Progress in Searching for Most of the Mass of the Universe

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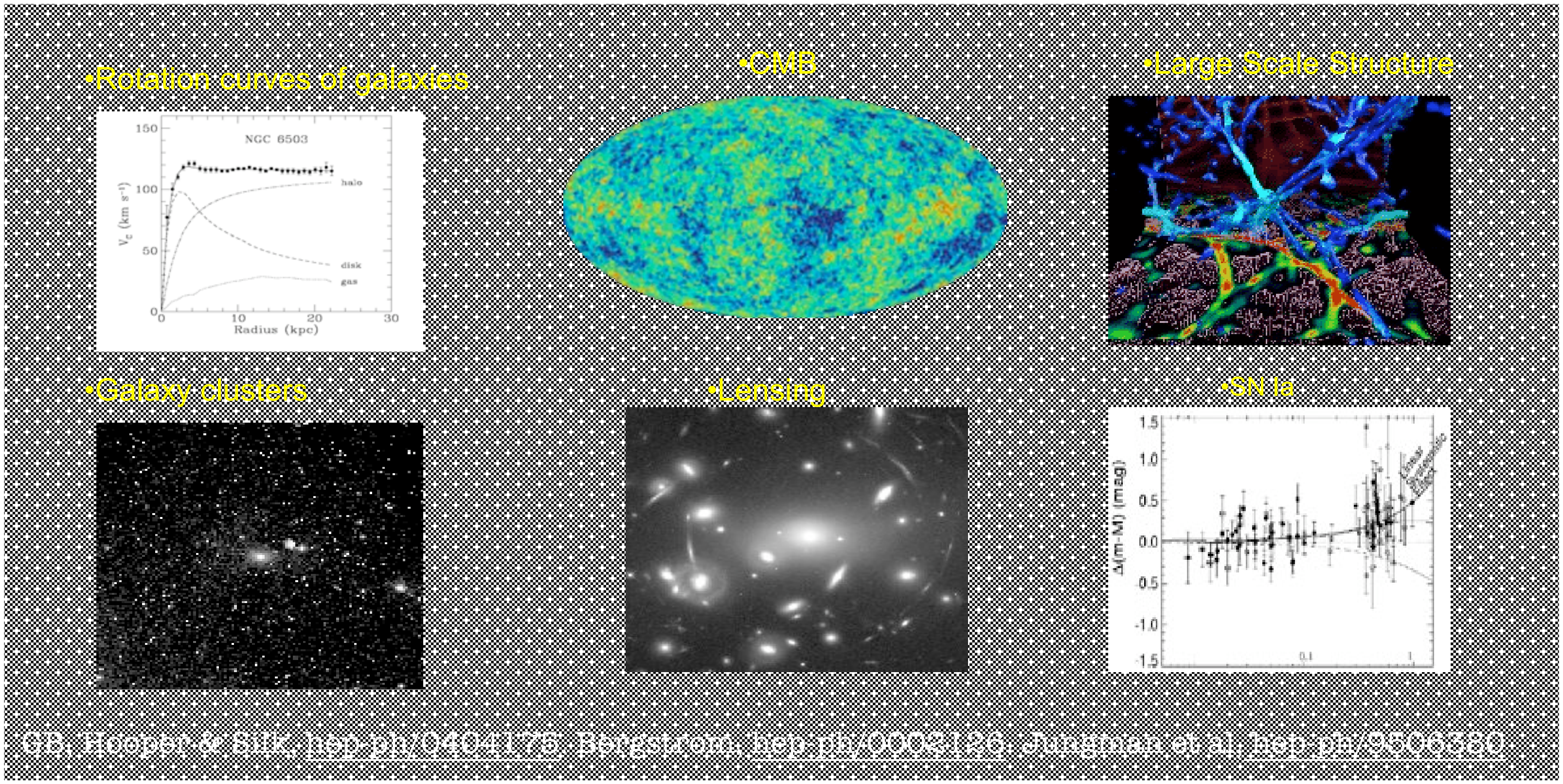
Dark matter candidates

Dark matter searches now and in the near future
- Axions
- Indirect detection of WIMPs
- Direct detection of WIMPs

Farther future, including accelerator comparisons

Evidence for Dark Matter

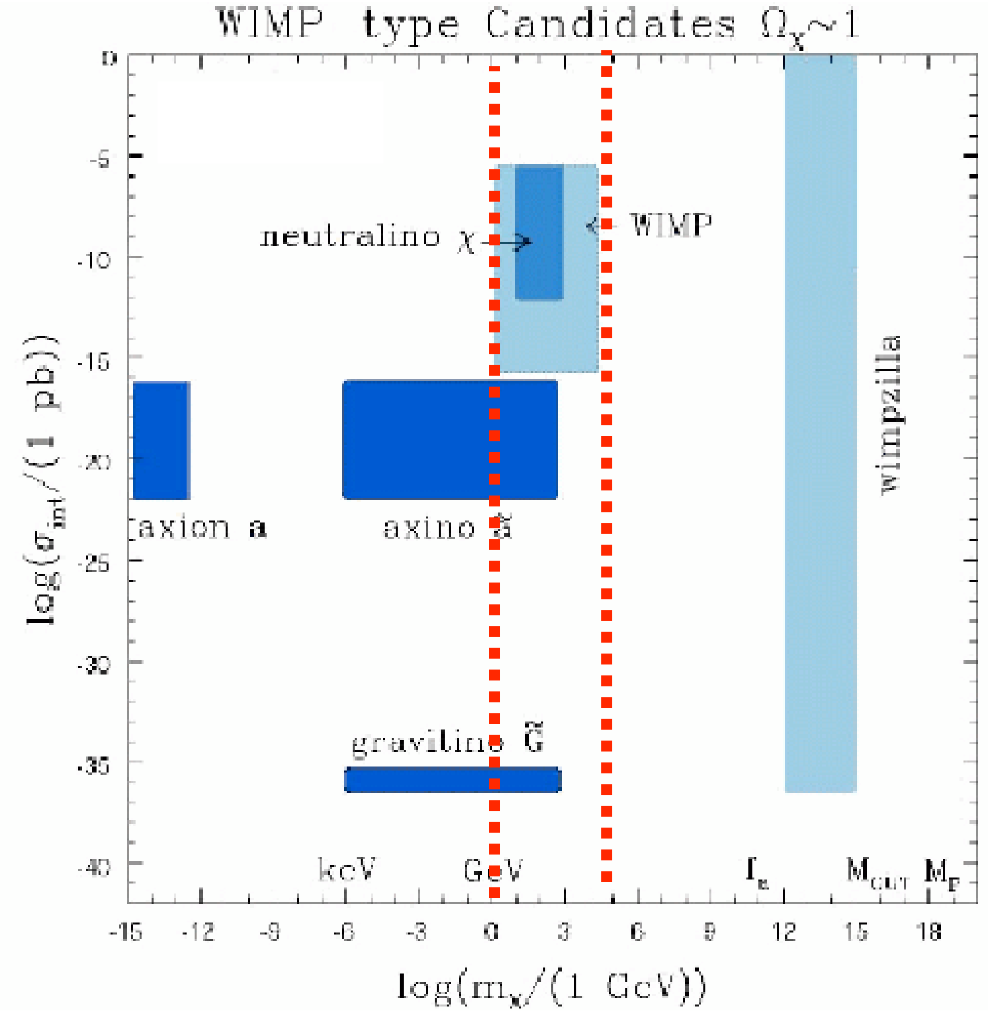
Independent observations at many length scales demonstrate existence of dark matter!



Particle Dark Matter Candidates

Current experiments only probing the easiest of a long list of candidates!

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworls DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



L. Roszkowski, http://www.shef.ac.uk/physics/idm2004/talks/

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Axion Searches

Axions invented to save QCD from strong CP violation

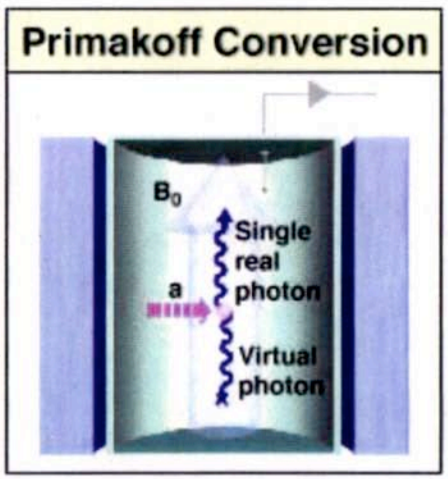
- QCD contains CP violating term which would lead to large neutron electric dipole moment; experiments suggest otherwise
- Axions would naturally suppress this term

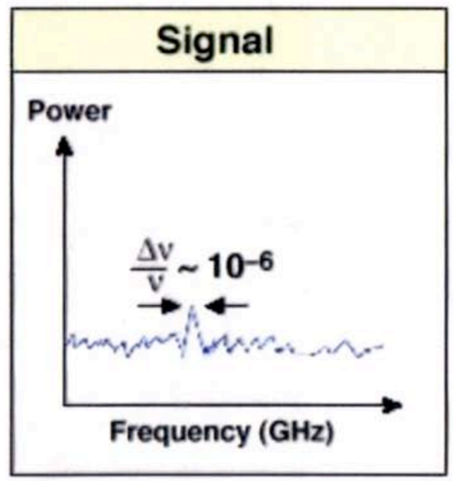
Couplings and masses

- Mass window of relevance to dark matter: 10^{-6}-10^{-3} eV
- Theoretical discussions of interaction rate ongoing (KSVZ vs. DFSZ models)

Method of detection

- Primakoff conversion, followed by detection of photon





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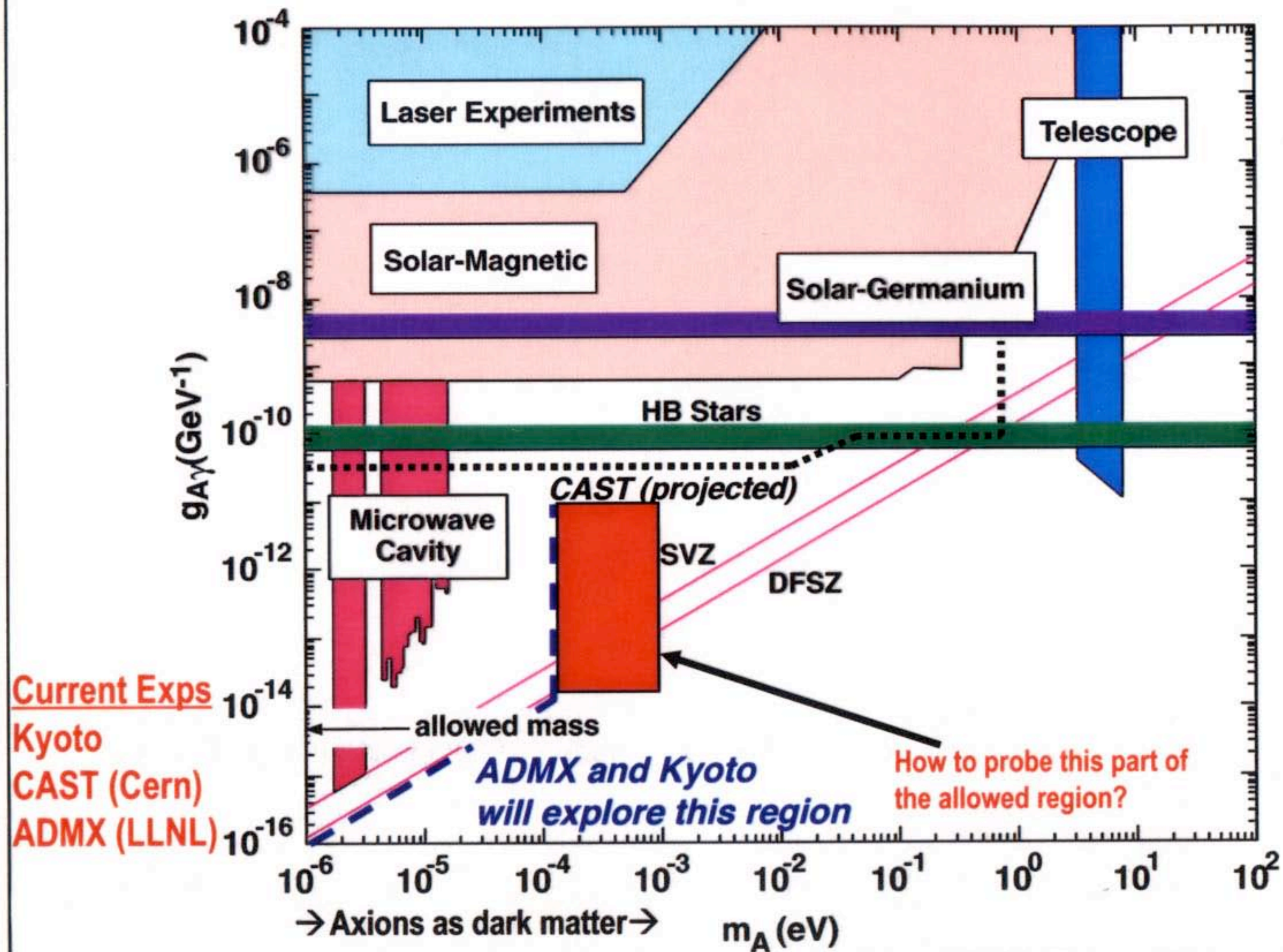
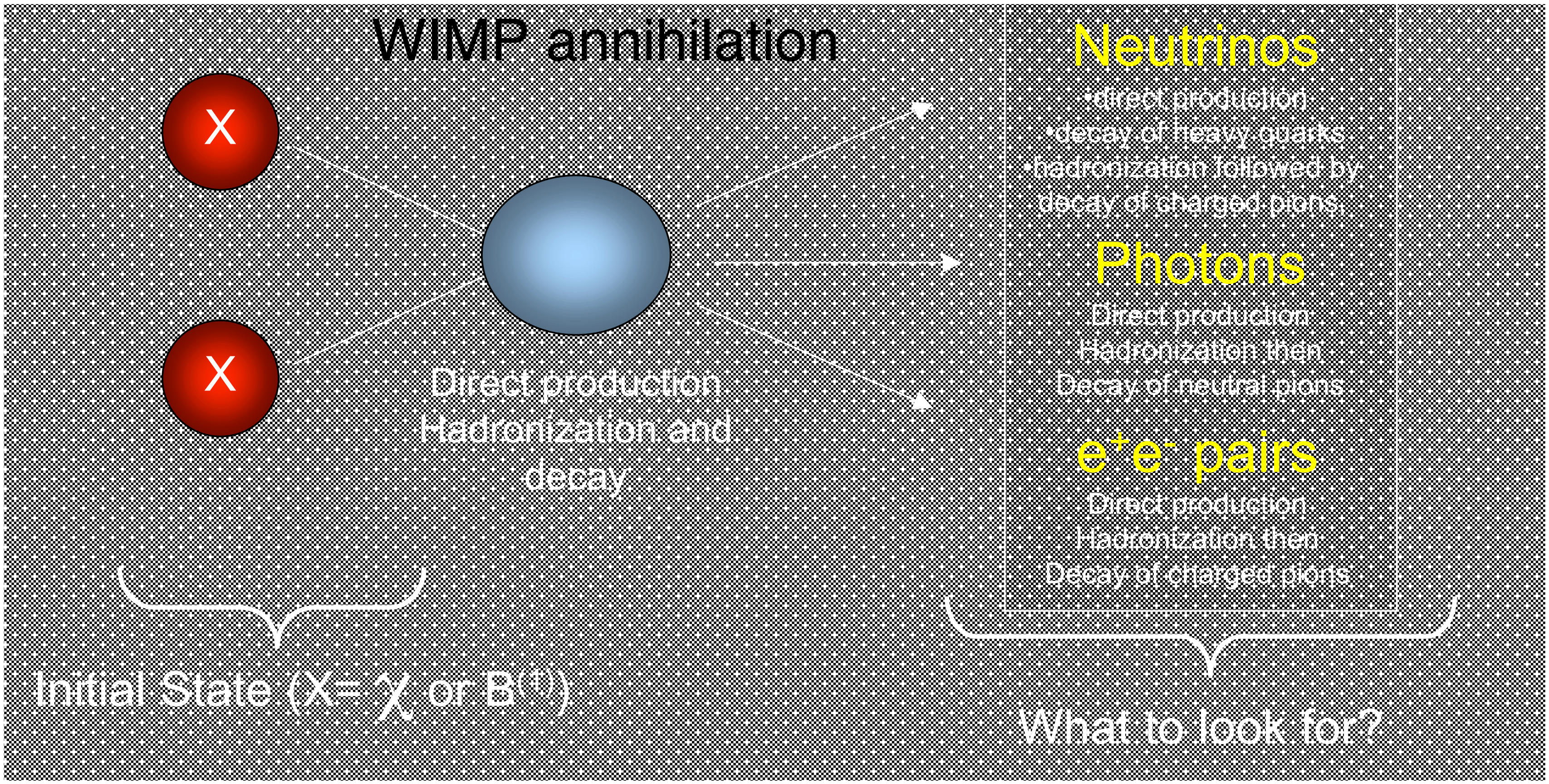
Summary of axion exclusion regions



Darin Kinion http://cfcp.uchicago.edu/workshops/dmd2004/talks/kinion.ppt

Indirect Detection of WIMP Dark matter



Main Problem: Other astrophysical processes can lead to these same signatures; how to know whether it is really WIMPs?

Indirect Detection of WIMP Dark matter

Look for regions where dark matter accumulates (galactic center, halo clumps, sun, earth...)

$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{4\pi M^2} \int_{\text{line of sight}} d\,s \rho^2 \left(r(s, \psi)\right)$$

Particle Physics
(annihilation cross section, Energy spectrum)

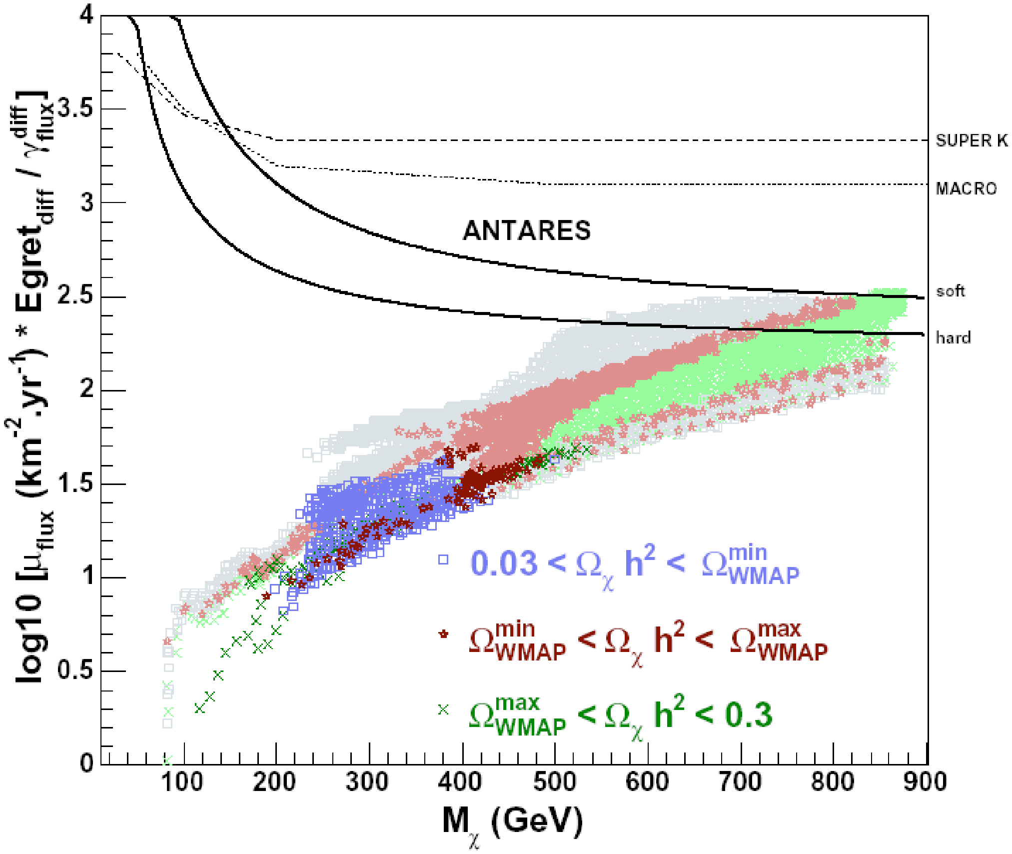
Astrophysics
(density, spatial distribution)

Density profile in the innermost regions of the volume where WIMPS accumulate is CRUCIAL for a detectable rate

See recent review by Bertone, Hooper, Silk (hep-ph/0404175)

Indirect detection: Neutrino Telescopes

So far: upper limits on the Neutrino-induced muon flux from the galactic center



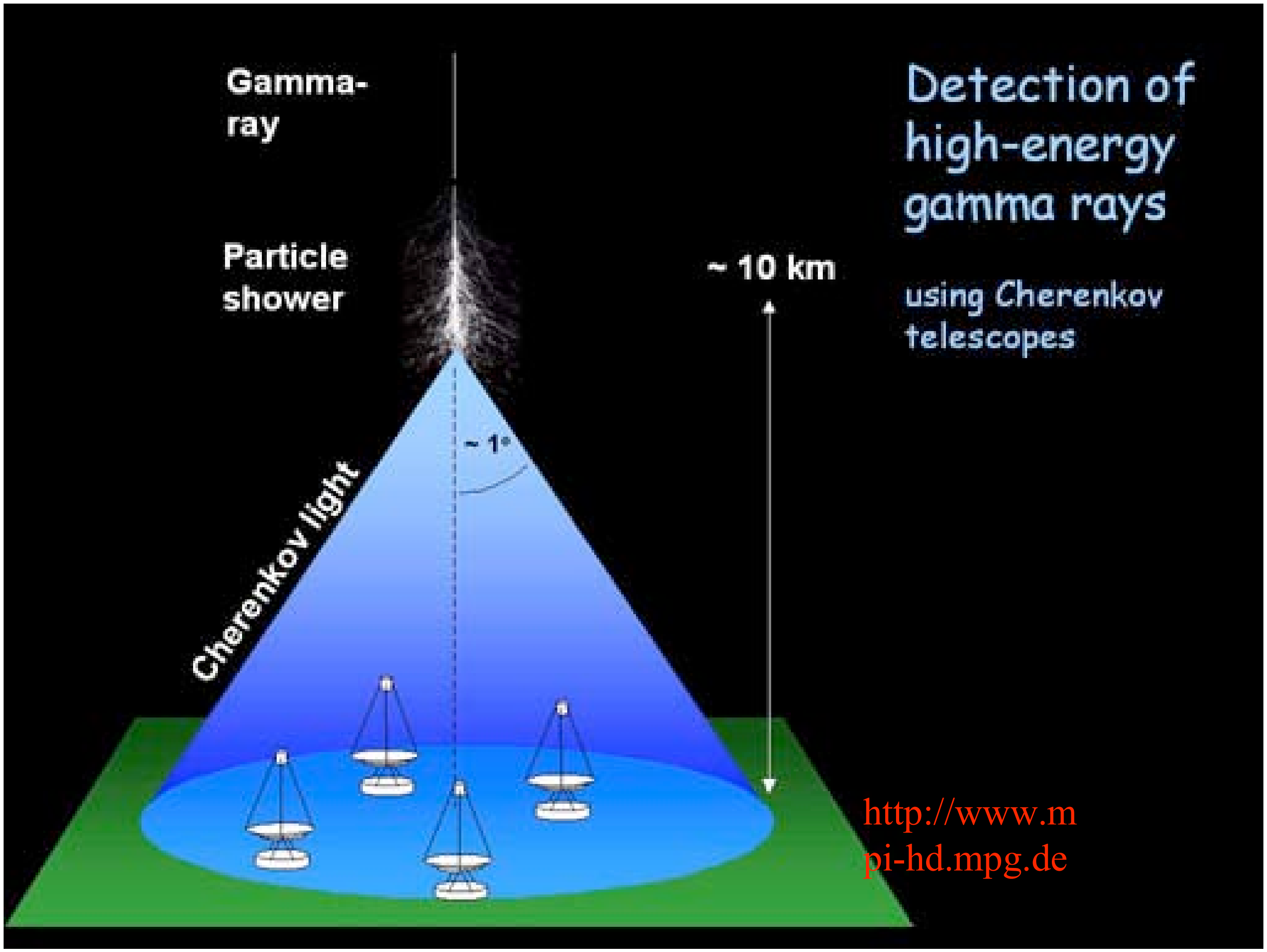
Current limits

Next generation of experiments (Antares, IceCube, Auger, …) may start to probe expected cold dark matter flux and masses

Bertone, Nezri, Orloff, Silk 2004. astro-ph/0403322

But how will we know if high energy ν's are really from WIMP annihilation?

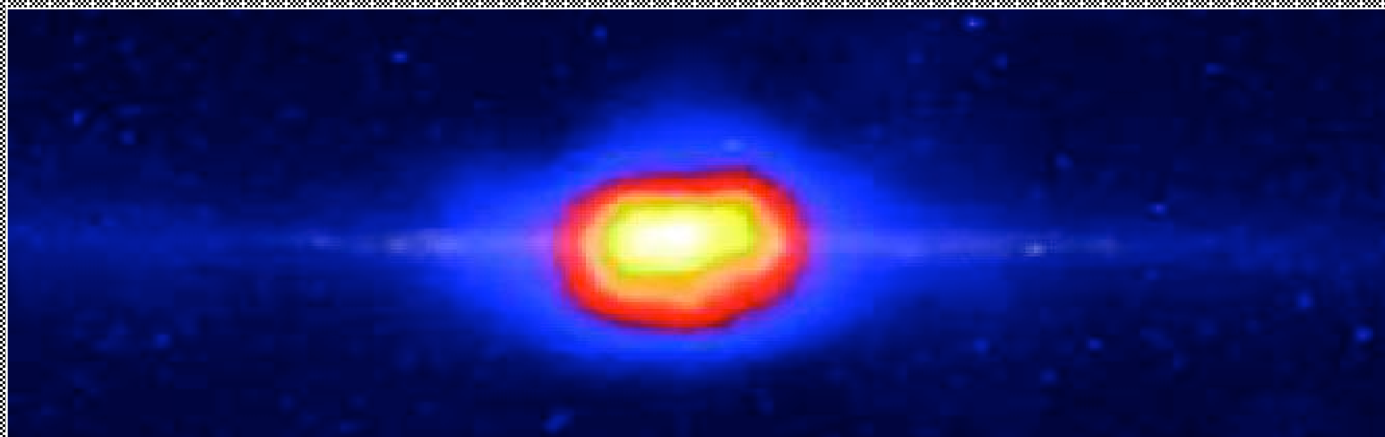
Indirect Detection: Air Cherenkov Telescopes



Current Exps
Magic
Cangaroo
Veritas
HESS

HESS has recently detected TeV γ's from the direction of the galactic center
Is this a sign of TeV-scale dark matter or an astrophysical accelerator?

Indirect Detection: Satellites



SPI (aboard INTEGRAL) map of the Galaxy @ 511 keV.

- Narrow emission line (few keV)
- Size of the emission region FWHM ~ 9 degrees
- Roughly corresponds to the size of the **bulge**
- Evidence for positron annihilation through *positronium*
- *Possible signature of 1-20 MeV dark matter (NOT SUSY)*

GLAST will significantly extend satellite capability for indirect DM detection in 2012

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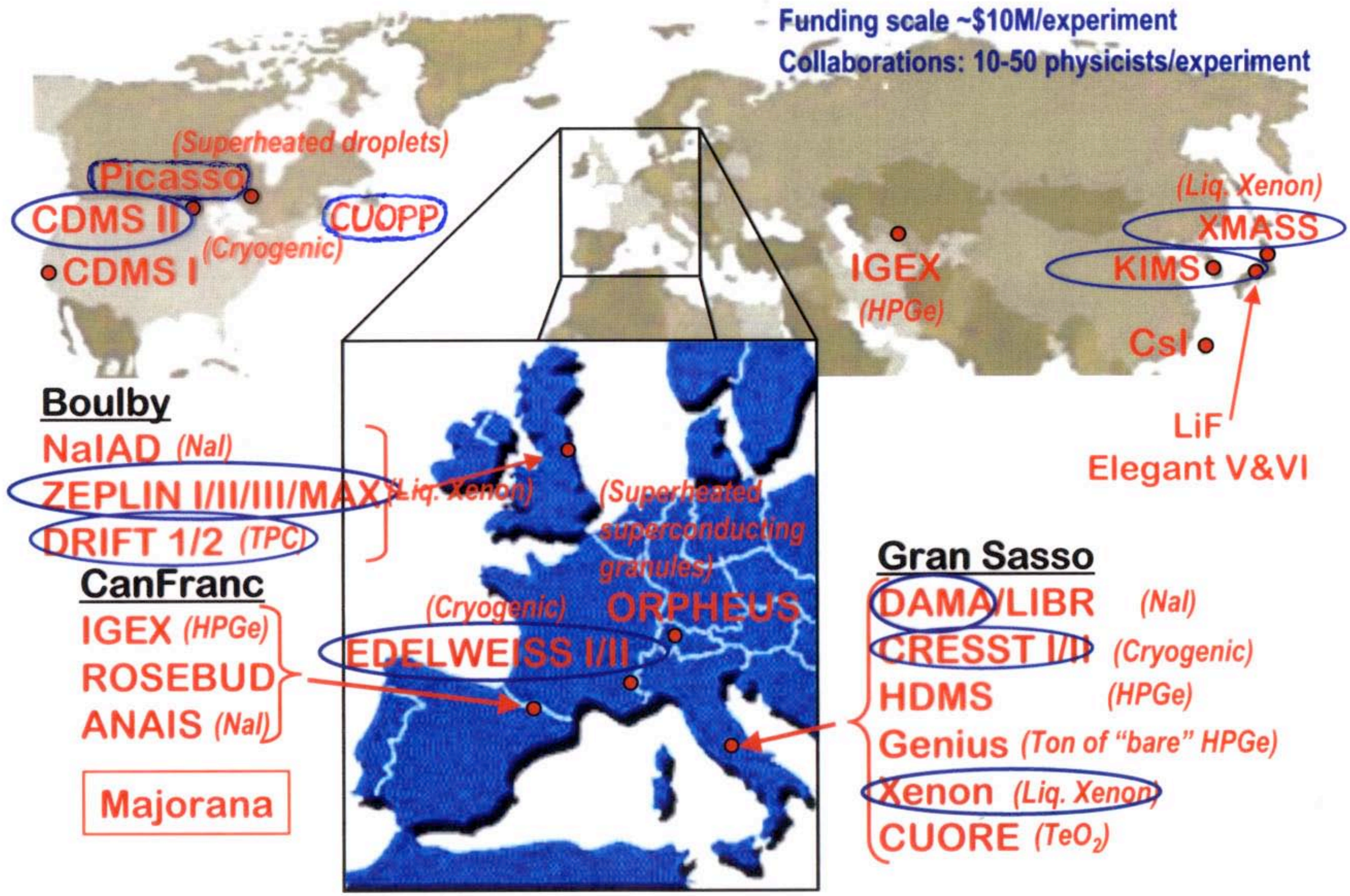
WIMP-detection Experiments Worldwide



Direct Detection

Elastic scattering

Expected event rates are low

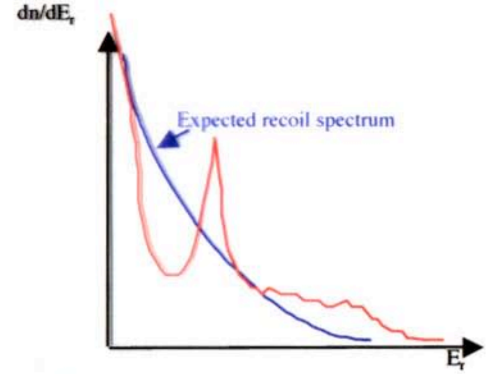
(<< radioactive background)

Small energy deposition (few keV)

<< typical in particle physics

Signal = nuclear recoil (electrons too low in energy)

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



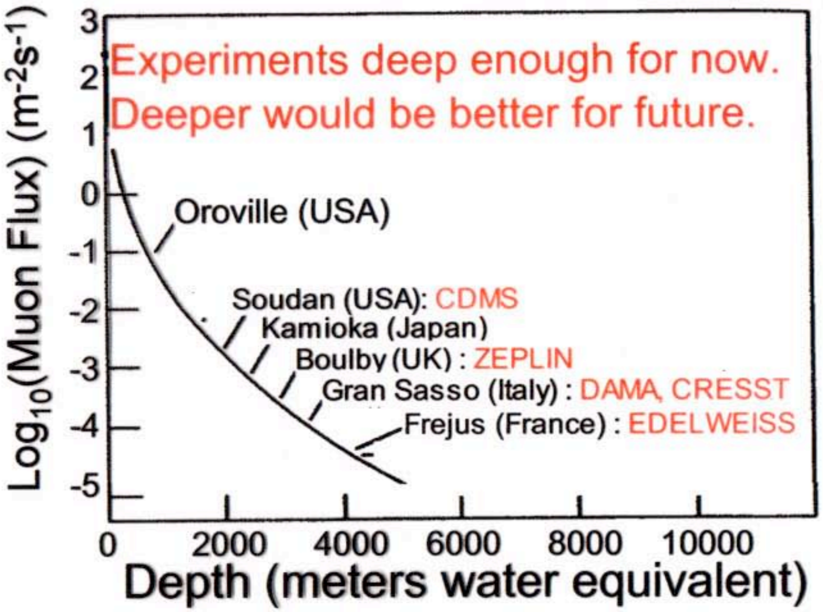
Signatures

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

Linked to galaxy

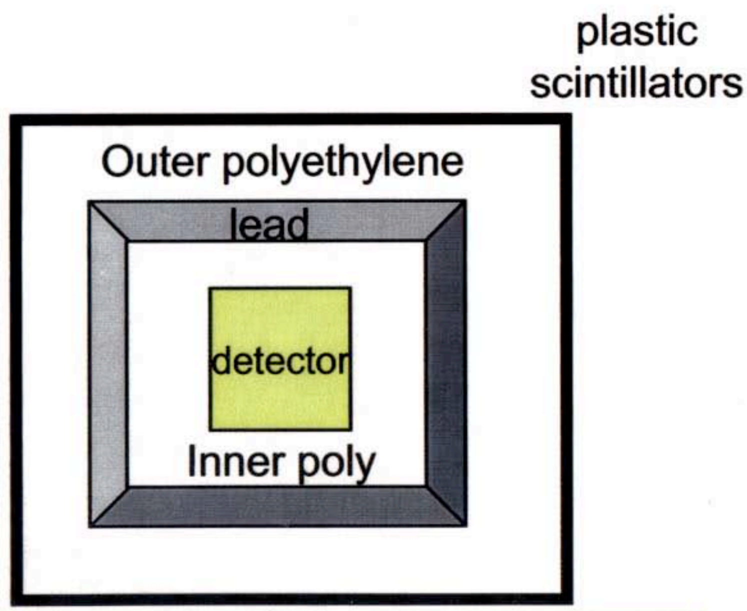
- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)

Eliminating the Background



- Put experiment underground so no cosmic-ray nuclei reach it; very few muons (and hence fast neutrons) if deep enough
- Surround detectors with active muon veto

- Use clean, low-radioactivity (= screened) materials
- Use passive shielding
  - → Copper or (ancient) lead for photons (~10x/5 cm)
  - → Hydrocarbon for low-energy neutrons (~10x/10 cm)



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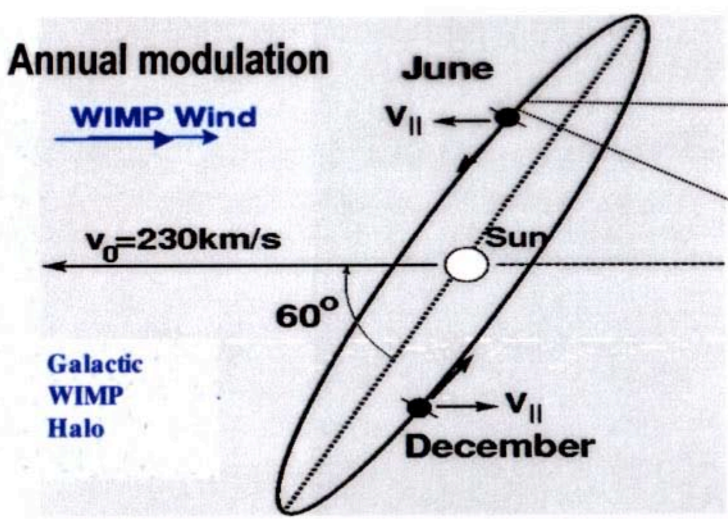
Directionality: Can we detect a WIMP wind?

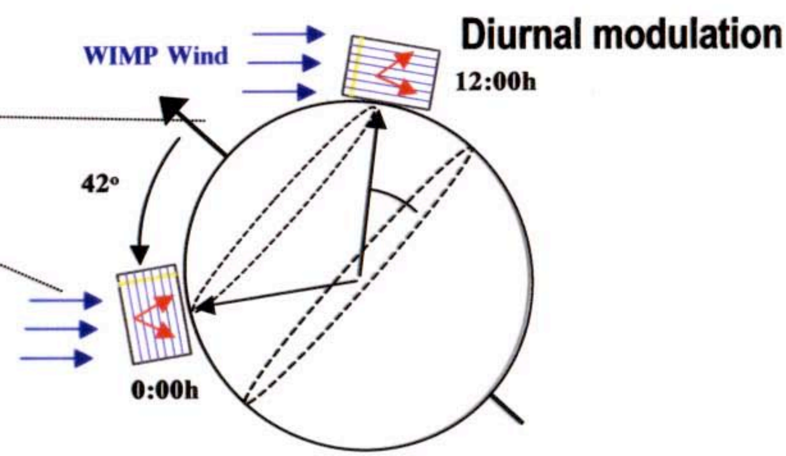
Look for variation in WIMP flux with time of year (annual)

Requires long exposure and large mass to measure small effect (~5%)

Look for directionality of WIMP nuclear recoils on a daily basis (diurnal)

Requires detectors which can reconstruct direction of recoil with reasonable precision





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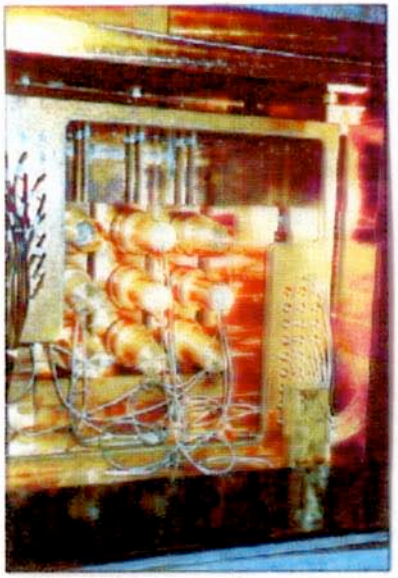
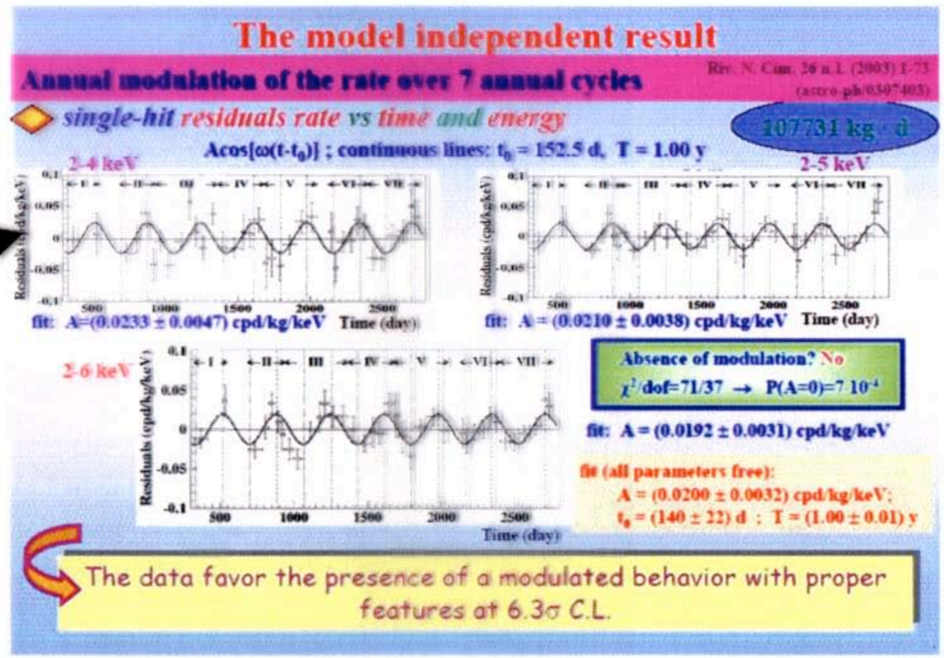
DAMA: Search for annual modulation



100 kg of NaI crystals read out by phototubes

Huge target mass, no background rejection

Deep underground (Gran Sasso, Italy)



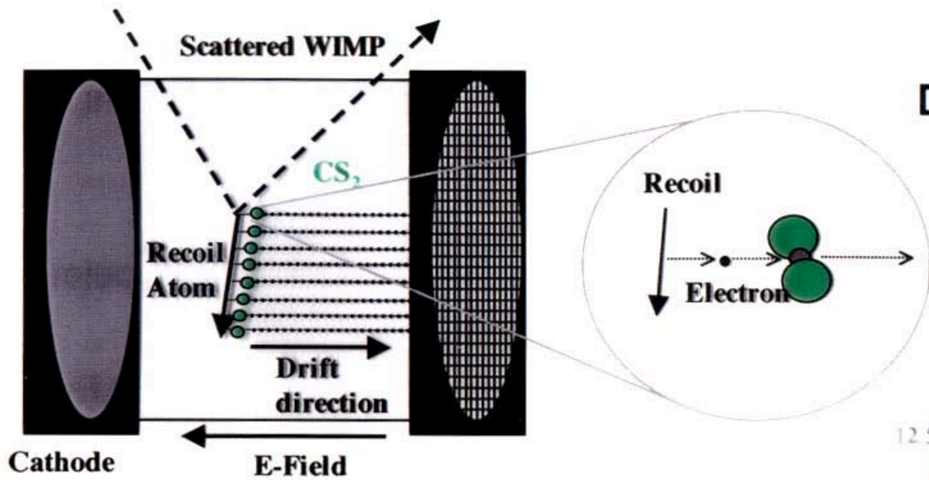
Claim a WIMP signal

6× annual modulation is observed in the rate.

BUT, the modulation is only a 5% effect and is all in the lowest energy bin.

Is this due to dark matter interactions or some other annual effect?
Not seen in CDMS or Edelweiss experiments, which have higher sensitivity!

DRIFT: Look for diurnal modulation

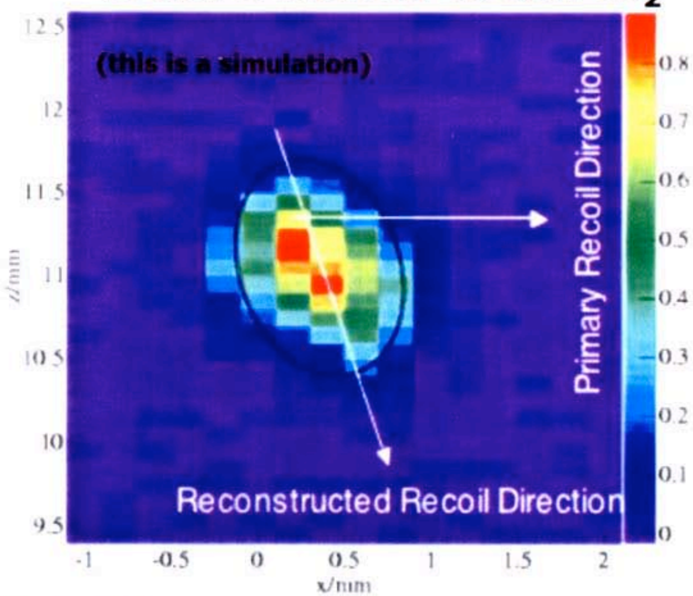


Drift negative ions in TPC

- No magnet
- Reduced diffusion

Electron recoils rejected via dE/dx, range

40 keV S recoil in 40 Torr CS_2



Model for realistic (advanced) detectors

- 40 Torr CS_2
- 1 $kVcm^{-1}$ drift field
- 200 μm resolution
- 10 cm drift
- ***SRIM2003 - recoil scattering and diffusion***

DRIFT I

- Cubic meter in Boulby since 2001
- Engineering runs completed

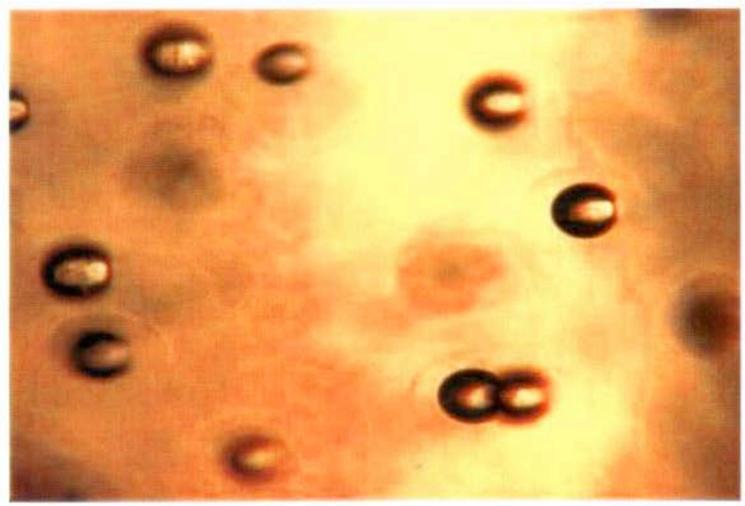
DRIFT II extension to 10 kg module proposed

- But very difficult to justify expense of larger target mass until signal seen

PICASSO

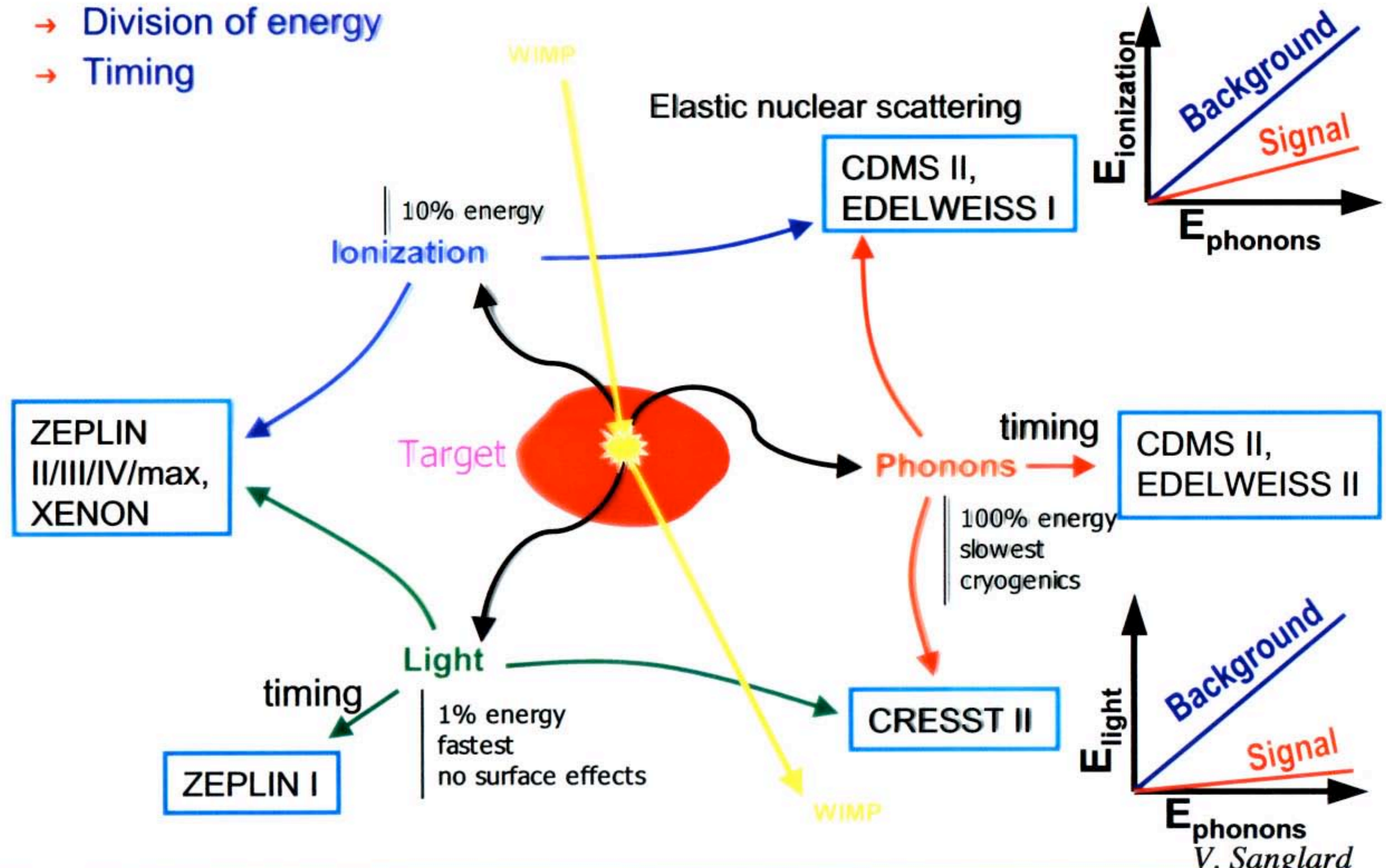
Superheated Droplet Detector

- Detector consists of tiny (5 to 100 μm) halocarbon liquid droplets (C_3F_8, C_4F_{10}...) embedded in a gel.
- The droplets are superheated - maintained at a temperature higher than their boiling point.



Nuclear-Recoil Discrimination

- 2 Differences between nuclear recoils and electron recoils
  - → Division of energy
  - → Timing



CRESST: Phonons and Scintillation

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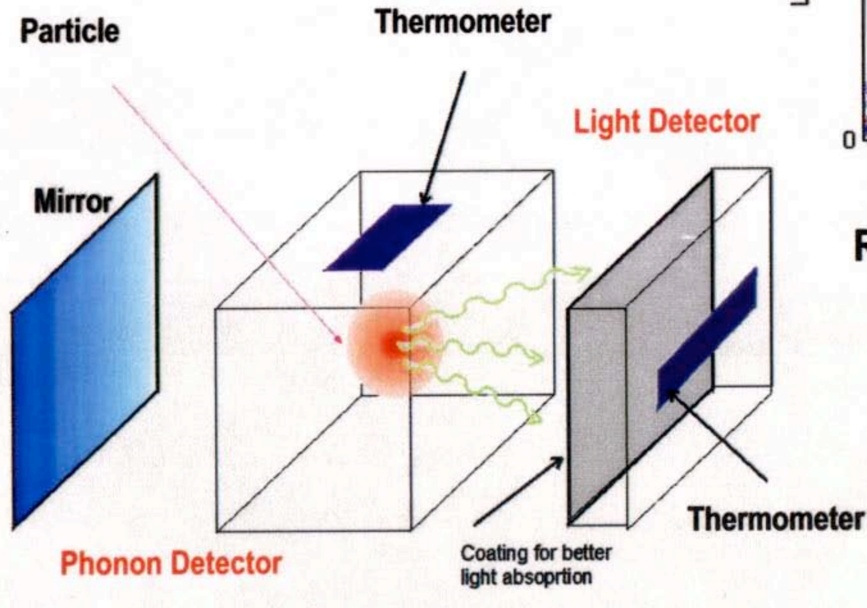
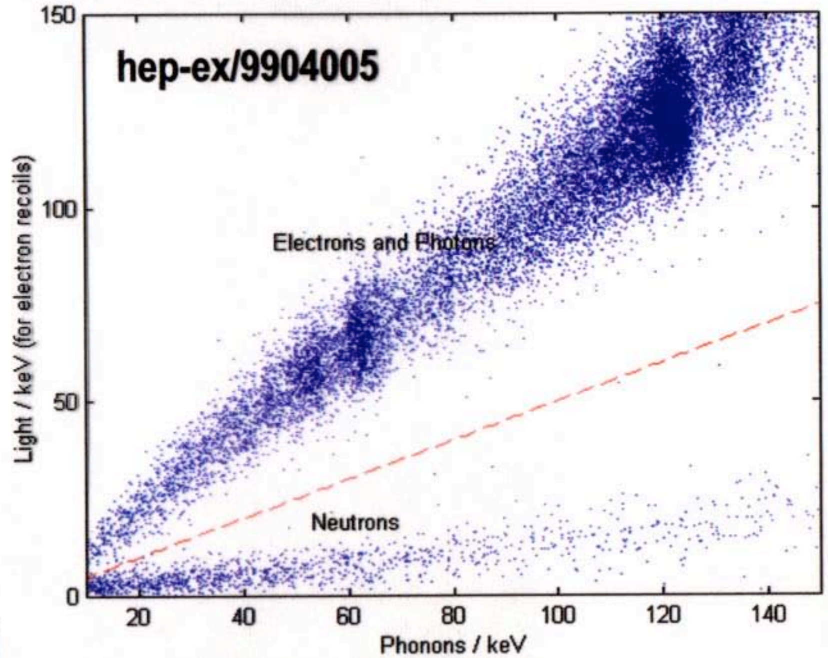
- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron interactions can be distinguished from nuclear recoils (WIMPs, neutrons, ...)



CRESST $CaWO_4$ Light vs. Phonons



Results from a 6g $CaWO_4$ prototype

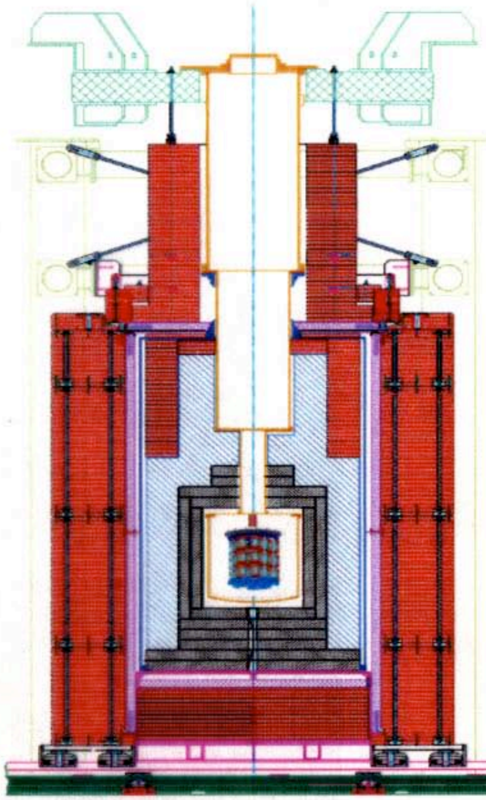
- No problem from surface electrons
- Very small scintillation signal
  - Scintillation threshold will determine minimum recoil energy
- Scaling up to 300g detectors
- May begin running in Gran Sasso in 2005

CRESST II Status and Plans

Upgrading since April 2004:

- Neutron moderator (installation ready)
- Muon veto (panels tested, ready for installation)
- New 66-SQUID channel readout for up to 33 detector modules / 10 kg target mass (ready and tested, presently being installed)
- New DAQ, electronics, detector holding
- Restart planned for end of 2005
- Impact of major construction at Gran Sasso unpredictable

Shielded cryostat



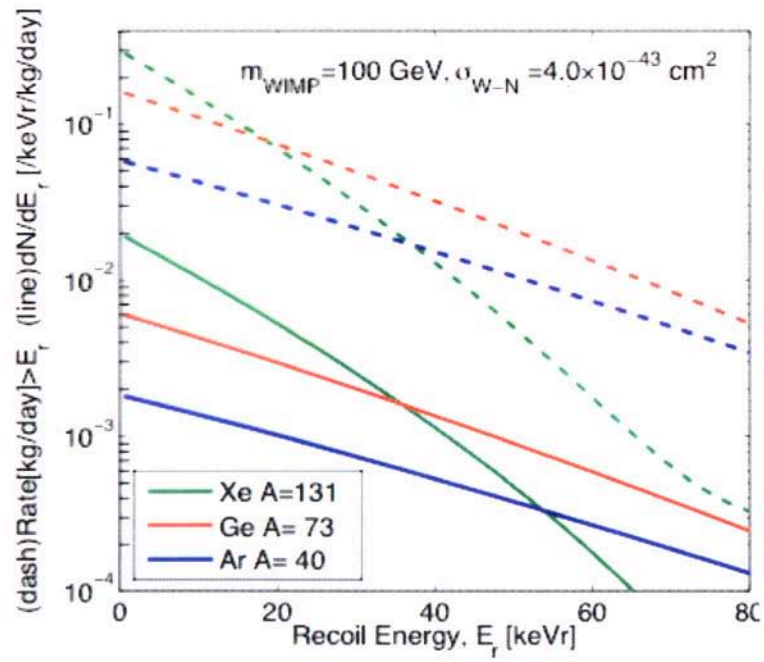
PE neutron moderator

Plastic scintill. μ-veto

W. Rau

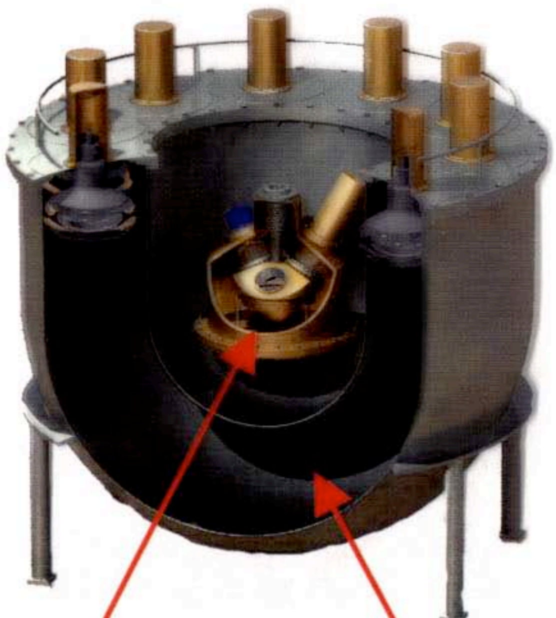
Promise of liquid Xenon.

- Good WIMP target.
- Readily purified
- Self-shielding - high density, high Z.
- Can separate spin, no spin isotopes
  - ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe, ^{134}Xe, ^{136}Xe
- Rich detection media
  - Scintillation
  - Ionization
- **Scalable to large mass**



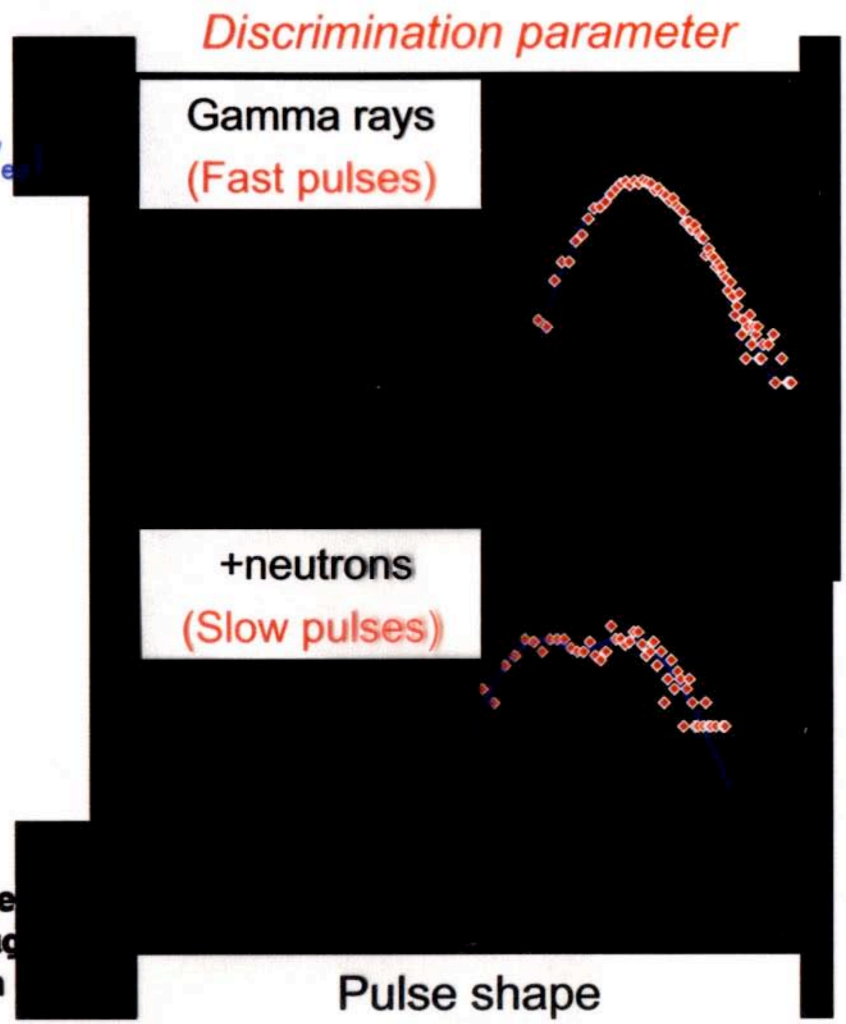
Liquid Xe: ZEPLIN I

- Single-phase (liquid only) detector
  - → Measure primary scintillation
  - → Pulse shape discrimination
  - → Resolution 100% at 40 keV (7 keV$_{ee}$)



5kg LXe target (3.2kg fid)
3 PMTs
Cu construction

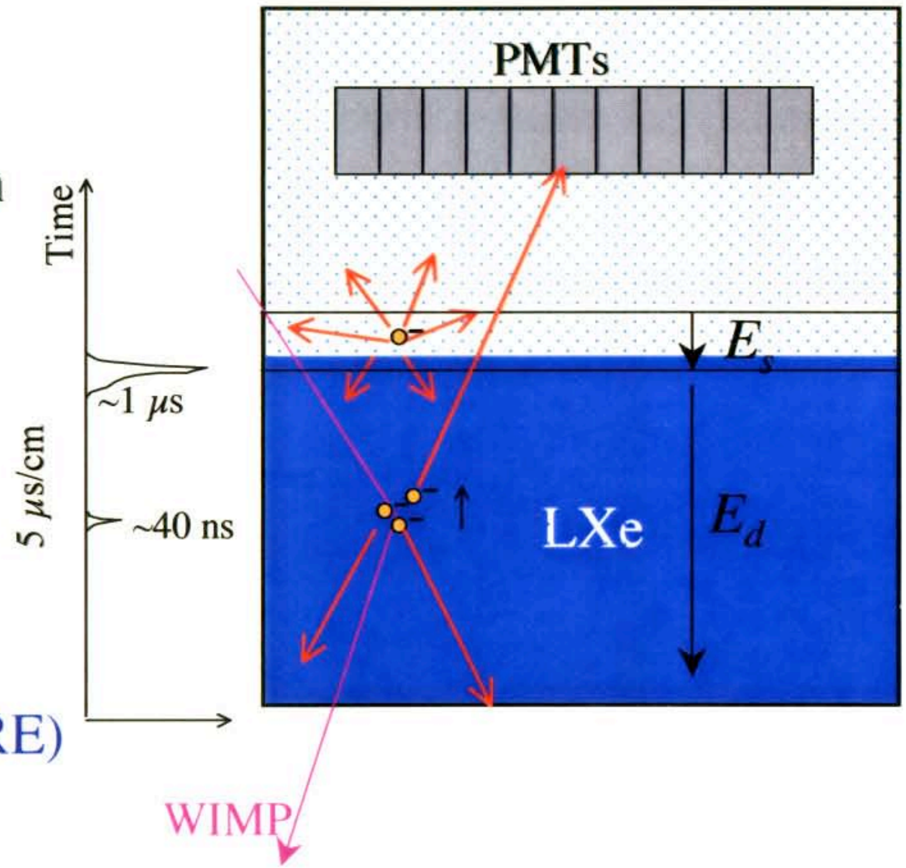
1 tonne Compton ve
PMT background ta
Gamma calibration
Neutron monitor



Dual Phase, LXe TPC

- Very good event location.
- Good discrimination despite small number of e^-, λ
- Need single charge, photon sensitivity

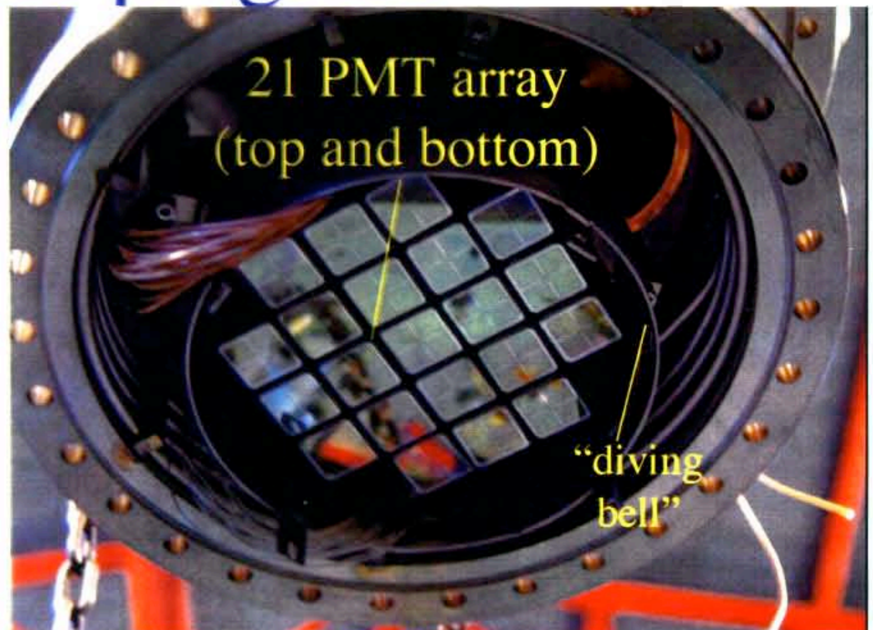
  Use charge amplification instead of increasing $\pi E/kT$.
- Competitors:
  - ZEPPLIN II, III
  - ITEP
  - XMASS_DM
- Ar detectors (Icarus, FLARE)
  - Charge drift easier.
  - ^{39}Ar background.

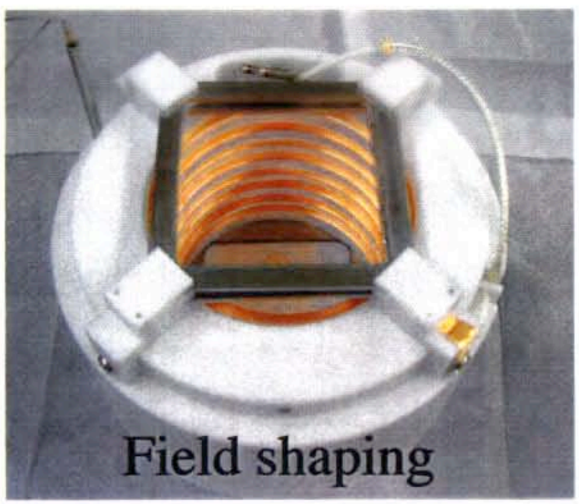


A. Bolozdynya, NIMA 422 p314 (1999).

XENON10 program

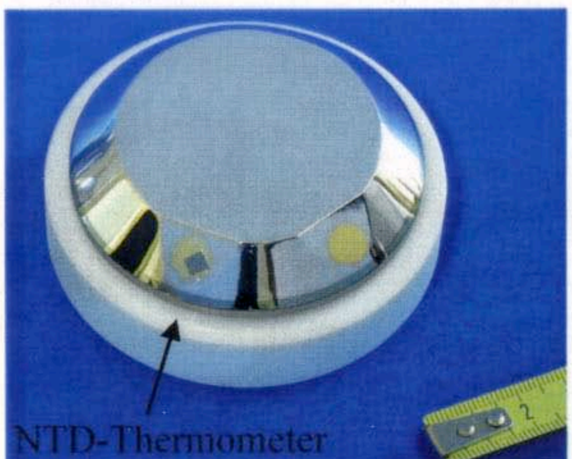
- Basic R&D demonstrated:
  - Discrimination of nuclear recoils at low energy.
  - 1 kg, 7 PMT detector.
  - > 1 m charge drift.
  - Stable cryogenics.
- 3 kg, 21 PMT detector now under operation.
  - This fall -> 10 kg detector. PMTs top + bottom.
- 10 kg detector in Gran Sasso in 2006





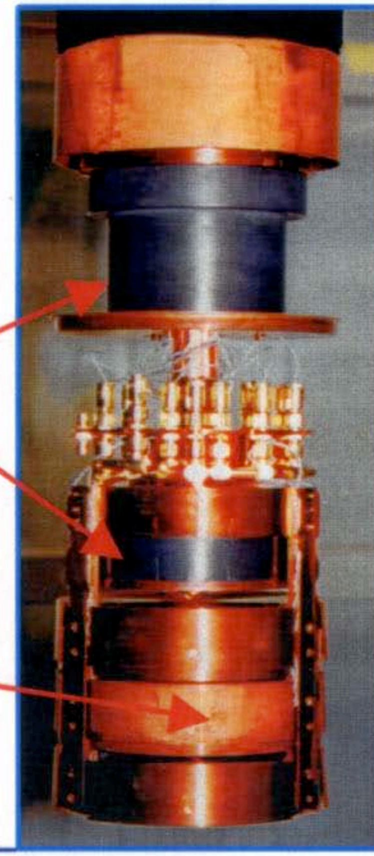
EDELWEISS I

- Ge with ionization readout and thermistor to read out temperature
  - → Easy to produce
  - → Good energy resolution



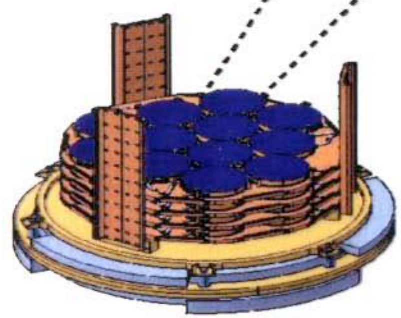
Archeological lead

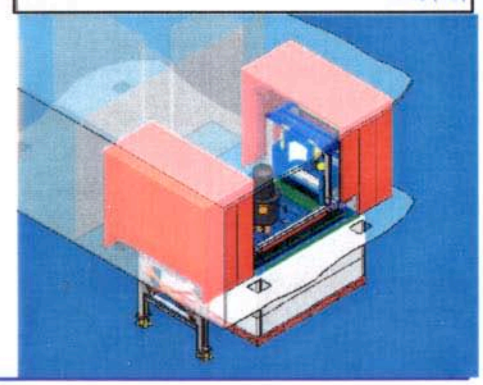
3 * 320 g Ge detectors: heat and ionization simultaneous readout
Installed May 2002



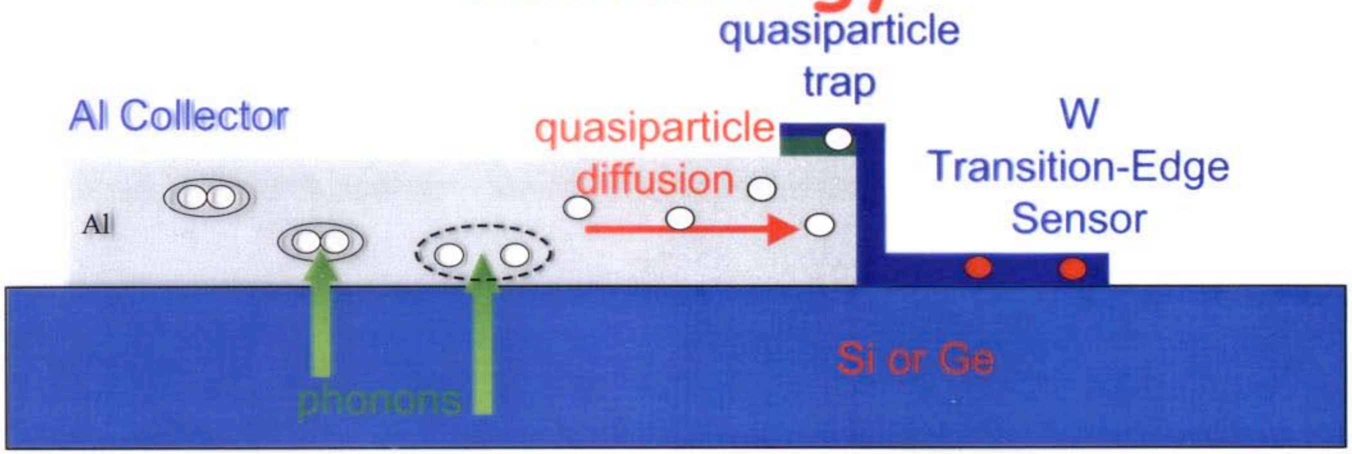
EDELWEISS-II

- Month delay expected due to tire-truck fire in Frejus tunnel in early June
- 120-detector cryostat
  - → Cooled to 12 mK at surface in June 2005
  - → To be tested at depth fall 2005
- More/better/cleaner detectors. 1[st] phase ~9 kg:
  - → 21x320g Ge NTD detectors (ready)
  - → 7x400g NbSi metal-insulator transition detectors (should be ready by end of year)
    - Slow (thermal) signal for bulk events. Additional fast (athermal) signal for surface events
- Improved shielding
  - → Increased polyethylene neutron shielding from 30 cm to 50 cm
  - → Ancient lead in place of copper
  - → Addition of μ veto





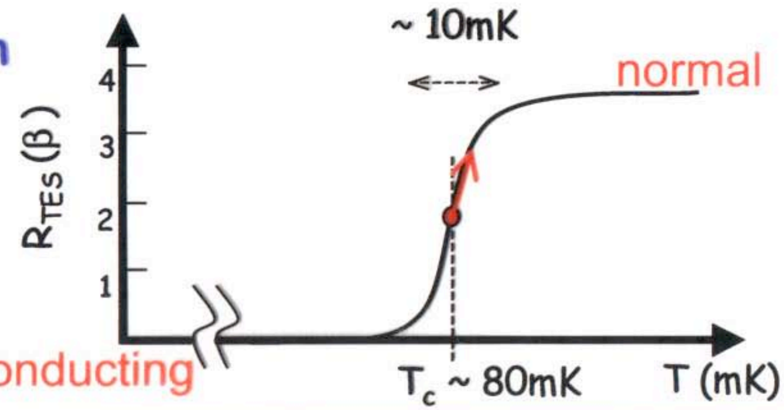
ZIP Detector Phonon Sensor Technology



W Transition-Edge Sensor: a really good thermometer

Measurement of athermal phonon signals maximizes information

Fast pulse, excellent energy and timing resolution



CDMS Active Background Rejection

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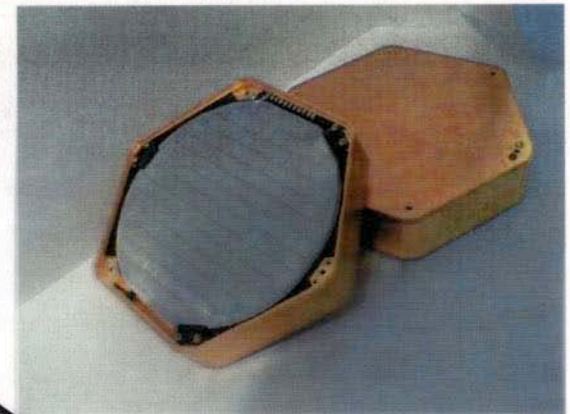
8 July 2005

Detectors with excellent event-by-event background rejection

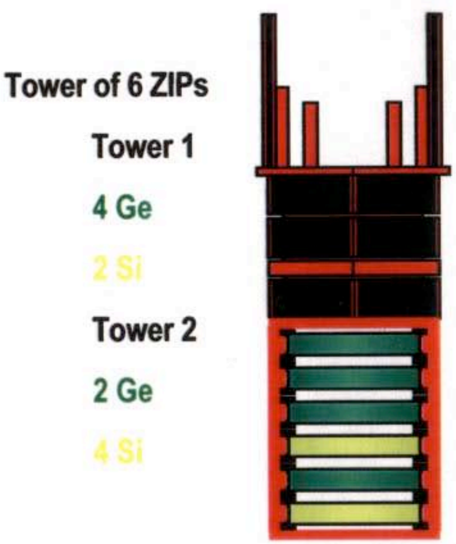


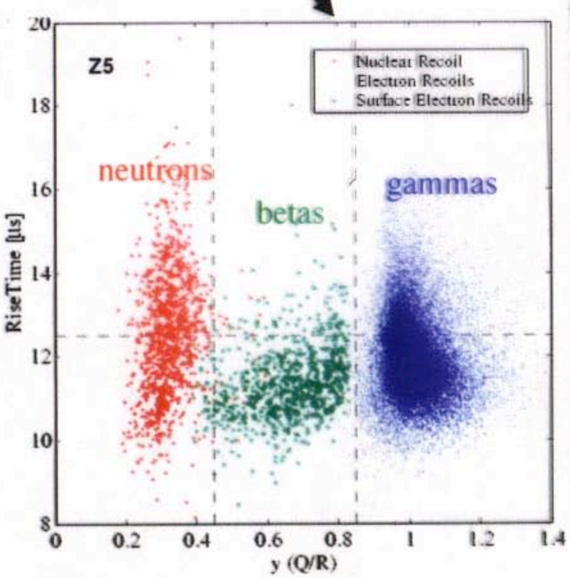
Measured background rejection:

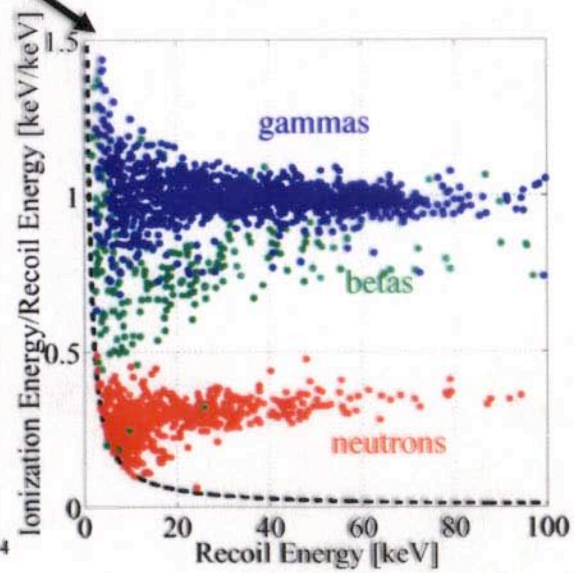
99.995% for EM backgrounds using charge/heat

99.4% for β's using pulse risetime as well

Much better than expected in CDMS II proposal!

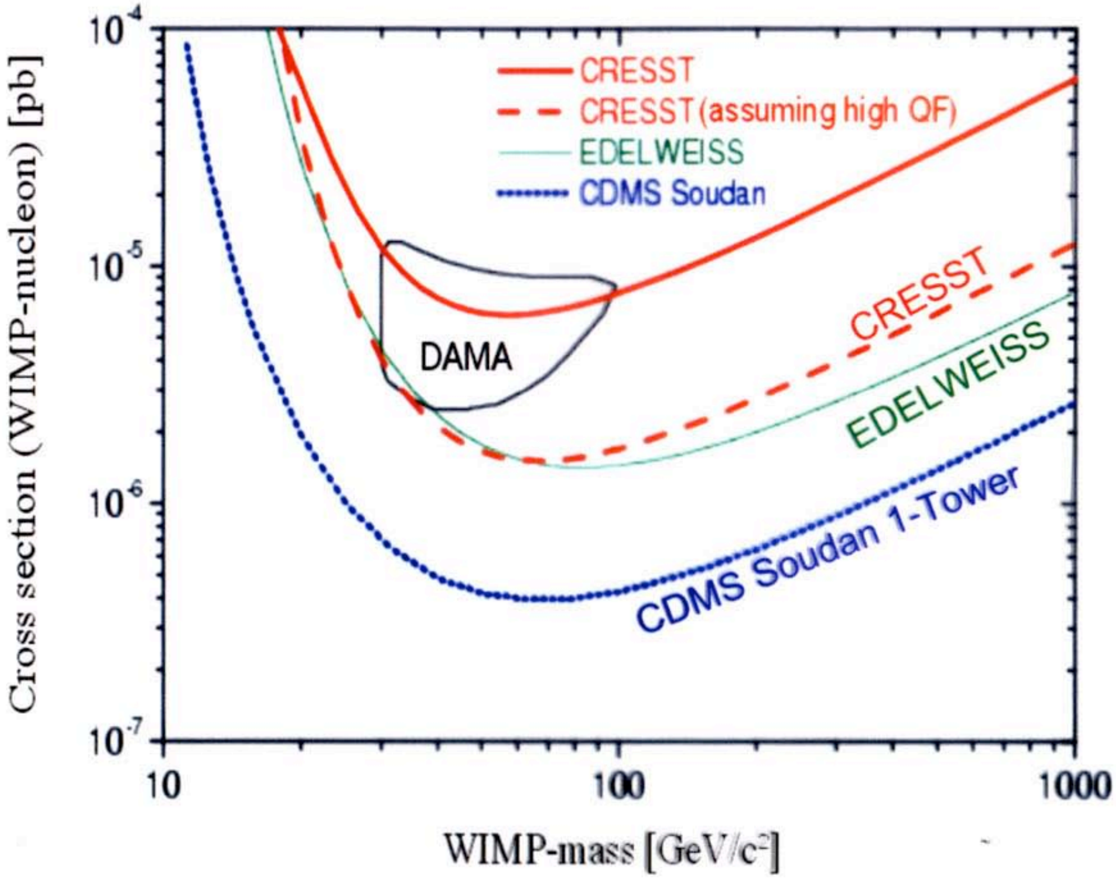






Limits on Spin-Independent Cross Section

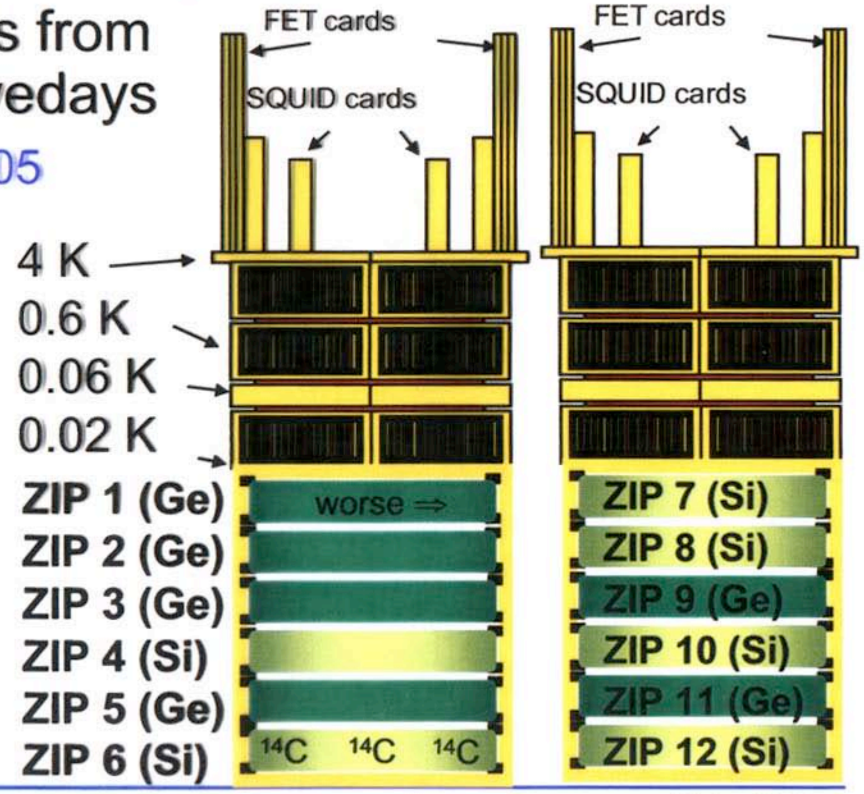
90% CL upper limits assuming standard halo, A^2 scaling

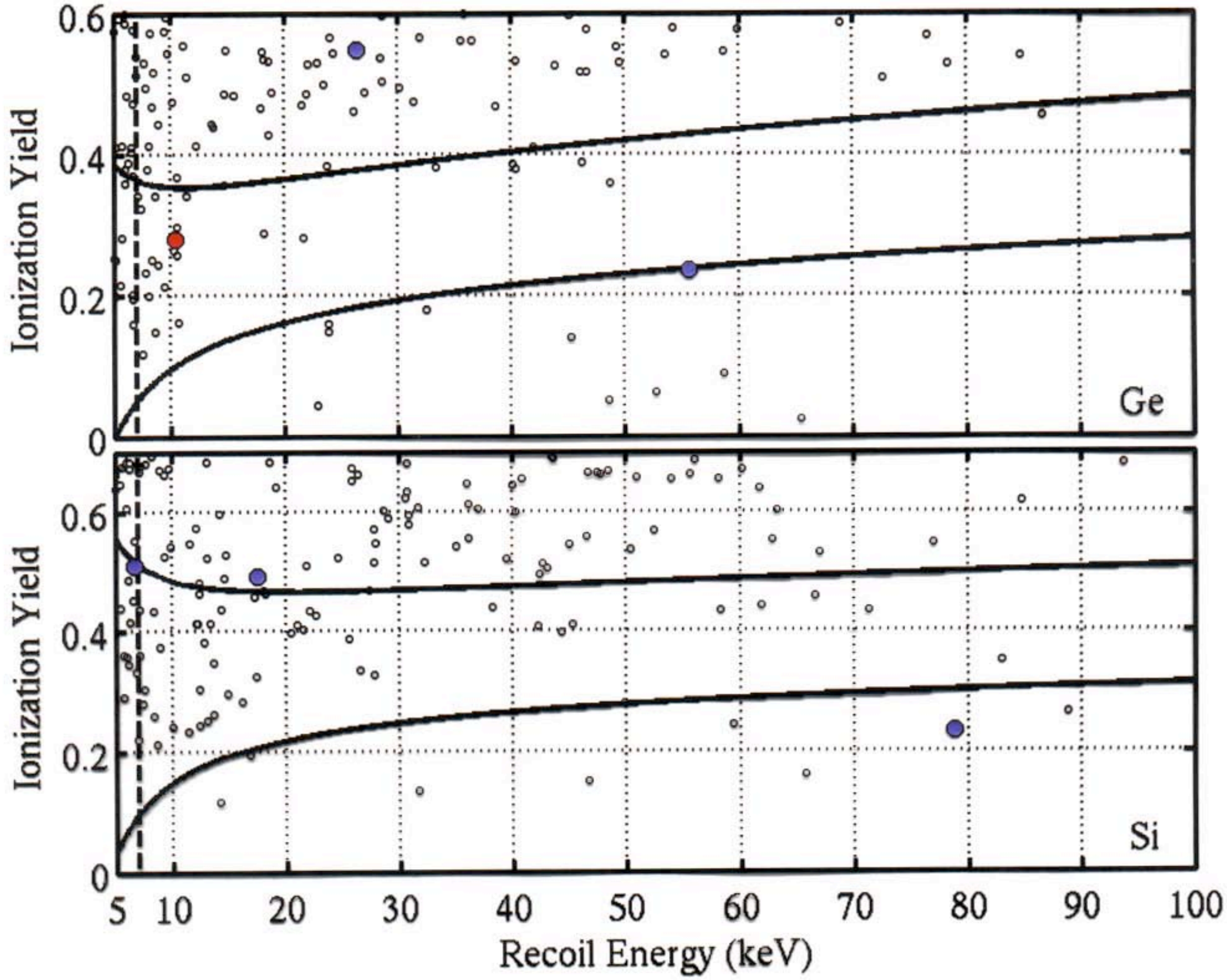


- Upper limits on the WIMP- nucleon cross section from CDMS II first run are 4×10^{-43} cm^2 for a WIMP with mass of 60 GeV/c^2
  - → Limits from EDELWEISS I, CRESST II, and ZEPLIN I (not shown here) are all about 4x higher
- Incompatible with DAMA signal if "standard picture" but some alternatives

First Year of Running CDMS II at Soudan

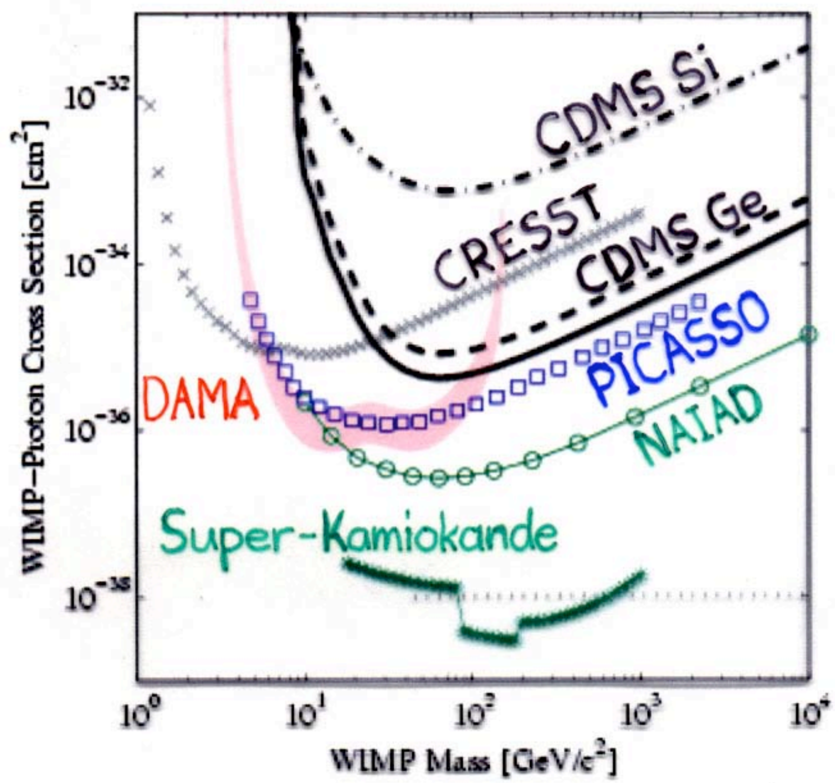
- Installed two towers of 6 detectors each in 2003
- Ran "Tower 1" October 2003-January 2004 for 53 livedays
  - → Same 4 Ge (1 kg) and 2 Si (0.2 kg) ZIPs run at Stanford
  - → Results published in PRL 93, 211301 (2004)
- Ran 12 detectors in 2 towers from March-August 2004 for 74 livedays
  - → Ge results announced April 2005
  - → Ge more sensitive to WIMPs since $\Rightarrow_{n\Rightarrow} \Rightarrow A^2$
  - → Si more sensitive to neutrons
  - → Si sensitive to lower-mass WIMP



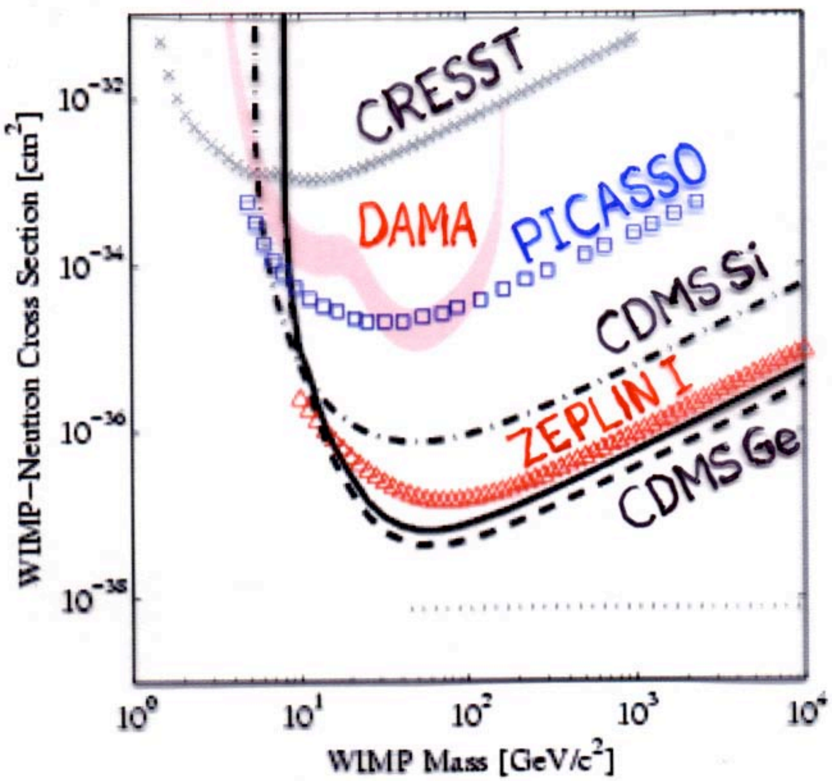


0.6
0.4
0.2
0
Ionization Yield
Ge
0.6
0.4
0.2
0
Ionization Yield
Si
5
10
20
30
40
50
60
70
80
90
100
Recoil Energy (keV)

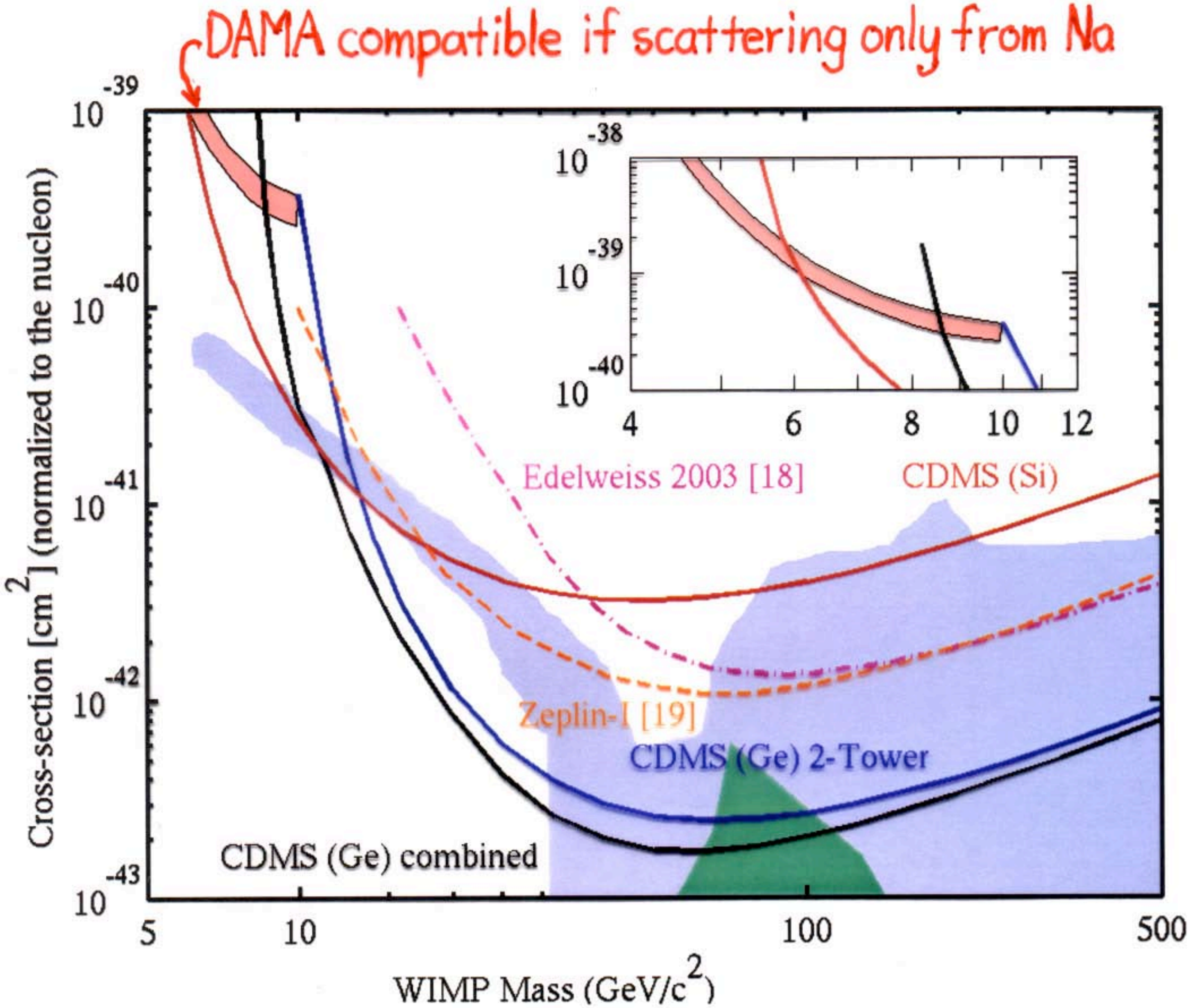
90% C.L. Upper Limits for Proton-WIMP σ



90% C.L. Upper Limits for Neutron-WIMP σ



7.73% ^{73}Ge, 4.68% ^{29}Si


DAMA compatible if scattering only from Na
Cross-section [cm^2] (normalized to the nucleon)
WIMP Mass (GeV/c^2)
Edelweiss 2003 [18]
CDMS (Si)
Zeplin-I [19]
CDMS (Ge) 2-Tower
CDMS (Ge) combined

The Near Future

CDMS

- 5 Towers Installed
- 2 years of running approved

SCDMS

- 25 kg at SNOLab or DUSEL
- Steps toward a ton

US Funding: not until SLAC/Fermilab colliders stop

UK Funding: competitive results from ZEPLIN II or ?

European consolidation

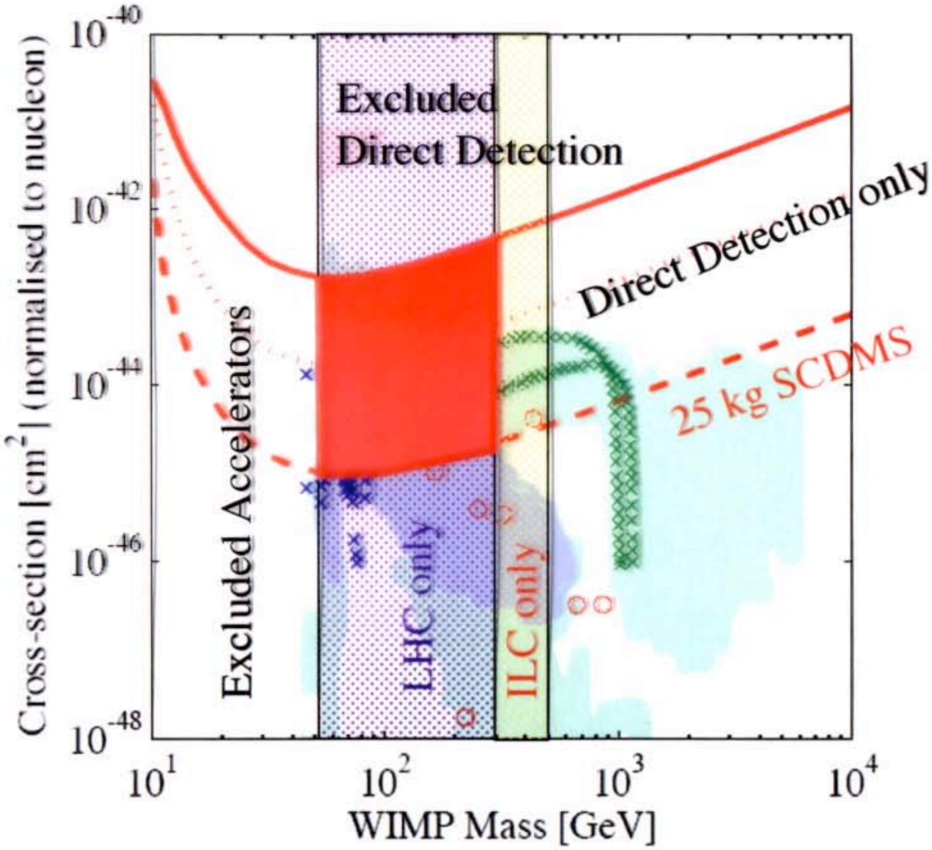
Ton-scale European Cryogenic Plans

EURECA

- Proposed *European Underground Rare Event search with a Calorimeter Array*
  - → Based on CRESST-II and EDELWEISS-II experience, with additional forces
  - → Baseline targets: Ge, $CaWO_4$ (*A* dependence)
  - → Mass: above 100 kg, up to ~ton
  - → Timescale: in the continuation of CRESST-II and EDELWEISS-II
  - → 2005: Statement of Interest

Shamelessly stolen from J. Gascon, ENTApP 2005

Complementarity between Direct Detection and Accelerators



Broad mass range of Direct Detection

- LHC has 2 Tev limit for gluino, squark, slepton =>≈300GeV for neutralino in most SUSY models
- Direct Detection may indicate a mass too large for LHC but reachable by ILC

Accelerators can reach down to lower elastic cross section

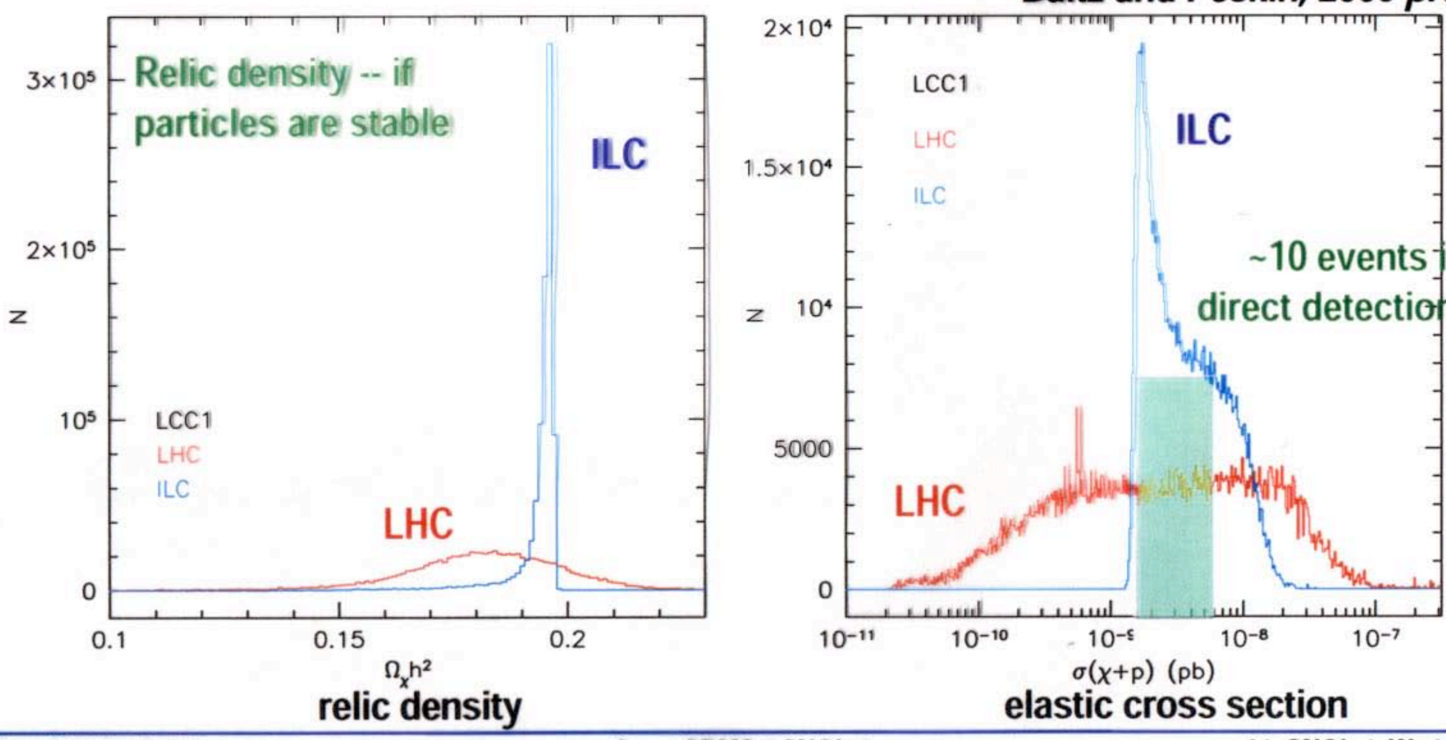
- Indicate order of sensitivity necessary for direct detection

Rich Physics in overlap region

WIMPs and SUSY

- **LHC/ILC constraints compared with direct DM searches**
  - Specify a benchmark model, eg, here 'LCC1'
  - Explore range of all models compatible with accelerator data
  - Constrain secondary parameters

Baltz and Peskin, 2005 prelim.



Dan Bauer
PIC2005
8 July 2005

Summary and Projections

If there is funding!

Cold Dark Matter

- Looking for 23% of the universe!
- Physics outside SM (Axions, WIMPs)

Broad range of experimental techniques

- Axion searches will soon cover more of the likely parameter space
- Intriguing hints from indirect searches for WIMPS
- Significant improvement in direct detection limits from CDMS

Growing scale of experiments

- Excellent prospects to see signal soon!
- Competitive reach for SUSY with LHC!
  - Direct detection sensitive to higher masses!
- Unfortunately, costs are also growing :(
  - Field will likely contract to a few big experiments.

90% CL upper limits assuming standard halo, A^2 scaling