Dark Matter Direct Detection

Rick Gaitskell,
Brown University
LUX Collaboration, Co-spokesperson
DOE

Particle Astrophysics Group, Brown University,
Department of Physics (Supported by US DOE HEP)
http://particleastro.brown.edu

24 years in dark matter

CDMS II: Winter
@Soudan Minnesota

Sanford Lab
LUX @Homestake,
South Dakota

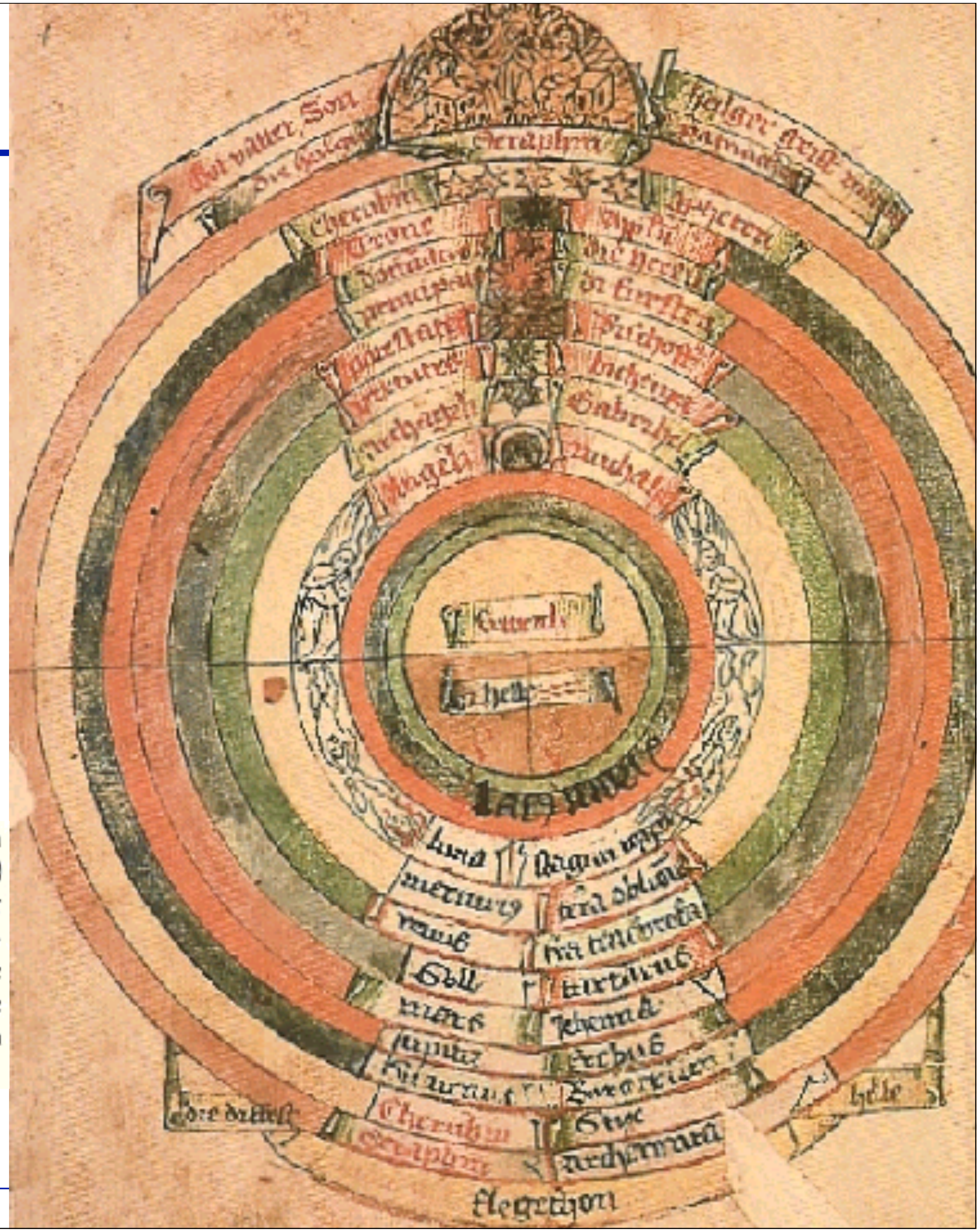
PHYSICS ITALIAN
STYLE XENON10
@ Gran Sasso

Gaitskell / Brown University

Medieval Universe

The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as well as the "Twelve Orders of the Blessed Spirits," the Cherubim and the Seraphim. German manuscript, c. 1450.

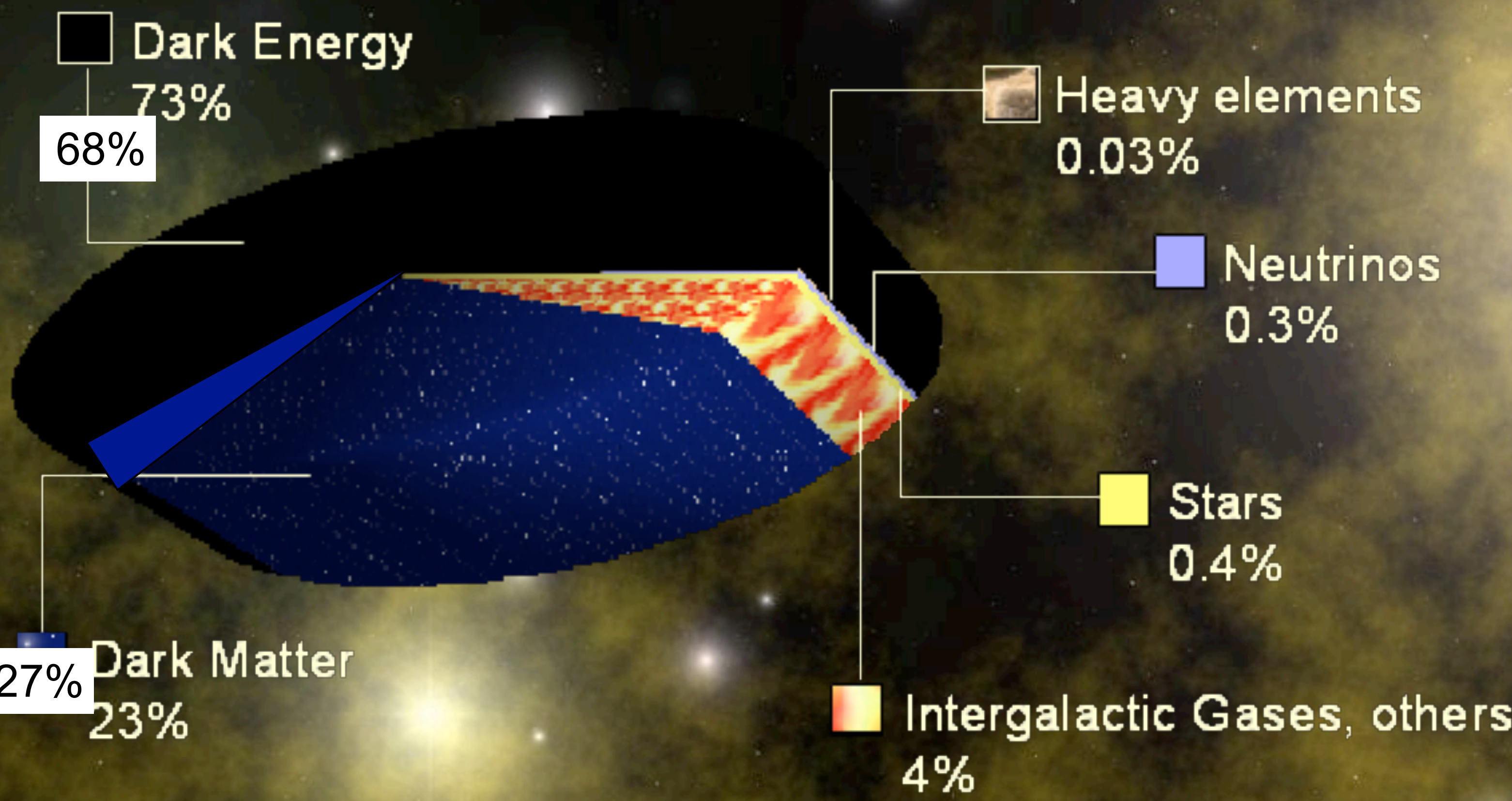
From Joel Primack, UC Santa Cruz



Confession

>95% of the Composition of the Universe is still unknown

What is the Universe made of ?



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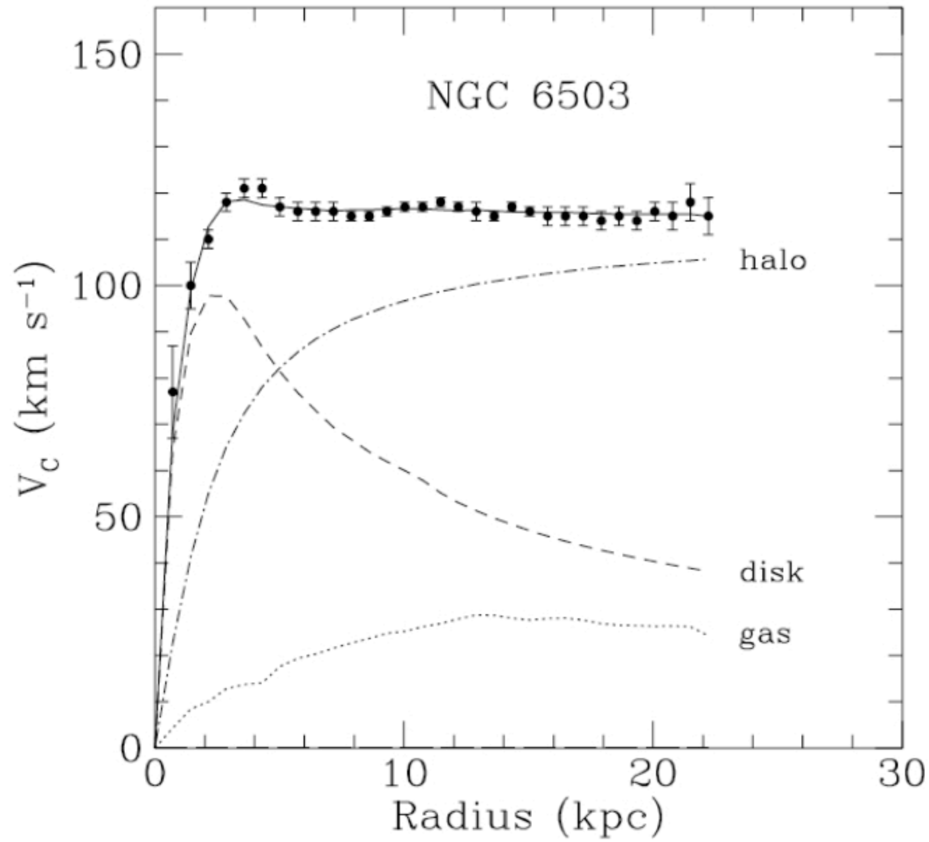
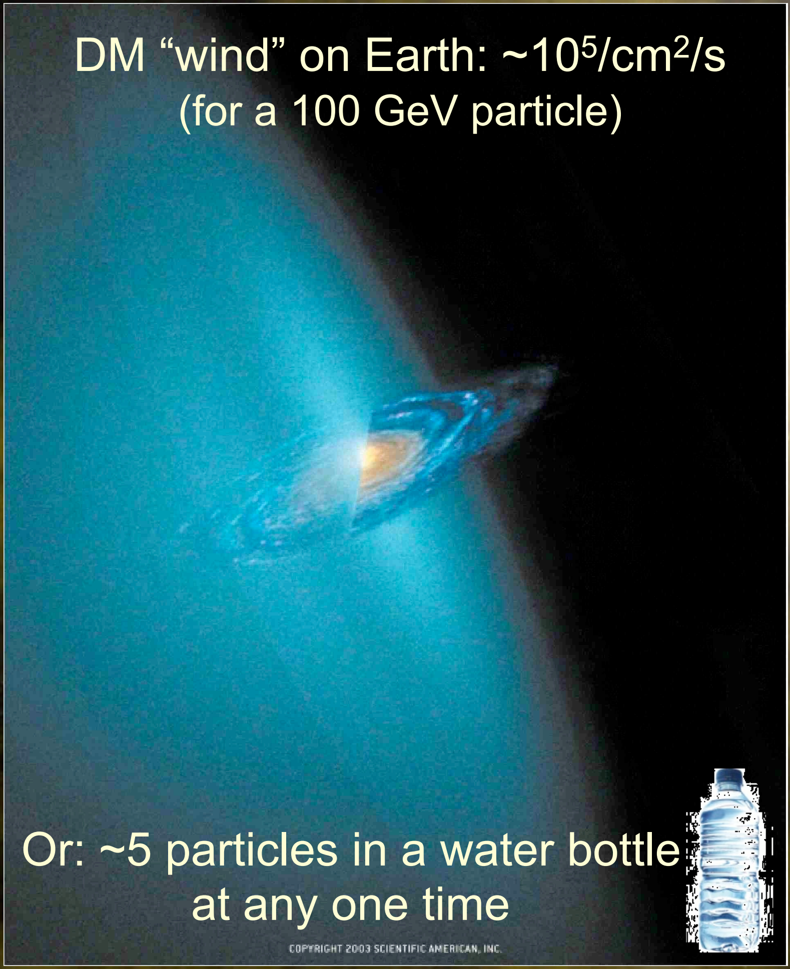
Galactic Rotation Curves



$$v = \sqrt{\frac{GM(R)}{R}}$$

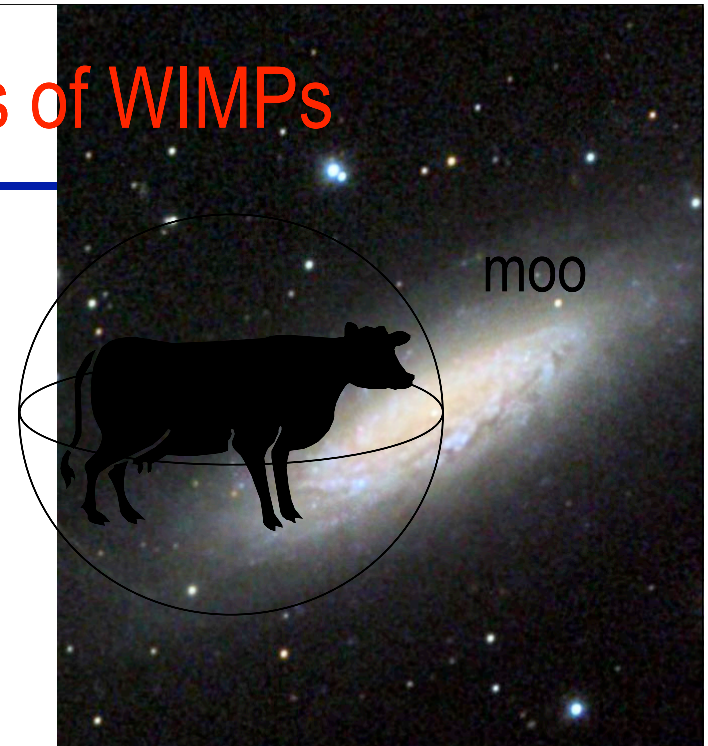
Galactic Dark Matter Halo

- **Basic idea**: each galaxy is surrounded by a homogeneous (?) cloud of massive, neutral, very weakly interacting particles, with a total mass ~5x of everything else
- Such a particle is generically called a **WIMP**, its exact nature remaining to be determined
- Halo's properties dictated by observations
  → We know how much total mass there is, and we can make educated guesses on the velocities distribution, particle mass, etc…
  with large (x3-100 !) uncertainties
- Massive neutrino already eliminated



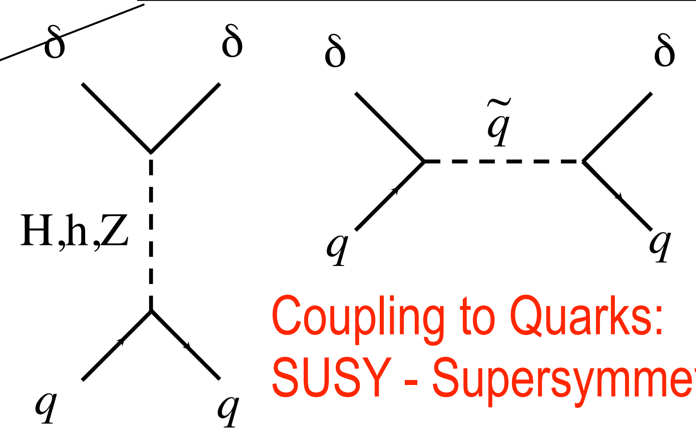
Direct Detection Astrophysics of WIMPs

- **Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo**
  - **"Spherical-cow" assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution**
  - **V_0= 230 km/s, v_{esc}= 650 km/s,**
  - **ρ = 0.3 GeV / cm^3**



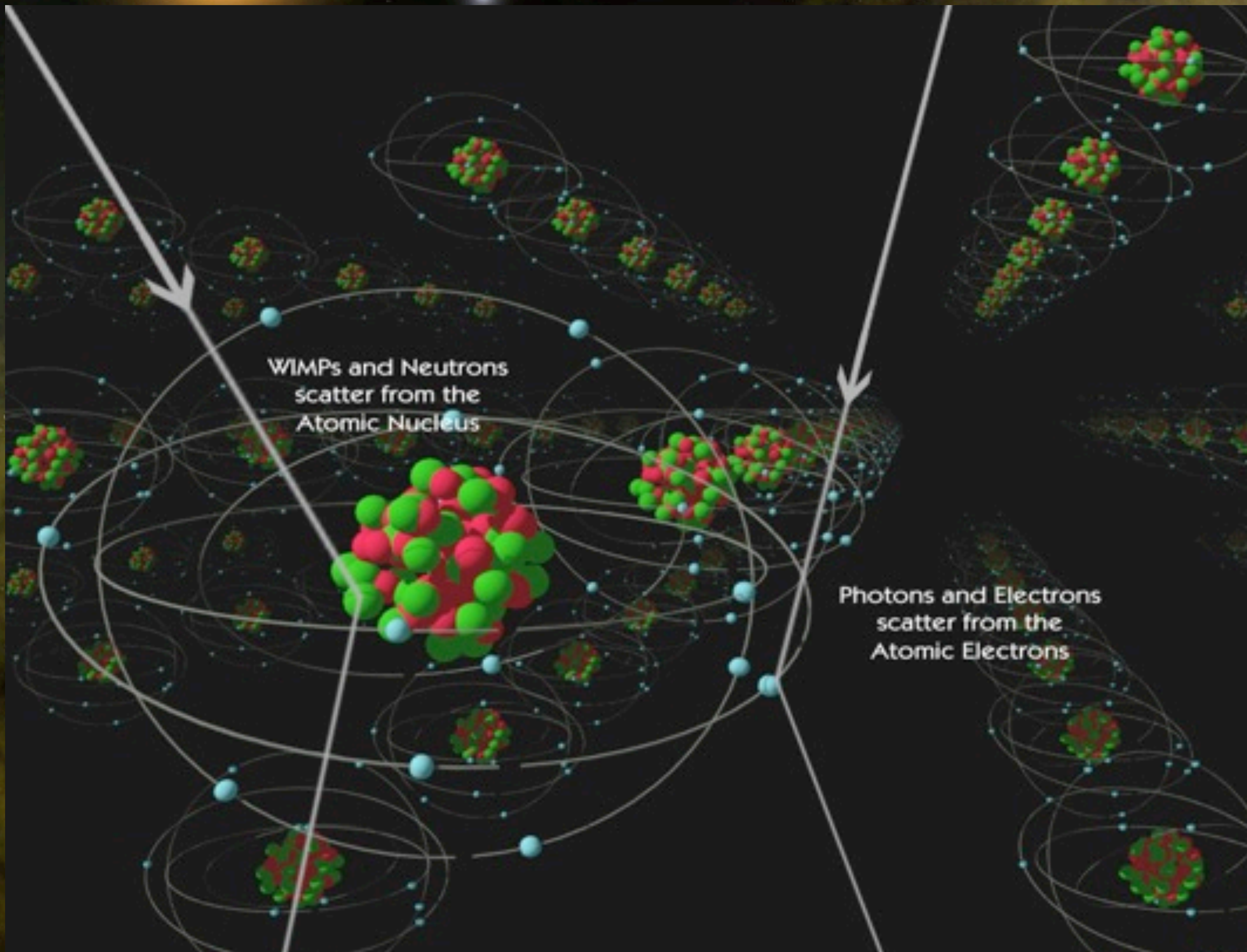
- **Energy spectrum of recoils is featureless exponential with 〈E〉 ~ 30 keV**
- **Rate (based on $\sigma_{n\chi}$ and ρ) is fewer than 1 event per kg of target per decade**
- **Nucleus recoils (not electron)**

"Contains ten 100-GeV WIMPs on average. 20 billion WIMPs pass through each second."



Coupling to Quarks:
SUSY - Supersymmetry

Interaction with Ordinary Matter



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Dark Matter Underground Searches - Silver Jubilee in 2012

- First publication on an underground experimental search for cold dark matter (Ahlen et al. 1987. PLB 195, 603-608).

http://www.pnnl.gov/physics/darkmattersymp.stm

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

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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[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*
[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

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

- 1986 operating a 0.8 kg Ge ionization detector at Homestake Mine, SD (adjacent to Ray Davis's operating Solar Neutrino Experiment)

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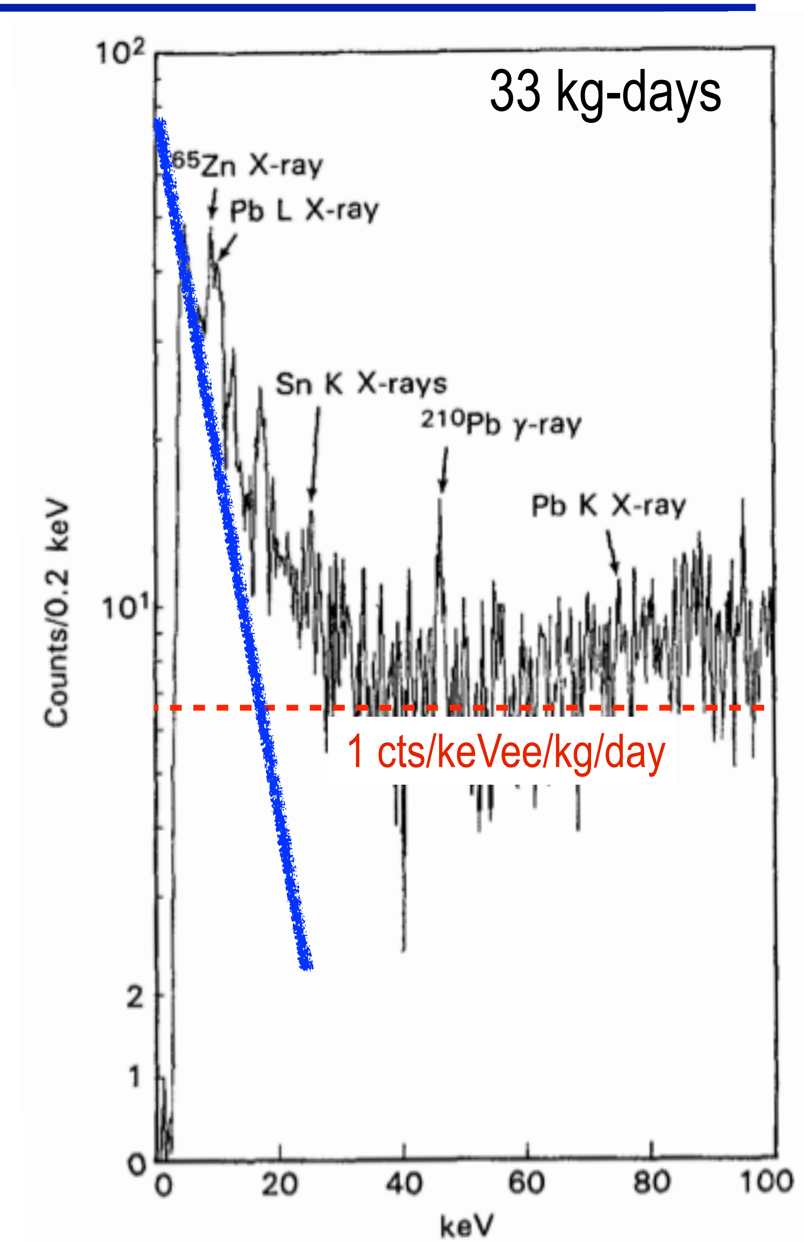
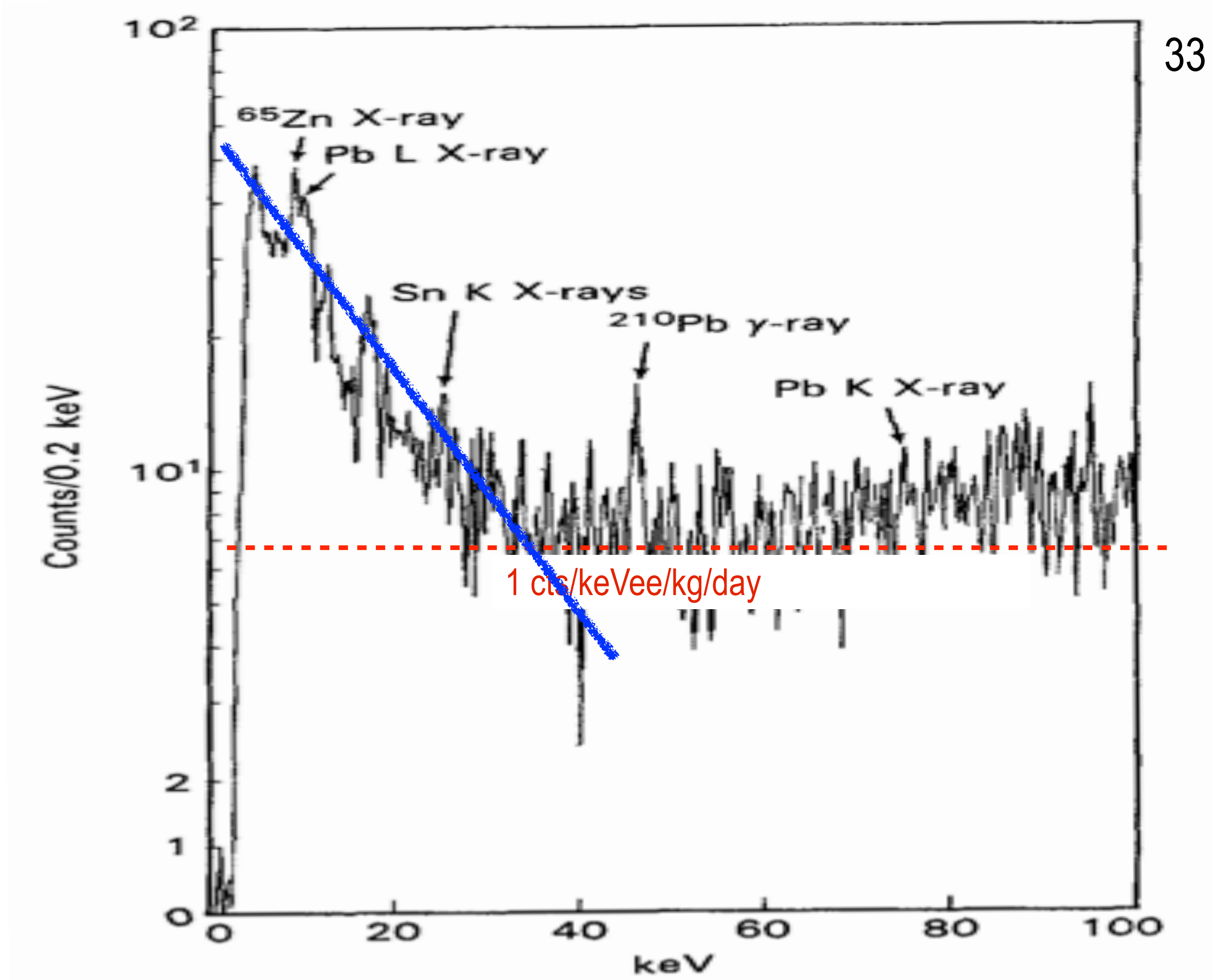
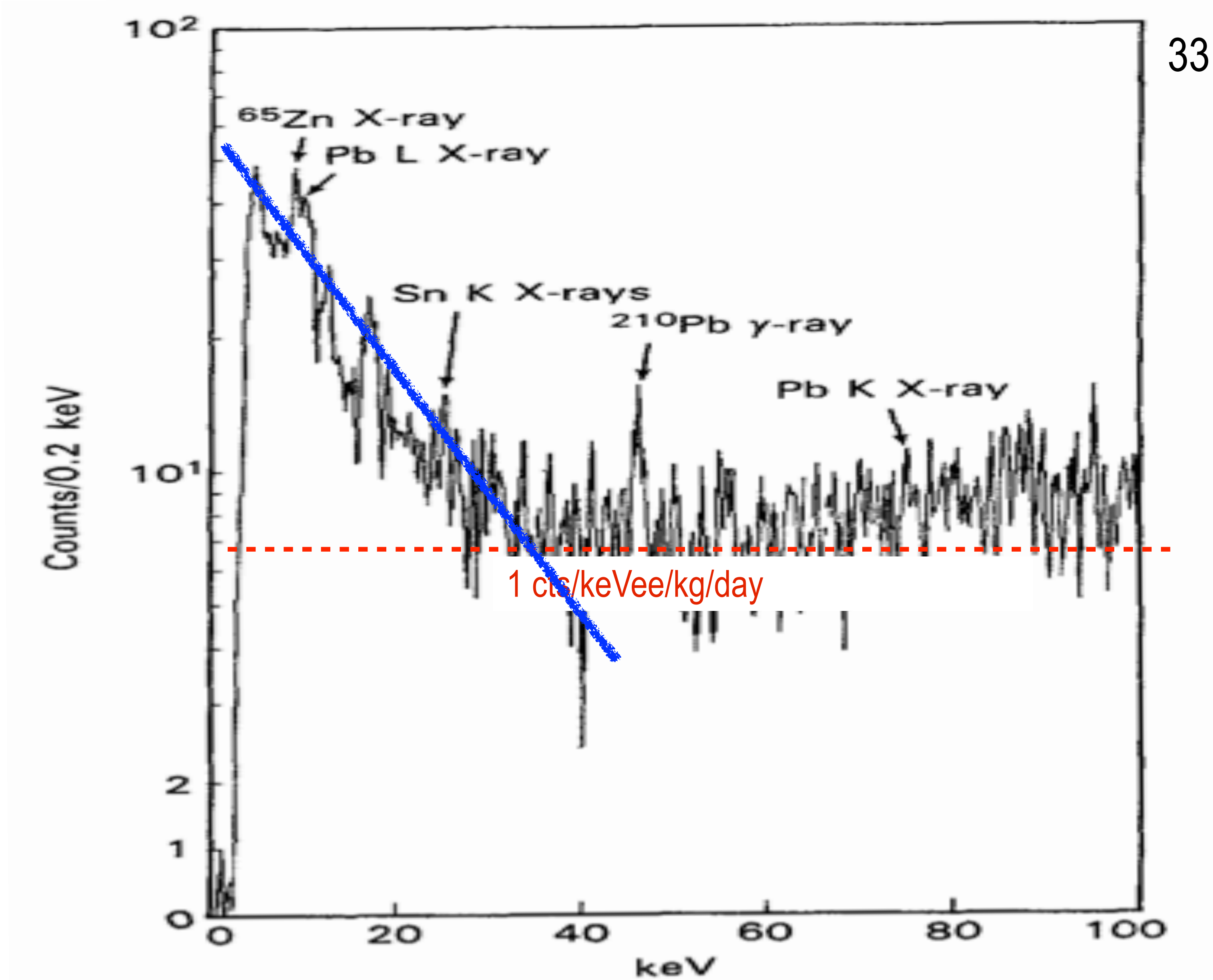


Varying Interaction Cross section



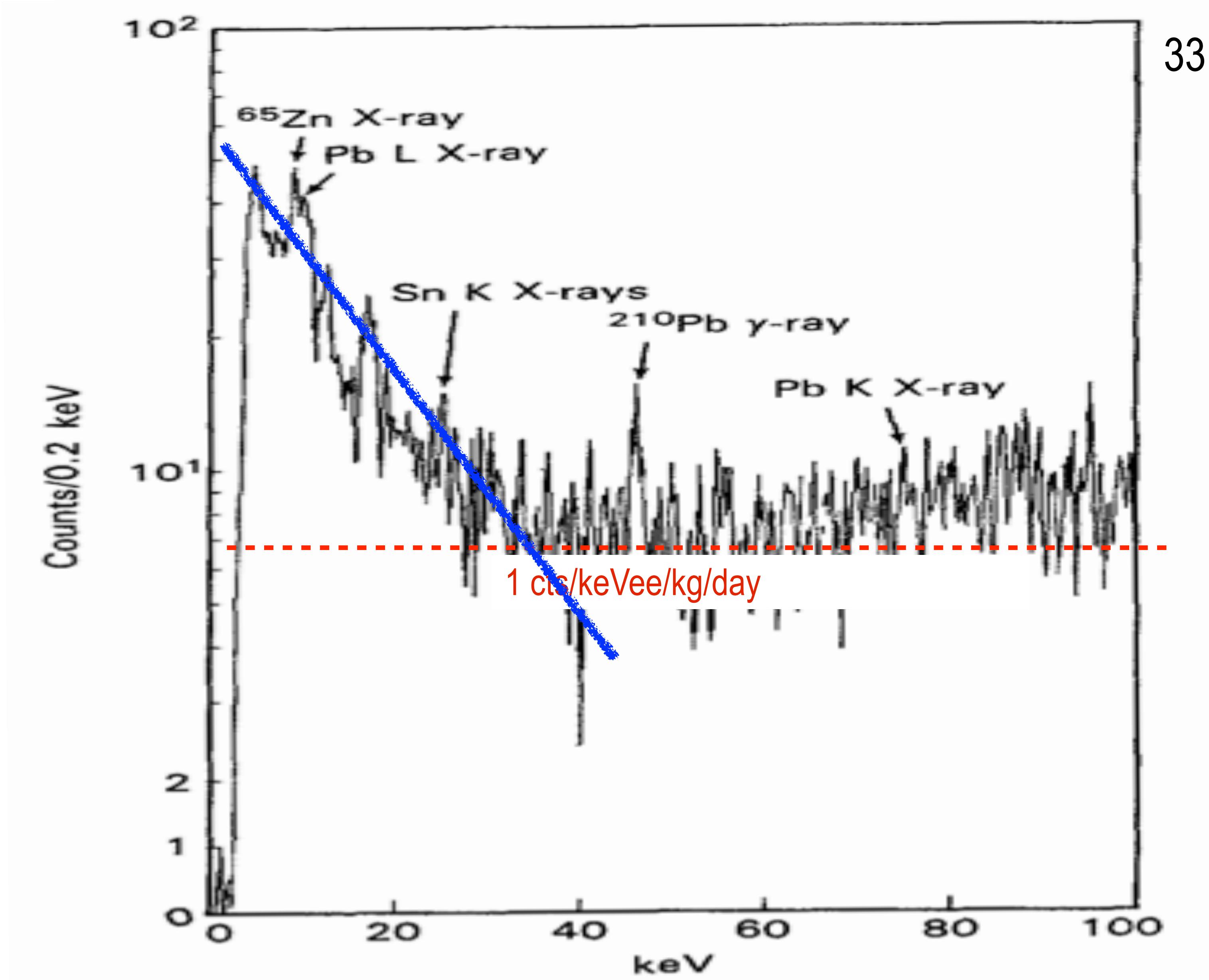
33 kg-days

Decreasing WIMP Mass



33 kg-days

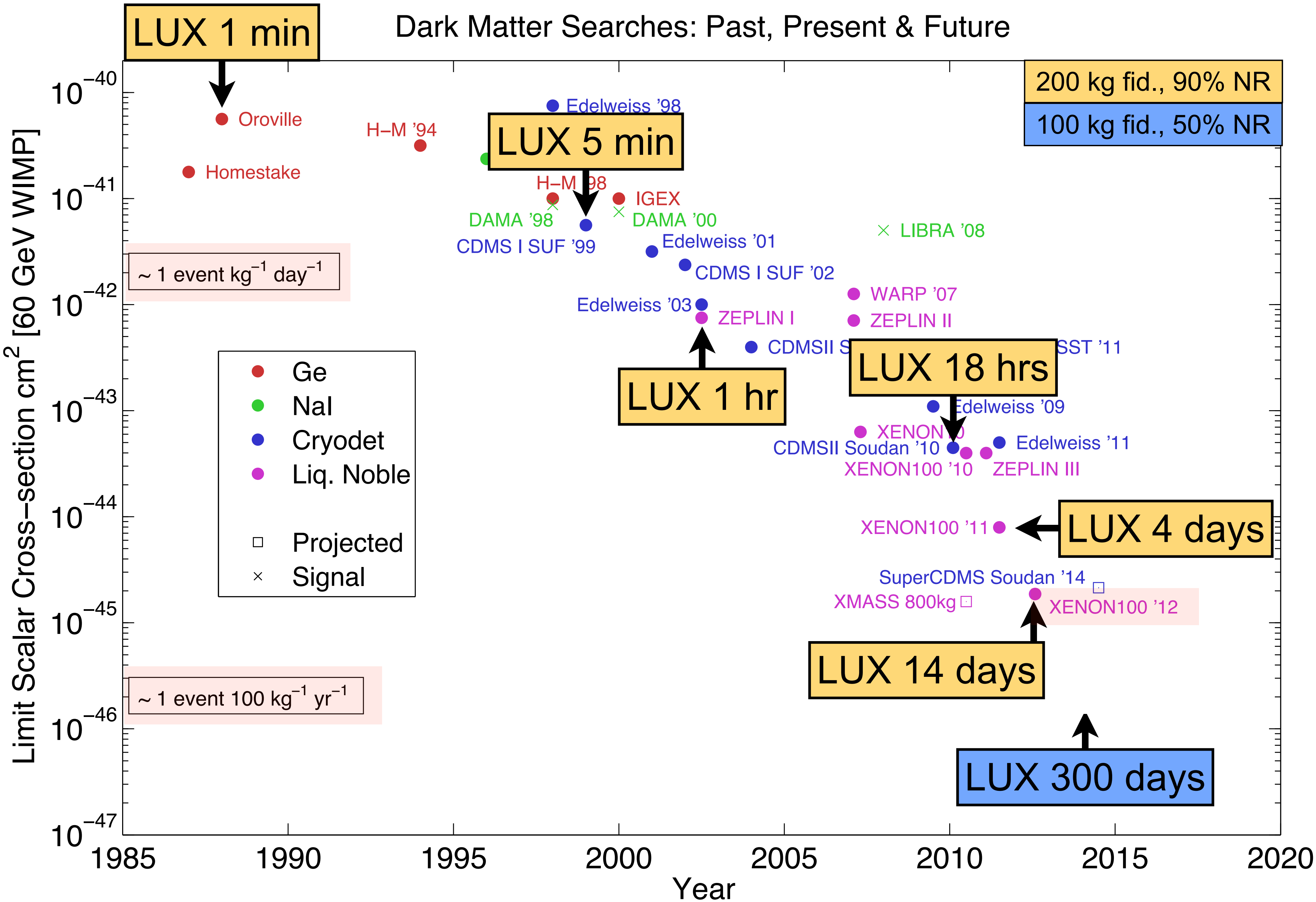
Increasing WIMP Mass



33 kg-days

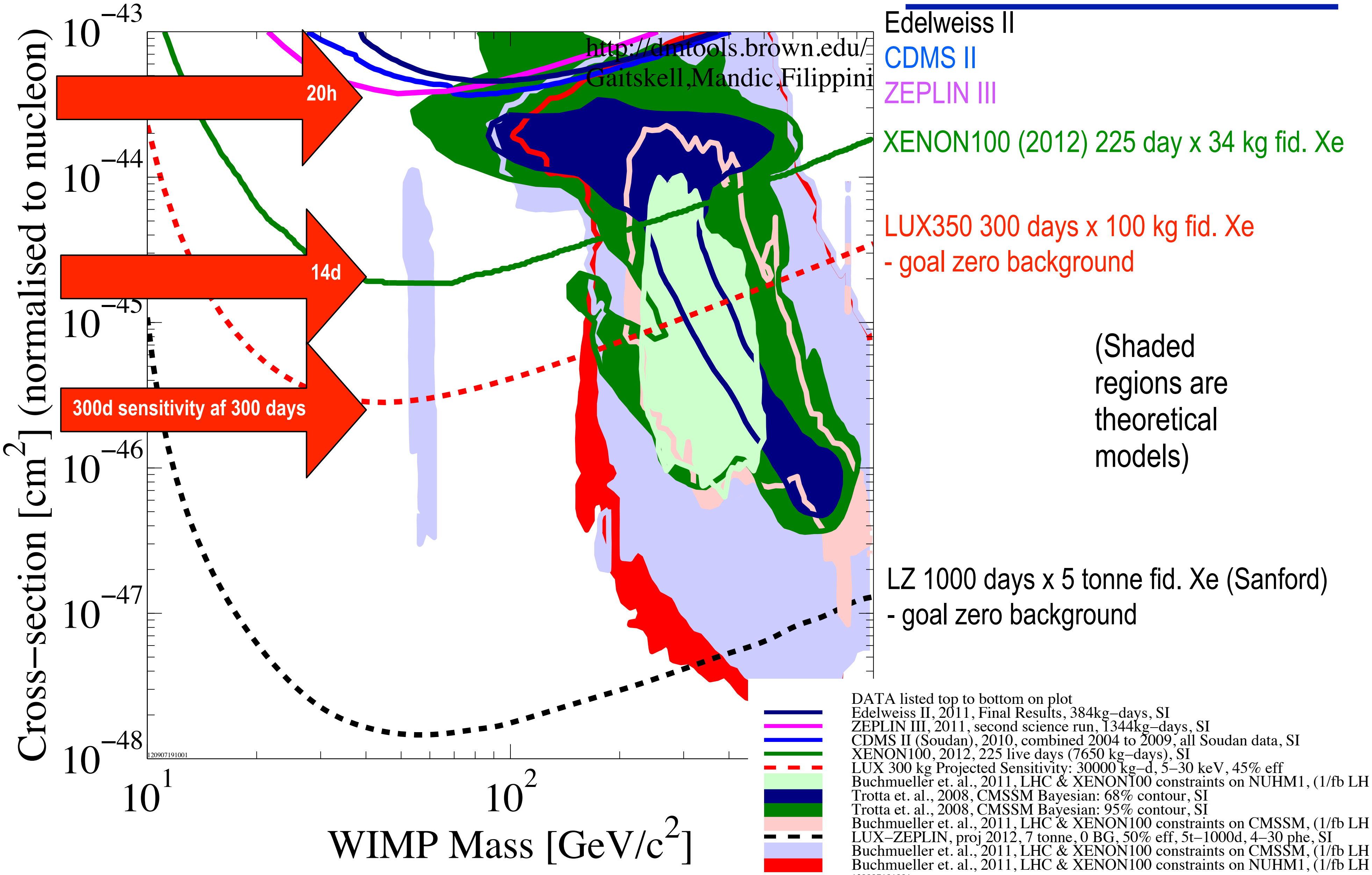
Techniques for dark matter direct detection

TYPE	DISCRIMINATION TECHNIQUE	TYPICAL EXPERIMENT	ADVANTAGE
Ionization	None (Ultra Low BG)	CoGENT, MAJORANA, GERDA	(Searches for ββ-decay, dm additional)
Solid Scintillator	pulse shape discrimination	LIBRA/DAMA, KIMS, DMIce	low threshold, large mass, but poor discrim
Cryogenic	charge/phonon light/phonon	SuperCDMS, CRESST EDELWEISS, EUREKA	demonstrated bkg discrim., low threshold, but smaller mass/higher cost
Liquid noble gas	light pulse shape discrimination, and/or charge/light	ArDM, Darkside, CLEAN, DEAP, LUX, XENON, XMASS, PANDA-X	large mass, good bkg discrimination
Bubble chamber	super-heated bubbles/ droplets	COUPP, PICASSO	large mass, good bkg discrimination
Gas detector	ionization track resolved	DRIFT, NEWAGE, DMTPC, MIMAC	directional sensitivity, good discrimination



Thanks to Carlos Hernandez Faham (Brown) for work on slides

Results (2012) / Sensitivity Curves



LUX Dark Matter Experiment

Rick Gaitskell, Brown University

Background Challenges

- Search sensitivity (low energy region <<100 keV)
  - Current Exp Limit < 1 evt/kg/year, ~< 10^{-3} evt/kg/day
  - Goal < 1 evt/10 tonne/year, ~< 10^{-6} evt/kg/day
- Activity of typical Human?

How Many Gammas/Second?

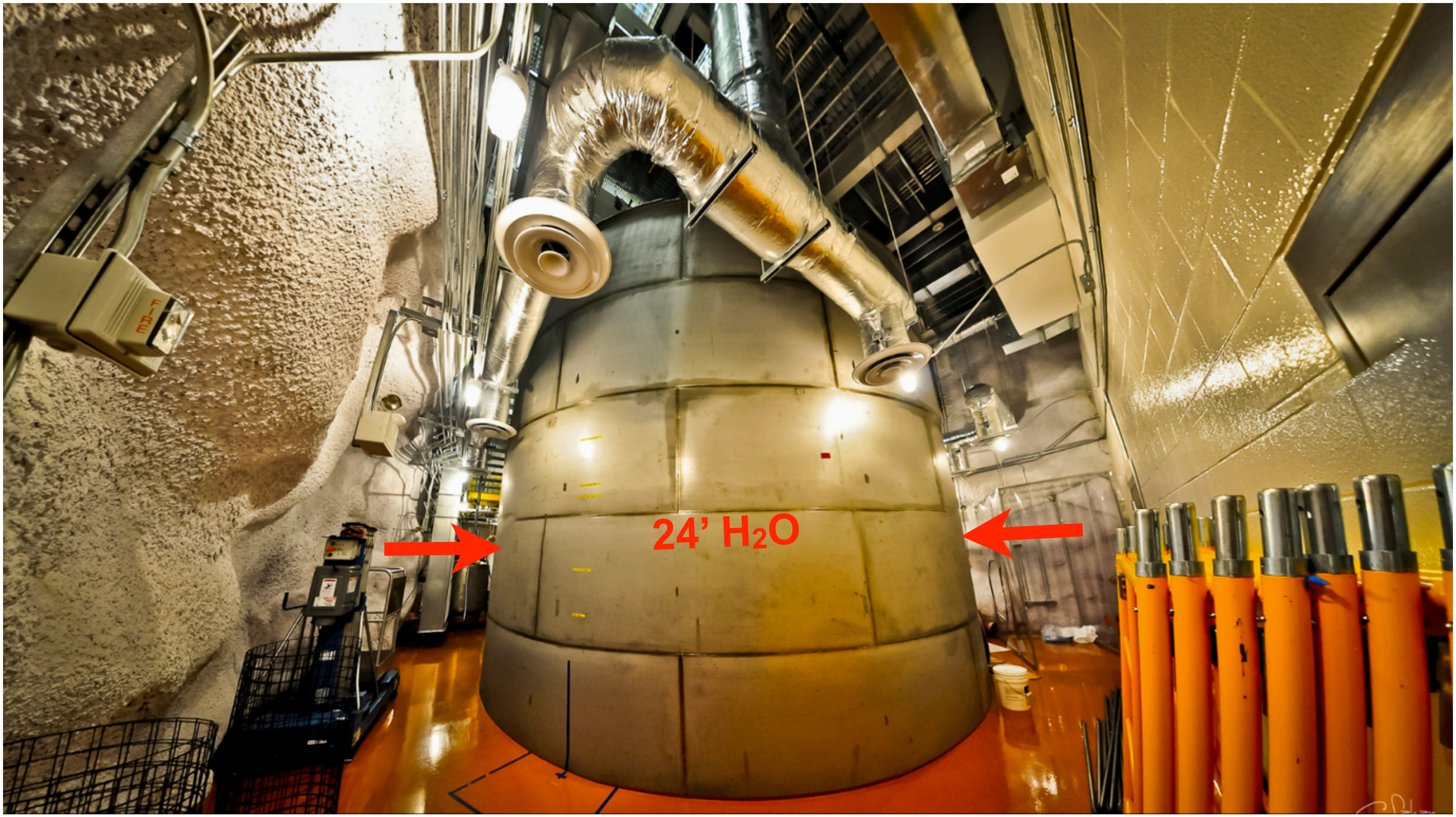
Gaitskell / Brown University

XENON10/100 Shield (Gran Sasso, Italy)

- Uranium
- Thorium
- Potassium-40
- Caesium-137

Gaitskell / Brown University

Ultra High Purity Water Tank at Sanford Lab



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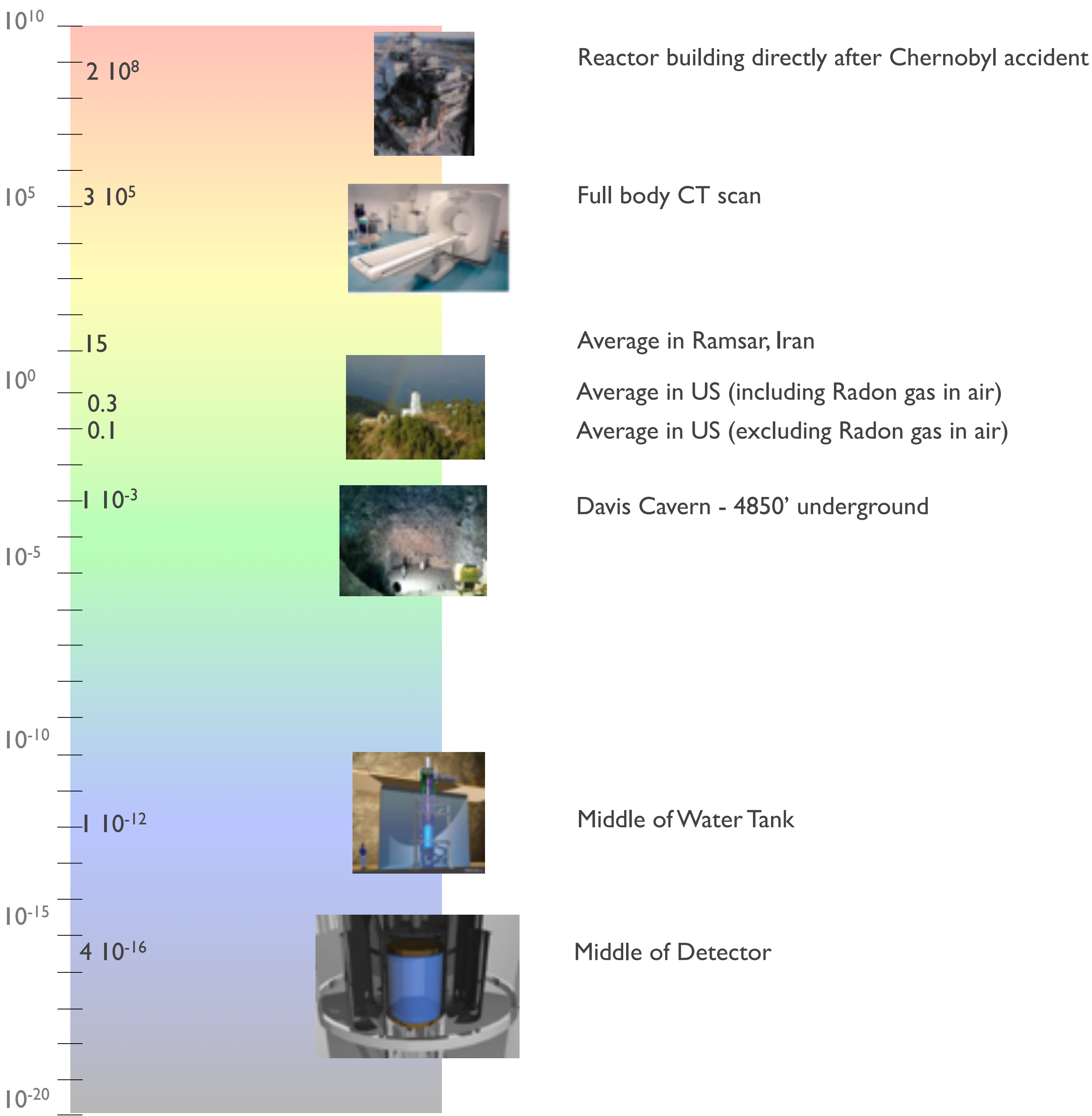
- Activity of typical Human?
- ~10 kBq (10^4 decays per second, 10^9 decays per day)
- Environmental Gamma Activity
  - Unshielded 10^7 evt/kg/day (all values integrated 0–100 keV)
  - This can be easily reduced to ~10^2 evt/kg/day using 25 cm of Pb
- Main technique to date focuses on nuclear vs electron recoil discrimination
  - This is how CDMS experiment went from 10^2 -> 10^{-2} evts/kg/day
  - Continue push for >>99.9999...% rejection e.g. COUPP Bubble Chamber, SuperCDMS
- Further Improvements
  - Reduction in External Gammas: e.g. High Purity Water Shield 4m gives <<1 evt/kg/year
  - Reduction in Gammas from Internal components - goal intrinsic U/Th contamination toward ppt (10^{-12} g/g) levels
  - Detector Target can exploit self shielding for inner fiducial if intrinsic radiopurity is good
- Environmental Neutron Activity / Cosmic Rays => DEEP
  - (α,n) from rock 0.1 cm^{-2} day^{-1}
  - Since <8 MeV use standard moderators (e.g. polyethylene, or water, 0.1x flux per 10 cm)
  - Cosmic Ray Muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate, but are rare and can be actively vetoed
  - Need for depth (DUSEL) - surface muon 1/hand/sec, Homestake 4850 ft 1/hand/month

Effective Radiation Exposure per Hour from Gamma Rays

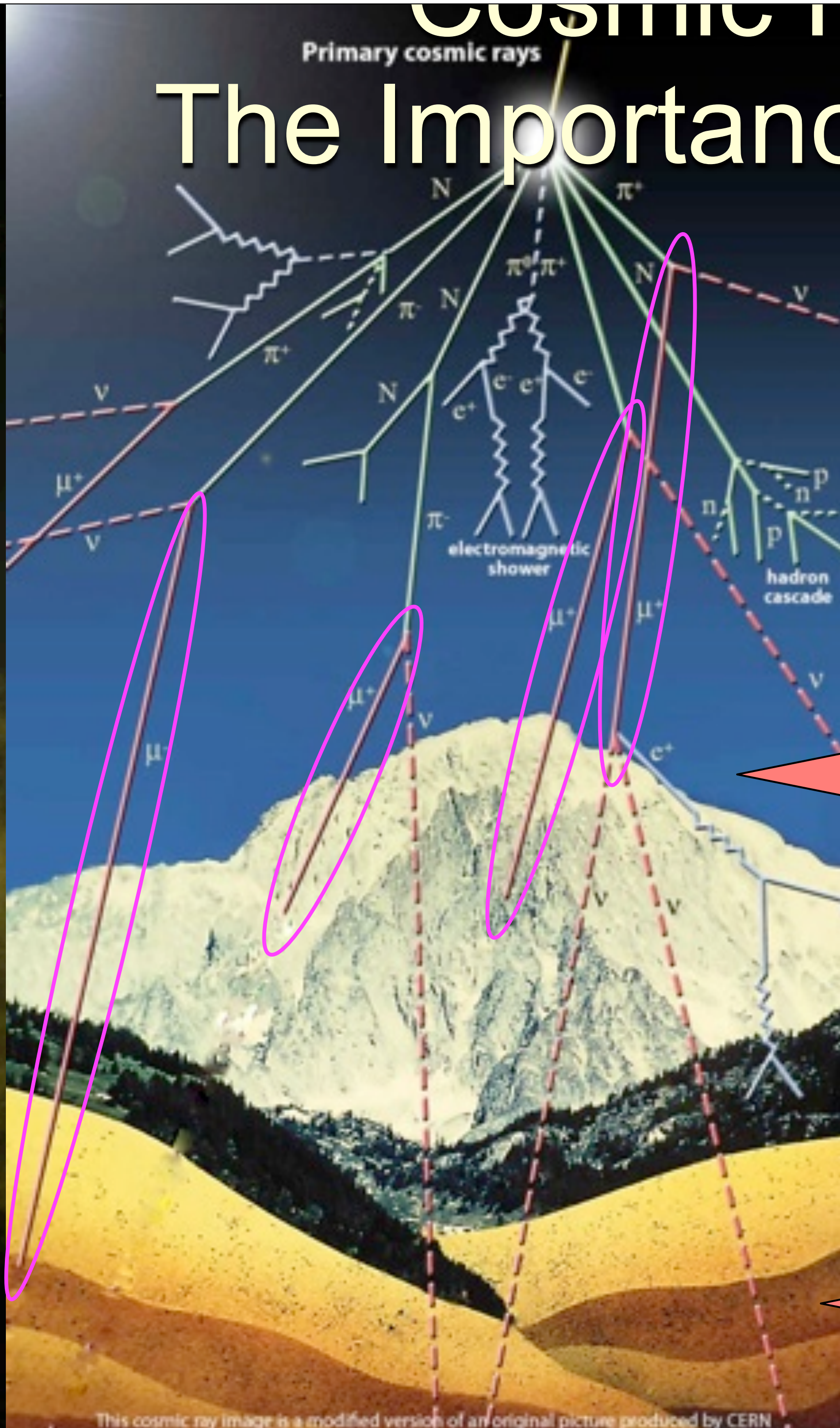


*1 Gy = 1 J/kg = 100 rad

COSMIC RAYS

I mile down

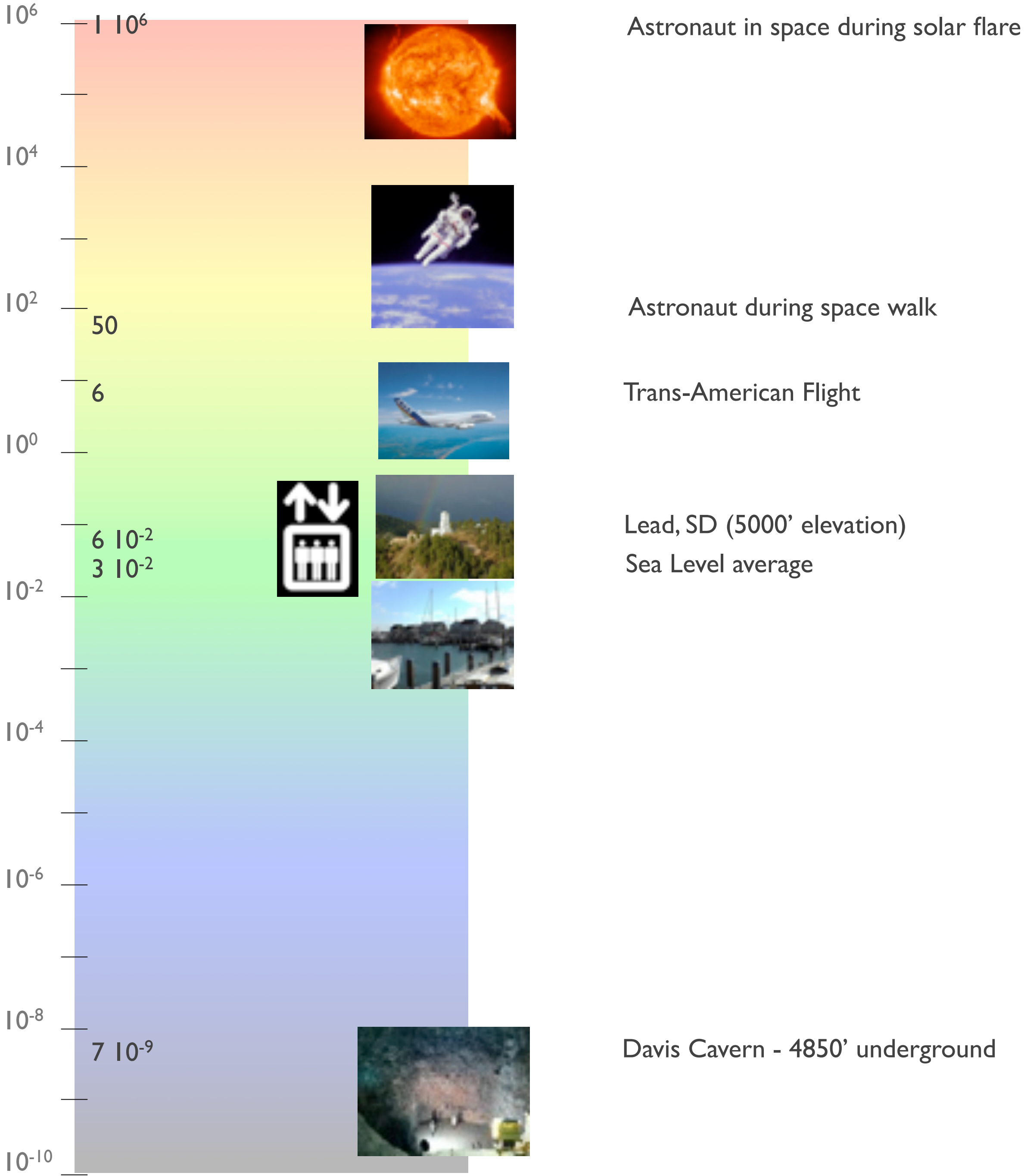
Cosmic Rays - The Importance of Depth



At the earth's surface cosmic ray muons pass through your hand at more than 1 every second

At a depth of 4850 ft underground in Sanford Lab, the rock overburden reduces the flux of cosmic muons through your hand to around 1 per year

Effective Radiation Exposure per Hour from Cosmic Rays



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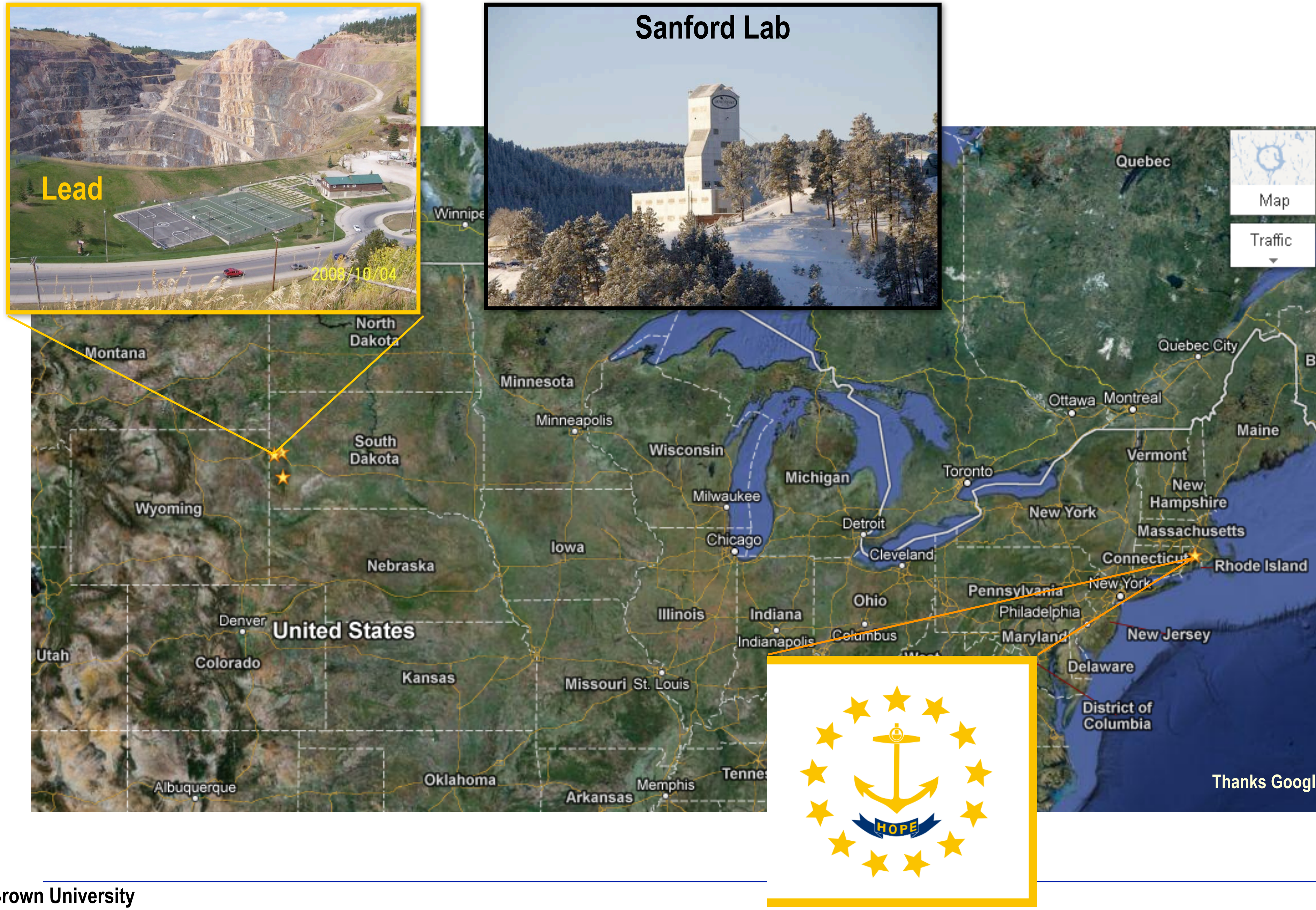
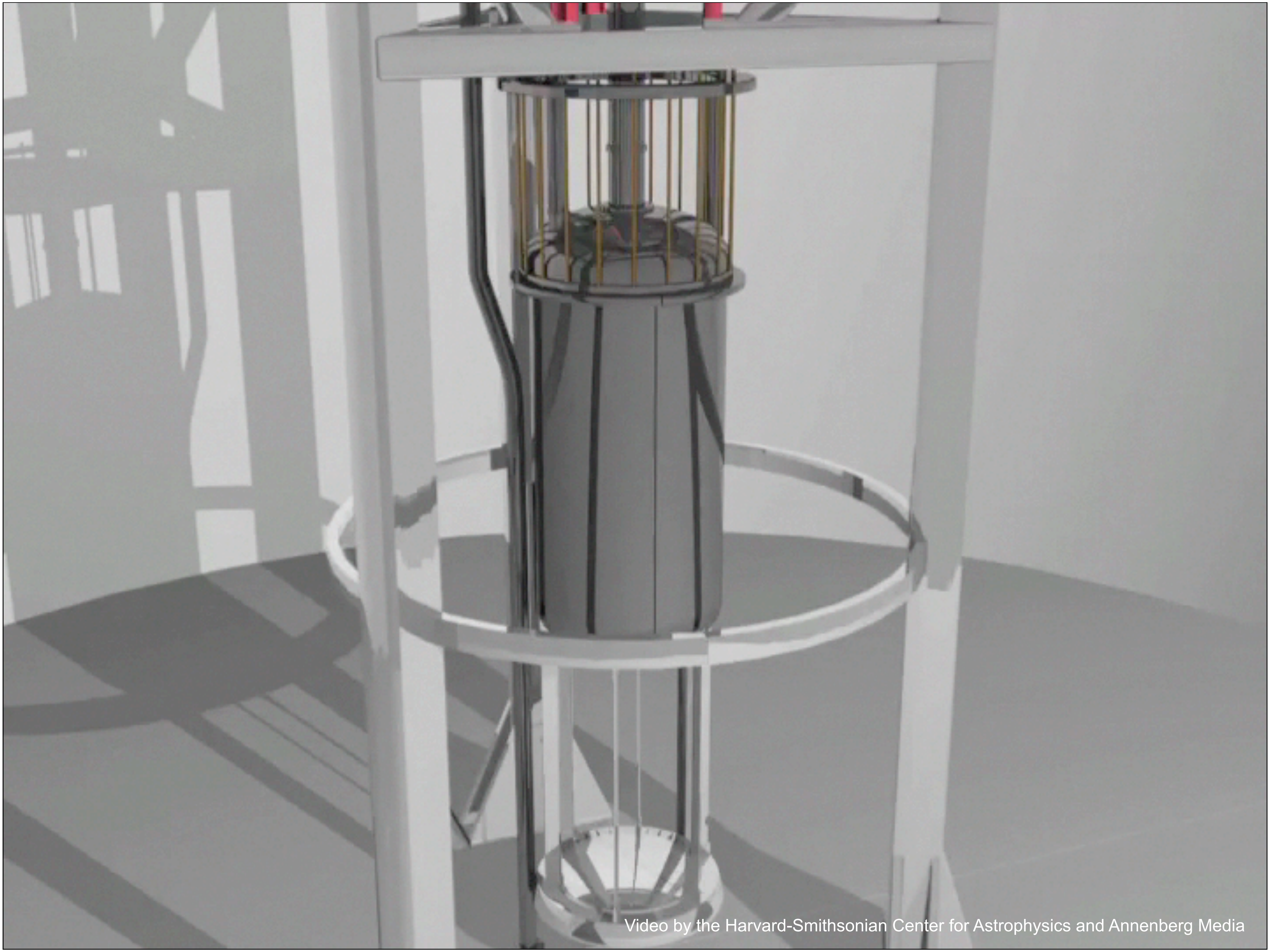
Many International Efforts

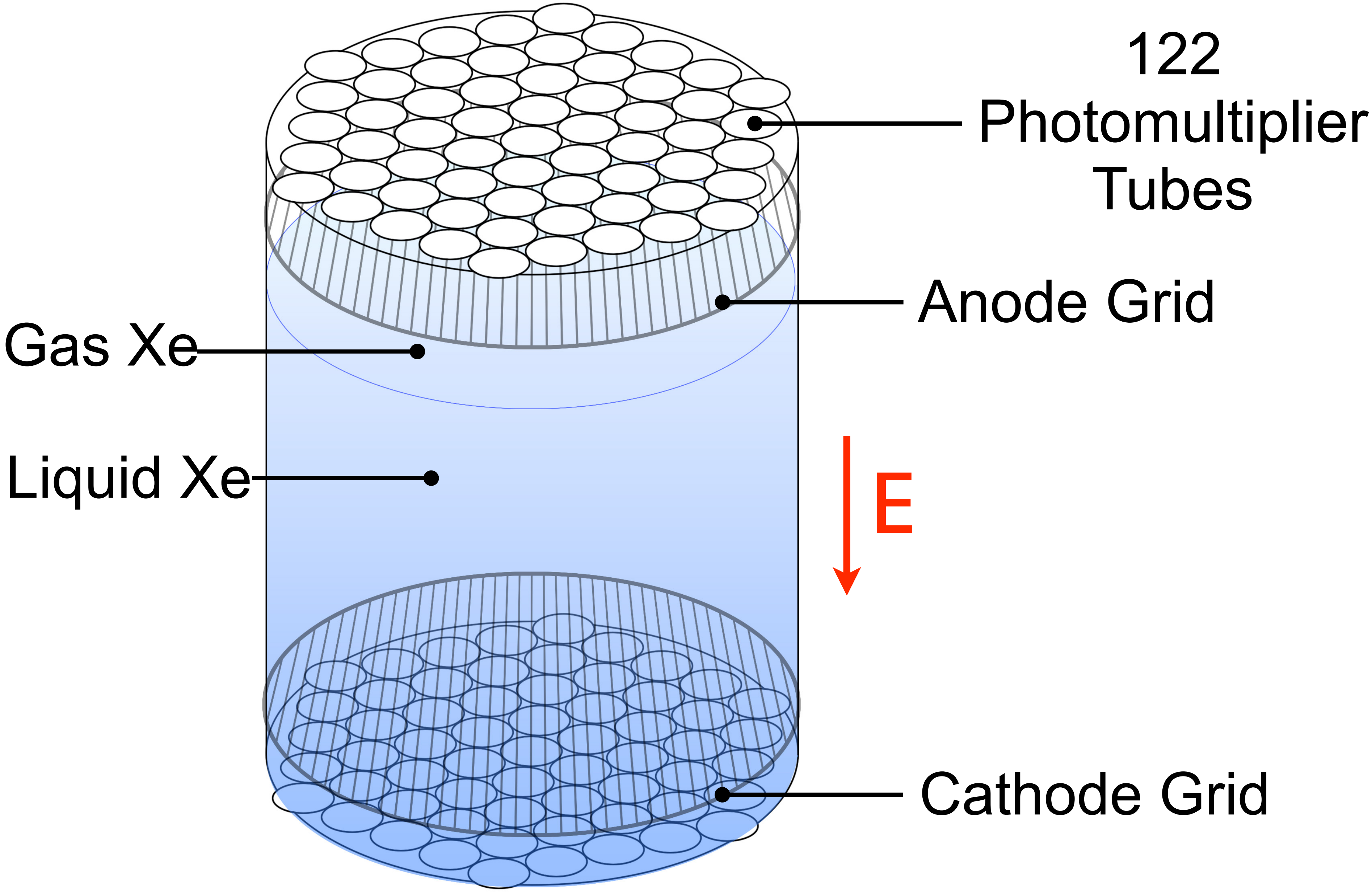
The Sanford Laboratory at Homestake

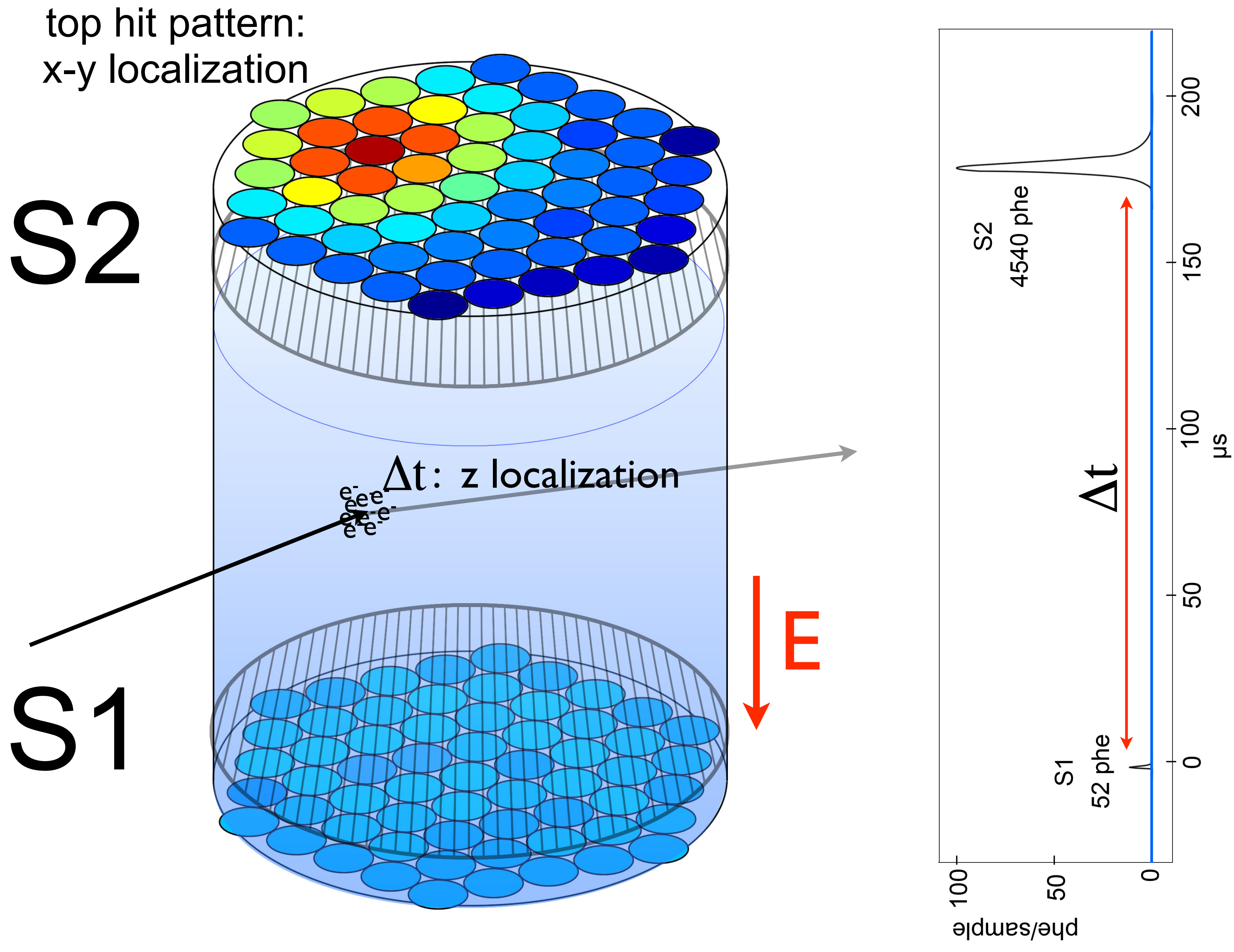



LUX @ Sanford Lab,
Homestake Mine, South Dakota

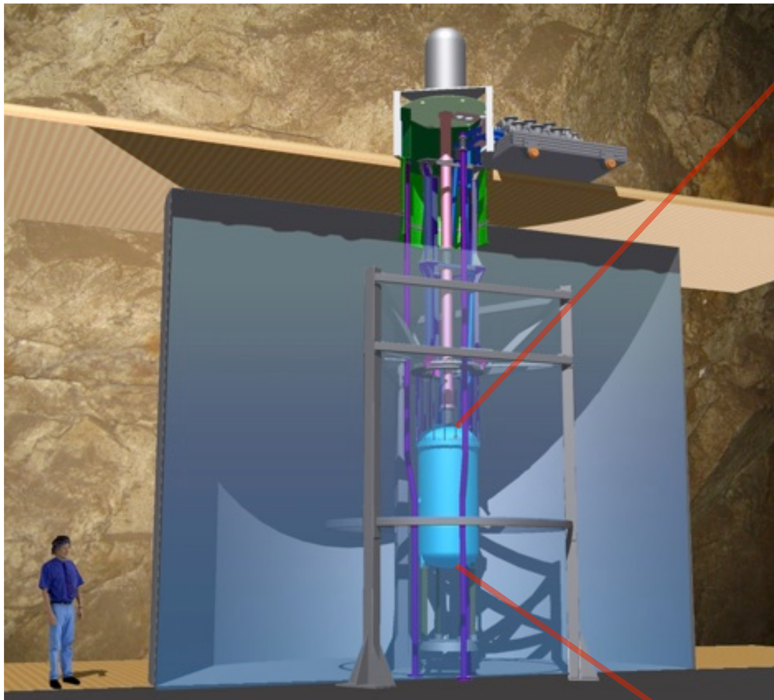
LUX @ Sanford Lab

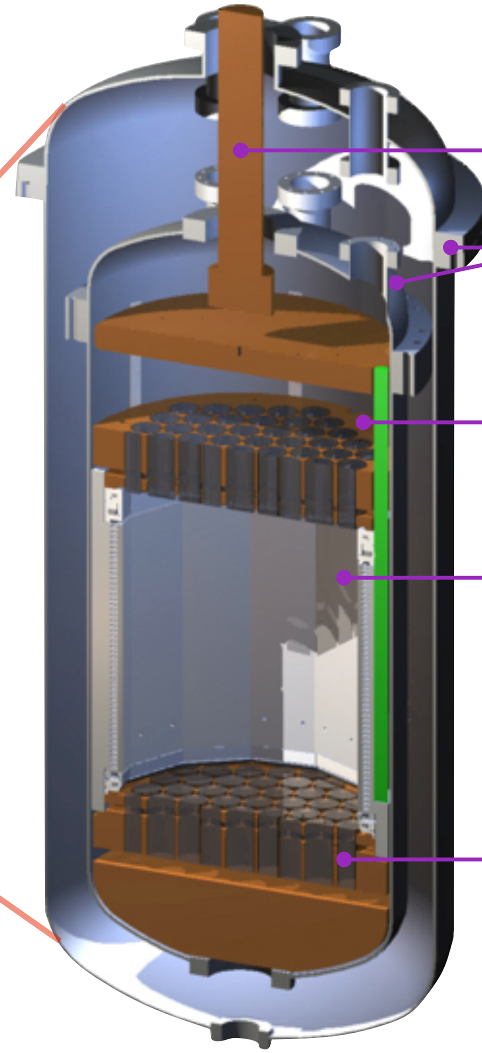

Video by the Harvard-Smithsonian Center for Astrophysics and Annenberg Media

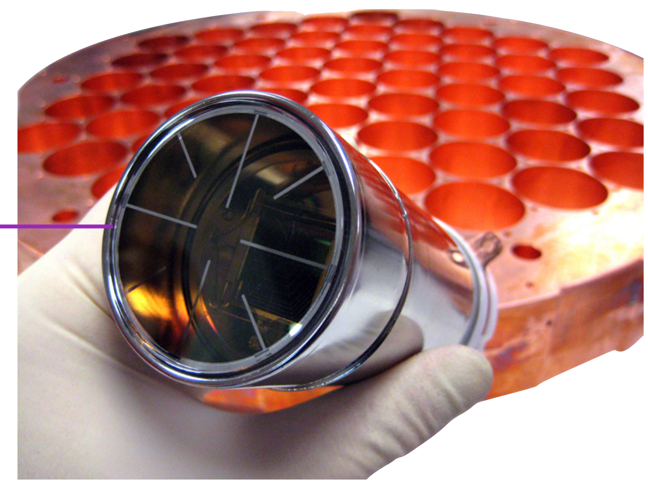

122
Photomultiplier
Tubes
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid


top hit pattern:
x-y localization
S2
S1
Δt : z localization
e-
E
S2
4540 phe
S1
52 phe
Δt
μs
phe/sample
0
50
100
150
200

LUX Anatomy





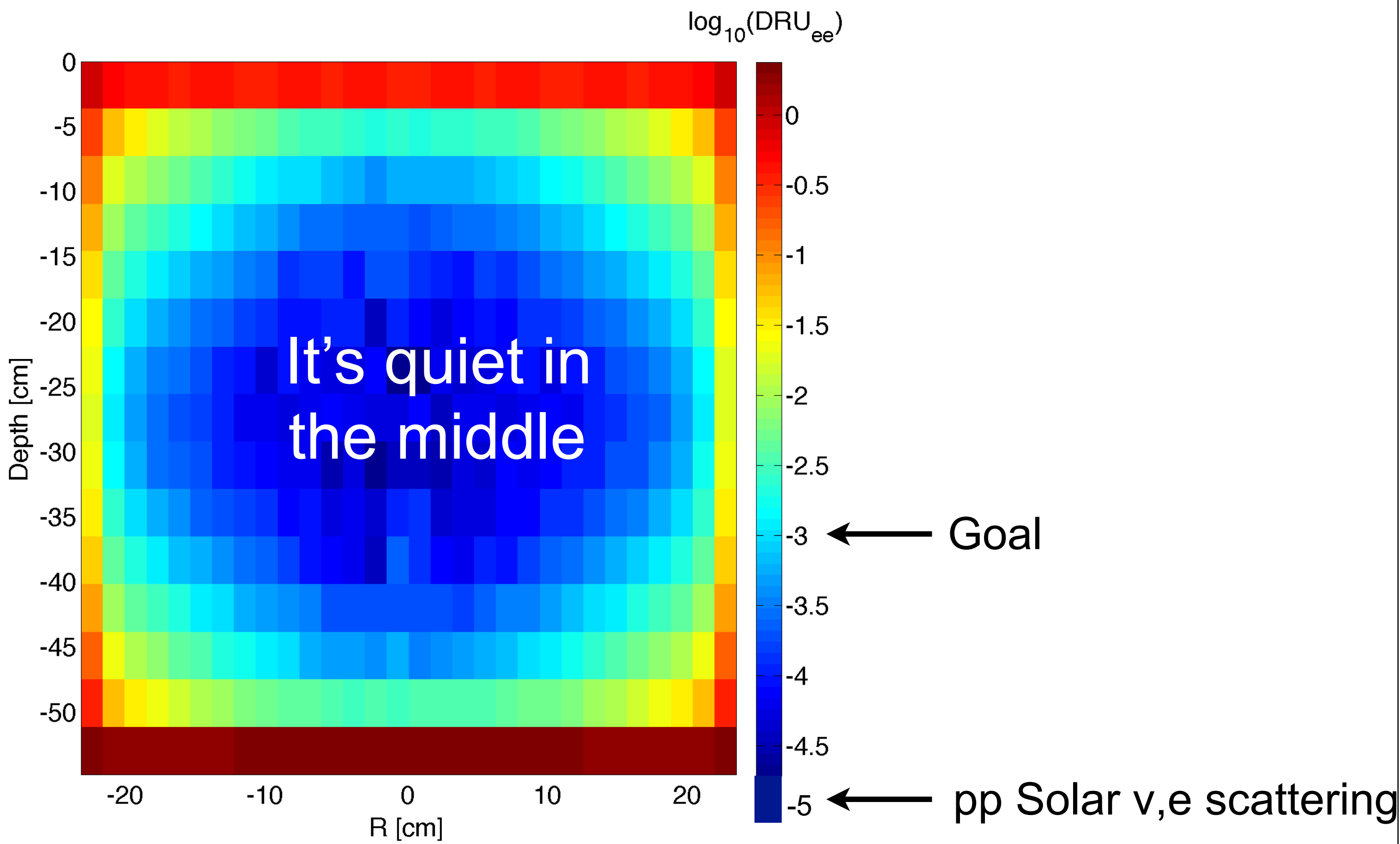


2” Hamamatsu R8778
Photomultiplier Tubes (PMTs)

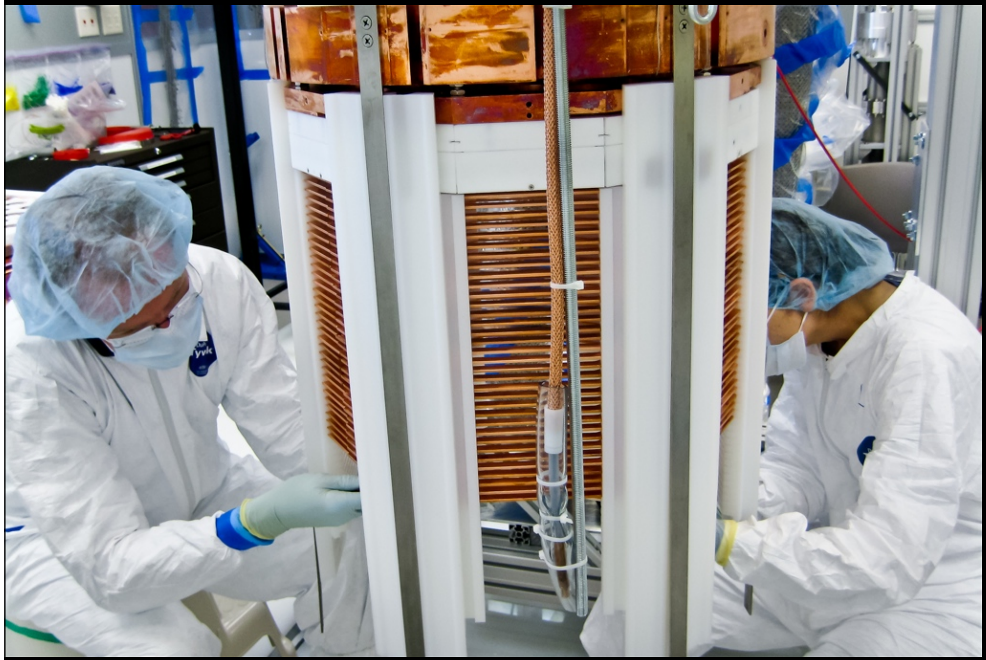
- 370 kg (300 kg active) LXe
- 122 PMTs (2” round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)

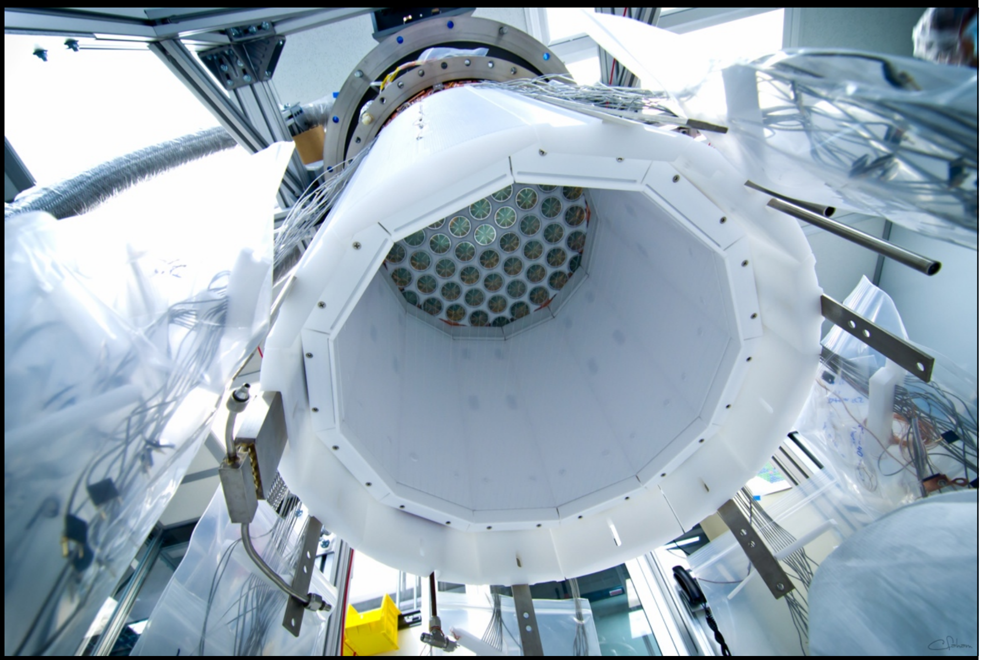
Xenon Self-shielding

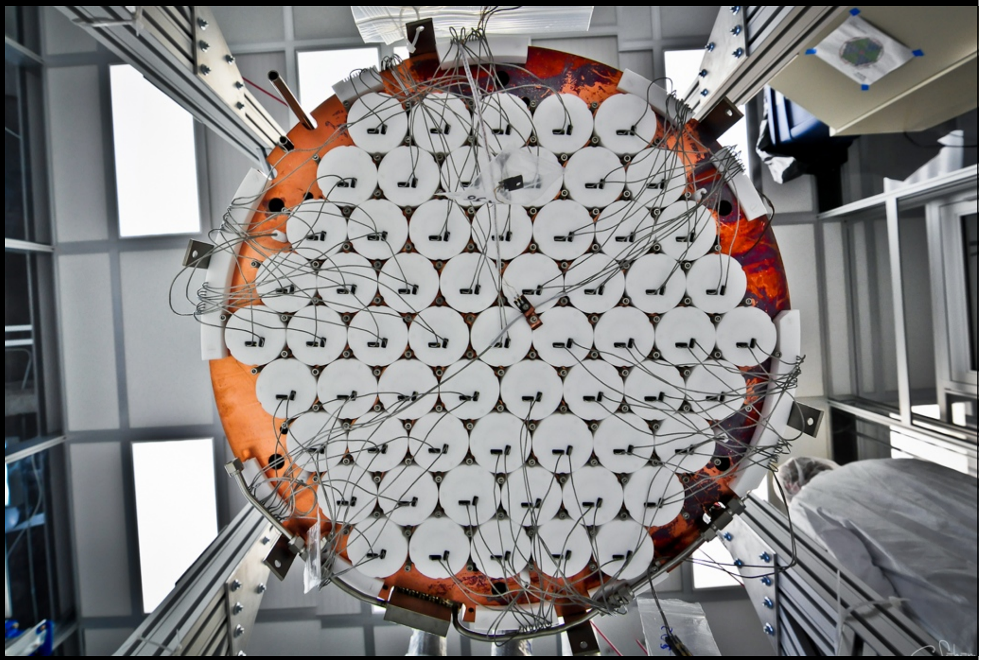
Single Scatter Events /keVee/kg/day



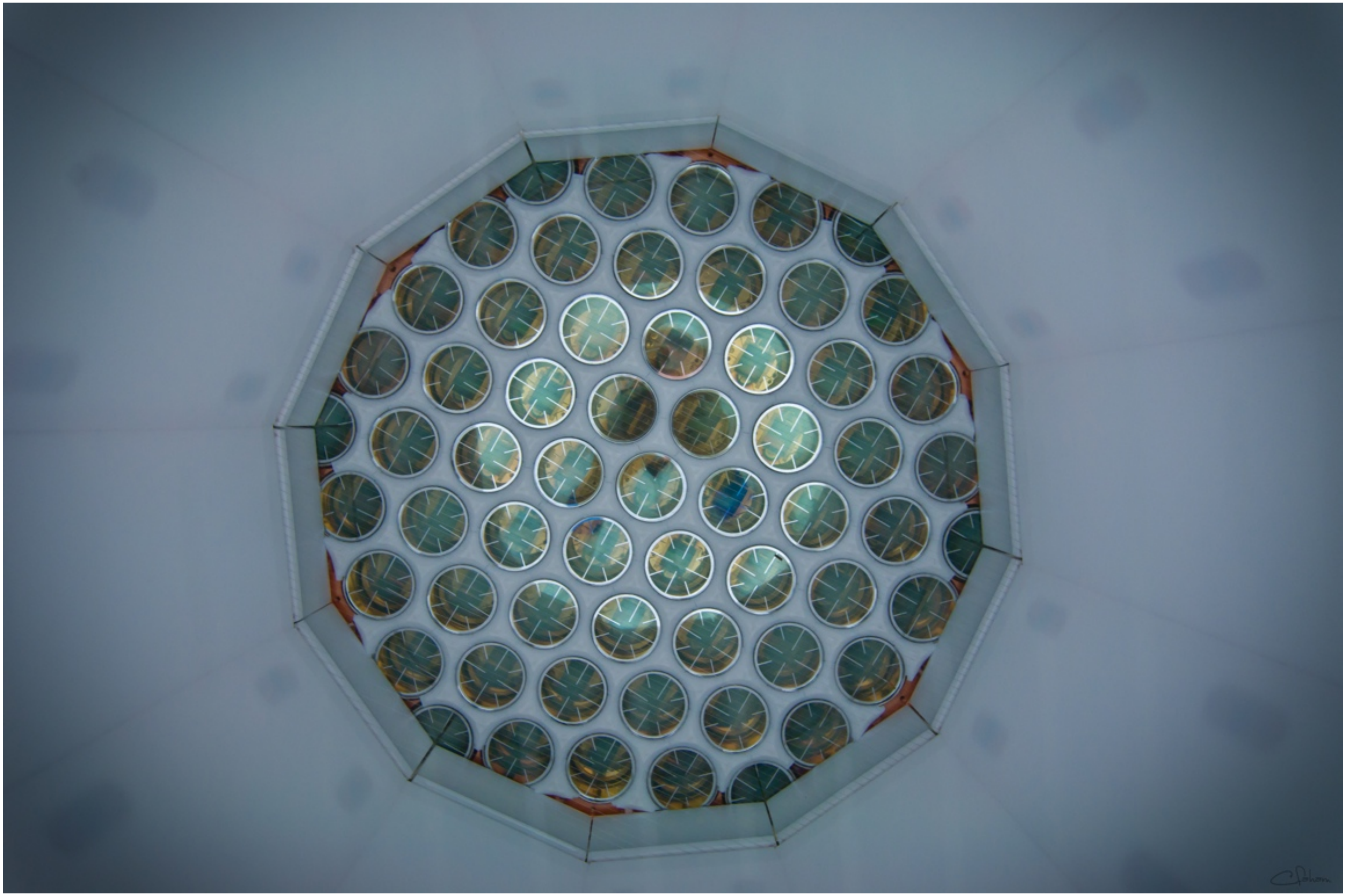
- Liquid xenon is a dense target at 3 g/cc.
- Self-shielding allows this technology to greatly benefit from scaling up.
- We expect ~1 ER in the fiducial volume/dm energy range every 4 days in LUX.



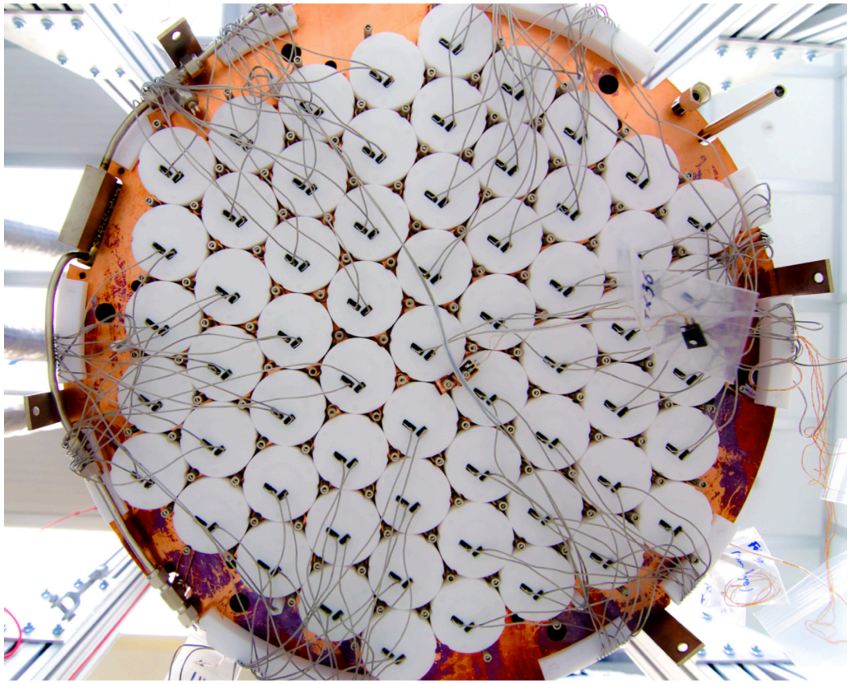


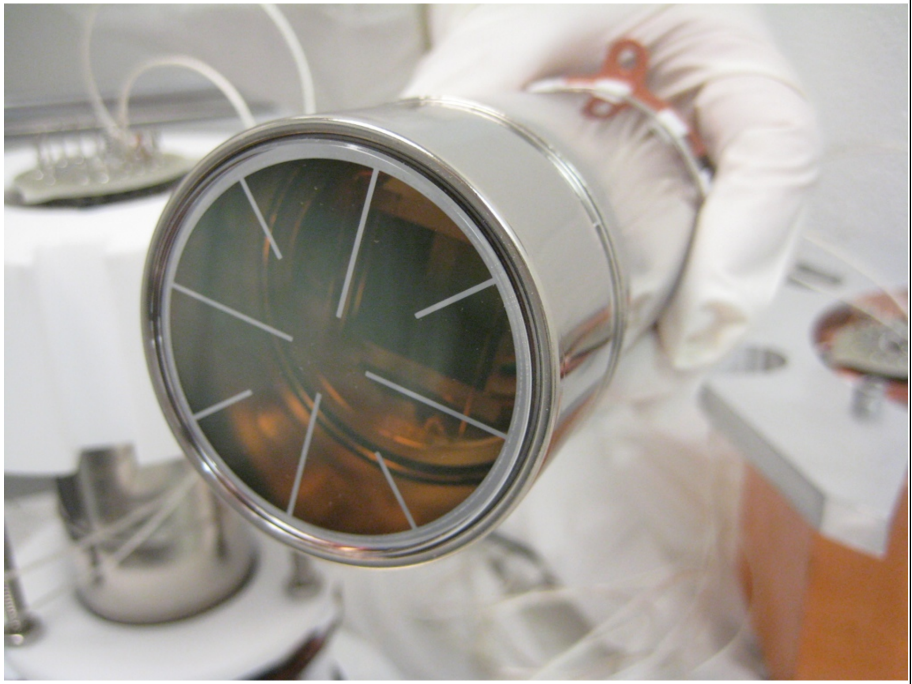


WIMP's eye view



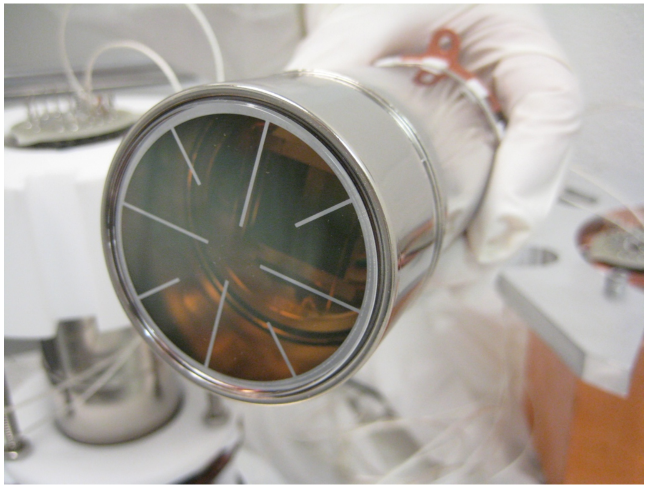
PMTs

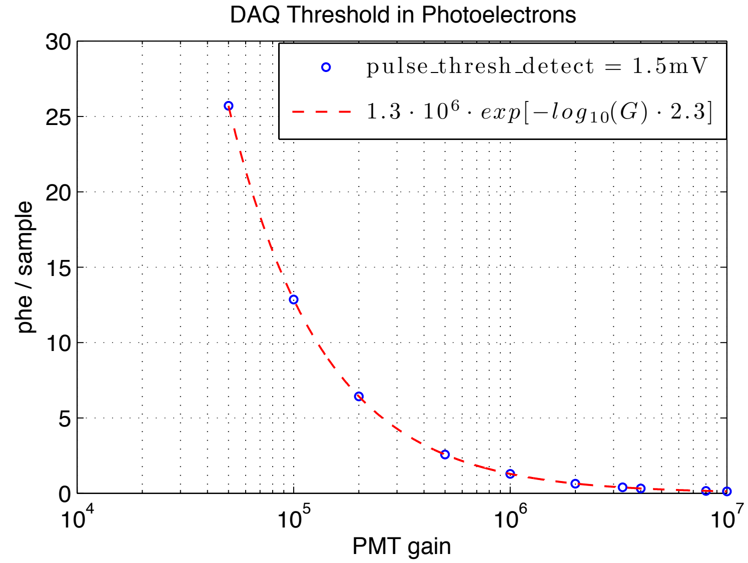


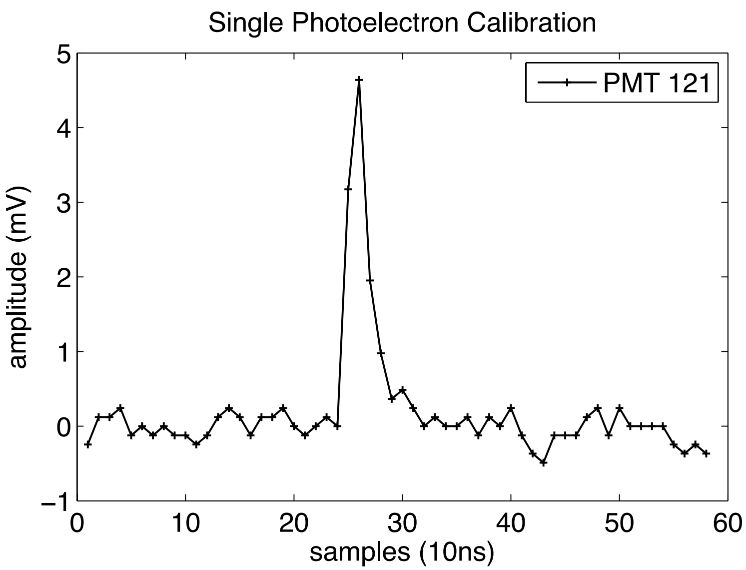


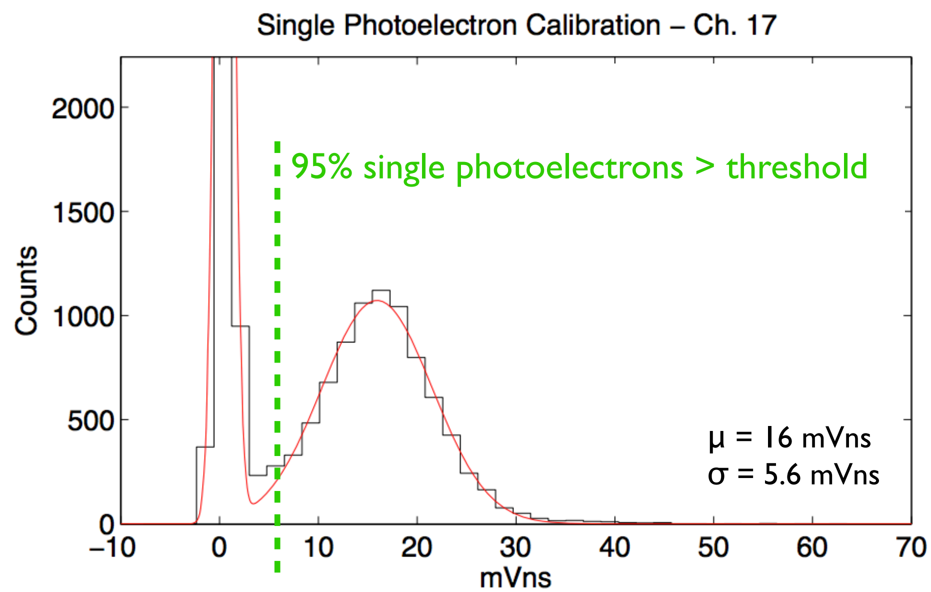
- Hamamatsu R8778
- 2 inch diameter
- Average QE of 33%
- Nominal gain of 4e6
- Ultra-low bg (12mBq/PMT)

Threshold

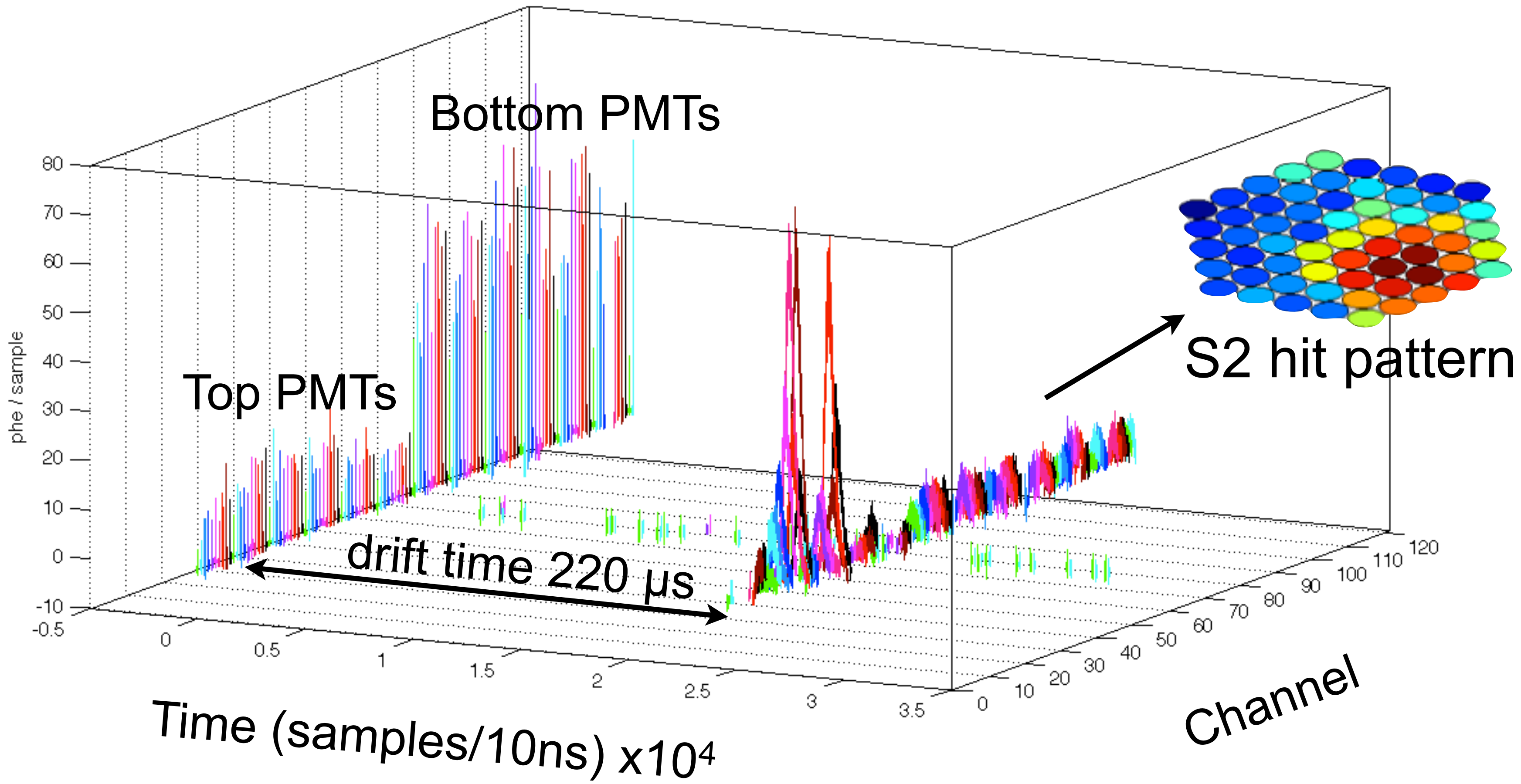



DAQ Threshold in Photoelectrons
pulse_thresh_detect = 1.5mV
$1.3 \cdot 10^6 \cdot exp[-log_{10}(G) \cdot 2.3]$
phe / sample
PMT gain
30
25
20
15
10
5
0
10^4
10^5
10^6
10^7

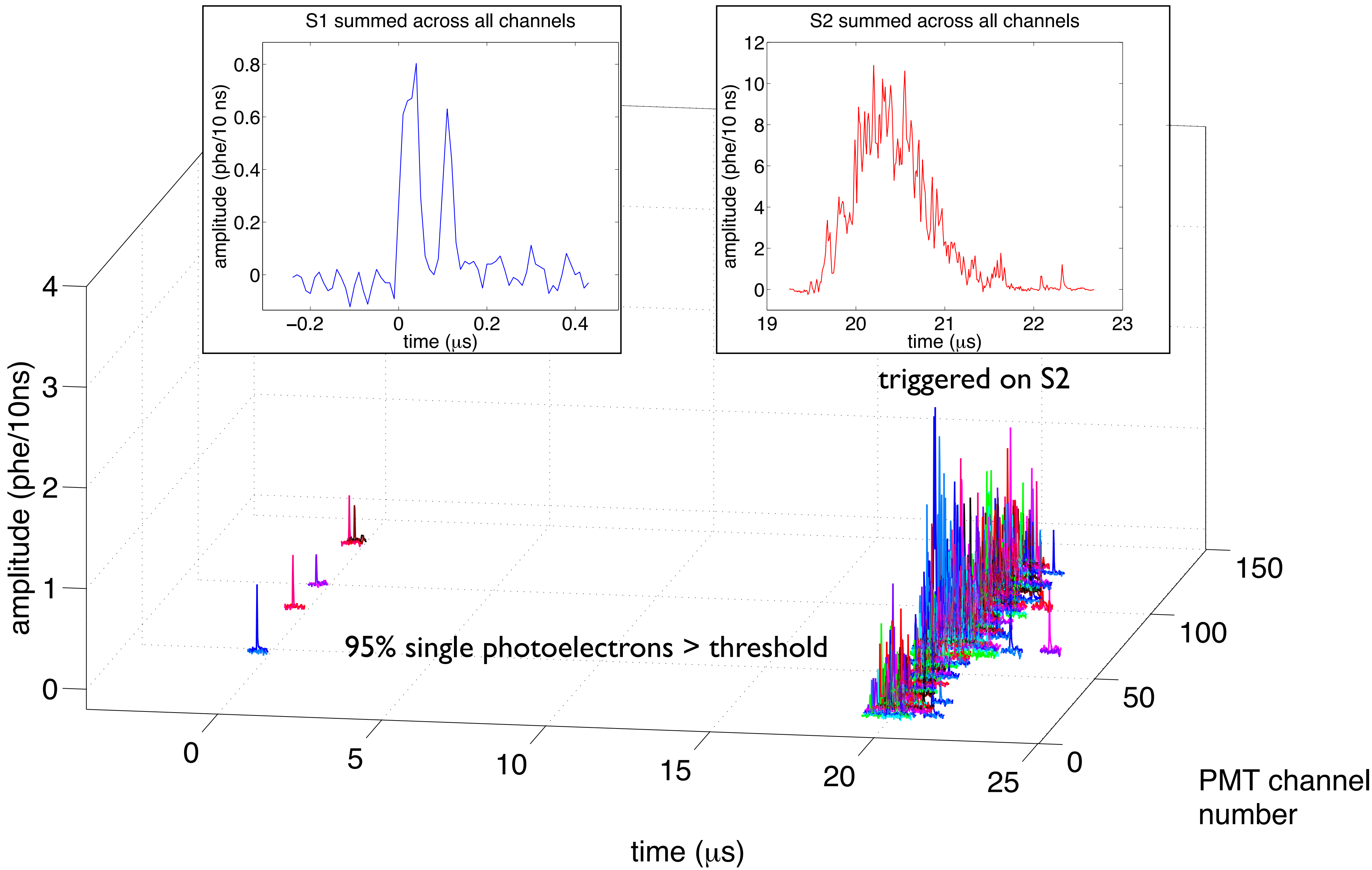

Single Photoelectron Calibration
PMT 121
amplitude (mV)
samples (10ns)
5
4
3
2
1
0
−1
0
10
20
30
40
50
60


Single Photoelectron Calibration – Ch. 17
95% single photoelectrons > threshold
μ = 16 mVns
σ = 5.6 mVns
Counts
mVns
2000
1500
1000
500
0
−10
0
10
20
30
40
50
60
70

Example of alpha particle in middle of LUX detector



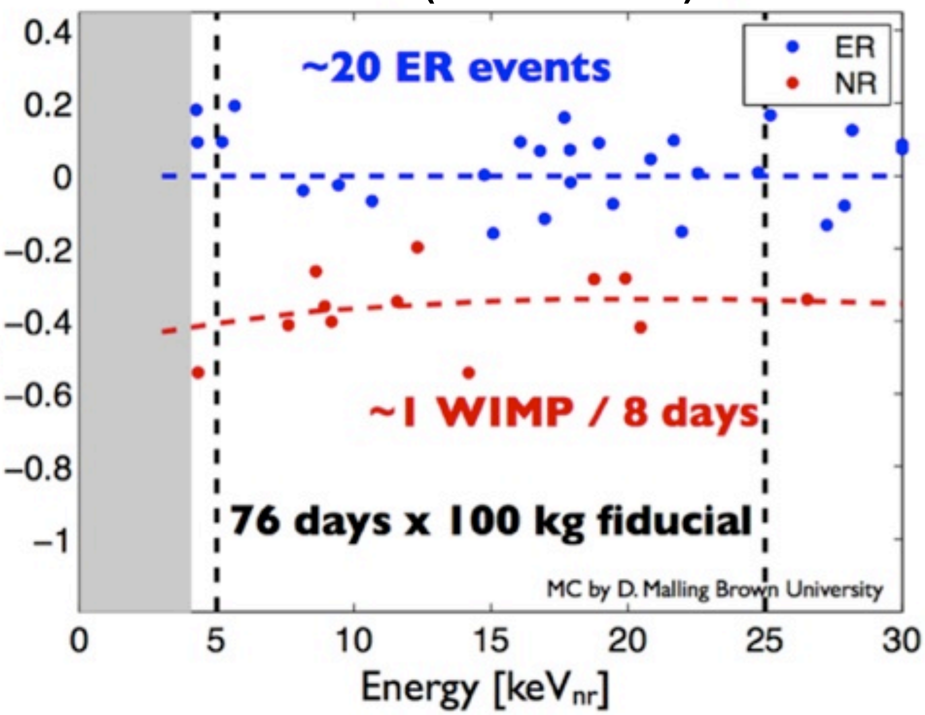
1.5 keV Compton Scatter



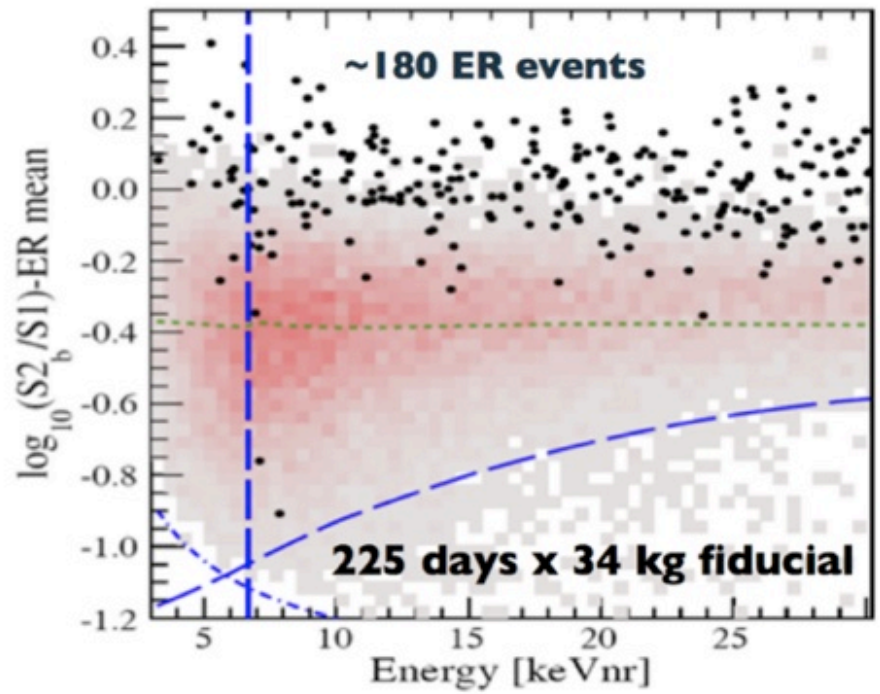
The first 76 days of LUX

Comparing nominally equivalent kg-days for 100 kg LUX fiducial versus 34 kg XENON fiducial but LUX has much greater sensitivity/kg-day because of cleaner signal/fewer BG events

LUX (Monte Carlo)



XENON100



arXiv:1104.2549

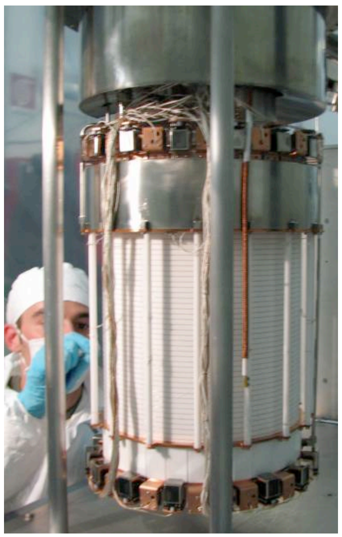
LUX signal and background expectation for 7,600 kg-days net exposure. WIMP events assume m = 100 GeV, σ = 3×10^{-45} cm^2. Assumes 100 kg fiducial. Given very low ER rate, can significantly increase fiducial in early running.

XENON100 7,600 kg-days result for comparison. Note higher ER rate - ~180 events primarily due to Compton scattering of external gamma background.

LUX Conclusion

- LUX detector moved from surface lab to deep underground lab @ Sanford July 2012
  - All detector/safety system commissioned and checkouts passed
  - Water shield / Muon veto - filled and operational
  - Experiment is working closely with Sanford Lab personnel who are focused on science mission
- Feb 2013: Detector Cooled Down and Xe Condensation
  - Successfully cooled and started operations using 370 kg liquid Xe target
- During 2013
  - Full checkout of all systems cold / circulation - achieve purity (collection of S2 throughout volume)
  - Multiple calibrations to establish detector response at low energy
  - During <u>this year we will conduct and report on the results from a 2+ month run looking for dark matter events</u>
- Ultimate Science Goal for LUX is to take 1 year of WIMP search data
  - Expect to continue LUX data-taking in 2014 and 2015

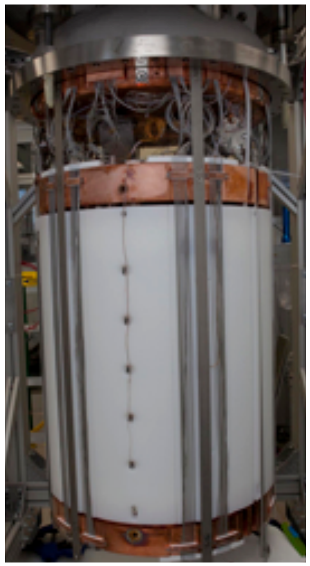
Liquid xenon and liquid argon TPCs



XENON100 at LNGS:

in conventional shield
161 kg LXe (~50 kg fiducial), 242 PMTs

in DM search



LUX at SURF:

in water Cherenkov shield
300 kg LXe (100 kg fiducial), 122 PMTs

in operation

PandaX at CJPL:

in conventional shield:
123 kg LXe (25 kg fiducial), 180 PMTs

in commissioning

ArDM at Canfranc:

in conventional shield
850 kg LAr
2 arrays of PMTs

in commissioning

DarkSide at LNGS

in liquid scintillator and water shield

50 kg LAr (depleted in 39Ar)

in commissioning

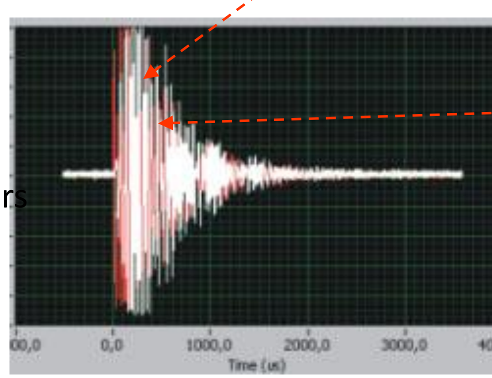
(thanks to Nigel J.T. Smith, SNOLab)

PICASSO Technique

- 150 μm droplets of C_4F_{10} dispersed in polymerised gel *
- Droplets superheated at ambient T & P (T_b= - 1.7 °C)
- Radiation triggers phase transition
- Events recorded by piezo-electric transducers
- Operating temperature determines energy threshold

Main attractive features:

- **low threshold $45^{O}C \rightarrow E_{th}$ = 2 keV**
- **inexpensive! 0.19 k$/kg ($C_4F_{10}$)**
- **insensitive to γ - background**



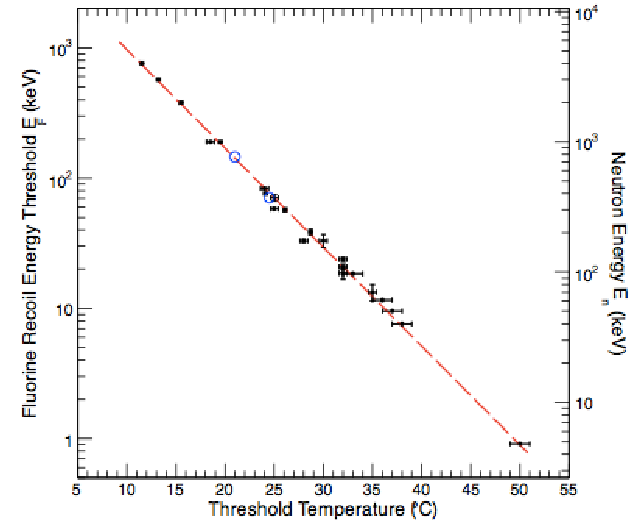
* Inspired by personal neutron dosimeters
@ Bubble Technology Industries, ON

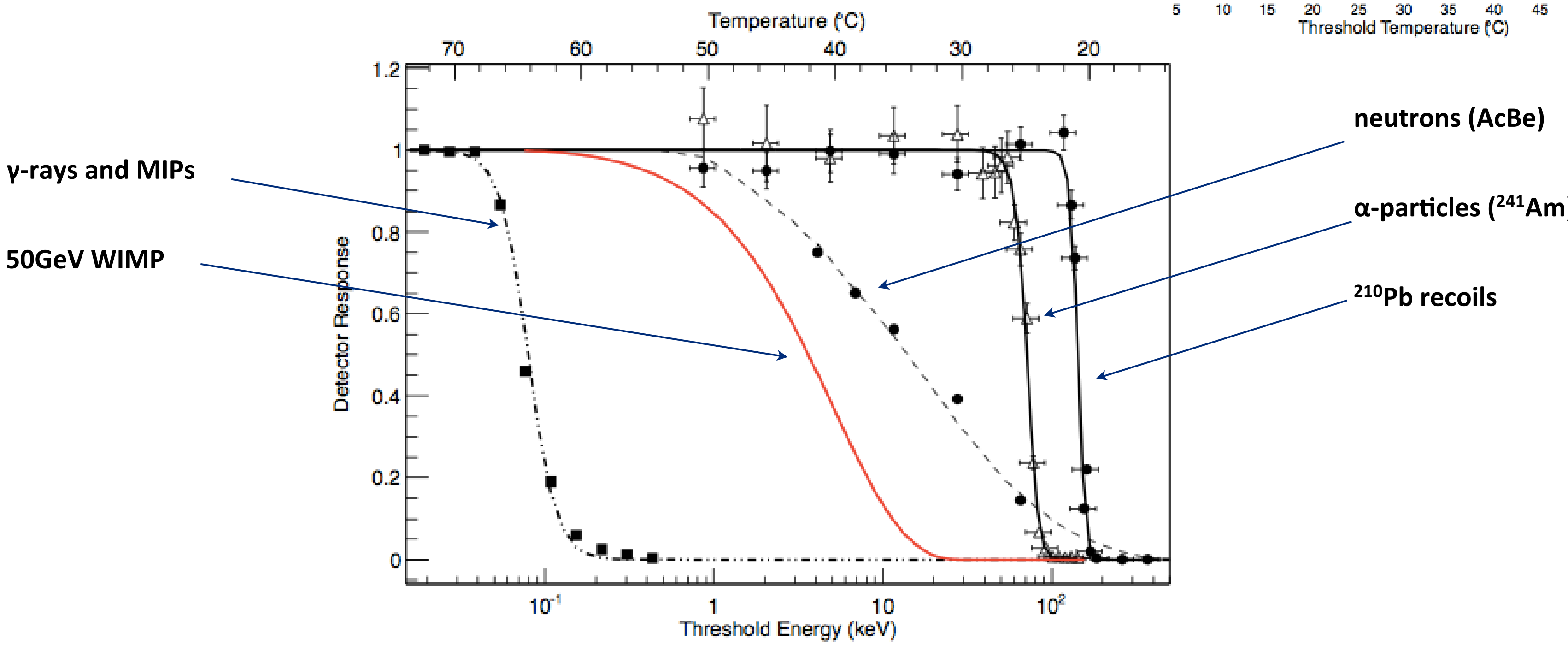
Slide from V.Zacek

(thanks to Nigel J.T. Smith, SNOLab)

Detector response

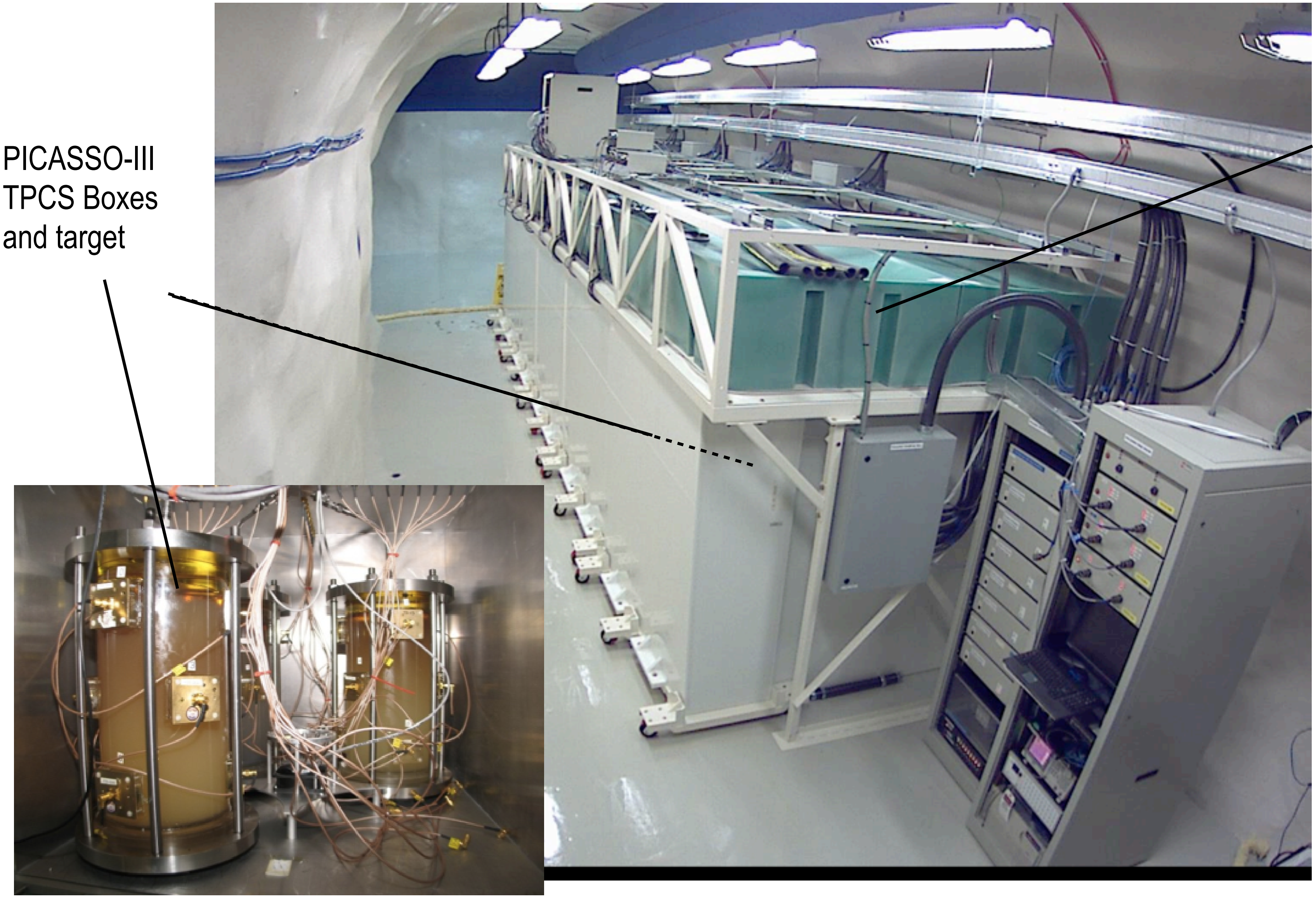
- Threshold detectors, depend on temperature
- Calibrate detector response for various incident species
  - mono-energetic neutron beams
  - poly-energetic neutron sources
  - alpha/nuclear recoils





(thanks to Nigel J.T. Smith, SNOLab)

PICASSO-III Deployment



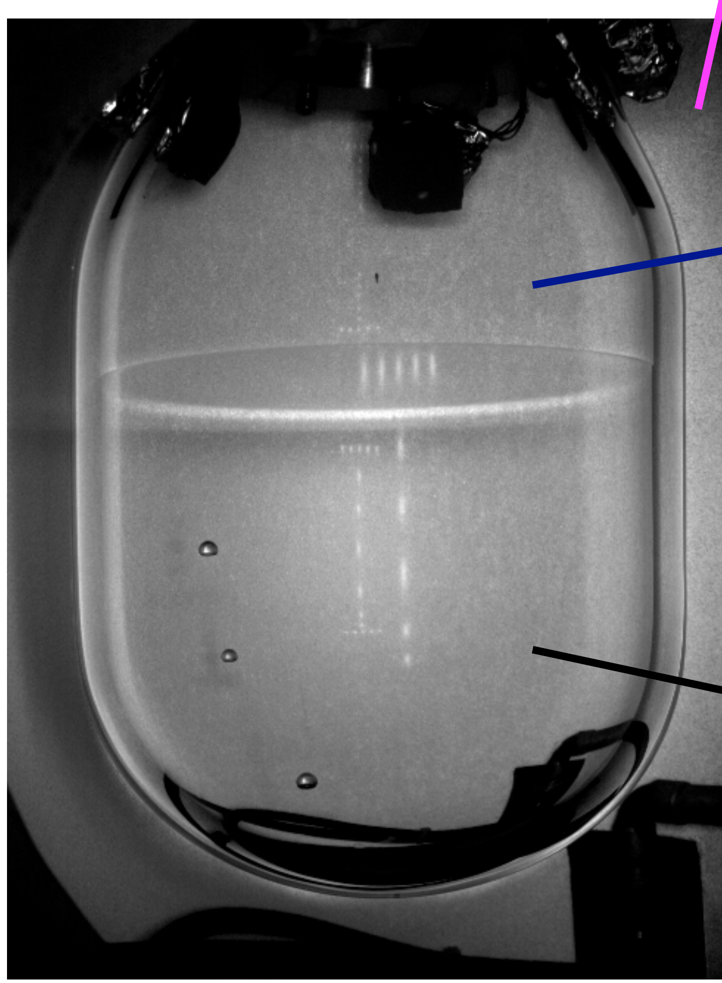
PICASSO-III
TPCS Boxes
and target

PICASSO-III
Water shield

(thanks to Nigel J.T. Smith, SNOLab)

COUPP 2l target

- Superheated fluid, CF_3I or other
  - F for spin-dependent
  - I for spin-independent
  - Other - e.g. C_3F_8 for a light WIMP search
- Particle interactions nucleate bubbles
- Cameras see the bubbles
- Recompress the chamber to start over



(thanks to Nigel J.T. Smith, SNOLab)

COUPP 2l Deployment

COUPP target and water/HDPE shielding

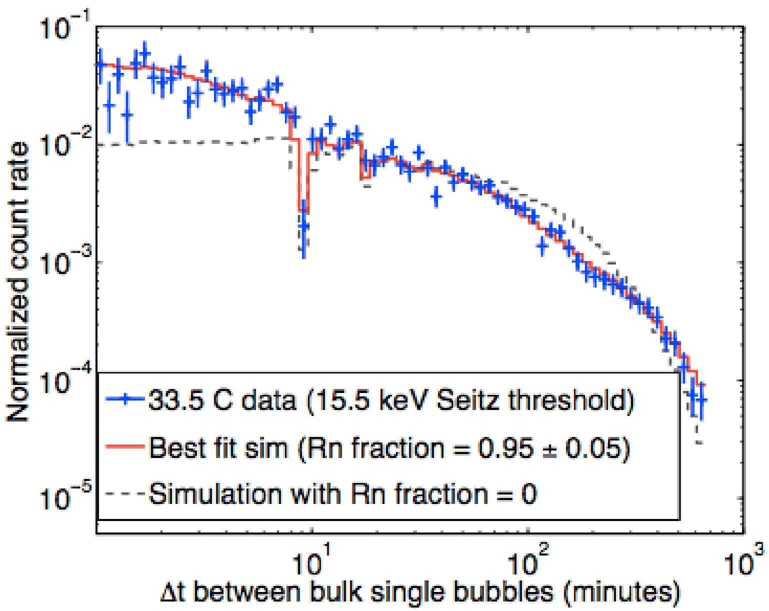
Pressurisation cart and glycol rig.

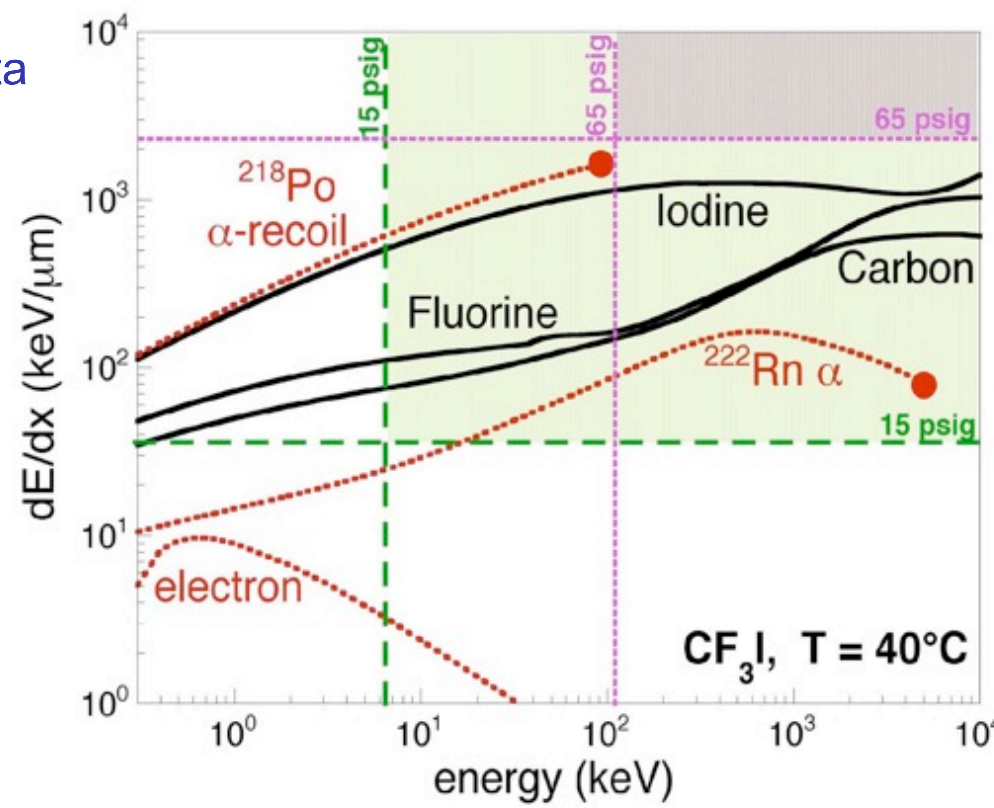
DAQ and control systems

(thanks to Nigel J.T. Smith, SNOLab)

COUPP: bubble nucleation

- Target material CF_3I
  - provides spin dependent (F) and spin independent (I) sensitivity
- Energy threshold determined from Seitz 'hot-spike' model of bubble nucleation
  - benchmarked against calibration data
  - alphas used as a cross check

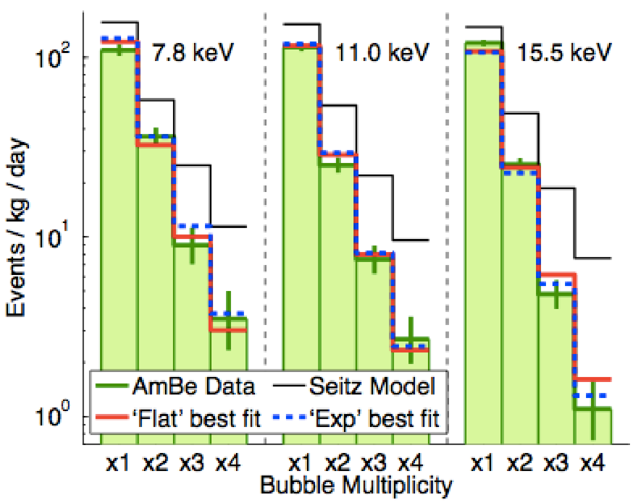


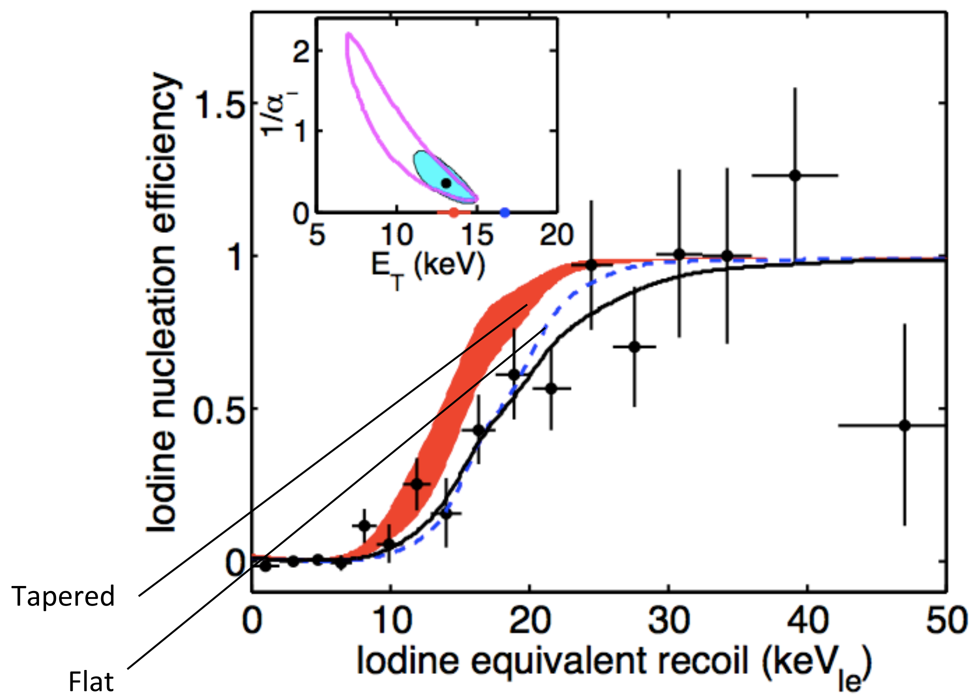


(thanks to Nigel J.T. Smith, SNOLab)

COUPP neutron recoil efficiency

- Bare Seitz model over-predicts the number of nucleation events at all multiplicities for AmBe neutron calibrations
- Two models developed to match observed efficiency to expectation
  - flat efficiency and tapered to 100%
- Dedicated pion beam tests completed at Fermilab to determine correct efficiency dependency





ArXiv: 1304.6001

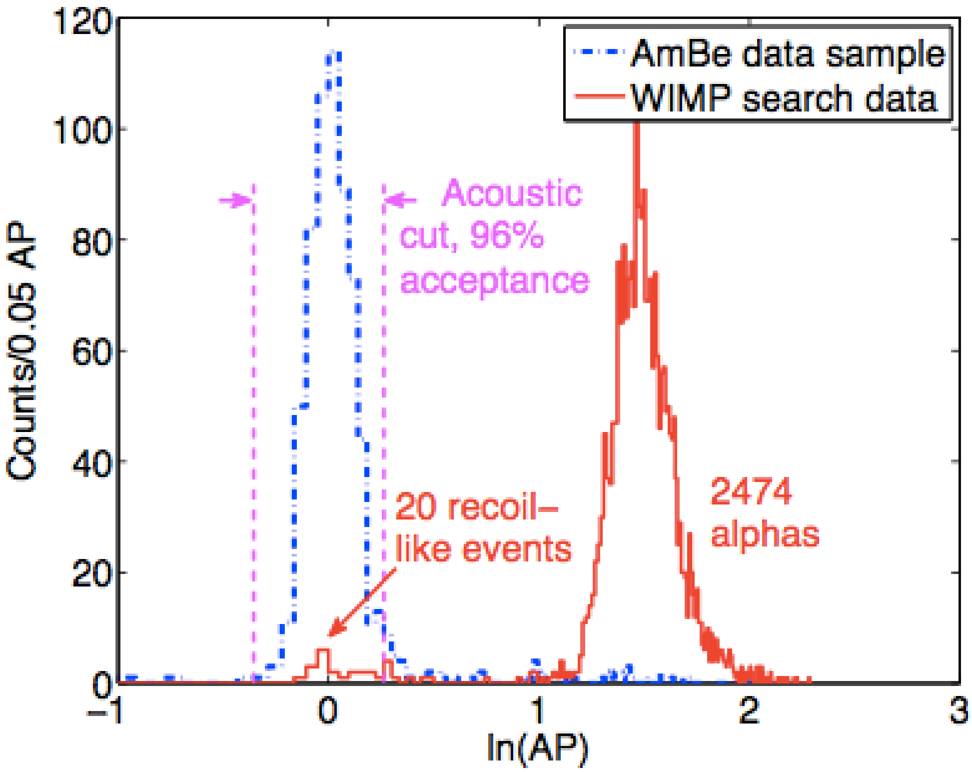
(thanks to Nigel J.T. Smith, SNOLab)

COUPP acoustic discrimination

- Extension of PICASSO result
- Frequency weighted acoustic power density integral

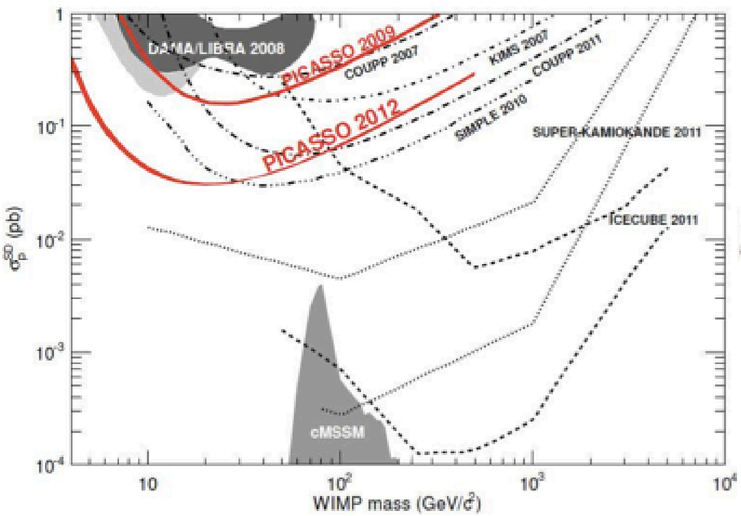
$$AP = A(T) \sum_j G_j \sum_n C_n(\vec{x}) \sum_{f^n_{min}}^{f^n_{max}} f \times psd^j_f,$$

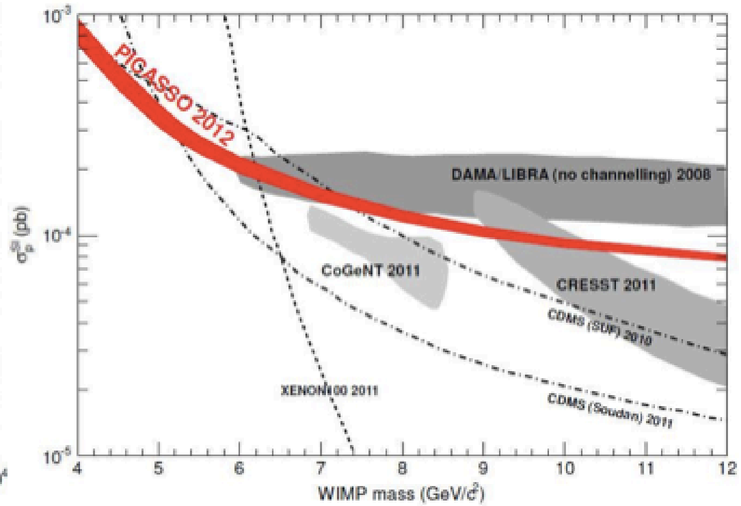
- Scaled to have unity at neutron calibration peak
- Clear discrimination against alpha recoils



(thanks to Nigel J.T. Smith, SNOLab)

2012 Results



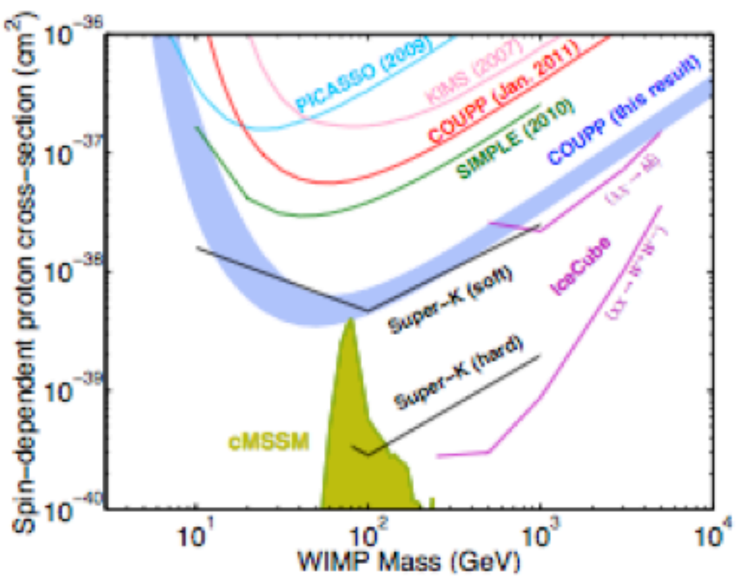


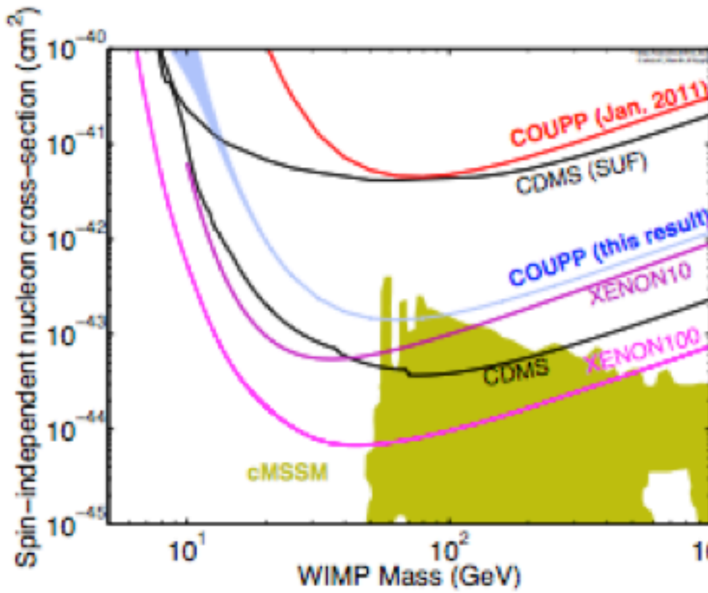
PICASSO

hep-ex/1202.1240

COUPP

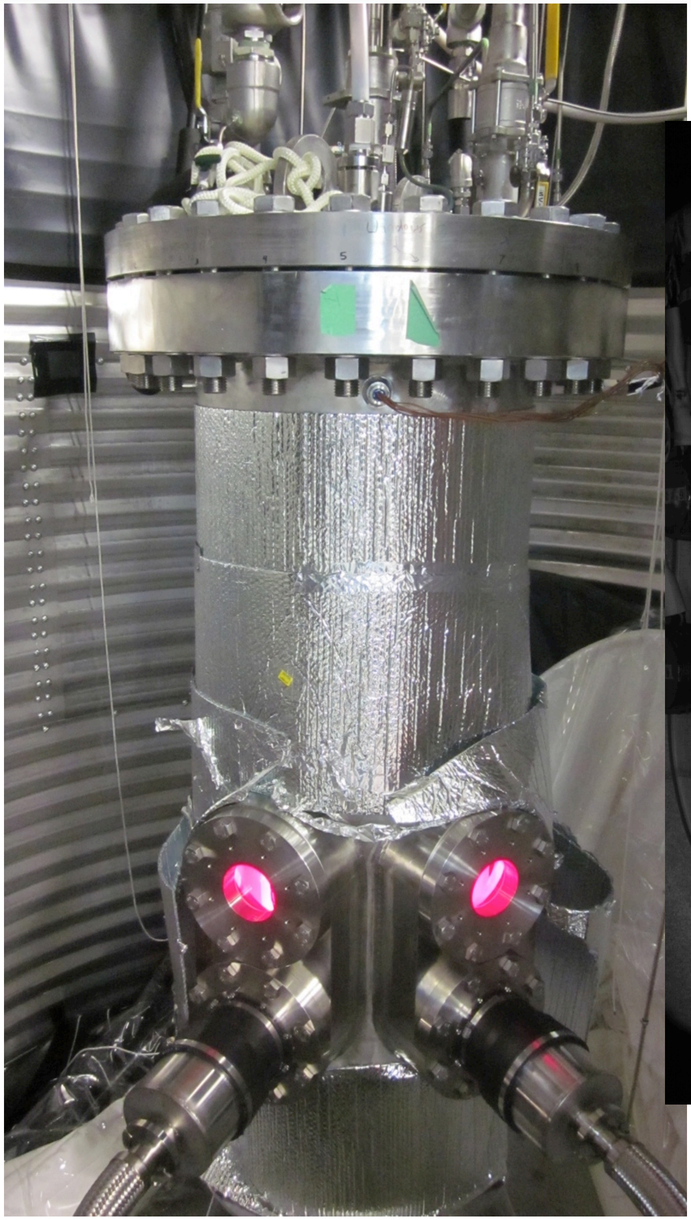
astro-ph/1202.3094

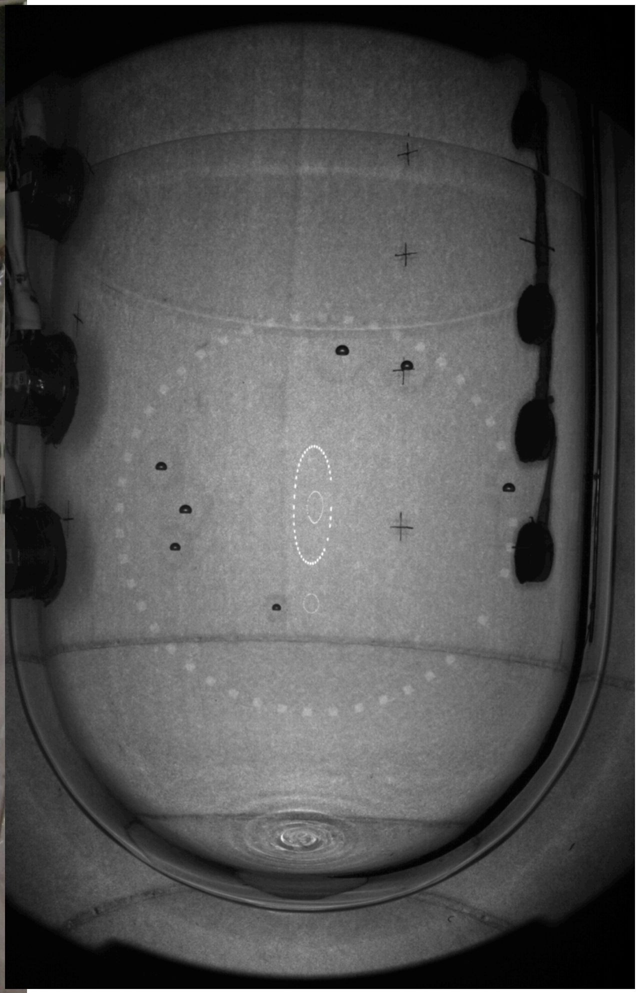




(thanks to Nigel J.T. Smith, SNOLab)

COUPP-60 Deployment





(thanks to Nigel J.T. Smith, SNOLab)

LOW MASS WIMPs?

- "Never trust data from your lowest or highest bins"
  - Limits your ability to understand systematics
  - However the challenge is measuring very small recoil energies convincingly above background

- Challenge to provide theory that reconciles all observations
  - And, frankly, some of the observations are patently systematics
- DAMA
  - Annual modulation - YES. But is it due to WIMPs?.
- CRESST
  - Mixture of many backgrounds and a WIMP signal
  - Incompatible with calibration data? / Calibration of multi-isotope target
- CoGENT
  - Annual modulation reduced in second year? / 'Known' backgrounds
  - New data very soon
- CDMS
  - 3 Si events on charge threshold. Underestimated leakage of known background?

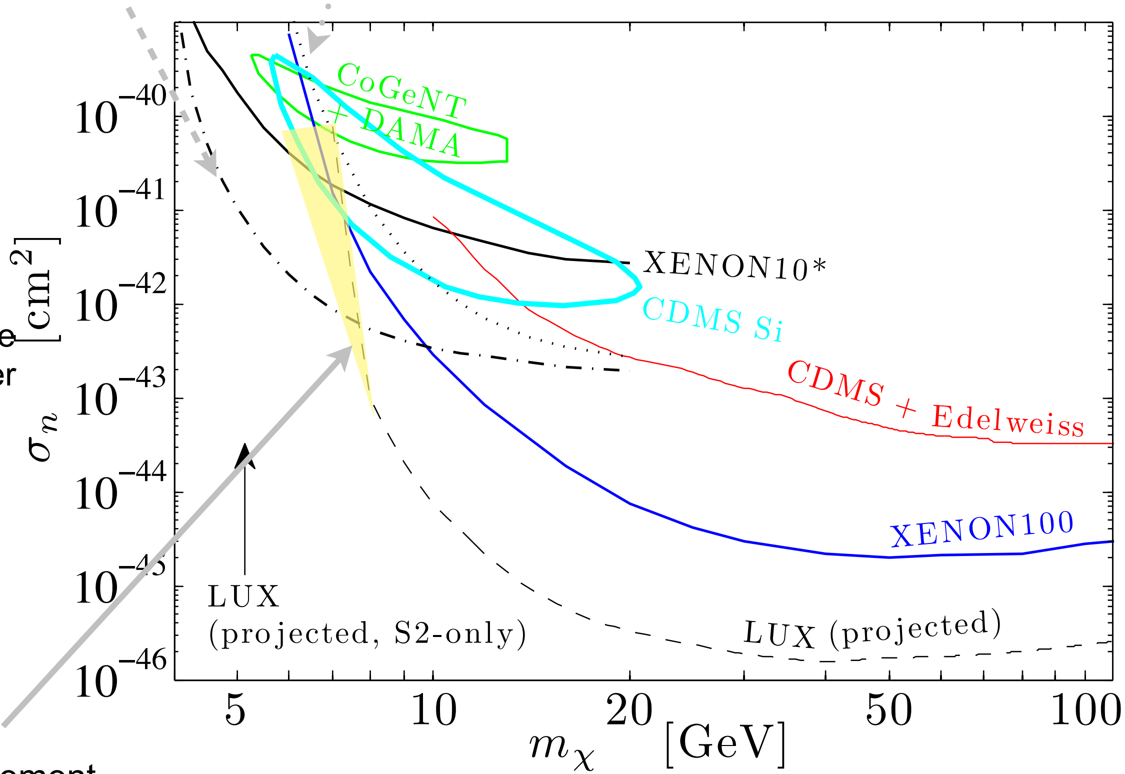
LUX "illustrative" projected sensitivity curve for S2-only analysis (Sorensen)

Assumptions for LUX S2-only limit (dash-dot)
- MORE THAN ORDER OF MAGNITUDE BETTER SENSITIVITY THAN EXISTING EXPERIMENTS
- R<10 cm (45 kg)
- 7 live days
- no electron diffusion (S2 width) rejection of top/bottom (in z) events
- 0.05 dru event rate, which is elevated above regular fiducial regions, since we assume conservatively we don't reject top/bottom (in z) events - THIS RATE IS ILLUSTRATIVE ONLY
- hard cutoff at 1.4 keV NR (~5 electrons in S2), same as in XENON10 S2-only analysis

Multi-tonne Detectors

A larger multi-tonne detector would gain additional sensitivity due to much lower effective dru background. Will improve sensitivity to lower cross-sections by factor >10. Expect electron diffusion over longer distances to assist z determination.

Assumptions for LUX S2-only limit (dotted)
- same as above but assumes a hard cutoff at 3 keV NR.
- Sensitivity is now very much less

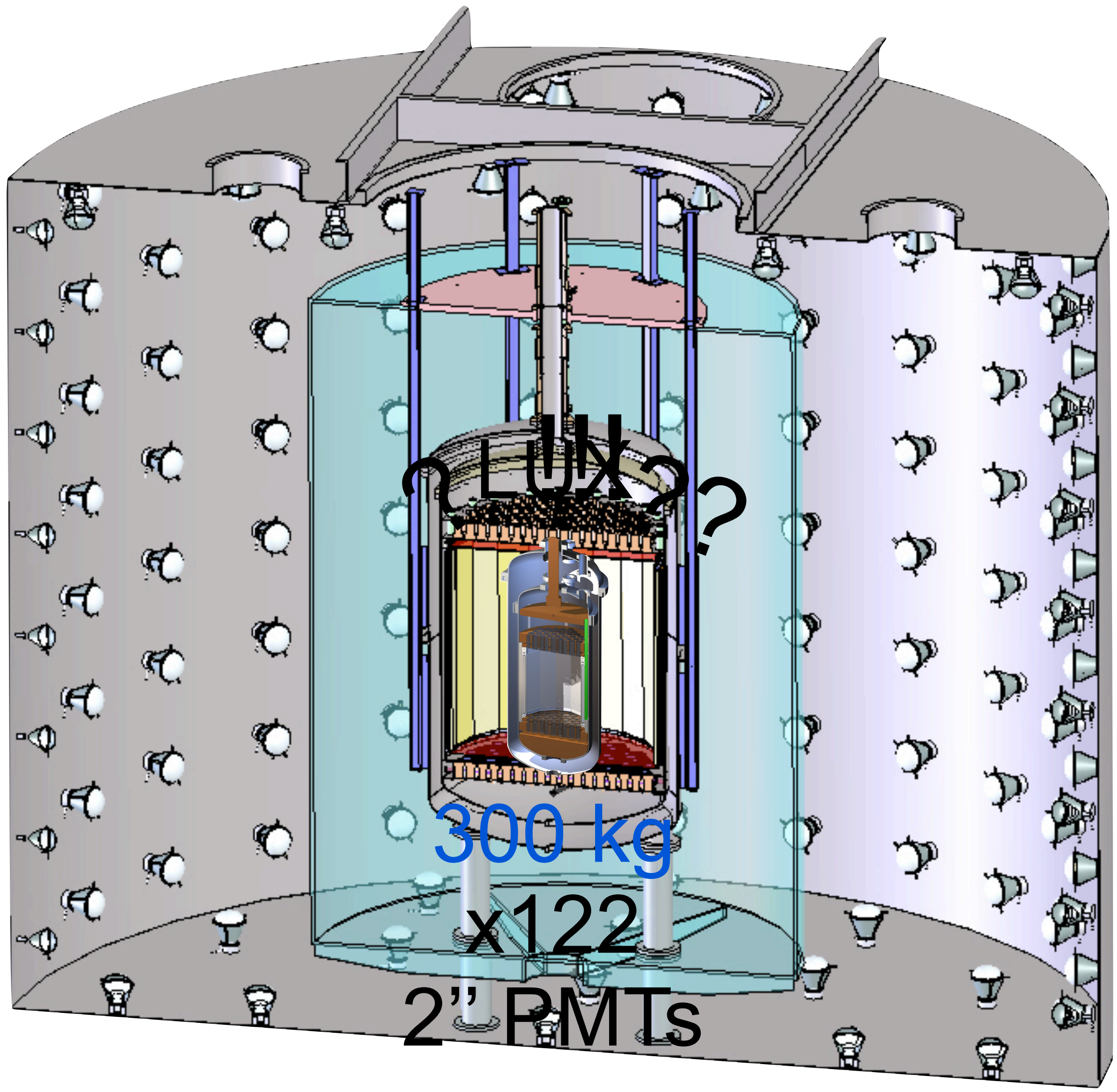


Assumptions for LUX S1+S2 limit (dashed)
- Yellow wedge indicates approximate improvement in standard LUX limit with a 3 keV NR threshold (instead of 4.4 keV)

XENON100 S2-only limit
- Not yet published a limit

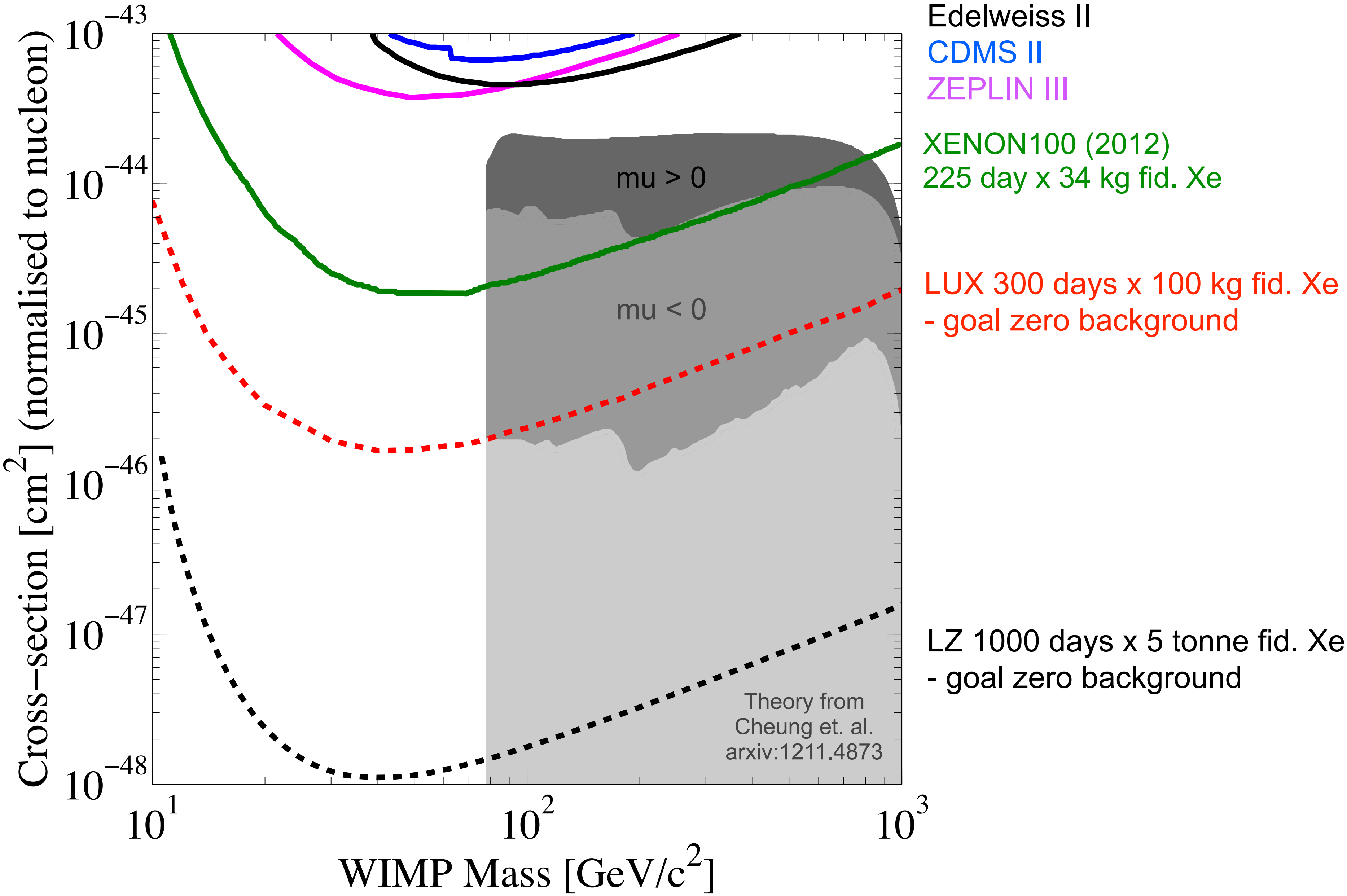
XENON100 S1+S2
- Used more optimistic assumptions for Leff and Qy than LUX is using

LUX+ZEPLIN = LZ



LZ
7 tonnes
x482
3’’ PMTs

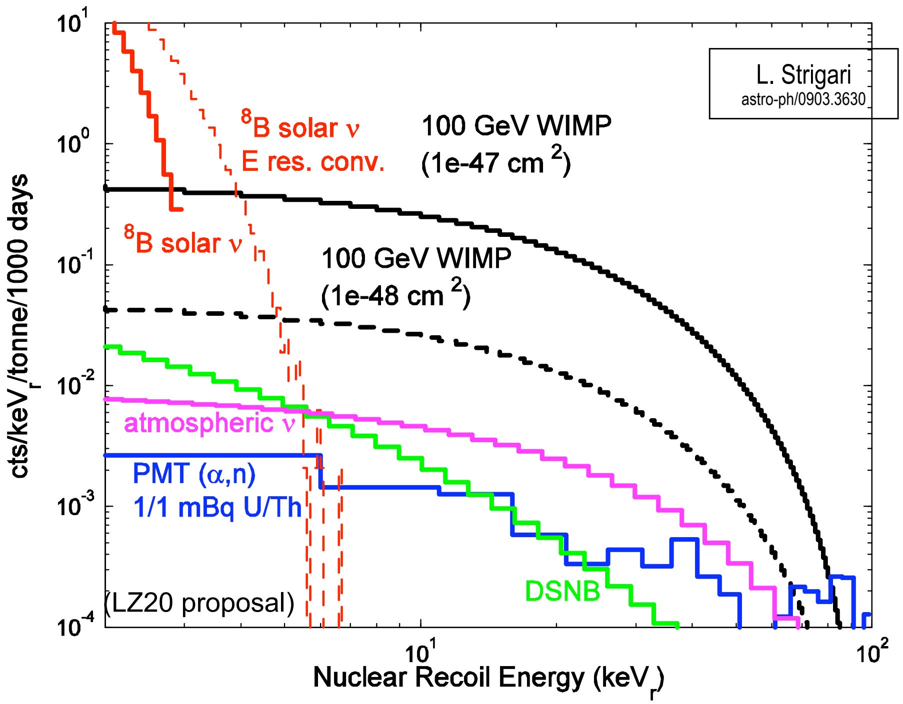
Expected sensitivity



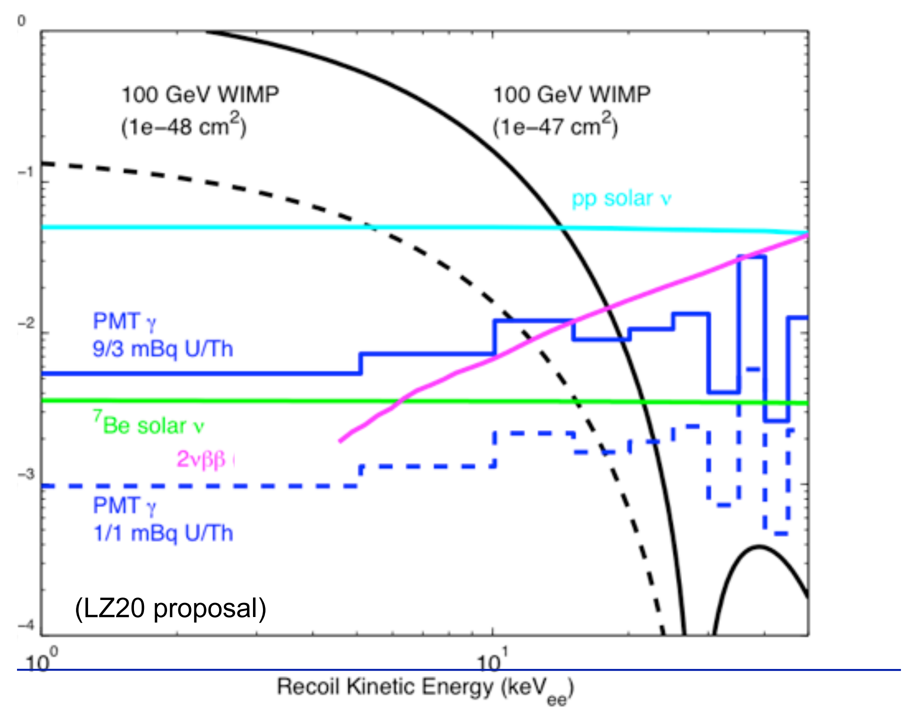
Xe ~100 tonnes Ultimate Search?

- Electron Recoil signal limited by p-p solar neutrinos
  - Reduced using ER background rejection
- Nuclear Recoil background: coherent neutrino scattering
  - ^{8}B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
- Reaches this fundamental limit for direct WIMP searches

Nuclear Recoils



Electron Recoils



Conclusion

- Cold Dark Matter very successful cosmology
  (shares the stage with Dark Energy)
  - WIMPs
  - Axion searches making progress on reaching dark matter region

- WIMPs - search strategy on multiple ways - all are placing constraints - positive/ uncontested signals remain elusive
  - Indirect annihilation daughters
  - Colliders production
  - Direct detection

- WIMPs continue to be highly sought-after by many direct detection experiments
  - Significant interest in low mass WIMPs <20 GeV exclusion/confirmation
  - WIMPs >20 GeV search sensitivity factor 5 improvement every year (average)

- Existing models suggest detection in current/next generation of detectors
  - Models beyond "fine-tuned", or hidden sector models