arXiv:1310.8214
Submitted to PRL October 30, 2013

First Dark Matter Search Results from the LUX Detector

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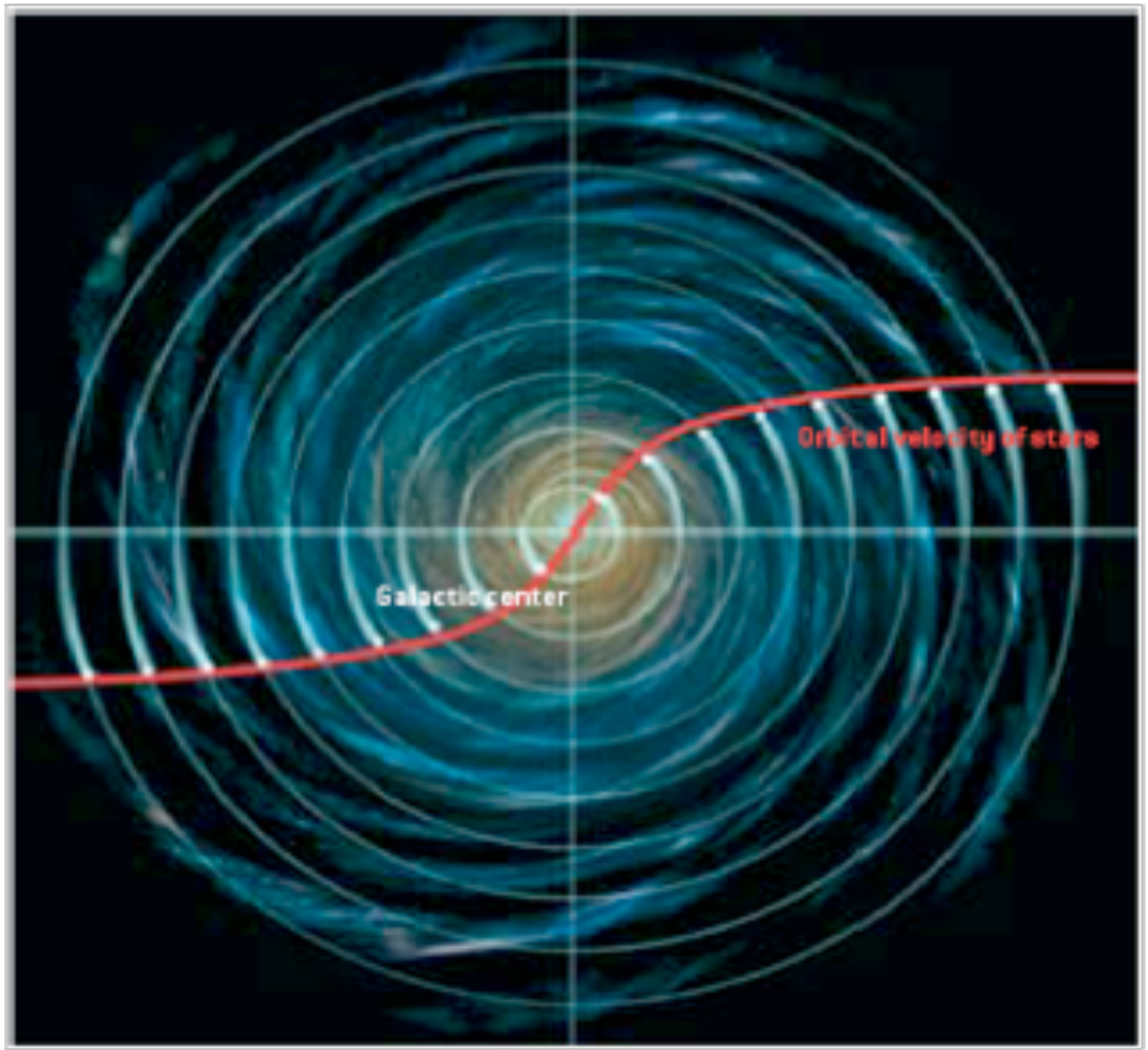
Case Western Reserve University
High Energy Seminar
University of Virginia
November 13, 2013

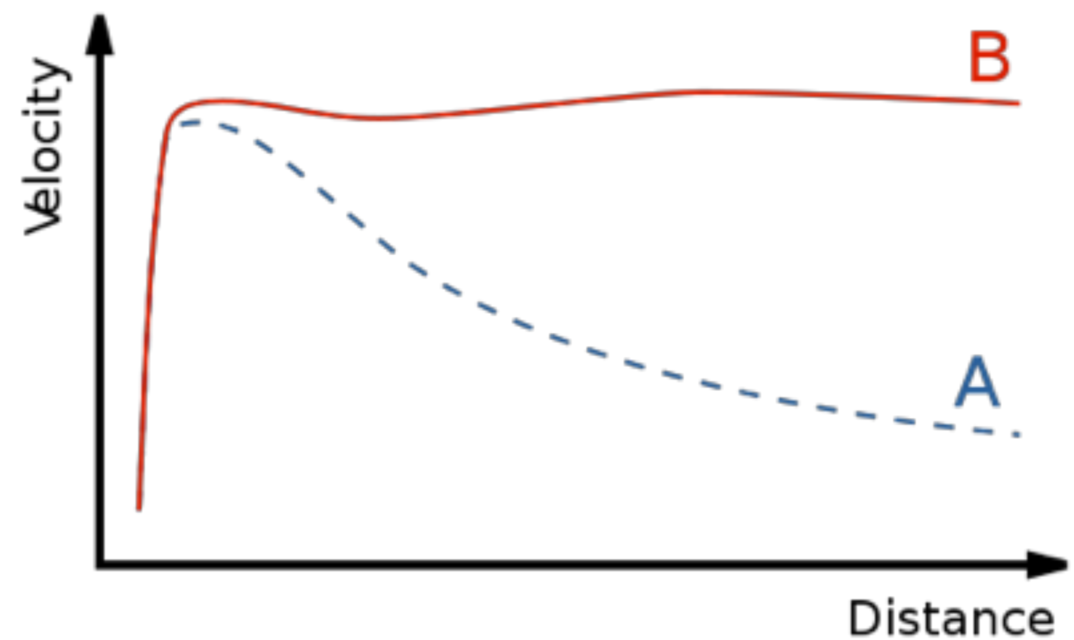
What do we know about dark matter?

It’s mysterious

We have a lot of indirect evidence...

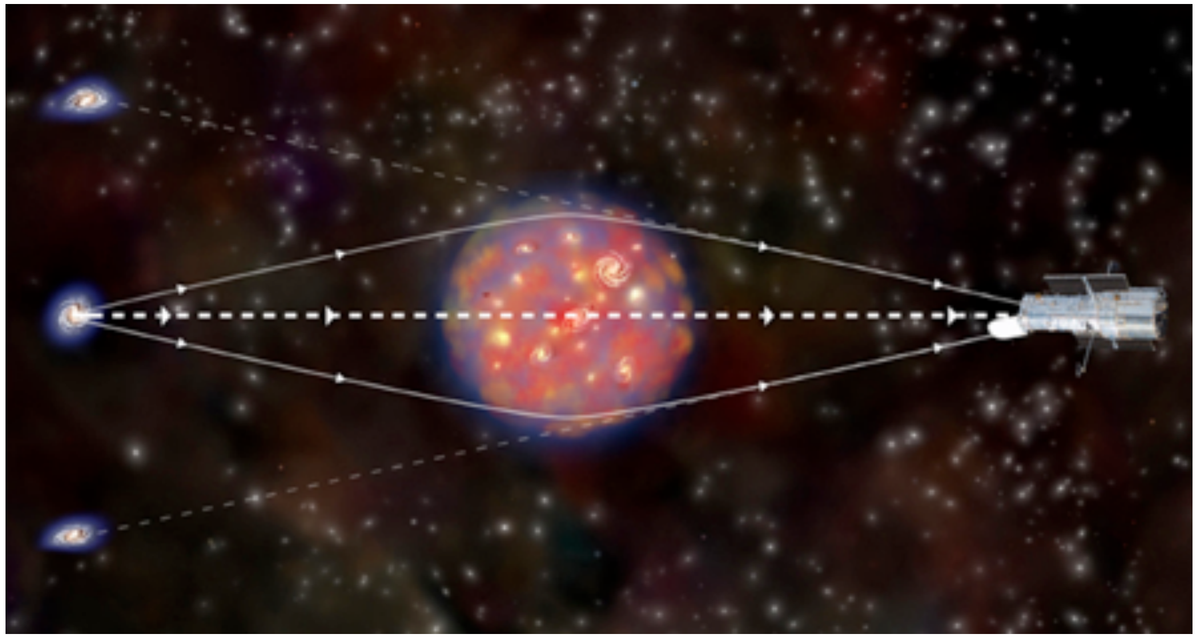
In rotation curves of elliptical galaxies...

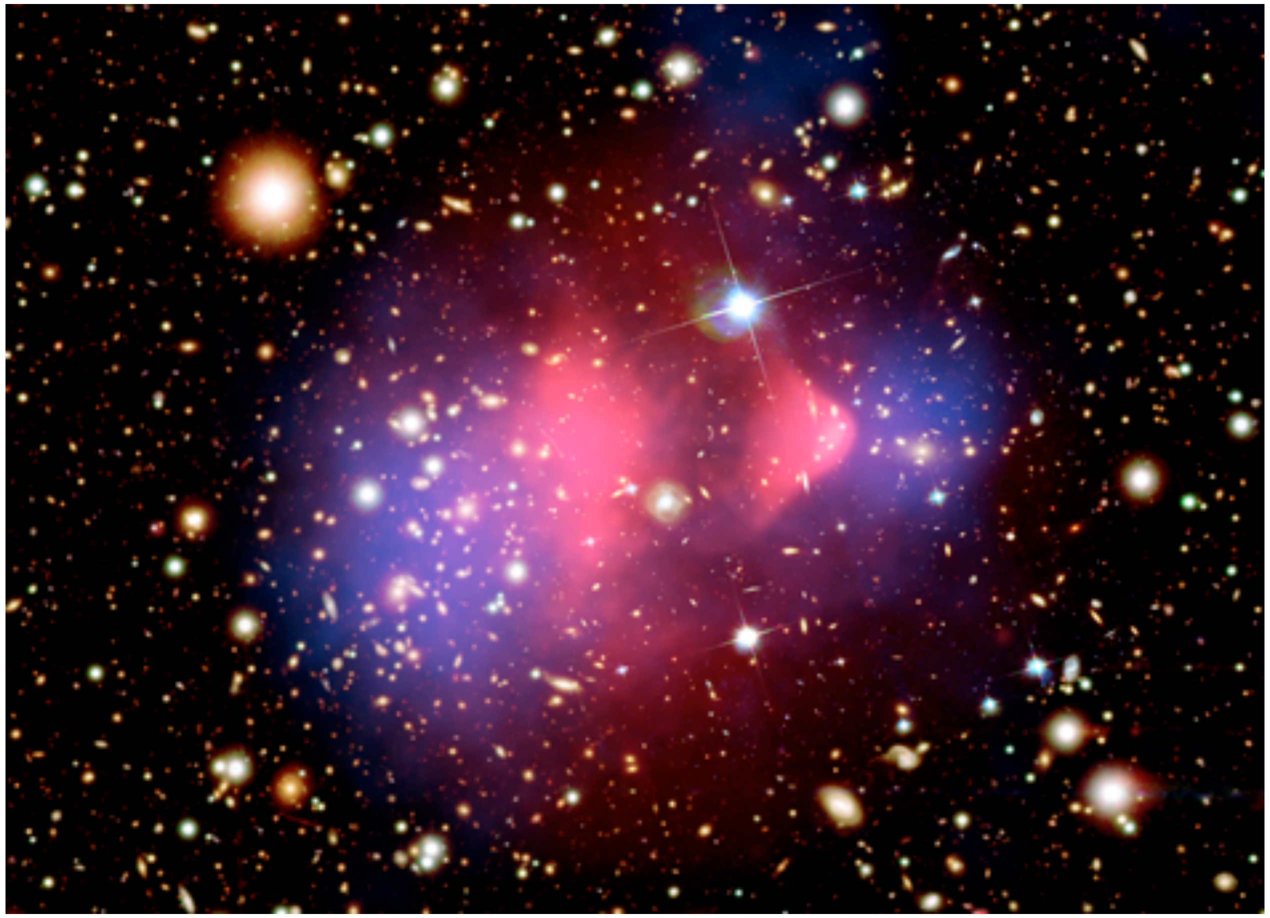




In collisions of galaxies..

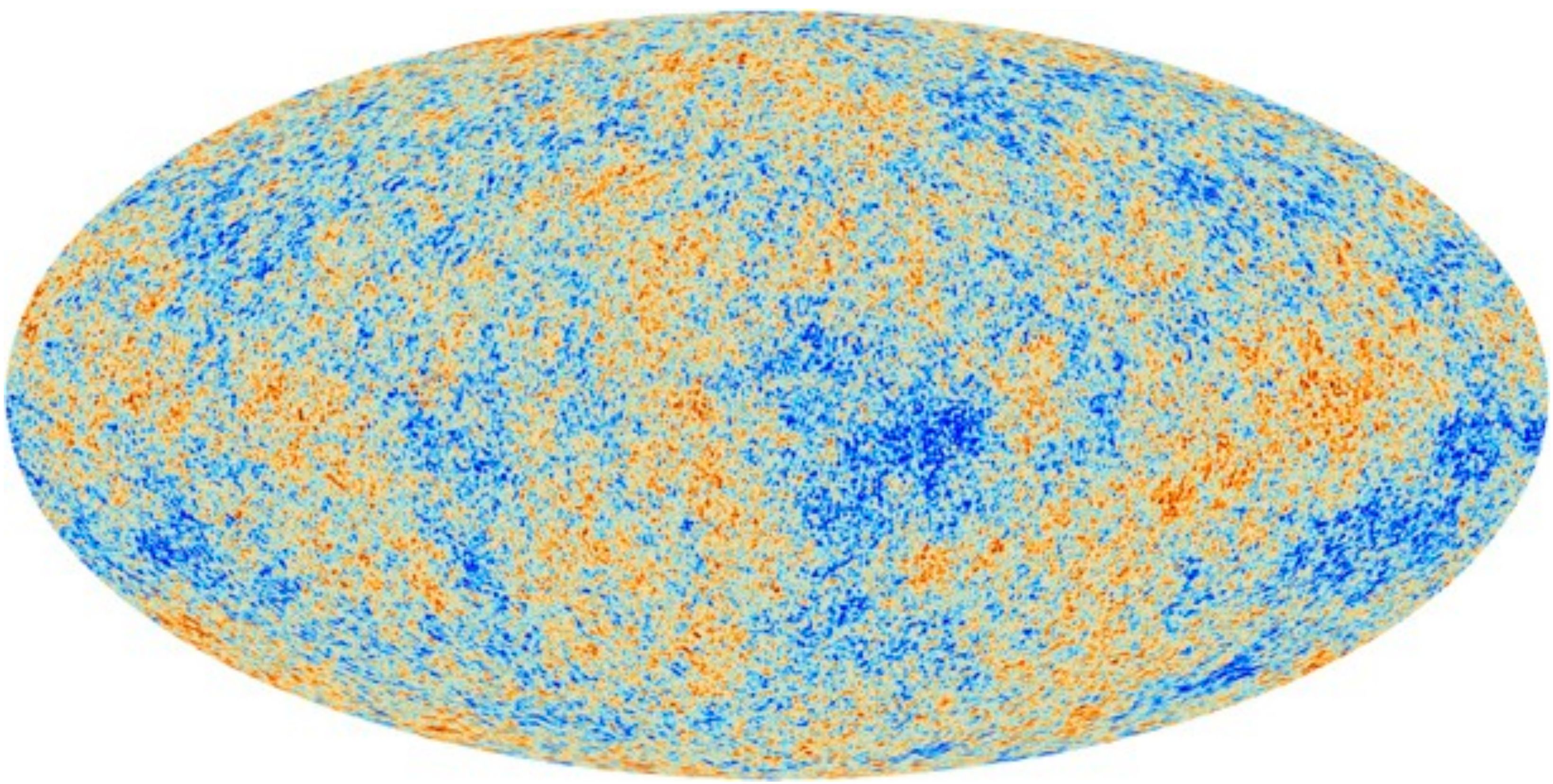
Use gravitational lensing to determine mass of clusters, while x-rays show hot gas and optical images show stars





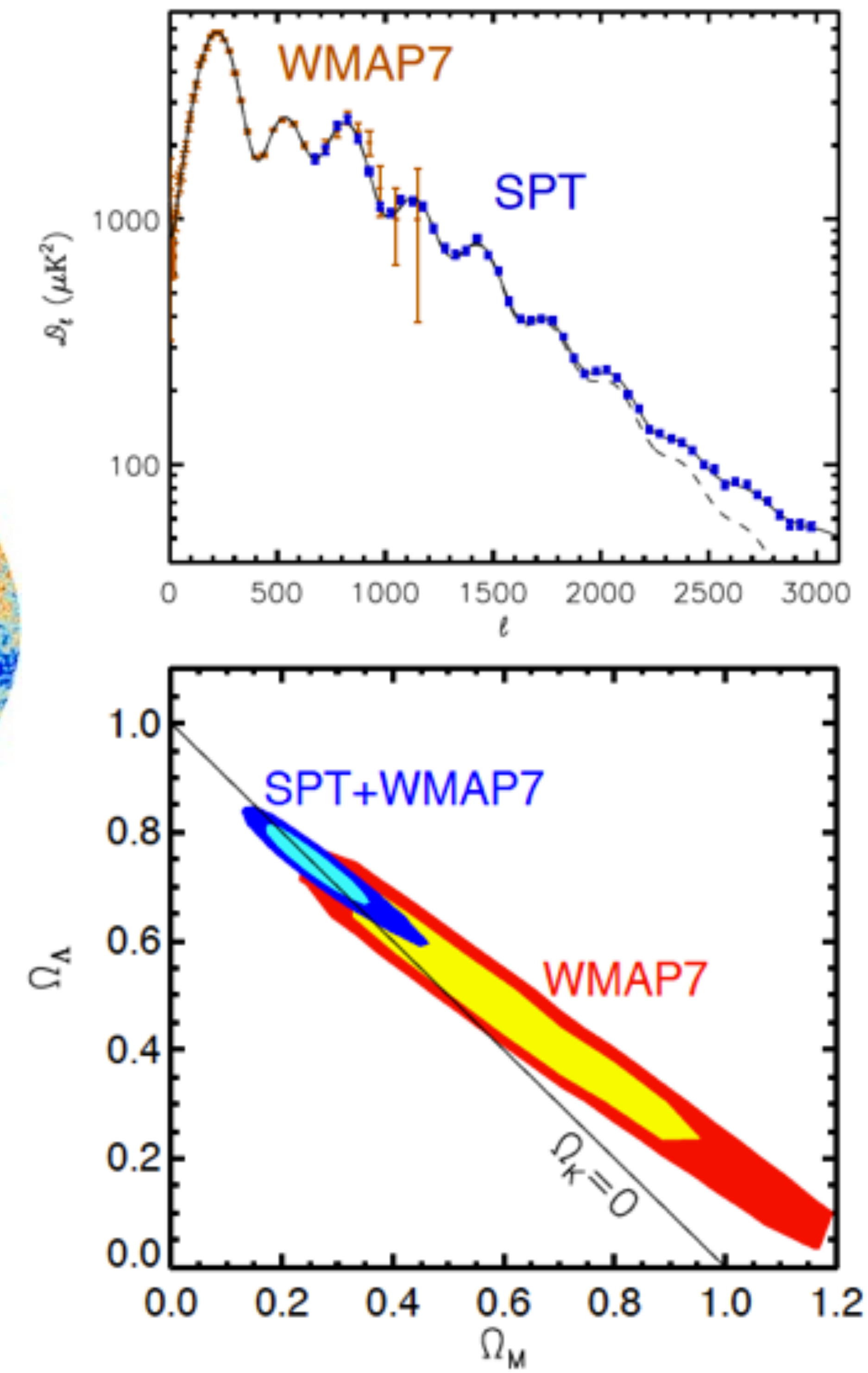
1E 0657-56, Bullet cluster

CMB moments

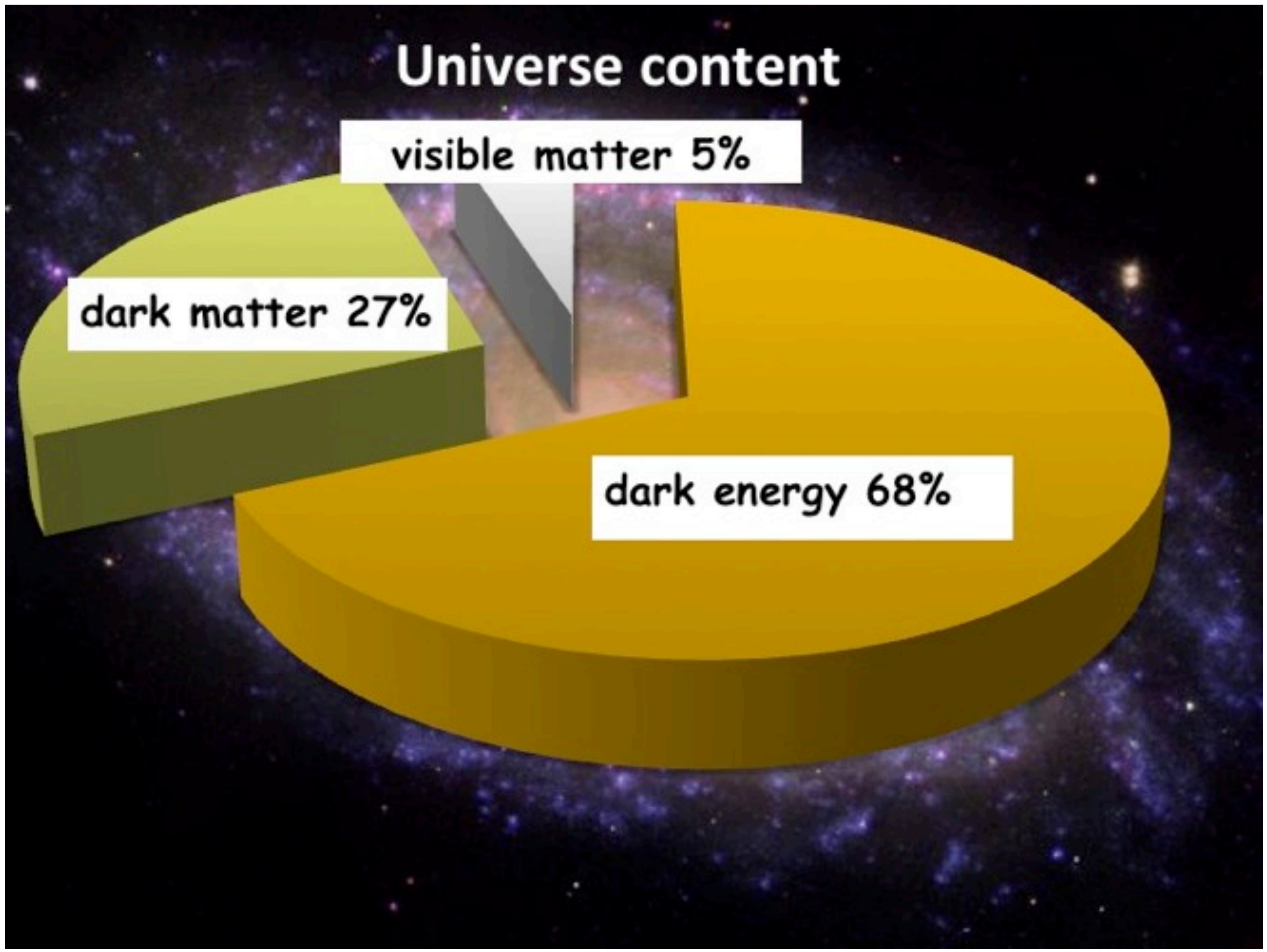


Planck CMB, ESA

K.T. Story et al., arXiv:1210.7231



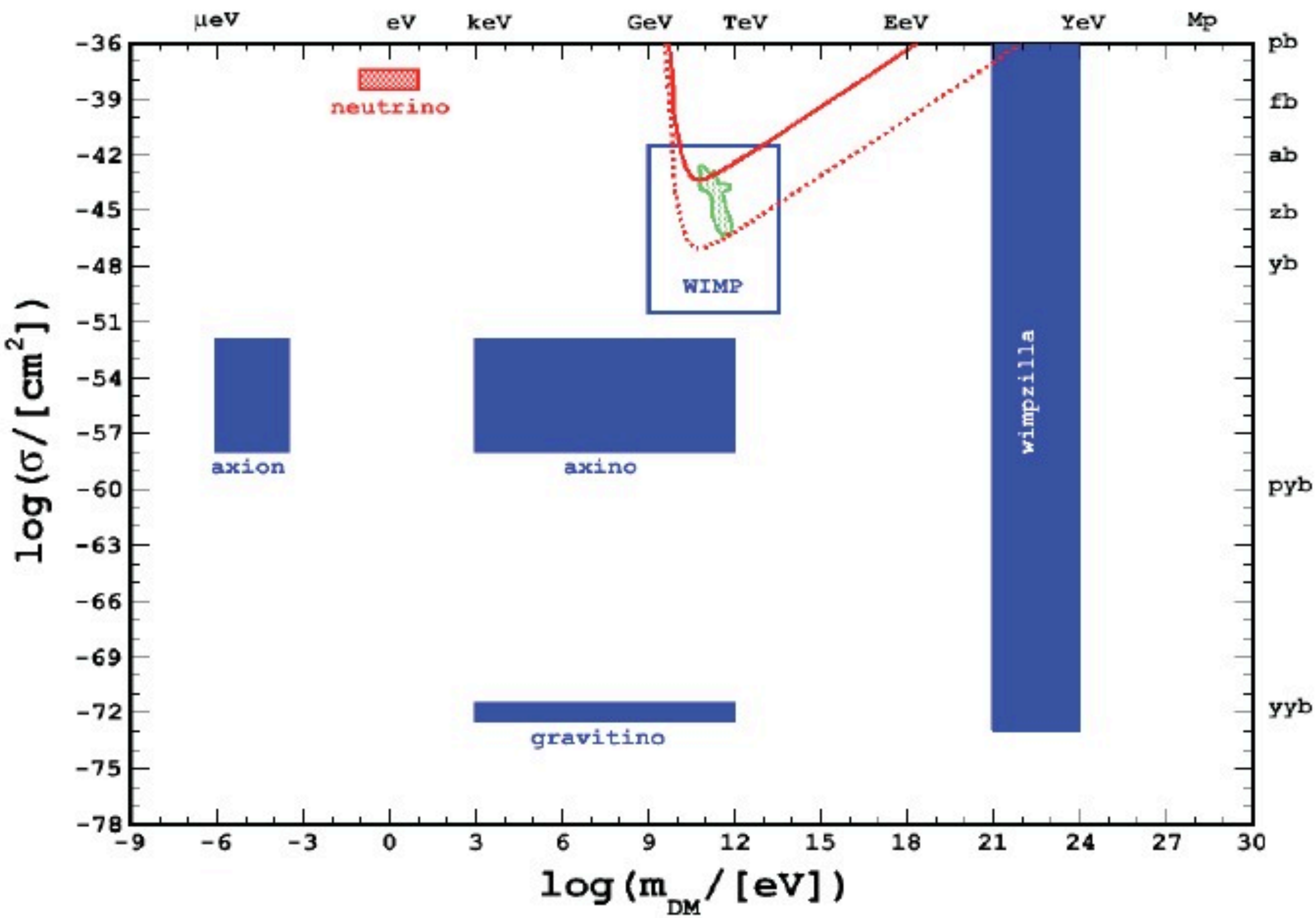
We believe it makes up ~25% of our universe



quantumdiaries.org

What **don’t** we know about dark matter?

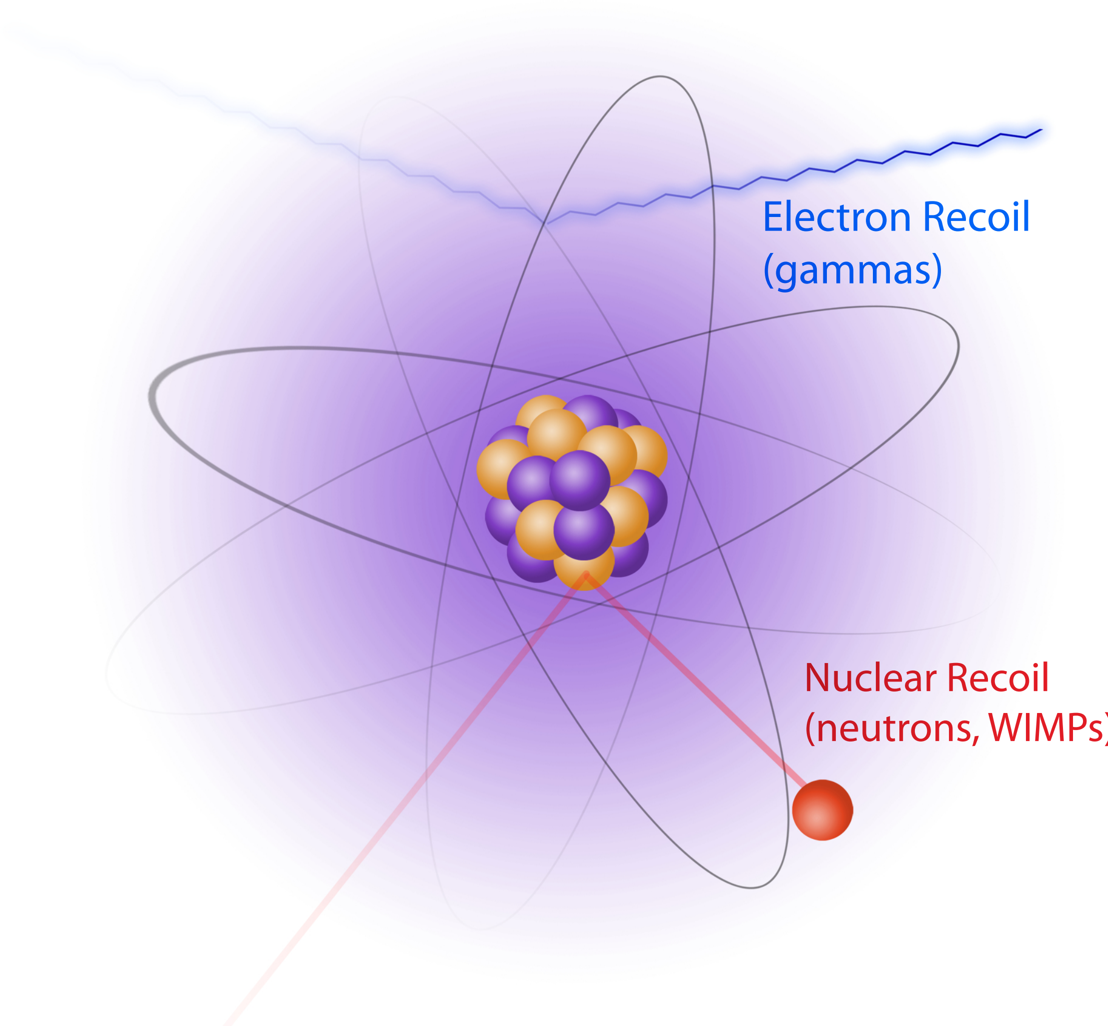
A lot!



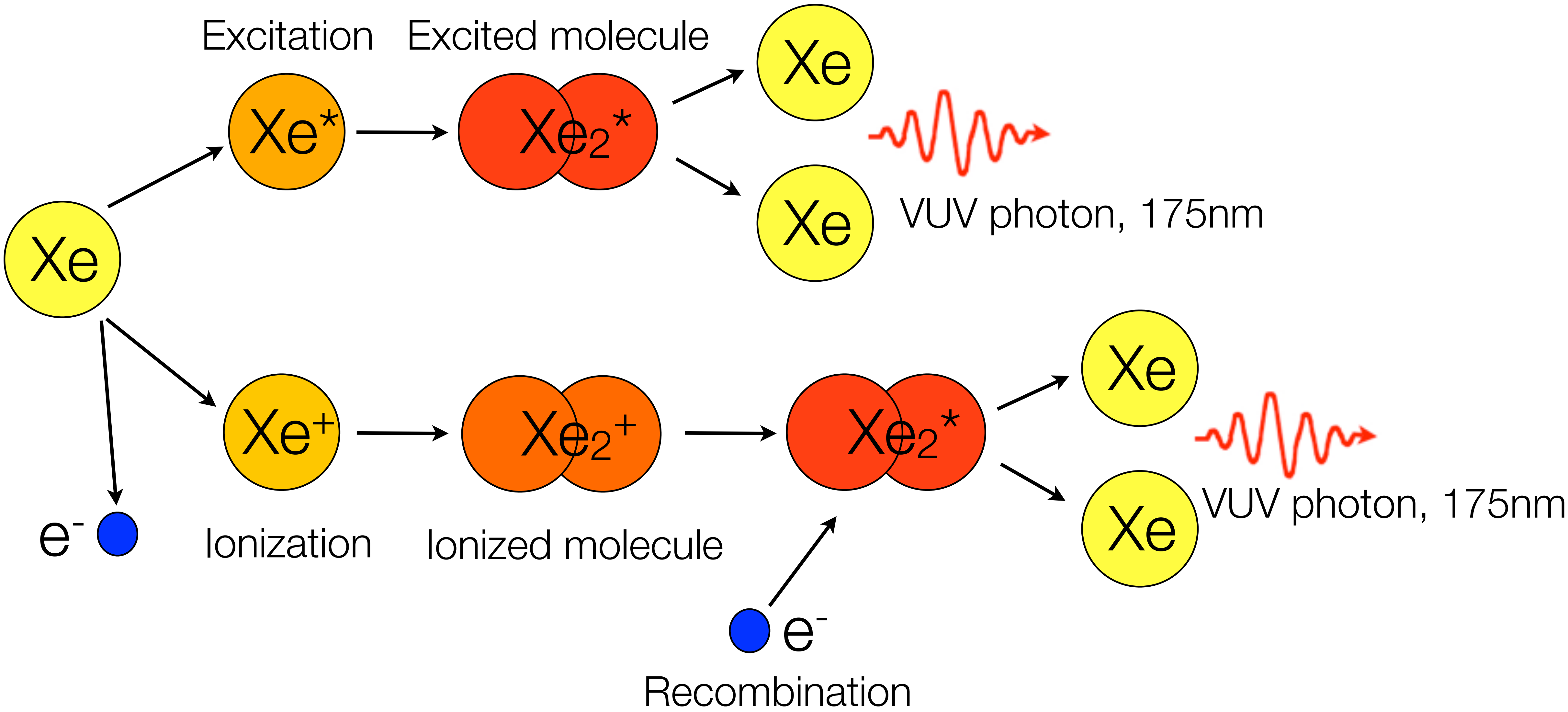
μeV
eV
keV
GeV
TeV
EeV
YeV
Mp
-36
-39
-42
-45
-48
-51
-54
-57
-60
-63
-66
-69
-72
-75
-78
pb
fb
ab
zb
yb
pyb
yyb
neutrino
WIMP
axion
axino
gravitino
wimpzilla
-9
-6
-3
0
3
6
9
12
15
18
21
24
27
30
log(σ/[cm²])
log(m_DM/[eV])

Basic idea of WIMP direct detection experiments

- Look for WIMPs **elastically** recoiling off a heavy nucleus
  - Reduce all non-DM backgrounds to ~ 0
  - Remaining events ⇒ DM signal

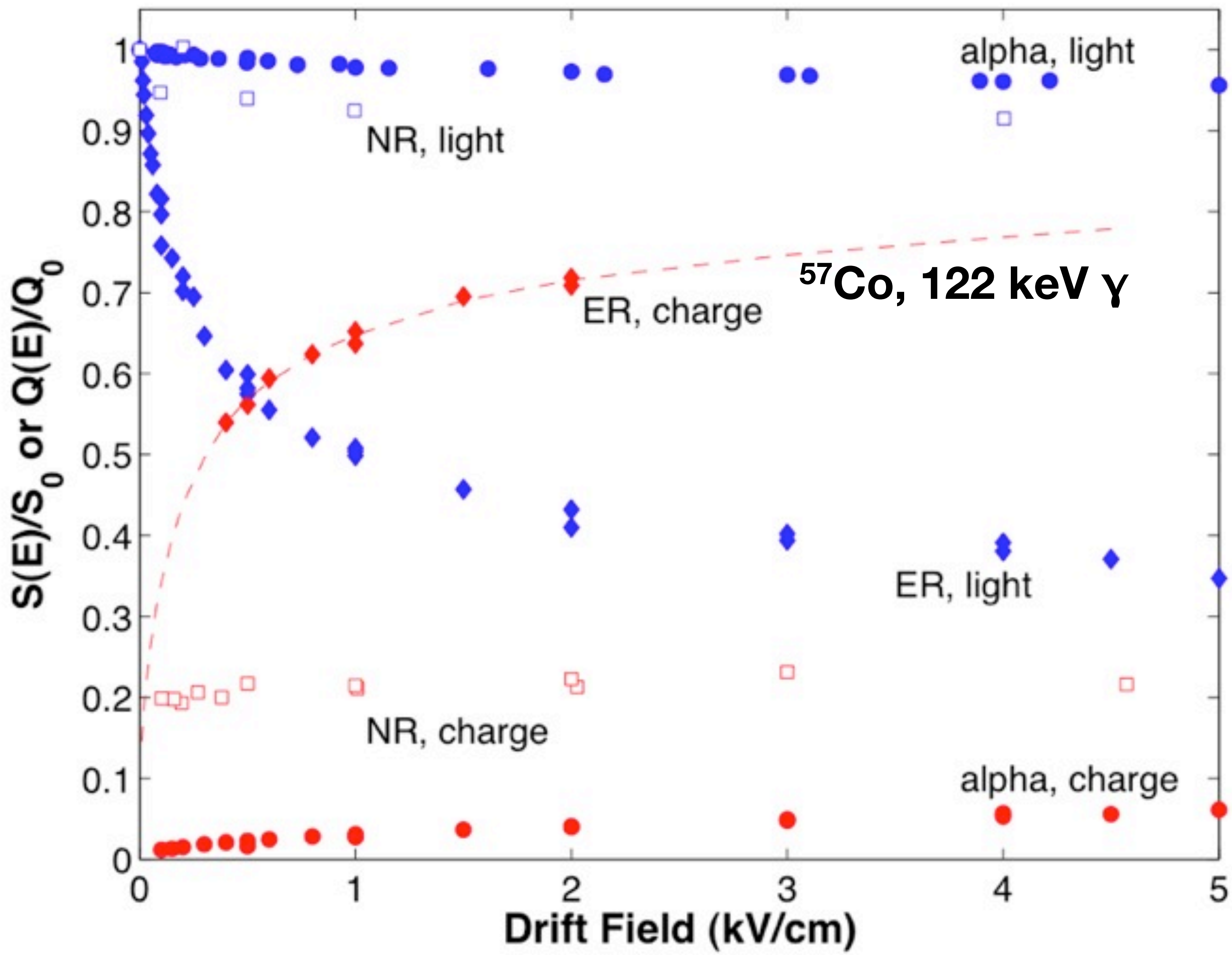


WIMP direct detection in noble liquids



All recoils produce light and charge

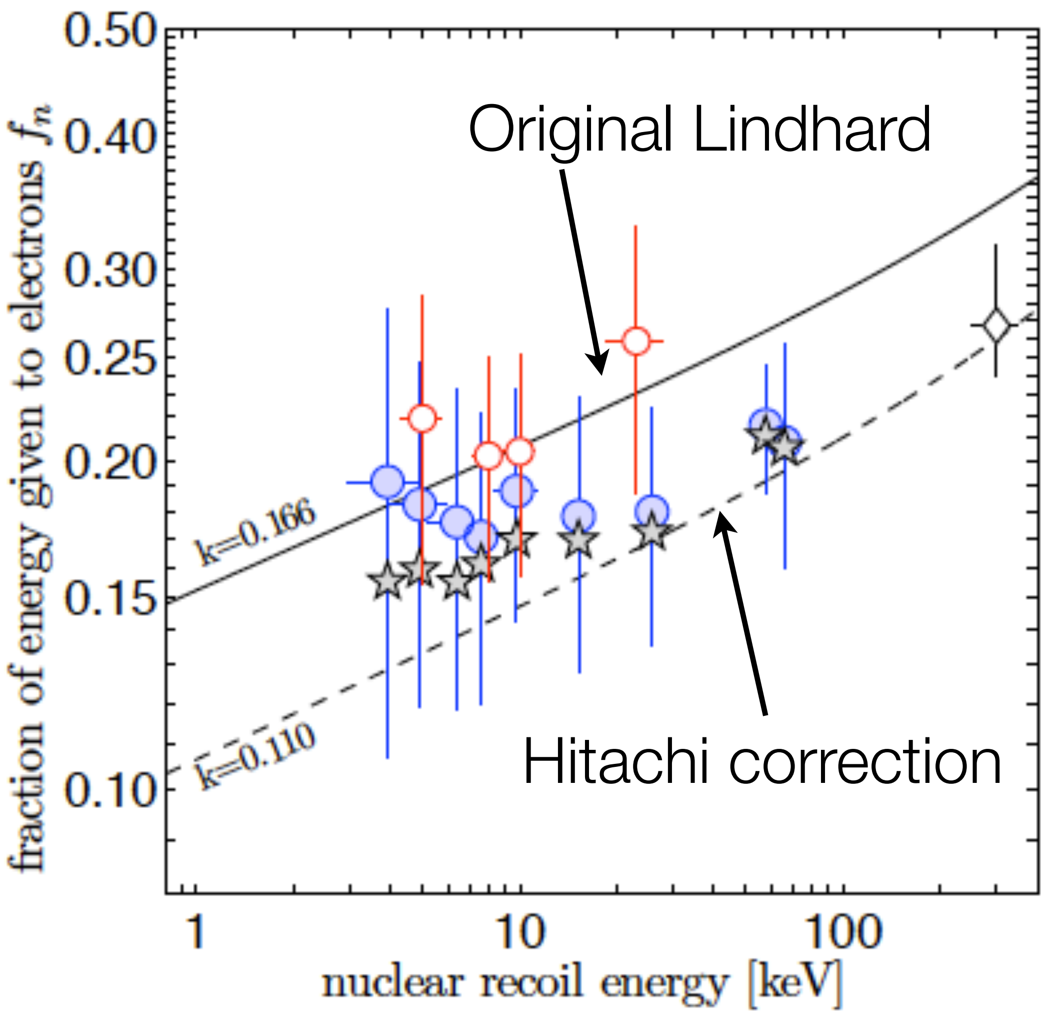
Use light vs charge to discriminate nuclear and electronic recoils



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

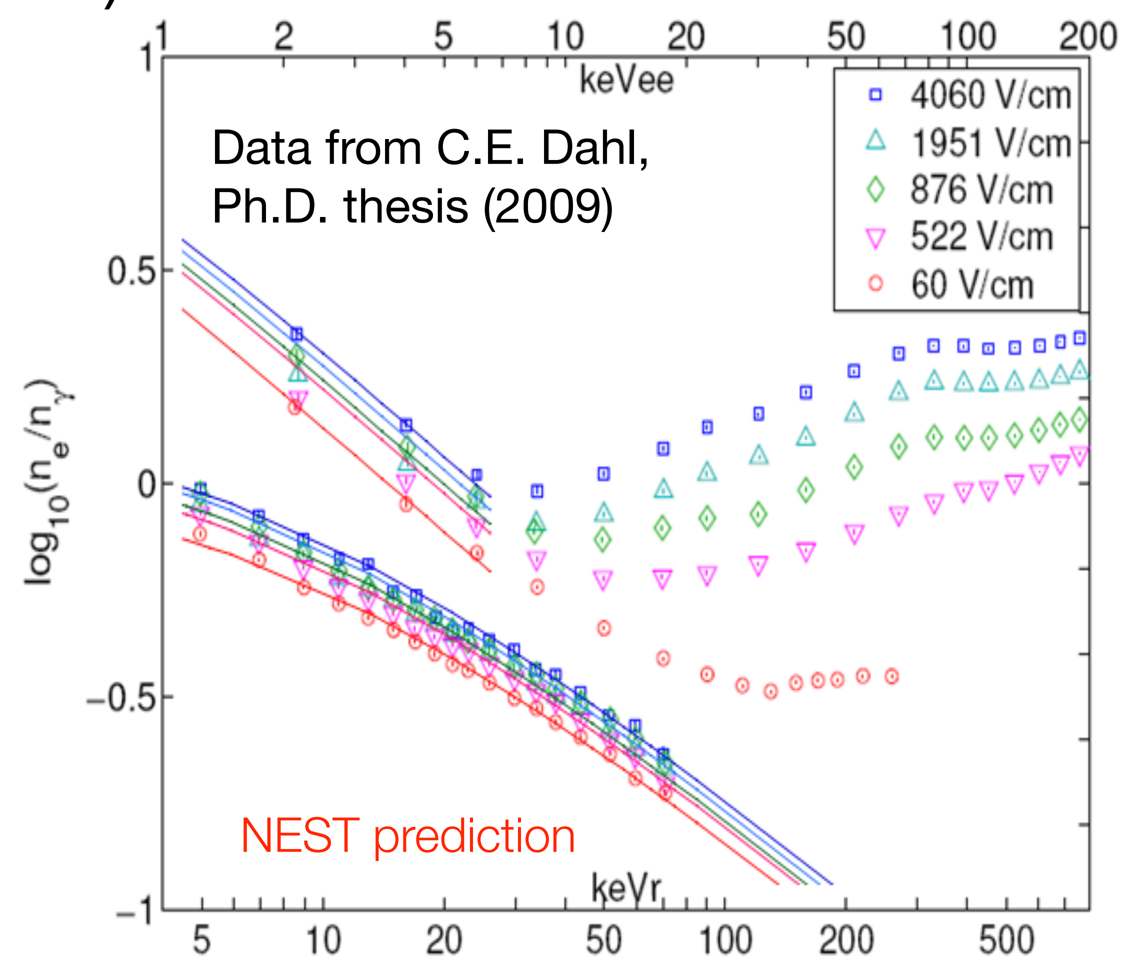
Noble Element Scintillation Technique (NEST)

$$E_{ee} = (n_\gamma + n_e)W$$
$$E_{nr} = \mathcal{L}^{-1}(n_\gamma + n_e)W$$



Uses full Lindhard model with Hitachi linear energy transfer (LET)

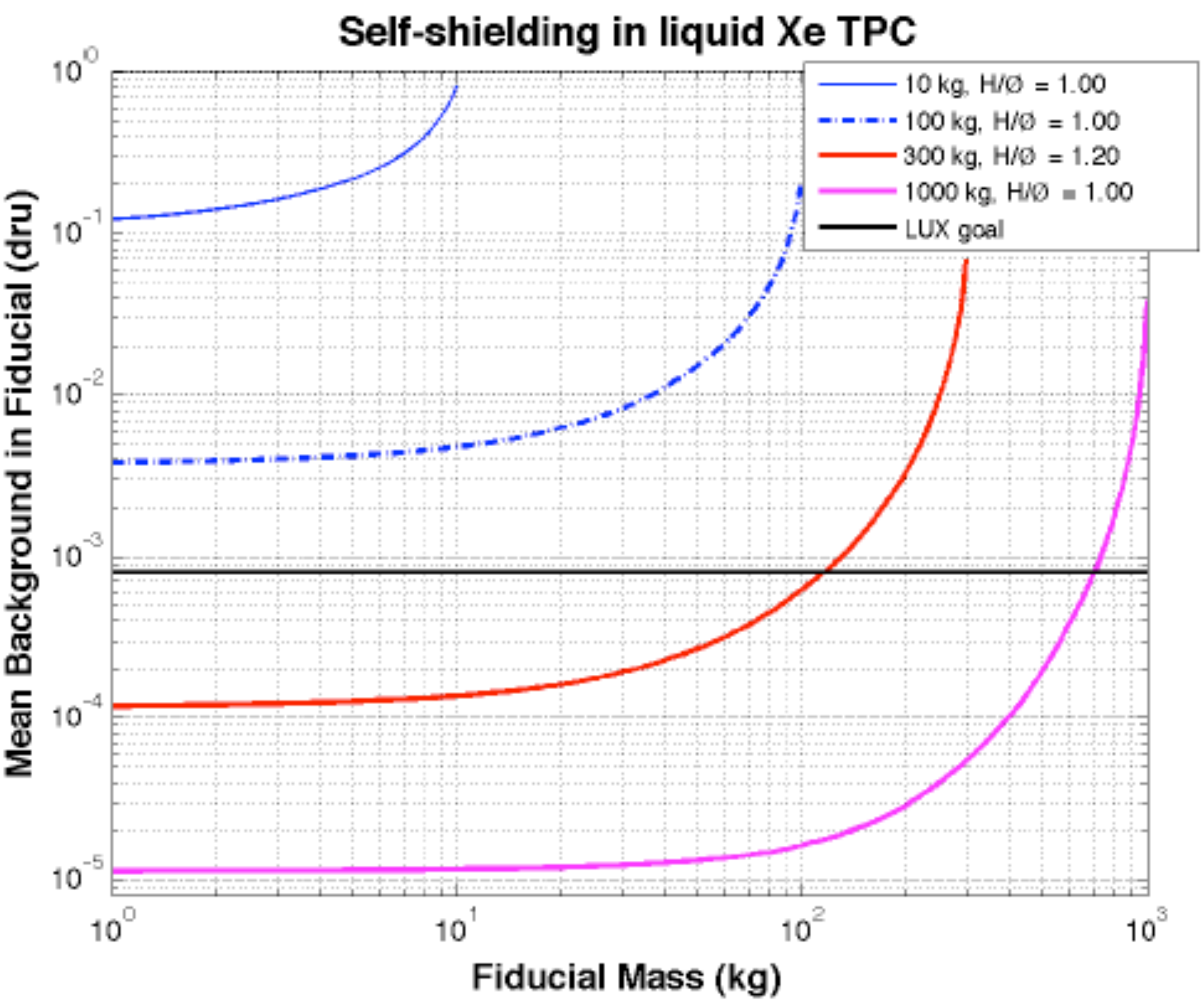
P. Sorensen and C.E. Dahl, Phys. Rev. D **83**, 063501 (2011)



Reproduces NR discrimination data

M. Szydagis et al., JINST 6, p10002 (2011)

Liquid xenon self-shielding



Make use of self-shielding to reduce external and internal backgrounds

The LUX Experiment

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 Group
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

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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

University of Edinburgh

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

University of Maryland

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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

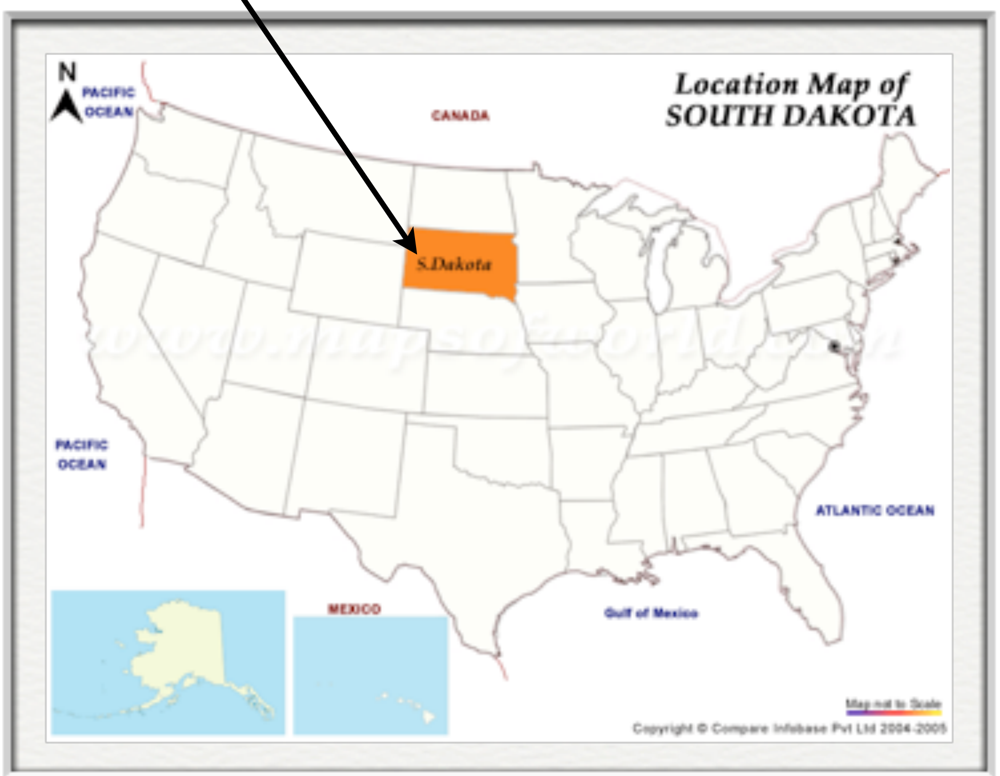
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

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

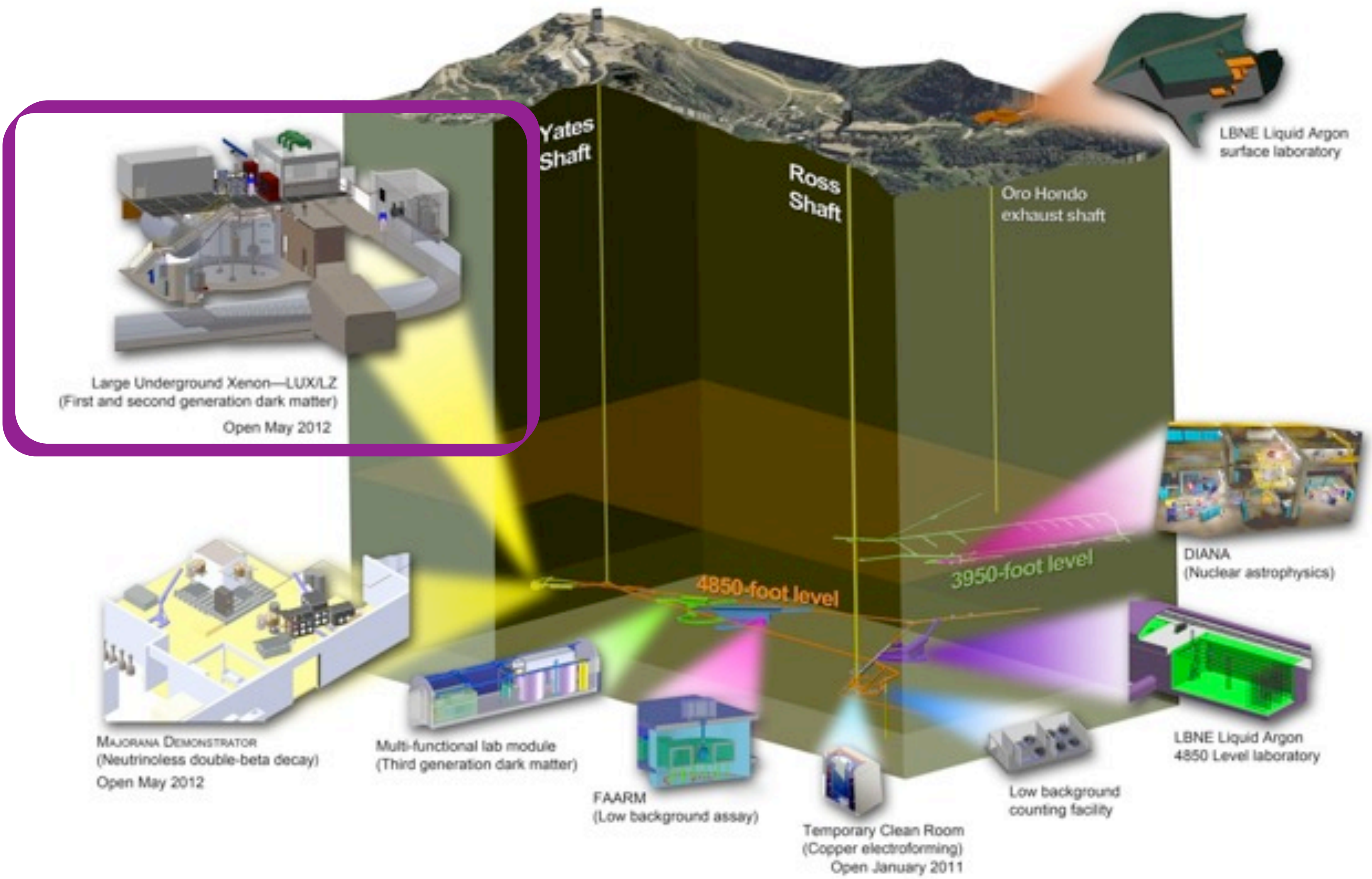
Sanford Underground Research Facility (SURF)

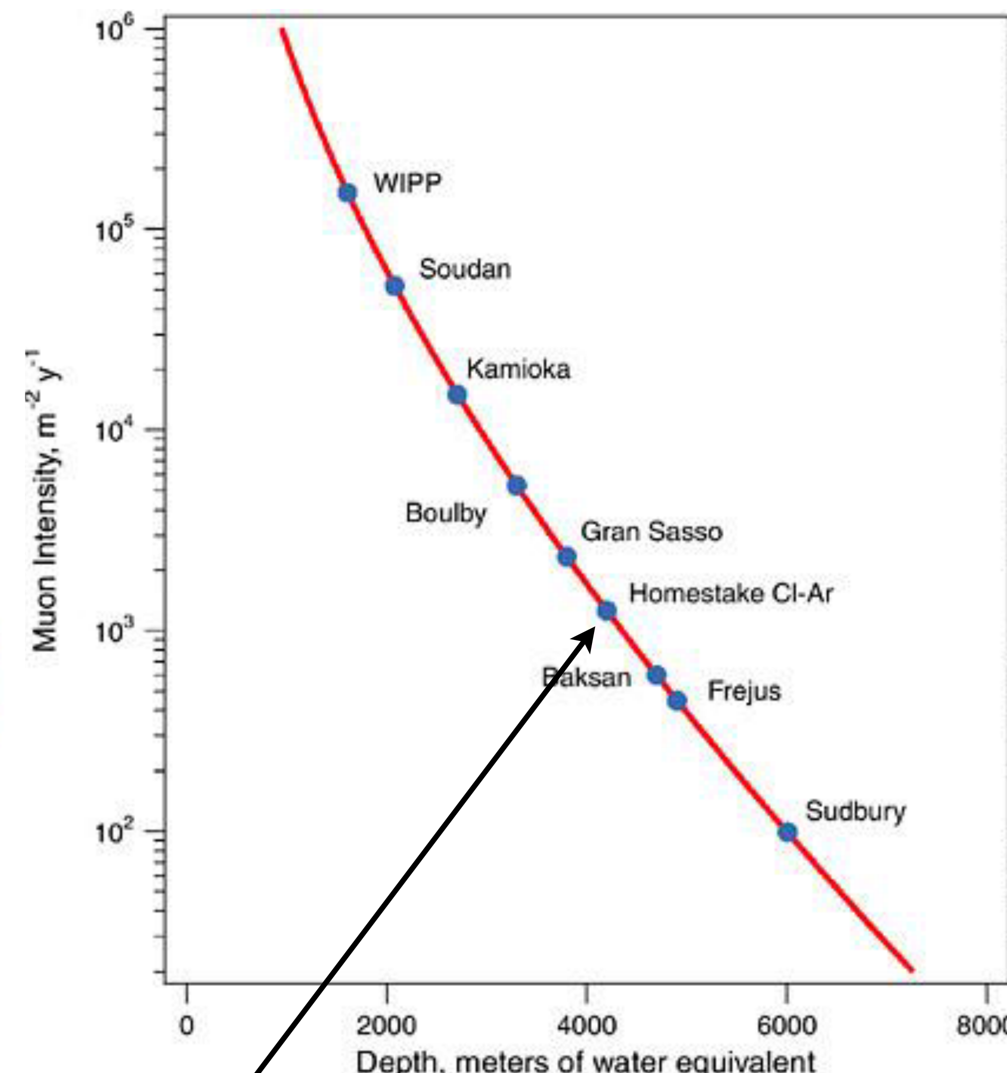
Lead, SD, located in Black Hills



Former Homestake gold mine - repurposed as a “science mine”

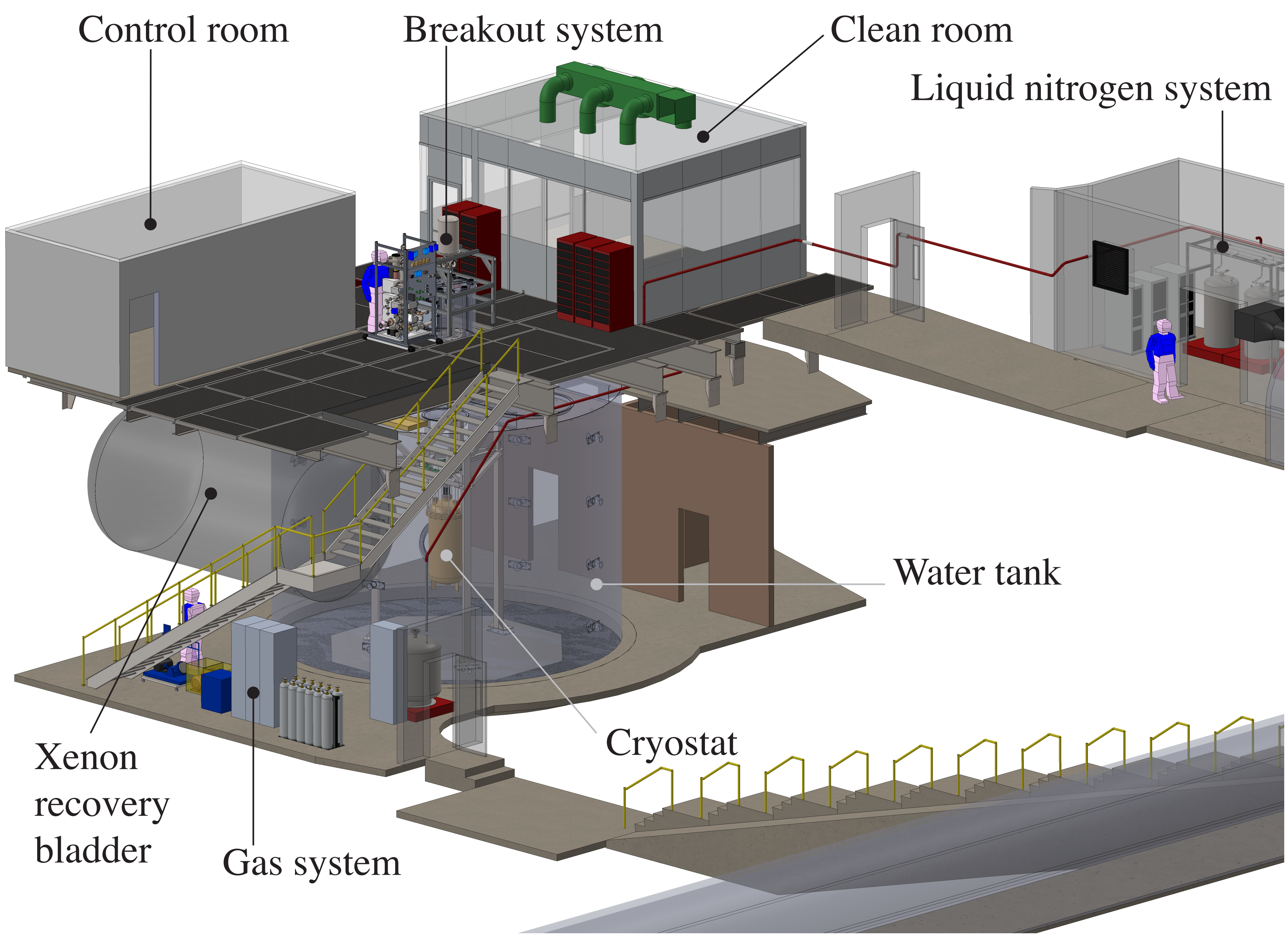
LUX at SURF



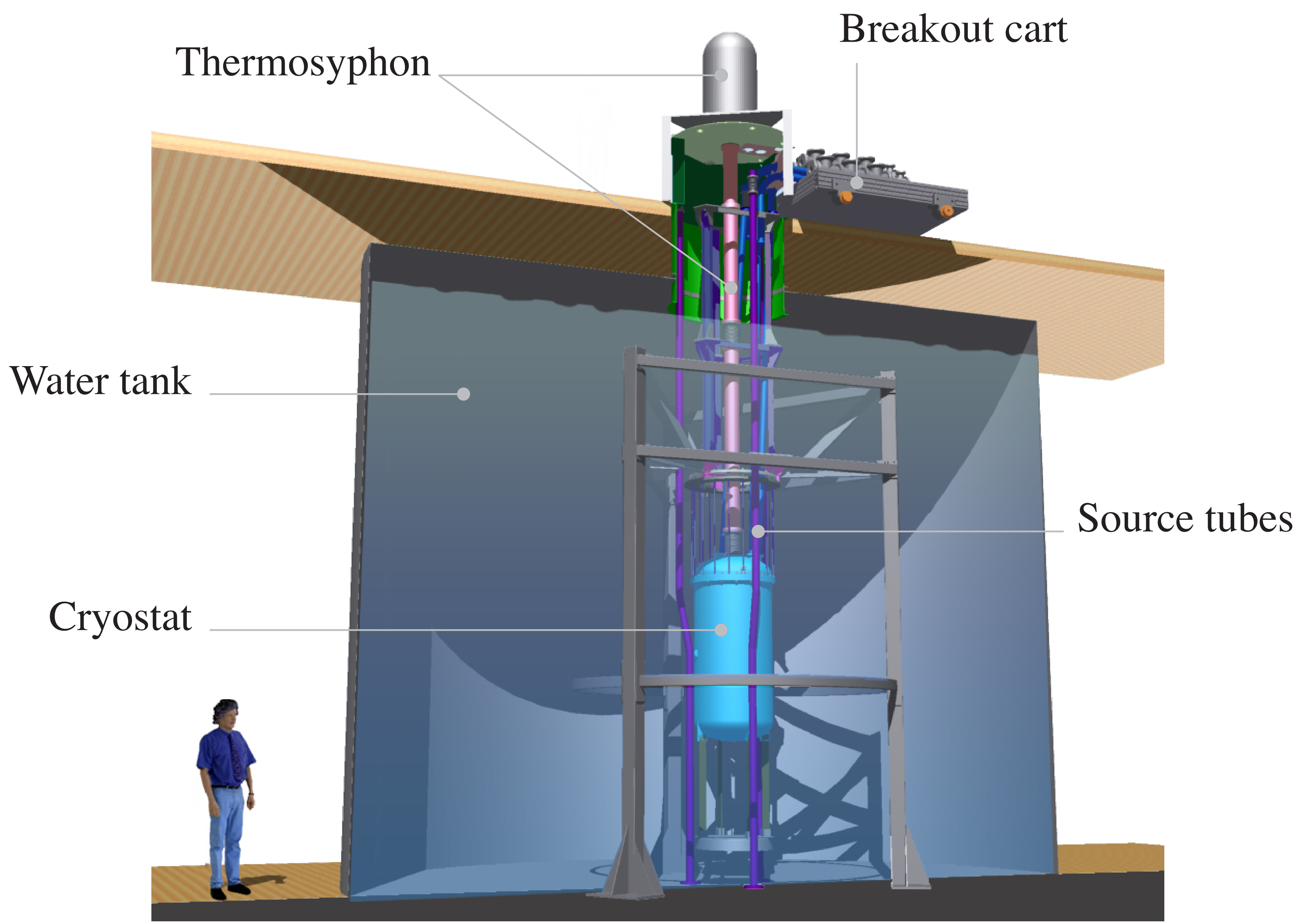


Muon flux at 4850' level reduced by 10^7 relative to the surface
$55.2\ m^{-2}s^{-1} \rightarrow 1\times10^{-5}\ m^{-2}s^{-1}$

LUX in the Davis Campus

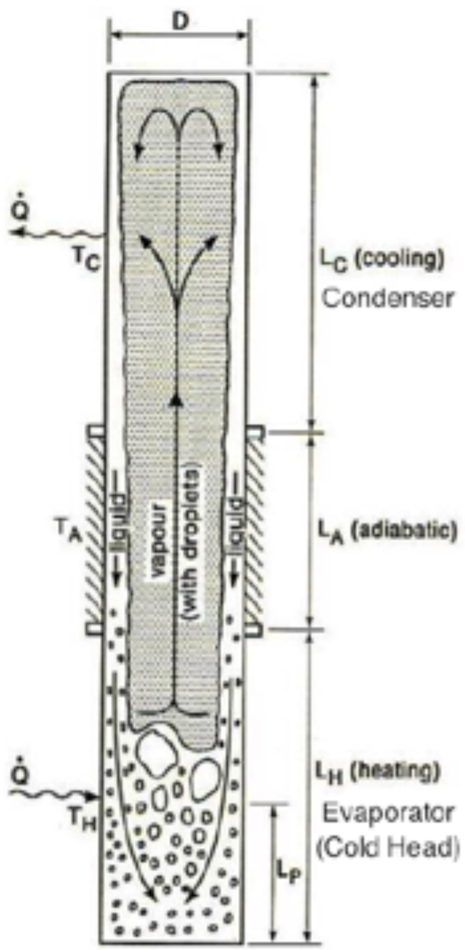


LUX Detector

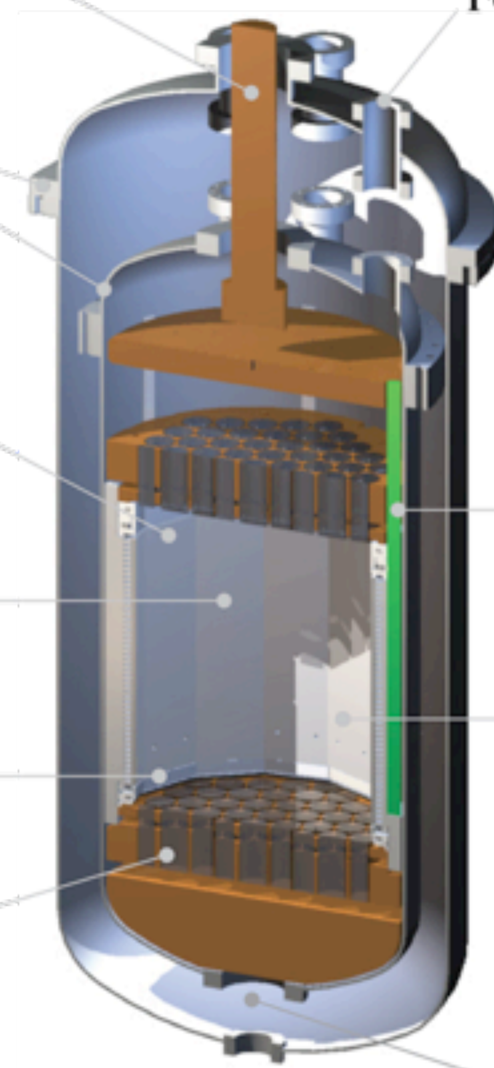


D. S. Akerib et al, Nucl. Instrum. Meth. A **704**, 111-126 (2013)

Cryostat

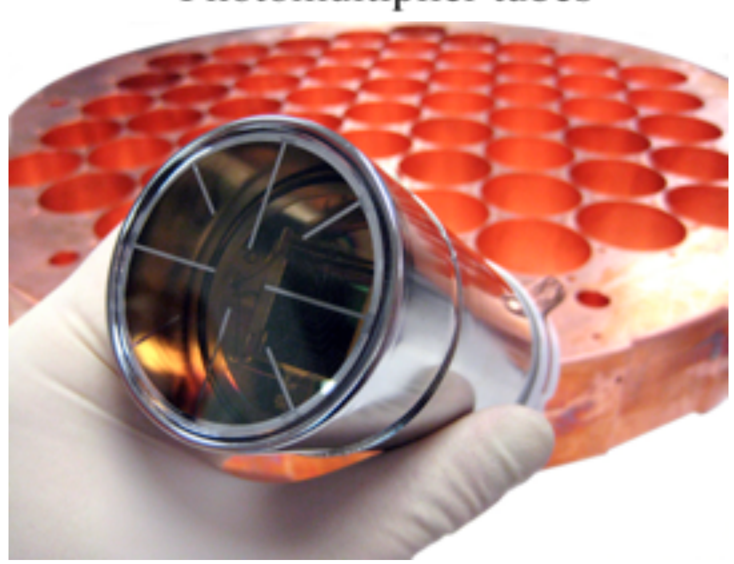


Use thermosyphons for efficient, passive cooling



Radiopure Ti < 0.2 mBq/kg

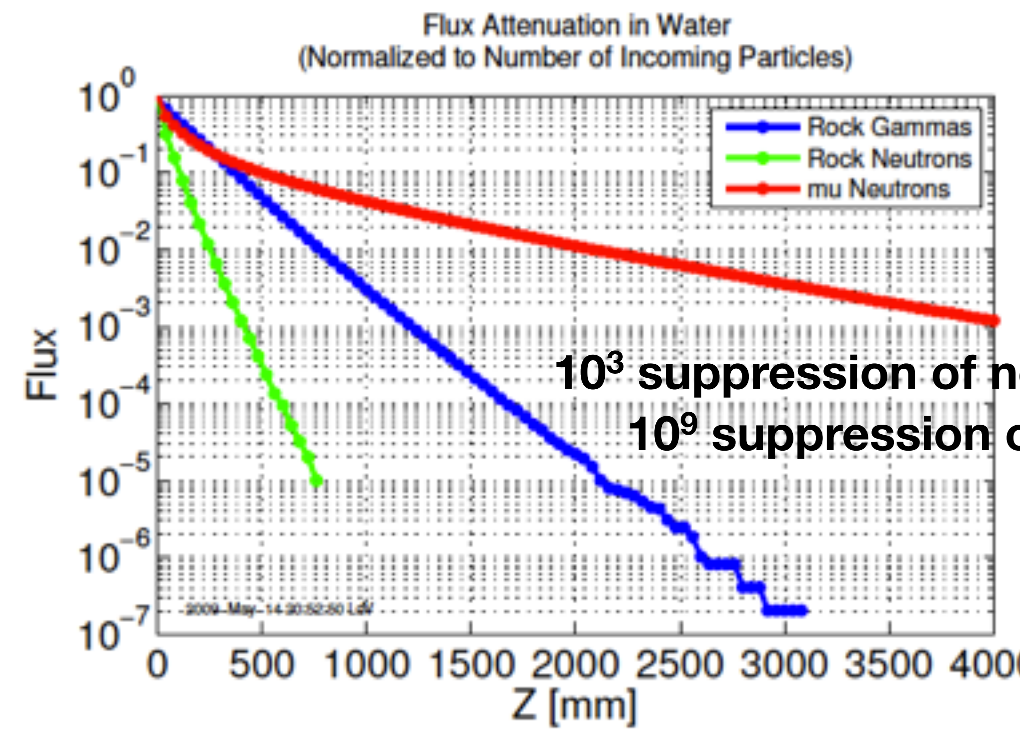
Constantly circulate and purify Xe in gas phase



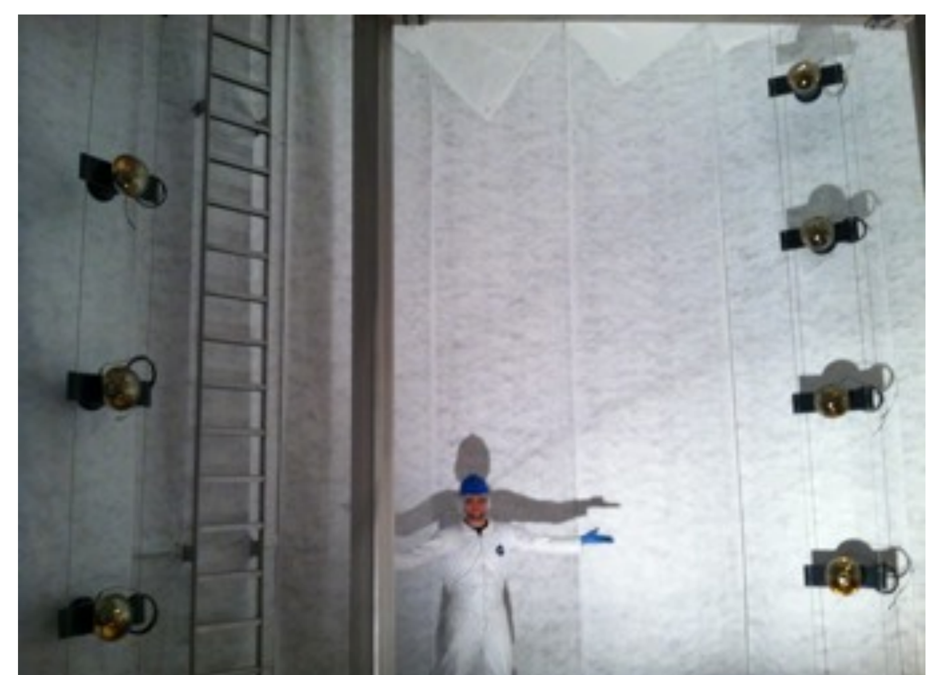
Hamamatsu R8778,
12 stage 2.2” PMTs
(61 top/61 bottom)

Water Shield

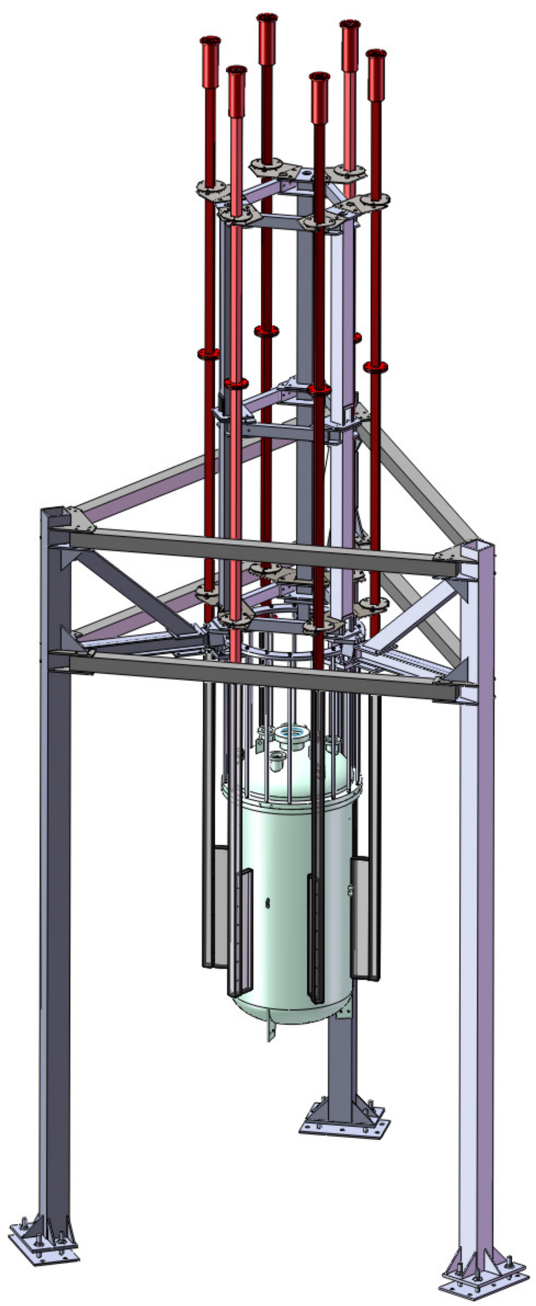
300 T de-ionized water shield,
20’ high, 25’ diameter SS tank to
reduce cavern & cosmogenic backgrounds

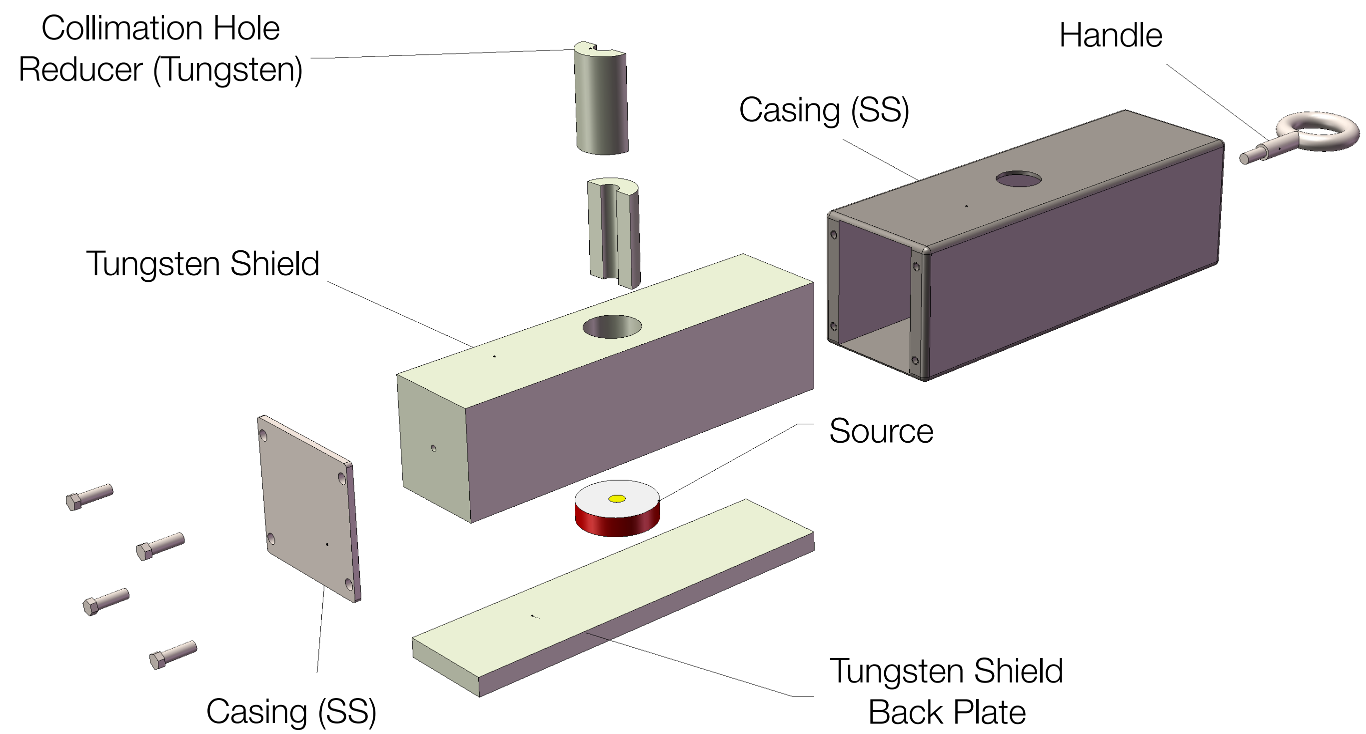


Instrumented with 20 Hamamatsu R7081 10” diameter PMTs for veto of coincident NR candidates



Detector calibration





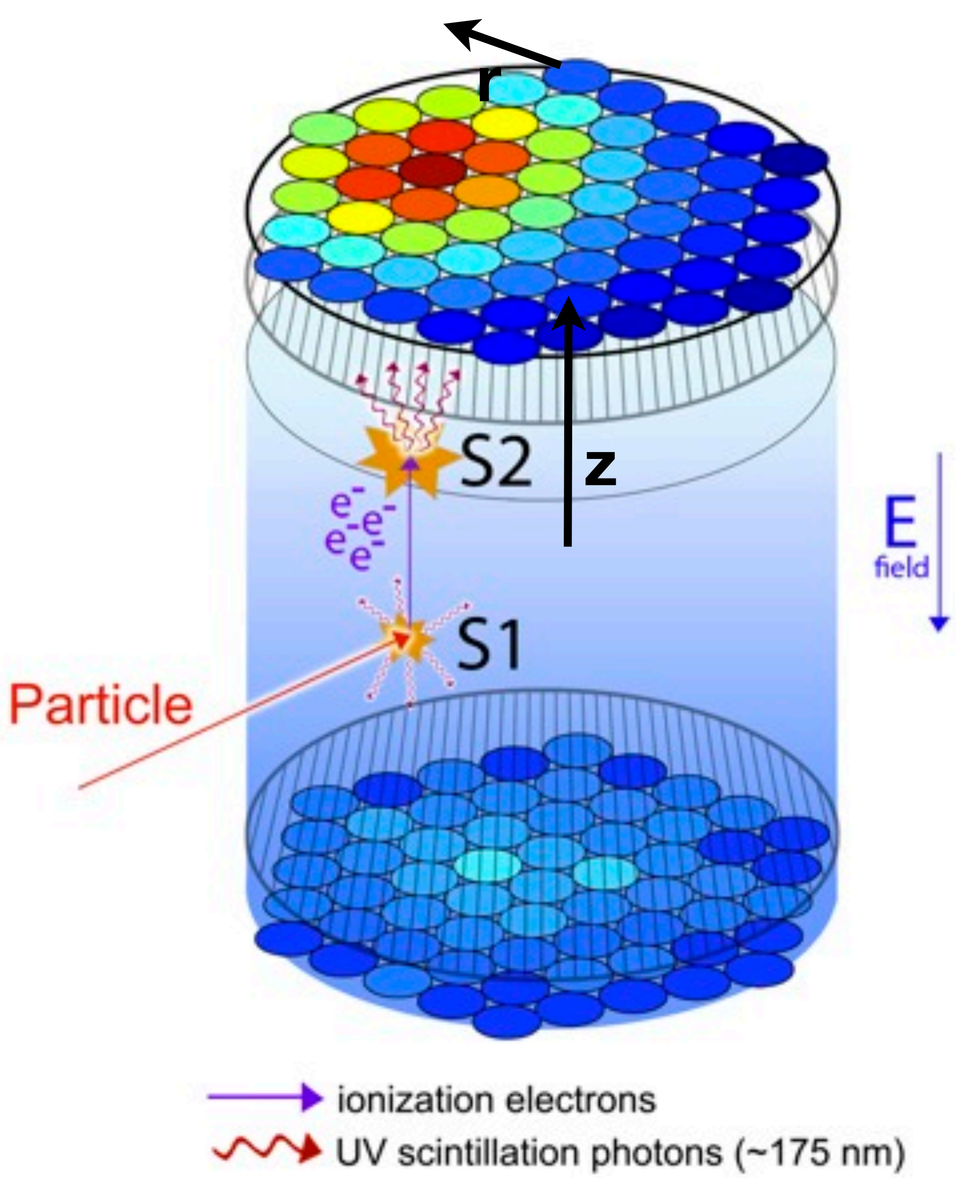
External sources:
^{241}AmBe, ^{252}Cf

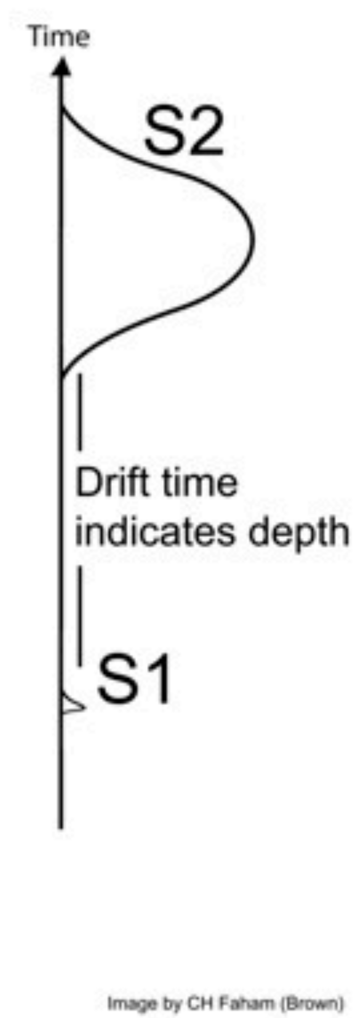
Internal sources:
^{83m}Kr, ^{3}H

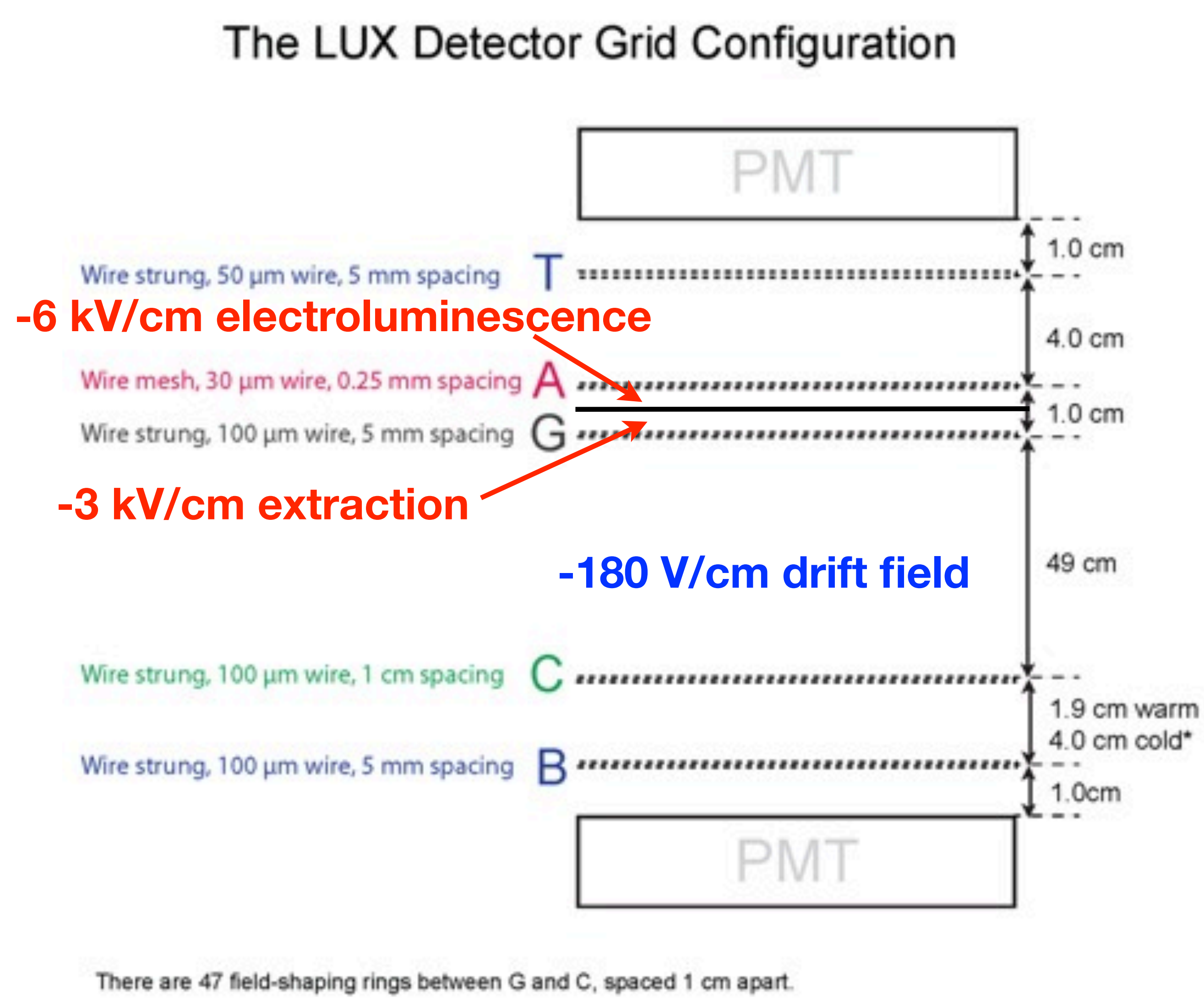
Due to self-shielding of LXe, internal sources preferable!

LUX - A TPC at heart

Read out light signals, corresponding to both initial scintillation (S1) and electroluminescence (S2)



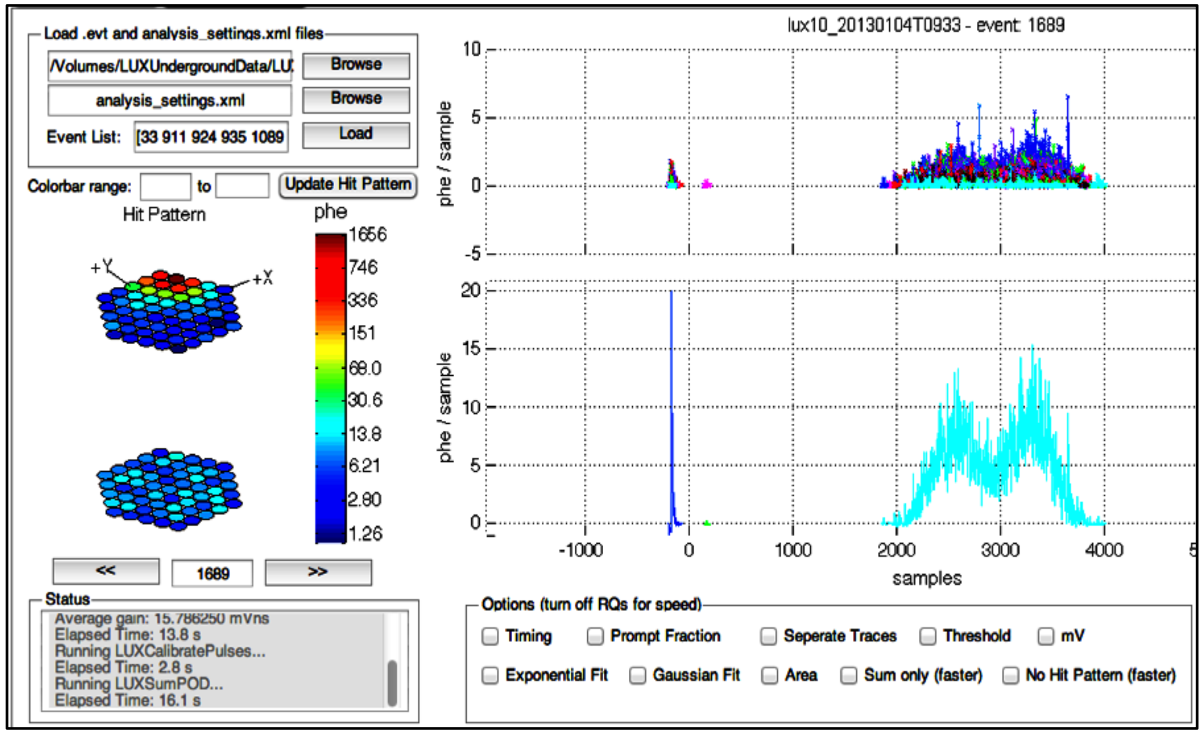




WIMP search data

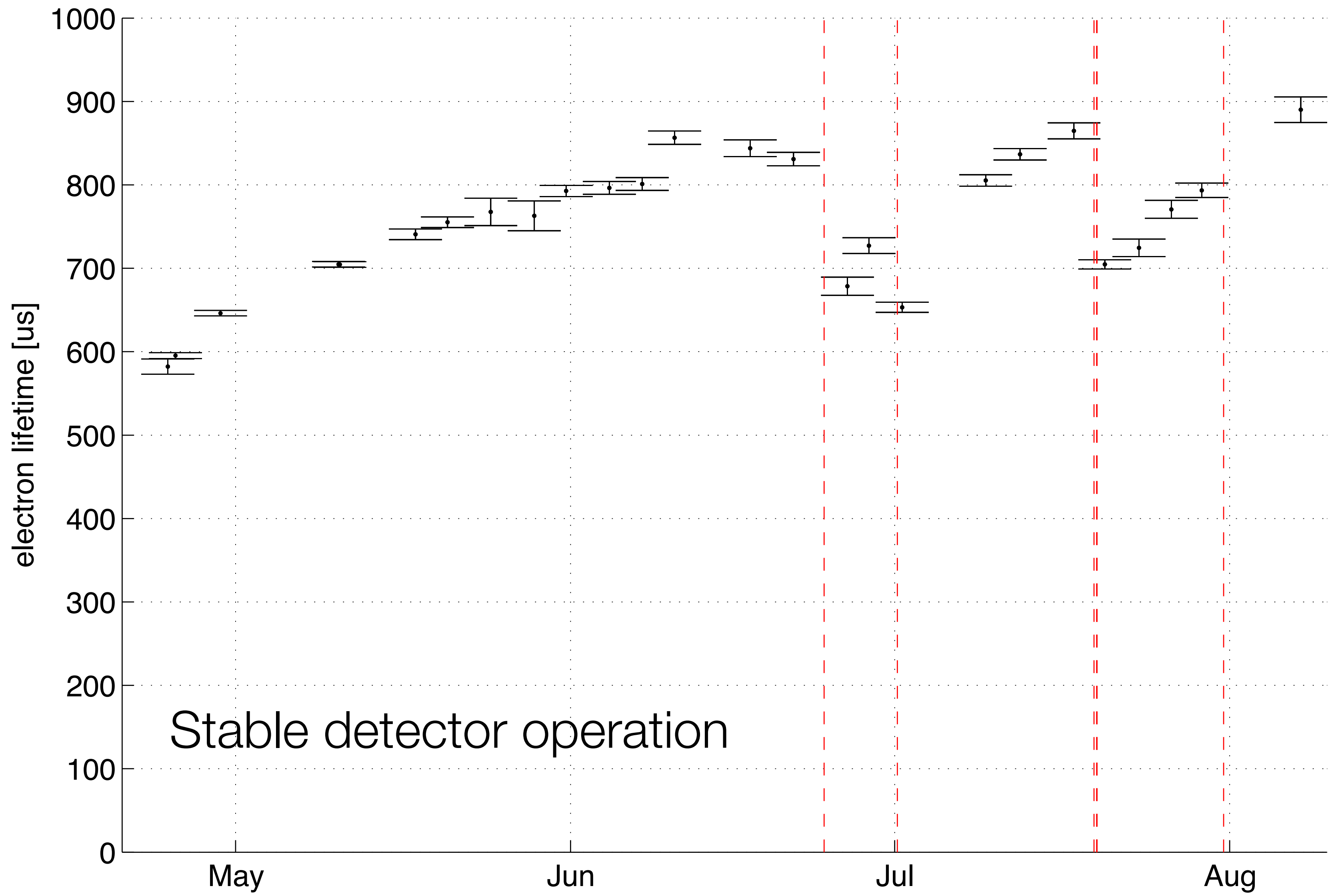
Underground operation since January, 2013

^{83m}Kr gas events injected into gas circulation line,
1.8 hr half life

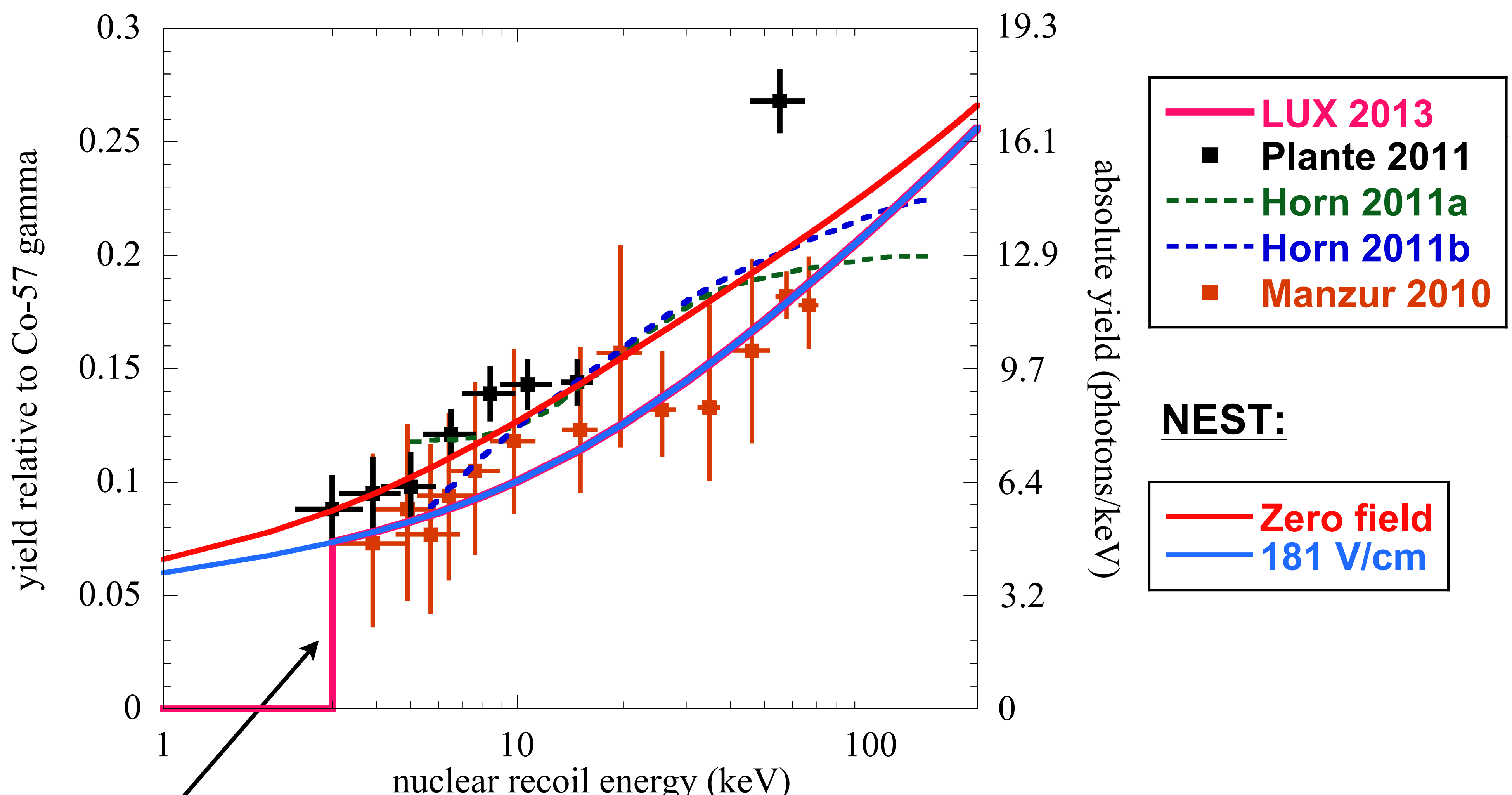


Data collection

Data-taking April 21 - August 8, 2013, 85 live days
Non-blind analysis!



Light and charge yields



"Chicago" cut ☺

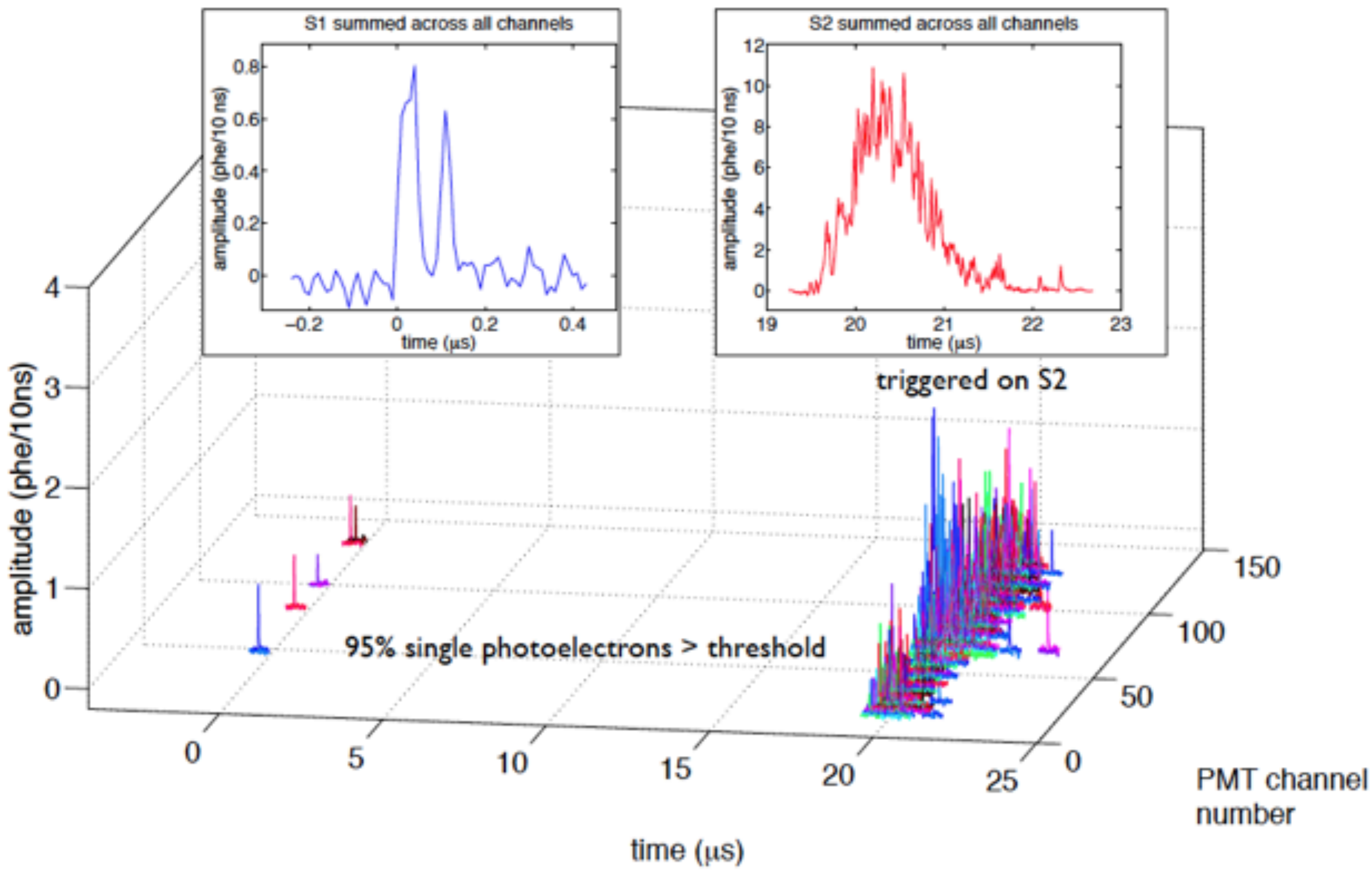
⇒ set hard threshold at 3 keVnr

Very conservative!

Photon detection efficiency: 0.14

Charge yield: 26 phe/e^-

Event selection



<u>Requirements for WIMP search candidate events</u>

S2 trigger (at least 2 trigger ch. ≥ 8 phe within 2 μs)

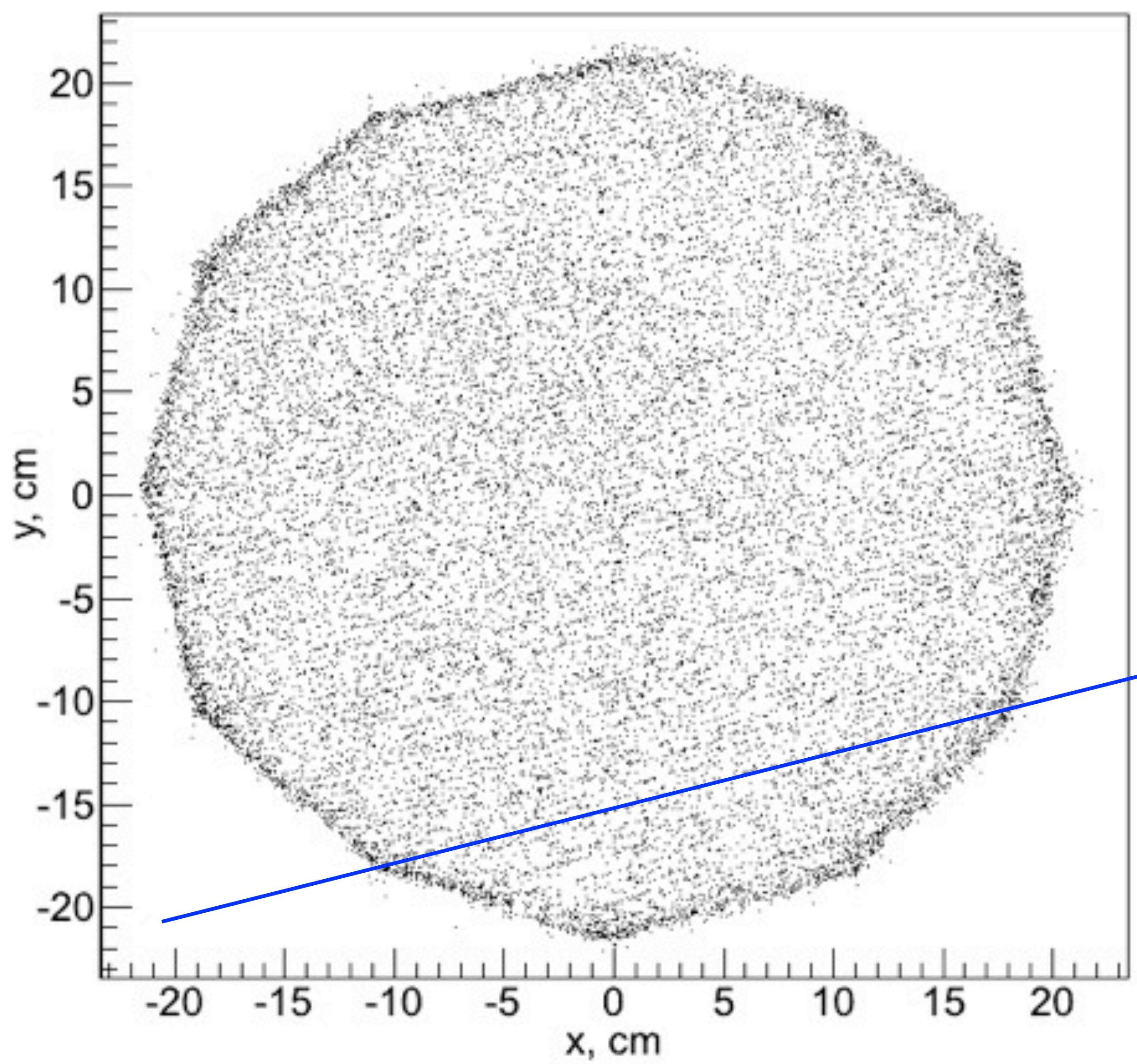
2 phe (2-fold coincidence) ≤ S1 ≤ 30 phe

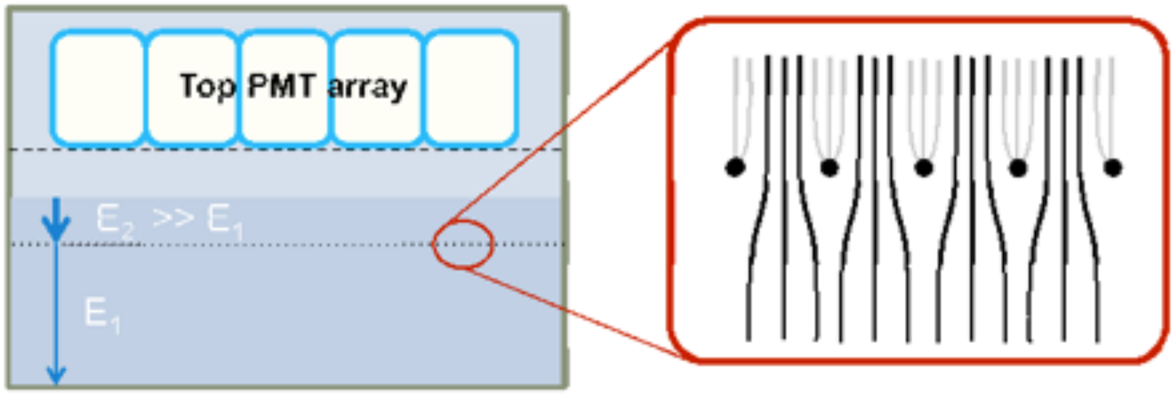
200 phe (8 e-) ≤ S2 ≤ 3300 phe

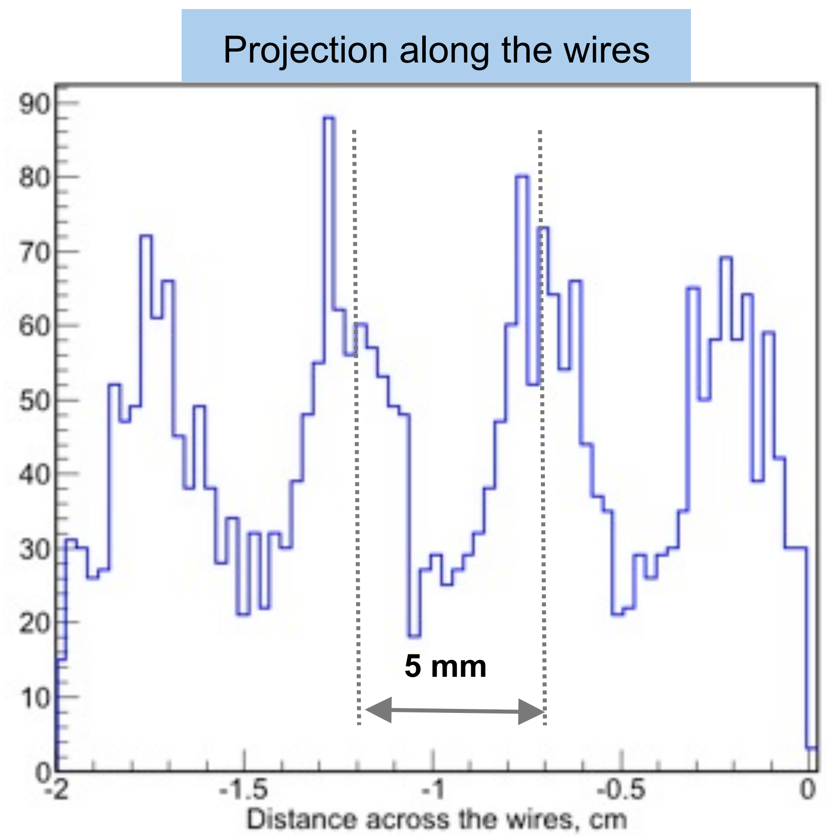
total area of other pulses in the event < 100 phe

Position reconstruction

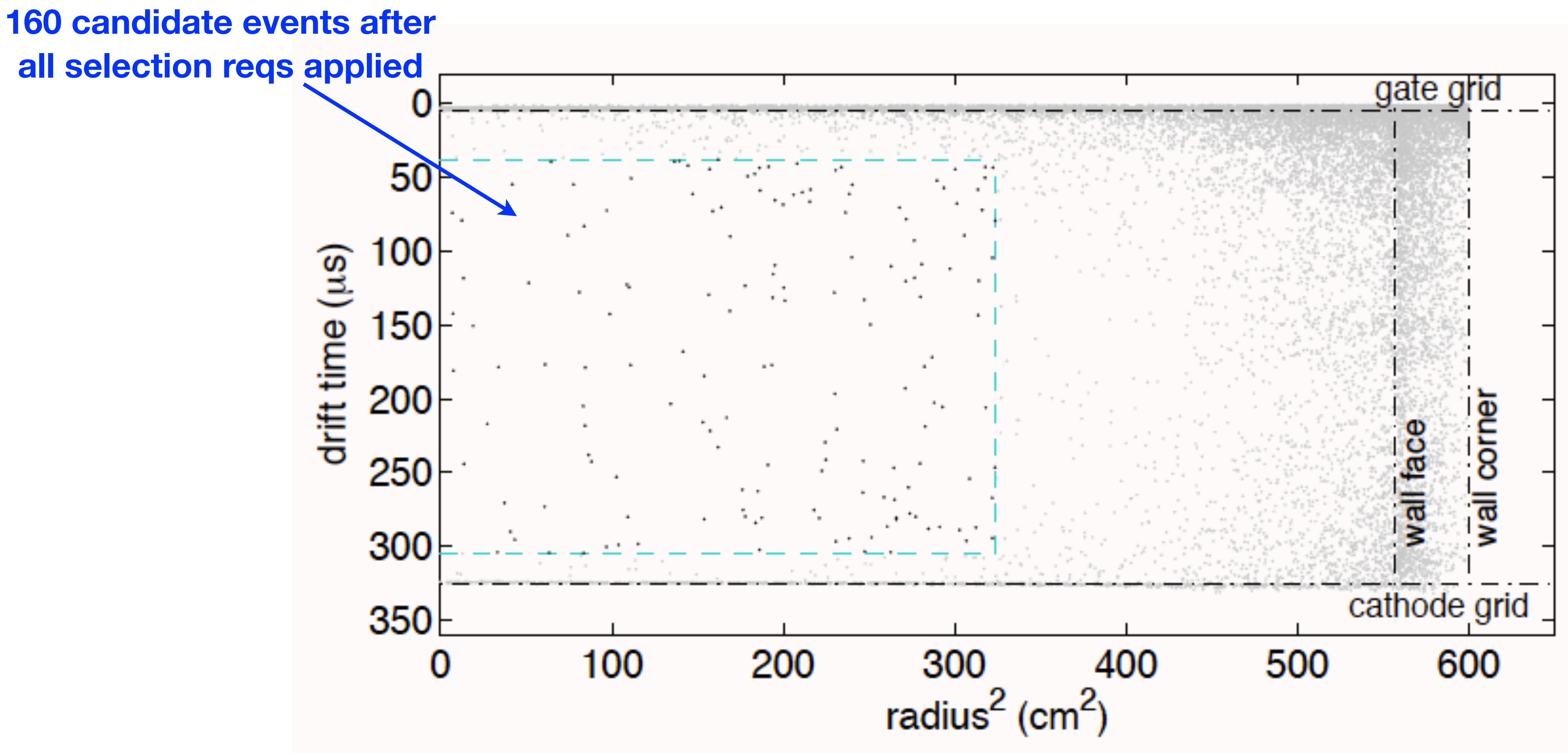
Resolve gate wire grid
for high energy events







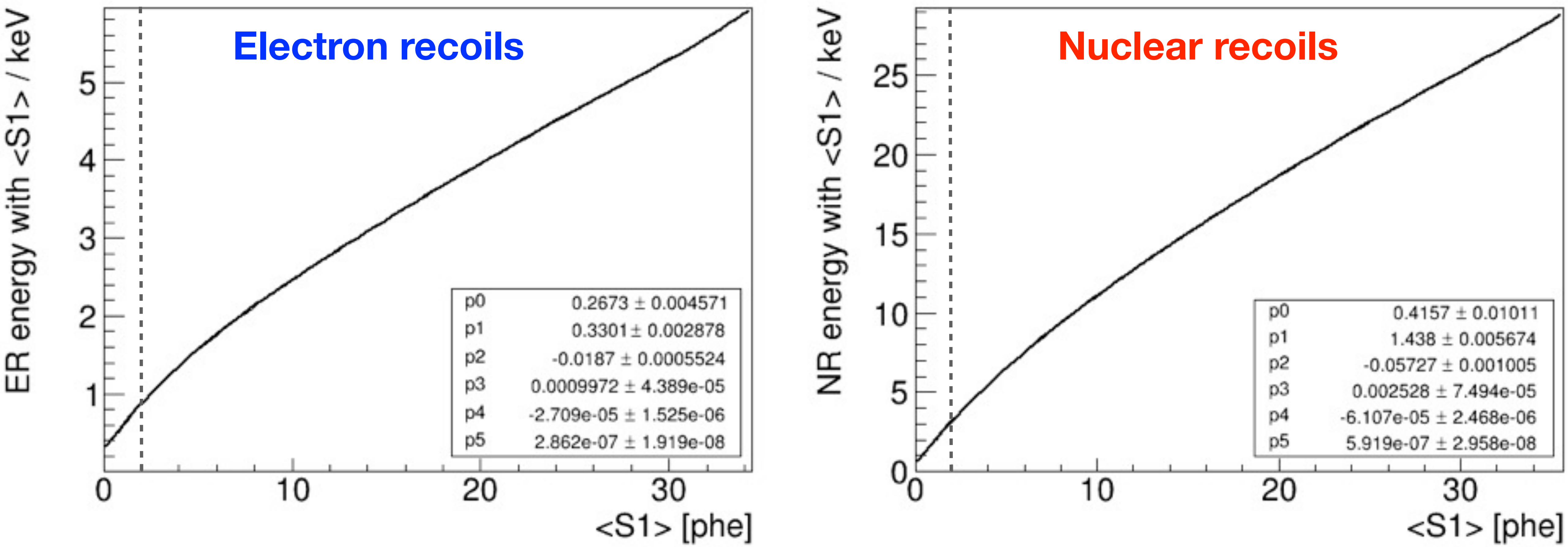
Fiducial volume



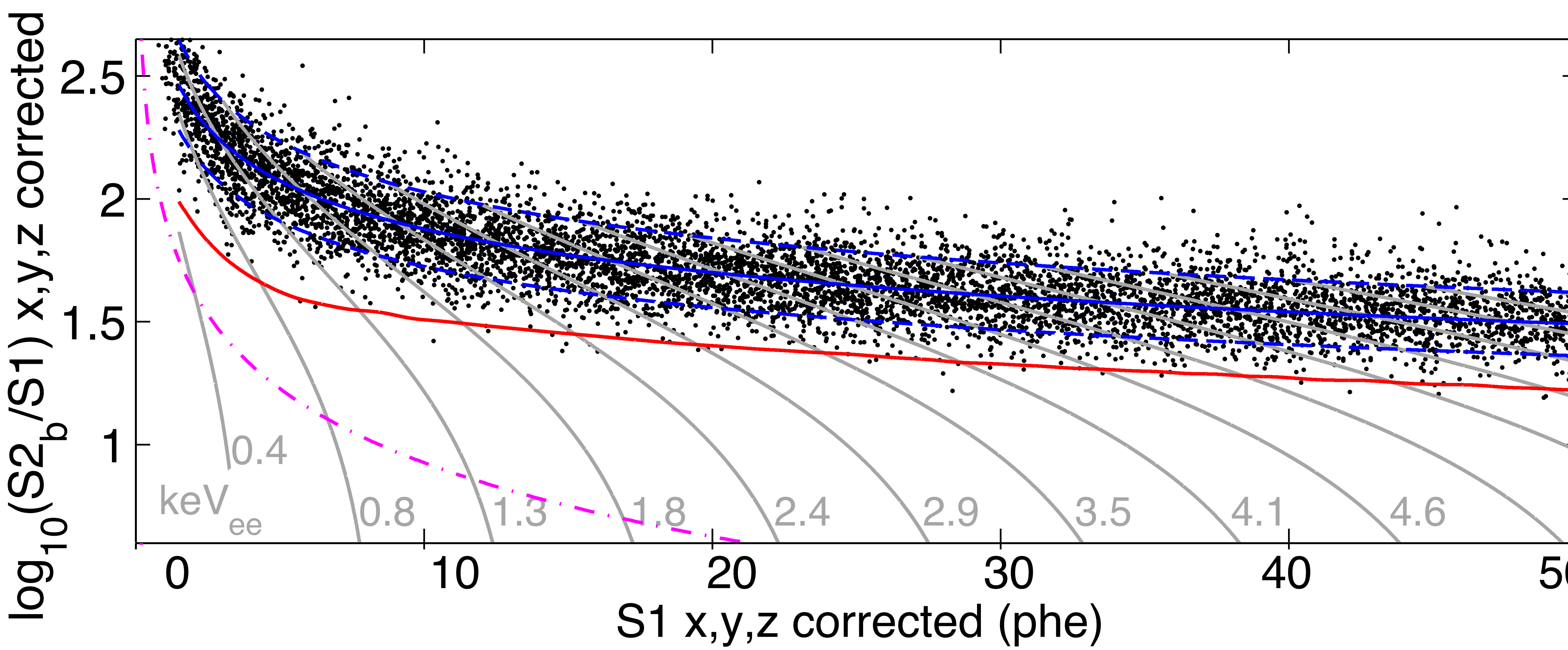
Define fiducial volume r < 18 cm, 7 < z < 47 cm, corresponding to 118 kg fiducial mass

Use S1 signal as energy scale

Parameterize ER and NR energies as a function of S1 size using NEST



Tritium calibration

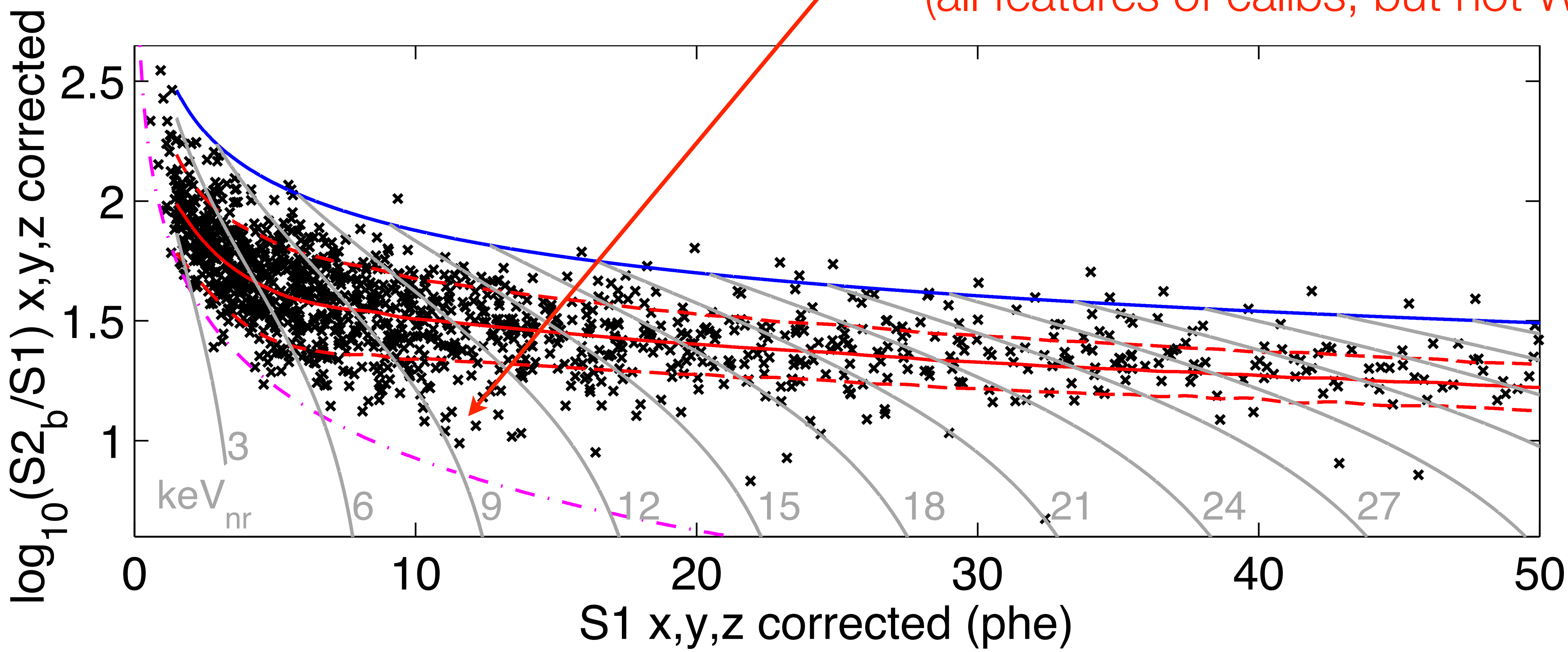


Parametrize as Gaussian, with power laws
for mean and sigma

$$\mu_i(S1) = A_m S1^{B_m}$$
$$\sigma_i(S1) = A_s S1^{B_s} - A_m S1_m^B$$

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

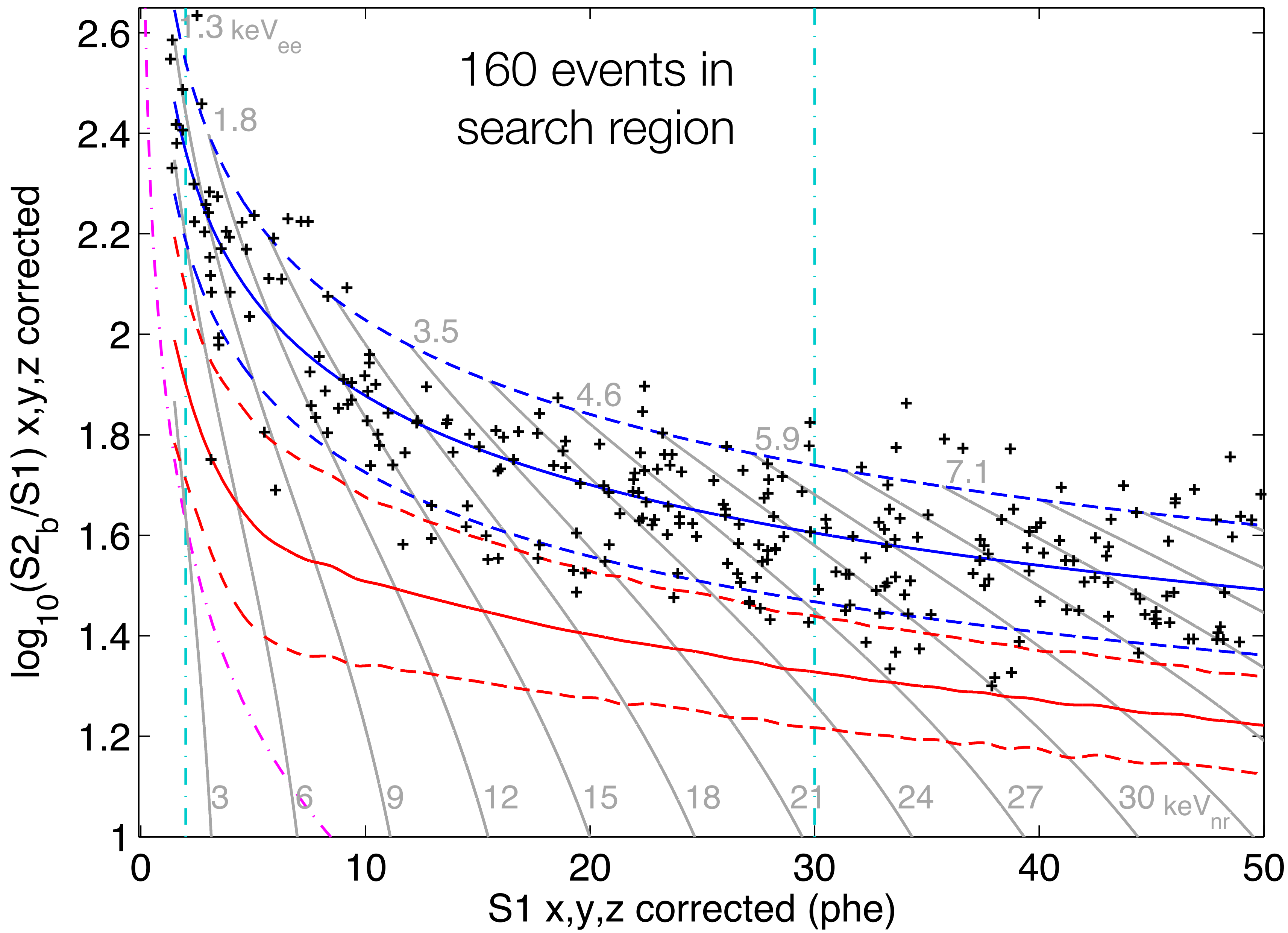
Events at low (S2$_b$/S1) due to neutron+X and multiple scatters where S2 is below reconstruction threshold
(all features of calibs, but not WIMPs!)



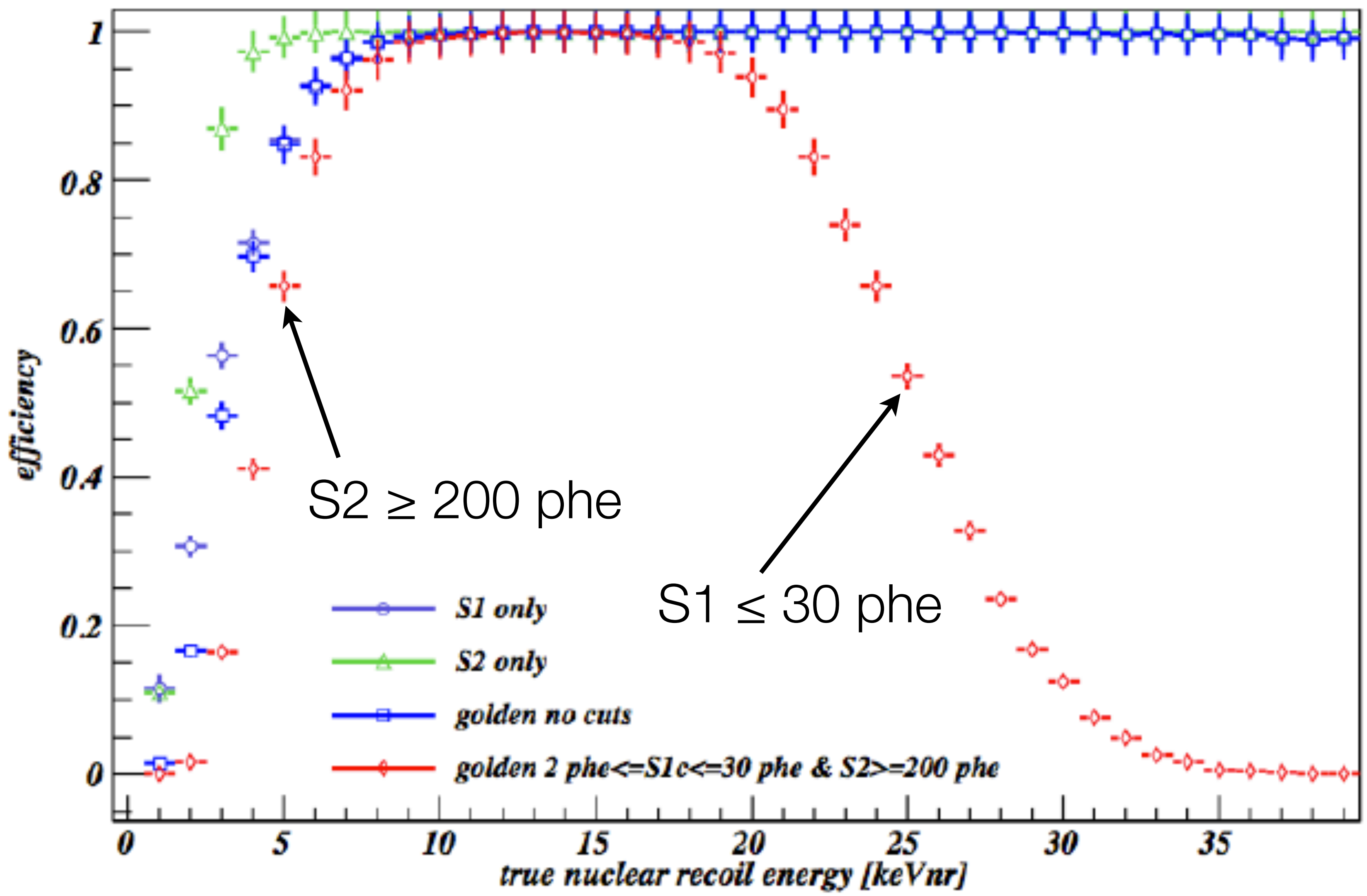
Parametrize as Gaussian, with power laws
for mean and sigma

$$
\begin{aligned}
\mu_i(S1) &= A_m S1^{B_m} \\
\sigma_i(S1) &= A_s S1^{B_s} - A_m S1^{B}_{m}
\end{aligned}
$$

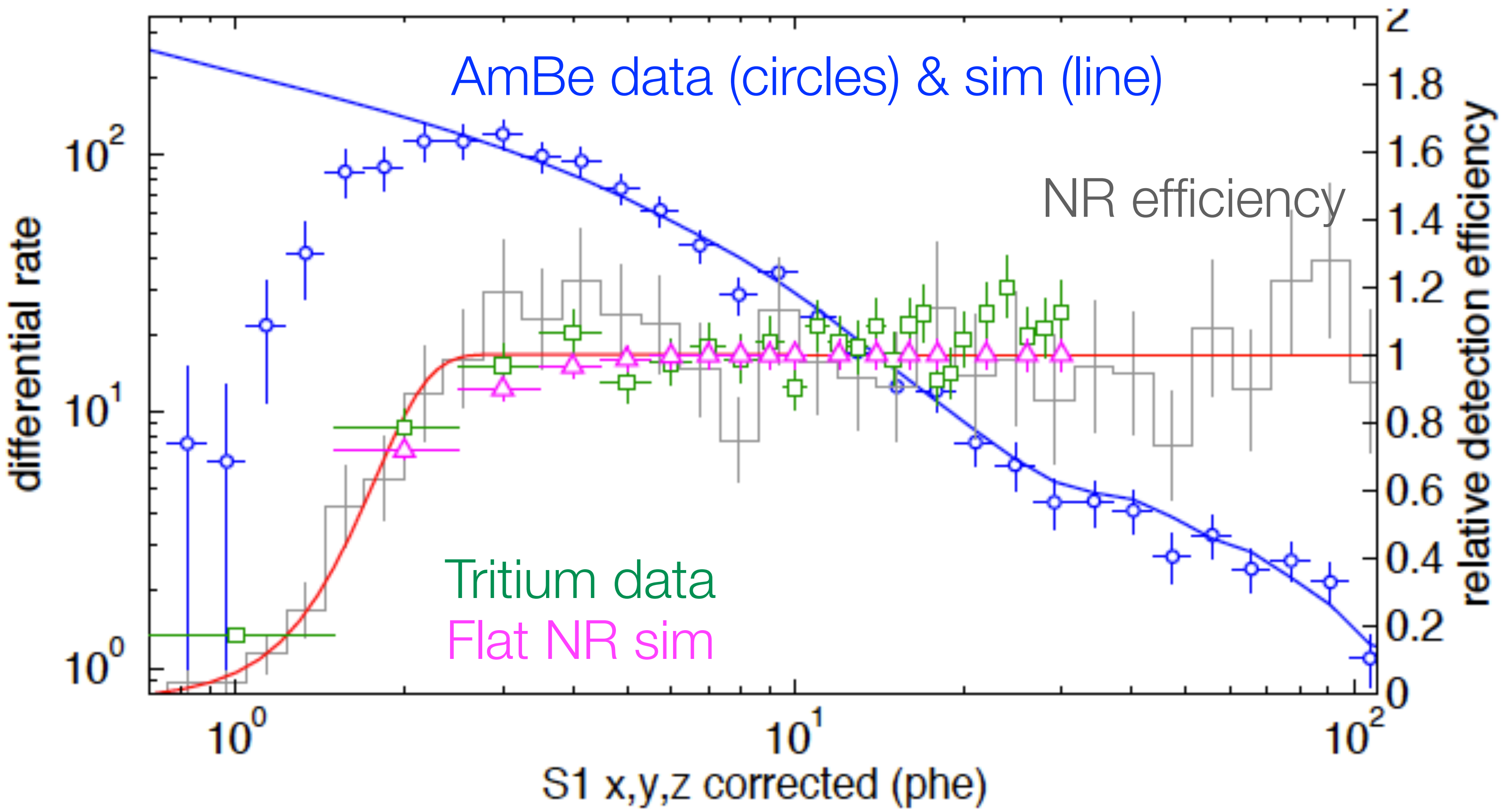
WIMP search data



Efficiency of pulse finding and selection



Several independent estimates of total efficiency



We find good agreement between the data and simulation-estimated efficiencies.

D.S. Akerib et al., Nucl. Instr. Meth. A **675**, 63 (2012)

The Likelihood

Use an extended likelihood

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

Discriminant between ER/NR

Energy

Discriminant against external/internal radiation

Observables: $\mathbf{x}$ = (S1, $\log_{10}$(S2/S1), r, z)

Parameter of interest: N_s

Nuisance parameters: N_{Compt}, N_{Xe-127}, $N_{Rn/Kr-85}$

Gaussian constrain to within 30% of the predicted rates

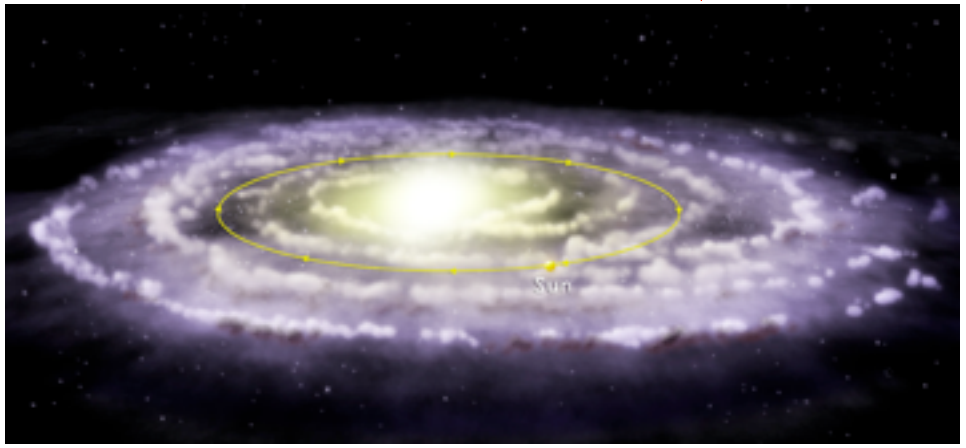
Predicted WIMP scattering

C. McCabe, Phys. Rev. D, **82**, 023530 (2010)

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{M_\chi} \int_{v_{min}}^{\infty} v f_\oplus(\vec{v}, \vec{v}_e) \frac{d\sigma}{dE_R} d^3v$$

$$\frac{d\sigma}{dE_R} = \frac{1}{2v^2} \frac{M_N \sigma_n}{\mu_{ne}^2} \frac{(f_p Z + f_n(A-Z))^2}{{f_n}^2} F^2(E_R)$$

Use standard isothermal halo model with cutoff



Use Helm form factor

$$F^2(E_R) = \left(\frac{3j_1(qR)}{qR}\right)^2 e^{-q^2s^2}$$

$$R = \sqrt{r^2 - 5s^2}$$

Velocity of solar system in the galaxy: $v_0 = 220$ km/s

Velocity of earth around the sun: $v_E = 245$ km/s

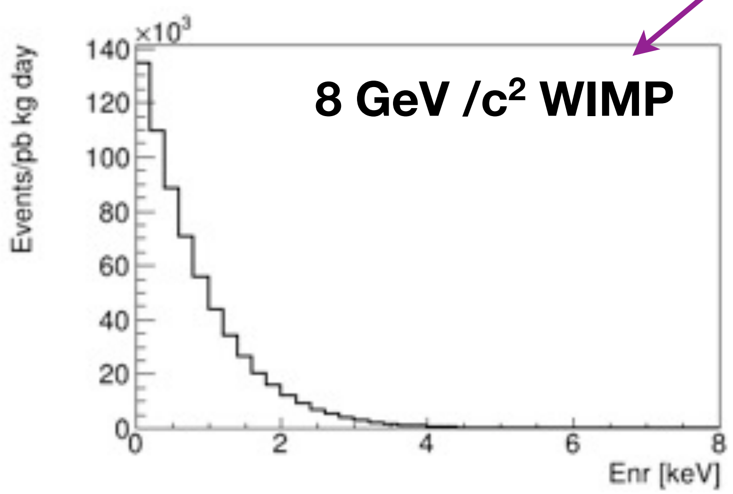
Galactic escape velocity: $v_{esc} = 544$ km/s

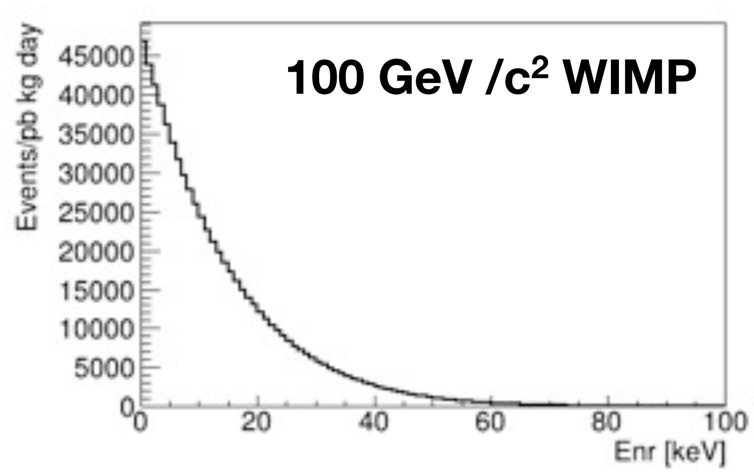
Local dark matter density: $\rho = 0.3$ GeV/c^2/cm^3

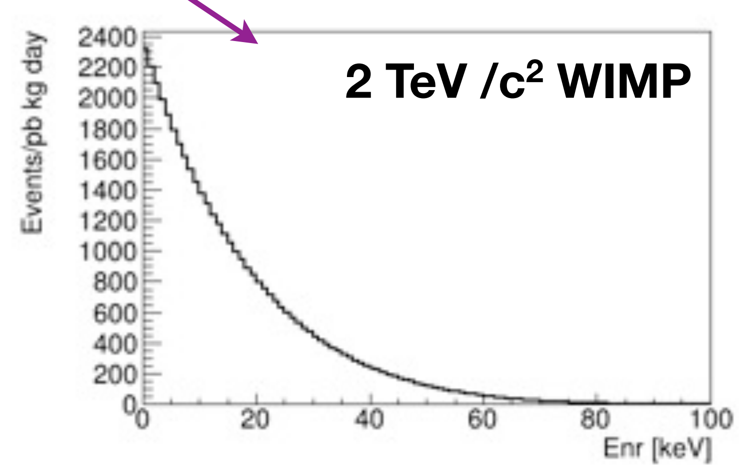
WIMP signal model

$$P_s(log_{10}(S2/S1)|S1)P_s(E_{NR}(S1))P_s(r)P_s(z)$$

$$P_s(E_{NR}(S1)) = \varepsilon(S1)\frac{dR}{dE_{NR}}(\sigma_0, m_{wimp}, \boldsymbol{\theta_{dm}})\frac{dE_{NR}}{dS1}$$





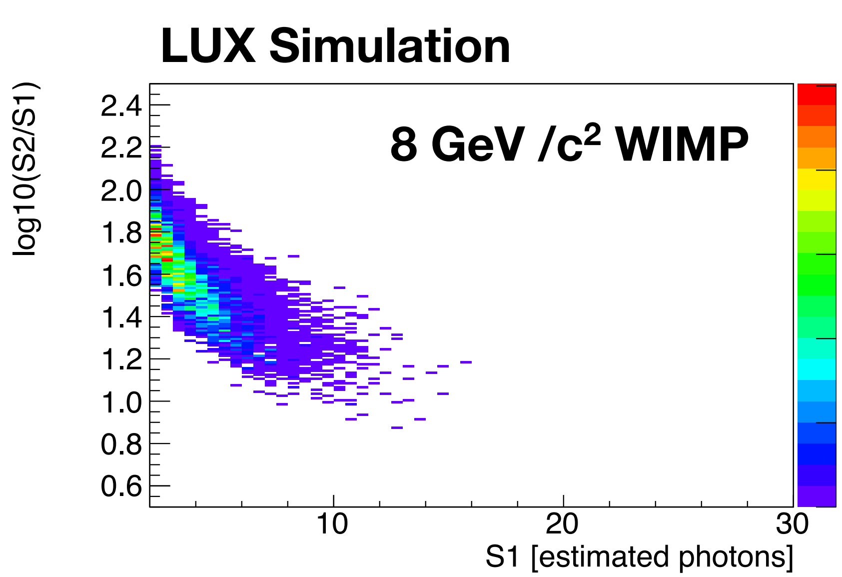


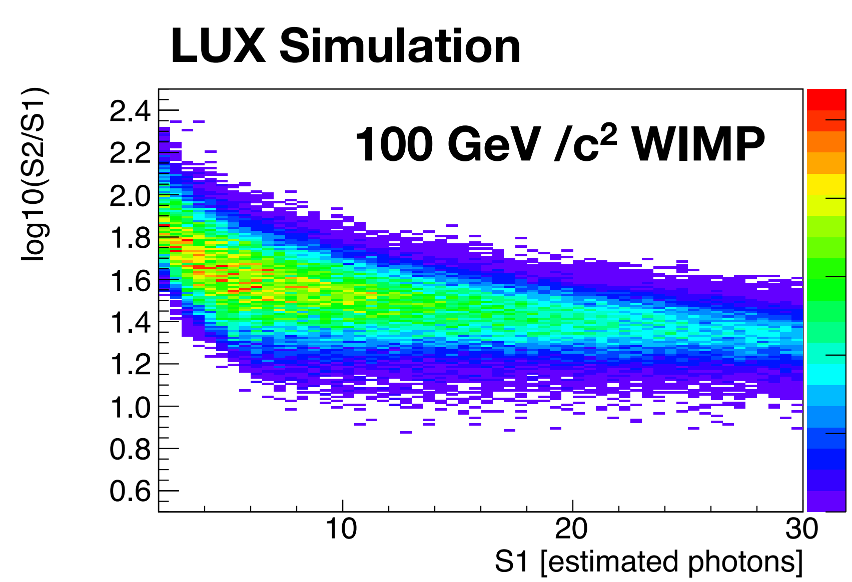
Use simulation in final model of WIMP signal

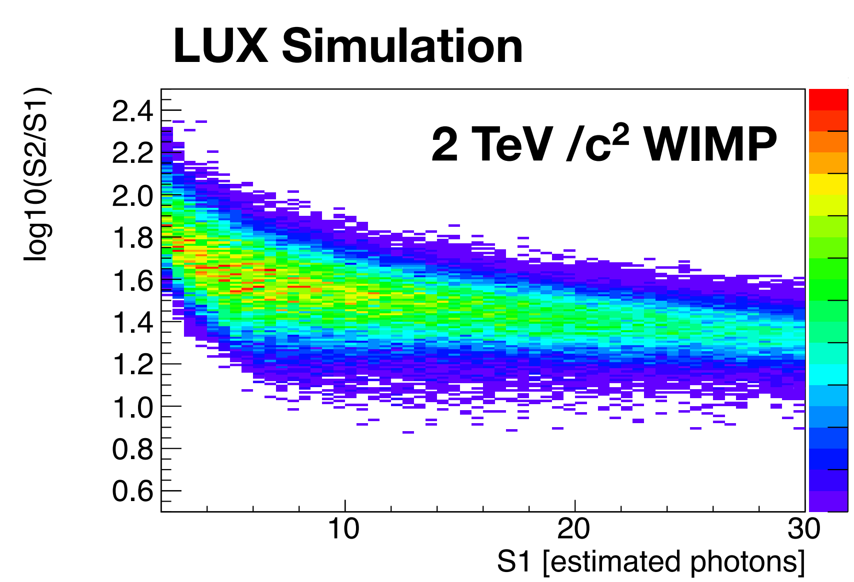
$$\underbrace{P_s(log_{10}(S2/S1)|S1)P_s(E_{NR}(S1))}_{\text{Use realistic simulation to model 2D pdf, includes resolution and efficiencies}}\underbrace{P_s(r)P_s(z)}_{\text{Model as uniform in }(r^2,z)}$$

Model as uniform in (r^2,z)

Use realistic simulation to model 2D pdf, includes resolution and efficiencies

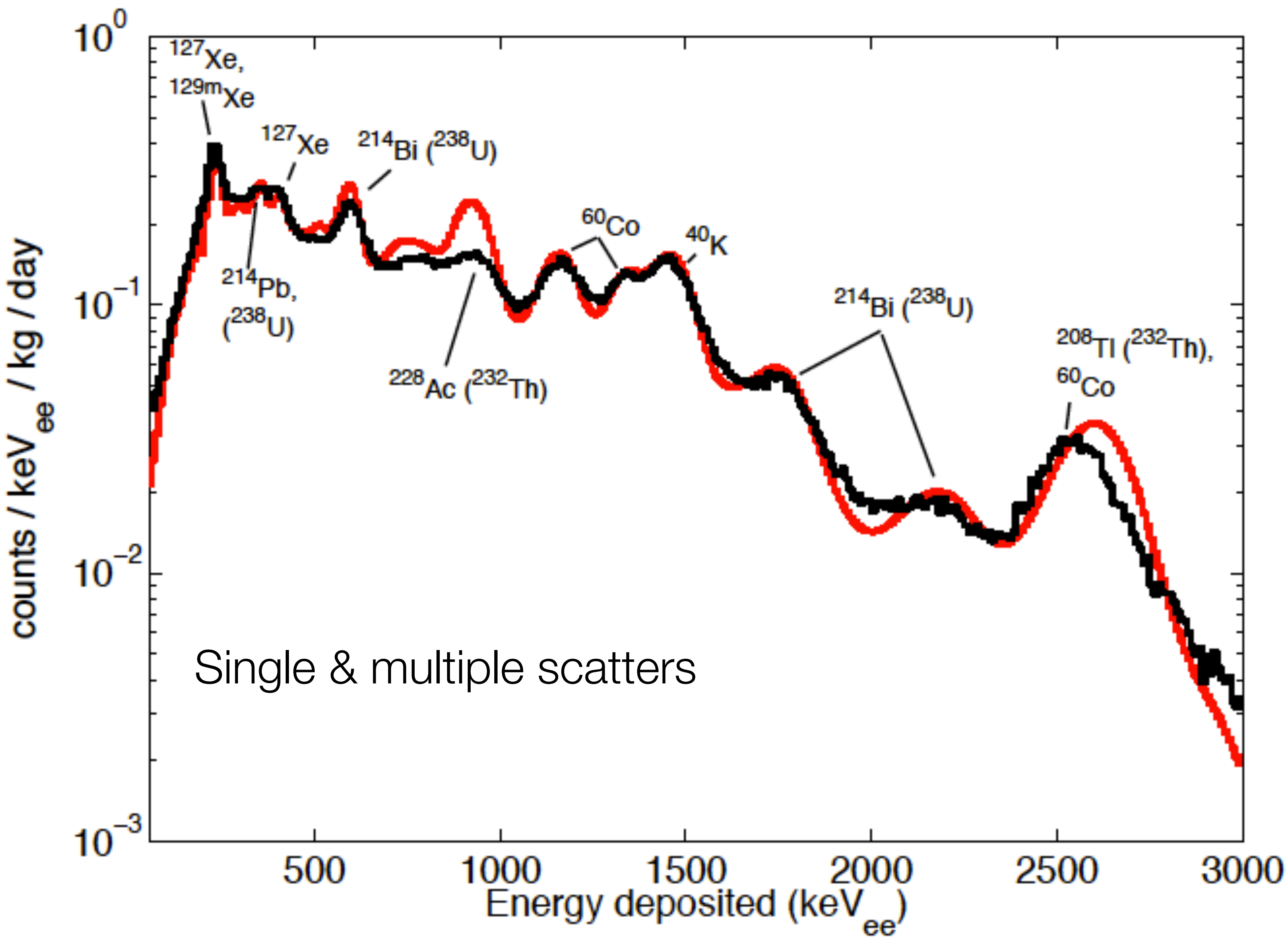






Radioactive materials background

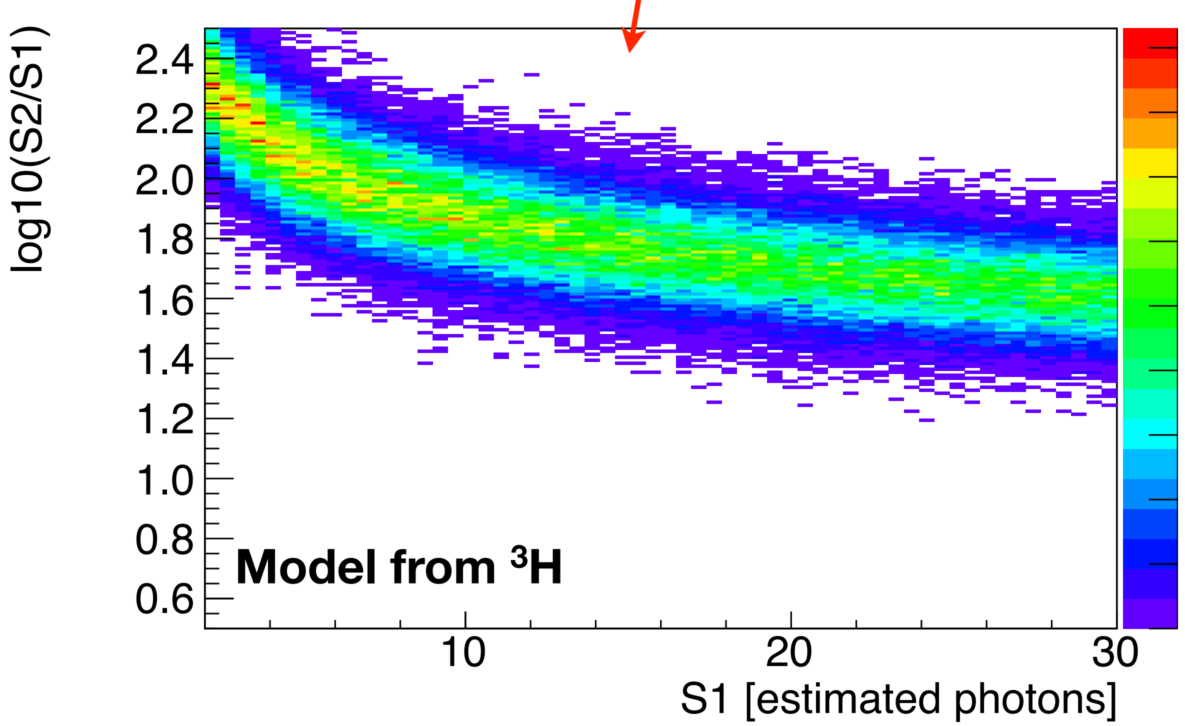
Tune simulation to match observed high-energy backgrounds

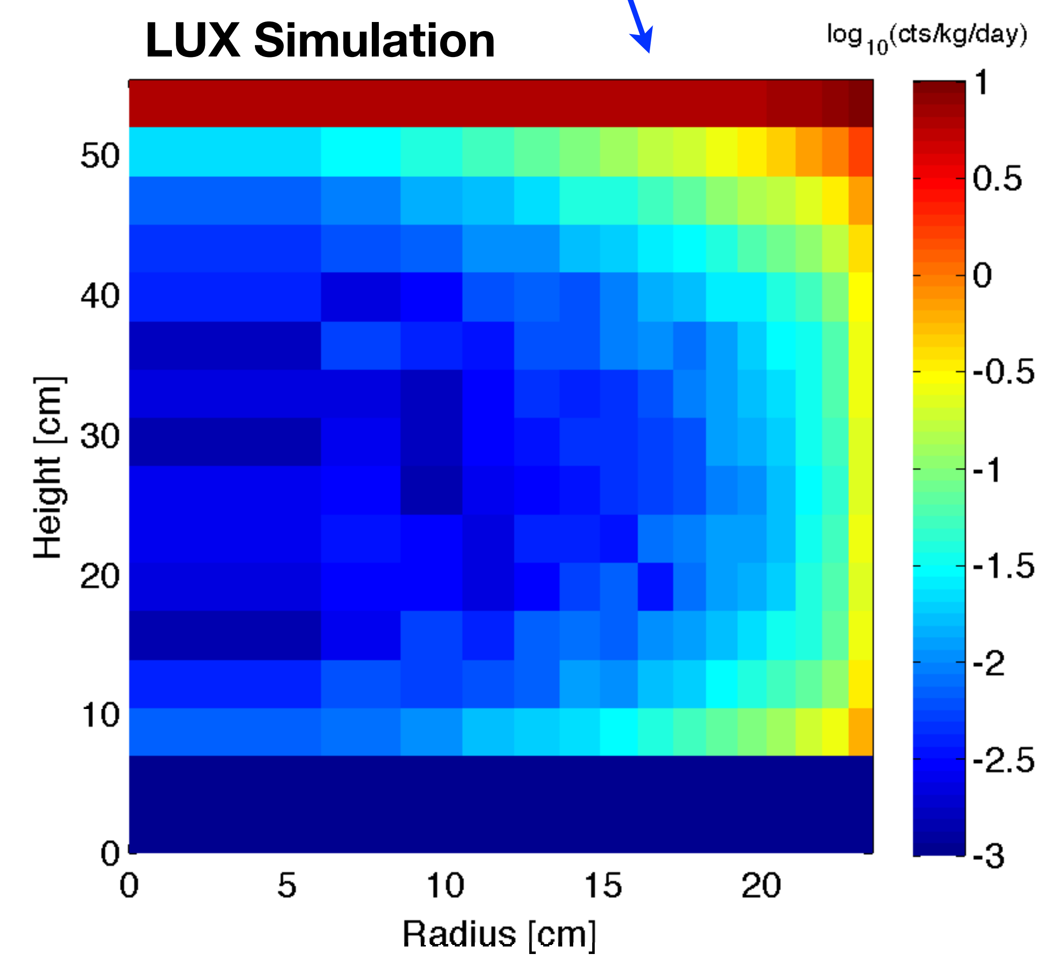


Radioactive materials model

$$P_{ER}(log_{10}(S2/S1)|S1)\,P_{Compton}(E_{ee}(S1))\,P_{Compton}(r,z)$$

Model as uniform in $E_{ee} \in [0.9, 5.1]$ keVee



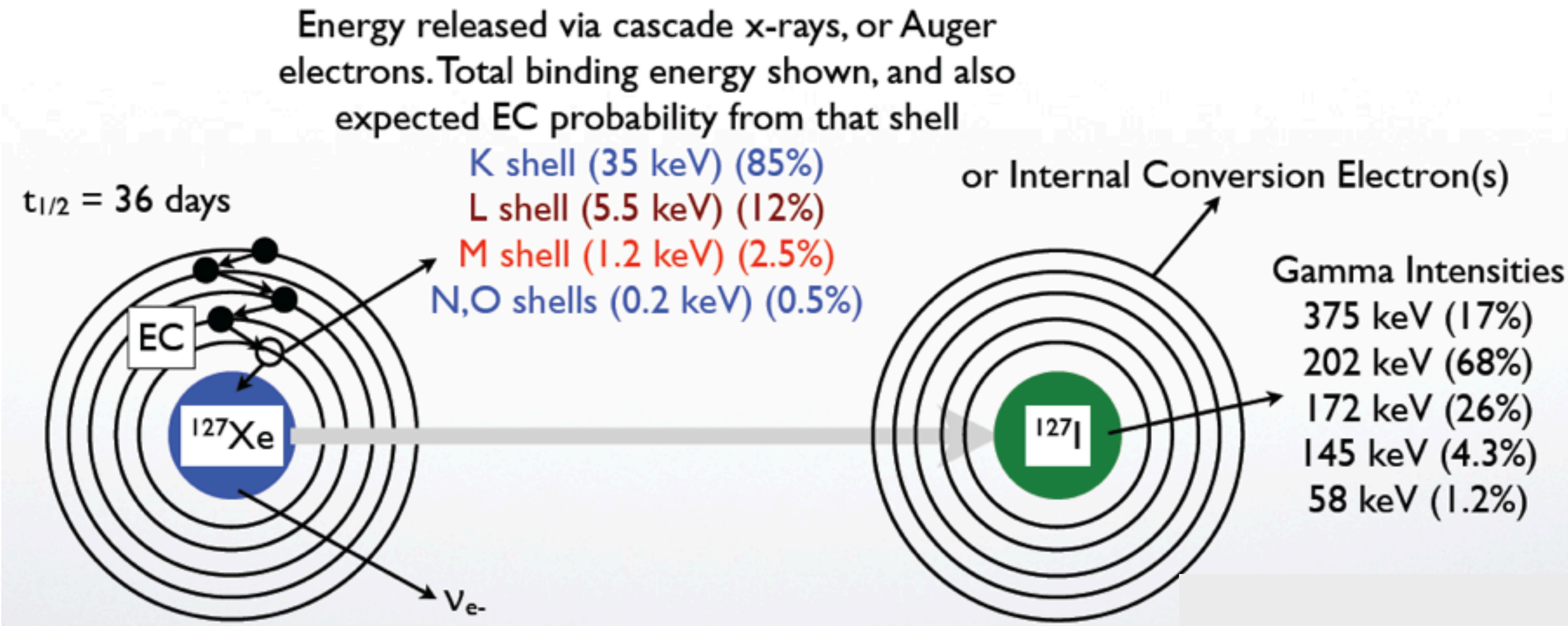


Predict 129 events in WIMP search data

^{127}Xe Background

Electron capture from S-wave orbital,

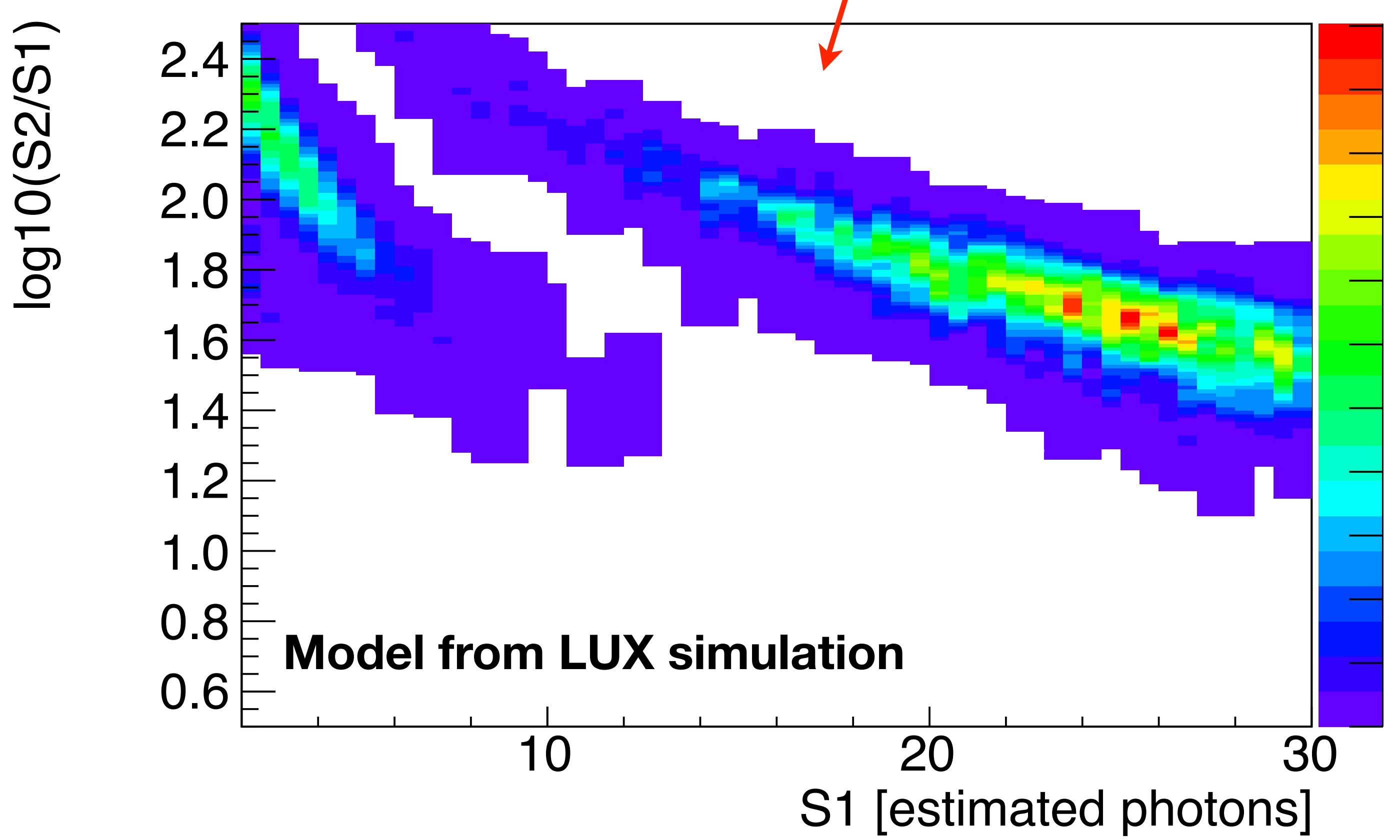
$p+e^{-}\rightarrow n+\nu_e$

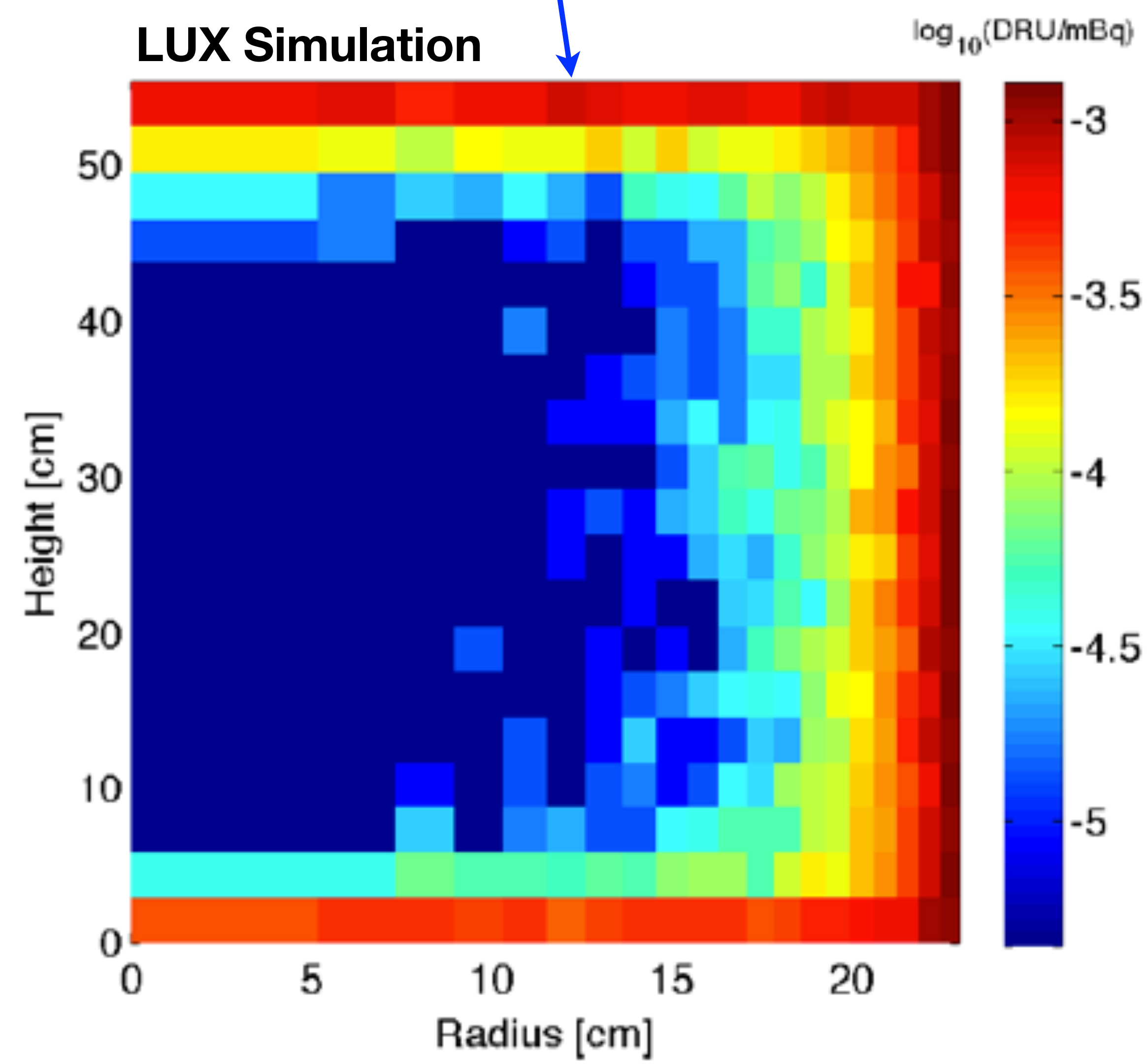


^{127}Xe model

$$P_{ER}(log_{10}(S2/S1)|S1)P_{^{127}Xe}(E_{ee}(S1))P_{^{127}Xe}(r,z)$$

Again use simulation to model pdfs, includes resolution and efficiencies





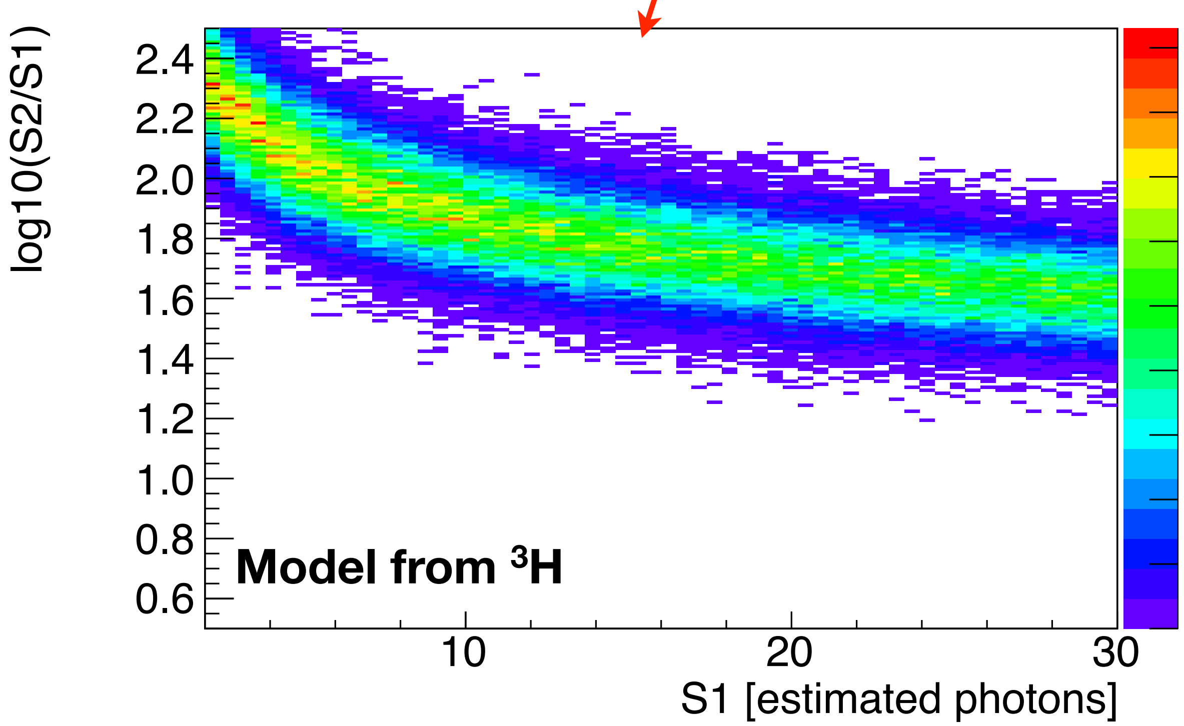
Predict 15 events in WIMP search region

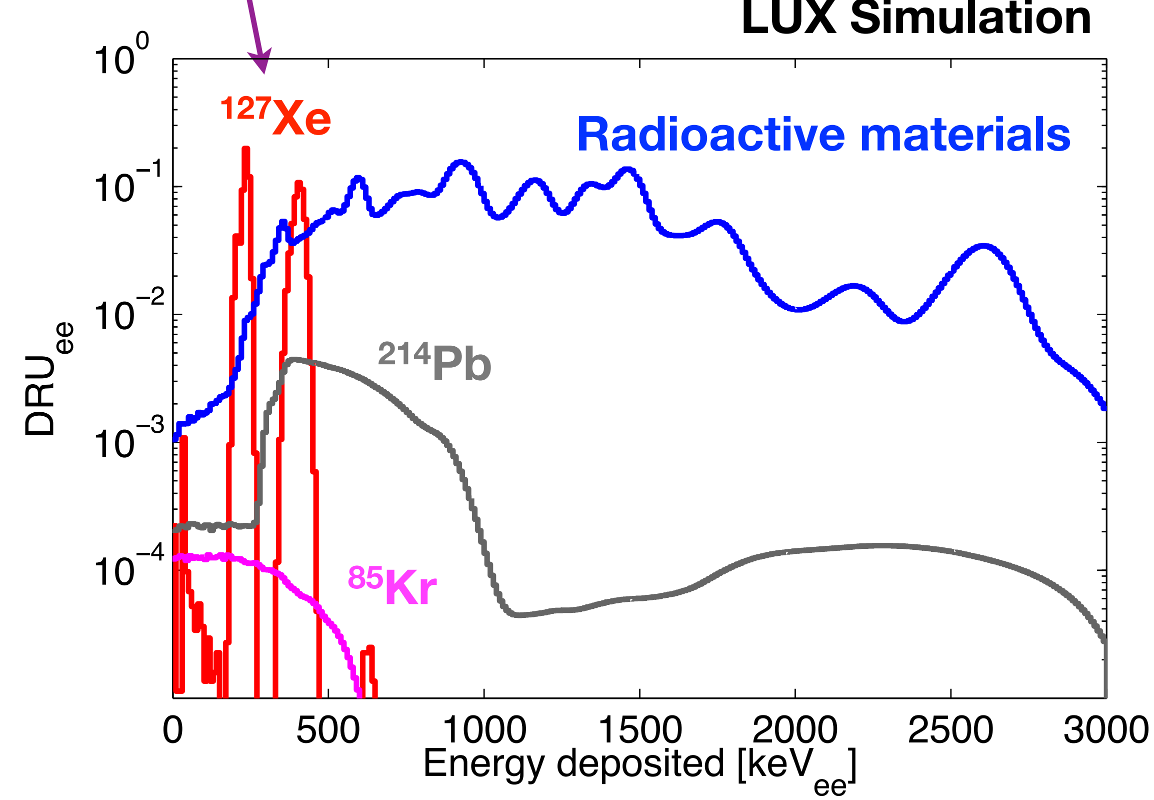
^{214}Pb/^{85}Kr background

$$P_{ER}(log_{10}(S2/S1)|S1)P_{Rn}(E_{ee}(S1))P_{Rn}(r)P_{Rn}(z)$$

Model as uniform in $E_{ee} \in [0.9, 5.1]$ keVee

Model as uniform in (r^2,z)



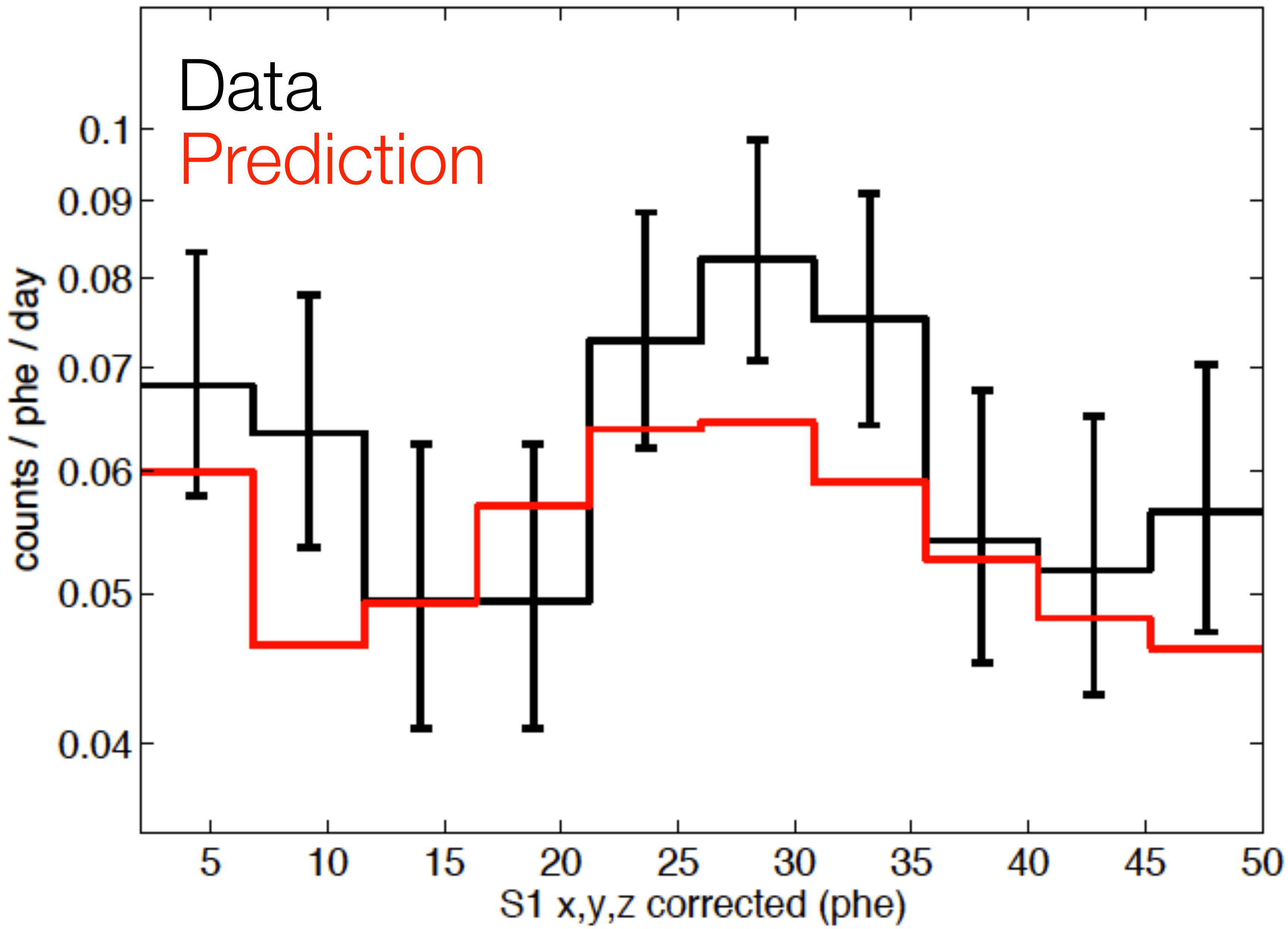


Predict 10 events in WIMP search region

Estimated background rates

Background Component	Source	10^{-3} [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	222Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{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	$3.1 \pm 0.2_{stat}$

Comparison of low energy data with predictions



Calculation of the upper limit

Set frequentist one-sided upper limit

Use profile likelihood ratio as test statistic

Fixed point to test

Nuisance parameters, not fixed

$$\lambda\left(\sigma_{\mathrm{test}}\right) \equiv \frac{\mathcal{L}\left(\sigma_{\mathrm{test}}, \hat{\hat{\boldsymbol{\theta}}}\right)}{\mathcal{L}\left(\hat{\sigma}, \hat{\boldsymbol{\theta}}\right)}$$

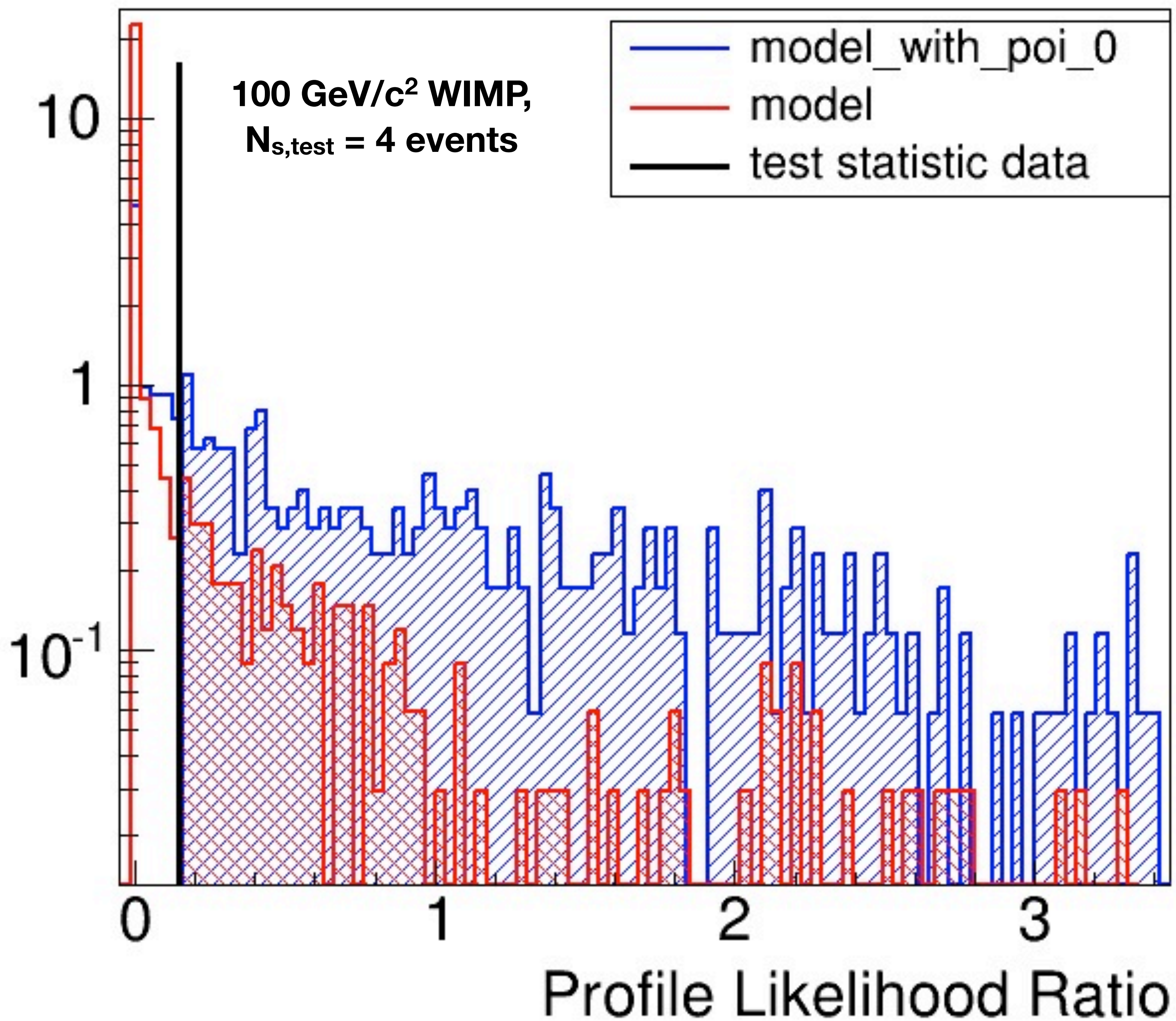
Value of maximum likelihood

$$q_{\sigma} = -2\ln\lambda\left(\sigma\right)$$

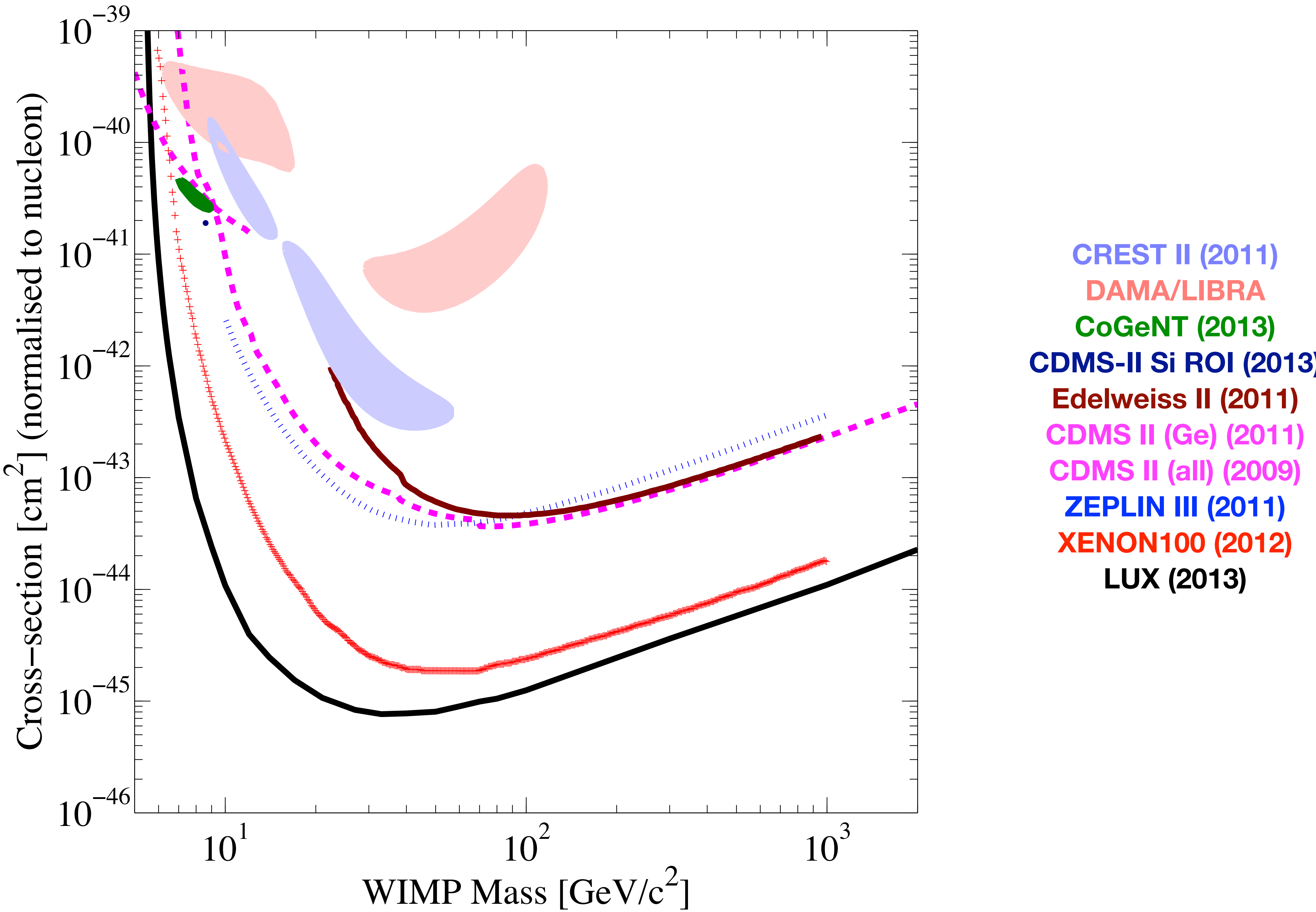
Generate pseudo-experiments for $\boldsymbol{\sigma}_{\mathrm{test}}$, compare the value of test statistic in data with the value of $q_{\sigma,i}$ from each pseudo-experiment

Set one-sided limit, so if ($\boldsymbol{\sigma}$-hat)$_i$ > $\boldsymbol{\sigma}_{\mathrm{test}}$, $q_{\sigma,i} = 0$

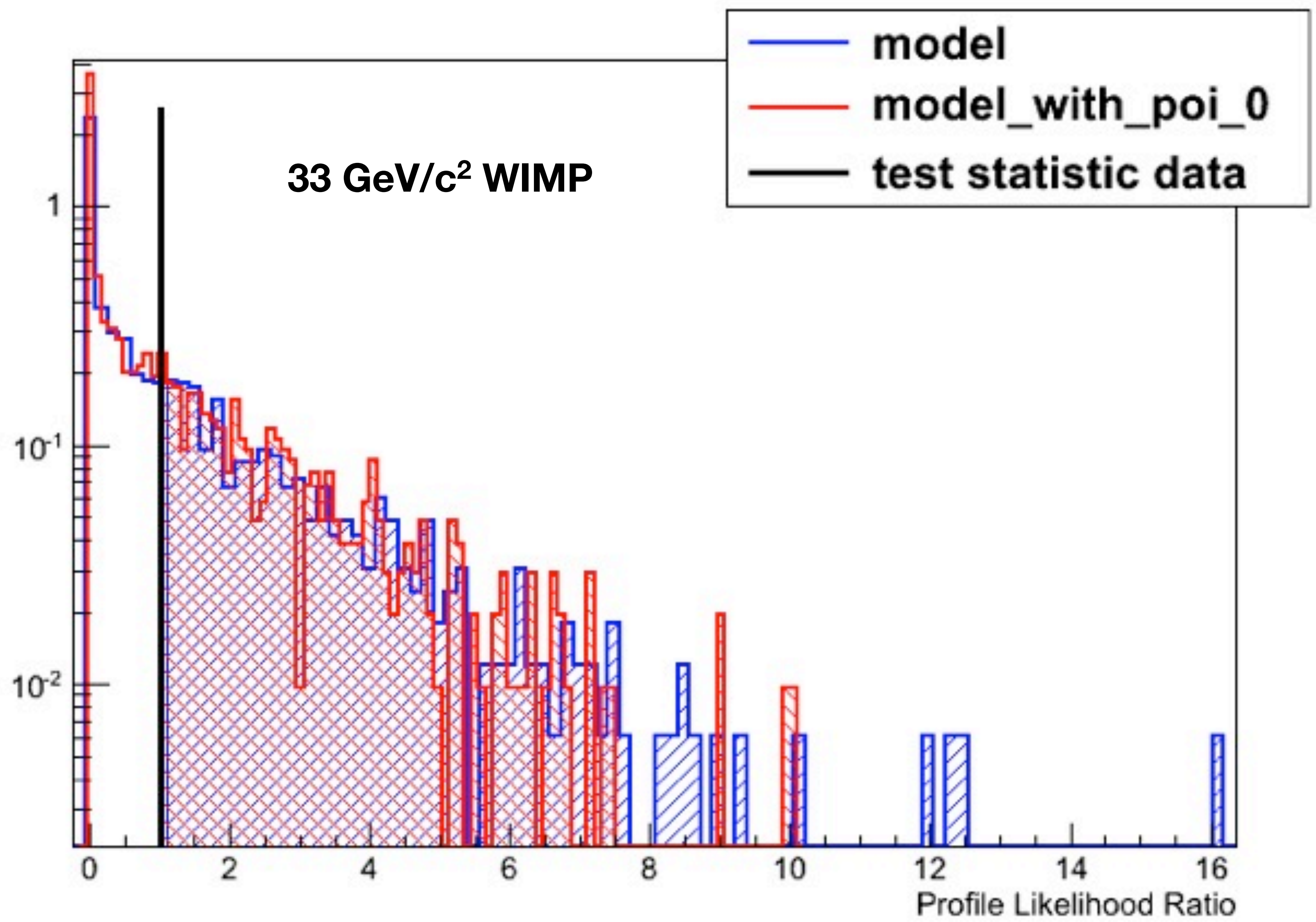
Hypothesis tests



First WIMP search results!



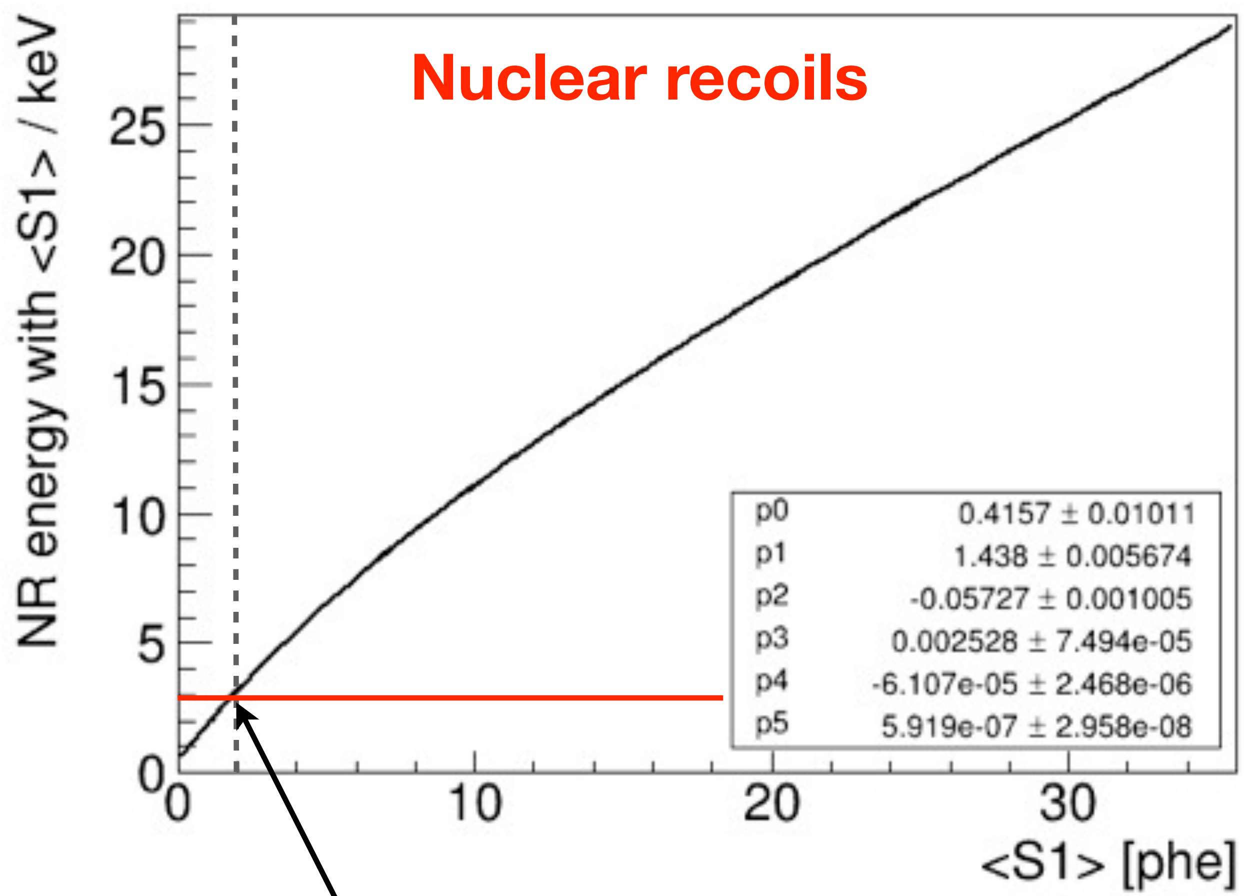
Null hypothesis test



Observe null p-value of 34% at 33 GeV/c^2, corresponding to 0.4σ significance

Discussion

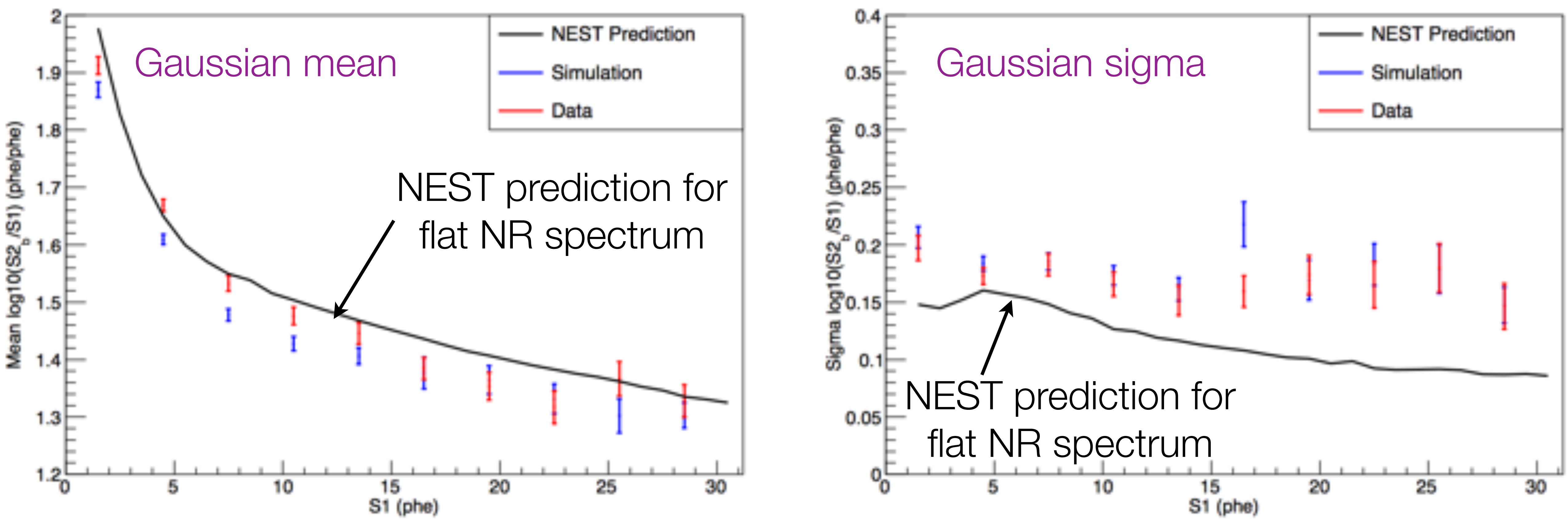
“Sub-threshold” fluctuations



Fluctuations from lower energies into WS in minimal, due to 3 keVnr cut-off

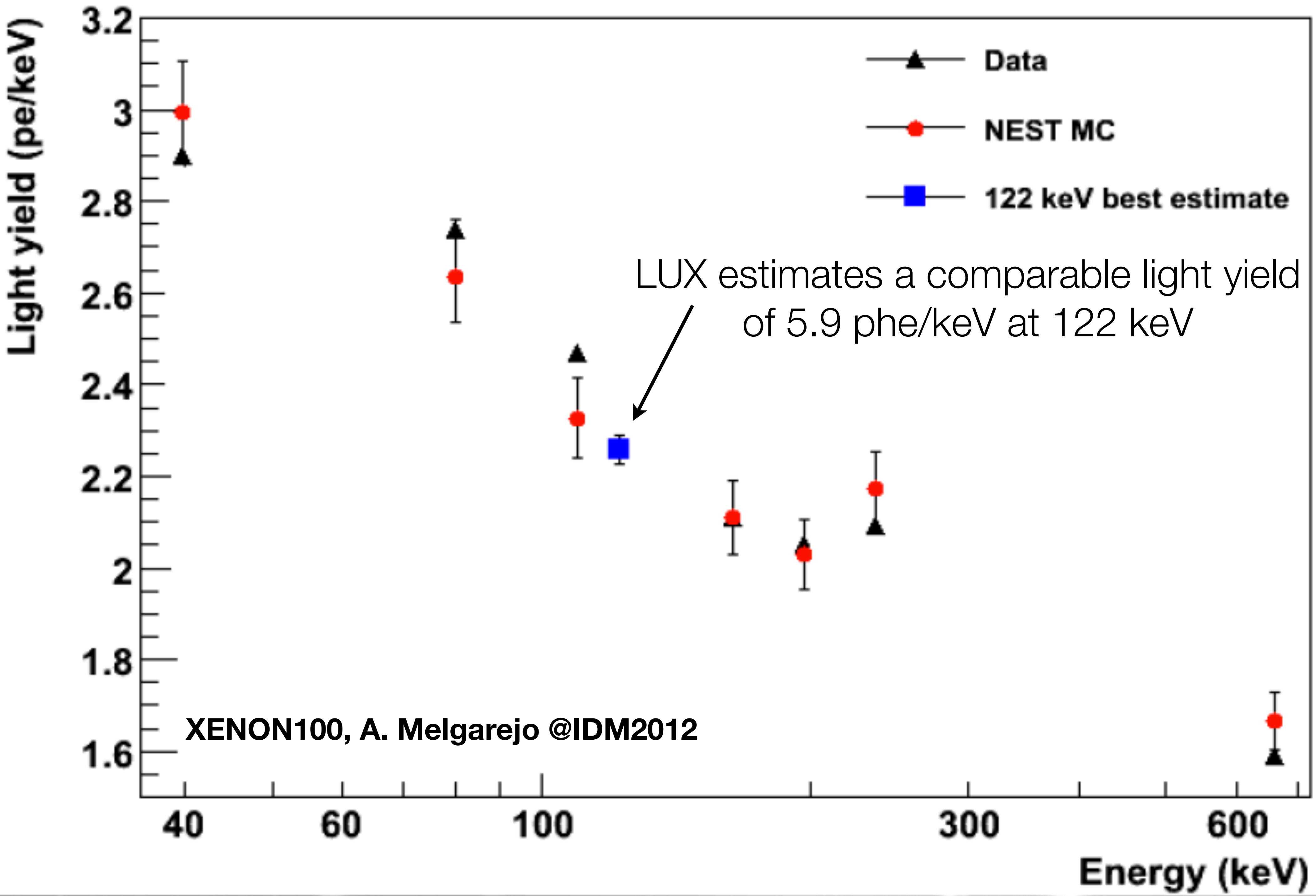
Systematic uncertainty on NR discrimination

We adjust the mean and width of the data (red) to match simulation (blue) and adjust NEST predictions by the same amount, treat shift in UL as a systematic uncertainty

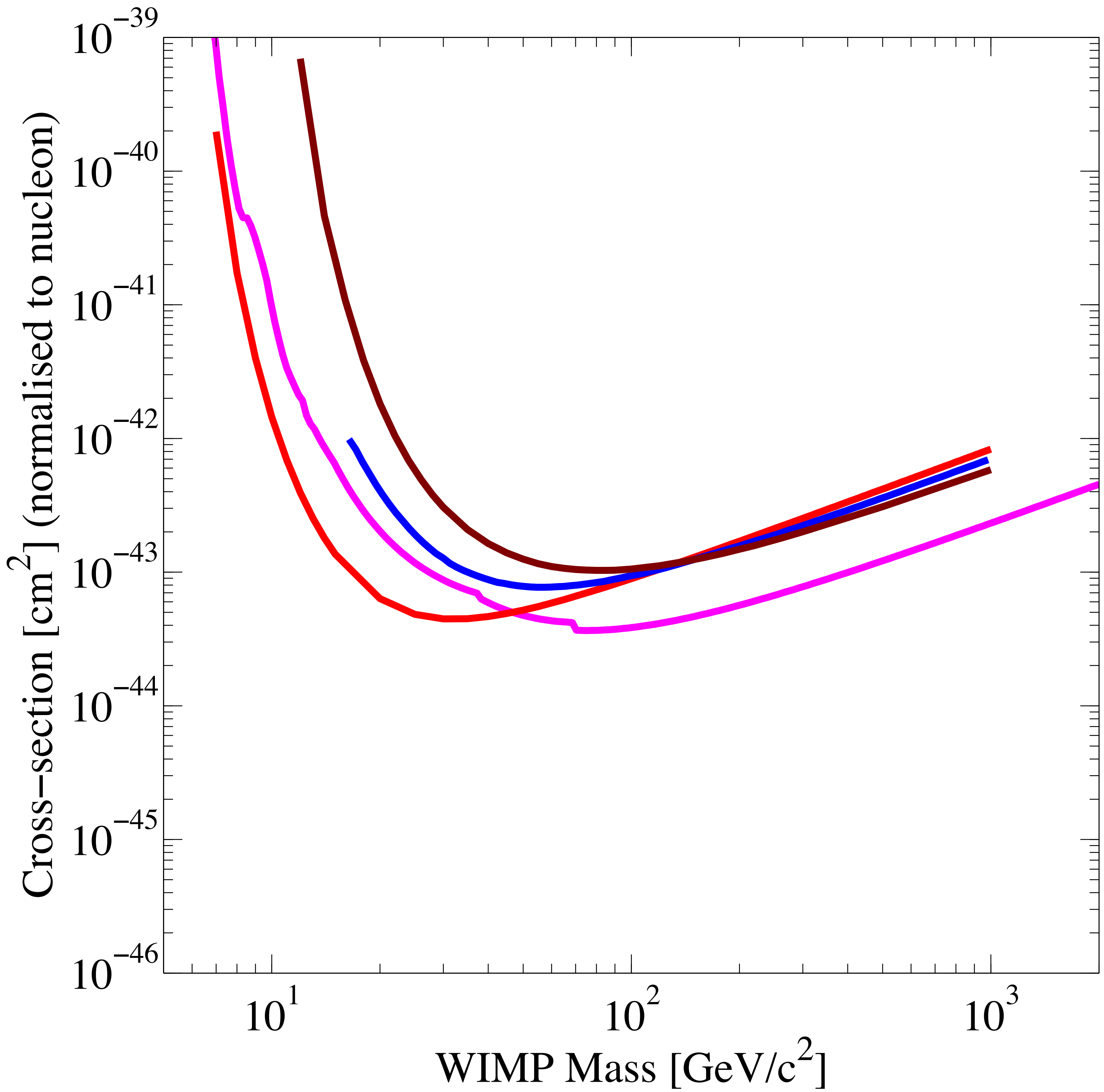


Find systematic shift of ~25% higher in the UL

Improved light collection with respect to Xenon100

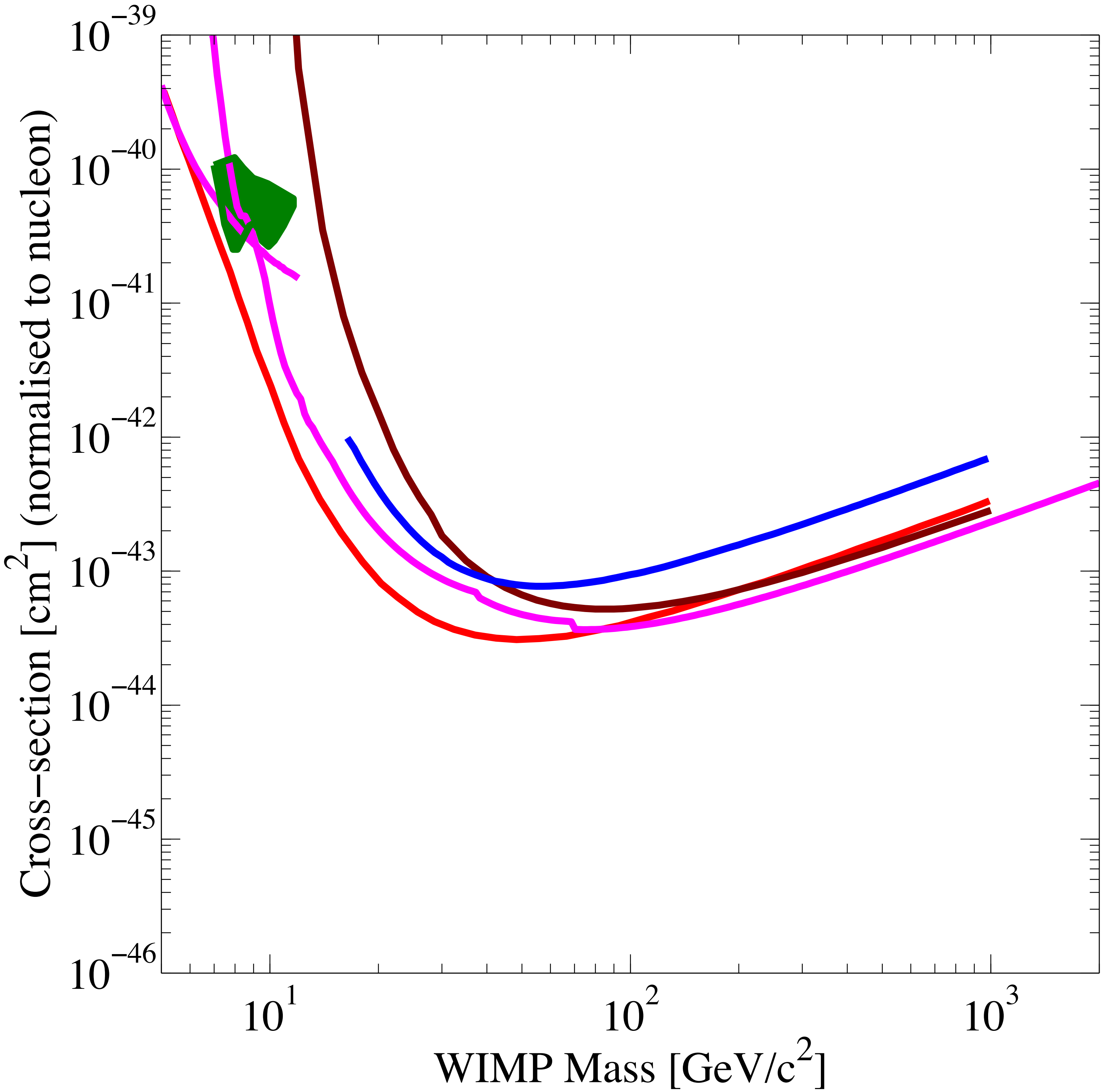


WIMP limits in 2009



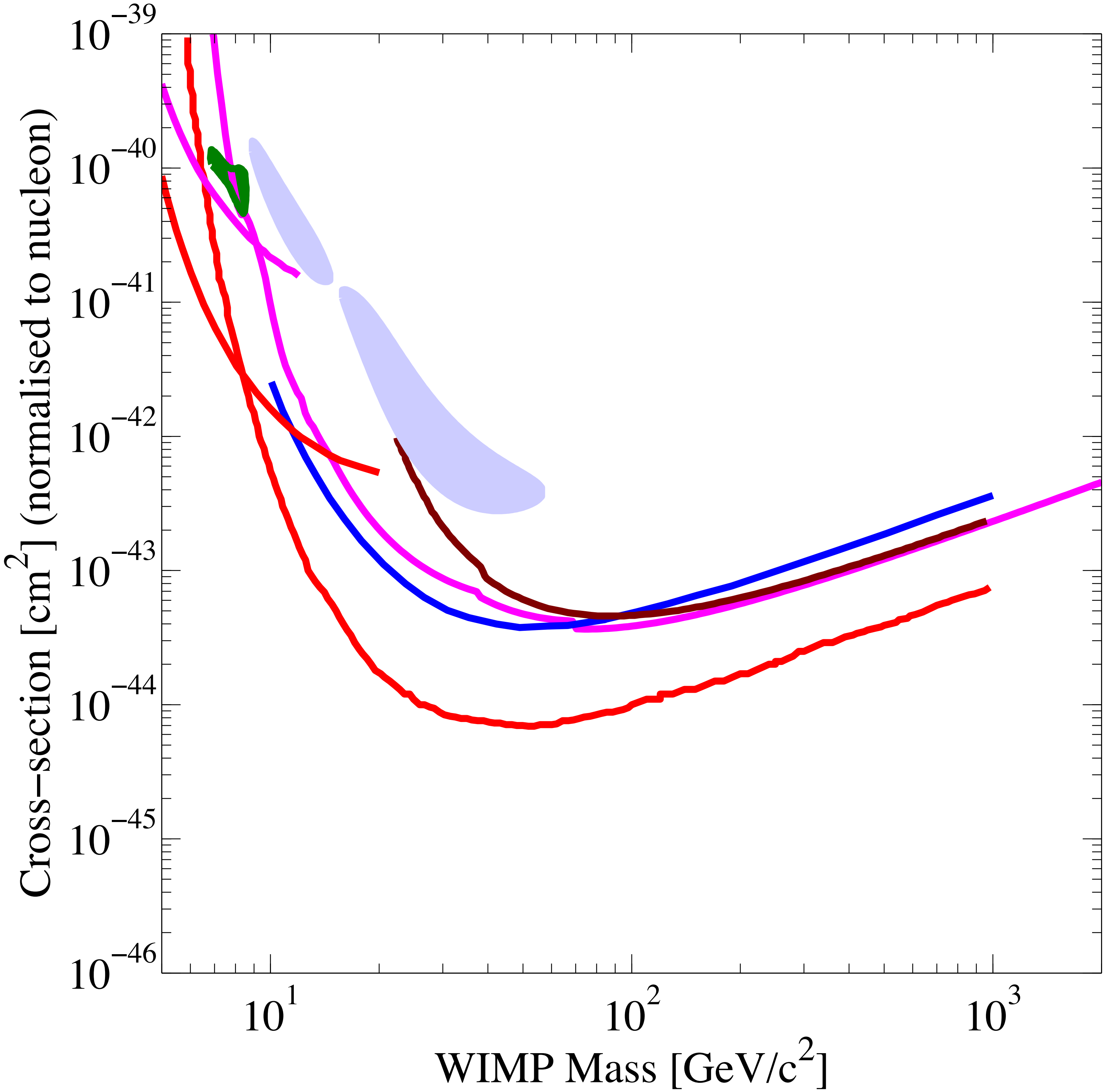
Edelweiss I (2009)
CDMS II (all) (2009)
ZEPLIN III (2009)
XENON10 (2008)

WIMP limits in 2010



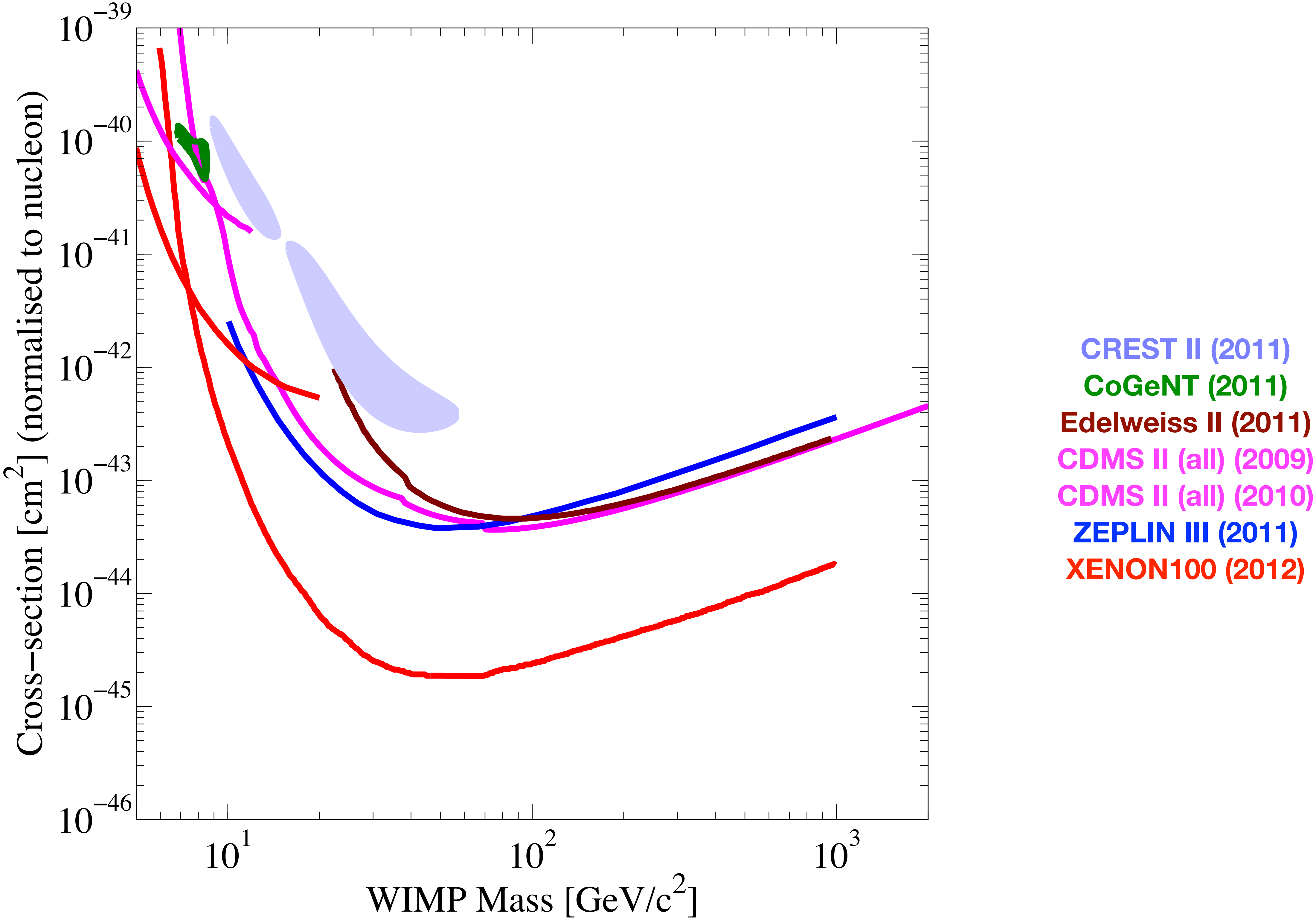
CoGeNT (2010)
CDMS-II Si ROI (2013)
Edelweiss II (2010)
CDMS II (all) (2009)
CDMS II (all) (2010)
ZEPLIN III (2009)
XENON100 (2010)

WIMP limits in 2011



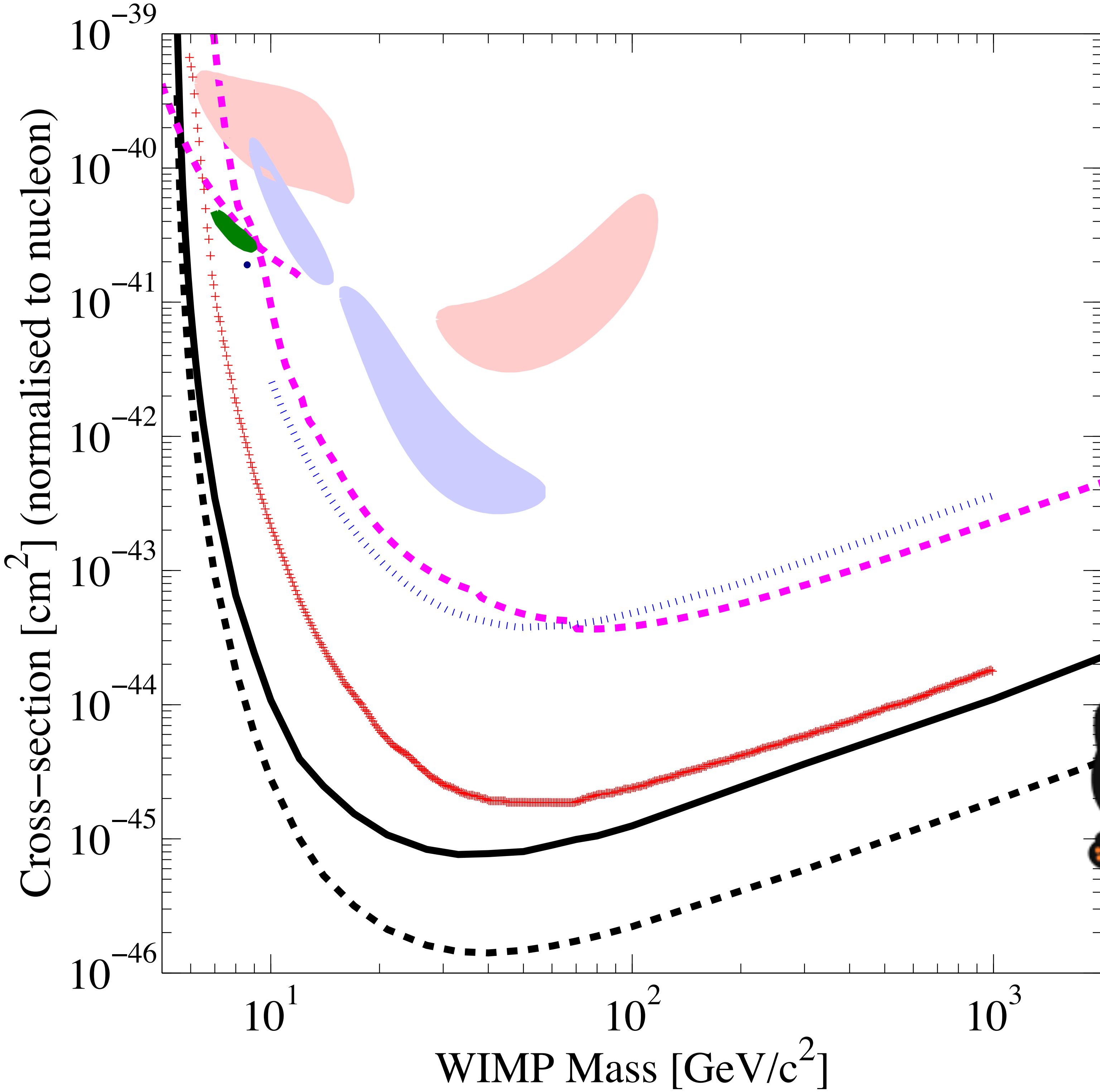
CREST II (2011)
CoGeNT (2011)
Edelweiss II (2011)
CDMS II (all) (2009)
CDMS II (all) (2010)
ZEPLIN III (2011)
Xenon10 (2011)
XENON100 (2011)

WIMP limits in 2012



Race to the bottom...

... in a good way



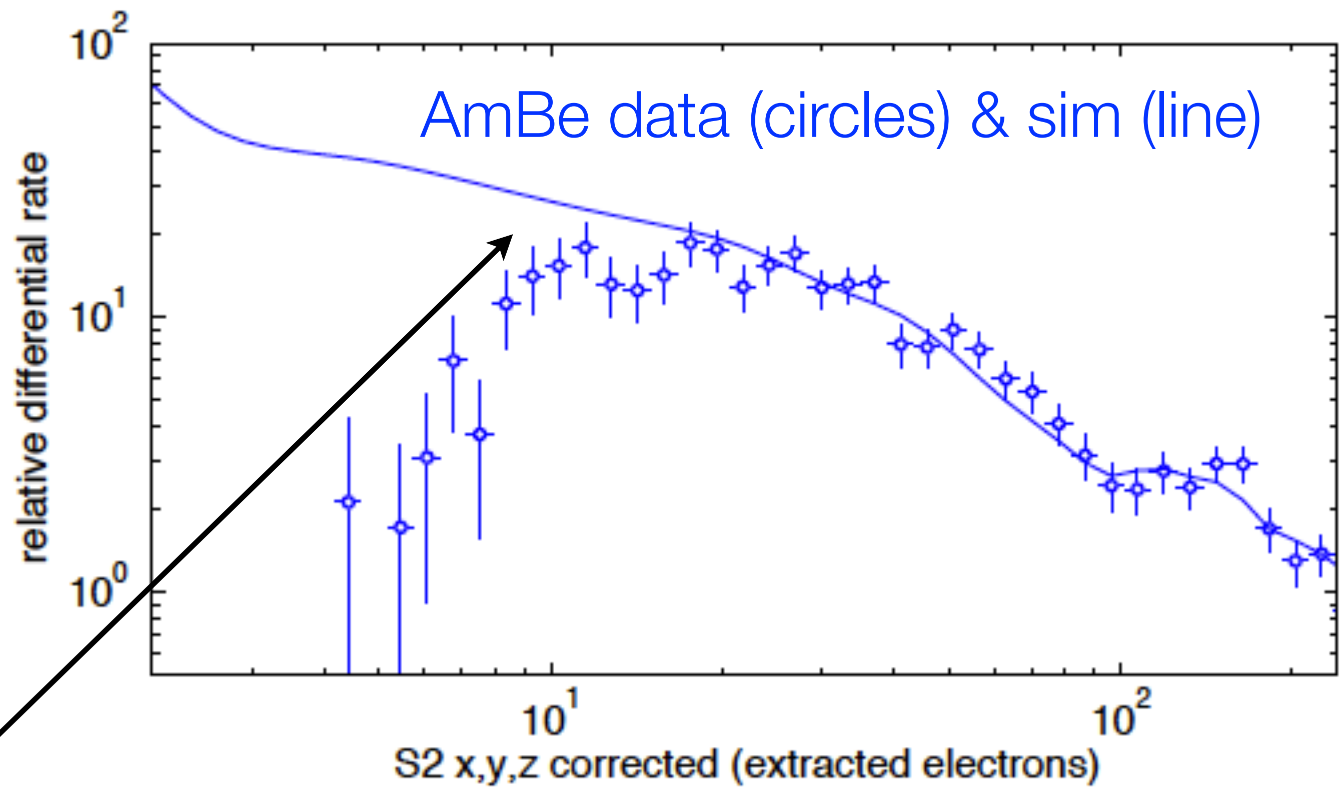
CREST II (2011)
DAMA/LIBRA
CoGeNT (2013)
CDMS-II Si ROI (2013)
CDMS II (Ge) (2011)
CDMS II (all) (2009)
ZEPLIN III (2011)
XENON100 (2012)
LUX (2013)
LUX - 300 d projected

Back-up

Table of events after selection requirements

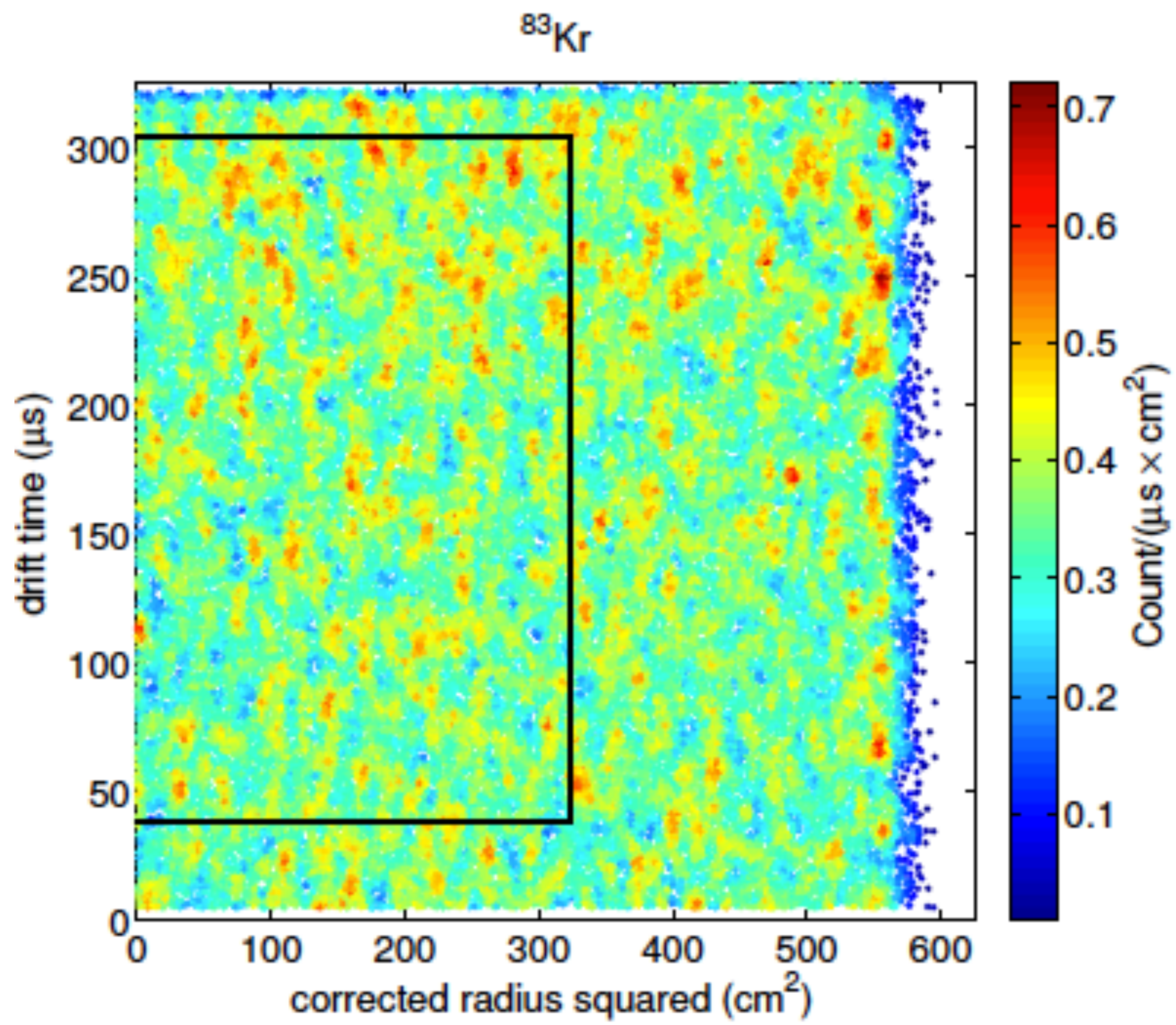
Cut	Events Remaining
all triggers	83,673,413
detector stability	82,918,902
single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

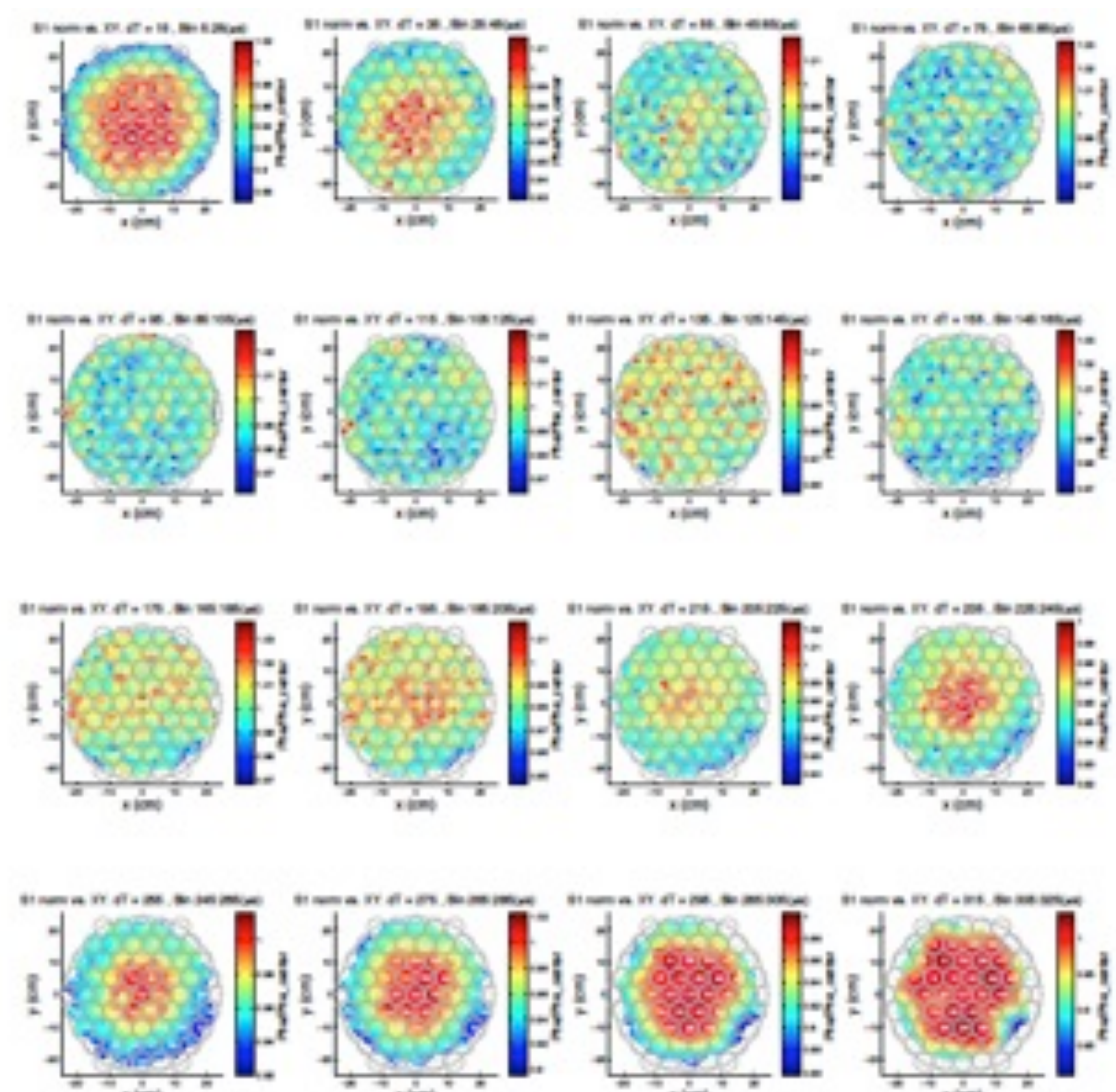
Validation of charge yield in simulation



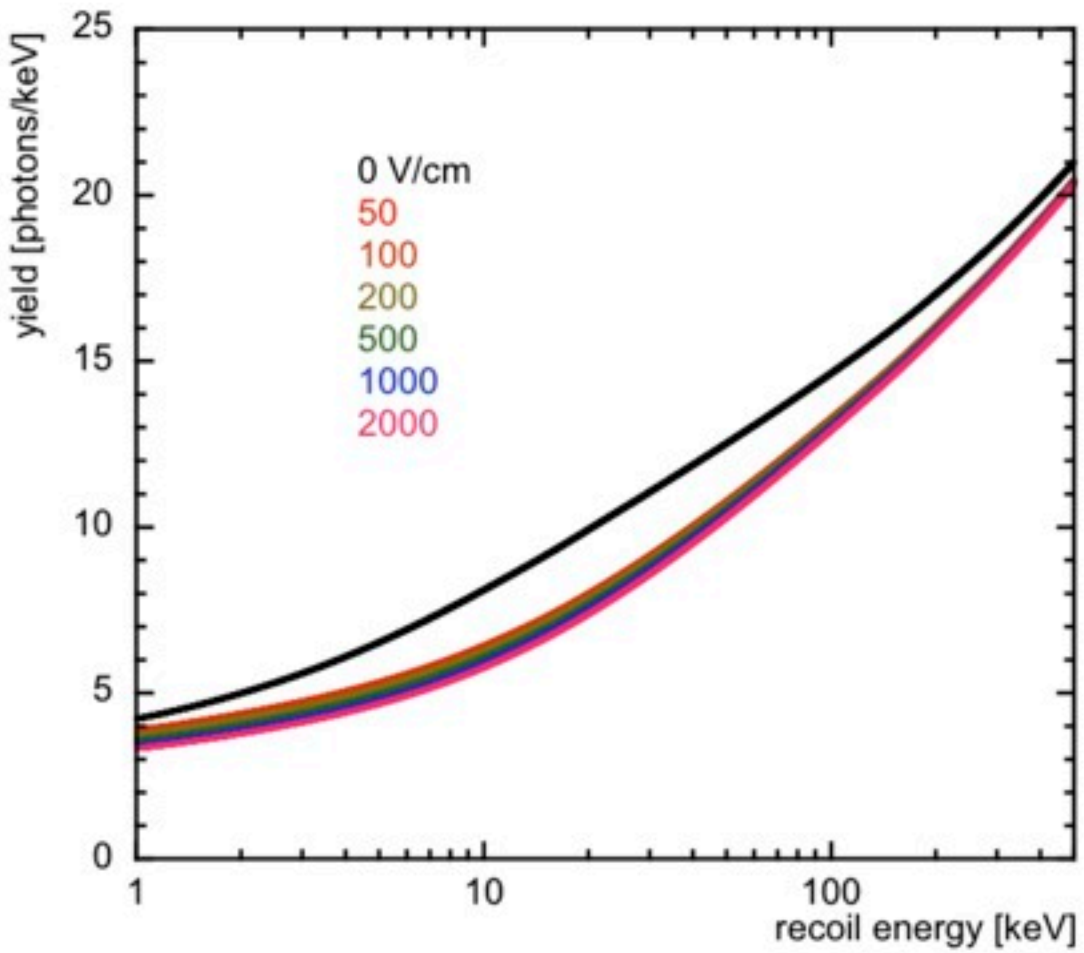
Turnover in data primarily due to S1 efficiency; we require signal scatter to reconstruct NR events

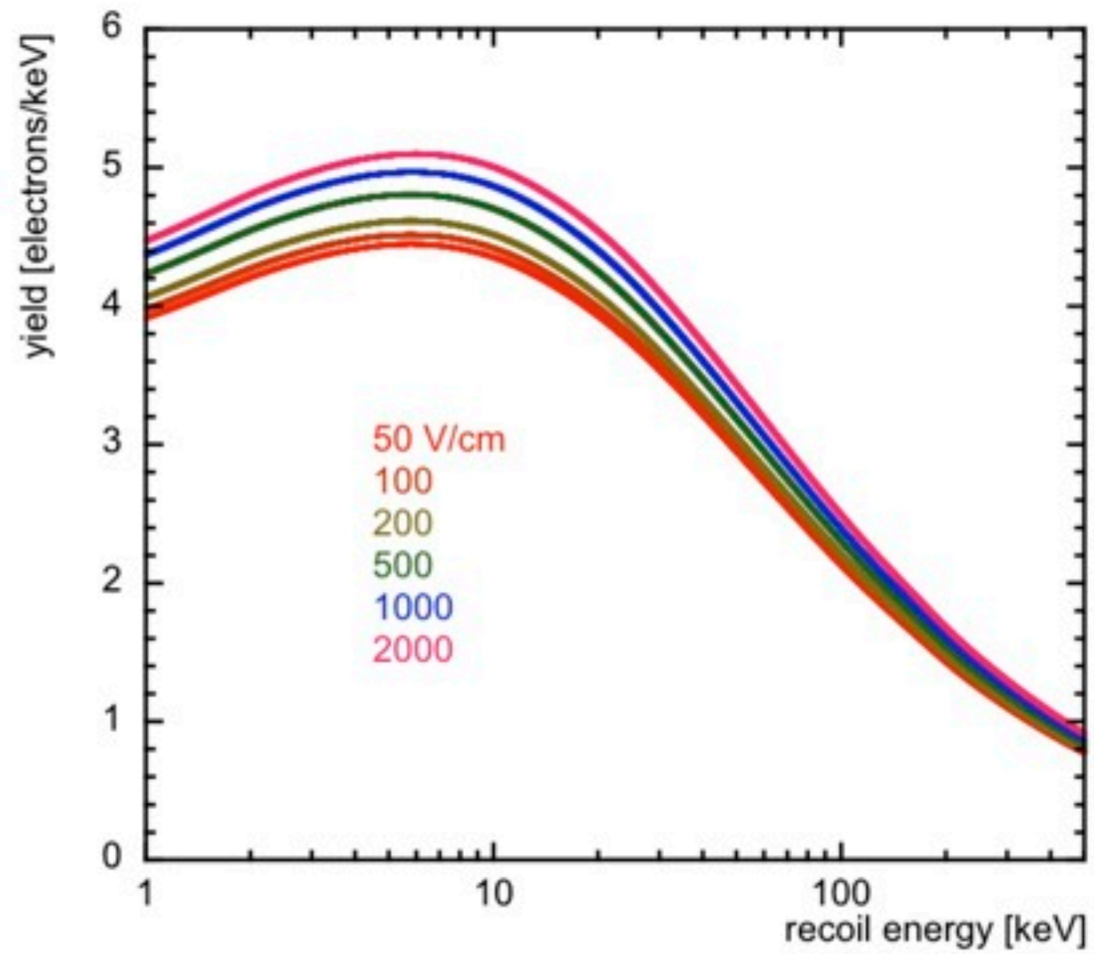
^{83}Kr source data



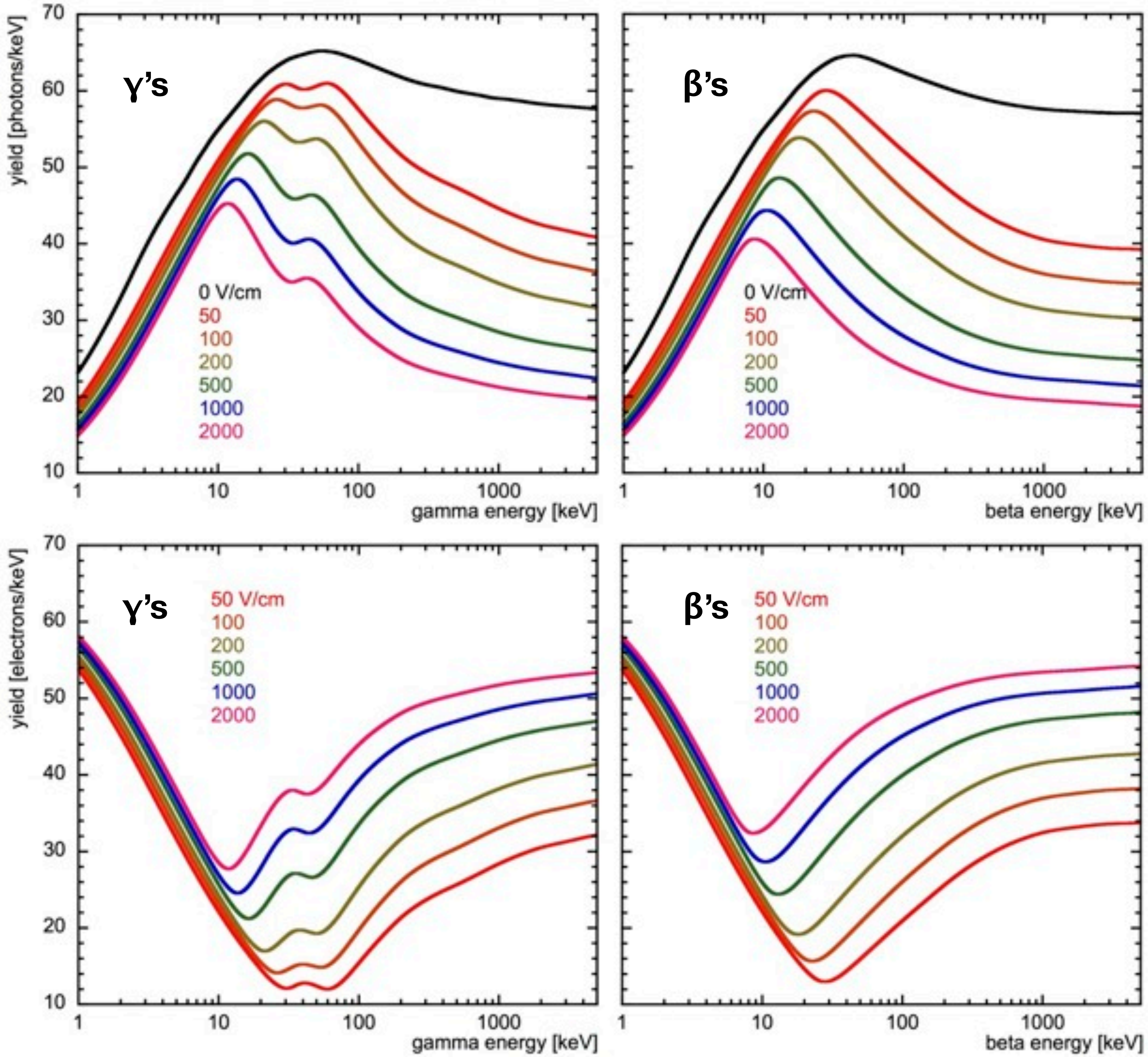


NEST - NR recoils

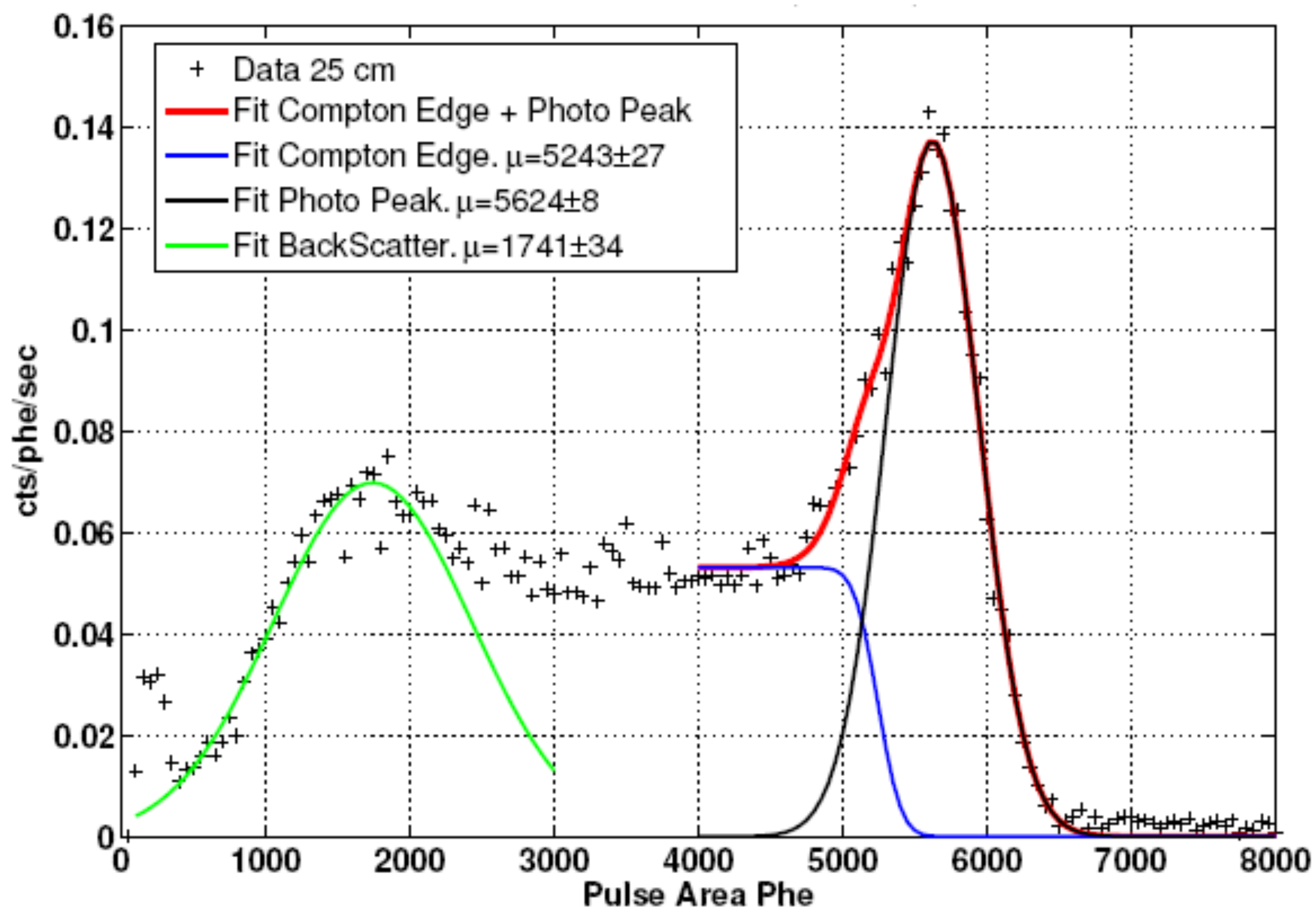




NEST - ER recoils

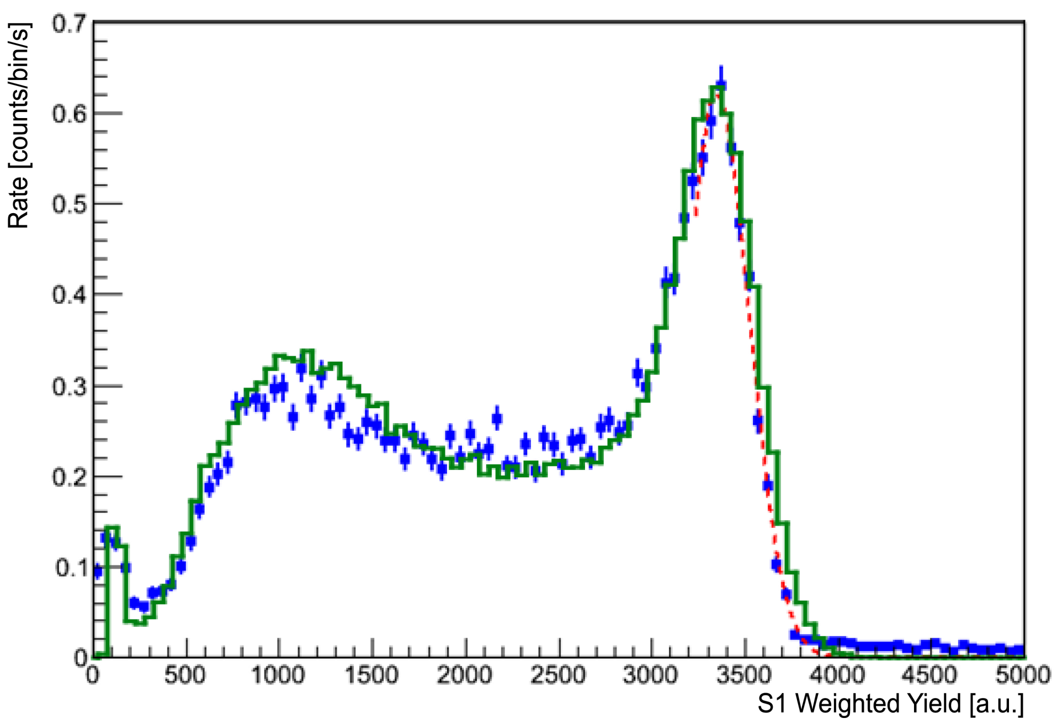


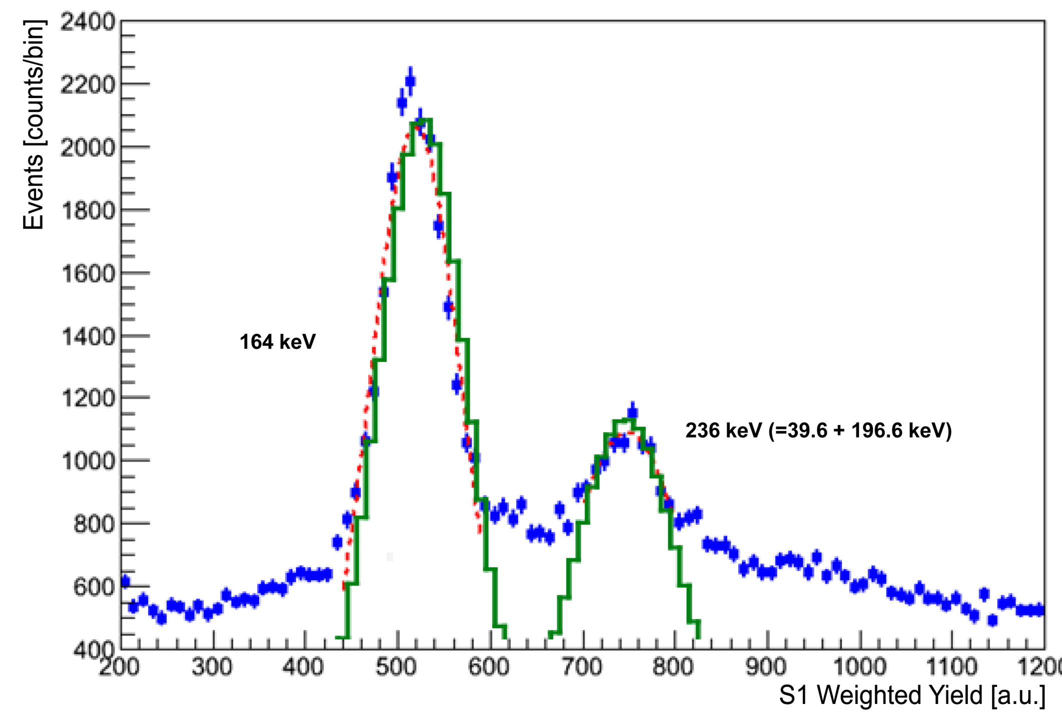
Surface commissioning - light collection



Obtain 8 phe/keV from a 662 keV γ (^{137}Cs source) at zero field
⇒ more than 2.5 times the value reported by Xenon100!

Surface commissioning - simulation tuned to data



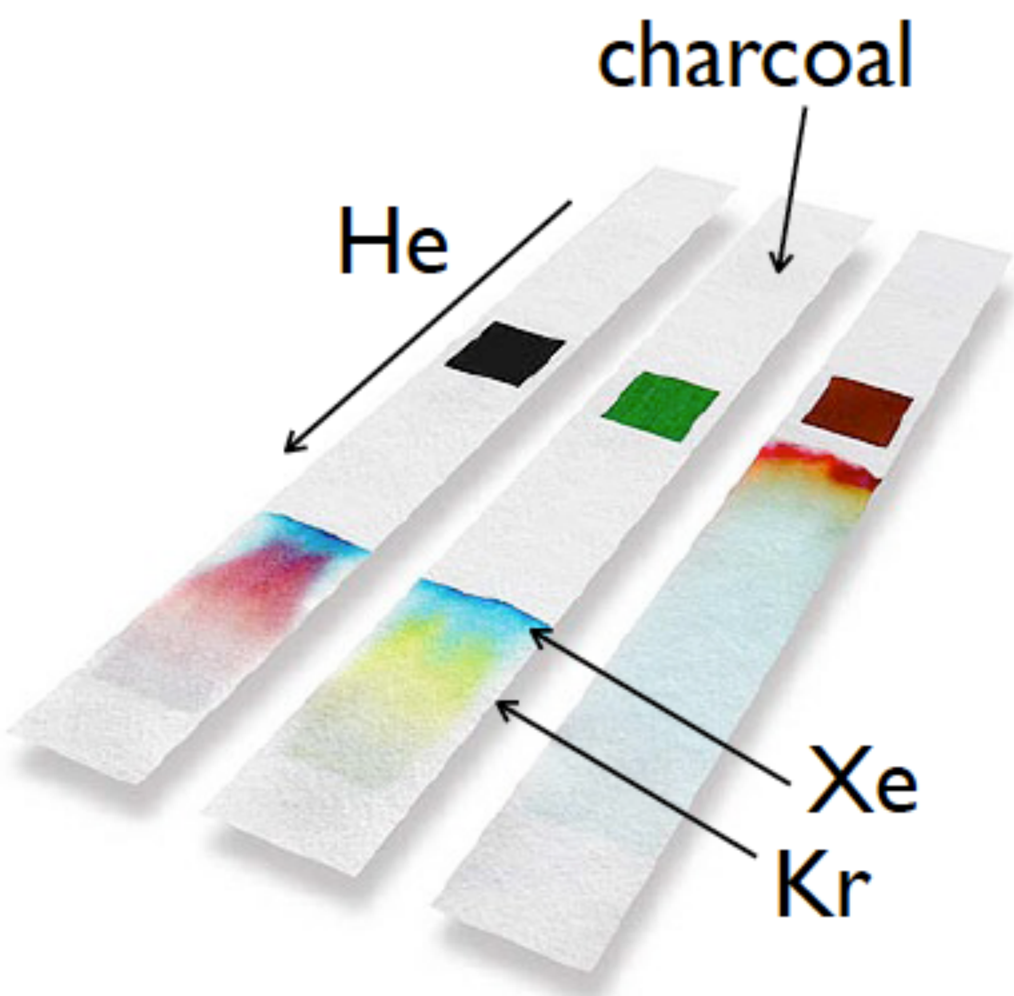


Simulation reproduces the resolution of the S1 energy distribution!

By tuning simulation to multiple sources, we extract:
PTFE reflectivity = 100^{+0}_{-2}%
photoabsorption length = 11^{+2}_{-1} m

^{85}Kr removal

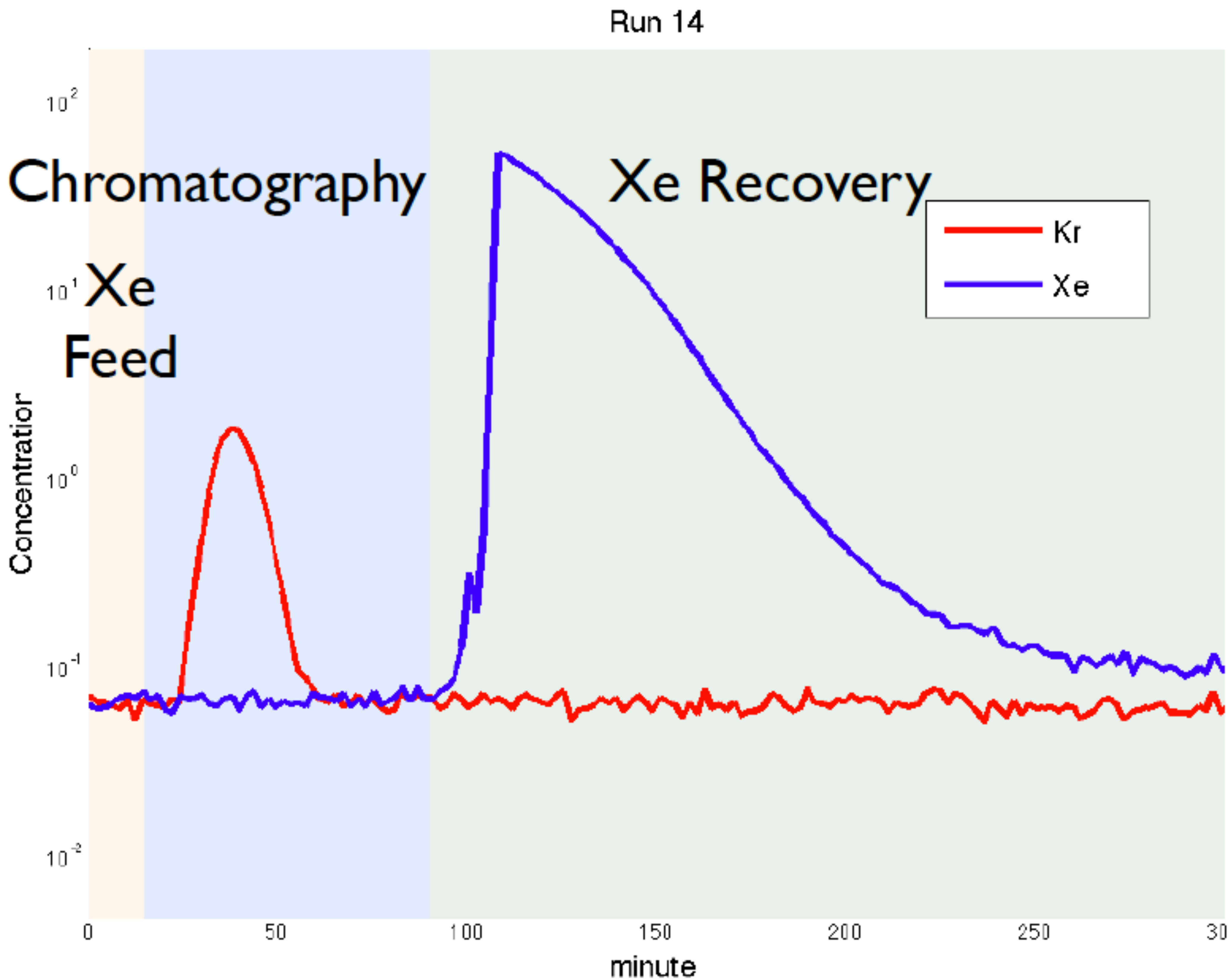
Use gas chromatography to remove Kr



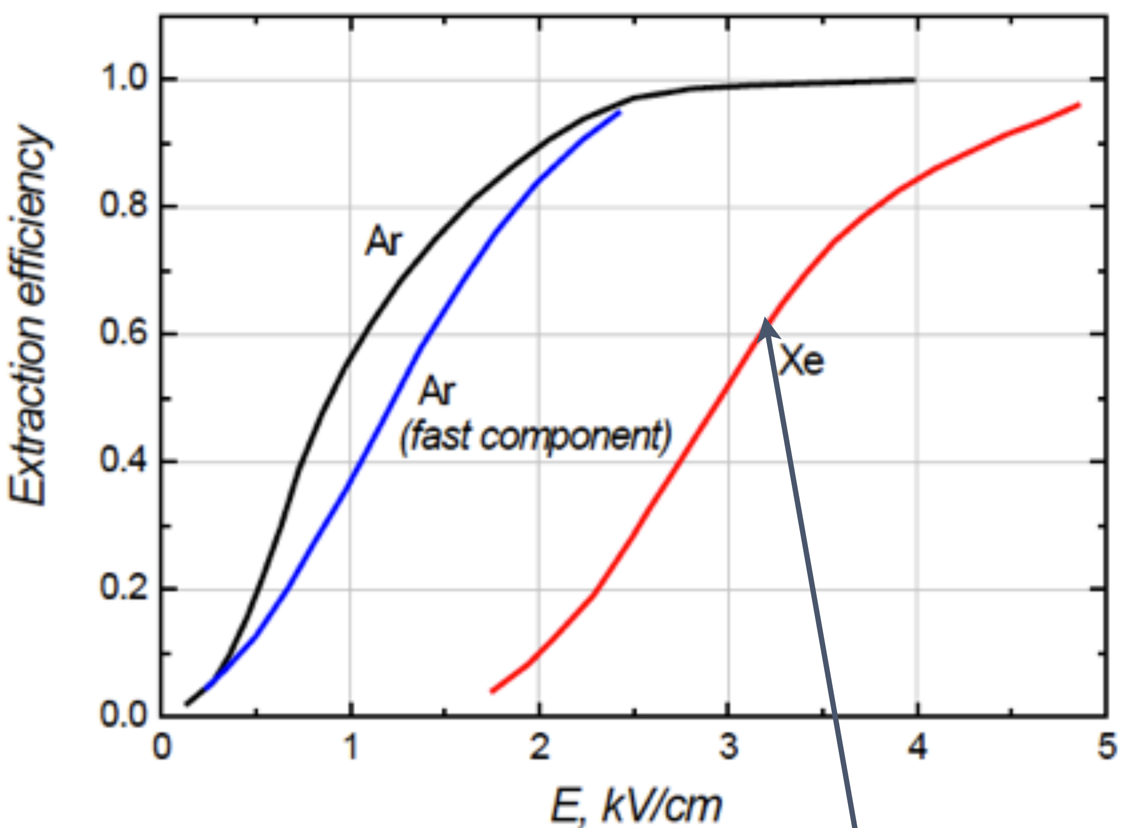
^{85}Kr is a "naked" beta emitter with half-life of 10.7 yrs

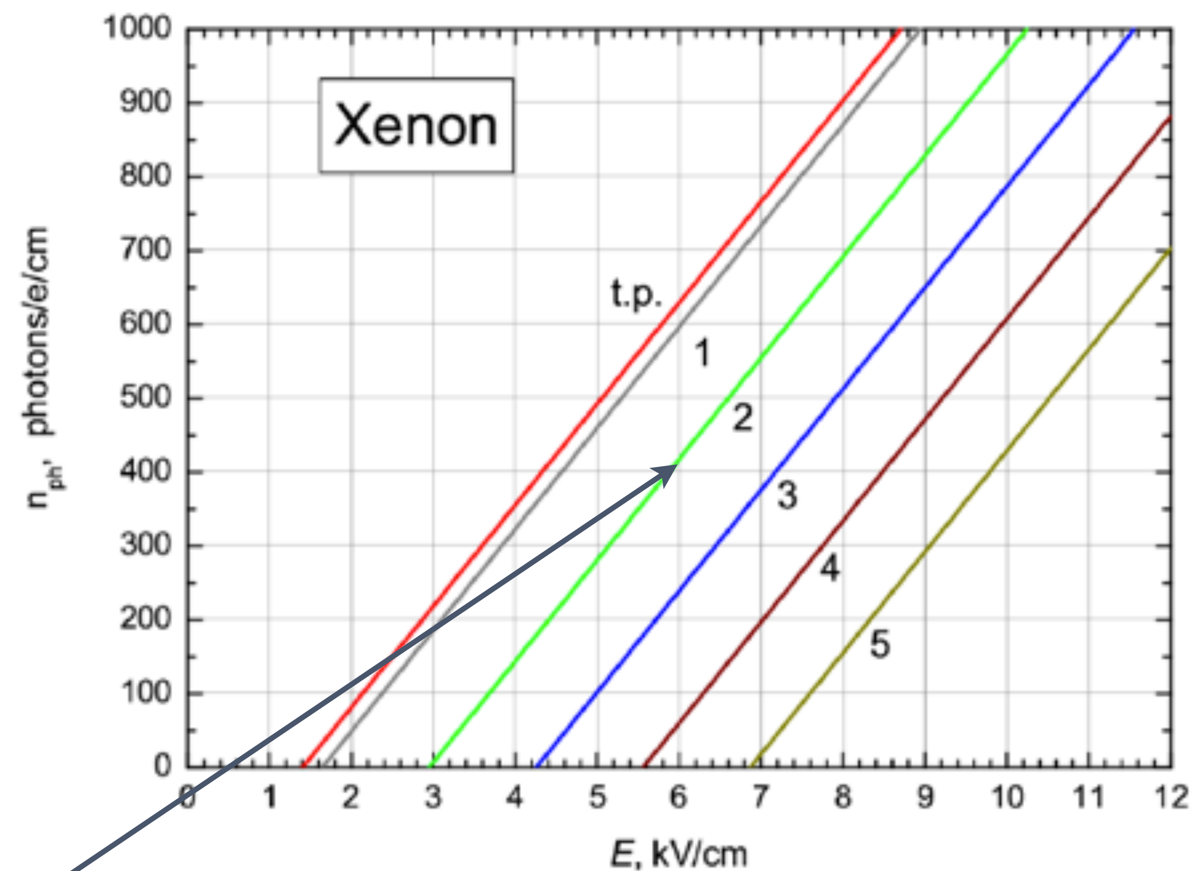
Use He as a carrier gas to pass the "dirty" xenon (100 ppb Kr contamination) through charcoal column - Xe 20 times "stickier" than Kr in charcoal

Goal: < 5 ppt Kr


Run 14
Chromatography
Xe Recovery
Xe
Feed
Kr
Xe
Concentratior
minute
0
50
100
150
200
250
300

Improvements in S2 threshold





LUX operating fields

$$\frac{dN_{ph}}{dx} = \alpha E - \beta P - \gamma \quad \text{[photons/e/cm]},$$

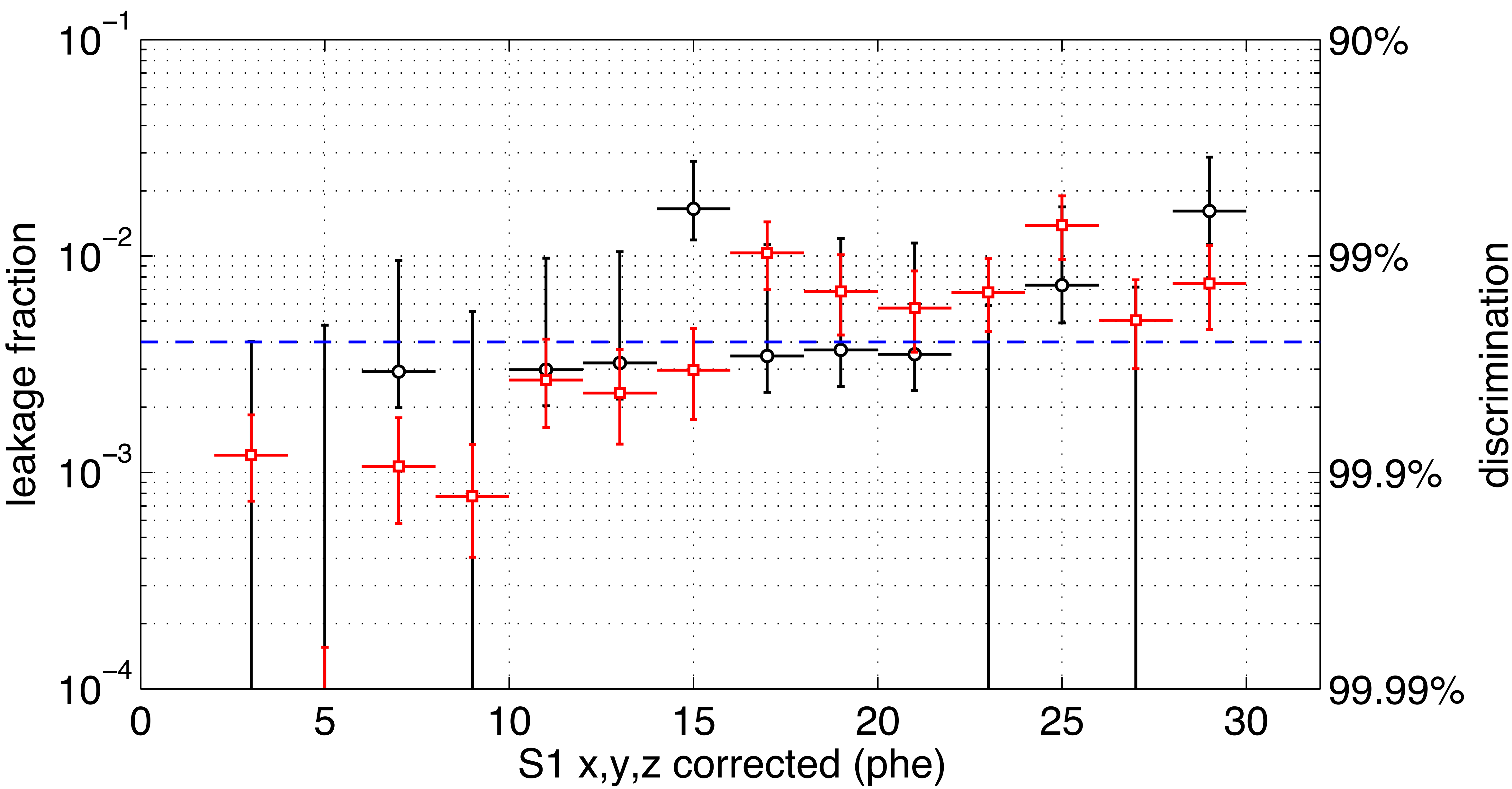
Electric field

Pressure

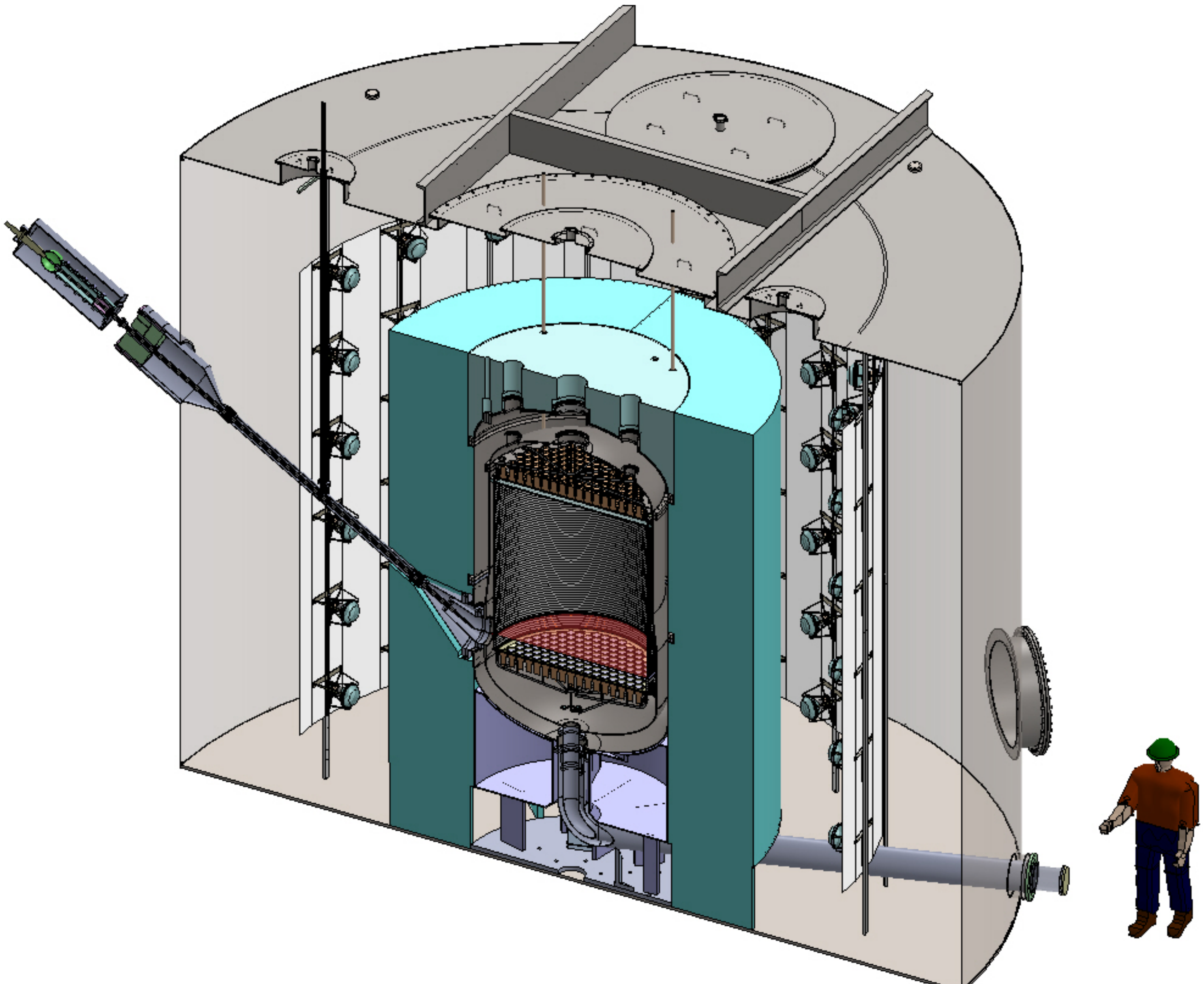
From Chepel and Araujo, arXiv:1207.2292

50% AmBe source NR discrimination

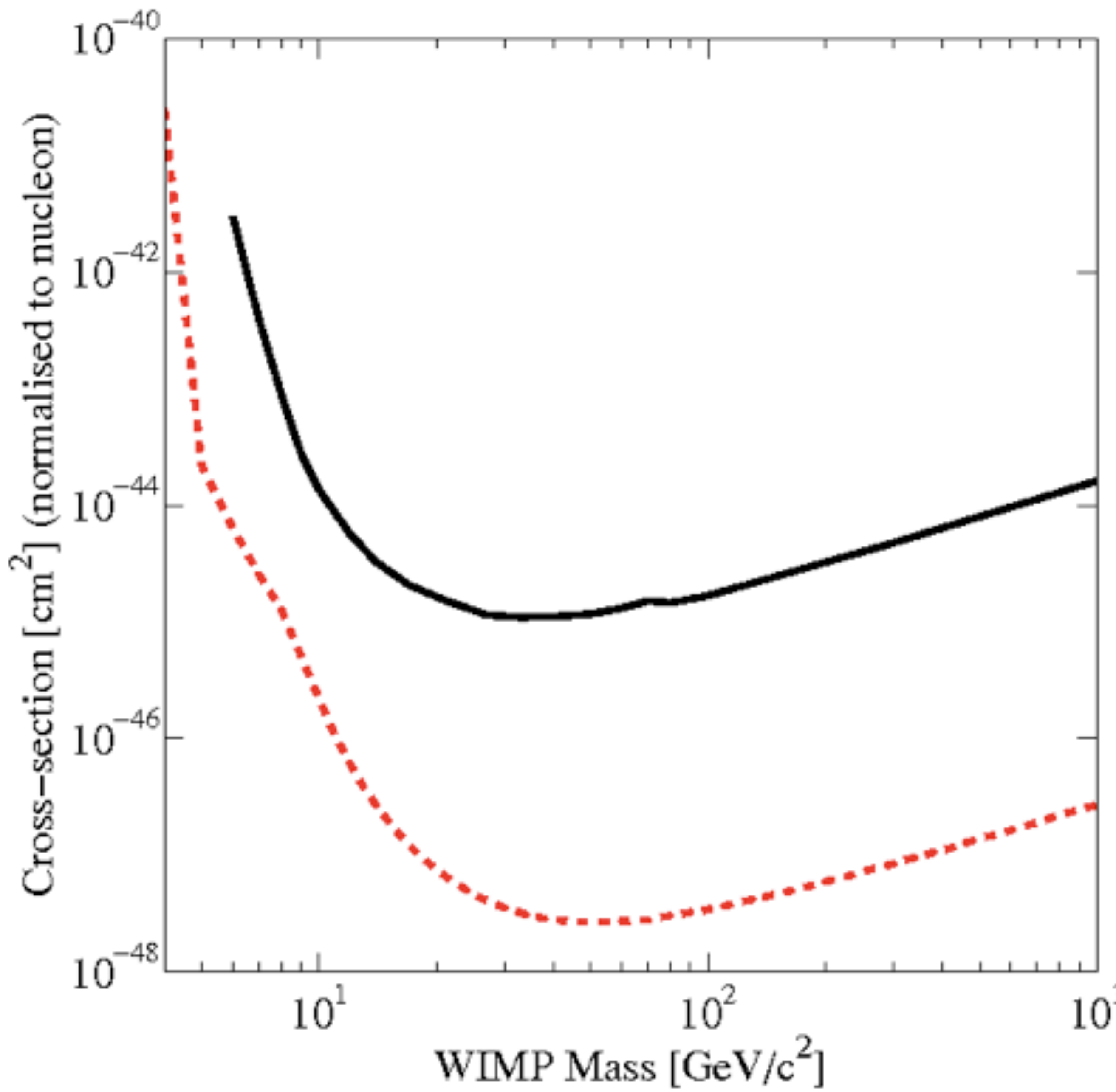
Mean “discrimination” at 50% NR acceptance (AmBe) of 99.6% between [2,30] phe



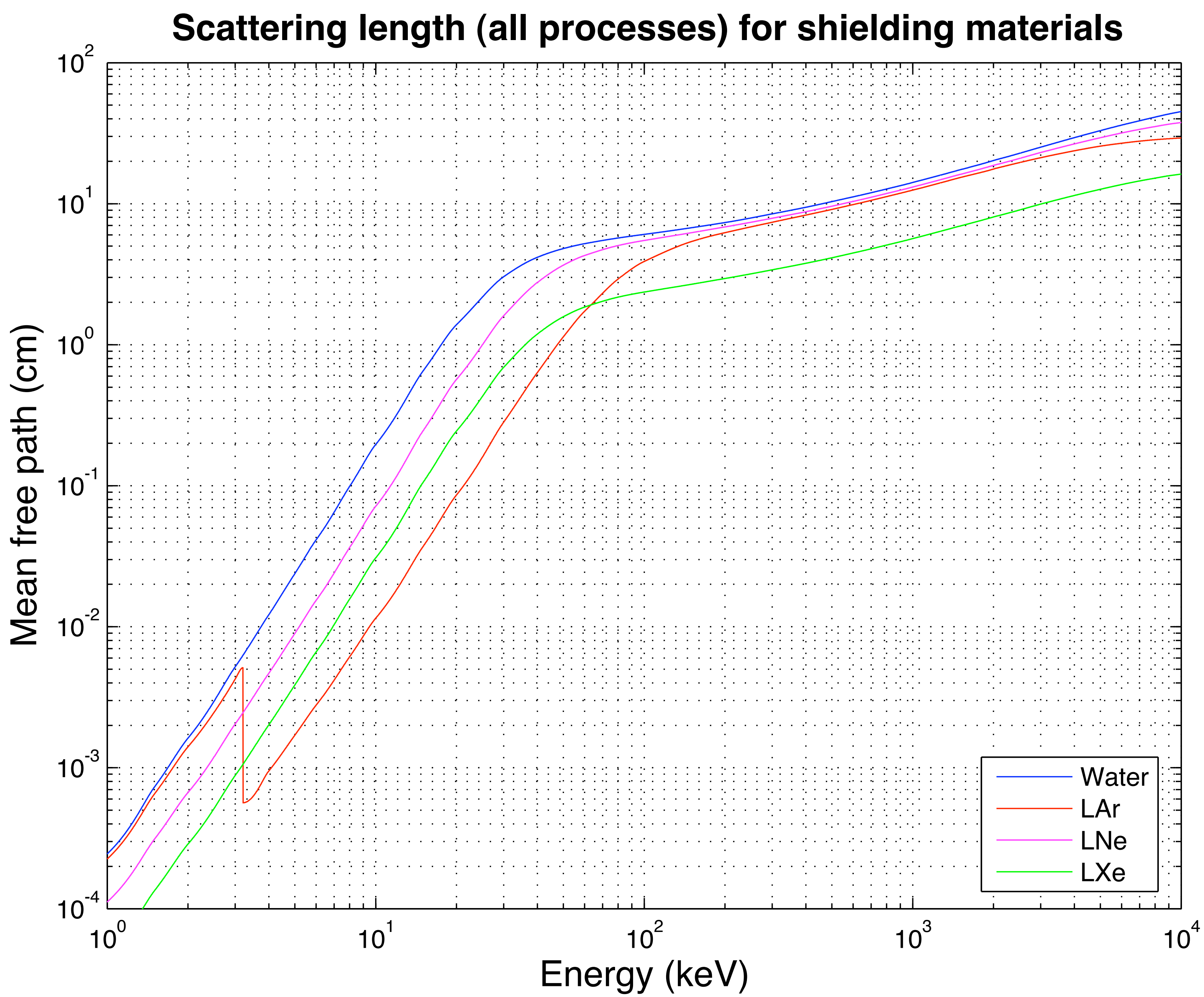
LZ detector

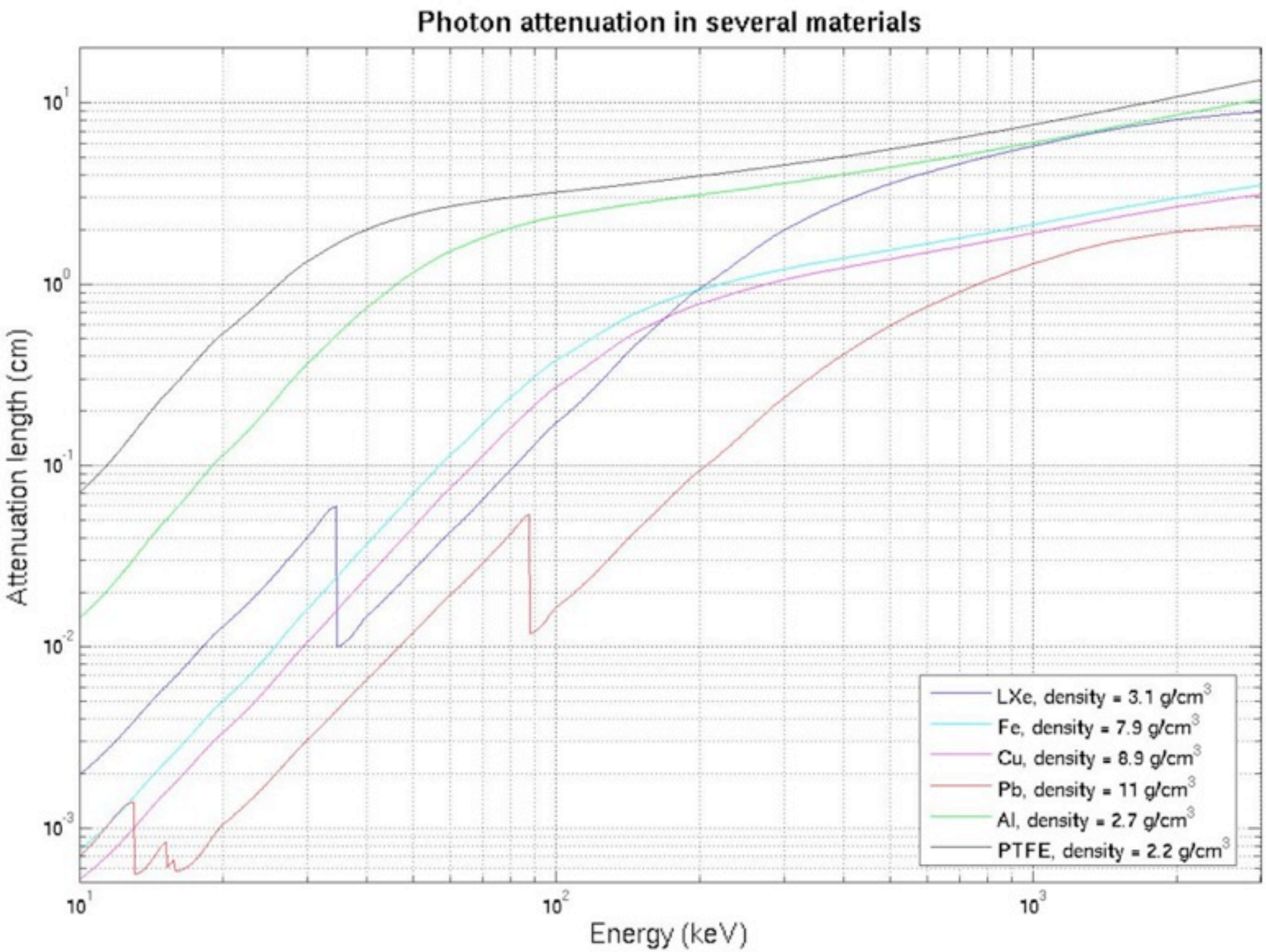


LZ projections



Mean free path length in LXe





Photon attenuation in several materials
Attenuation length (cm)
Energy (keV)
LXe, density = 3.1 g/cm^3
Fe, density = 7.9 g/cm^3
Cu, density = 8.9 g/cm^3
Pb, density = 11 g/cm^3
Al, density = 2.7 g/cm^3
PTFE, density = 2.2 g/cm^3

PMT light response functions