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Search for Dark Matter

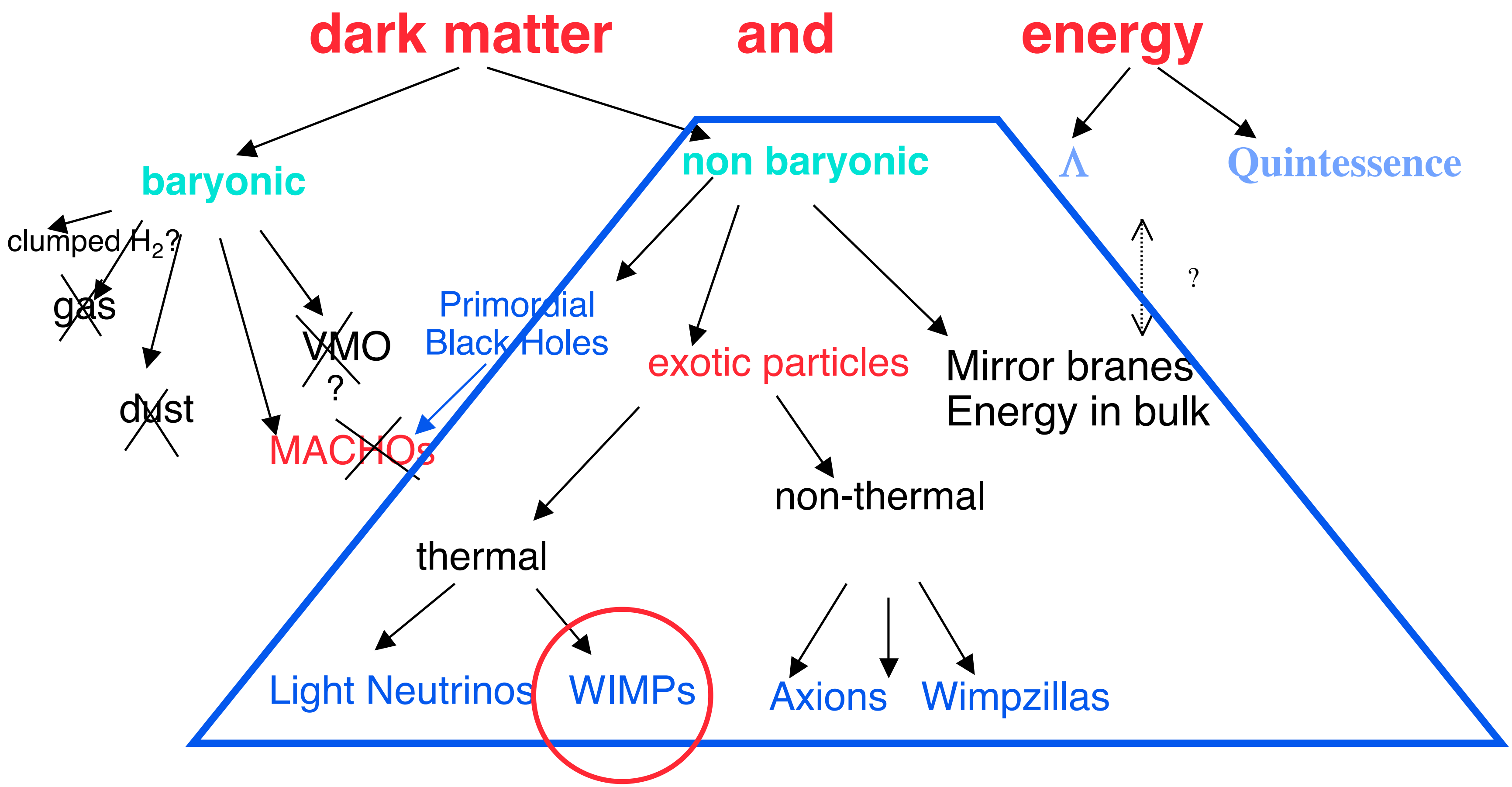
Lecture 4: WIMPs Direct Detection

Cryogenic detectors

Current status

Future

Deciphering the Nature of Dark Matter



Weakly Interactive Massive Particles

Particles in thermal equilibrium
+ decoupling when nonrelativistic

Freeze out when annihilation rate $\approx$ expansion rate

$$\Rightarrow \Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3/s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2} \qquad \rho_\chi \approx \frac{M_{EW}^2 T^3}{M_{Pl}}$$

Generic Class

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale

(e.g. supersymmetry) => significant amount of dark matter

We have to investigate this convergence!

A loop hole: Gravitinos

Can be the Lightest Supersymmetric Particle (LSP)

Unfortunately no good method for detection
(purely gravitational interaction)

Regain of interest because of leptogenesis

e.g. W. Buchmuller et al hep-ph/040614
High reheating=> overproduction of gravitinos, whose decays inject too much entropy
Ways out: make it very heavy >50TeV/c^2 or make it the LSP!

Constraints in SSM parameters

Decay of next to lightest supersymmetric particle (NSP) occurs after Big Bang Nucleosynthesis and injects entropy: too much would destroy agreement between CMBR and BBN synthesis results

$$\eta_{CMB} = \frac{n_B}{n_\gamma} = 6.1\,^{+0.3}_{-0.2}\,10^{-10} \qquad \eta_{BBN} = \frac{n_B}{n_\gamma} = 5.9 \pm 10^{-10}$$

Possible if

$$\Omega_{NSP} \leq 10^{-2}\Omega_b h^2 \approx 10^{-4}$$

Same exercise and indeed regions of parameter space are allowed (Ellis et al., hep-ph 0312262)!

Note: we loose the naturalness of the cross section

Except maybe in specific gauge coupling models (W. Buchmuller et al Phys. Lett B 574 (2003) 156)

$$\Omega_{3/2}h^2 \approx 0.05 - 0.2$$

Direct Detection

Elastic scattering

Expected event rates are low

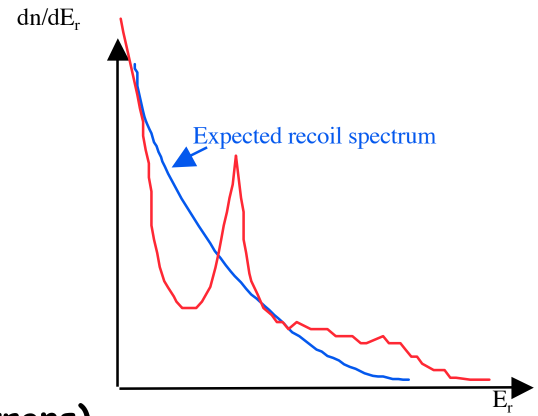
(<< radioactive background)

Small energy deposition (≈ few keV)

<< typical in particle physics

Signal = nuclear recoil (electrons too low in energy)

≠ Background = electron recoil **(if no neutrons)**



Signatures

- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

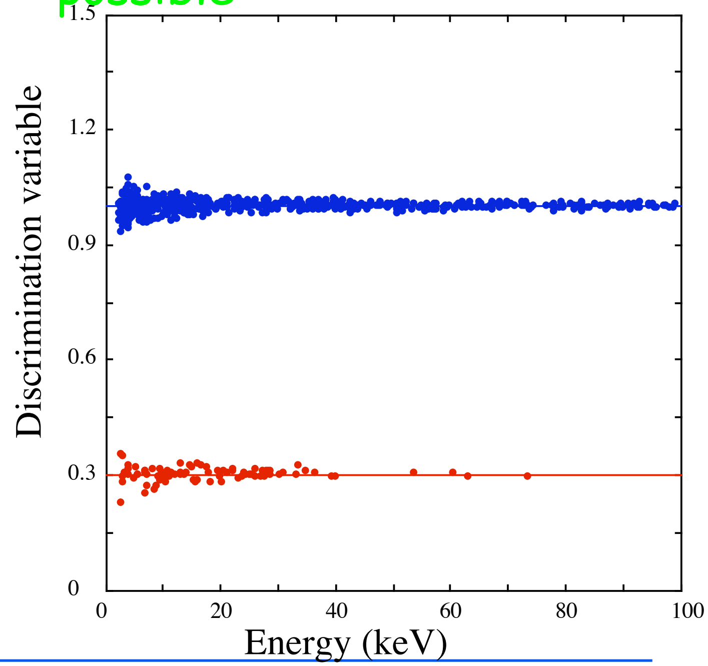
Linked to galaxy

- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)

Background Limited!

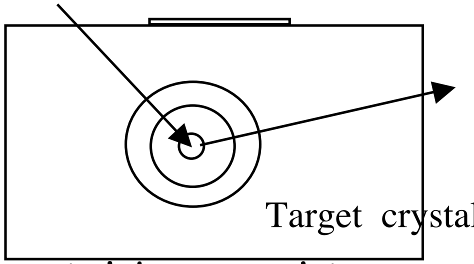
3 fundamental strategies

Aggressively tackle the background	Statistical method	Actively reject the background
State of the art: Heidelberg Moscow Extreme proposal: GENIUS 12m Ø liq. N_2 tank 10^4 improvement on current level	• Multiple scattering • Pulse shape discrim. • Annual modulation Large mass => simple detectors e.g. NaI	Active rejection with the best possible discrimination <= Best technology signal to noise no dead region/tails As much information as possible



Cryogenic Detectors

Principle: Phonon mediated detectors



Goals

- Sensitivity down to low energy

  Phonons measure the full energy (no ionization yield, quenching factor)

- Active rejection of background: recognition of nuclear recoil

  Combine with low field ionization measurement

  e.g. CDMS I and II

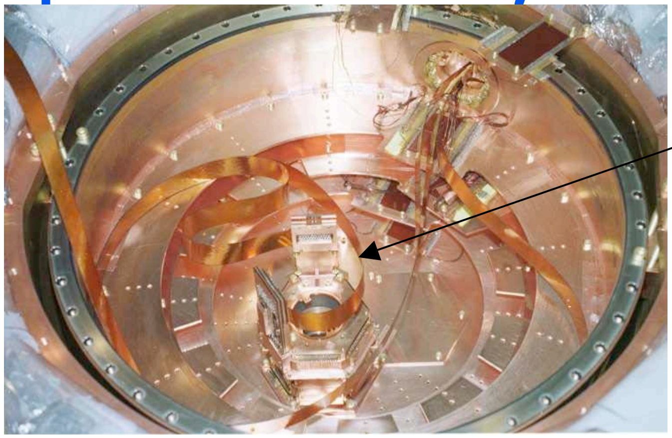
  EDELWEISS

  or photon (CRESST II)

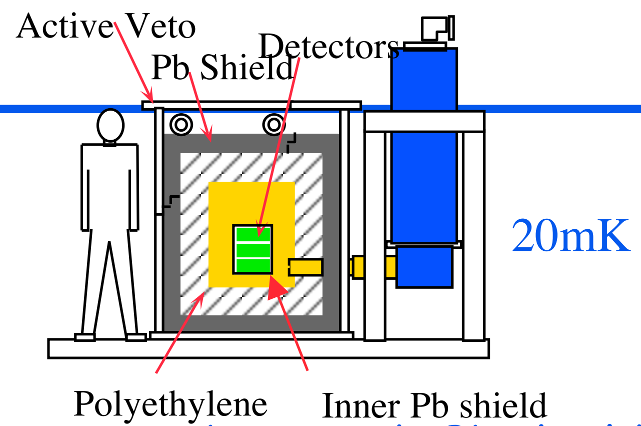
- More information on rare events

But: operation at very low temperature!

ex: CDMS I



CDMS I



View down tunnel (Icebox at far end)

Icebox inside Pb shielding

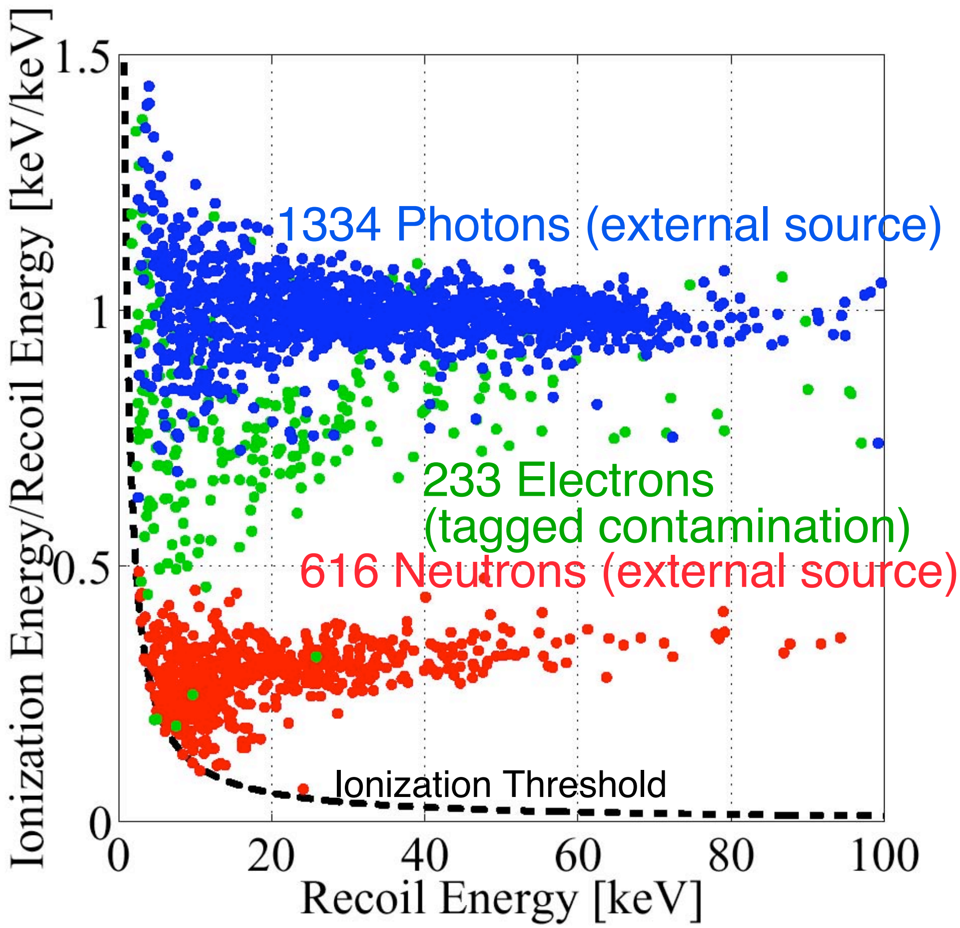
CDMS Background Discrimination

Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil

Most background sources (photons, electrons, alphas) produce electron recoils

Particles (electrons) that interact in surface "dead layer" of detector result in reduced ionization yield

WIMPs (and neutrons) produce nuclear recoils



Detectors provide near-perfect event-by-event discrimination against otherwise dominant bulk electron-recoil backgrounds

Very good (>95%) against surface electron-recoil backgrounds

Surface electrons ("betas")

Ionization collection has to be at small voltage

Drift in electric field creates Neganov-Luke phonons

e.g. at 3 V total voltage already as many phonons created in drift as original ones

Ionization carriers are created hot

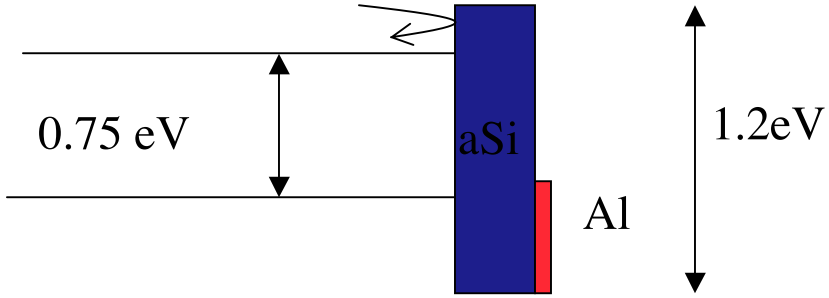
They can back diffuse in the field and be trapped on electrode

Dead layer of the other of a few 10μm where ionization is not fully collected

Ways out

Surface amorphous silicon layer: larger gap=> partial reflection

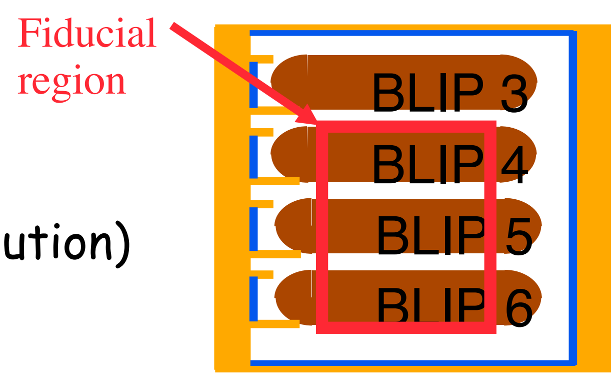
Tom Shutt



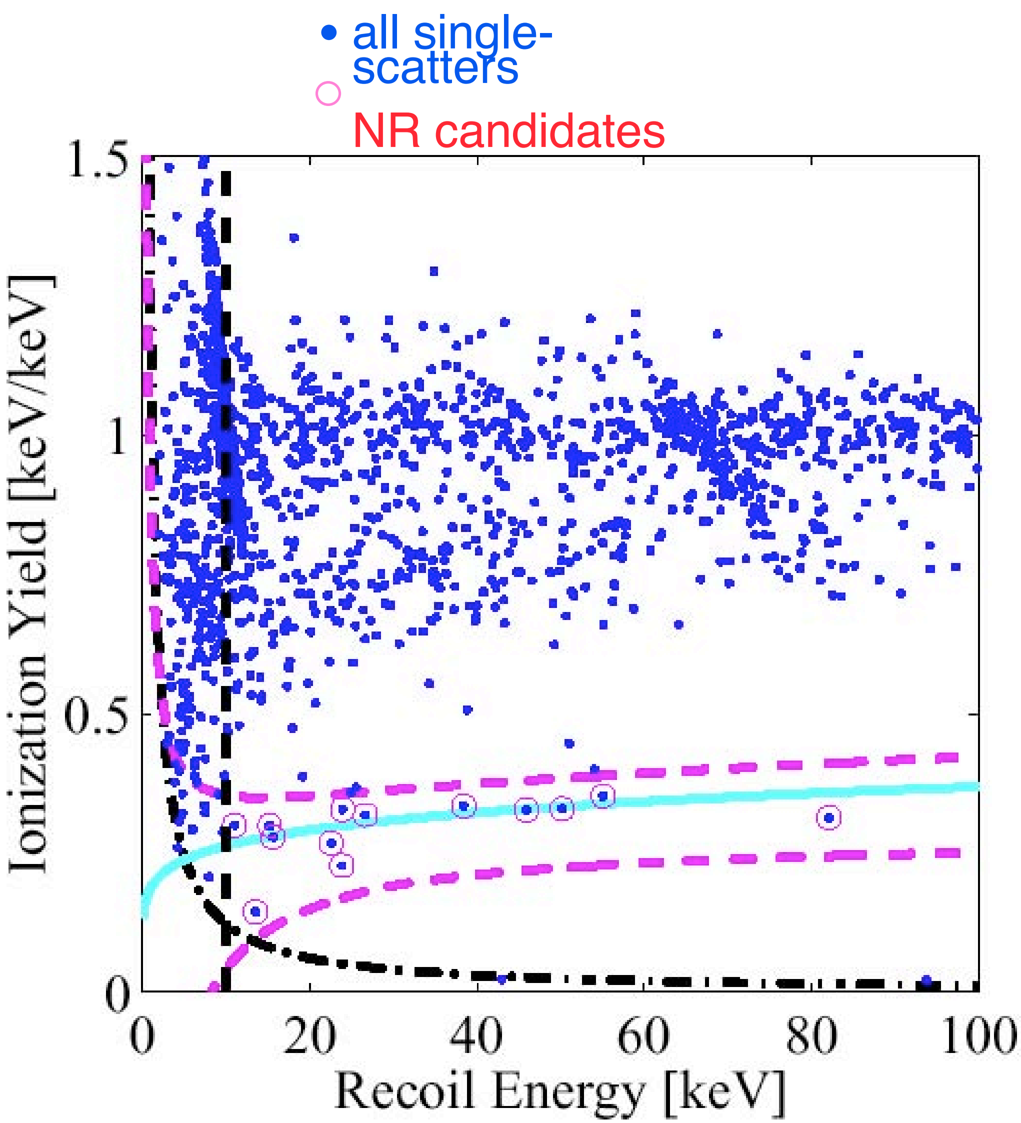
Work at as large a voltage as possible (but resolution)

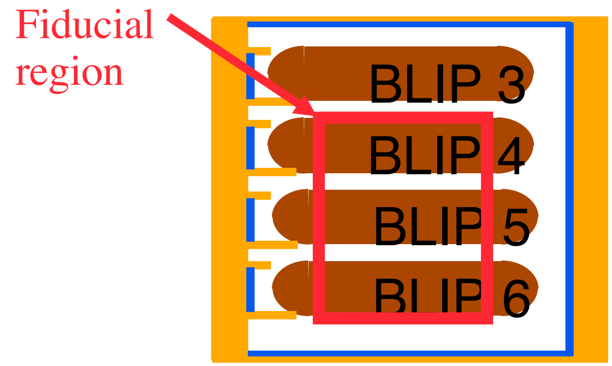
Self shielding

Use phonon pulse shape discrimination



1999 Run Ge BLIP Data Set





Entire 45 live days operation Ge BLIPs = 12.4 kg-days

Gamma and electron bands well separated from NR band

NR candidates are truly NR's

See a total of 13 events > 10 keV
➜ ~ 1 event/kg/day

Even though this event rate is in the region of the DAMA signal, cannot be WIMPs

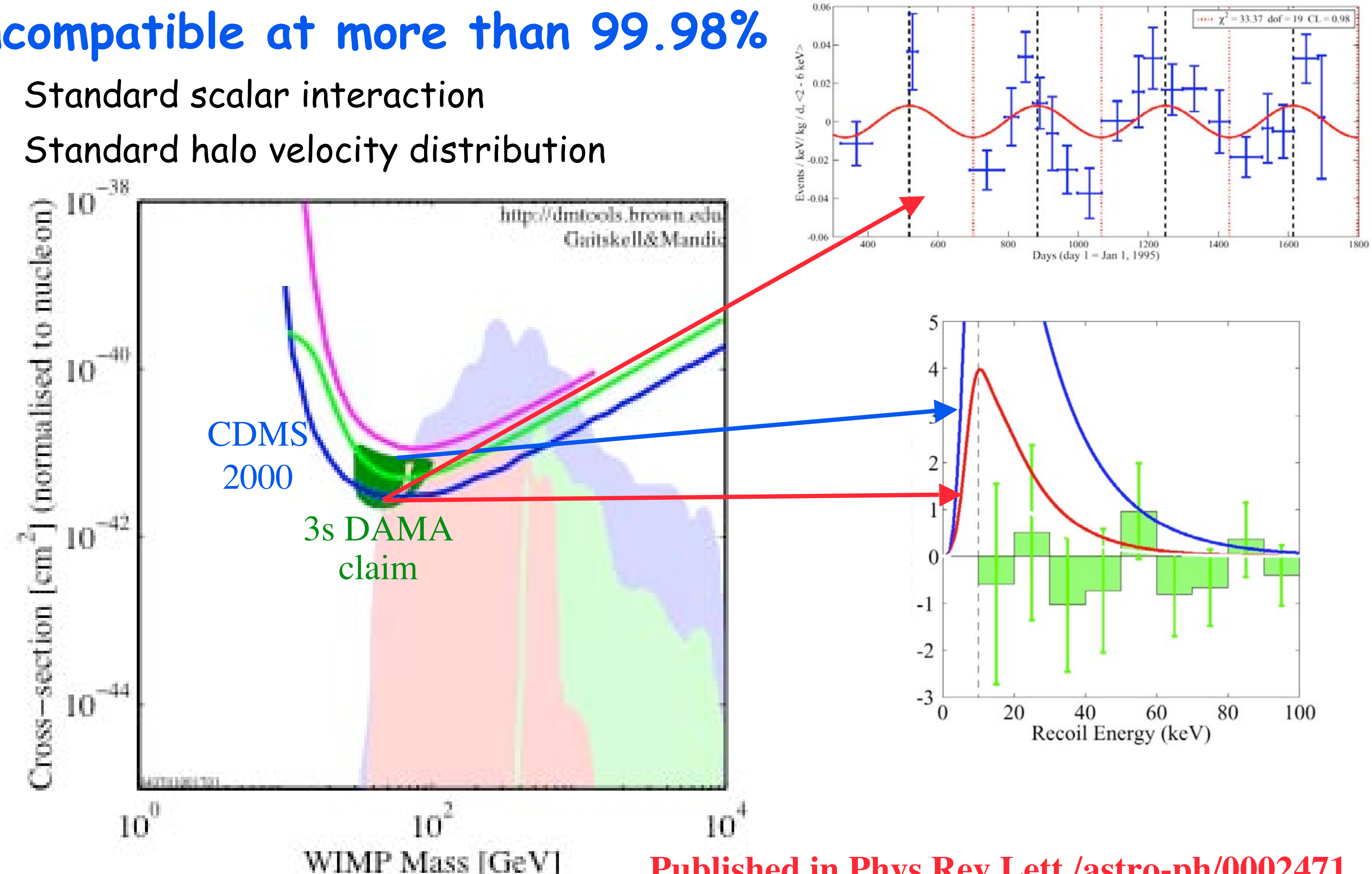
<= 4 multiple events Neutrons (17 m.w.e.)

CDMS and DAMA Feb 2000

Incompatible at more than 99.98%

Standard scalar interaction

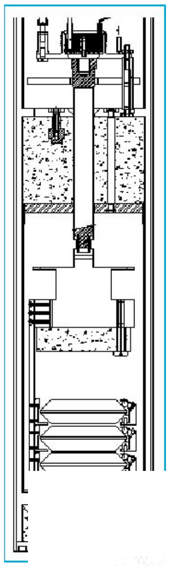
Standard halo velocity distribution

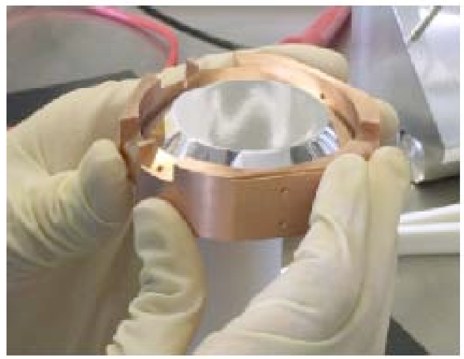


Published in Phys Rev Lett./astro-ph/0002471

EDELWEISS

Similar technology to CDMS I

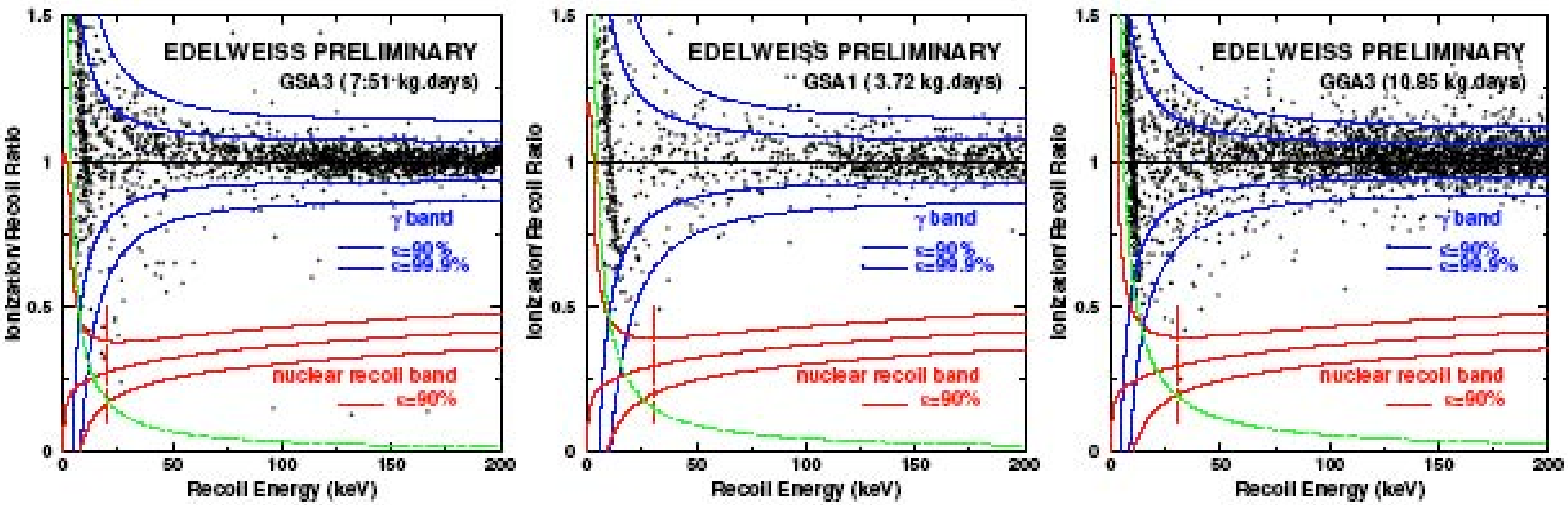




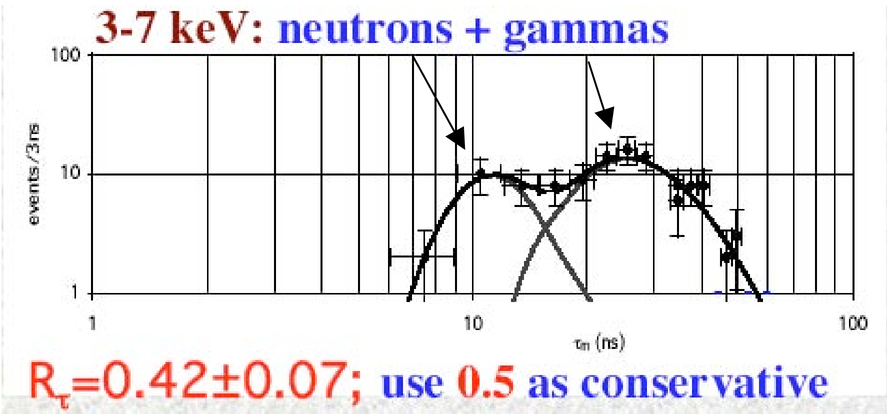
Edelweiss

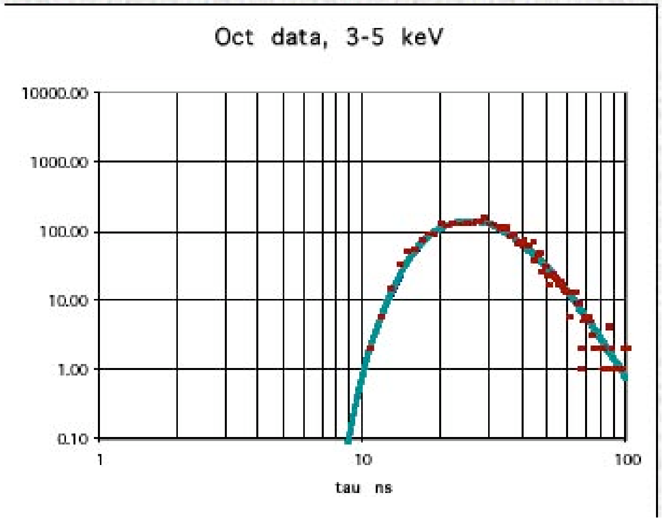
Deep underground (Frejus)
30 cm parafine, 20cm Pb ,10 cm Cu
No active veto

2 events which limit their sensitivity (neutrons?)



Zeplin





ZEPLIN I

- Recombination allowed
- Only scintillation signal measured
- Discrimination is based on pulse shape

Unfortunately no calibration underground

2000-2004

CDMS I

CDMS confirms its story at shallow depth

Blue curves

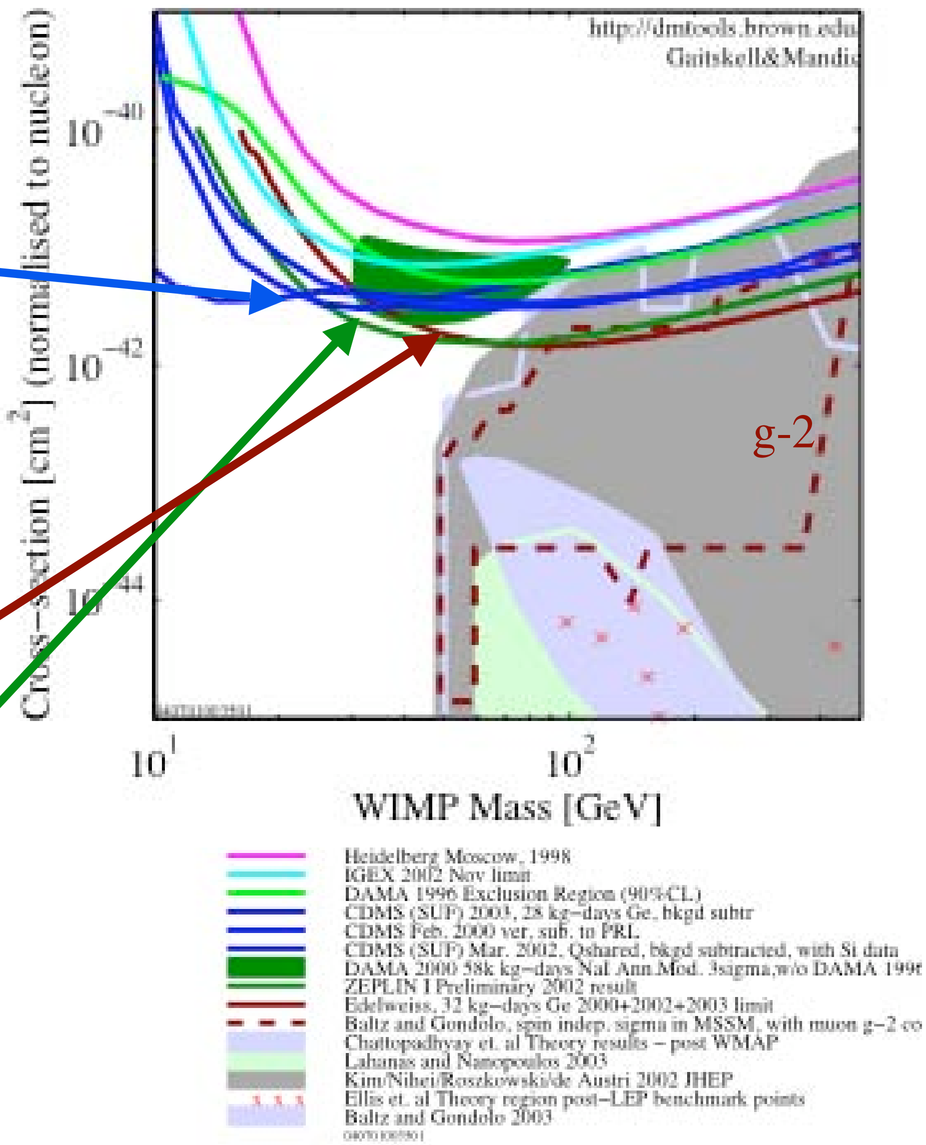
- Enlargement of fiducial region
- New detector technology (CDMSII detectors)
- Additional neutron moderation

EDELWEISS: same story

already located deep
Underground, takes the lead at high mass
But some events begin to appear neutrons?

ZEPLIN 1

Liquid Xenon with scintillation
No in situ calibration

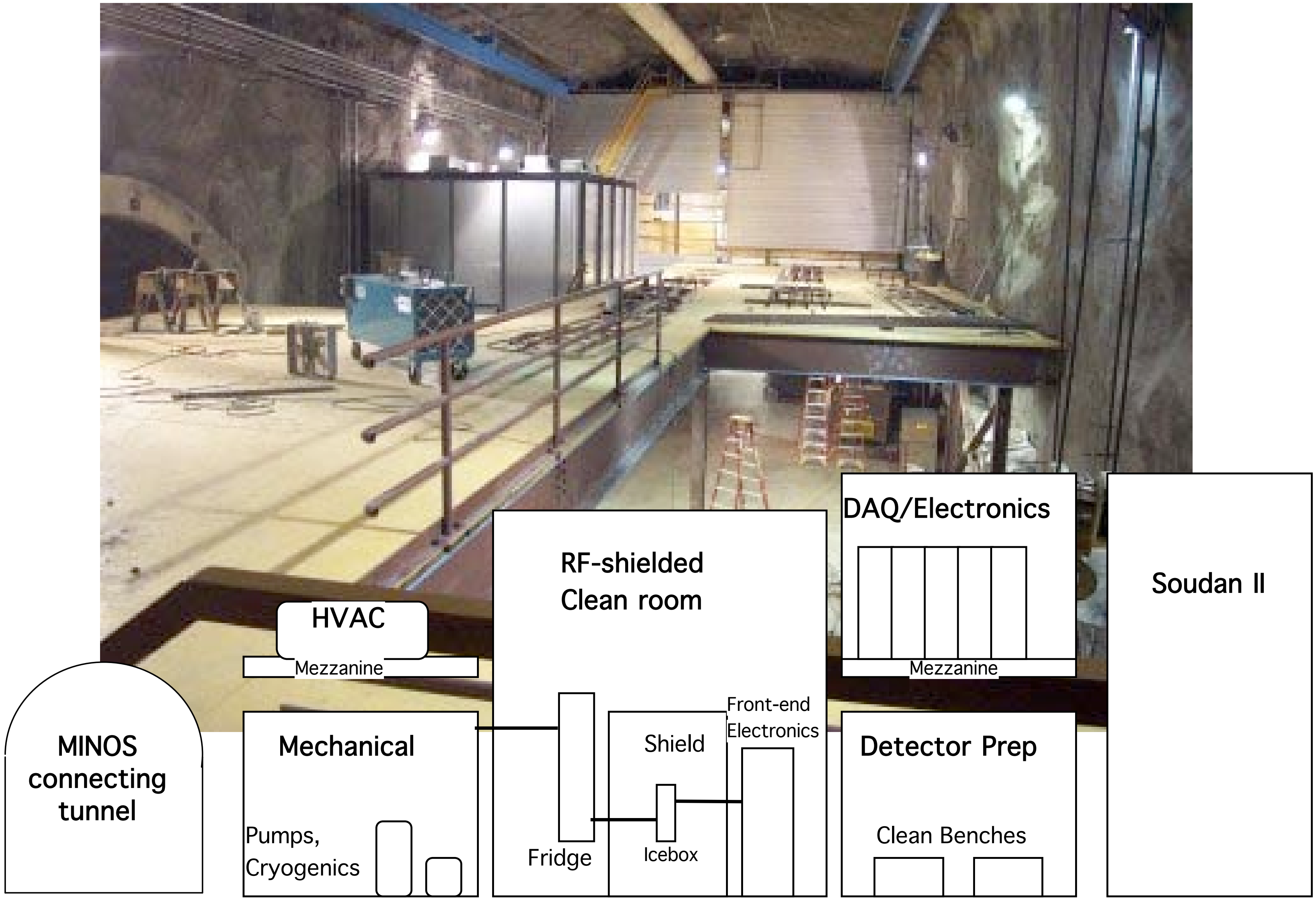


CDMS II strategy

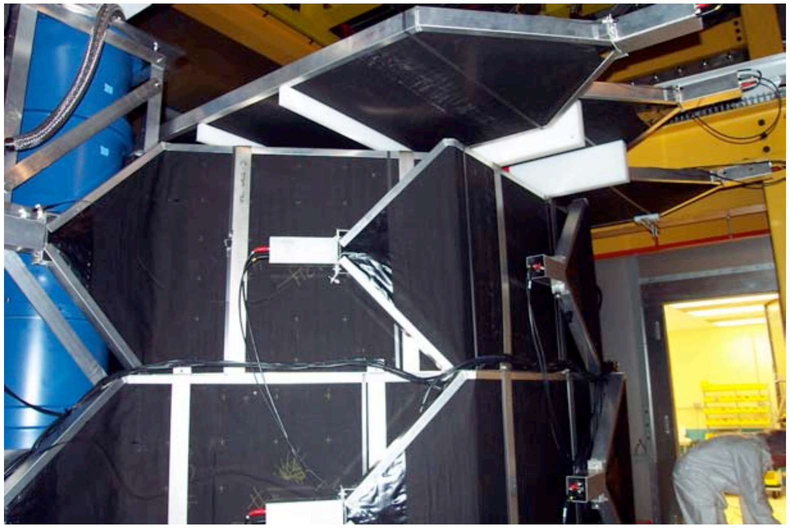
3 elements

- Go deep underground (Soudan)
- Careful Neutron shielding strategy
- Athermal phonon sensing to get more information about the events

Experimental Setup in the Soudan Mine



CDMS II Shielding



Active muon veto

40 cm outer polyethylene

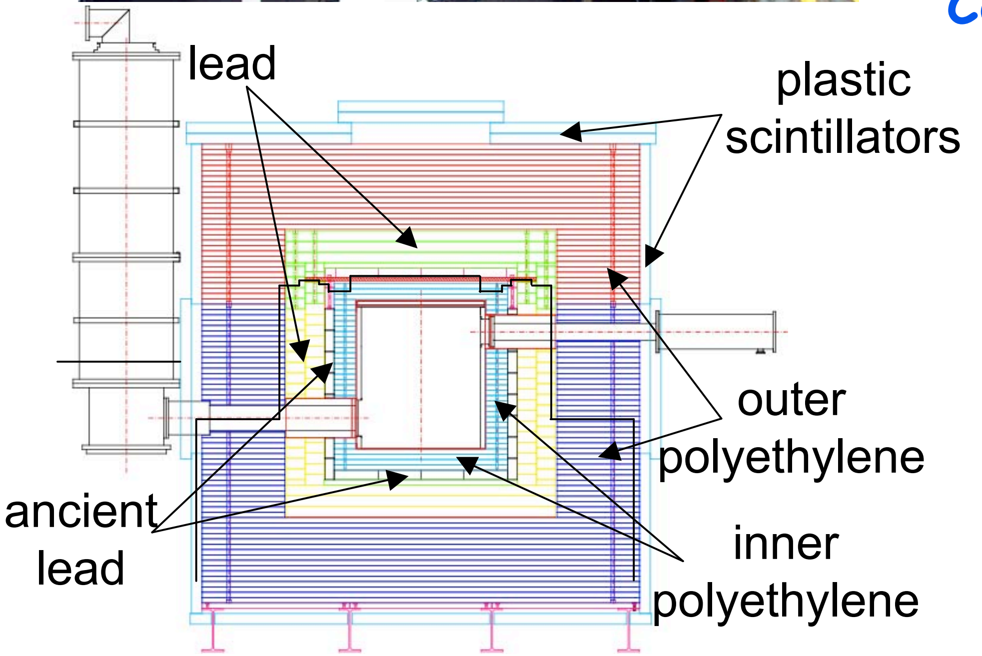
Removes neutrons from (α,*n*)

22.5 cm lead shielding

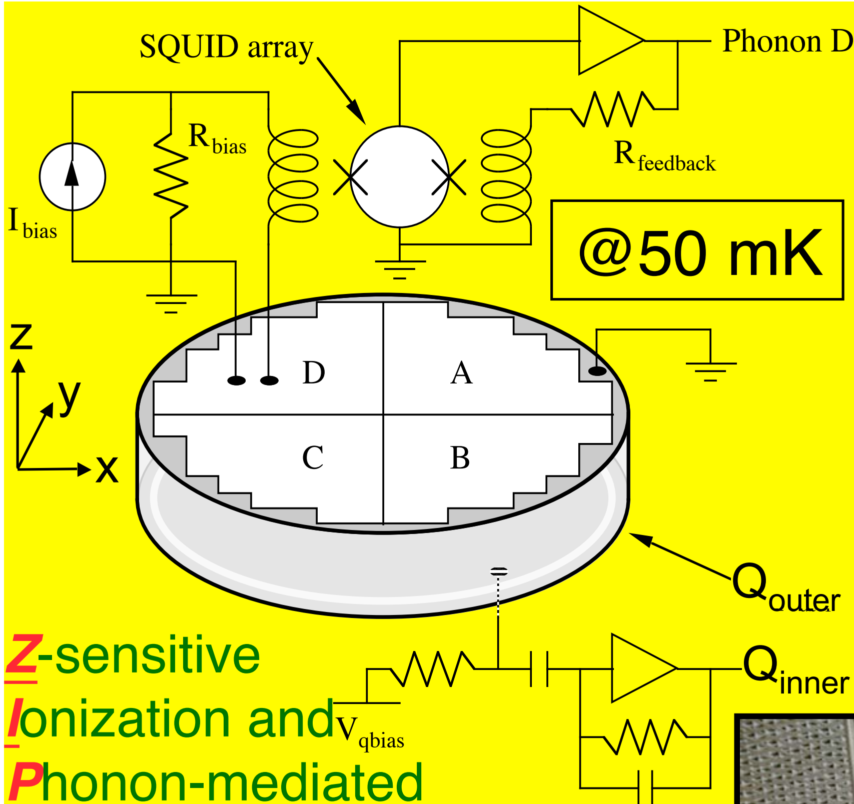
10 cm inner polyethylene

Reduces neutrons from muons

Copper cryostat



Really Cool Detectors: ZIPs



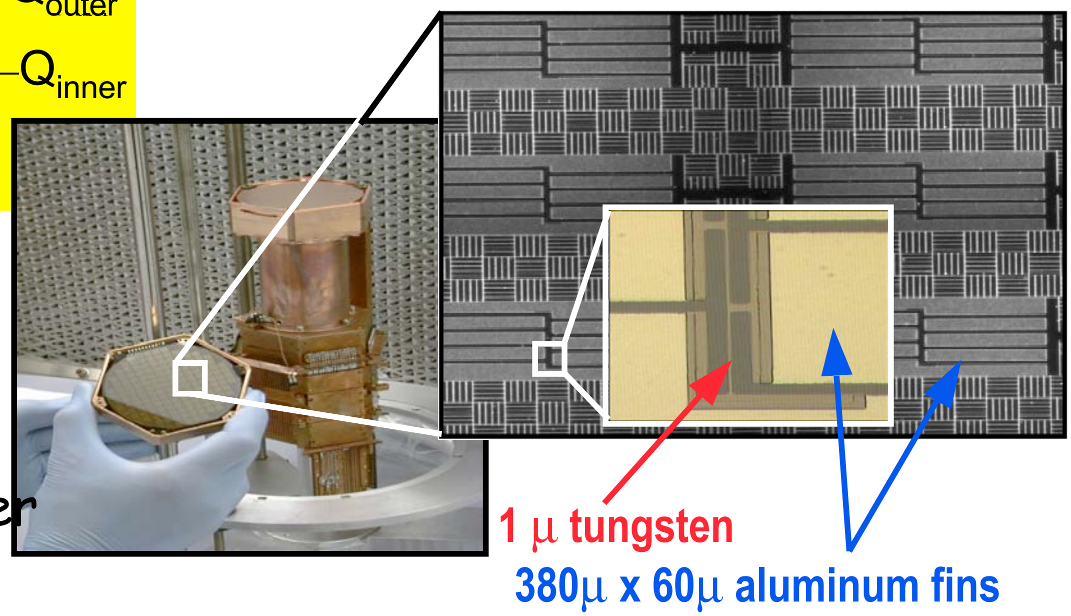
250 g Ge or 100 g Si crystal

1 cm thick x 7.5 cm diameter

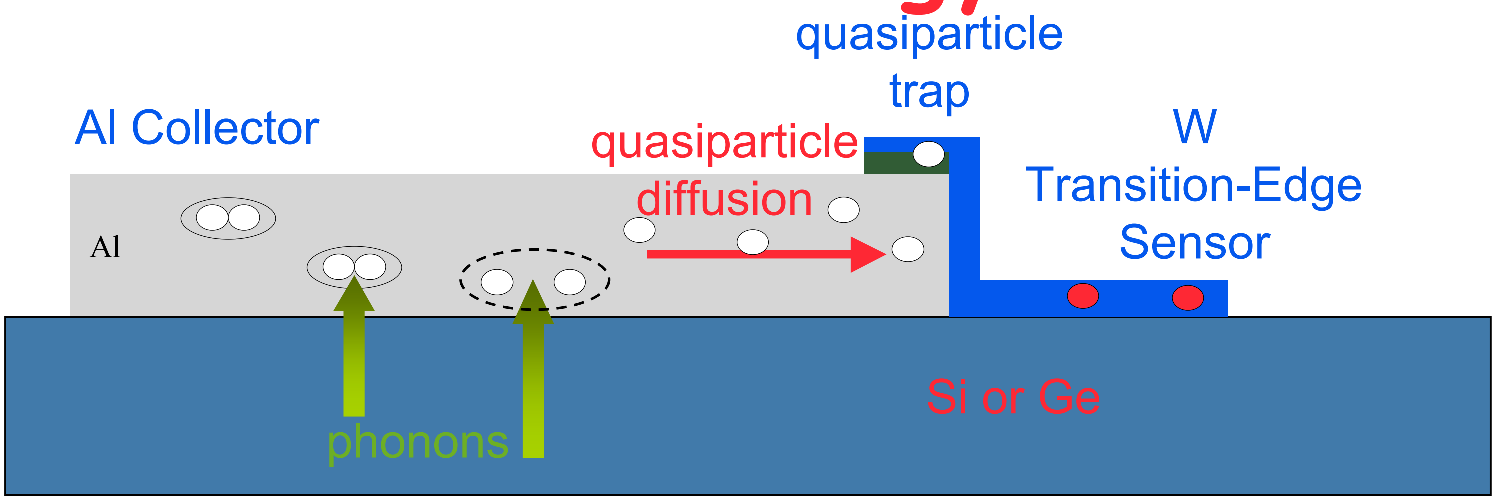
Photolithographic patterning

Collect athermal phonons

Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge



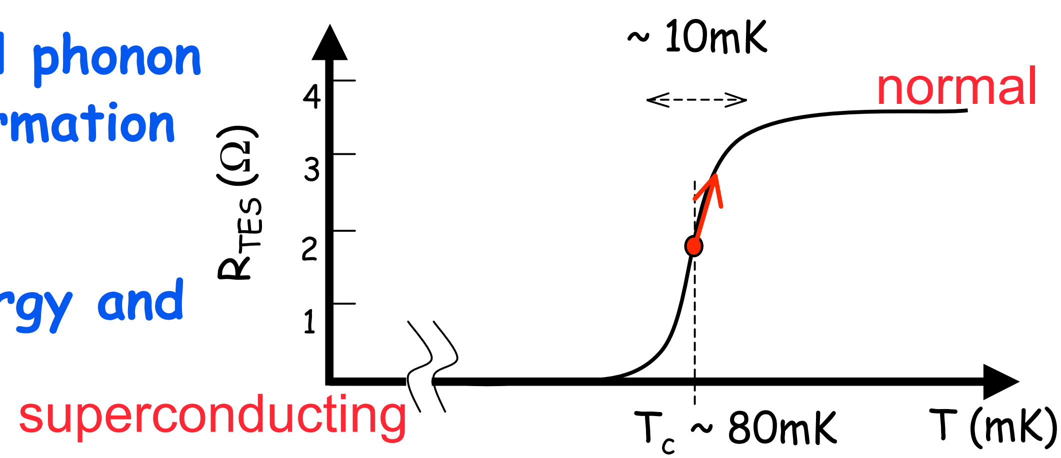
ZIP Detector Phonon Sensor Technology



W Transition-Edge Sensor:
a really good thermometer

Measurement of athermal phonon signals maximizes information

Fast pulse, excellent energy and timing resolution

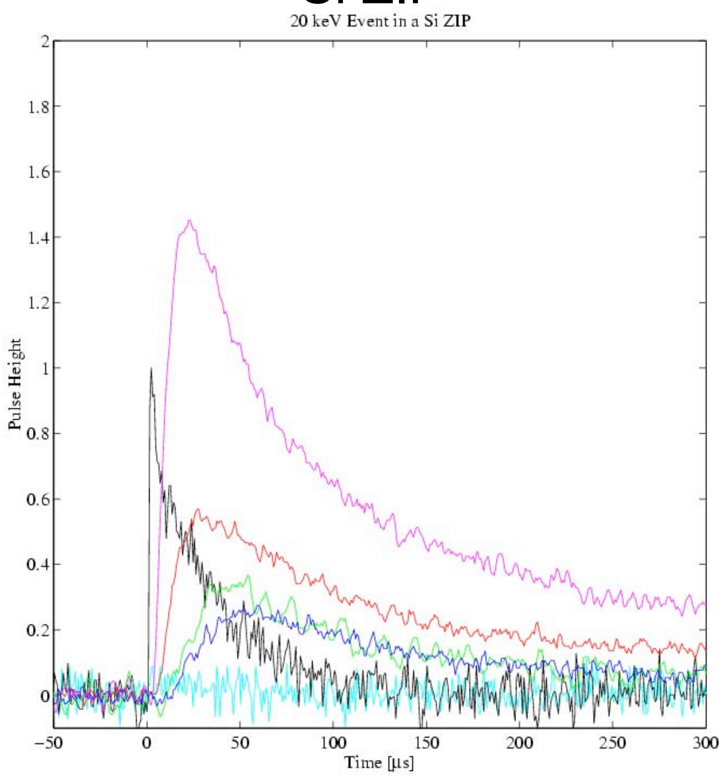


The ZIP Detector Signal

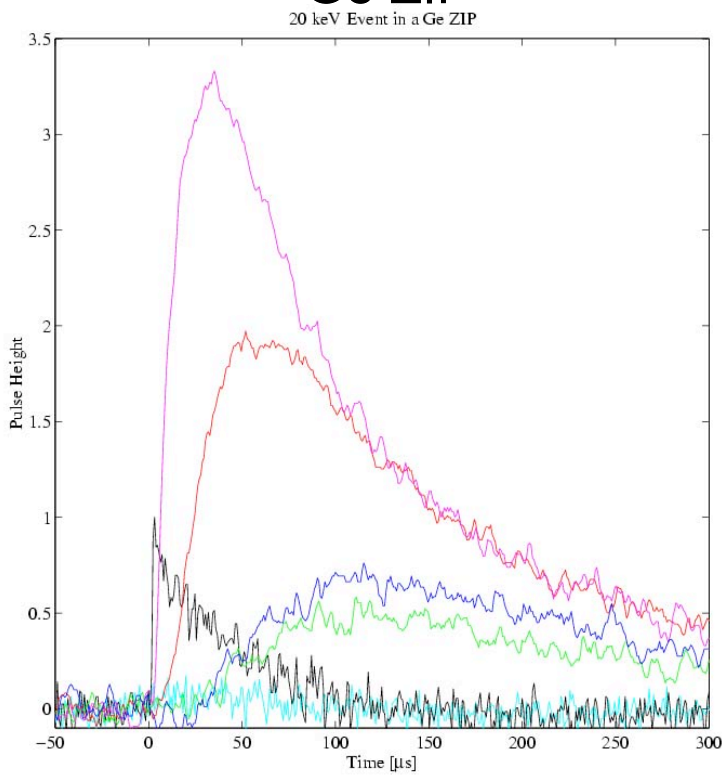
Charge & Phonon signals occur on a similar timescale

20 keV (true recoil energy) in a Si & Ge ZIP

Si ZIP



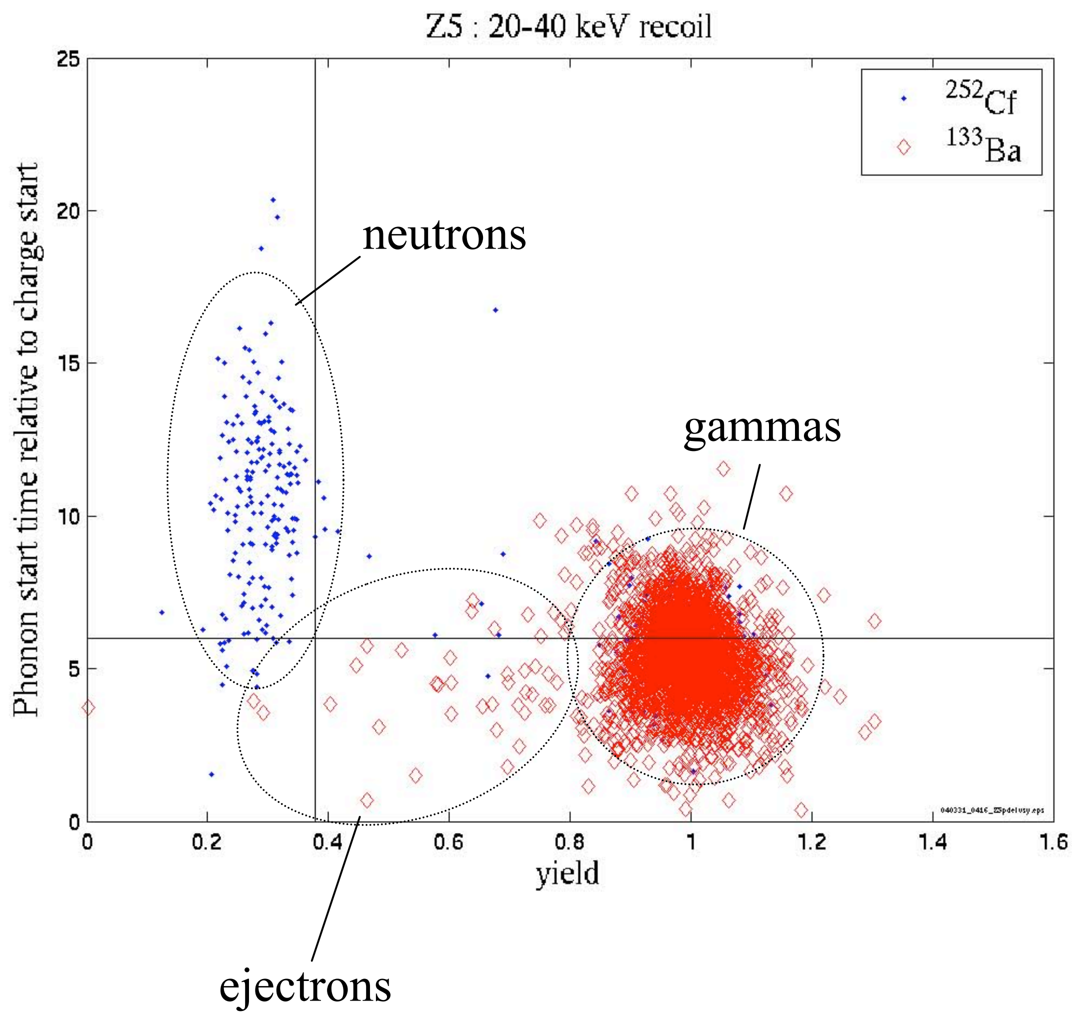
Ge ZIP



(EXCELLENT S/N FOR 20 KeV TRUE RECOIL ENERGY)

^{133}Ba γ & ^{252}Cf neutron calibrations

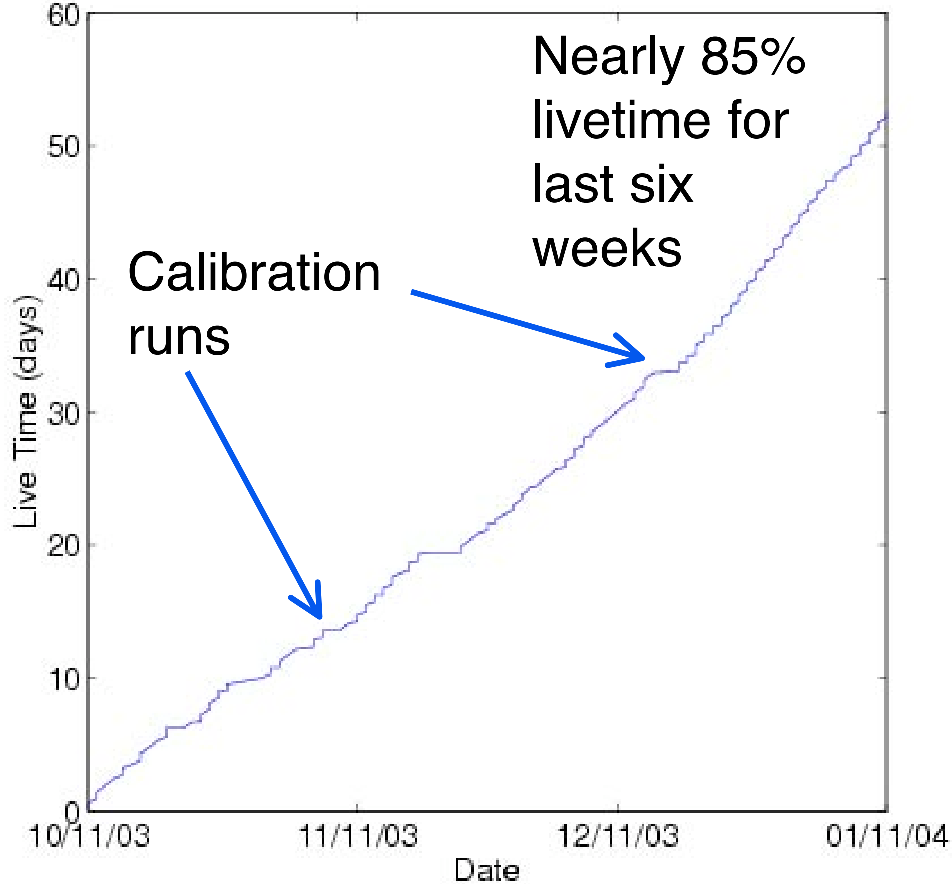
Use phonon risetime and charge to phonon delay for discrimination of surface electrons "betas"

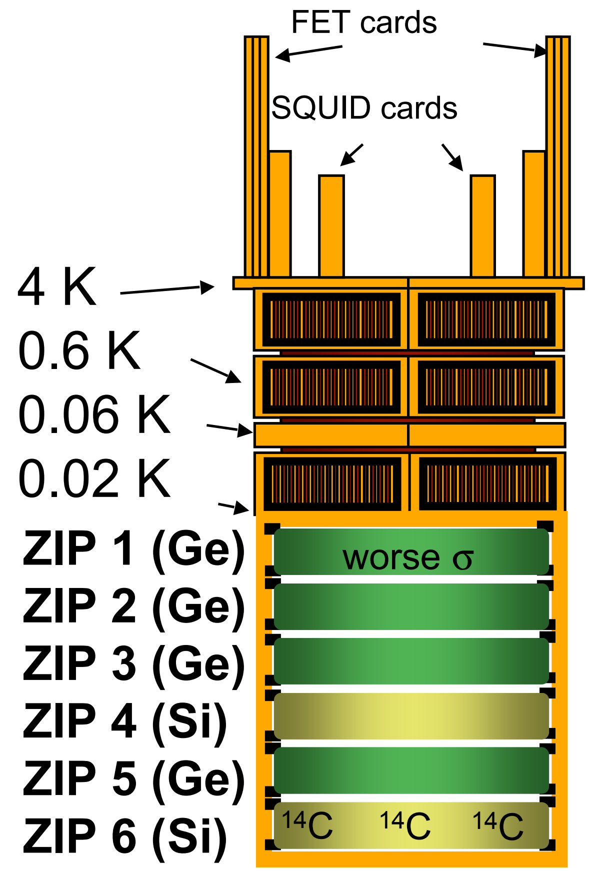


First Run of CDMS II at Soudan

October 2003- January 2004 run of "Tower 1"

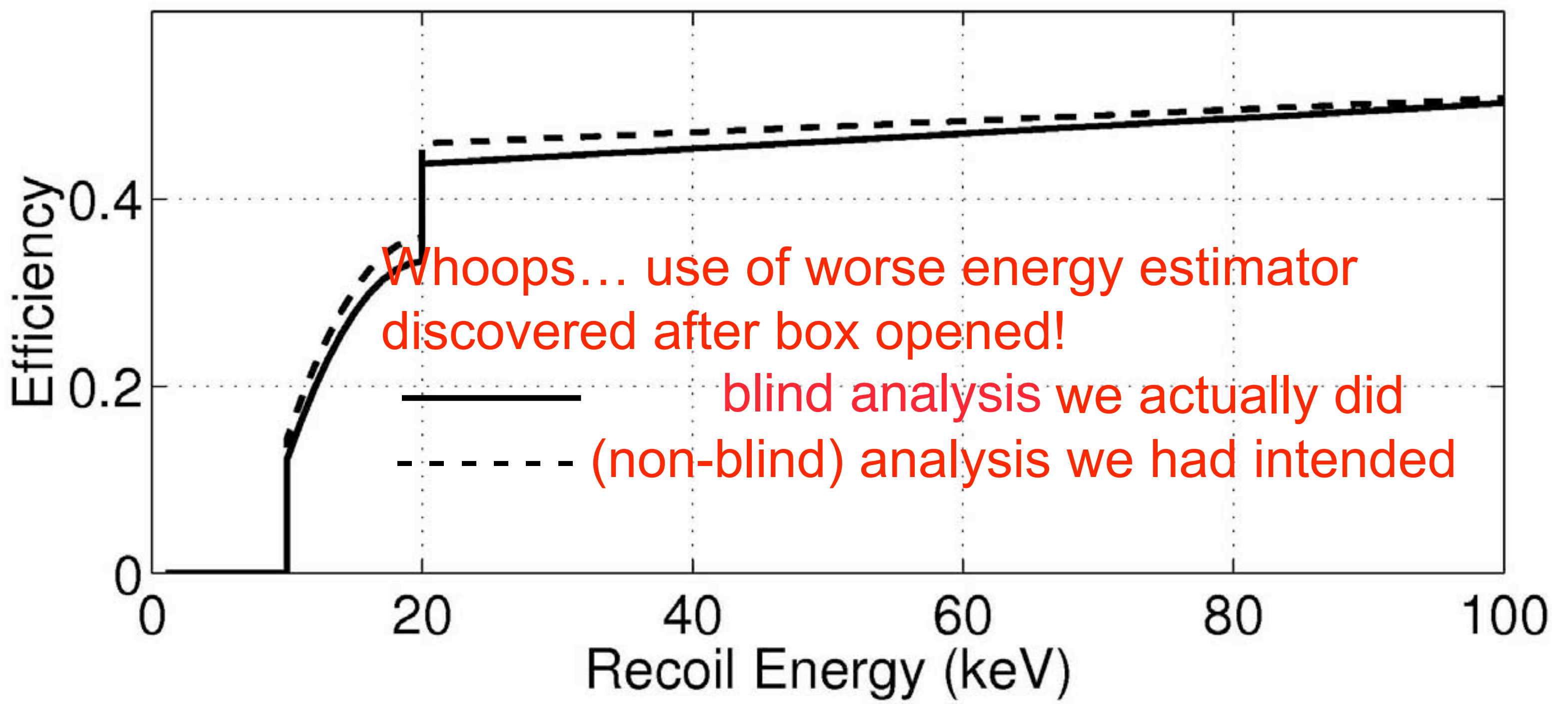
- Same 4 Ge (1 kg) and 2 Si (0.2 kg) ZIPs run at Stanford
- Photon and electron rejection both better than proposal
- 62 "raw" livedays, 53 livedays after cutting times of poor noise, etc.





Cuts and Efficiencies

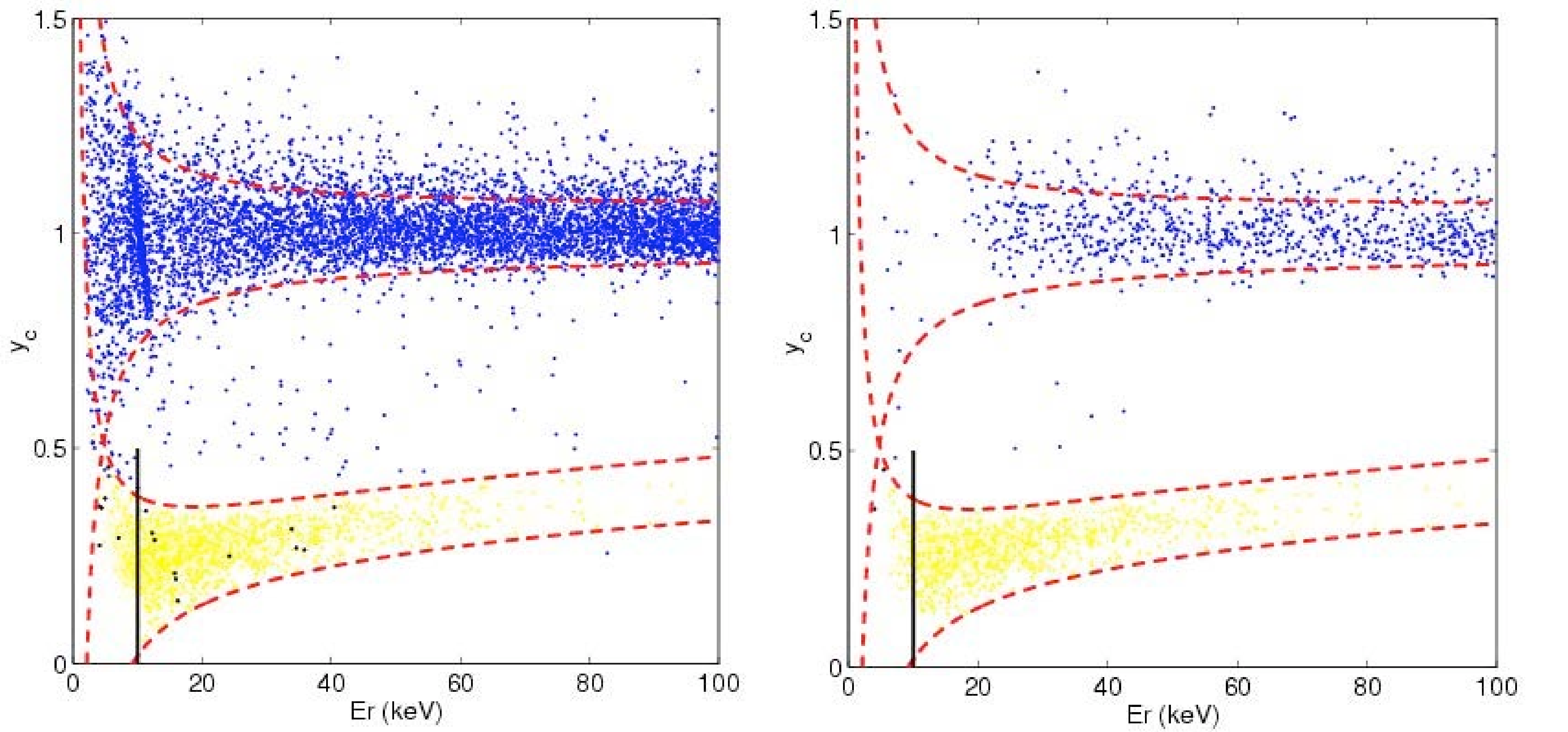
- Defined by calibration samples
- Blind analysis: data on low-yield events from WIMP-search run `in the box' until cut definitions completed
- Opened box on March 20th



WIMP search data with Ge detectors

In 92 days between October 11, 2003 and January 11, 2004, we collected 52.6 live days - a net exposure of 22 kg-d after cuts

Below data are shown before (left) and after (right) timing cuts



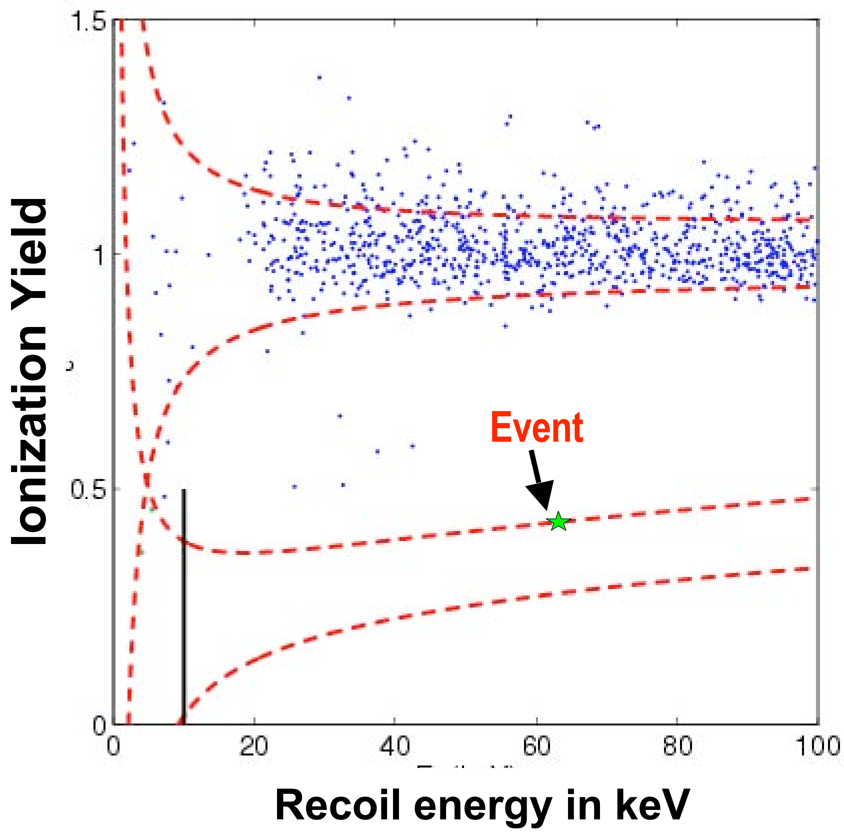
(yellow points are from neutron calibration)

With Optimal Code

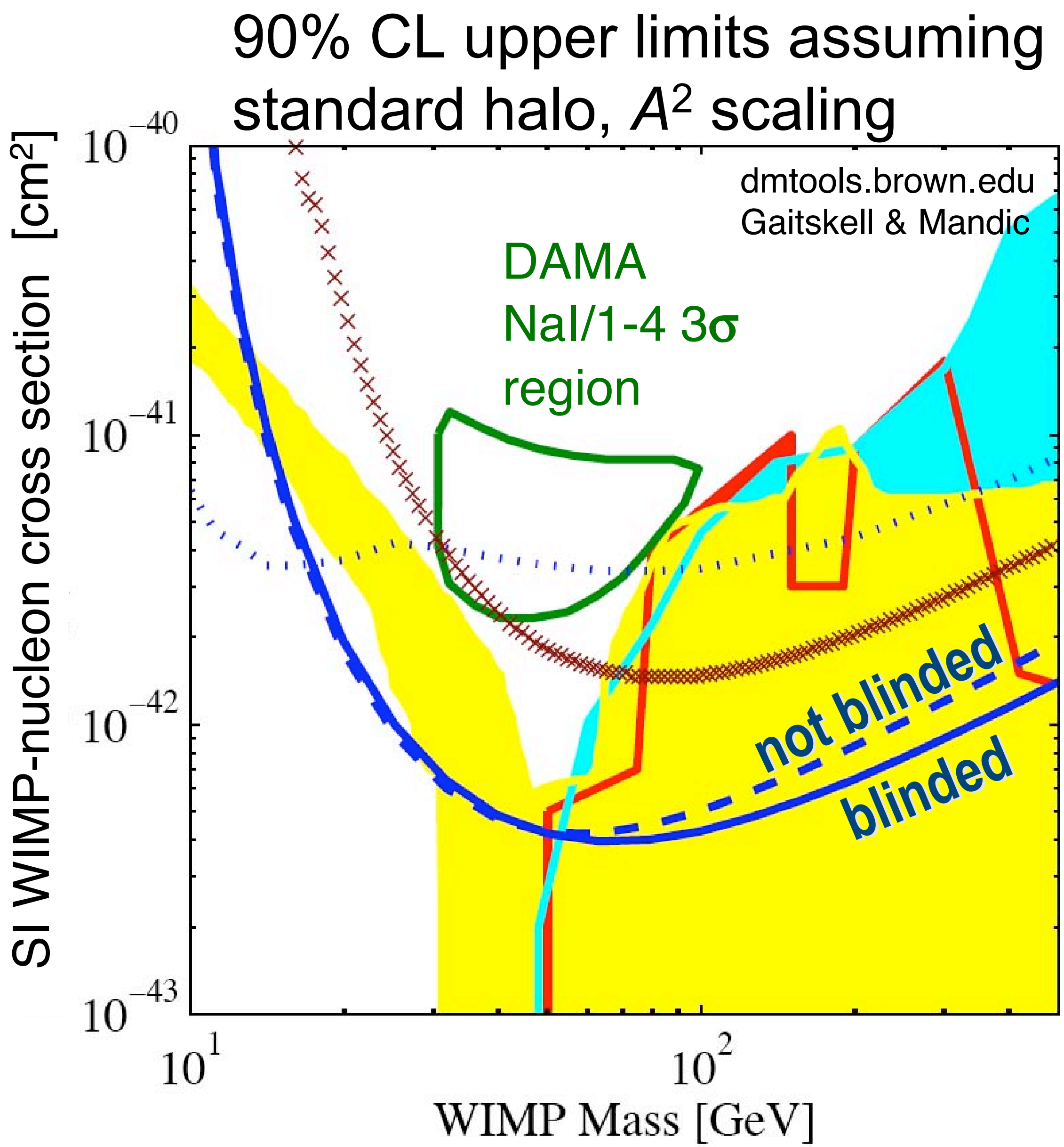
Formally not blind

Because we discovered the error after opening the box

Howver cuts determined only from calibration data.



Resulting Experimental Upper Limits



Upper limits on the WIMP- nucleon cross section are 4×10^{-43} cm^2 for a WIMP with mass of 60 GeV/c^2

- Factor of 4 below best previous limits (EDELWEISS xxx)
- Factor of 8 below ••••CDMS-SUF ••••

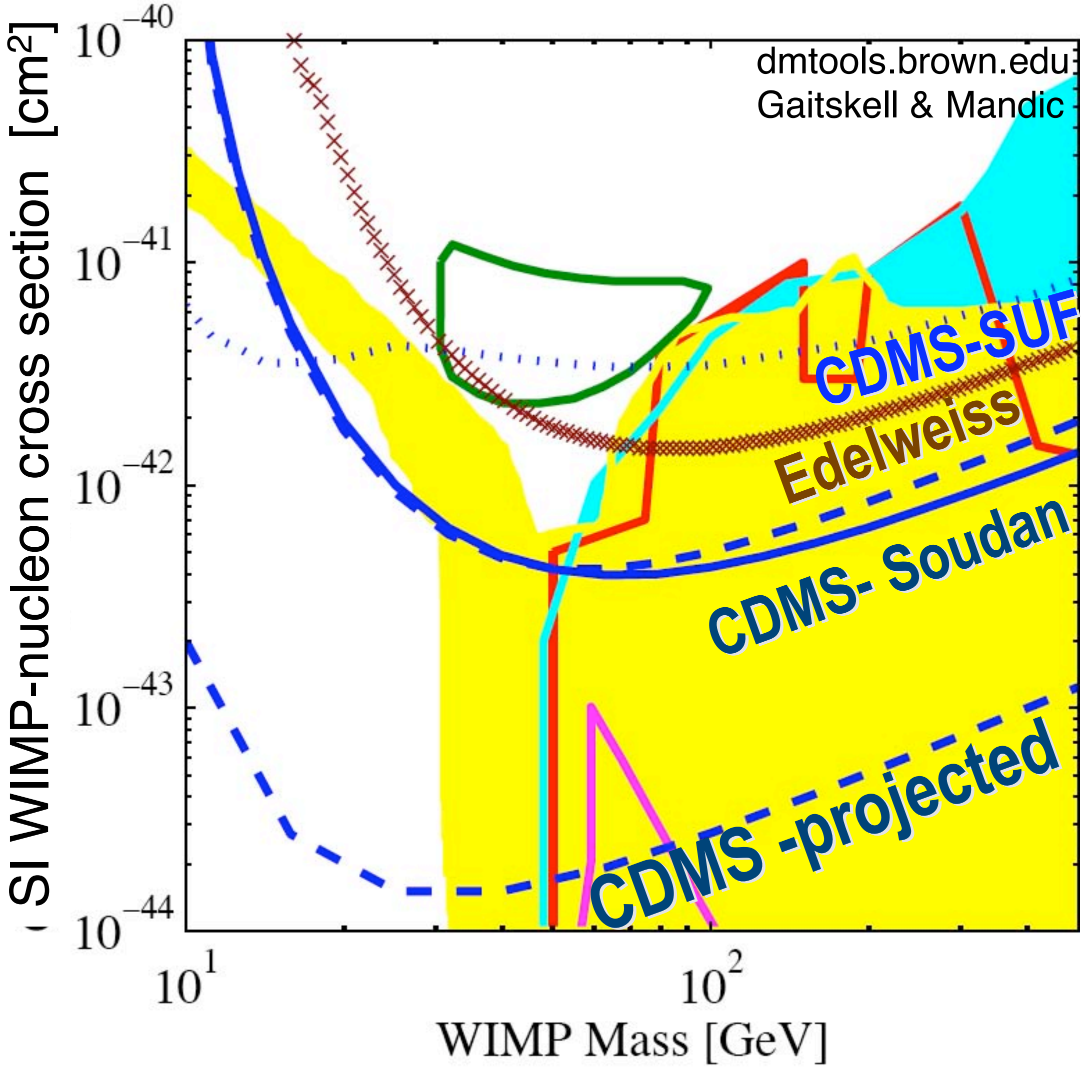
Incompatible with DAMA signal if "standard picture" but many alternatives

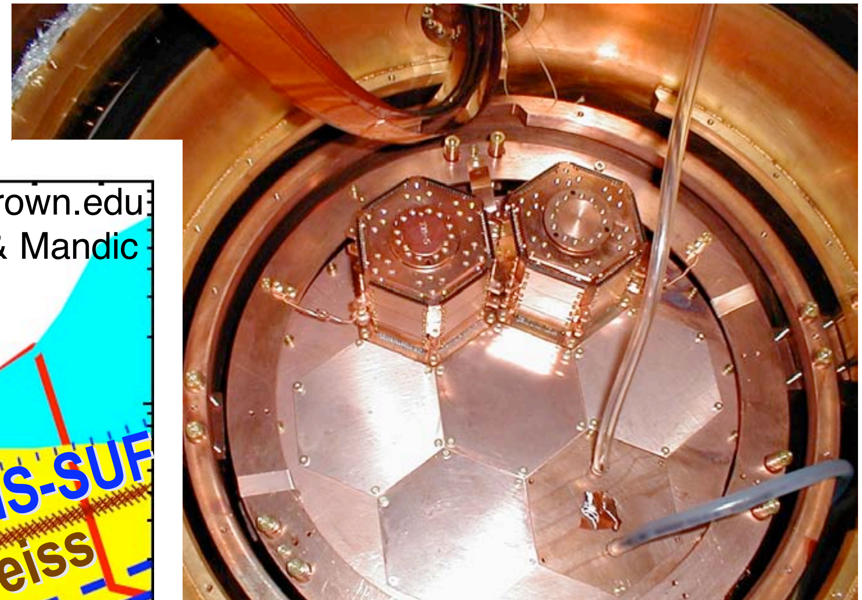
Excludes large regions of SUSY parameter space under some frameworks

Bottino et al. 2004 in yellow
Kim et al. 2002 in cyan
Baltz & Gondolo 2003 in red

Projected CDMS Sensitivity

Running 12 detectors since March 2004





Double exposure and sensitivity by end of summer

10 more detectors ready

8 more in fabrication

4 kg of Ge, 1.5 kg of Si to run throughout 2005 (+?)

Improve sensitivity x10 - x20

2nd Generation

Check DAMA (NaI)

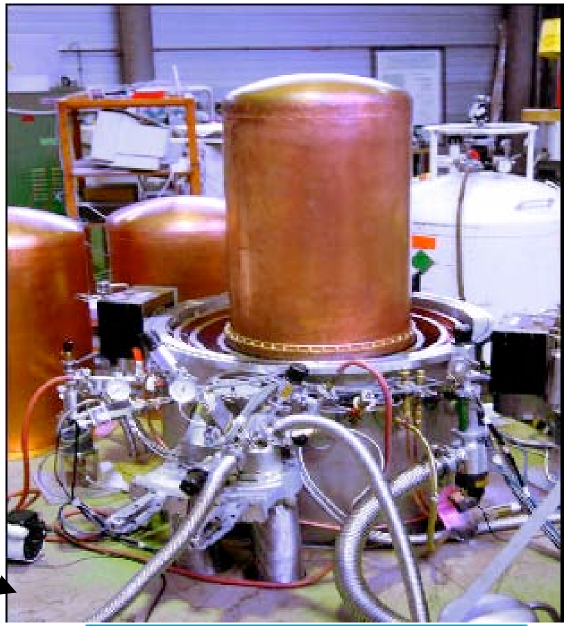
Libra (Rome), ANAIS (Spain)

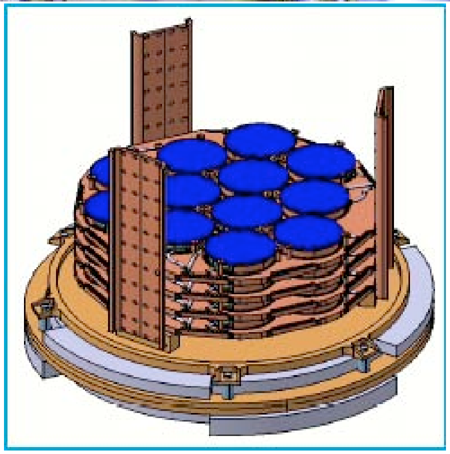
XMASS

Cryogenic Detectors

CDMS II, EDELWEISS II, CRESST II

Similar reach with complementary assets





+ test new technologies

Naked Ge detectors (Genino)

Xenon Ionization + Scintillation

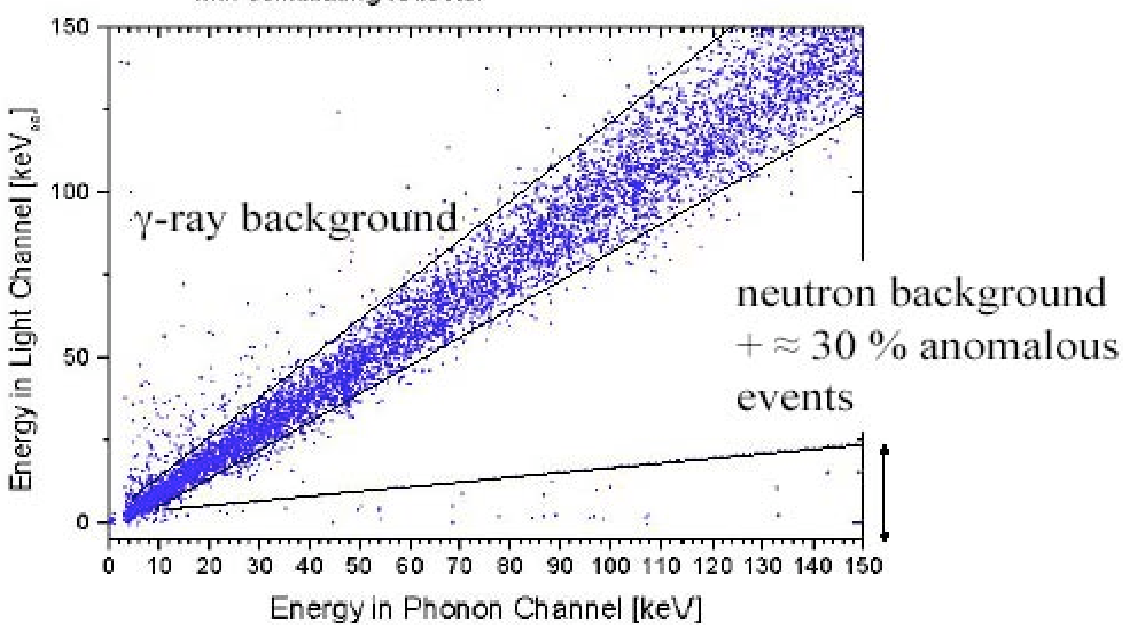
CRESST

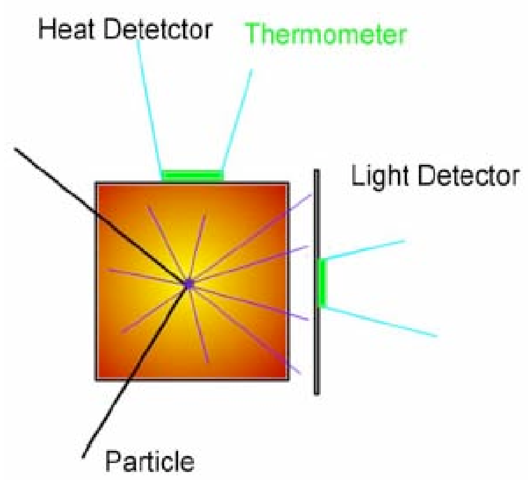
- High rejection:

  99.7% E > 15 keV

  99.9% E>20 keV
- 9.7 kg.day data
- Only half of the data analyzed.
- Data without neutron shield.
- Sensitivity limited by n.

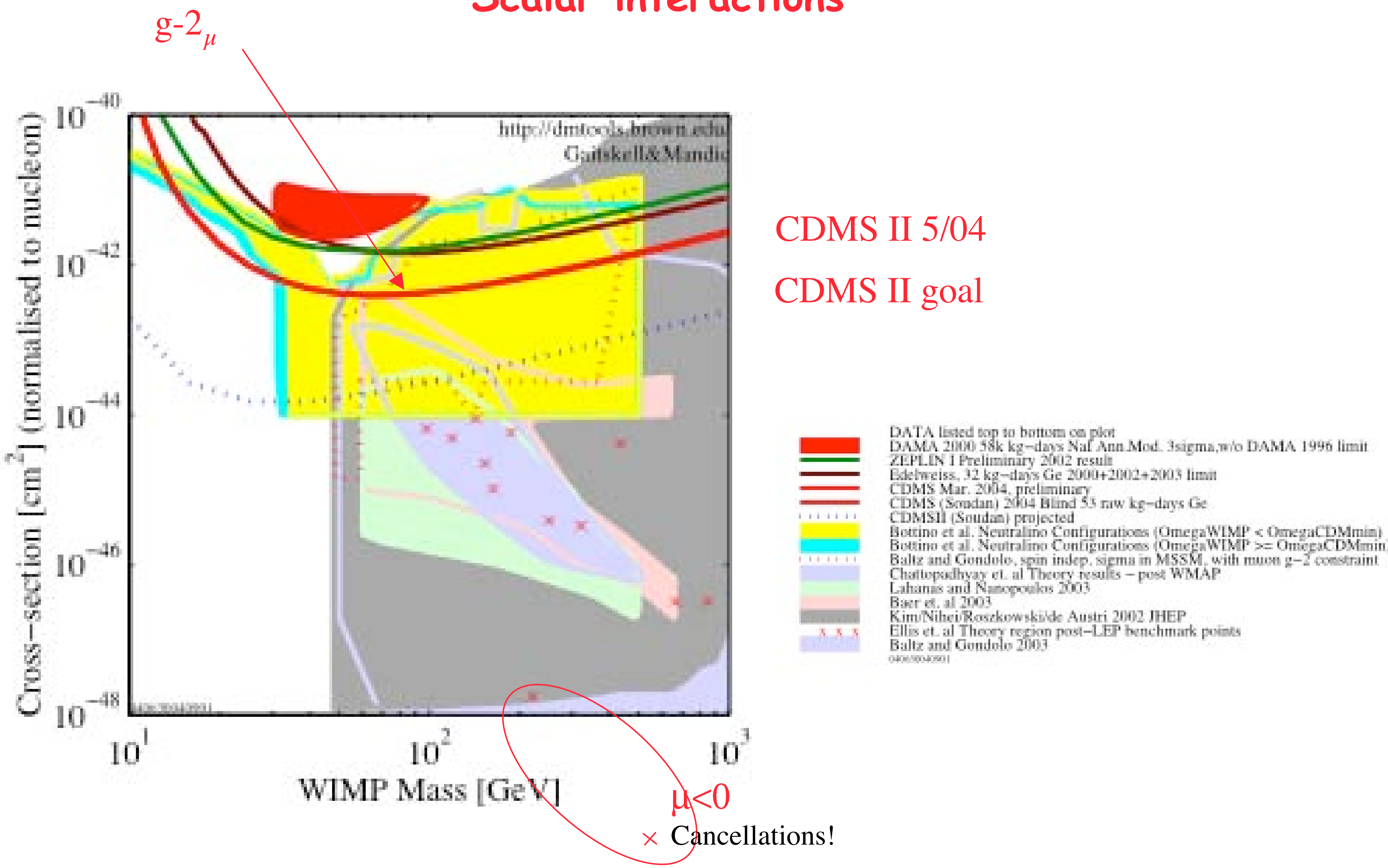
Run28 (Daisy, bck 10 to 74, 9.052 kg days)
with scintillating reflector





SUSY Calculations

Scalar interactions

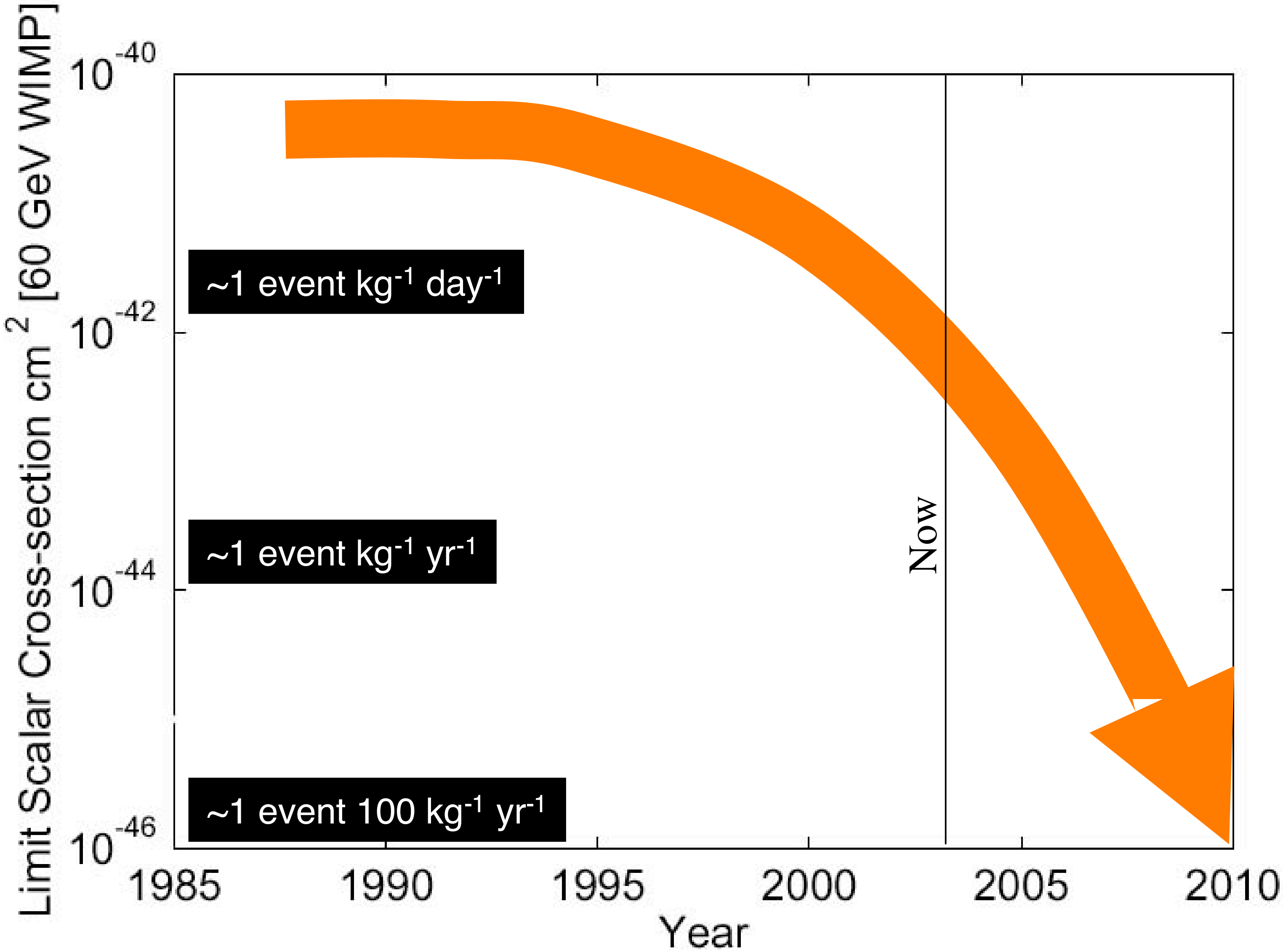


× Cancellations!

Direct Detection: History & Future

90% CL Limit on Cross section for 60 GeV WIMP (scalar coupling)

After Gaitskell (astroph 0106200)



Going to Large Masses

With ≈ event by event discrimination

2 routes

- Extrapolate cryogenic technologies (demonstrated leaders)
  - surface electron reduction
  - increase mass
  - simplify technology

- Liquid Xe : ionization +phonon

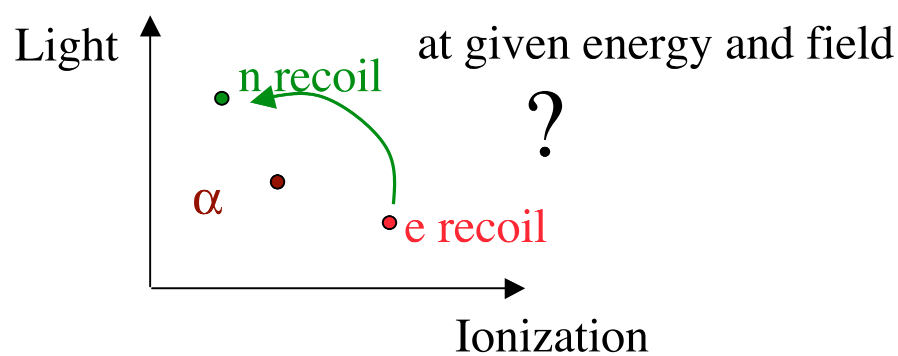
Hope that it scales "gracefully" to large masses)

But main parameters of the technology have not yet been measured

Main problems: threshold
edges

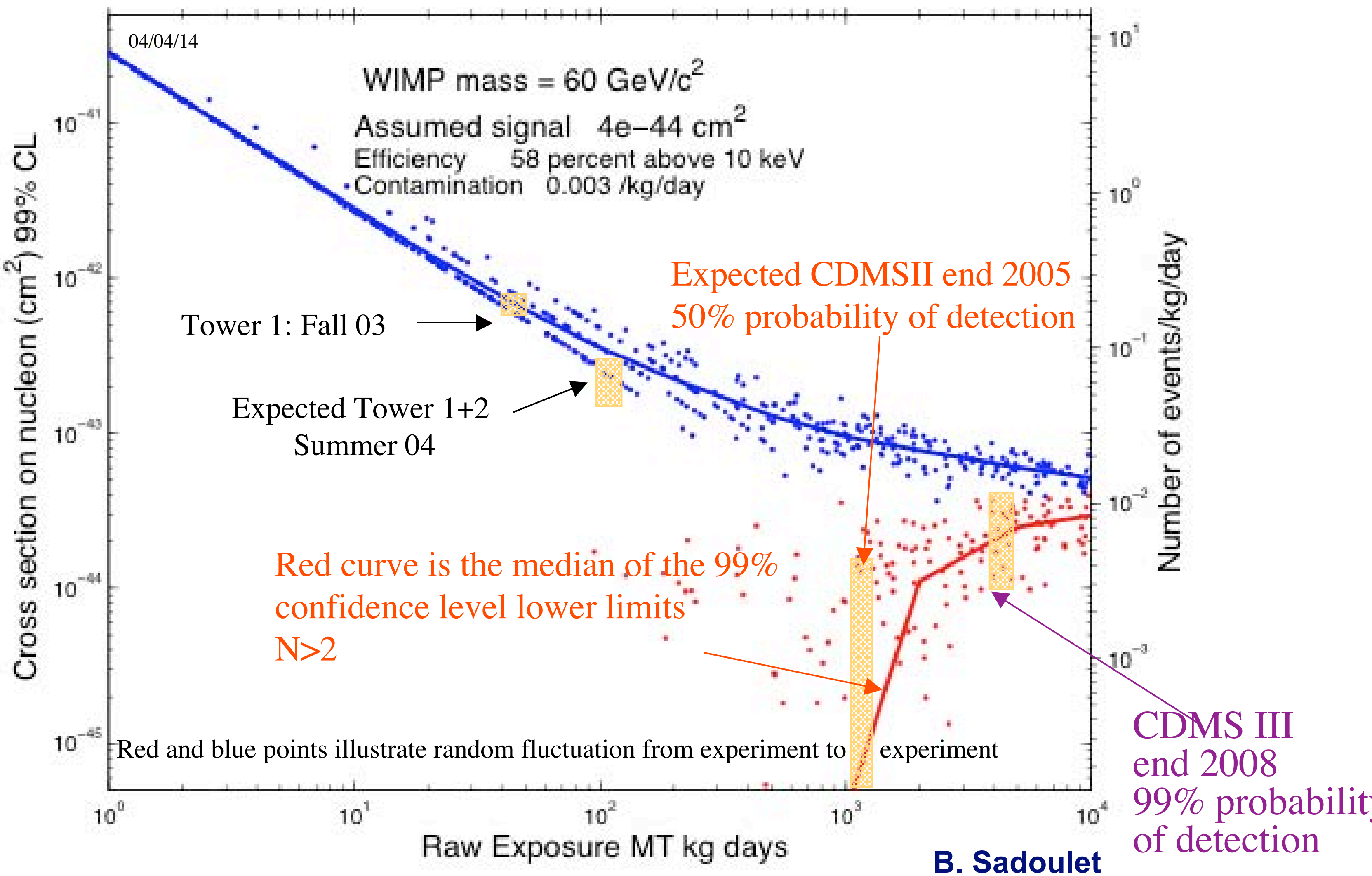
Liquid Ne (CLEAN) Threshold?

Liquid Ar? Problem with ^{39}Ar?



CDMS Potential Reach

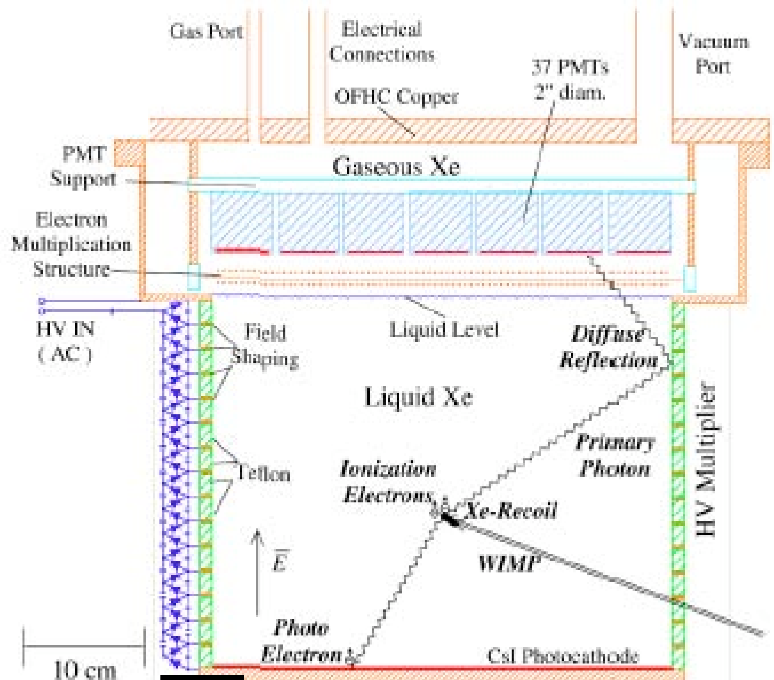
Simulation of limits based on our extended Feldman-Cousins likelihood ratio test



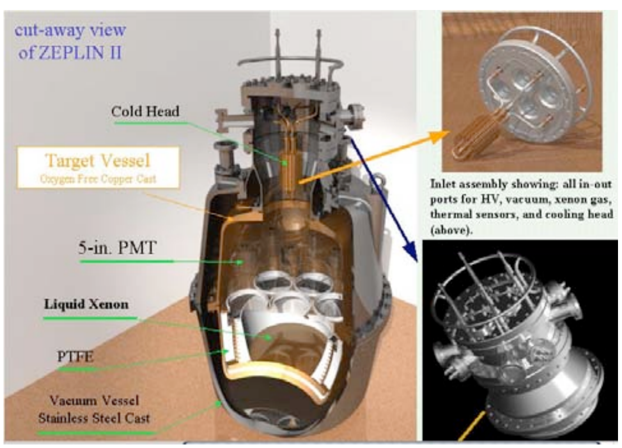
B. Sadoulet

2 approaches to Xenon

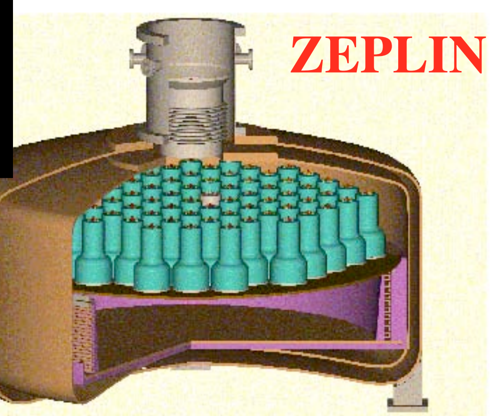
US Xenon project



Zeplin series



~1000 kg



Directionality

Essential if we have a signal

Recoil ≈ 100Å in solid or liquid

- Low pressure gastime projection chamber (DRIFT)

  Clever trick of charge exchange on CS_2 to limit diffusion

  main problems: mass 170g/m^3

  ratio of active mass/inert mass

  shielding (cf HELLAS)

- Phonon directionality: very hard
- Mechanical recoil very very hard

DRIFT setup

- Low Pressure CS_2 (40 Torr) 1 m^3, 0.167 kg, 20 micron diameter wires 2 mm pitch.
- 1 mm track for nuclear recoils
- Many calibration runs with ^{55}Fe (5.9 keV X-rays)
- Neutron Calibration with ^{252}Cf.
- Polypropylene shielding (~ 50 cm).
- Dark matter run started.
- Energy threshold 15 keV.