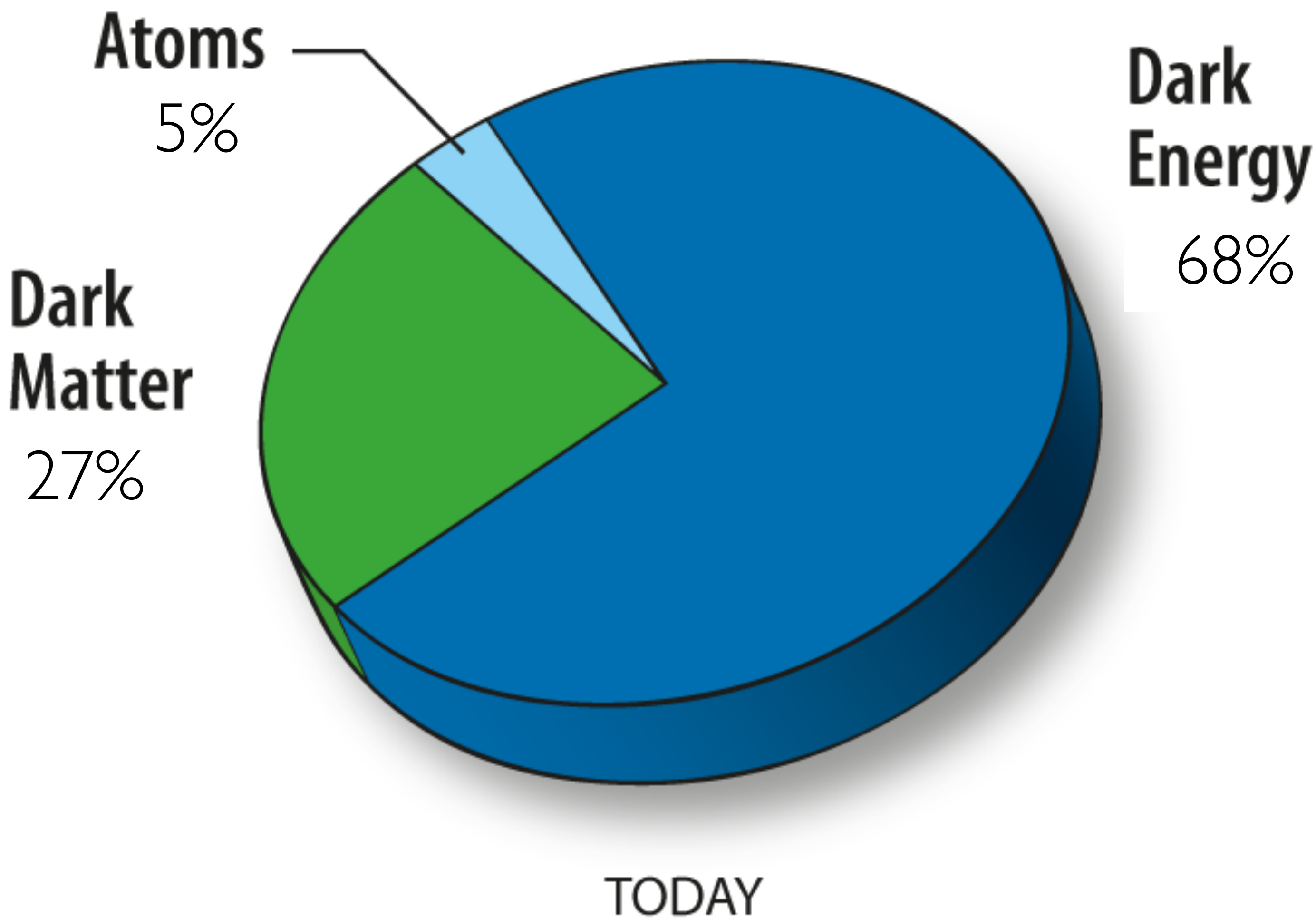
The race to detect dark matter in the laboratory (or hit the neutrino floor trying)

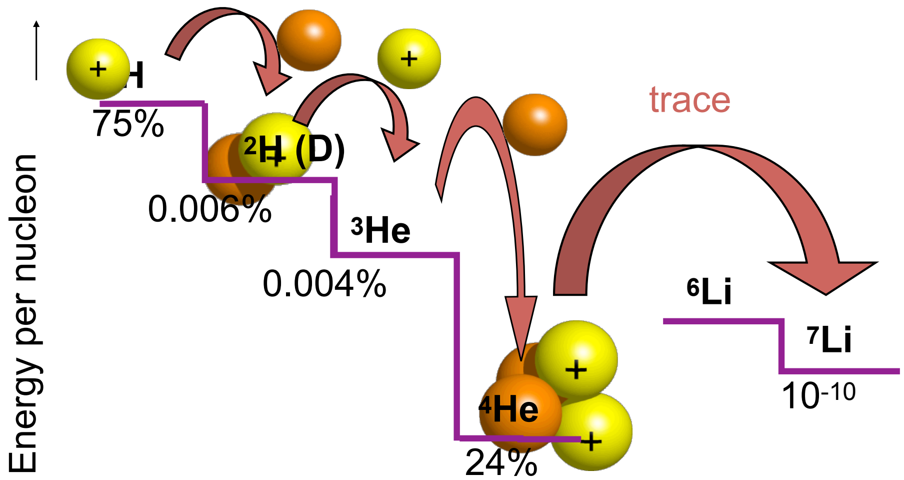
Simplified contents of the universe

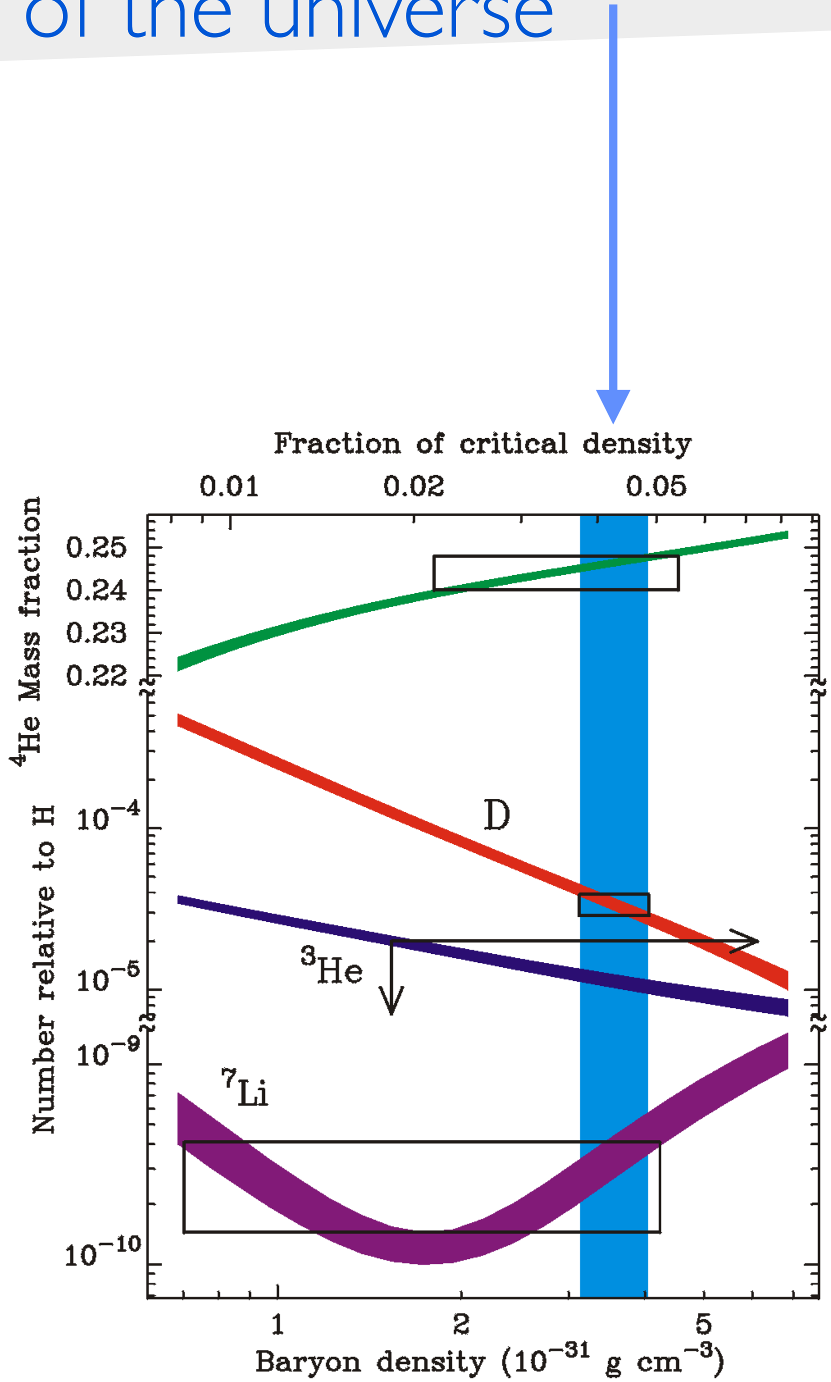


graphic courtesy of NASA

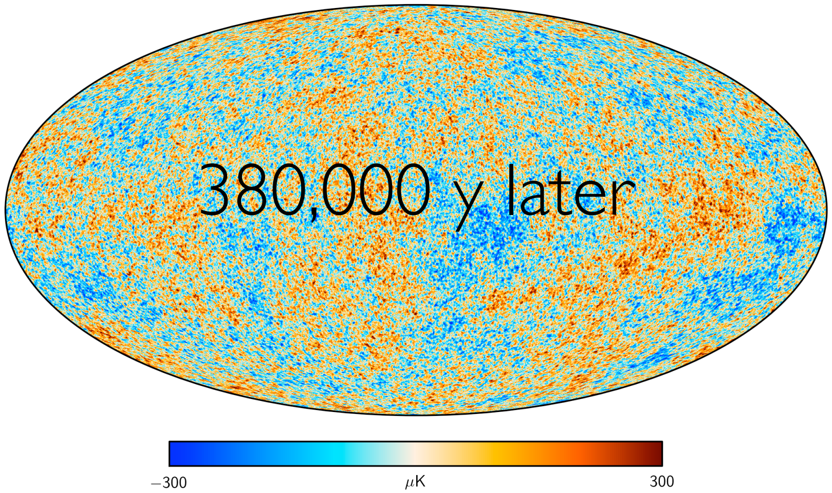
We know the baryon content of the universe

big bang nucleosynthesis



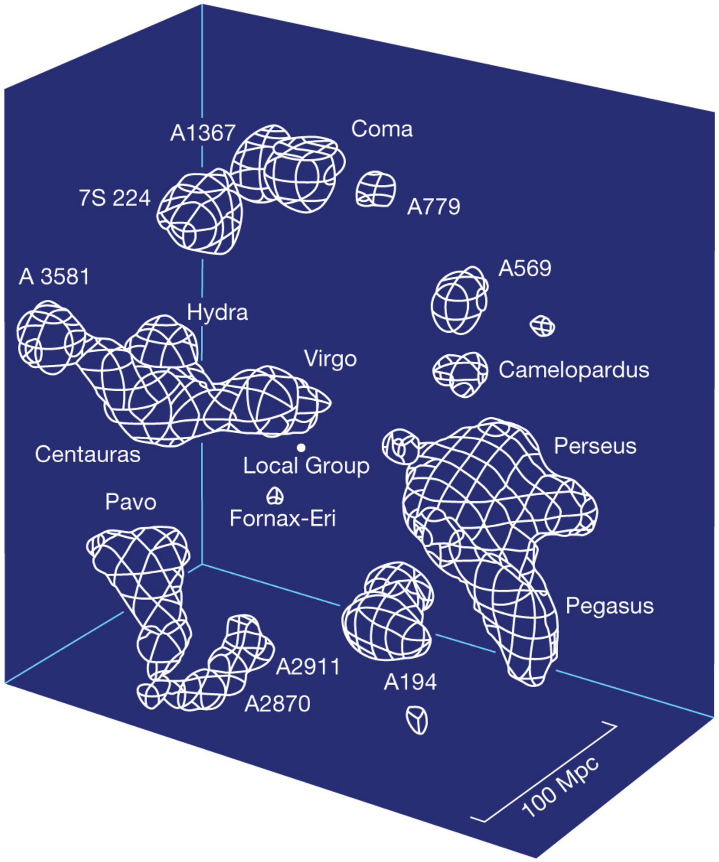


Simplest model for evolution of the universe requires non-baryonic dark matter



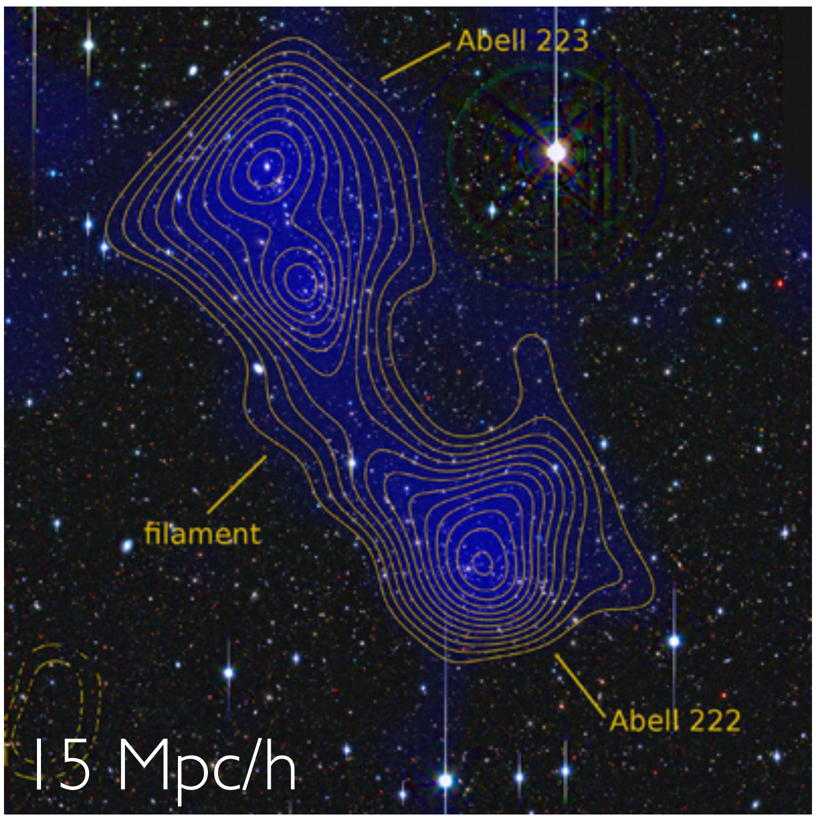
ΔT

ΔM

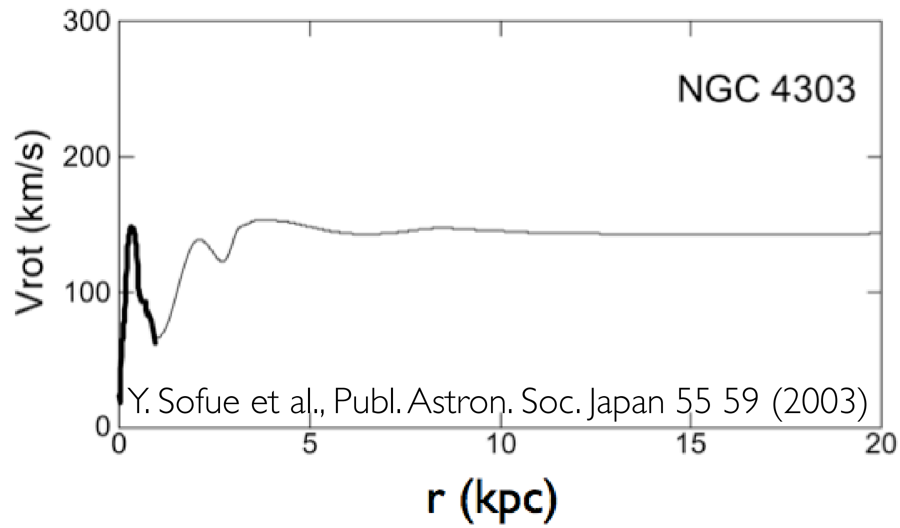


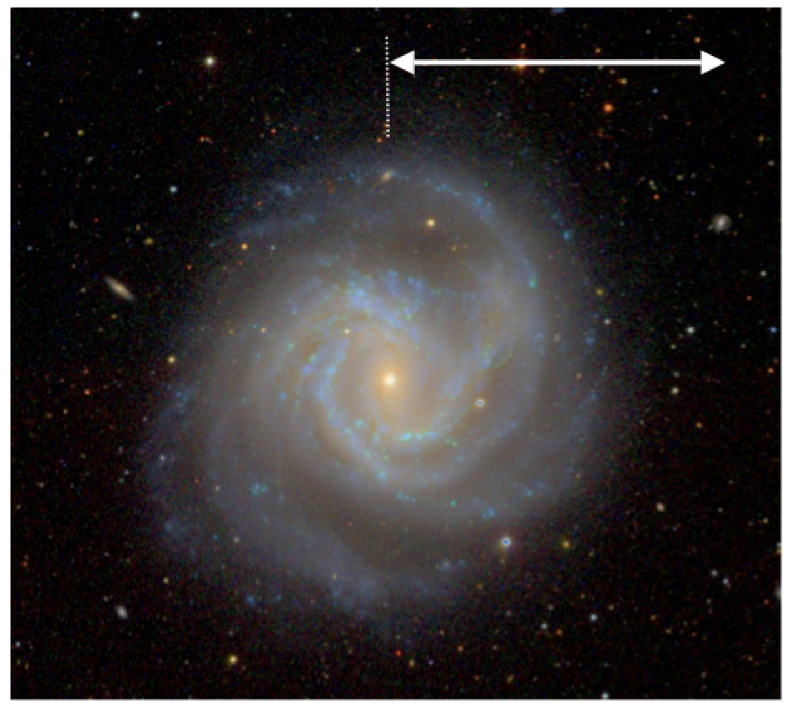
The existence of dark matter is an observational result

- Non-luminous matter is observable from gravitational interactions
- Its distribution follows ordinary matter



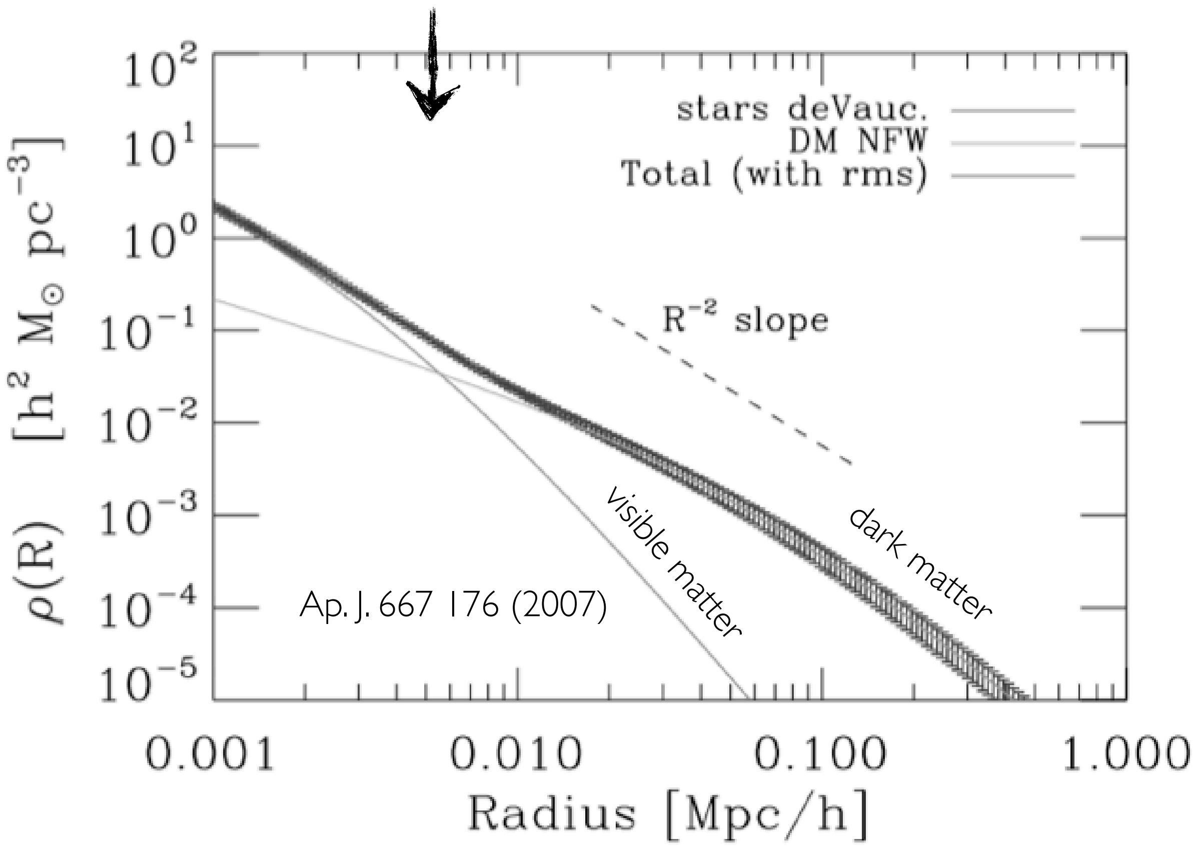
Nature 487 202 (2012)





Dark matter distribution follows ordinary matter (galactic dark matter halo)

stacked weak lensing galaxy profiles



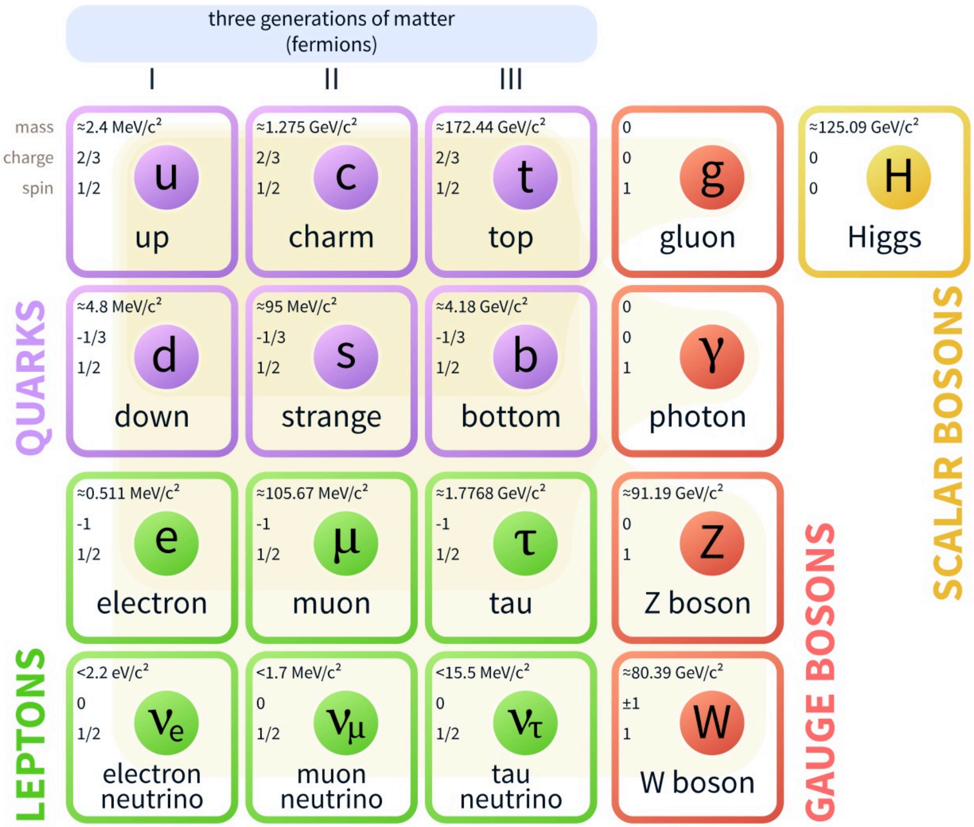
galactic velocities: ~0.001c

a 100 GeV particle has:
E ~ 50 keV

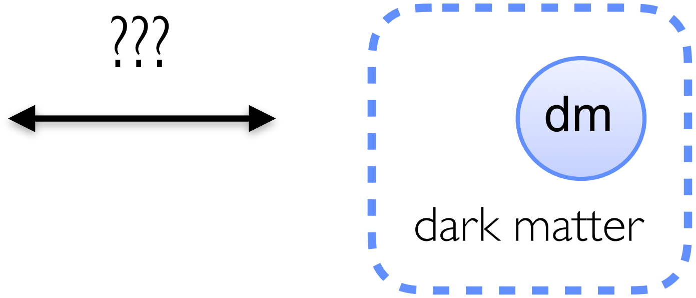
if it scatters elastically with a target atom on earth, typical energy deposits are O(10) keV

cf. arXiv:1311.6524

Standard model of particle physics does not account for non-baryonic dark matter



wikipedia graphic



Early seed of today's WIMP-search experiments

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

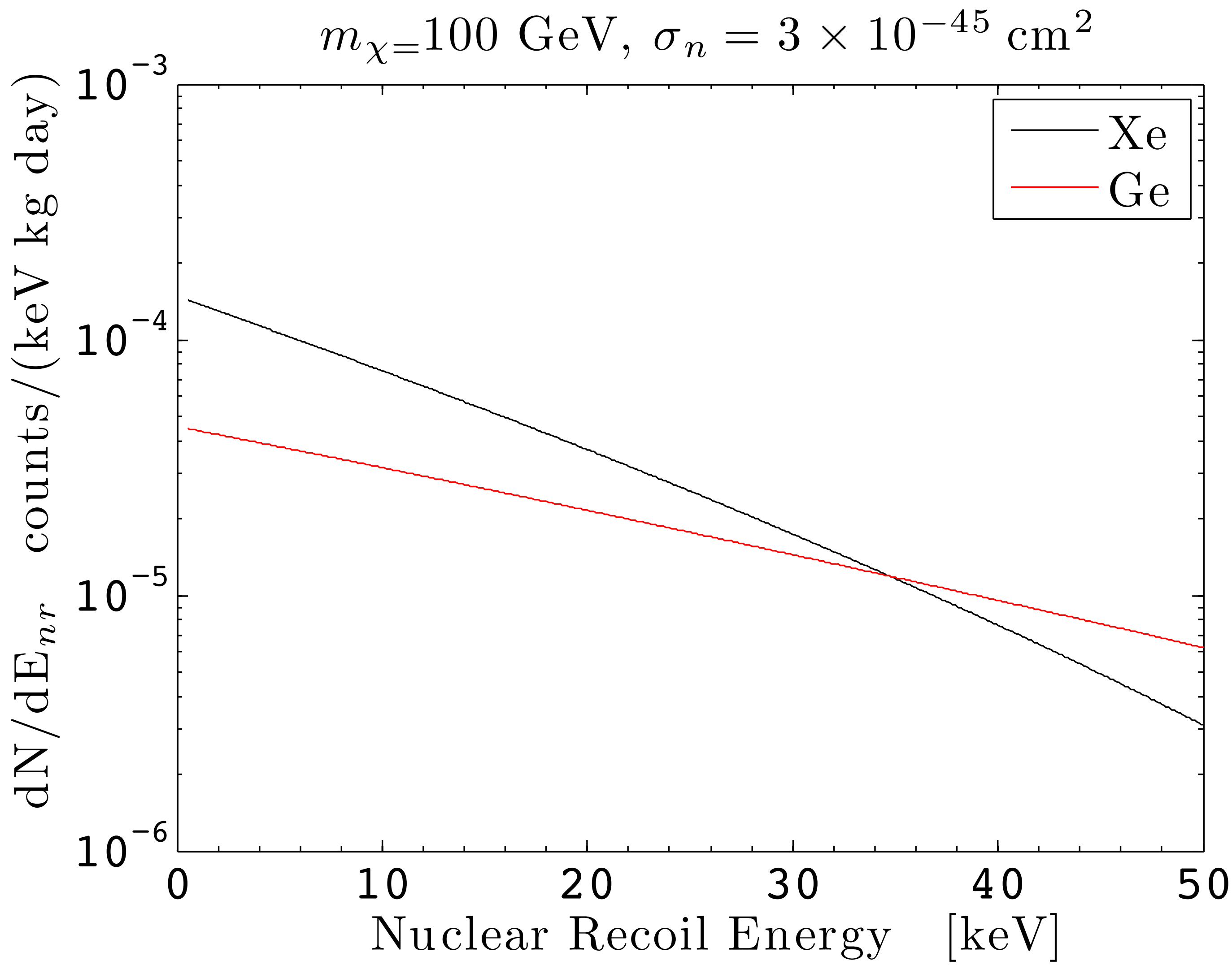
Detectability of certain dark-matter candidates

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.

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

Predicted WIMP-nucleon scattering spectra



Reprise of introduction

More dark matter than ordinary matter in the universe

Distribution follows ordinary matter — eg a halo of DM surrounding the Milky Way

Electromagnetic interactions absent or highly suppressed

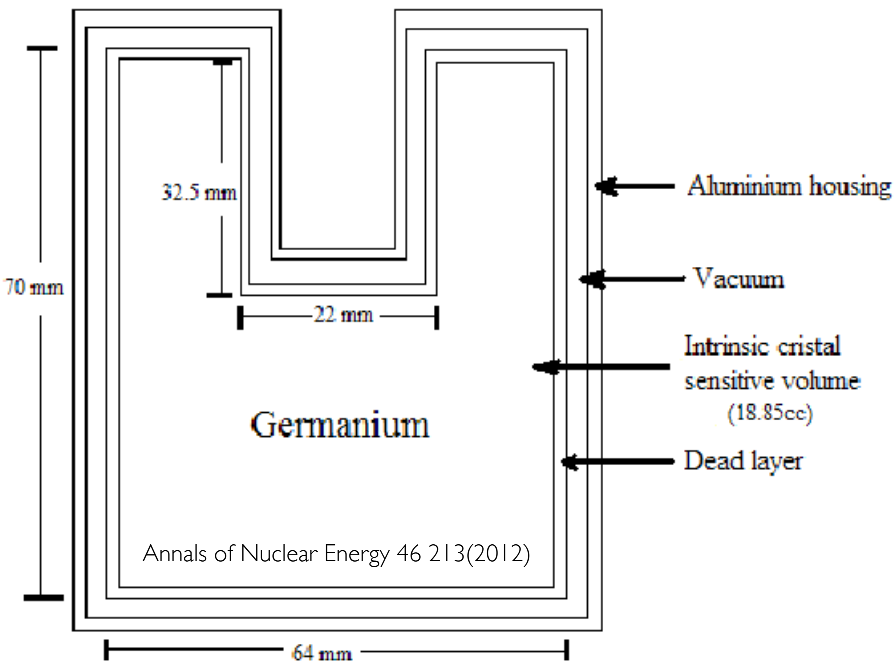
WIMPs are a prime candidate for dark matter. Their cross section with ordinary matter is unknown

keV-scale scattering interactions expected, for all the simplest models

keV? No problem, right?

A 0.7 kg germanium spectrometer

available signal: ~330 e-/keV



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

Ahlen et al. Phys Lett B 195 603 (1987)

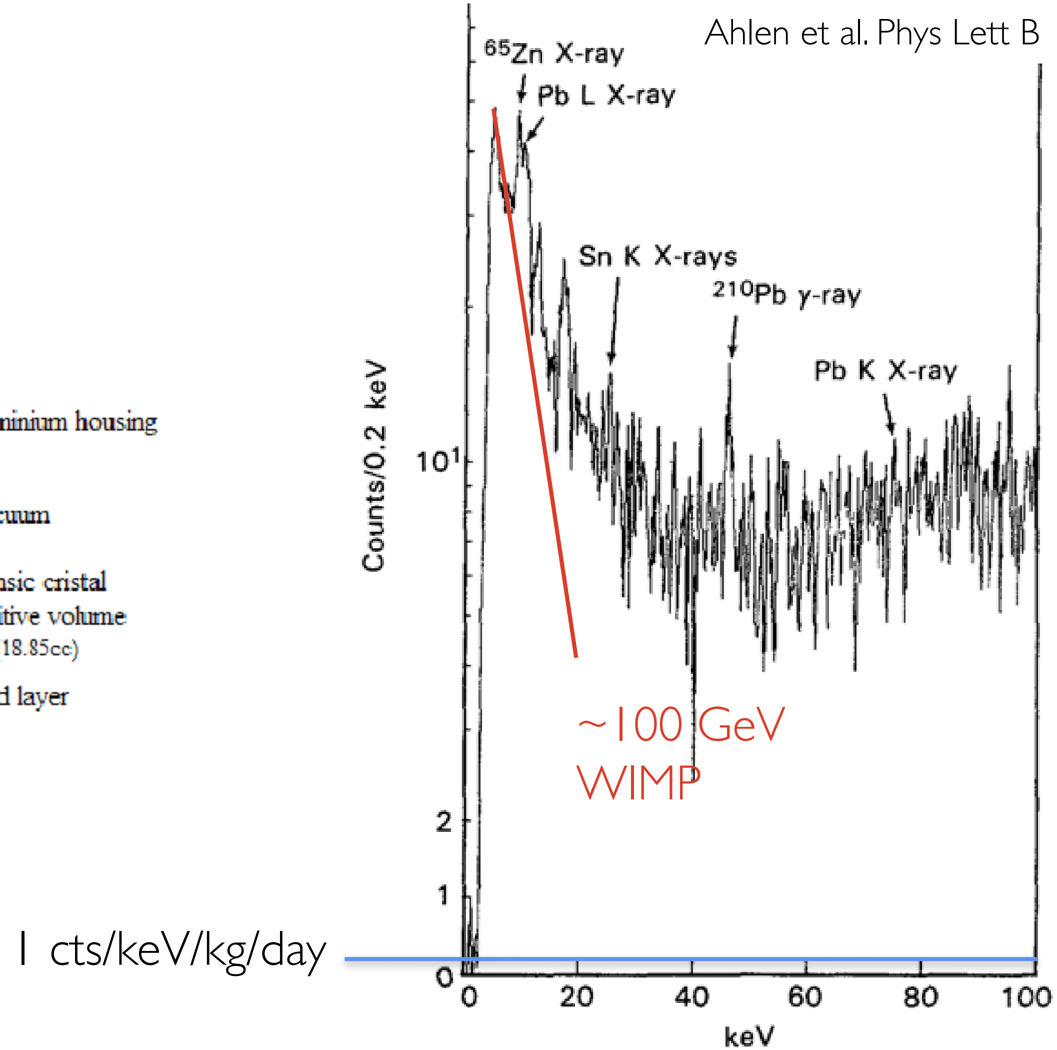
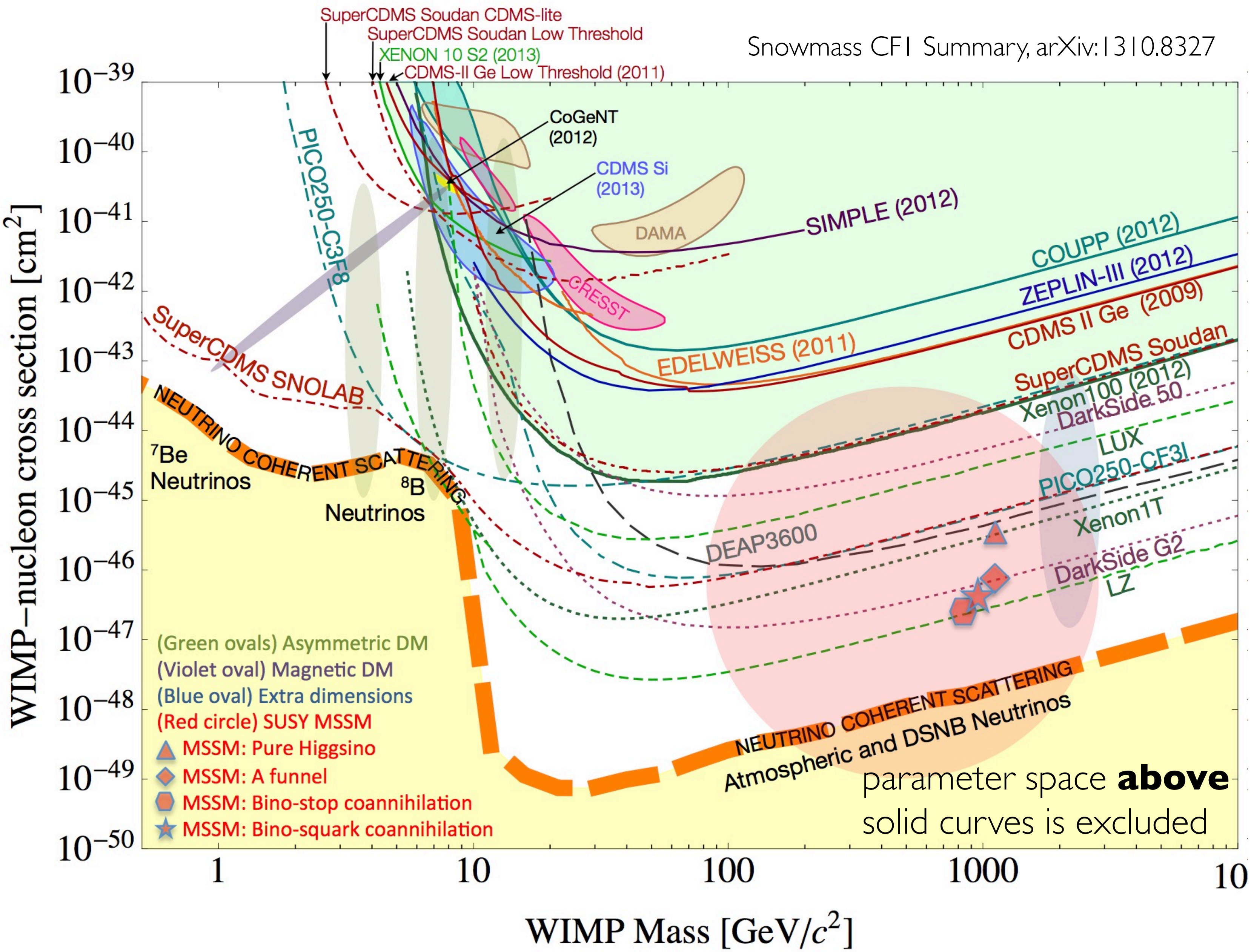
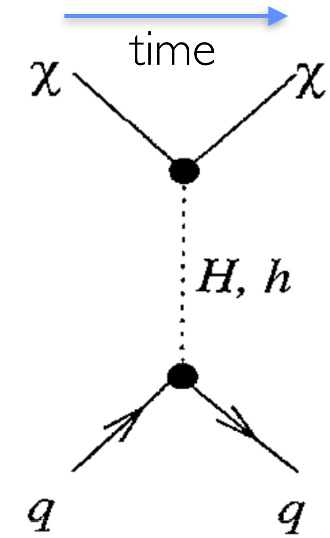


Fig. 2. 1000 h of data from the Ge spectrometer are shown The width of each channel is 0.2 keV. The identified peaks result from the decay products of radioactivity in the exposed solder.

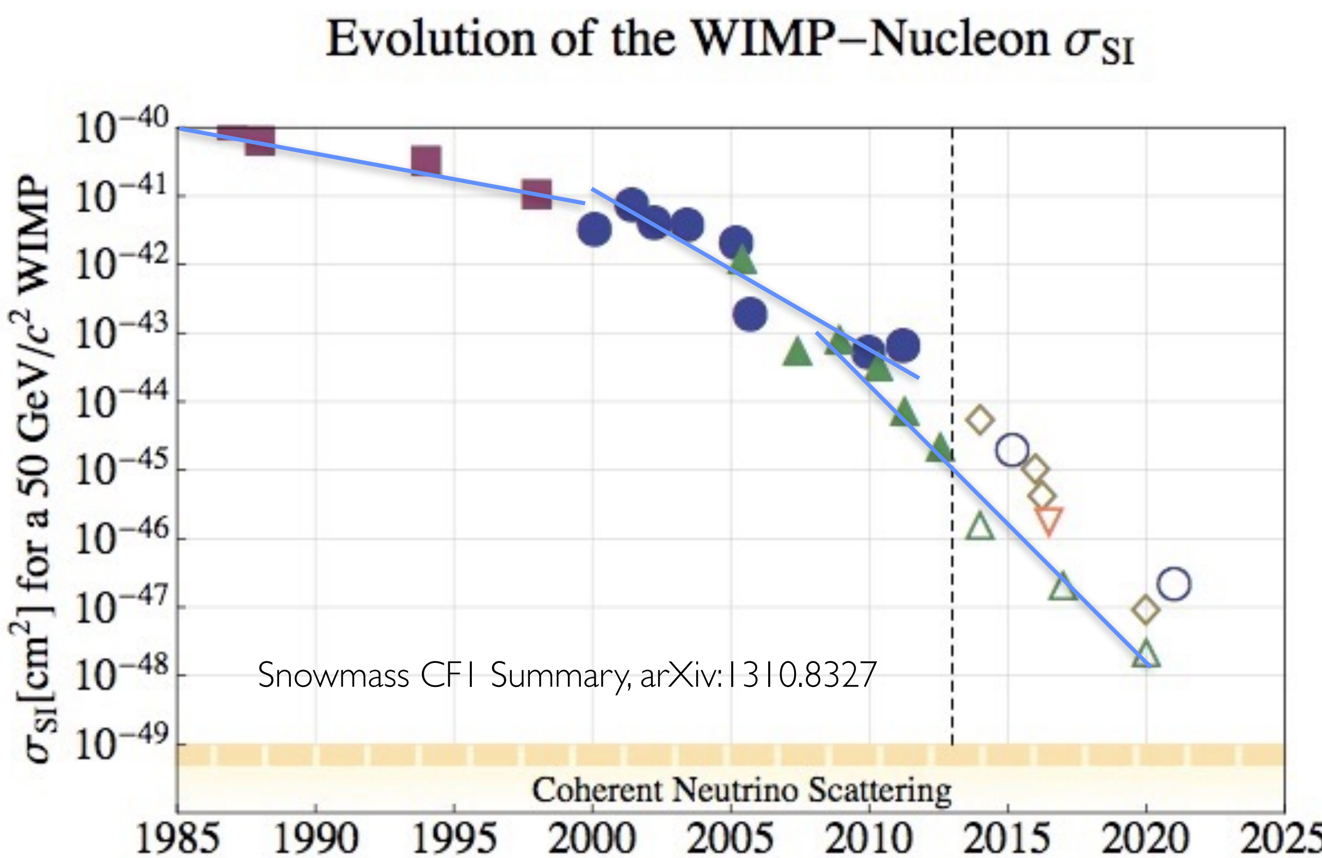
Lay of the land: dark matter parameter space





Evolution of detector technology

	community label	my label
■	crystal	has walls, single-channel energy reconstruction
●	cryogenic	partial walls, dual-channel energy reconstruction
▲	liquid xenon	no walls! dual-channel energy reconstruction
◇	liquid argon	ibid, but loaded with radioactive 39Ar
☆	back to crystal?	just like the green triangles, except crystal



I propose to add ☆

"physicists confirmed dark matter in 1998"

WIRED

NICK STOCKTON SCIENCE 05.16.17 7:00 AM

PHYSICISTS CAN'T AGREE ON WHAT SCIENCE EVEN MEANS ANYMORE

radiation. And the hypotheses predict that these traits will conform to certain numerical measurements. Some of these criteria have been met; for instance, in 1998 physicists found proof of dark energy[4], which accounted for 70 percent of the missing matter that inflation had predicted. Confirming other criteria has been more elusive.

[4] UPDATE 05/16/17 3:40pm ET — Previously this sentence said physicists confirmed dark matter in 1998.

A 10 kg x 25 array of NaI scintillator (DAMA) —

detecting dark matter since ~1998

- crystal

available signal: ~40 photons/keV

arxiv:1805.10486

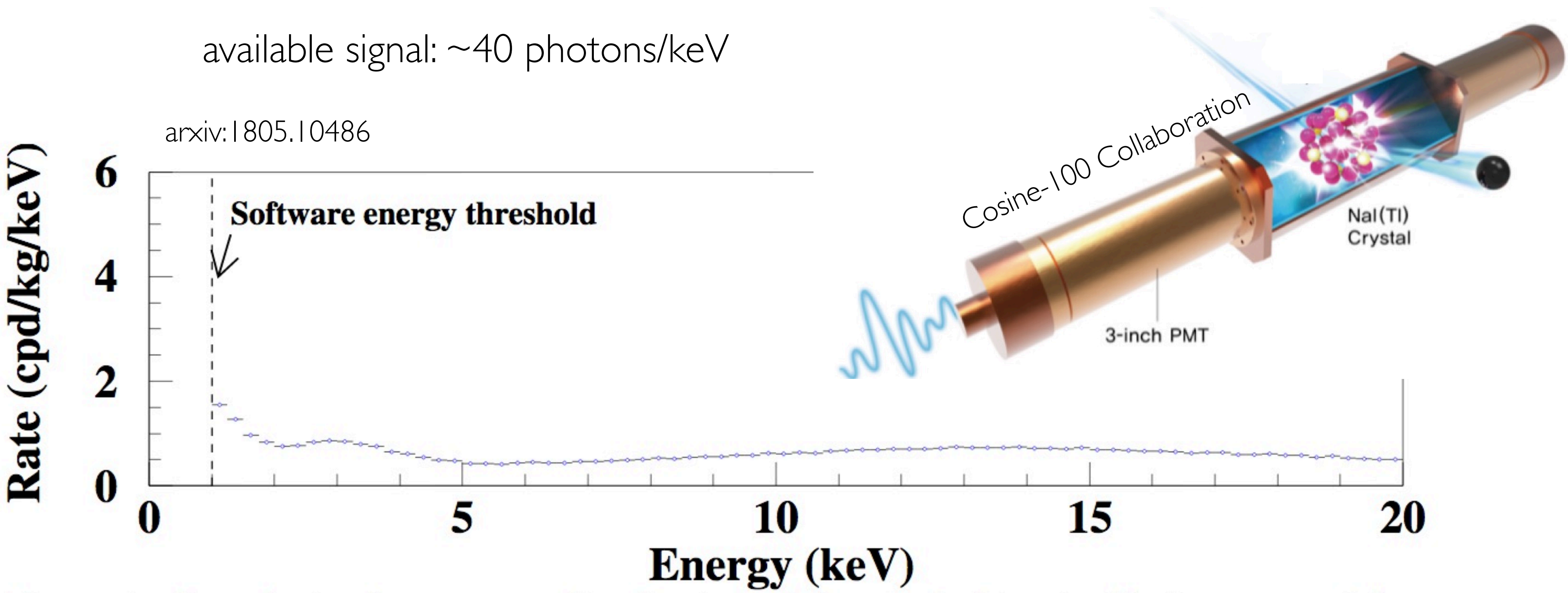
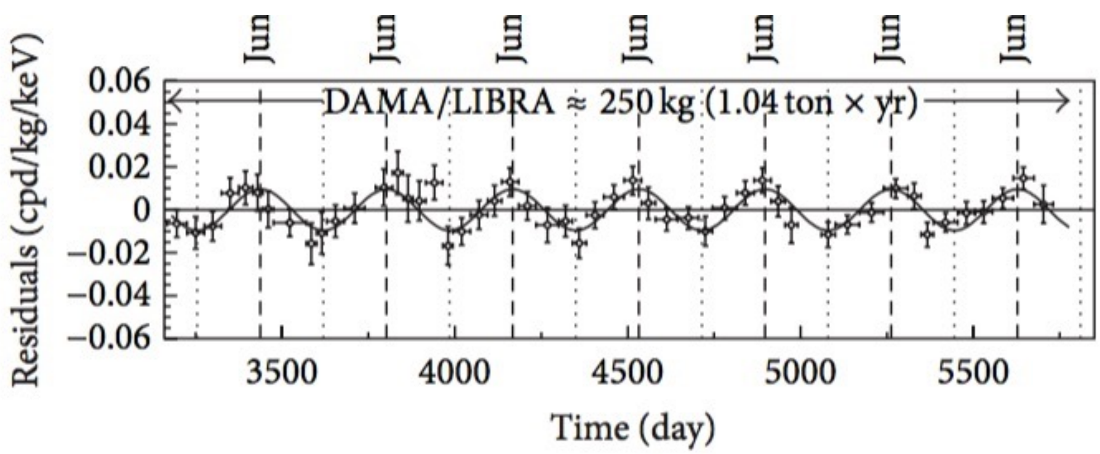
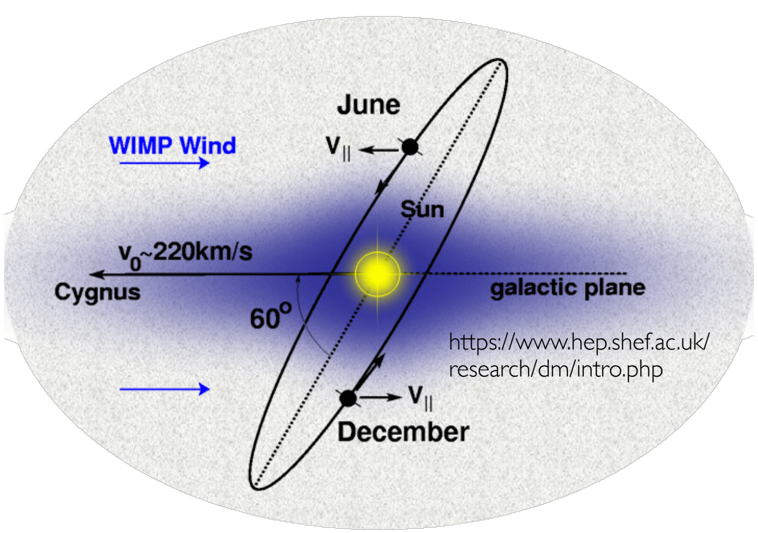


Figure 1: Cumulative low-energy distribution of the *single-hit* scintillation events (that is each detector has all the others as veto), as measured by the DAMA/LIBRA–phase2 in an exposure of 1.13 ton $\times$ yr.

Detection claim due to annual modulation signature

cf. COSINE experiment, *Nature* **564**, p83–86 (2018)

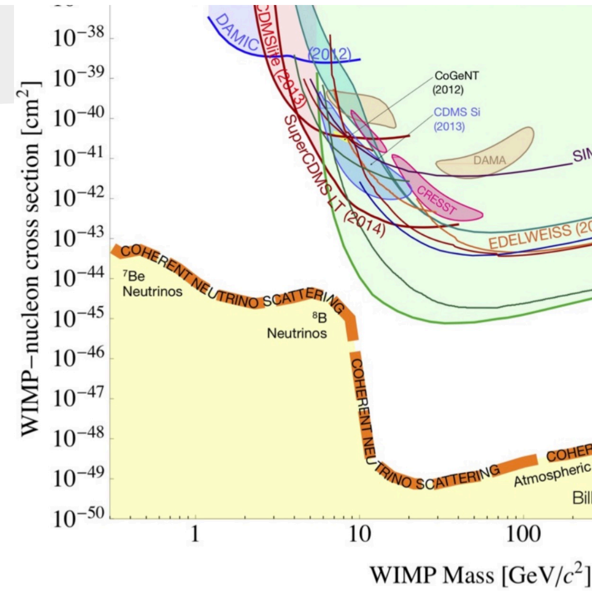




"No systematic or side reactions able to mimic the exploited DM signature have been found or suggested by anyone over more than a decade."
—DAMA Collaboration

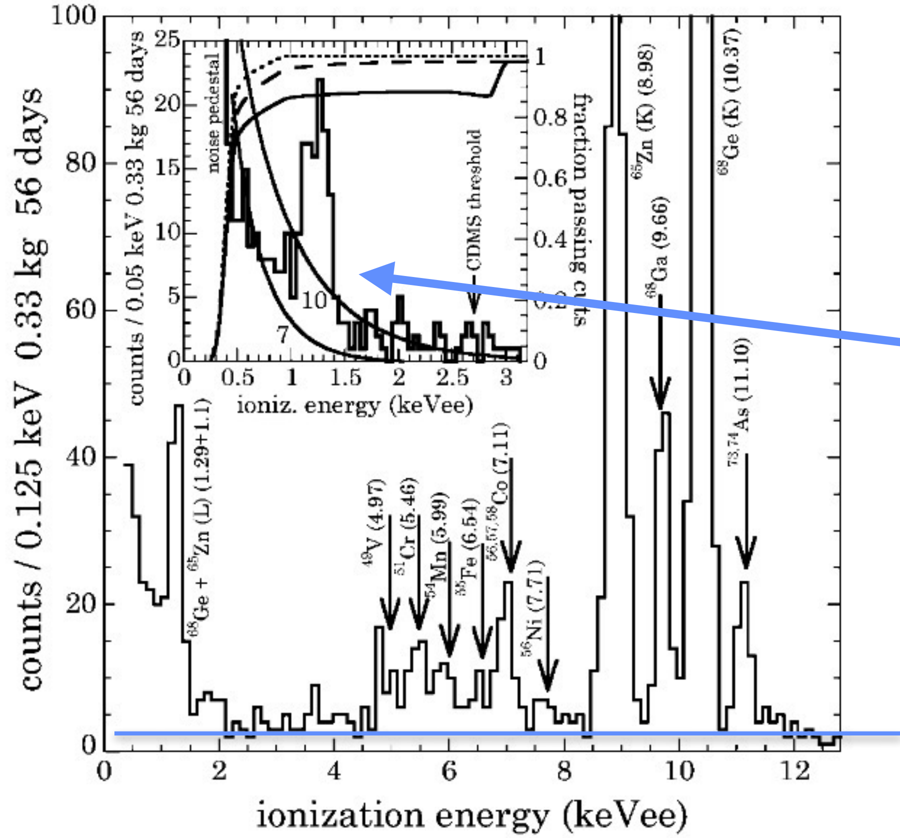
cf. Pradler et al, Phys Lett. B 720 (2013) 399
Nygren, arXiv:1102.0815
McKinsey, recently posted to arXiv

CoGeNT tacit detection claim



- crystal

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

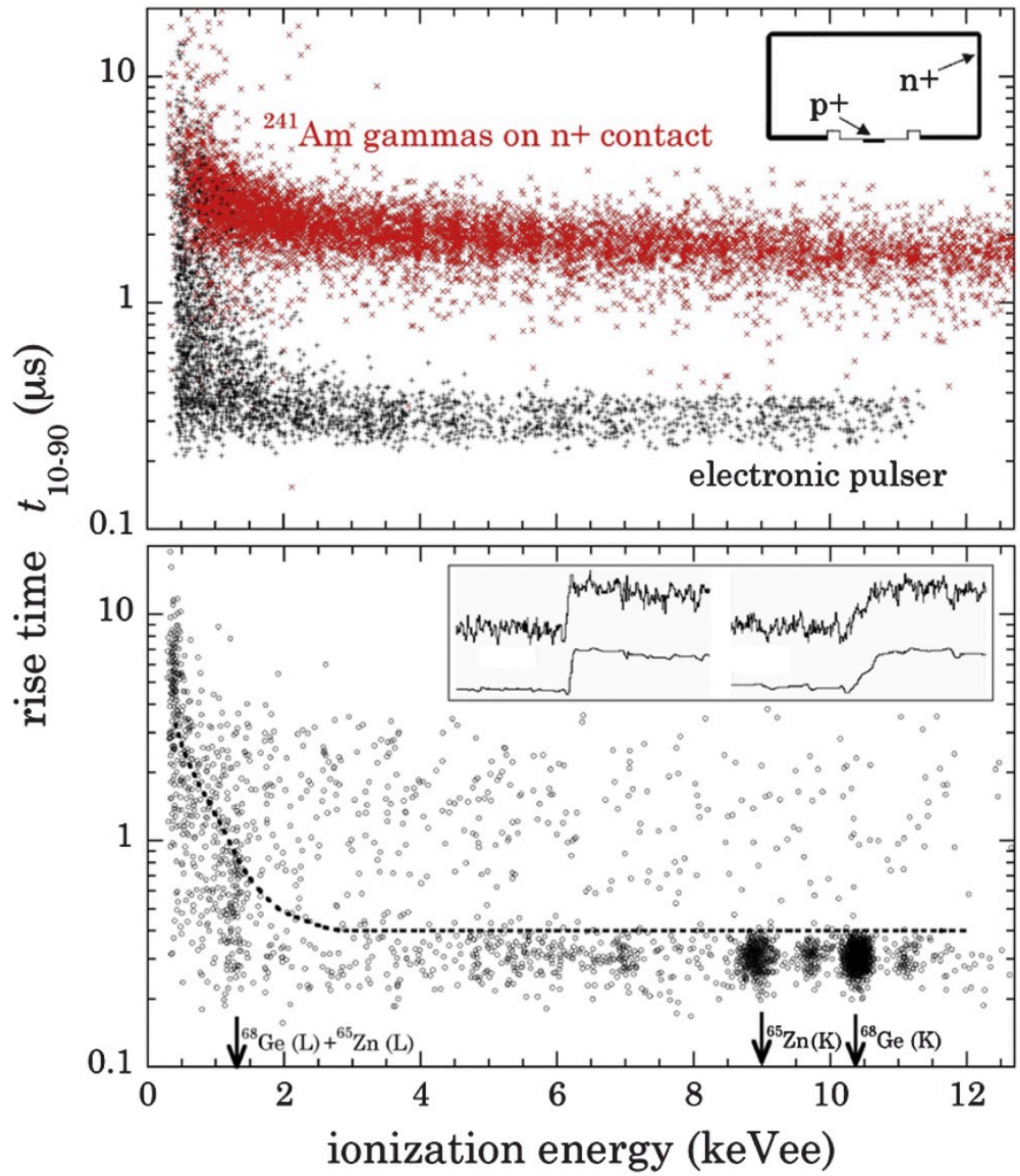


1 cts/keV/kg/day

"It is tempting to consider a cosmological origin. Past experience prompts us to exhaust less exotic possibilities." —CoGeNT, 2011

Discrimination of surface and bulk events in CoGeNT

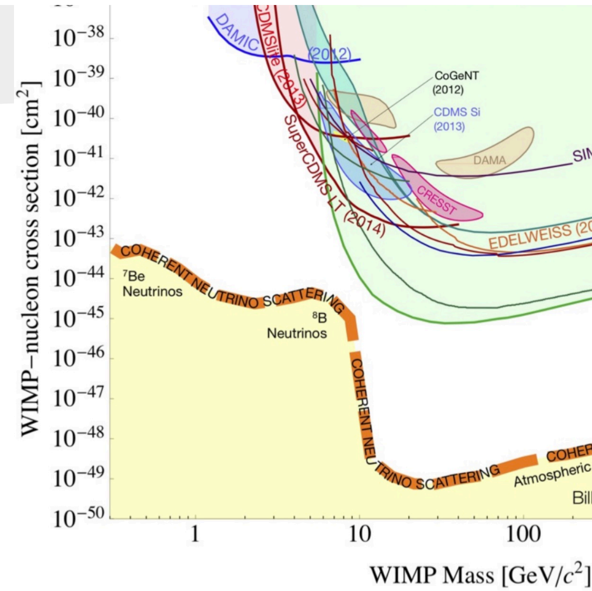
Aalseth et al. Phys Rev Lett 106 131301 (2011)

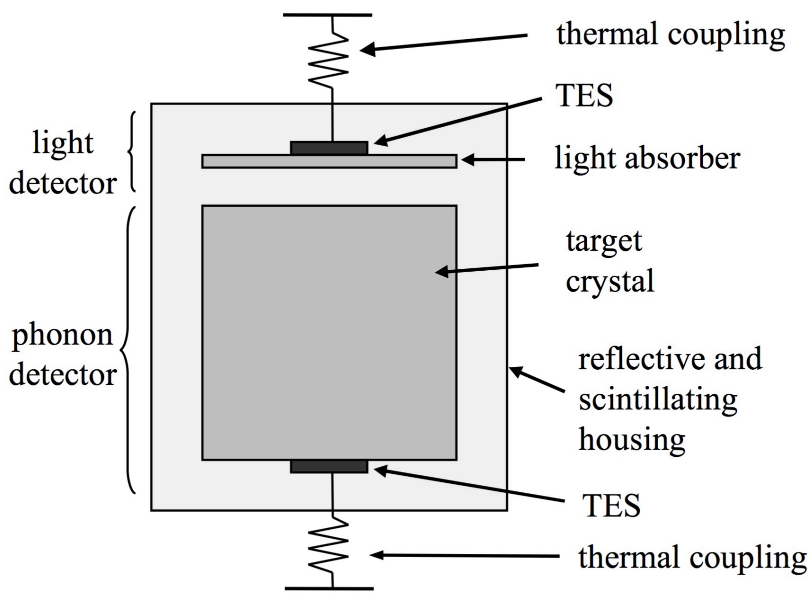


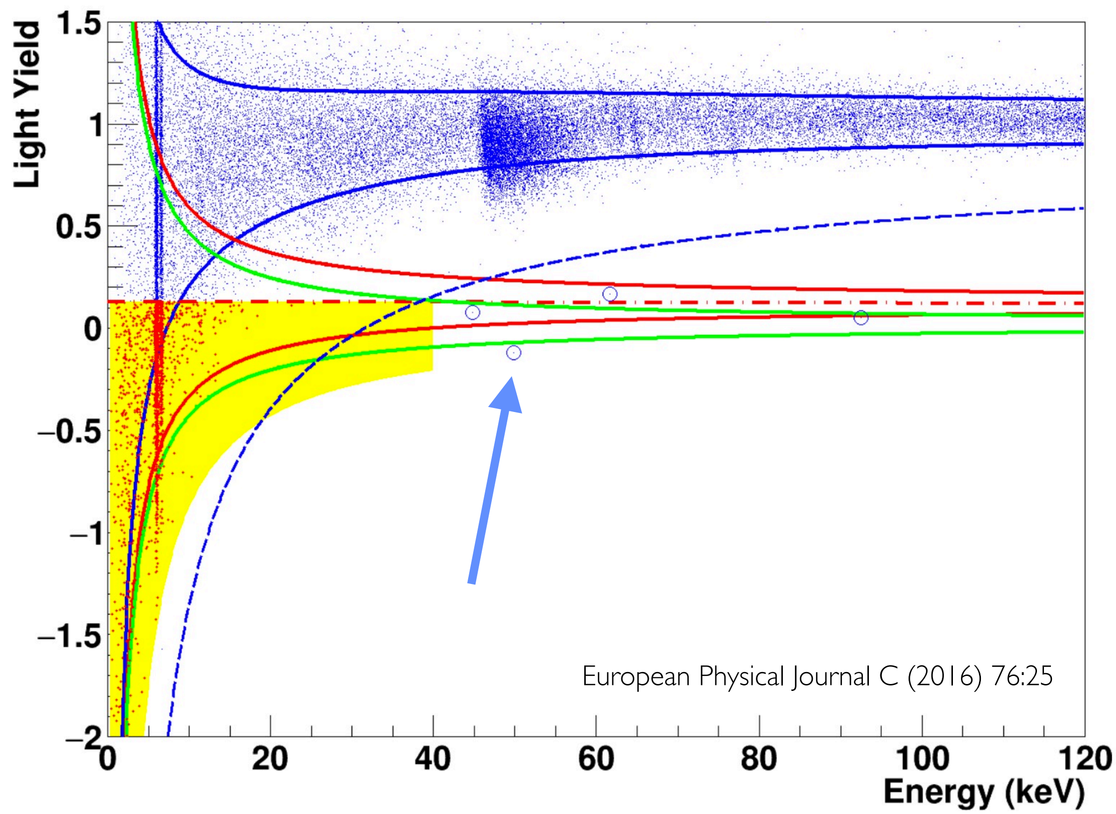
"There is also the addition of a Pb-210 **[surface]** background estimate" —CoGeNT, 2012 (comments section of arXiv:1208.5737)

CRESST anomaly

- cryogenic

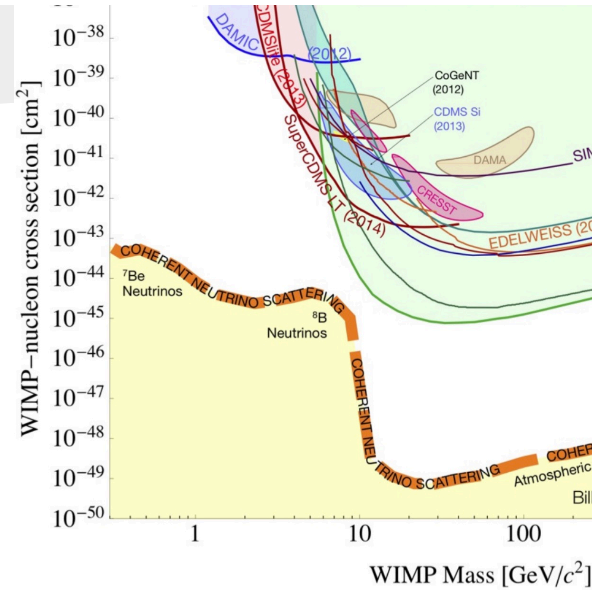


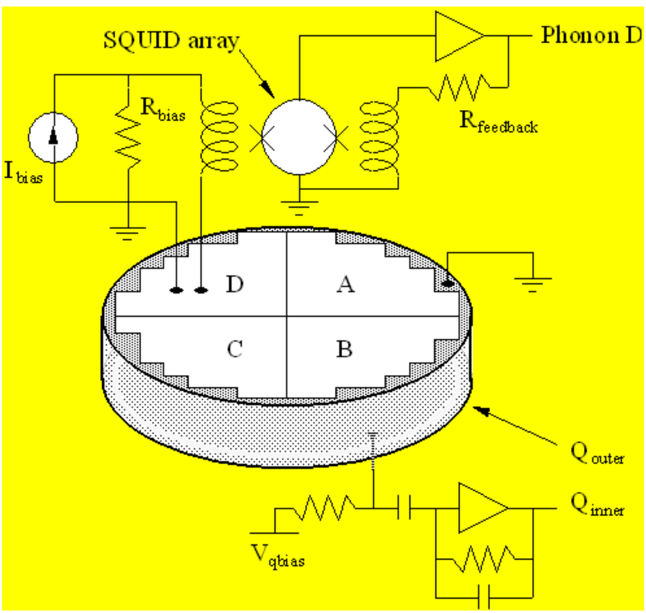


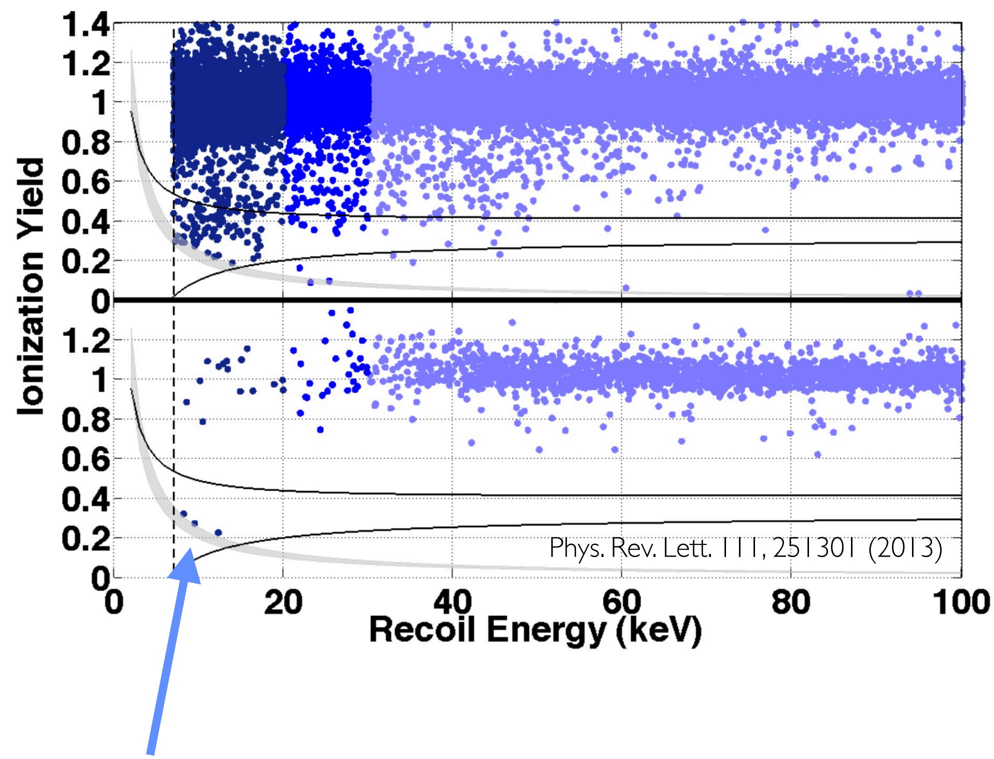


CDMS anomaly

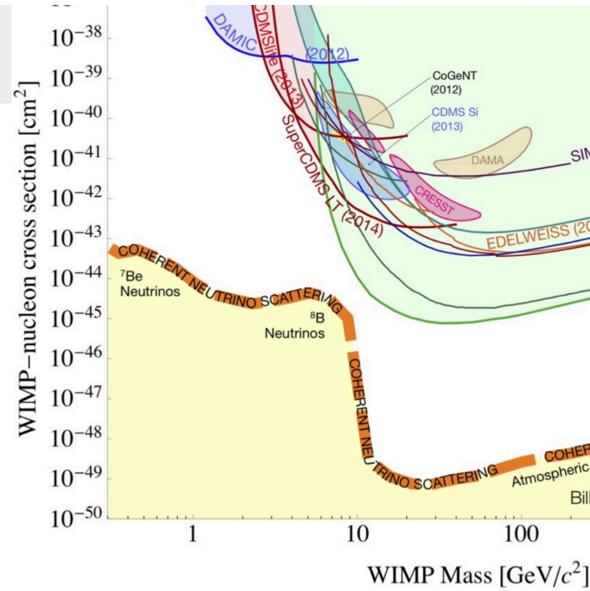
- cryogenic

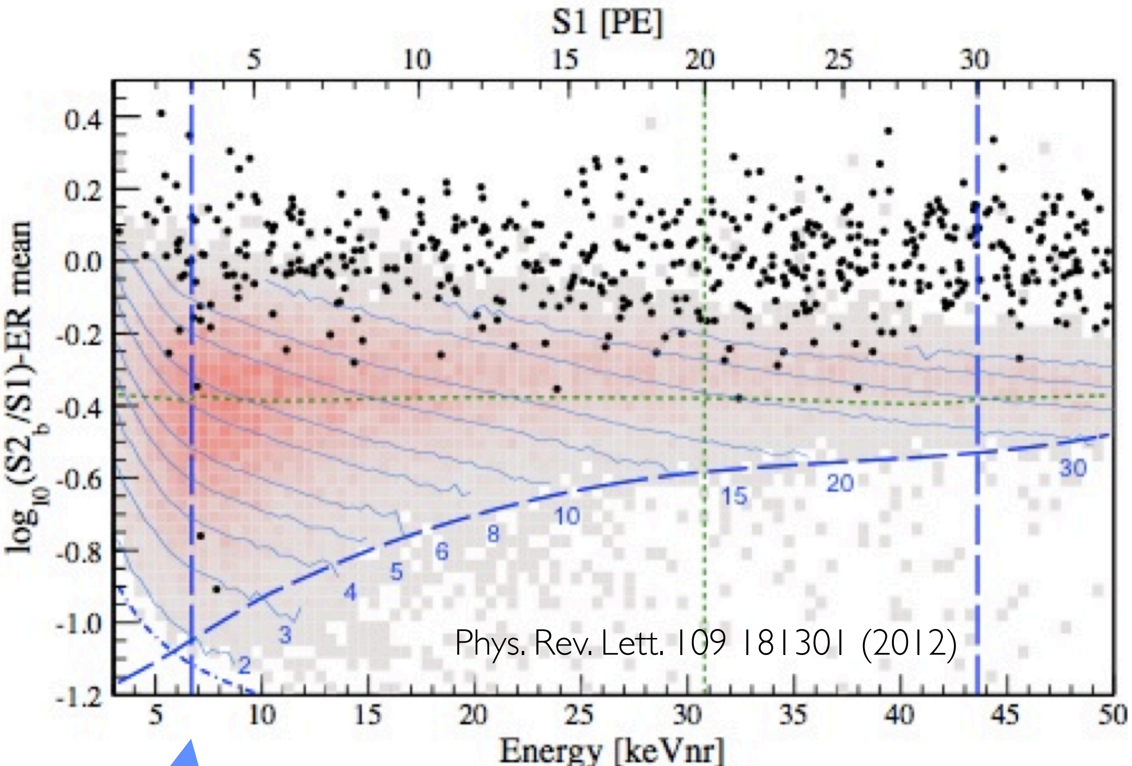






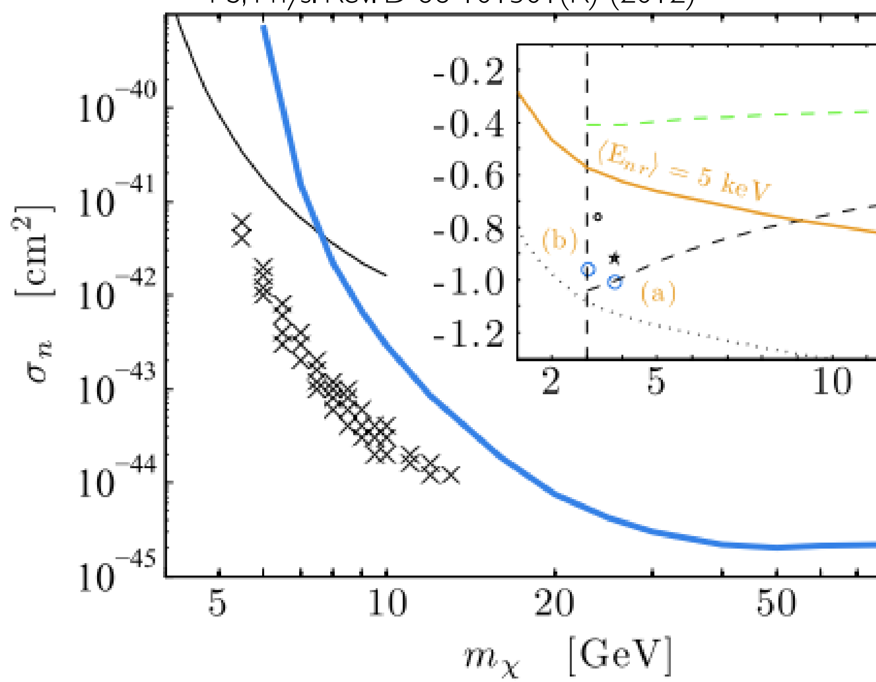
XENON100 anomaly





Phys. Rev. Lett. 109 181301 (2012)

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



PHYSICAL REVIEW D **88,** 015021 (2013)

Xenophobic dark matter

Jonathan L. Feng,[1,*] Jason Kumar,[2,†] and David Sanford[3,‡]

[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697, USA*
[2]*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*
[3]*Department of Physics, California Institute of Technology, Pasadena, California 91125, USA*
(Received 20 June 2013; published 15 July 2013)

We consider models of xenophobic dark matter, in which isospin-violating dark matter–nucleon interactions significantly degrade the response of xenon direct detection experiments. For models of near-maximal xenophobia, with neutron-to-proton coupling ratio $f_n/f_p \approx -0.64$, and dark matter mass near 8 GeV, the regions of interest for CoGeNT and CDMS-Si and the region of interest identified by

“God made the bulk, surfaces were invented by the devil”

—W. Pauli
as quoted in Growth, Dissolution, and Pattern Formation in Geosystems (1999)

surfaces lead to:

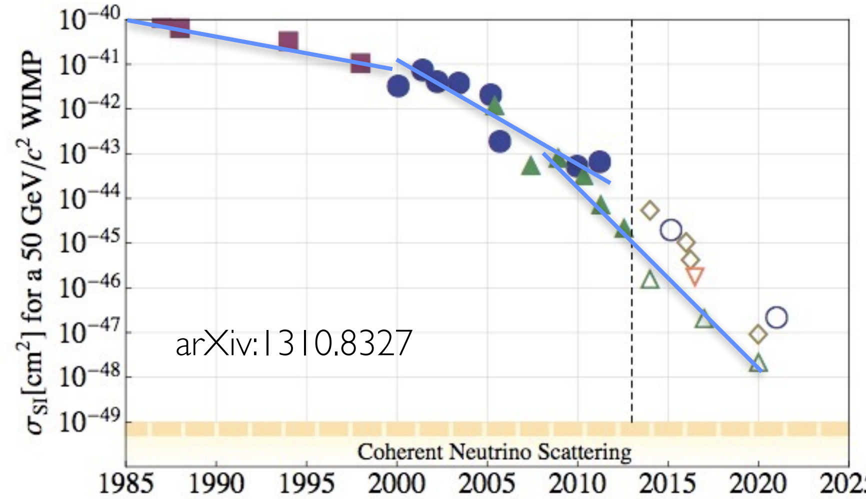
- a dead layer in charge collection
- an opaque layer in scintillation detection

=> spurious events near energy threshold

meanwhile,

xenon TPCs have no walls!!

Liquid noble gas TPC



▲ liquid xenon

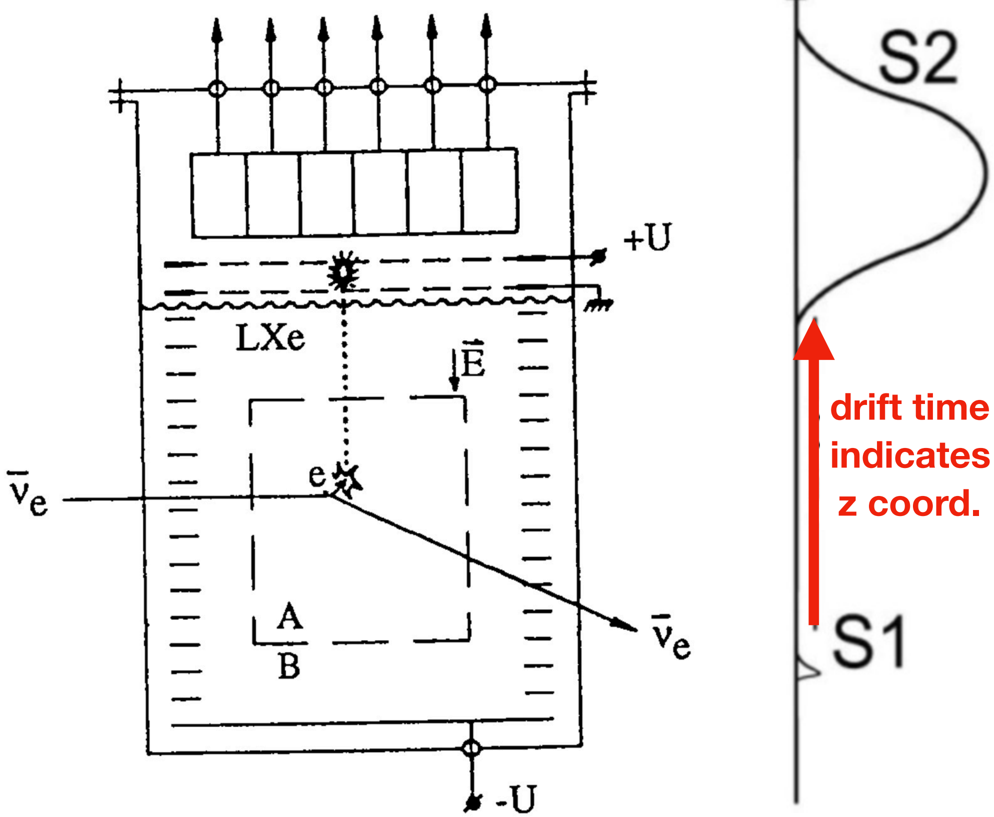
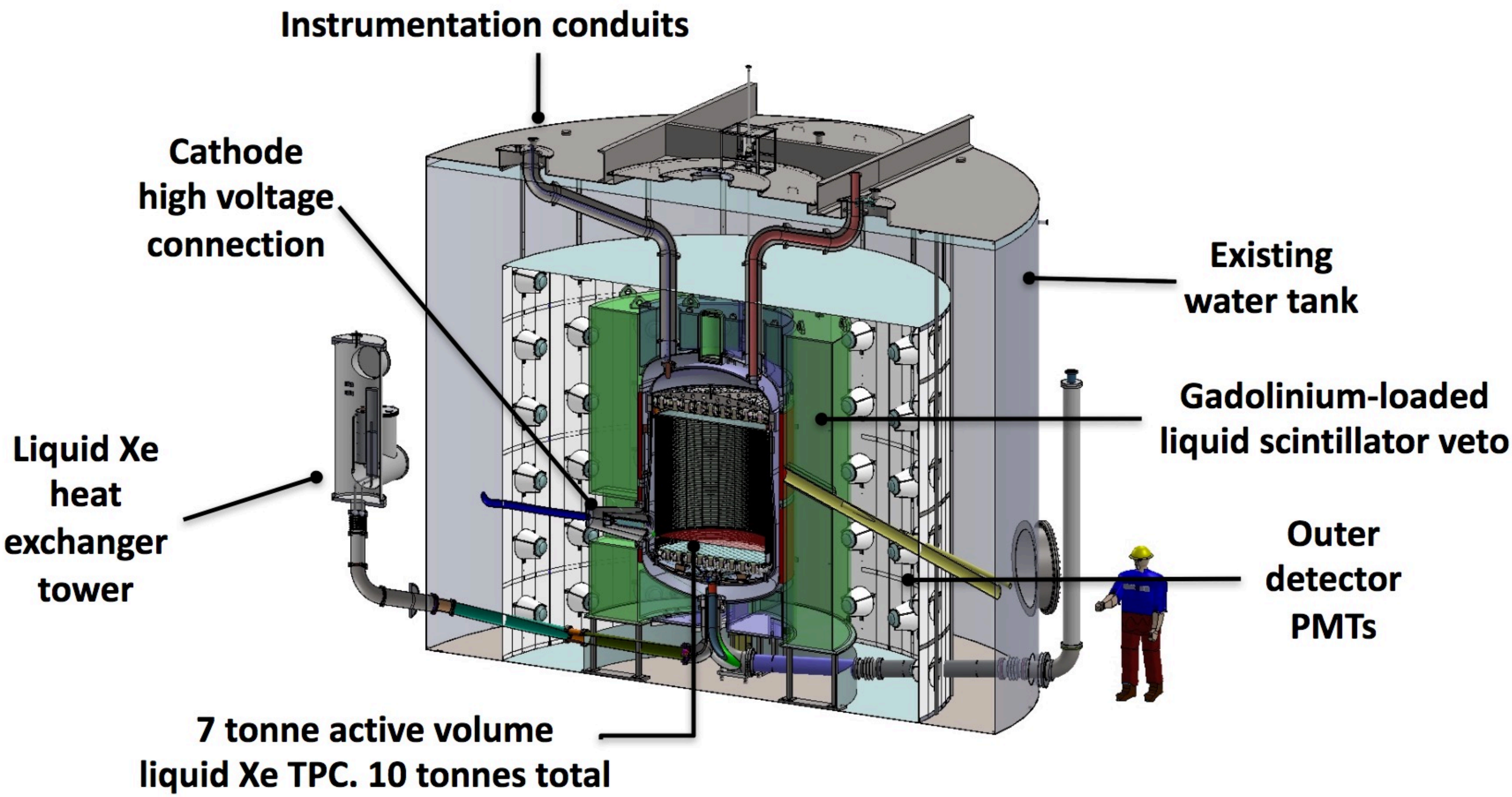


Fig.4. LXe time-projection scintillating drift chamber as wall-less detector for measurements of magnetic momentum neutrino.

Bolozdyna et al., IEEE Trans. Nucl. Sci. 42 (1995) 565

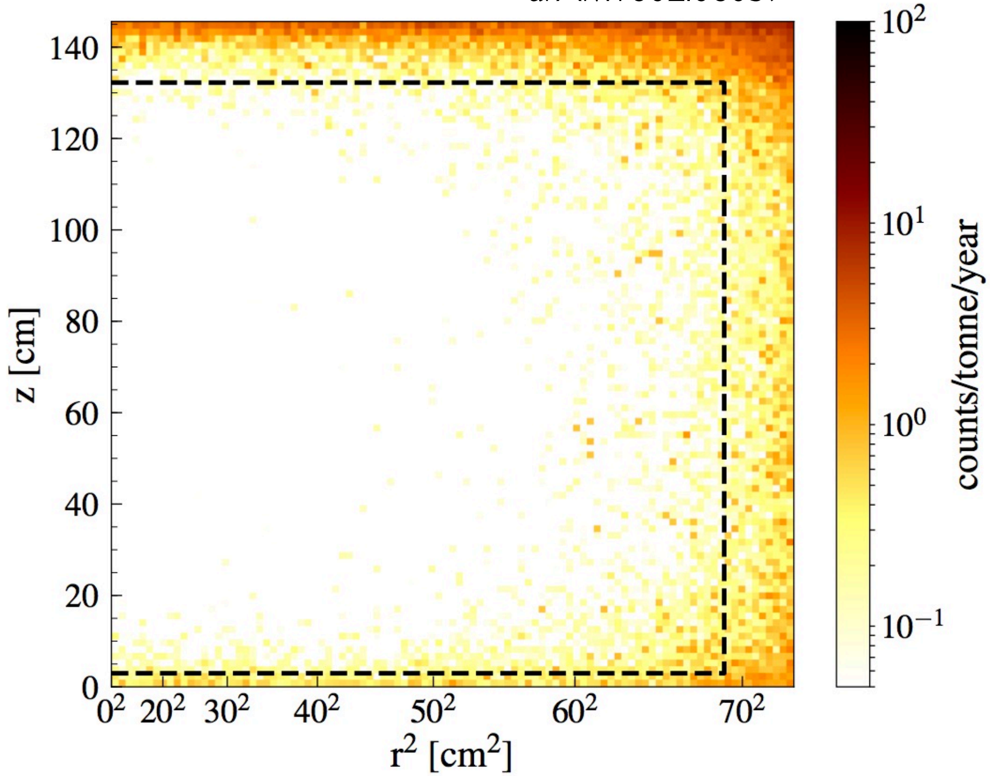
LZ was designed to detect WIMPs

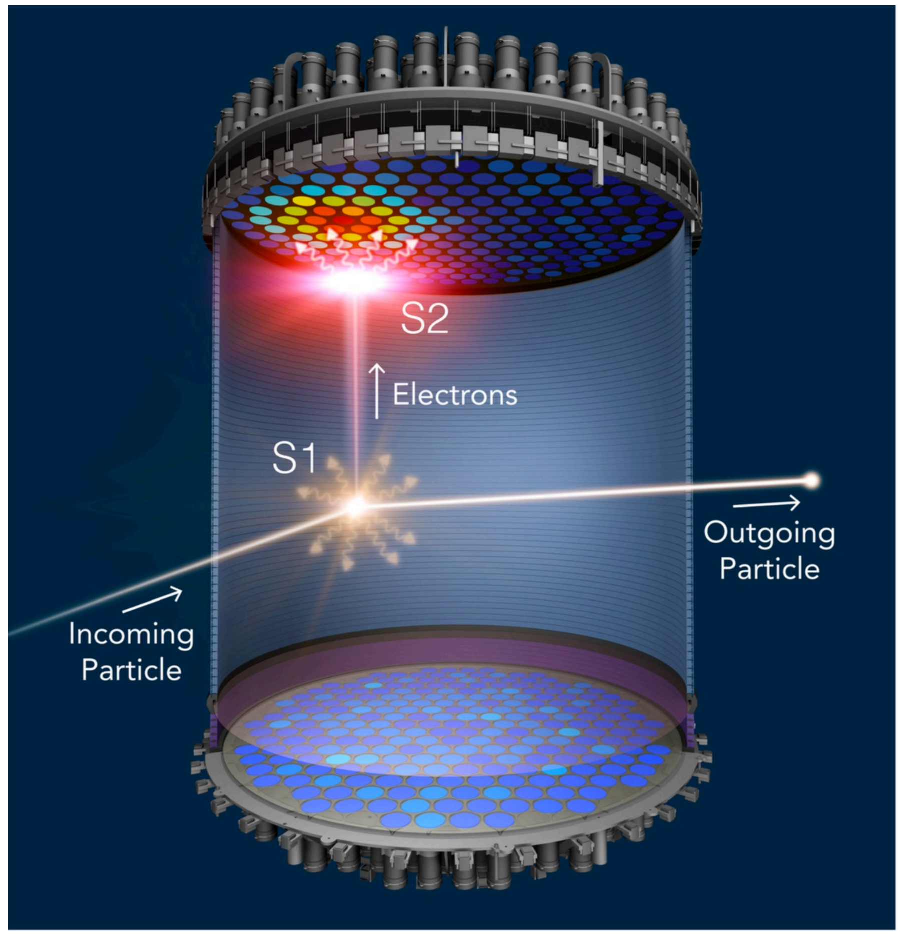
lzdarkmatter.org



(x,y,z) vertex reconstruction effectively removes the walls

arXiv:1802.06039





One or Two?

1. Having figured out how to avoid spurious low-energy signals, we can build a larger a liquid xenon TPC for a discovery-class experiment to search for dark matter. The End!

2. As sensitivity improves, new pathologies and backgrounds have an opportunity to transition from sub-dominant to dominant

LUX: state of the art in 2014

sub-dominant →
1e-4 events/keV/kg/day

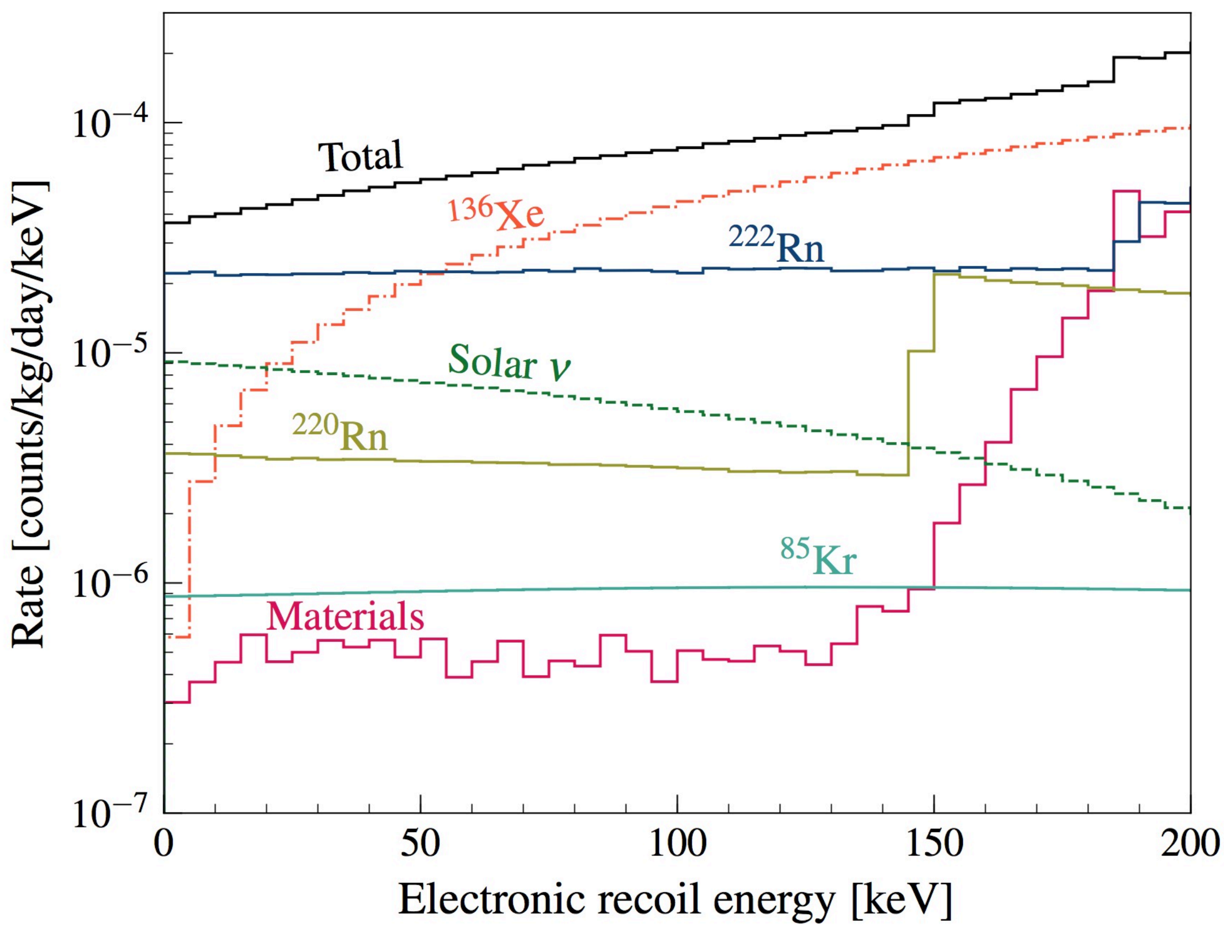
Source	Background rate, $mDRU_{ee}$
γ-rays	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	0.11–0.22 (90% C. L.)
^{85}Kr	$0.13 \pm 0.07_{sys}$
Total predicted	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Total observed	$3.6 \pm 0.3_{stat}$

Phys. Rev. Lett. 112, 091303 (2014)

LZ: aiming for state of the art in 2020

NOT
sub-dominant
2e-5 events/keV/kg/day

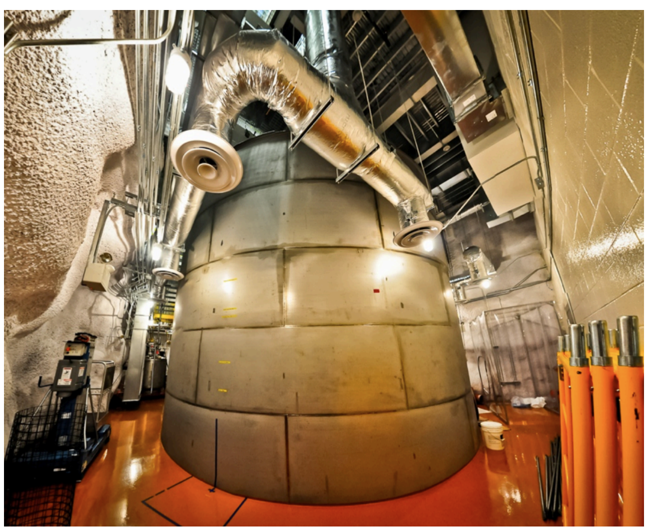
arXiv:1802.06039



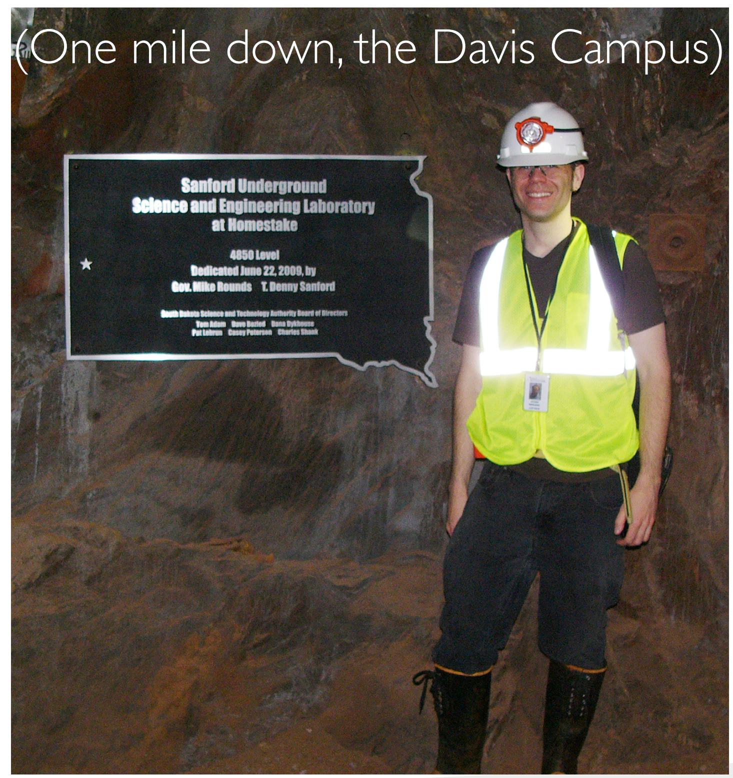

RADON: It's radioactive and it's real.
Radon is an odorless underground radioactive gas that can enter your home through cracks in the foundation.
Radon is a known human carcinogen and leading cause of lung cancer.
Our state geology puts Pennsylvanians at risk of high radon levels.
RADON GAS
Protect yourself and your loved ones: Do a home radon test.
DIY test kits are easy, inexpensive, and sold at hardware stores.
radon
86
Rn
[222]
pennsylvania
DEPARTMENT OF ENVIRONMENTAL PROTECTION
dep.pa.gov/radon
1-800-23RADON

LZ will be deployed at SURF, one mile underground

The Black Hills of South Dakota: Sanford Underground Research Facility

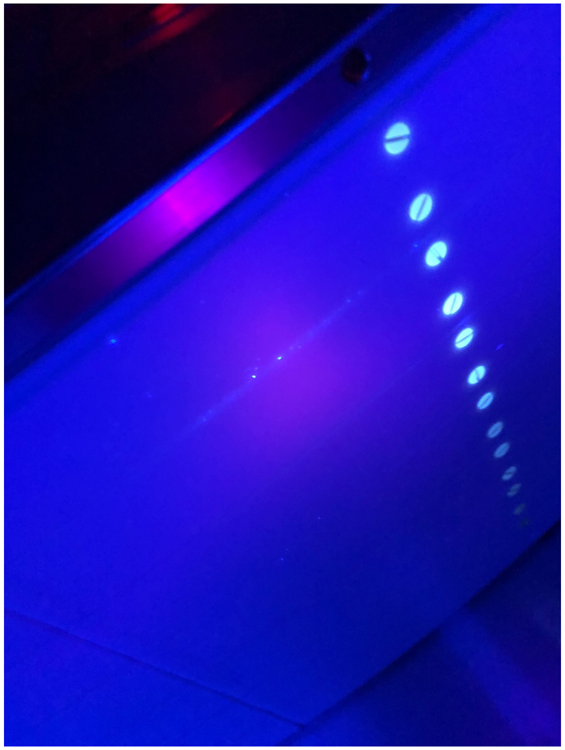


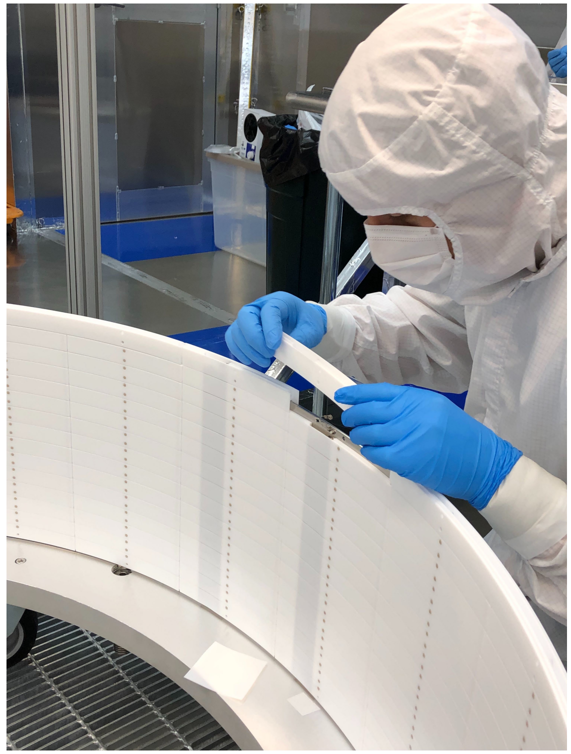
(Two flights down)
LZ water tank shield

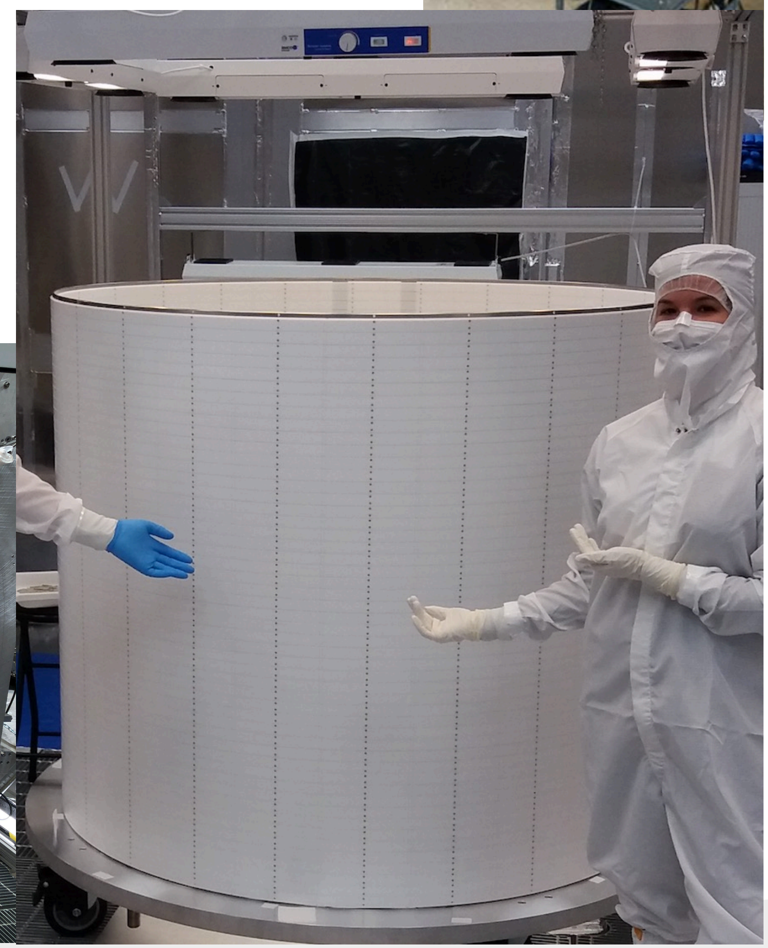


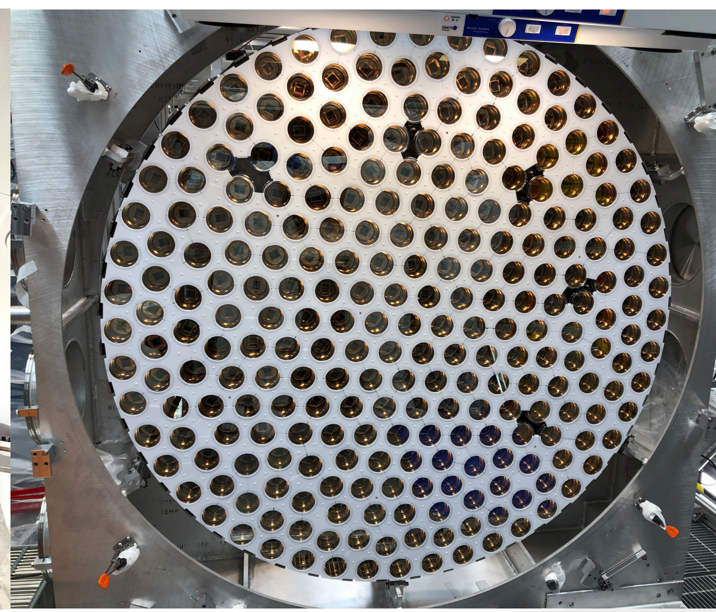
(One mile down, the Davis Campus)

Building LZ at the surface in a reduced-radon cleanroom



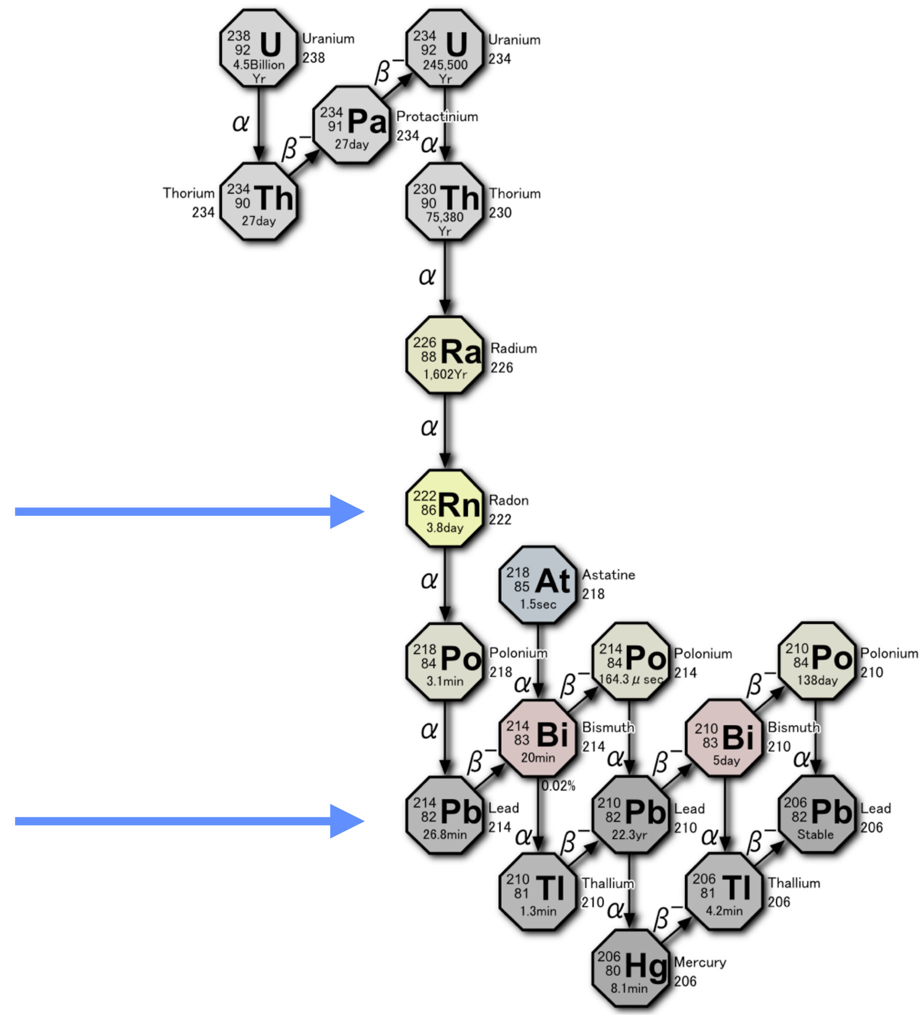






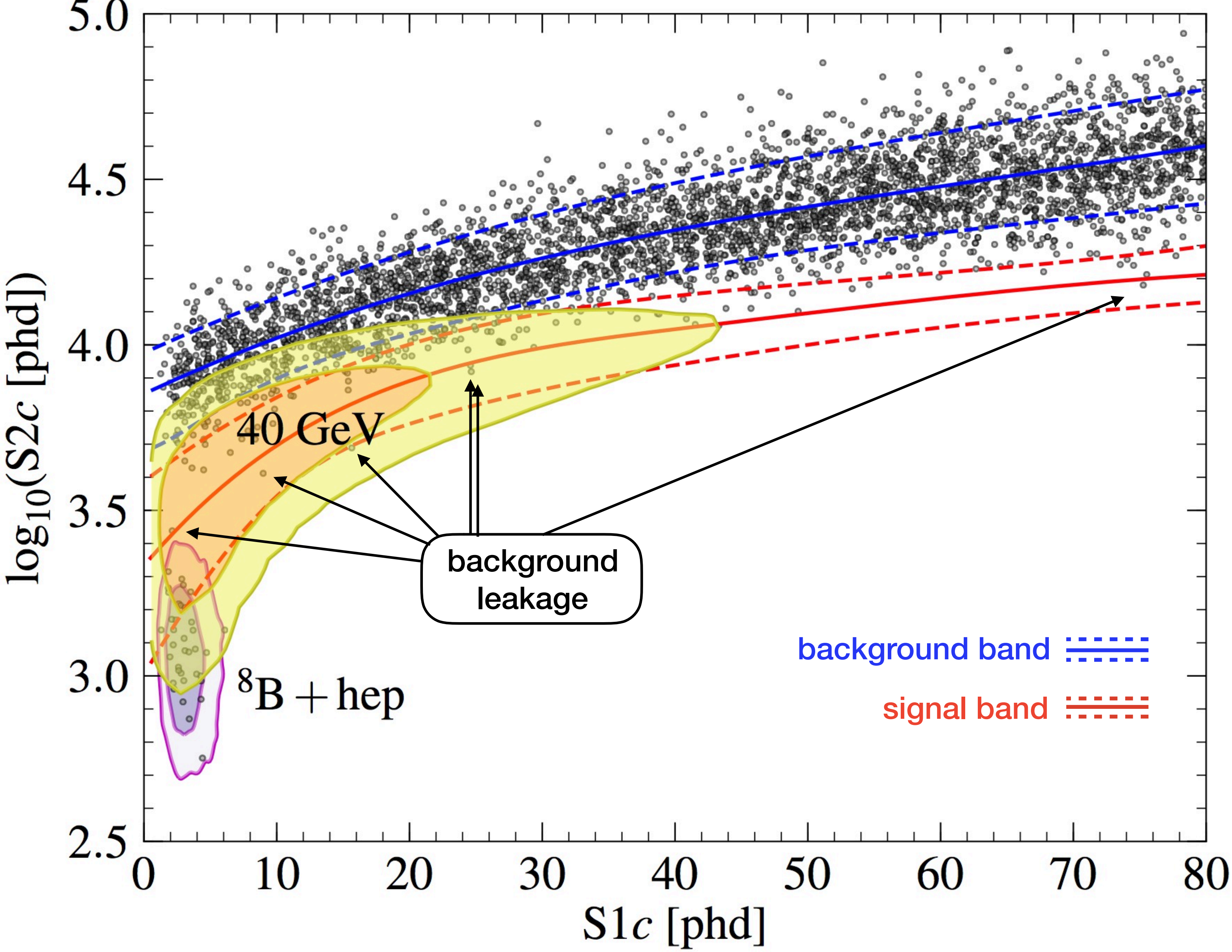
Why radon is such a tricky issue

1. Radon diffuses out of detector construction materials
2. It dissolves into the liquid xenon
3. Its daughter 214Pb has a 10.6% branching beta decay directly to ground



LZ has good, but imperfect discrimination

LZ 5600 kg x 1000 days search:



1150 BG events

832 from Rn

200 from solar nu

< 1 atm. nu

40 8B+ hep nu

Internal backgrounds !!

LZ radon mitigation strategy is comprehensive

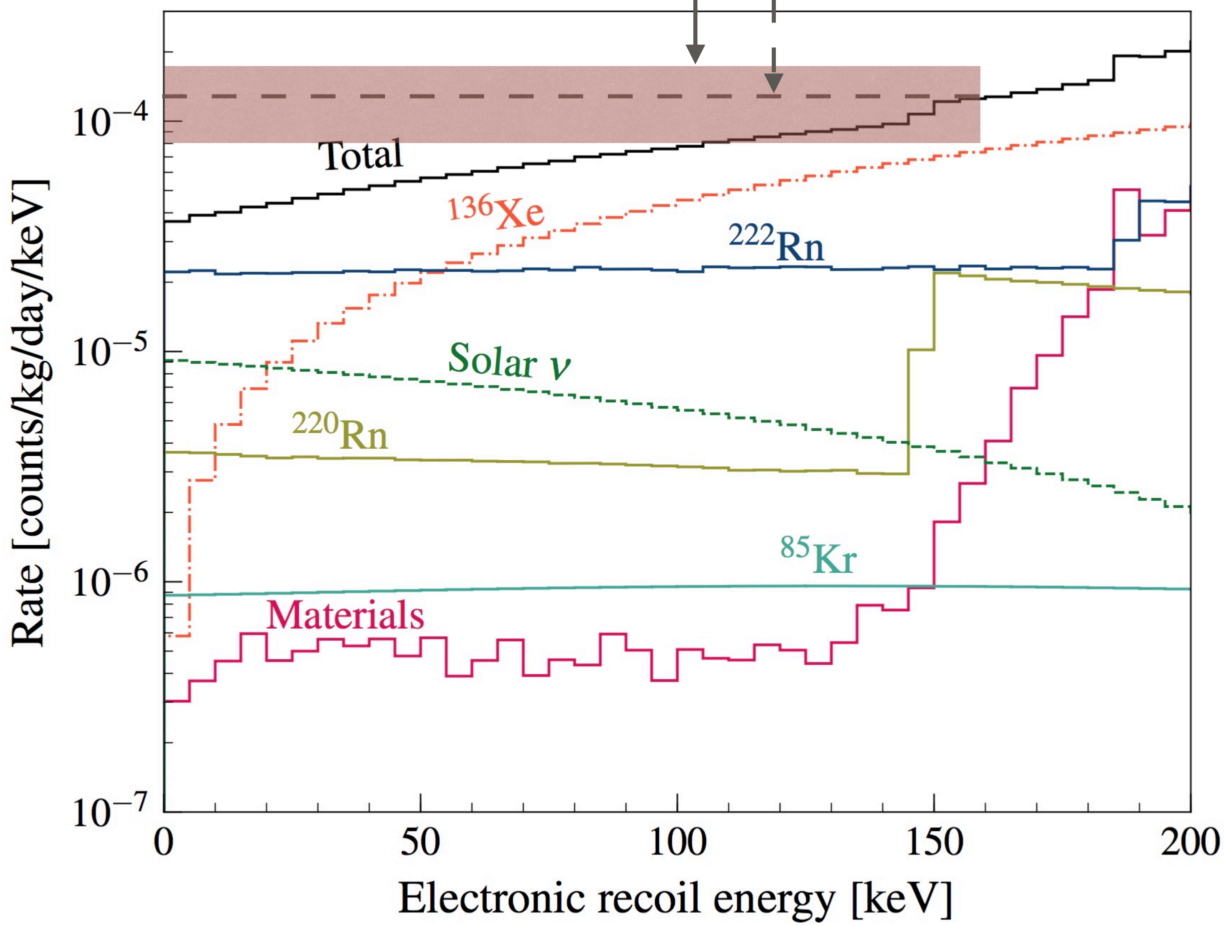
1. Massive material screening campaign. Build out the 238U
2. Massive cleanliness campaign. Build LZ clean
3. Charcoal trap radon reduction loop on gas-phase radon emanation

Comment on radon reduction results to date

Active area of R&D.

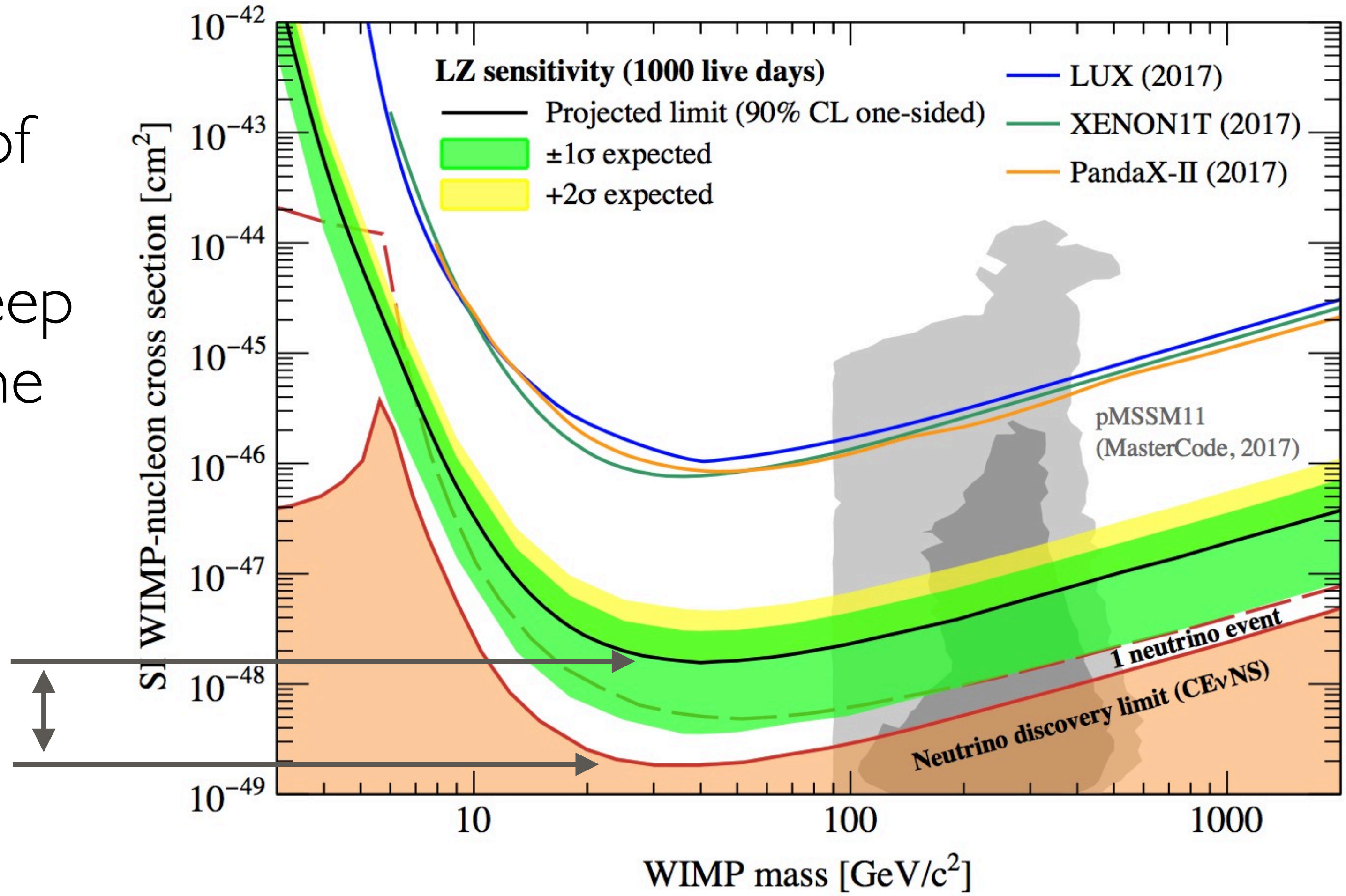
HARD.

XENON1T prediction w/o cryogenic distillation (dash)
and measured w/ cryogenic distillation (shaded)



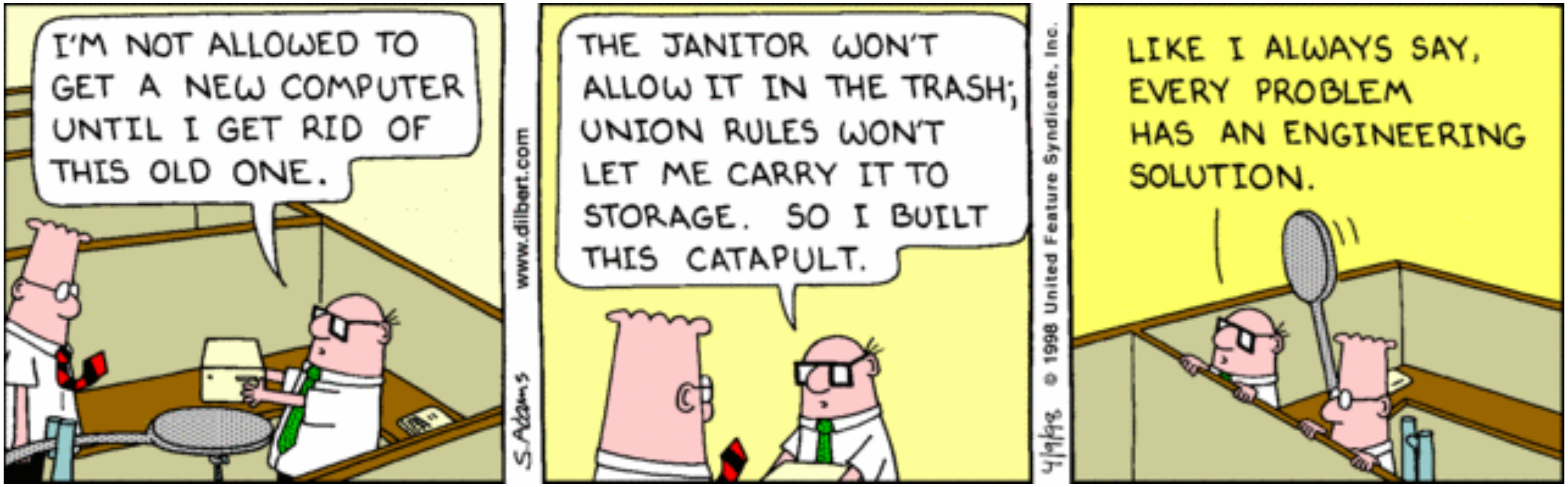
Projected LZ sensitivity in 2025

LZ will detect a significant number of solar neutrinos, but radon is going to keep LZ from reaching the neutrino floor

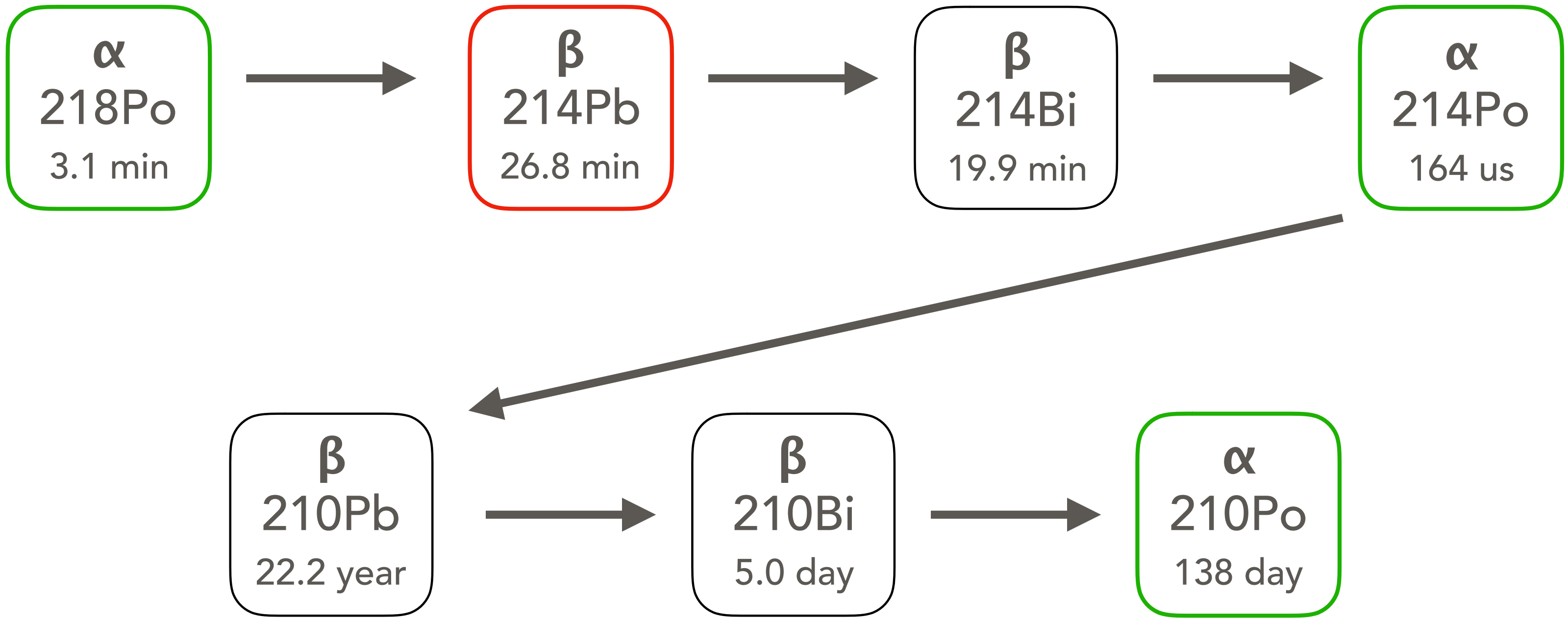


"radon rug" (?)

“Every problem has an instrumentation solution”

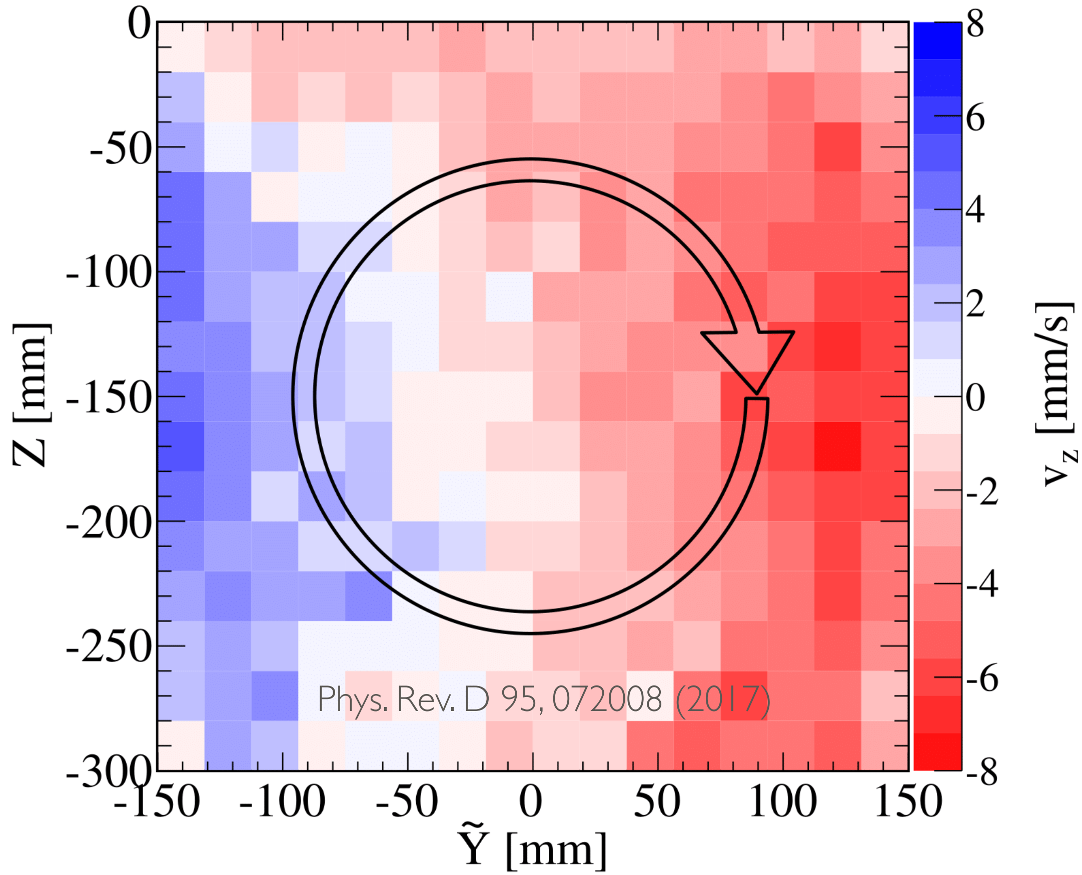


Refinement of the problem



Convective fluid flow in liquid xenon

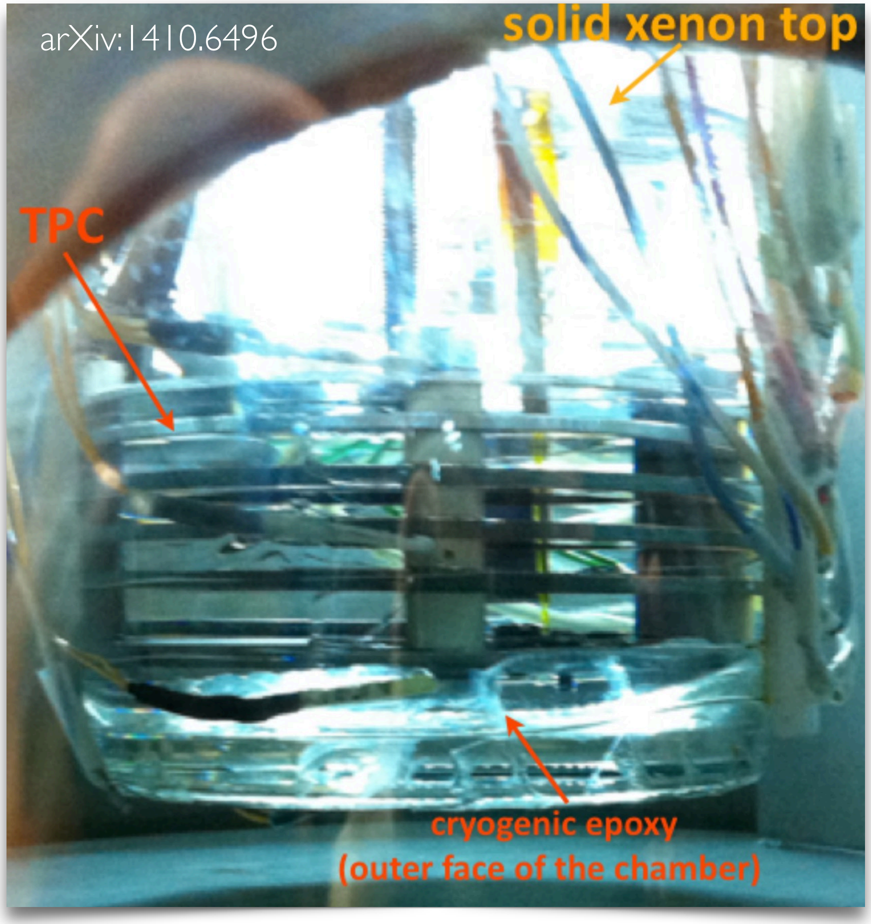
~mm/s => ~6 cm/min



i.e. too fast

Instrumentation solution: crystallize

- crystalline xenon TPC instead of liquid xenon TPC
- Radon isn't soluble in a crystal
- In a crystal, radon decay daughters would stay at the same (x,y,z) as the parent



Similar particle detection properties

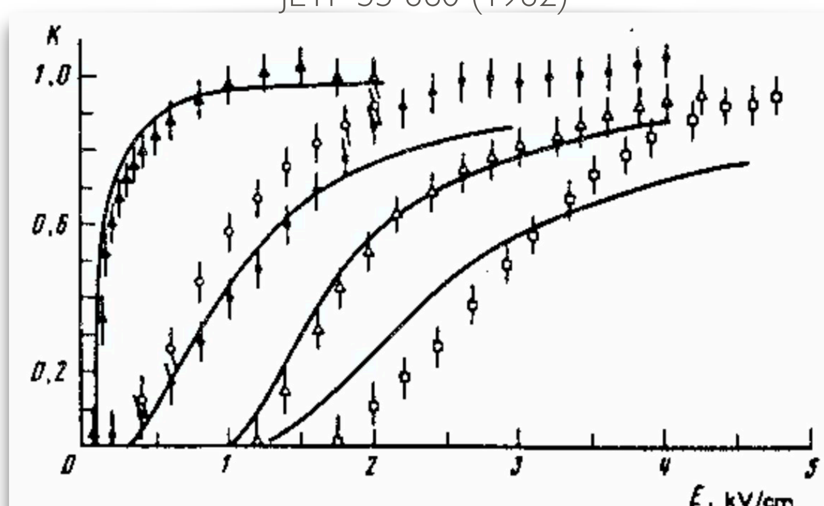
- Solid and liquid xenon have similar physical properties
  - electron mobility
  - electron emission
  - band gap (hence W-value)
  - density (20% bonus!)
- cf. arXiv:1410.6496 and arXiv:1508.05903

Phys Rev B 10 4464 (1974)

TABLE II. Comparison of transport parameters in solid and liquid xenon. Values of other data used in the calculations are also quoted.

	Solid $T=161.2$ °K	Liquid $T=163$ °K	Unit
E_G	9.272	9.22	eV
G	1.063	1.084	eV
ϵ_∞	2.00 [a]	1.85 [b]	...
m^*	0.31 [c]	0.27	electron mass
μ	4.5×10^3 [d]	2.2×10^3 [e]	$cm^2\,V^{-1}\,sec^{-1}$
τ_p	8.0×10^{-13}	3.4×10^{-13}	sec
L	7.1×10^{-6}	3.3×10^{-6}	cm
β	1.36×10^{10} [f]	0.58×10^{10} [g]	dyn/cm^2
$\lvert a\rvert$	3.8×10^{-9}	4.2×10^{-9}	cm
$\lvert E_{1CB}\rvert$	0.93	1.01	eV

JETP 55 860 (1982)



Similar cryogenic requirements

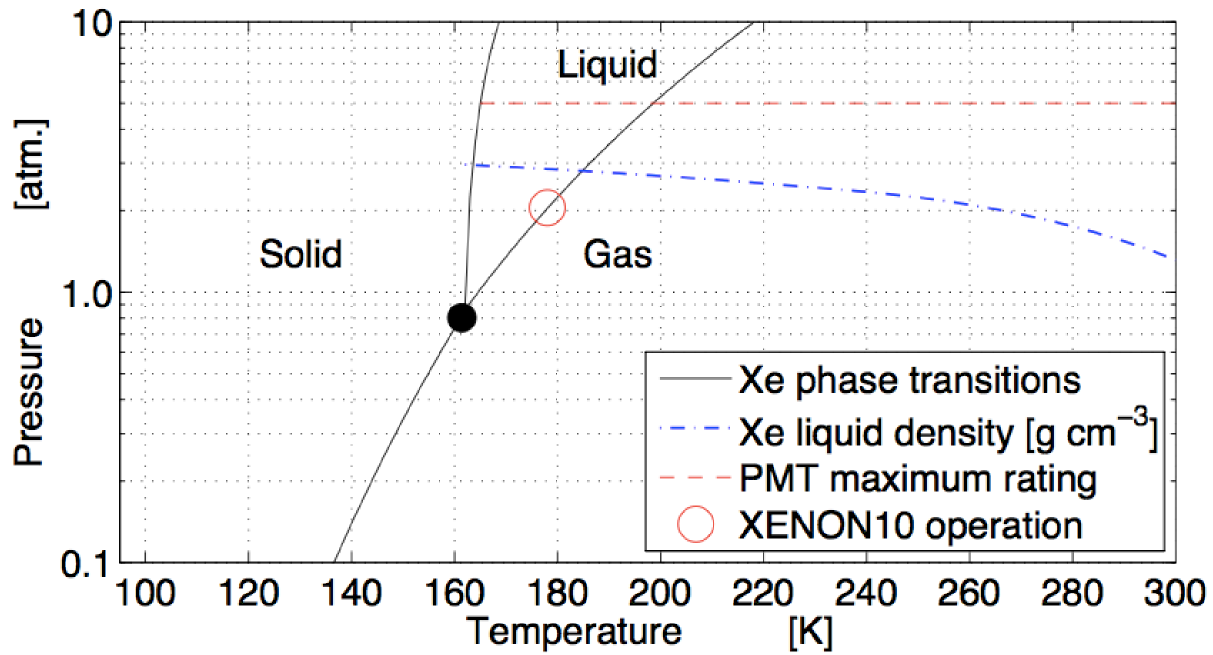
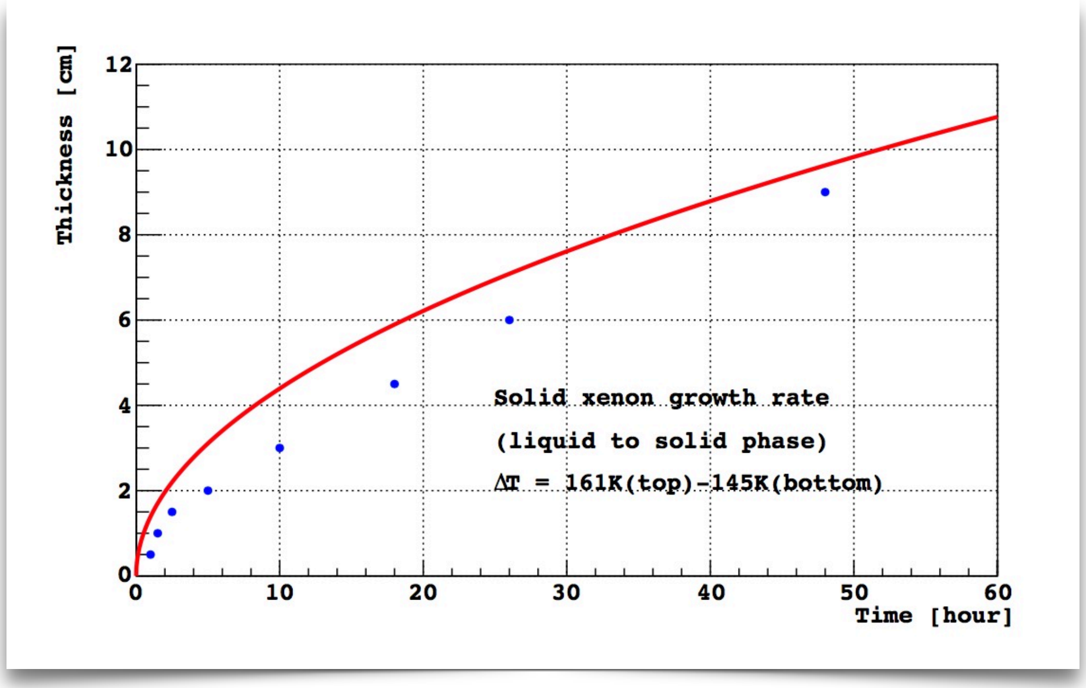


Figure 3.22: Phase Diagram for Xe (data from [127]) and liquid Xe density (data from [123]). For dual-phase operation as in XENON10, the comfortable operating window is indicated by the red circle. Higher pressures are excluded out of consideration for the PMTs (which are rated to a maximum of 5 atm, above which they will crush). Lower temperatures dictate a lower vapor pressure, which reduces the efficiency of the $S2$ proportional scintillation (Sec. 2.2.4). It is also necessary to stay safely above the 161 K, to exclude the possibility of sublimation.

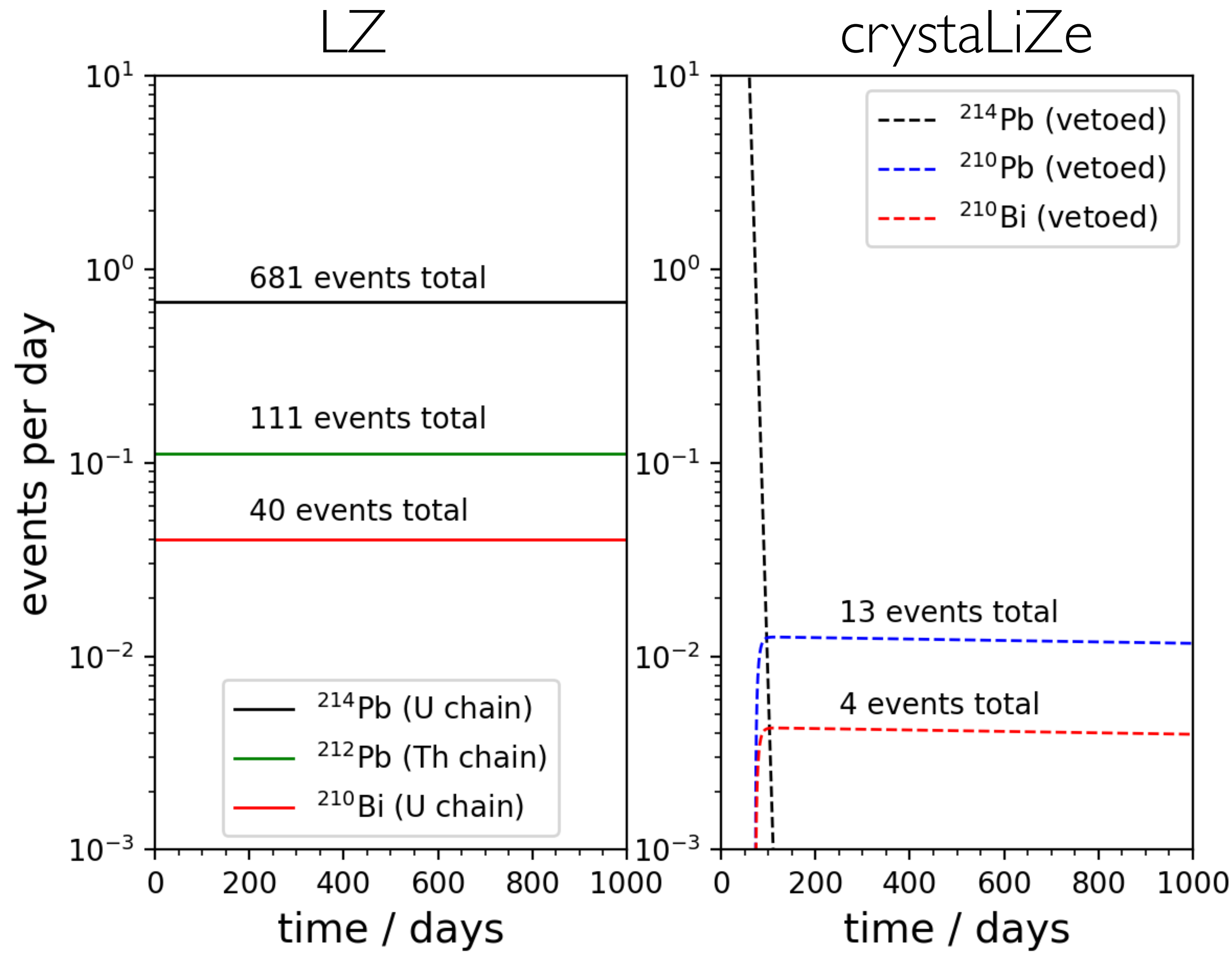
Crystal growth will be a key technical challenge

- Need to retain high purity while crystalizing
    - would take O(1 year) to crystallize LZ
    - Need to control outgassing of impurities
- Need more precise temperature control to maintain crystal growth

arXiv:1410.6496

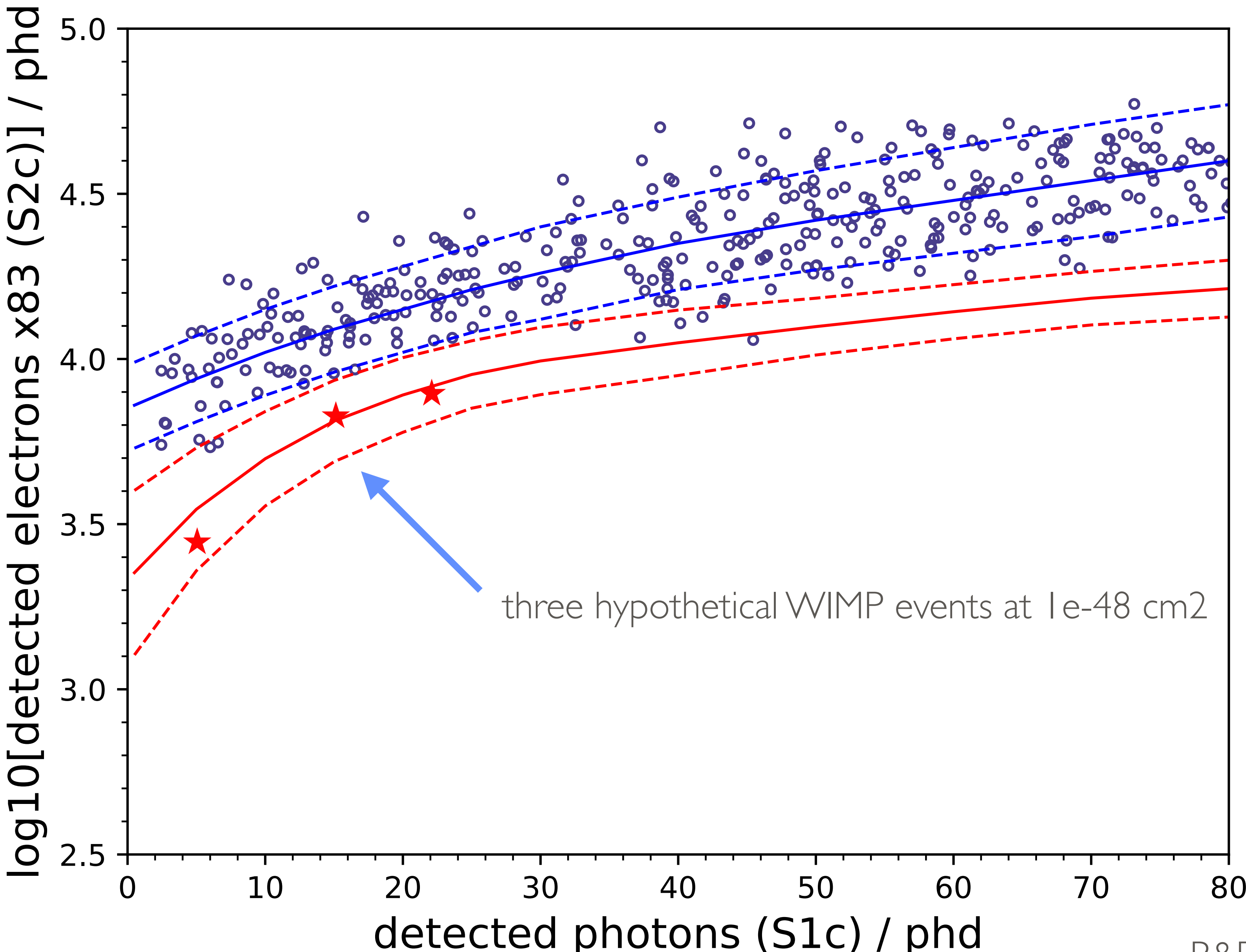


Radon events in LZ and in crystaLiZe



crystaLiZe projected result

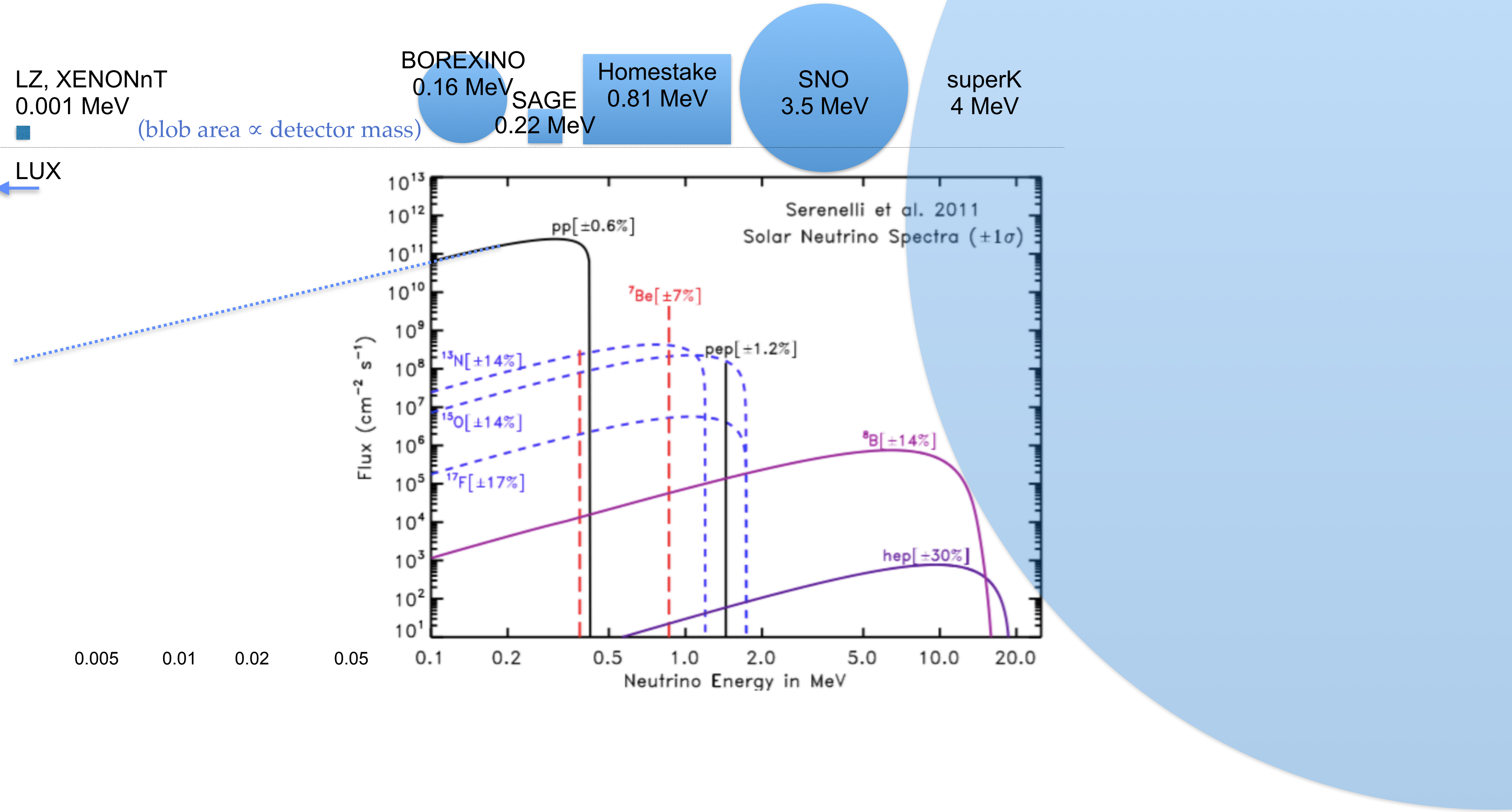
crystaLiZe 5600 kg x 1000 days search:



370 BG events
17 from Rn
200 from solar nu
<1 atm. nu
40 8B+hep nu

R&D underway in B70A

Thank you



LZ, XENONnT
0.001 MeV
(blob area ∝ detector mass)
LUX
BOREXINO
0.16 MeV
SAGE
0.22 MeV
Homestake
0.81 MeV
SNO
3.5 MeV
superK
4 MeV
Serenelli et al. 2011
Solar Neutrino Spectra (±1σ)
pp[±0.6%]
7Be[±7%]
pep[±1.2%]
13N[±14%]
15O[±14%]
17F[±17%]
8B[±14%]
hep[±30%]
Flux (cm−2 s−1)
Neutrino Energy in MeV
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0