The LUX-ZEPLIN Experiment:

Direct Detection with Liquid Xenon

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Yale

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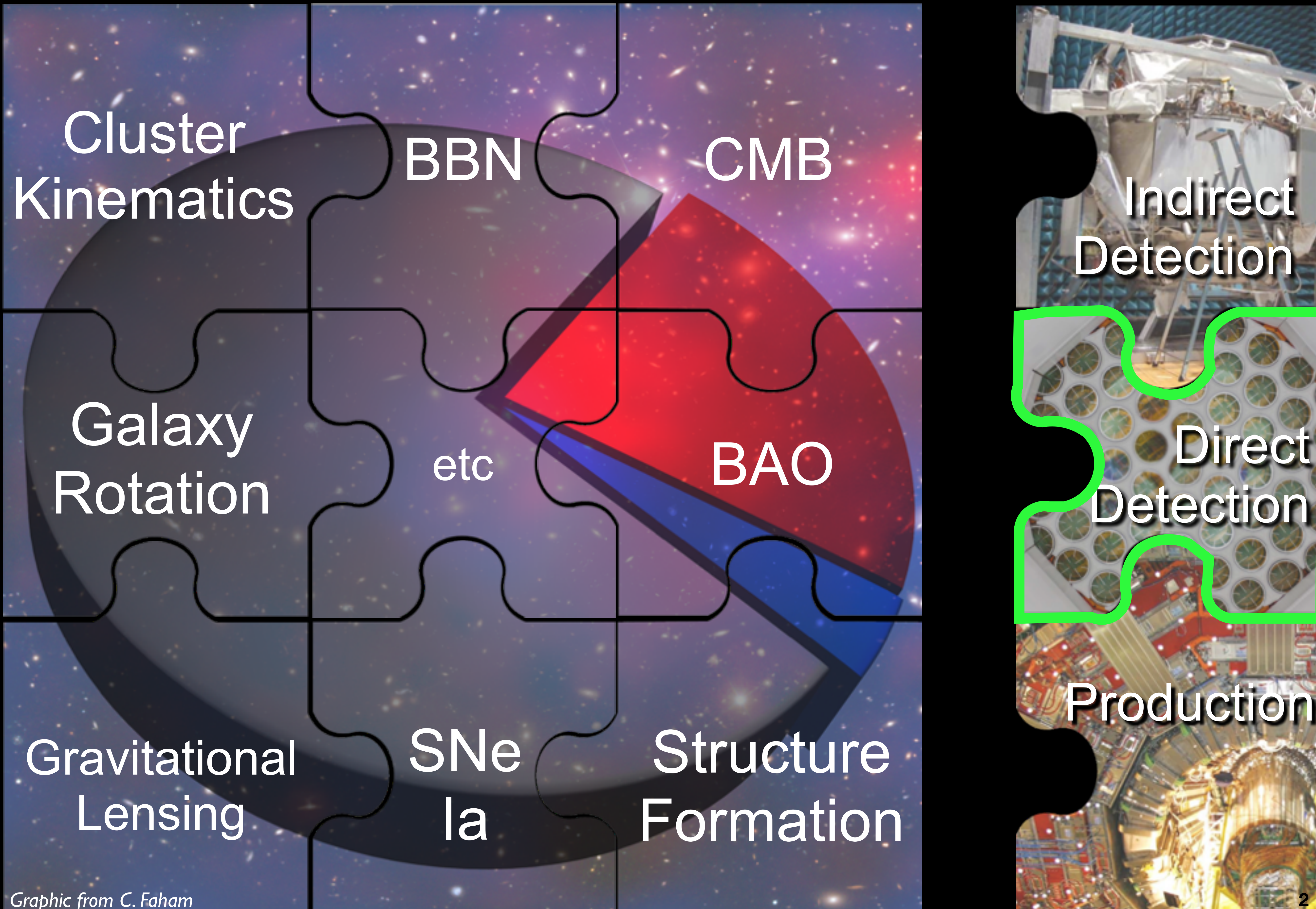
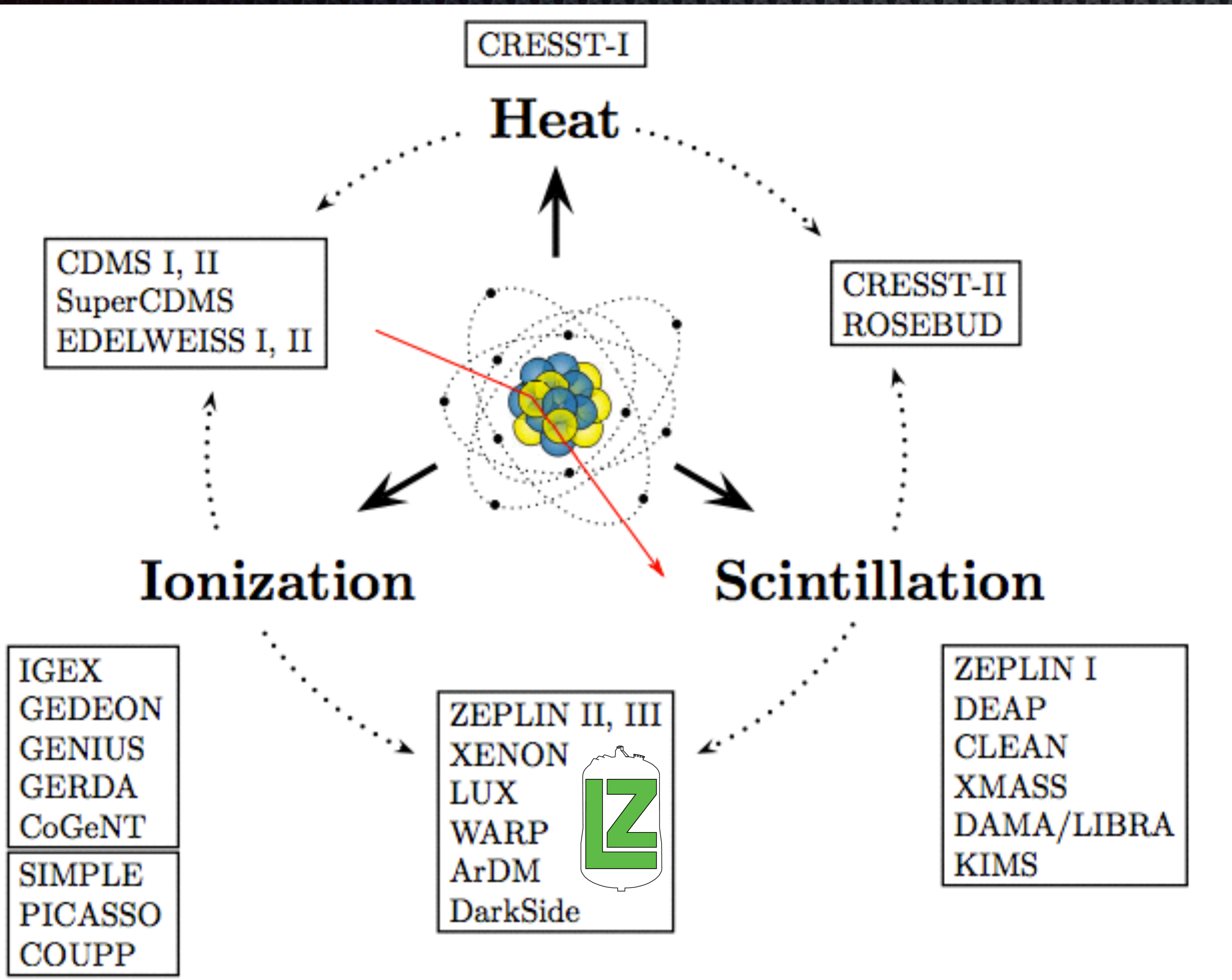
Let’s jump straight into LZ’s piece of the dark matter puzzle.



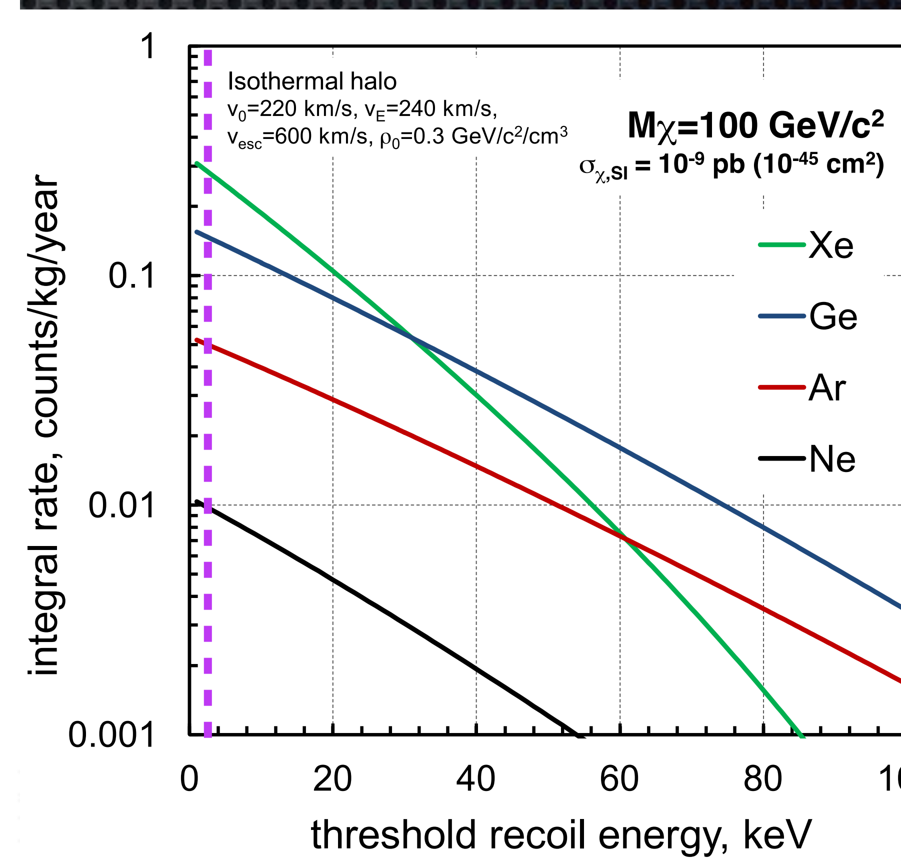
Graphic from C. Faham

WIMP direct detection = a dark matter particle runs into the nucleus of an atom; the nuclear recoil is detected



Important factors

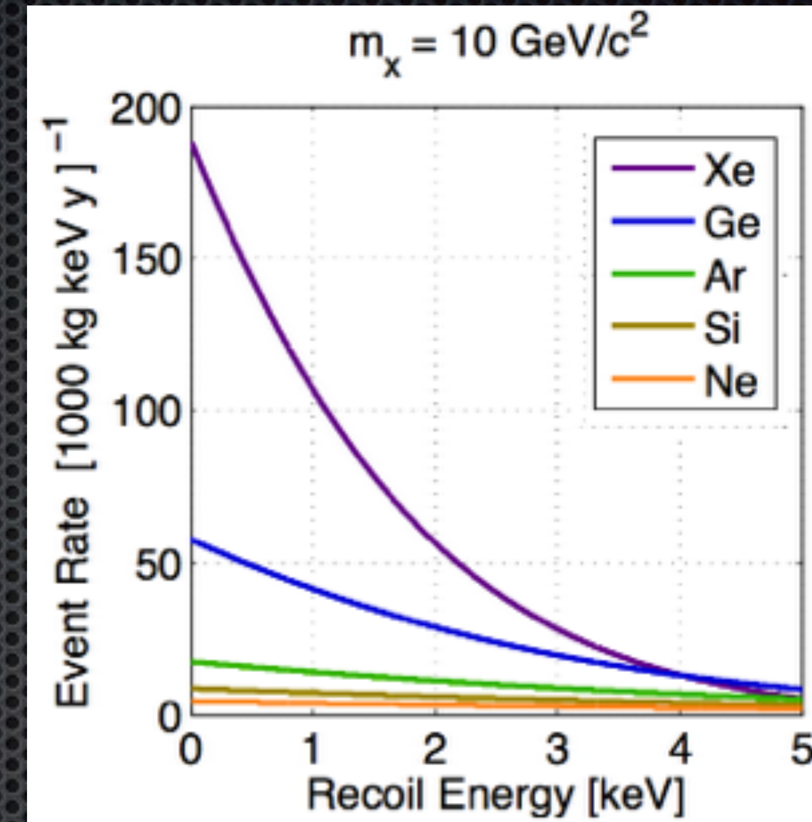
- large mass
- low-radioactivity
- low-energy threshold
- high acceptance
- ability to identify and reject backgrounds (discrimination)



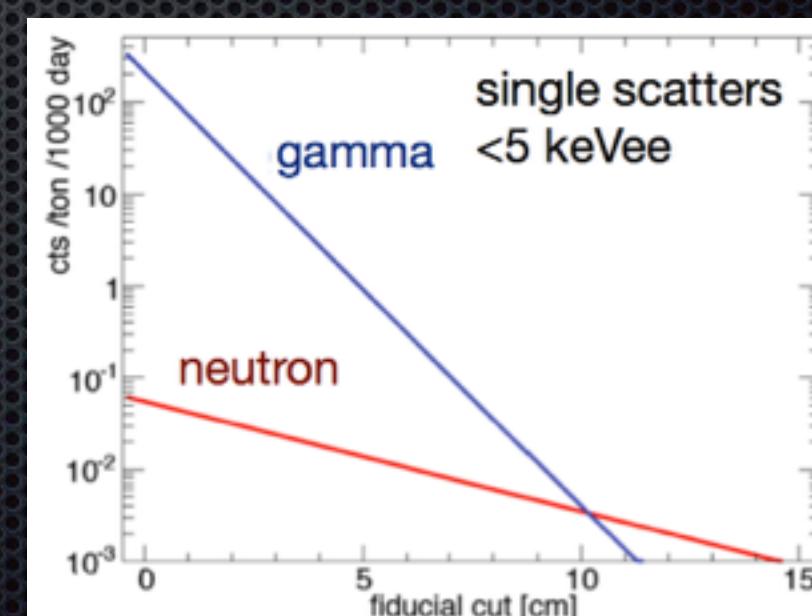
Why xenon?

Xenon
Atomic Number: 54
Atomic Mass: 131.3 amu
Noble element

- It is *relatively* inexpensive and easy to obtain. 
- It is a big atom creating a target with lots of mass and short attenuation lengths for x-ray, gamma, and beta backgrounds.
- It is easily purified and does not have long-lived radioactive isotopes.
- Ionization electrons can be drifted over long distances (i.e. detectable!).
- In addition to ionizing, energy depositions in xenon create short-lived excited diatomic states, which de-excite and emit 175 nm VUV scintillation light. This is not reabsorbed by atomic xenon and it propagates freely in LXe (i.e. detectable!).
- It is scalable. The ZEPLIN-I mass was ~3 kg; LUX has ~300 kg; LZ will have ~7,000 kg.



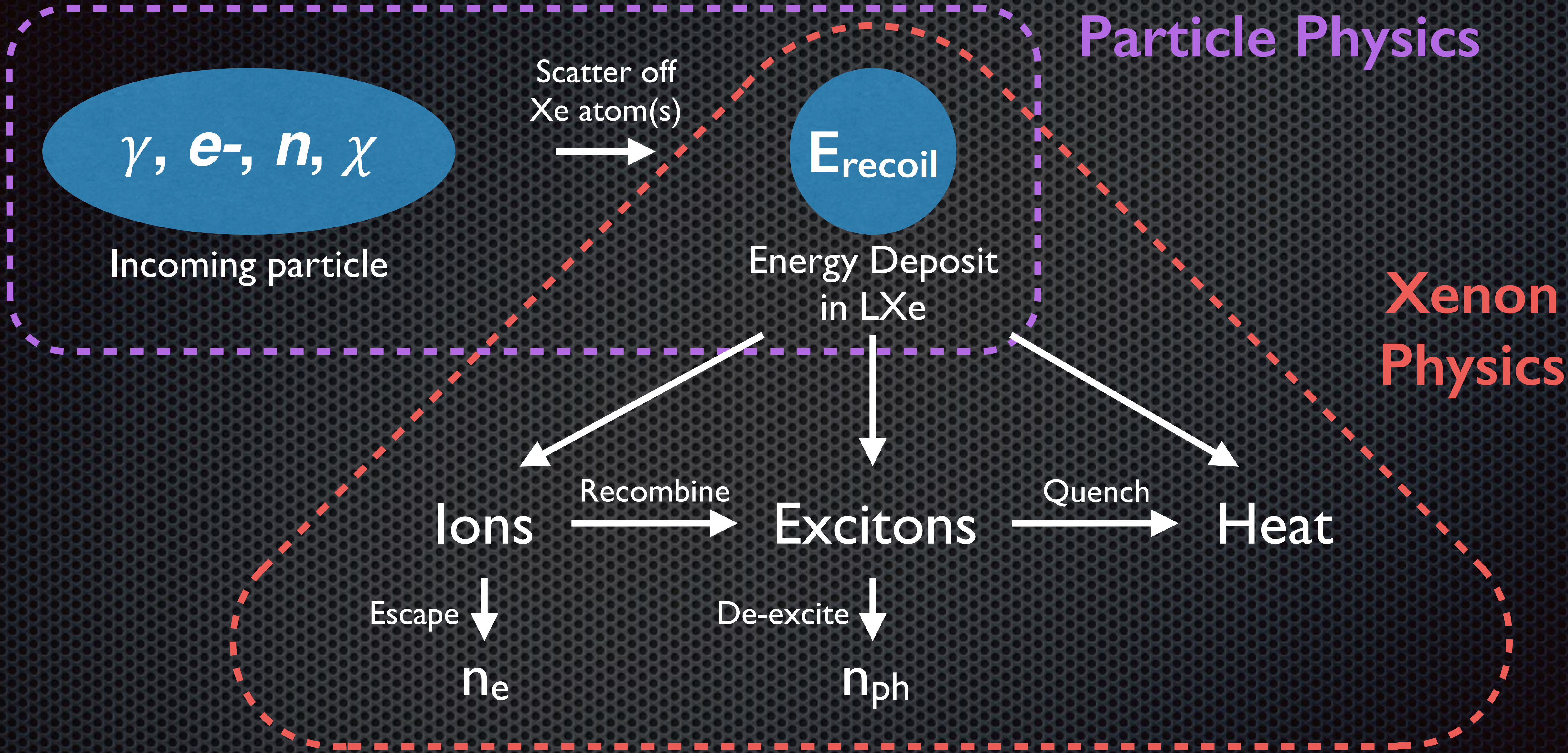
Rate ~ $A^2\mu^2$ for coherent nuclear scattering



Xenon detectors self-shield

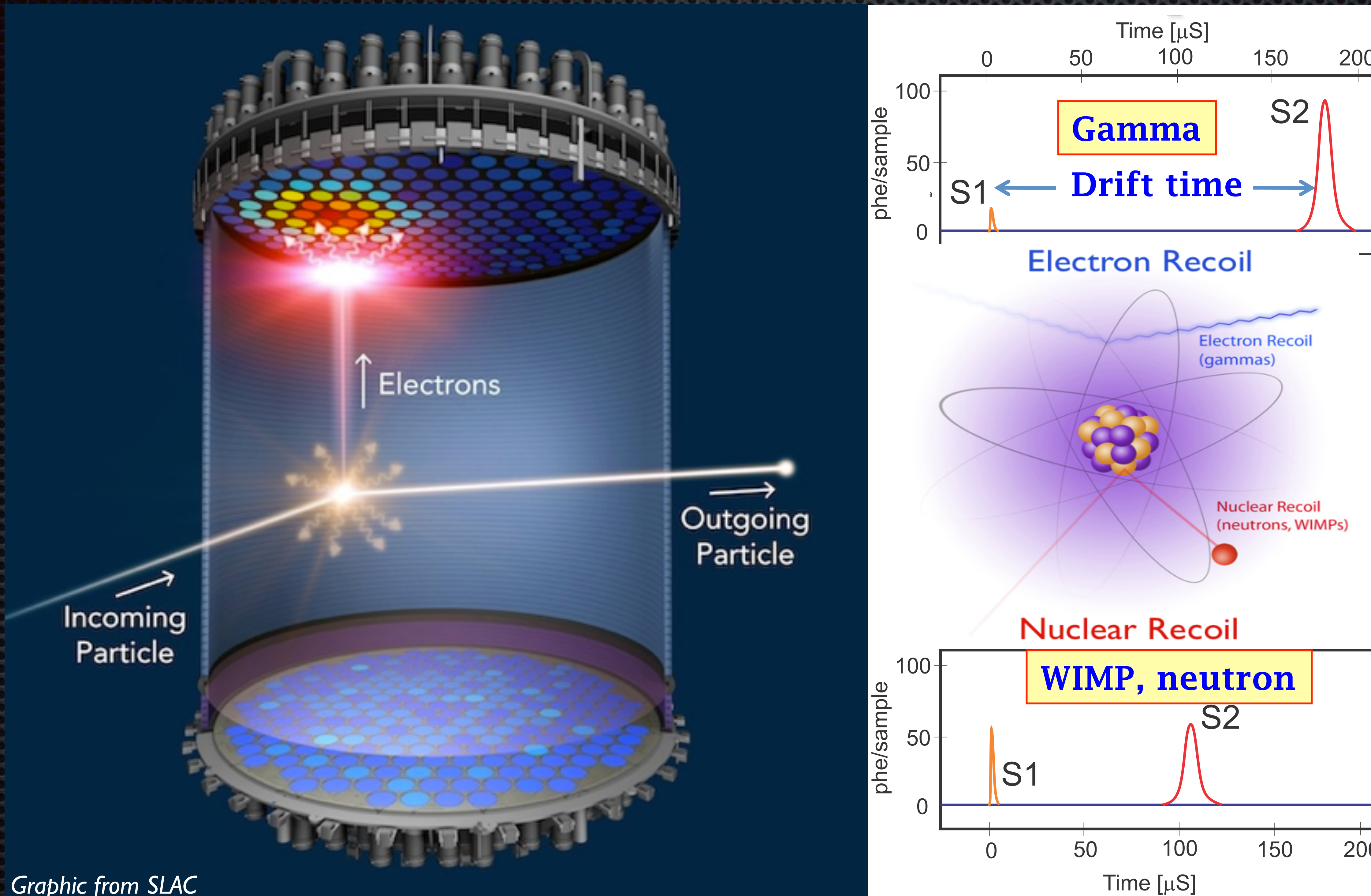
(Plots from S. Hertel, June 2015, LBL workshop)

Particle interactions in liquid xenon

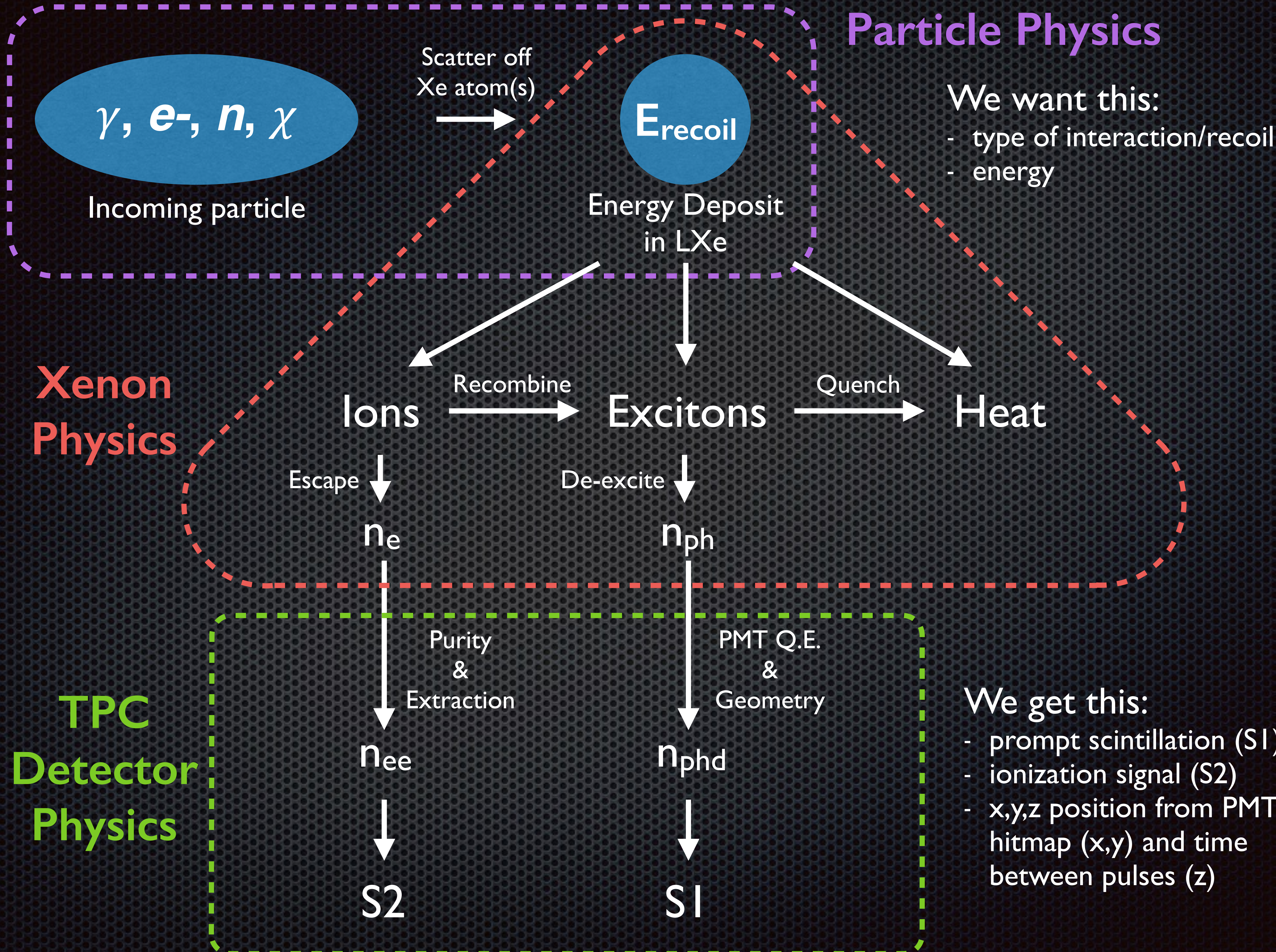


We receive information through two channels—light and charge. The initial ratio of ionization, excitation, and heat is dependent on the type of recoil, and n_e and n_{ph} varies nonlinearly with energy. We design our detectors to maximize our collection of light and charge.

Two-phase time projection technique



Detection volumes like this are called time projection chambers, "TPCs"



Particle Physics
γ, e-, n, χ
Incoming particle
Scatter off
Xe atom(s)
E recoil
Energy Deposit
in LXe
We want this:
- type of interaction/recoil
- energy
Xenon
Physics
Ions
Recombine
Excitons
Quench
Heat
Escape
De-excite
n e
n ph
TPC
Detector
Physics
Purity
&
Extraction
PMT Q.E.
&
Geometry
n ee
n phd
S2
S1
We get this:
- prompt scintillation (S1)
- ionization signal (S2)
- x,y,z position from PMT hitmap (x,y) and time between pulses (z)

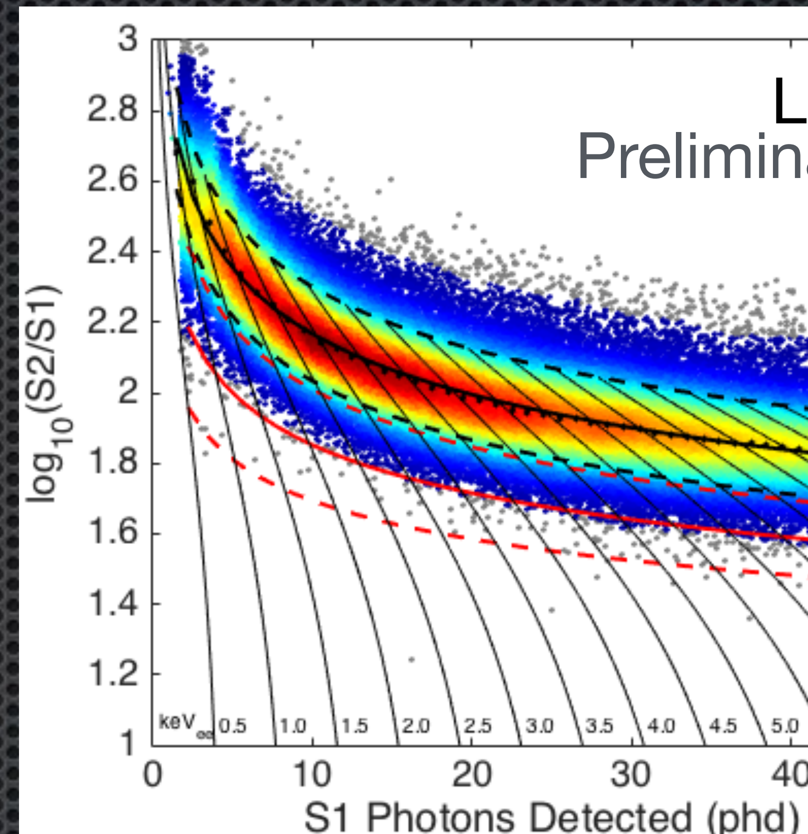
Event discrimination in liquid xenon

Electron recoils (ER)

- Incoming particle types: photon, beta
- Characterized by a higher ratio of charge to light
- WIMP events will not be ER
  - ER = background

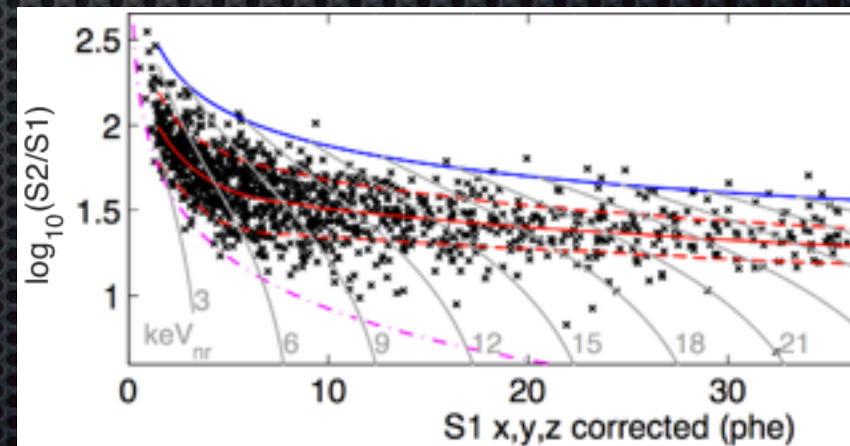
Nuclear recoils (NR)

- Incoming particle types: neutron, WIMP
- Characterized by a lower ratio of charge to light
- The NR signals of neutrons are indistinguishable from those of WIMPs



LUX Collab., in prep.

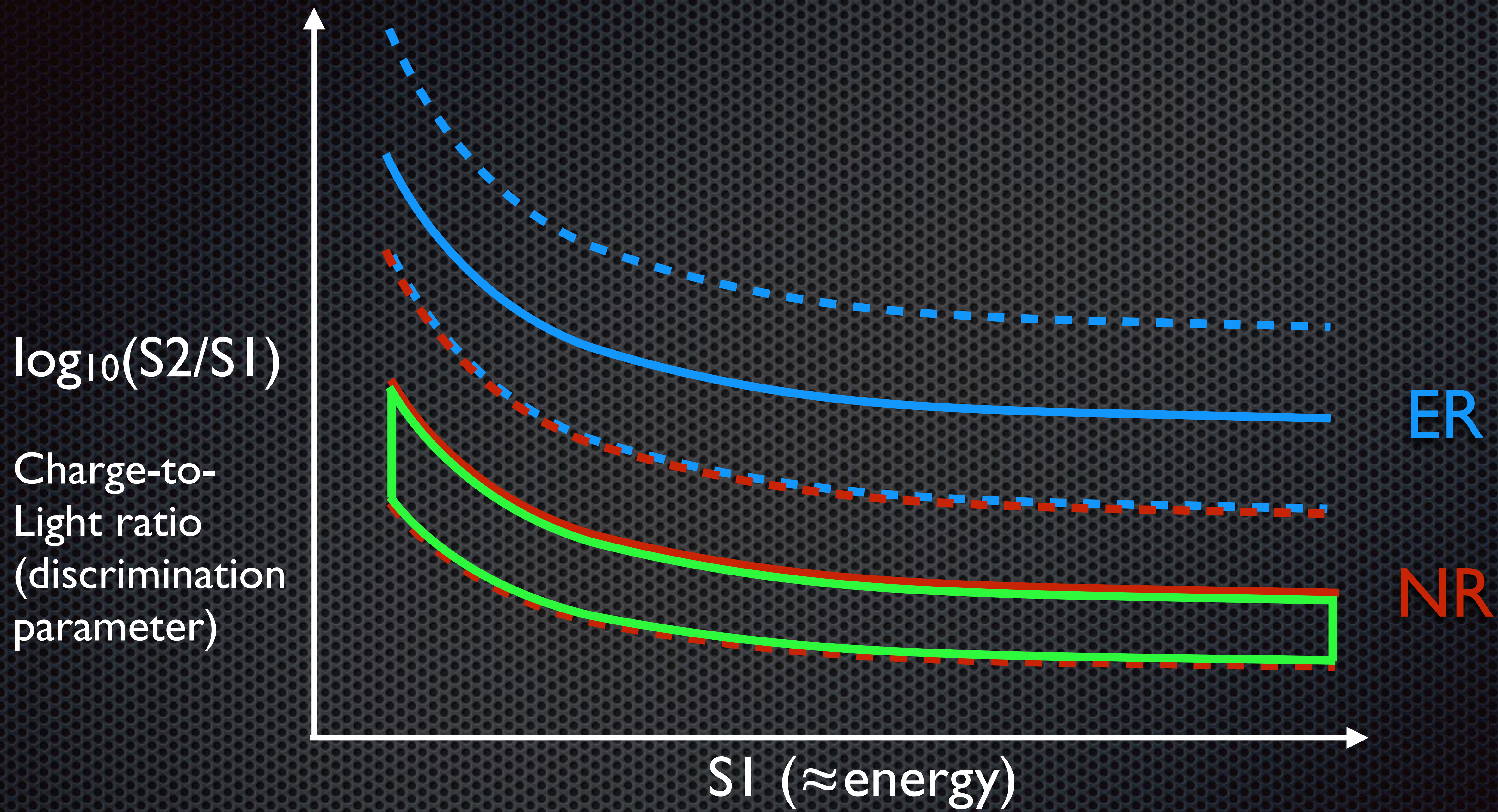
LUX ER response to betas from internal tritium decays provided by a CH_3T injection



LUX Collab., 2013

LUX NR response to calibration neutrons from external AmBe and Cf-252 sources

Where we look for dark matter

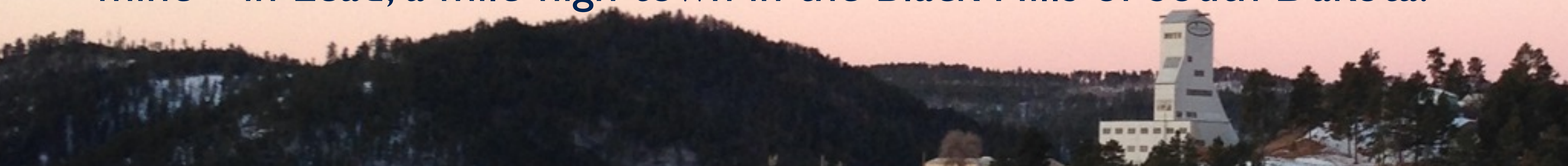


A detector's ER/NR discrimination is typically reported as "X% ER rejection at 50% NR acceptance." Given typical background rates and previously excluded WIMP cross-sections, discrimination >99% is a must.

ZEPLIN-III (FSR):	99.987%
ZEPLIN-III (SSR):	99.6%
LUX:	99.6%
LZ baseline:	99.5%

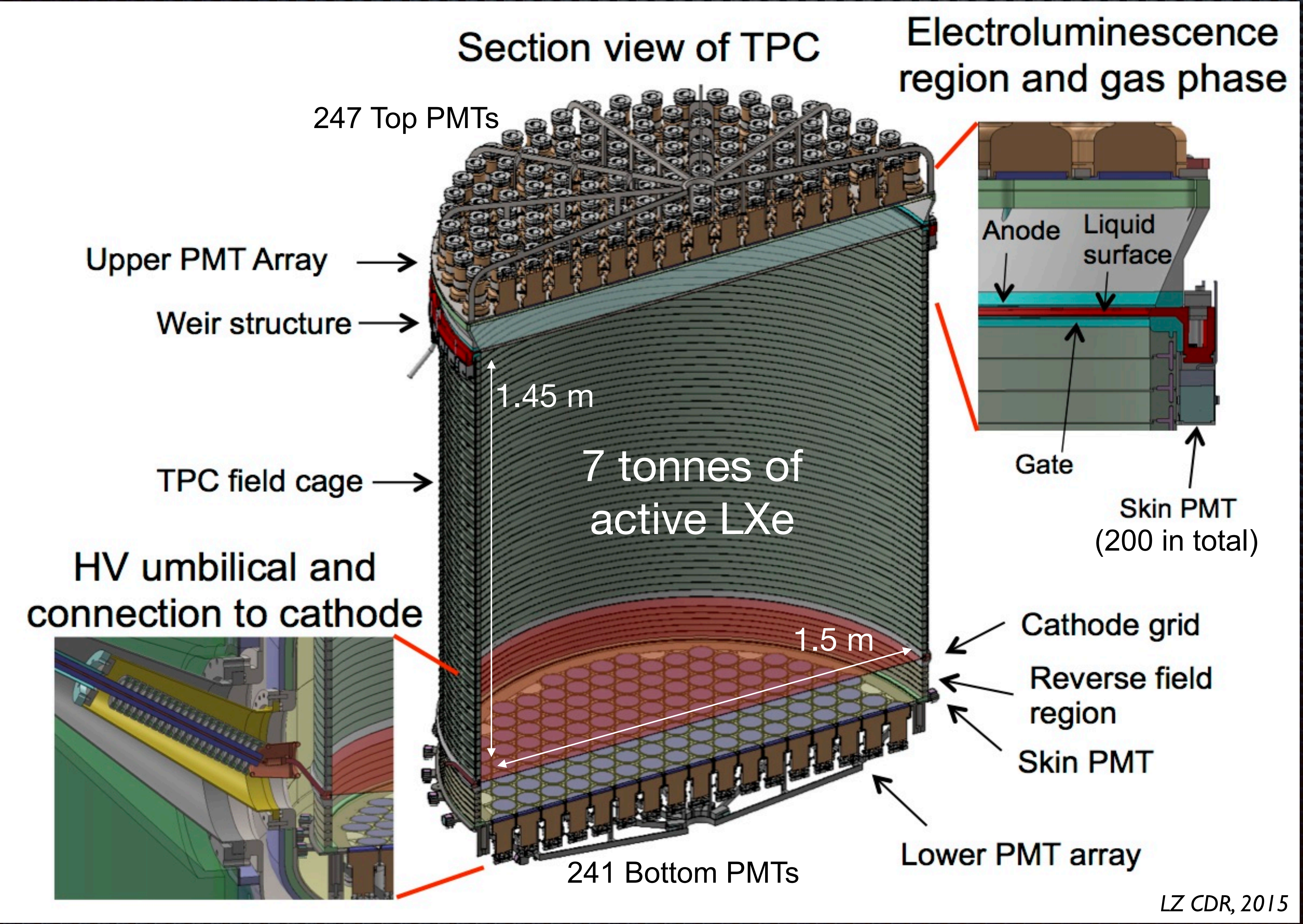
Overview of the LZ Experiment

- A collaboration of 30 institutions and ~190 people, including a large contingent from UC Berkeley and LBNL.
  - LBNL scientists, staff, and management: B. Edwards, M. Gilchriese*, M. Hoff, K. Lesko*, J. Saba, P. Sorensen*, W. Waldron, S. Dardin, M. Barclay (* = scientist in physics division)
  - UCB faculty: R. Jacobsen, D. McKinsey
  - UCB/LBNL post-docs: E. Bernard, B. Edwards, A. Dobi, S. Hertel, M. Horn, K. O'Sullivan
  - UCB grad students: K. Kamdin, K. Oliver-Mallory (***and room for more!***)
  - Transplanted Yale grad students: E. Boulton, E. Pease, L. Tvrznikova
- Two-phase xenon time projection chamber (TPC)
- 10 tonnes of xenon with 7 T "active" and 5.6 T within the projected fiducial volume
- The LZ detector will inherit the Davis Cavern from the LUX detector. This cavern is 4850' below the surface and is part of the Sanford Underground Research Facility (SURF)—formerly the Homestake gold mine—in Lead, a mile-high town in the Black Hills of South Dakota.

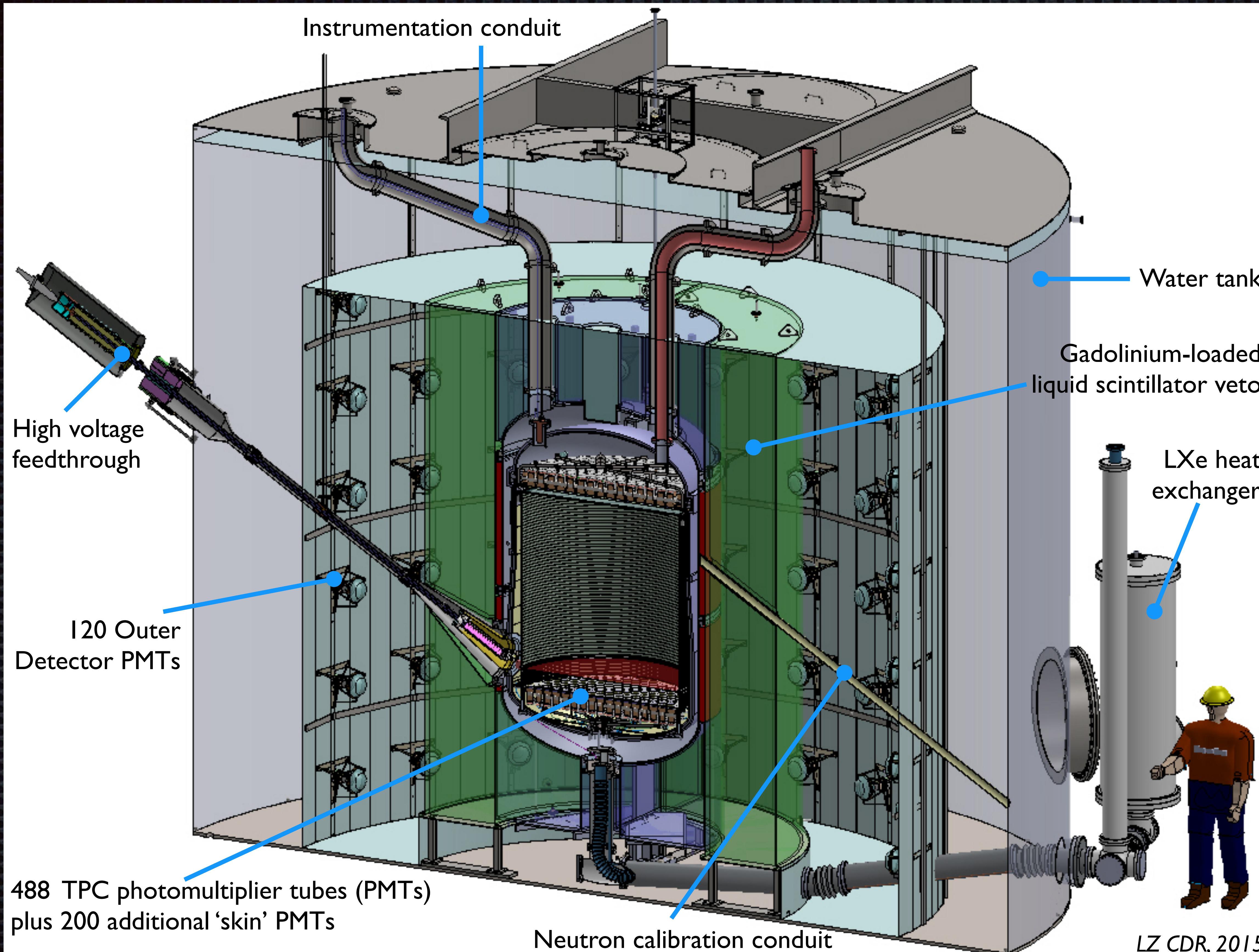


Sunrise at SURF before an underground shift for the LUX experiment (E. Pease, 2015)

The LZ TPC



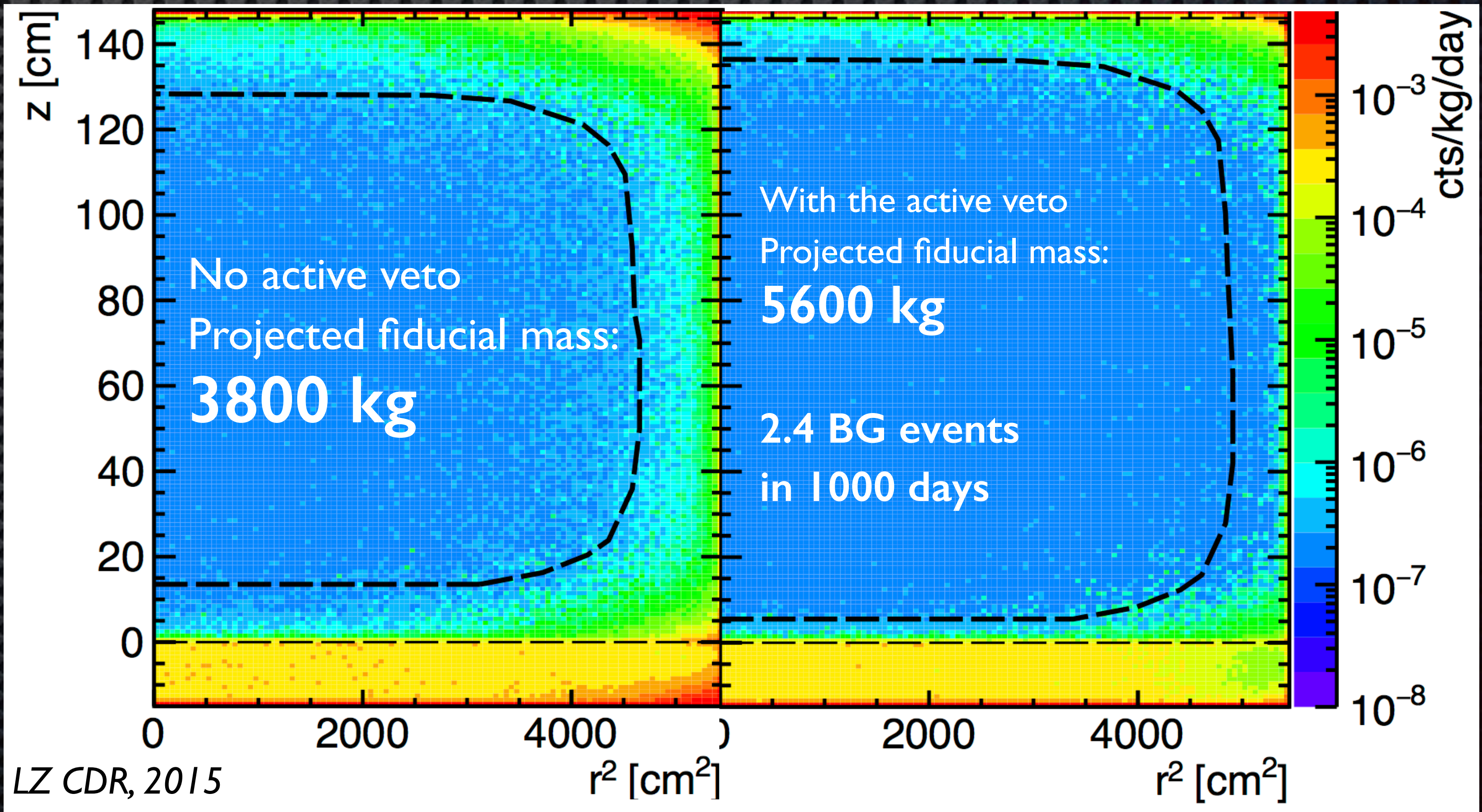
LZ CDR, 2015


Instrumentation conduit
Water tank
Gadolinium-loaded
liquid scintillator veto
LXe heat
exchanger
High voltage
feedthrough
120 Outer
Detector PMTs
488 TPC photomultiplier tubes (PMTs)
plus 200 additional 'skin' PMTs
Neutron calibration conduit
LZ CDR, 2015

Background minimization and rejection

- External to the TPC
  - 4850 feet of earth (4200 meters water equivalent) - passive
  - 80,000 gallon water tank - passive
  - Outer scintillator and PMTs - active
  - Instrumented xenon ‘skin’ - active
- TPC and detector itself
  - Extensive assay of all materials to inform selection of components with minimal radioactivity
- Internal to the TPC
  - Kr removal goal of <15 ppq—10^{-15} (g Kr)/(g Xe)—using gas chromatography
  - Constant circulation and purification, plus in situ sampling system for constant Xe assay capability
  - Neutrinos will be our dominant background!

Item	ER cts	NR cts
Total components	11.9	0.32
Dispersed radionuclides (Rn, Kr, Ar)	54.8	-
^{136}Xe 2νββ	53.8	-
Neutrinos (ν-e, ν-A)	271	0.5
Total events	391.5	0.82
WIMP background events (99.5% ER discrimination, 50% NR acceptance)	1.96	0.41
Total ER+NR background events	2.37	



Let's pause and appreciate this…

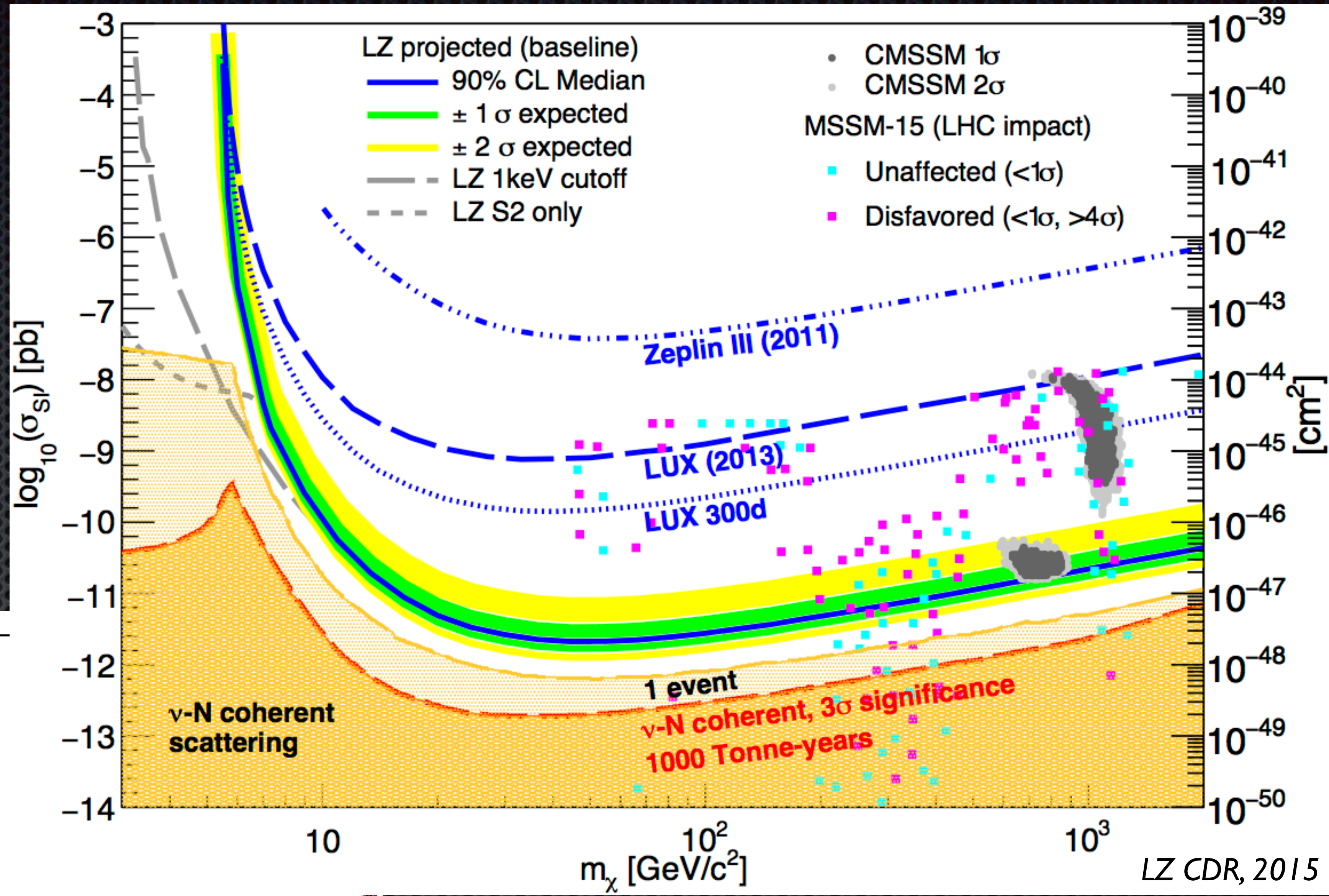
Item	Mass kg	U mBq/kg	Th mBq/kg	^{60}Co mBq/kg	^{40}K mBq/kg	n/yr	ER cts	NR cts
R11410 PMTs	93.7	2.7	2.0	3.9	62.1	373	1.24	0.20
R11410 bases	2.7	74.6	29.1	3.6	109.2	77	0.17	0.03
Cryostat vessels	2,140	0.09	0.23	≈0	0.54	213	0.86	0.02
OD PMTs	122	1,507	1,065	≈0	3,900	20,850	0.08	0.02
Other components	-	-	-	-	-	602	9.5	0.05
Total components							11.9	0.32
Dispersed radionuclides (Rn, Kr, Ar)							54.8	-
^{136}Xe $2\nu\beta\beta$							53.8	-
Neutrinos (ν-e, ν-A)							271	0.5
Total events							391.5	0.82
WIMP background events (99.5% ER discrimination, 50% NR acceptance)							1.96	0.41
Total ER+NR background events							2.37	

- 5600 kg target mass (current largest Xe target: LUX ~120 kg)
- Exposed for 1000 days

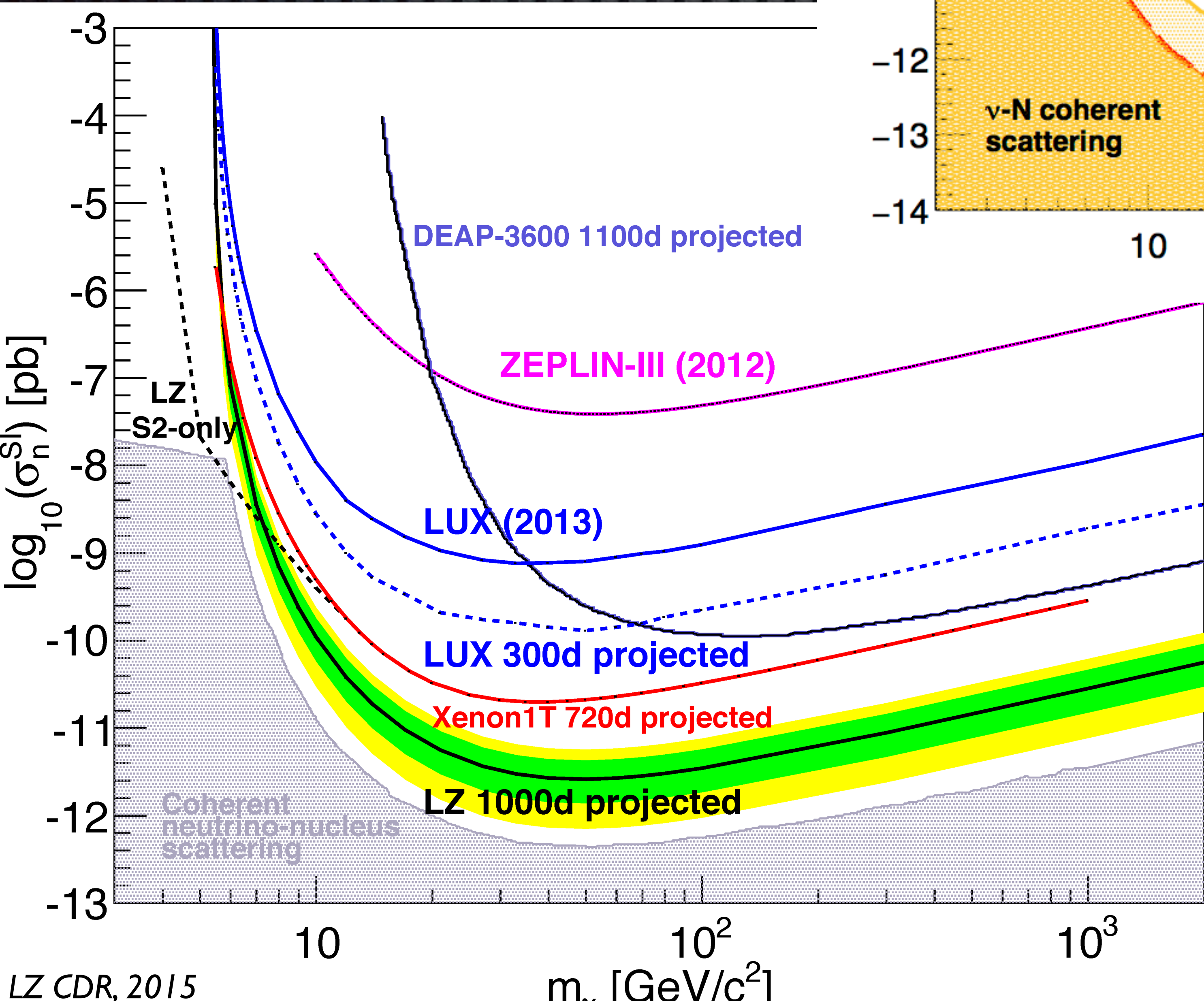
Fewer than <u>3</u> background events in the WIMP search region

Where does that get us relative to other experiments?

Projected sensitivity



LZ CDR, 2015



LZ CDR, 2015

Pushing towards the "neutrino floor" or "neutrino limit"

- the cross-section sensitivity at which our NR signal is overwhelmed by neutrino-nucleus coherent scattering

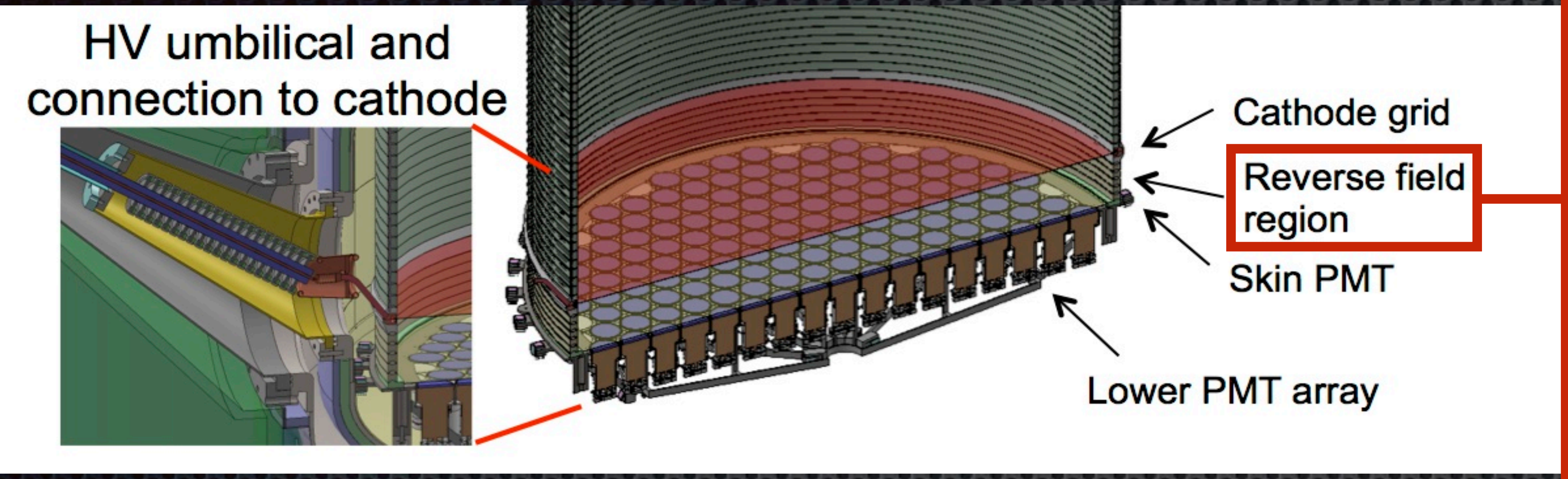
The following slides show our ongoing preparations and R&D to achieve this plan

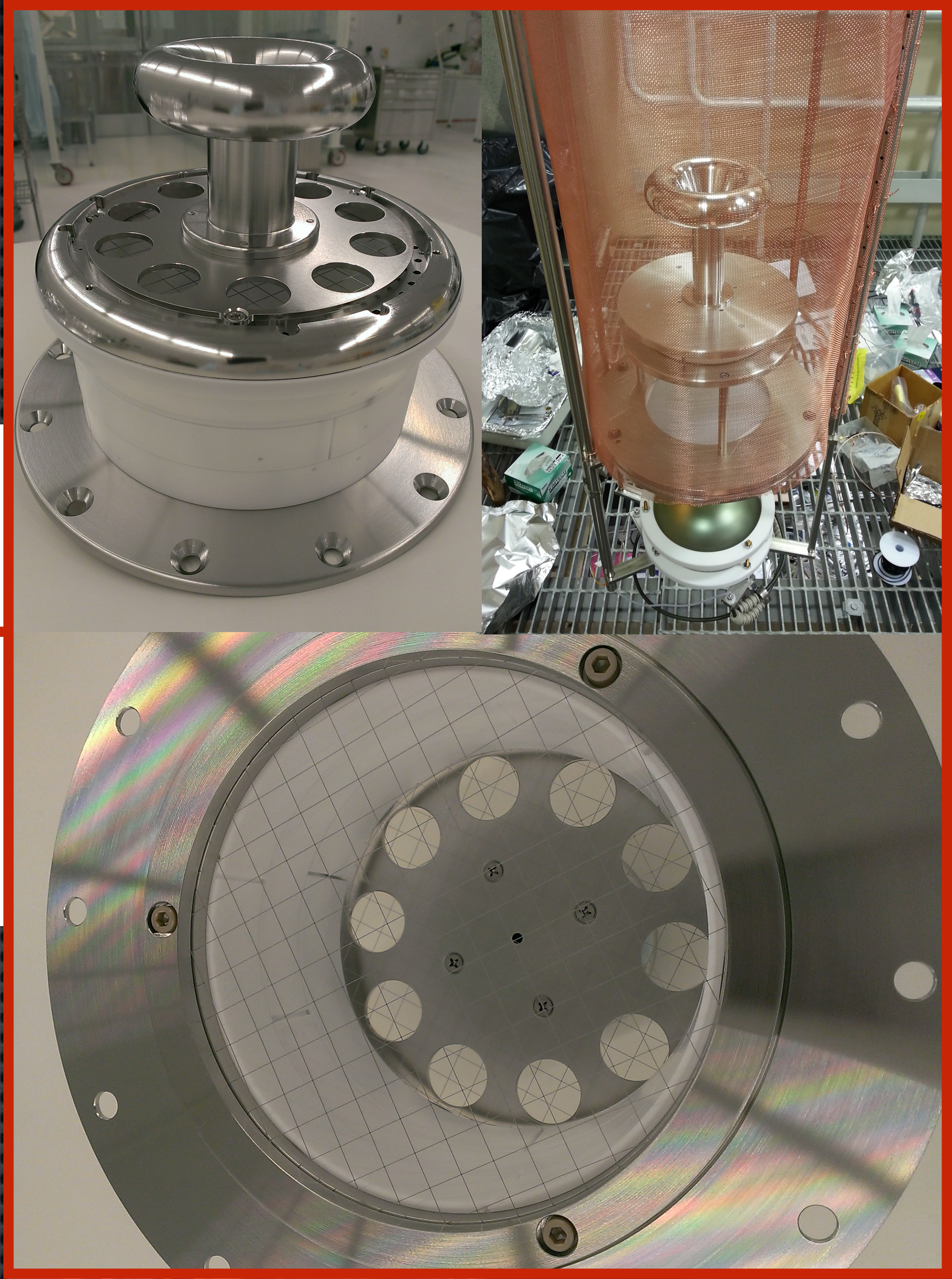
What do we need…

- Good light collection
- High voltage/high fields for drifting and extracting electrons *
- High radiopurity for xenon and detector materials *
- Stable and quiet electronics for data acquisition
- Good circulation with constant purification/removal/monitoring of electronegative impurities
- A variety of calibration sources with reliable means of deployment *
- An ambitious but feasible detector design *

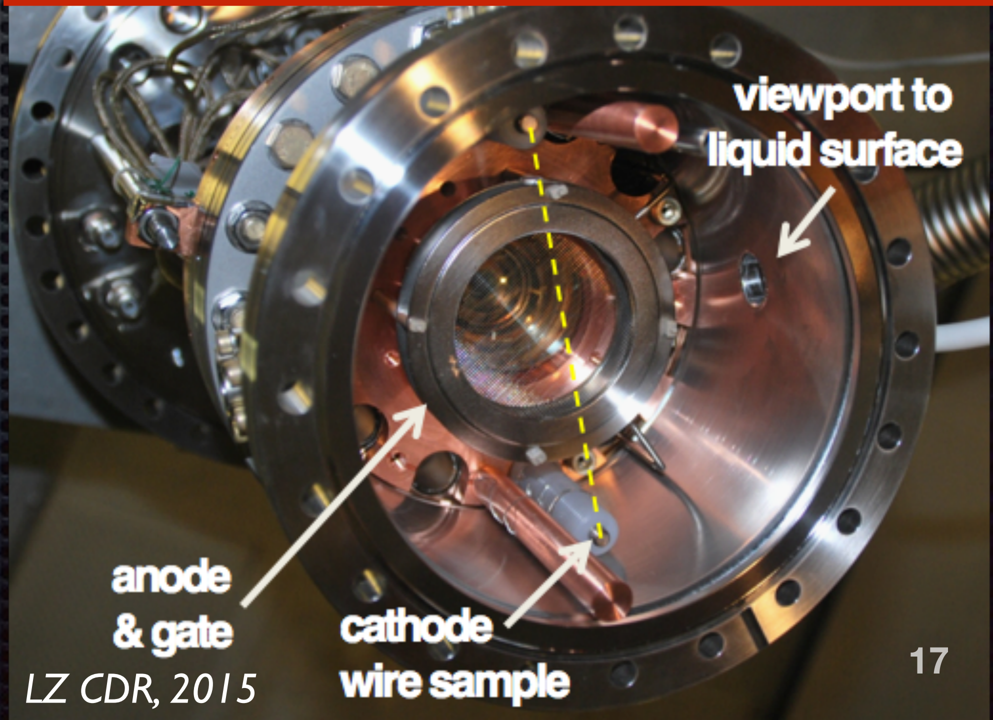
* =

High voltage studies





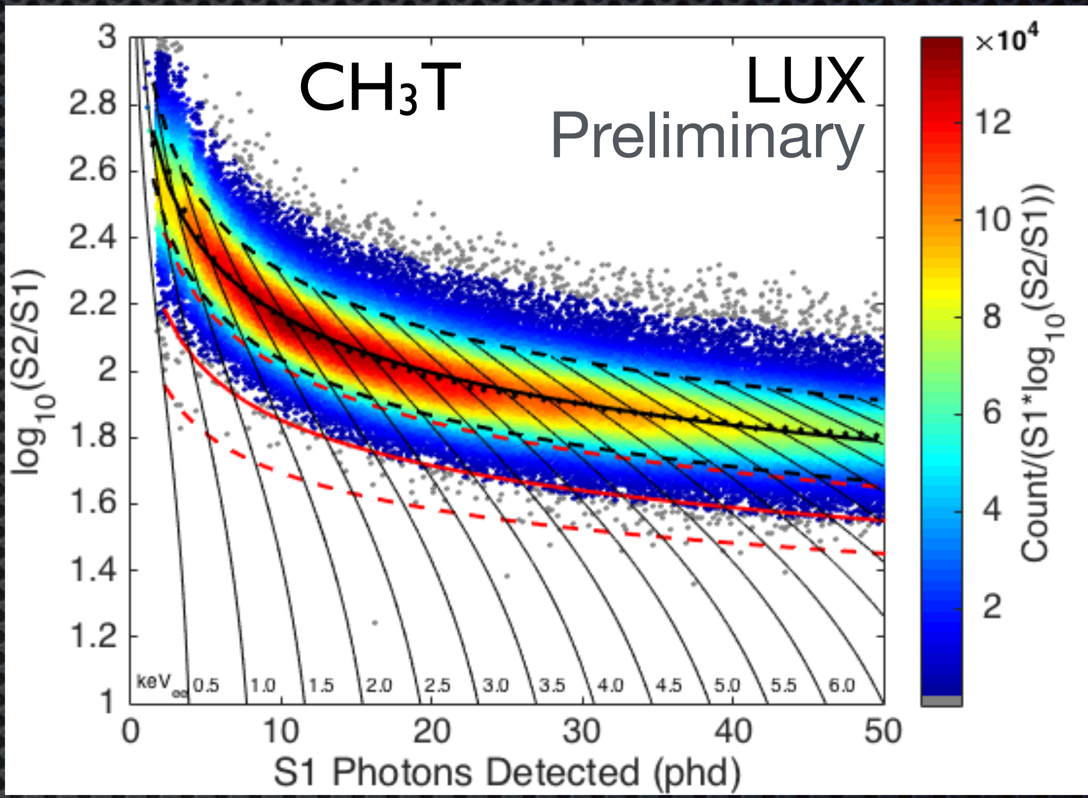
- The LZ cathode design voltage is 200 kV. Our nominal operating goal is 100 kV (700 V/cm drift).
- A cathode high voltage (HV) feedthrough has been tested successfully to 200 kV at Yale. It is now here at LBNL and we will use it in upcoming HV tests (Dan McKinsey).
- Frames, wires, and feedthroughs for the non-cathode grids are under test at LBNL (Peter Sorensen) and in the UK.
- A prototype 100 kg LXe TPC is being fabricated at LBNL and assembled for testing at SLAC



LZ CDR, 2015

Detector calibrations

- LUX has set the new standard for LXe detector calibrations (partly because we had to!)
  - Xenon self-shields, so internal sources are required for low energy calibration through the entire active region
- LZ will use many of the same sources and techniques, and will do even more than LUX.



Used in LUX; will be used in LZ	Not used in LUX; will be used in LZ
Kr-83m; ~weekly	Activated xenon; Xe-129m, Xe-131m
Tritiated methane, CH	Rn-220
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator	

LZ physics potential beyond WIMP detection

- Other dark matter candidates
  - Effective field theory models
- Neutrinoless double beta decay
  - Xe-136 is a candidate for this process and it exists in 8.9% natural abundance
  - Even without enrichment, LZ could be competitive with current exclusion limits.
- External neutrino physics
  - Solar
  - Supernova
  - Sterile

LZ physics potential before LZ

- Liquid noble physics at high field
- Liquid noble physics (period)
- Absolute measurement of electron extraction
- Low-background counting and analysis
- Calculation of sensitivities to other DM models, other particles, and rare processes
- Lots still to discover in data from LUX to apply to LZ

In closing

- The LZ project is in full swing. Procurement of the xenon, PMTs, and cryostats has started.
- Small Xe detectors at LBNL, LLNL, Yale (moving soon to UC Berkeley), U Michigan, UC Davis, Imperial College, and MEPhI are testing components and prototypes.
- LZ benefits from the excellent LUX calibration techniques and understanding of backgrounds.
- LZ sensitivity is expected to be limited by neutrino-induced background.

Sunset at SURF after an underground shift for the LUX experiment (E. Pease, 2014)

Want to know more about LZ?

- Get in touch with members of the UC Berkeley/LBNL group.
    - LBNL physics division: M. Gilchriese, K. Lesko, P. Sorensen
    - UC Berkeley faculty: R. Jacobsen, D. McKinsey
    - UC Berkeley/LBNL post-docs: E. Bernard, A. Dobi, B. Edwards, S. Hertel, M. Horn, K. O'Sullivan
    - UC Berkeley grad students: K. Kamdin, K. Oliver-Mallory
    - Transplanted Yale grad students: E. Boulton, E. Pease, L. Tvrznikova
- The LZ Conceptual Design Report was released on September 9, 2015. There are more details, diagrams, and text on all the content presented in these slides.
    - Check it out here: http://hep.ucsb.edu/LZ/CDR/

Thank you.

Extra slides

LZ Timeline

Past highlights

2012
- March: LZ collaboration formed
- May: First collaboration meeting
- September: DOE CD-0 for G2 dark matter experiments

2013
- November: LZ R&D report submitted

2014
- July: LZ Project selected in US and UK

2015
- April: DOE CD-1/3a approval, similar in UK
- Now: Procuring xenon, PMTs, cryostat

Coming attractions

2016
- April: DOE CD-2/3b approval, baseline, all fab starts

2017
- June: Begin preparations for surface assembly at SURF

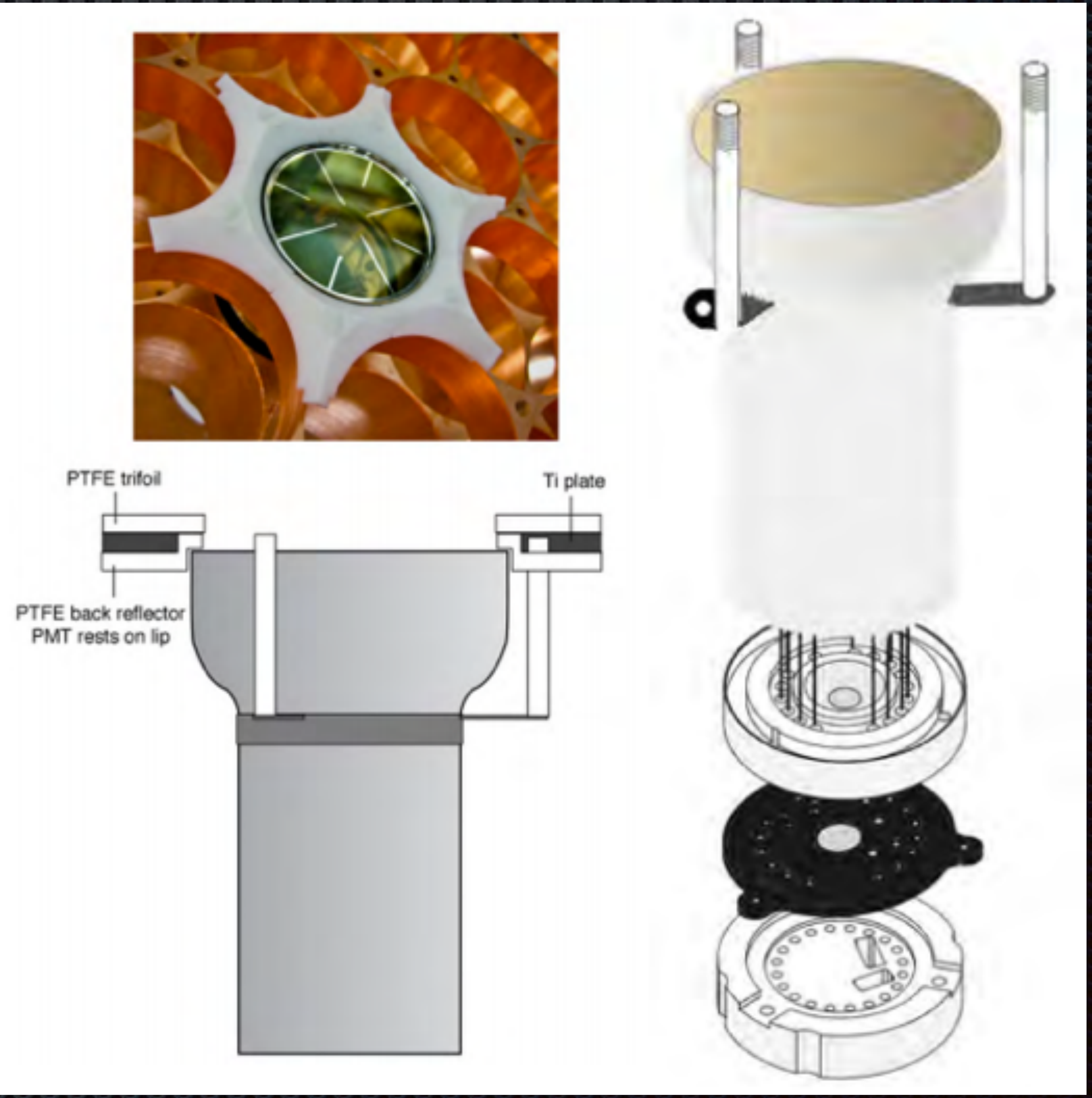
2018
- July: Begin underground installation

2019
- Feb: Begin commissioning & running

Photomultiplier tubes (PMTs)

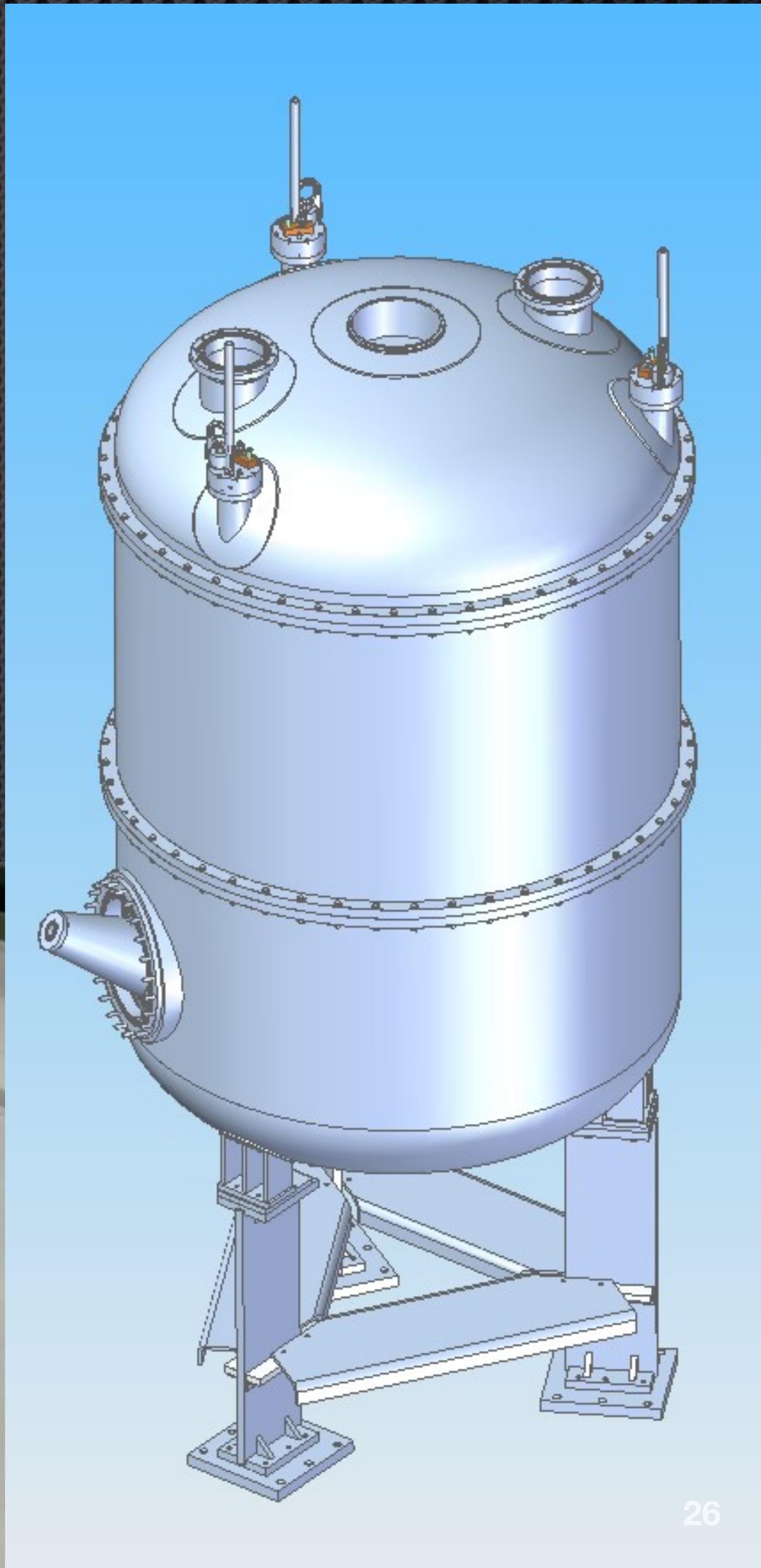
- R11410-22 3" PMTs for TPC region
  - 488 in total!
  - Extensive development program, 50 tubes in hand, benefit from similar development for XENON, PANDA-X and RED
  - Materials ordered and radioassays started prior to fabrication.
  - First production tubes early 2016.
  - Joint US and UK effort

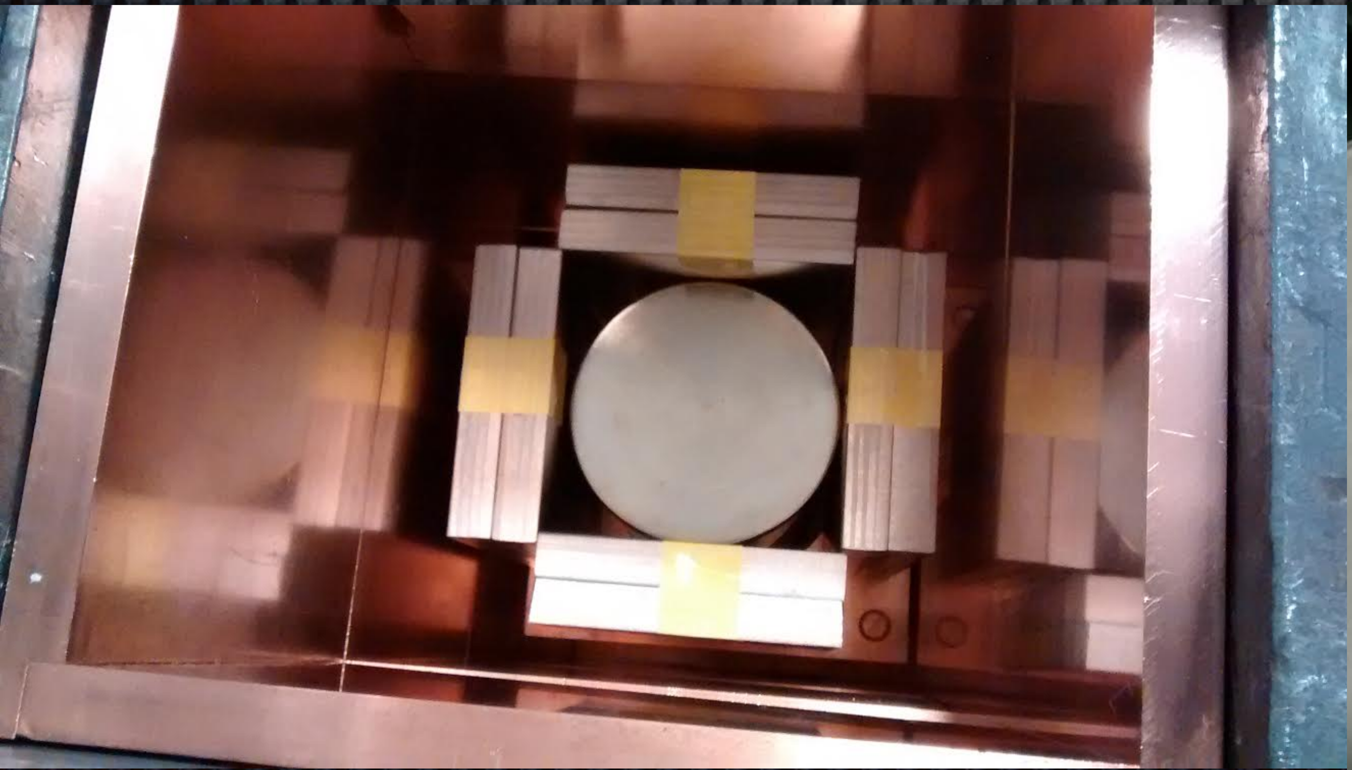
- R8520-406 1" for skin region
  - Considering using 2" or 3" PMTs for additional veto capability in the bottom dome region (would recycle tubes from older detectors)

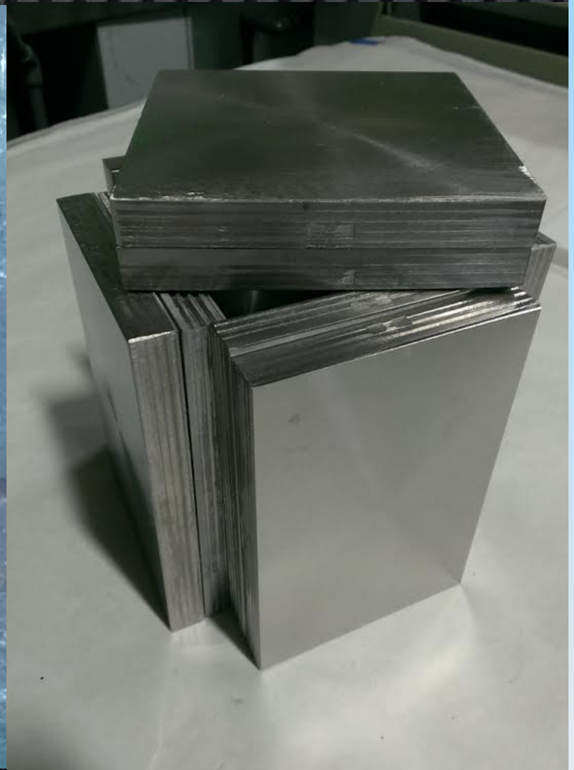


Cryostat vessels

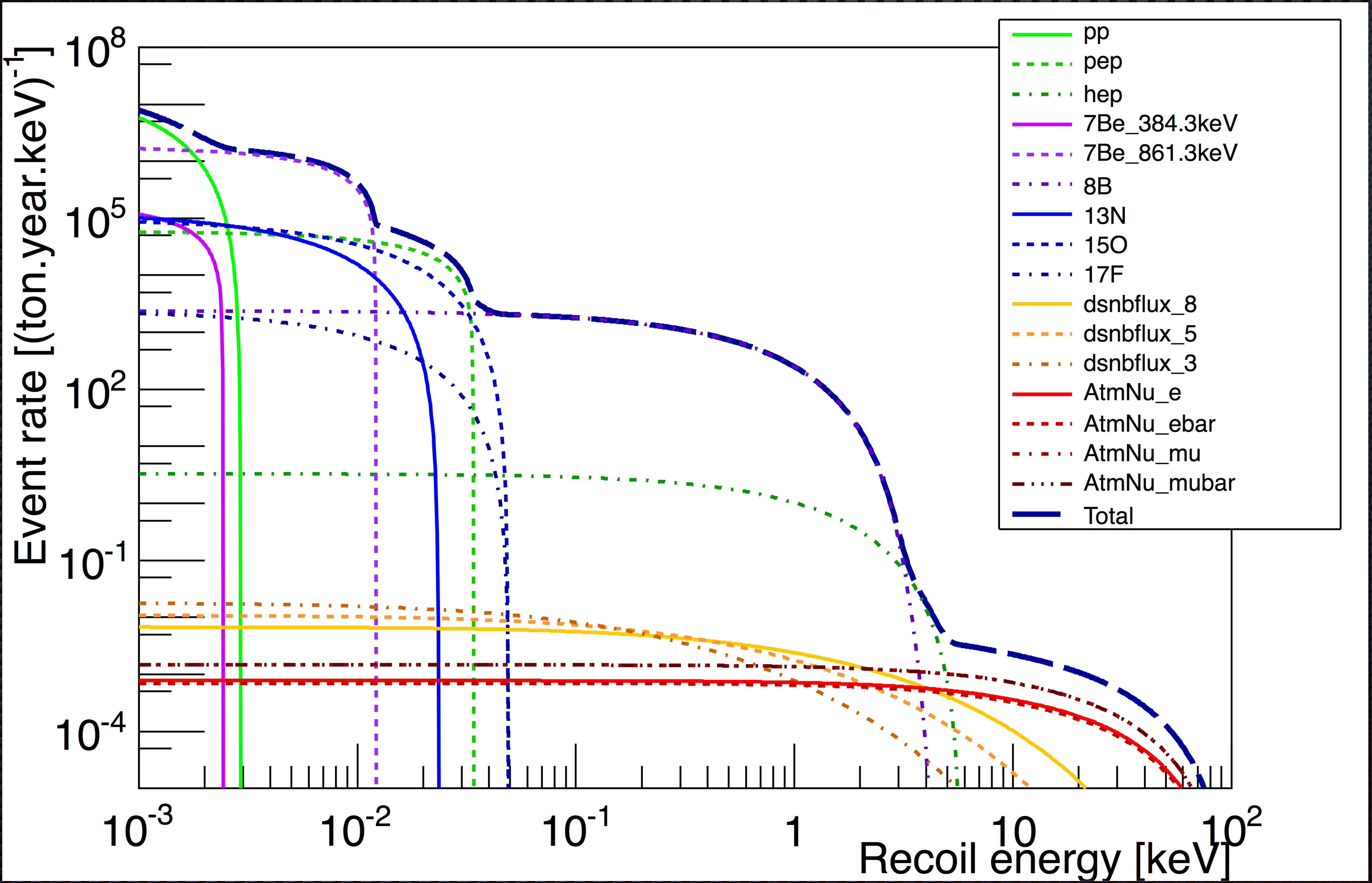
- The cryostats will be made from low background titanium (with stainless steel advanced as a backup in case of higher than expected backgrounds)
- A Ti slab for all vessels and other parts has been assayed
- The vessels will contribute < 0.05 NR+ER counts in the fiducial volume during the 1000 day run (after cuts).







Xenon recoil spectrum for neutrinos



Direct detection over the past 30 years