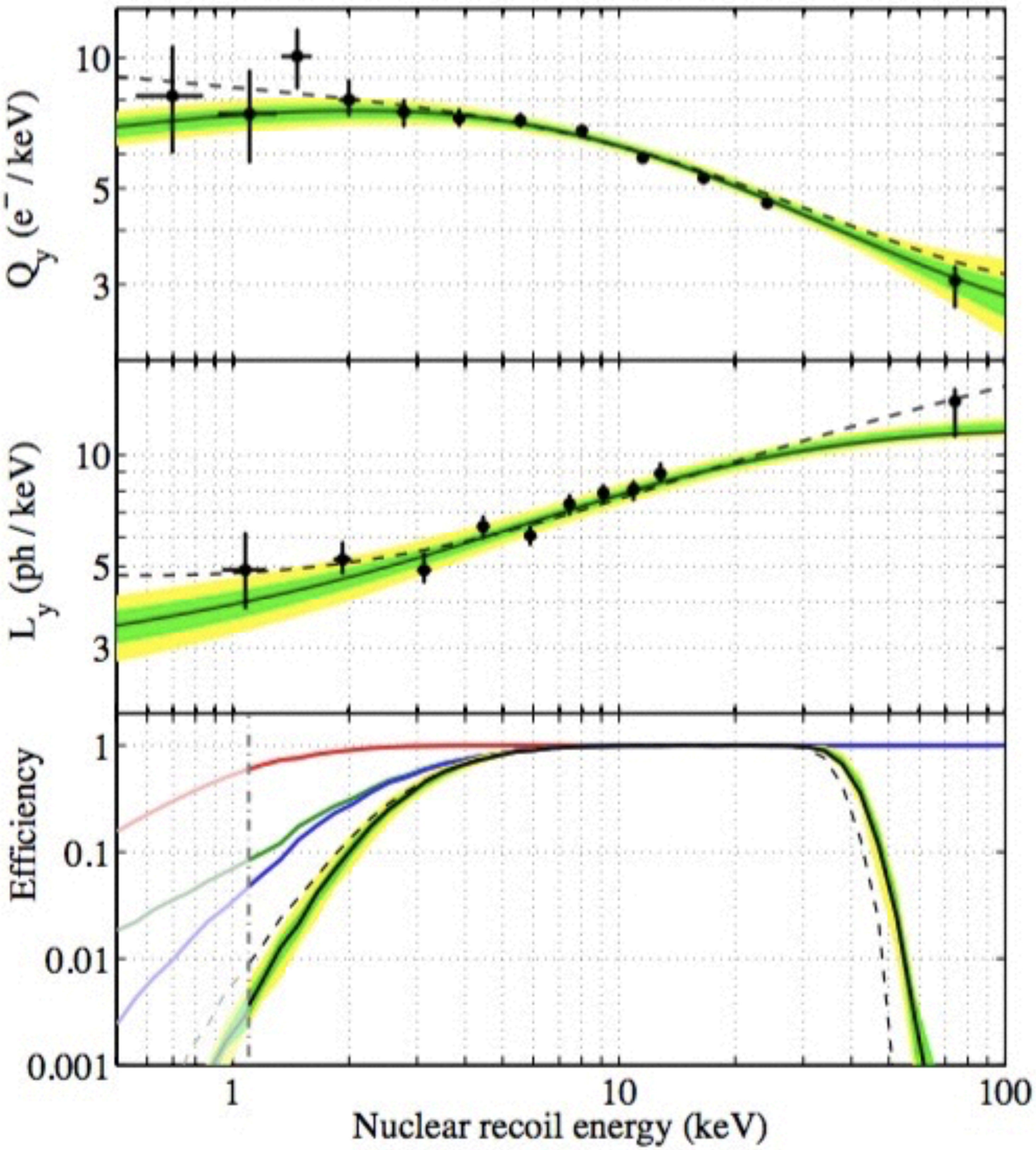

- given flux, LZ could constrain $\theta_W$ to 4.5 % at momentum transfers of ~10 keV (leveraging luminosity, Borexino pp flux). arXiv:1604.01025
- given $\theta_W$, LZ could reduce pp flux uncertainty to 2.2% from ~11% (helps with solar models) arXiv:1604.01025

In trying to isolate this peculiarity, if it exists at all and is not simply an illusion, we must beware of a danger well known to explorers of both the micro- and macrocosmic -- that of confusing the thing observed with the mind of the observer, of constructing not a picture of external reality but simply a mirror of the thinker.

-- Edward Abbey, Desert Solitaire

extra slides follow

# Energy calibration in liquid xenon



# DAMA

Bernabei et al, Nucl. Instr. Meth. (2007)

- ~2% annual modulation at ~ 2 keV... now in its Nth year at $N^2$ sigma significance
- attempts to duplicate with NaI have so far not achieved comparable energy threshold (~1 keV) and low counting rate (~1 dru)
- inconsistent with null results from numerous experiments
- "the mother of invention"

# Example: inelastic dark matter

Phys. Rev. D **64**, 043502 (2001)

in brief:

(i) A dark matter particle, $\chi_1$, with zero or highly suppressed elastic scattering cross sections off of nuclei.
(ii) A second state, $\chi_2$, heavier than $\chi_1$ by an amount $\delta = m_2 - m_1$, which is of the order of a typical halo WIMP kinetic energy. Generally, we need $\delta \sim$ 100 keV for weak-scale values of the $\chi_1$ and $\chi_2$ masses.
(iii) An allowed scattering off of nuclei with an inelastic transition of the dark matter particle, i.e., $\chi_1 + n \longrightarrow \chi_2 + n$.

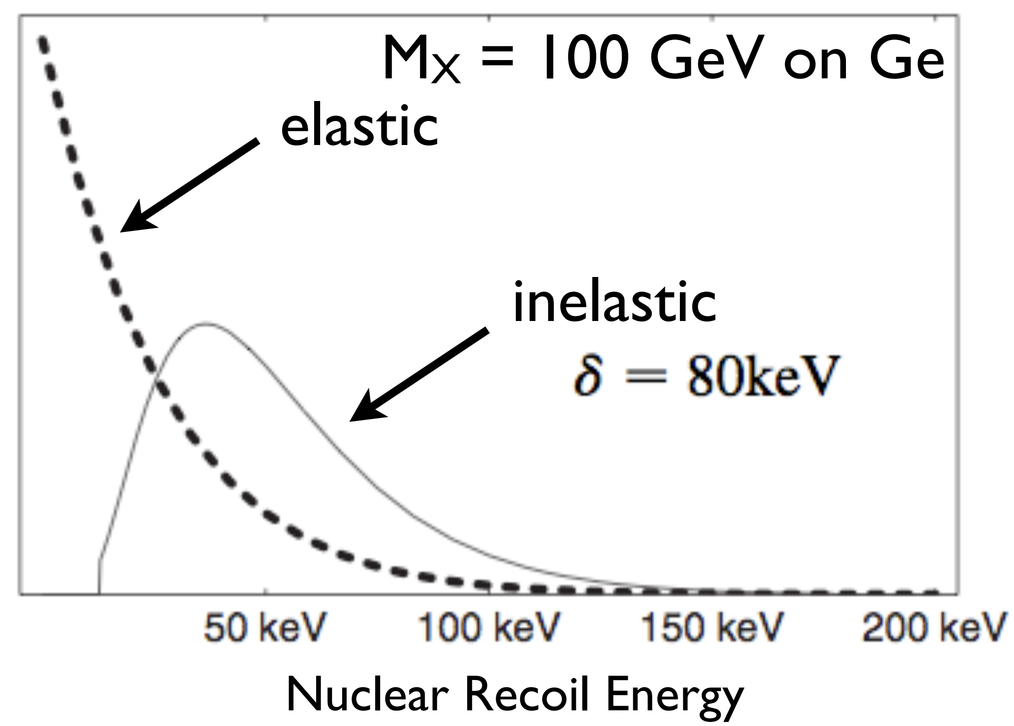
consequences:

Broadly speaking, the iDM scenario can have three effects on dark matter experiments:
(i) An overall suppression of signal, favoring heavier targets over lighter ones.
(ii) An energy-dependent suppression of signal, suppressing rates of low energy events more than those of high energy events.
(iii) An enhancement of the modulated signal relative to the unmodulated signal.

need at least

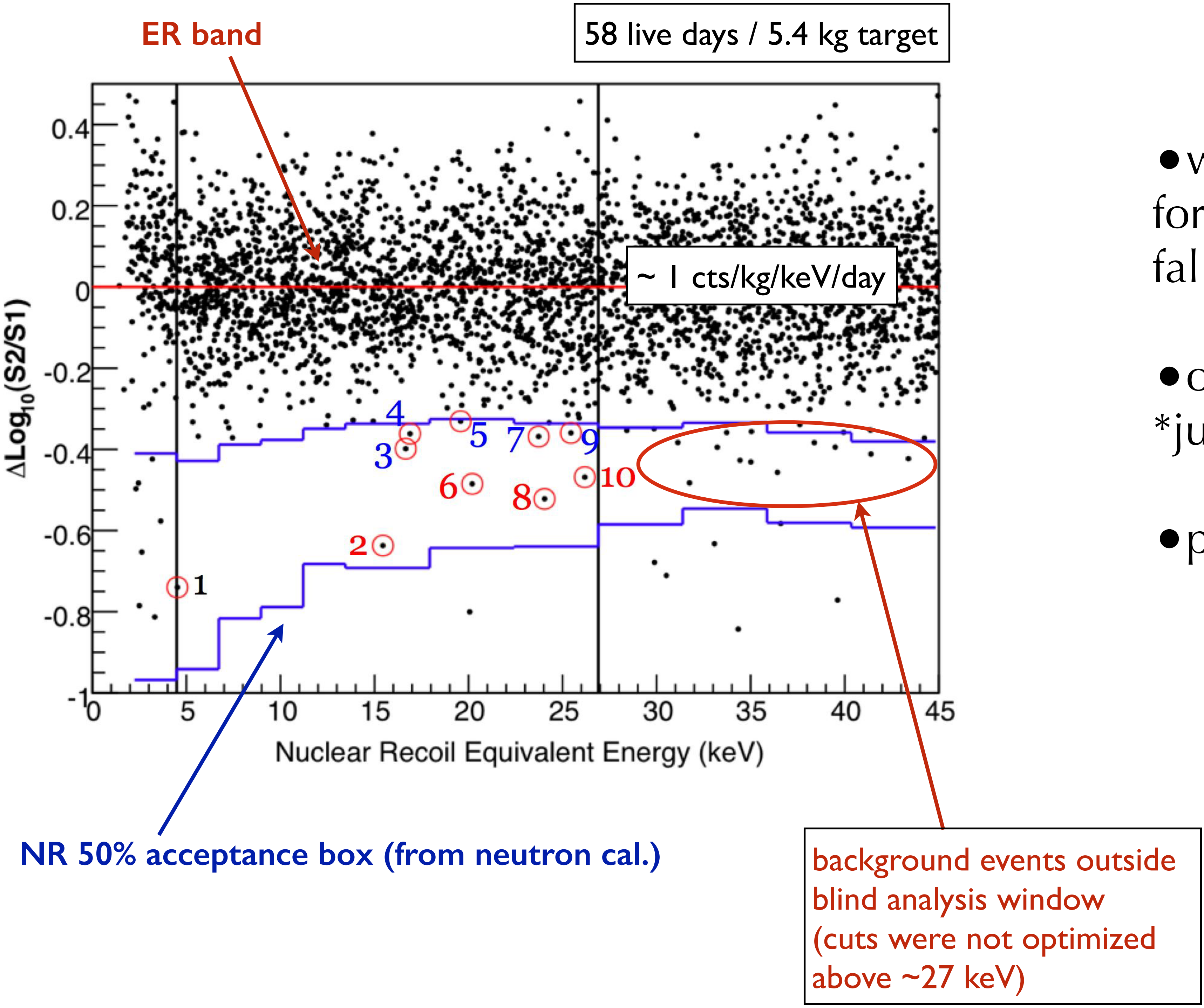
$$v_{\rm min} \simeq \sqrt{2\delta/\mu}$$

to scatter

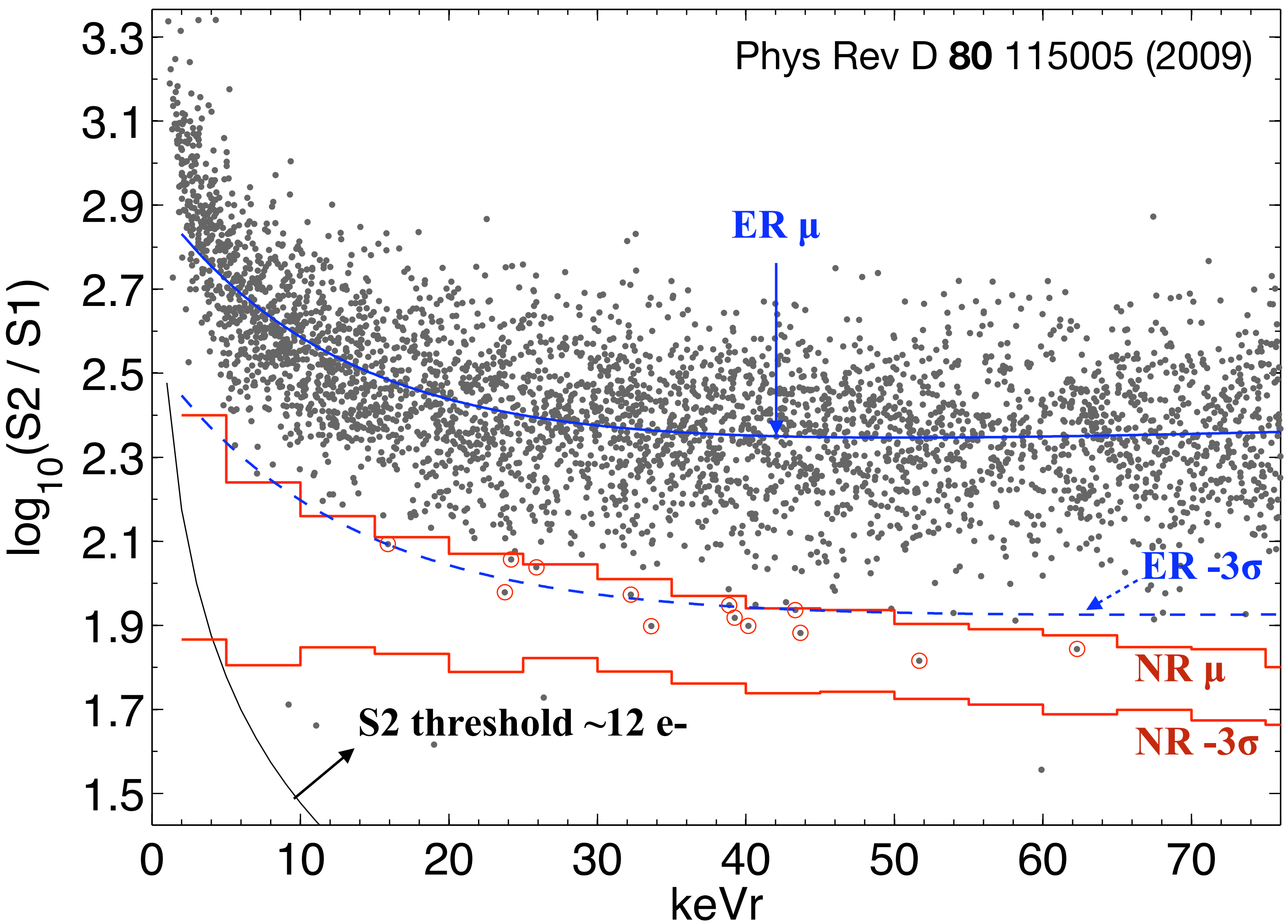


# XENON10, 2007

Phys. Rev. Lett. **100** 021303 (2008)

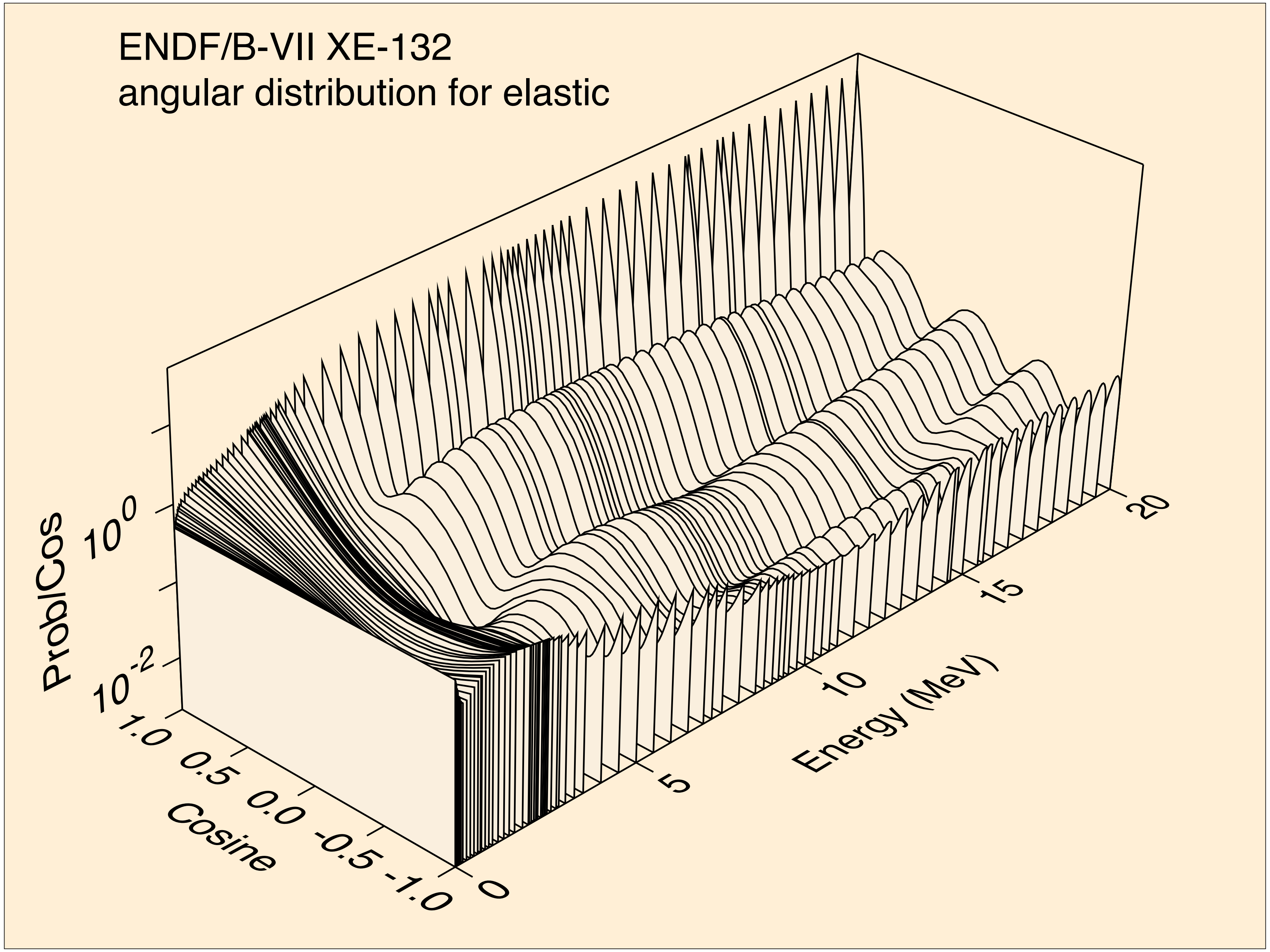


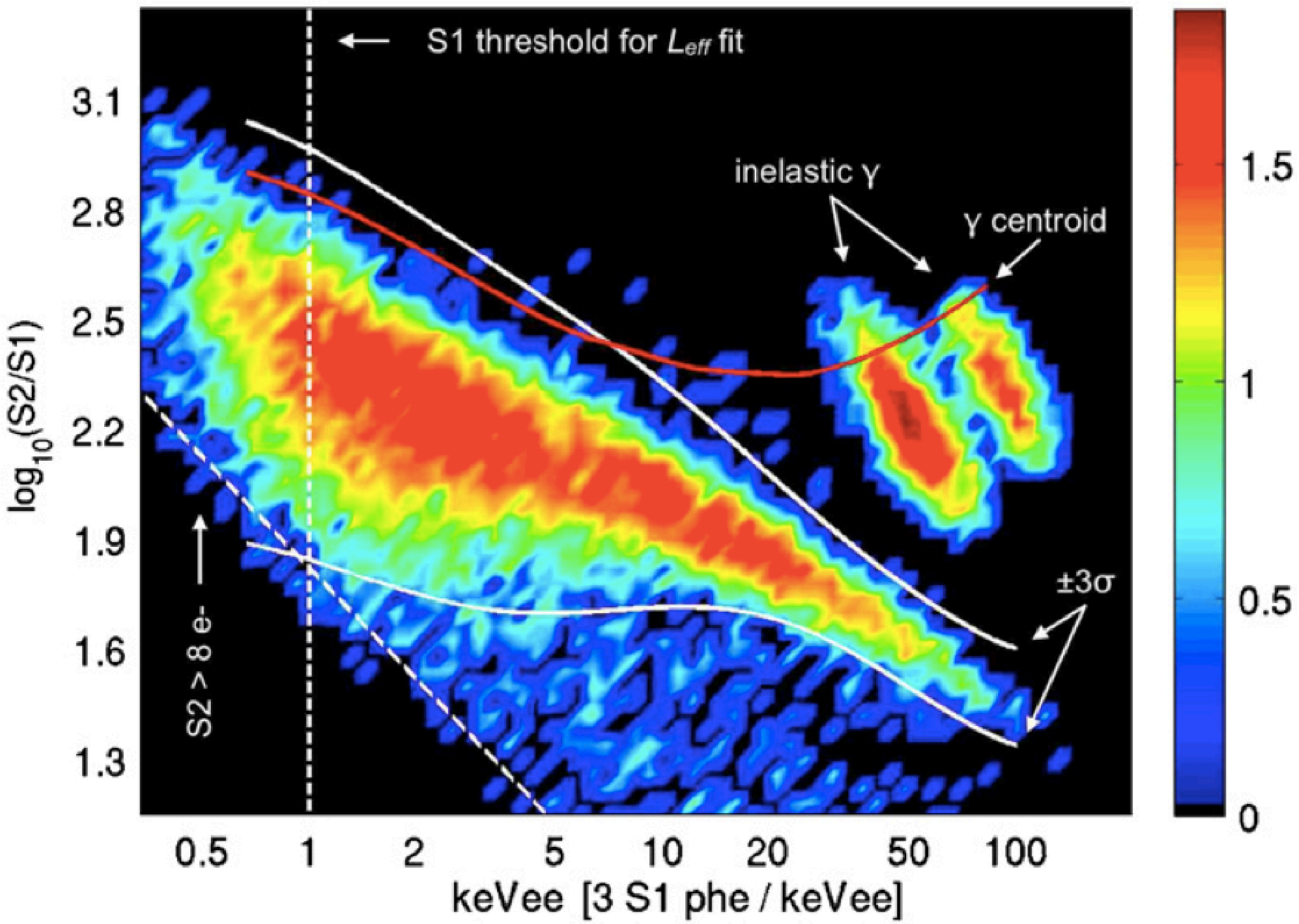

- we were looking exclusively for a low energy, exponentially falling signal!
- our reported results looked *just* like the iDM prediction!
- prompted a re-analysis




- re-analysis confirmed signal-like event population!
- now generally understood to be due to background processes
- signal interpretation ruled out by later experiments e.g. XENON100

# Neutron scattering on xenon




S1 threshold for $L_{eff}$ fit
inelastic γ
γ centroid
±3σ
S2 > 8 e-
3.1
2.8
2.5
2.2
1.9
1.6
1.3
$\log_{10}$(S2/S1)
0.5
1
2
5
10
20
50
100
keVee [3 S1 phe / keVee]
1.5
1
0.5
0