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A Xenon Bubble Chamber for Direct Dark Matter Detection

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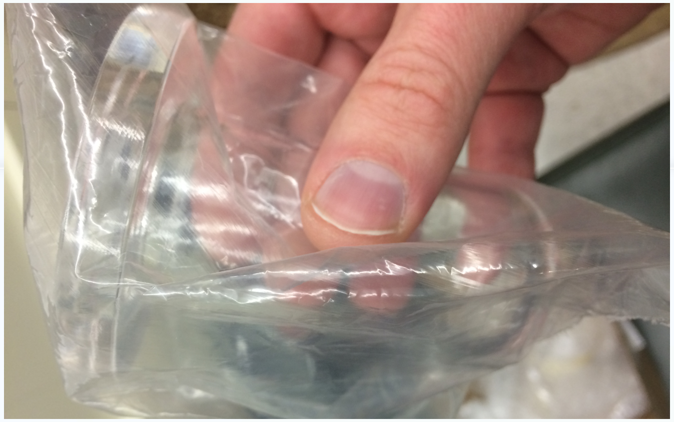


A Xenon Bubble Chamber

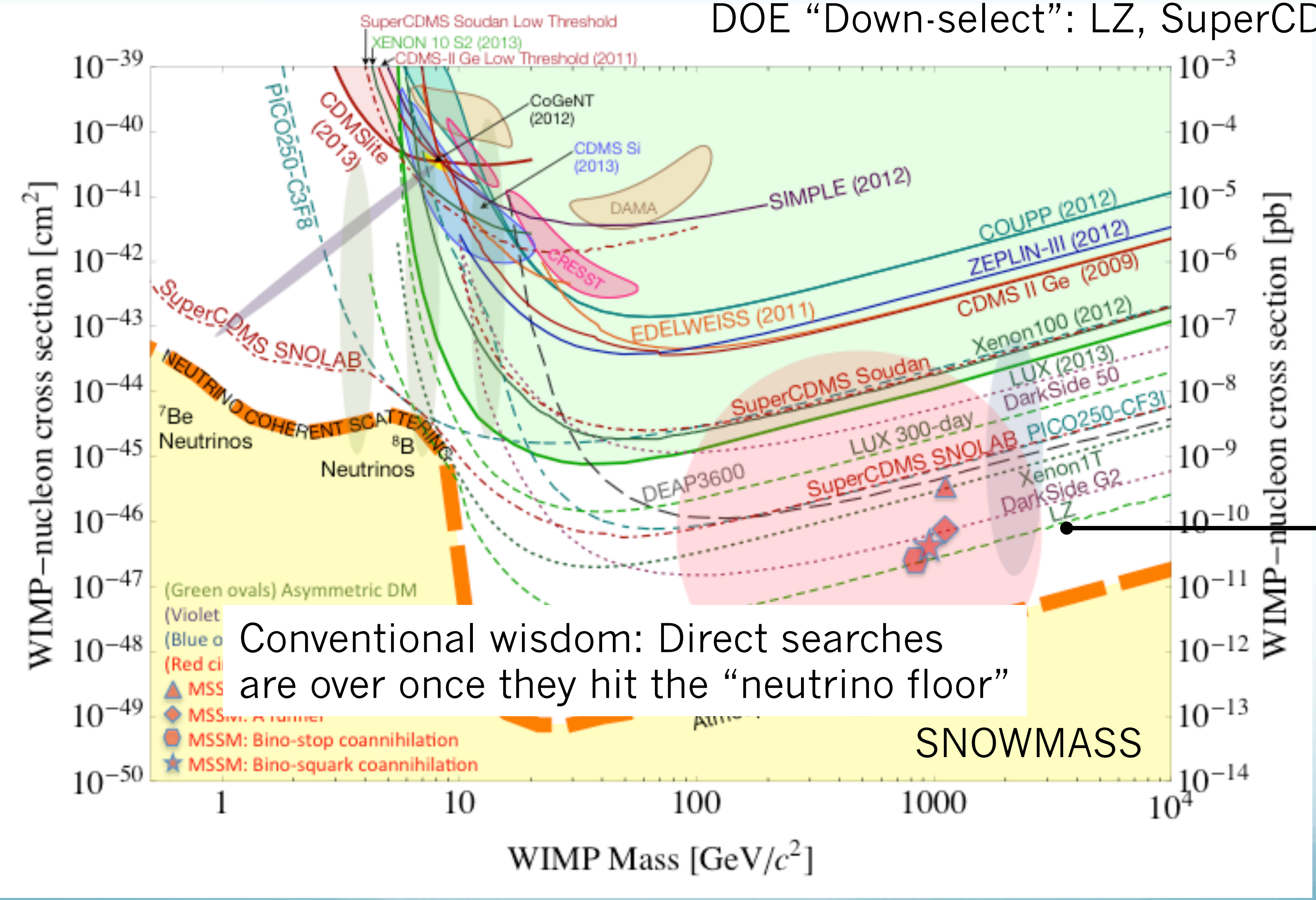
For Direct Dark Matter Detection

Matthew Szydagis
The University at Albany

Friday Colloquium 01/30/15

Direct WIMP Detection Saga

DOE "Down-select": LZ, SuperCDMS

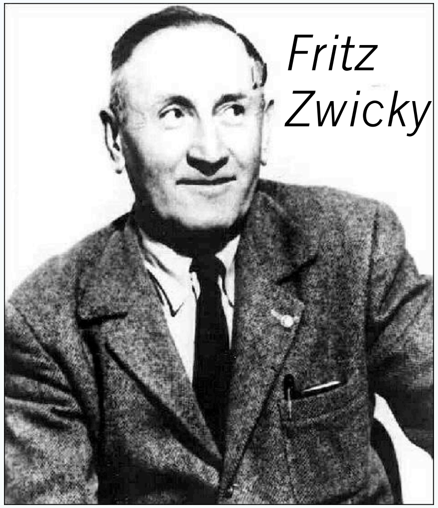


LZ, 1000 days X 5600 kg

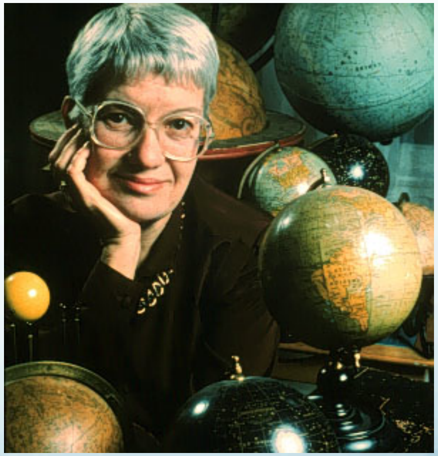
2017 turn-on

Historical Perspective

- In 1933 Swiss astronomer Fritz Zwicky discovered that there was "insufficient" luminous matter in the stars of the Coma cluster
- Conclusion based on looking at the kinetic energies of galaxies
- Coined the term "dark matter"
- In 1950 American astronomer Vera Rubin found a new piece of the puzzle: intragalactic rotation curves
- Today - wealth of indirect evidence, but **conclusive** detection elusive



Fritz Zwicky



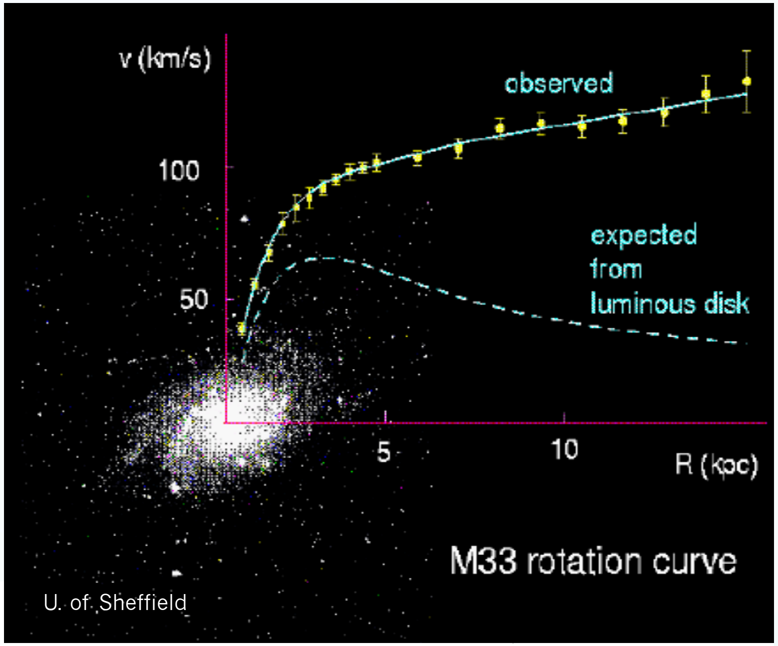
Vera Rubin

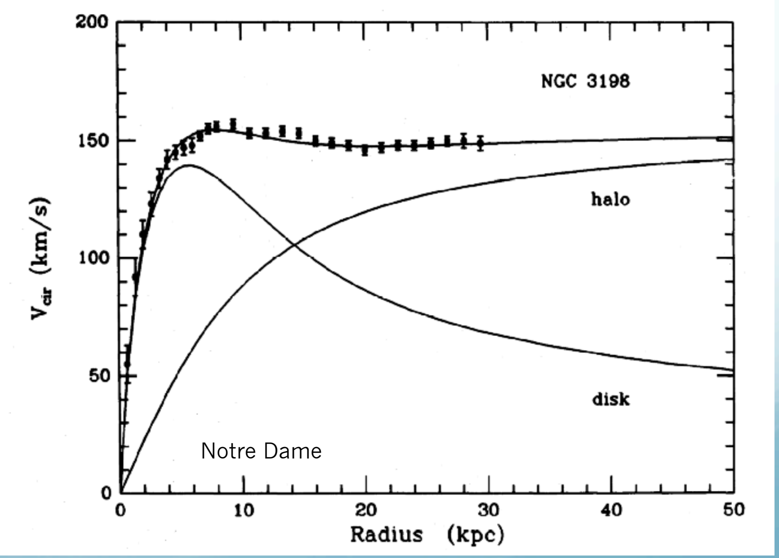
Rotation Curves

- Galactic rotation curves consistently exhibit unexpected behavior
- Intragalactic rotational velocities gravitationally consistent with there being more matter than is visible in the stars

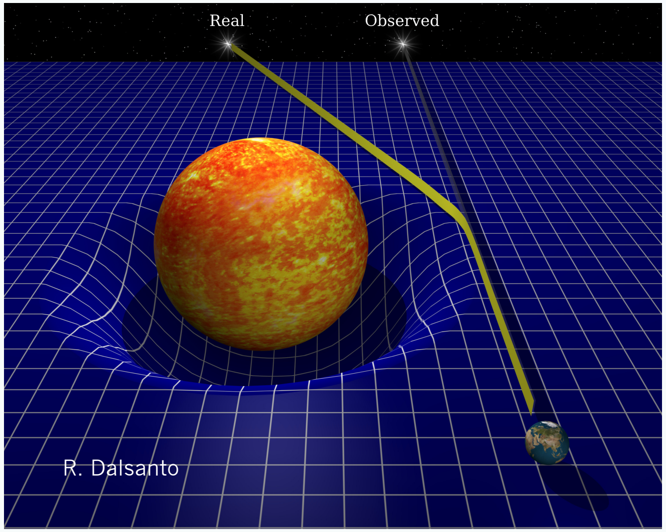
$$F = \frac{GM_\odot m}{r^2} = \frac{mv^2}{r}$$

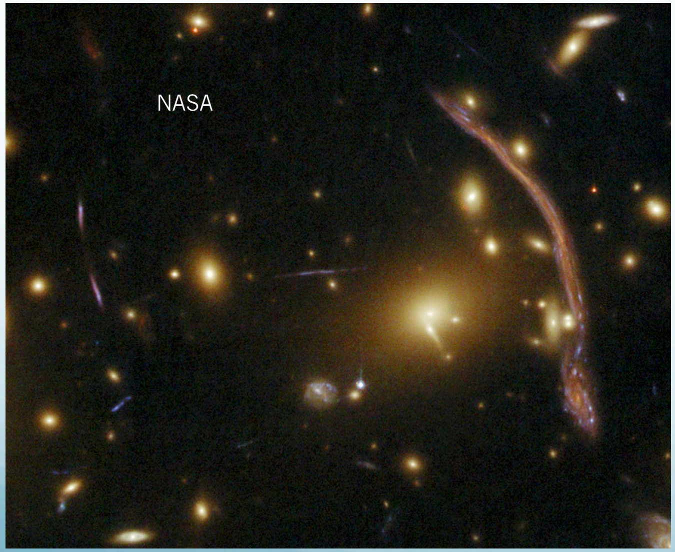
$$v = \sqrt{\left(\frac{GM_\odot}{r}\right)}$$





Gravitational Lensing





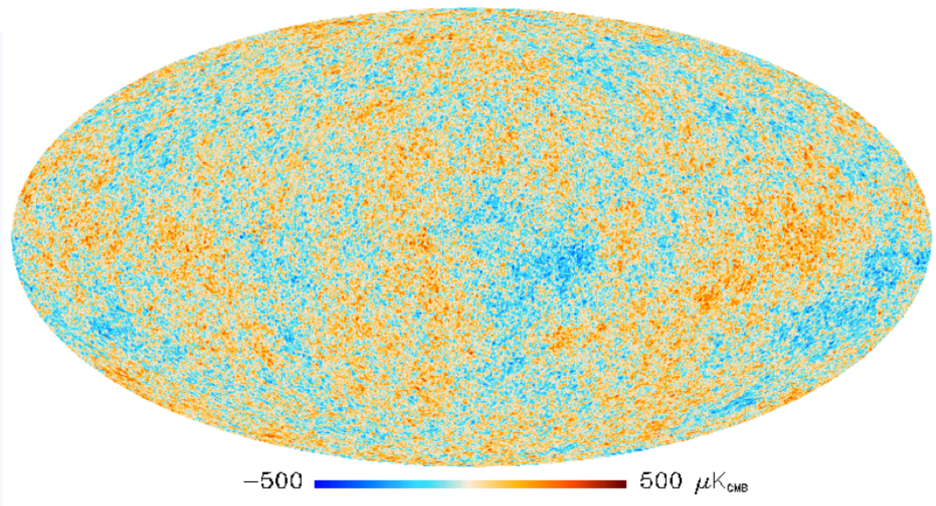
- Gravitational distortion of light by matter enables a calculation of the mass of the matter doing the distorting
- Predicted by Einstein (general relativity) and first hint observed during a solar eclipse in 1919, but not as a galactic-scale lens until 1979
- Gravitational lensing studies concur with the rotation curves

Baby Bullet Cluster

- Hot x-ray emitting gas in red superimposed on image
- Probable dark matter in blue (mapped via gravitational lensing study)
- Galaxies collided but dark matter evaded

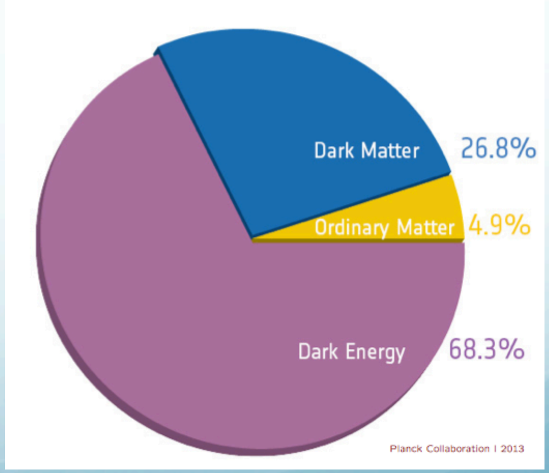
Cosmic Microwave Background

- CMB is an "echo": snapshot from 370,000 years after Big Bang, when photons and the plasma decoupled
- CMB favors model where 27% of energy content of universe is in matter, but non-baryonic particles
- Best fit for explaining the angular power spectrum of the temperature anisotropy

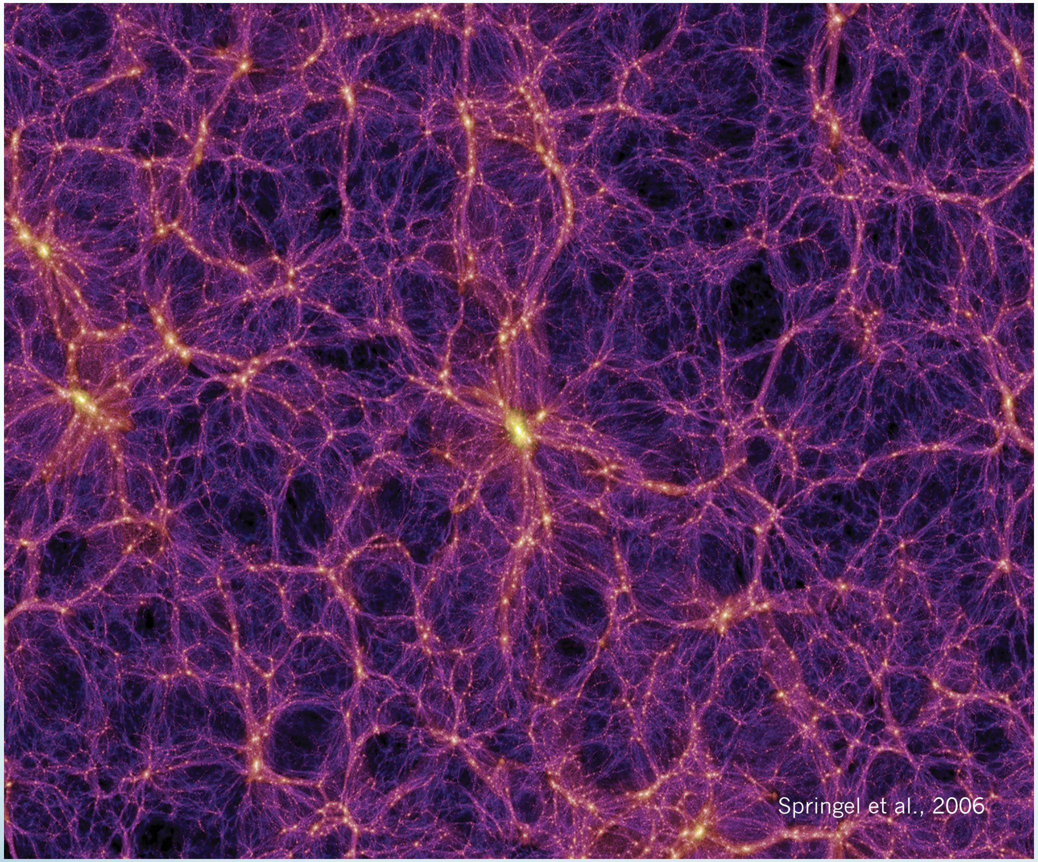


Planck collaboration 2013

Standard Cosmological Model



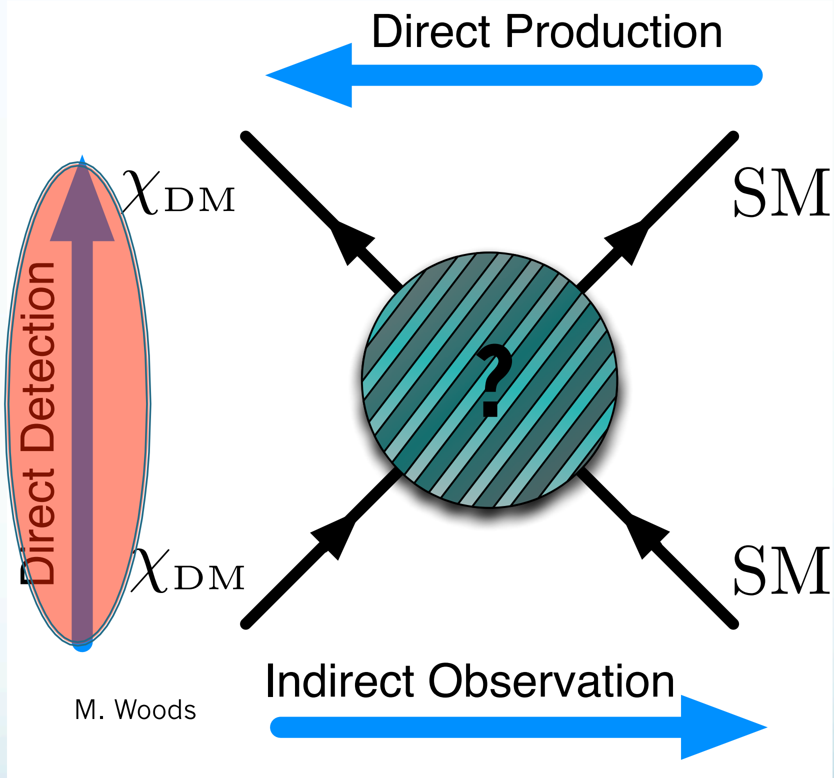
Large-Scale Structure



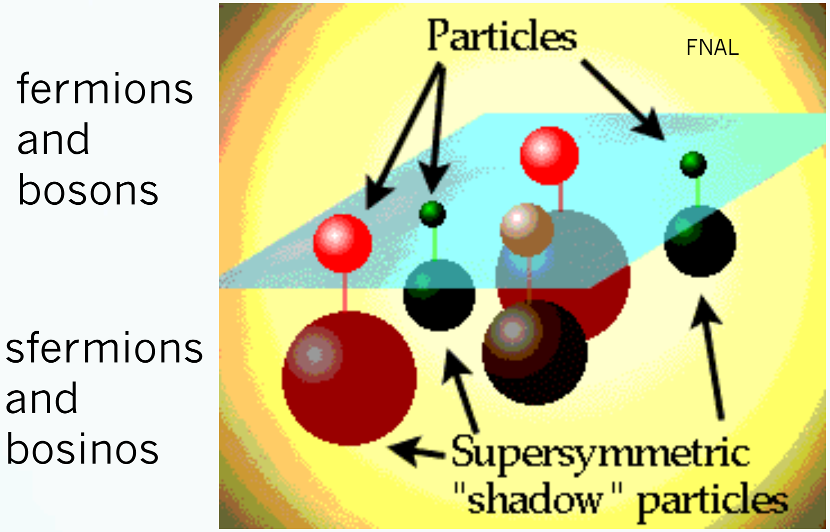
- Observations (baryon acoustic oscillation, galaxy clusters) and simulations agree well when the presence of *cold* (non-relativistic) dark matter assumed
- Need dark matter to interact weakly (as in rarely -- not necessarily via the weak force), mainly gravitationally

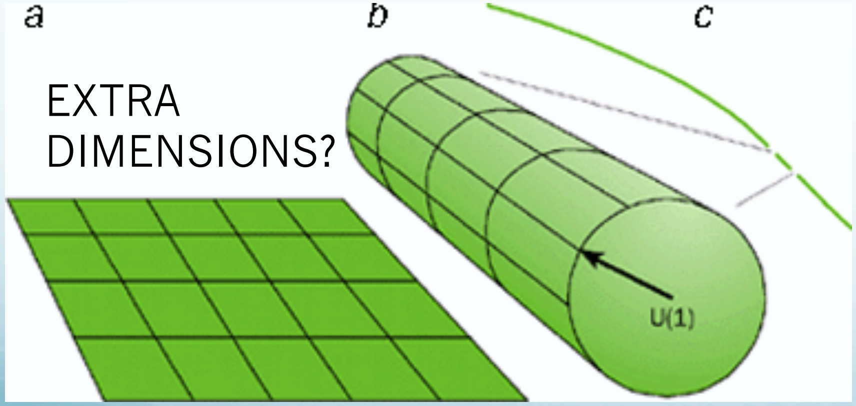
Strategies for Detection

- Indirect detection of dark matter (DM) self-annihilation into Standard Model (SM) particles (γ 's or ν 's)
- Direct detection
- Production of dark matter particles from the high-energy collisions of a particle accelerator (LHC)



Candidate Particles

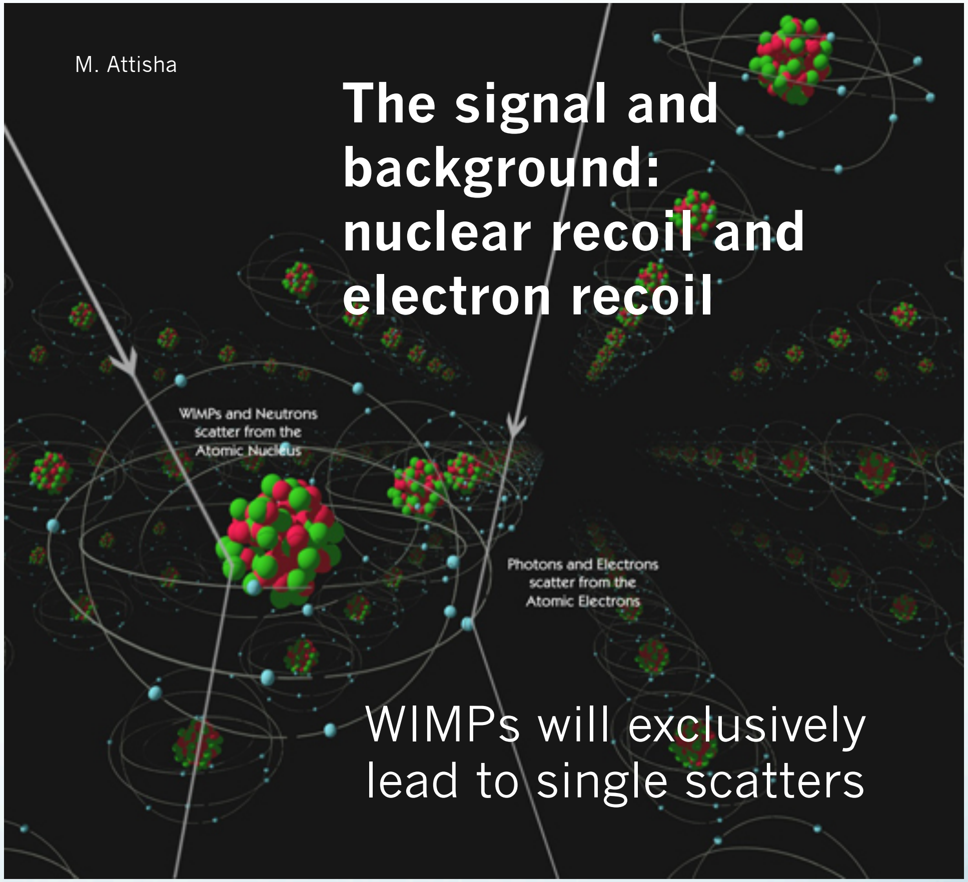




- The WIMP, or, the Weakly Interacting Massive Particle = vanilla candidate
- But, no Standard Model particle has all its traits
  - Cold/non-relativistic (so, must be heavy)
  - Can't be baryons (would result in disagreement with CMB measurements)
  - Interacts very "weakly"
  - Stable, or very long-lived
- Supersymmetry or Kaluza-Klein theory (higher dimensions) => WIMPs

Direct Detection Method

- Most searches are geared toward finding WIMPs, in a model-independent fashion
- In most WIMP models, WIMP-nucleon scattering cross-section is dominant
- Experiments deployed underground, because depth reduces cosmic ray background



Low-energy nuclear recoils (NR) are expected from WIMPs, and electron recoils (ER) constitute background (BG) one must avoid misidentifying as NR

Response of a Detector

- Atoms can be excited and scintillate and/or be fully ionized by NR/ER
- Recoils can also cause lattice vibrations
- Recoiling species can boil superheated liquids
- Oftentimes searches combine two methods
- Given rare interaction, figure of merit = target mass X exposure

Current Paradigm

CoGeNT

IONIZATION or CHARGE

(LEADER AT LOW MASS; ONE OF EARLIEST EXPERIMENTS)

(CURRENT LEADER IN SENSITIVITY)

LUX

CDMS

SCINTILLATION or LIGHT

CRESST

DAMA

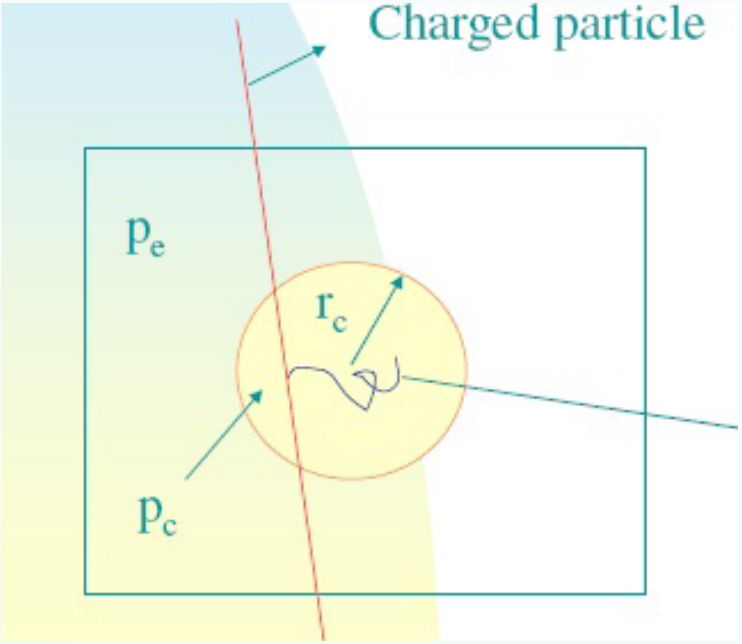
PHONONS or HEAT

PICO (=COUPP*+PICASSO)

Not comprehensive

*For dark matter results from COUPP, see Phys. Rev. D 86, 052001 (2012) and earlier

More Basic Principles



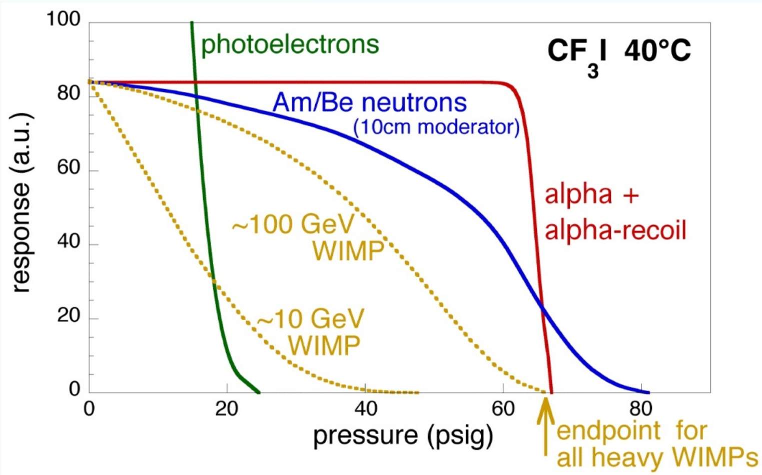
$$E > E_c = 4\pi r_c^2\left(\gamma - T\frac{\partial\gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3\rho_v\frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P$$

$$\mathrm{d}E/\mathrm{d}x > E_c/(ar_c)$$

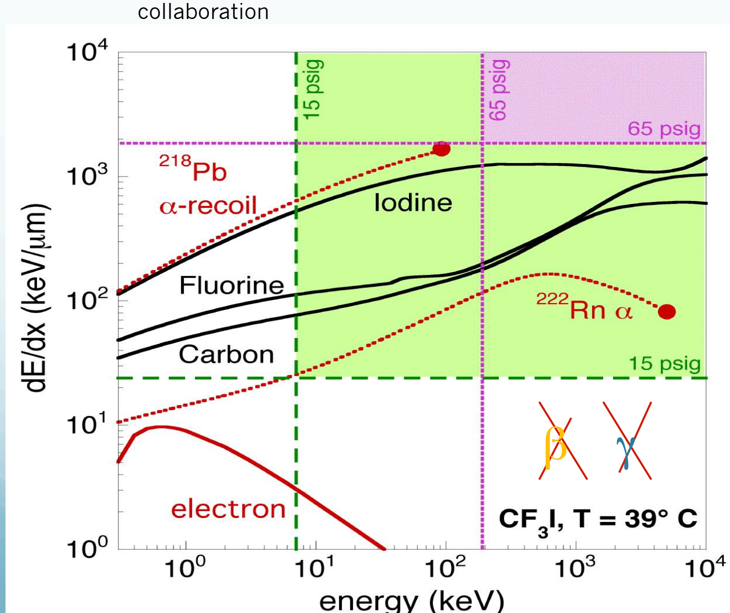
Inherent MIP rejection because of dE/dx threshold

- Ionizing particle leads to δ-rays, which Coulomb scatter and induce local heating
- If incident particle deposits sufficient energy within short distance, protobubble born
- Threshold detector
  - Critical energy
  - Critical stopping power (dE/dx)
  - Thresholds function of temperature, pressure
- Described by Seitz “hot spike” theoretical thermodynamic model of bubble nucleation

Background Rejection

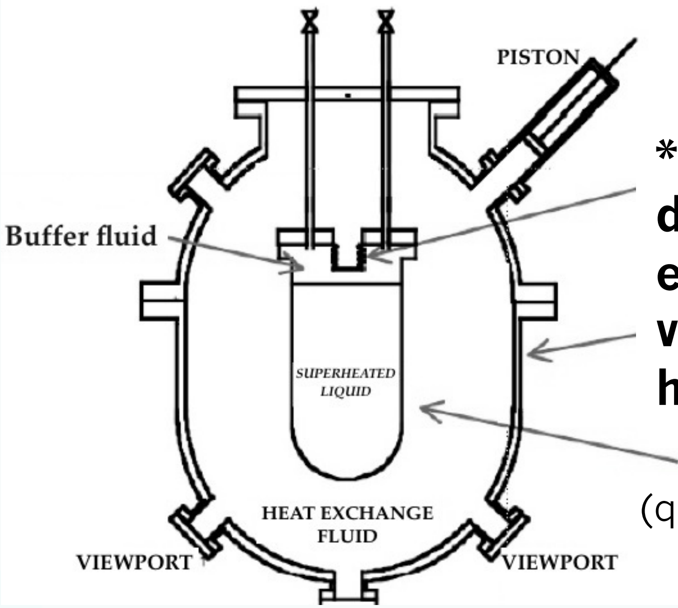


COUPP
collaboration



- A nuclear recoil goes above threshold but not electron
- Alpha emission constitutes flat background: avoid or tag
  - Liquid purification
  - Half-life identification
  - Unique acoustics
- Neutrons are like WIMPs
  - Veto muon-induced
  - Moderate with water shield
  - Main way to calibrate (AmBe, ^{252}Cf, ^{88}YBe, DD gun)
  - Short mean free path

Chamber Design and Operation



(quartz lets UV through)

***Plan for a new design: no external pressure vessel, no hydraulic fluid**

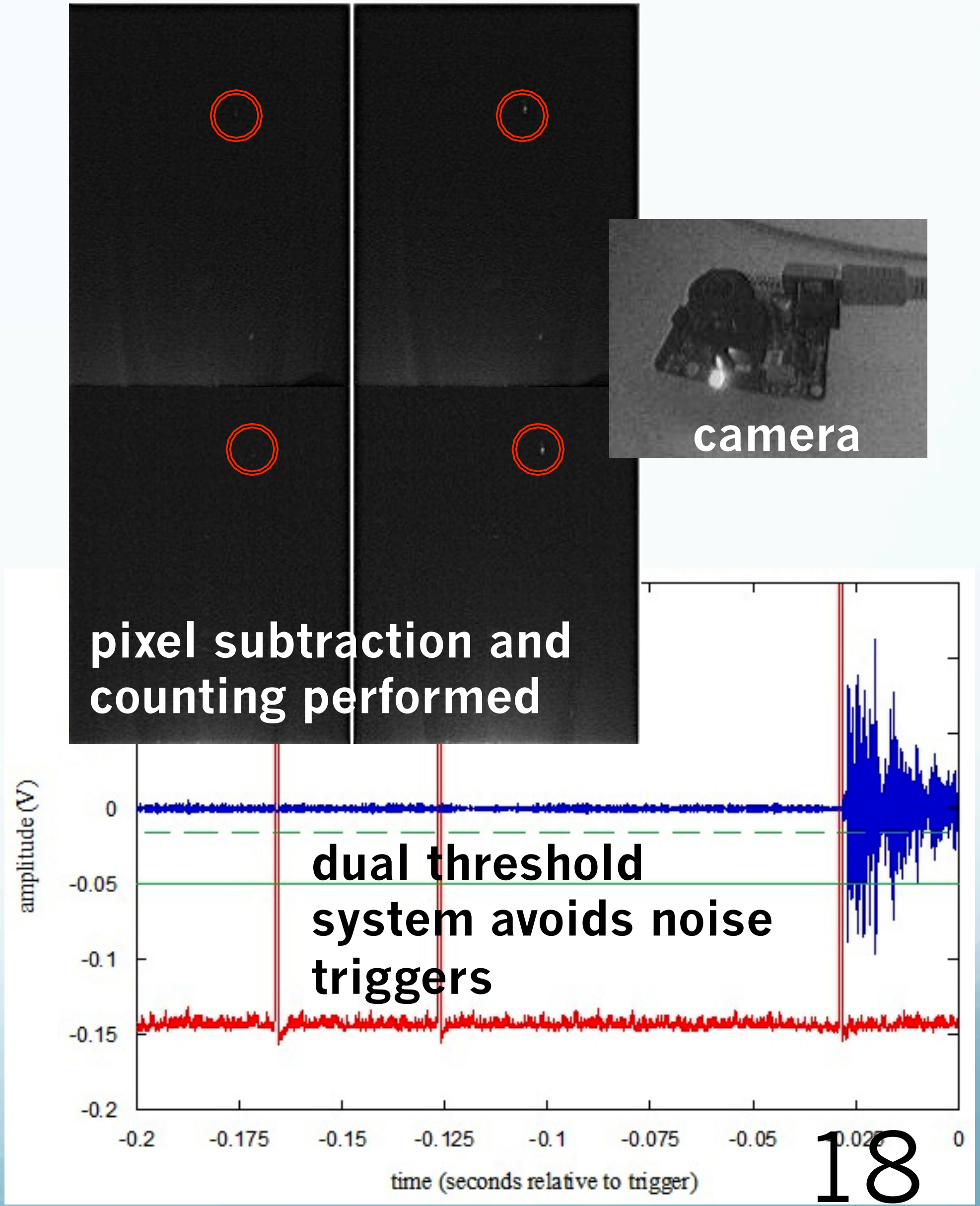
Pressure must quickly be raised above vapor pressure upon bubble detection, to coax bubble to condense.

The vessel with active liquid is placed inside a larger vessel full of a passive hydraulic fluid.

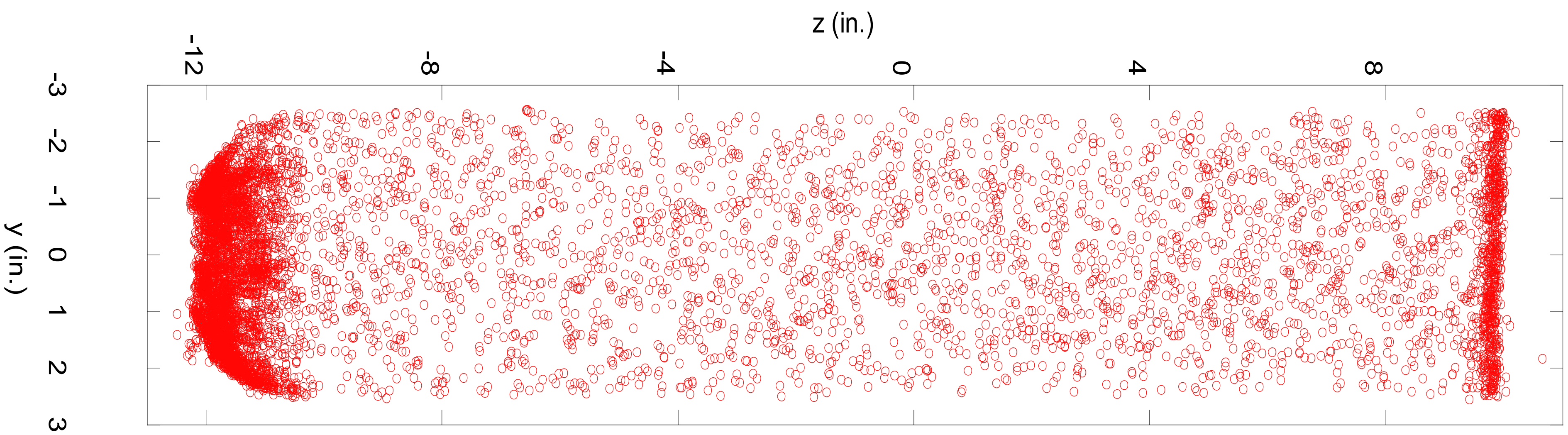
- Temperature is fixed, and a piston is used to control the pressure and thereby determine the threshold
- Piston presses on hydraulic fluid in exterior pressure vessel
  - which presses on a bellows
  - which presses on buffer liquid (something immiscible)
  - which presses on the active fluid

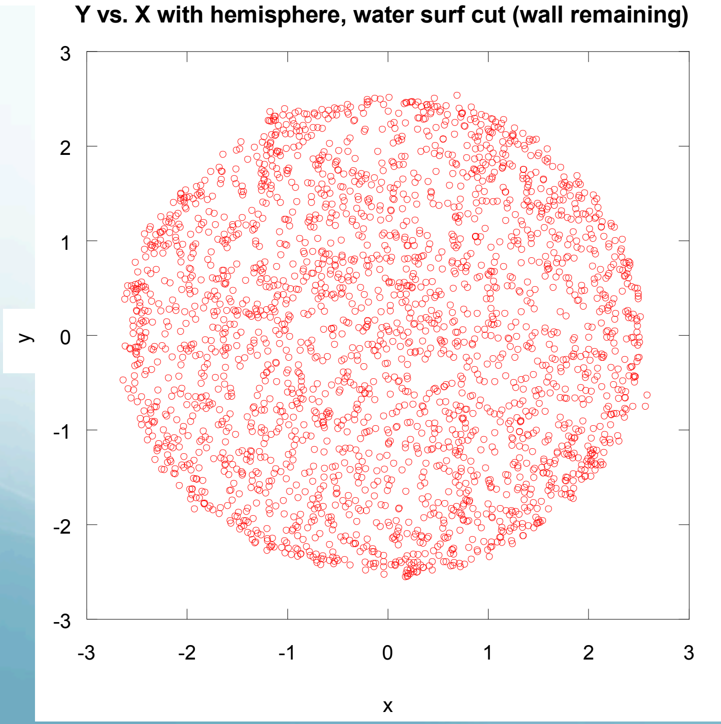
Triggering Mechanisms

- Pressure
  - Less dense and rapidly growing bubble pushes liquid out of the way
  - Less useful in large vessels
- Visual
  - Orthogonal cameras allow for 3-D position reconstruction and easiest disambiguation of multiple bubble events
  - Traditional and primary
- Audio
  - Better primary trigger if cameras slow
  - Instrumental in setting muon veto coincidence window in COUPP



3D Optical Reconstruction





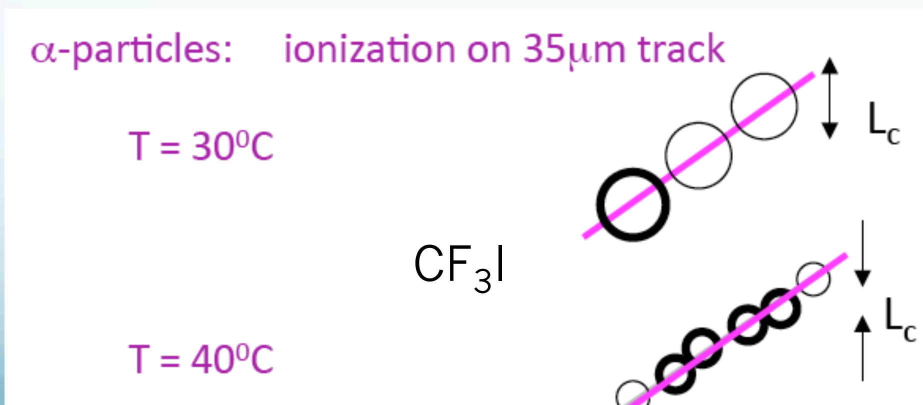
- Example from 15 kg CF_3I device deployed in Chicagoland tunnels
- Thick layer of buffer (water) interface events seen, as in all COUPP detectors, likely from particulates
- Fiducialization is excellent and sub-mm position resolution seen

Acoustic Discrimination

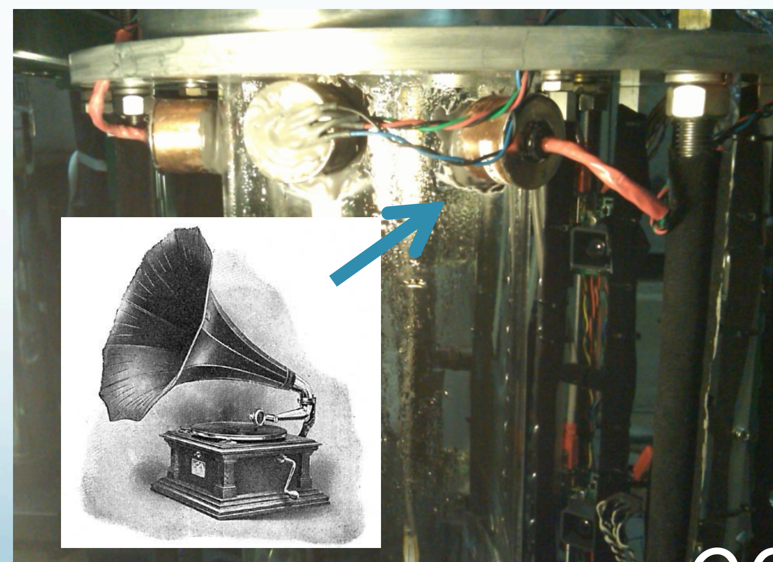
- Use of acoustics, even as trigger, not new idea: Glaser, SIMPLE, PICASSO (SDDs)
- Acoustic energy related to unique distance scale of energy transfer for different particles to the volume

Glaser (1955)

In order to see events more interesting than muons passing straight through the chamber, we took advantage of the violence of the eruption which produces an audible "plink" at each event. A General Electric variable-reluctance phonograph pickup was mounted with its stylus pressing against the wall of the chamber. Vibration signals occurring during the quiescent period after the expansion were allowed to trigger the lights and take pictures. In this way we saw tracks of particles passing through the chamber in various directions,

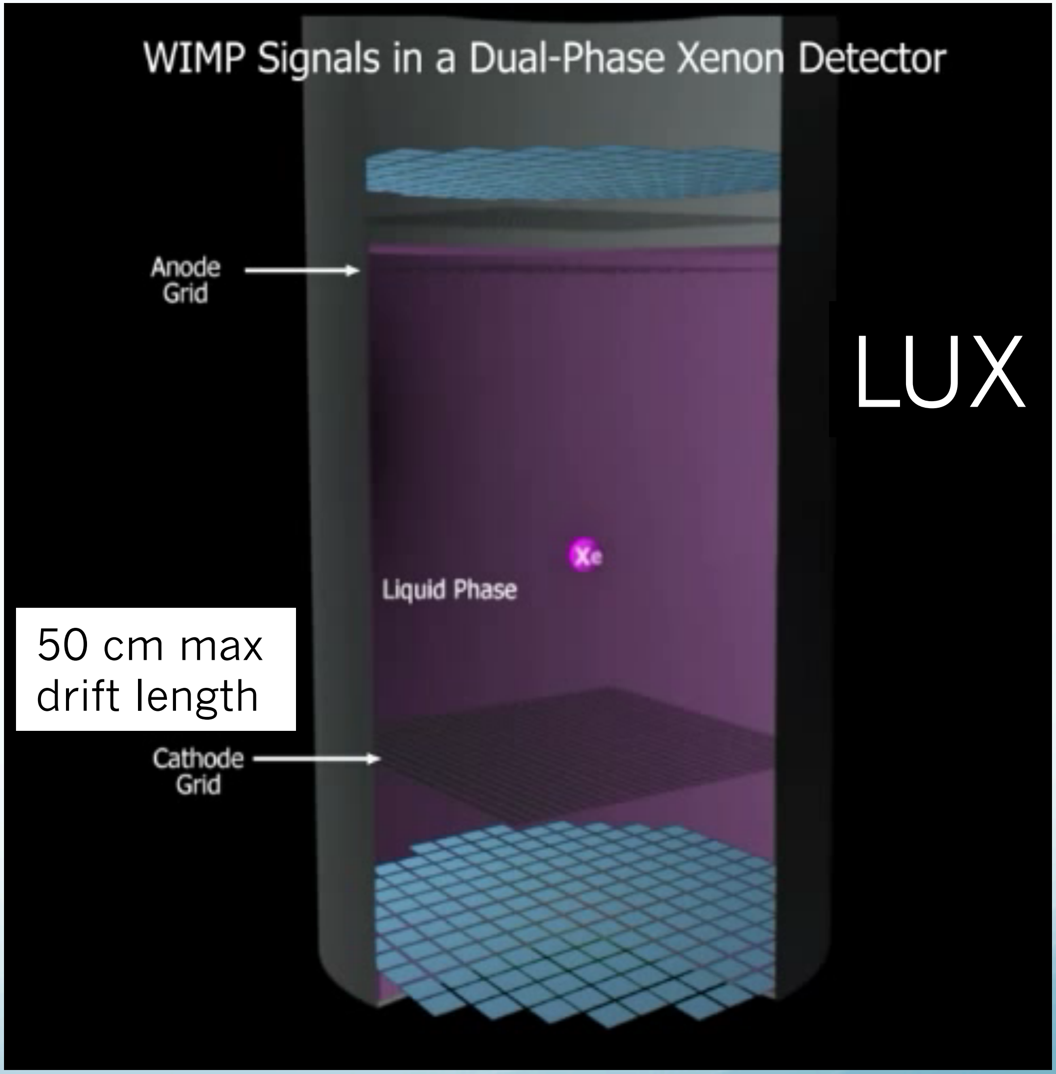


α's capable of creating multiple protobubbles (merge into one) along their dense ionization trails, with each serving as individual sound sources (microscopically)



How a 2-phase Xe TPC Works

- LUX an example of one type of time-projection chamber (full XYZ info), technology invented by D. Nygren at LBNL
- S1 (primary, liquid) and S2 (secondary, gas) scintillation, the latter drifted charge
  - Ratio: charge (via S2)/ light (S1) forms the heart of the NR vs. ER discrimination
- XY fiducialization from the S2 PMT hit map



For the first WIMP search result from LUX, see Phys. Rev. Lett. 112, 091303 (2014)

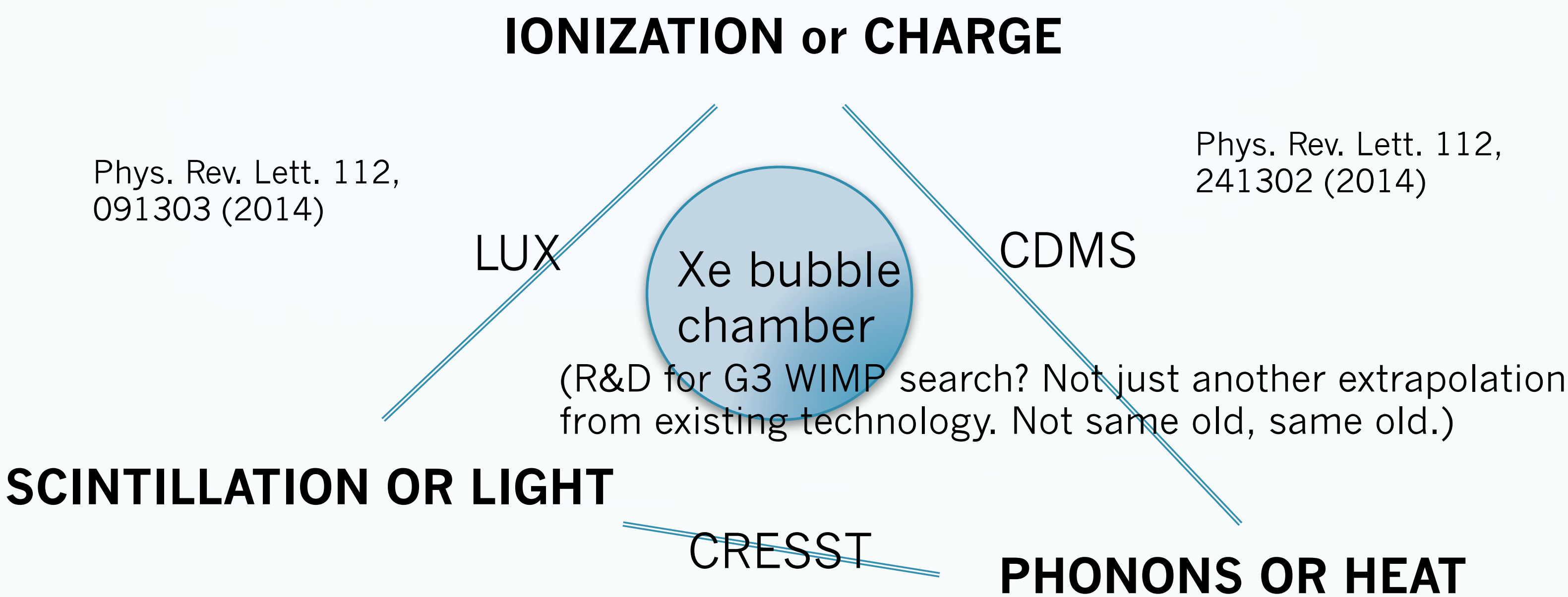
Technology Contrast

- Experiments like PICO blind to ER BGs to better than 1 part in 10^{10} at low superheat, but recoil energy = ??
  - Latter issue overcome with operating pressure or temperature sweep: energy, *dE/dx* thresholds change
  - But, only one channel with which to study signal
- Detector like LUX misidentifies ER as NR with a 1 in 10^2-10^3 chance but *has* event energy reconstruction
  - Mis-ID issue surmountable with low-BG construction
  - High density of liquid xenon provides excellent self-shielding of not only alphas, but gammas
- Xenon-based experiments (XENON, ZEPLIN, LUX) leading the field for better part of a decade to date

But is that the whole story? NO.

- Why not merge these two technologies and have BOTH energy reconstruction AND fantastic rejection of electromagnetic backgrounds? Each technology has something crucial for discovery which the other lacks
- A xenon bubble chamber was attempted successfully in the past, and was thought not to work originally, because energy lost into scintillation instead of bubbling
  - Scintillation intentionally quenched PhysRev.102.586
  - Not the right thing to do for a dark matter experiment. Not seeing gammas is a strength, not a weakness!
- Xenon could be first of many liquid noble chambers: confirm signal. Everything turns into a bubble chamber if you go low enough in pressure and/or hot enough

Paradigm Shift



- Unprecedented attempt at capturing all 3 dimensions of discrimination. (Start simple though: light and heat, no field)
- The people thus far
  - Eric Dahl, Northwestern University and FNAL
  - Matthew Szydagis, University at Albany SUNY
  - Hugh Lippincott, FNAL
  - Michael Crisler, FNAL

Are funded to do it RIGHT NOW

And I already have detector parts coming in.

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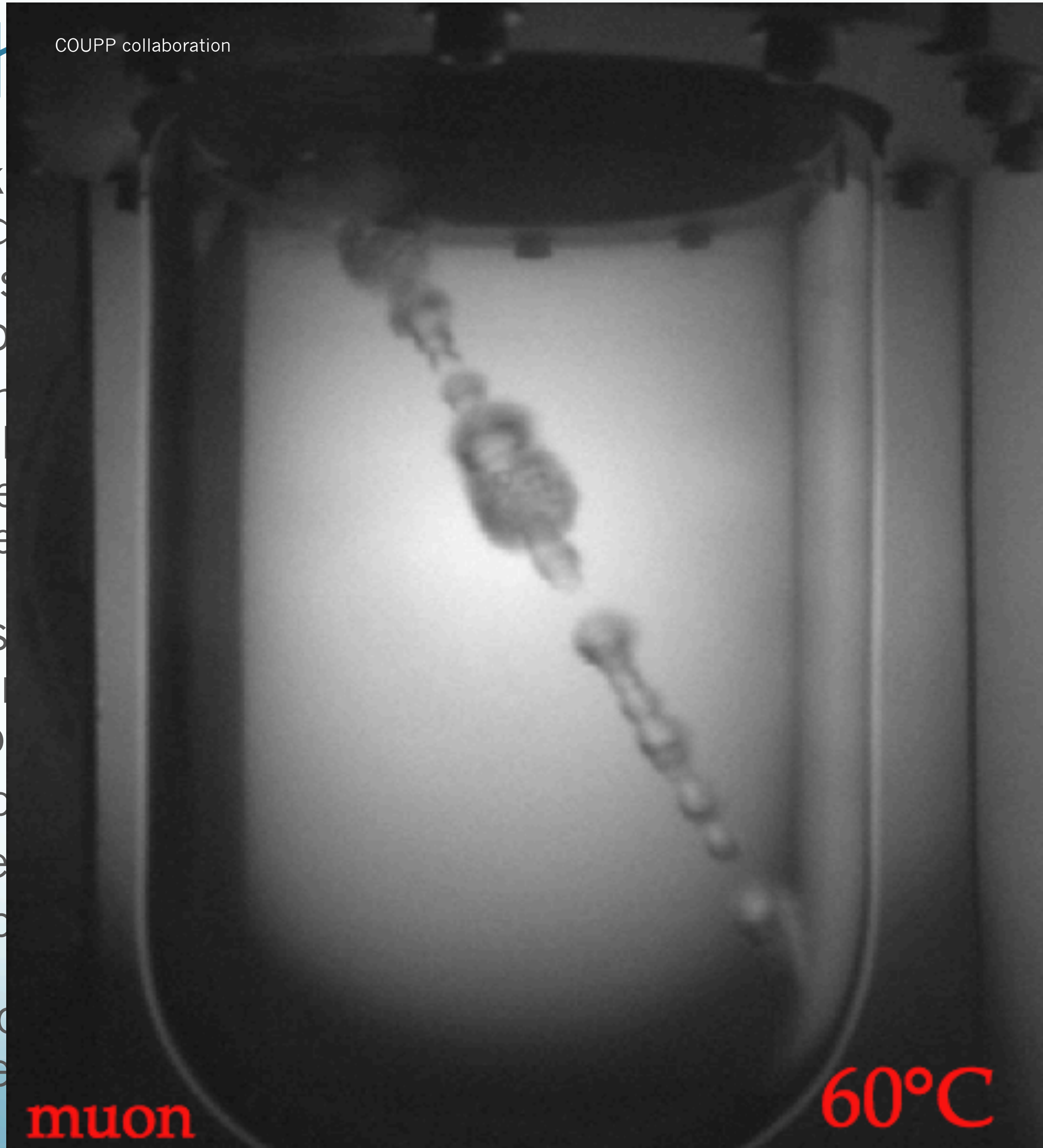

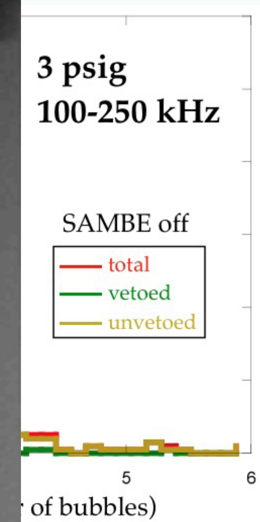

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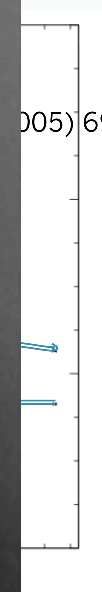

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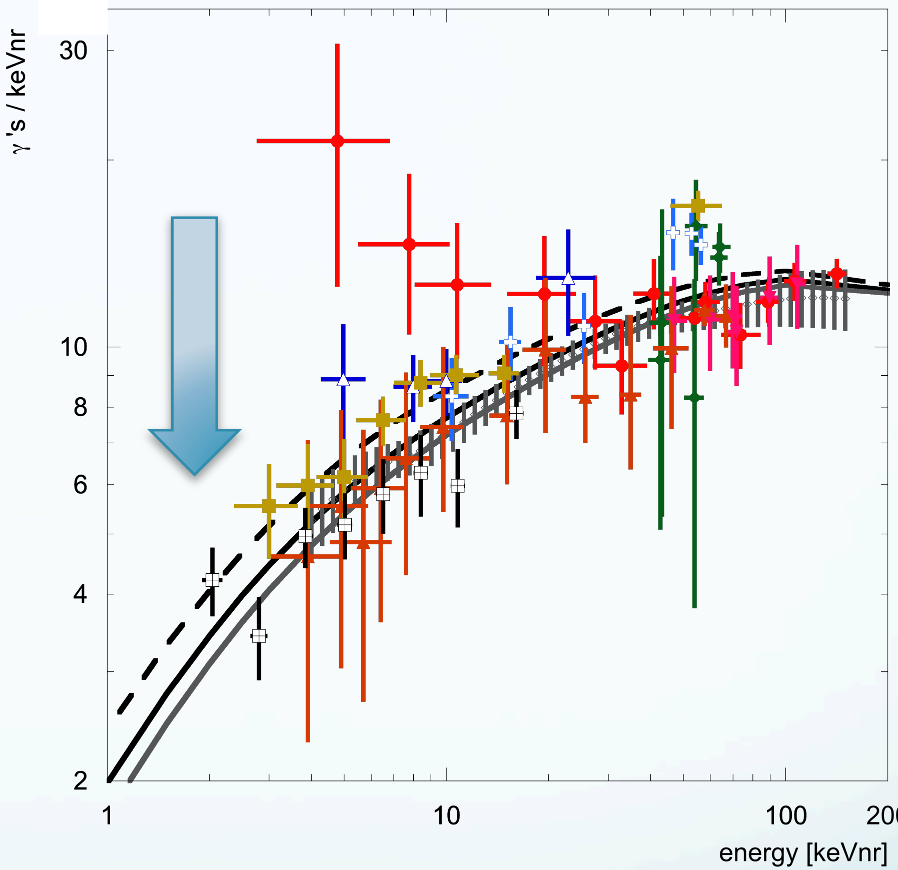
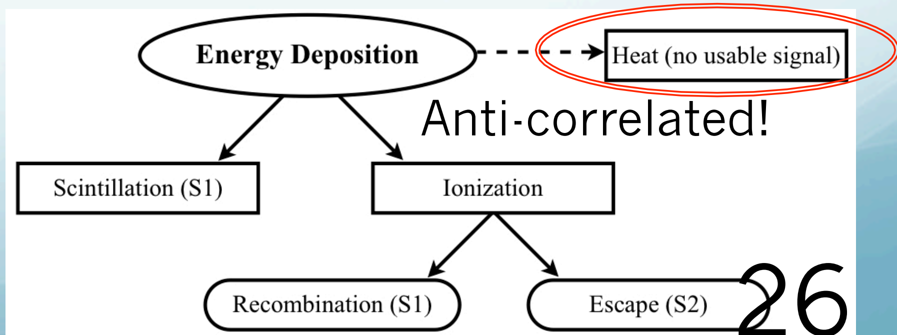
Another Advantage

- Bubble chamber turns "disadvantage" of Xe into an advantage: decreasing NR S1 + S2 at low energies means more energy is going into heat
- And heat means bubbles, in a superheated system
- In theory, almost no limit to energy threshold: keep lowering pressure and raising temperature – at the cost of worse ER misidentification, but one can start at orders of magnitude better than LUX: start at PICO levels



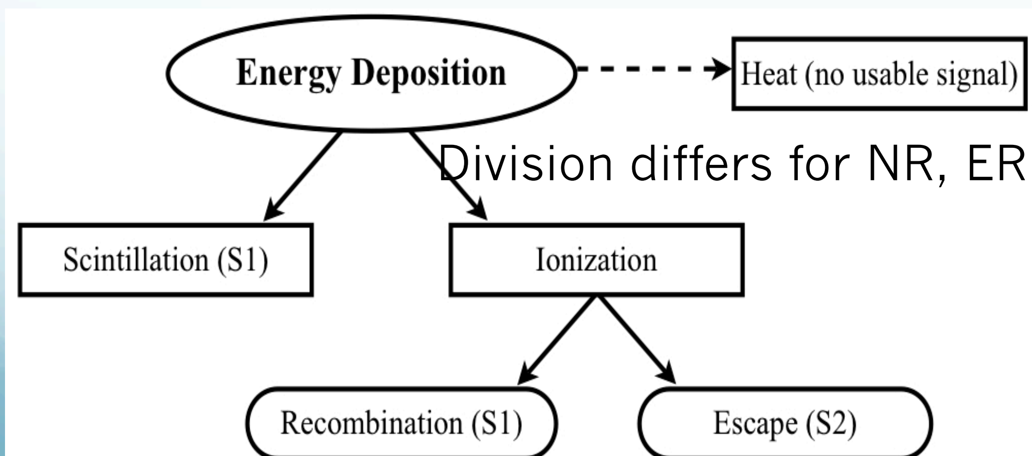


Building Smarter, Not Larger

- There is still a lot of parameter space, especially at sub-GeV WIMP masses, where the thresholds of Xe-TPC-based experiments force an inevitable turn-up in limits
- Larger detectors must have greater turn-up: cannot push reflectivity and purity much more
- Probably no $$ for another step past 7-ton LZ. Need to built smarter, not bigger/costlier. Lack of discovery does not mean stop looking. There is cause for optimism!
- S2-only can take you only so far: discrimination is lost, so how can a conclusive discovery be made?
- Low-mass WIMP controversy is not likely to go away any time soon, even if experiments like LUX appear to rule such a WIMP out. Must consider concordance of others (CoGeNT, CDMS, CRESST, DAMA)

Understanding Xenon Physics

- Energy deposited in 3 channels; "heat," prominent for NR, reduces light (S1) and charge (S2) compared to ER
- Excitation and recombination lead to S1, while escaping ionization electrons lead to S2
- Scintillation comes from decaying molecules, not atoms (excitons and ions form dimers). Not absorbed before detected: therefore Xe, Ar, etc. transparent to own light



This physics is described in

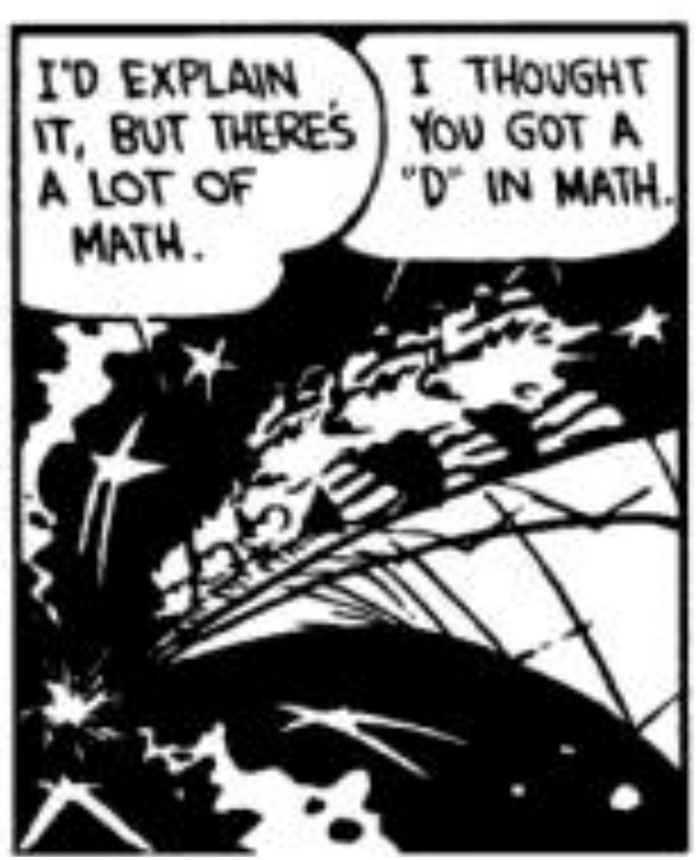
M. Szydagis et al., JINST 8 (2013) C10003. arXiv:1307.6601

M. Szydagis et al., JINST 6 (2011) P10002. arXiv:1106.1613

J. Mock et al., JINST 9 (2014) T04002. arXiv:1310.1117

Physics Handled by NEST

- **N**oble **E**leme ue is a data-driven mode ation and ionization yie as a function of particle type dx or energy
- Provides a fu mulation with
  - Mean yields
  - Energy reso ing backgrounds
  - Pulse shap
- Canon of exi uids and gases combed at U learned

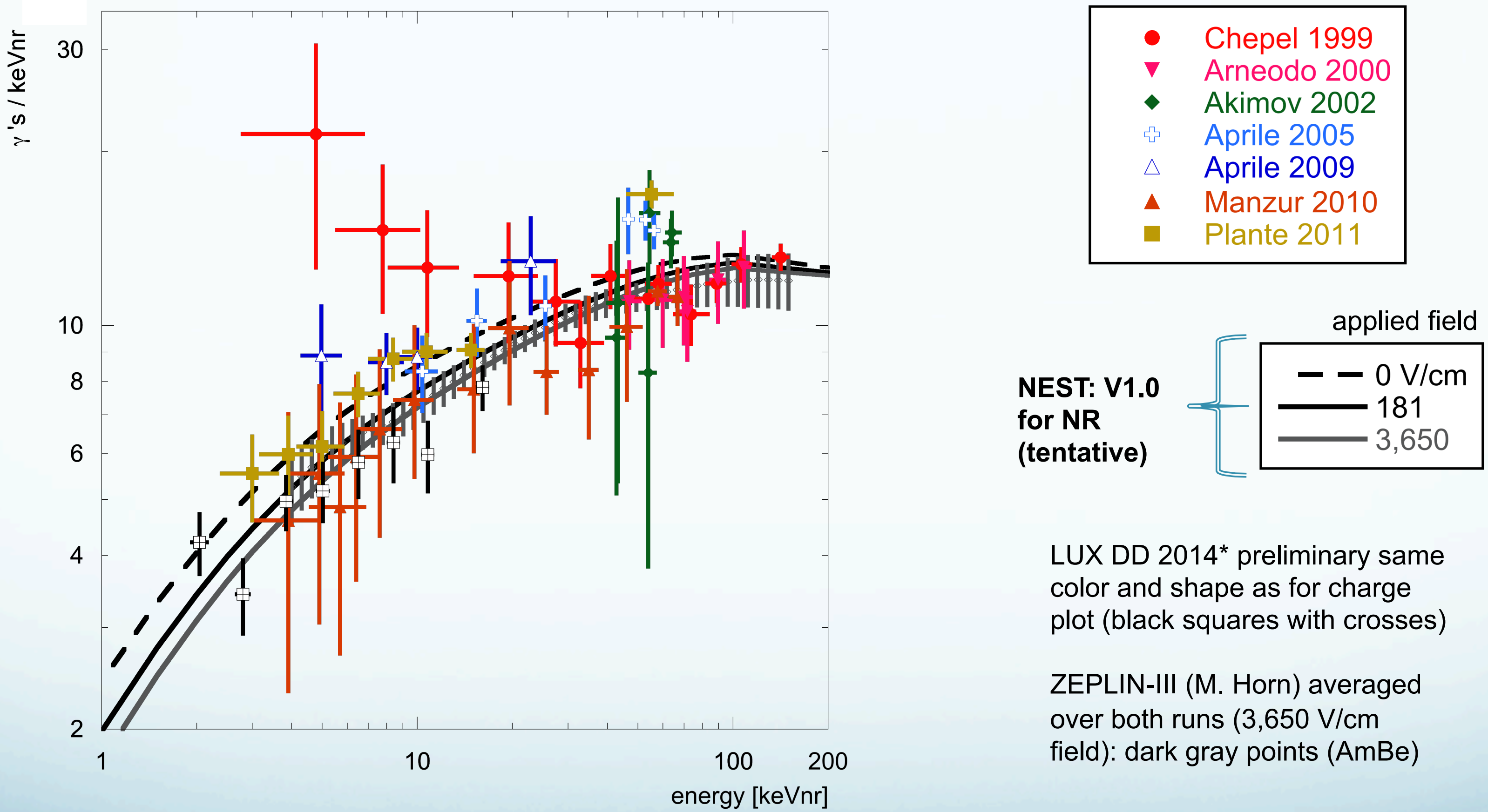


I will pass over the technical details of the microphysics in NEST and cut to the chase

- Simulations critical for understanding any detector (lesson from collider physics: Higgs discovery)

nest.physics.ucdavis.edu, albany.edu/physics/NEST.shtml

NR Light Yield

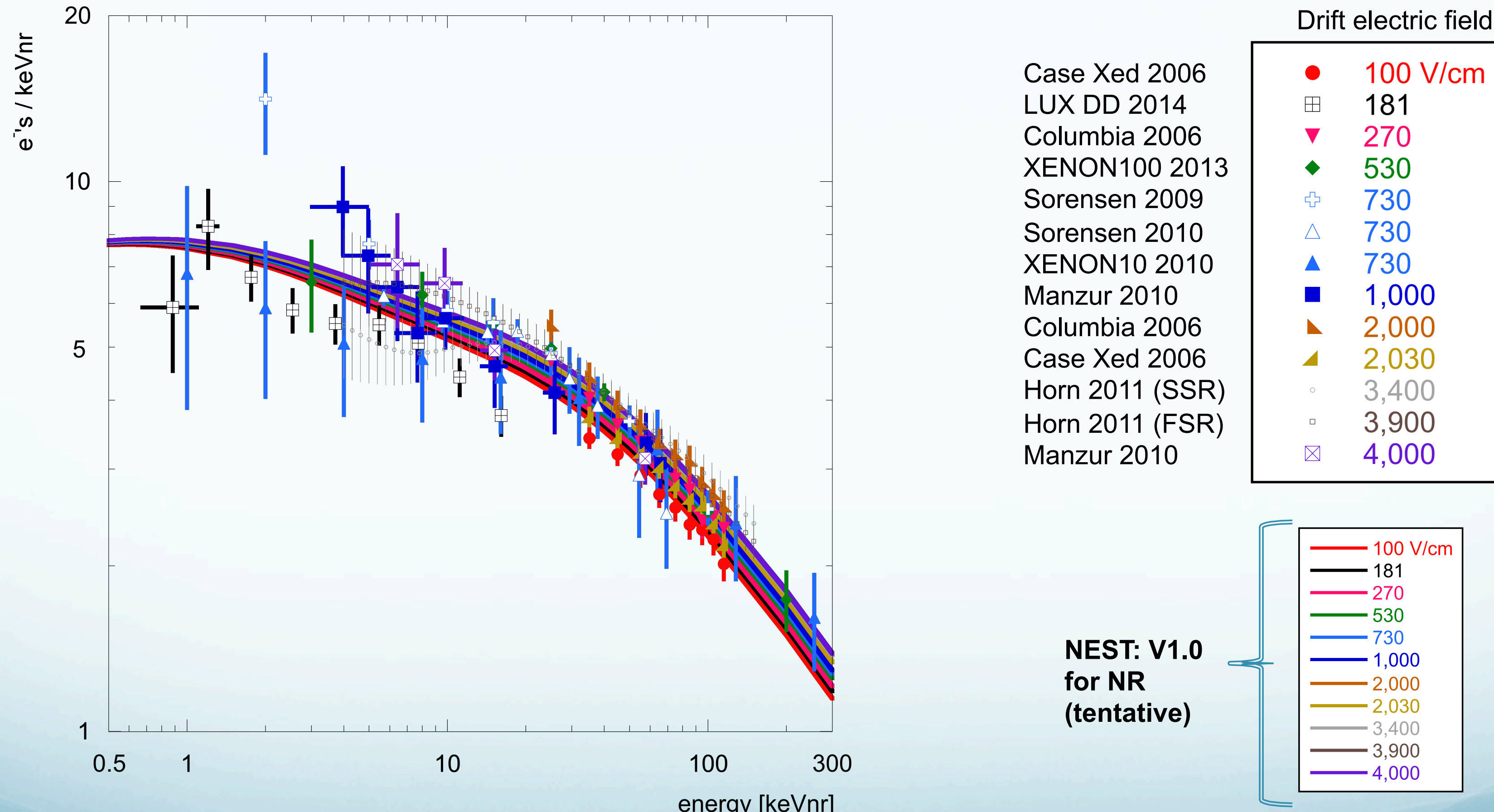


LUX DD 2014* preliminary same color and shape as for charge plot (black squares with crosses)

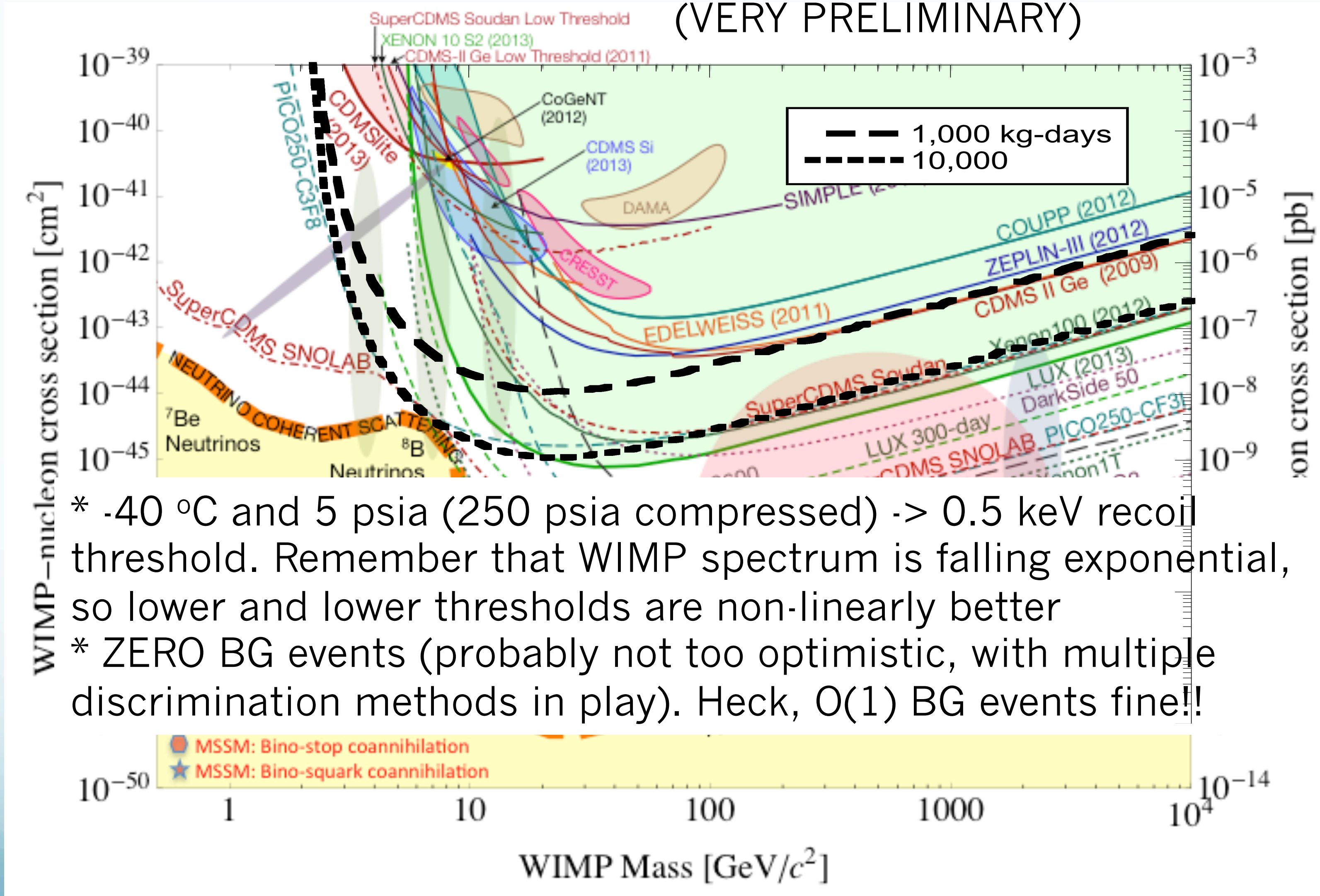
ZEPLIN-III (M. Horn) averaged over both runs (3,650 V/cm field): dark gray points (AmBe)

* http://pa.brown.edu/articles/20140219_jverbus_lux_llwi.pdf

NR Charge Yield



Projected Sensitivity



* -40 ^{o}C and 5 psia (250 psia compressed) -> 0.5 keV recoil threshold. Remember that WIMP spectrum is falling exponential, so lower and lower thresholds are non-linearly better
* ZERO BG events (probably not too optimistic, with multiple discrimination methods in play). Heck, O(1) BG events fine!!

CONCLUSIONS

- Dark matter is probably there, and there is a fairly agnostic way to directly look for one candidate, WIMPs, by waiting for nuclear recoils to produce a signal
- LUX and other results in conflict with low-mass WIMP interpretations of other data. (More data to come!)

- A xenon bubble chamber may spell the death knell for low-mass WIMPs, or discover them
- It has many other applications, but no time to get into them today: coherent neutrino scattering, neutrinoless double-beta decay, compact reactor monitoring

Special thanks to C. Eric Dahl, who came up with these ideas at the same time as me, if not earlier

Thank You