Dark Matter Physics Requirements for Liquid Argon TPCs

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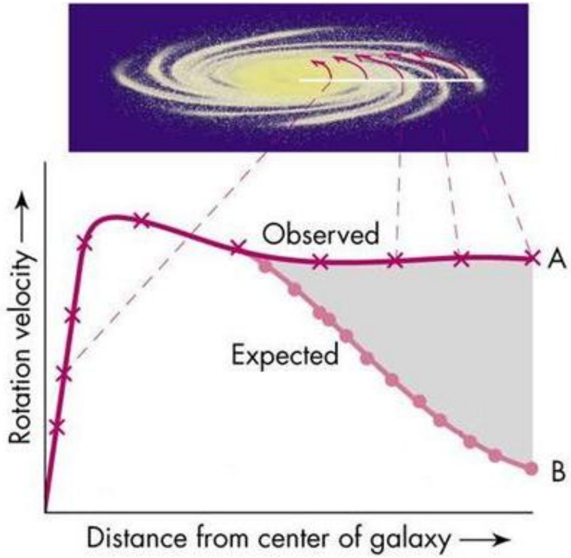
Fermilab

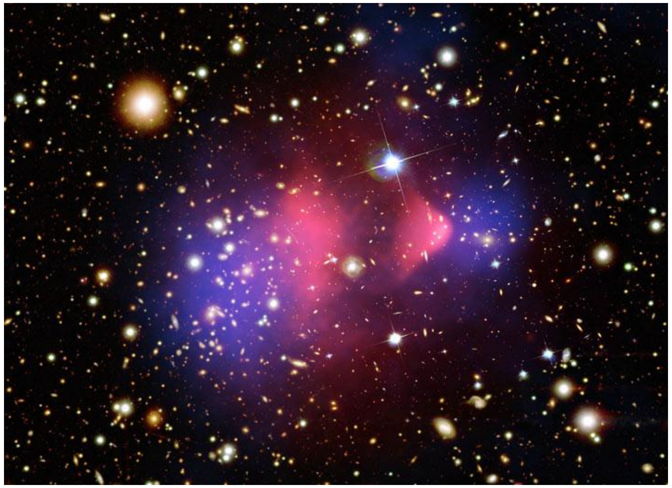
Outline

- WIMP dark matter basics
- WIMP signal in a dual phase LArTPC
- Backgrounds and how to beat them
- Summary

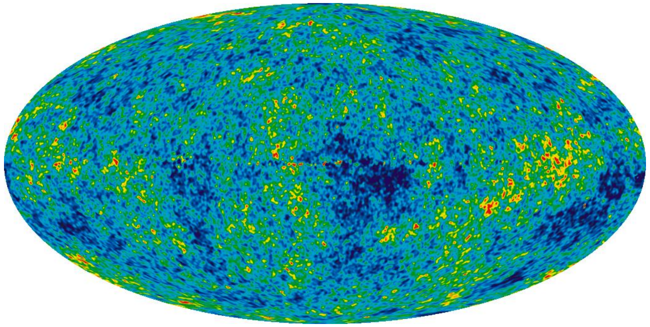
Evidence for dark matter: Compelling at all scales

Single galaxies

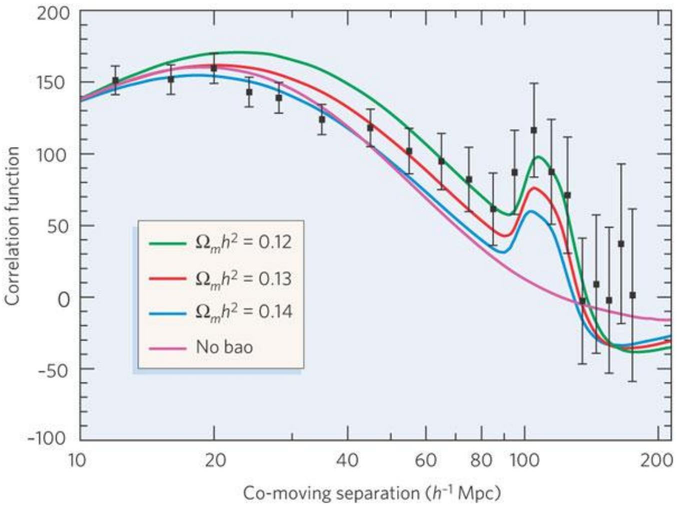




Galaxy clusters



The whole observable universe



WIMP Dark Matter Basics

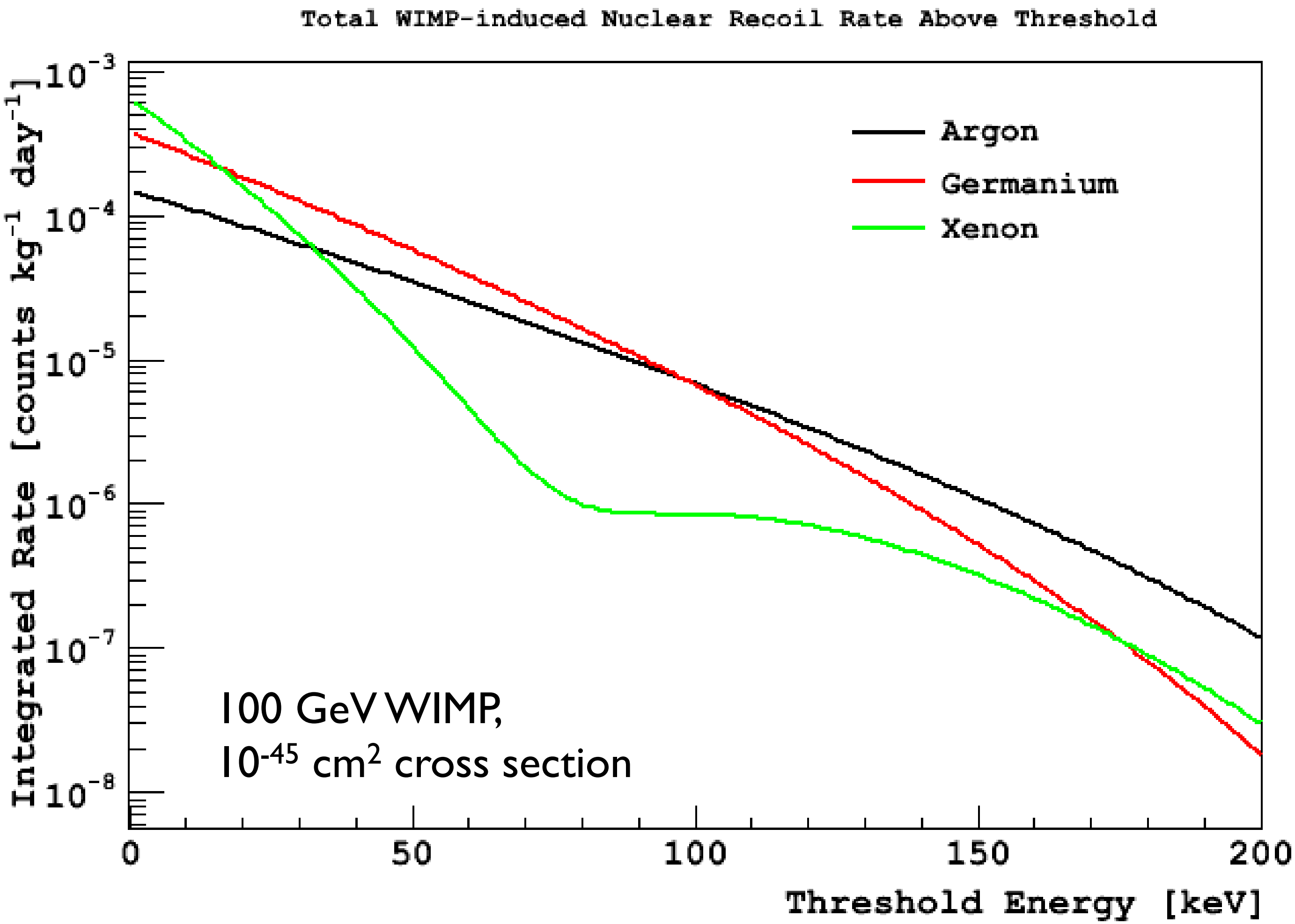
- For most experimental searches, dark matter means WIMP: weakly interacting massive particle
- Often identified with LSSP neutralino; acts like heavy neutrino with only neutral-current interactions
- Standard assumptions:
  - WIMPs are a non-interacting gas on average at rest w.r.t. the galaxy
  - Energies follow Maxwellian velocity distribution with average velocity ~300 km/s with cutoff at galactic escape velocity
  - Local density ~0.3 GeV/cm^3; per-particle mass is a free parameter. For 100 GeV wimp, flux would be ~10^5 /cm^2/s

Expected detector response to WIMPs

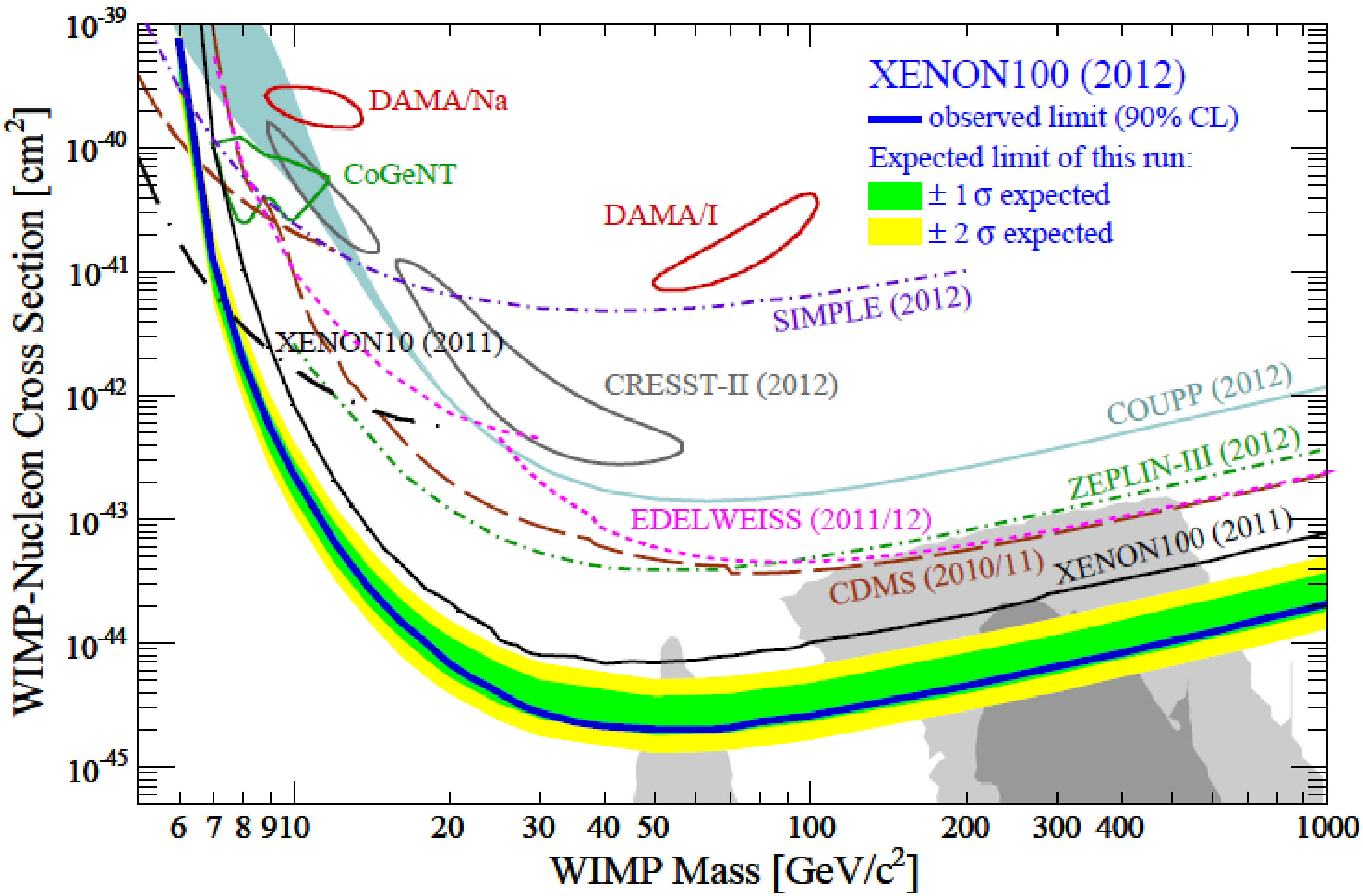
$$\frac{dR}{dE_R} = \frac{N_0 \sigma_n \rho_D M_T}{2A\mu_n^2 M_D} \left(Z\frac{f_p}{f_n} + (A - Z) \right)^2 F^2(q) \int_{v_{min}}^{\infty} \frac{f(v_D, v_E, v_{esc})}{v_D} dv_D$$

- WIMP-nucleon cross section and local WIMP density
- Coherent scattering factor. If fp=fn (isospin symmetry), reduces to A_2
- Nuclear form factor, accounts for imperfect coherence at larger momentum transfer (i.e. smaller propagator wavelength) and larger nucleus
- Velocity distribution function. v_E term introduces seasonal modulation. Only upper tail of velocity distribution above v_{min} can cause recoil of energy E_R

Expected detector response to WIMPs



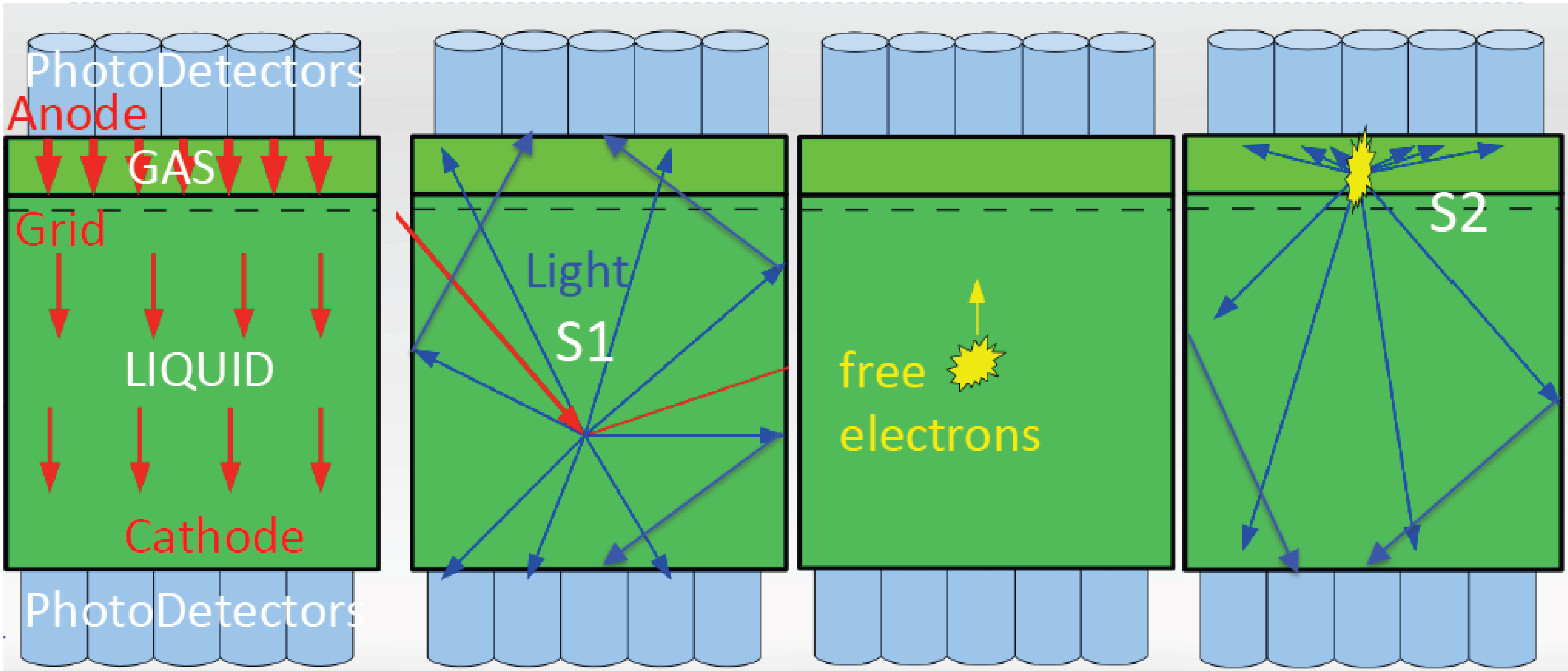
What is our current sensitivity?



Summary of WIMP signals

- Low energy recoiling nucleus: O(10-100) keV
  - Events are pointlike: no tracks!
  - Too little charge released per event to measure directly
  - Environmental radioactivity becomes a background
- Very low rate: current limits are O(10) events/ton/year
- Compare to:
  - Atmospheric argon: 10^{10} decays/ton/year from ^{39}Ar
  - Clean copper: ~10^7 decays/ton/year
  - One fingerprint: ~20 decays/year
  - One 8 in. "low background" PMT: ~300 neutrons/year
  - Detector must be made of ultraclean components assembled in cleanroom environment

Dual Phase Electroluminescence TPC



Liquid active volume with small drift field Gas multiplication volume

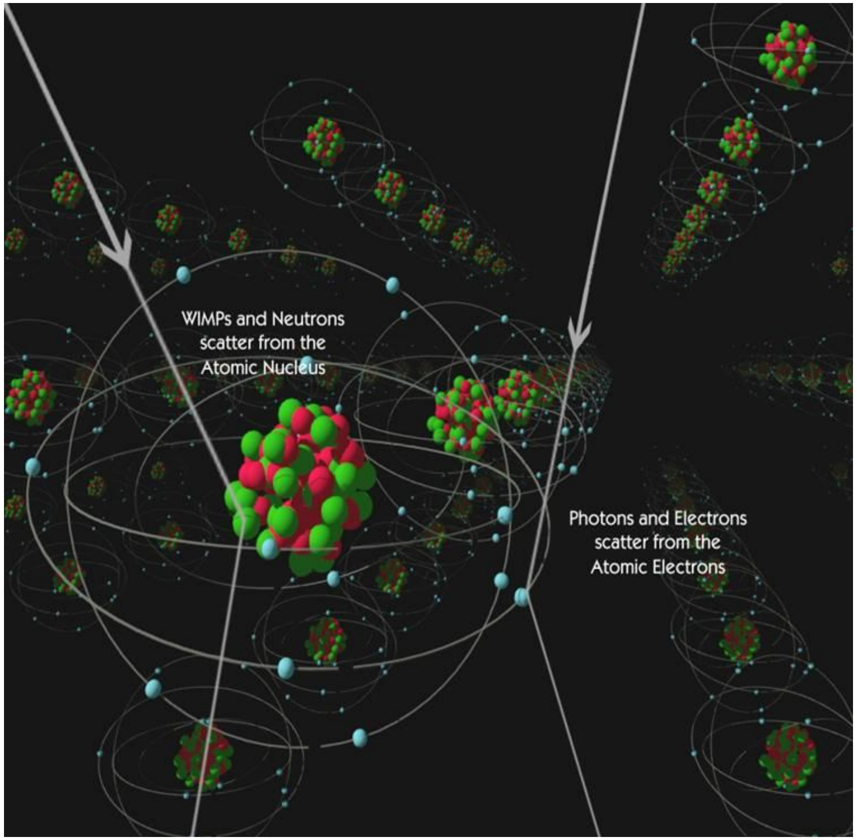
Primary interaction creates scintillation (S1)

Ionized electrons drift toward gas region

High field in gas makes secondary scintillation (S2) (light-gain only)

Why use a LArTPC for WIMP search?

- Most environmental radiation is gammas; LArTPCs very good at discriminating nuclear recoils from electron recoils
- Alphas on surfaces removed by 3D position reconstruction
- Neutrons (slightly) removed by identifying multiple scatters

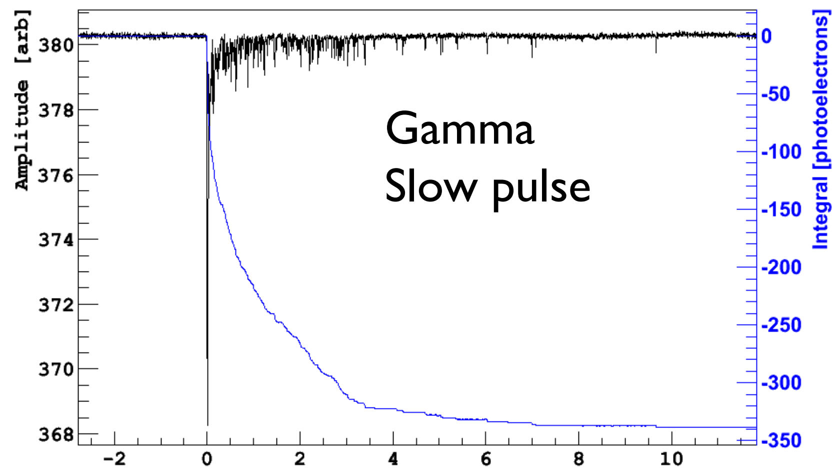


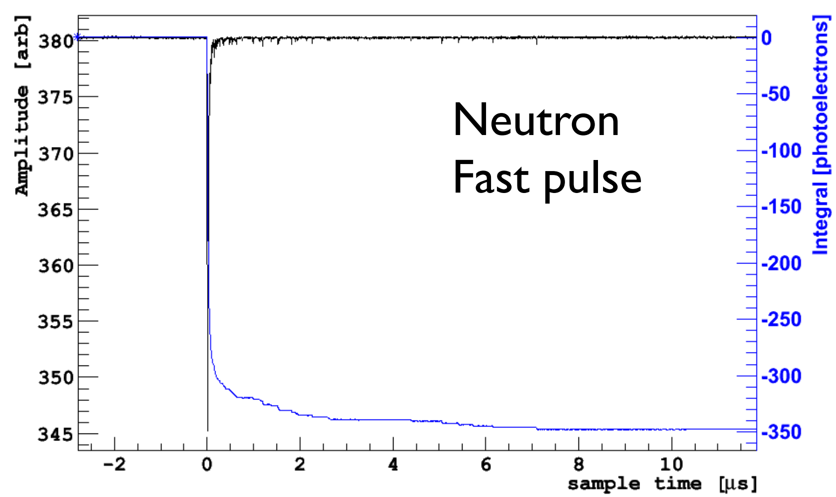
Gamma discrimination in LArTPCs

- Nuclear recoils have high dE/dx compared to electrons
- High dE/dx => high ionization density => high ion recombination
- High dE/dx => higher singlet excitation
- Therefore:
  - NRs have faster scintillation pulses than ERs
  - NRs have lower scintillation to ion extraction ratio (S2/S1) than ERs

Primary Scintillation (S1)

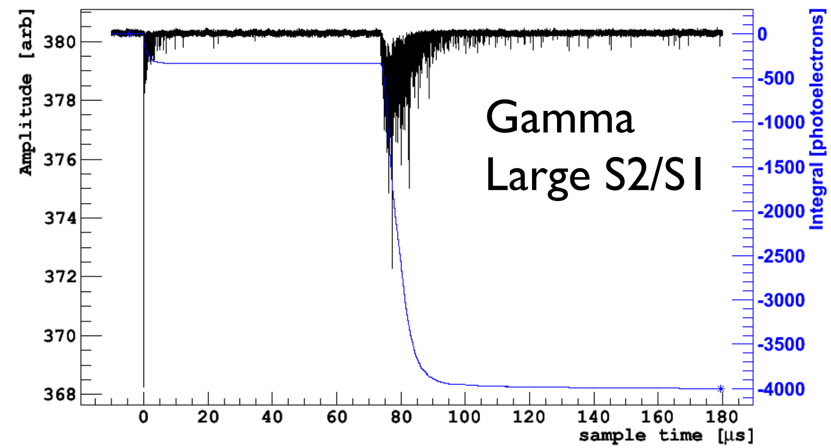
- Puse Shape Discrimination (PSD) parameter usually prompt/total
- At low energies, spread of PSD is from Poisson fluctuations of number of photoelectrons => need high light collection efficiency (>~5 p.e./keV)
- Impurities like N_2 can reduce slow component at few ppb level => need ultra-clean!

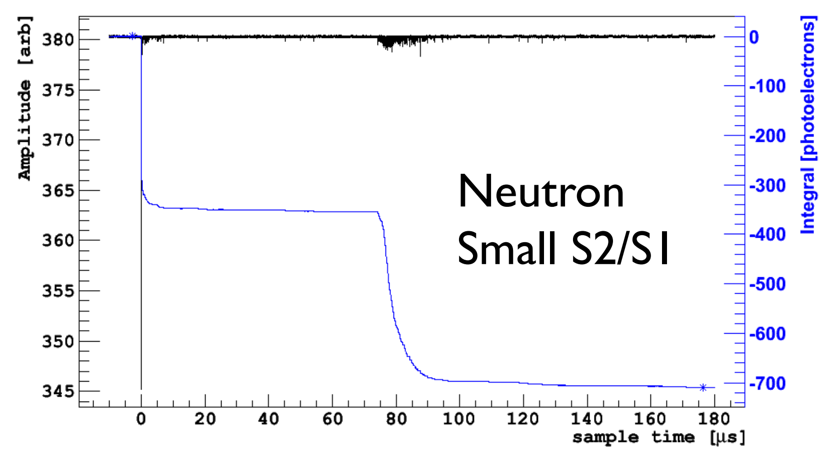




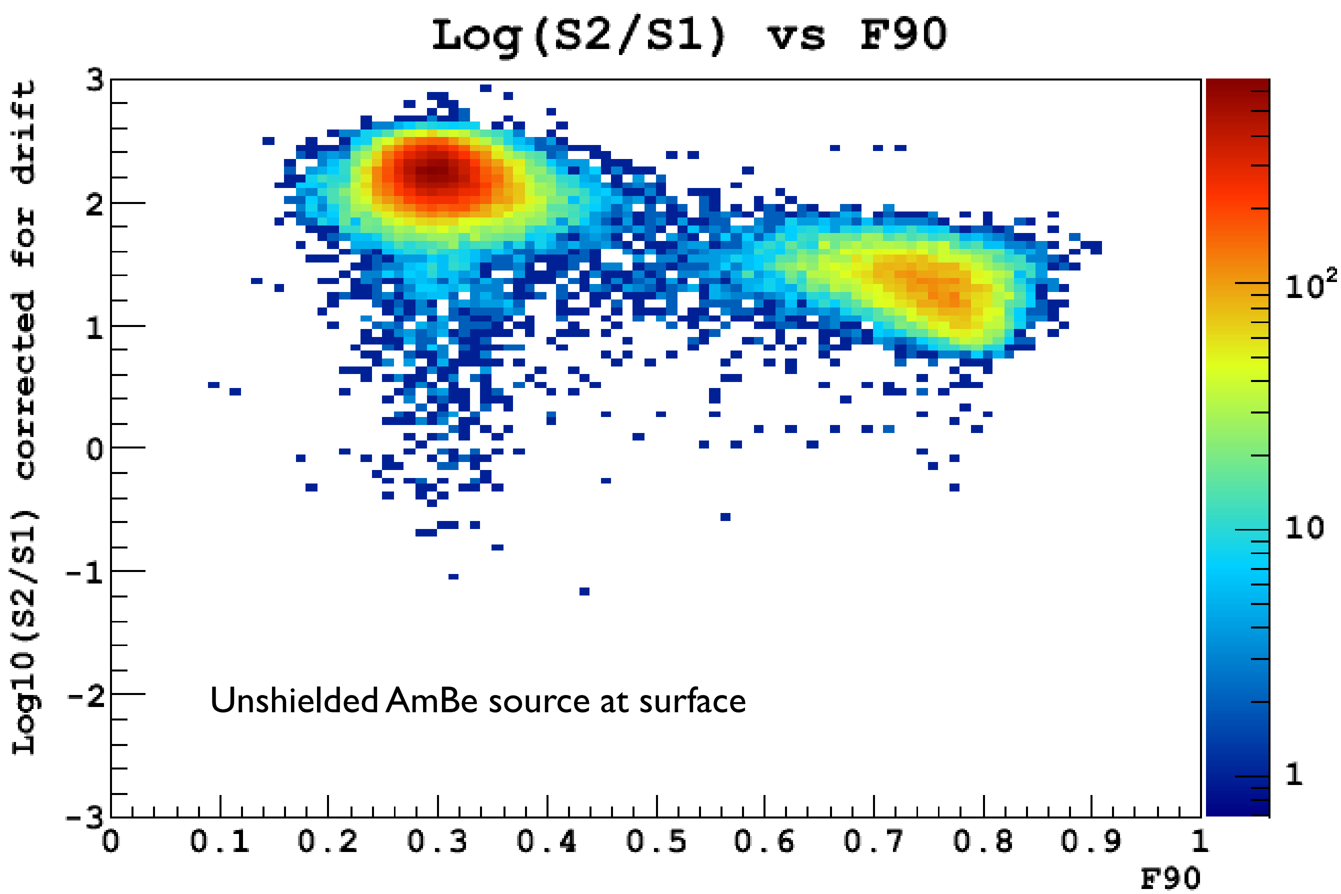
Electroluminescence scintillation (S2)

- Impurities like O_2 can capture drifting charge
- Need uniform EL gain vs position and time: gas pocket must be level, stable temperature and pressure
- With ~few 100s of microsecond drift times, pileup becomes serious problem at ~100s of Hz





Gamma background rejection ~10^8-10^9



Argon-39 and underground argon

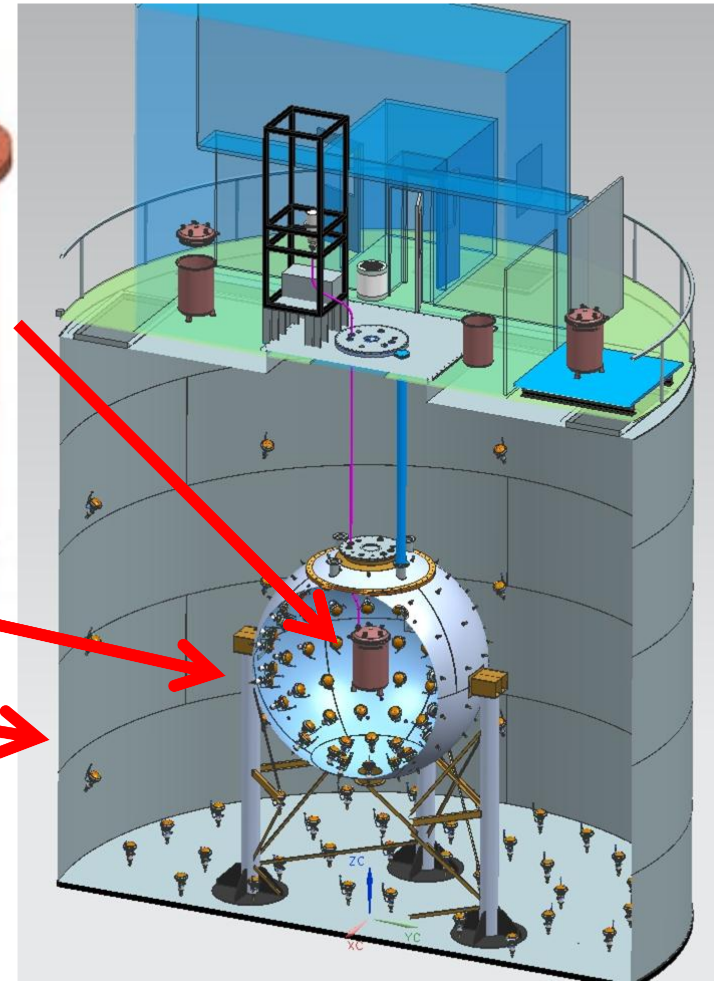
- ^{39}Ar beta decays (Q=565 keV) at ~1 Bq/kg in natural argon
- Pileup killer at ~ton scale
- Made in upper atmosphere by cosmic rays => reduced levels underground
- FNAL currently producing ~0.5 kg/day argon with < 0.65% ^{39}Ar rate relative to commercial argon

What about neutrons?

- Other than multiple scattering, neutrons look like strongly interacting WIMPs
- Two flavors:
- Radiogenic: from U, Th in detector materials and experiment hall.
  - Energy a few MeV, so not too penetrating
  - Very clean detector materials, lots of passive shielding, active vetoes
- Cosmogenic: from cosmic ray showers
  - Energies up to GeV, very penetrating
  - Go deep underground, veto the muons/showers

Example: DarkSide-50

- 50 kg underground argon (~33 kg fiducial)
- 4m boron liquid scintillator neutron veto
- 11m water-cherenkov muon veto/shield
- Located in LNGS in Italy under > 1 km of mountain



Summary

- WIMP events are ultra low rate, very low energy
- Background reduction+rejection is everything
- Detector must be made of ultra-clean materials in clean room environment, sited deep underground with lots of shielding
- Gamma rejection requires high light yield, good, stable charge collection, high purity argon
- Even with good rejection, need low-radioactivity argon to beat pileup at ~ton scale