The race to detect dark matter with noble liquids.

T. Shutt

Case Western Reserve University

The Fact of Dark Matter

- Galactic rotation curves
- Galaxy clusters
  - Galaxy velocities
  - X-ray Temperature
  - S-Z effect
  - Lensing
- Big bang nucleosynthesis
- CMB anisotropy
- Large-scale structure growth

Normal matter plasma:

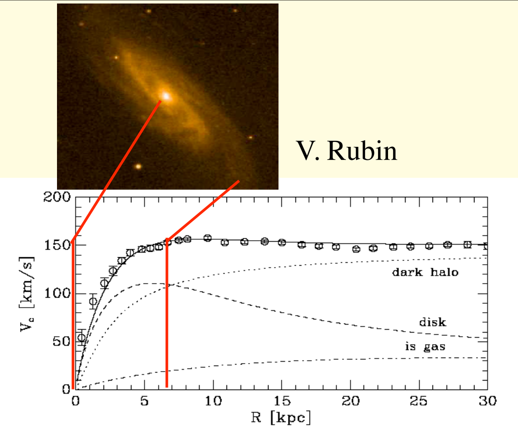
$$\frac{\delta\rho}{\rho}(Z=1000)\approx 10^{-5}$$

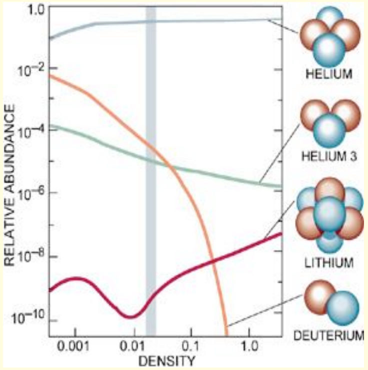
$$\frac{\delta\rho}{\rho}\propto\frac{1}{Z+1}$$

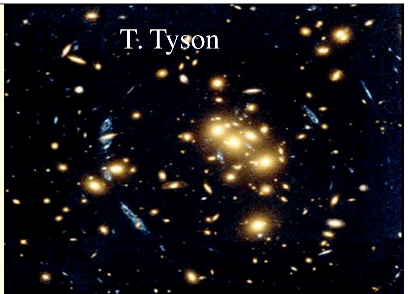
If only normal matter:

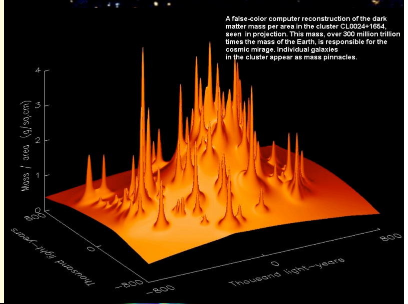
$$\frac{\delta\rho}{\rho}(today)\approx 10^{-2}$$

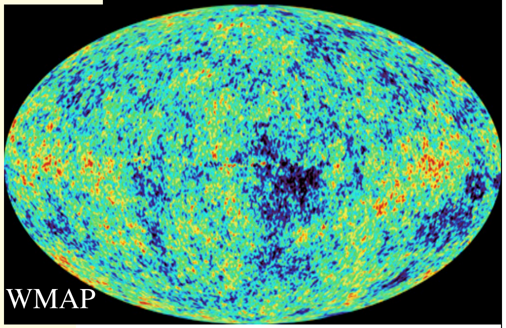
Structure growth requires (cold) dark matter.

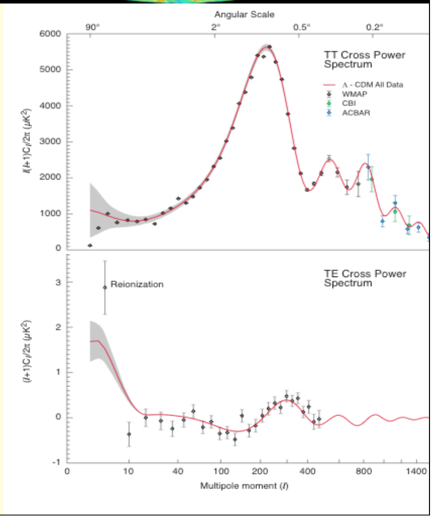




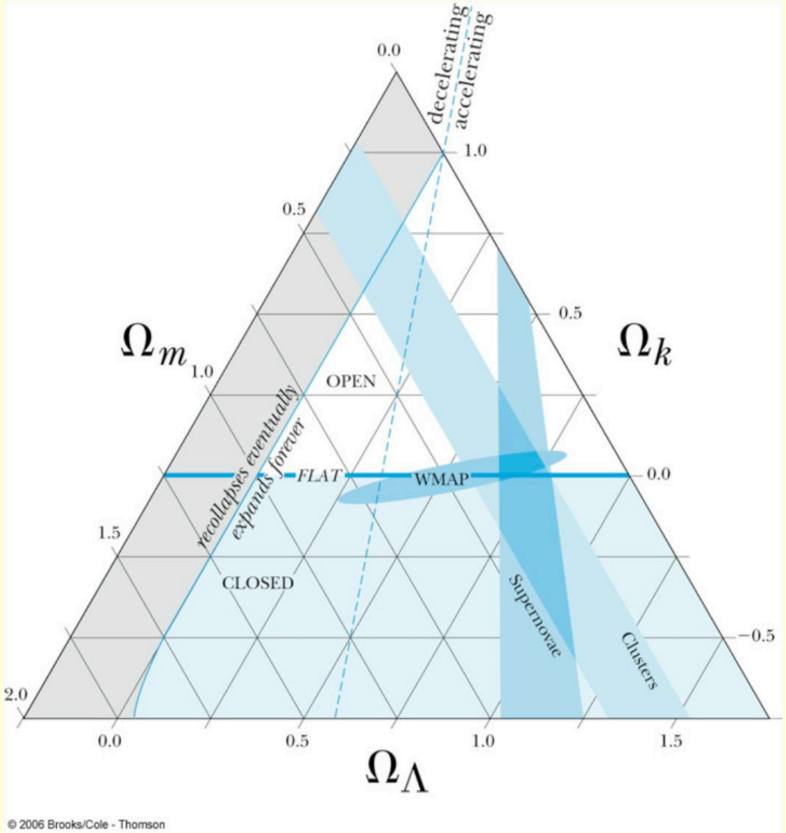








Cosmic Concordance



Inventory of the universe

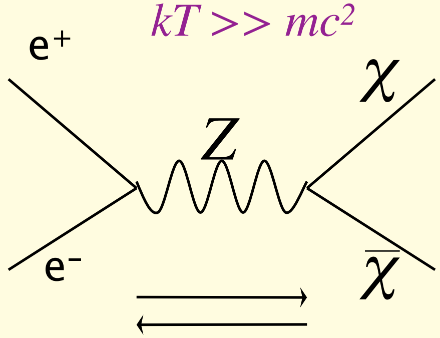
dark energy	≈ 0.73
dark matter	≈ 0.23
baryons	≈ 0.04
(stars+planets	≈ 0.004)
neutrinos:	≈ 0.001-0.015
total	1

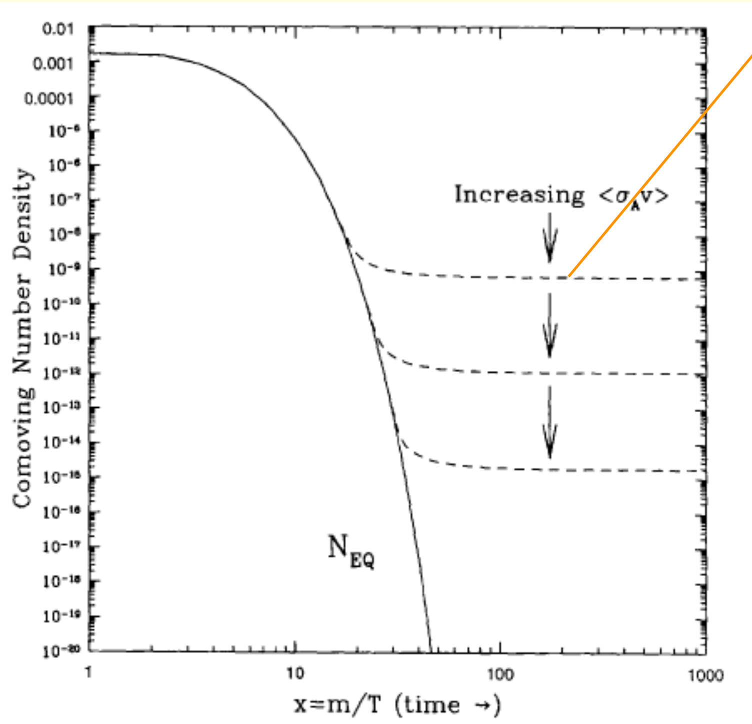
Possible forms of Dark Matter

- Particles:
  - Cold Dark Matter (CDM): non-relativistic in early universe. Rules out *neutrinos*.
  - Some sort of weakly-interacting particle.
  - Non-interacting particle.
- Planets, black holes?
  - How to form them *before* BBN, CMB last-scatter?
- No dark matter - modified gravity. (e.g, MOND, TeVeS)
  - Must match data on huge range of length scales.

WeaklyInteractingMassiveParticleS

Matter-antimatter plasma,
*kT >> mc*²





Freezeout:

universe too "thin" for annihilation

$$\Gamma = n_\chi \langle \sigma_A v \rangle = H$$

today:

$$\Omega_\chi h^2 \cong \frac{3\times 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_A v \rangle}$$

With σ ~ weak

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2}\cdot 1 \sim \frac{(10^{-2})^2}{(100\mathrm{GeV})^2} \sim 10^{-27}\,\mathrm{cm}^3/\mathrm{s}$$

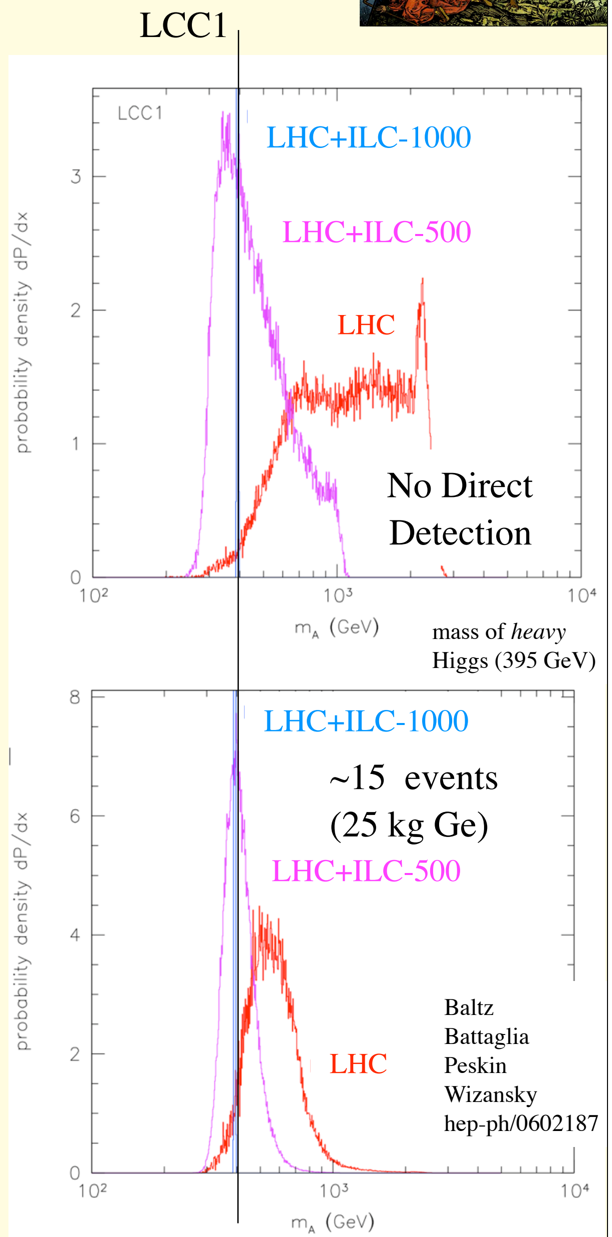
$\Omega_\chi \sim 1$

New weak physics = dark matter!

WIMPs and Supersymmetry

- Lightest SUSY particle thought to be stable, weak
  - Neutralino: Zino + Bino + Higgsino
- SUSY almost guaranteed to produce some dark matter in big bang
- Direct detection complementary to collider measurements
  - Linear Collider Cosmology working group study of LHC/ILC constraints.
    - Specific LCC1 benchmark model shown.
  - Direct detection needed to verify LSP stability.
- Other weak physics: Kaluza-Klein

but WIMPS ≠ Supersymmetry



WIMPs in the Halo

Dark matter "Halo" surrounds all galaxies, including ours.

Density at Earth:

$\rho \sim 300\ m_{\text{proton}}/\text{liter}$

$m_{wimp} \sim 100\ m_{proton}.$

3 WIMPS/liter!

Maxwellian velocity distribution

$\langle v \rangle \approx 230$ km/s

$\sim 10^{-3}$ c

Halo uncertainties not important for *direct* dark matter detection

Direct detection of WIMPs

(Goodman and Witten, '86)

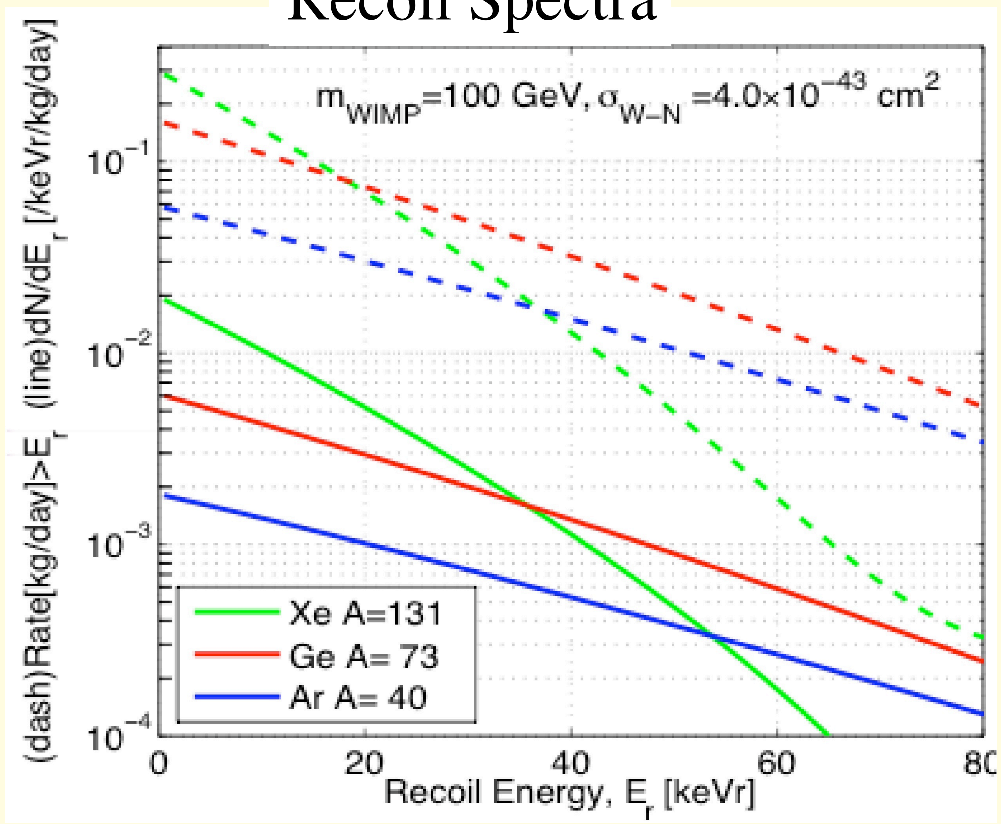
- Scatter on nuclei
  - Highest rate, energy
- Spin and non-spin interactions
- Spin independent: coherent

$$\lambda = \frac{h}{mv} \sim R_{nucleus}$$

$$\sigma \propto A^2$$

Rate: < 10^{-2} events/kg/day, or much lower

Recoil Spectra



- Coherence lost if:

$$\lambda < R_{nucleus}$$

I don't have time to talk about:

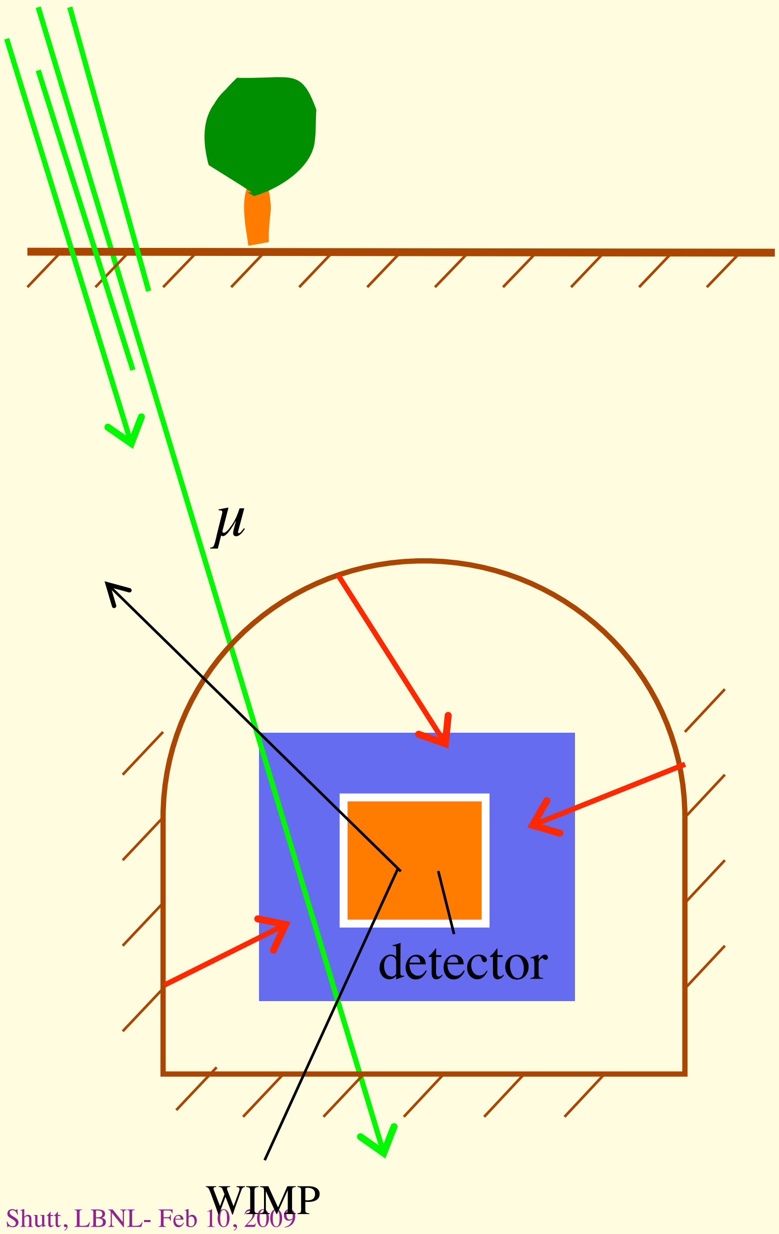
- Indirect searches - annihilation of WIMPs
  - Rate non-zero: dark matter is dominant mass in galaxy
  - Capture in Sun, annihilate to neutrinos, search with IceCube, etc.
  - Annihilation to gammas at galactic center: Fermi-GLAST
  - WIMPs annihilate to e^+, e^- or p^+, p^- - recent PAMELA e^+ excess
- Axionic dark matter
- Other dark matter: self-interacting, inelastic, strongly-interacting, warm, fuzzy.
- WIMP models in supersymmetry: Neutralino
- Supersymmetry at LHC

Detecting rare events.

- Problem: radioactivity
  - Ambient: 100 events/kg/sec.
  - Pure materials in detector

- Shield against outside backgrounds

- Underground to avoid muons



Most radioactivity: electron recoils

Why Roman lead is special.

U, Th in rock: 2 ppm ≈ 10^7 decays/day/kg

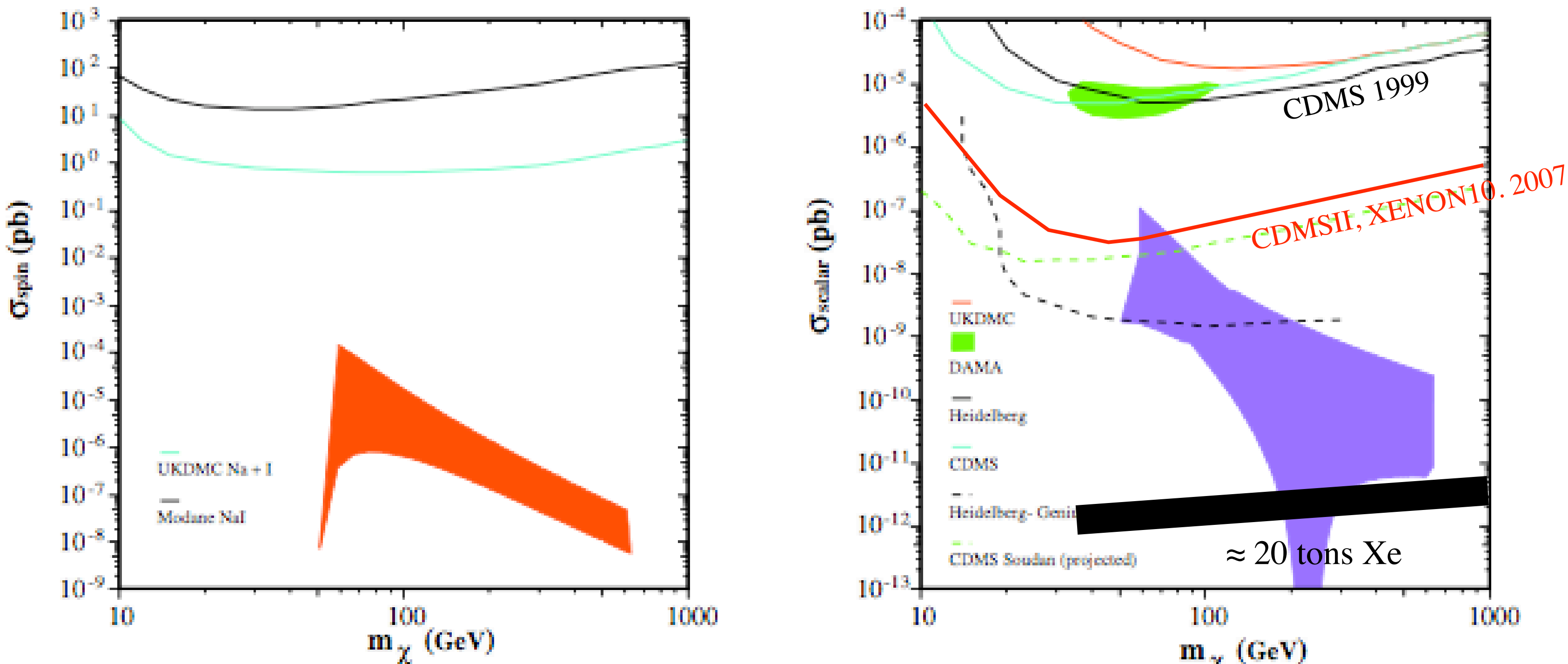
Crude smelting removes U, Th from Pb.

^{210}Pb at bottom of U decay chain remains.

$T_{1/2}$= 22 years

How big a detector do we need?

J. Ellis, A. Ferstl, K. Olive, *Phys.Lett.* **B**481 (2000) 304-314



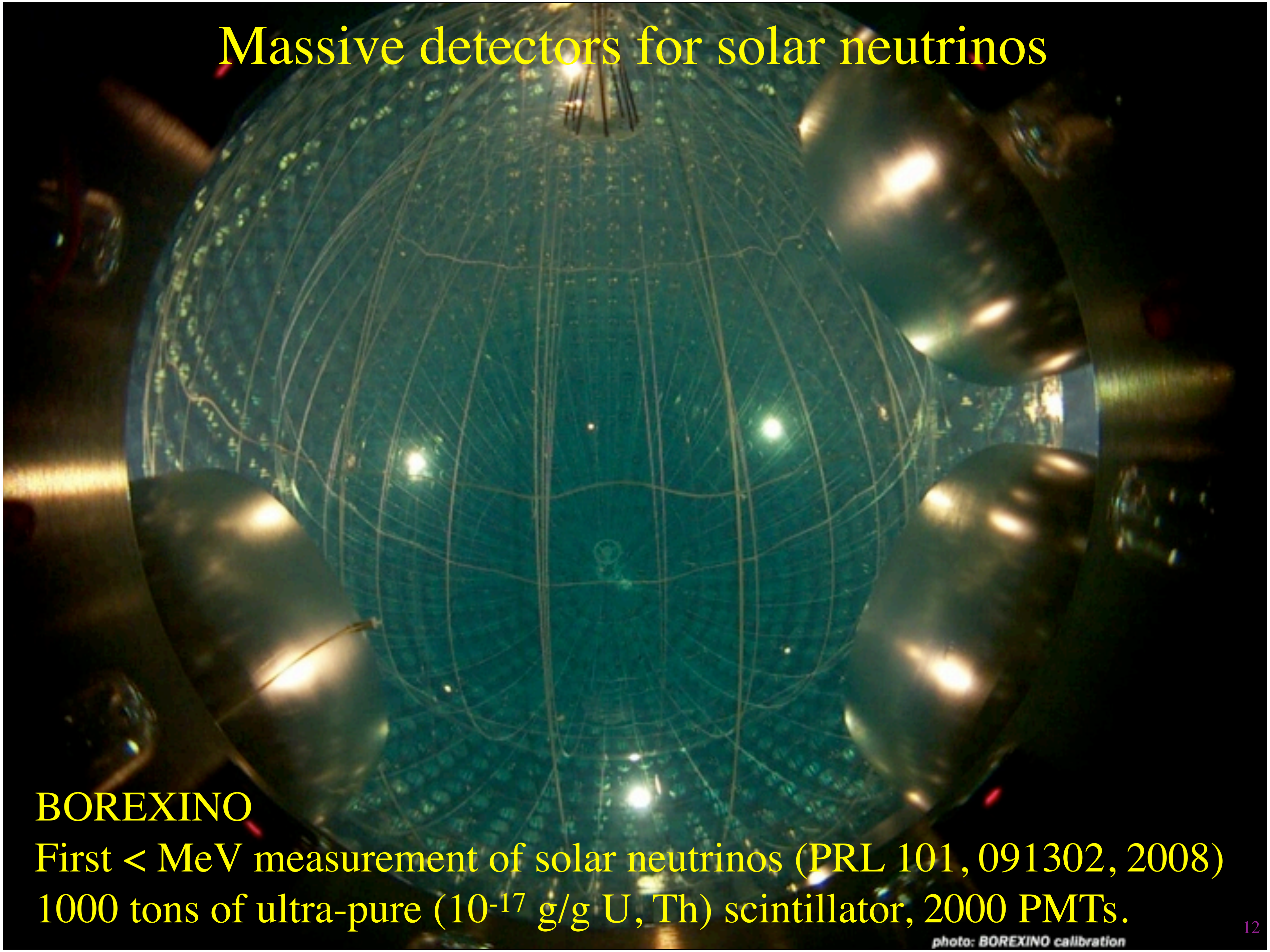
Spin dependent couplings

Spin independent couplings

a predominant $U(1)$ gaugino (Bino) composition for the LSP. Our results fall considerably below many of the possible predictions in the literature [10], and may discourage some faint-hearted experimentalists. However, we think they provide a realistic estimate of the target

We should not want our experimental colleagues to be too downcast by the long road they appear to have to cover in order to probe the minimal universal MSSM framework utilized here. For example, there are surely some supersymmetric models that predict larger

Massive detectors for solar neutrinos



BOREXINO

First < MeV measurement of solar neutrinos (PRL 101, 091302, 2008)

1000 tons of ultra-pure (10^{-17} g/g U, Th) scintillator, 2000 PMTs.

Two approaches to low backgrounds

- Better living through physics: sophisticated detectors:
  (CDMS)

- Better living through chemistry: pure, large detectors:
  (Borexino)

- Can we get best of both?
  - Mass
  - Highly specific, sophisticated event information.

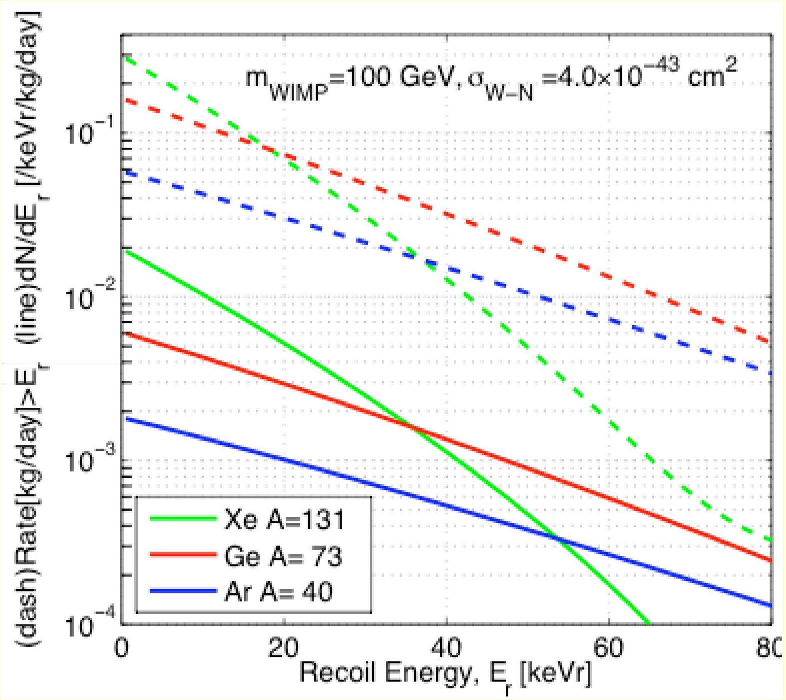
Liquified Noble Elements

- Liquid target:
  - Readily purified
  - *Scalable to large masses*

- Liquid scintillator: ^{14}C fatal for dark matter
  - Even in petroleum - 10^{-18}
  - ^{14}C: U->*a* + rock -> n -> $^{14}N(n,p)^{14}C$

- Xe, Ar, Ne(?)
  - Xe: 165 K, λ=175 nm
  - Ar: 87.3 K, λ =128 nm, ^{39}Ar - 1 Bq/kg.
  - Ne: 27.1 K, λ =80 nm, (bubbles -> no charge)

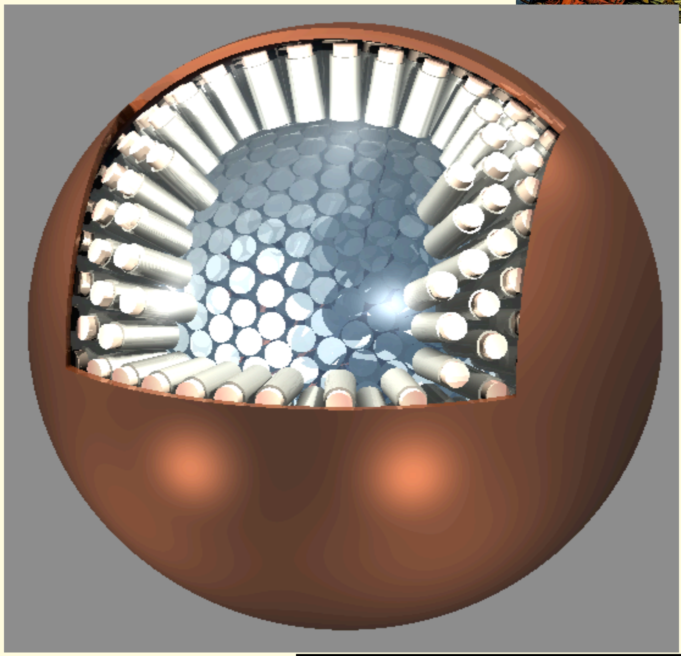
- Signals: ionization & scintillation
  - Single photons, electrons readily measured

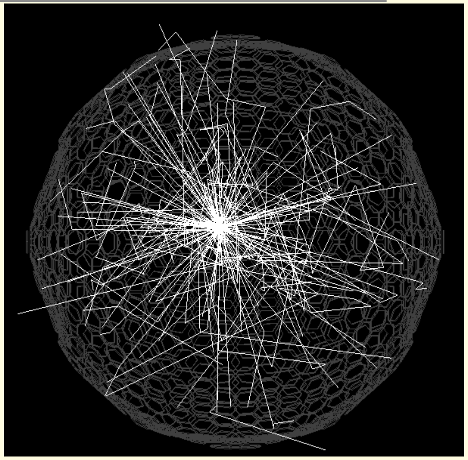


Single Phase detectors

- Scintillation signal.
  - Cryogenic versions of Chooz, Kamland, Borexino.
- Rayleigh scattering:
  - Position reconstruction poor.
  - Need large volume to reject Rn-daughters on surface.
  - Multiple-vertex events hard to distinguish.
- PMTs: highly radioactive
  - Self-shielding in large detector
  - LXe best for this

XMASS: 800 kg total, 100 kg fiducial



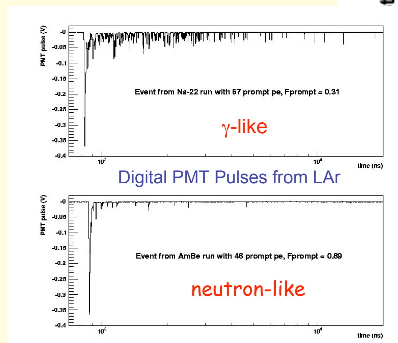


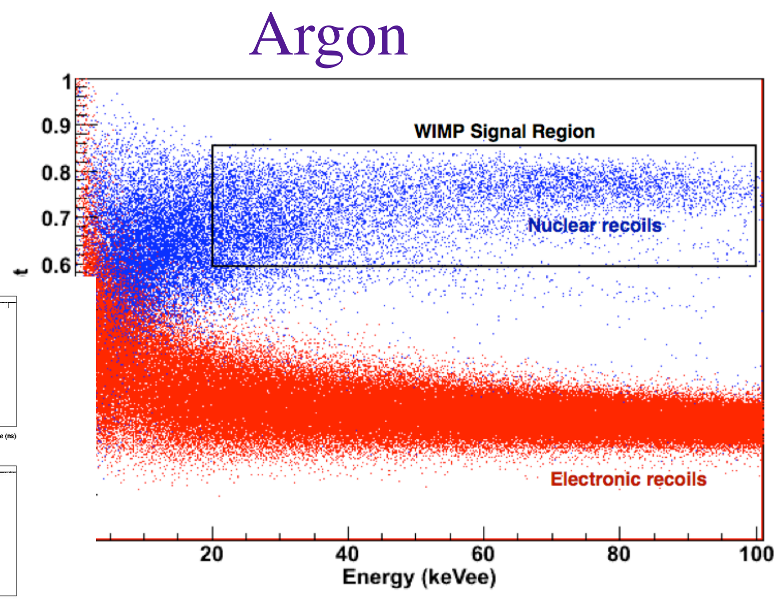
(Seidel, Lanou, Yao, 2002)

	λ (nm)	L theory (cm)	L exp (cm)
Ne	78	60	
Ar	128	90	66
Xe	174	30	30-50

Scintillation pulse shape discrimination (PSD)

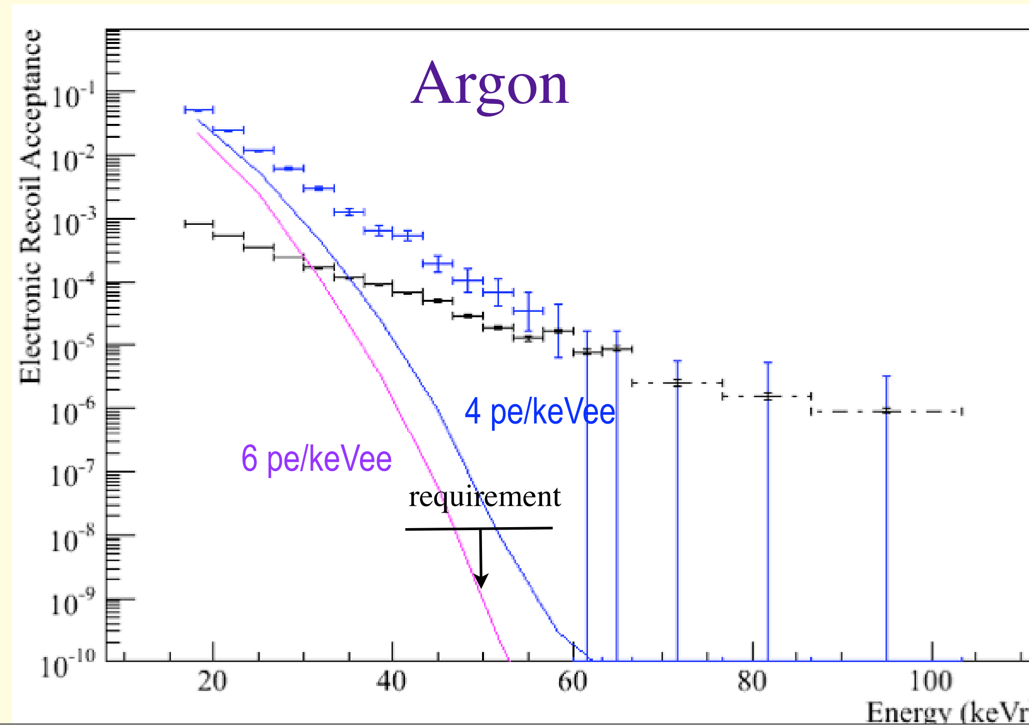
- Scintillation from excimer state:
  - $Ar^* + Ar \rightarrow Ar_2^*$
  - Triplet (long lived)
  - Single (short lived)





Data: Mini-Clean (McKinsey/Yale)

- Electron vs Nuclear recoils:
  - Nuclear recoils don't populate triplet



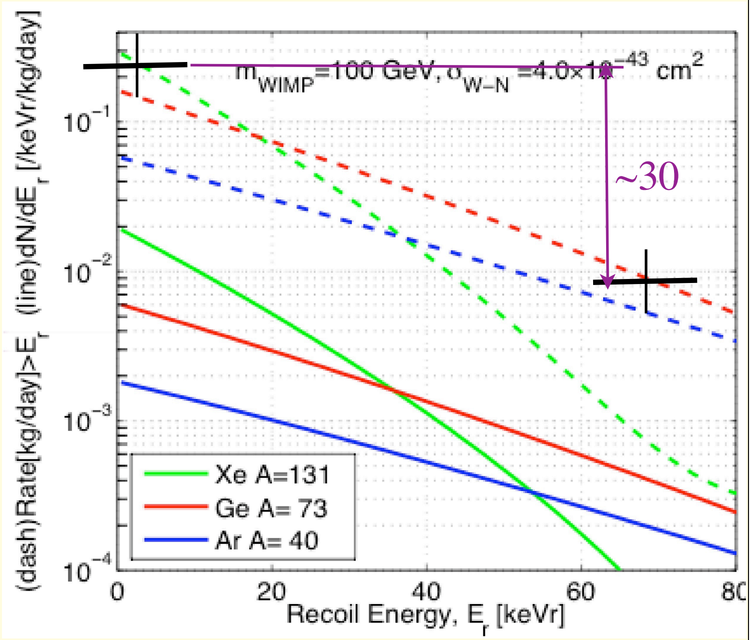
- Discrimination
  - Ar: powerful
  - Xe: ok at high energy
  - Ne: good

The Ar story

- ^{39}Ar: produced in atmosphere
  - 1 Bq/kg background.
  - β decay, 269 yr half life, Q=565 keV.

- Fatal?
  - Effective loss of mass
  - Pile-up, especially for dual phase.

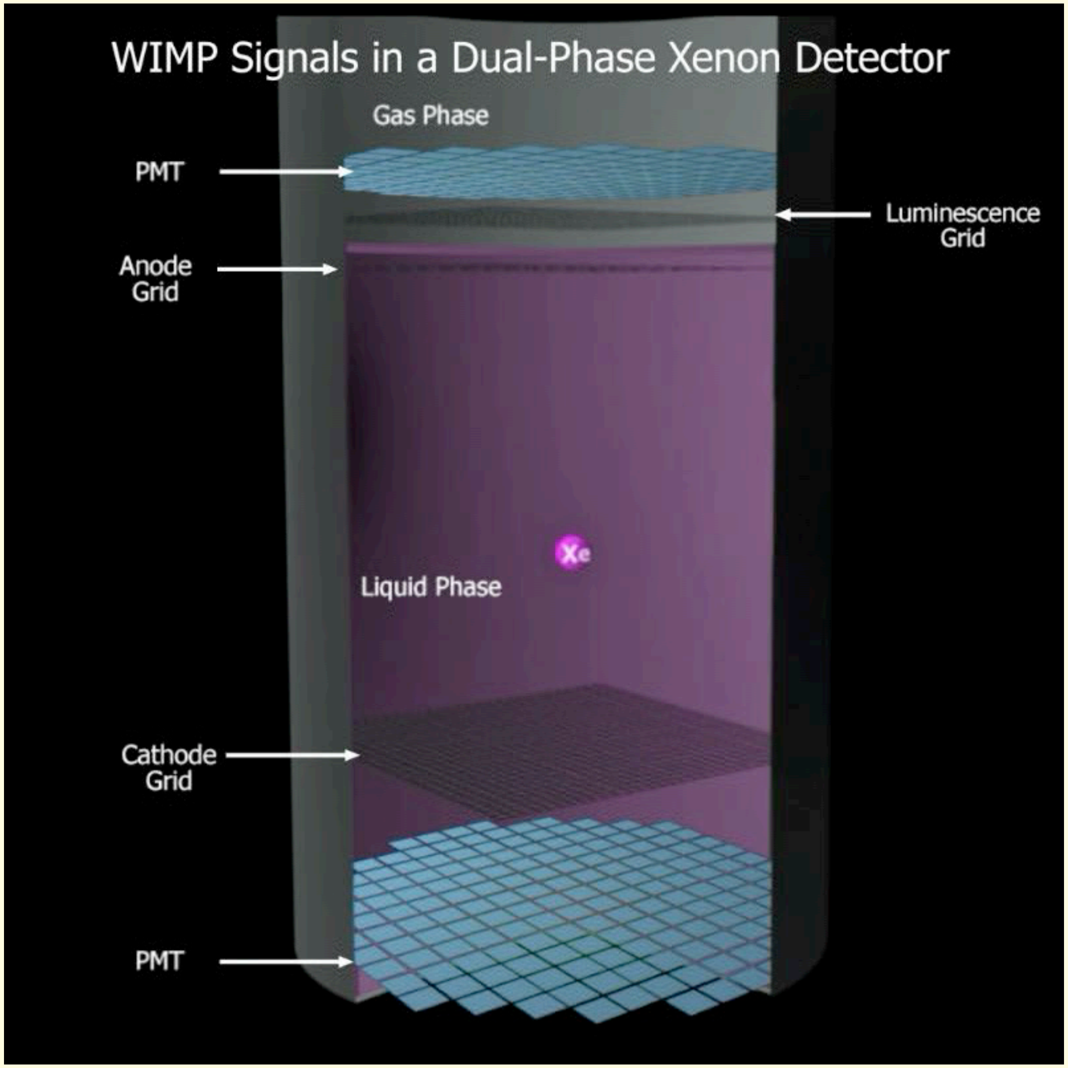
- Worldwide hunt for old Ar
  - Issue: $^{39}K(n,p)^{39}Ar$
    - All ^{40}Ar from $^{40}K \rightarrow {}^{40}Ar+e^{+}+\nu$
  - He reserve
    - 20 reduction recently shown.
    - Cost?
  - Antarctic lakes?



Dual phase time projection chamber

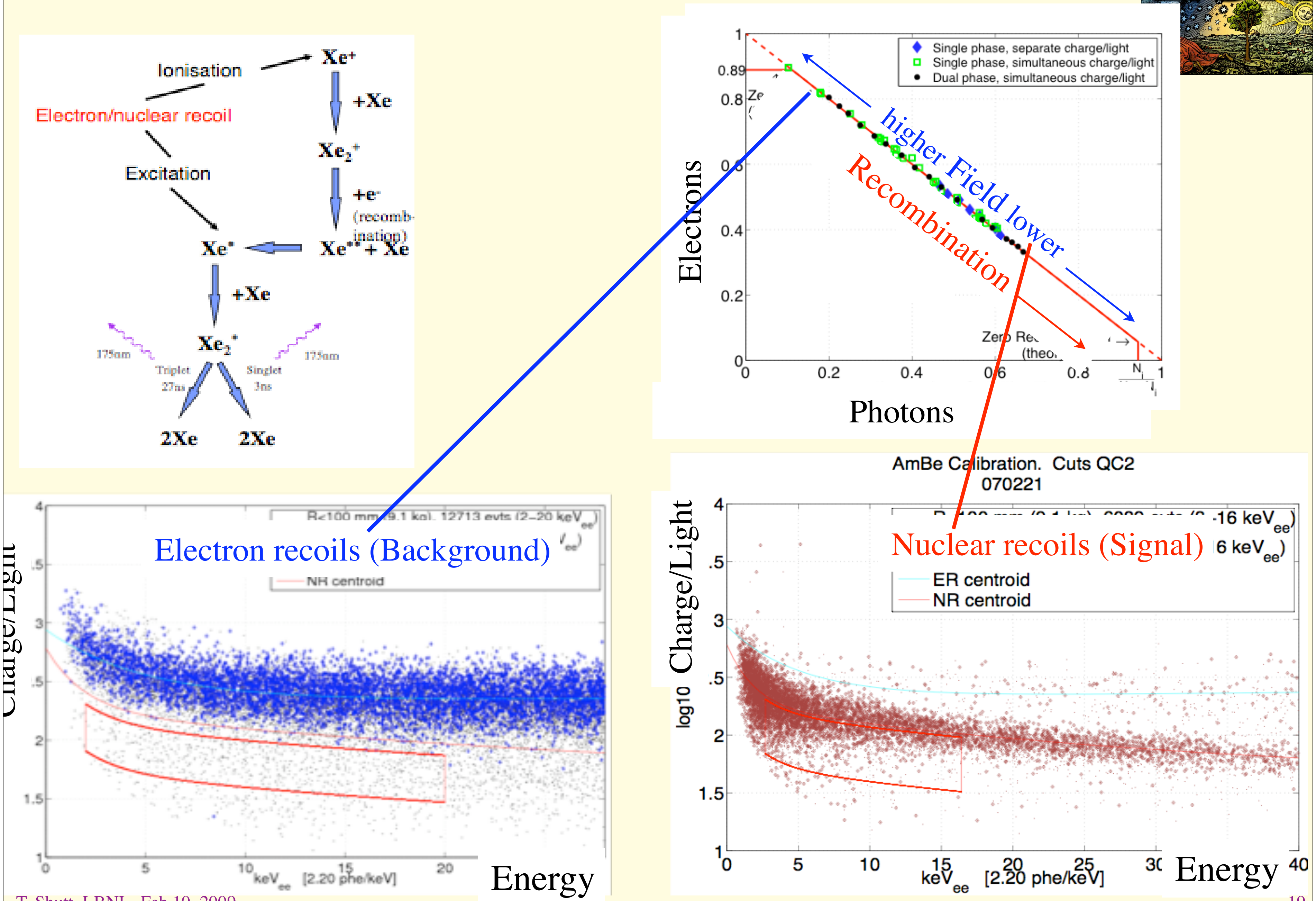
- Can measure single electrons and photons.
- Charge yield reduced for nuclear recoils.
- Good 3D imaging
  - *Eliminating edges crucial.*

- Works for Xe and Ar.
  - But too slow for ^{39}Ar.

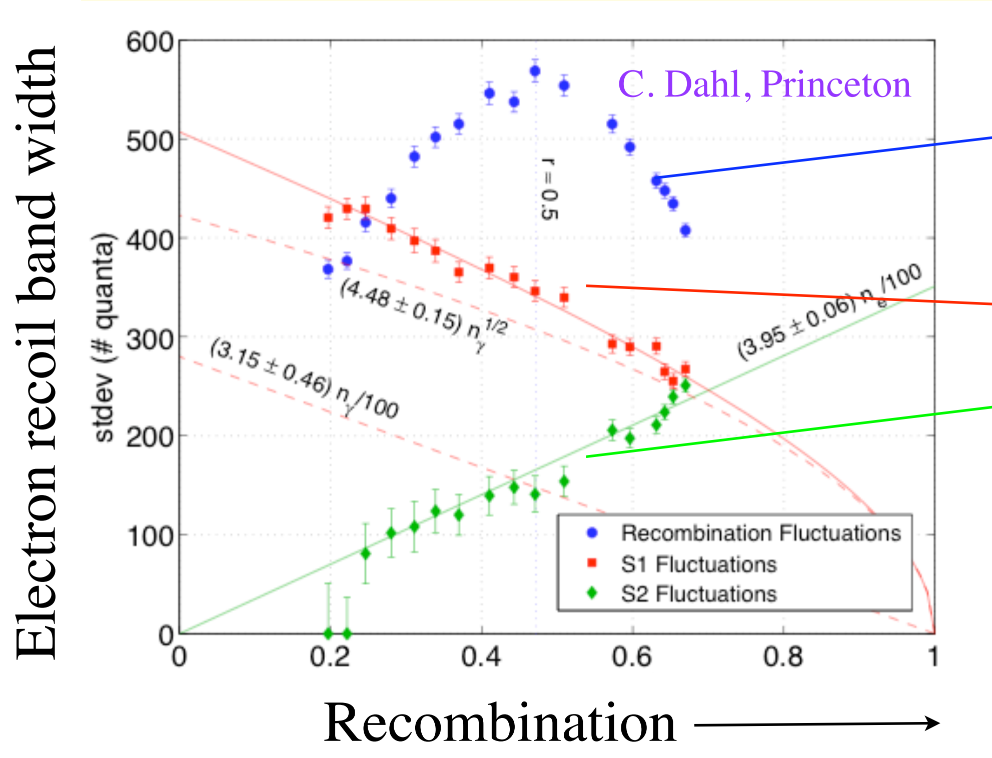


A. Bolozdynya, NIMA 422 p314 (1999).

Recombination - based discrimination



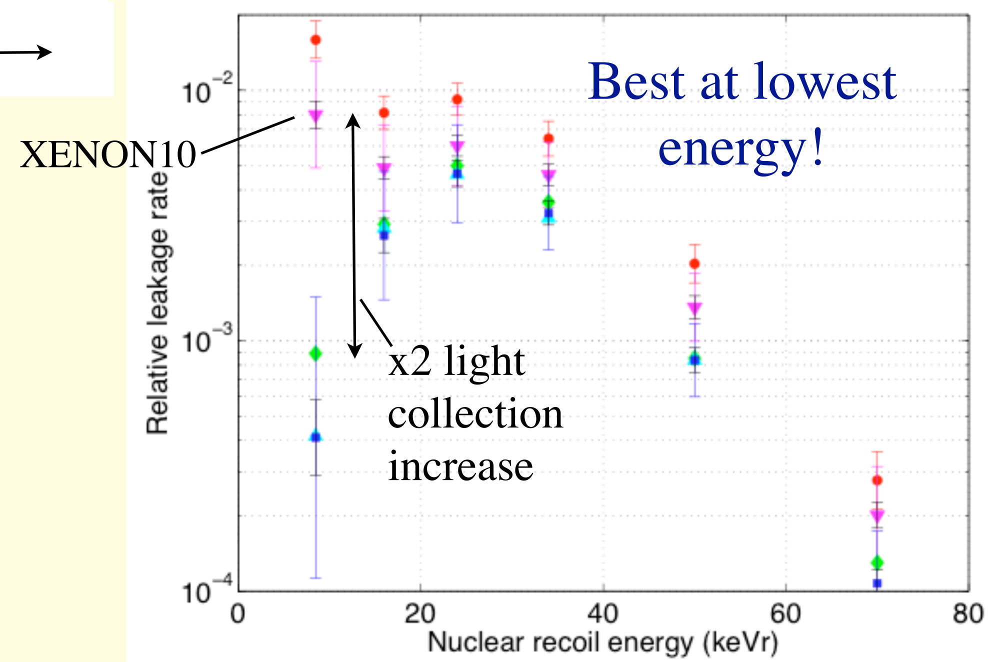
Discrimination Fundamentals



- Fluctuations in recombination
- Light collection statistics

\+ Other linear terms

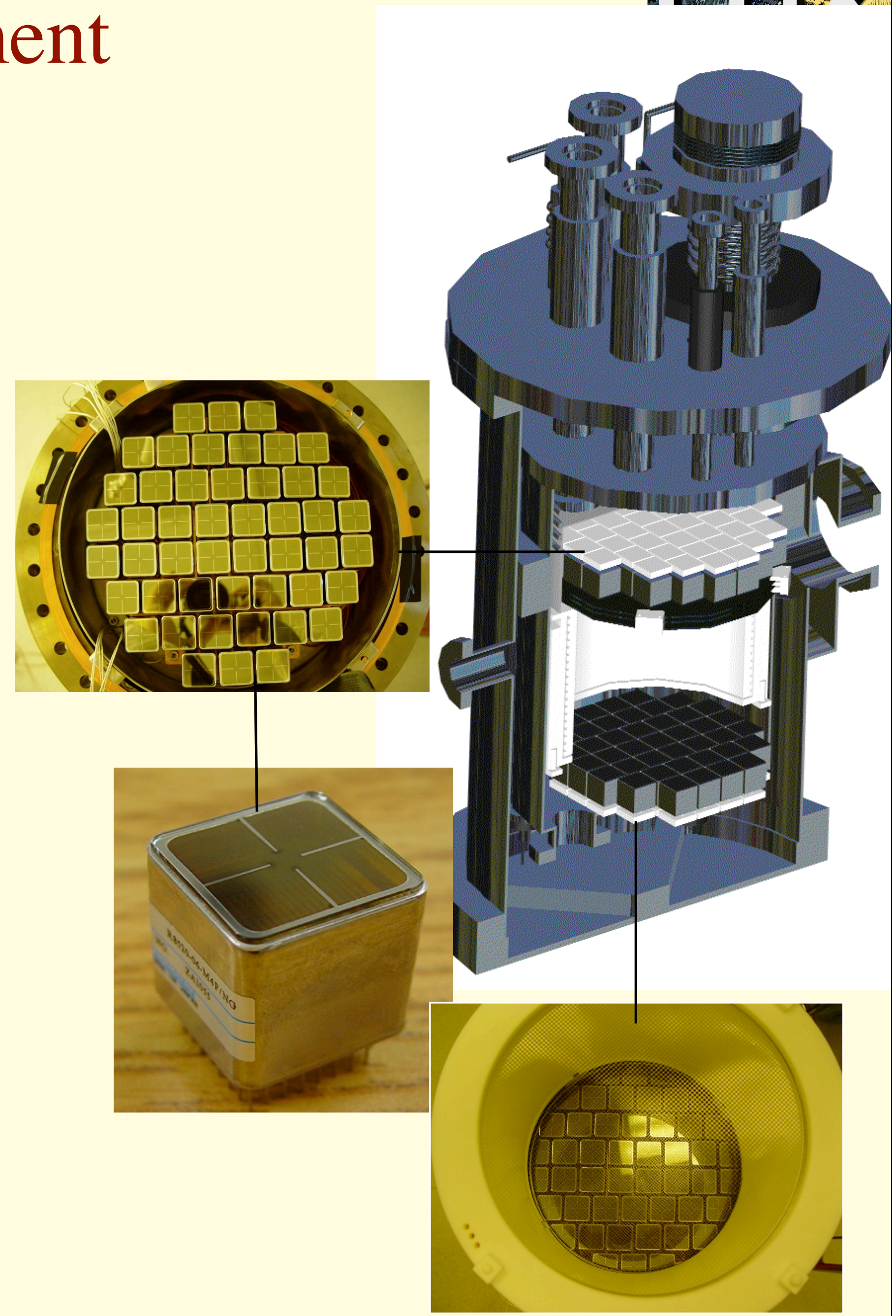
Discrimination Level



Discrimination improves at lowest energy!

XENON10 Experiment

- 15 kg active liquid xenon: 15 cm scale.
- Hamamatsu R8520 1''×3.5 cm PMTs
- 48 PMTs top, 41 PMTs bottom array
- Cooling: Pulse Tube Refrigerator (PTR)
- 90W, coupled via cold finger (LN2 for emergency)



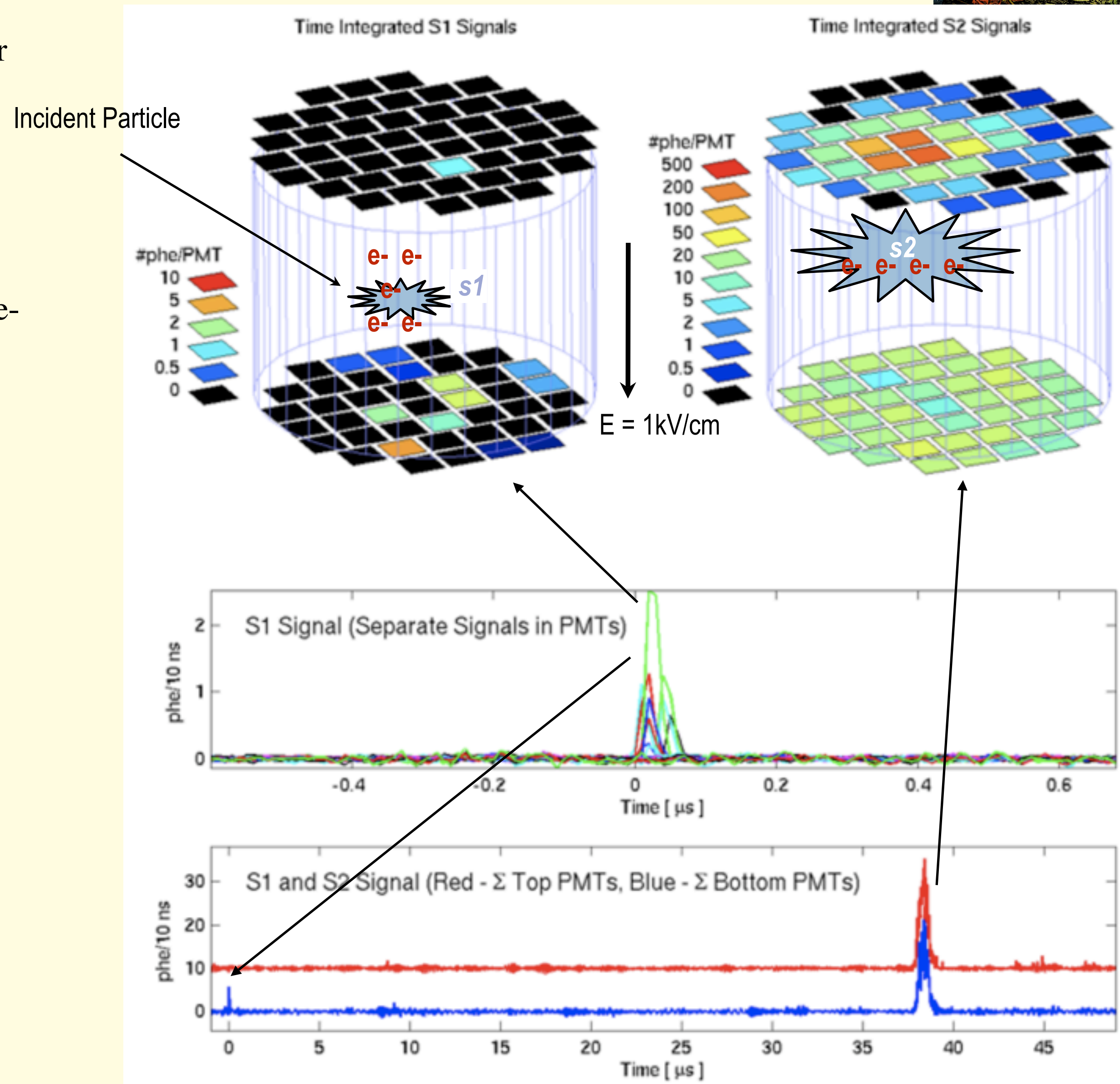
XENON10 Events

Example: Low Energy Compton Scatter

- S1=15.4 phe ~ 6 keVee
- Drift Time ~38 μs => 76 mm

s1: Primary Scintillation Created by Interaction LXe

s2: Secondary Scintillation Created by e- extracted & accelerated in GXe



$(s2/s1)_{ER} > (s2/s1)_{NR}$

Expect > 99% rejection efficiency of γ/n Recoils…

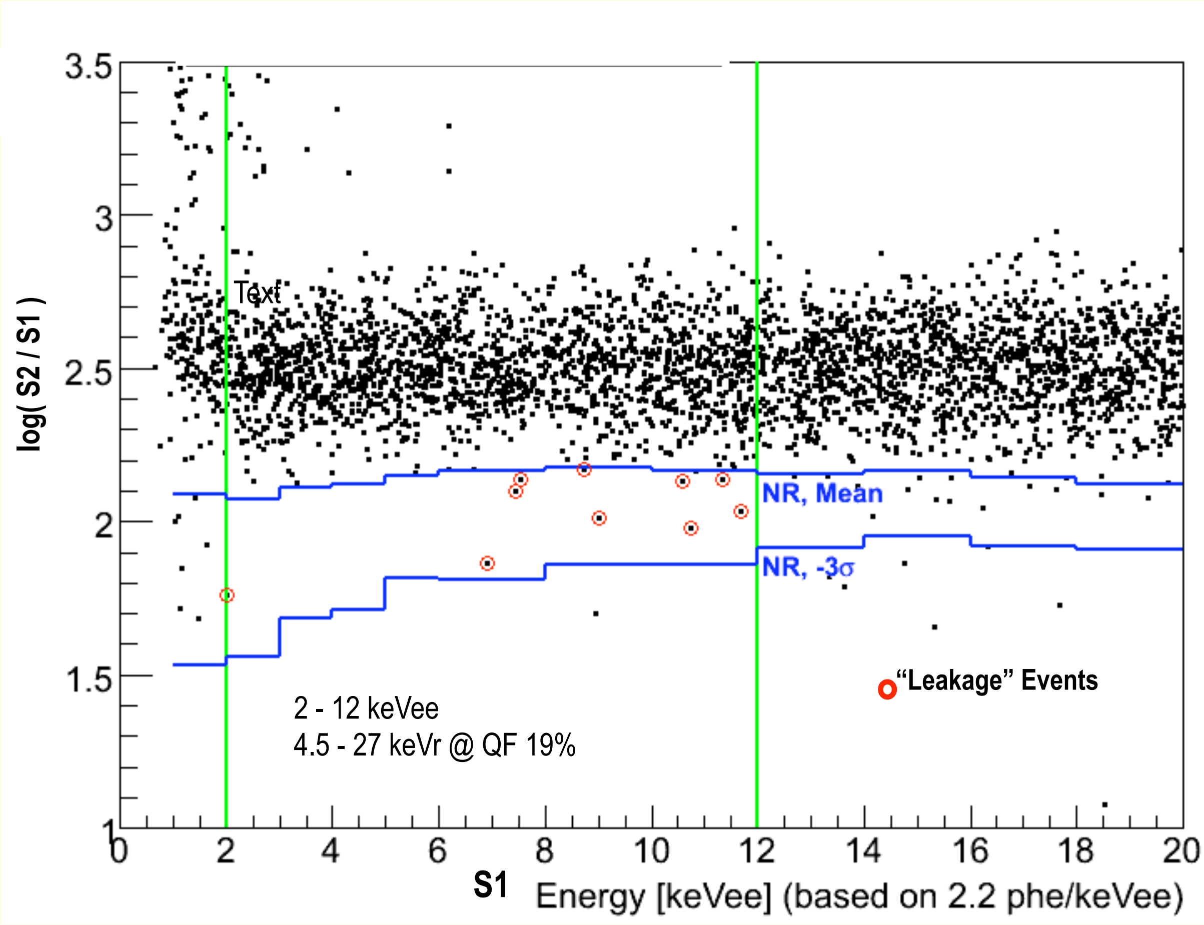
Reduction of Backgrounds =>

Reduction of Leakage Events

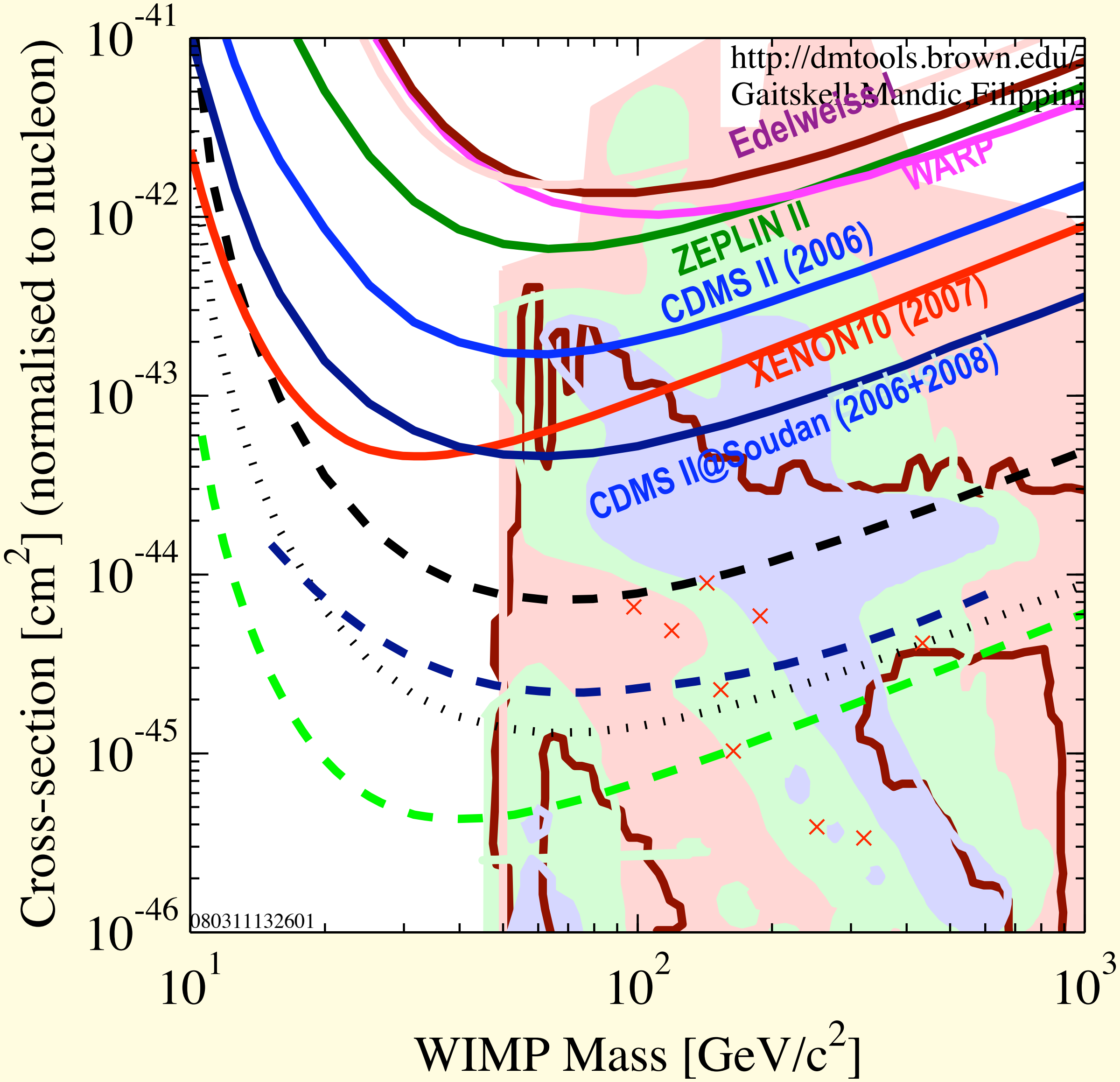
XENON10 WIMP search data

- Blind Analysis
- 58.6 days, 5.4 kg fiducial
- ~50% acceptance of Nuclear Recoils
- 2-12keVee / 4.5-27 keVr
  - Assuming QF 19% 4.5-27 keVr
- 10 events in the “box” after all primary analysis blind cuts
  - Calibration expectation: 7.0 +2.1-1.0 (gaussian)
  - Data: 5 ~gaussian; 5 non-gaussian

“Straightened ER Scale”



Current search status



So we haven’t seen anything.

How do we fully test the weak scale?

- Current limits ~5x10^{-44} cm^2.
- Goal: 10^{-47} cm^2, or better

*Side effects include conflation of objective and subjective

Next phase liquid noble experiments

- XMASS - 800 kg (100 kg fiducial). Xe single-phase
  - Kamioka
  - Funded. Under construction.
- WARP - 100 kg dual phase Ar
  - Gran Sasso
  - Funded, commissioning
- XENON100 - 70 kg active + 70 kg veto. Xe two-phase
  - Gran Sasso
  - Funded, commissioning.
- LUX - 300 kg active. Xe two-phase
  - SUSEL (Homestake, South Dakota)
  - Funded. Under construction.
- DEAP/MiniCLEAN - 360 and 3600 kg single phase Ar (+Ne?)
- ArDM - large dual phase Ar - 800 kg Ar dual phase

The LUX Collaboration

Brown
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CWRU
A. Bolozdynya
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Rochester
T. Ferbel
U. Schroeder
F. Wolfs

U. SouthDakota
D.Mei

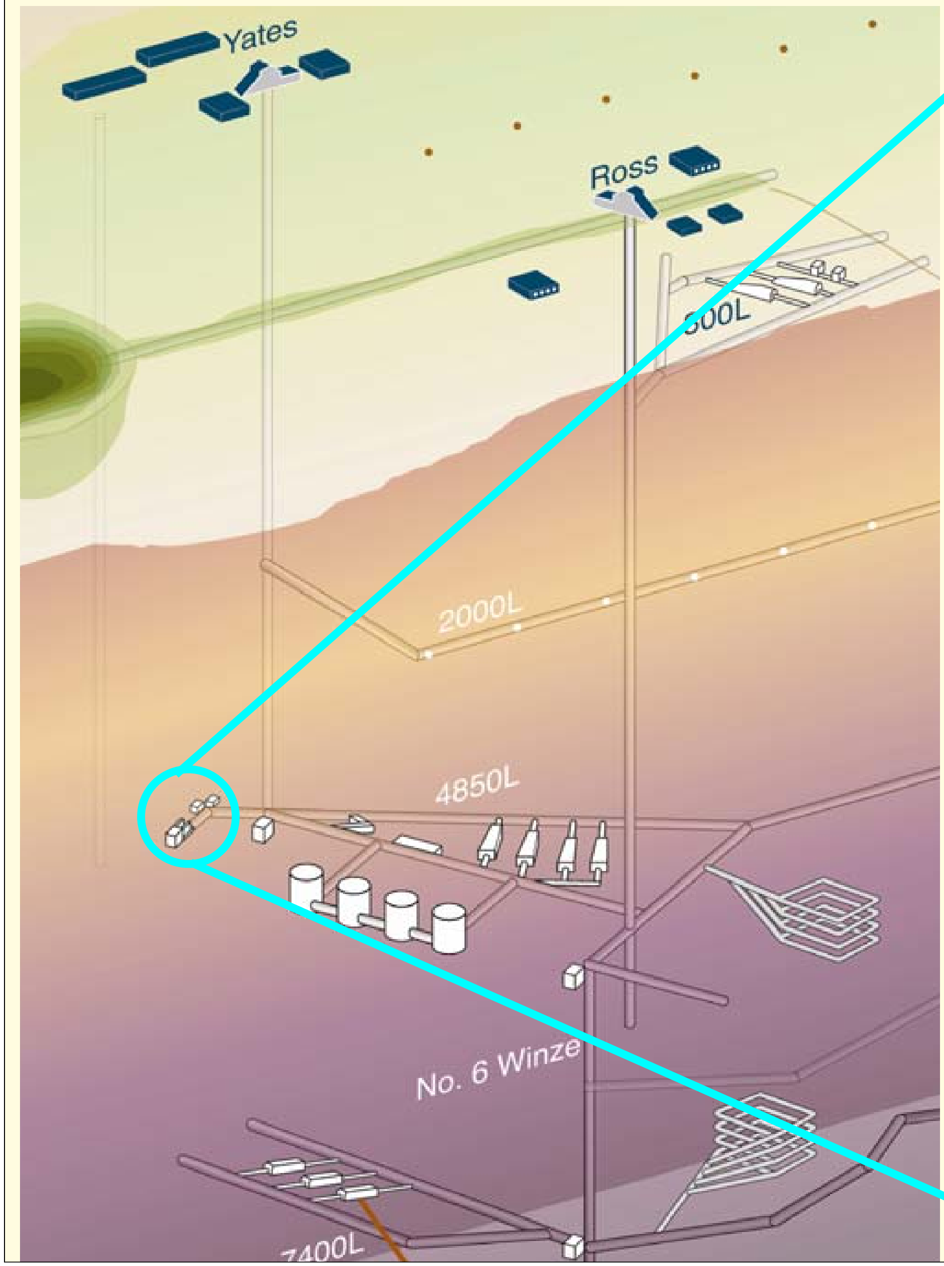
TAMU
J. White

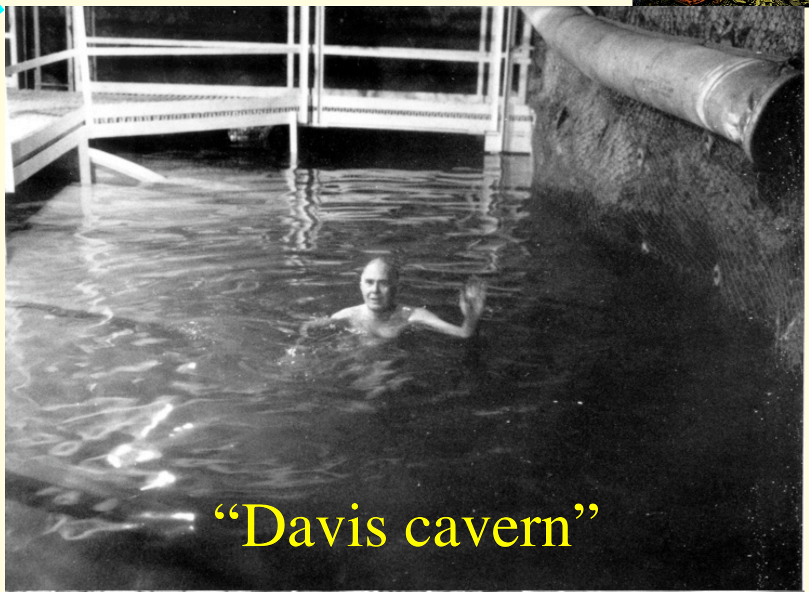
Yale
D. McKinsey

Expertise in dark matter search, noble gas techniques, water detectors, high energy physics and large scale deployments (under/above grounds)

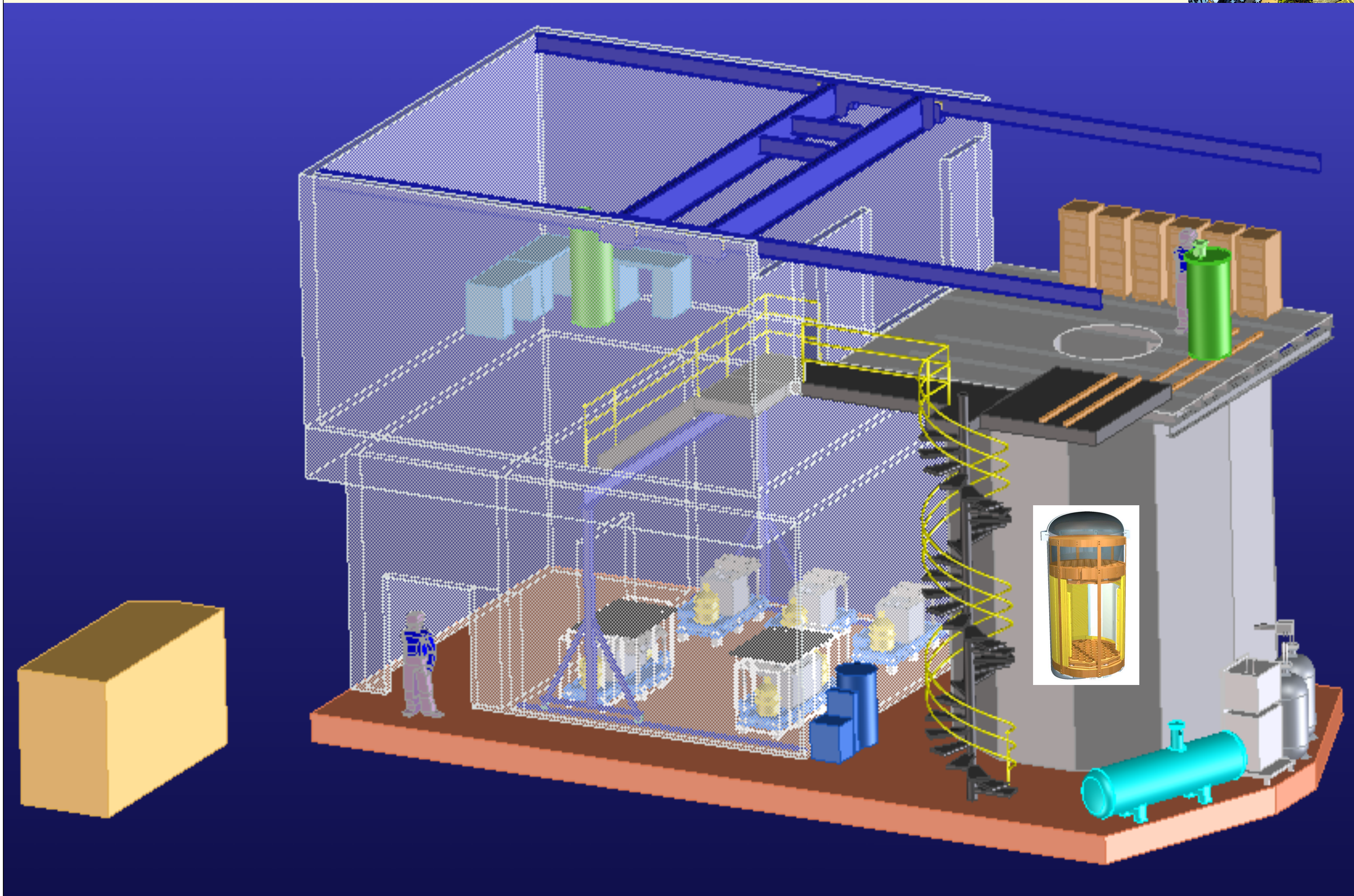
LUX Collaboration

Sanford Lab - Homestake

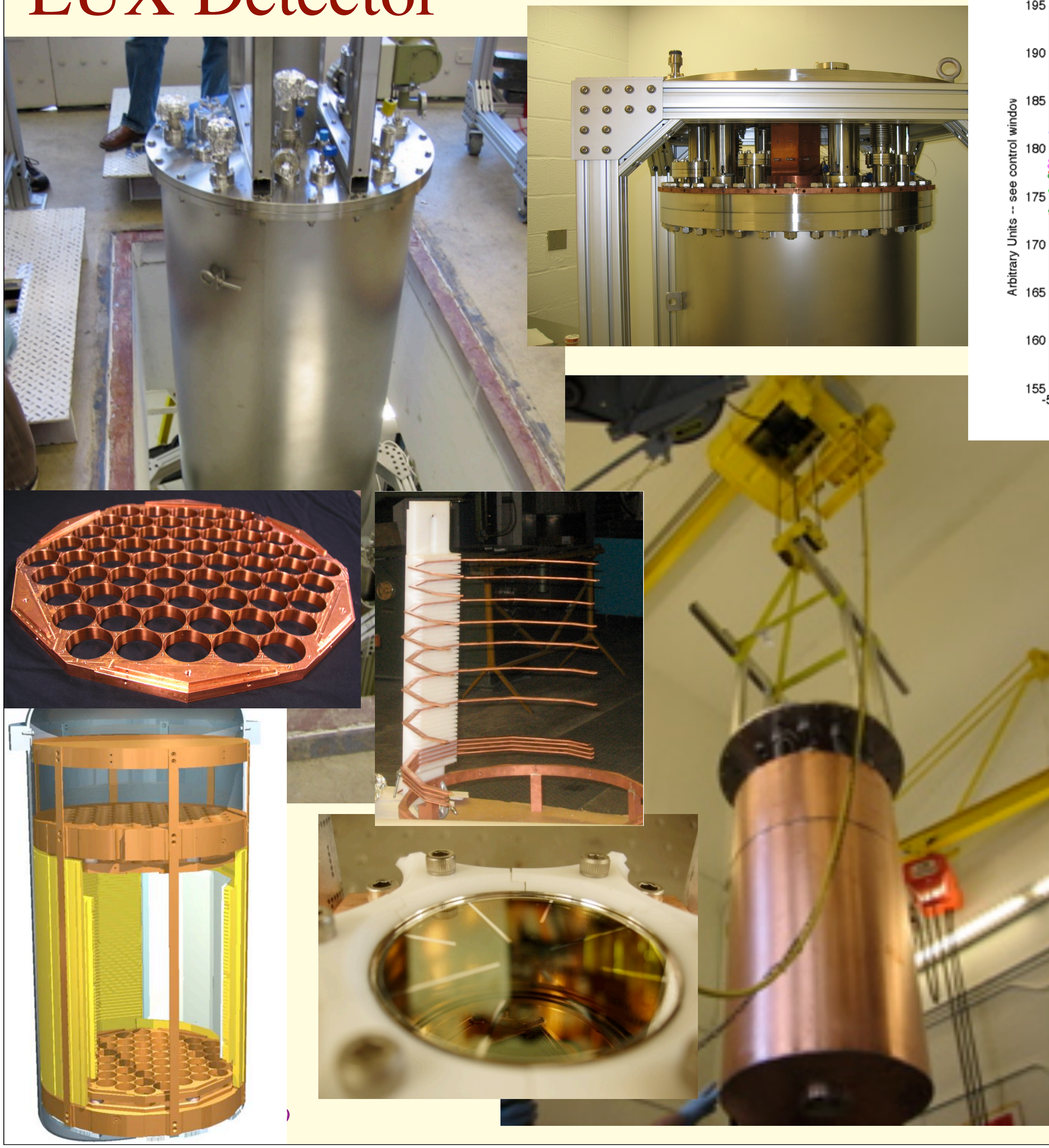


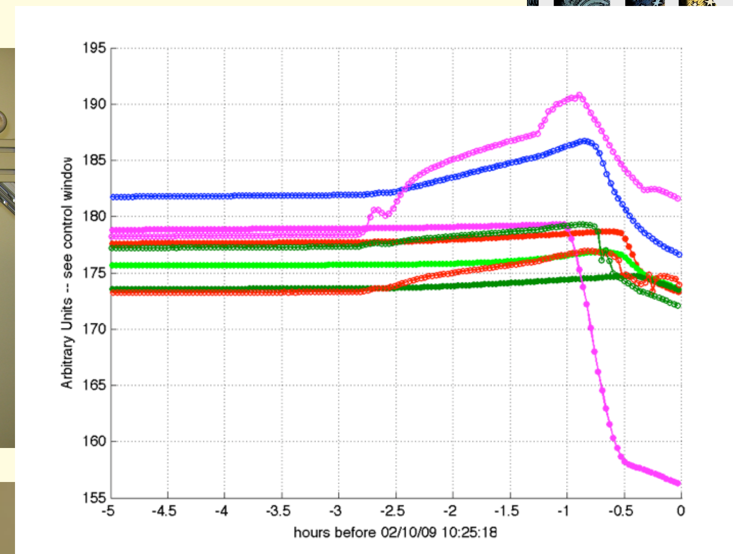


LUX in Davis Cavern at Homestake



LUX Detector

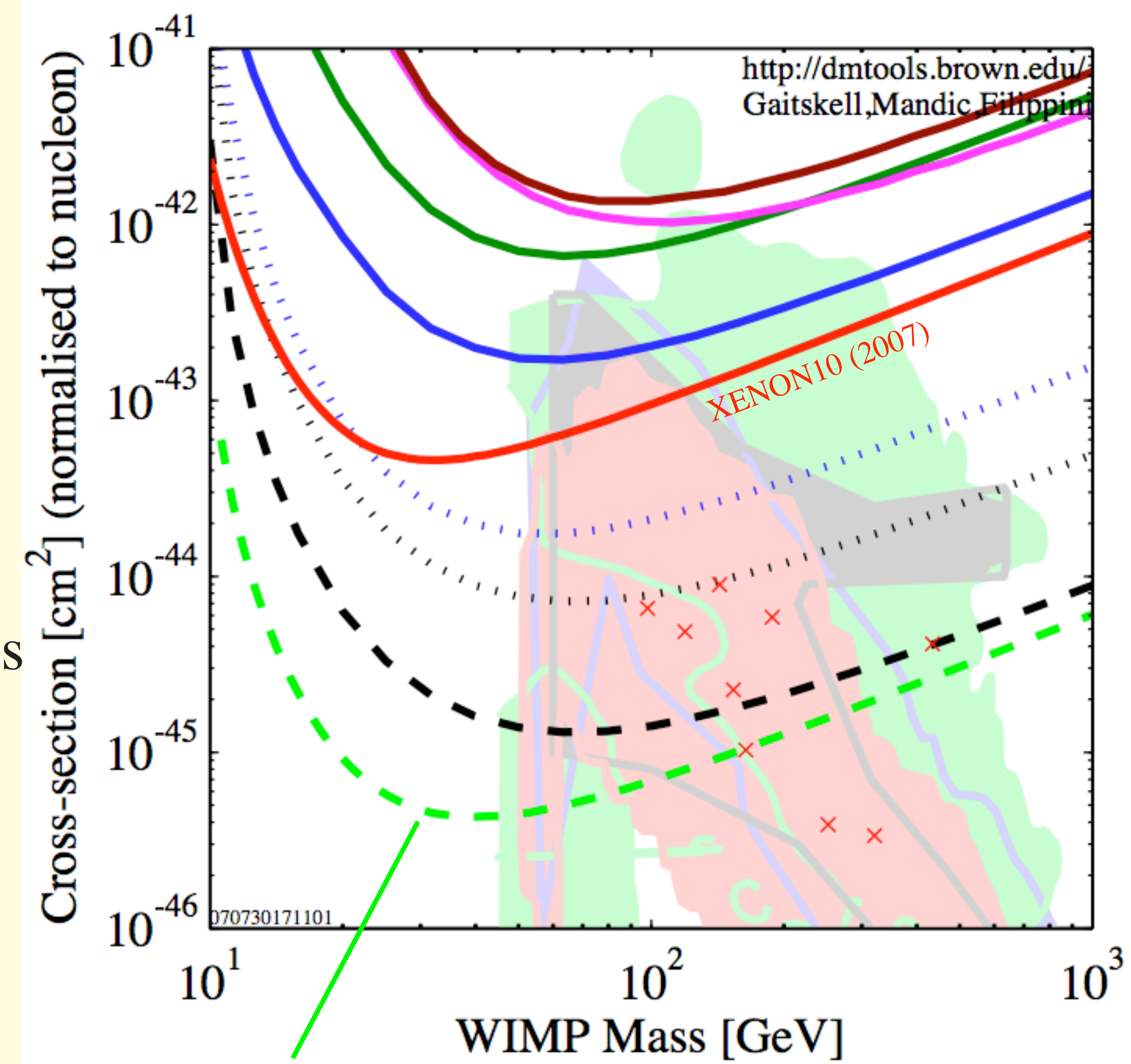




- Full scale prototype cryostat with 50 kg Xe under test.
- Final, Ti cryostat, internal parts under fabrication
- Integration at Sanford lab surface, June 09.

LUX potential

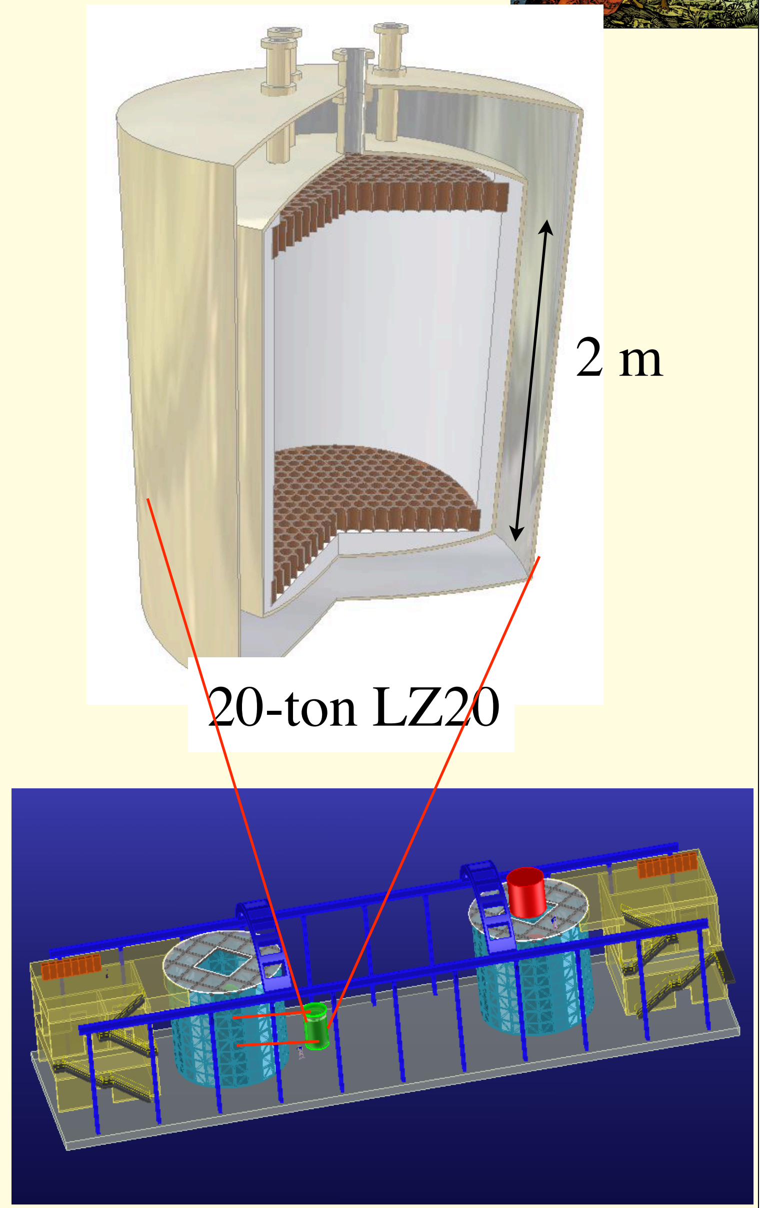
Begin operations
end of 2009



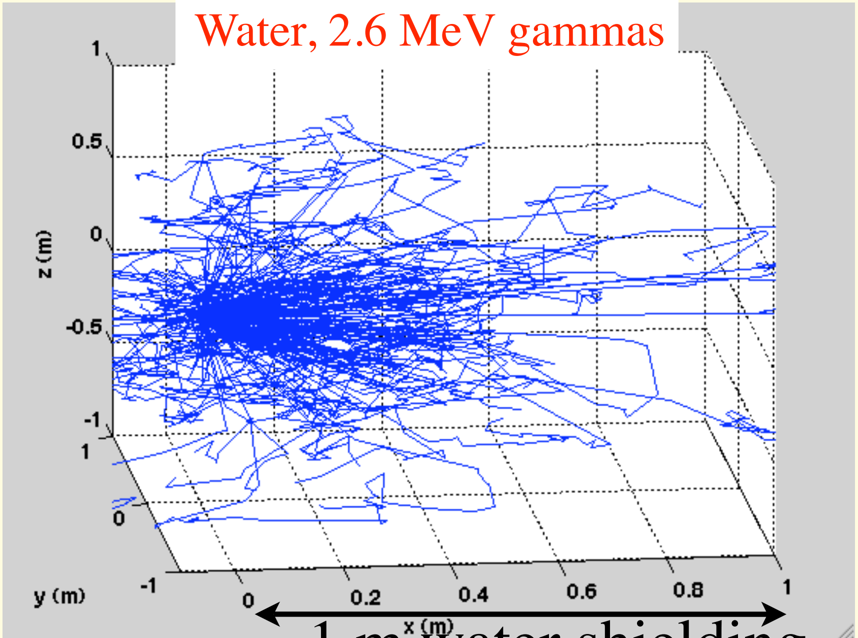
3.9 WIMPs at 7x10^{-46} cm^2 (100 GeV) in 1 year

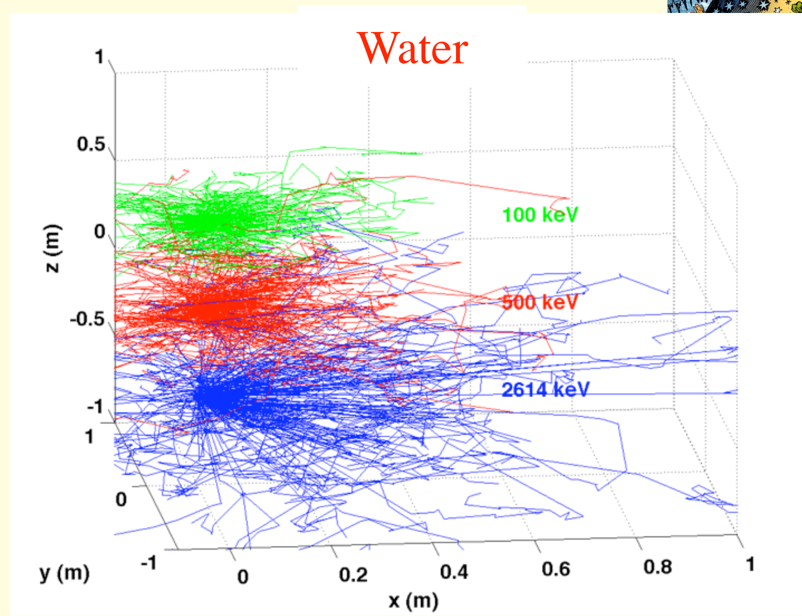
LZ20

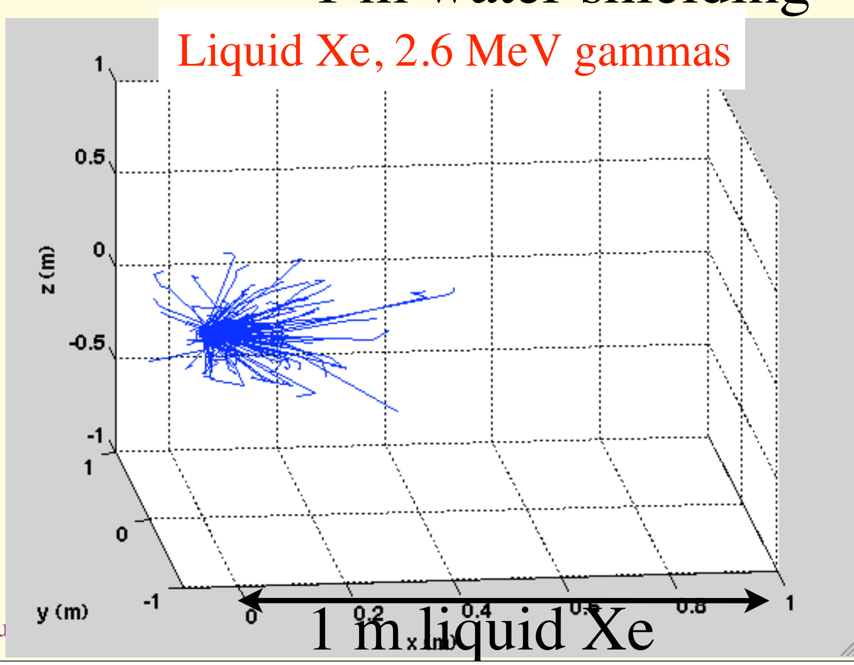
- New collaboration between LUX, and ZEPLIN III.
  - ZEPLIN III: largest European LXe dark matter collaboration: UK, Portugal, Russia
- LZ3: 3 ton, at Sanford Lab
  - Proposals: Sept. 09.
- LZ20: proposed part of ISE for DUSEL
  - 20 ton LXe mass
  - “ultimate” direct dark matter detection experiment

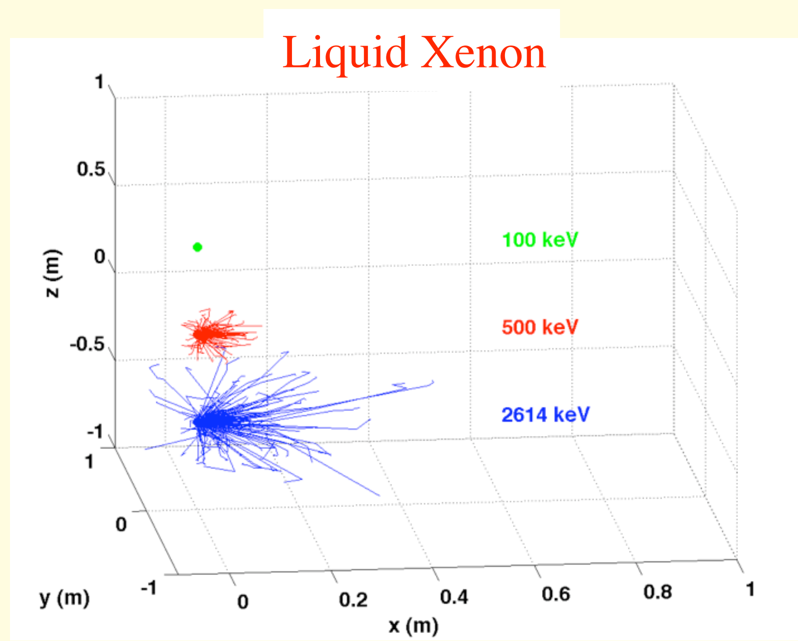


Shielding Gamma Rays









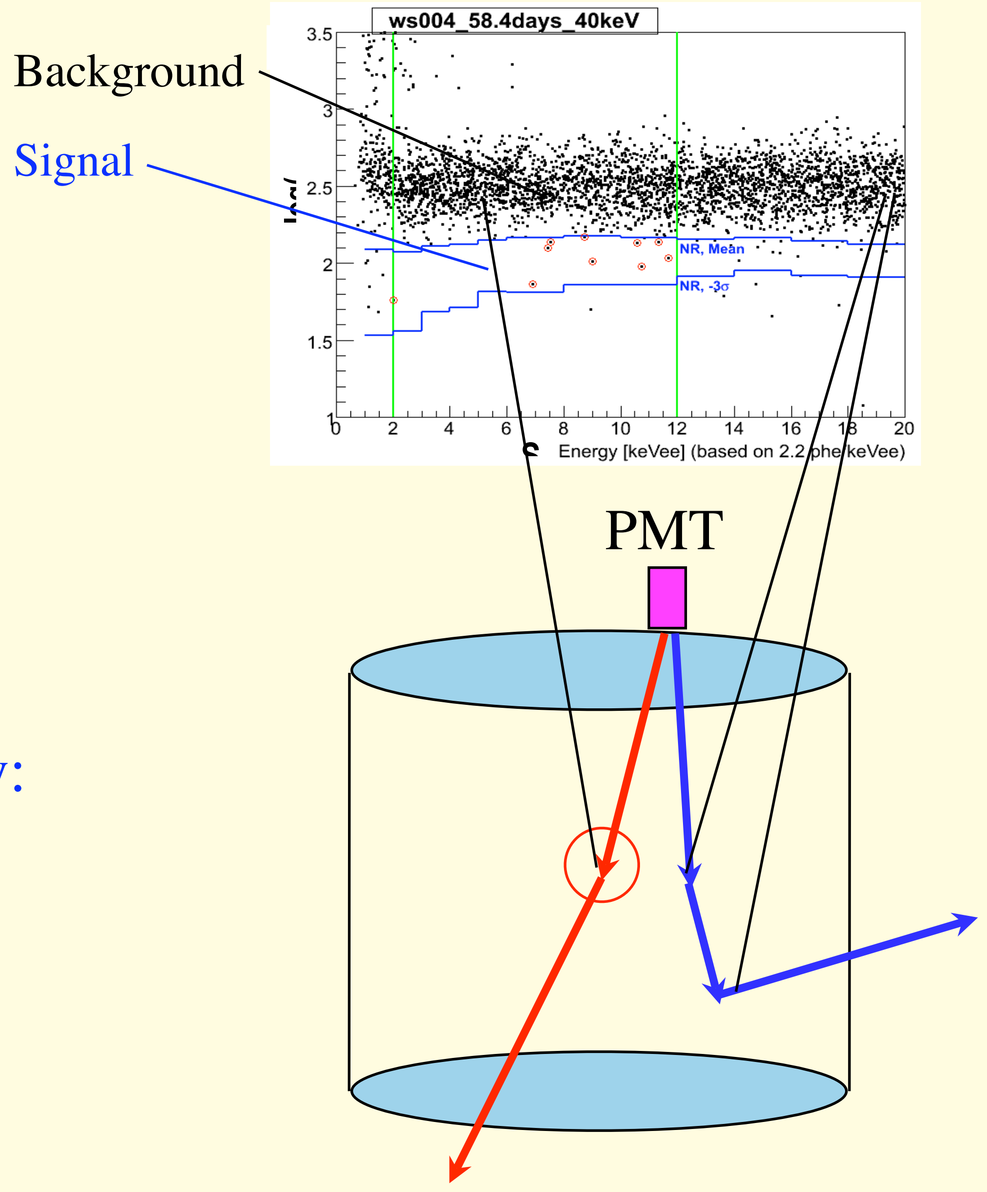
Single Scatters of MeV photons

- Dominant background in foreseeable future

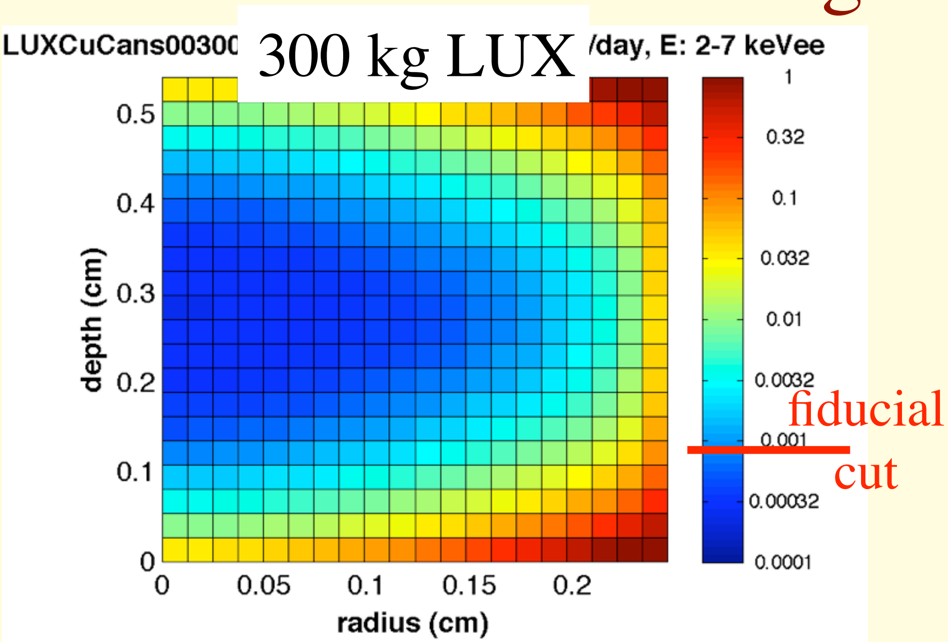
- Rare

- Can approximate analytically:

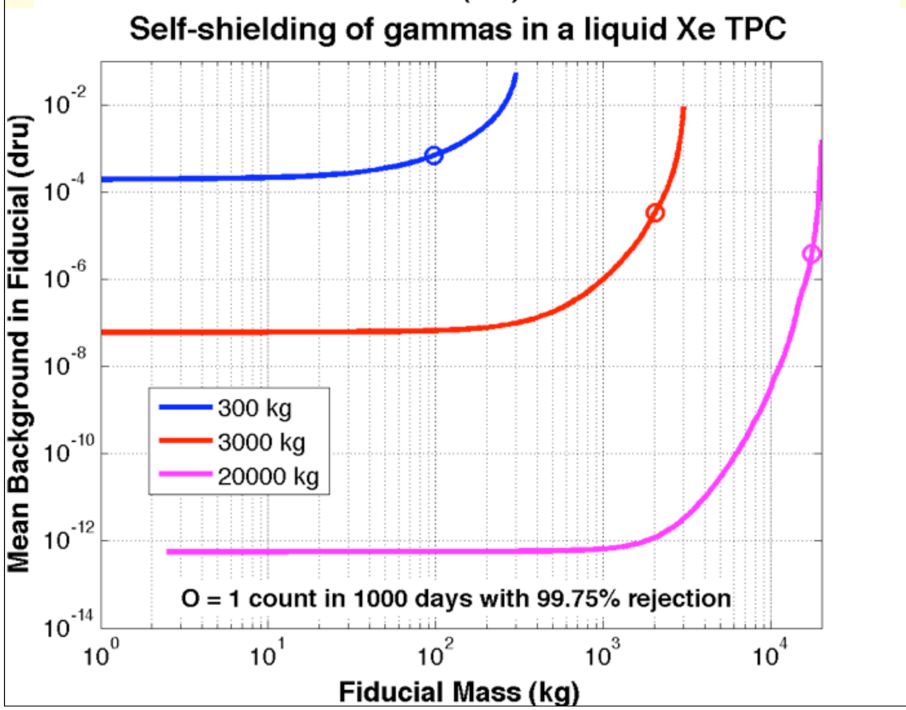
$$P(L) \cong \frac{L}{\lambda} e^{-\frac{L}{\lambda}}$$

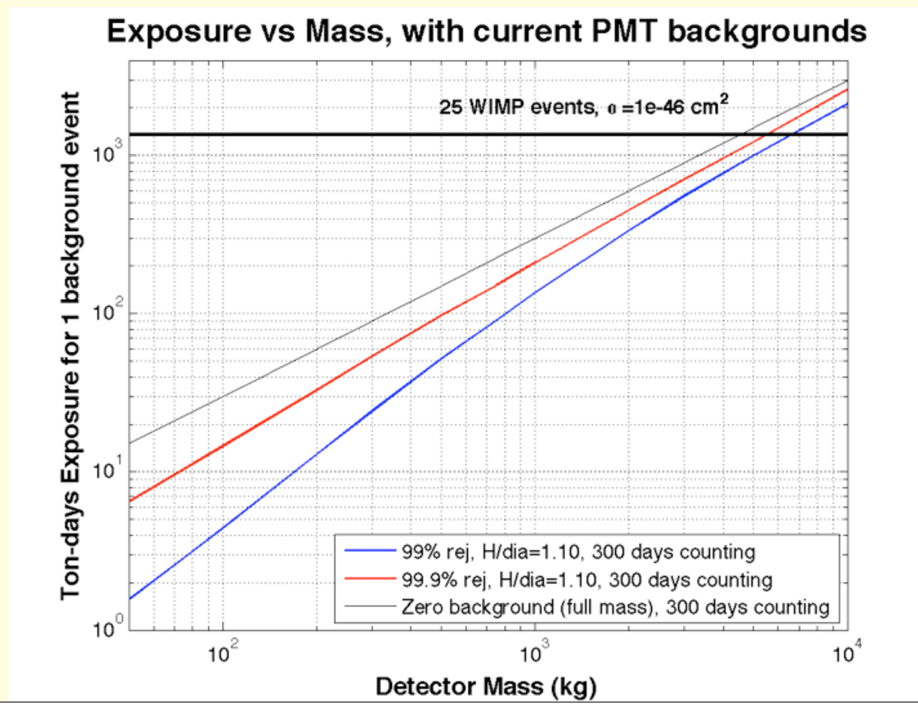


Self-shielding in liquid xenon



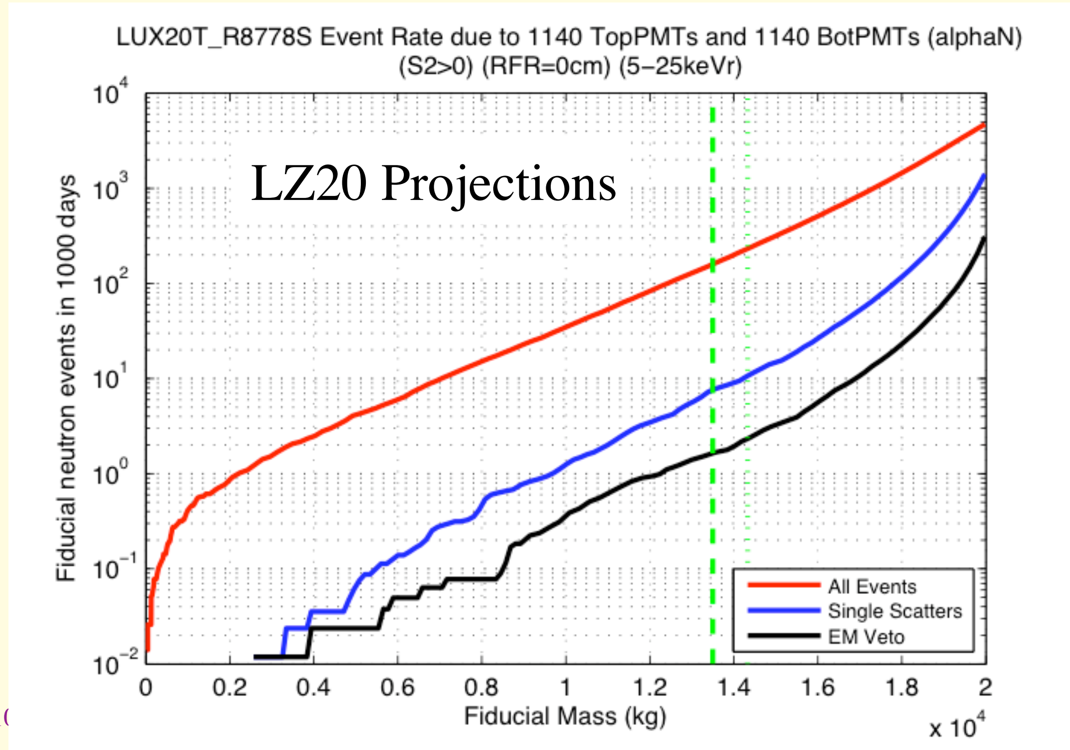
Effective for detectors large compared to ~10 cm gamma penetration distance: few 100 kg and up.



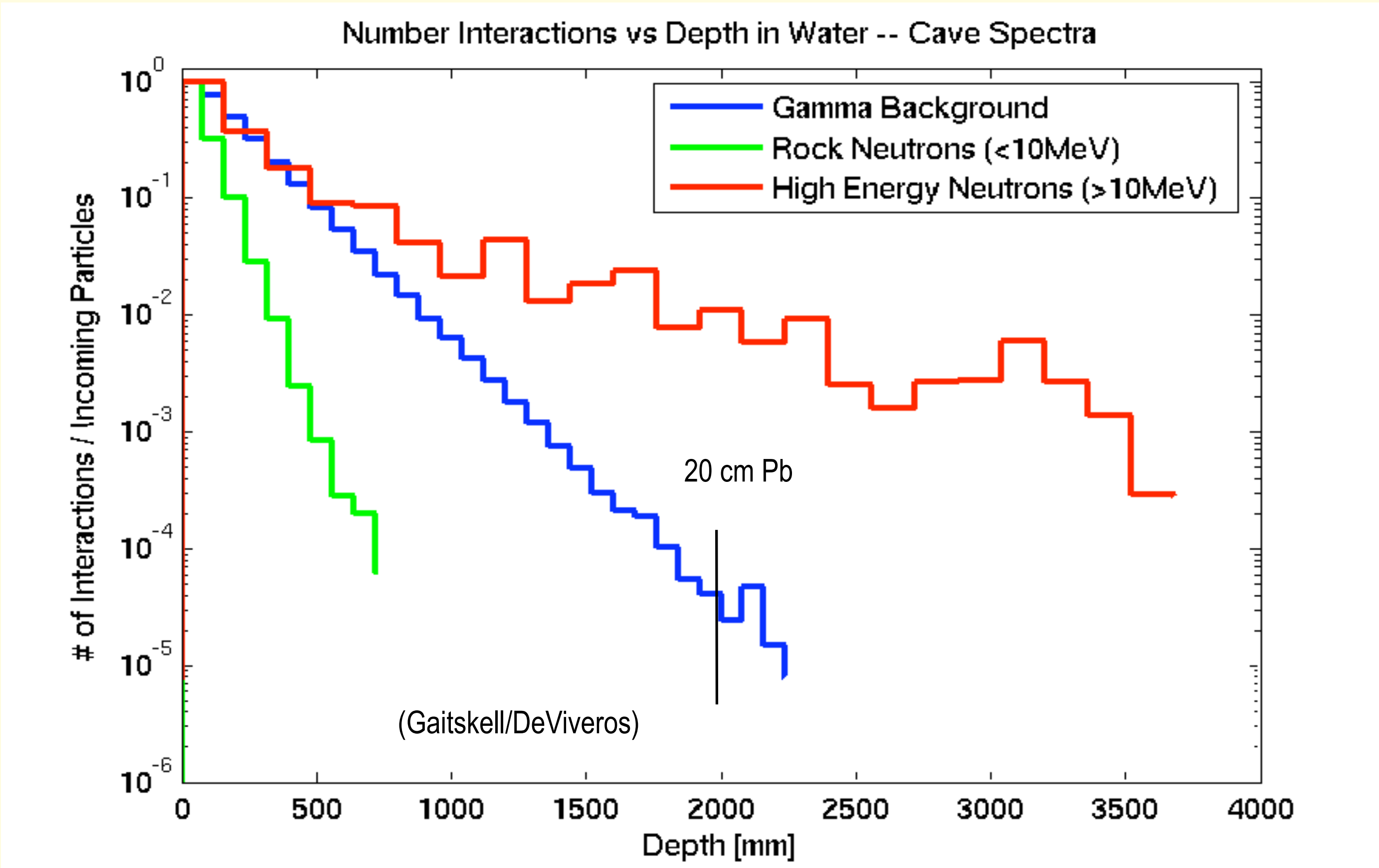


Internal Neutron Backgrounds

- (alpha,n) and fission neutrons, mostly from PMTs
- Most multiply scatter - cut in TPC
  - Also capture gammas
- 13 ton fiducial with conservative PMT baseline
  - Working towards ~10-fold improvement
- Active tagging in outer shield: 100-fold improvement(?)



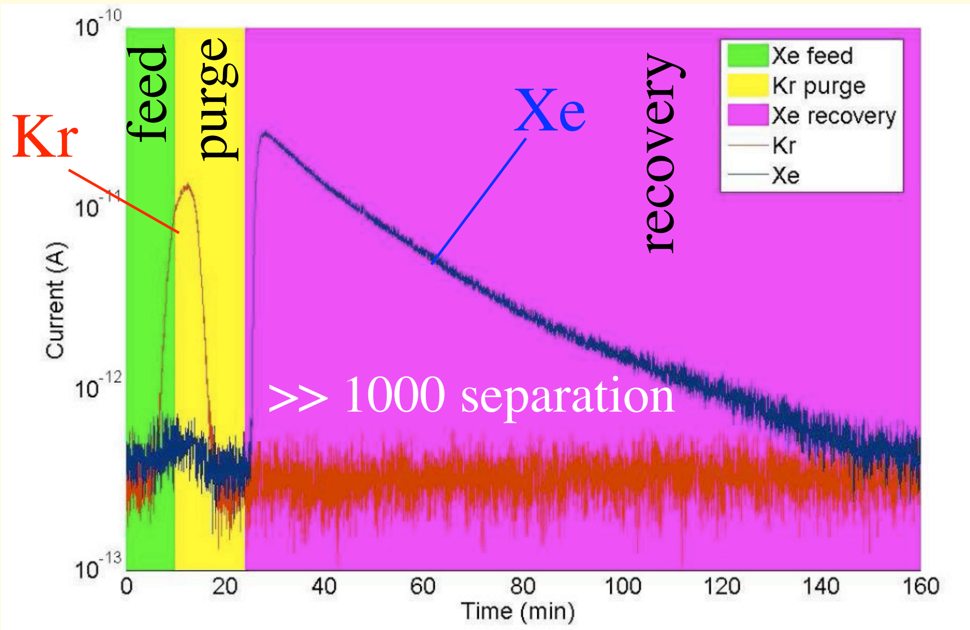
Large-scale water shield

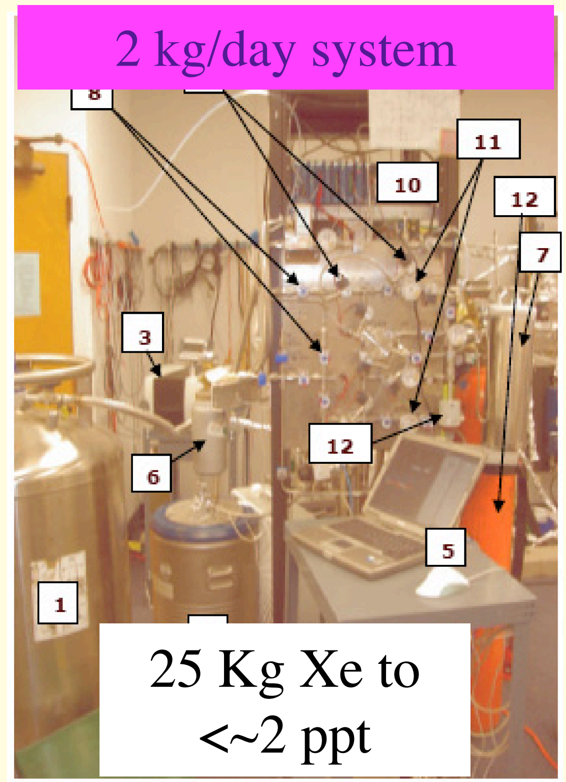


- Lowest-known background shielding material
- Very effective for high energy neutrons
- Cherenkov muon veto
- Economical scaling to very large size.

Internal backgrounds

- ^{85}Kr - beta decay
  - Goal for 20 tons scale: 10^{-14} Kr/Xe.
  - Chromatographic system: < ~2 ppt to date

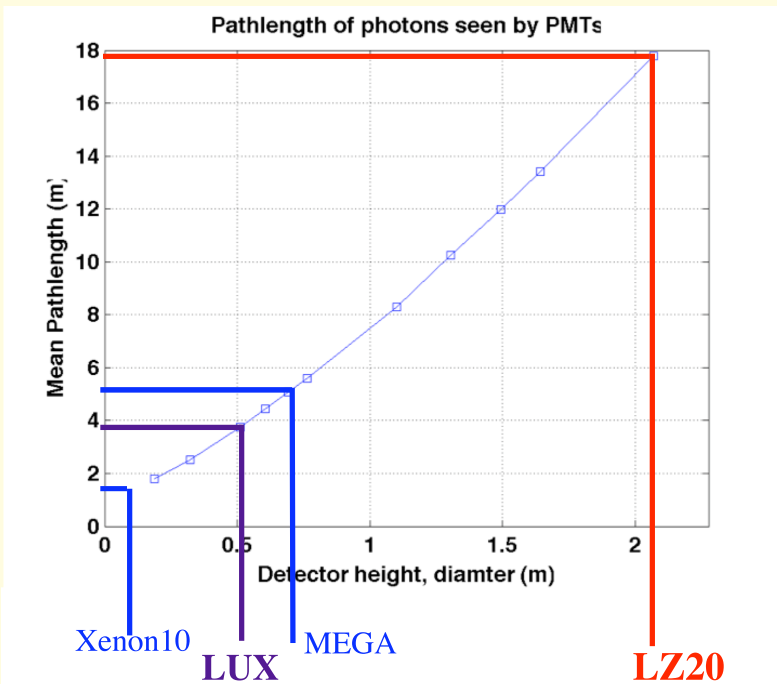




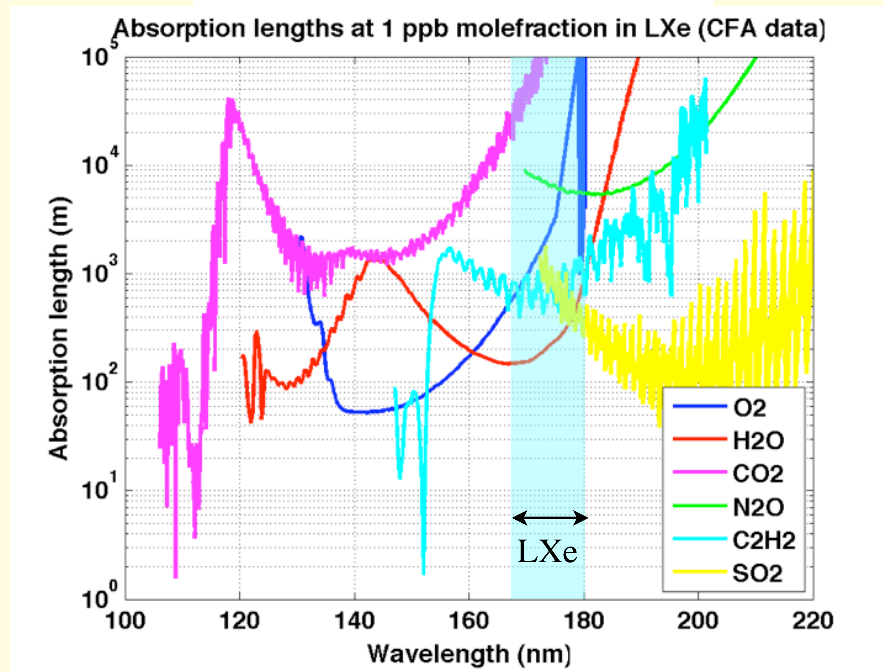
- Rn: require ~ < mBq total.
- Other gasses: ^{3}H, ^{14}C. Should be manageable.
- Xe: much easier to purify than water (SNO), liquid scintillator (Borexino).

Light collection at the 20-ton scale

- Rayleigh scattering: Not yet dominant
- PTFE walls: extraordinarily reflective at 175 nm (7eV)
  - 98% or greater: "mirrored box"
  - Need systematic, reliable measurements
- Absorption on common gasses (primarily 0_2, H_2O)
  - Need ~0.1 ppb, comparable to requirements for charge drift
- Purification is primary challenge



0.1 ppb: 1 km => 2% loss

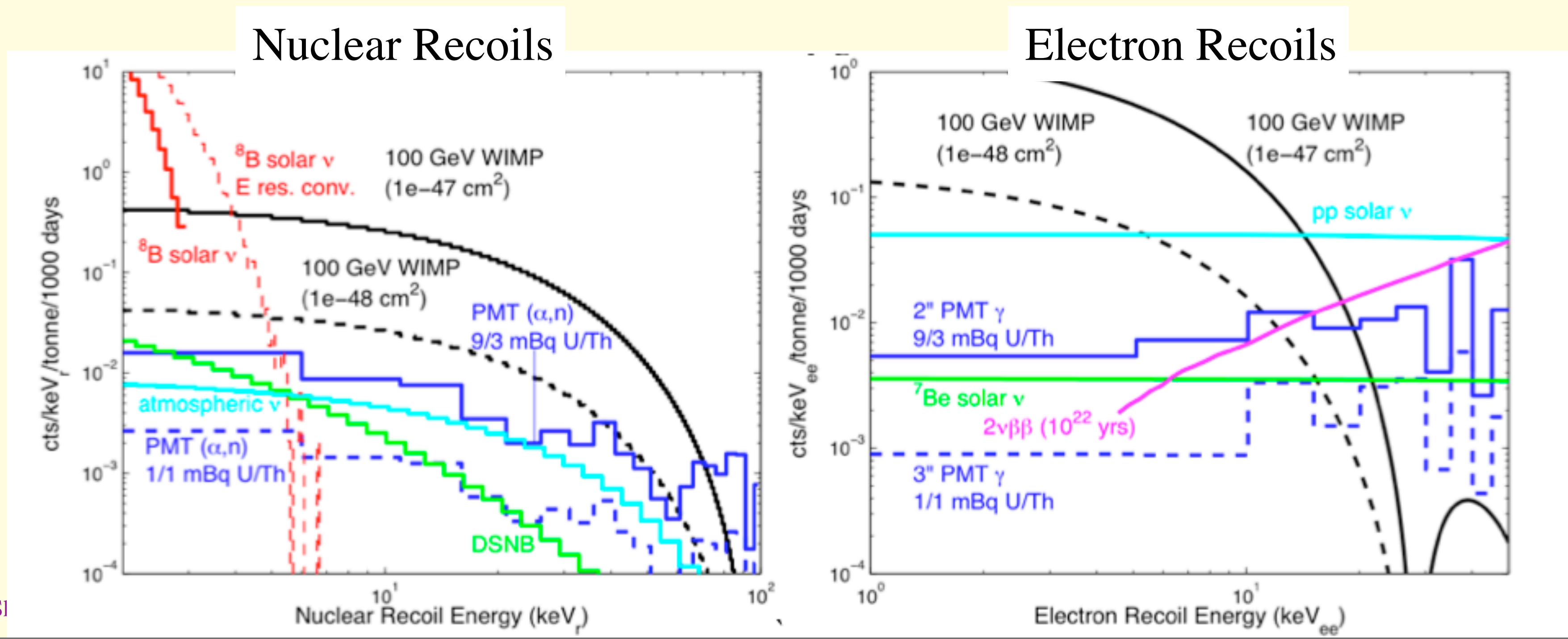


Challenges for 20 tons

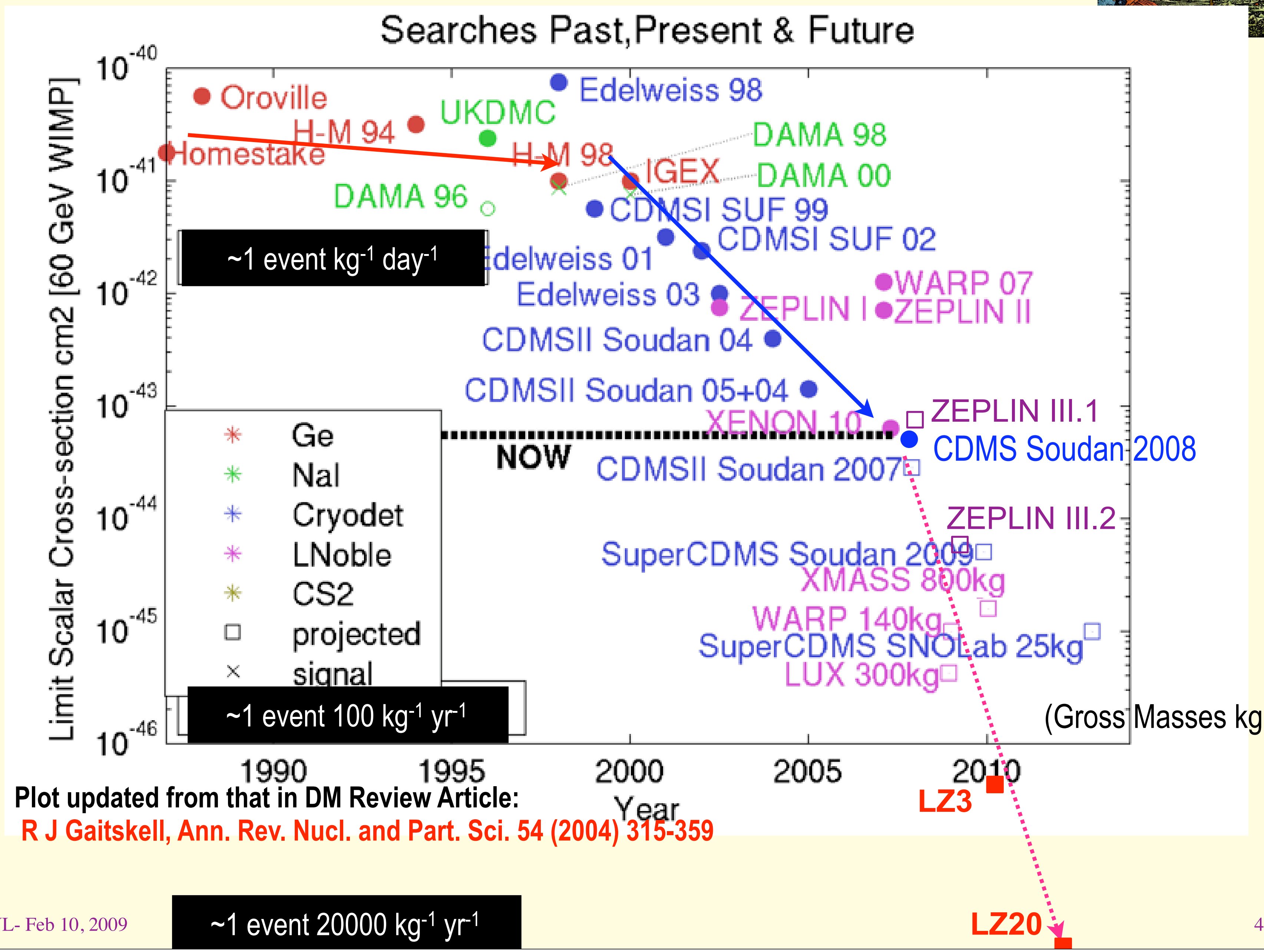
- Purity: Charge and light collection
  - Need focussed program, similar to FNAL LAr effort
  - Cryogenics and purification methods
- Enhanced radiopurity requirements, Rn, Kr.
  - Near state of the art for neutrino experiments (SNO, Borexino).
- Active scintillator outer shield
  - Goal - 99% neutron, 90-99% gamma tag: increase fiducial mass to ~90%.
- High voltage: improved discrimination at 500-1000 kV?
- Mechanics, safety
- Application of proven principles, but need development for 20 ton scale.
  - Need high level of assurance for positive dark matter detection
  - Opportunity for significantly increased detector performance.
- Xe procurement.
  - World production ~45 tons/year

Backgrounds and Sensitivity

- Electron recoil signal limited by p-p solar neutrinos
  - Subdominant with current background rejection.
- Nuclear recoil “background”: coherent neutrino scattering
  - ^{8}B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
- LZ20 reaches this fundamental limit for direct WIMP searches



LZ20 in Context



Plot updated from that in DM Review Article:

R J Gaitskell, Ann. Rev. Nucl. and Part. Sci. 54 (2004) 315-359

Other physics

- Double beta decay of ^{136}Xe.
  - Requires very low radioactivity
  - Enhanced by isotopic separation
- Solar neutrinos
  - With isotopic Xe separation, can measure pp and ^{7}Be full solar spectrua above 1 keV.
  - Very accurate rate determination
- Coherent neutrino scattering: not yet measured
  - ^{8}B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
  - Depending on discrimination, could envision larger mass.

- Something unexpected in next 4-5 decades of cross section?

Conclusion

- Dark matter science compelling
- With LXe, we now have the tools to either detect or strongly disfavor weakly interacting dark matter.
- LZ20 will reach the irreducible neutrino limit.
- Direct search for dark matter is natural complement to LHC.
- LZ20 is ideal flagship dark matter experiment in ISE
- We believe this is a very good opportunity for LBL