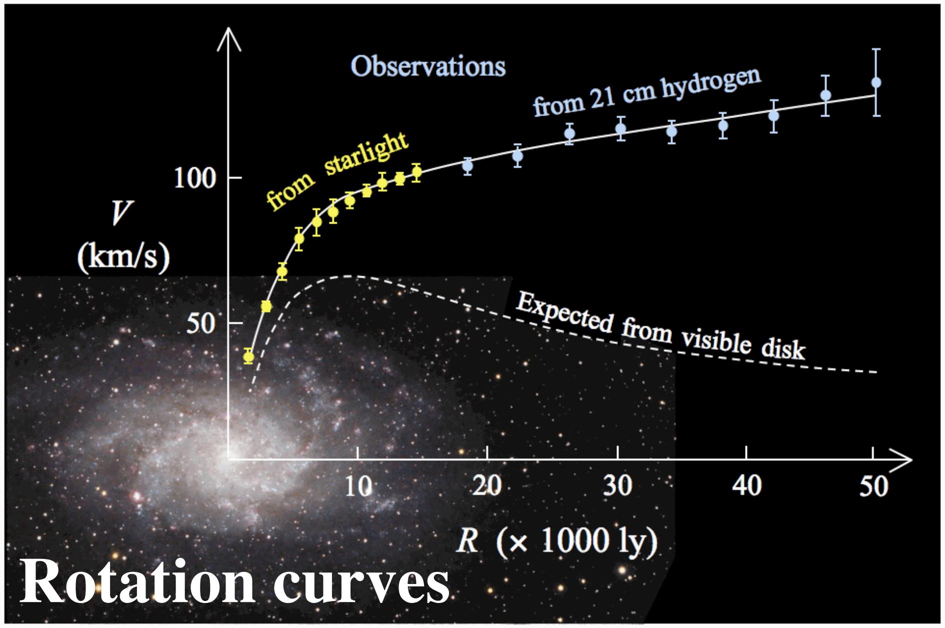
Down-to-earth searches for cosmological dark matter

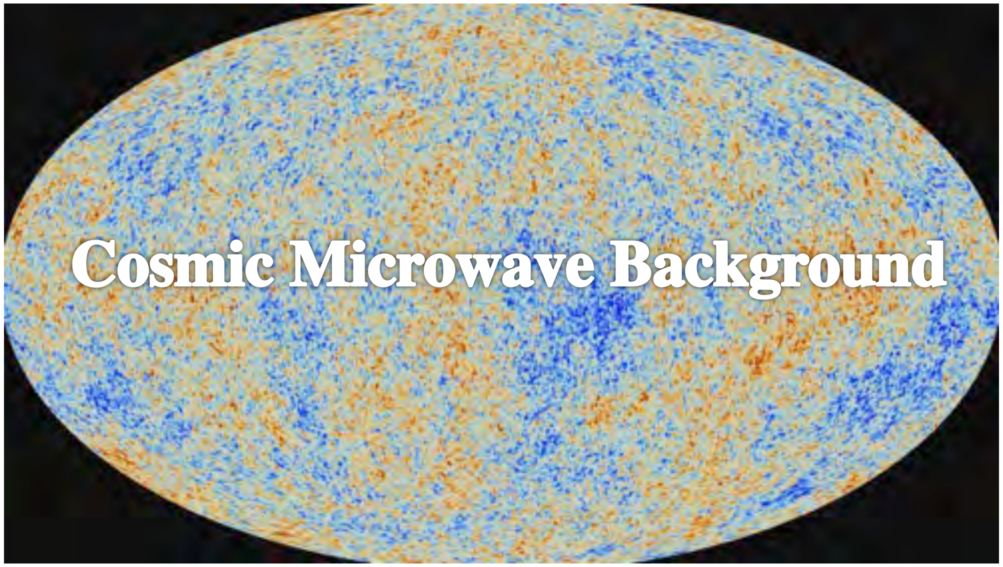
Carter Hall, University of Maryland
October 19, 2016

Astrophysical evidence for dark matter

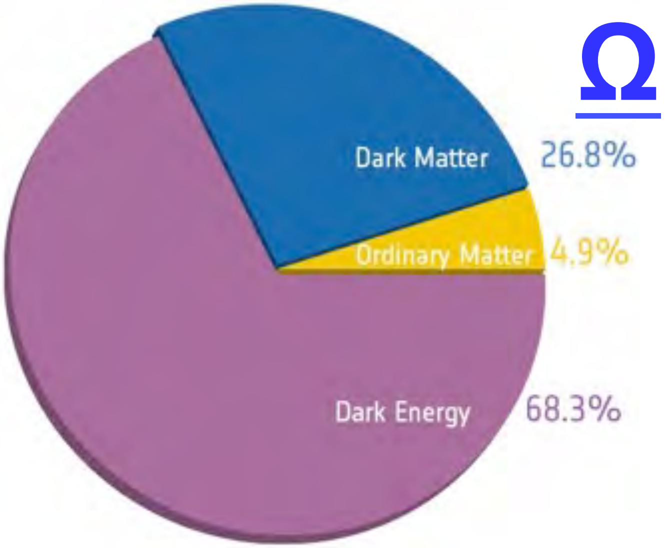
Galaxy cluster collisions



Rotation curves

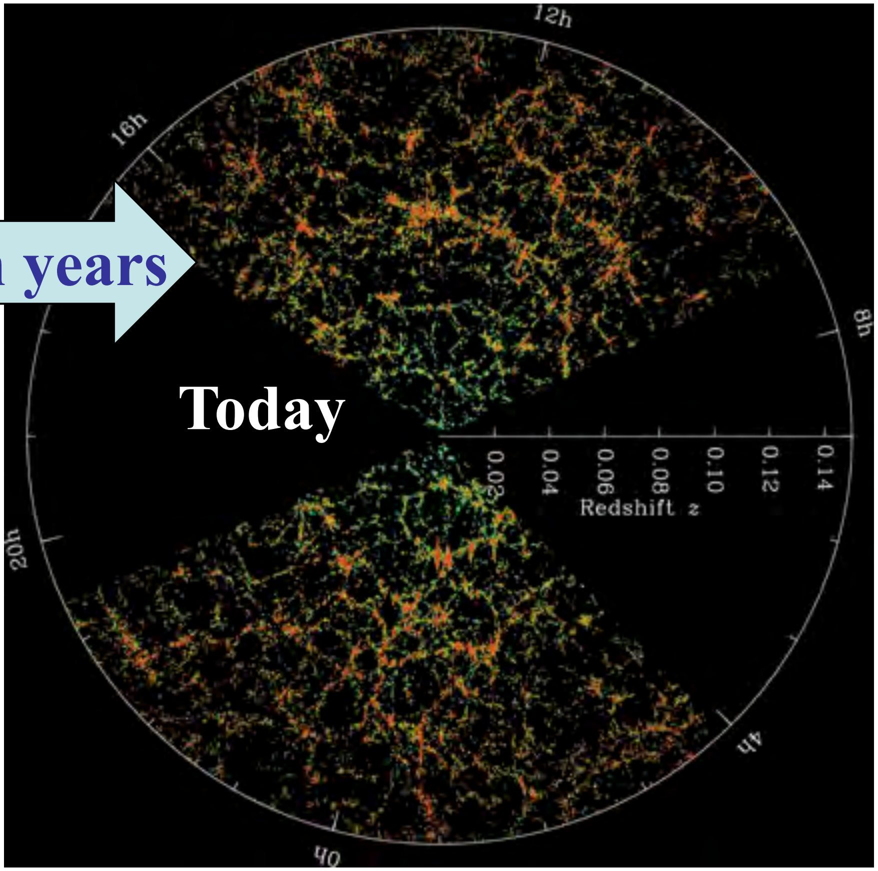


Cosmic Microwave Background



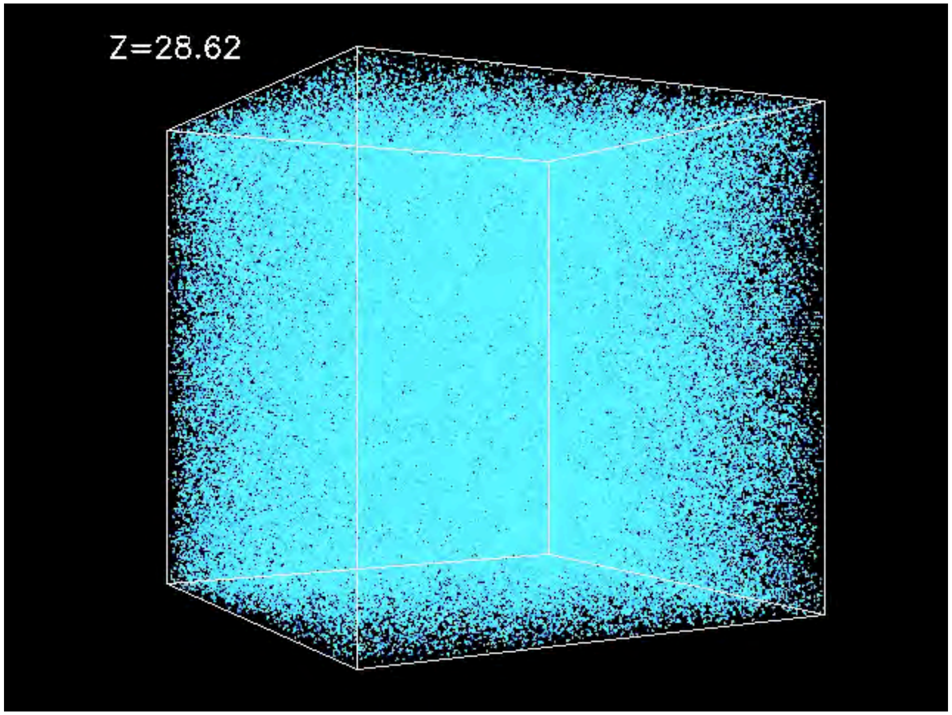
380,000 years
after the big bang

13.9 billion years



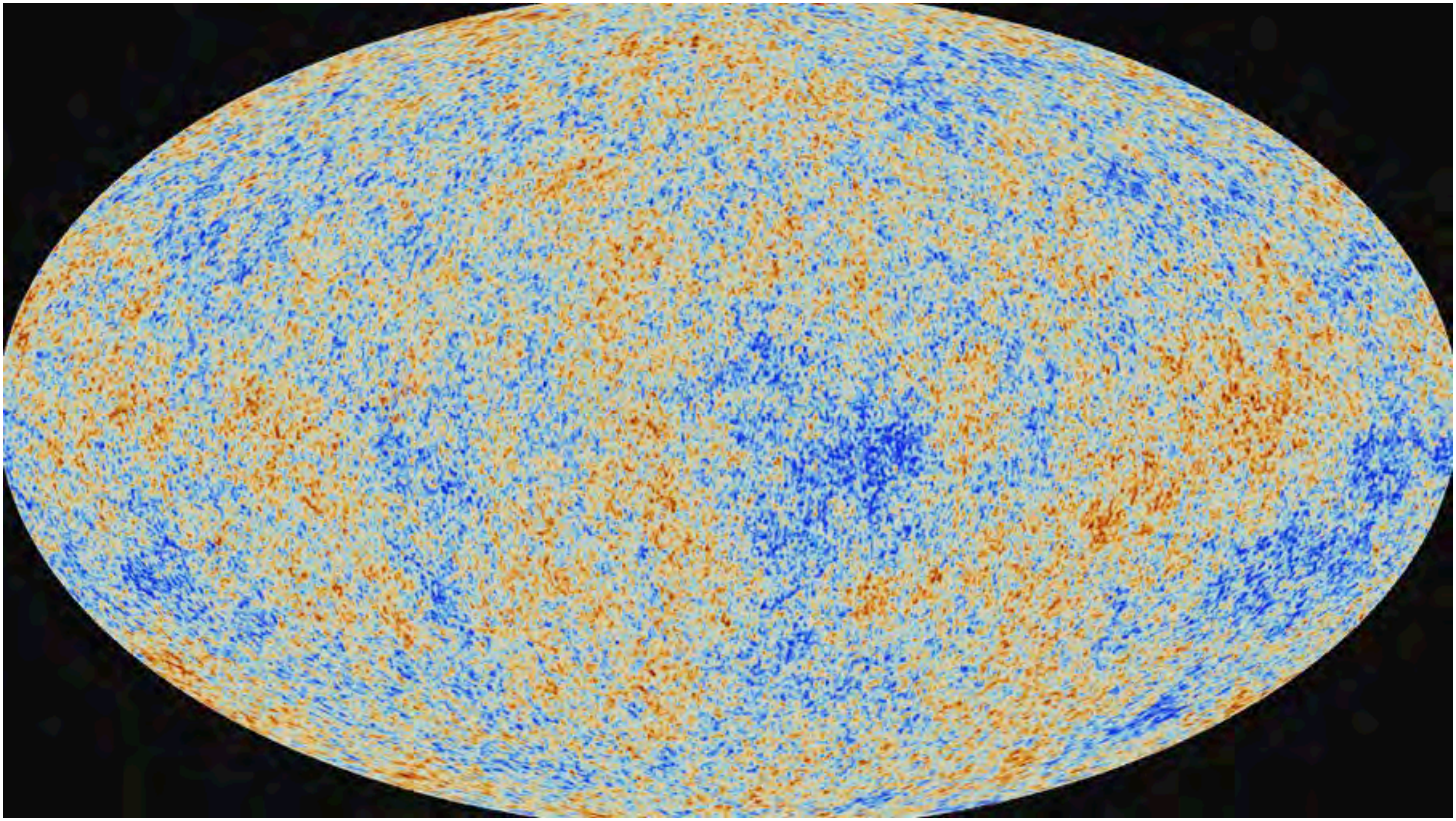
Today

Credit: Andrey Kravtsov, KICP, U. Chicago



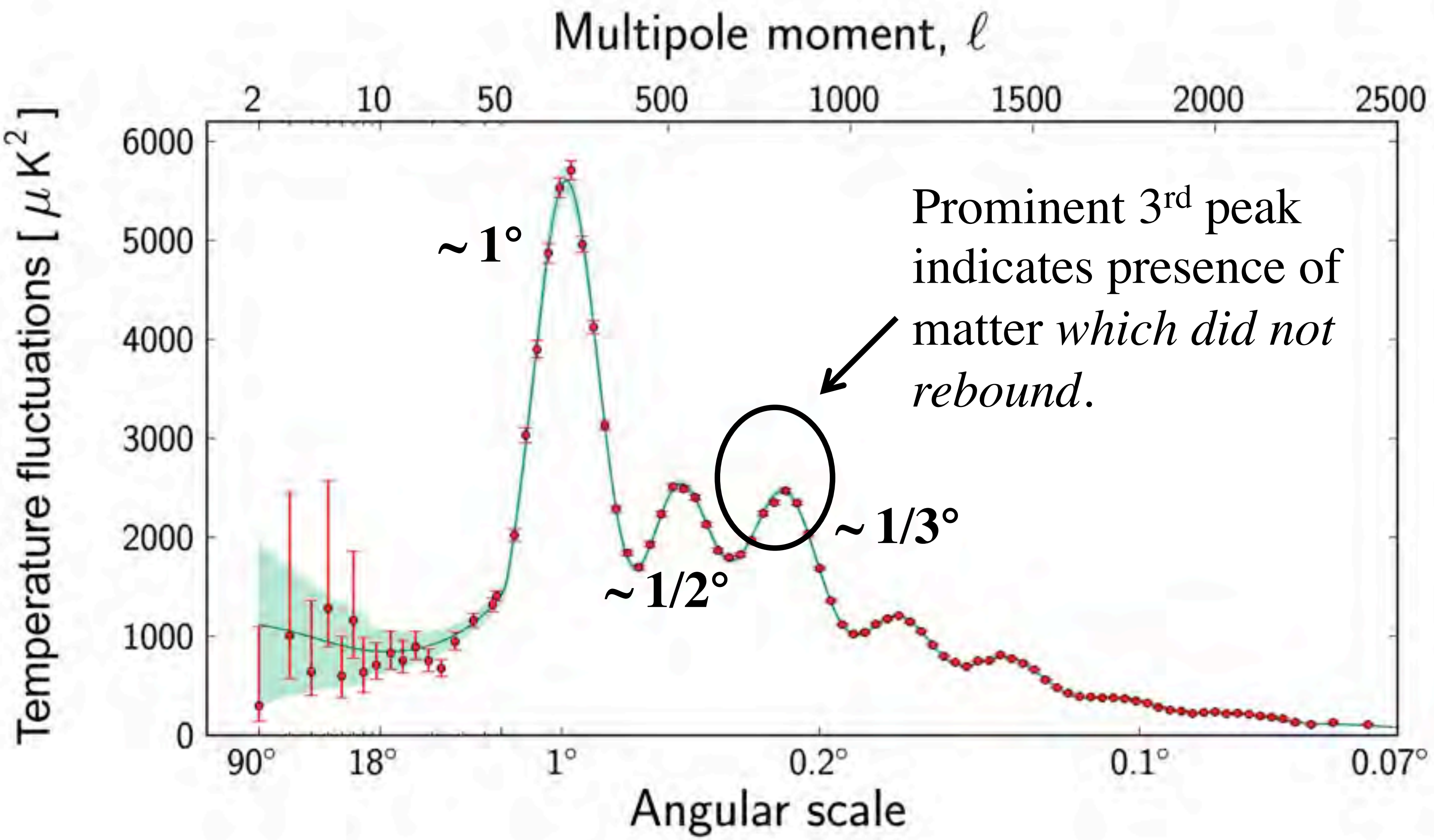
1970's - 1980's:
Cold dark matter
is needed to seed
the formation of
galaxy clusters

Temperature and density fluctuations are 1 part in 10^5.

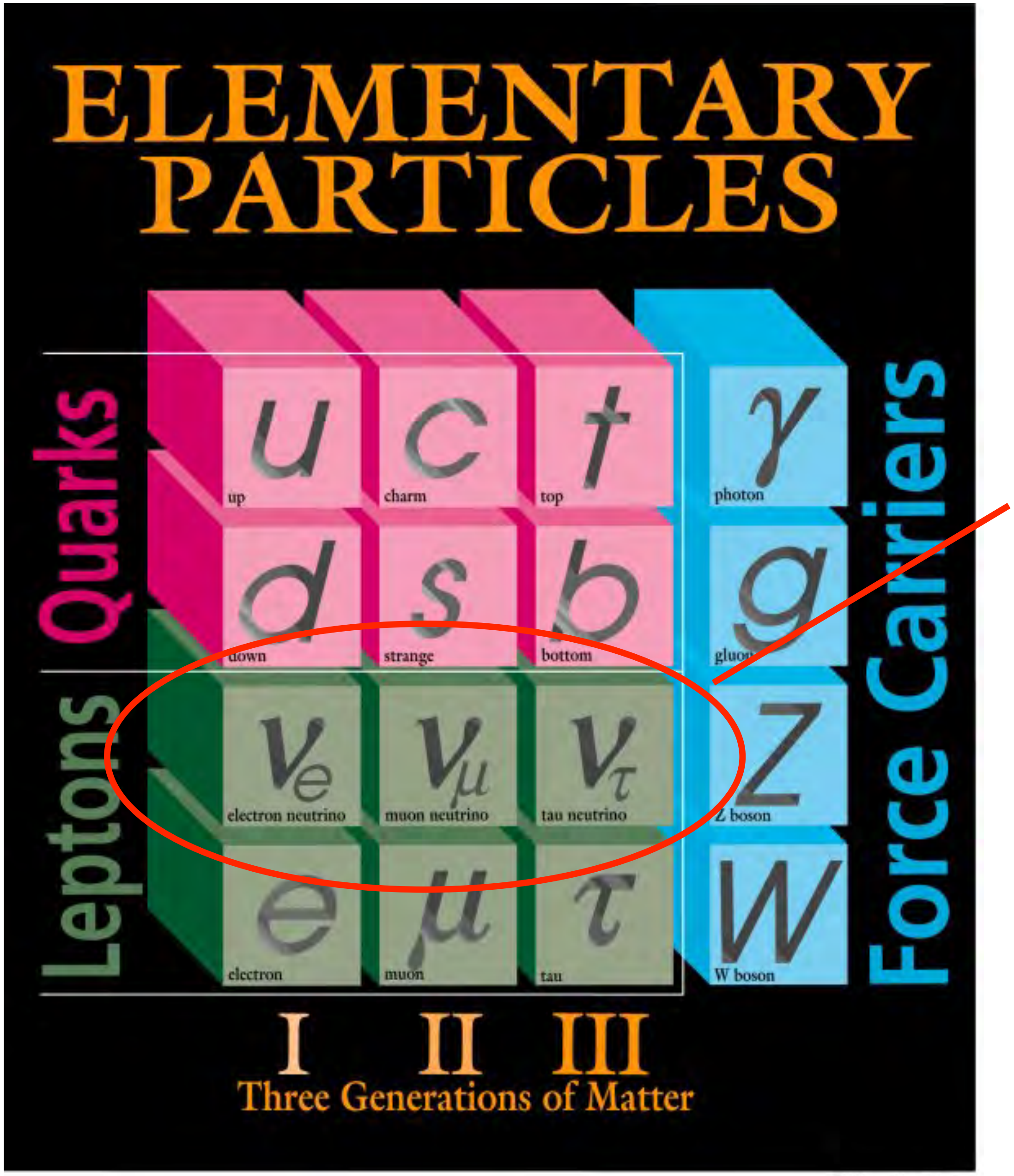


The cosmic microwave background anisotropy imaged Planck (2014).

CMB multipole expansion - measured by Planck (2014)



Prominent 3rd peak indicates presence of matter *which did not rebound*.



Fermilab 95-759

Neutrinos? –
not heavy enough

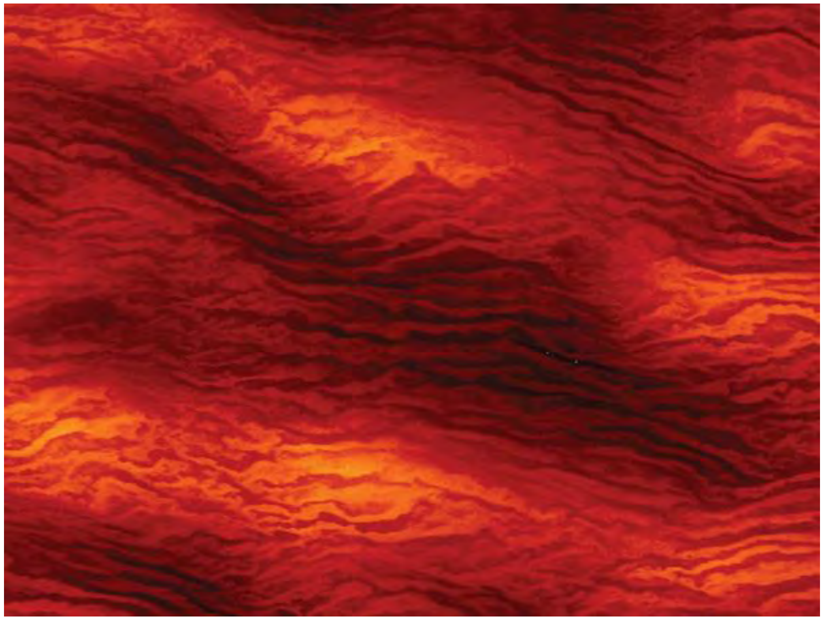
generalize

'Weakly
Interacting
Massive
Particle'

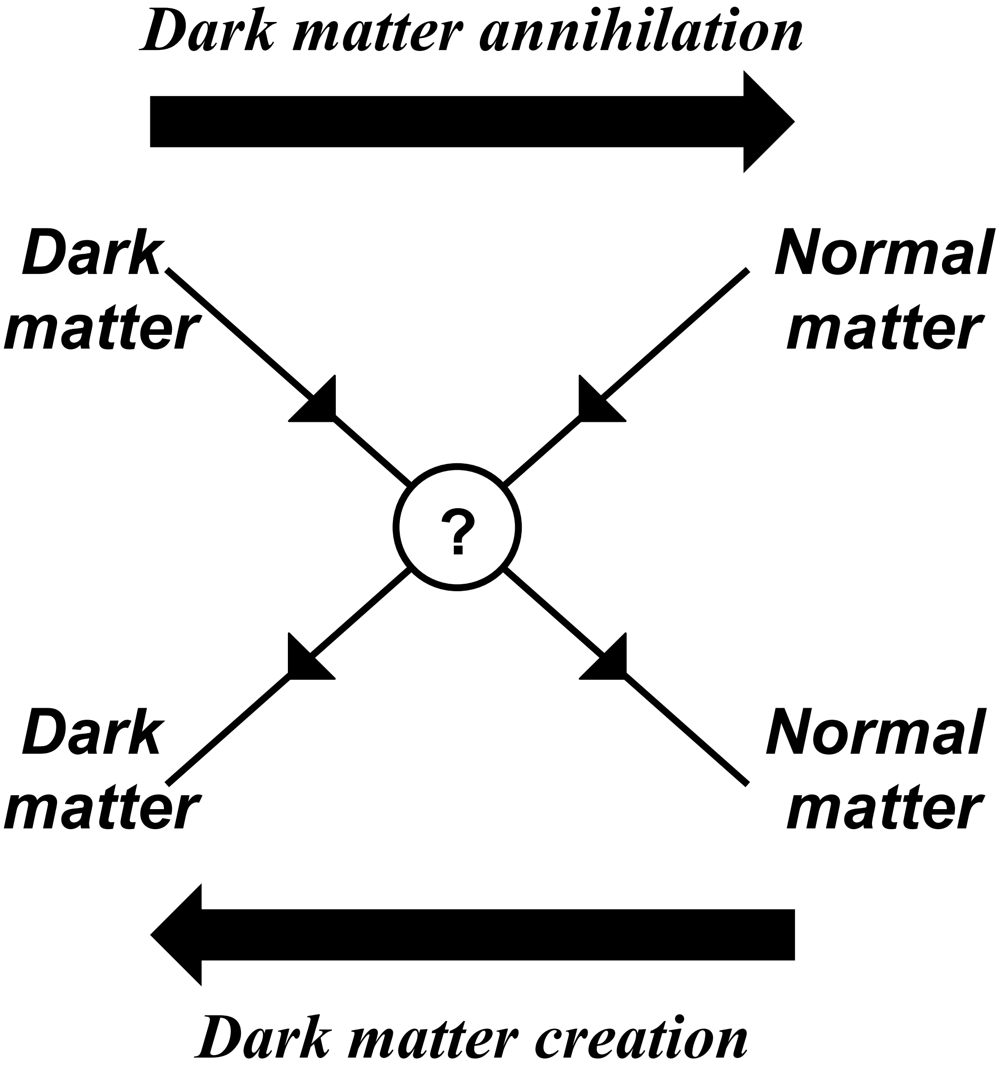
The thermal hypothesis:

Was the dark matter an interacting component in the very early universe?

Early universe plasma



Age of universe ~ 1 nanosecond;
Temperature ~ 100 GeV



Dark matter annihilation

Dark matter

Normal matter

?

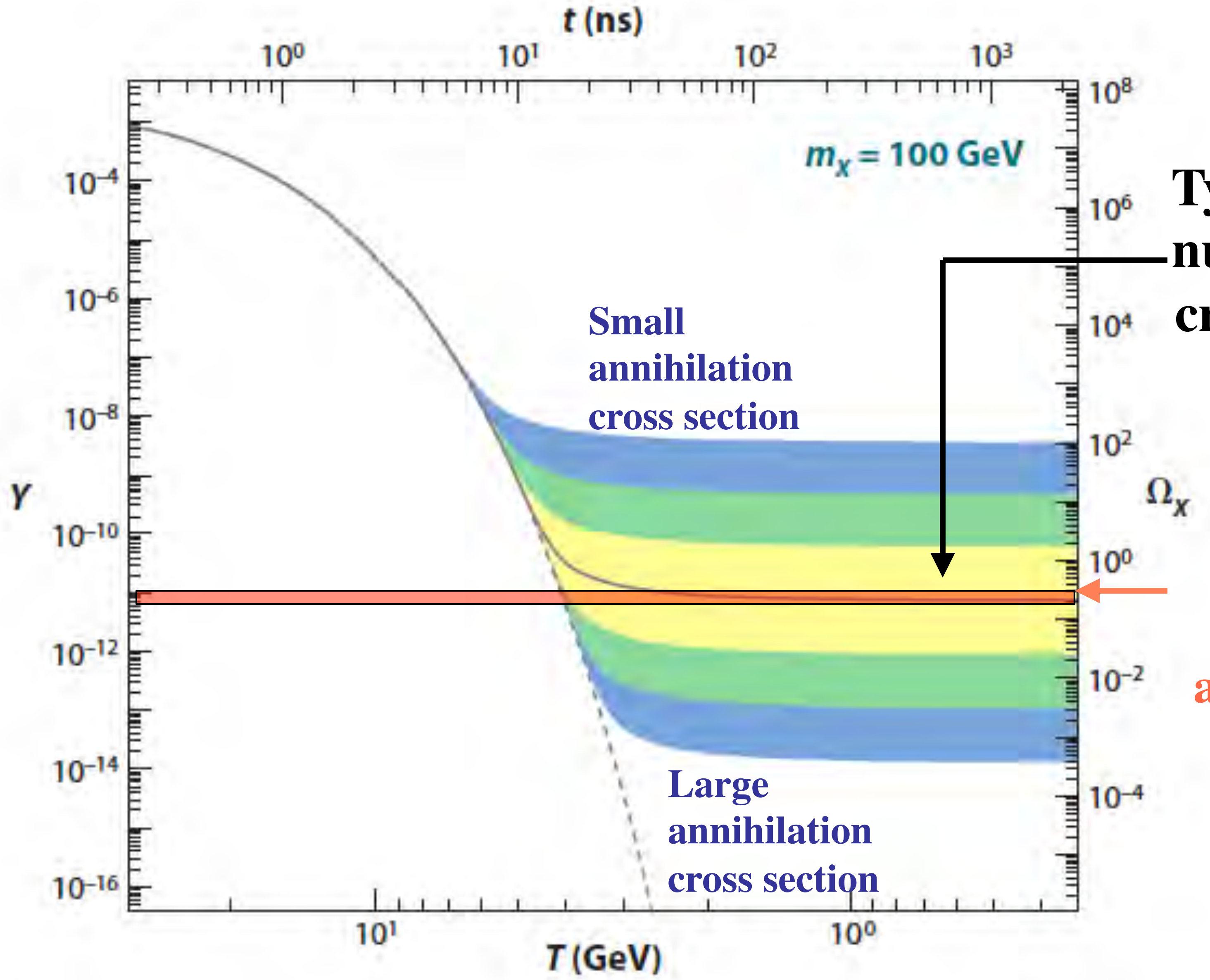
Dark matter

Normal matter

Dark matter creation

The thermal hypothesis:

Was the dark matter an interacting component in the very early universe?



Small annihilation cross section

Large annihilation cross section

Typical weak nuclear force cross sections

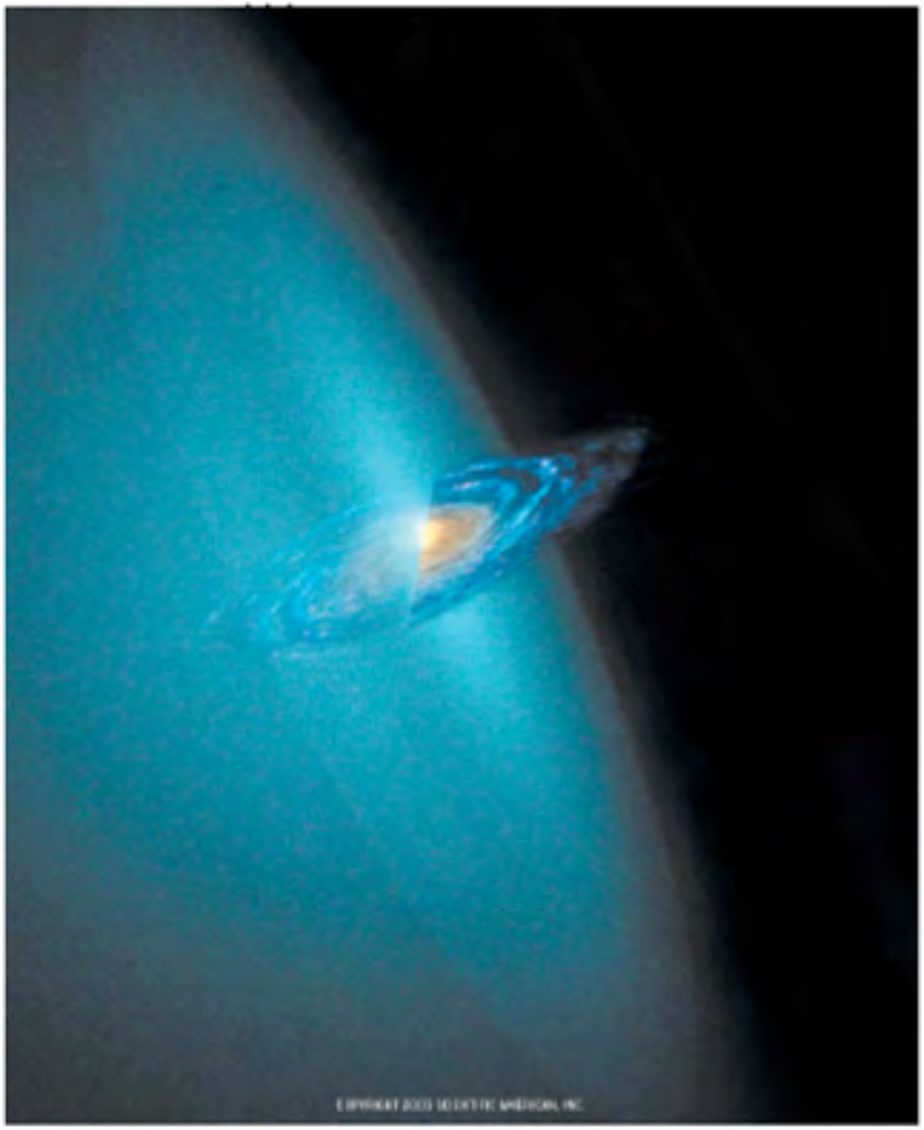
Correct dark matter abundance

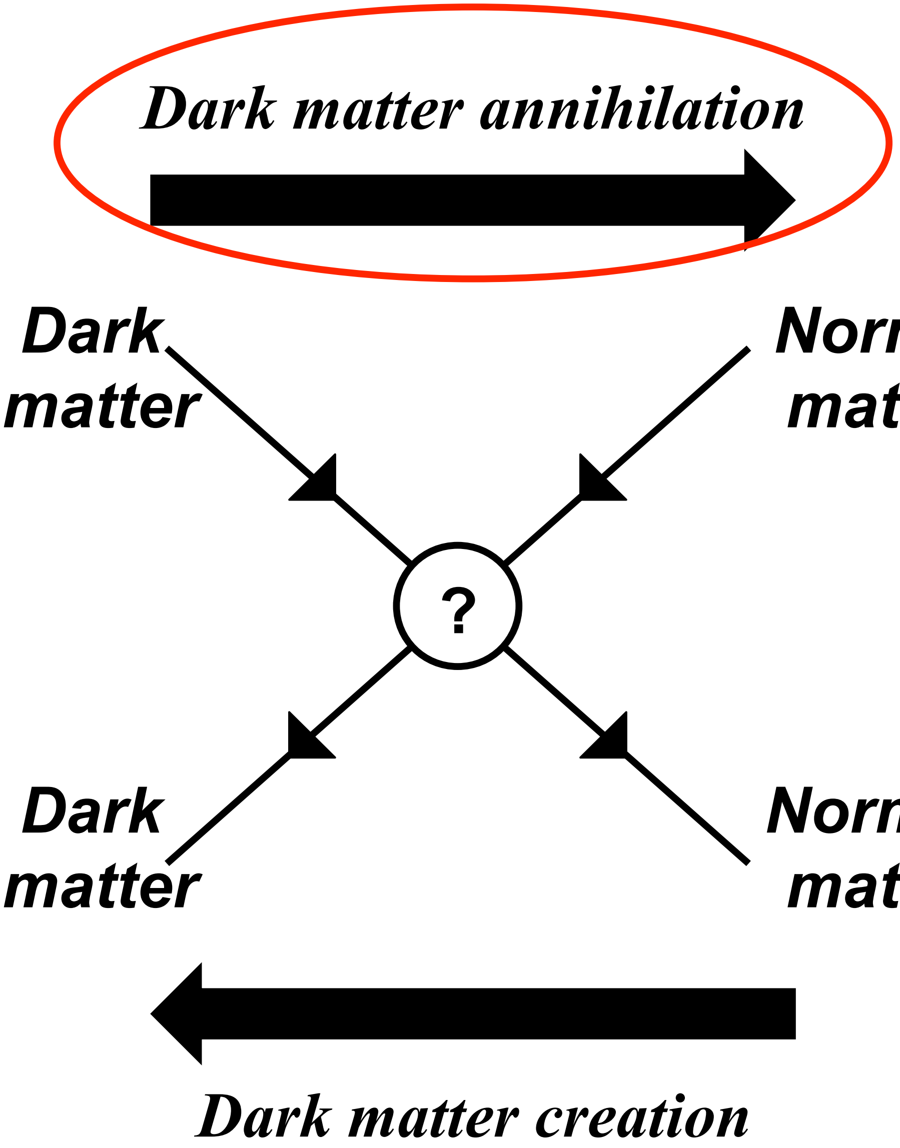
J. Feng, Annu. Rev. Astron. Astrophys. 2010. 48:495–545

The Milky Way’s dark matter halo

- **Typical orbital vel.** = 230 km/sec
  ~ 0.1% speed of light

- Density: ~ 300 m_{proton} / liter
  - **WIMPs** (~100 GeV): 3 per liter
- deBroglie wavelength:
  - **WIMPs**: larger than a nucleus. Coherent scalar scattering on ordinary nuclear matter, $\sigma \sim A^2$
- Production:
  - **WIMPs**: thermal





Dark matter annihilation

Dark matter

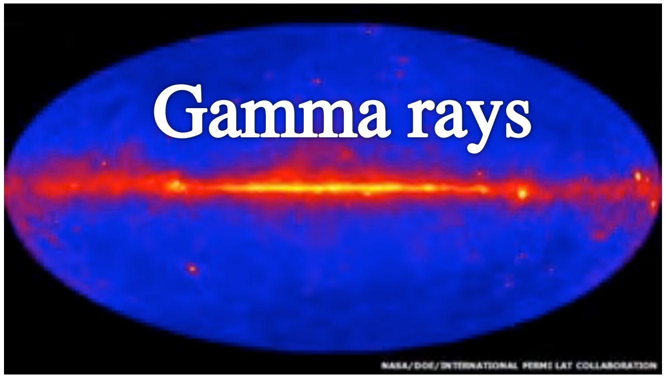
Normal matter

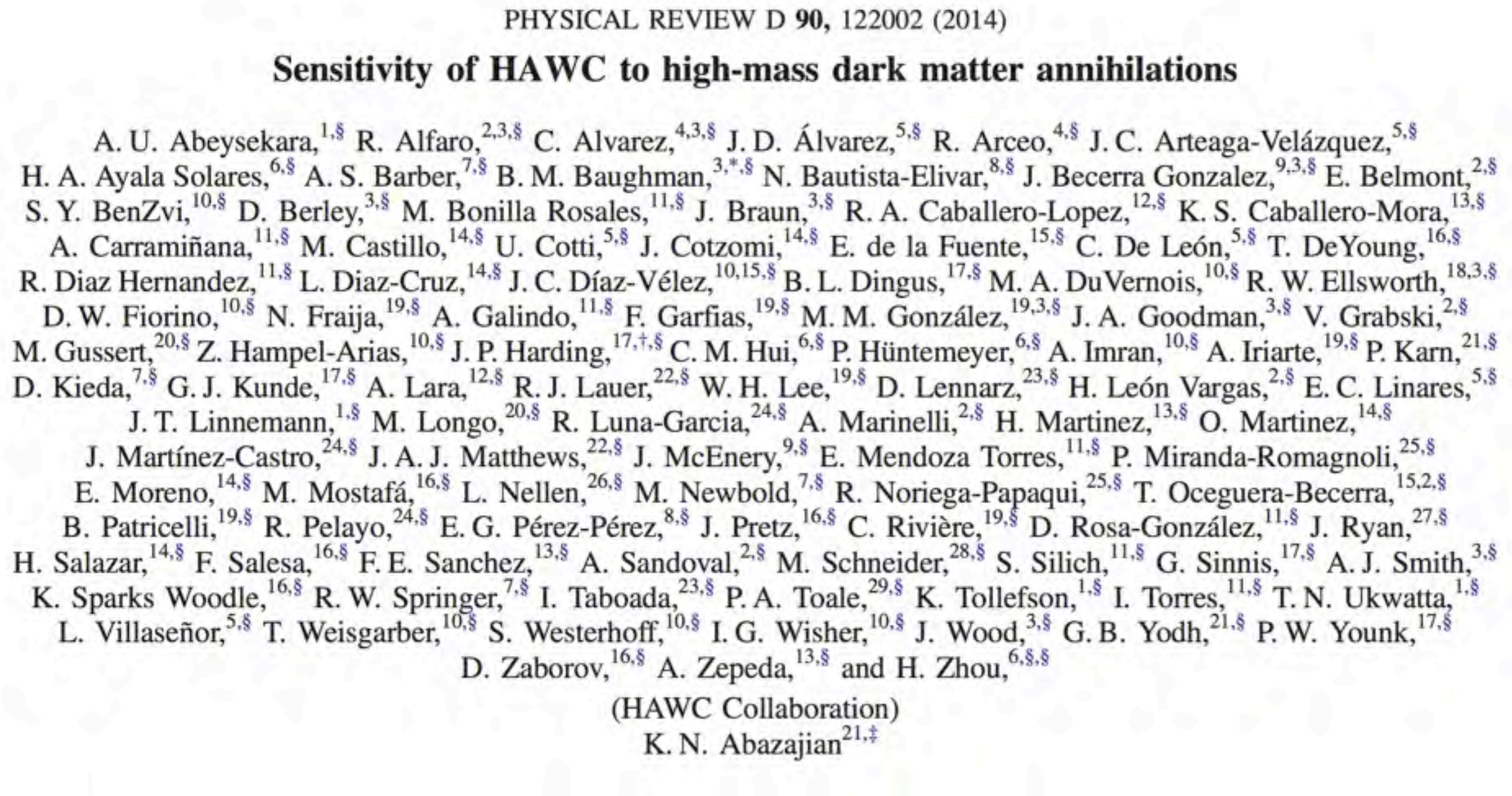
?

Dark matter

Normal matter

Dark matter creation




PHYSICAL REVIEW D **90,** 122002 (2014)

Sensitivity of HAWC to high-mass dark matter annihilations

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H. A. Ayala Solares,[6,§] A. S. Barber,[7,§] B. M. Baughman,[3,*,§] N. Bautista-Elivar,[8,§] J. Becerra Gonzalez,[9,3,§] E. Belmont,[2,§]
S. Y. BenZvi,[10,§] D. Berley,[3,§] M. Bonilla Rosales,[11,§] J. Braun,[3,§] R. A. Caballero-Lopez,[12,§] K. S. Caballero-Mora,[13,§]
A. Carramiñana,[11,§] M. Castillo,[14,§] U. Cotti,[5,§] J. Cotzomi,[14,§] E. de la Fuente,[15,§] C. De León,[5,§] T. DeYoung,[16,§]
R. Diaz Hernandez,[11,§] L. Diaz-Cruz,[14,§] J. C. Díaz-Vélez,[10,15,§] B. L. Dingus,[17,§] M. A. DuVernois,[10,§] R. W. Ellsworth,[18,3,§]
D. W. Fiorino,[10,§] N. Fraija,[19,§] A. Galindo,[11,§] F. Garfias,[19,§] M. M. González,[19,3,§] J. A. Goodman,[3,§] V. Grabski,[2,§]
M. Gussert,[20,§] Z. Hampel-Arias,[10,§] J. P. Harding,[17,†,§] C. M. Hui,[6,§] P. Hüntemeyer,[6,§] A. Imran,[10,§] A. Iriarte,[19,§] P. Karn,[21,§]
D. Kieda,[7,§] G. J. Kunde,[17,§] A. Lara,[12,§] R. J. Lauer,[22,§] W. H. Lee,[19,§] D. Lennarz,[23,§] H. León Vargas,[2,§] E. C. Linares,[5,§]
J. T. Linnemann,[1,§] M. Longo,[20,§] R. Luna-Garcia,[24,§] A. Marinelli,[2,§] H. Martinez,[13,§] O. Martinez,[14,§]
J. Martínez-Castro,[24,§] J. A. J. Matthews,[22,§] J. McEnery,[9,§] E. Mendoza Torres,[11,§] P. Miranda-Romagnoli,[25,§]
E. Moreno,[14,§] M. Mostafá,[16,§] L. Nellen,[26,§] M. Newbold,[7,§] R. Noriega-Papaqui,[25,§] T. Oceguera-Becerra,[15,2,§]
B. Patricelli,[19,§] R. Pelayo,[24,§] E. G. Pérez-Pérez,[8,§] J. Pretz,[16,§] C. Rivière,[19,§] D. Rosa-González,[11,§] J. Ryan,[27,§]
H. Salazar,[14,§] F. Salesa,[16,§] F. E. Sanchez,[13,§] A. Sandoval,[2,§] M. Schneider,[28,§] S. Silich,[11,§] G. Sinnis,[17,§] A. J. Smith,[3,§]
K. Sparks Woodle,[16,§] R. W. Springer,[7,§] I. Taboada,[23,§] P. A. Toale,[29,§] K. Tollefson,[1,§] I. Torres,[11,§] T. N. Ukwatta,[1,§]
L. Villaseñor,[5,§] T. Weisgarber,[10,§] S. Westerhoff,[10,§] I. G. Wisher,[10,§] J. Wood,[3,§] G. B. Yodh,[21,§] P. W. Younk,[17,§]
D. Zaborov,[16,§] A. Zepeda,[13,§] and H. Zhou,[6,§,§]

(HAWC Collaboration)
K. N. Abazajian[21,‡]

HAWC projected five-year sensitivity (start 2015)

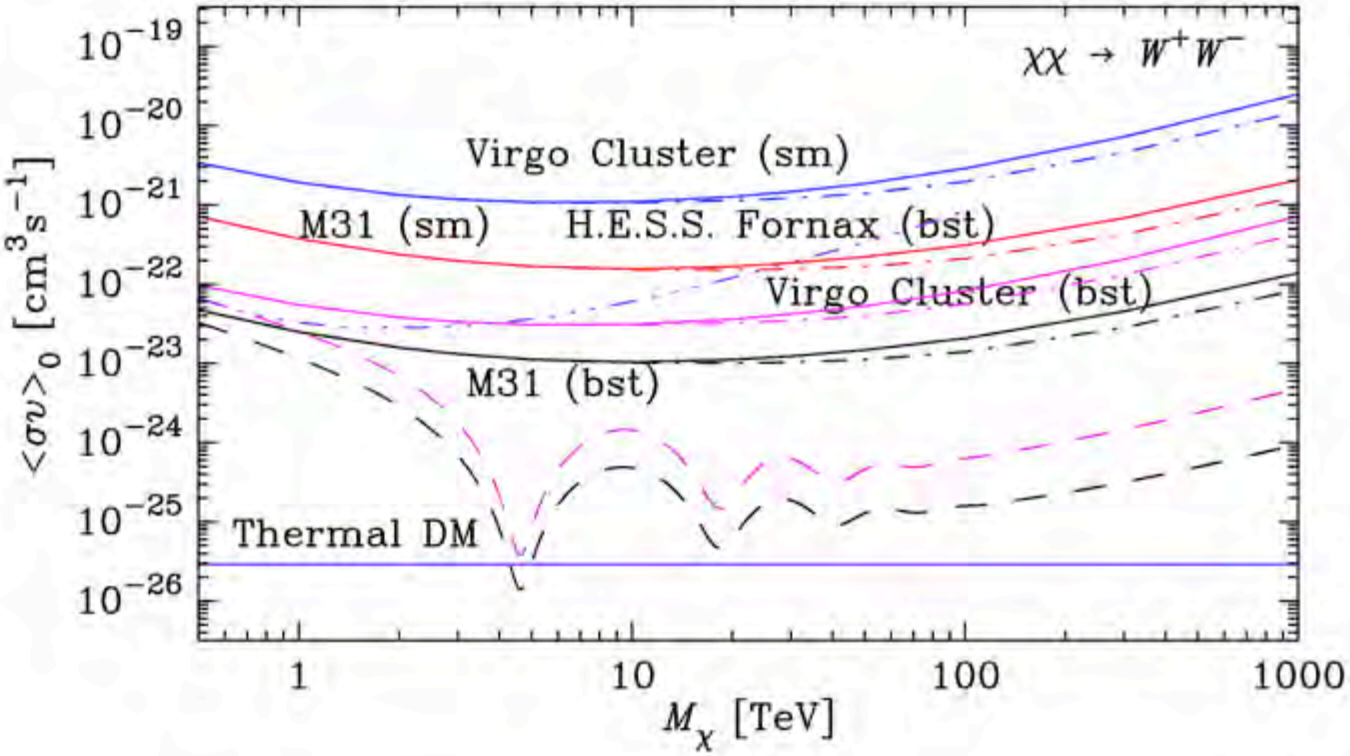
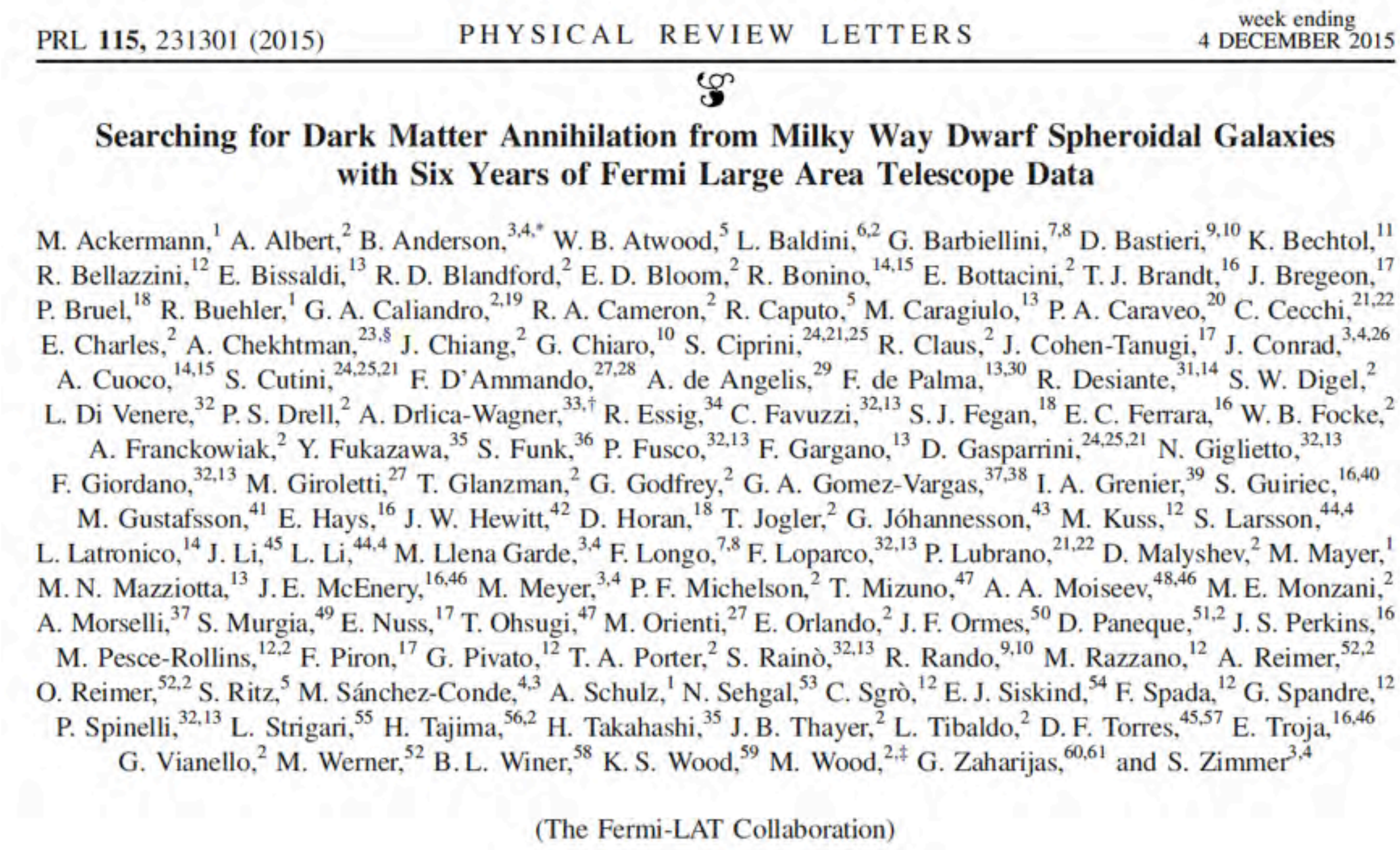


FIG. 3 (color online). The projected dark matter limits from the Virgo cluster and the galaxy M31 for HAWC after five years, for the $b\bar{b}$, $t\bar{t}$, $\mu^+\mu^-$, $\tau^+\tau^-$, and W^+W^- dark matter annihilation channels. From top to bottom, the curves are for the Virgo cluster with a smooth (sm) NFW profile (blue), M31 with a smooth (sm) NFW profile (red), the substructure-boosted (bst) Virgo cluster (magenta), and the substructure-boosted (bst) M31 (black). The triple-dot-dashed purple line is the limit from the H.E.S.S. observatory observations of the Fornax cluster [41], boosted (bst) using the substructure boost model of Ref. [31]. The dot-dashed purple line is the limit from the Fermi-LAT observations of the Virgo cluster [36], boosted (bst) using the substructure boost model of Ref. [31]. For the $\mu^+\mu^-$ channel, both the H.E.S.S. Fornax limit and the Fermi-LAT Virgo limit are for a combination of prompt emission and IC emission. Here we employ the substructure boost of 35 for the Virgo cluster, 15 for M31, and 29 for the Fornax cluster, based on Ref. [31]. The solid curves are the dark matter limits for just the prompt gamma-ray emission, and the dot-dashed curves are the limits considering both the prompt gamma-ray mission and the IC emission from electrons and positrons scattering on the CMB. In the W^+W^- plot, the dashed curves are the limit on the early-universe annihilation cross section when natural Sommerfeld enhancement is included in the cross section today (with $v_{\rm rel} \sim 300$ km s^{-1}). The width of the gray bands above the smooth Virgo cluster lines to the right of the figure indicate the range in the dark matter limit for all masses due to possible uncertainty from the point-source subtraction in the analysis. The solid purple line shows the expected dark matter thermal cross section. All limits are at 95% CL.

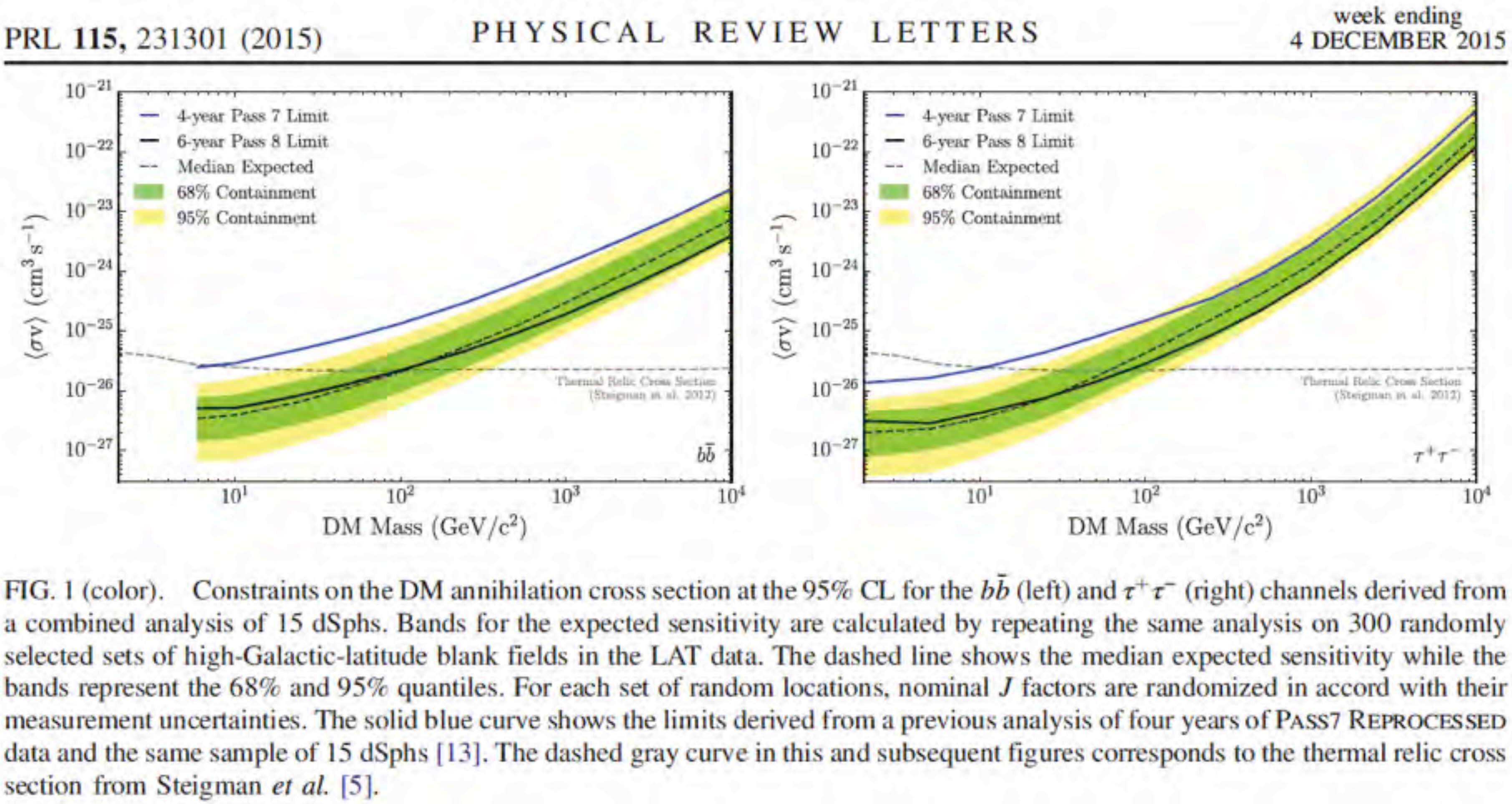


PRL 115, 231301 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data

M. Ackermann,[1] A. Albert,[2] B. Anderson,[3,4,*] W. B. Atwood,[5] L. Baldini,[6,2] G. Barbiellini,[7,8] D. Bastieri,[9,10] K. Bechtol,[11] R. Bellazzini,[12] E. Bissaldi,[13] R. D. Blandford,[2] E. D. Bloom,[2] R. Bonino,[14,15] E. Bottacini,[2] T. J. Brandt,[16] J. Bregeon,[17] P. Bruel,[18] R. Buehler,[1] G. A. Caliandro,[2,19] R. A. Cameron,[2] R. Caputo,[5] M. Caragiulo,[13] P. A. Caraveo,[20] C. Cecchi,[21,22] E. Charles,[2] A. Chekhtman,[23,§] J. Chiang,[2] G. Chiaro,[10] S. Ciprini,[24,21,25] R. Claus,[2] J. Cohen-Tanugi,[17] J. Conrad,[3,4,26] A. Cuoco,[14,15] S. Cutini,[24,25,21] F. D'Ammando,[27,28] A. de Angelis,[29] F. de Palma,[13,30] R. Desiante,[31,14] S. W. Digel,[2] L. Di Venere,[32] P. S. Drell,[2] A. Drlica-Wagner,[33,†] R. Essig,[34] C. Favuzzi,[32,13] S. J. Fegan,[18] E. C. Ferrara,[16] W. B. Focke,[2] A. Franckowiak,[2] Y. Fukazawa,[35] S. Funk,[36] P. Fusco,[32,13] F. Gargano,[13] D. Gasparrini,[24,25,21] N. Giglietto,[32,13] F. Giordano,[32,13] M. Giroletti,[27] T. Glanzman,[2] G. Godfrey,[2] G. A. Gomez-Vargas,[37,38] I. A. Grenier,[39] S. Guiriec,[16,40] M. Gustafsson,[41] E. Hays,[16] J. W. Hewitt,[42] D. Horan,[18] T. Jogler,[2] G. Jóhannesson,[43] M. Kuss,[12] S. Larsson,[44,4] L. Latronico,[14] J. Li,[45] L. Li,[44,4] M. Llena Garde,[3,4] F. Longo,[7,8] F. Loparco,[32,13] P. Lubrano,[21,22] D. Malyshev,[2] M. Mayer,[1] M. N. Mazziotta,[13] J. E. McEnery,[16,46] M. Meyer,[3,4] P. F. Michelson,[2] T. Mizuno,[47] A. A. Moiseev,[48,46] M. E. Monzani,[2] A. Morselli,[37] S. Murgia,[49] E. Nuss,[17] T. Ohsugi,[47] M. Orienti,[27] E. Orlando,[2] J. F. Ormes,[50] D. Paneque,[51,2] J. S. Perkins,[16] M. Pesce-Rollins,[12,2] F. Piron,[17] G. Pivato,[12] T. A. Porter,[2] S. Rainò,[32,13] R. Rando,[9,10] M. Razzano,[12] A. Reimer,[52,2] O. Reimer,[52,2] S. Ritz,[5] M. Sánchez-Conde,[4,3] A. Schulz,[1] N. Sehgal,[53] C. Sgrò,[12] E. J. Siskind,[54] F. Spada,[12] G. Spandre,[12] P. Spinelli,[32,13] L. Strigari,[55] H. Tajima,[56,2] H. Takahashi,[35] J. B. Thayer,[2] L. Tibaldo,[2] D. F. Torres,[45,57] E. Troja,[16,46] G. Vianello,[2] M. Werner,[52] B. L. Winer,[58] K. S. Wood,[59] M. Wood,[2,‡] G. Zaharijas,[60,61] and S. Zimmer[3,4]

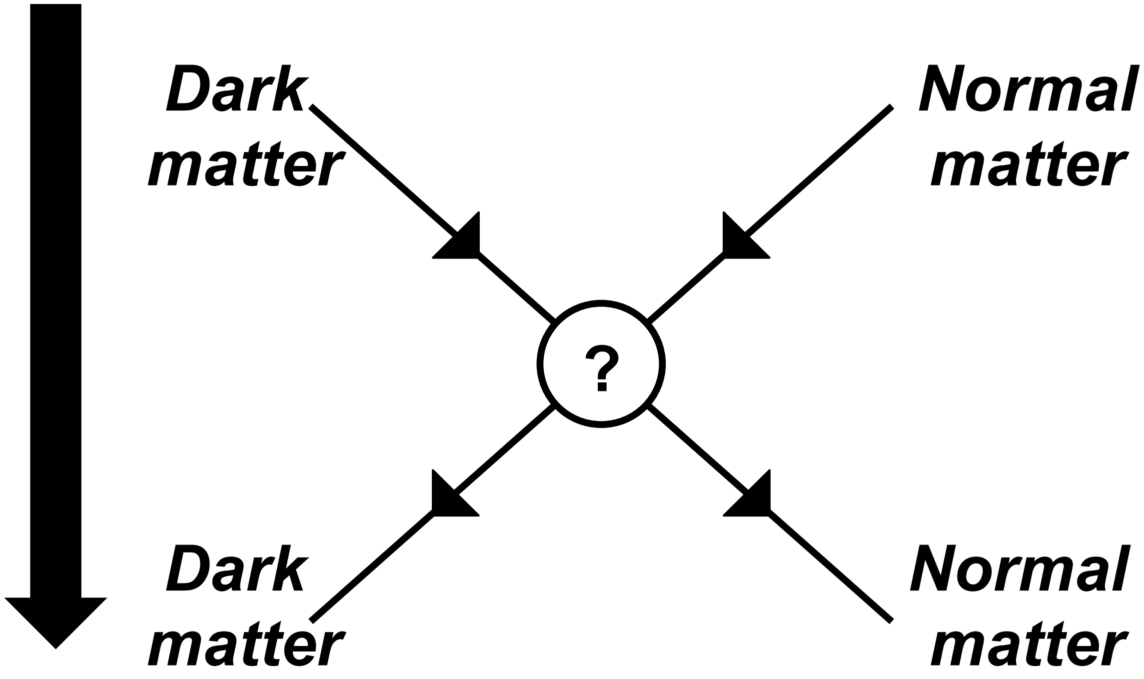
(The Fermi-LAT Collaboration)



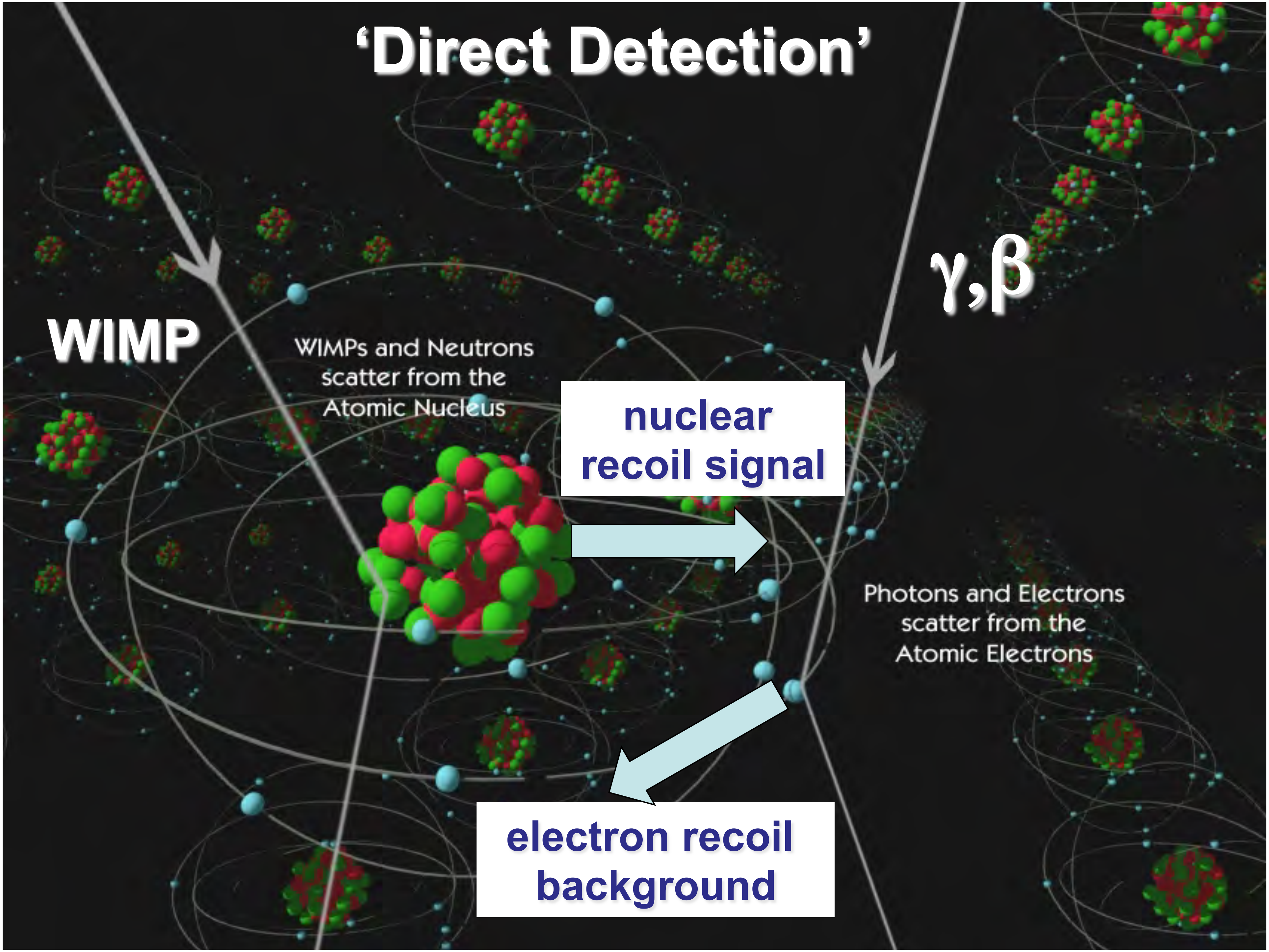
PRL **115,** 231301 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

FIG. 1 (color). Constraints on the DM annihilation cross section at the 95% CL for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of PASS7 REPROCESSED data and the same sample of 15 dSphs [13]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman *et al.* [5].

‘Direct detection’



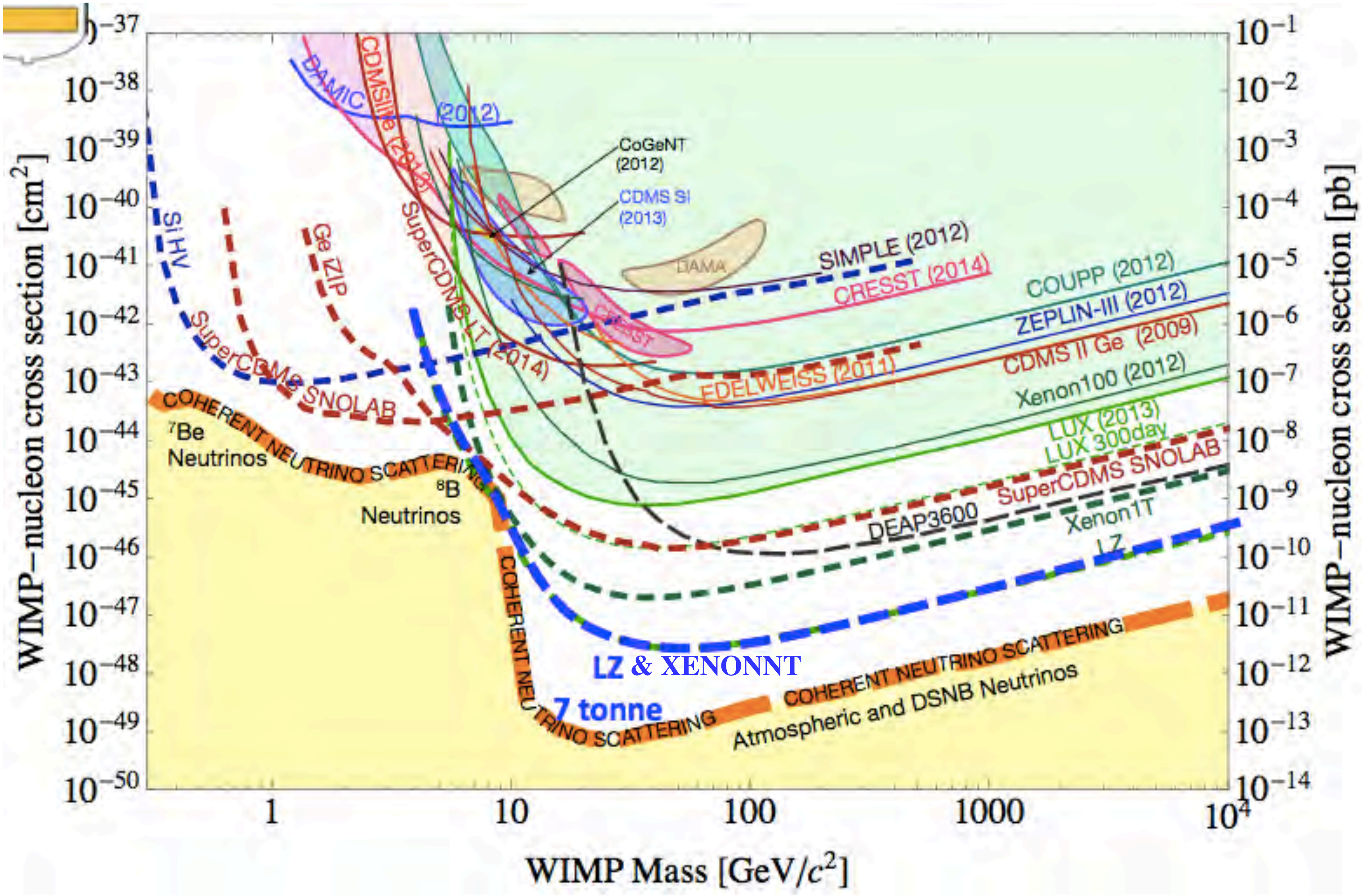
'Direct Detection'



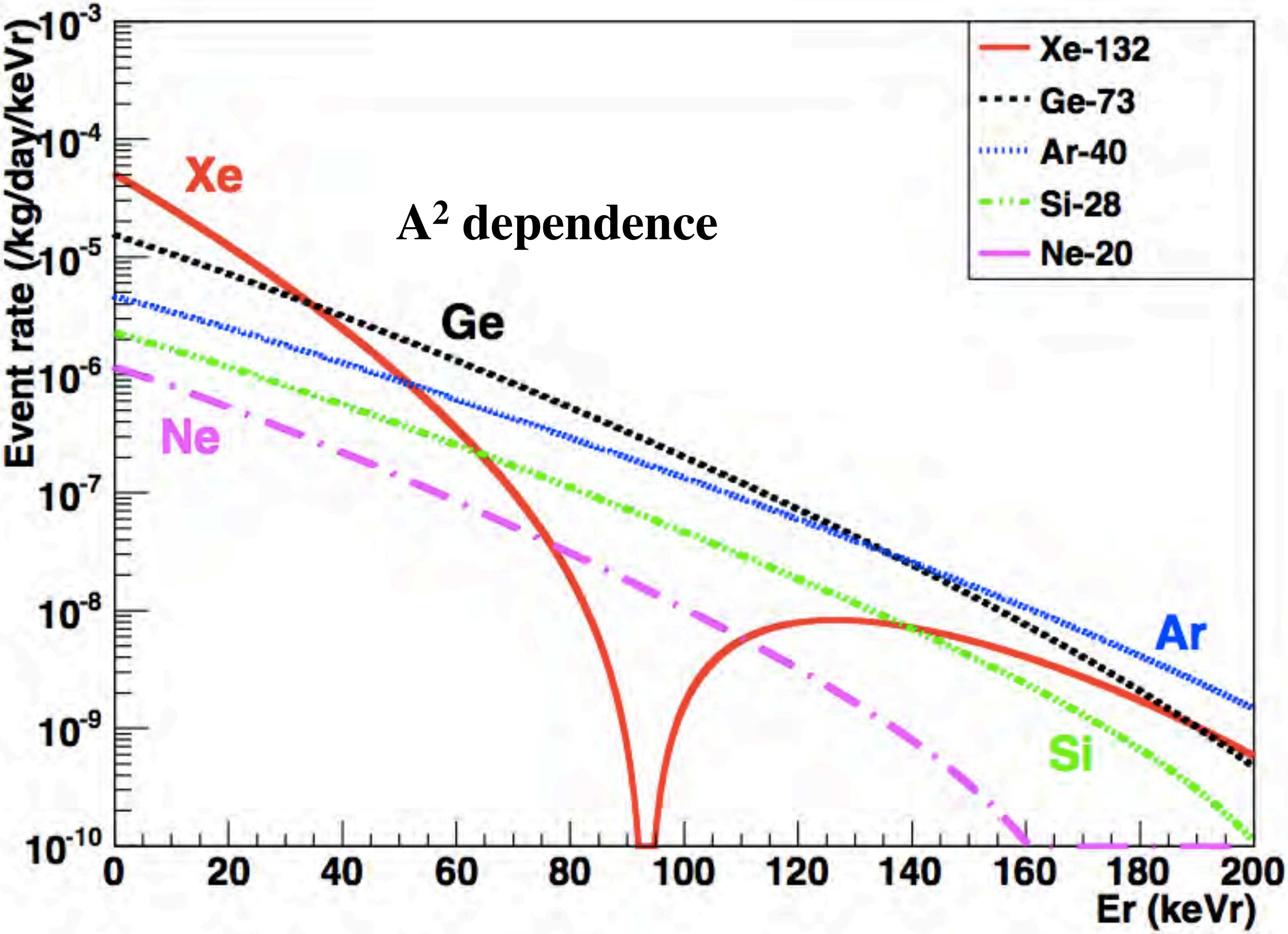
nuclear recoil signal

electron recoil background

The parameter space of direct detection



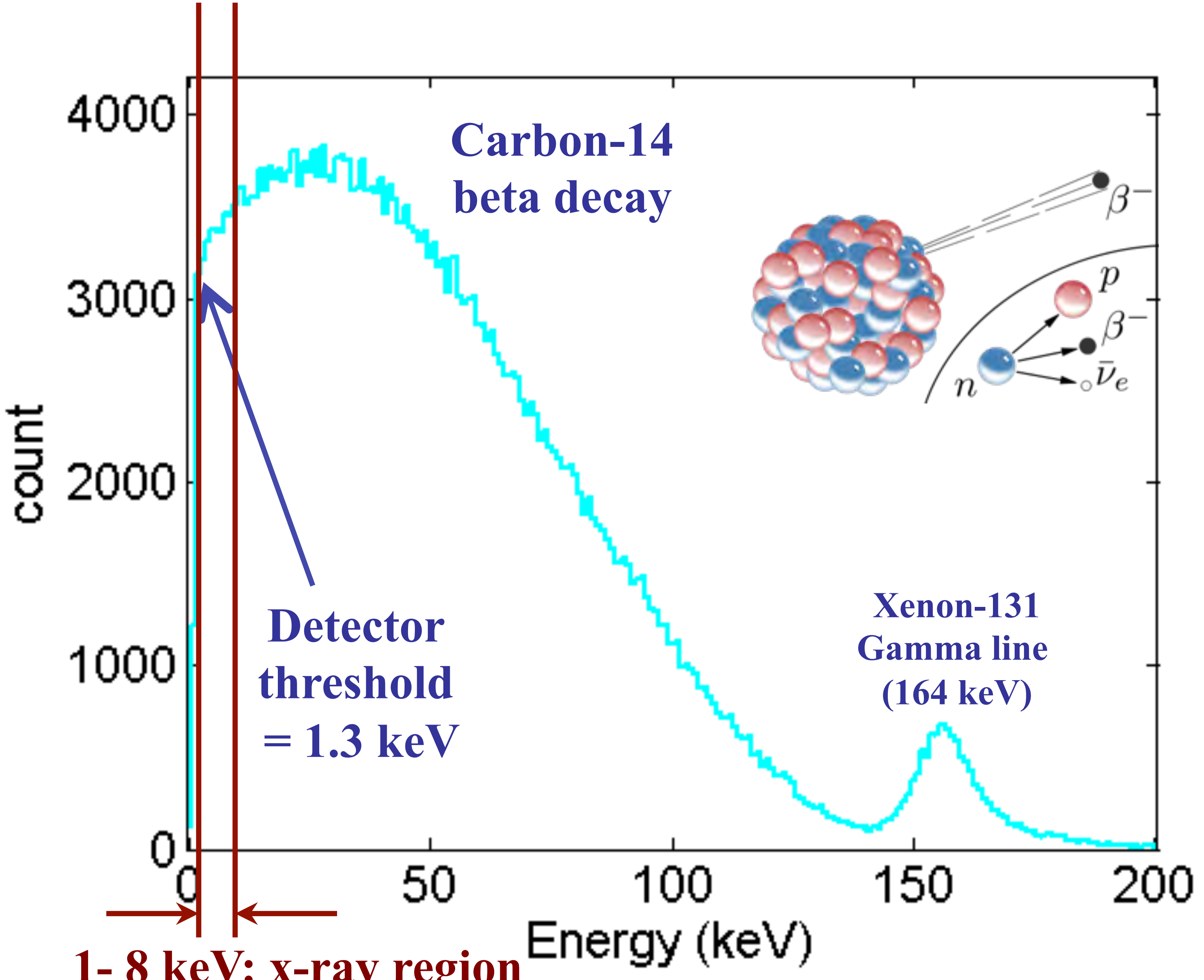
Nuclear recoil energy spectra



A^2 dependence

From: arXiv:1107.1295

Calibration of LUX: Beta spectrum of Carbon-14



Carbon-14 beta decay

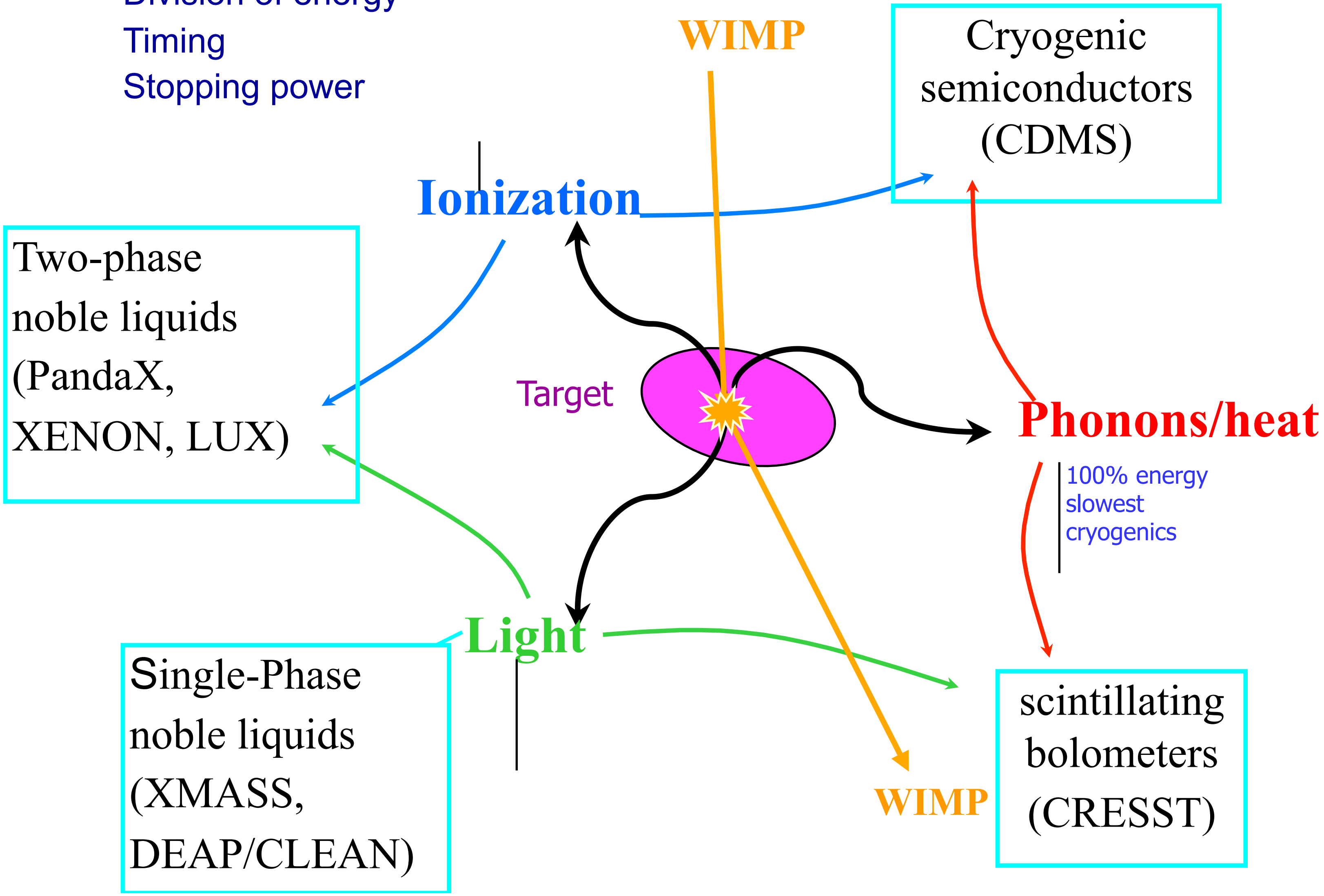
Detector threshold = 1.3 keV

Xenon-131 Gamma line (164 keV)

1- 8 keV: x-ray region

Detection modes for ionizing radiation

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power



WIMP

Cryogenic
semiconductors
(CDMS)

Ionization

Two-phase
noble liquids
(PandaX,
XENON, LUX)

Target

Phonons/heat

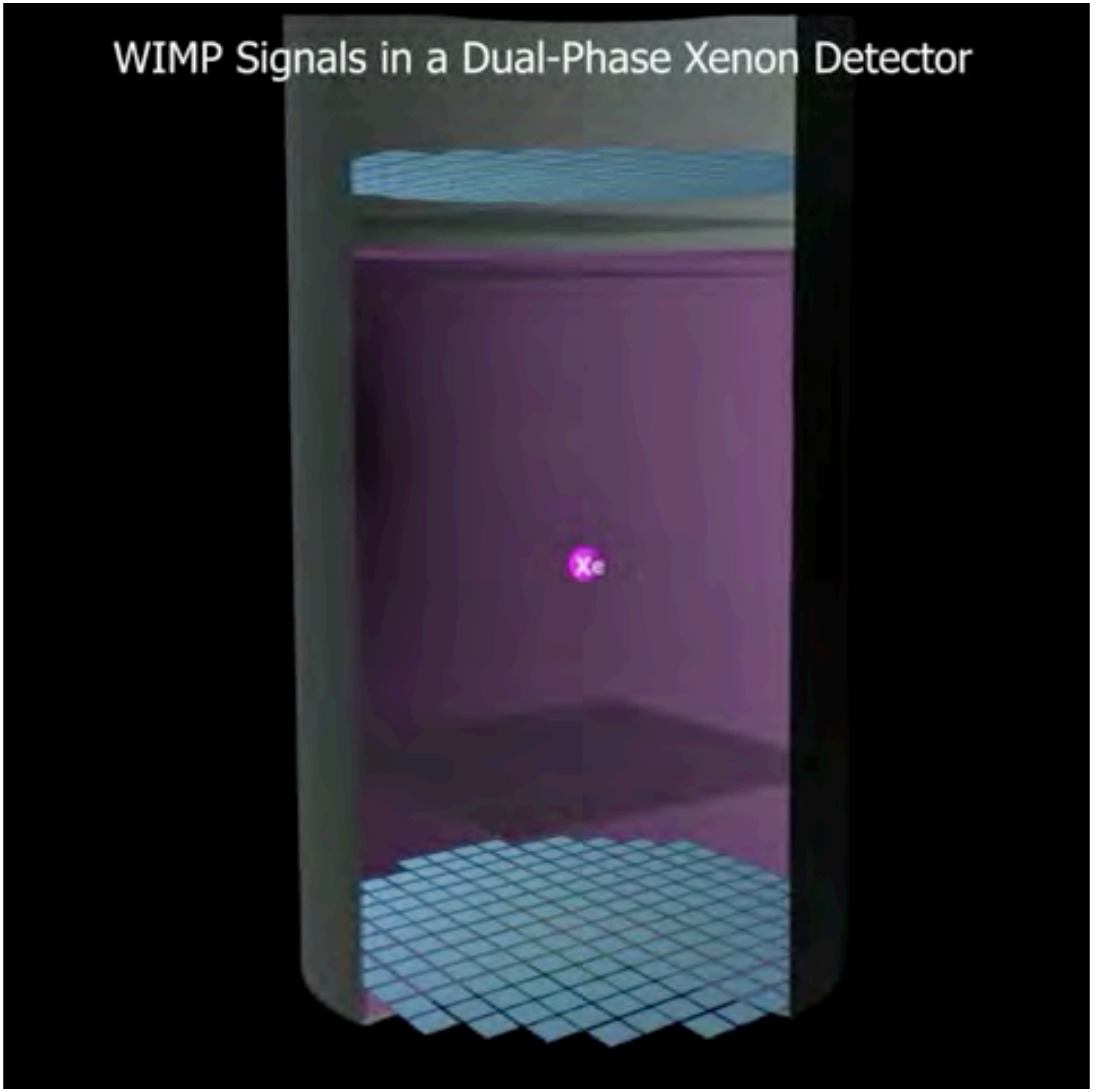
100% energy
slowest
cryogenics

Light

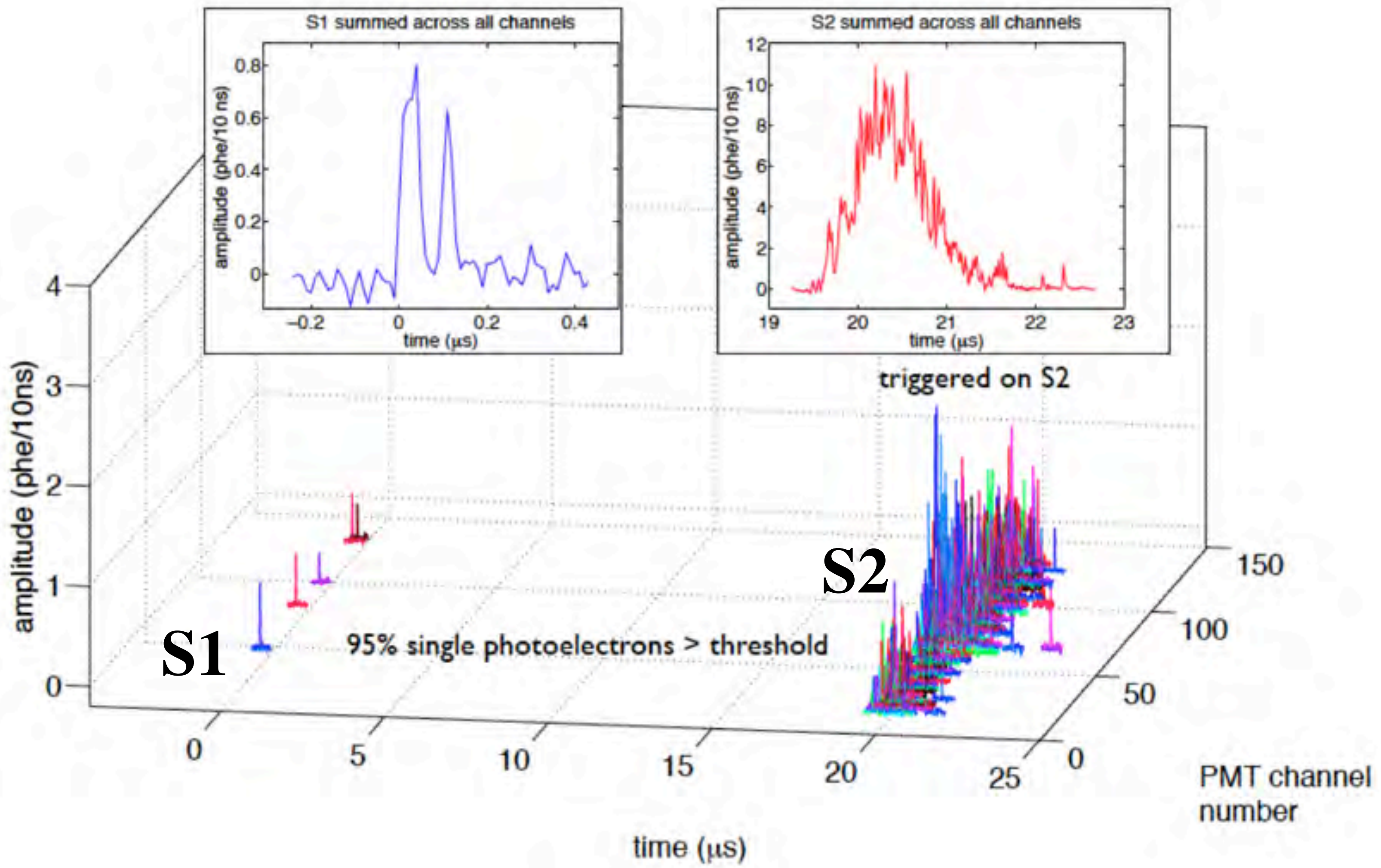
Single-Phase
noble liquids
(XMASS,
DEAP/CLEAN)

WIMP

scintillating
bolometers
(CRESST)


WIMP Signals in a Dual-Phase Xenon Detector
Xe

Typical Event in LUX



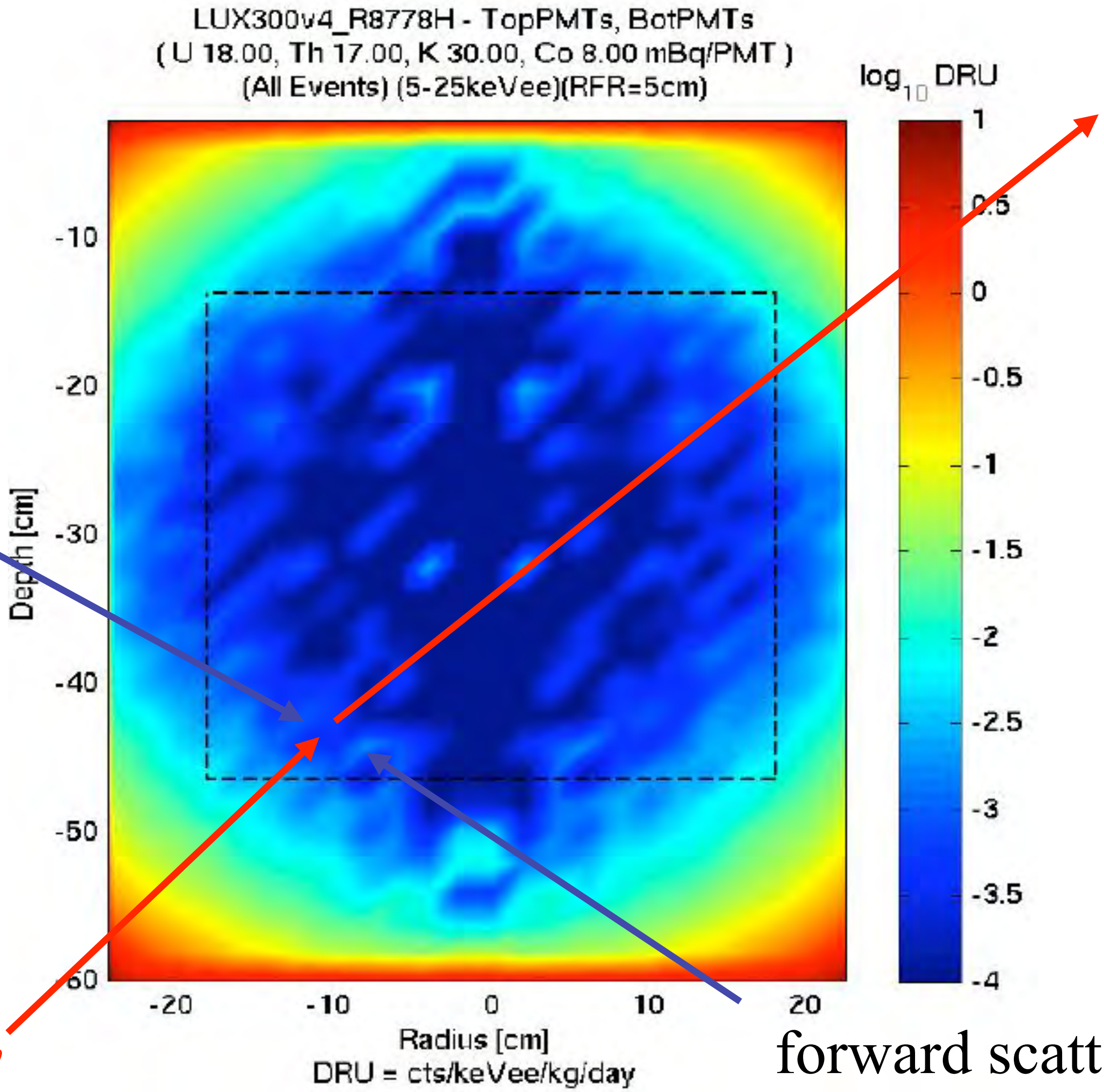
triggered on S2

S2

S1

95% single photoelectrons > threshold

Strong background rejection from kinematics



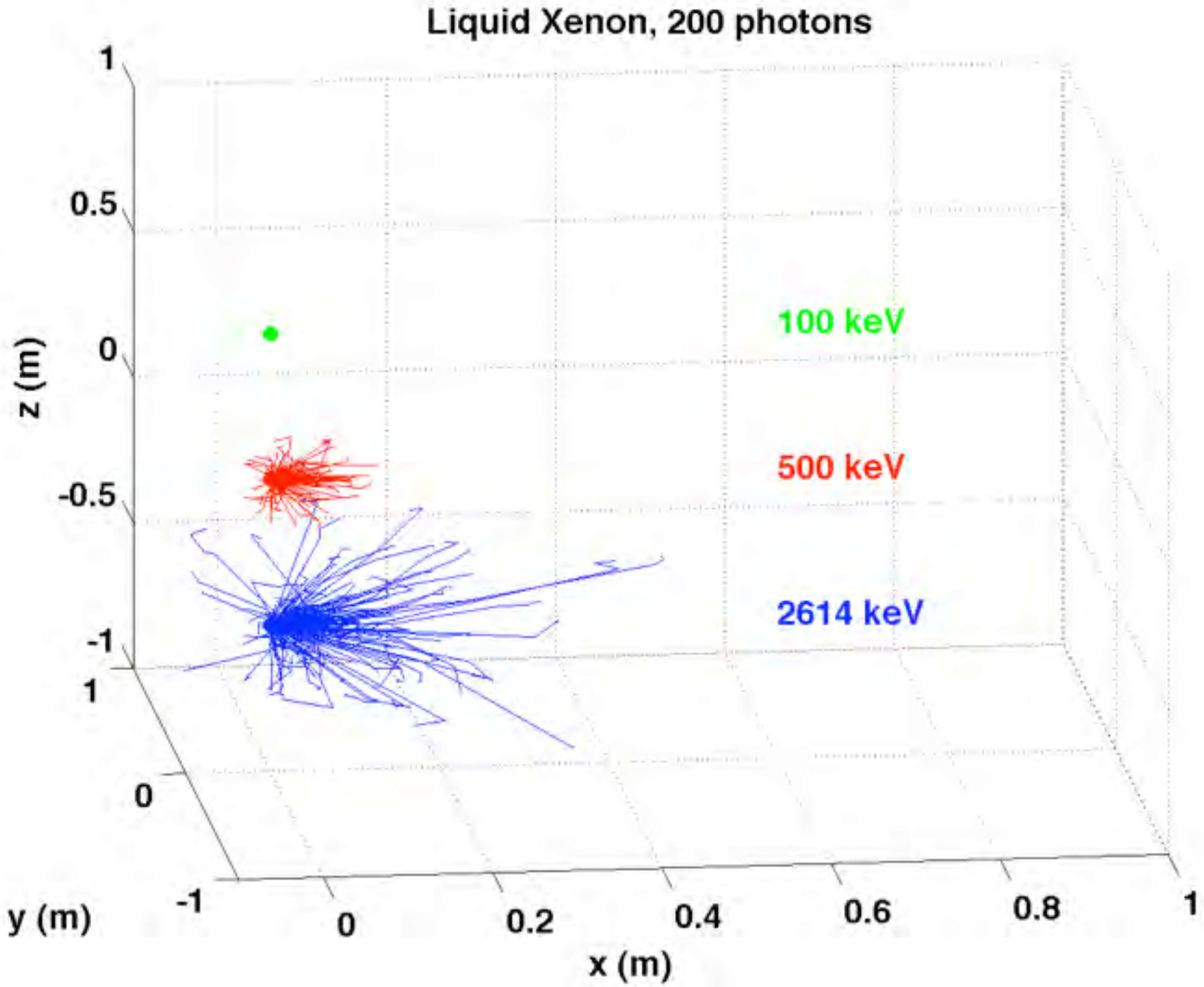
must
cross
full volume
without
interacting
again

~ keV
deposition

~ MeV γ

forward scattering

Simulation of self-shielding in liquid xenon



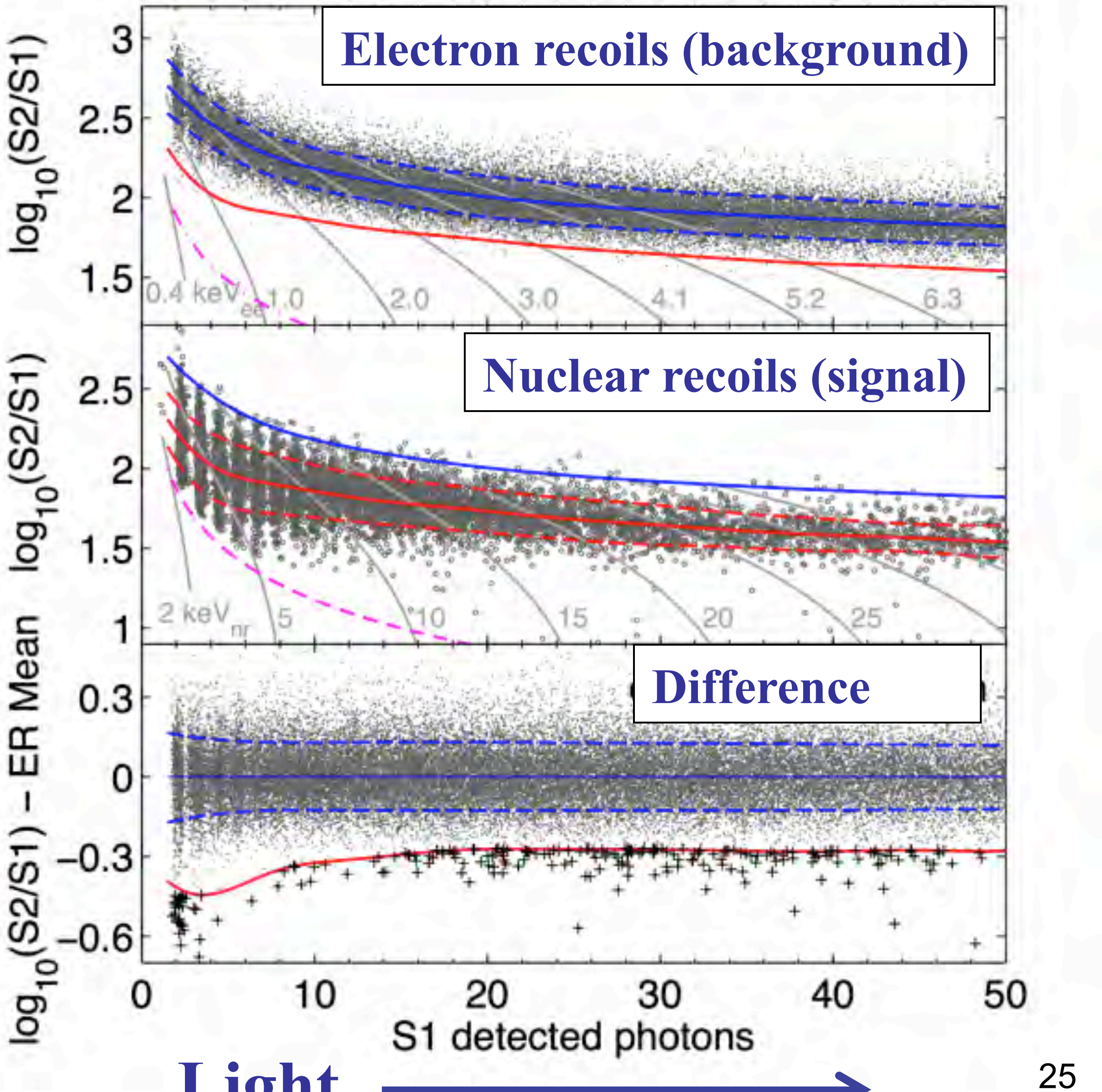
Volume cut rejects most gamma backgrounds.

Particle ID: recoil discrimination in LUX

Charge/Light

Charge/Light

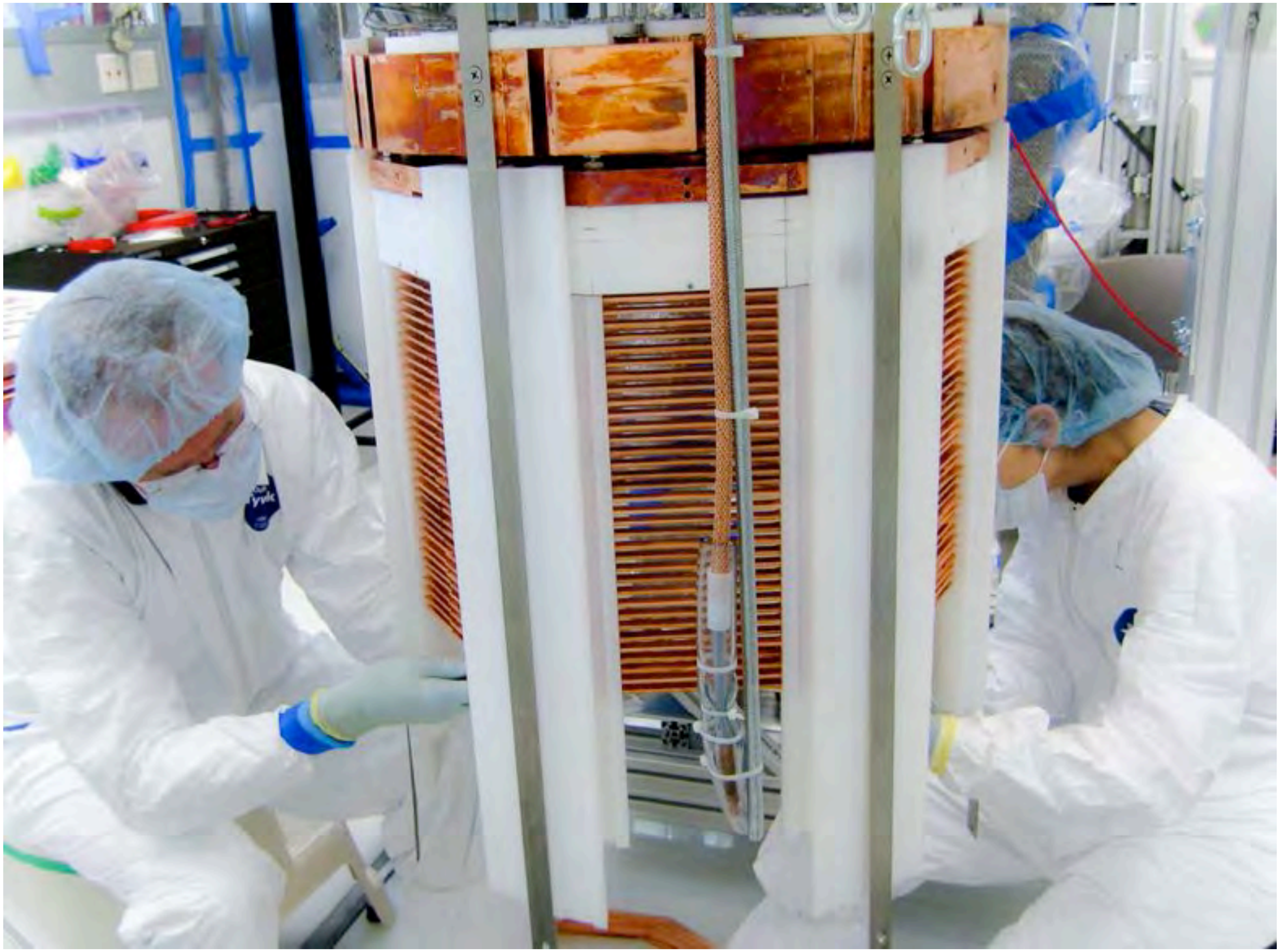
Charge/Light



Electron recoil rejection factor: 200 -500

Light →

LUX assembly – 2010 - 2011



370 kg of liquid xenon

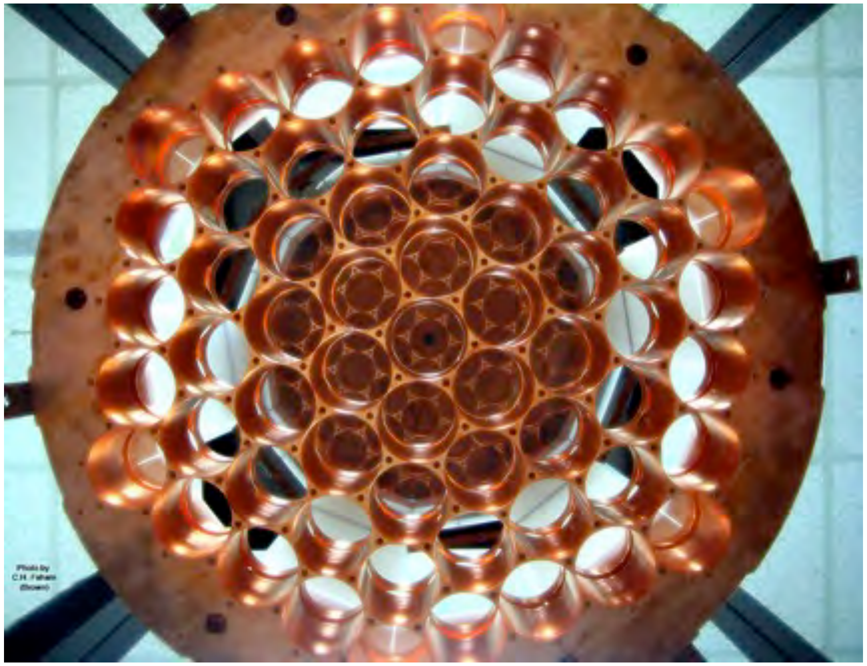


Photo by
C.H. Faham
(Brown)

Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank
South Dakota USA

Davis Cavern @ SURF, March 2011

Davis Campus dedication, May 30, 2012

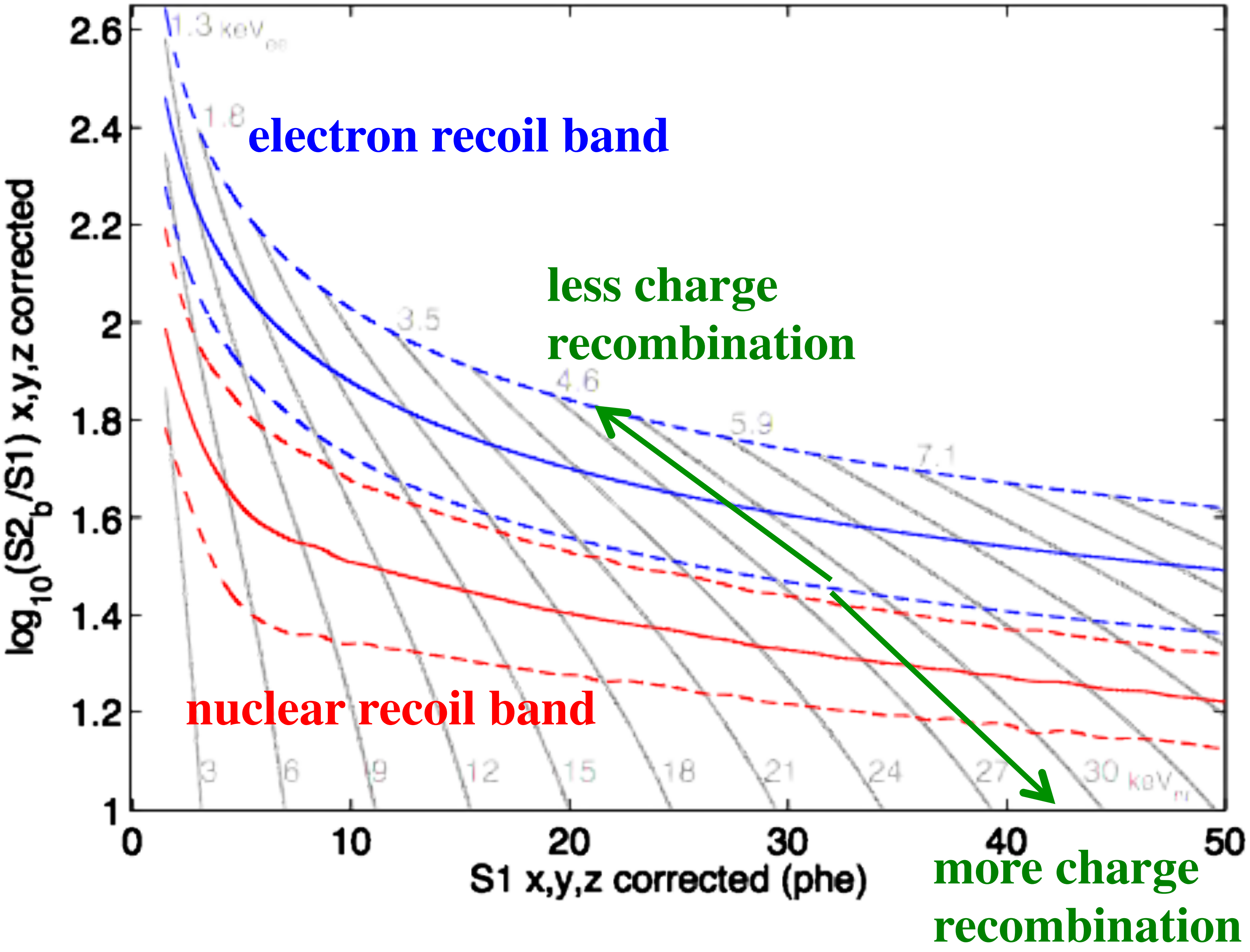
Davis Campus water tank, home of LUX

Ana Davis,
widow of Ray Davis

On top of the water shield, Sept. 2012

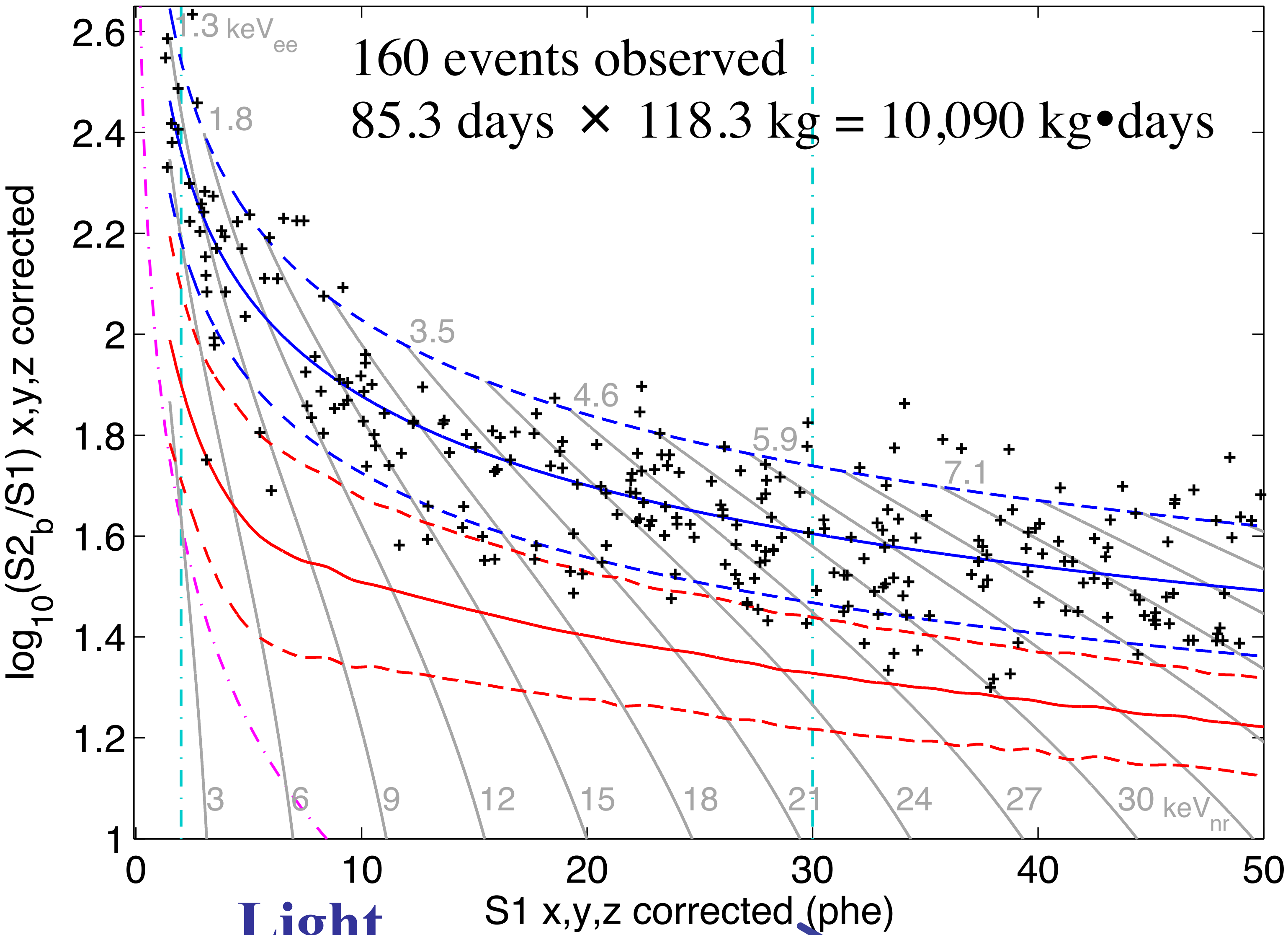
LUX installed underground, Sept. 2012

LUX recoil bands and energy scales



LUX WIMP search data (2013)

Charge
Light



160 events observed

85.3 days × 118.3 kg = 10,090 kg•days

Light →

2013 initial results (Run 3): Phys.Rev.Lett. 112 (2014) 091303.

2015 re-analysis of Run 3: Phys.Rev.Lett. 116 (2016) 161301.

The New York Times

SPACE & COSMOS

Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly

By DENNIS OVERBYE OCT. 30, 2013

Inside the Large Underground Xenon dark matter detector.

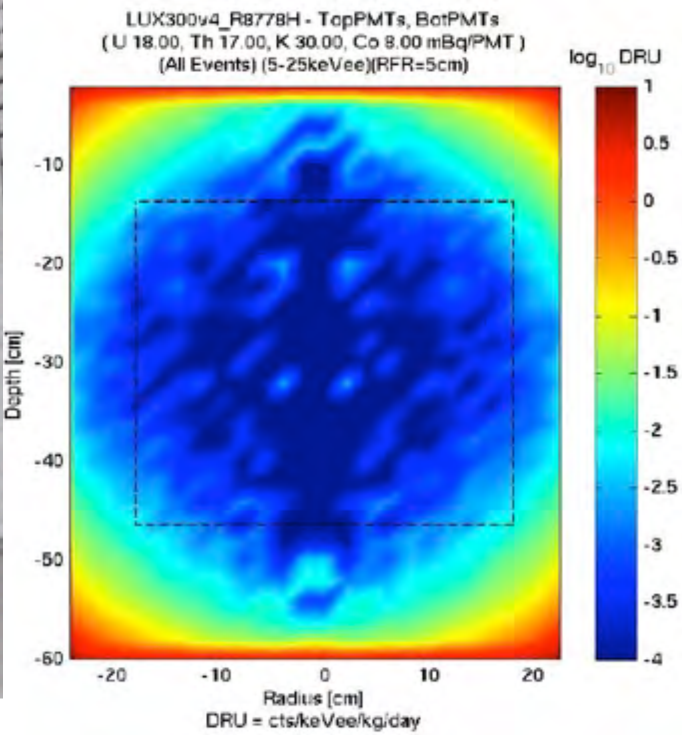
Matthew Kapust/South Dakota Science and Technology Authority

October 30, 2013

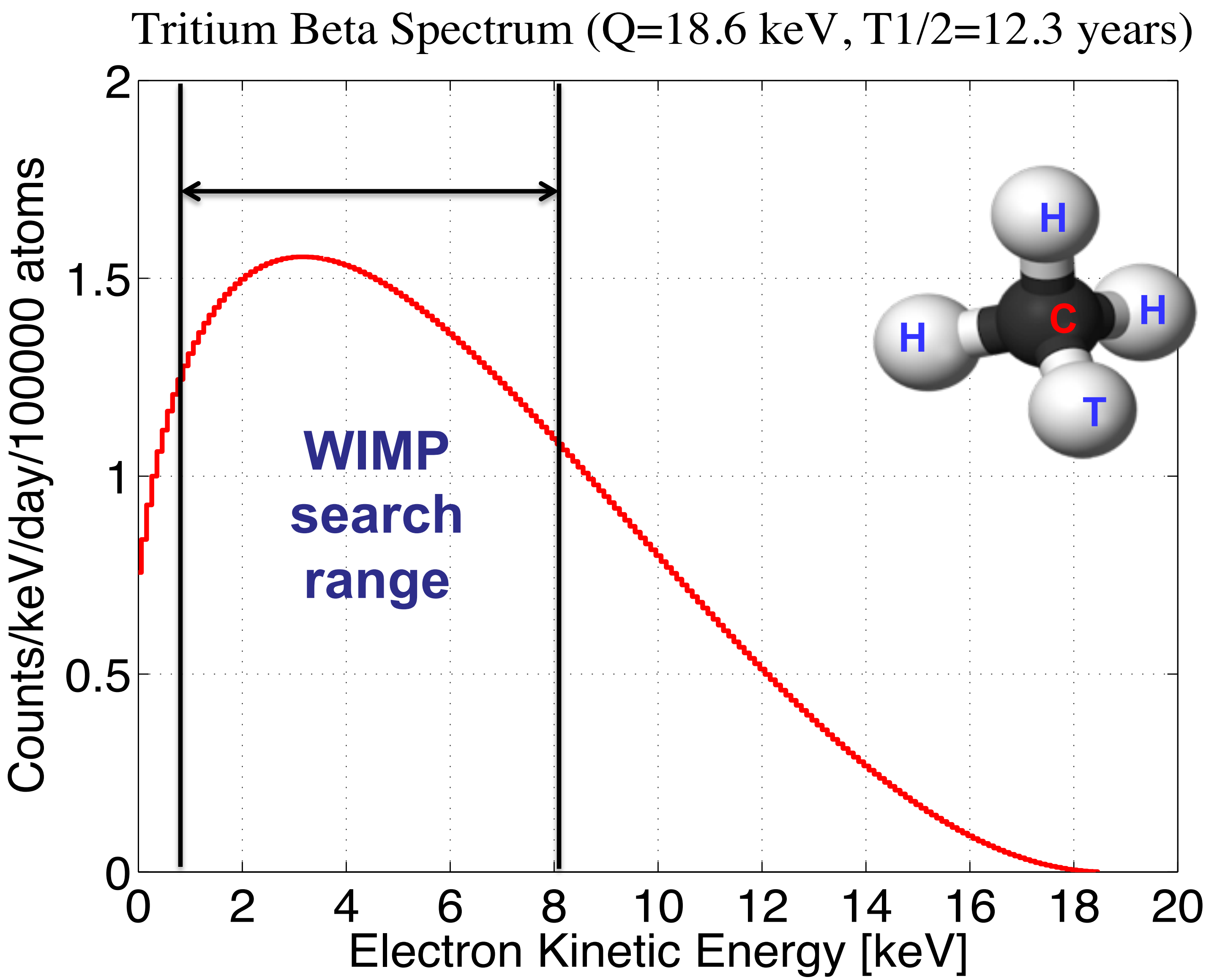
Calibration: external gamma sources (^{137}Cs)

Calibration source guide tubes

Self-shielding makes external gamma sources mostly ineffectual



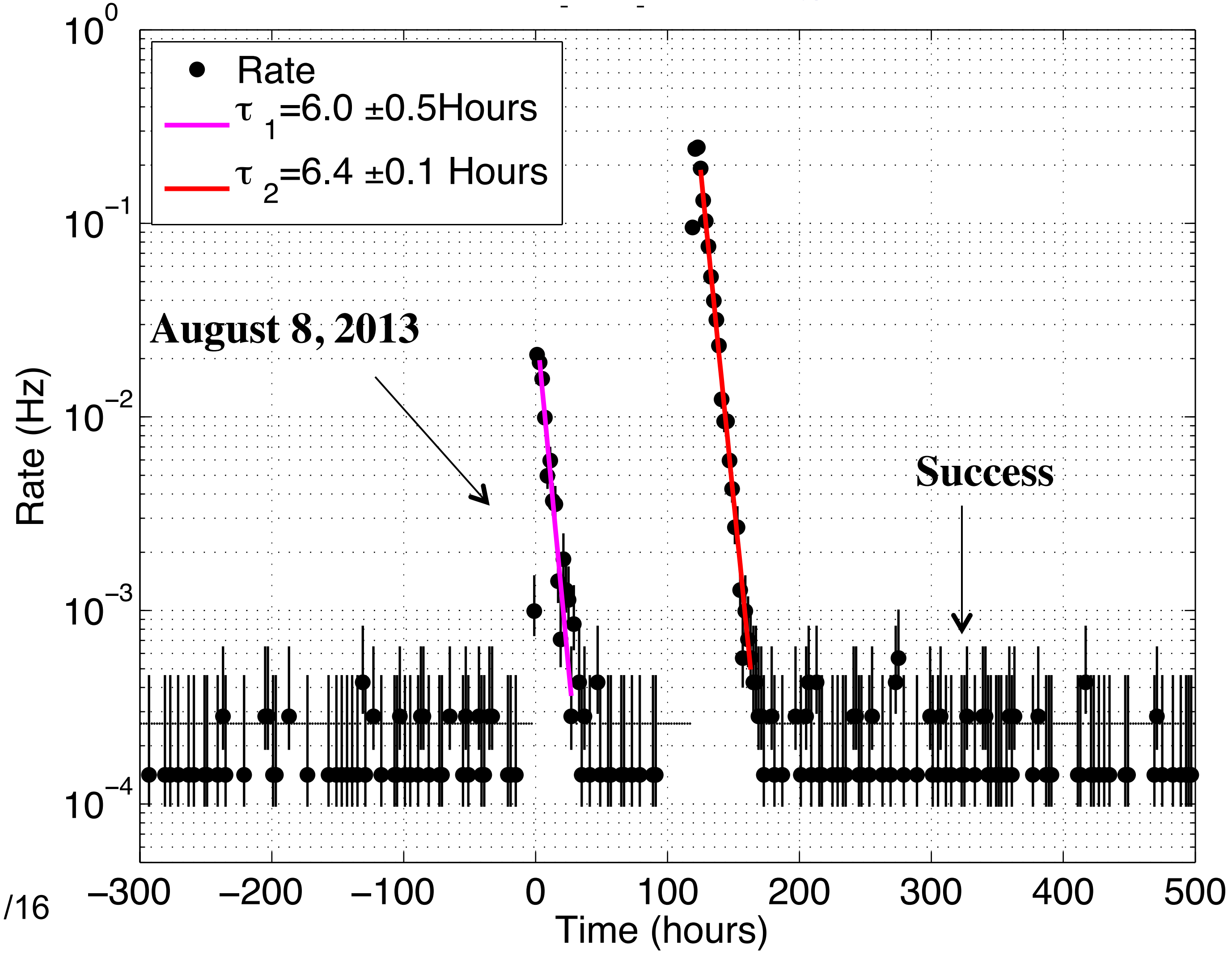
Tritium: an ideal electron-recoil band calibration source



Tritium Beta Spectrum (Q=18.6 keV, T1/2=12.3 years)

Injection and removal of tritium from LUX, August 2013

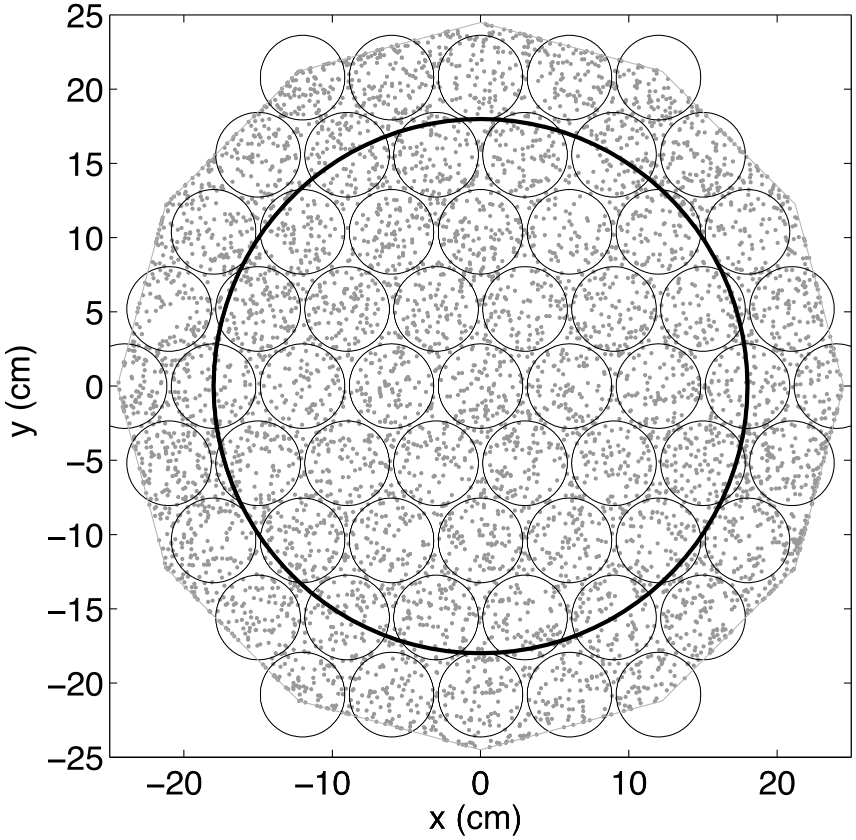
Fiducial count rate for S1 < 150 PE

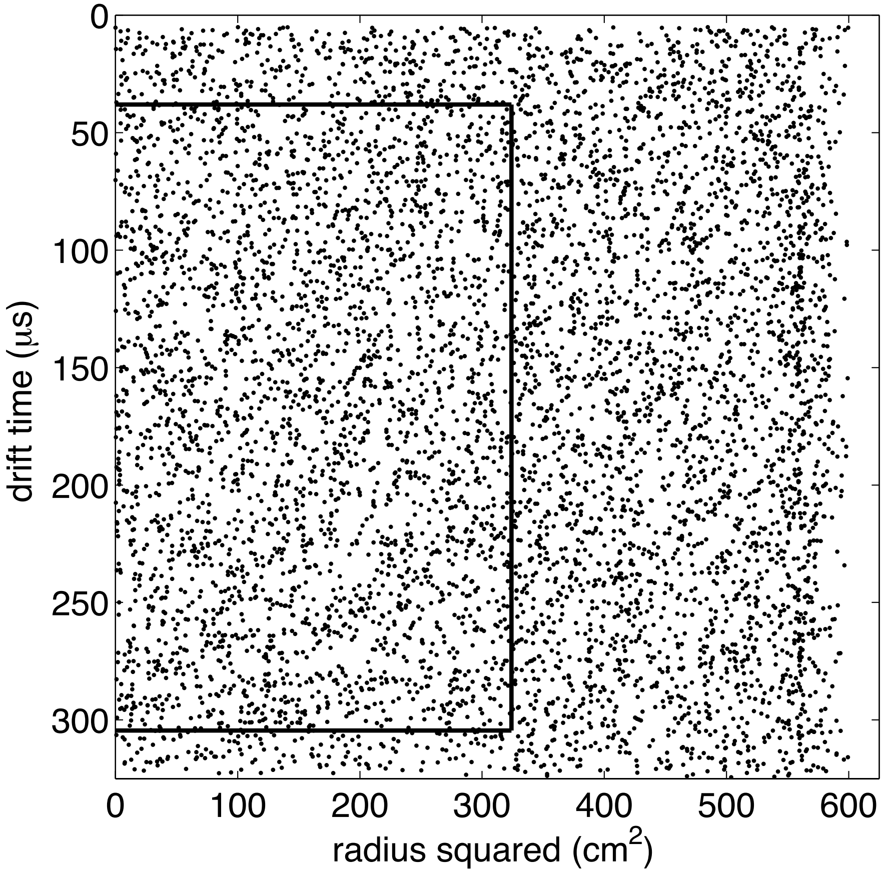


August 8, 2013

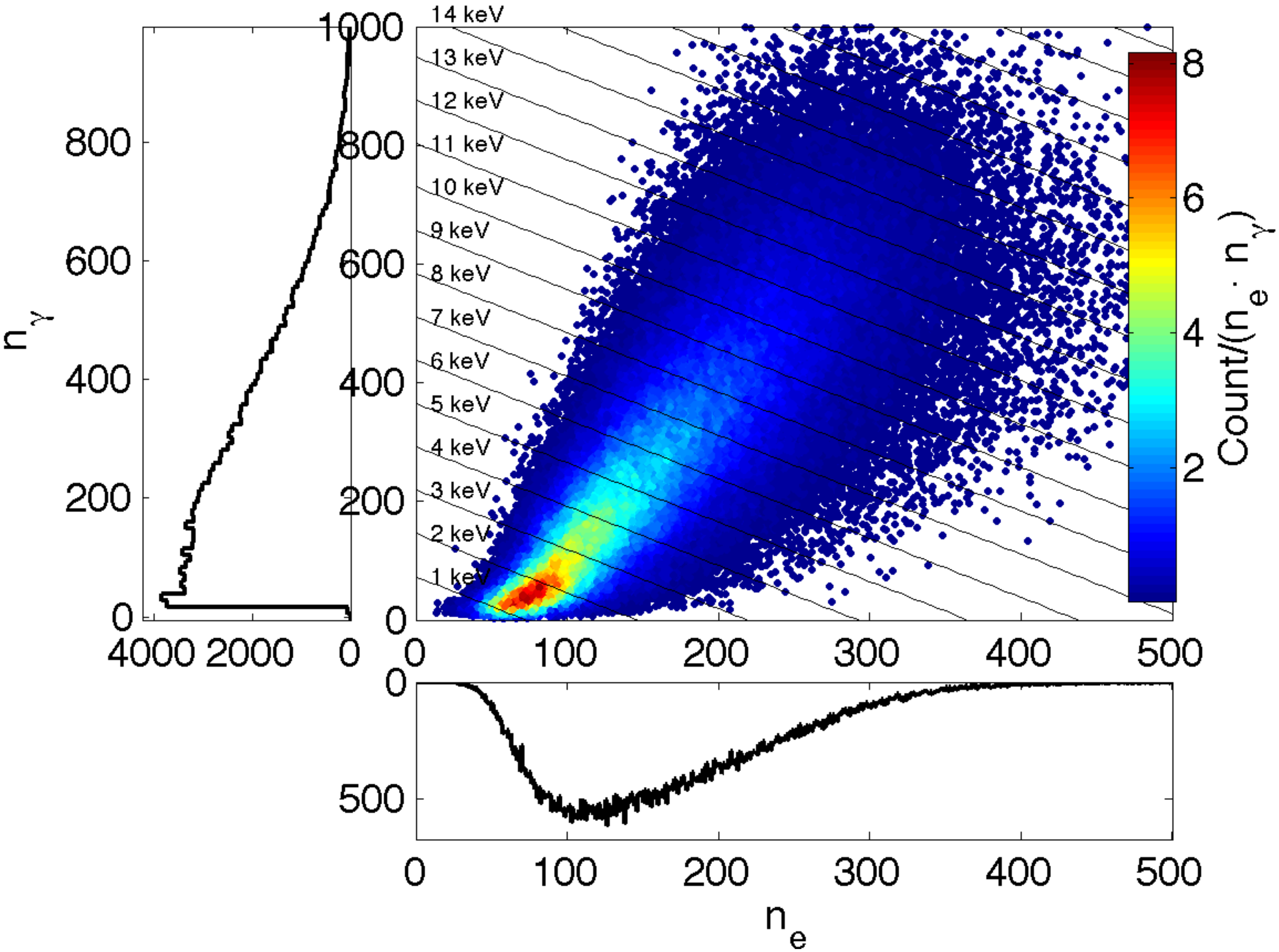
Success

Tritium event locations in LUX – August 2013



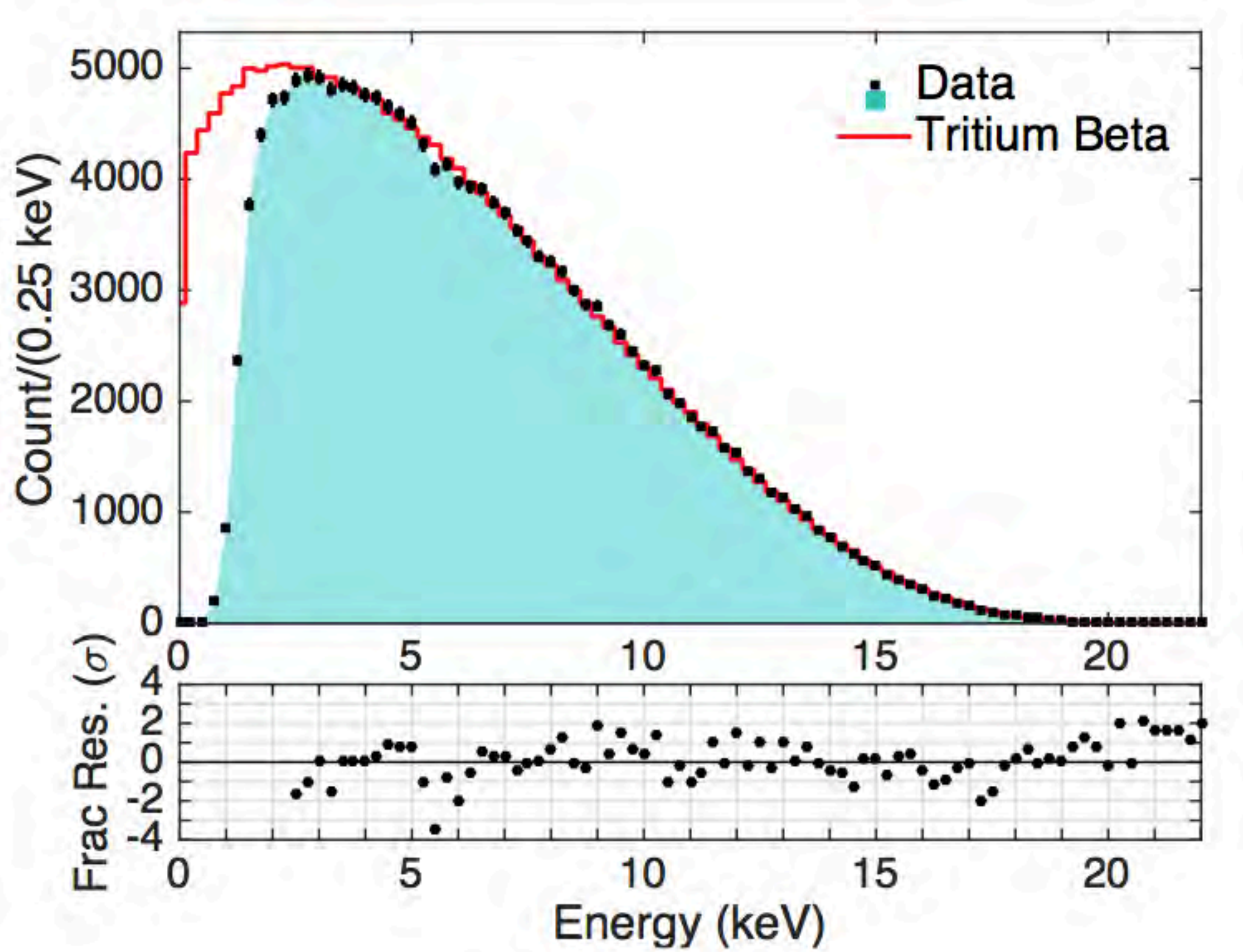


Charge vs Light from tritium in LUX at 170 V/cm



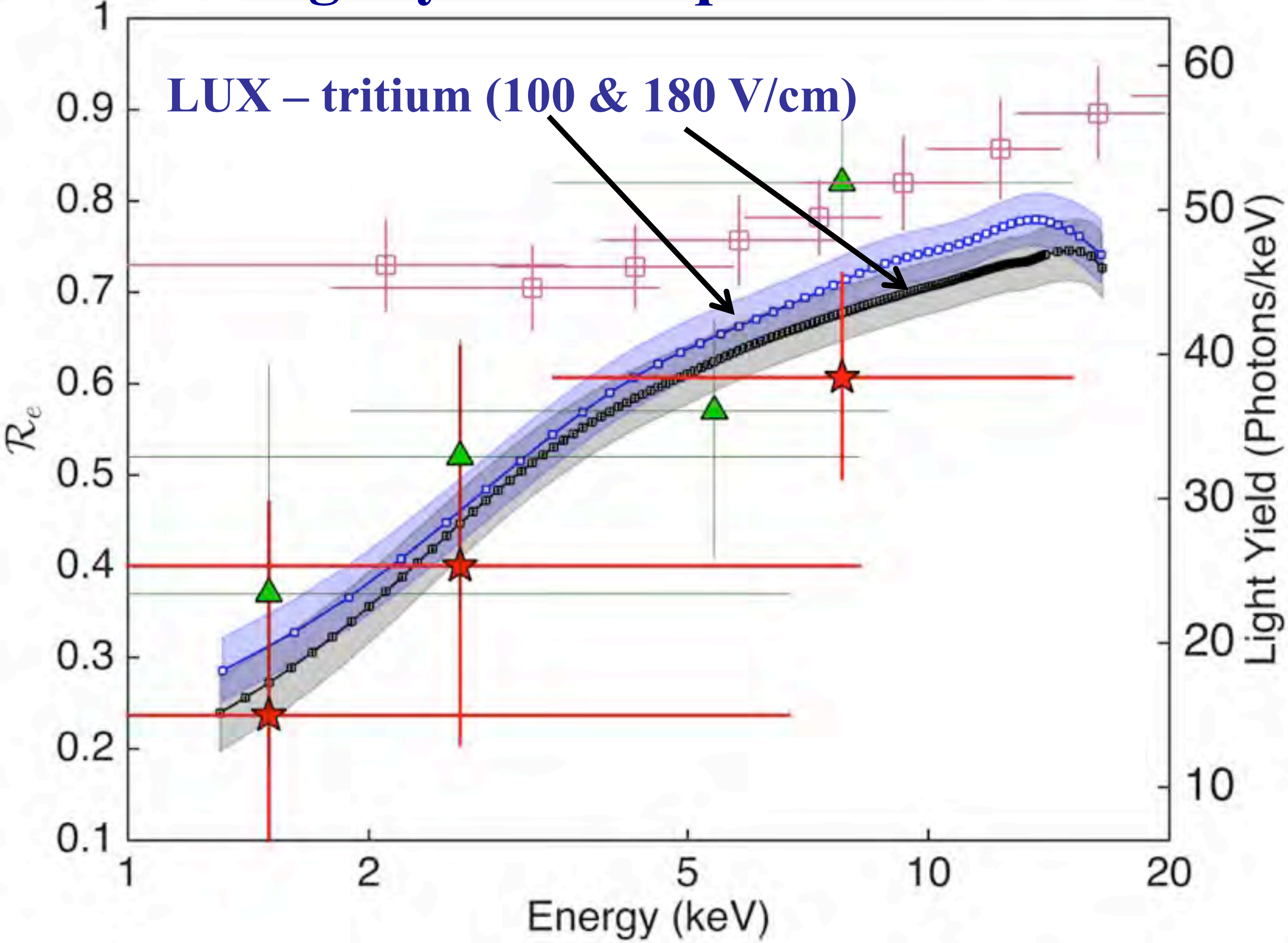
178,000 fiducial tritium events

Tritium "combined-energy" spectrum



178,000 fiducial tritium events

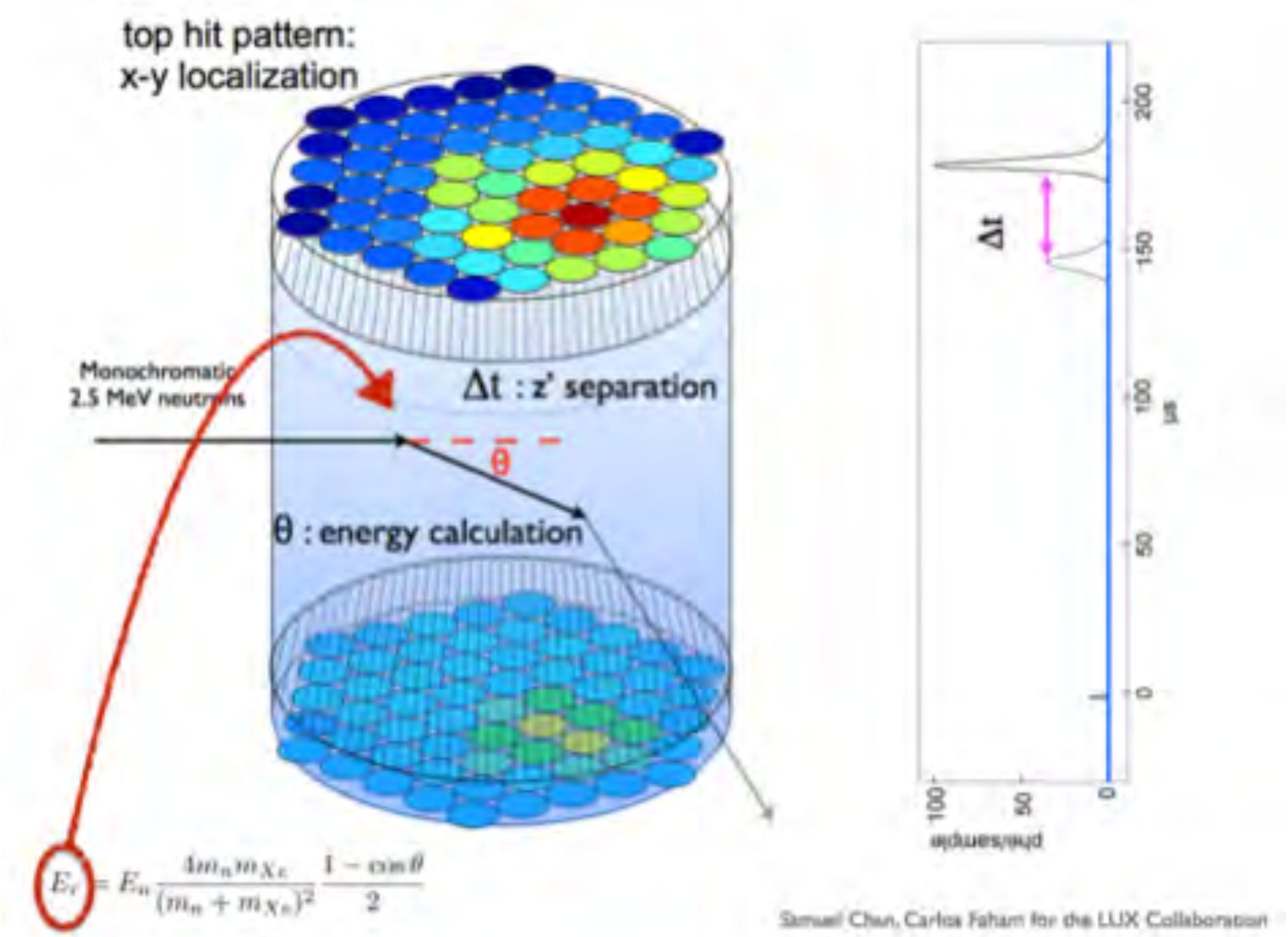
Light yield of liquid xenon



LUX – tritium (100 & 180 V/cm)

Nuclear-recoil calibration w/mono-energetic neutrons

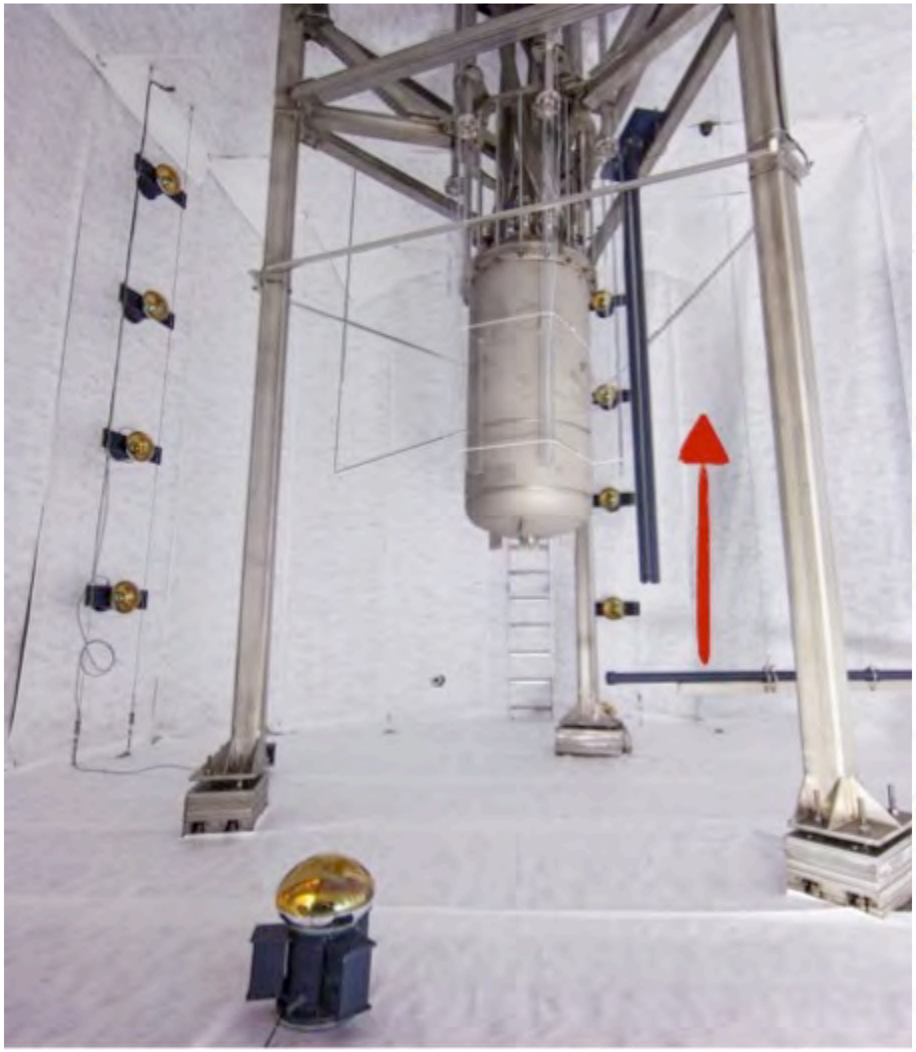
$D + D \rightarrow n + {}^{3}He \quad E_n = 2.45$ MeV

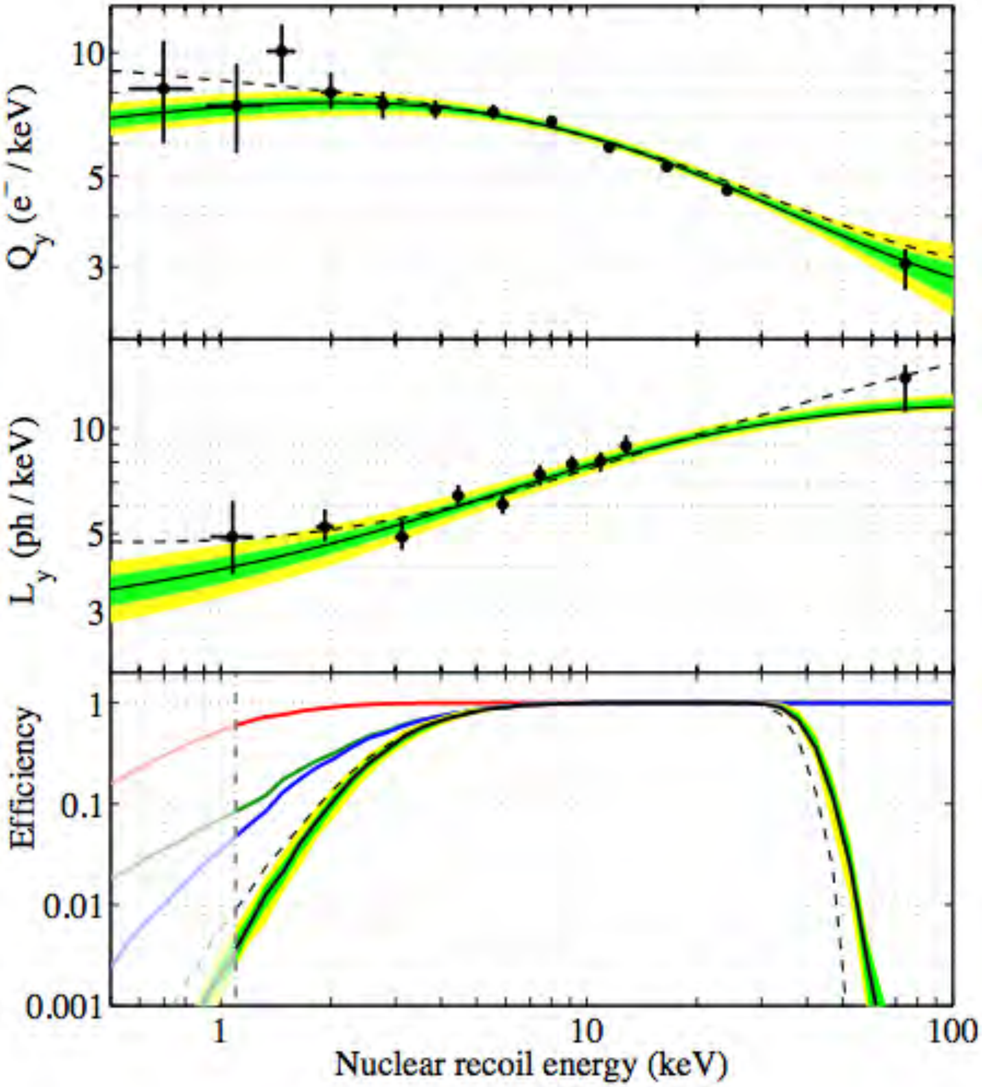


$$\boxed{E_r} = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Samuel Chan, Carlos Faham for the LUX Collaboration

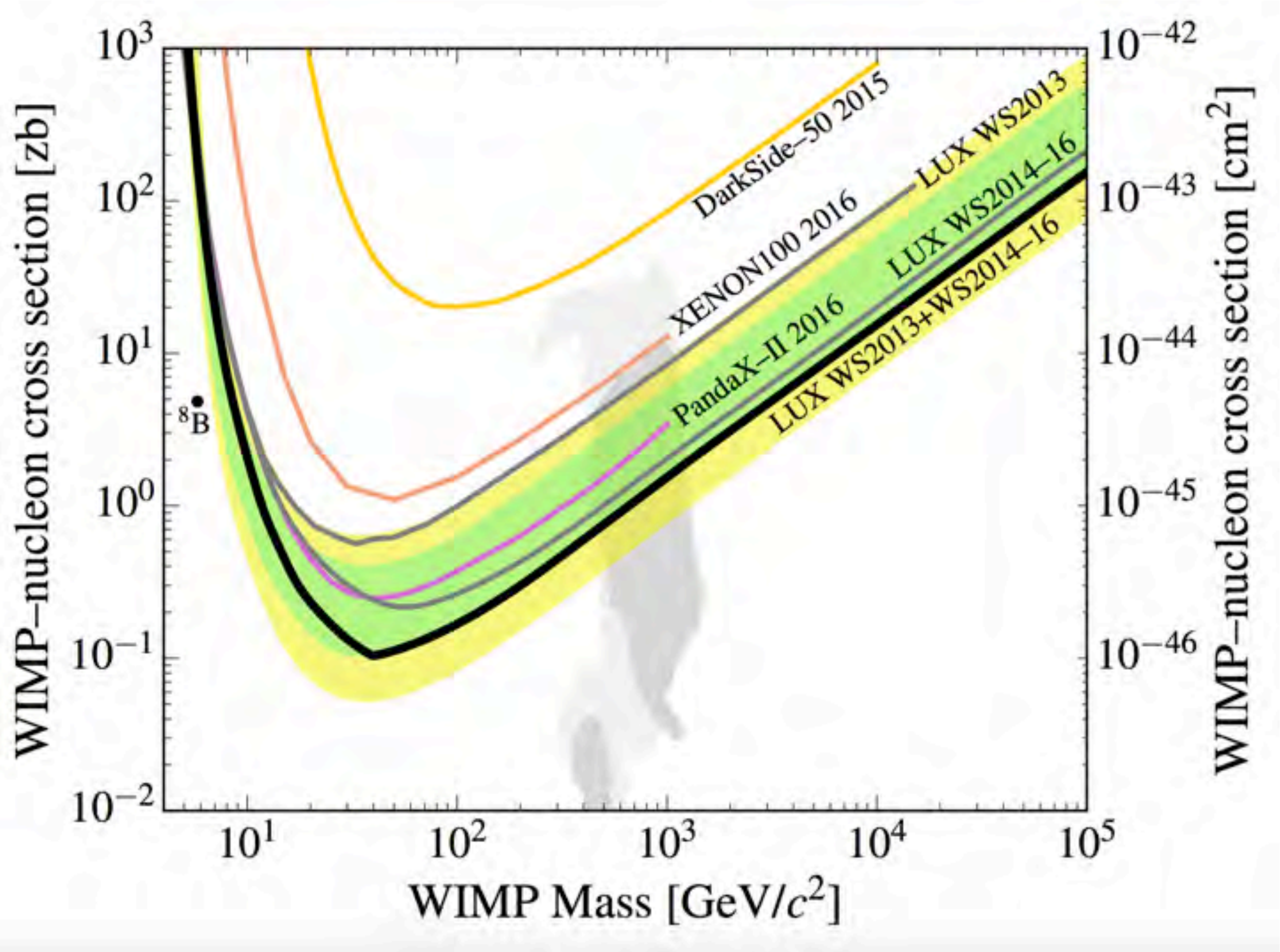
Nuclear-recoil calibration of LUX
Neutron scattering with a neutron generator





LUX final WIMP search results –

Run 3 & 4 combined, 2013 - 2016



LUX Run 3 & 4 (2016): arXiv:1608.07648

LUX -> LZ (2020)

Scale up LUX fiducial mass by x40

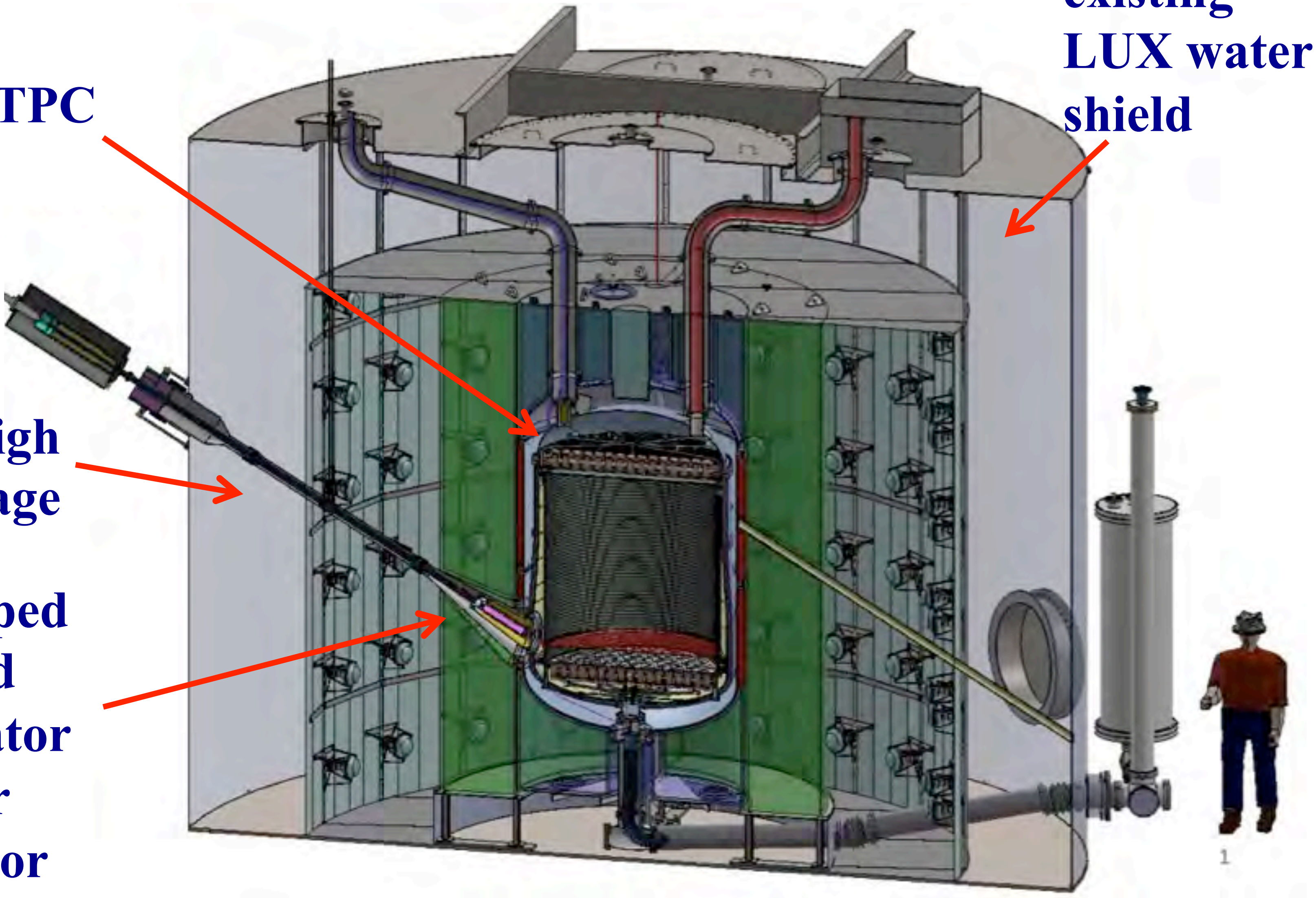
LZ:

Total Xe - 10 Ton

Active Xe – 7 Ton

Fiducial Xe – 5.6 Ton

The LZ Experiment – coming in 2020



Xe TPC

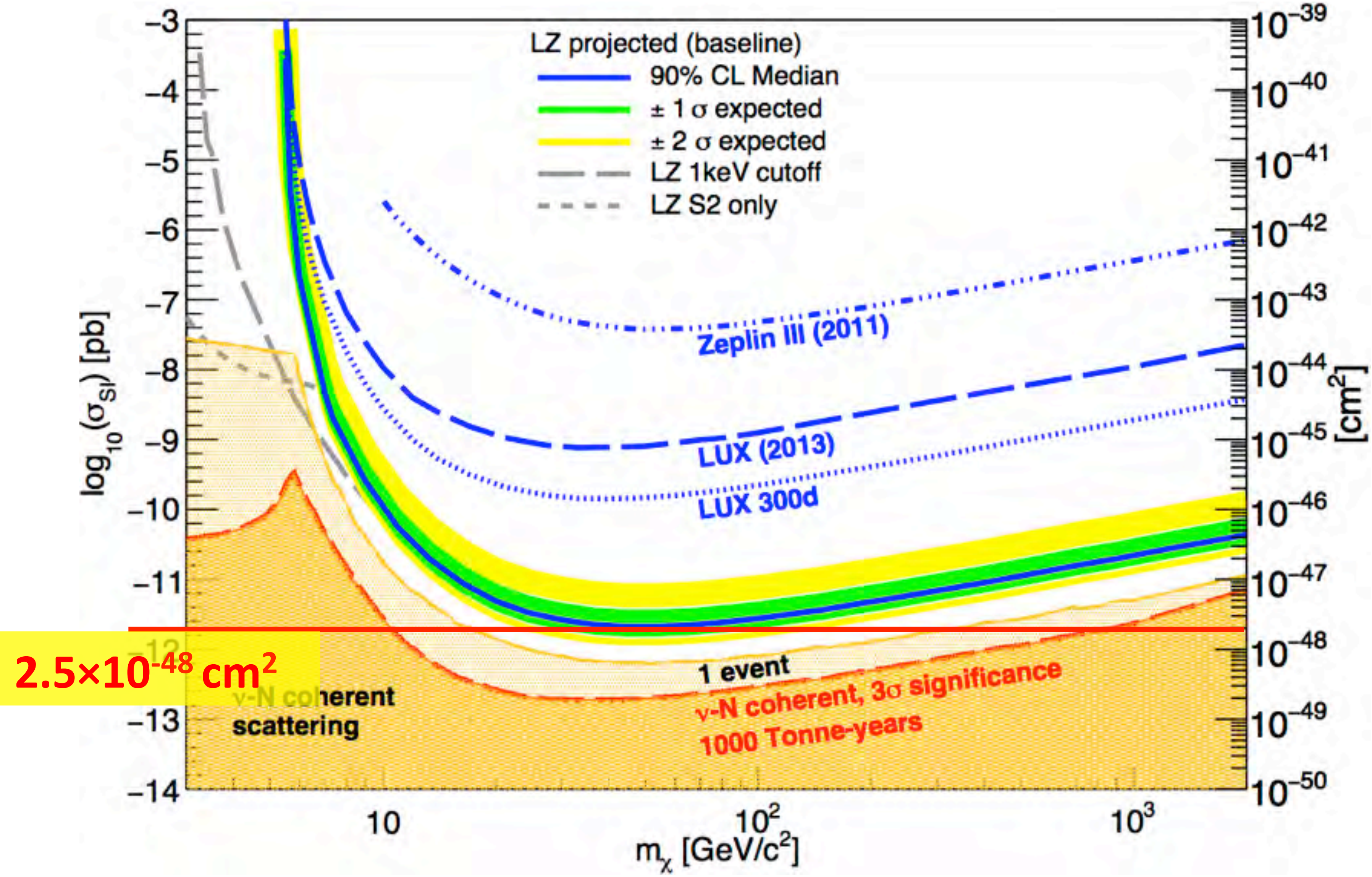
existing
LUX water
shield

50 kV high
voltage

Gd-doped
liquid
scintillator
outer
detector

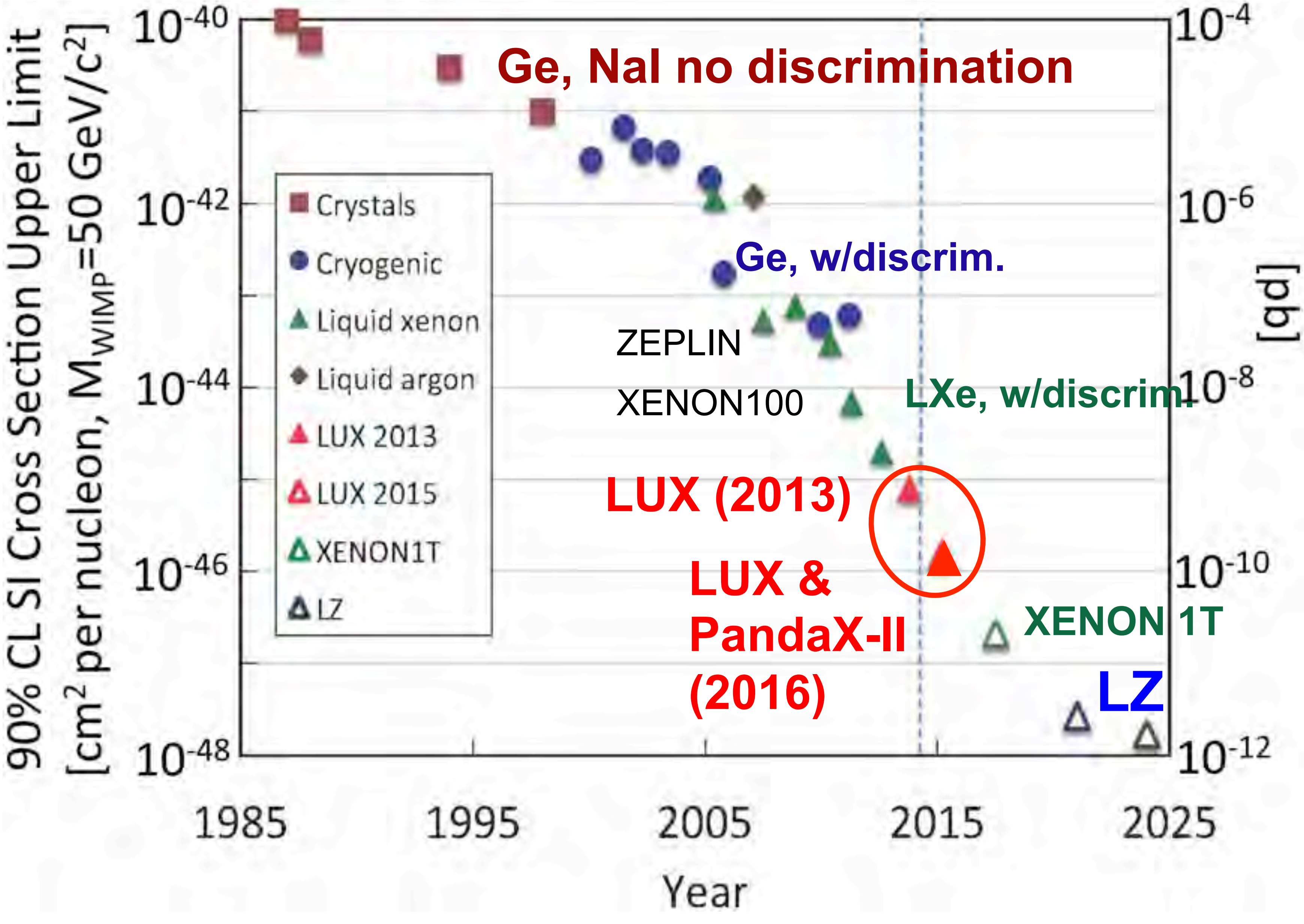
LZ Sensitivity

(5.6 Tonnes, 1000 live days)



2.5×10^{-48} cm^2

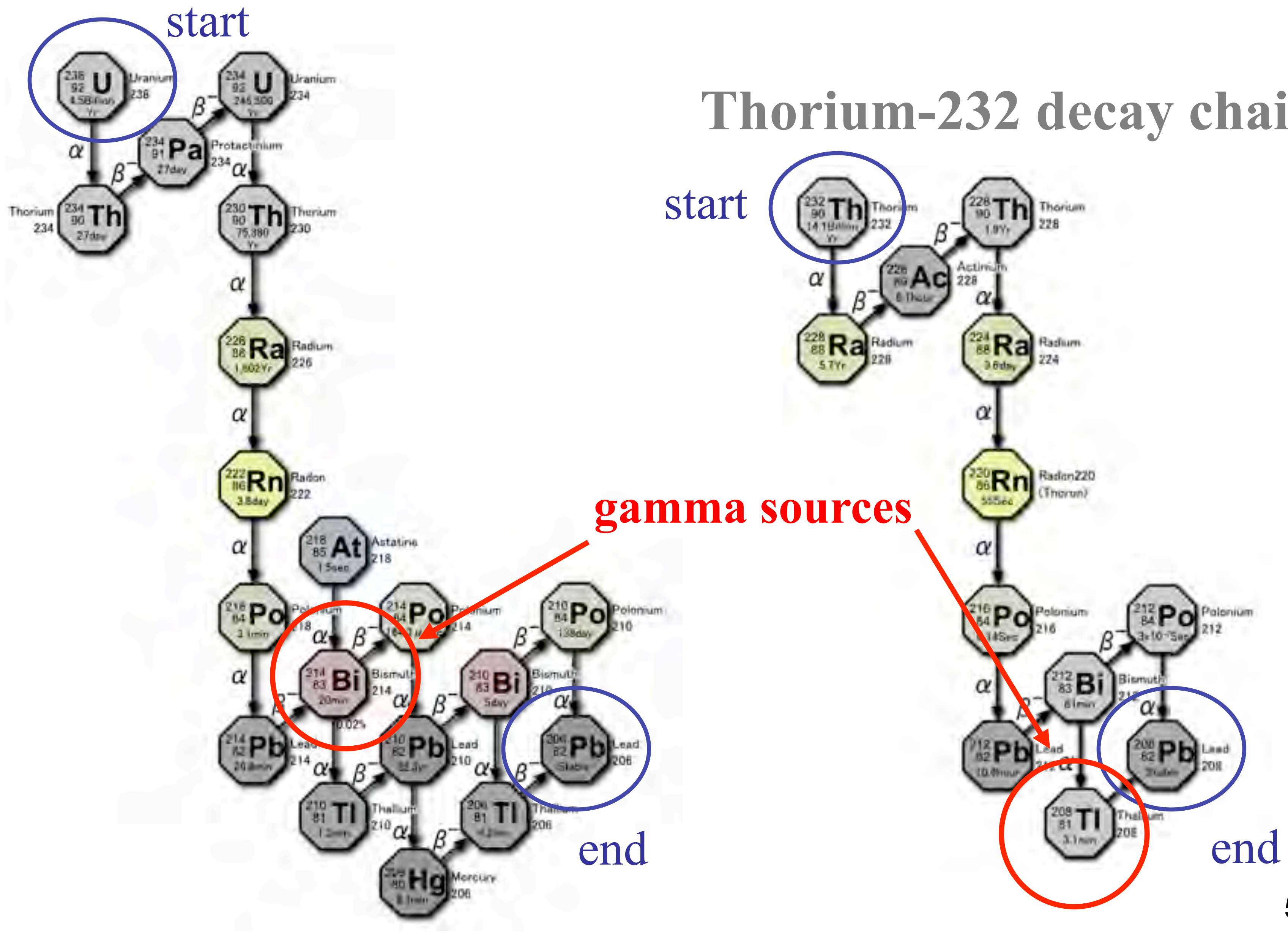
History of WIMP sensitivity @ 50 GeV



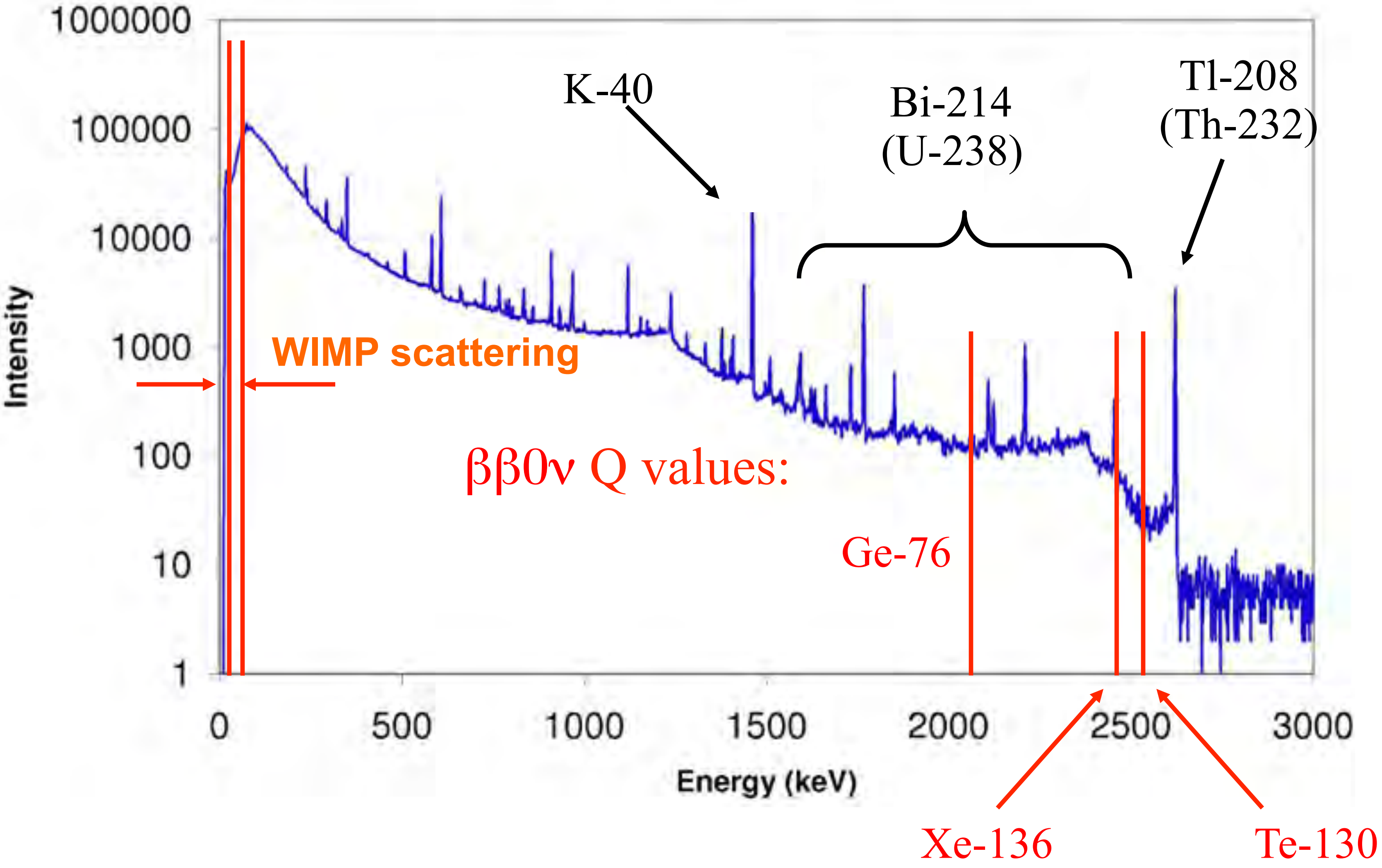

LUX-ZEPLIN
S.U.R.F.

Uranium-238 decay chain

Thorium-232 decay chain



Ordinary radioactive decay here on earth



K-40

Bi-214
(U-238)

Tl-208
(Th-232)

WIMP scattering

ββ0ν Q values:

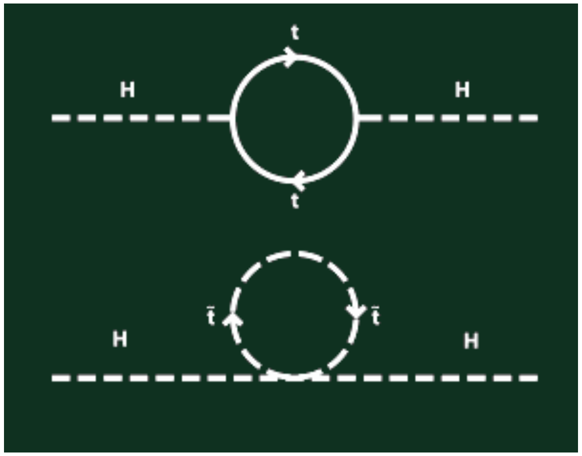
Ge-76

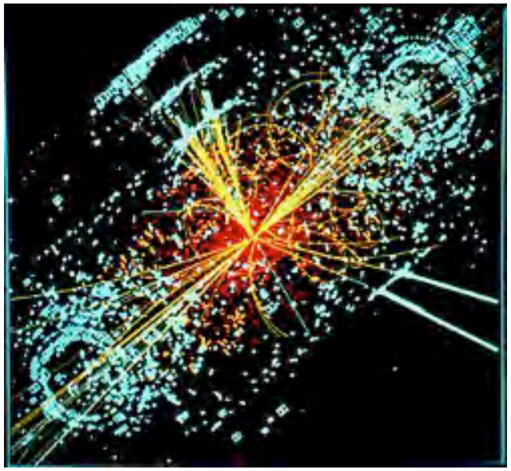
Xe-136

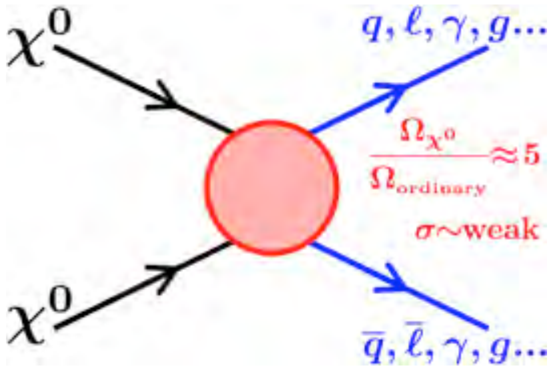
Te-130

Two problems from particle physics

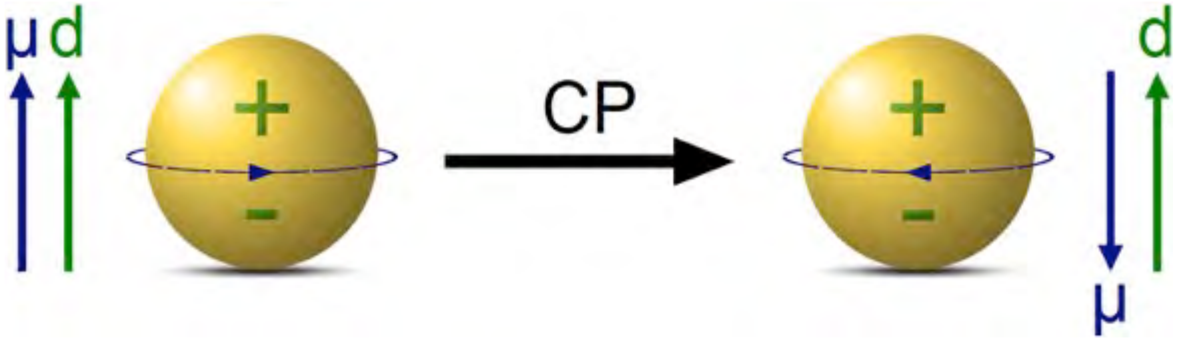
1) Why is the weak scale so light? ➔ New weak physics? ➔ WIMPs

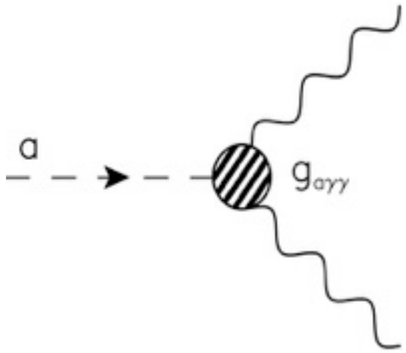




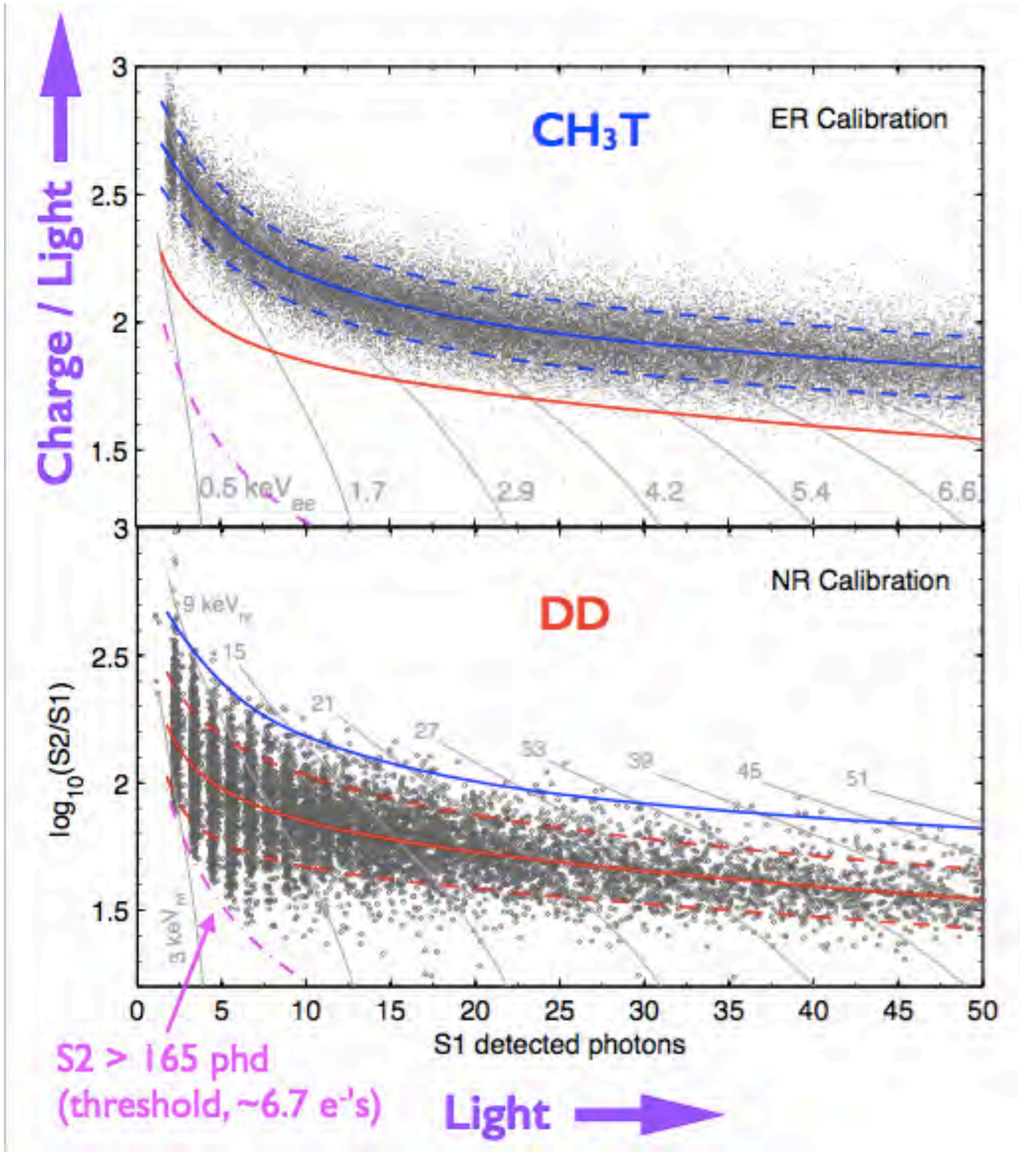


2) Why no CP violation in QCD ? ➔ Peccei-Quinn symmetry?➔ Axions



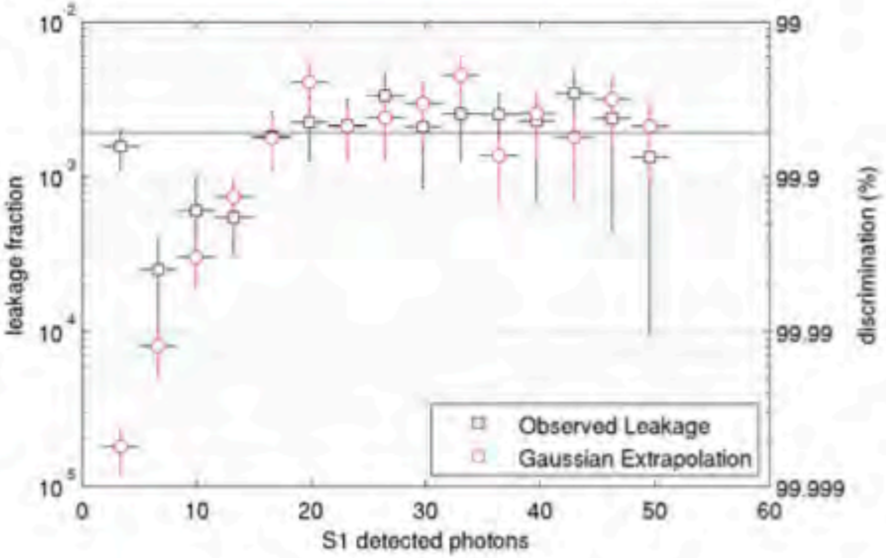


Electron-recoil and nuclear-recoil calibration data



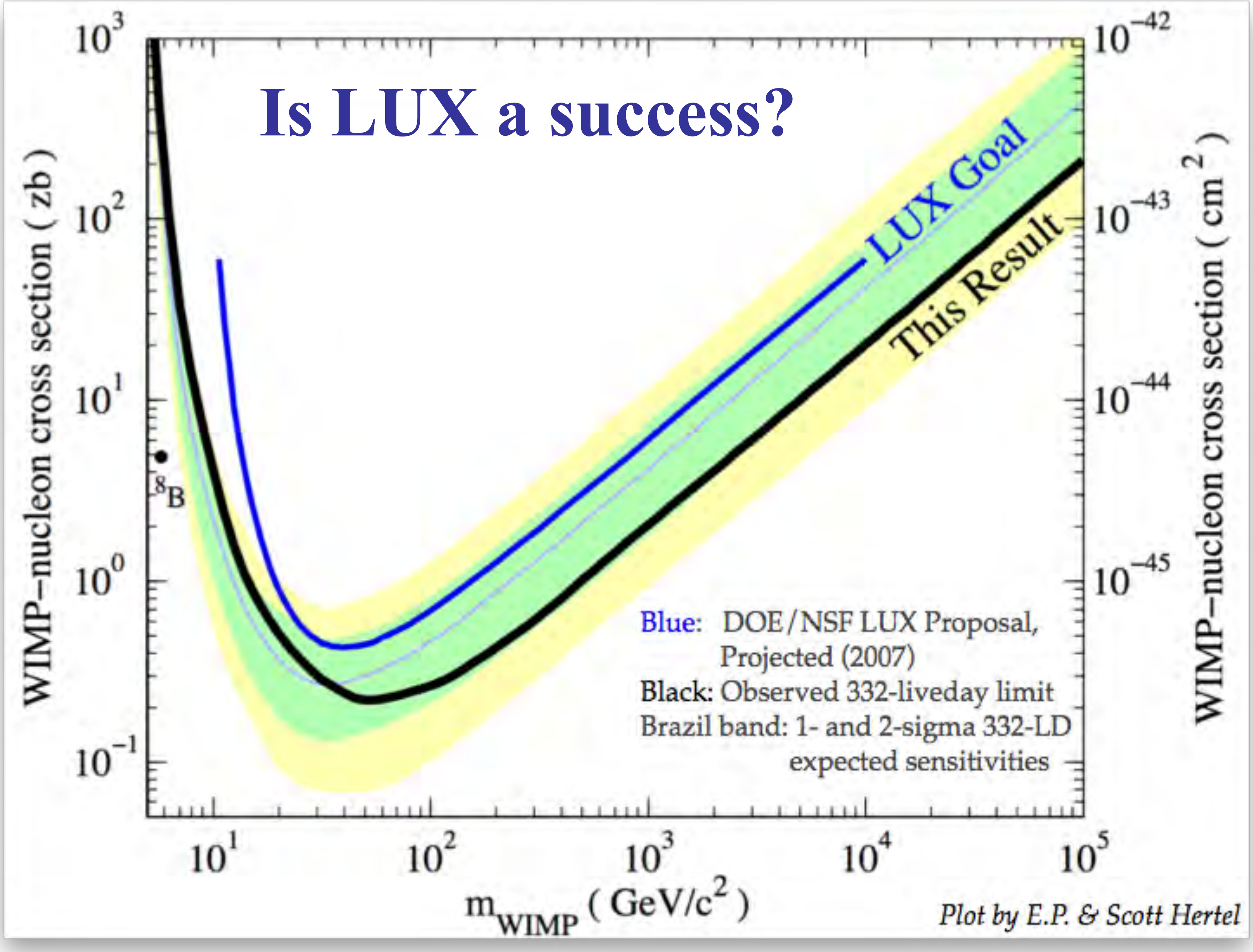
S2 > 165 phd
(threshold, ~6.7 e⁻'s)

99.8 % background rejection in
low energy region of interest



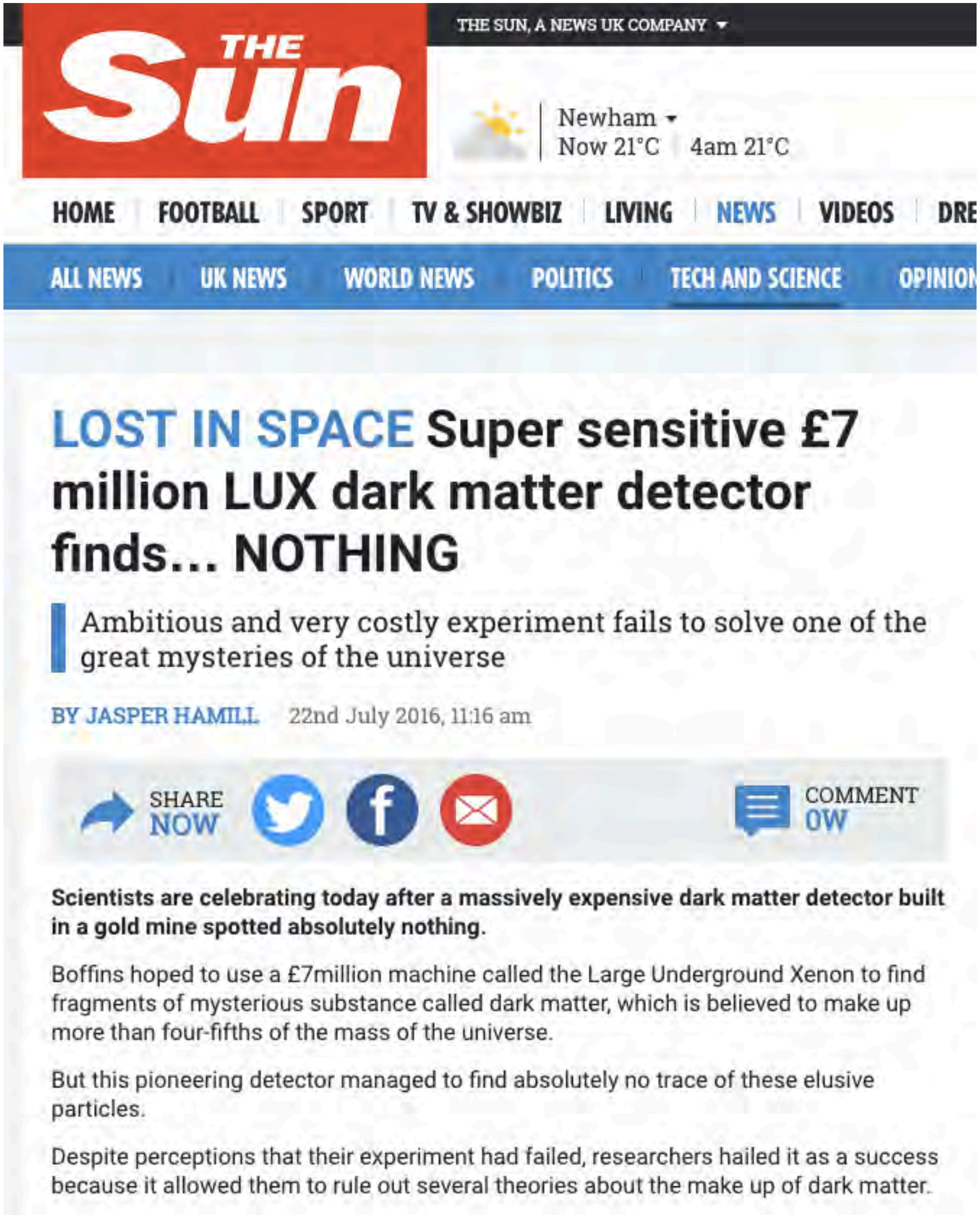
Gray contours indicate constant energies
using a S1-S2 combined energy scale

Is LUX a success?



Plot by E.P. & Scott Hertel

July 22, 2016



LOST IN SPACE Super sensitive £7 million LUX dark matter detector finds… NOTHING

> Ambitious and very costly experiment fails to solve one of the great mysteries of the universe

BY JASPER HAMILL 22nd July 2016, 11:16 am

Scientists are celebrating today after a massively expensive dark matter detector built in a gold mine spotted absolutely nothing.

Boffins hoped to use a £7million machine called the Large Underground Xenon to find fragments of mysterious substance called dark matter, which is believed to make up more than four-fifths of the mass of the universe.

But this pioneering detector managed to find absolutely no trace of these elusive particles.

Despite perceptions that their experiment had failed, researchers hailed it as a success because it allowed them to rule out several theories about the make up of dark matter.