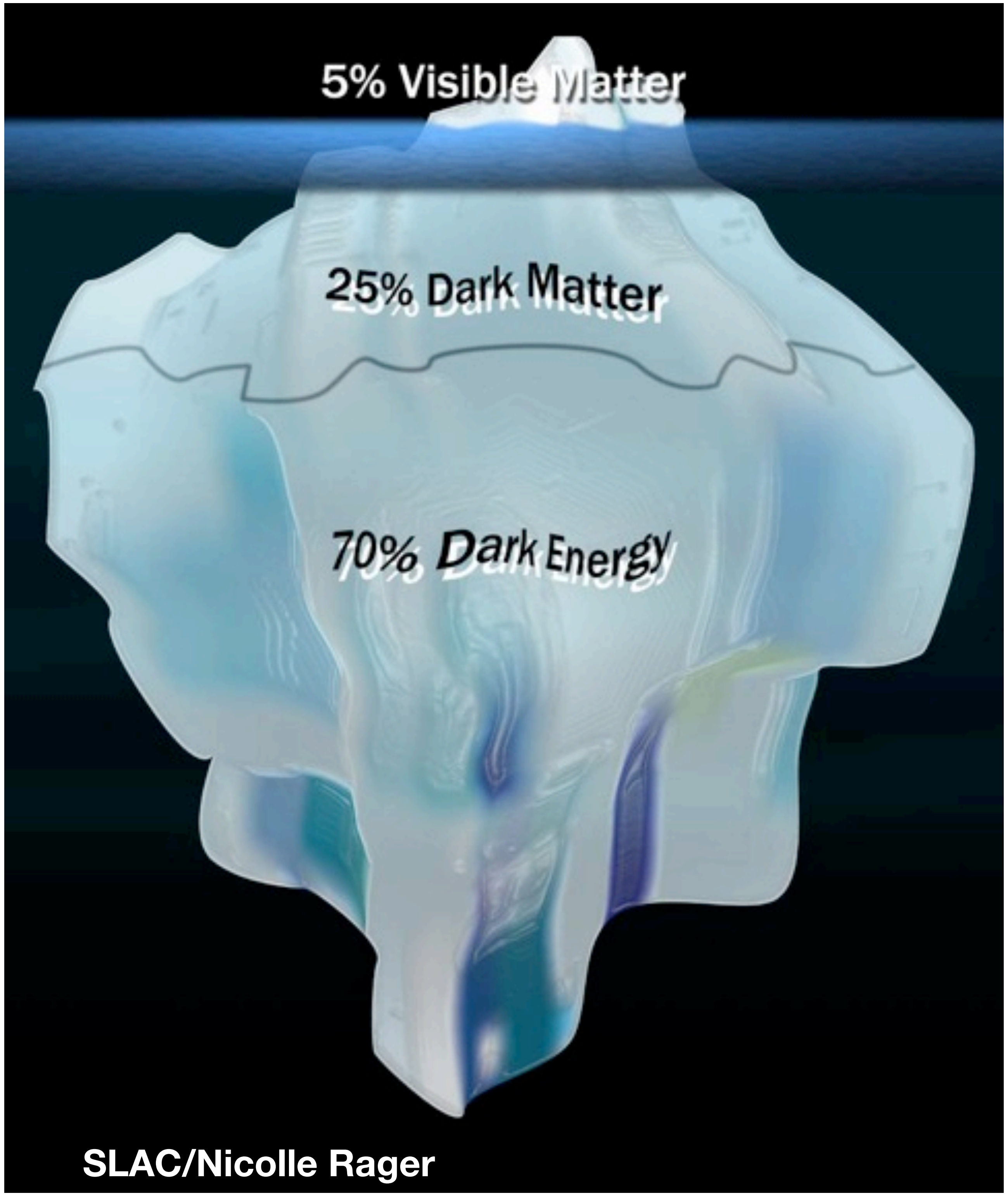
The LUX and LZ Dark Matter Program: First Science and Upcoming Plans

Karen Gibson
RPM Seminar
LBNL
February 19, 2014



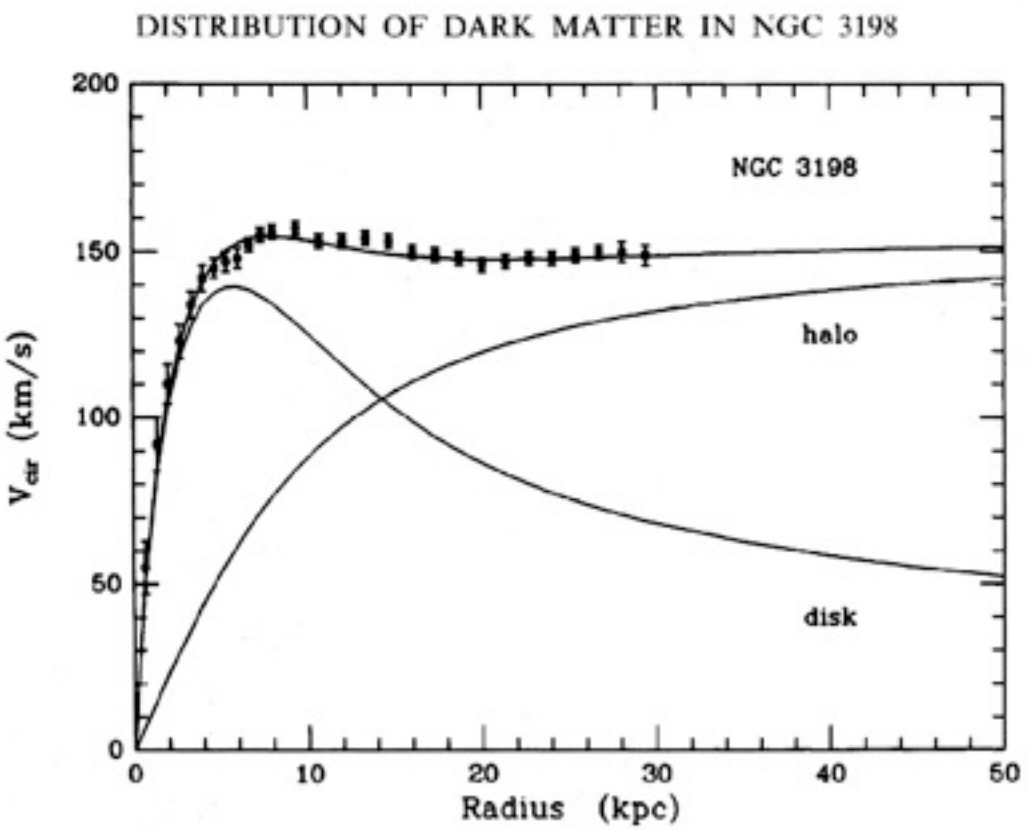
SLAC/Nicolle Rager

In general the relation of the experimental sciences to the question of life can be expressed thus. Question: Why do I live? Answer: In infinite space, in infinite time, infinitely small particles change in infinite complexity, and when you understand the laws of these changes, then you will understand why you live.
-Leo Tolstoy, *Confession*

Why search for dark matter?

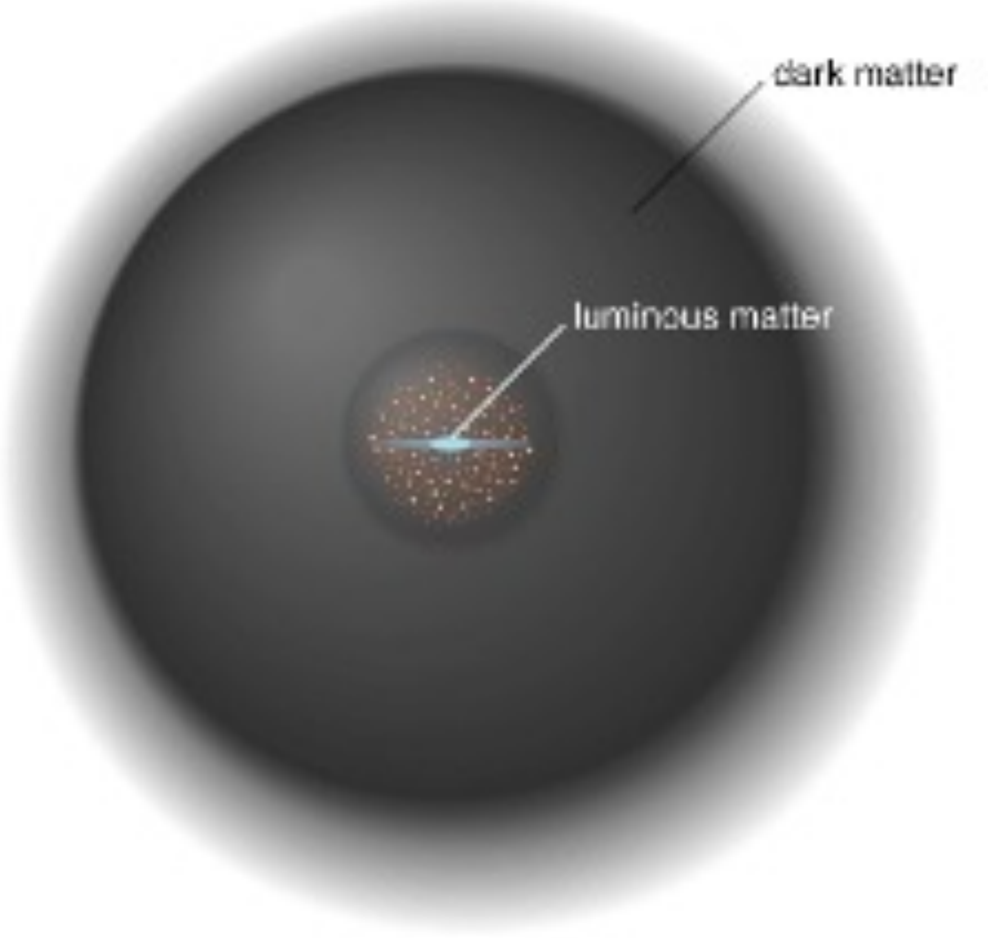
Evidence for dark matter in spiral galaxy rotations

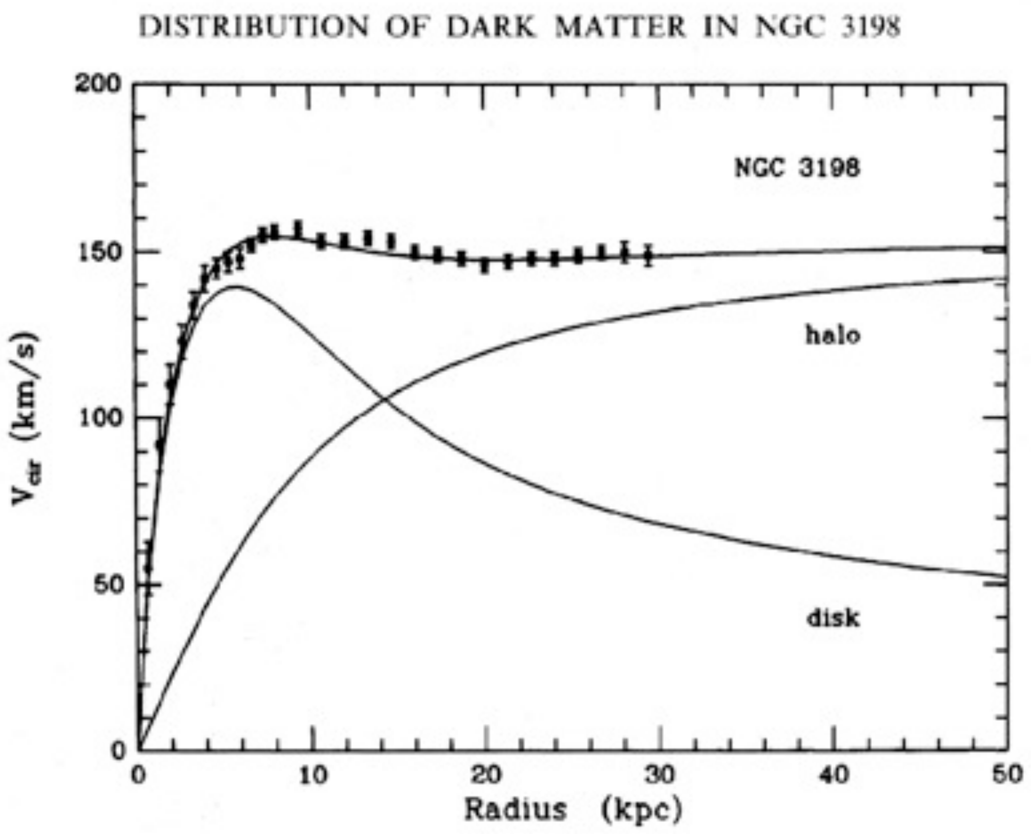
John Vickery & Jim Matthes/Adam Block/NOAO/AURA/NSF



$$v(r) = \sqrt{\frac{GM(r)}{r}} \propto \text{constant} \qquad \Rightarrow M\left(r\right) \propto r$$

Evidence for dark matter in spiral galaxy rotations



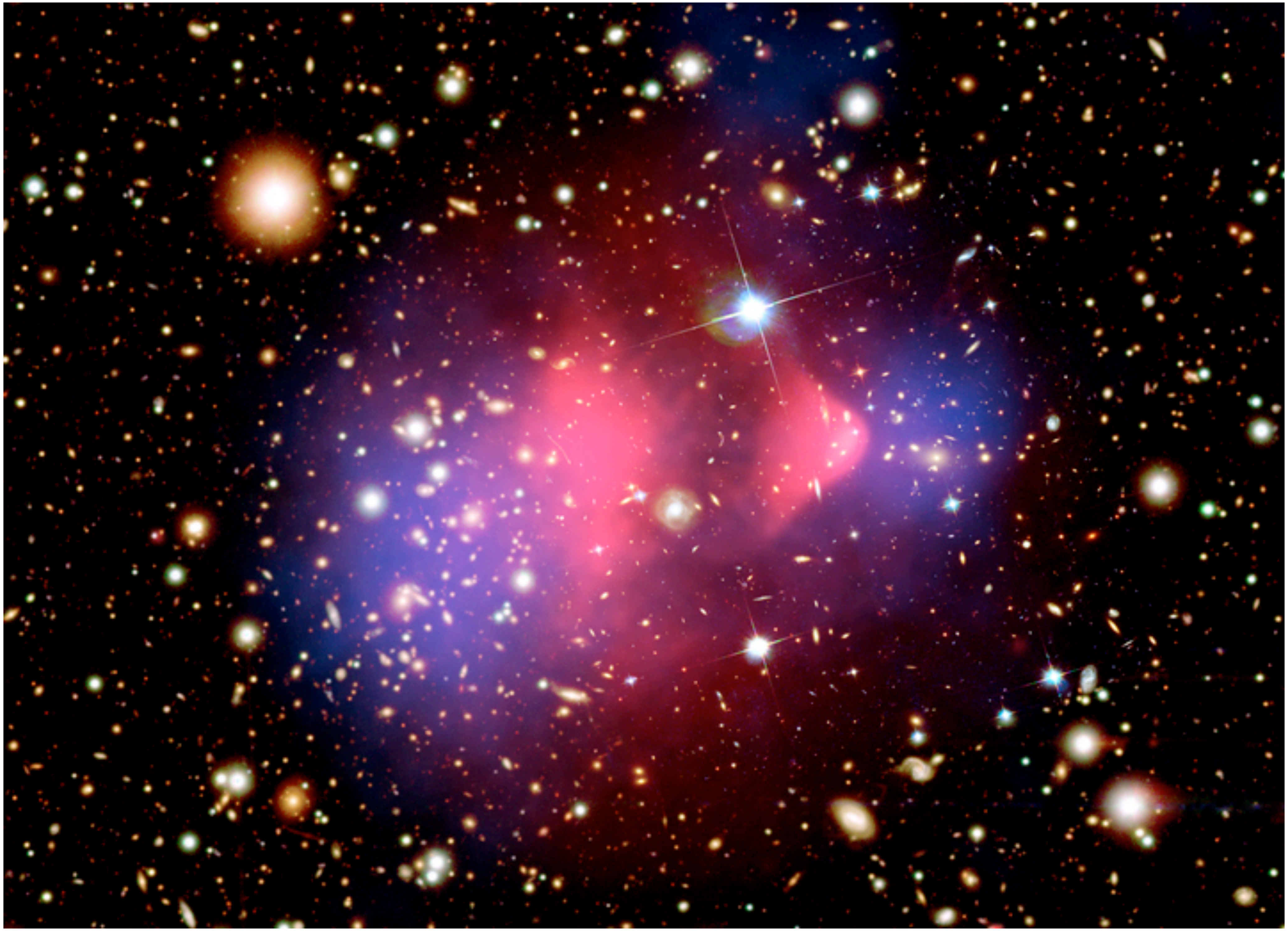


$$v(r)=\sqrt{\frac{GM(r)}{r}}\propto \text{constant} \qquad \Rightarrow M\left(r\right)\propto r$$

Assume isothermal dark matter halo
(e.g. NFW profile)

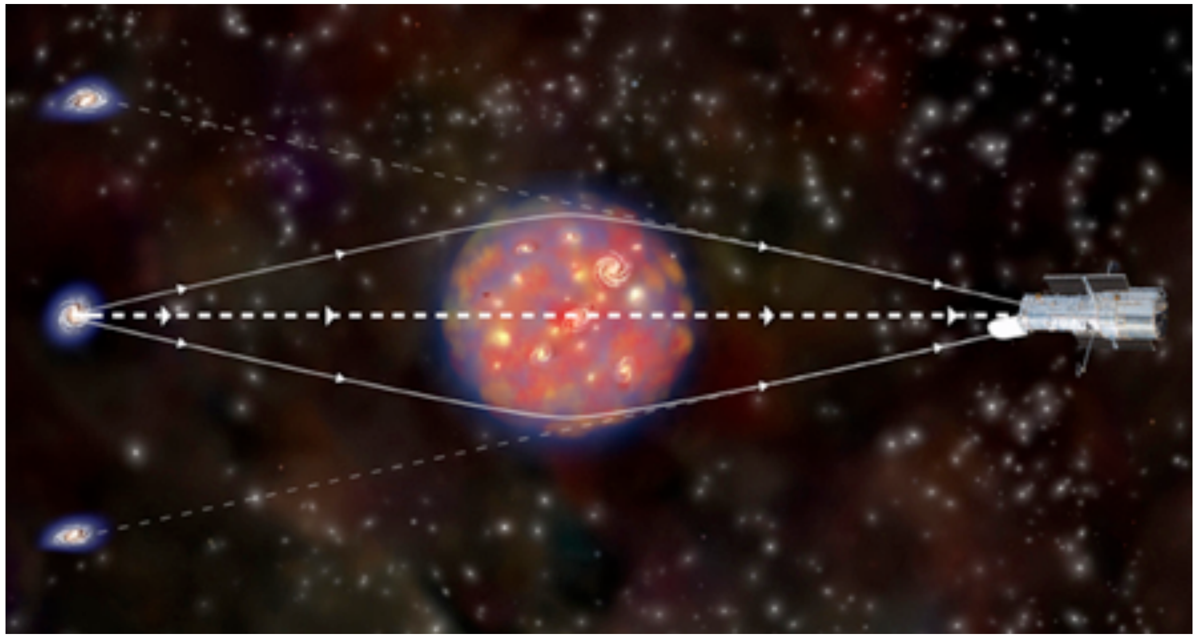
$$\rho\left(r\right)=\frac{\rho_0}{\frac{r}{R_s}\left(1+\frac{r}{R_s}\right)^2}$$

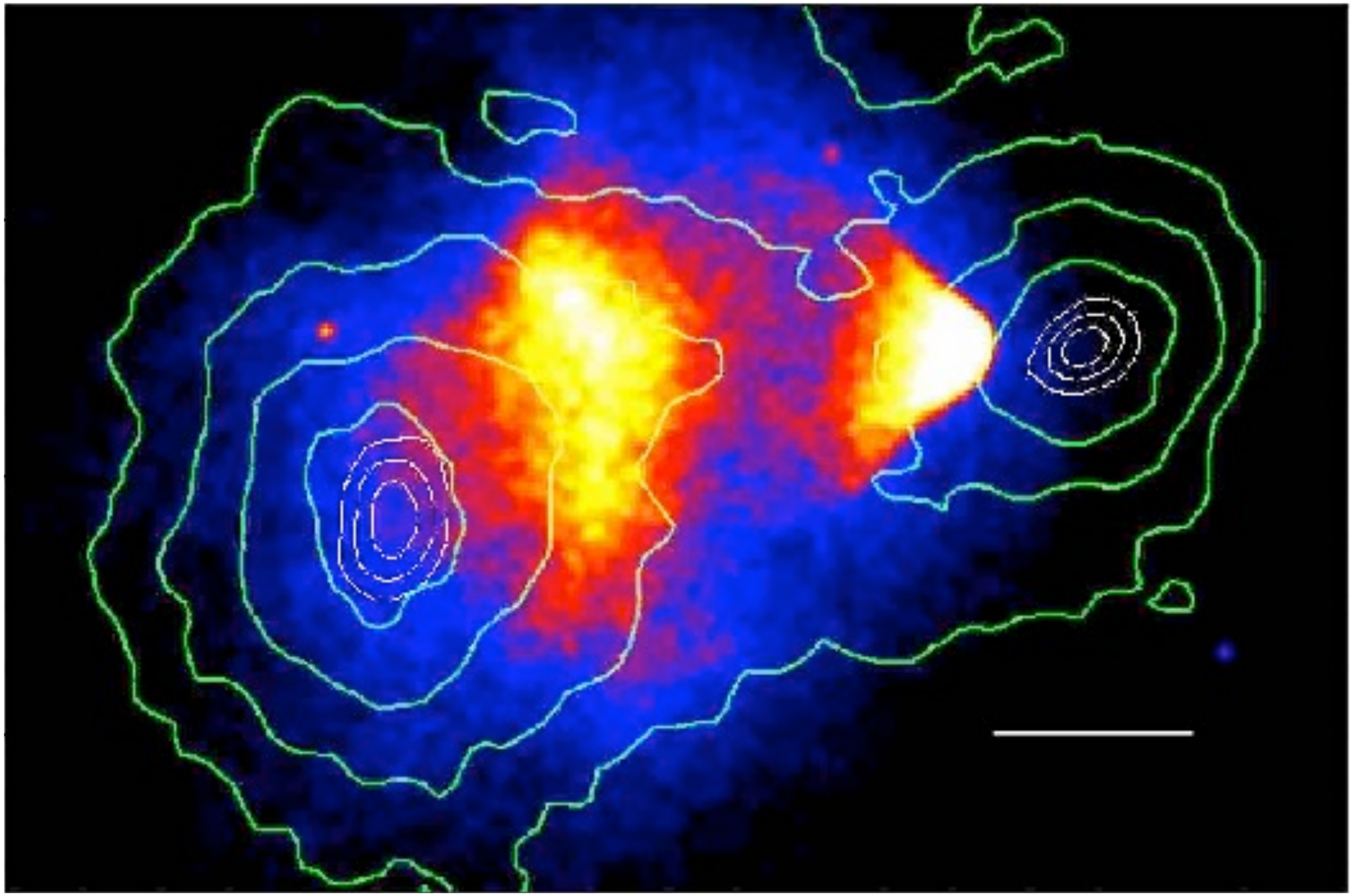
Evidence for dark matter in collisions of galaxies



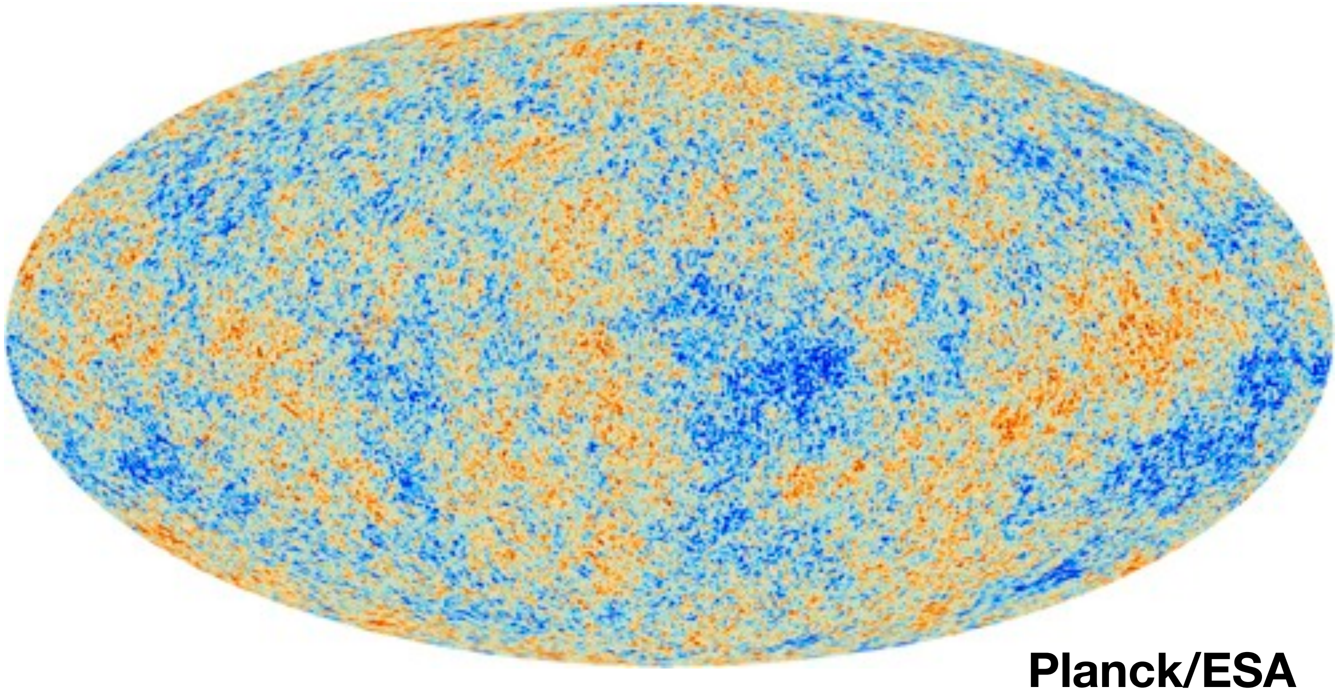
1E 0657-56, Bullet cluster

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

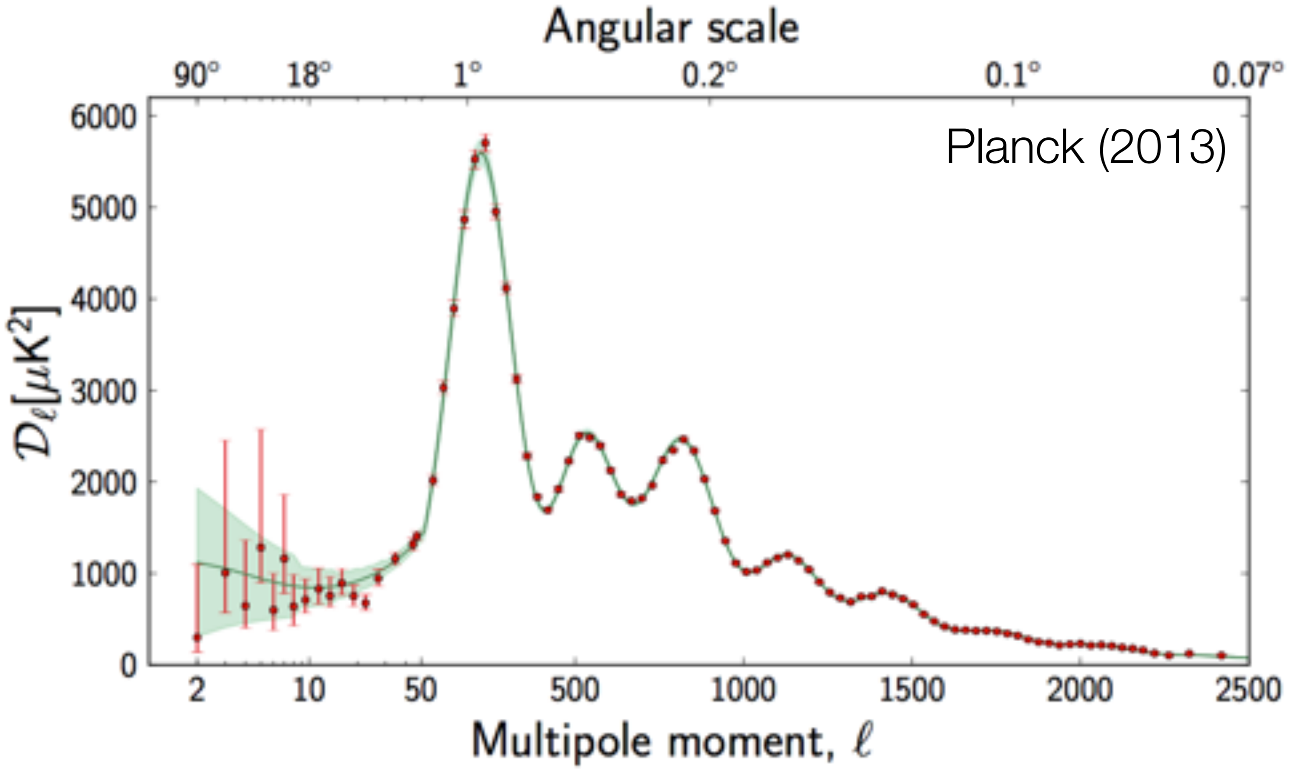




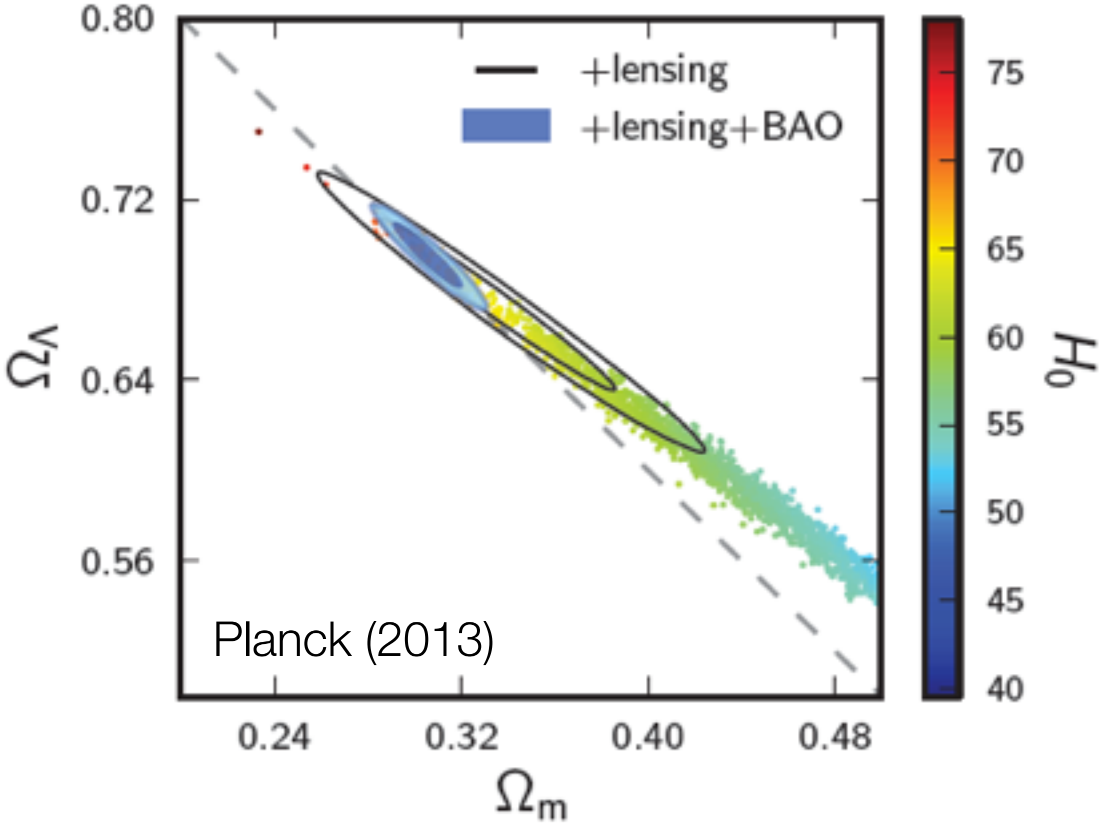
Evidence for dark matter in the CMB



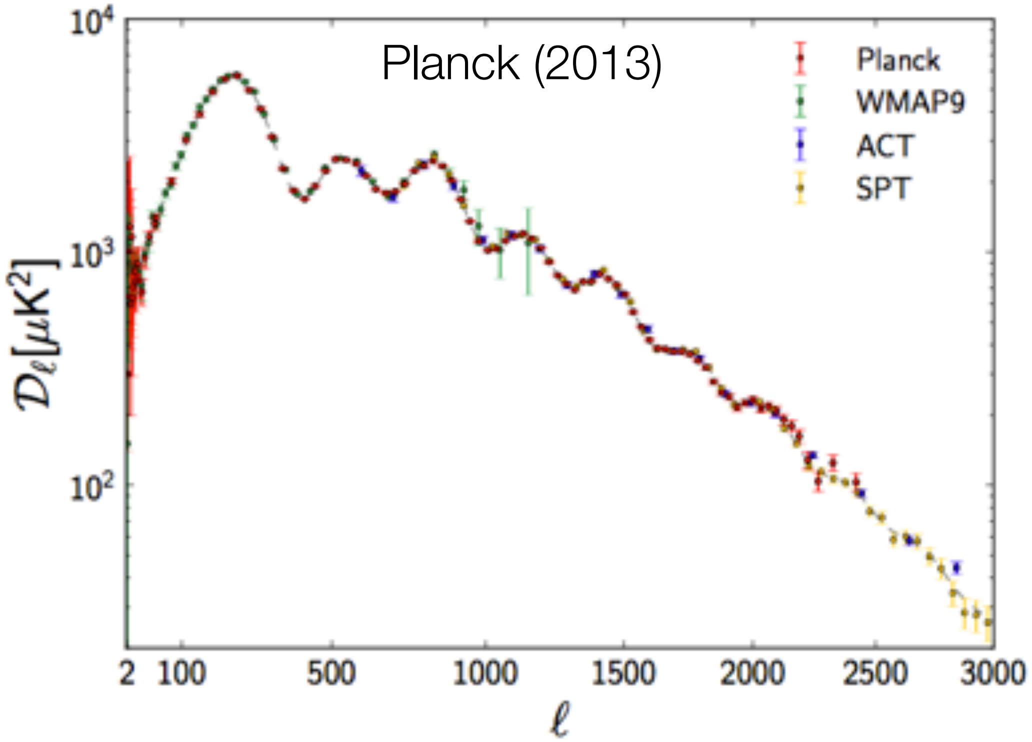
Planck/ESA



Planck (2013)

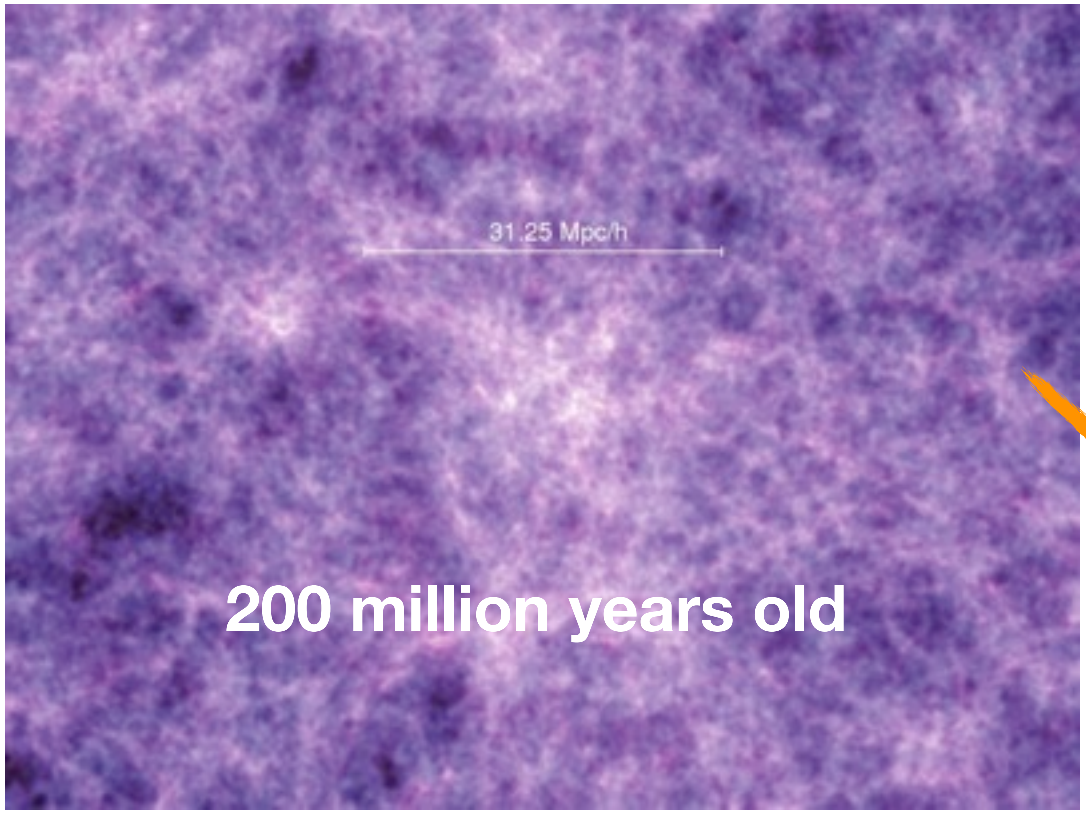


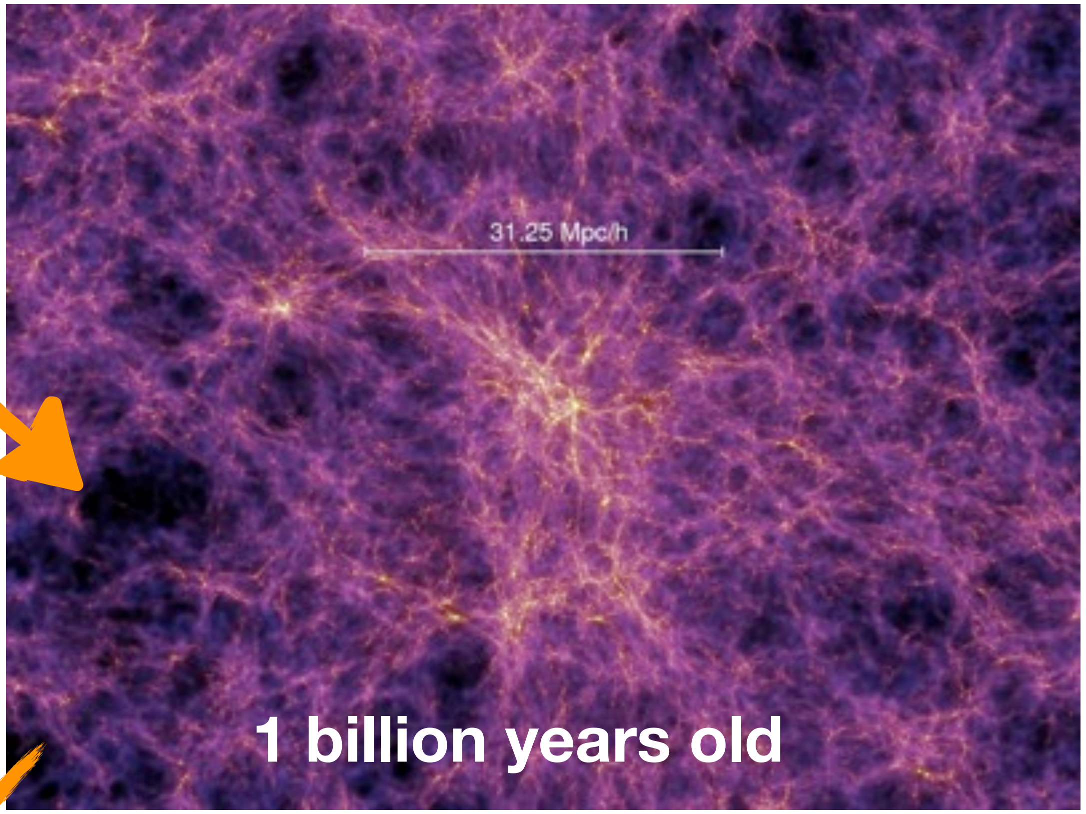
Planck (2013)

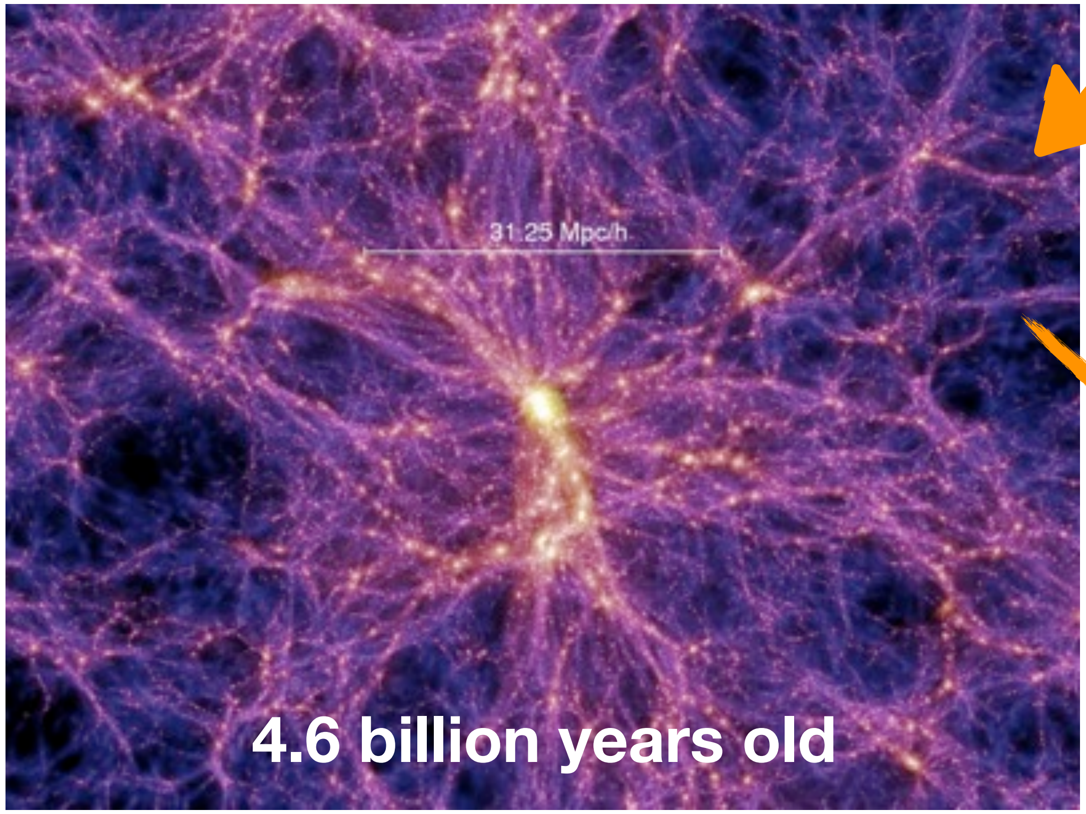


Planck (2013)

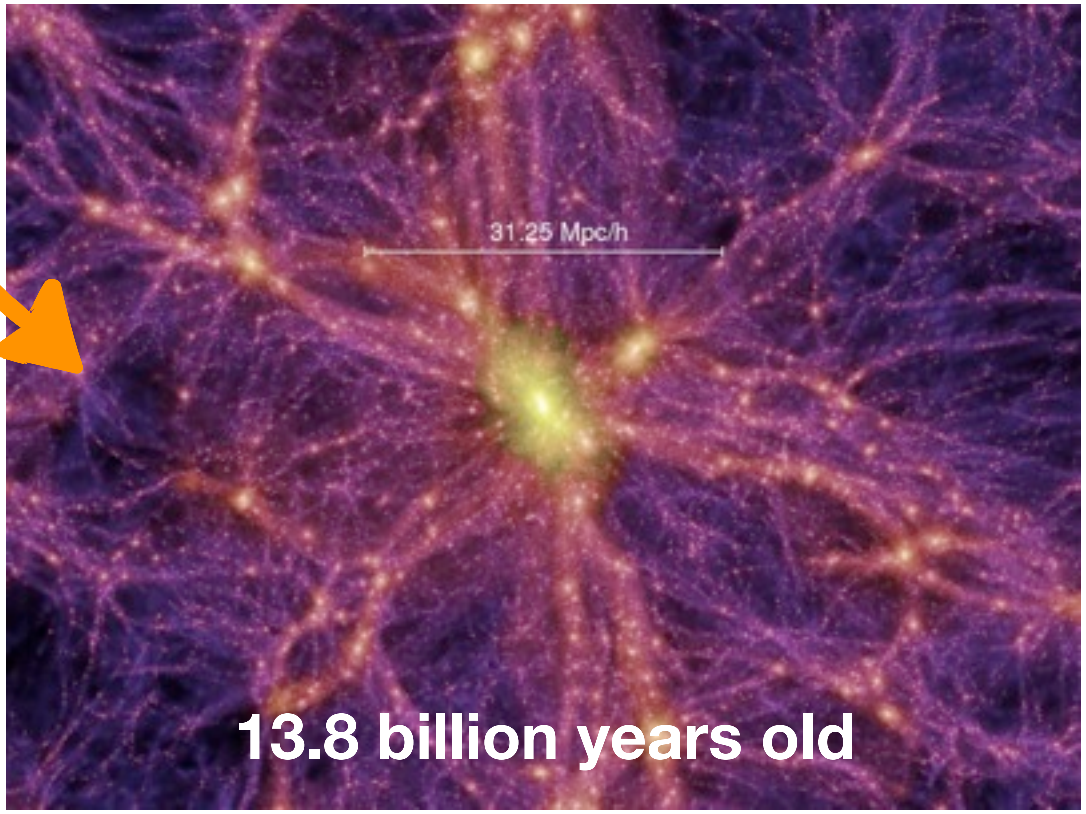
Simulations of structure formation support cold dark matter



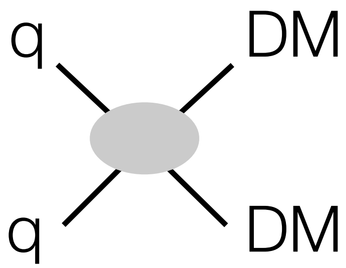




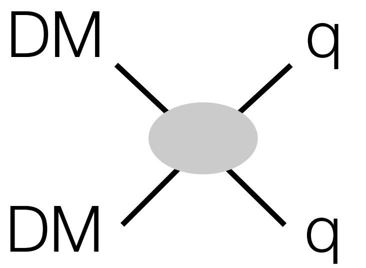
Millenium simulation, Springel et al (2005)



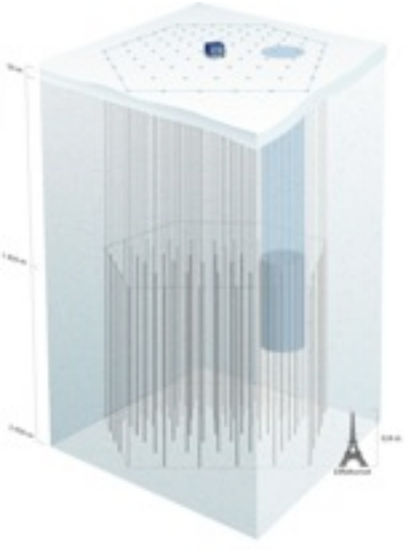
Many different ways to search for WIMP dark matter...

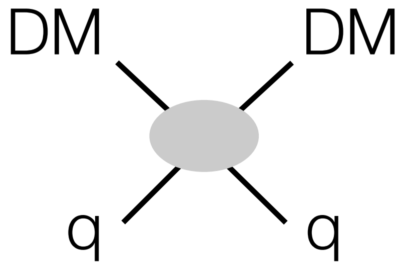


production



annihilation





scattering

WIMP dark matter in the Milky Way


ESO/L Calçada

Standard Halo Model
→smooth mass, velocity distributions

Model WIMP velocity with Maxwell-Boltzman distribution:

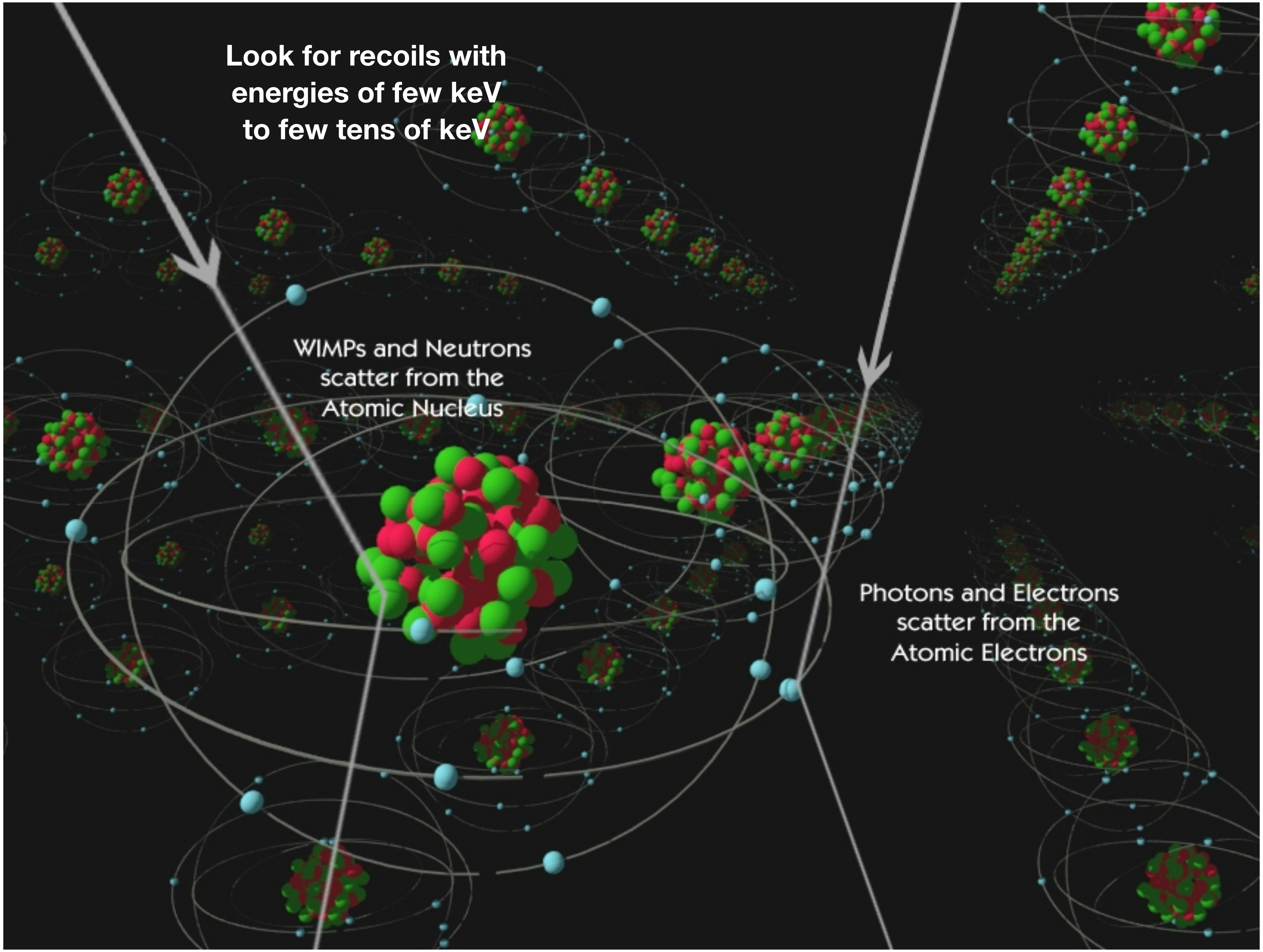
$$f(v) \propto e^{-v^2/v_0^2}$$

Assume:

$\rho_0 = 0.3$ GeV/c^2/cm^3
(3 WIMPS/L for m_χ =100 GeV)

$v_0 = 220$ km/s
$v_e = 232 + 15 \sin(2\pi y)$ km/s
$v_{esc} = 544$ km/s

Dark matter scattering - direct detection searches



Look for recoils with energies of few keV to few tens of keV

Predicted WIMP scattering

$$\boxed{\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{\infty} d^3v \frac{d\sigma}{dE_R} \cdot vf\left(v, v_e\right)}$$

Generic relation for WIMP scattering cross section

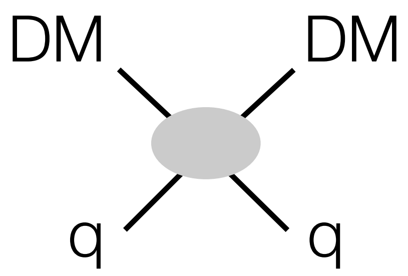
$$\frac{d\sigma}{dE_R} = \frac{m_A \sigma_{0,A}}{2\mu_A^2 v^2} F^2\left(E_R\right)$$

$$\frac{dR}{dE_R} = N_T \frac{m_A \sigma_{0,A}}{2\mu_A} F^2\left(E_R\right) \cdot \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{\infty} d^3v \frac{f\left(v, v_e\right)}{v}$$

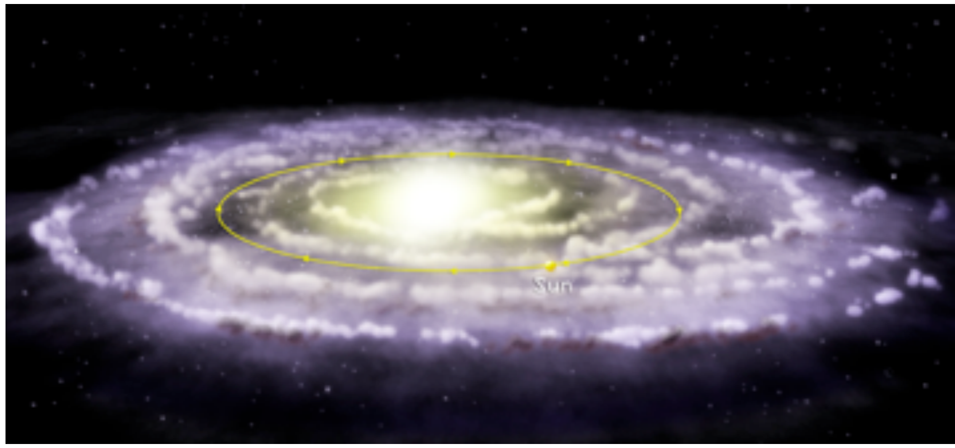
particle physics

nuclear physics

astrophysics



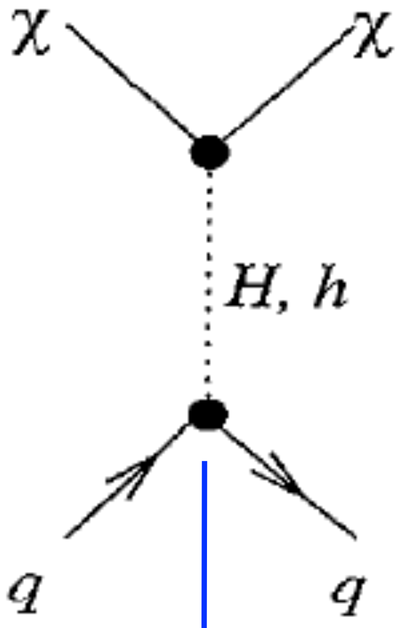
$$F^2\left(E_R\right) = \left(\frac{3j_1(qR)}{qR}\right)^2 e^{-q^2 s^2}$$



Spin-independent scattering

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

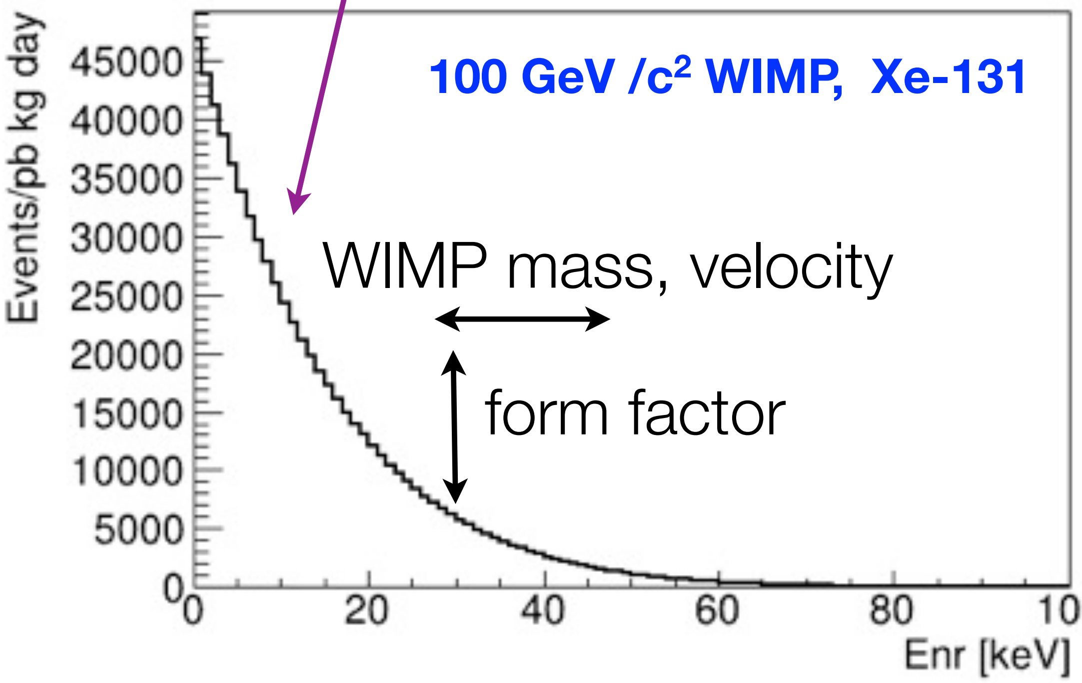
$$\frac{dR}{dE_R} = N_T \frac{m_A \sigma_{0,A}}{2\mu_A} F^2(E_R) \cdot \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{\infty} d^3v \frac{f(v, v_e)}{v}$$



$$\boxed{\sigma_{0,A} = \sigma_{0,n} \frac{\mu_A^2}{\mu_n^2} \frac{\left(f_p Z + f_n (A-Z)\right)^2}{f_n^2}}$$

Assume $f_n = f_p \Rightarrow \sigma_{0,A} \propto A^2$

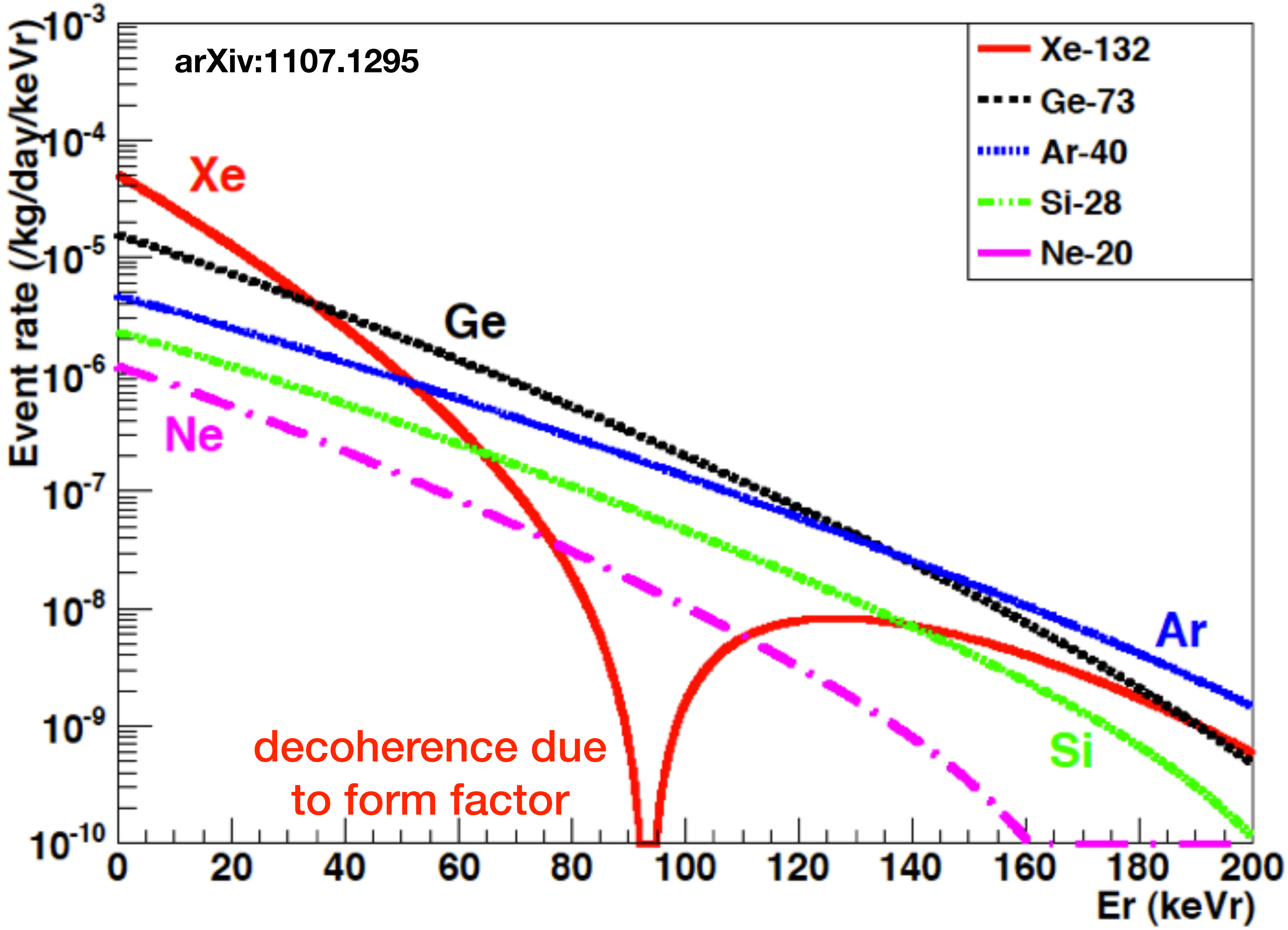
$$\propto e^{-E_R m_A / 2\mu_A^2 v_0^2}$$



WIMP mass, velocity

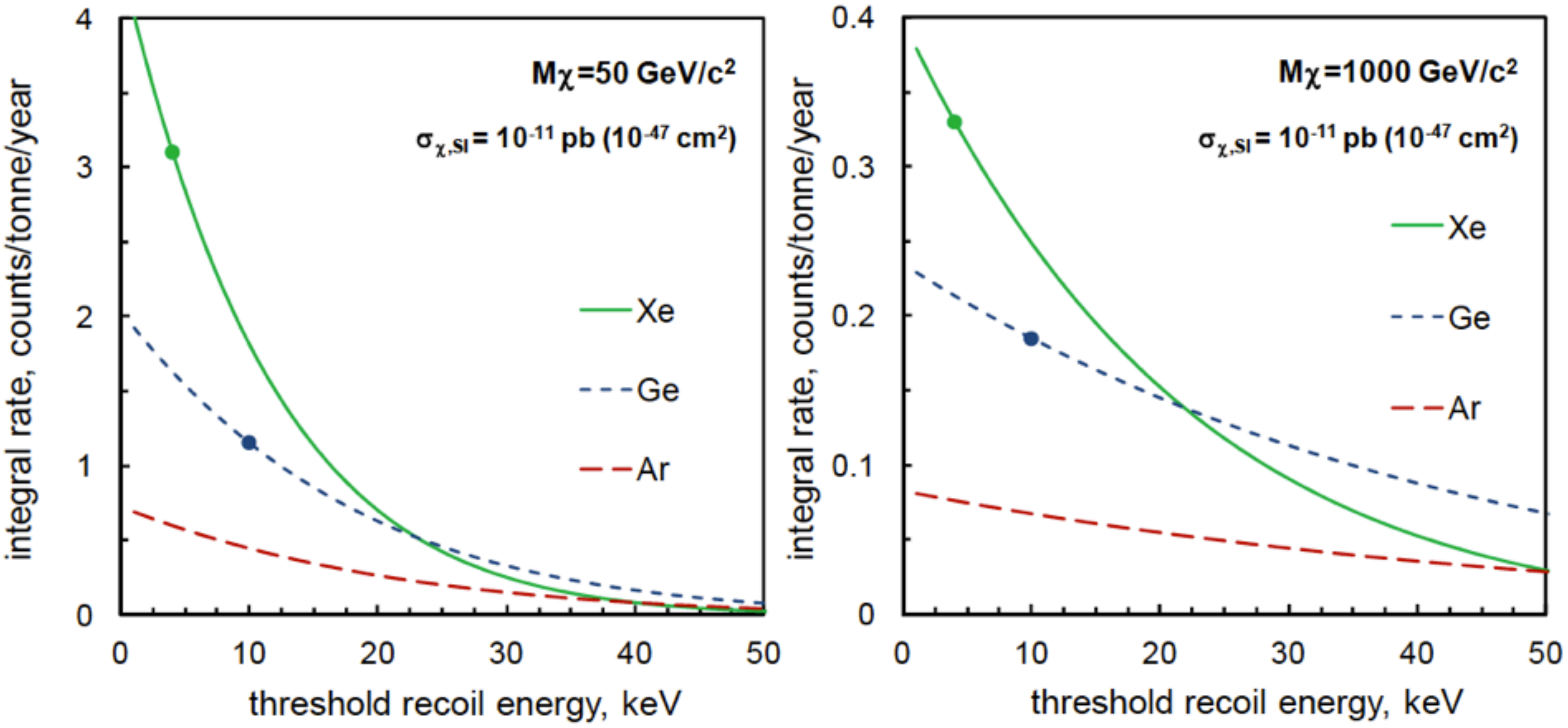
form factor

Scattering rate for different targets

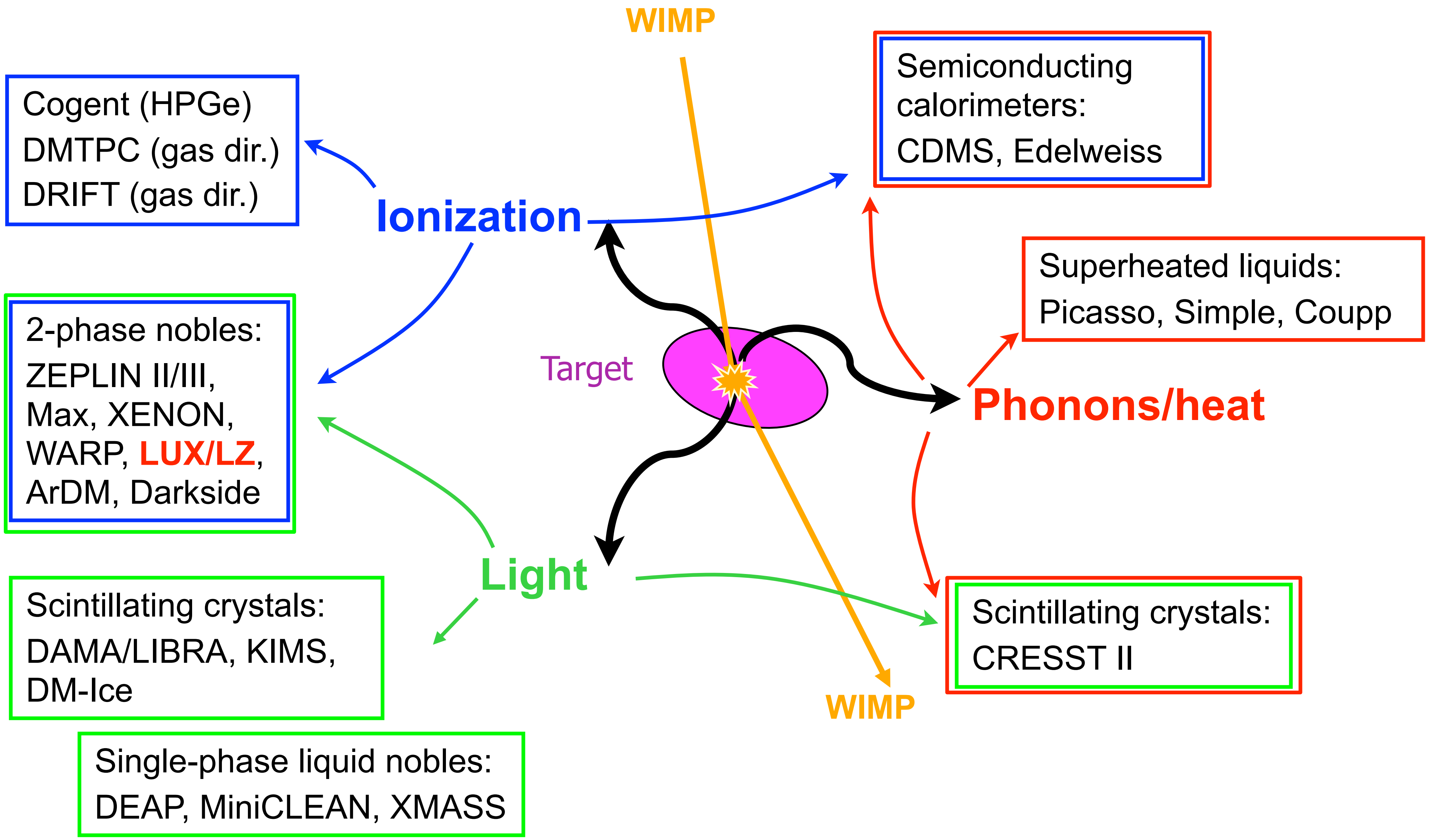


decoherence due to form factor

Total rates including detector threshold



Experiments search via light/charge/heat signals



Cogent (HPGe)
DMTPC (gas dir.)
DRIFT (gas dir.)

Semiconducting calorimeters:
CDMS, Edelweiss

Superheated liquids:
Picasso, Simple, Coupp

2-phase nobles:
ZEPLIN II/III,
Max, XENON,
WARP, **LUX/LZ**,
ArDM, Darkside

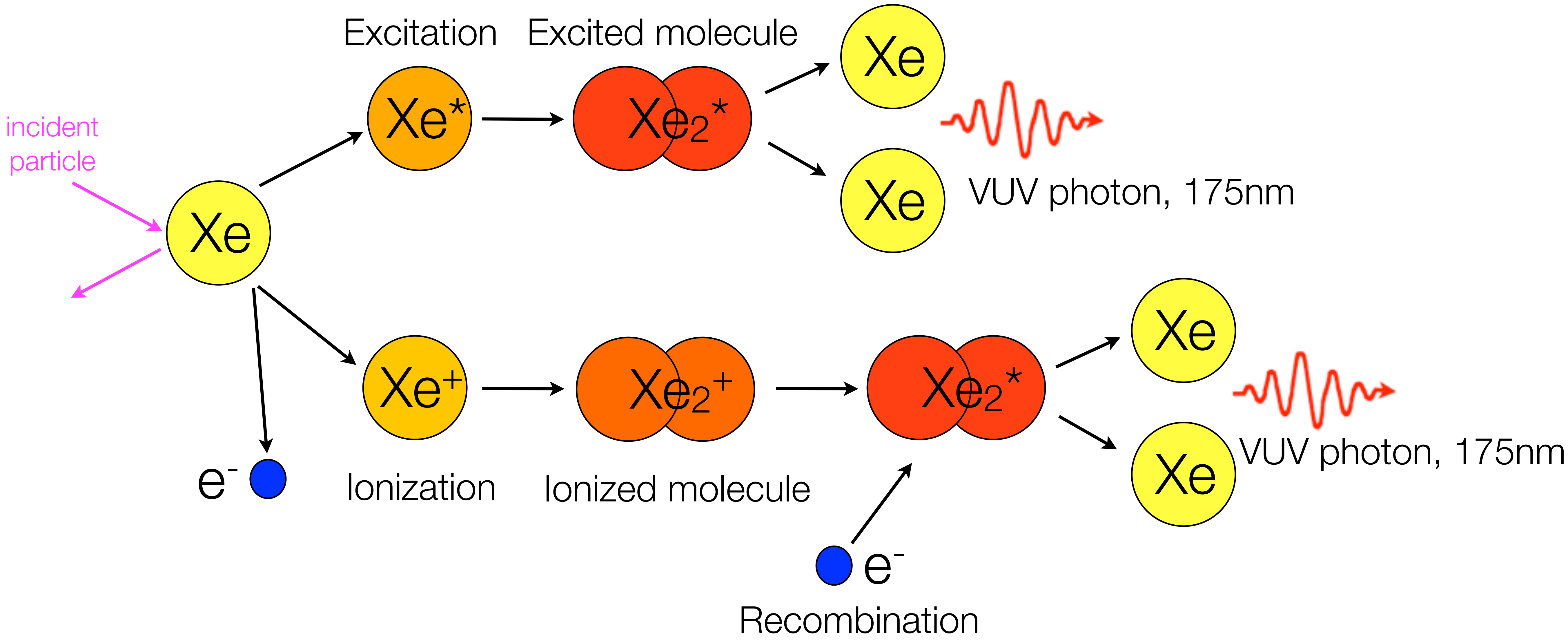
Scintillating crystals:
DAMA/LIBRA, KIMS,
DM-Ice

Scintillating crystals:
CRESST II

Single-phase liquid nobles:
DEAP, MiniCLEAN, XMASS

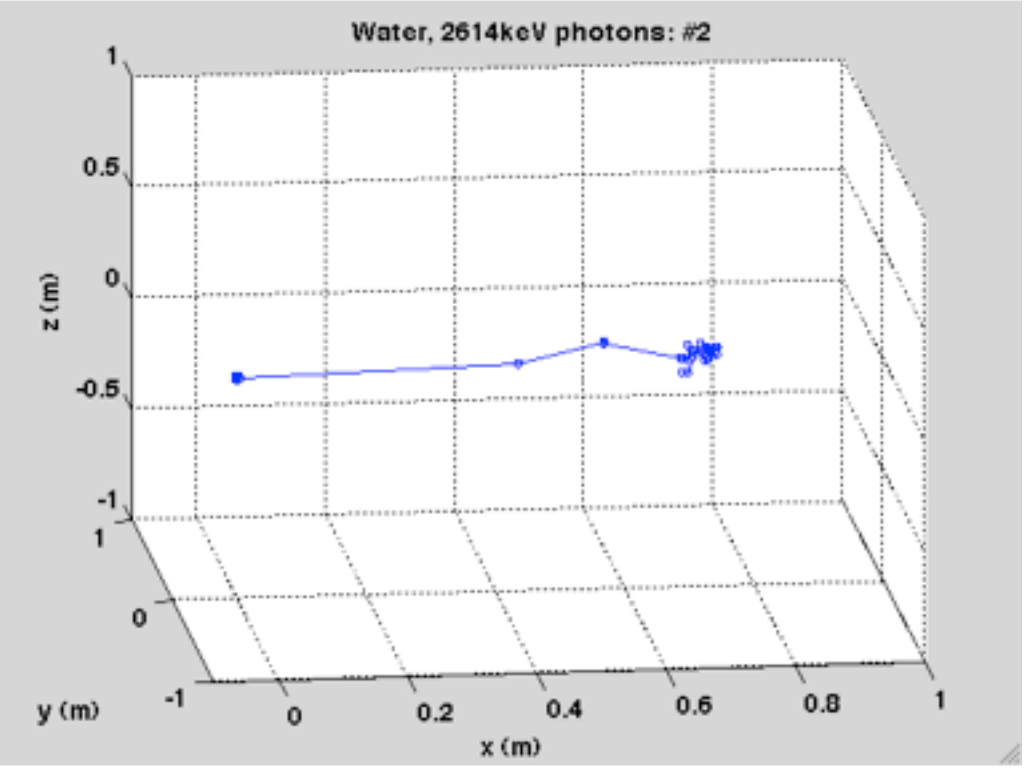
Xenon scintillation

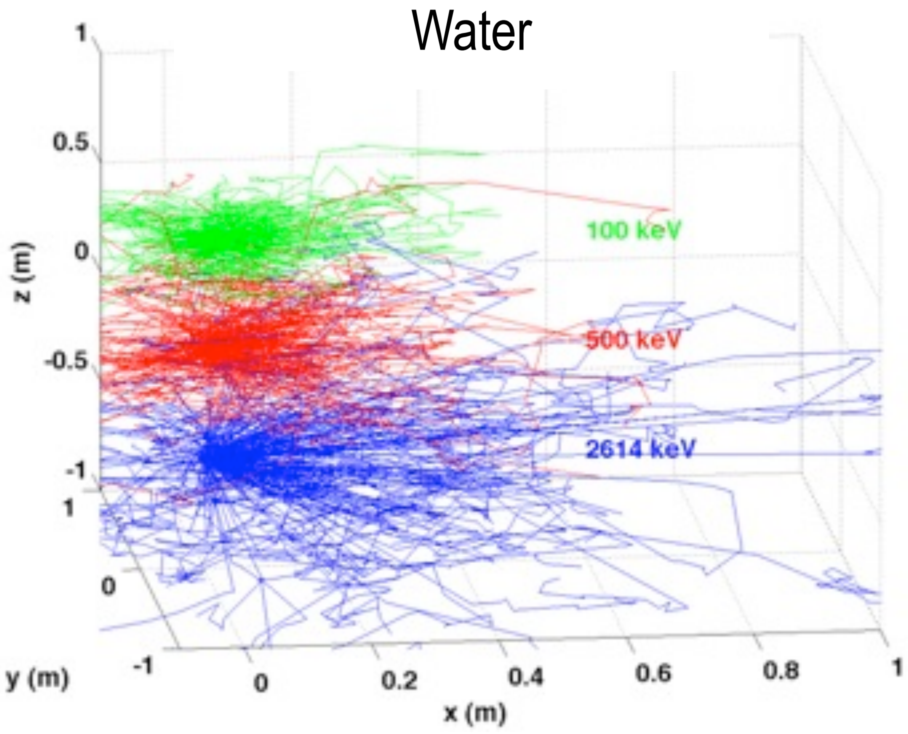
All recoils produce light and charge - use the ratio of charge to light to distinguish electronic and nuclear recoils

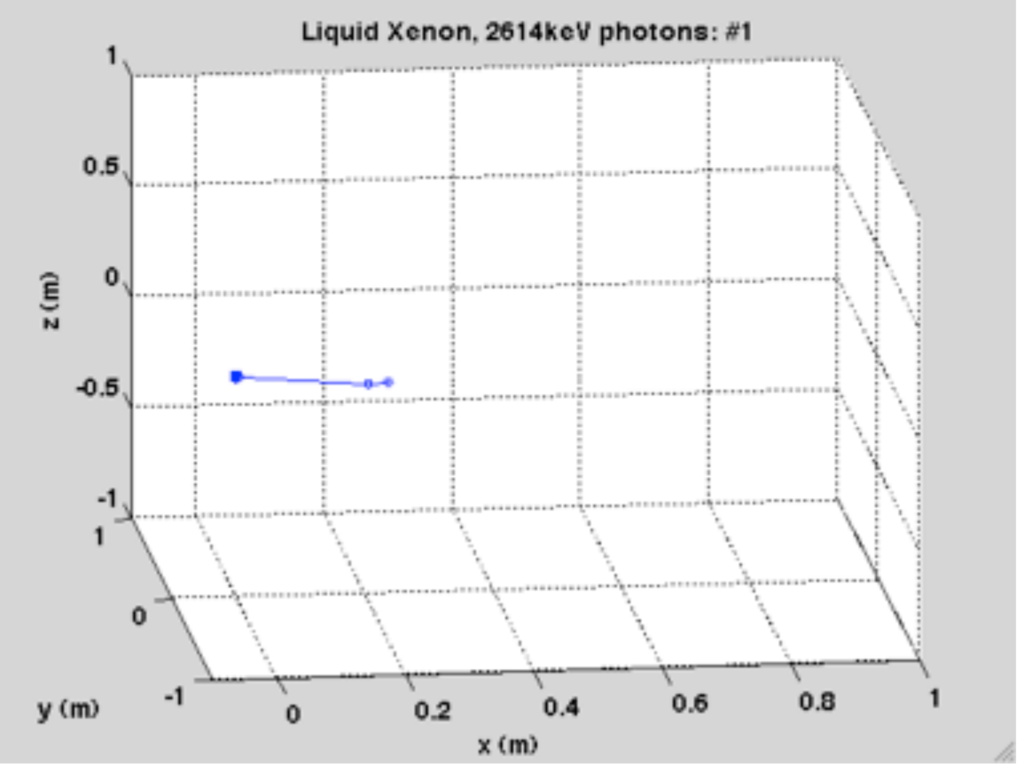


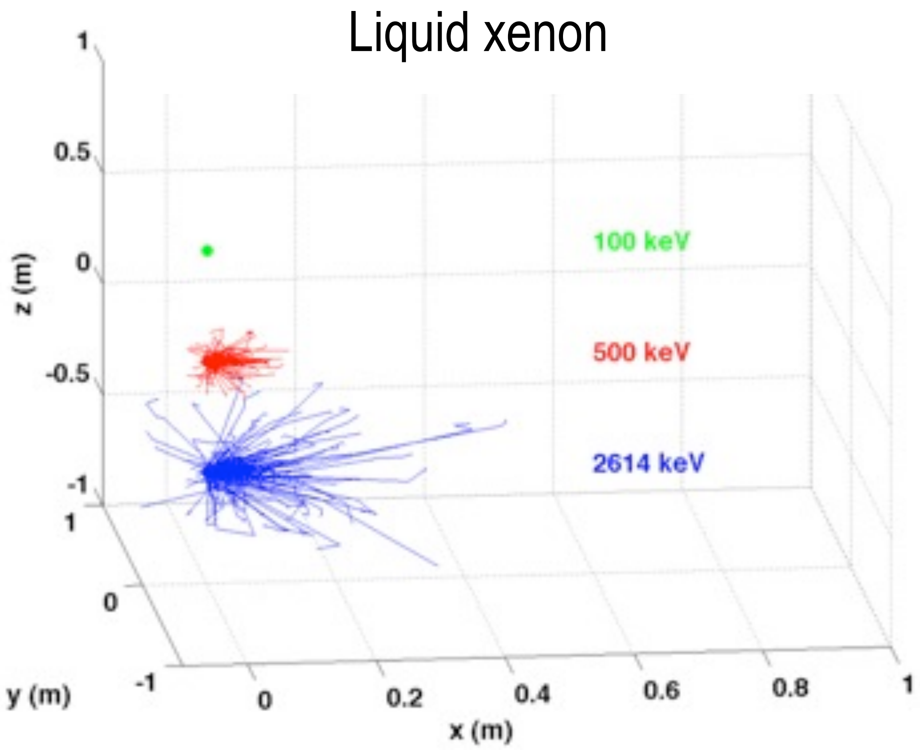
An applied electric field lowers the number of electrons available to recombine!

Self-shielding in liquid xenon




Water




Liquid xenon

The Large Underground Xenon Experiment

The true adventurer goes forth aimless and
uncalculating to meet and greet unknown fate.
- O Henry

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

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

110 researchers from 17 institutions and 3 countries

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

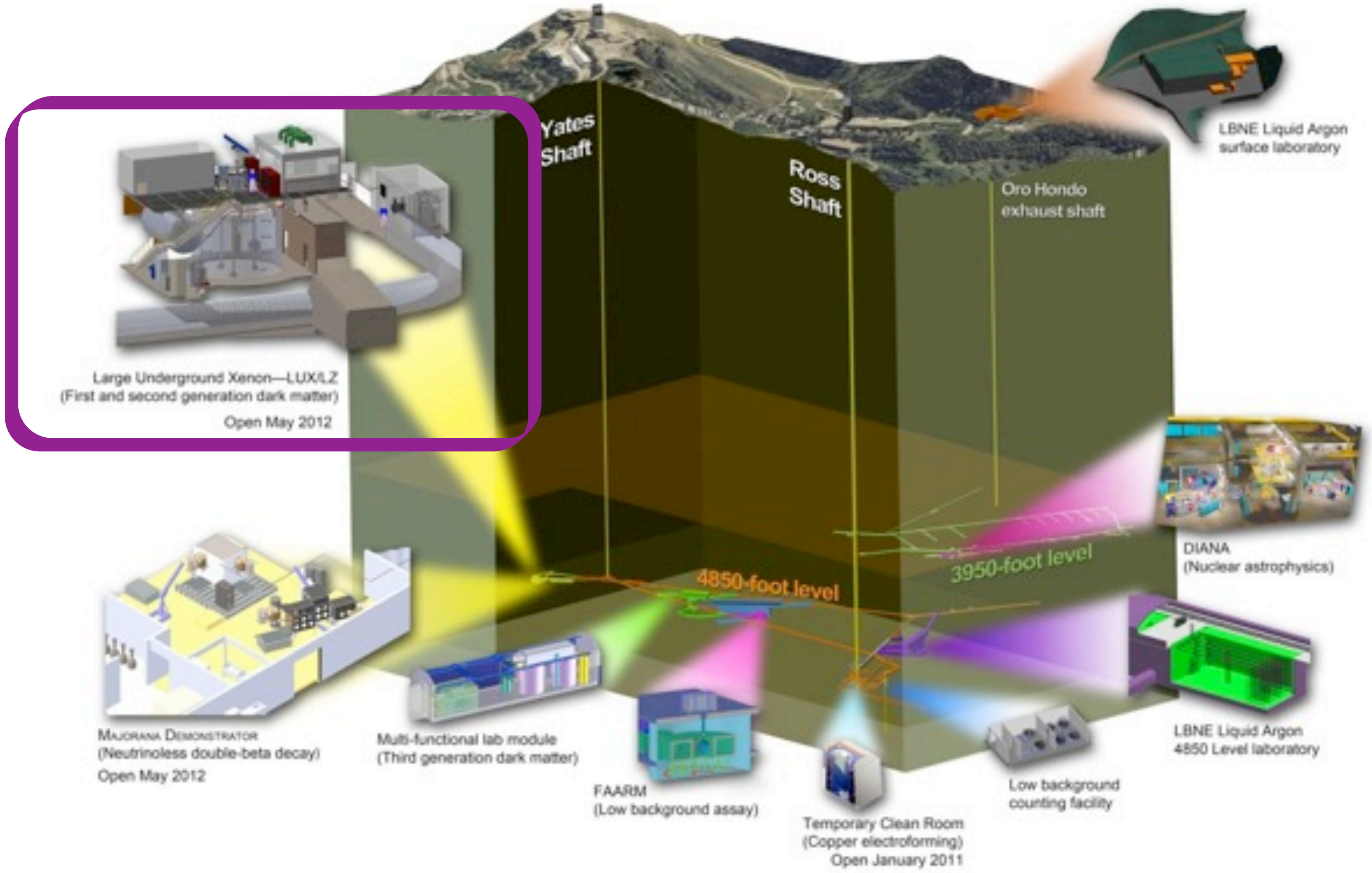
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

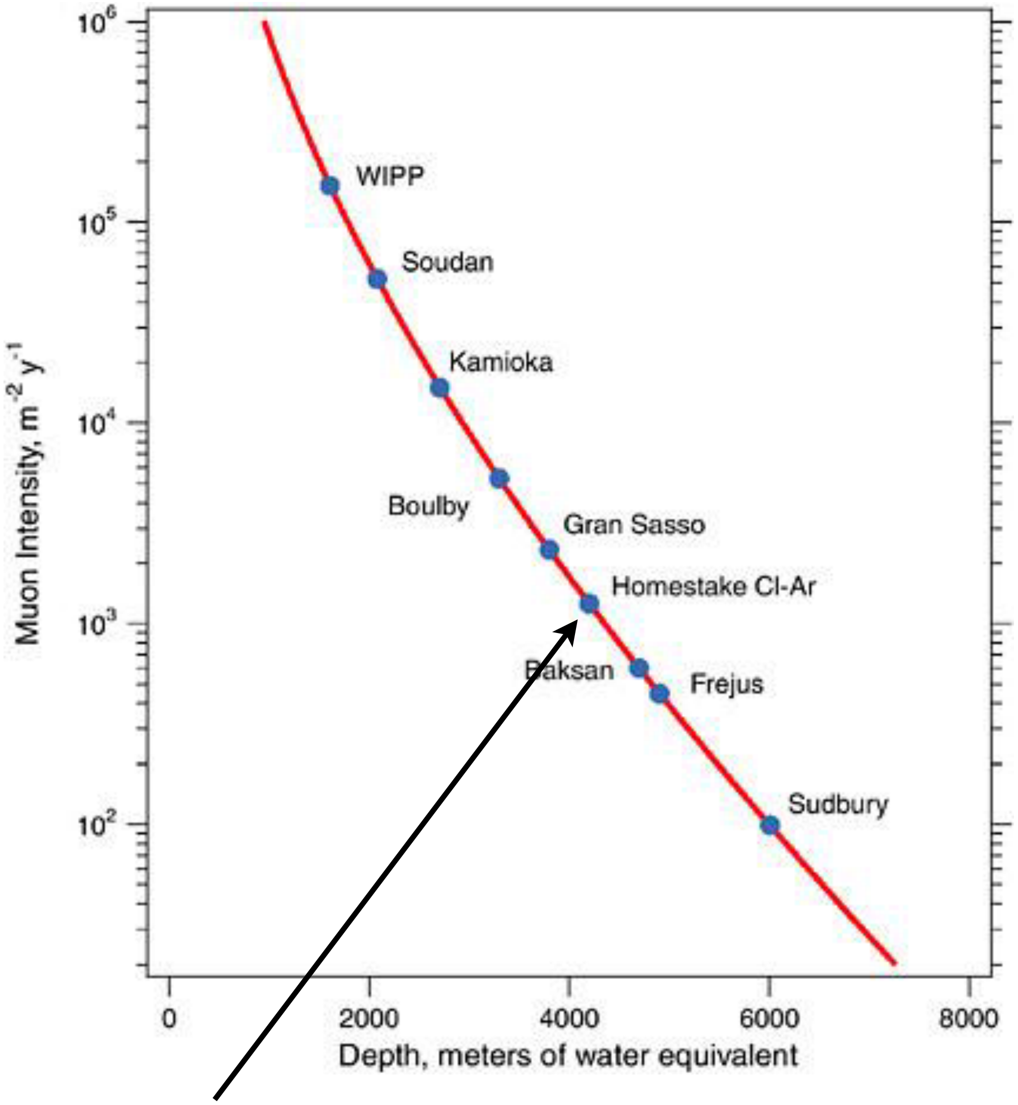
Yale

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

LUX at SURF

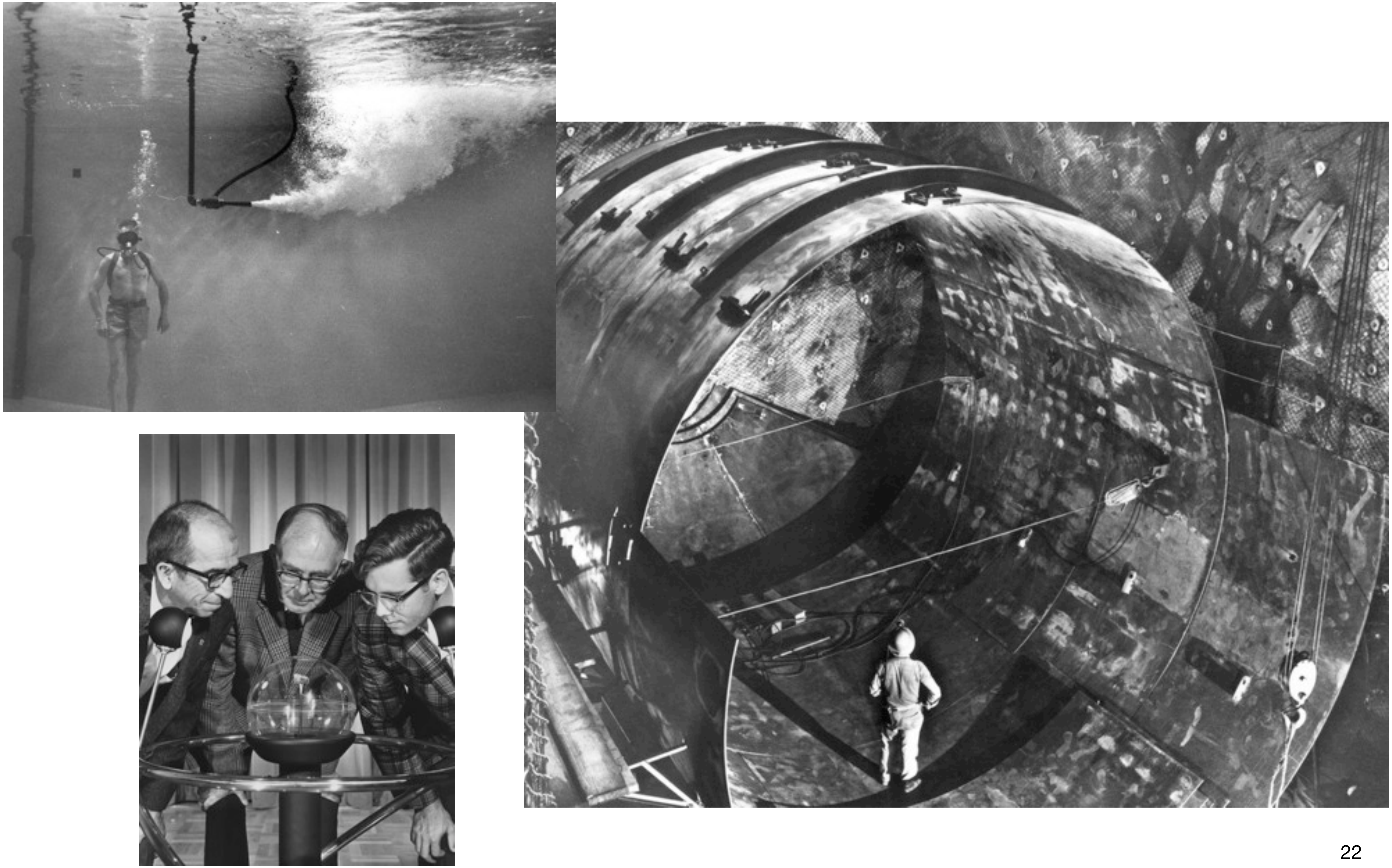
Sanford Underground Research Facility (SURF), located in Lead, SD



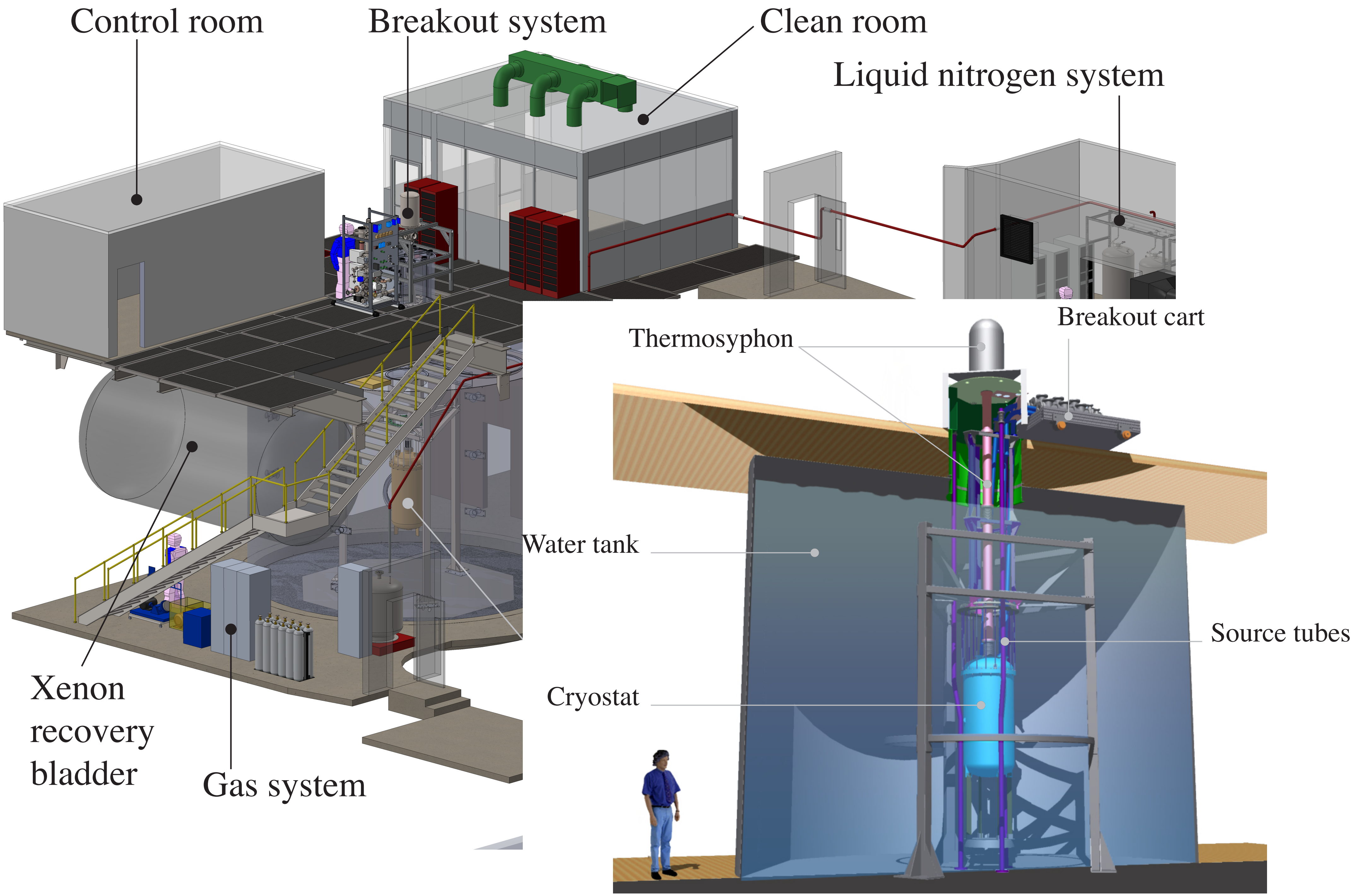


Muon flux at 4850’ level reduced by 10^7 relative to the surface
55.2 m^{-2}s^{-1} → 1×10^{-5} m^{-2}s^{-1}

Davis campus was also the site of the Homestake solar neutrino experiment

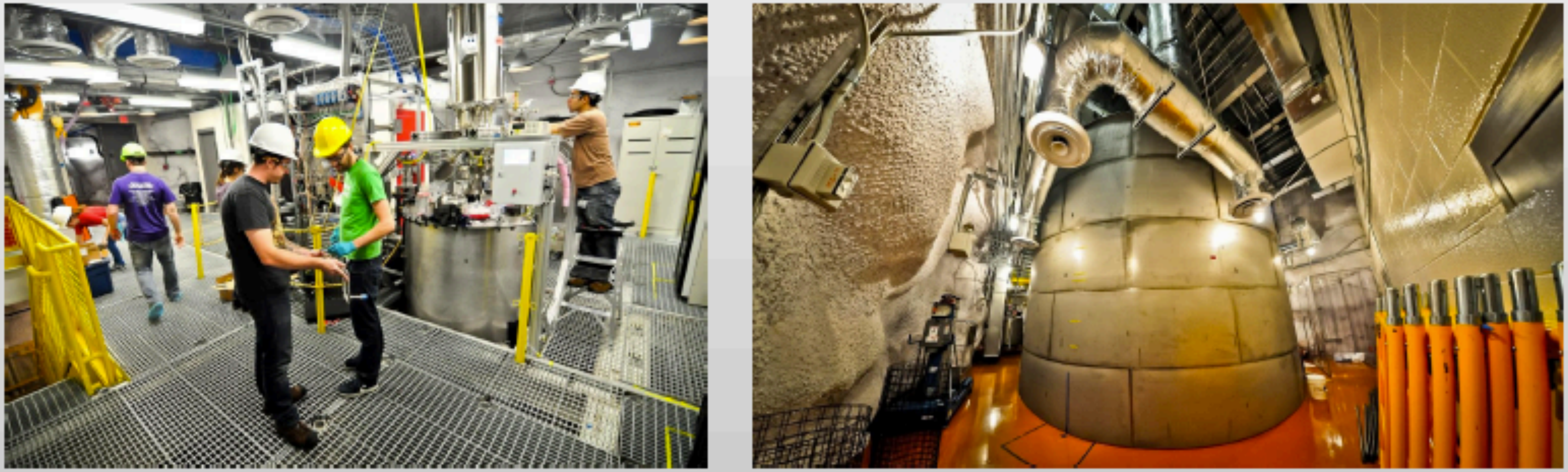


The LUX detector



Detector deployment underground

Detector transported underground July 11-12, 2012, deployed in autumn of 2012



LUX - A TPC at heart

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

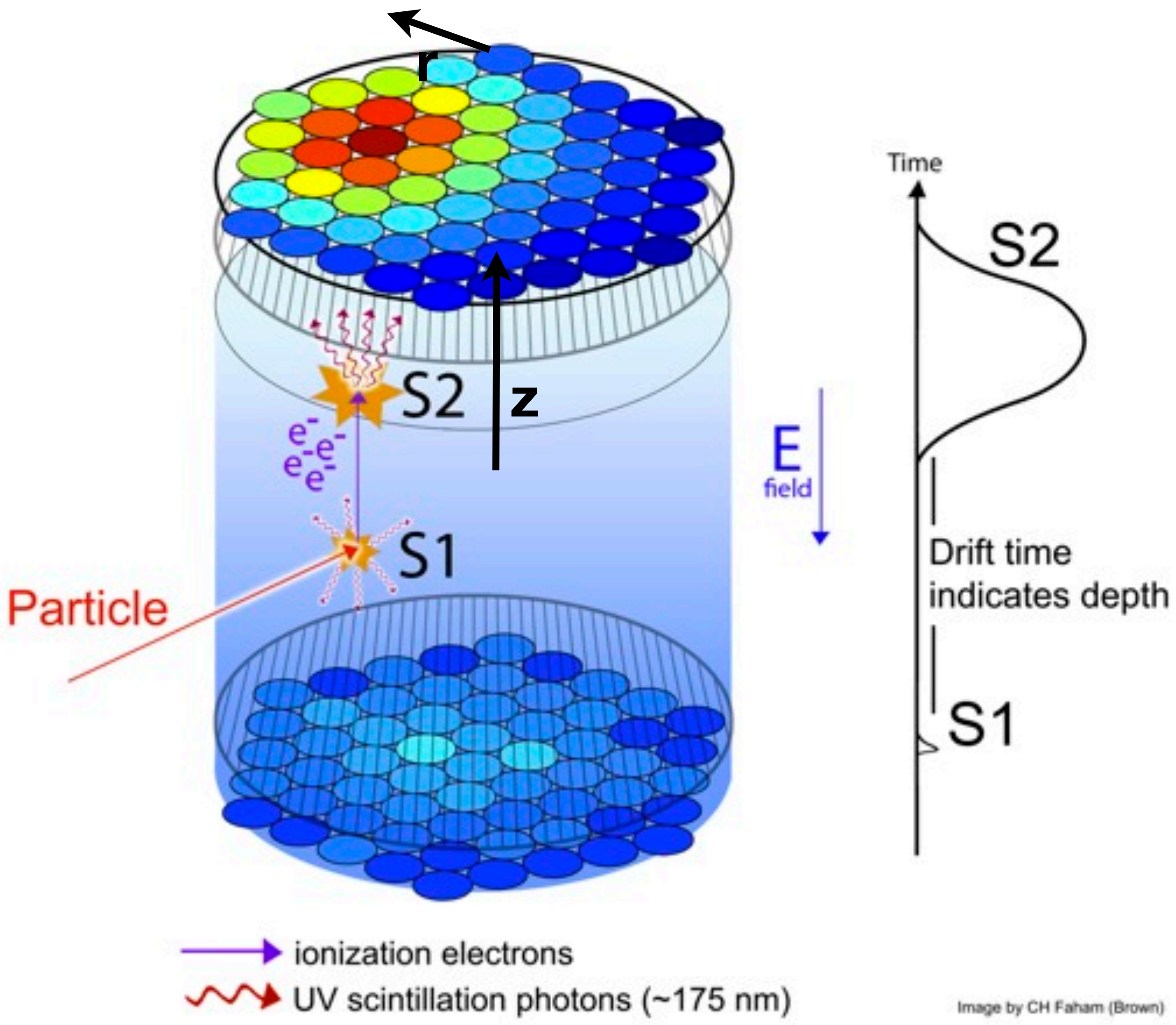
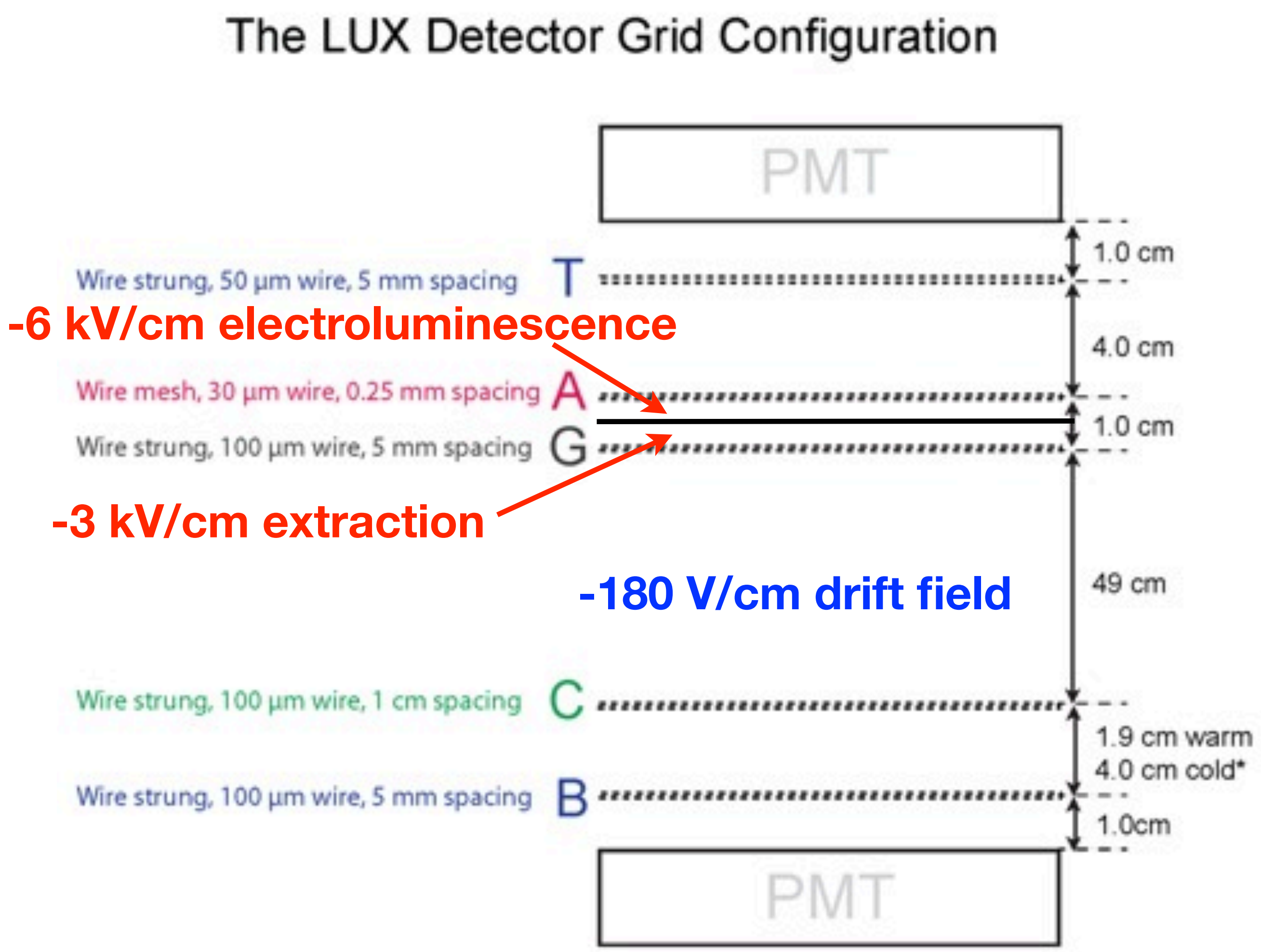


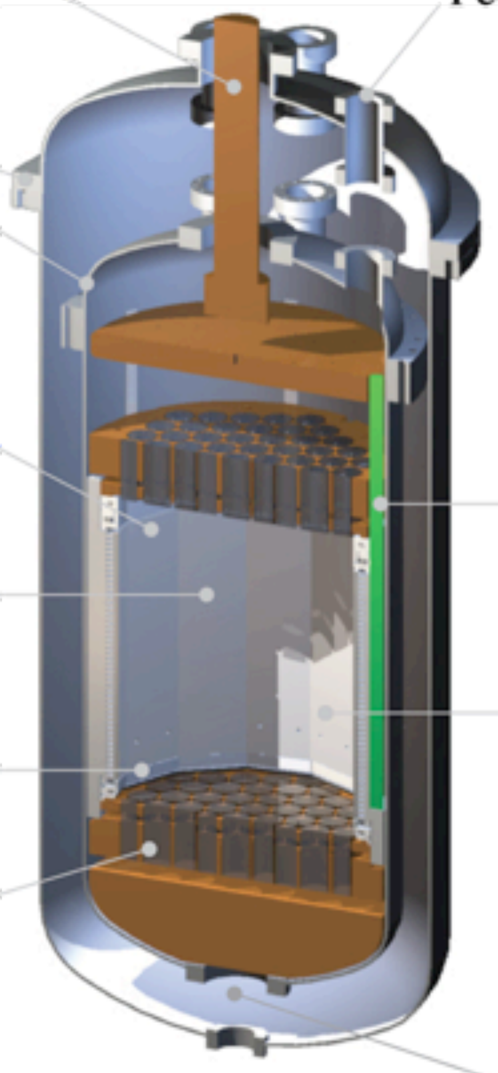
Image by CH Faham (Brown)



There are 47 field-shaping rings between G and C, spaced 1 cm apart.

Cryostat

Use thermosyphons for efficient, passive cooling



Top thermosyphon

Feedthroughs

Titanium cryostats

Radiopure Ti

< 0.2 mBq/kg

Anode and electron extraction grids

Constantly circulate and purify Xe in gas phase

Xenon recirculation and heat exchanger

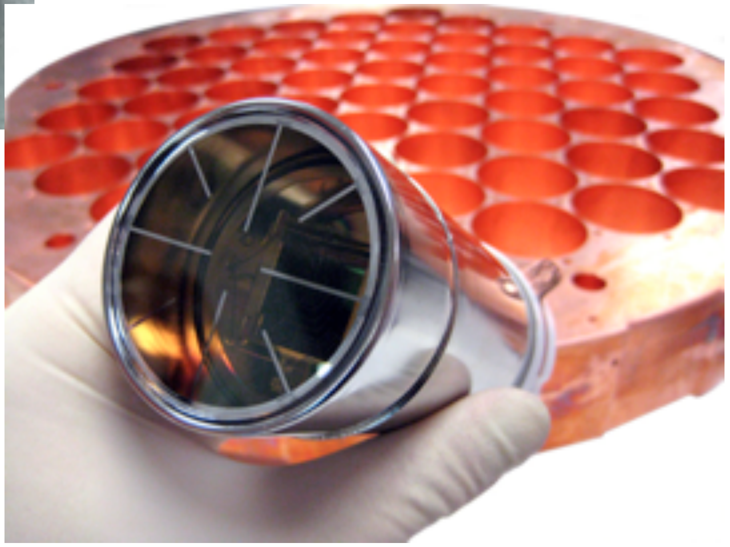
300 kg active liquid xenon

PTFE reflector panels

Cathode grid

Photomultiplier tubes

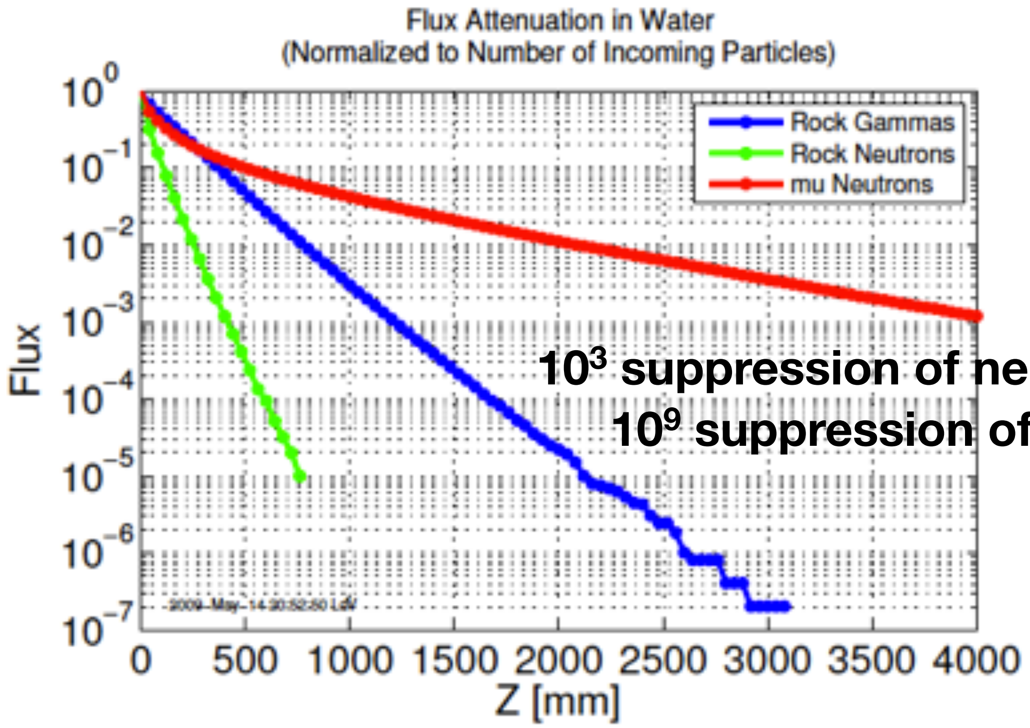
Bottom thermosyphon



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

Water Shield

300 tonnes ultrapure water shield (>18 MOhm-cm),
20’ high, 25’ diameter SS tank to reduce cavern & cosmogenic backgrounds



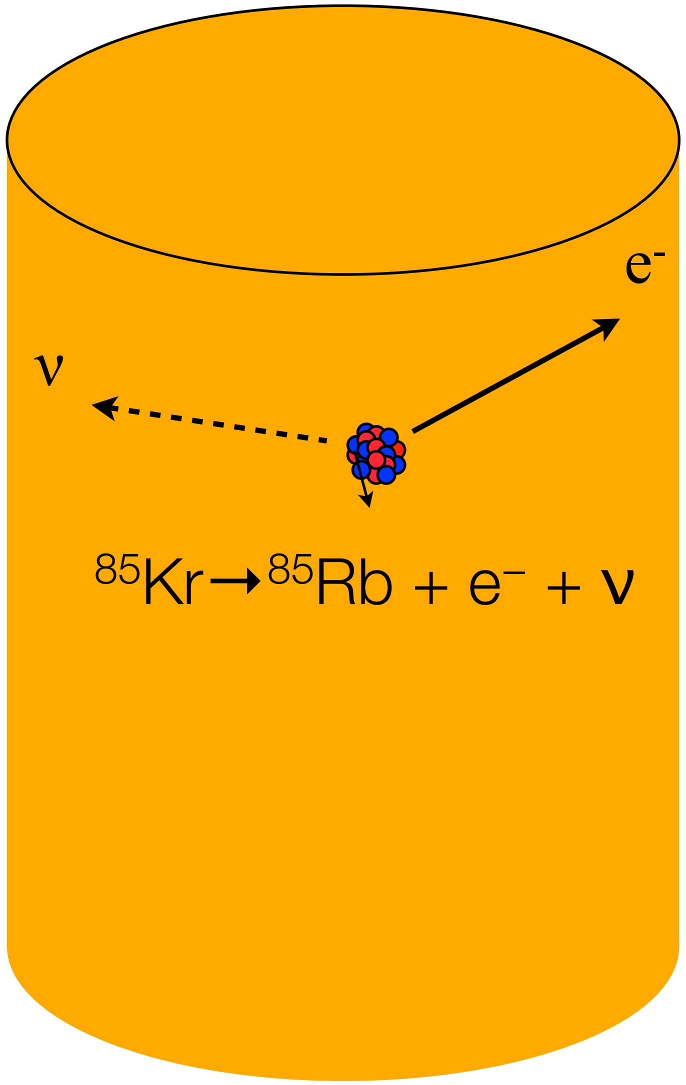
10^3 suppression of neutrons
10^9 suppression of γs

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

^{85}Kr internal background

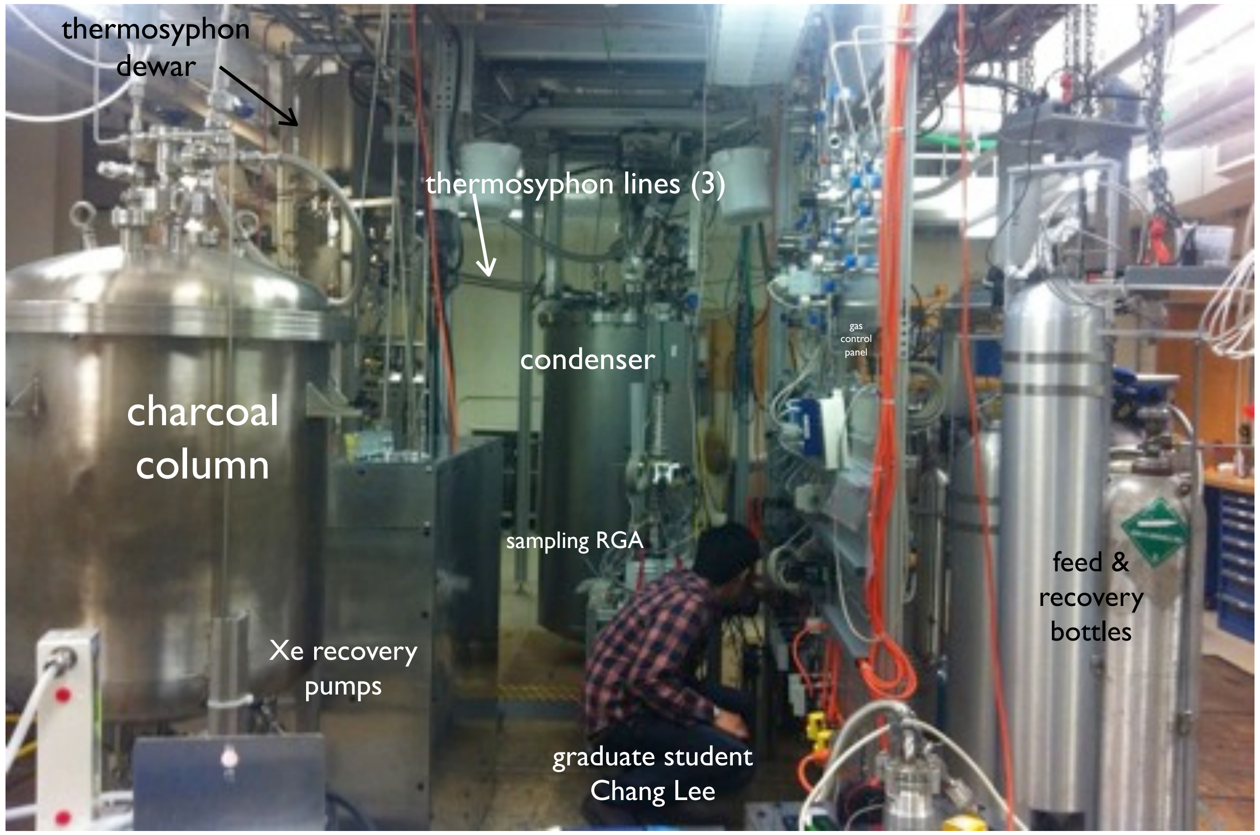
- β decay with $t_{1/2}$ =10.7 y
- Noble gas → non-reactive
- Not removed by self-shielding
- ~100 ppb in purchased Xe
  →20 ppt ~ 122 PMTs

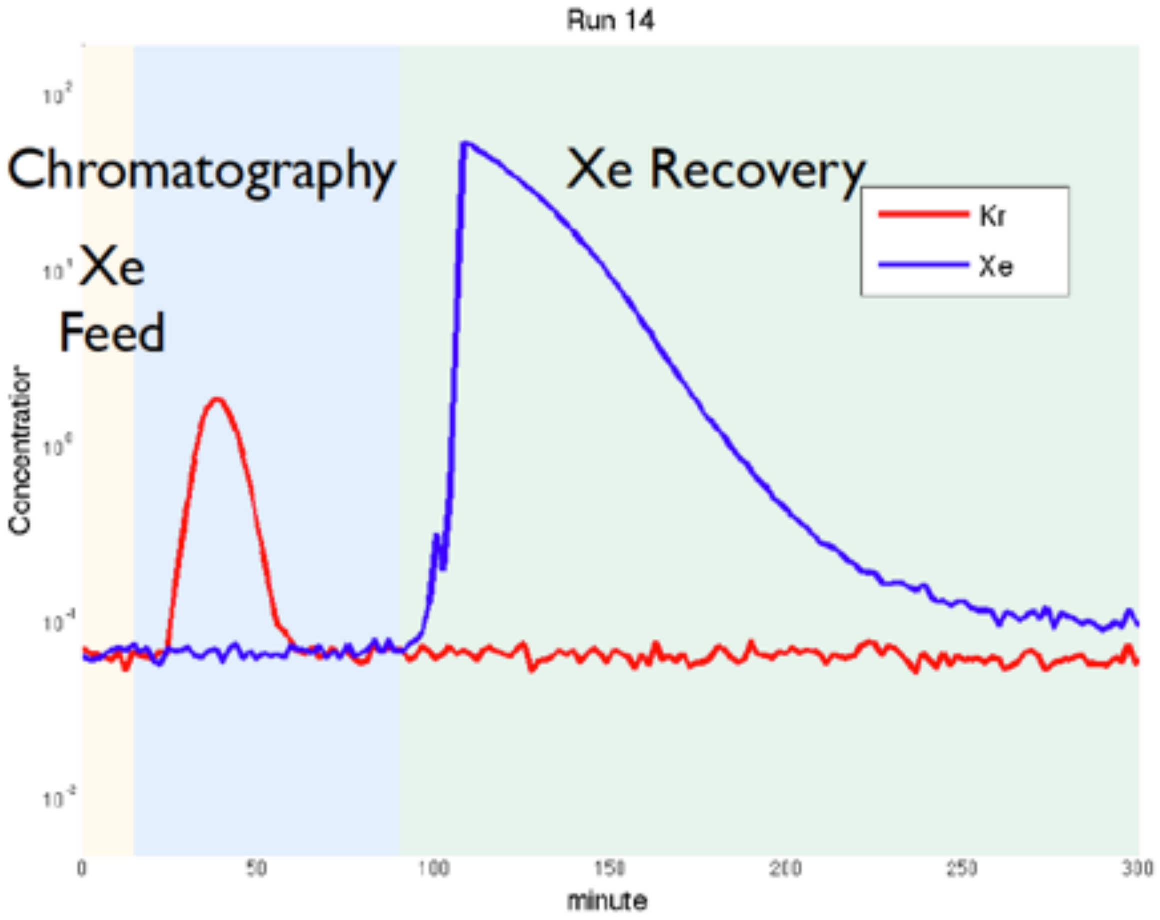
LUX goal: < 5 ppt Kr



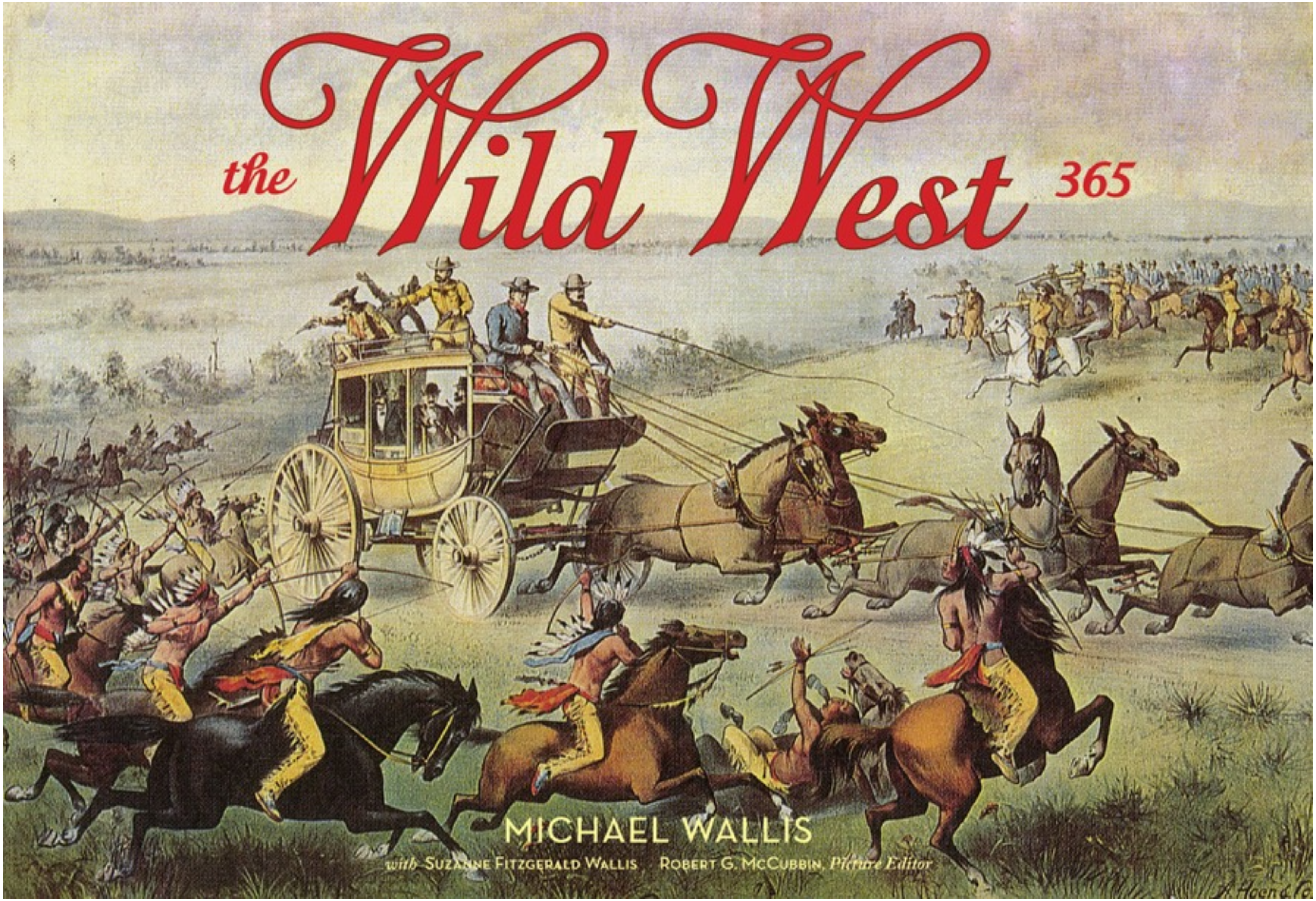
$^{85}\mathrm{Kr} \rightarrow {}^{85}\mathrm{Rb} + e^{-} + \nu$

Use gas chromatography to remove ^{85}Kr





Charcoal chromatography removal system developed and operated at Case Western
→ processed 400 kg LUX xenon from 130 ppb to 4 ppt (average of 50 kg/wk processed during production running)



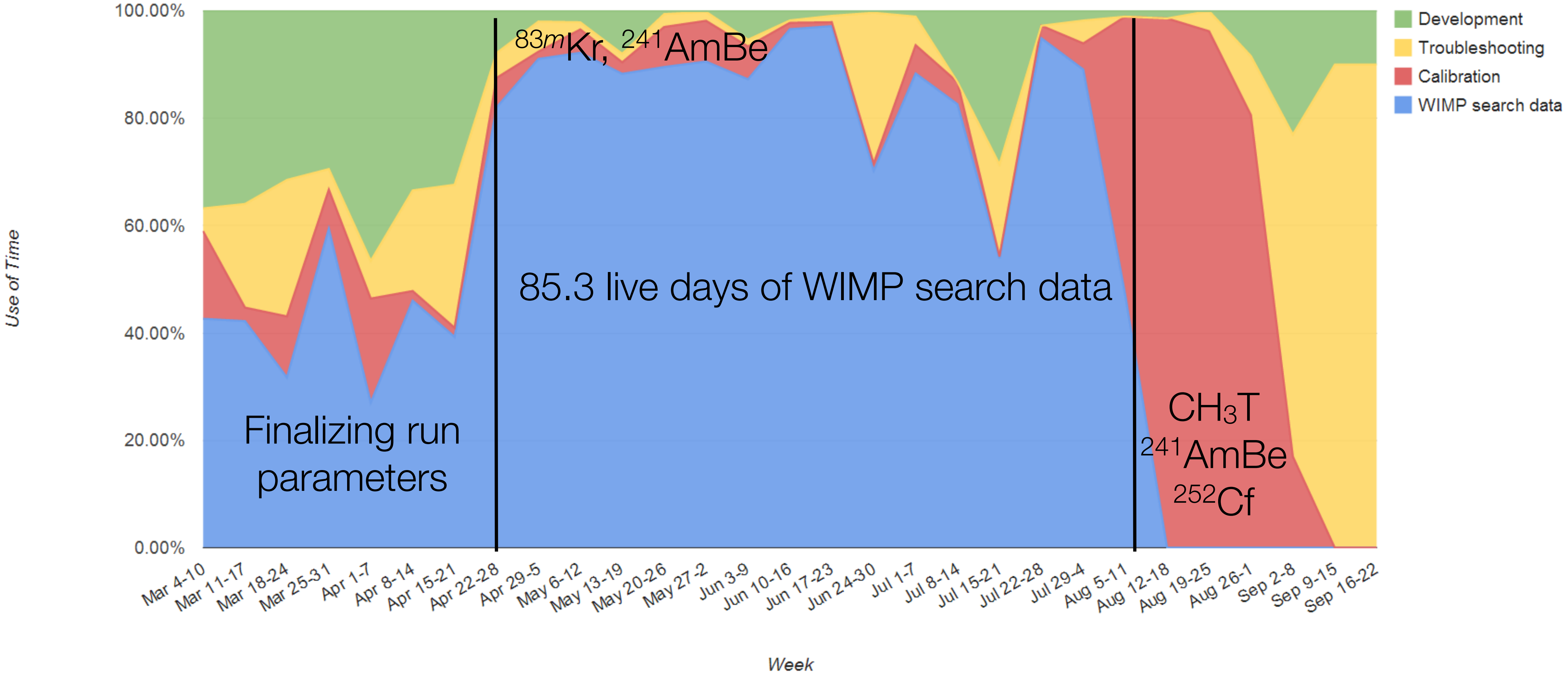
First LUX WIMP Search

D.S Akerib et al, arXiv:1310.8214, accepted for publication in PRL

> And I understood that all of these sciences were very interesting, very attractive, but that they are precise and clear in inverse proportion to their applications to the questions of life...
> -Leo Tolstoy, *Confession*

Underground operation since January, 2013

Operate with xenon gas in January 2013,
liquify xenon mid-Feb 2013!



^{83m}Kr, ^{241}AmBe

Finalizing run parameters

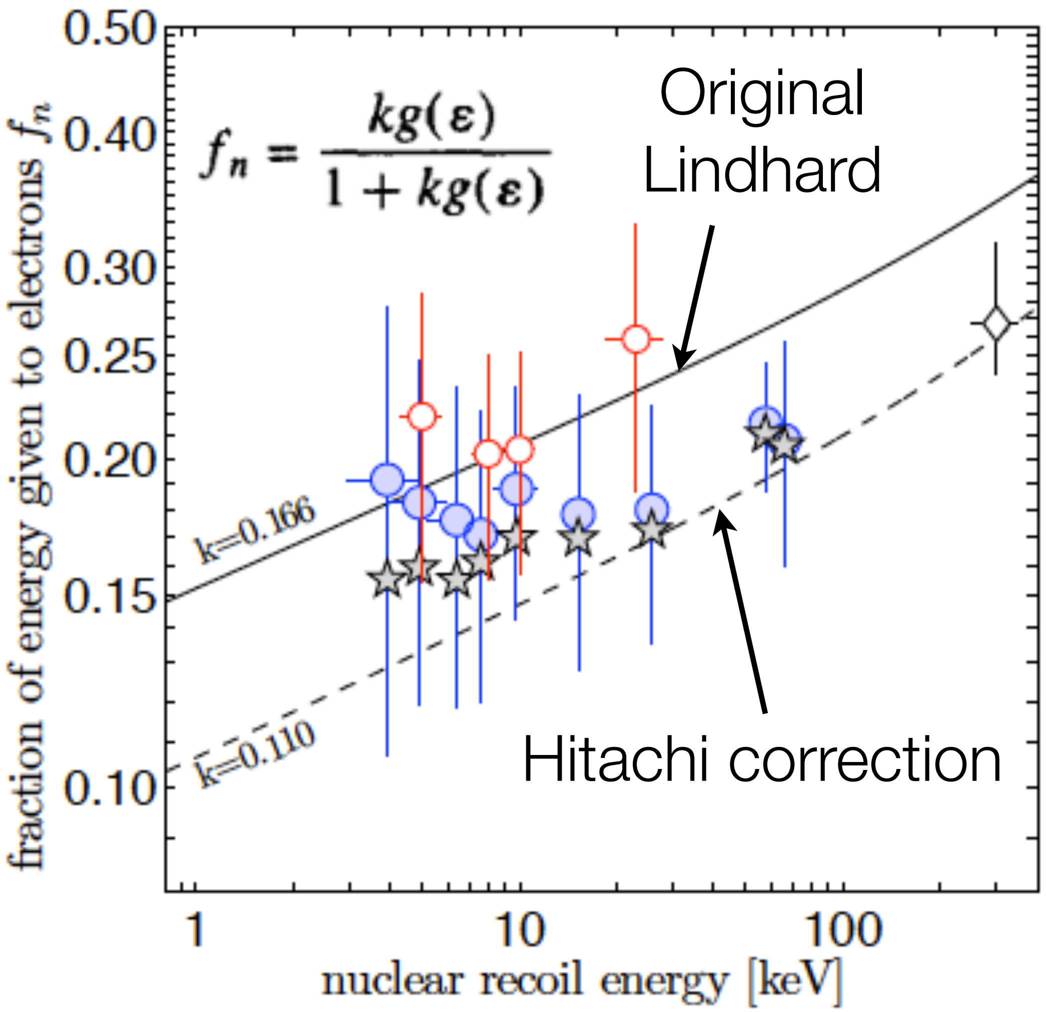
85.3 live days of WIMP search data

CH$_3$T
^{241}AmBe
^{252}Cf

WIMP search data for **non-blind** analysis collected April 21 - August 8, 2013

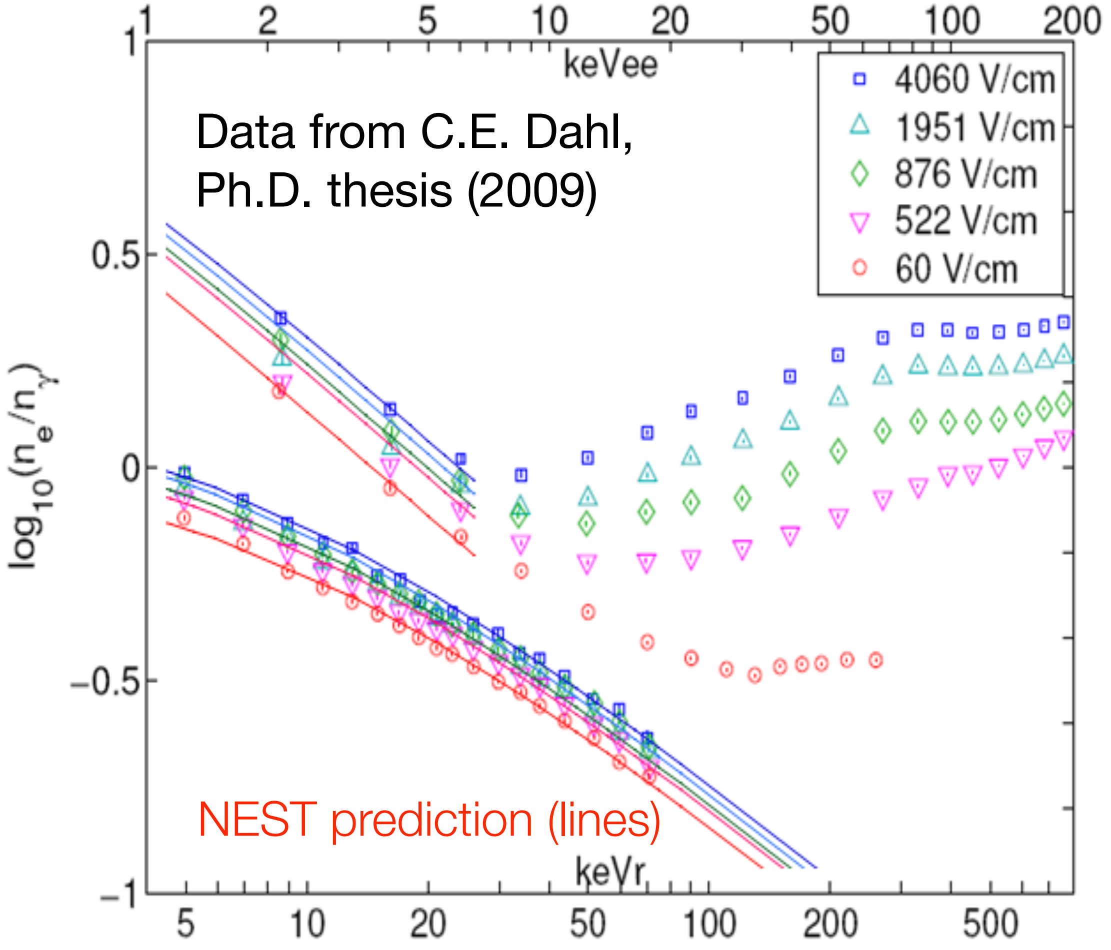
Noble Element Scintillation Technique (NEST)

$$E_{ee} = \left(n_\gamma + n_e\right) W\,,$$
$$E_{nr} = f_n^{-1}\left(n_\gamma + n_e\right) W$$



Original Lindhard

Hitachi correction



Data from C.E. Dahl, Ph.D. thesis (2009)

NEST prediction (lines)

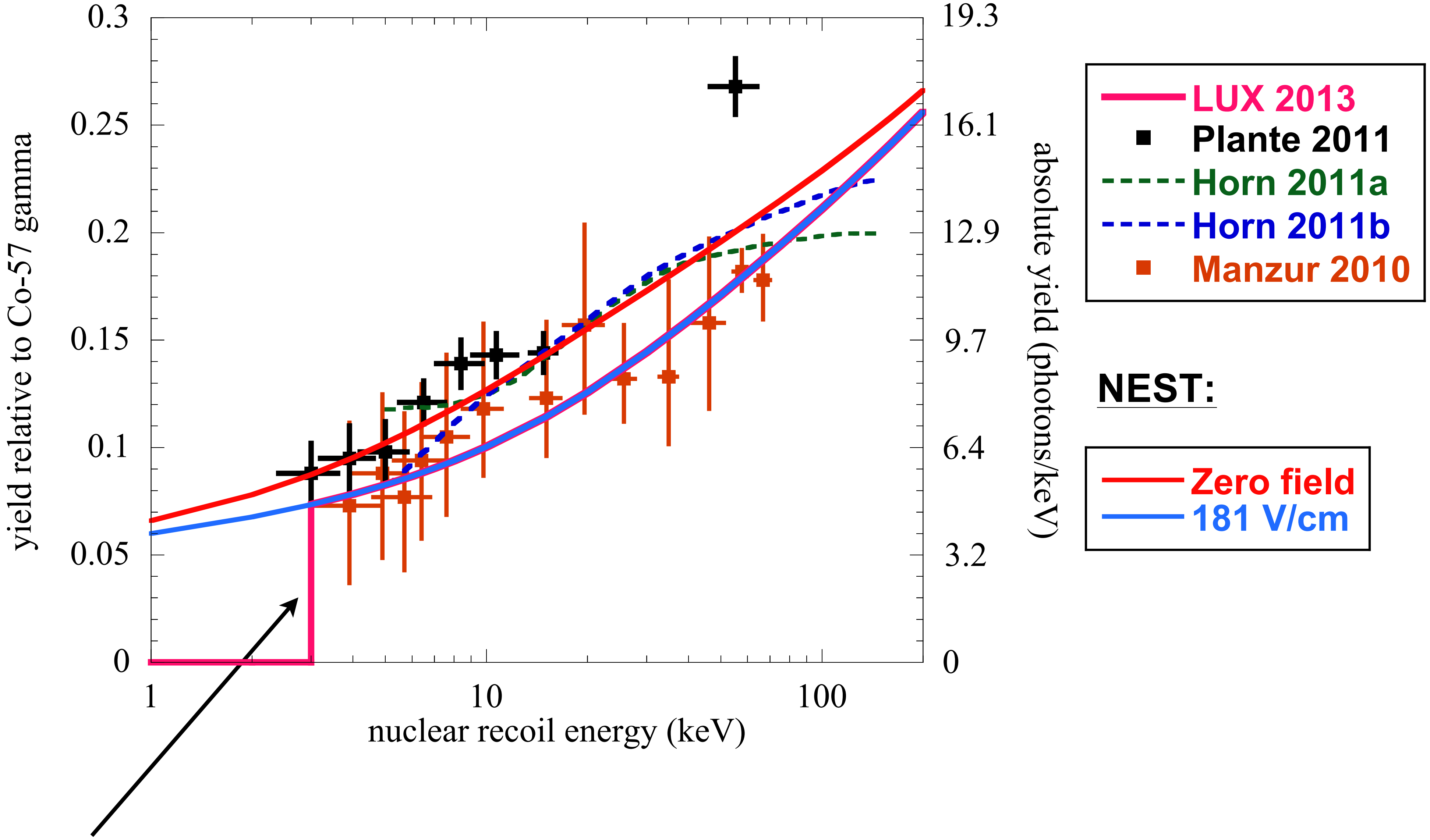
Uses full Lindhard model with Hitachi linear energy transfer (LET)

Reproduces NR discrimination data

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

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

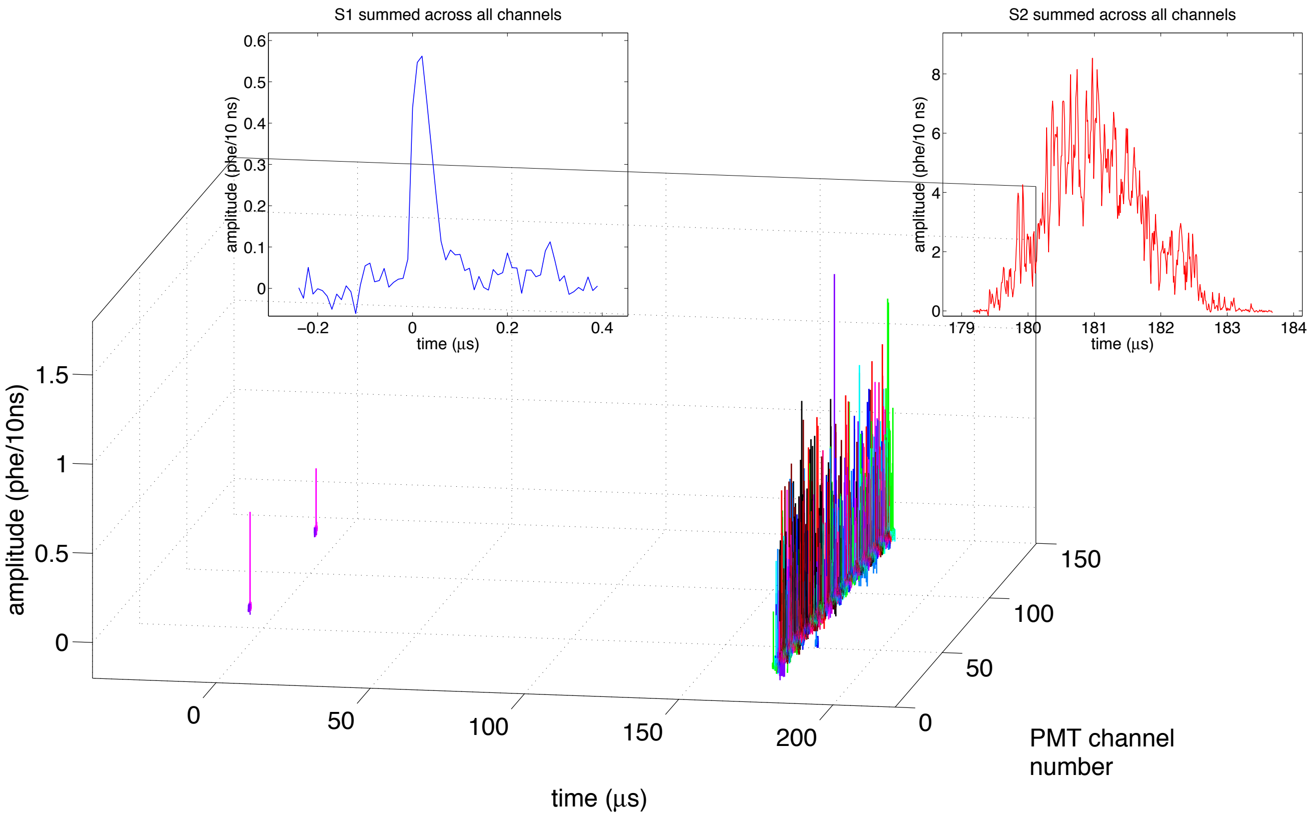
Light and charge yields



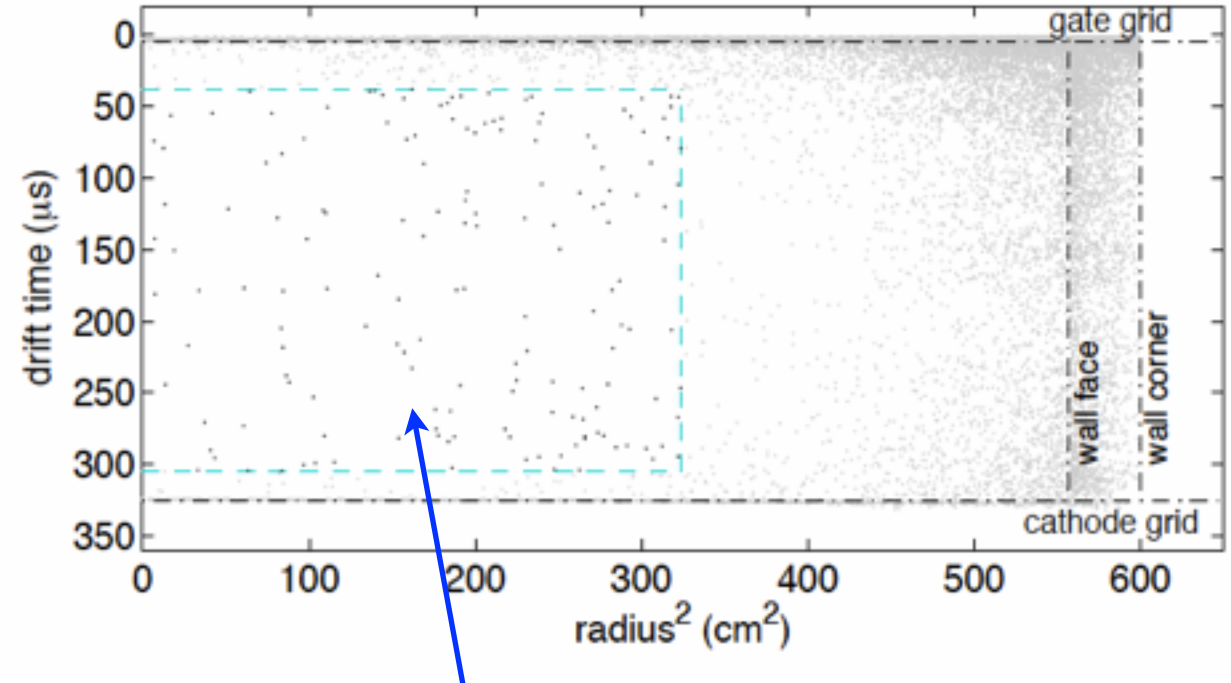
Set hard threshold at 3 keVnr
Very conservative!

Photon detection efficiency: 0.14
Charge yield: 26 phe/e^-

Event selection



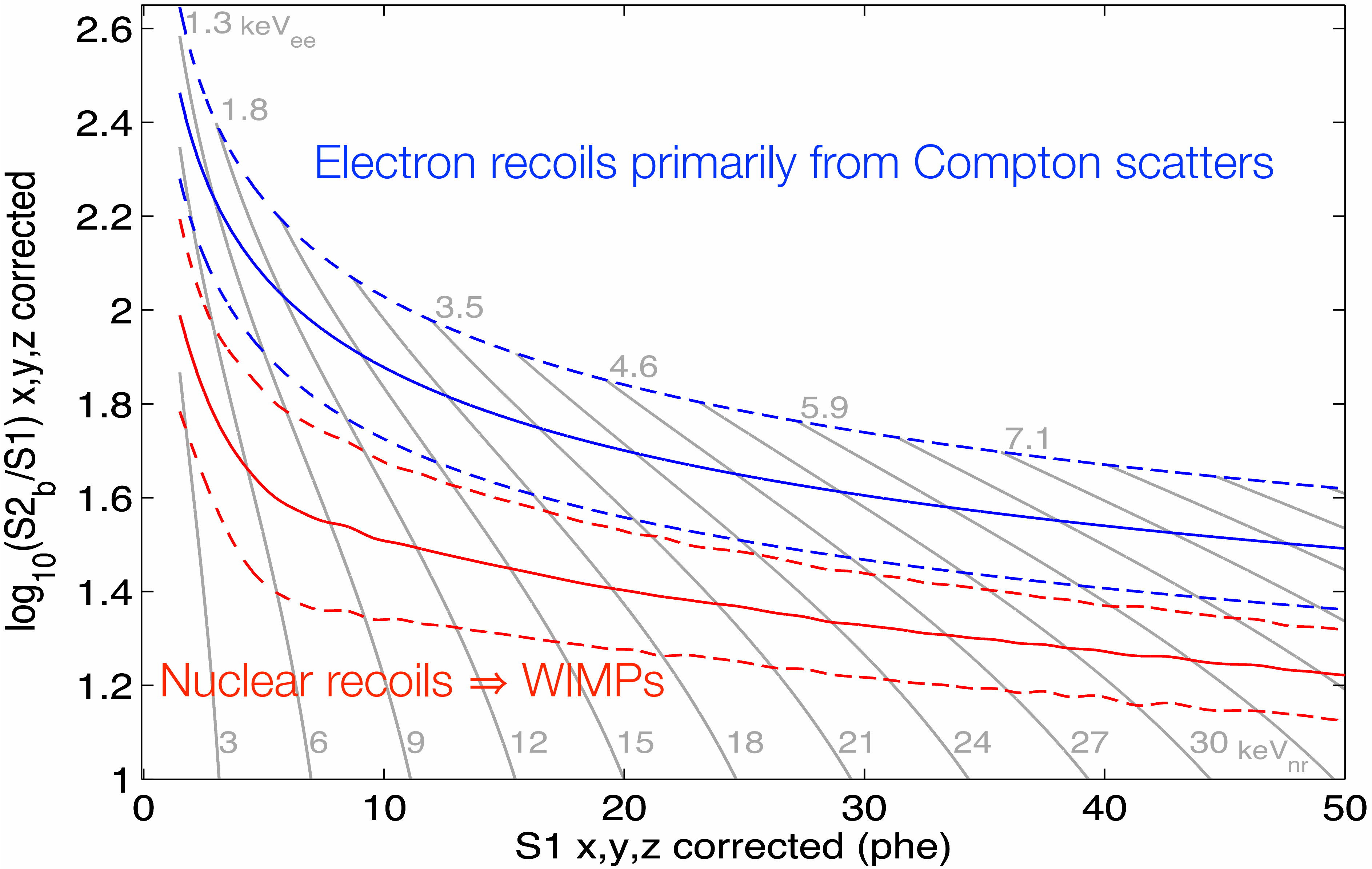
Define fiducial volume r < 18 cm,
7 < z < 47 cm,
corresponding to 118±6 kg



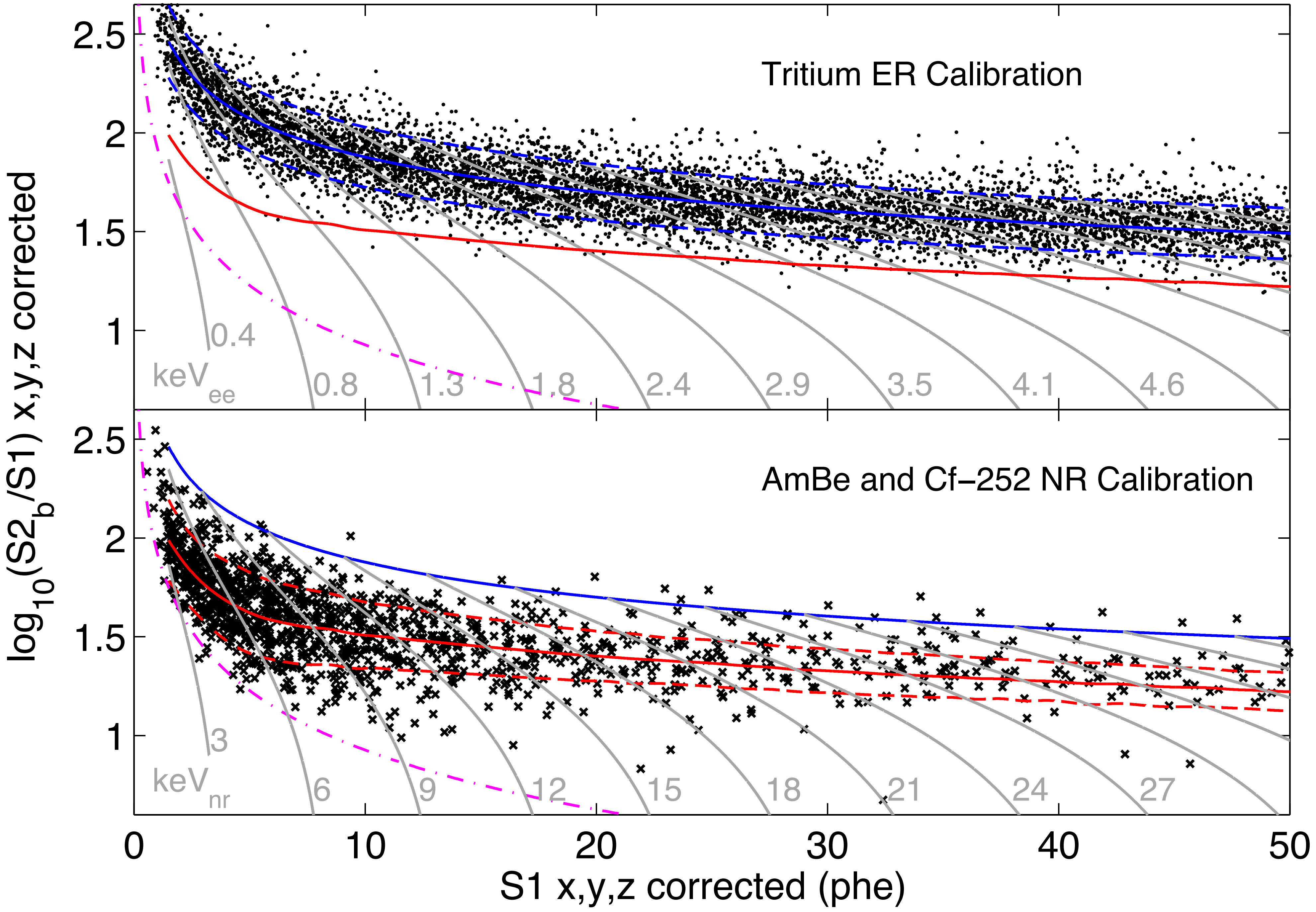
160 candidate events after all selection reqs applied

Requirements for WIMP search candidate events
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

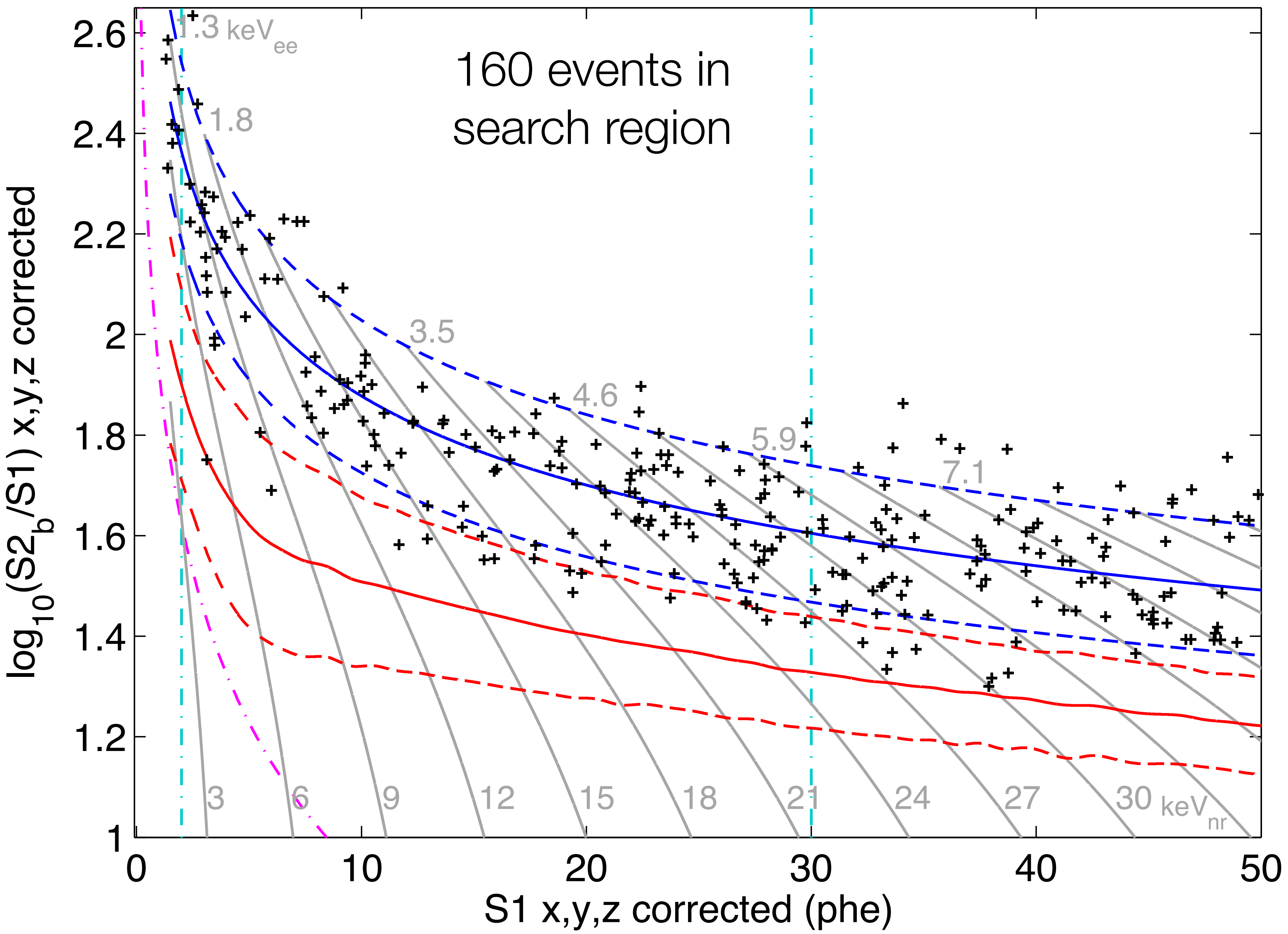
Separation of electronic and nuclear recoils with charge to light ratio



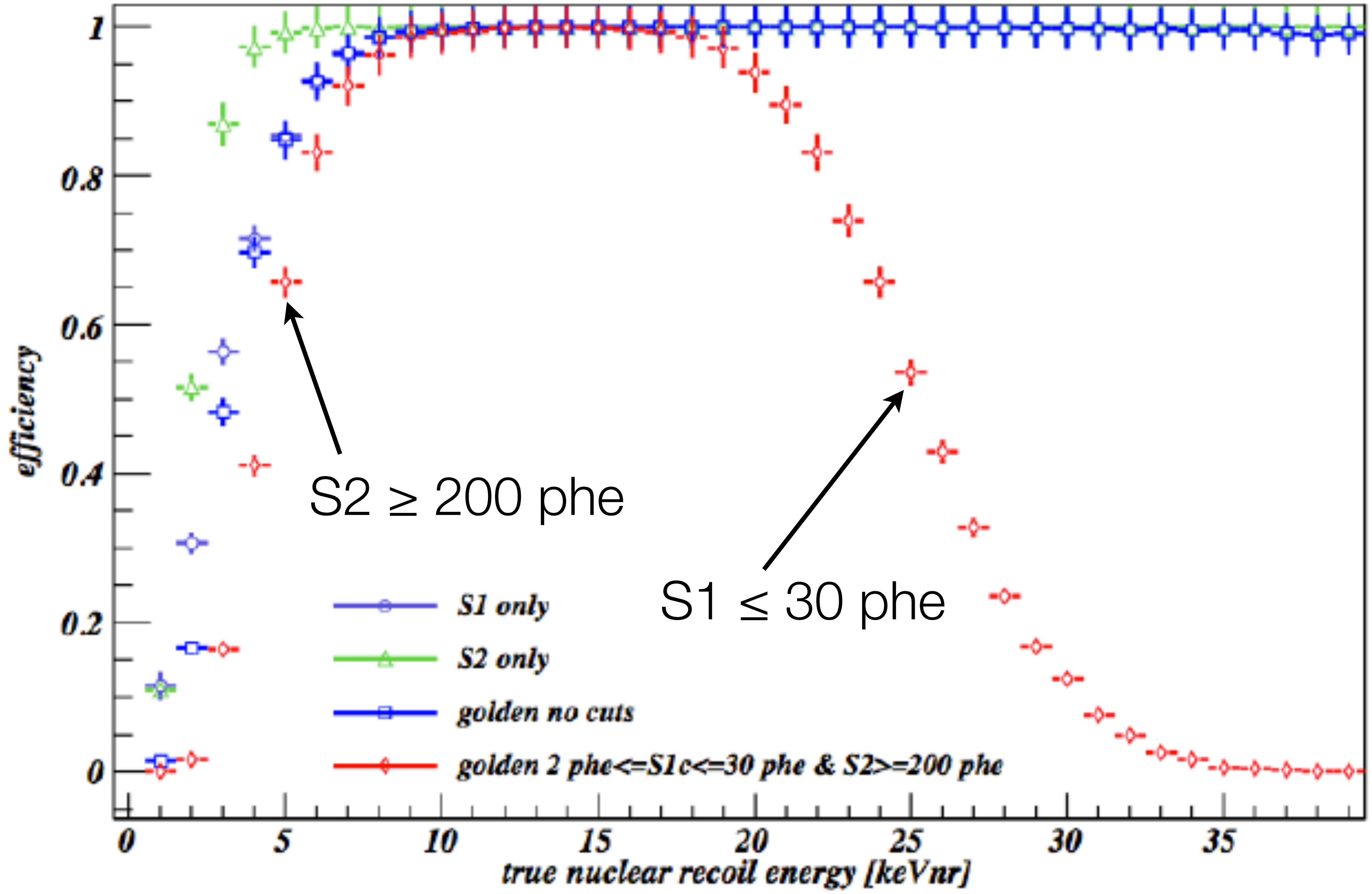
Electronic and nuclear recoil calibrations



WIMP search data, charge to light ratio



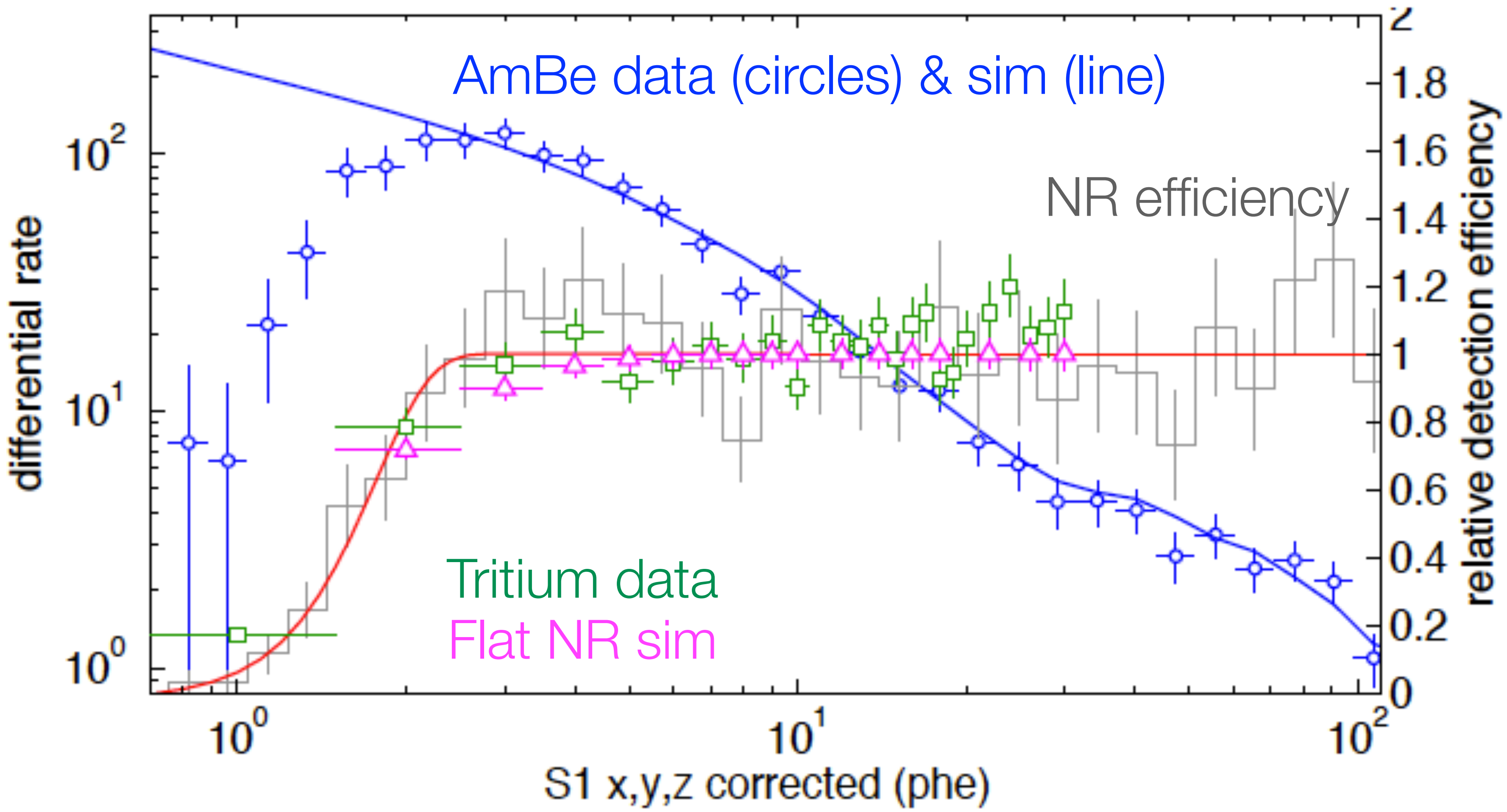
Efficiency of pulse finding and selection



S2 ≥ 200 phe

S1 ≤ 30 phe

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)

Use an extended likelihood in WIMP search

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

Discriminant between ER/NR

Energy

Discriminant against external/internal radiation

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

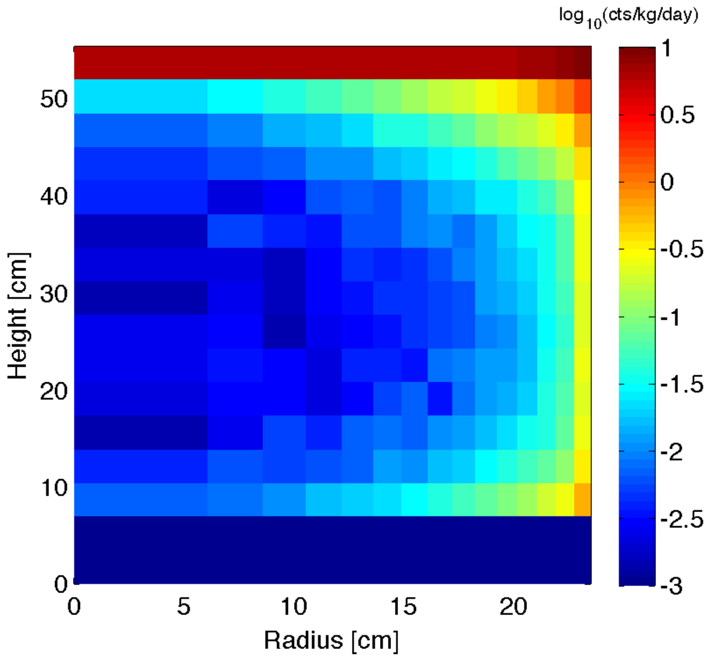
Parameter of interest: N_S

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

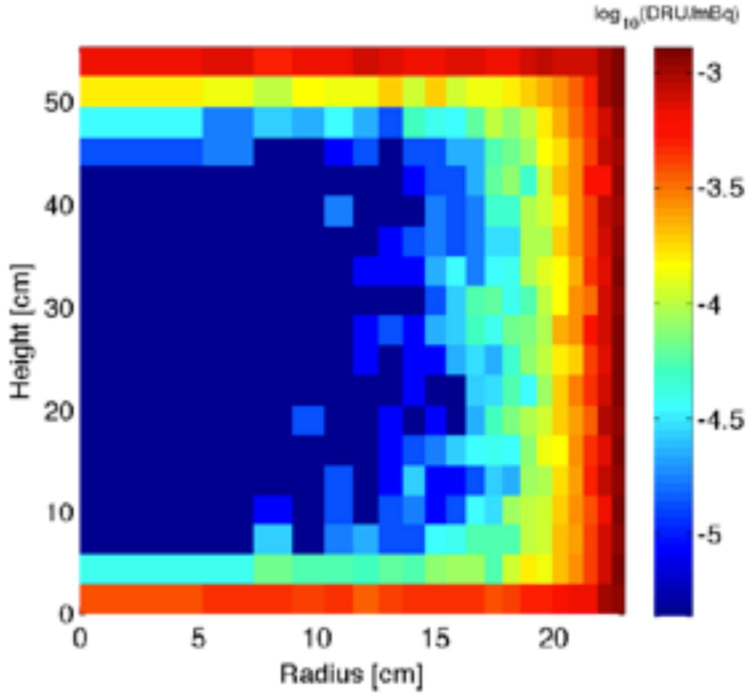
Gaussian constrain to within 30% of the predicted rates

Backgrounds

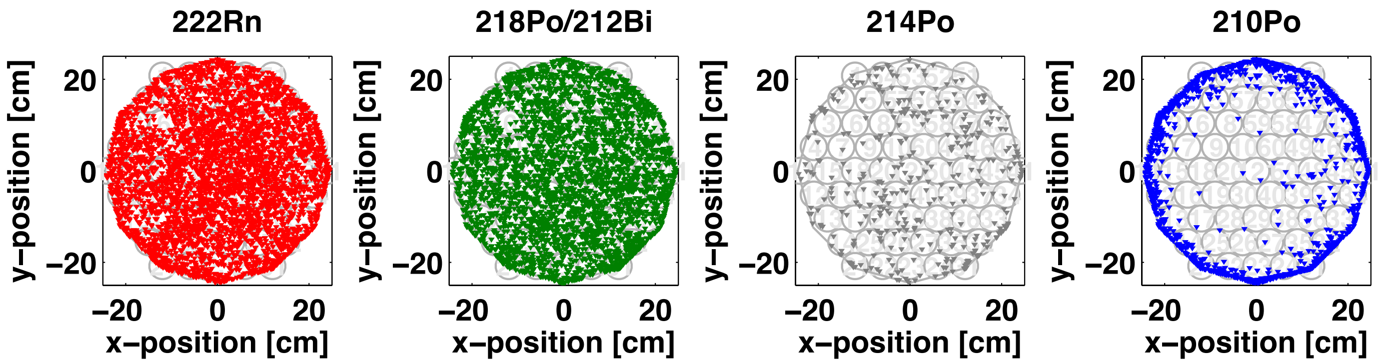
1) Internal radioactivity, predicted by simulation/screening → 129 events



2) Cosmogenically-activated ^{127}Xe ($t_{½}$ = 36.5d) → 15 events



3) ^{214}Pb (observe 18 mHz steady rate of ^{222}Rn in detector) and residual ^{85}Kr (4 ppt) → 10 events



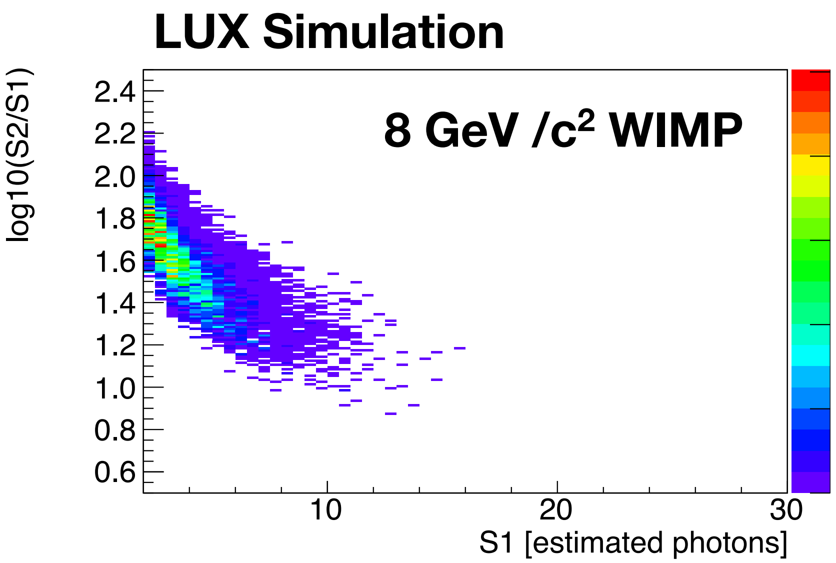
^{210}Po rate reflects ^{210}Pb plate-out on surfaces prior to underground deployment

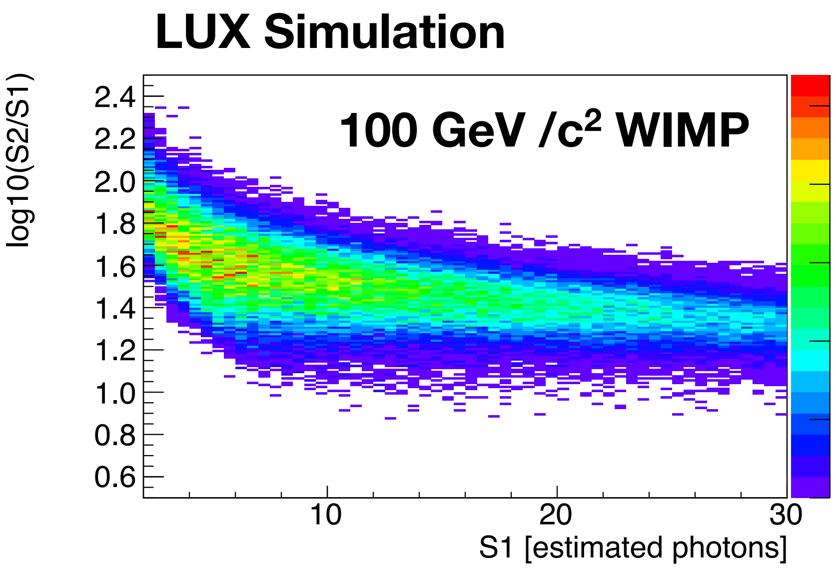
Use simulation in final model of WIMP signal

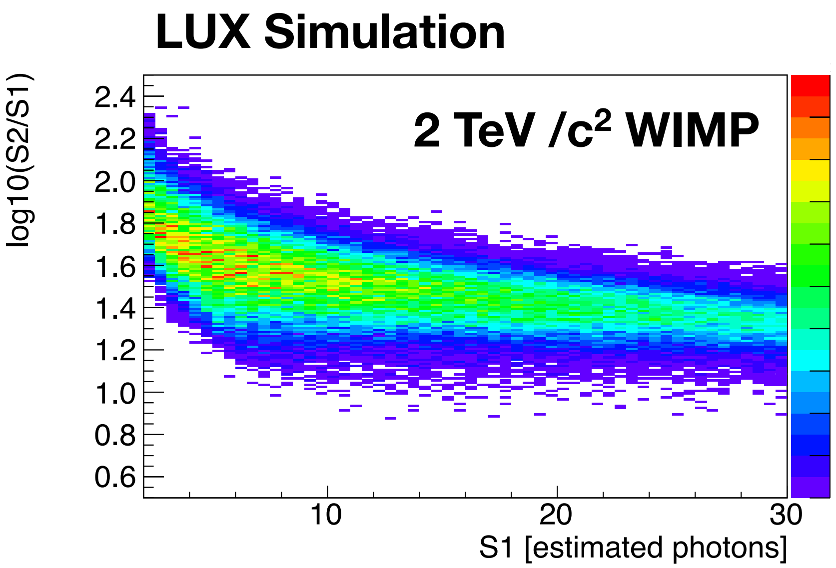
$$P_s(log_{10}(S2/S1)|S1)P_s(E_{NR}(S1))P_s(r)P_s(z)$$

Model as uniform in (r^2,z)

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


LUX Simulation

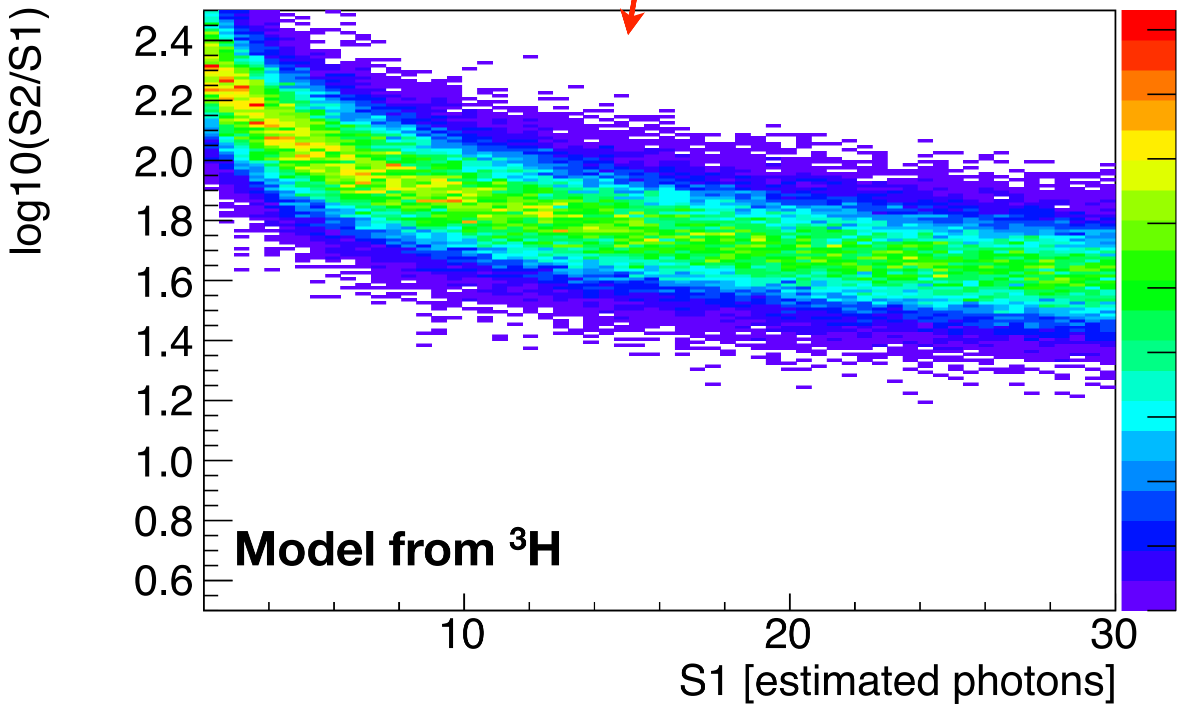

LUX Simulation

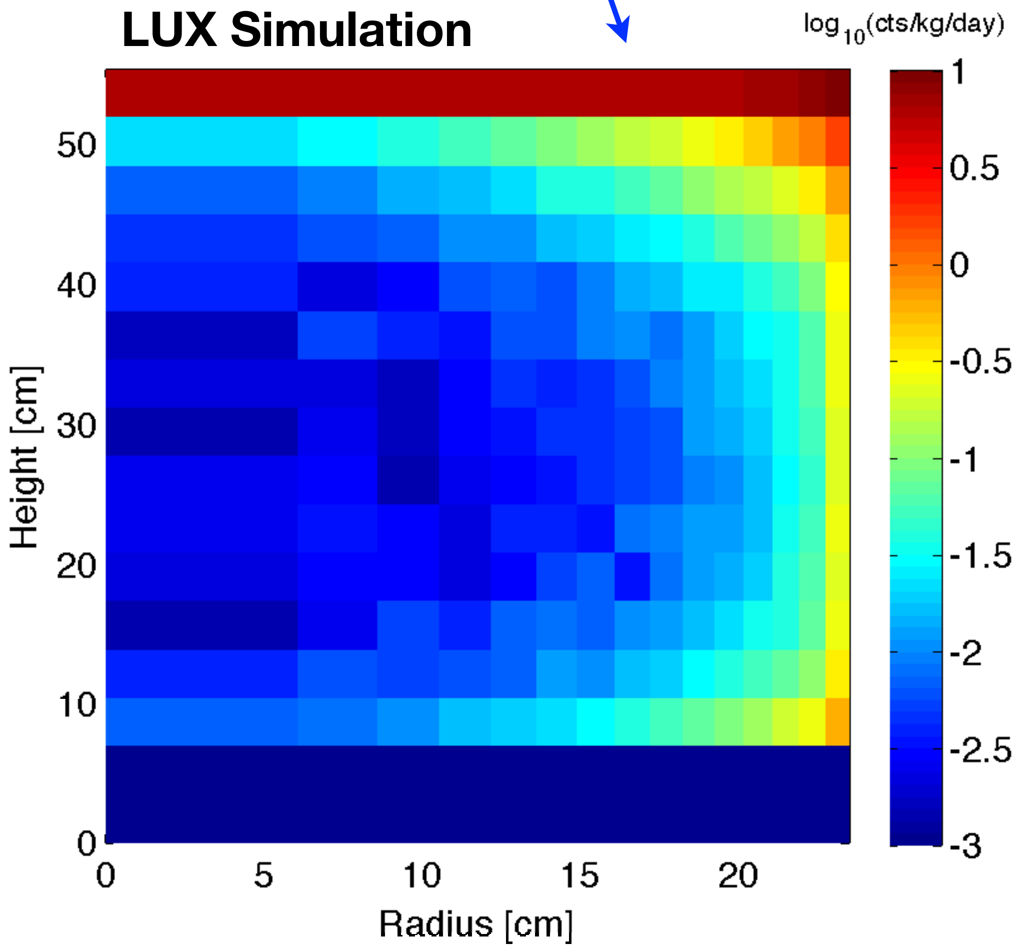

LUX Simulation

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



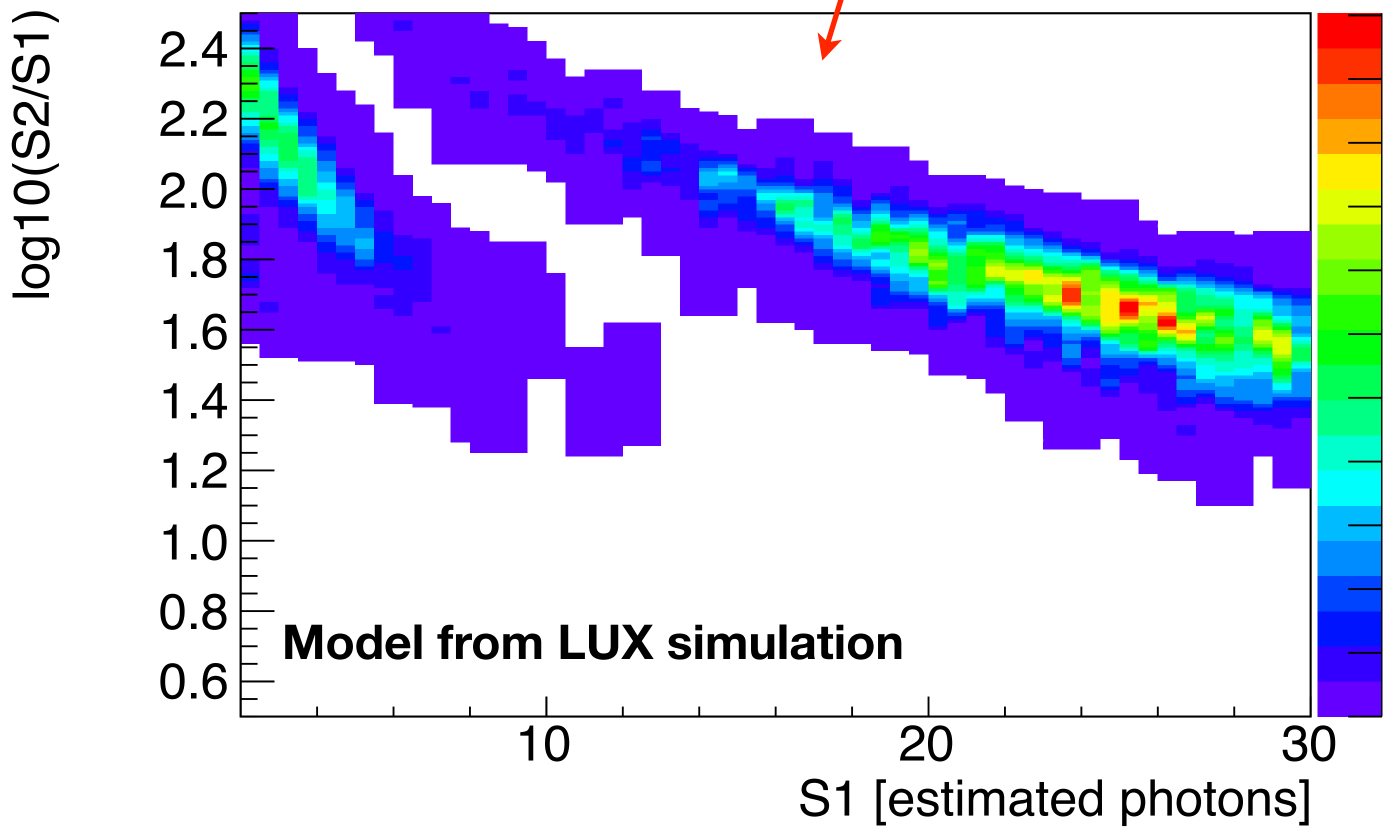


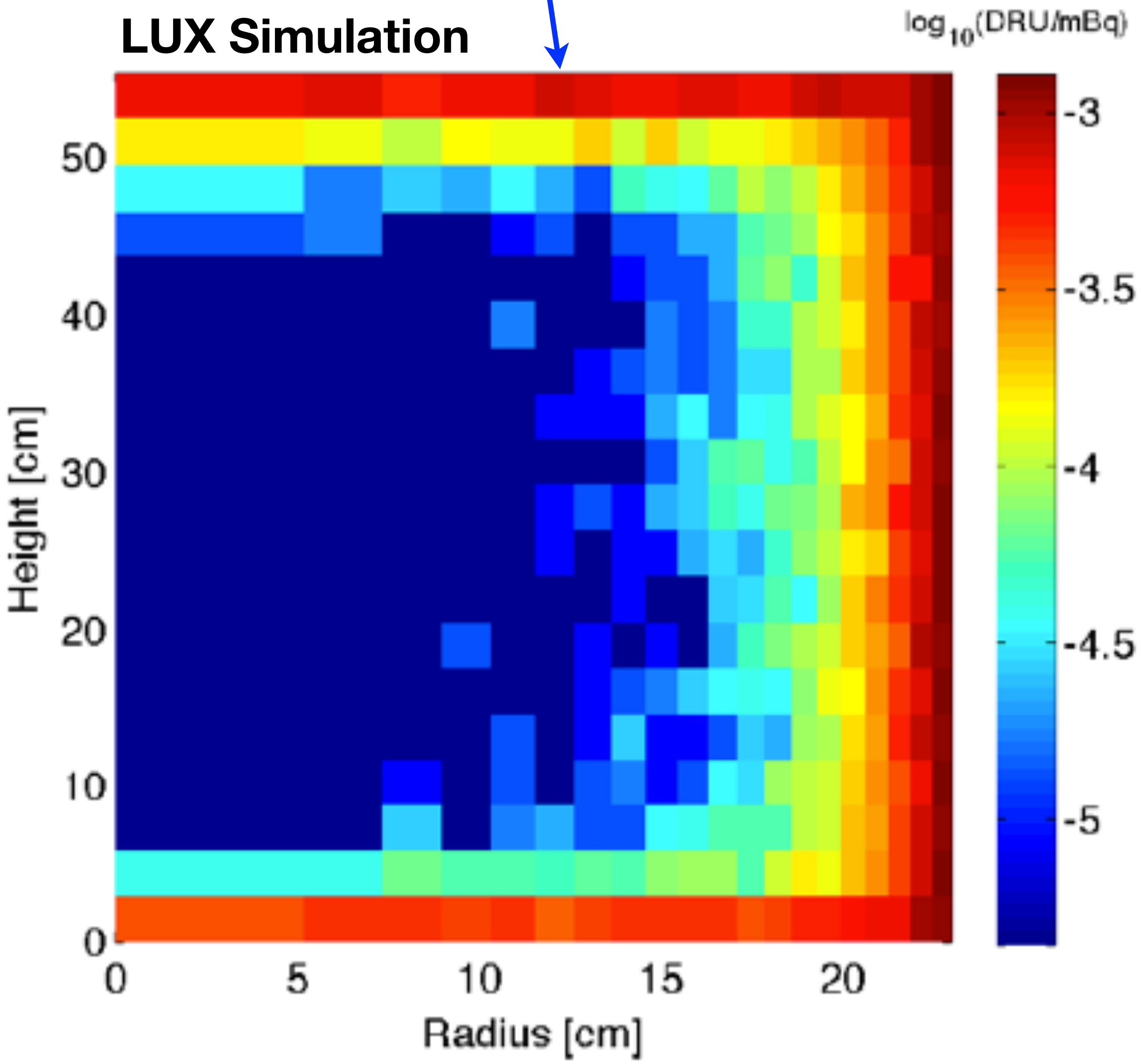
Predict 129 events in WIMP search data

^{127}Xe model

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

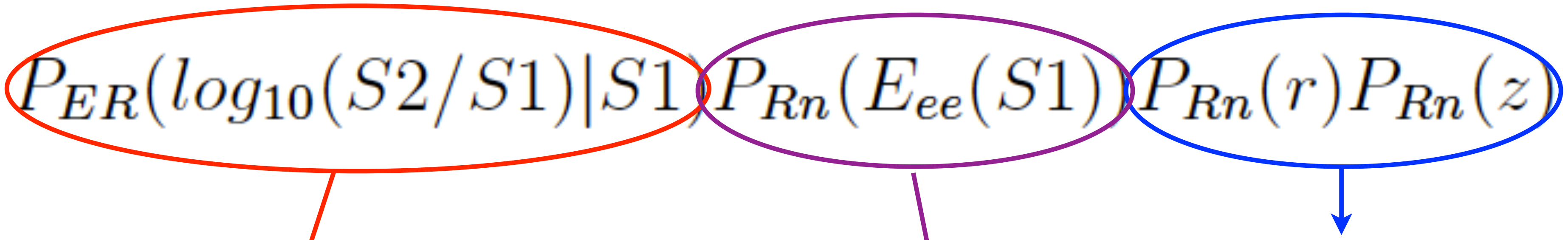
Again use simulation to model pdfs, includes resolution and efficiencies





Predict 15 events in WIMP search region

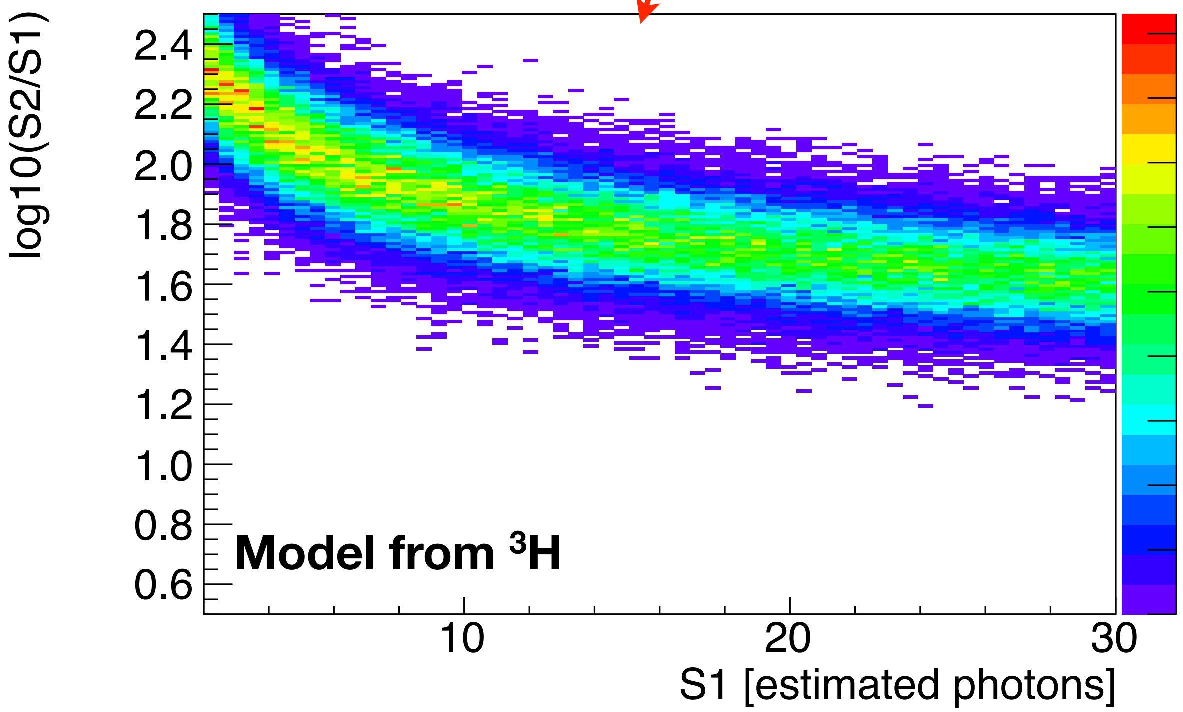
^{214}Pb/^{85}Kr model

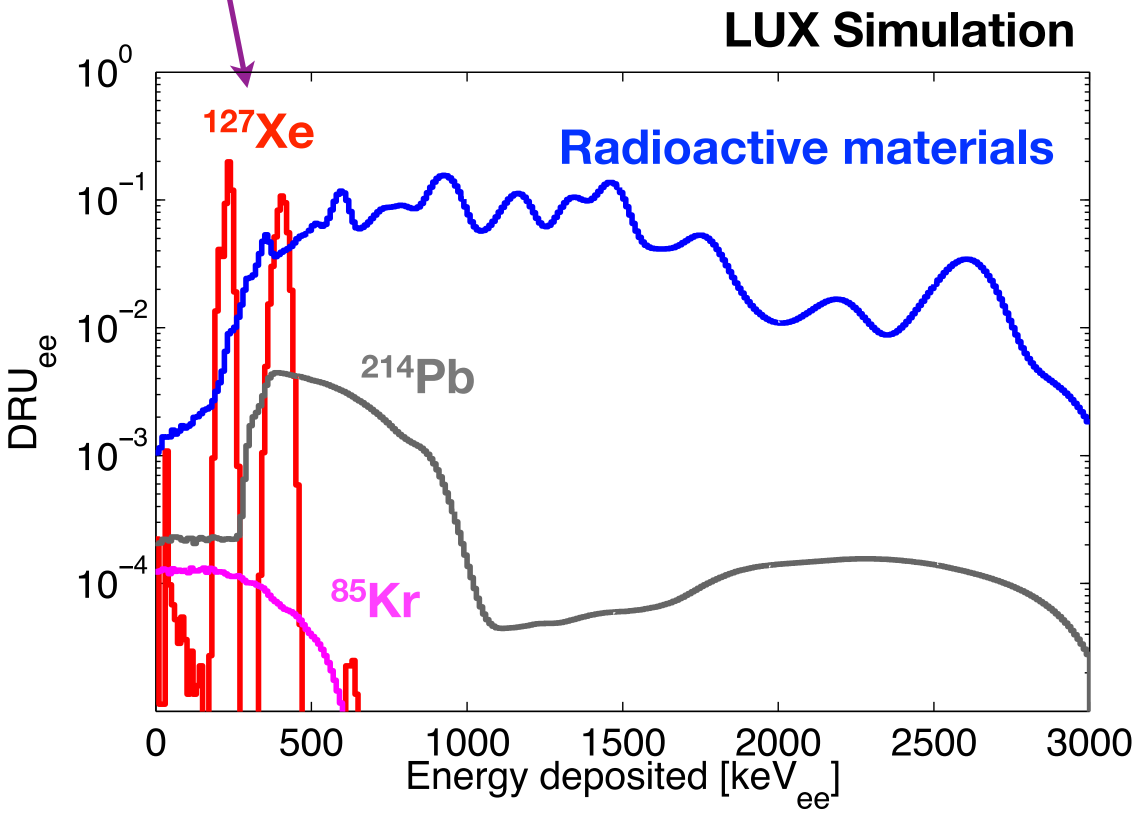


$$P_{ER}(log_{10}(S2/S1)|S1)P_{Rn}(E_{ee}(S1))P_{Rn}(r)P_{Rn}(z)$$

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

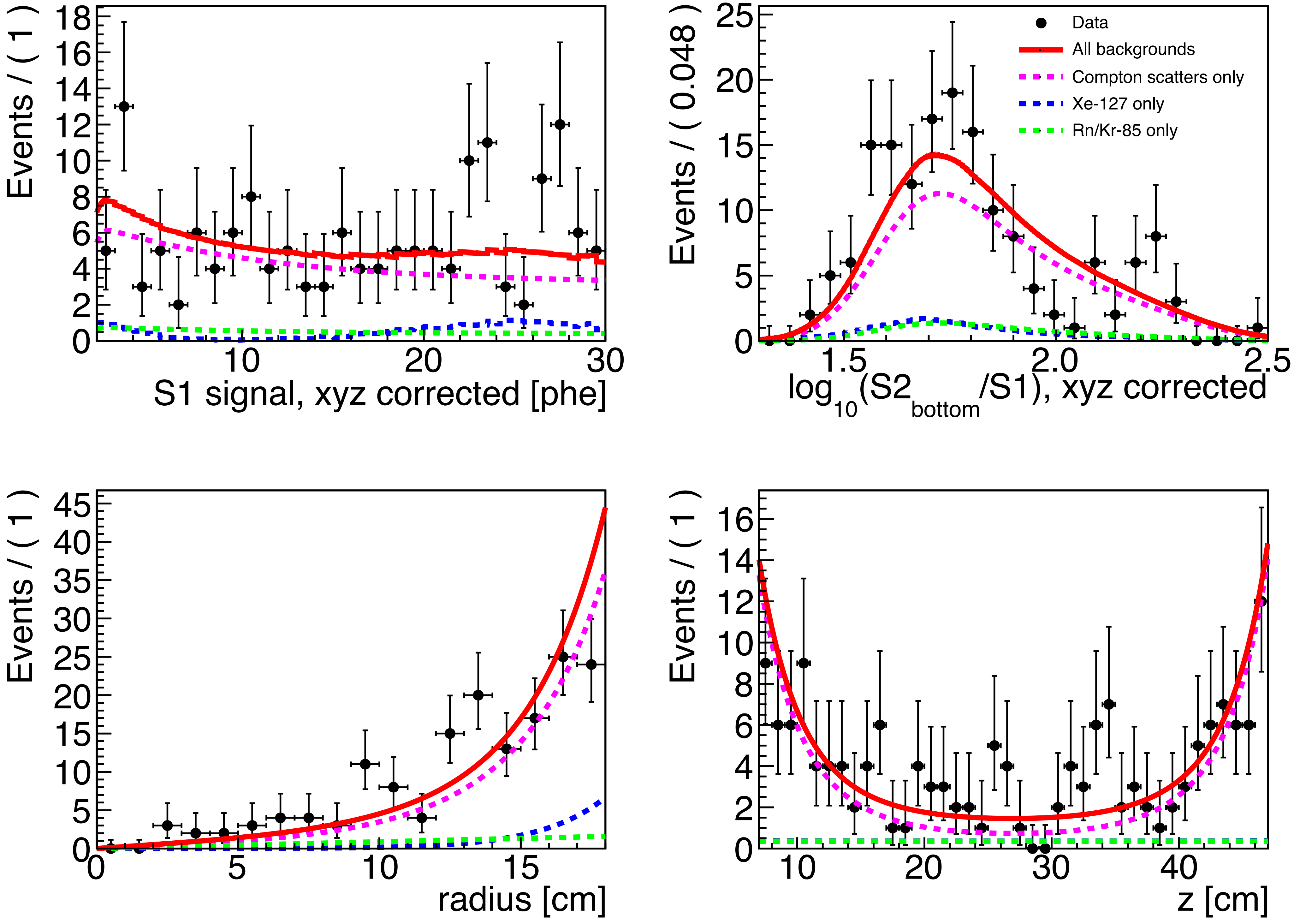
Model as uniform in (r^2,z)





Predict 10 events in WIMP search region

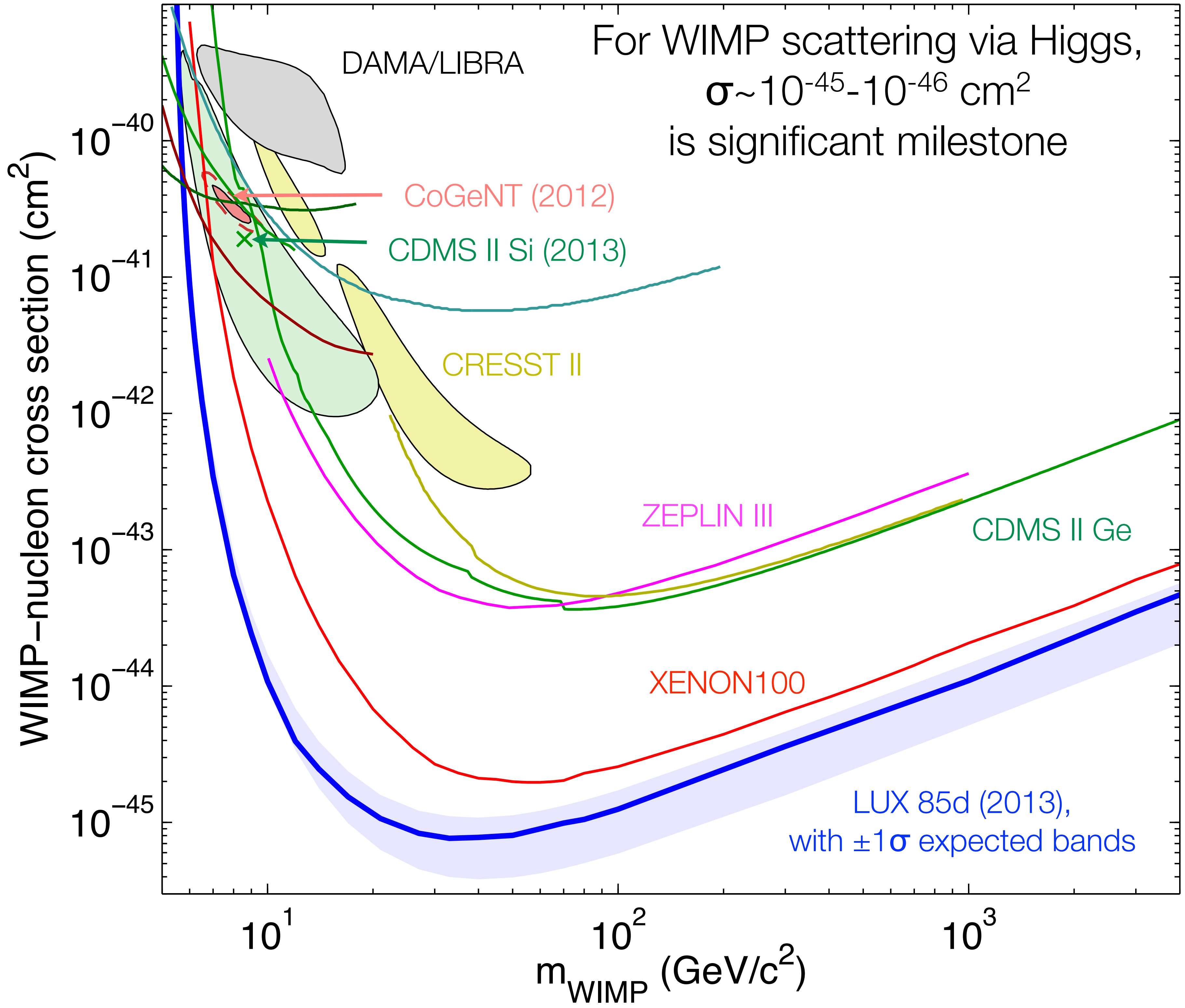
Fit projections



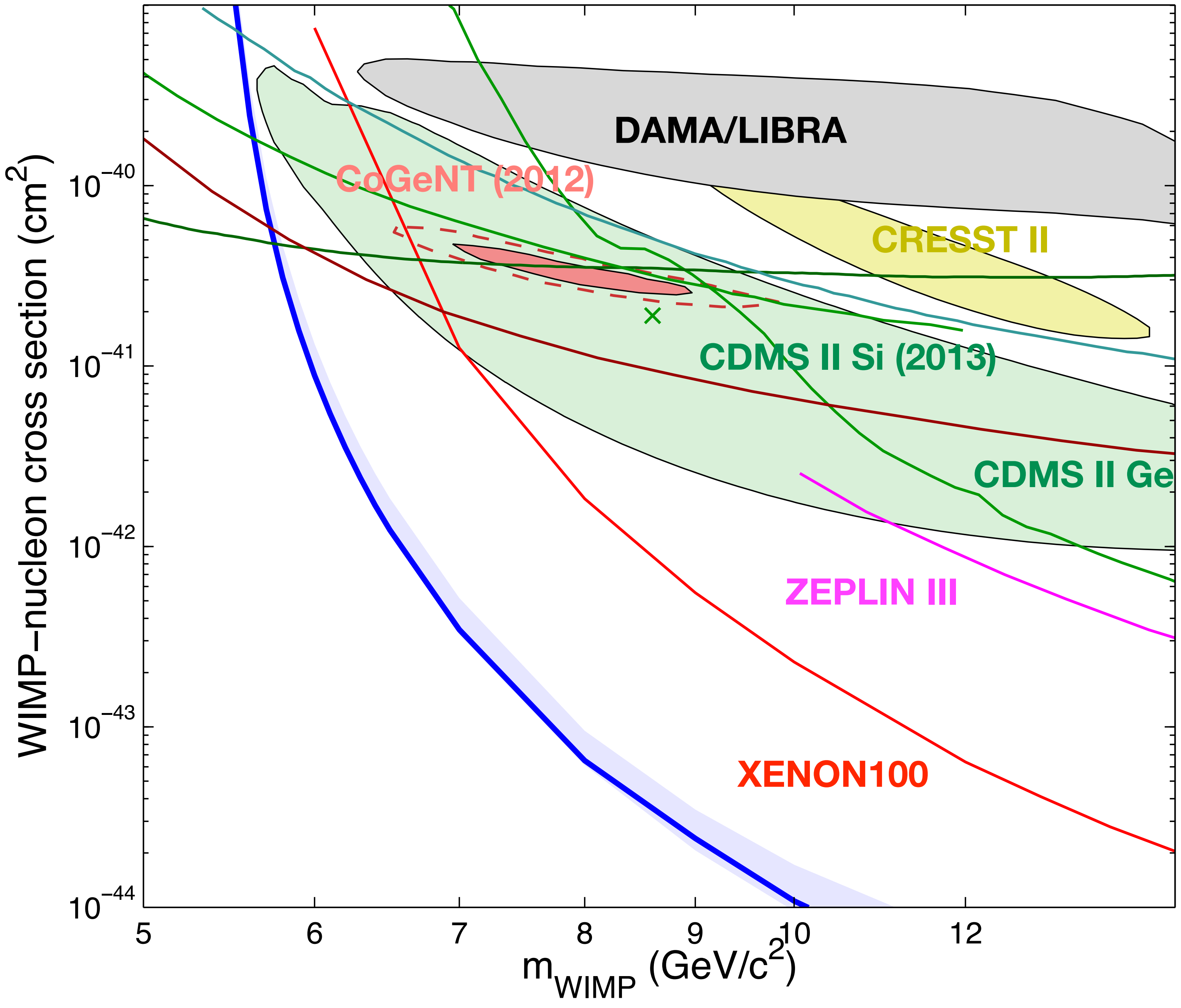
Estimated background rates

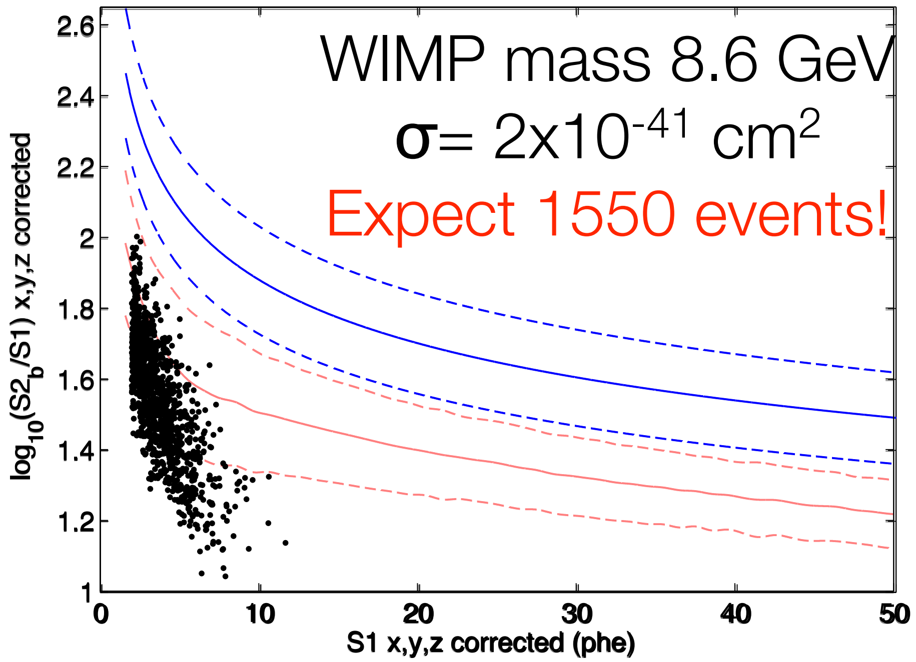
Background Component	Source	10^{-3} [evts/keVee/kg/day]
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	222Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{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	$3.1 \pm 0.2_{stat}$

First WIMP search results



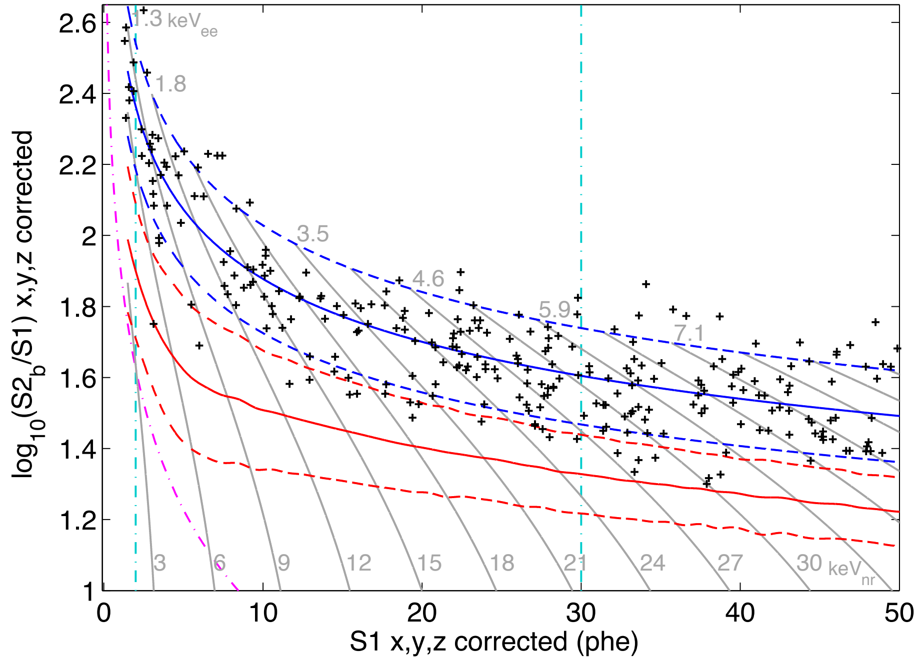
Low mass WIMP limit



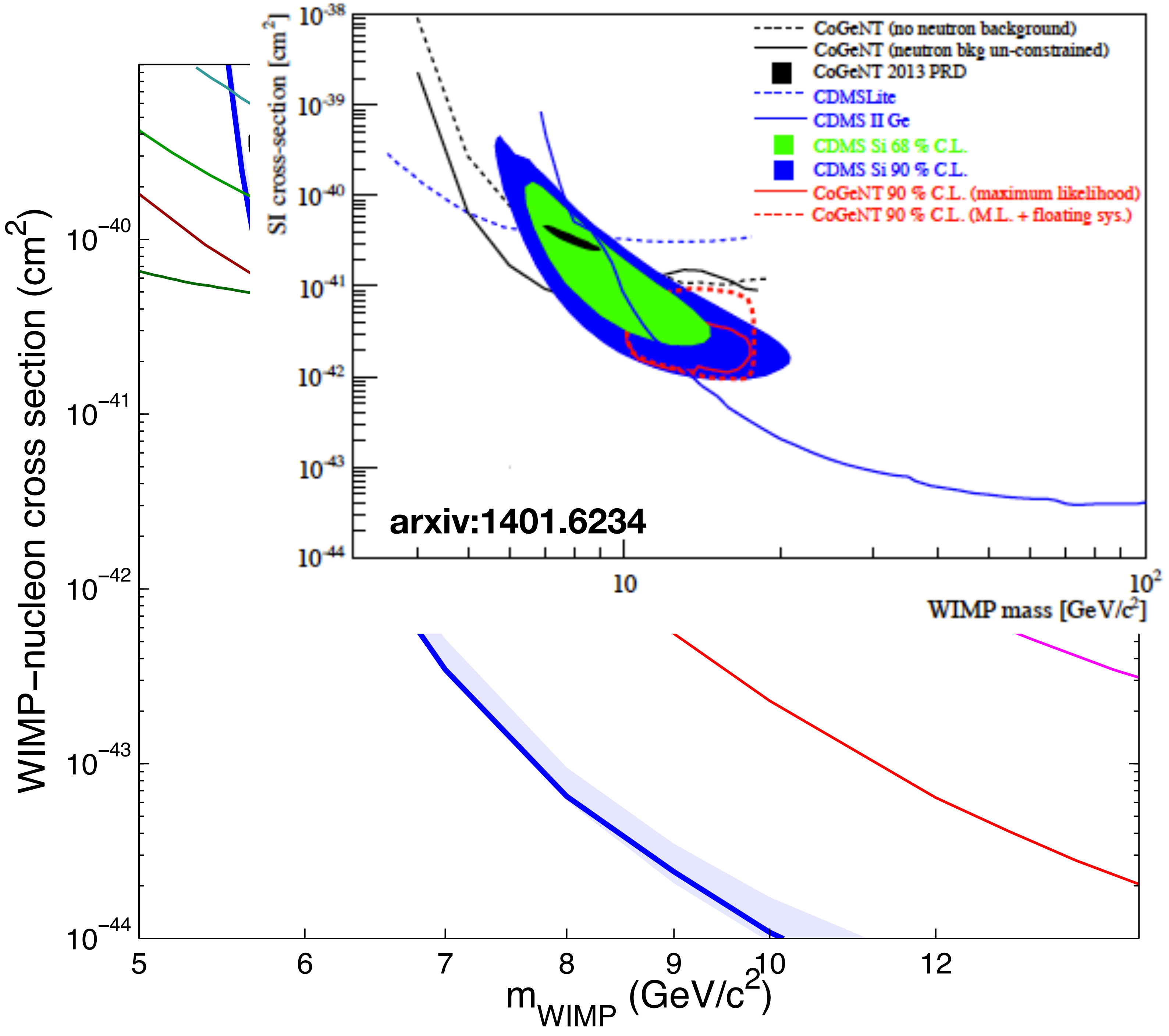

WIMP mass 8.6 GeV

$\sigma = 2\times10^{-41}$ cm^2

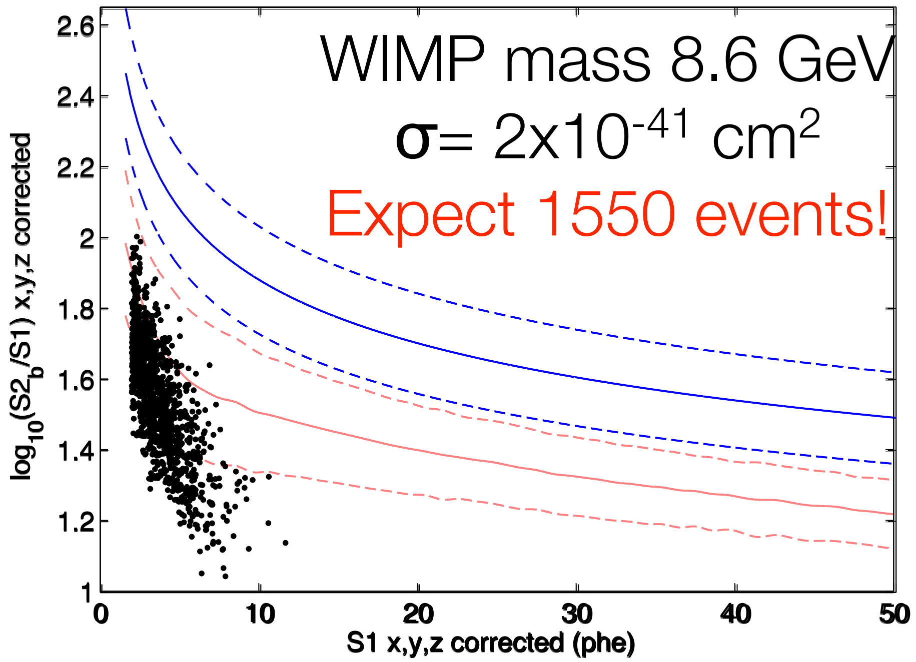
Expect 1550 events!



Low mass WIMP limit



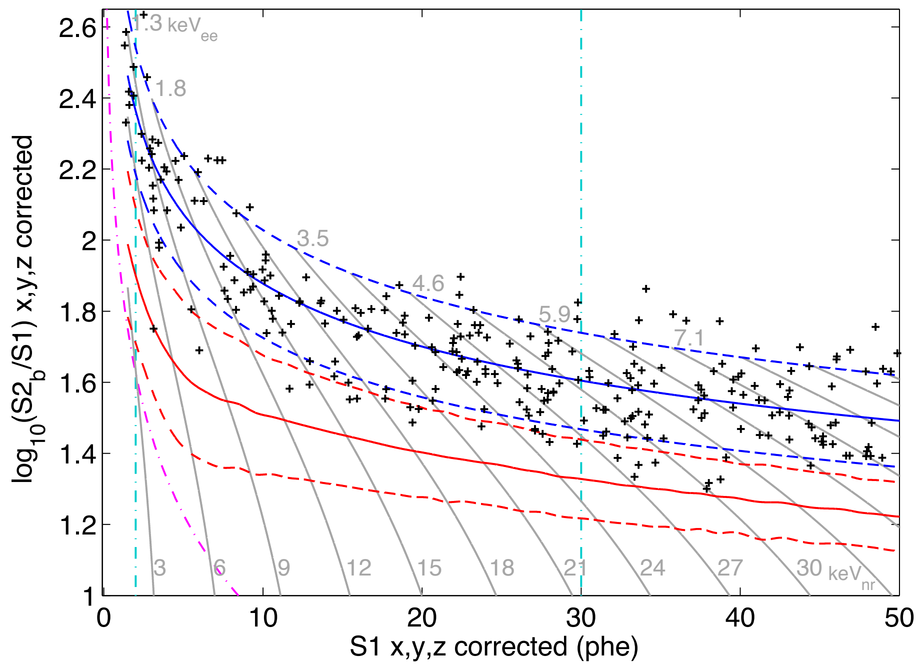
arxiv:1401.6234



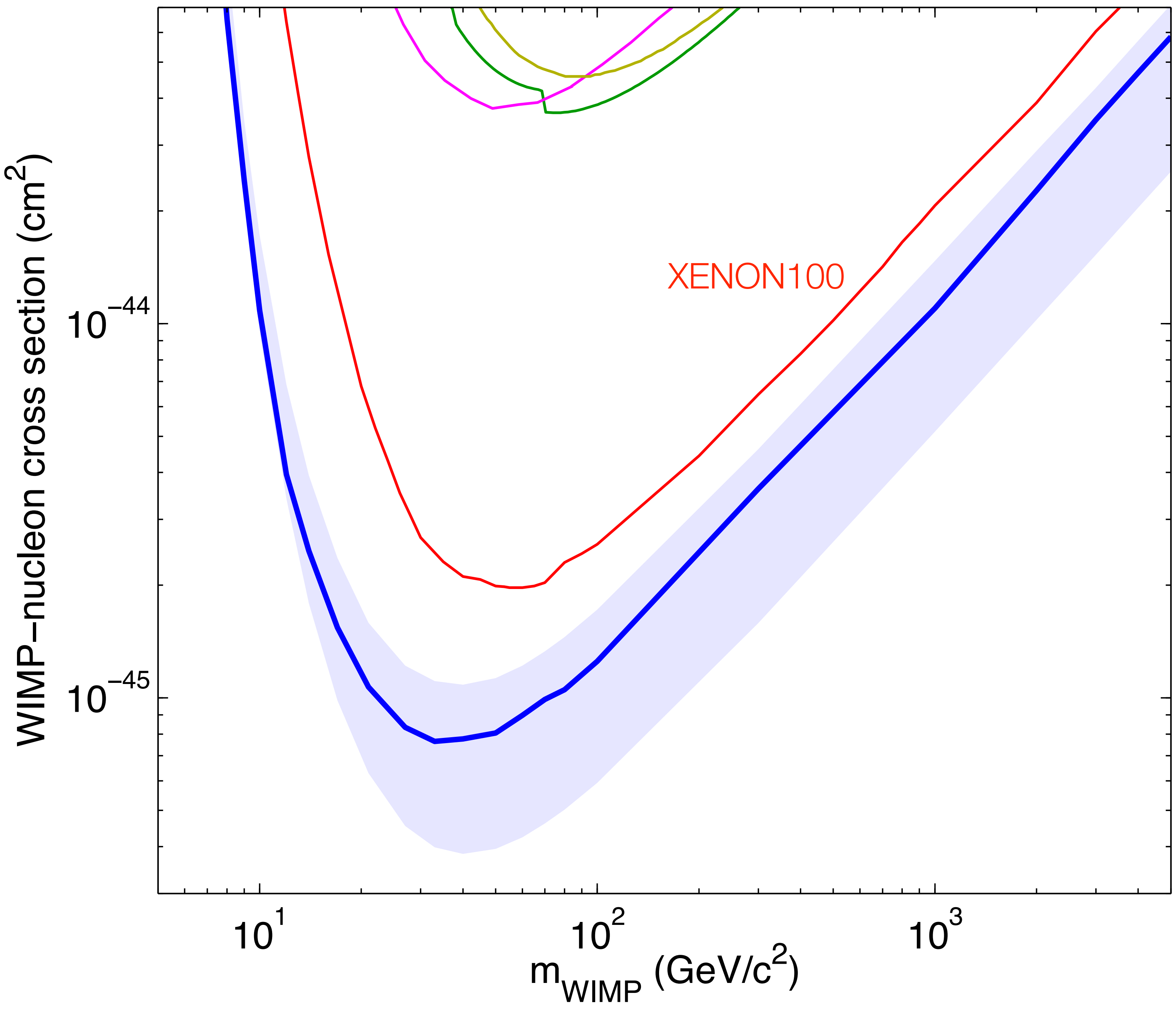
WIMP mass 8.6 GeV

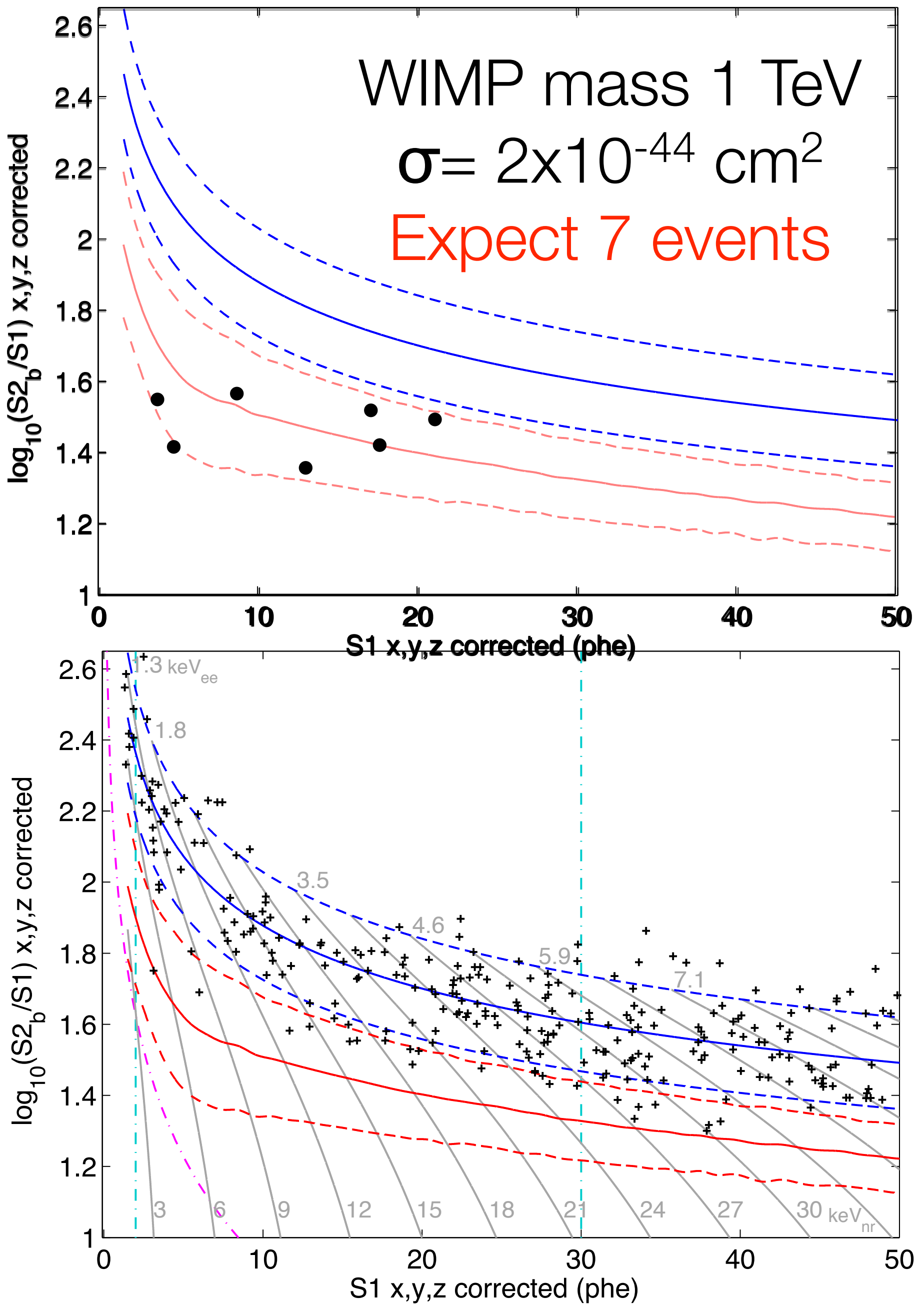
σ= 2x10^{-41} cm^2

Expect 1550 events!



High mass WIMP limit



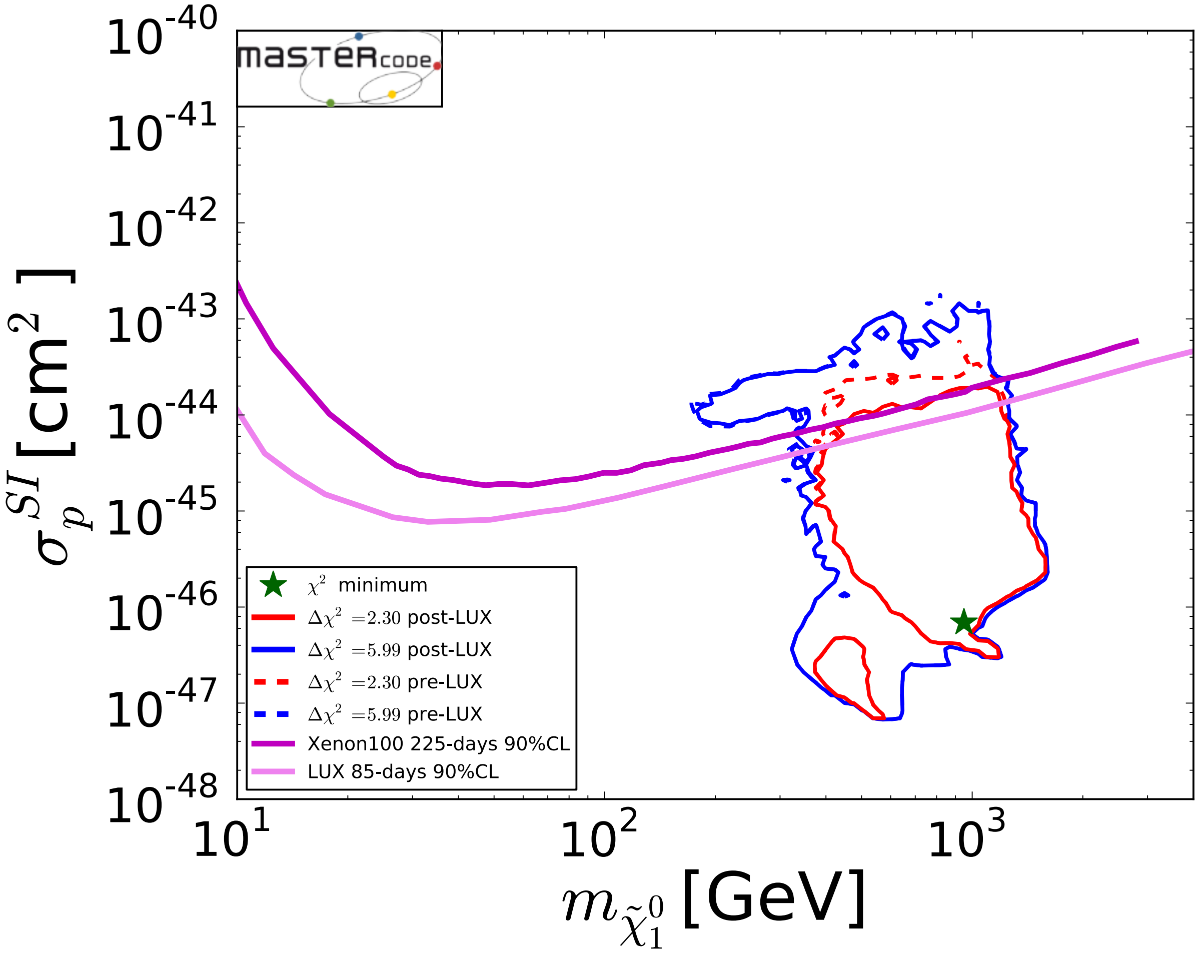

WIMP mass 1 TeV

σ= 2x10^{-44} cm^2

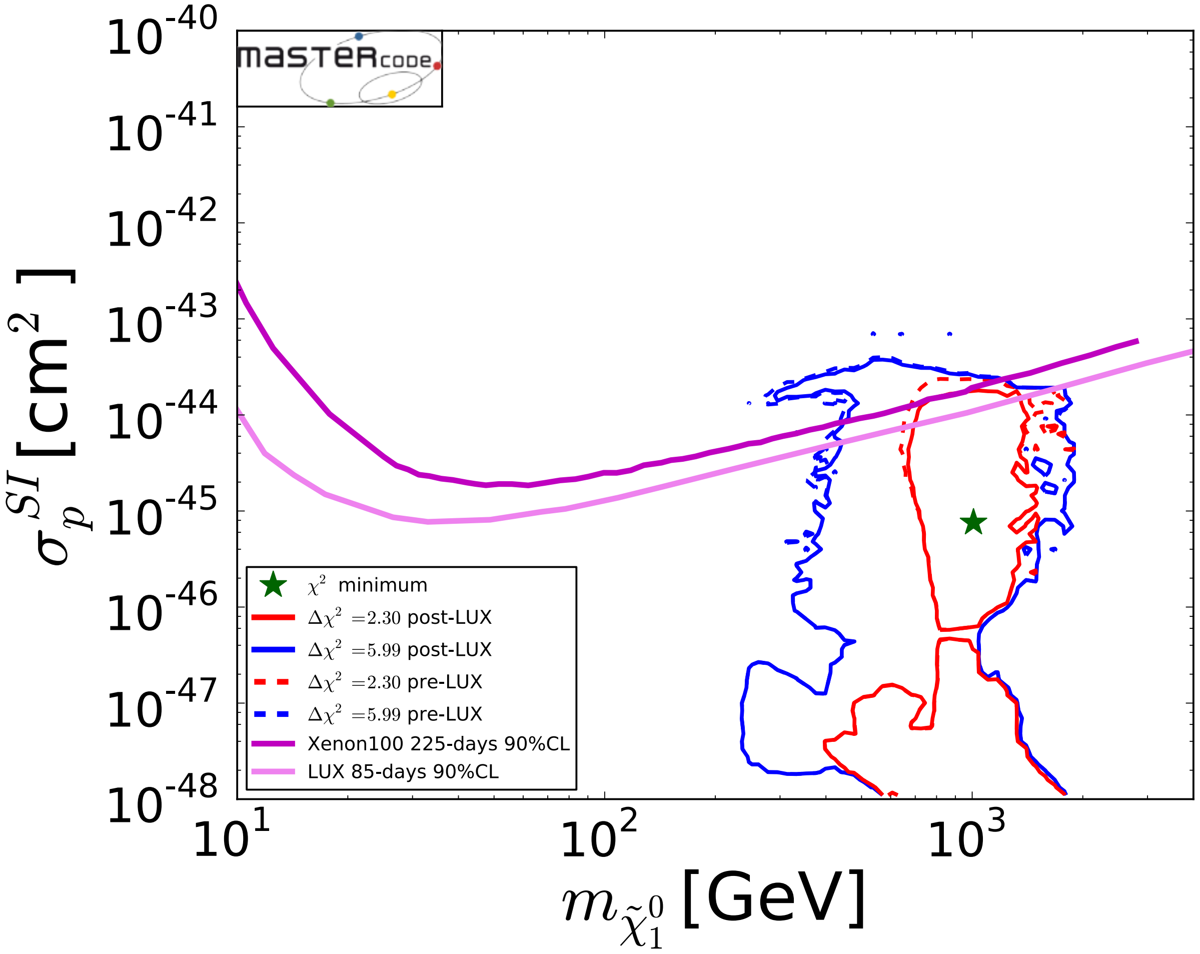
Expect 7 events

High mass - a few SUSY models

CMSSM

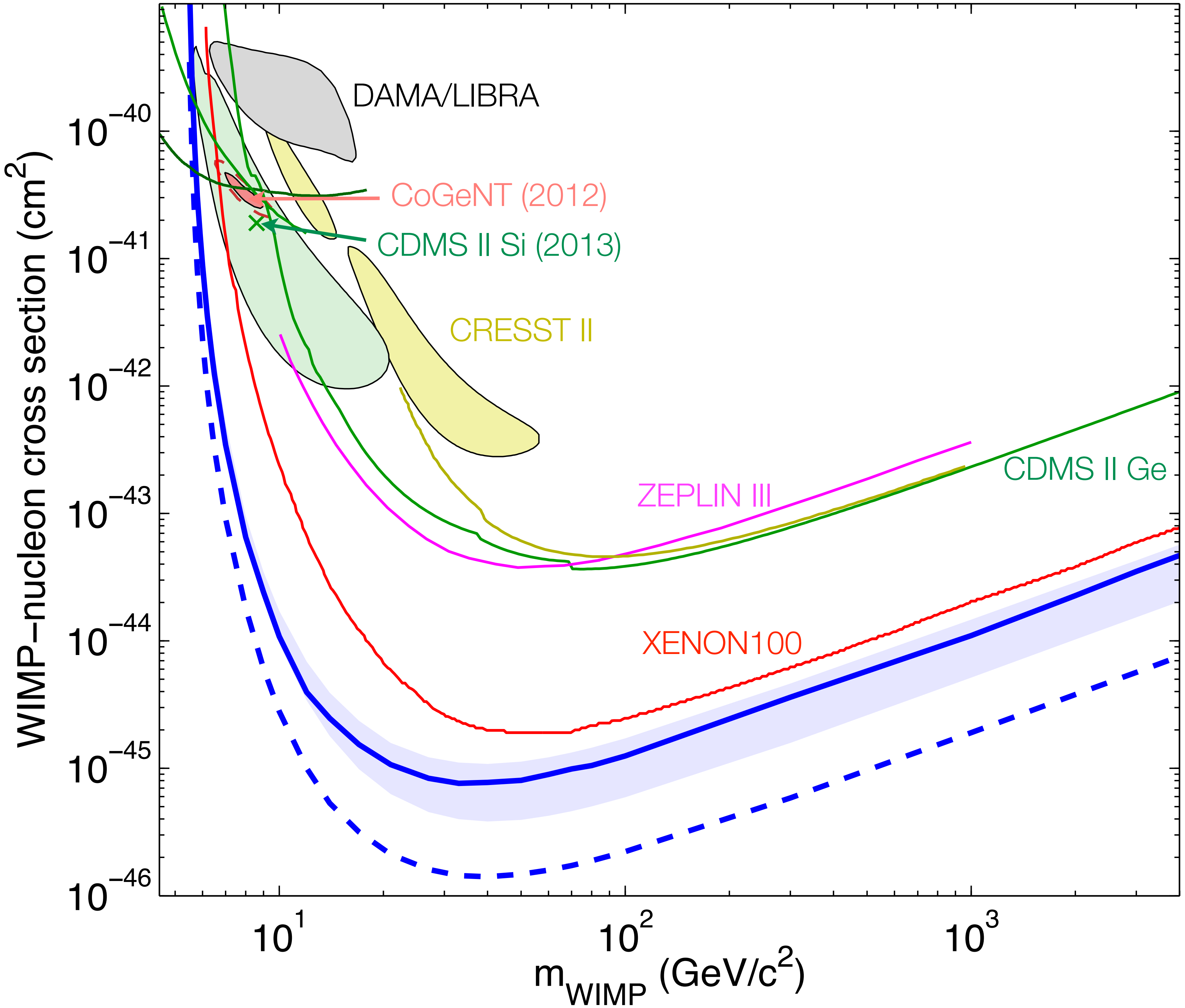


NUHM1



MasterCode project, O. Buchmüller, et al.

300 day WIMP search

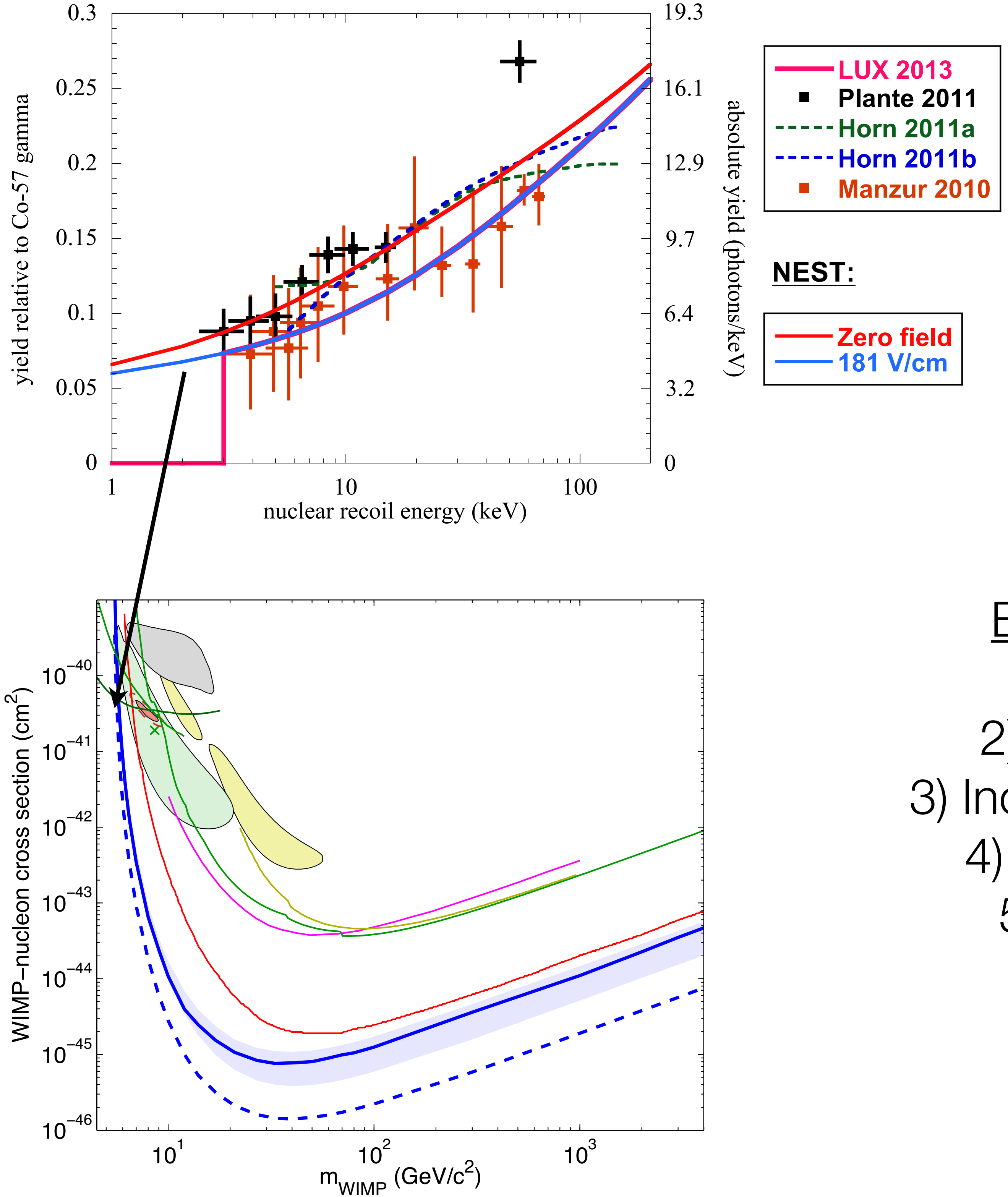


Projected limit assuming no improvements in analysis or drift field

LUX 85d (2013), with ±1σ expected bands

Projected LUX 300 d search (2014)

Possible improvements to initial WIMP analysis



Add calibrations

1) Higher CH3T calibration stats

2) Calibrate nuclear recoils in situ via DD neutron generator

Enhance signal and background models

1) Use combined energy scale

2) Explicitly include resolution, efficiencies

3) Include uncertainty on position reconstruction

4) Build recombination fraction into models

5) Revisit discrimination parametrization

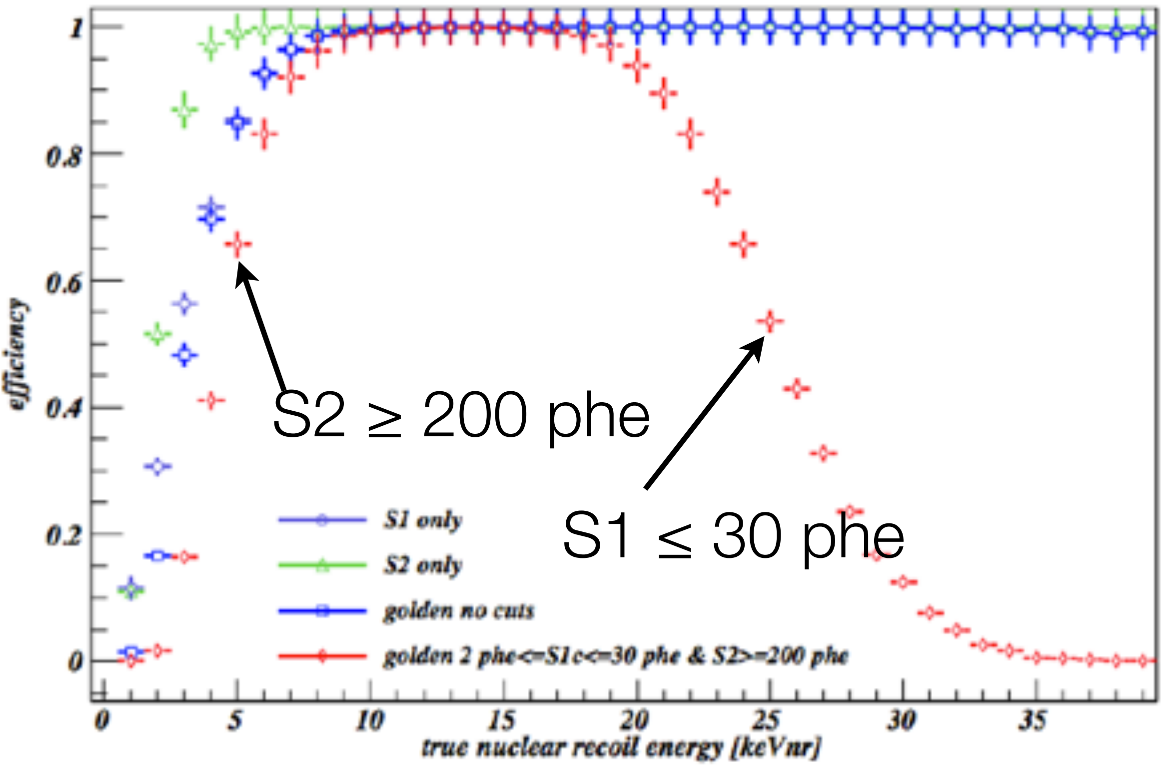
$$E_{ee} = \left(n_\gamma + n_e\right) W\,,$$
$$E_{nr} = f_n^{-1}\left(n_\gamma + n_e\right) W$$

Additional background studies would be a benefit

Lowering the energy threshold makes a big difference in sensitivity to low mass WIMPs

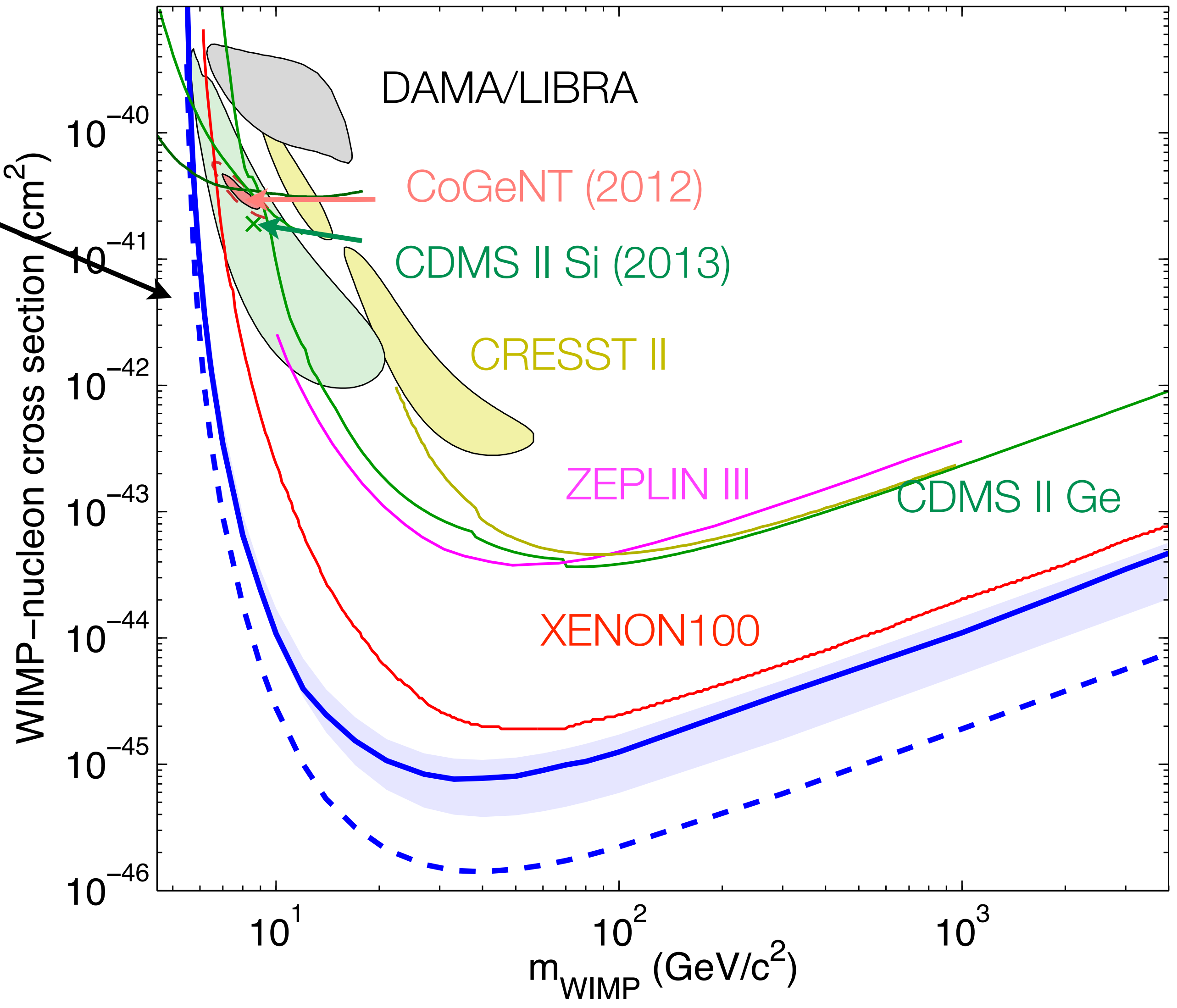
Optimize selection for WIMP sensitivity

1) Lower S1 threshold
2) Extend upper S1 range
3) Improve S2 ID to lower threshold of S2



S2 ≥ 200 phe

S1 ≤ 30 phe



Programs of background studies that can inform the understanding of isolated backgrounds that contribute to our current S2 thresholds, fiducial volume are highly desirable...

Reblind the data and reanalyze...

The Need to Know

Ryan McGinness (2008)

The LUX-ZEPLIN Experiment

I do the impossible, because the possible anyone can do.

- Pablo Picasso

US Groups

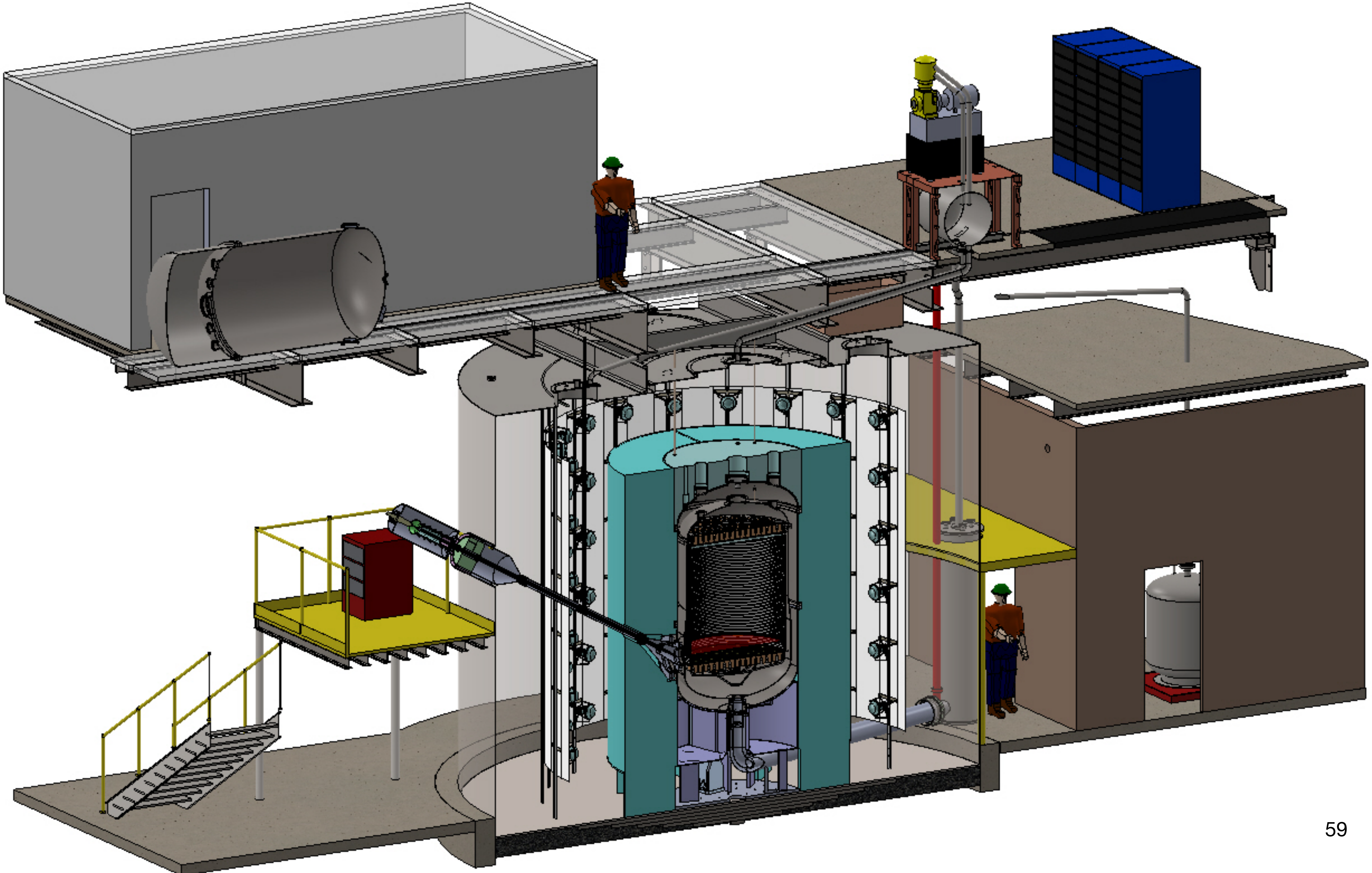
Brookhaven National Laboratory
Brown University
Case Western Reserve University
LLNL
SLAC
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority
Texas A&M University
University Of Alabama
University of California, Berkeley/LBNL
University of California, Davis
University of California, Santa Barbara
University of Maryland
University of Rochester
University of South Dakota
University of Wisconsin
Physical Sciences Laboratory, Wisconsin
Washington University
Yale University

Non-US Groups

Imperial College, London
LIP – University of Coimbra
Moscow Engineering Physics Institute
Oxford University
STFC Daresbury Laboratory
STFC Rutherford Appleton Laboratory
University College, London
University of Edinburgh
University of Sheffield

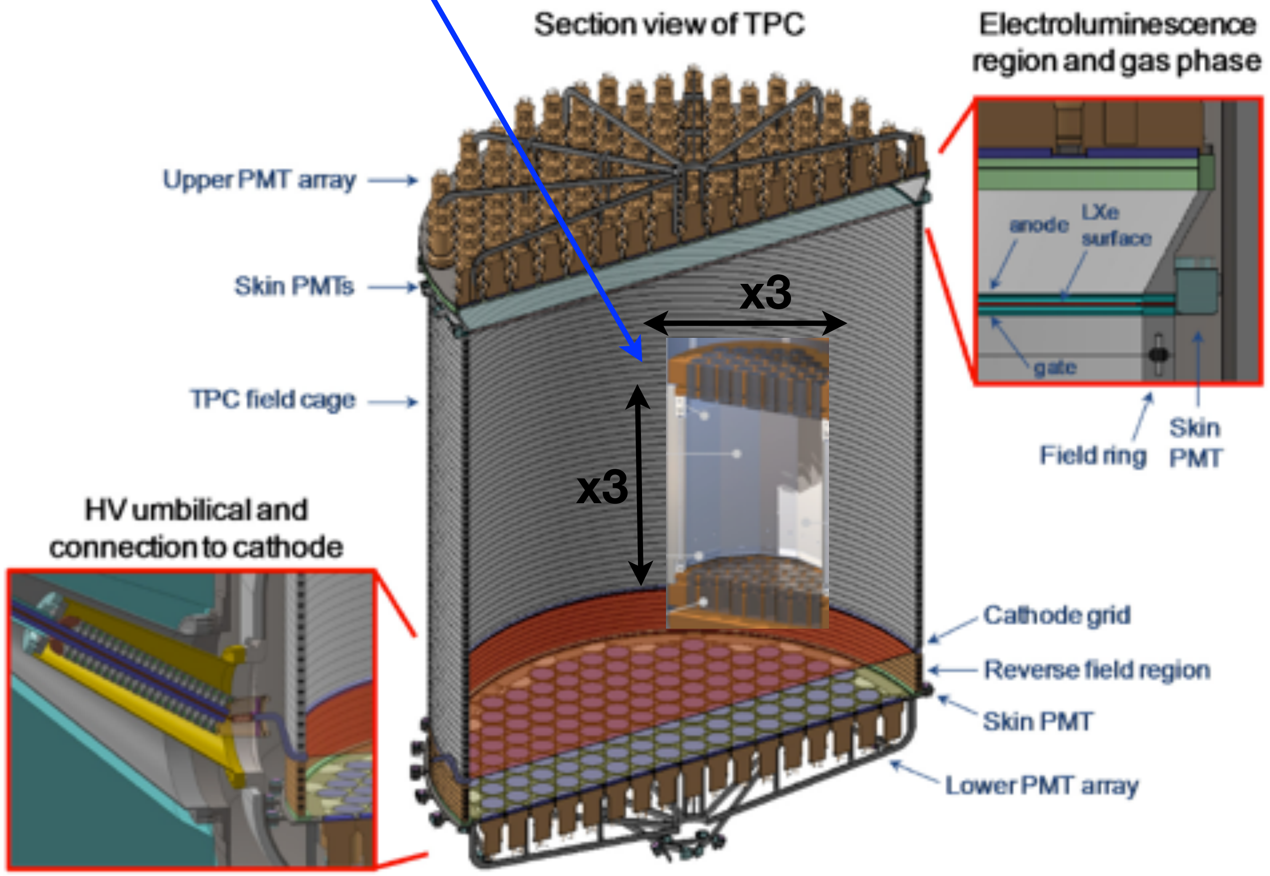
LZ Collaboration - currently 28 institutions!

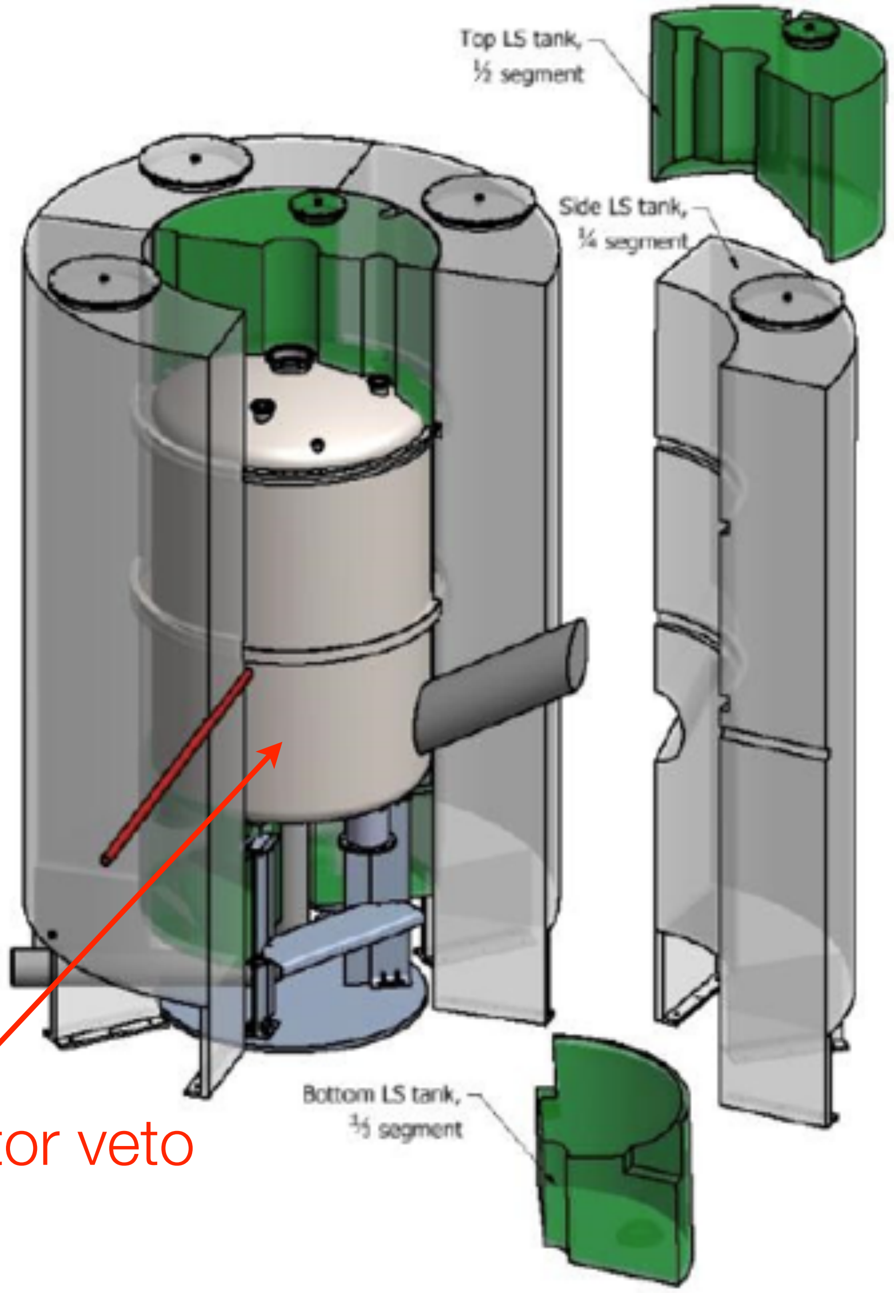
The LZ detector



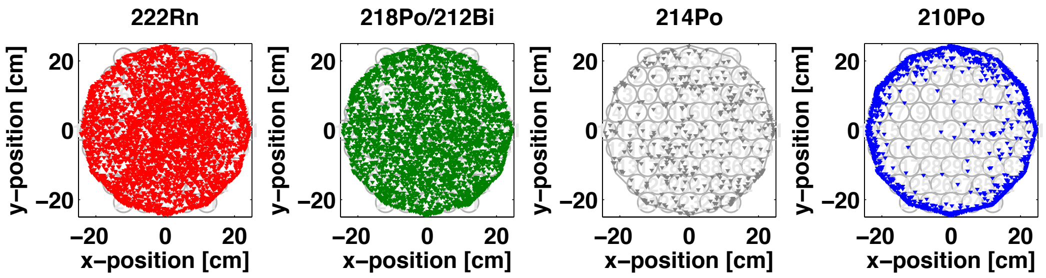
Scale up the detector, scale down the backgrounds...

LZ detector volume 27 times larger than LUX





Add scintillator veto



Reduce internal backgrounds...

Learn from LUX/ZEPLIN experiences...

LUX

Water tank deployment

Ti vessels

Thermosyphon cryogenics

Dual-phase heat exchanger system

Xe purity analytical systems

Kr removal to very low levels

Low background PMTs

In-situ calibrations

Electronics

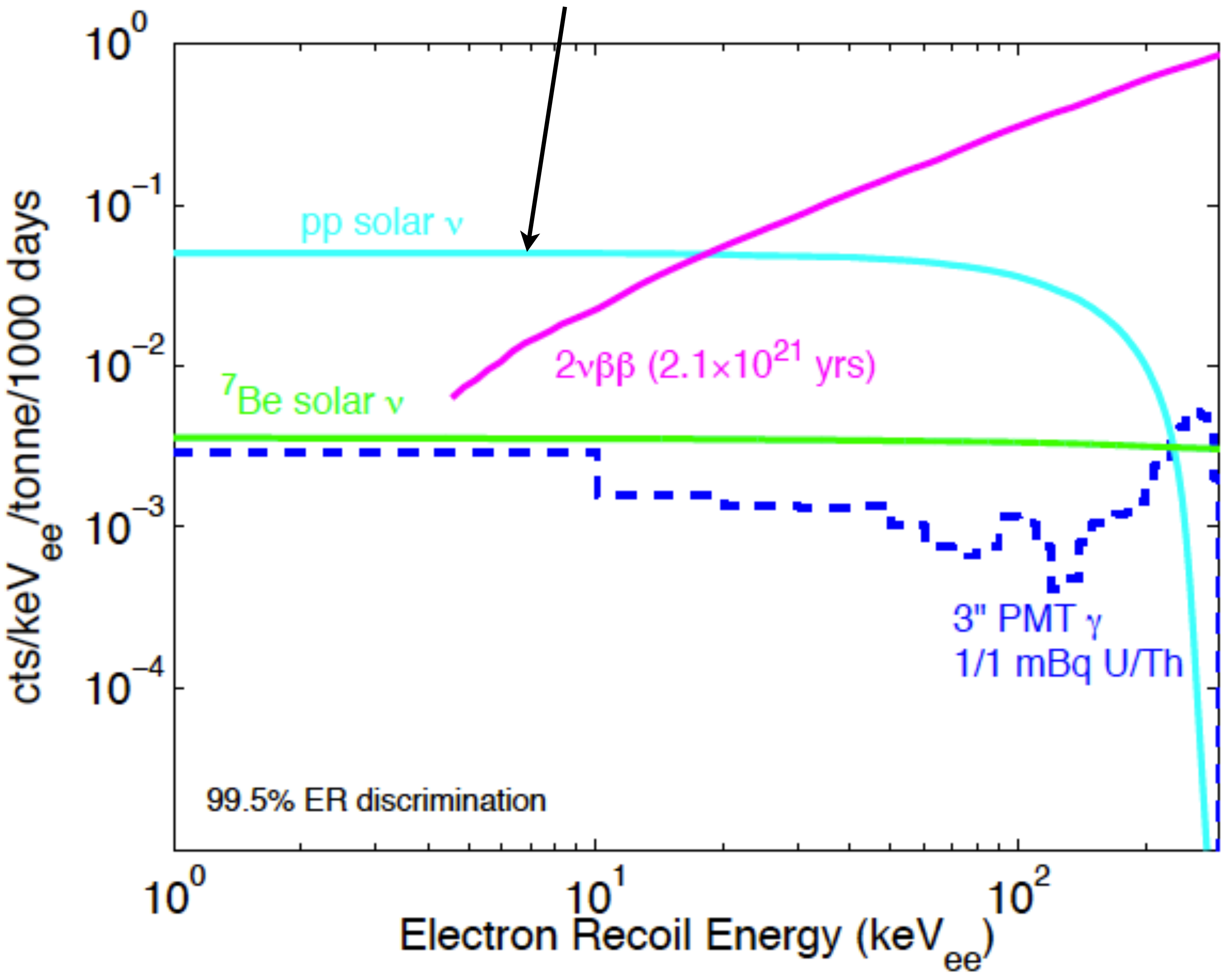
Davis campus infrastructure

ZEPLIN III

background rejection at high field

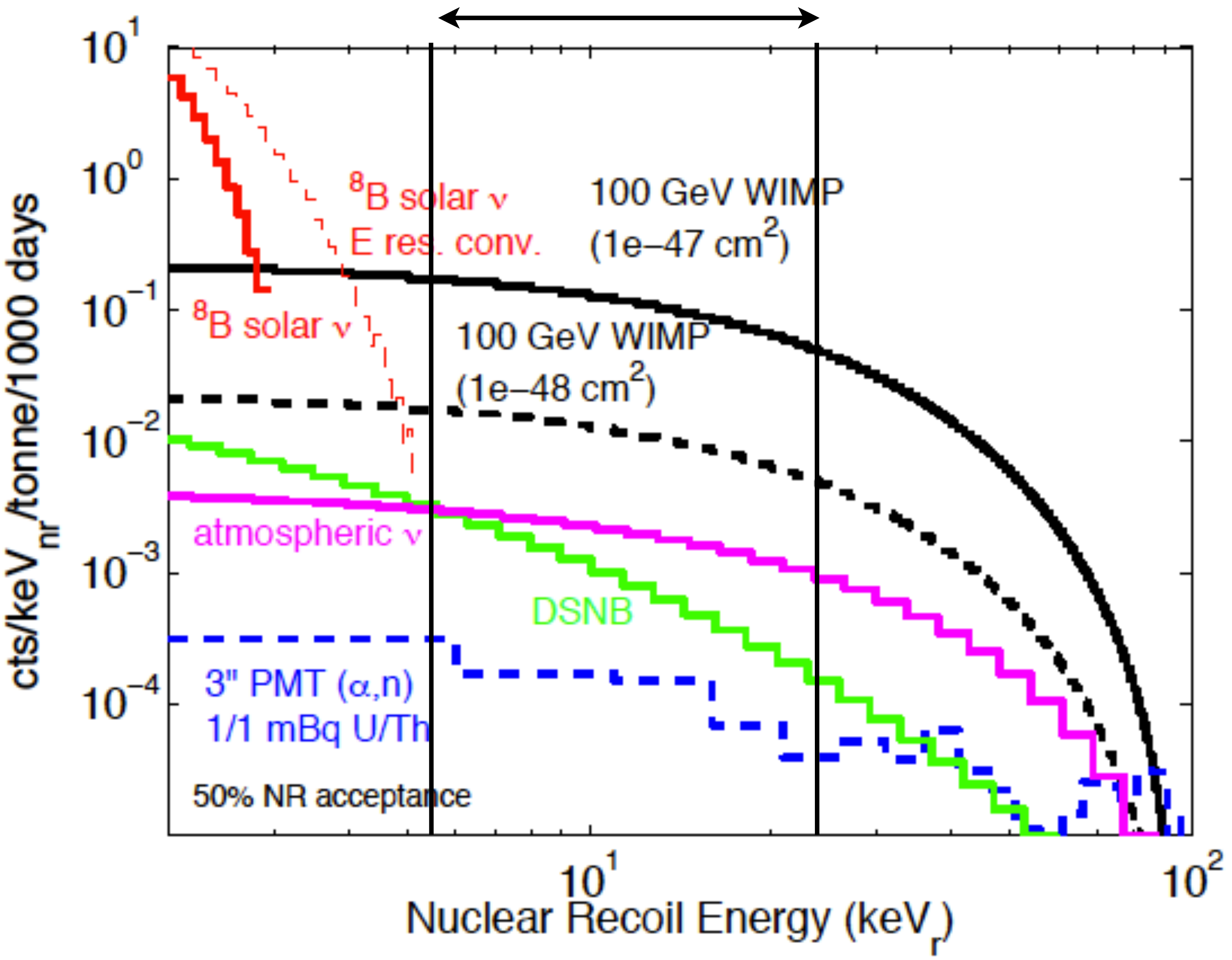
LZ can have sensitivity to solar neutrinos

~250 pp solar in 6T, 1000 d in 5 $\mathrm{keV_{ee}}$ window

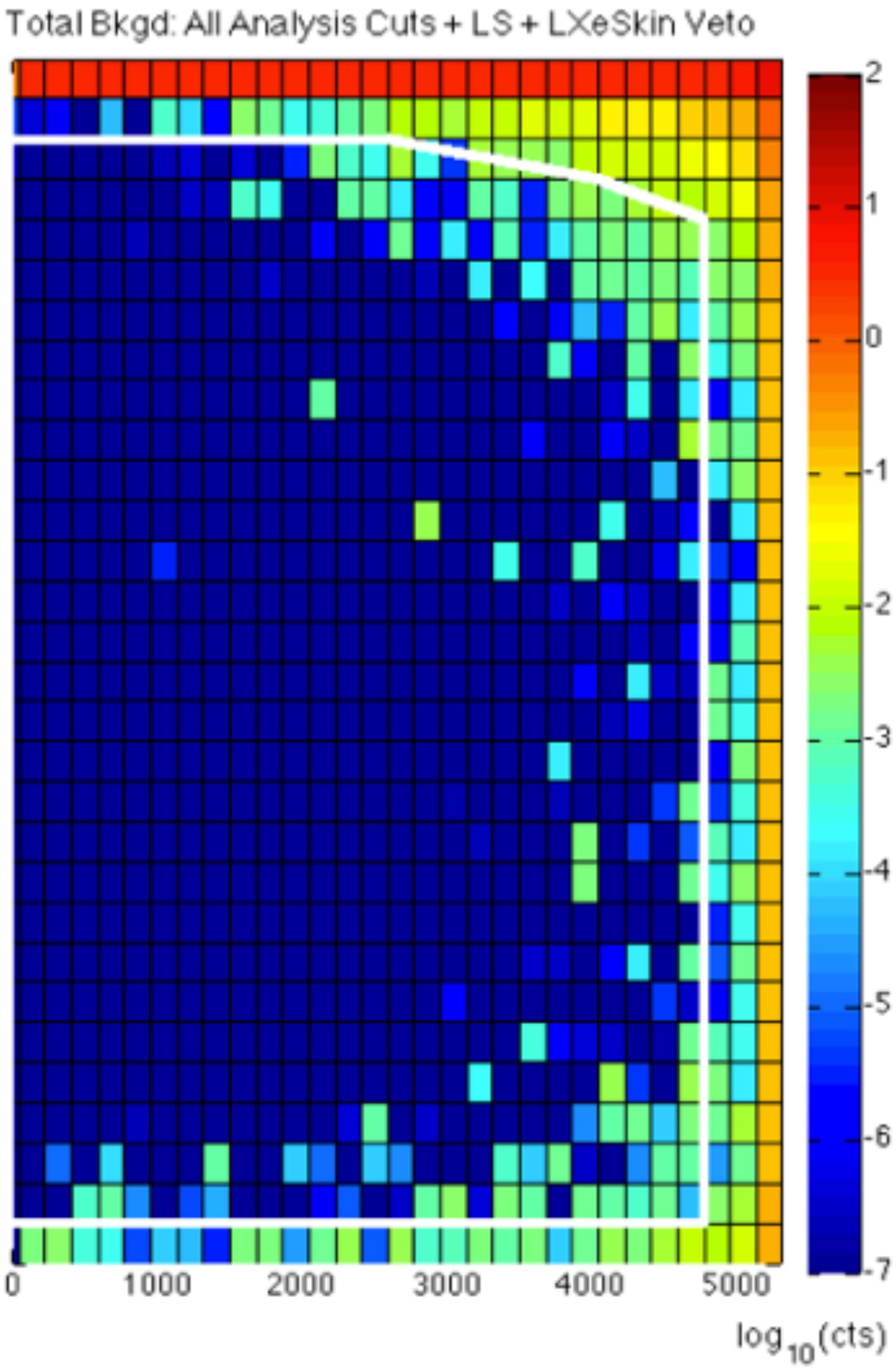


Want sensitivity to pp solar ν signal if possible -
need to be much more careful with backgrounds!

“Ultimate” WIMP sensitivity limited by coherent ν’s



Current LUX WIMP search window

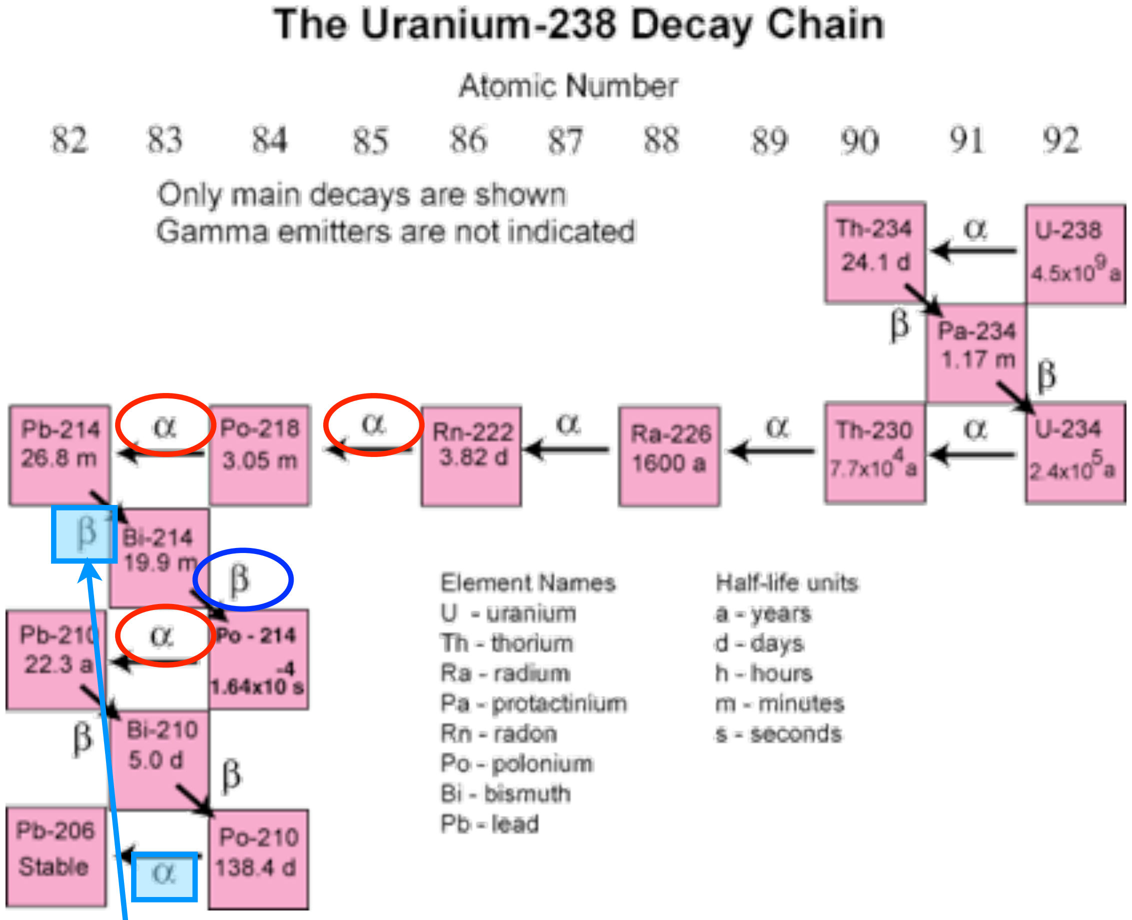


Total Bkgd: All Analysis Cuts + LS + LXeSkin Veto

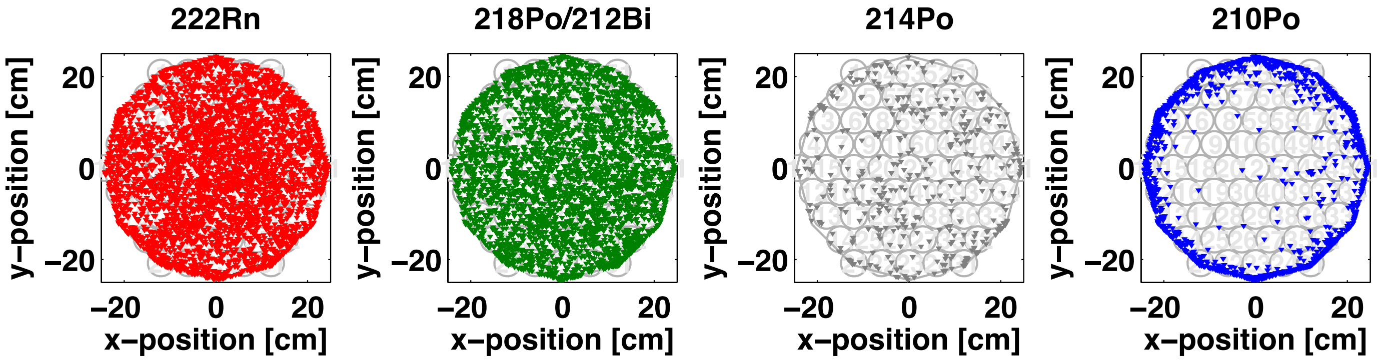
Rn screening program

Need significant reduction in internal backgrounds:
1) Reduce ^{85}Kr to 0.01 ppt
2) Require much more stringent screening for ^{222}Rn daughters
→ keep ^{214}Pb β decay to 10% of pp solar ν rate, require 0.6 mBq of ^{222}Rn

Desire screening sensitivity to O(1 μBq) level, limit each major component to ~10-30 μBq

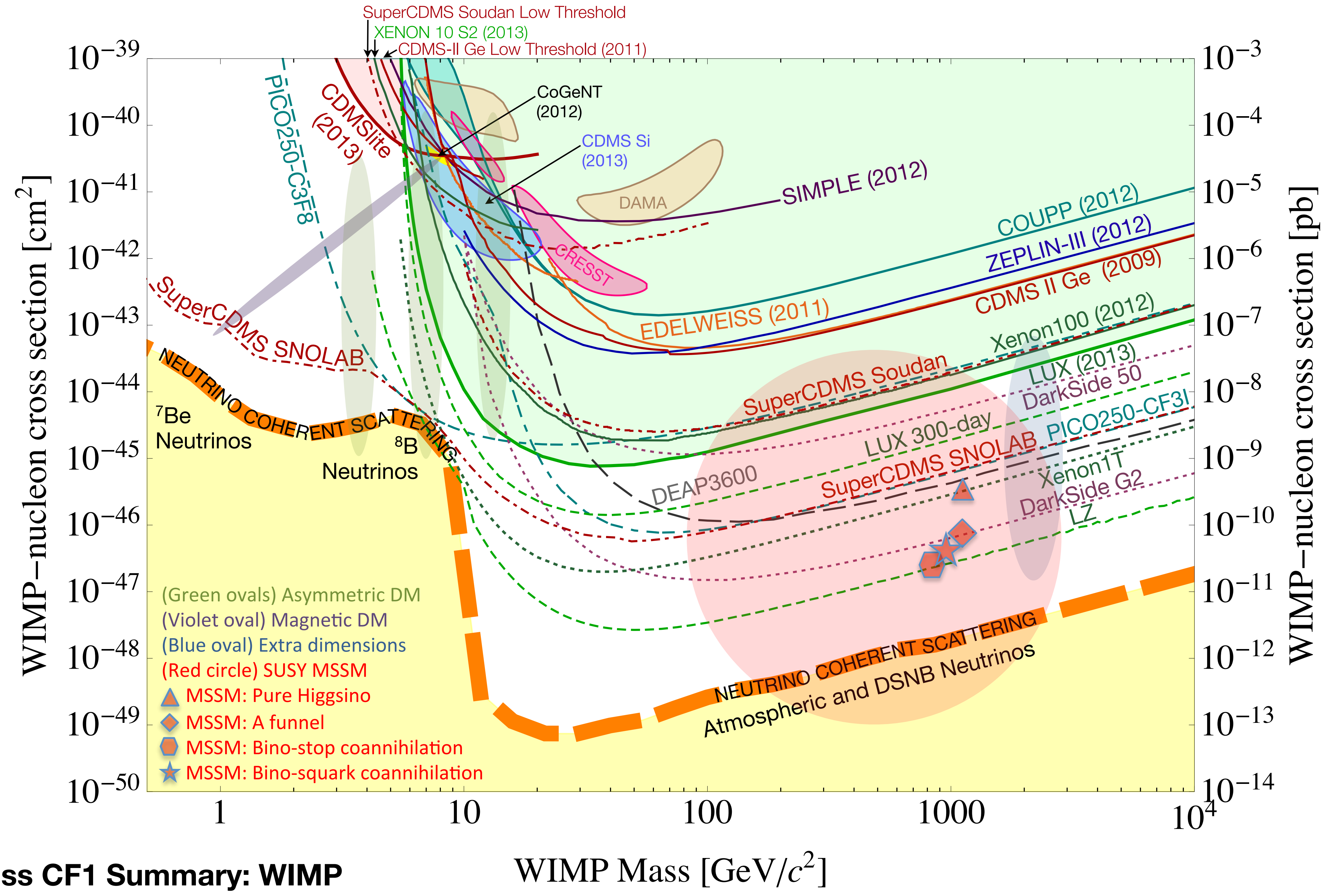


Potential backgrounds in DM search region



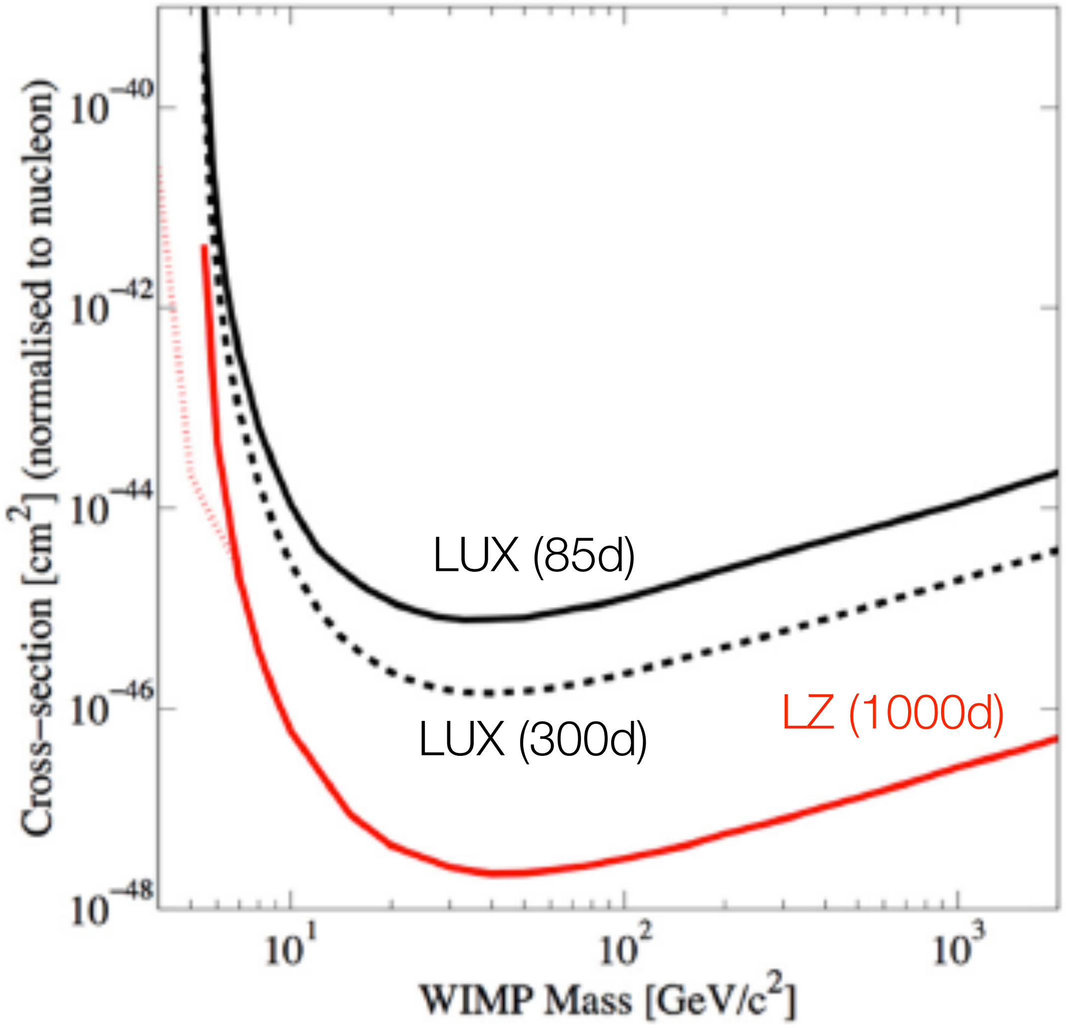
a posteriori estimate of 8.3 mBq ^{214}Pb in LUX!

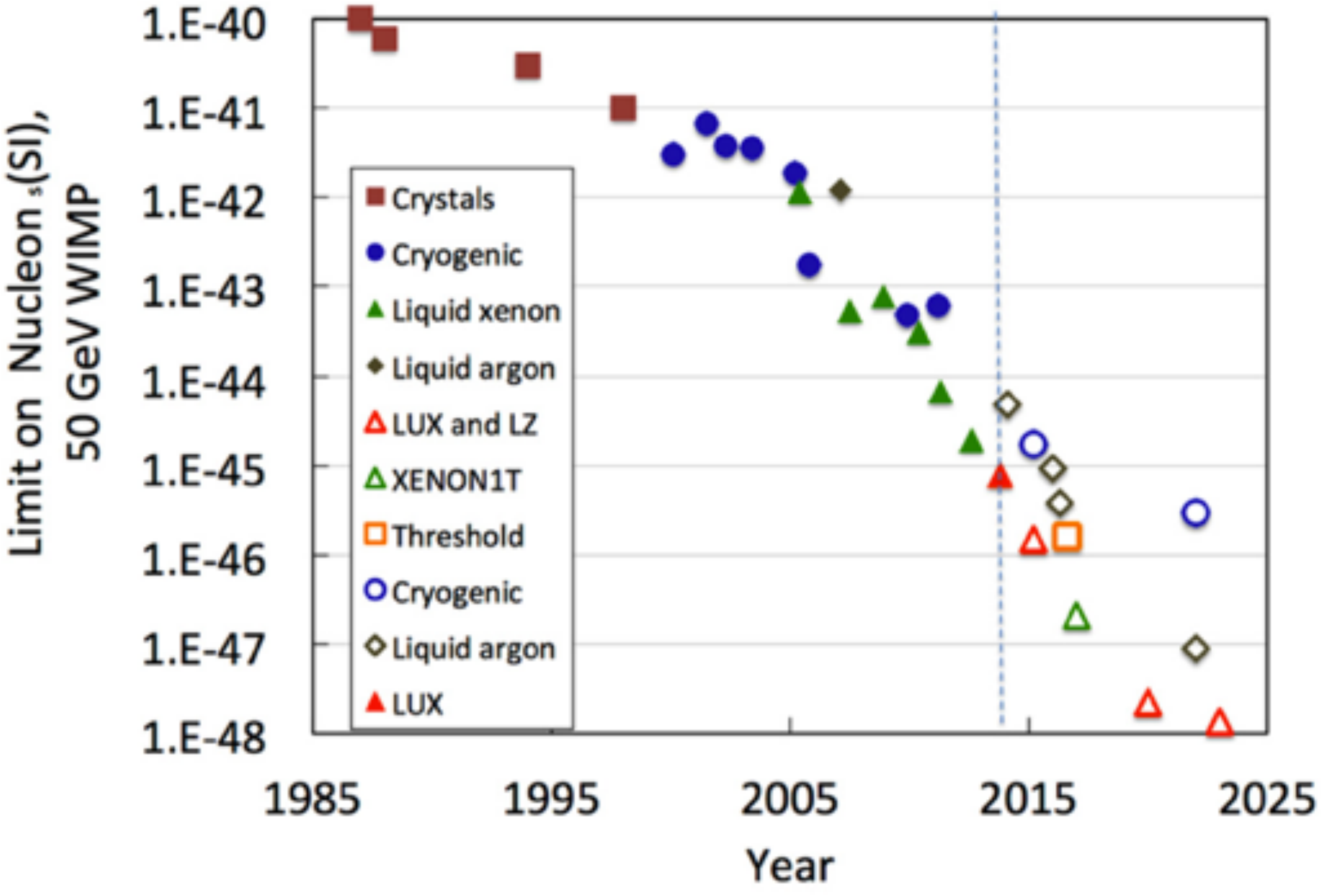
The “big picture” in direct detection experiments



“Snowmass CF1 Summary: WIMP Dark Matter Direct Detection”, arXiv:1310:8327

A race to the bottom...

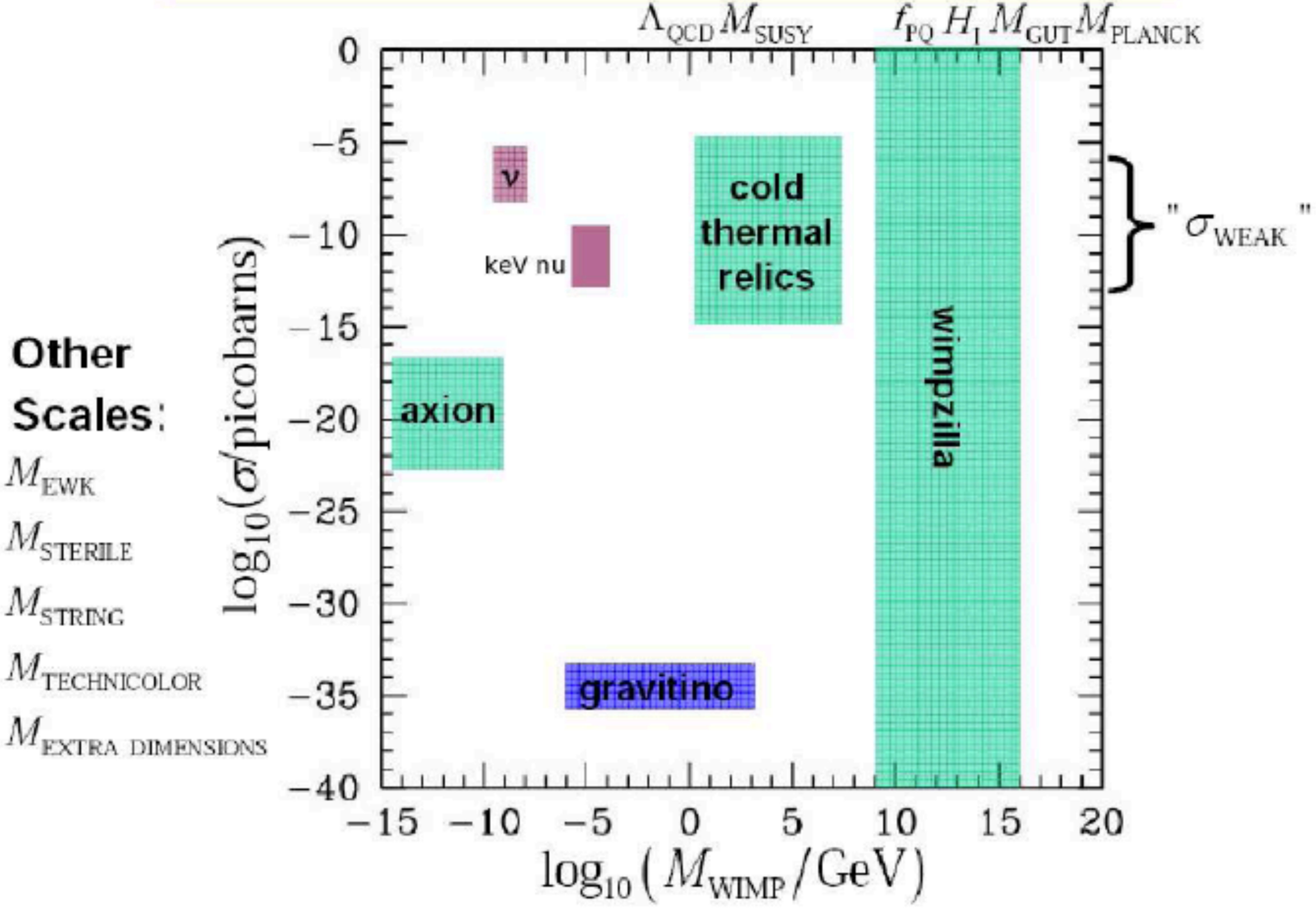




LUX/LZ will be the experiments to beat for the next decade!

Back-up

Particle Dark Matter Candidates



Thomas Schwetz-Mangold, ISAPP 2011

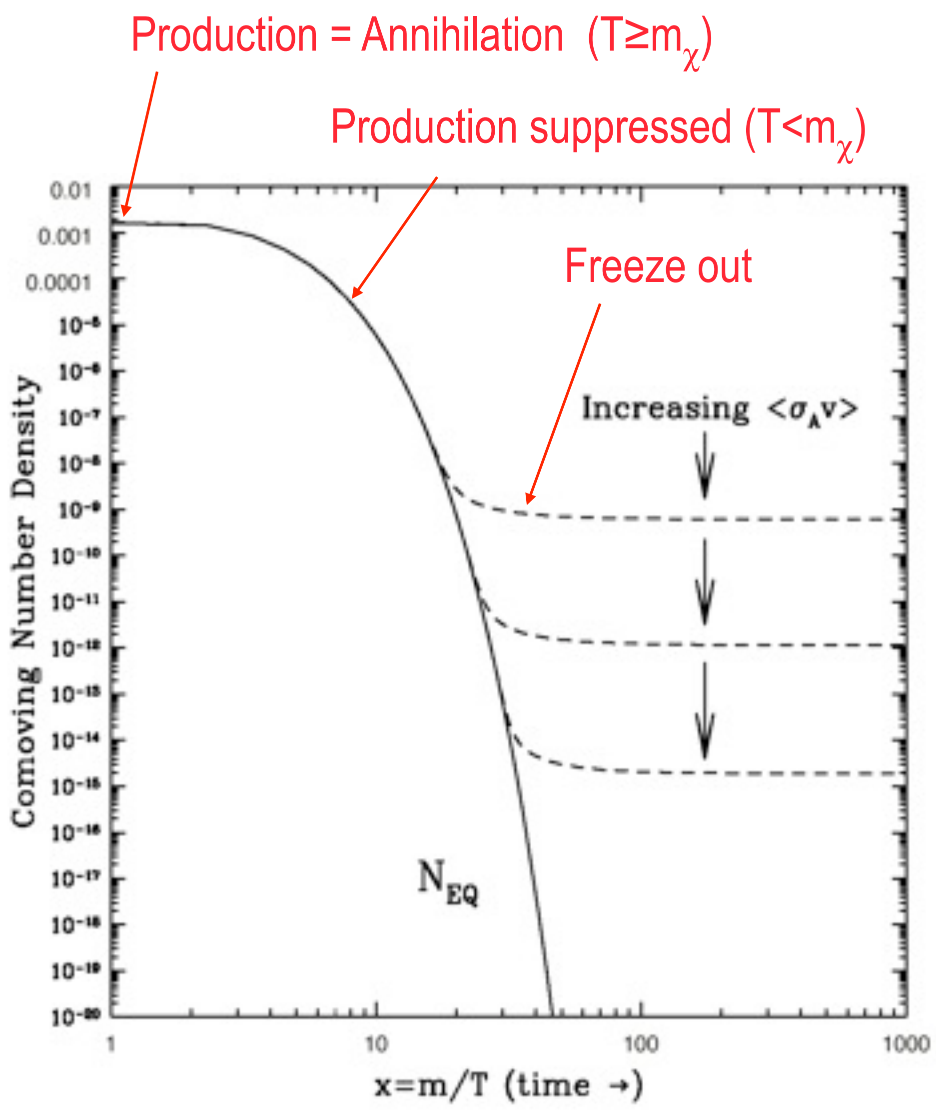
Thermal freezeout of dark matter

New stable states are produces in early universe when
$H > \Gamma$
where $\Gamma \sim n\langle\sigma v\rangle$

$$n \propto e^{-m_{WIMP}/T}$$

$$\Omega_{WIMP} \approx \frac{10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

For $\Omega_{WIMP} \approx 1$, interaction rate at electroweak scale ($\sigma \sim 1/\text{few TeV}^2$) gives correct relic abundance



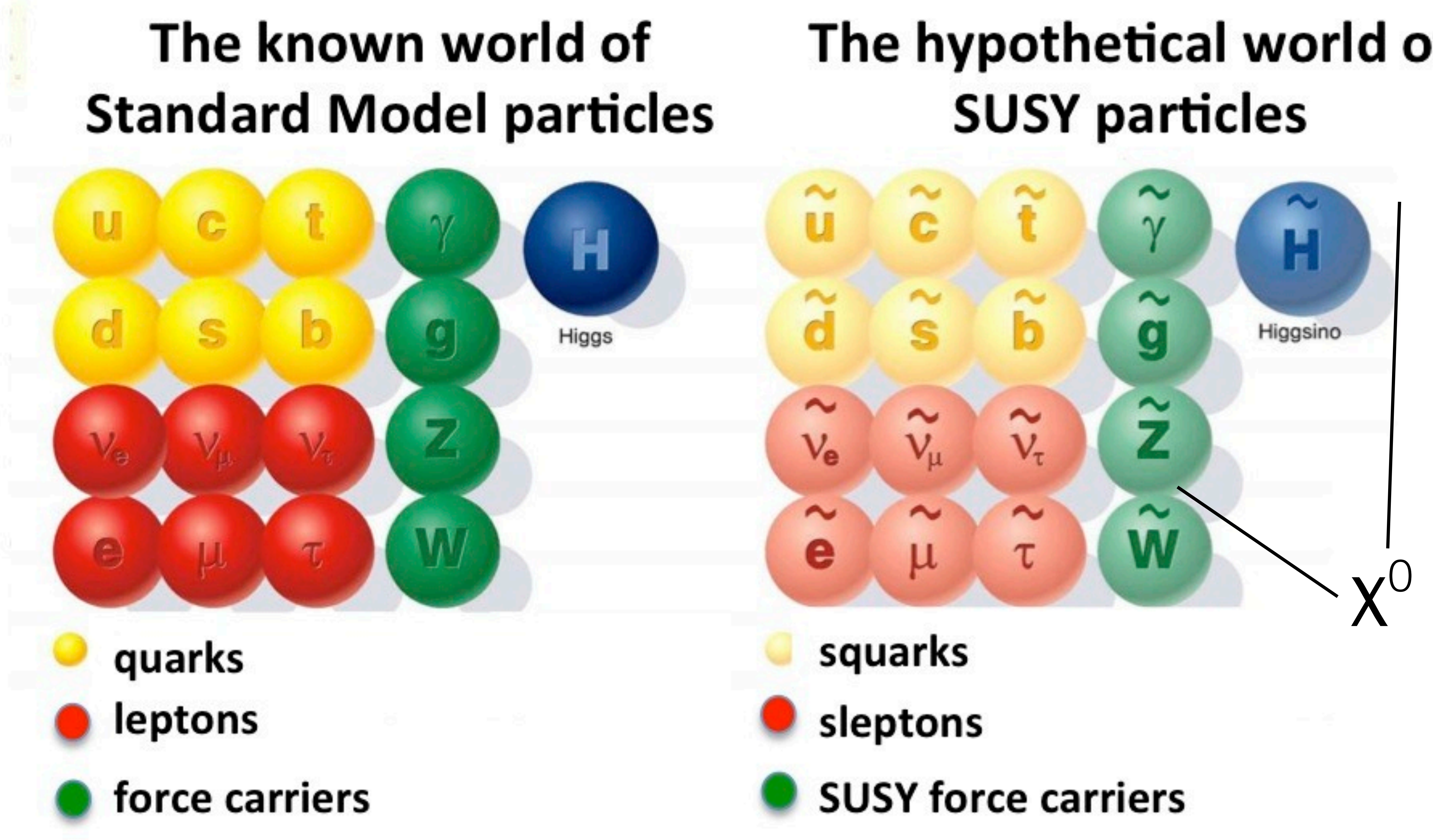
Production = Annihilation $(T \geq m_\chi)$

Production suppressed $(T < m_\chi)$

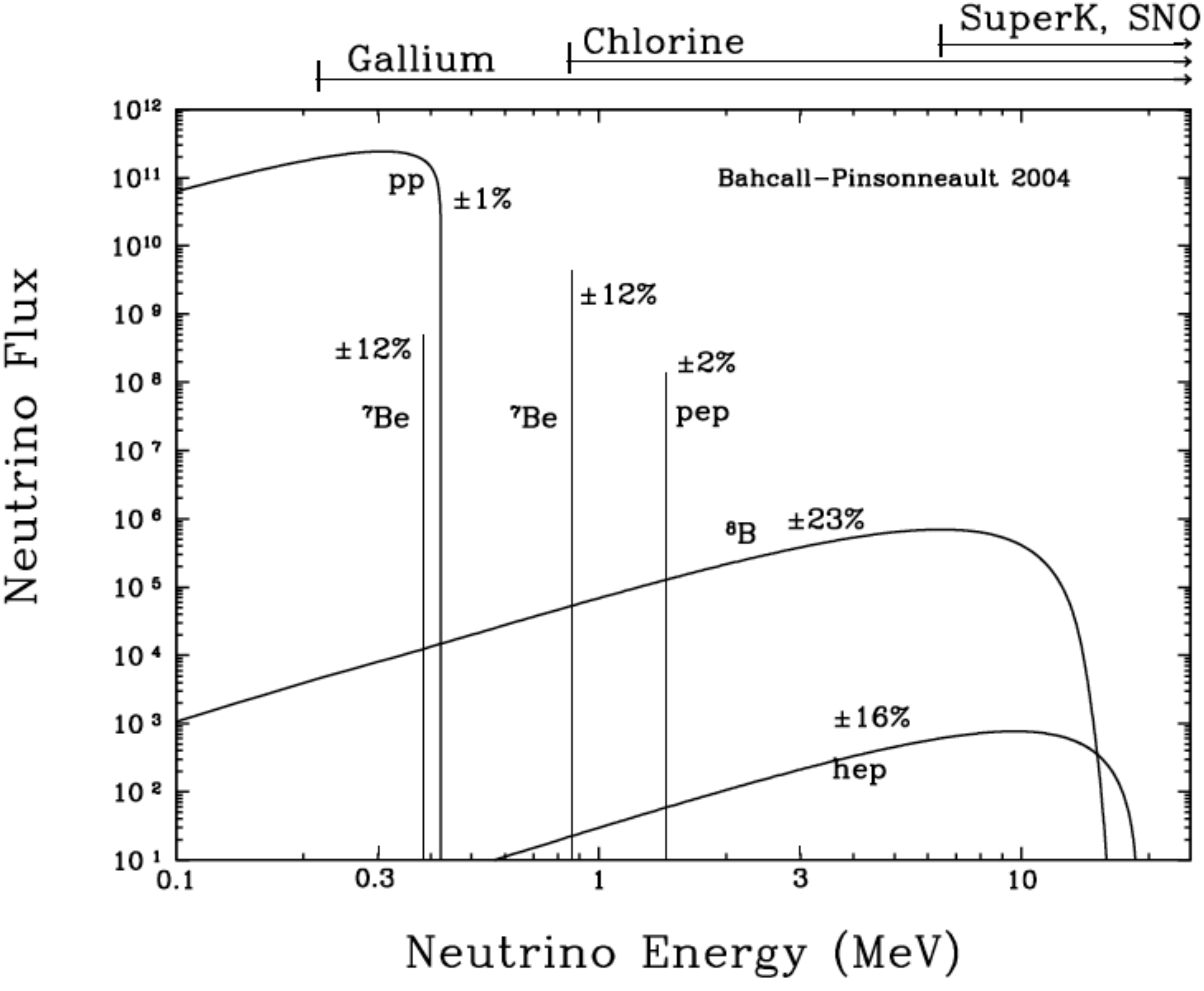
Freeze out

$T_{FO} \sim m/20$ → non-relativistic

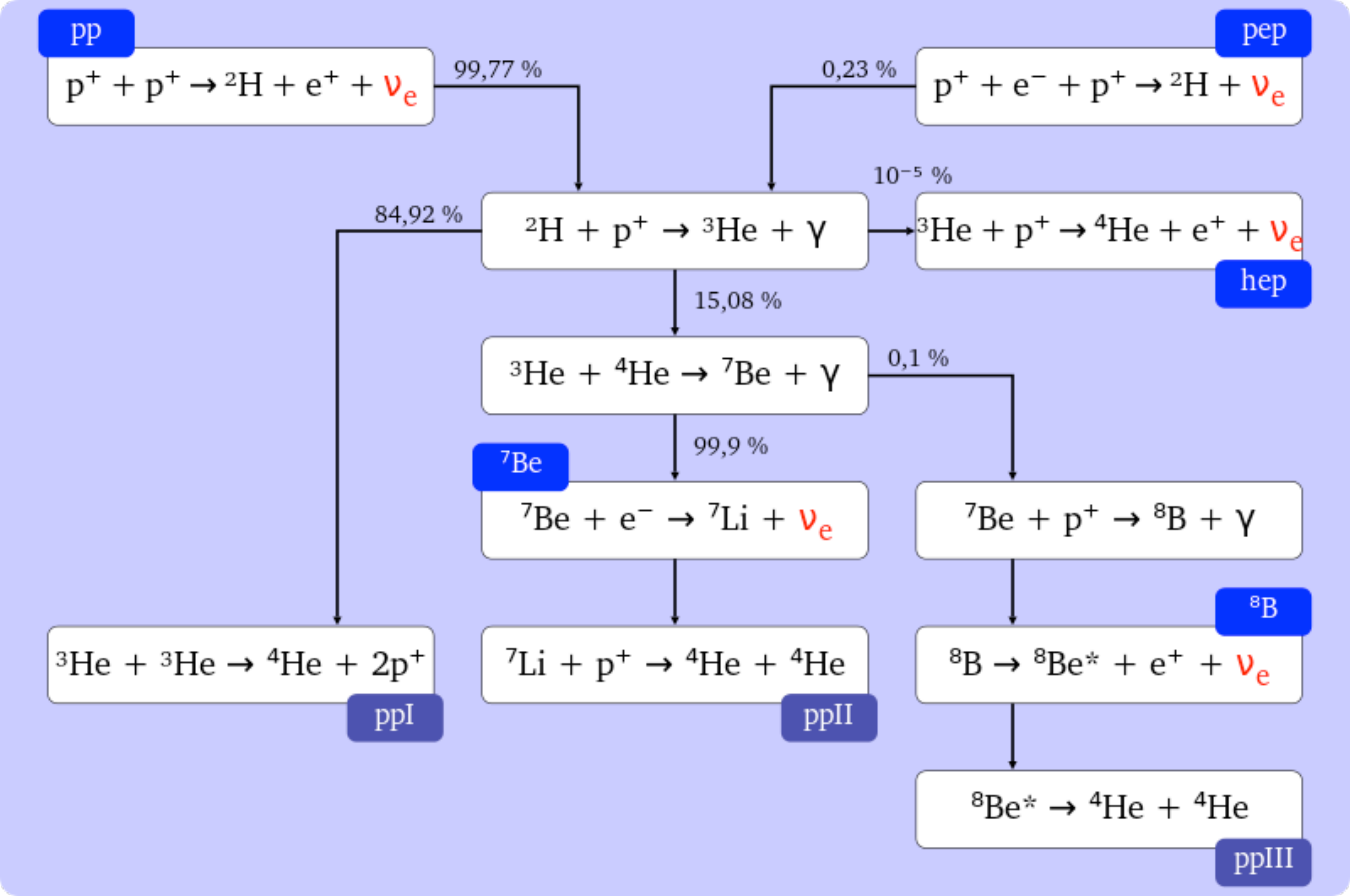
Supersymmetry has long been favored to provide a WIMP candidate...



Accurate measurement of pp solar ν flux would constrain solar model



Bachall and Pena-Garay, arXiv:hep-ph/0404061



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

0,23 %

$^2H + p^+ \rightarrow {}^3He + \gamma$

84,92 %

10⁻⁵ %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

0,1 %

99,9 %

⁷Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

⁸B

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

ppIII

Projected LZ background rates

LZ R&D report

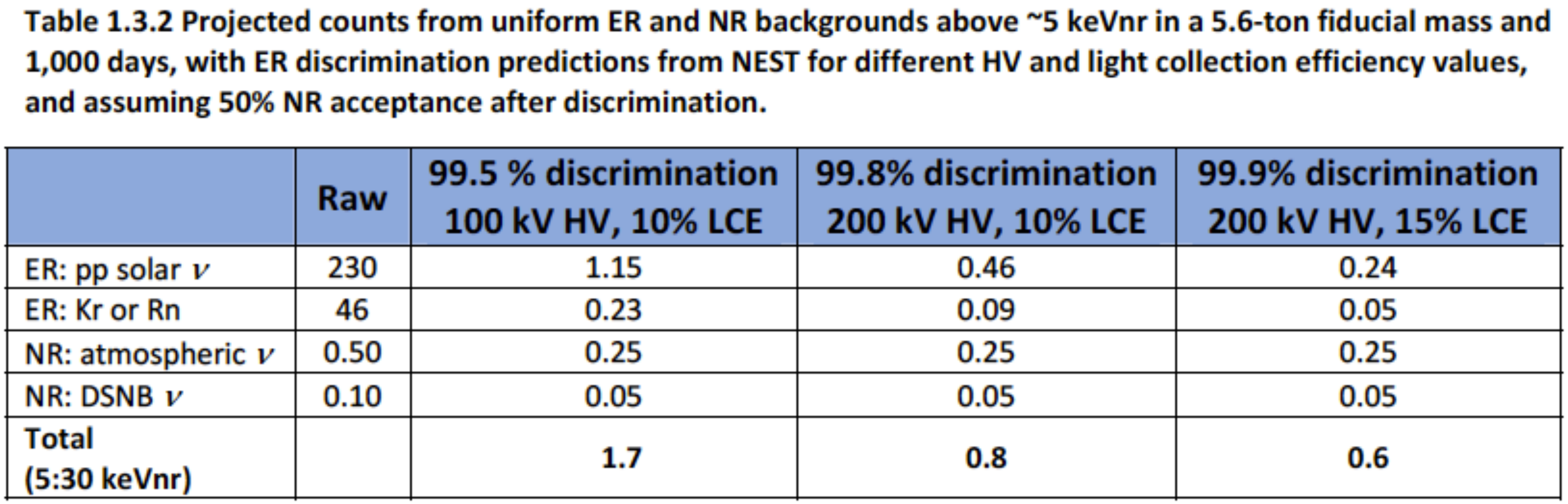
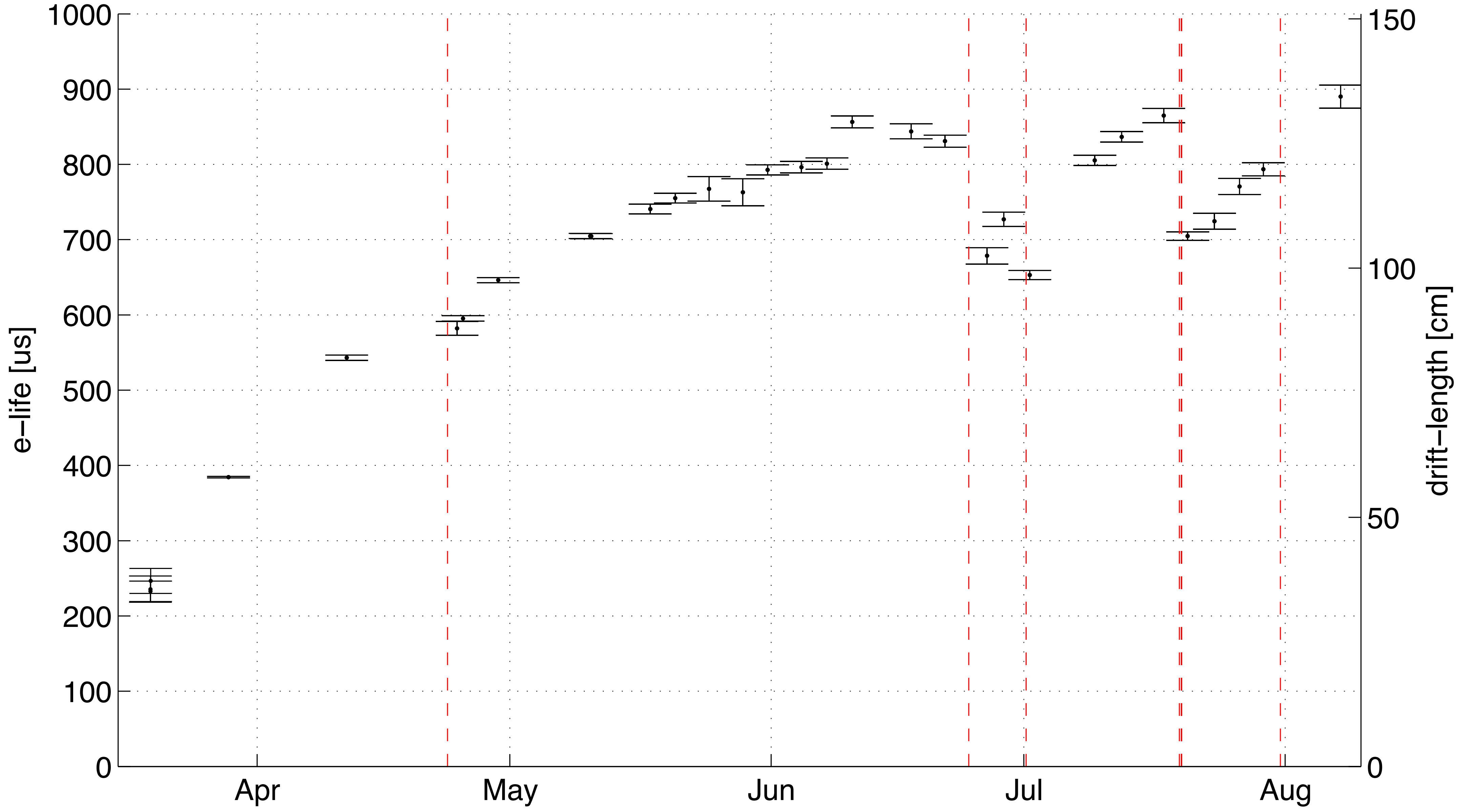


Table 1.3.2 Projected counts from uniform ER and NR backgrounds above ~5 keVnr in a 5.6-ton fiducial mass and 1,000 days, with ER discrimination predictions from NEST for different HV and light collection efficiency values, and assuming 50% NR acceptance after discrimination.

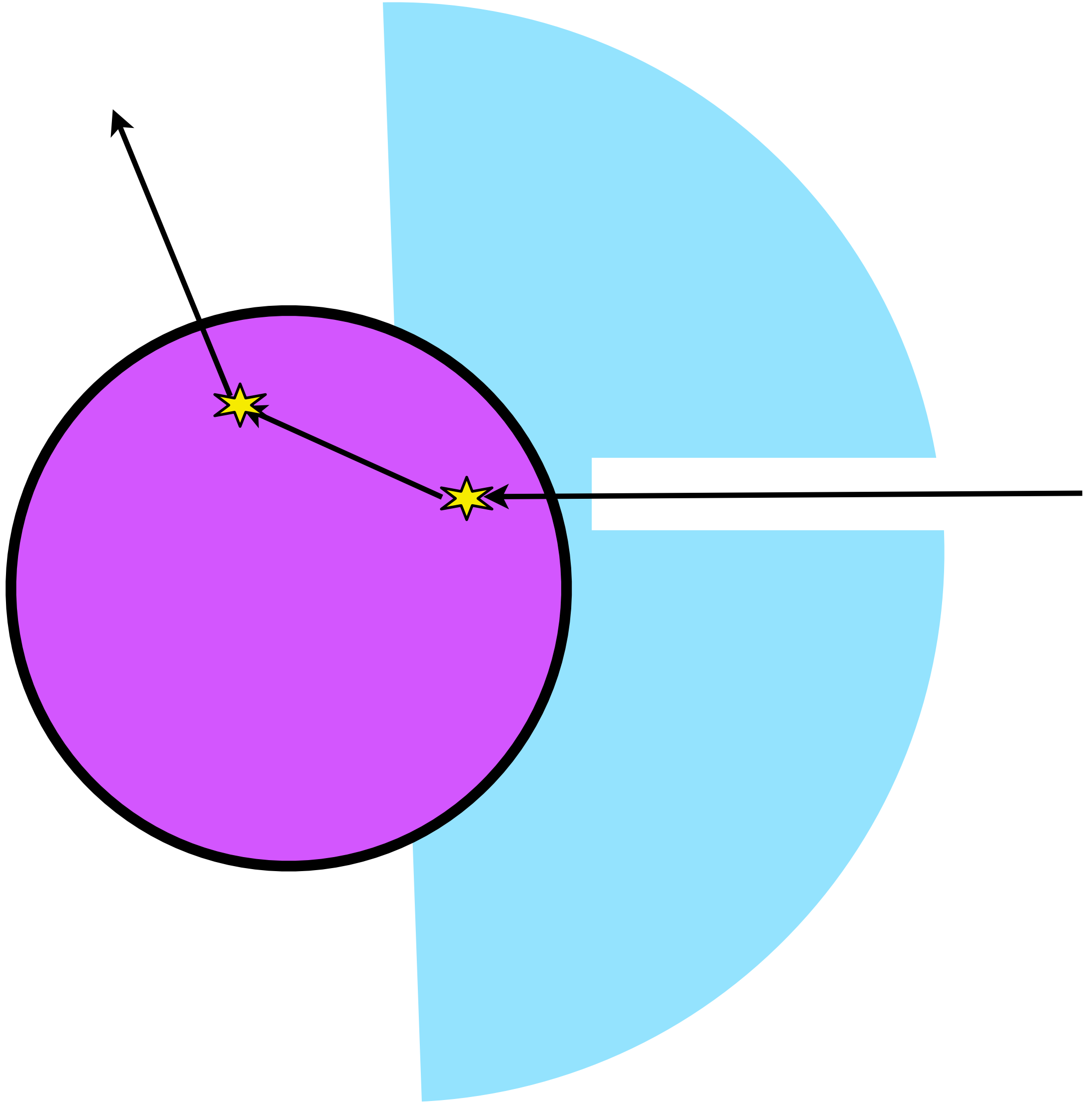
	Raw	**99.5 % discrimination 100 kV HV, 10% LCE**	**99.8% discrimination 200 kV HV, 10% LCE**	**99.9% discrimination 200 kV HV, 15% LCE**
ER: pp solar ν	230	1.15	0.46	0.24
ER: Kr or Rn	46	0.23	0.09	0.05
NR: atmospheric ν	0.50	0.25	0.25	0.25
NR: DSNB ν	0.10	0.05	0.05	0.05
Total (5:30 keVnr)		**1.7**	**0.8**	**0.6**

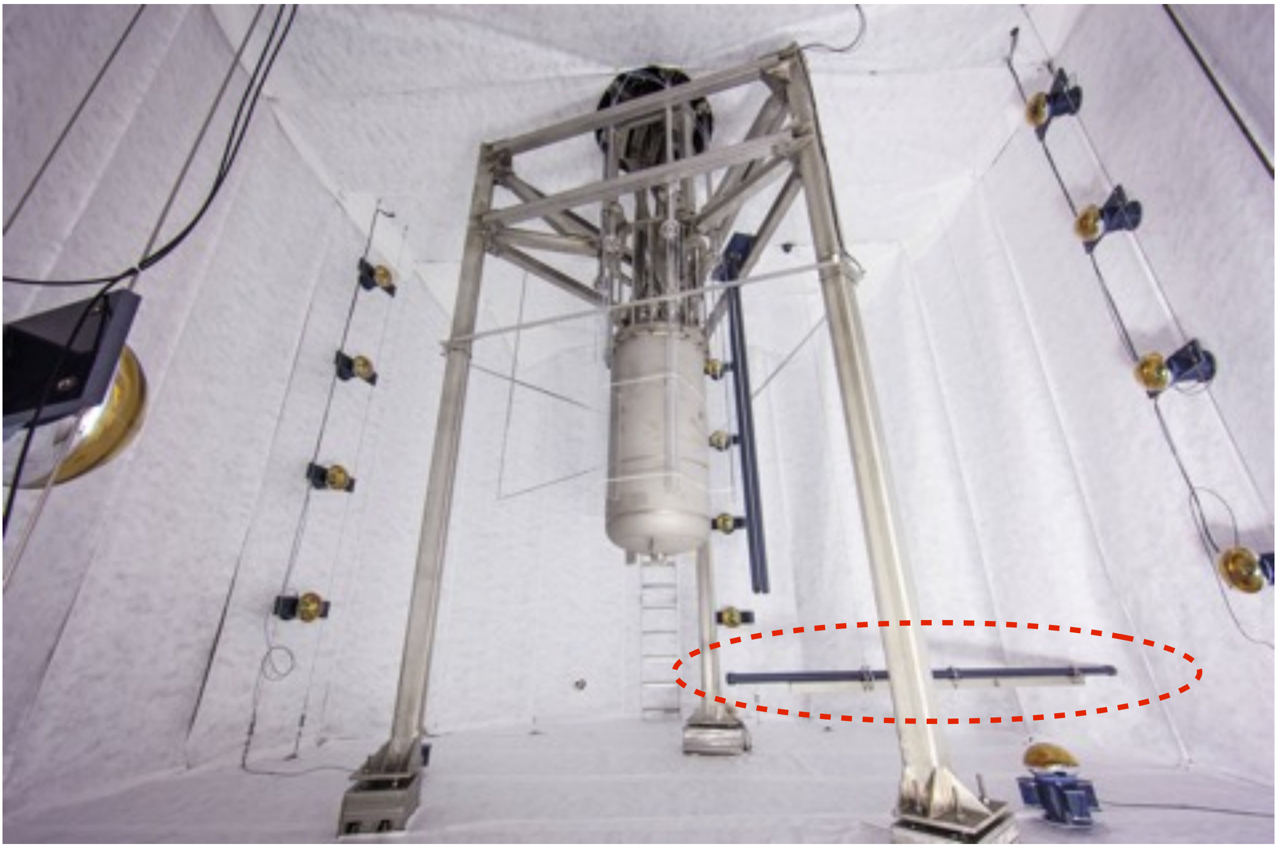
Electron lifetime during first WIMP search



In-situ low-energy nuclear recoil calibration

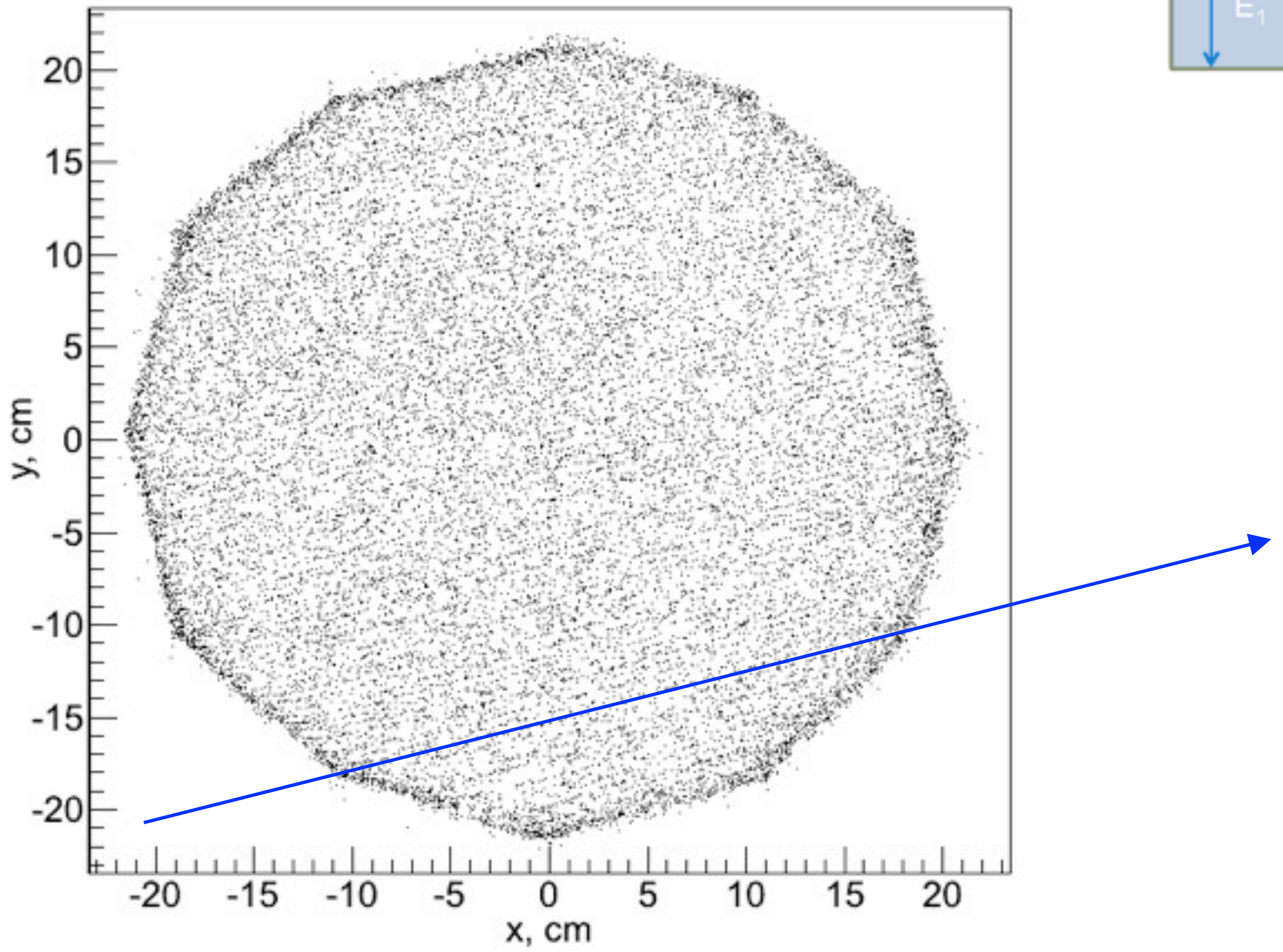
- Mono-energetic neutron beam (DD generator), water collimated
- x-y imaging determines kinematics
- Separate S2 signals, combined S1 signal
- Results anticipated @ Lake Louise

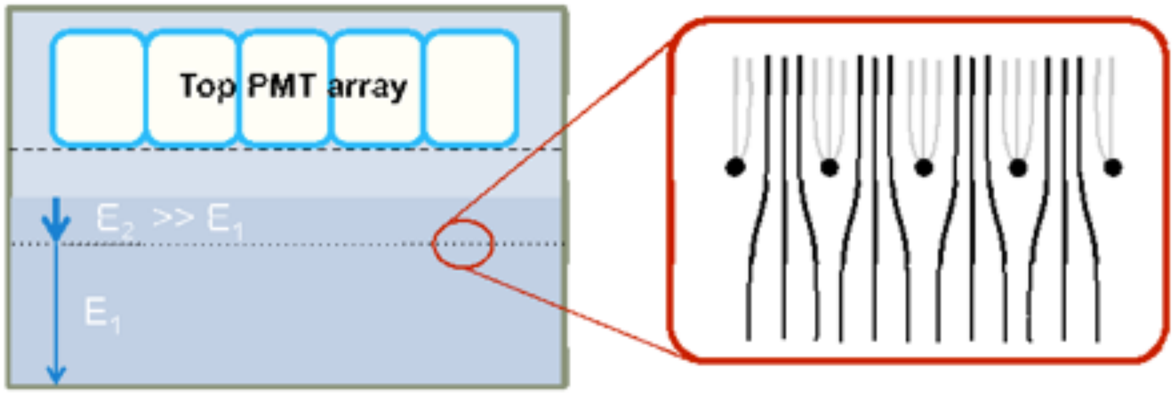




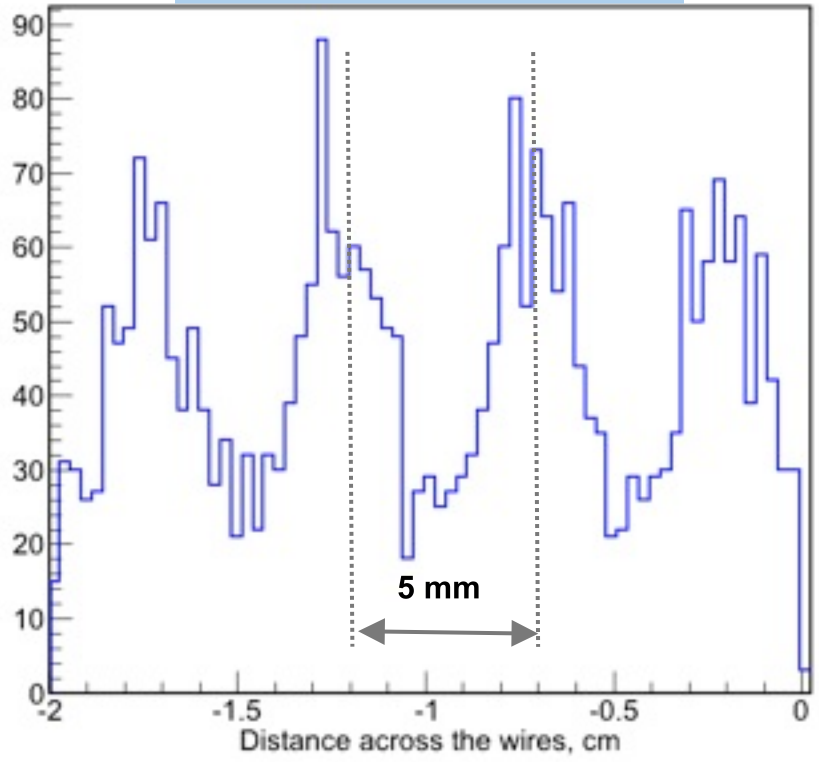
Position reconstruction

Resolve gate wire grid for high energy events





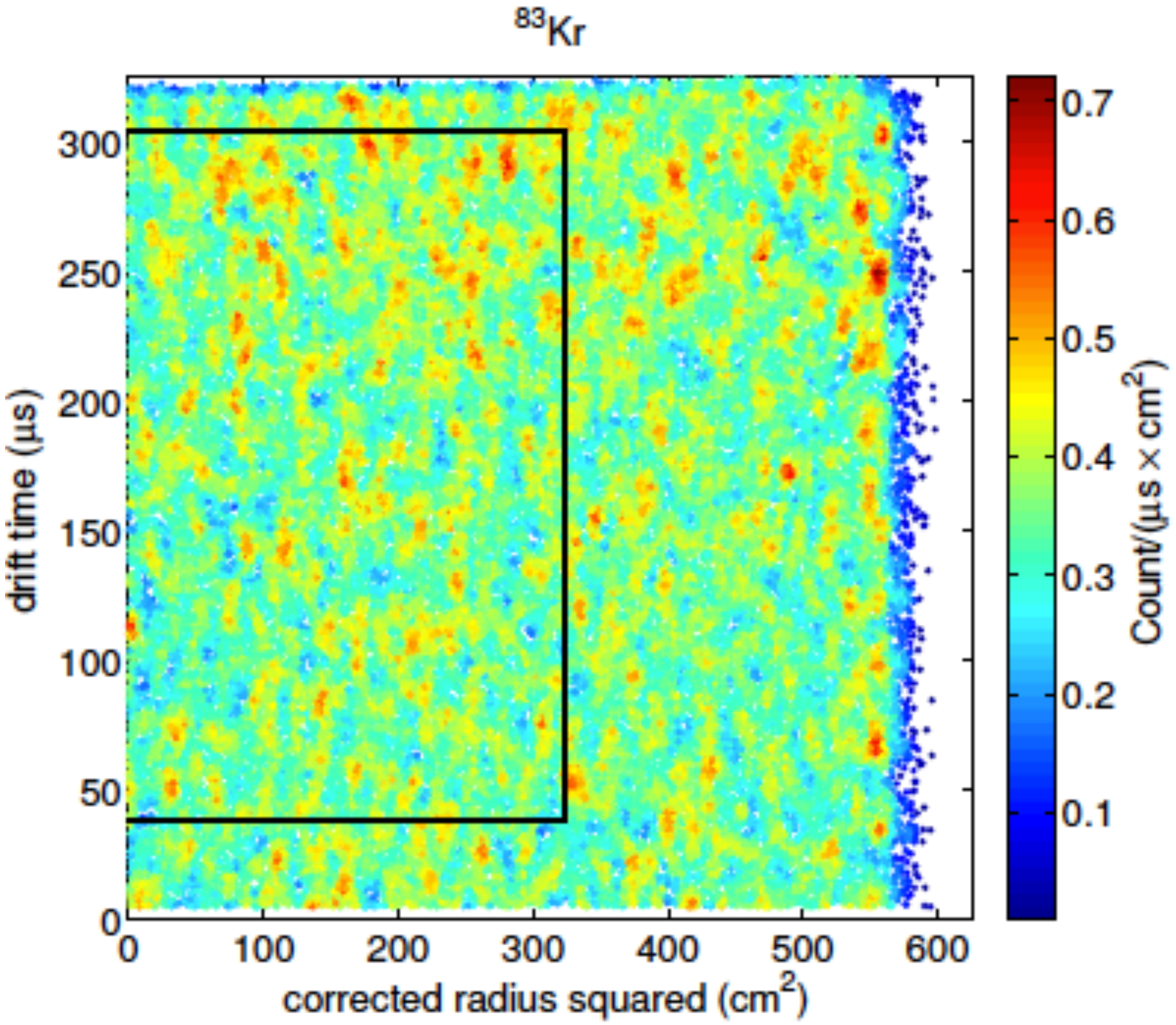
Projection along the wires

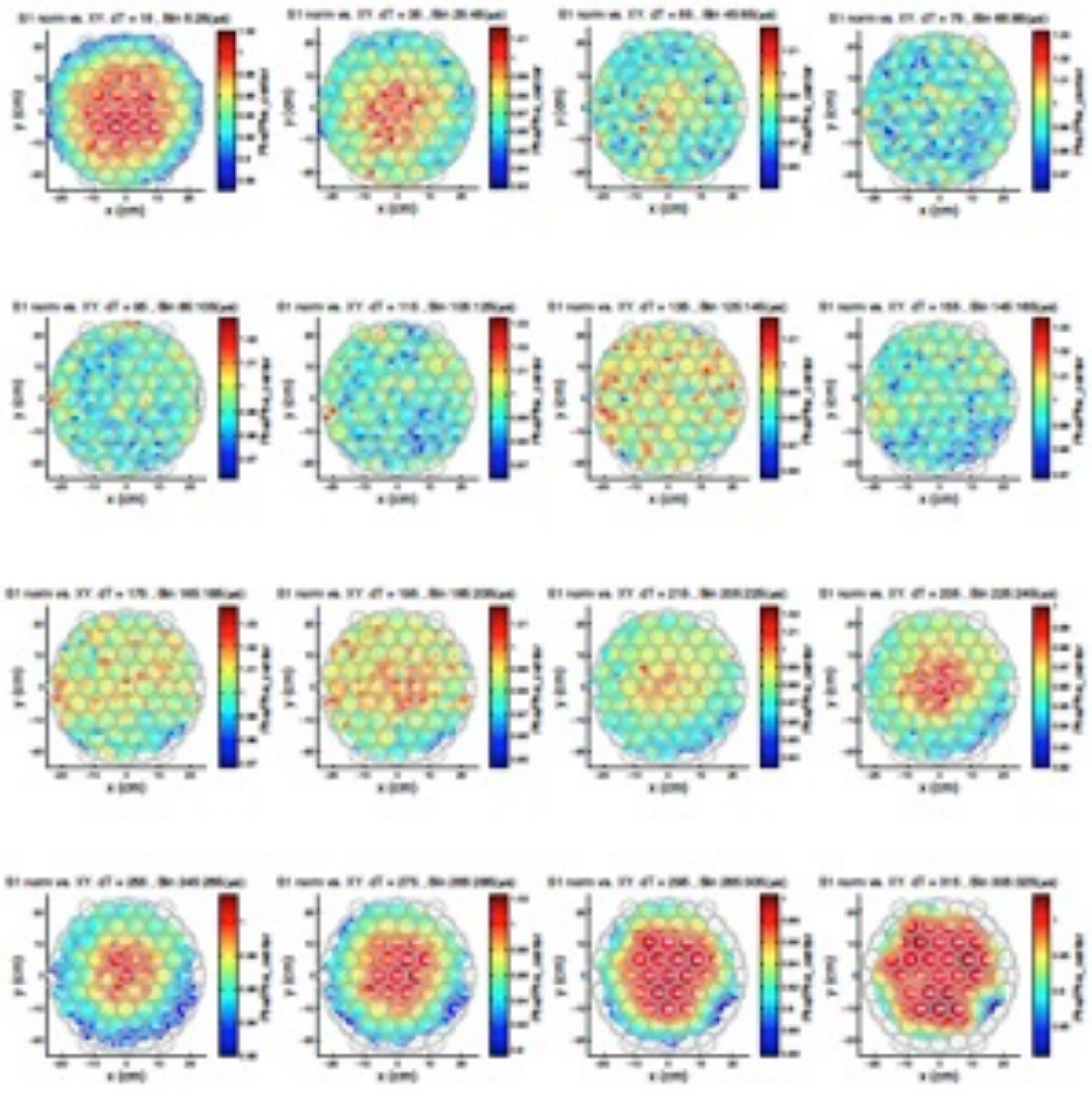


Use ^{83m}Kr source data to calibrate light response

Internal source with 1.8 hr half-life

Two internal conversion electrons: 32 keV followed by 9 keV



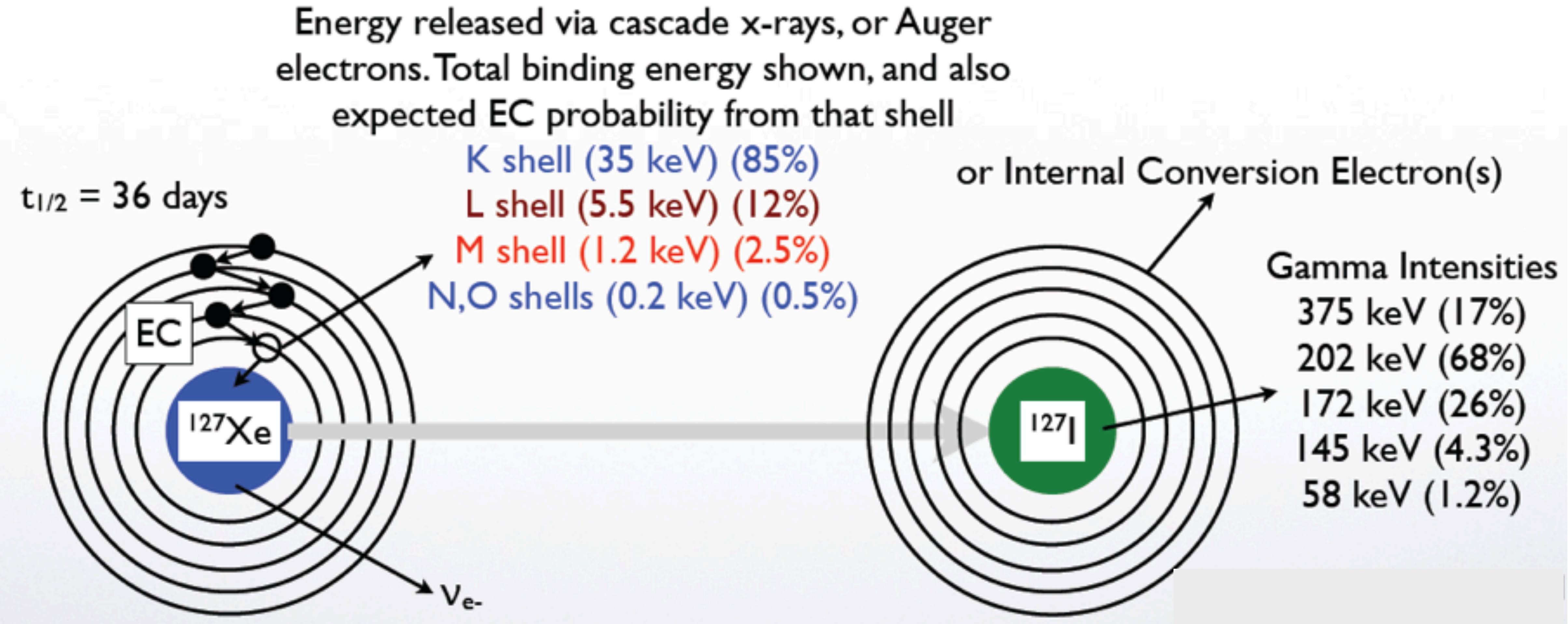


Define fiducial volume r < 18 cm, 7 < z < 47 cm, corresponding to 118±6 kg fiducial mass

^{127}Xe Background

Electron capture from S-wave orbital,

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



Energy released via cascade x-rays, or Auger electrons. Total binding energy shown, and also expected EC probability from that shell

K shell (35 keV) (85%)
L shell (5.5 keV) (12%)
M shell (1.2 keV) (2.5%)
N,O shells (0.2 keV) (0.5%)

or Internal Conversion Electron(s)

Gamma Intensities
375 keV (17%)
202 keV (68%)
172 keV (26%)
145 keV (4.3%)
58 keV (1.2%)

Set frequentist one-sided upper limit

Use profile likelihood ratio as test statistic

Fixed point to test

Nuisance parameters, not fixed

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

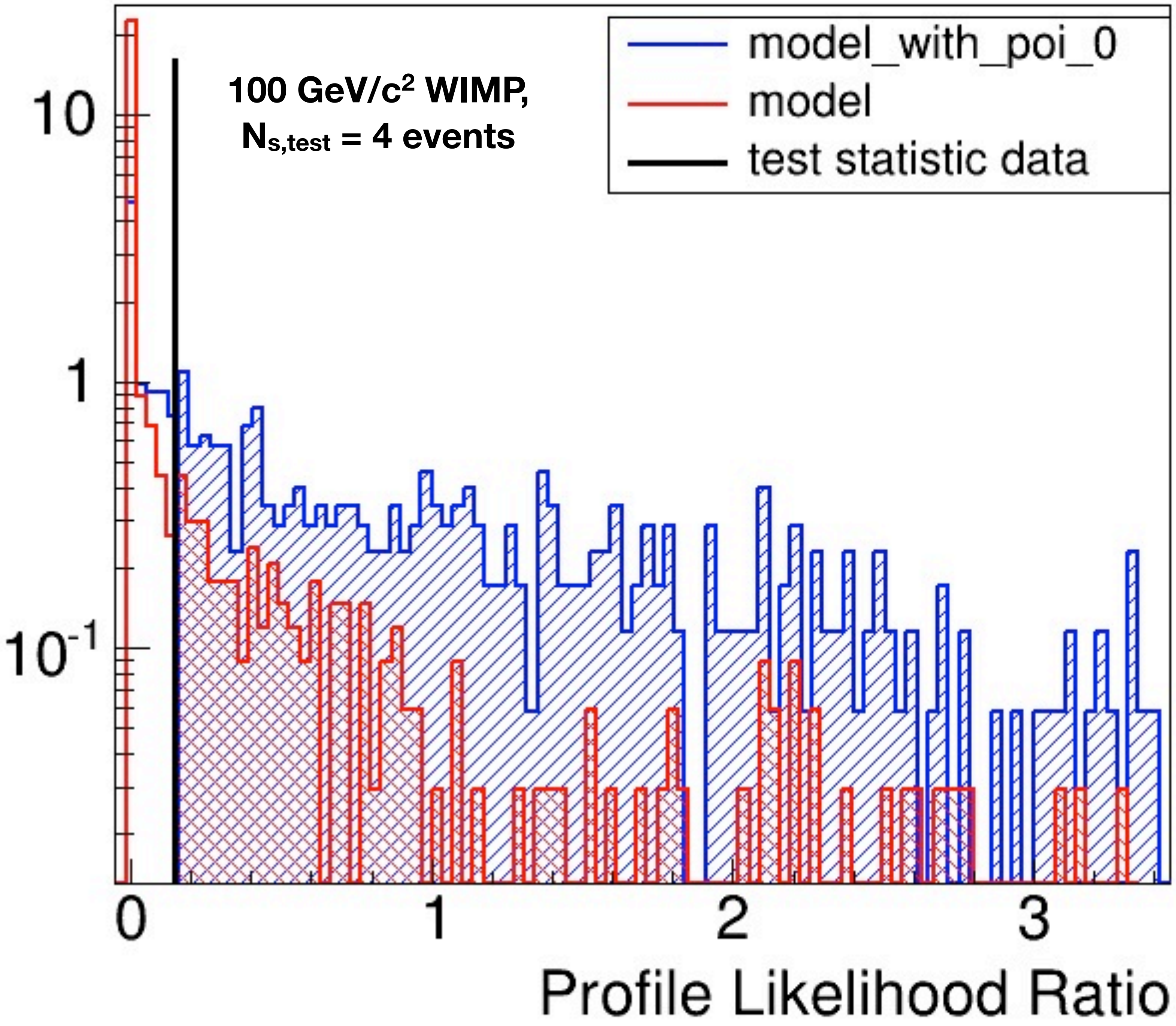
Value of maximum likelihood

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

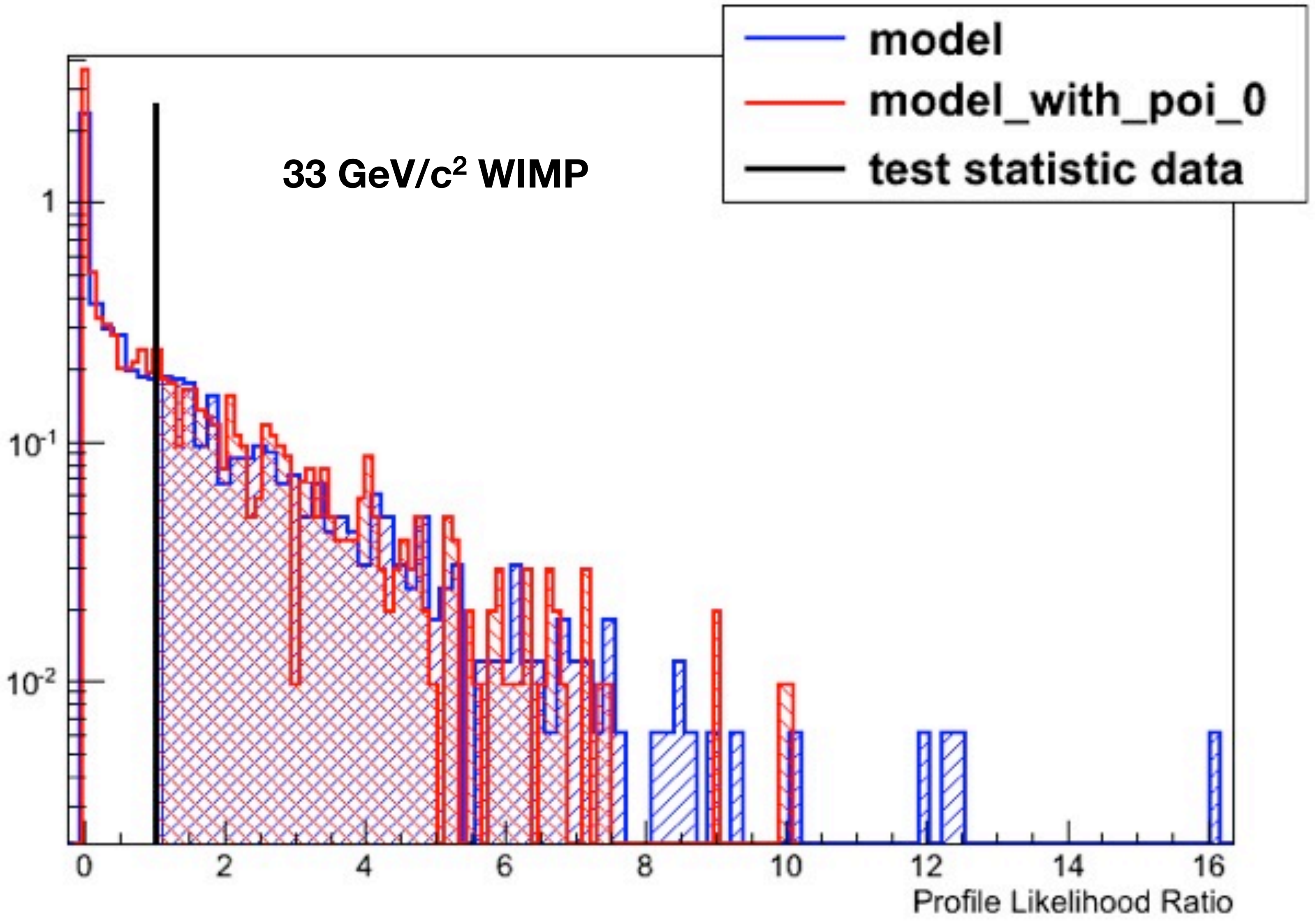
Generate pseudo-experiments for $\boldsymbol{\sigma}_{\text{test}}$, compare the value of test statistic in data with the value of $q_{\sigma,i}$ from each pseudo-experiment

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

Hypothesis tests

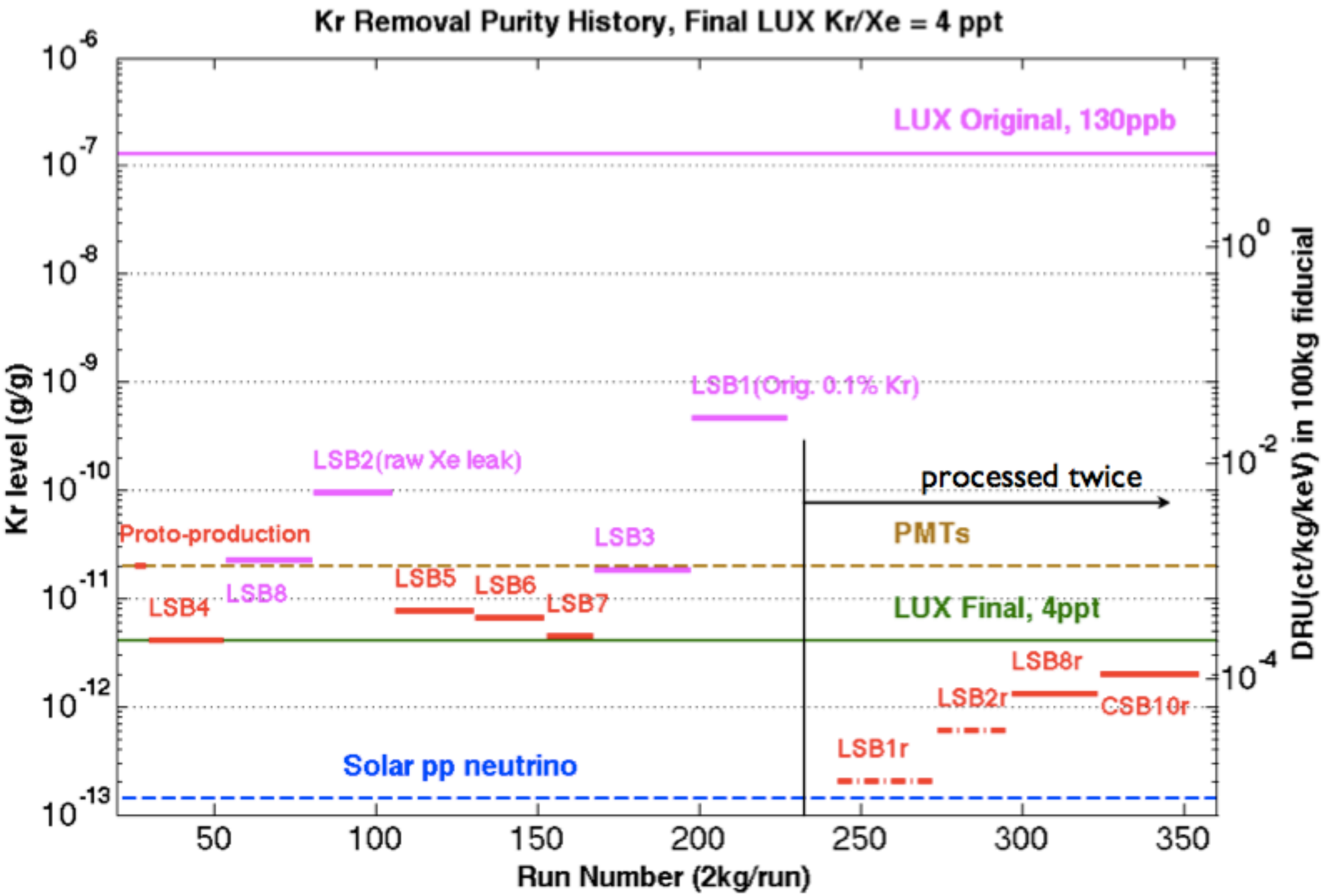


Null hypothesis test

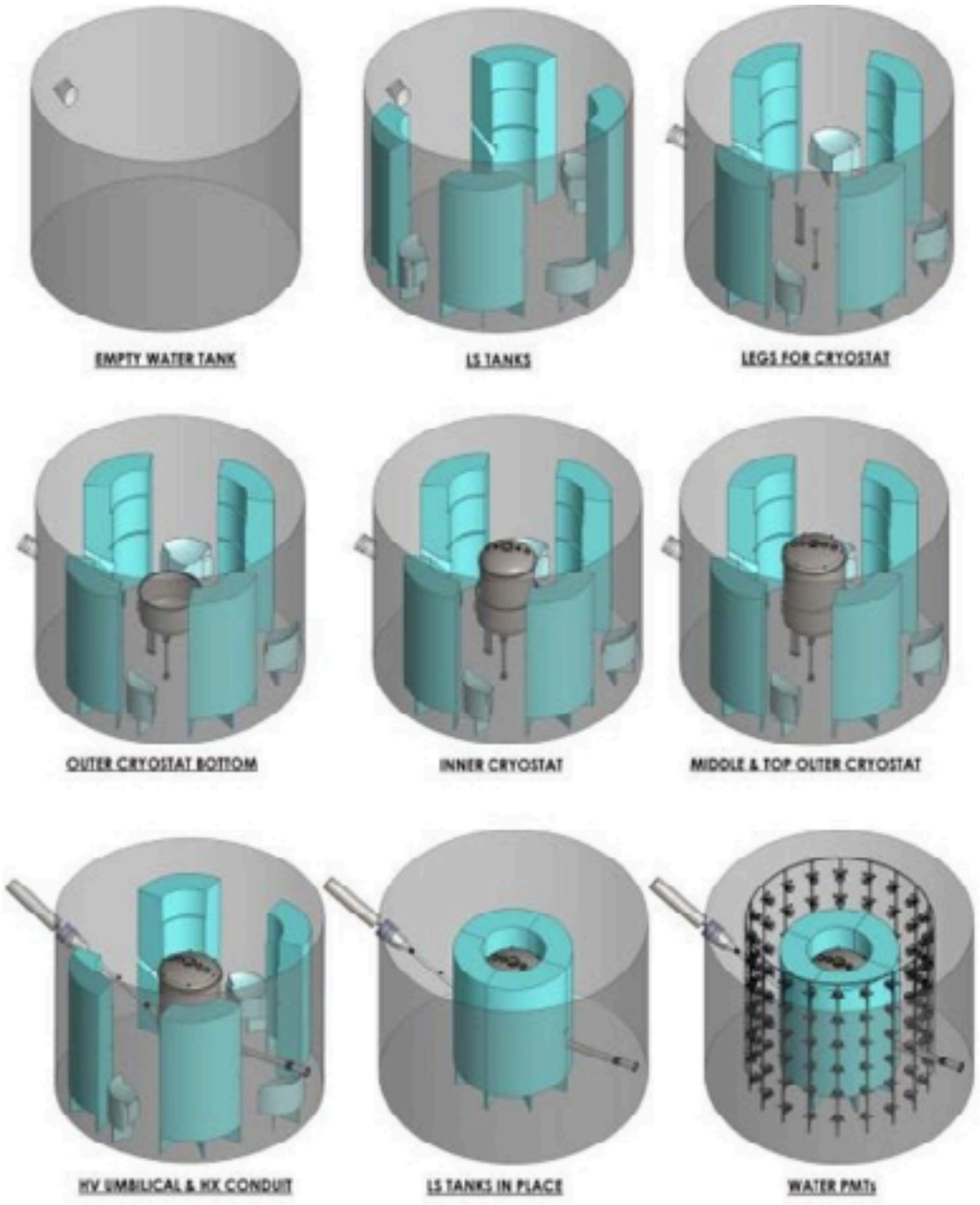


Observe null p-value of 34% at 33 GeV/c^2, corresponding to 0.4σ significance

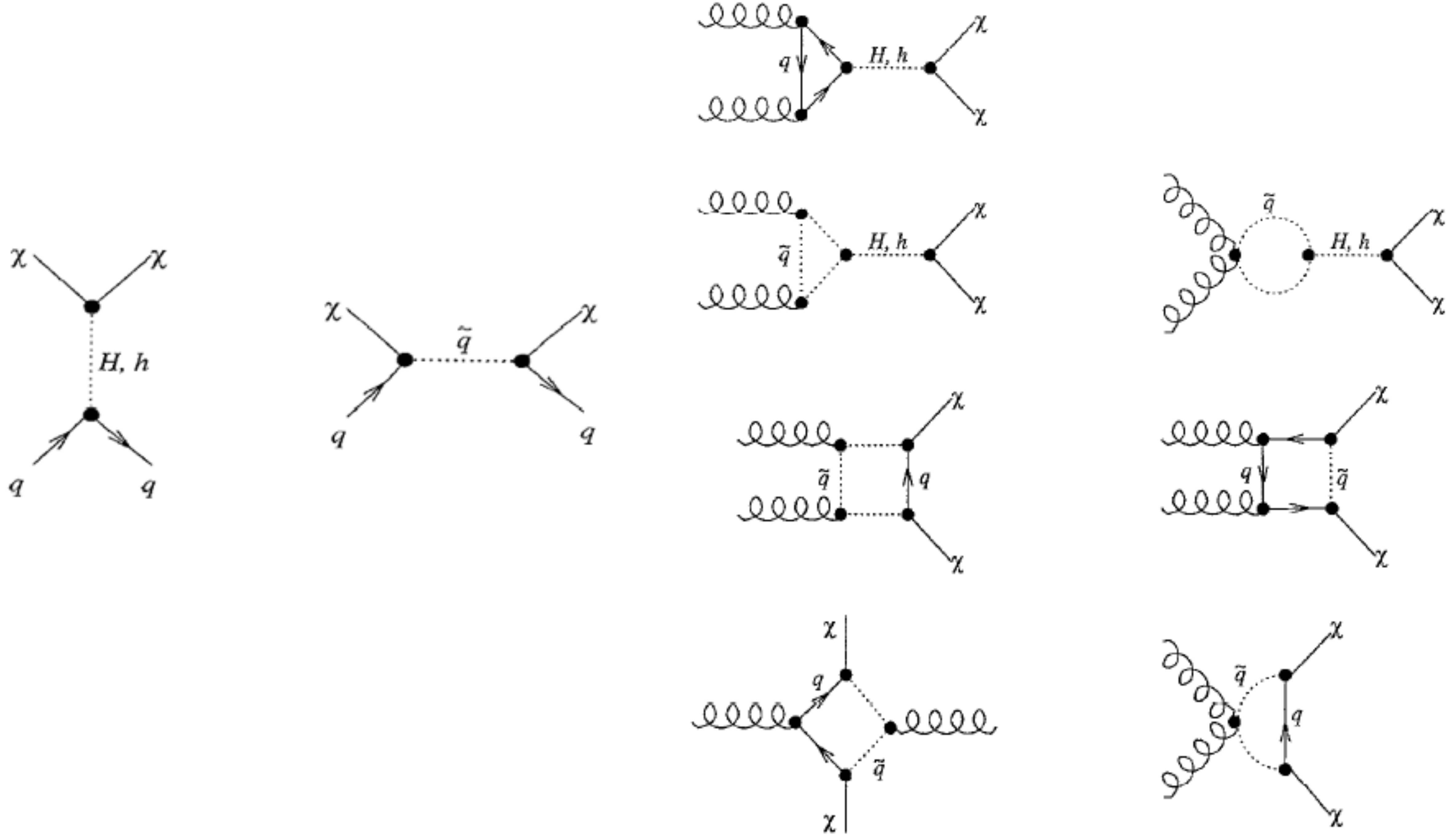
LUX Kr removal



LZ deployment



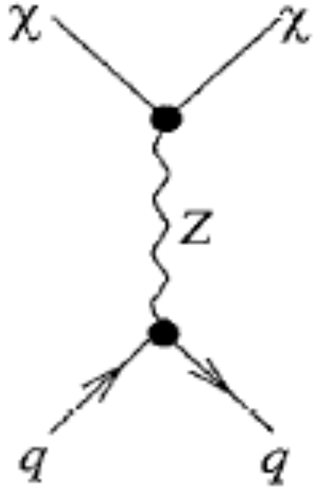
Spin-independent contributions to WIMP scattering from quarks and gluons

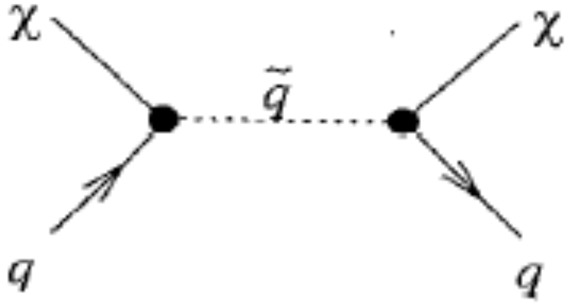


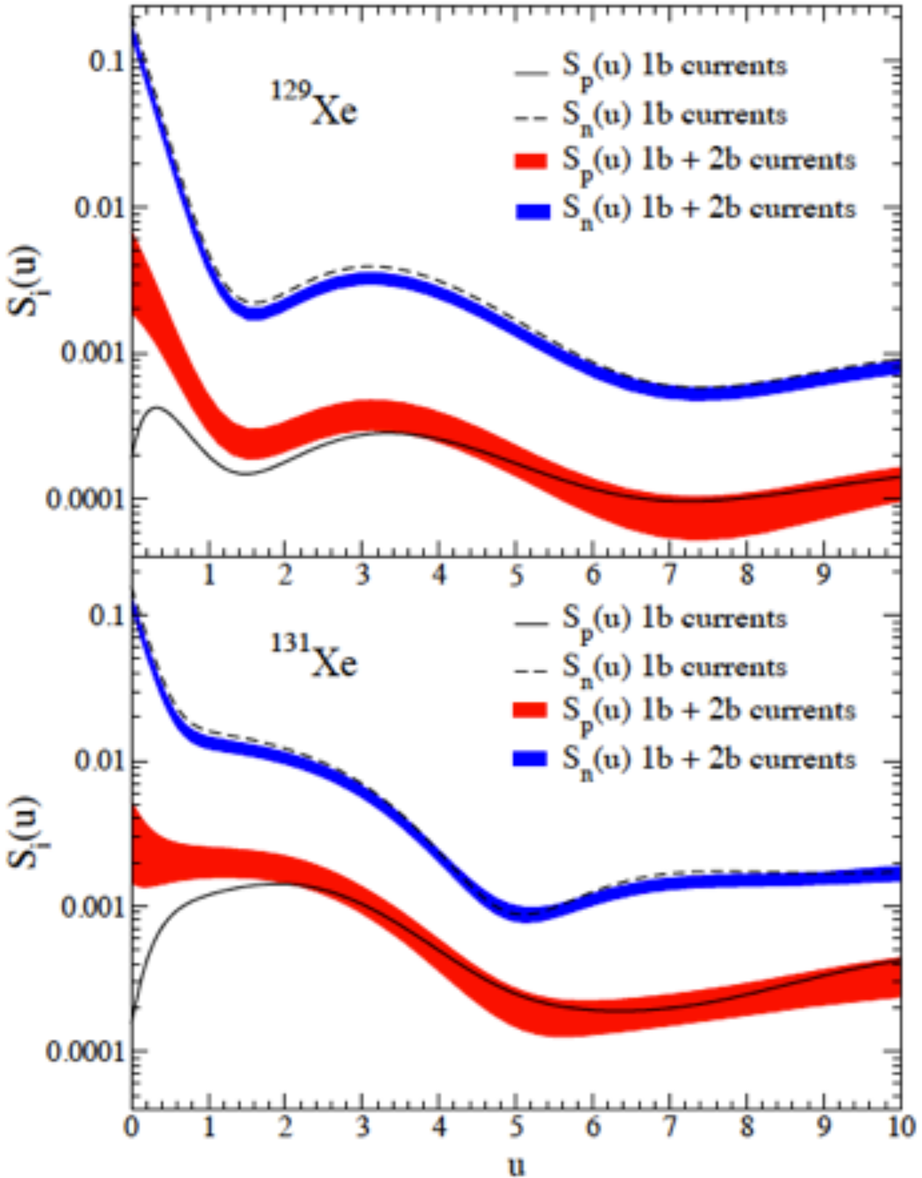
Spin-dependent scattering

$$\frac{dR}{dE_R} = N_T \frac{m_A \sigma_{0,A}}{2\mu_A} S_A\left(E_R\right) \cdot \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{\infty} d^3v \frac{f\left(v, v_e\right)}{v}$$

$$\boxed{\sigma_{0,A} = \frac{4\mu_A^2 \pi \sigma_{0,n}}{3\mu_n^2 \left(2J+1\right)}}$$

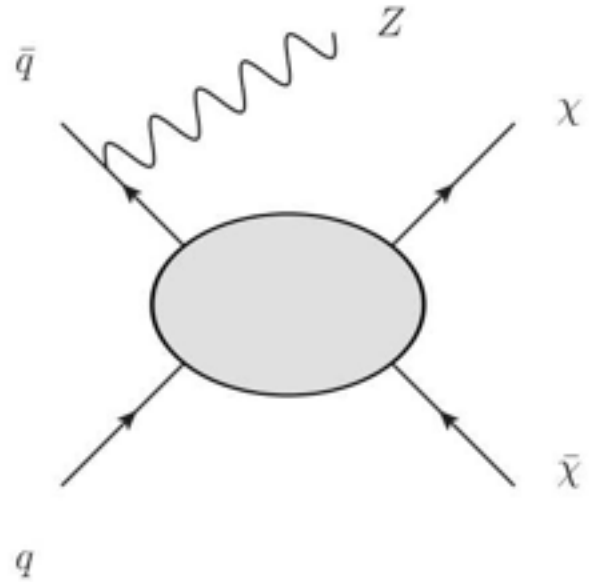


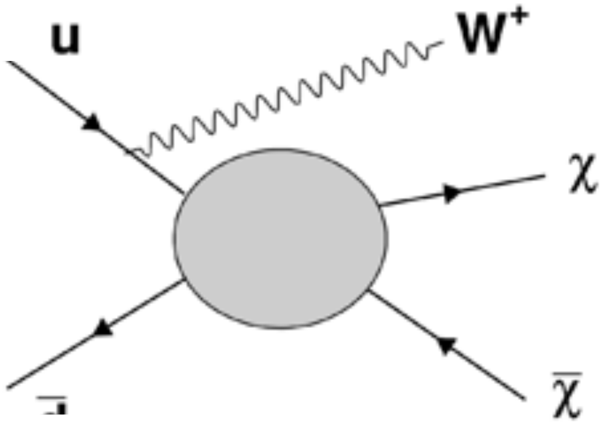




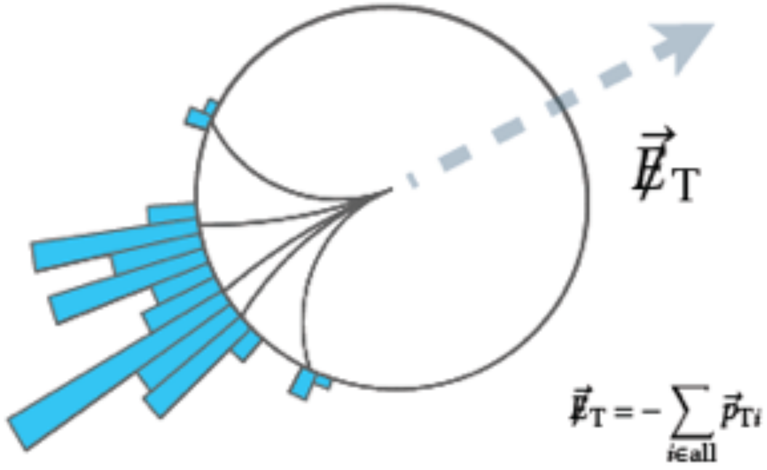
Klos, Menendez, et al (2013)

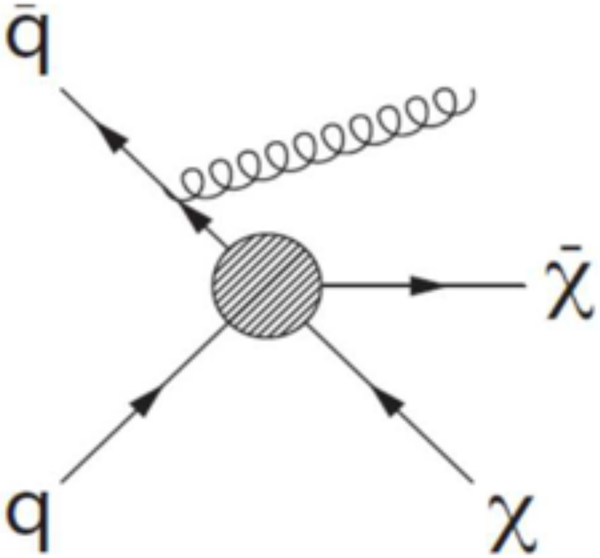
Dark matter production - collider searches





In the most generic dark matter searches, look for initial state radiation + missing energy



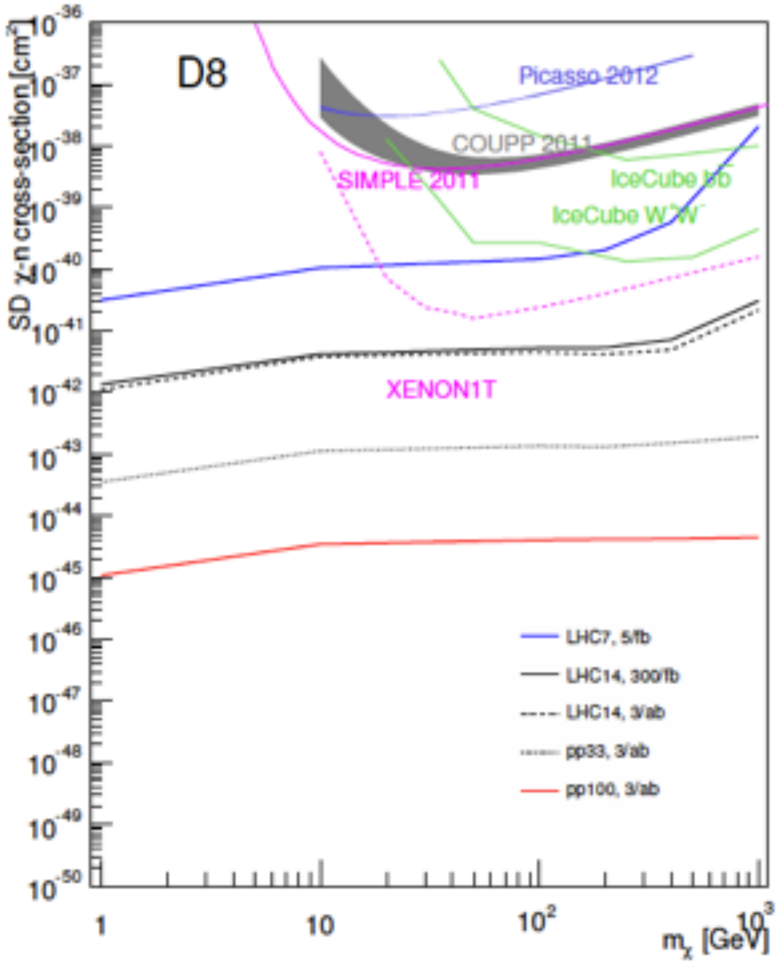


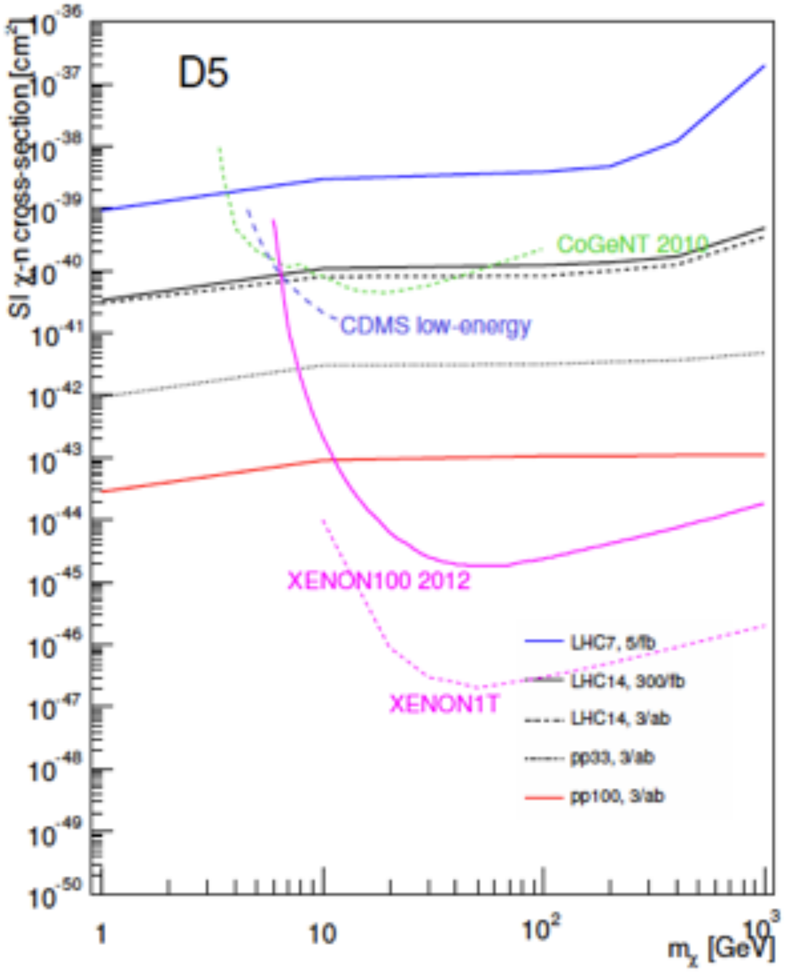
Collider sensitivity

For comparison with direct detection experiments, convert to scattering off nucleon

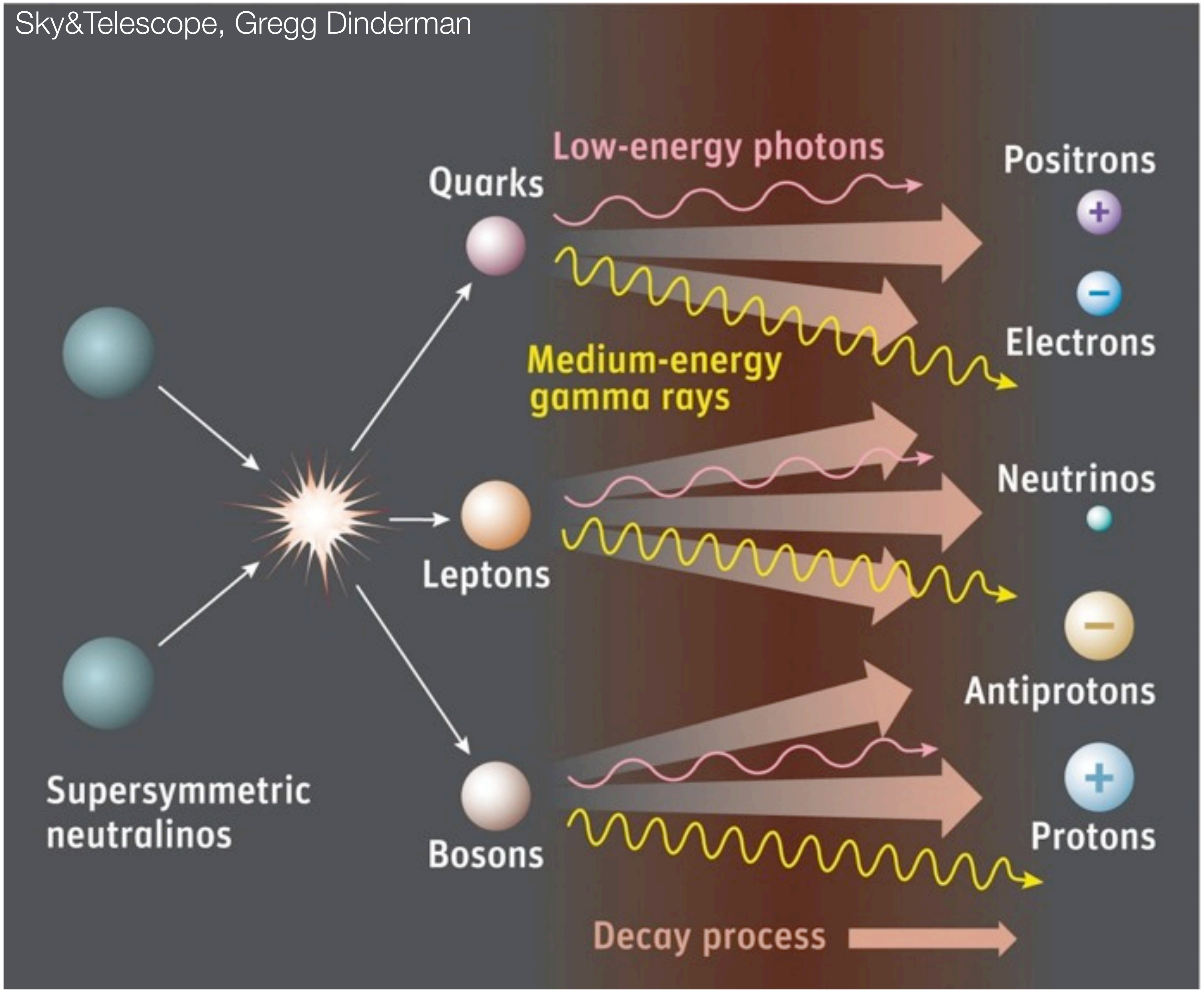
$$\sigma_{SI}^{UL} = 9\frac{\mu^2\sigma_{\chi\chi}^{UL}}{\pi M^4\sigma_{\chi\chi}^{calc}} \text{ where } \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

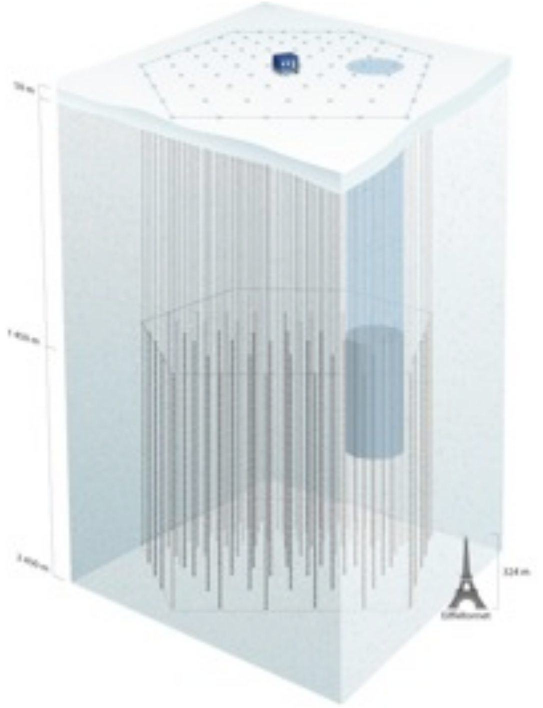
Zhou et al, axxiv:1307.5327





Dark matter annihilation - indirect searches


Sky&Telescope, Gregg Dinderman

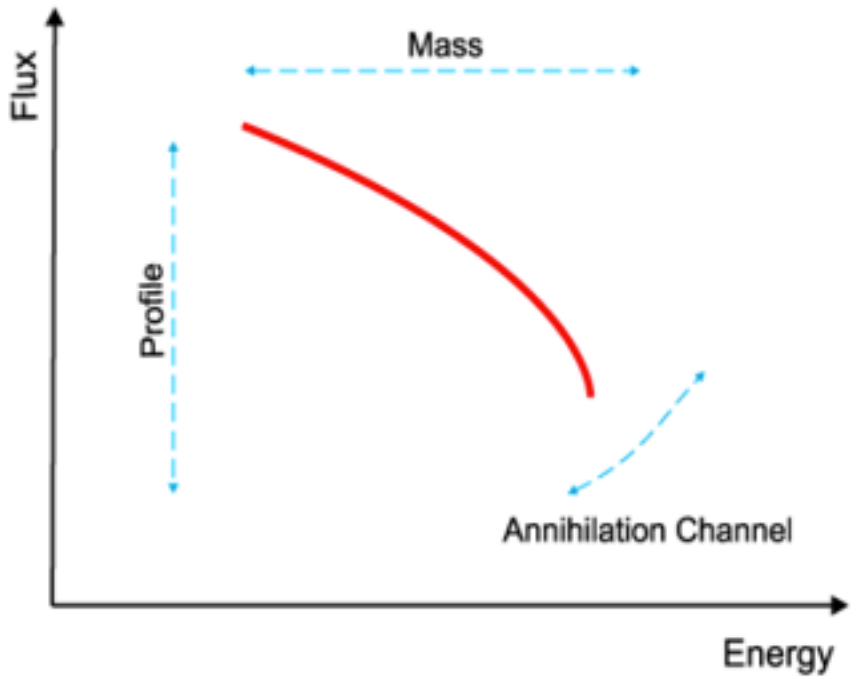


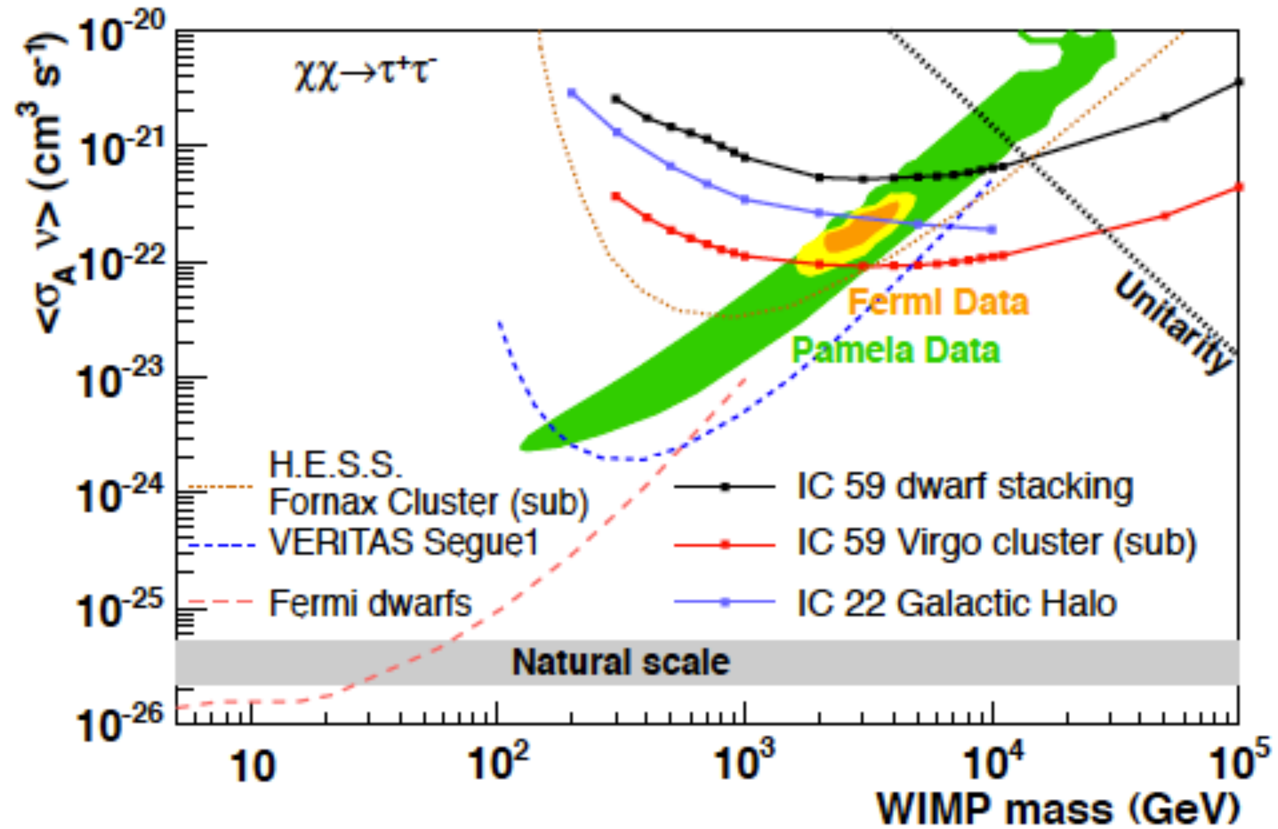
Indirect search limits

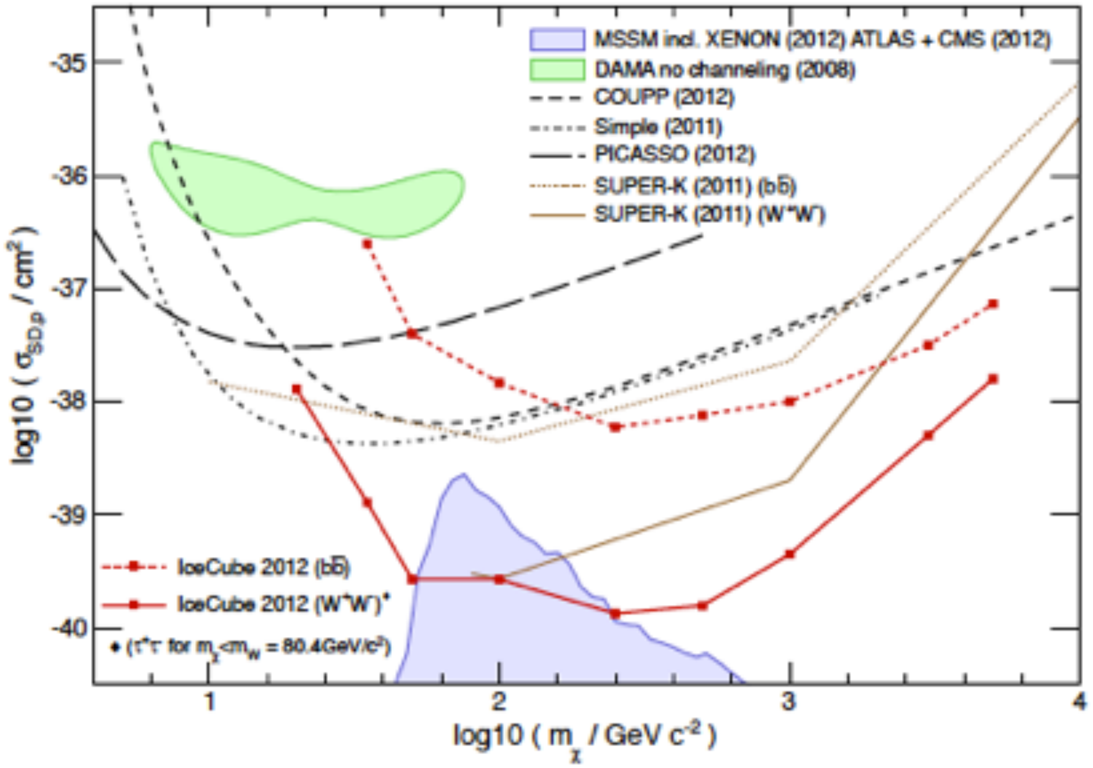
$$\frac{d\Phi}{dE} = K \cdot J$$

$$K_{\mathrm{ann}} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{\langle\sigma v\rangle}{2m_\chi^2} \qquad J_{\mathrm{ann}}(\psi) = \frac{1}{4\pi}\int_{los} \mathrm{d}s\ \rho^2(s,\psi)$$

$$K_{\mathrm{decay}} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{1}{m_\chi \tau_\chi} \qquad J_{\mathrm{decay}}(\psi) = \frac{1}{4\pi}\int_{los} \mathrm{d}s\ \rho(s,\psi)$$

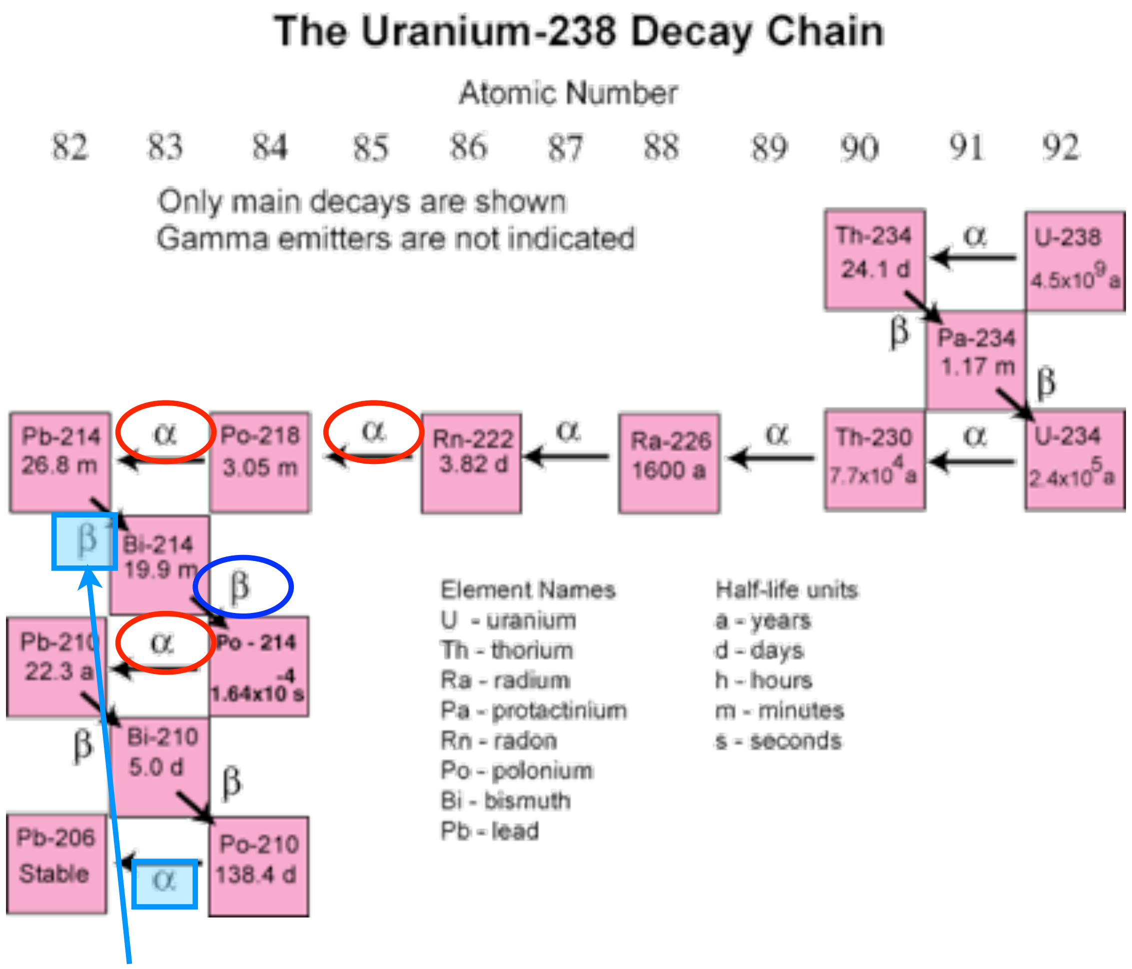




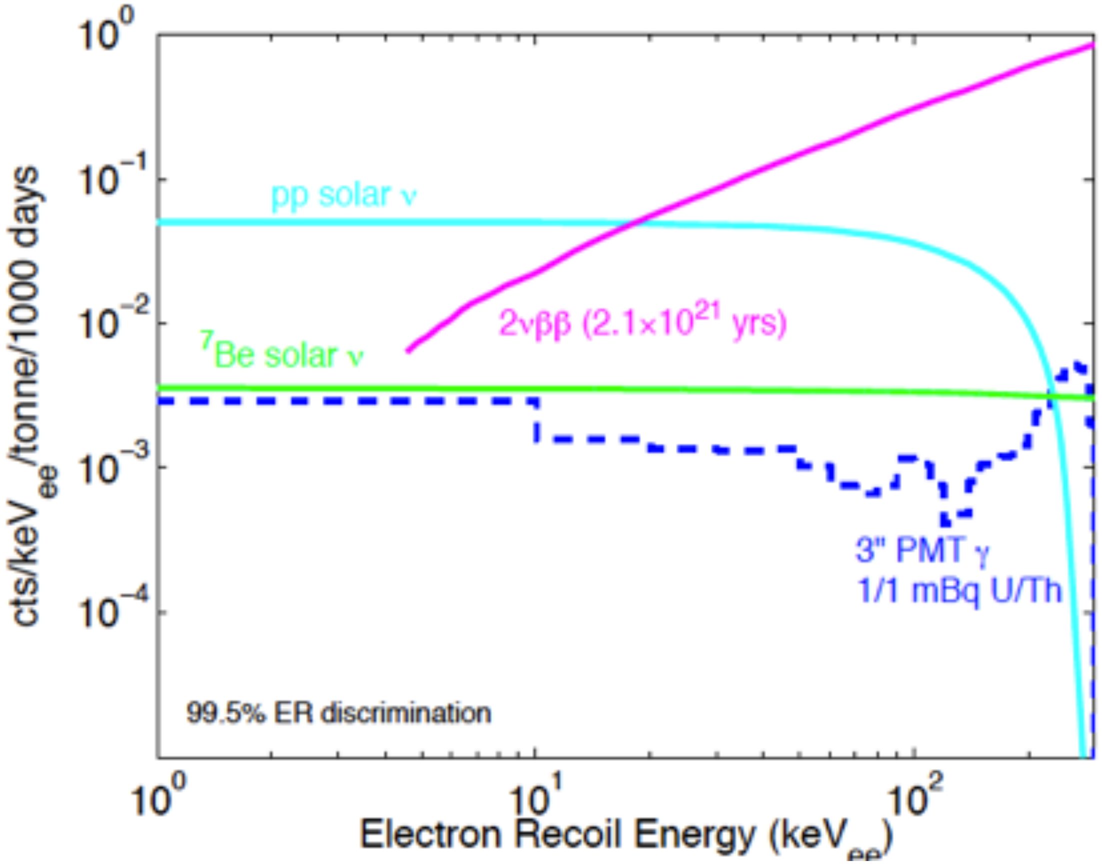


Rn screening program

- Rn screening for LZ experiment
    - Broadly useful capability with applications in many experiments
        - 0νββ
        - Dark matter
        - Low background physics in general
    - As L3 manager, LZ project has built in funds based on my cost estimates for Rn system at Case/UMD
    - Would like to have multiple systems, one at home lab, another developed underground near detector
- To meet LZ goal of observing pp solar ν, need to limit ^{214}Pb β decay background from ^{222}Rn emanation → require ≤ 0.67 mBq of ^{222}Rn decays in active region (0.01 dru/(mBq/kg))
    - Require that each item is limited to 0.035mBq emanation
    - Assuming 10 major detector components (e.g., cables, PMTs, feed-throughs, etc.) and a margin of error of 100% in meeting target rate
    - Desire screening sensitivity to O(1 μBq) level (may want/ need to screen only a fraction of total item)

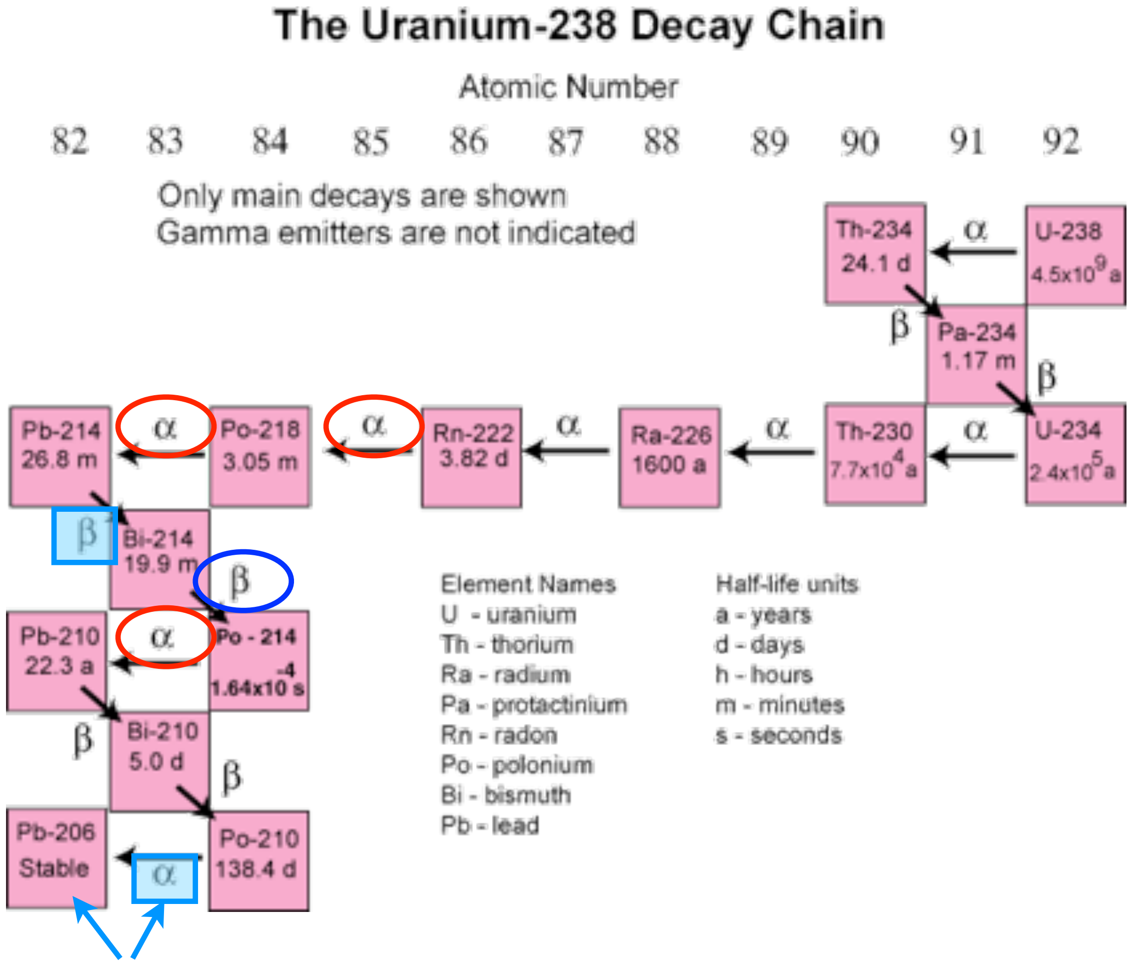


Background to solar ν signal, potential background to DM search

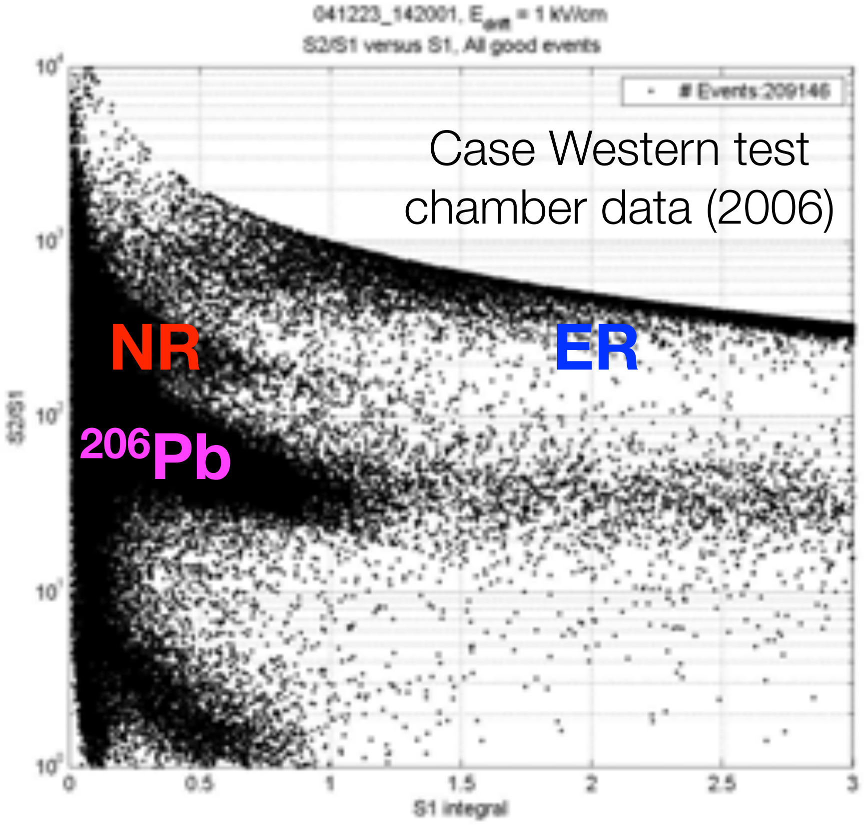


LZ background studies

- Develop small test Xe chamber for background studies
    - ^{206}Pb recoils are a major background in WIMP search, can significantly affect energy threshold → study backgrounds in ^{210}Pb plated on samples of PTFE
    - Excellent research experience for students, postdocs to learn to operate Xe chamber- can play vital role in LZ commissioning, operations
    - Opportunity to contribute expertise to large test chambers developed at SLAC/LBNL

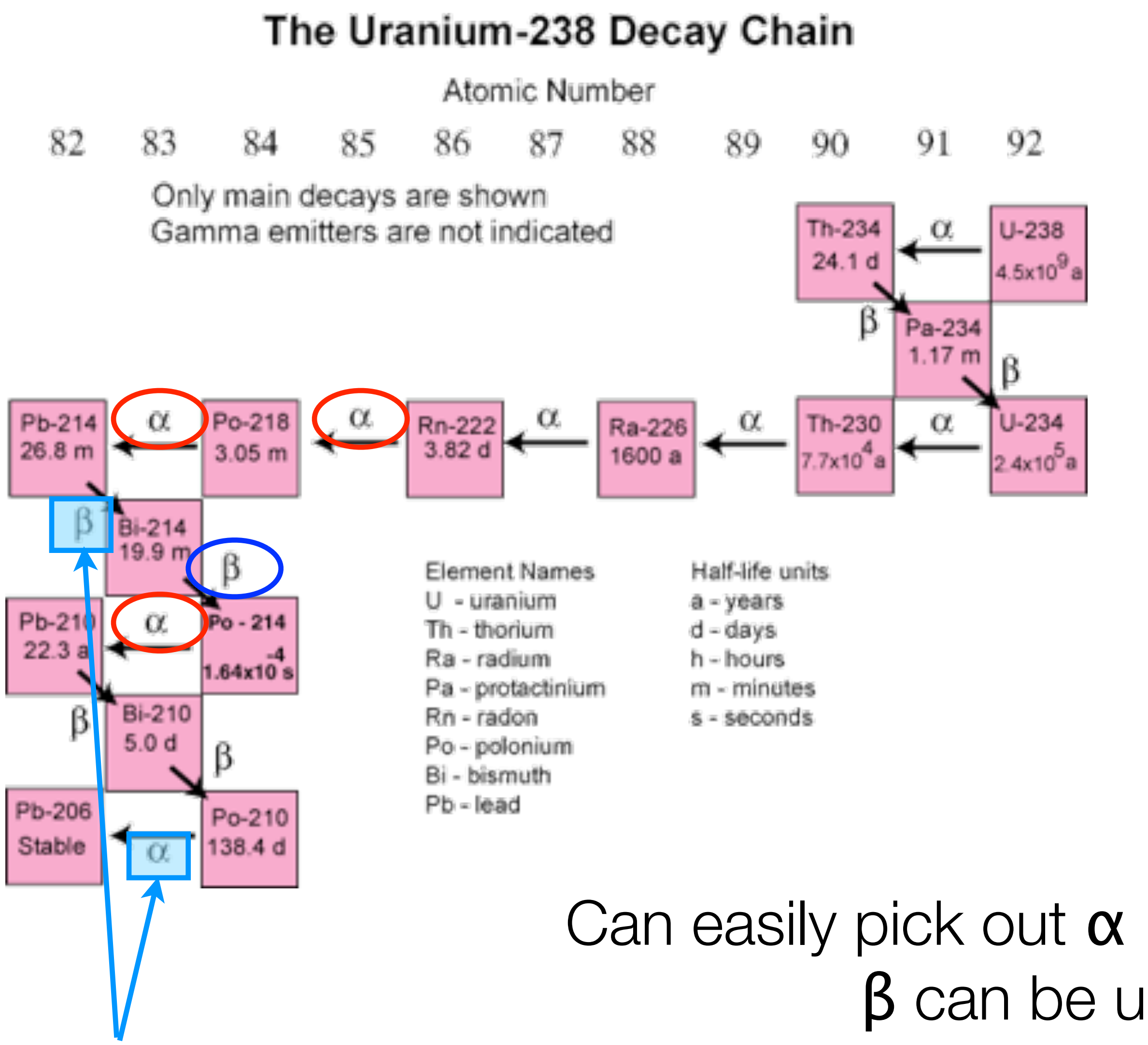


^{210}Pb will plate onto the walls, half of the time see the α decay in detector, half the time see the ^{206}Pb recoil

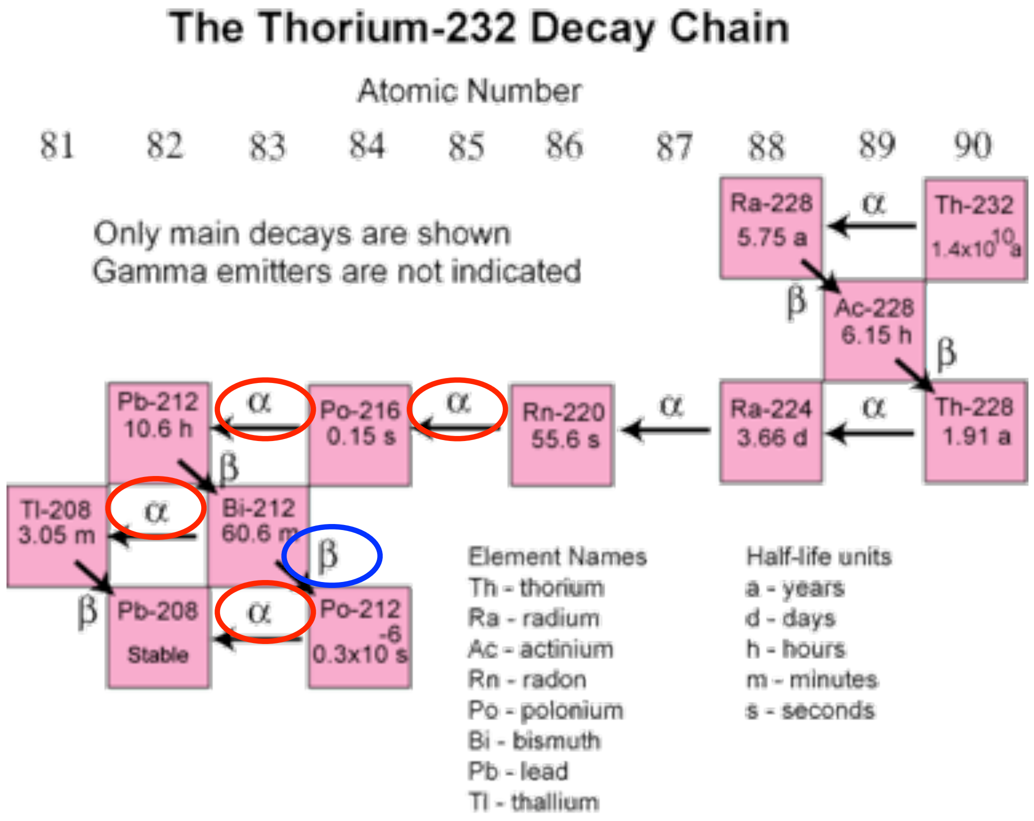


Case Western test chamber data (2006)

Radon-related backgrounds

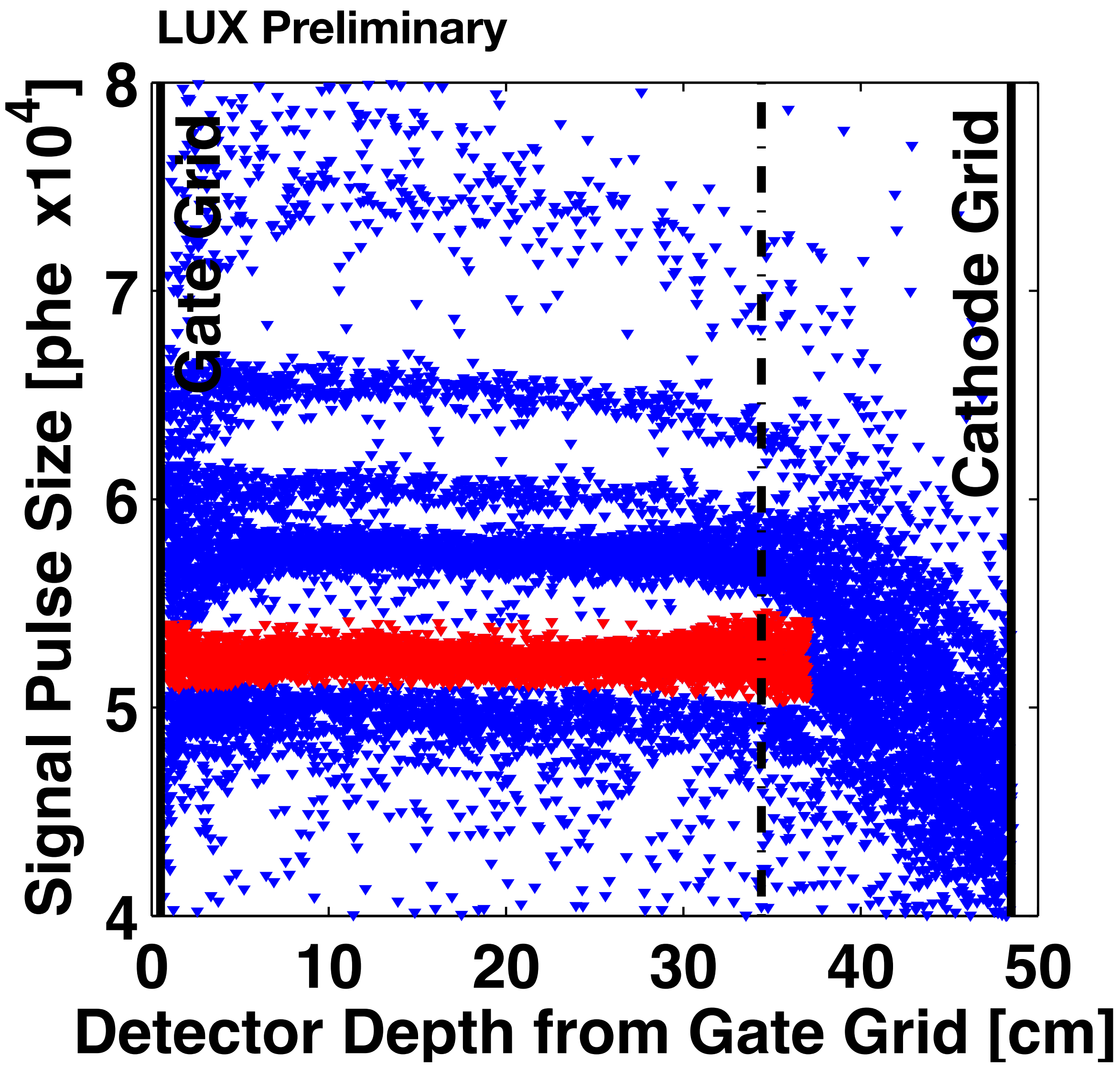


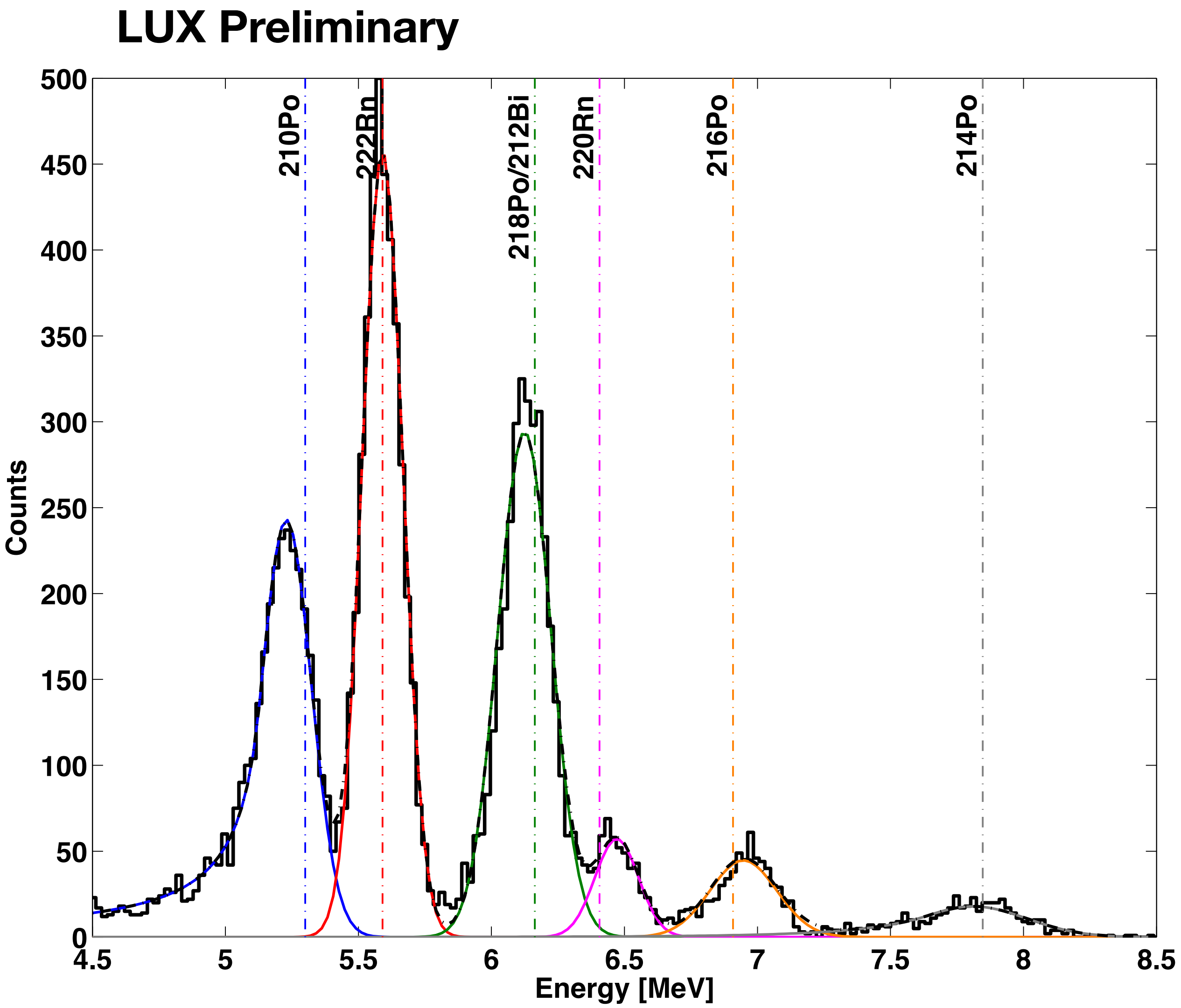
Potential backgrounds in DM search region



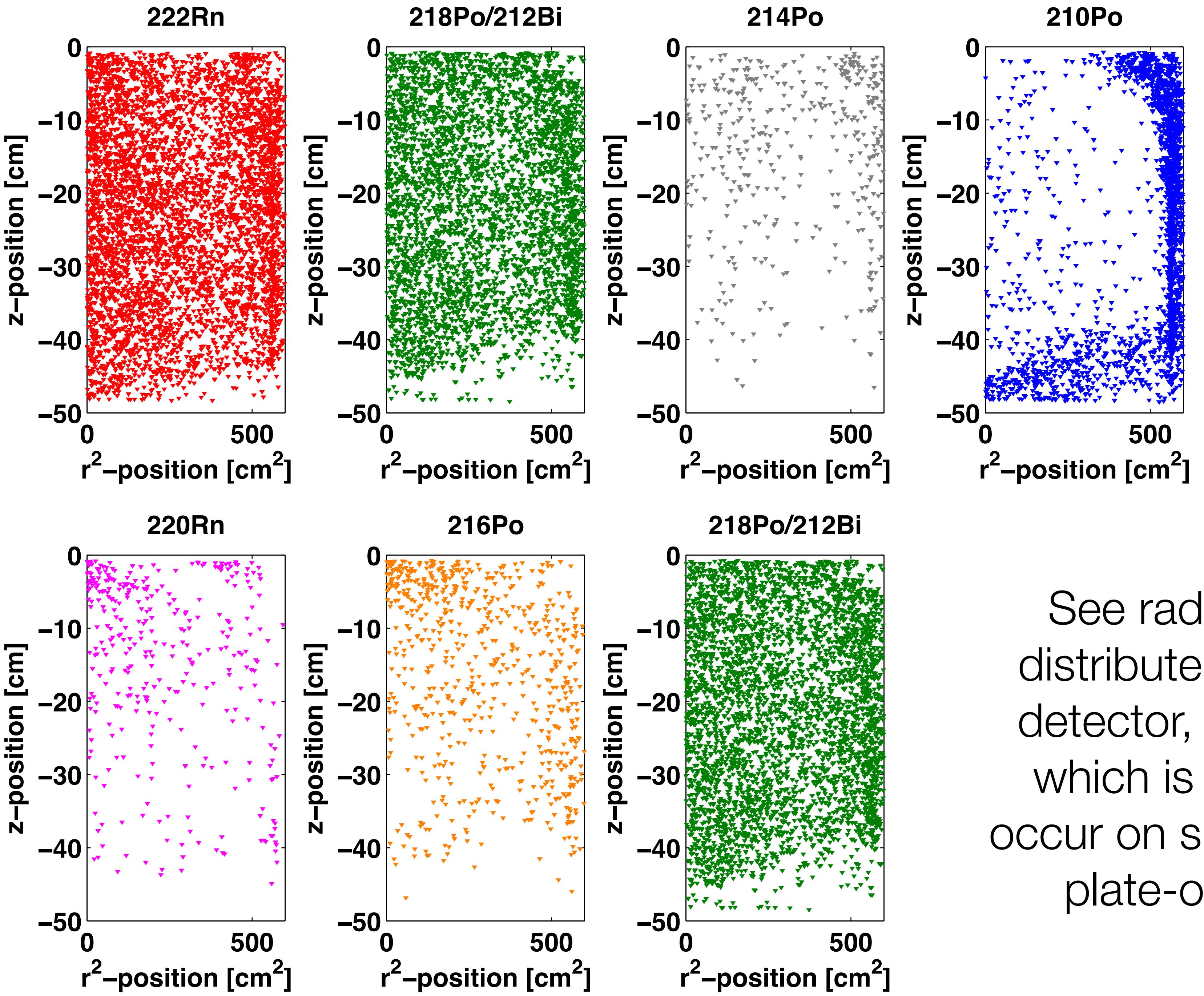
Can easily pick out α recoils in data due to high light to charge ratio, β can be used to tag Bi-Po coincident decays

Estimating Rn-related backgrounds in data



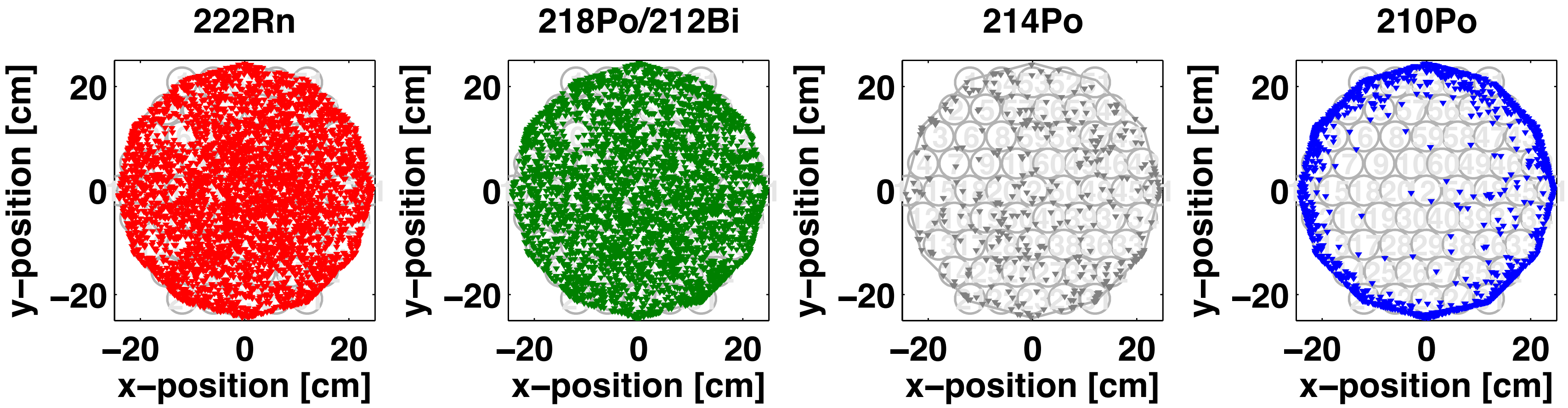


Where are the Rn daughters located?

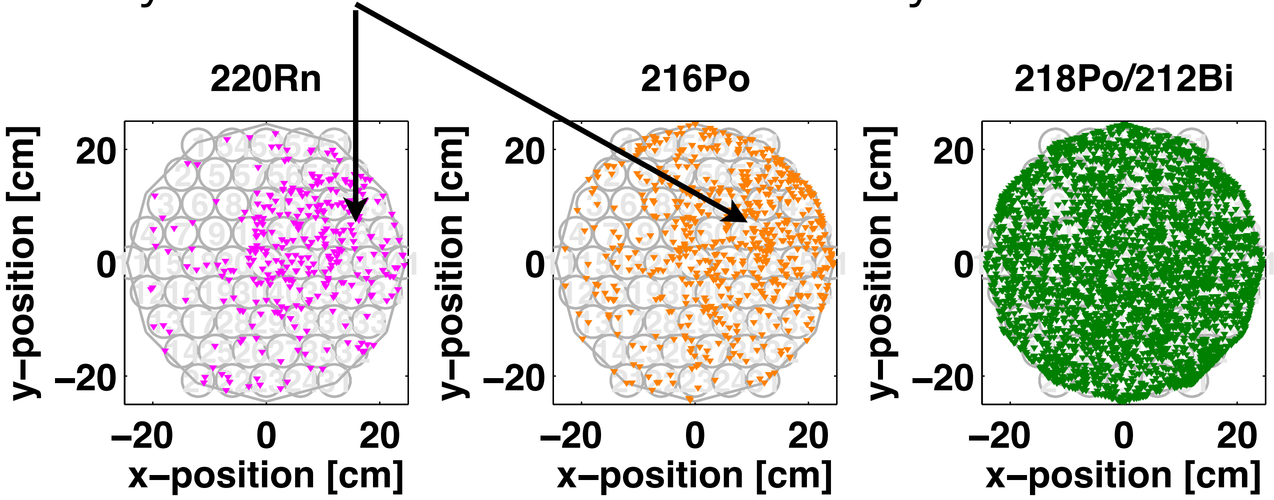


See radon progeny distributed throughout detector, except ^{210}Po which is expected to occur on surfaces due to plate-out of ^{210}Pb

Top-down view of Rn progeny

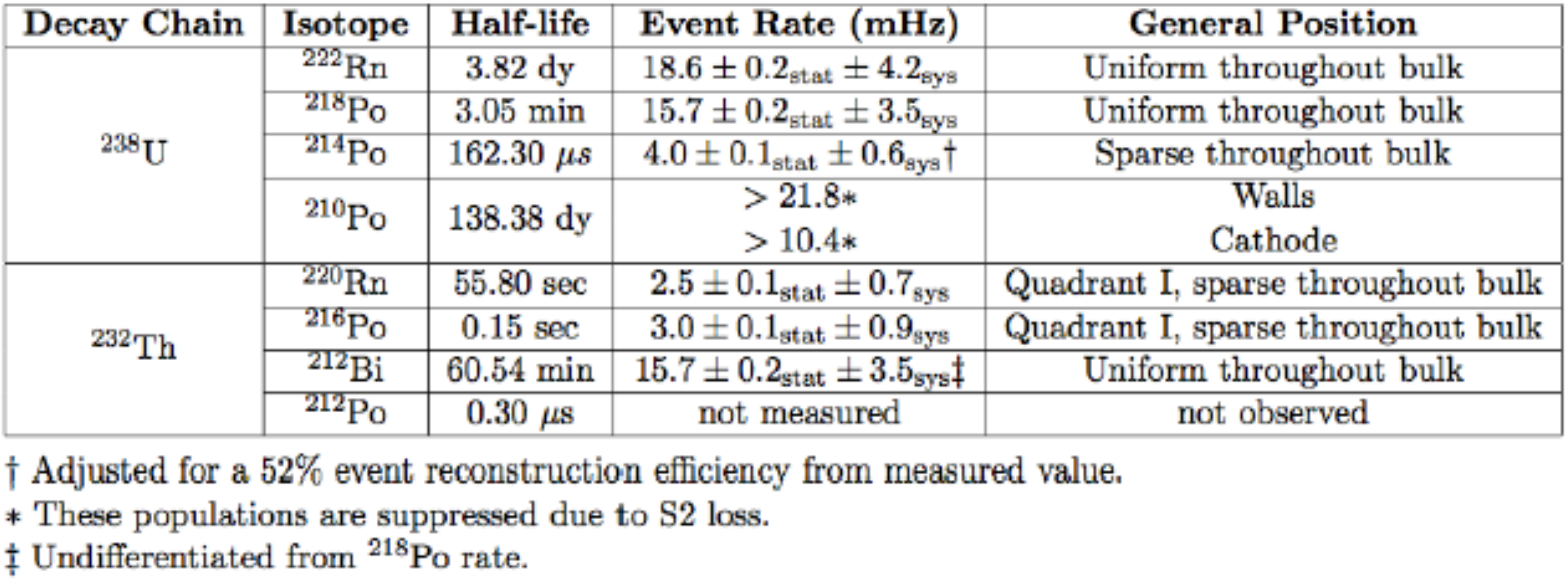


See x-y localization of thoron decays



Measured rates of α recoils from Rn chain

LUX Preliminary



Decay Chain	Isotope	Half-life	Event Rate (mHz)	General Position
^{238}U	^{222}Rn	3.82 dy	$18.6 \pm 0.2_{\text{stat}} \pm 4.2_{\text{sys}}$	Uniform throughout bulk
	^{218}Po	3.05 min	$15.7 \pm 0.2_{\text{stat}} \pm 3.5_{\text{sys}}$	Uniform throughout bulk
	^{214}Po	162.30 μs	$4.0 \pm 0.1_{\text{stat}} \pm 0.6_{\text{sys}}\dagger$	Sparse throughout bulk
	^{210}Po	138.38 dy	$> 21.8*$ $> 10.4*$	Walls Cathode
^{232}Th	^{220}Rn	55.80 sec	$2.5 \pm 0.1_{\text{stat}} \pm 0.7_{\text{sys}}$	Quadrant I, sparse throughout bulk
	^{216}Po	0.15 sec	$3.0 \pm 0.1_{\text{stat}} \pm 0.9_{\text{sys}}$	Quadrant I, sparse throughout bulk
	^{212}Bi	60.54 min	$15.7 \pm 0.2_{\text{stat}} \pm 3.5_{\text{sys}}\ddagger$	Uniform throughout bulk
	^{212}Po	0.30 μs	not measured	not observed

† Adjusted for a 52% event reconstruction efficiency from measured value.

∗ These populations are suppressed due to S2 loss.

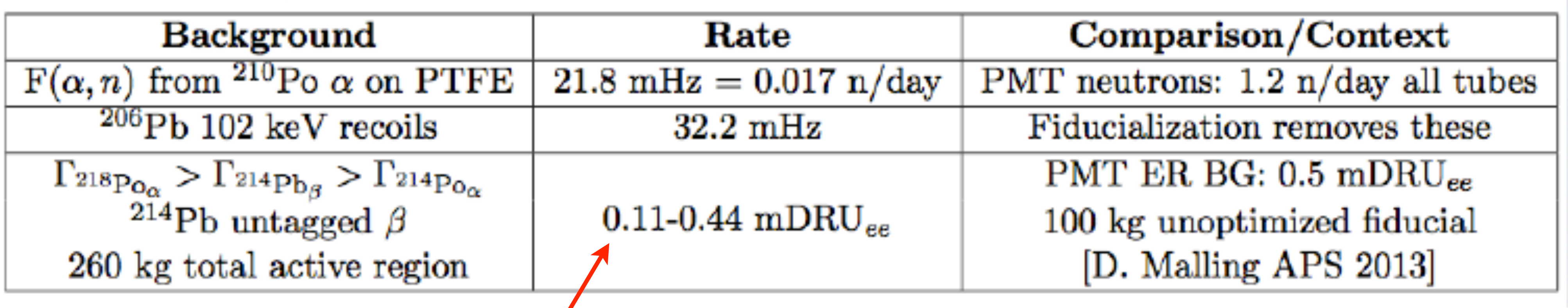
‡ Undifferentiated from ^{218}Po rate.

Observe ~20 mHz ^{222}Rn rate, approximately stable during underground operation
Also observe 3 mHz ^{220}Rn rate ⇒ ^{232}Th contamination in detector

^{210}Po rate reflects ^{210}Pb plate-out on surfaces prior to underground deployment

Implications

LUX Preliminary



Background	Rate	Comparison/Context
F(α, n) from ^{210}Po α on PTFE	21.8 mHz = 0.017 n/day	PMT neutrons: 1.2 n/day all tubes
^{206}Pb 102 keV recoils	32.2 mHz	Fiducialization removes these
$\Gamma_{^{218}\mathrm{Po}_\alpha} > \Gamma_{^{214}\mathrm{Pb}_\beta} > \Gamma_{^{214}\mathrm{Po}_\alpha}$ ^{214}Pb untagged β 260 kg total active region	0.11-0.44 mDRU$_{ee}$	PMT ER BG: 0.5 mDRU$_{ee}$ 100 kg unoptimized fiducial [D. Malling APS 2013]

Range bounded by measured ^{218}Po and ^{214}Po α recoil rates

See approximately steady rate of radon progeny during underground running, the sources of which are under investigation. However,

contributions to our WIMP search background are within previous background estimations.

Extensions in theoretical ideas about DM

Self-interacting dark matter
Dark mediated dark matter
Flavor-changing dark matter

What as experimentalists can we do to think about ways that we could be missing possible DM signals?