Dark Matter: Direct Detection

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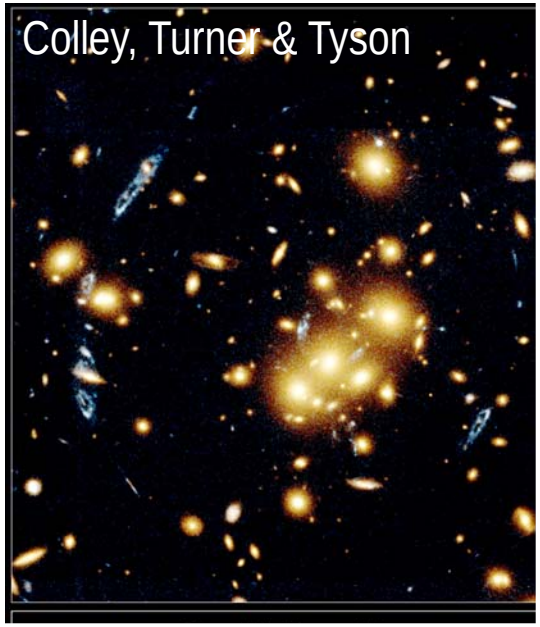
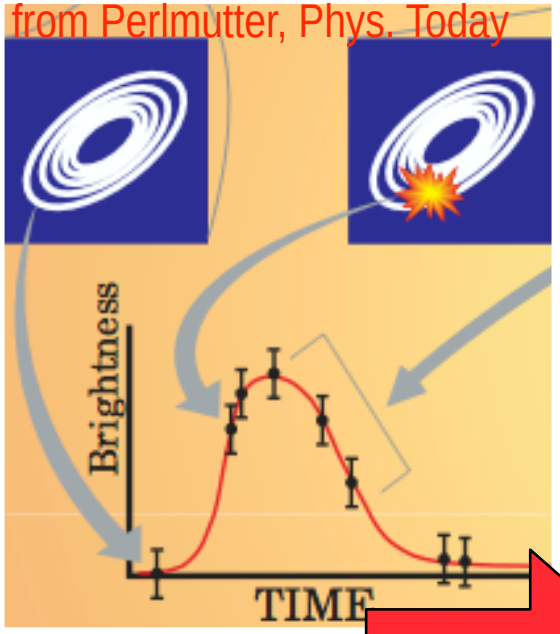
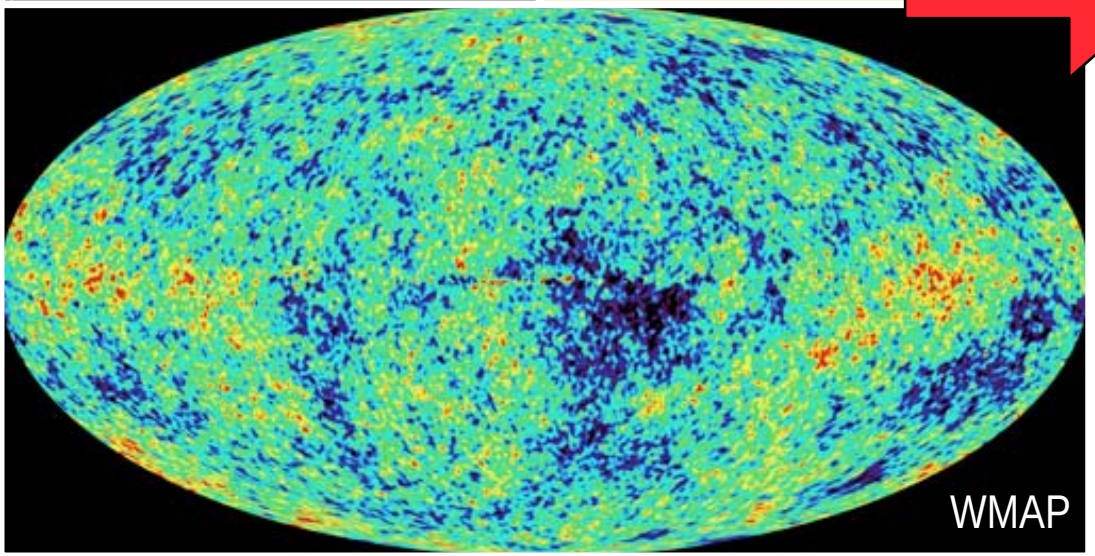
Case Western Reserve University
CDMS Collaboration

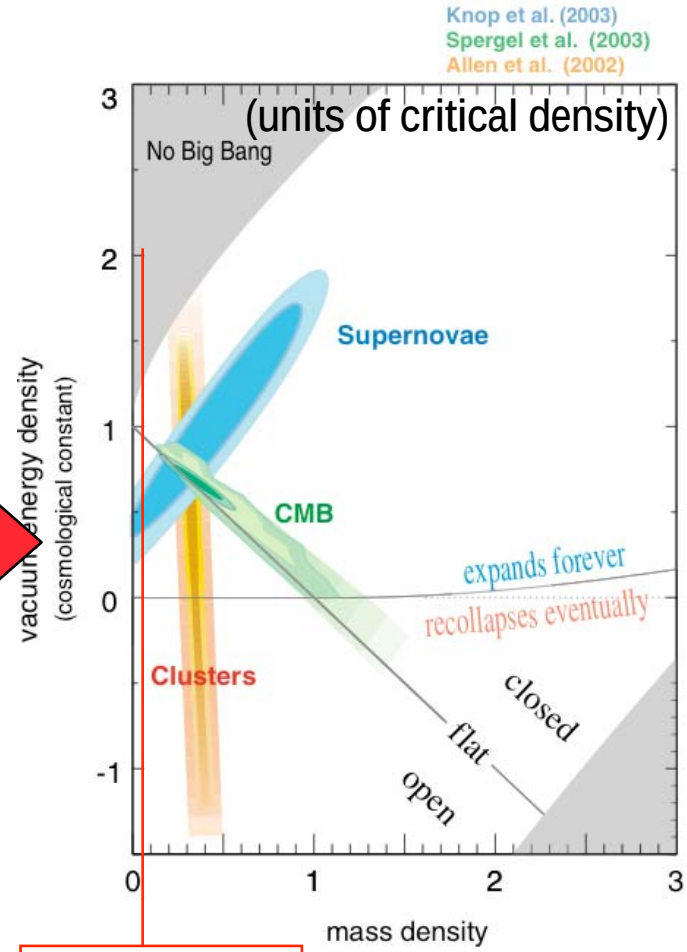
NDM ’06
Paris
7 September 2006

Standard Cosmology







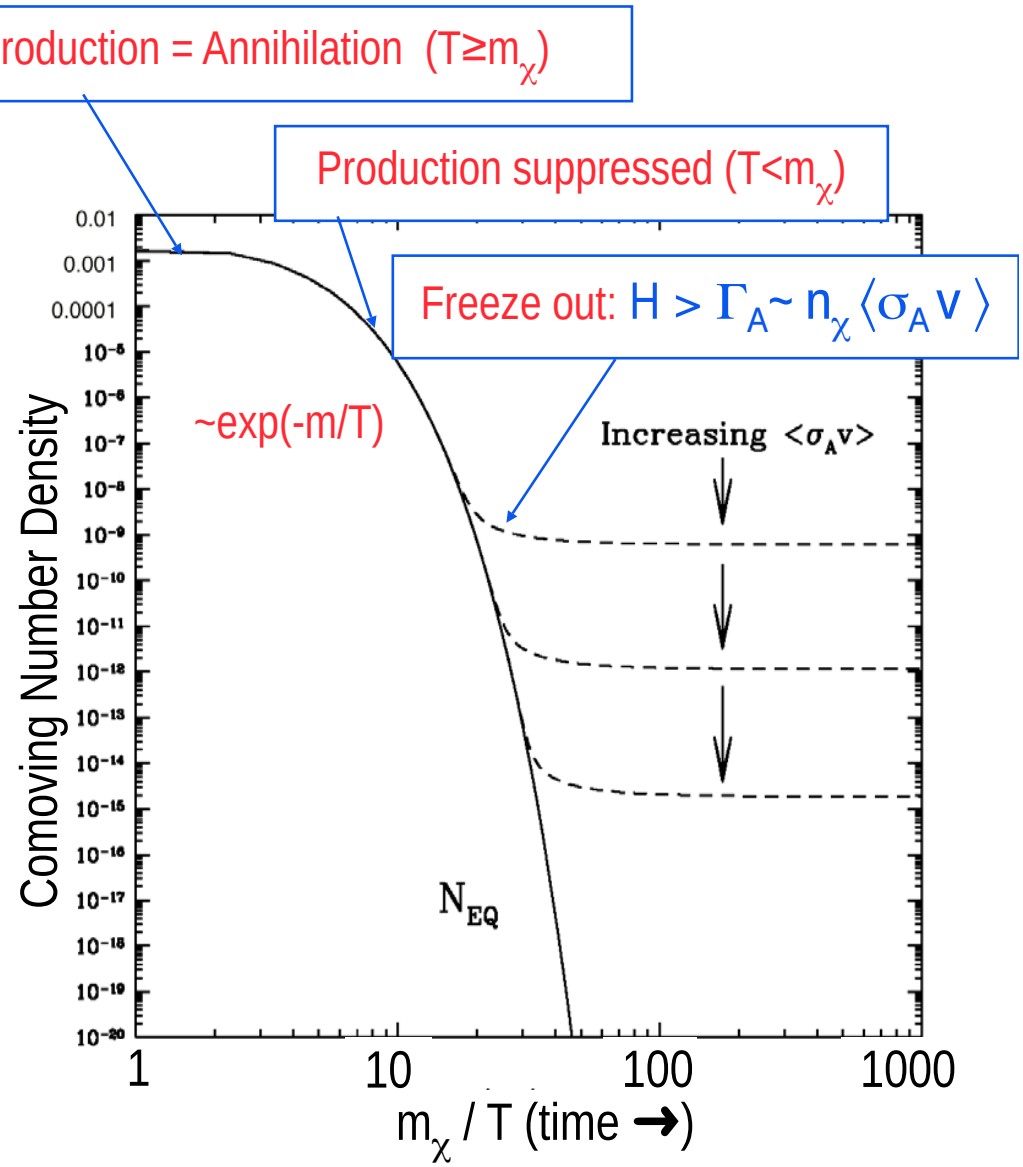


baryons: too few by 5x

Non-Baryonic Dark Matter

- Matter density
  - $\Omega_{Matter} = 0.30 \pm 0.04$
- Big Bang Nucleosynthesis
  - $\Omega_{Baryons} = 0.05 \pm 0.005$
- Nature of dark matter
  - Non-baryonic
  - Large scale structure predicts DM is 'cold'
- WIMPs – Weakly Interacting Massive Particle
  - ~10--1000 GeV Thermal relics
  - $T_{FO} \sim m/20$
  - $\sigma_A \sim$ electroweak scale

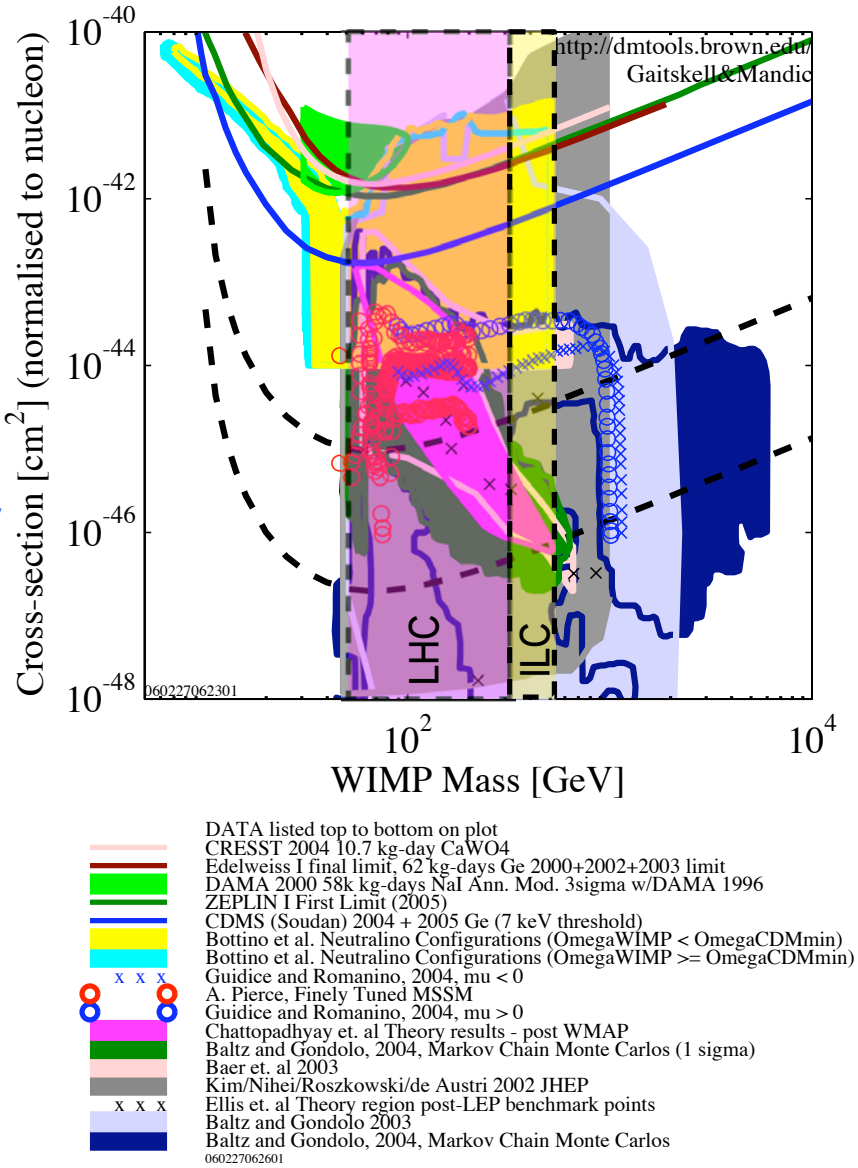
SUSY/LSP



SUSY Dark Matter: elastic scattering cross section

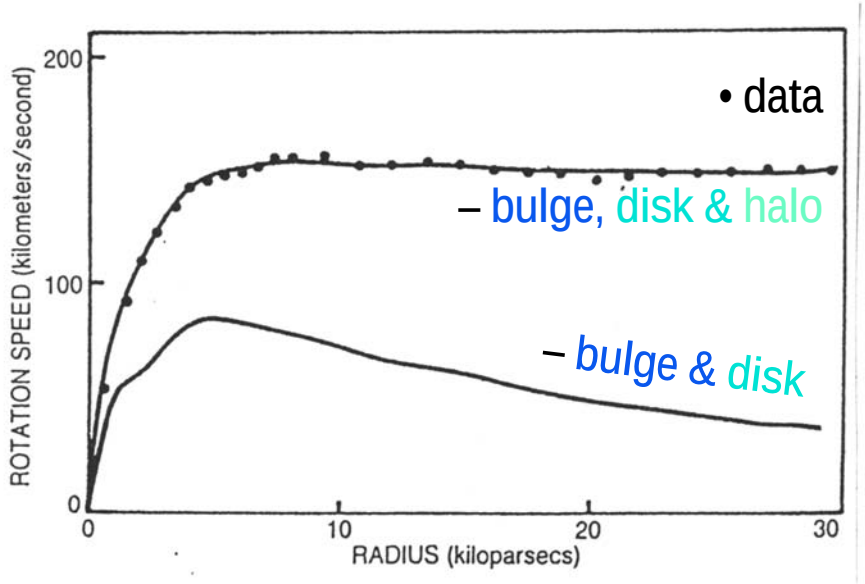
- The 'standard' progress plot
  - Direct-search experimental bounds
- Theory
  - Sample SUSY parameter space
  - Apply accelerator and model-specific particle physics constraints
  - Apply cosmological bound on relic density

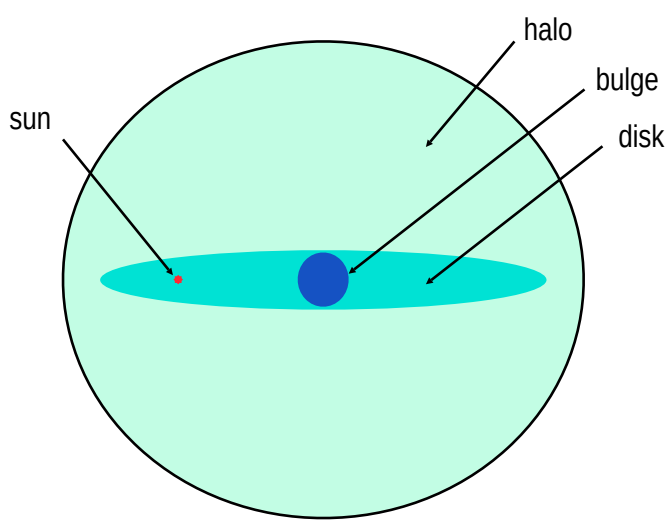
⇒ Extract allowed region for WIMP-nucleon cross-section versus WIMP mass



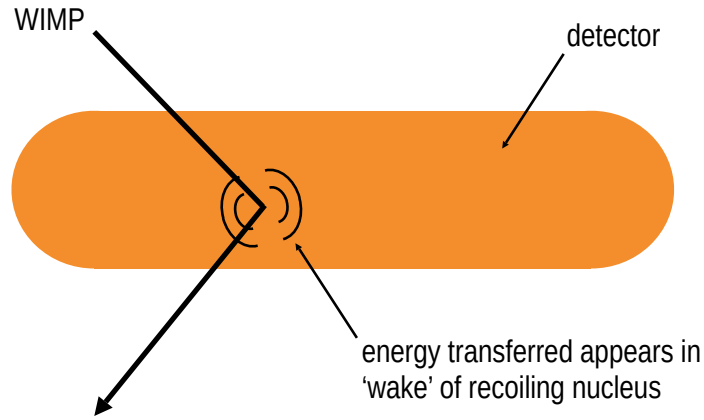
Broad theoretical landscape: much of it testable with next and next-next generation DM searches and/or next and next-next accelerators

WIMPs in the Galactic Halo



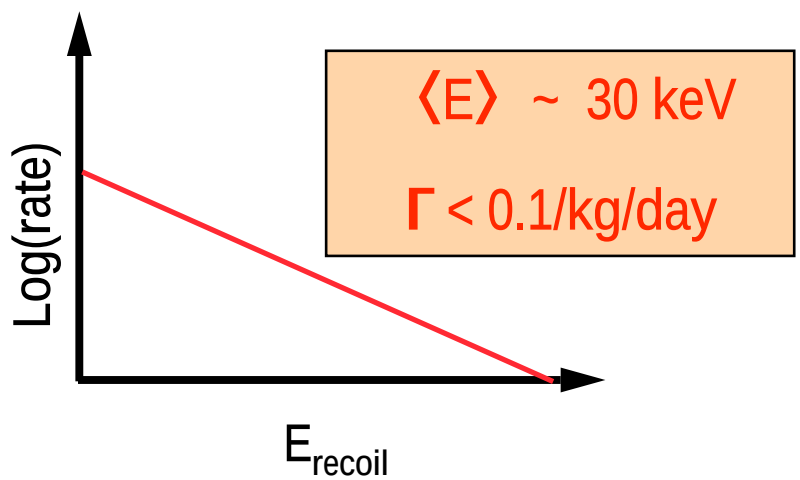


The Milky Way



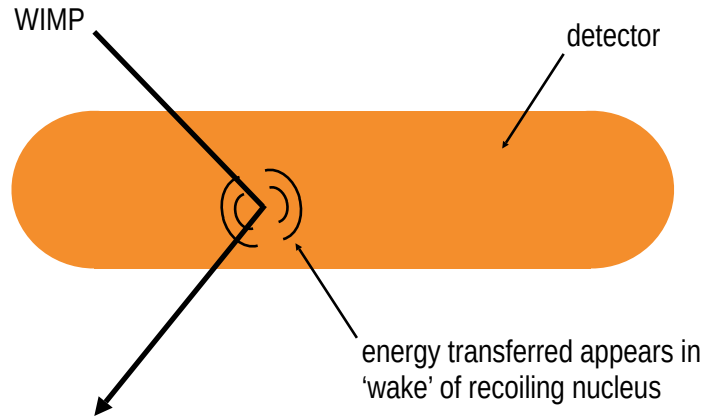
WIMP-Nucleus Scattering

Scatter from a Nucleus in a Terrestrial Particle Detector



WIMPs in the Galactic Halo

- Exploit movements of Earth/ Sun through WIMP halo
  - Direction of recoil -- most events should be opposite Earth/Sun direction (Spergel 1988)
  - Annual modulation -- harder spectrum when Earth travels with sun (Drukier, Freese, & Spergel 1986)



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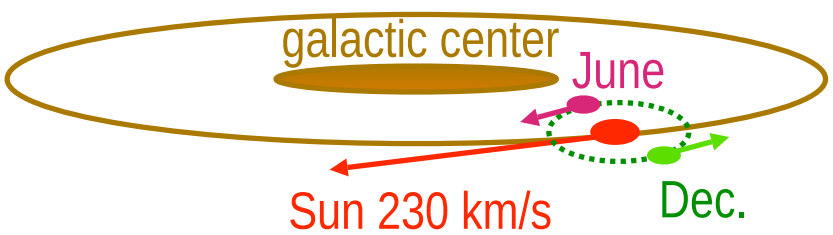
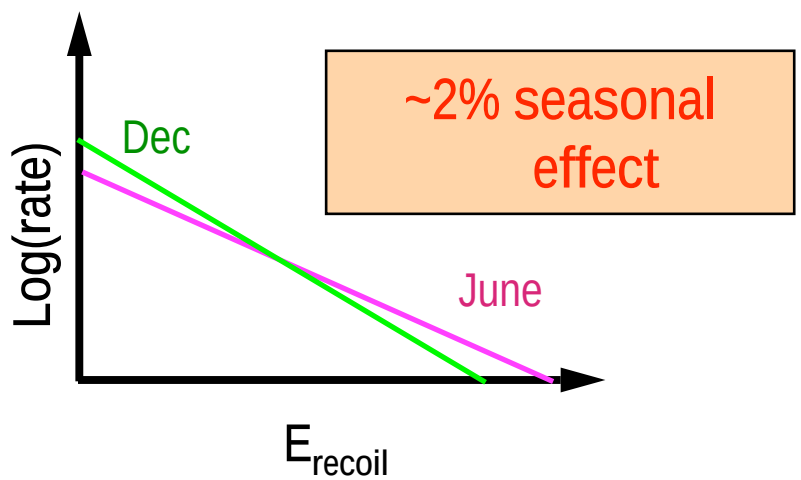
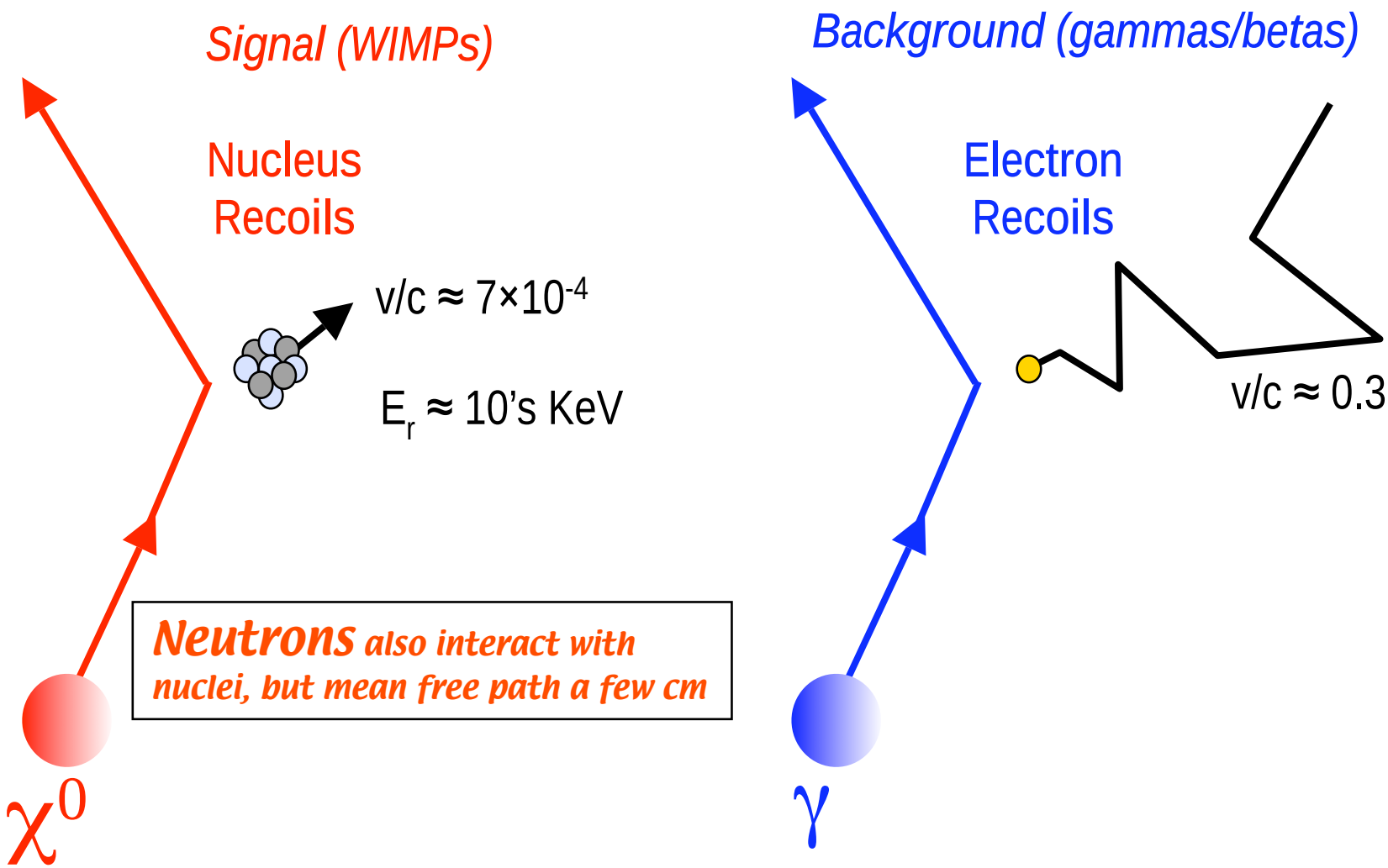


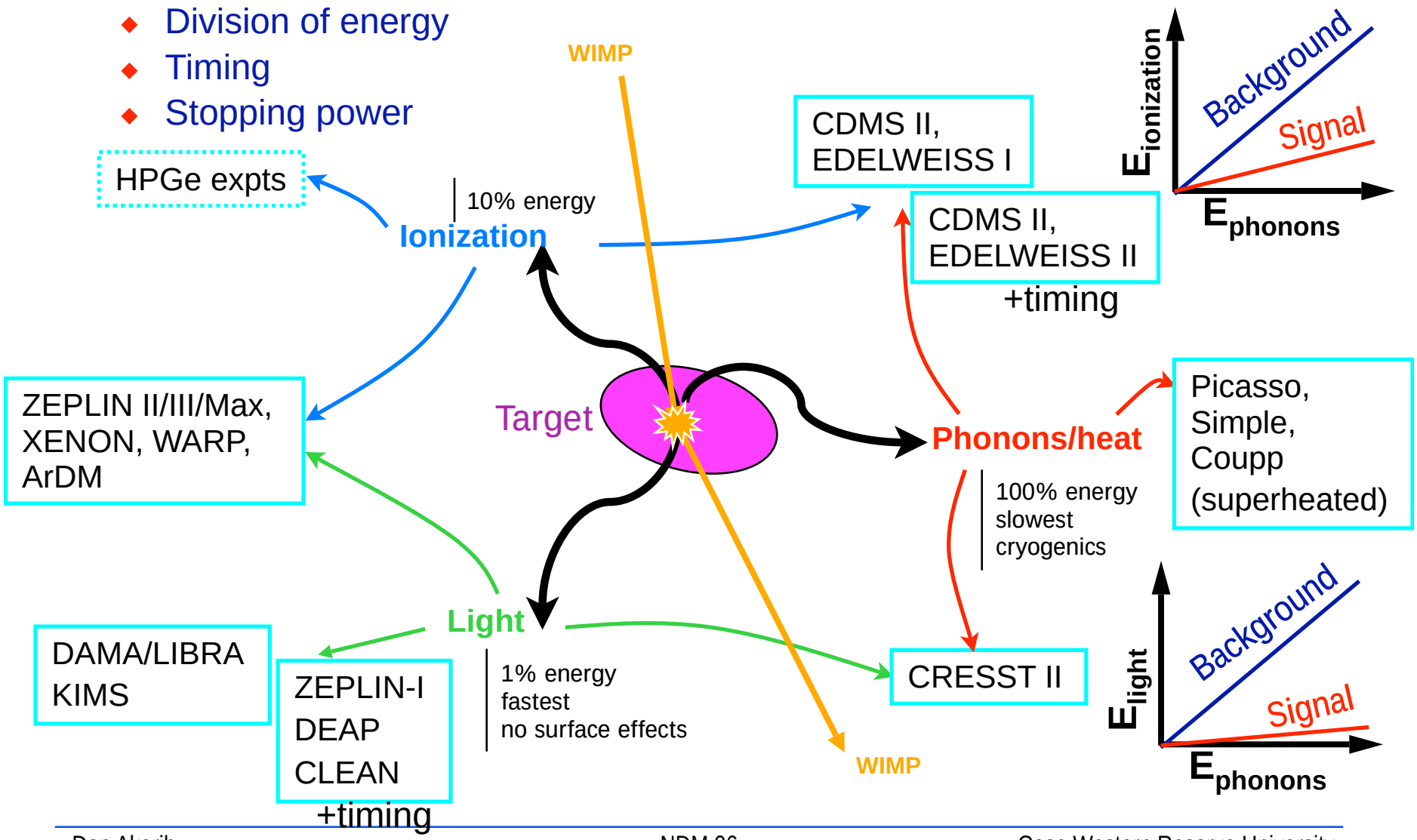


The Signal and Backgrounds



Nuclear-Recoil Discrimination

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power



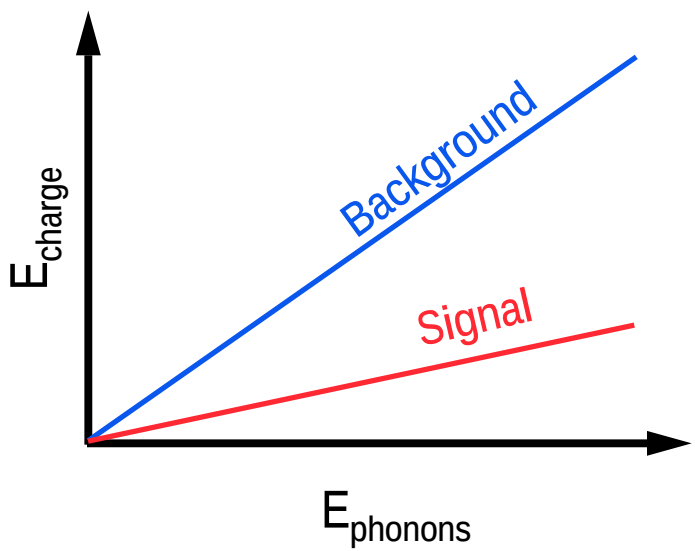
Background suppression: Recoil Discrimination

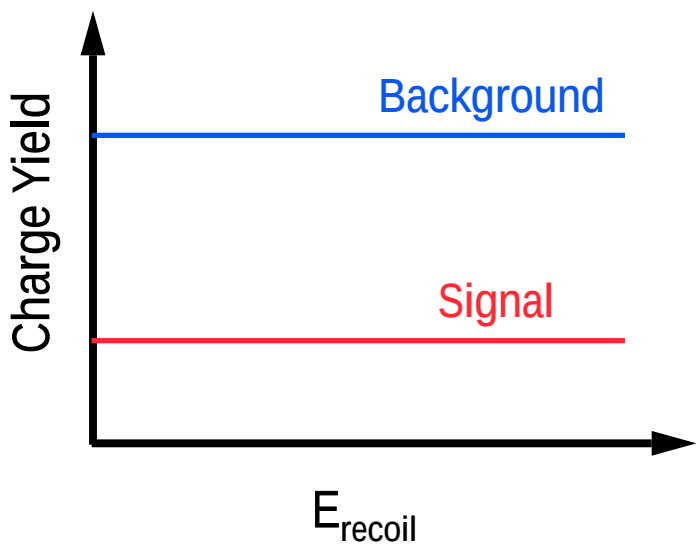
WIMPs 'look' different – recoil discrimination

Photons and electrons scatter from electrons

WIMPs (and neutrons) scatter from nuclei

In CDMS, EDELWEISS, CRESST:
(light replaces charge)





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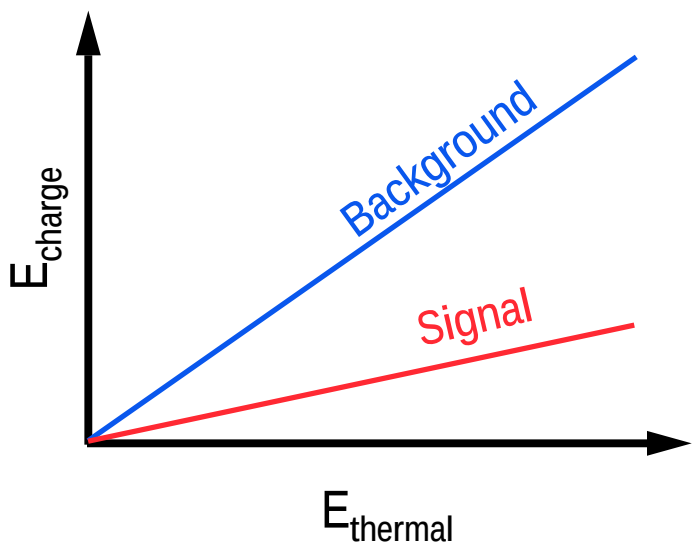
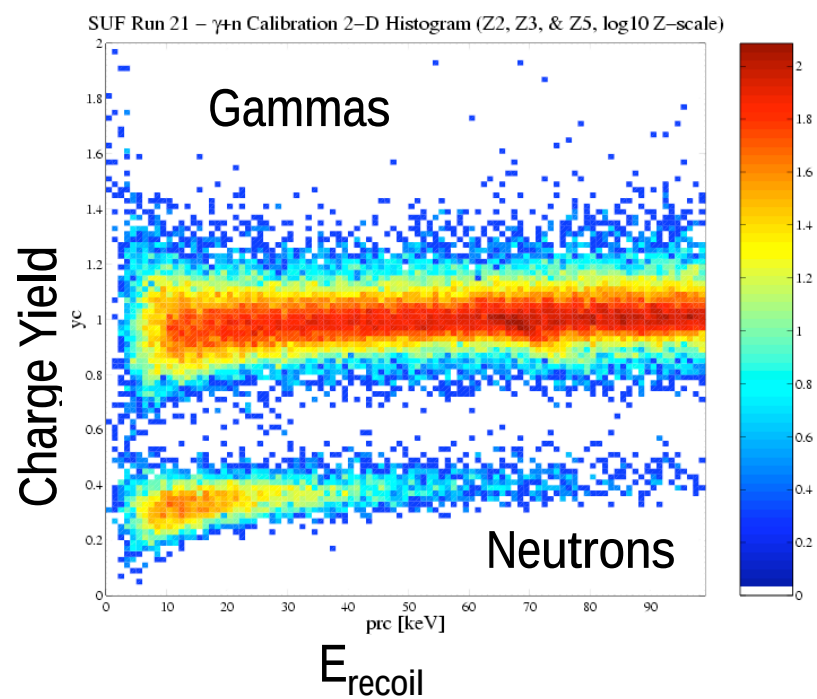


CDMS



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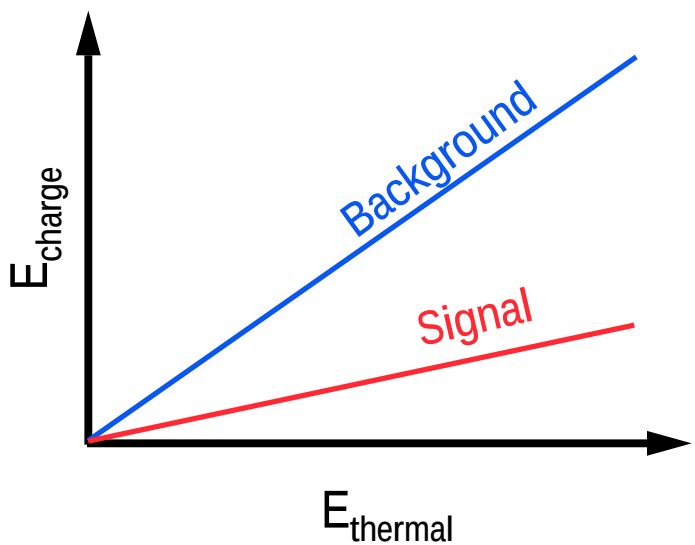
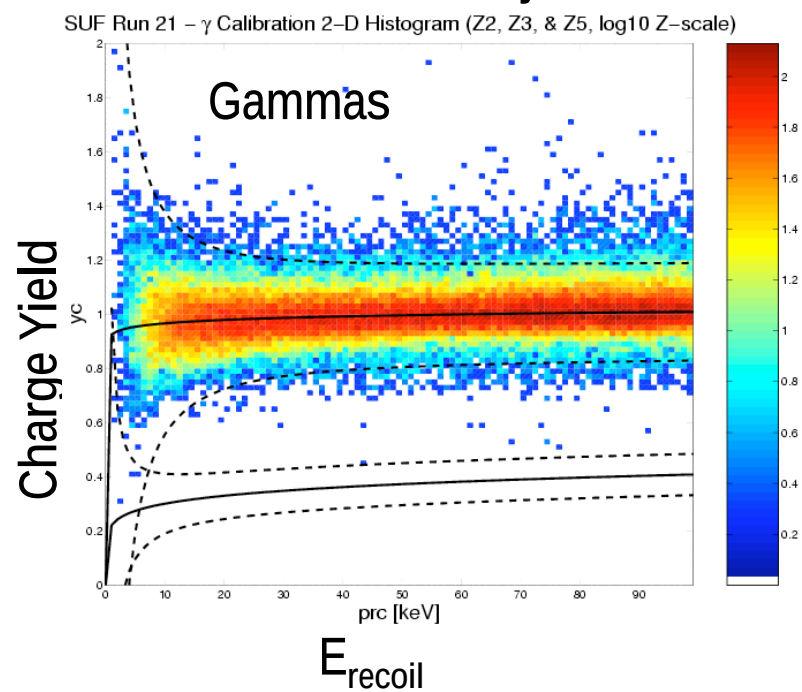


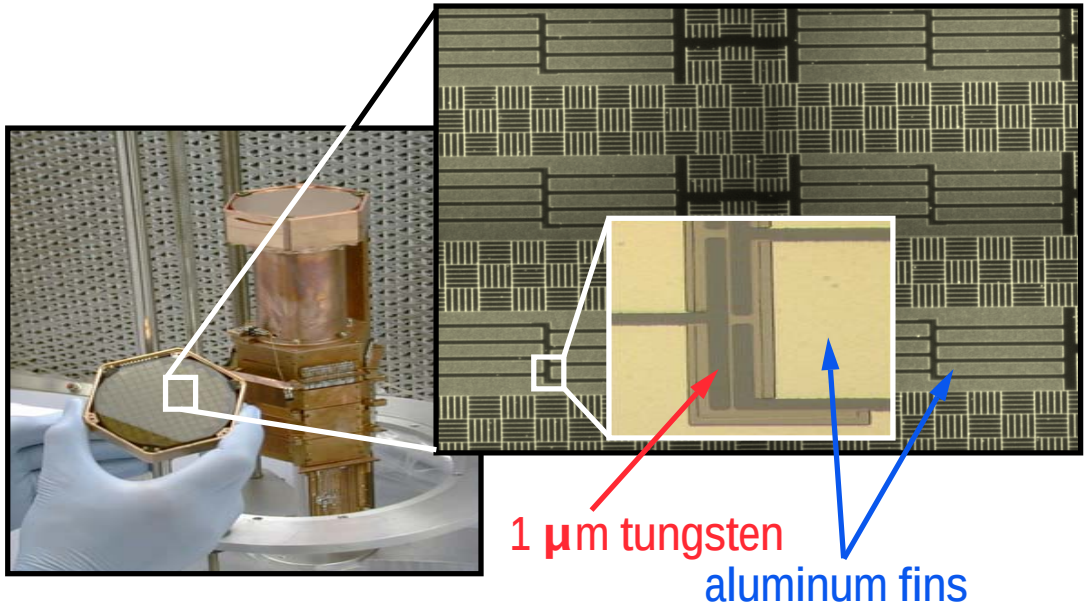
>50000:1 rejection CDMS

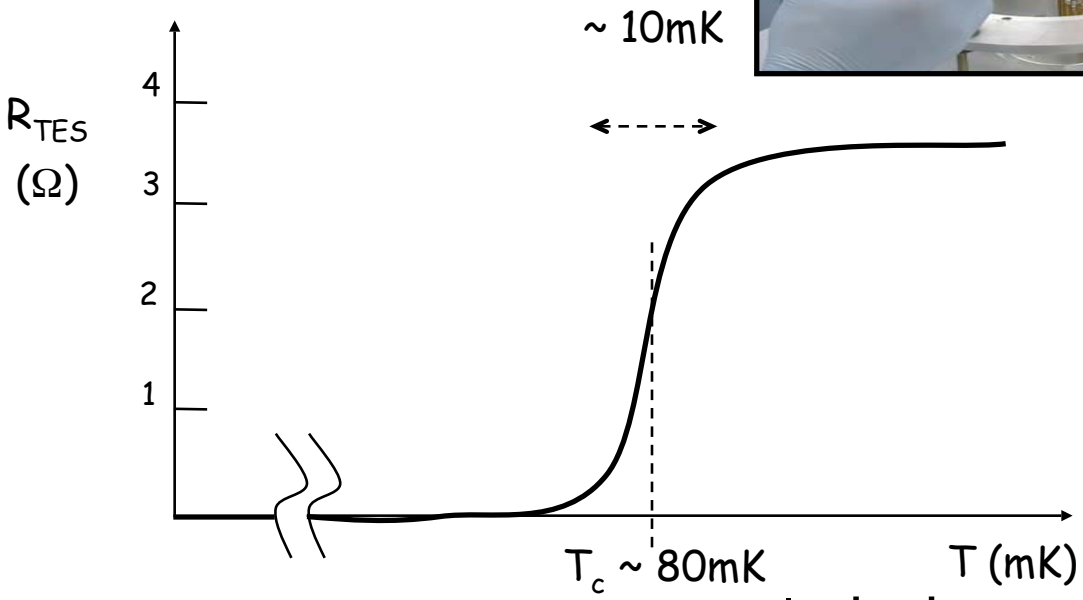


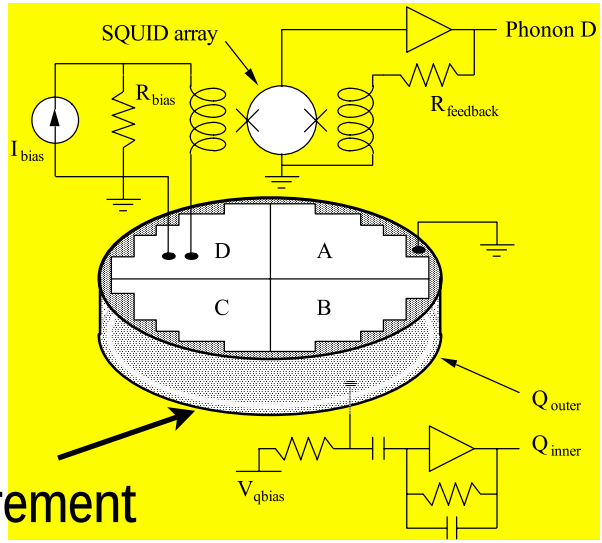
CDMS: Cryogenic "ZIP" detectors

Superconducting films that detect minute amounts of heat

Transition Edge Sensor sensitive to fast athermal phonons



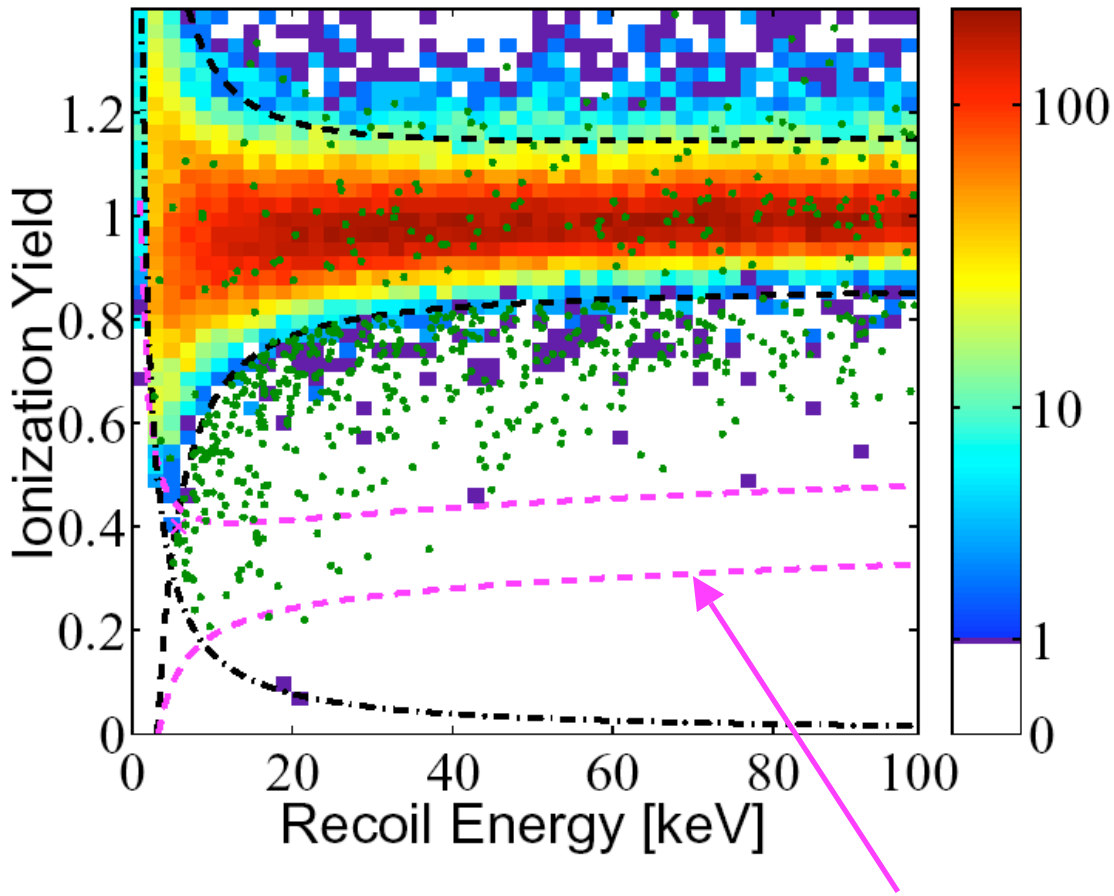




Ionization measurement

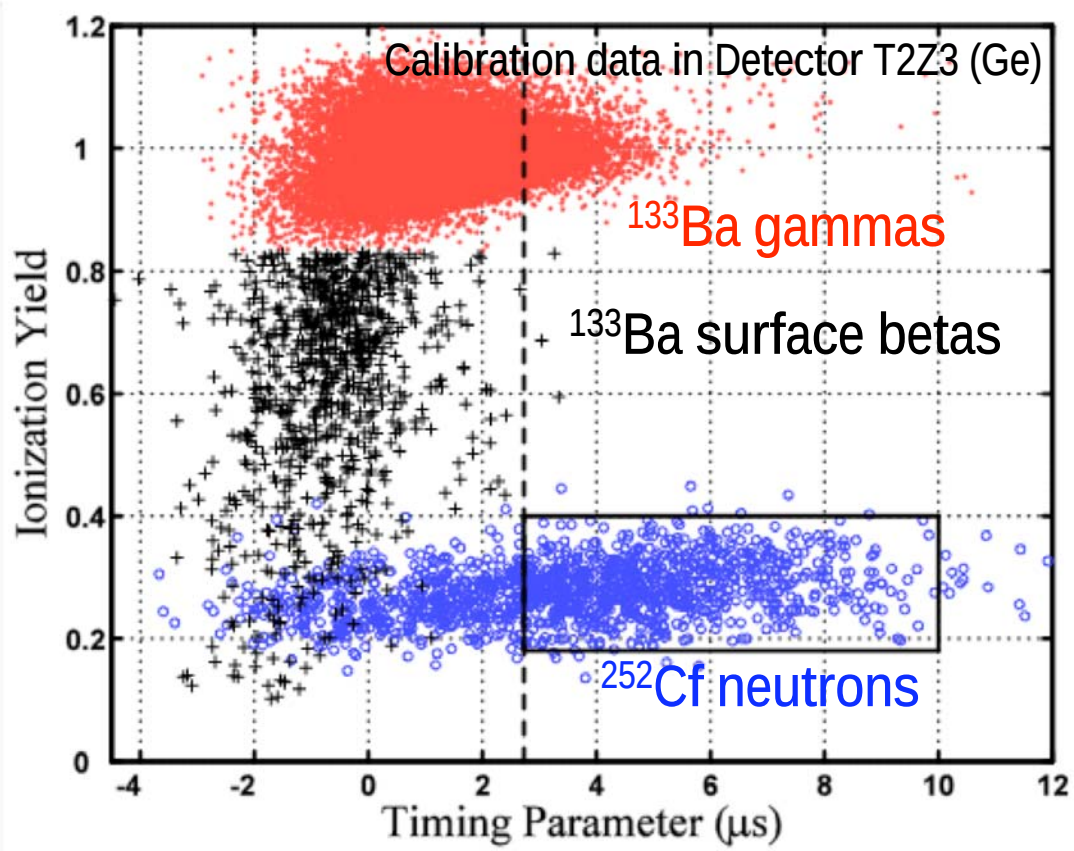
Beta backgrounds

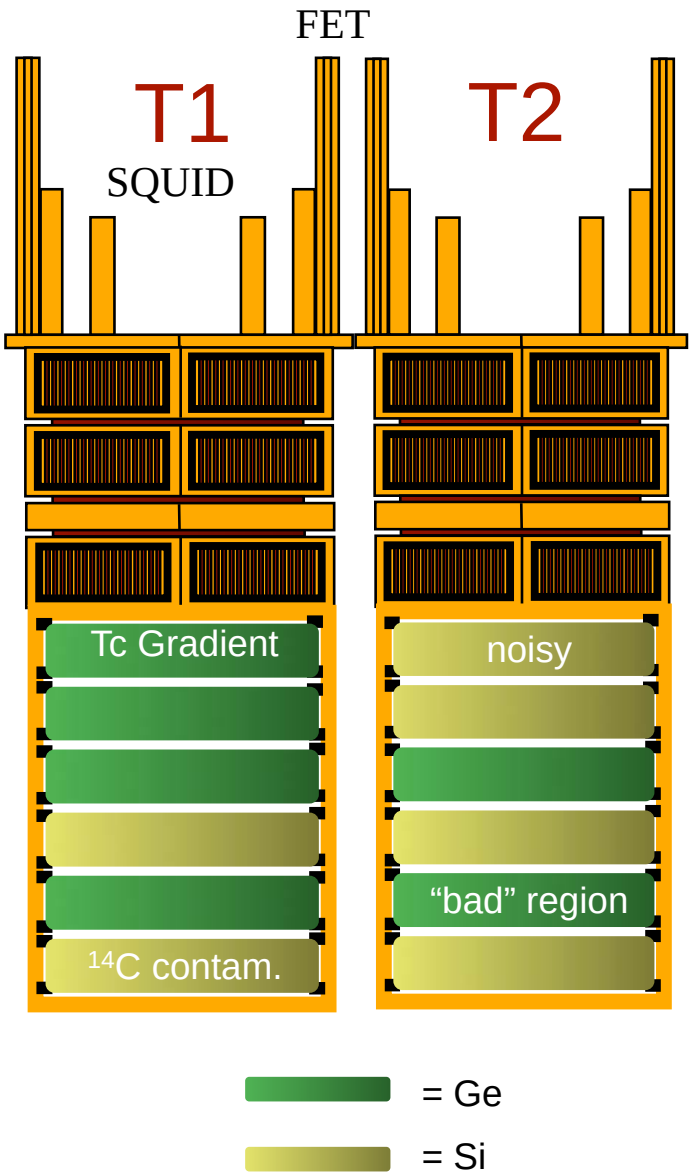
- electrons that interact in surface “dead layer” of detector result in reduced ionization yield



Mask signal region: Blind analysis to minimize bias

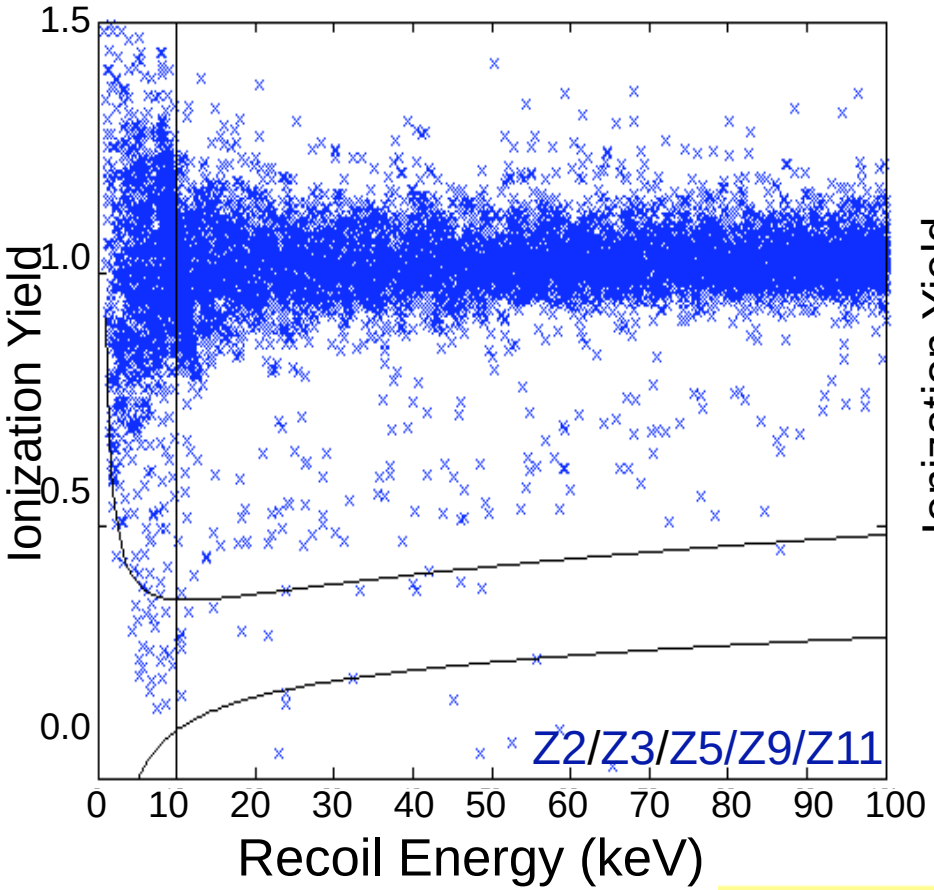
- Cuts set on calibration data and non-masked WIMP-search data
  - timing parameter
  - ionization yield
  - problem detectors/channels



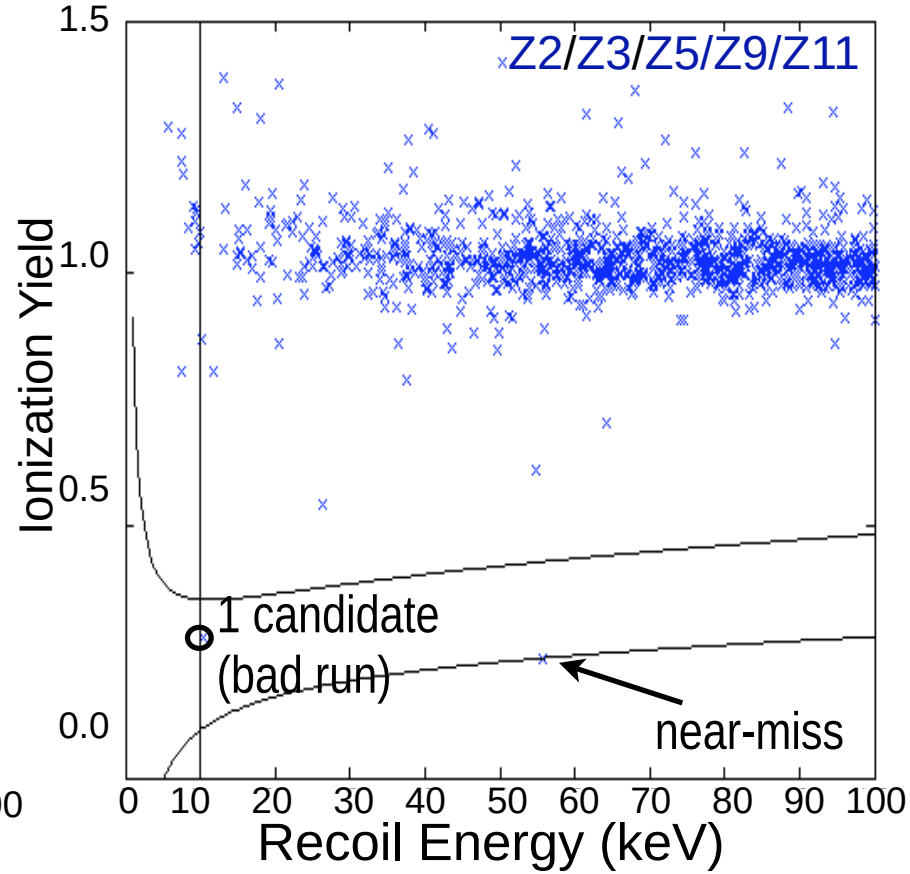


Second Soudan Run WIMP-search data

Before timing cuts



After timing cuts

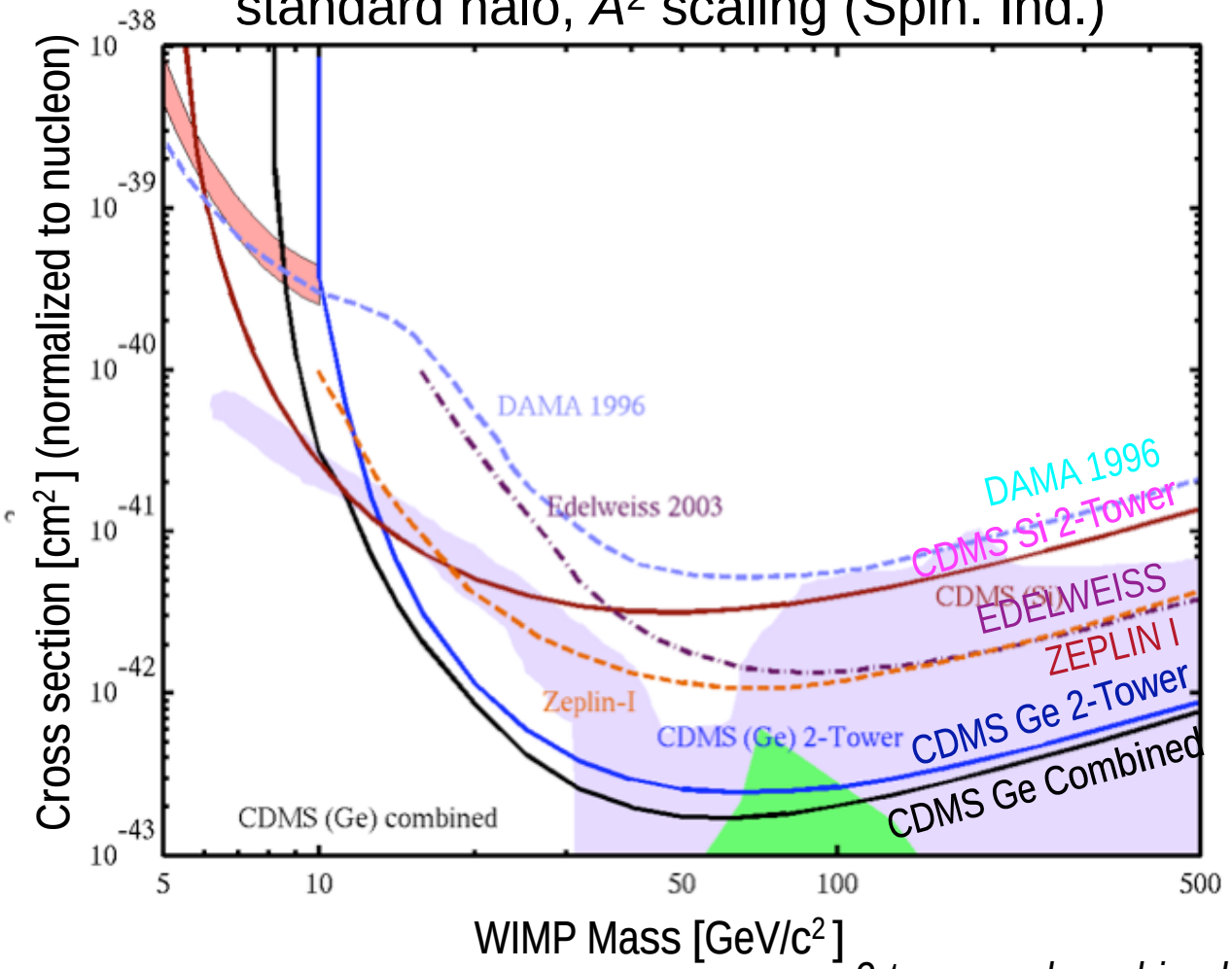


34 kg-d after cuts

ESTIMATE BKG: 0.4 ± 0.2 (sys.) ± 0.2 (stat.) electron recoils, 0.05 recoils from neutrons expected.
Optimized for ~0.5 background events

1st Year CDMS Soudan Combined Limits

90% CL upper limits assuming standard halo, A^2 scaling (Spin. Ind.)



- Upper limits on the WIMP- nucleon cross section are 1.7×10^{-43} cm^2 for a WIMP with mass of 60 GeV/c^2
  - Factor 10 lower than any other experiment
- Excludes regions of SUSY parameter space under some frameworks
  - Bottino et al. 2004 in magenta (relax GUT Unif.)
  - Ellis et al. 2005 (CMSSM) in green

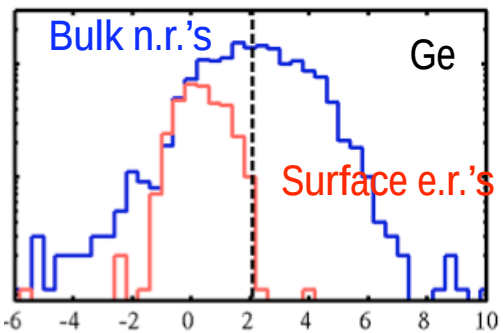
*2-tower and combined (53 kg-d): PRL **96**, 011302 (2006)*

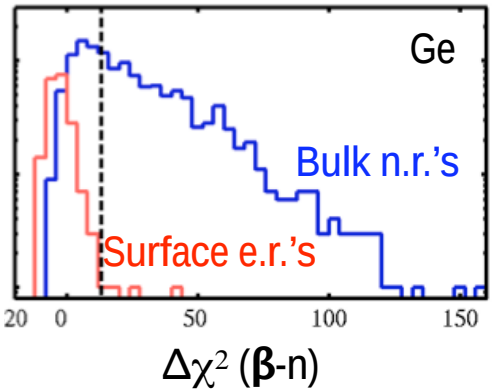
*1-tower (19 kg-d): PRL **93**, 211301 (2004); PRD **72**, 052009 (2005)*

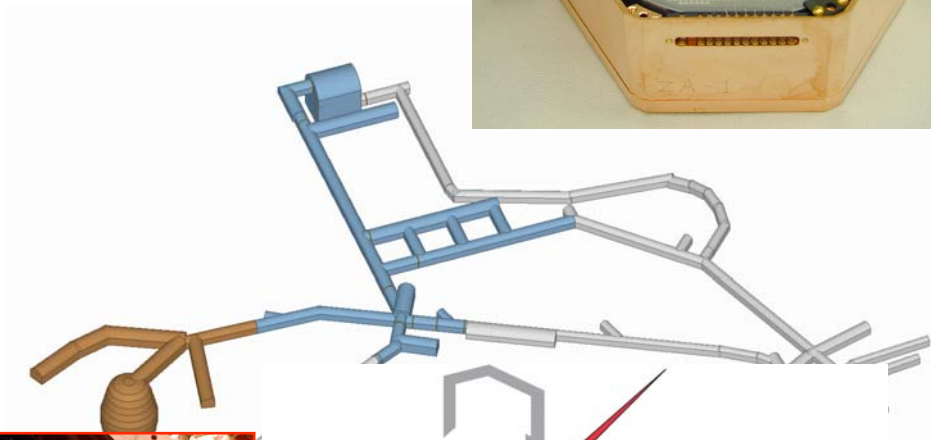
Next for CDMS: Soudan + SuperCDMS 25kg

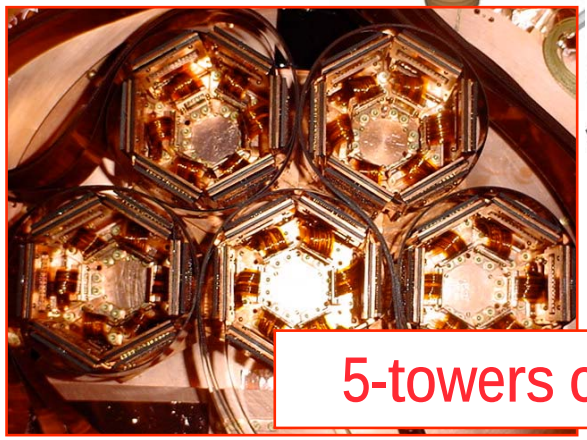
- Improved analysis to maintain goal of 0.5 leakage events
- 5 towers at Soudan (5 kg of Ge) -- 10x sensitivity improvement
- SuperCDMS approved for space by SNOLAB
- Proposed 25-kg phase 10x sens. (under review)
  - next step towards ton-scale goal

1”-thick 0.6-kg









SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L’EXCELLENCE

5-towers cold at Soudan (5 kg Ge)

1st Year CDMS Soudan Combined Limits

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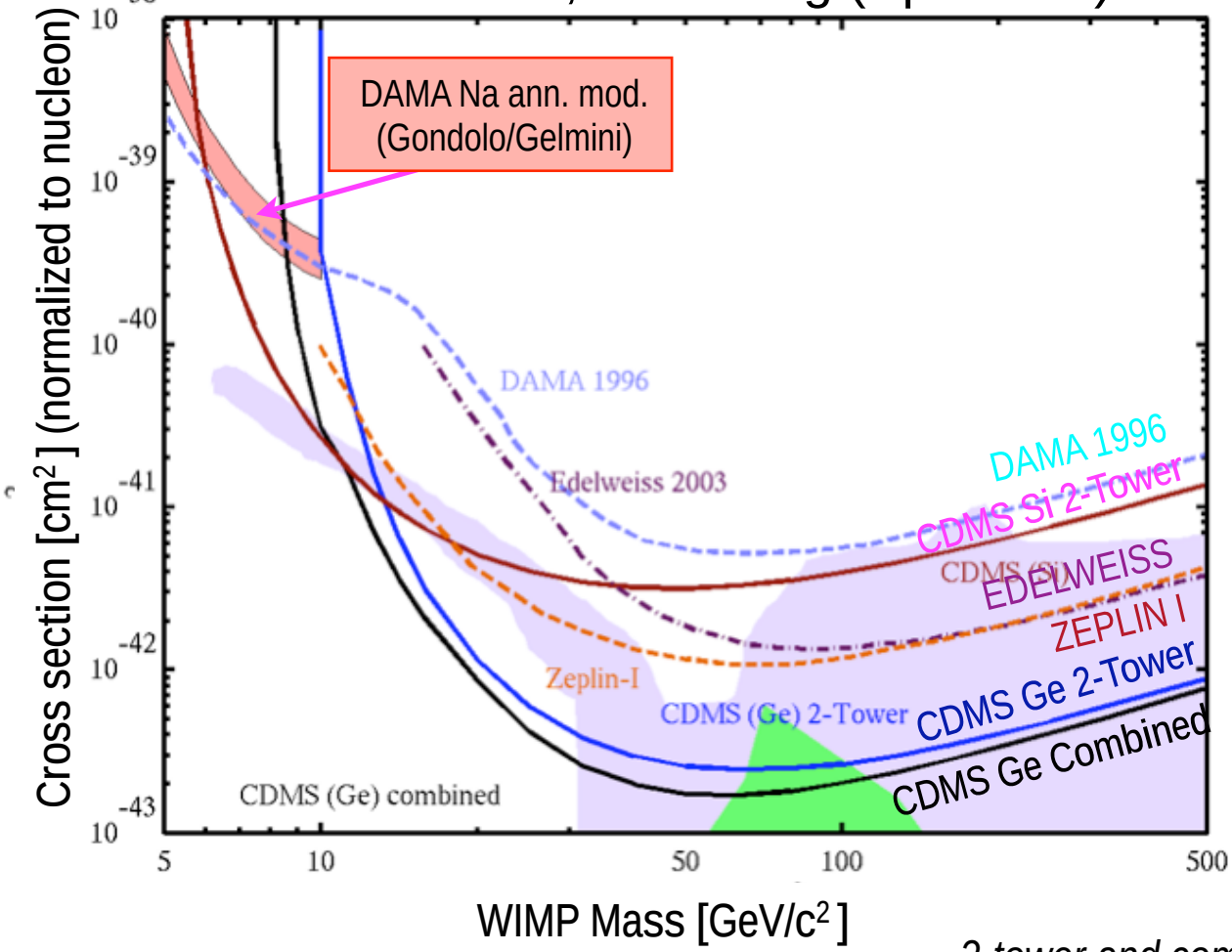

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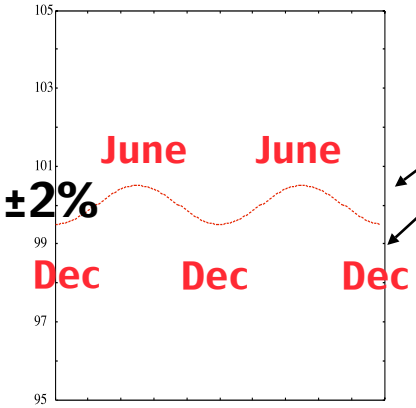
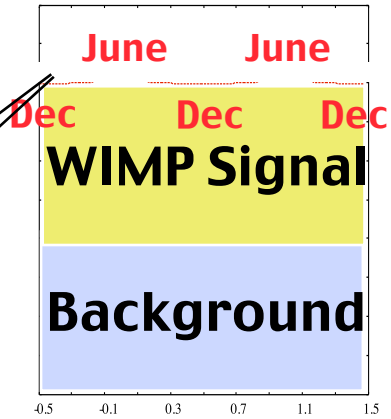
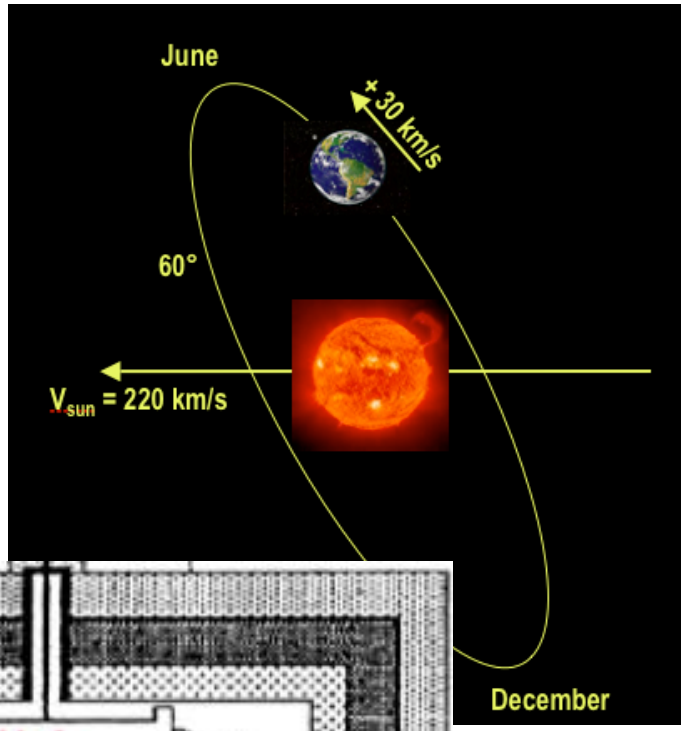
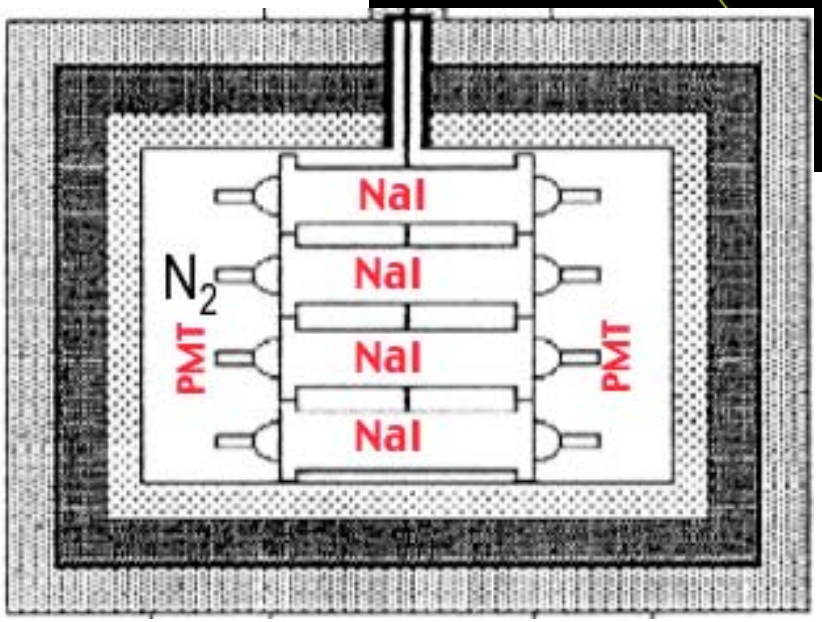
DAMA: NaI & Annual Modulation





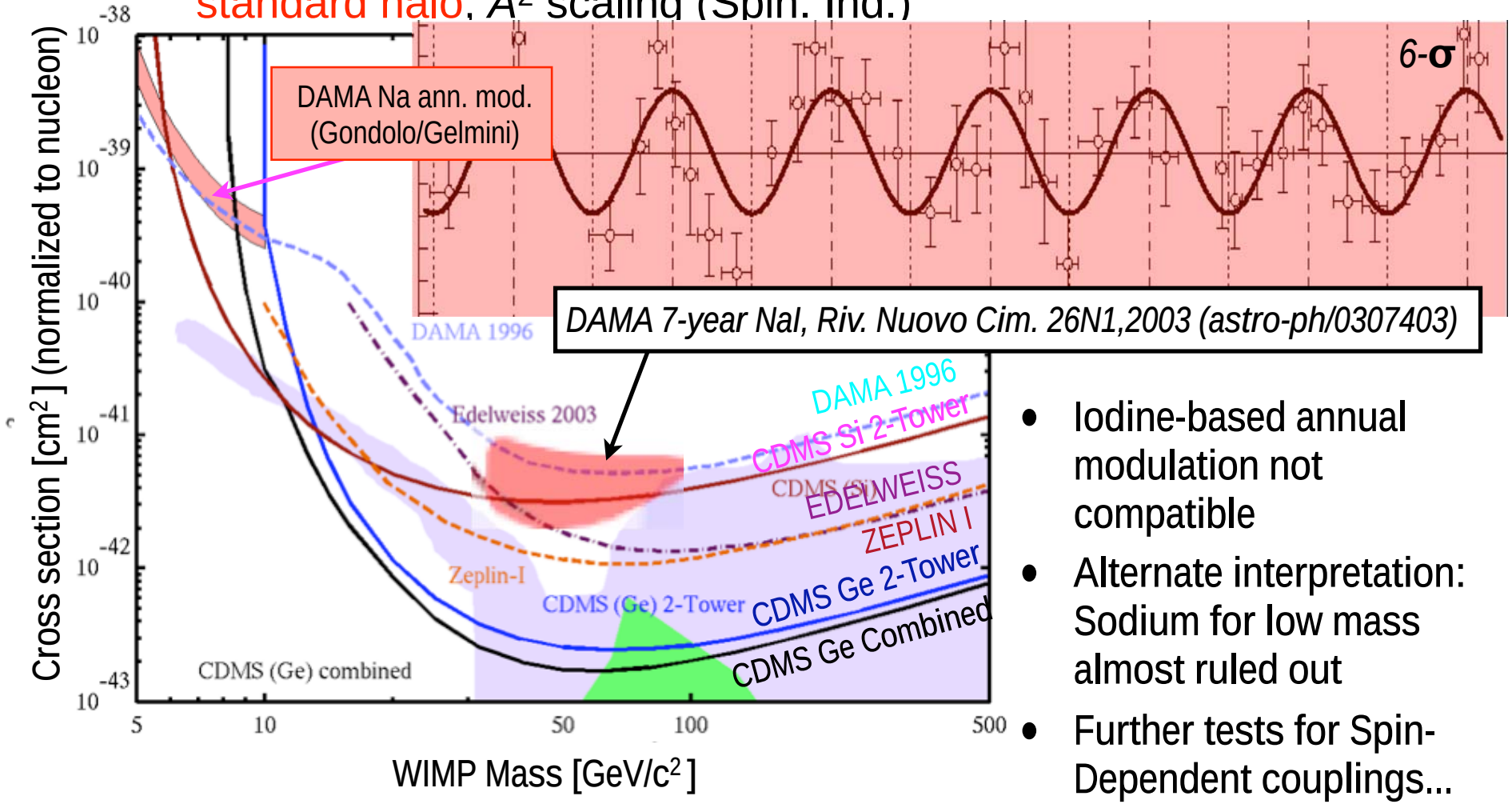




100-kg detector mass: measure energy for each event, but no rejection of gamma background

CDMS Soudan Limits and DAMA

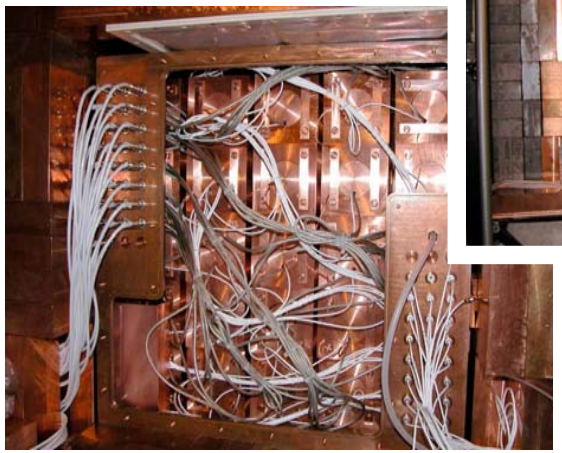
90% CL upper limits assuming
standard halo, A^2 scaling (Spin. Ind.)



- Iodine-based annual modulation not compatible
- Alternate interpretation: Sodium for low mass almost ruled out
- Further tests for Spin-Dependent couplings...

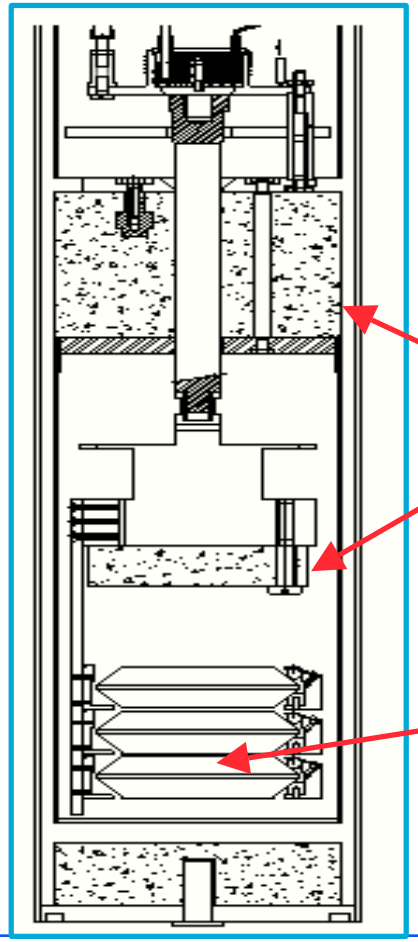
DAMA → LIBRA

- LIBRA
  - Large sodium Iodide Bulk for RAre processes
  - 250 kg with improved radiopurity
  - Operating since 2003
- Further R&D toward 1-ton
  - NaI(Tl) radiopurification started



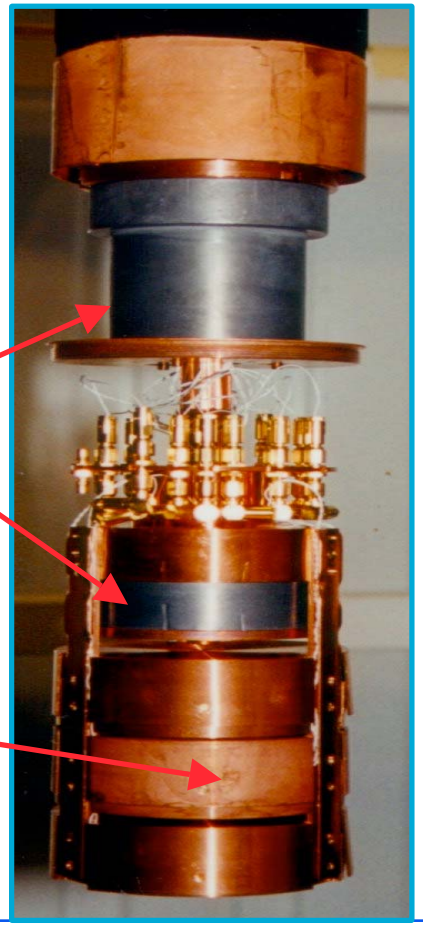
Edelweiss-I in Frejus Tunnel: "1 kg" stage

- First data taking in Fall 2000 at 4800 mwe depth
- Detector improvements: 2nd data set early 2002
- 3rd data taking: October 2002 - March 2003



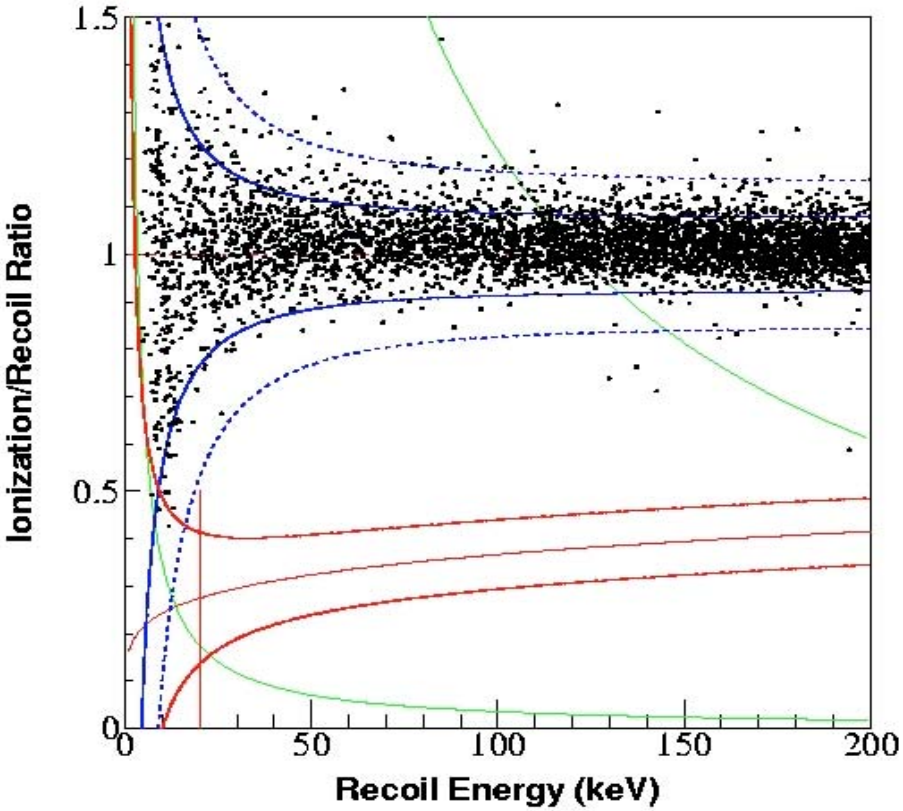
Archeological lead

3 * 320 g Ge detectors: heat and ionization simultaneous readout (NTD thermistor) Installed May 2002

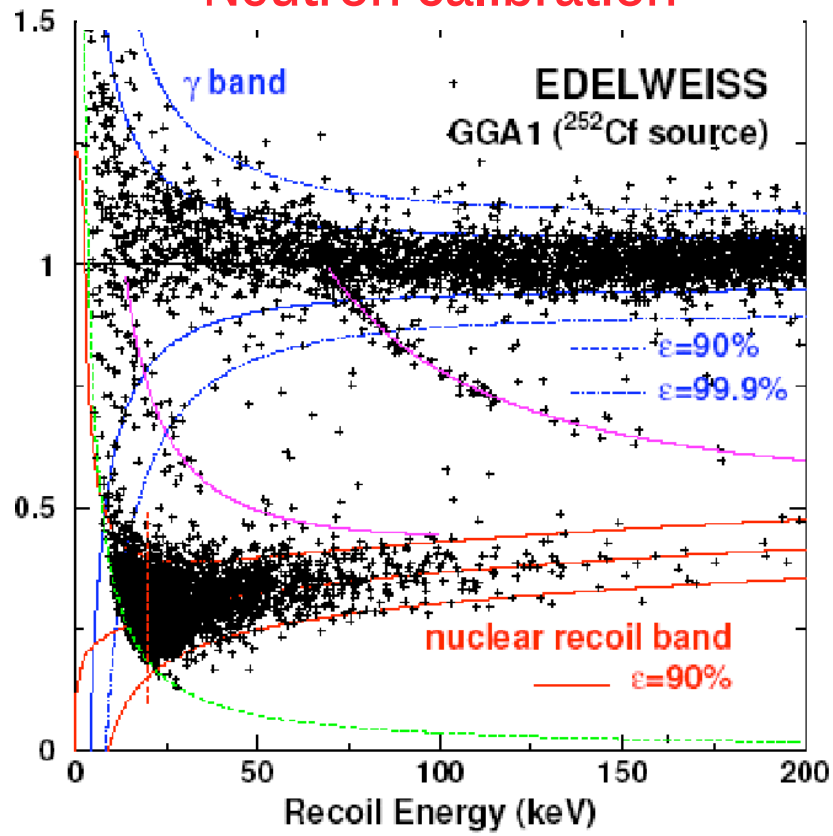


Edelweiss-I: Recoil discrimination

Gamma calibration



Neutron calibration



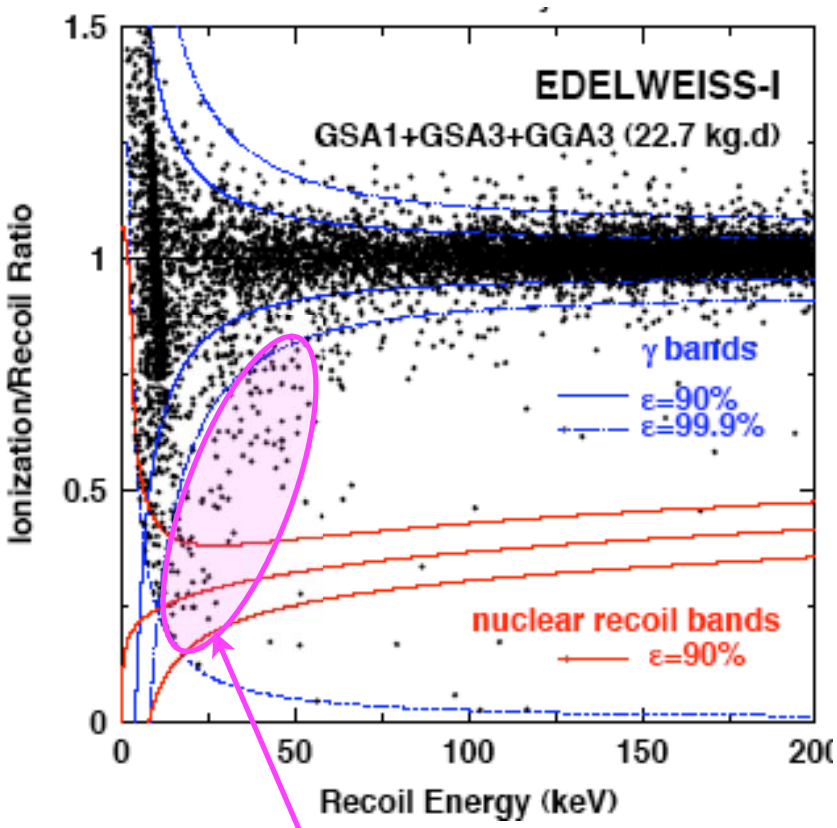
Nuclear recoil discrimination down to 20 keV threshold

γ-ray rejection > 99.99 %

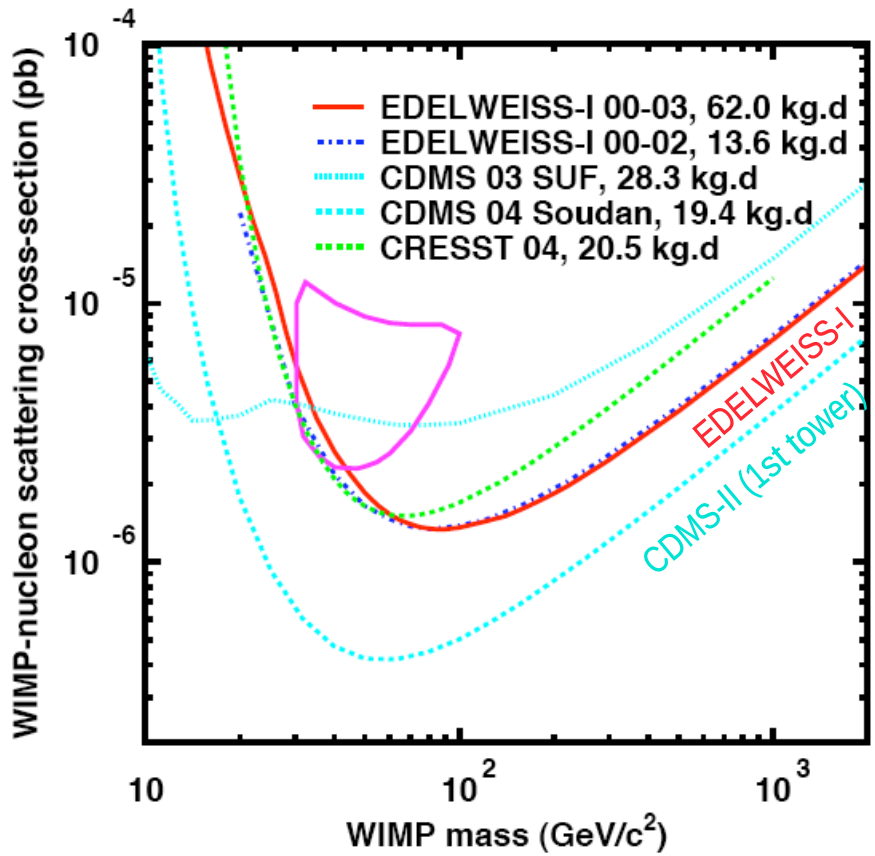
EDELWEISS-I results

- 2000-2003: Exposure of ~60 kg-d
  - Three nuclear recoil candidates (30-100keV) consistent with neutron bkg

WIMP search data (partial)



WIMP cross section limit

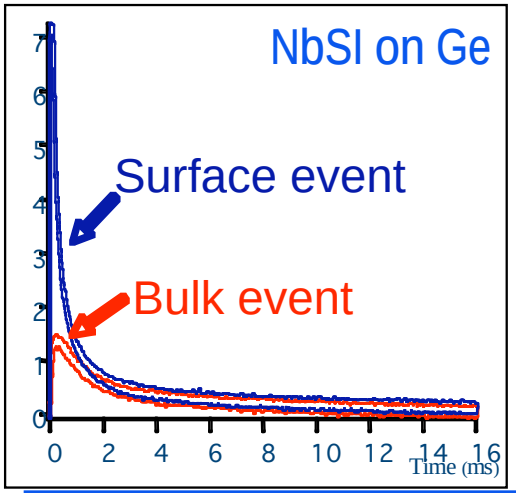


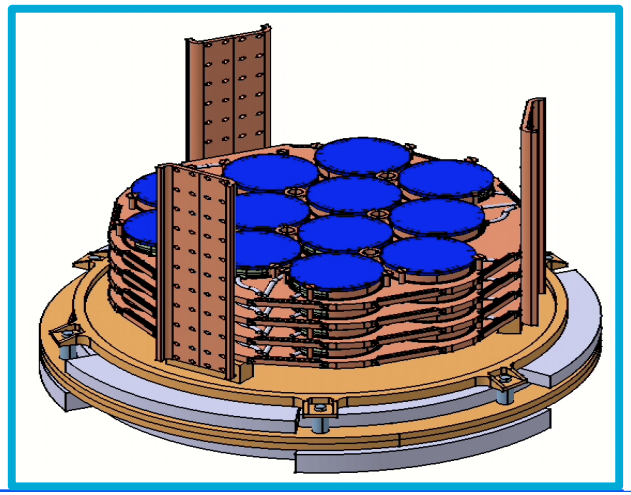
Low-yield surface recoils

Phys. Rev. ***D71****, 122002, 2005 (astro-ph/0503265)*

Edelweiss-II

- 100-detector cryostat operating in Modane
- 28 detectors ready w/goal of ~10^{-48} cm^2:
  - 21 x 320-g NTD on Ge: improved charge collection
  - 7 x 400-g NbSI on Ge: metal-insulator transition - fast timing for surface/bulk event discrimination
- Commissioning run started
  - 6 x 320-g NTD on Ge
  - 1 x 200-g + 1 x 400-g NbSi on Ge
- Plan to propose expansion to 100-module array

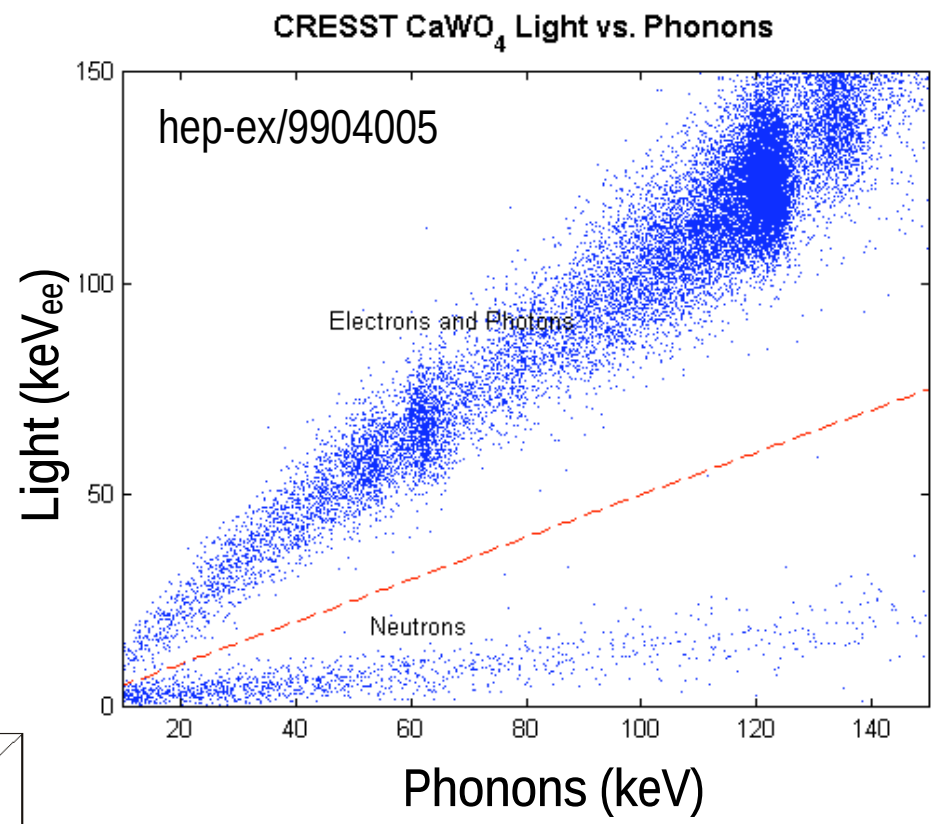


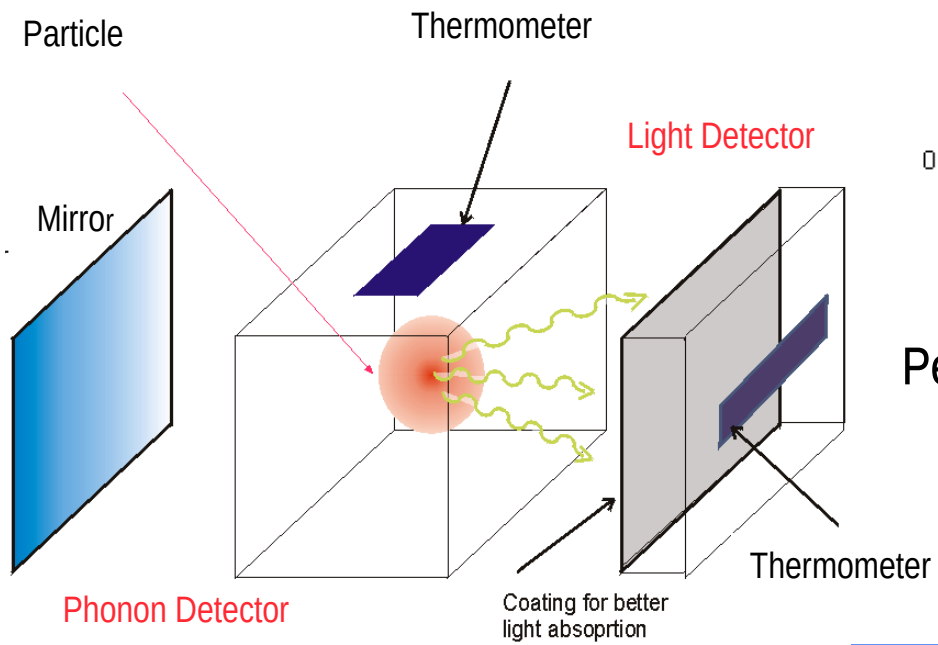


See next talk: R. Lemrani

CRESST II: Phonons and Scintillation

- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron interactions can be distinguished from nuclear recoils (WIMPs, neutrons)

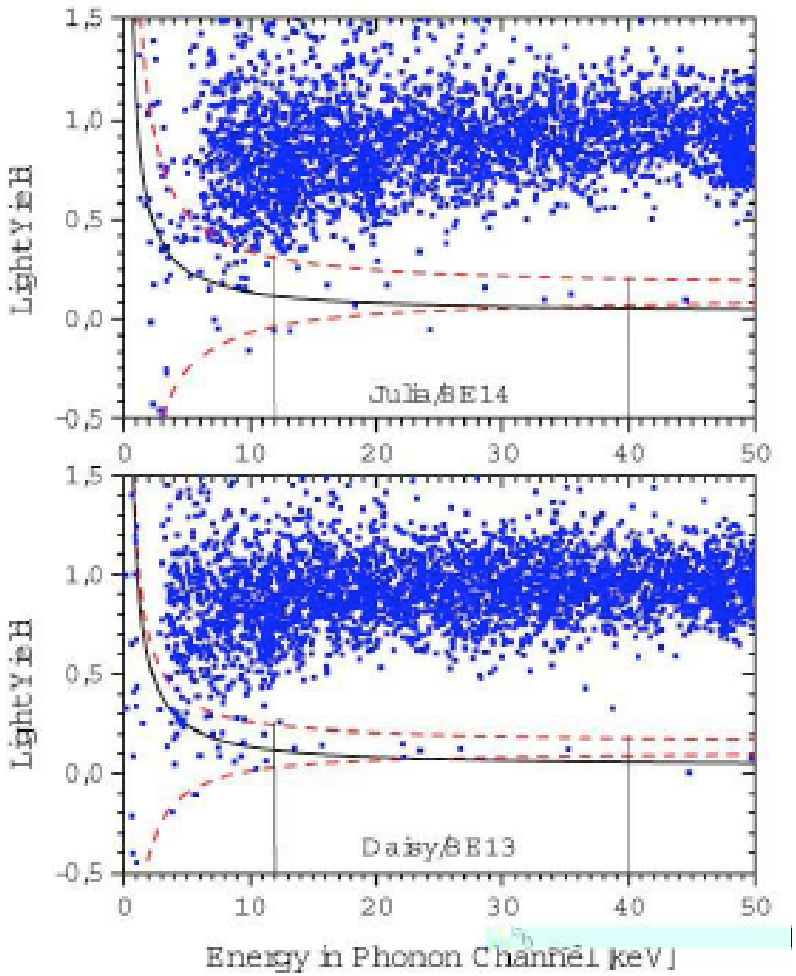




Performance from a 6-g $CaWO_4$ prototype

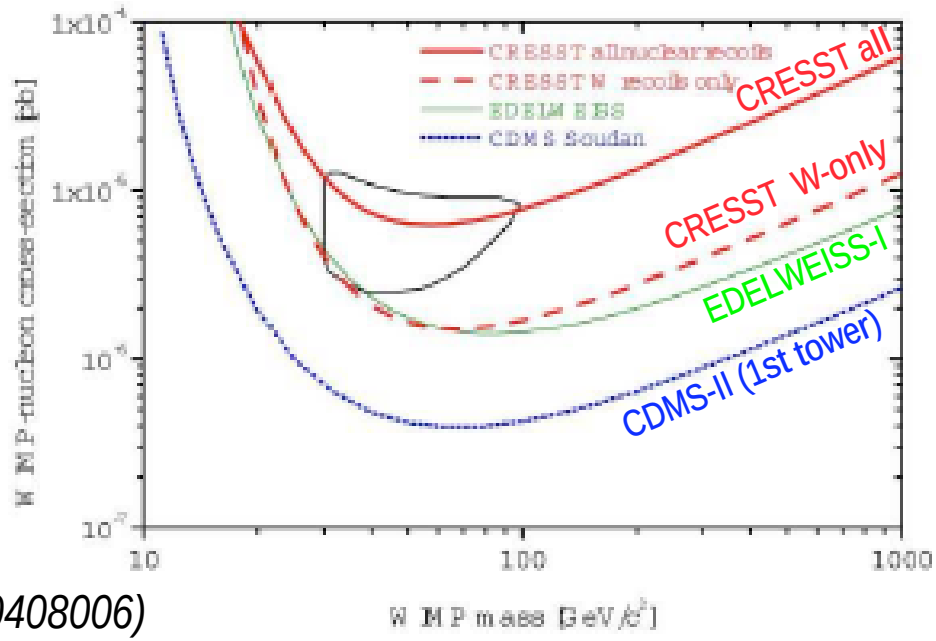
- Very small scintillation signal for tungsten recoils
- Scaled up to 300g detectors

CRESST II: Phonons and Scintillation



Results from 20.5 kg-d exposure of two 300-g $CaWO_4$ prototypes

- No neutron shielding
- Observe low-yield events consistent with neutron rates and oxygen cross section & light yield
- Claim no tungsten recoils in light yield region below oxygen yield (not distinct from noise)



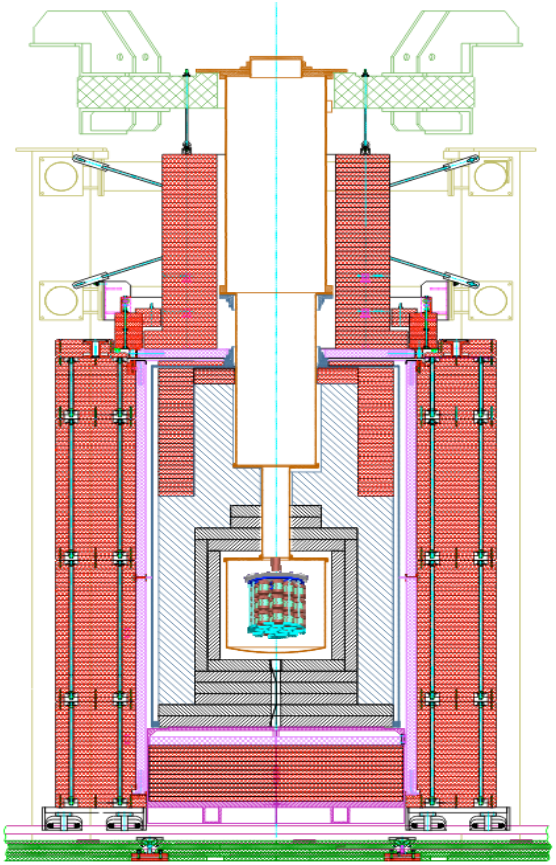
Astropart. Phys. ***23,*** *325-339, 2005 (astro-ph/0408006)*

CRESST II Status and Plans

- 2-year upgrade nearly complete:
  - Installed neutron moderator, muon veto, new 66-SQUID channel readout for up to 33 detector modules / 10 kg target mass
  - New DAQ is installed
  - Electronics, detector holder system in progress
  - Expect to be taking data in Fall 2006 with 8 detectors (2.4 kg)

- With EDELWEISS, formed EURECA collaboration ➔ ton-scale experiment

Shielded cryostat



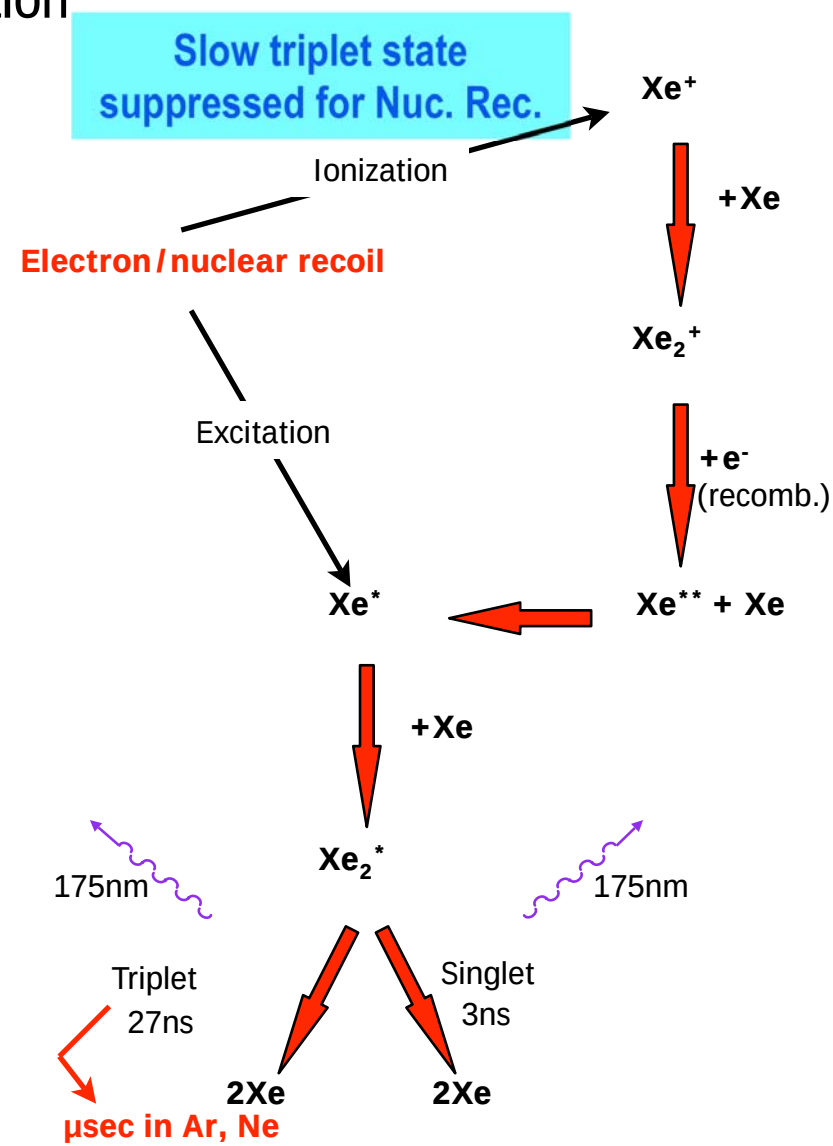
PE neutron moderator

Plastic scintill. μ-veto

Liquid Noble Detectors: Xe, Ar, Ne

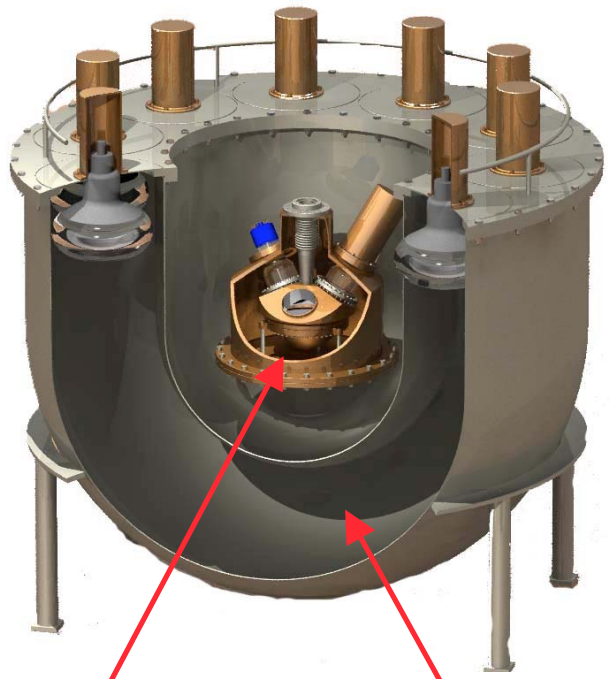
- Atomic excimer states: recoil discrimination
  - Pulse Shape Discrimination
  - Secondary ionization signal
- May readily scale to large mass
- Challenges
  - discrimination at low threshold
  - backgrounds from PMT's and
    - ^{87}Kr in LXe
    - ^{39}Ar in LAr (1 Bq/kg!)

Element	Single phase	Double phase
Xenon	ZEPLIN I, XMASS	ZEPLIN, XENON, XMASS
Argon	DEAP, CLEAN	WARP, ArDM
Neon	CLEAN	SIGN



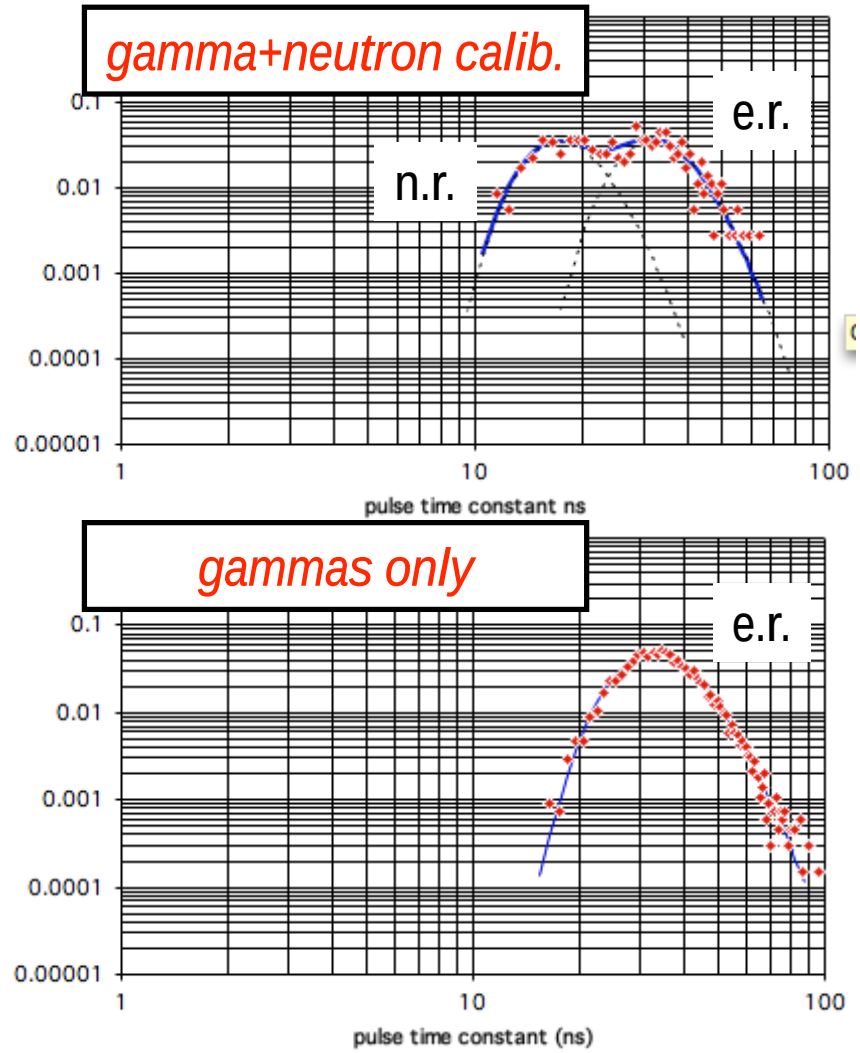
UK Collaboration: Zeplin I

- Single-phase detector
  - Measure primary scintillation
  - Pulse shape discrimination



5kg LXe target (3.1kg fid)
3 PMTs
Cu construction
Polycold cryogen cooling

1 tonne Compton veto

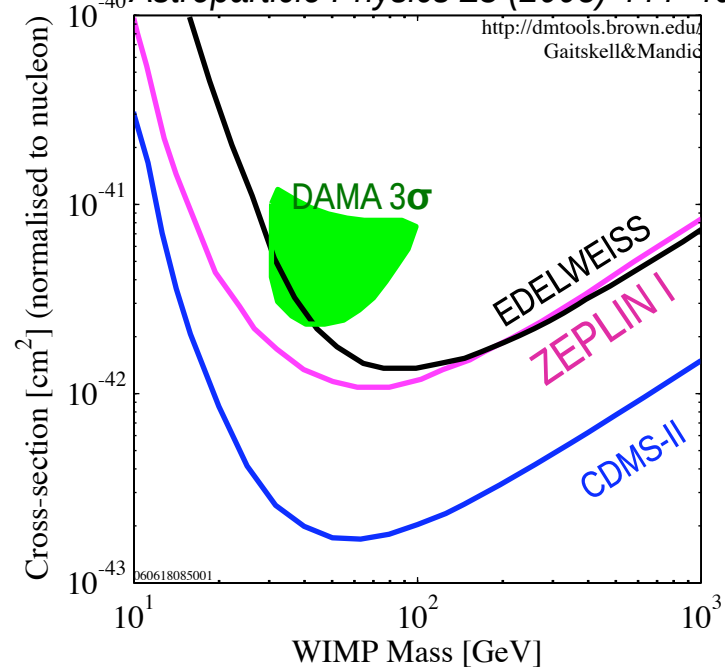


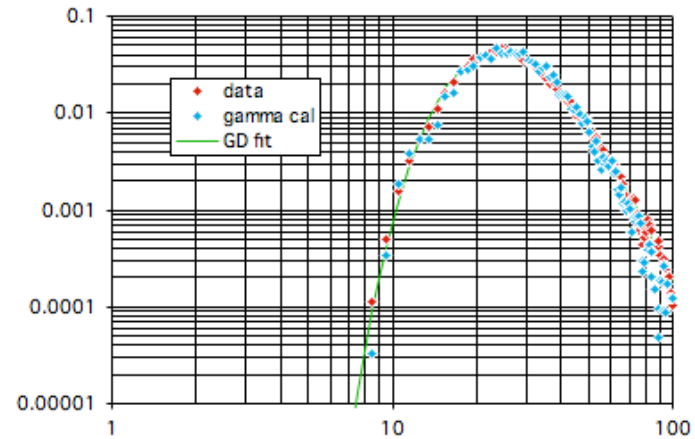
Pulse shape

Zeplin I: DM limit on Xenon target

- 230 kg-days in 3.1-kg fiducial mass
  - Gamma calibration data from contemporaneous veto events
  - Systematics dominated — no in situ neutron calibration
    - Trouble recondensing target
    - Reliance on surface-lab calibrations
- Some controversy...
  - Published critique of systematics (A. Benoit *et al.*, *Phys. Lett.* ***B637*** *(2006) 156-160*)
    - challenges assumptions of event populations used to limit excess nuclear recoils
  - Formal response in preparation
- Program evolved to 2-channel technique...

Astroparticle Physics ***23*** *(2005) 444–462*

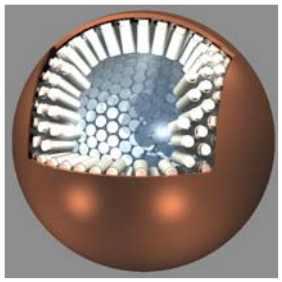


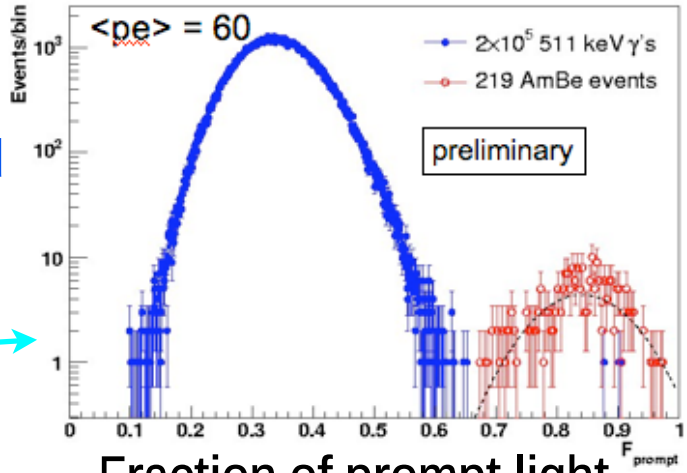


Pulse shape

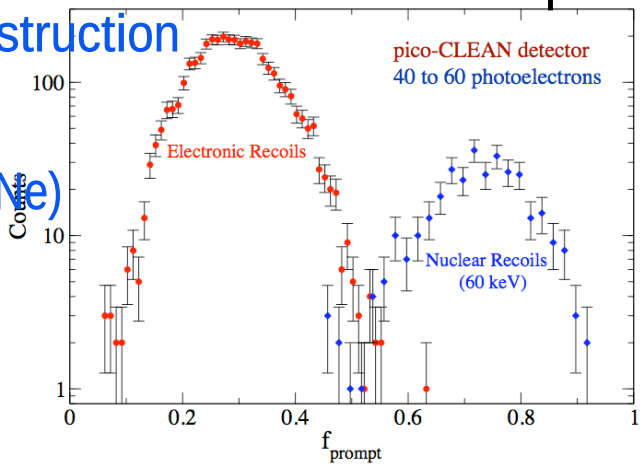
Current Single-phase projects in Xe, Ar, Ne

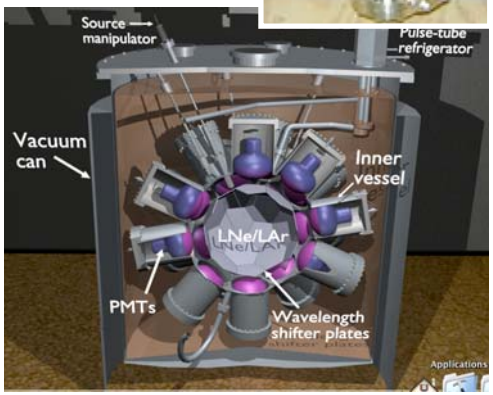
- Pulse-shape discrimination and/ or self-shielding
- XMASS
  - Self-shielding of LXe
  - 100-kg prototype: clean fiducial volume *limited* by misreconstructed wall events ➜ PTFE light guides
  - Next: Larger spherical detector
- DEAP
  - PSD in 1-kg prototype (LAr)
  - DEAP-1 (10 kg) under construction
- CLEAN
  - PSD in 200-g prototype (LNe)
  - 4-kg w/2-PMT (LAr & LNe)





Fraction of prompt light

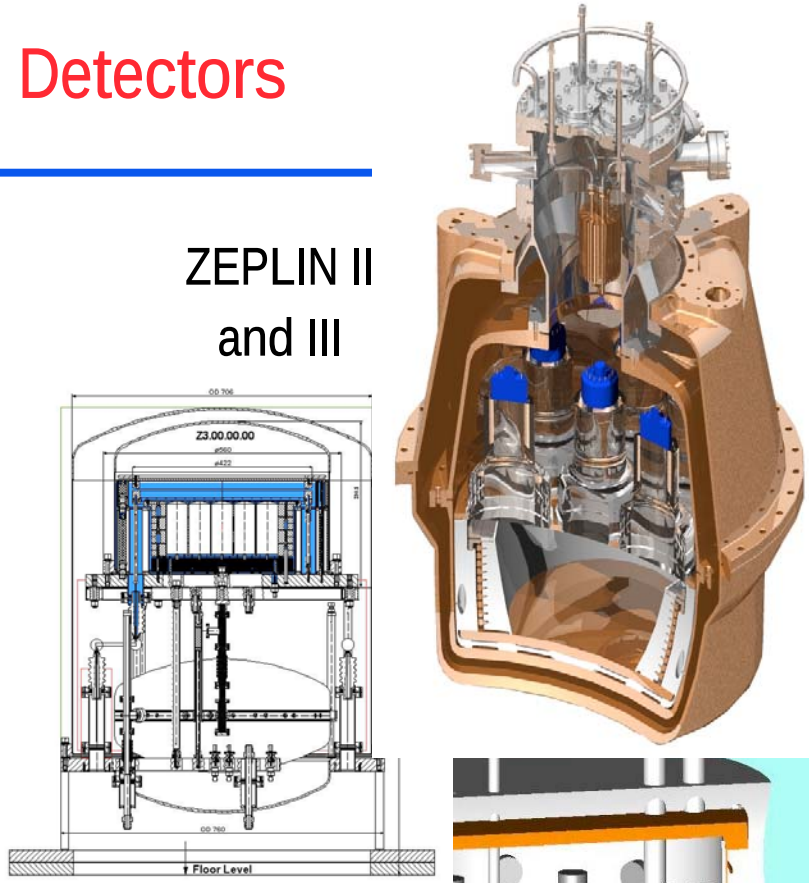


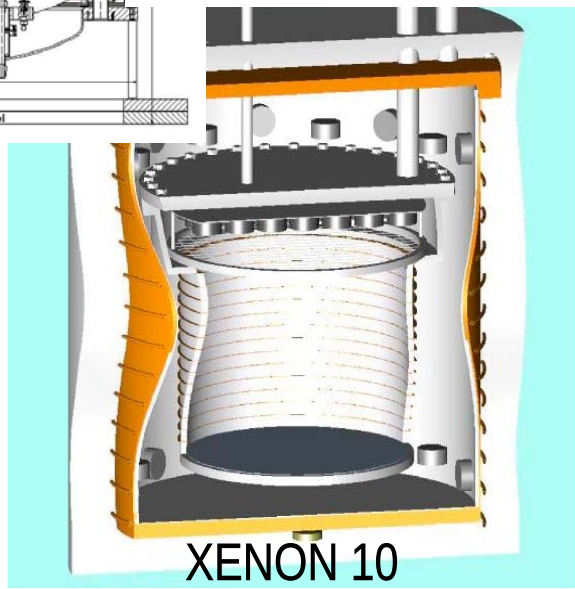


Two-phase Xenon Detectors

- Active technical explorations
  - variety of light/charge collection schemes
    - PMTs in liquid or gas
    - Immersed photocathode
  - Drifted charge gives smaller secondary electroluminescence for NR's
  - high voltage generation
  - ^{87}Kr purification schemes
- ZEPLIN II - taking data at Boulby
  - 30-kg target mass
  - 7 PMTs in gas phase
- ZEPLIN III - constructed
  - 6-kg target mass w/high (<8kV/cm) fields
  - 36 PMTs in liquid (defeat internal reflection)
- XENON 10 - taking data at LNGS
  - 15-kg target mass
  - 89 low-bkg PMTs in gas phase

ZEPLIN II and III



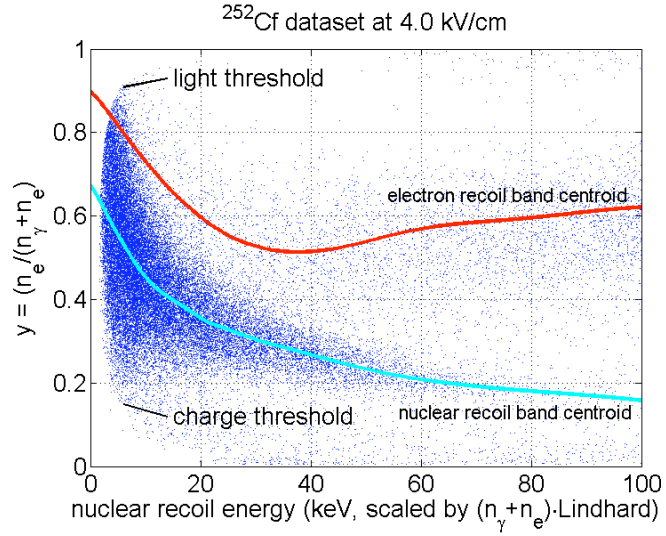


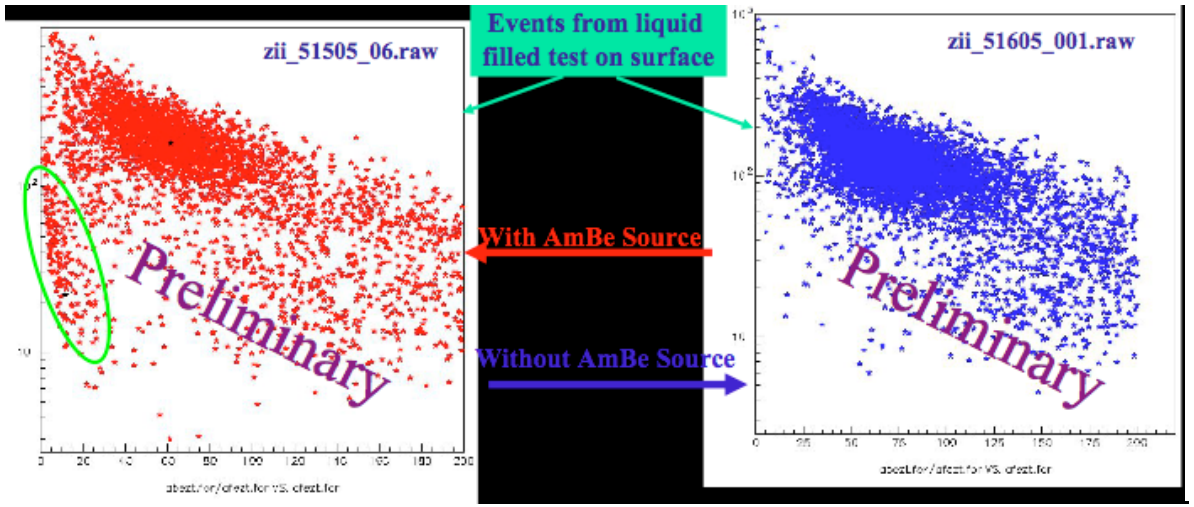
XENON 10

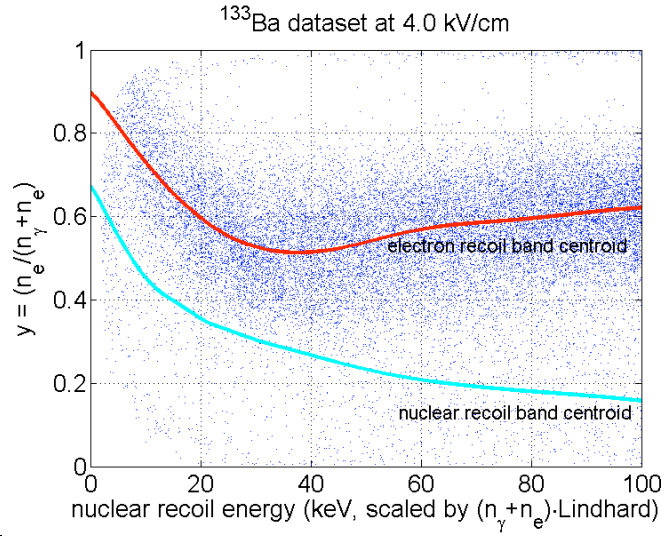
Two-phase Xenon: discrimination/performance

- Recoil discrimination at low energy
- XENON-10
  - prototype data ~99% rejection at 5 keV
  - Full XENON-10 characterization in progress
- Zeplin-II
  - Recoil discrimination in full-detector operation in Boulby

...stay tuned!



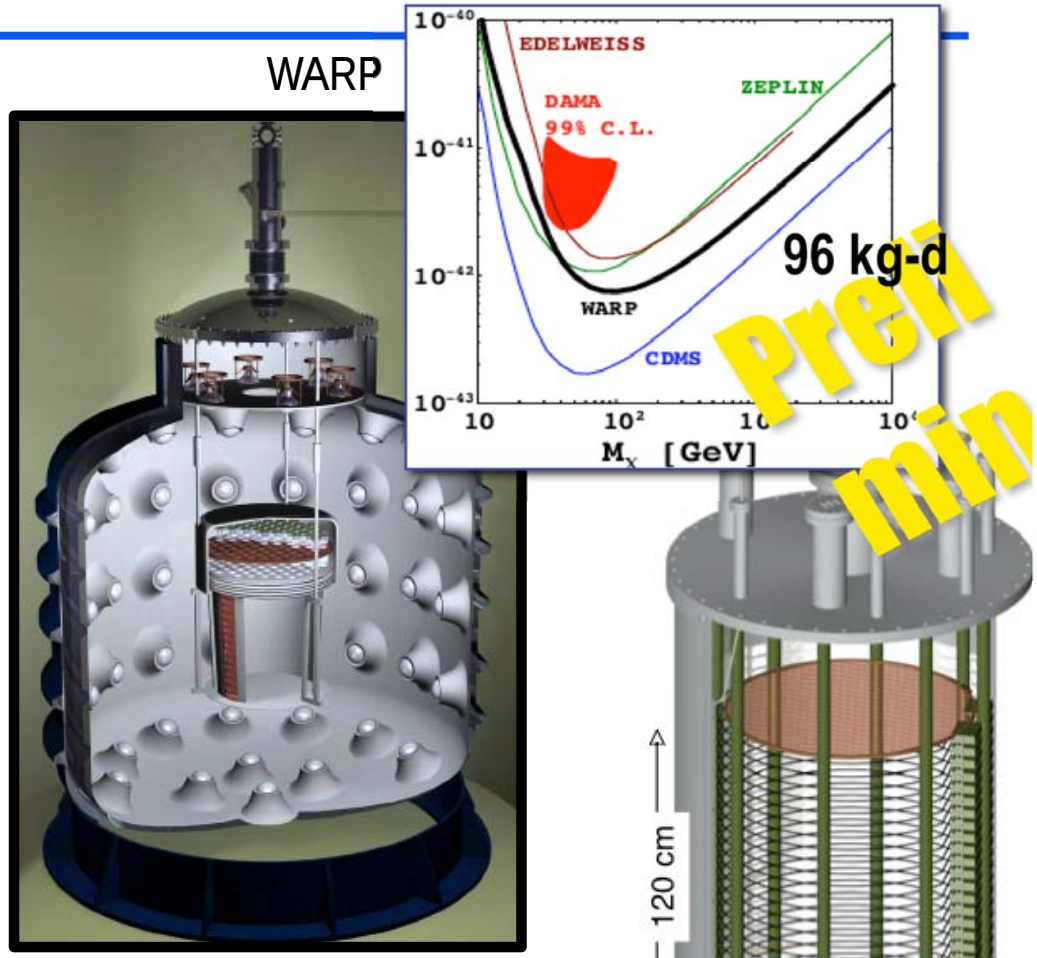




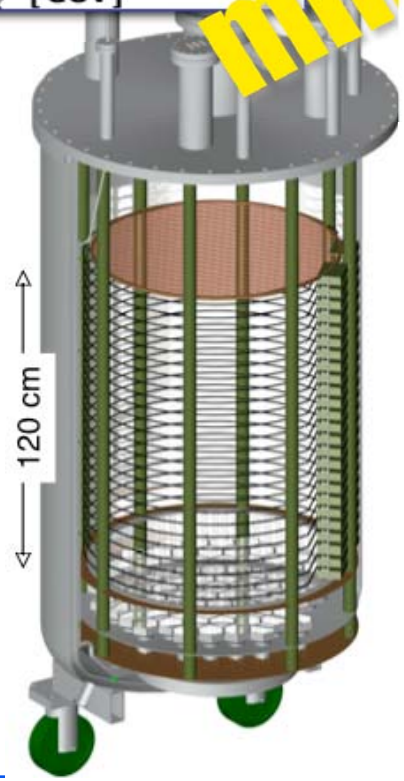
Two-phase Argon Detectors: WARP and ArDM

- PSD and secondary scintillation from ionization drift
- WARP
  - 3.2 kg prototype running at Gran Sasso
  - Preliminary results reported
  - 100-kg detector w/800-kg active veto under construction
- ArDM
  - LEMs for ionization readout
  - PMTs for primary scintillation
  - 1 ton prototype in construction

WARP



100-l detector

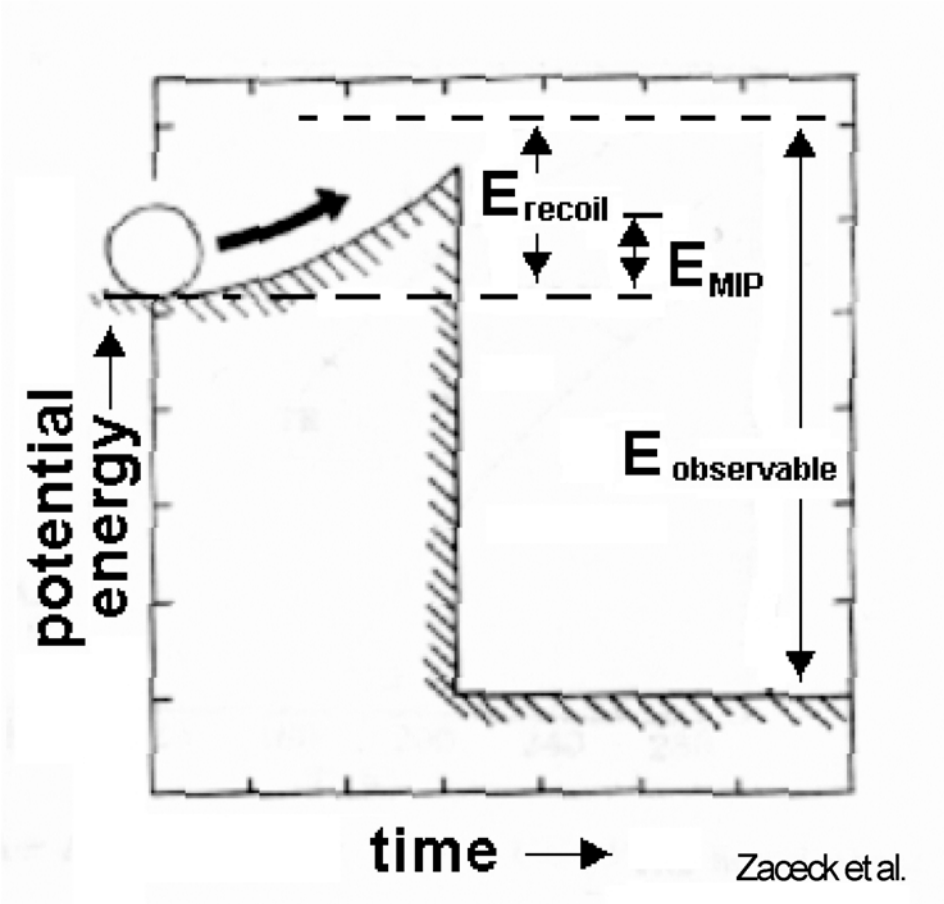


ArDM

G. Fiorillo and S. Navas: next session

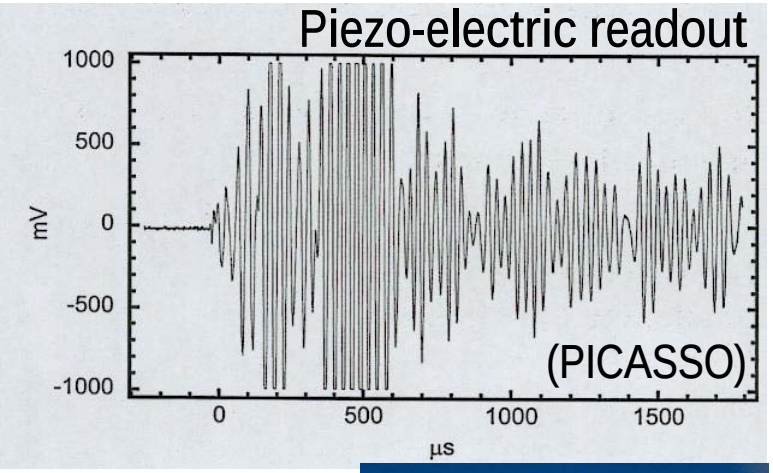
Superheated liquids: immune to EM backgrounds

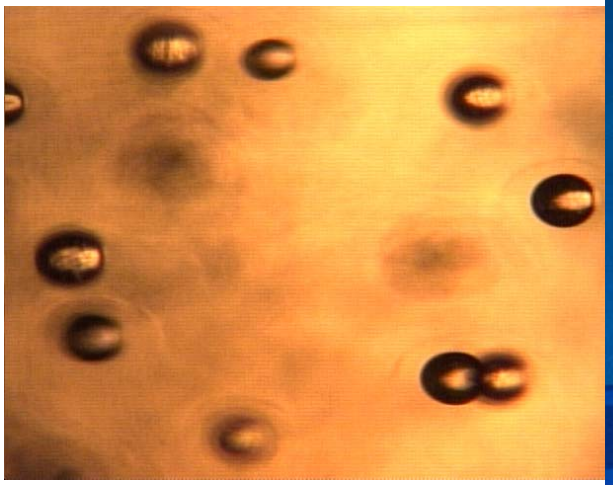
- Principle: Superheated liquid
  - Requires nucleation energy to overcome surface tension and form bubble
  - Tune thermodynamic parameters
    - Insensitive to min. ionizing and low-energy electron recoils
    - Sensitive to higher-energy-density nuclear recoils
  - Threshold detector - release of stored energy enhances observability



Superheated Droplet Detectors: PICASSO and SIMPLE

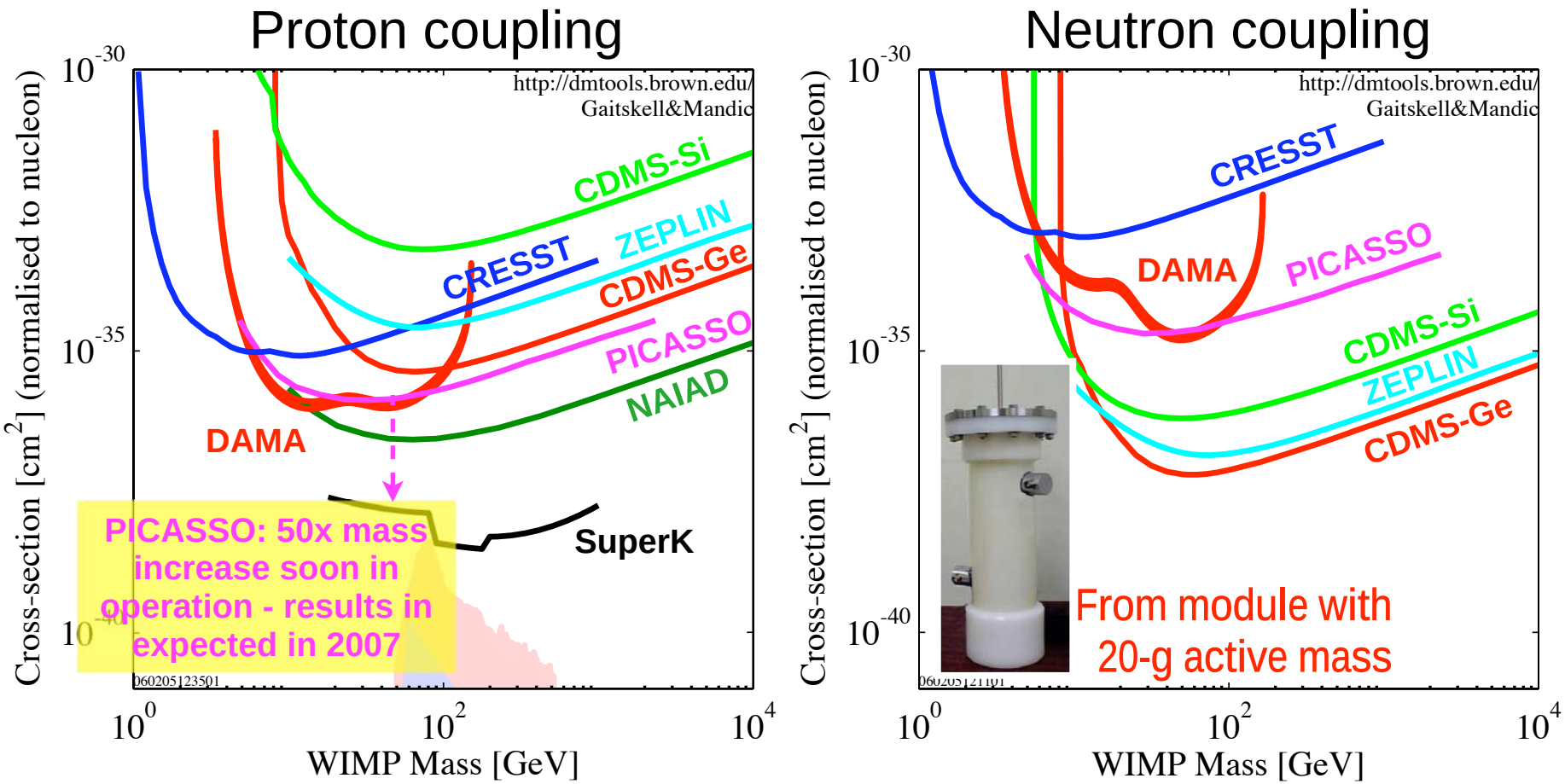
- Superheated droplets, eg, freon, in a passive gel matrix – neutron dosimetry
  - Only high-ionization energy density tracks – nuclear recoils, alphas – sufficient to cause nucleation (droplet explosion)
  - Insensitive to gammas, betas, & minimum ionizing particles
  - Freon: ^{19}F – high ***SD*** coupling
- Challenges
  - Energy information – vary temperature in threshold detector
  - Develop large-A nucleus for spin-independent coupling
  - Mass scale up
  - Radiopurity of gel matrix (alphas)





microscopic bubble chambers

PICASSO Spin-Dependent WIMP limits

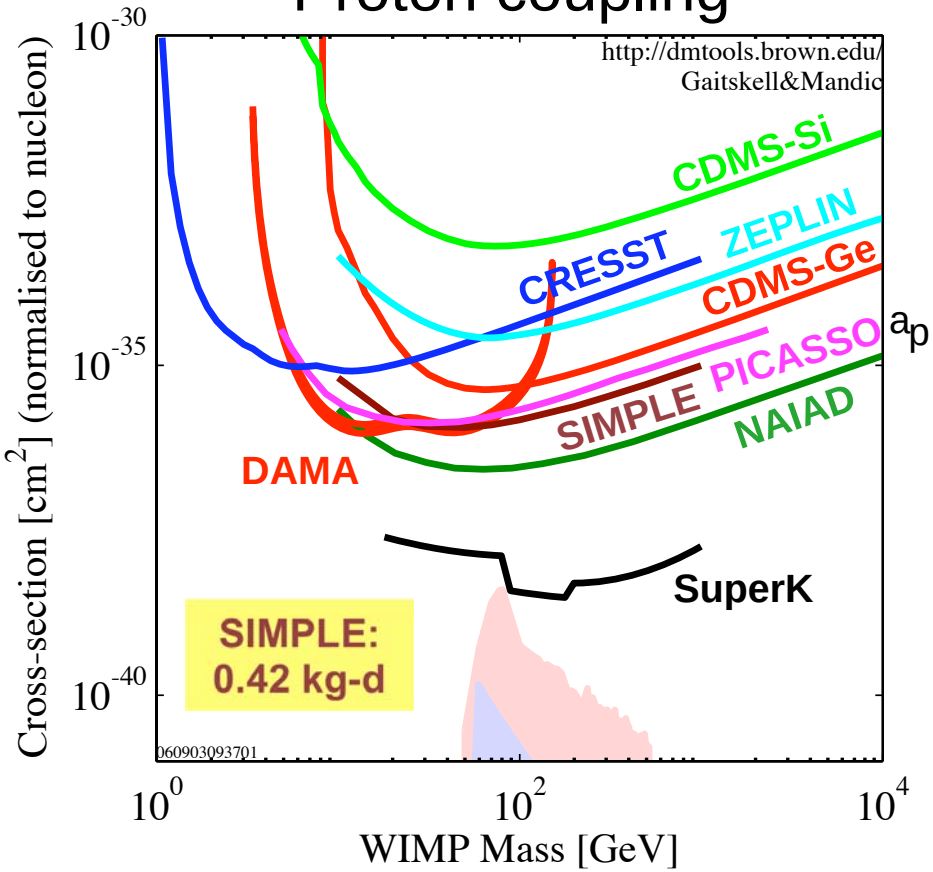


When spin independent coupling suppressed, rate dominated by axial coupling to unpaired nucleon

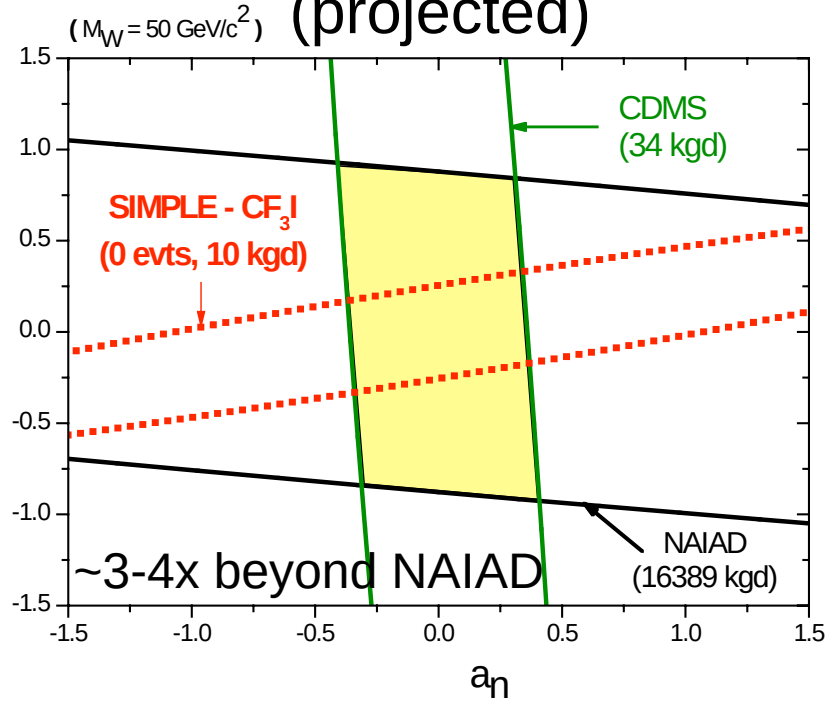
(DAMA regions from Savage, Gondolo and Freese)

SIMPLE Spin-Dependent WIMP limits

Proton coupling



Model independent (projected)



Goal is 30-100 kg-d C_2ClF_5 exposure in 2007, and further development towards 10 kg-d CF_3I

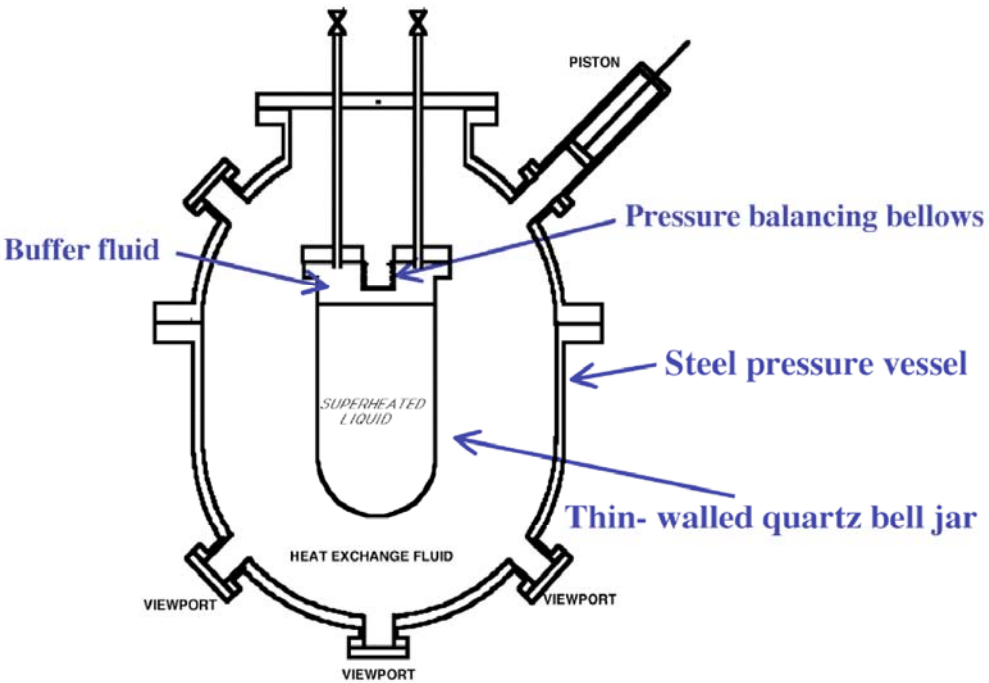
When spin independent coupling
by axial coupling to unpaired nu

SIMPLE & PICASSO – technical exchanges, and MOU for joint for scale-up

(DAMA regions from Savage, Gondolo and Freese)

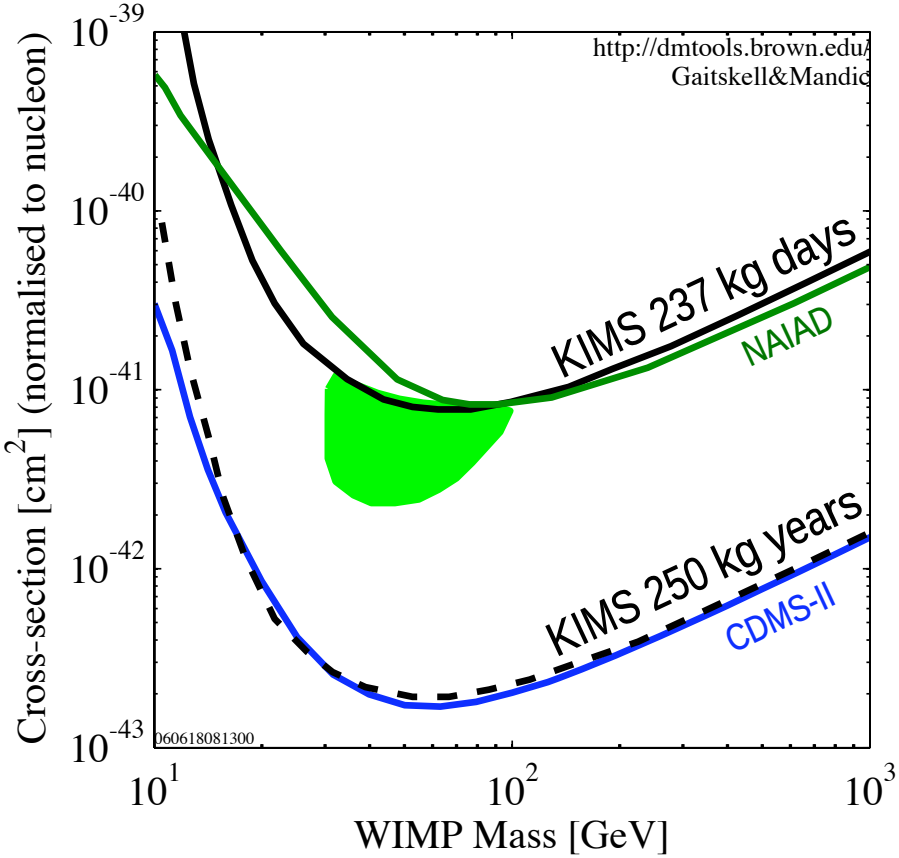
COUPP: Bubble Chamber Revival

- 2-kg CF_3I Bubble Chamber – Univ. of Chicago and Fermilab
- Tune thermodynamic parameters — immunity to elec. recoils: 10^9 gamma rejection!
- Two principal challenges:
  - passivate nucleation from vessel walls ⇒ trigger rate ~ laboratory neutron background ✔
  - internal alpha backgrounds - work in progress



KIMS Experiment: CsI(Tl)

- Korea Invisible Mass Search
- Similar to DAMA but CsI
- Success in reducing intrinsic radiocontaminants
  - ^{137}Cs - water purity during prep
  - ^{87}Rb - reduced through repeated re-crystalization
- 6.6 kg prototype results
- Running 35 kg array
  - bkg ~5 cts/(keV kg day)
- Building 100 kg array
  - target of 2 cts/(keV kg day)
- Cross check of DAMA
  - SD couplings
  - annual modulation

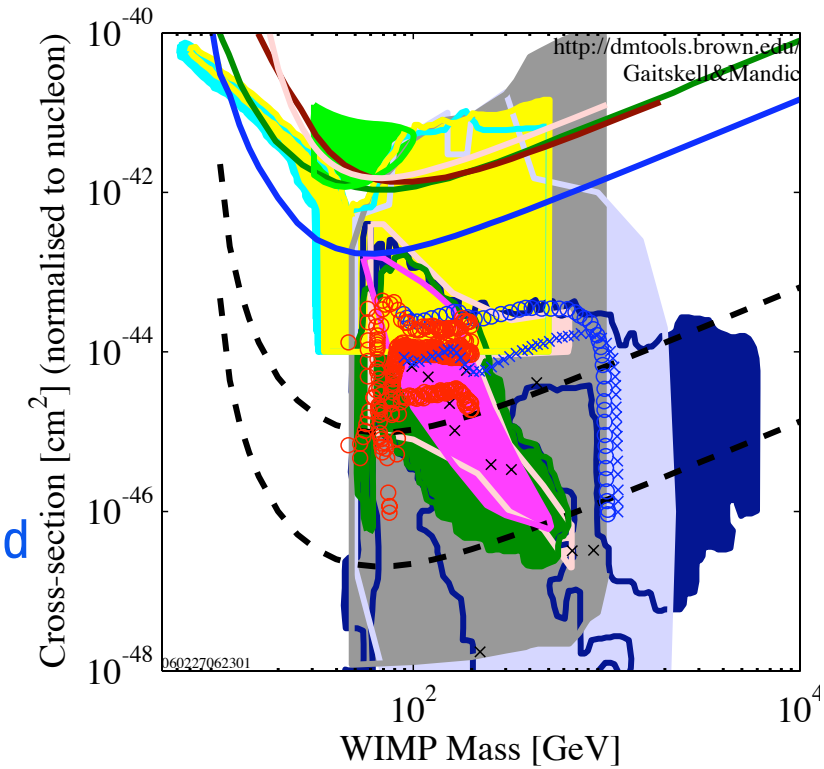


Phys. Lett. ***B633*** *(2006), 201-208*

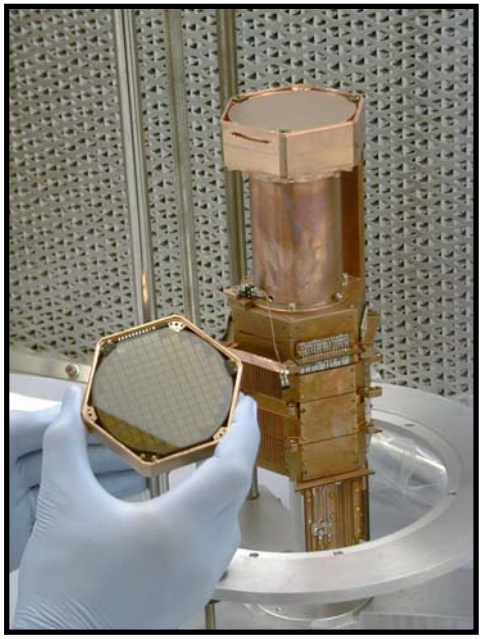
S.K. Kim's talk in next session

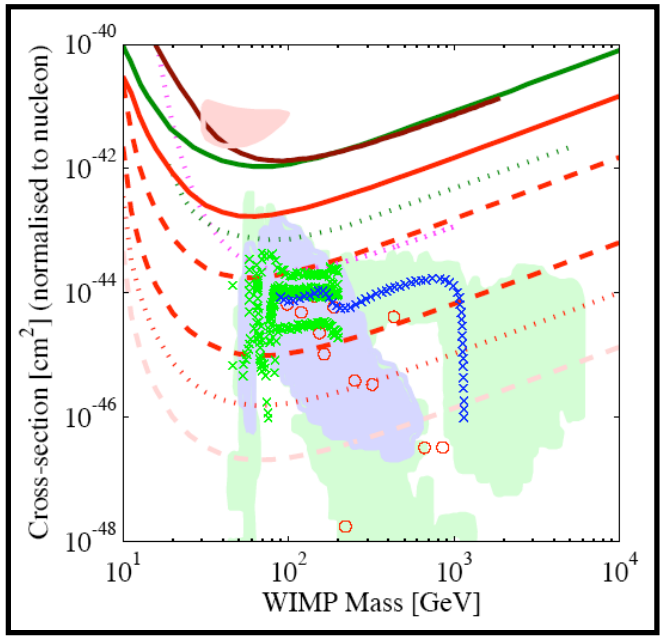
Summary

- Dark matter remains a fundamental mystery
  - Possible solution lies in new fundamental particle physics
    - Establishing a concordant model requires laboratory and astrophysical meas.
      - particle mass, lifetime, relic density, halo
  - Astro. signal from annihilation products
- Significant recent advances in sensitivity
  - Cryogenic expts poised for next data runs
  - Critical demonstrations of liquid nobles and other new technologies
  - Cross check of DAMA nearly complete
  - Followup with directional detectors (eg, DRIFT) - galactic origin
  - Next 5-10 years looks very exciting!



Thank you…




Cross-section [cm^2] (normalised to nucleon)
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^1
10^2
10^3
10^4
WIMP Mass [GeV]