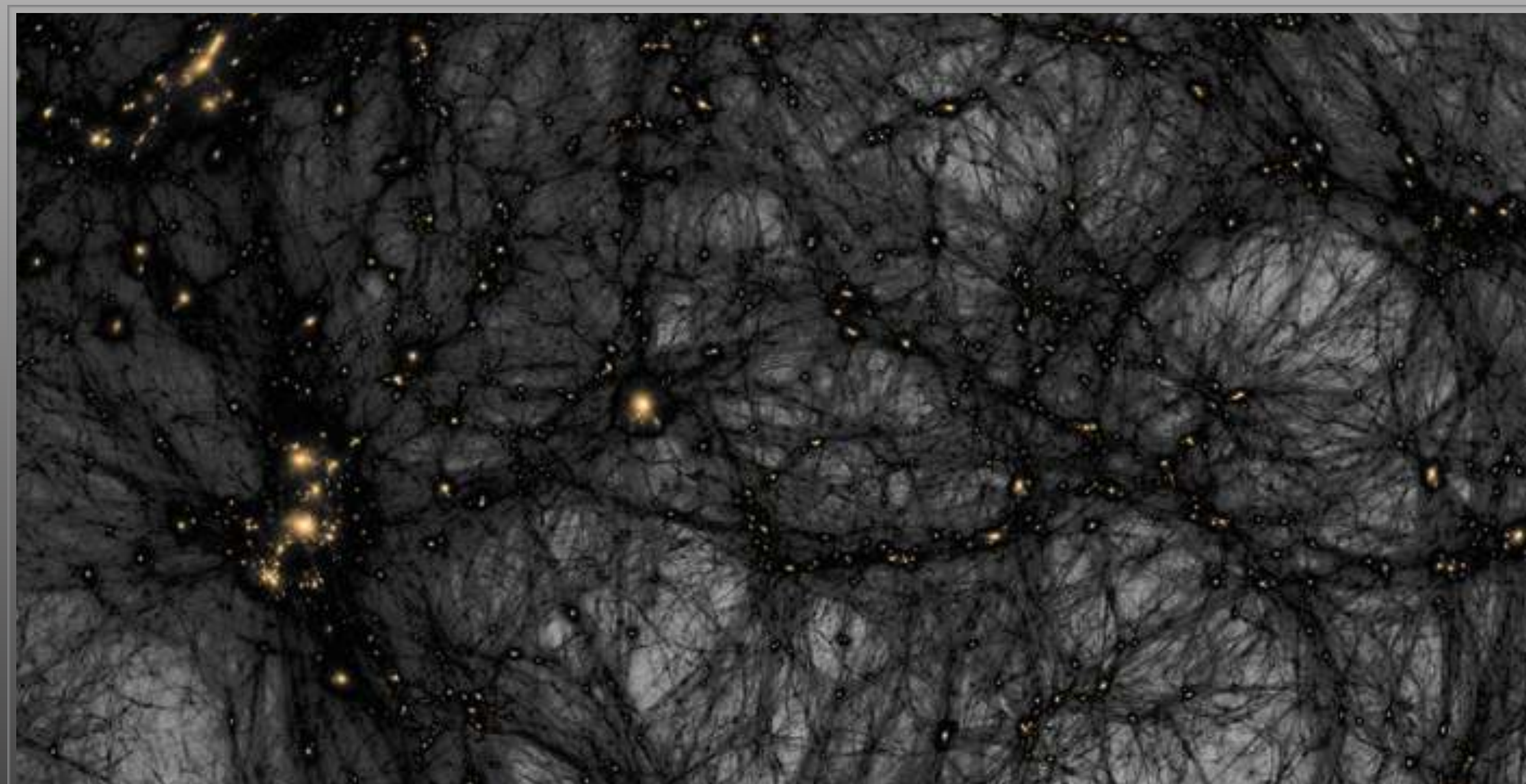


LUX & LZ

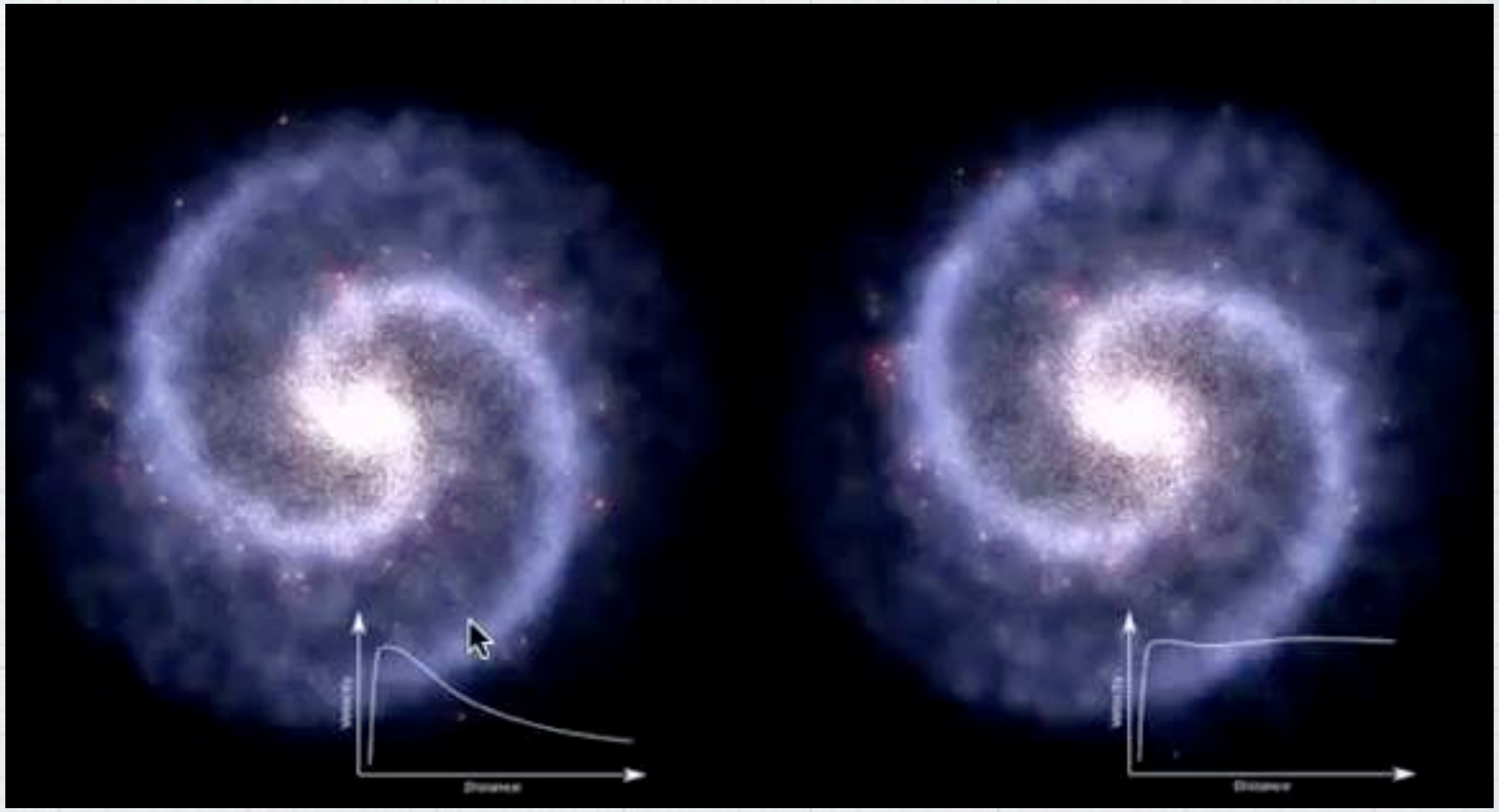
The hunt for DARK MATTER

Lea Reichhart - SHEP Seminar 09/01/2015

http://www.calacademy.org/discovering-dark-matter

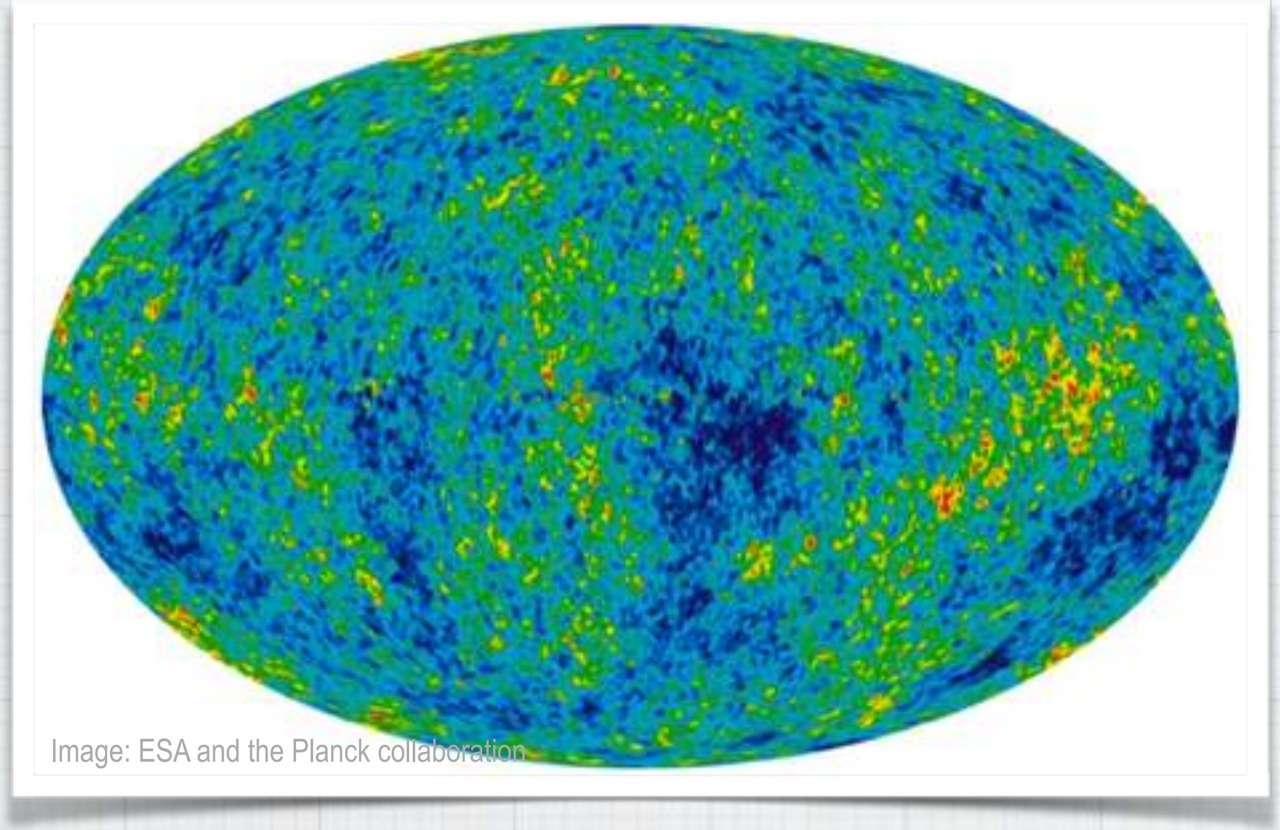
Early evidence for Dark Matter

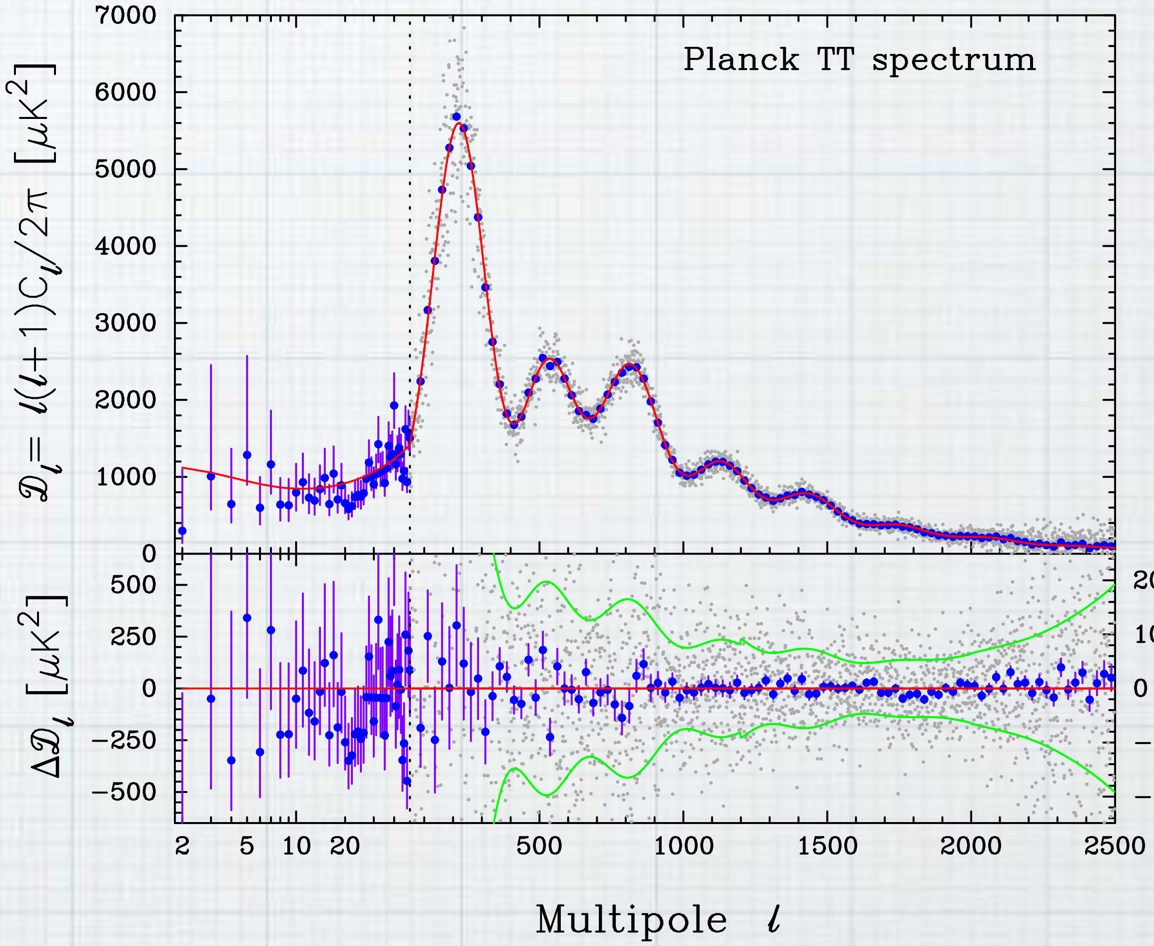
* Fritz Zwicky (1930s) and Vera Rubin (1970s) measure rotational velocities of galaxies and clusters
* Expect Keplerian fall-off, but observe flat rotation curves
* Galaxies are rotating too fast
* Implies presence of much more mass in systems



Much much more evidence since then

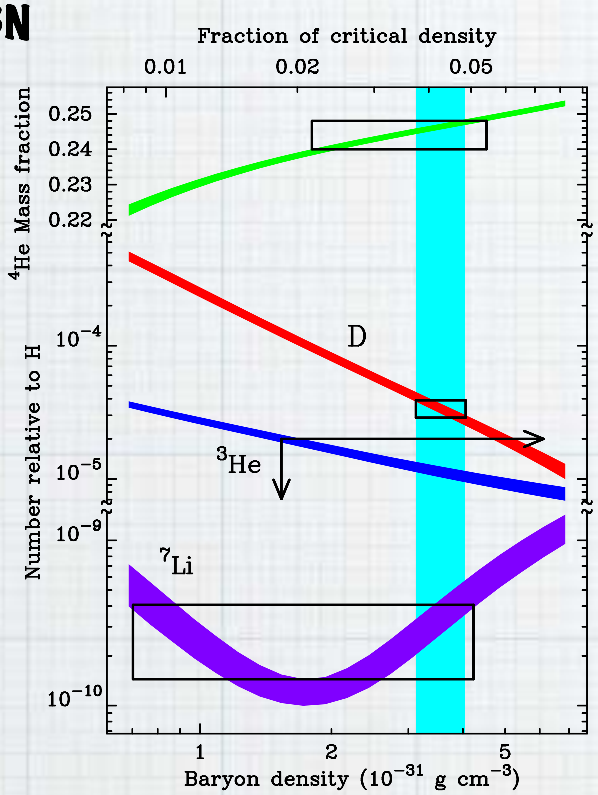
CMB + BAO: precision tests of ΛCDM



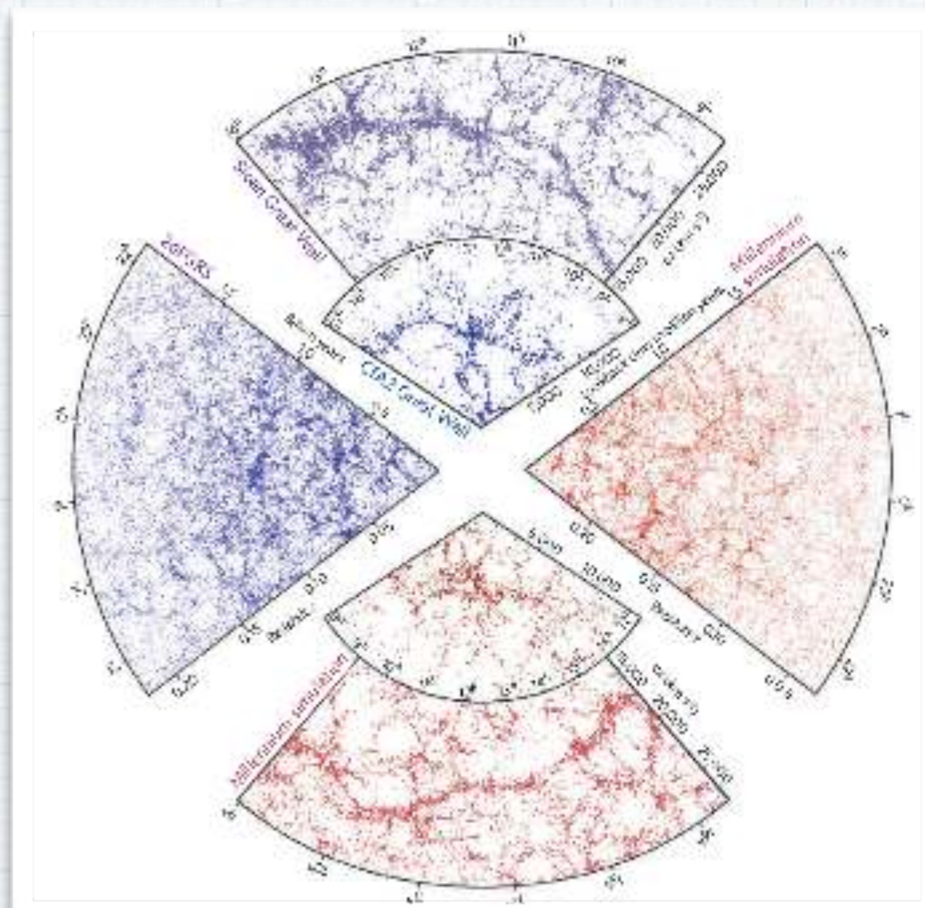


Much much more evidence since then

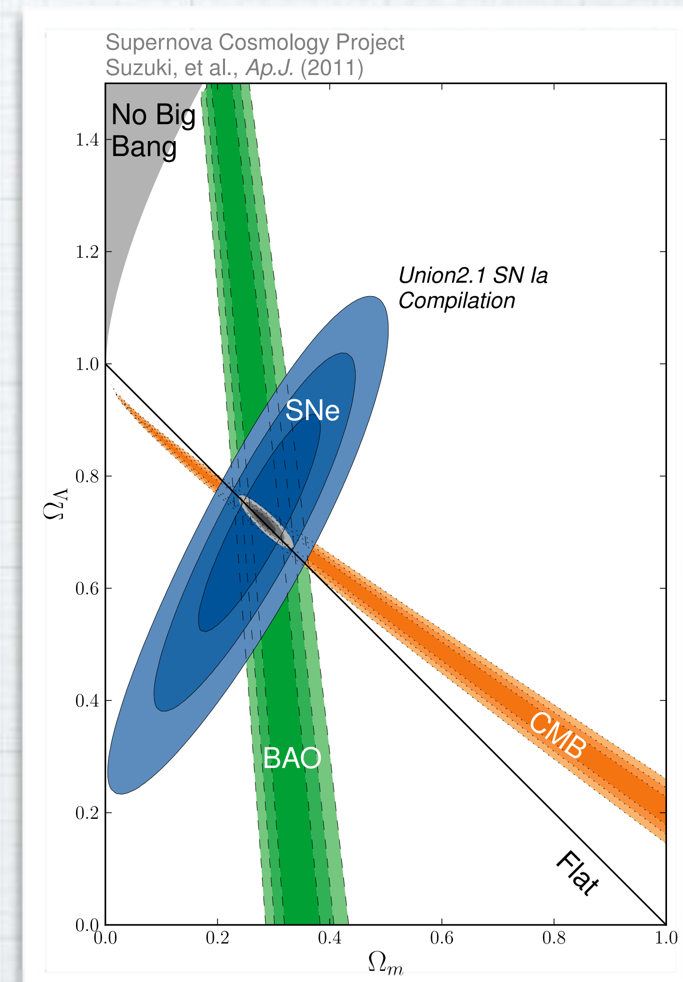
BBN



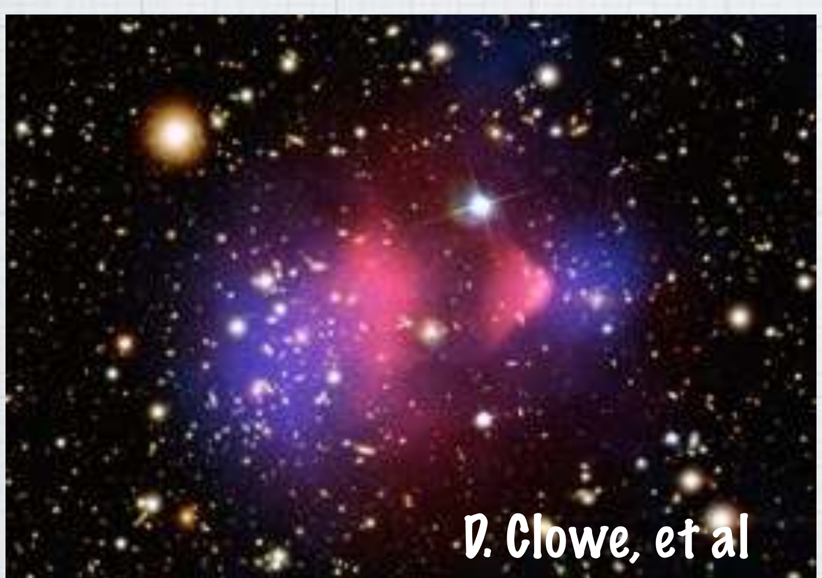
Large scale structure → CDM



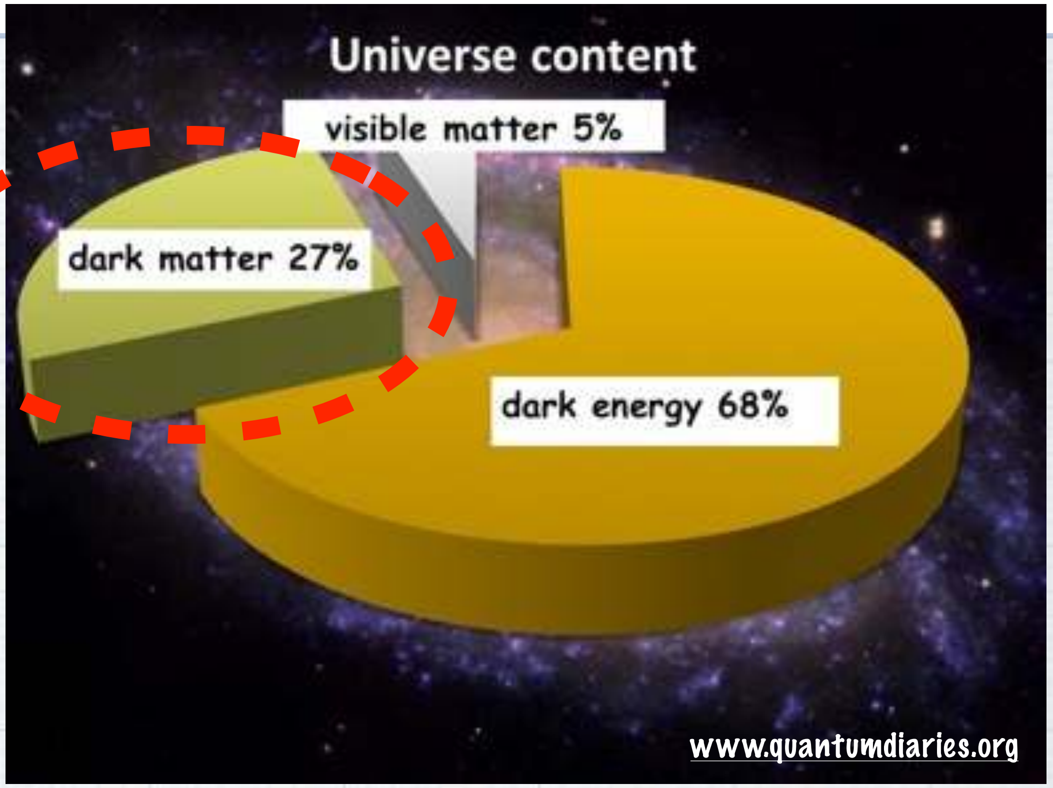
BAO + SNe + CMB



Gravitation lensing

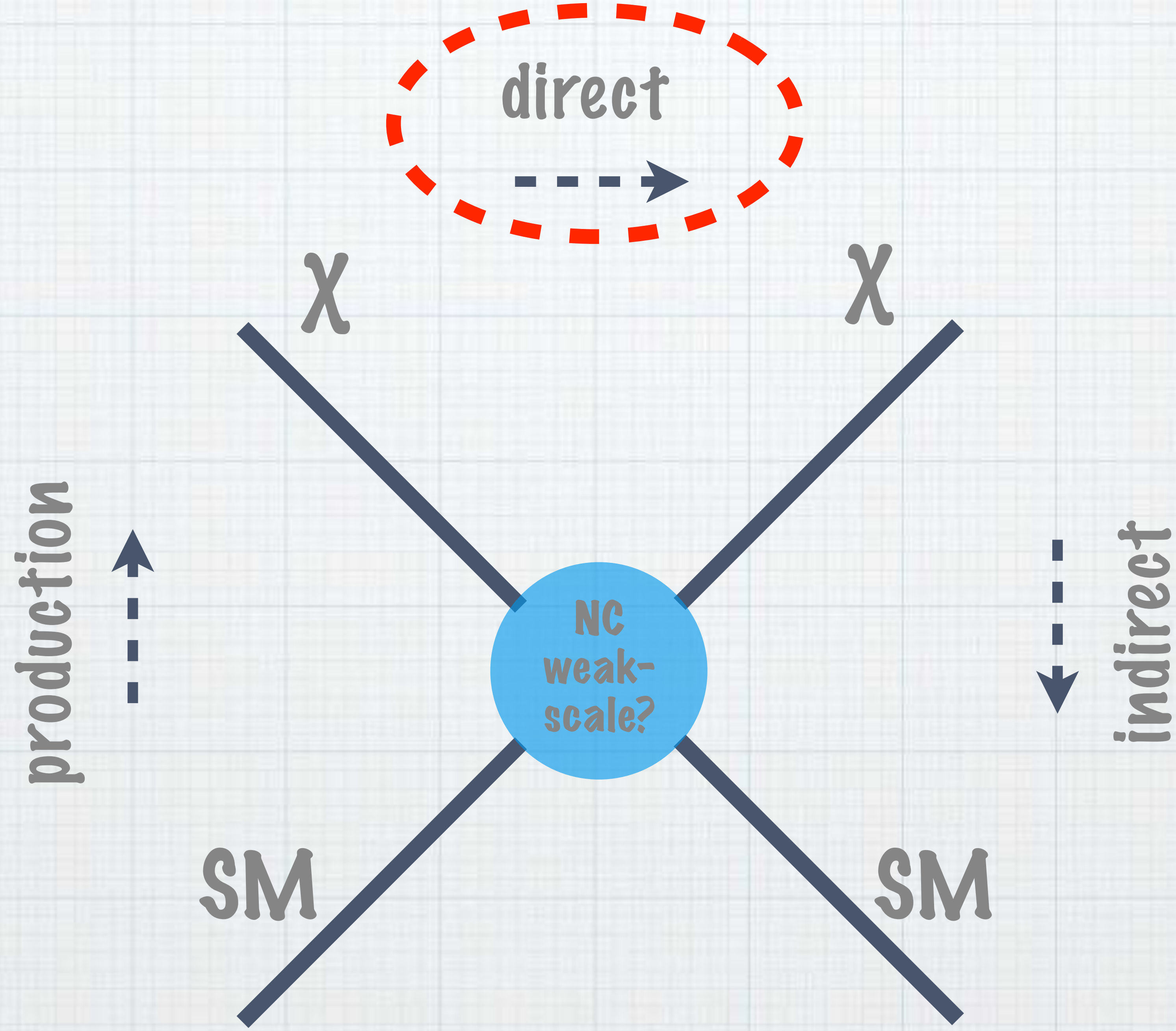


Dark Matter properties



* WIMPs favoured candidates for Cold Dark Matter (alternatives: axions, sterile neutrinos, ...)
  * Interacts only weakly with normal matter
  * Expected to be neutral
  * Cold: Non-relativistic freeze-out
* Requires beyond standard model physics:
  * Super-symmetry: LSP neutralino, $\sigma \sim 10^{-40}$ to 10^{-50} cm^2, Mass range GeV→TeV
  * Universal Extra Dimensions: Stable KK, similar detection properties as neutralino

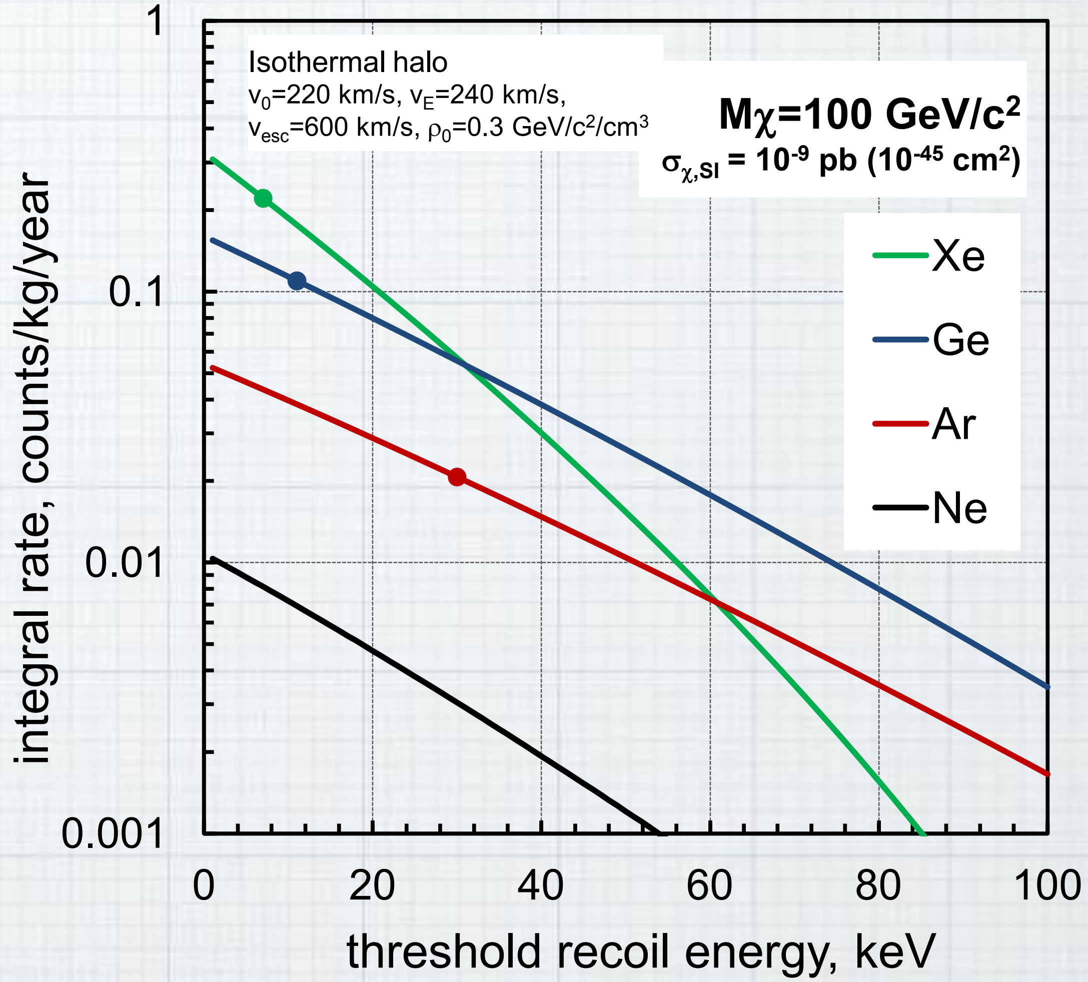
Detecting Dark Matter



Direct detection of galactic dark matter

Vitaly Chepel, Henrique Araújo
Journal-ref: 2013 JINST 8 R04001

* Elastic scattering of galactic WIMPs off target nuclei in terrestrial detector
* WIMP speed ~ 220 km/s expect recoils O(10) keV
* Estimated local density: 0.3±0.2 GeV/cm³
* Spin-independent cross section ∝ A^2
* Less than ~ 1 event/kg/year
* Requires SM backgrounds ~0 (underground operation)



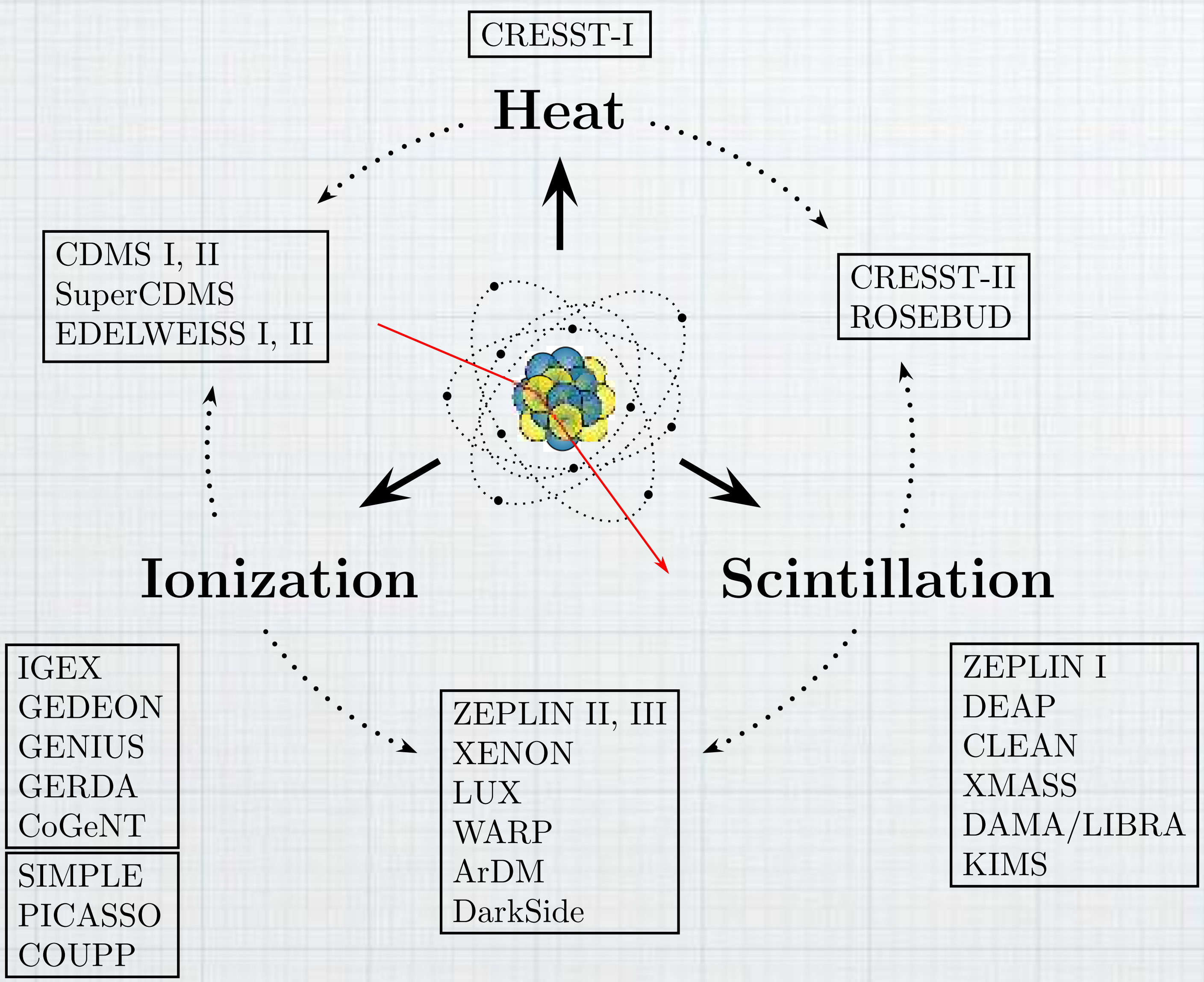
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_0}{m_N m_\chi}\int_{v_{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}(v, E_R)\, \mathrm{d}v\,.$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_N}{2\mu_N^2 v^2}\left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right)$$

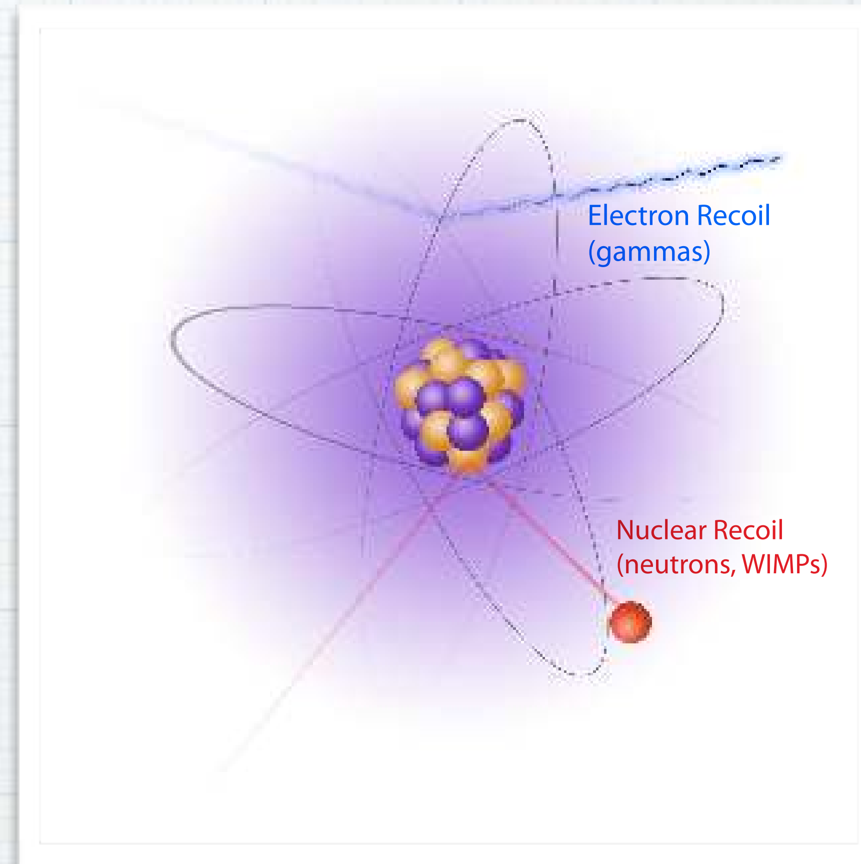
$$\sigma_0^{SI} = A^2\left(\frac{\mu_N}{\mu_n}\right)^2 \sigma_n$$

Direct detection techniques

* Requirements: large mass (scalability), low-radioactivity, low-energy threshold, high acceptance, discrimination (ability to reject electron recoils)



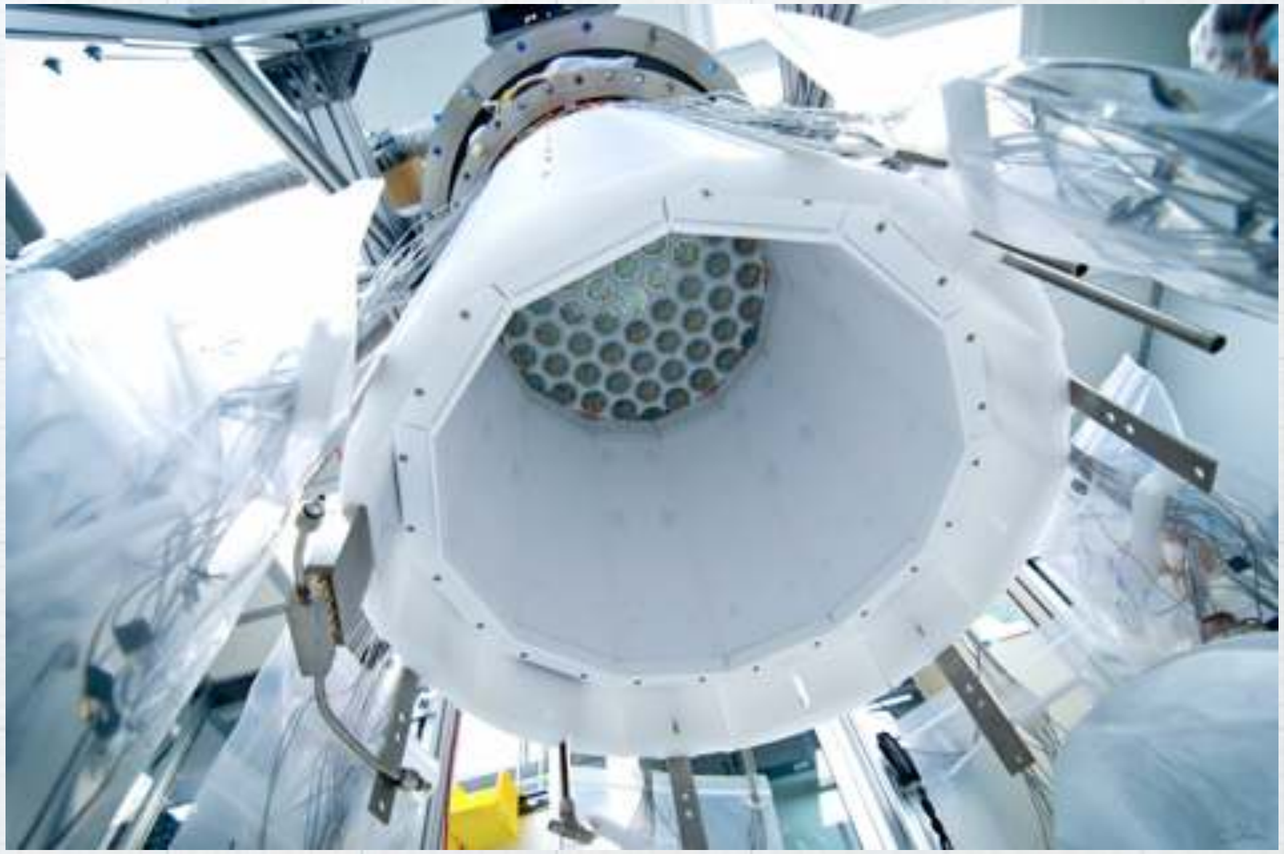
Plante 2012, XENON100 thesis



- Nuclear recoil (NR): WIMPs and neutrons scatter predominantly off nucleus
- Electron recoil (ER): Interact predominantly with electrons

The Large Underground Xenon (LUX) experiment

The worlds largest dual-phase xenon time-projection chamber



The LUX collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Karen Gibson	Postdoc
Tomasz Biesiadzinski	Postdoc
Wing H To	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student

Imperial College London

Henrique Araujo	PI, Reader
Tim Sumner	Professor
Alastair Currie	Postdoc
Adam Bailey	Graduate Student

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Carlos Hernandez Faham	Postdoc
Victor Gehman	Scientist
Mia Ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors
Dennis Carr	Mechanical Technician
Kareem Kazkaz	Staff Physicist
Peter Sorensen	Staff Physicist
John Bower	Engineer

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Luiz de Viveiros	Postdoc
Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

SD School of Mines

Xinhua Bai	PI, Professor
Tyler Liebsch	Graduate Student
Doug Tiedt	Graduate Student

SDSTA

David Taylor	Project Engineer
Mark Hanhardt	Support Scientist

Texas A&M

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Bob Svoboda	Professor
Richard Lander	Professor
Britt Holbrook	Senior Engineer
John Thomson	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Postdoc
Richard Ott	Postdoc
Jeremy Mock	Graduate Student
James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Dean White	Engineer
Susanne Kyre	Engineer
Carmen Carmona	Postdoc
Curt Nehrkorn	Graduate Student
Scott Haselschwardt	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer
Lea Reichhart	Postdoc
Sally Shaw	Graduate Student

SUNY Albany

Matthew Szydagis	PI, Professor

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc

University of Maryland

Carter Hall	PI, Professor
Attila Dobi	Graduate Student
Richard Knoche	Graduate Student
Jon Balajthy	Graduate Student

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Mongkol Moongweluwan	Graduate Student

University of South Dakota

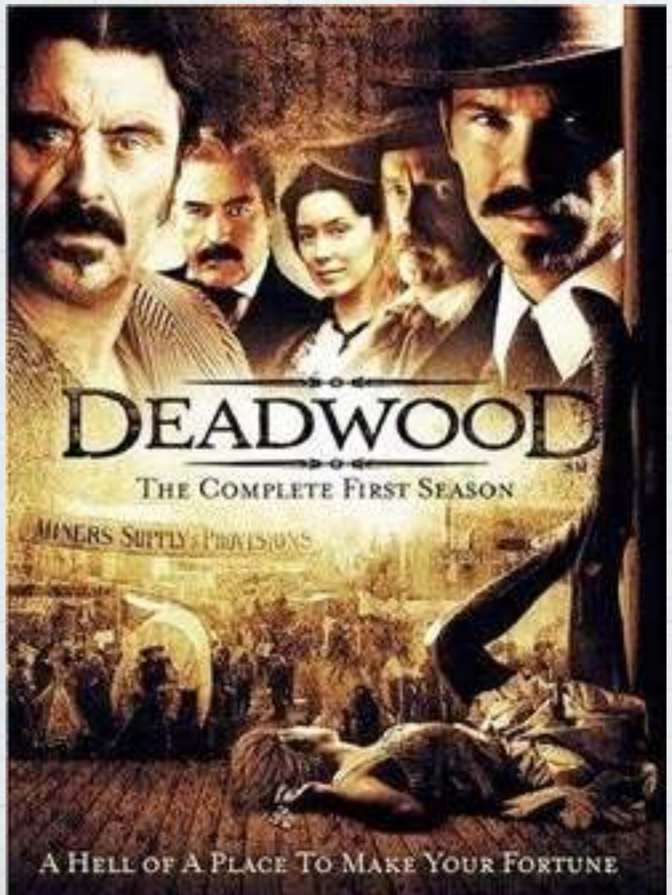
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

Yale

Daniel McKinsey	PI, Professor
Peter Parker	Professor
Sidney Cahn	Lecturer/Research Scientist
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

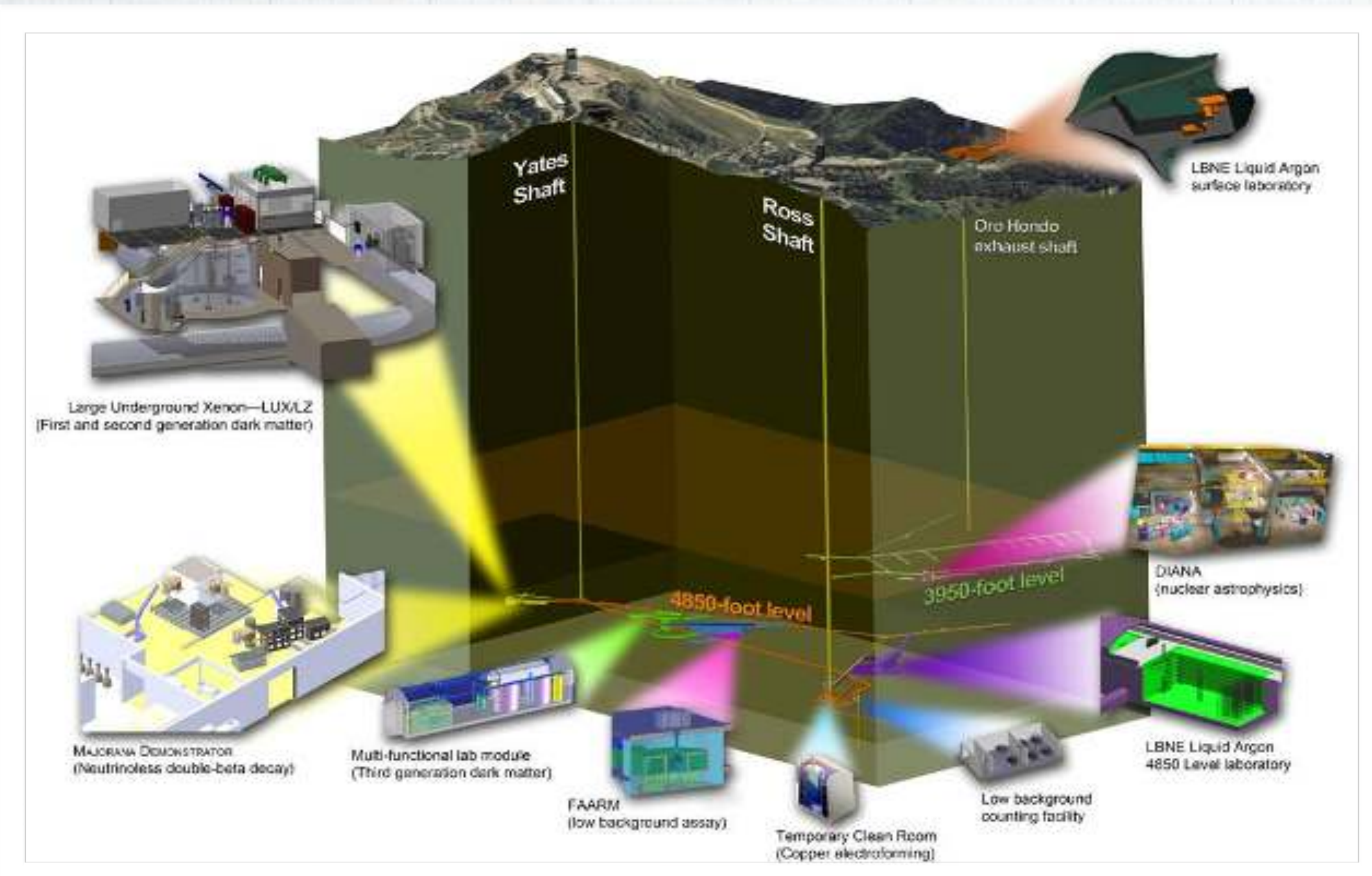
Sanford Underground Research Facility (SURF)

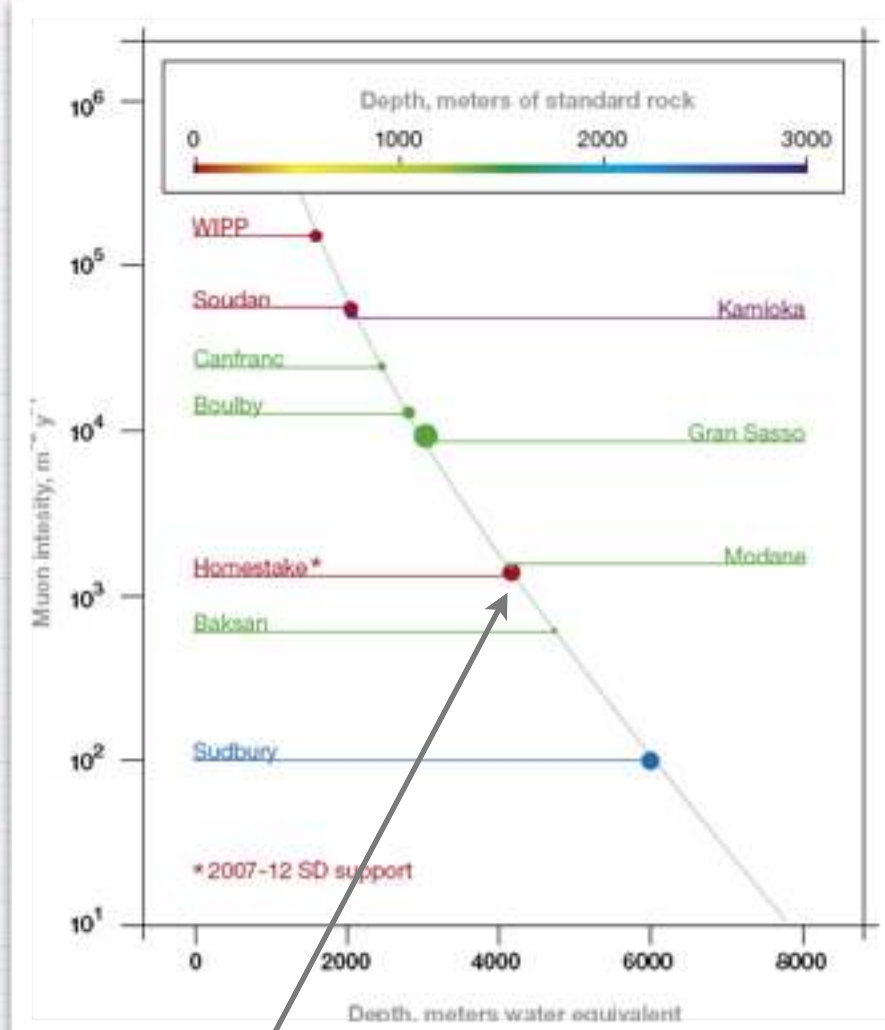
Former Homestake gold mine - refurbished for science only



Lead, SD, located in the Black Hills

Sanford Underground Research Facility (SURF)

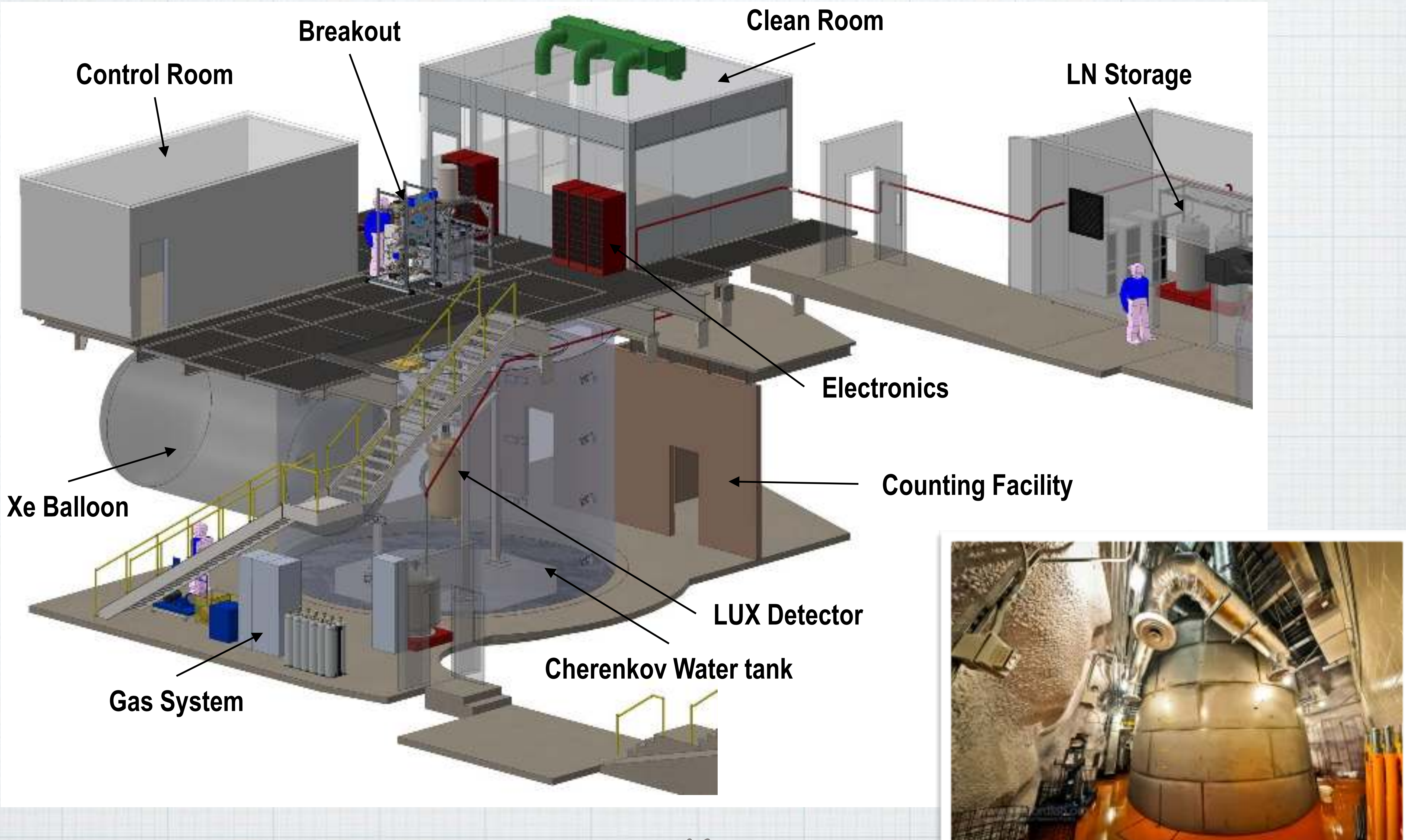




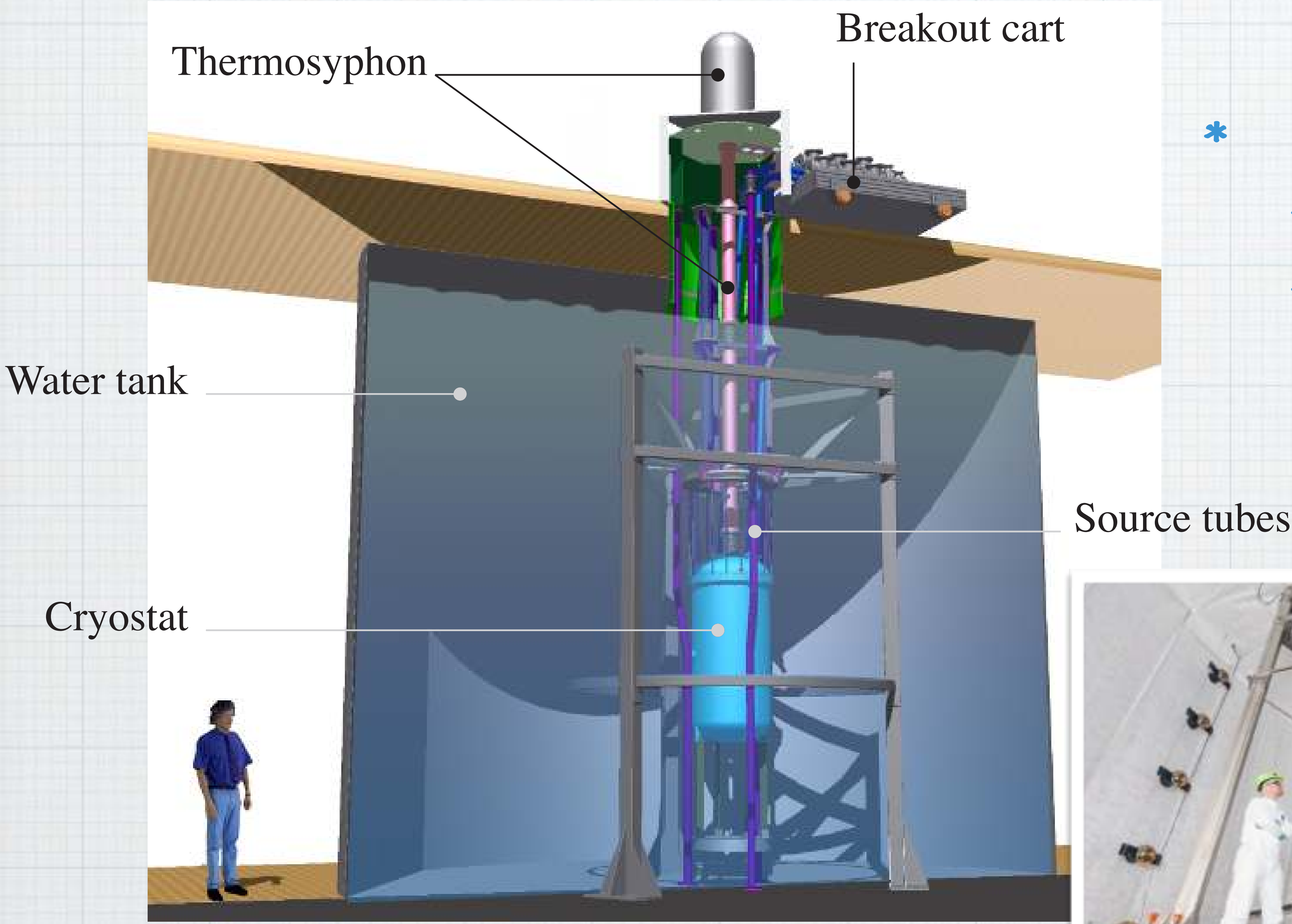
Muon flux at 4850′ level reduced by 10^7

$55.2\ m^{-2}s^{-1} \rightarrow 1\times10^{-5}\ m^{-2}s^{-1}$

LUX in the Davis Cavern

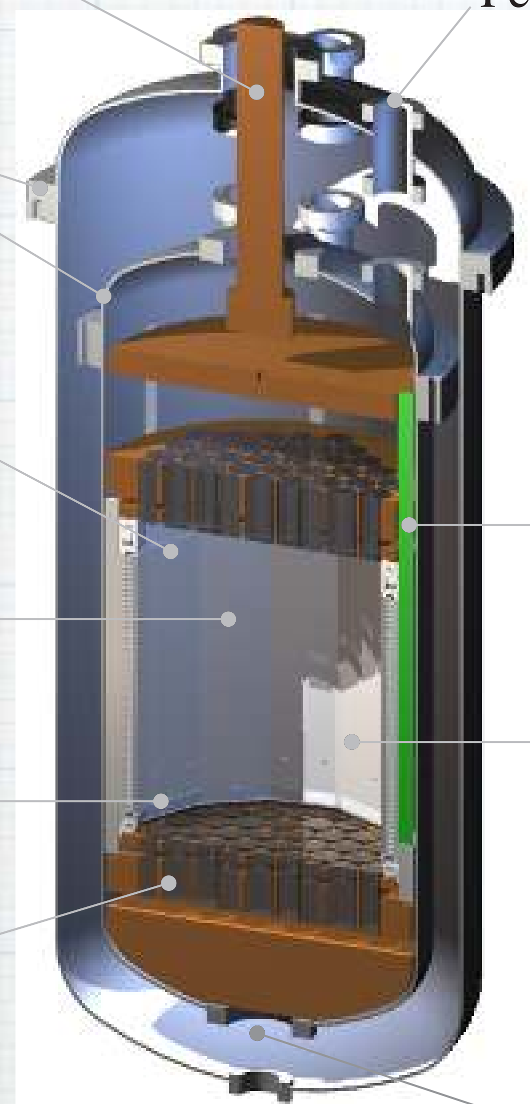


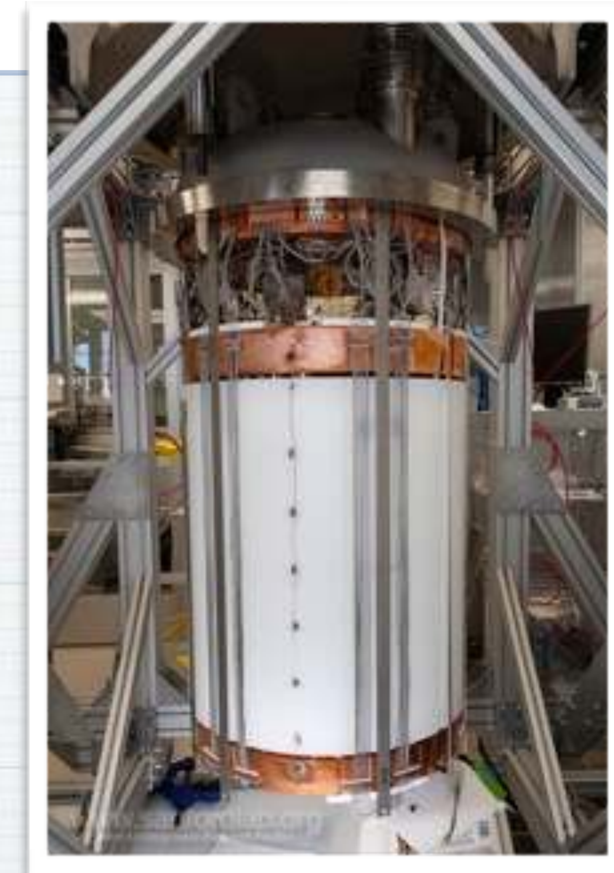
An ultra low background environment for LUX

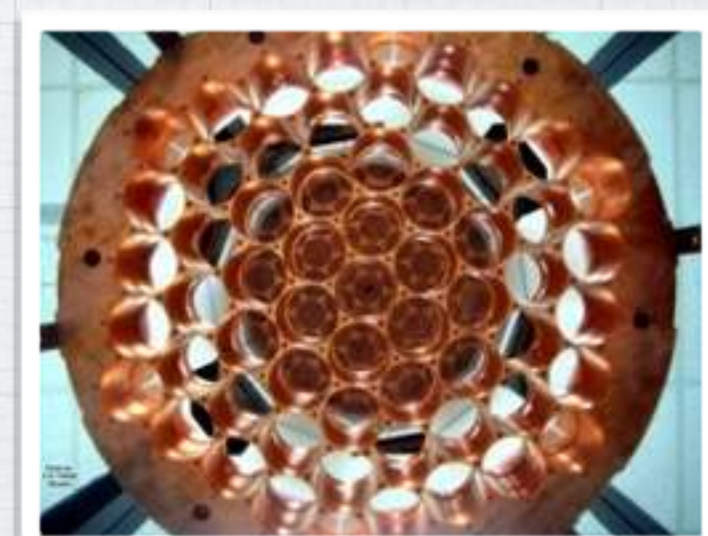


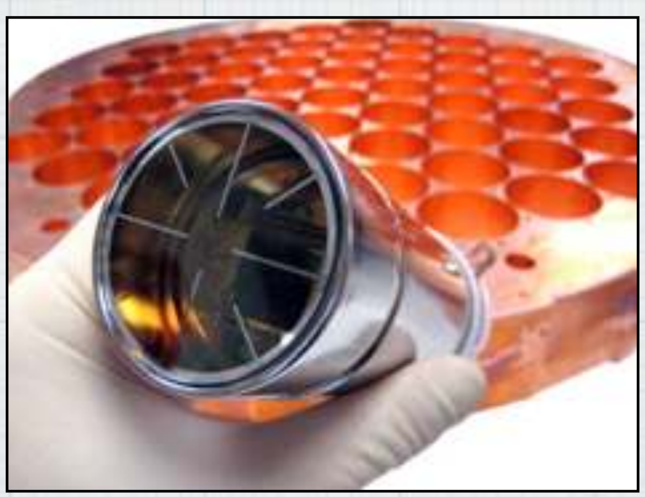
- 300 tonne water tank
  - 6.1 m in height
  - 7.6 m in diameter

The LUX instrument





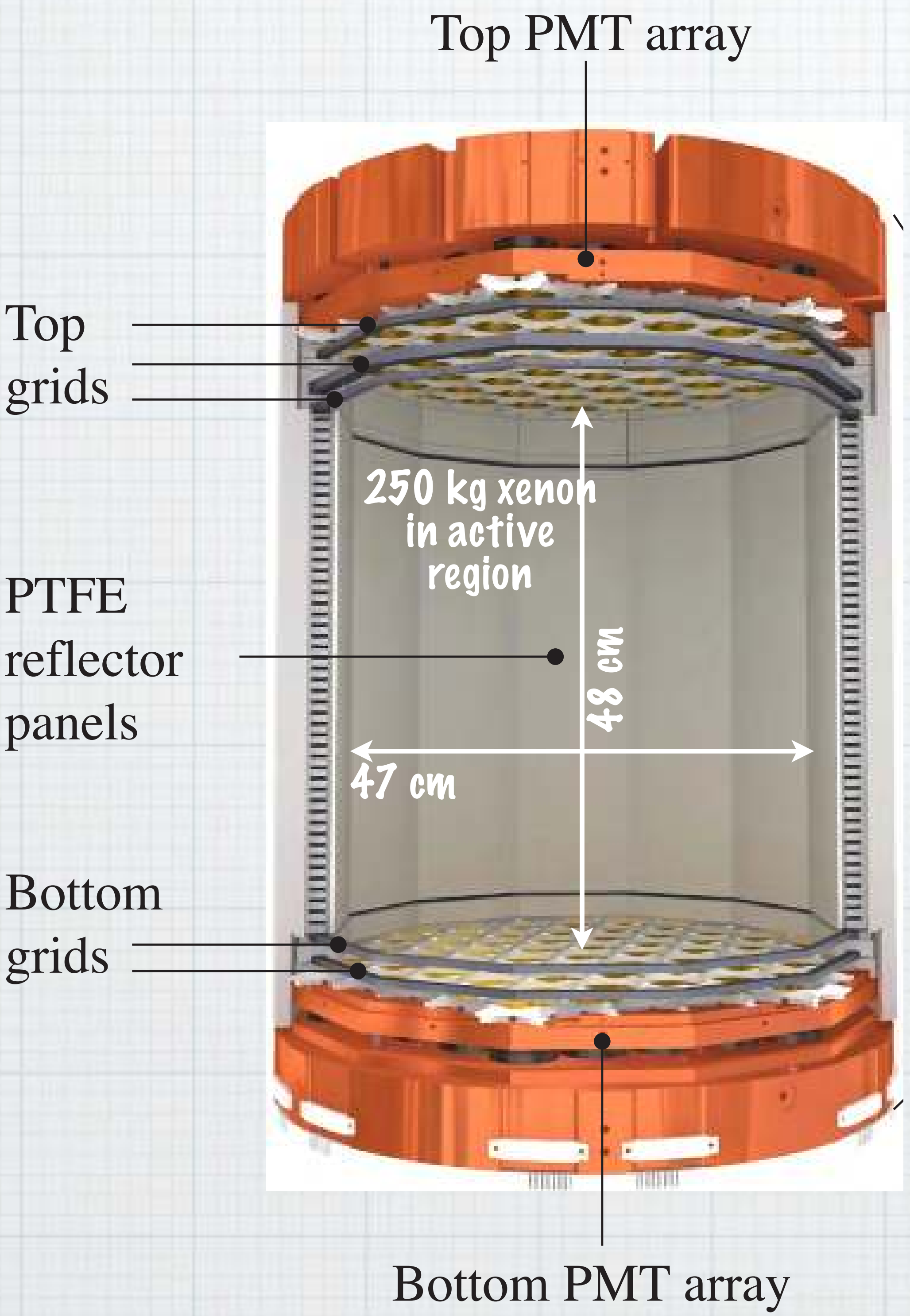


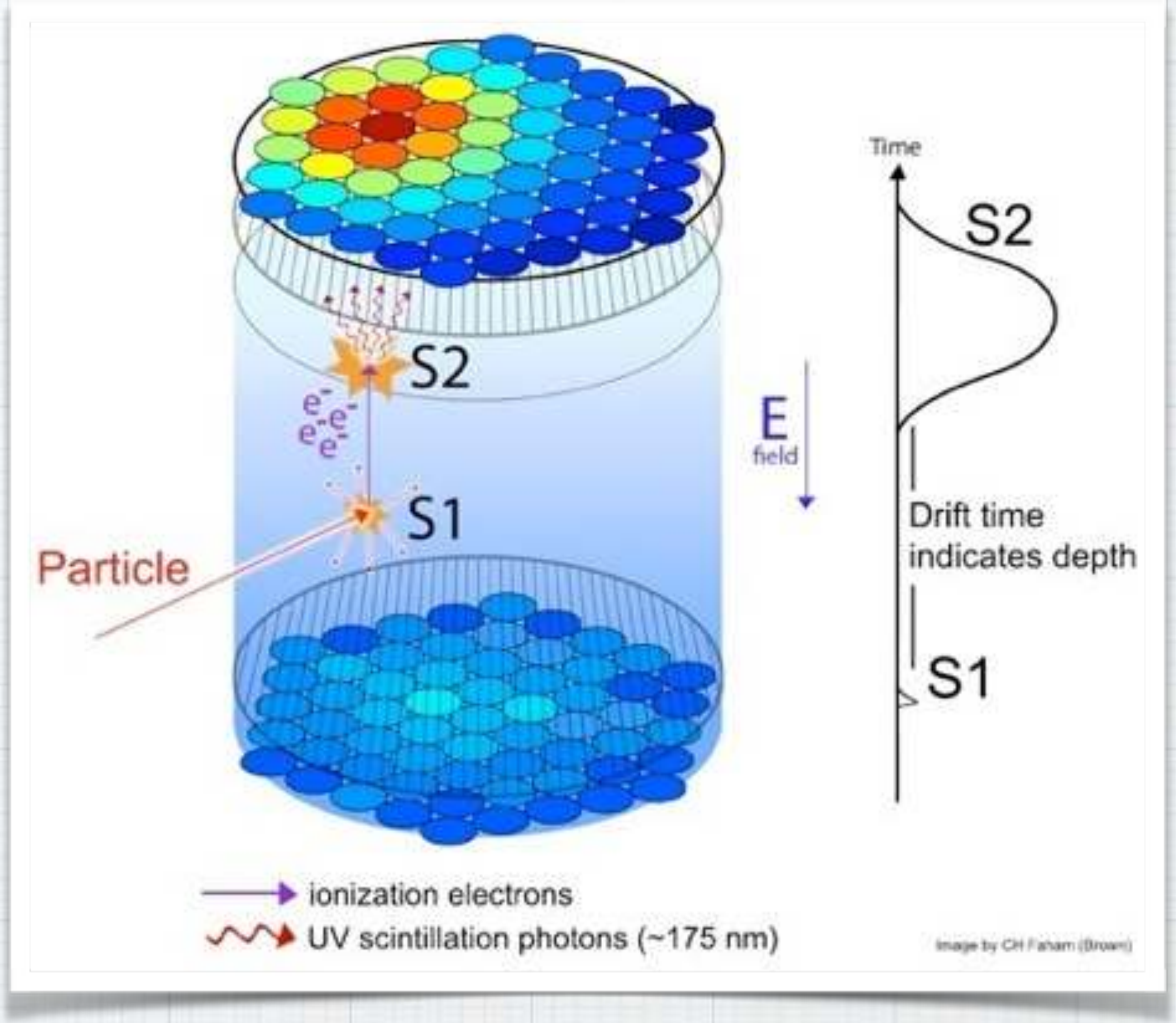


Hamamatsu R8778 PMTs (61 top, 61 bottom)

Full description of LUX:
NIM. A 704, 111-126(2013), arXiv:1211.3788

The LUX instrument

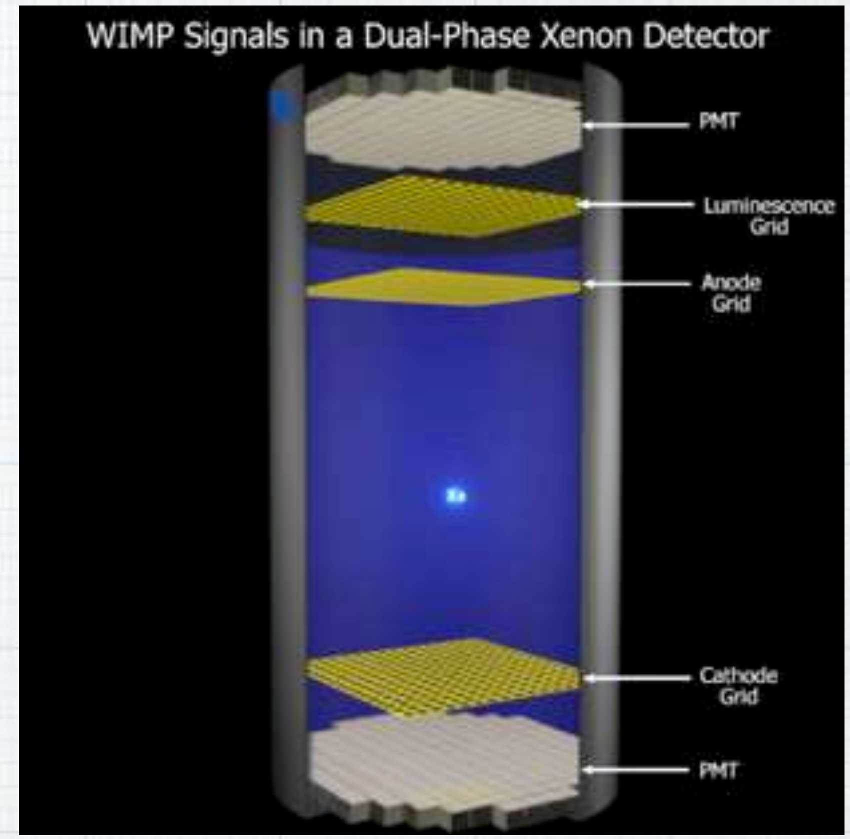


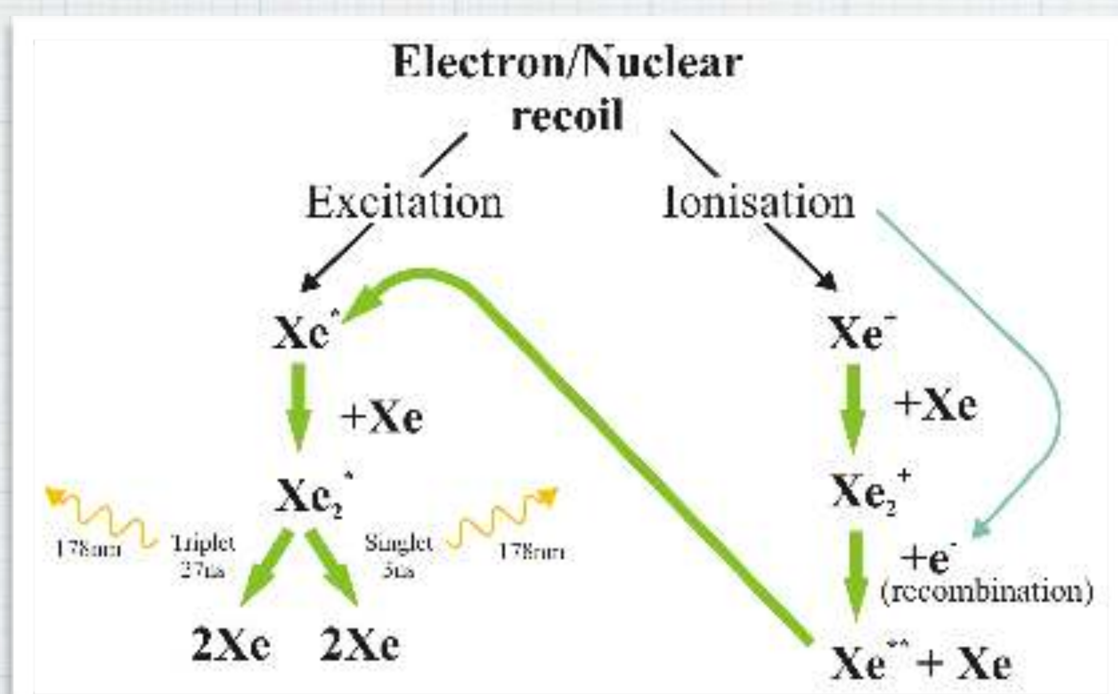


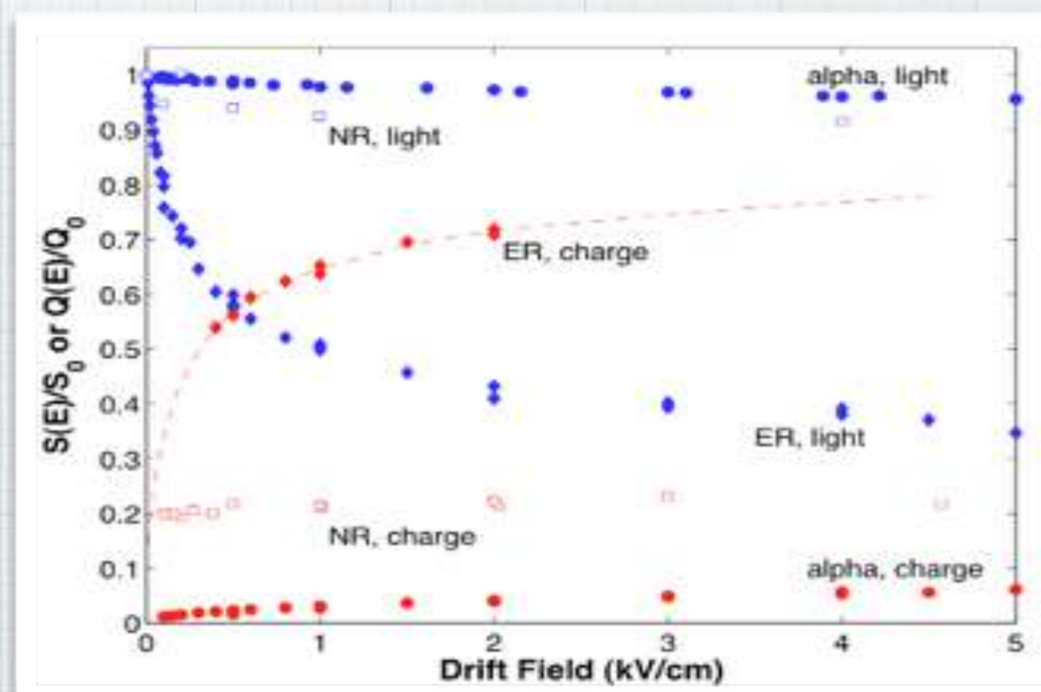
- Primary scintillation: PDE of 14%
- S2 single electron extraction efficiency: 65%
- Single extracted electron: 26 phe/e-

Principle of detection: dual phase xenon TPC

* S1 - Primary scintillation signal
  —> light yield ~60 ph/keV (ER, 0 field)
  —> NR threshold ~5 keV
* S2 - Secondary ionisation signal from electroluminescence
  —> Nuclear recoil threshold < 1 keV
* 3D position (mm resolution) from drift time and S2 XY
* S2/S1 particle discrimination
  —> ER/NR discrimination (>99.5% rejection)
* Recoil energy correlated to S1 and S2
* Powerful Xe self-shielding



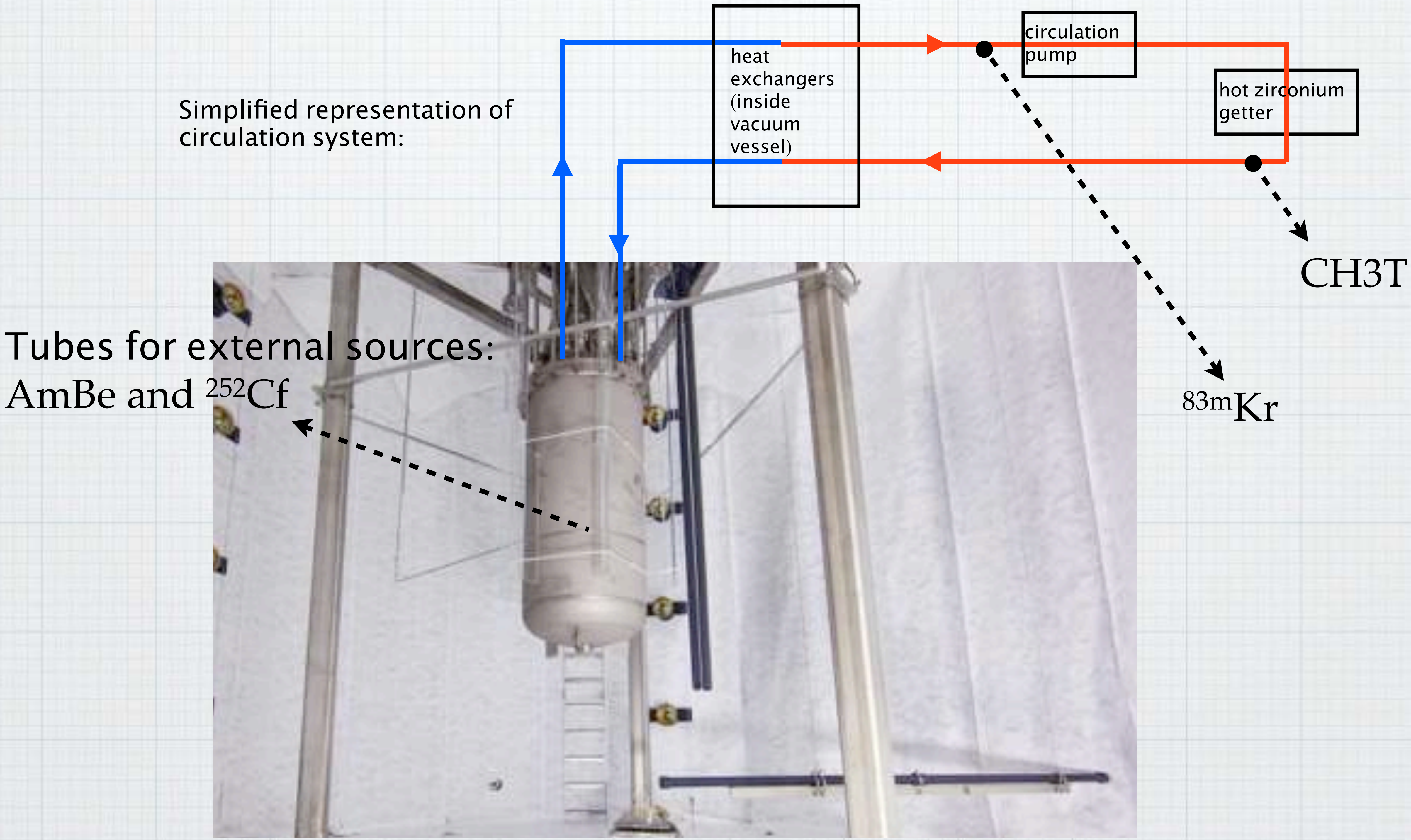




E. Aprile et al., Phys. Rev. Lett. 97, 081302 (2006)

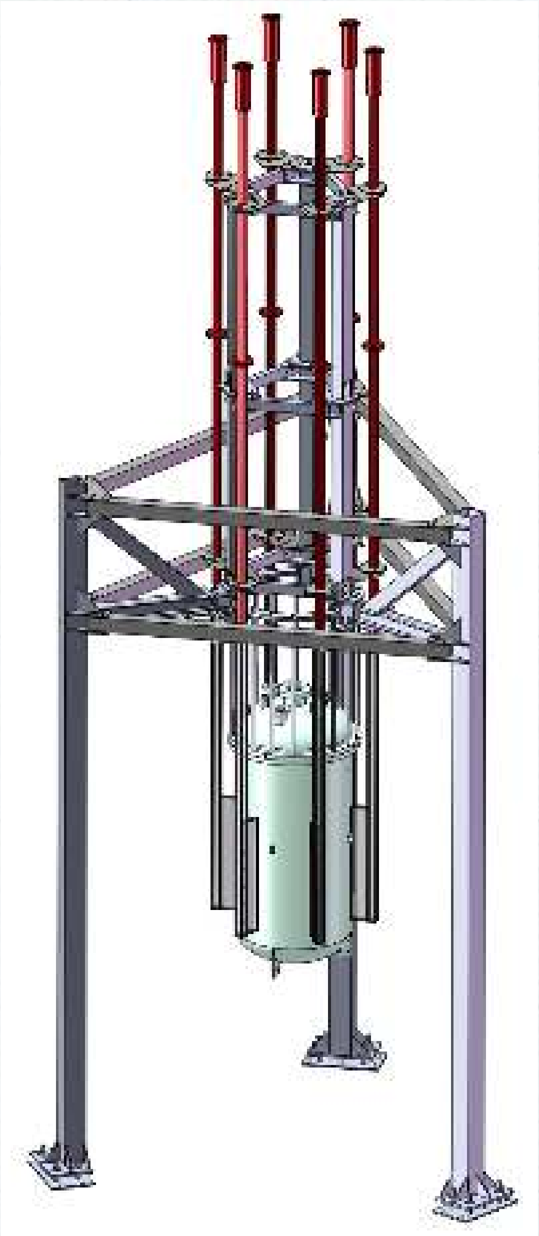
Calibrating LUX

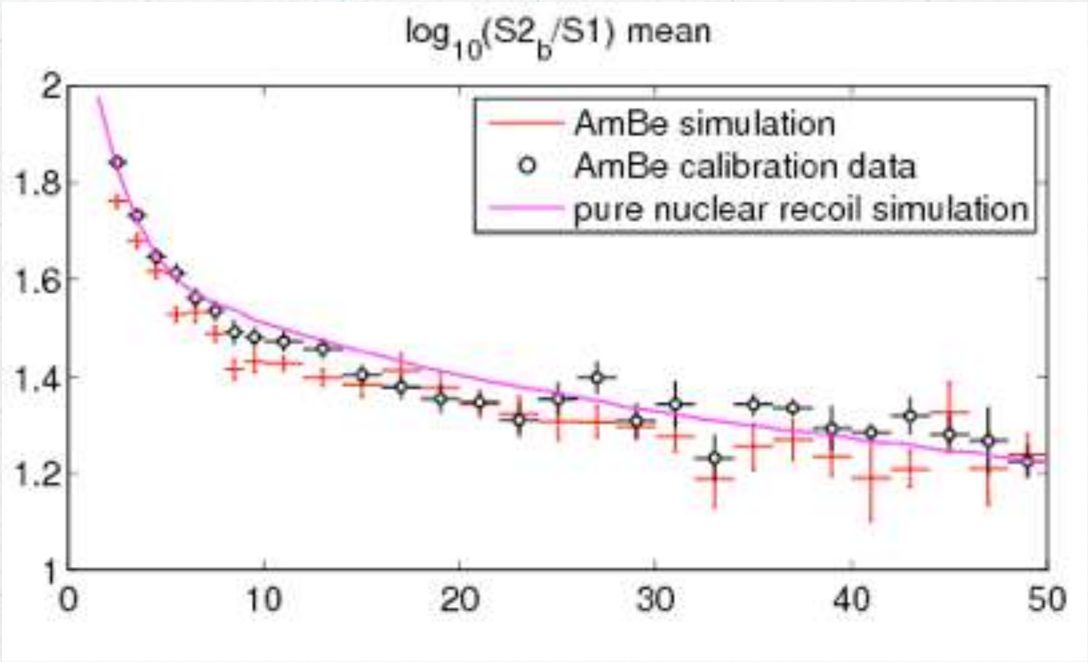
An array of calibration techniques: internal & external



Calibrating LUX - NR

* External sources via source tubes:
    * Americium-beryllium (AmBe) and ^{252}Cf: low energy neutrons → **WIMP-like**
    * Used for NR efficiency, to validate NR simulations

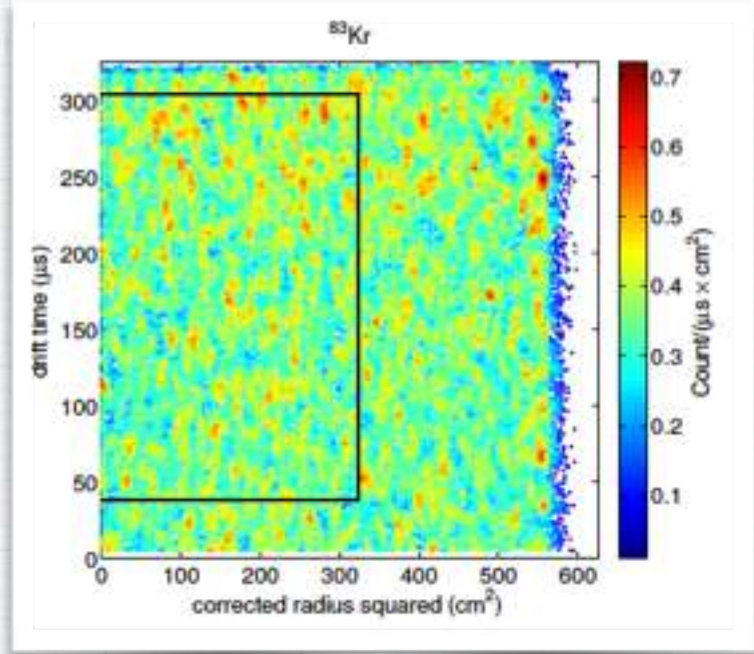




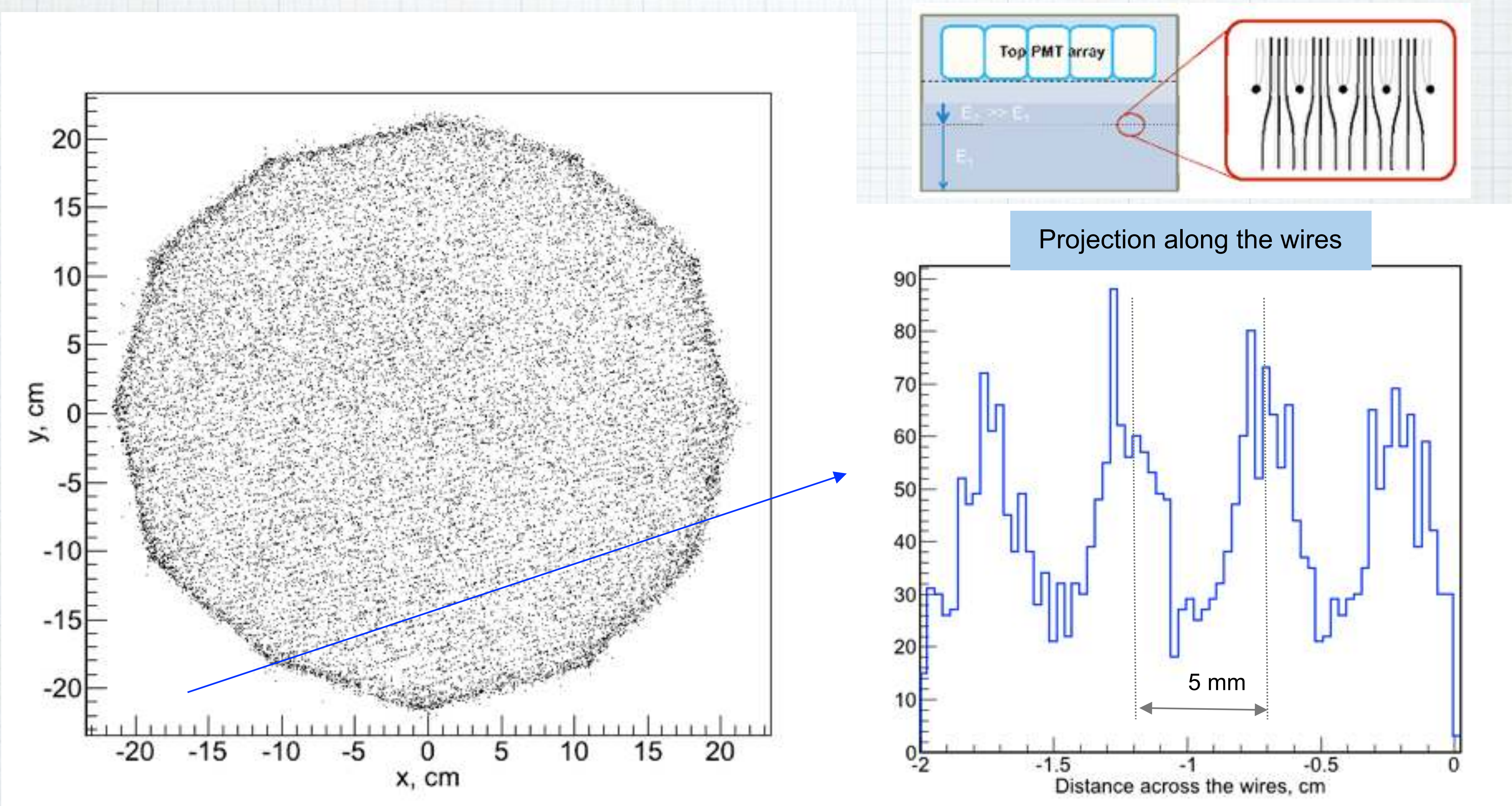
Calibrating LUX - ER

* Xenon self-shielding → internal sources injected into circulation system:
* ^{83m}Kr: half-life ~1.8 hours, 32.1 + 9.4 keV betas
  - Used for:
    - Electron lifetime drift length measurements (>130 cm)
    - Position reconstruction and S1 light corrections
* Tritiated methane (CH3T): low energy betas with high stats, uniform and high purity
  - Beta decay with T1/2 = 12.6 y
  - <E> = 5.9 keV, end point 18.6 keV
  - Used to define ER band and low energy threshold
    - efficiently removed by getter

^{83}Rb coated charcoal plummed into gas system → ^{83m}Kr

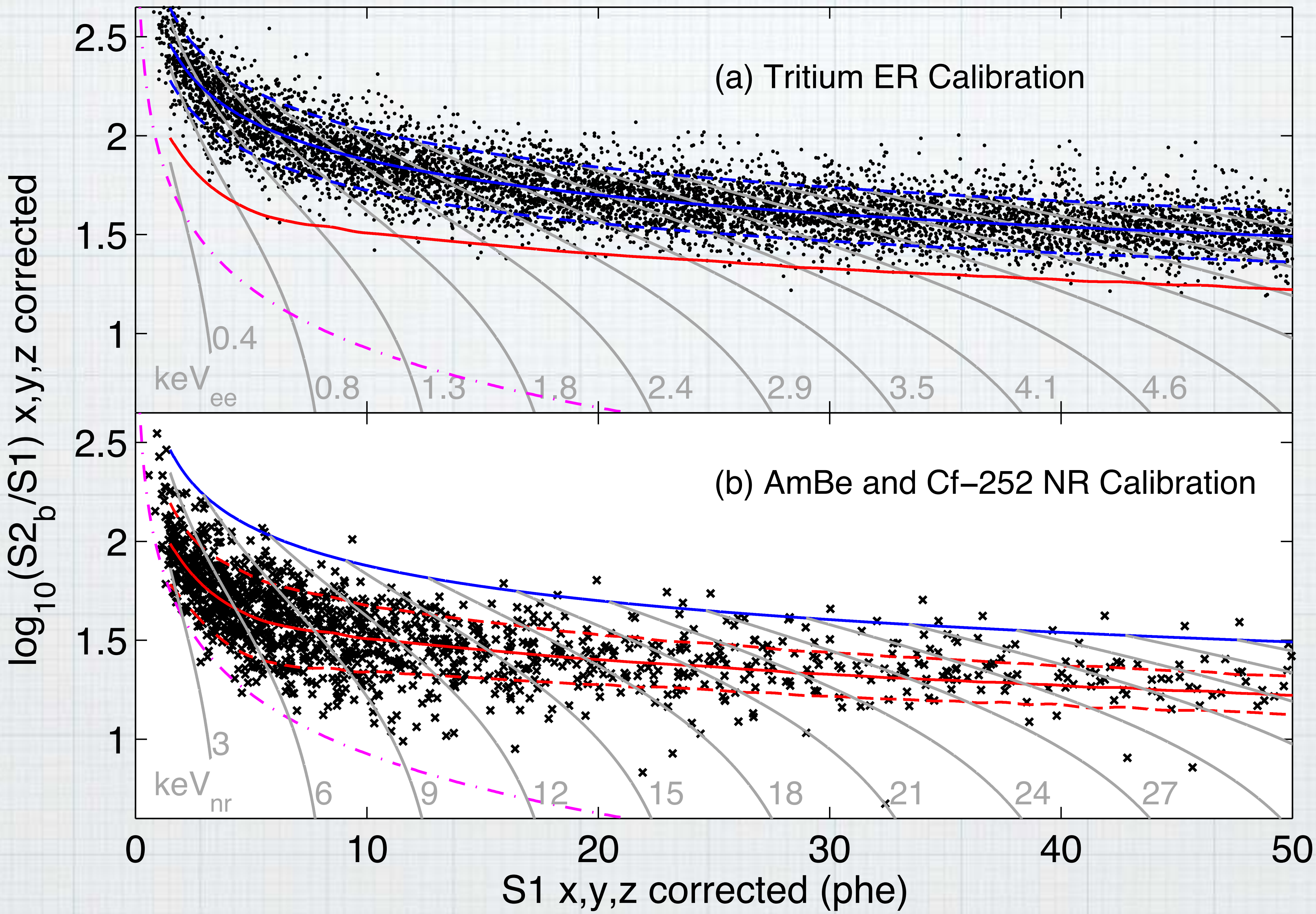


Position reconstruction



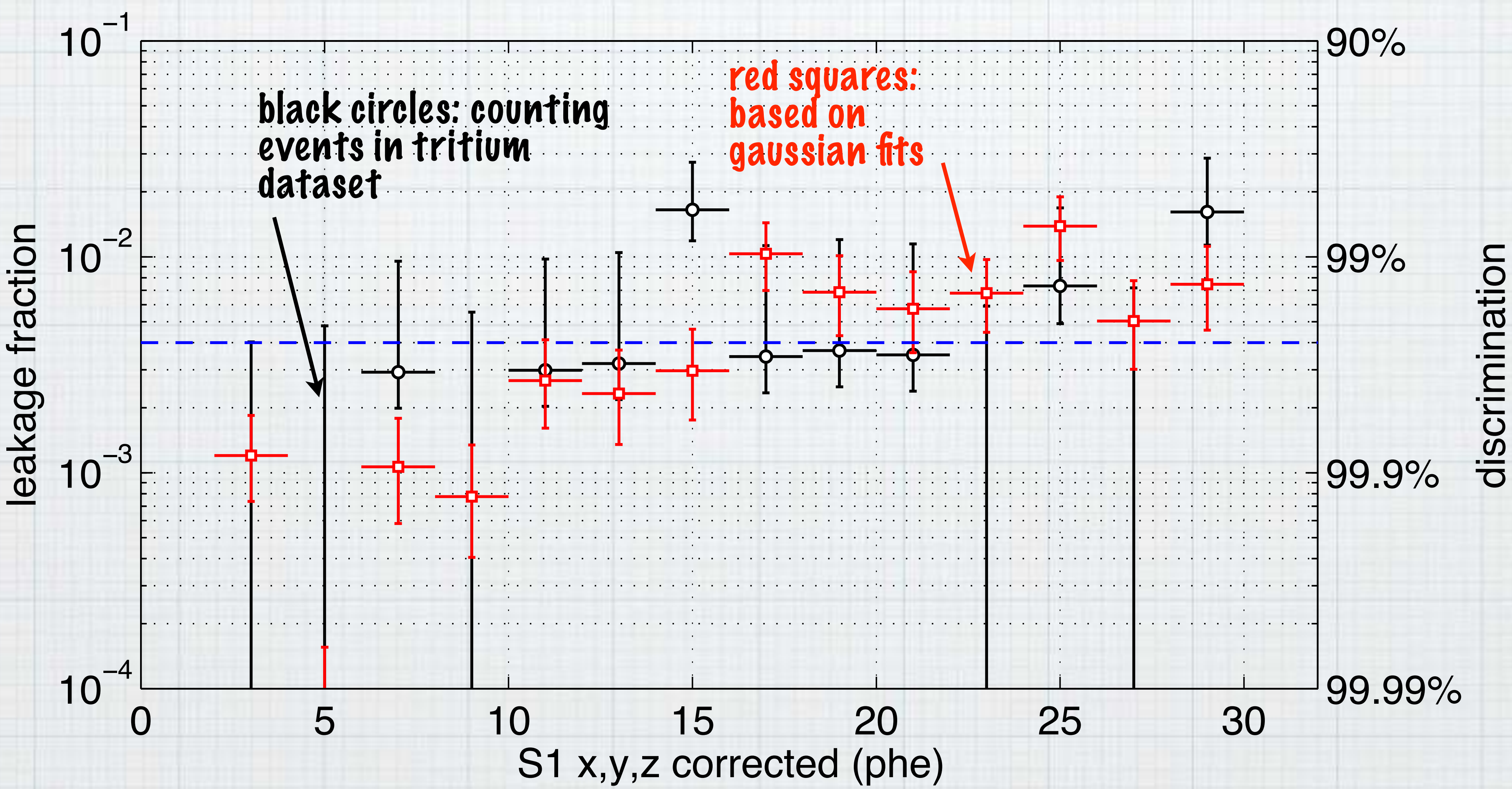
* 4-6 mm resolution for S2 signals in WIMP search region
* improves to ~3mm at greater energies

Calibrations - ER and NR bands

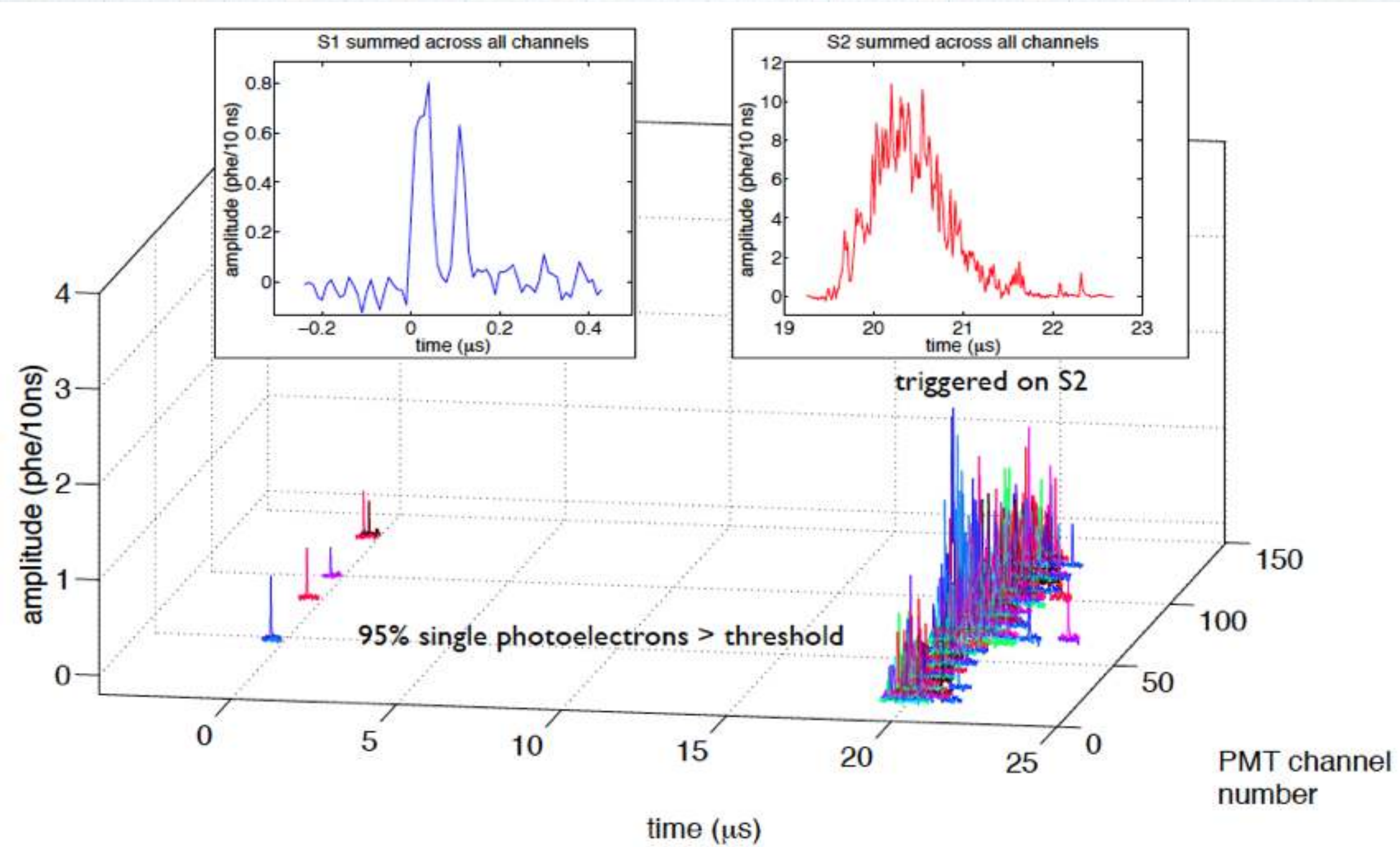


Discrimination

- For 50% NR acceptance average discrimination measured to be 99.6% in range S1 2-30 phe.

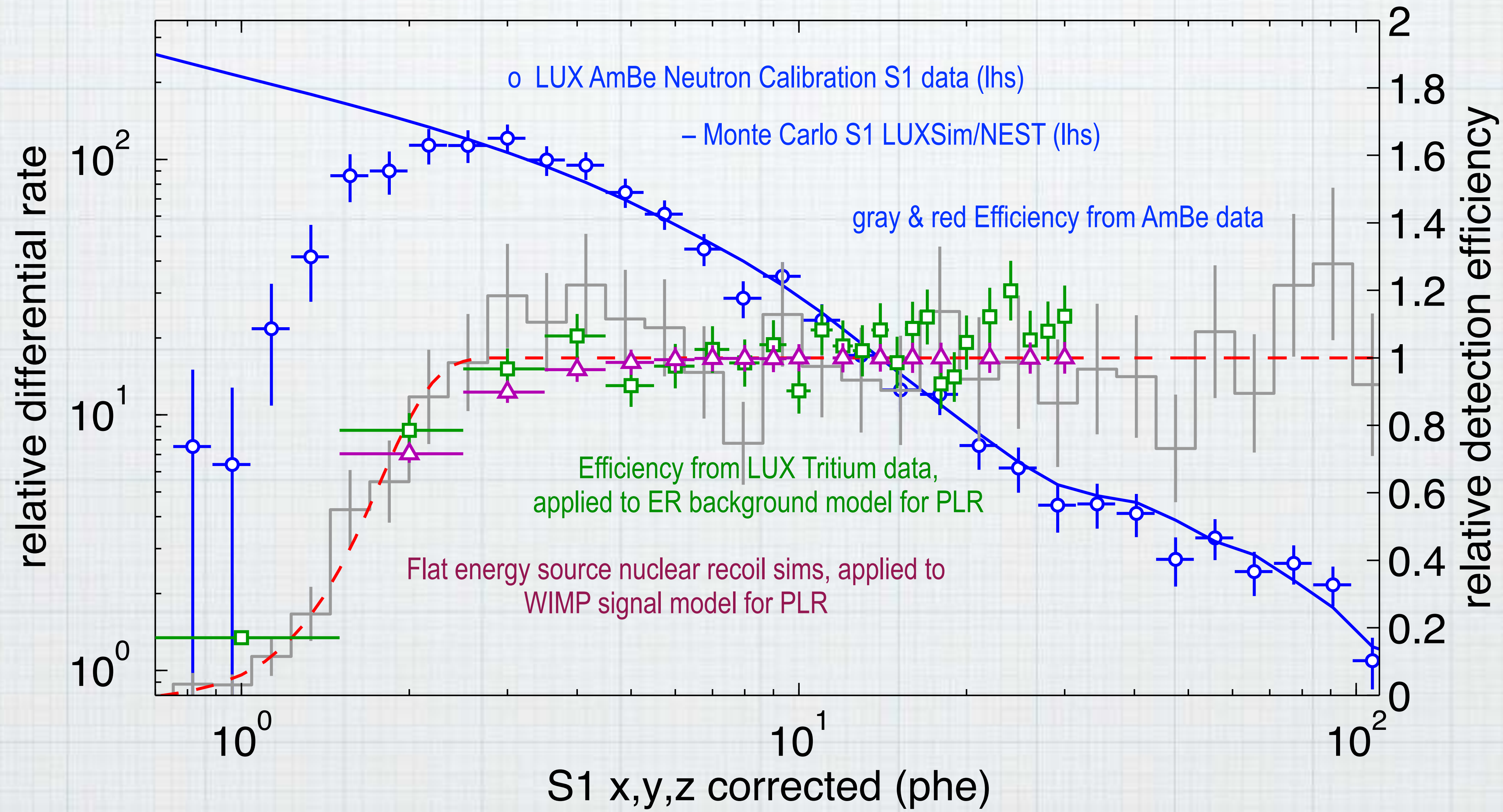


A LUX event - 1.5 keV electron recoil

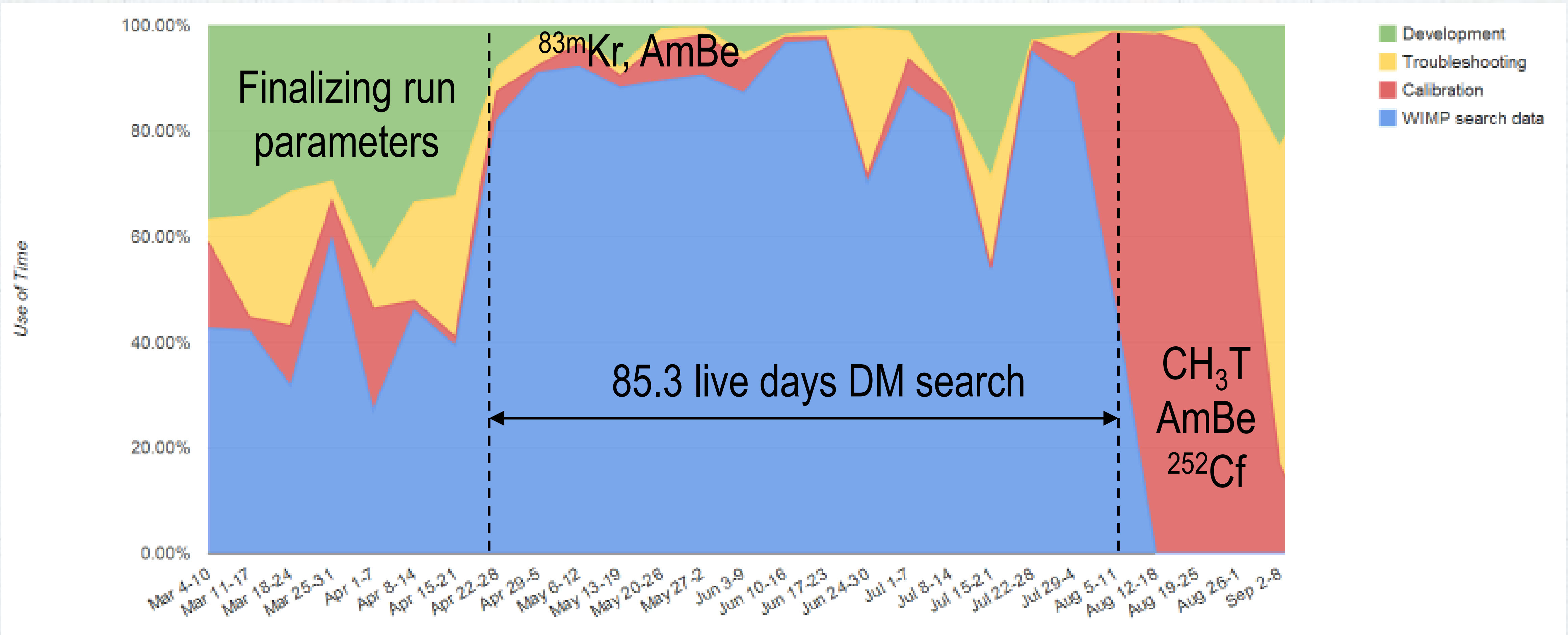


Efficiency

* Independent measures using AmBe, tritium, LED calibrations and full MC simulation of NR events (includes analysis cuts)

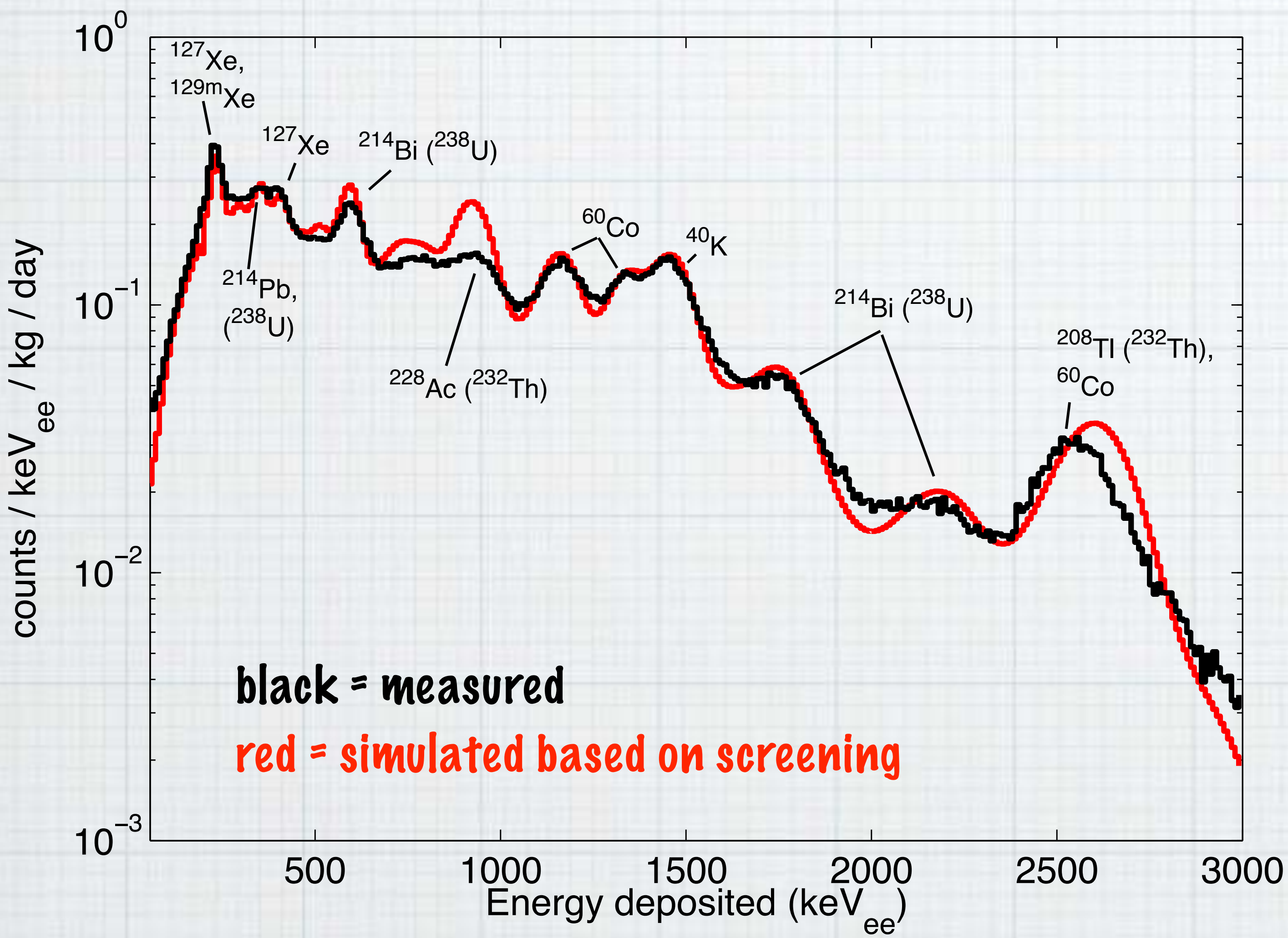


Run 3 data-taking



* LUX moves underground in July 2012
* Detector cool-down January 2013, Xe condensed mid-February 2013
* Kr and AmBe calibrations throughout, CH3T after WIMP search

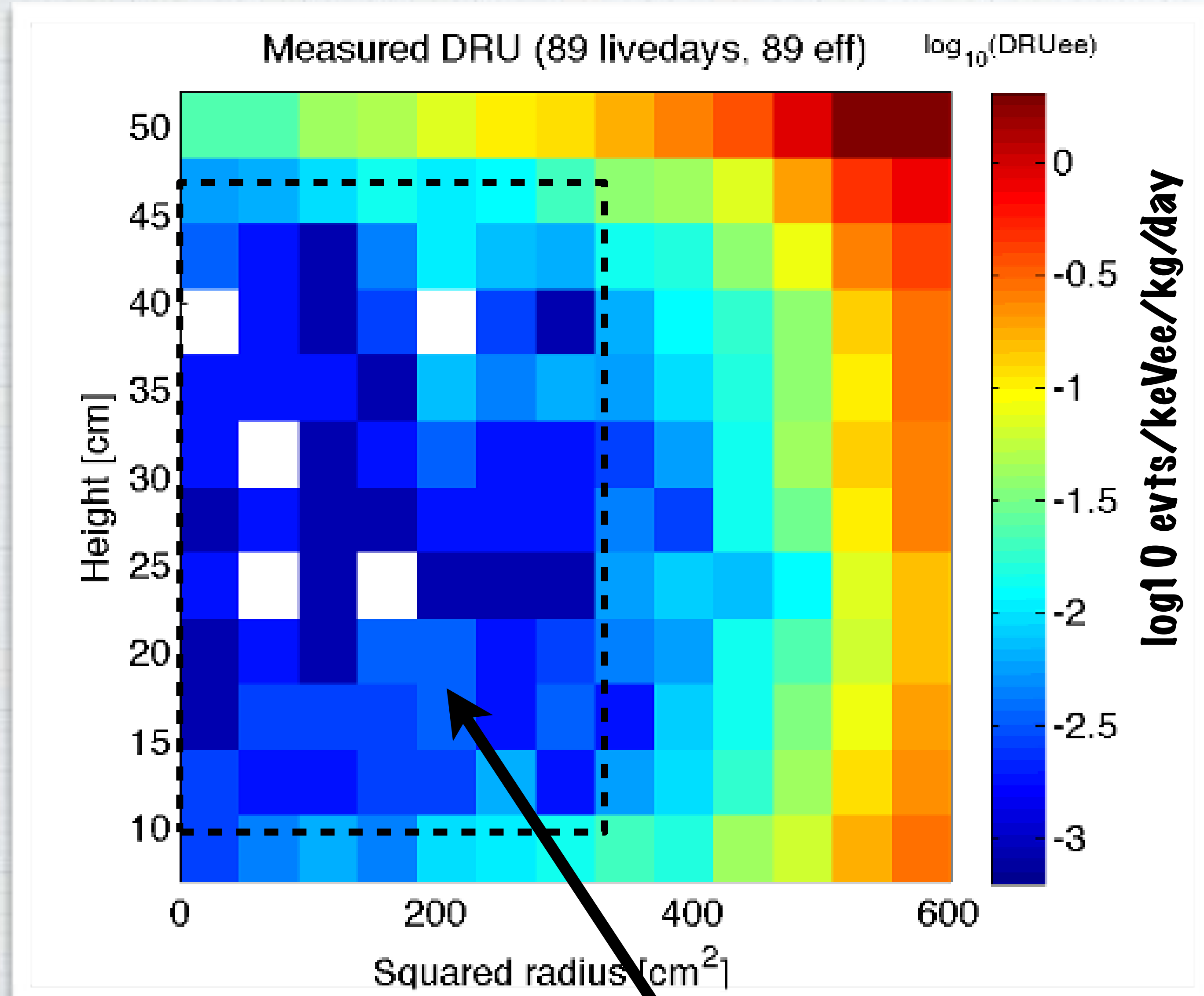
Backgrounds in LUX



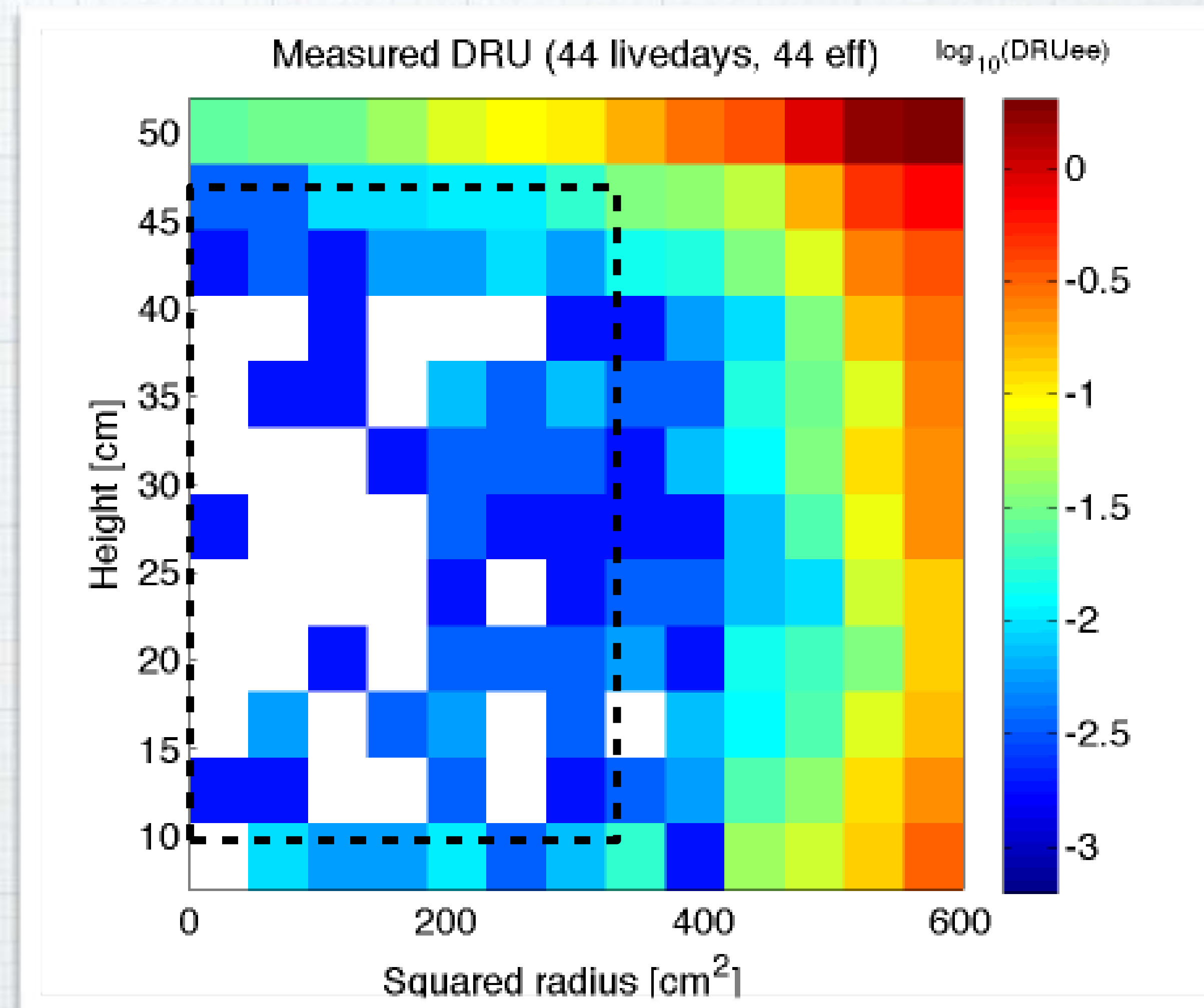
Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	^{222}Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.6 \pm 0.3_{stat}$

* Neutron background predicted to be 0.06 events in 85.3 day (90% C.L. from multiple scatter analysis of 0.37)

Backgrounds in LUX



...and still dropping



118 kg
3.1+/-0.2 mdru
r<18 cm & z=7-47 cm

The most radioactively quiet place in the world!

Run 3 event selection and cuts - step by step...

Cut	Events Remaining
all triggers	83,673,413
detector stability	82,918,902
single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* Non-blind analysis:
  * Application of minimum set of cuts in order reduce tuning and bias of event acceptance
* Hardware trigger: at least two trig. channels > 8 phe within 2 μs window (8 PMTs per trig. channel)

Run 3 event selection and cuts - step by step...

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S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* Remove periods of live-time when liquid level, gas pressure or grid voltages were out of nominal ranges:
    * Less than 1.0 % live-time loss!
    * $\Delta T < 0.2$ K
    * $\Delta P/P < 1\%$
    * liquid level variation <0.2 mm

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S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* Exactly 1 S2 and 1 S1 as identified by the pulse finding/classification:
    * Separate S1s from S2s using pulse shape and PMT hit distributions
    * S1s identification includes a two fold PMT coincidence requirement

Run 3 event selection and cuts - step by step...

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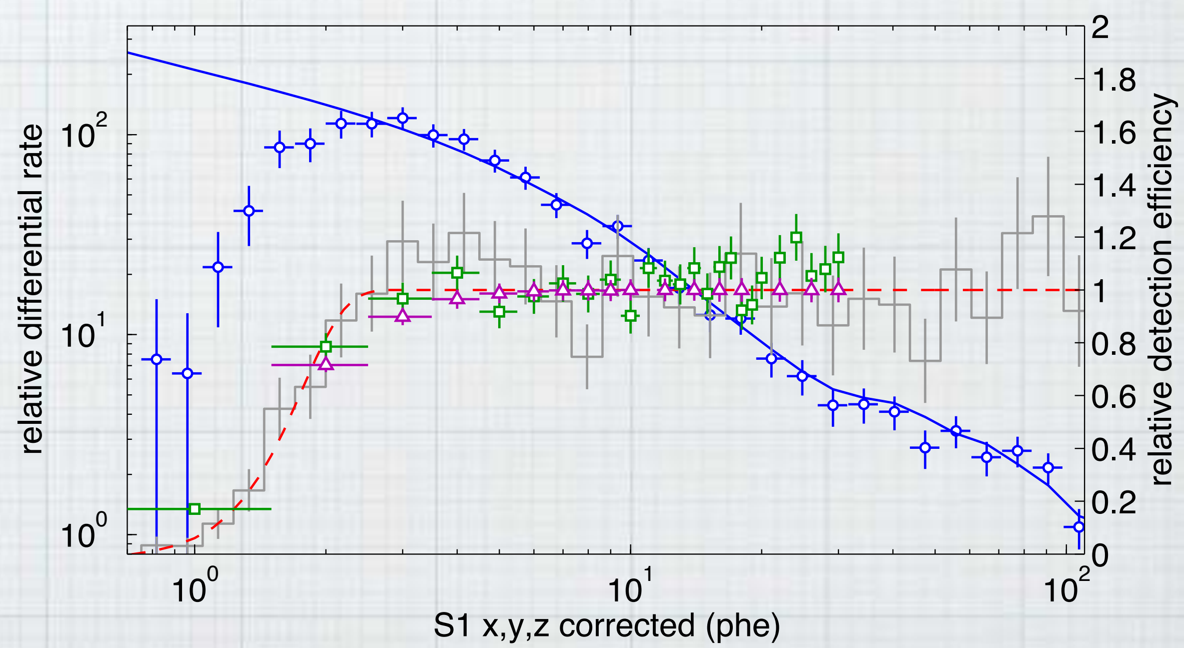
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* Accept events with S1 between 2-30 phe (0.9-5.3 keVee, ~3-25 keV_{nr}):
  * 2 phe analysis threshold allows sensitivity down to low WIMP masses
  * Upper limit avoids ^{127}Xe 5 keV_{ee} activation



Run 3 event selection and cuts - step by step...

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single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* S2 threshold cuts subdominant to S1:
  * 200 phe (~8 single electrons)
  * Removes small S2 edge events and single electron events

Run 3 event selection and cuts - step by step...

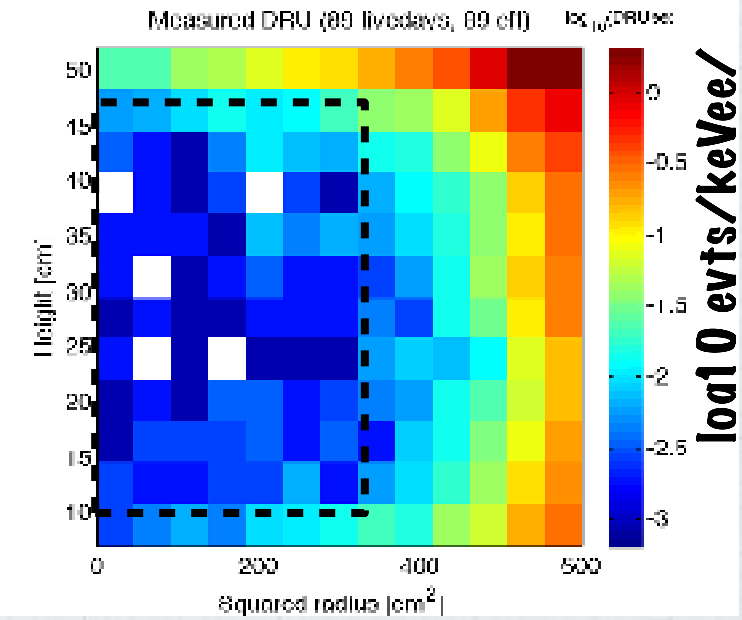
Cut	Events Remaining
all triggers	83,673,413
detector stability	82,918,902
single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

* Require less than 100 phe (< 4 extracted electrons) of additional signal in 1 ms period around S1 and S2 signals:
  * Simple cut to removes additional single electron events following large S2 signals
  * Only 0.8% hit on live-time

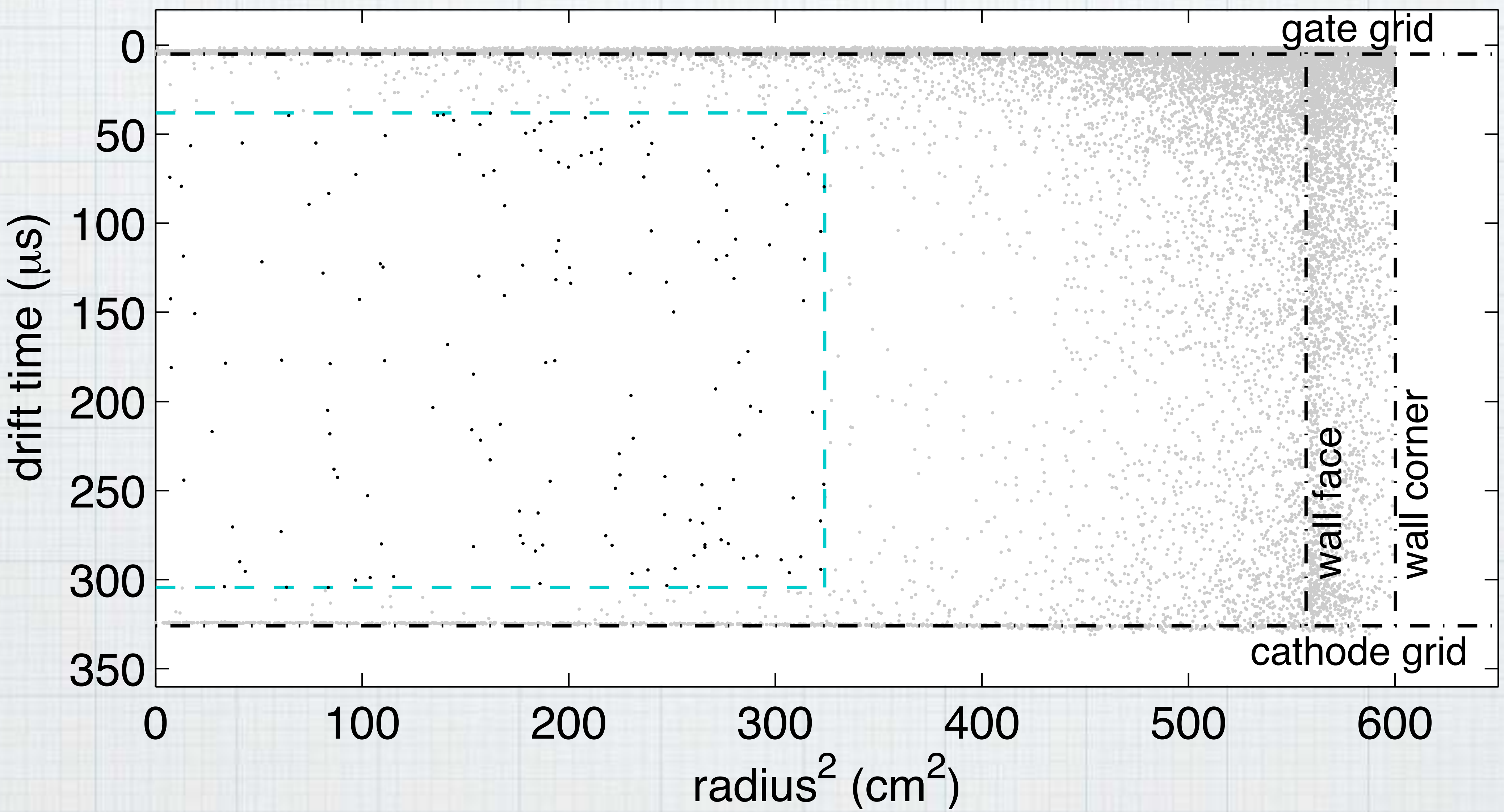
Run 3 event selection and cuts - step by step...

Cut	Events Remaining
all triggers	83,673,413
detector stability	82,918,902
single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

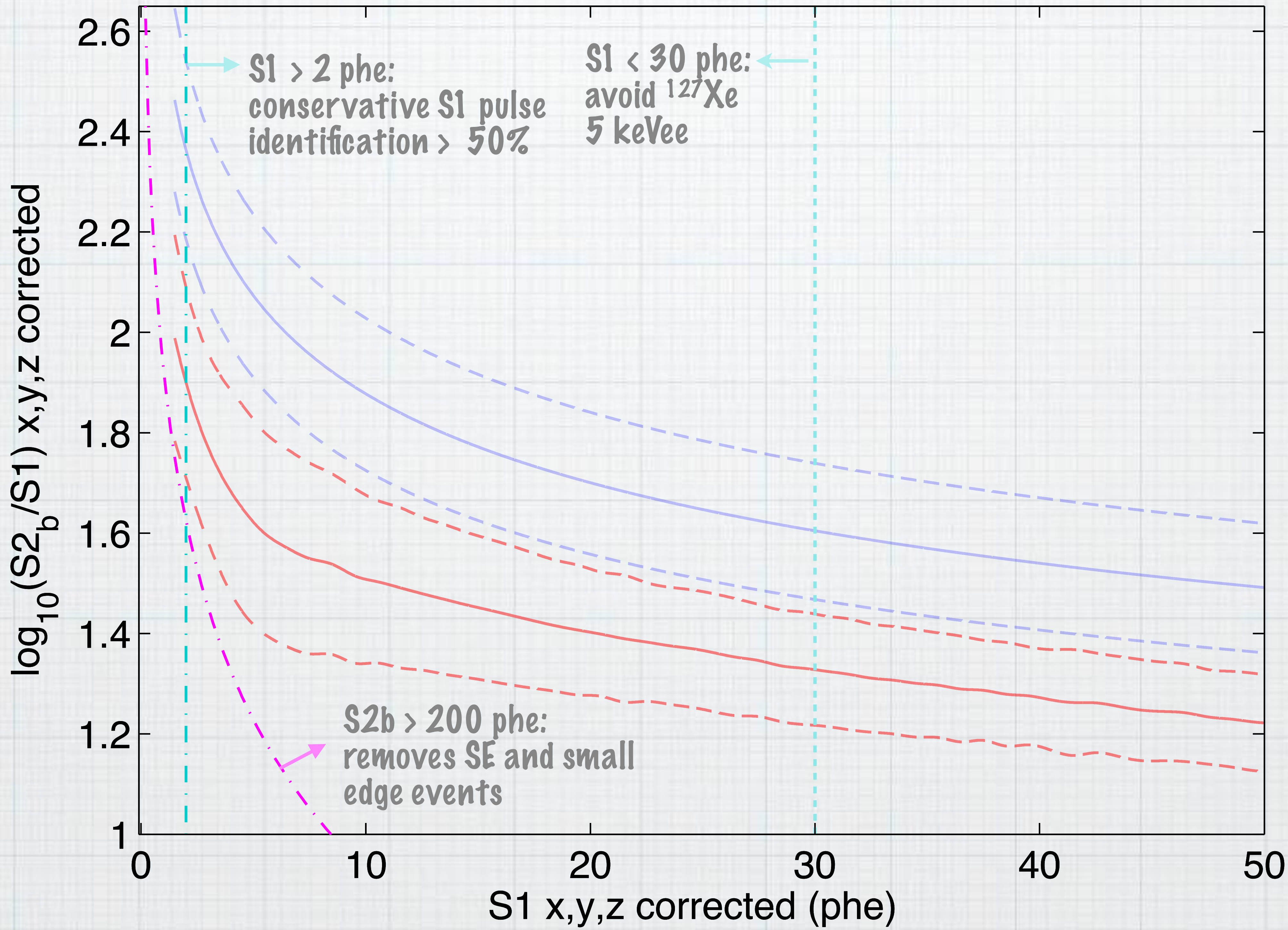
* 118 kg fiducial volume defined by:
  * Z cut: 38 < drift time < 305 μs (320 μs is max drift time) corresponding to 7 cm < z < 47 cm
  * Reconstructed radial position < 18 cm



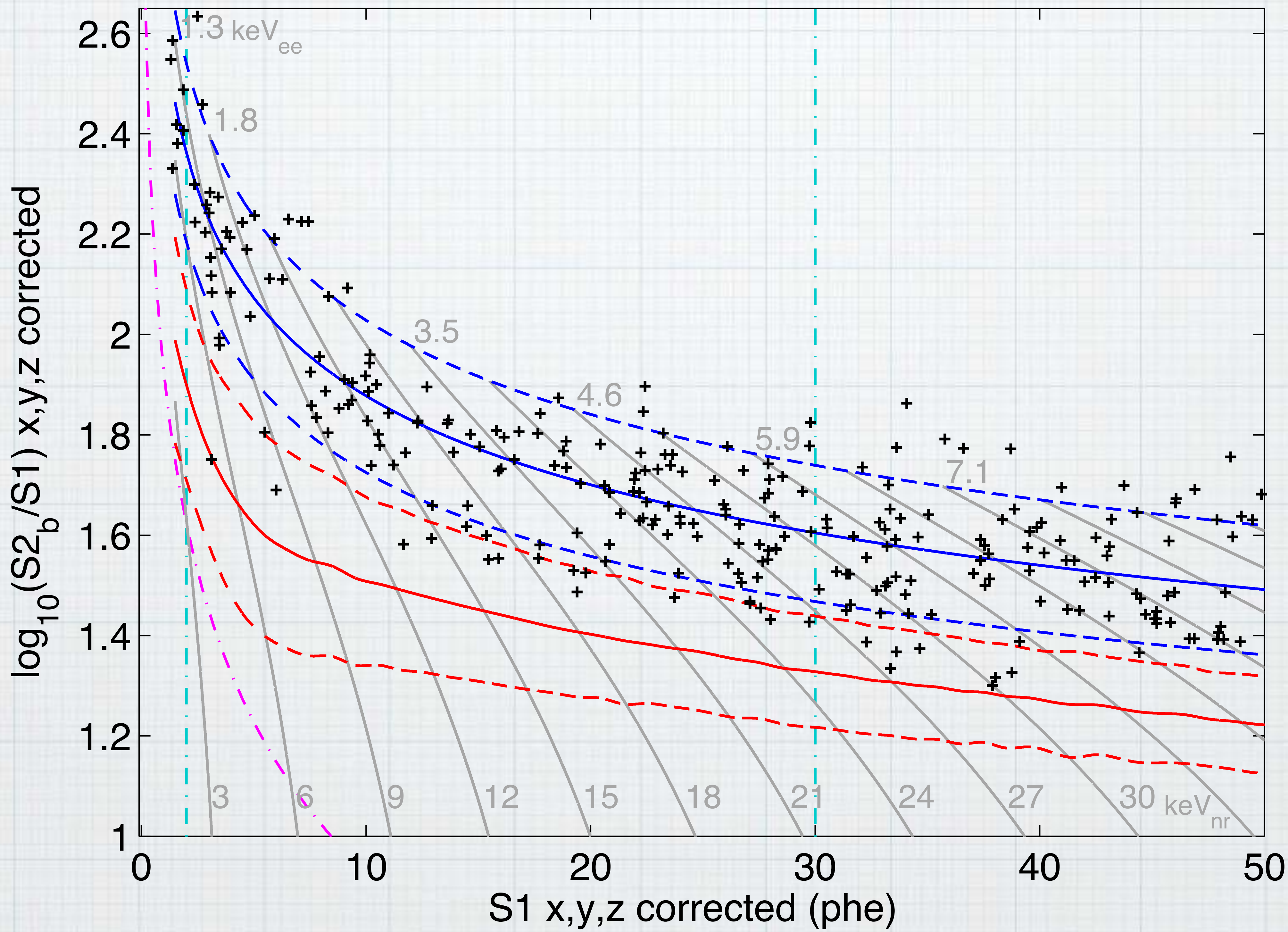
LUX WIMP search data, 85.3 live-days, 118 kg FV



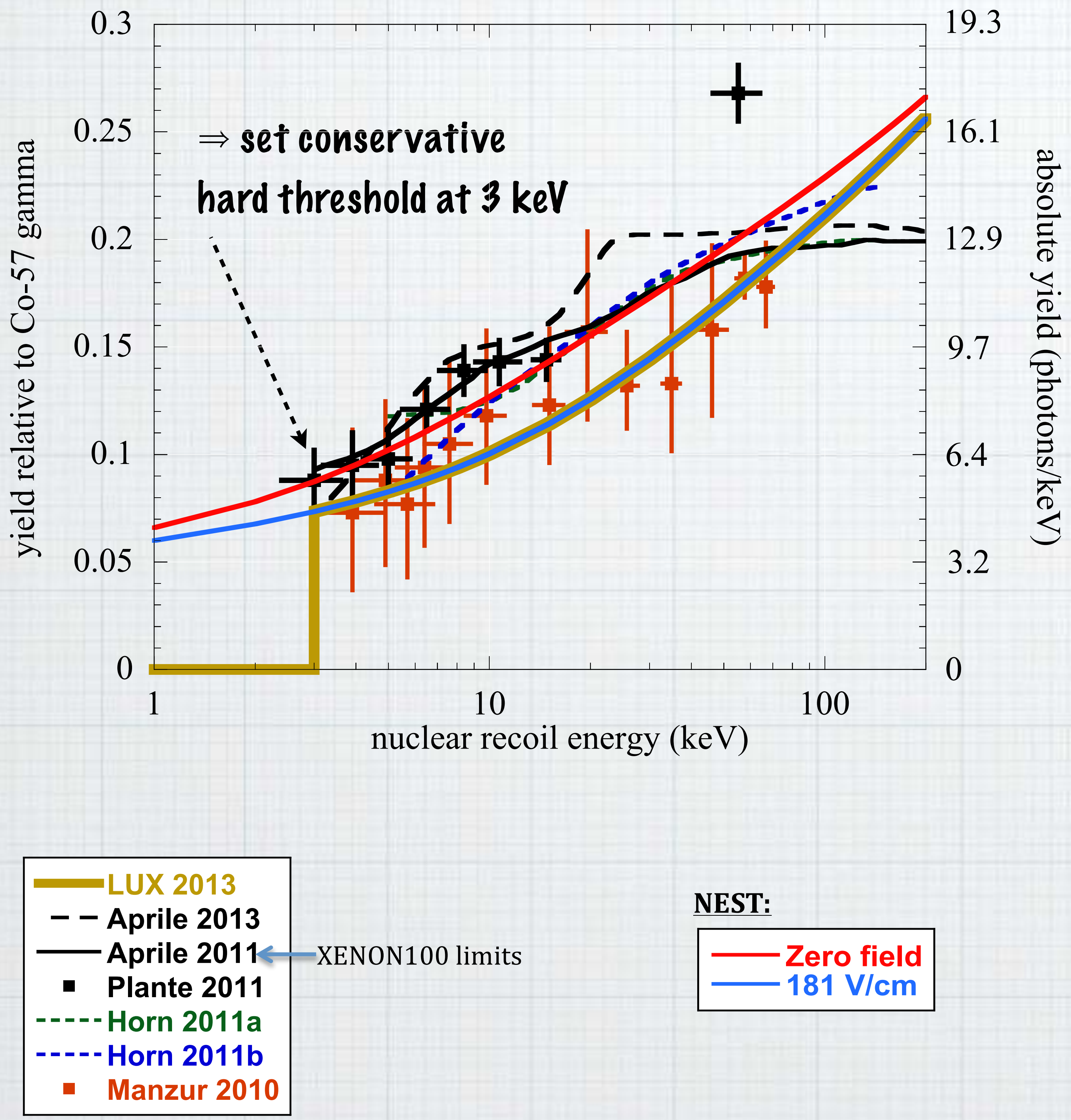
LUX WIMP search data, 85.3 live-days, 118 kg FV



LUX WIMP search data, 85.3 live-days, 118 kg FV

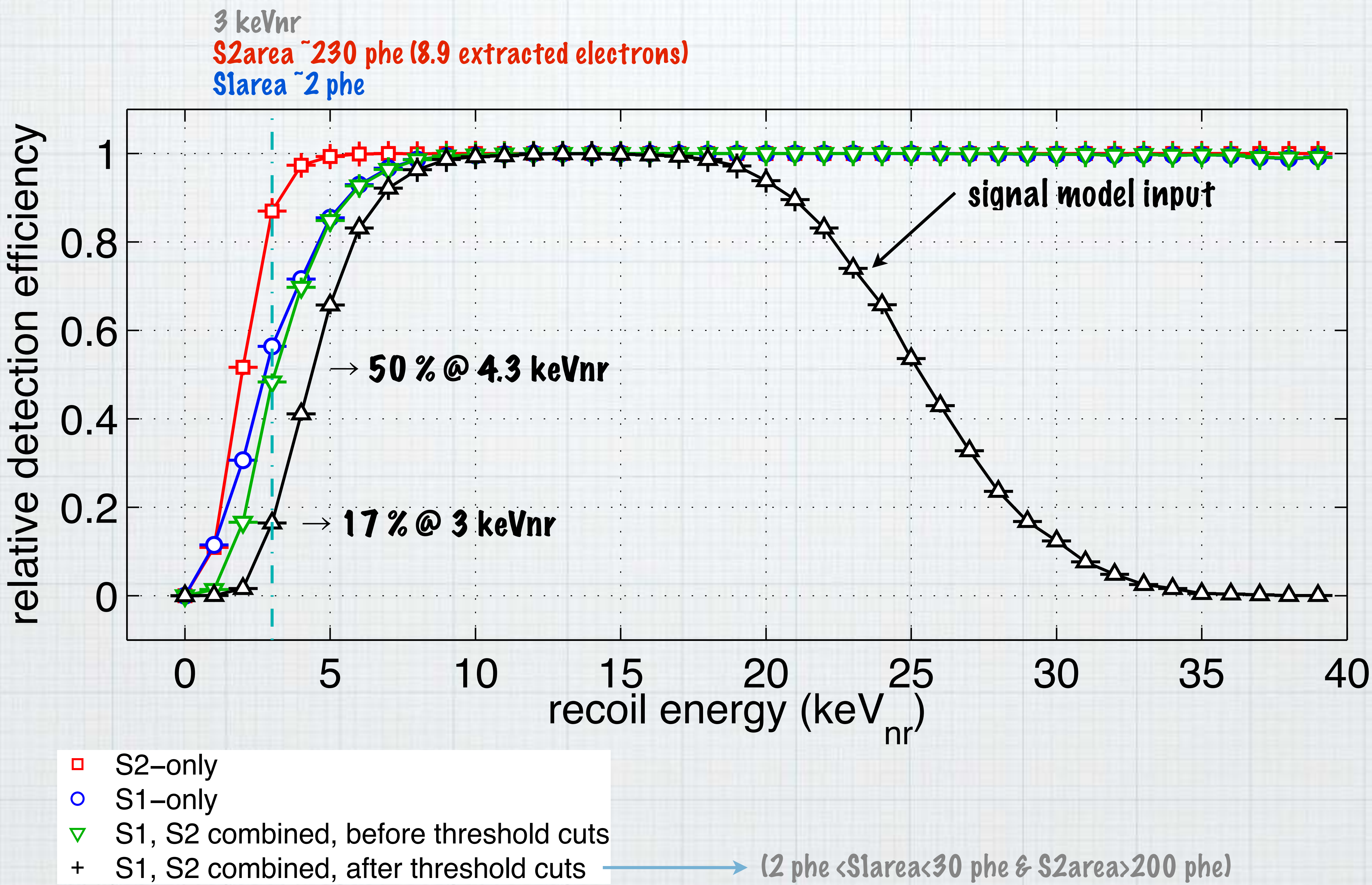


Light and charge yields



* Noble Element Simulation Technique M. Szydagis, JINST 6, P10002 (2011) and JINST 8 C10003 (2013)
* Uses full Lindhard model with Hitachi correction Sorensen and Dahl, Phys. Rev. D 83 , 063501
* conservative approach: ~0.8 of light at 181 V/cm compared to 0 V/cm
* No fine-tuning of NEST to fit LUX data. Only uses experimental parameters (light collection efficiency, extraction efficiency and phe/e-) as input.
* Primary scintillation: PDE of 14%
* Single extracted electron: 26 phe/e-

NR acceptance



Profile likelihood ratio for limits

* Unbinned maximum likelihood comparing data with prediction on event by event basis.

4 observables: x = S1, log10(S2/S1), r and z

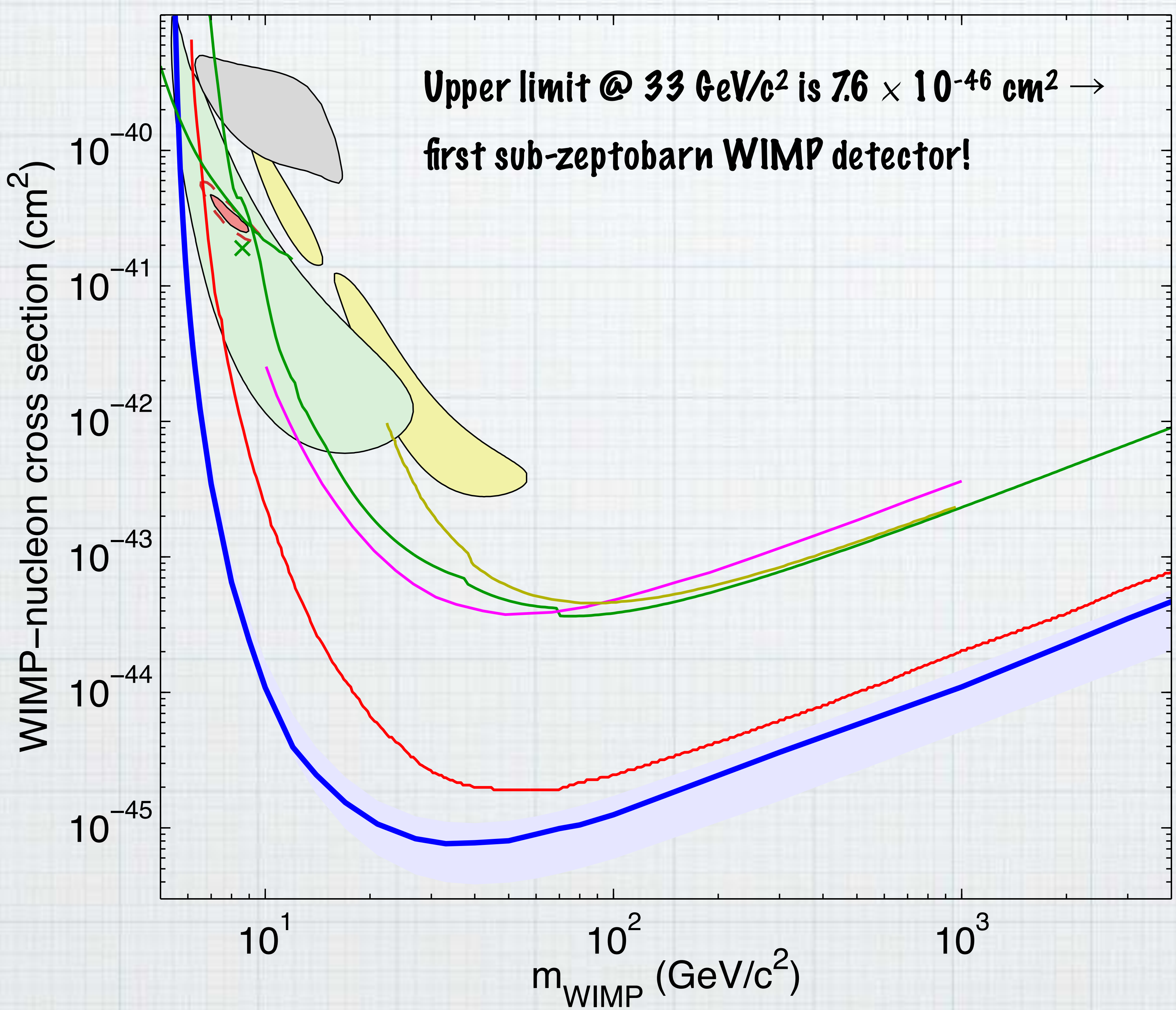
$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}})$$
$$+ N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}}) + N_{Rn} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Rn}})$$

WIMP signal PDF:
- WIMP dE/dR for given mass
- efficiency from validated NR sims
- Ns is parameter of interest

Backgrounds as nuisance parameters:
- detector efficiencies included
- 30% uncertainty on overall rate

Ratio of this to null hypothesis used to create test statistic and extract 90% C.L. upper limit

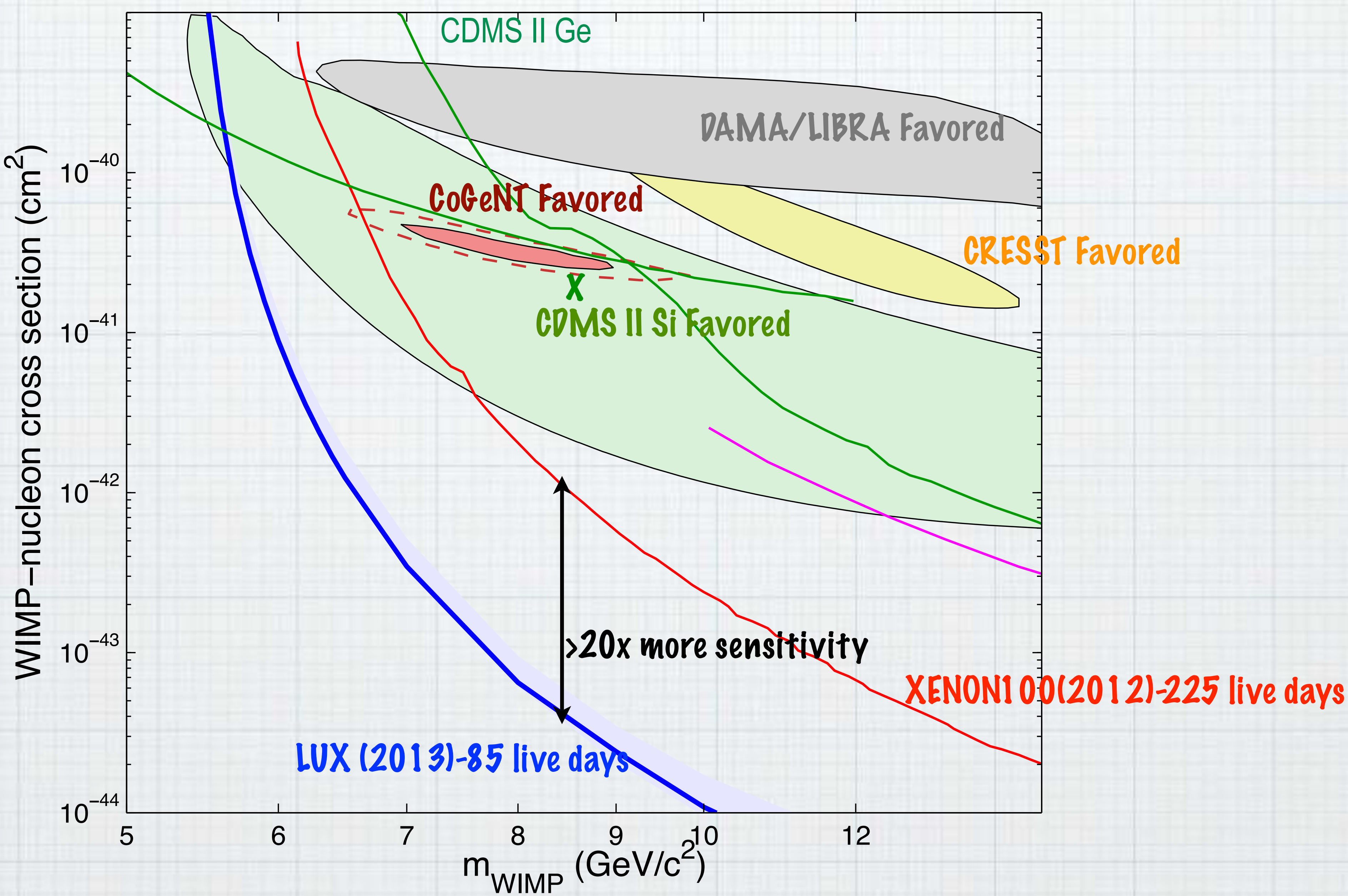
Spin-independent sensitivity



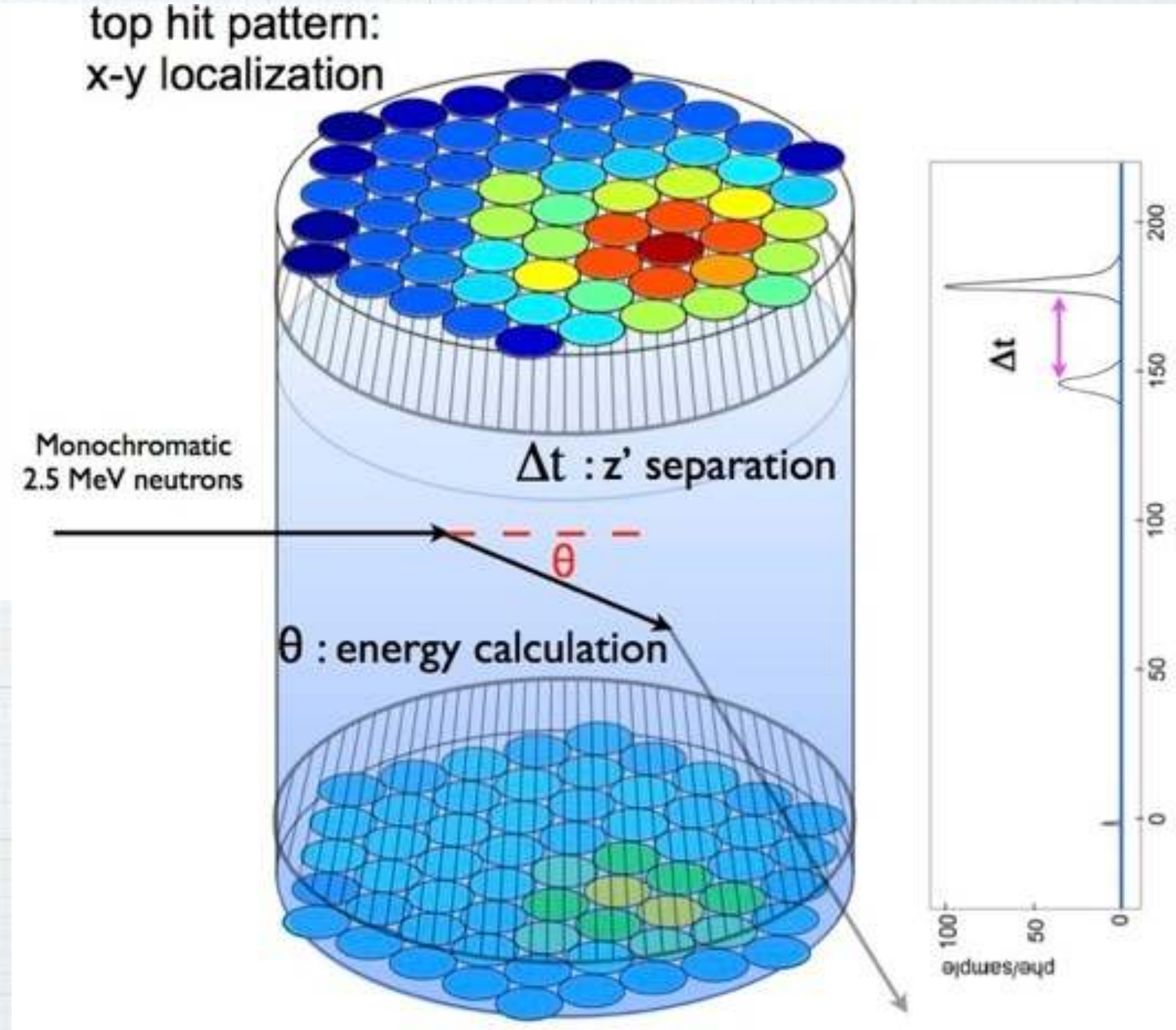
XENON100(2012)-225 live days

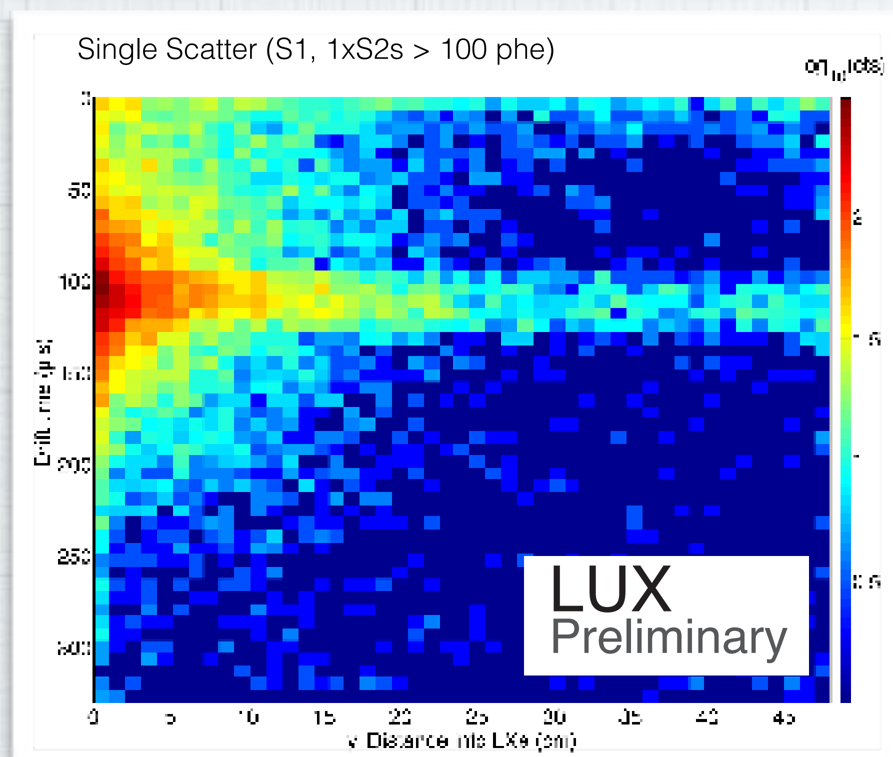
LUX (2013)-85 live days: 90% upper limit

Low-mass WIMPs excluded



Deuterium-Deuterium neutron generator



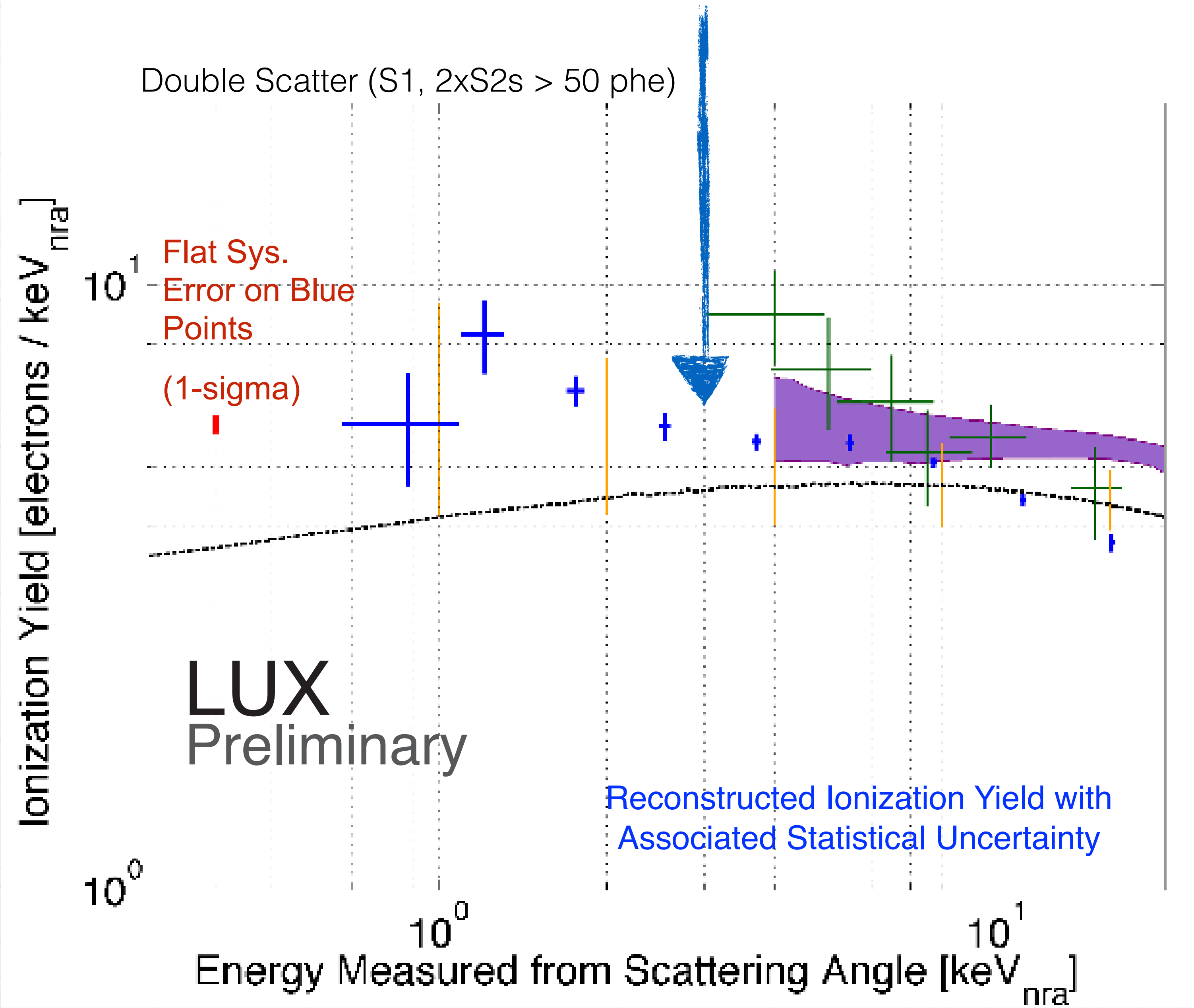


$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

NR absolute charge yield

* Absolute charge yield measured from multiple scatter to below 1 keV
* Sensitivity for recoils below Run 3 cut-off

Run 3 WIMP result 3 keVnr conservative cut off



Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)

Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

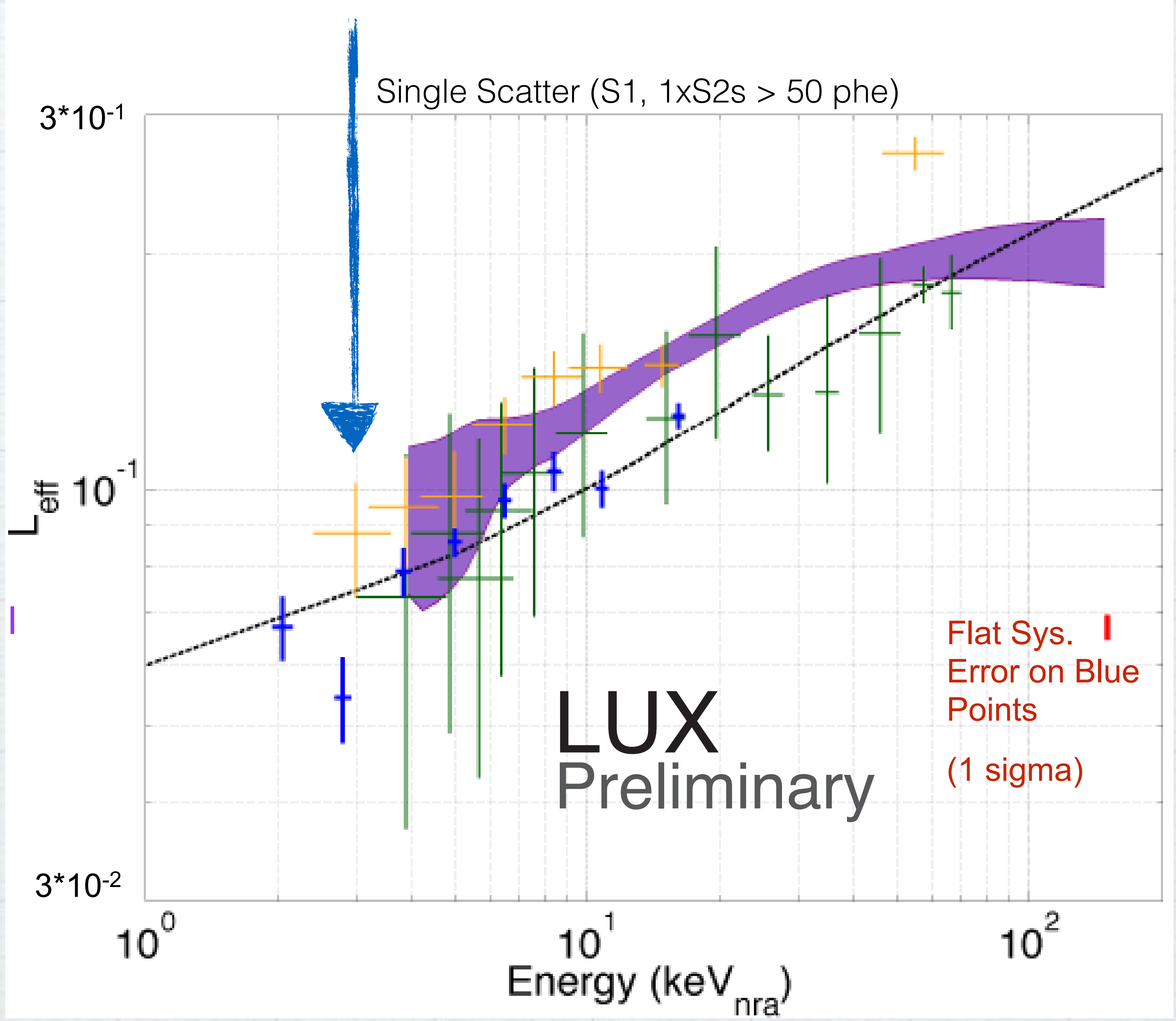
Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)

Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm

NR relative scintillation light yield

- using single scatters
- Detector simulation to simulate single-scatter spectra
- Fit for L_{eff} in slices of S2 using χ^2 minimisation between data and simulated S1-spectra
- Energy scale from charge yield measurement

Run 3 WIMP result 3 keVnr conservative cut off



Blue Crosses - LUX Measured L_{eff}; reported at 181 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)

Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)

Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)

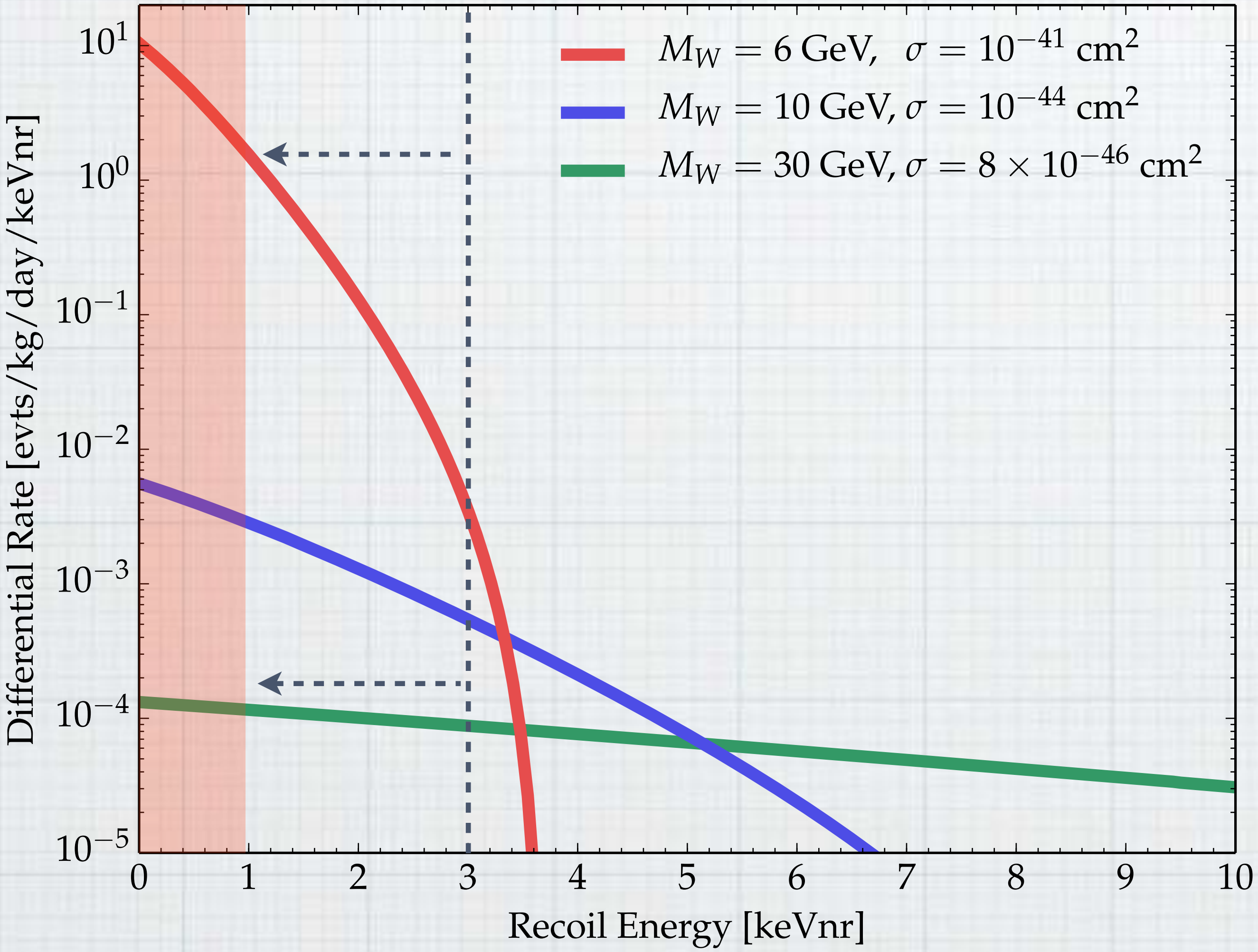
Black Dashed Line - Szydagis et al. (NEST) Predicted Scintillation Yield at 181 V/cm

Full details:
http://www.pa.ucla.edu/sites/default/files/webform/20140228_jverbus_ucla2014.pdf
(forthcoming paper in preparation)

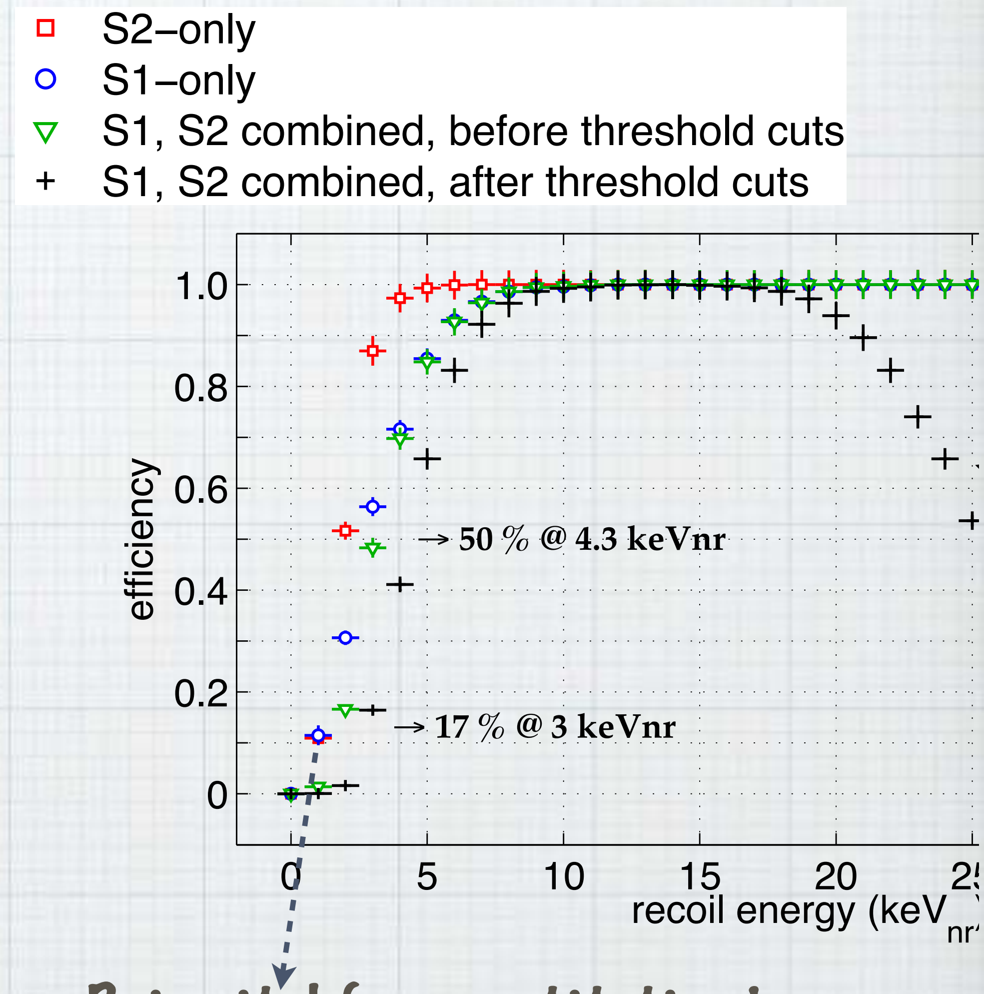
NR relative scintillation efficiency

What does this mean for low-mass WIMP sensitivity

* Decreasing cut-off from 3 keV to 1 keV means we expect almost 1000 * more signal for a WIMP mass of 6 GeV.



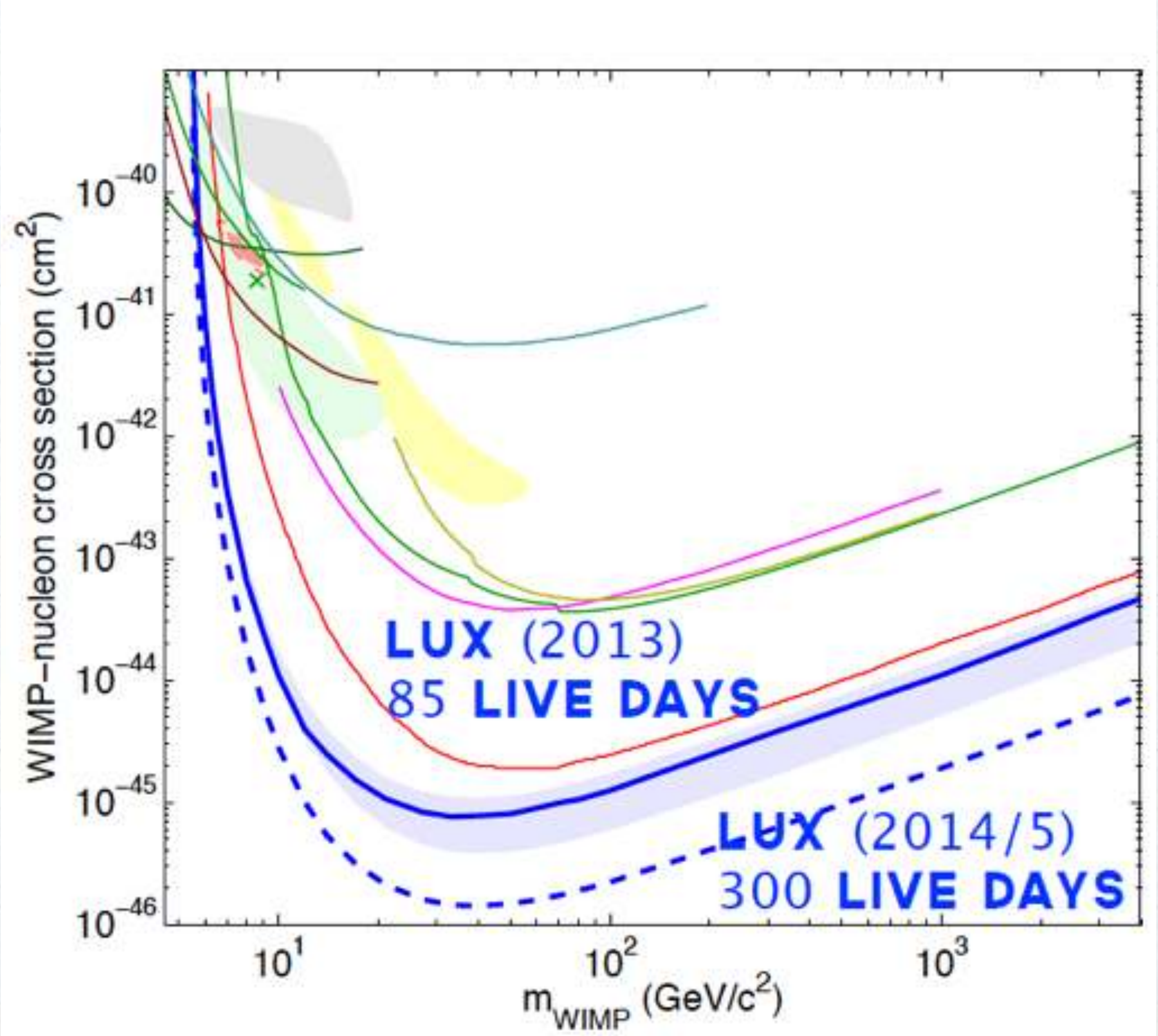
Calculation courtesy of Aaron Manalaysay



Potential for sensitivity down to < 1 keV

What's next: LUX 300 day run

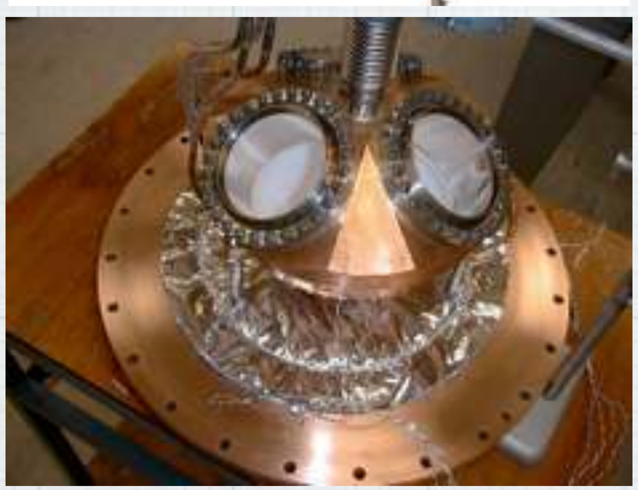
* Run04: A 300 live-day run with results expected in 2015/16.
  * Predicted increase in sensitivity of a factor 3-5 in comparison to 85 days result.
  * Still discovery potential!



Longer term: LUX-ZEPLIN (LZ)

ZEPLIN - Dark Matter program at Boulby Mine, UK

ZEPLIN I



* Single phase, 3 PMTs, 5/3.1 kg
* Run 2001-04
* Limit: $1.1*10^{-6}$ pb

ZEPLIN II

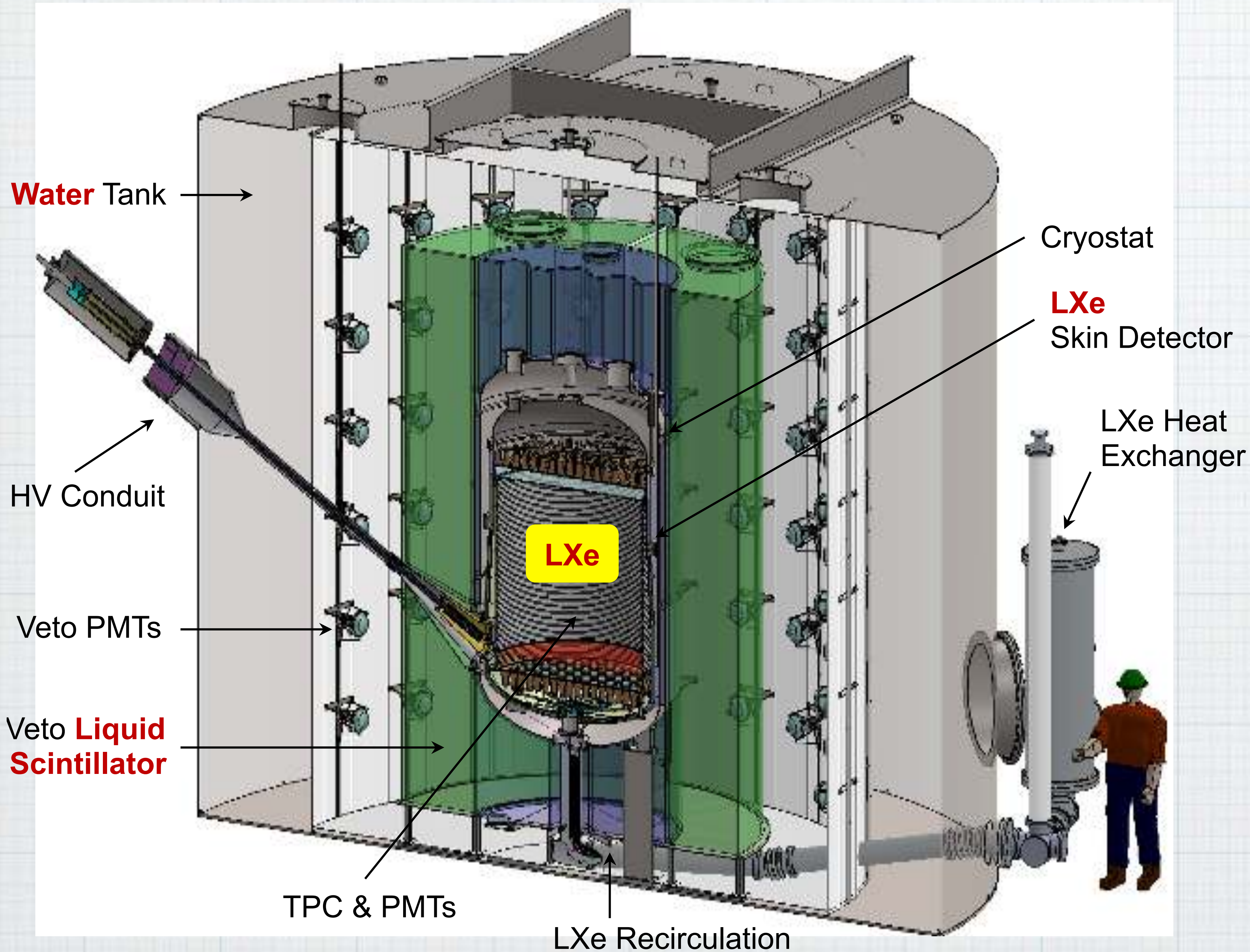
The first 2-phase LXe Dark Matter detector!

* Double phase, 7 PMTs,
* moderate E field, 31/7.2 kg
* Run 2005-06
* Limit: $6.6*10^{-7}$ pb

ZEPLIN III

* Double phase, 31 PMTs,
* high E field, 10/6.4 kg
* Run 2009-11
* Limit: $3.9*10^{-8}$ pb

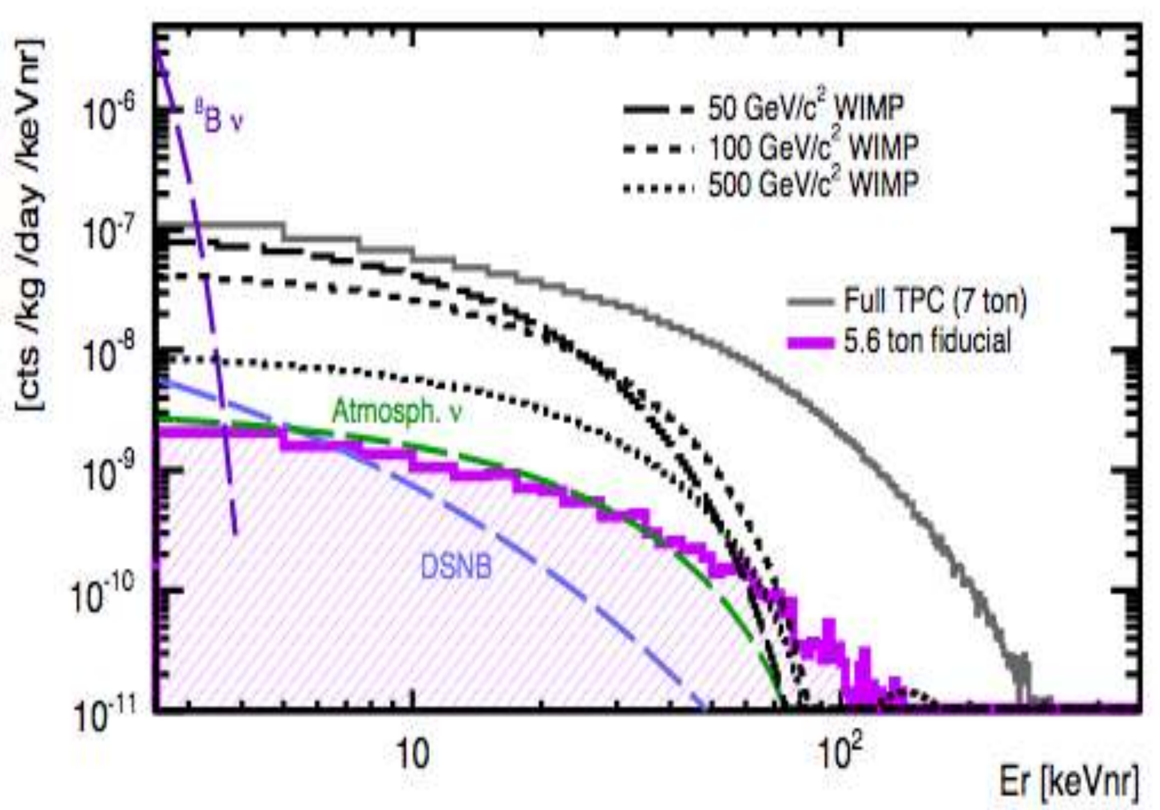
Longer term: LUX-ZEPLIN (LZ)



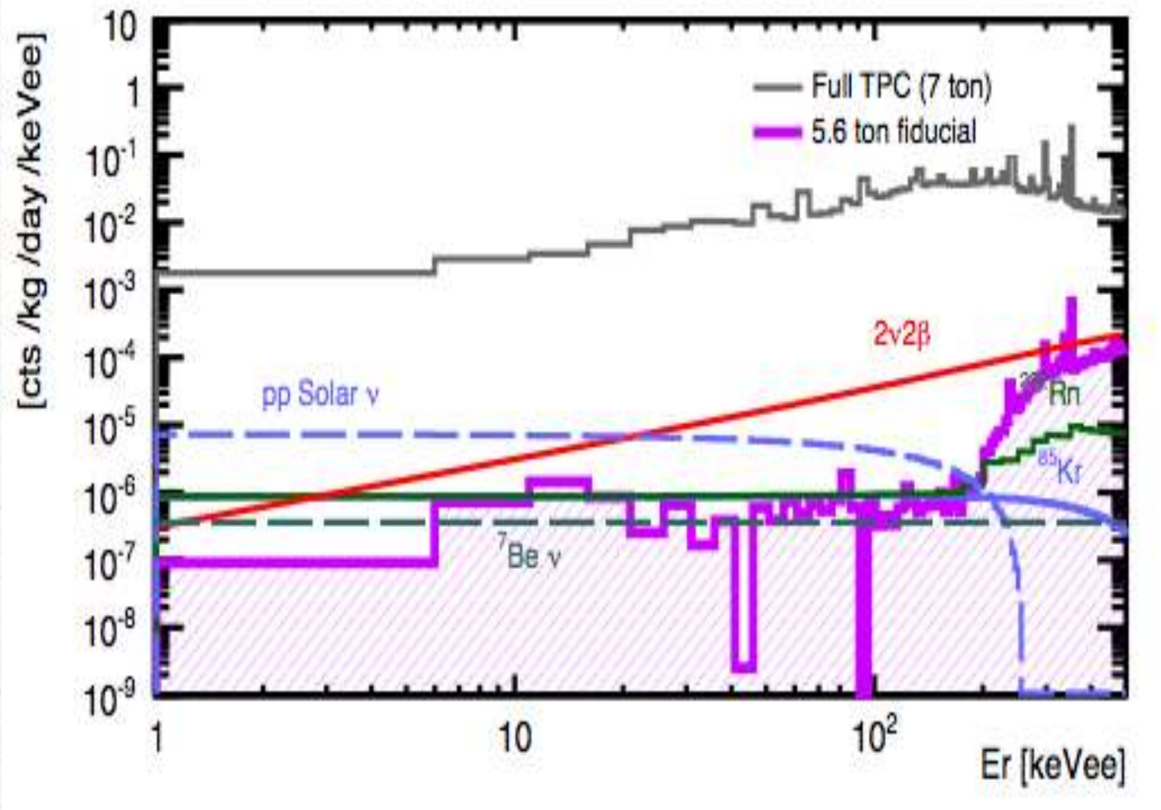
* Linear size: 3x LUX
* Active mass: 28x LUX
* Sensitivity: >100x LUX
* instrumented LXe Skin
* Outer Veto Detector
* Water tank from LUX

Longer term: LUX-ZEPLIN (LZ)

NR

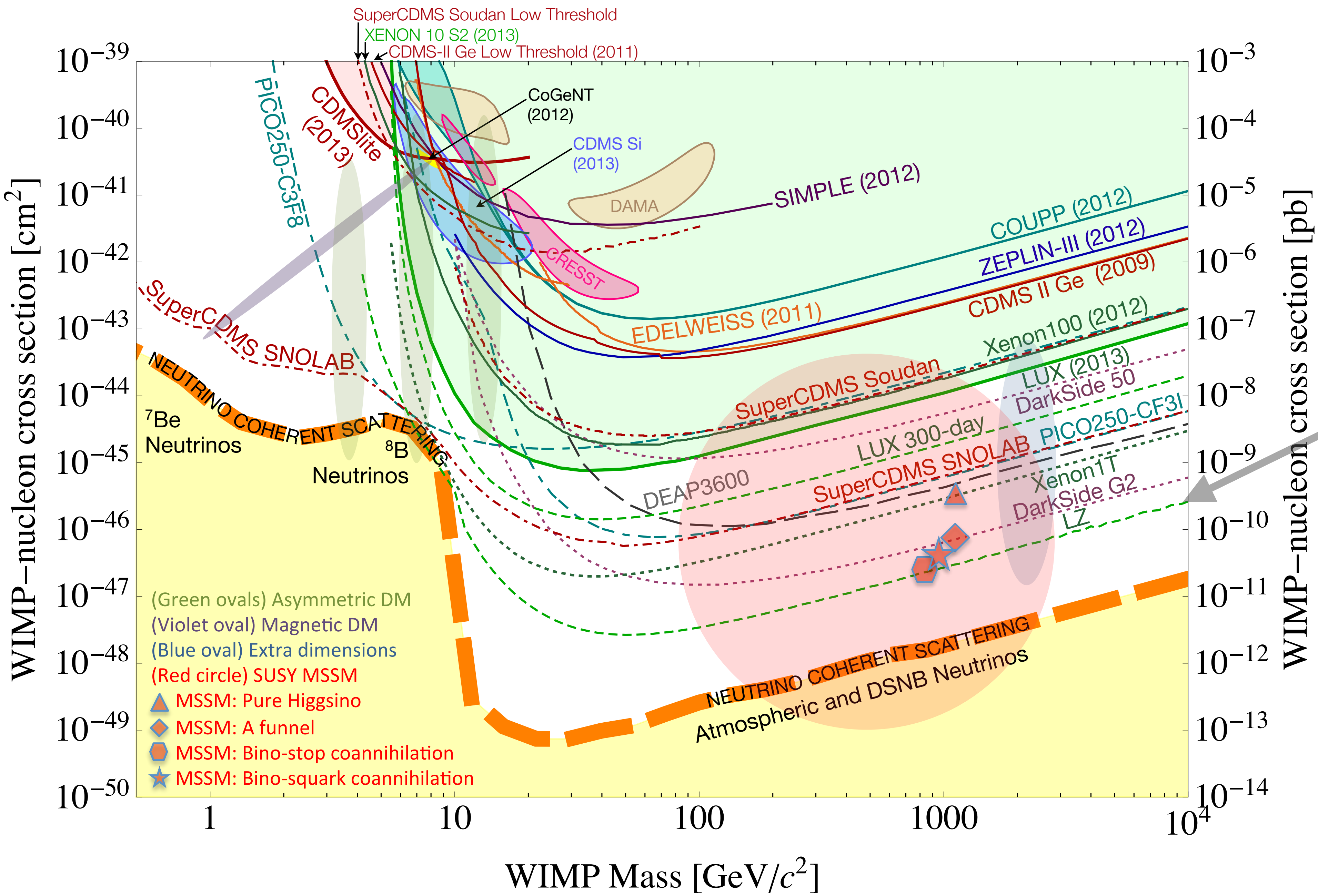


ER



- Dominant backgrounds from astrophysical neutrinos → interesting in itself!
  - Coherent ν-A scattering, solar pp ν-e scattering ~1.9 events in 1,000 days
- Radioactivity from detector materials (n, γ)
  - Radiopure construction, self-shielding & veto strategy - clean ~5.6-tonne fiducial
  - Limit for contribution set to 10% of pp solar ν background
- Intrinsic electron recoil backgrounds in the liquid xenon (β)
  - ER discrimination, prior purification (^{85}Kr) and material assay (Rn) subdominant

Onwards and downwards

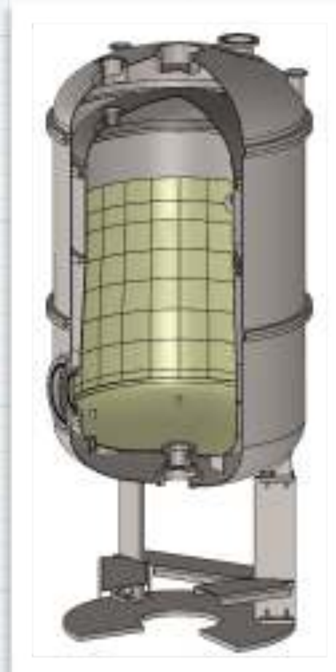


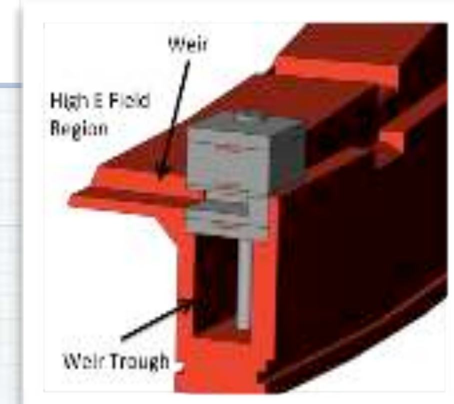
sensitivity goal 2×10^{-48} cm^2 at a WIMP mass of 50 GeV/c^2

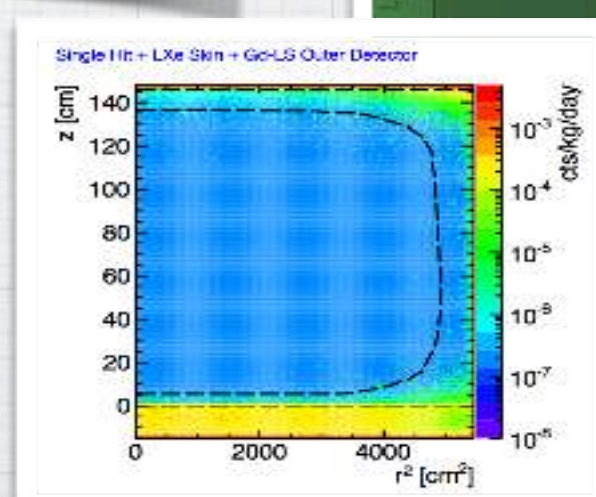
Figure from SNOMASS CF1 WIMP Dark Matter Detection summary

LZ - UK R&D

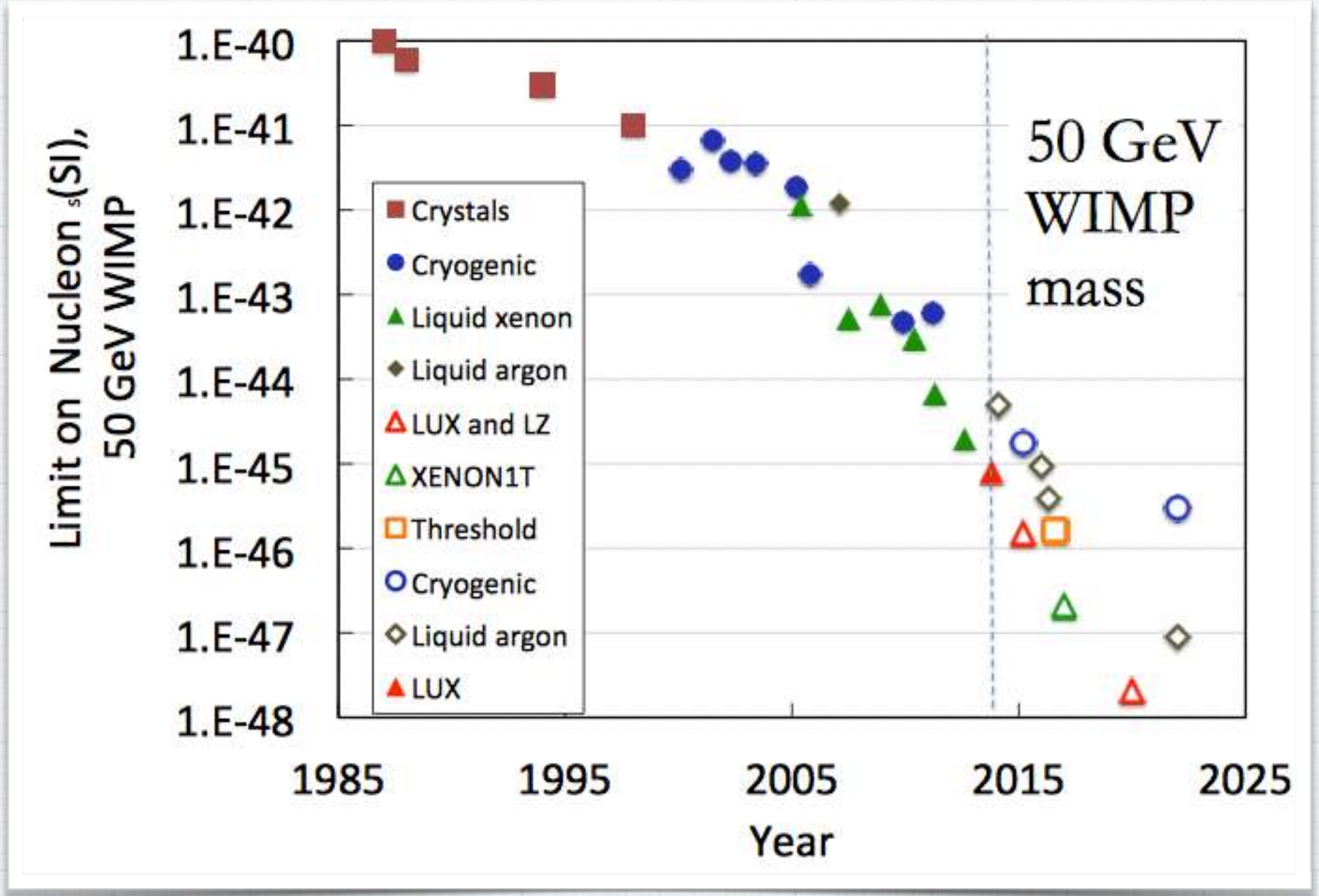
- Cryostat design
- LXe level sensors
- Source delivery driver
- Cold HV-feedthrough
- Slow-control test bench
- LXe system test
- Background simulations
- Screening (HPGe, ICPMS)
- ...







LZ and all 'G2' Projections



Summary

* With 85.3 live-days LUX set world's best limit on spin-independent scattering:
  * 90% U.L. of 7.6×10^{-46} cm^2 at 33 GeV/c^2 $\rightarrow$ first sub-zeptobarn WIMP detector
  * Previous world best sensitivity improved by a factor of about 3 at higher WIMP masses and significantly (by a factor of 20) at low-energy due to low energy threshold.
  * Strong disagreement with low-mass hints of signal!
* Low-energy neutron calibration post Run 3 provided direct measurement of NR energy scale in LUX
  * Expect re-analysis of first WIMP-search data with reduced threshold
* LUX at the frontier of dark matter direct detection - exciting times ahead with the 300 day run, WIMP discovery possible!
* LUX-ZEPLIN proposed successor will approach irreducible background limit for direct detection experiments.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