Understanding WIMP Searches

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Co-Spokesperson, LUX Collaboration
Ex-Spokesperson, LZ Collaboration

Particle Astrophysics Group, Brown University, Department of Physics

(Supported by US DOE HEP)

see information at

http://particleastro.brown.edu/

http://luxdarkmatter.org

BBC, Nov 2014

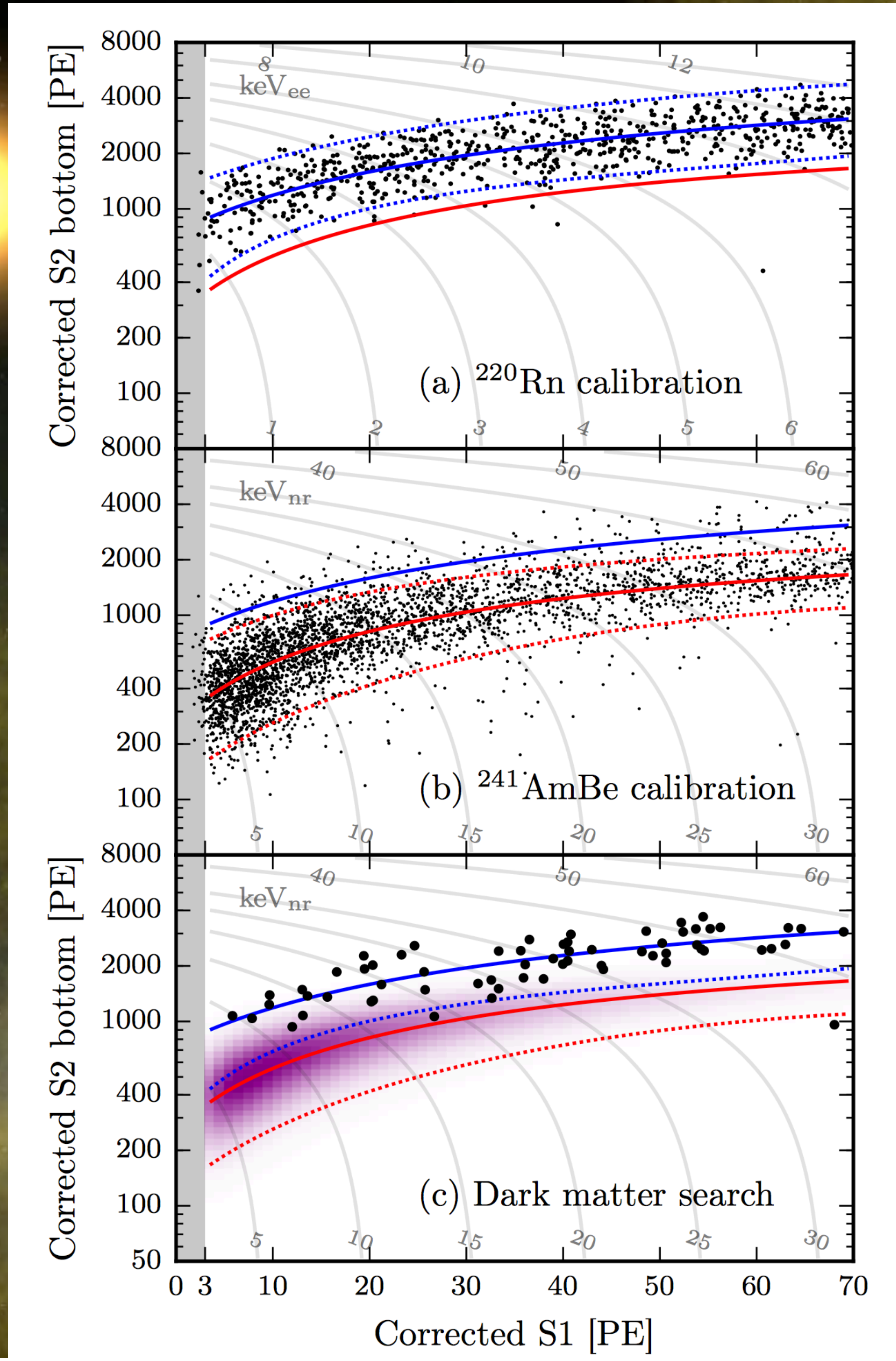
Gaitskell / Brown University

- What does it take to find WIMPs directly?
- Have we already discovered WIMPs?
- Have we got what it takes to (re)discover them?
  - Acc: $/TeV
  - Indirect Detection: Annihilation in Galactic Center expected to be strong, but do we understand BGs? Dwarf Galaxies Weak Signal, but lower systematic in BG
  - Direct Detection: ~1 / kg / Century to < 1 / tonne / Century
- Complementarity / This Talk Focuses on Direct Detection

How can we be so confident we are seeing nothing?

How can we be so confident we are seeing something?

How can we be so confident we are seeing dark matter?



XENON1T First Results
ArXiV 1705.06655

28 years in dark matter

CDMS II: Winter
@Soudan Minnesota

Sanford Lab
LUX & LZ @Lead,
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]

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[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
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[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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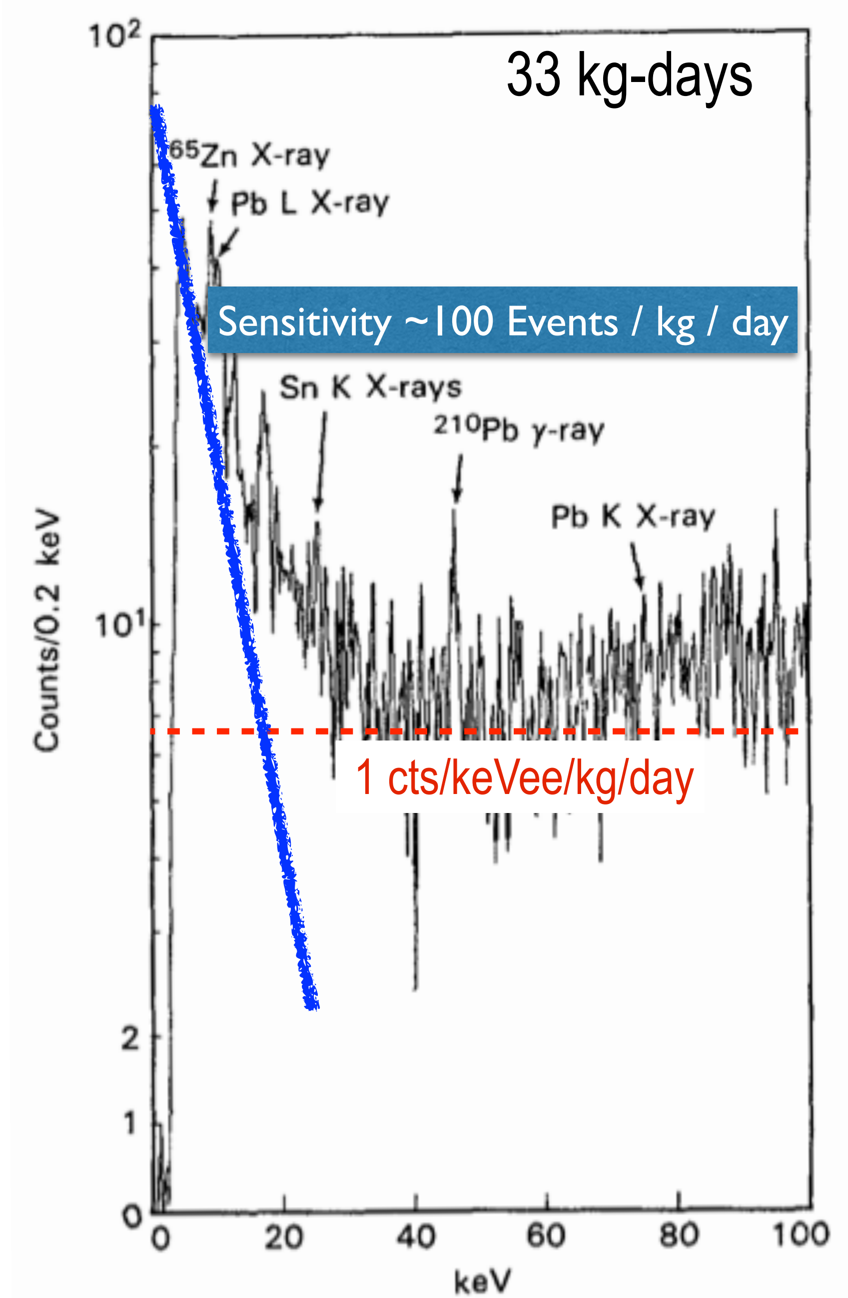
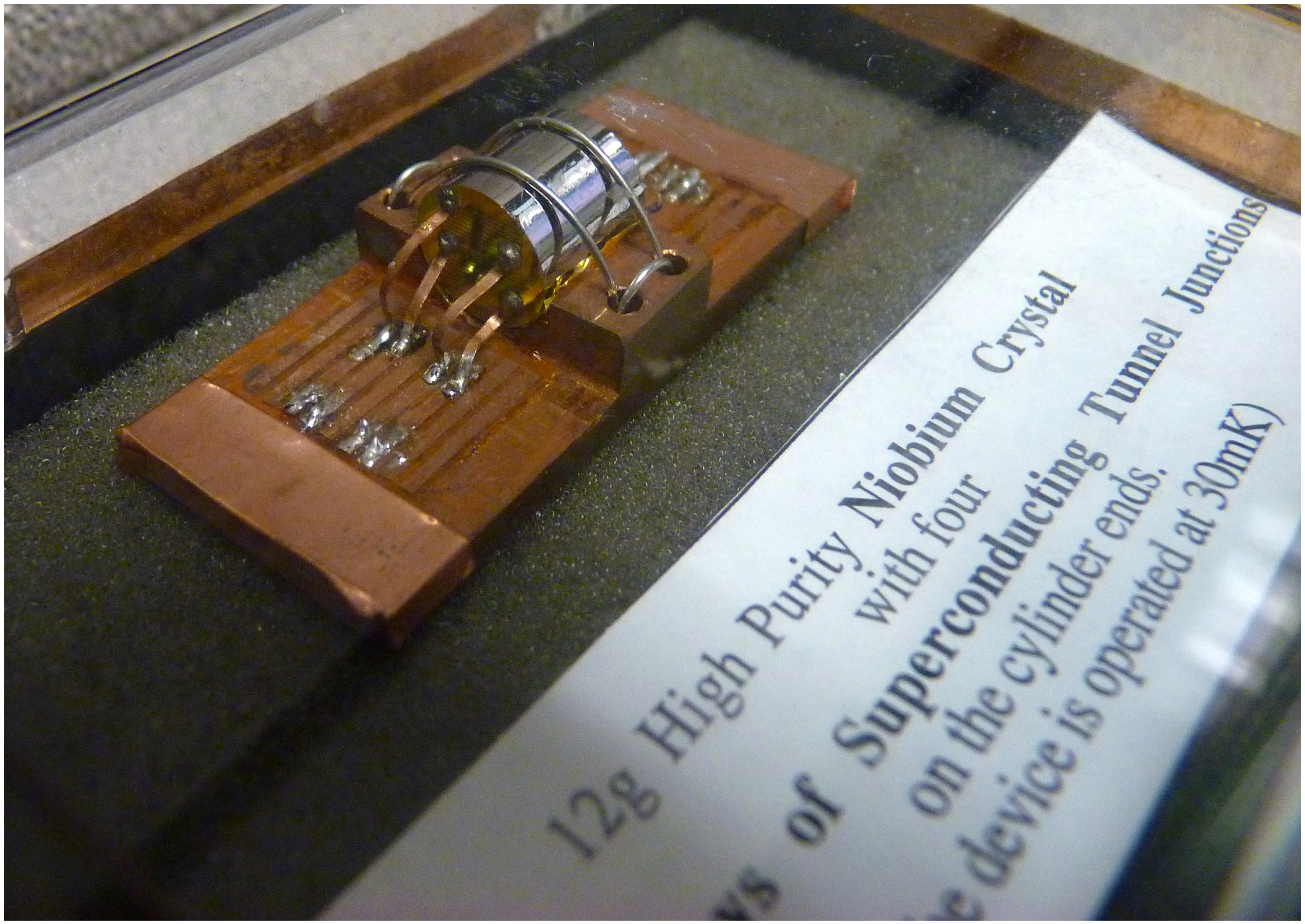
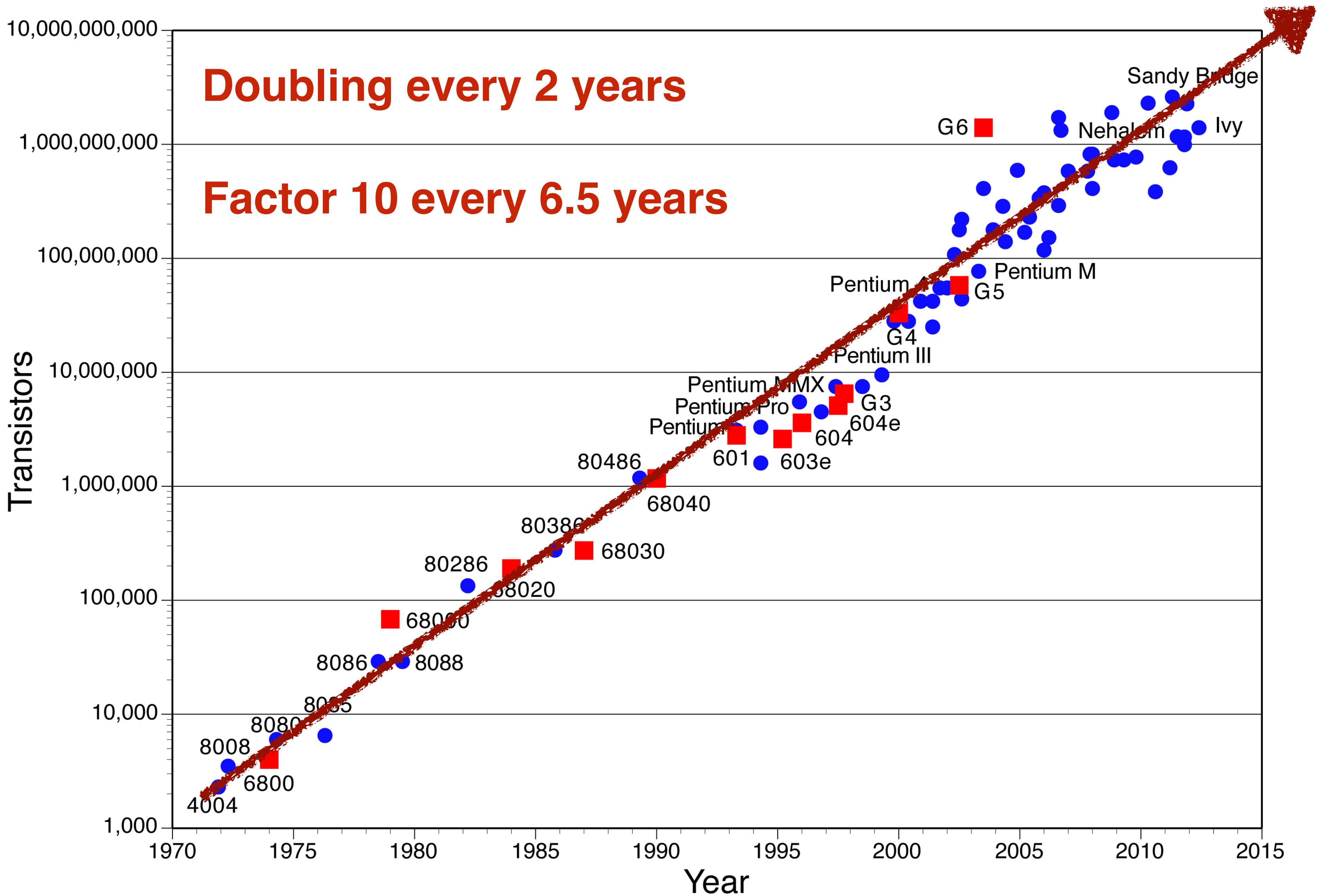


Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

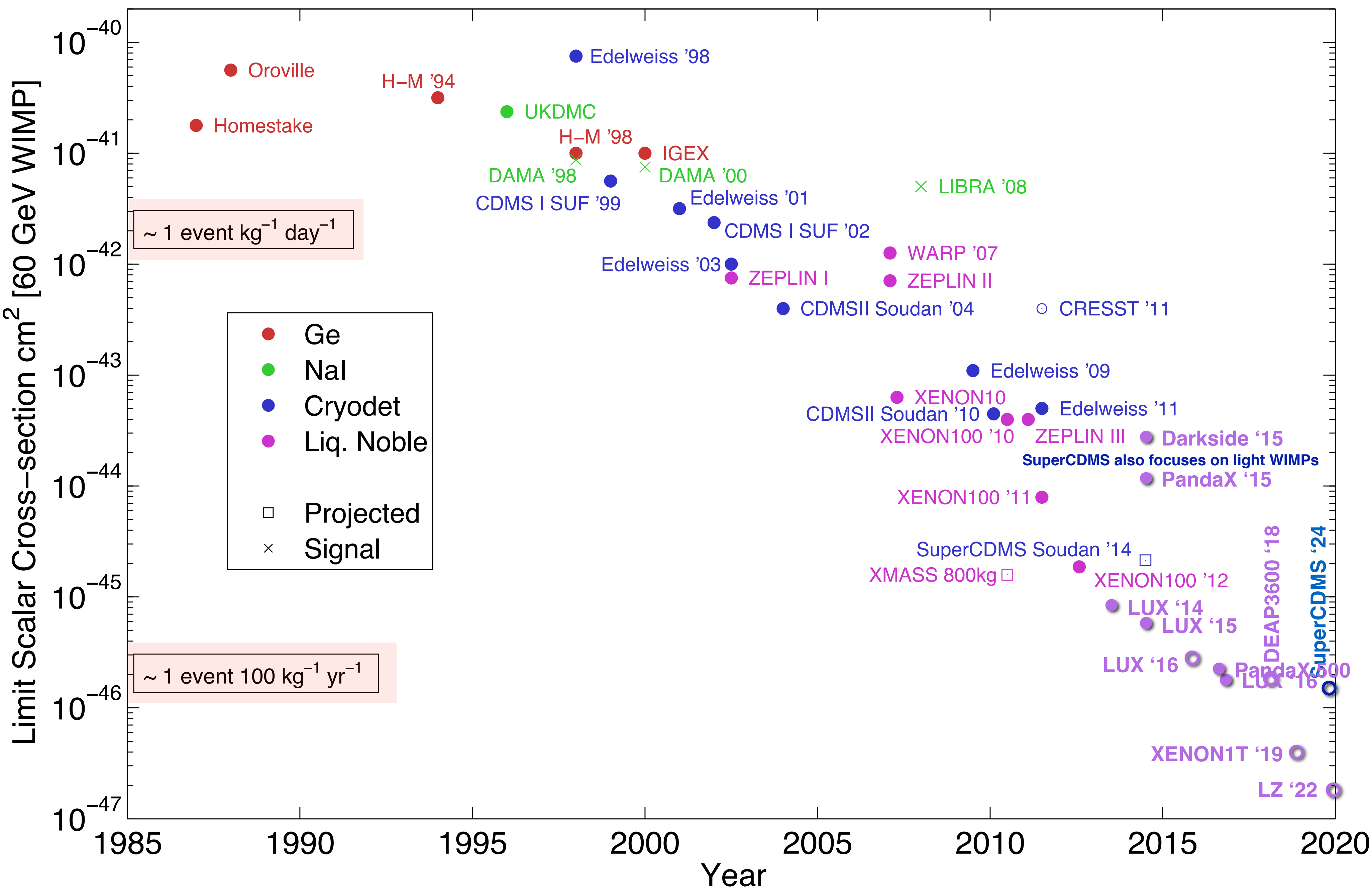
- 1 cm long - 12 g - 250 eV Threshold - “State of the Art in 1991”
  - Superconducting Tunnel Junction arrays detecting phonons and quasiparticles from Nb

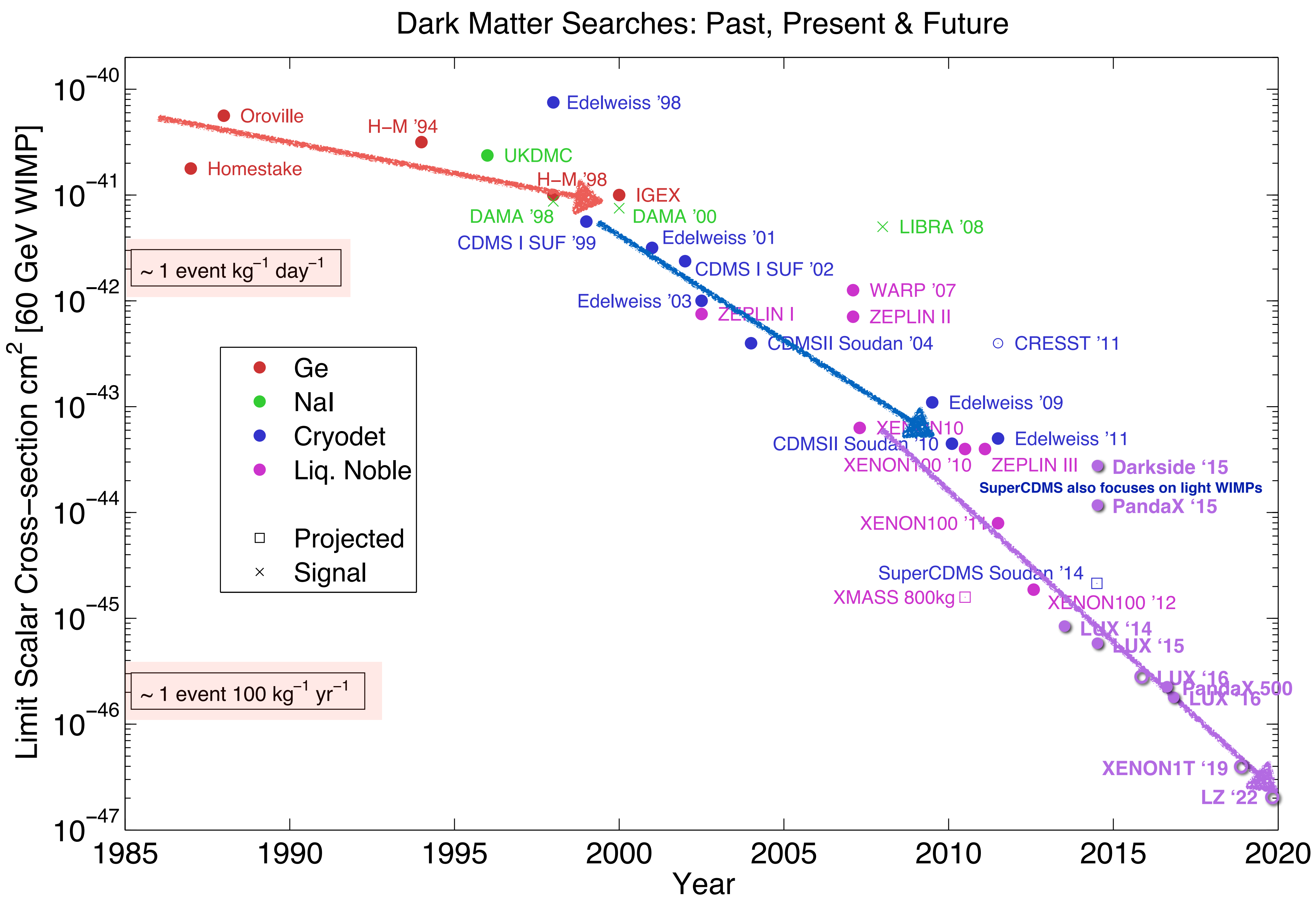


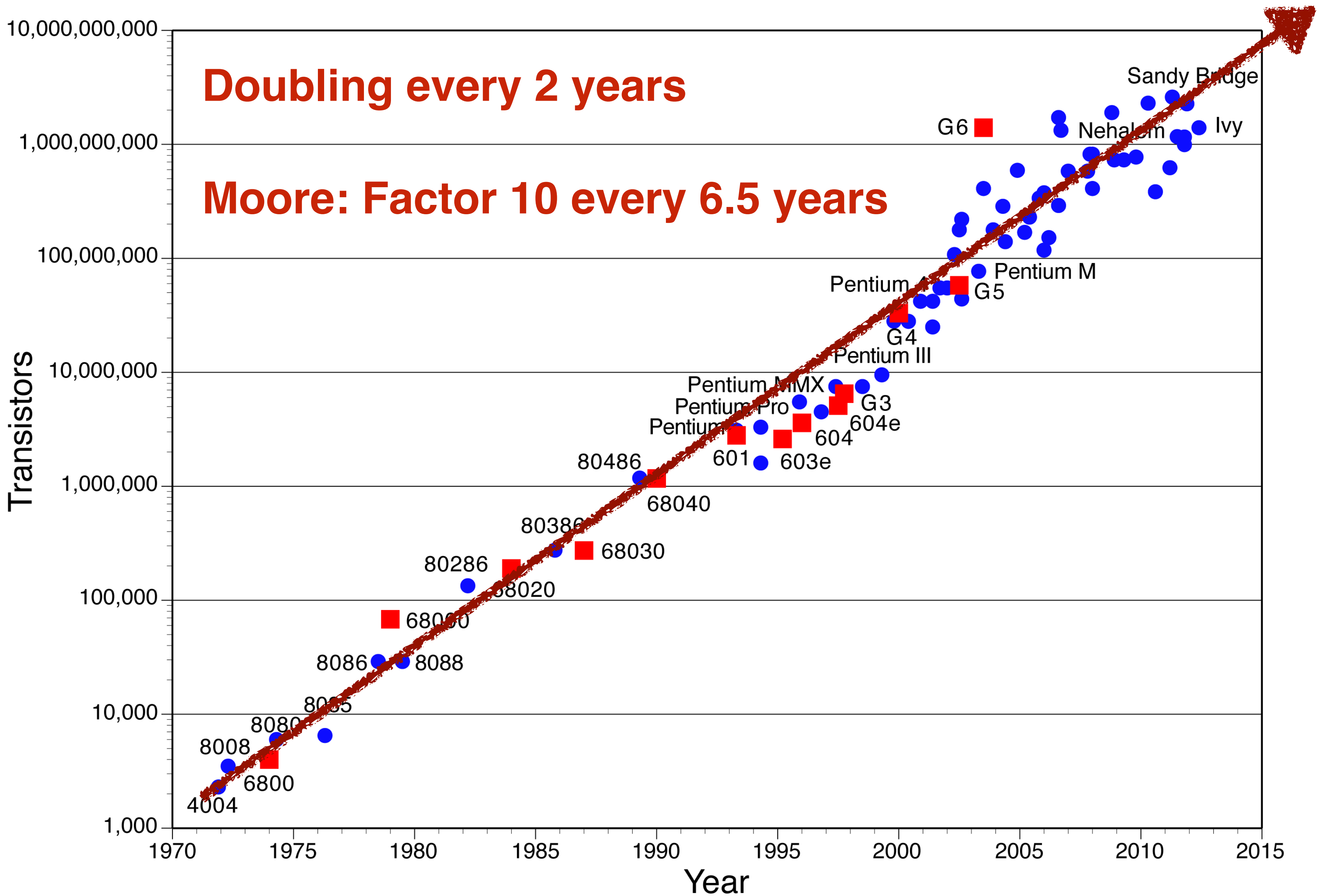


http://education.mrsec.wisc.edu/SlideShow/images/computer/Moores_Law.png

Dark Matter Searches: Past, Present & Future




Dark Matter Searches: Past, Present & Future
Limit Scalar Cross–section cm^2 [60 GeV WIMP]
Year
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
1985
1990
1995
2000
2005
2010
2015
2020
~ 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
UKDMC
Edelweiss '98
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '01
LIBRA '08
CDMS I SUF '02
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
PandaX 500
LUX '16
XENON1T '19
LZ '22



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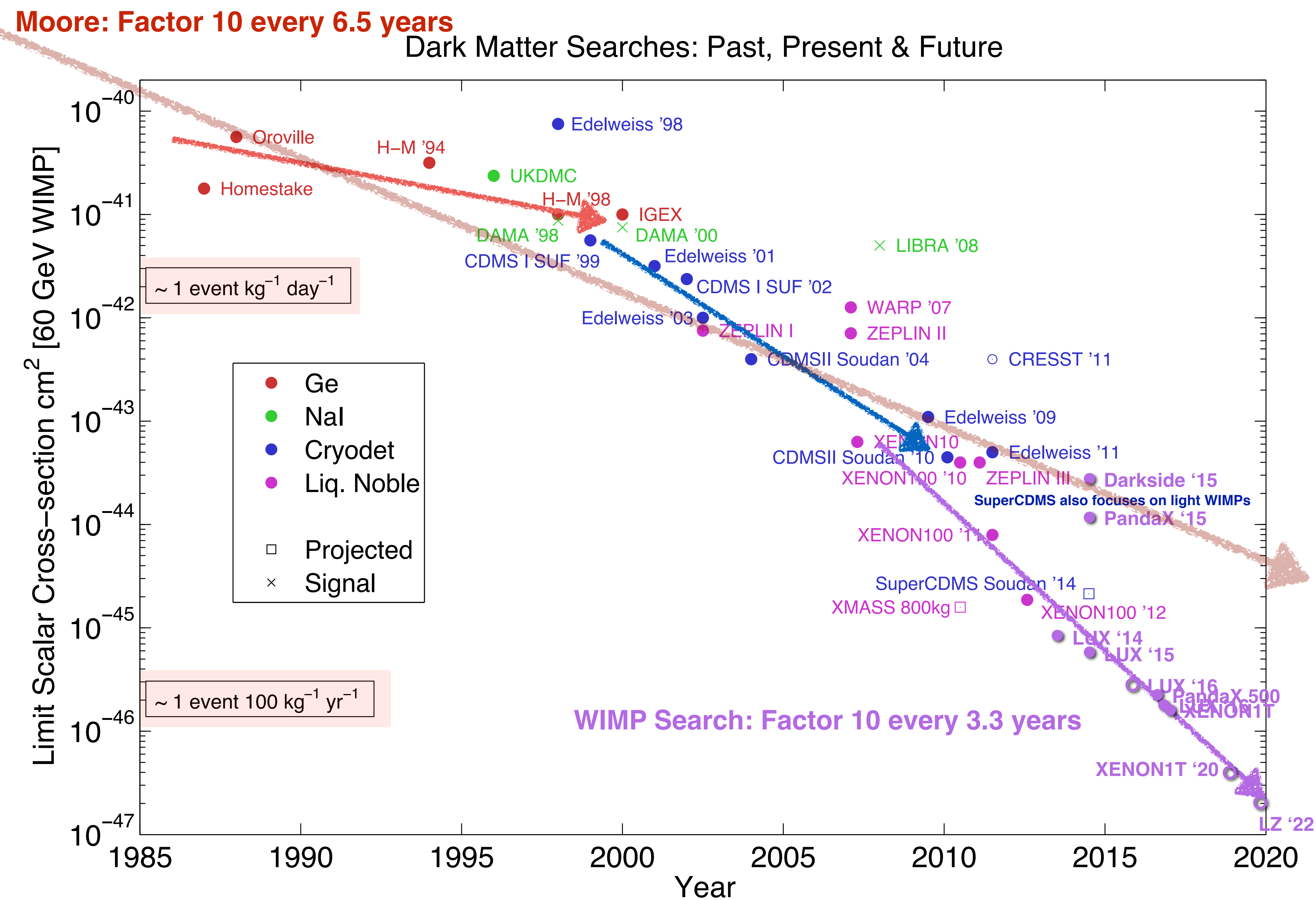

Moore: Factor 10 every 6.5 years
Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section cm^2 [60 GeV WIMP]
Year
~ 1 event kg^{-1} day^{-1}
~ 1 event 100 kg^{-1} yr^{-1}
Ge
NaI
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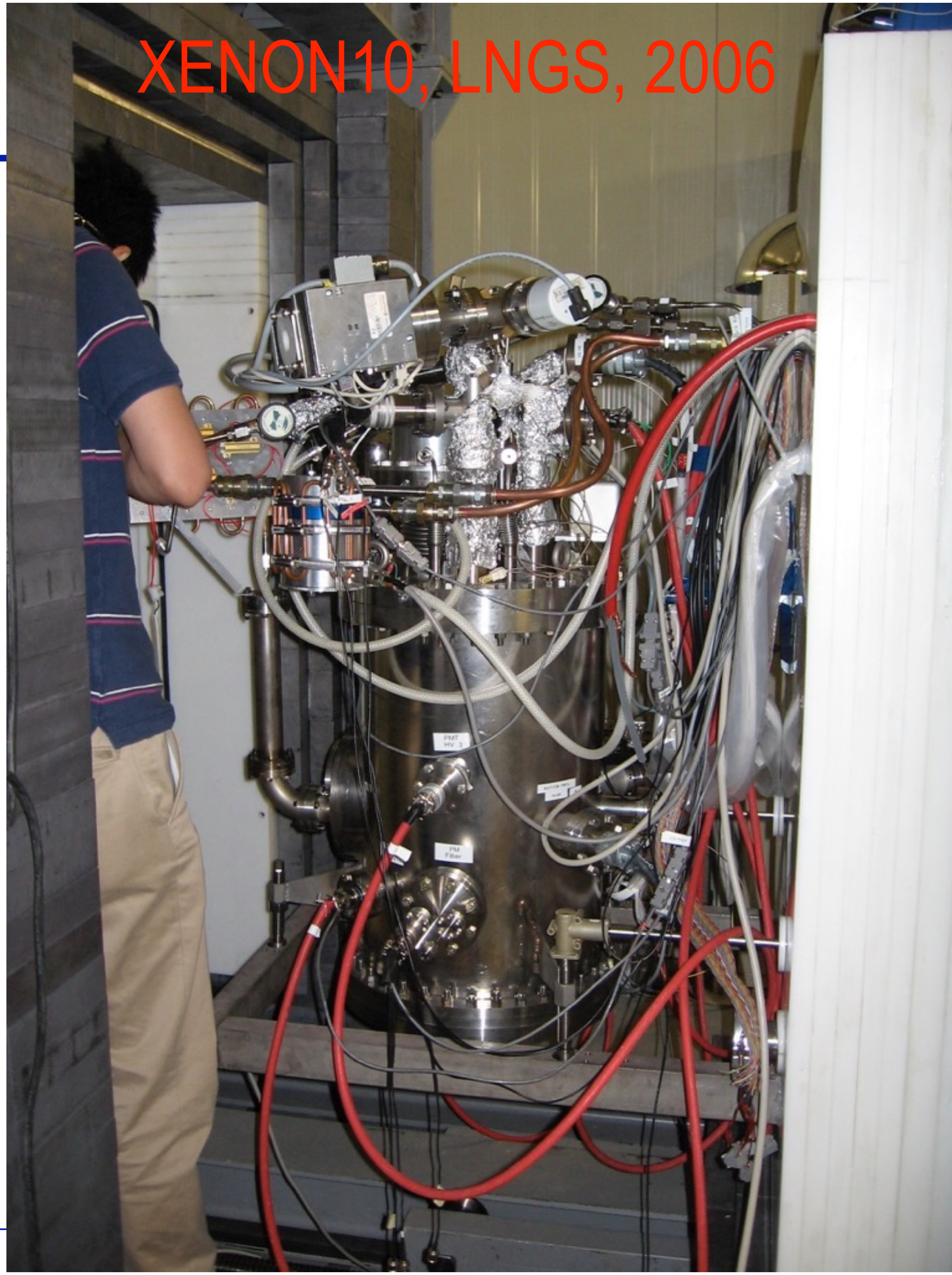
Edelweiss '01
CDMS I SUF '02
LIBRA '08
WARP '07
ZEPLIN II
Edelweiss '03
ZEPLIN I
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
Darkside '15
SuperCDMS also focuses on light WIMPs
PandaX '15
XENON100 '11
SuperCDMS Soudan '14
XMASS 800kg
XENON100 '12
LUX '14
LUX '15
LUX '16
PandaX 500
XENON1T
WIMP Search: Factor 10 every 3.3 years
XENON1T '20
LZ '22


XENON10, LNGS, 2006


XENON10, LNGS, 2006

LUX, Sanford Lab, 2010

LUX, Sanford Lab, 2011

Sanford Lab, May 2012

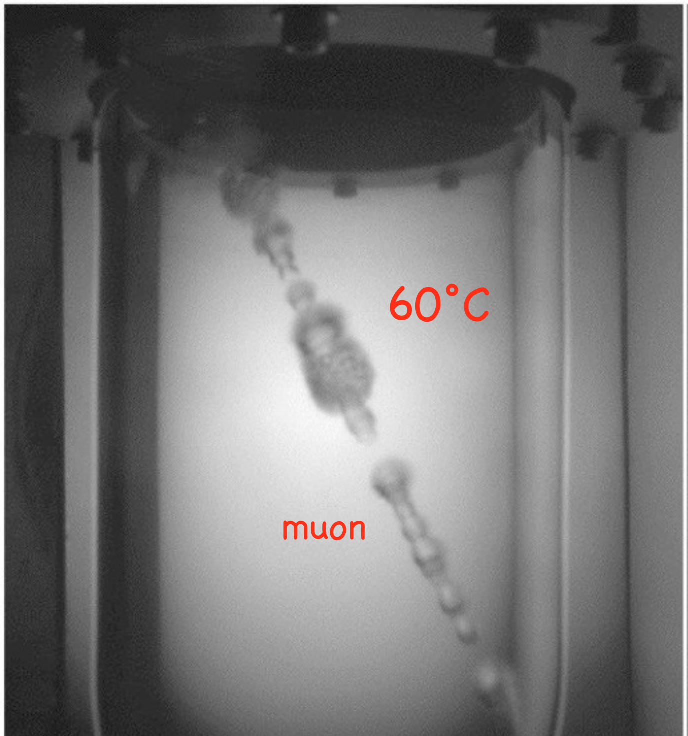
Idealized Dark Matter Direct Detection Experiment

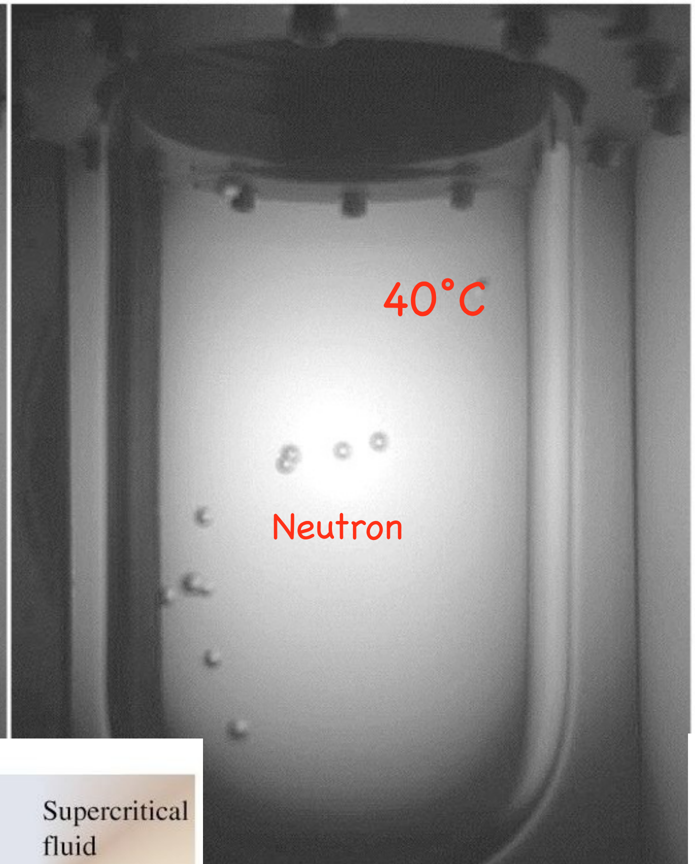
- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
  - We almost have this in PICO (COUPP) bubble chambers

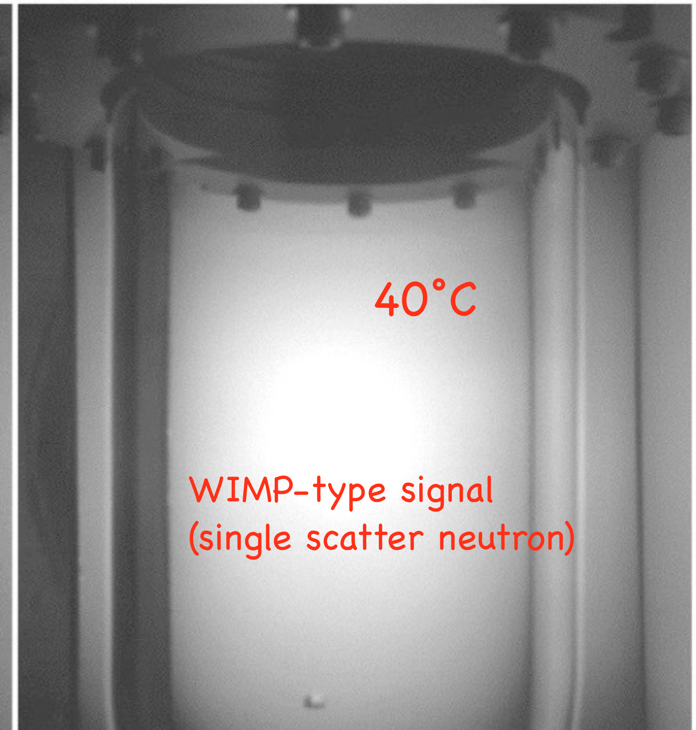
COUPP: bubble chamber reimagined

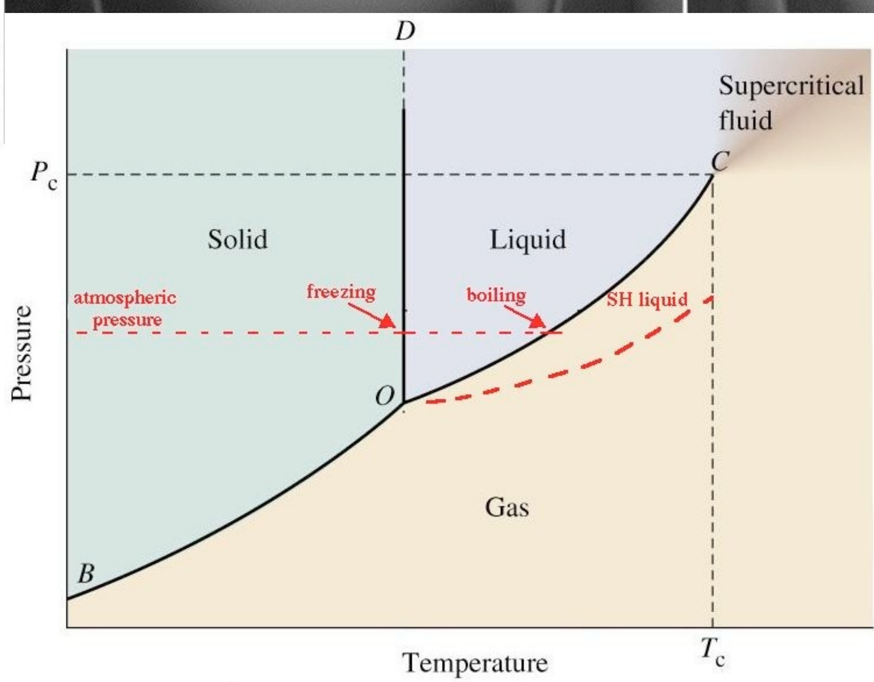
Conventional BC operation (high superheat, MIP sensitive)

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





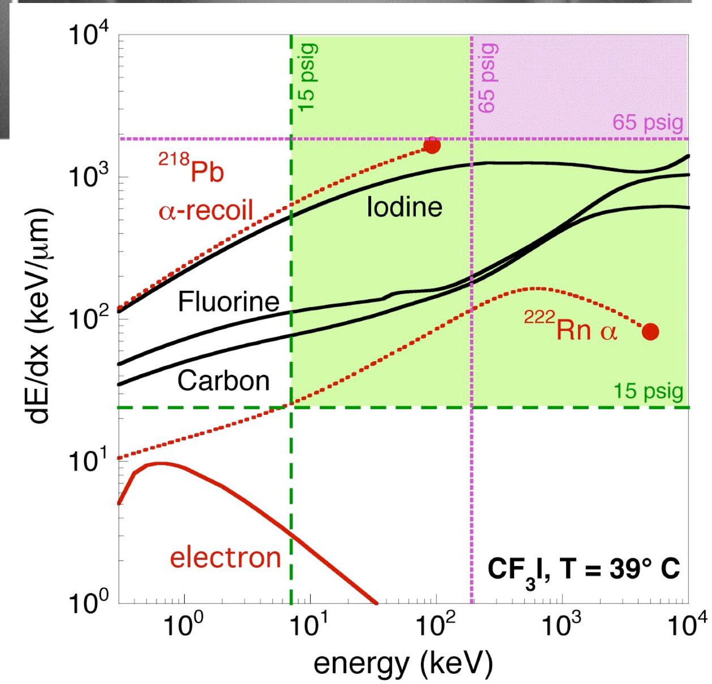




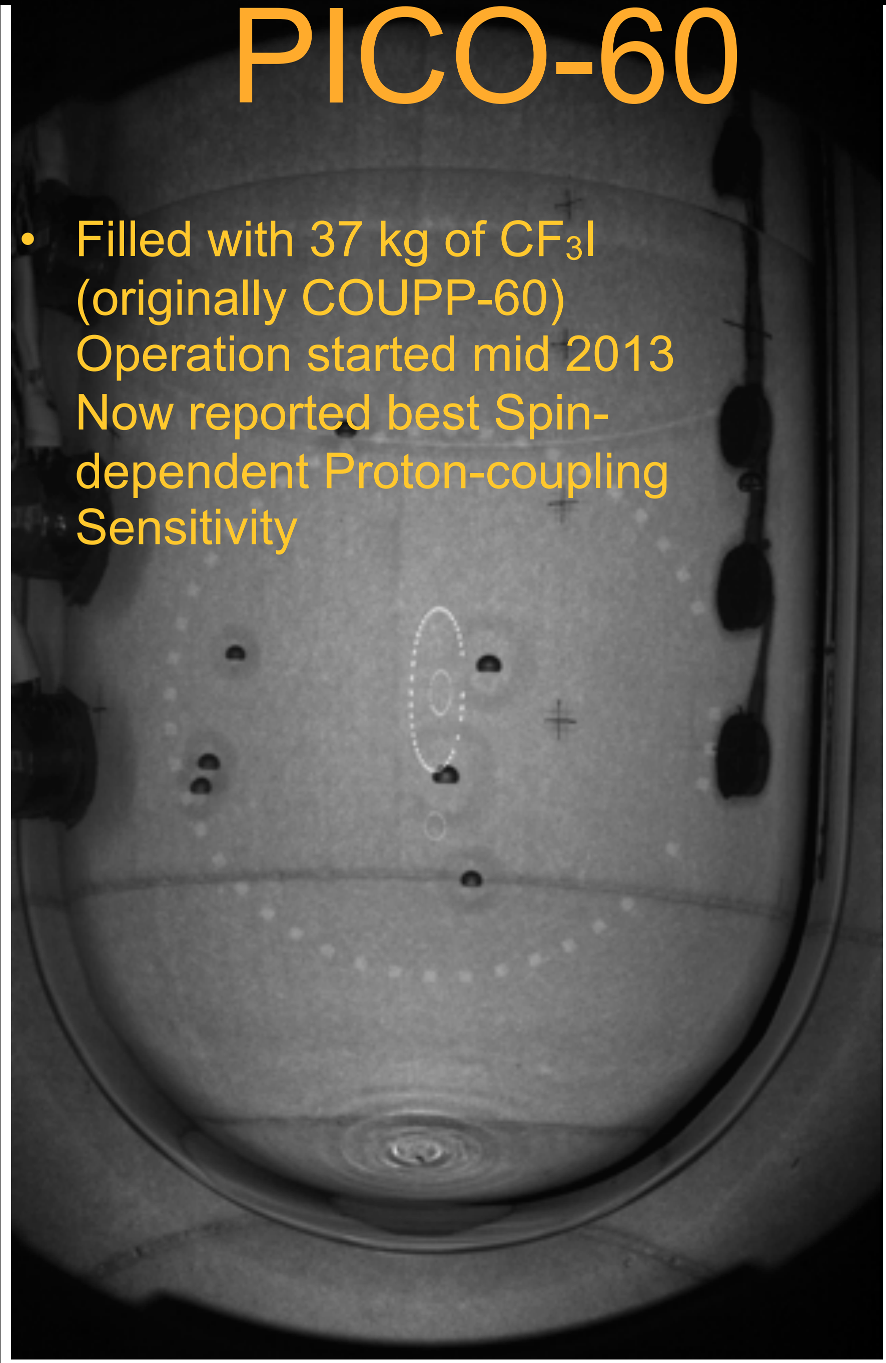
CF_3I,
Also C_3F_8, C_4F_{10}, CF_3Br

γ or e^- rejection > 10^{10}

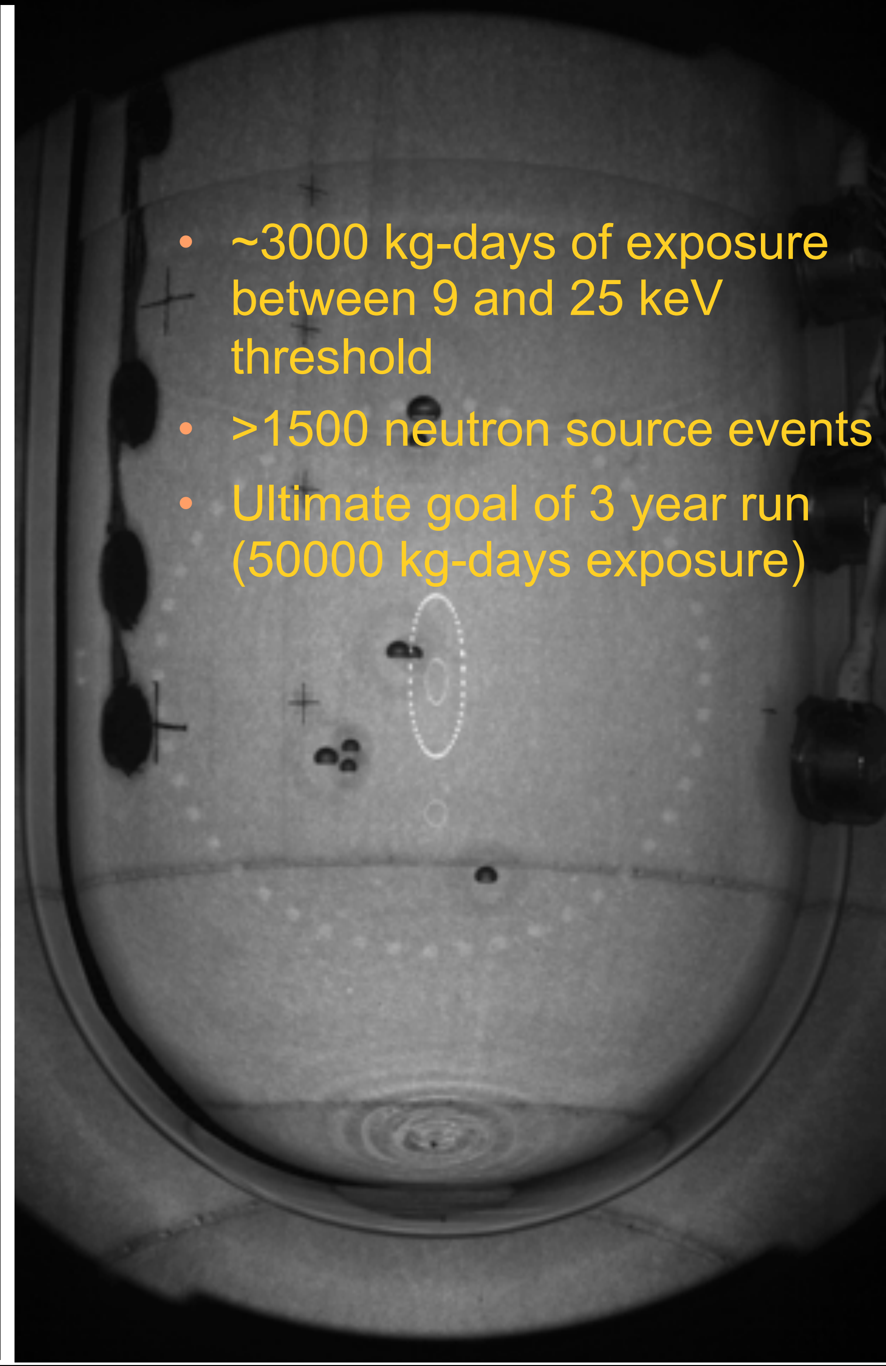
Juan Collar, UChicago:
ultra-clean Bubble Chamber:
Bolte et al., NIM A577 (2007) 569
Science 319 (2008) 933,
Phys. Rev. Lett. 106 (2011) 021303



PICO-60

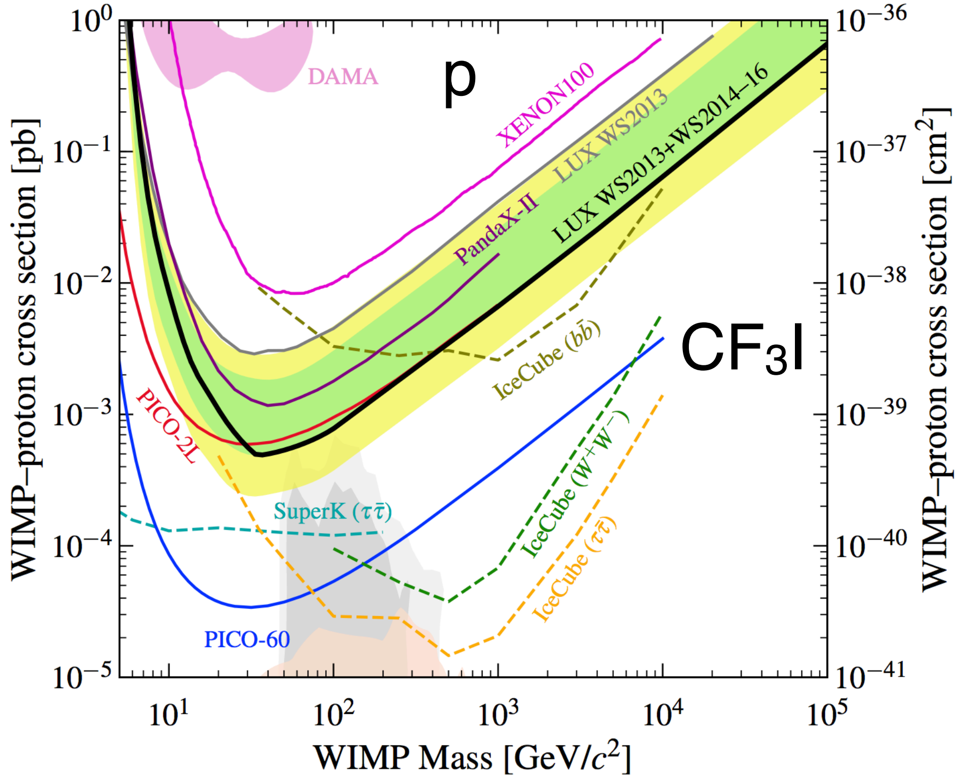


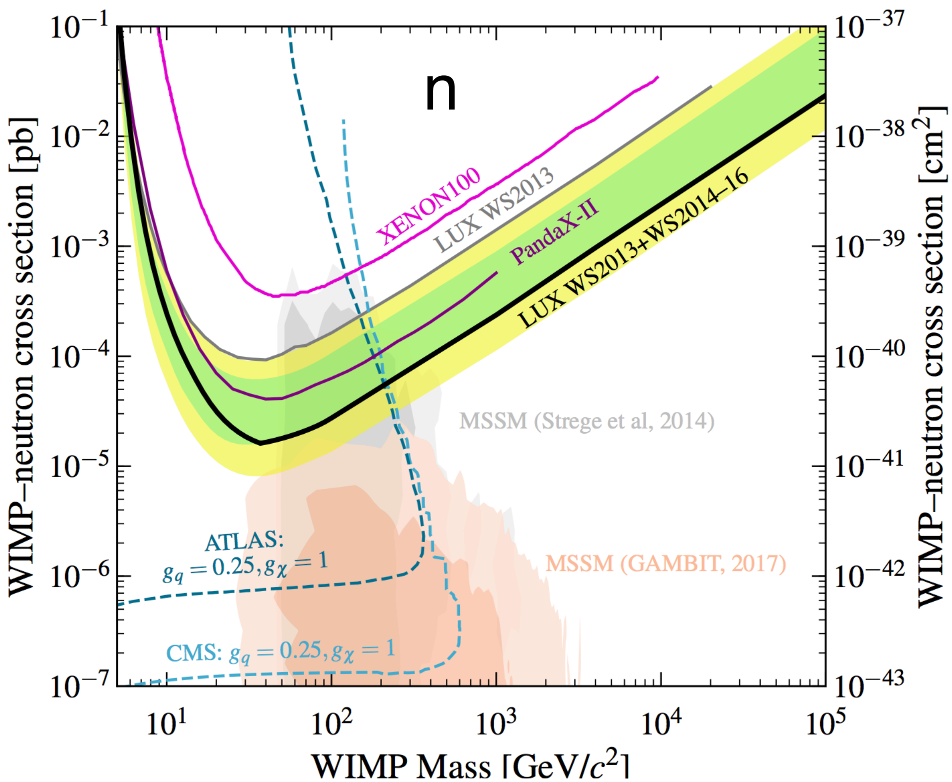
- Filled with 37 kg of CF_3I (originally COUPP-60) Operation started mid 2013 Now reported best Spin-dependent Proton-coupling Sensitivity

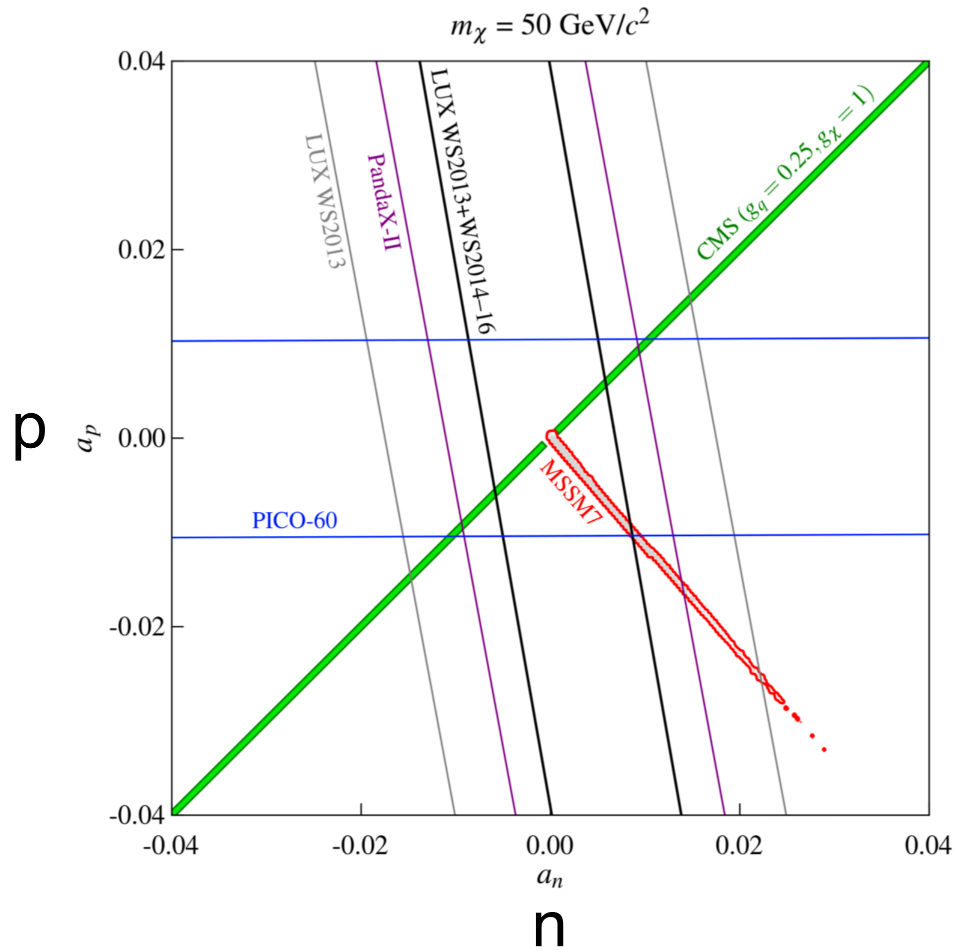


- ~3000 kg-days of exposure between 9 and 25 keV threshold
- >1500 neutron source events
- Ultimate goal of 3 year run (50000 kg-days exposure)

SPIN DEPENDENT COUPLINGS







Idealized Dark Matter Direct Detection Experiment

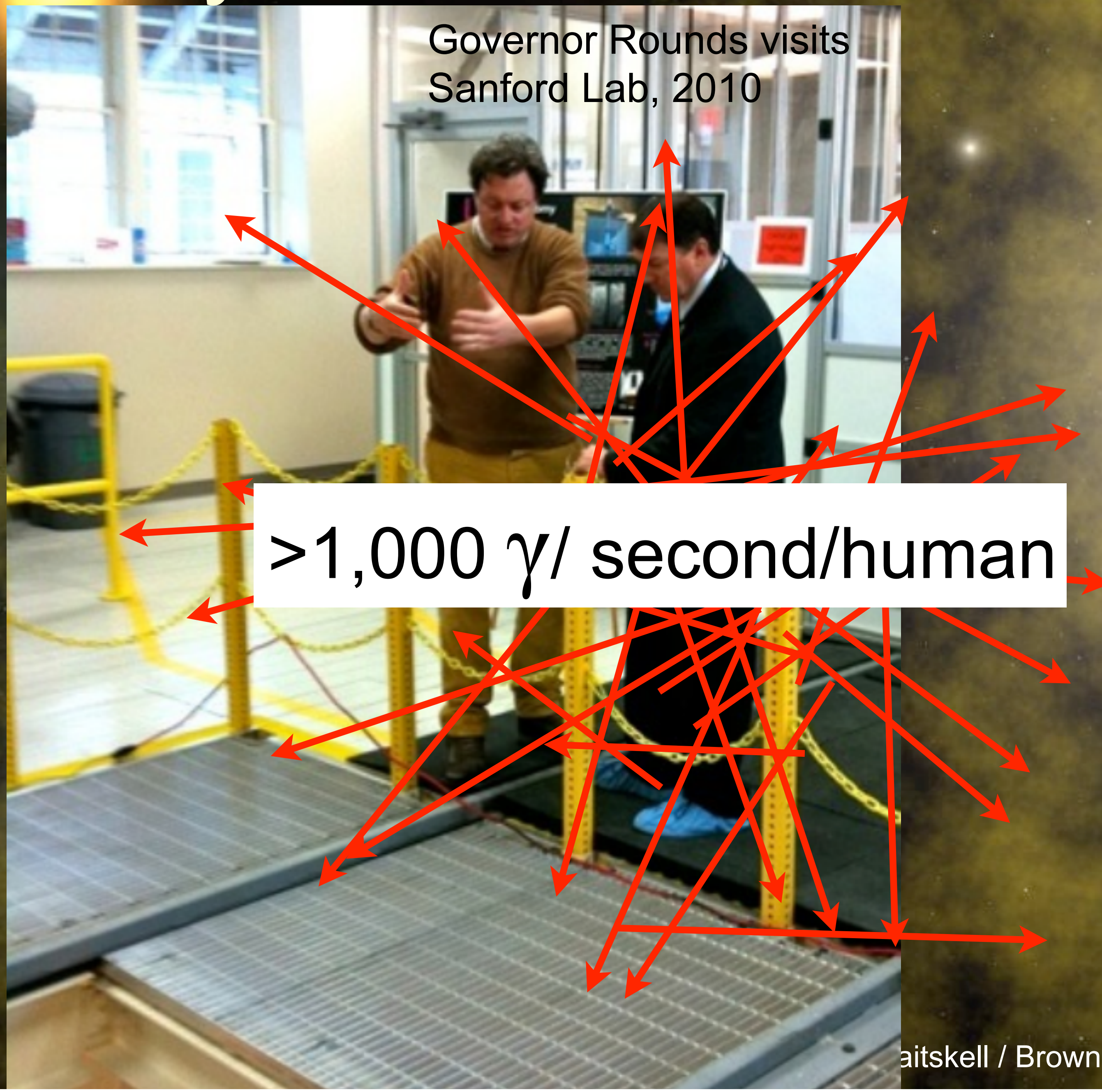
- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - "Platonic ideal"
  - We almost have this in PICO (COUPP) bubble chambers

- 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 dark matter beam off test 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

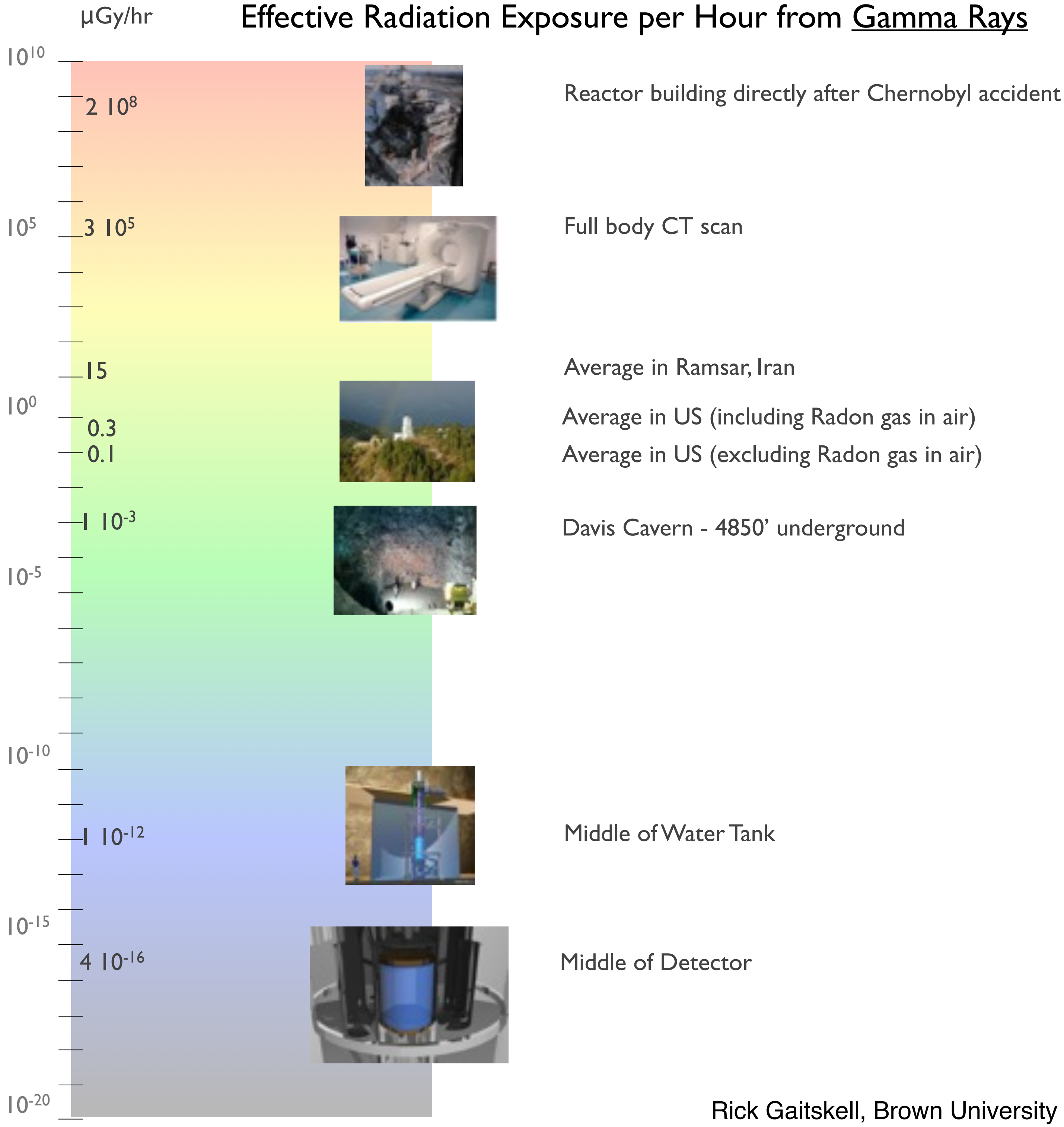
  - We also want to do physics with recoil energy spectrum / target dependence
  - Maybe we can return to the platonic ideal … reduce competing backgrounds

How Many Gammas/Second?



aitskell / Brown University

Effective Radiation Exposure per Hour from Gamma Rays

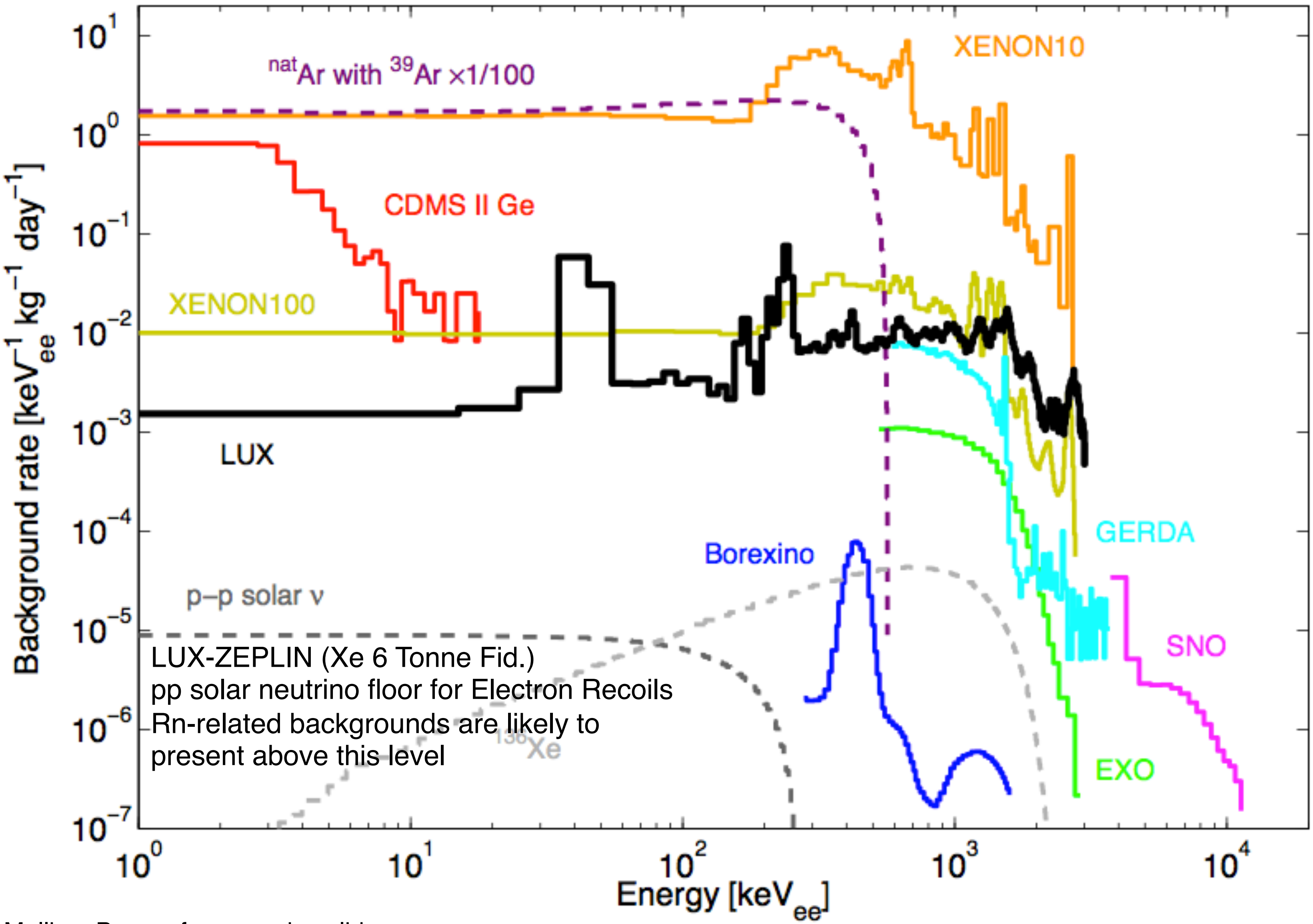


Rick Gaitskell, Brown University

*1 Gy = 1 J/kg = 100 rad

Reduction in Backgrounds

- Electron Recoil Events



Thanks to David Malling, Brown, for preparing slide

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

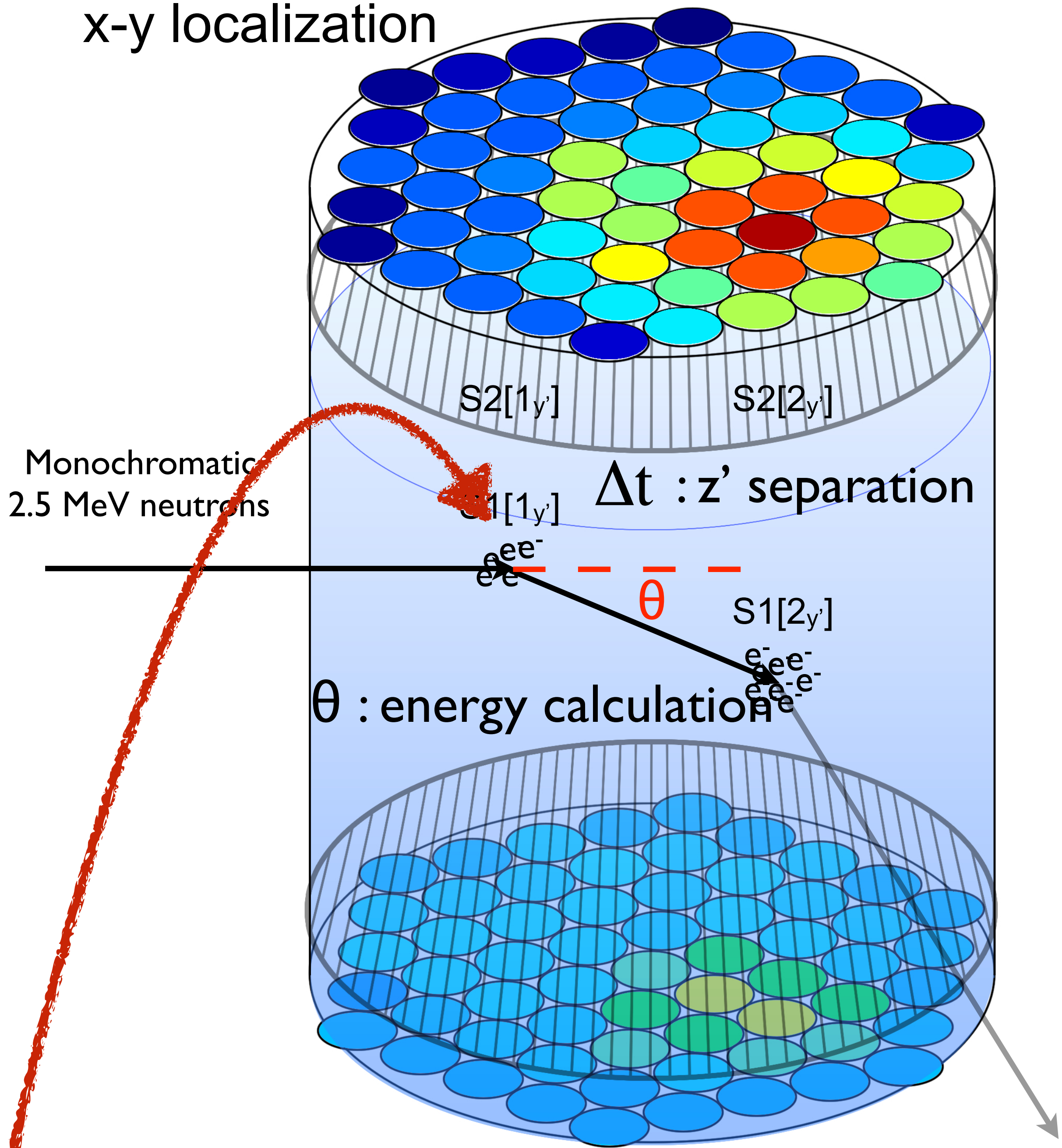
LUX in Water Tank - First Run 2013 / Last Run Ended Sept 2016

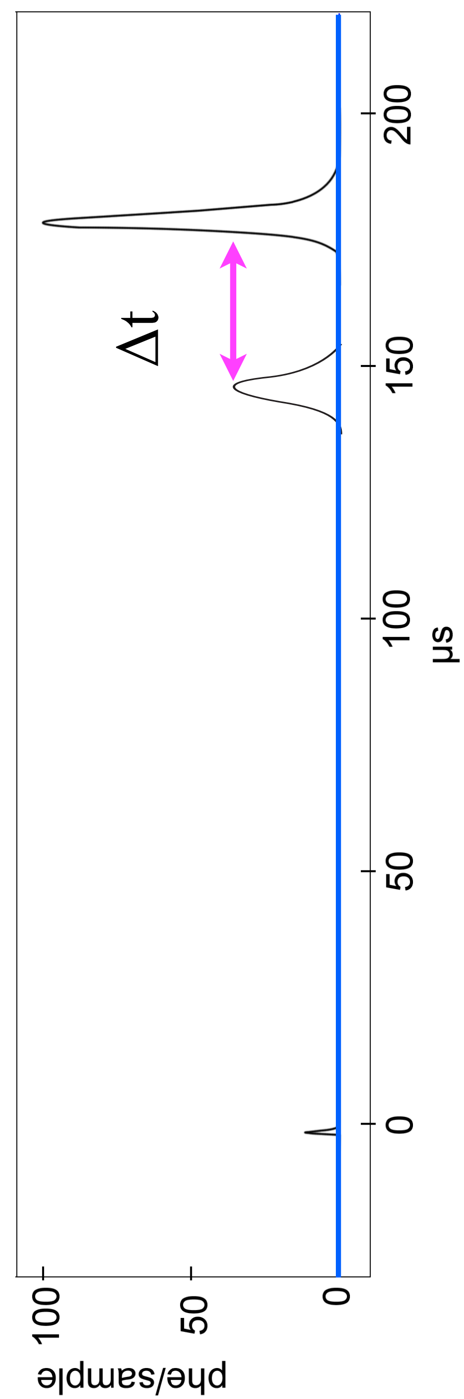
LUX major papers:

arXiv:1512.03133
arXiv:1512.03506
arXiv:1602.03489
arXiv:1608.05381
arXiv:1608.07648
arXiv:1610.02076
arXiv:1704.02297
arXiv:1705.03380

At Invisibles '17 from LUX & LZ
Shaun Alsum, U. Wisconsin-Madison
Maria Francesca Marzioni, U. Edinburgh

top hit pattern:
x-y localization





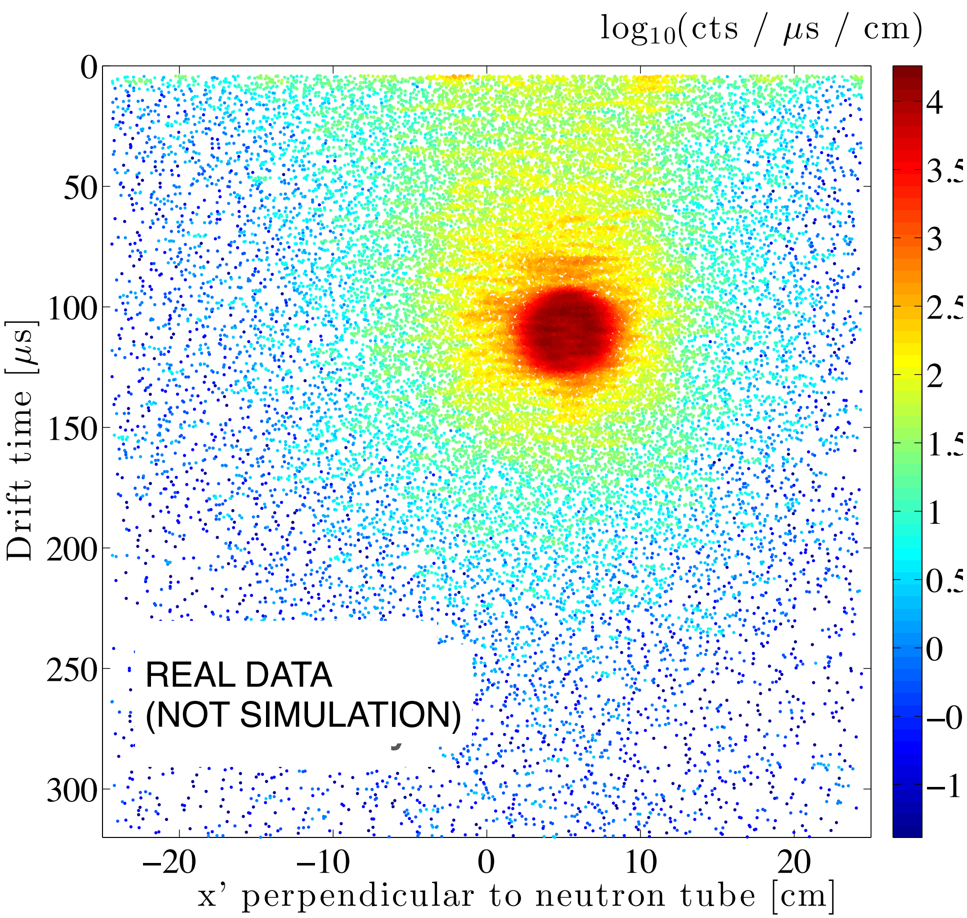
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

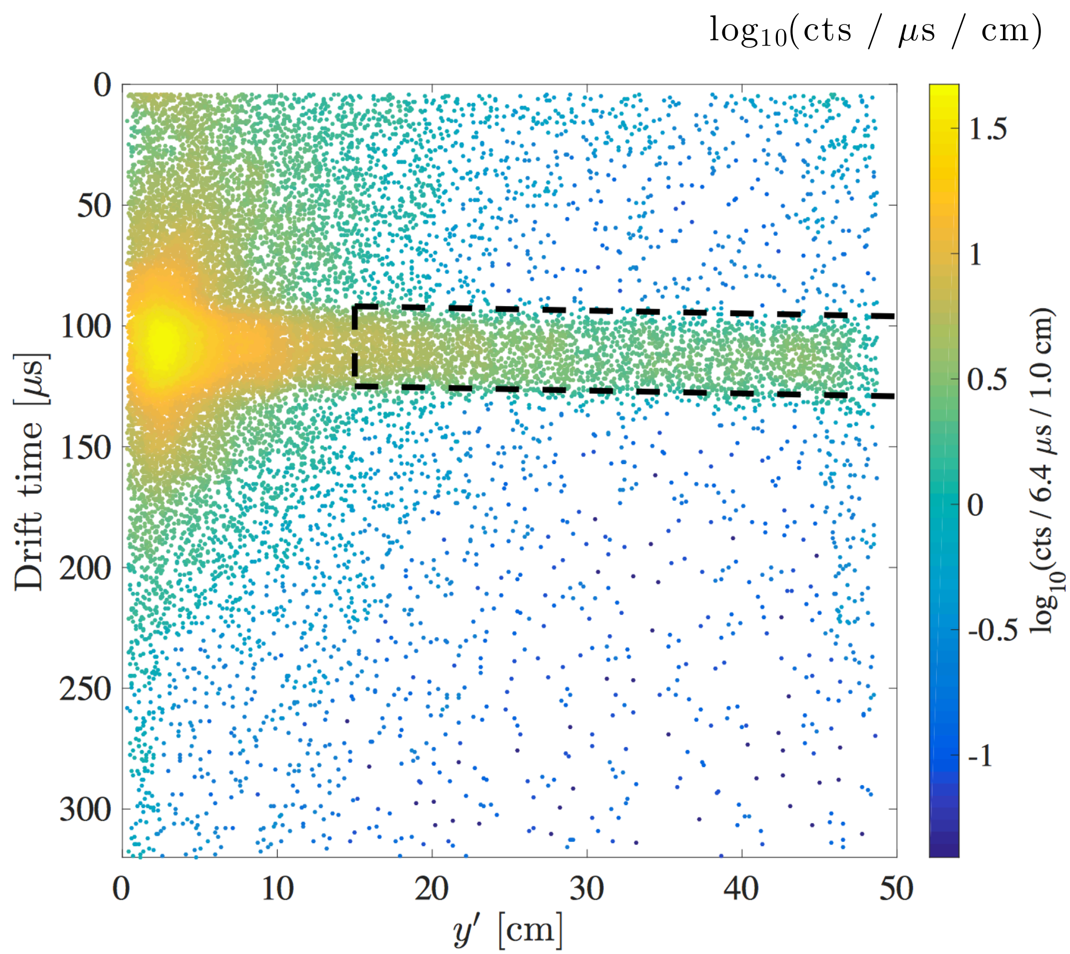
Samuel Chan, Carlos Faham for the LUX Collaboration

Beam Projection in Active Region

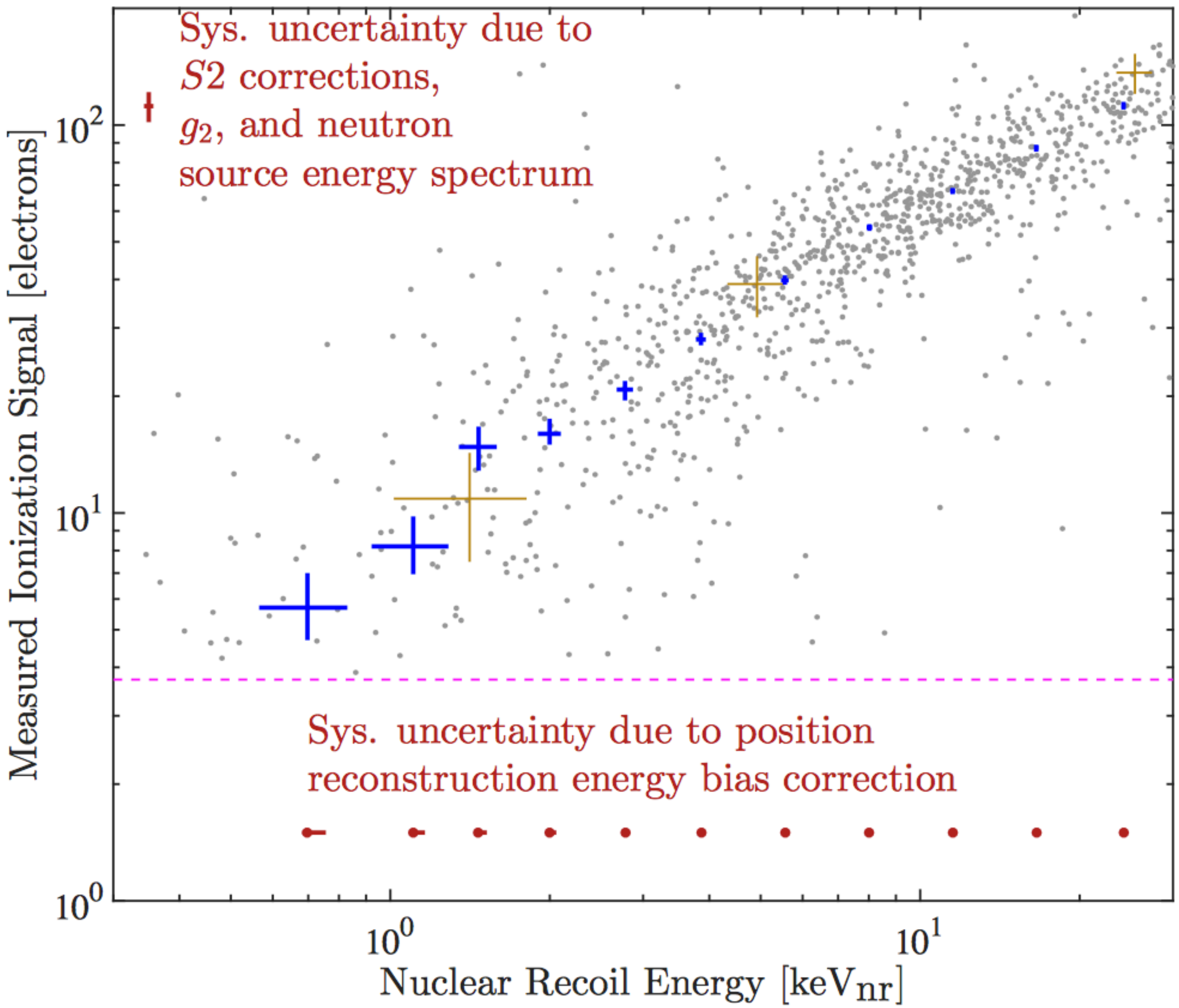
- The shine from neutron scatters in passive detector materials is visible.
- Historically, NR calibrations have significant systematics associated with neutrons scattering in passive material.
  - We can fiducialize away from such backgrounds!

arXiv:1608.05309
arXiv:1608.05381



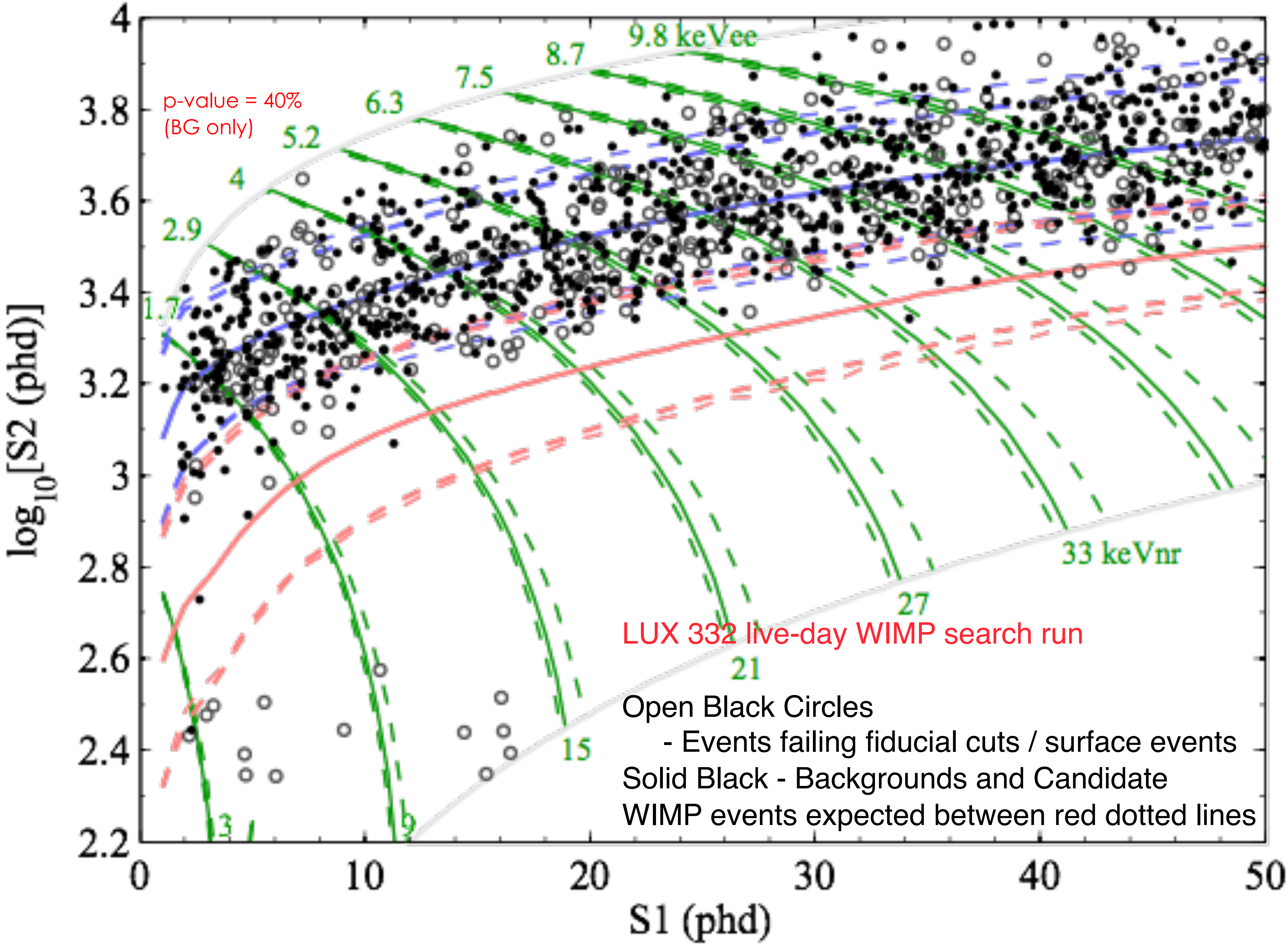


Neutron Calibration of Xe Response



Gold + show uncertainties from INDIVIDUAL scattering events

Blue + show error weighted combination of all events



p-value = 40%
(BG only)
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
9
3
LUX 332 live-day WIMP search run
Open Black Circles
- Events failing fiducial cuts / surface events
Solid Black - Backgrounds and Candidate
WIMP events expected between red dotted lines
$\log_{10}$[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50

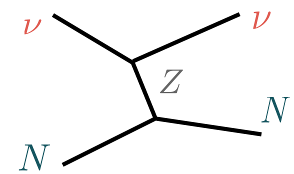
Estimation of Backgrounds

- Actually perform a full likelihood analysis for all S1,S2 signal space, so these numbers are simply to give you a sense of the relative contributions
- Bulk volume, but leakage at all energies
- Low-energy, but confined to the edge of our fiducial volume
  - Our likelihood analysis includes position information, so these events have low WIMP(signal) likelihood
- In the bulk volume, low-energy, in the NR band

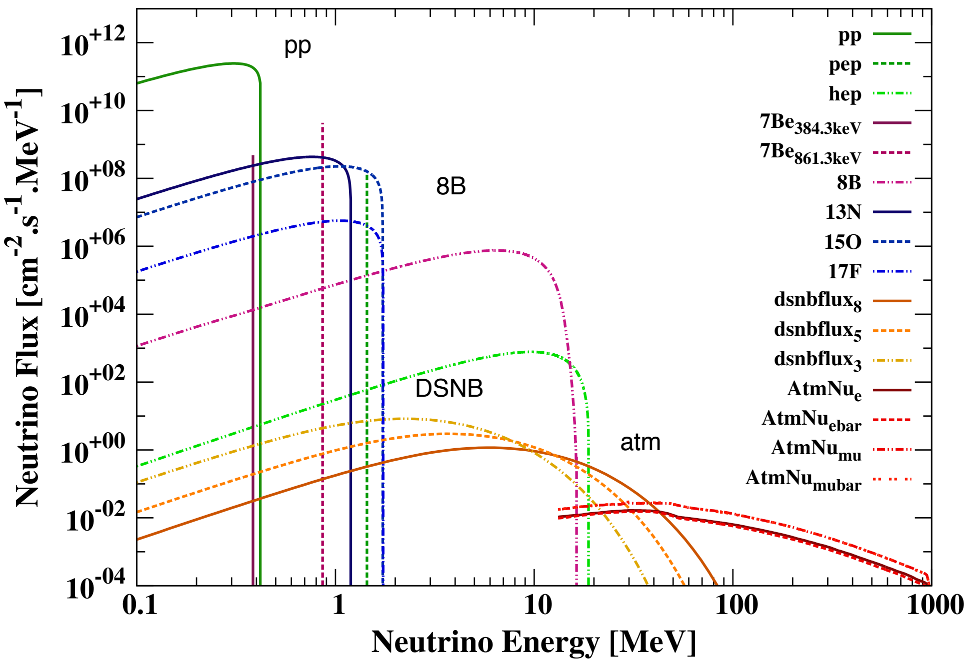
Background	Expected number below NR median
External gamma rays	1.51 ± 0.19
Internal betas	1.2 ± 0.06
Rn plate out (wall background)	8.7 ± 3.5
Accidental S1-S2 coincidences	0.34 ± 0.10
Solar ^{8}B neutrinos (CNNS)	0.15 ± 0.02
Neutrons	0.3 ± 0.03

Expected Neutrino Backgrounds

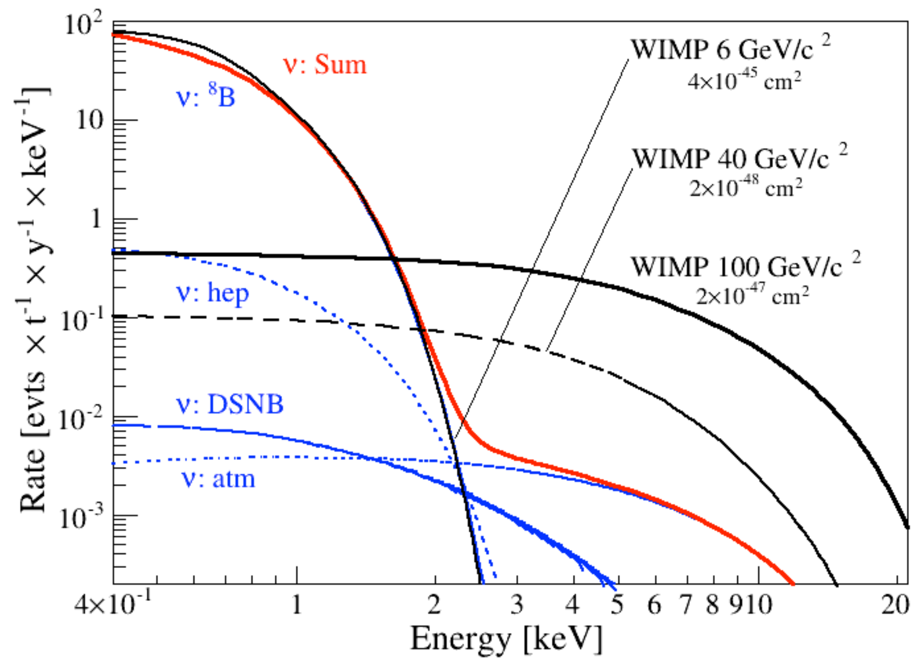
- Neutrino-nucleus coherent scattering (solar) could be observed in Xe TPC



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

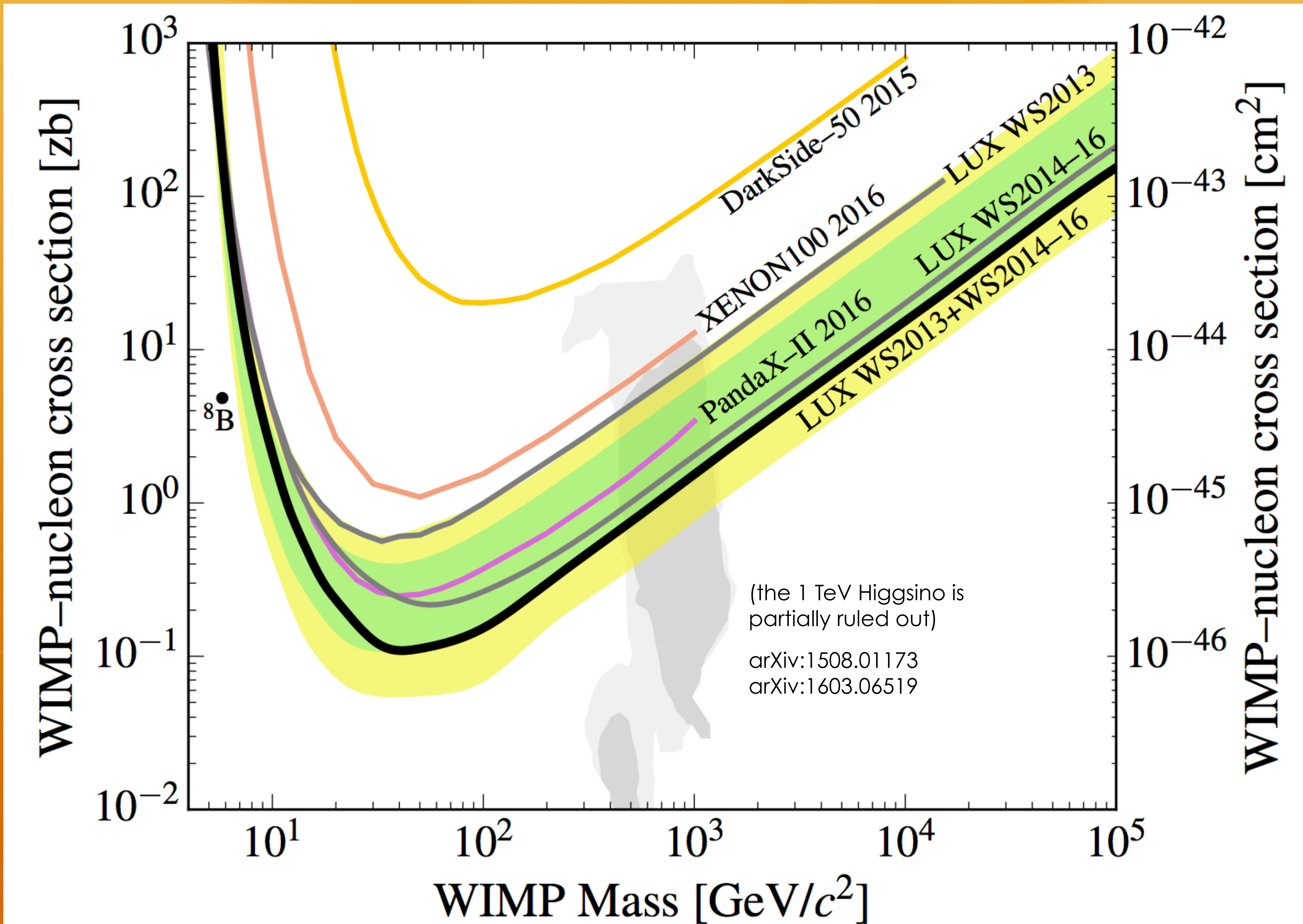


F. Ruppin et al., 1408.3581



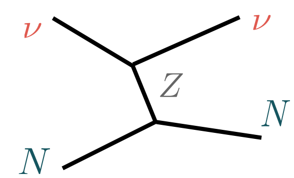
Laura Baudis et al., JCAP01 (2014) 044

Both LUX Runs WS2013+WS2014-2016 Combined
PRL Jan 2017 / arXiv:1608.07648



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



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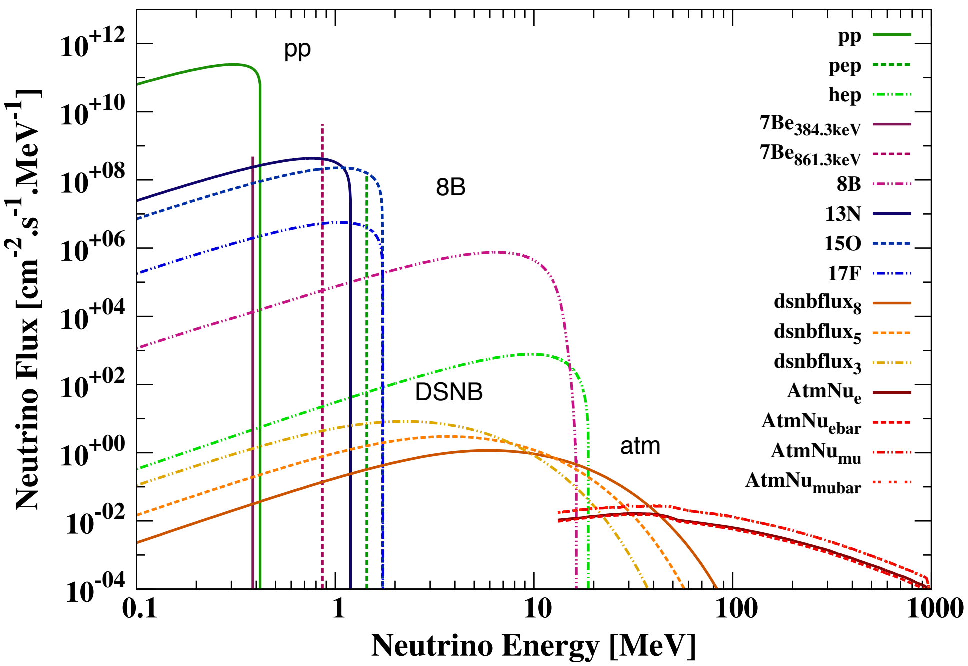
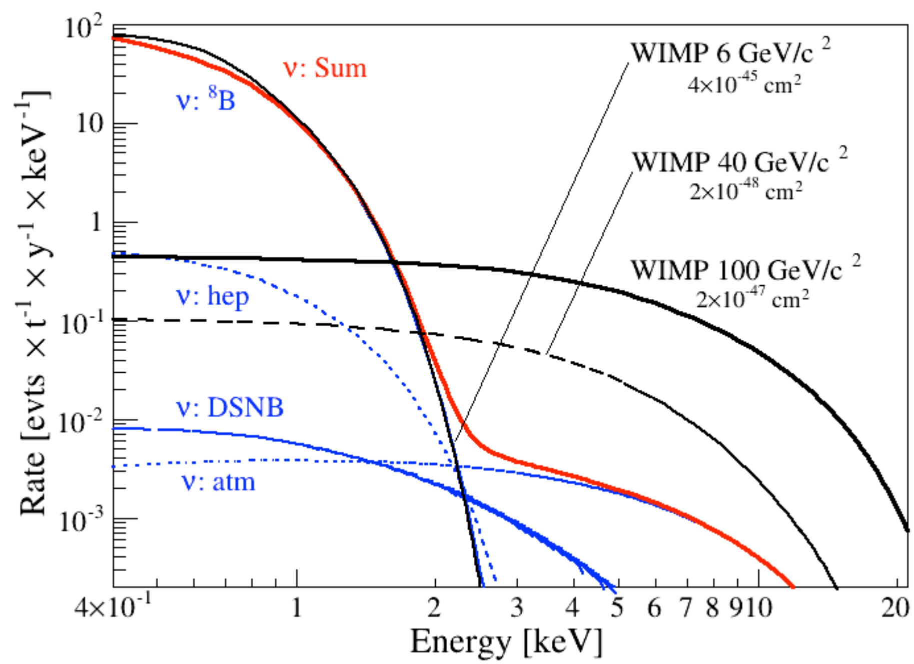


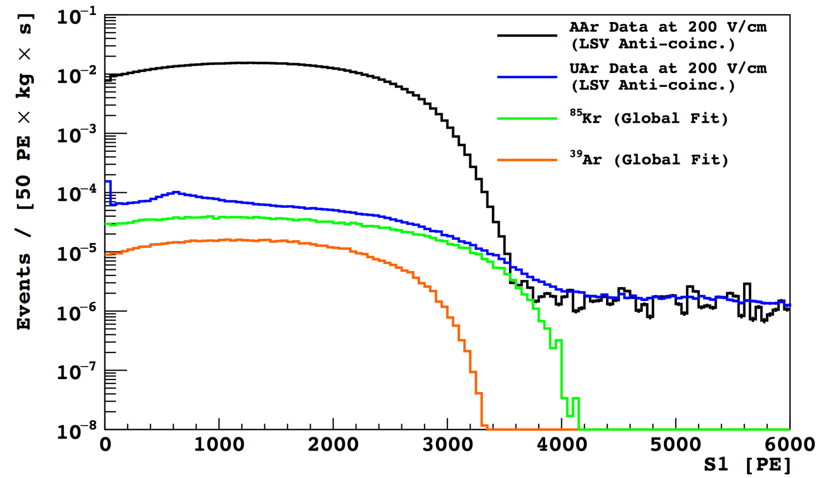
F. Ruppin et al., 1408.3581



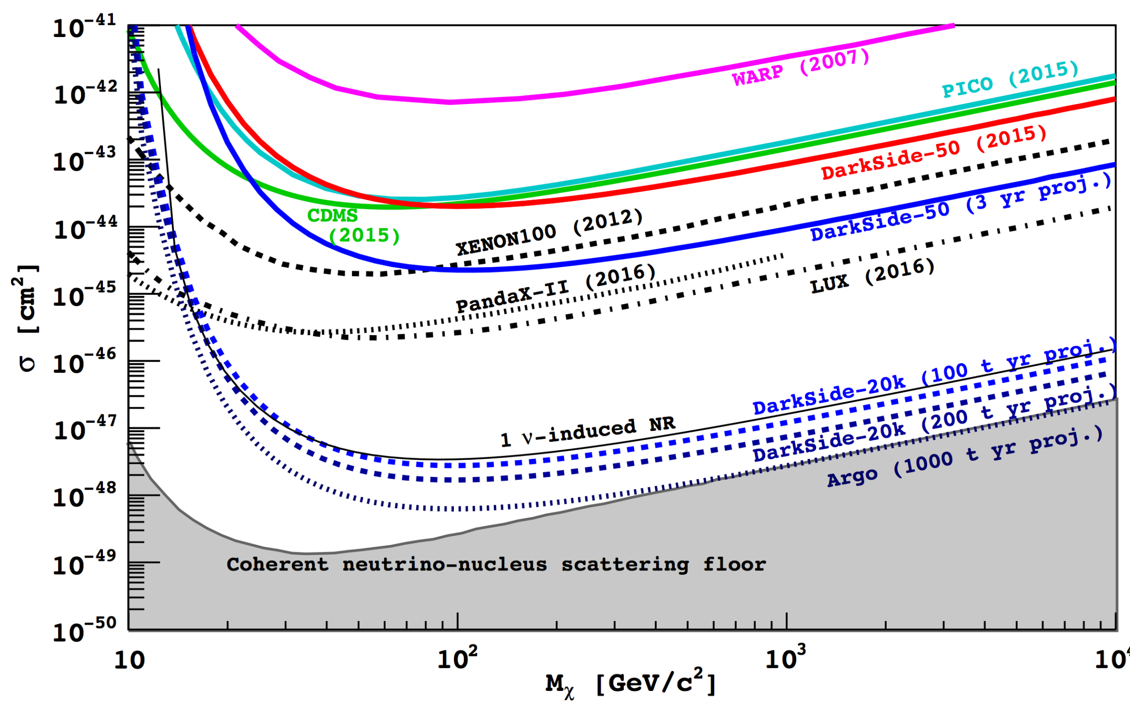
Laura Baudis et al., JCAP01 (2014) 044

WIMP Searches: Large Mass Liquid Argon Detectors

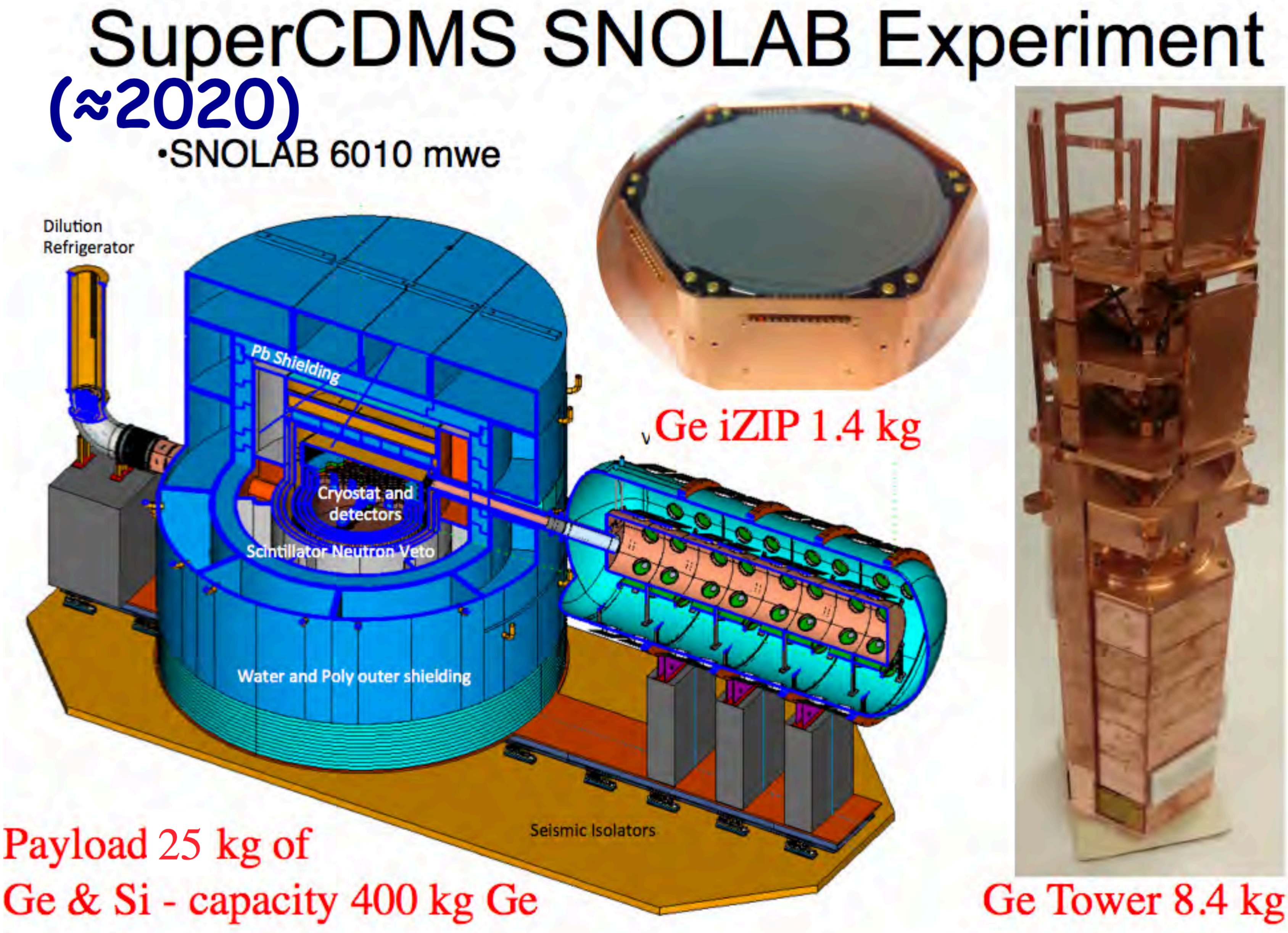
- Current WIMP Search Results
  - Last reported WIMP search results from Darkside-50 (50 kg active mass) in 2015 (Phys. Rev D. / See arXiv:1510.00702) - used low activity Ar - {Add Sensitivity Limit}
  - DEAP 3600 (3.6 tonnes total Ar mass) completed ~2 years ago. Awaiting first search results / results on backgrounds - possibly at TAUP 2017 in July
  - miniCLEAN (~300 kg active) still awaiting first search results. Operational issues.
  - ArDM. Status not clear.



- New Argon Collaboration
  - Darkside-20k (20 tonnes)
  - Research groups from Darkside, DEAP, ArDM, MiniCLEAN plan to collaborate
  - Approved by INFN and LNGS in April 2017

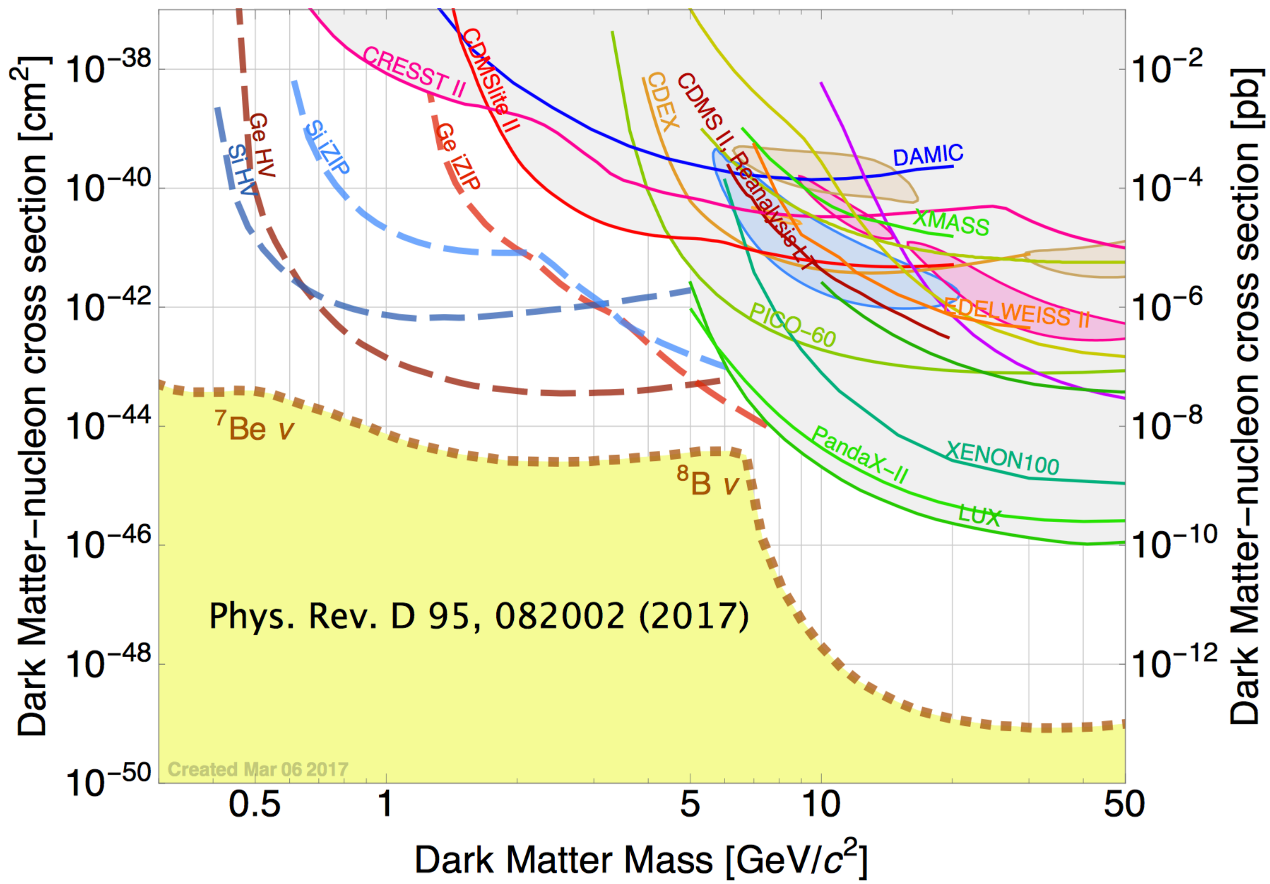


WIMP Searches: SuperCDMS



SuperCDMS

- First Payload will be modest - 2 iZIPs+ 2HV
- Optimal Interval
- No background subtraction initially (although will develop new proj. including)
- No nuclear recoil discrimination for HV
  - 3H dominant for Ge
  - 32Si dominant for Si
- Recovering nuclear recoil discrimination at low mass, e.g., through ≤10eV rms phonon resolution in HV det. -> Neutrino Floor
- Possible Merger: SuperCDMS+Eureca

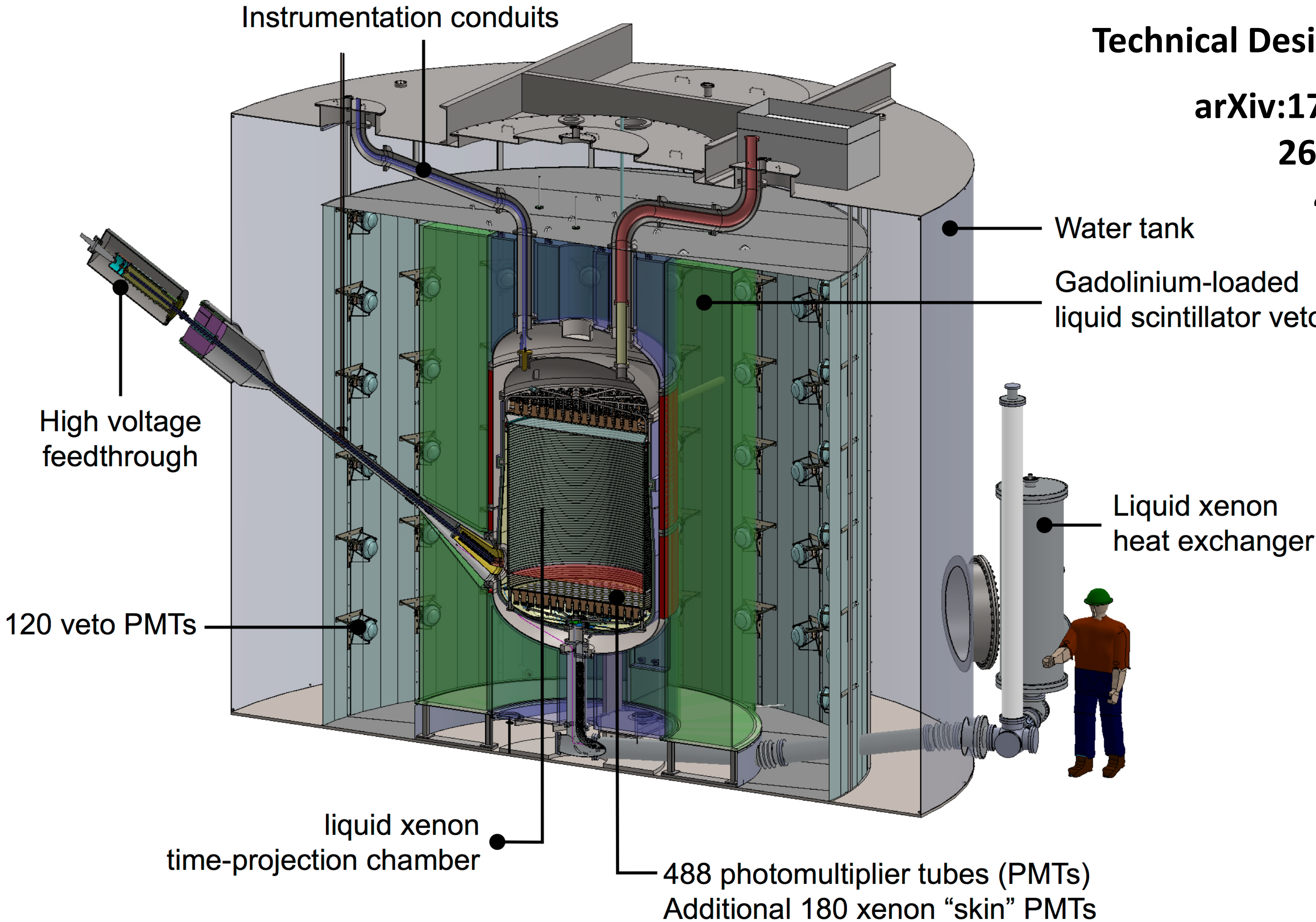


LZ Detector - 10 tonnes Xe

Replaces LUX at the Sanford Underground Research Facility (SURF)

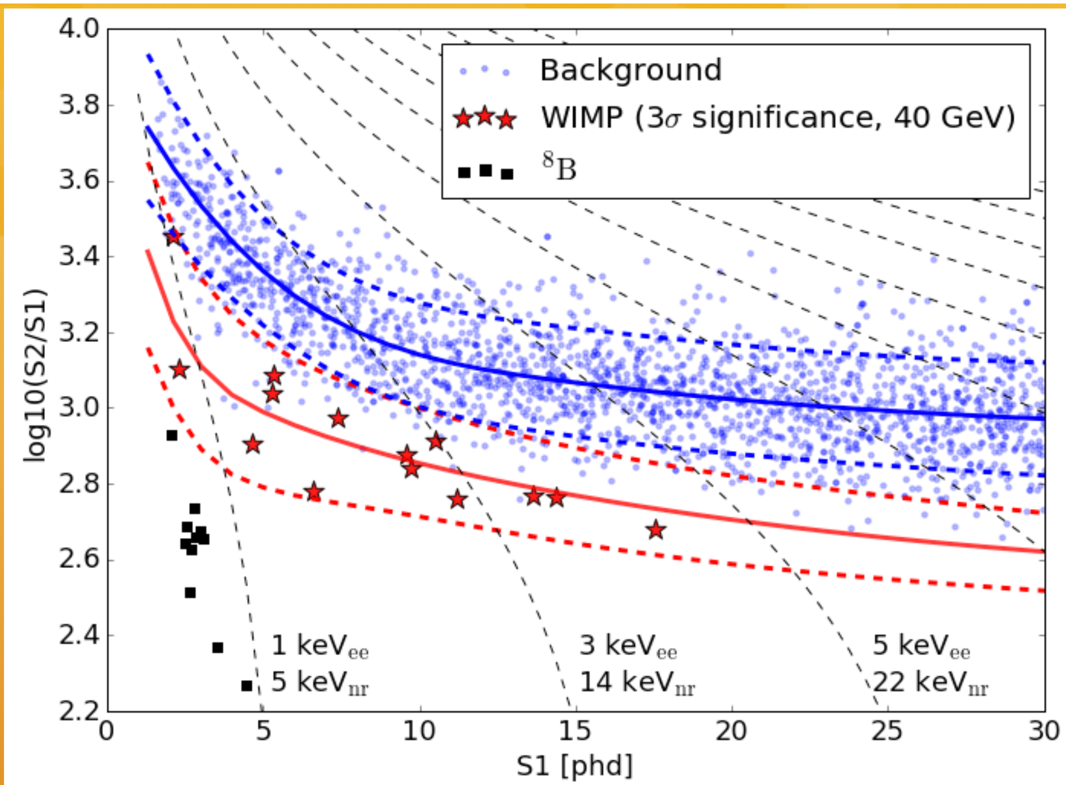
Technical Design Report

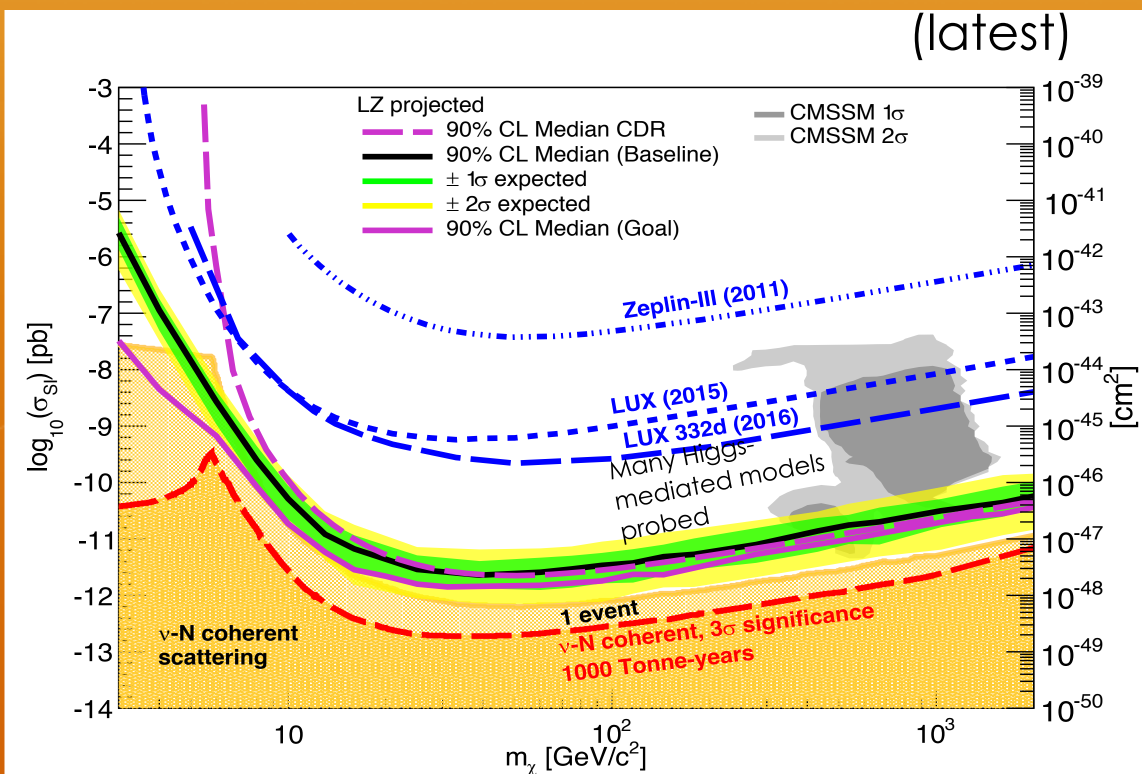
arXiv:1703.09144
260 Authors
400 Pages



LZ's Reach

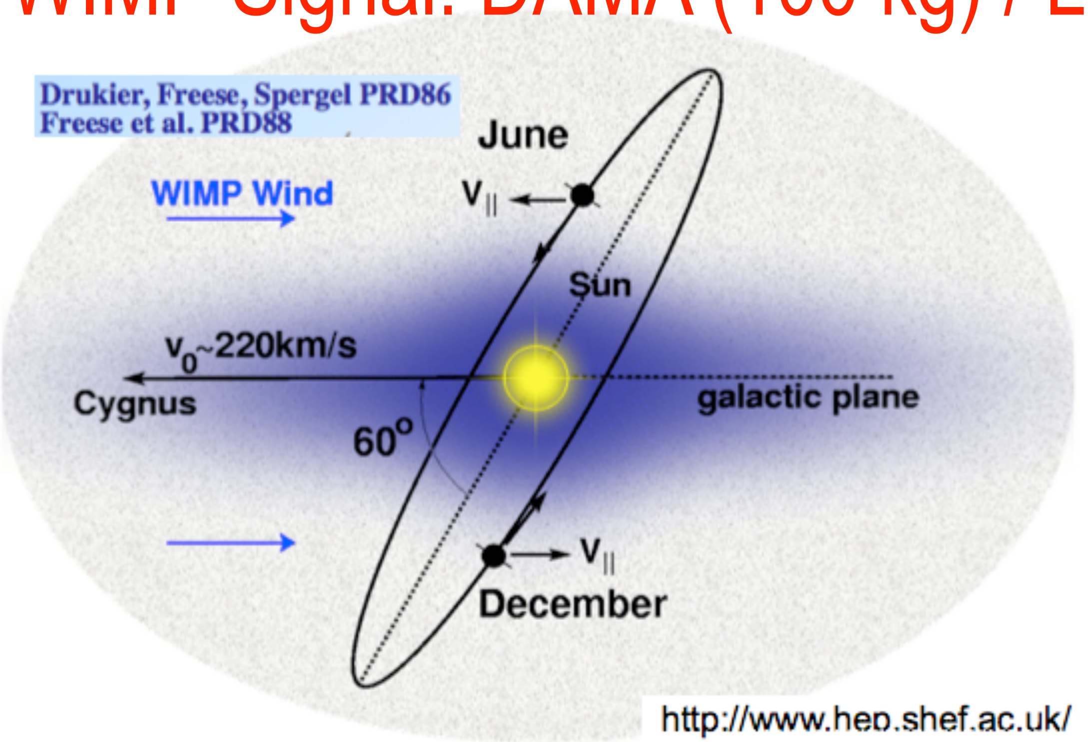
- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial mass
  - Due to unique triple veto
- GOALS: < 3 x 10^{-48} cm^2, at 40 GeV. Clip ν shoulder



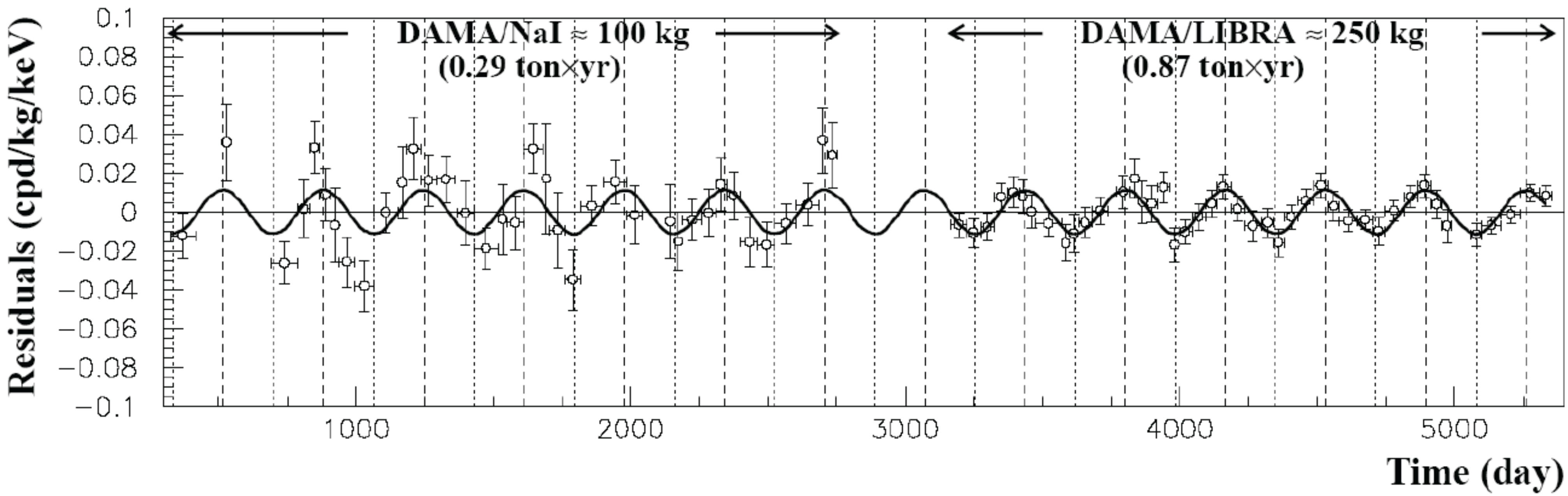


*plot and models from LZ's Conceptual Design Report, arXiv:**1509.02910**

WIMP Signal: DAMA (100 kg) / LIBRA (250 kg) NaI @ LNGS

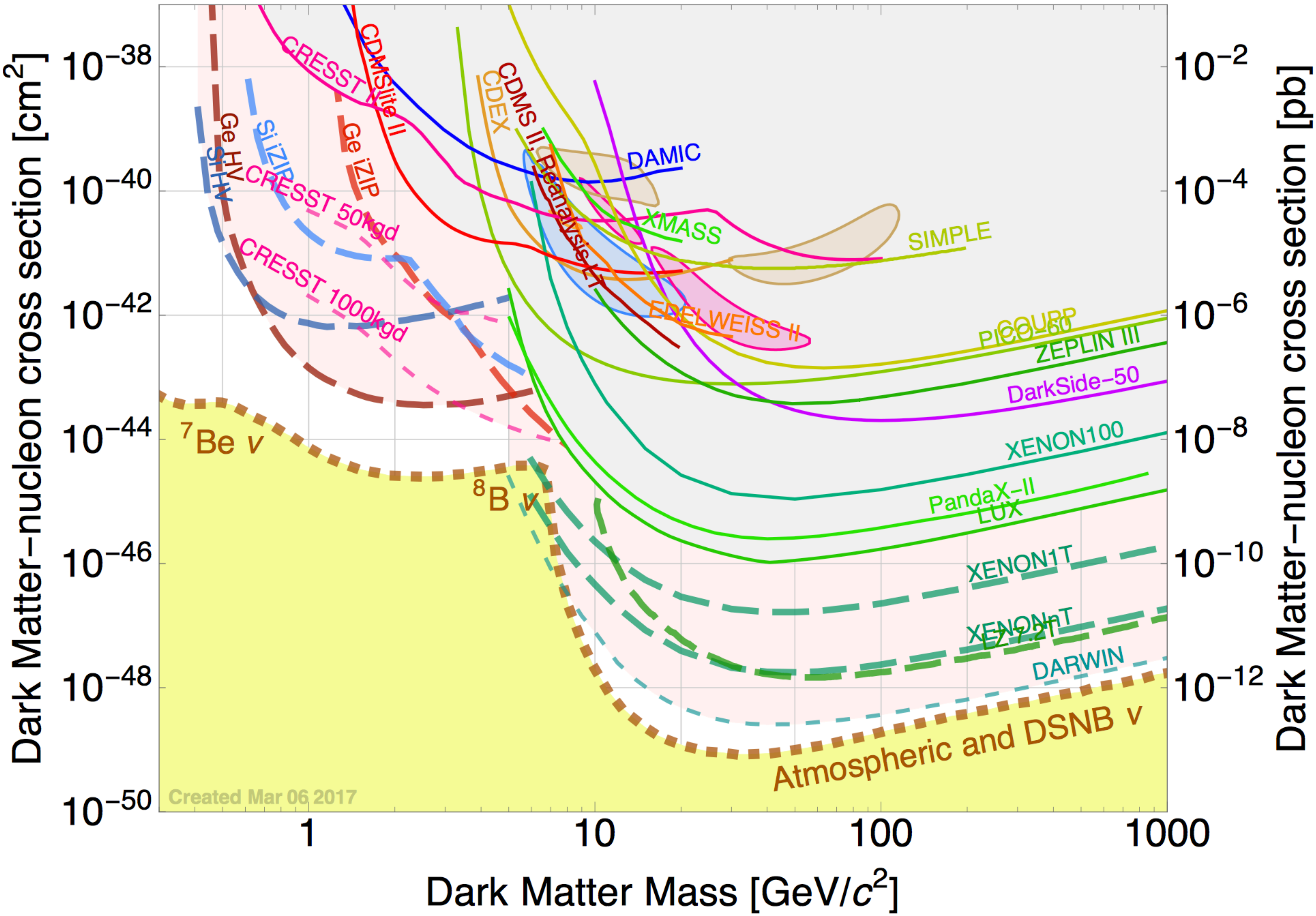


- Annual Modulation
  - Significance is 9.3σ
  - 1-2% effect in bin count rate
  - Appears in lowest energy bins
  - Can another experiment observe this effect?



DAMA/LIBRA

9.3 σ C.L.



Dark Matter–nucleon cross section [cm²]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c²]
10⁻³⁸
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
10⁻⁴⁶
10⁻⁴⁸
10⁻⁵⁰
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
1
10
100
1000
CRESST
CDMSlite II
Ge HV
Si HV
Si iZIP
Ge iZIP
CRESST 50kgd
CRESST 1000kgd
CDEX
CDMS II, Reanalysis
DAMIC
XMASS
SIMPLE
EDELWEISS II
COUPP
PICO-60
ZEPLIN III
DarkSide-50
XENON100
PandaX-II
LUX
XENON1T
XENONnT
LZ 7.2T
DARWIN
⁷Be ν
⁸B ν
Atmospheric and DSNB ν
Created Mar 06 2017

DAMA/LIBRA

9.3 σ C.L.

REPORTED IN 2013… since then?…

Phase 2
- improved PMTs with better light collection. 5.5-7.5 phe/keVee -> 10 phe/keVee, lower energy threshold ~2 keVee
- Data taking began in 2011 so 6+ annual cycles
- We expect first report with ~1 tonne x year. So results very soon

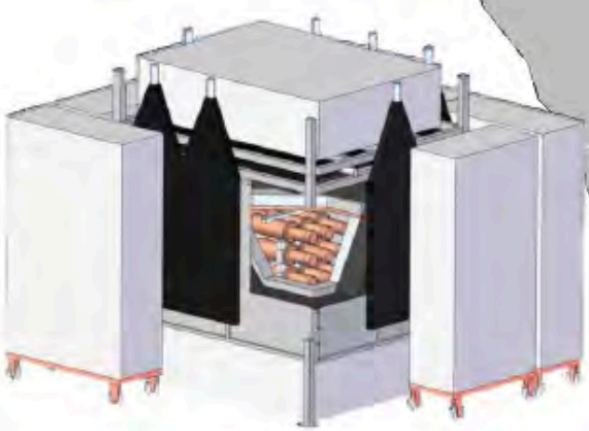
Global NaI(Tl) Collaborative Effort

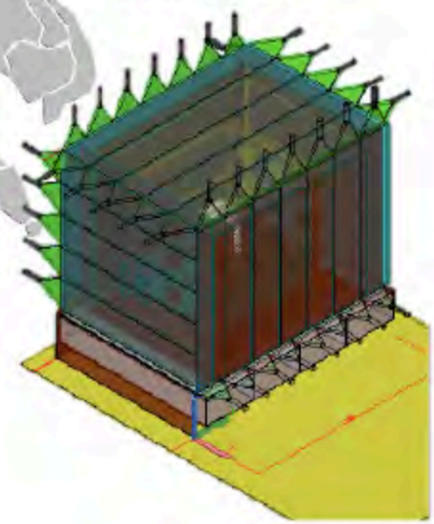
Boulby

Canfranc

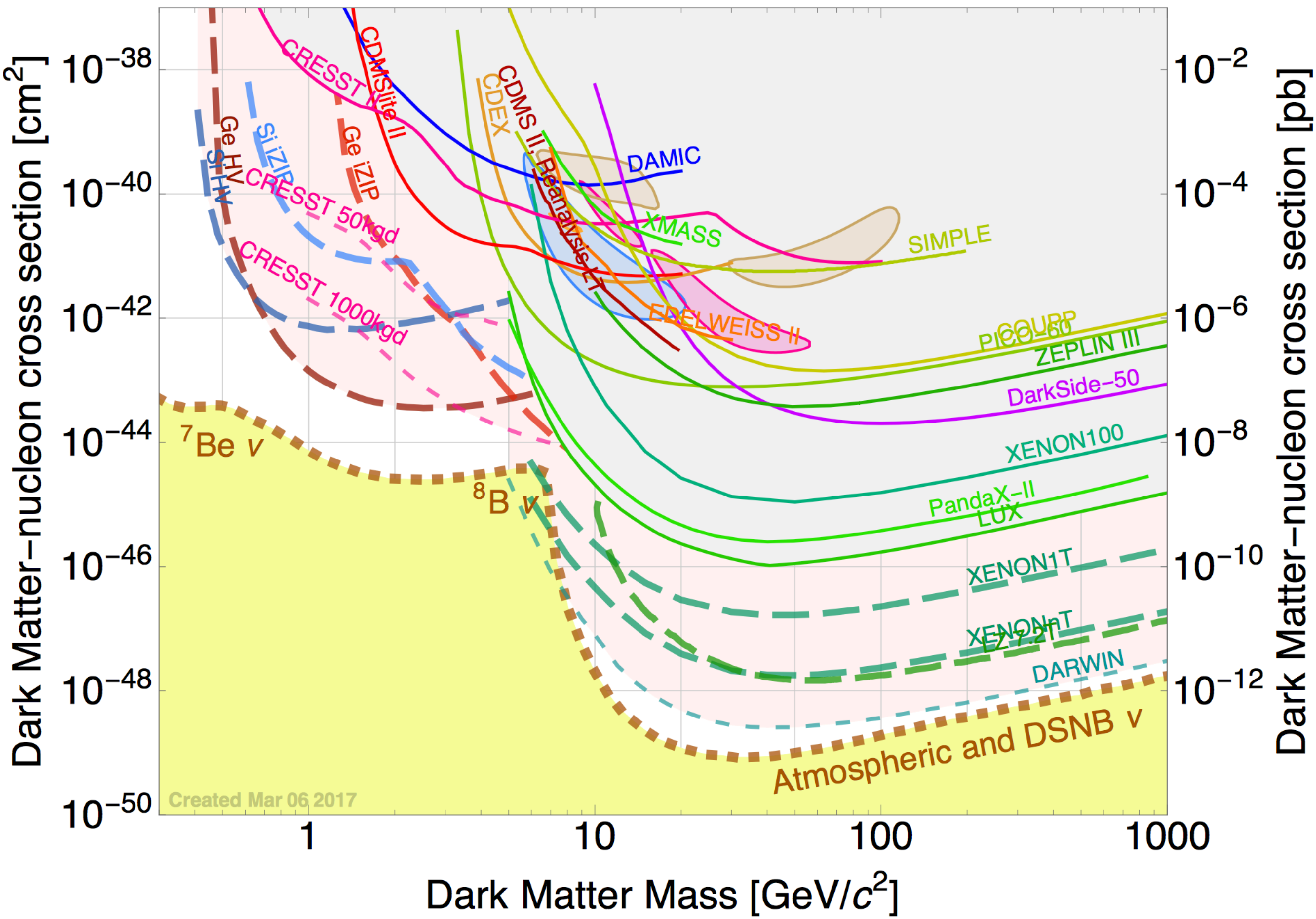
Yangyang

ANAIS	DM-Ice	KIMS
University of Zaragoza	Yale University	Seoul National University
Canfranc Laboratory	University of Wisconsin	Sejong University
University of Washington	Sheffield University	Kyungpook National University
	University of Illinois	Yonsei University
	University of Alberta	Ewha Womans University
	Fermilab NAL	Seoul City University
	Boulby Laboratory	Korea Res. Inst. of Standard Sci.
		Tsinghua University





Princeton Low Activity NaI Program



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Si HV
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CRESST 50kgd
CRESST 1000kgd
⁷Be ν
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Atmospheric and DSNB ν
Created Mar 06 2017

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

Empirical Points Worth Considering

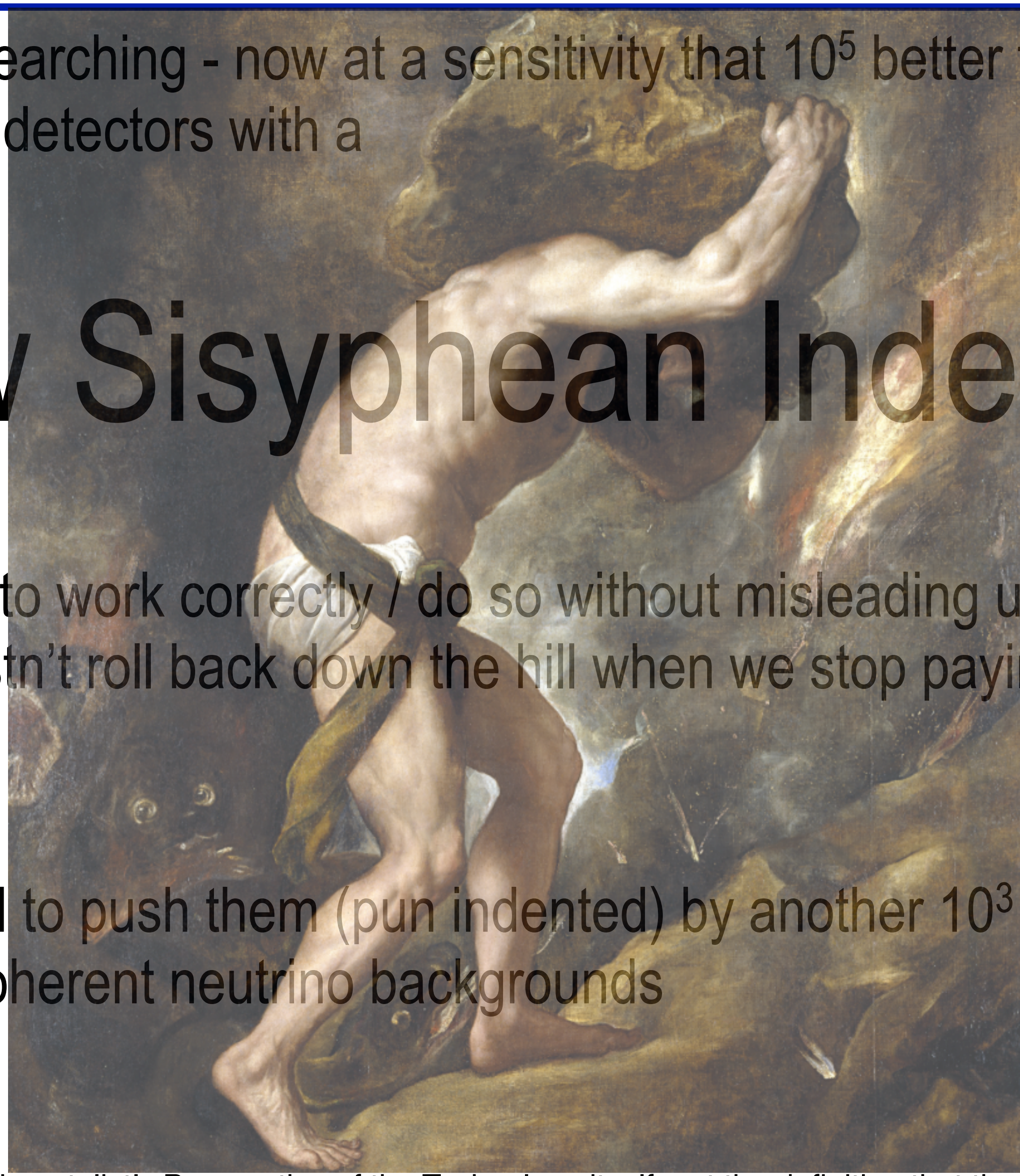
- You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram - Attributable, in spirit to Rutherford (I believe)

- 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

- In dark matter we are often forced to push our detectors into condensed matter regimes or ultra low background levels (at low energy) that have not been studied before
  - We must show conservative approach to calibration/interpretation of signal excesses
  - Ensure there is adequate study of the more mundane explanations

- An ideal dark matter detector could be a single bit showing WIMP event/No WIMP event if we had perfect discrimination… an extra few bits of energy information would assist determination of particle/astrophysics
  - Reality is that we need as much information as we can to differentiate rogue signals from genuine WIMPs

The Practical Matter of a Rare Event Search



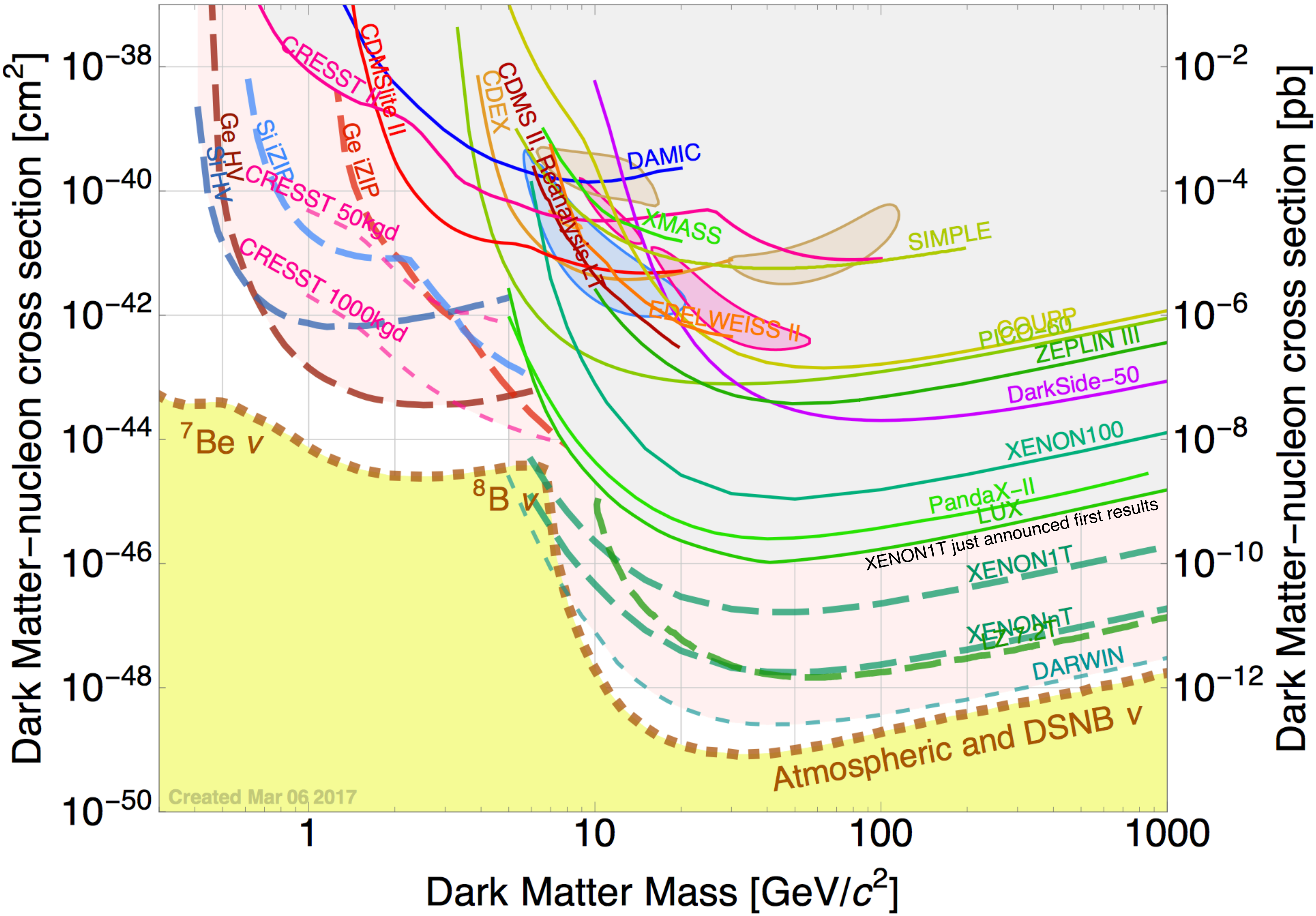
- In 30th year of searching - now at a sensitivity that 10^5 better than the first round - we need detectors with a

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 10^3 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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XENON1T just announced first results
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Si HV
Ge HV
Si iZIP
Ge iZIP
CRESST 50kgd
CRESST 1000kgd
⁷Be ν
⁸B ν
Atmospheric and DSNB ν
Created Mar 06 2017

Conclusions - Direct Detection

- New Results Announcements Recent/Expected in 2017
  - Xe: LUX Full exposure published / PandaX 500 rolling updates / XENON1T just reported first result
  - DEAP3600 - look toward announcement at TAUP
  - DAMA Phase 2 = 1 tonne x year
  - SuperCDMS@Soudan - Final high threshold results
- US Selection Process of G2 "Generation 2" Dark Matter Experiments: LZ, SuperCDMS, ADMX
  - LZ completed CD3B in September 2016 - construction is fully underway at Sanford Lab for operation in 2020
  - SuperCDMS CD2/3B Seeking permission to start construction in Dec 2017
- Europe
  - XENONnT will be installed after 3 years of XENON1T data, construction underway
  - DarkSide20k (20 tonne) seeking approval from multiple agencies
- 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 > factor 20 in the last three years (Compare 5 orders of magnitude in the last 25 years => we are accelerating progress)
  - New larger detectors are being delivered in order to keep this rate of improvement
- The Spectre of Discovery is always upon us, and is a great responsibility
  - Clearly, multiple detectors / multiple techniques will be required to build a robust case of discovery