Shining Some Light on Dark Matter:

The MiniCLEAN Direct Detection Experiment

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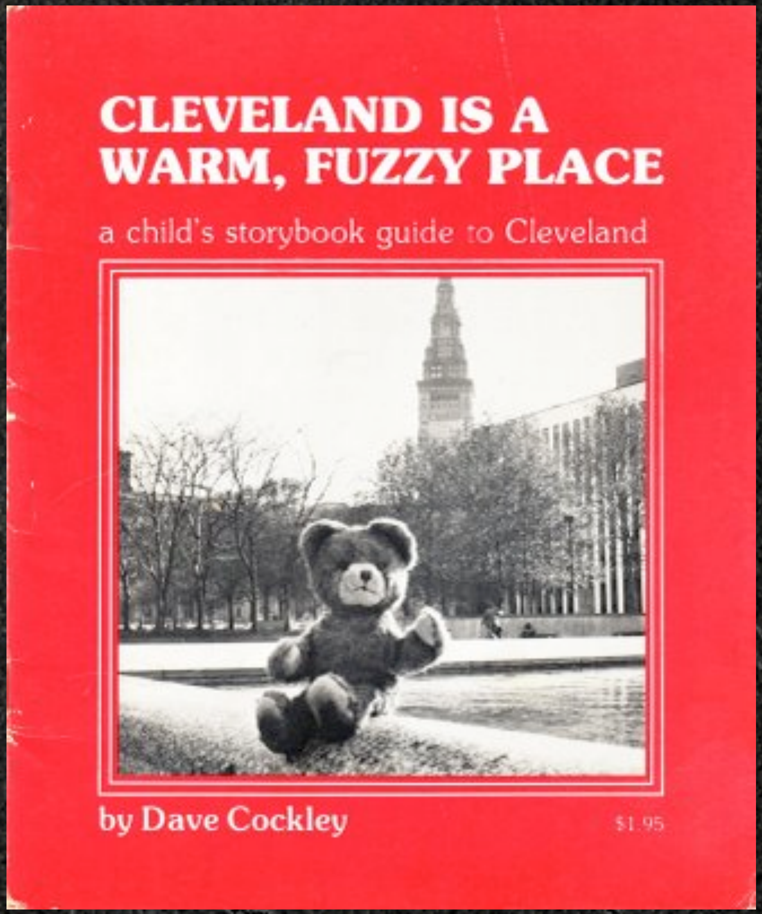
SMU February 11, 2013

Outline

- Dark Matter Evidence and ΛCDM
  - WIMPs
- Direct Detection Overview
- Liquid Noble Detection
- MiniCLEAN
  - Design
  - Backgrounds
  - Construction Pictures



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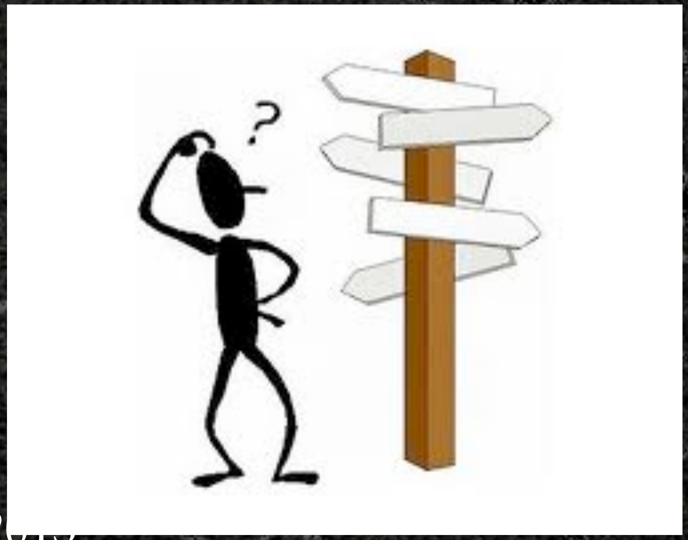

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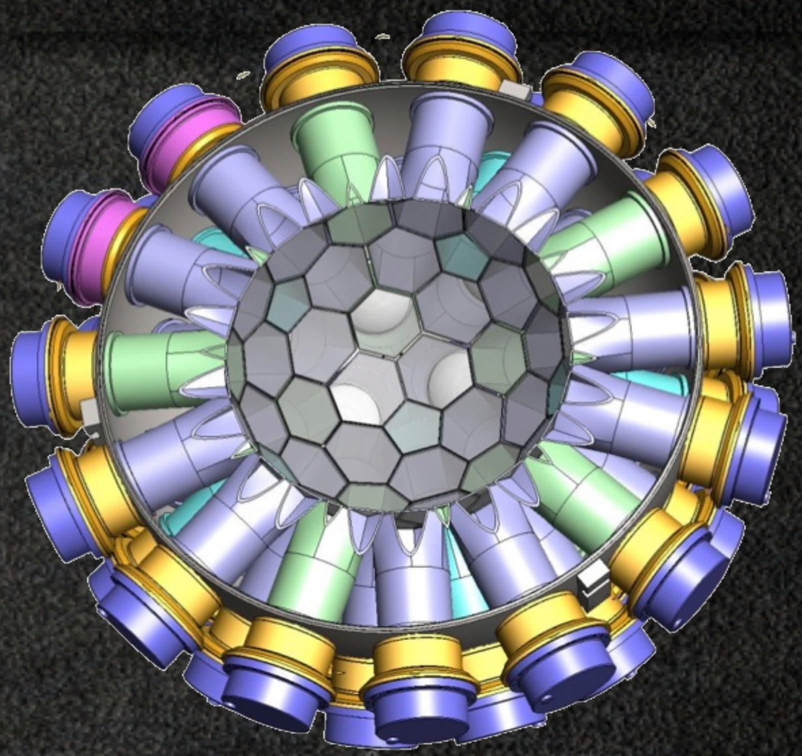
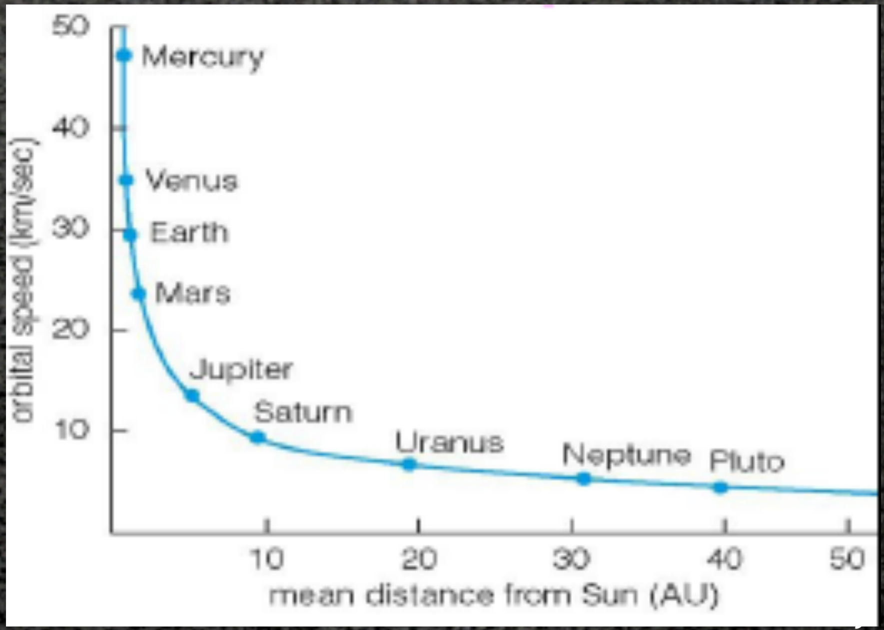


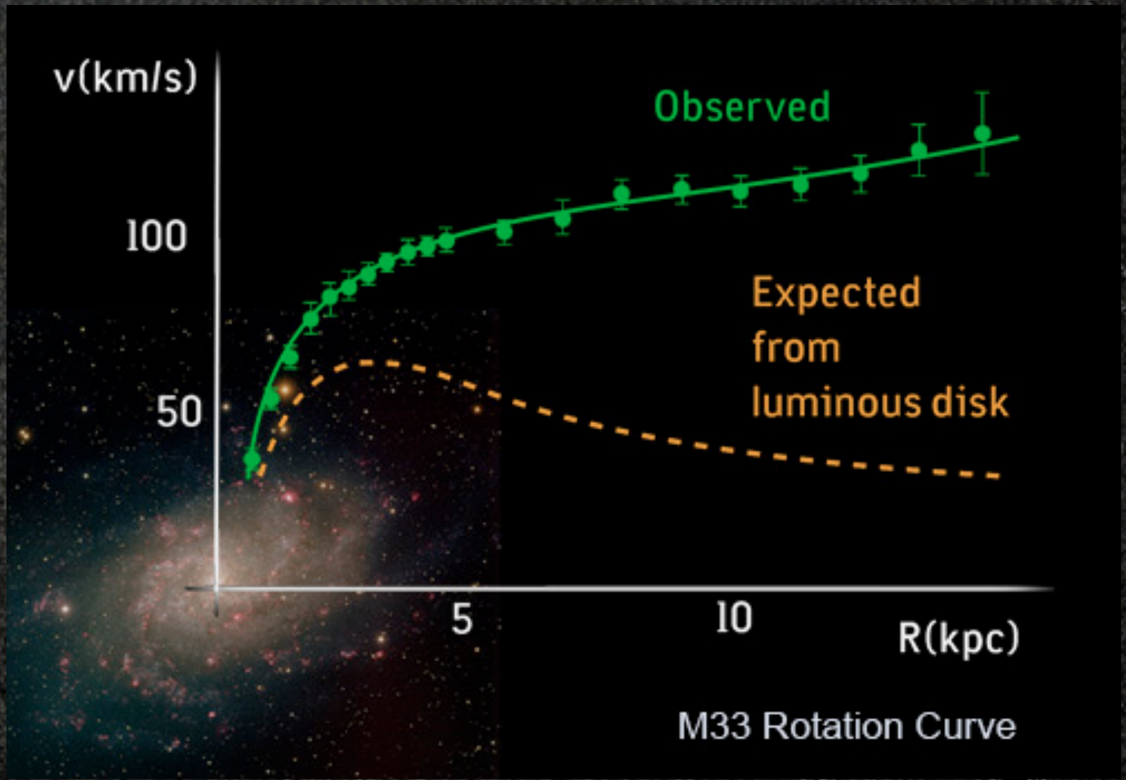
Early Evidence

Fritz Zwicky studied galaxy velocities in clusters in the 1930s, Vera Rubin measured star velocities in galaxies in the 1960s

$$M_r = \frac{r v^2}{G}$$



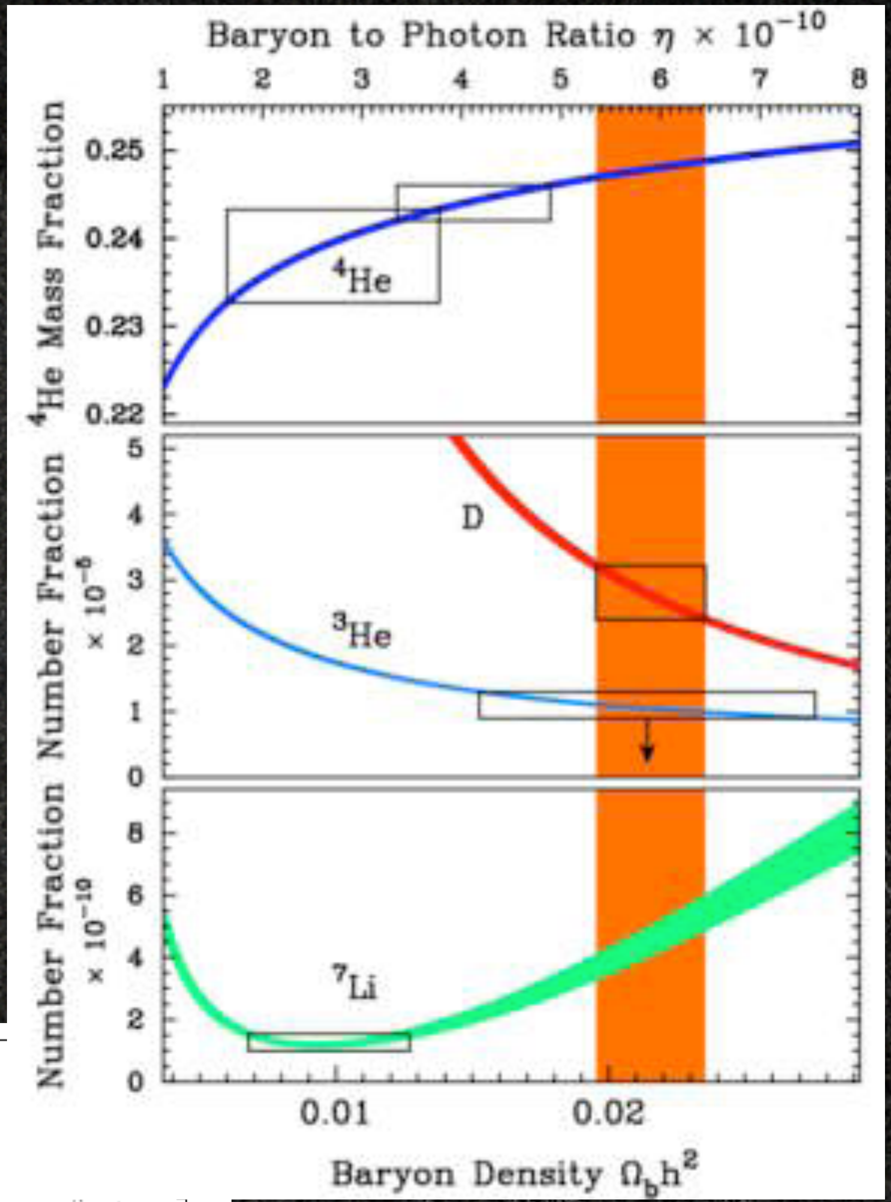
There is more mass than we expect from the luminous matter we see.

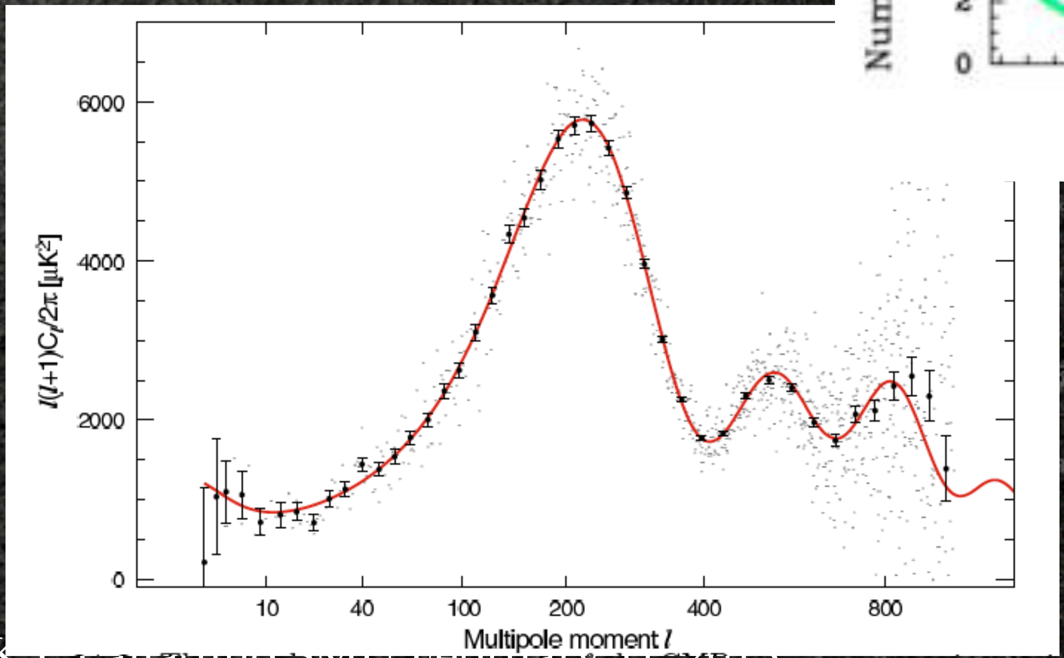


Galaxy rotation curves: Star velocities from Doppler shifts do not match predictions

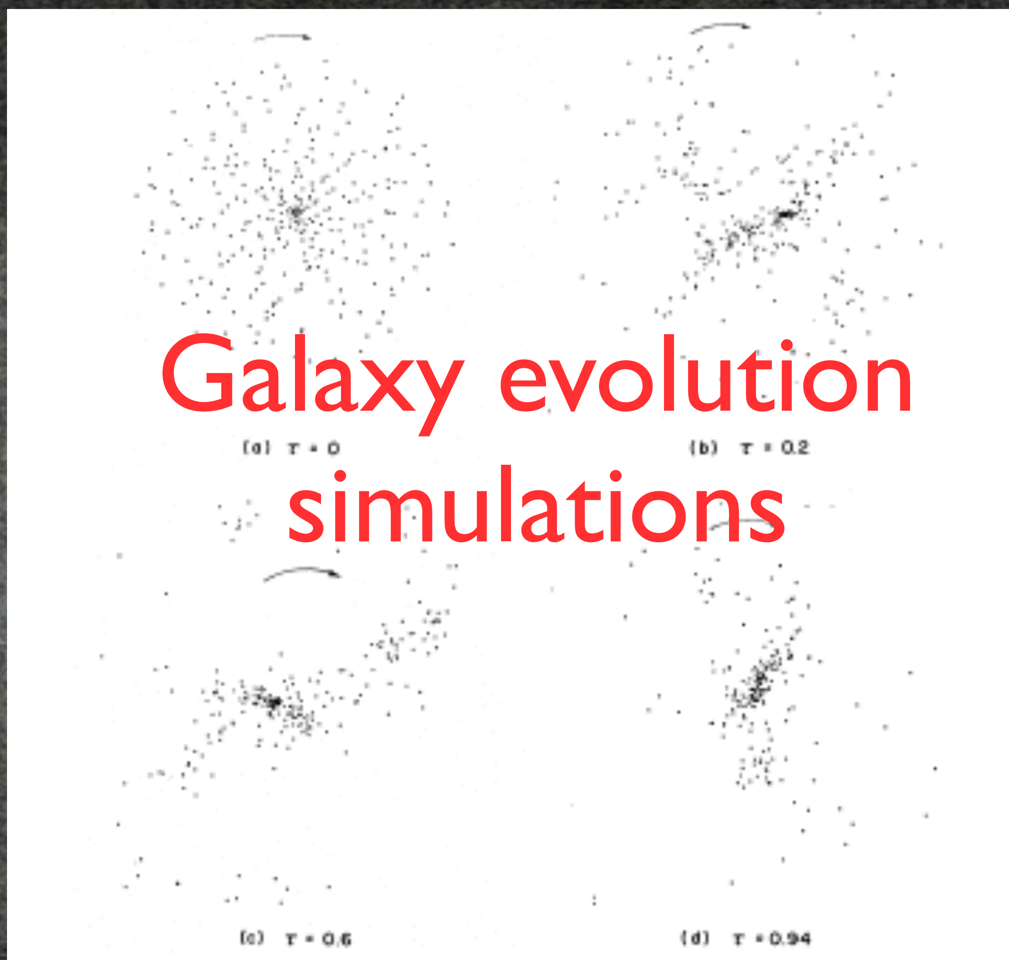
Non-Baryonic

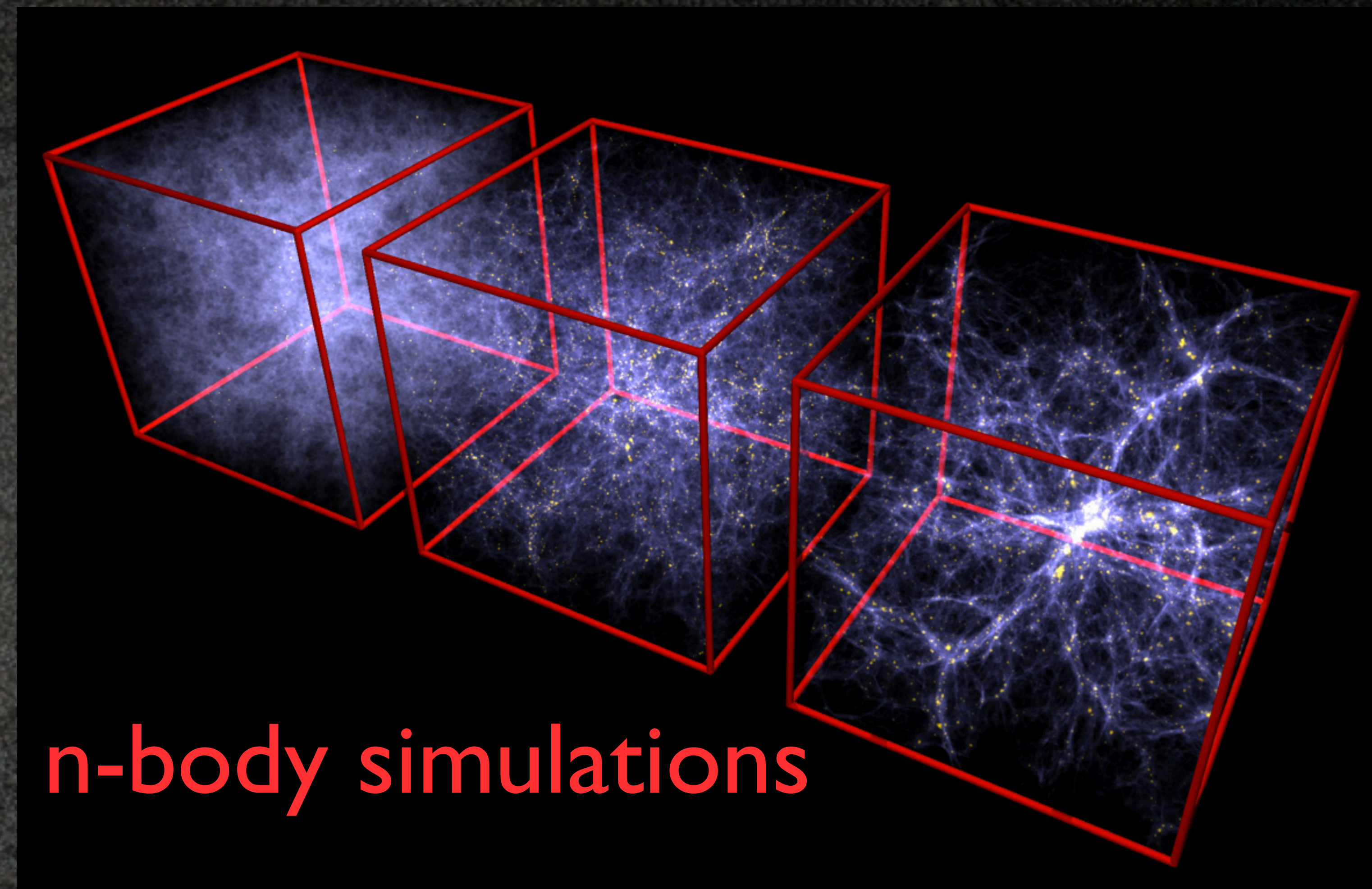
- Indications of the non-baryonic nature of dark matter from:
  - Big Bang nucleosynthesis
  - Cosmic Microwave Background Spectrum
  - Cluster lensing and X-ray data

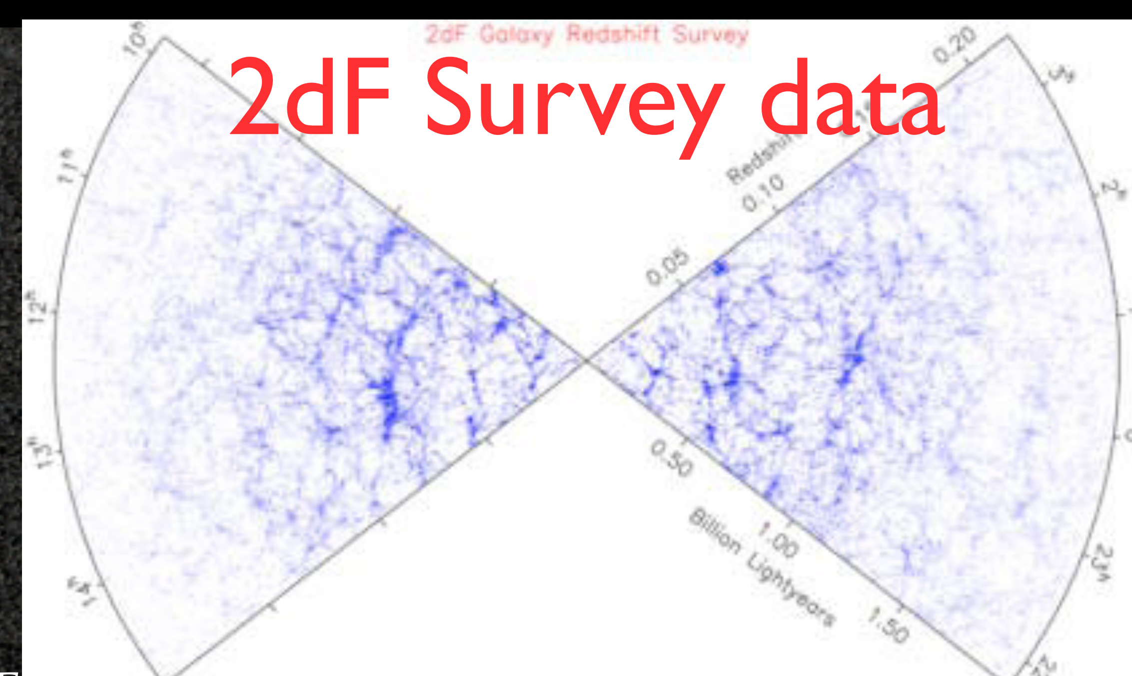




Structure Formation

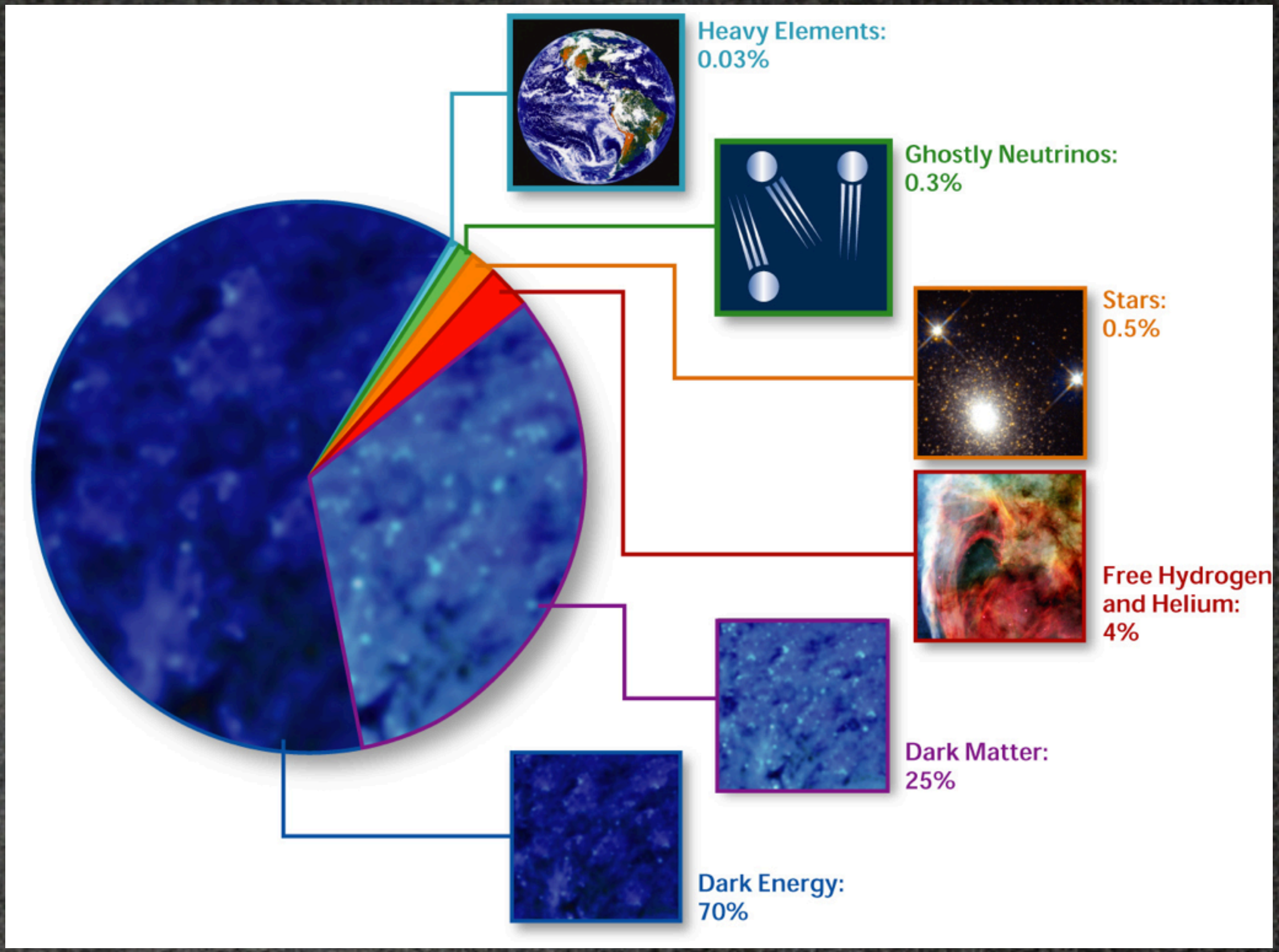


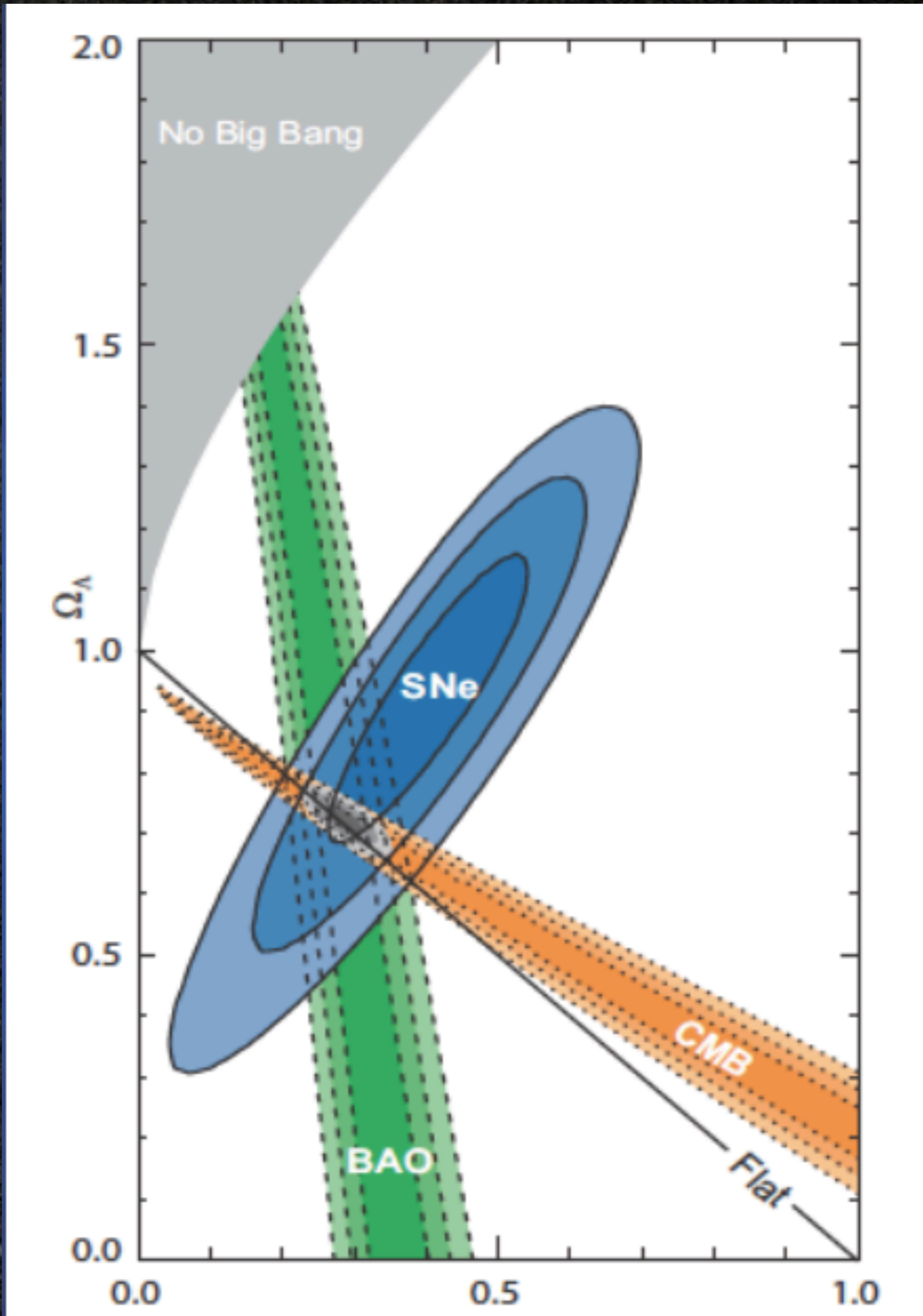




- Simulations of galaxy and cluster formation match observation when cold dark matter is included: and it dominates!

Concordance



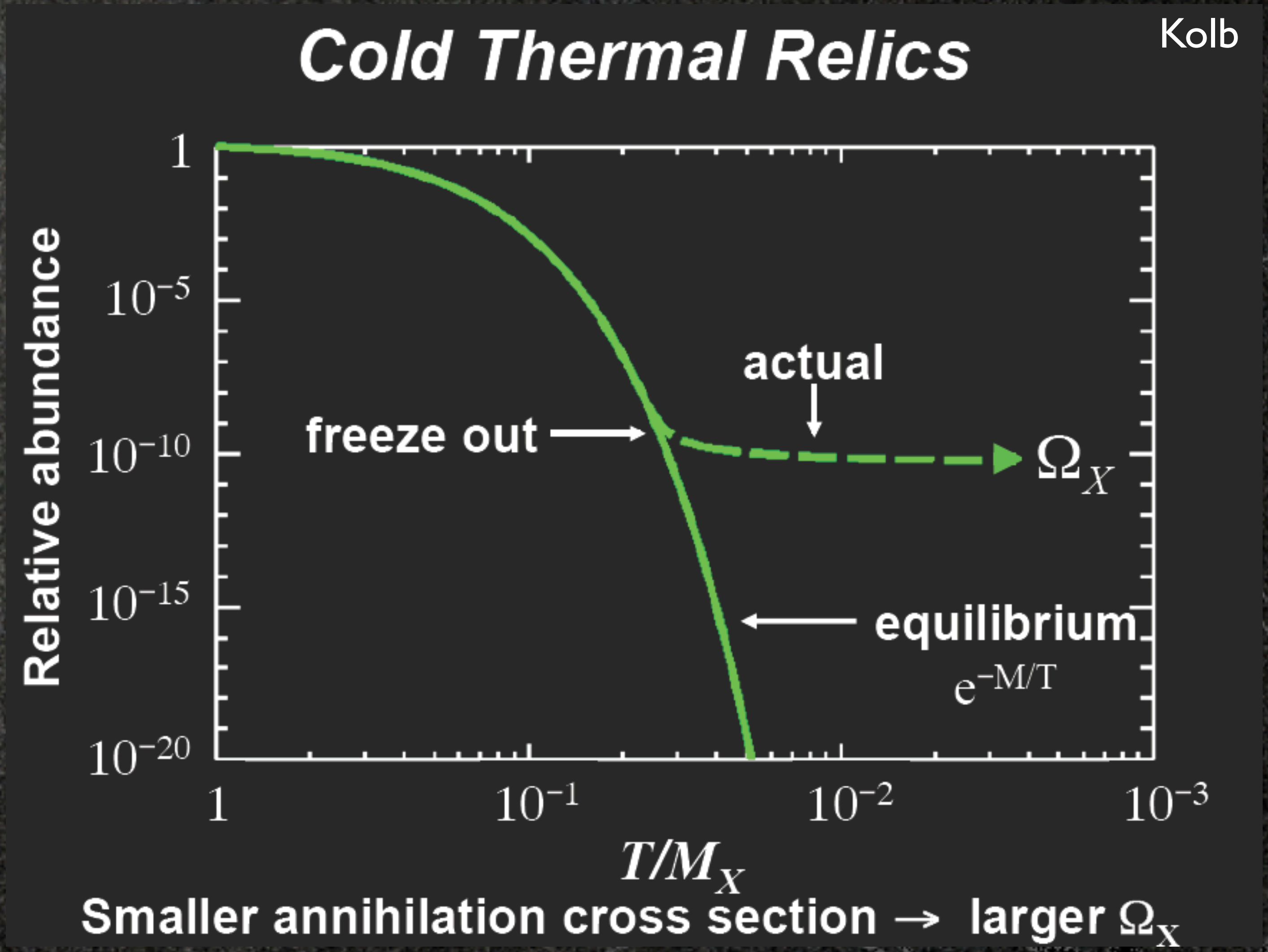


Kowalski et al. 2008

- Isotropy, homogeneity, flat universe, dark energy, cold dark matter, big bang, inflation
- Local Dark Matter density: 0.3 GeV / cm^3

WIMP Miracle

Particles with masses of ~100 GeV and interactions at the weak scale would give current dark matter density of .3 GeV / cm^3



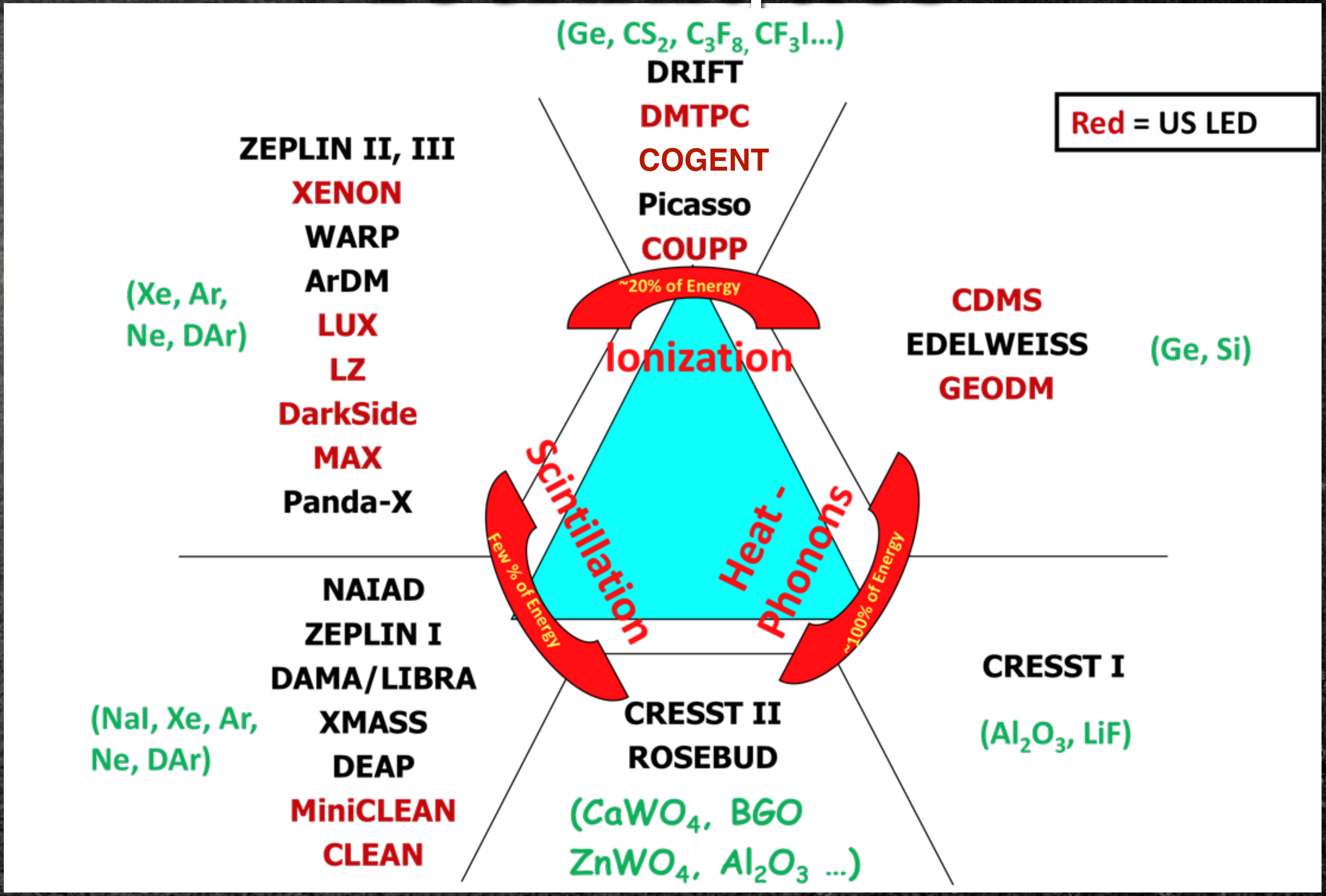
WIMPs fit naturally with SuSY: lightest neutralino, the LSP

Direct Detection Needs

- Ability to see low energy WIMP induced recoils
  - Radiogenically pure
  - Low threshold (< 100 keV)

- Ability to distinguish nuclear recoils
  - Difference between electronic recoils & nuclear recoils
  - Difference between alphas and nuclear recoils
  - Position reconstruction and fiducialization
- Shielding from radiogenic and cosmogenic backgrounds

Direct Detection Techniques



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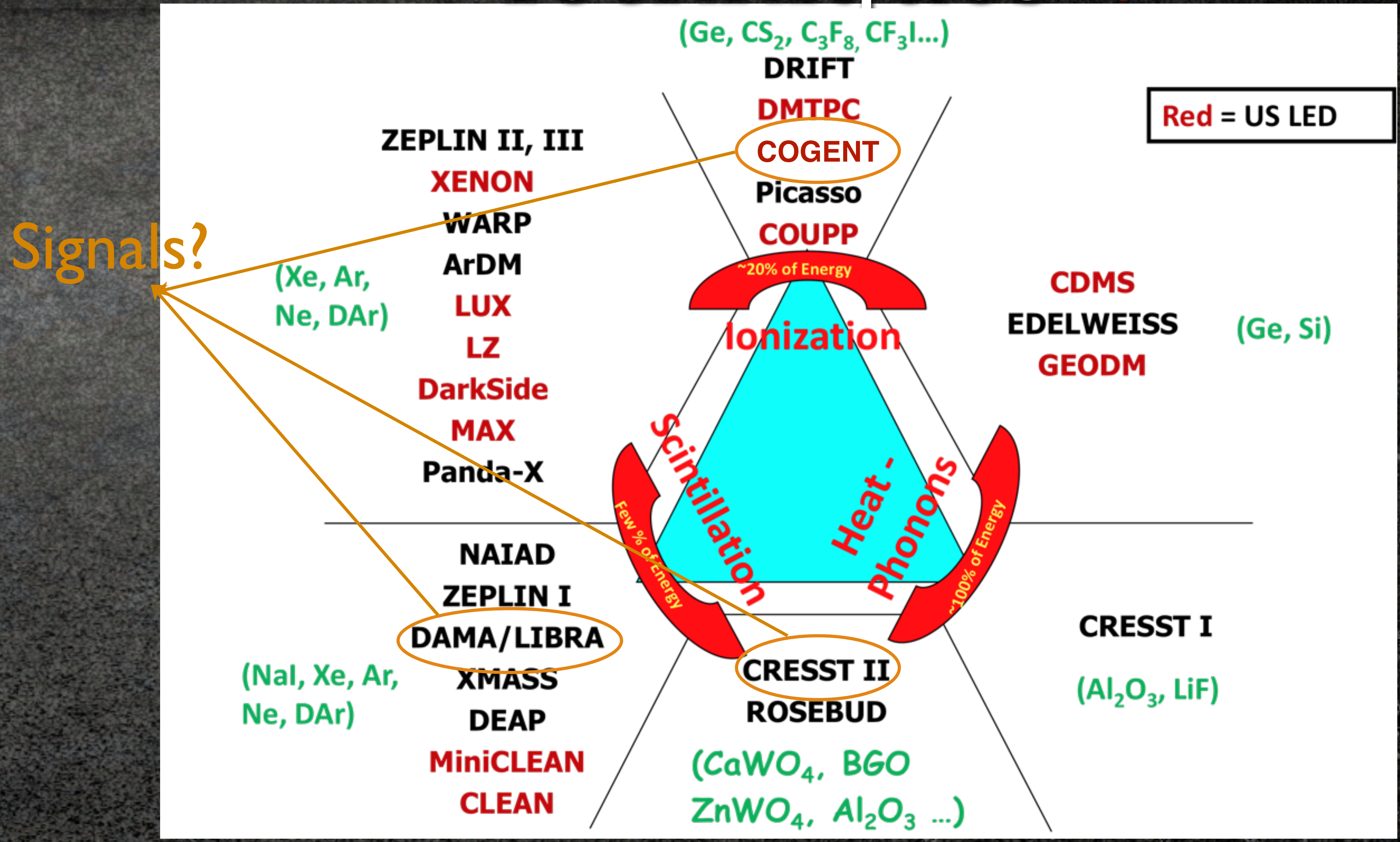

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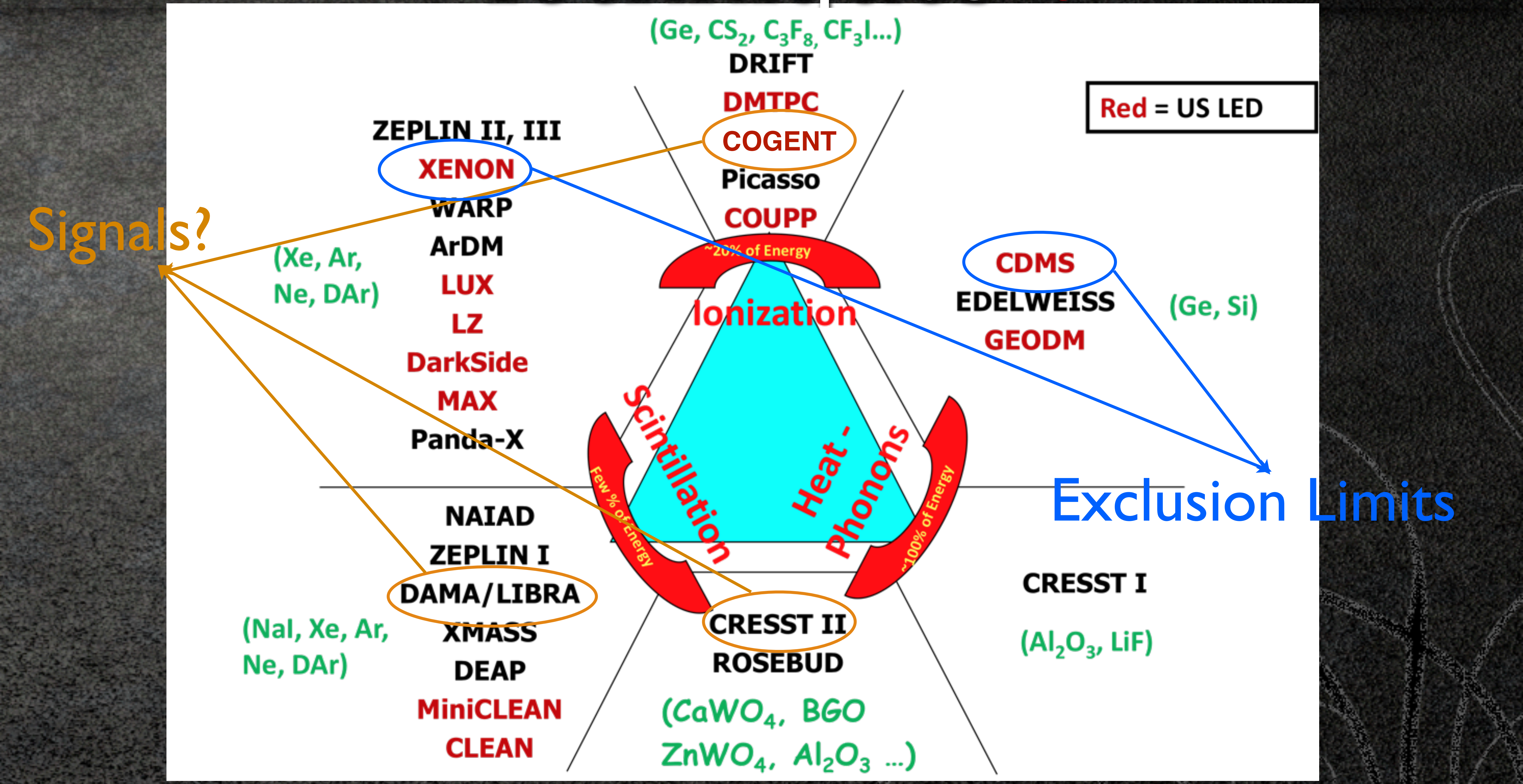
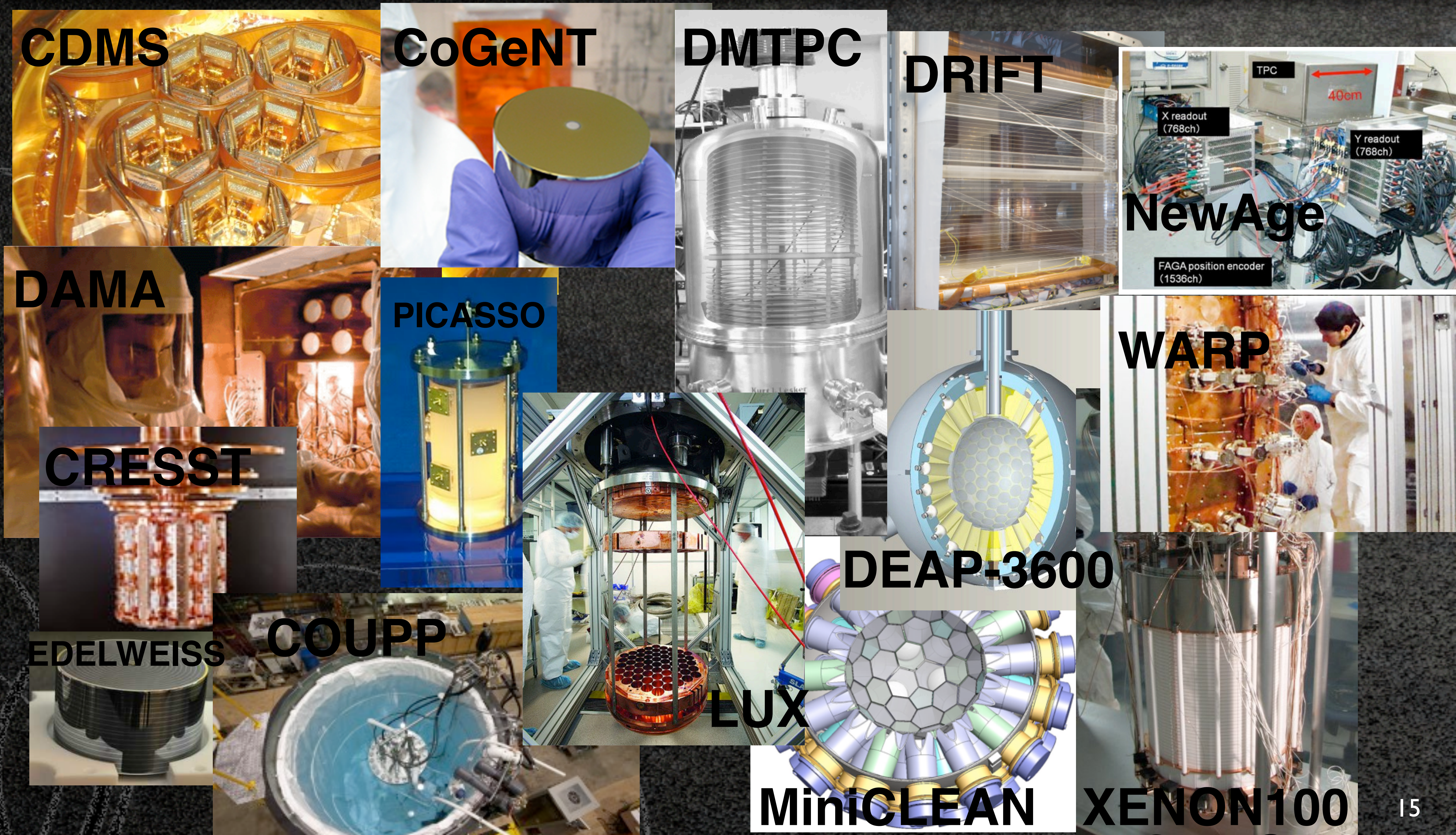
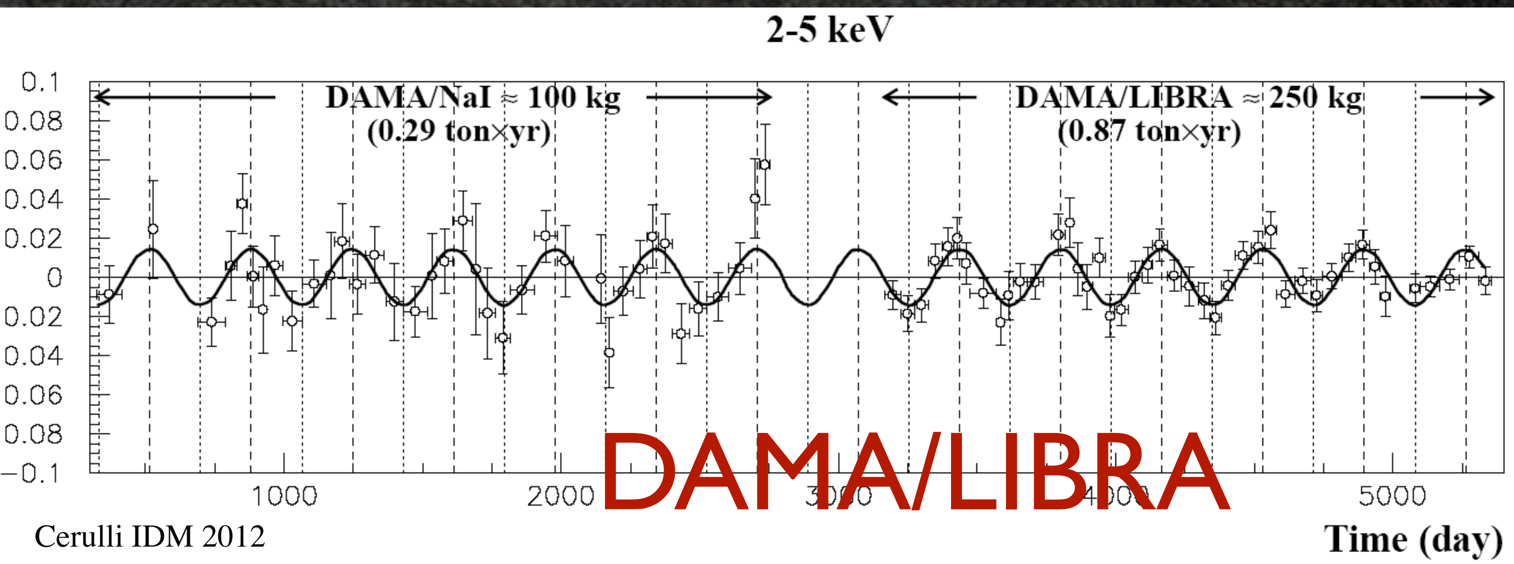


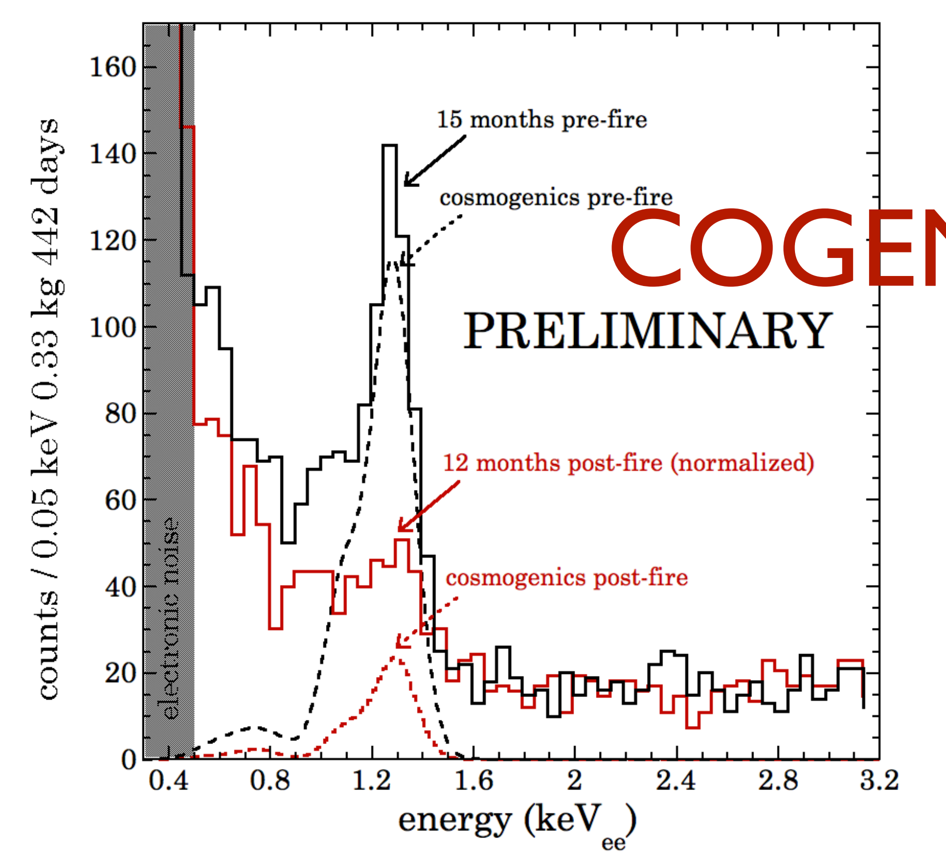
Direct Detectors



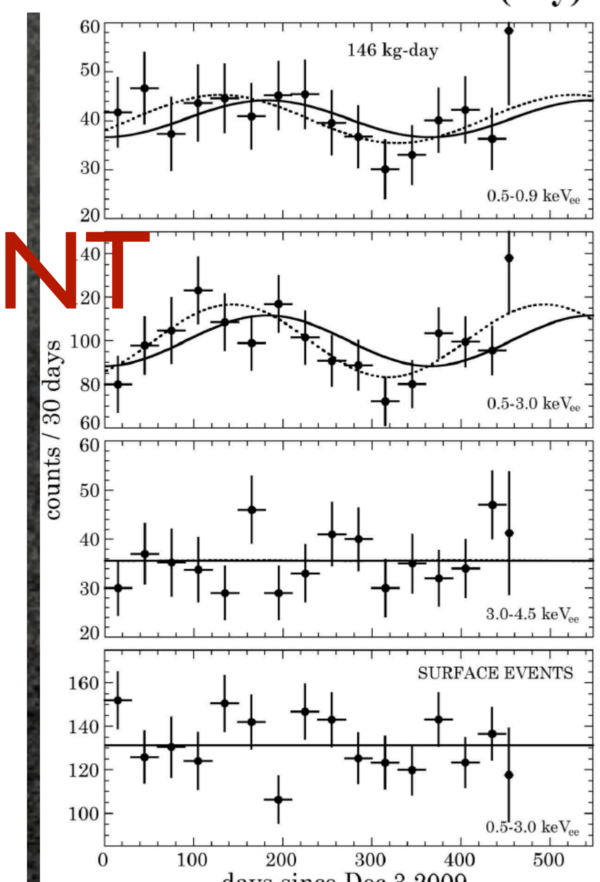
Signals?



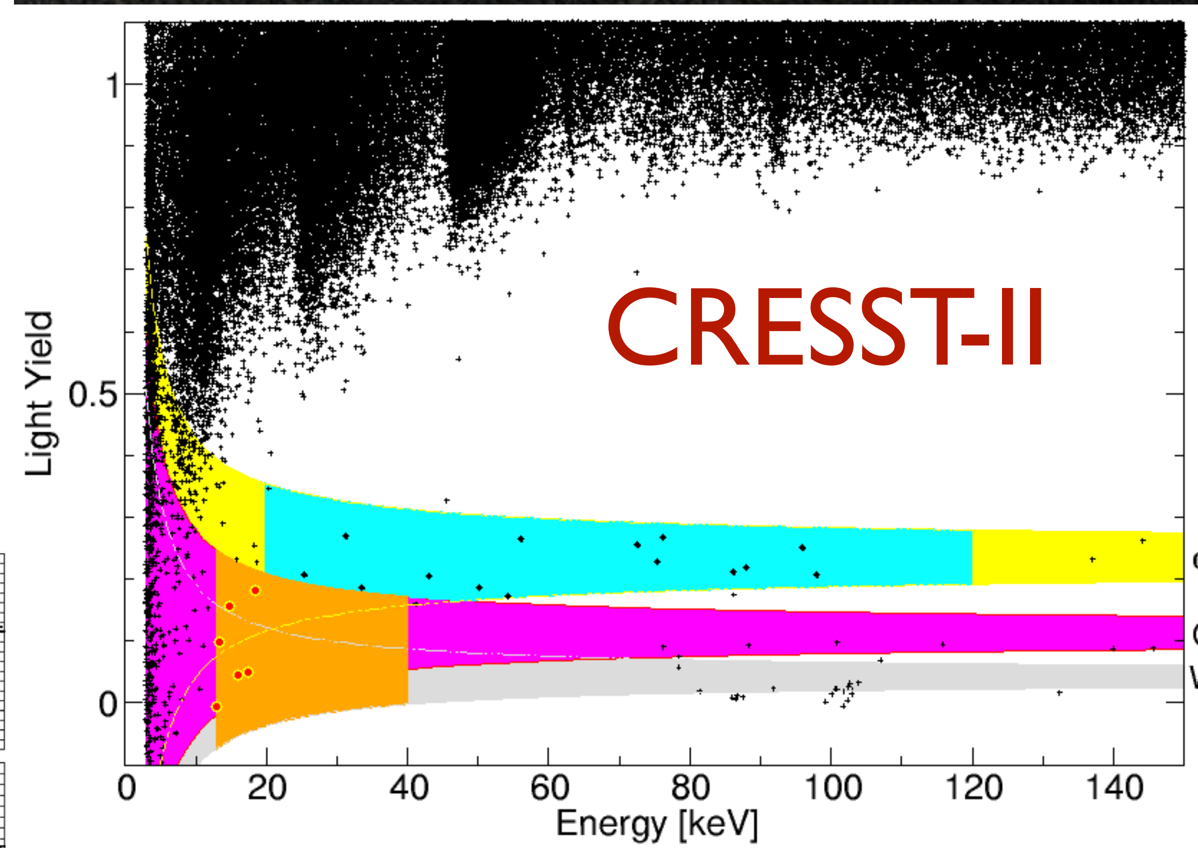
Cerulli IDM 2012



J. Collar IDM 2012



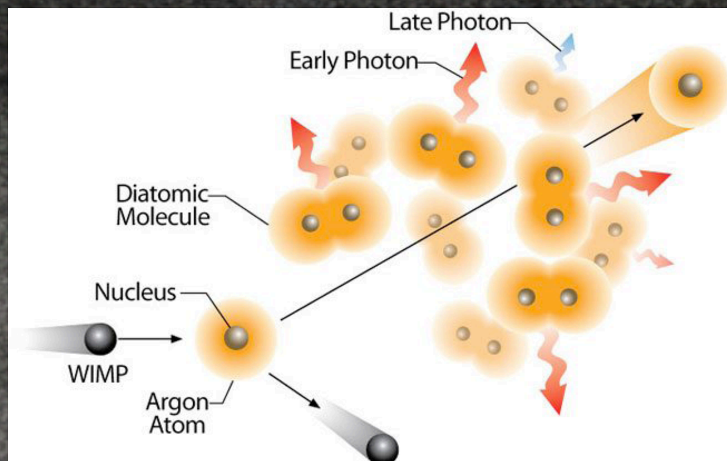
Aalseth et al. arXiv:1106.0650



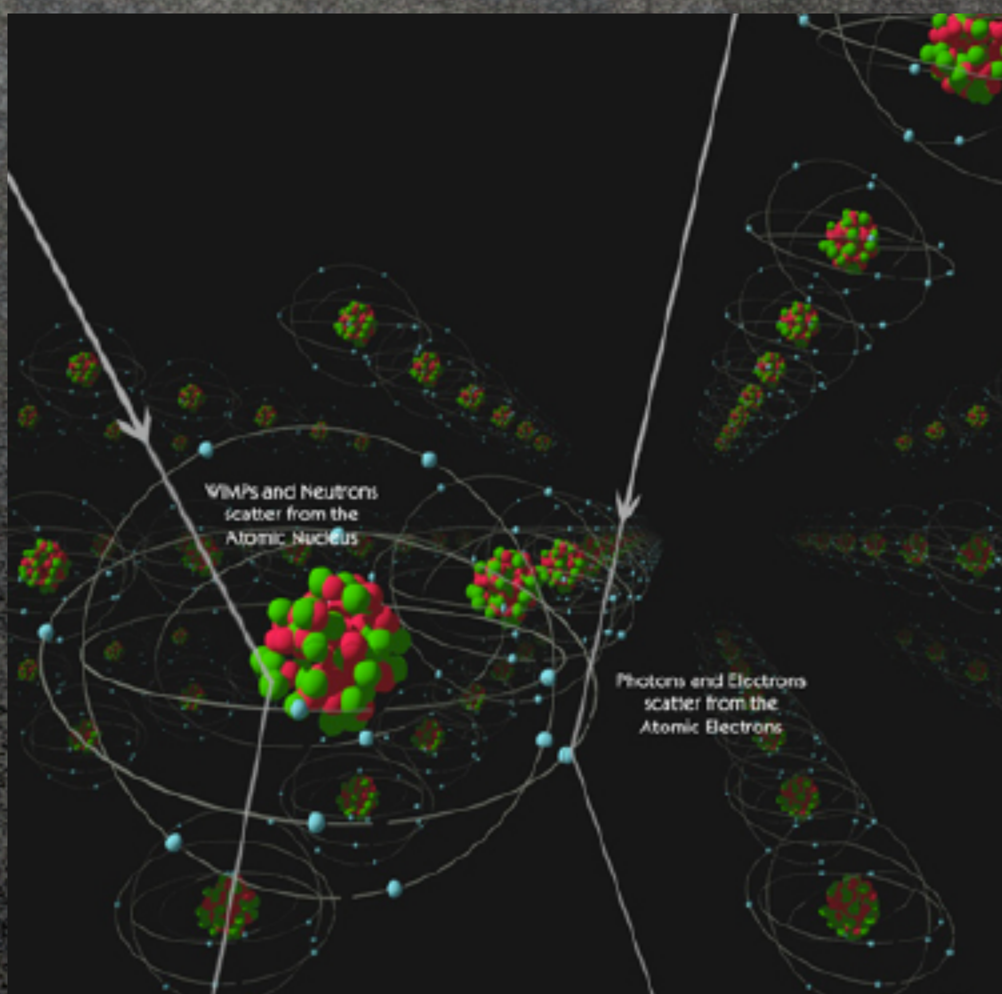
Angloher et al. arXiv:1109.0702

Annual Modulation
and excesses at low energy
Indicate 5-10 GeV WIMP?

Noble Liquid Detection



After a recoil liquid noble atoms ionize, and form dimers, recombine with and then de-excite and create scintillation, the molecules may be in singlet or triplet states with different lifetimes

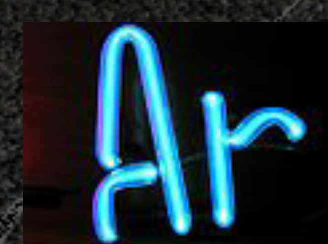


Courtesy Michael Attisha

Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30

Lippincott et al Phys Rev C78; 035801 (2008)



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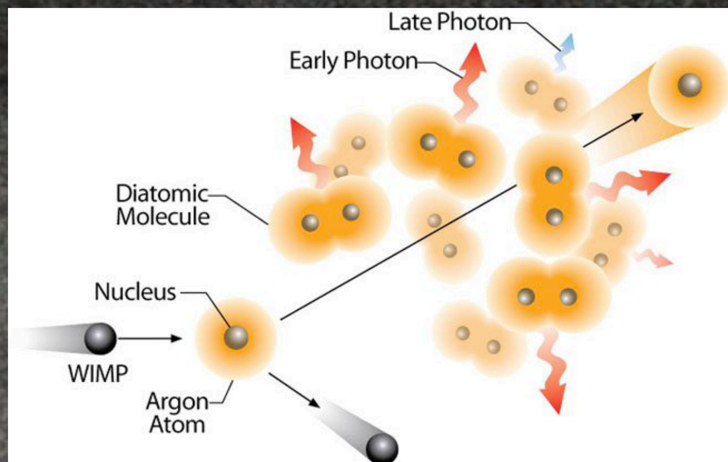

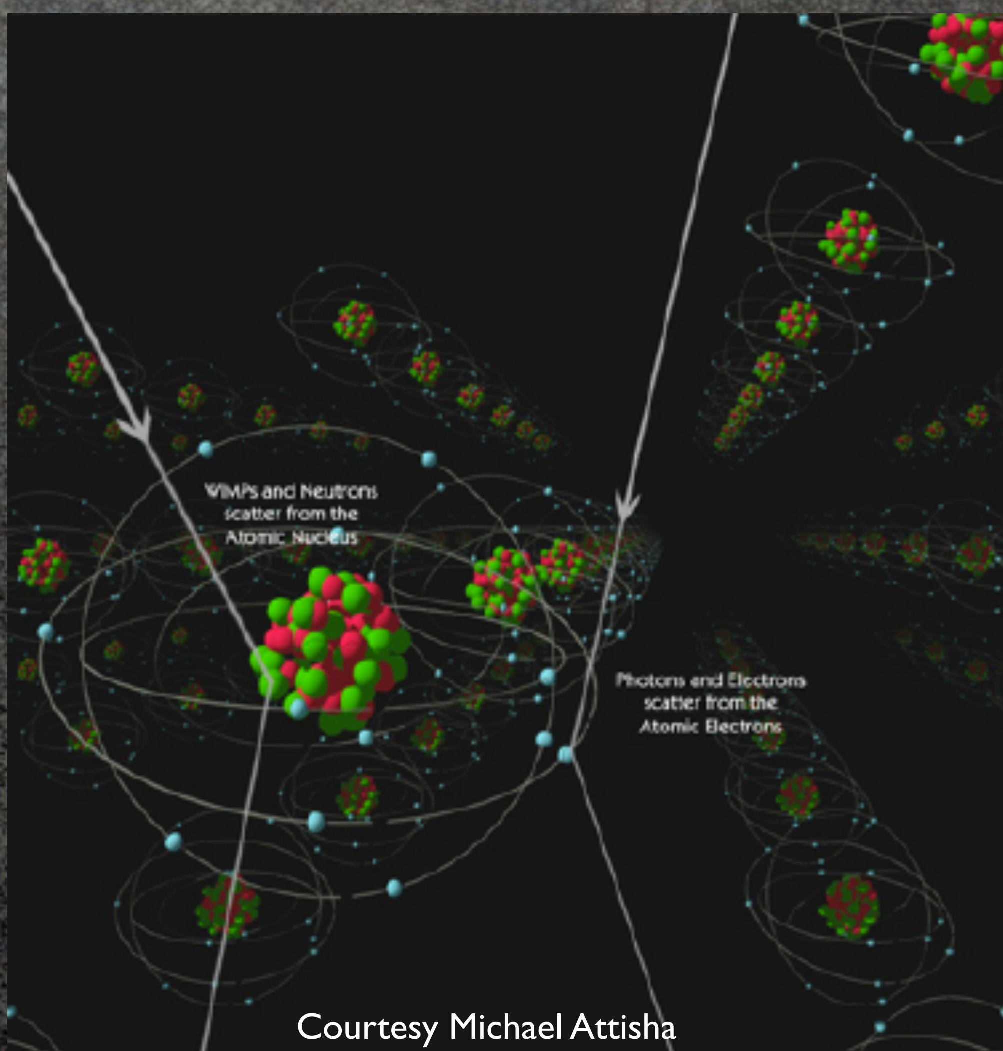

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Xe: Most Light

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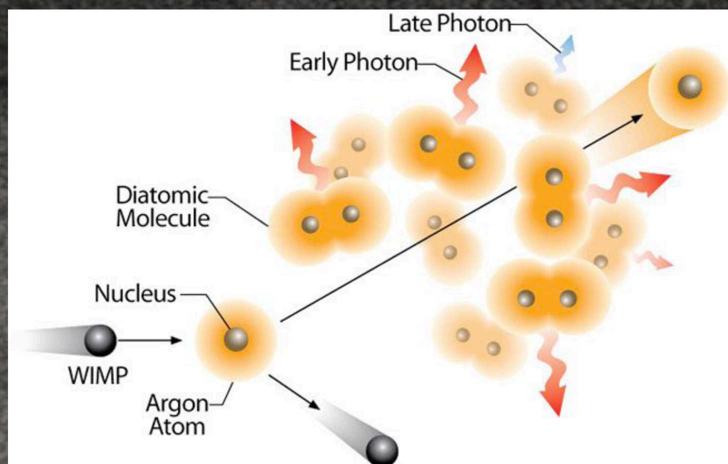

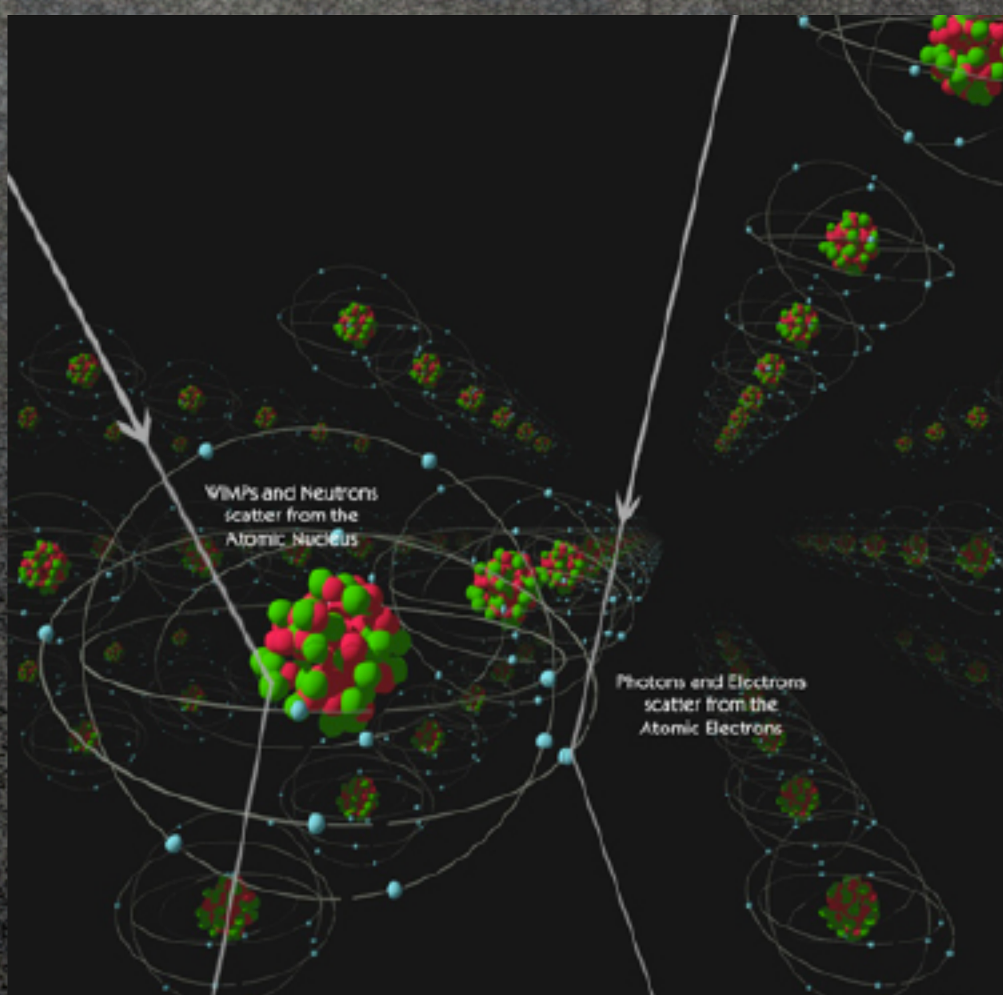

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Xe: UV Light, visible to PMTs

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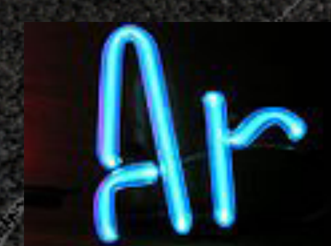

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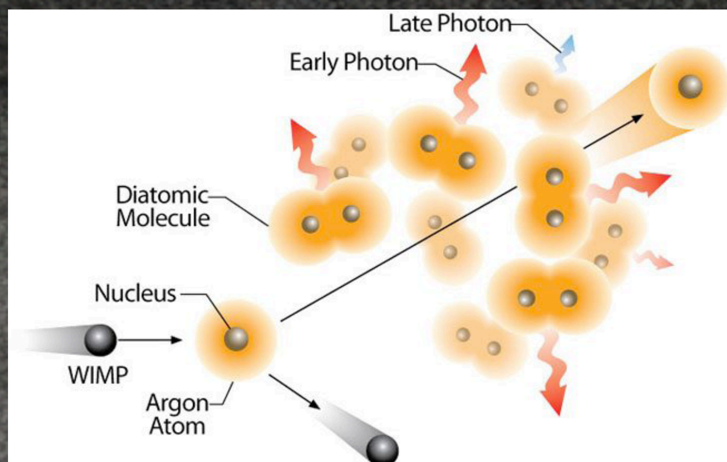

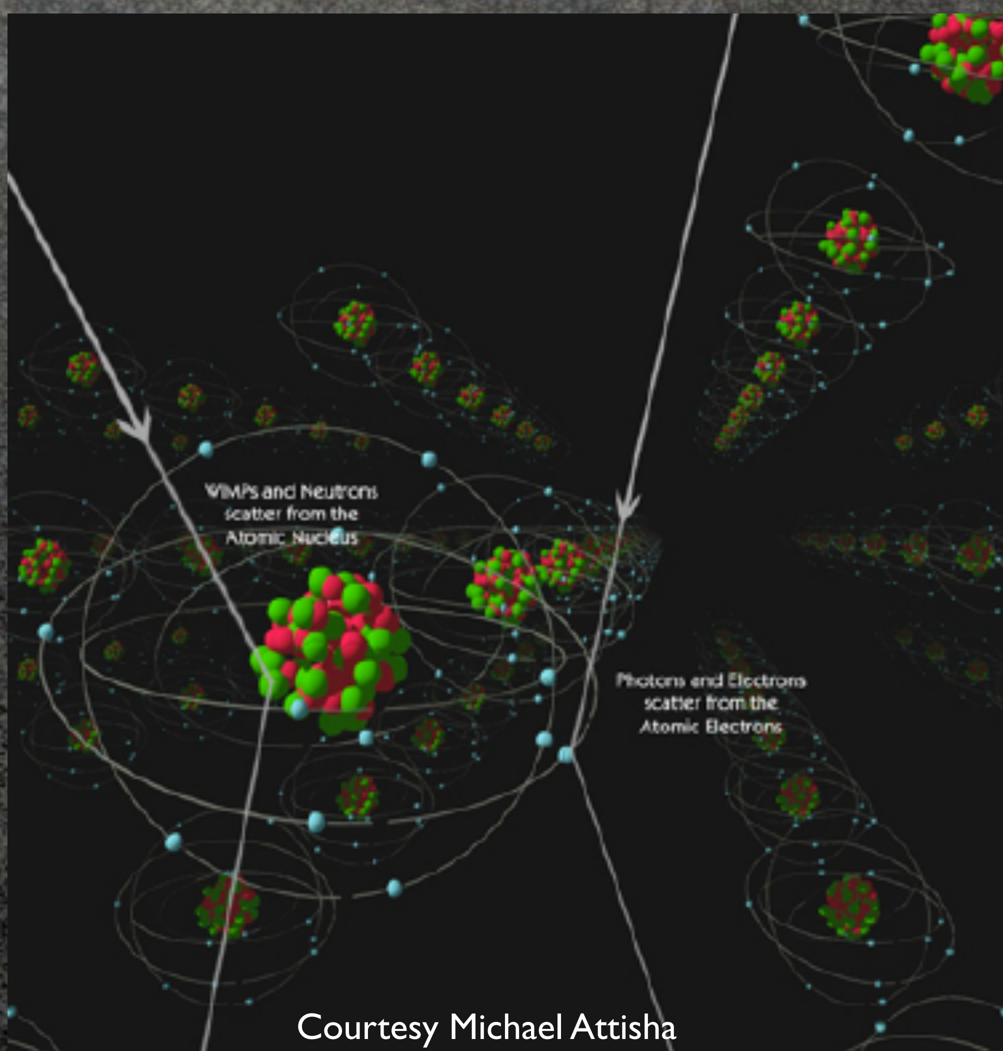

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Ar, Ne: EUV Light, wavelength shifting needed

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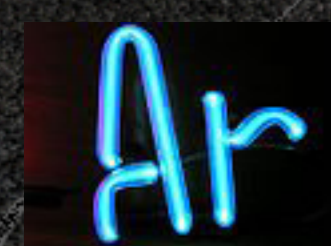

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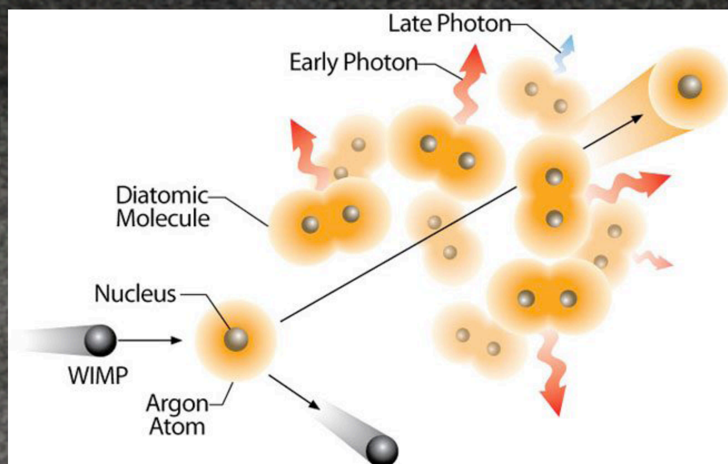

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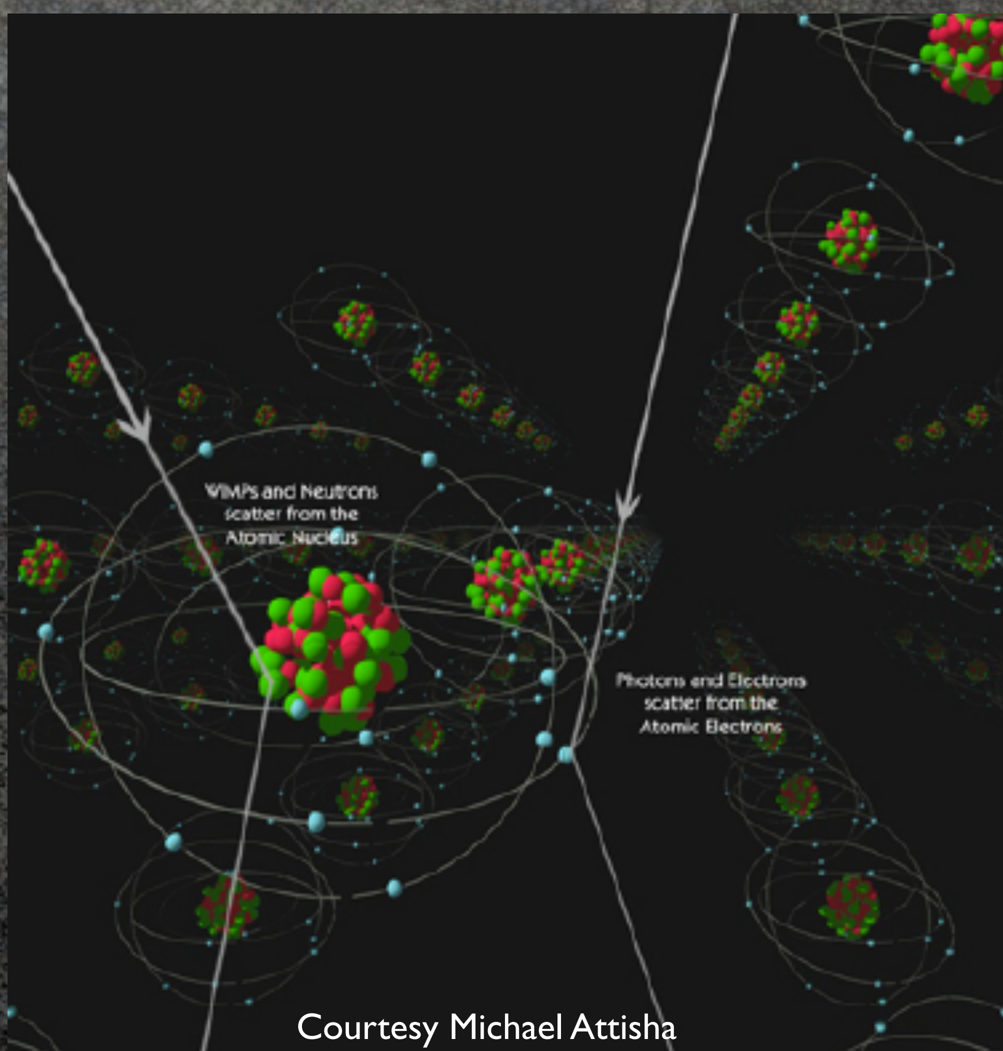
Ar, Ne: Orders of Magnitude time constant differences



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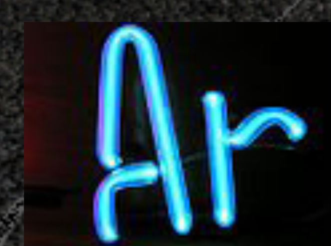

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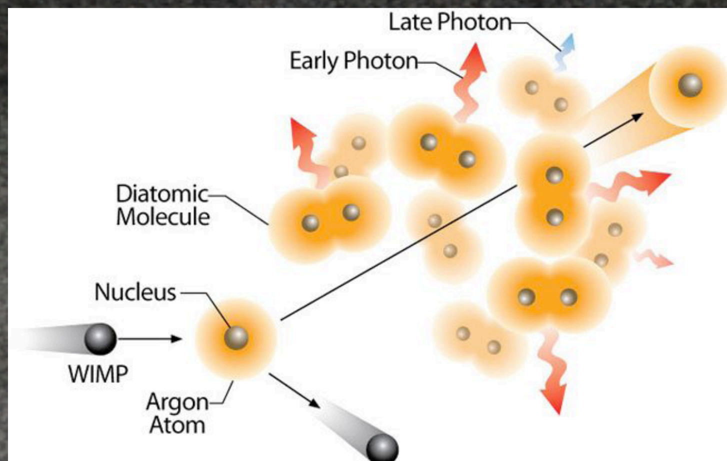

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Ar: Differential populating of singlet and triplet states

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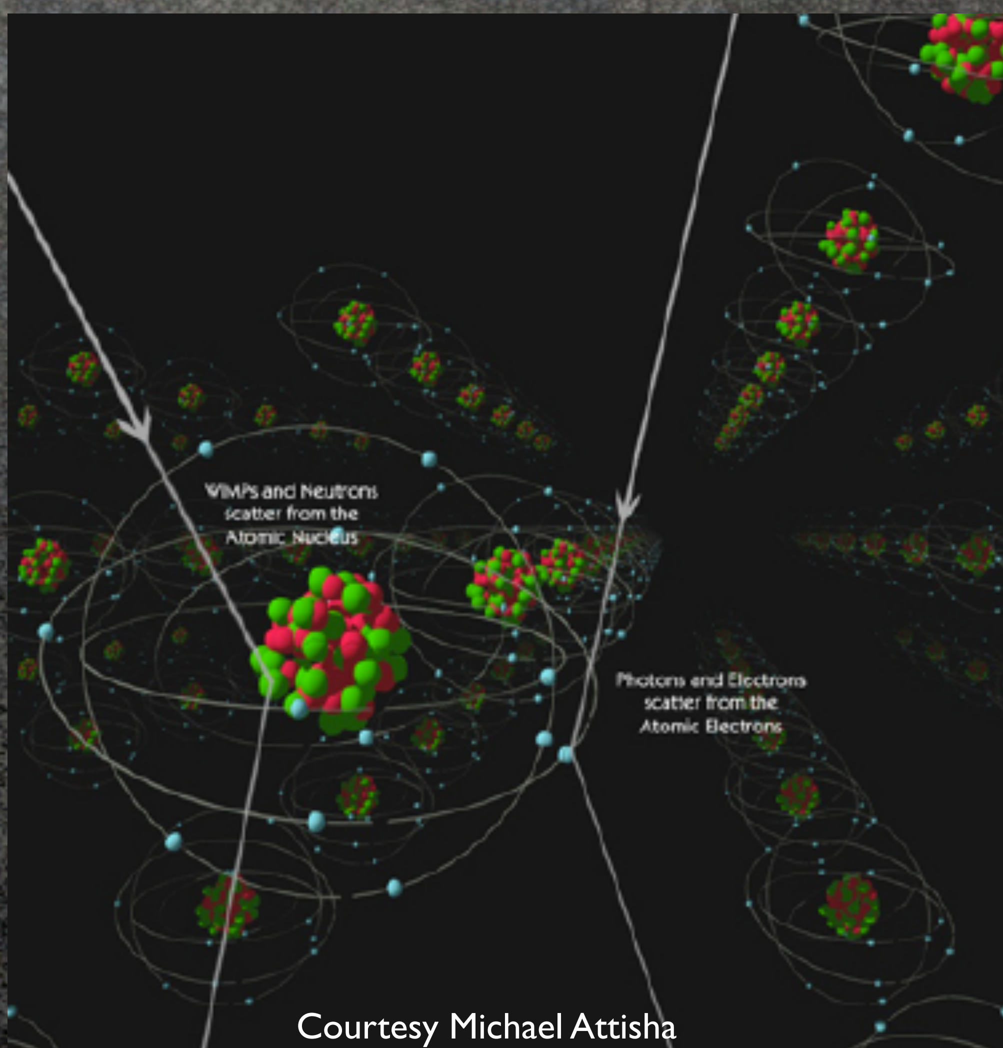

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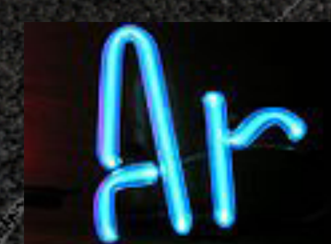
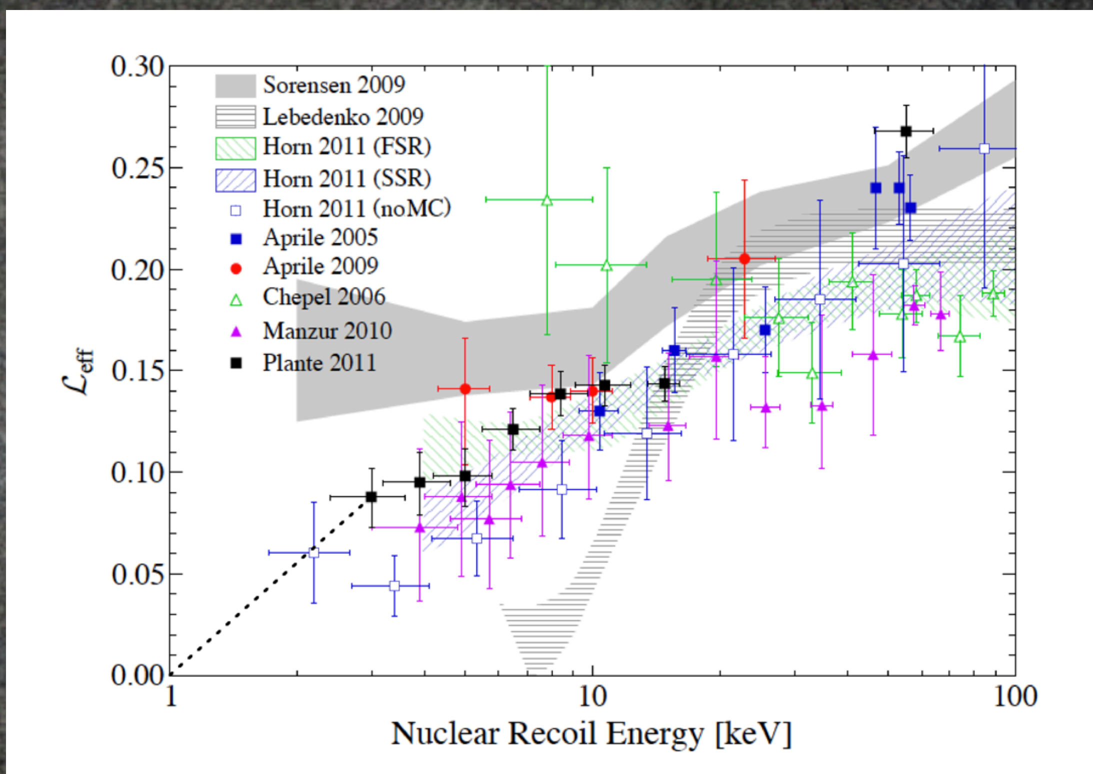


Quenching Factor



J. Collar IDM 2012

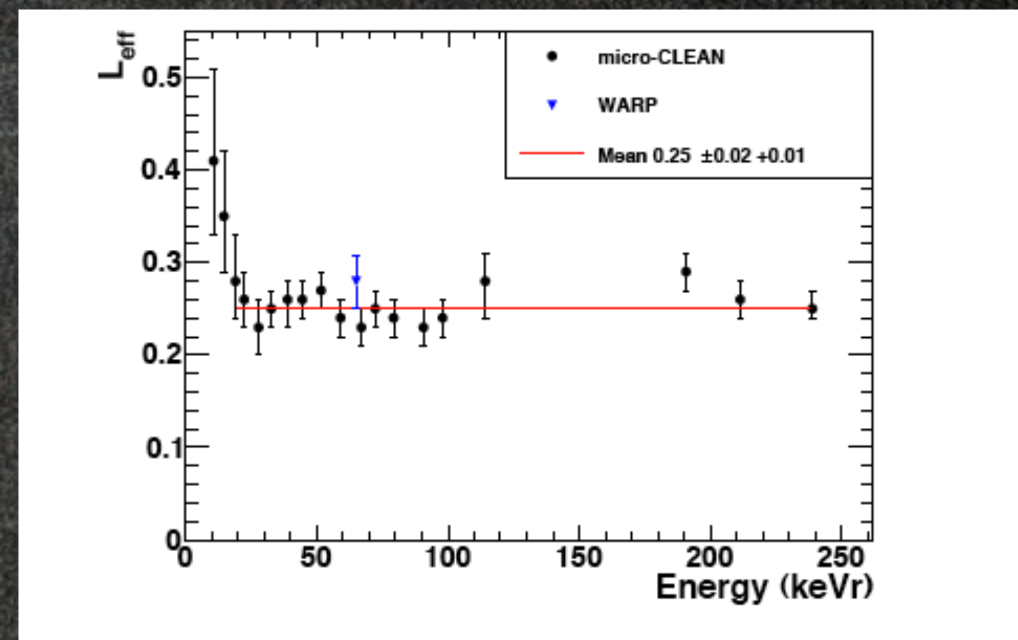


FIG. 8: (Color online) Scintillation efficiency as a function of energy from 10 to 250 keVr. The weighted mean (red line) is generated from the data above 20 keVr and puts the mean scintillation efficiency at 0.25. The value measured by WARP is 0.28 at 65 keVr [3].

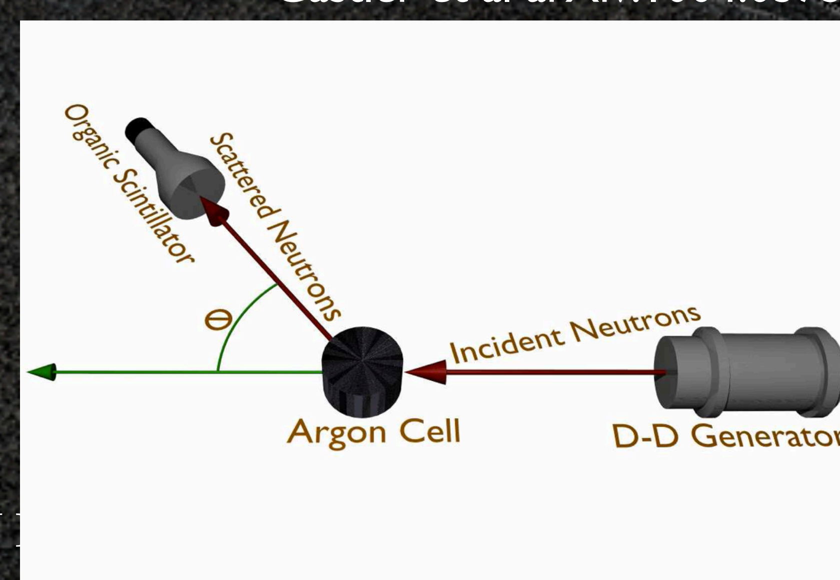
Gastler et al arXiv:1004.0373

Energy difference between nuclear and electronic recoils

Much less controversial than L_{eff} in LXe

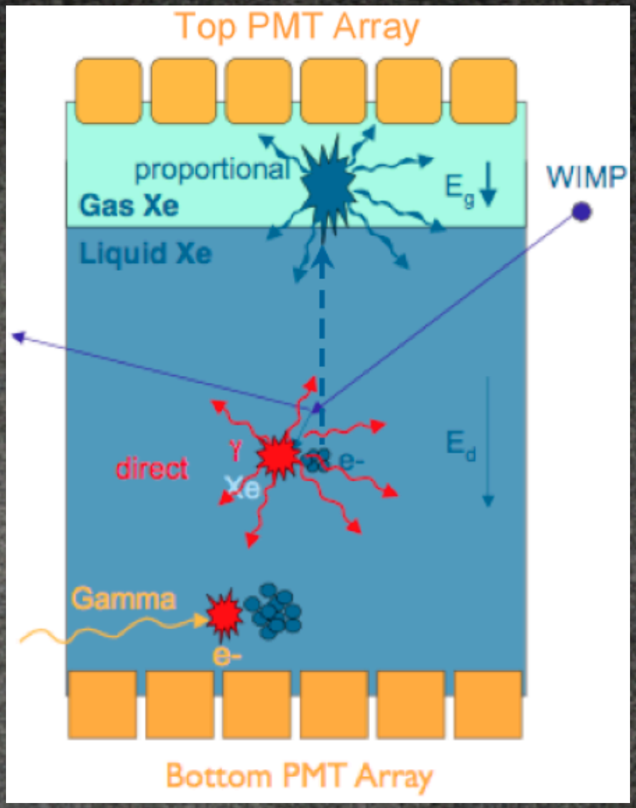
Mean of 0.25 above 20 keVr

MiniCLEAN expected threshold of 12.5 keVee = 50 keVr

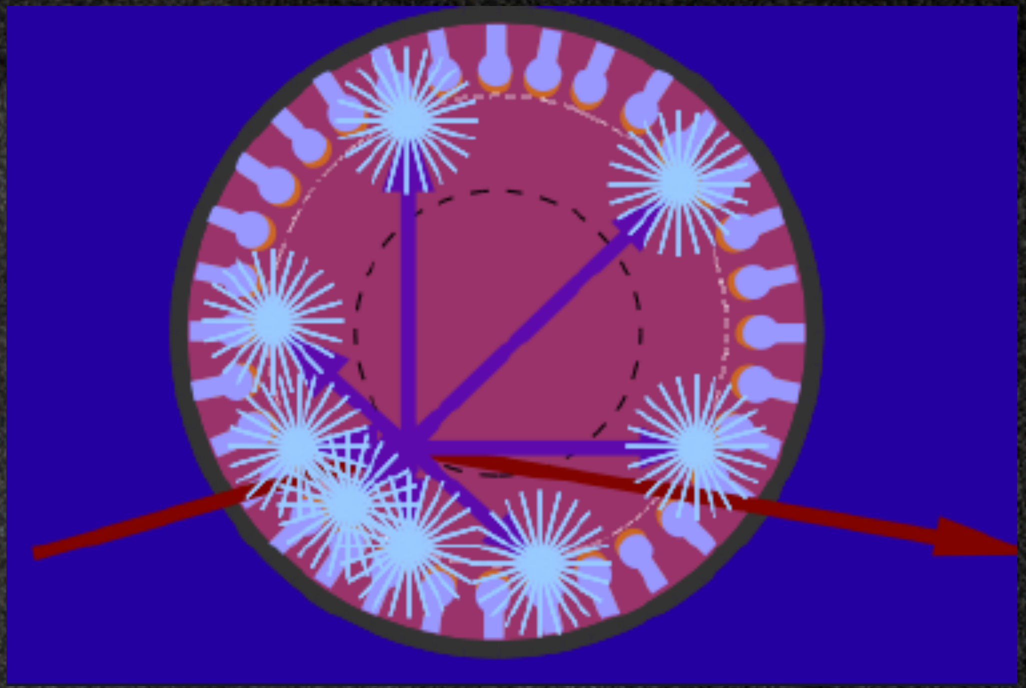


Double vs Single Phase

Double



Single



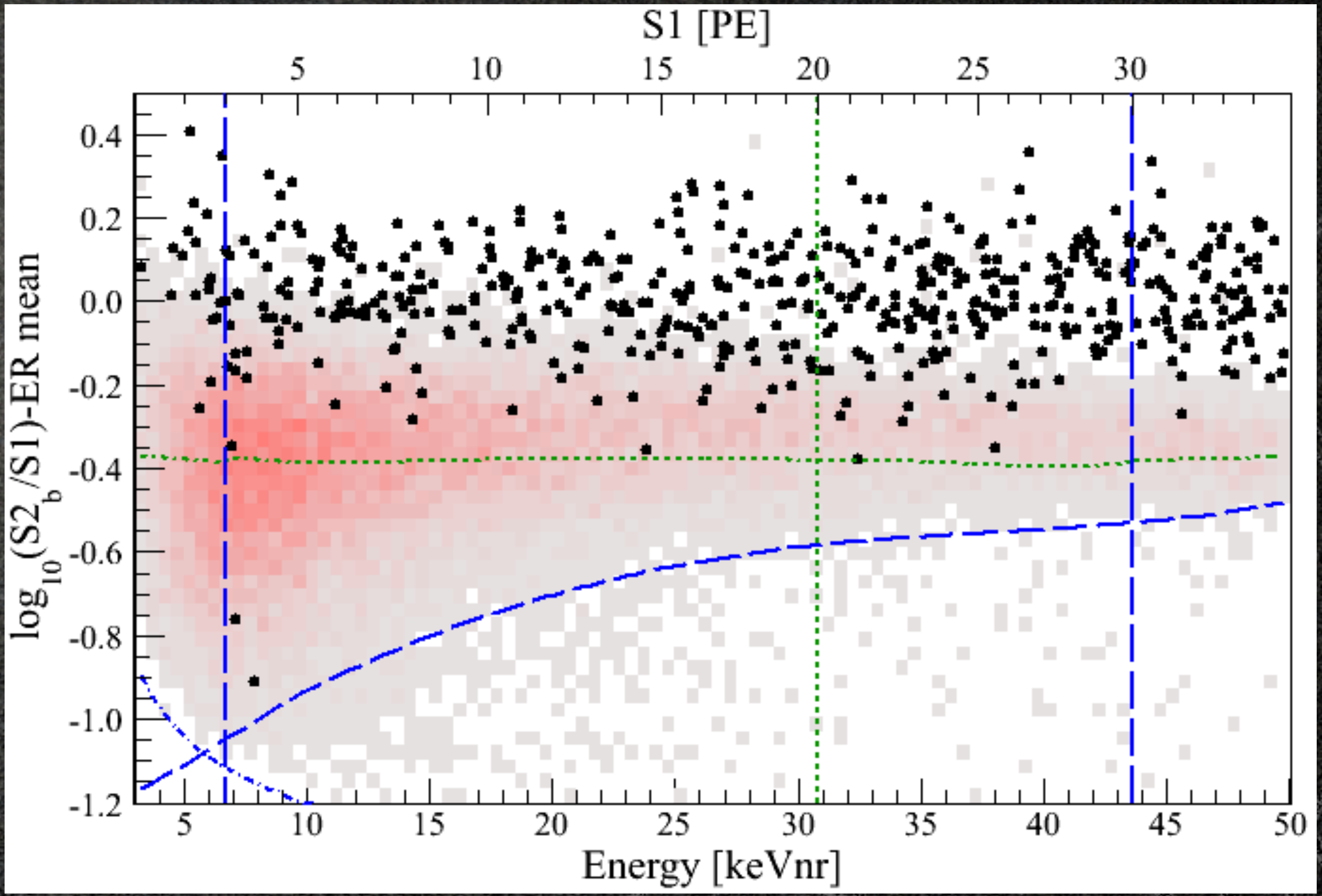
- Ionized and excited states
- Primary Scintillation (S1) with some recombination and de-excitation in the liquid
- Ions drift in TPC electric field
- Amplification region in gas creates proportional light (S2)
- S2/S1 provides particle ID
- Events are hundreds of microseconds (set by electron drift velocity)
- Strong position reconstruction

- Ionized and excited states
- Scintillation with recombination and de-excitation in the liquid
- Pulse shape discrimination provides particle ID
- Events are tens of microseconds (set by triplet lifetime)
- Position reconstruction with charge distribution, t.o.f. with larger detectors

Xenon 100

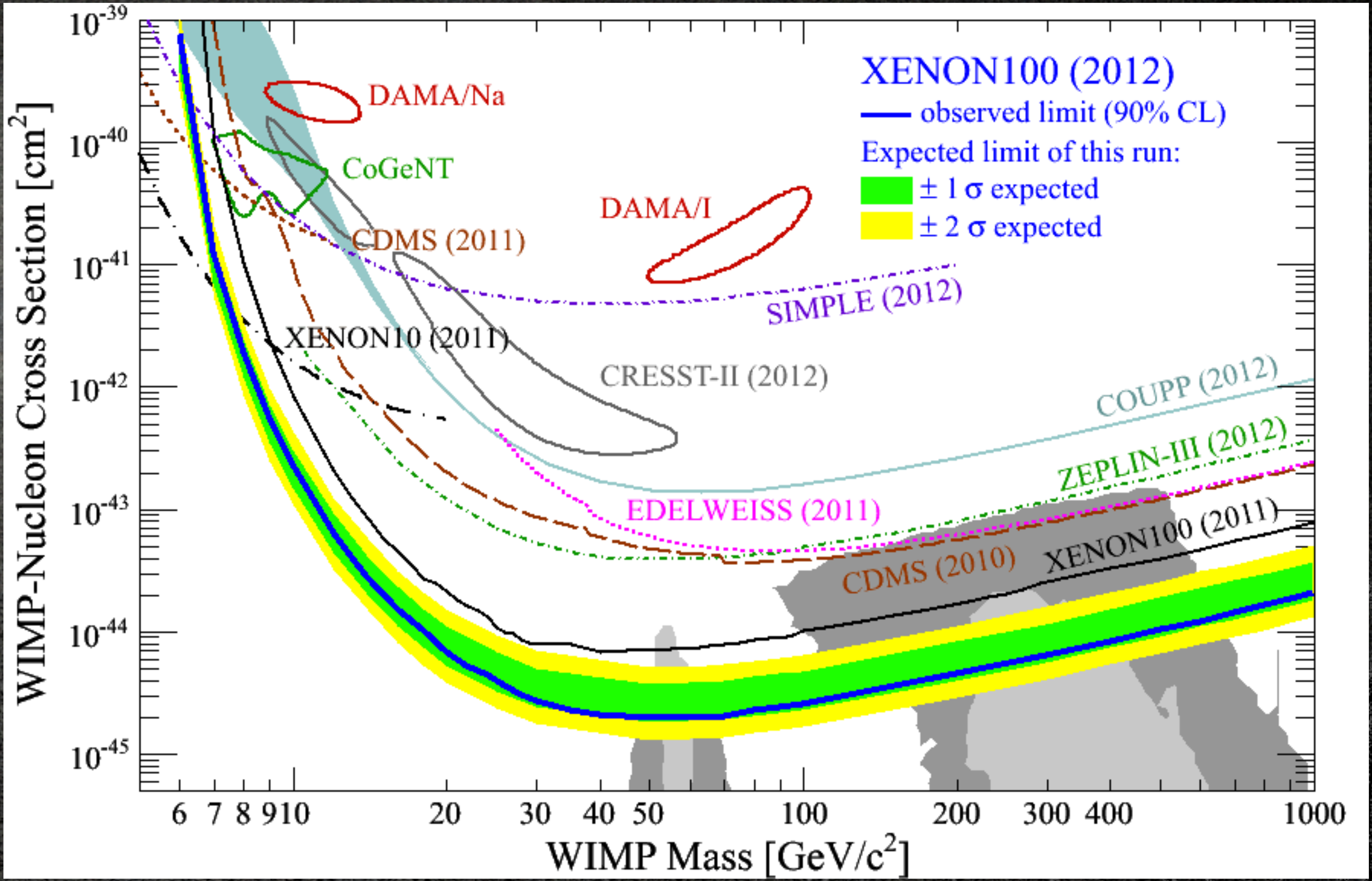
2 events on background of 1.0 +/- 0.2

Likely to be due to gamma backgrounds in regions inaccessible to charge amplification coincident with other gammas (informally from the Xenon 100 collaboration)



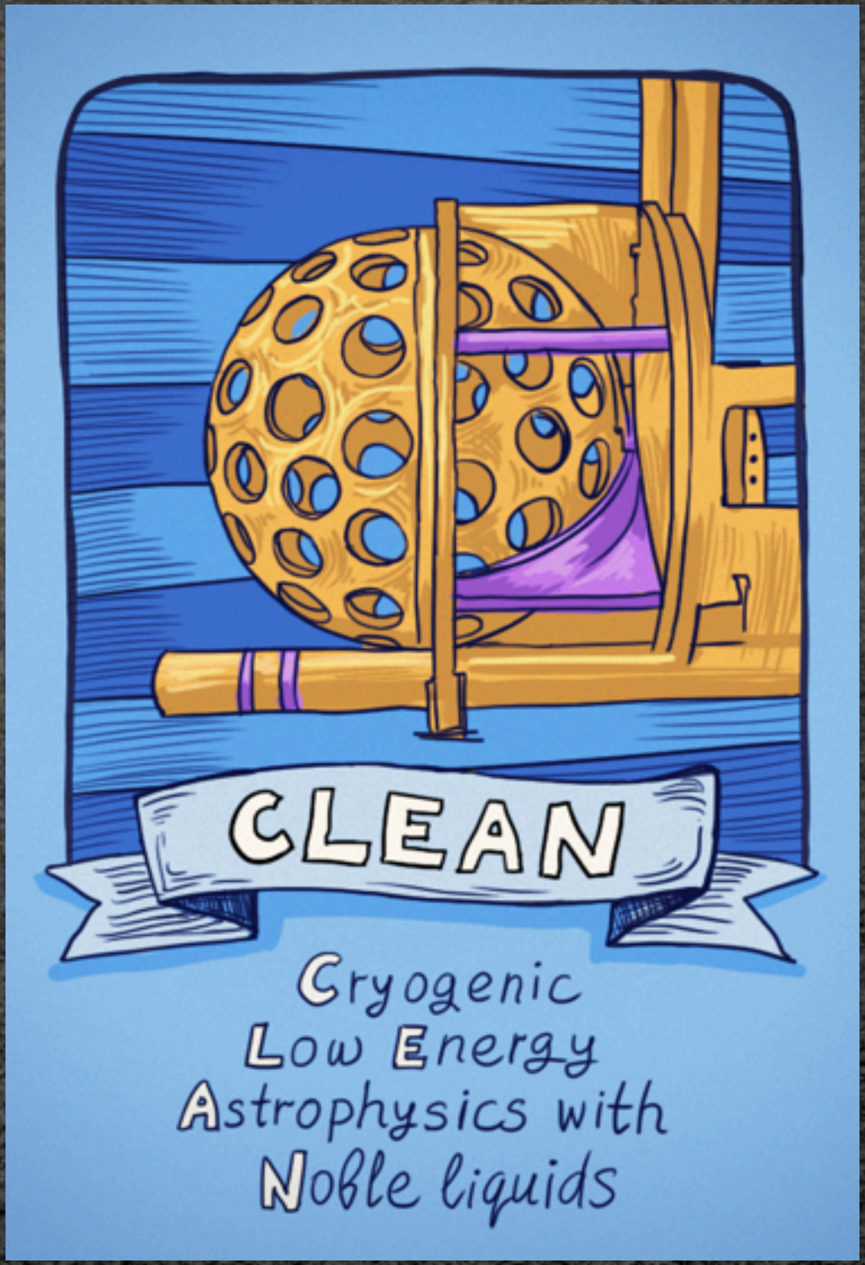
Melgarejo IDM 2012

Current Limits



Melgarejo IDM 2012 arXiv: 1207.5988

MiniCLEAN



CLEAN

AREA OF RESEARCH:
Direct detection of dark matter and low-energy neutrinos

TECHNOLOGY:
Single-phase liquid argon detector

FUN FACT:
CLEAN can operate with interchangeable targets of liquid argon and liquid neon

INSTITUTIONS:
Boston University; Los Alamos National Laboratory; MIT; National Institute of Standards and Technology; Royal Holloway University of London; SNOLAB; Syracuse University; University of New Mexico; University of North Carolina, Chapel Hill; University of Pennsylvania; University of South Dakota; Yale University

CLEAN

TARGET:
LAr, LNe

Mass:
500 kg target, 150 kg fiducial

Light collection:
92 8" Hamamatsu R5912-02 MOD PMTs

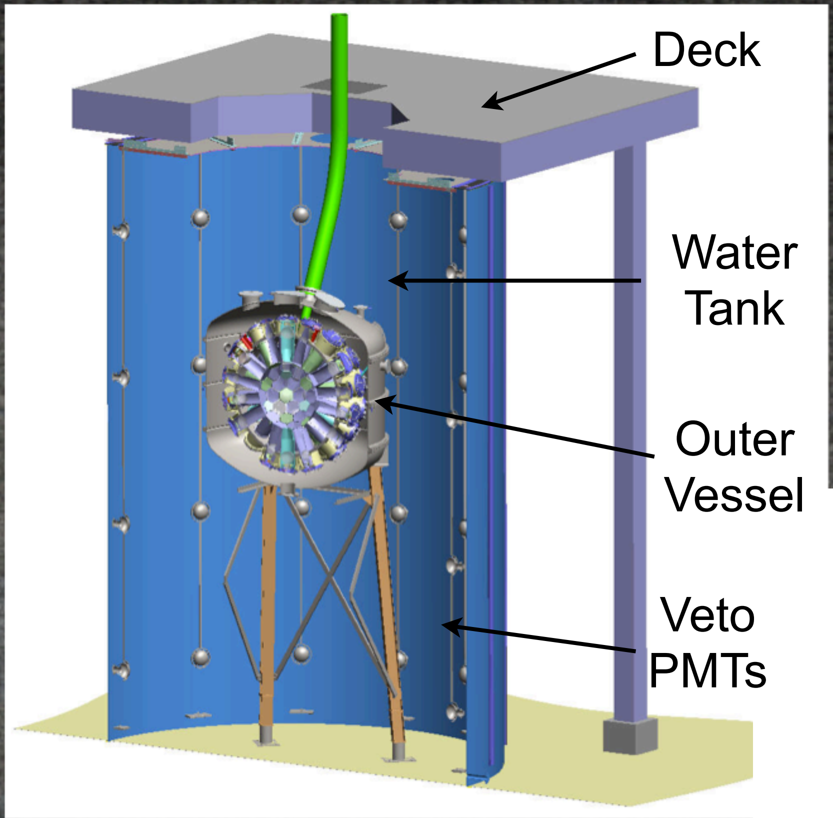
Vessel:
stainless steel, with modular optical cassettes inserted

Shielding:
10 cm acrylic & 20 cm Ar, in ~8m water shield

Sensitivity:
SI cross section 2 x10^{-45}cm^2

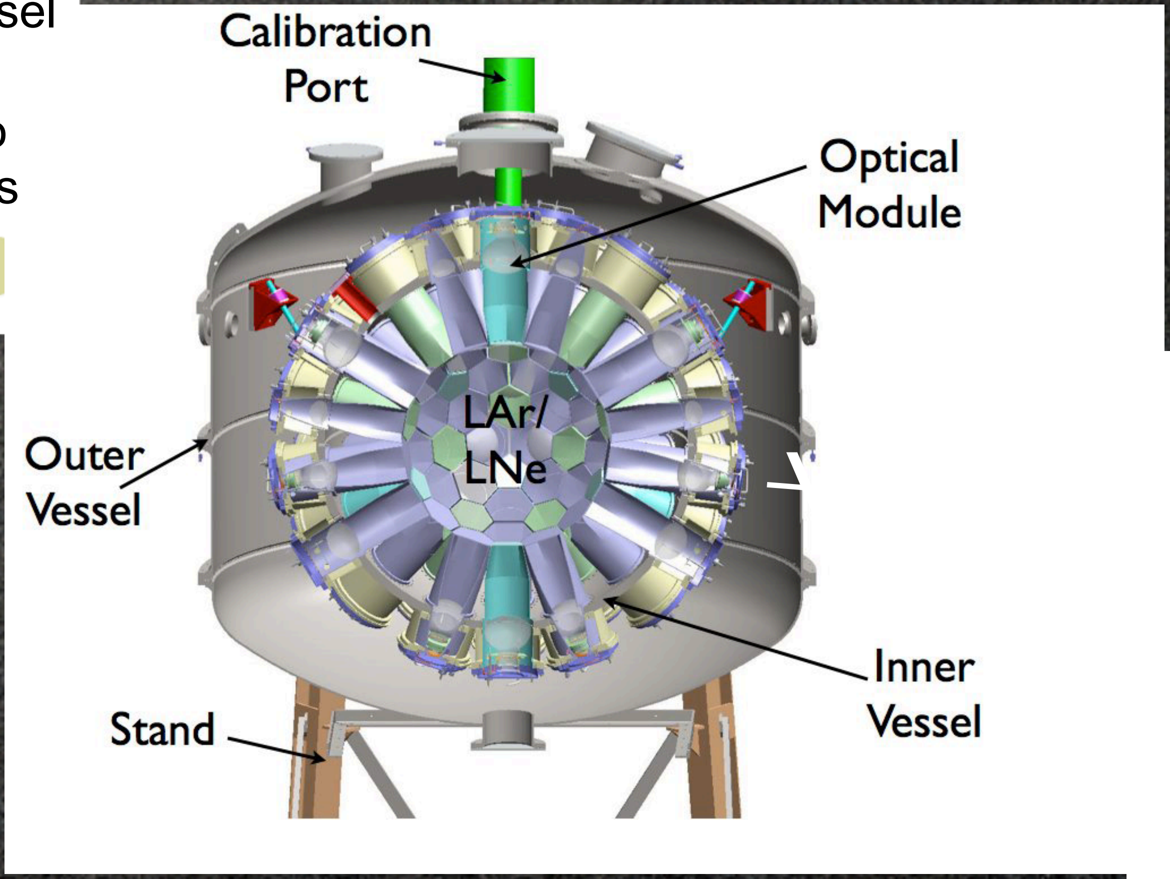
http://www.symmetrymagazine.org/article/november-2012/voyage-to-snolab

MiniCLEAN Design

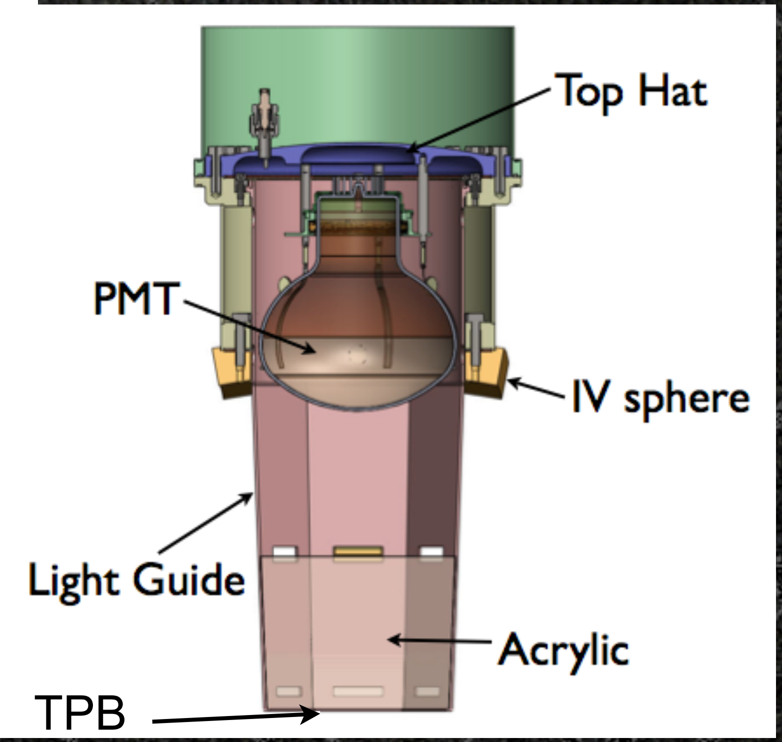


Outer Vessel: ~1.25 m radius
Inner Vessel: ~ .7 m diameter,
~500 kg LAr
Target radius: ~.4 m
Fiducial radius: ~.3 m, 150 kg LAr

Water veto tank:
25 ft. tall
18 ft. diameter
48 veto PMTs
~1.5 m water on sides
~3.5 m water from bottom



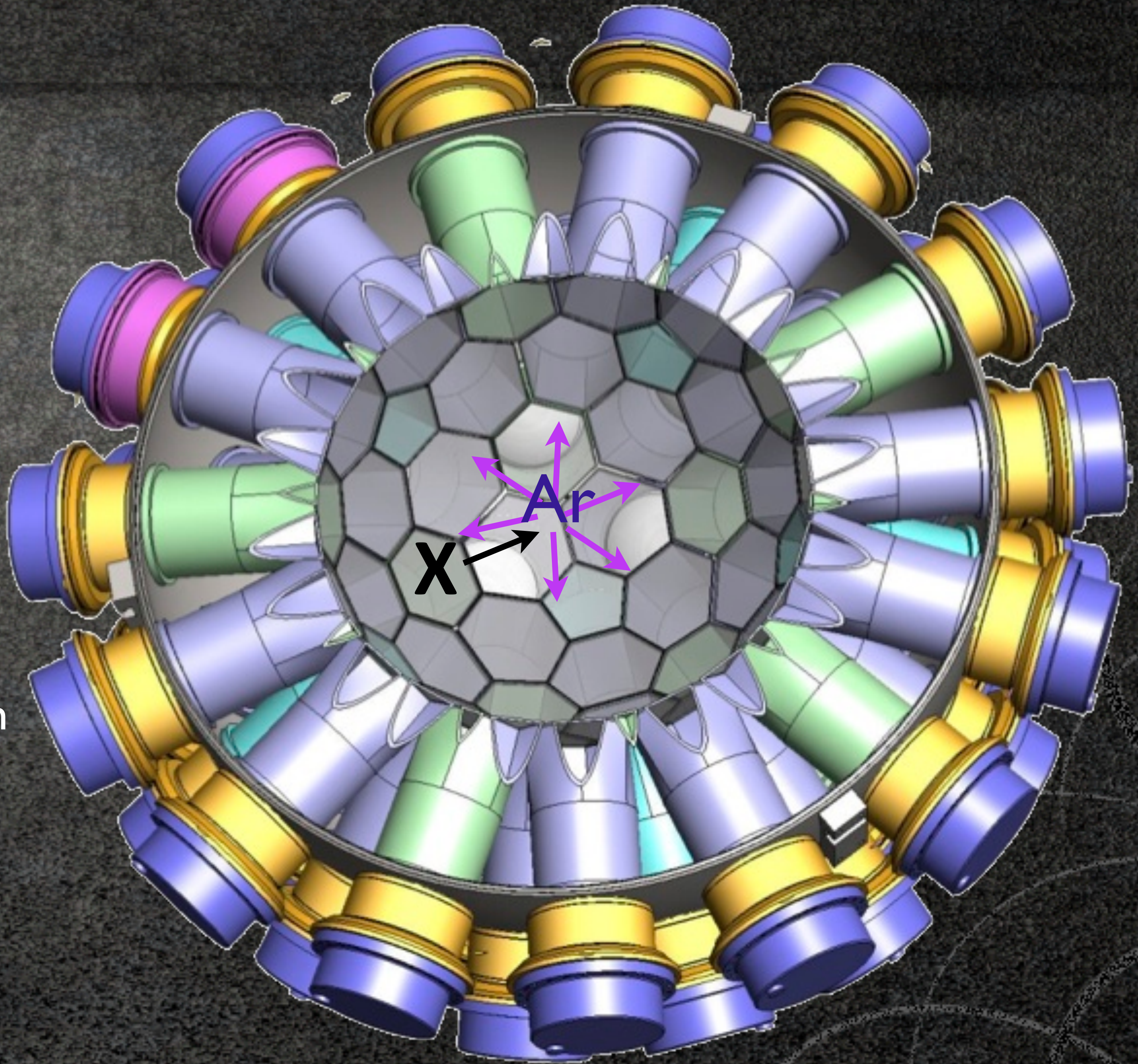
4π coverage
92 modular optical cassettes
PMTs are cold



A WIMP Event

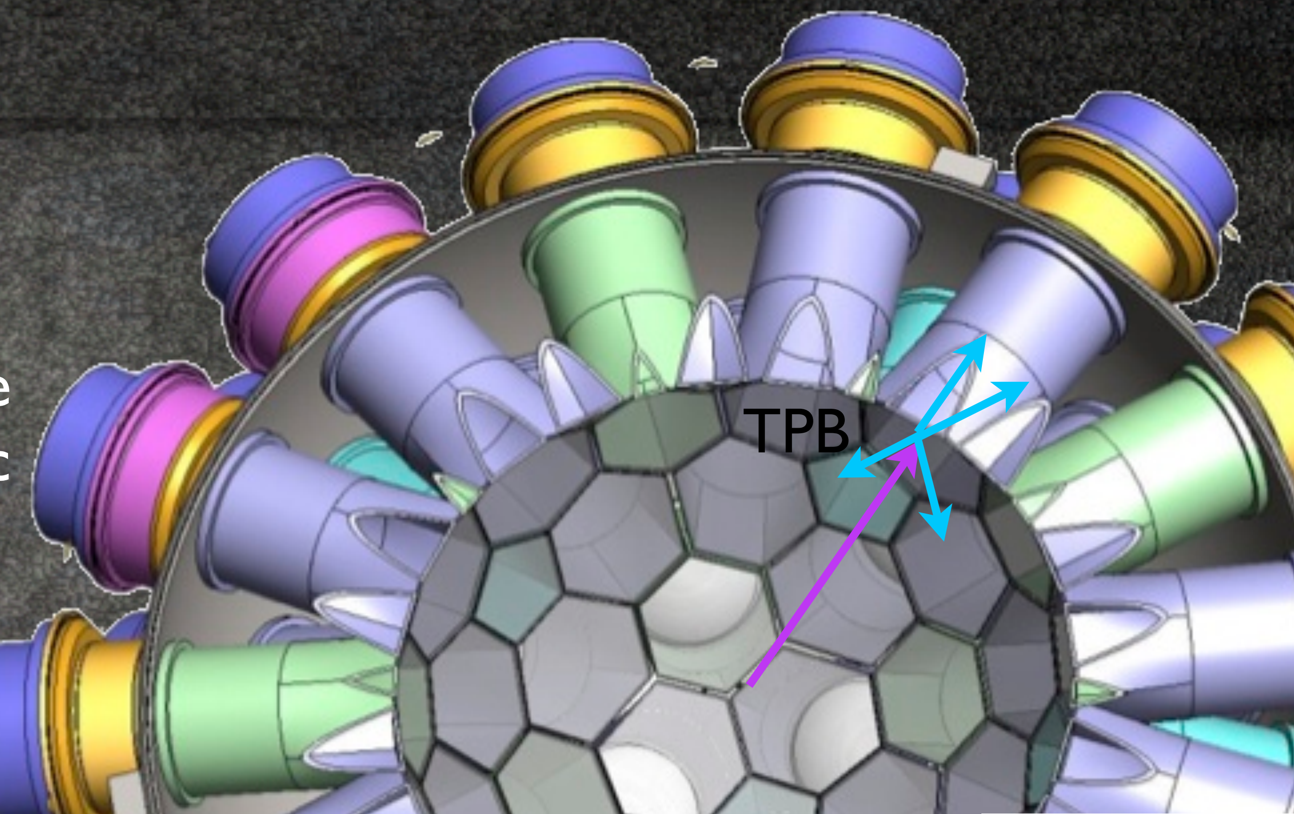
A WIMP, **X**,
has a coherent
elastic scatter
with an argon
nucleus

The nuclear recoil
then causes EUV
scintillation, 128 nm

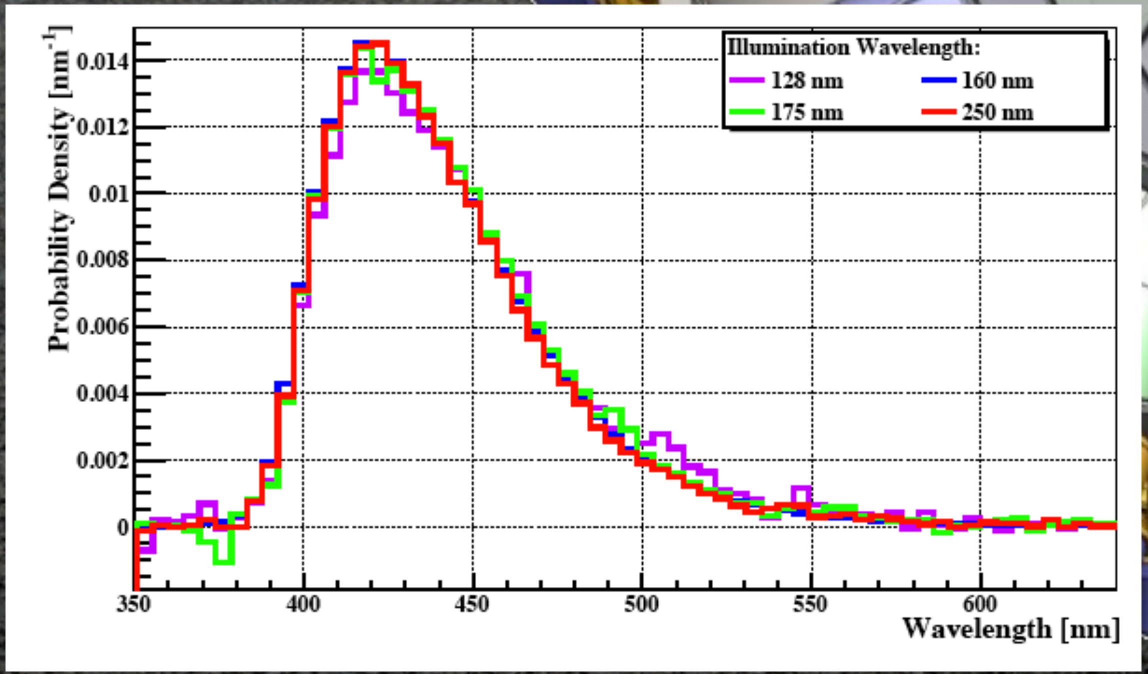


TPB Re-emission

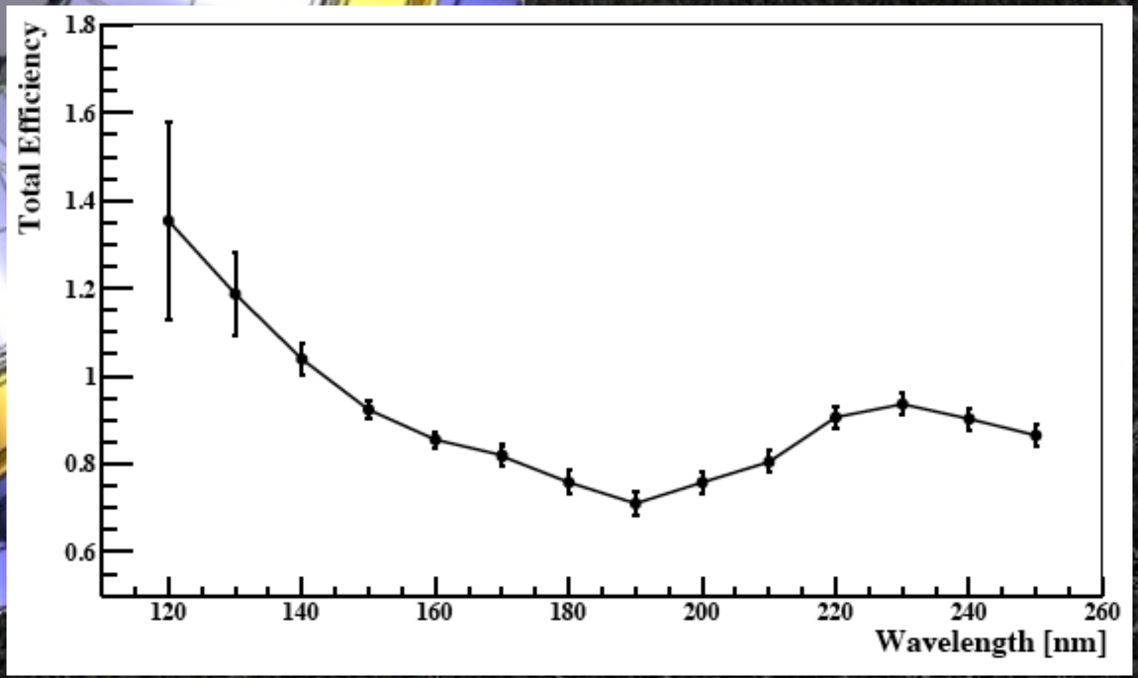
The UV light is absorbed by the TPB wavelength shifter, an evaporative coating on the acrylic face, which re-emits visible light



TPB Coating done at International Vacuum



TPB Re-emission spectrum
Gehman et al. NIM A654 (2011) 116-121



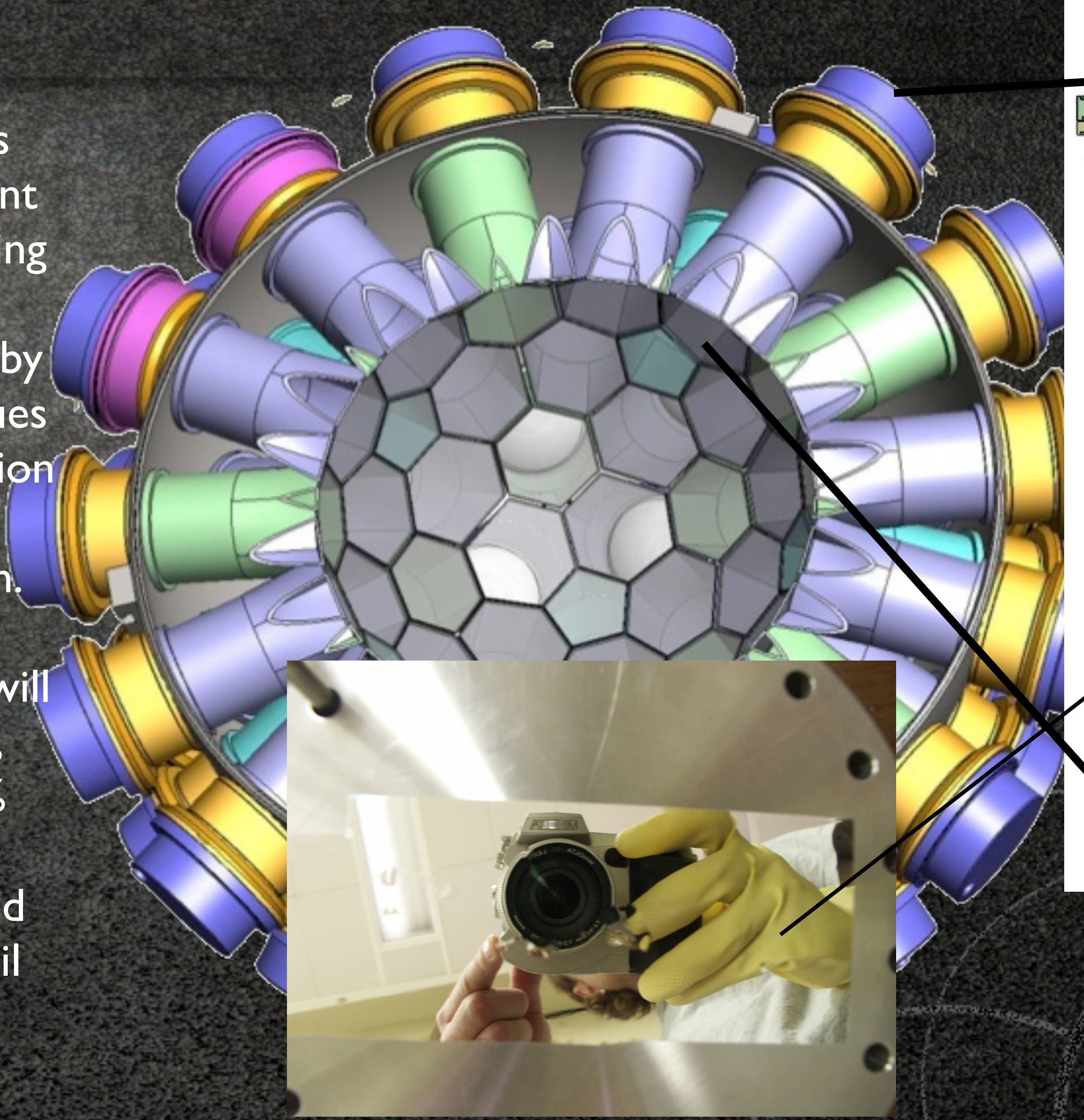
TPB Emission Efficiency

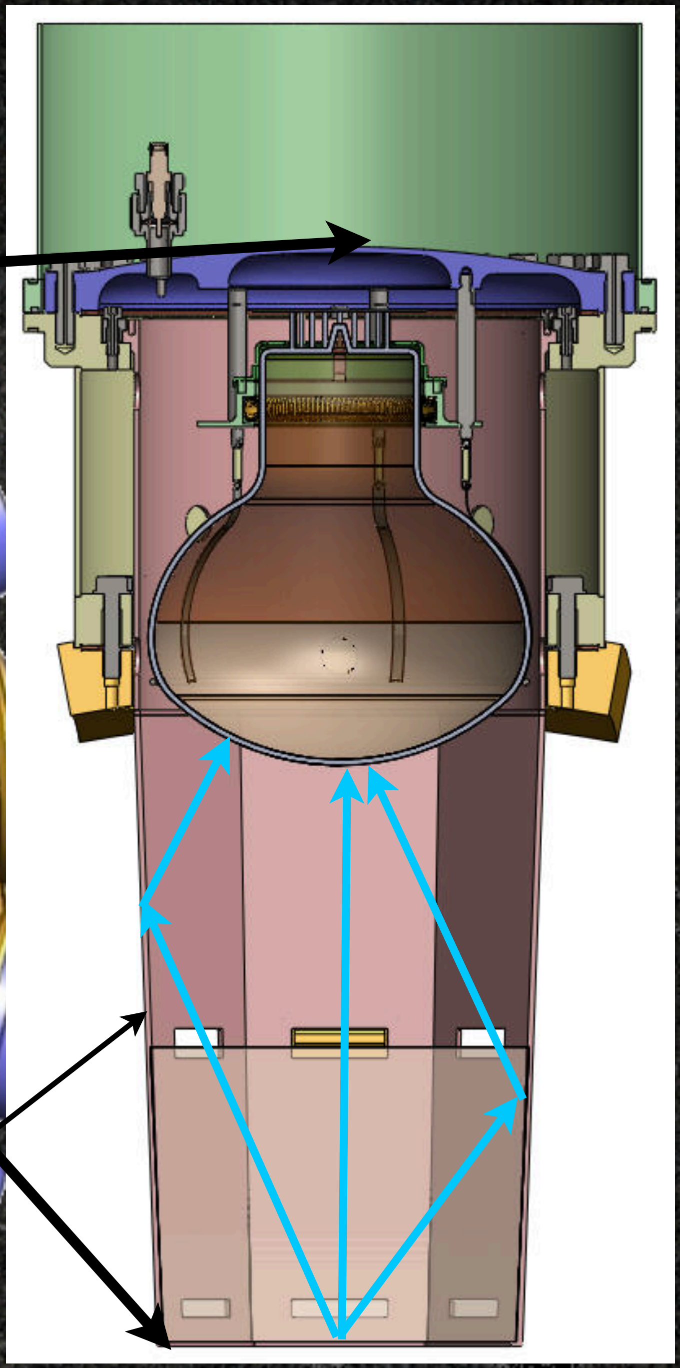
Lightguide

Light then travels through transparent acrylic. UV absorbing acrylic was surprisingly found by our DEAP colleagues to be best, absorption lengths of ~few meters at 420 nm.

Acrylic plug sides will be silver coated, reflectivity >95%

Lightguide covered with 3M DESR foil reflector.



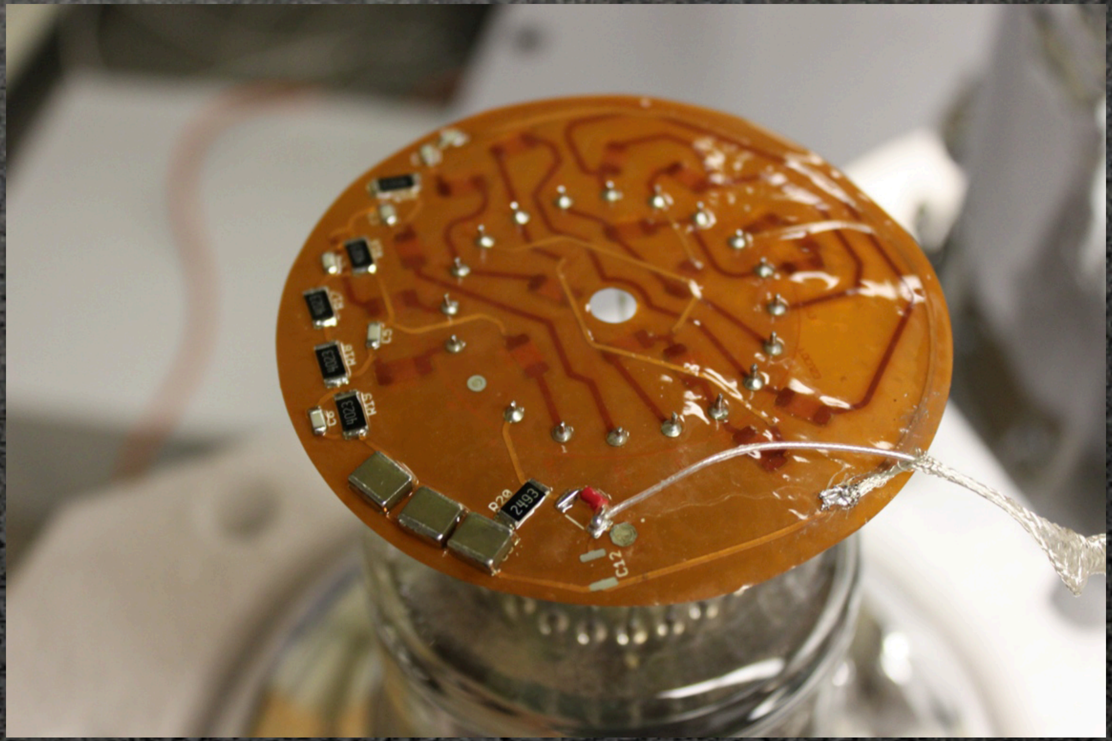


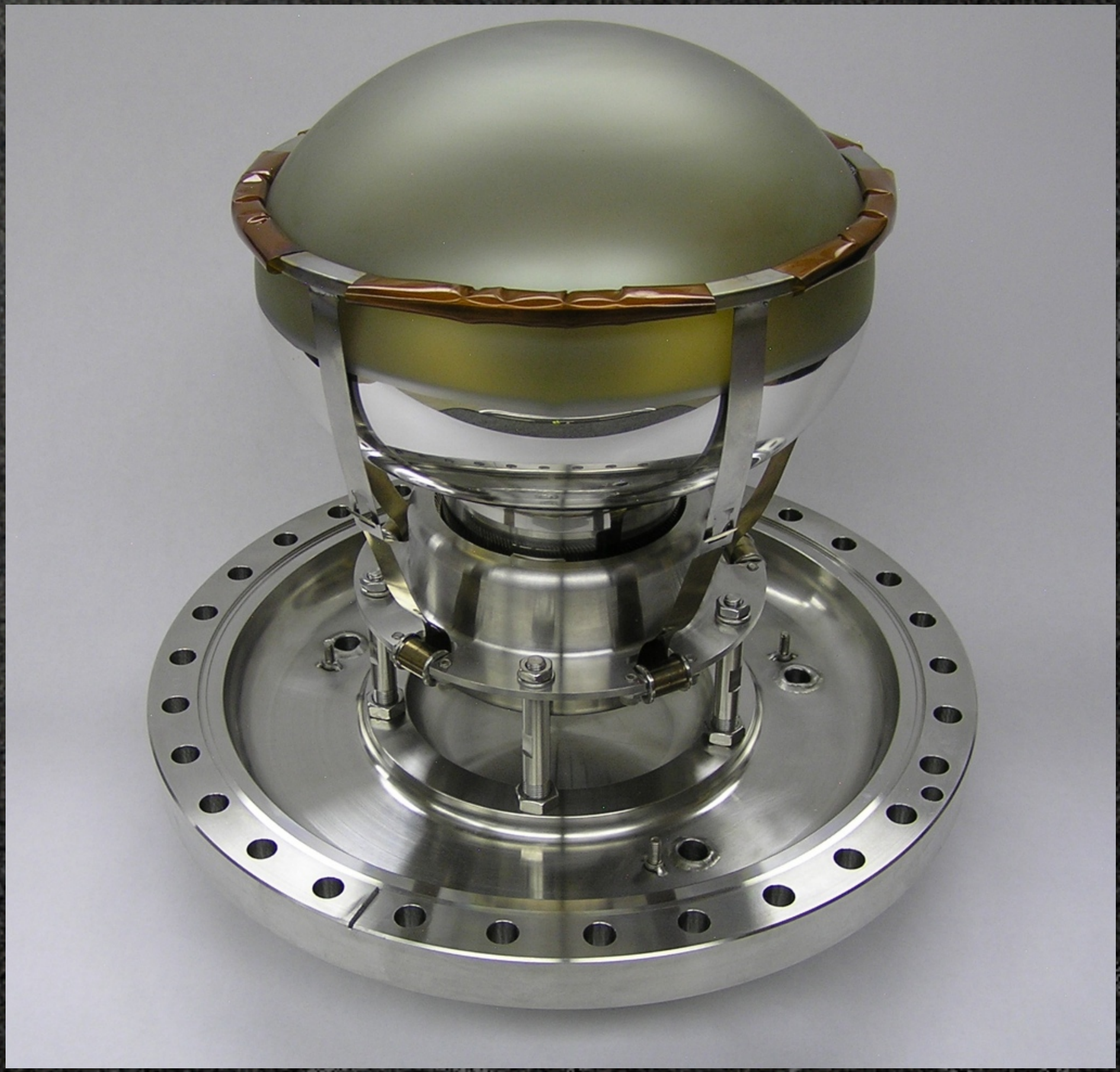
PMTs and Bases

PMTs are 8” Hamamatsu R5912-02MOD
14 dynodes, Pt underlay, frosting

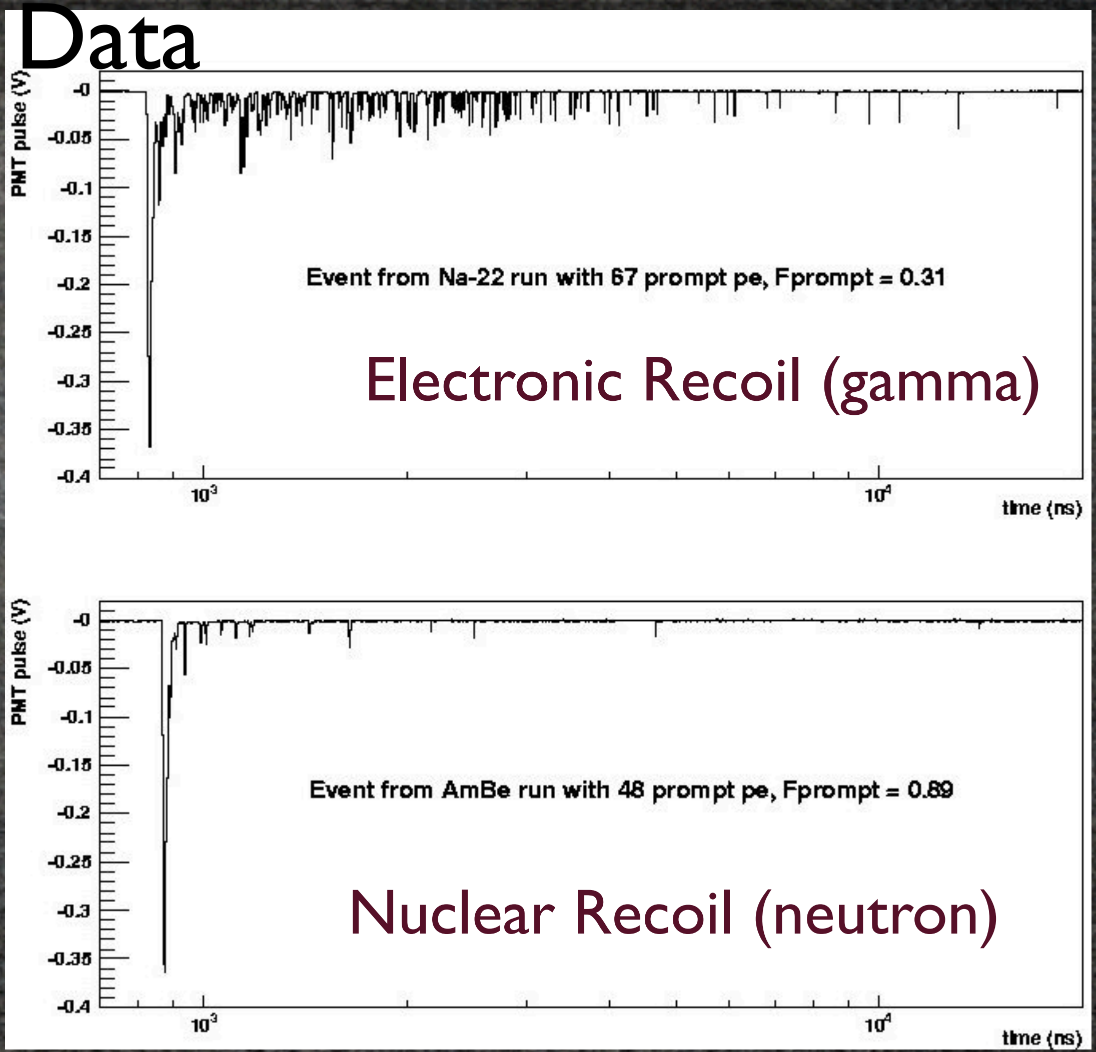
<u>From whole optics chain we expect 6 p.e./keV</u>

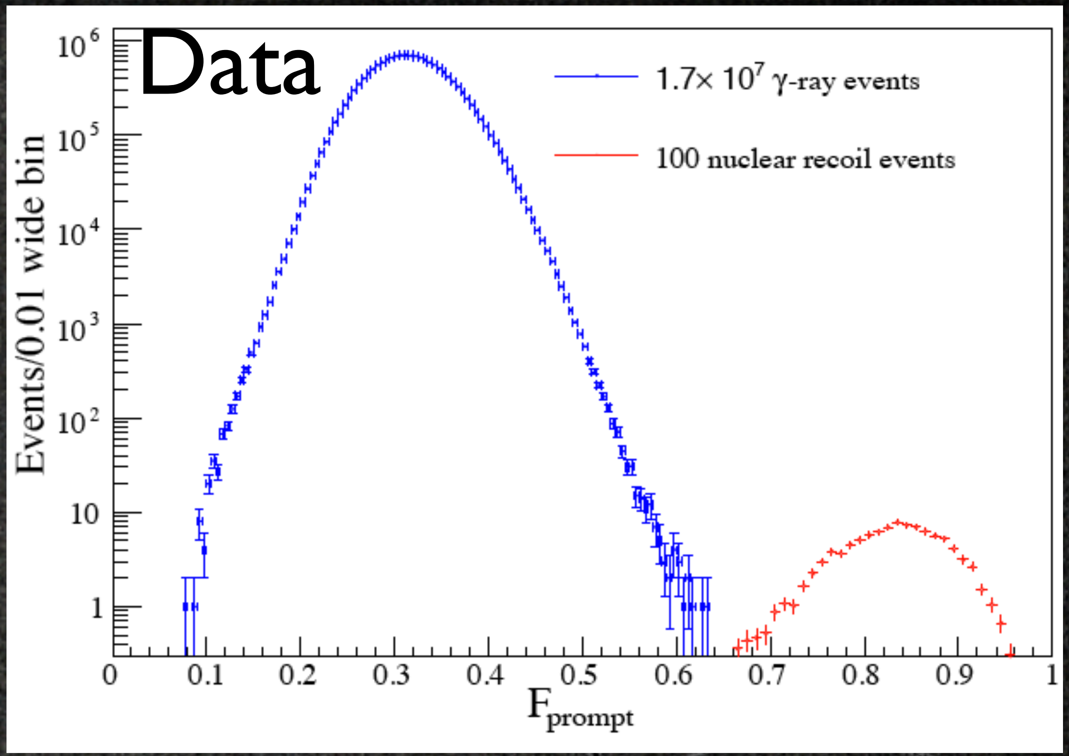
Bases: single layer kapton with conformal coating
low mass Gore HV cable



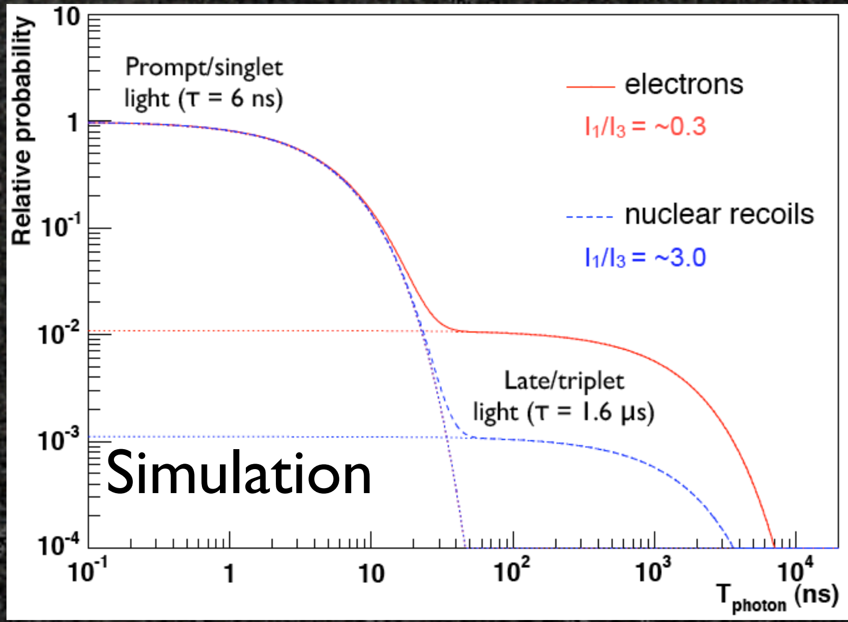


Pulse Shape Discrimination





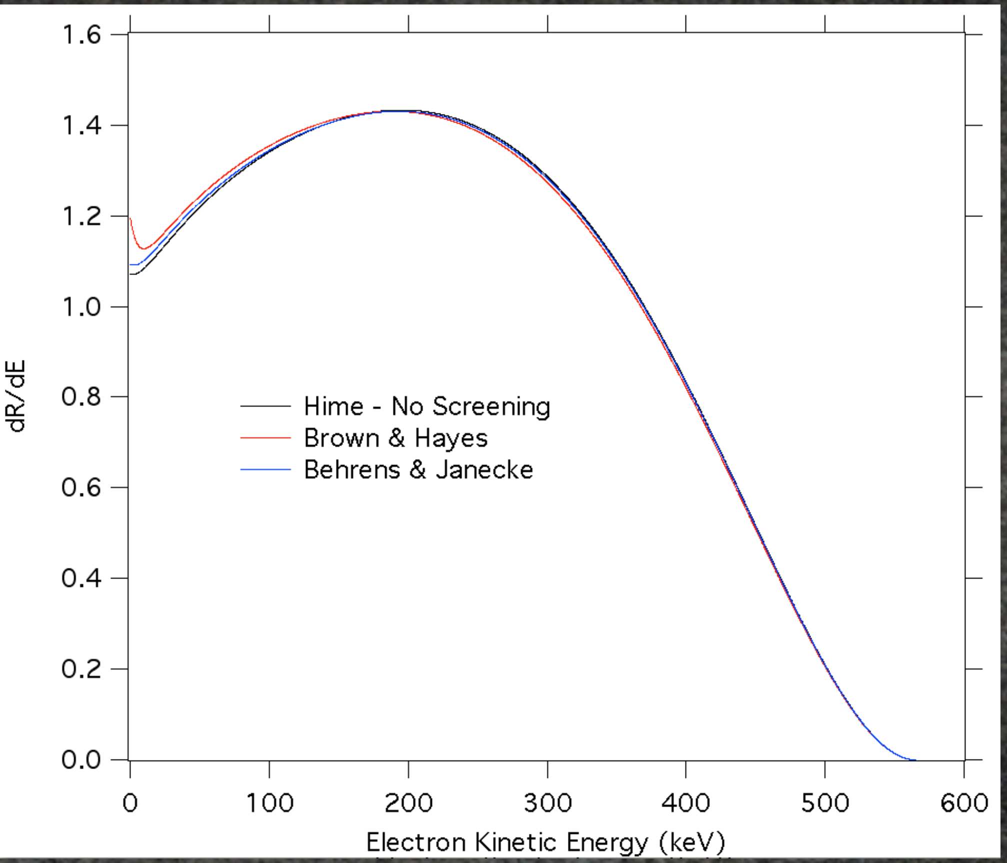
Boulay et al. arXiv:0904.2930



In LAr, $t_{singlet}$ = 6 ns, $t_{triplet}$ = 1.6 us
F_{prompt} ~ .3 for electron recoils, .7-.8 for nuclear
How well can discrimination work?
DEAP-1 has demonstrated (stat. Limited)
< 6 x 10^{-8} 43<E< 86 keV_{ee}
Necessary in LAr because of ^{39}Ar

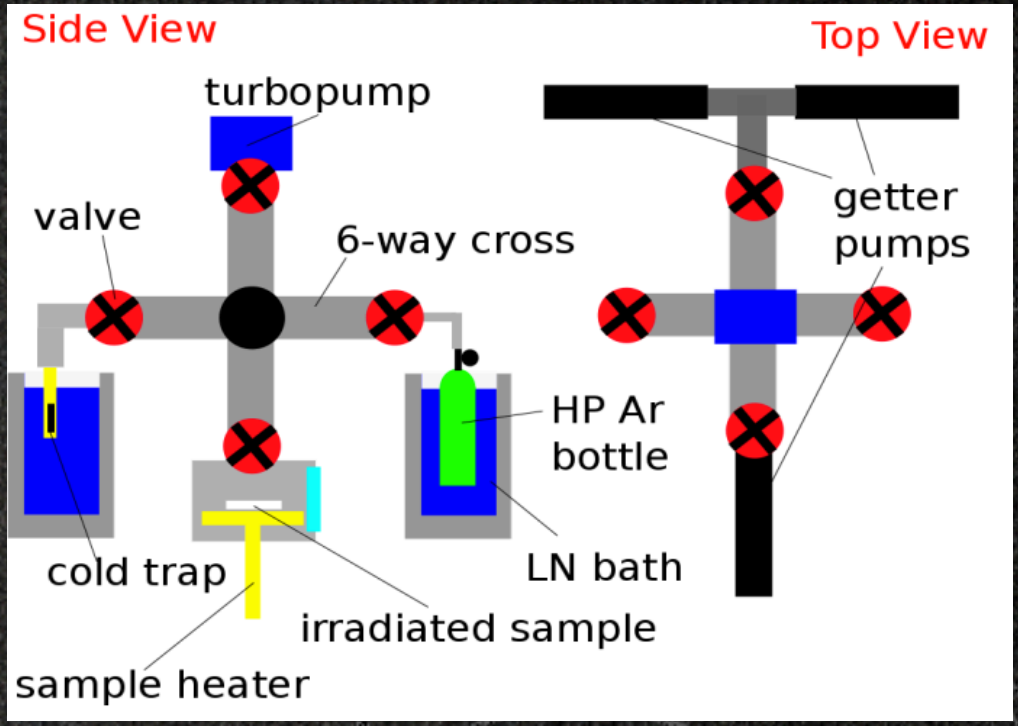
Boulay and Hime, Astropart. Phys. **25**, 179 (2006)

^{39}Ar Spike



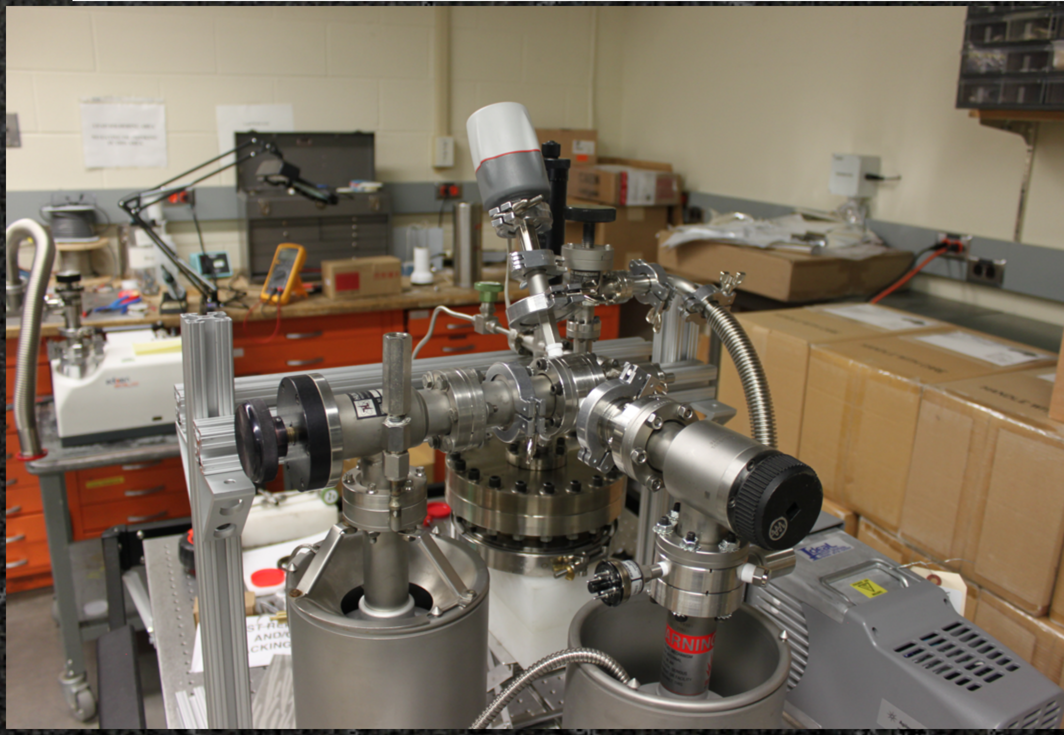
MiniCLEAN will dope with ^{39}Ar to establish PSD for larger detectors (rejection of 10^{-10}) plan to increase

event rate 3-10 x



KCl target from TRIUMF proton beam, other LANL groups want Si and Al isotopes, we will obtain

~1.7 μCi of ^{39}Ar to spike our natural argon



Background Simulations

- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons

Background: Electronic

- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons

U/Th Gammas from PMTs:
~7x10^{9}/yr
high energy, large radius,
fail Fprompt cut

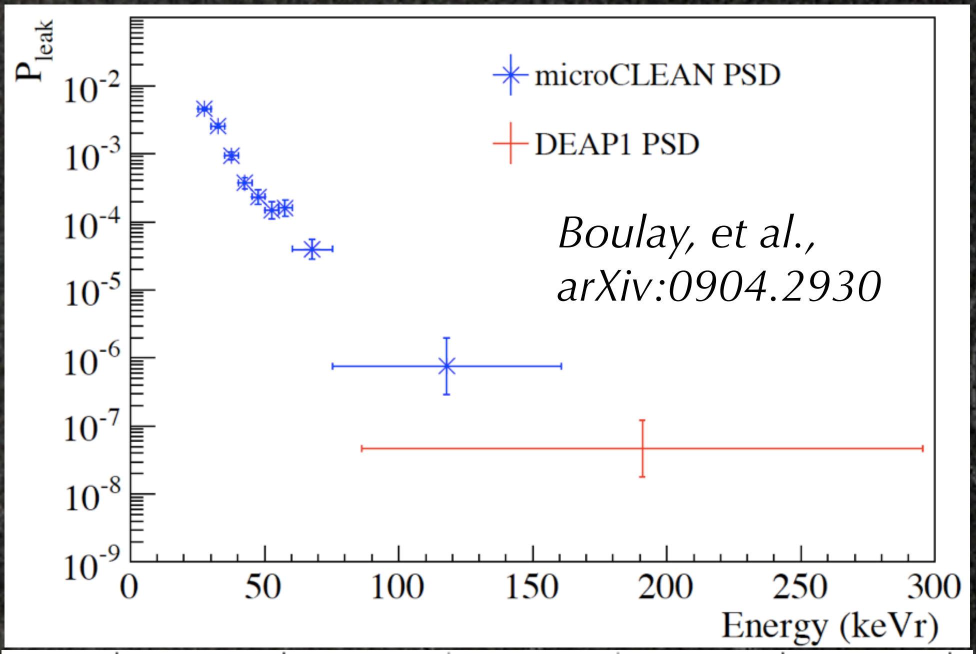
1 Bq/kg ^{39}Ar ⟶ Requires 1 x 10^{-9} discrimination

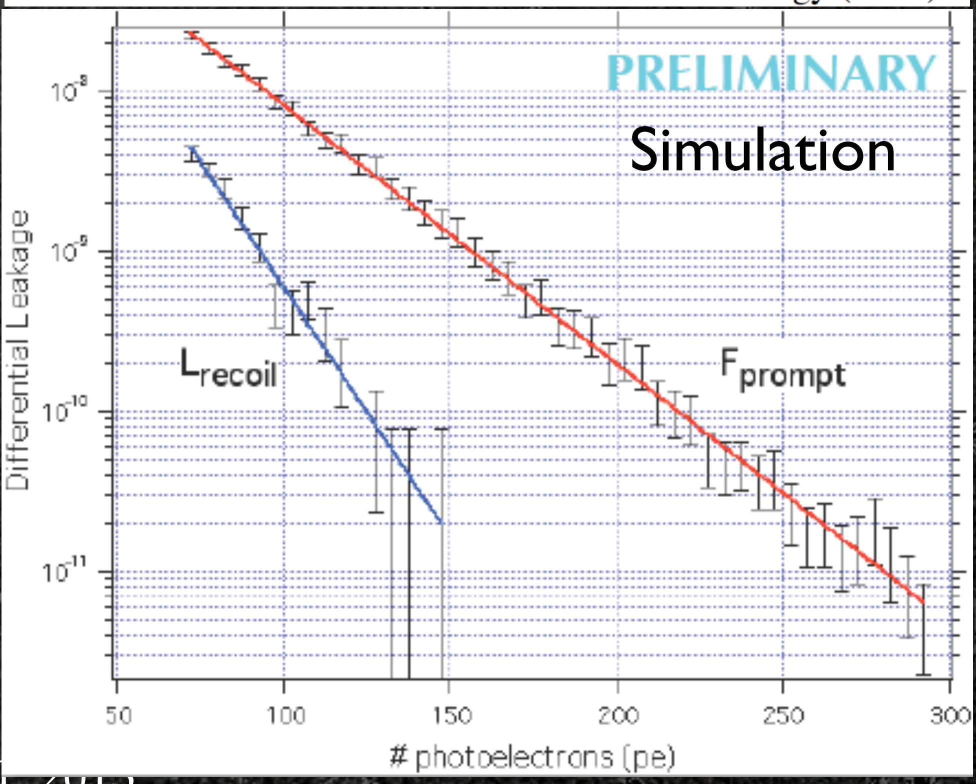
Results from
DEAP-1 at SNOLab
(C. Jillings CAP'11):
Rejection < 3 x10^{-8}
120-240 p.e.

Likelihood ratio, Lrecoil,
computed using the p.e.
arrival times increases
the separation between
nuclear and electronic recoils.

Threshold of 12.5 keV$_{ee}$
<1 ^{39}Ar background /yr.

MiniCLEAN collaborators
are looking at DEAP-1 data
to study L_{recoil} near threshold.

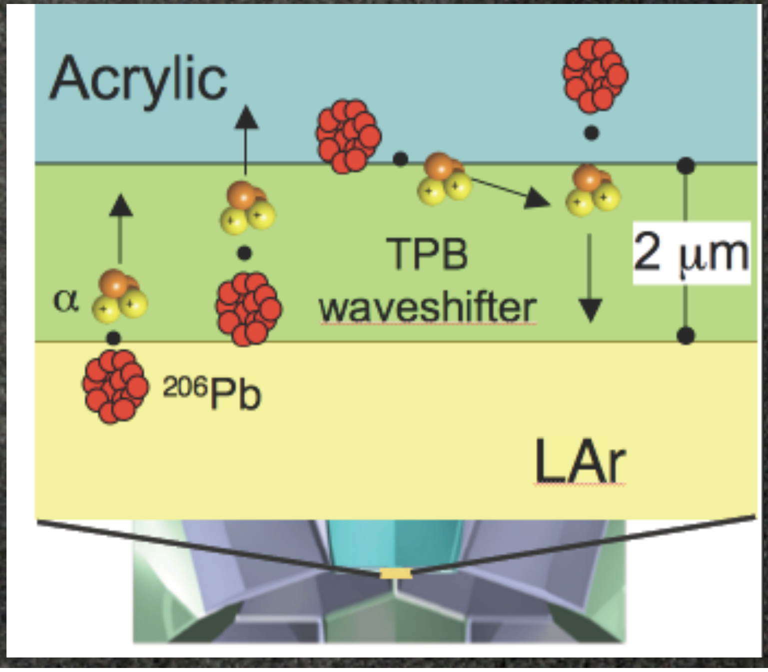


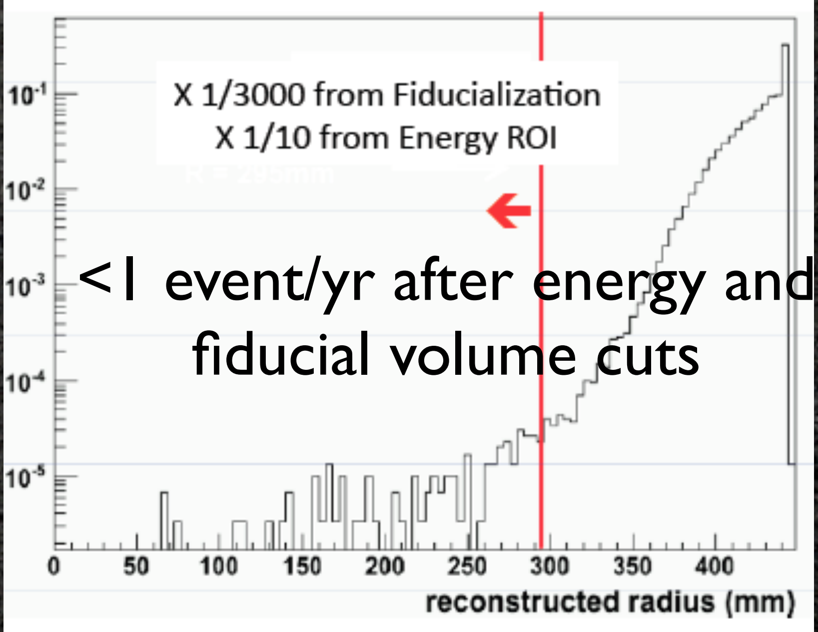


Background: Alphas

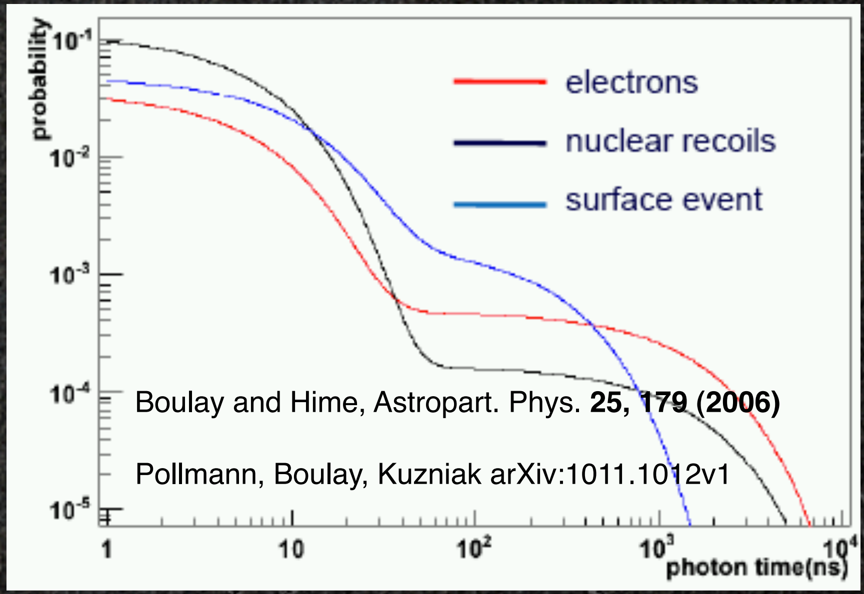
- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons

Rn daughters plating out on TPB can be a dangerous background

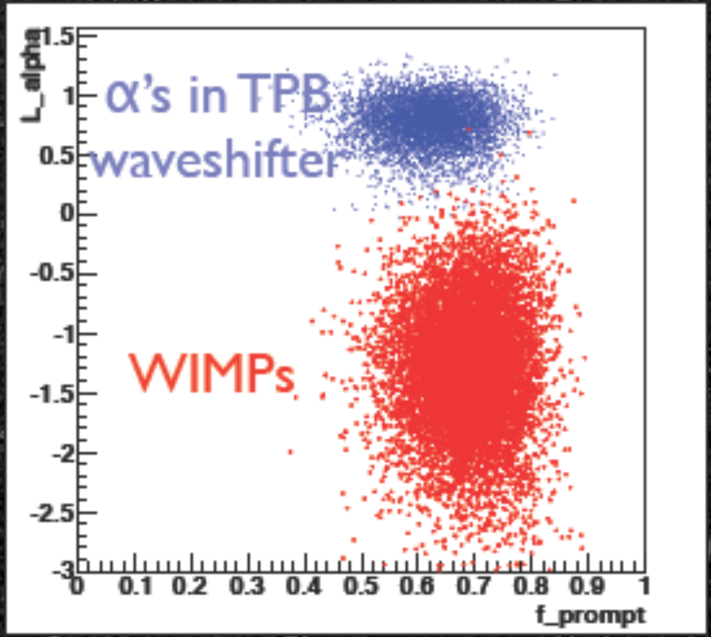




Improved discrimination:



B. Wang APS'11



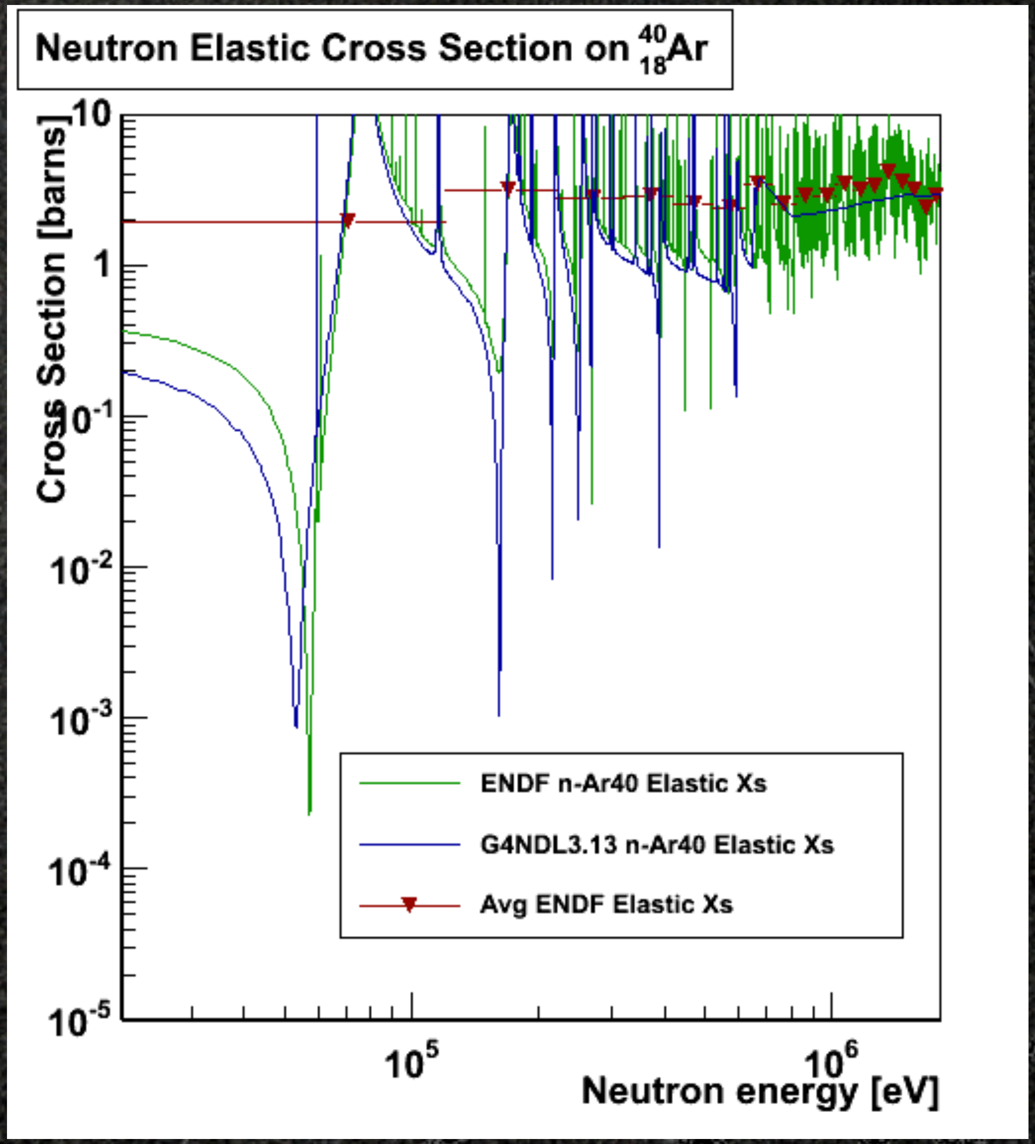
Background: Neutrons

- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons

Neutron Verification

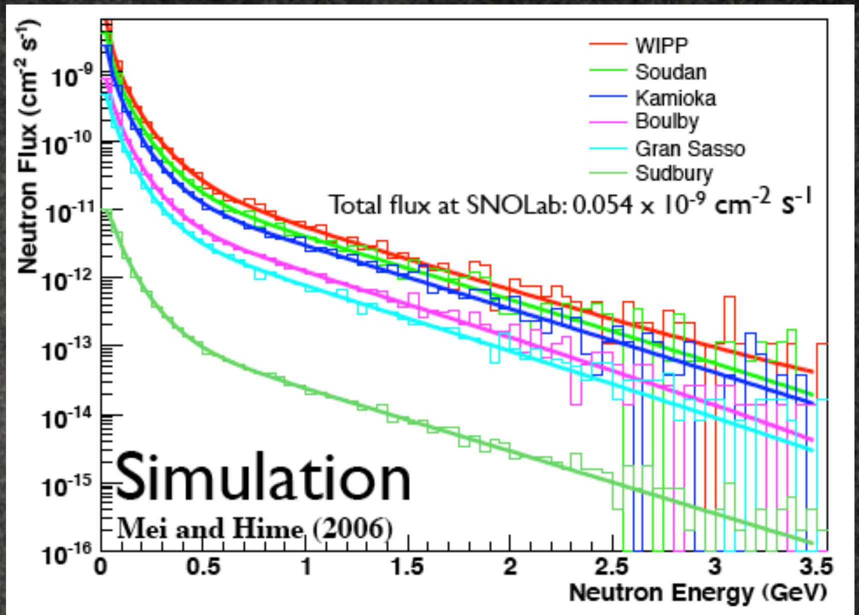
Checked low energy neutron physics in Geant4 (Neutron_HP, using cross sections from G4NDL3.13)

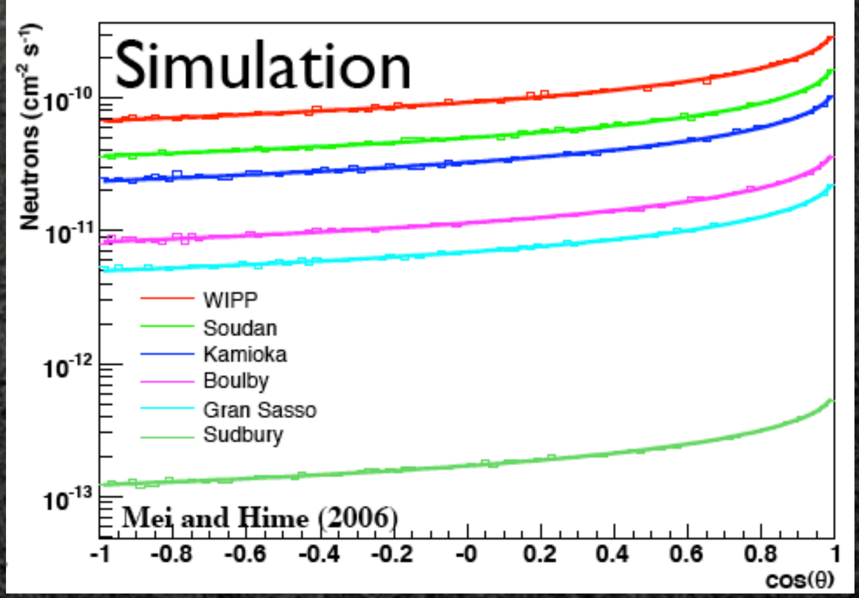
Interference between s-wave and hard-sphere scattering gives deep resonant dip in the elastic cross-section



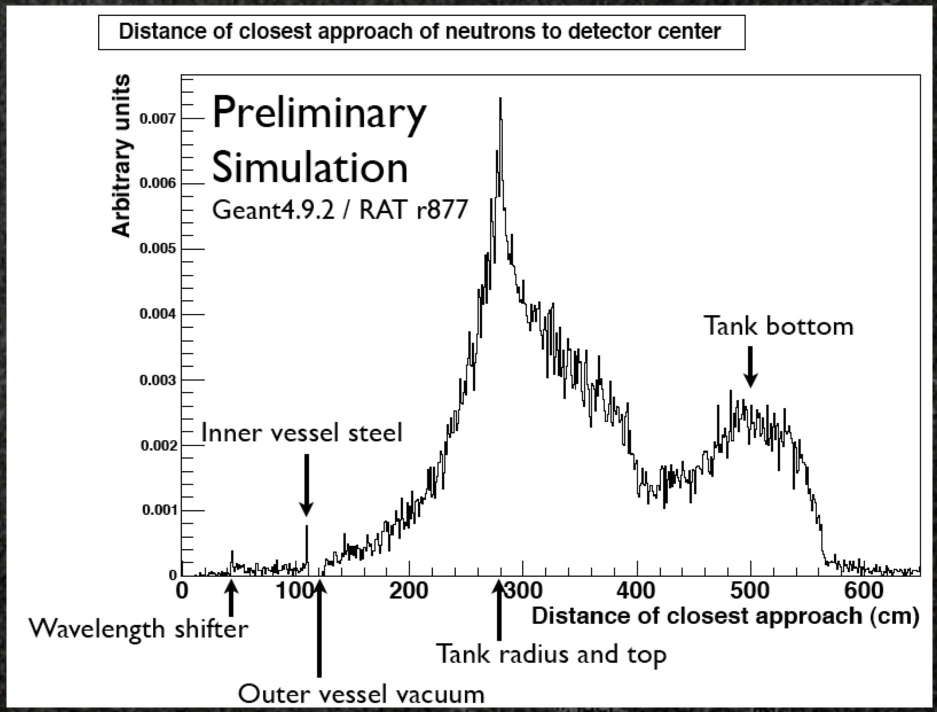
Background: Neutrons

- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons





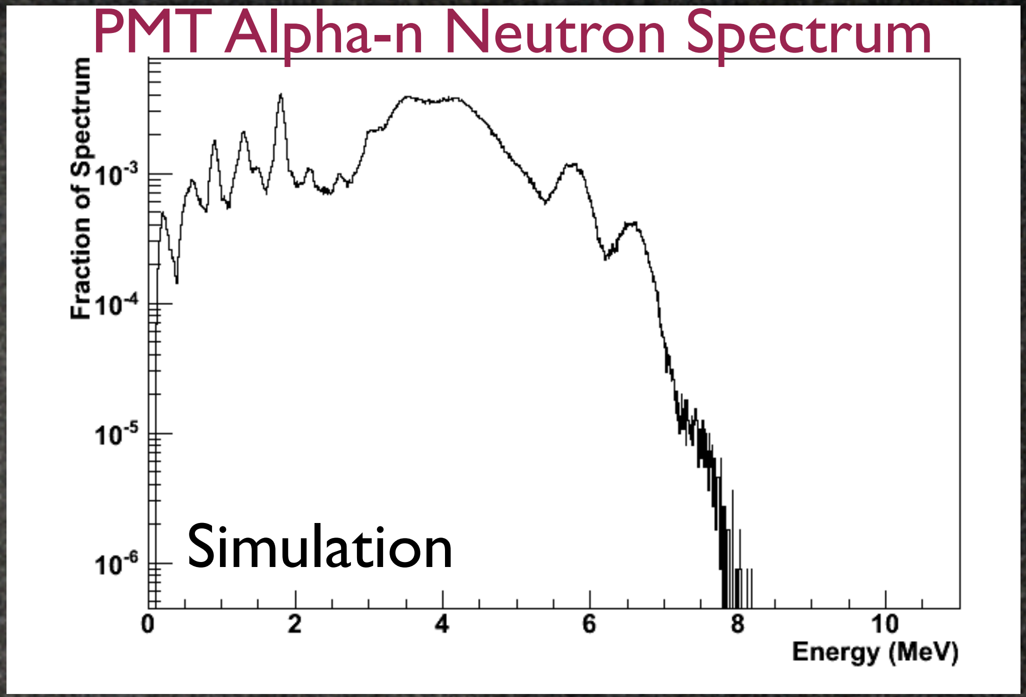
Simulation of Mei & Hime neutron distribution
<<1 event/yr

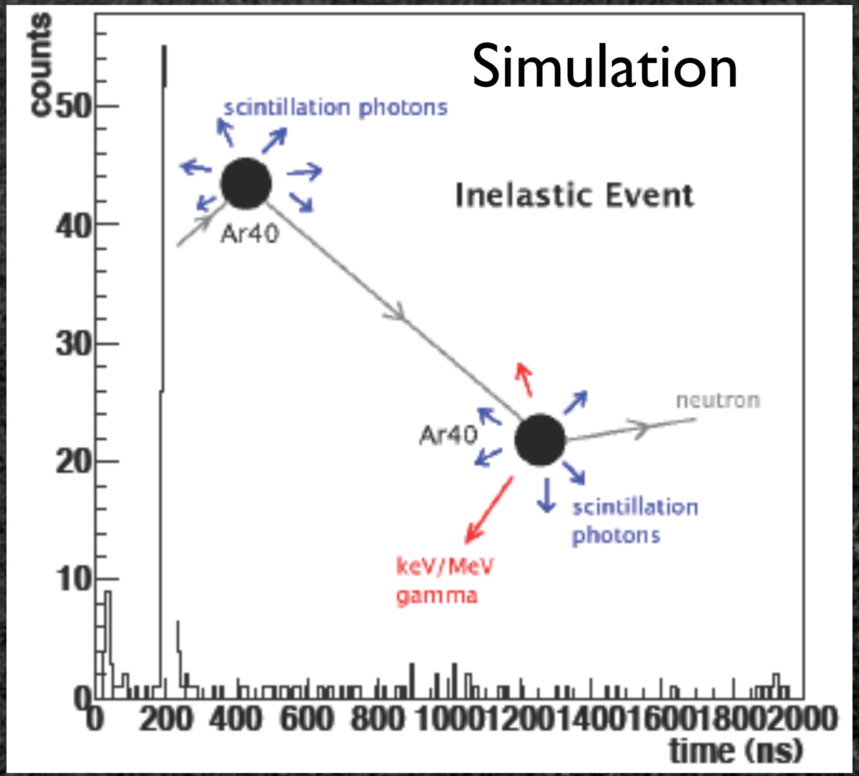


S. Jaditz APS '11

Background: Neutrons

- ^{39}Ar beta-decay
- Gamma Rays
- Surface Alphas
- Cosmogenic Neutrons
- Alpha-n Neutrons





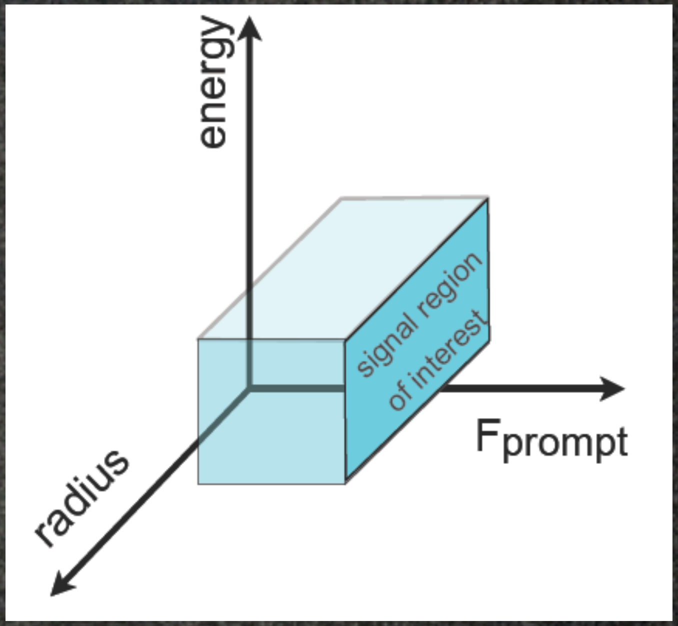
U/Th decay chain alphas in PMT glass produce neutrons (primarily off Boron)

Neutrons will have multiple scatters - and >90% scatter inelastically

~few events/yr prior to Lrecoil and multi-scatter cuts

Background Simulations

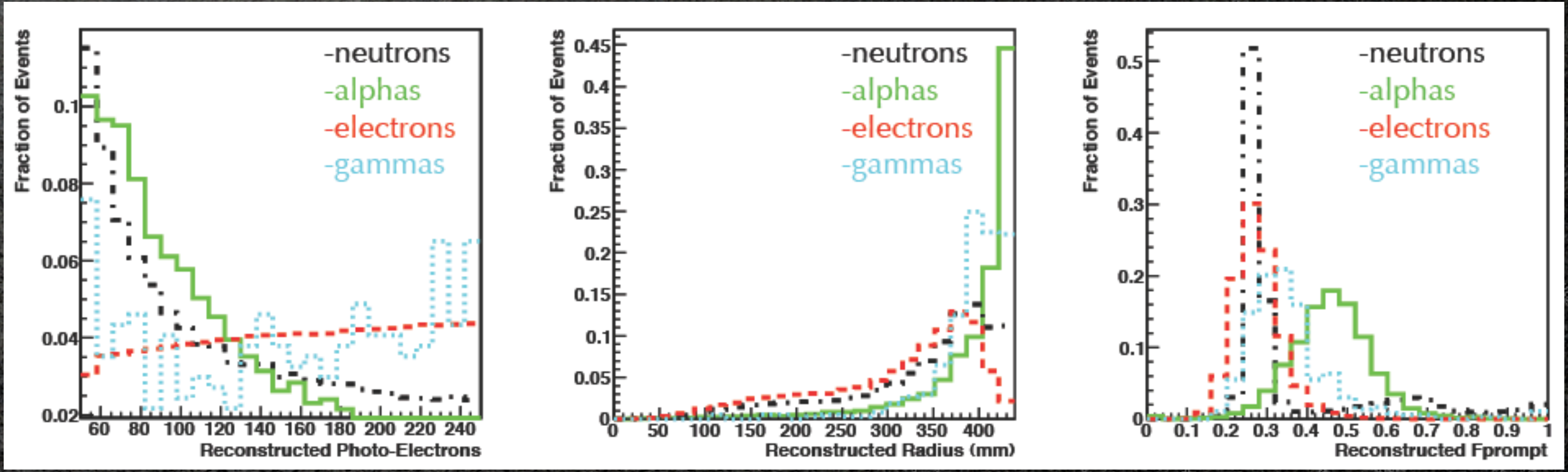
Current Simulation of Backgrounds
Reconstructed Distributions
No Cuts
All Unit Normalized



Planned Analyses

Analysis with a blind signal box defined by radius, energy and particle ID

Likelihood-based fit for PDF of signal over background using calibration data



Making It So

SNOLab Cube Hall

Construction: Veto Tank

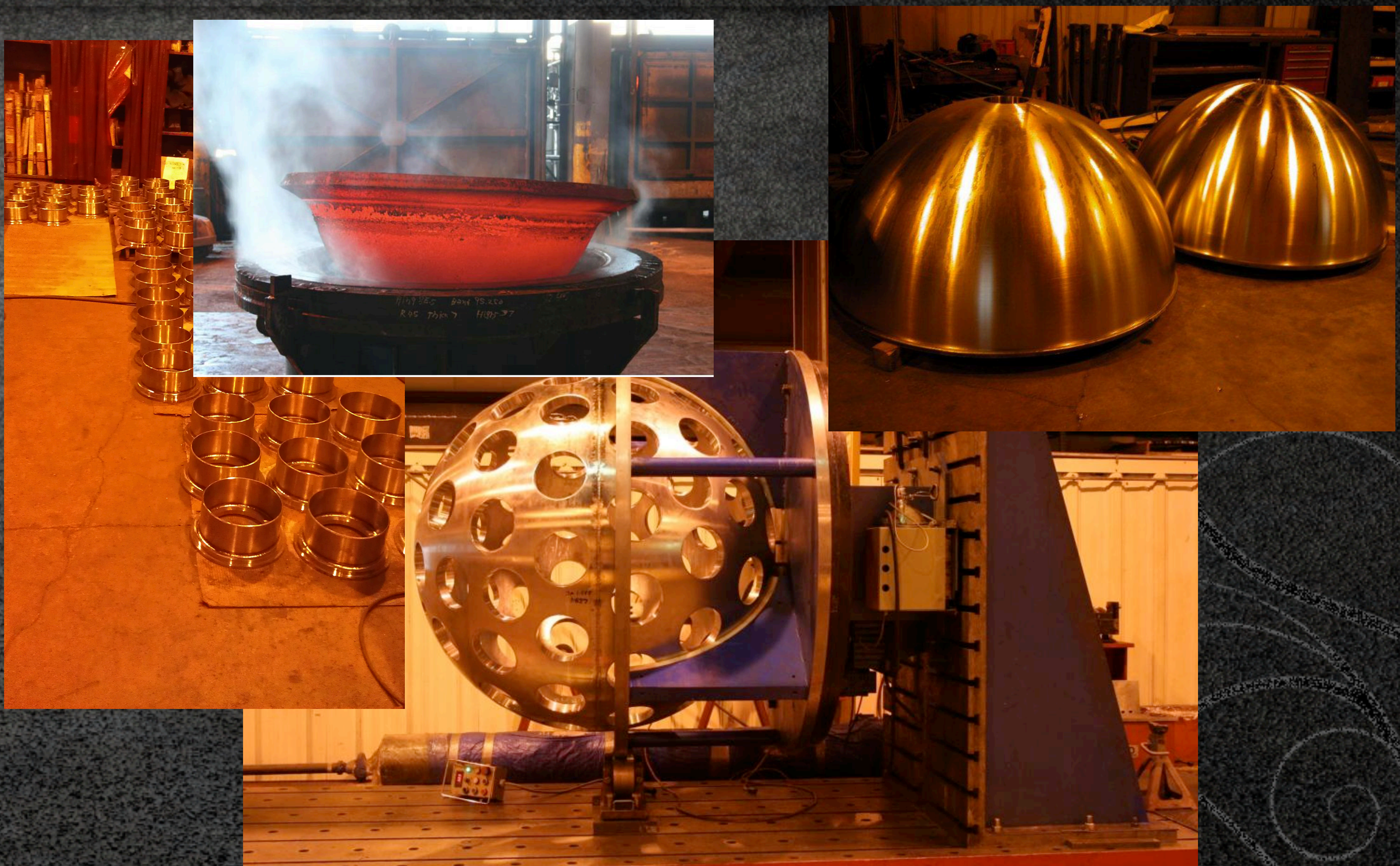
Veto String Test Assembly at Bates Lab, MIT

Construction: Outer Vessel

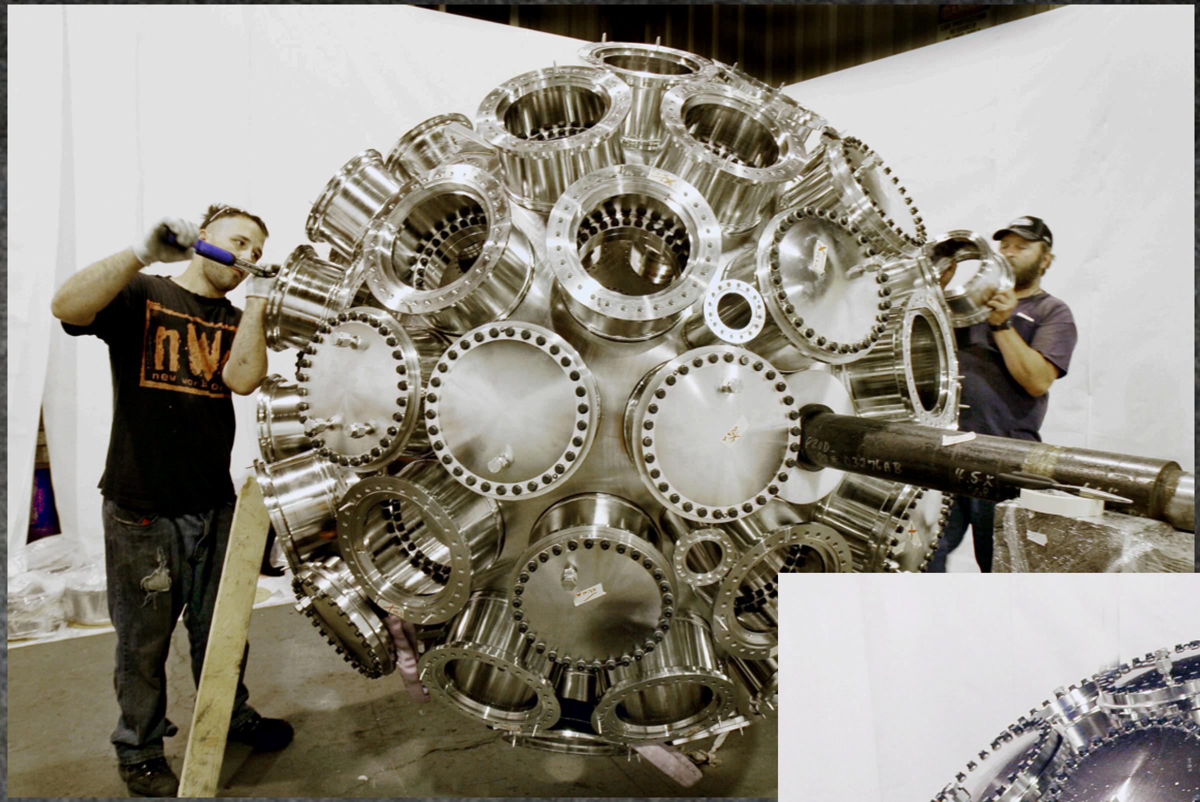
Outer Vessel Transport

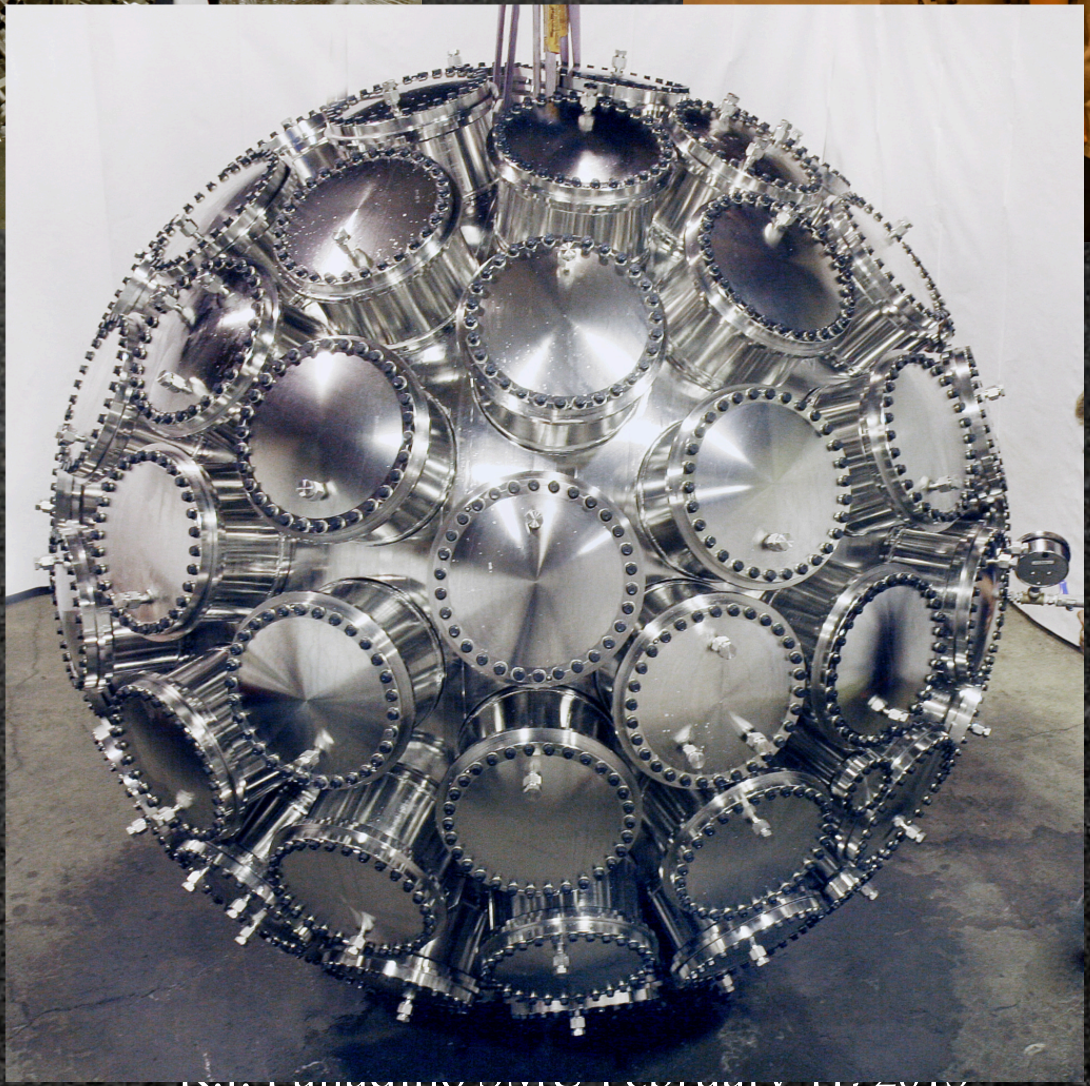
Outer Vessel Transported Underground 2 Weeks Ago

Construction: Inner Vessel



IV Pressure and Vacuum Test





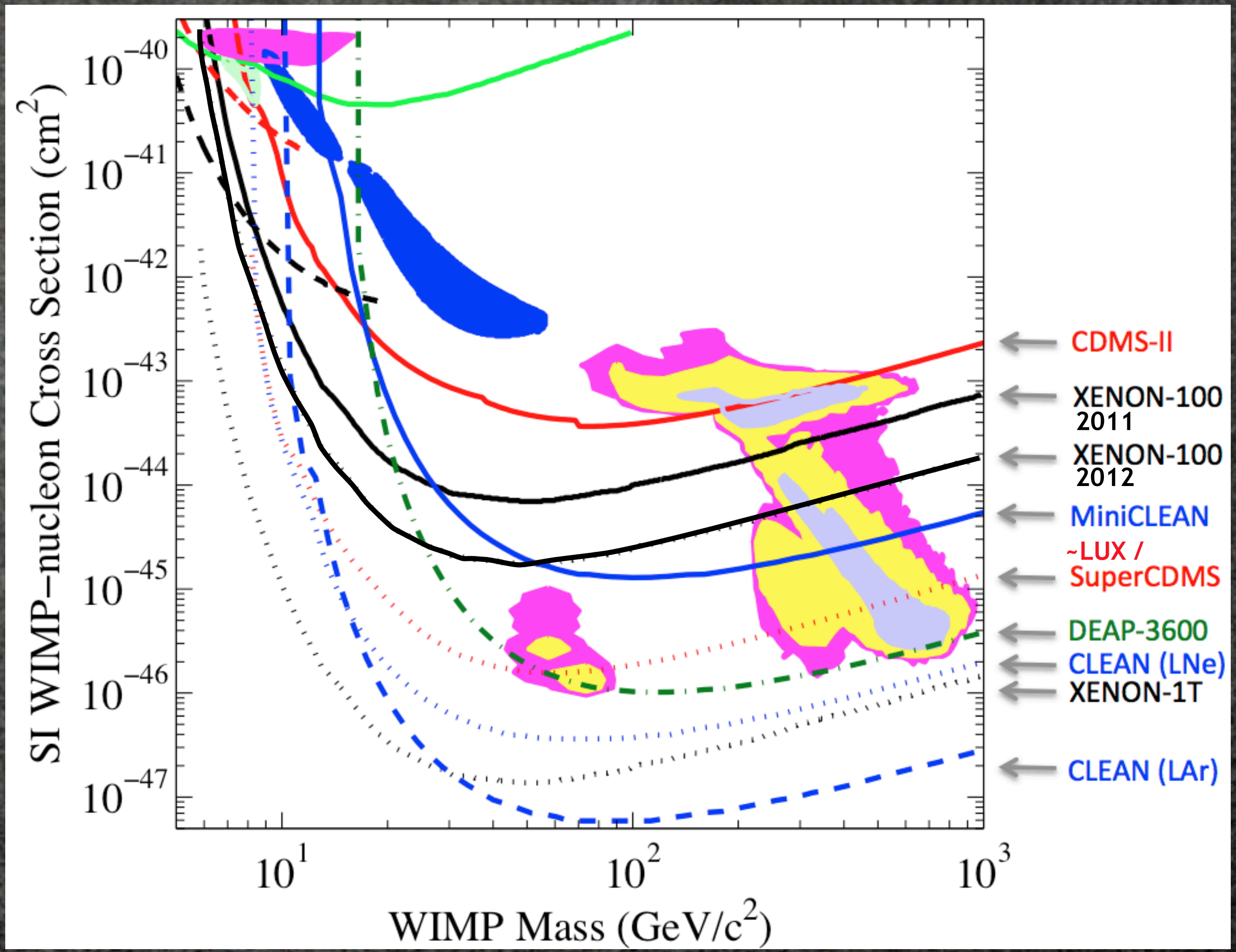
Assembly, Pressure test and Vacuum test completed at Winchester Precision Technologies, in NH, in September 2012

Inner Vessel Transport

Inner Vessel Transported Underground December 9th, 2012

IV Underground

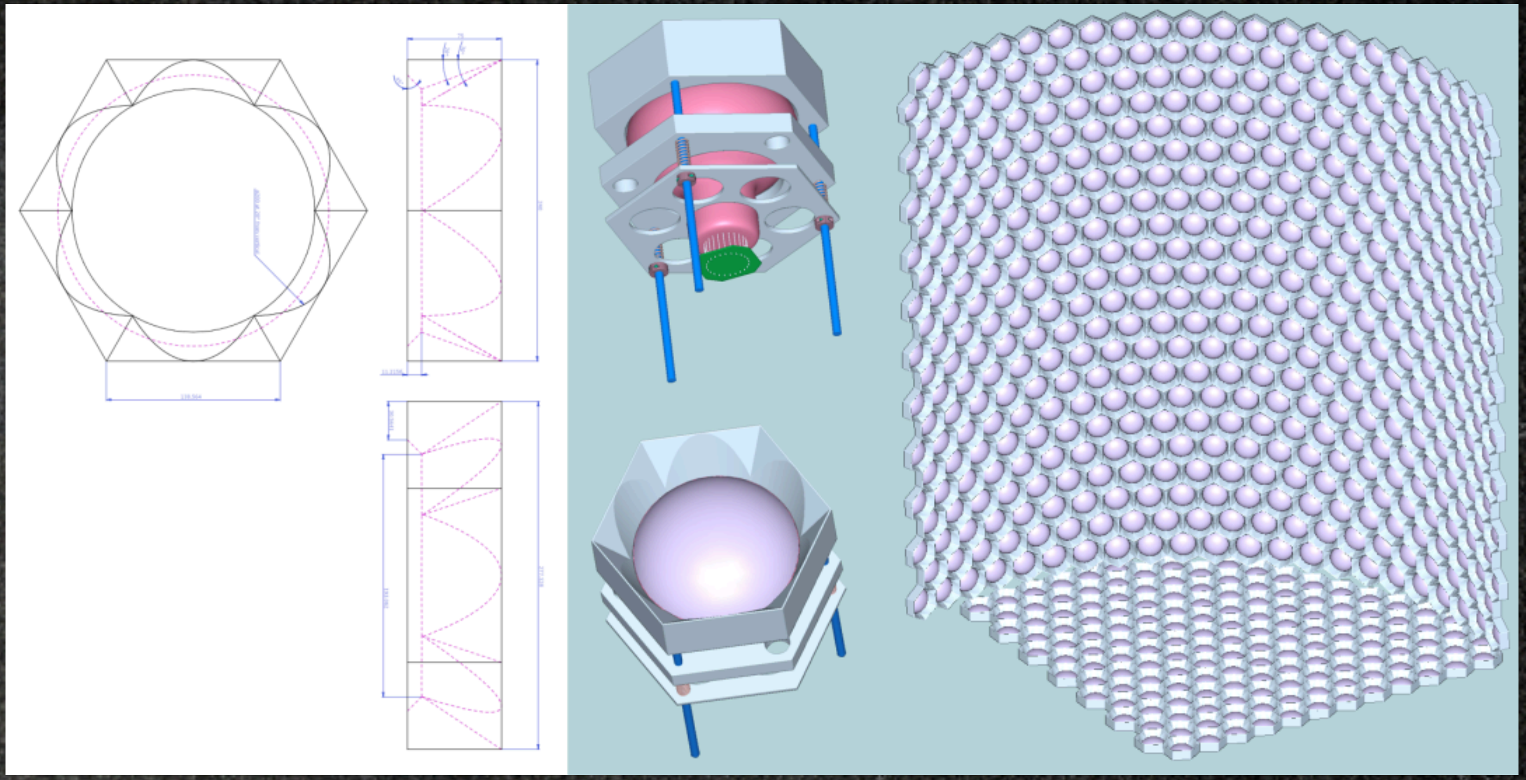
Program Goals

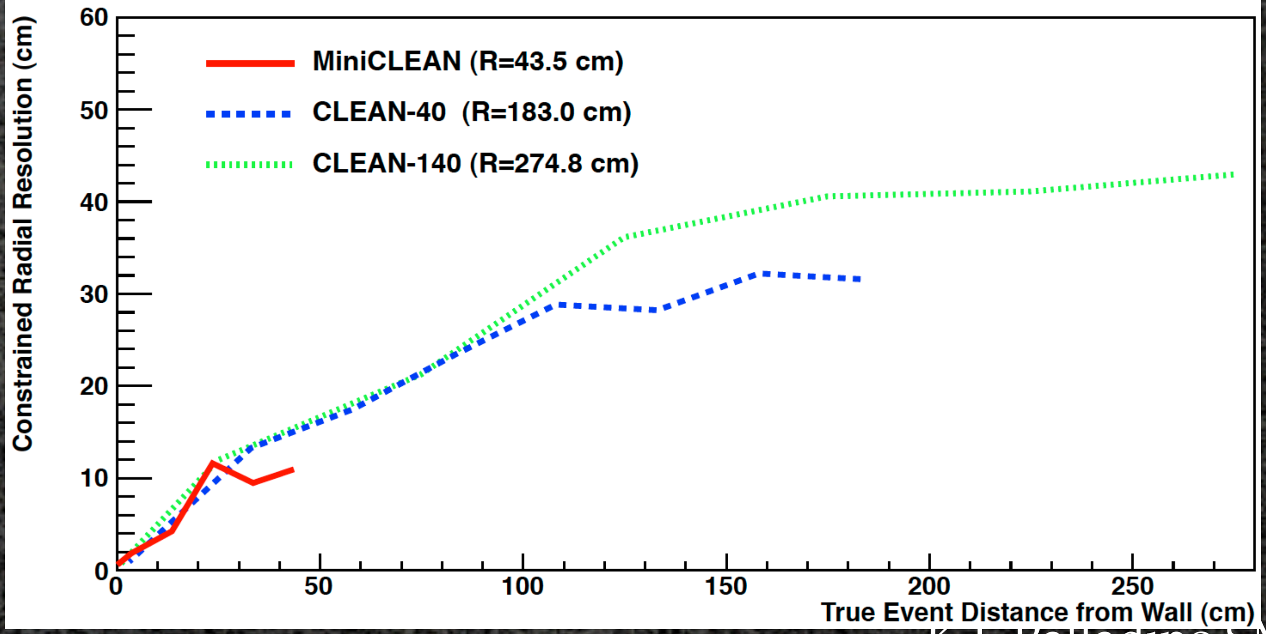


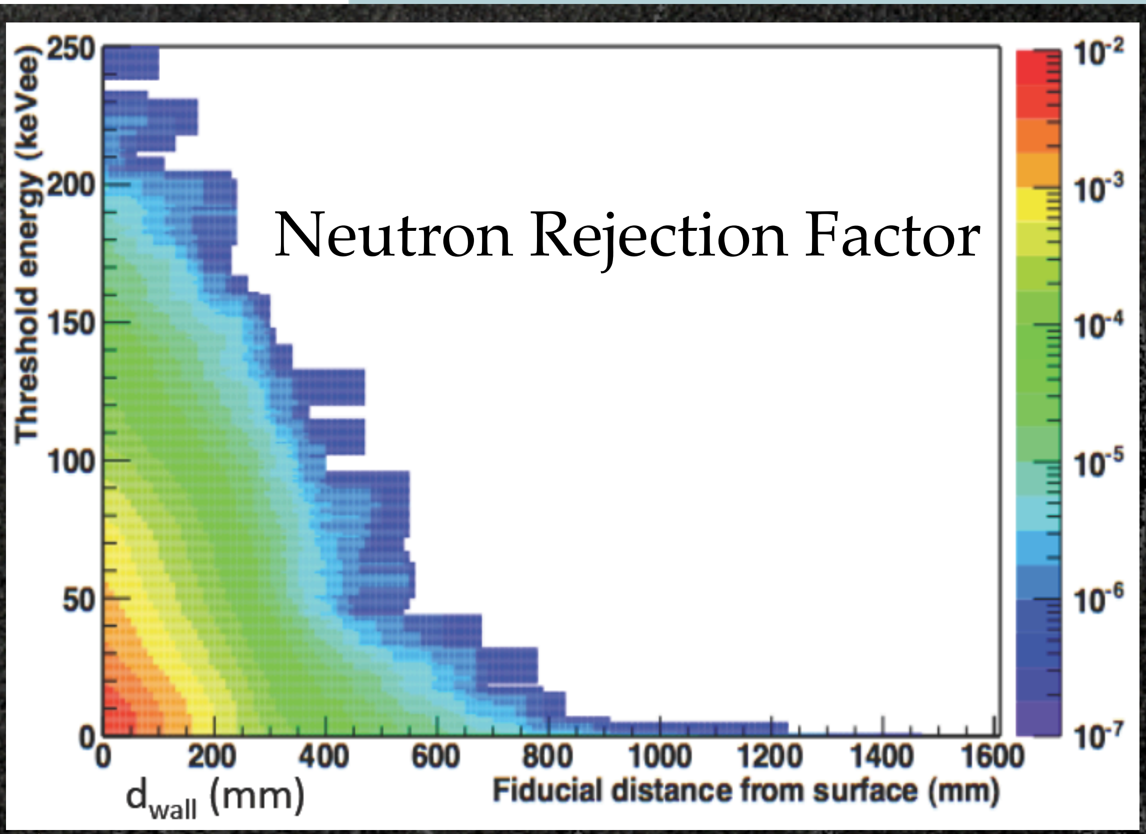
- WIMP sensitivity to 2 x 10^{-45} cm^2 from two year run
- Show Position/energy/Particle ID reconstruction
  - PSD is the primary goal of MiniCLEAN in 2013: Achieved with ^{39}Ar spike
- Measure background rates in-situ
- Constrain systematics with calibration

CLEAN

- 45T CLEAN detector proposed in G2
- Simple cylindrical design
- 15T fiducial volume, capable of seeing ~15 events a year if a 10^{-46} cm^2 cross section







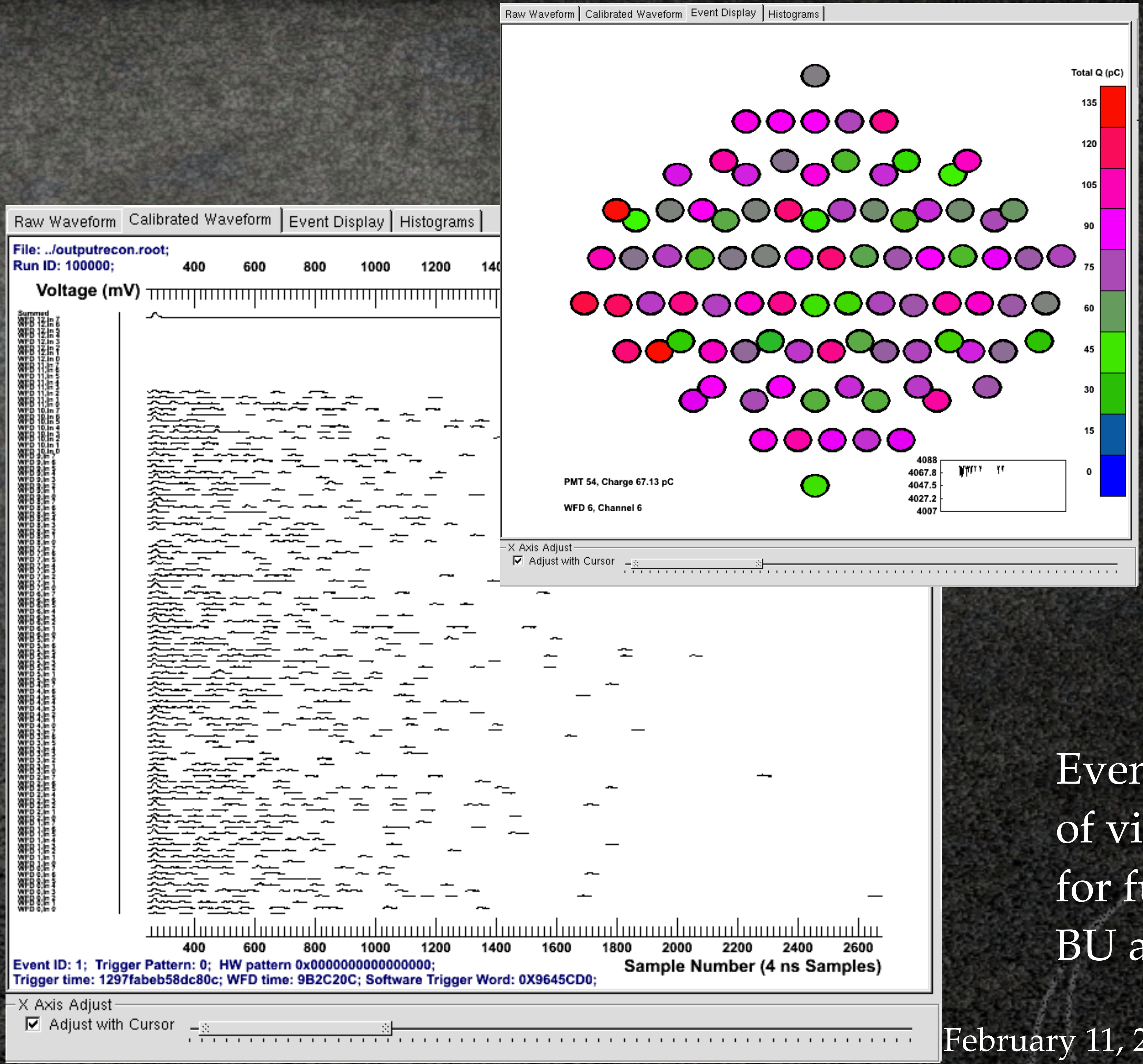
Conclusion

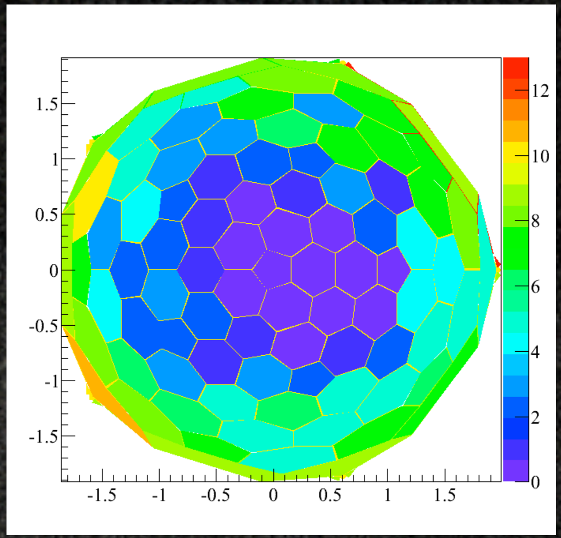
Punxsutawney Phil (Keith Srakocic - AP)

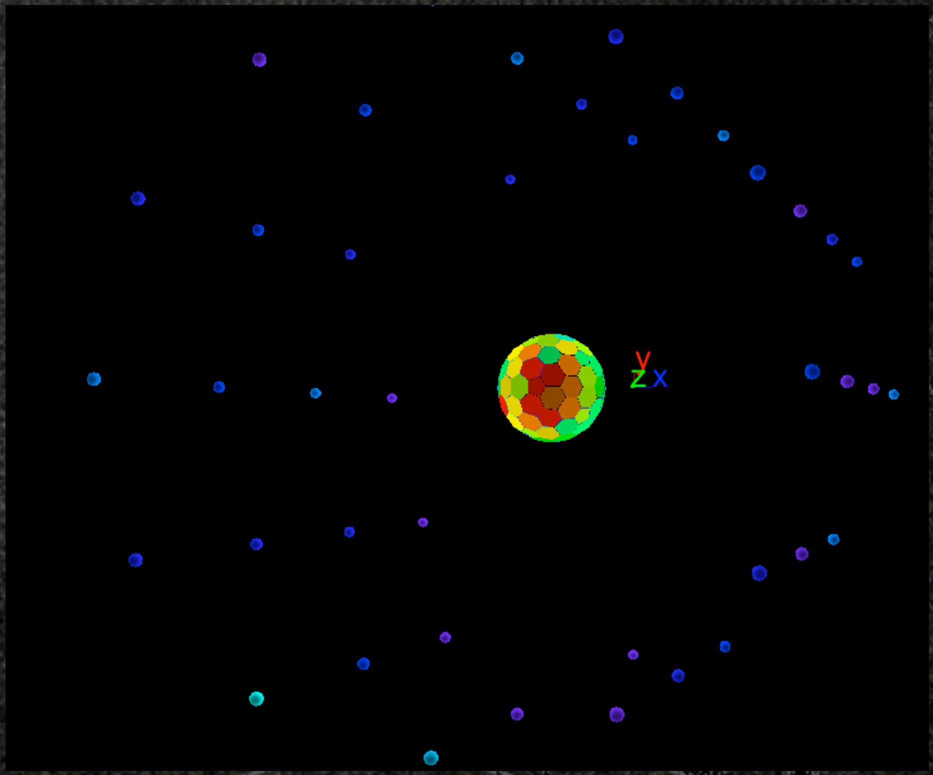
- MiniCLEAN will be running summer 2013
- ^{39}Ar spike in MiniCLEAN Fall 2013
- Liquid Noble detectors in single and dual phase are scalable
- Next generation dark matter detectors will probe far in the WIMP phase space

Backup Slides

Simulation → Operation Software

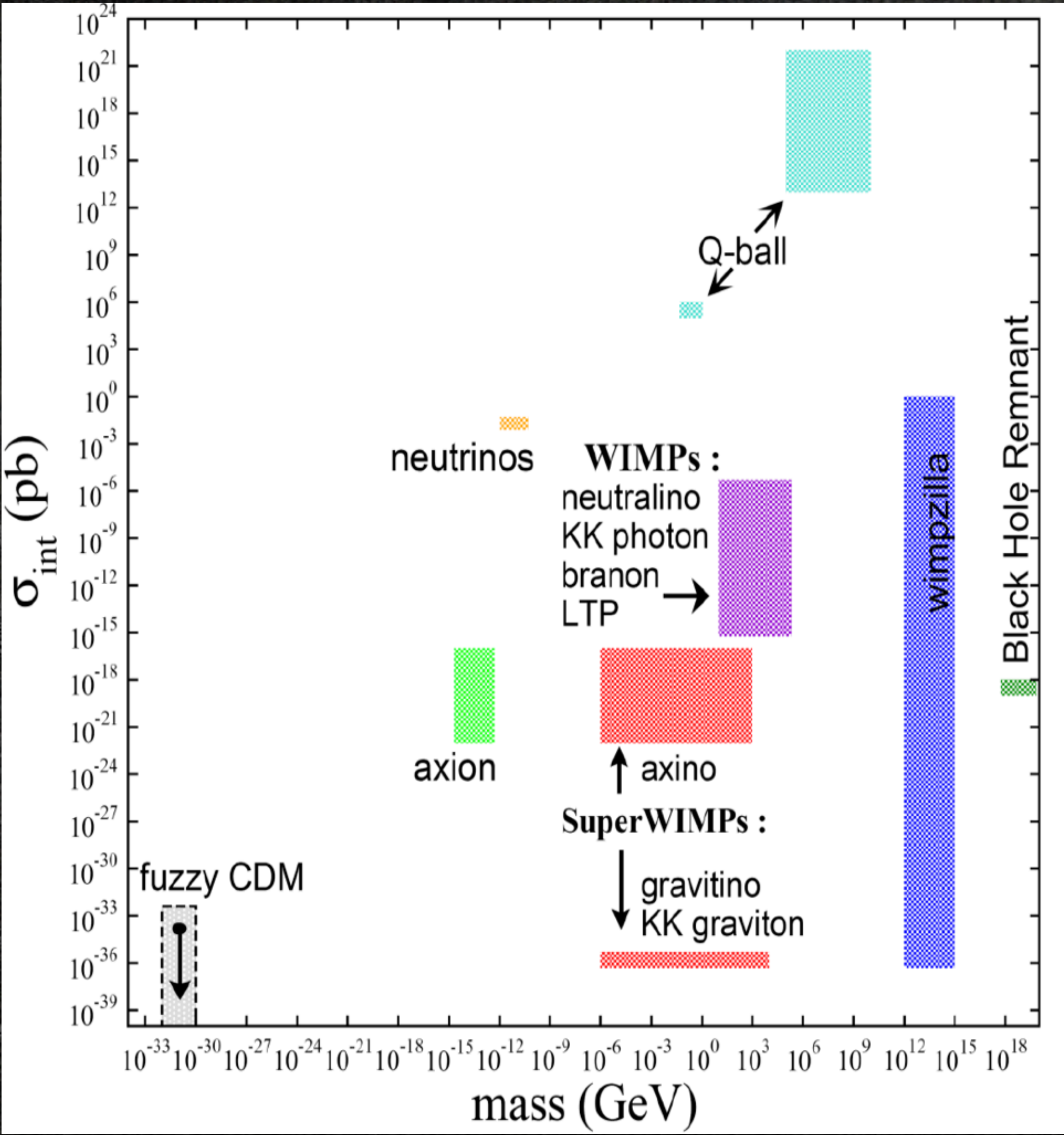






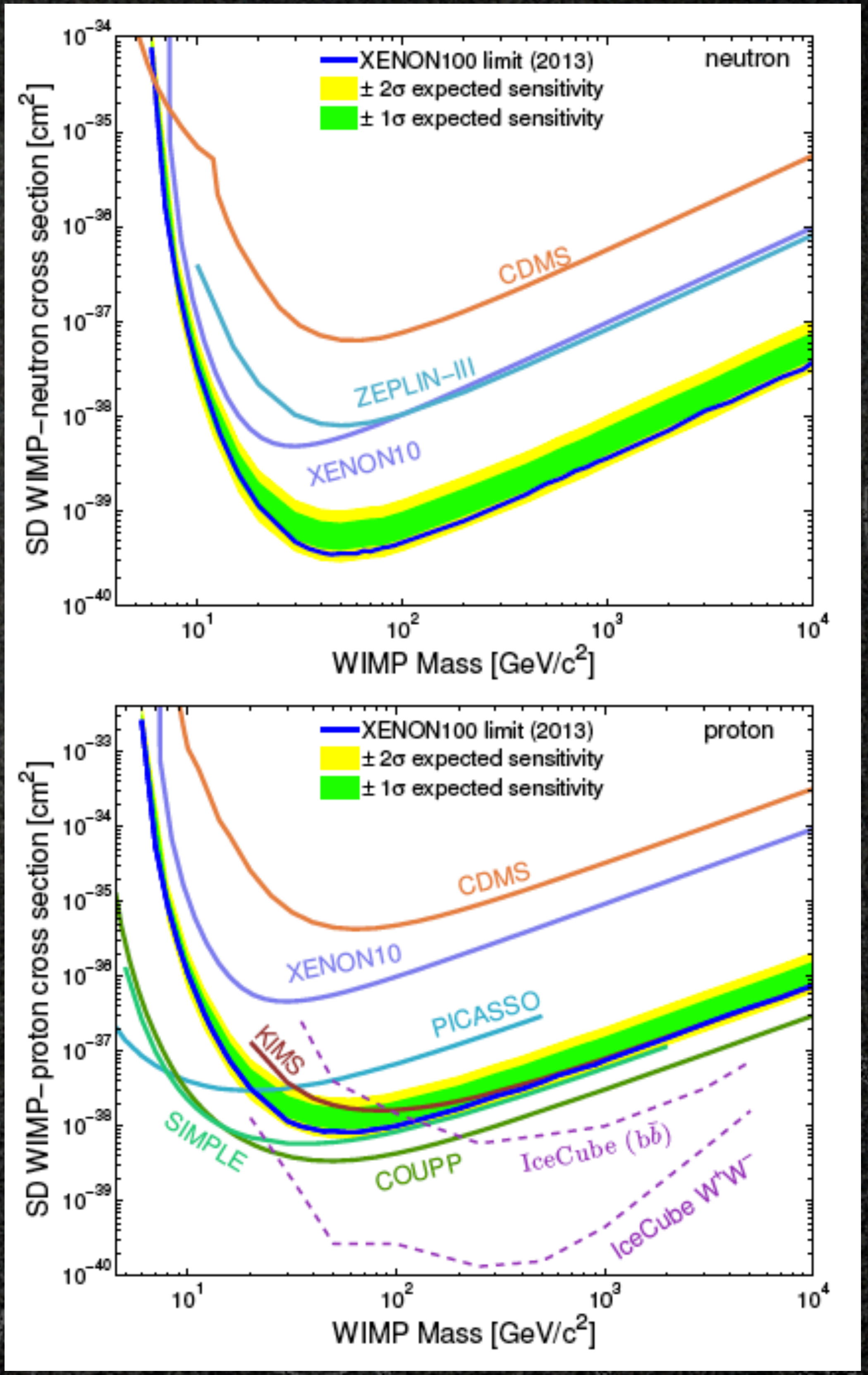
Event viewers utilizing a number of views and organizational tools for future troubleshooting, from BU and UPenn software groups

Dark Matter Parameter Space

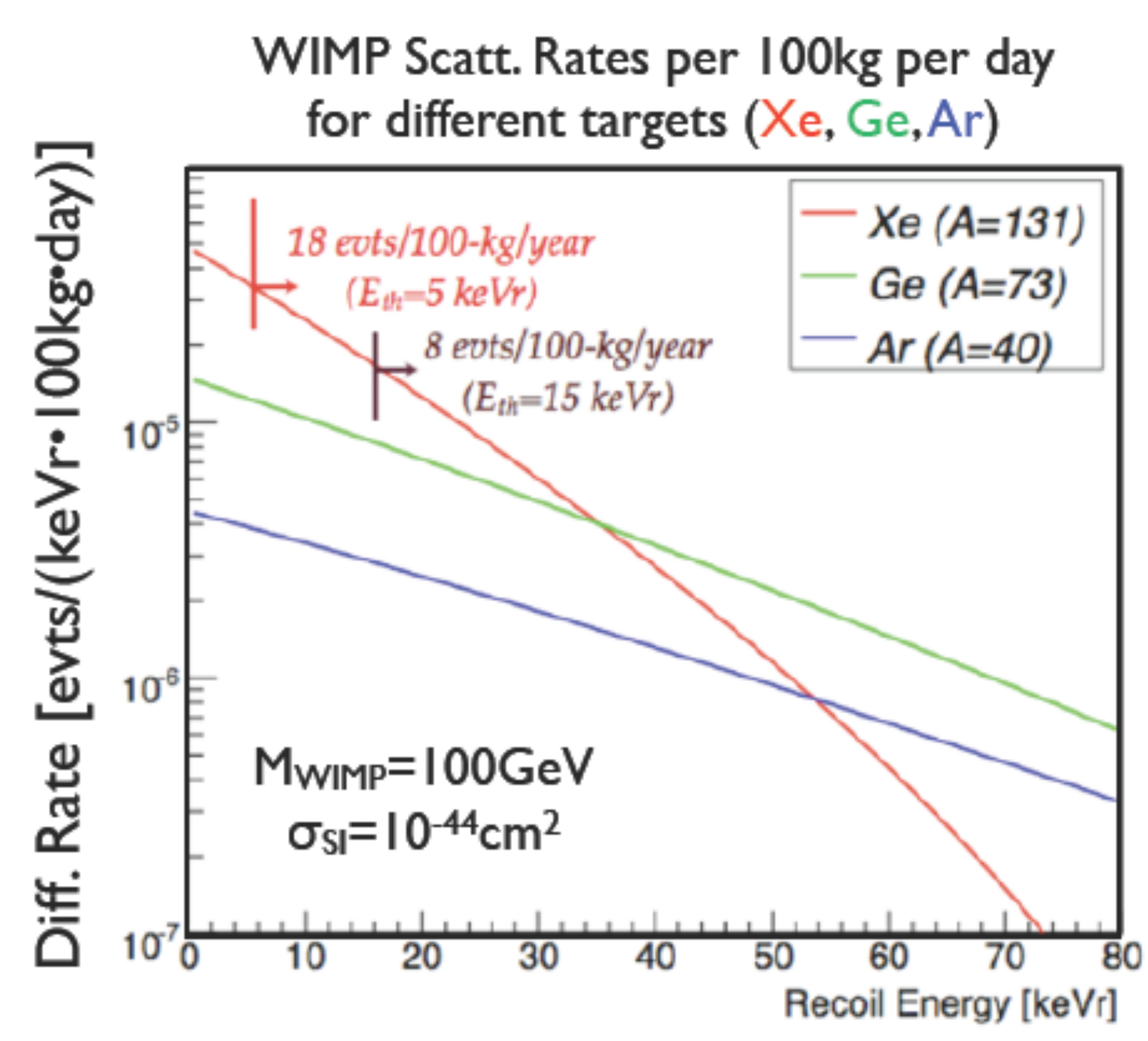


Spin-dependent

- Spin dependence for unpaired nucleons: don't see A^2 enhancement, do see xs ~ J(J+1)
- Spin-dependent may indicate that dark matter is it's own antiparticle
- Latest results from Xenon100 arXiv:1301.6620

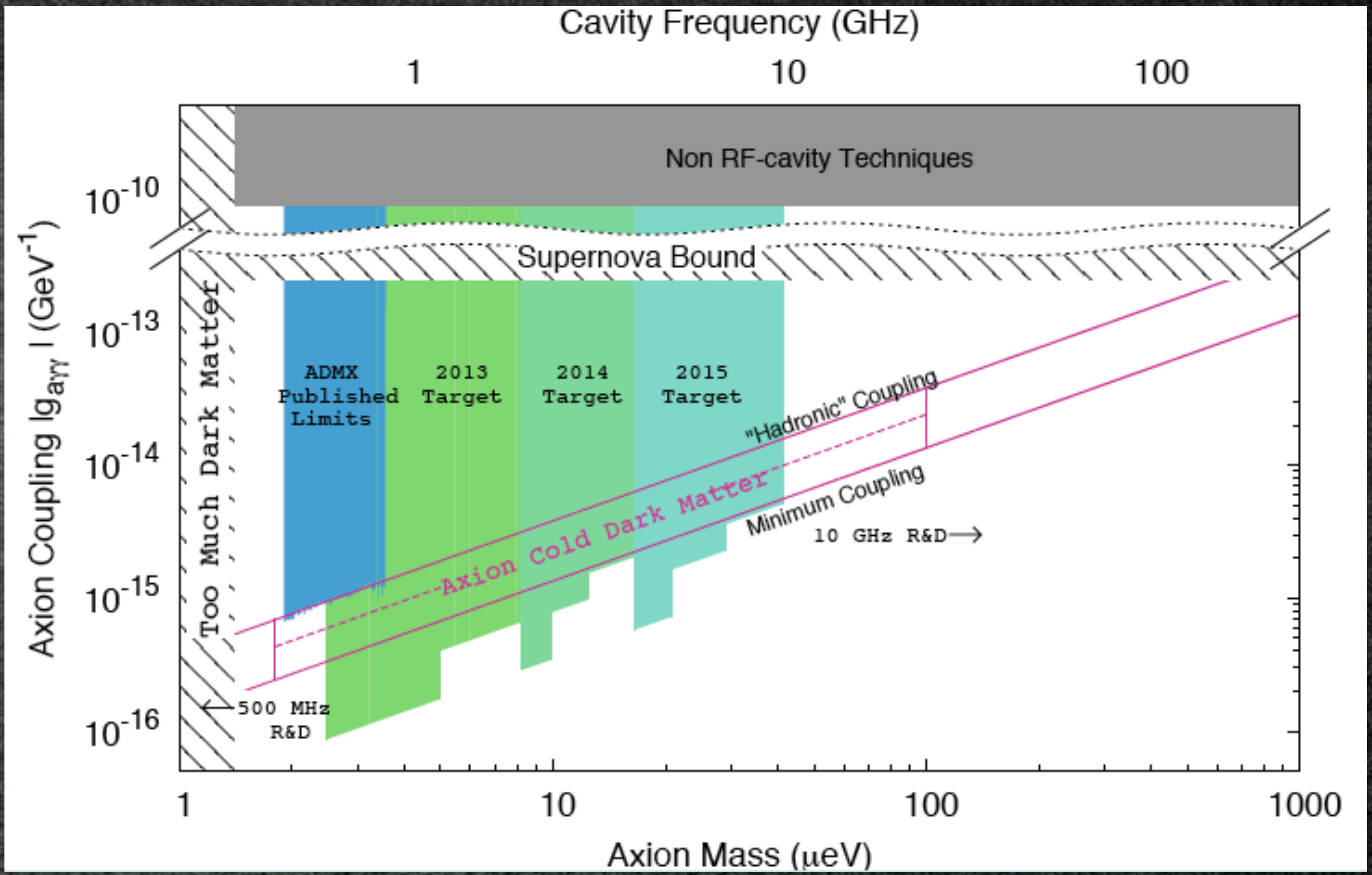


Event Rates



P. Decowsksi Aspen 2013

Axions



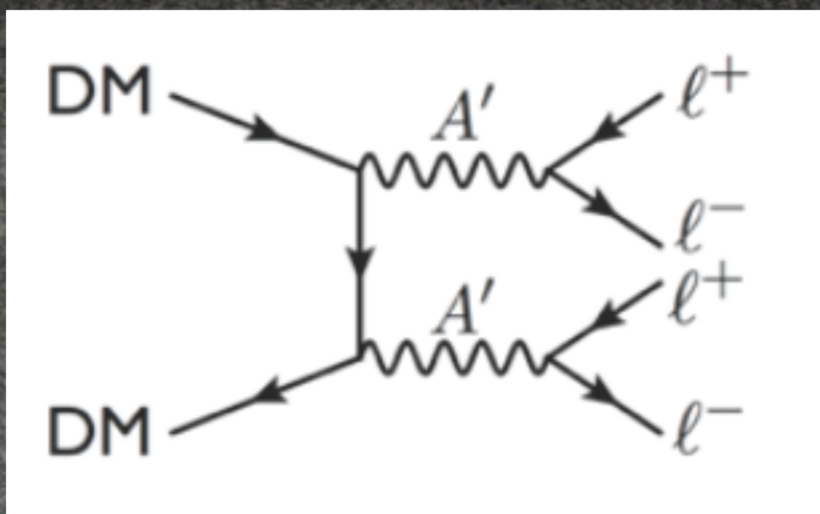
L. Rosenberg, IDM 2012

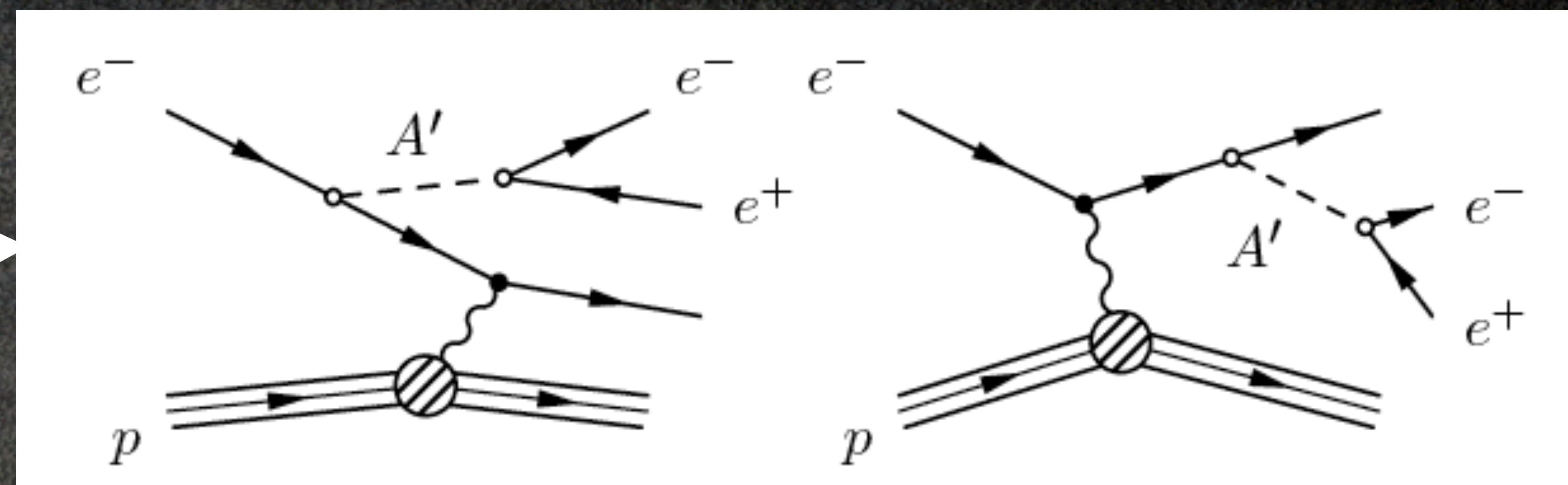
- Axions are light pseudoscalars that enforce strong CP conservation
- Dark matter mass window: 10^{-6} ev < m < 10^{-2} eV
- axion-$\gamma\gamma$ coupling has few parameters and little model dependence: good place to look

Light shining through walls, and solar experiments probe higher couplings & masses

Microwave cavity experiments have greatest reach in the Dark Matter region, ADMX is the leading program, which will have statements soon about axion cold dark matter

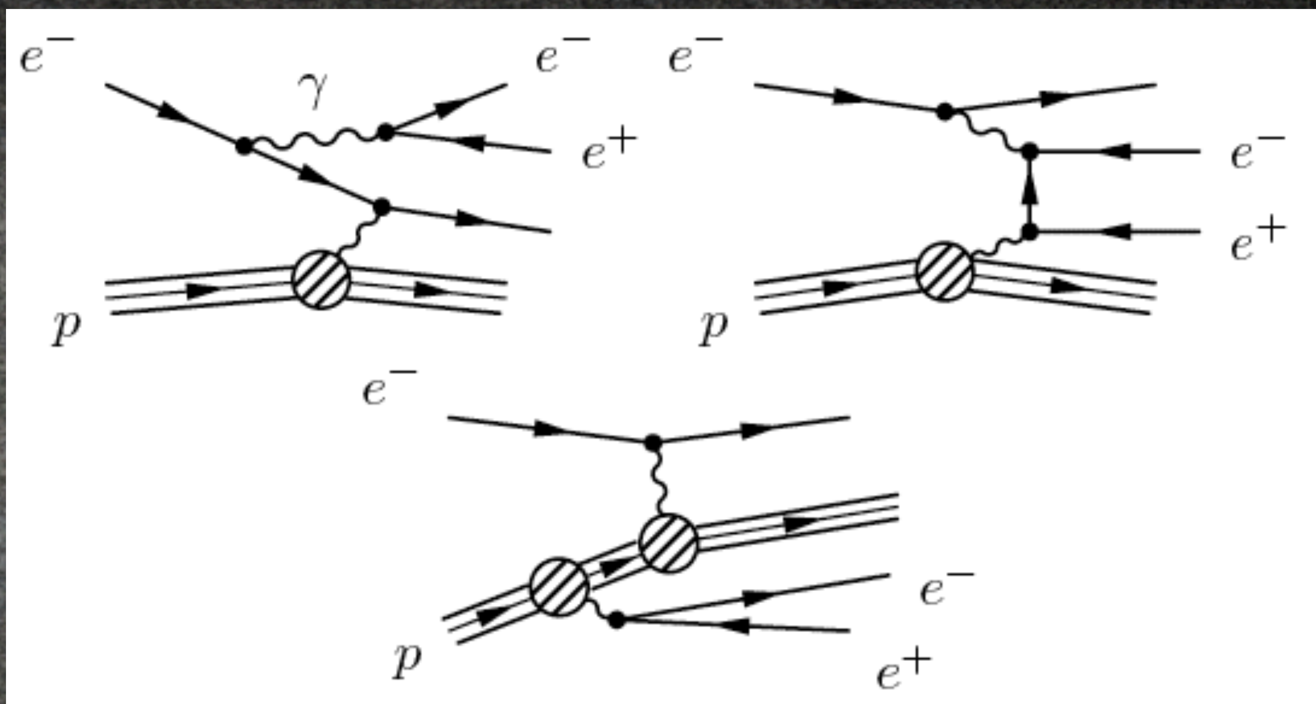
Dark Forces





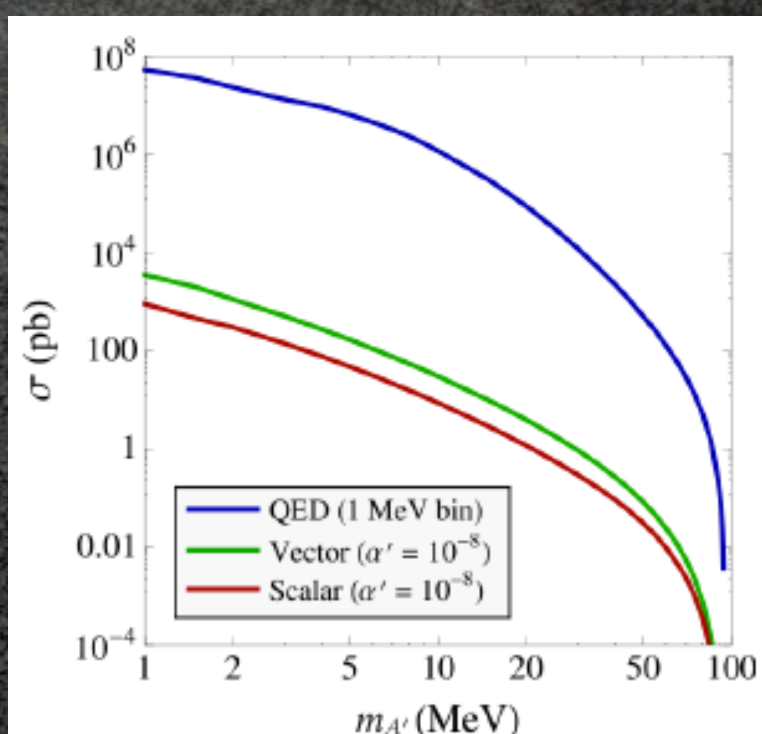
- Indirect detections (positron excess, lack of antiproton excess, WMAP haze) could be explained by a dark sector with "heavy photon" new boson A′, and mA′ < 1 GeV
- Can also explain muon g-2
- Fixed target experiments can look for A′ production and decay

A′ & Backgrounds

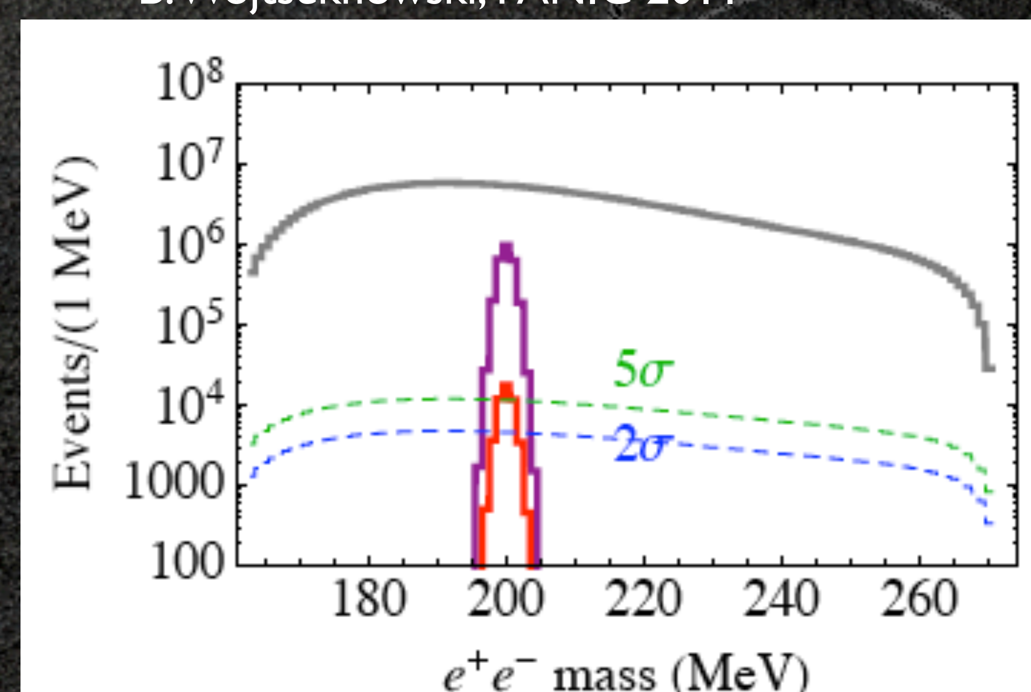


- Standard QED processes look the same as A′ production and decay
- Backgrounds are 10^4 times more likely
- Signals will be a narrow resonance on a smooth background, excellent mass resolution is needed

R. Russell, PANIC 2011

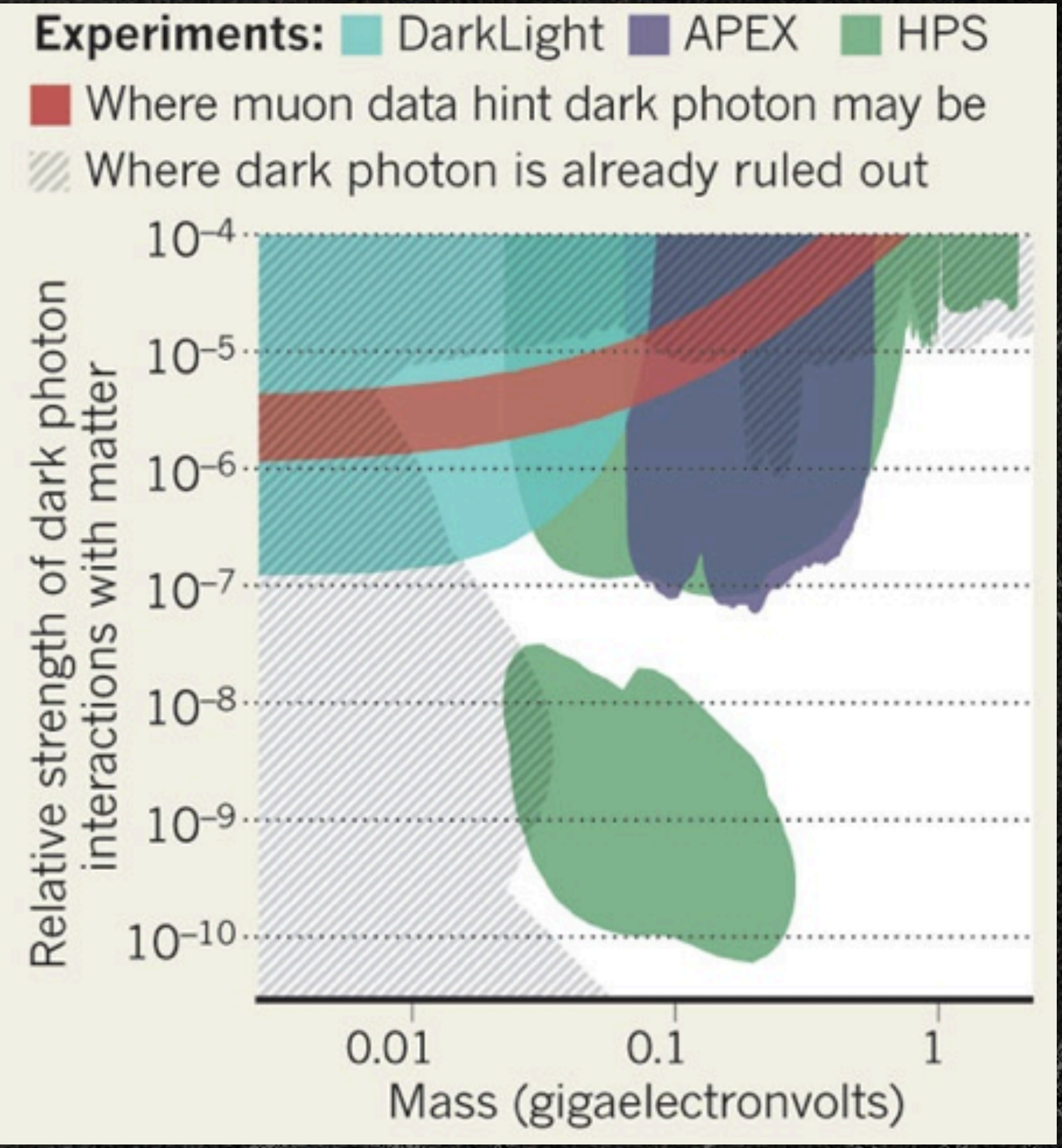


B. Wojtsekhowski, PANIC 2011



A′ Experiments

- **HPS** (Heavy Photon Search): forward spectrometer behind CLAS, 200-500 nA beams at 2.2 and 6.6 GeV with a tungsten target
- **APEX** (A Prime Experiment) : using the HRS in Hall A, 80 uA at 4 energies from 1.1 to 4.5 GeV with tantalum and tungsten targets
- **DarkLight** (Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target): compact solenoidal detector surrounding the target, using the J-Lab FEL, 10 mA current at 100 MeV with a hydrogen target



Nature News, R. Essig