A Xenon Bubble Chamber

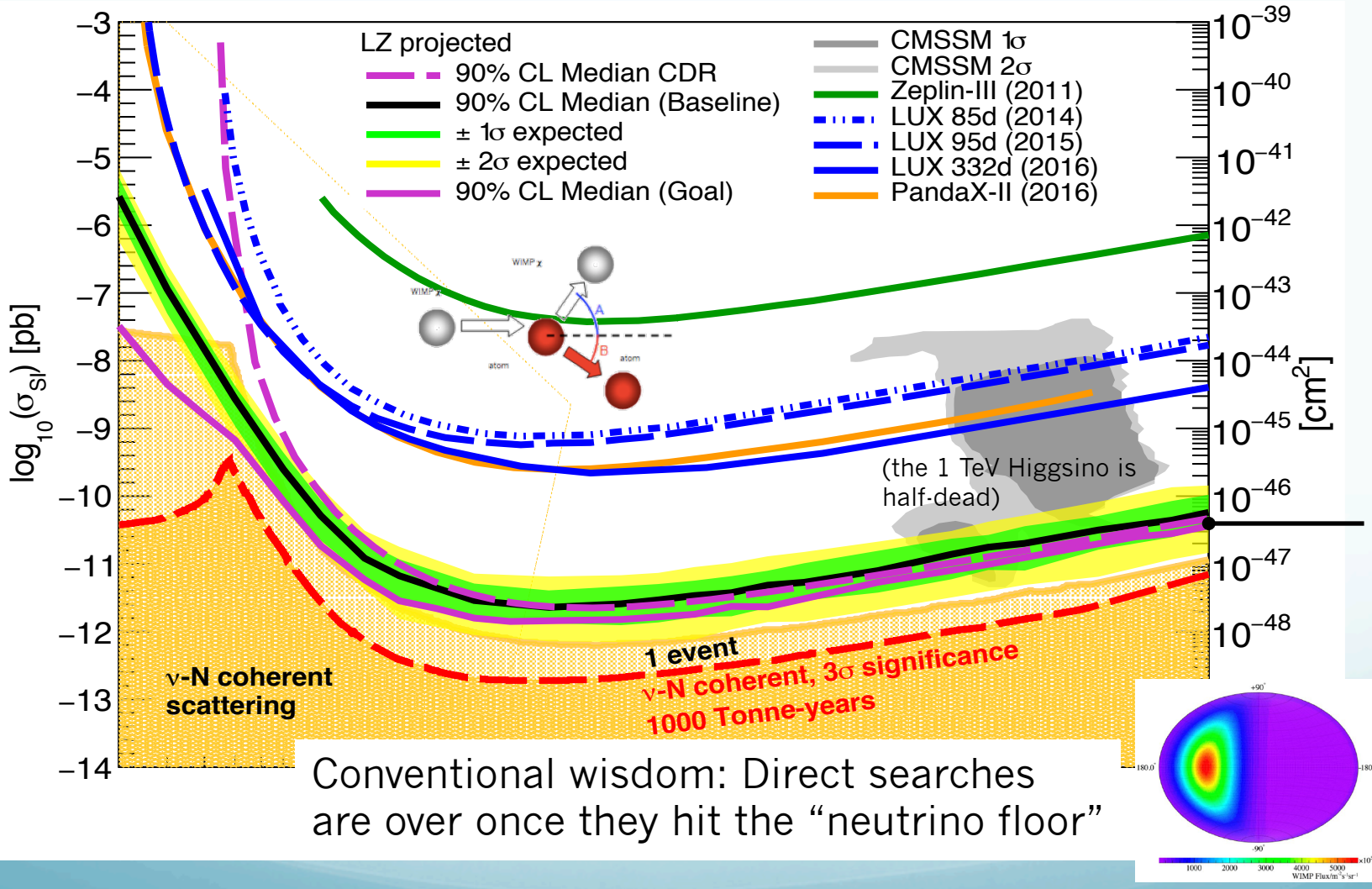
A New Technique

Matthew Szydagis
The University at Albany, State University NY

3rd LBNL Workshop DDDM 12/06/16

Direct WIMP Detection Saga

DOE "Down-select": LZ, SuperCDMS



Conventional wisdom: Direct searches are over once they hit the "neutrino floor"

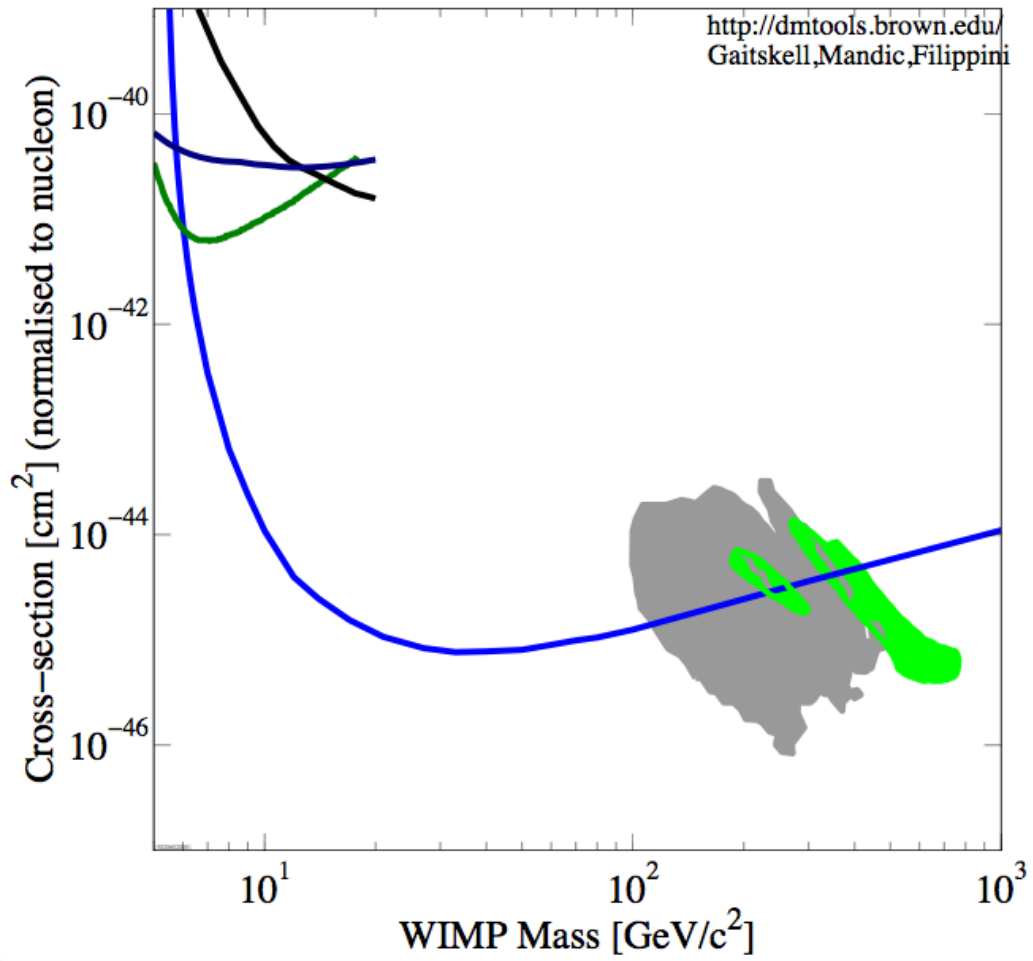
LZ, 1000 days X 5600 kg

2017 constr uction


SuperCDMS
LZ
NEW YORK
XENON
EMPIRE STATE
NCC1701
The victors of the G2 hunger games...

Historical Perspective

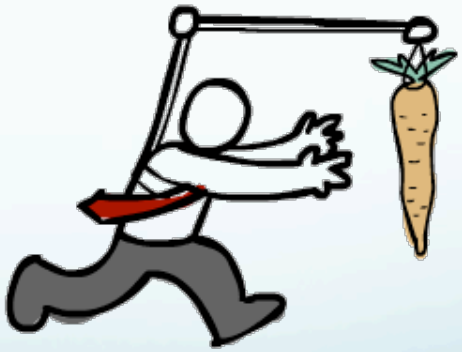
Time Progression of Sensitivity



Dolls within dolls

from 2000-2013

Closing in on Higgs coupling?



Animation courtesy of
Aaron Manalaysay, UC Davis

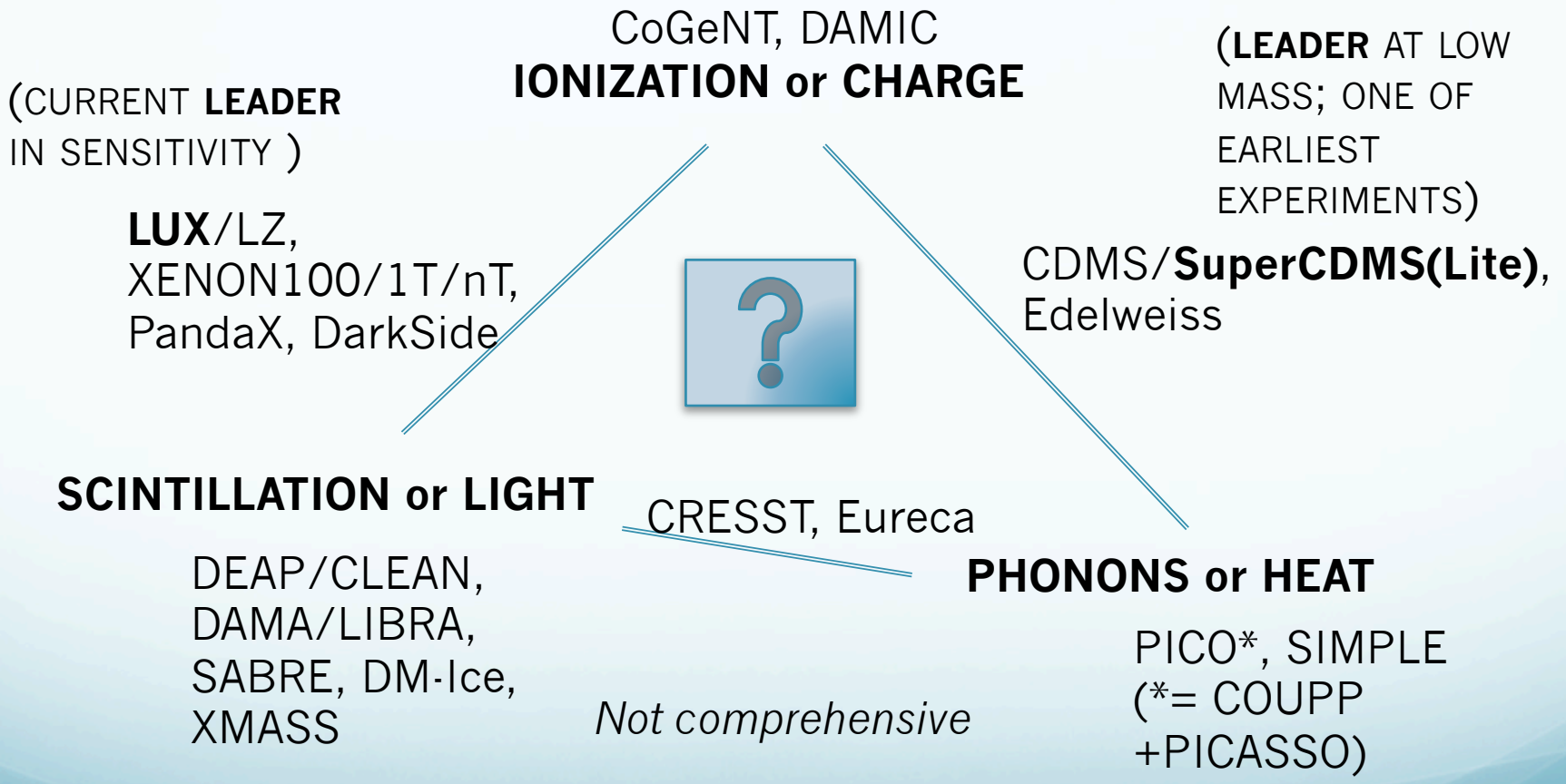
"I have not failed. I've just found 10,000 ways that won't work." — *Thomas A. Edison*

The 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

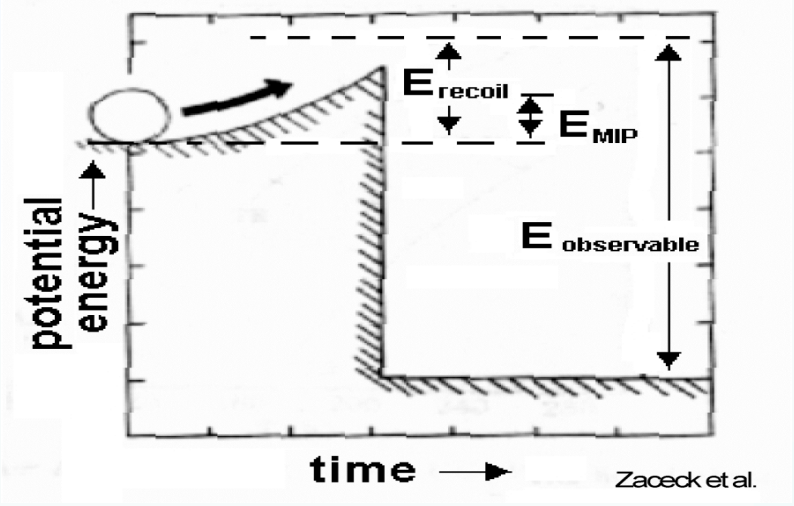
Current Paradigm

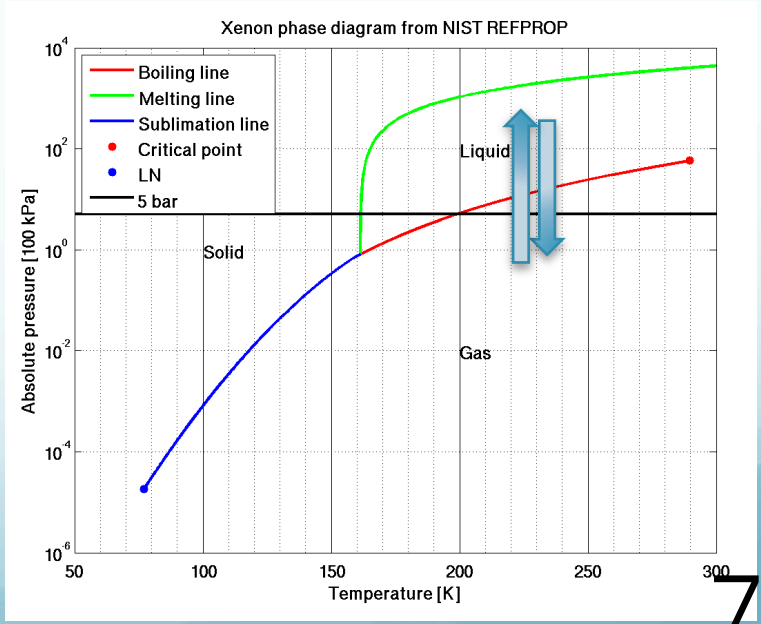
Some Loss of Information



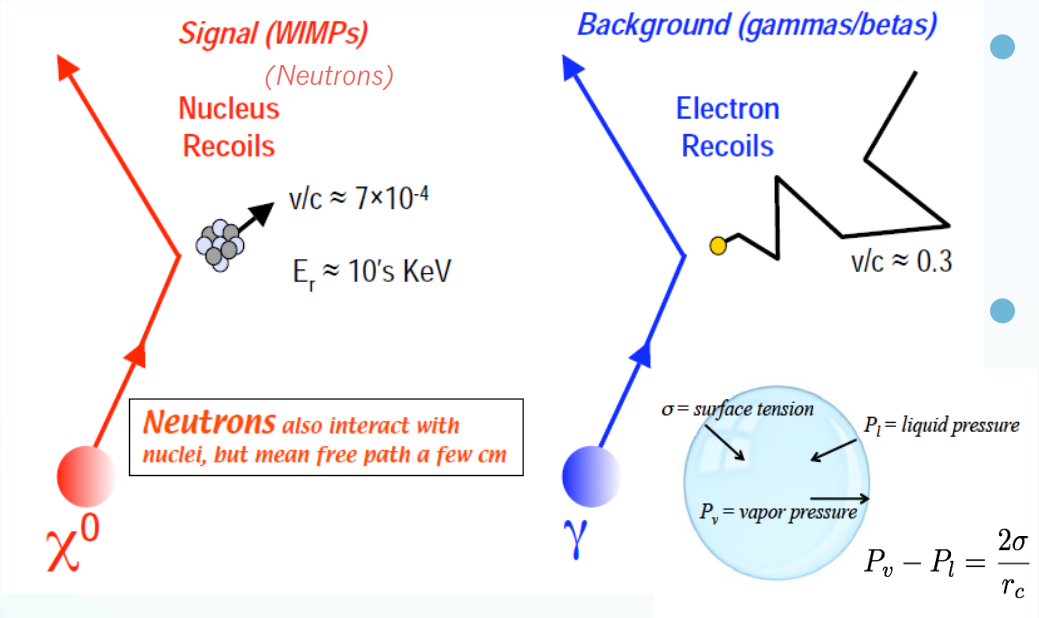
How a Bubble Chamber Works

- Metastable: in liquid phase, below the vapor pressure
- Bubbles induced by nuclear recoils
- Reapplication of traditional HEP technique
- Scalable, with target liquid swappable
- It's what happens when you try to boil water in the microwave, and your container is "too" smooth





More Basic Principles



- 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

A nuclear recoil goes above threshold, but not electron!

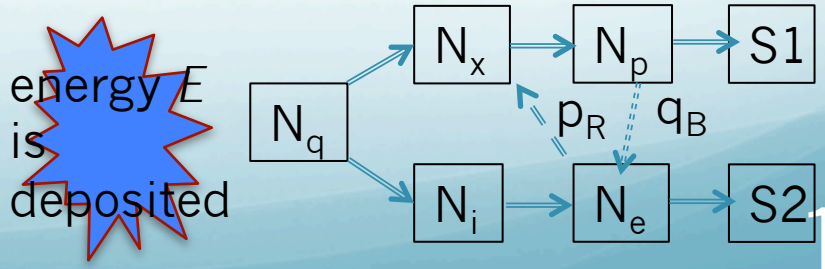
$$E > E_c = 4\pi r_c^2 \left(\gamma - T\frac{\partial \gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P$$

$$dE/dx > E_c/(ar_c)$$

Inherent MIP BG rejection because of dE/dx threshold

How a 2-phase XeTPC Works

- LUX an example of 1 type of time-projection chamber (full *XYZ* info)
  - D. Nygren at LBNL
- S1 (primary, liquid) and S2 (secondary, gas) scintillation, the latter drifted charge
  - Ratio: charge (via S2) to light (S1) forms the heart of the NR v. ER discrimination
- XY fiducialization from the S2 PMT hit map, and self-shielding from density: multiple-scat



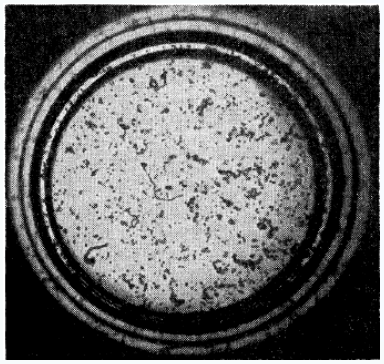
Technology Contrast

- Experiments like PICO blind to ER, to better than 1 in 10^{10} @low superheat, but *E*=? (multiples are scatters)
  - Latter is issue but overcome with operating pressure, or temperature sweep: energy + *dE/dx* thresholds changed
  - But, only one channel with which to study a signal
  - 100% efficiency above (sub-keV) NR threshold (steplike)
  - Alphas discriminated against acoustically
- 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 (~3 g/cm^3) and Z of LXe help
  - ~50% *acceptance* above a soft ~3-4 keV min threshold
  - Alphas are much brighter than NR (in S1)
- Xenon-based experiments (XENON, ZEPLIN, LUX, PandaX) leading field for better part of decade now!!! (SI, SD-n) But projects like PICO in the lead for SD-p

But is that the whole story? NO.

- Why not merge these two technologies and have BOTH energy reconstruction AND fantastic rejection of ER backgrounds? Each technology has something crucial for discovery which the other one lacks currently
- 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 via additive 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 noble liquid chambers: confirm signal. Almost anything turns into bubble chamber if go low in pressure / high in temperature
  - If you can pick anything, pick something that scintillates
  - Already proven to work: Dahl (see ICHEP 2016 poster)

A Paradigm Shift


Glaser

IONIZATION or CHARGE

Xe bubble chamber??

(R&D for G3 WIMP search?)

SCINTILLATION or LIGHT

PHONONS or HEAT

Unprecedented calibration abilities for existing experiments (LZ test bed e.g.)

- Find a temperature and pressure which optimizes energy resolution and S2/S1 discrimination of ER, at a particular liquid density
- Piezo acoustic sensor testing
- Sub-keV ER and NR, and summing of all 3 channels for NR

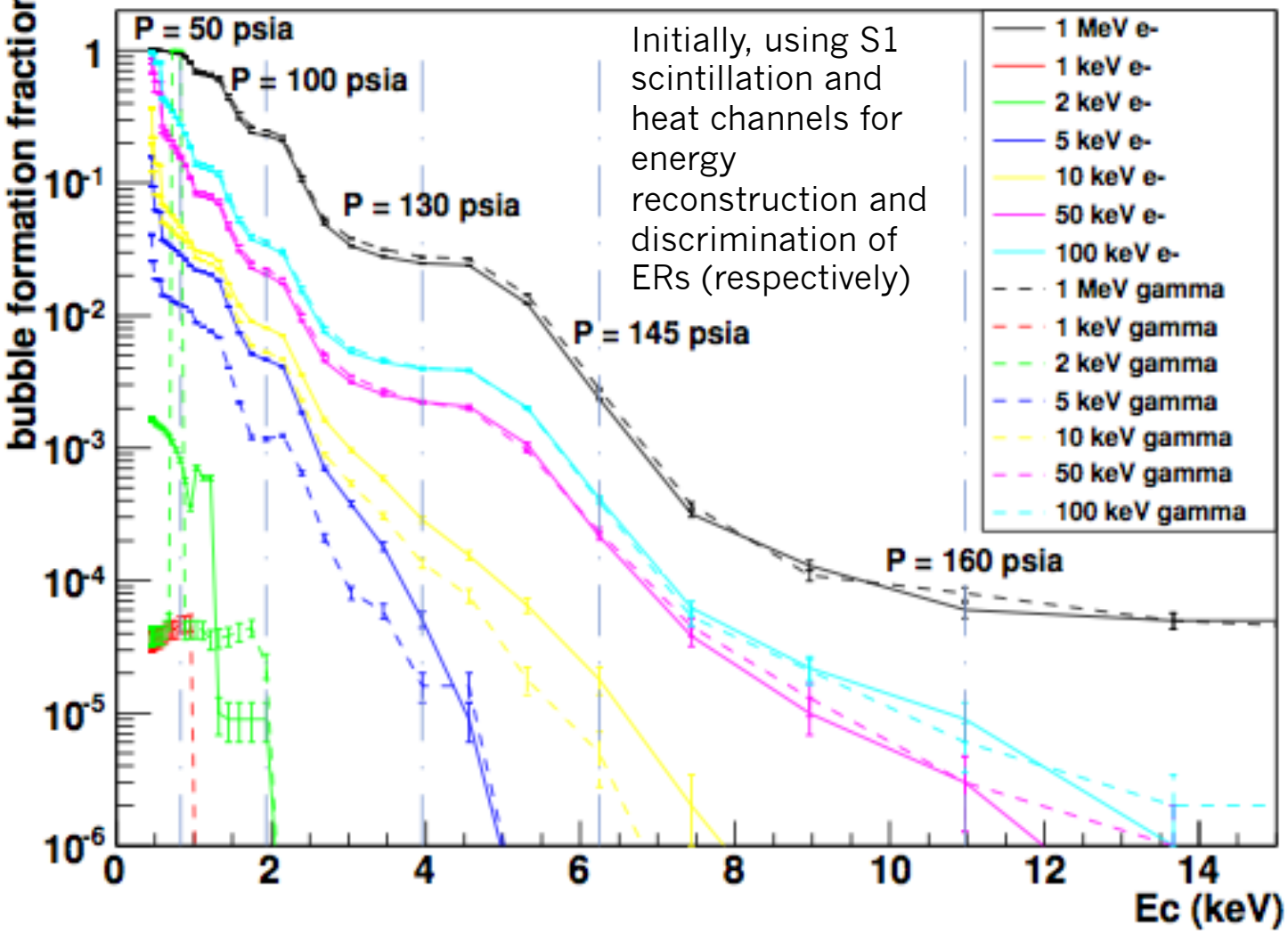
- Unprecedented attempt at capturing all 3 dimensions of discrimination. (But start simple: light and heat, no field)

S2 WITHIN BUBBLE?! http://arxiv.org/abs/1505.02316

- Near-100% fiducial volume (current generation 40-50%)
- Or reverse: supercooling and do phonon instead of bubble
- Gas when you want it to be and liquid otherwise: potential for directionality more easily than with large gas detectors

Looks Very Promising

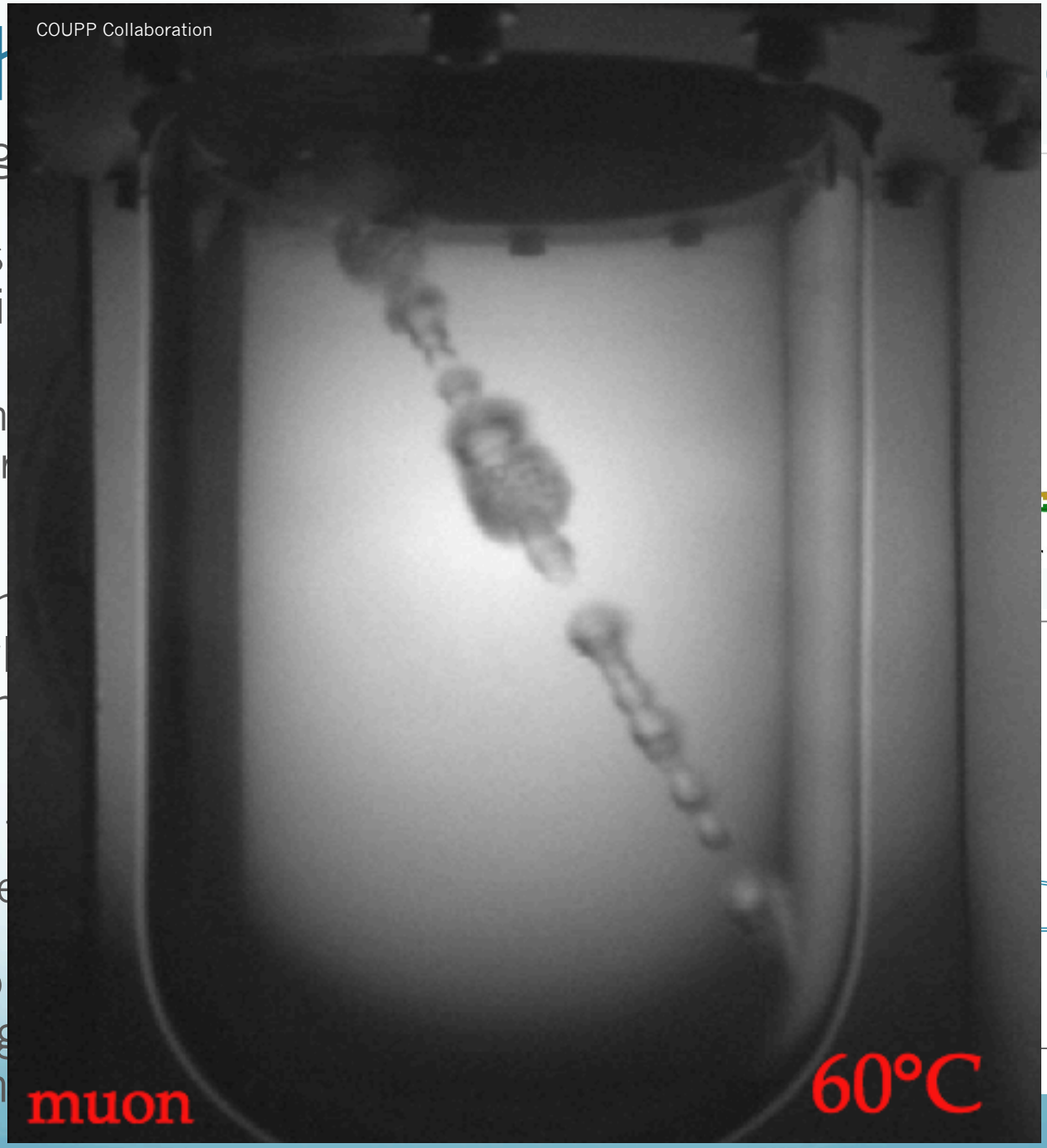
Levy et al. arXiv:1601.05131 (JINST)

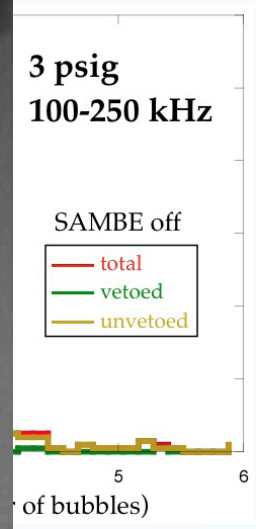


Many other applications, but no time to get into them today: coherent neutrino scattering, neutrinoless double-beta decay, compact reactor/portal monitoring

Fourth ons?

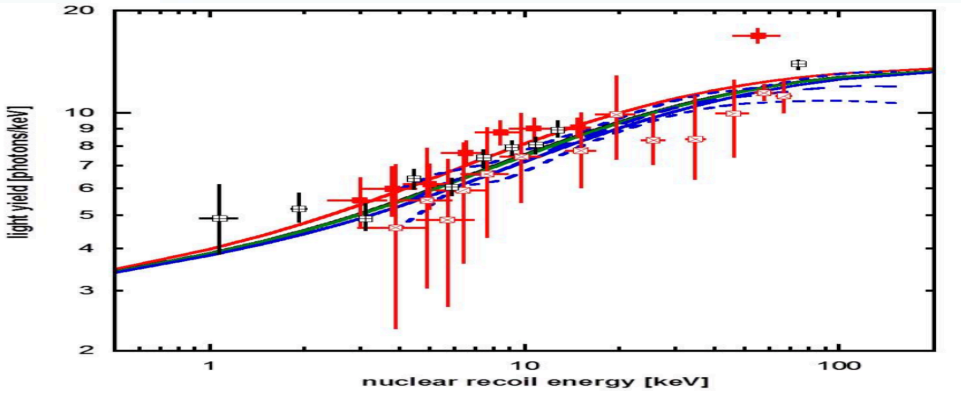
- In 15 kg showed vis-à-vis using pi
  - When low-th louder some
- Pulse sh popularl in xenon
  - Go to
  - Dope
  - Get be
- Directio high deg and ligh

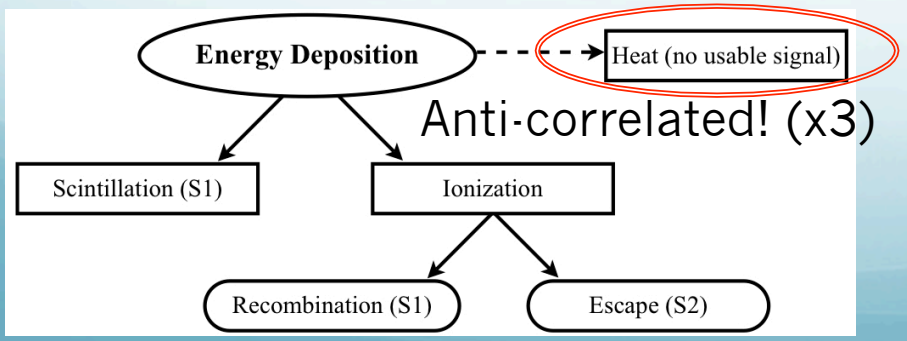


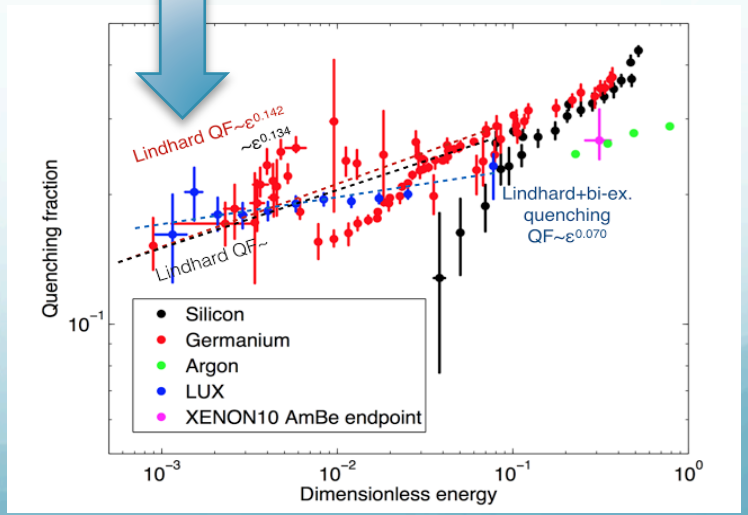


Another Benefit

- Bubble chamber turns "disadvantage" of Xe into an advantage: decreasing NR S1's + S2's at low energies means more energy is going into heat
  - Bubbles! If superheated
- ~No limit to E-threshold: keep lowering pressure, or raising temperature
  - Worse ER leakage, but one can start at orders of magnitude better than LUX: start at PICO levels







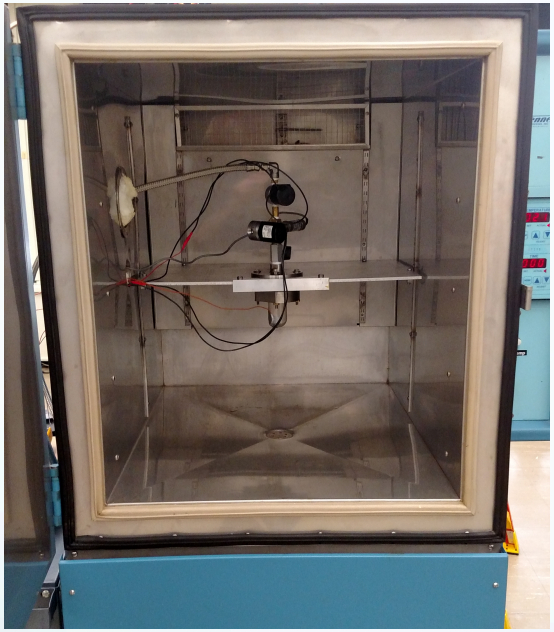
But E must be con-served

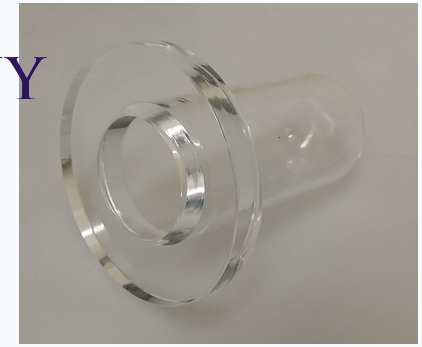
Building Smarter, Not Larger

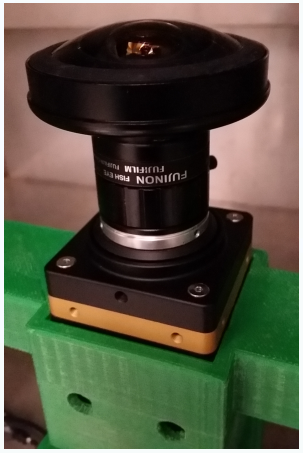
- There is still a lot of parameter space, especially at sub-GeV WIMP masses, where the thresholds of Xe-TPC-based experiments force an inevitable turn-up in limits
- Larger detectors must have greater turn-up: cannot push reflectivity and purity much more
- What if XENON, LZ, DARWIN, ARGO see nothing??? 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?
- Arduous interest in low-mass WIMPs is not likely to go away any time soon even if experiments (LUX, XENON) rule out (DAMA/CoGeNT), as high-masses remain shy.

UAlbany Prototype O(100 g) Xe

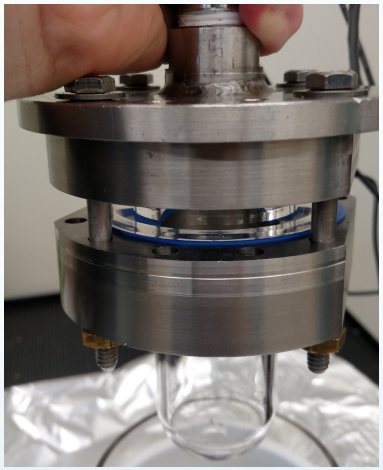
UNIVERSITY AT ALBANY
State University of New York

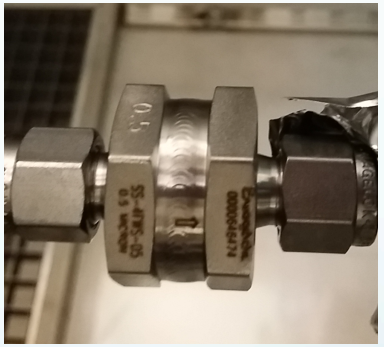


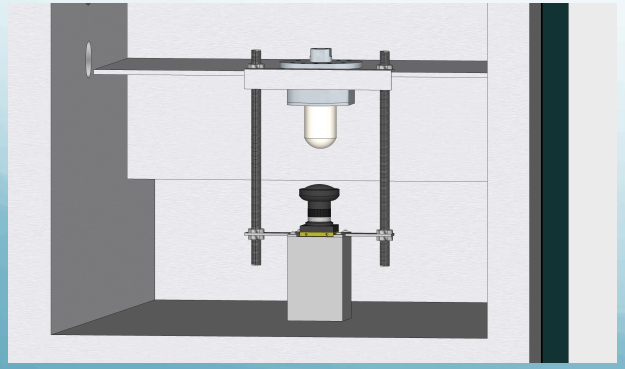


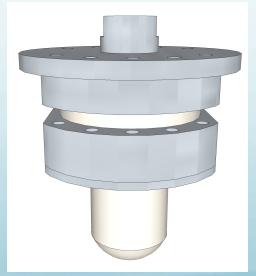


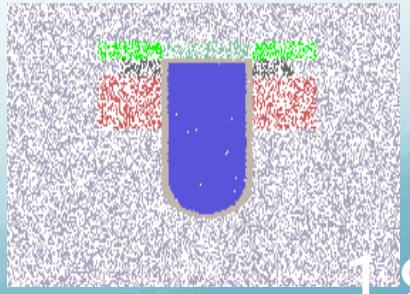
UALBANY





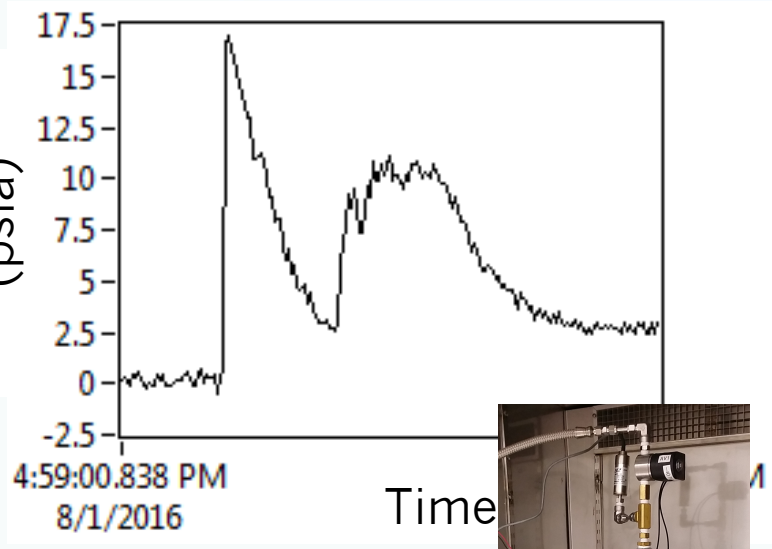


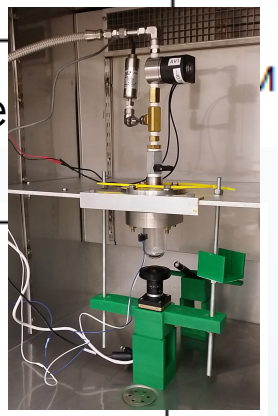




First Bubbles: Water Demo

Thick quartz vessel: no outer pressure vessel with hydraulic fluid

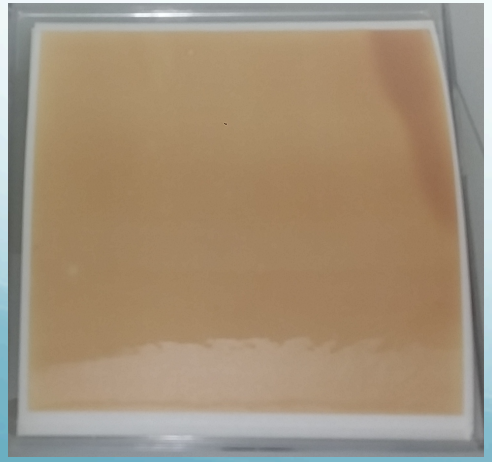


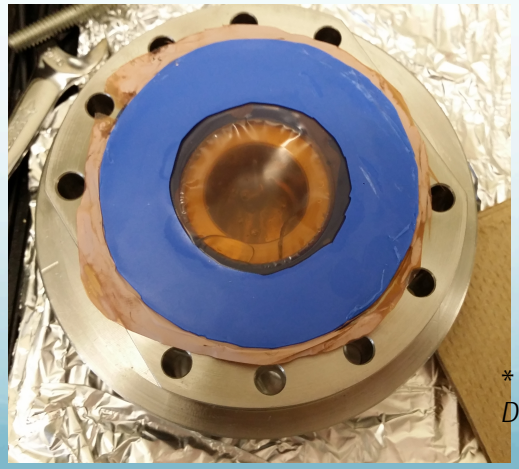


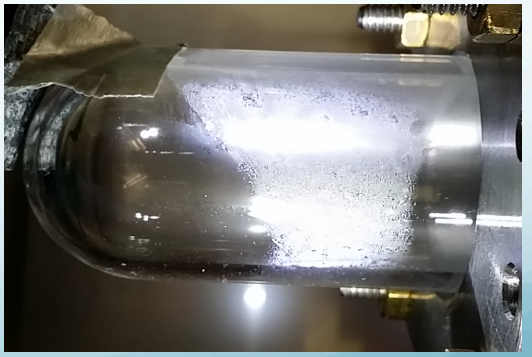
- For a test of full system including DAQ, MPPC SiPMs, PMTs, and all electronics, the trigger, etc.
  - Water is cheaper, safer to waste/lose! Successful leak tests at high P and low T
- Cherenkov radiation, from cosmic-ray muons for instance, is an excellent stand-in for Xe light (UV)
- Potentially interesting in its own right (ton-scale water Cherenkov bubble chambers for ν physics?)

Big Steps Forward on Purity

- Using a membrane permeable to a gas but not to a liquid
  - Keeps dust (nucleation sites, BG!) out of active volume
  - Tiny holes prevent liquid entry due to surface tension, but too small (< critical radius even at low threshold) for nucleation
- Can withstand huge pressure differentials without break
- No need for bellows, and removes problem of buffer (silicone oil in our case) contaminating Xe, quenching Ly
  - Avoids need for thermal gradient (Z-dependent threshold)
  - No crazy moving-seal quartz piston idea needed anymore
- Synthetic quartz vessel may avoid the need for TPB* (WLS)





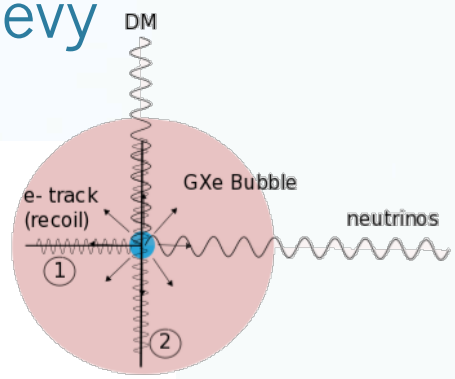


** Nevertheless, thanks to Mani Tripathi and UC Davis group for providing TPB coating of quartz*

Another Crazy Idea

Directionality using S2: C. Levy

(S2 not needed for position recon strictly speaking)



Compression and Decompression pressure system

To prevent nucleation sites

Quartz tube

Oil

Needed to create superheat

Incident particle

S2

e-

S1

Bubble

LXe

alternating electric field

Needed to keep the S2 within the bubble

Camera

(CCD, with red LED, for seeing). WLS may allow VUV seen here

Photon Sensor

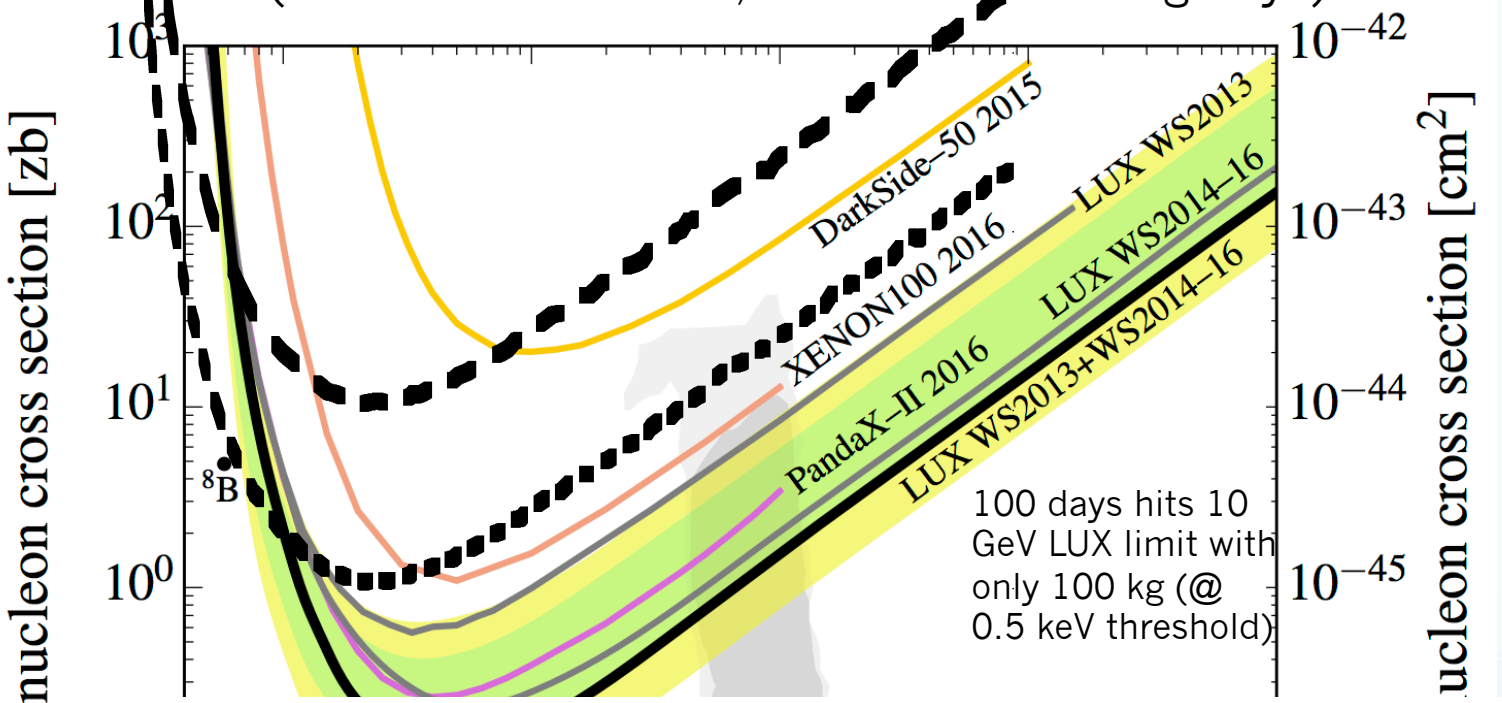
piezo-electric sensor

field coating is being studied, RPI (E. Brown)

Also, can pull a DAMA: run a stable detector quietly many years. Look for an annual mod

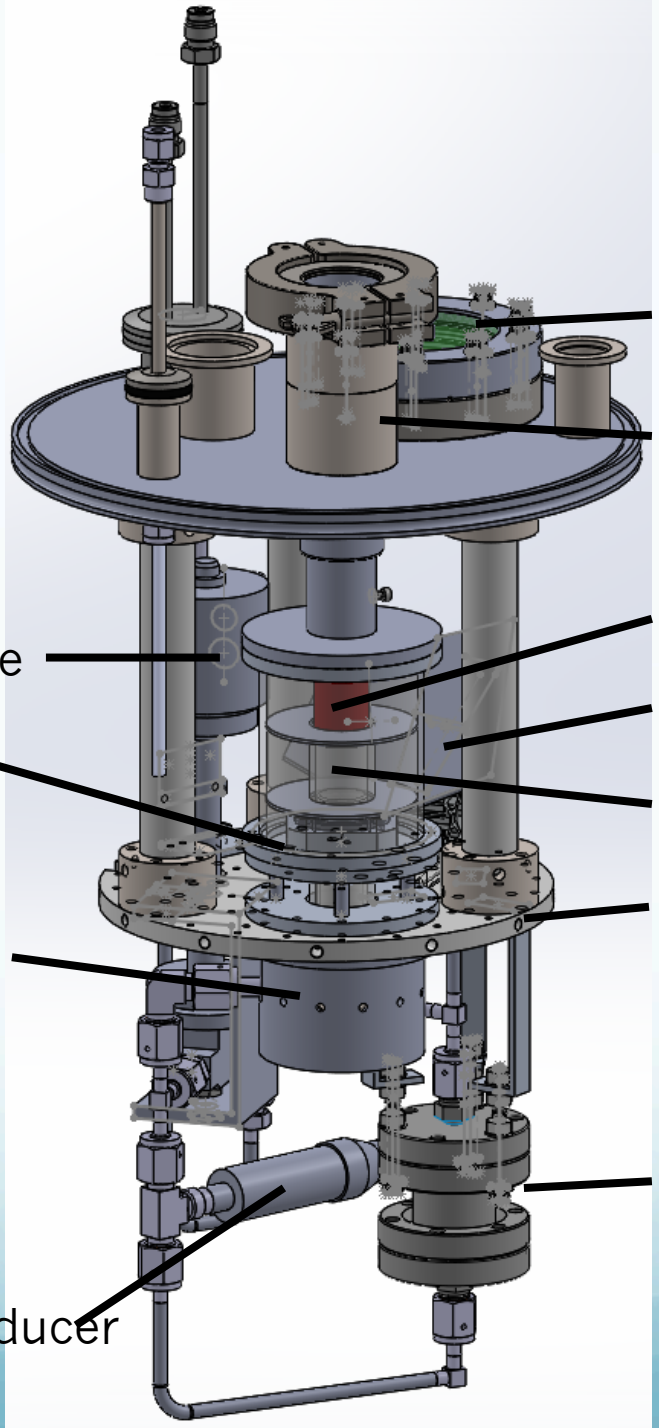
Projected Sensitivity

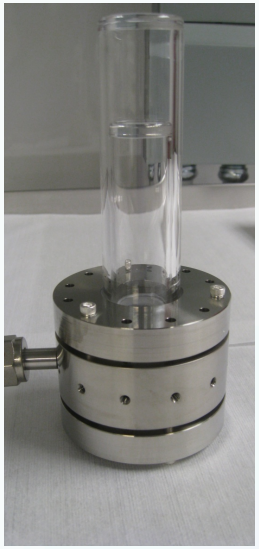
(VERY PRELIMINARY, 10^3 and 10^4 kg-days)



* -40 °C (optimal e- mobility), 5 psia (250 psia compressed) => 0.5 keV threshold, possible at low vacuum. Remember WIMP spectrum falling exponential: lower thresholds non-linearly better
* ZERO BG events (probably not too optimistic, with multiple discrimination methods in play). Heck, O(1) BG events is fine!!

North-western's chamber



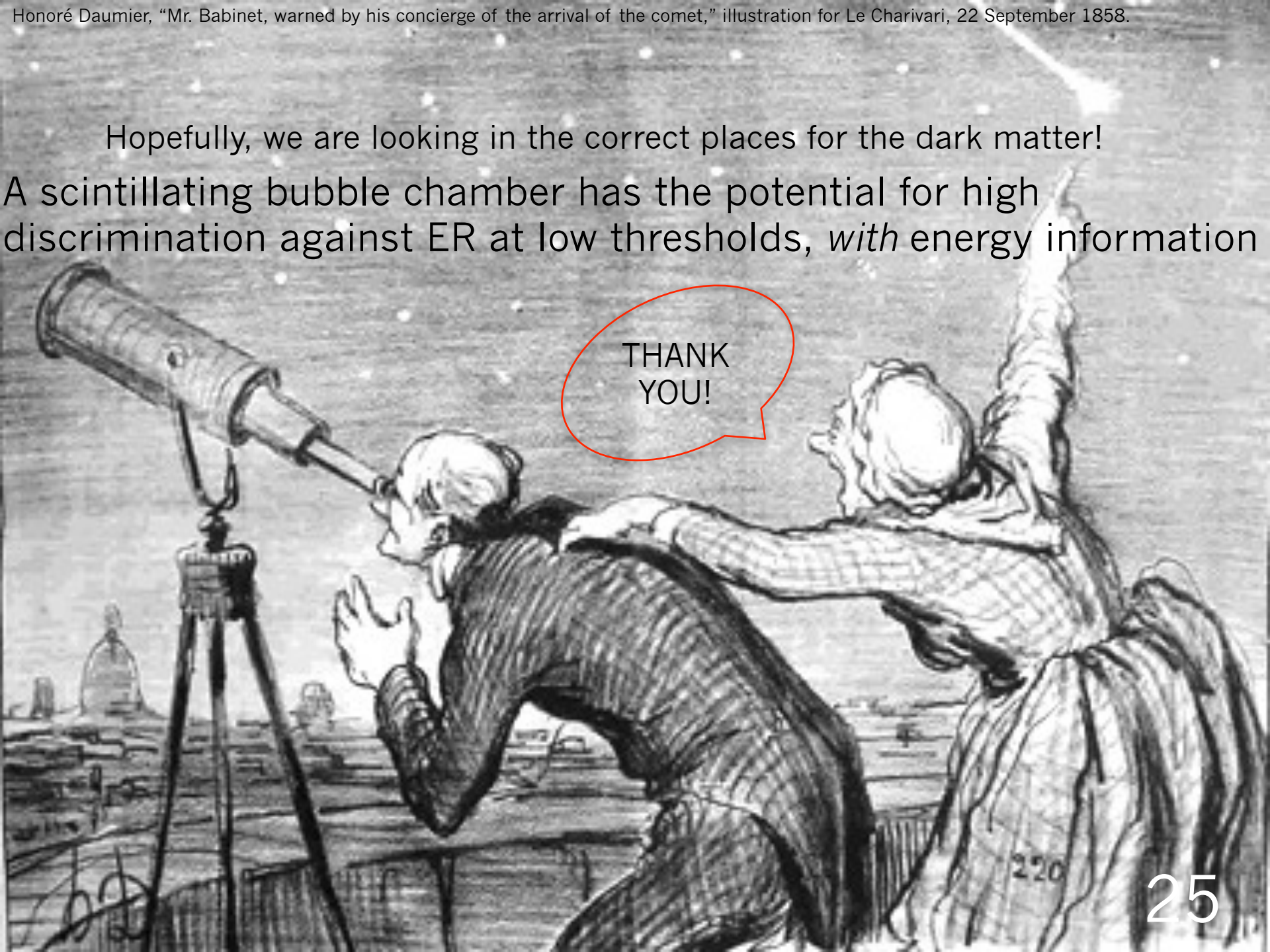


slide courtesy of Jianjie Zhang, from this same worksho p but last year

CONCLUSIONS: A Discovery Machine

- Huge benefits over the existing detector technologies!
  - BNL liked idea so much they gave me free xenon ☺
- New idea but also a merging of existing vetted ones
- No one currently at center of WIMP "detection triangle"
  - Multiple robust event reconstruction methods possible
  - 1st DM detector w/ 3(+) channels: light, charge, heat?
- Can go to even lower masses with Ar, Ne, or even He: target swapping, at different T's/P's (Xe good for Ly)
  - Fluorinated organic scintillators for good SD-p sensitivity!
  - Xe is just an example most familiar with myself (LUX/LZ)
- We can combine the mains advantages of LXe TPCs (energy reconstruction, density) with bubble chambers (blindness to ER BGs and visibility of "heat channel")
  - NR -> bubble & low light, when ER more light, no bubble

Special thanks to Eric Dahl FNAL/NU, who came up with ideas at same time as me - if not earlier.



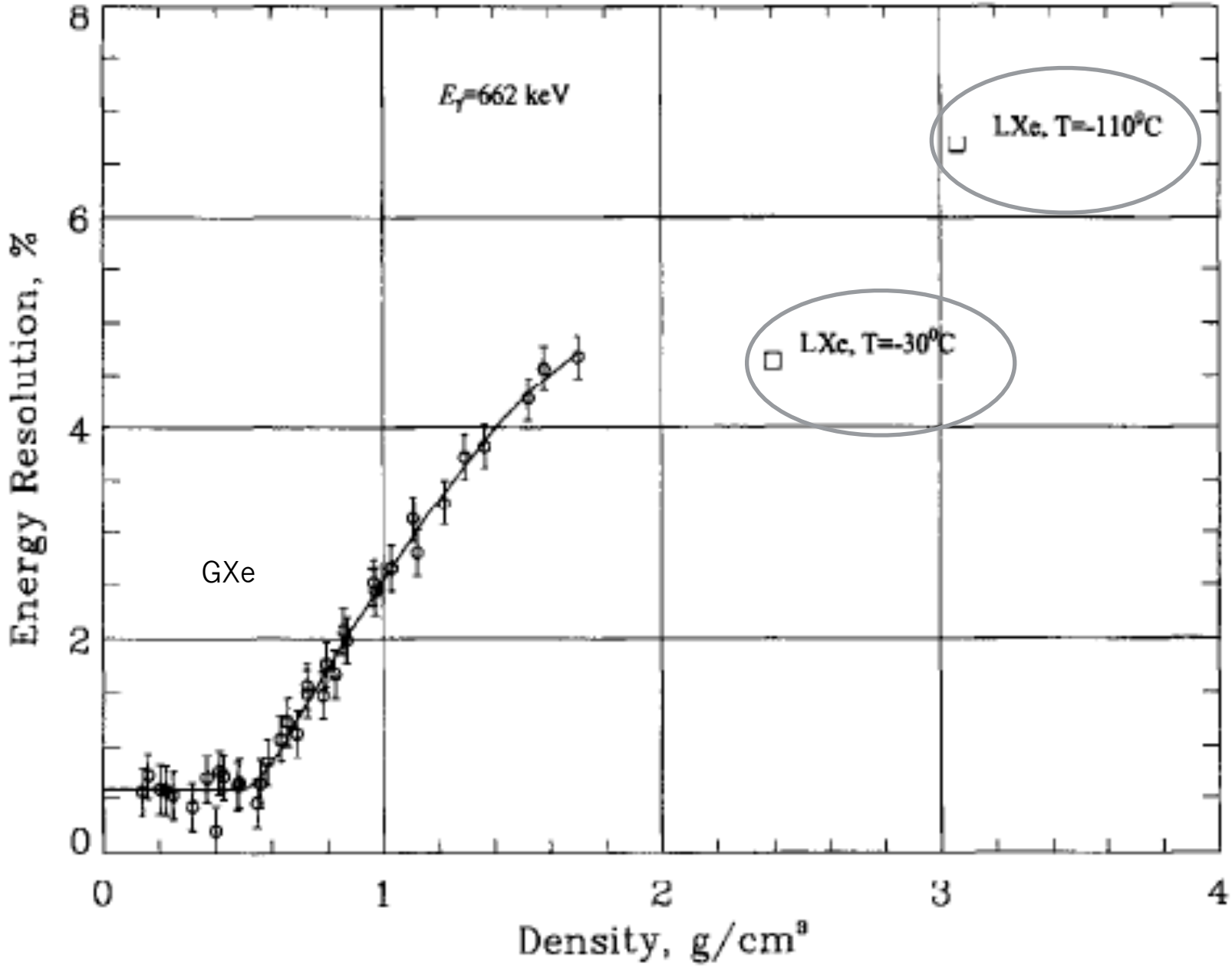
Honoré Daumier, “Mr. Babinet, warned by his concierge of the arrival of the comet,” illustration for Le Charivari, 22 September 1858.

Hopefully, we are looking in the correct places for the dark matter!

A scintillating bubble chamber has the potential for high discrimination against ER at low thresholds, *with* energy information

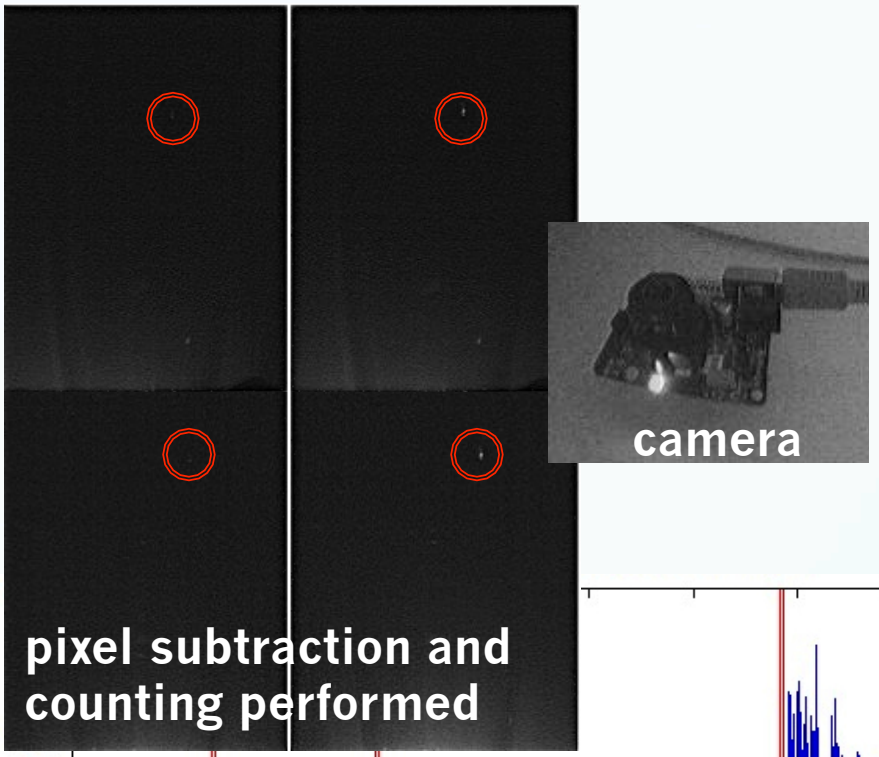
backup

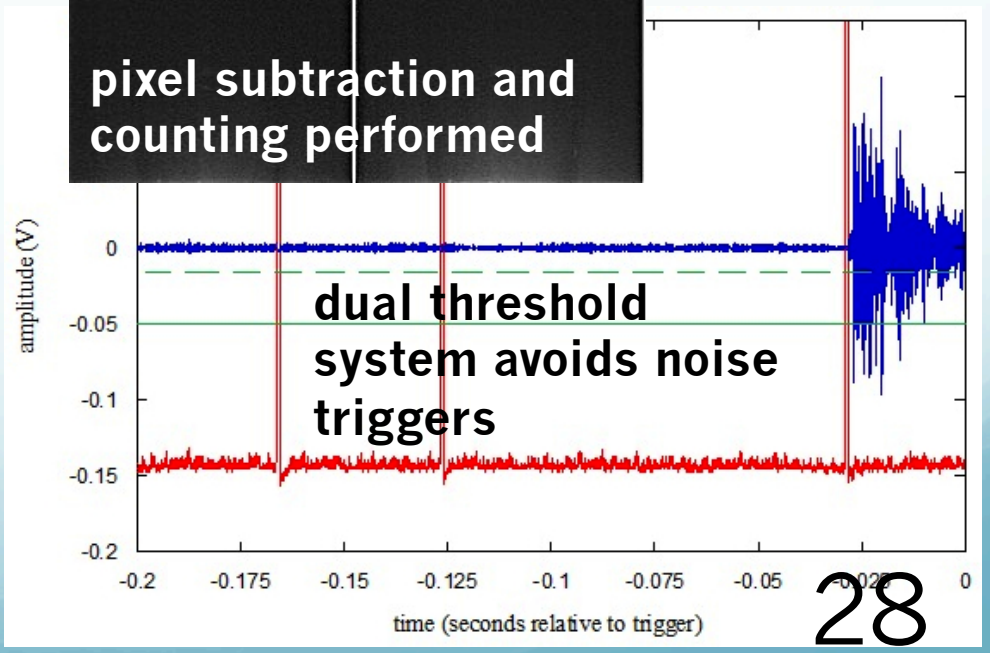
- additional materials


E_γ=662 keV
LXe, T=-110°C
LXe, T=-30°C
GXe
Energy Resolution, %
Density, g/cm³
0
2
4
6
8
0
1
2
3
4

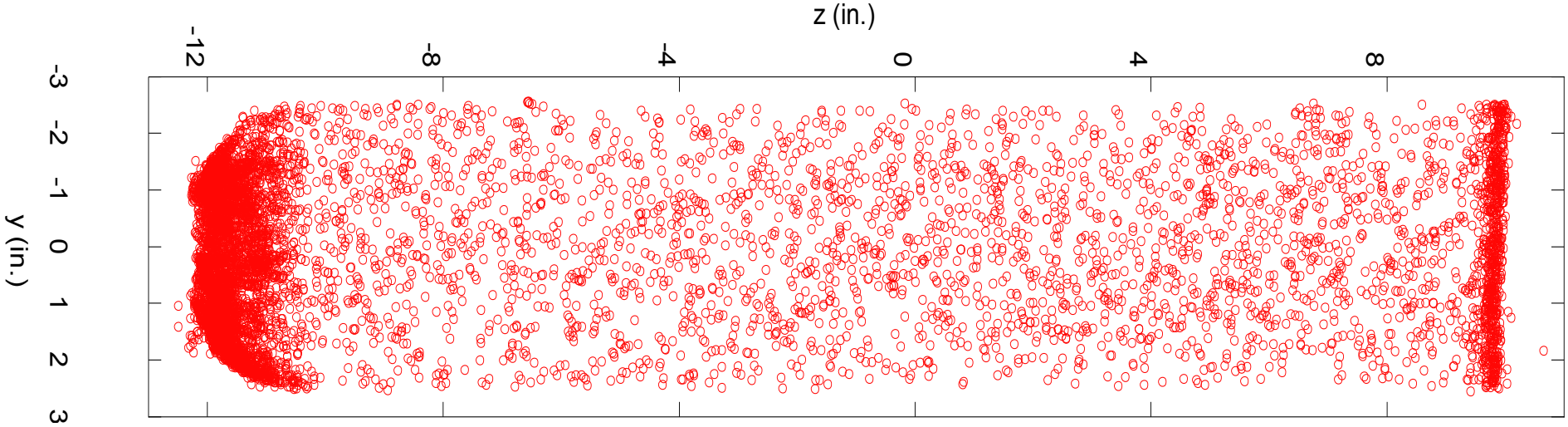
Triggering Mechanisms

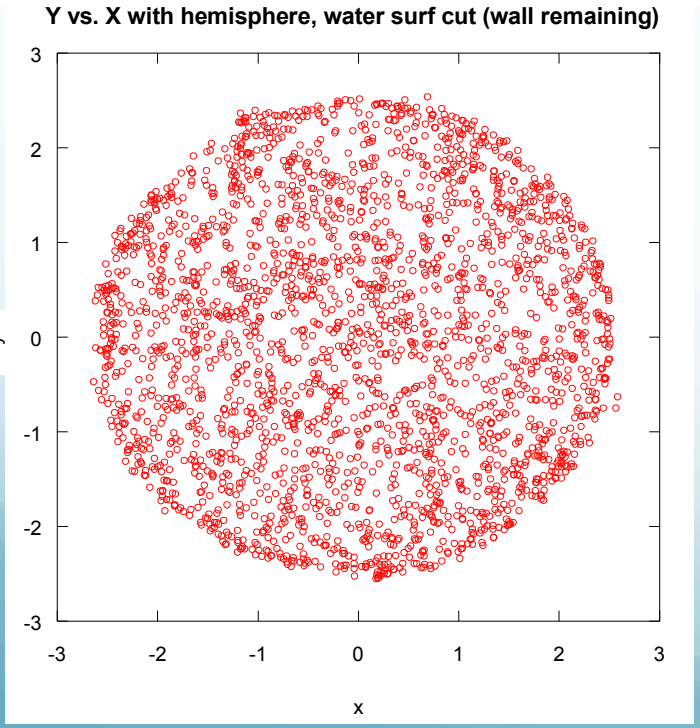
- Pressure
  - Less dense and rapidly growing bubble pushes liquid out of the way
  - Less useful in large vessels
- Visual
  - Orthogonal cameras allow for 3D position reconstruction and easiest disambiguation of multiple bubble events
  - Traditional and primary
- Audio
  - Better primary trigger if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



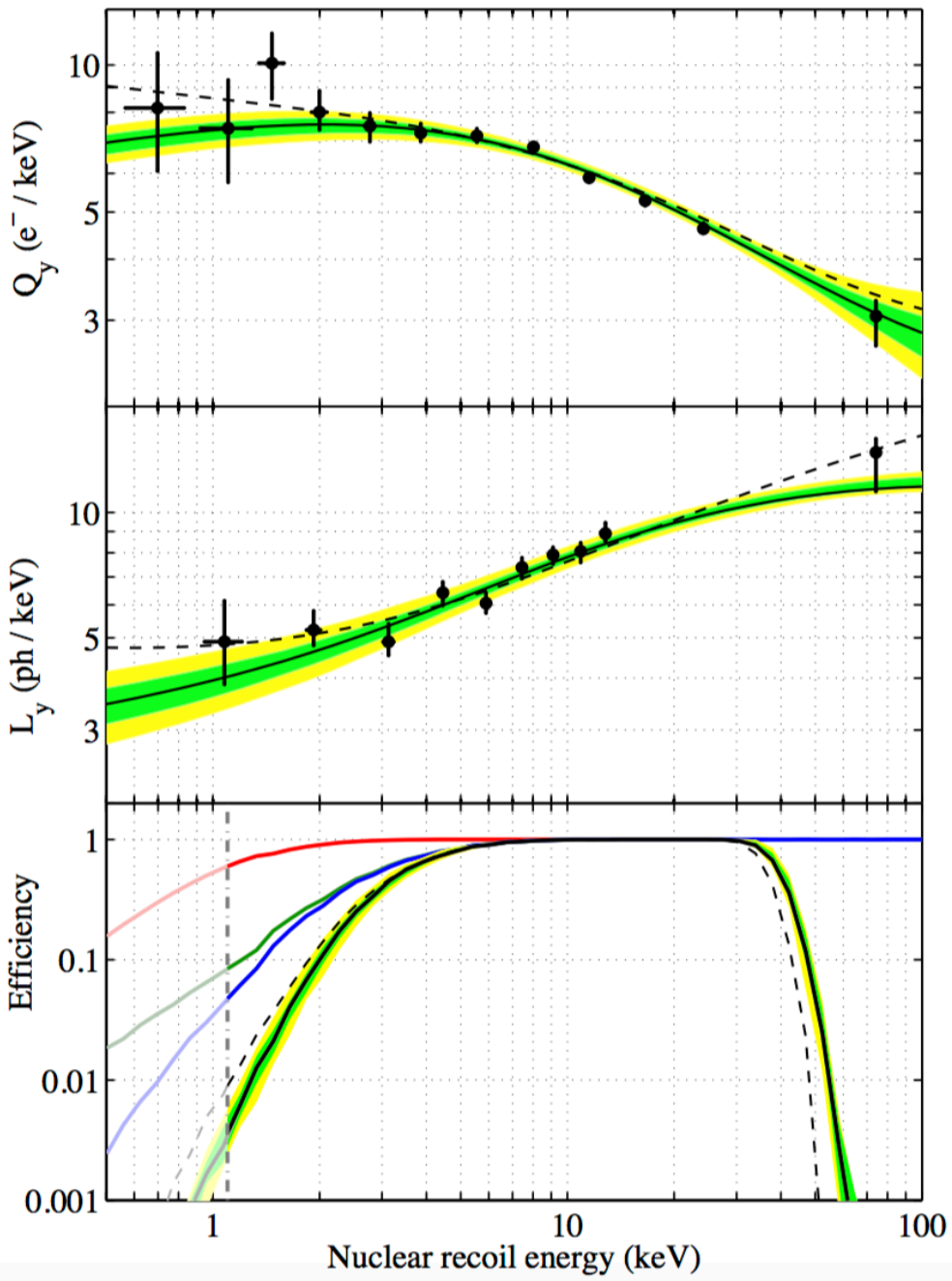


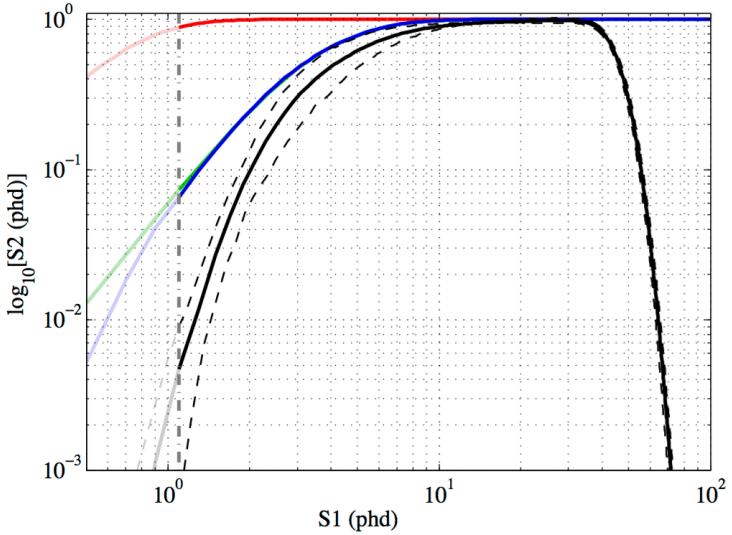
3-D Optical Position Recon





- 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





Caption: Efficiencies for NR event detection, estimated using simulation with parameters tuned to D-D calibration. In descending order of efficiency—red: detection of an S2 ($\geq$2 electrons emitted); green: detection of an S1 ($\geq$2 PMTs detecting photons); blue: detection of both an S1 and an S2; black: detection passing analysis selection criteria, including thresholds in *S1* and raw S2 size. Solid curves indicate exposure-weighted means, the variation in time and detector position are indicated for the final efficiency.