Looking for WIMP Dark Matter using Ultra-Cold Detectors and Other Techniques

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Case Western Reserve University
CDMS Collaboration

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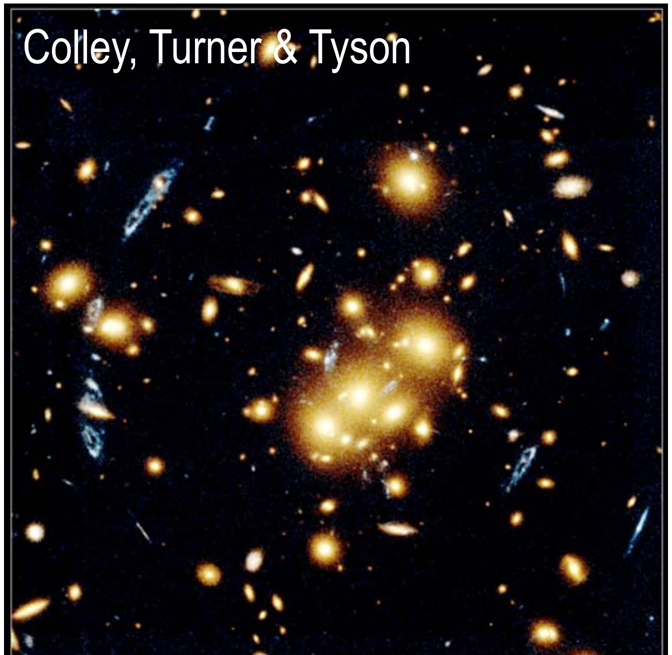
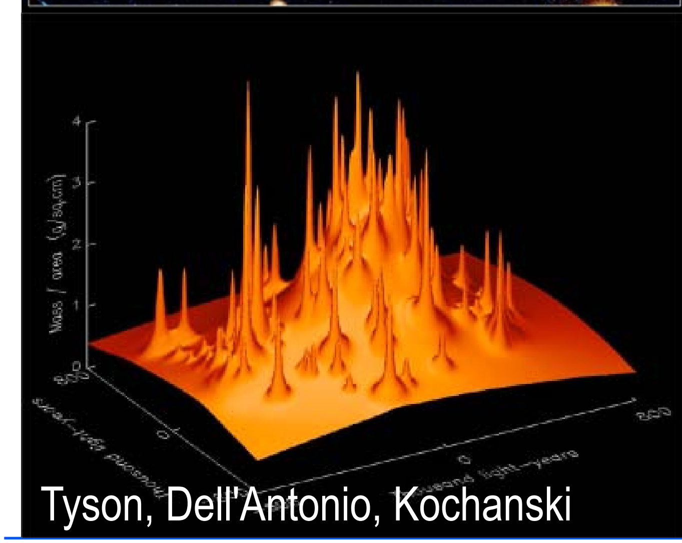
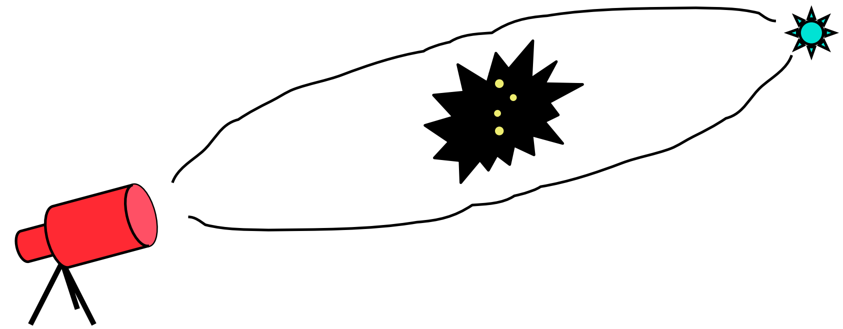
15 April 2007

Dynamical Evidence: Galaxy clusters





Clusters – 1-10 Mpc



Independent methods:

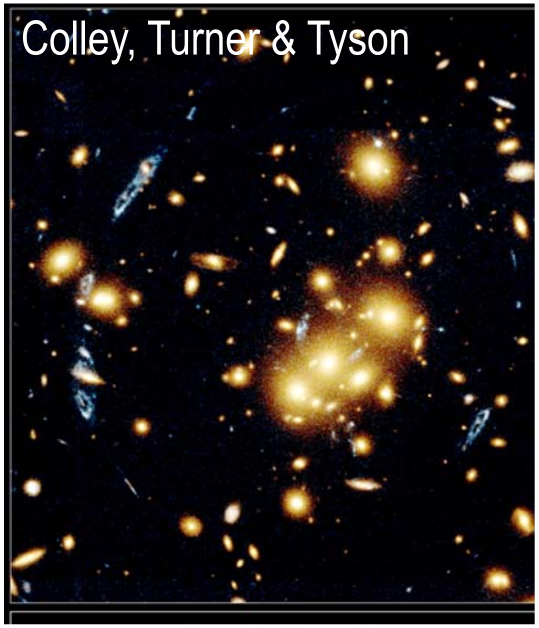
- **Lensing**
- **Virial thm:** $\langle T \rangle = -\frac{1}{2}\langle U \rangle_{dyn}$
- **X-rays from bound gas**

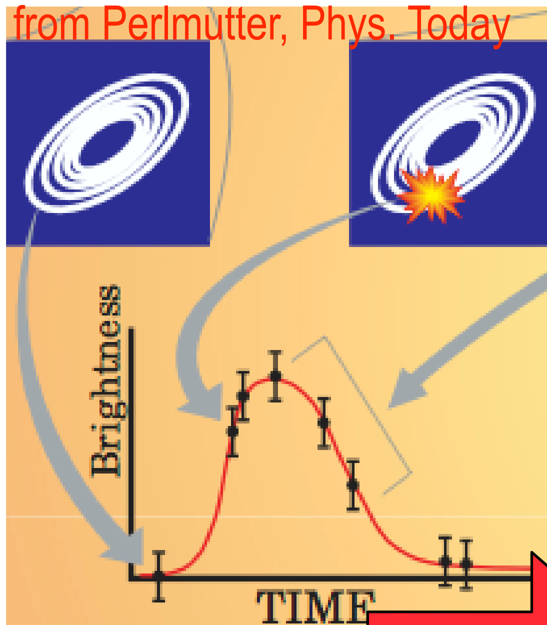
→ $\Omega_m = \rho/\rho_{crit} = 0.30 \pm 0.03$

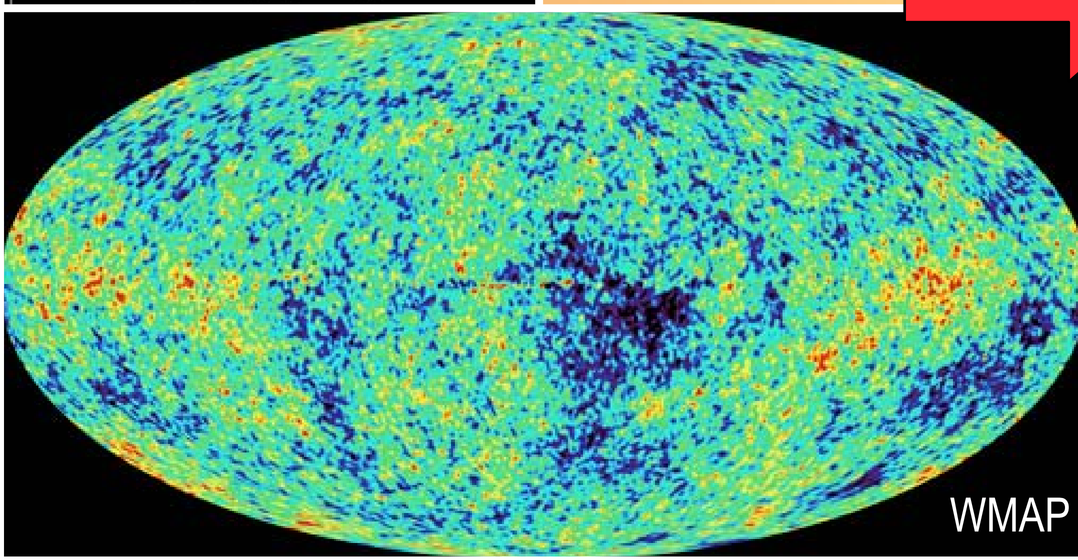
→ dark matter dominates

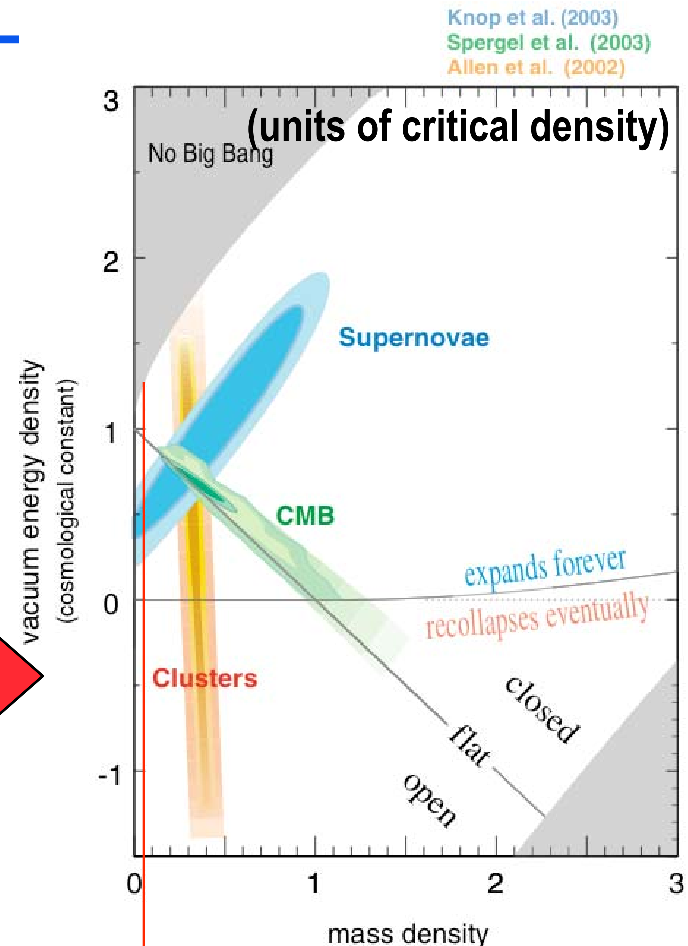
$\rho_{dark} > 30\ \rho_{lum}$

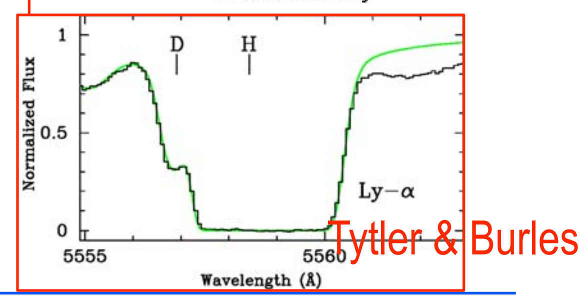
Standard Cosmology





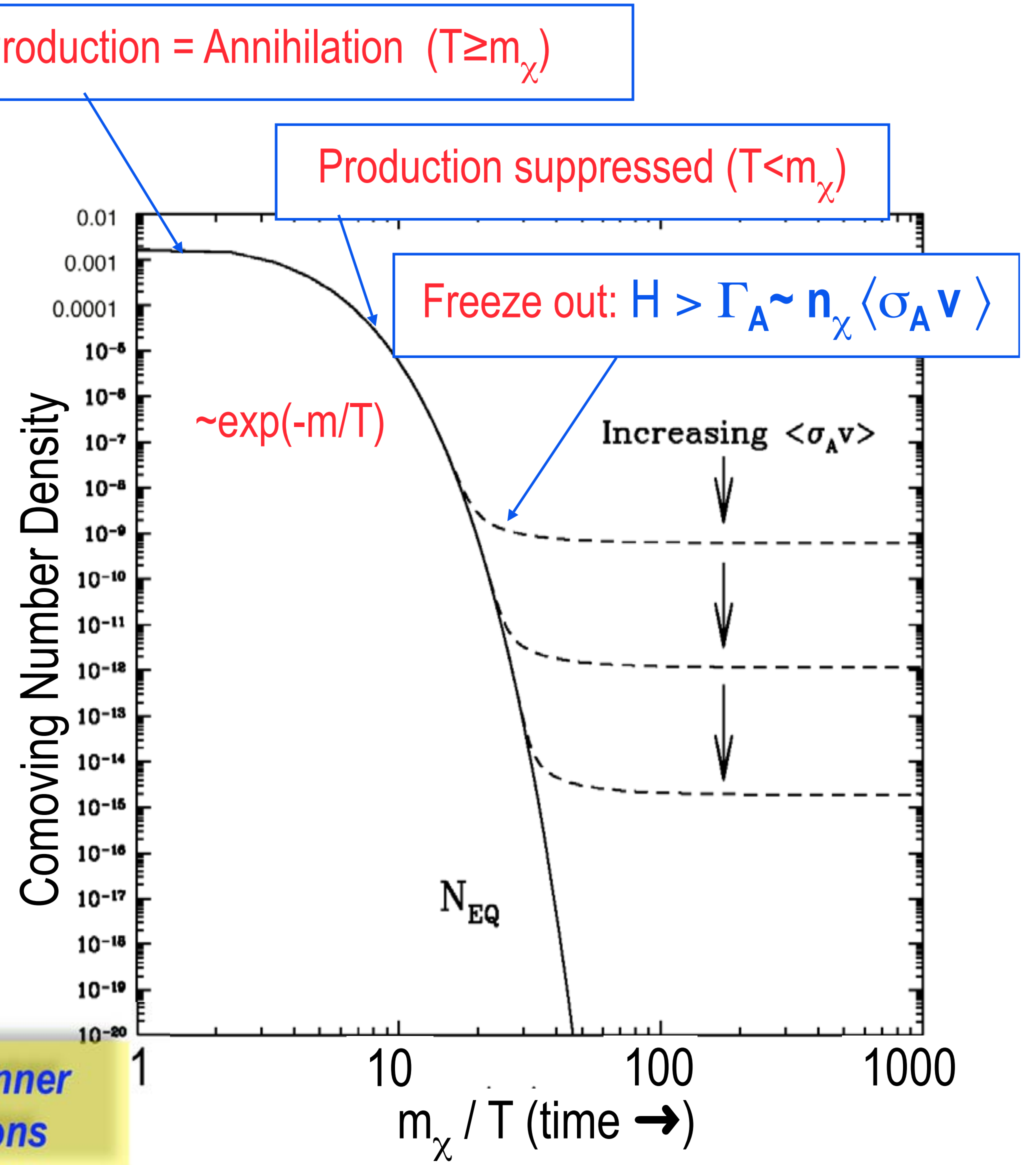






Non-Baryonic Dark Matter

- **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



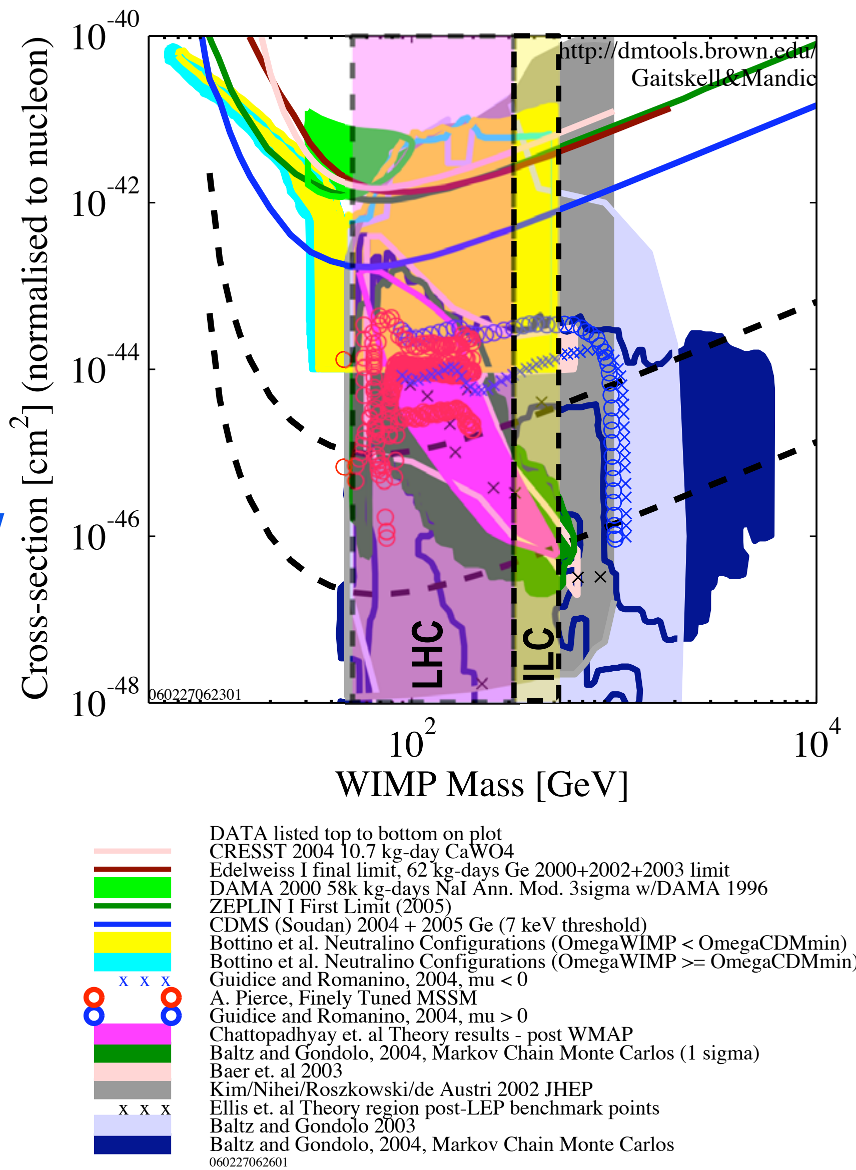
SUSY/LSP

D. Tanner Axions

SUSY Dark Matter: elastic scattering cross section

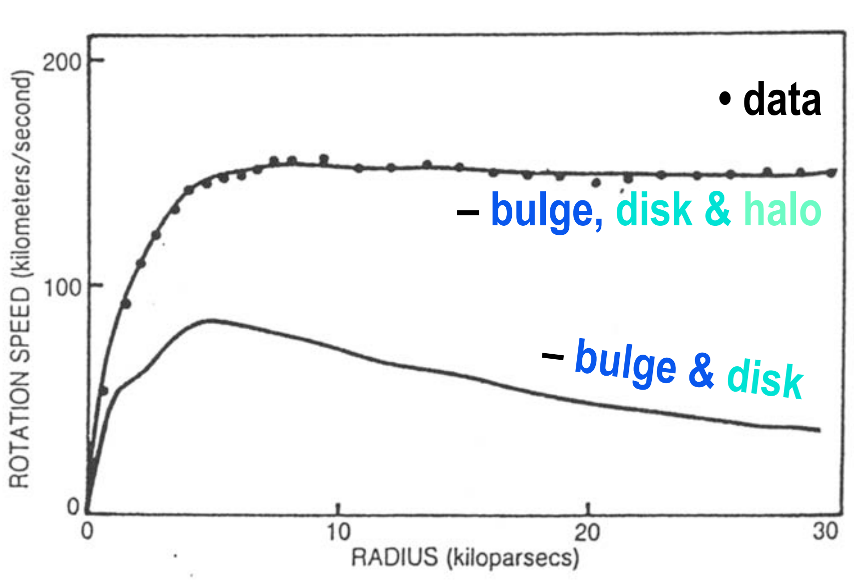
- The 'standard' progress plot
  - Direct-search experimental bounds
- Theory
  - Sample SUSY parameter space
  - Apply accelerator and model-specific particle physics constraints
  - Apply cosmological bound on relic density

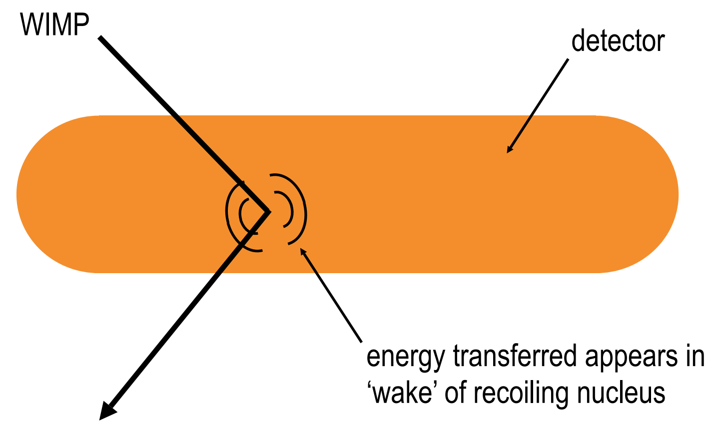
⇒ Extract allowed region for WIMP-nucleon cross-section versus WIMP mass



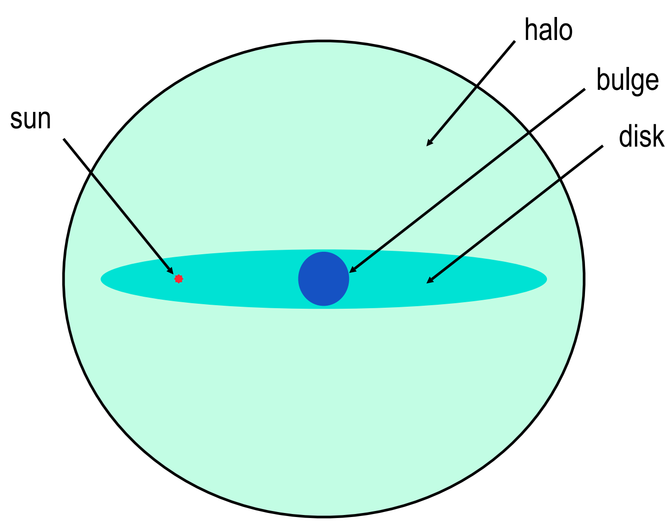
Broad theoretical landscape: much of it testable with next and next-next generation DM searches and/or next and next-next generation accelerators

WIMPs in the Galactic Halo



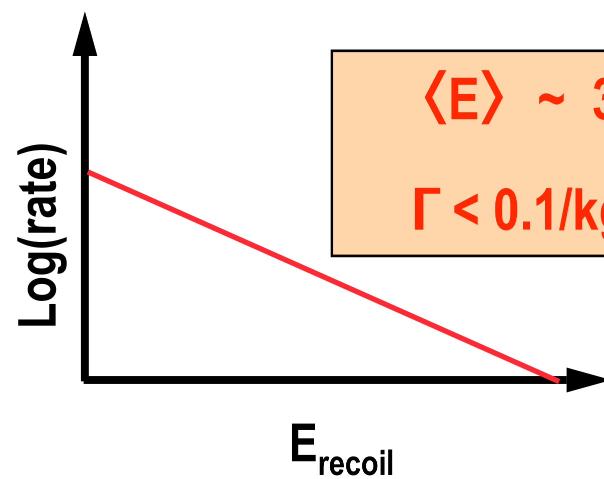


WIMP-Nucleus Scattering



The Milky Way

Scatter from a Nucleus in a Terrestrial Particle Detector

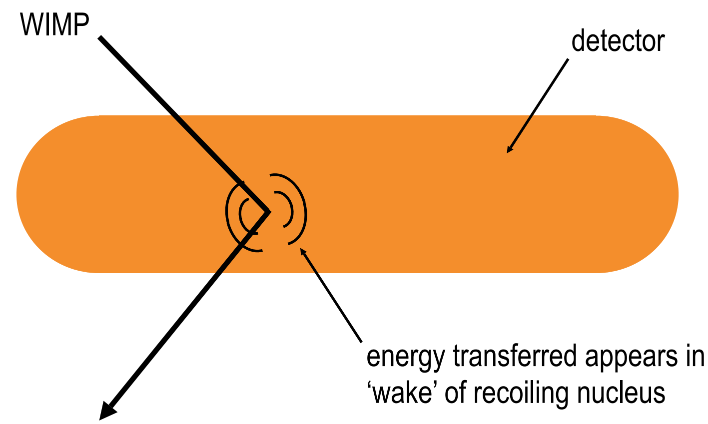


$\langle E \rangle \sim 30$ keV

$\Gamma < 0.1$/kg/day

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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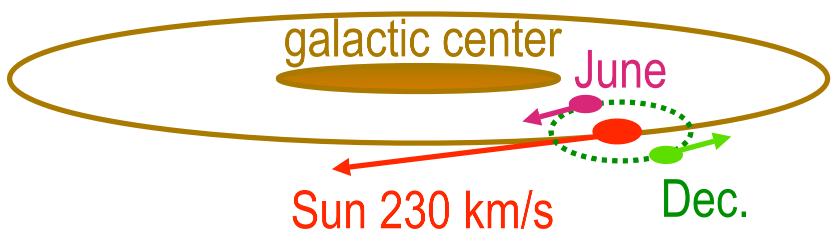

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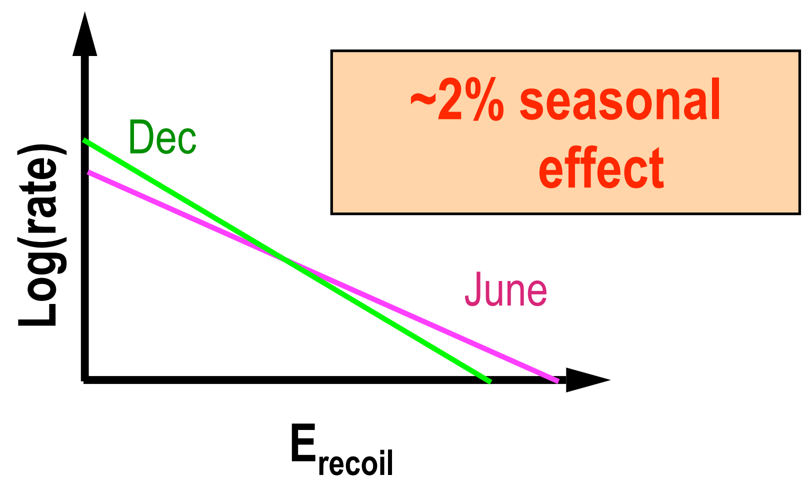
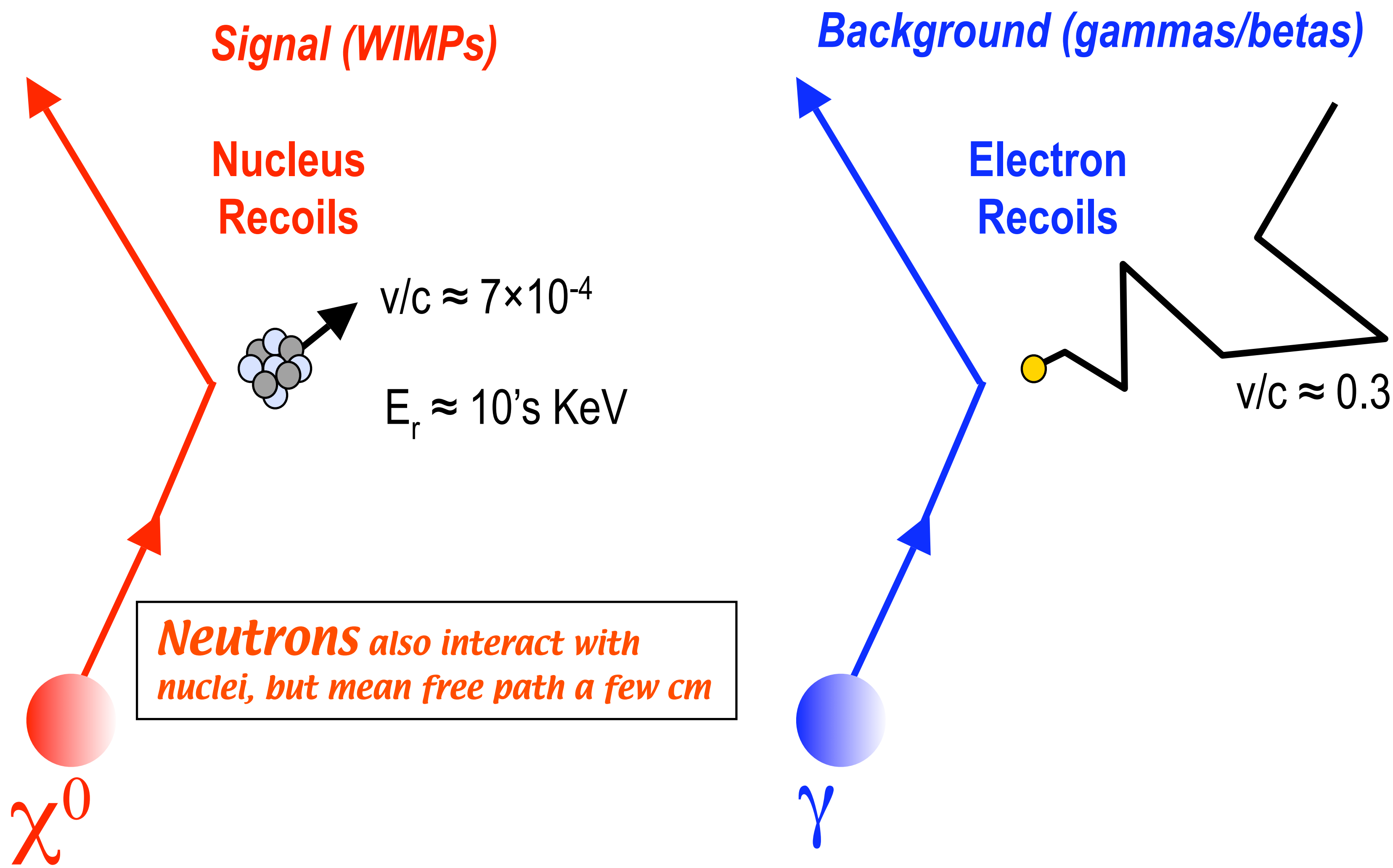
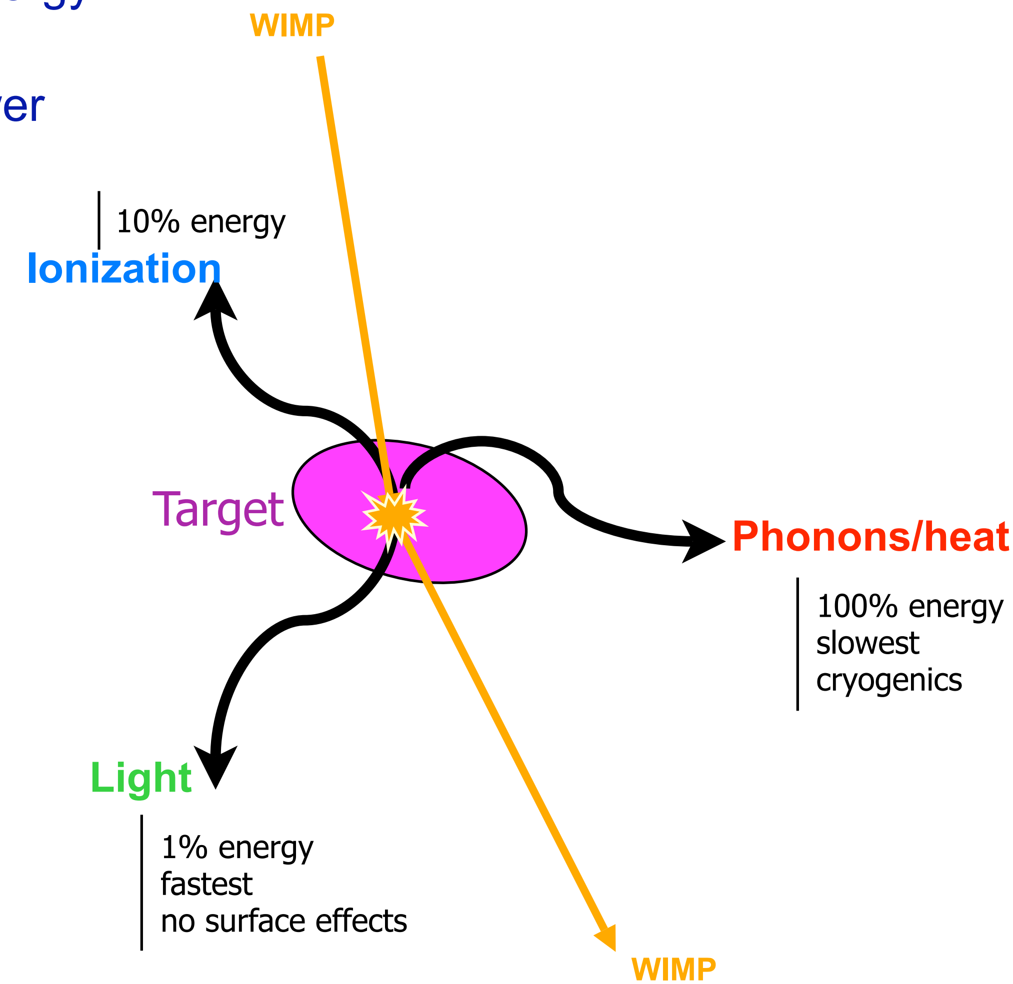


The Signal and Backgrounds



Nuclear-Recoil Discrimination

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



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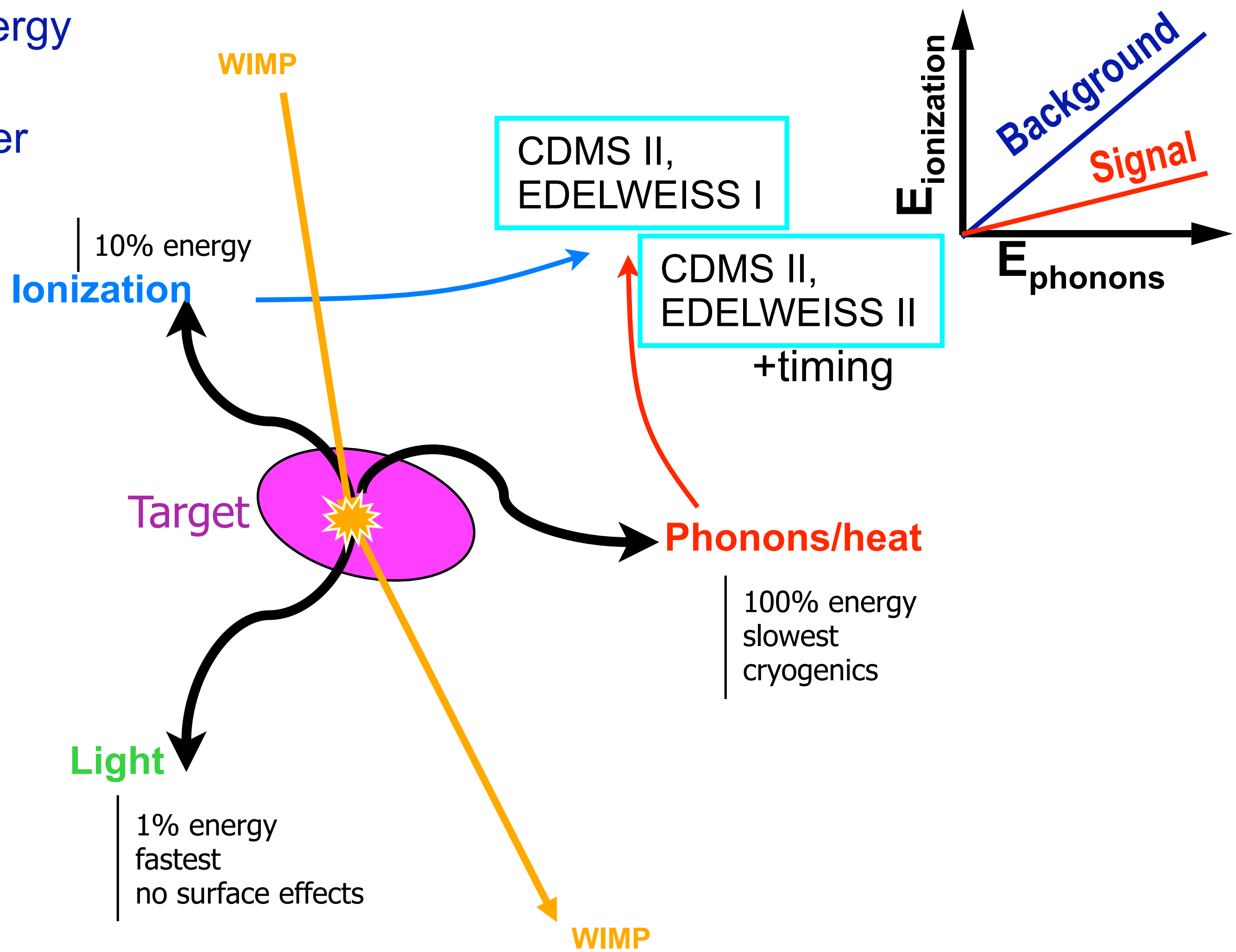

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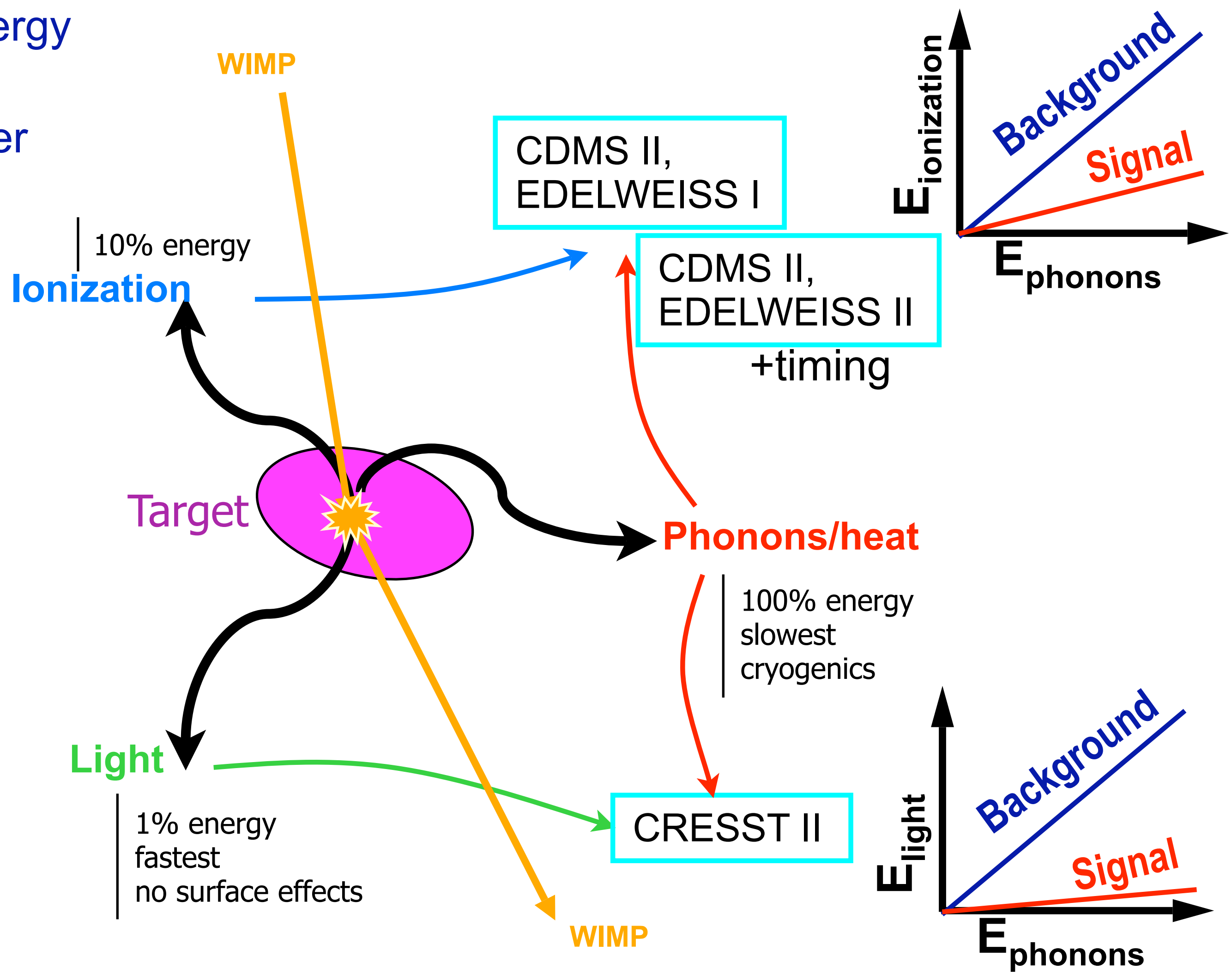

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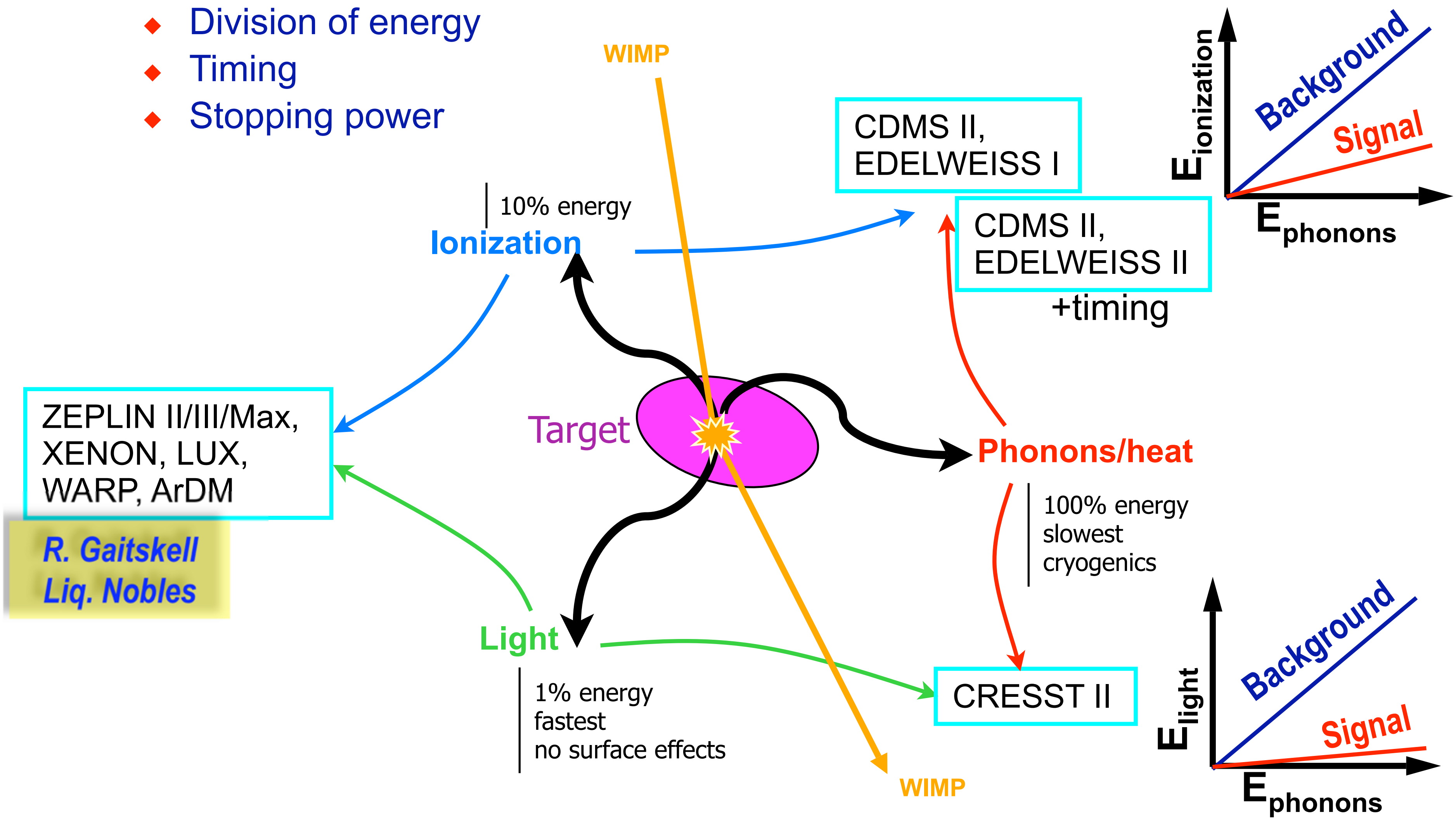

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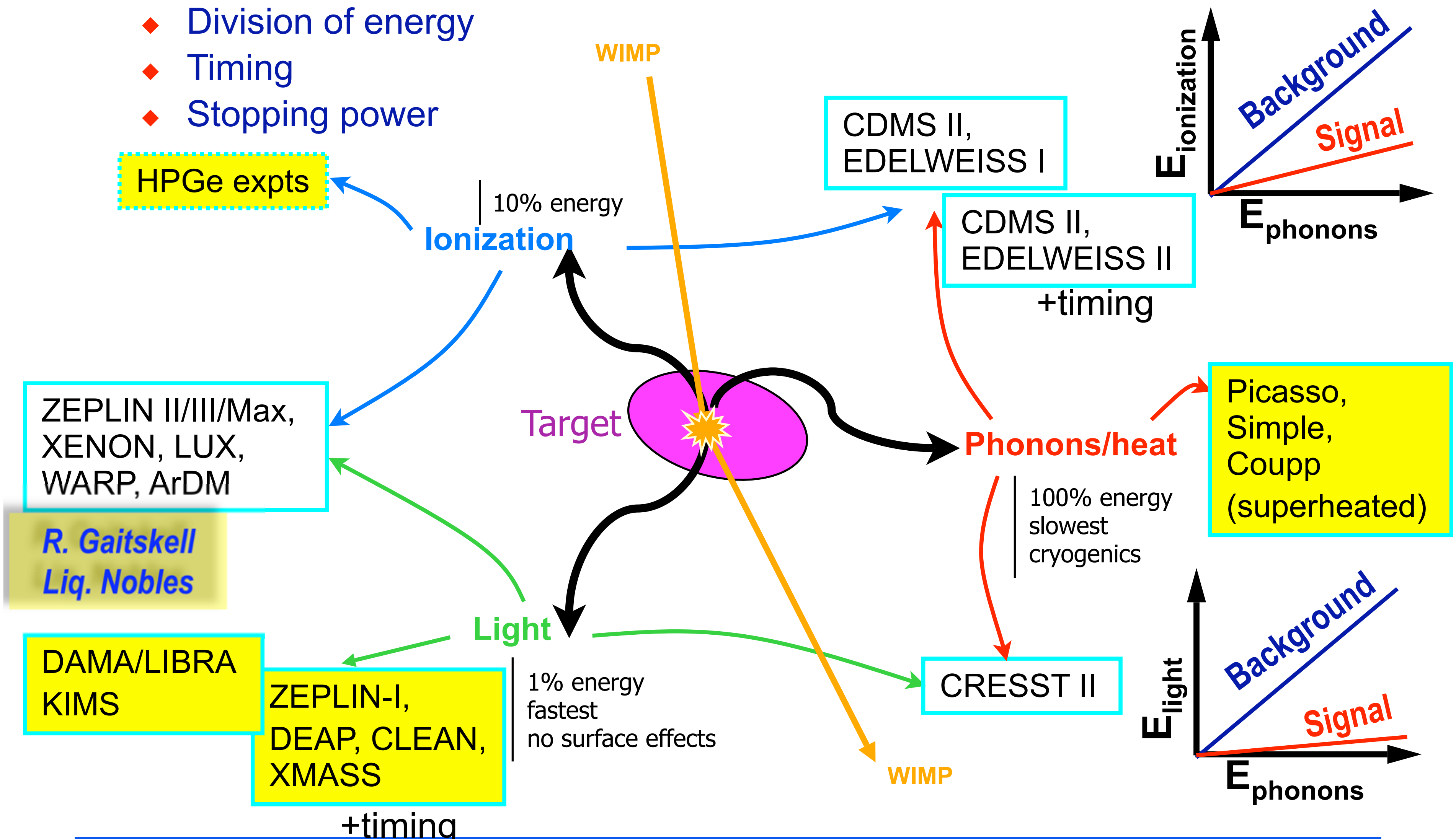


Background suppression: Recoil Discrimination

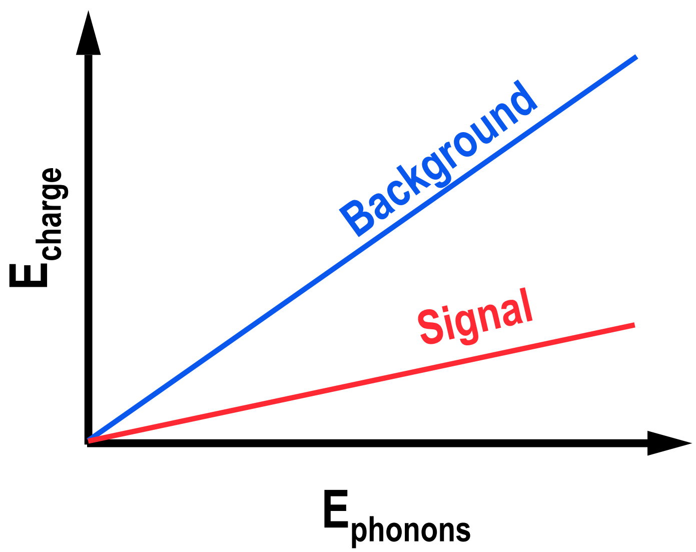
WIMPs 'look' different – recoil discrimination

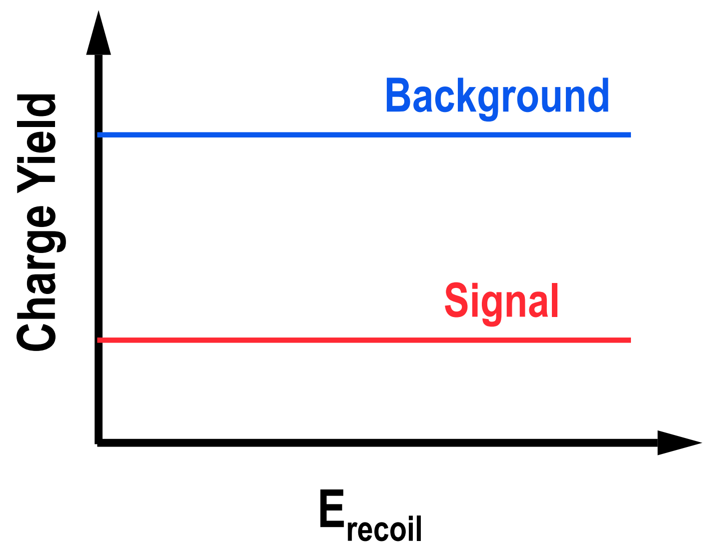
Photons and electrons scatter from electrons

WIMPs (and neutrons) scatter from nuclei

In CDMS, EDELWEISS, CRESST:

(light replaces charge)





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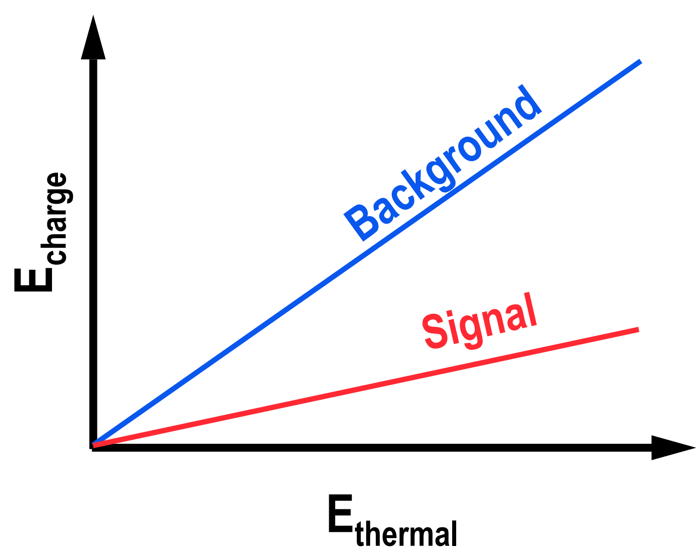
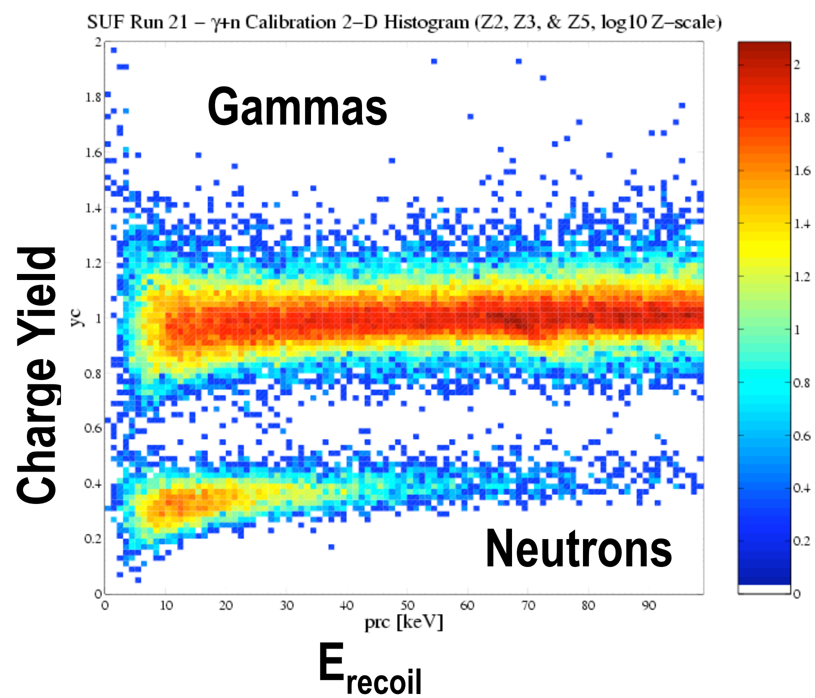
CDMS





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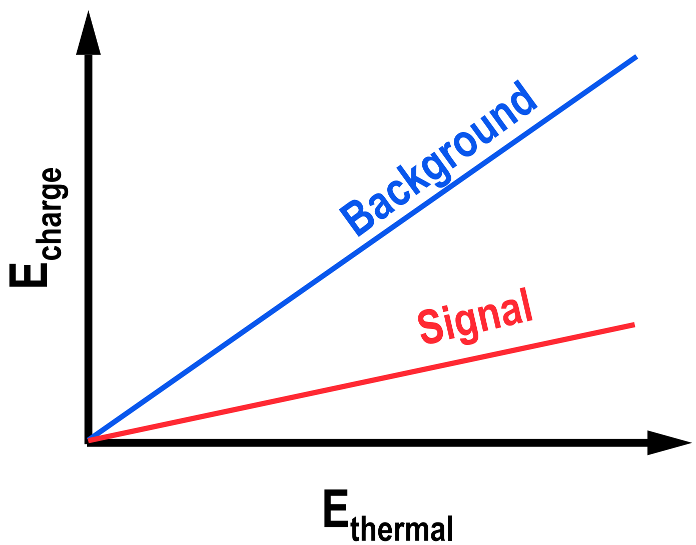
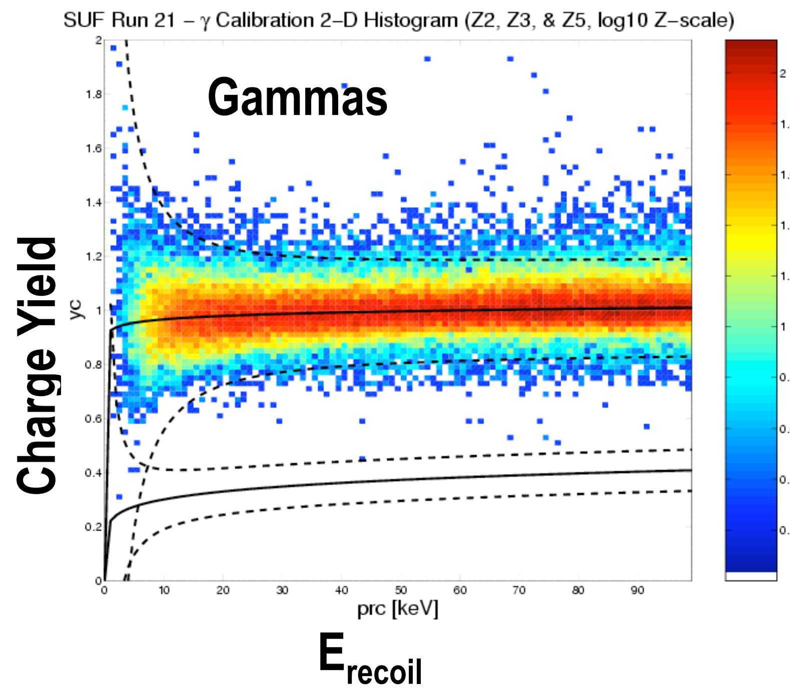


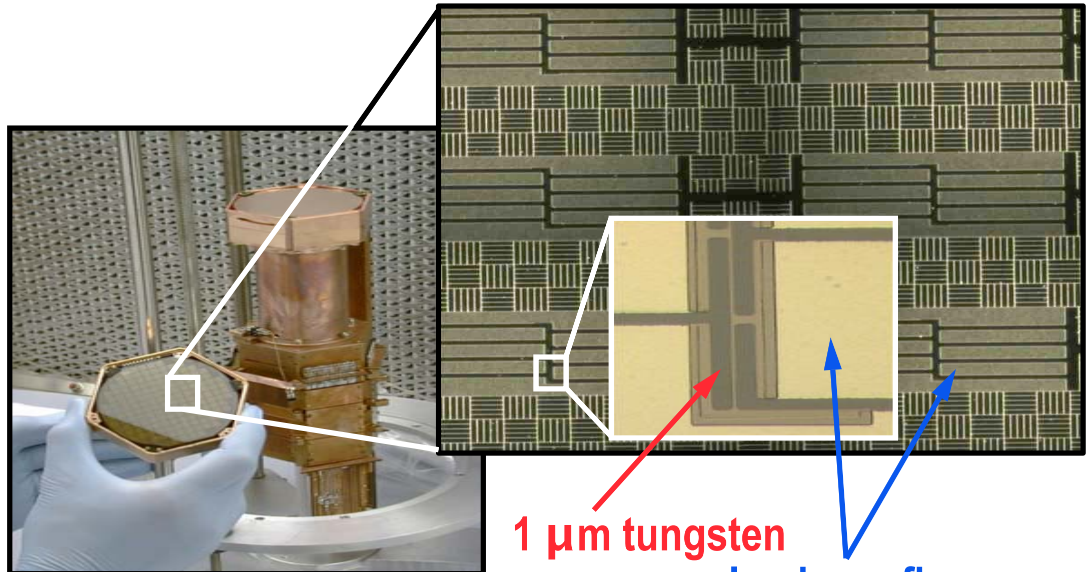
>50000:1 rejection CDMS

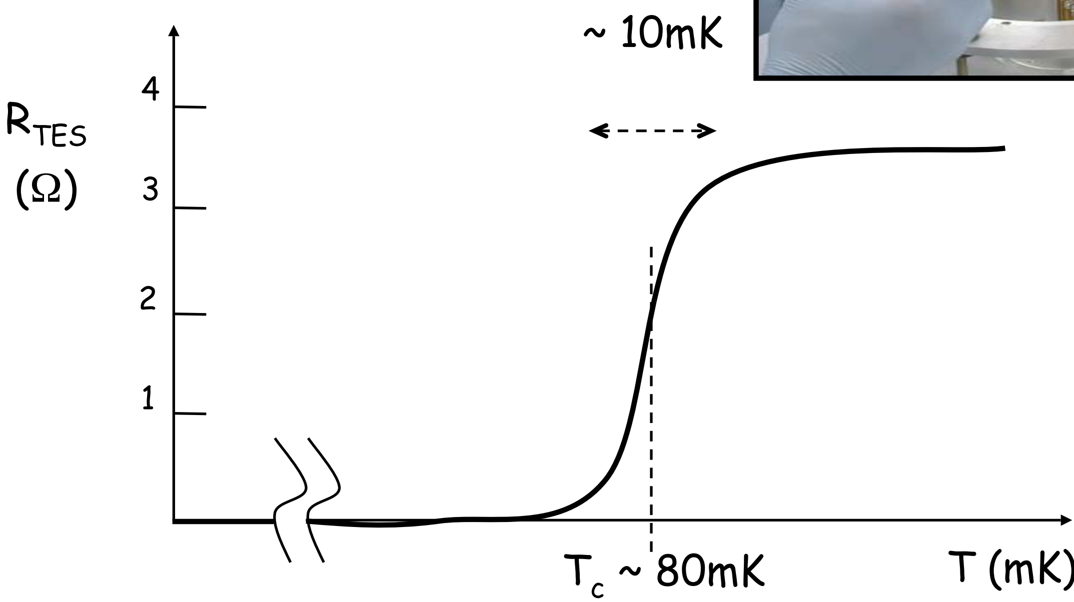


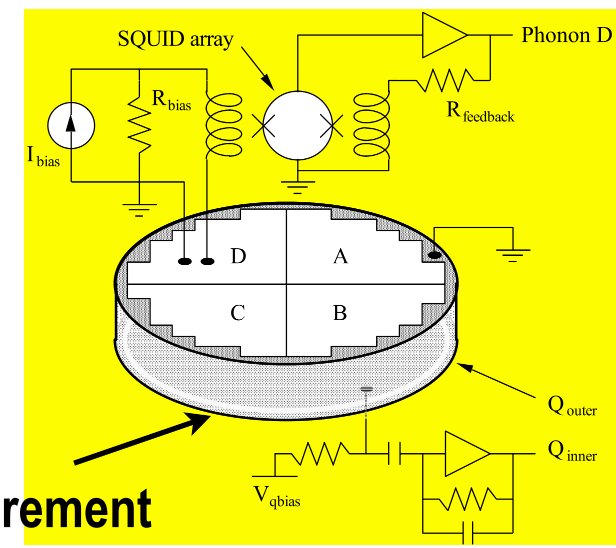
CDMS: Cryogenic “ZIP” detectors

Superconducting films that detect minute amounts of heat

Transition Edge Sensor sensitive to fast athermal phonons

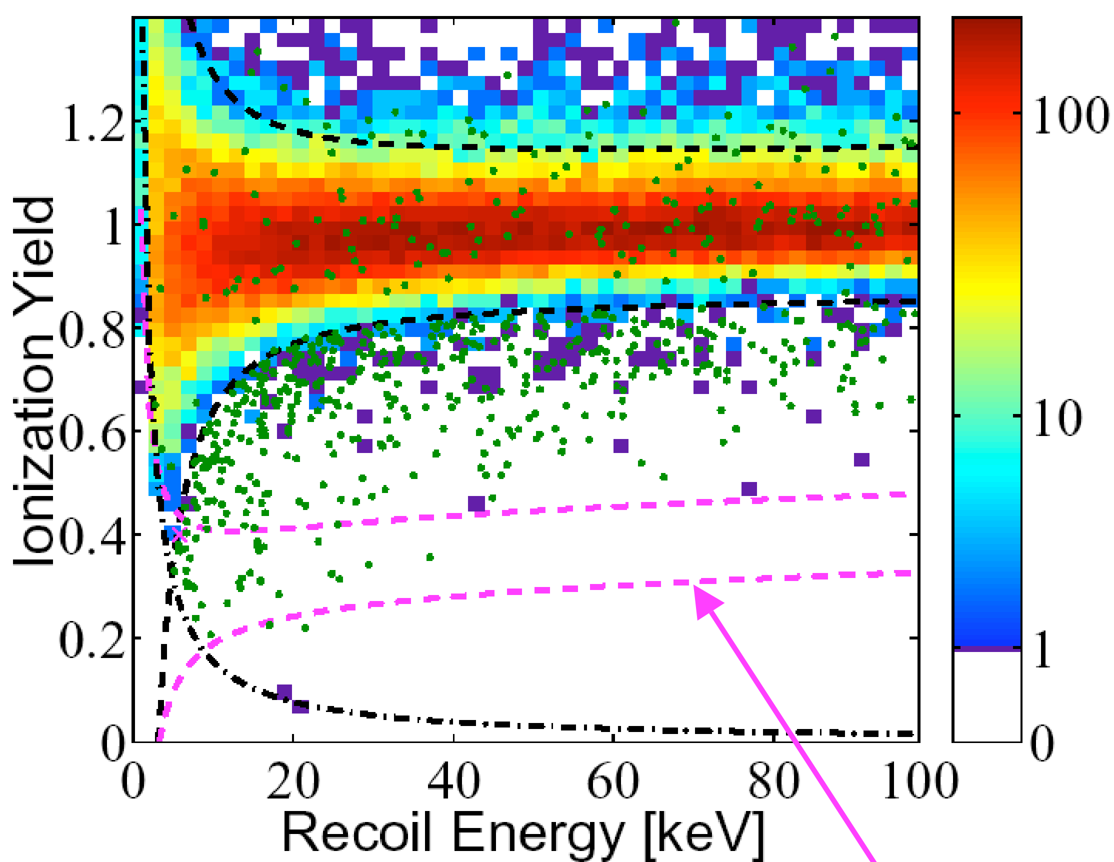






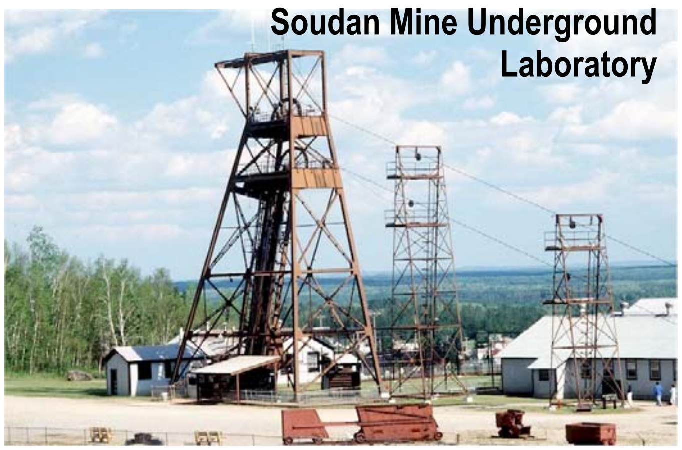
Surface backgrounds: low-energy betas

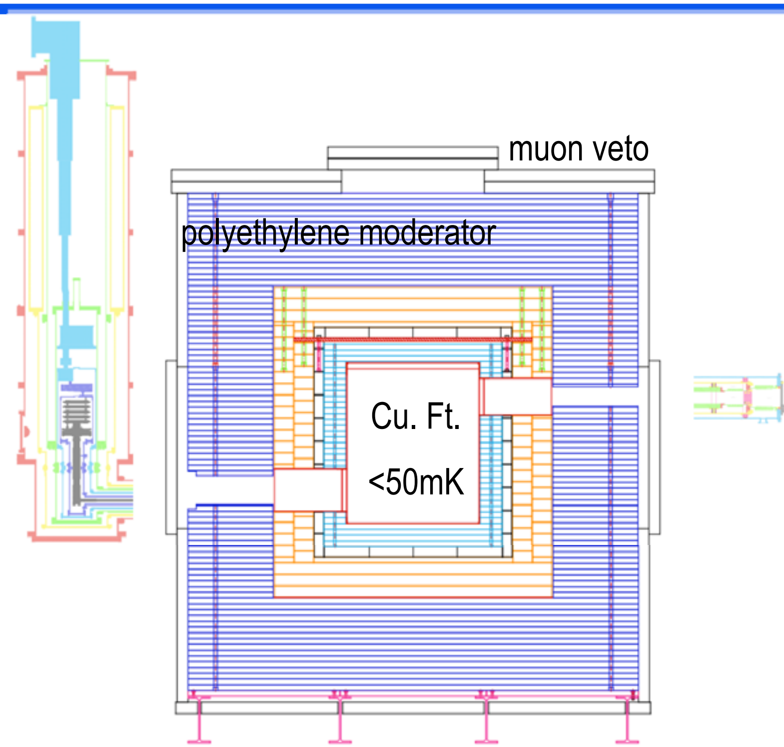
• electrons that interact in surface “dead layer” of detector result in reduced ionization yield

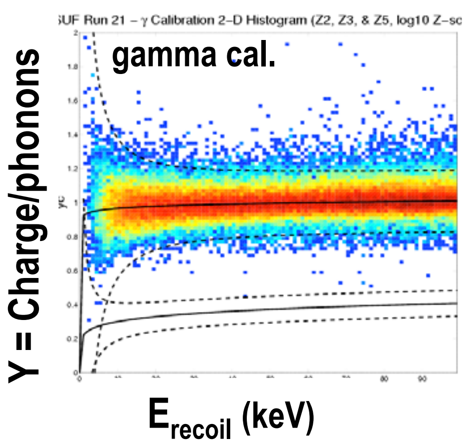


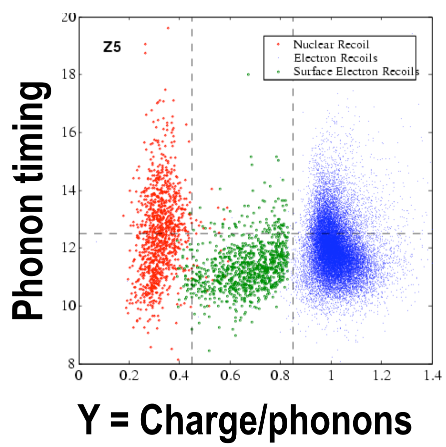
Nuclear-recoil WIMP-signal region

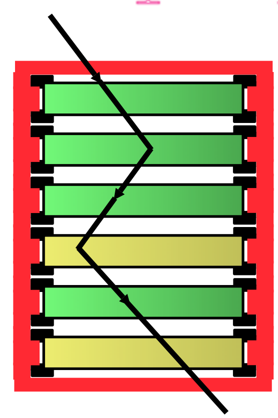
Overall Strategy: gammas, betas, neutrons

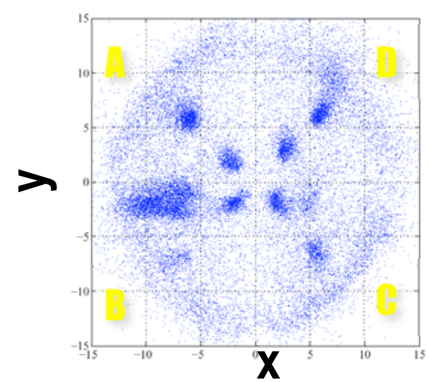






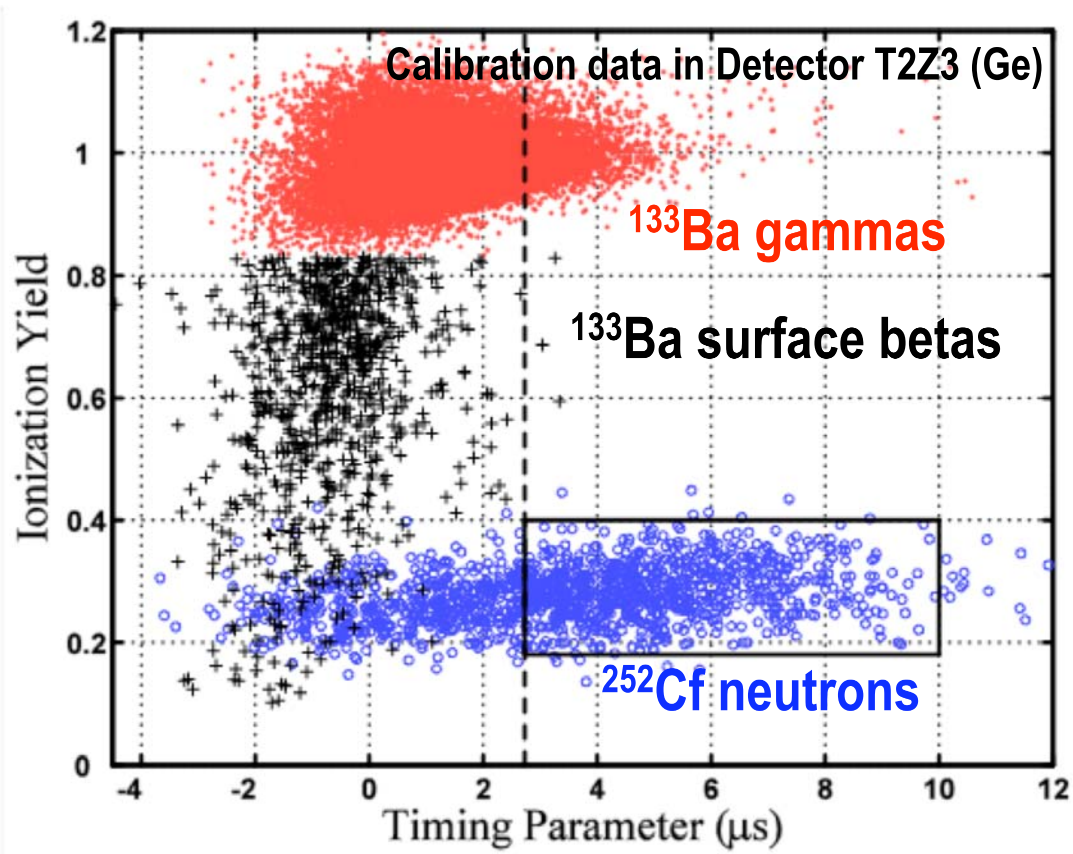


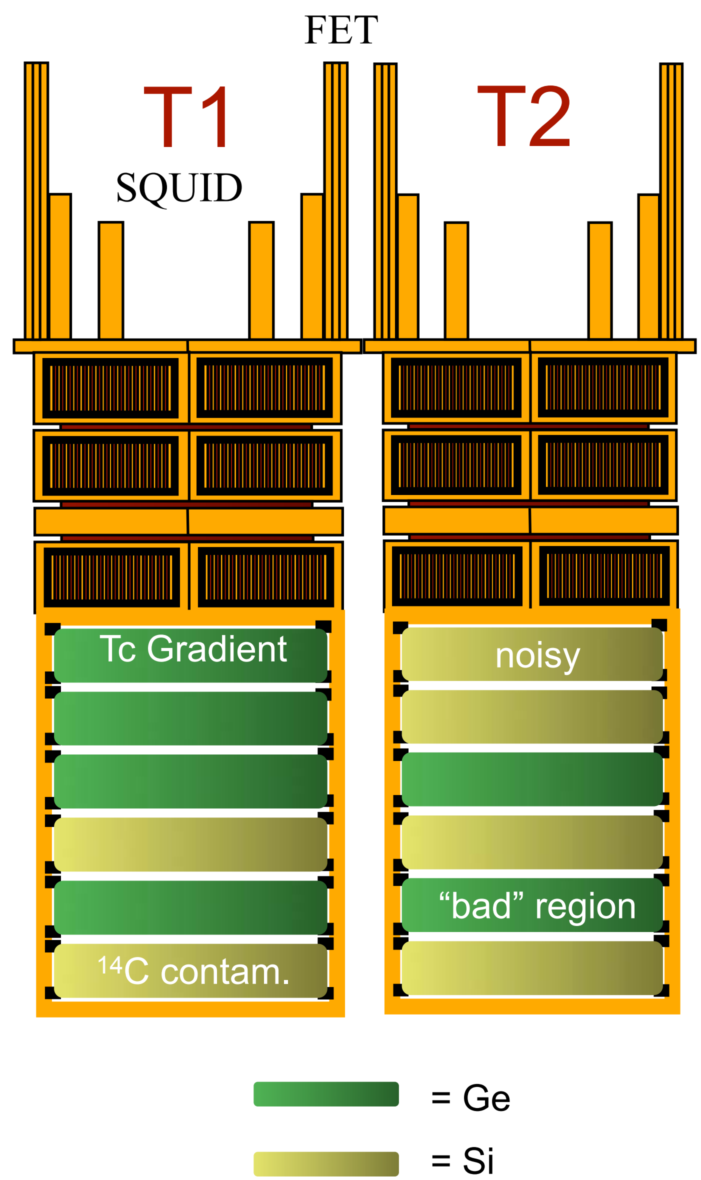




Mask signal region: Blind analysis to minimize bias

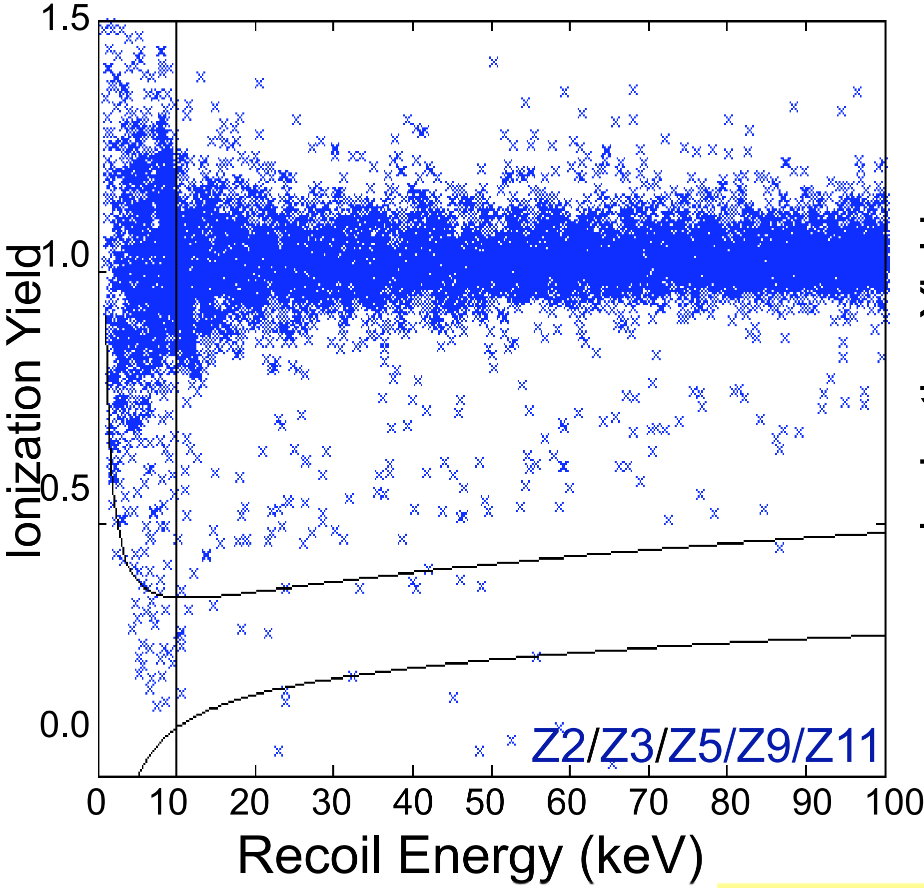
- Cuts set on calibration data and non-masked WIMP-search data
  - timing parameter
  - ionization yield
  - problem detectors/channels



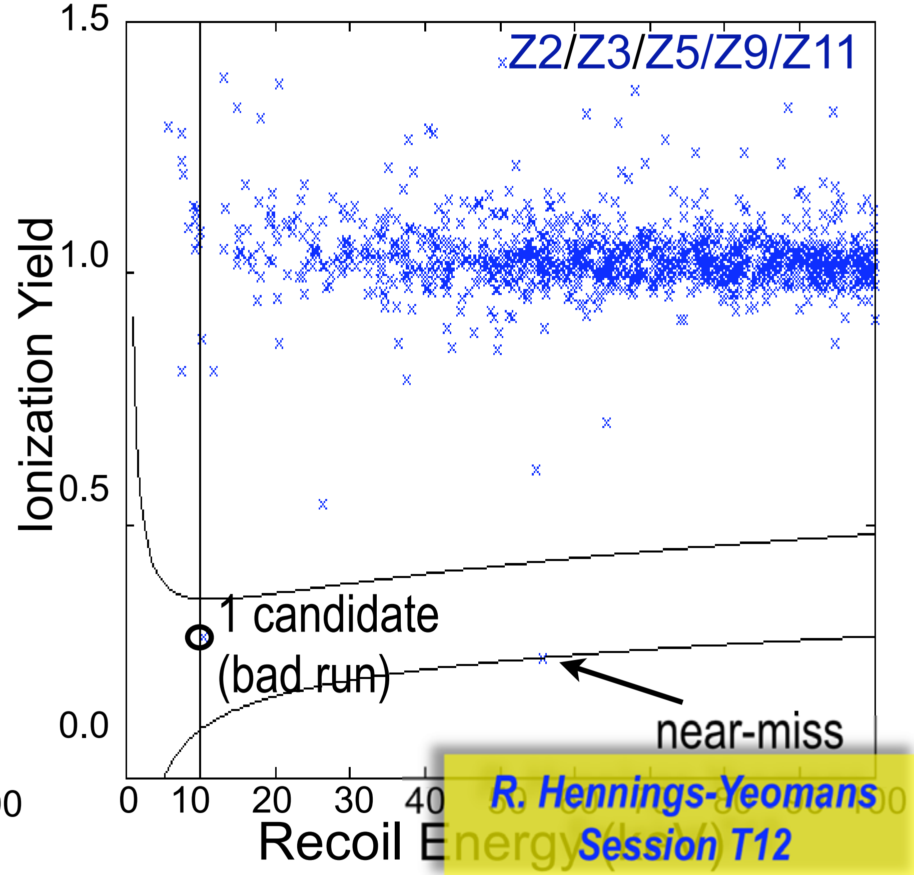


Most recent Soudan WIMP-search data: 2 towers

Before timing cuts



After timing cuts

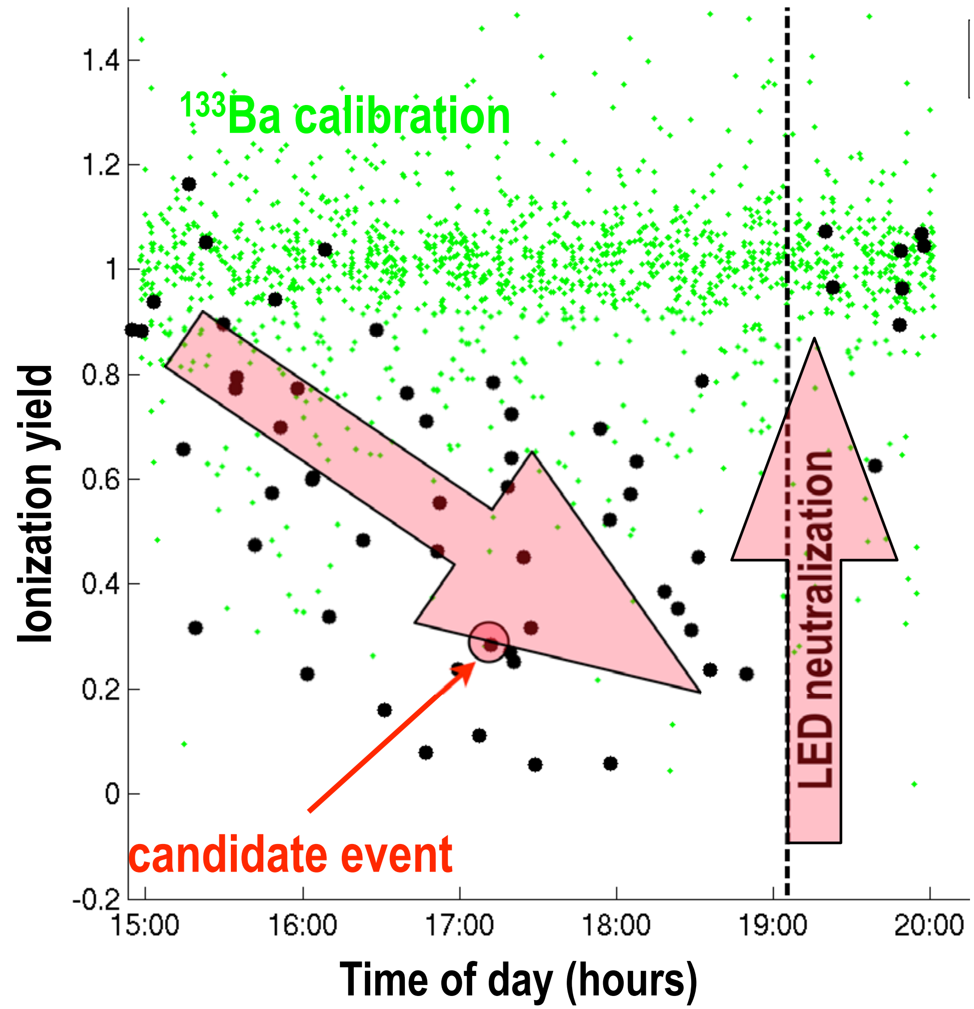


ESTIMATED BKG: 0.4 ± 0.2 (sys.) ± 0.2 (stat.) electron recoils,
0.05 (Geant3) → 0.005 (Geant4/Fluka/MCNPX) neutron recoils.
Optimized for ~0.5 background events

34 kg-d after cuts

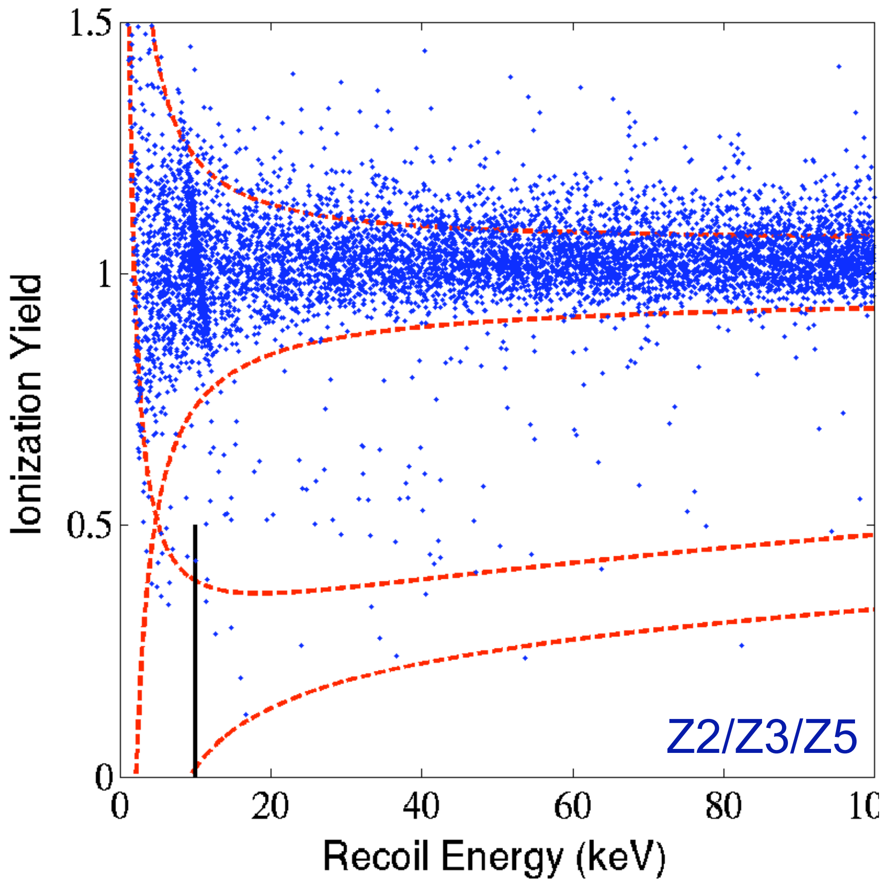
Candidate event: Got WIMP? No...

- **Automatic LED flash every 4 hours to discharge trapping sites**
- **The one candidate event comes from a run with poor neutralization!**
  - anomalous population of low-yield events
  - improved screening for next run
  - anyway, consistent with background
  - included (worsen) upper limit on cross section

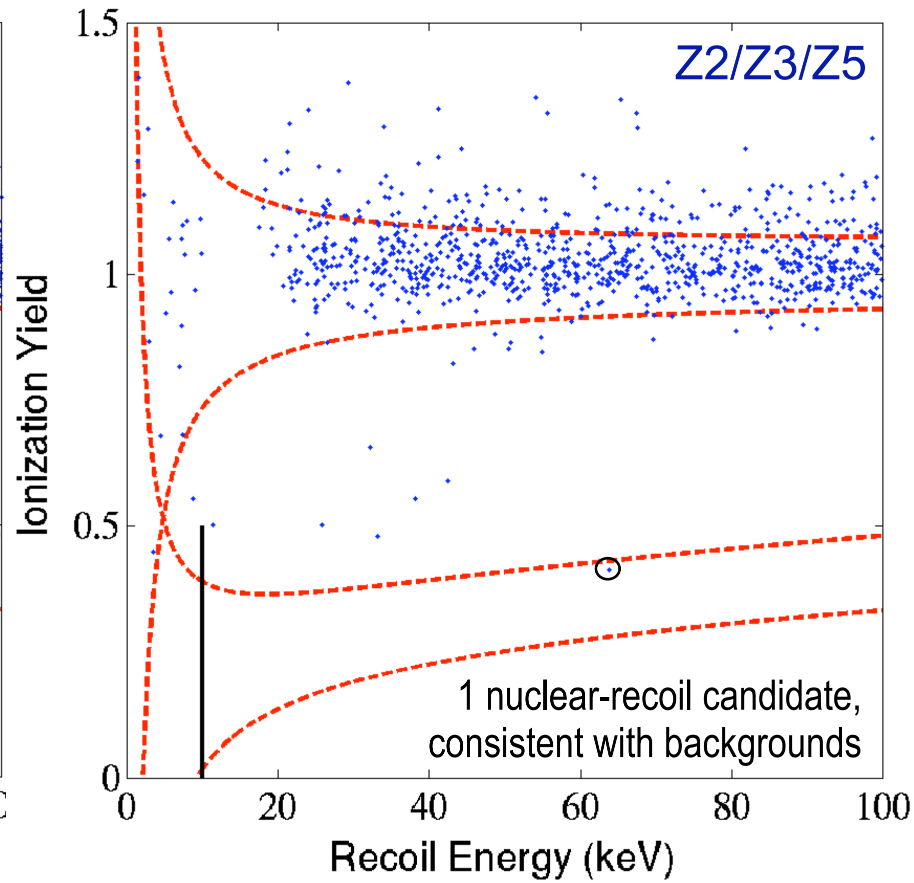


Previous Soudan Run: first tower only

Before timing cuts



After timing cuts



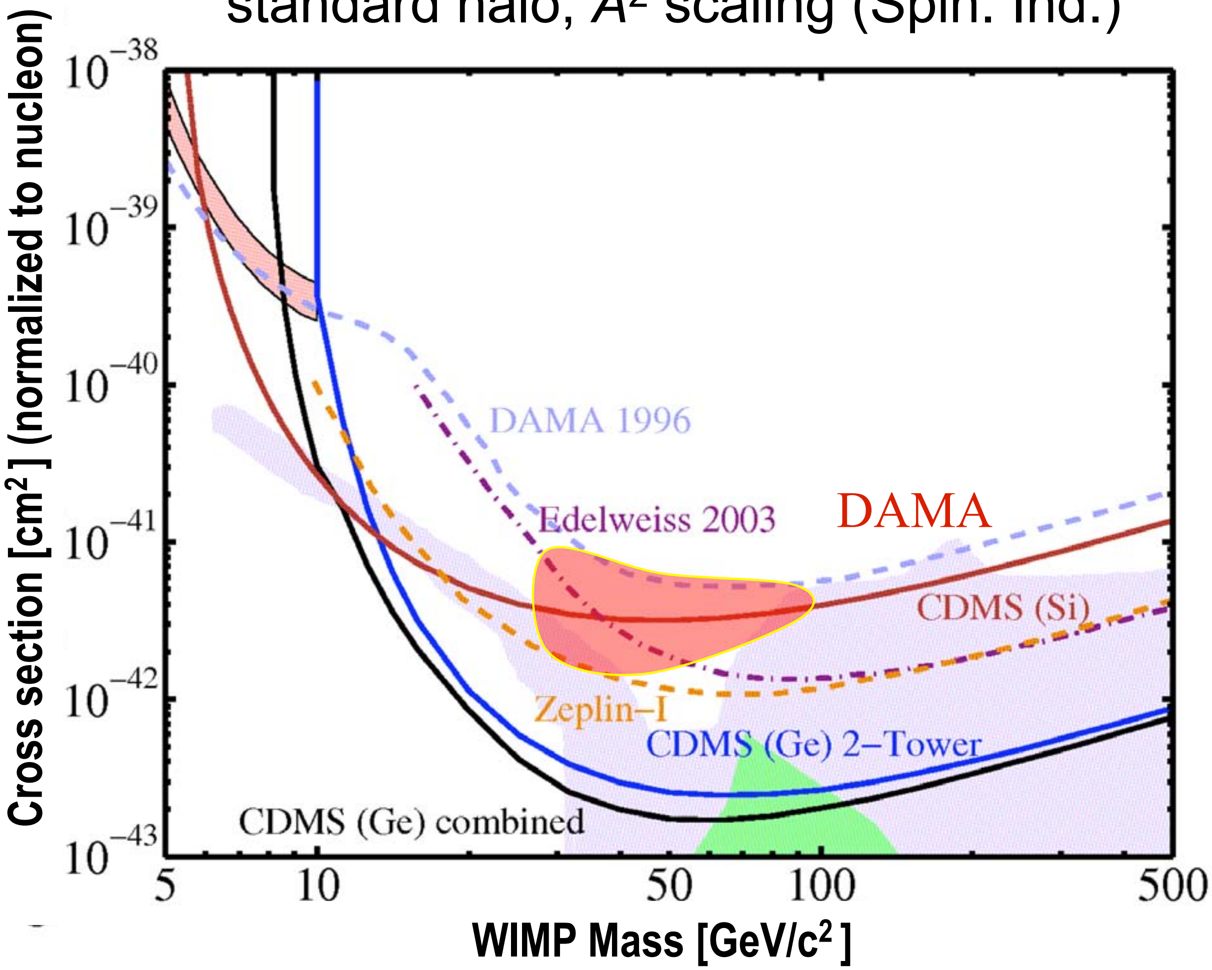
19 kg-d after cuts

0.7 ± 0.35 misidentified electrons (w/Z1)

0.02 (G3) → 0.002 (G4/Fluka/Mcnpx) neutron recoils (w/ Z1)

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 8 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)*

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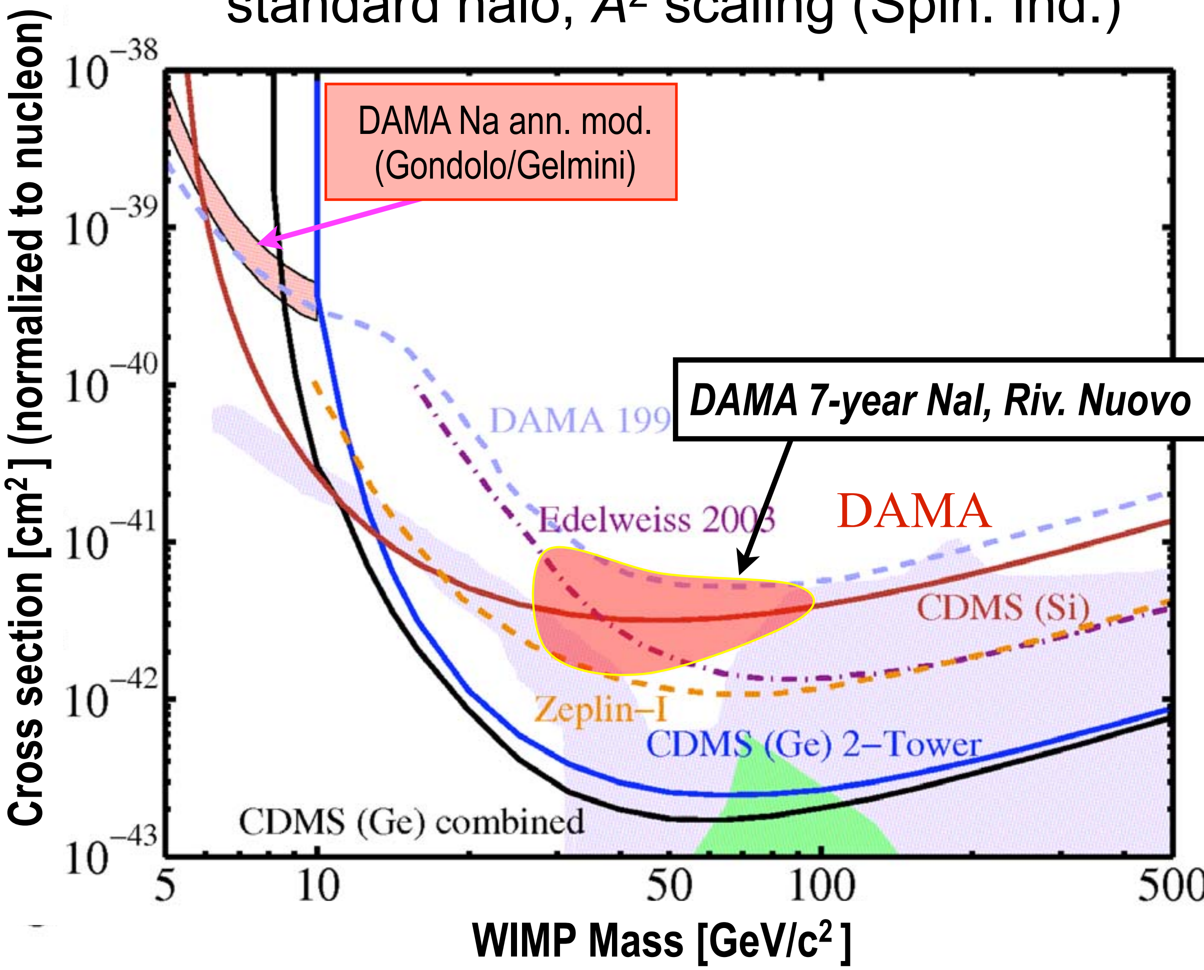

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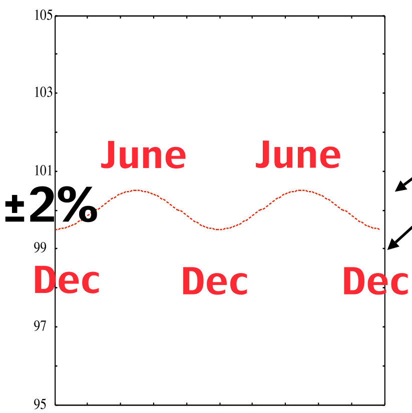
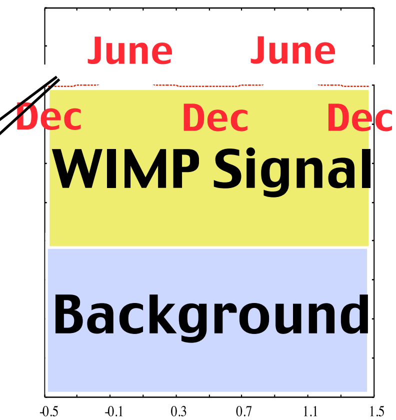
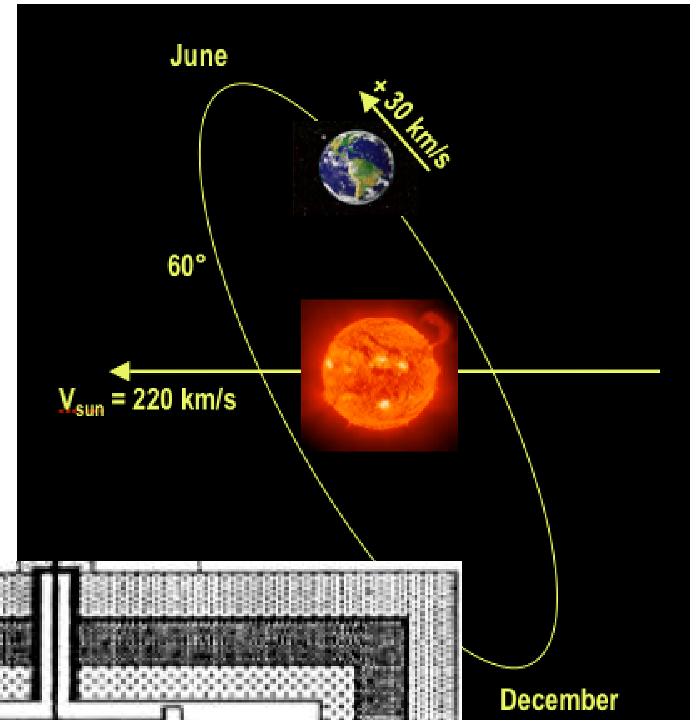
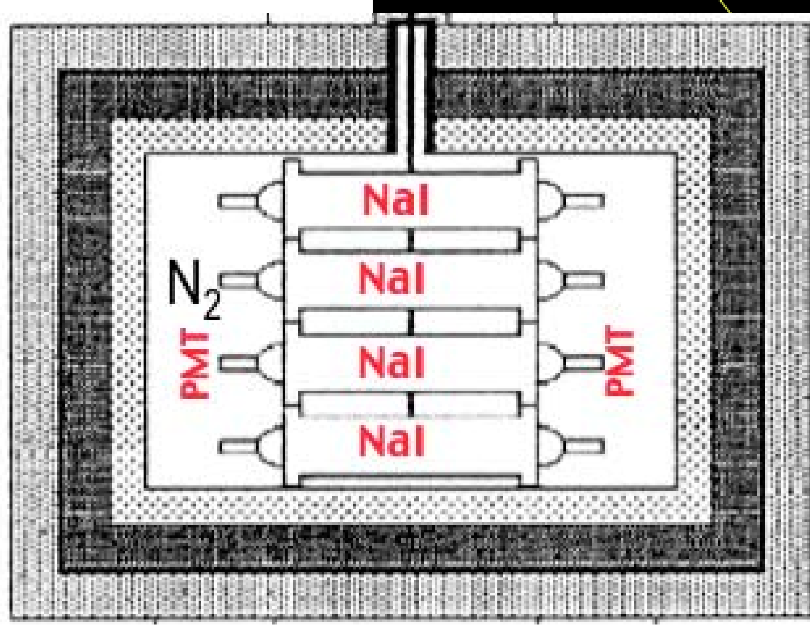
DAMA: NaI & Annual Modulation



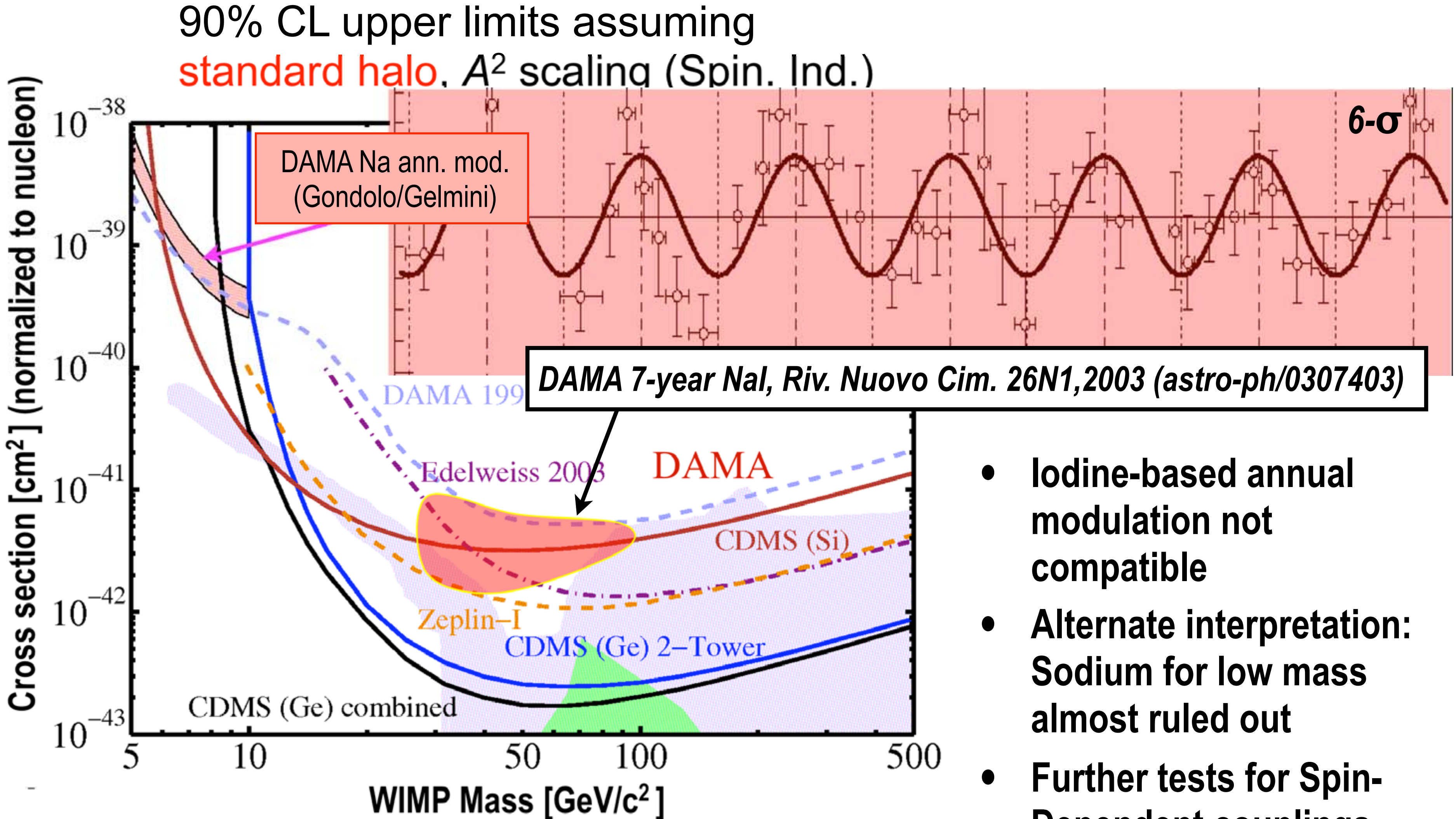






100-kg detector mass: measure energy for each event, but no rejection of gamma background

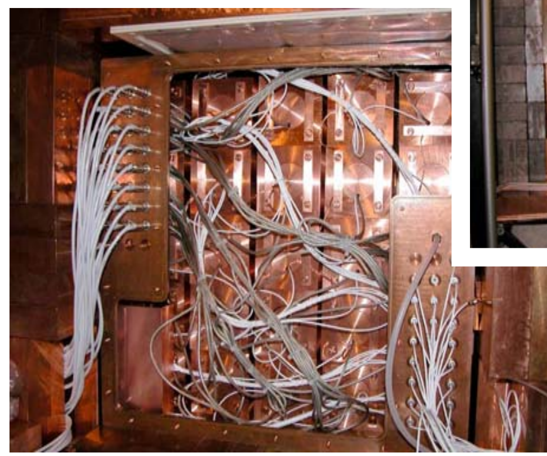
CDMS Soudan Limits and DAMA

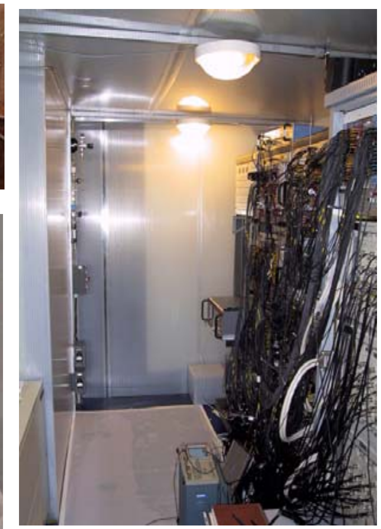


- **Iodine-based annual modulation not compatible**
- **Alternate interpretation: Sodium for low mass almost ruled out**
- **Further tests for Spin-Dependent couplings...**

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

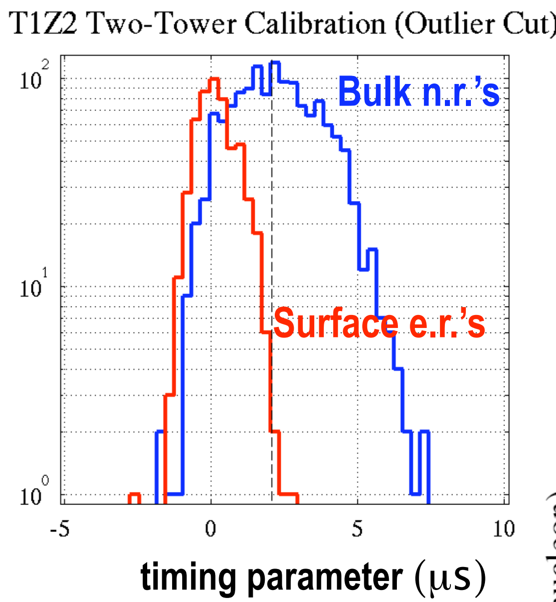


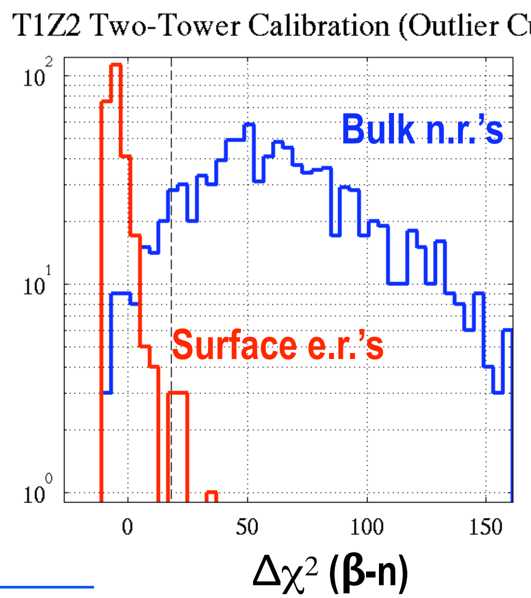


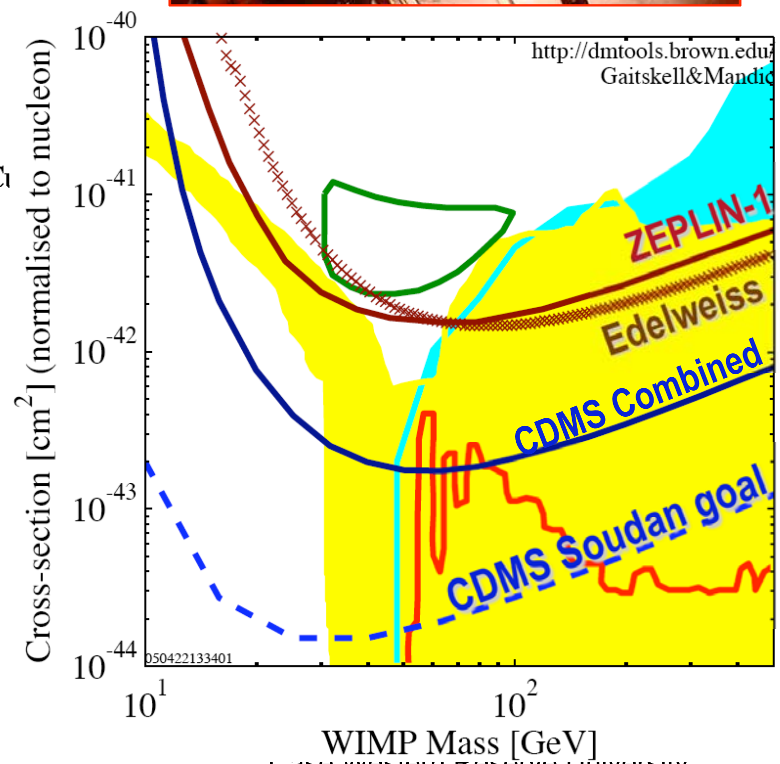

Completing CDMS-II at Soudan

- **Continue running with zero expected background**
  - Improved analysis
  - Cleaner towers
    - 4 kg Ge
    - 0.9 kg Si
  - 4x data in hand
  - On track for 8x by early '08

X. Qiu & J. Fillipini
Session T12

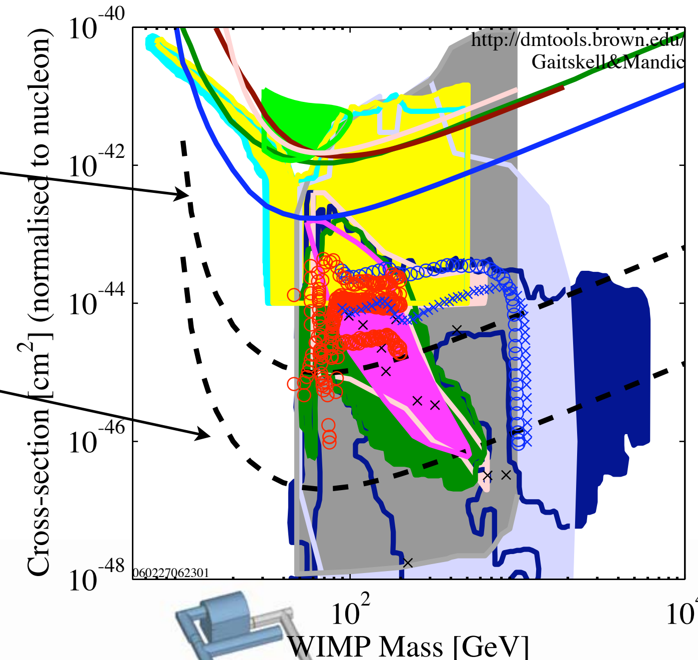


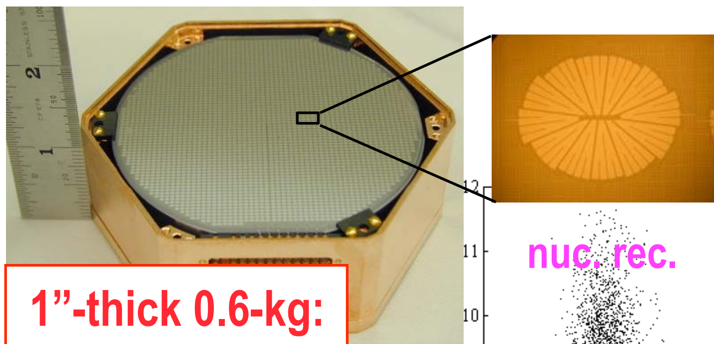




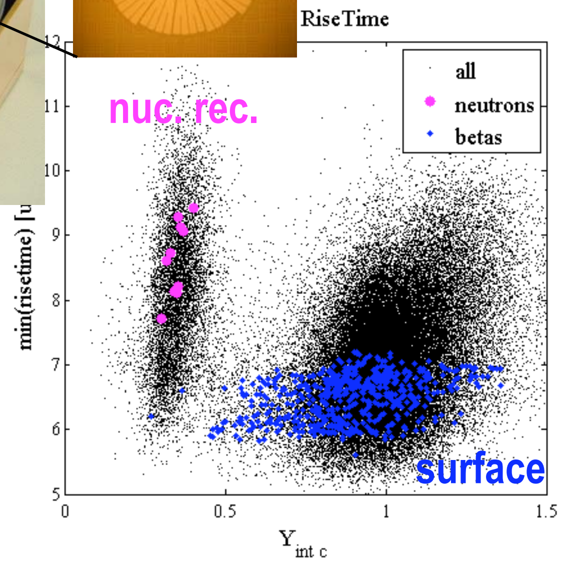
Next for CDMS: SuperCDMS 25 kg

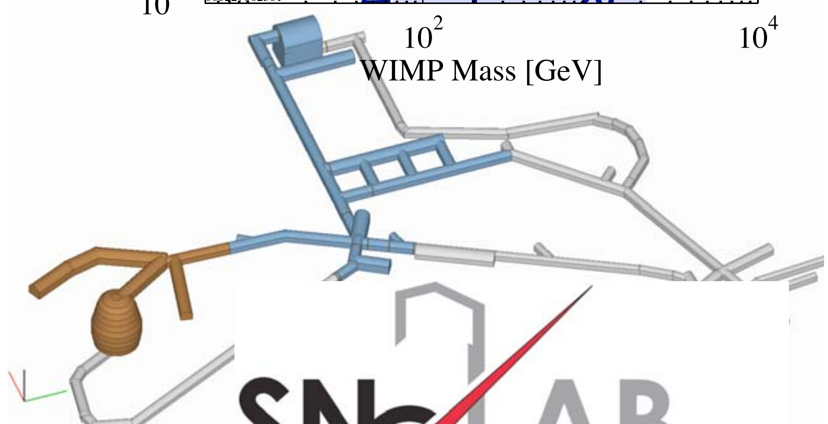
- **Proposed 25-kg experiment based on updated 42 x 600-g Ge ZIPs**
  - 120x beyond current limits
  - 15x beyond CDMS-II goal
  - Approved for space at SNOLAB
  - Next step towards ton-scale goal
- **Detector fab/demonstration underway**





1"-thick 0.6-kg:
3x fiducial
mass per s.a.



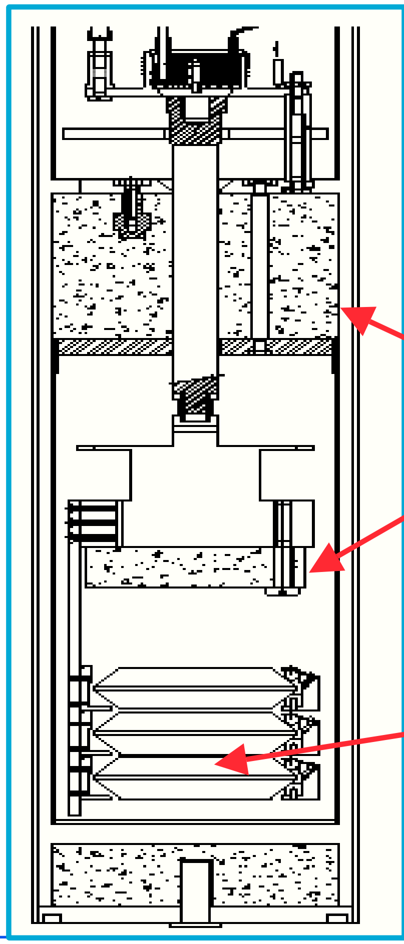


SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

M. Pyle
Session E14

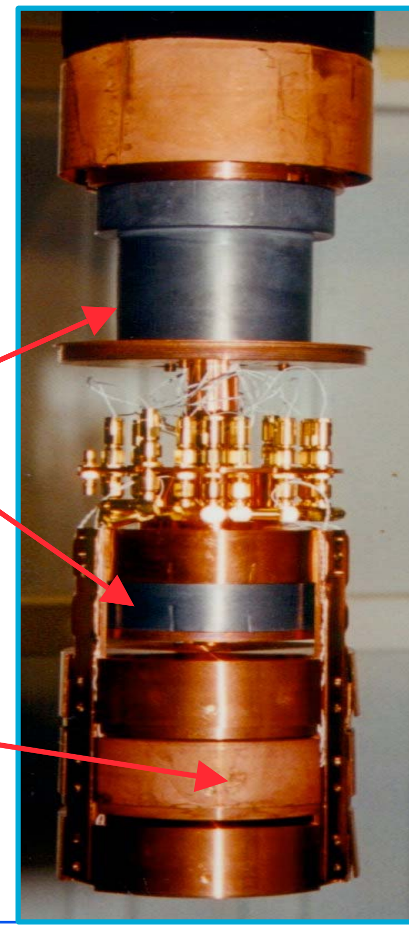
Edelweiss-I in Frejus Tunnel: "1 kg" stage

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



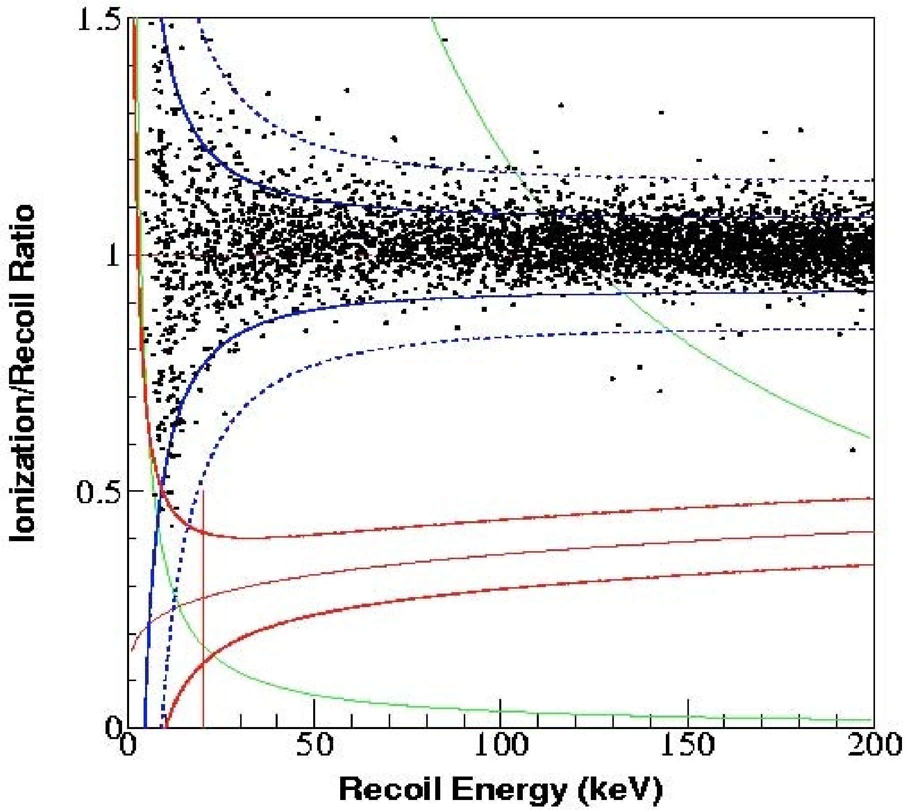
Archeological lead

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

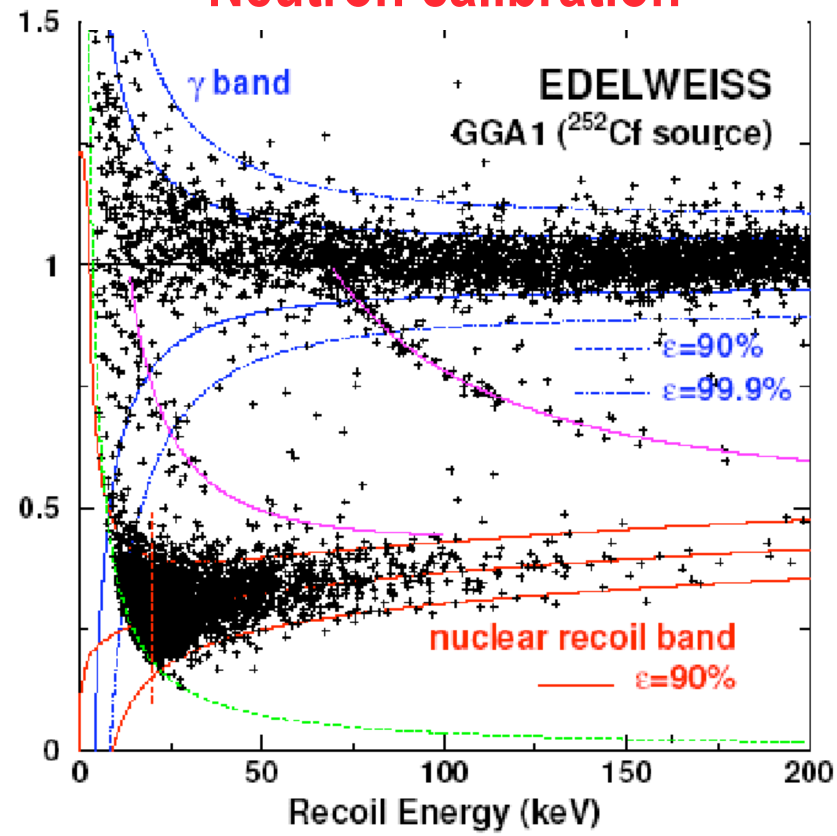


Edelweiss-I: Recoil discrimination

Gamma calibration



Neutron calibration



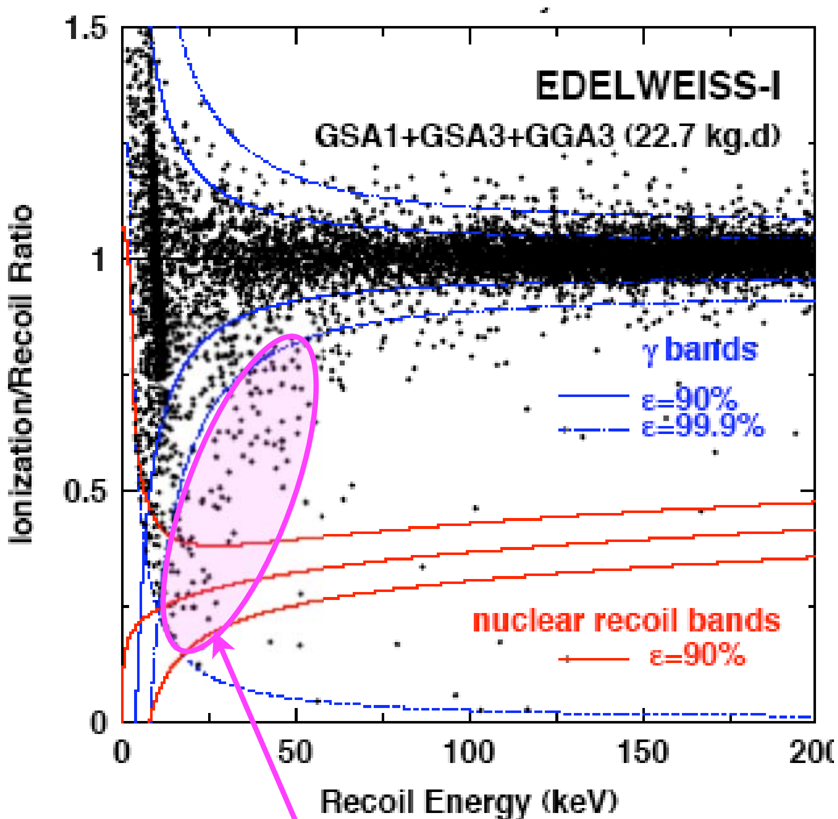
Nuclear recoil discrimination down to 20 keV threshold

γ-ray rejection > 99.99 %

EDELWEISS-I results

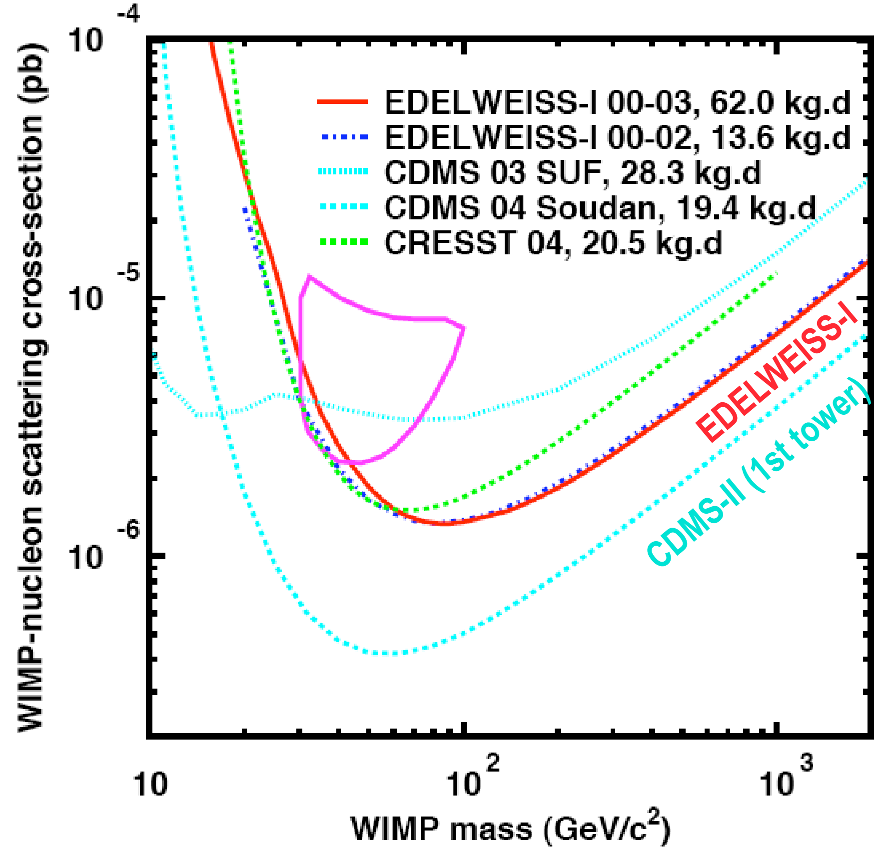
- **2000-2003: Exposure of ~60 kg-d**
  - Three nuclear recoil candidates (30-100keV) consistent with neutron bkg

WIMP search data (partial)



Low-yield surface recoils

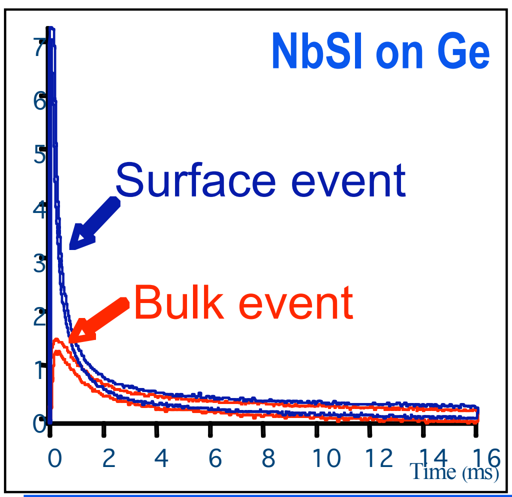
WIMP cross section limit

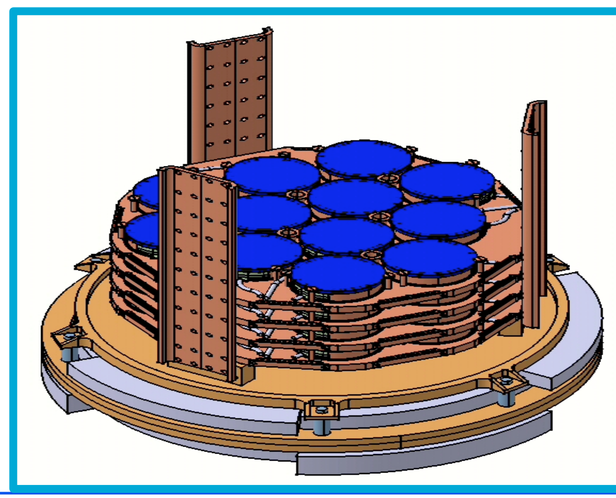


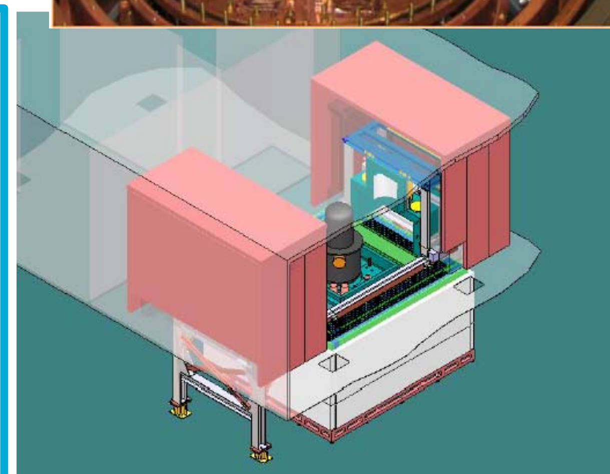
Phys. Rev. ***D71****, 122002, 2005 (astro-ph/0503265)*

Edelweiss-II

- **100-detector cryostat operating in Modane**
- **Commissioning run completed w/7 detectors**
- **26 detectors *now cold* → ~10^{-44} cm^2:**
  - 22 x 320-g NTD on Ge: improved charge collection
  - 4 x 400-g NbSI on Ge: metal-insulator transition - fast timing for surface/bulk event discrimination
  - Commissioning started in Feb 07
- **Plan to propose expansion to 100-module array**

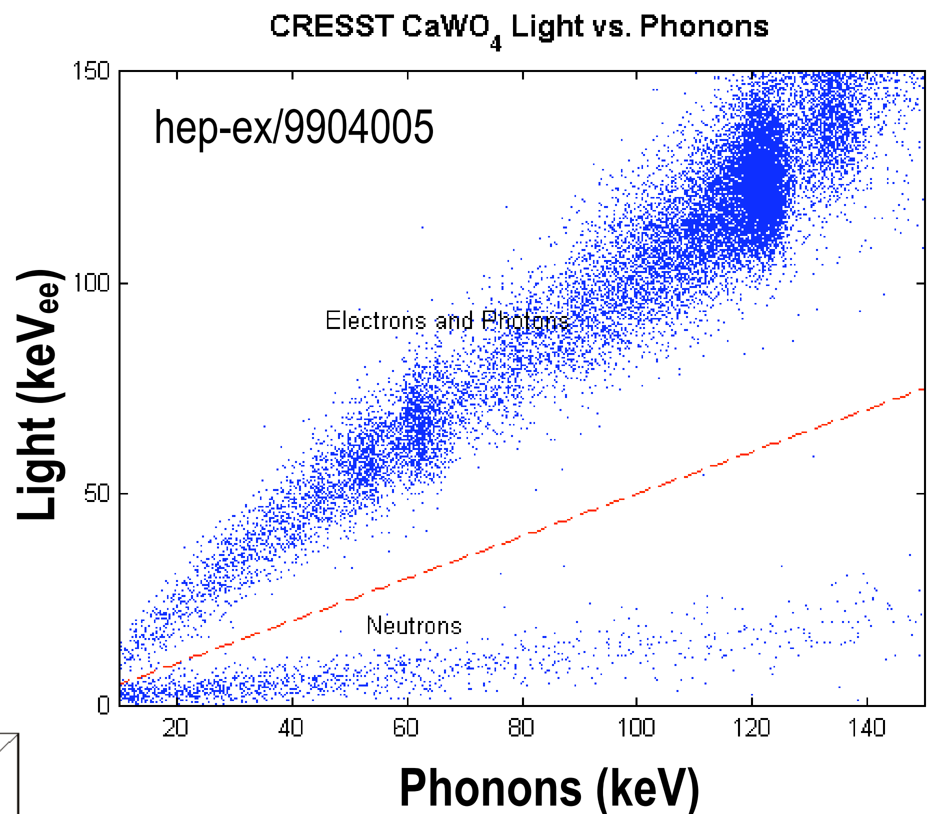


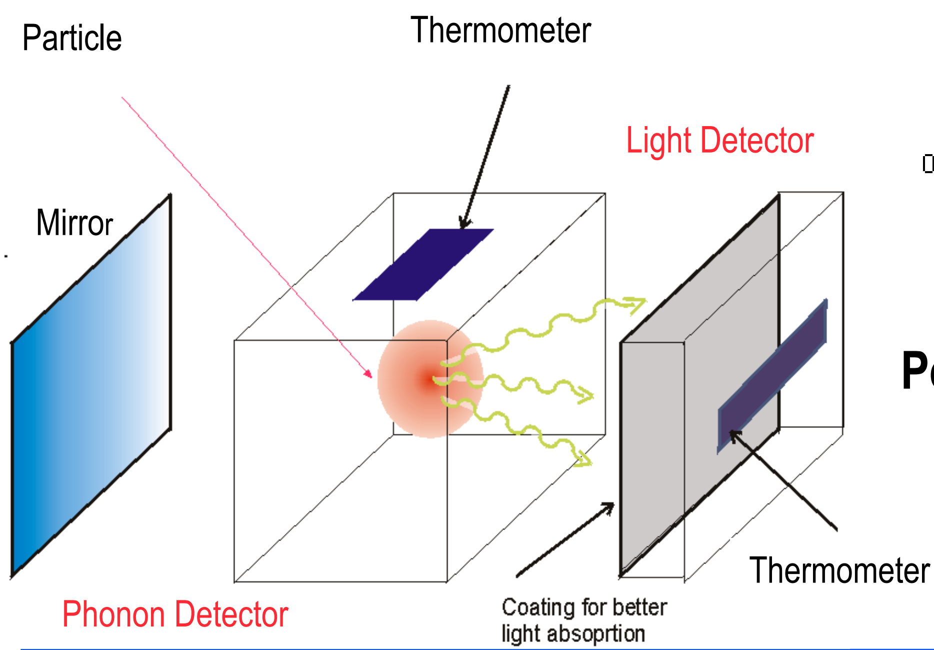




CRESST II: Phonons and Scintillation

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

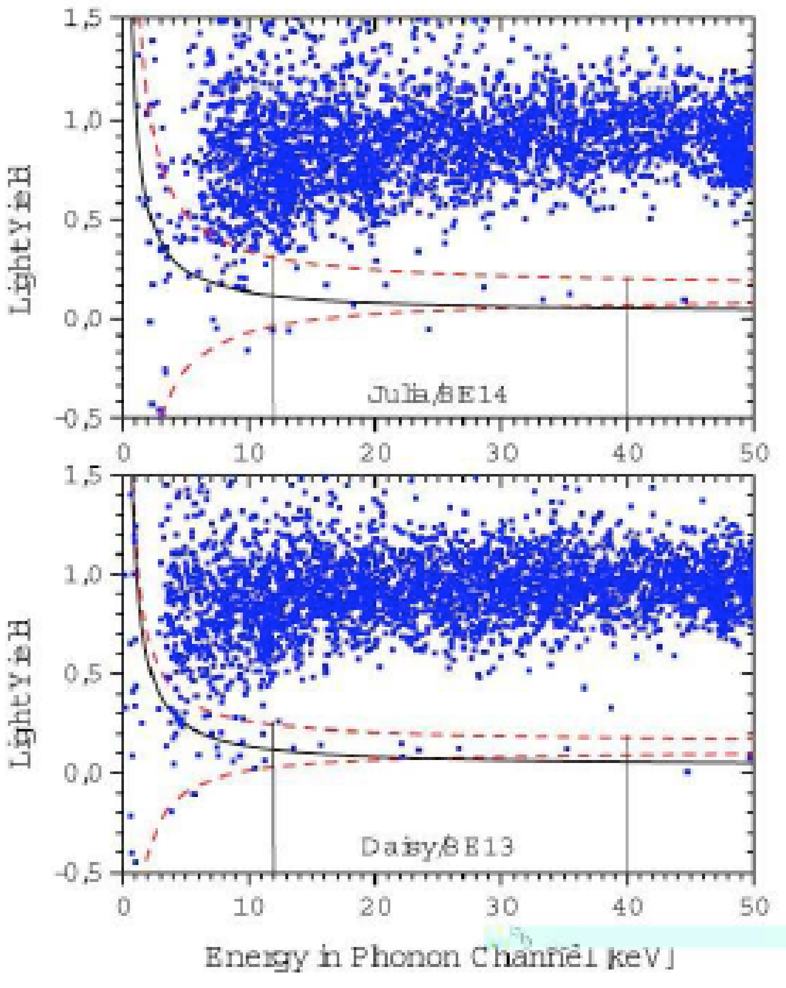




Performance from a 6-g $CaWO_4$ prototype

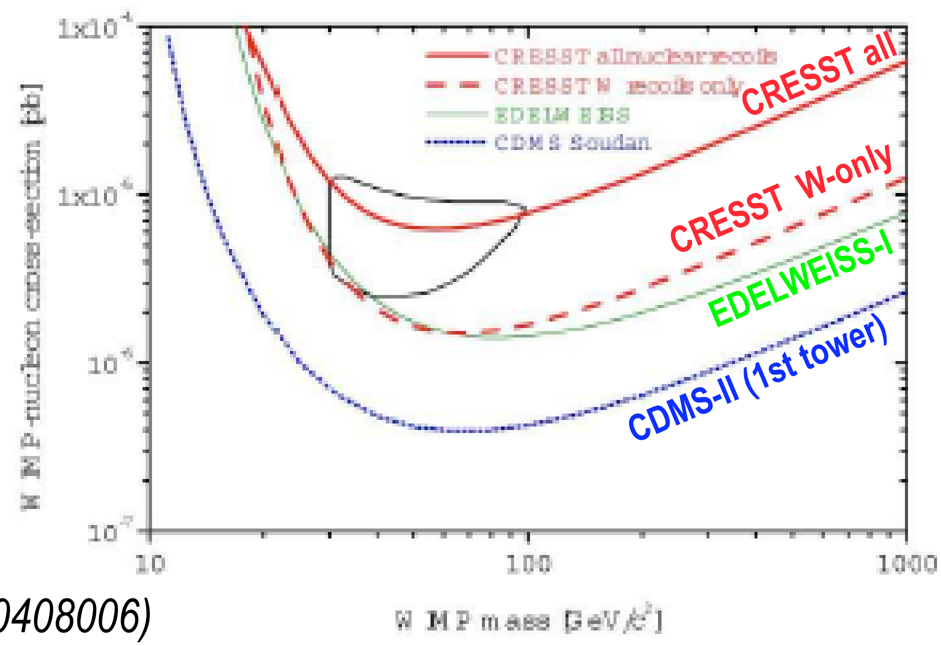
- Very small scintillation signal for tungsten recoils
- Scaled up to 300g detectors

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
- No tungsten recoils in light yield region below oxygen yield (consistent with noise)



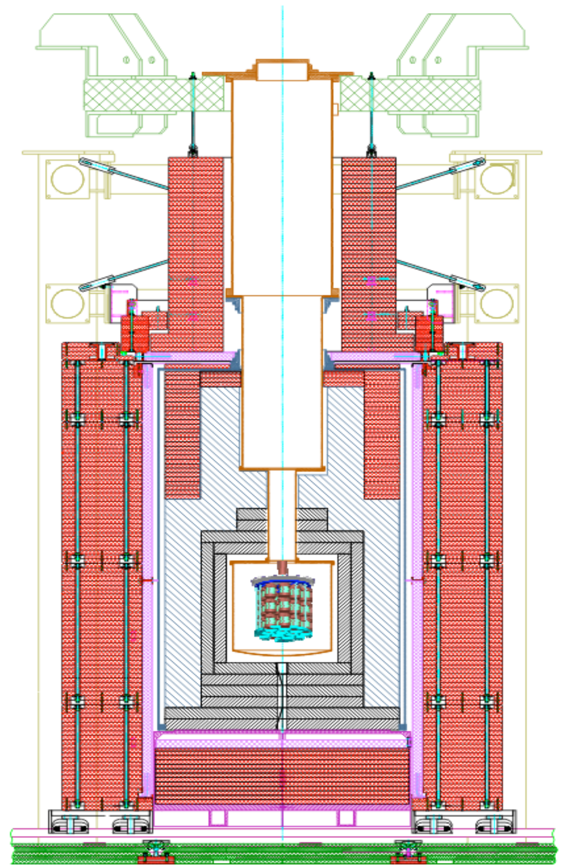
Astropart. Phys. ***23,*** *325-339, 2005 (astro-ph/0408006)*

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
  - Commissioning with 8 detectors (2.4 kg)

- **With EDELWEISS, formed EURECA collaboration → ton-scale experiment**

Shielded cryostat

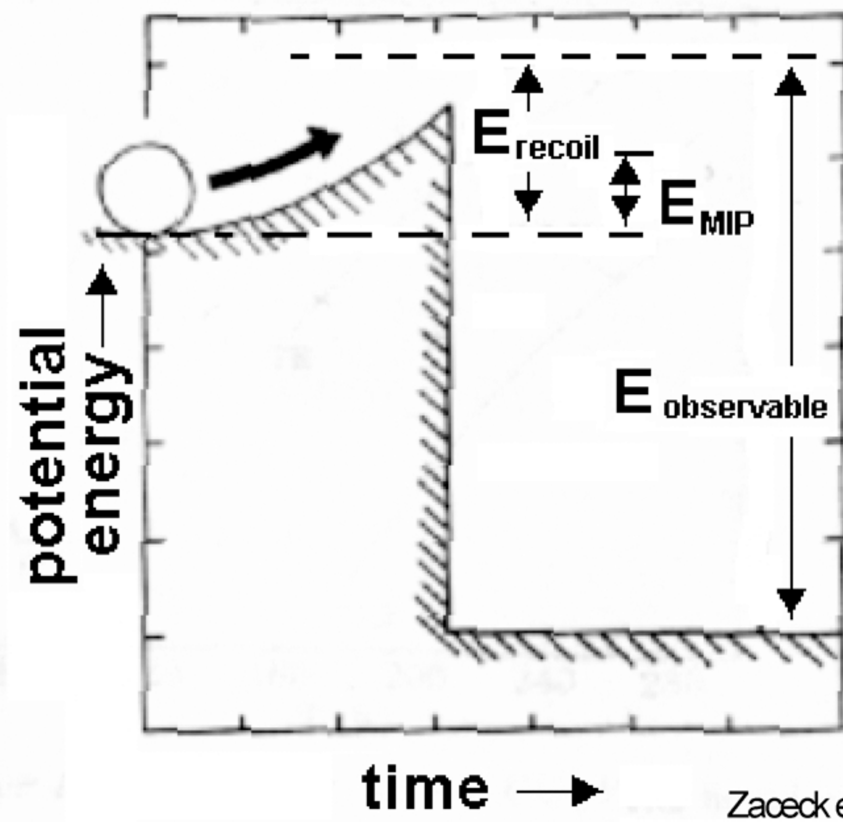


PE neutron moderator

Plastic scintill. μ-veto

Superheated liquids: immune to EM backgrounds

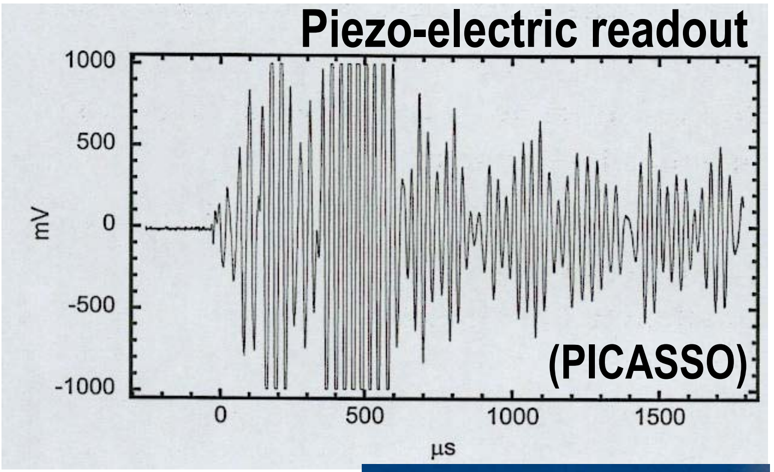
- Principle: Superheated liquid
  - Requires nucleation energy to overcome surface tension and form bubble
  - Tune thermodynamic parameters
    - Insensitive to min. ionizing and low-energy electron recoils
    - Sensitive to higher-energy-density nuclear recoils
  - Threshold detector - release of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

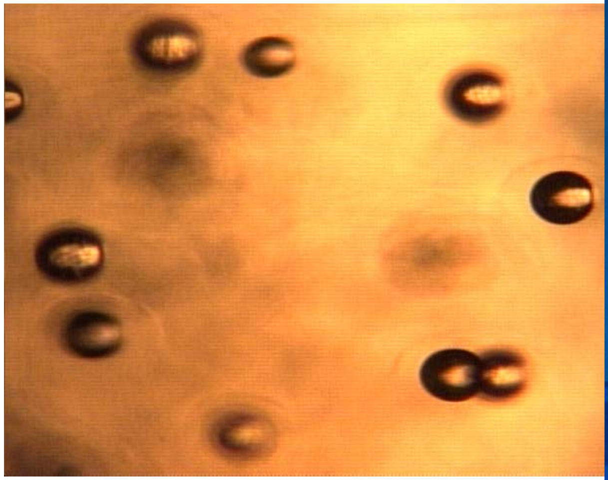


Zacek et al.

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)

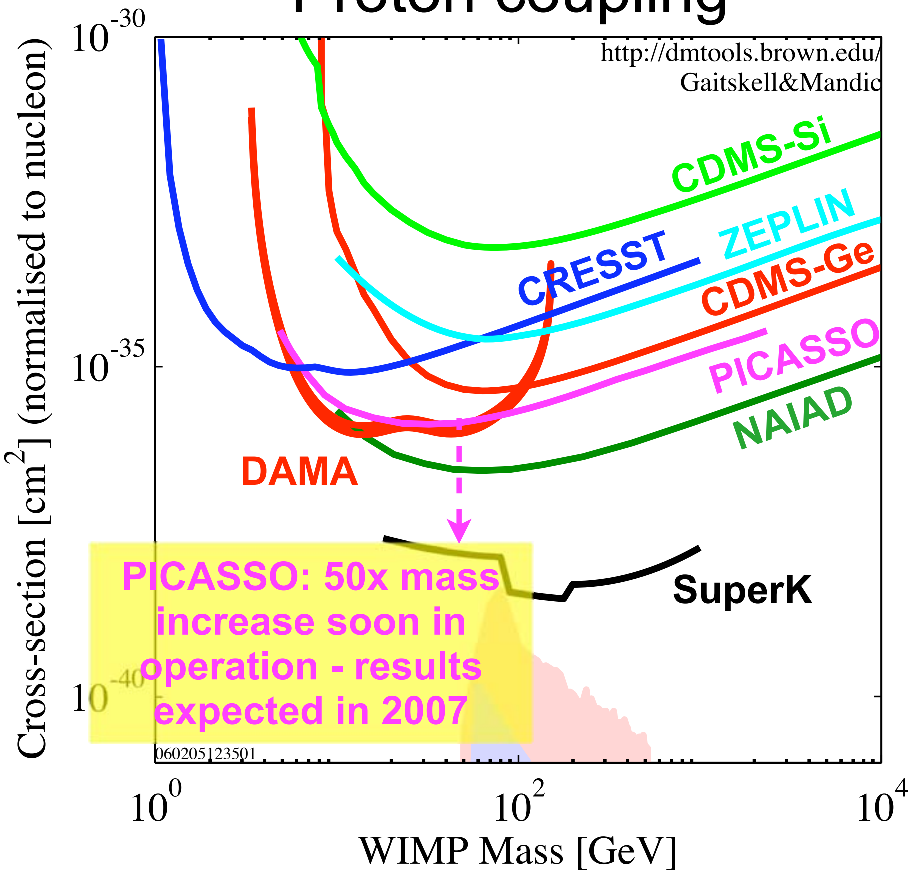




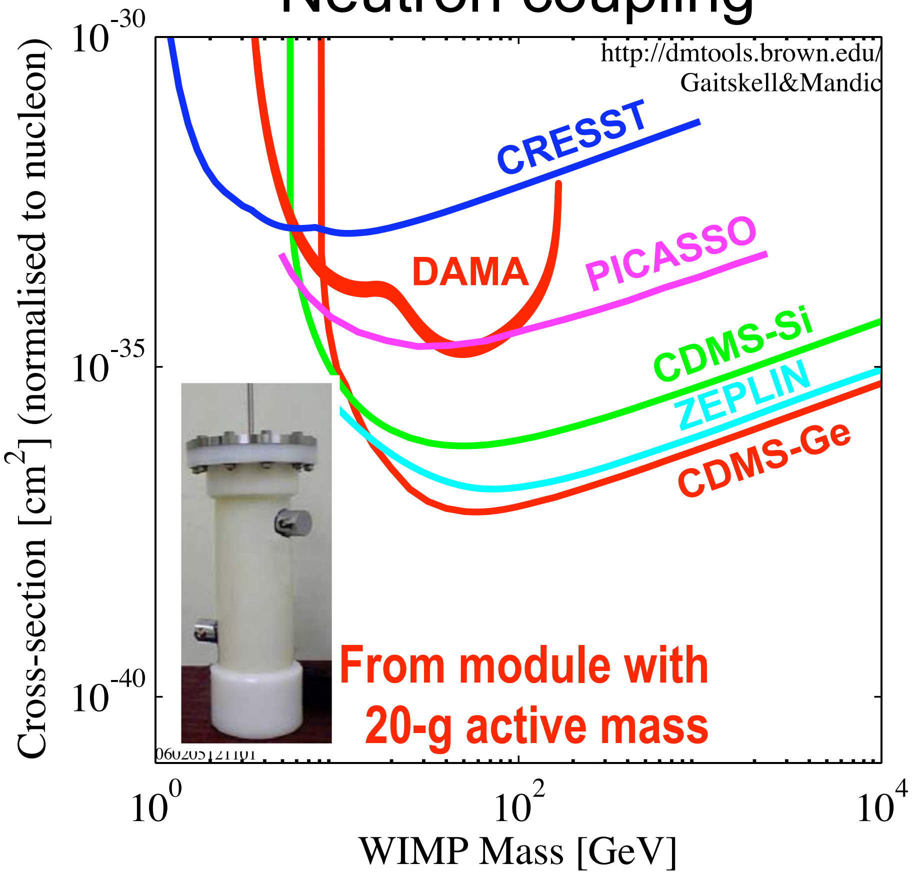
microscopic bubble chambers

PICASSO Spin-Dependent WIMP limits

Proton coupling



Neutron coupling

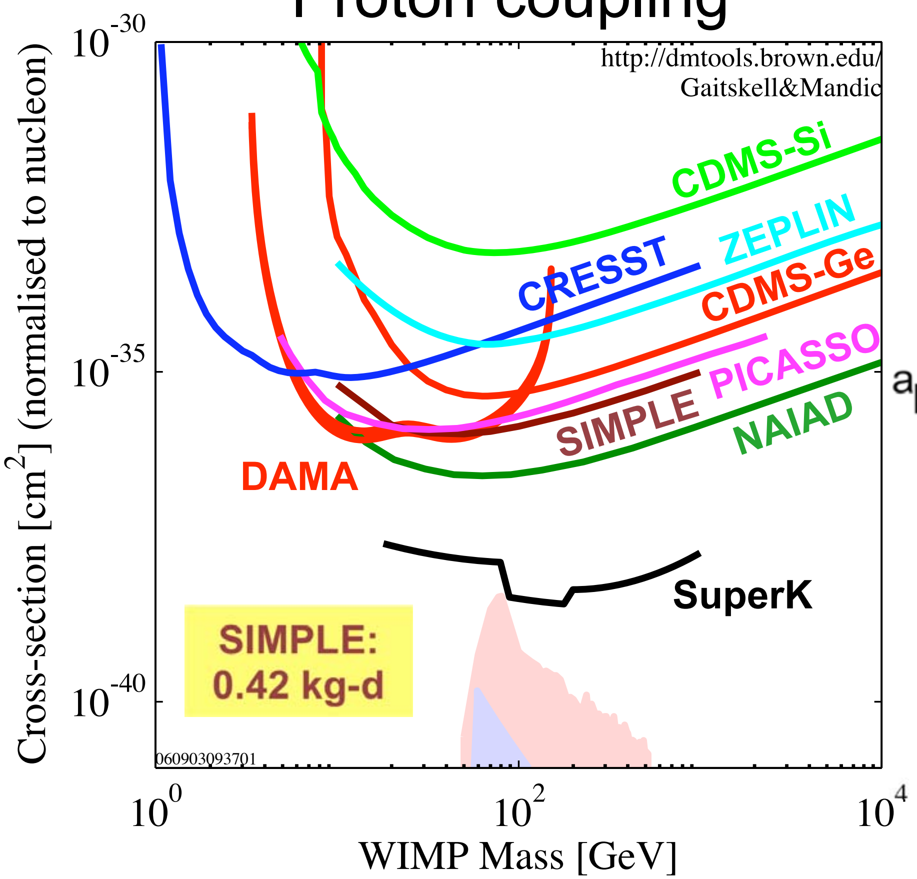


When spin independent coupling suppressed, rate dominated by axial coupling to unpaired nucleon

(DAMA regions from Savage, Gondolo and Freese)

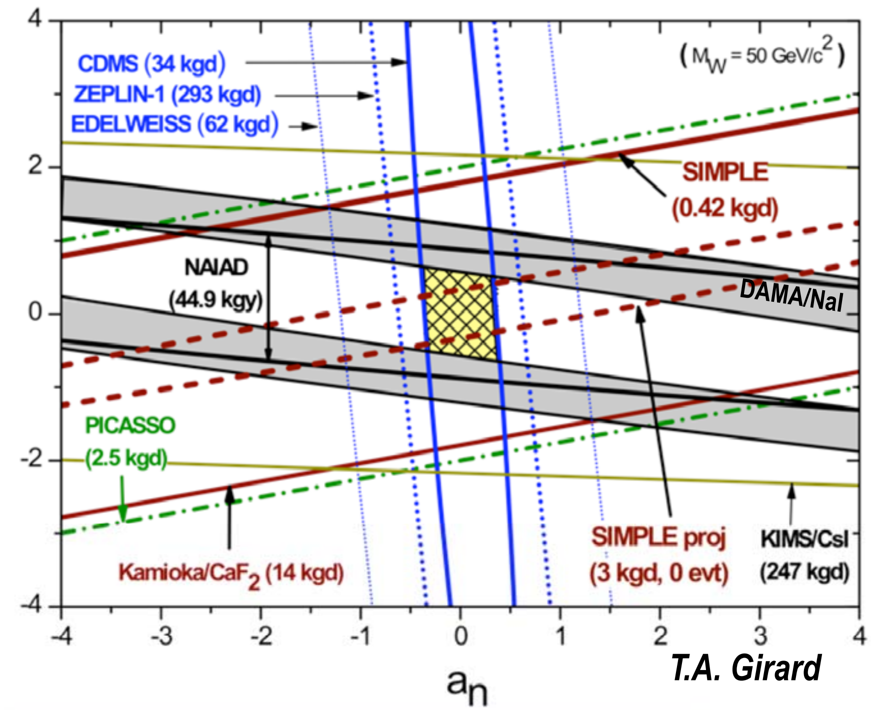
SIMPLE Spin-Dependent WIMP limits

Proton coupling



Model independent (projected)

(a la D.R. Tovey et al. Physics Letters B 488(2000))



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

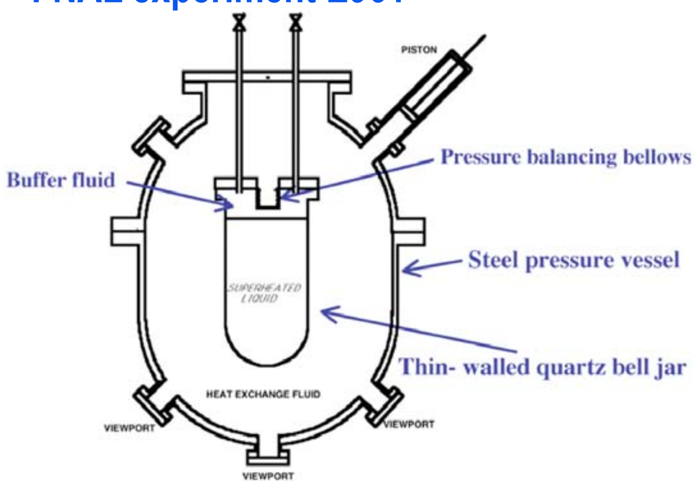
When spin independent coupling by axial coupling to unpaired nu

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

(DAMA regions from Savage, Gondolo and Freese)

COUPP: Bubble Chamber Revival

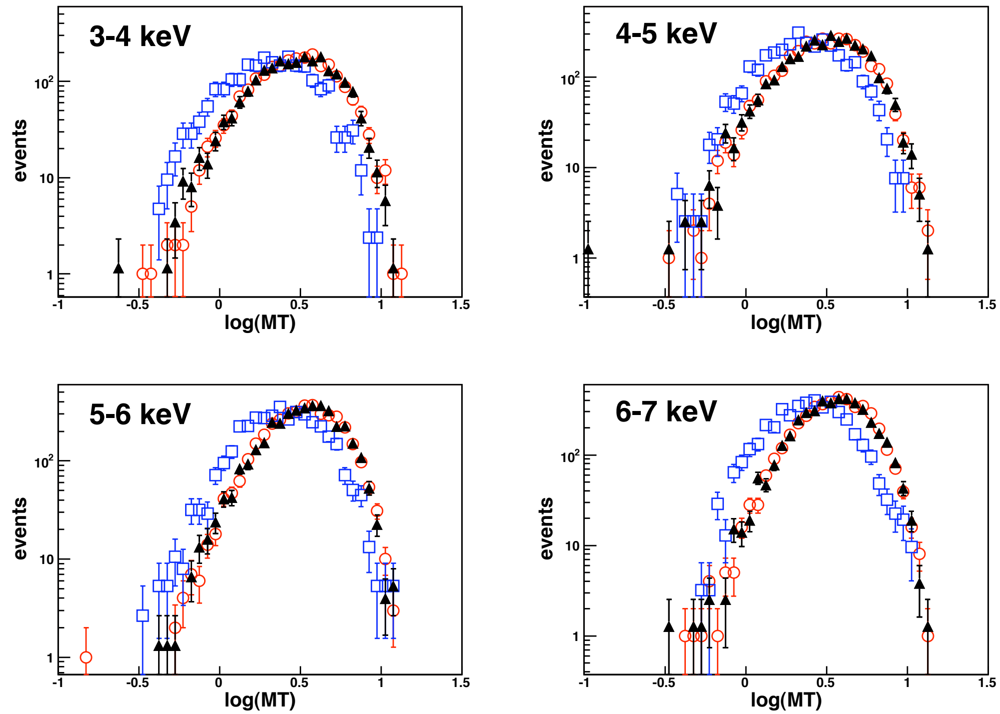
- 2-kg CF_3I Bubble Chamber – U. of Chicago, U. of Indiana/South Bend, and Fermilab
- Tune thermodynamic parameters — immunity to elec. recoils: 10^{10} gamma rejection!
- Two principal challenges:
  - passivate nucleation from vessel walls ⇒ trigger rate ~ laboratory neutron background ✔
  - internal alpha backgrounds - work in progress
- 80 kg mass target under construction
  - FNAL experiment E961



http://www-coupp.fnal.gov/

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
- **New results from 35 kg**
  - 4 x 8.7 kg crystals
  - 3409 kg-days
- **Building 100 kg array**
  - target of 2 cts/(keV kg day)
- **Cross check of DAMA**
  - Iodine couplings
  - annual modulation



○ electron recoils (gamma cal.)
□ nuclear recoils (neutron cal.)
▲ WIMP search

Phys. Lett. ***B633*** *(2006), 201-208 and arXiv:0704.0423 (new 35-kg results)*

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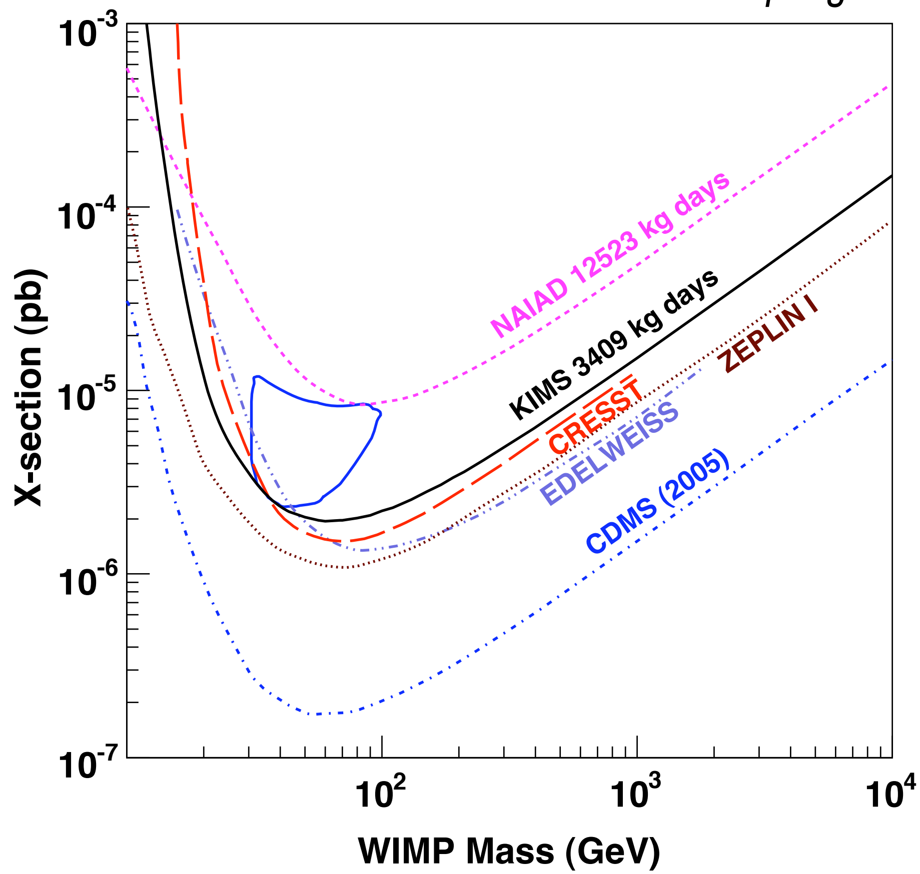
Direct crosscheck on SI Iodine coupling



Phys. Lett. ***B633*** *(2006), 201-208 and arXiv:0704.0423 (new 35-kg results)*

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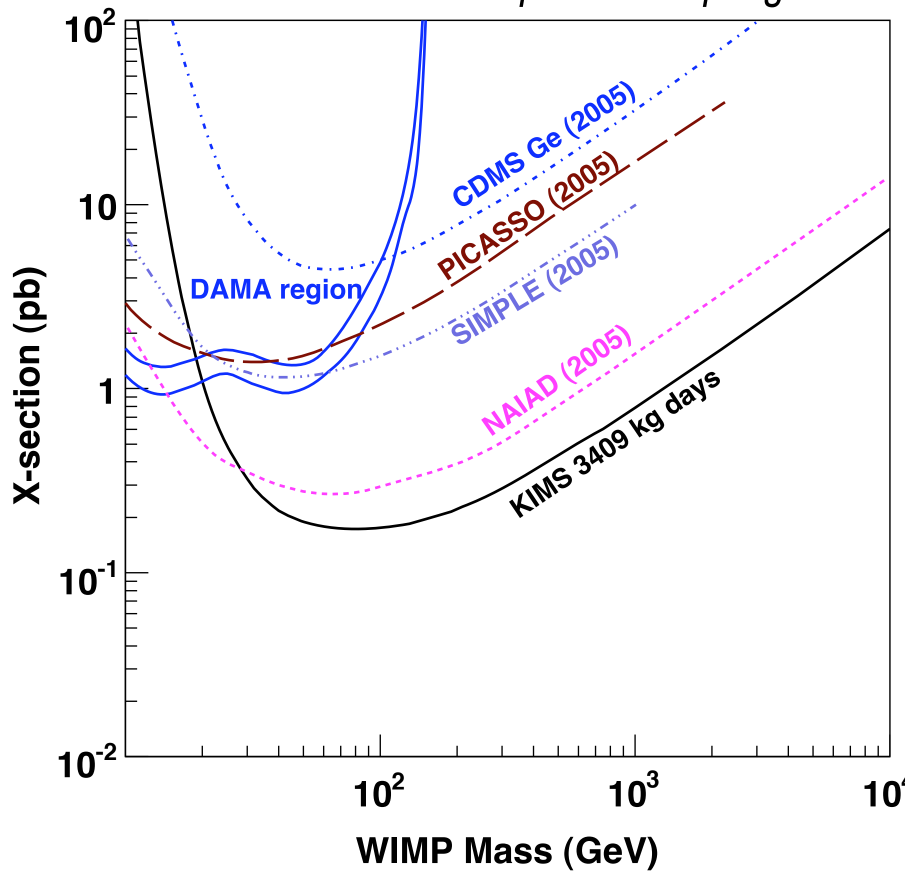
Best limit on SD proton coupling

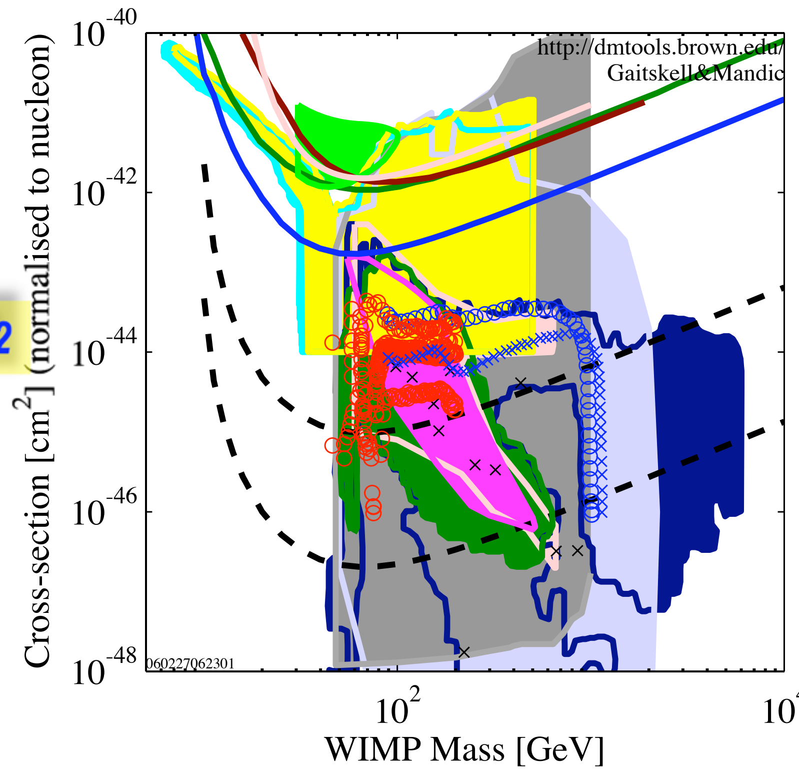


Phys. Lett. ***B633*** *(2006), 201-208 and arXiv:0704.0423 (new 35-kg results)*

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: ongoing data runs
  - Several new technologies (+see next talk!)
  - Cross check of DAMA nearly complete
  - Followup with directional detectors (e.g., DRIFT) - galactic origin
  - Next 5-10 years looks very exciting!

Session T12



The CDMS Collaboration

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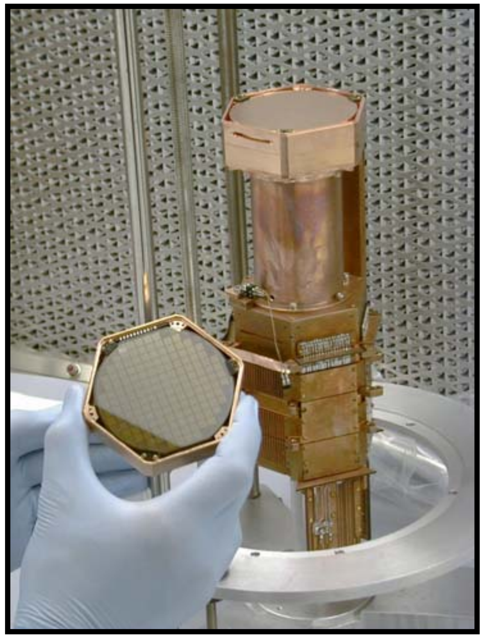
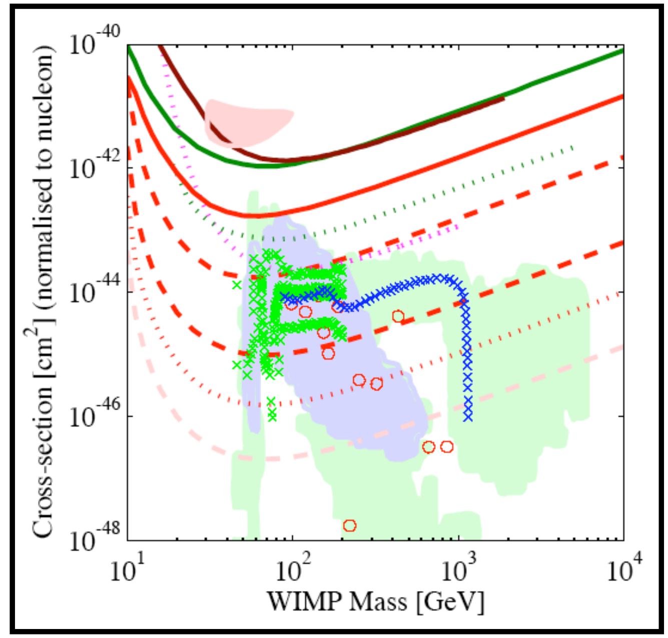
With thanks to NSF and DOE...

Thank you…





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