State of the Dark Matter Direct Detection Field

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Particle Astrophysics Group, Brown University, Department of Physics

(Supported by US DOE HEP)

see information at
http://luxdarkmatter.org
http://particleastro.brown.edu/
http://gaitskell.brown.edu

Dark Matter Underground Searches - Silver Jubilee

- 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

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Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

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

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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.

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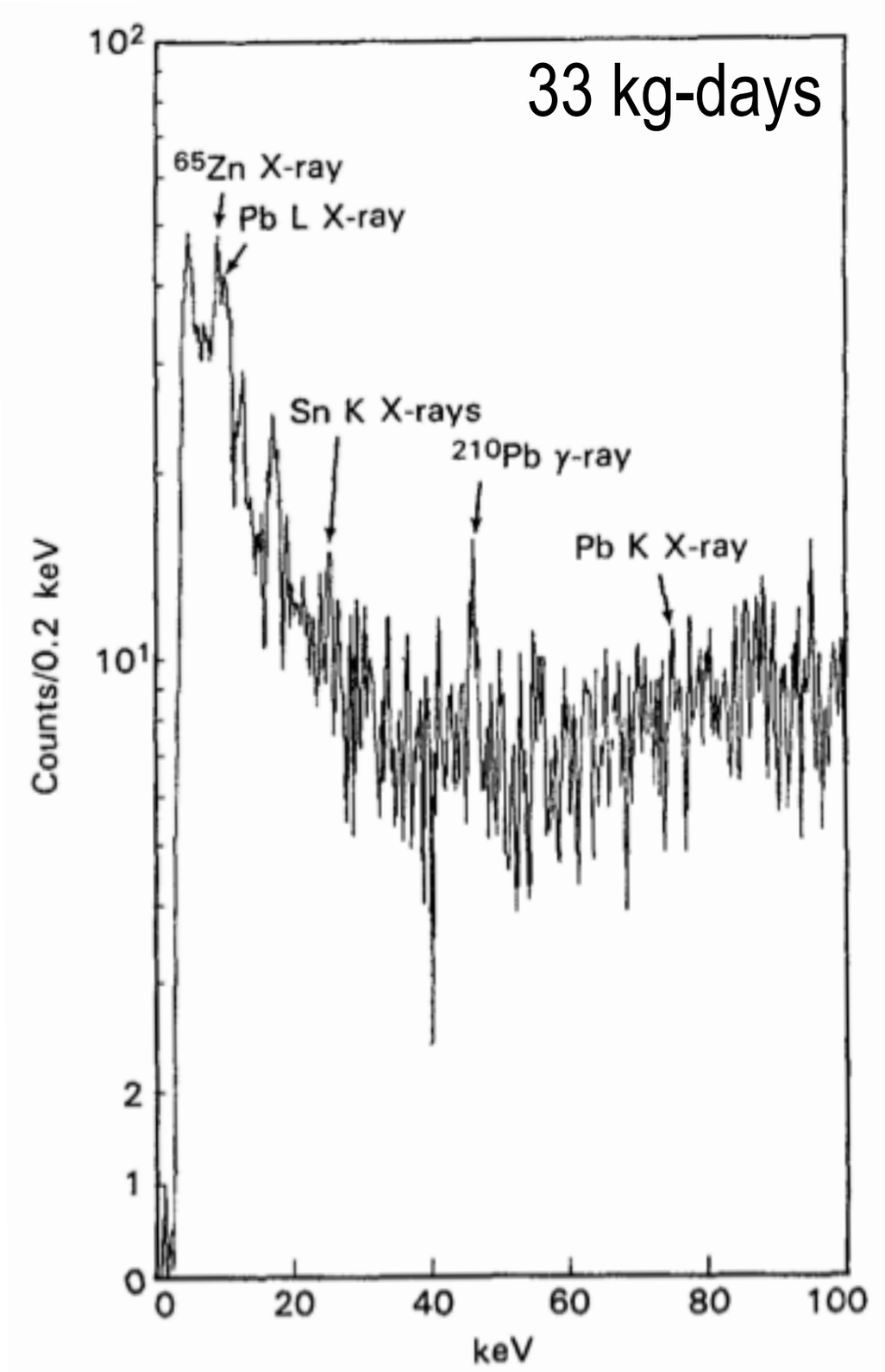

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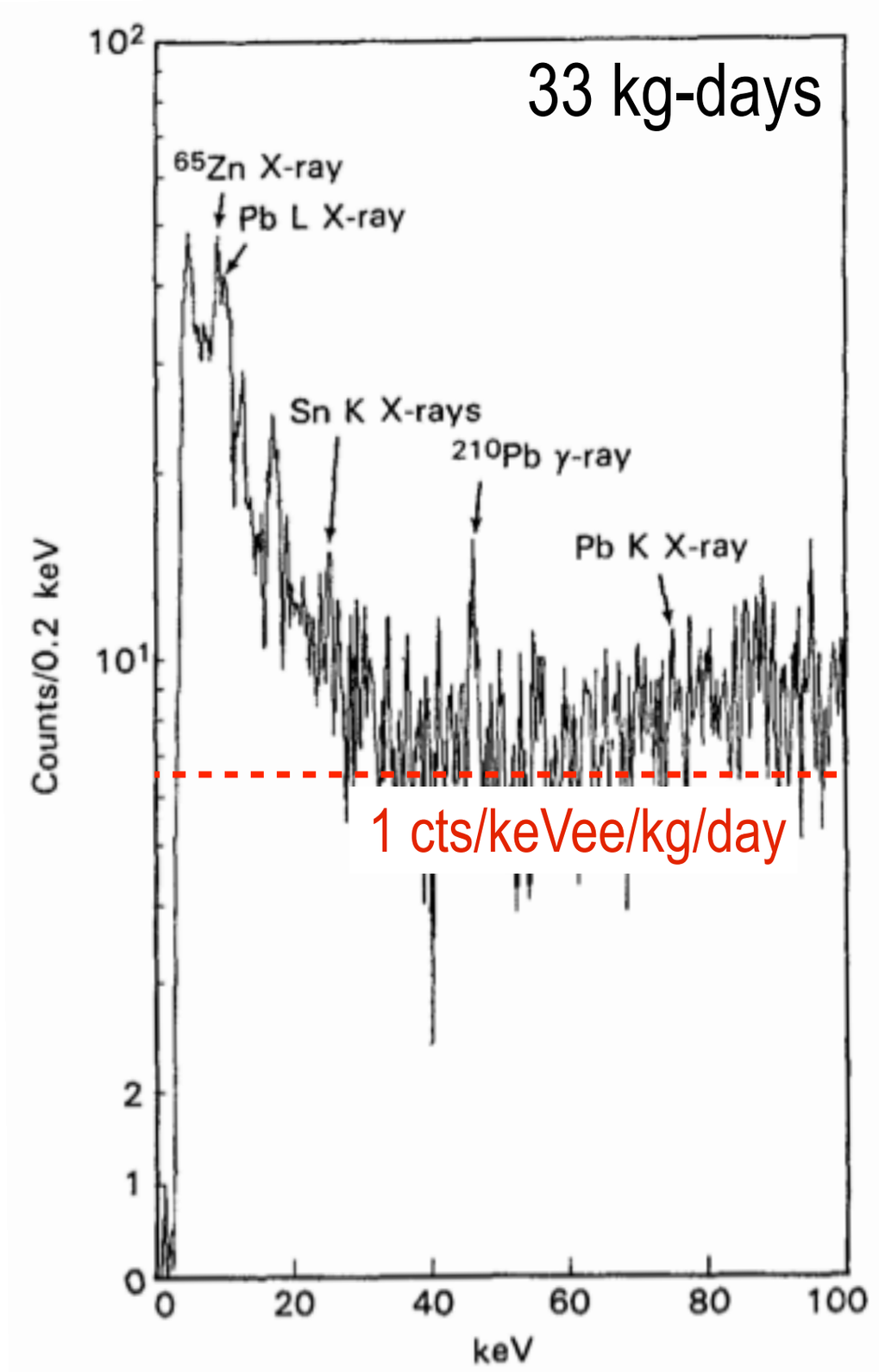

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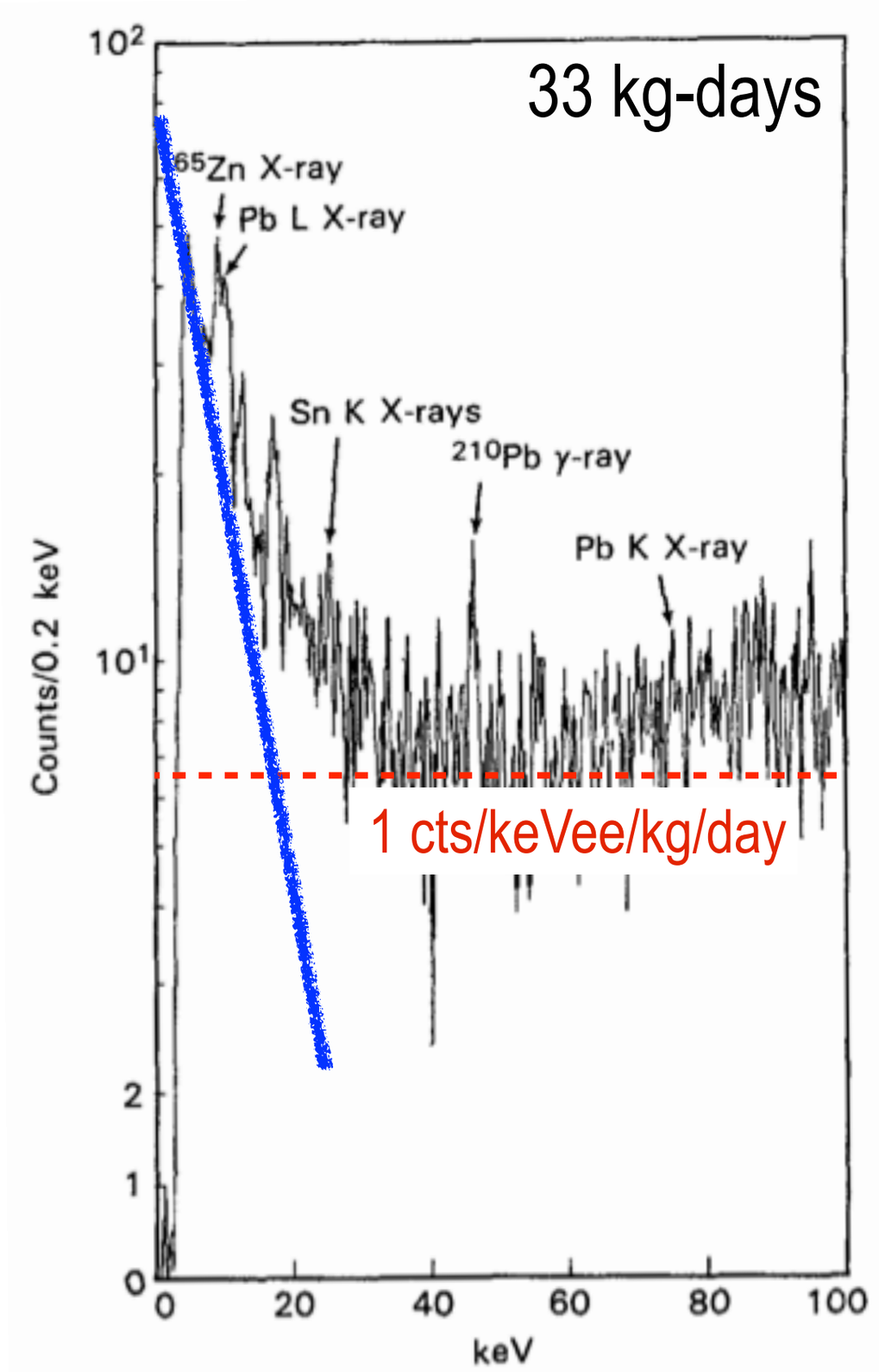
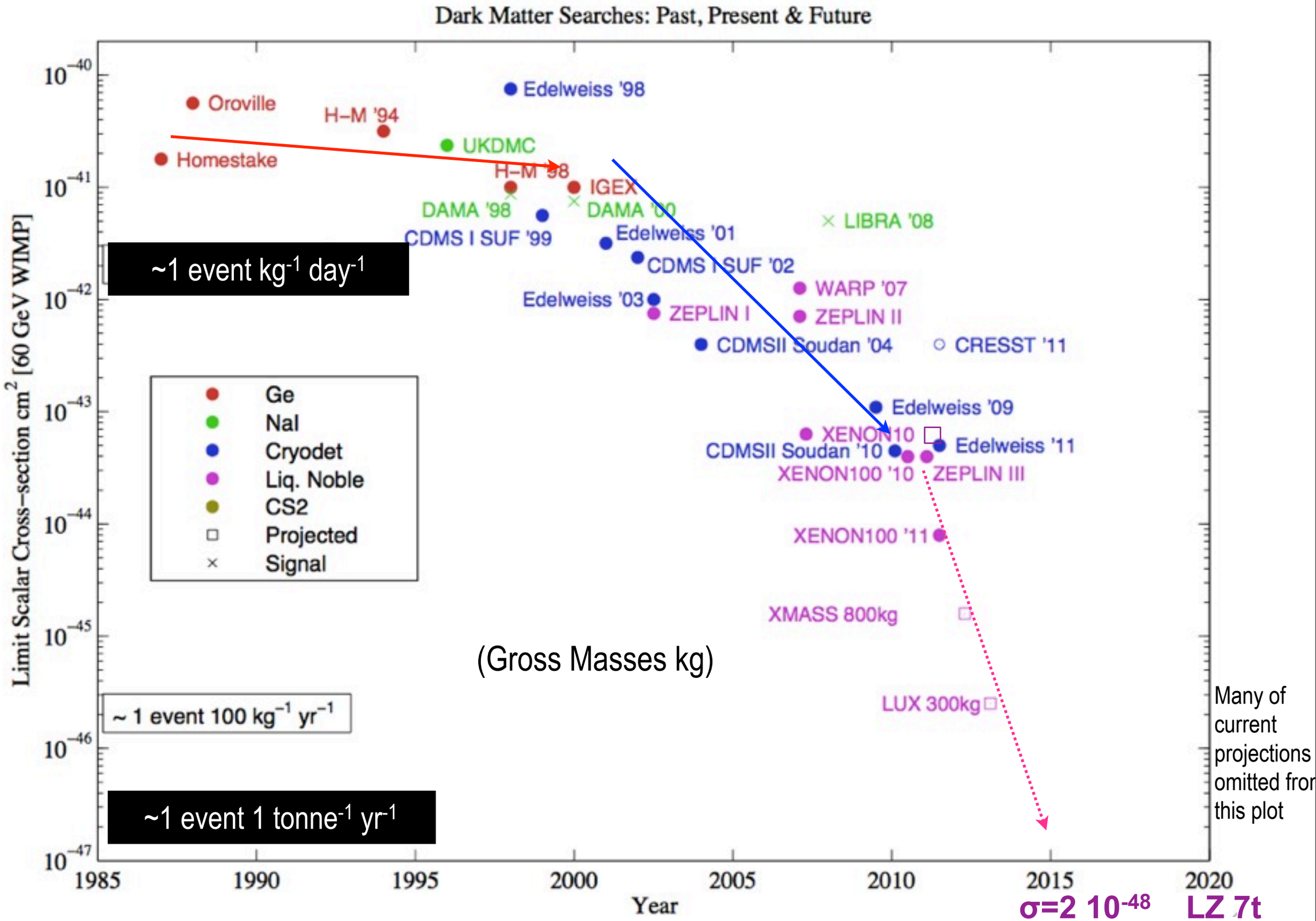


DM Direct Search Progress Over Time (2012)

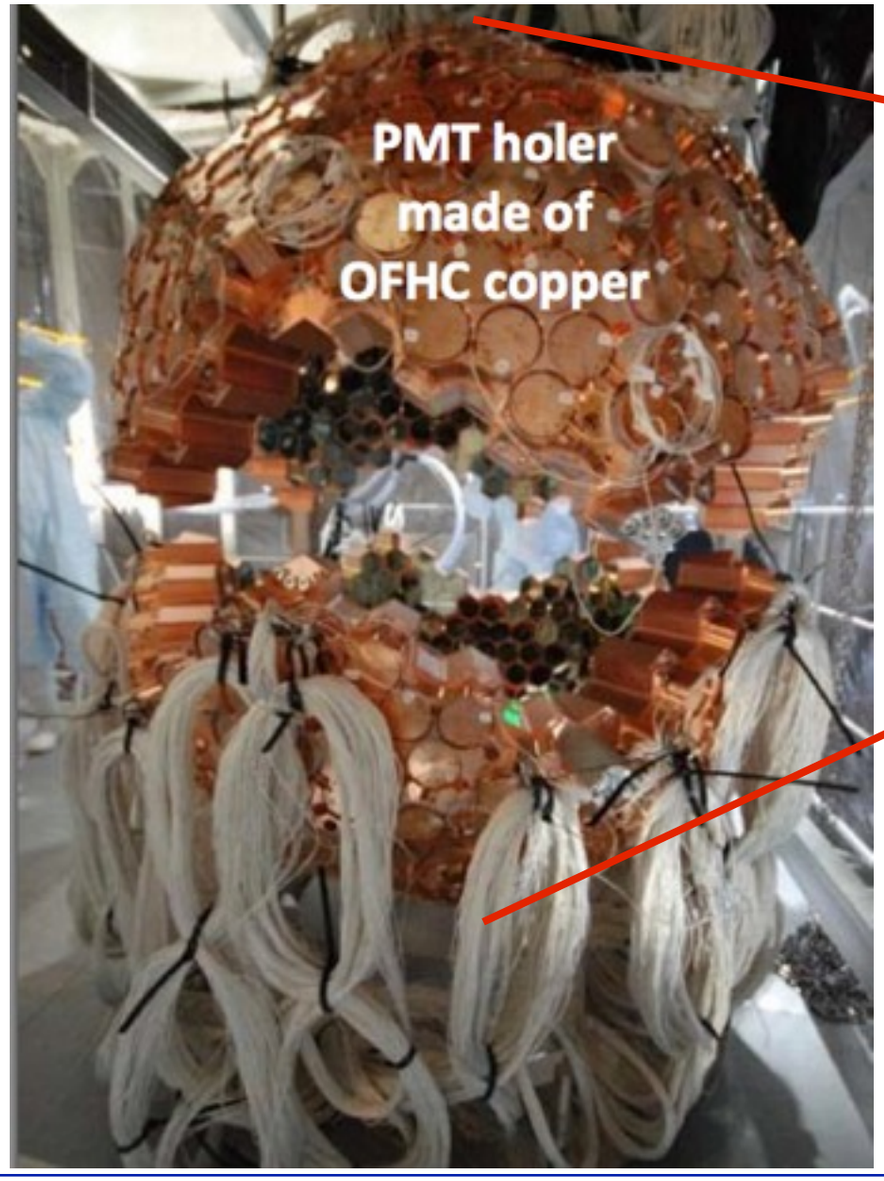
Plot does not track low mass WIMPs 10 GeV

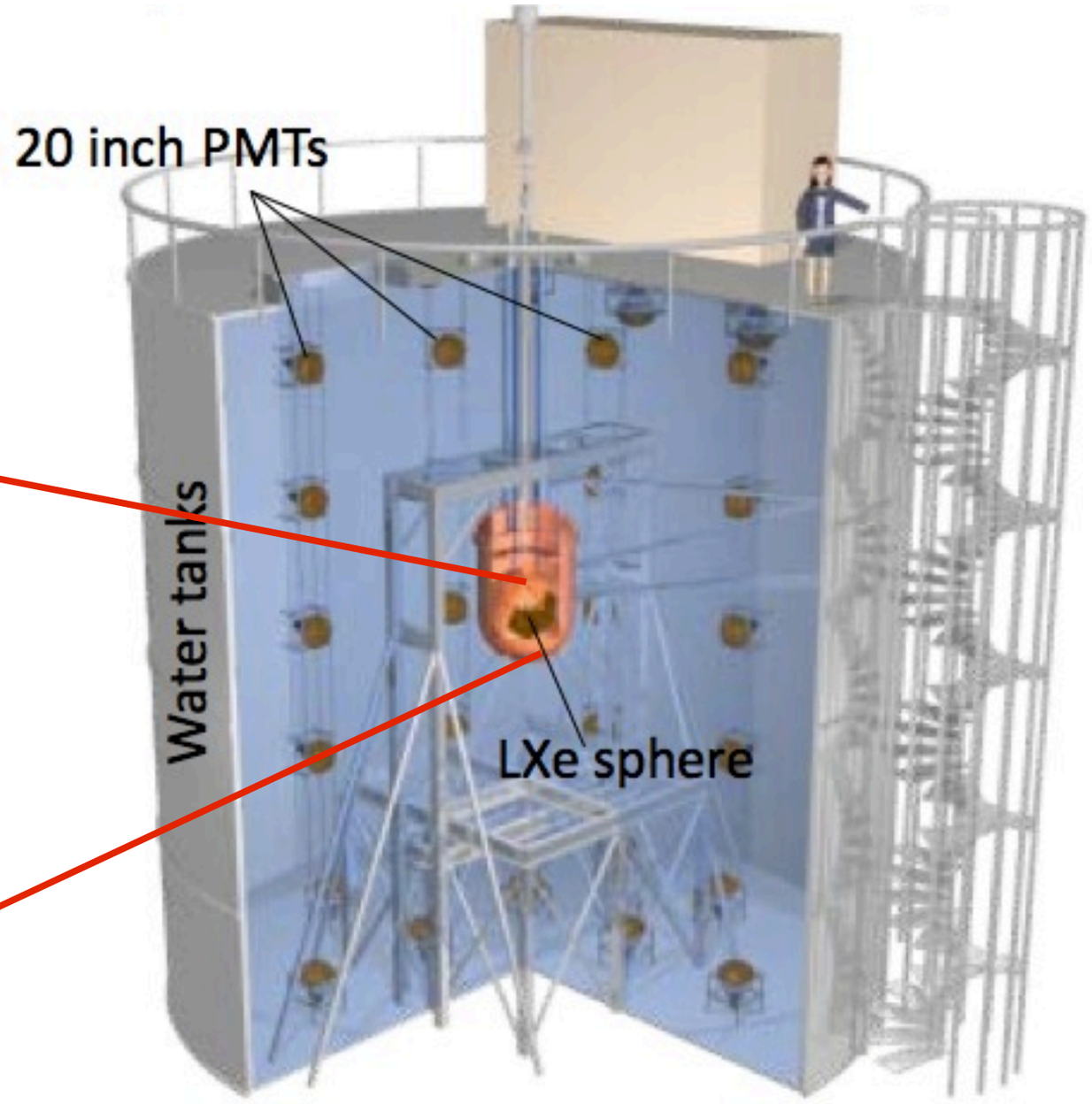


XMASS

Figures from from Jing Liu, TAUP 2011

- 800 kg LXe (~100 kg fiducial)
- S1 only
- 642 PMTs covering >60% of inner surface

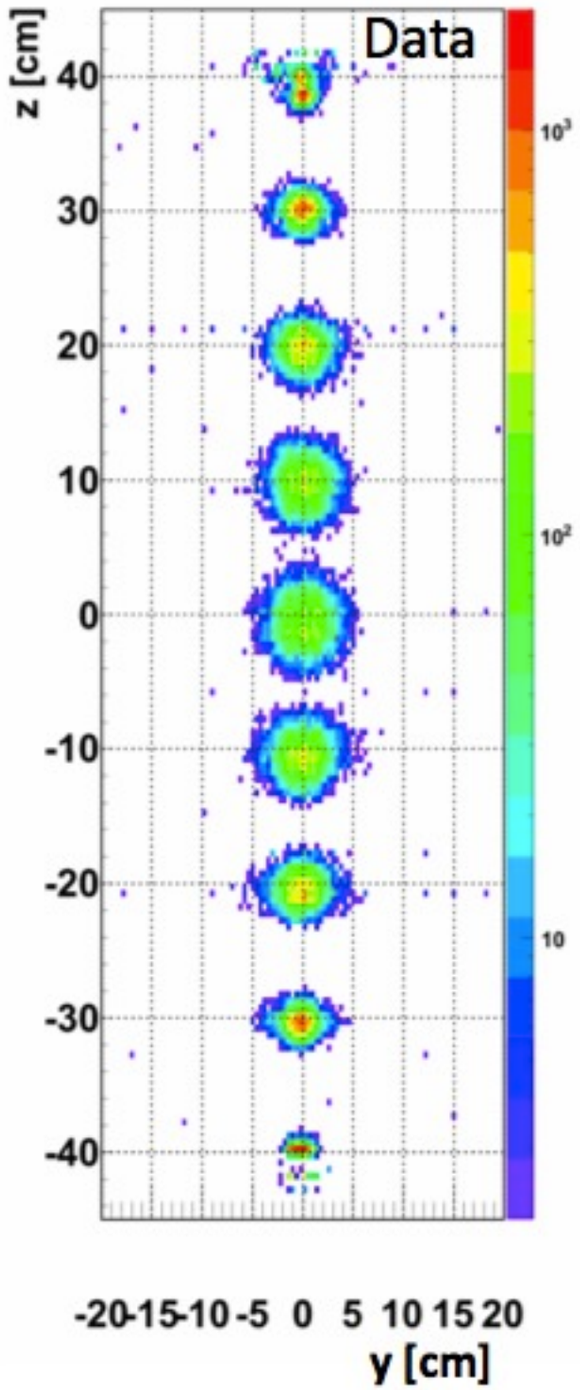


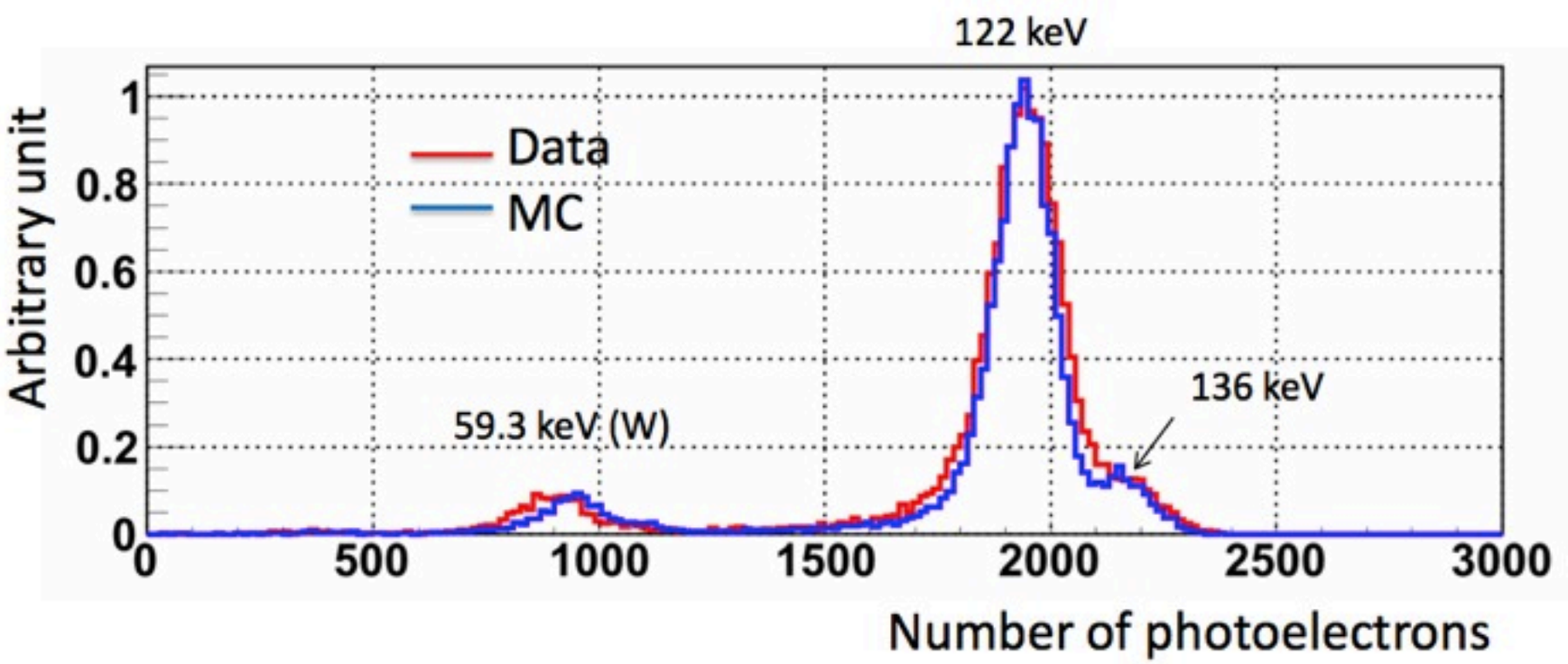


Plots from from Jing Liu, TAUP 2011

XMASS Light Yield and Position Reconstruction

- Light Yield
  - ➡ ^{57}Co at center of detector
  - ➡ 15.9 ± 1.2 phe/keV
- Position Reconstruction (122 keV ϒ - ^{57}Co)
  - ➡ RMS 1.4 cm at z = 0 cm
  - ➡ RMS 1.0 cm at z = ±20 cm





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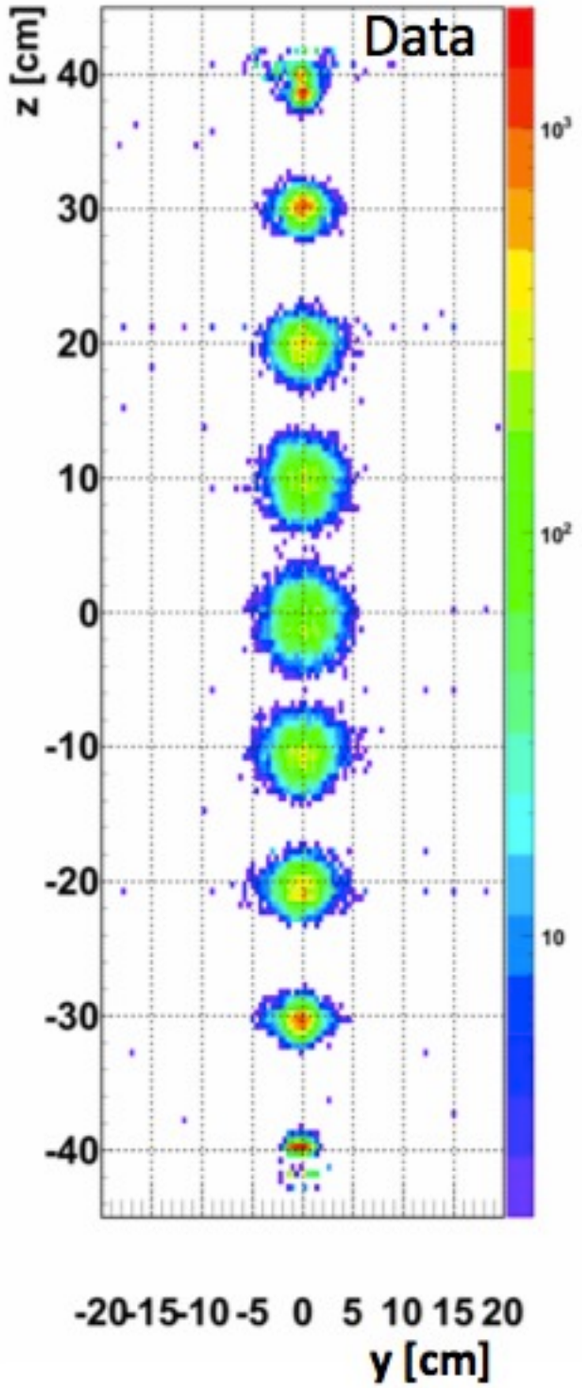
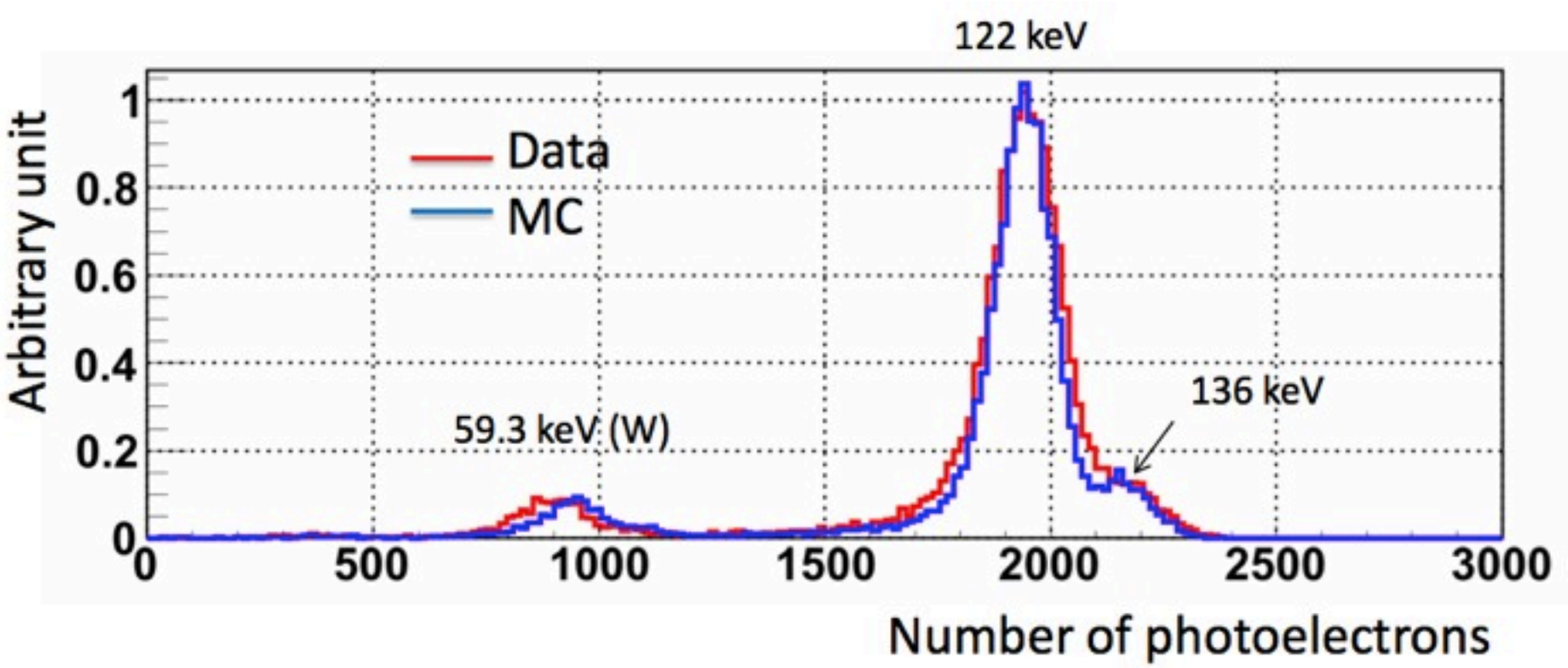


Position Reconstruction Tails?



XMASS Anticipated SI Sensitivity

- Construction of the XMASS detector finished late 2010
- Physics results will be announced soon
  - ~1 year of exposure / ~100 kg fiducial
  - Annual modulation?
- JPS Meeting (March 23, 2012)
  - Unexpected alpha activity at surfaces (see next slide)
- Likely challenges in event analysis
  - Mis-reconstruction of position for events taking place outside fiducial to inside fiducial
  - Regions of Xe which are poorly light coupled to central region giving bg of low phe events from higher energy bg
  - Note that if low mass WIMP hypothesis is correct then high rate of single NR events taking place throughout volume.
    $\sigma \sim 2\times10^{-40}$ cm^2 +8 GeV gives 100/kg/day >2 keVr
    - >=3 phe events @ 1 per second (10% Leff)
    - Competition would be thermal phe ~100 Hz/PMT, accidental coinc. 100 ns, so 3 phe substantially suppressed
    - Note the hit patterns would be different. DM events would be more clustered since most of mass is round edge of central region.

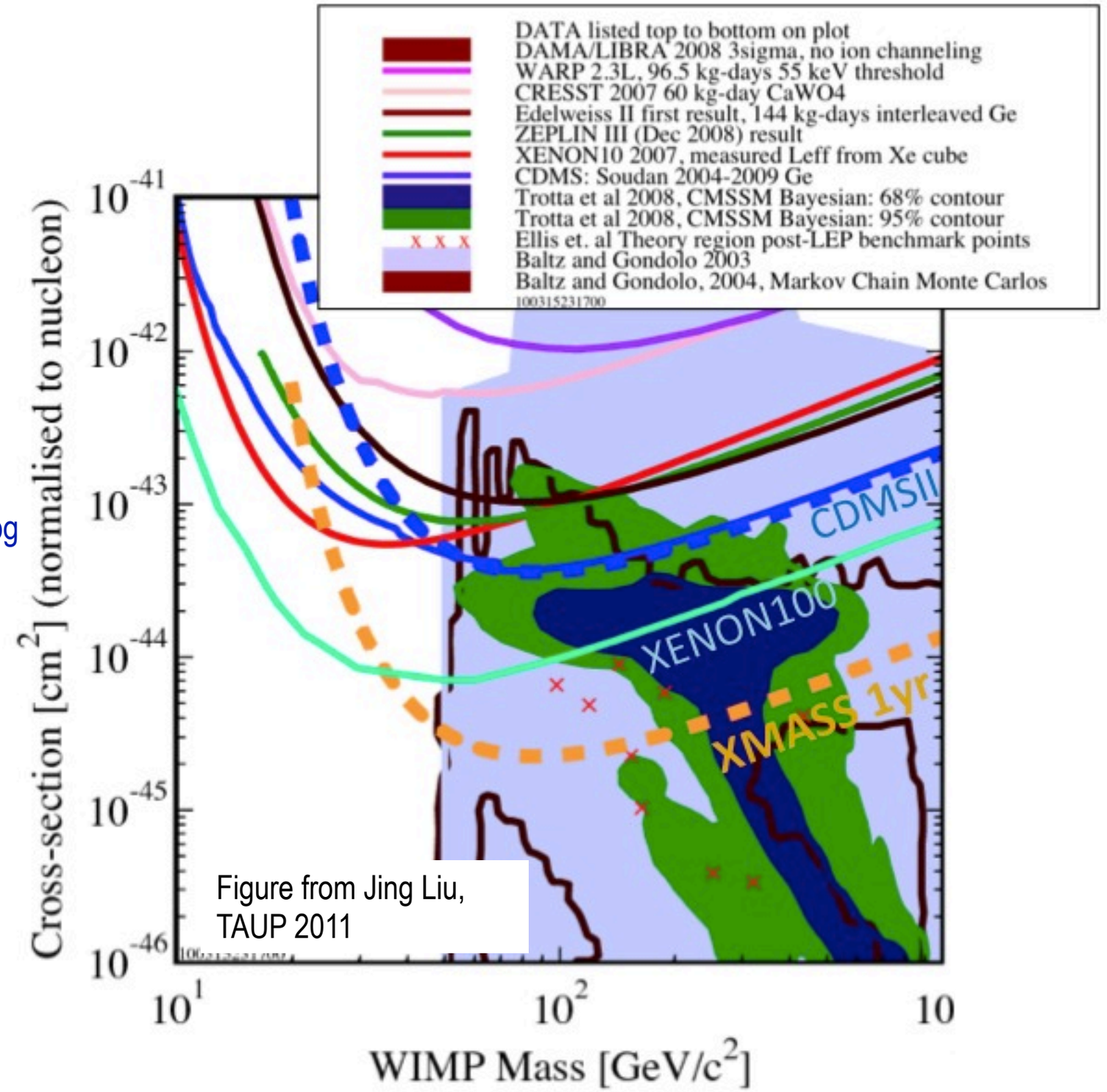


Figure from Jing Liu, TAUP 2011

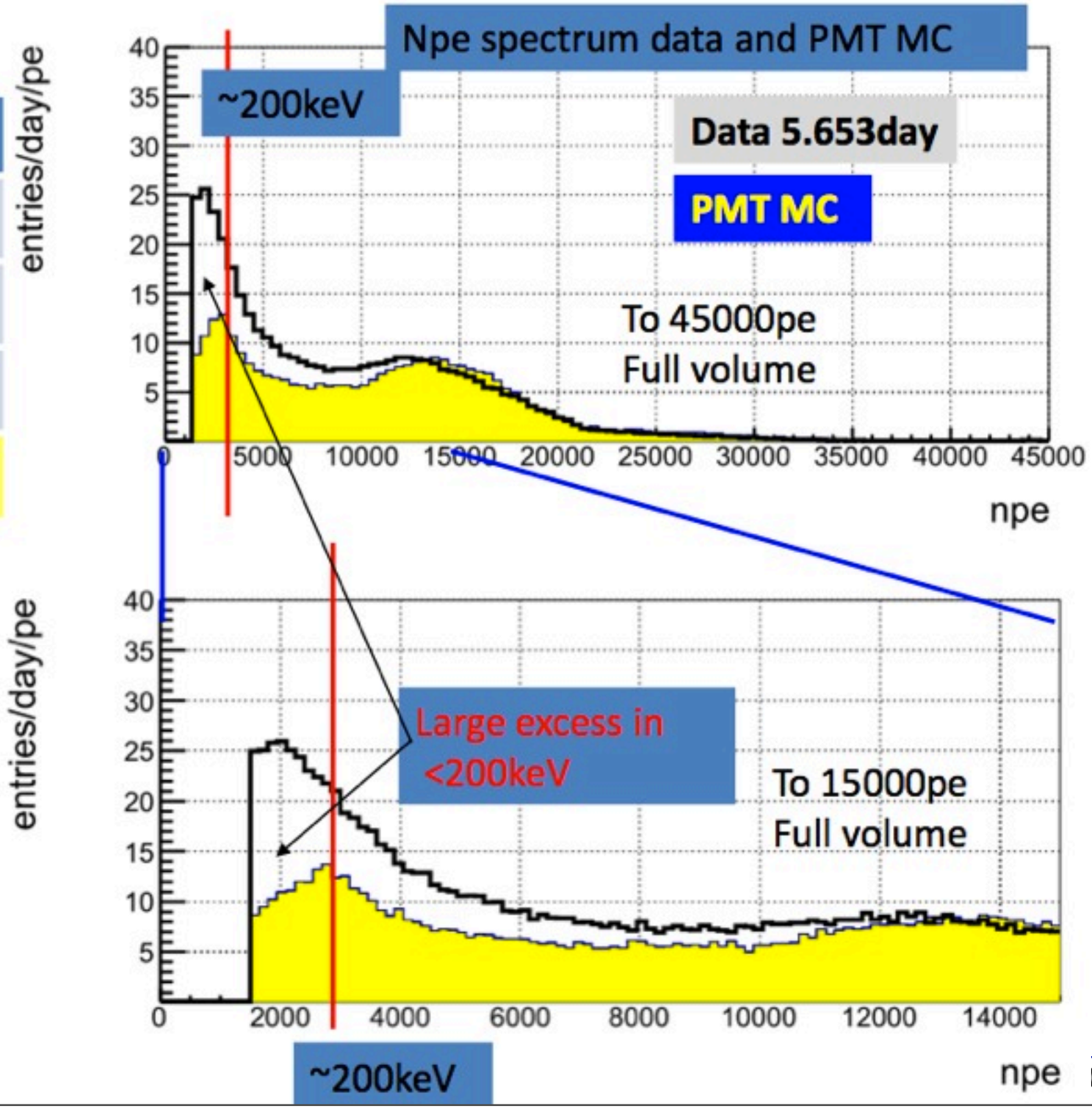
Presented by XMASS at JPS Meeting 2012 (thanks, to Y Suzuki)

Comparison between data and MC of PMT gamma >100keV

Activity of PMT

RI in PMT	Activity per 1PMT(mBq/PMT)
238U-chain	0.70+/-0.28
232Th-chain	1.51+/-0.31
40K-chain	9.10+/-2.15
60Co-chain	4.09+/-0.22

These value are measured by HPGe detector.
Only 60Co is scaled about +40% from HPGe result.
Detail will be explained by hosokawa.



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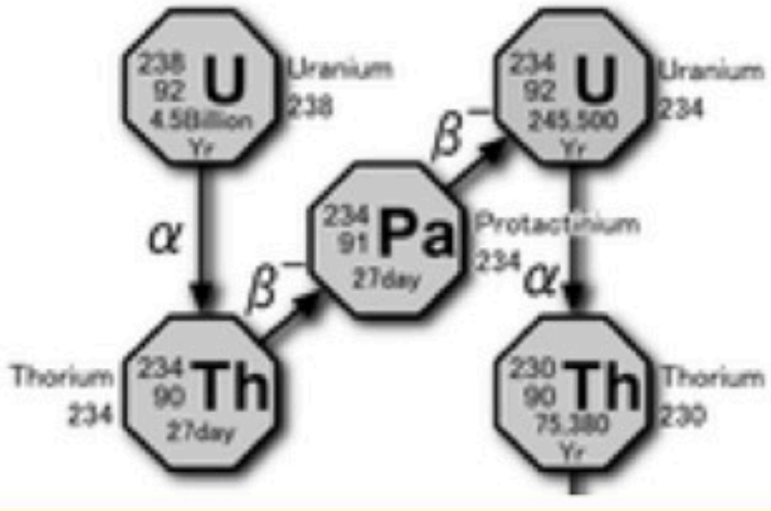
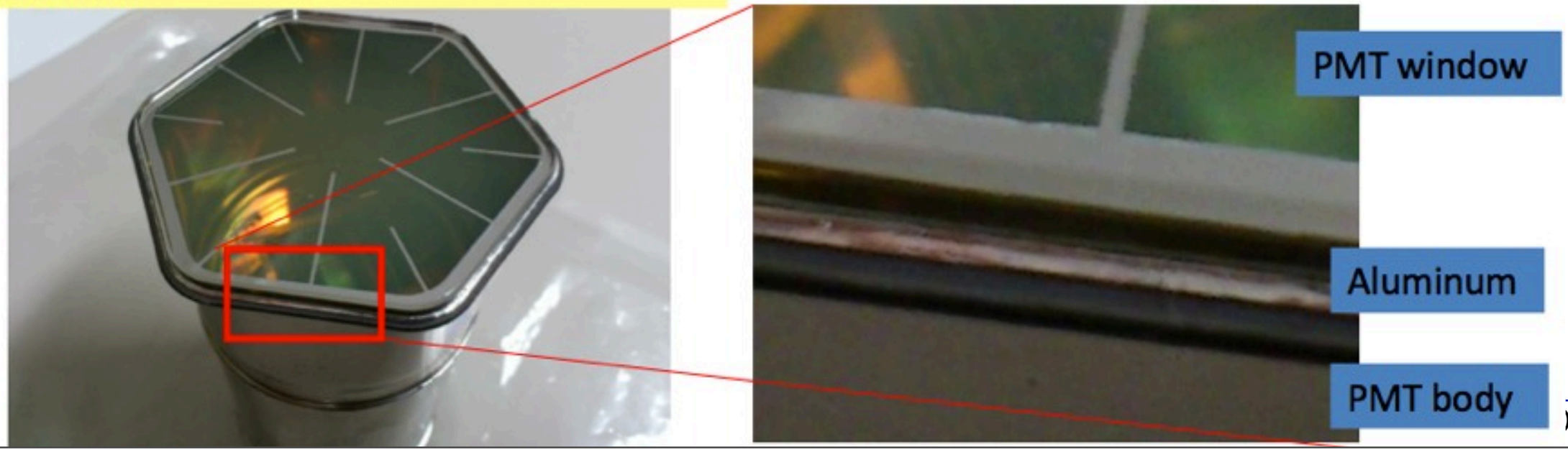
2. Evaluation of background
Aluminum for PMT window sealing



RI	Activity (per detector)	Measured/estimated by
238U-230 Th	1.8Bq	HPGe detector measurement
214Pb, 214Bi	<35mBq	
232Th	120mBq	
235U-231Pa	83mBq	Natural abundance 0.73% of 238U
210Pb	1.8Bq	HPGe detector measurement + scaled

~200g Aluminum are used in detector.
Main contribution are 238U-230 Th and 210Pb.
RI are distributed in bulk.
Actually, this material are faced to liquid xenon



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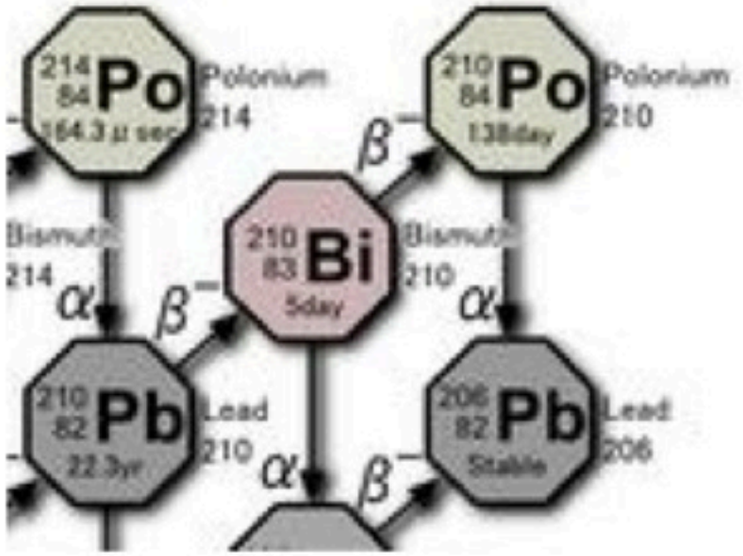
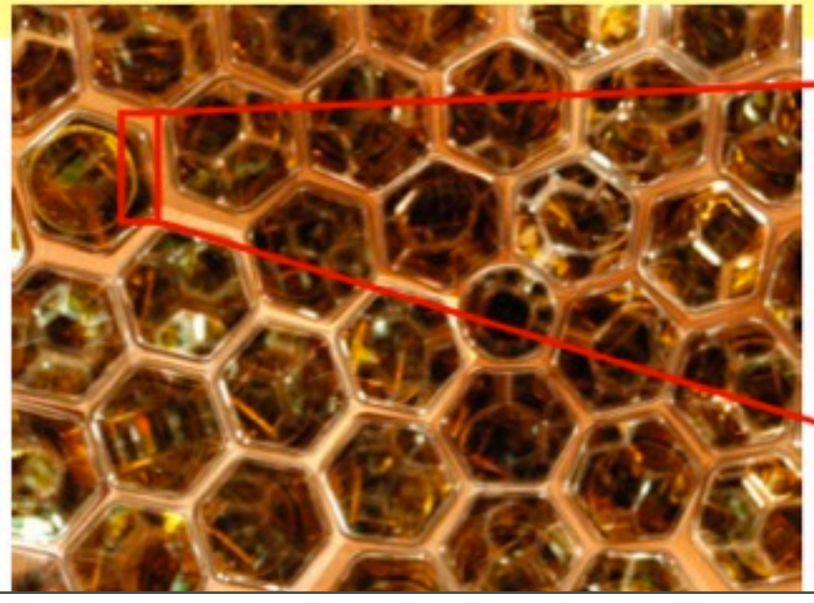
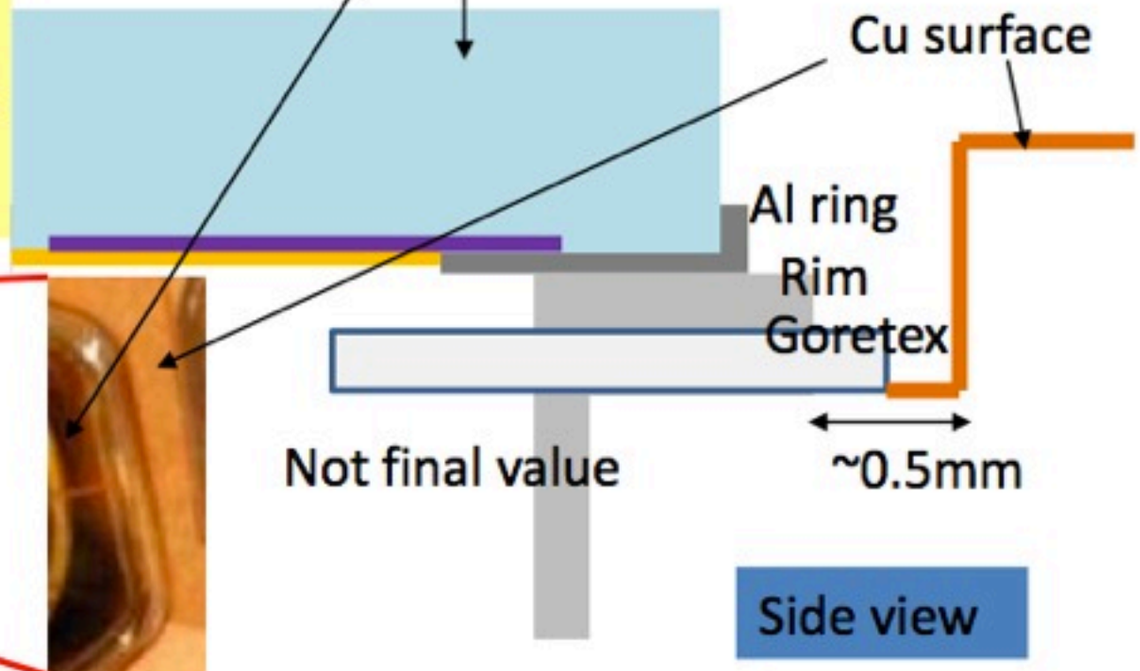
2. Evaluation of background 210Pb in detector surface

- The 222Rn should be put to detector in the construction work. (actually, we cared the environment in construction work).
- Also we can observe the alpha events from 210Po in surface by FADC data.
  - (高知尾理 :XMASS実験 : バックグラウンド6、FADCを用いた波形弁別による解析)
- Now ~40mBq 210Pb are applied in Cu surface for background evaluation.



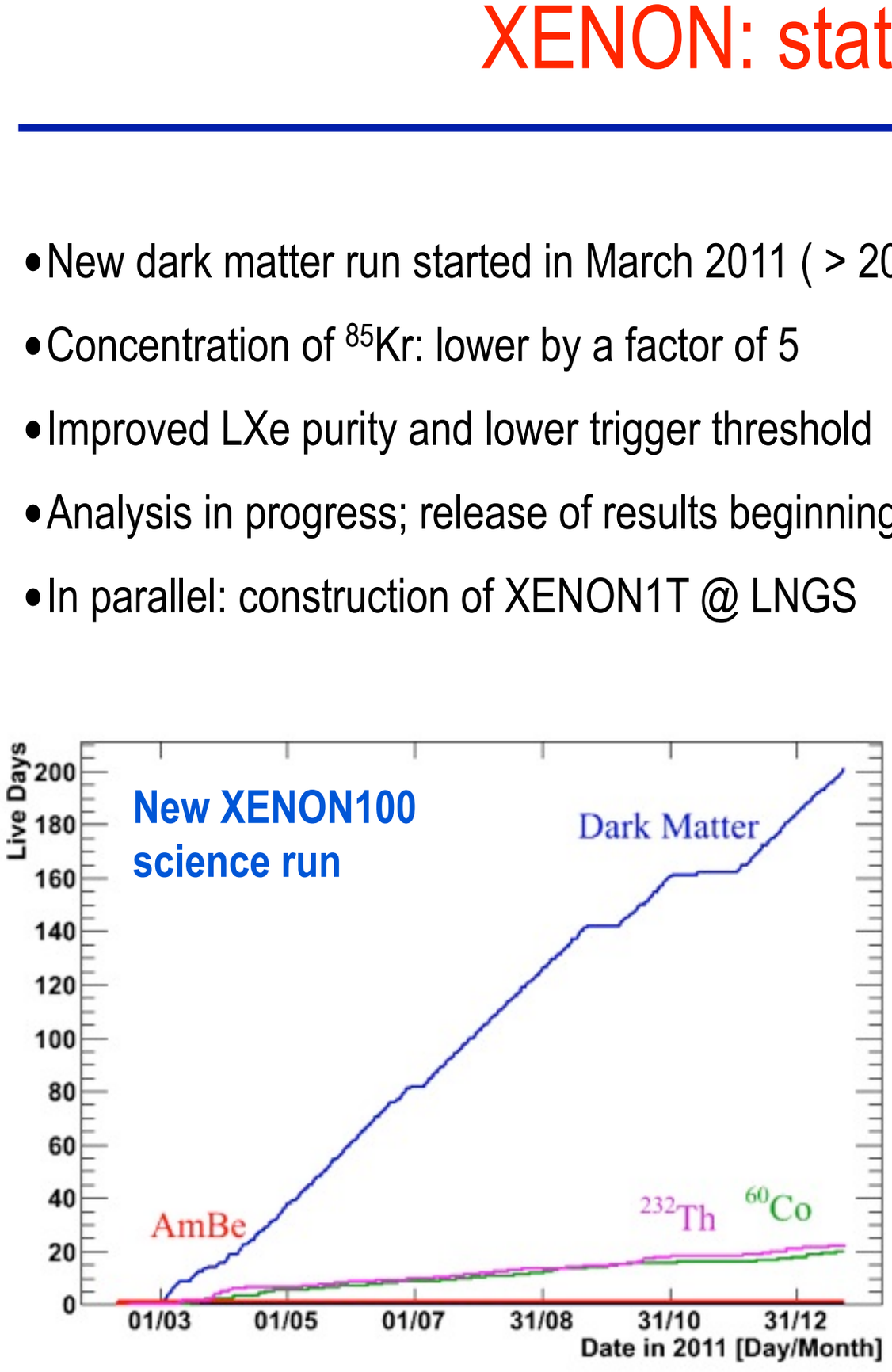


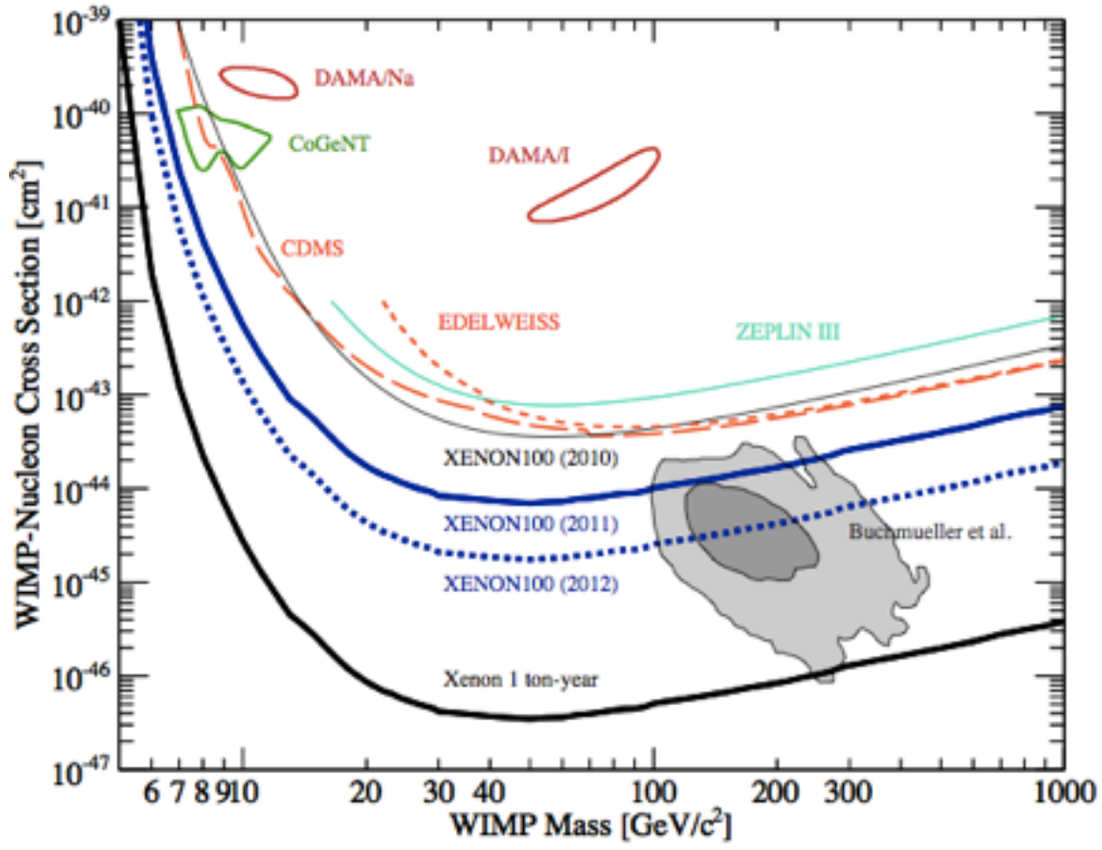


XENON: status and sensitivity

Slide Reformatted from Laura Baudis, PANIC 2011

- New dark matter run started in March 2011 (> 205 live days of data)
- Concentration of ^{85}Kr: lower by a factor of 5
- Improved LXe purity and lower trigger threshold
- Analysis in progress; release of results beginning of April
- In parallel: construction of XENON1T @ LNGS



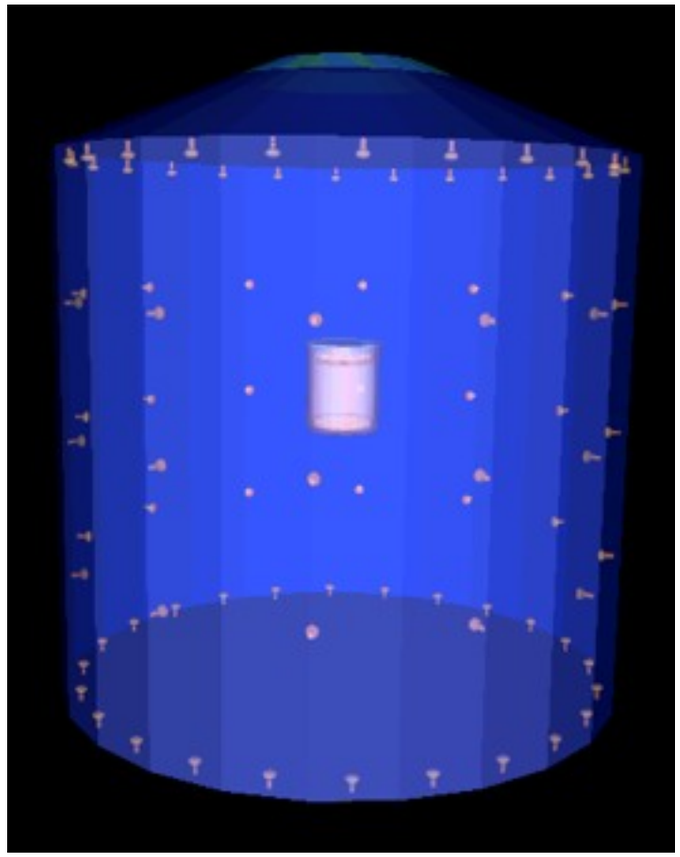


The XENON Dark Matter Program

XENON100

In conventional shield at LNGS
2008 - 2012; taking science data

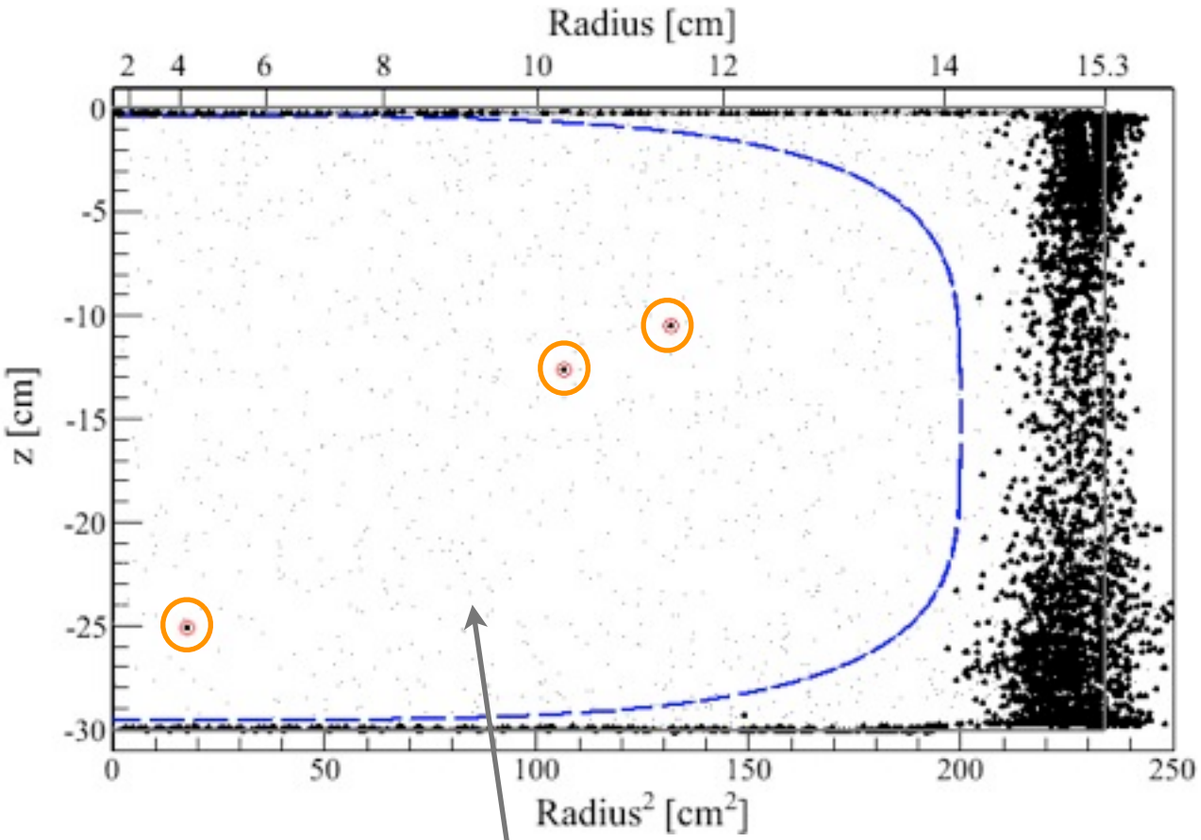
XENON1T

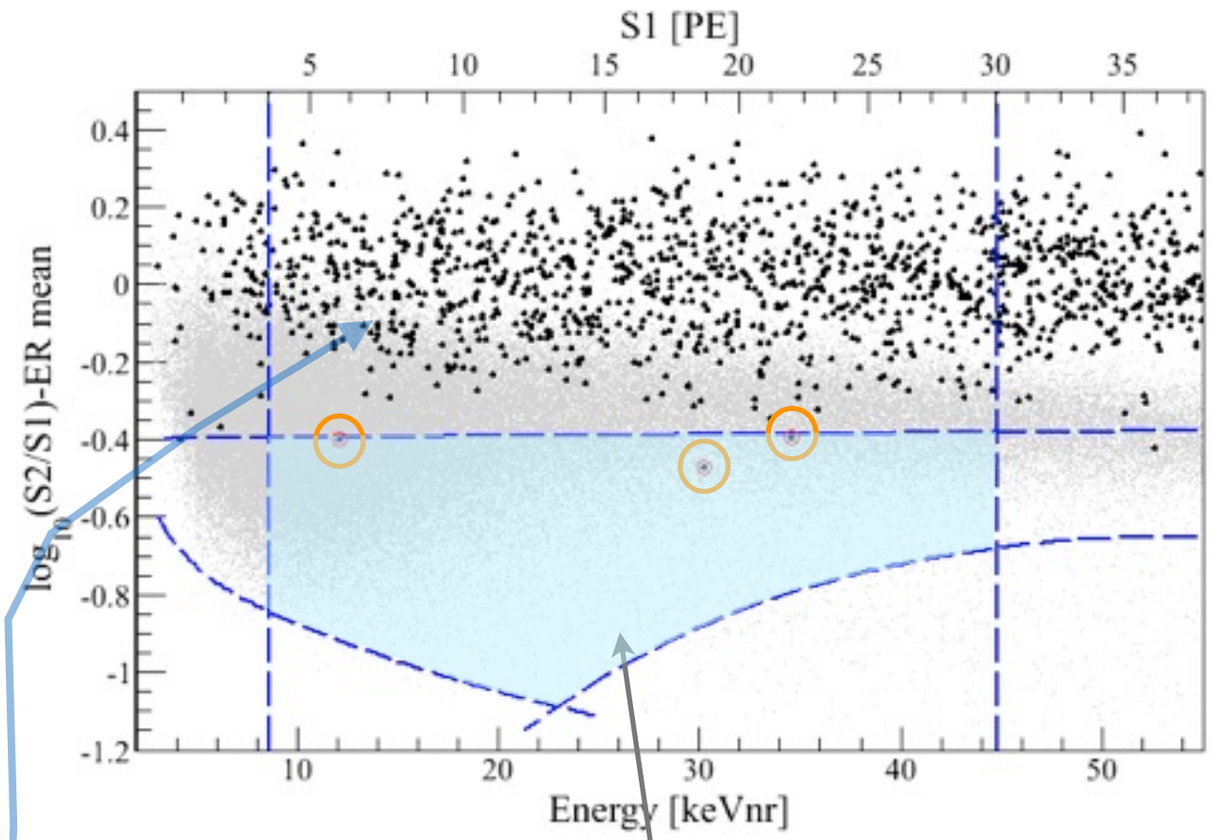


In water Cerenkov shield at LNGS
2011- 2015; construction start in 2012

XENON100: Recent Results

- Exposure: **~ 1471 kg-days** (48 kg fiducial mass); January - June 2010



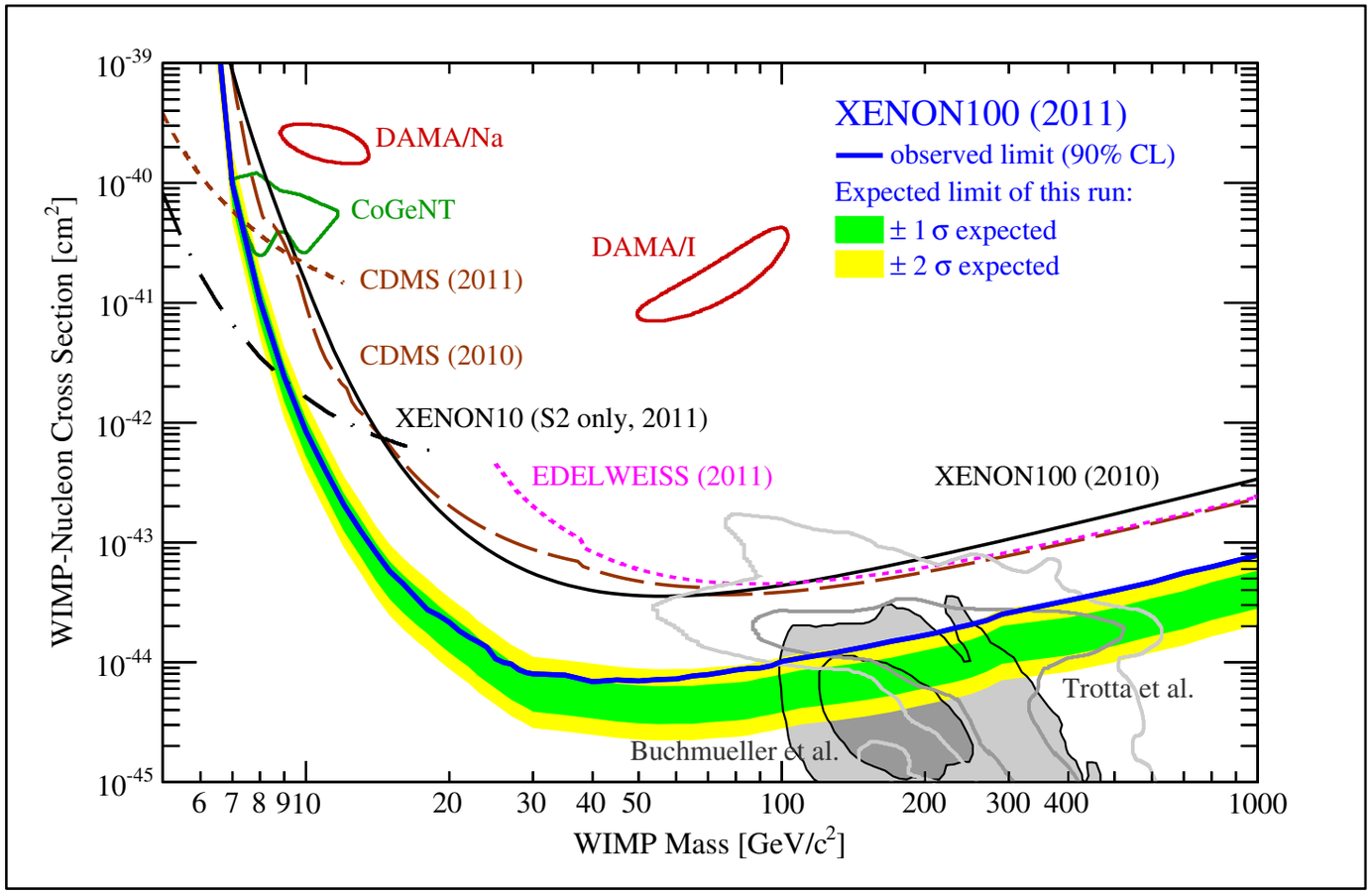


Fiducial mass region:
48 kg of liquid xenon
900 events in total

Signal region:
3 events are observed
1.8 ± 0.6 gamma leakage events expected
0.1 ± 0.08 ± 0.04 neutron events expected

XENON100: Recent Results

Phys. Rev. Lett. 107, 131302 (2011)



Green/yellow bands:

1- and 2-σ expectation, based on zero signal

Limit (dark blue):

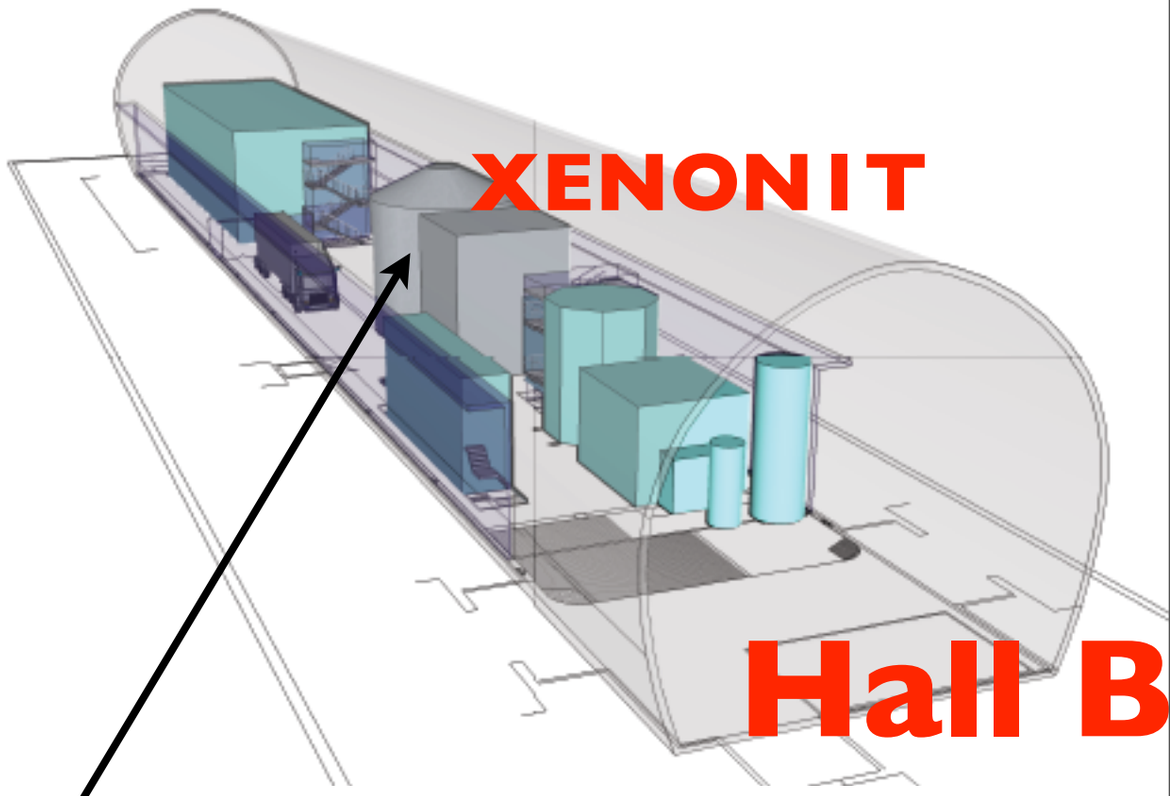
1.5 - 2 σ worse, given 2 events at high S1

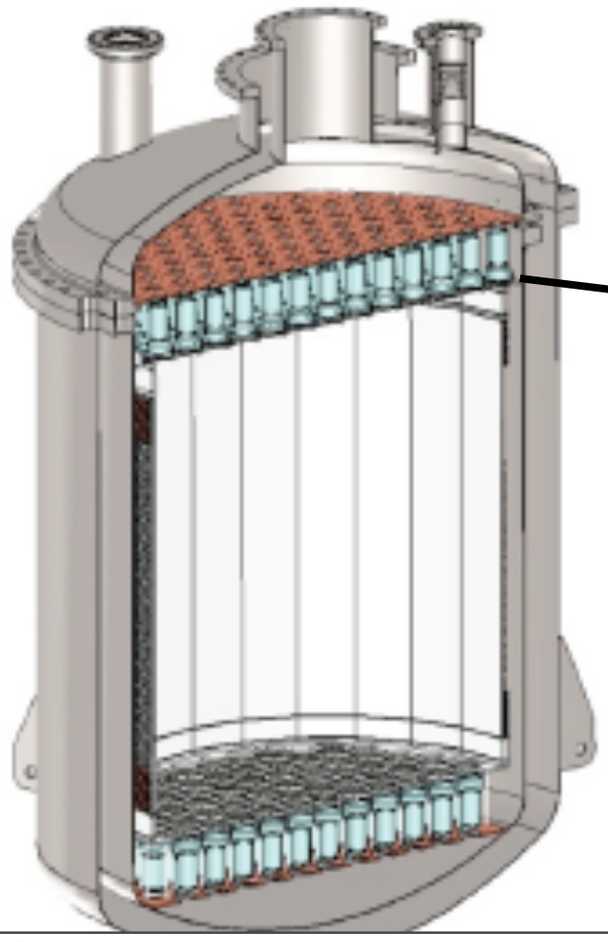
Limit at M_W = 50 GeV:

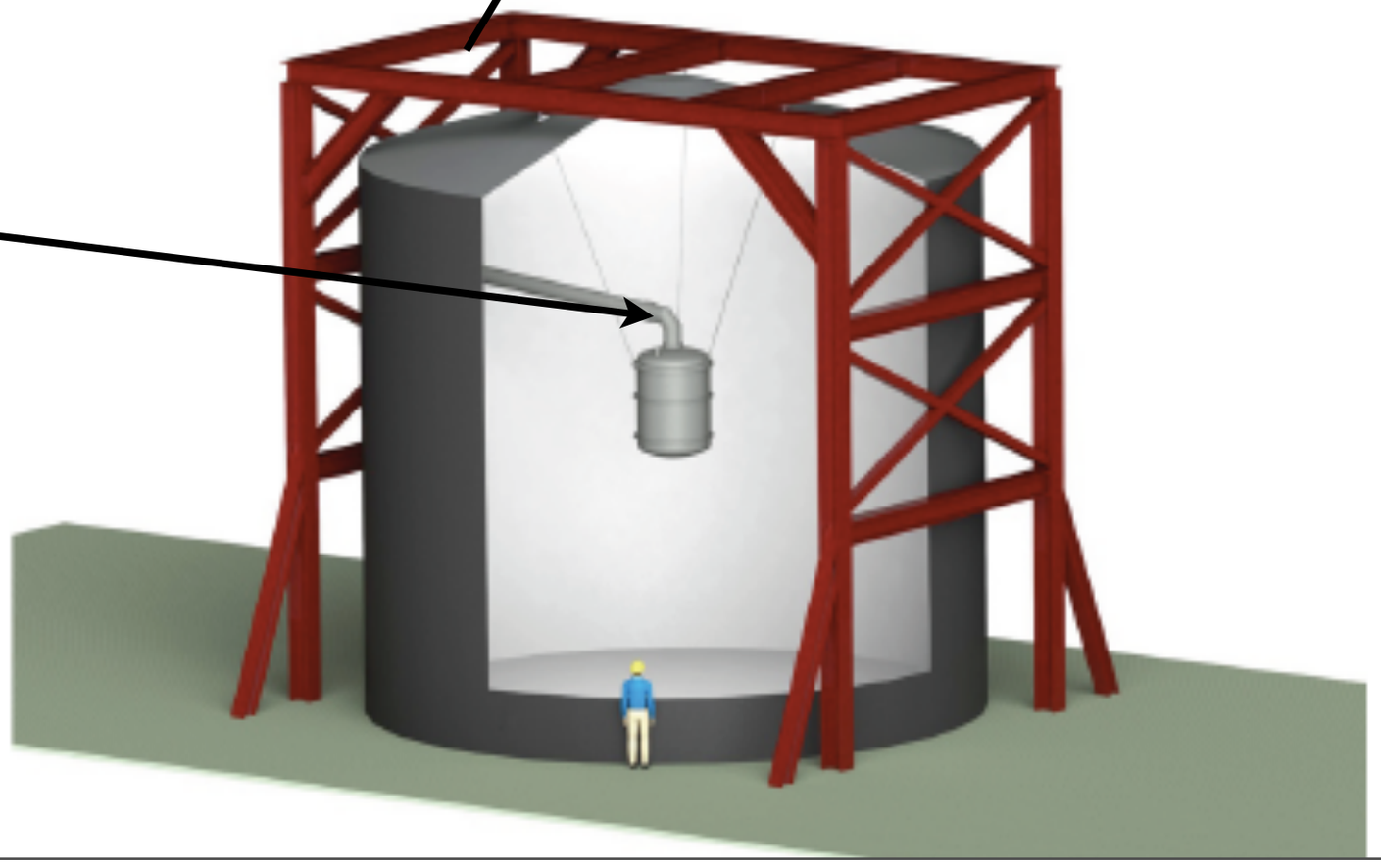
7×10^{-45} cm^2 (90% C.L.)

XENONIT

1m drift TPC with 2.2 ton (1 ton fiducial) LXe
10 m water shield as Cerenkov Muon Veto
100 x less background than XENON100
Approved by INFN for installation at LNGS
Majority of funding secured
Major systems design near completion
Construction start in LNGS Hall B in 2012
Science Data projected to start in 2015
Sensitivity: 2 x 10^{-47} cm ^{2} after 2 yrs of data

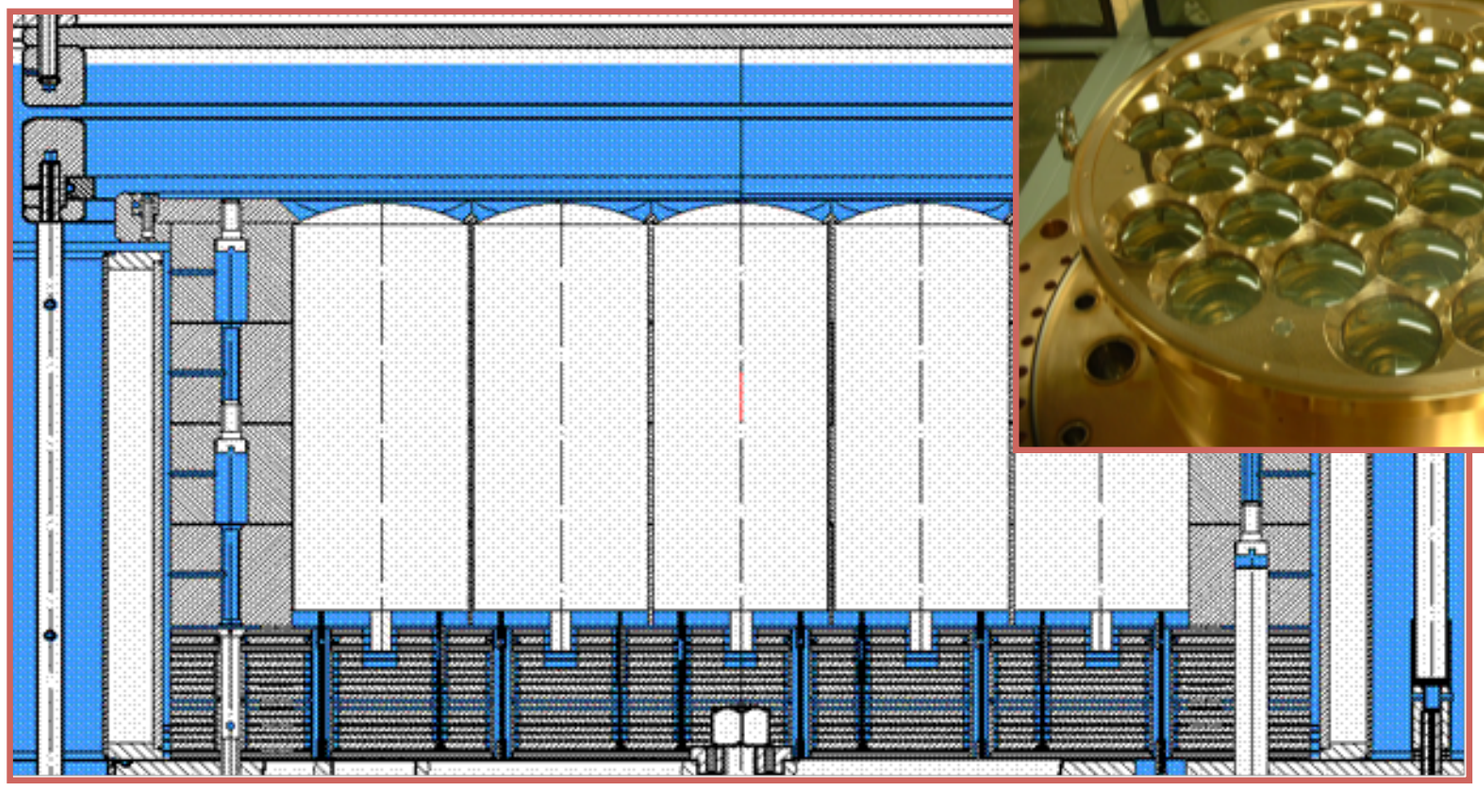


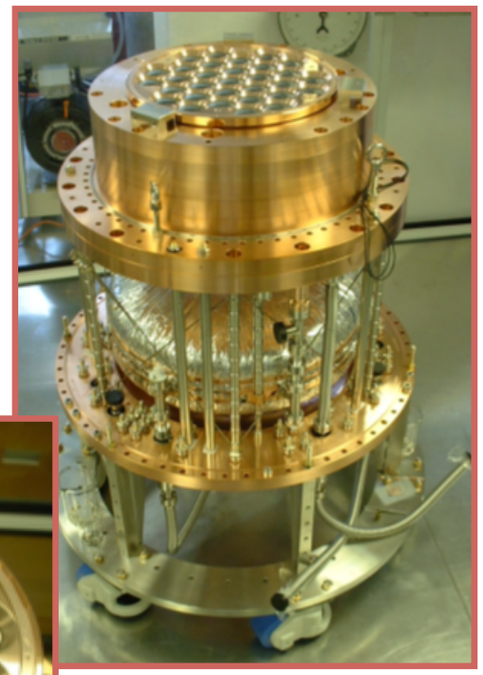




ZEPLIN-III: High-Field, Two-Phase Xenon Emission Detector

- Time projection chamber with 12 kg liquid xenon (6.5 kg fiducial)
- Readout of scintillation (S1) and ionisation (S2) with array of 31 PMTs
- Strong electric field (~4 kV/cm in liquid), no extraction grids
- Construction: low background and xenon-friendly materials

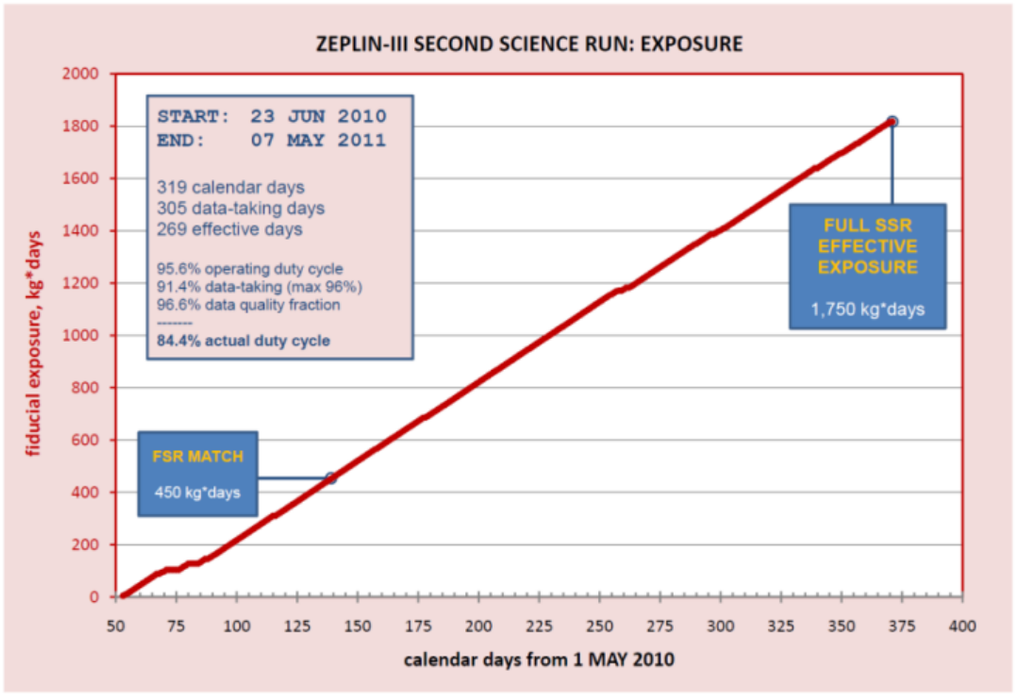




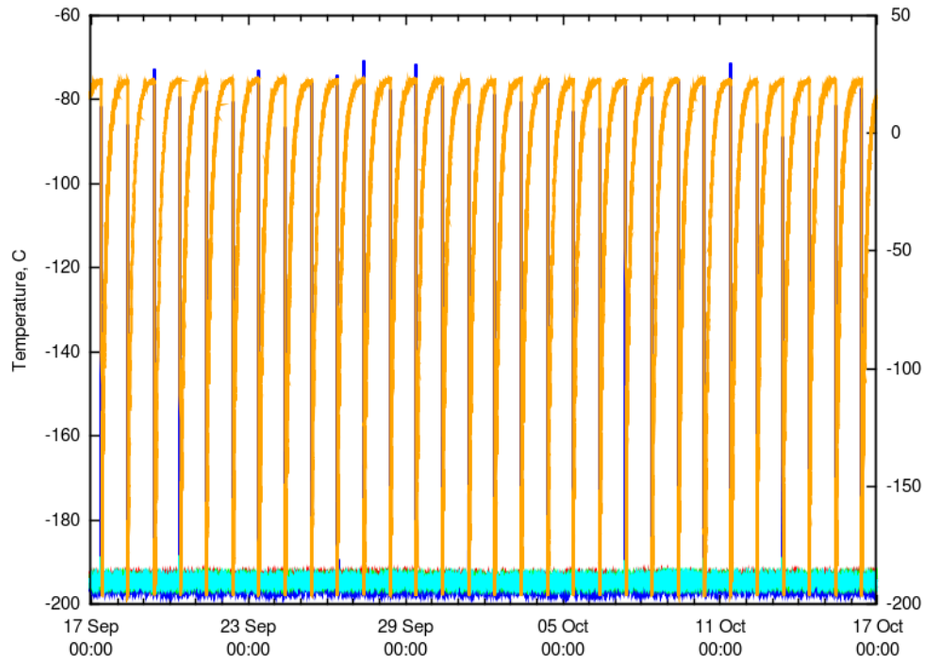
Boulby Science Runs

Slide Reformatted from H. Araujo

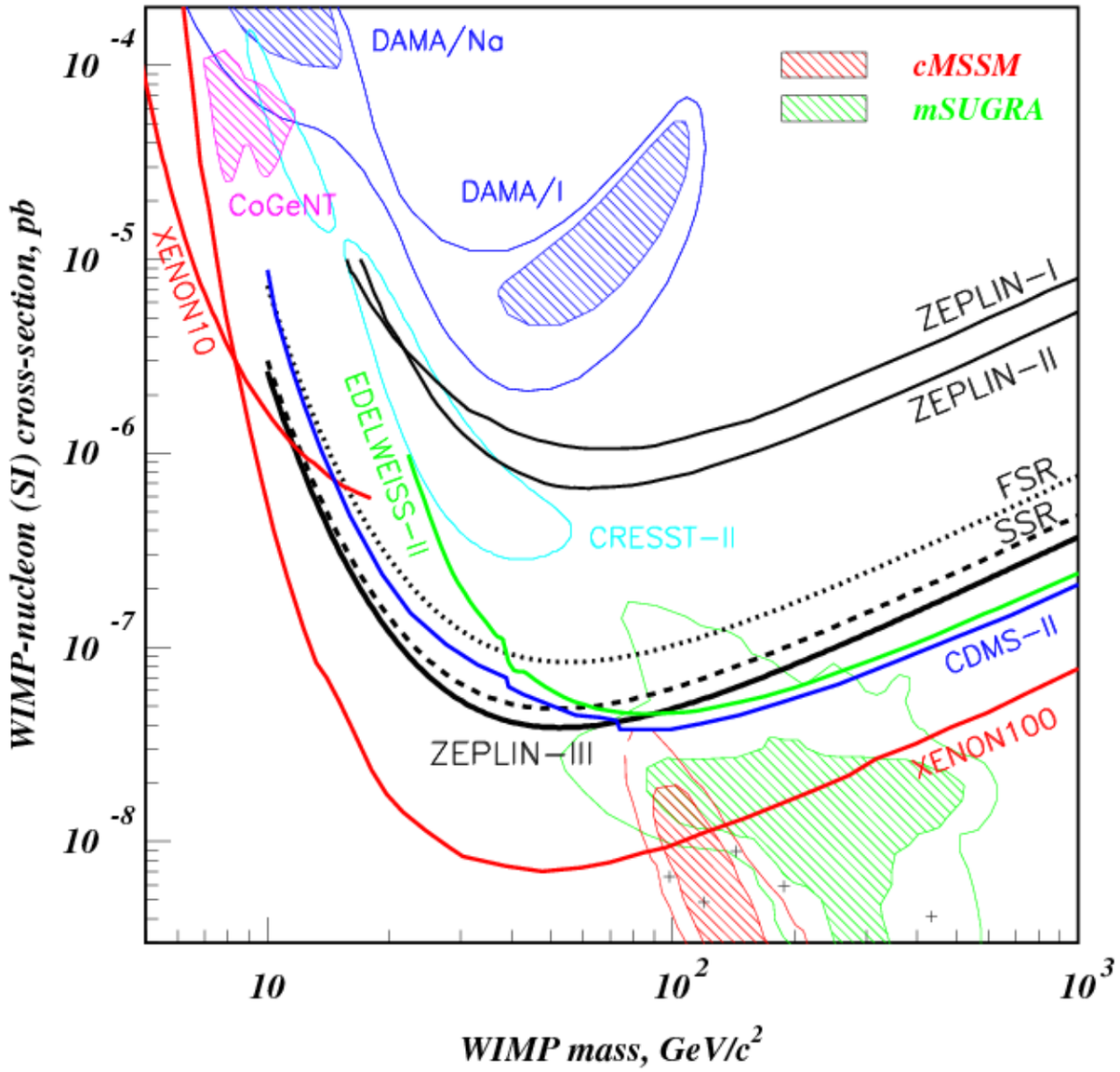
- **First science run (FSR) at Boulby: 83 days in 2008**
  Strong constraints on WIMP-nucleon scattering XS
- **Phase-II upgrades commissioned in 2009/10**
  New photomultiplier array (ultra-low background)
  New anti-coincidence veto (background reduction, diagnostic)
  New calibration hardware (reduction of systematics)
  System automation (improved stability, underground effort)
- **Second science run (SSR) 23 JUN 2010 to 7 MAY 2011**
  Longest run of any noble liquid WIMP detector (319 days)
  Effective fiducial exposure ~560 kg*days (4x FSR)

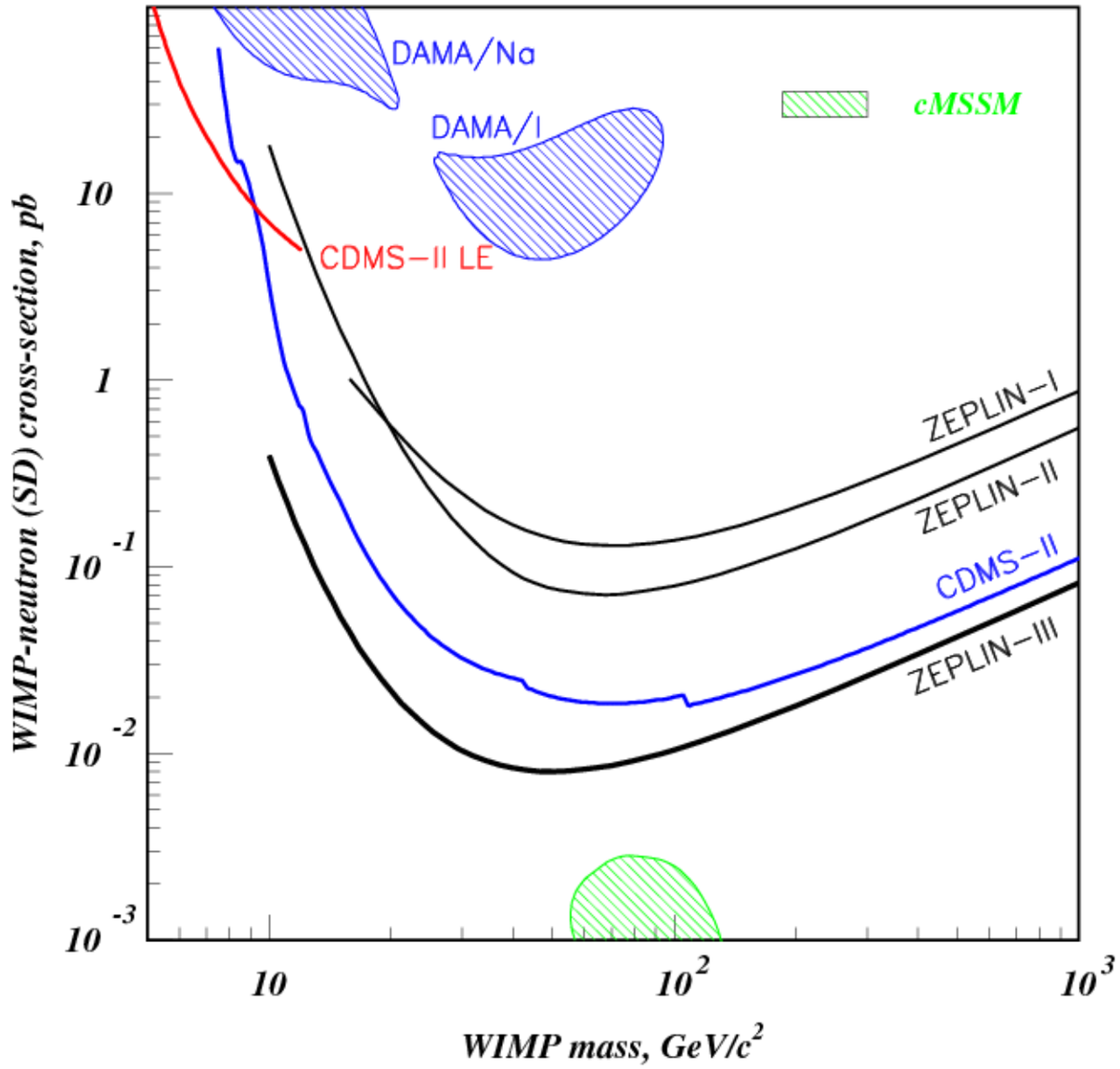


One month's worth of daily LN2 refills



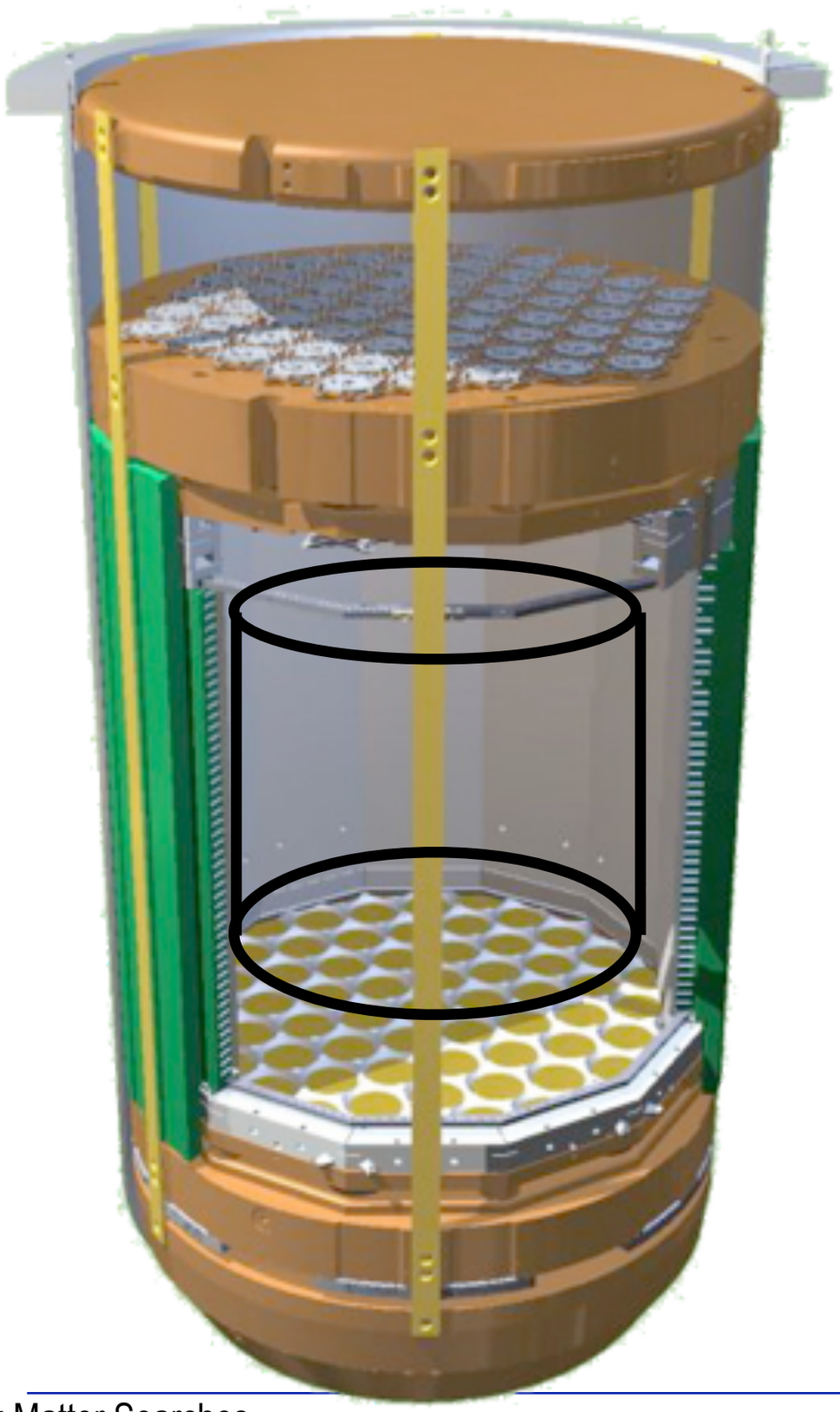
ZEPLIN III Limits





Akimov *et al.*, Phys Lett B, in press (2012)
arxiv:1110.4769

LUX WIMP Sensitivity



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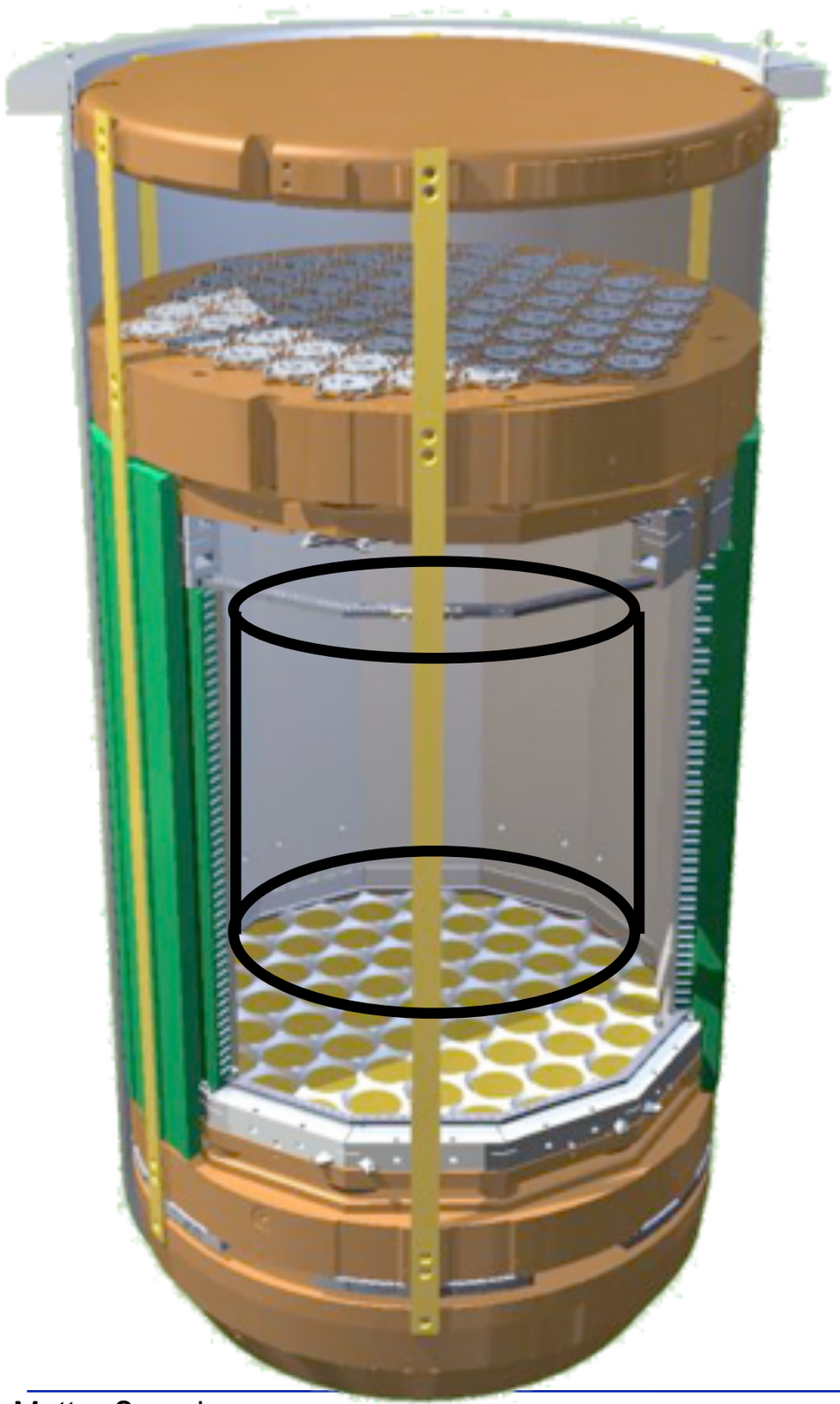


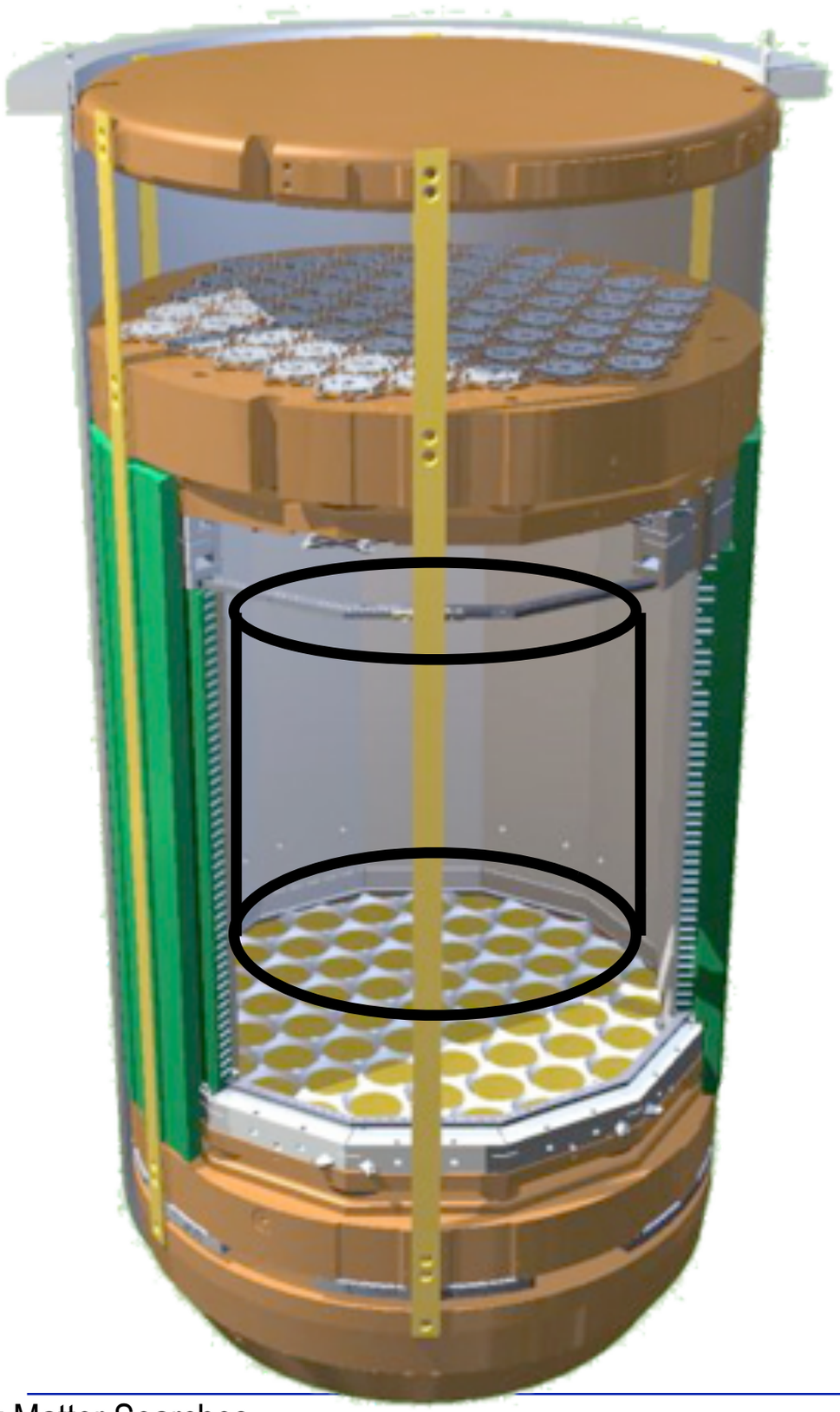
In < 4 live days we will surpass sensitivity of all existing results for dark matter direct detection experiments

Large, very quiet fiducial

Expect ~1 electron recoil event per 4 days

in 100 kg 5-30 keVr energy range

LUX WIMP Sensitivity



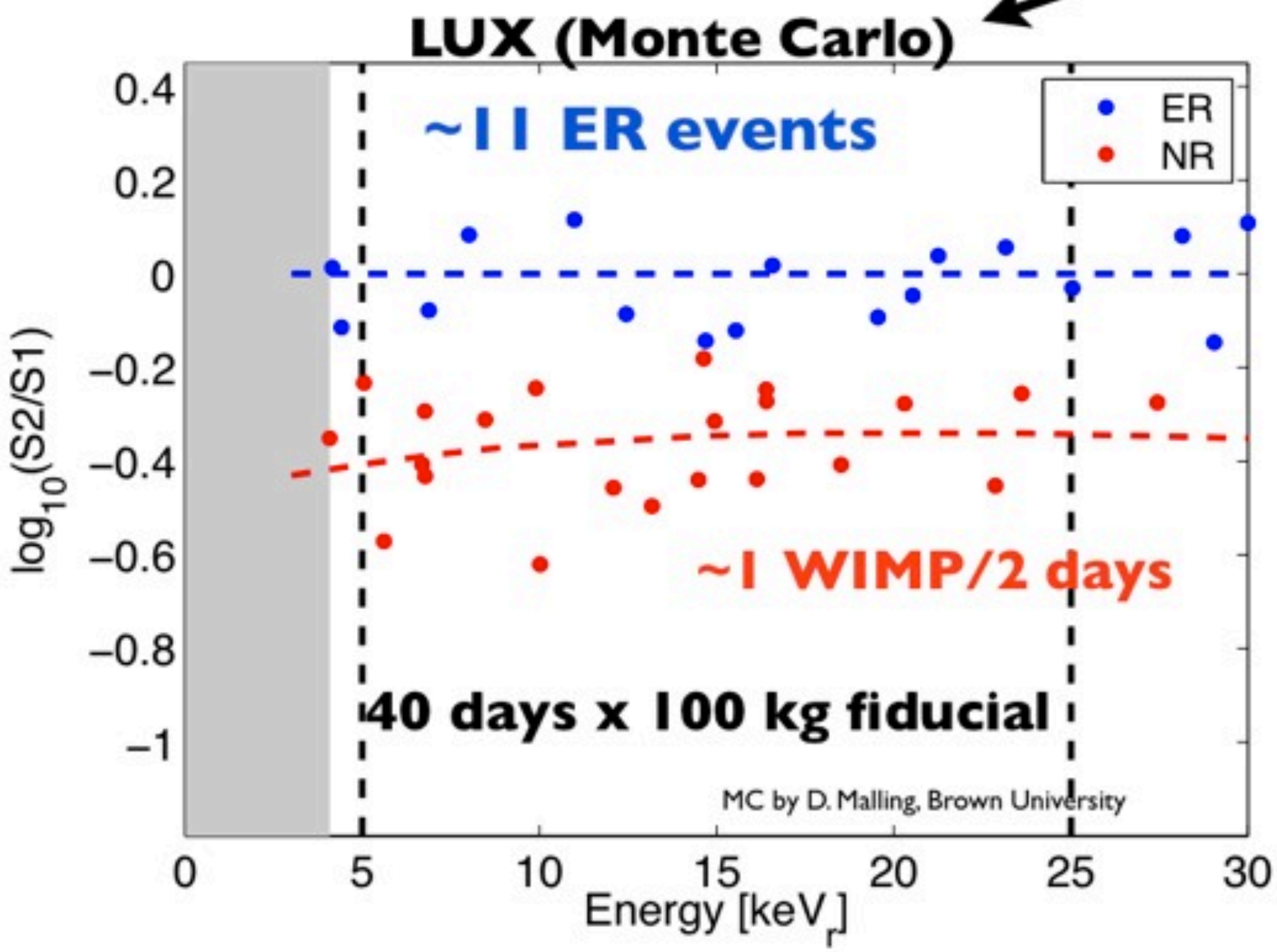
In < 4 live days we will surpass sensitivity of all existing results for dark matter direct detection experiments

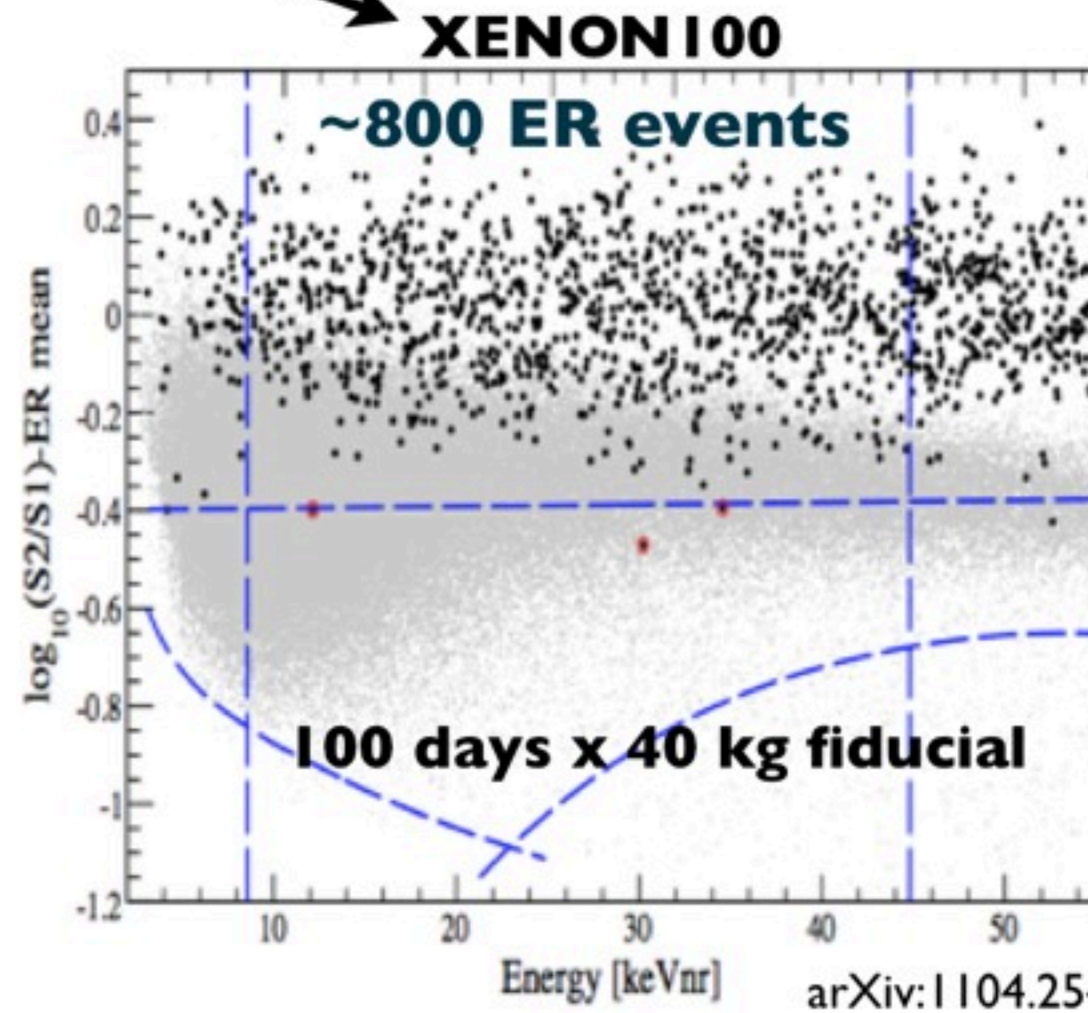
Large, very quiet fiducial
Expect ~1 electron recoil event per 4 days
in 100 kg 5-30 keVr energy range

Focus on discovery ... we must design detectors with high contrast for signal ...

LUX Performance: The First 40 Days

comparing nominally equivalent kg-days for 100 kg LUX fiducial versus 40 kg XENON fiducial
but LUX has much greater sensitivity/kg-day because of cleaner signal/fewer bg events





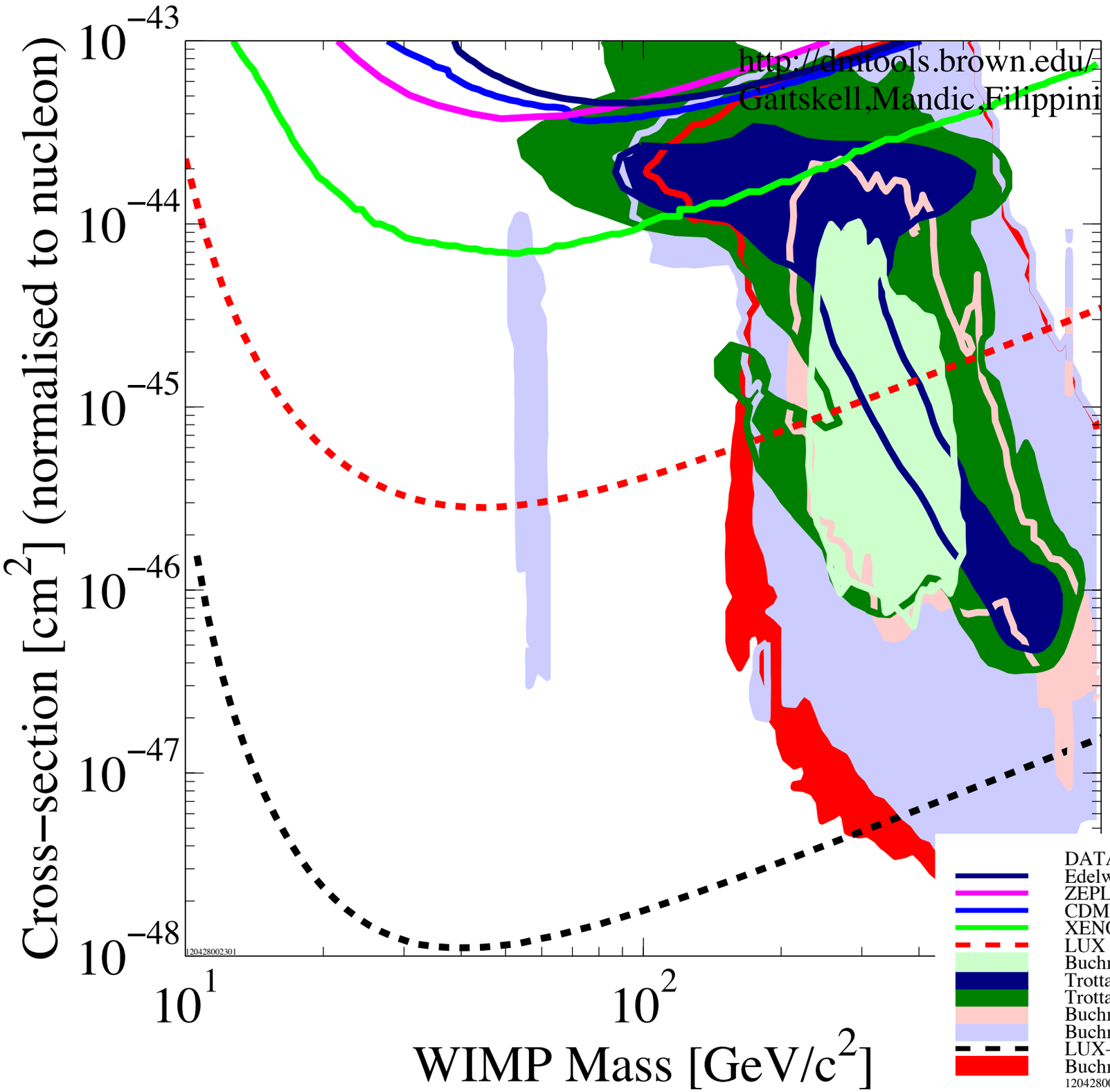
arXiv:1104.2549

LUX signal and background expectation for 4,000 kg-days net exposure. WIMP events assume m = 100 GeV, σ = 1×10^{-44} cm^2. Assumes 100 kg fiducial. Given very low ER rate, can significantly increase fiducial in early running.

XENON100 4,000 kg-days result for comparison. Note higher ER rate - ~800 events in 100 days x 40 kg fiducial ~60% due to 85Kr with remaining 40% due to Compton scattering of external gamma background.

- **Red Points (LUX plot):** WIMP events after only 40 days (nominally same kg-day exposure to XENON100 run) assuming a WIMP model for mass 100 GeV at current best 90% CL Exclusion Limit m = 100 GeV, σ = 1×10^{-44} cm^2.
- **Blue Points (LUX plot):** Total # of single scatter electron recoil events in LUX (before any other cuts) after 40 days of running. Expect only 11 ER events in 100 kg fiducial x 40 days for a net 4,000 kg exposure.
- **LUX - Strong Emphasis on WIMP Discovery / Plan to run LUX for 300 days**

Results (2012) / Sensitivity Curves



Edelweiss II
CDMS II
ZEPLIN III
XENON100 (2011) 100 day x 40 kg fid.

LUX350 300 days x 100 kg fid. Xe (Sanford)
- goal zero background

LZ 1000 days x 5 tonne fid. Xe (Sanford)
- goal zero background

DATA listed top to bottom on plot
Edelweiss II, 2011, Final Results, 384kg−days, SI
ZEPLIN III, 2011, second science run, 1344kg−days, SI
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LUX 300 kg Projected Sensitivity: 30000 kg−d, 5−30 keV, 45% eff
Buchmueller et. al., 2011, LHC & XENON100 constraints on NUHM1, (1/fb LH
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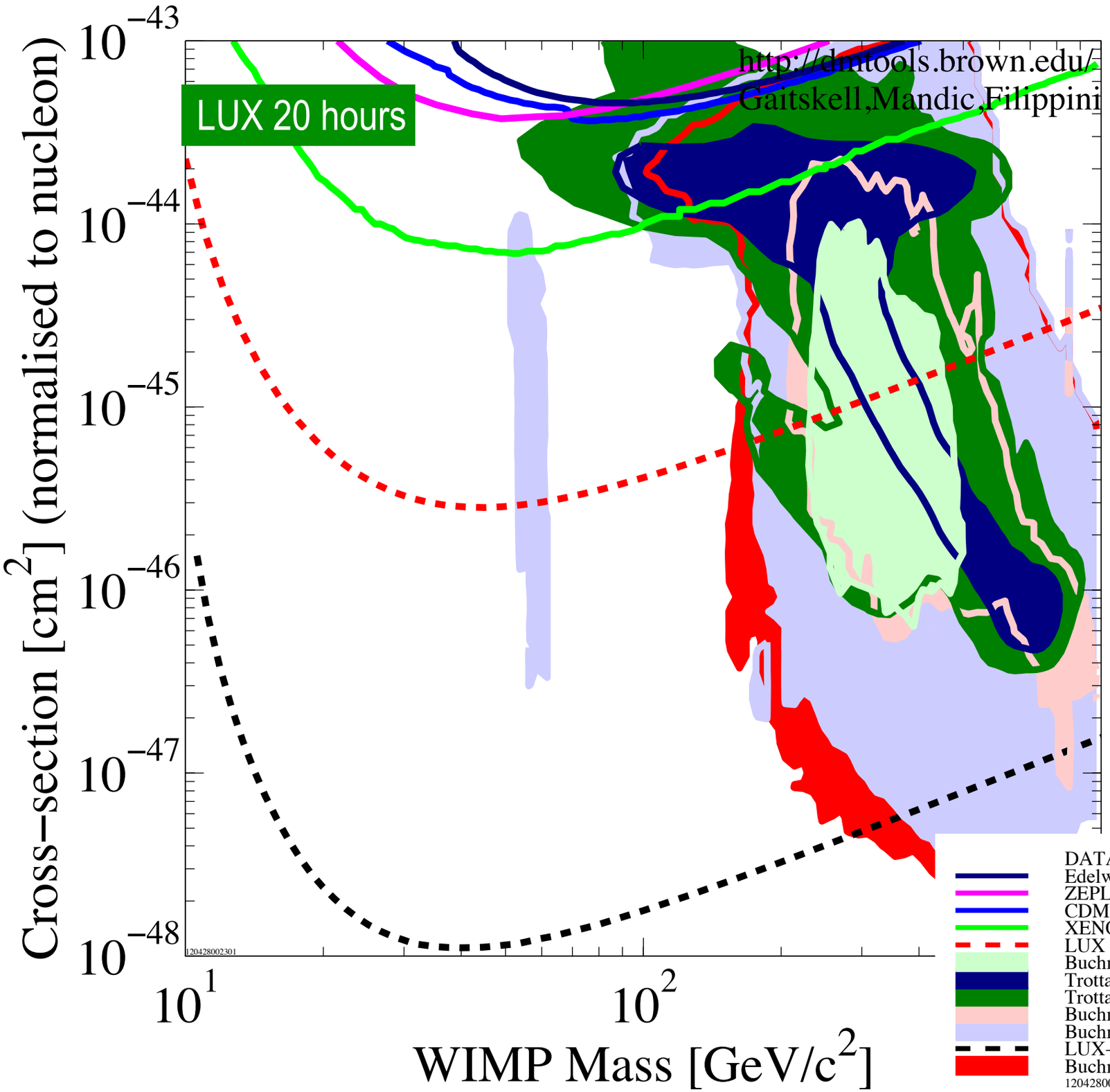
LUX−ZEPLIN, projection 2012, 7 tonne, 0 BG, 50% eff, 5t−1000days, SI
Buchmueller et. al., 2011, LHC & XENON100 constraints on NUHM1, (1/fb LH
120428002301

Results (2012) / Sensitivity Curves



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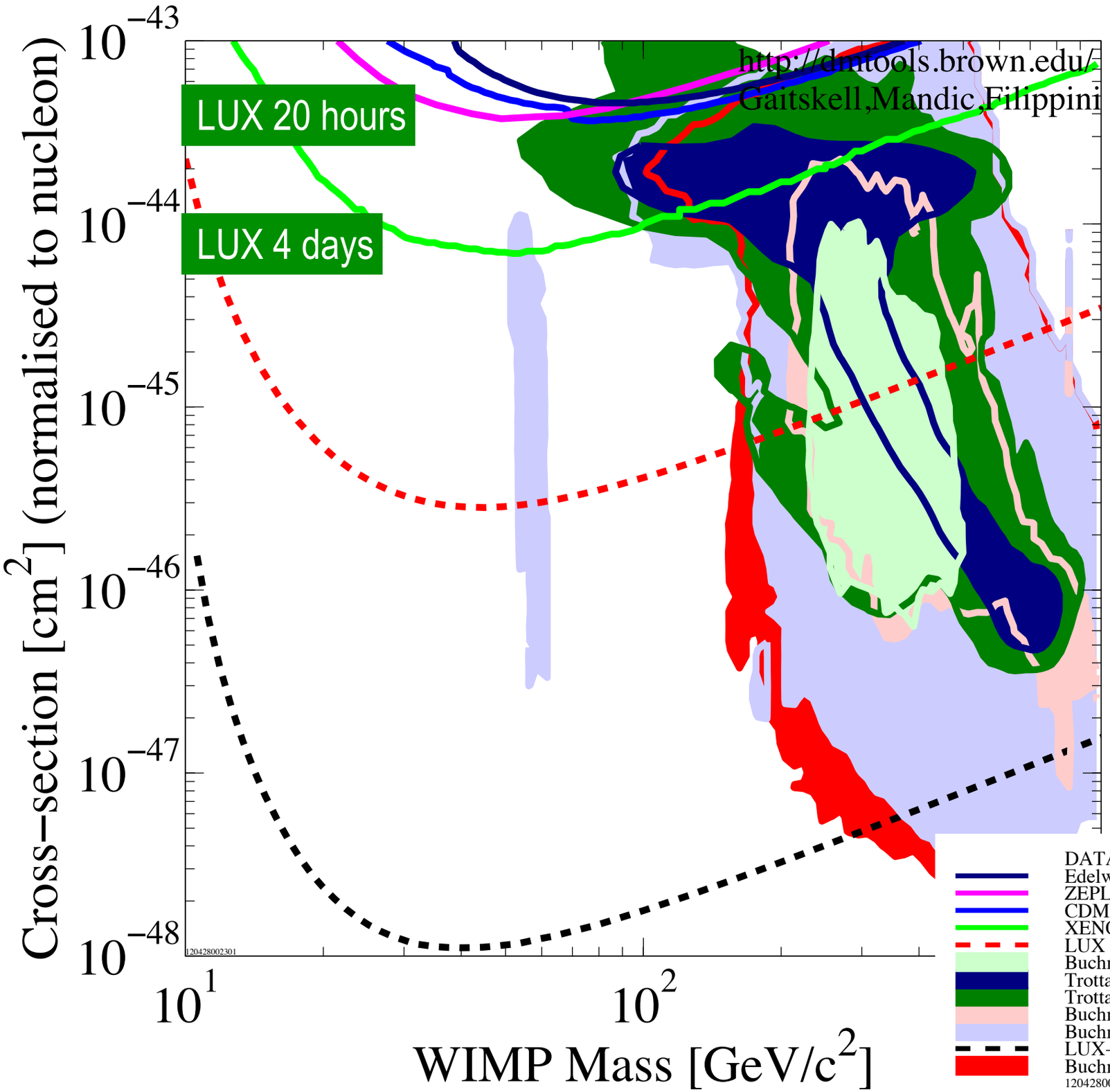

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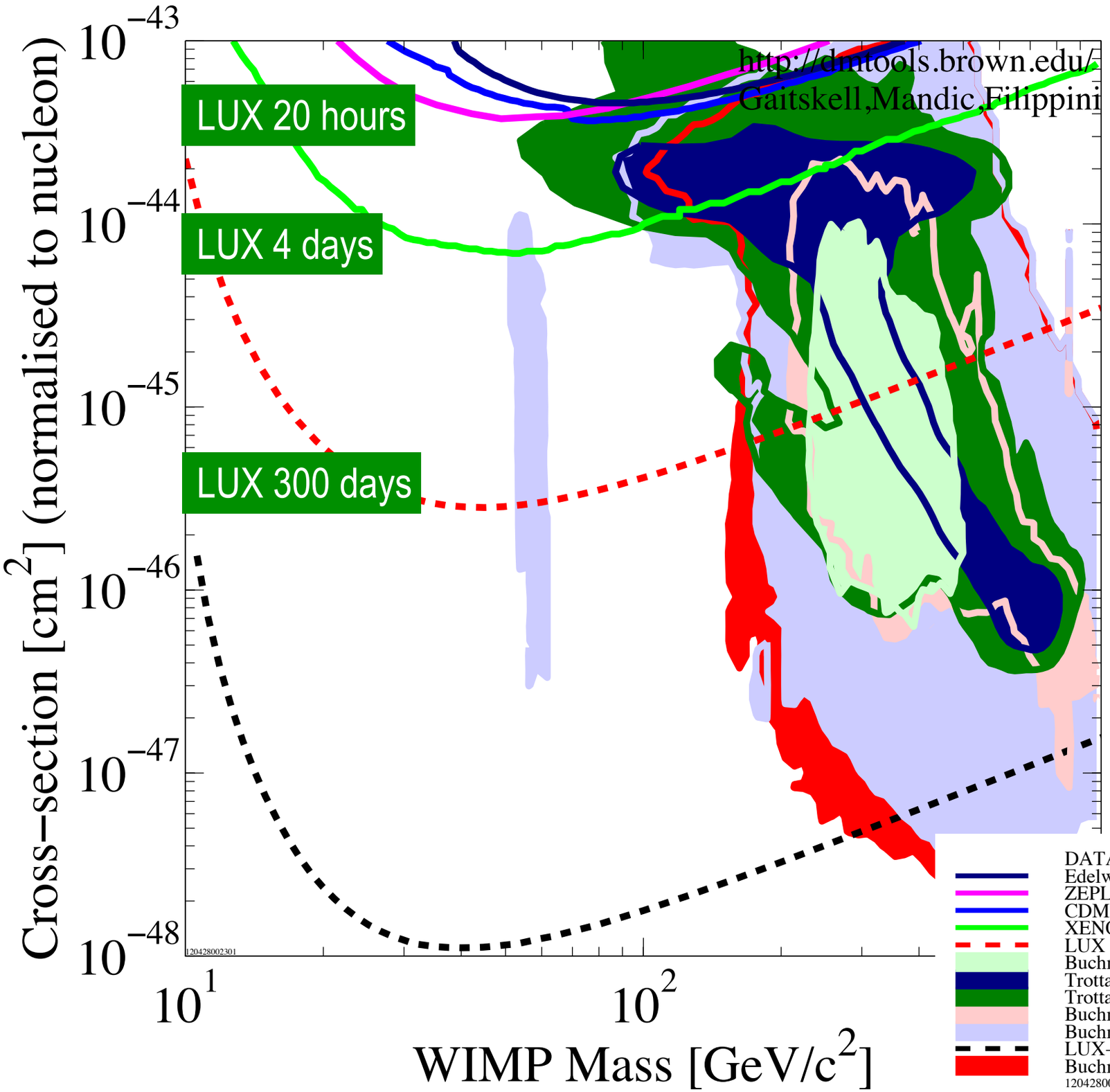

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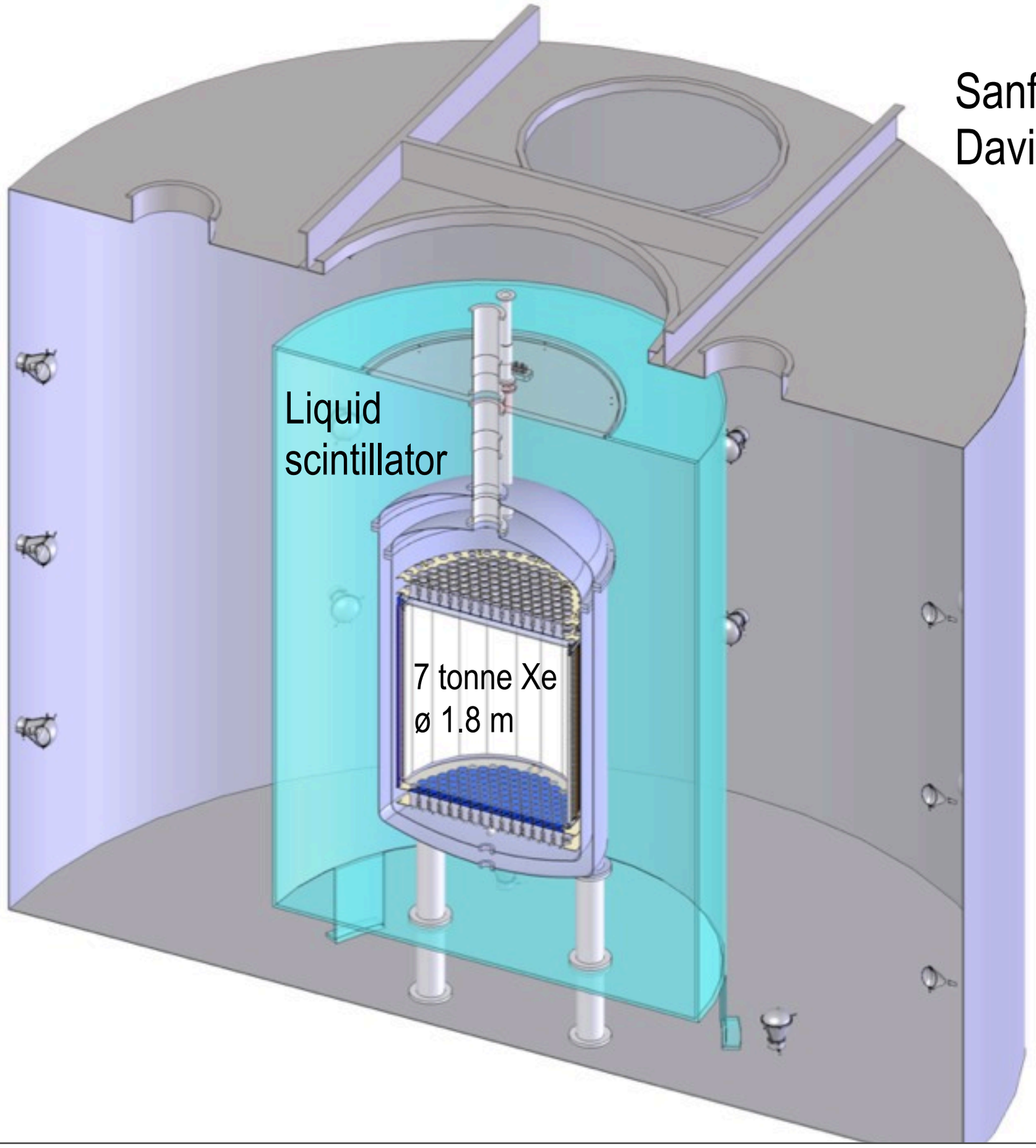
LZ 7 Tonne at Sanford Lab - Generation 2 (2013+) - Proposed



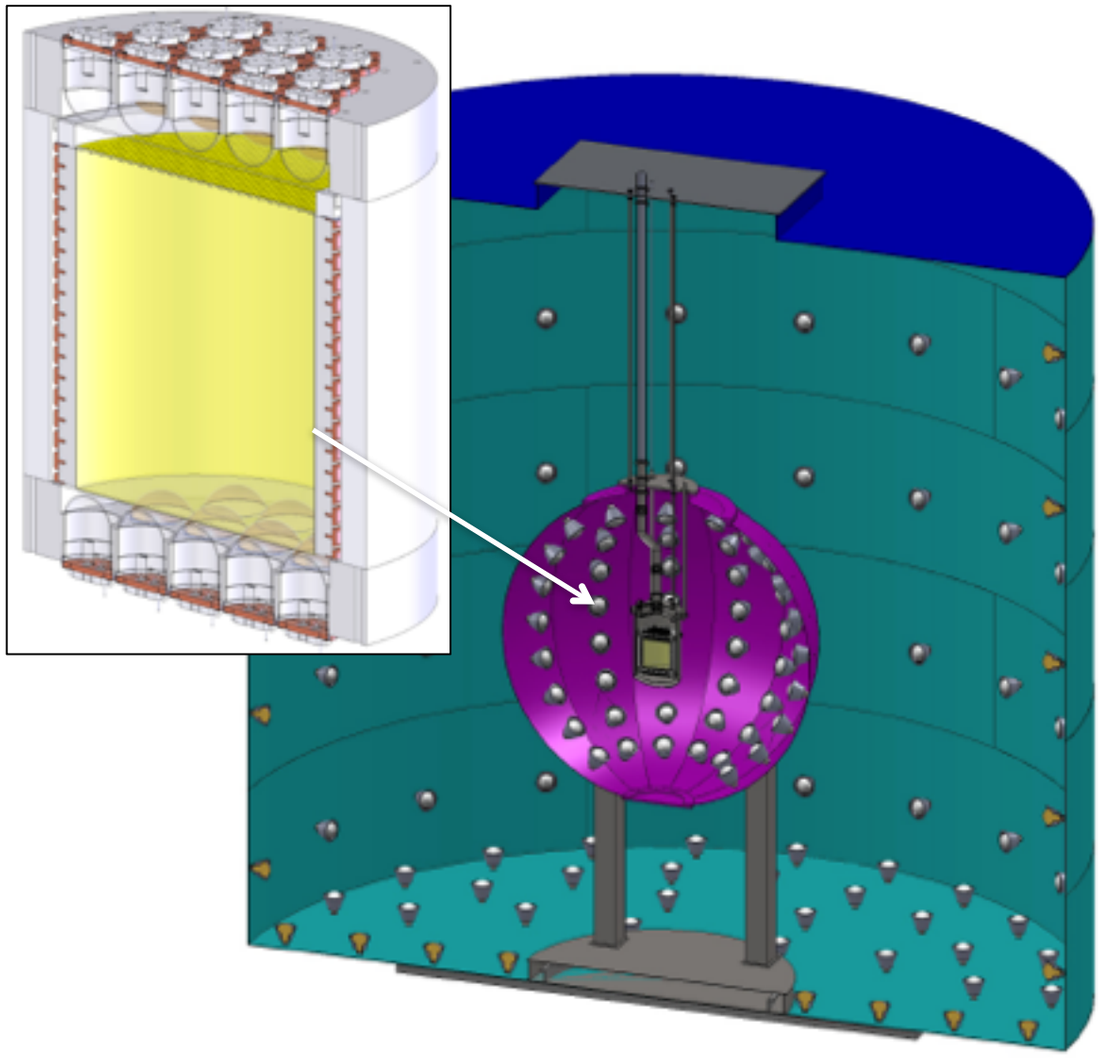
Sanford Lab
Davis Lab Water Tank

Slide Reformatted from E. Aprile

PandaX

- Detector to be operated in Jingping Lab in Szechwan Province (SW China)
  - ~10 x 10 m Hall was excavated as part of hydroelectric project
  - Excavation for main lab is still under consideration by Chinese Government. Not yet in 5 year plan
- Design and Technical lead by Kaixuan Ni, Shanghai Jiao Tong University and also Karl Gibone. Both formerly on XENON10.
  - Very similar to XENON100 and LUX designs
- Initial operation with 130 kg LXe in active region, 30 kg fiducial
  - Testing at University
  - Current cryostat fabricated from unscreened stainless
  - Pancake design (15 cm drift) that will allow expansion of the active region vertically using most of same hardware
  - Goal is for 60 cm drift version (500 kg) to be working in 2014-2015

DS-50 DarkSide DS-10



- Estimated background:
  - <0.05 events in 0.1 ton*year above 20keV$_{rec}$
- Depleted Argon procurement/purification by Fall 2012
- Detectors ready by Fall 2012 (?)
- Commissioning start Q4 2012 (?)

- 10 kg prototype, filled with atmospheric Argon, currently installed @ LNGS surrounded by a passive water shield
- Running since May 2012
- Huge improvements in Light Yield;
- Study backgrounds and background rejection for DarkSide technology;

DarkSide

- (Note that WARP program appears to be at an end)

- A null background strategy for direct dark matter searches

- Dark Matter direct detection program @ LNGS:
  - G1 step: DS-50, 10^{-45} cm^2 goal
  - G2 step: DS-5k, 10^{-47} cm^2 goal

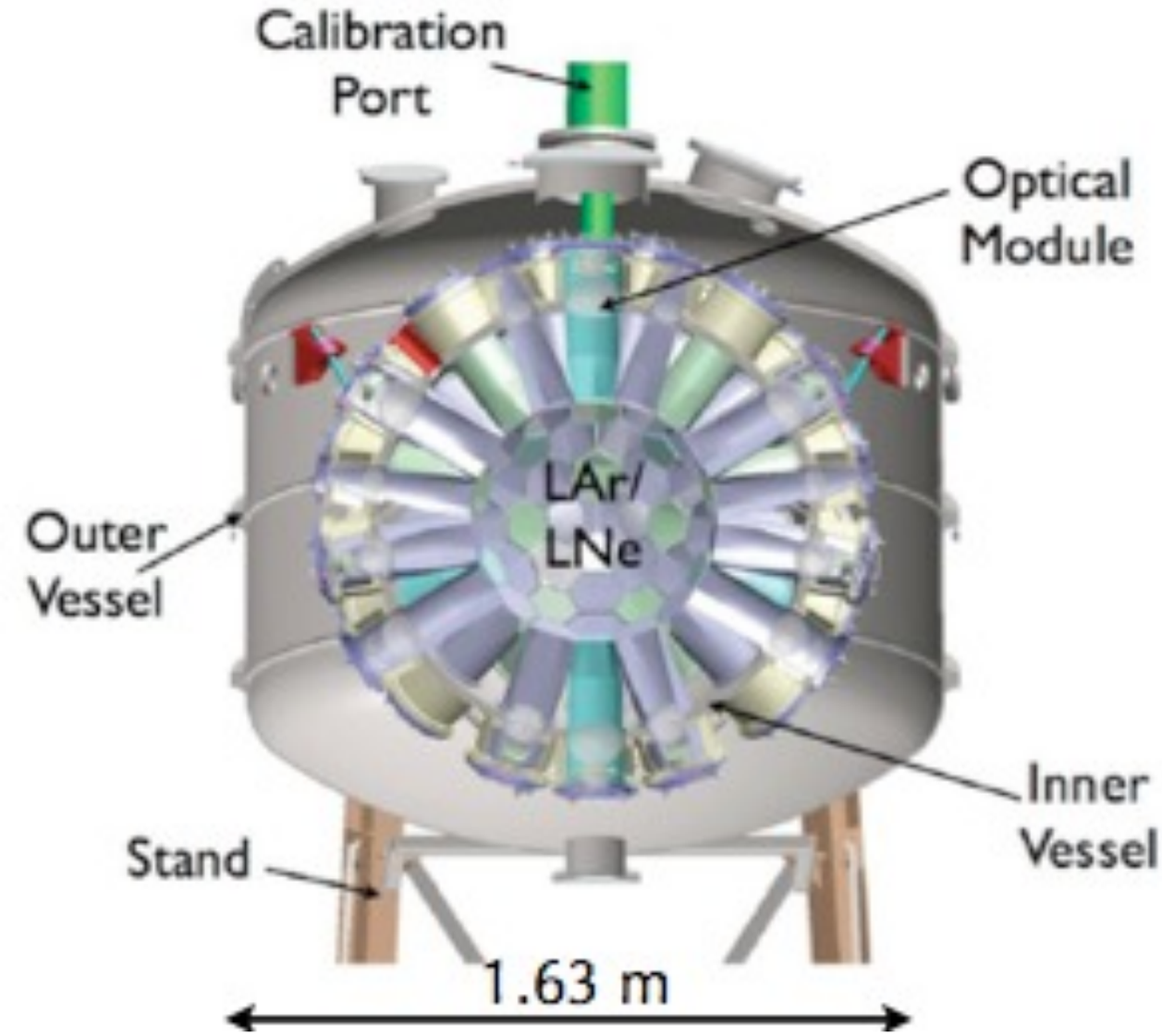
- Two-phase Argon Time Projection Chamber detector:
  - Underground Argon naturally depleted in ^{39}Ar *(see F.Calaprice talk)*
    - ^{39}Ar content relative to atmospheric < 1%;
    - 80 kg collected;
  - Three semi-independent methods for rejecting background:
    - Pulse Shape of light signal
    - Charge/Light ratio
    - 3D reconstruction

- Active/Passive suppression of the background:
  - Scintillator-based neutron veto (à la Borexino)
  - Water Tank muon veto (refurbishing the existing Borexino CTF tank)

MiniCLEAN

Figures from from J. Monroe, TAUP 2011

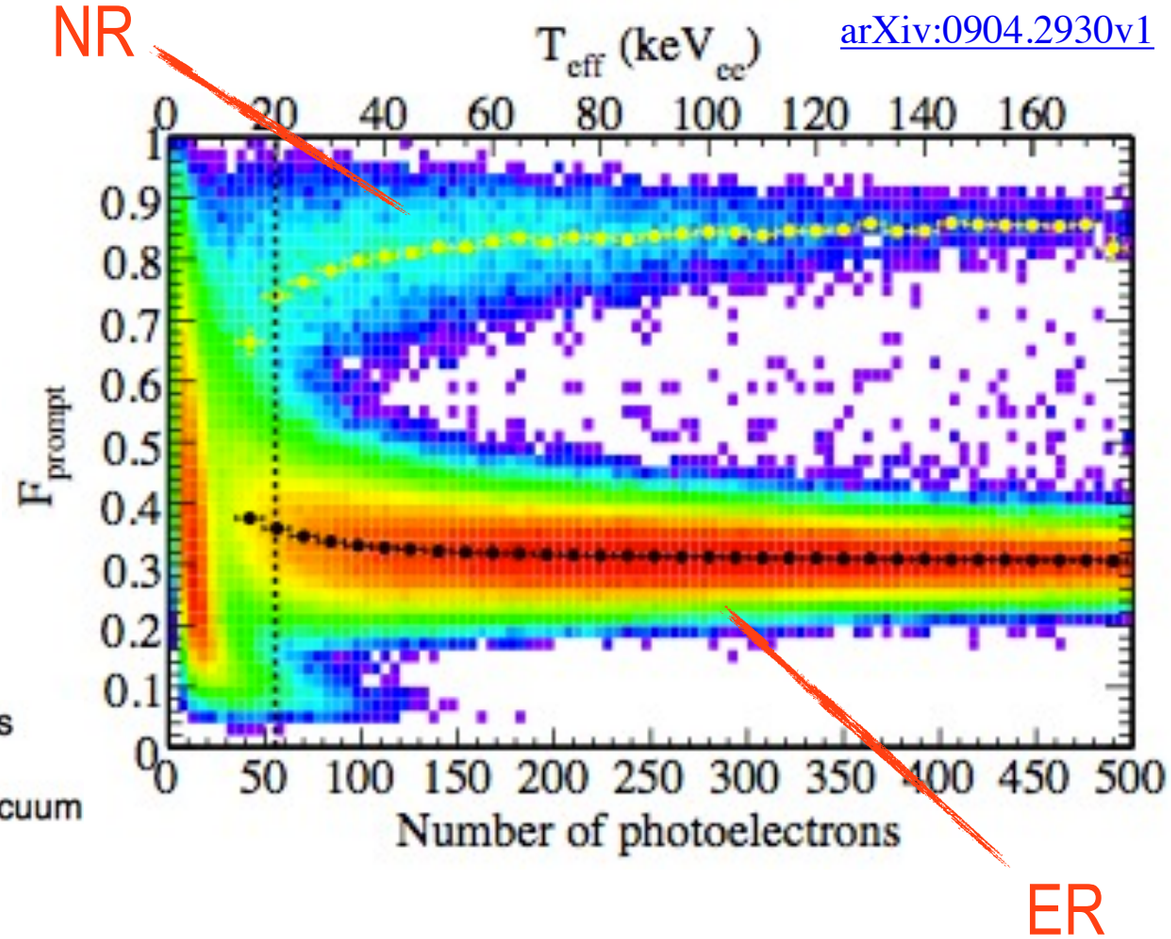
- 300 kg LAr (150 kg fiducial)
  - LNe target can be exchanged
- LAr proof-of-principle detector
  - Use PSD to eliminate ER backgrounds
    - ^{39}Ar β (1 Bq/kg) and PMT gammas
      - –DEAP-1 measured <3*10^{-8} rejection (120-240 phe)
  - Demonstrate effective position reconstruction at low energies
    - Needed for fiducialization / neutron multiple scatter rejection
  - Allow very low Rn exposure during construction
    - Minimize ^{210}Pb accumulation

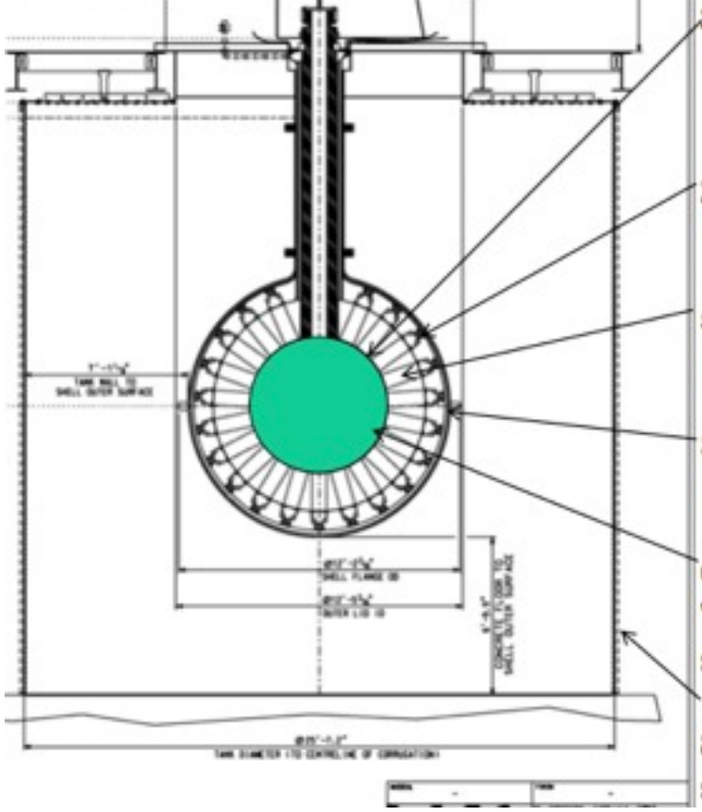


DEAP-3600

Figure from from M. Boulay, TAUP 2011

- DEAP-1 (7 kg)
  - Ar PSD - ER rejection: <3*10-8
- DEAP-3600 (3600 kg)
  - SNOLAB
  - Anticipated end of construction: 2013
  - Target sensitivity 10^{-46} cm^2
  - Collaborated with Princeton group to produce 3600 kg of depleted Ar (~25x)





85 cm radius acrylic sphere contains 3600 kg LAr
(55 cm, 1000 kg fiducial, sealed vacuum vessel to control backgrounds)

255 8" PMTs
(Hamamatsu R5912 HQE)

50 cm acrylic light guides and fillers for neutron shielding (from PMTs)

Steel shell for safety to prevent cryogen/water mixing (AV failure)

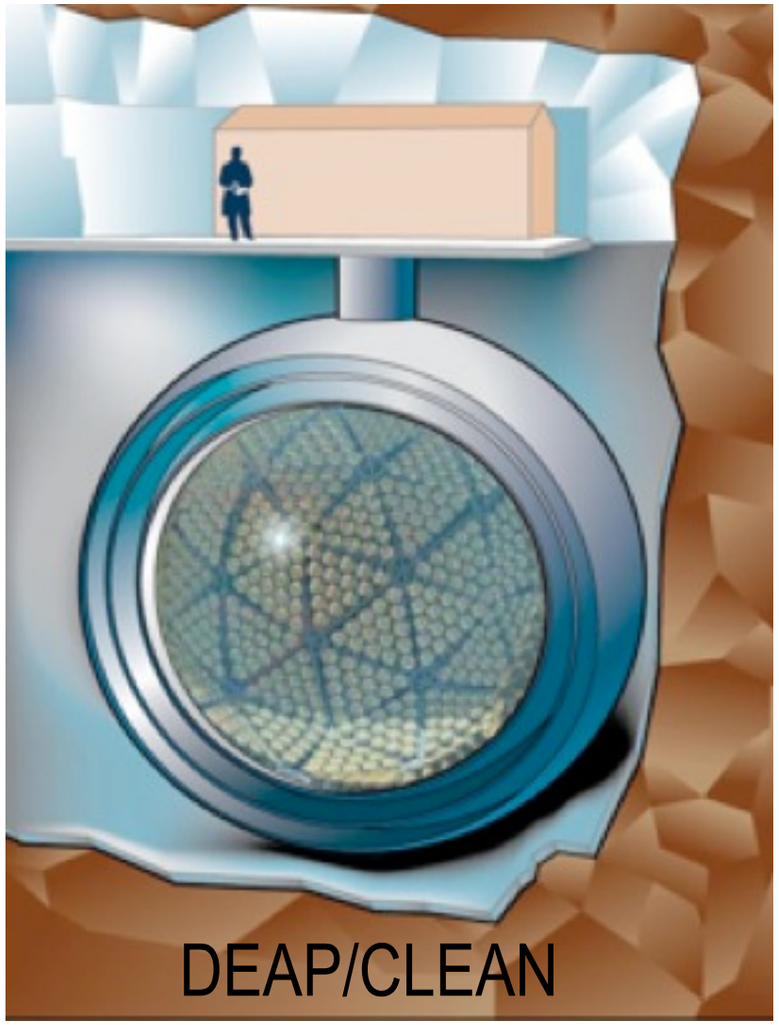
Only LAr, acrylic, and WLS (10 g) inside of neutron shield

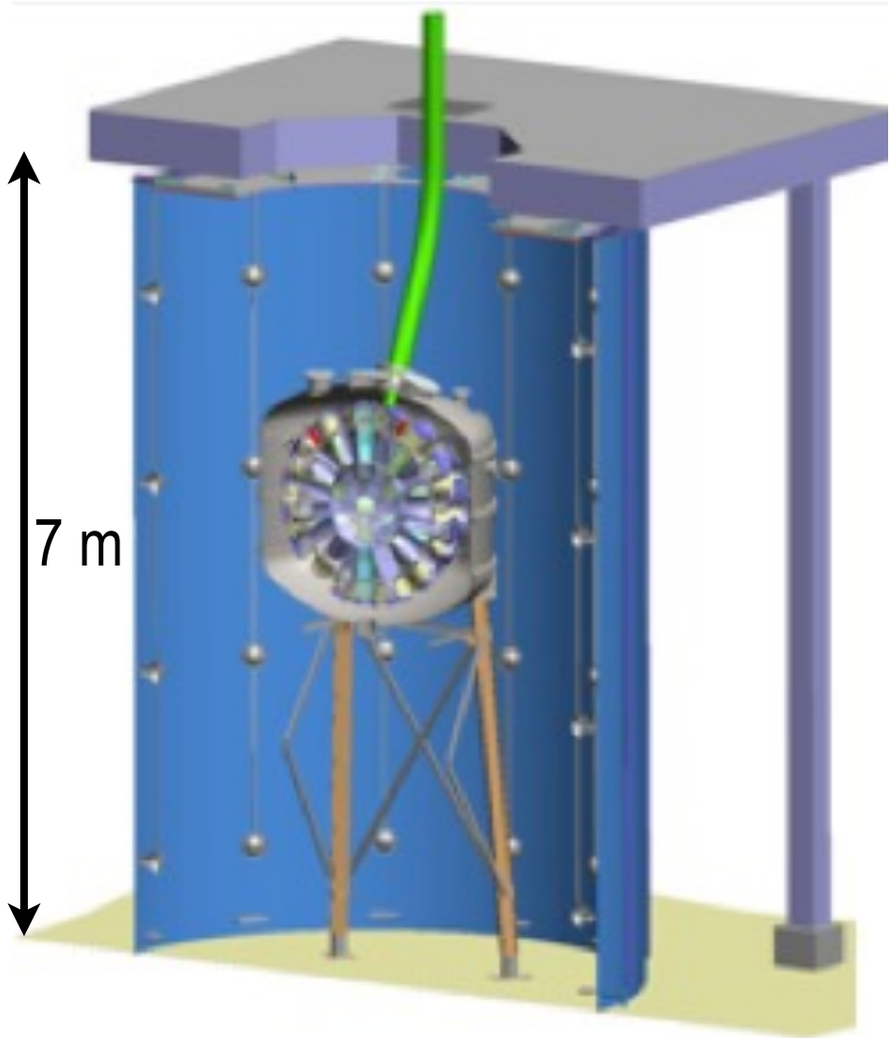
8.5 m diameter water shielding sized for reduction of (α,n) from rock

DEAP/CLEAN Timetable

Information and figures from from J. Monroe, TAUP 2011

- MiniCLEAN (150 kg fiducial)
  - construction: 2010-2013 (?)
  - running: 2013 (?)-2015
  - target sensitivity: $2*10^{-45}$ cm^2
- DEAP-3600 (1000 kg fiducial)
  - construction: 2010-2013
  - running: 2013-2017
  - target sensitivity: 10^{-46} cm^2
- DEAP/CLEAN (10 T fiducial)
  - target sensitivity: 10^{-47} cm^2





MiniCLEAN

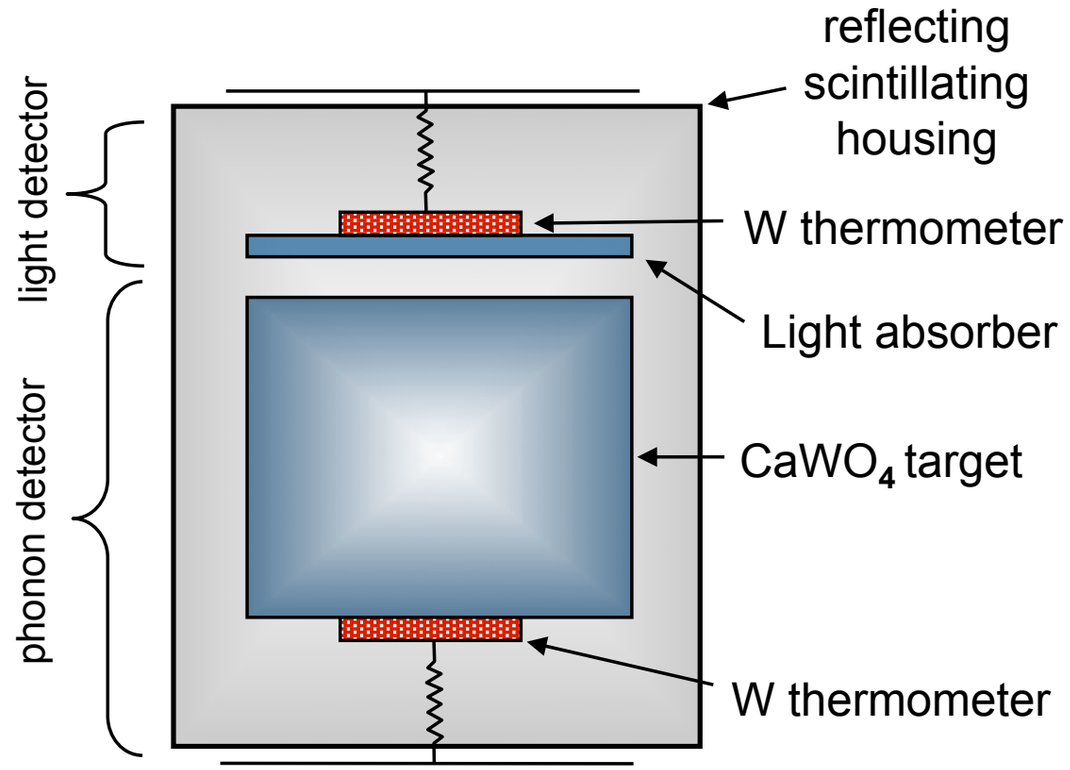
CRESST Cryogenic Detectors

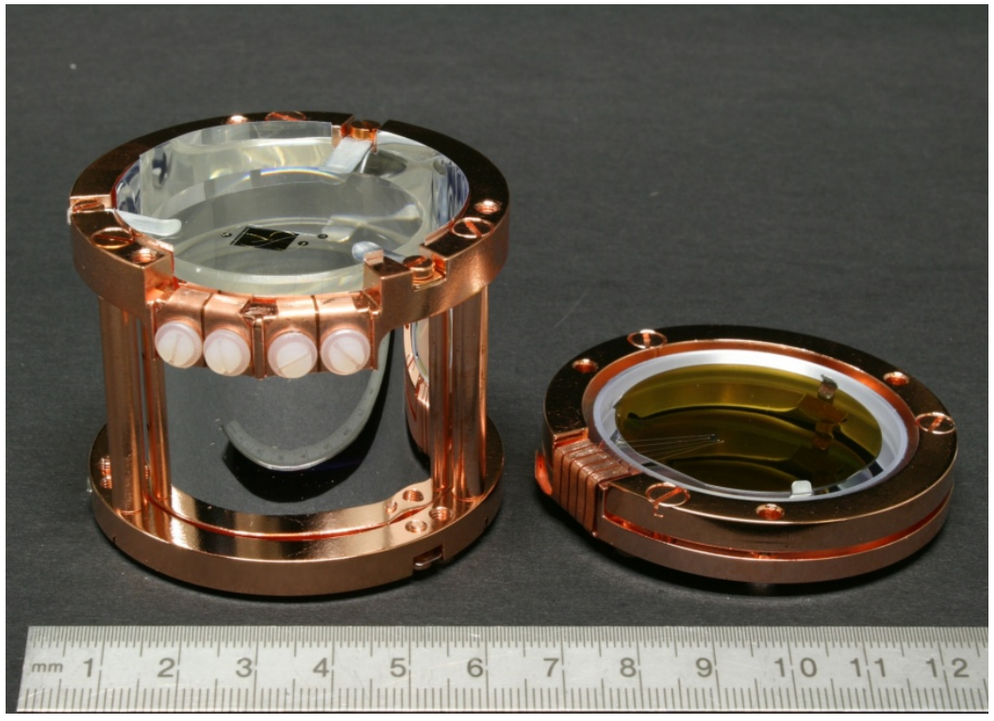
Slide Reformatted from F. Petricca, TAUP 2011

- Target crystals operated as **cryogenic calorimeters** (~10 mK)
  - energy deposition in the crystal:
    - mainly phonons
      - –temperature rise detected with W-thermometers
      - –measurement of deposited energy (sub keV resolution at low energy)
    - small fraction into scintillation light

- Separate **cryogenic light detector** to detect the light signal

- Detector Module:
  - Simultaneous measurement of:
    - **deposited energy E in the crystal** (independent of the type of particle)
    - **scintillation light L** (characteristic of the type of particle)





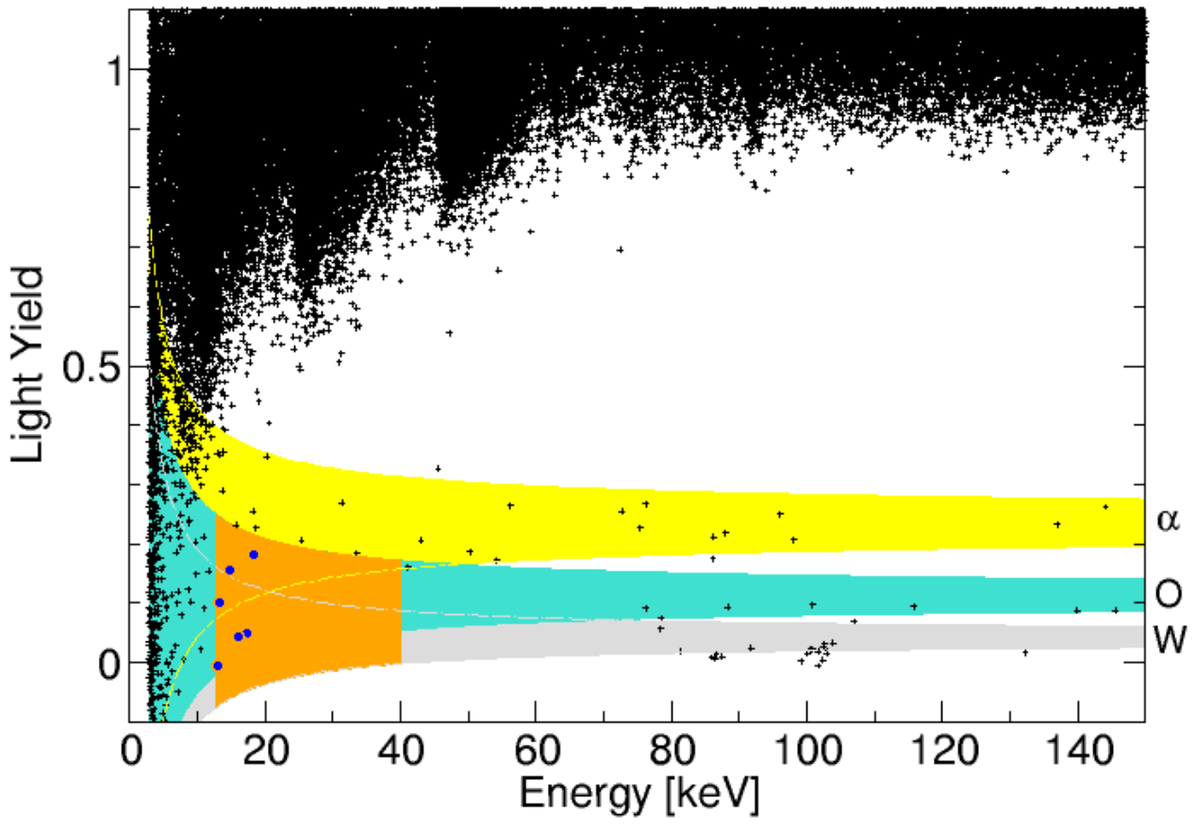
Signal Significance

- Net exposure: 730 kg days
  - 67 accepted events

- Results of Likelihood Analysis
  - Two regions of (mass,c-s) favour an additional signal of WIMPs in addition to background events
  - M1 global best fit (4.7 σ)
  - M2 slightly disfavored (4.2 σ)

- Known background sources are not sufficient to explain data

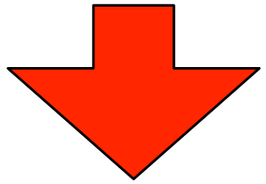
- Large background contribution
  - Reduction of background is necessary



	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

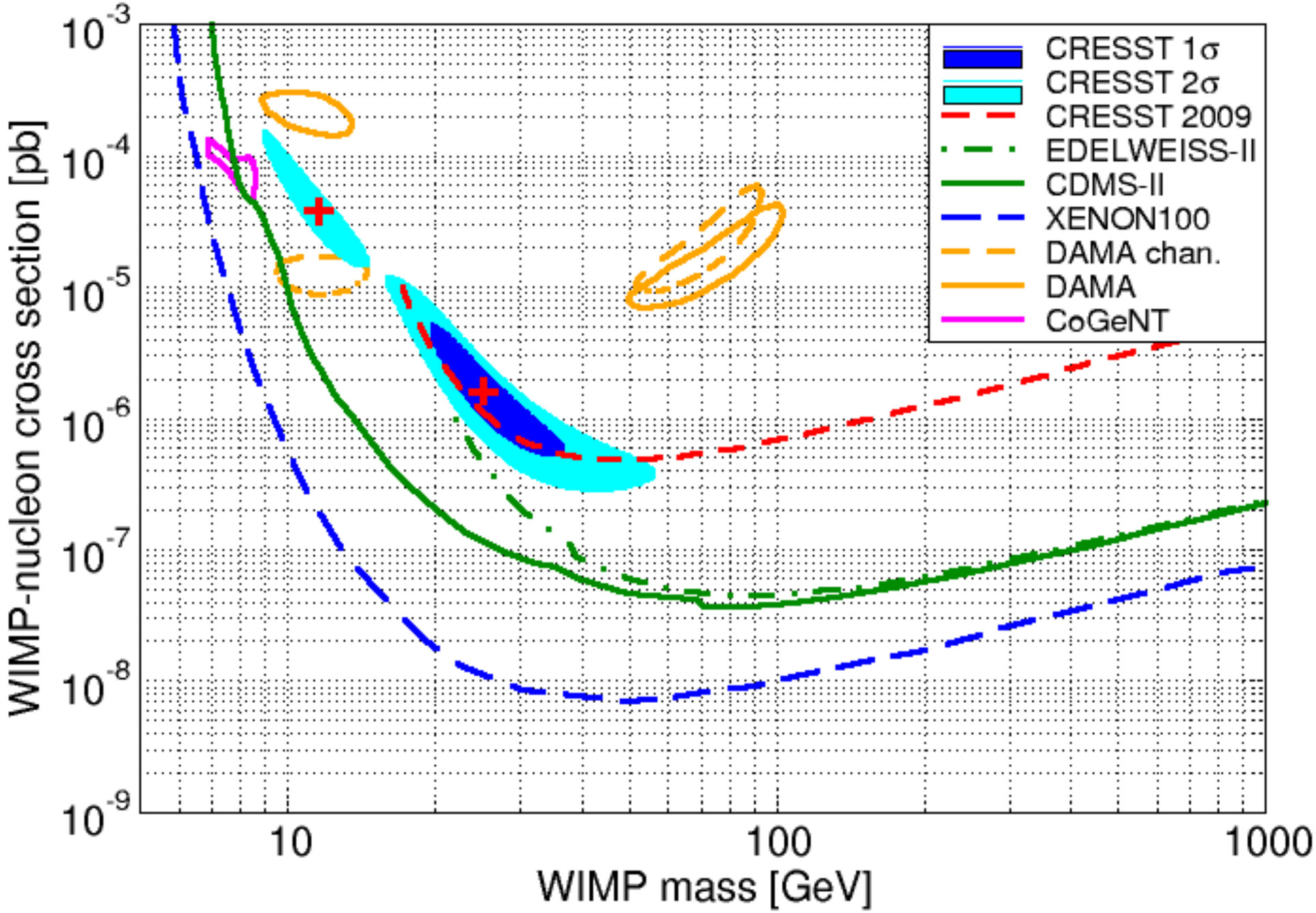
CRESST-II New Analysis

- Florian Reindel (MPI/TUM) - Diploma Thesis
  - Improved energy calib / new pulse shape cut - adaptive for noise changes / improved coincidence window-cut / new analysis allowed fully blind cuts
  - New analysis total 52 events in 572 kg d compared to 67 events in 730 kg d
  - Reduced significance of WIMP signal component
    - 1.9σ for lowest mass, 13 GeV WIMP, hypothesis
    - 2.5σ for 29 GeV WIMP hypothesis



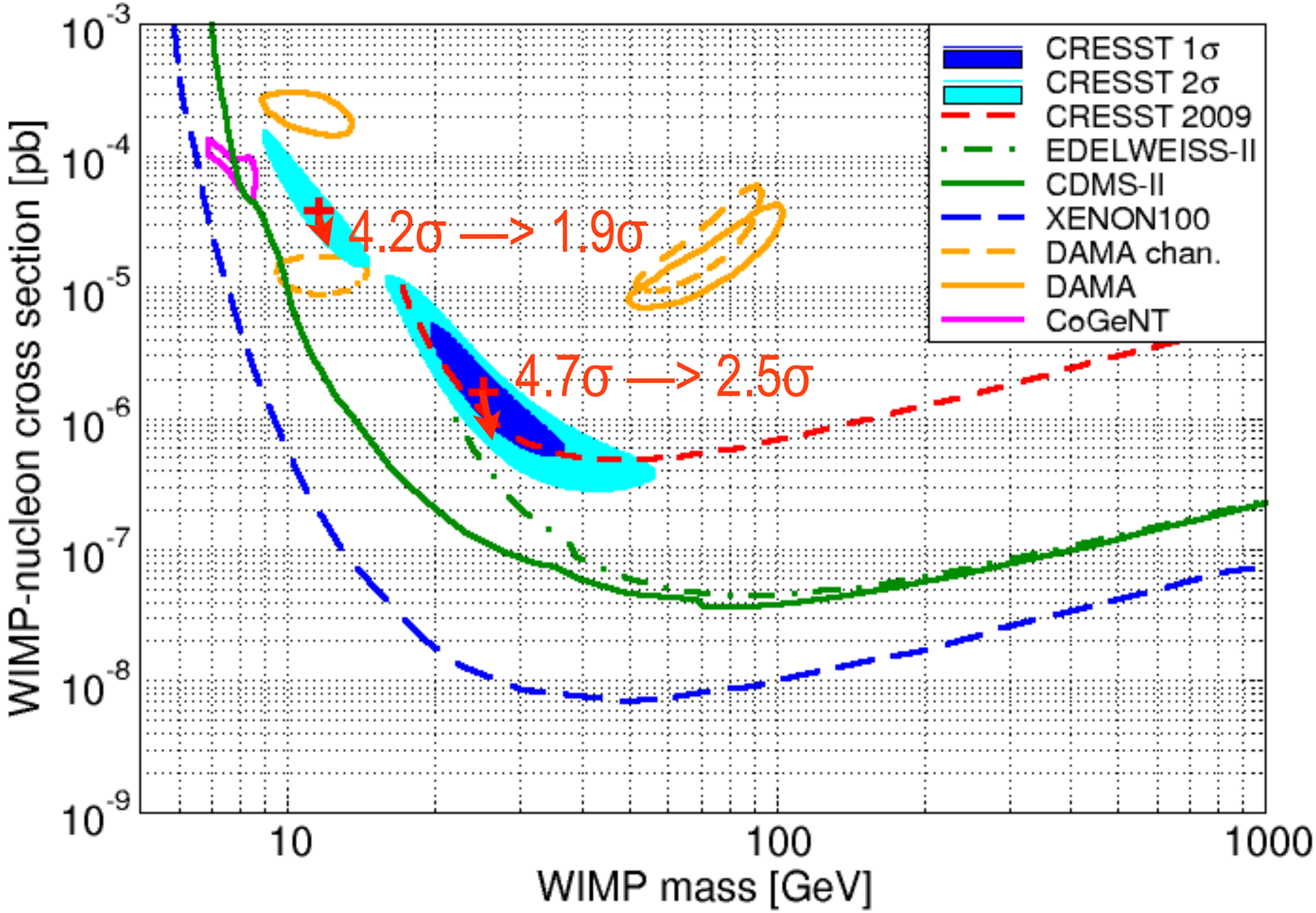
	Analysis of this Work		Analysis of [1]	
	M1	M2	M1	M2
e/γ-Events	8.0	8.0	8.0	8.0
α-Events	9.8	9.6	11.5	11.2
Neutron Events	7.7	9.1	7.5	9.7
Pb Recoils	11.1	12.5	15.0	18.7
Signal Events	13.0	10.2	29.4	24.2
m_χ [GeV]	28.9	13.0	25.3	11.6
σ_{WN} [pb]	$7.6 \cdot 10^{-7}$	$1.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$
Significance	2.5σ	1.9σ	4.7σ	4.2σ

CRESST-II Results



Next CRESST run aims to reduce backgrounds further to improve contrast of any signal

CRESST-II Results

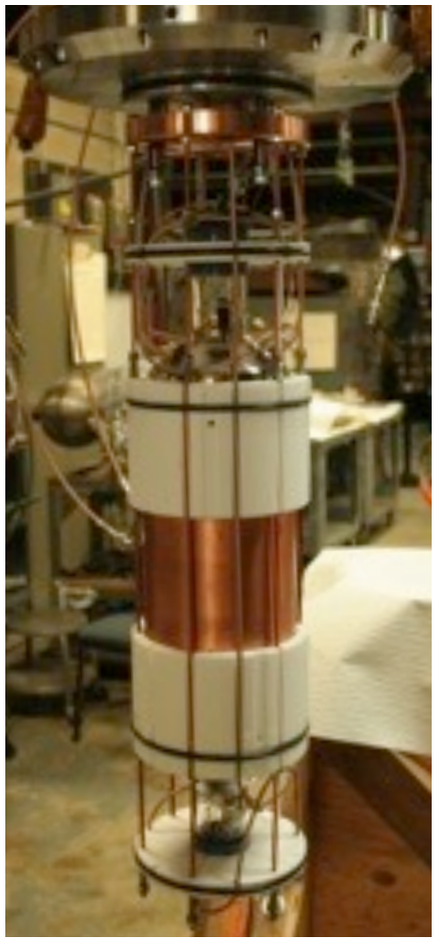


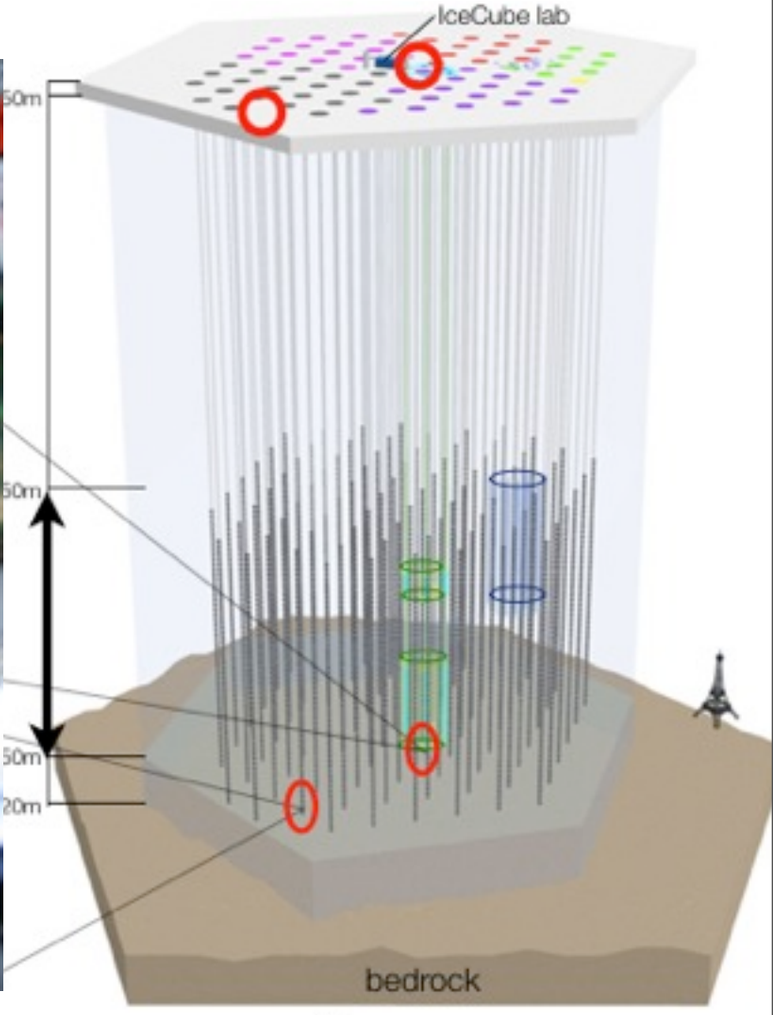
Next CRESST run aims to reduce backgrounds further to improve contrast of any signal

DM-Ice-17 (kg)

Slide reformatted from Reina Maruyma, DM2012

- 17 kg of NaI(Tl) (formerly part of NaIAD) deployed as a feasibility study at the South Pole Dec. 2010
- Continuous operation since Jan. 2011
- Data transmitted via satellite
- Analysis underway





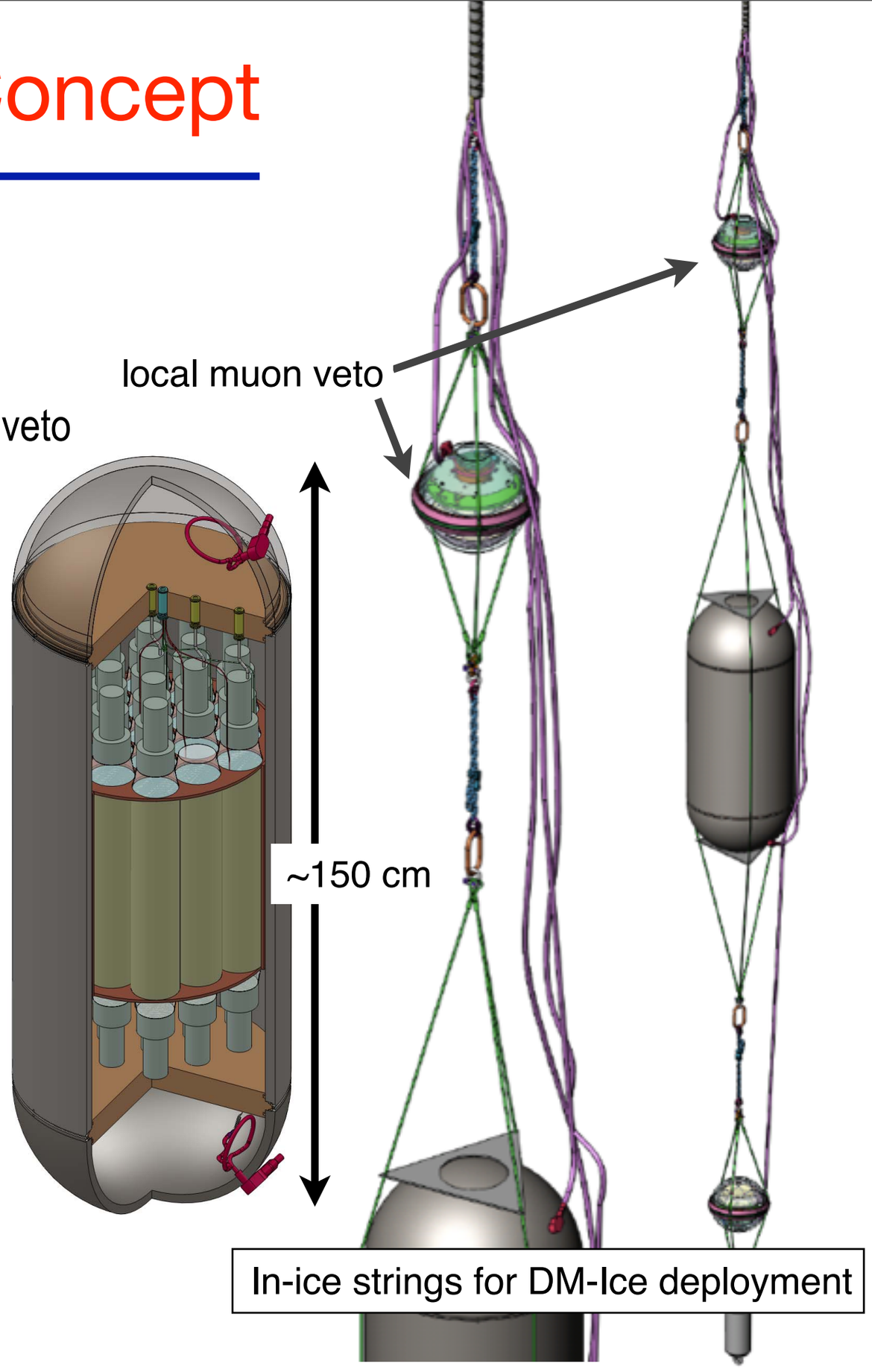
DM-Ice Concept

Detector
- 250–500 kg NaI(Tl)
- Closely-packed inside pressure vessel for coincidence veto
- Two PMTs/Crystal

Location
- South Pole, ~ 2500 m deep in the ice
- Near the center of IceCube for additional veto

Pressure vessel
- Withstand > 7000 psi of freeze-back pressure
- Low-background stainless steel
- Low background copper shielding where needed

Electronics
- Pulse digitization inside the vessel
- Power from SP Station or IceCube Counting Lab
- Remotely controllable

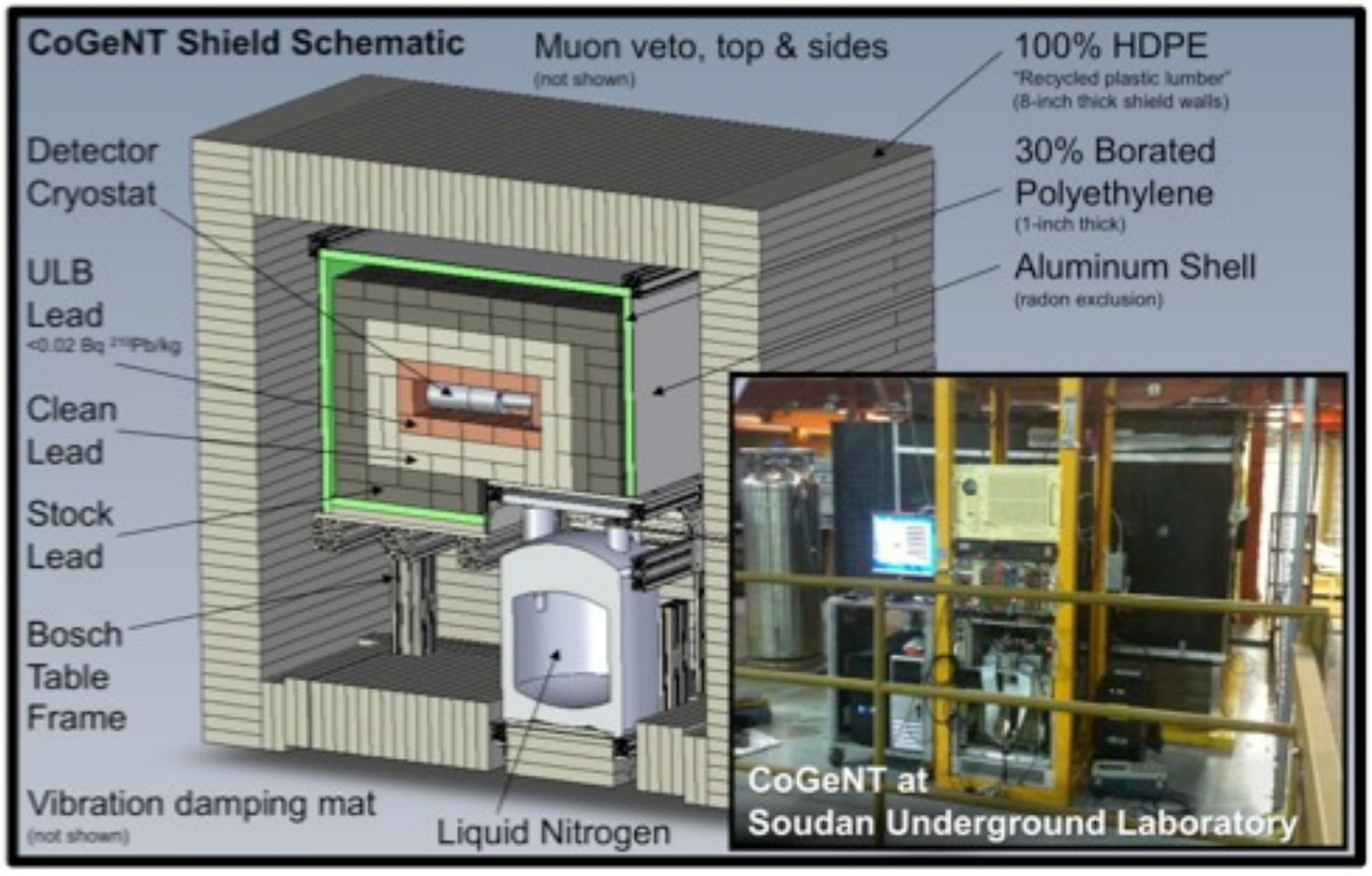


Slide from Reina Maruyma, DM2012

CoGeNT Experiment

- Single 440 g HPGe ionization spectrometer
- Located in Soudan Underground Lab
- Timeline
  - Data taking started Dec. 2009
  - Soudan Fire Mar. 2011
  - Data taking resumed July 2011

Figures/Information from
D Fustin (UChicago Thesis, 2012)
J Collar (Brown Colloquium, Feb 2012),
E Dahl (Stanford Colloquium, Feb 2012),
J. Orrell, TAUP Sept 2011



Making an excellent detector even better:

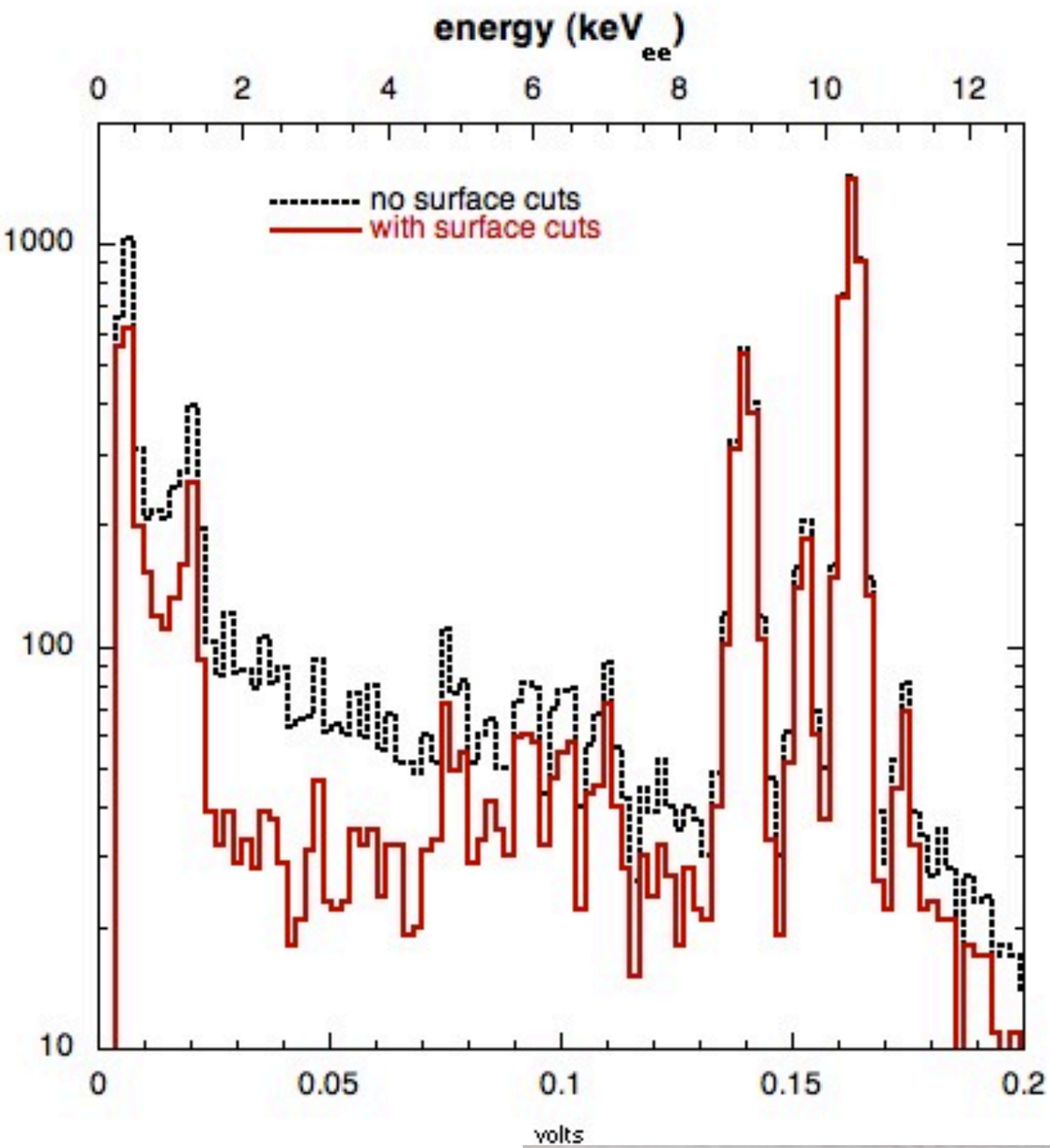
J Collar, Feb 2012

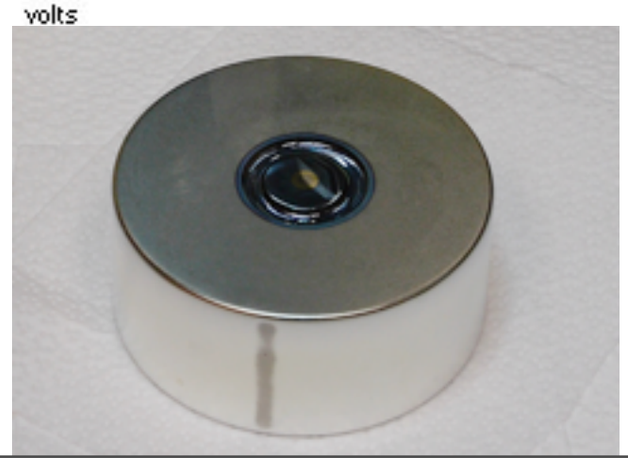
PPCs can reject surface events using rise-time cuts

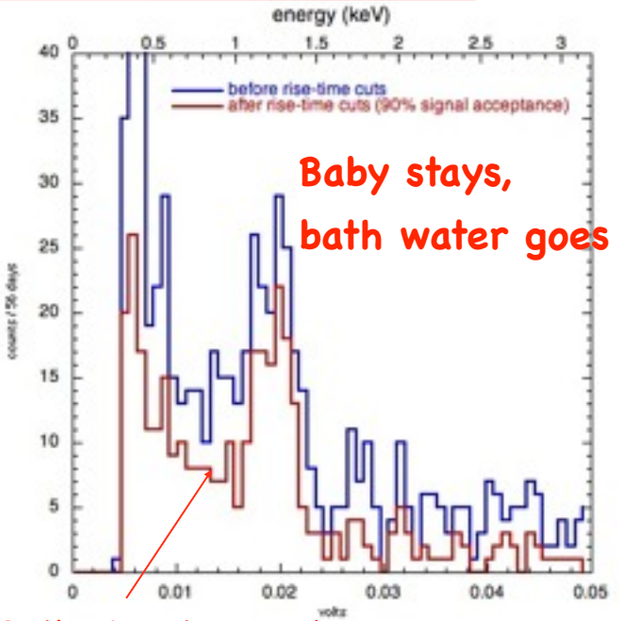
Based on a phenomenon ~40 years old (embarrasing!)

COGENT running
~20 m away from CDMS
(just to keep them honest... ;-)

NOT nearly "best effort" yet.
MAJORANA Demonstrator
background goal is ~x1000 lower

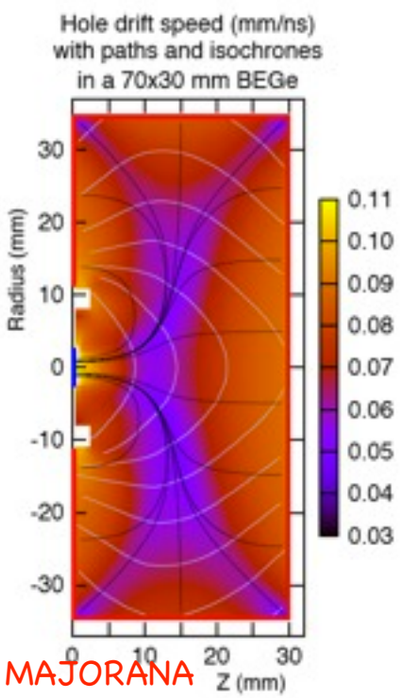






Baby stays,
bath water goes

Bulk signal acceptance
monitored down to 1 keVee
via L/K EC peak ratios and pulser calibrations.
Working on characterizing
surface background rejection
(large exposure required).



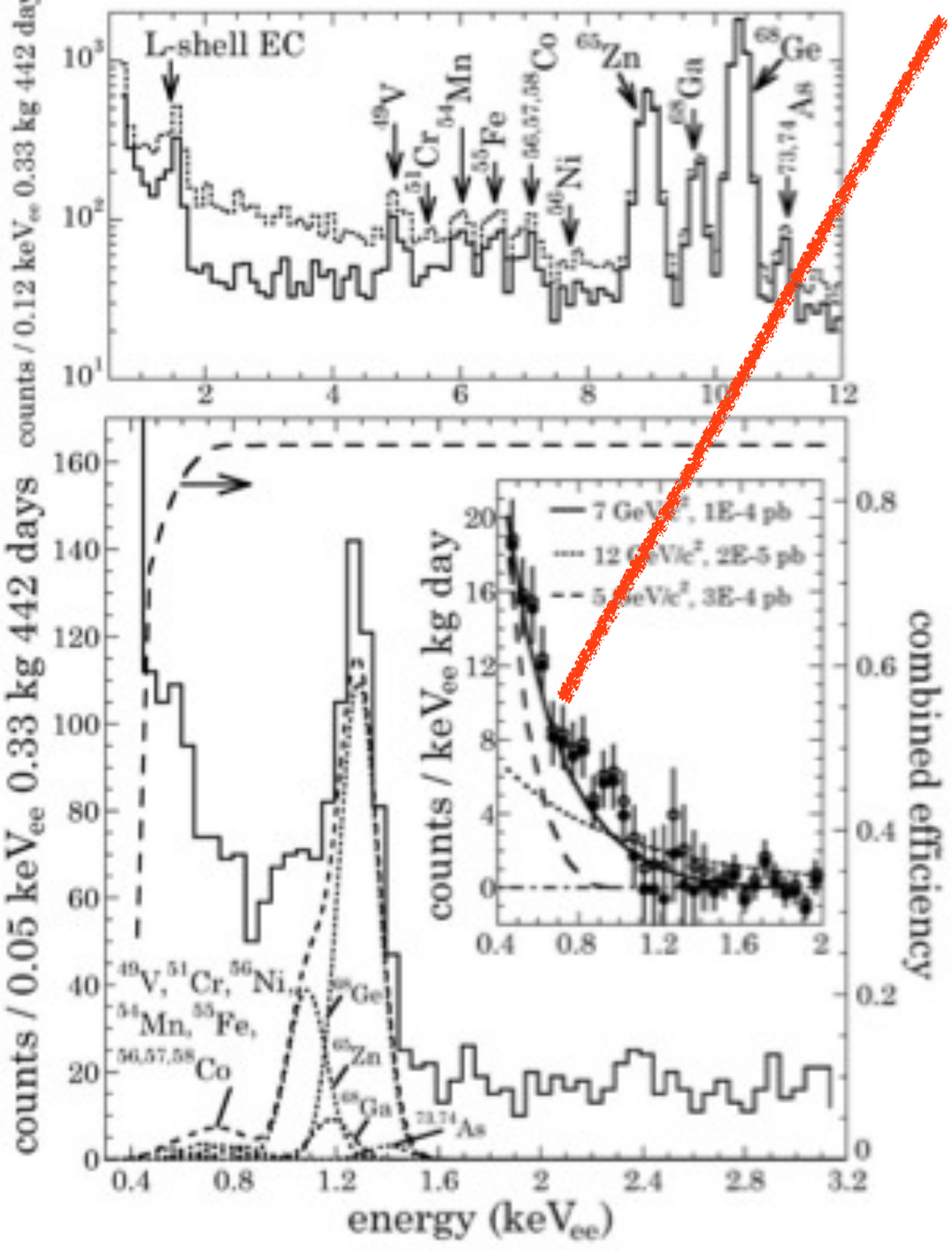
Charge Collection time modelled (small 100 ns correction)

MAJORANA BEGe (ORNL simulation)

CoGeNT Results

arXiv:1106.0650v3

~7 GeV WIMP spectrum?



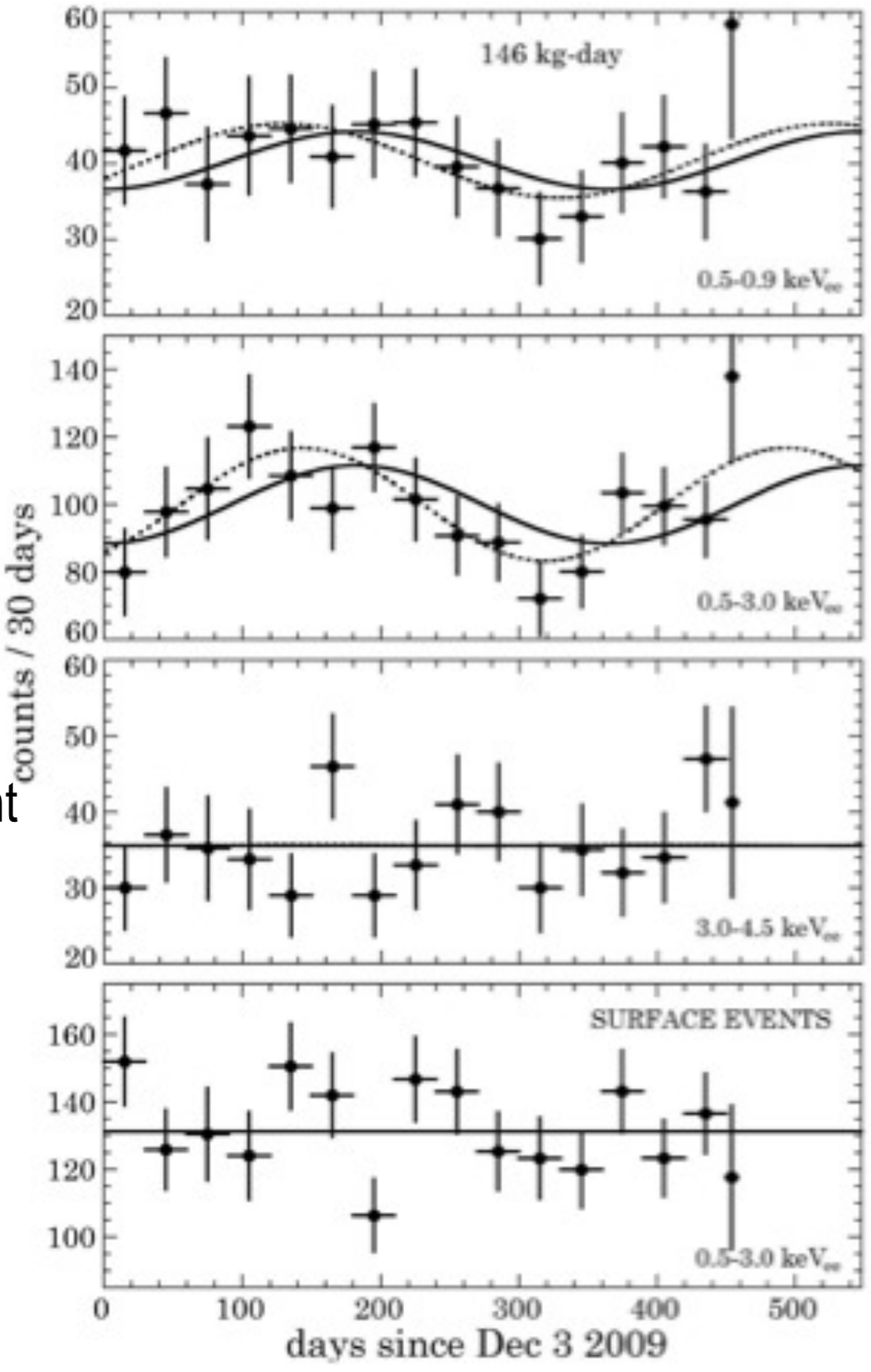
period: 347±29 d

mod. amplitude: 16.6±3.8%

minimum: Oct. 16±12 d

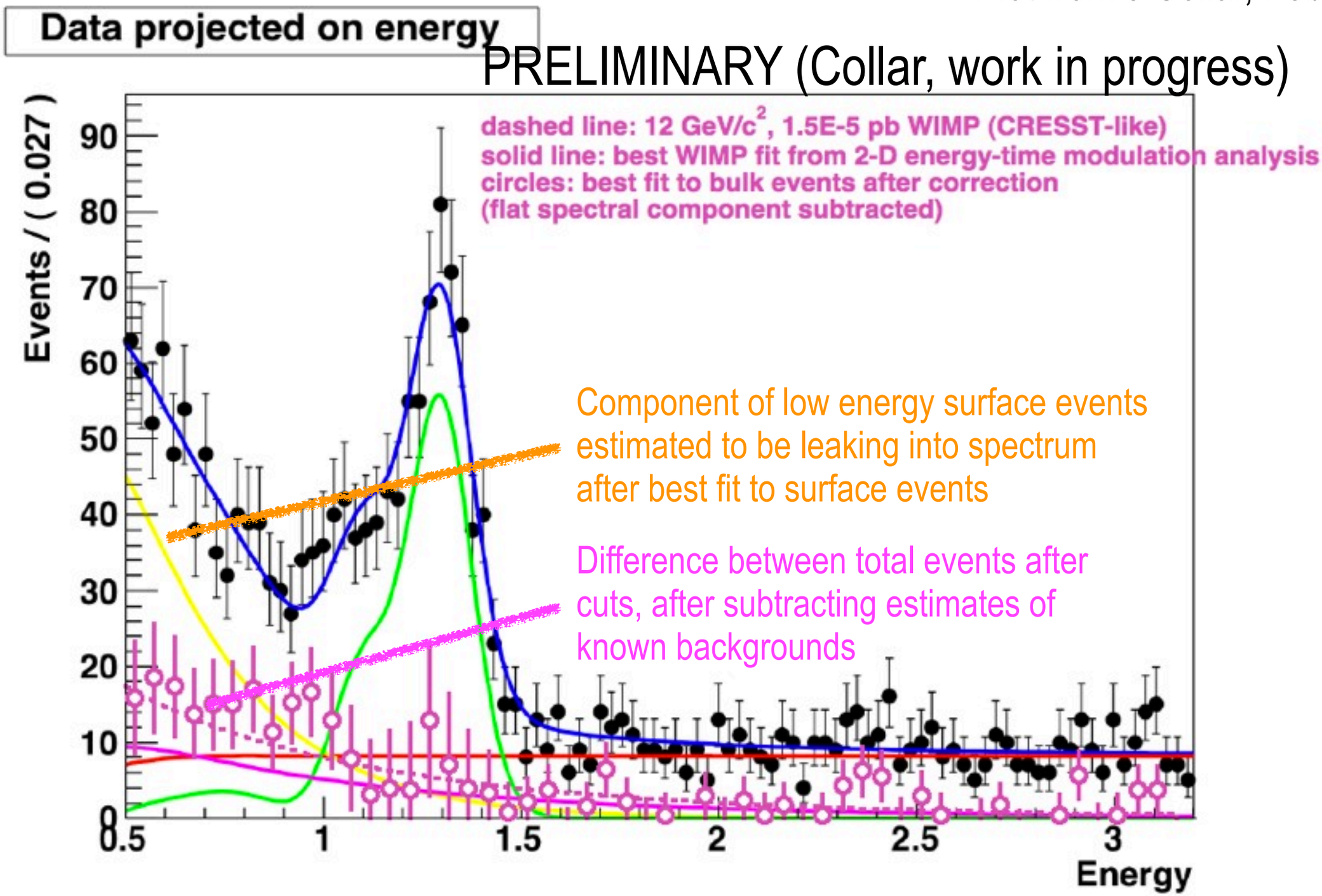
2.8σ better fit with mod than with null

but 16% consistent with null



Recent GoGeNT Analysis

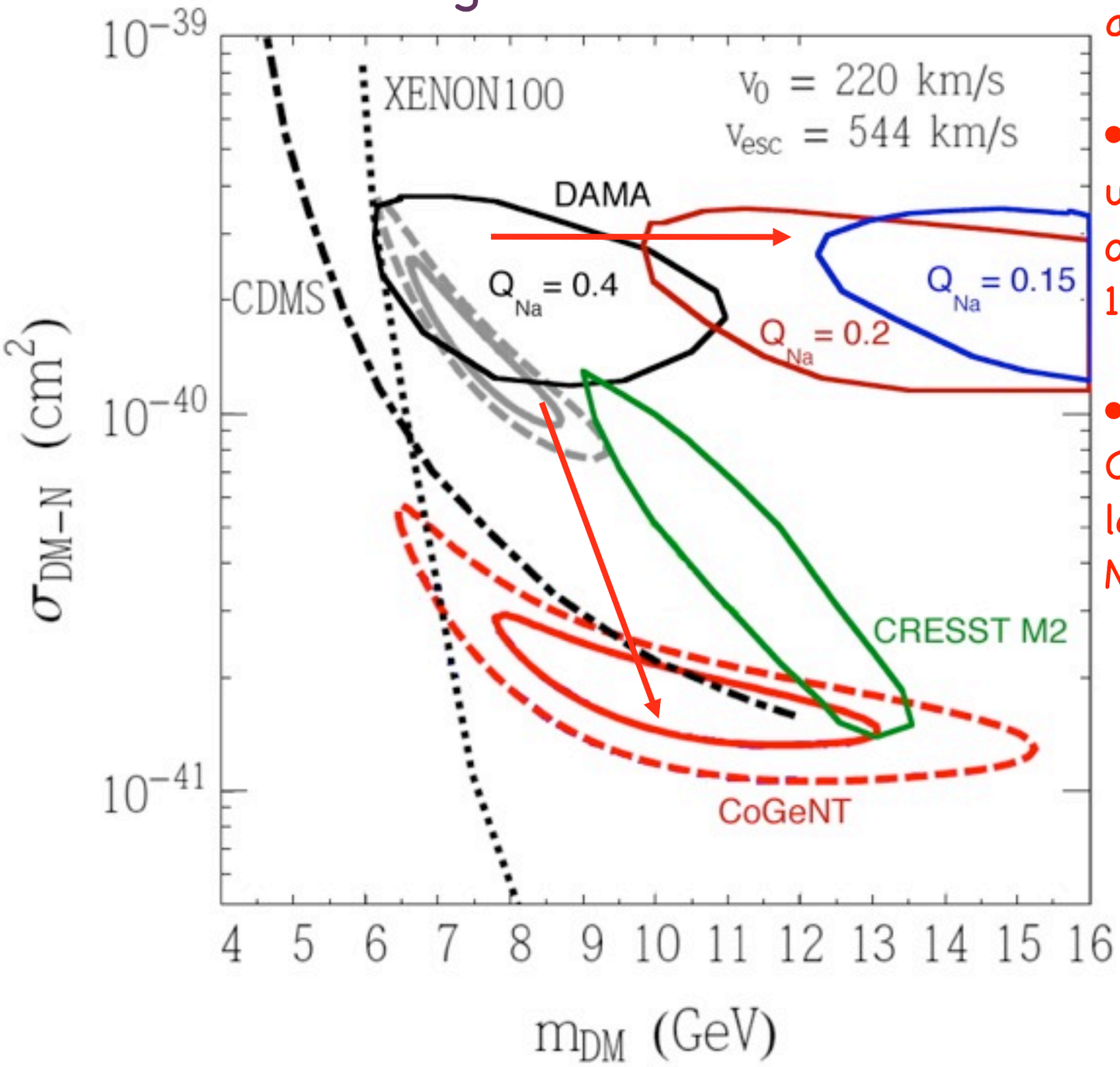
Plot from J Collar, Feb 2012



Spectral and modulation analysis in CoGeNT seem to point to a similar WIMP mass & coupling,
BUT then modulated amplitude is definitely not what you would expect from a vanilla halo (way too large).

Are DAMA, CoGeNT and CRESST in agreement, or not at all?

Ring Around the Rosie...



- Including surface event contamination next to threshold brings spectral and modulation CoGeNT analyses in close agreement at ~10-15 GeV.

- However, Q_{Na}~0.4 seems extremely unlikely after UC measurement, regardless of theoretical prejudice (see arXiv: 1007.1005).

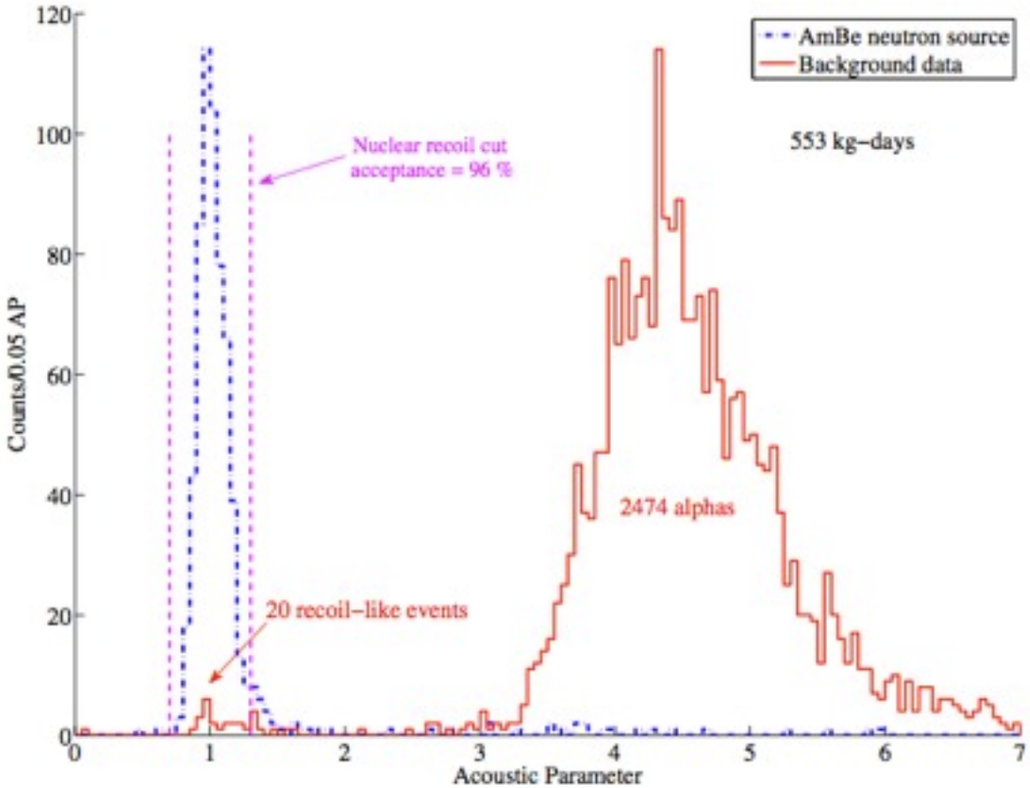
- ... and the modulation observed by CoGeNT would be order-of-magnitude larger than expected from a standard Maxwellian halo.

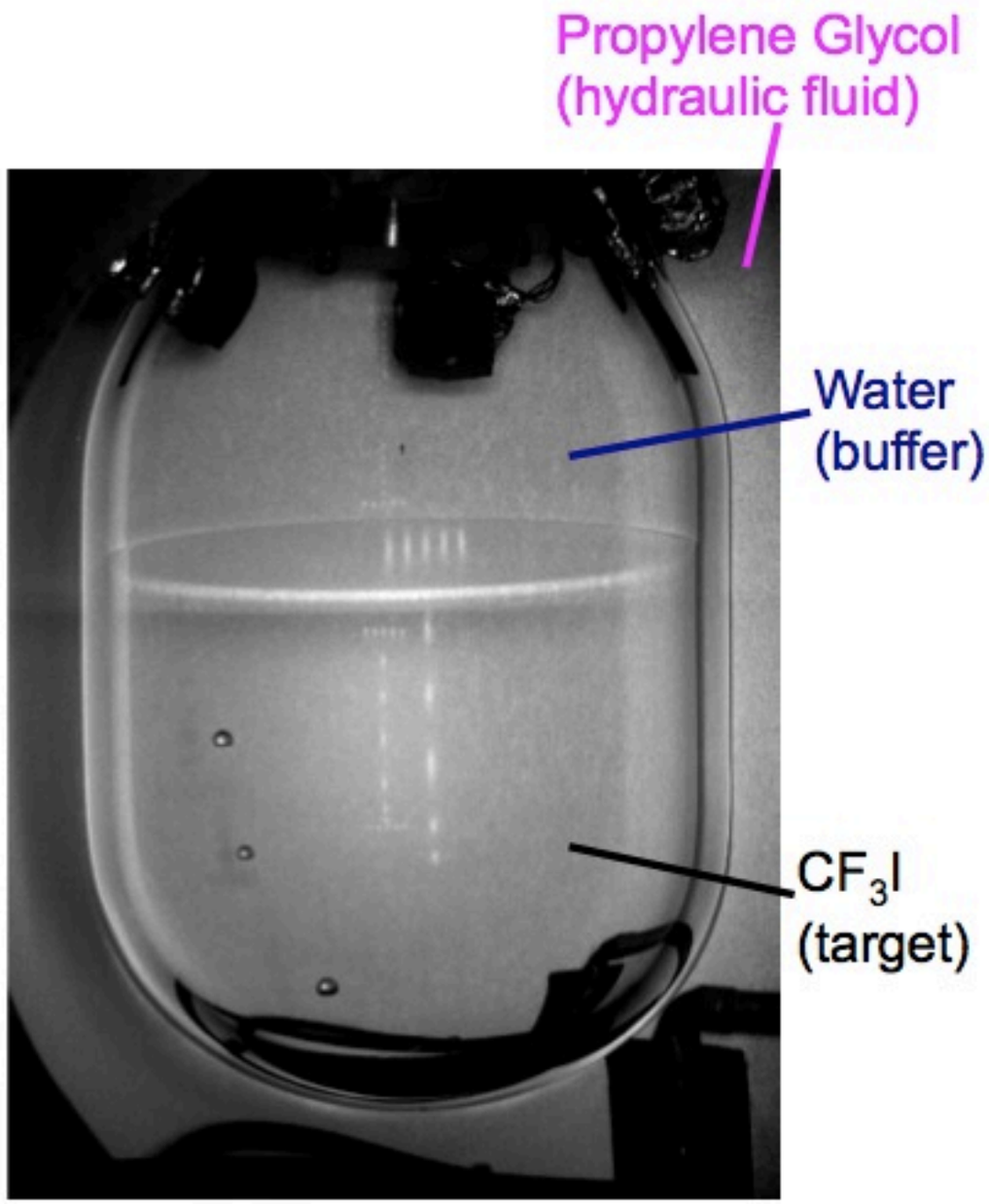
J Collar

COUPP: Bubble Chamber

Figures from H. Lippincott, TAUP 2011

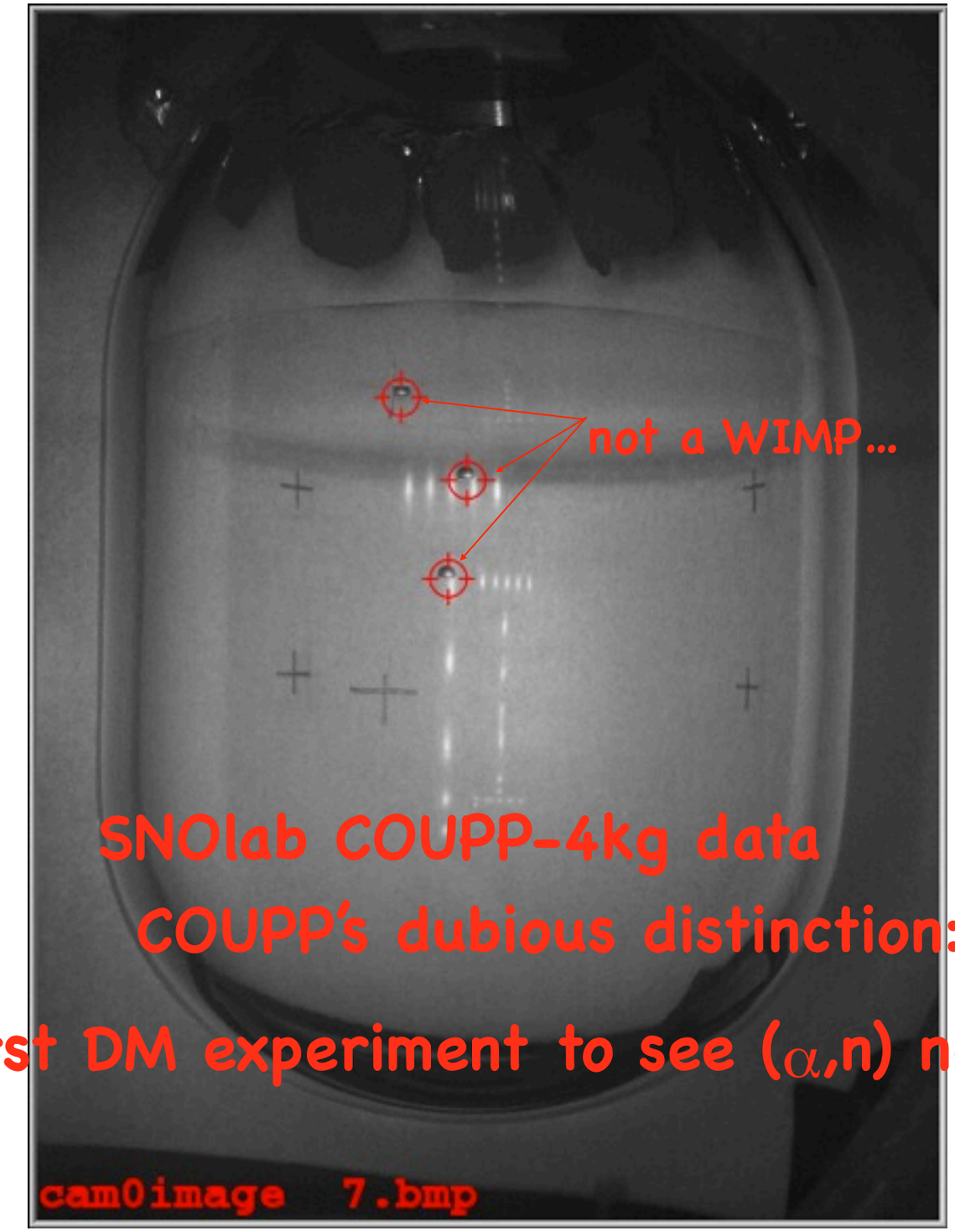
- Superheated Fluid
  - CF_3I or C_3F_8
- Bubble nucleation from particle interactions
  - Temperature and pressure tuned to eliminate bubble production from ER
    - –ER have lower dE/dx
- COUPP-4 demonstrated acoustic alpha discrimination
  - 98.9% alpha rejection - alphas “louder” than NR

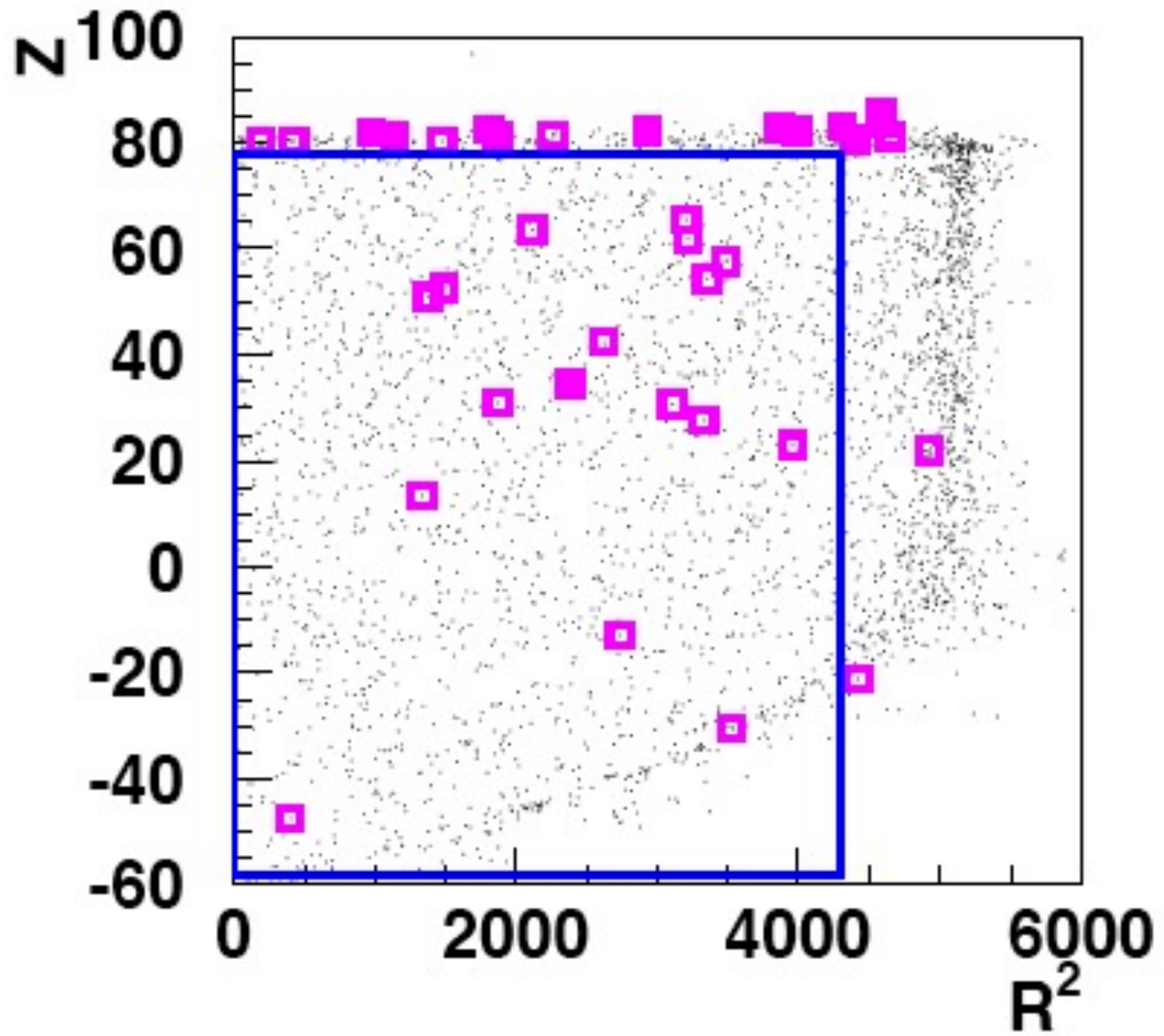




(α,n) Neutrons

From Piezo-electric Sensors and From View Window Glass





SNOlab COUPP-4kg data

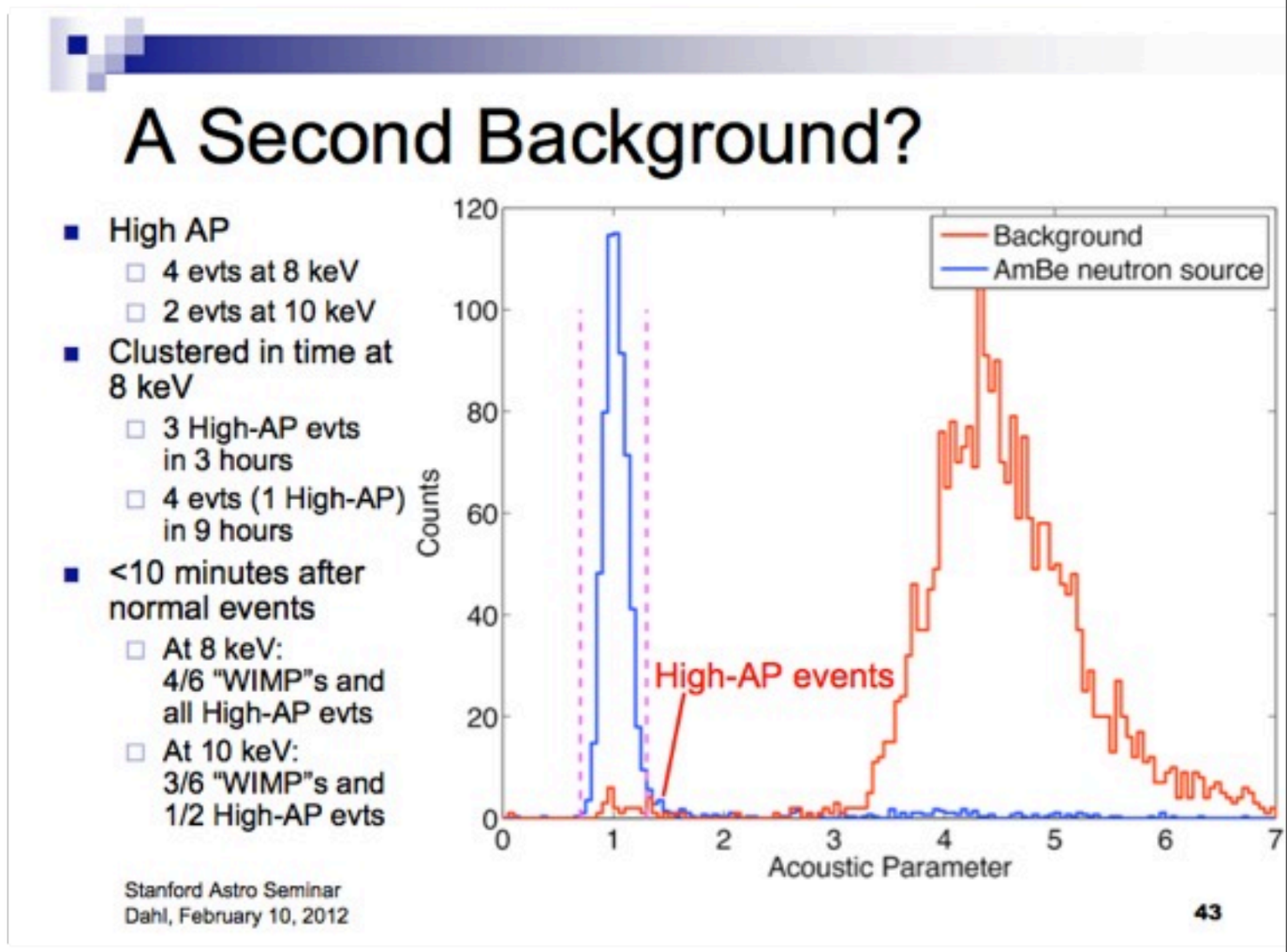
COUPP's dubious distinction:

first DM experiment to see (α,n) neutrons

In agreement with Po-210 and U, Th in PZT

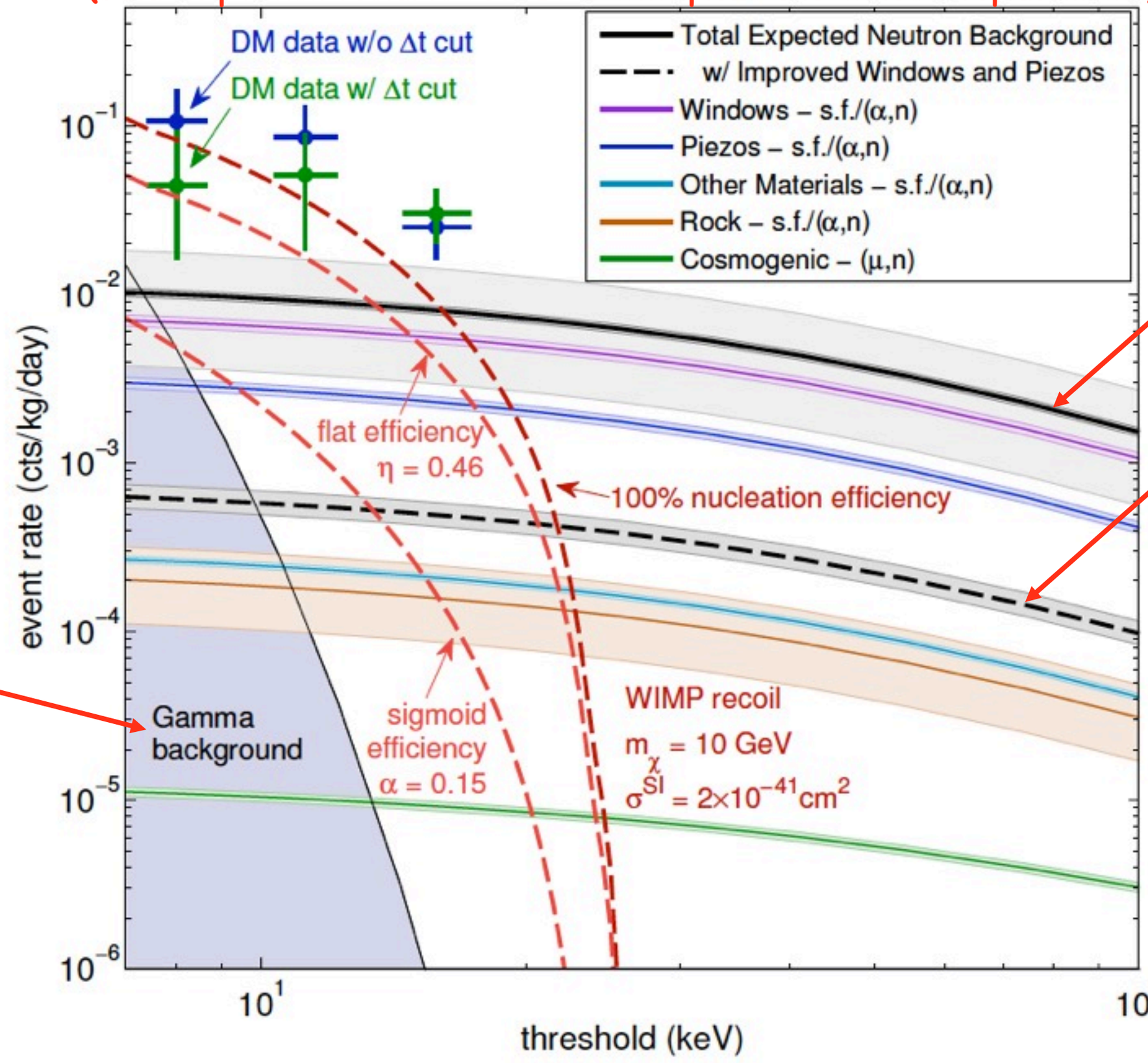
and inspection windows. Replacement in progress.

- Analysis of Data From COUPP-4 is more complex
  - In addition to the (α,n)-> neutron NR (nuclear recoil) events from internal backgrounds …
    - can be estimated from multiple scattering seen in detector
  - … there are also single NR events which would be selected as WIMP events …
    - … Except that they appear to be time correlated with other NR single events and earlier
    - They occur too soon after other NR evts if assumed they appear (Poisson) randomly
    - Either DM is very clumpy on light-sec scales (not serious)
    - Of some process is generating spontaneous single NR events in the middle of the detector?
      - –Suspect photo-disintegration of molecules Chemistry at target upper interface forming precipitates that float around inside target -> change target?
    - Note 15 keV threshold data does not contain these events



Present COUPP-4kg Status

(Data Acquisition restarts Feb. 2012 with piezo and window replacements)



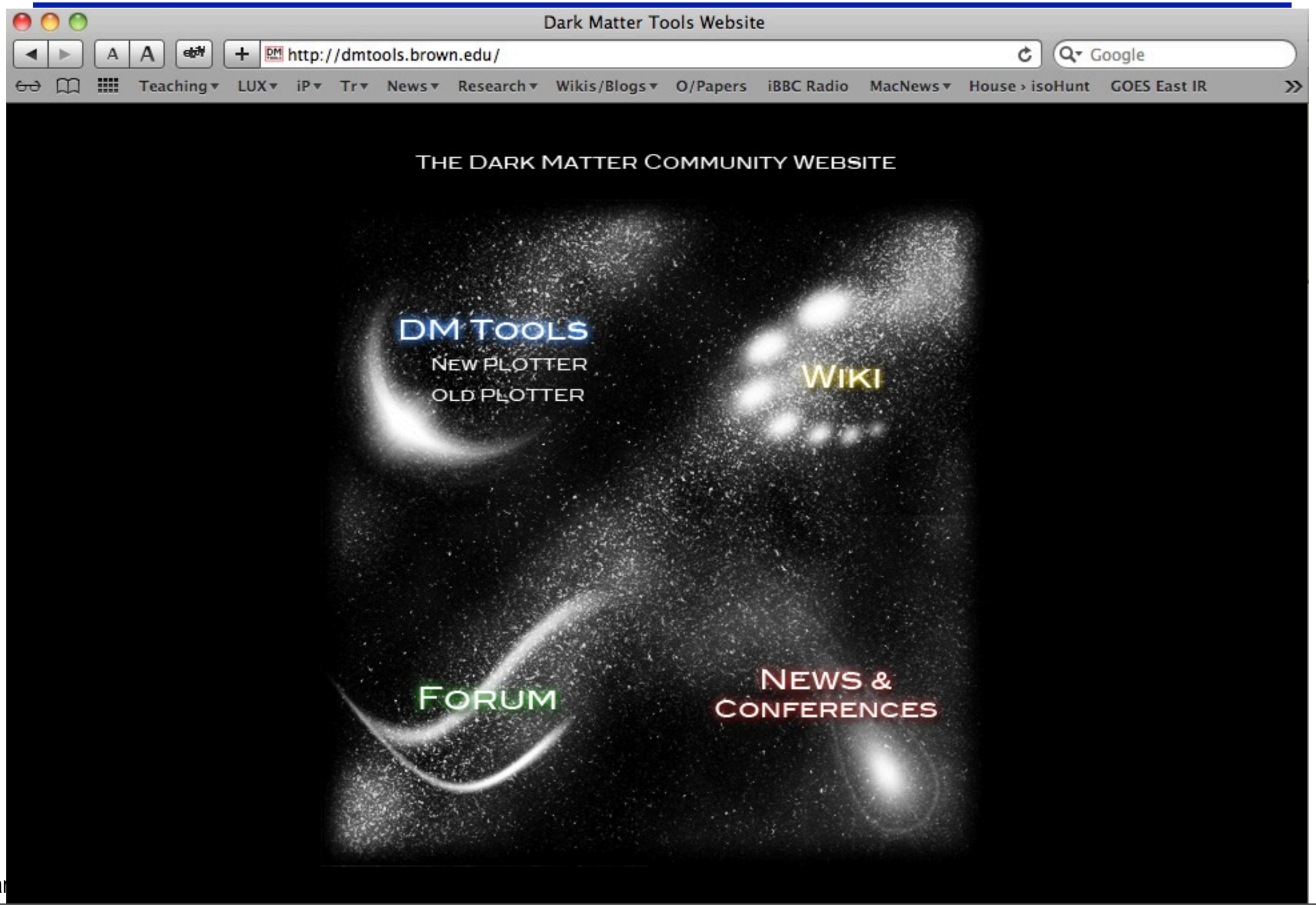
Present neutron background (two methods of estimation agreeing)

Next 4kg run expectation

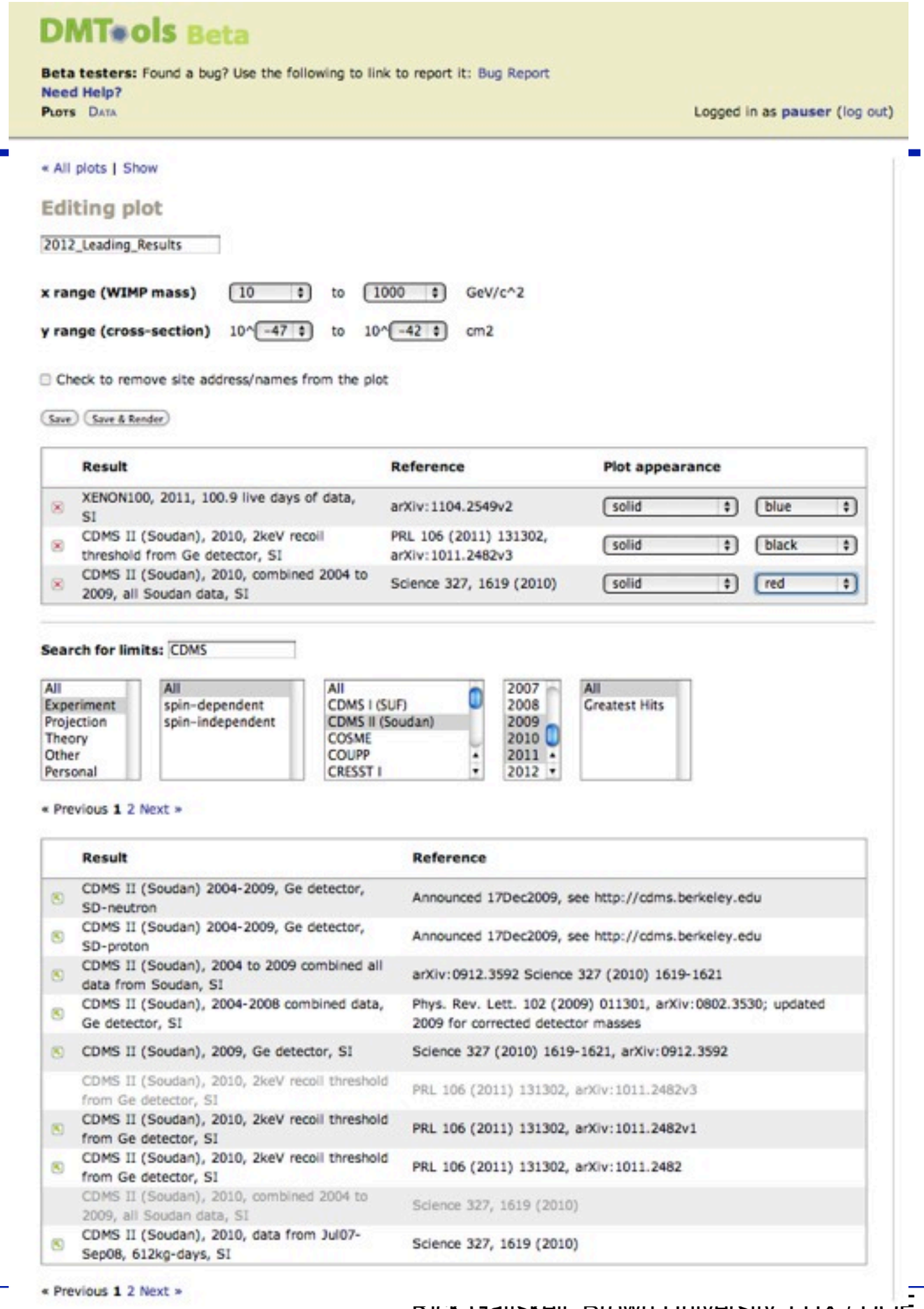
(further piezo purification in progress, expected additional x25 reduction for 60kg chamber)

Based on measurement of gamma flux at position of CF3I, and of gamma rejection factor.

New DMTools Plotter



- http://dmtools.brown.edu
  - ➡ New DMTools has finished beta testing
    - Replaces old plotter - offline
  - ➡ Allows more dynamic selection of data
  - ➡ Store plots for recall/edit later
  - ➡ All datasets can be uploaded/downloaded



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  - Completed surface run. Moving to underground lab in May 2012, for operation Nov 2012