Searching for dark matter in the Black Hills of South Dakota:

First results from the LUX experiment

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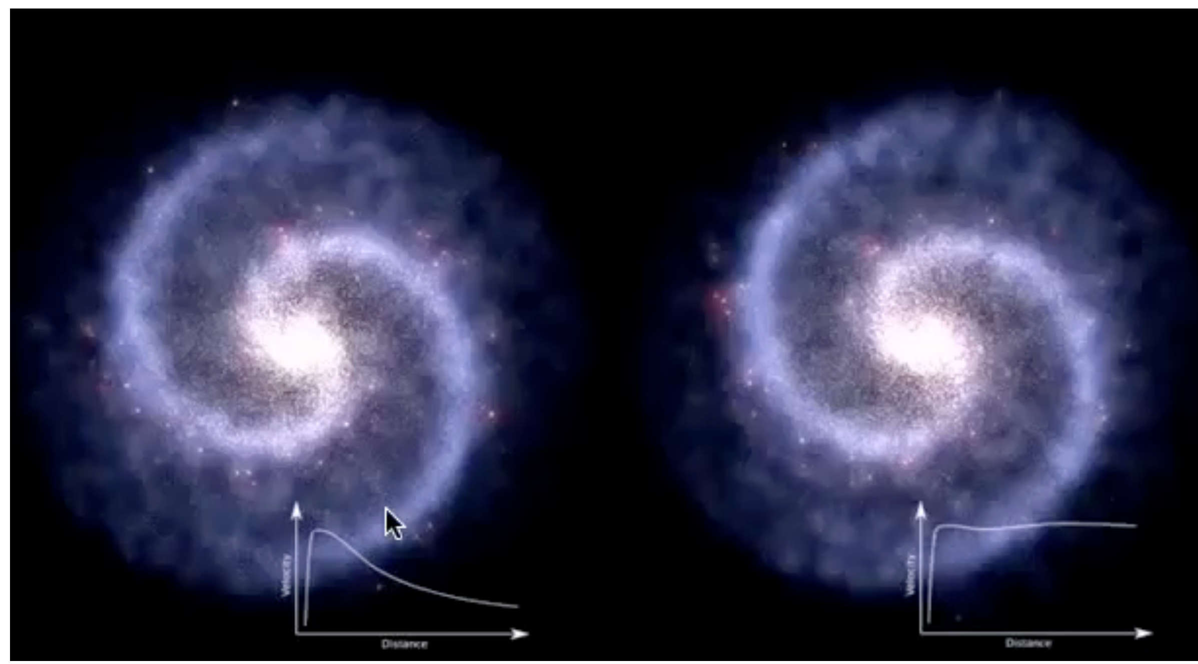
Contents

- Brief introduction to Dark Matter
- Direct detection of galactic WIMPs
- The LUX dark matter experiments at SURF
- First results from LUX

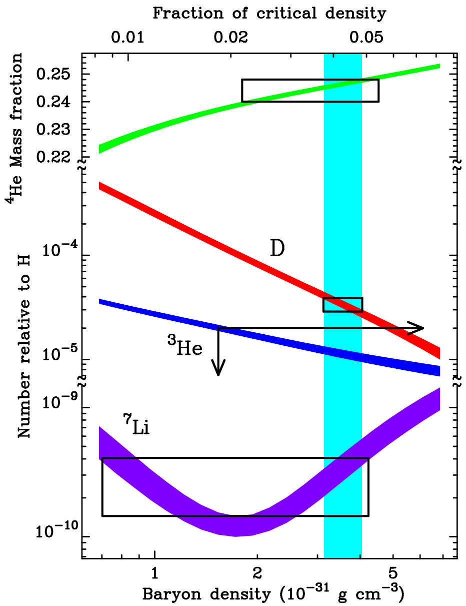
Early evidence for Dark Matter

- 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

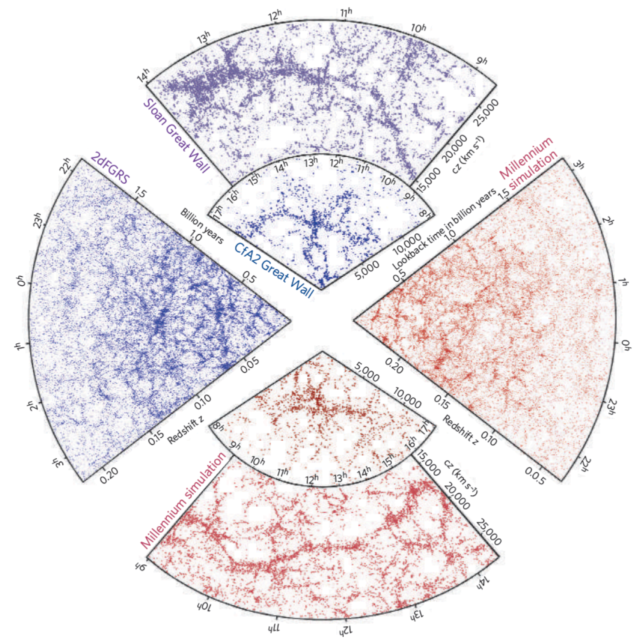


Much much more evidence since then

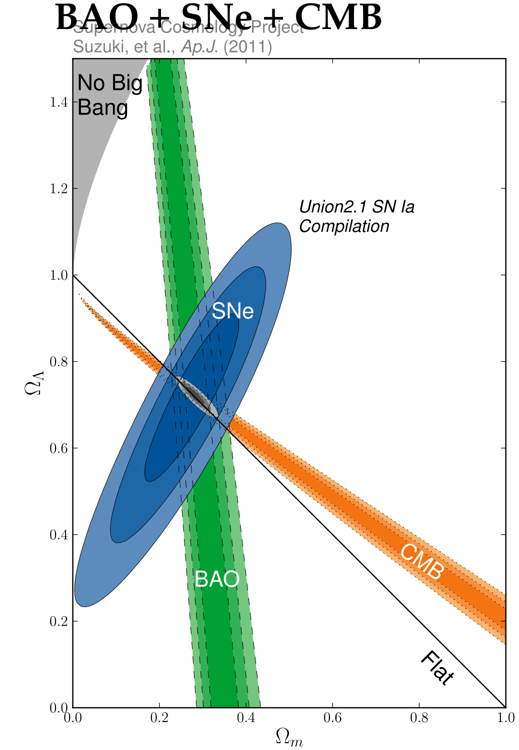
BBN



Large scale structure → CDM

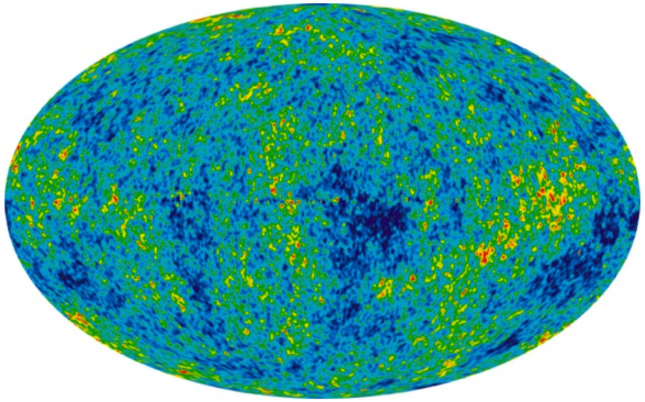


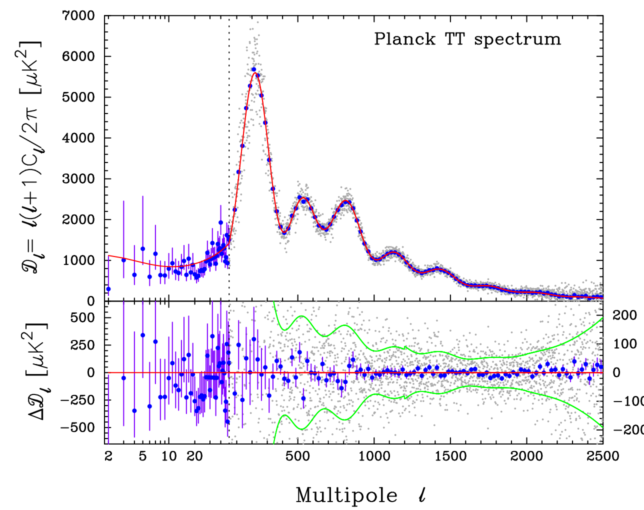
BAO + SNe + CMB



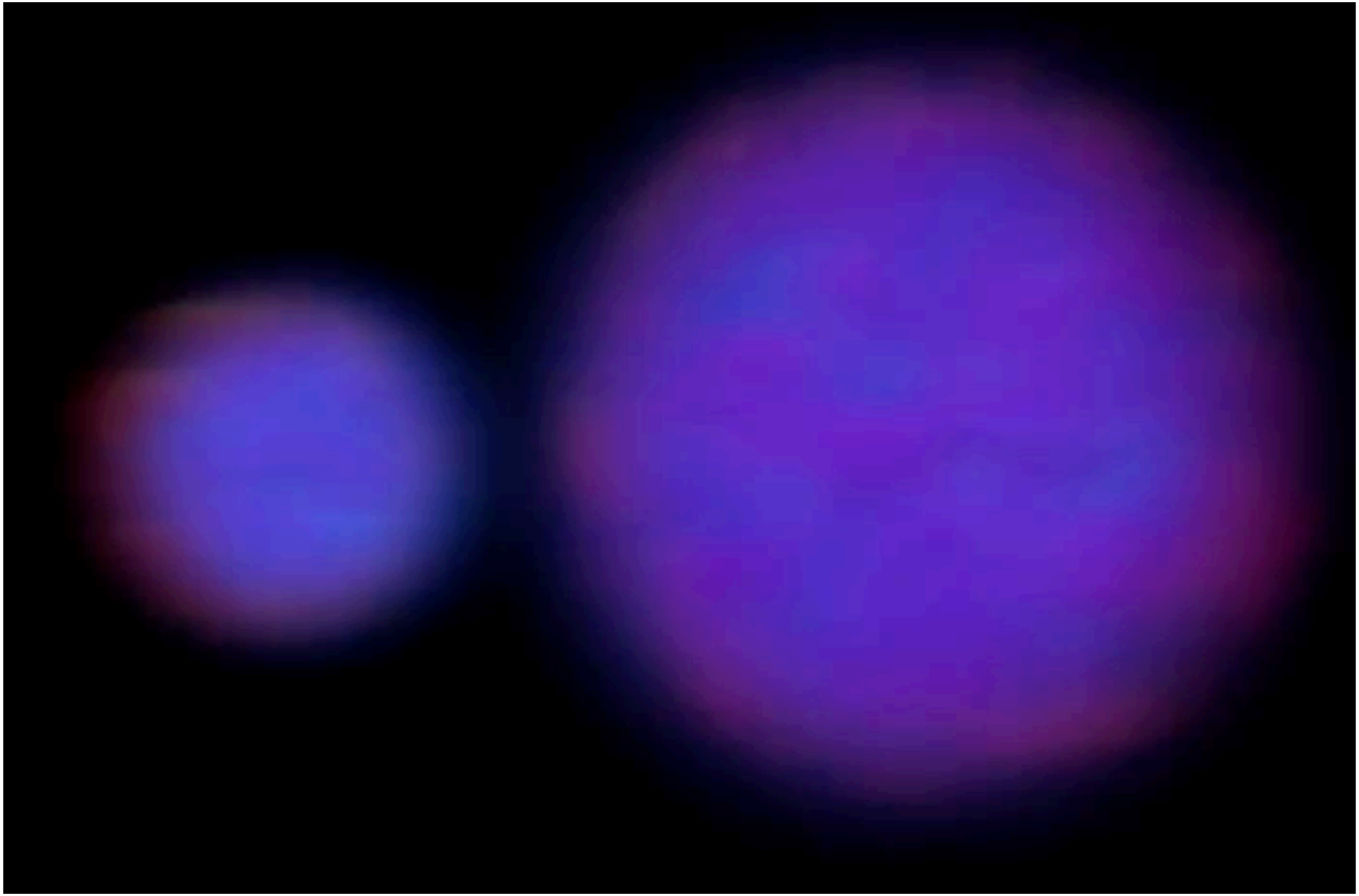
Gravitation lensing

CMB + BAO: precision tests of ΛCDM



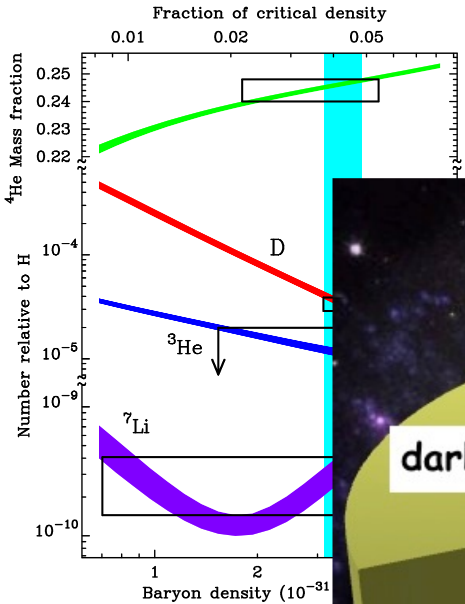


Bullet Cluster (1E 0657-56)



Much much more evidence since then

BBN



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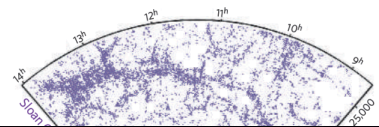
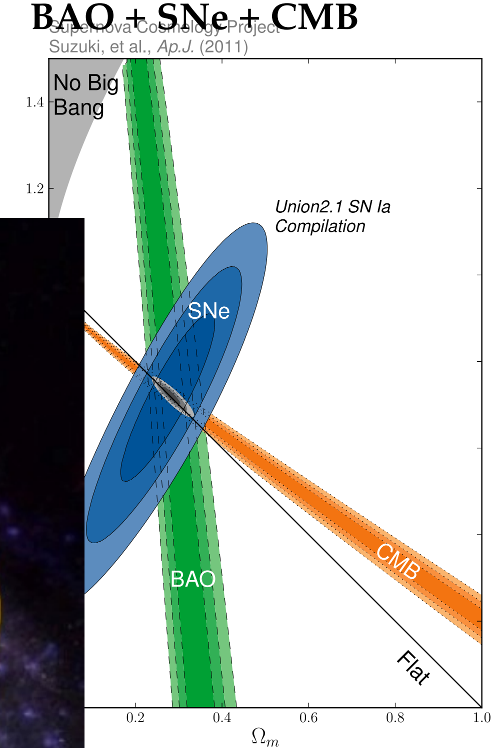
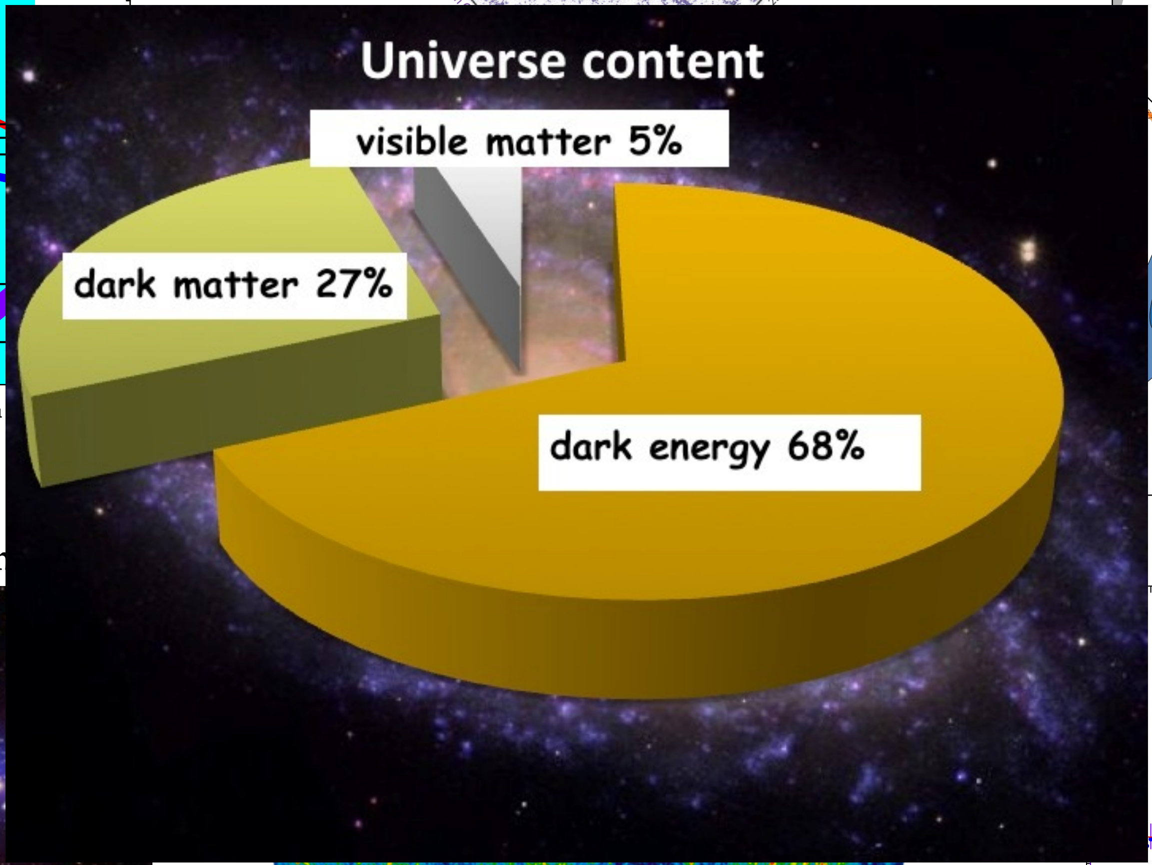
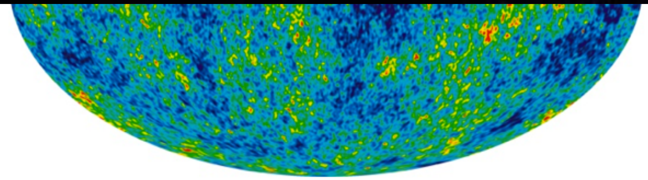


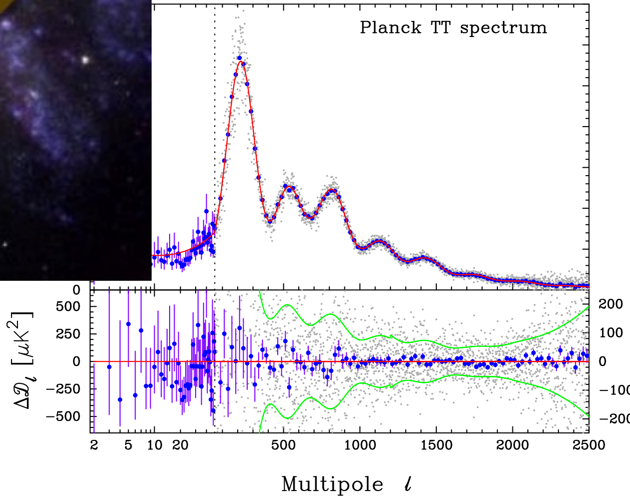
BAO + SNe + CMB





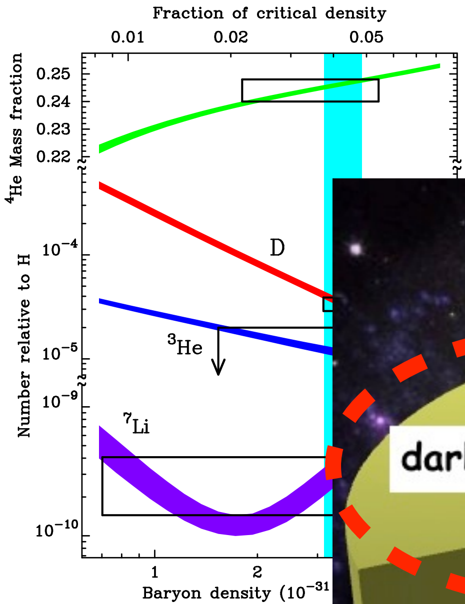
Gravitation lensin



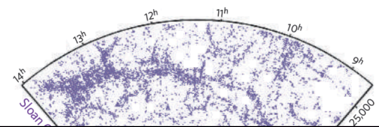


Much much more evidence since then

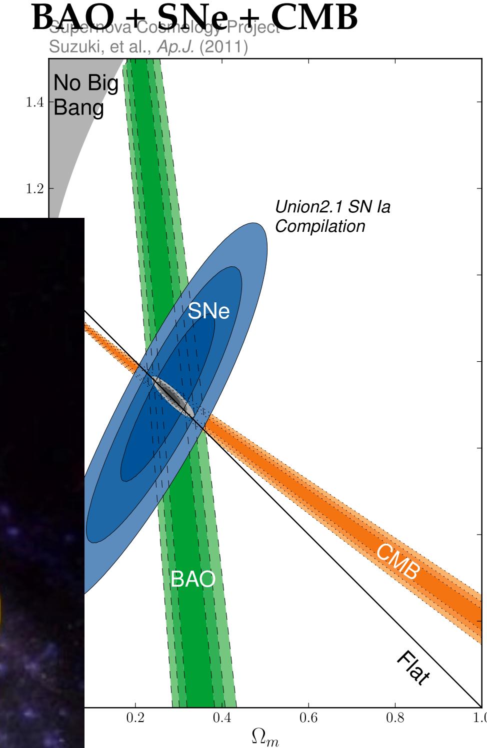
BBN

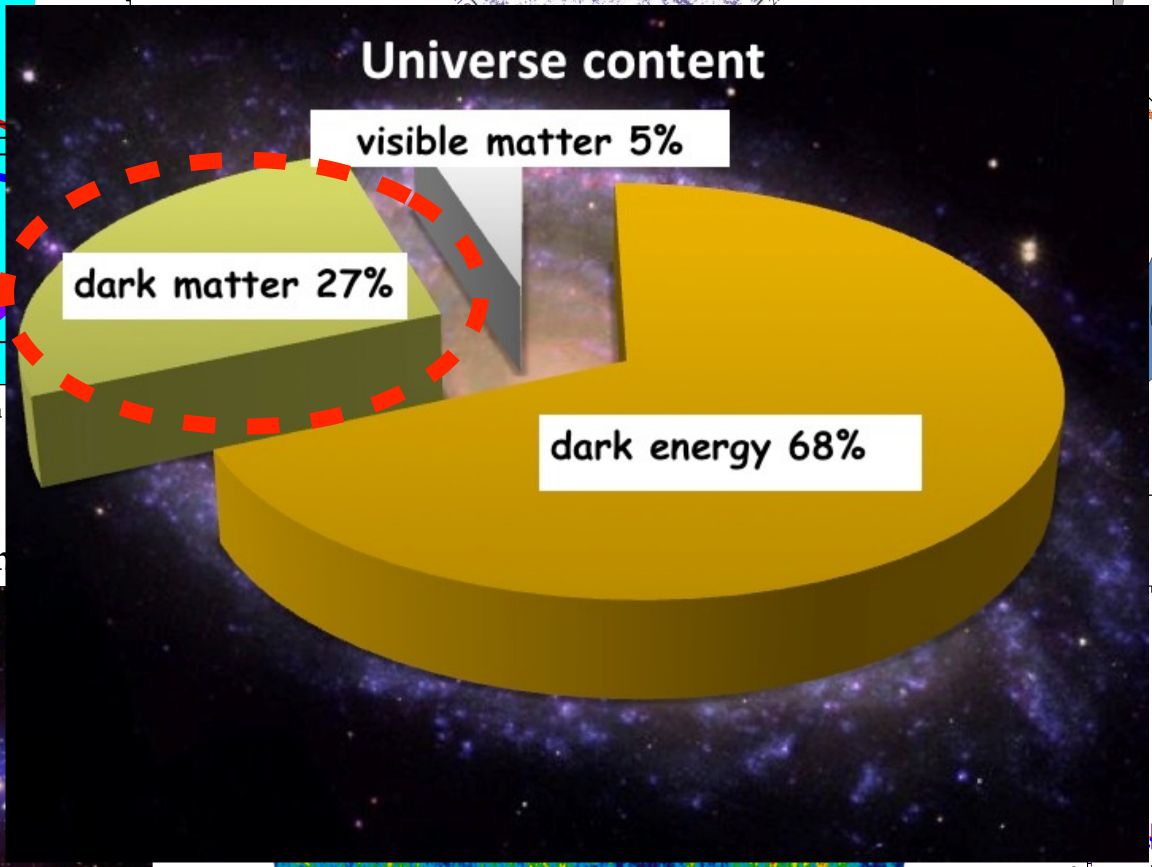


Large scale structure → CDM

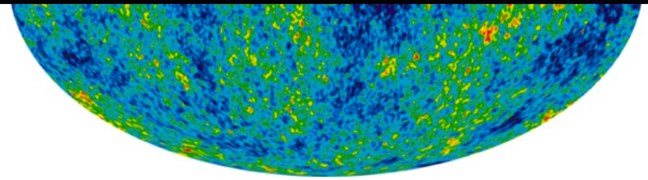


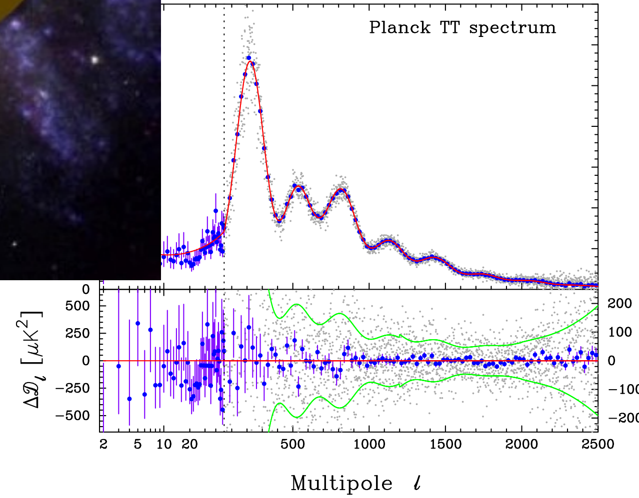
BAO + SNe + CMB





Gravitation lensin

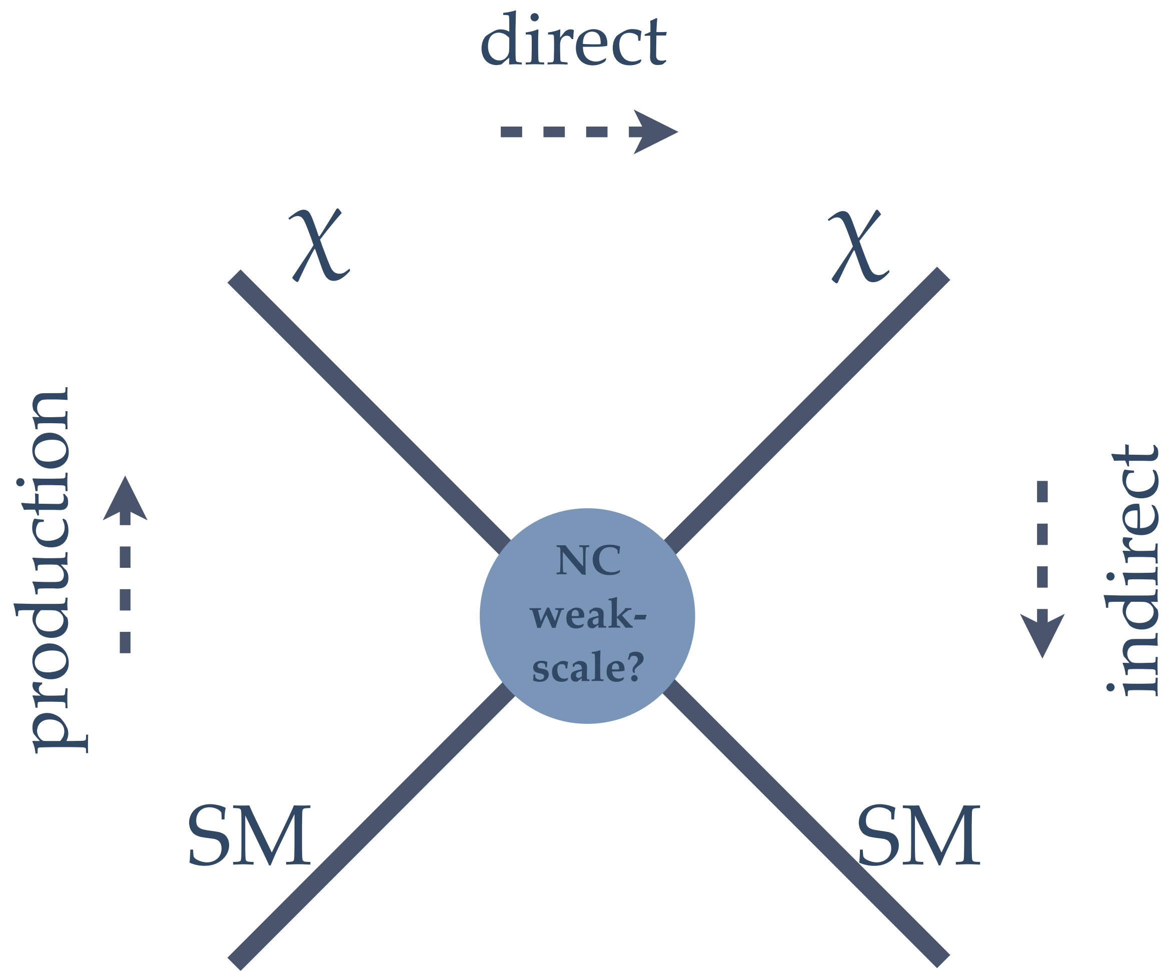




Dark Matter properties

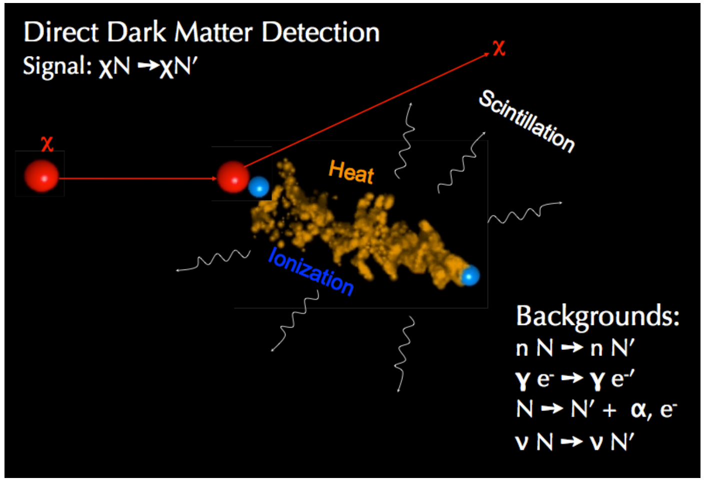
- Interacts only **weakly** with normal matter
- Expected to be **neutral** in most scenarios
- **Cold**: Non-relativistic freeze-out
- **WIMPs** favoured candidates for Cold Dark Matter
  (alternatives: axions, sterile neutrinos, ...)
- Requires **beyond standard model** physics:
  - Super-symmetry: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

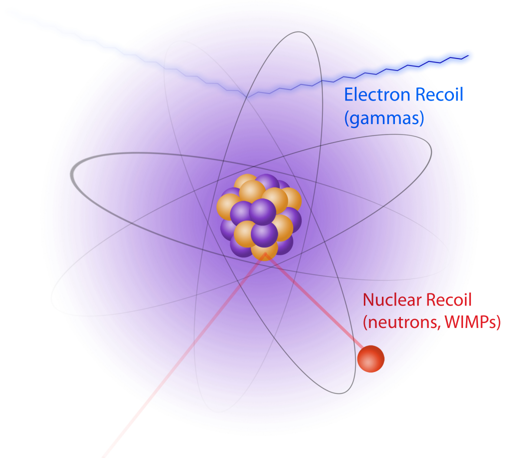
Detecting Dark Matter

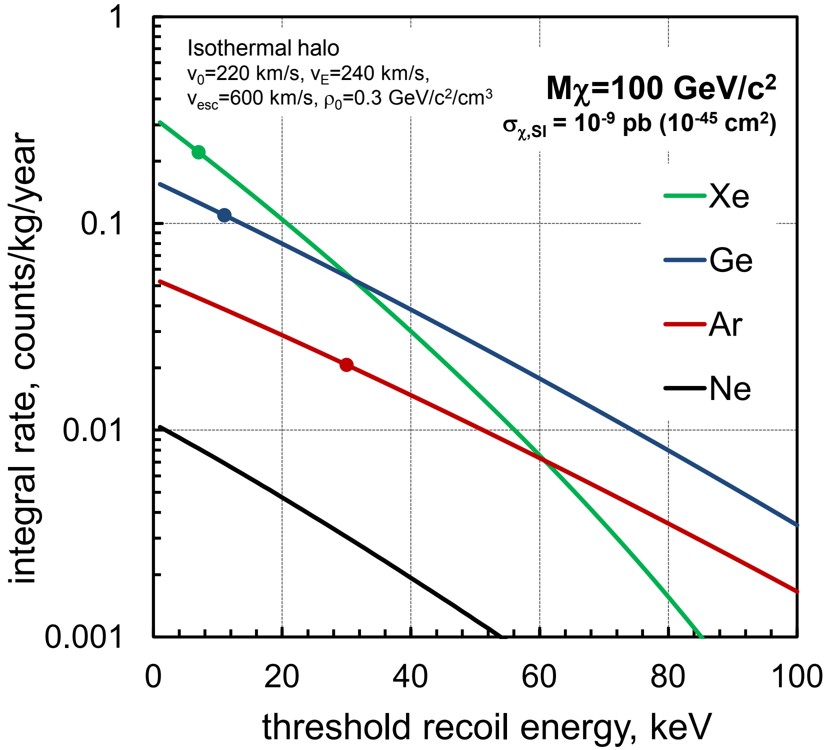


Direct detection of galactic dark matter

- Elastic scattering of galactic WIMPs off target nuclei in terrestrial detector
- WIMP speed ~ 220 km/s
  expect recoils O(10 keV)
- Spin-independent cross section ∝ A^2
- Expect ~ 1 event/kg/year
- Requires SM backgrounds ~0
  (underground operation)

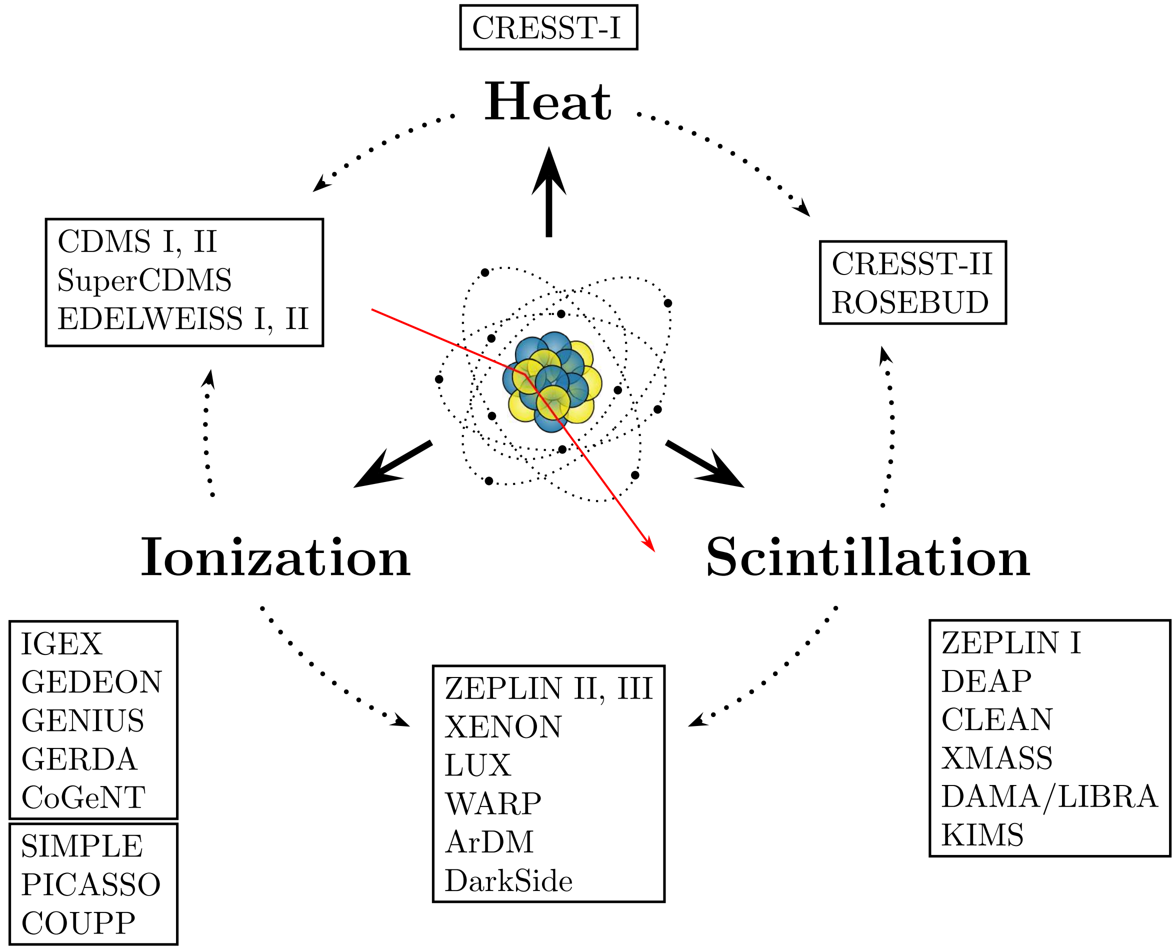




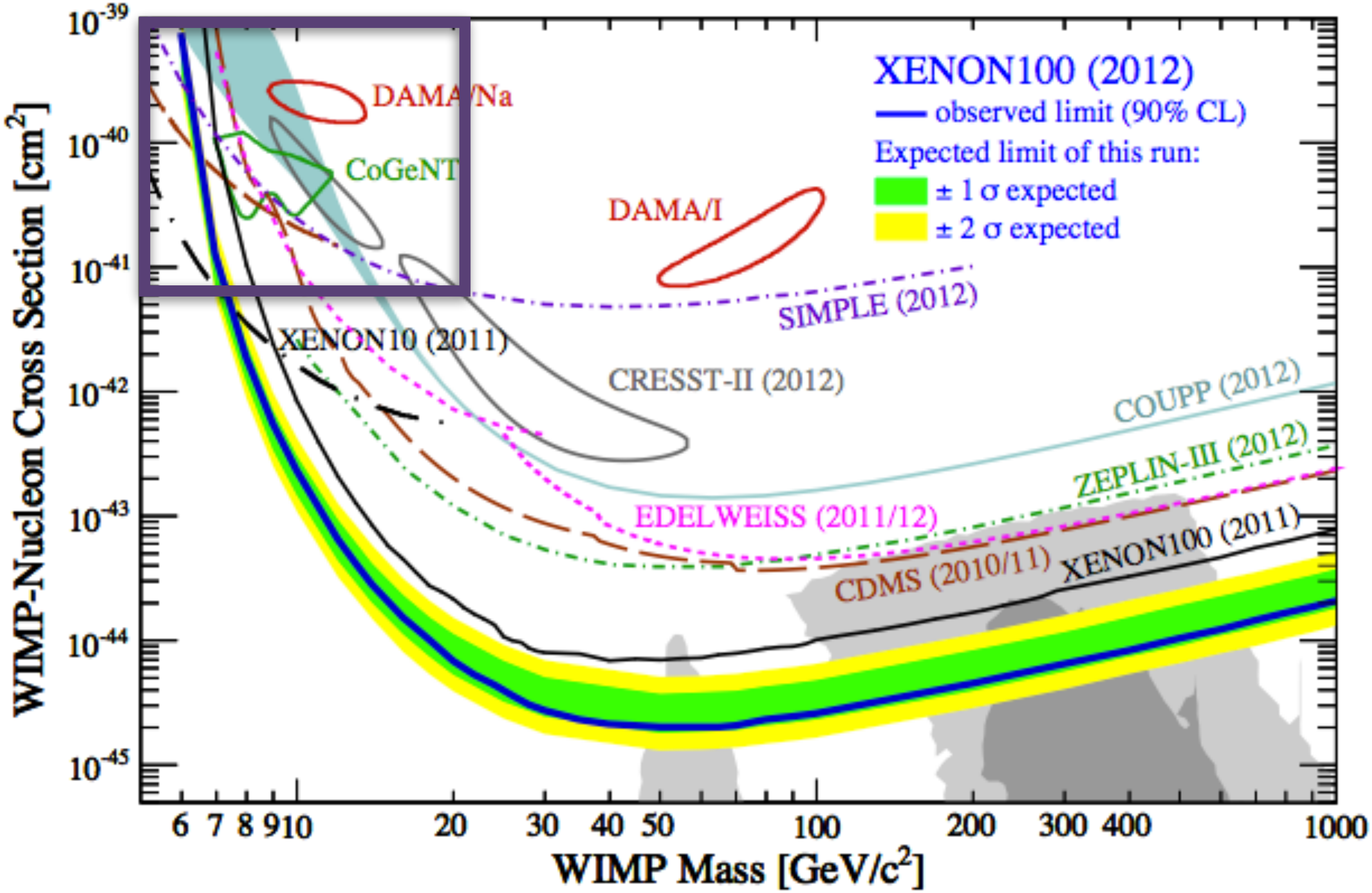


Direct detection techniques

- Requirements: large mass, low-radioactivity, low-energy threshold, high acceptance, discrimination



WIMP search status < 30th October 2013



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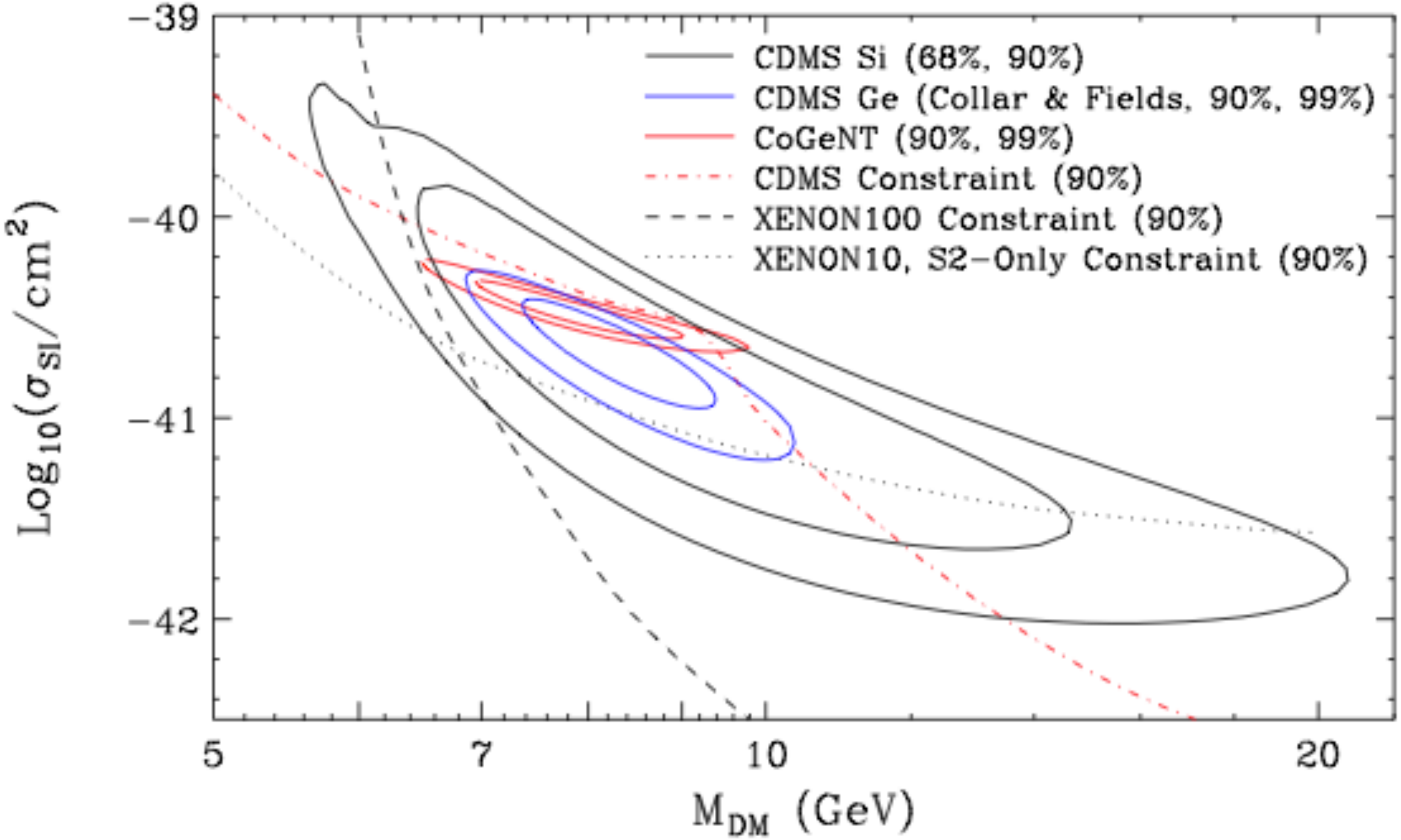


The Large Underground Xenon (LUX) experiment

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	Postdoc
Victor Gehman	Scientist
Mia Ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv.
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
Matthew Szydagis	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

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

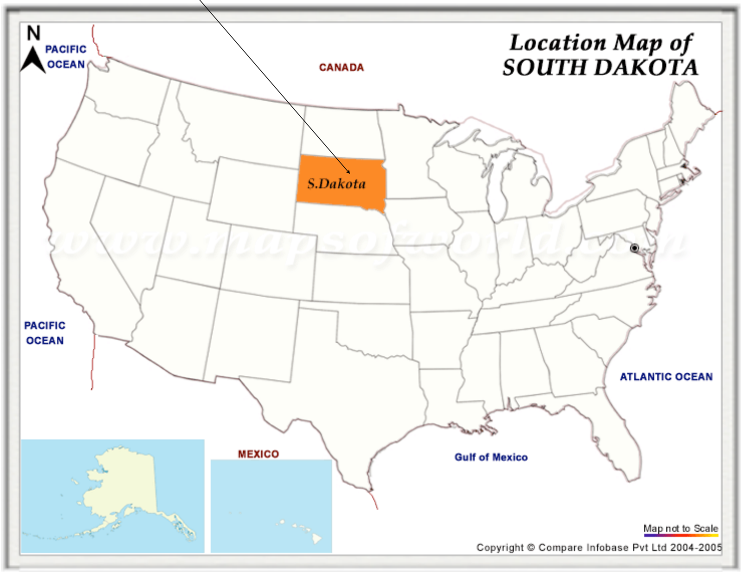
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

Yale

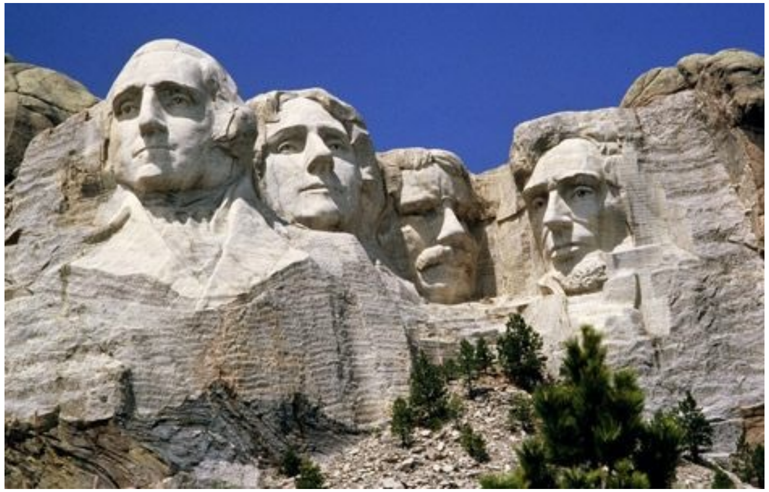
Daniel McKinsey	PI, Professor
Peter Parker	Professor
Sidney Cahn	Lecturer/Research
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg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

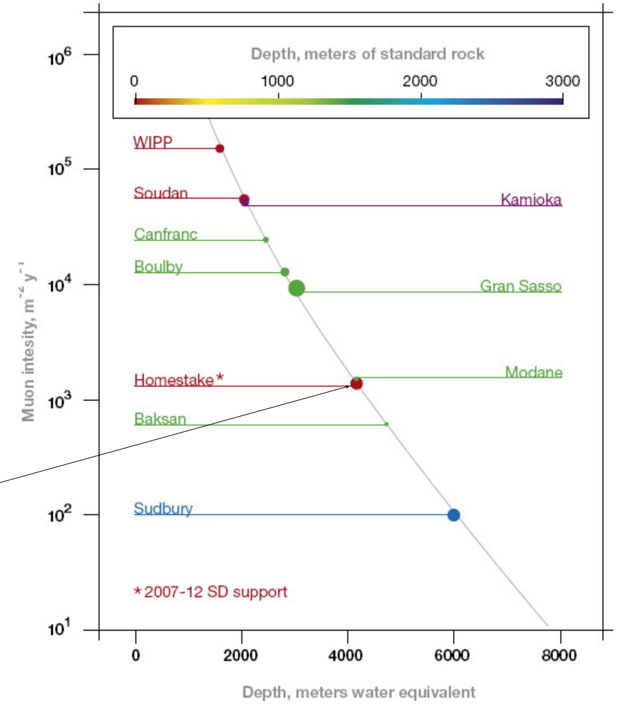
Sanford Underground Research Facility (SURF)

Lead, SD, located in Black Hills



Former Homestake gold mine - refurbished for science only

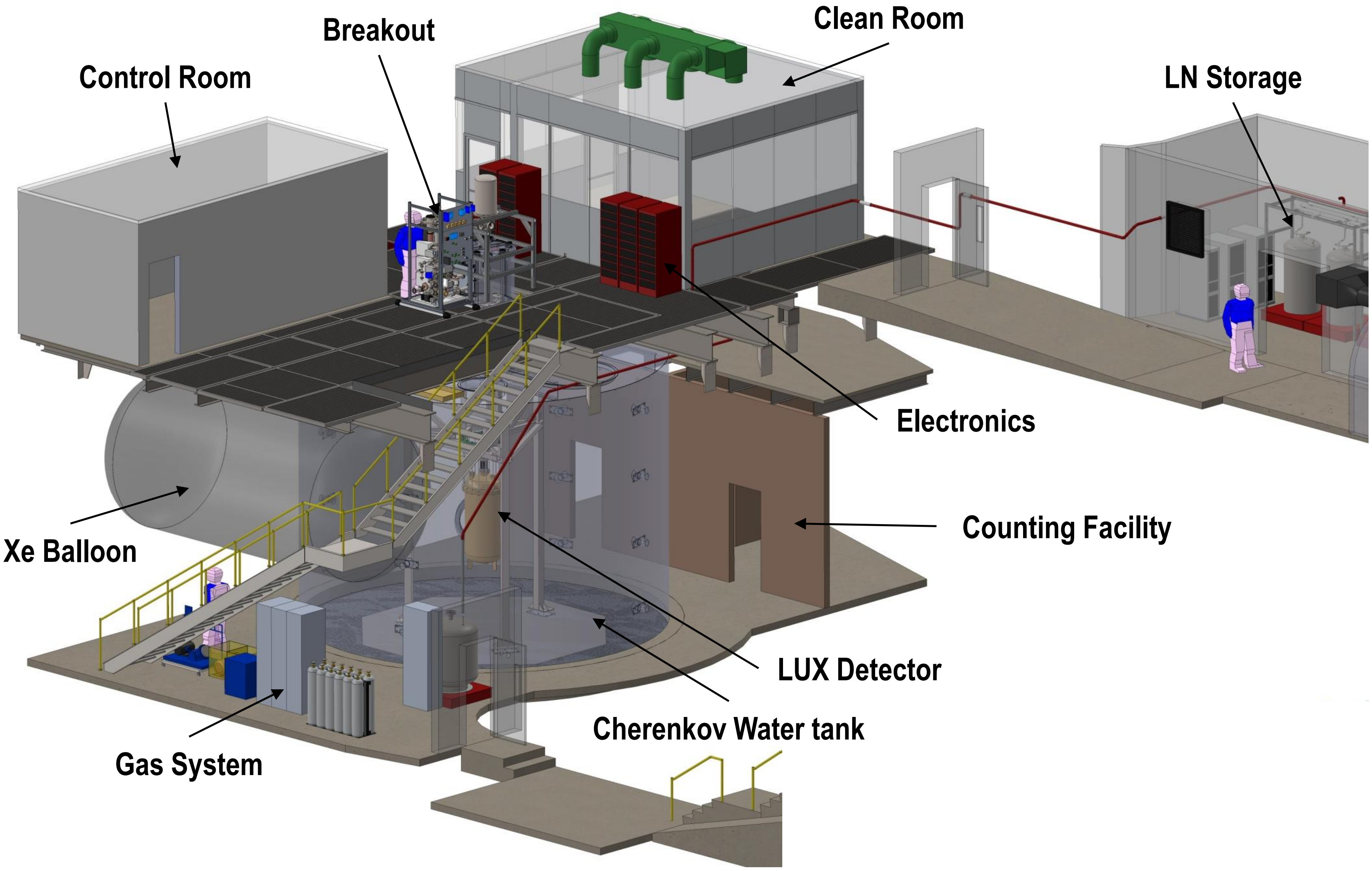




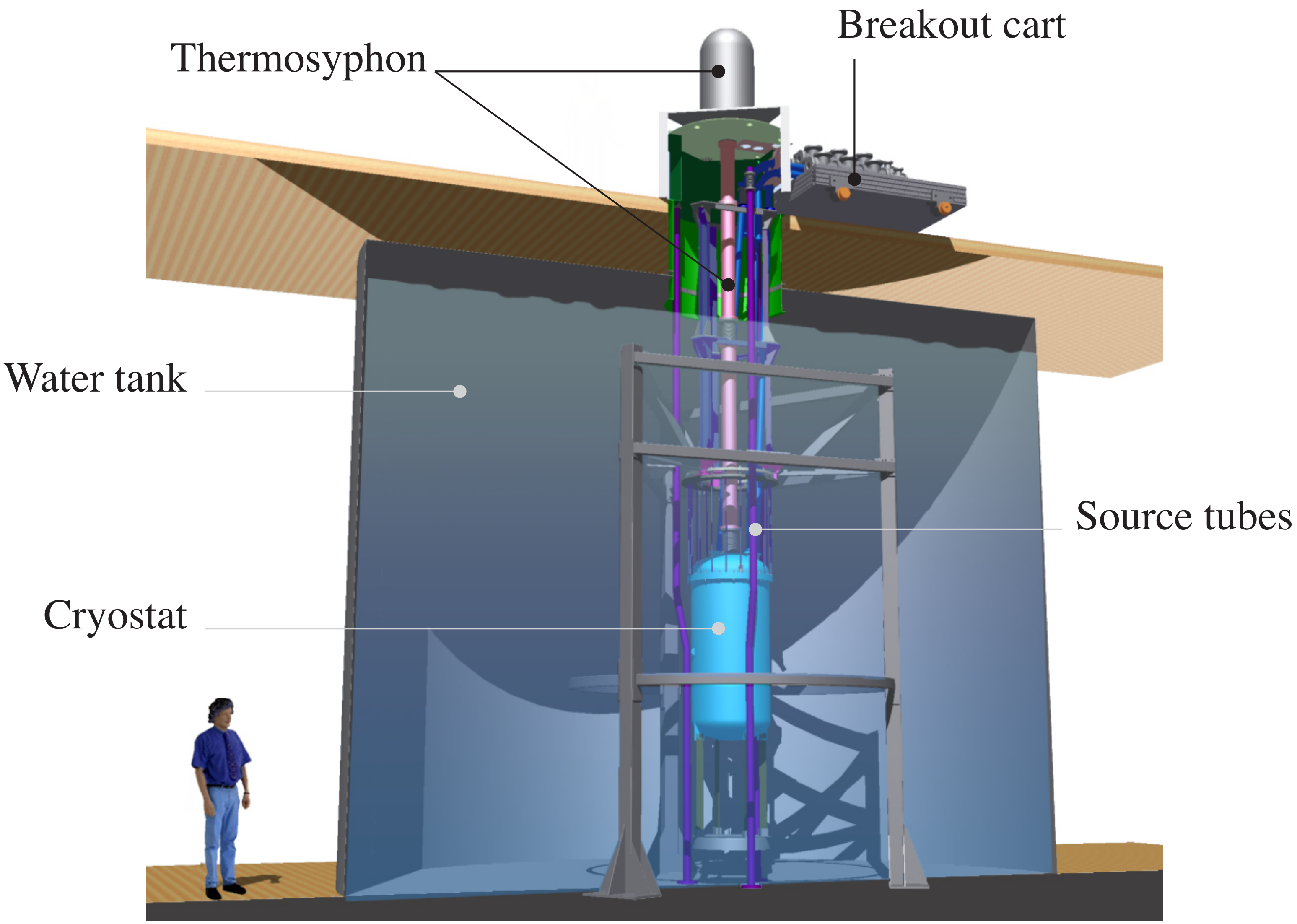
Muon flux at 4850' level reduced by 10^7

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

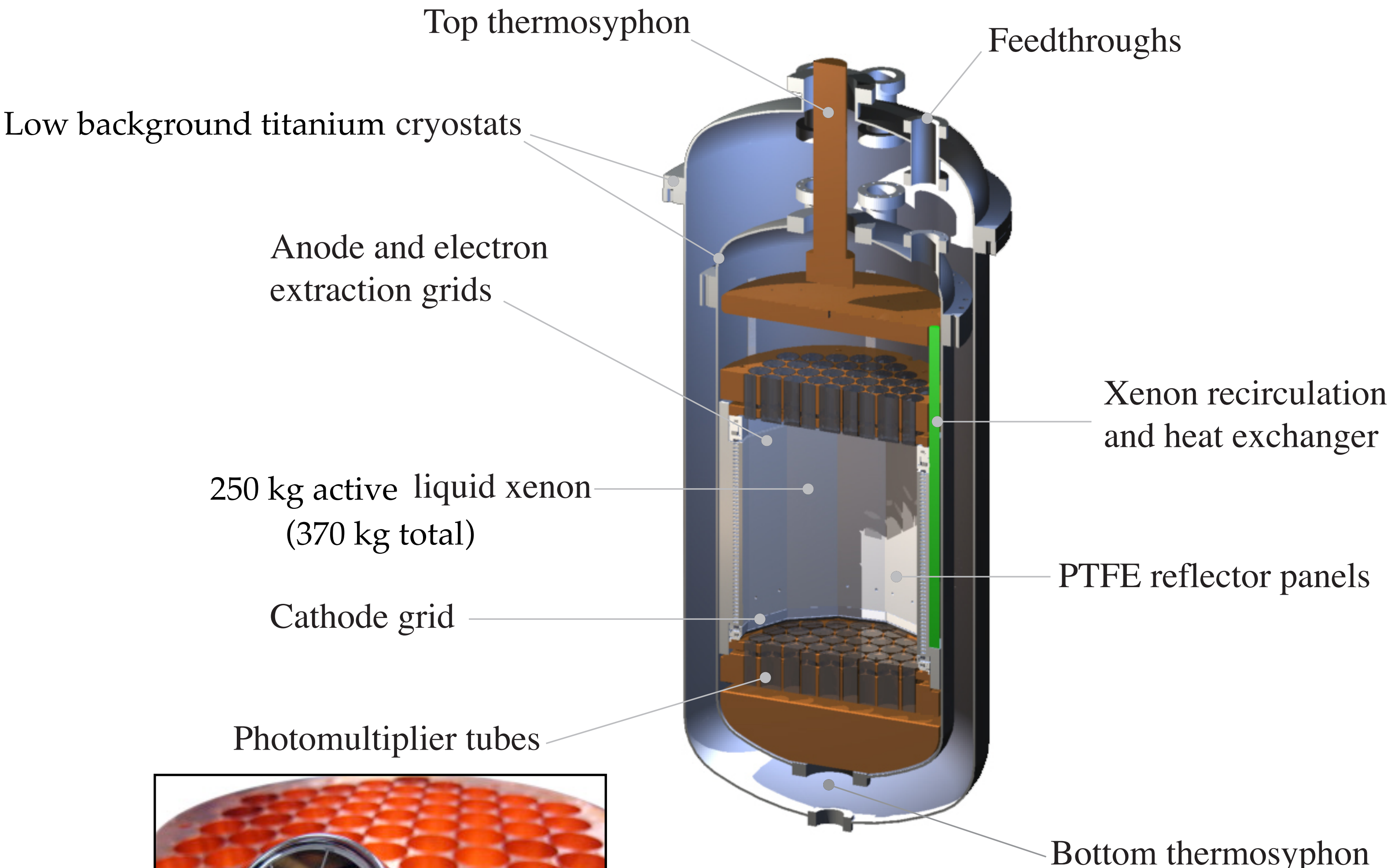
LUX in the Davis Cavern

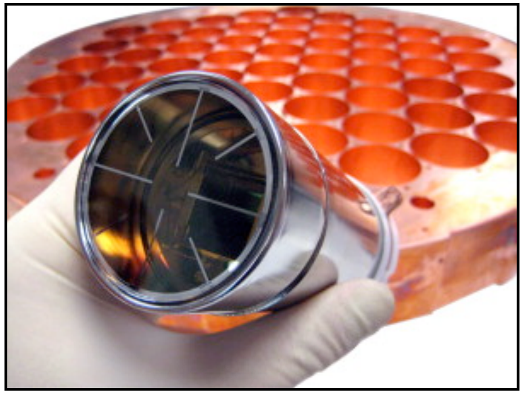


An ultra low background environment



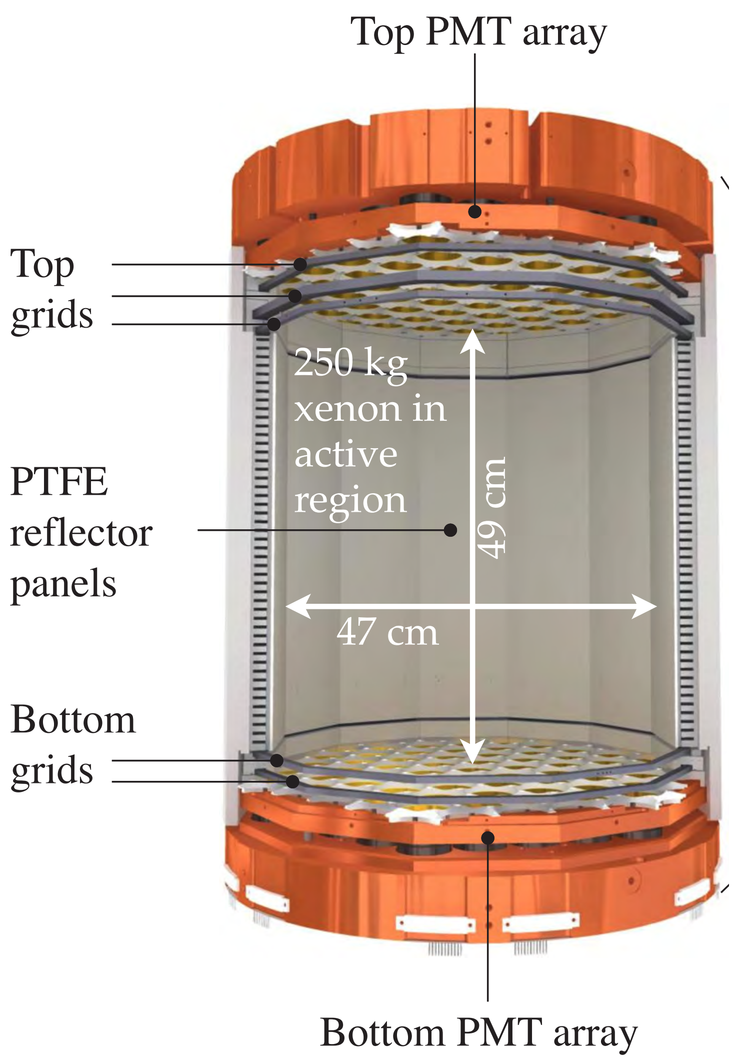
The LUX cryostat



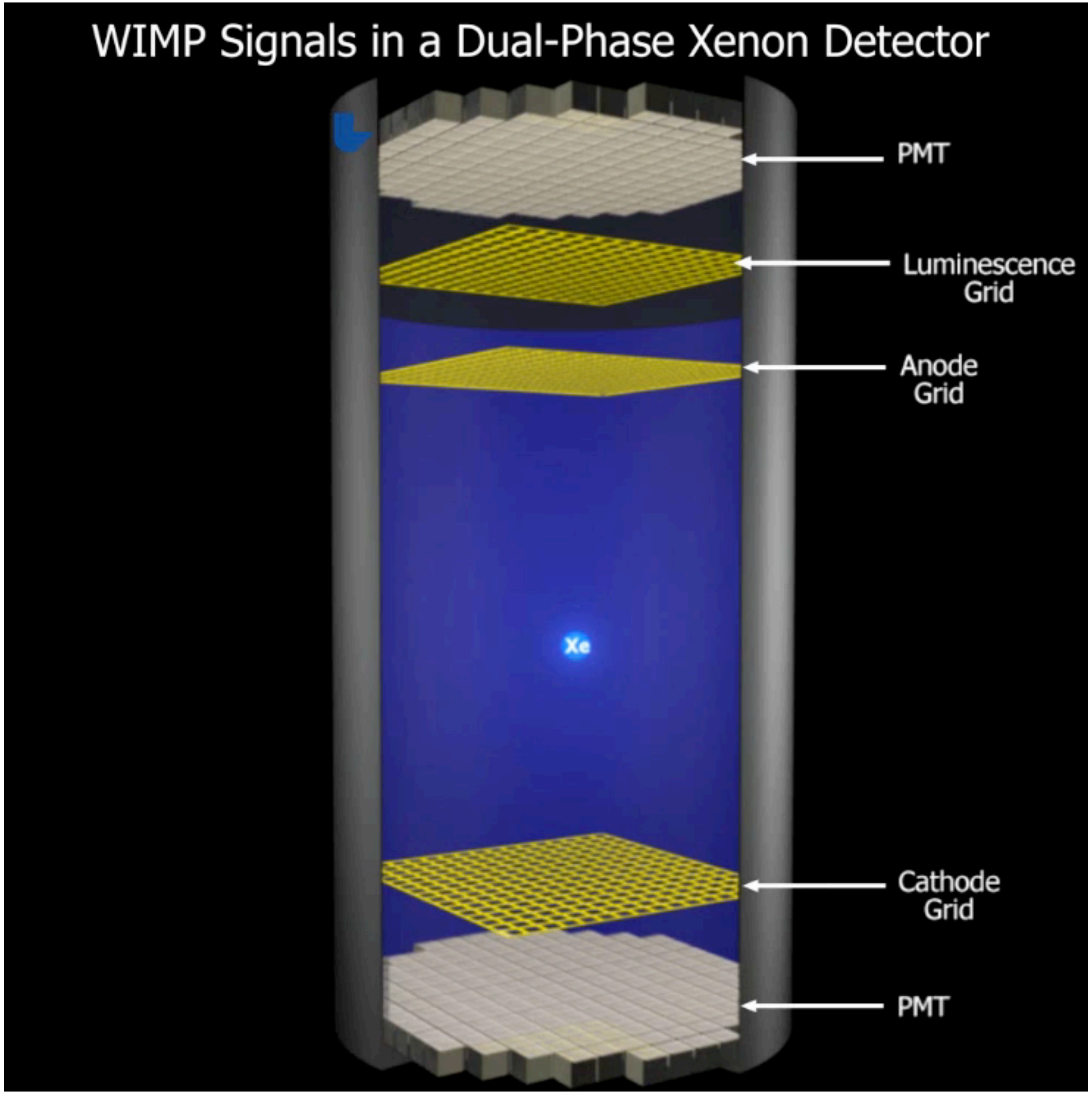


Hamamatsu R8778 PMTs (61 top, 61 bottom)

The active region of LUX

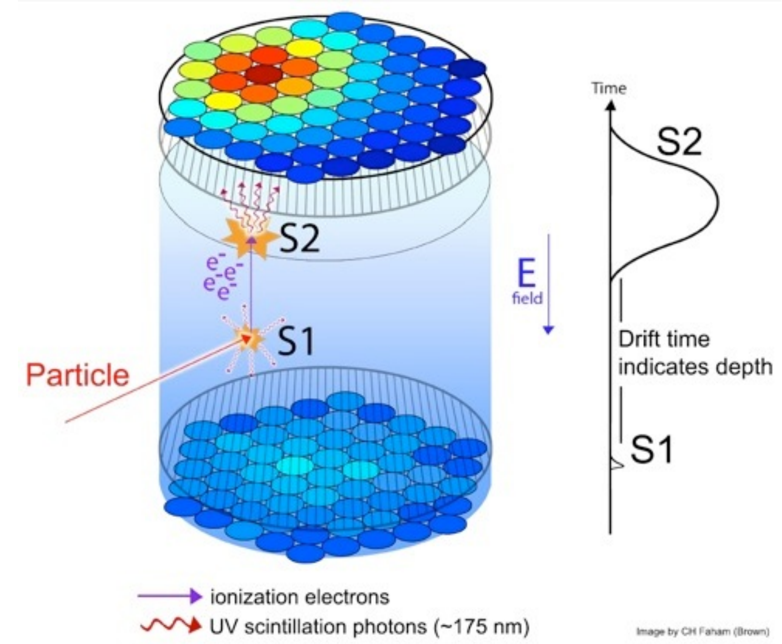


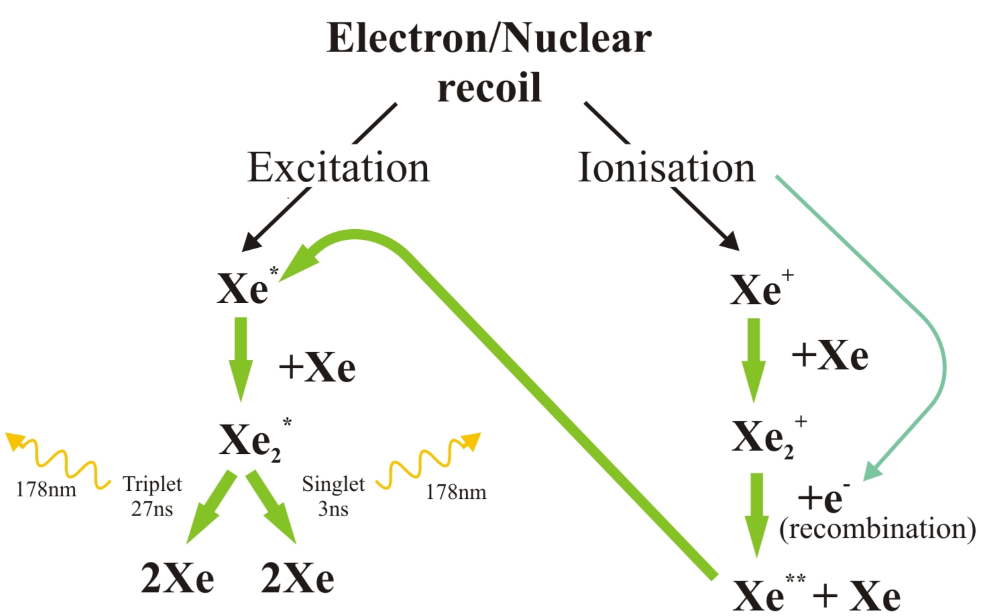
Principle of detection: dual phase xenon TPC

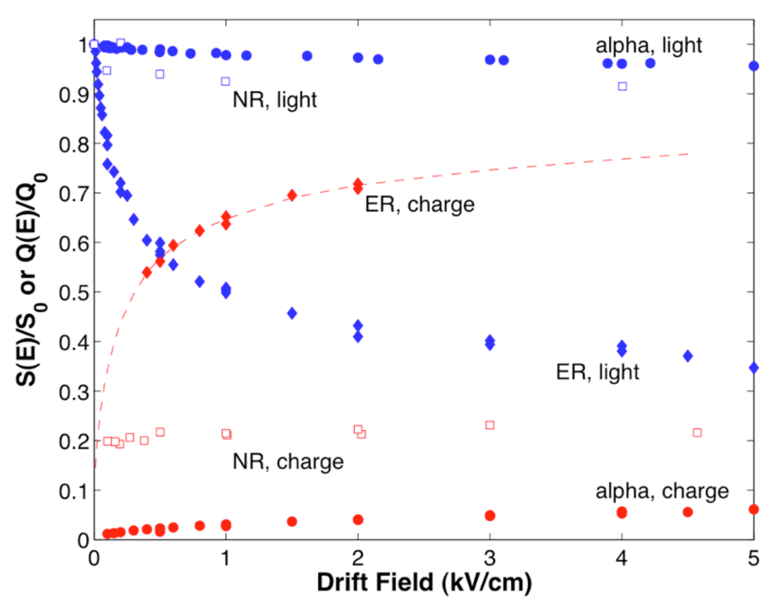


Principle of detection: dual phase xenon TPC

- Primary scintillation (S1) and secondary ionization signal from electroluminescence (S2)
- 3D position (mm resolution)
- S2/S1 particle discrimination
- Recoil energy correlated to S1 and S2
- Powerful Xe self-shielding





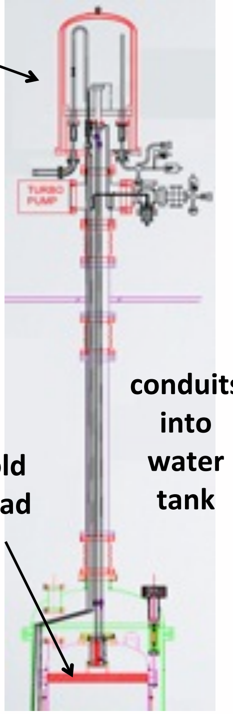


E. Aprile et al., Phys. Rev. Lett. **97**, 081302 (2006)

LUX supporting systems

Circulation gas and sampling

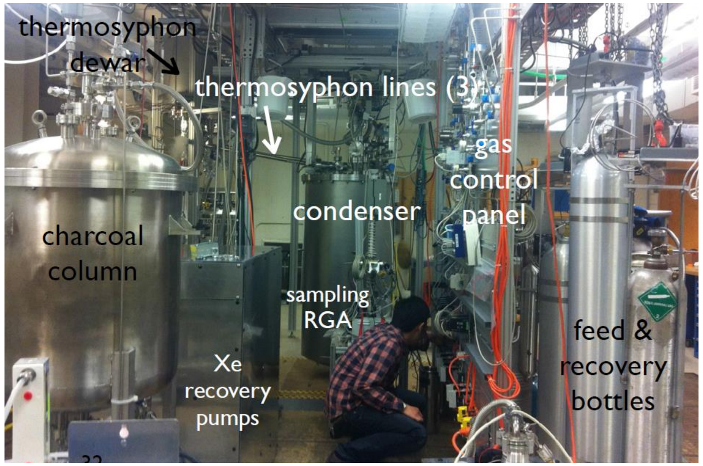
Thermosyphon



LUX Thermosyphon

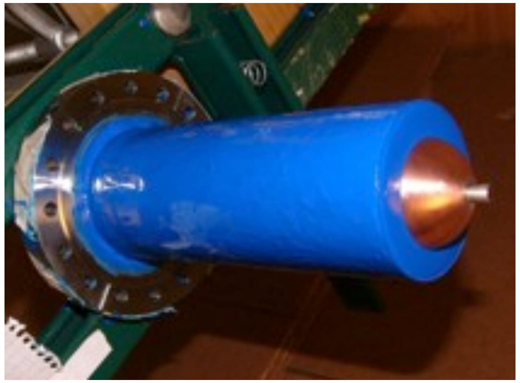
Xe storage

Kr removal facility

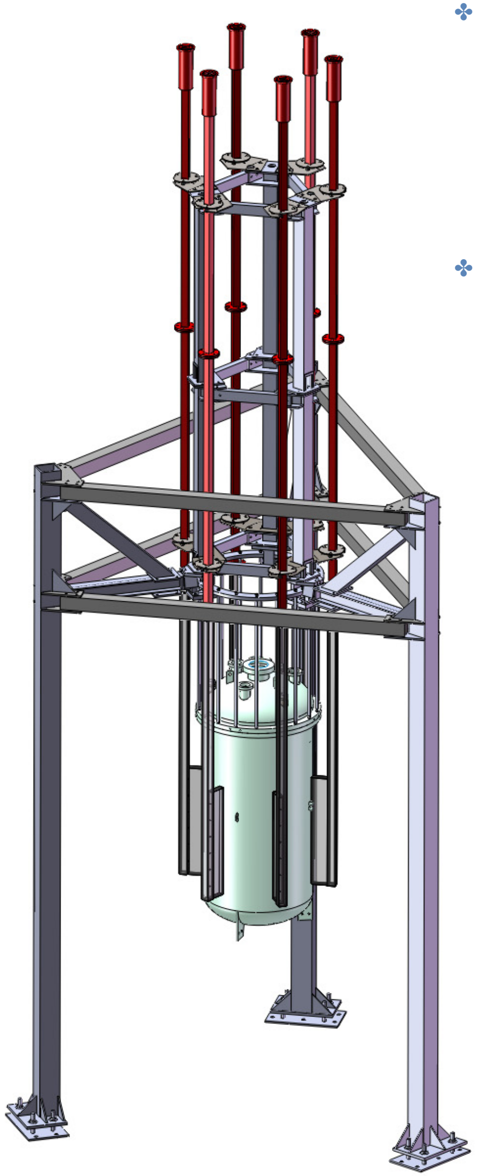


130 ppb to 3.5 ppt!

Cathode HV feedthrough



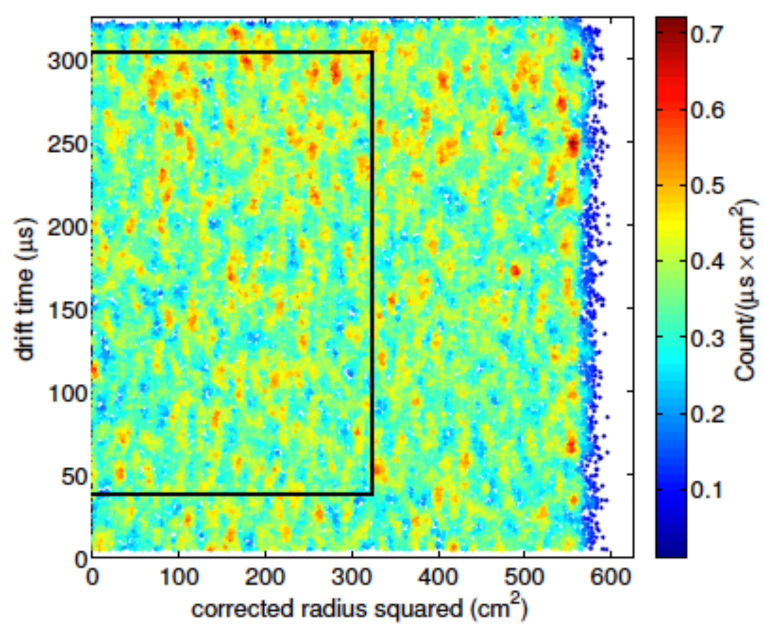
Calibrating LUX



- External sources via source tubes:
  - Americium-beryllium (AmBe) and ^{252}Cf: low energy neutrons → validating NR models and detector sims, NR efficiencies

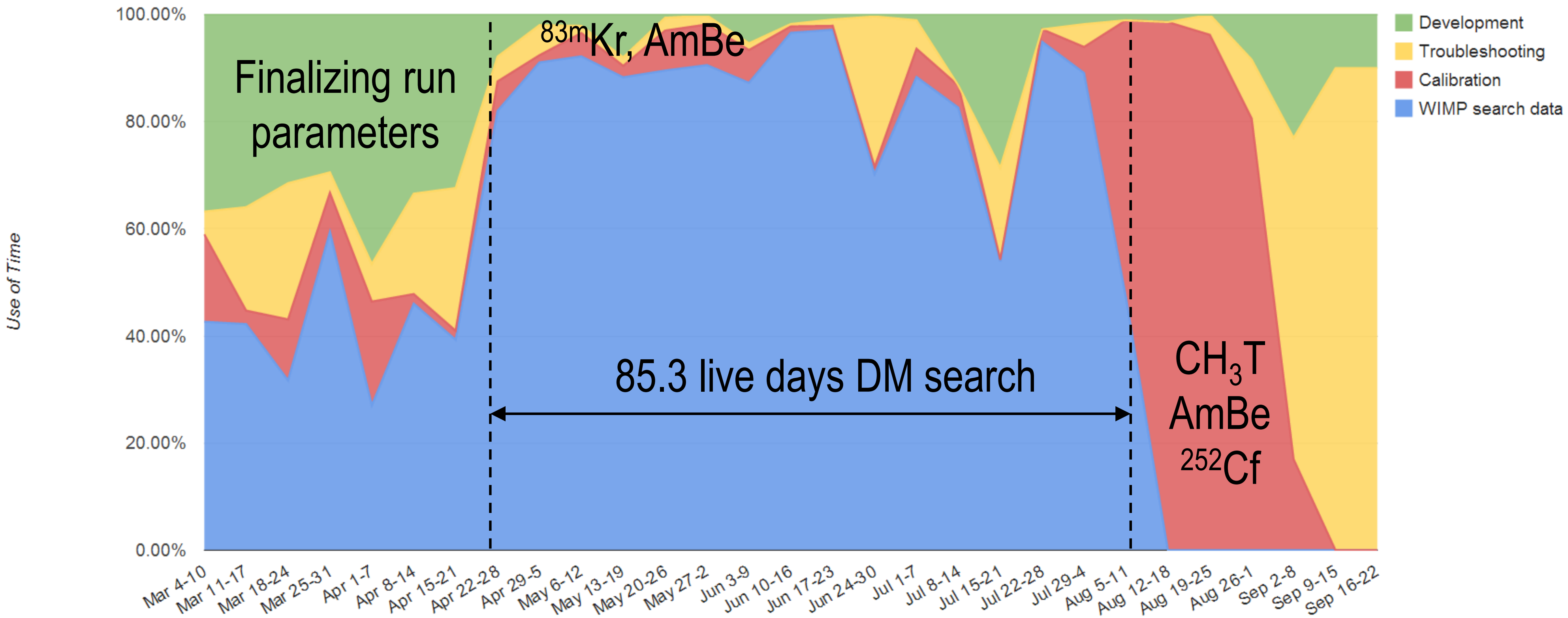
WIMP-like

- Xenon self-shielding → internal sources injected into circulation system:
  - ^{83m}Kr: half-life ~1.8 hours, 32.1 + 9.4 keV betas → weekly purity & xyz maps; drift length >130 cm
  - Tritiated methane (CH3T): low energy betas (end point 18 keV) High stats, uniform and high purity → ER band, ER acceptance



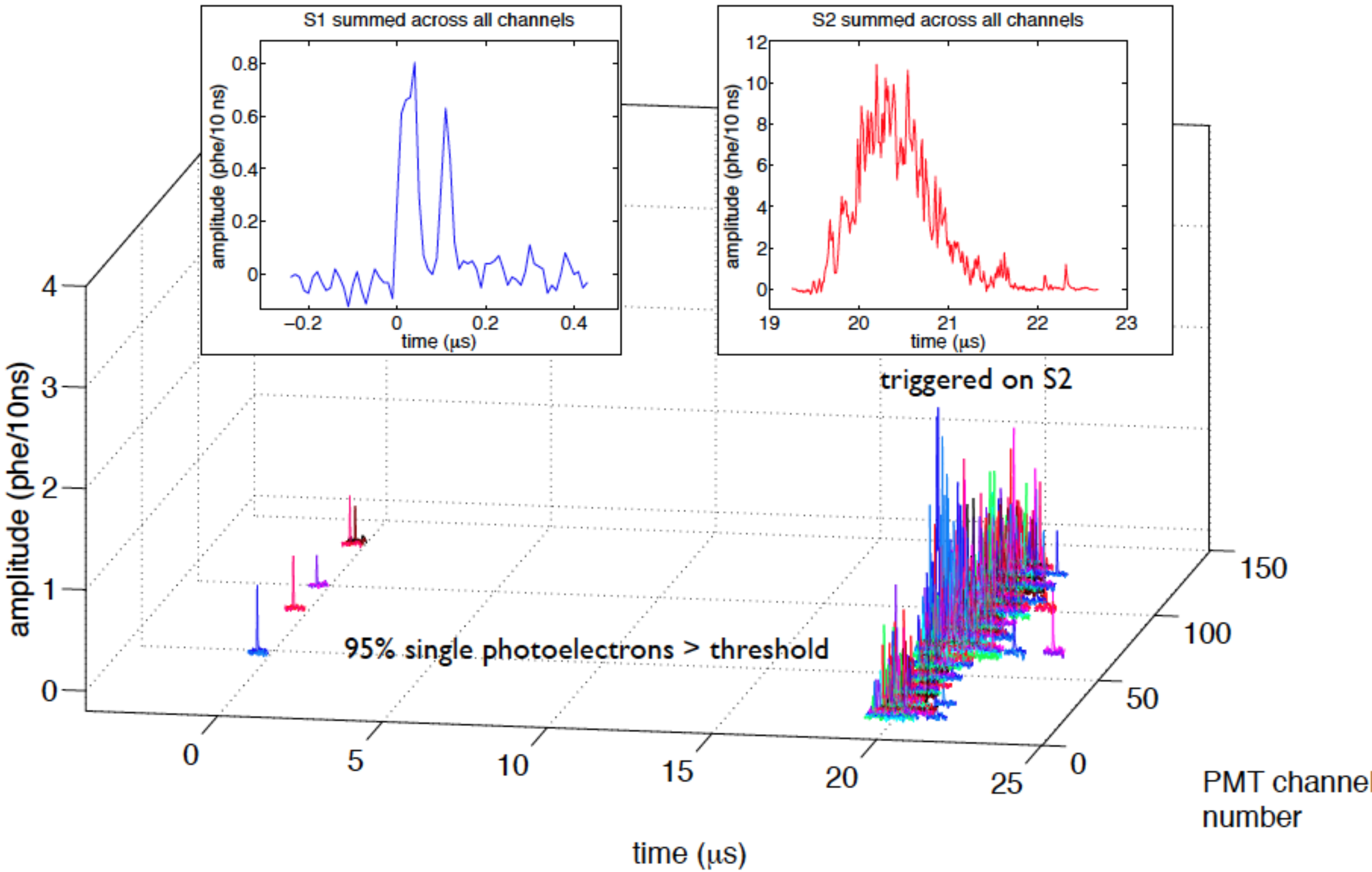
First dark matter results from LUX

Run 3 data-taking



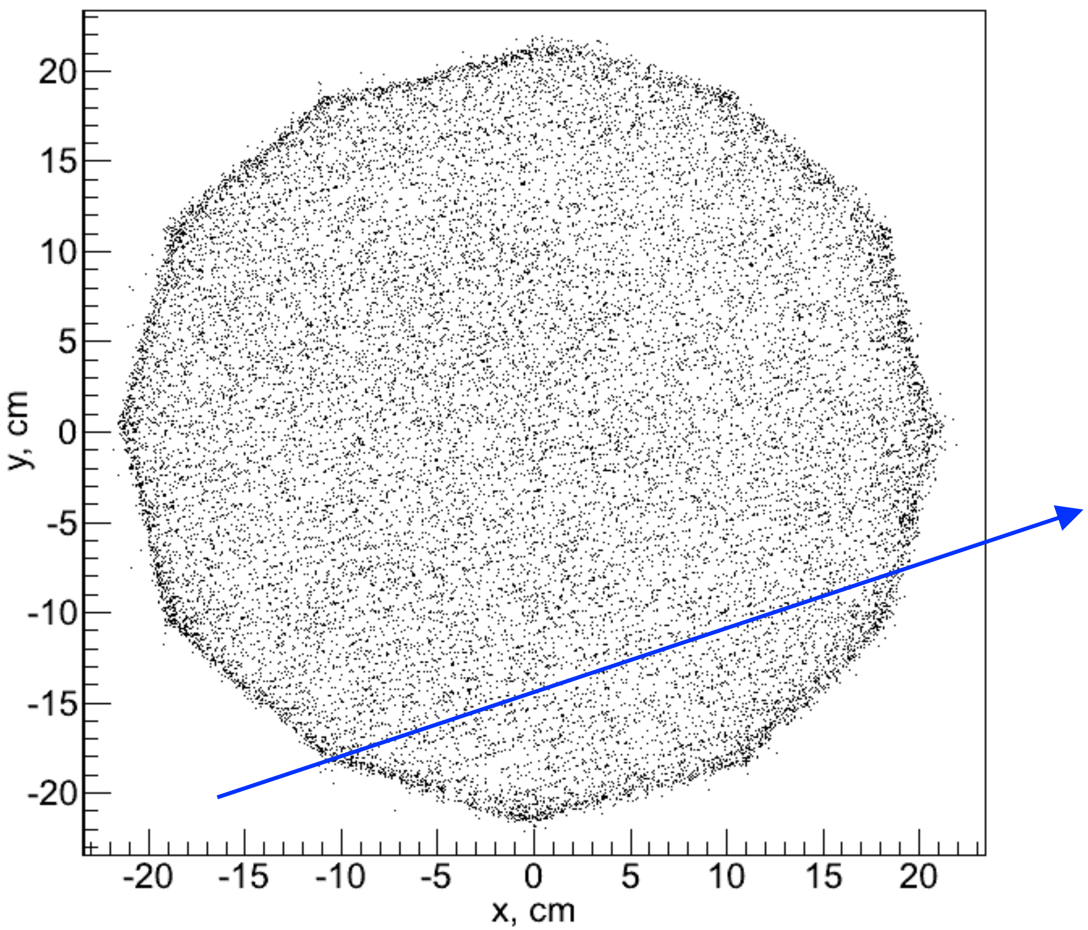
- LUX moves underground in July 2012
- Detector cool-down January 2013, Xe condensed mid-February 2013
- Kr and AmBe calibrations throughout, CH3T after WIMP search

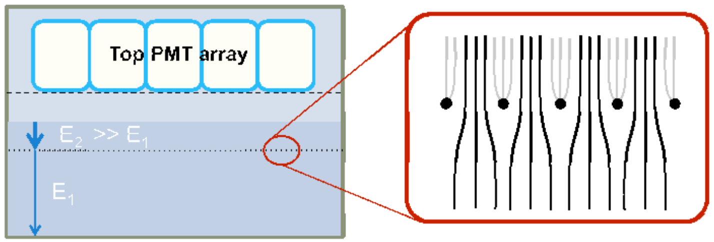
A LUX event - 1.5 keV electron recoil

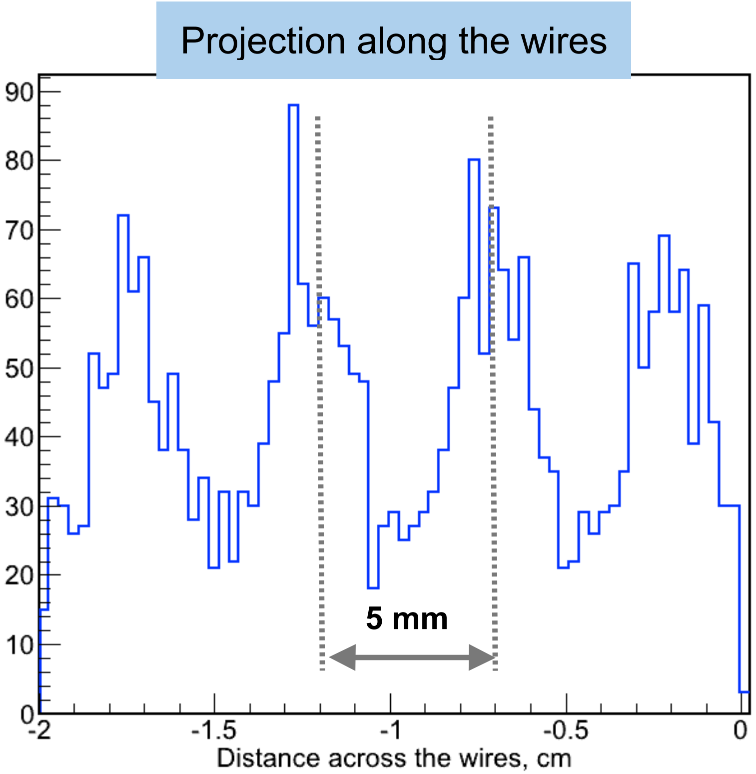


Position reconstruction

- Drift time (1.5 mm/μs) for Z-position,
- XY position fitting S2 hit pattern with LRFs from internal calibrations

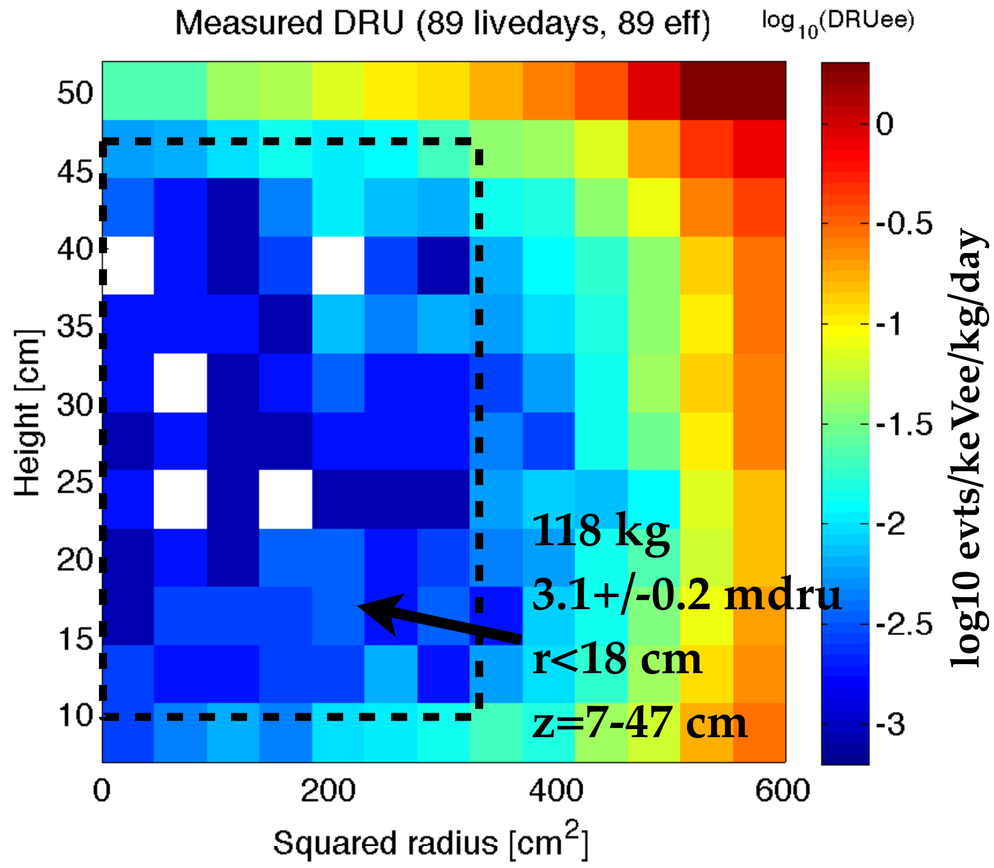






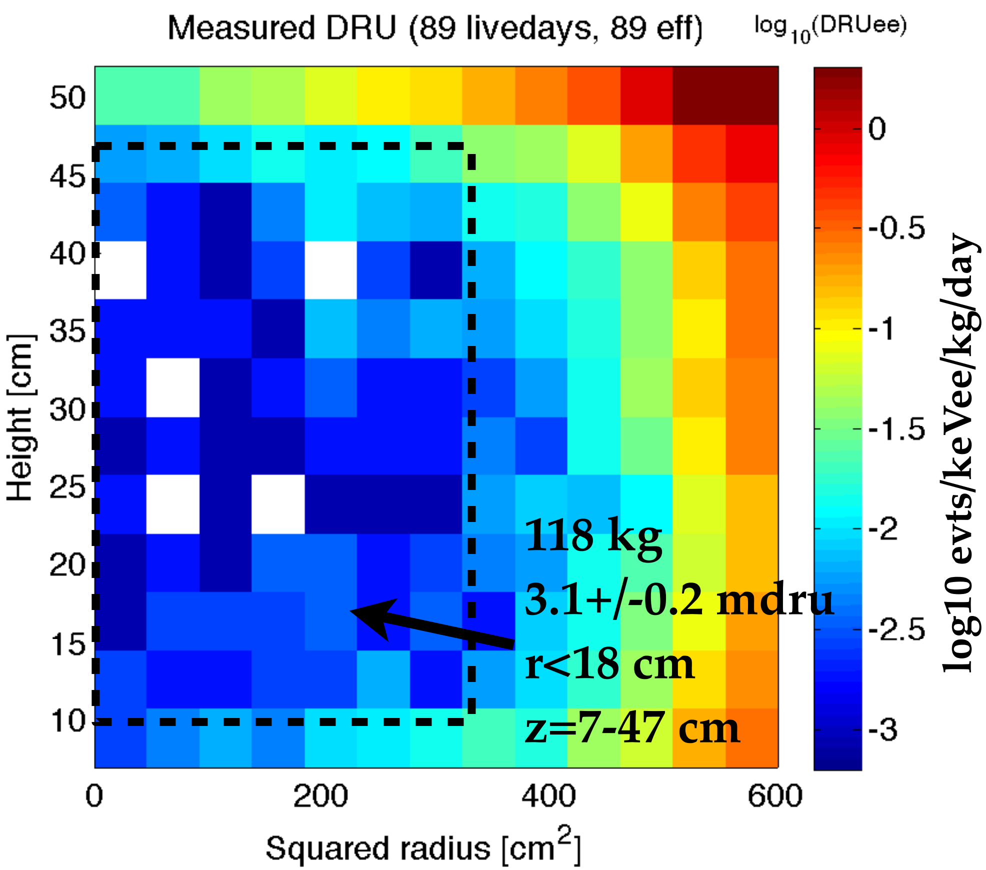
Backgrounds in LUX

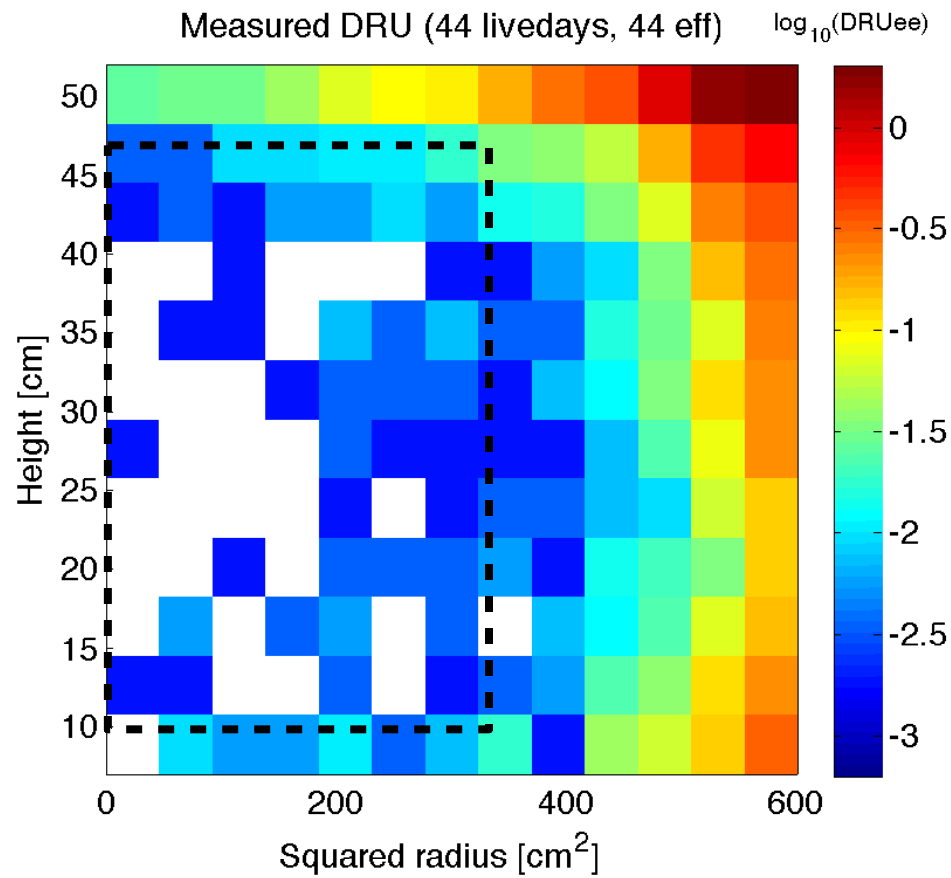
Source	Background rate, $mDRU_{ee}$
γ-rays	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	0.11–0.22 (90% C. L.)
^{85}Kr	$0.13 \pm 0.07_{sys}$
Total predicted	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Total observed	$3.1 \pm 0.2_{stat}$



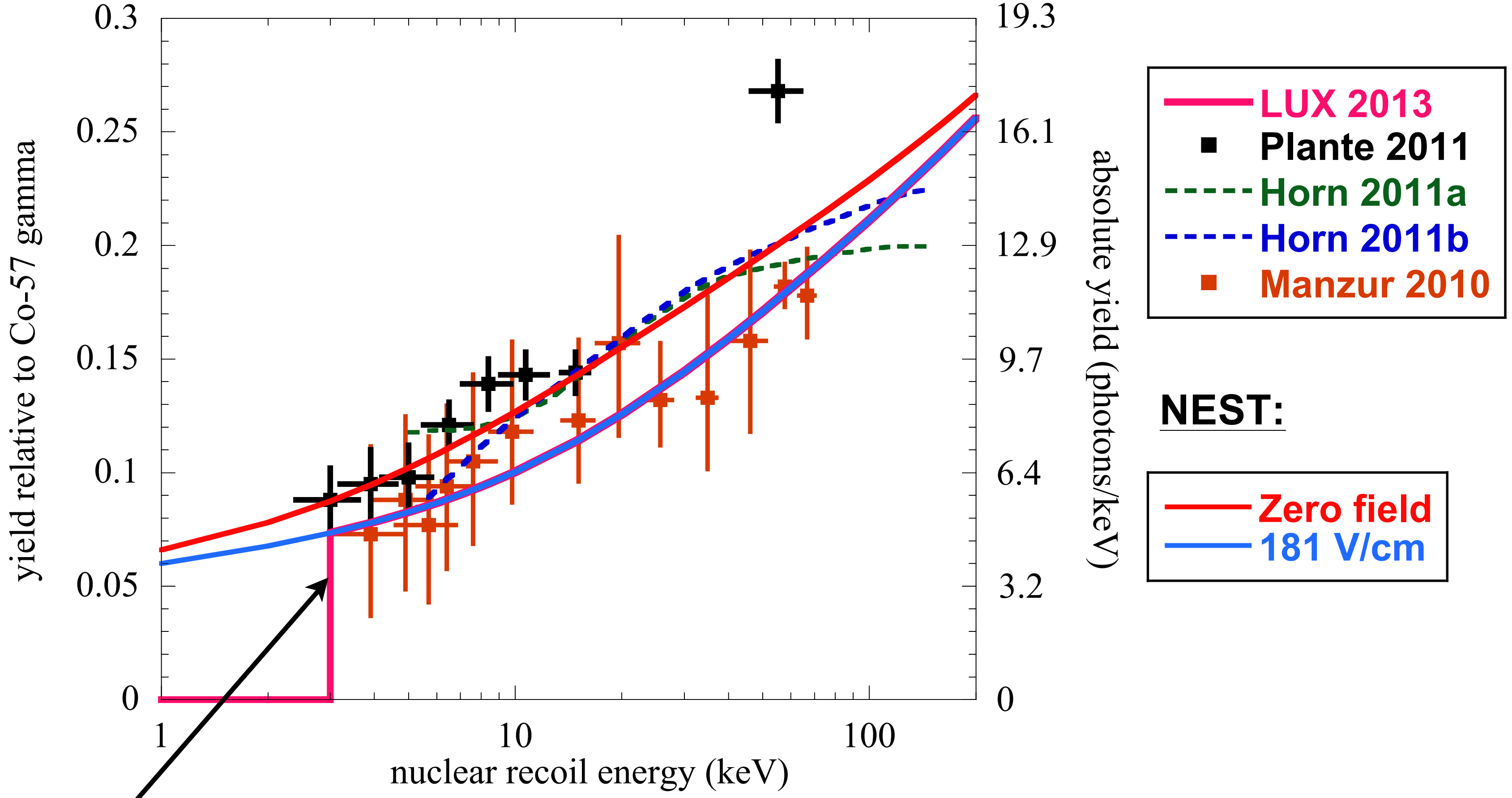
The most radioactively quiet place in the world!

…and still dropping!





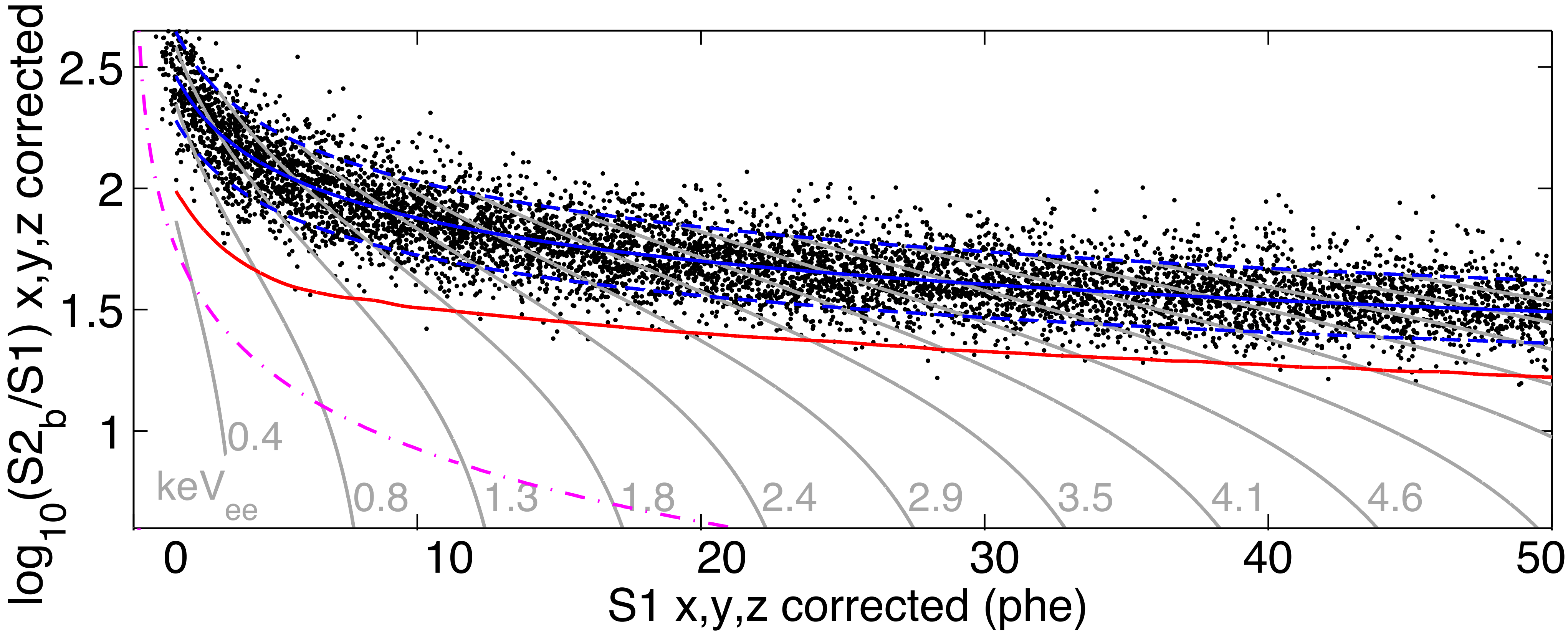
Light and charge yields



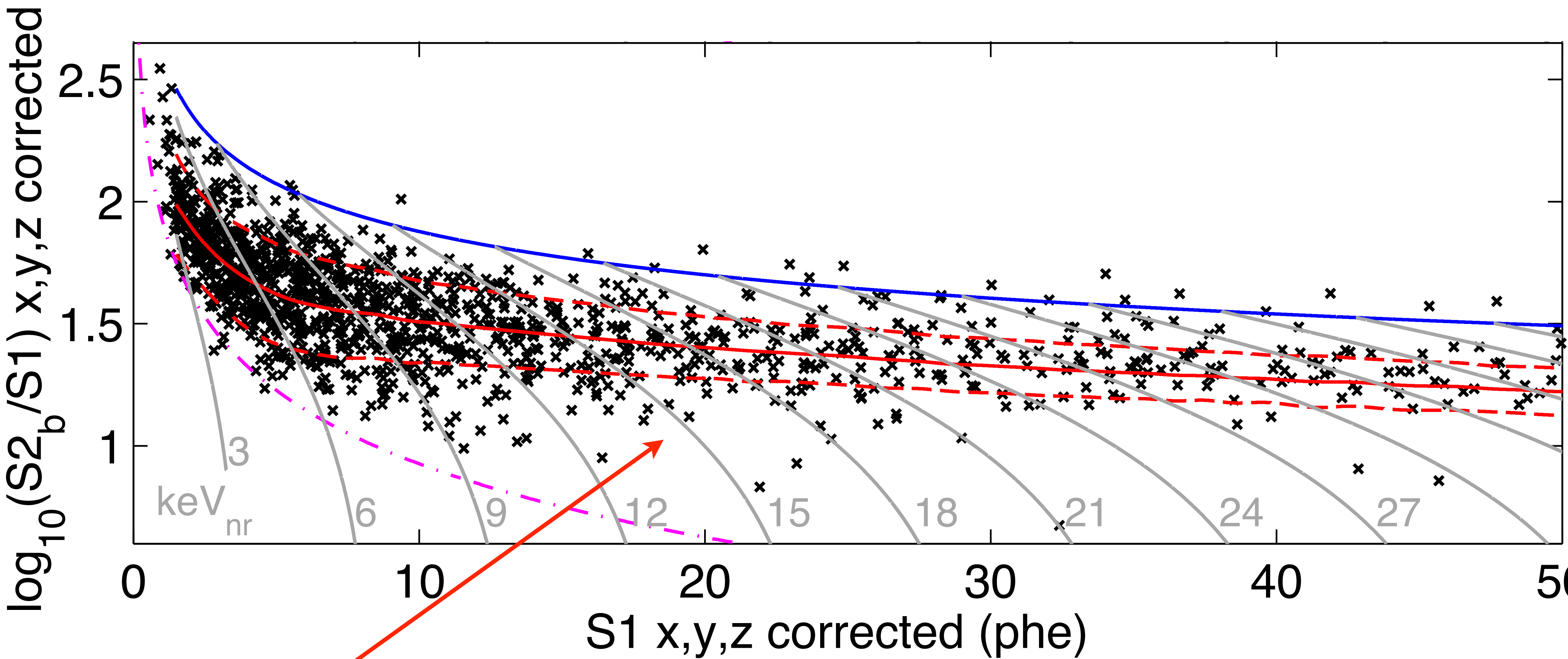
⇒ set hard threshold at 3 keVnr
Very conservative!

Photon detection efficiency: **14%**
Charge yield: **26 phe/e$^-$**

Tritium Calibration

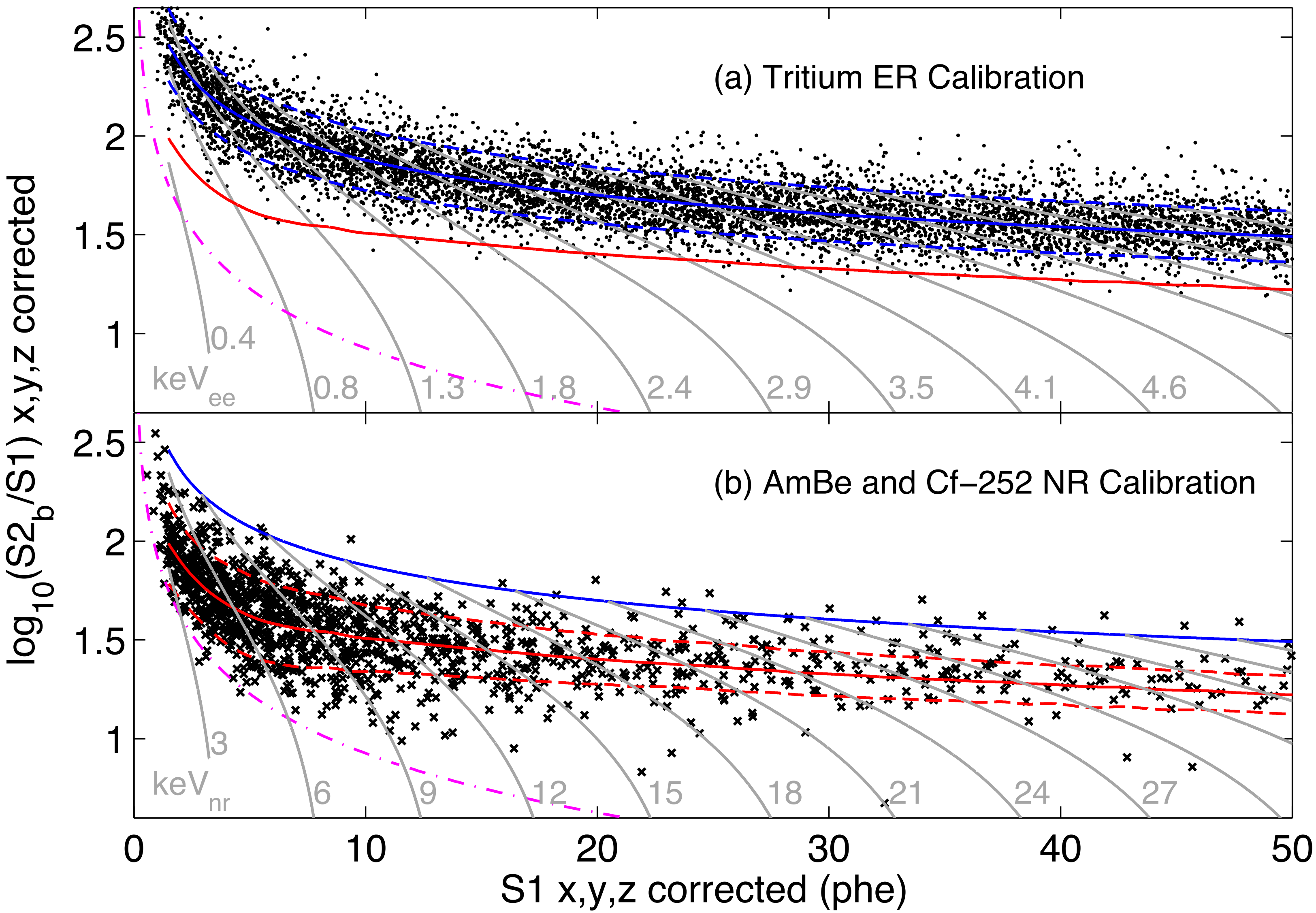


^{241}AmBe & ^{252}Cf calibration



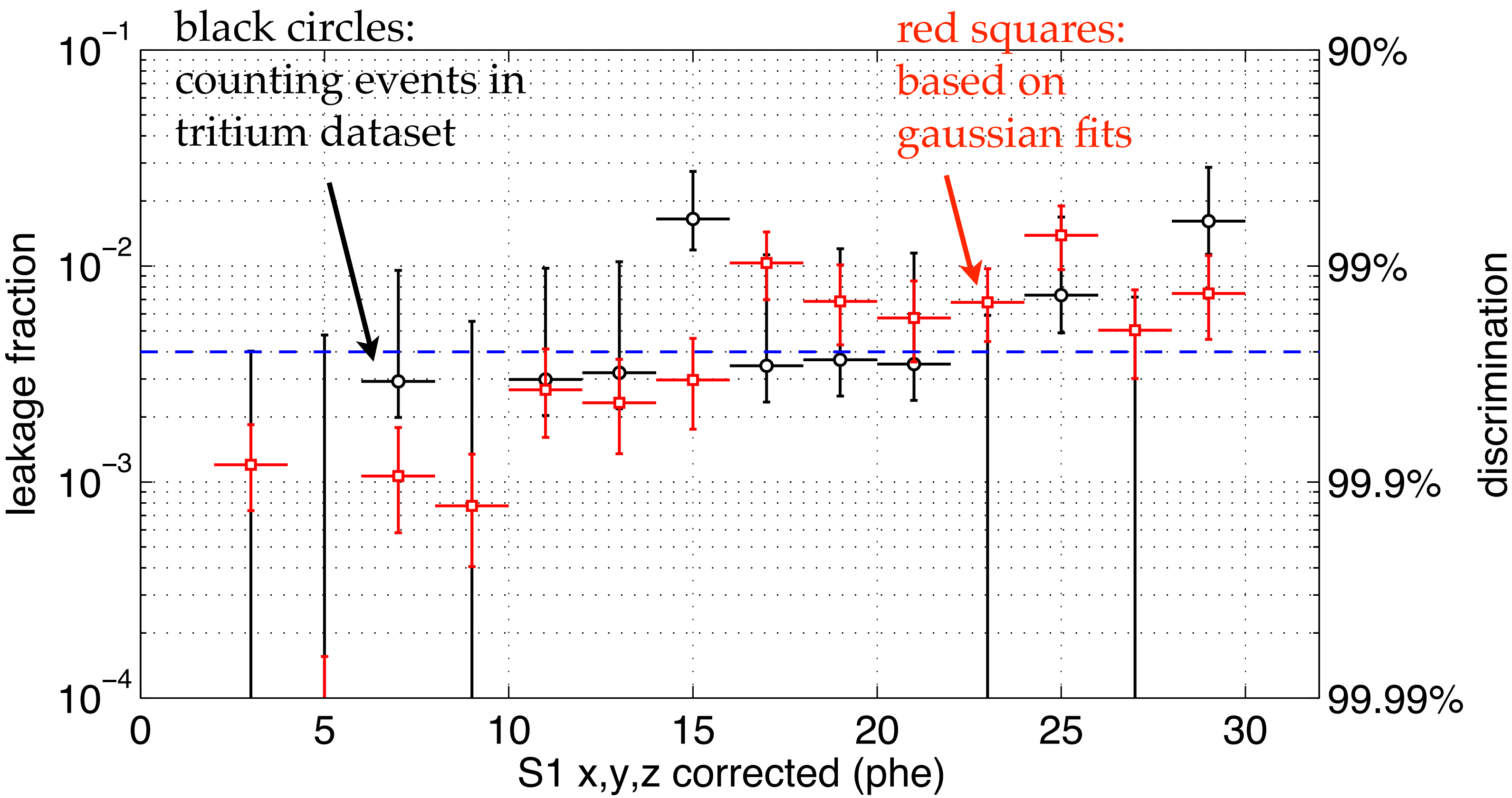
NeutronX and multiple scatters in calibration, but not WIMP data

Calibrations



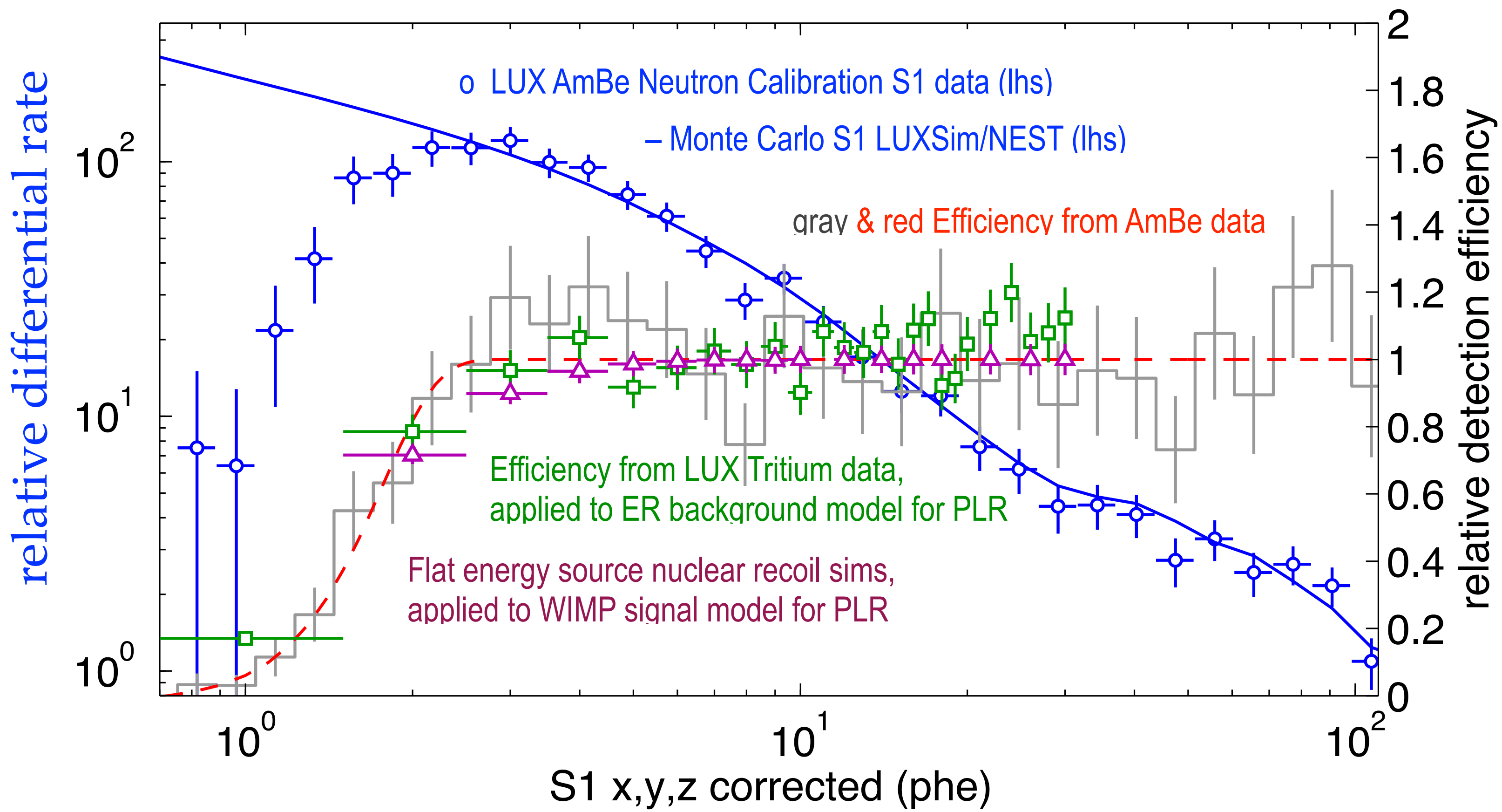
Discrimination

- For 50% NR acceptance at 181 V/cm average discrimination **99.6%**

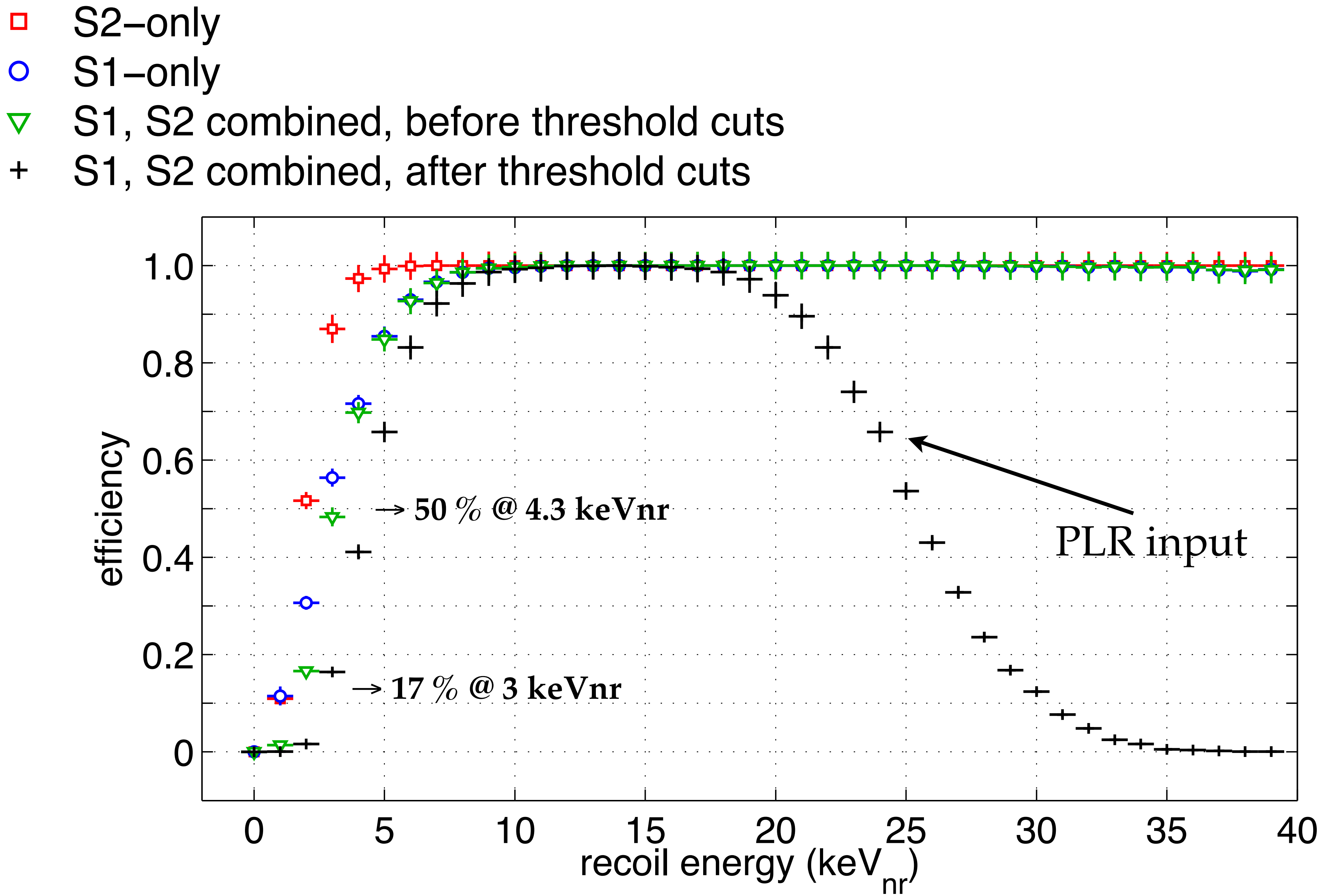


S1 efficiency

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



NR acceptance



Run 3 event selection and cuts

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!
- Hardware trigger: at least two trig. channels > 8 phe within 2 μs window (8 PMTs per trig. channel)
  - $>$ 99% efficient for raw S2 $>$ 200 phe

Run 3 event selection and cuts

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

- 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!

Run 3 event selection and cuts

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

- 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

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

- Accept events with S1 between 2-30 phe (0.9-5.3 keVee, ~3-18 keVnr):
  - 2 phe analysis threshold allows sensitivity down to low WIMP masses
  - Upper limit avoids ^{127}Xe 5 keVee activation

Run 3 event selection and cuts

Cut	Events Remaining
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single scatter	6,585,686
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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

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detector stability	82,918,902
single scatter	6,585,686
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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 in 0.1-1 ms following large S2 signals
  - Only 0.8% hit on live-time

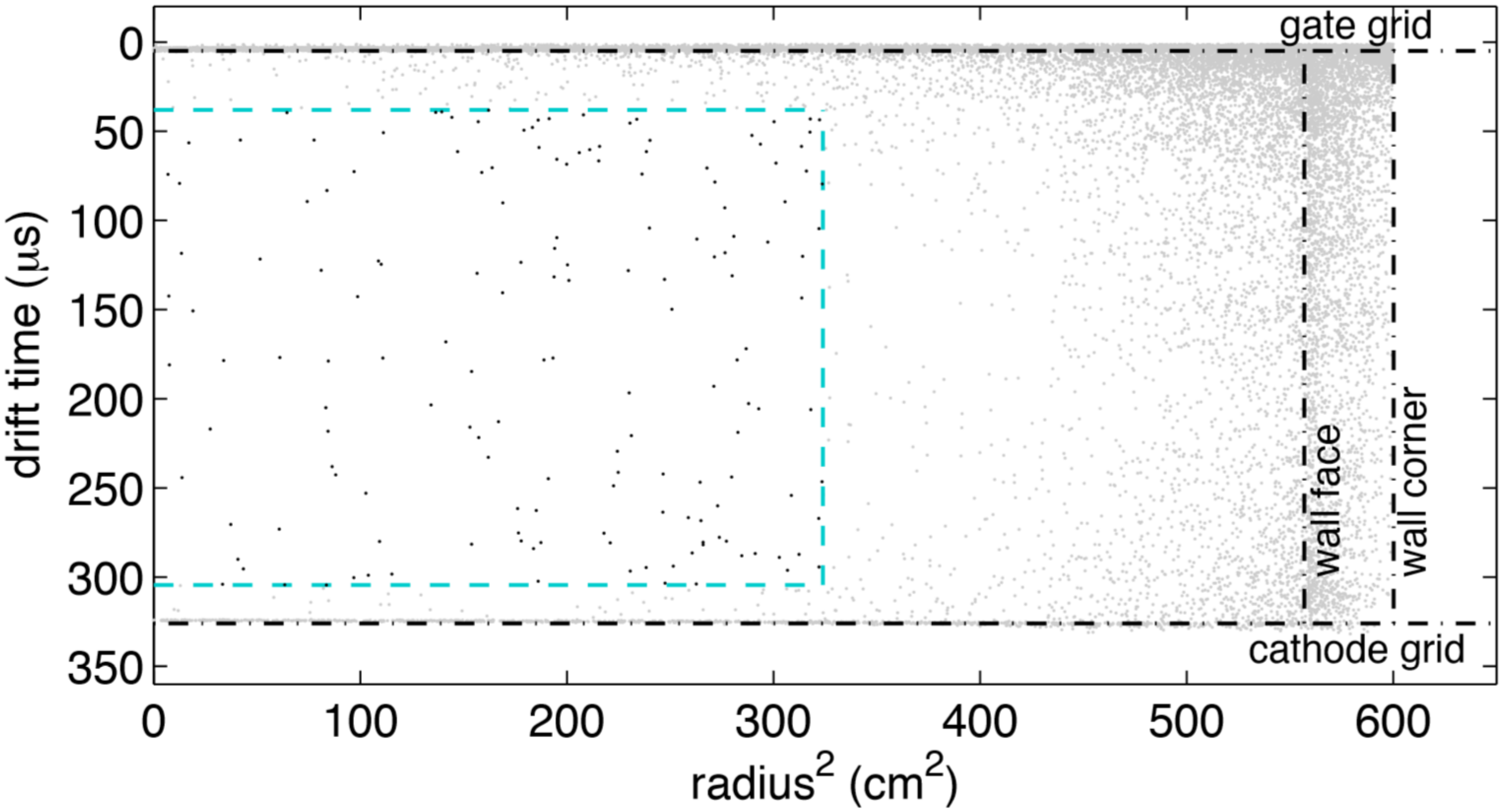
Run 3 event selection and cuts

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

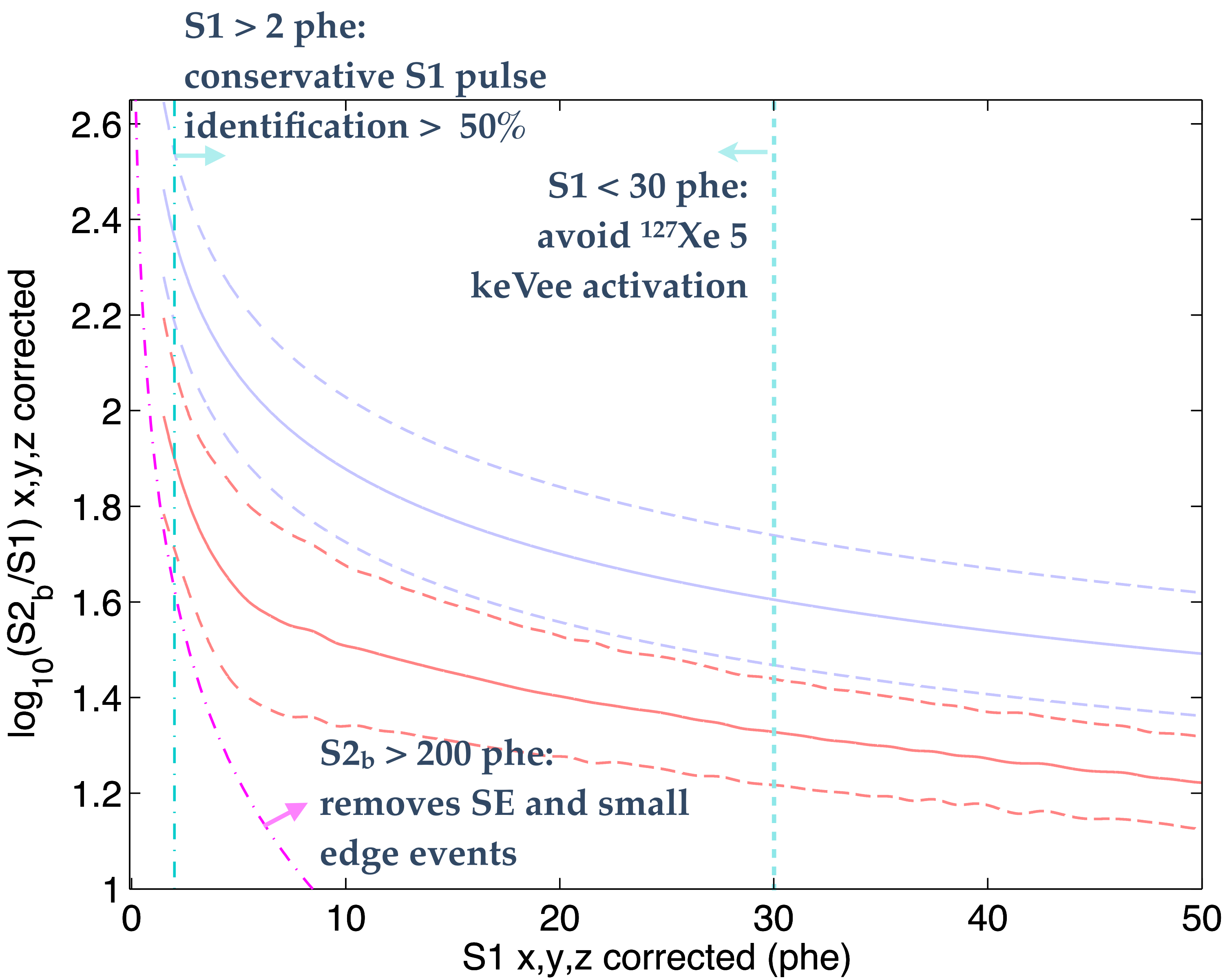
- 118 kg fiducial volume defined by:
  - Z cut: 38 < drift time < 305 μs (320 μs is max drift time)
  - Reconstructed radial position < 18 cm

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

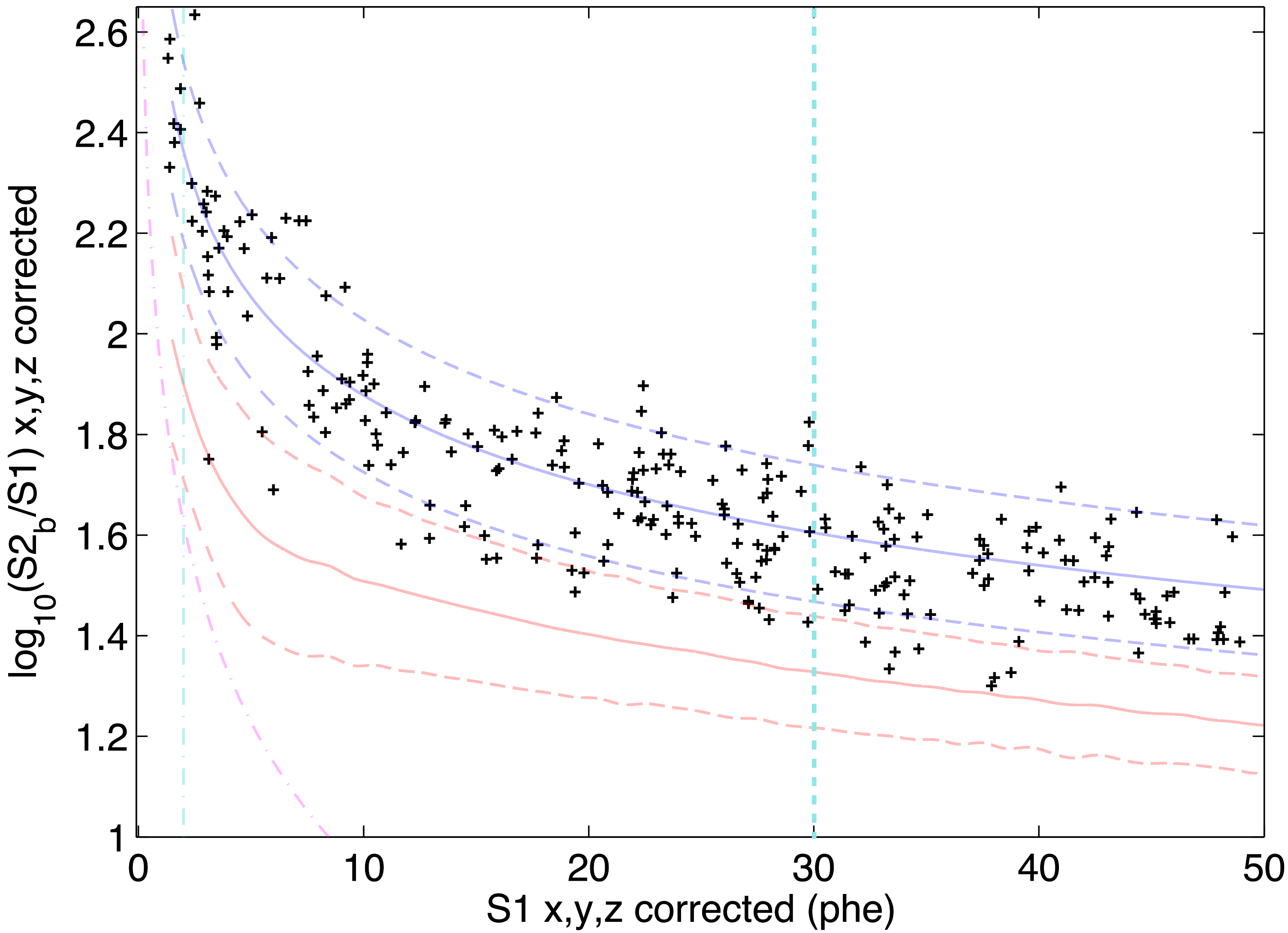
- After all selection cuts:
  160 candidate events in fiducial (r < 18 cm and 7 cm < z < 47 cm)



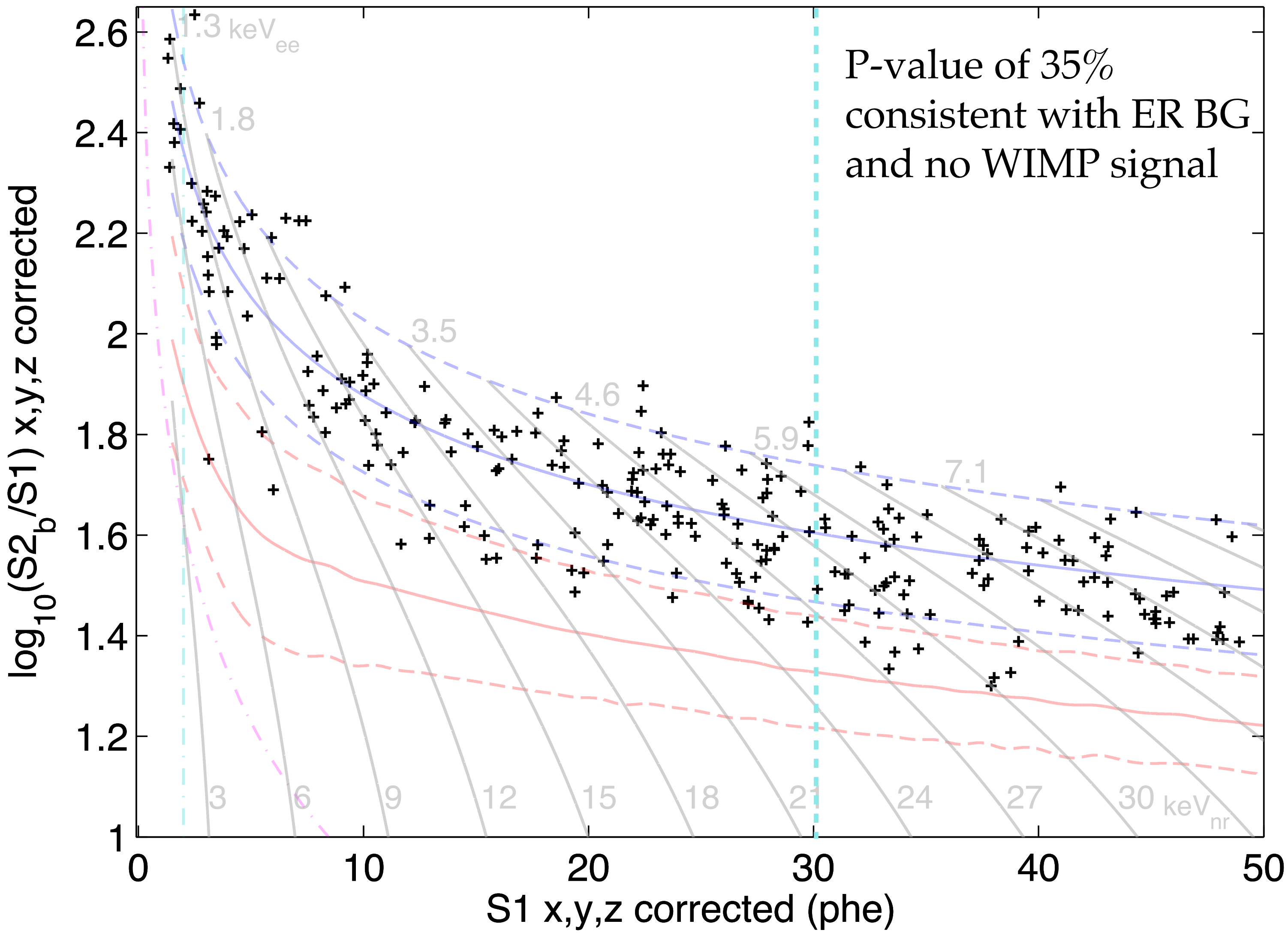
LUX WIMP search data, 85.3 live-days, 118 kg FV



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



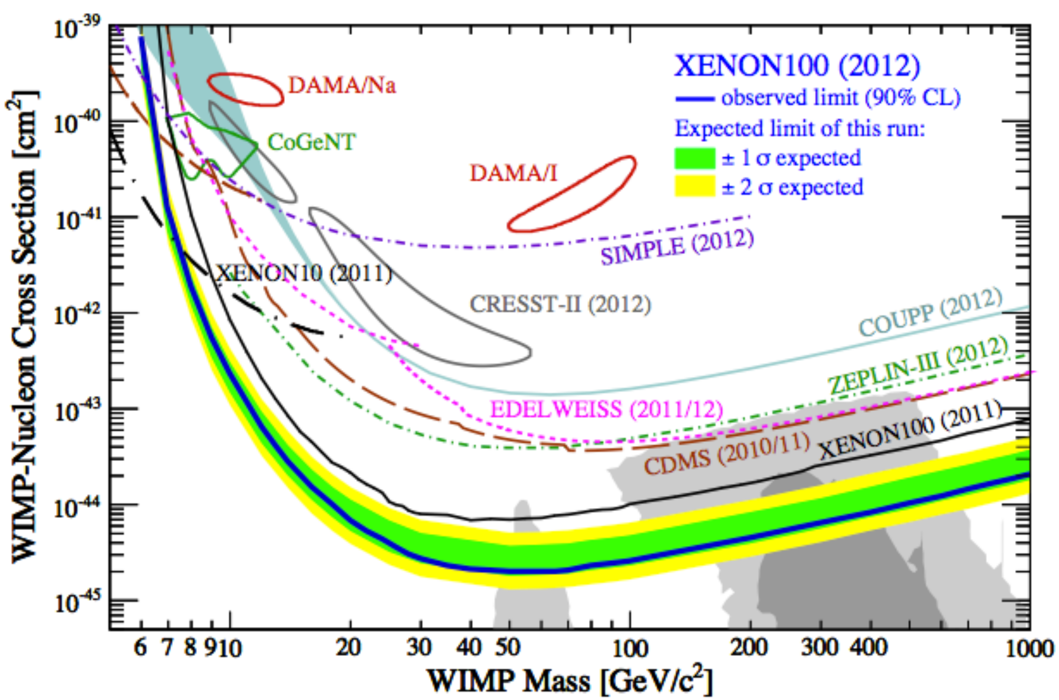
LUX WIMP search data! 85.3 live-days, 118 kg FV

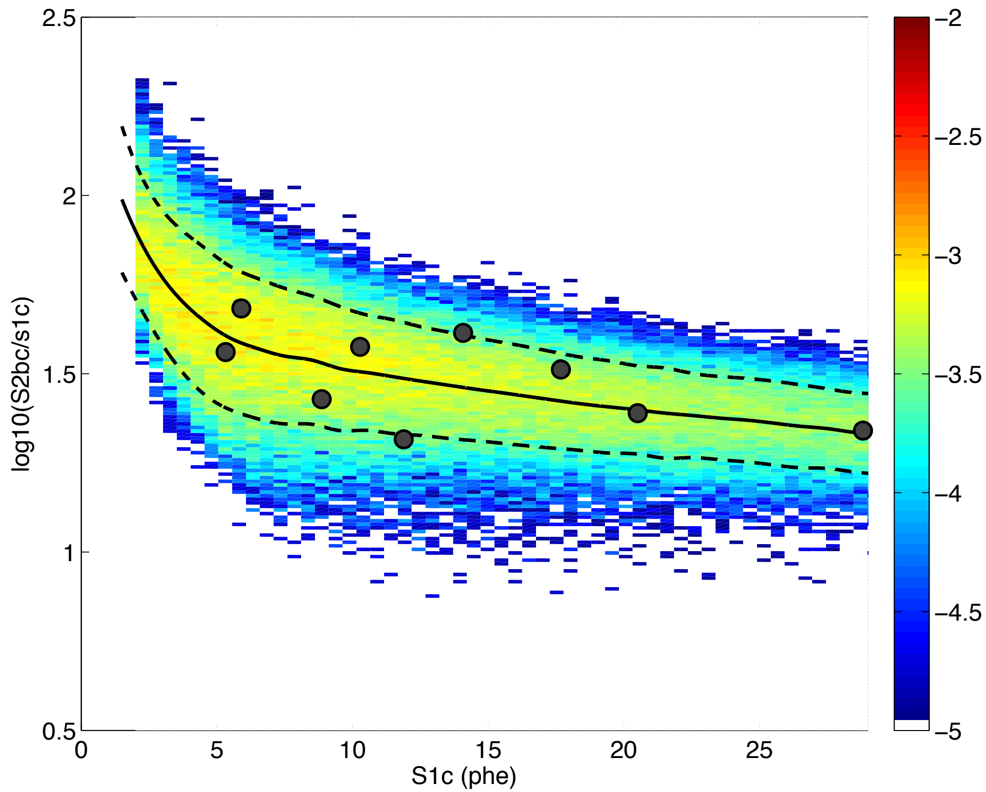


Simulated response for hypothetical WIMP signals

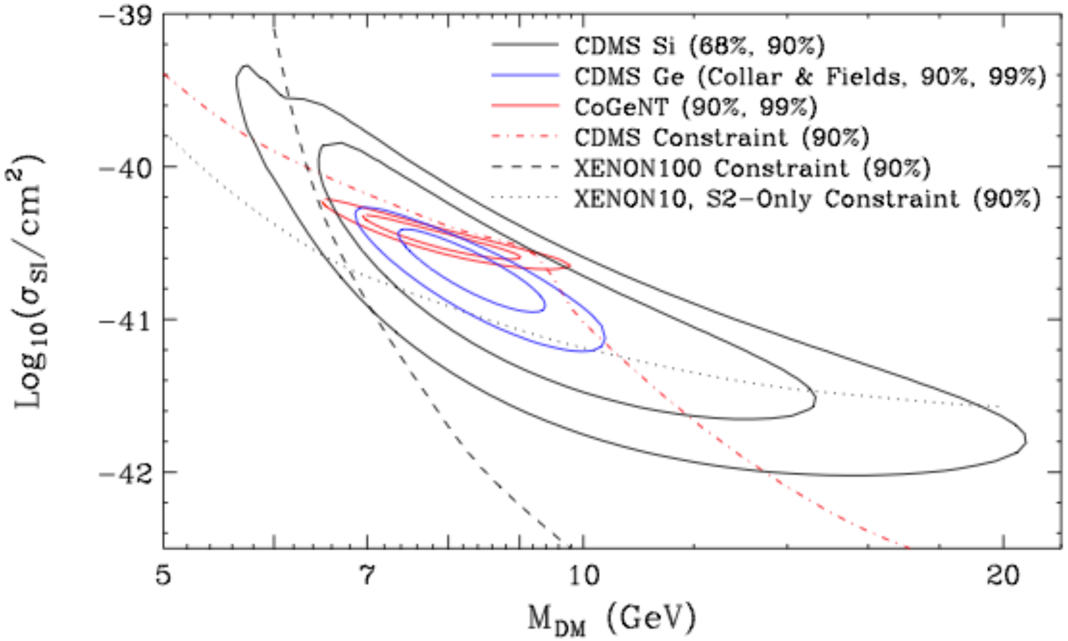
For 1000 GeV WIMP @ 1.9 ×10^{-44} cm^2, XENON100 90% CL:

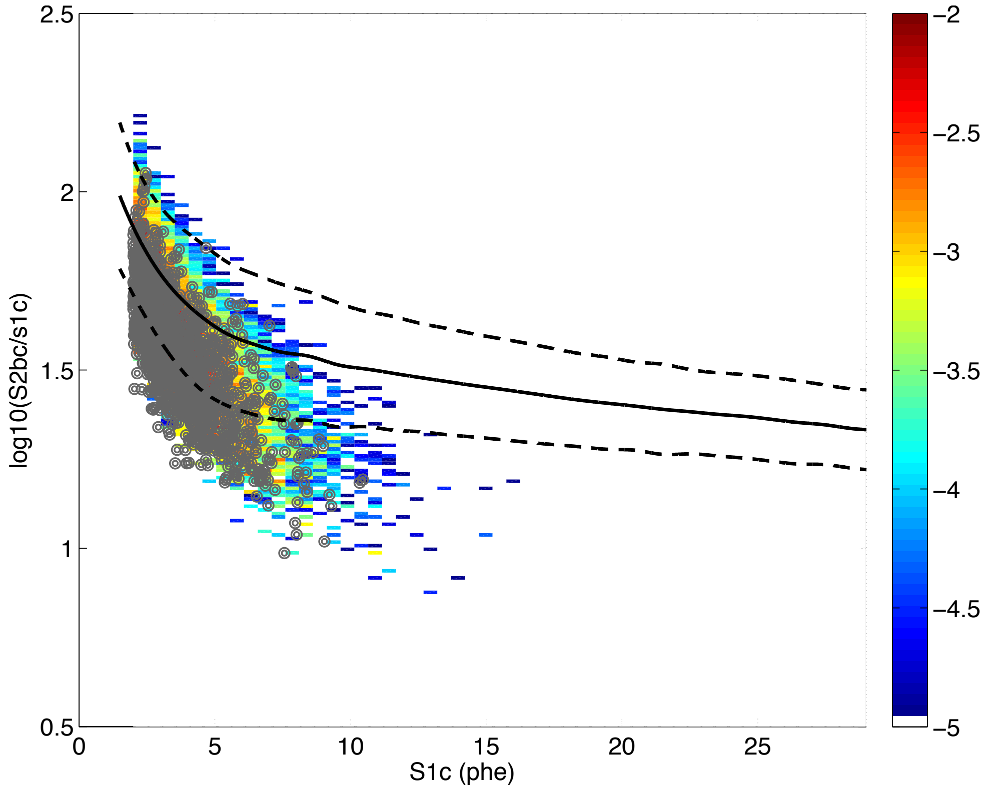
→ **expect 9 WIMPs in LUX search**





Simulated response for hypothetical WIMP signals





For 8.6 GeV WIMP @ 2.0 $\times 10^{-41}$ cm^2, CDMS II Si (2012) 90% CL ….

→ **expect 1550 WIMPs in LUX search**

Profile likelihood ratio for limits

- Unbinned maximum likelihood compare data with prediction on event by event basis.

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

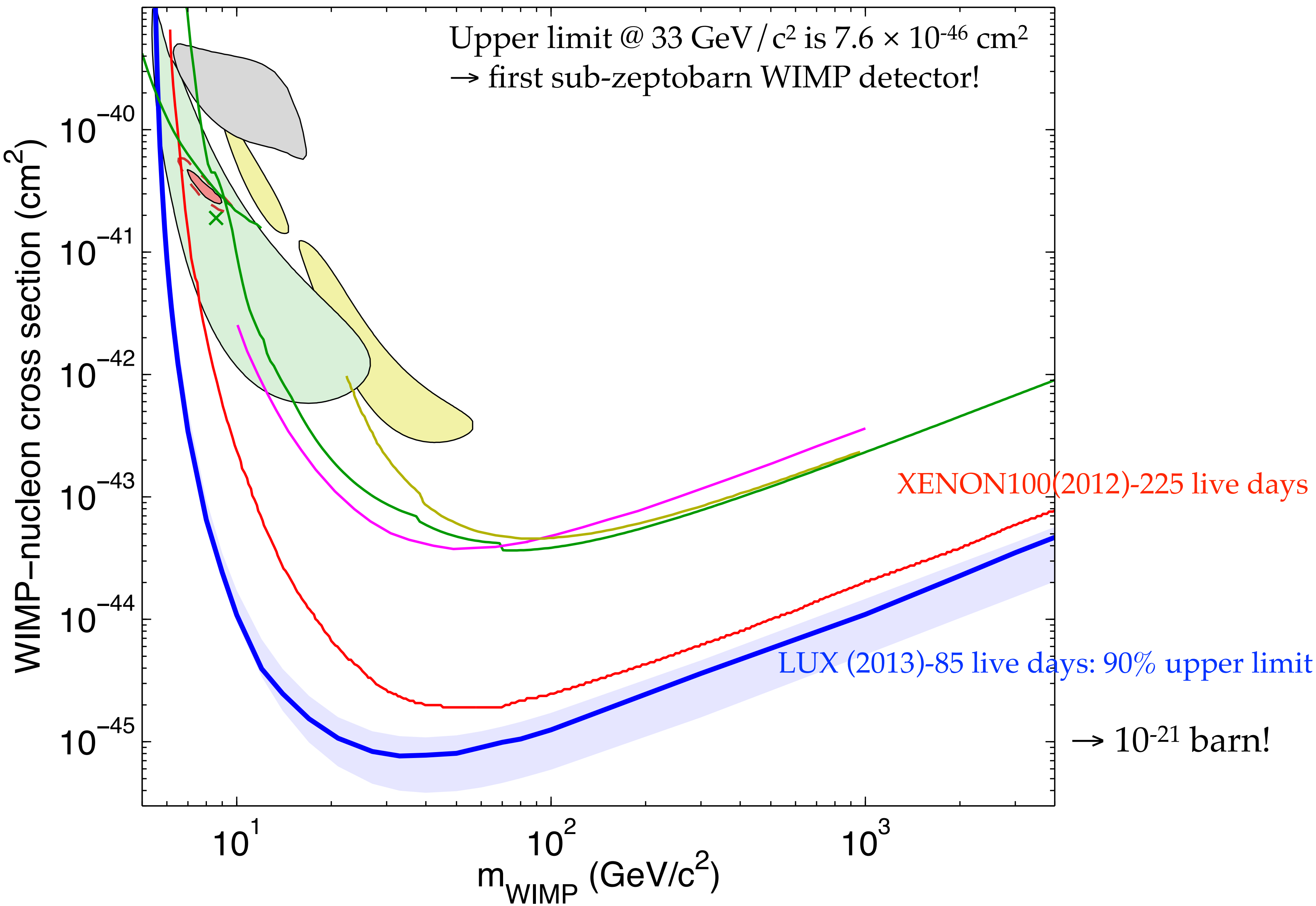
$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + \underline{N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}})}$$
$$\underline{+ N_{Xe-127} P_{ER}(\boldsymbol{x};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

WIMP signal PDF:
- WIMP dE/dR for given mass (see earlier)
- efficiency from validated NR sims
- N_s is parameter of interest

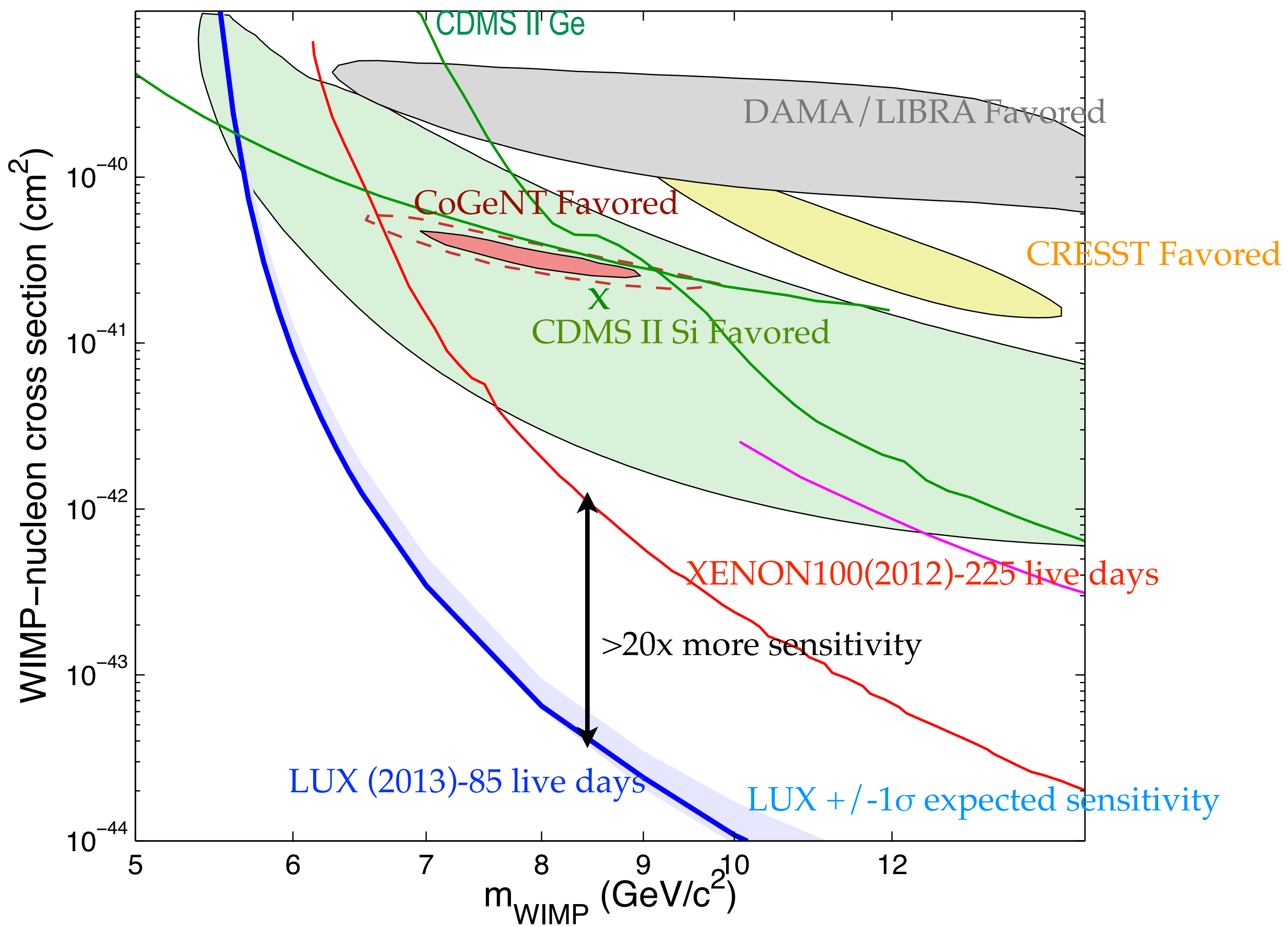
Backgrounds as nuisance parameters:
- detector efficiencies included
- 30% uncertainty on overall rate

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

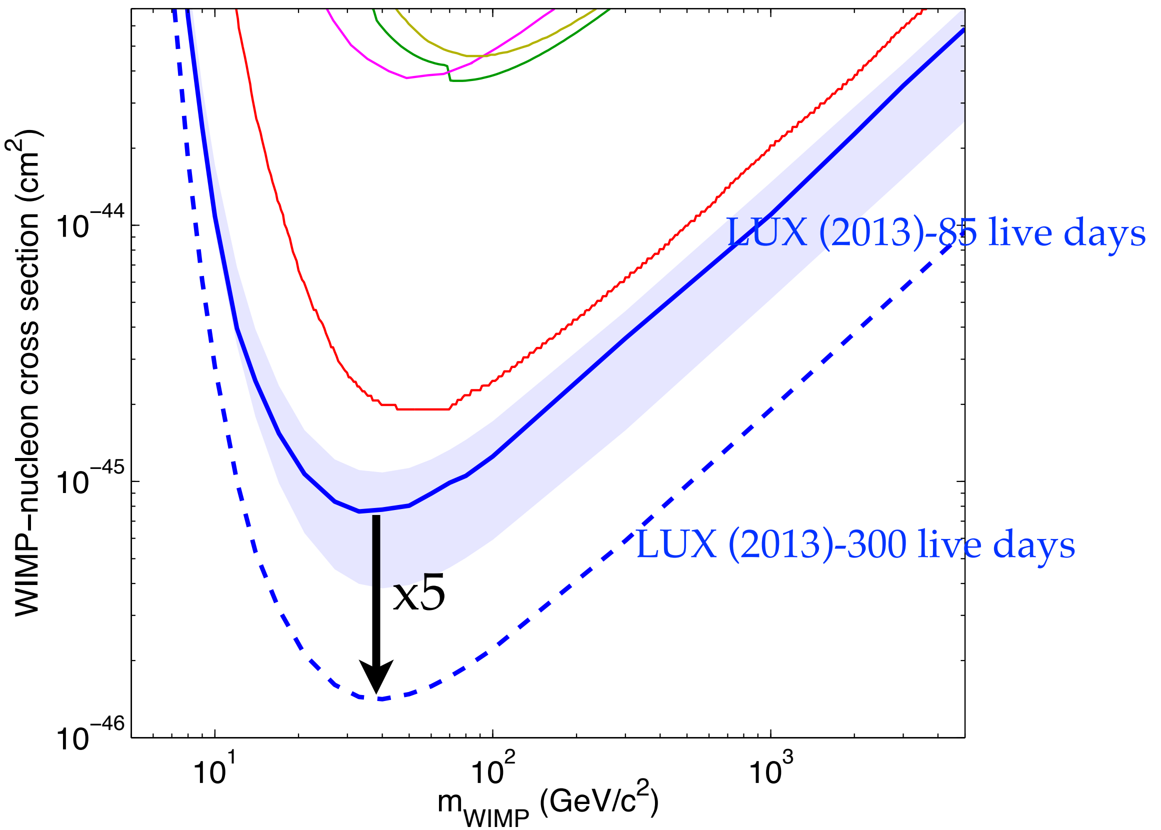
Spin-independent sensitivity



Low-mass WIMPs excluded

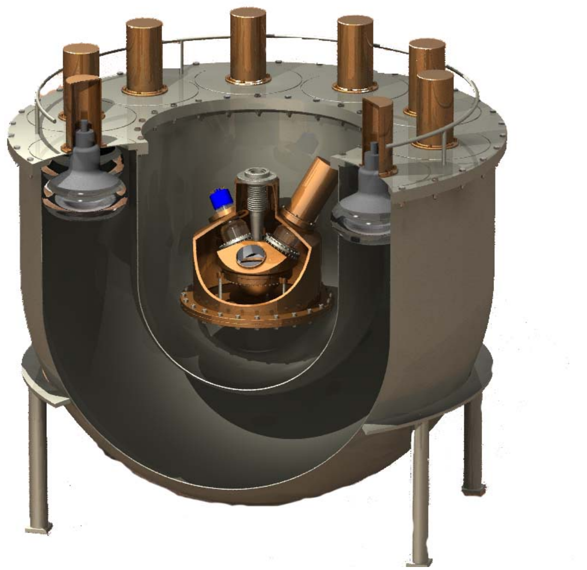


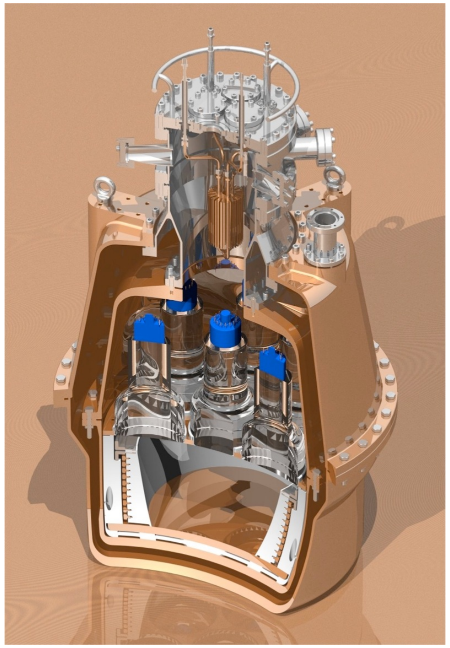
What's next: LUX 300 day run



- 300 day run planned for 2014/2015
- Cosmogenic cool-down plus potential for further improvements (E-field, cals., …)
- Still not background limited and expect factor of ~5 improvement in sensitivity → discovery possible!

The ZEPLIN programme at Boulby Mine





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

Single-phase

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

The first 2-phase LXe Dark Matter detector!

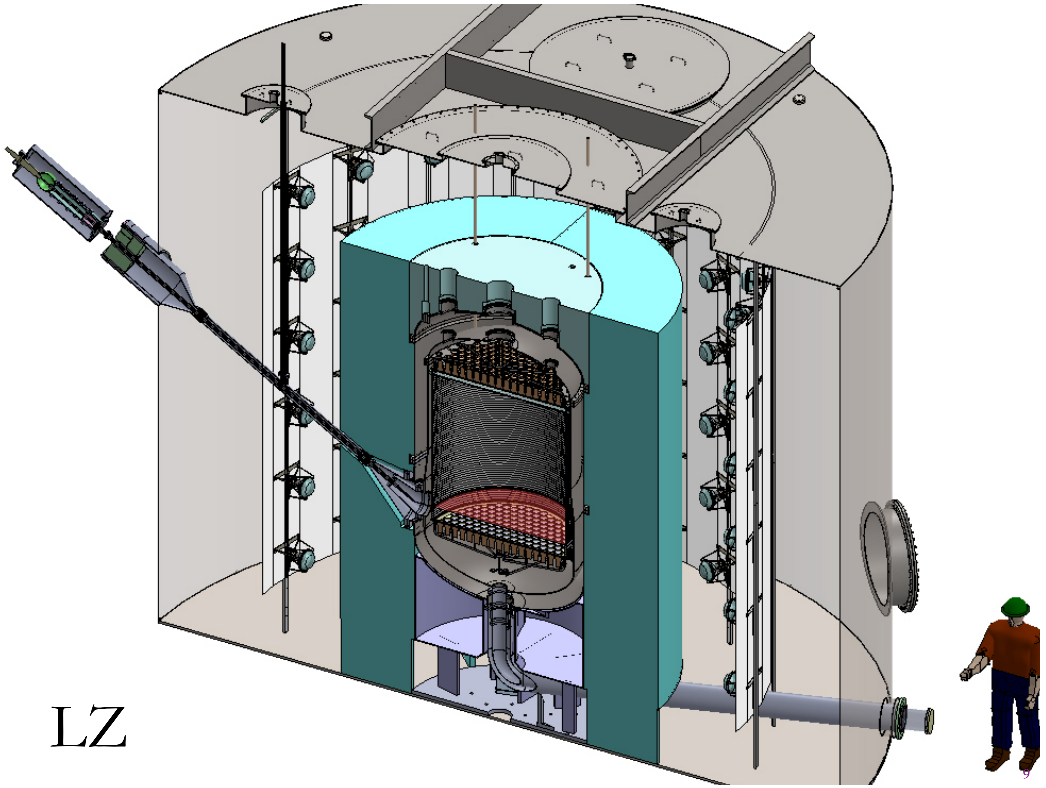
ZEPLIN III
Double phase, 31 PMTs,
high E field, 10/6.4 kg
Run 2009-11
Limit: $3.9*10^{-8}$ *pb*

Europe's most sensitive SI
World's best WIMP-neutron SD

Longer term: LUX-ZEPLIN (LZ)

- 20 times LUX Xenon mass, active scintillator veto, Xe purity at sub ppt level
- Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds

Same water tank as LUX



LZ

Onwards and downwards

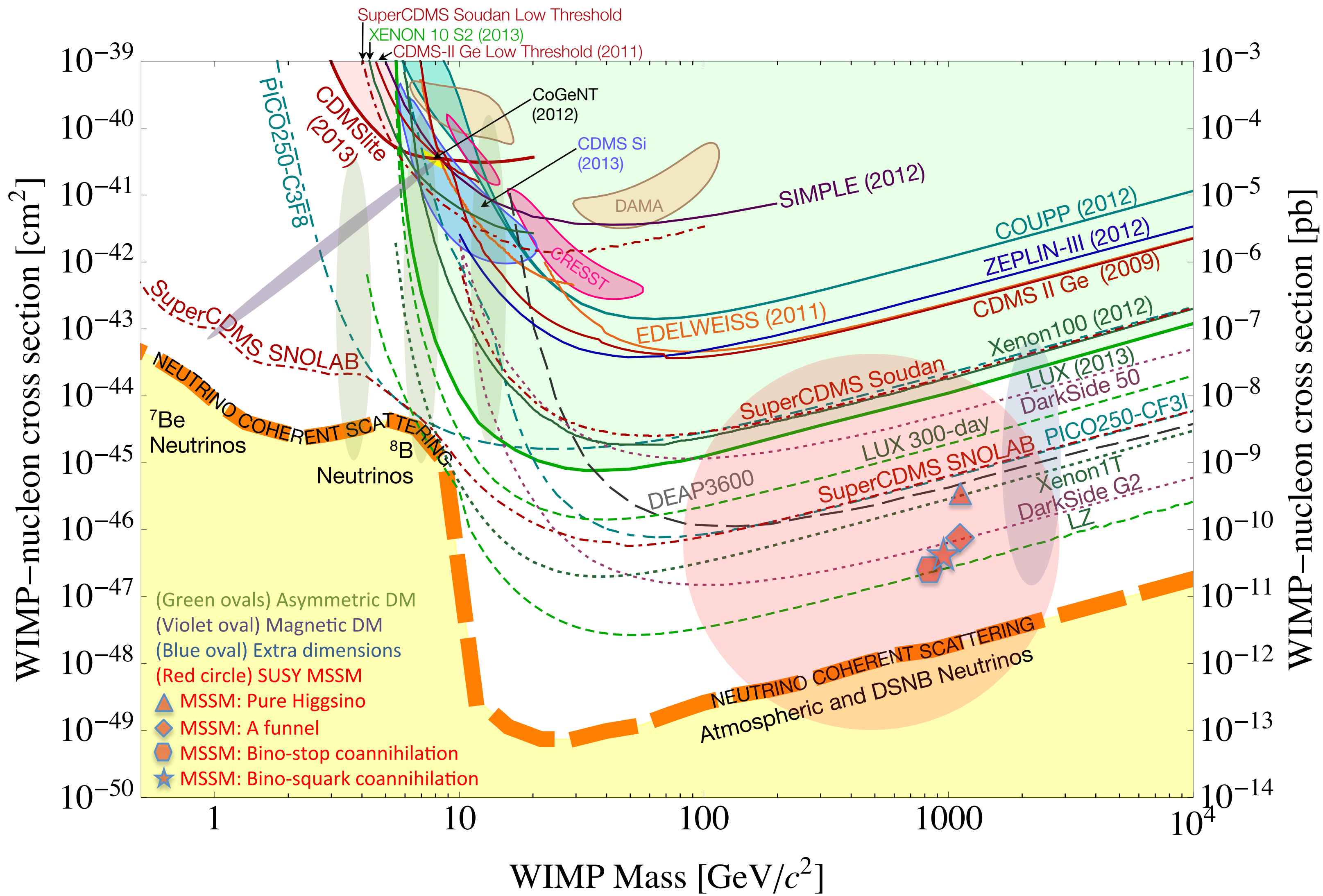
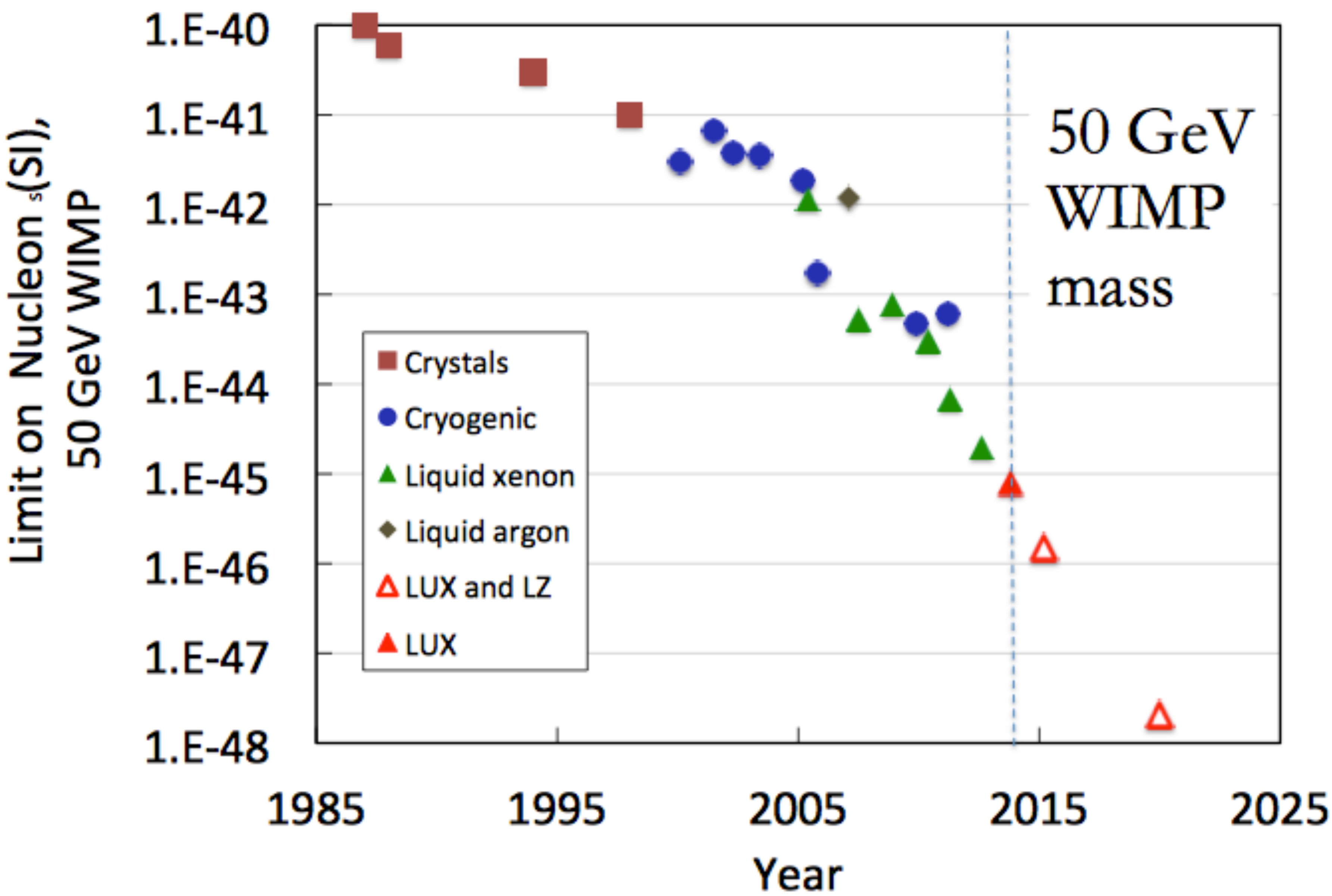
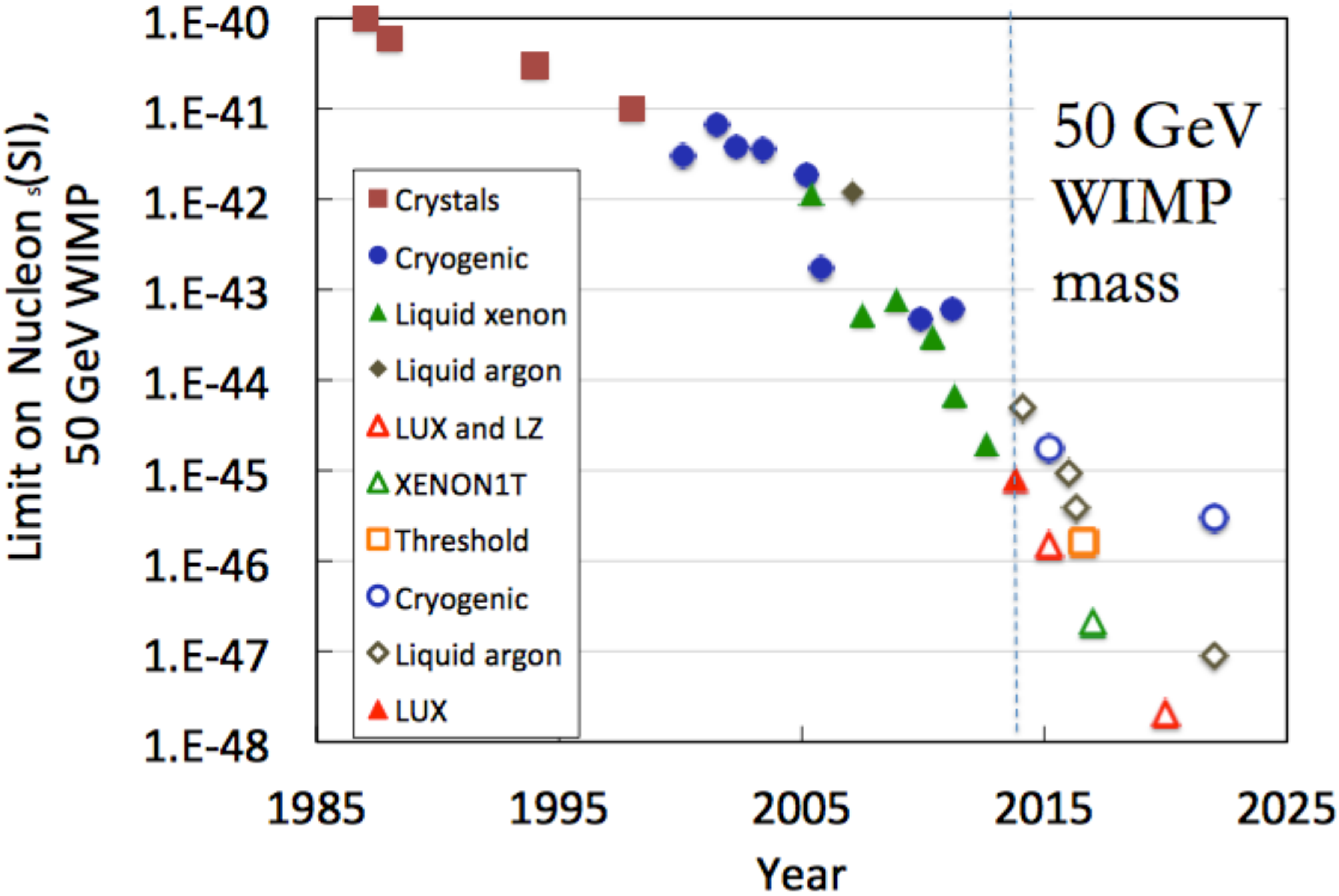


Figure from SNOMASS CF1 WIMP Dark Matter Detection summary

LZ Projections



LZ and all 'G2' Projections



Summary

- With 85.3 live-days LUX set world's best limit on spin-independent scattering:
  - 90% UL 7.6×10^{-46} cm^2 @ 33 GeV / c^2 → first sub-zeptobarn WIMP detector
  - Low-mass WIMPs fully excluded by LUX
  - Results paper accepted by PRL, expect more to follow
- 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