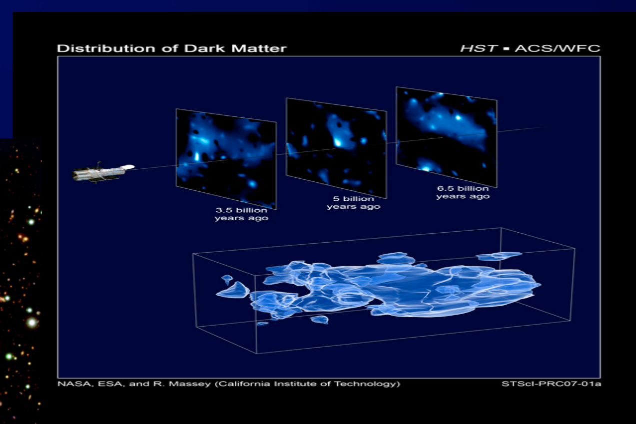
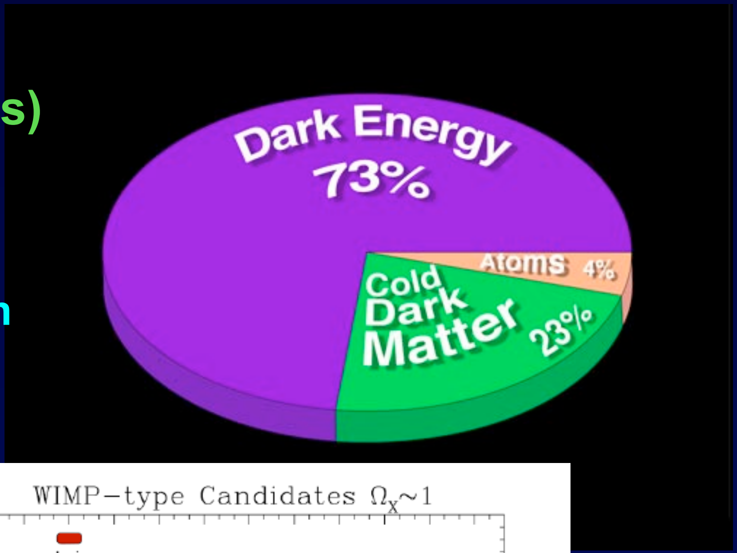
Status of Experimental Dark Matter Searches

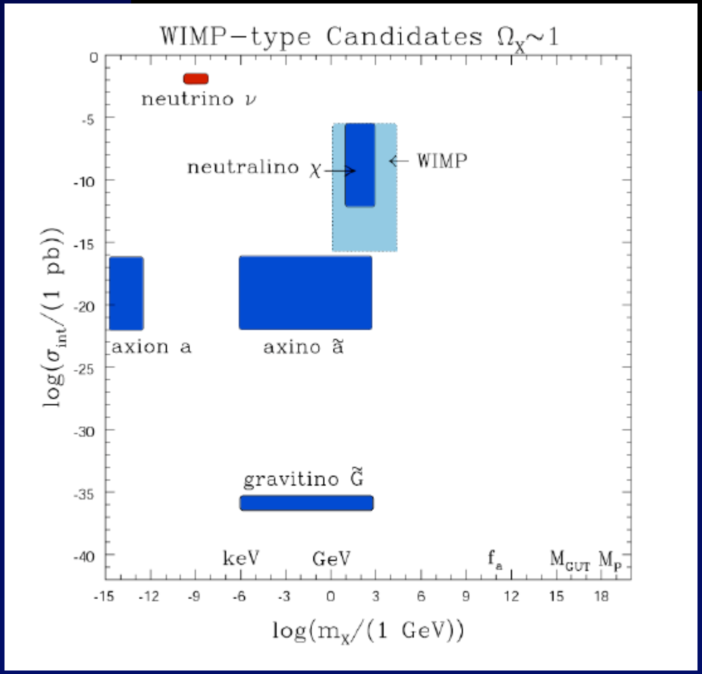
Bruno Serfass - UC Berkeley



Particle Dark Matter Zoo

- Weakly Interacting Massive Particles (WIMPs)
  - particle with electroweak scale interactions with normal matter
  - Ex: SUSY neutralino, Kaluza-Klein particle in universal extra dimensions
- Axions
  - Restores CP-symmetry in QCD
- Neutrinos
  - only massive (sterile) neutrinos can be cold or warm
- And..
  - SUSY gravitinos, axinos,…





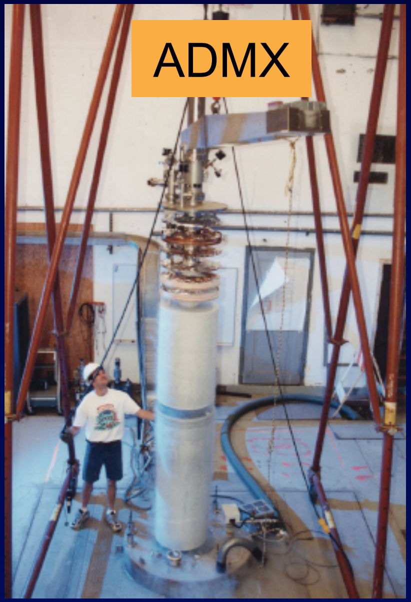
(Roszkowski 2004)

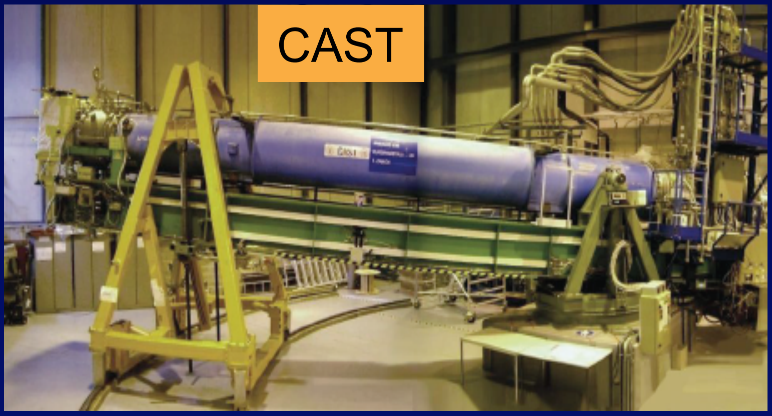
Searching for Axions

- Light pseudoscalar particle
  - introduced to solve strong CP problem
  - weak couplings
  - born non-relativistic (cold dark matter)

- Detection rely on induced coupling to photons

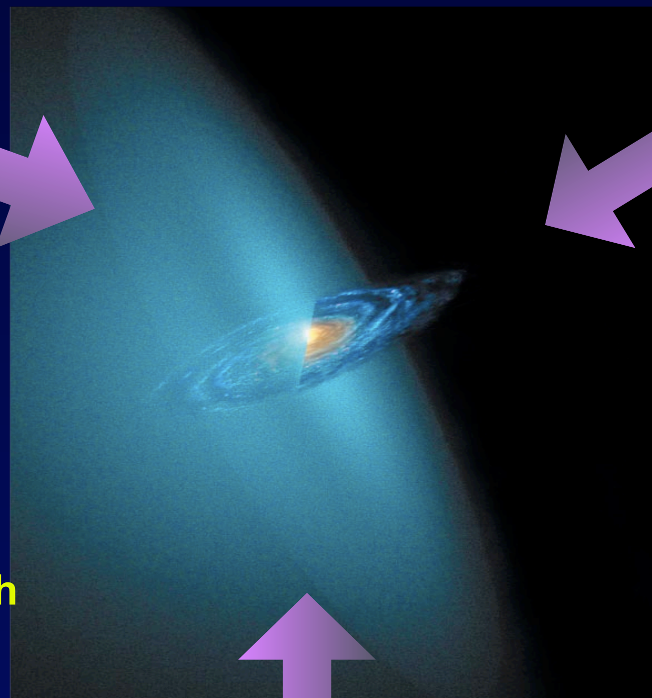
- Techniques:
  - **CAST:** conversion of solar axions to photons in magnetic field (using LHC prototype magnet B~10T)
  - **ADMX:** high-Q resonance cavity in an external B field

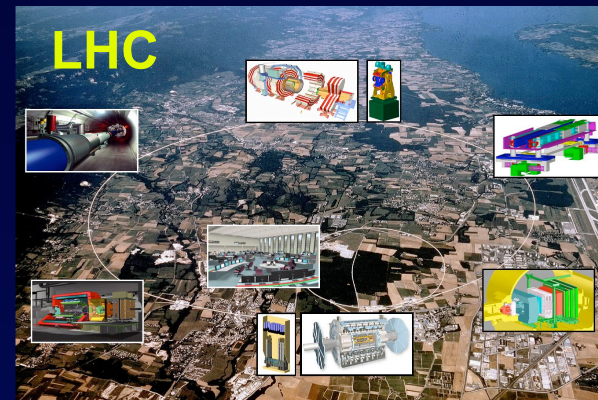




Searching for WIMPs

WIMP scattering on Earth





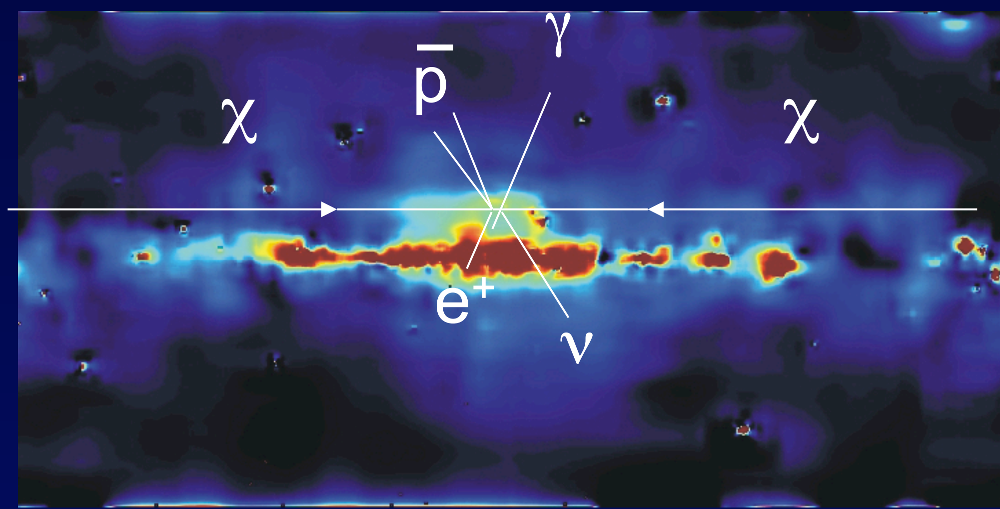
WIMP production on Earth

WIMP annihilation in the cosmos

Indirect Dark Matter Search

If WIMPs density becomes large enough (galactic cores, Sun, Earth), annihilation can occur in spite of low cross sections

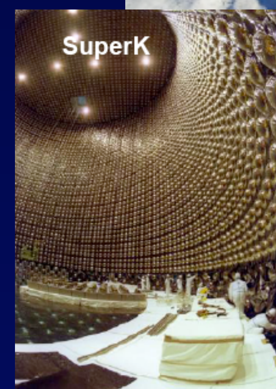
- **Annihilation products:**
  - neutrinos
  - gamma rays,
  - e+, e-, p, anti-p, etc

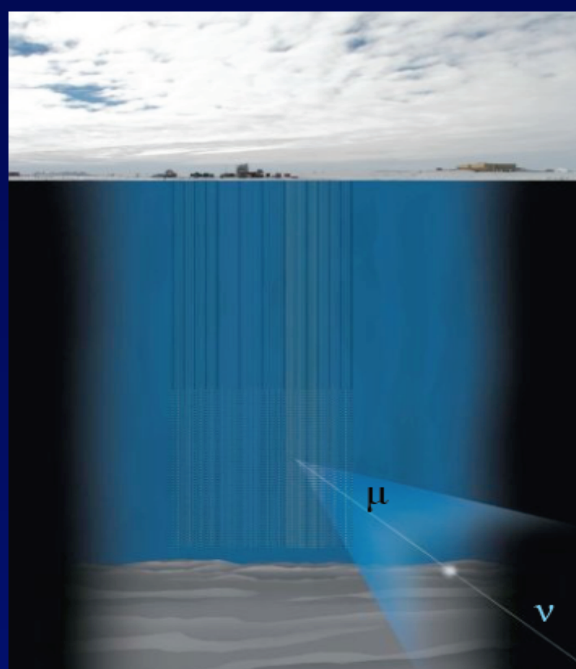


- **Experiments:**
  - Ground: Neutrino telescopes such as IceCube, Antares,…
  - Ground: Imaging Atmospheric Cherenkov Telescopes such as HESS II, MAGIC II, VERITAS,… (10^{17} eV to 10^{20} eV)
  - Satellite: FERMI-LAT, PAMELA,… (50 MeV – 500 GeV)

Neutrino Experiments

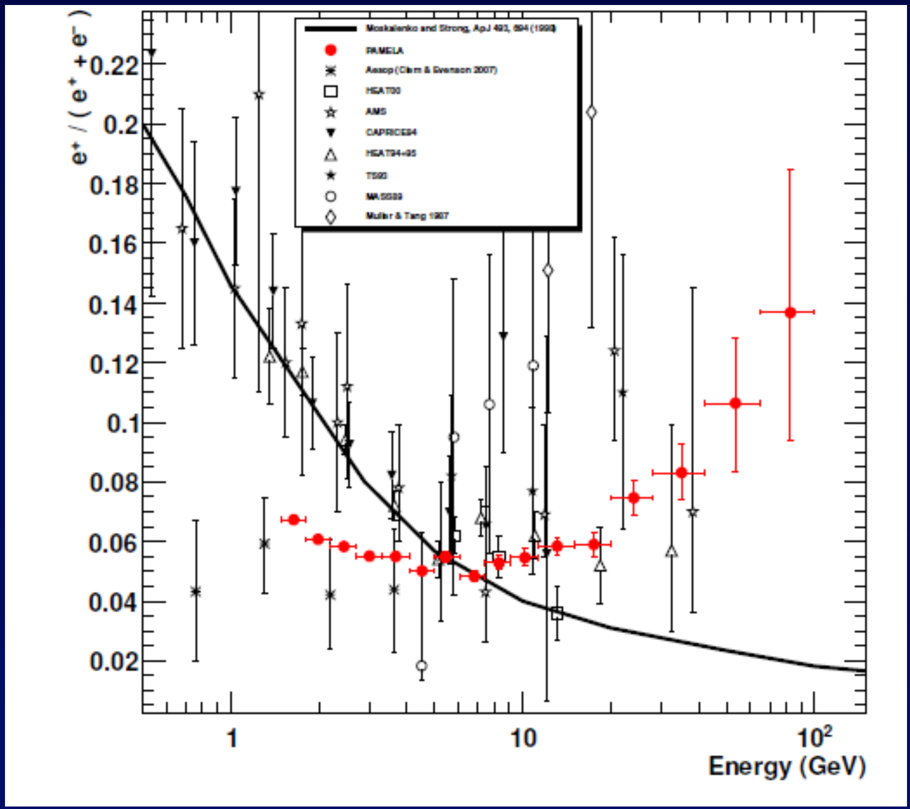
- Potential neutrinos sources from WIMPs annihilation: Sun, Earth, Galactic Centre
- Search for υ_{μ} via upward-going μ in υ telescope
- Sensitive to SUSY relevant mass range >100GeV

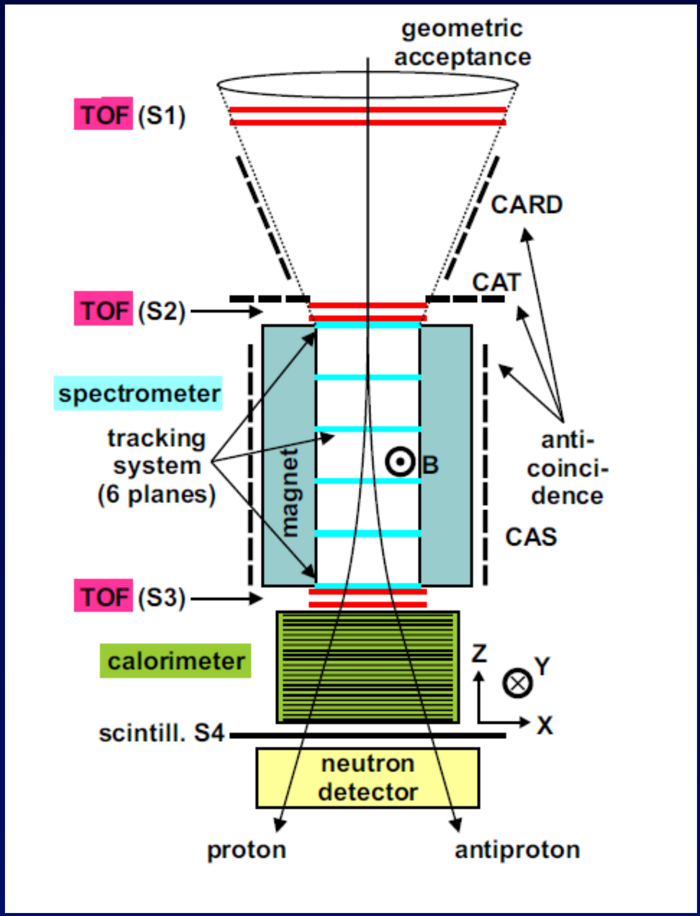




Pamela Satellite Experiment

- Launched in Spring 2007
- Measure e^-/e^+, p/anti-p, He/anti-He



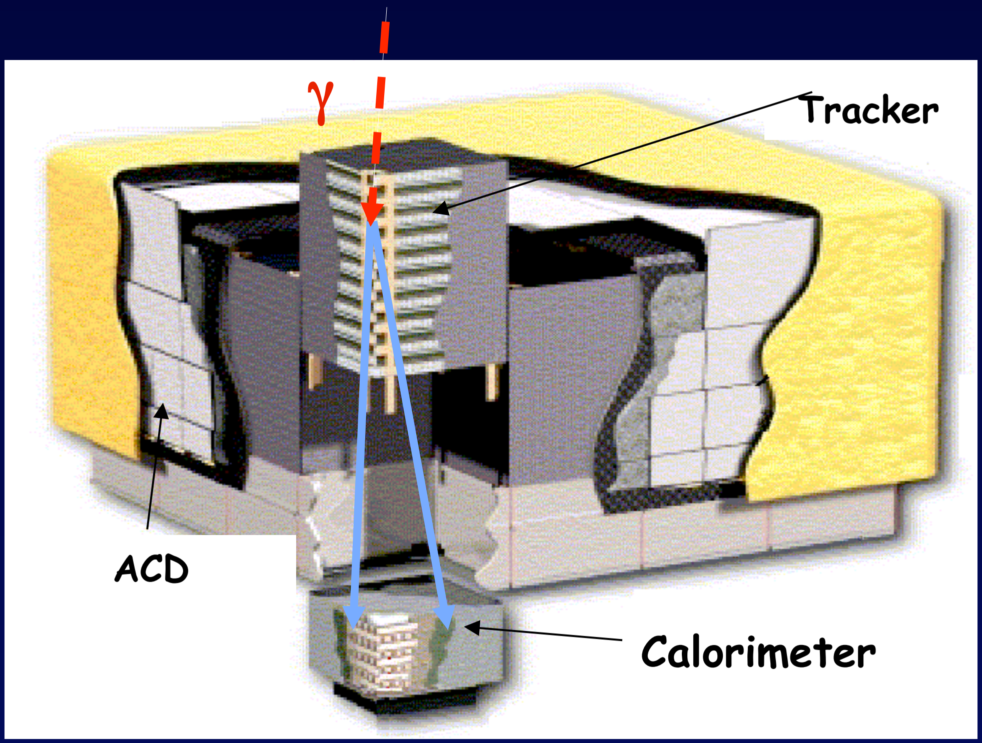


Positron fraction increases above 10 GeV

- pulsars?

Fermi Large Area Telescope (LAT)

- Launched 11 June 2008
- Measure flux of cosmic gamma rays and (e^{-}+e^{+}) with E=20 MeV to >300 GeV
- Precision Si-strip tracker
  - gamma ID
  - photon direction
- CsI calorimeter
  - photon energy
- Anticoincidence Detector (ACD)
  - reject background of charge cosmic rays
  - self veto effect at high energy



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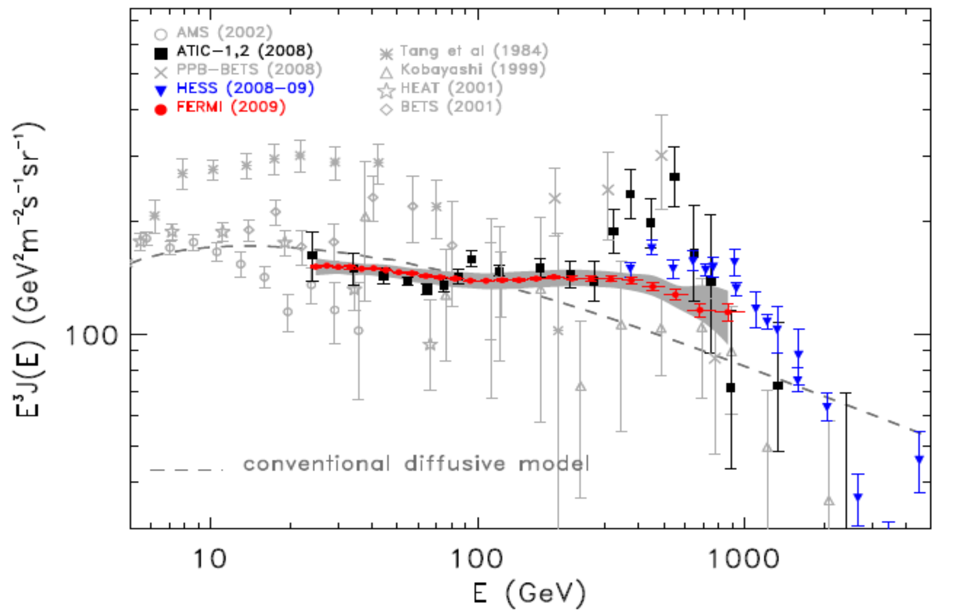


J. Chang et al., Nature **456**, 362 (2008)
F. Aharonian et al., Phys. Rev. Lett. **101**, 261104 (2008)
A. A. Abdo et al., Phys. Rev. Lett. **102**, 181101 (2009)
F. Aharonian et al., arXiv:0905.0105v1

- ➢ FERMI-LAT results does not confirm ATIC electron flux excess
- ➢ FERMI-LAT results does not confirm EGRET observation of an “all sky” excess in the GeV range

Summary DM Indirect Search

- No convincing Dark Matter signal found
- Pamela confirms HEAT positron excess (10-100 MeV)
  - nearby pulsars?
- ATIC e+ e- (300 – 800 GeV) excess not confirm by FERMI and HESS
- EGRET “GeV excess” not validated by FERMI
- Neutrino telescope coming full speed

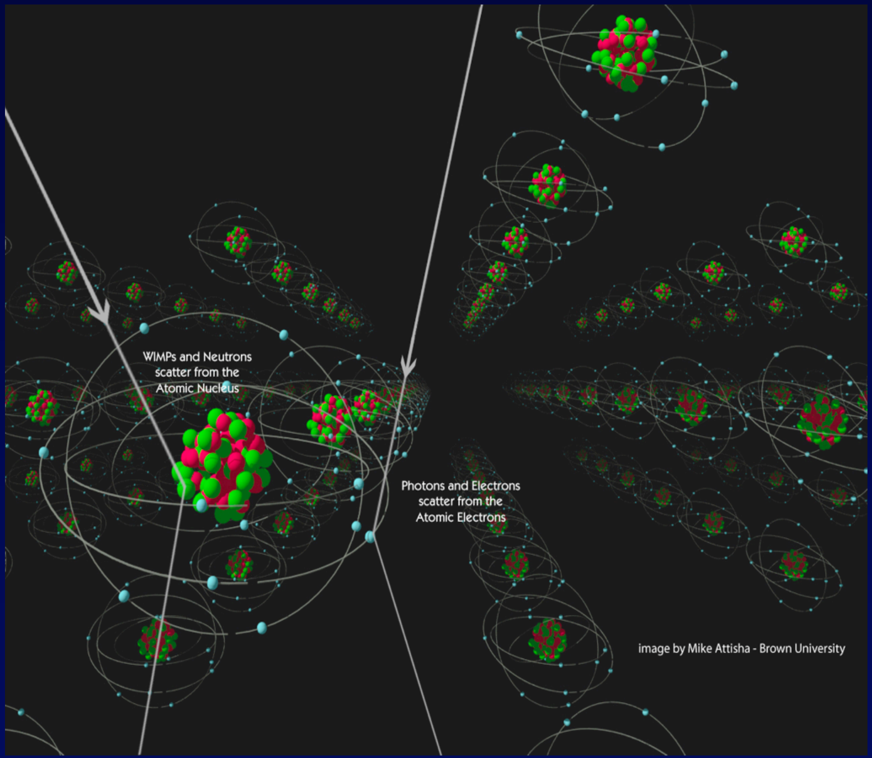
Direct Detection of WIMPs

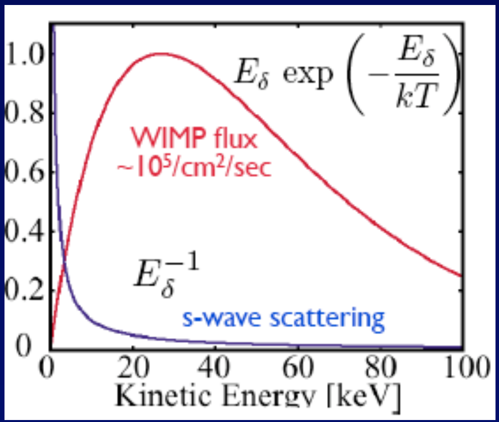
If WIMPs are the halo, detect them via **elastic scattering** on target nuclei (nuclear recoils)

Energy spectrum and rate depend on target nucleus masses and WIMP distribution in Dark Matter Halo:

Standard DM halo assumptions:

- Isothermal and spherical
- Maxwell- Boltzmann velocity distribution
  <V>= 270 km/s, ρ = 0.3 GeV / cm^3





- Energy spectrum of recoils
  ~ falling exponential with <E> ~ 15 keV
- Rate (based on $\sigma_{n\chi}$ and ρ) << 1 event /kg/day

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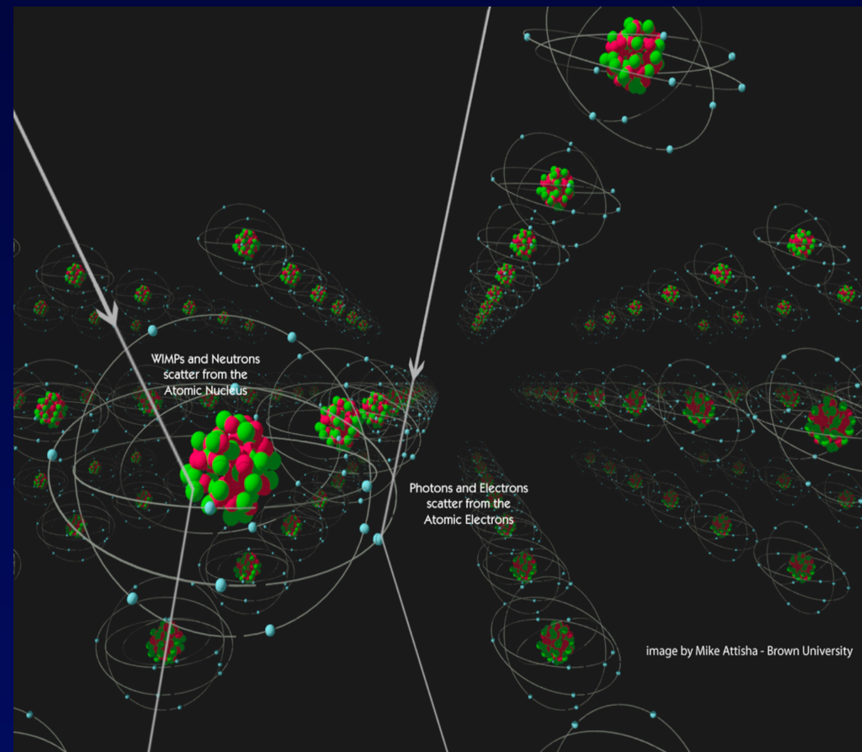

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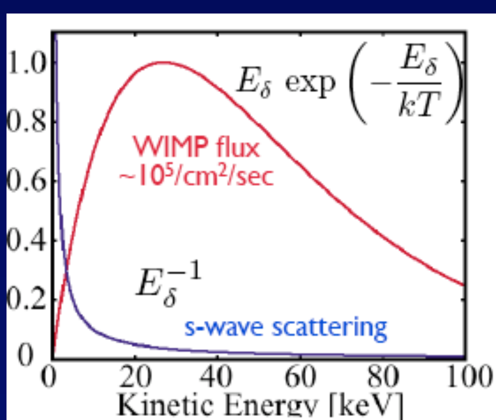


- Low Energy threshold needed (~10 keV)
- Good background rejection
- Large exposure (high target mass)

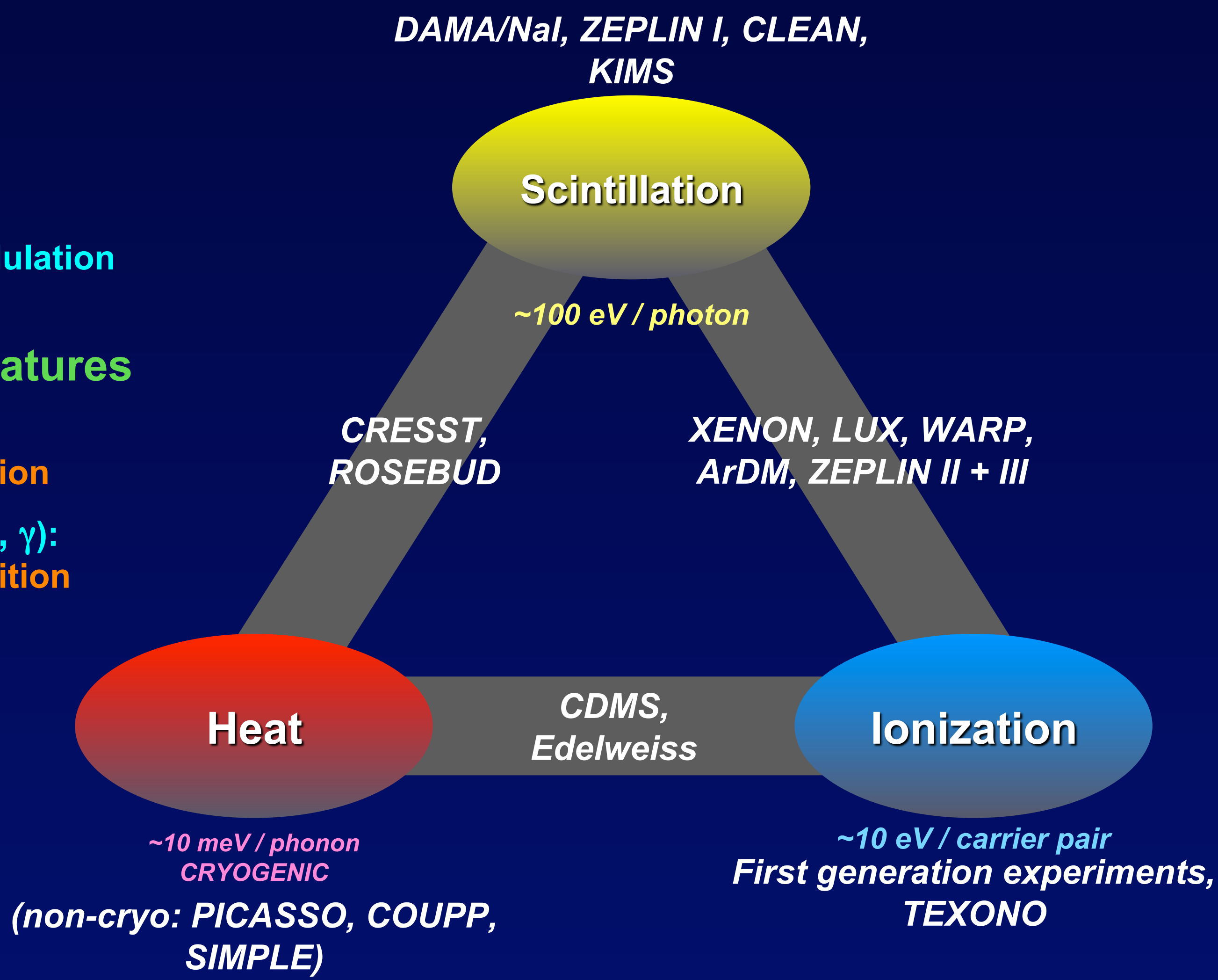
Direct Detection Strategies

Goal: find a very small WIMP signal in presence of many other background particles interacting in detectors

Techniques:

- Statistical signature
  - annual modulation
  - diurnal direction modulation

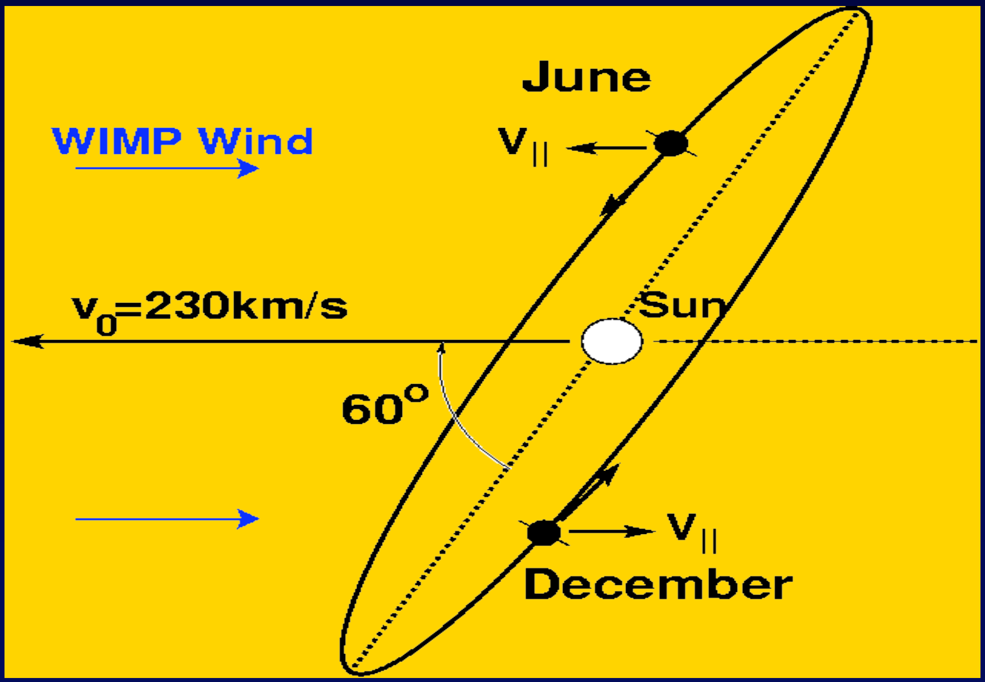
- Event by event signatures
  - Nuclear recoils:
    dense energy deposition
  - Electron recoils (α, β, γ):
    sparse energy deposition



Annual modulation

- Sun travels through the DM cloud at 270 km/s

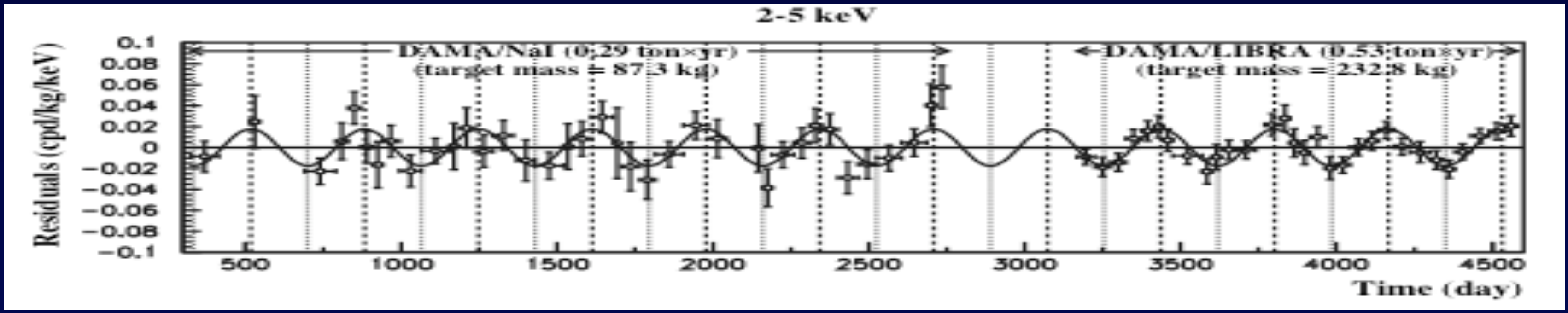
- Earth adds or subtracts 15 km/s to solar velocity



➢ Expect a few ± 1 % modulation in rate, energy deposition depending on target and threshold

Annual modulation

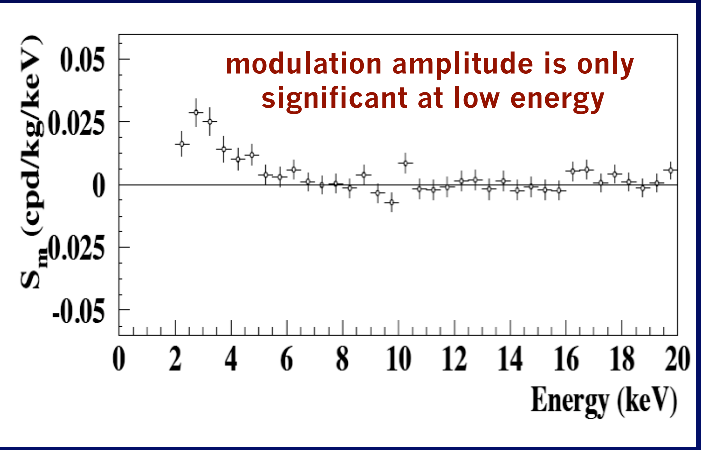
Clear modulation observed by DAMA/LIBRA



- DAMA/NaI 100 kg NaI(Tl) radiopure scintillators , 0.29 tonne.year data

- DAMA/LIBRA 250 kg NaI(Tl) lower activity crystals, shielding and PMTs, 0.53 tonne.year analysed

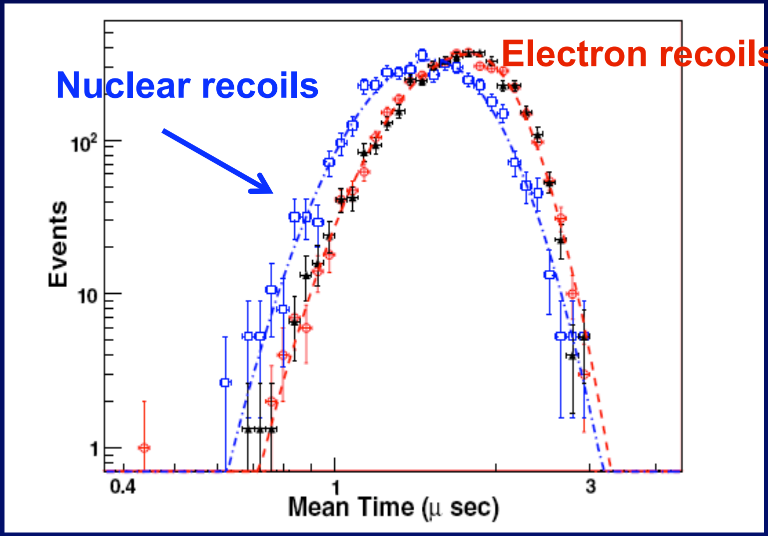
- 3.0 x 10^5 kg-days, 7+4 annual cycles
- count single scatter, no background rejection
- 8.3 sigma CL evidence of DM detection
  - No modulation seen in multiples and above 6 keV
  - various systematic effects studied (temperature, pressure, muon flux,..) showing no modulation
- 'Natural' WIMP candidate in contradiction with other experiments

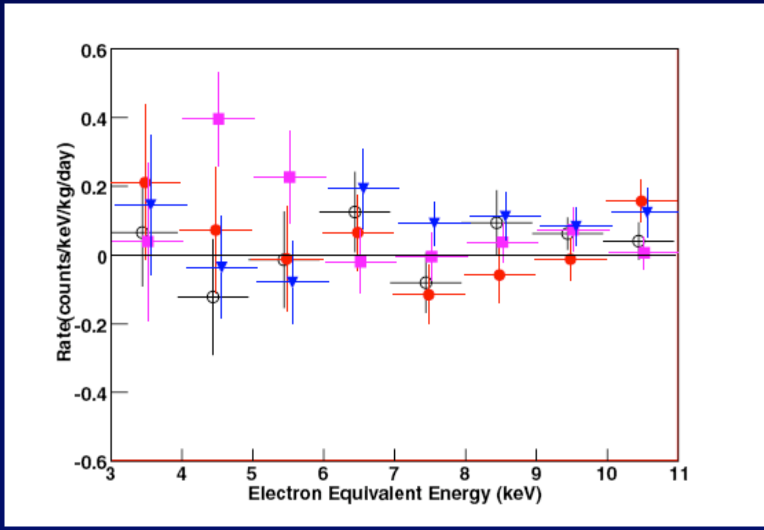


Annual modulation

KIMS: Korea Invisible Mass Search (Yangyang)

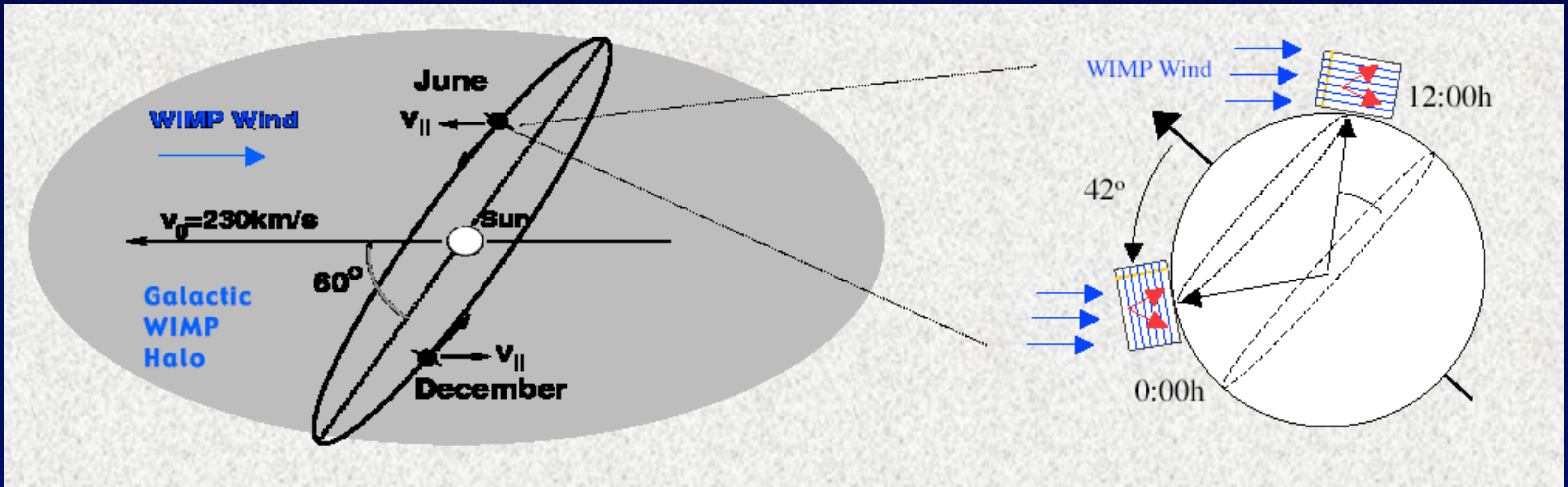
- Currently data taking with 12 (104.4 kg) CsI scintillators (Cs-133, I-127) providing SD and SI interactions
- Successful reduction of Cs-137 contamination
- Moderate background rejection by Pulse Shape Discrimination
- 3409 kg-days results with 4 crystals PRL 99, 091301 (2007) consistent with null observation





Diurnal modulation

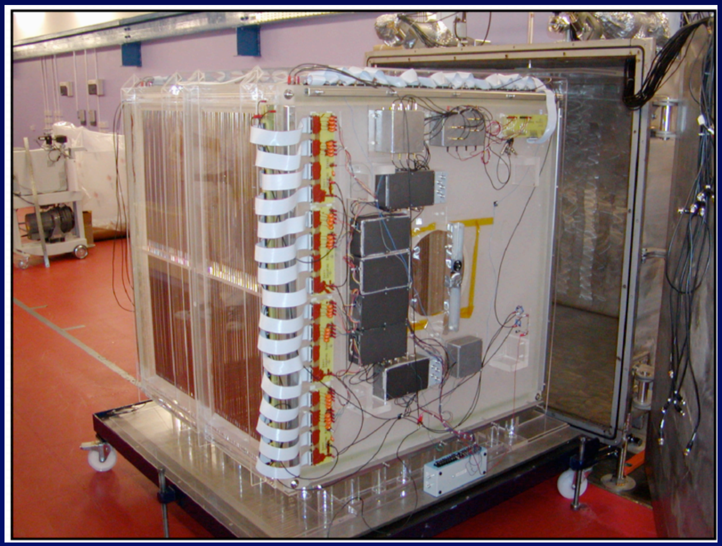
- Standard halo model for WIMPs in our galaxy suggests that the axis of recoils changes in the 24 hours (Earth)
- Axis of recoil is a cosmological signature for WIMPs.

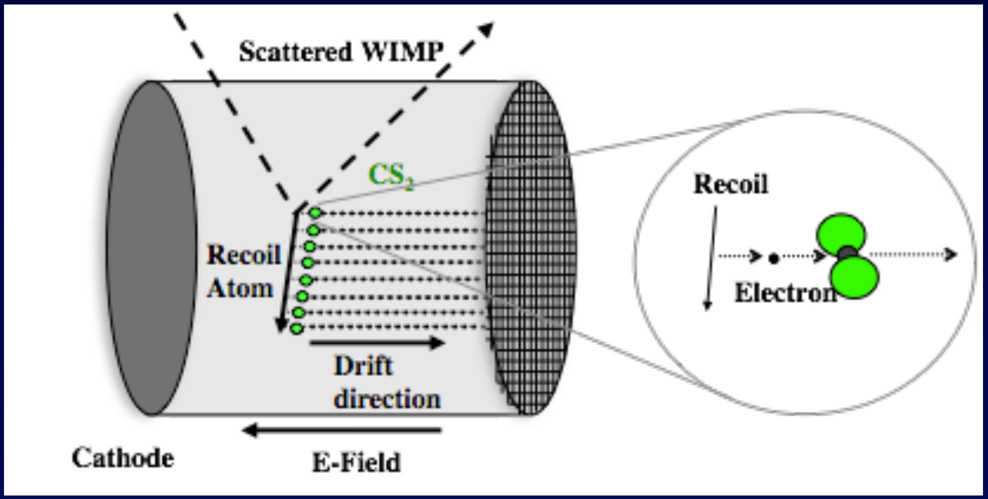


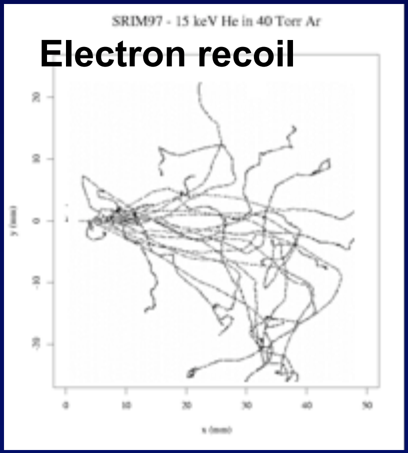
Directionality: Time Projected Chambers

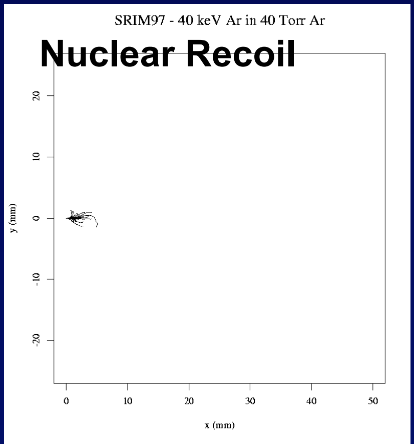
➢ DRIFT (Boulby)

- Sensitive to direction of recoiling nucleus
- Drift negative ions (CS_2 molecule) in TPC
  - remove magnetic field
  - reduces diffusion
- Excellent gamma/beta rejection base on track size





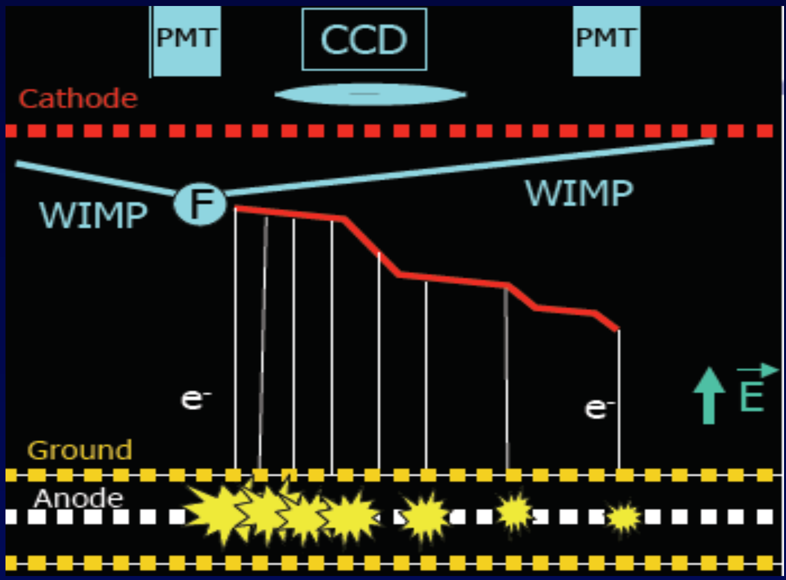


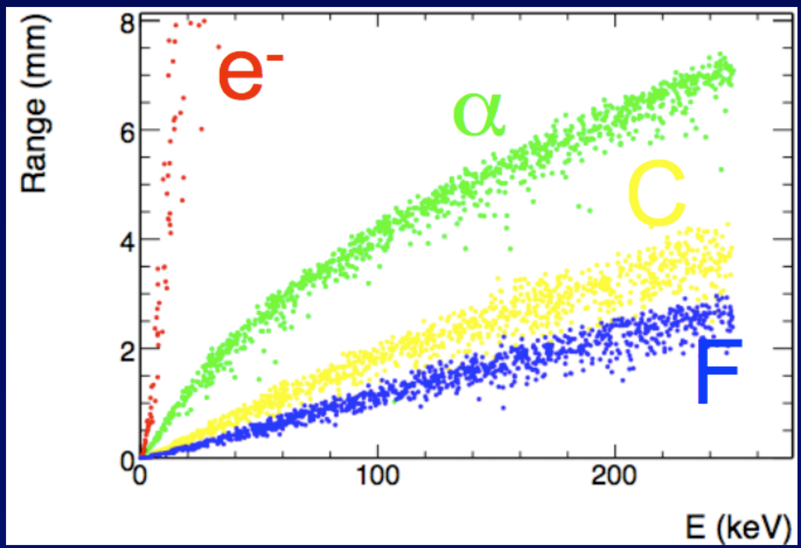


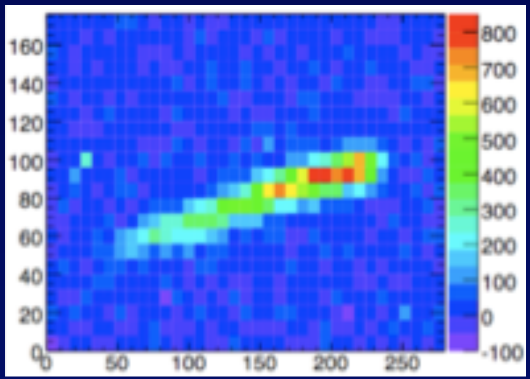
Directionality: Time Projected Chambers

➢ DMTPC

- CCD based detector with directional sensitivity
- Total energy is given by amount of light deposited
- PMTs for trigger, Z information
- Excellent gamma/beta rejection base on track size







- surface run background data at MIT (3.3kg, exposure 44 kg.days)
- $1m^3$ in fabrication, plan for underground operation at WIPP

(Very) Low Temperature Detectors

Dielectric crystal (Al_2O_3, Ge, Si, $CaWO_4$,etc) cooled to temperatures as low as 0.01 K

- Small energy deposit from a particle interaction significantly change the temperature of the absorber ($\Delta T = E/C$)
- Out of equilibrium (athermal) phonons can be easily distinguished and counted in order to measure deposited energy

Advantages:

- after an interaction (event), all excitations transform to heat

  ➔ Good resolution

- Phonon excitation ~10-6 eV compare to few eV for conventional semiconductor detectors

  ➔ Low threshold

However: complexity of the experiments

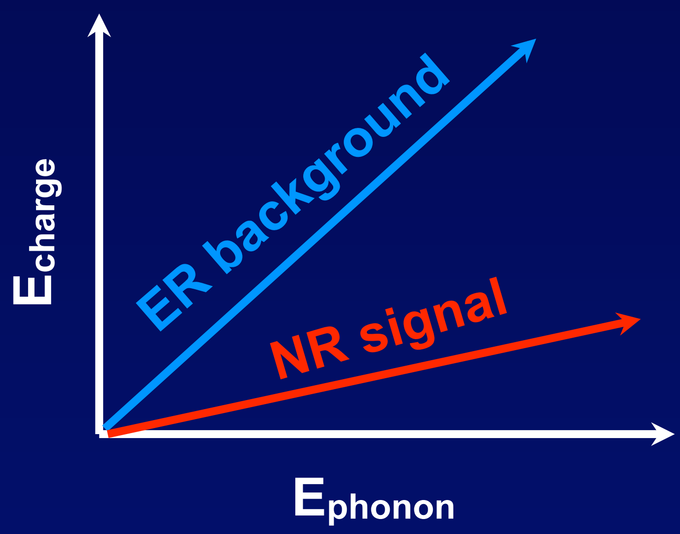
(Very) Low Temperature Detectors

However, heat is not enough!

Need another (simultaneous) measurement: ionization (CDMS, Edelweiss) or light (CRESST)

- amount of charge (light) created in semiconductor after an event depends on the type of interaction: “Quenching factor” (Q)
- Quenching factor for an electron recoil (most backgrounds) event is bigger than for nuclear recoil events (WIMPs)

➔ Event by event discrimination



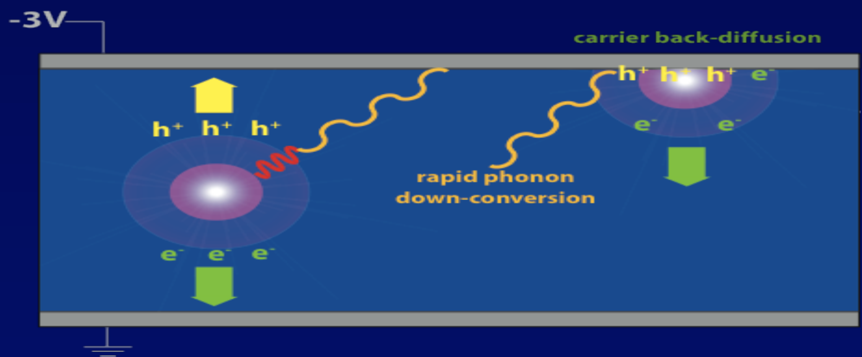
(Very) Low Temperature Detectors

CDMS/Edelweiss:

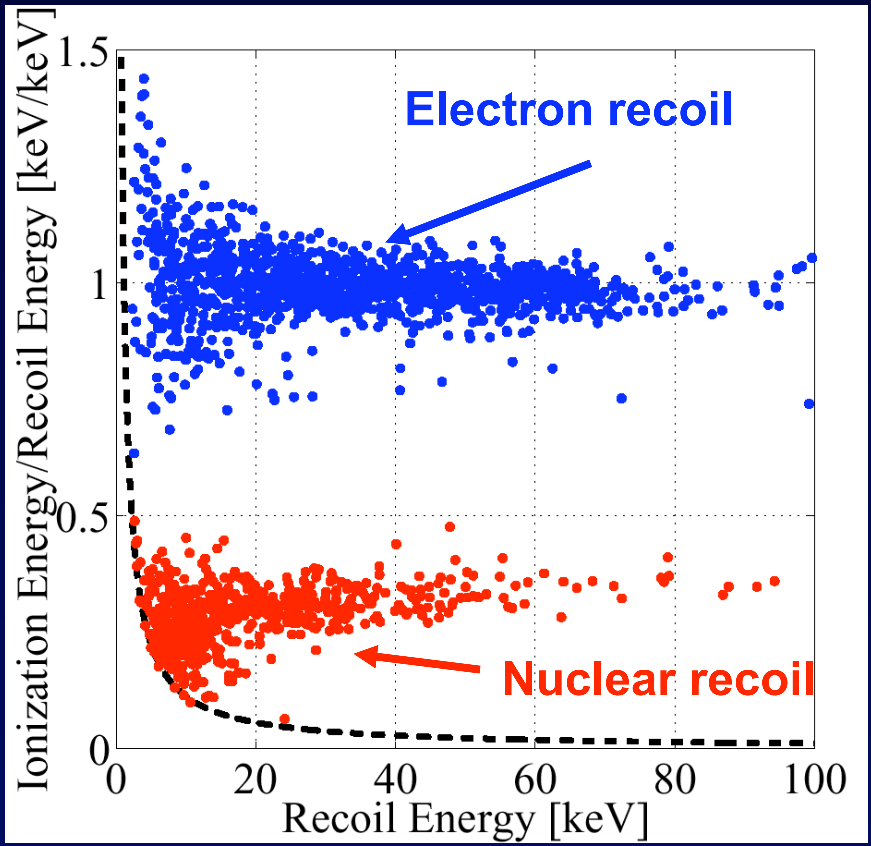
Near surface events can mimic nuclear recoil events due to loss of charges into "wrong" electrode

Solutions:

- use timing information of the athermal phonons (CDMS current, Edelweiss R&D)



- use asymmetry of charge energy collection between the 2 sides (Edelweiss current and CDMS future)



➔ recent breakthrough that should enable background free ton scale cryogenic experiment

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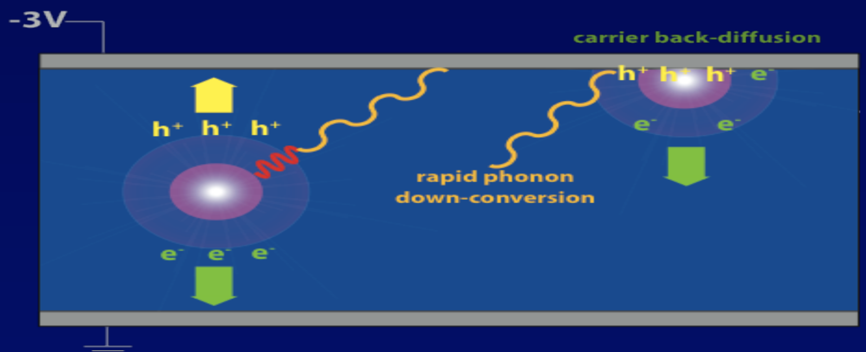

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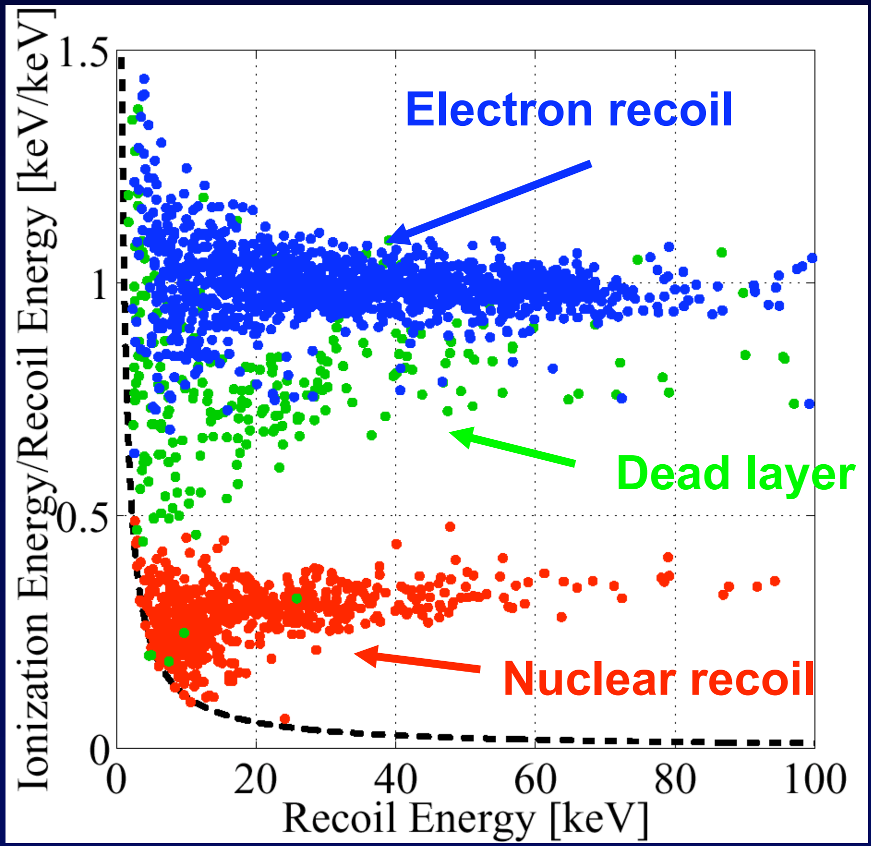

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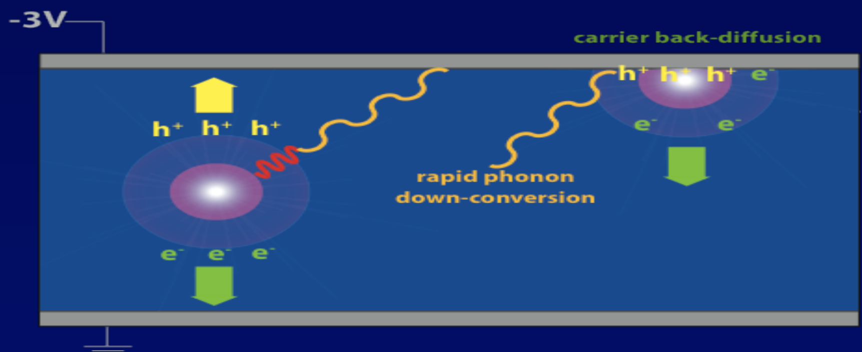

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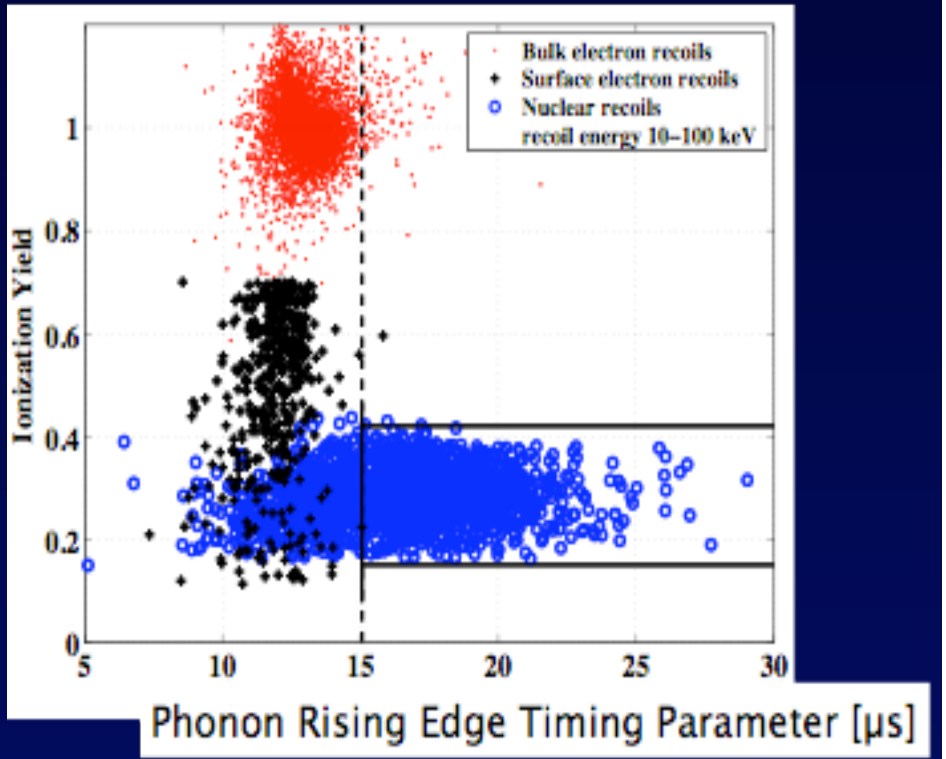

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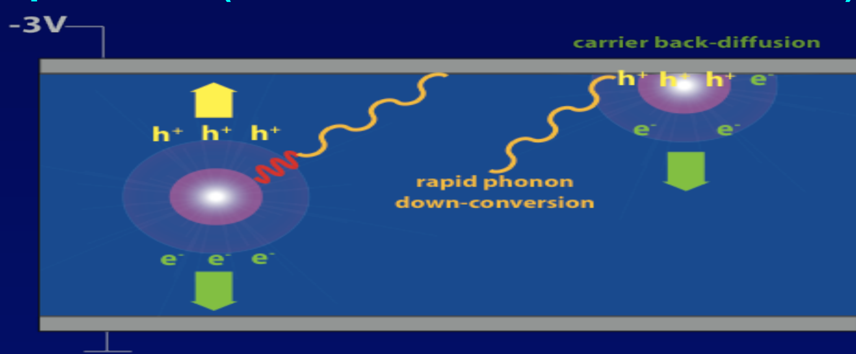

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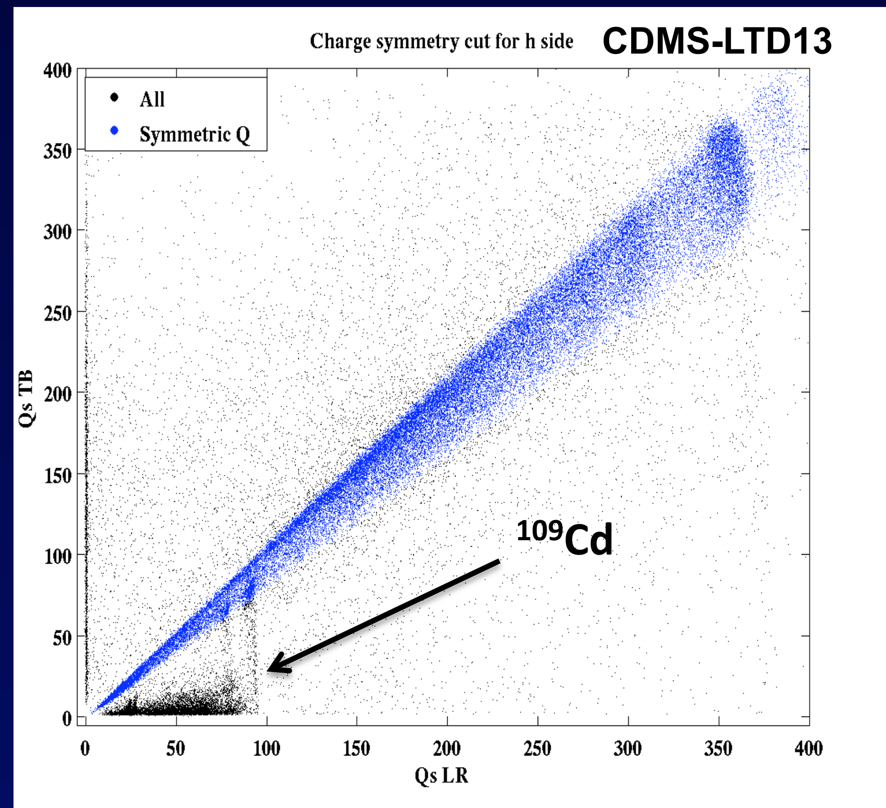

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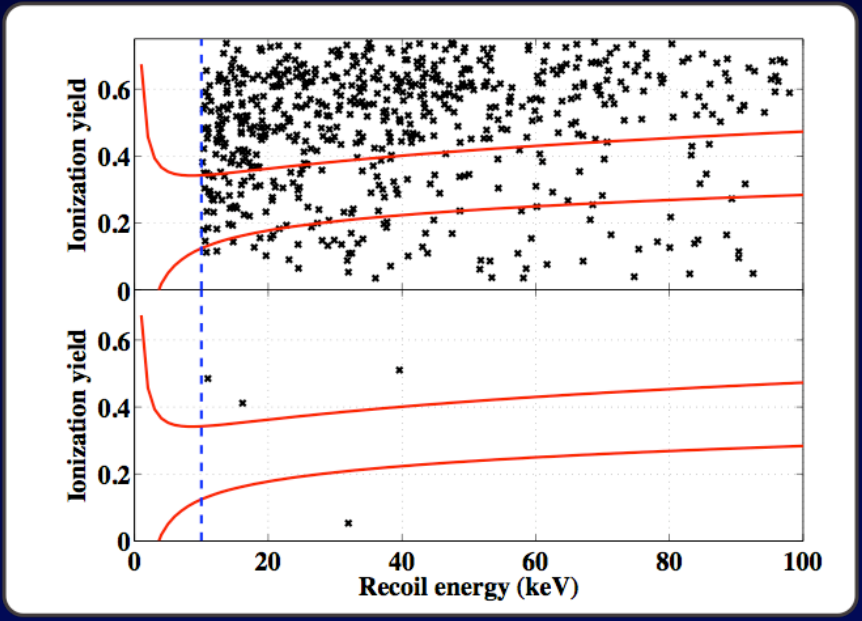
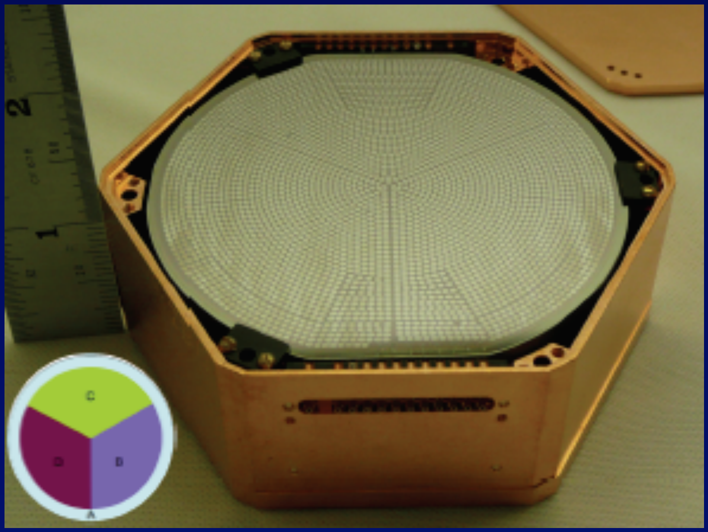
(Very) Low Temperature Detectors

CDMS II (Soudan)

- 1 cm thick 250g Ge (16 detectors), 100g Si
- collect athermal phonons on one side, ionization on the other
- ~400 raw kg.d analyzed, no events found after timing cut (2008)
- final CDMSII results with an addition of ~750 kg.d early fall 2009





SuperCDMS (Soudan):

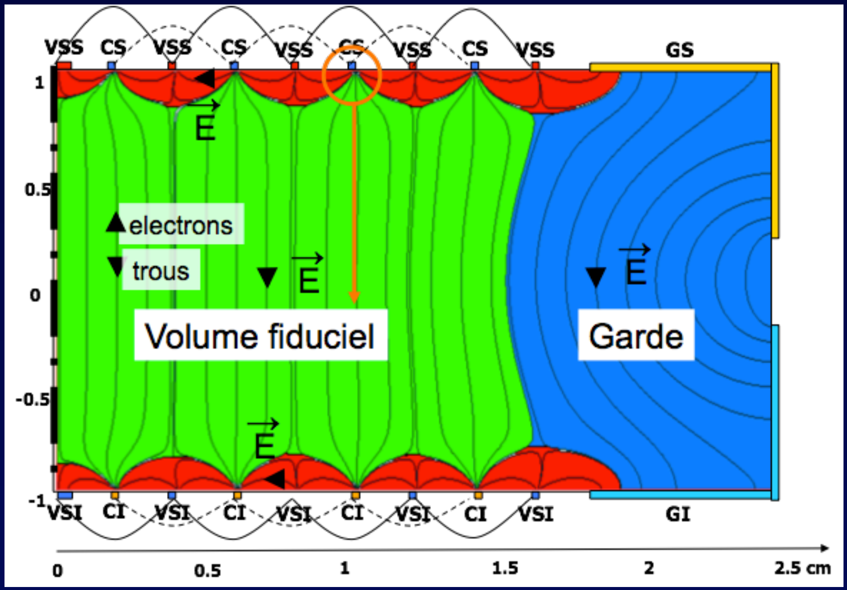
- bigger detectors 1cm -> 2.5 cm thick
- 5 detectors installed, currently being comissionned
- 20 more (16kg total) will be installed in 2010

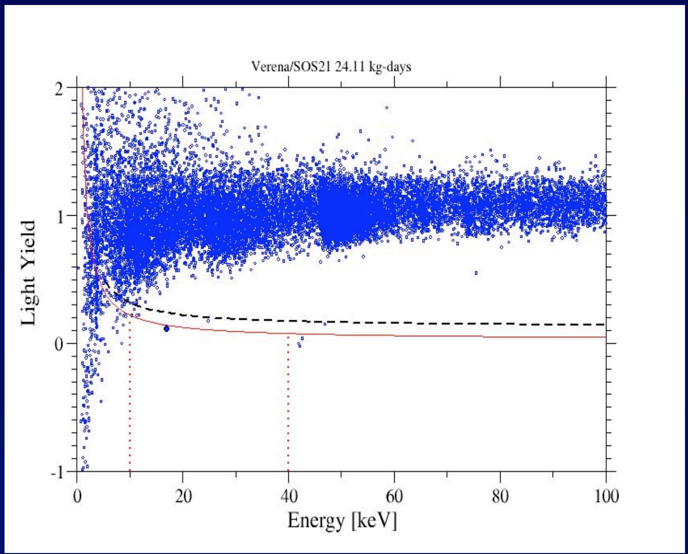
  -> will reach 5 x 10-45 cm2 by end 2011

(Very) Low Temperature Detectors

➢EDELWEISS (Modane)

- NTD Ge thermistors for phonon
- NbSi for athermal phonons
- 23 x 320 NTD, 7x400g NbSi installed
- Full running from Jan 2009





➢CRESST (Gran Sasso):

- Discimination through scintillation/phonon ratio
- no surface events background
- 10 kg array
- Latest results from 48 kg.days:
  - 2 crystals
  - 3 events in n.r region

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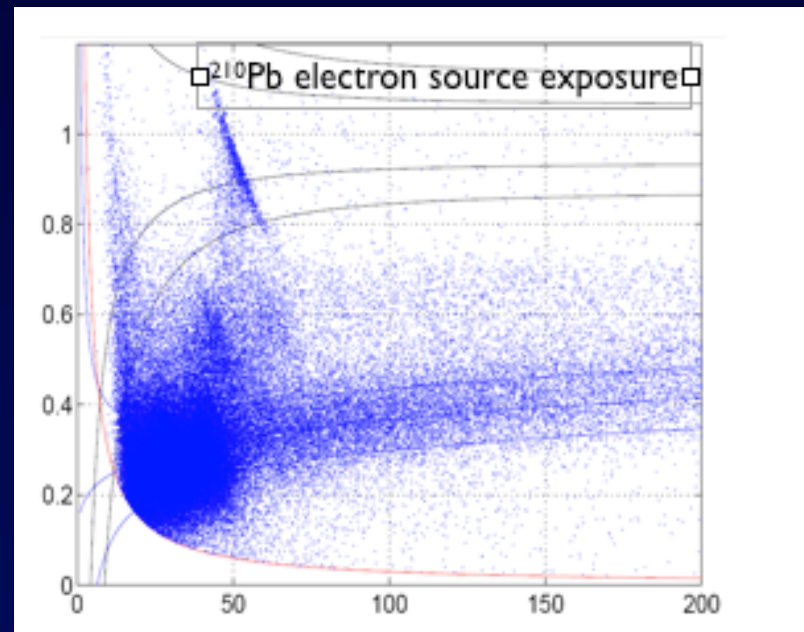

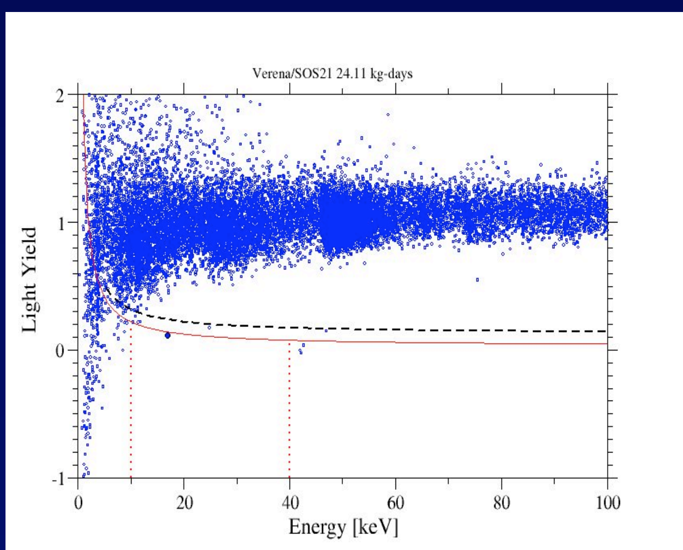

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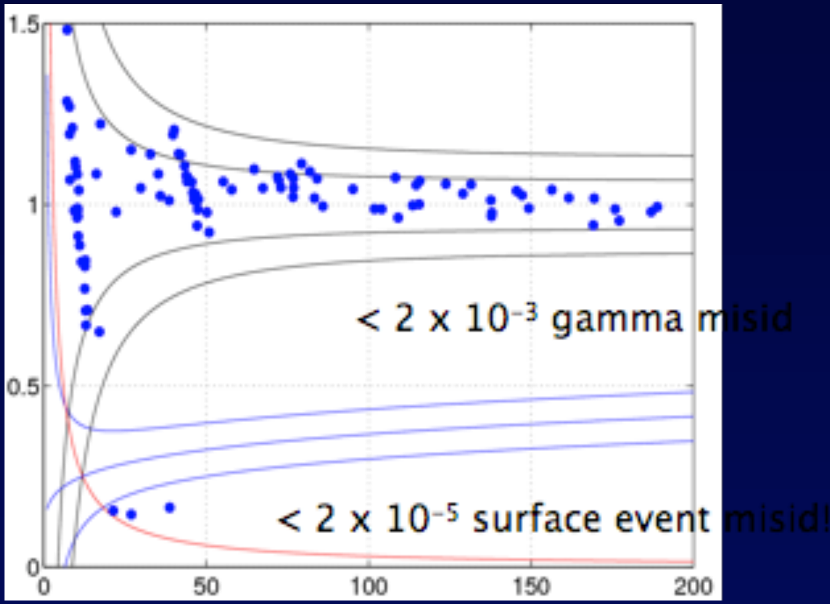
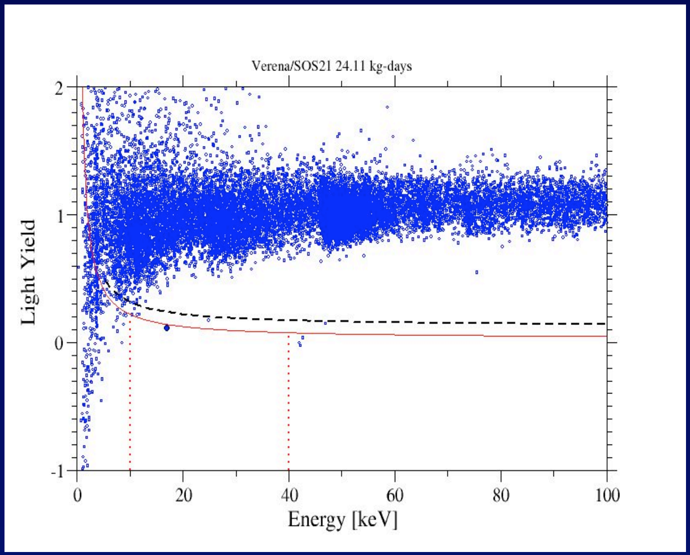




➢CRESST (Gran Sasso):

- Discimination through scintillation/phonon ratio
- no surface events background
- 10 kg array
- Latest results from 48 kg.days:
  - 2 crystals
  - 3 events in n.r region

(Liquid) Noble Gas Detectors (Xe, Ar, Ne)

Nuclear/electron recoil discrimination methods:

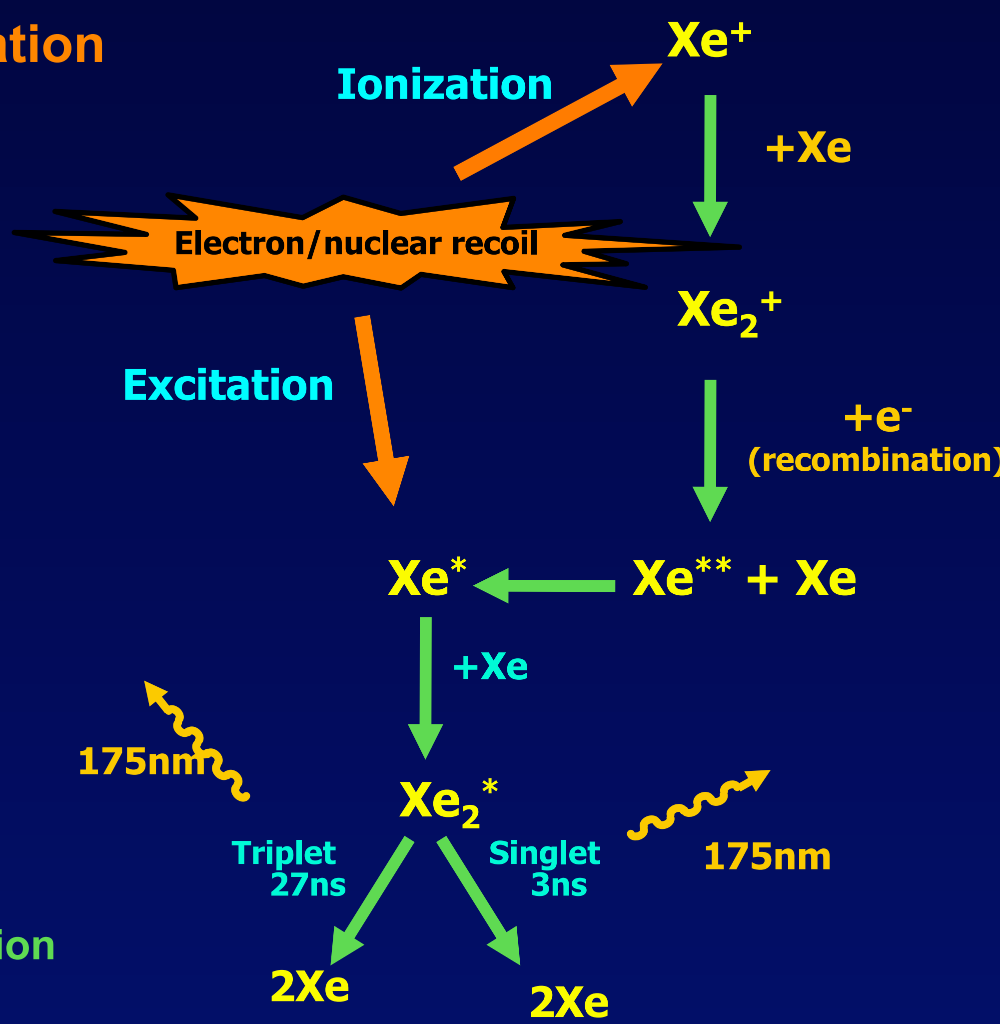
- singlet/triplet ratio 10:1 nuclear recoil:electron recoil (pulse shape discrimination)

  Time constants (singlet/triplet):
  Xe: 3ns/27ns, Ar 10/1500ns

- Ionization and direct excitation ratio

Implementation:

- **Single phase:** measure scintillation only
- **Double phase:** measure also ionisation through electroluminescense



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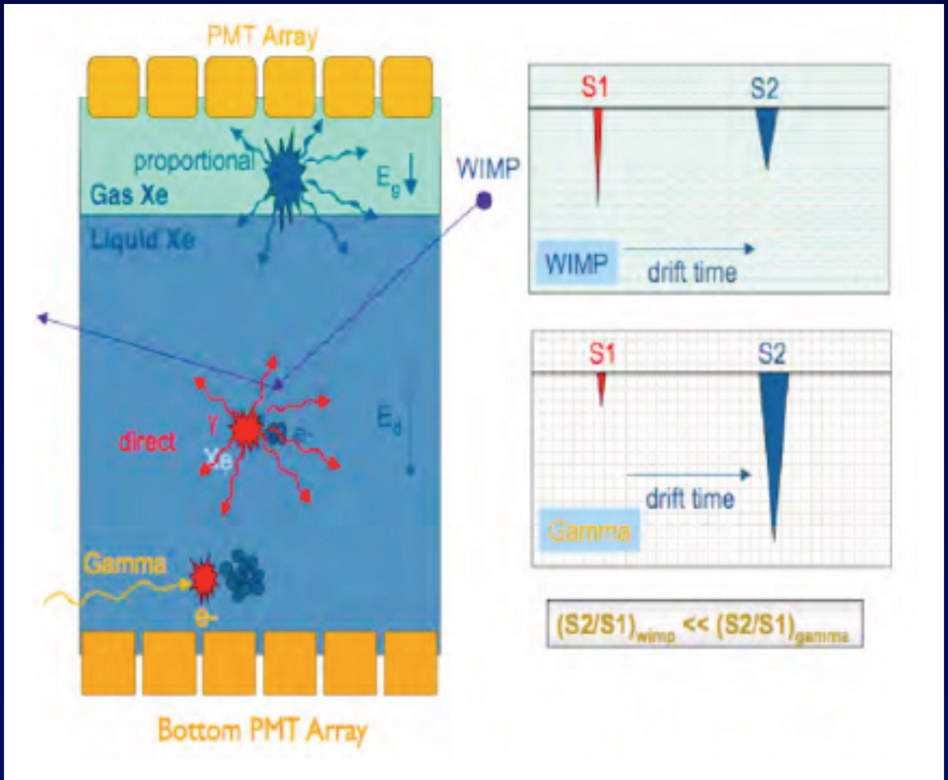

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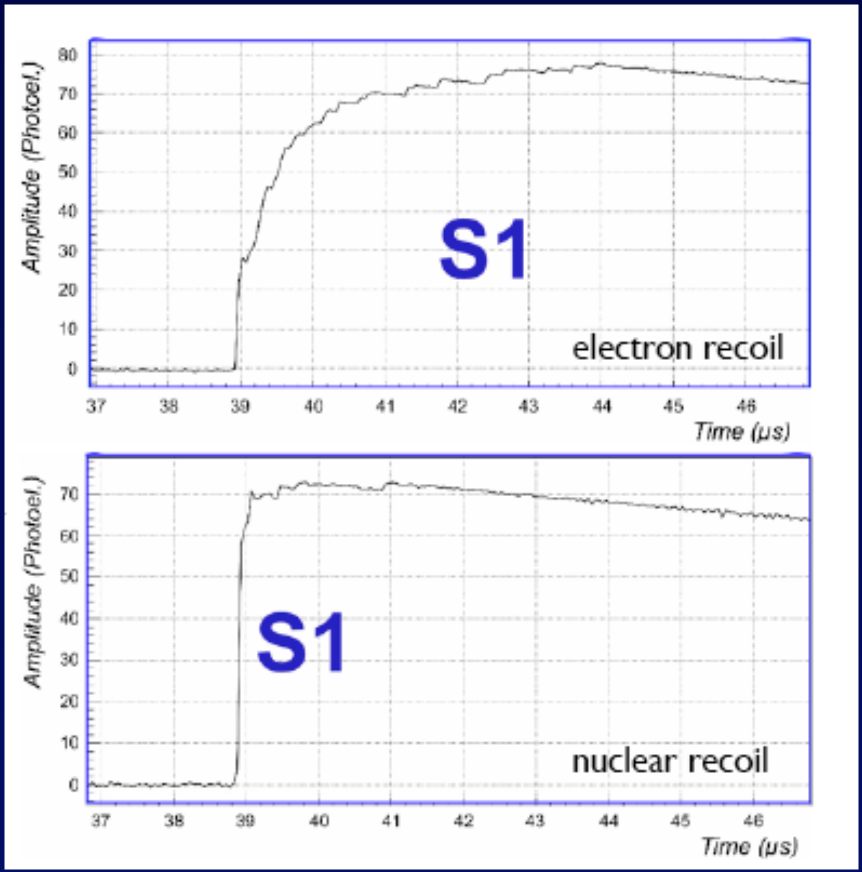

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Liquid Xenon: XENON10

- Gran Sasso Underground Laboratory
- 22 kg Xe target mass, 15 kg active
- Dual phase, with 48 1" PMTs in gas, 41 in liquid
- Measure scintillation & ionization
  - S1: Direct scintillation signal in Lxe
  - S2: Proportional scintillation in GXe

Results (2007):

- Blind analysis on 58.6 days
- good light collection (5 pe/keV)
- 10 events after all cuts, 6.8 expected from gamma leakage
  - Scale up needed to reduce background by self-shielding, need to maintain ionization and light collection efficiency

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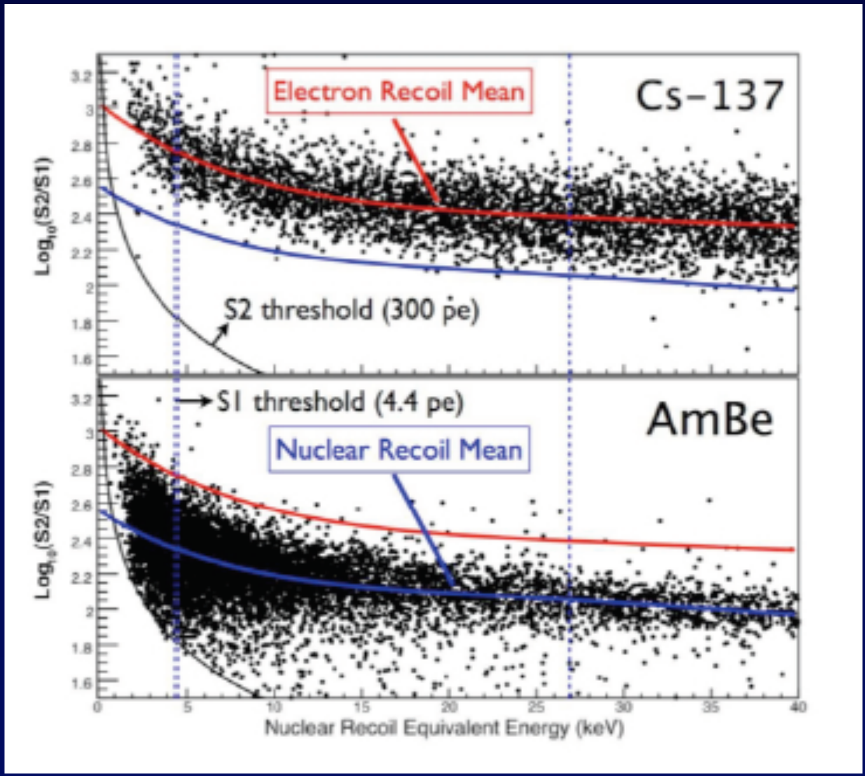

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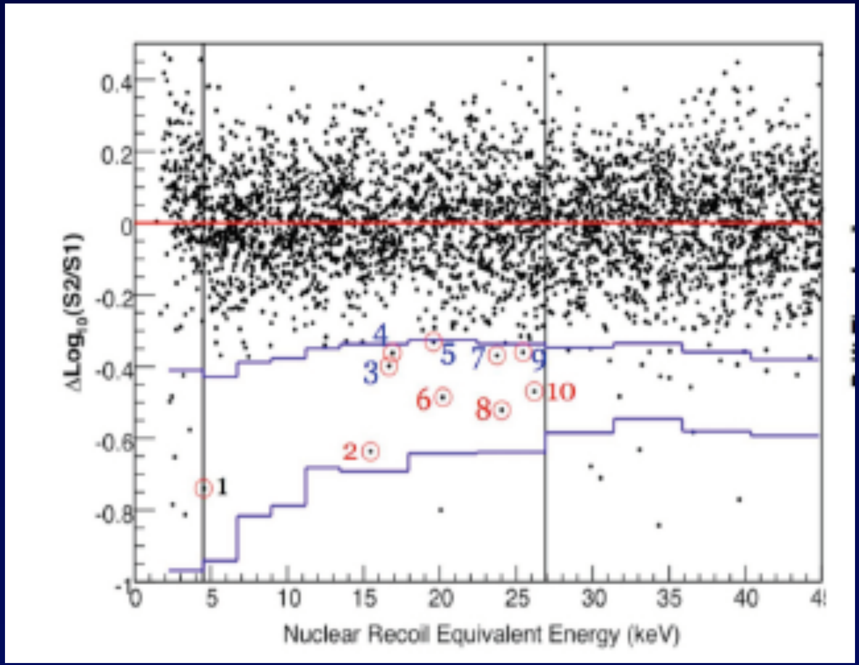

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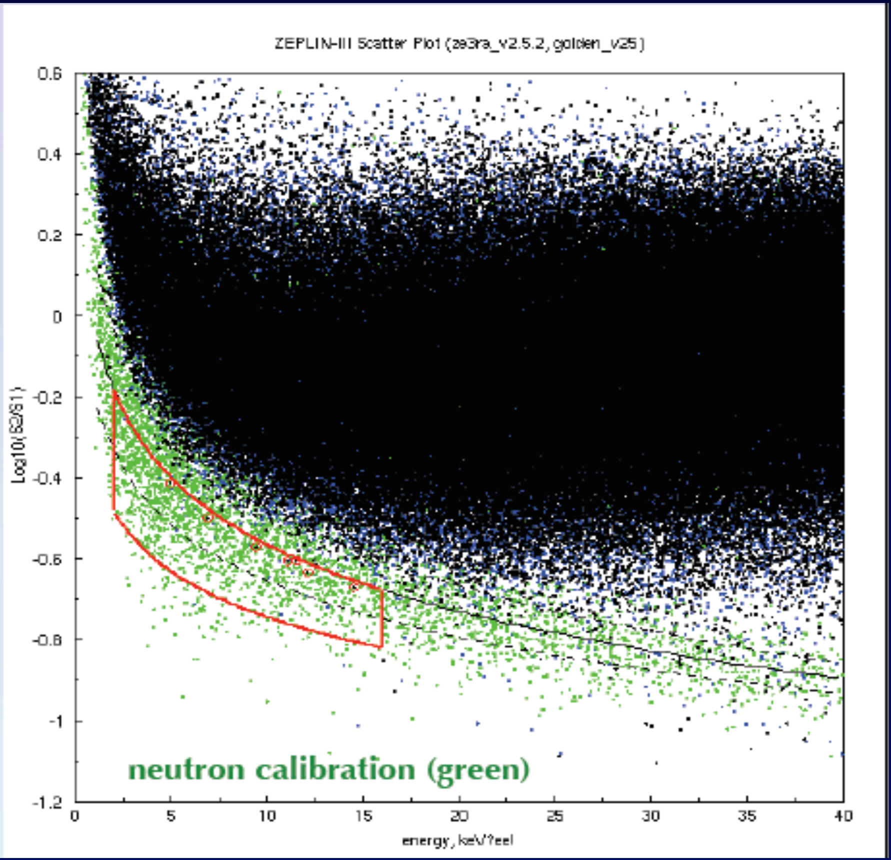
Liquid Xenon: ZEPLIN III

- Boulby Mine
- 12 kg target mass
- Dual phase, 31 2" PMTs
- Low-Background Xenon



Results:

- 83 days operation
- expect 1.2±0.6 neutron events (from PMTs)
- 7 events within signal box observed, extrapolation from leakage fits gives 11.3±3.0

Liquid Xenon: near future

XENON100 (Gran Sasso):

- _upgrade from XENON10, 50 kg fiducial, 170 kg total, 1” PMT: 98 top, 80 bottom
- cold and operating since mid-2008, physics running to begin by end 2009
- XENON 100+: 100-kg fiducial w/QUPID

LUX (Sanford/Homestake):

- XENON10(part)+ZEPLIN
- 350 kg Dual Phase Xe TPC, fully funded
- 3D-imaging via TPC defines 100 kg fiducial volume

XMASS (Kamioka):

- Single phase detector (scintillation readout), self-shielding only
- 800 Kg total, 100 Kg fiducial
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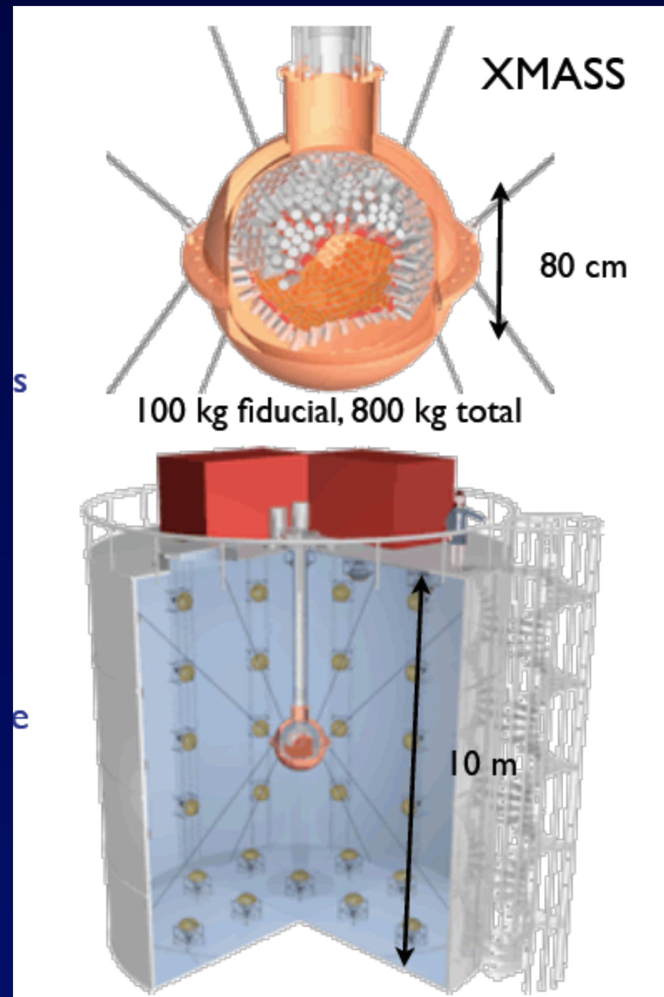

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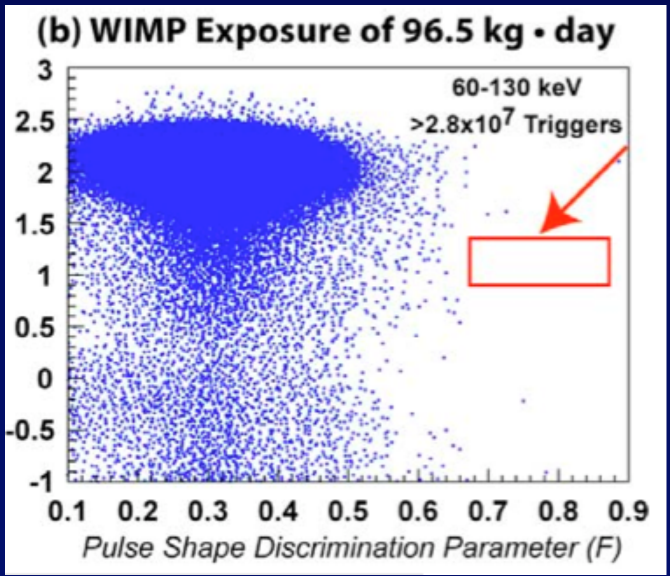
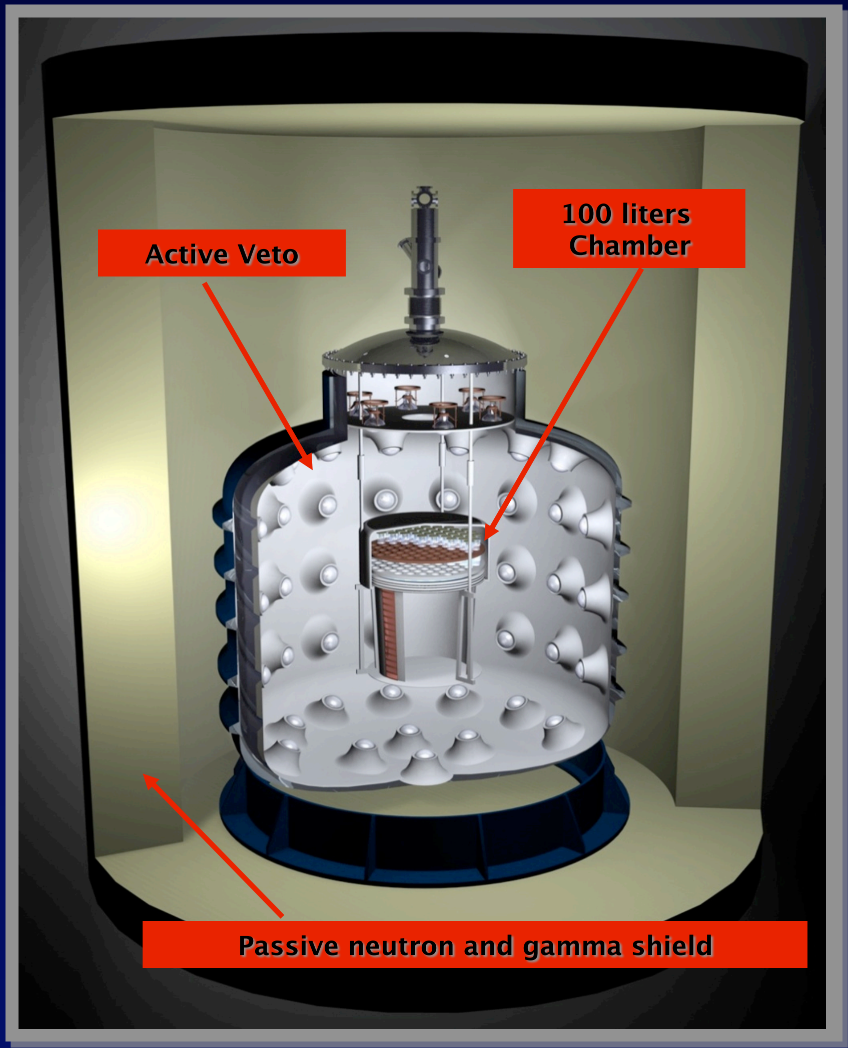
Liquid Argon

Dual discrimination: Pulse shape and secondary scintillation From ionization

WArP (Gran Sasso):

- 2 phase Argon detector
- 140-kg detector being commissioned
- passive water shield, active LAr shield
- Excellent results from 3.2 kg detector





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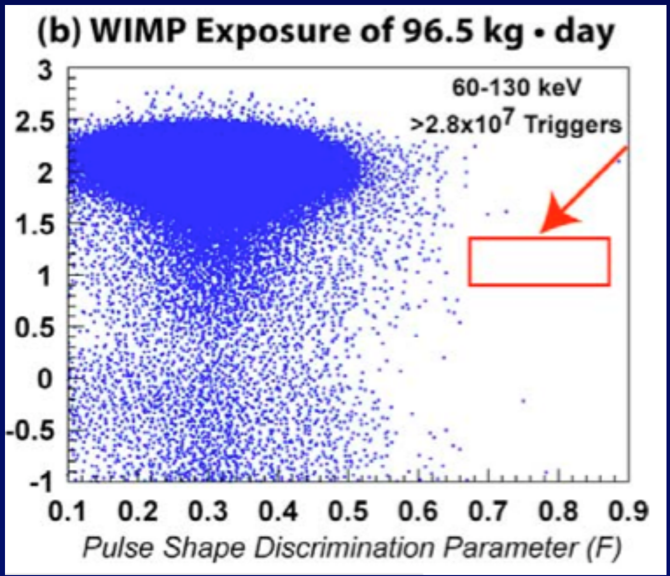


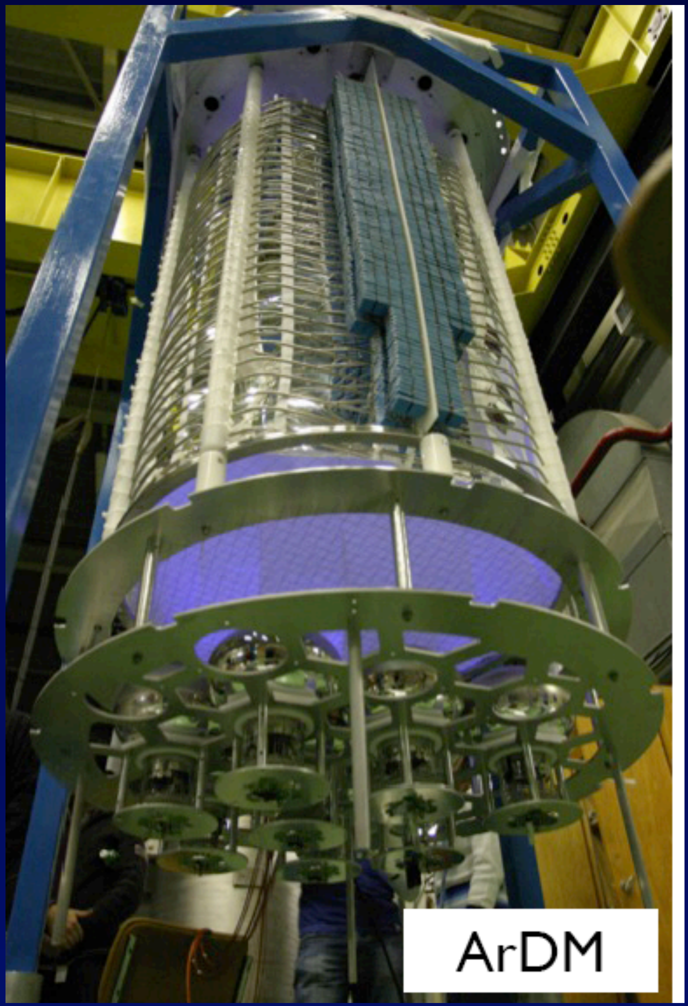
Liquid Argon

ArDM (CERN, Canfranc):

- 2 phase Argon detector
- 850 kg target mass
- First time operated at CERN, light yield consistent with expectation
- Will be moved underground end 2010

DEAP/CLEAN:

- Single-phase Ar/Ne
- miniCLEAN: 150 kg fiducial, 500 kg total
- hall at SNOLAB under construction
- detector under construction



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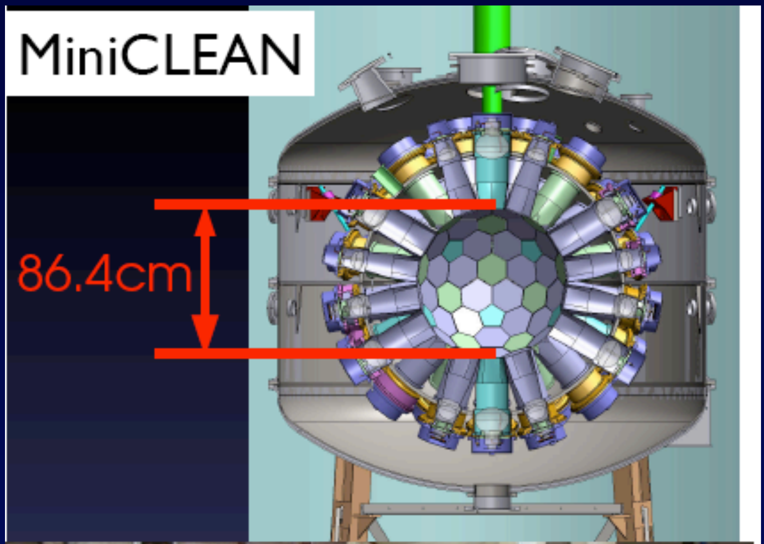

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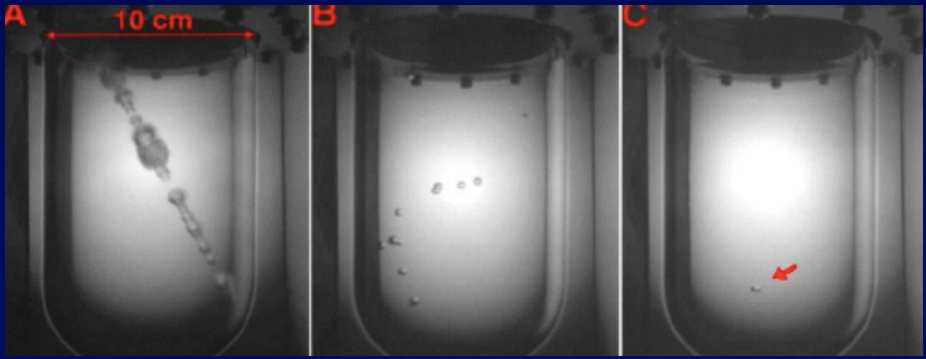
Metastable Bubble Chamber Detectors

- Superheated fluid
- Energy density effect: min. ionizing and low energy ER deposition density too small to nucleate bubbles (intrinsic rejection, no data cuts needed)
- threshold, controlled by temperature, pressure
- Readout:
  - acoustic (ultrasound)
  - motion sensing(video)
- inexpensive, easily scalable
- Assorted nuclei: spin dep. (F) or indep. (I and Br)

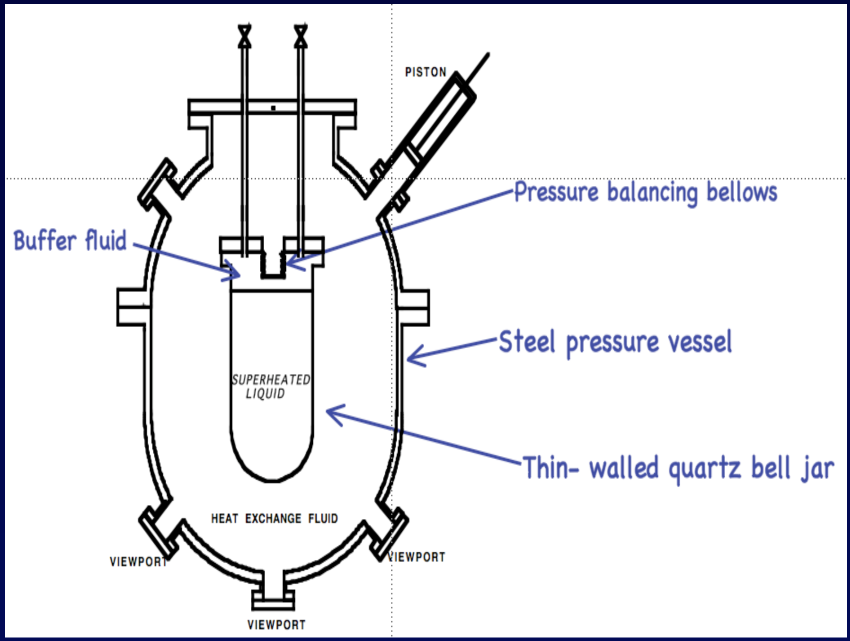
COUPP

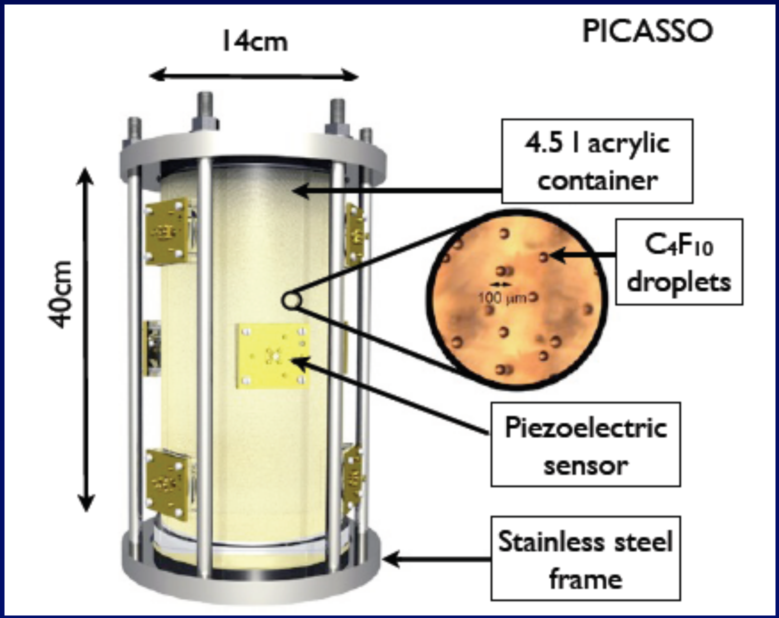


Metastable Bubble Chamber Detectors

➢COUPP (Fermilab)

- various target (CF_3I), 2kg prototype
- $>10^{10}$ rejection of γ (10 keV)
- 4, 15, 60 kg chamber coming, 500 kg to follow
- Moving underground (SNOlab or Sounda) in 2010





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- bubbles C_4F_{10} in CsCl gel, acoustic readout
- demonstrated NR/alpha discr. via acoustic pulse height
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- 1.9 kg running since brg. 2009

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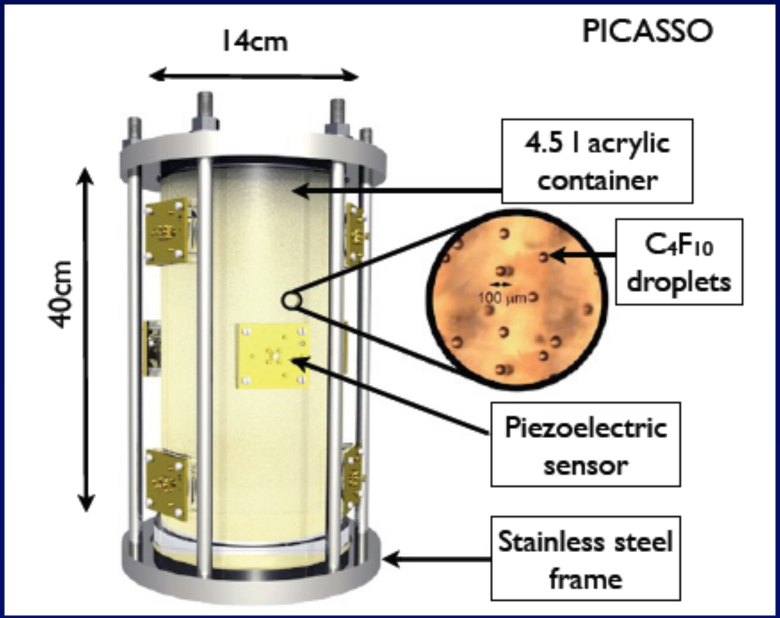

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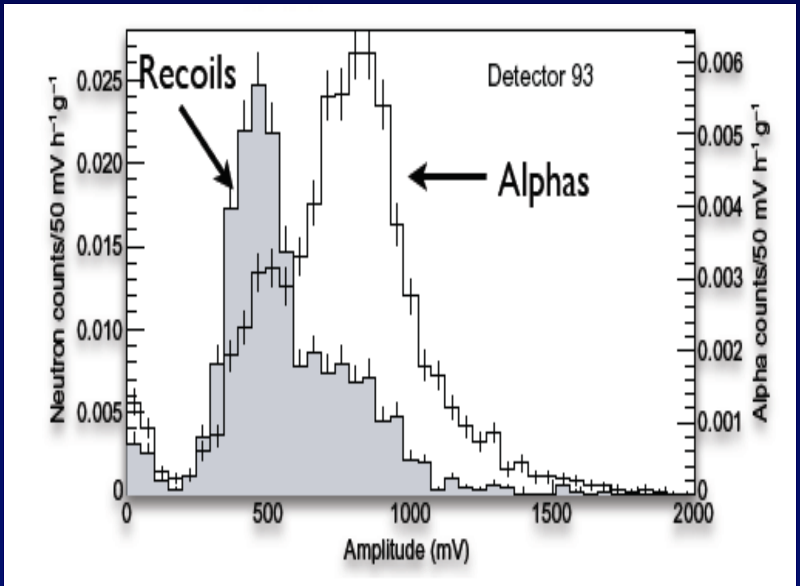

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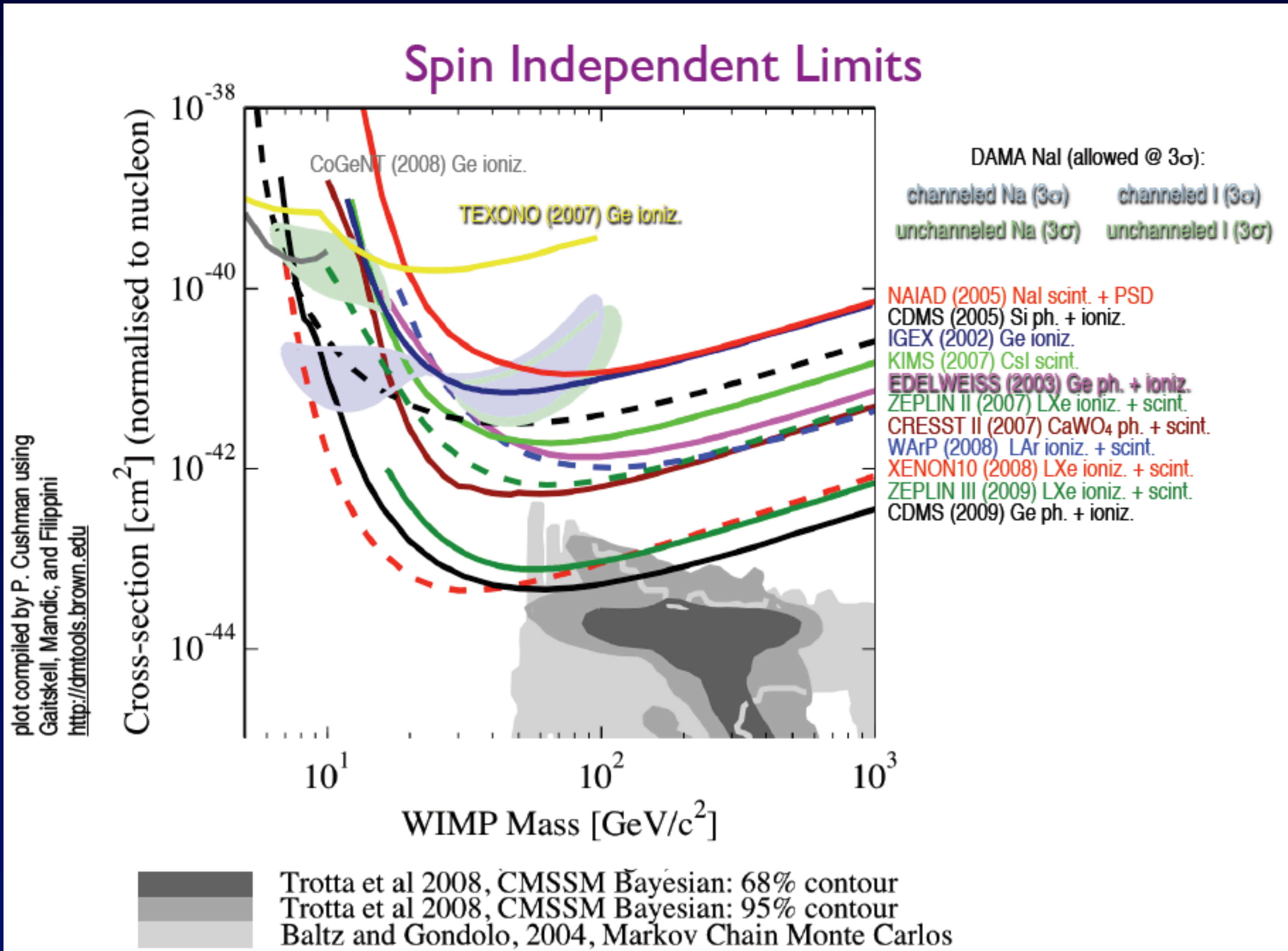
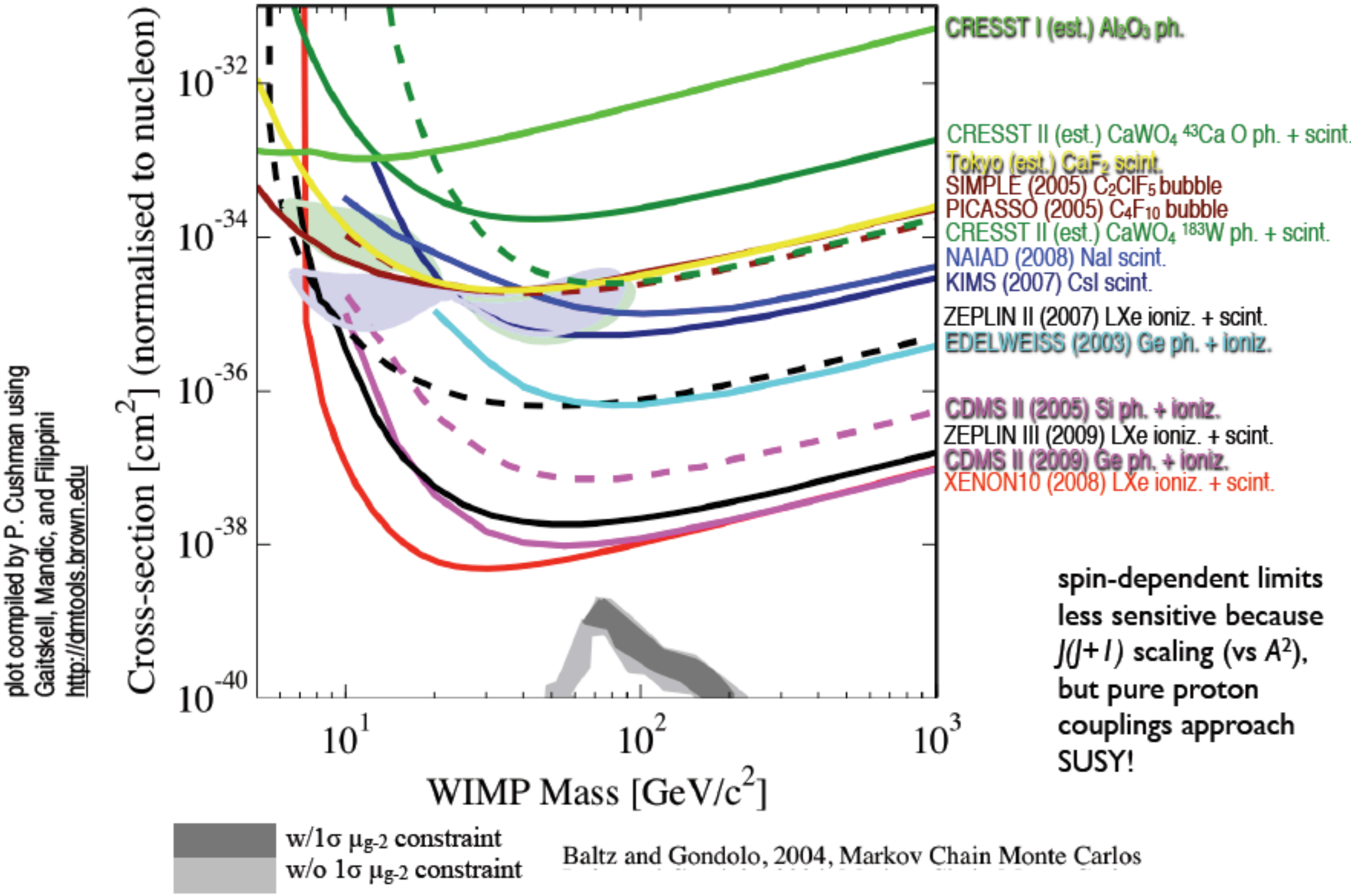


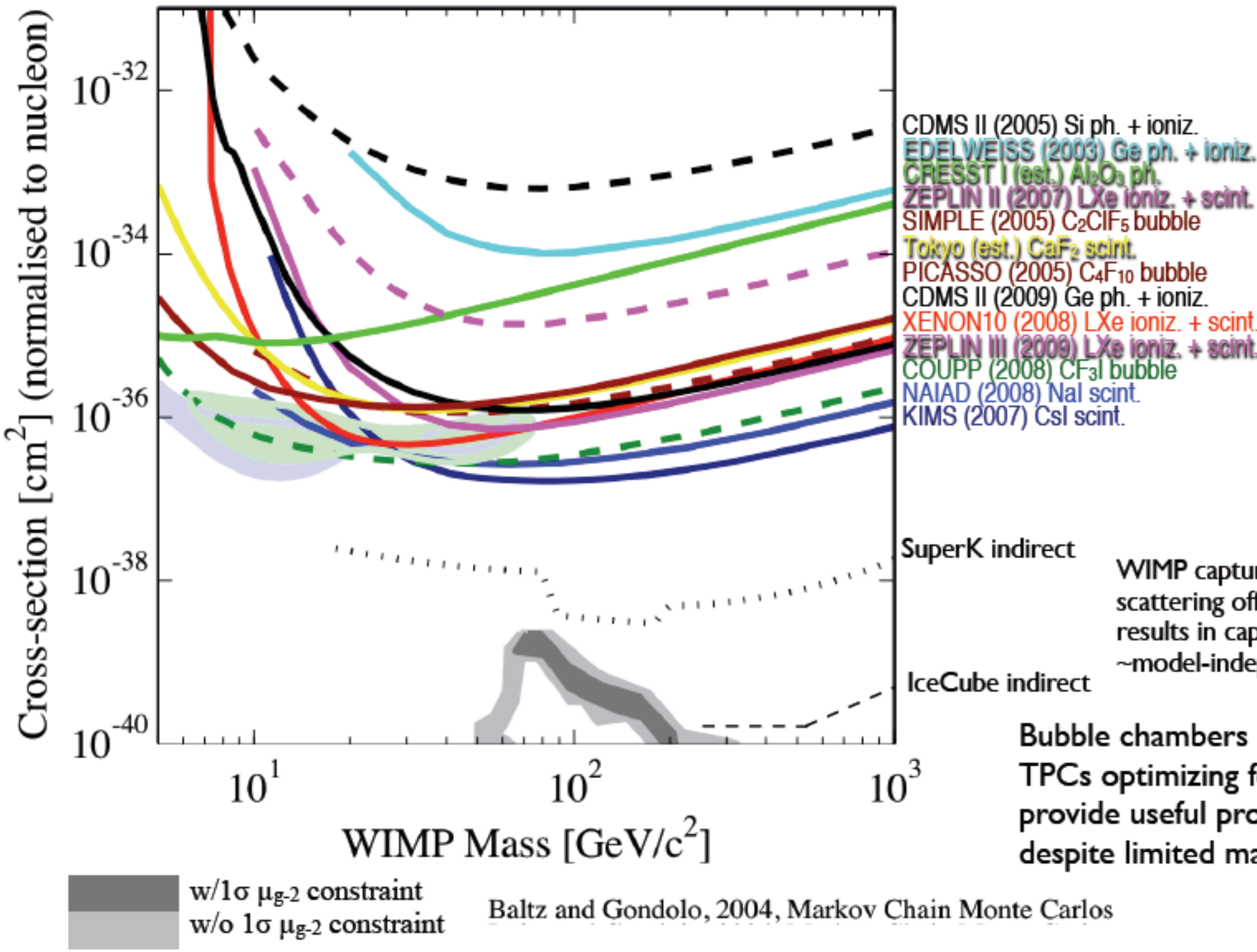
Spin Independent Limits
Cross-section [cm^2] (normalised to nucleon)
WIMP Mass [GeV/c^2]
CoGeNT (2008) Ge ioniz.
TEXONO (2007) Ge ioniz.
DAMA NaI (allowed @ 3σ):
channeled Na (3σ)
channeled I (3σ)
unchanneled Na (3σ)
unchanneled I (3σ)
NAIAD (2005) NaI scint. + PSD
CDMS (2005) Si ph. + ioniz.
IGEX (2002) Ge ioniz.
KIMS (2007) CsI scint.
EDELWEISS (2003) Ge ph. + ioniz.
ZEPLIN II (2007) LXe ioniz. + scint.
CRESST II (2007) CaWO4 ph. + scint.
WArP (2008) LAr ioniz. + scint.
XENON10 (2008) LXe ioniz. + scint.
ZEPLIN III (2009) LXe ioniz. + scint.
CDMS (2009) Ge ph. + ioniz.
plot compiled by P. Cushman using
Gaitskell, Mandic, and Filippini
http://dmtools.brown.edu
Trotta et al 2008, CMSSM Bayesian: 68% contour
Trotta et al 2008, CMSSM Bayesian: 95% contour
Baltz and Gondolo, 2004, Markov Chain Monte Carlos

Spin Dependent Limits: Pure Neutron Coupling



spin-dependent limits less sensitive because $J(J+1)$ scaling (vs A^2), but pure proton couplings approach SUSY!

Spin Dependent Limits: Pure Proton Coupling



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WIMP capture in Sun: scattering off p results in capture, ~model-independent

Bubble chambers and TPCs optimizing for SD to provide useful progress despite limited mass.

Conclusion

- Complementarity of techniques is obvious: direct and indirect detection, colliders

- Clear modulation observed by DAMA/LIBRA
  - 'Natural' WIMP candidate in contradiction with other experiments.
  - Lower mass WIMPs?

- Direct detection detectors experiment scaling up
  - complementarity of targets, backgrounds, detection techniques
  - Future of direct DM Search? Plenary talk from Cristiano Galbiati this conference

- Indirect DM detection: multimessenger and multiwavelength studies underway