Status of the Search for WIMP Dark Matter

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PI, LZ Collaboration

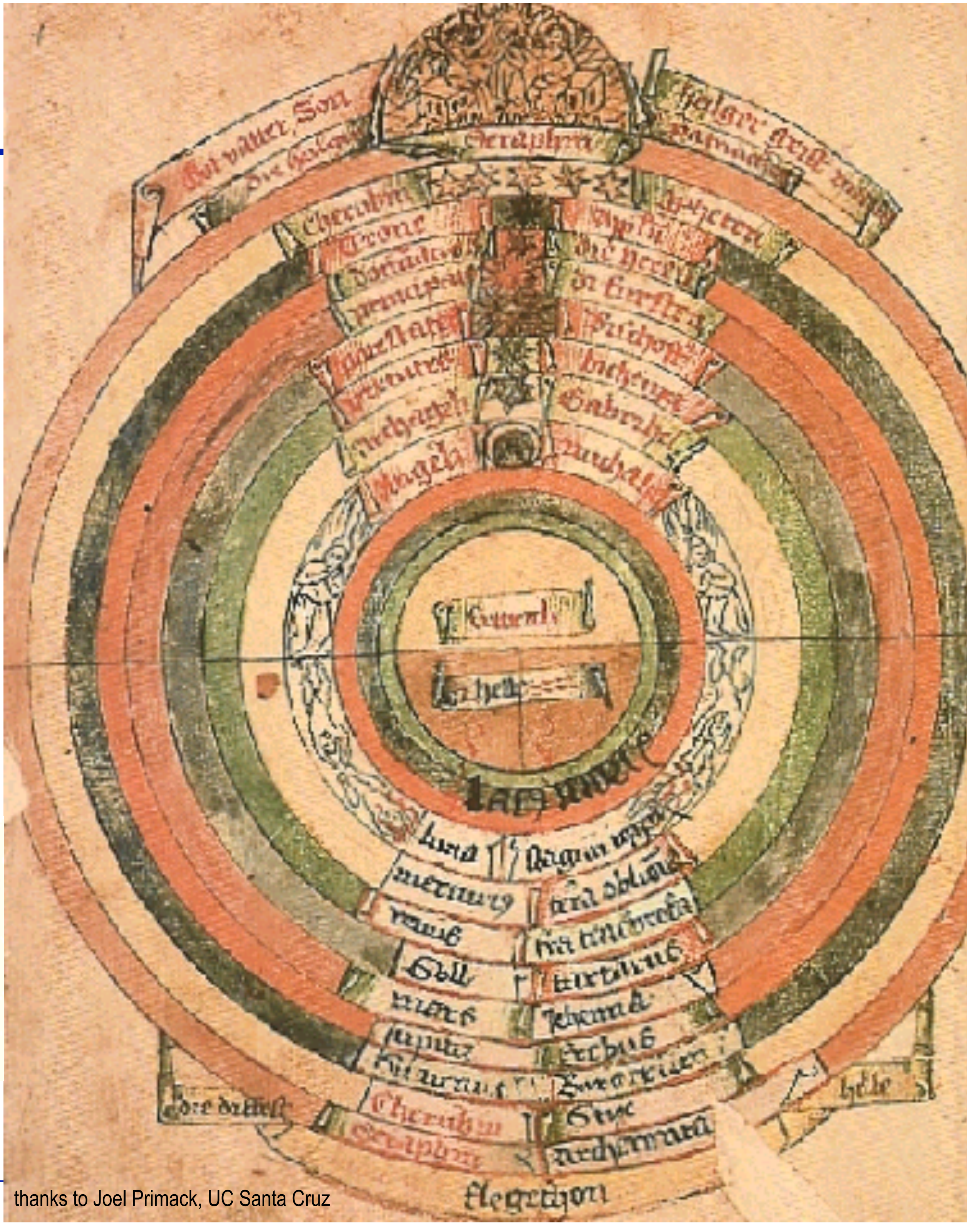
Particle Astrophysics Group, Brown University, Department of Physics

(Supported by US DOE HEP)

see information at

http://particleastro.brown.edu/

Medieval Universe



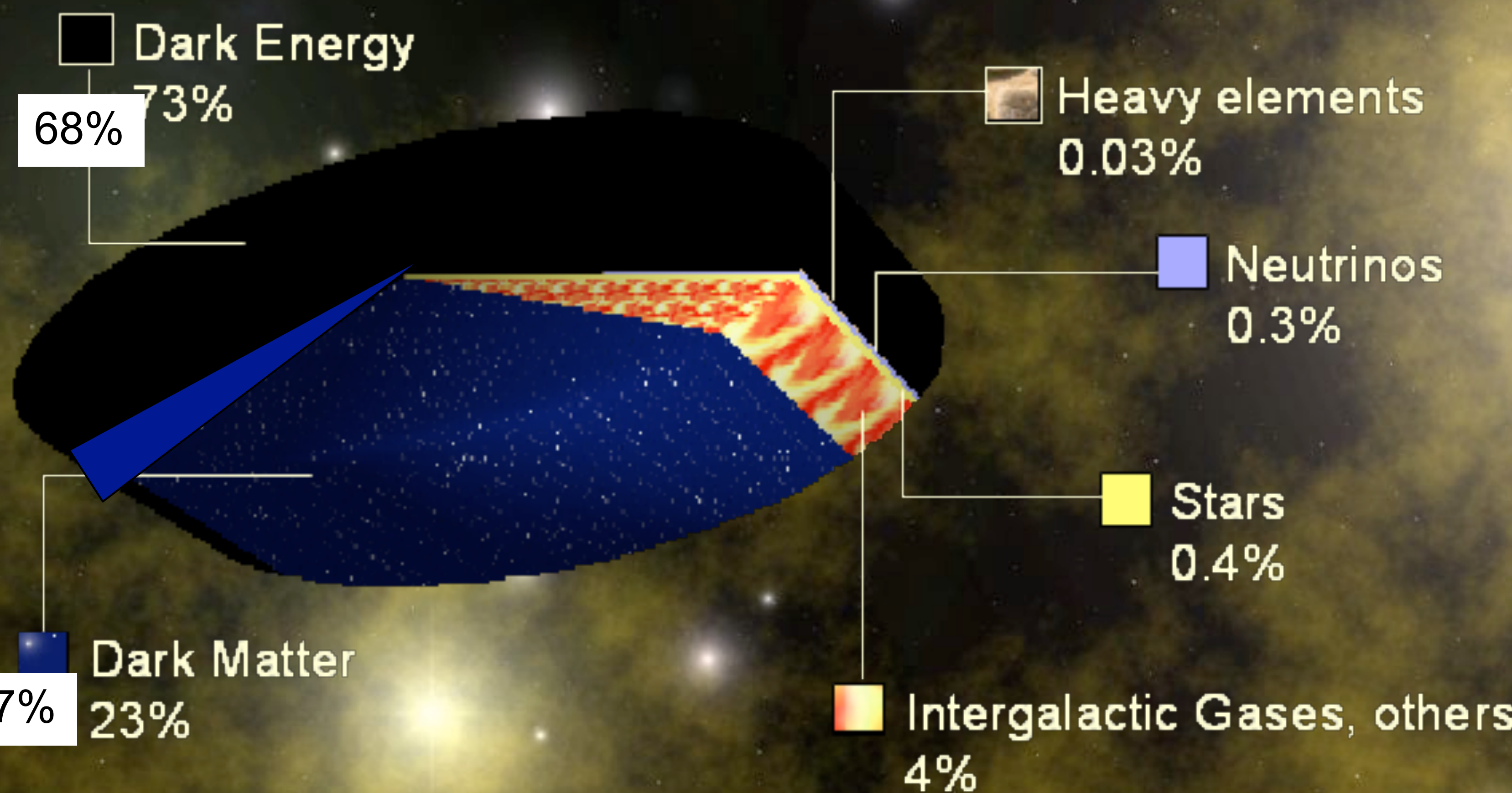
The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as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

thanks to Joel Primack, UC Santa Cruz

Confession

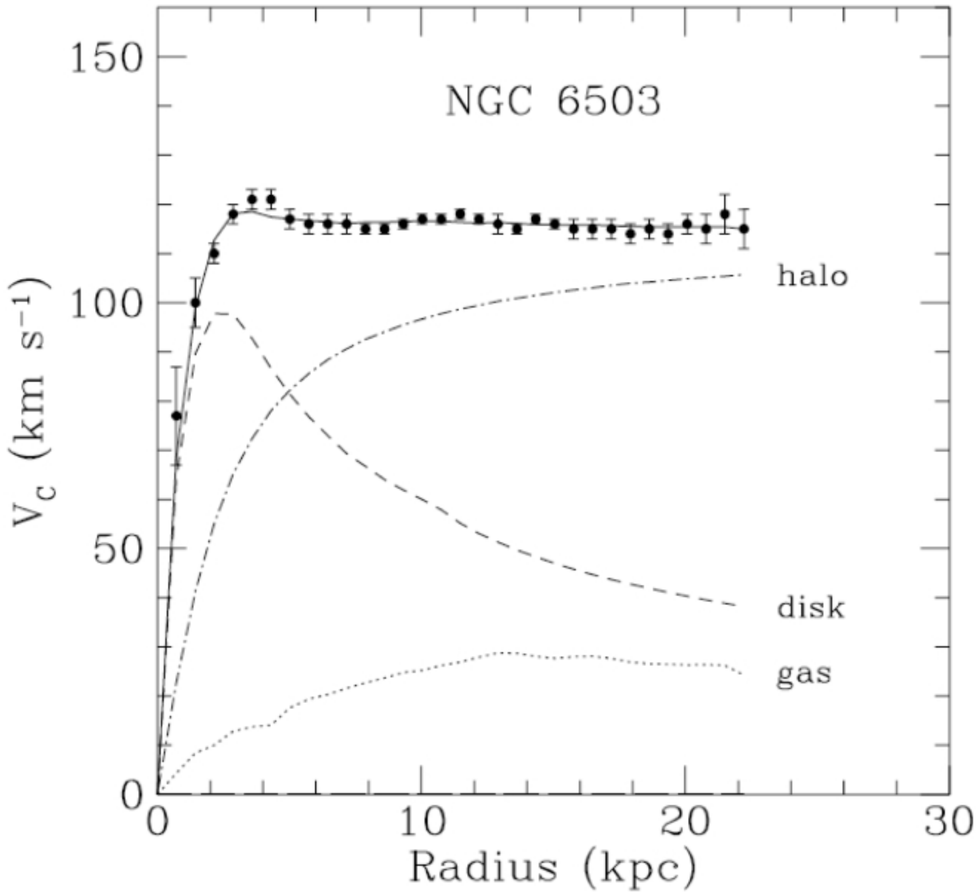
>95% of the Composition of the Universe is still unknown

What is the Universe made of ?



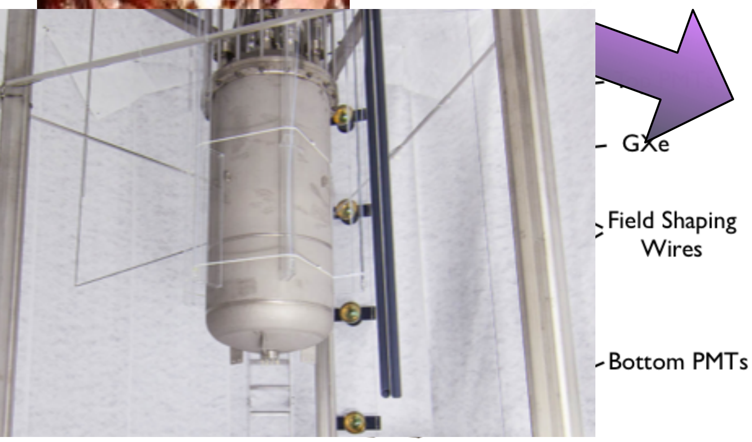
Gaitskell / Brown University

Galactic Rotation Curves

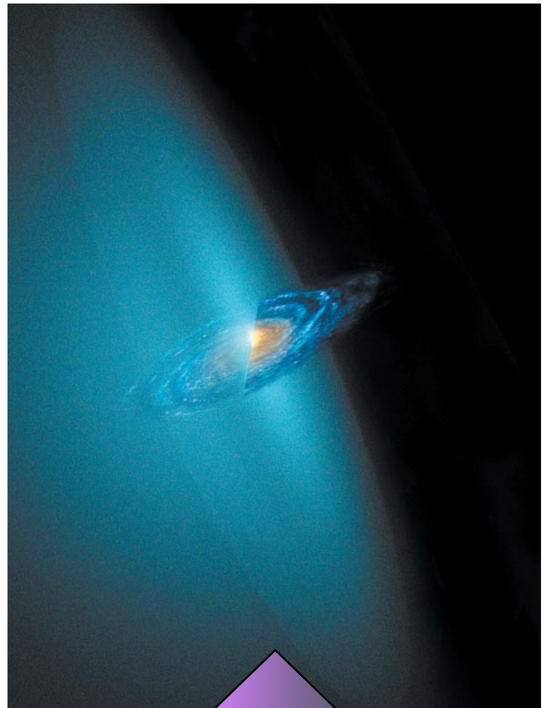


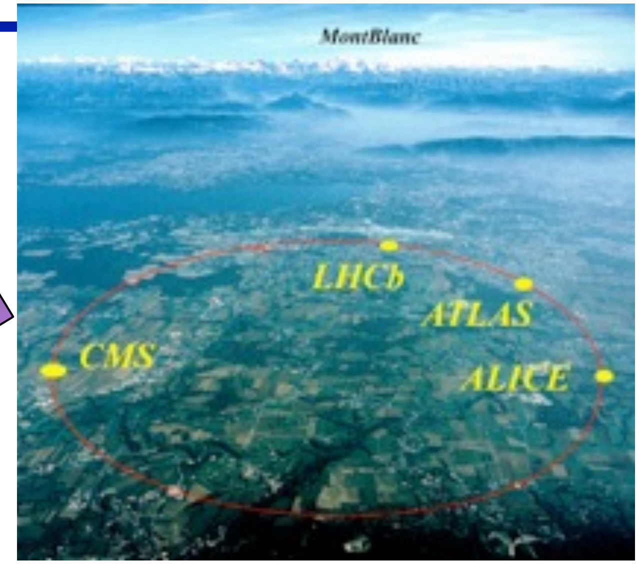
$$v = \sqrt{\frac{GM(R)}{R}}$$

Complementary Approaches to WIMP Detection



Halo made of WIMPs





WIMP production on Earth

WIMP scattering on Earth:
e.g. LUX: currently leading the field

WIMP annihilation in galaxy substructure

Air Cherenkov Telescopes
HESS,MAGIC,Veritas => ACT

Also anti-particle sig.
e.g. Pamela / HEAT / AMS

Neutrinos
e.g. SuperK / ICE3

Fermi Satellite 2008->
γ= 2 - 200 GeV

- What does it take to find WIMPs directly?

- Have we discovered WIMPs?

- Have we got what it takes to (re)discover them?
  - –Acc: $/TeV
  - –I.D.: Annihilation in Galactic Center expected to be strong, but do we understand BGs?
    Dwarf Galaxies Weak Signal, but lower systematic in BG
  - –D.D.: ~1 / kg / Century to < 1 / tonne / Century
- Complementarity
  / This Talk Focuses mainly on Direct Detection

Solution for Naturalness & LSP DM appears challenging

- A full natural model CMSSM in trouble after LHC Run 1
  - Fine tuning required of
    - Weak Scale
    - Higgs Mass
    - Relic Density (special co-annihilation or resonant effects required)
- Move to more pragmatic Approach
  - Simplified Models
  - Effective Field Theories

Indirect Detection

- 90’s: Egret , SuperKamikande, HEAT
- 2003 INTEGRAL (511 keV line)
- 2008 PAMELA (rising e+ fraction, antiproton spectrum)
- 2010- FERMI Satellite Hint of Galactic Center γ-Ray Excess
- 2013- FERMI γ-Ray Excess Limits on Dwarf Galaxies
- 2013 AMS-02 First Science Results
- 2014 AMS-02 Extended Energy

- Air Cherenkov Telescopes: HESS, VERITAS, MAGIC (CTA)

27 years in dark matter

CDMS II: Winter
@Soudan Minnesota

Sanford Lab
LUX & LZ
@Homestake, South
Dakota

PHYSICS ITALIAN
STYLE XENON10
@ Gran Sasso

Dark Matter Underground Searches - 1987

- 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]

[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*
[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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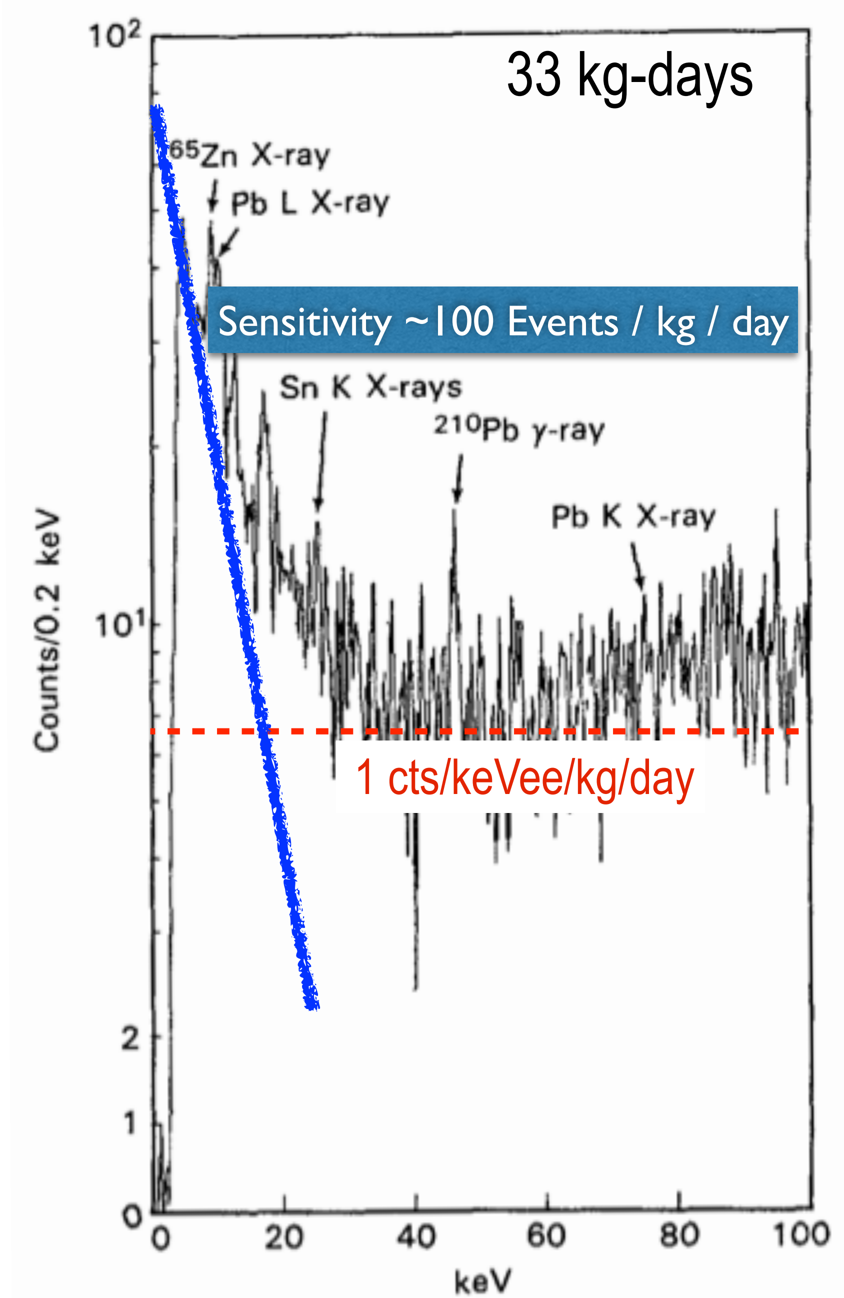
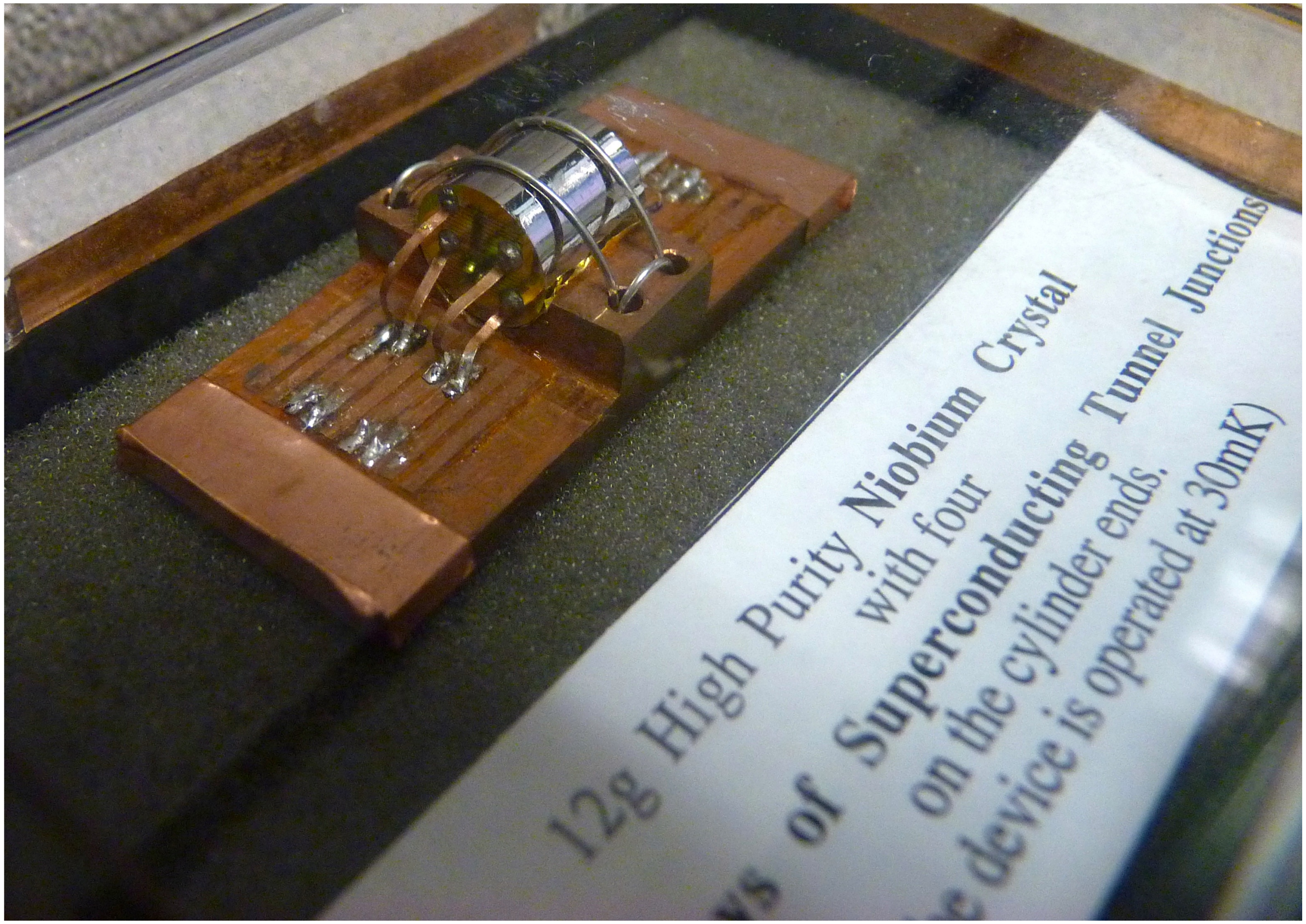
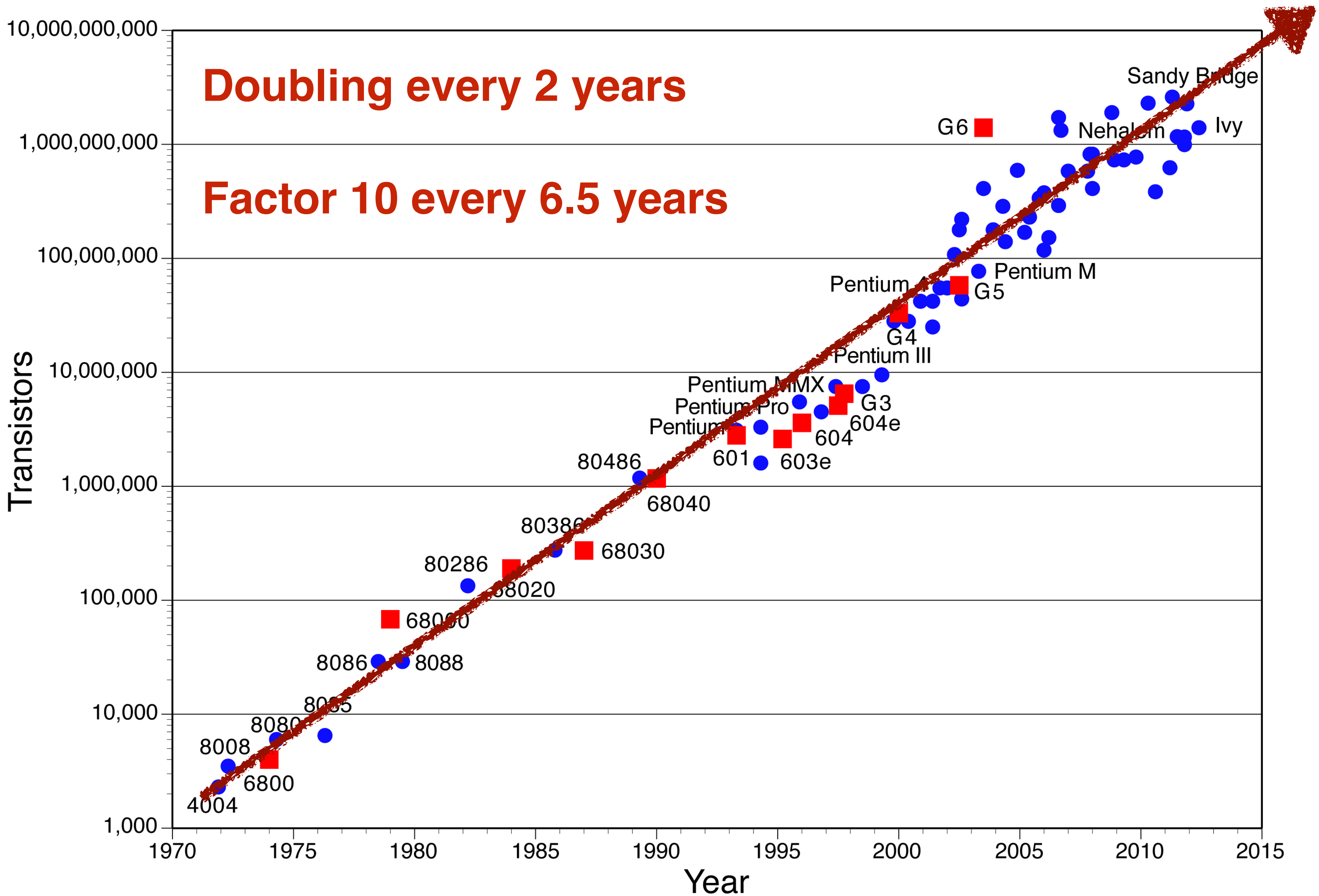


Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

- 1 cm long - 12 g - 250 eV Threshold - “State of the Art in 1991”
  - Superconducting Tunnel Junction arrays detecting phonons and quasiparticles from Nb





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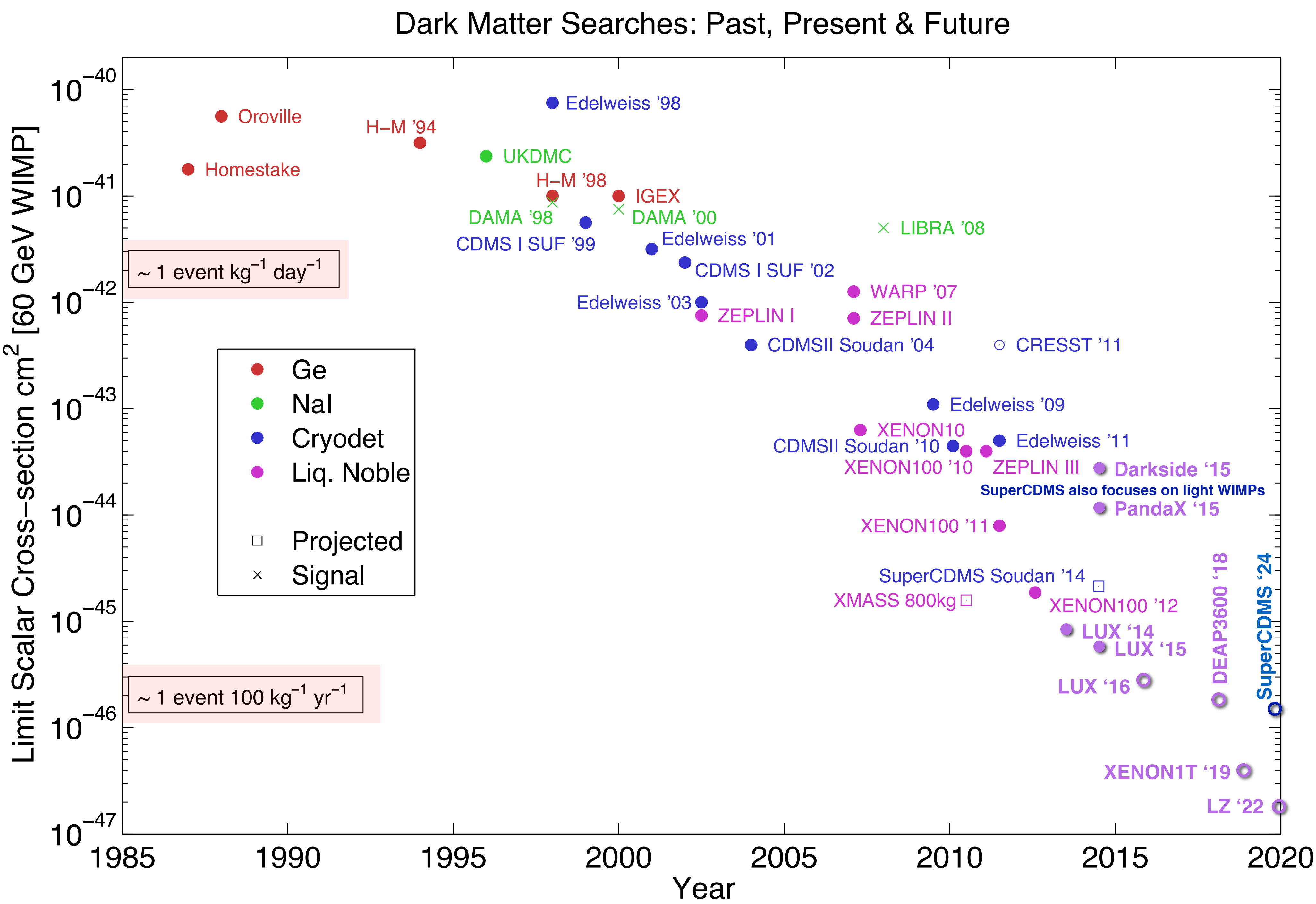
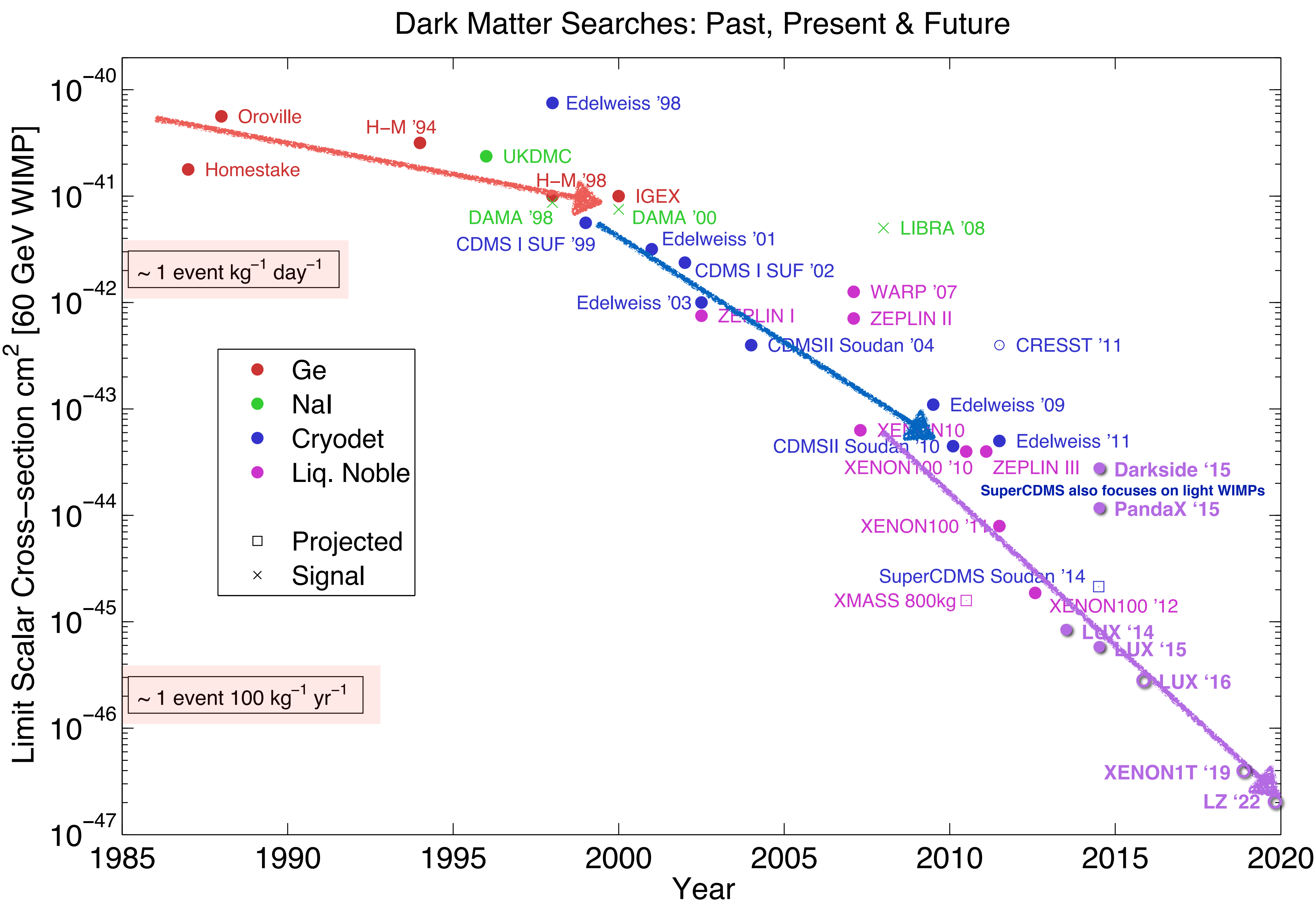

Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section cm^2 [60 GeV WIMP]
Year
~ 1 event kg^{-1} day^{-1}
~ 1 event 100 kg^{-1} yr^{-1}
Ge
NaI
Cryodet
Liq. Noble
Projected
Signal
Oroville
Homestake
H–M '94
H–M '98
UKDMC
IGEX
DAMA '98
DAMA '00
Edelweiss '98
CDMS I SUF '99
Edelweiss '01
CDMS I SUF '02
LIBRA '08
WARP '07
Edelweiss '03
ZEPLIN I
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
Darkside '15
SuperCDMS also focuses on light WIMPs
PandaX '15
XENON100 '11
SuperCDMS Soudan '14
XMASS 800kg
XENON100 '12
LUX '14
LUX '15
LUX '16
DEAP3600 '18
SuperCDMS '24
XENON1T '19
LZ '22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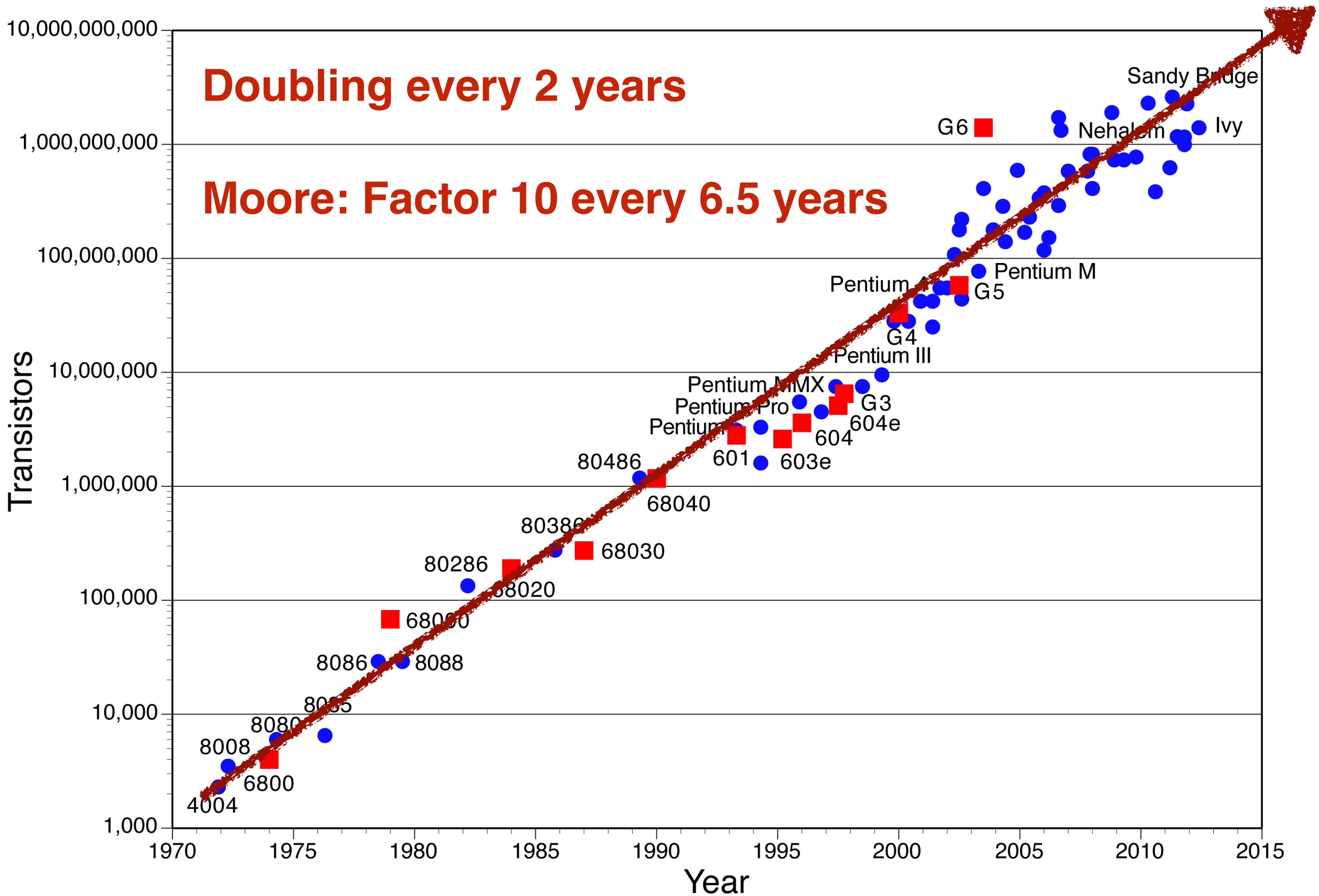

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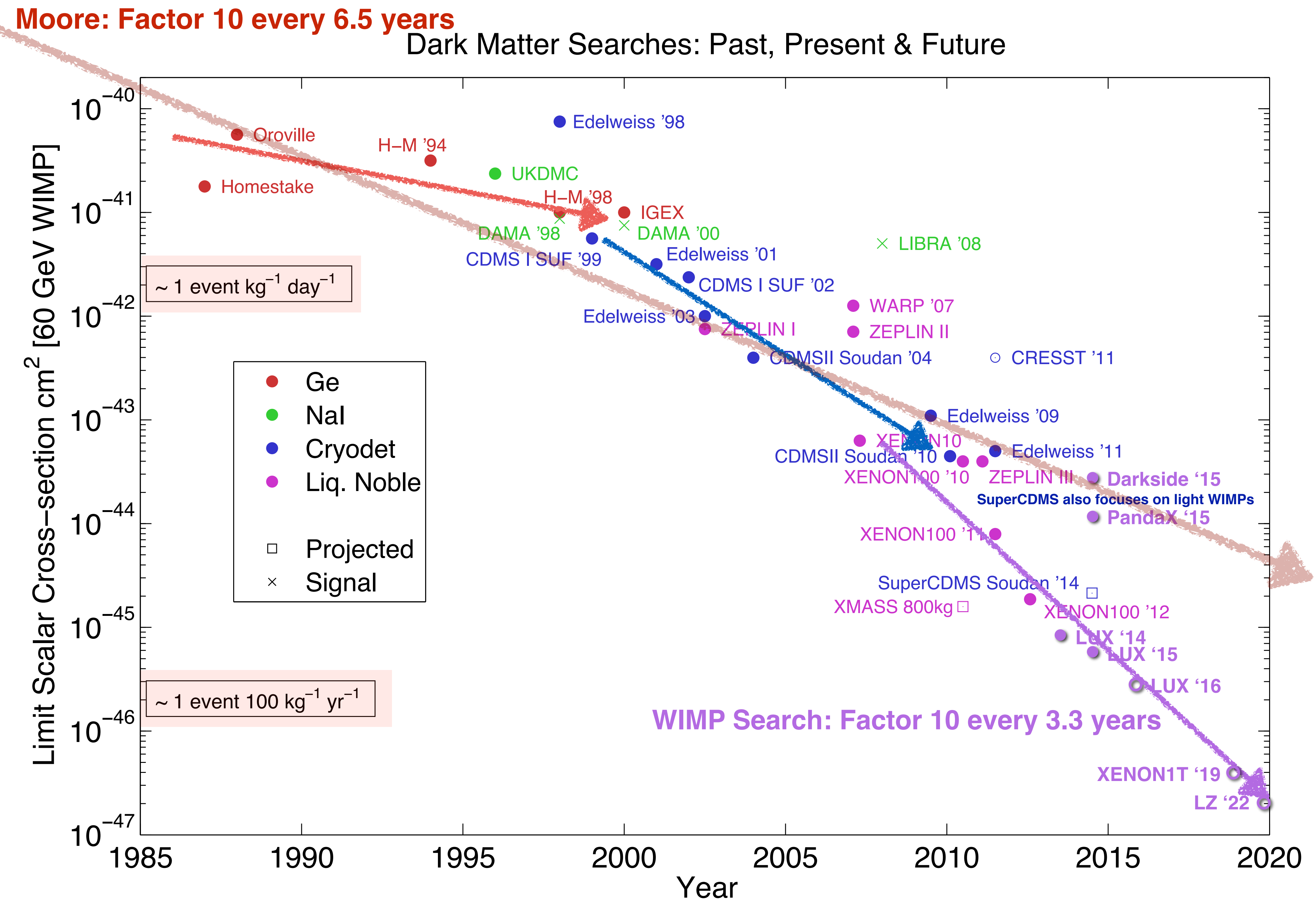

Moore: Factor 10 every 6.5 years
Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section cm² [60 GeV WIMP]
Year
~ 1 event kg⁻¹ day⁻¹
~ 1 event 100 kg⁻¹ yr⁻¹
Ge
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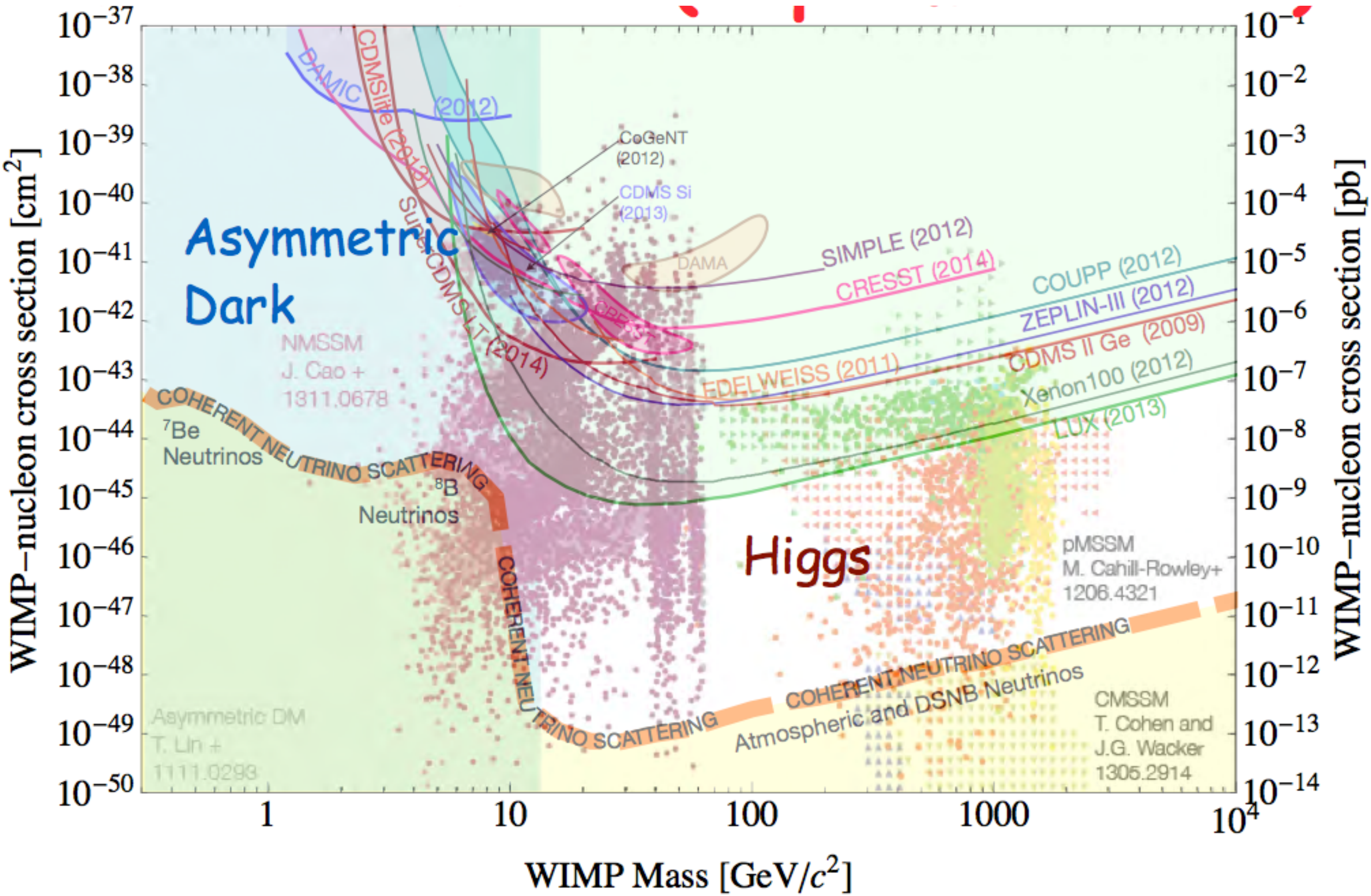
WIMP Search: Factor 10 every 3.3 years
XENON1T '19
LZ '22

WIMP MODEL REACH



Many International Efforts

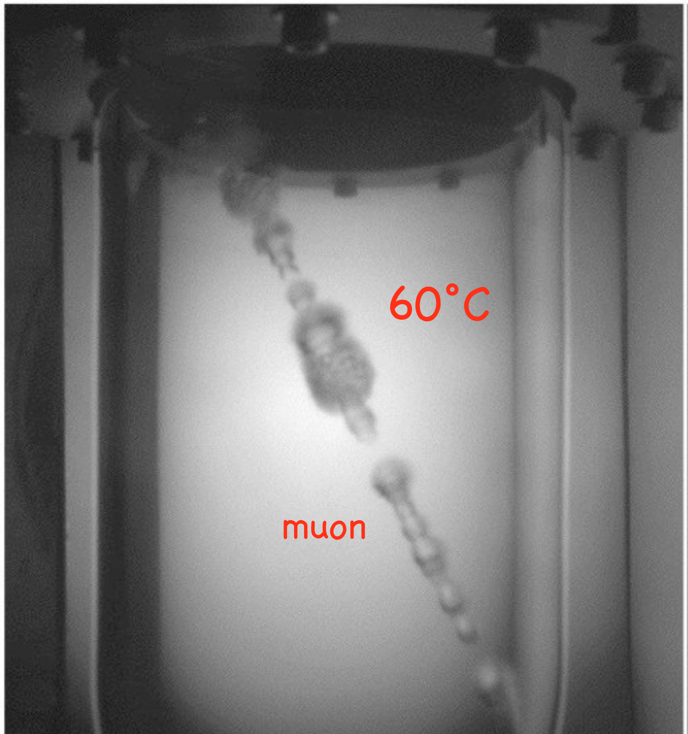
Idealized Dark Matter Direct Detection Experiment

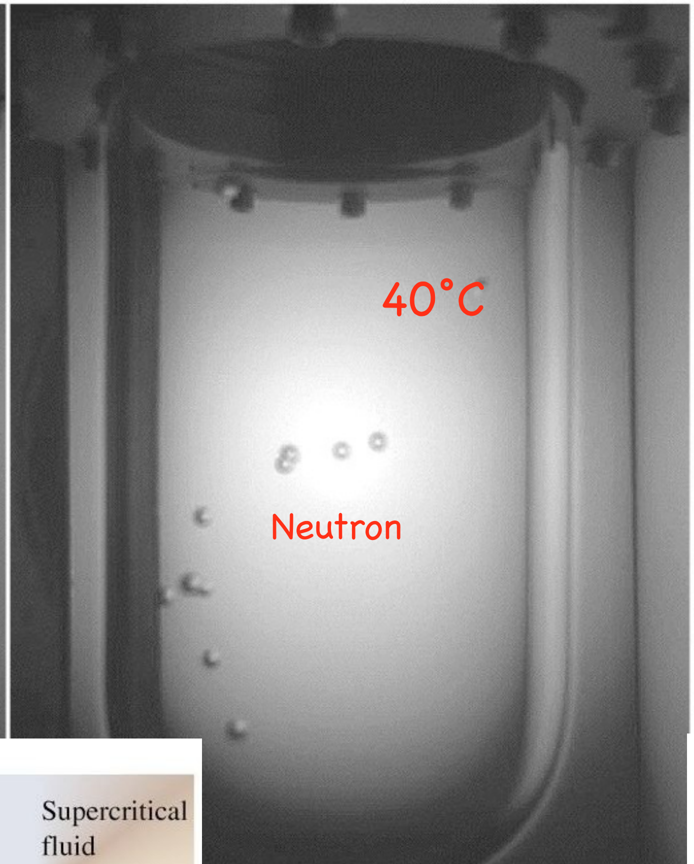
- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
  - We almost have this in PICO (COUPP) bubble chambers

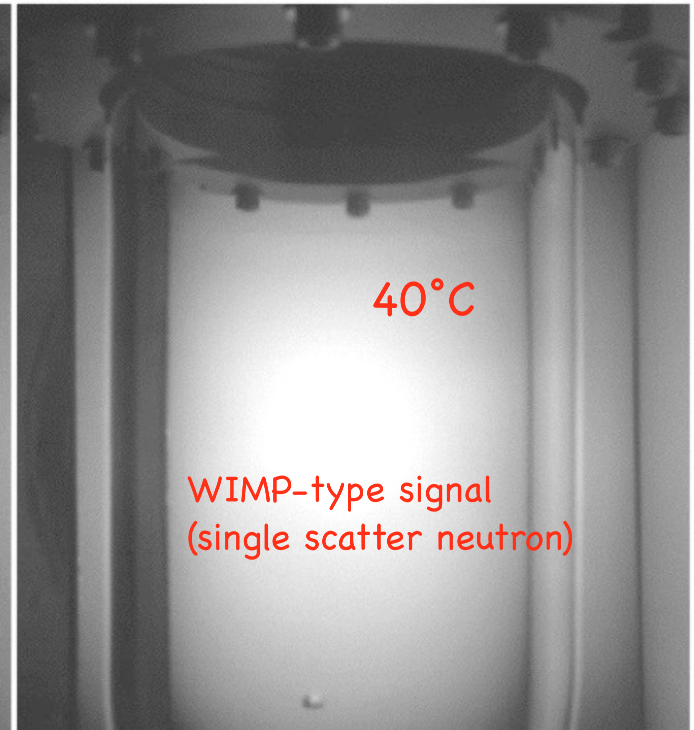
COUPP: bubble chamber reimagined

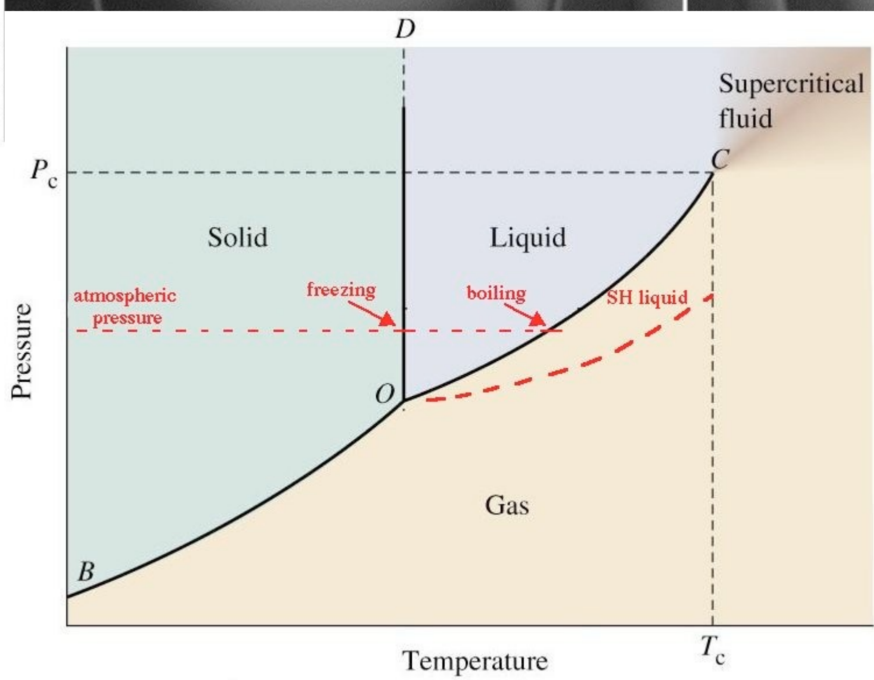
Conventional BC operation
(high superheat, MIP sensitive)

Low degree of superheat, **sensitive to nuclear recoils only**





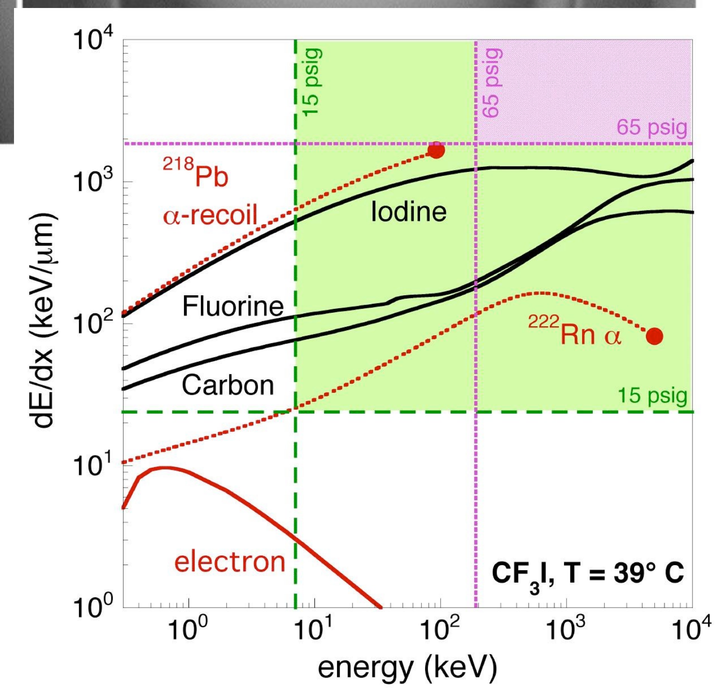




CF_3I,
Also C_3F_8, C_4F_{10}, CF_3Br

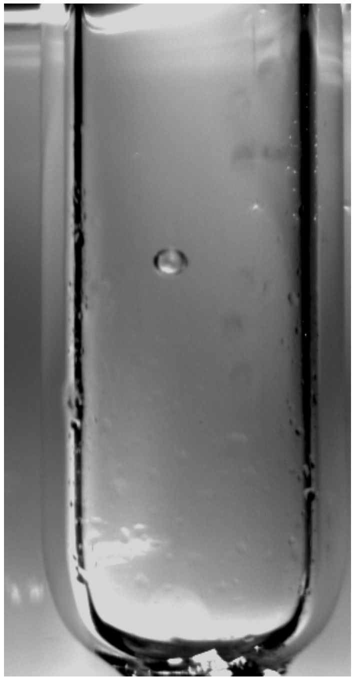
γ or e^- rejection > 10^{10}

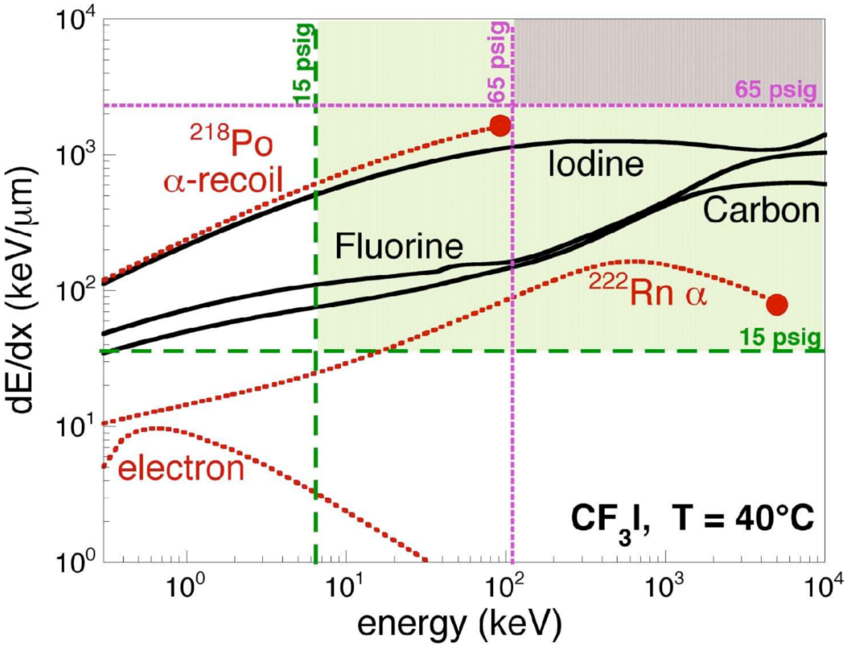
Juan Collar, UChicago:
ultra-clean Bubble Chamber:
Bolte et al., NIM A577 (2007) 569
Science 319 (2008) 933,
Phys. Rev. Lett. 106 (2011) 021303

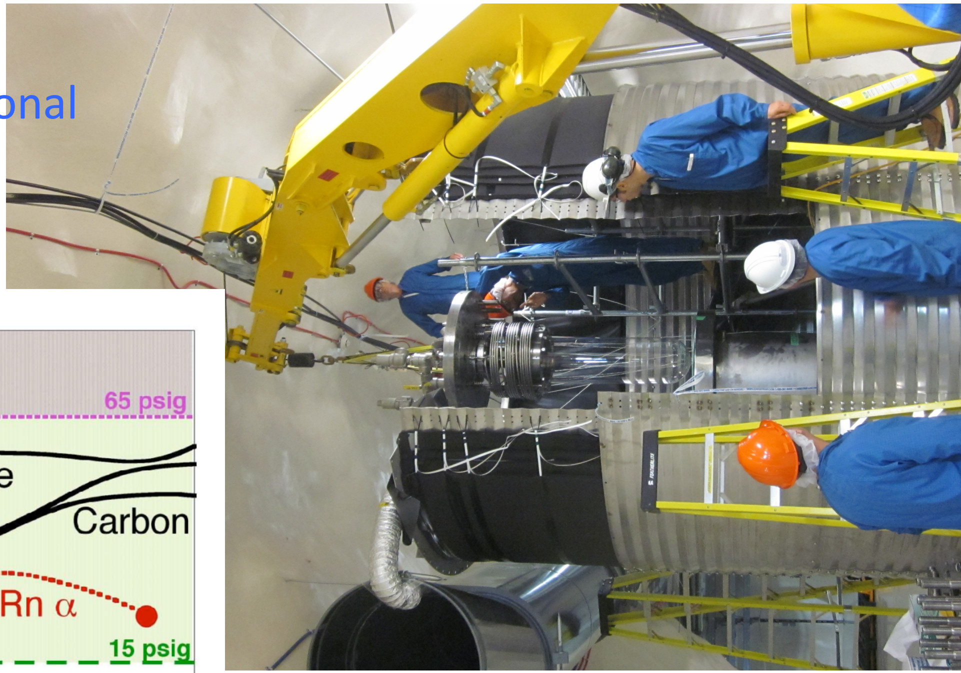


PICO: Bubble Chamber Dark Matter Search

- PICO collaboration operates two bubble chambers at SNOLAB: PICO-2L (2 liters C_3F_8 target) and PICO-60 (20 liters CF_3I target in 2013-2014 Run).
- Comparison of rates on different targets allows unique tests of signal, background models.
- Thermodynamic conditions tuned to reject backgrounds according to specific energy loss (dE/dX).
- Acoustic signals from bubble growth provide additional background discrimination.



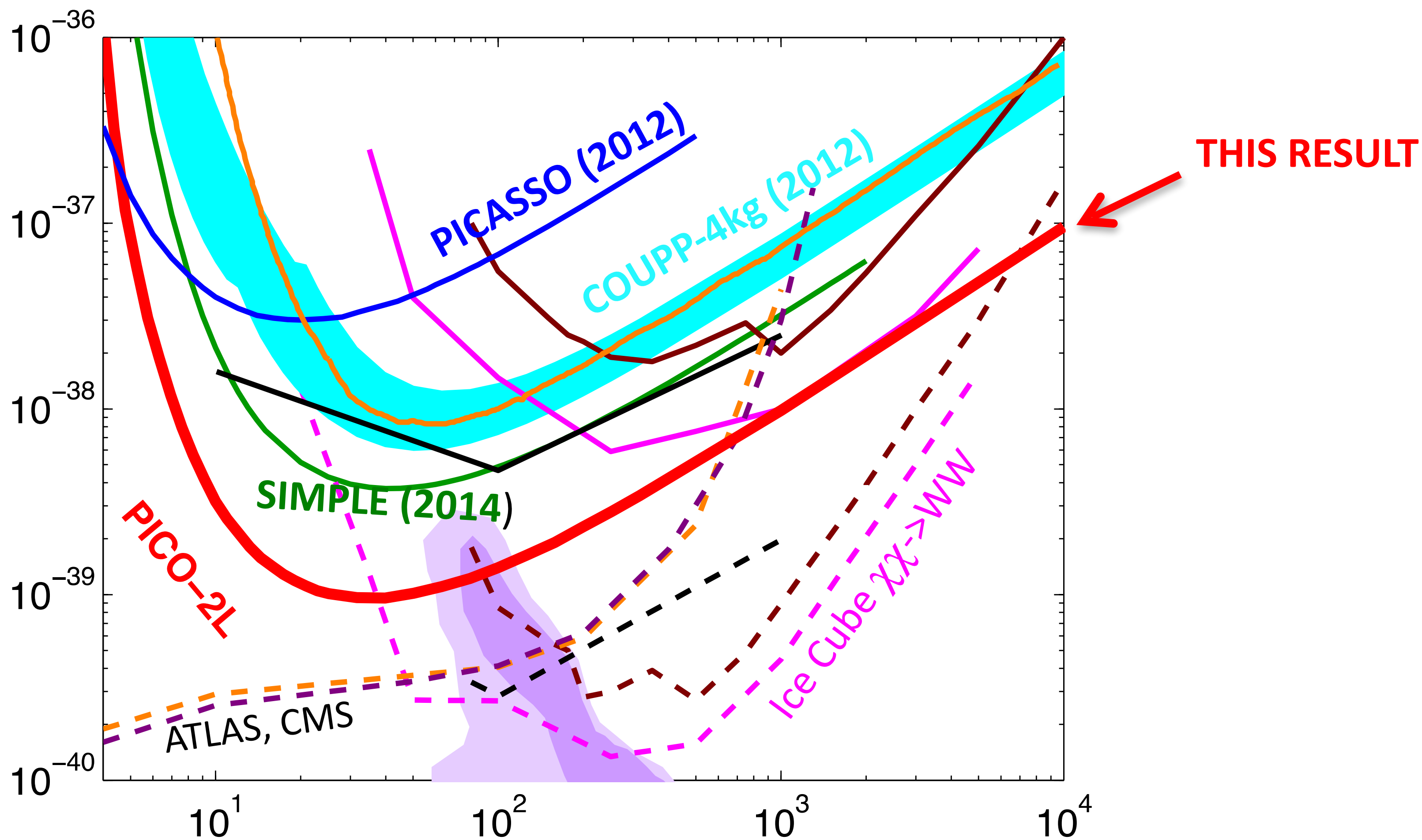




PICO-60 Detector

PICO-2L 2015 ArXiv/ PRL Submission

- Results from 2013-2014 run published to ArXiv (1503.00008) & submitted to PRL.
- 211 kg days exposure of C3F8 target with thresholds from 3.2 keV to 8.1 keV.
- 12 recoil-like background events.
- First direct detection result to probe realistic spin-dependent couplings (MSSM).



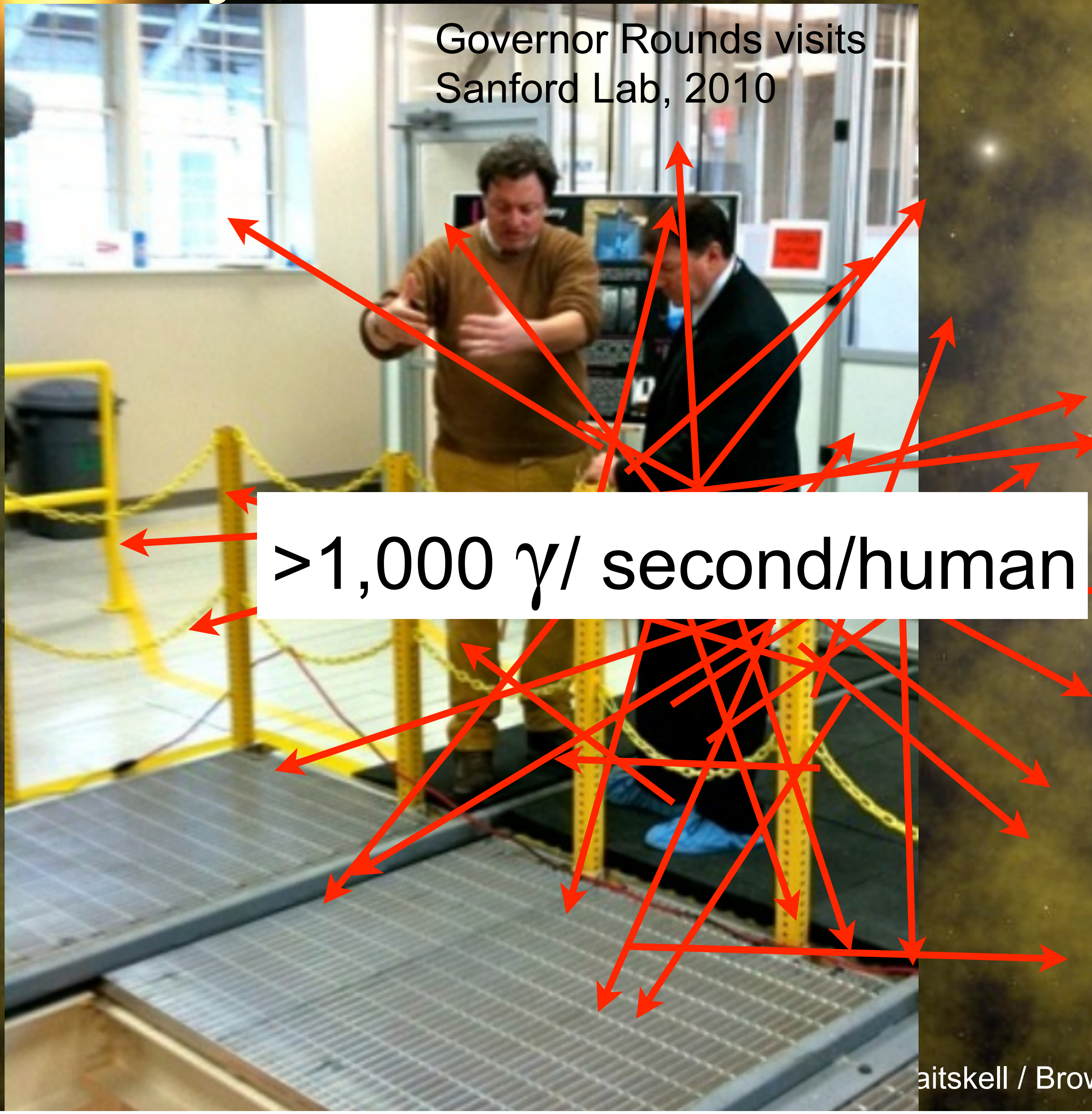
Idealized Dark Matter Direct Detection Experiment

- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
  - We almost have this in PICO (COUPP) bubble chambers

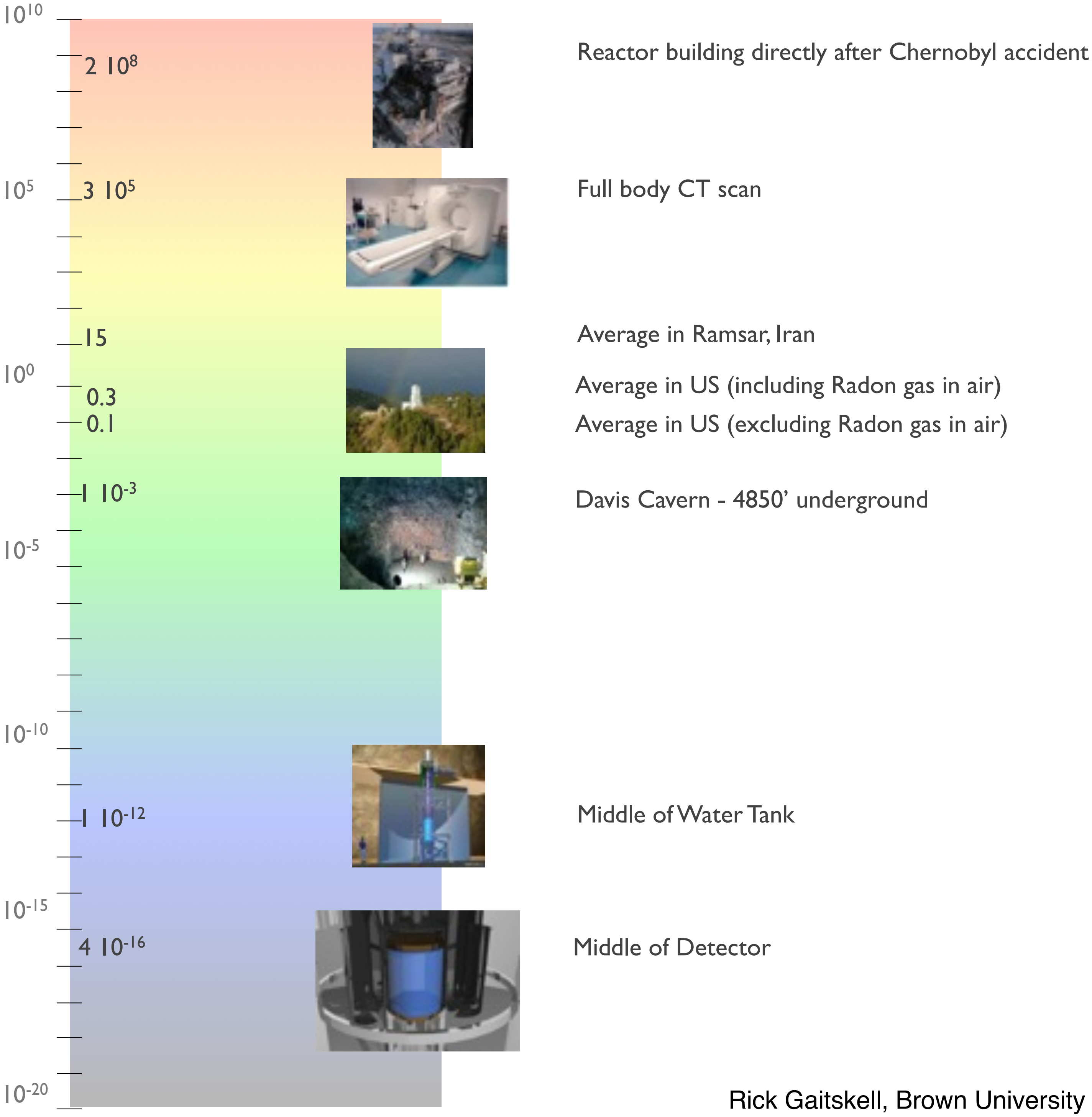
- However,
  - We will naturally be skeptical of the occasional events - do they fit the pattern
    - CF3I nuclear recoil events were time clustered
  - The absence of a <u>dark matter beam off test</u> means that it is particularly difficult to address the possibility of misidentification of backgrounds/systematic

- So we require more information about each event
  and for the detector response to be as homogeneous as possible
  - We also want to do physics with recoil energy spectrum / target dependence
  - Maybe we can return to the platonic ideal … reduce competing backgrounds

How Many Gammas/Second?



Effective Radiation Exposure per Hour from Gamma Rays

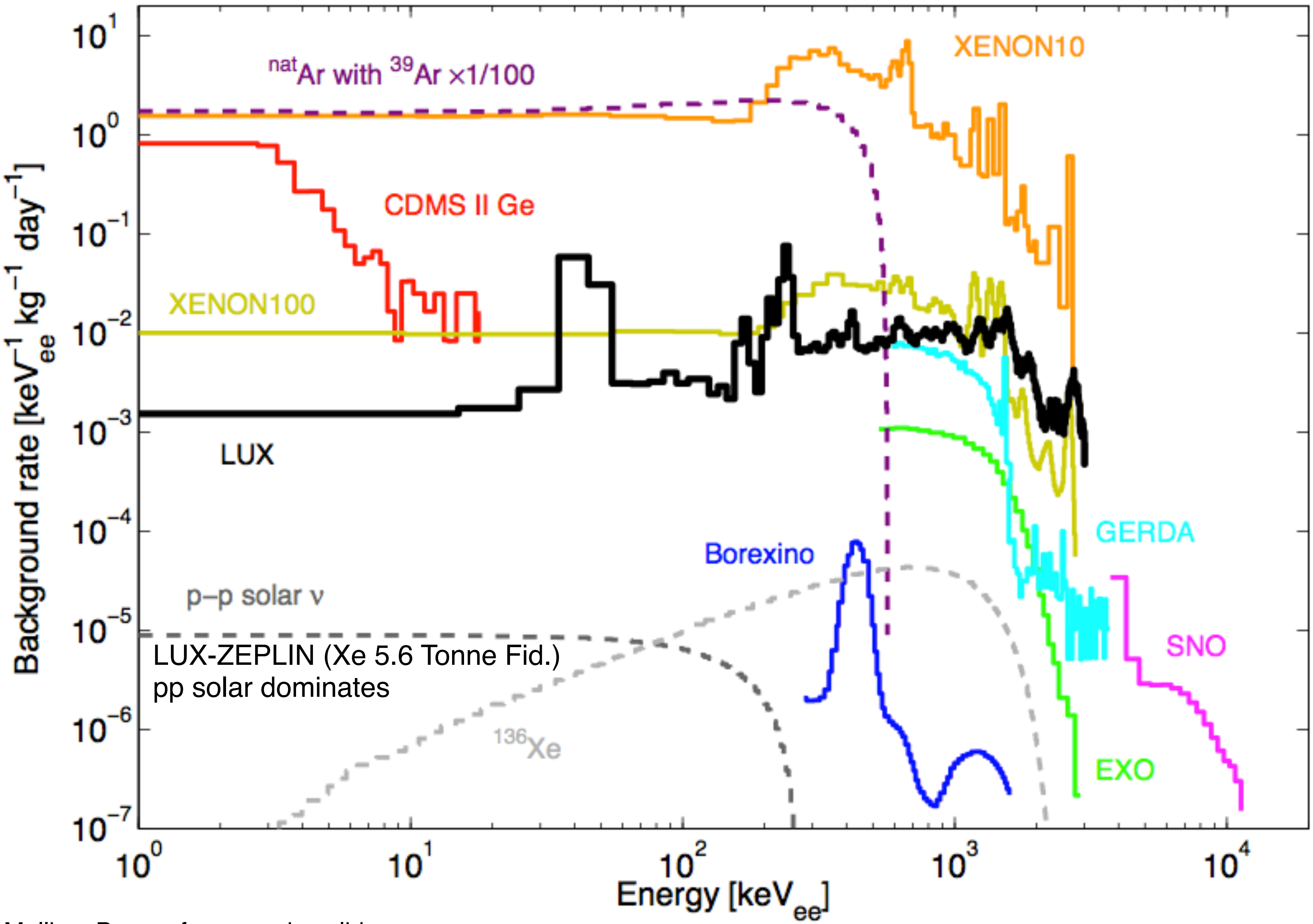


Rick Gaitskell, Brown University

*1 Gy = 1 J/kg = 100 rad

Reduction in Backgrounds

- Electron Recoil Events

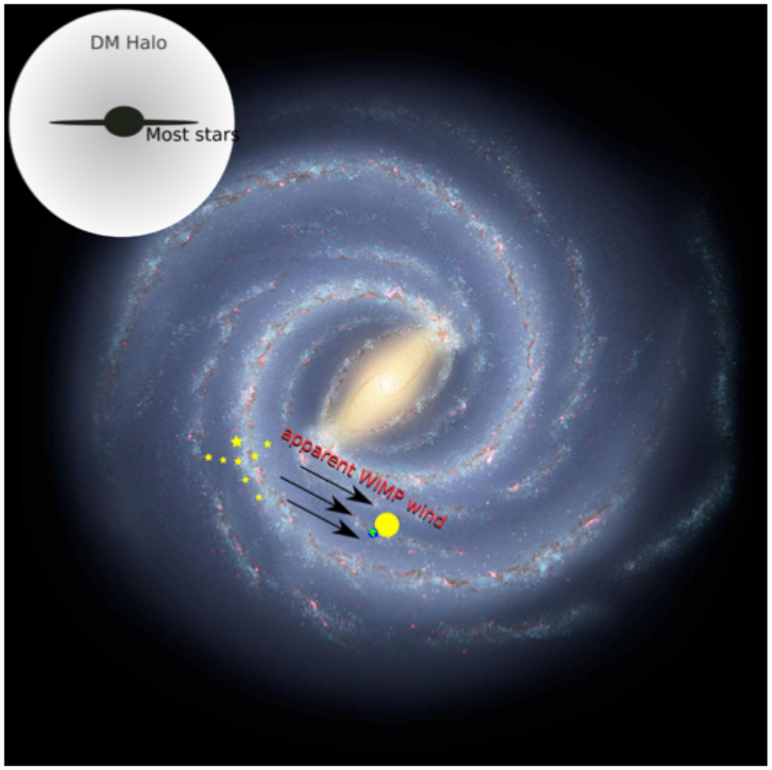


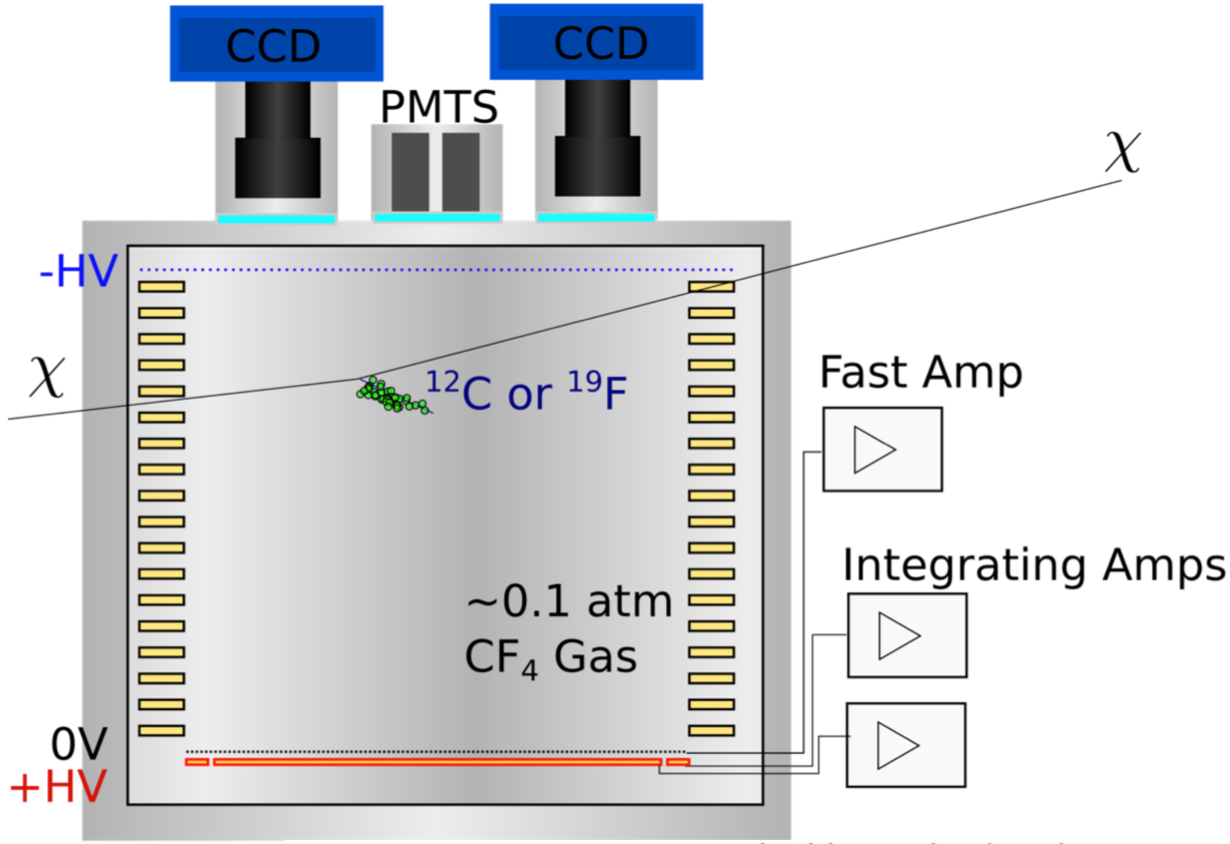
Thanks to David Malling, Brown, for preparing slide

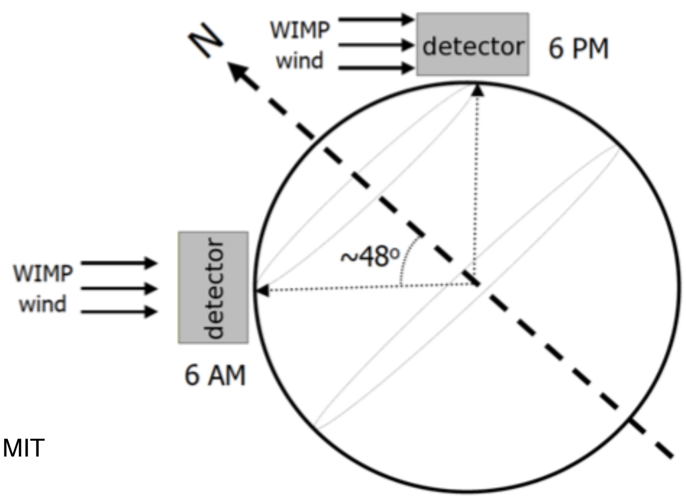
Idealized Dark Matter Direct Detection Experiment

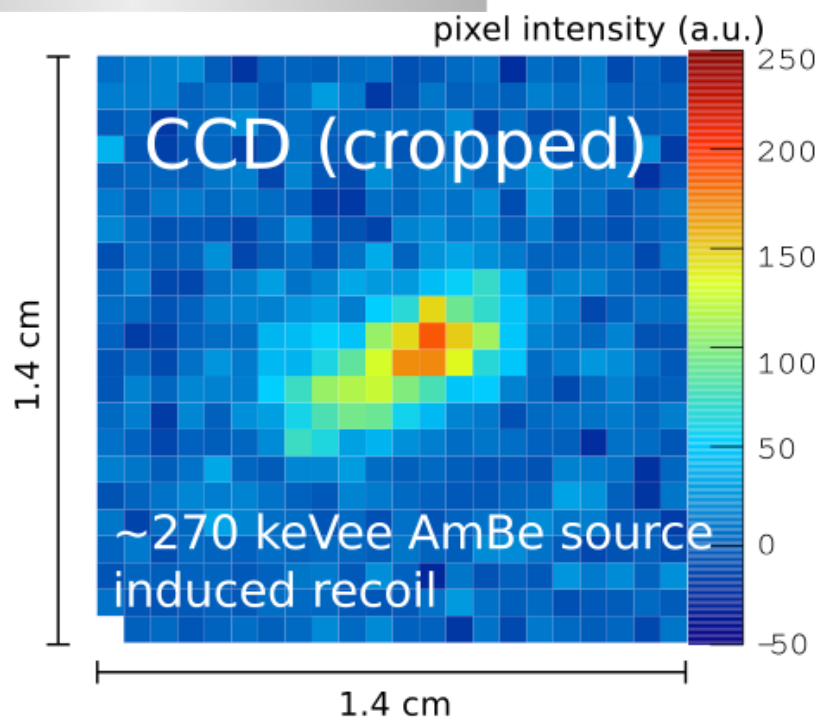
- Or a Signal that is Directional - a population of recoils that show strong correlation with a direction pointing away from Cygnus
  - Gas Targets (Low Density)

Directional - DMTPC





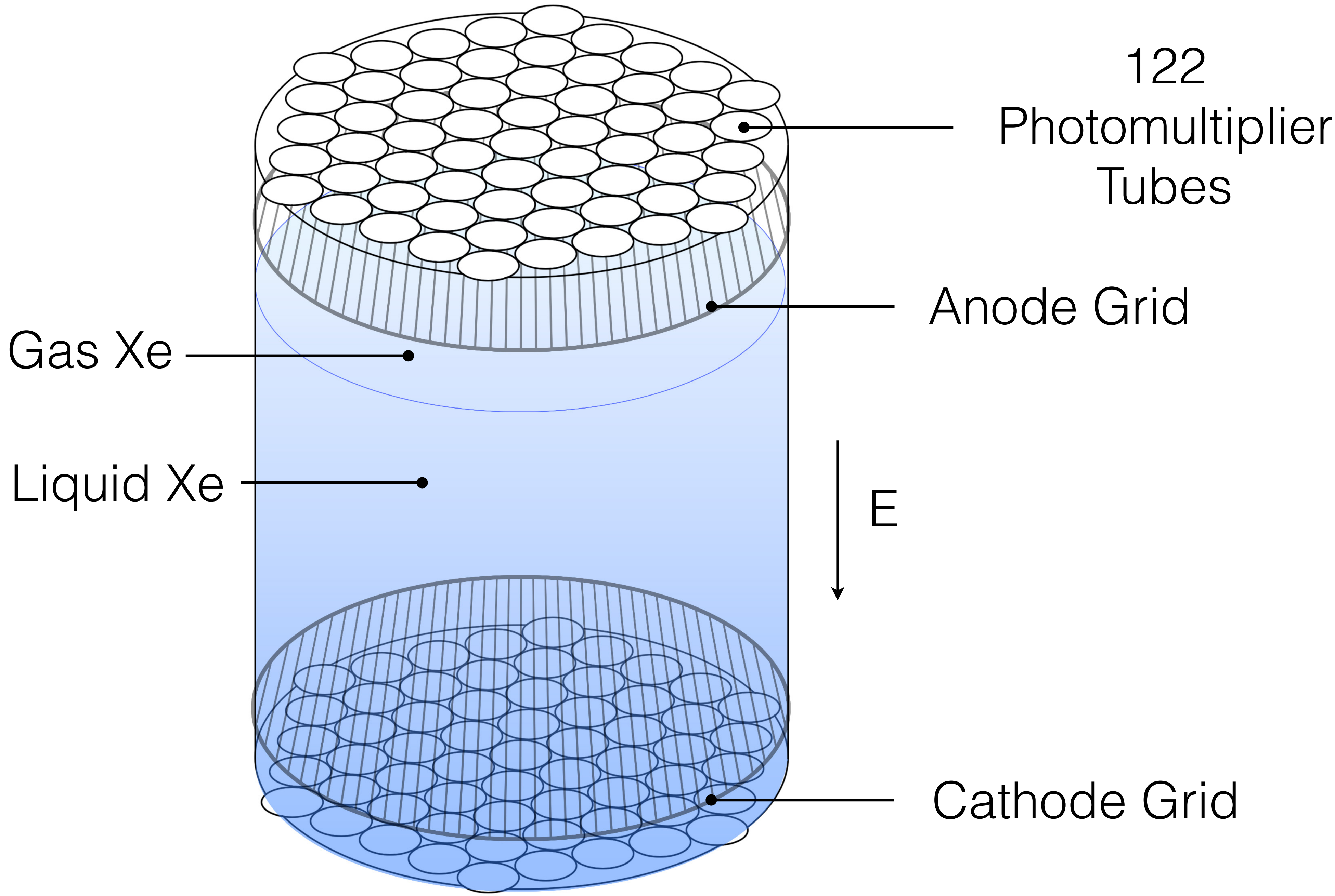


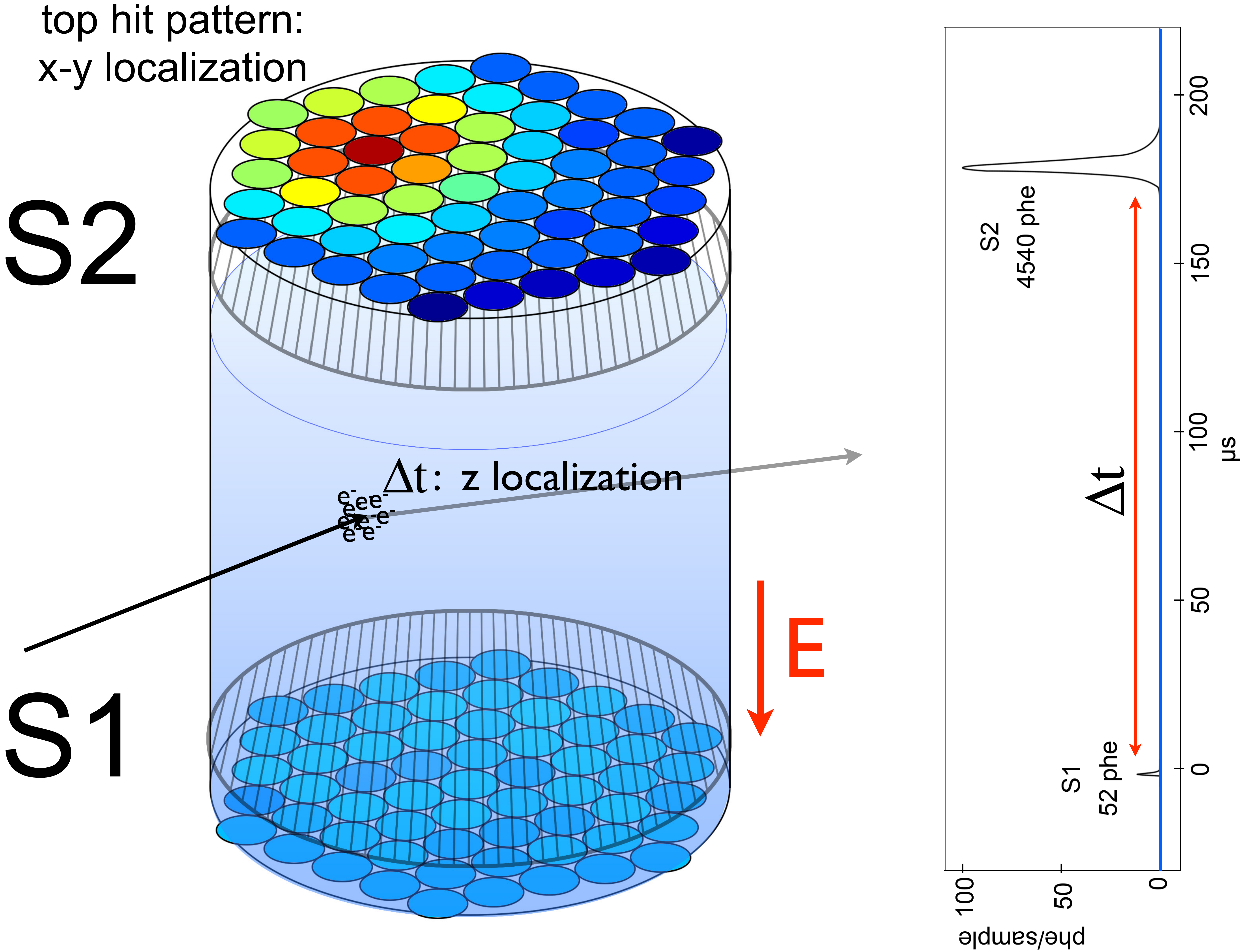


C Deaconu, MIT

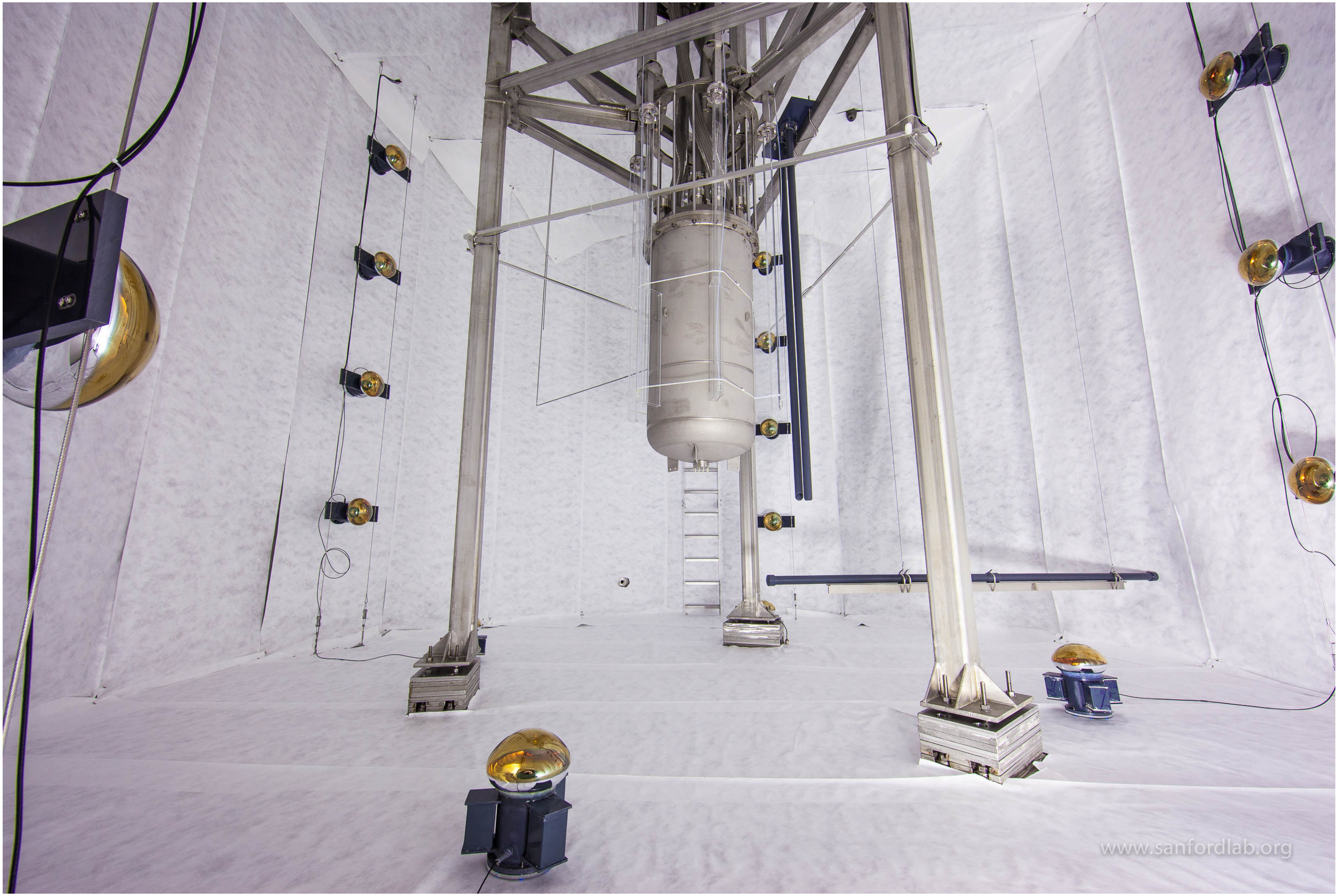
Recent Key Sensitivity Improvements

- Some targets have been scaling in size significantly
  - Provides raw sensitivity for lower cross sections - Club Sub Zepto $<10^{-45}$ cm^2 (<1 events/kg/century)
    - In 2 years sensitivity to 50 GeV WIMPs has improved by a factor 10. Recent LUX detector sensitivity ~10 / kg / Century
- Low Mass WIMPs - energy thresholds very important for sensitivity
  - Improving energy sensitivity/thresholds
    - Greater rate of sensitivity improvement for low mass WIMPs , all the way down to 3 GeV WIMPs
  - Improvements => Potential Signals - seen in multiple detectors, motivated detector energy threshold reduction
  - We have re-spawned quite an industry - smaller mass detectors able to make interesting contributions
- Very Low Energy Calibrations (Electron Recoil + Nuclear Recoil) are being hotly pursued in a range of materials
  - Some calibrations are up-ending previous shibboleths
  - Others are showing convergence in the understanding of response of specific targets
- Importance of Background Calibrations/Discrimination with very High Statistics
  - Allows Convincing Use of Likelihood Models for Signal + Background
  - Accuracy of Monte Carlos has become remarkable good
  - But requires the right detector geometry/calibrations in order to be credible
- Improving understanding of the detector response/physics of target material
  - In 90's/00's we saw a lot of effort in phonon, quasiparticle, electron-hole
  - In 00's/10's have seen tremendous progress in photon/ionization, and superheated liquids

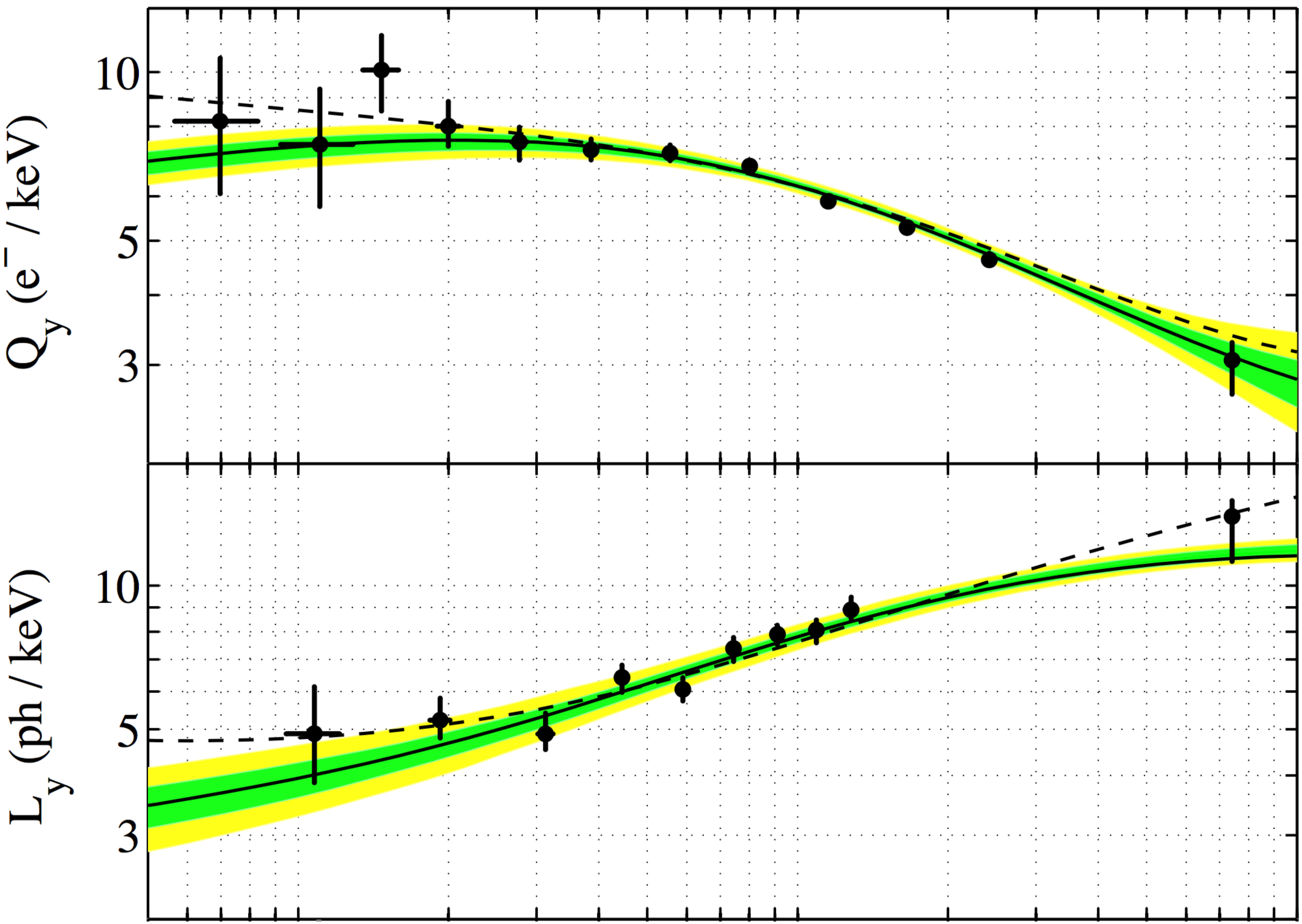

122
Photomultiplier
Tubes
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid


top hit pattern:
x-y localization
S2
S1
Δt: z localization
E
S2
4540 phe
S1
52 phe
Δt
phe/sample
μs

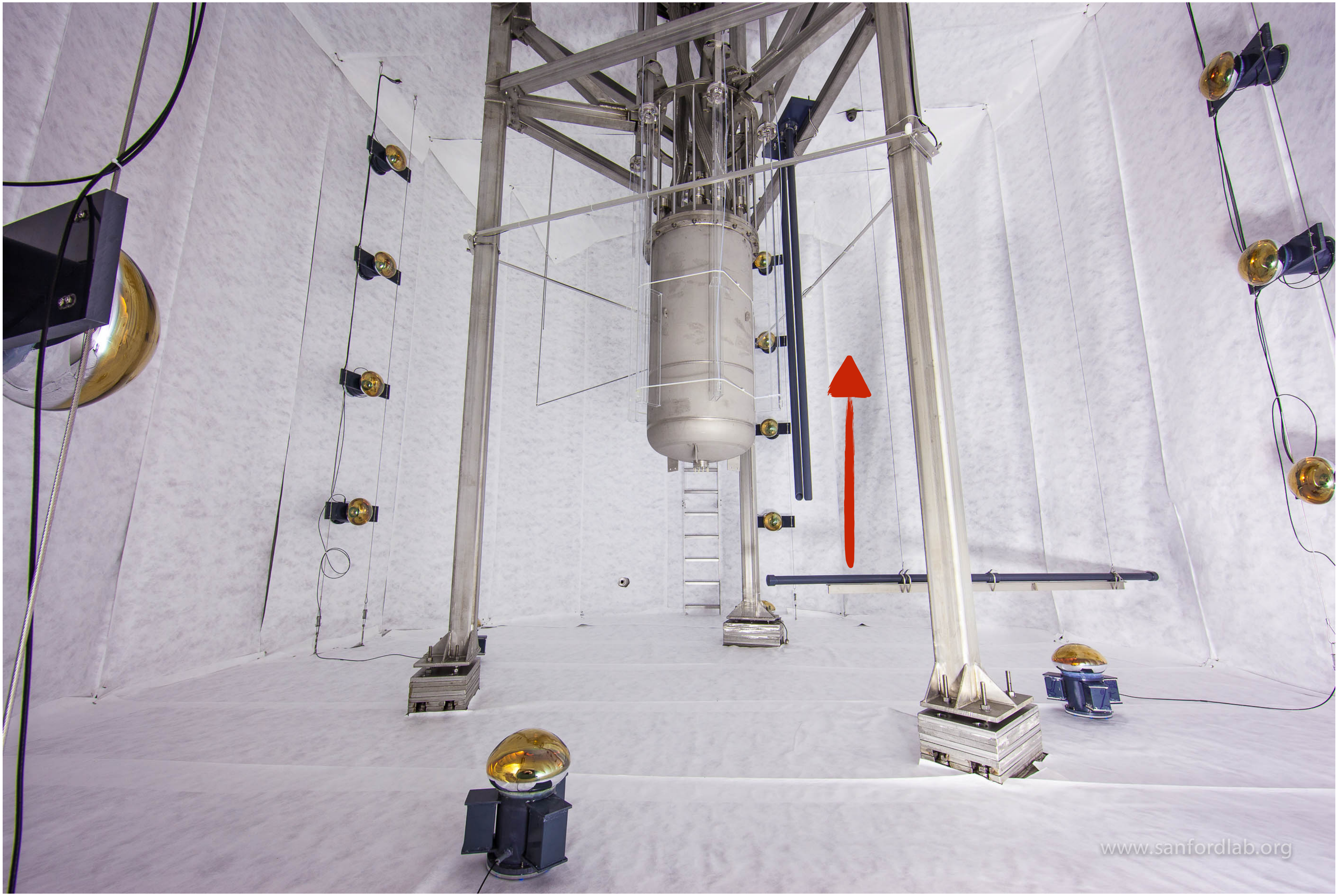
LUX in Water Tank - First Run 2013



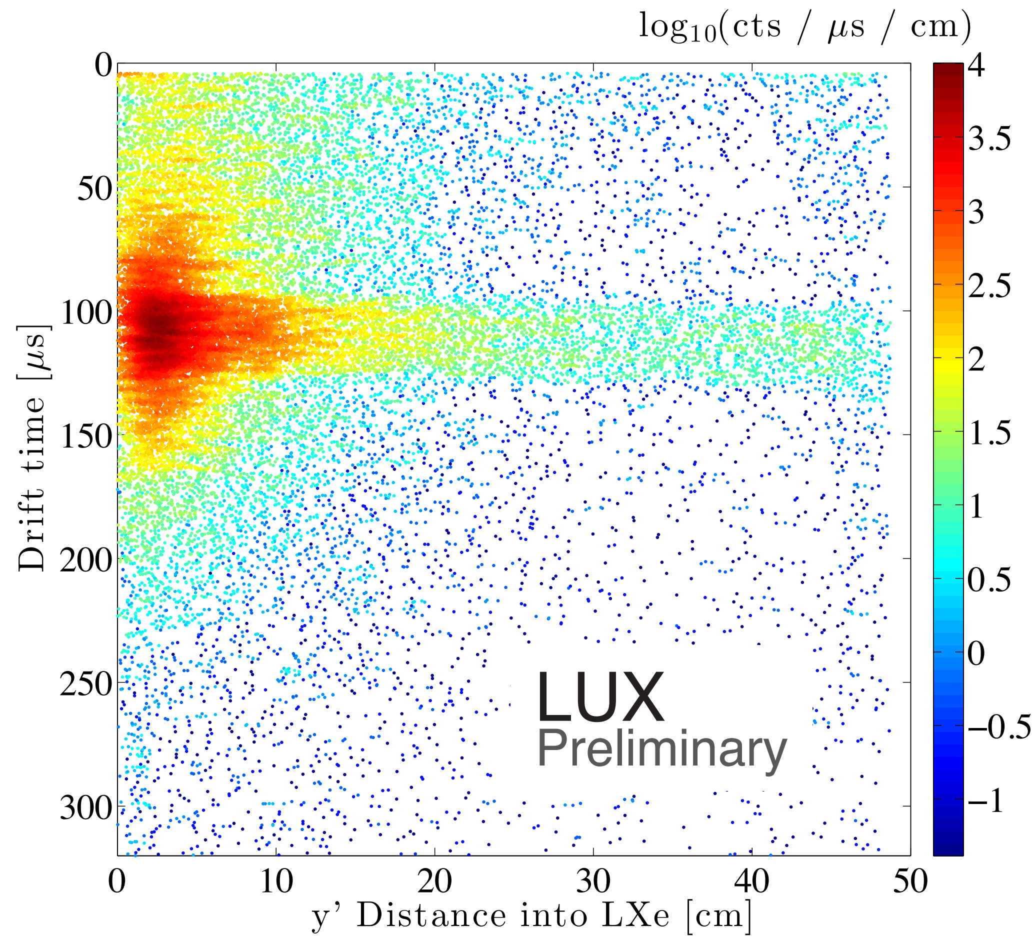
New Nuclear Recoil Calibration for Charge and Light (2015)



Neutron Conduit Installed in the LUX Water Tank

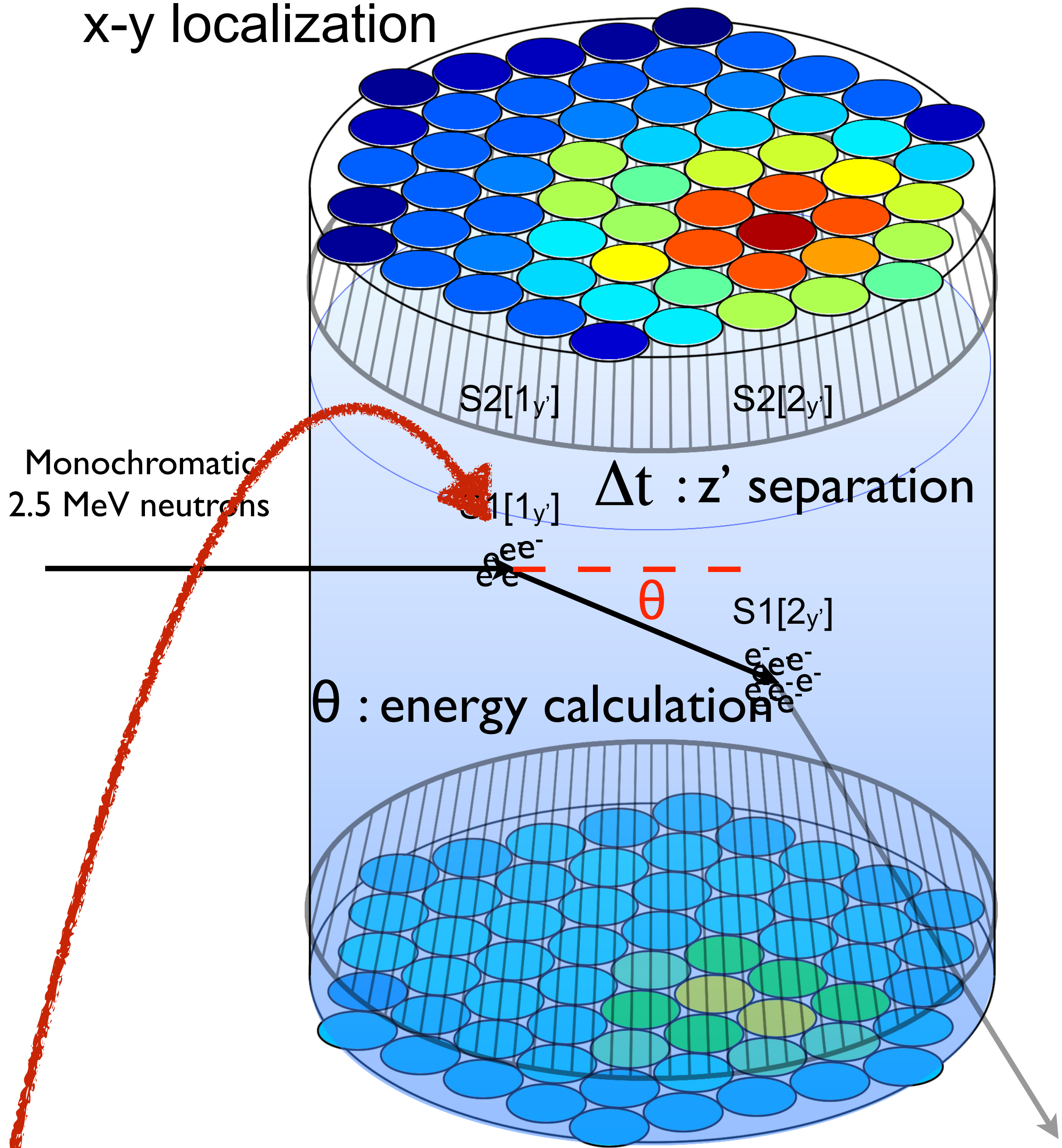


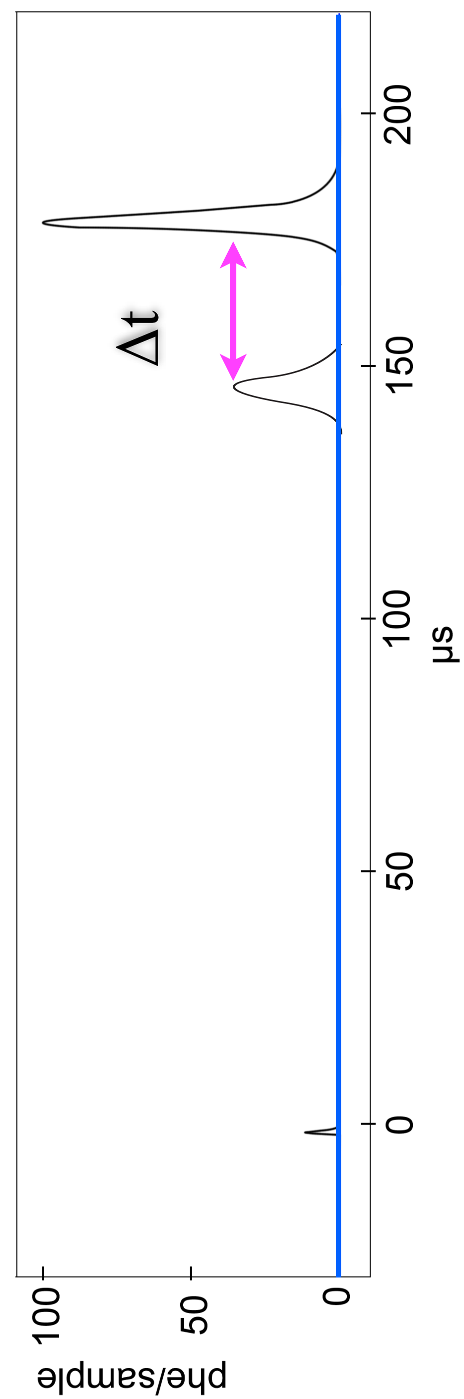
Adelphi Technology, Inc. DD108 Neutron Generator Installed Outside LUX Water Tank



- Neutron generator/beam pipe assembly aligned 17 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 107 live hours of neutron tube data used for analysis

top hit pattern:
x-y localization

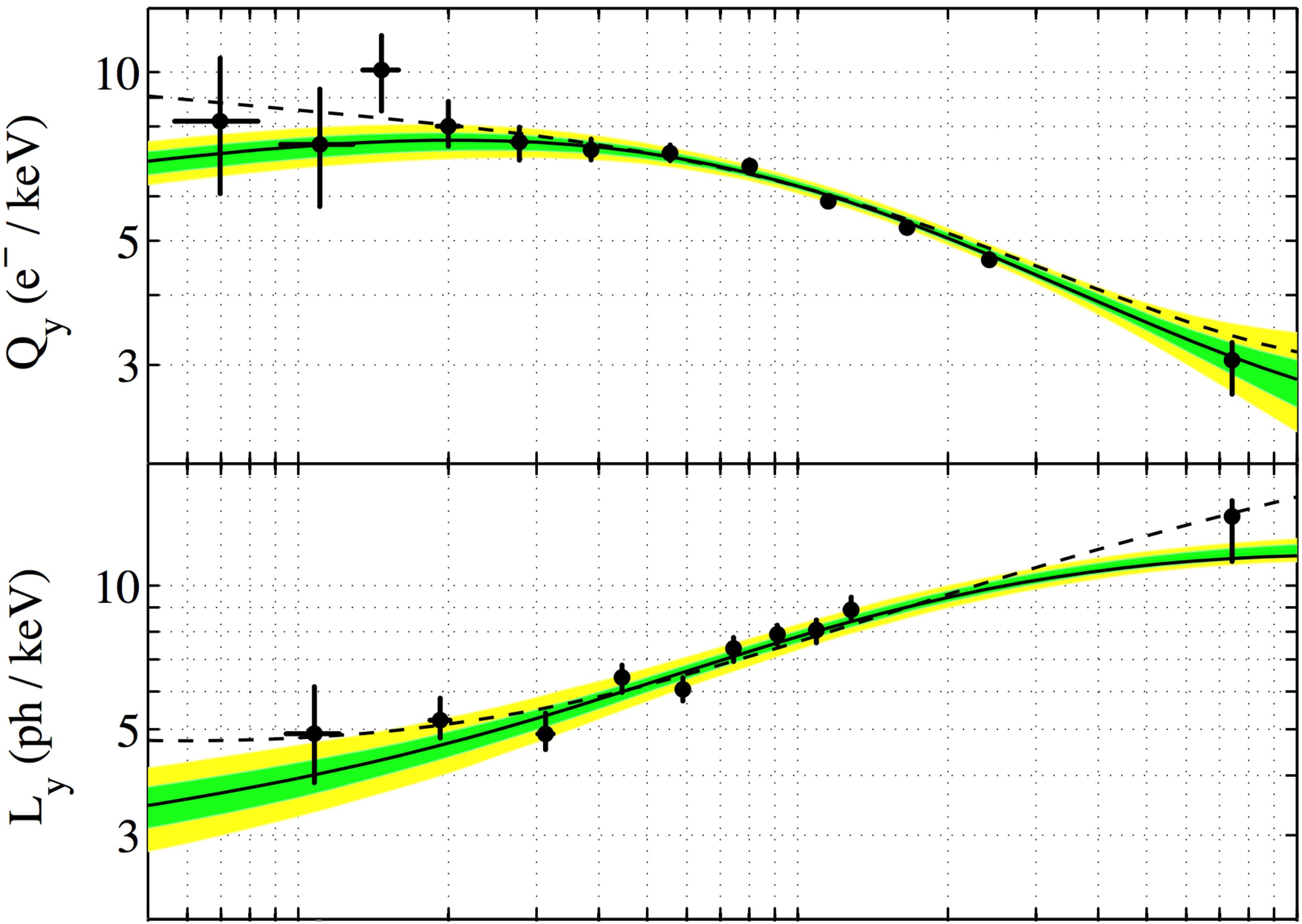




$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

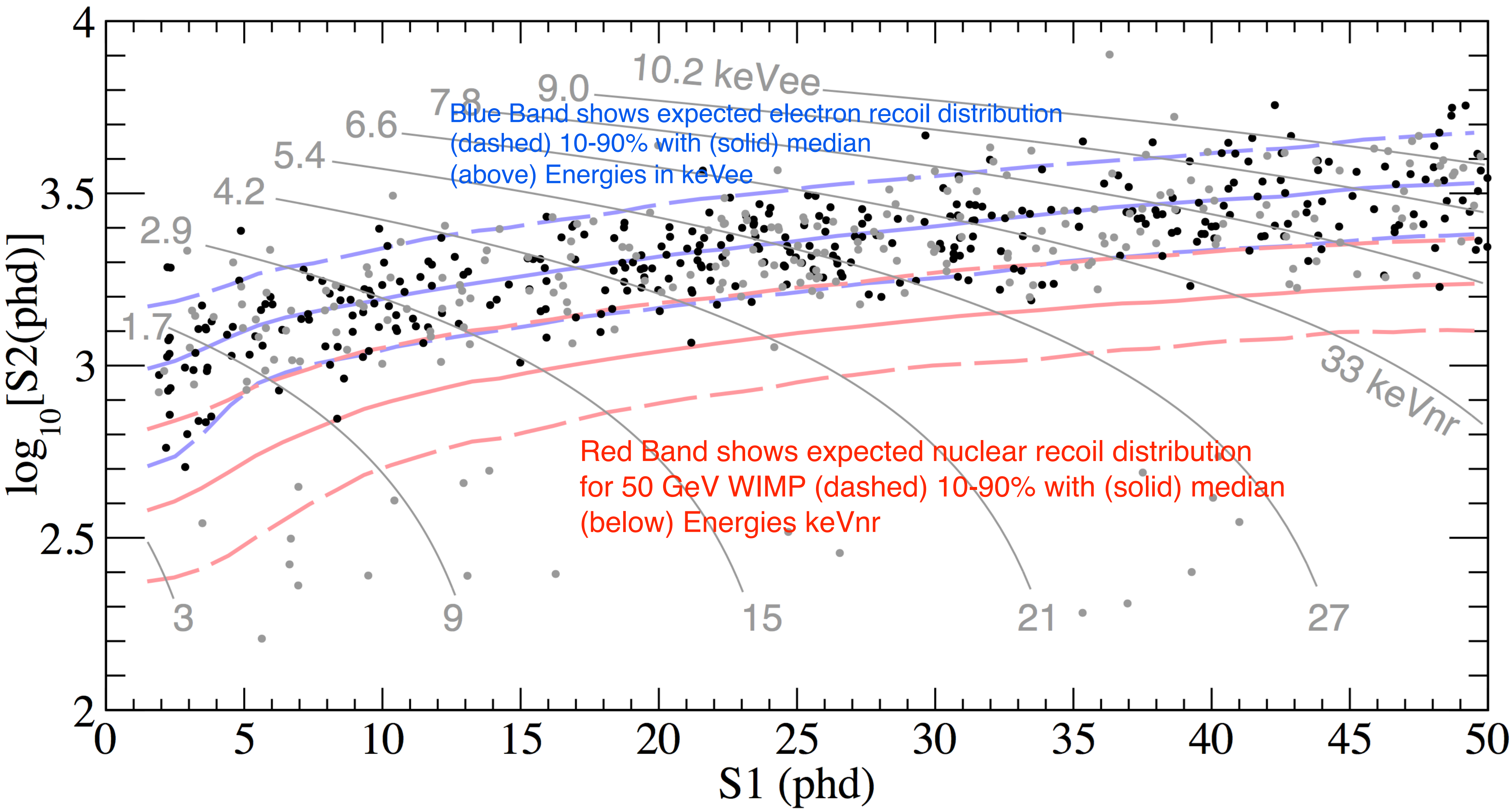
Samuel Chan, Carlos Faham for the LUX Collaboration

New Nuclear Recoil Calibration for Charge and Light (2015)



New Analysis Just Announced this week (December 2015)
95 live days x 145 kg fiducial mass

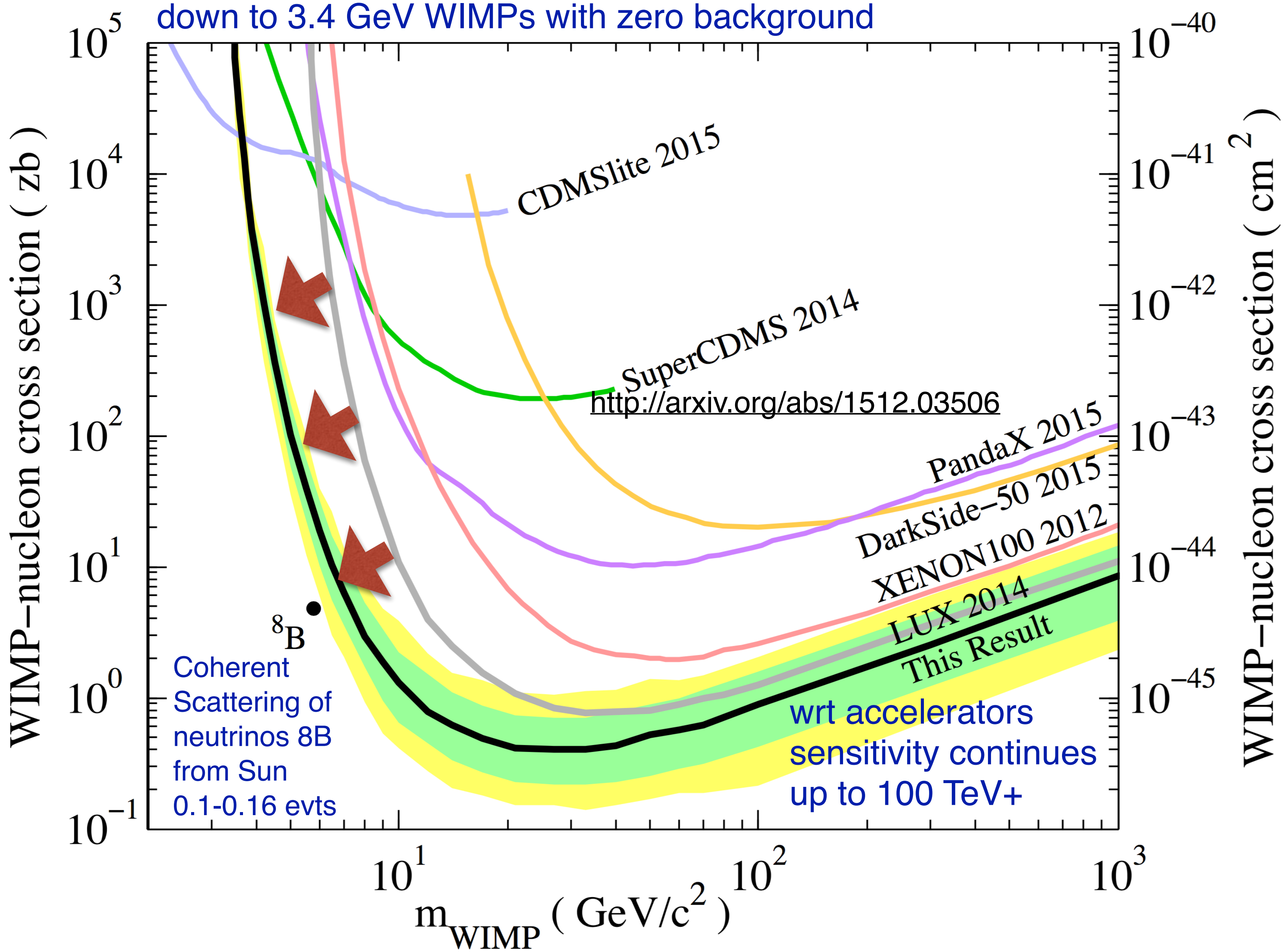
- Complete re-anaysis of data taken in 2013
- (black) Radius < 18 cm (grey) Radius 18-20 cm   Max Radius 24 cm



Pushing Low Mass Search - New LUX Result

http://arxiv.org/abs/1512.03506 Submitted to PRL

Search sensitivity improved significantly to look down to 3.4 GeV WIMPs with zero background



LUX in Water Tank - Second Run 2014-2016

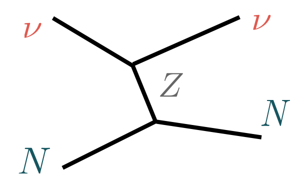
LUX Summary

- New LUX Analysis of 2013 data
  - Calibrated response and acceptance efficiencies with low systematics all the way down to 1.1 keVnr
  - Improved by >20x sensitivity at 8 GeV mass, >2x at 33 GeV mass
  - Gives world-leading sensitivity at >=3.7 GeV mass
  - No evidence for WIMP candidate events in data - signal distributions fully consistent with background model
    - Internal Backgrounds (in Xenon): Ar-37, Kr-85m, Xe-127

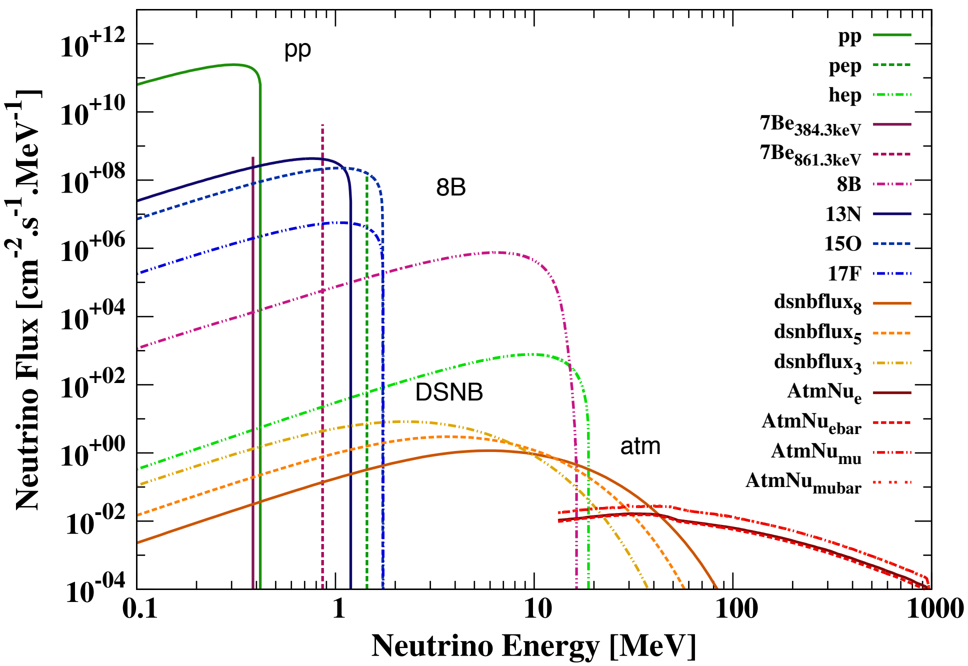
- LUX has continued to take WIMP Search data in late 2014, 2015 and will do until mid 2016
  - Goal is >300 live days
  - Detector will then be removed from Sanford Lab/Davis Lab to make way for LZ Experiment

Expected Neutrino Backgrounds

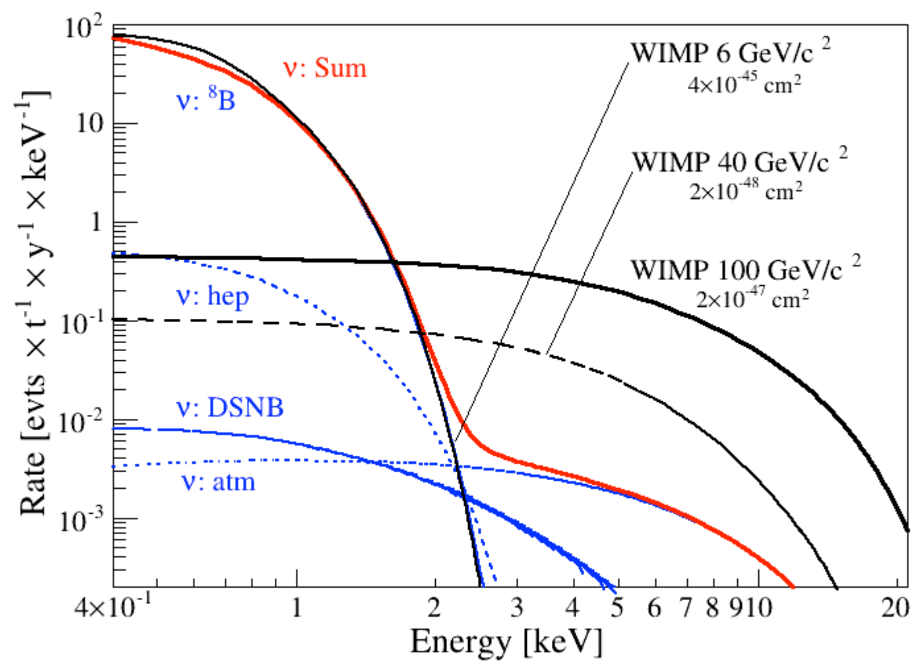
- Neutrino-electron scattering provides a “conventional” background that will dominate electron recoil rates in inner fiducial region of 10 tonne Xe detector
  - Requires ER rejection at 99.5%+ level to remove
- Neutrino-nucleus coherent scattering (solar, atmospheric and supernovae neutrinos) ultimately becomes WIMP search background



$$\nu + N \longrightarrow \nu + N$$



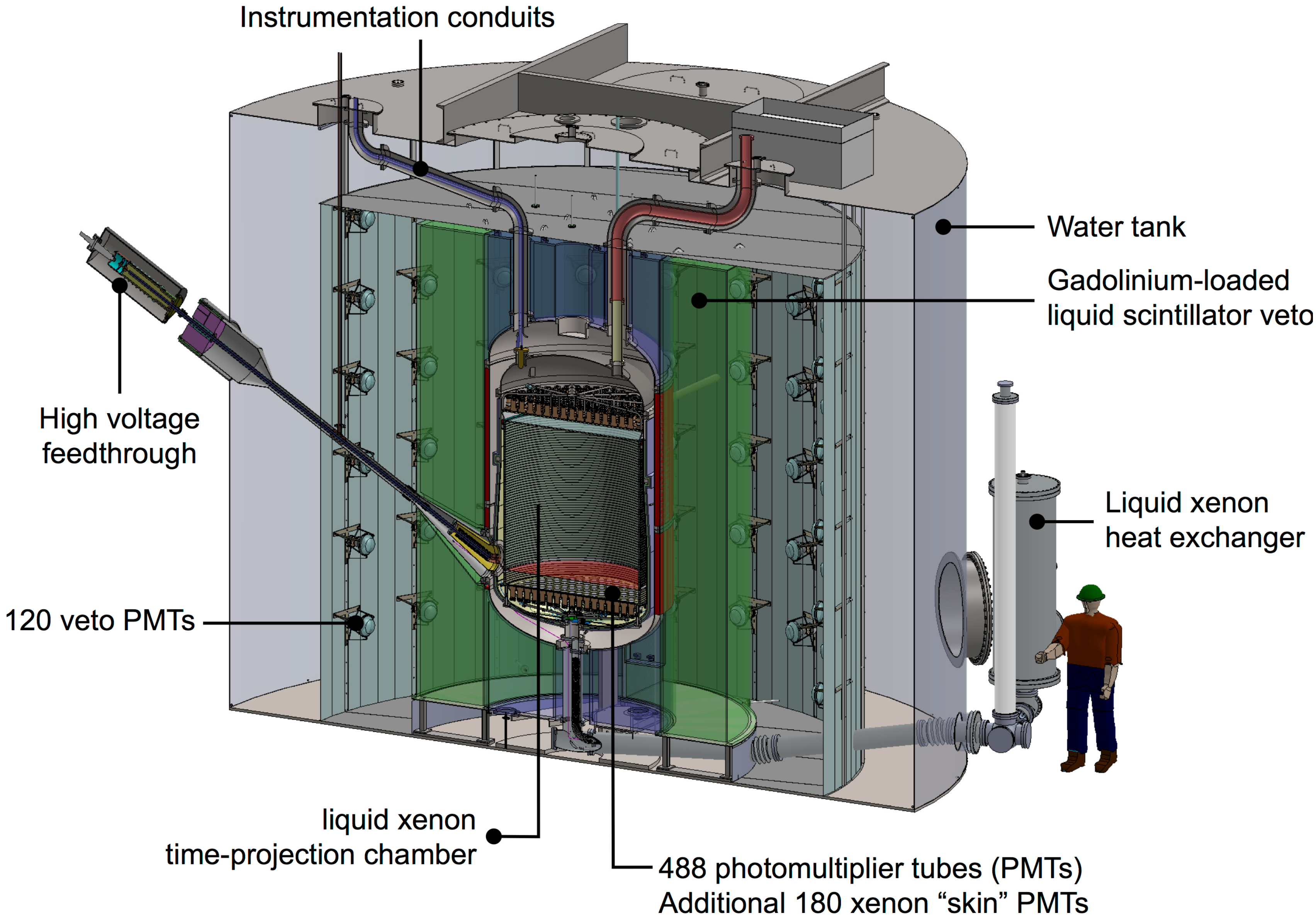
F. Ruppin et al., 1408.3581



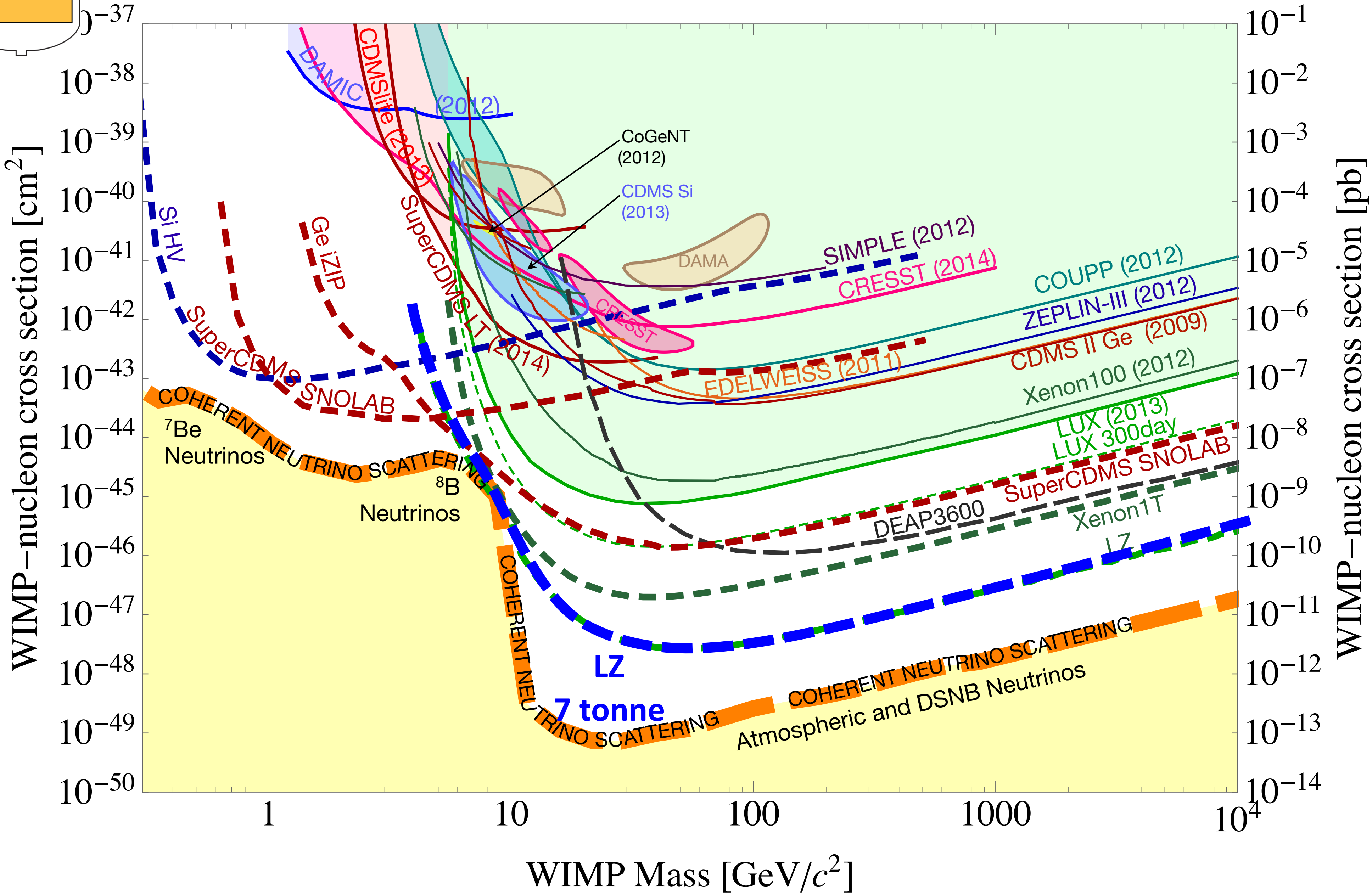
Laura Baudis et al., JCAP01 (2014) 044

LZ Detector - 10 tonnes Xe

Replaces LUX at the Sanford Underground Research Facility (SURF)



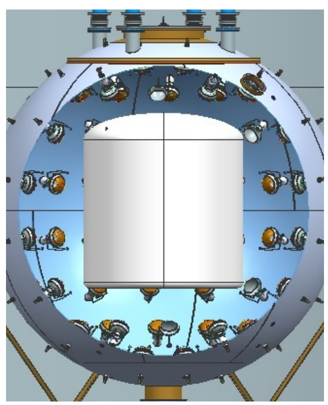
LZ on Snowmass über Plot



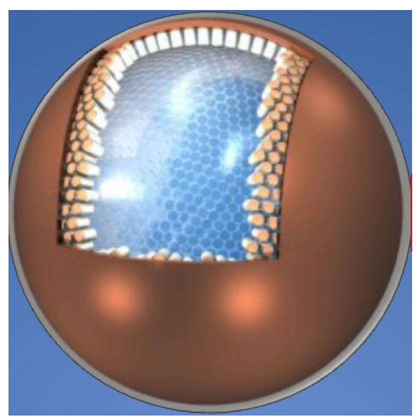
Future noble liquid detectors

- **Commissioning: XENON1T (3.3 t LXe) at LNGS**
- Project fully underway LXe: LUX-ZEPLIN 10t (First dark 2019)
- Proposed XMASS 5t LXe
- Proposed LAr: DarkSide 20 t LAr, DEAP 50 t LAr

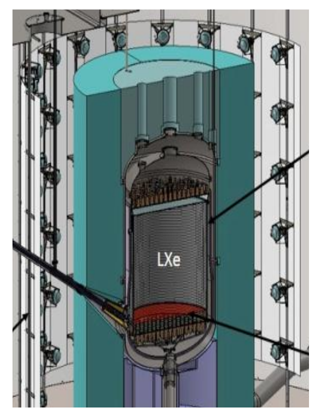
XENON1T: 3.3 t LXe



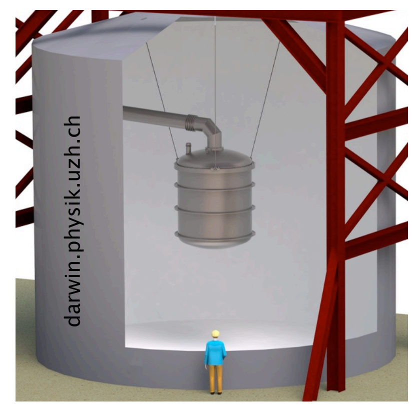
DarkSide: 20 t LAr



XMASS: 5t LXe



LZ: 7t LXe



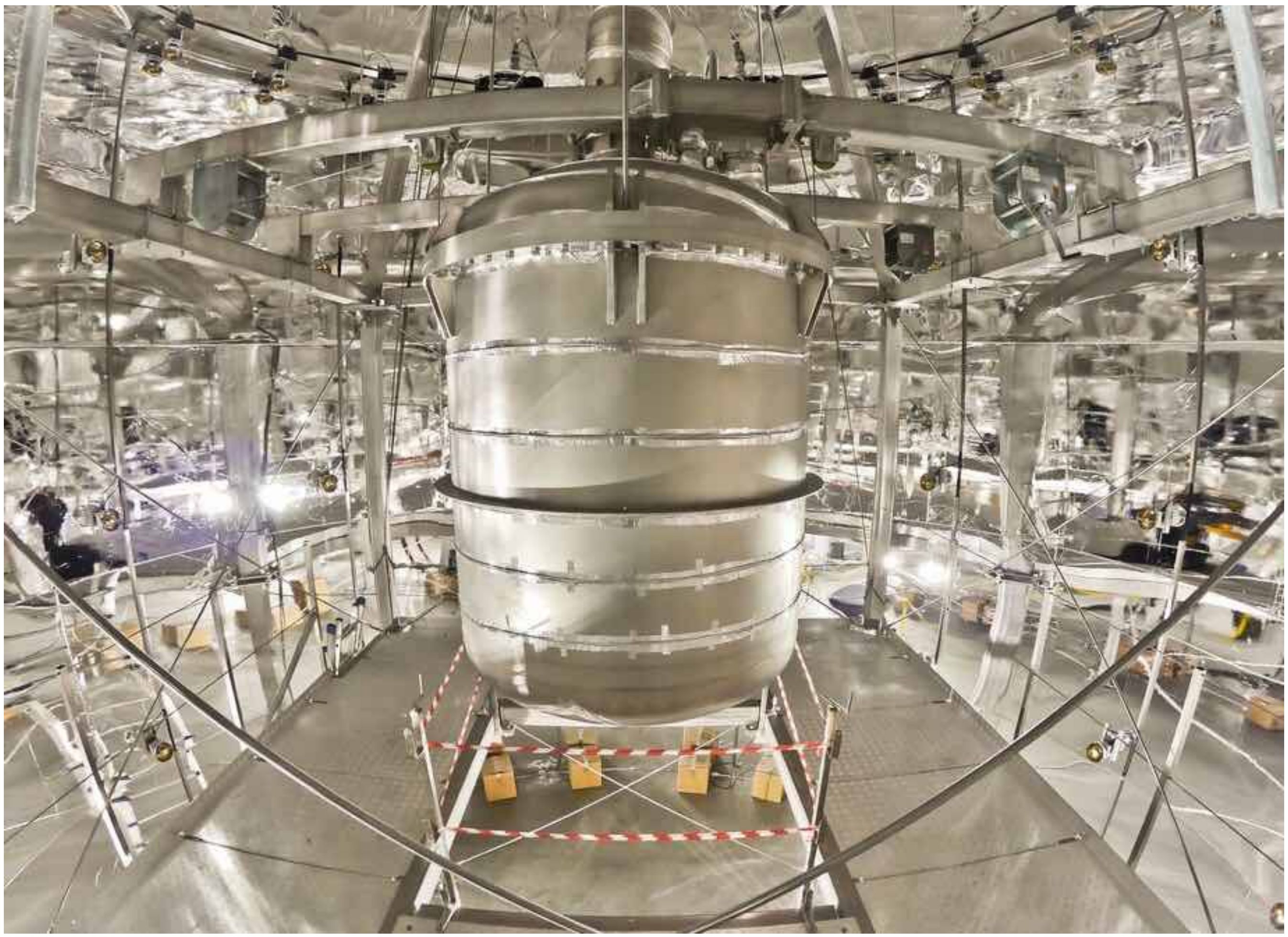
DARWIN: 50 t LXe

XENON1T Systems

Elena Aprile, Session B2: Dark Matter I

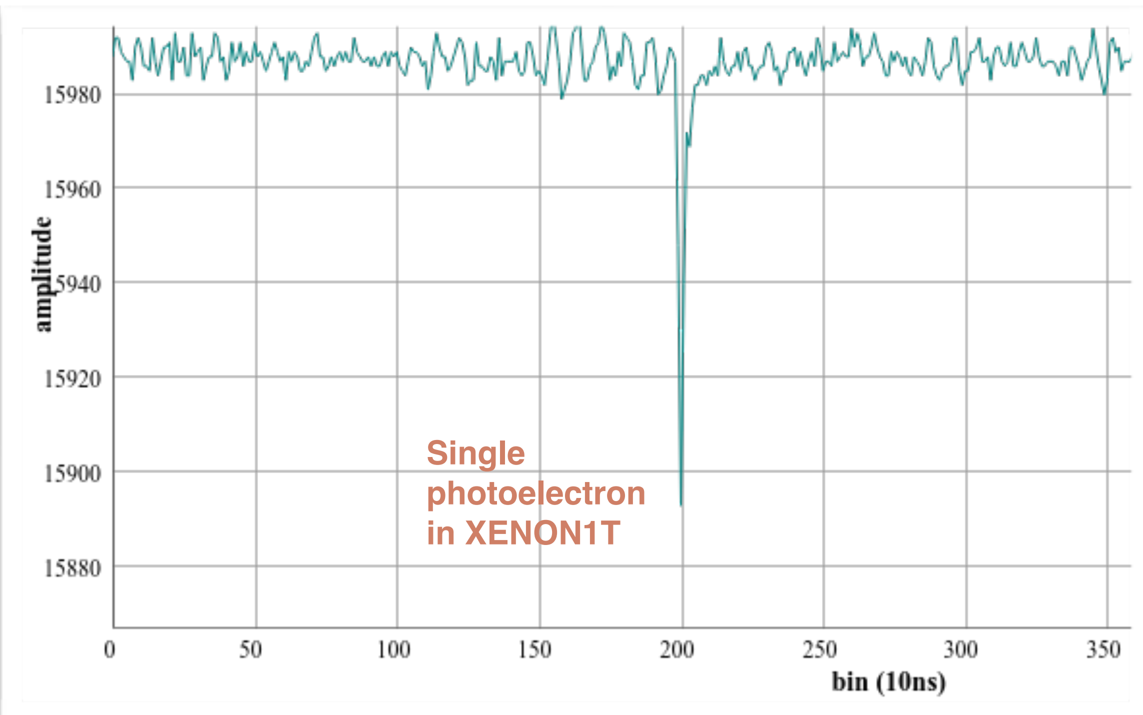
XENON1T: status of construction work

- Water Cherenkov shield, cryostat support, service building, electrical plant completed
- Cryostat, cryogenics, storage, purification, cables, fibres installed and commissioned

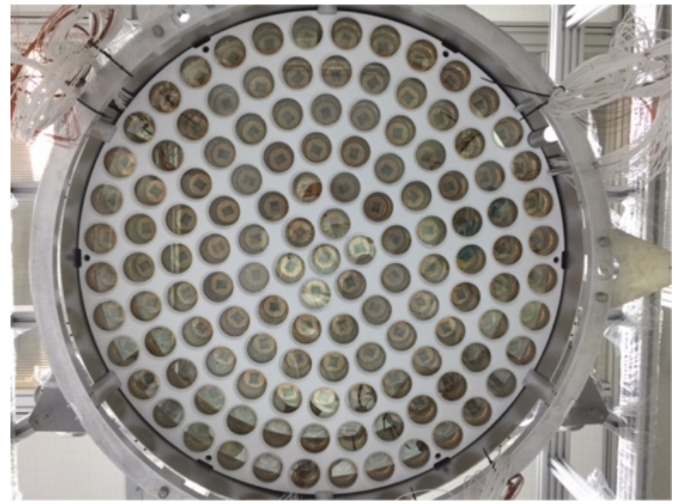


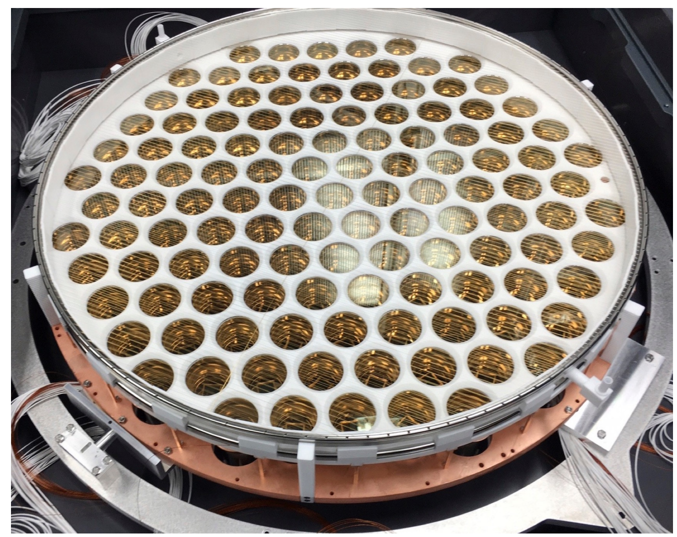
XENON1T: first light

- Underground in November 2015, cryostat closed
- Next steps: Rn emanation measurement
- **Single photoelectron acquired with the new DAQ after cryostat was closed**



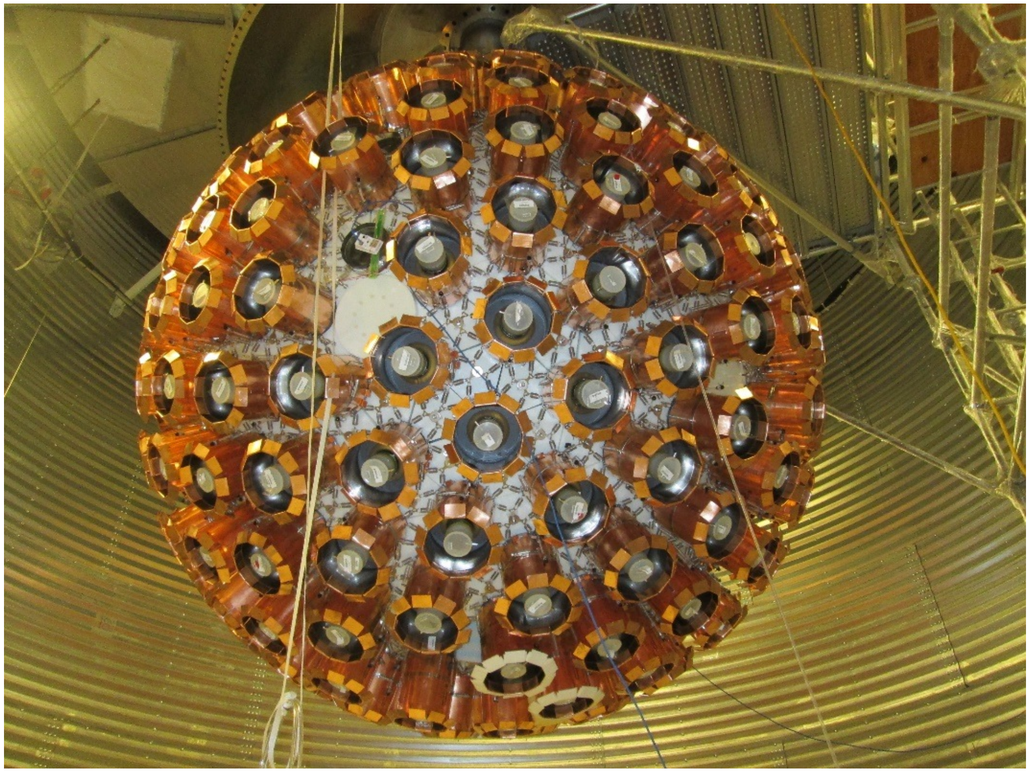
Top array: 127 PMTs





Bottom array: 121 PMTs

DEAP-3600 Detector at SNOLAB



Completed inner detector
255 8” R5912HQE PMTs
installed in water shield tank

Steel Containment Sphere
in 8m diameter water shield tank

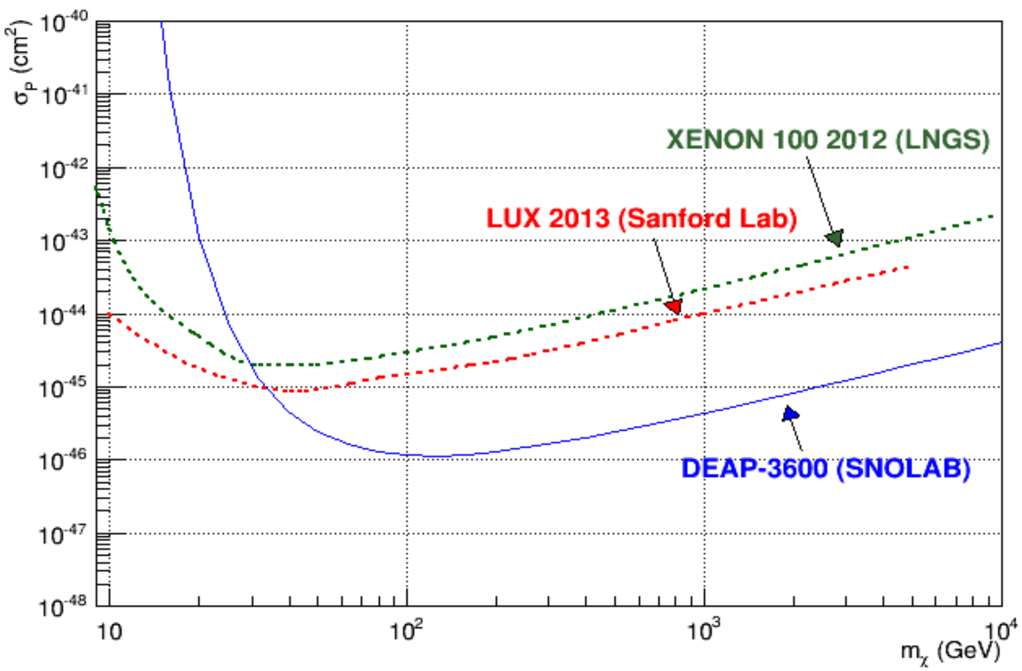
DEAP-3600 Dark Matter Search at SNOLAB

Project Overview

3.6 tonnes liquid argon in ultraclean acrylic vessel, 255 8-inch HQE PMTs

1 tonne fiducial mass designed for < 0.2 background events/year

10^{-46} cm^2 sensitivity for ~100-GeV WIMP with 3-year exposure



Project Timeline

Argon gas runs and in-situ background measurements, commissioning	Fall 2015
Physics Data start	Early-Mid 2016

Future Project

Planning for development of future 50-tonne argon experiment (photo-detector development, low-background argon and engineering proposal)

The Practical Matter of a Low Energy Rare Event Search

- Dark Matter signals will be expected to appear first in the lowest energy bins of an experiment that is still in search mode
- Unfortunately, that is also where the first indications that systematics are starting to dominate

Thresholdinos

- You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram - Attributable, in spirit to Lord Rutherford (I believe)
- It is difficult to control systematics that may cause events to be in edge bins/tails
  - This is particularly important when a result is dependent on subtle effects
- And we will need to push the detectors by another 10^4 before we reach the irreducible coherent scattering atm. neutrino backgrounds

The Practical Matter of a Rare Event Search

- In 28th year of searching - now at a sensitivity that 10^5 better than the first round - we need detectors with a

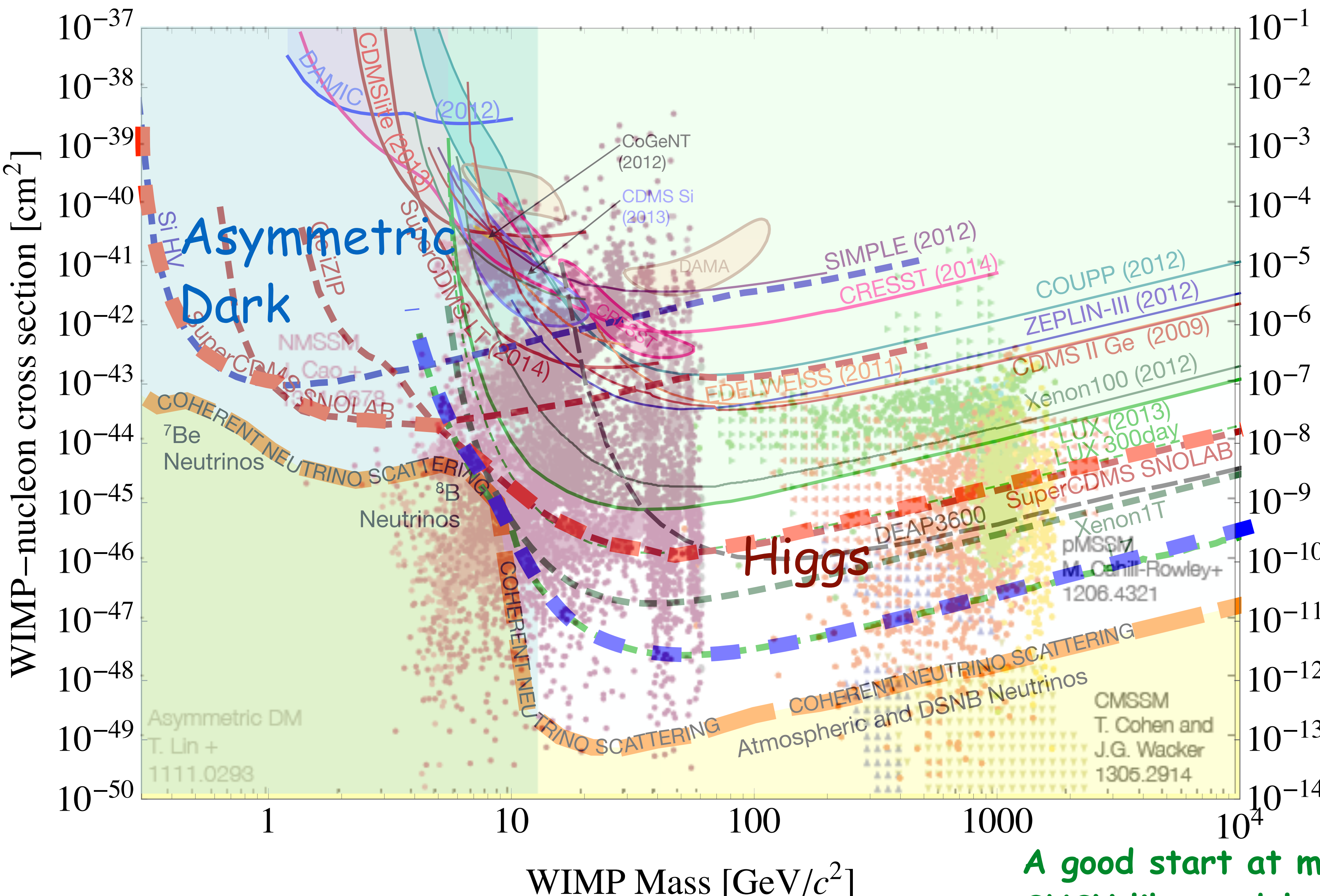
Low Sisyphean Index †

- They must want to work correctly / do so without misleading us / low complexity - mustn't roll back down the hill when we stop paying attention for a moment

- And we will need to push them (pun indented) by another 10^4 before we reach the irreducible coherent neutrino backgrounds

† Experimentalist's Perspective of the Technology itself, not the definition that the task can never be completed

Future Searches



A good start at mapping SUSY like models

Conclusions - Direct Detection

- US Selection Process of G2 “Generation 2” Dark Matter Experiments: LZ, SuperCDMS, ADMX
  - LZ completed CD1 and will do CD2/3B in April 2016
  - SuperCDMS CD1 Nov 2015
    - This would allow a more competitive program to be backed with multiple targets
- New Results Expected in 2016
  - LUX >300 day exposure
  - DEAP3600
  - XENON1T preliminary results from early running
- Low Mass WIMP signal(s) - sensitivity has improved by three orders of magnitude since 2012
  - Critically there has also been an improvement in our understanding of potential systematics in detector response
  - This Focus - Has brought the best out of people. Yes, we are combative, but that is the spice that makes the best sauce, and it has caused us to hone our arguments, and improve our detailed understanding of the detectors/backgrounds
  - Calibration strategies that can provide abundant statistics, and have low systematic uncertainties are critically important
- We have improved the sensitivity to 50 GeV WIMPs by over an order of magnitude in the last two years (Compare 5 orders of magnitude in the last 25 years => we are accelerating progress)
  - Let us look forward to doing something similar over coming years

Brown Particle Astrophysics Group - Postdoc Position

- https://academicjobsonline.org/ajo/jobs/6834

- Search currently active

- Postdoctoral Position in Experimental Particle Astrophysics/High Energy Experiment with my Particle Astrophysics group

END