Bernard Sadoulet
Dept. of Physics /LBNL UC Berkeley
UC Institute for Nuclear and Particle Astrophysics and Cosmology (INPAC)

Dark Matter Searches

Particle Cosmology

Non baryonic dark matter
(Axions)
WIMPs: a generic consequence of new physics at TeV scale
Direct Detection of WIMPs

Noble Liquids

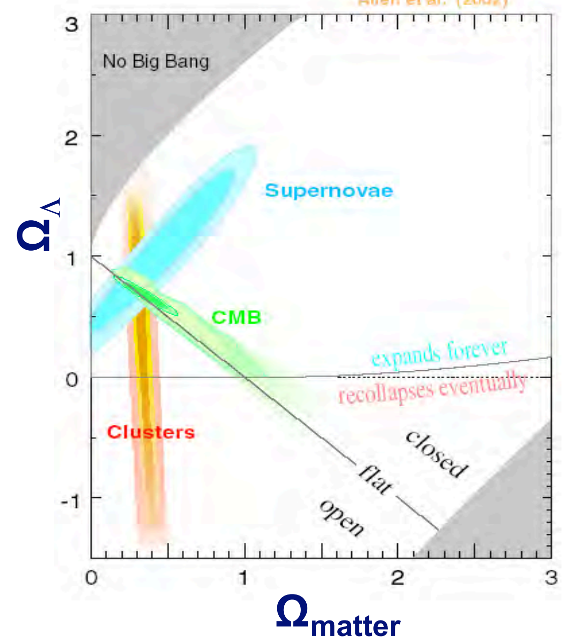
Phonon Mediated Detectors

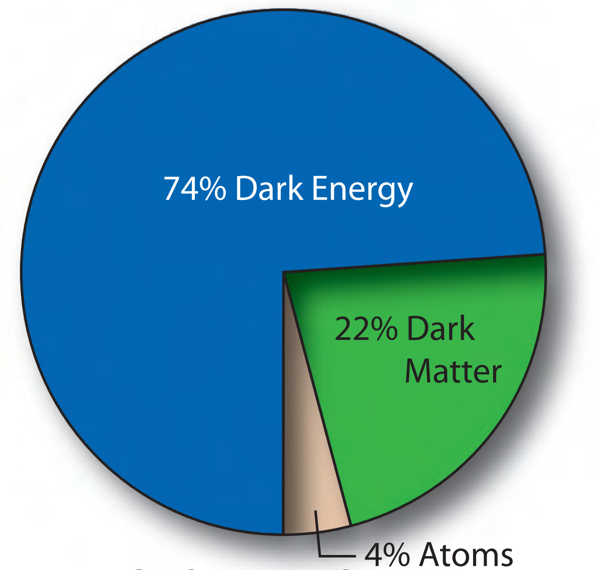
DAMA

Future of Underground Science DUSEL

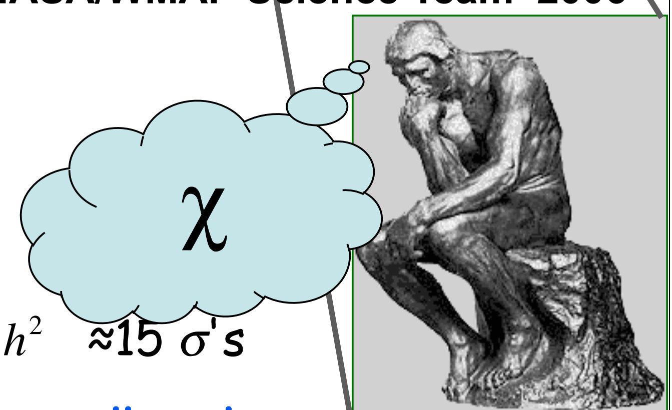
Standard Model of Cosmology

A surprising but consistent picture





NASA/WMAP Science Team 2006



Not ordinary matter (Baryons)

$$\Omega_m >> \Omega_b = 0.047 \pm 0.006 \text{ from} \left| \begin{array}{c} \text{Nucleosynthesis} \\ \text{WMAP} \end{array} \right.$$

+ internally to WMAP $\Omega_m h^2 \neq \Omega_b h^2$ ≈15 σ's

Mostly cold: Not light neutrinos ≠ small scale structure

$m_\nu < .17 eV$ Large Scale structure+baryon oscillation + Lyman α

Standard Model of Particle Physics

Fantastic success but

Model is unstable

Why is W and Z at ≈100 M_p?

Need for new physics at that scale

supersymmetry

additional dimensions

Flat: Cheng et al. PR 66 (2002)

Warped: K.Agashe, G.Servant hep-ph/0403143

In order to prevent the proton to decay, a new quantum number

=> Stable particles: Neutralino

Lowest Kaluza Klein excitation

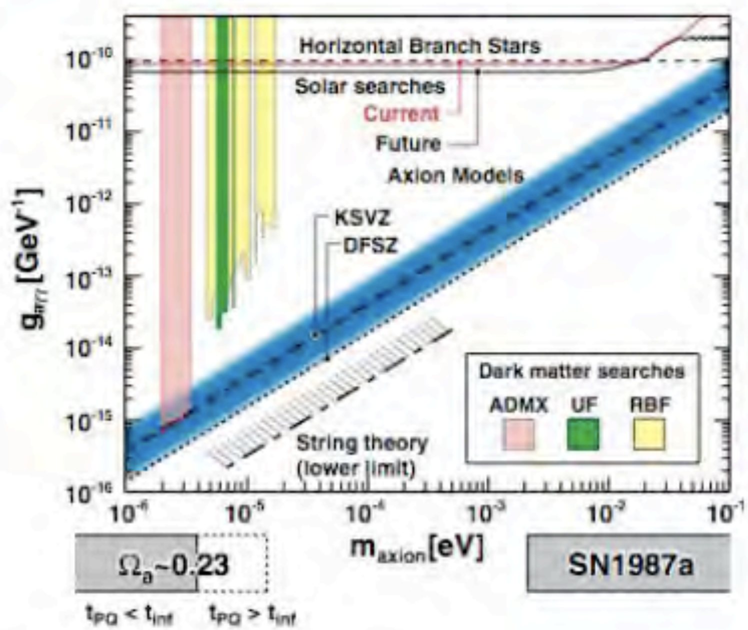
QCD violates CP

We need e.g. dynamic restoration : Peccei Quinn Symmetry: Axions

Neutrino sector

Can there be e.g. a relatively light sterile neutrino?

Axions



Cosmology bounds $m_a > 1\ \mu eV$

- *$\Omega_a \propto m_a^{-7/6}$, ~ O(1) for 1-10 μeV*
- *Why it is a good DM candidate*

Astrophysics bounds $m_a < 1$ meV

- *Sn1987a, stellar evolution & lab*

Most model $g_{a\gamma\gamma}$ banded within ~10

- *Lower limit to $g_{a\gamma\gamma}$ from string theory*
- *Witten & Svrček, hep-th/0605206*

Microwave technology

Reaching cosmologically interesting range
ADMX Will cover lowest decade of 3 decades still open

Particle Cosmology

Bringing both fields together: a remarkable concidence

Particles in thermal equilibrium
+ decoupling when nonrelativistic

Freeze out when annihilation rate ≈ expansion rate

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

Generic Class

Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale
(e.g. supersymmetry or additional dimensions)
=> significant amount of dark matter

Weakly Interacting Massive Particles

2 generic methods:

Direct Detection= elastic scattering

Indirect: Annihilation products

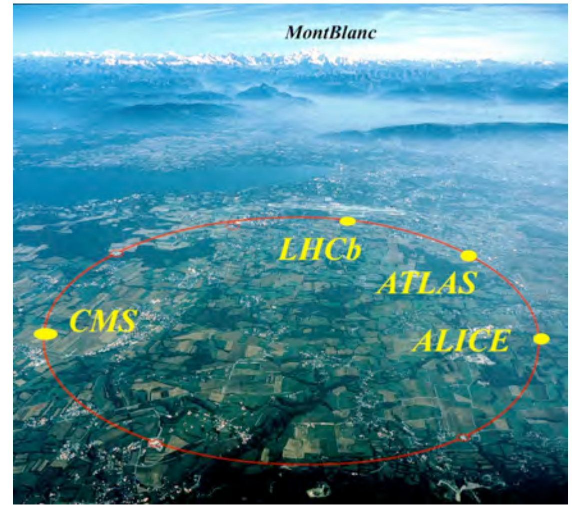
γ's e.g. 2 γ's at E=M is the cleanest
ν from sun &earth ≈ elastic scattering
$e^+, \bar{p}$ dependent on trapping time

+ Large Hadron Collider

3 Complementary Approaches

WIMP scattering on Earth:
e.g. CDMS : currently leading the field

Halo made of WIMPs
1/2 shown for clarity



WIMP production on Earth

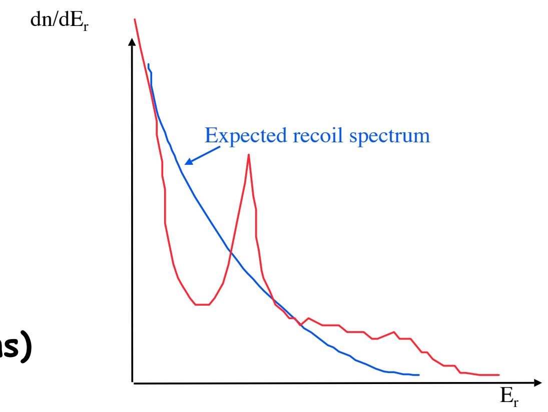
WIMP annihilation in the cosmos

GLAST
Launched 11 June 2008

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

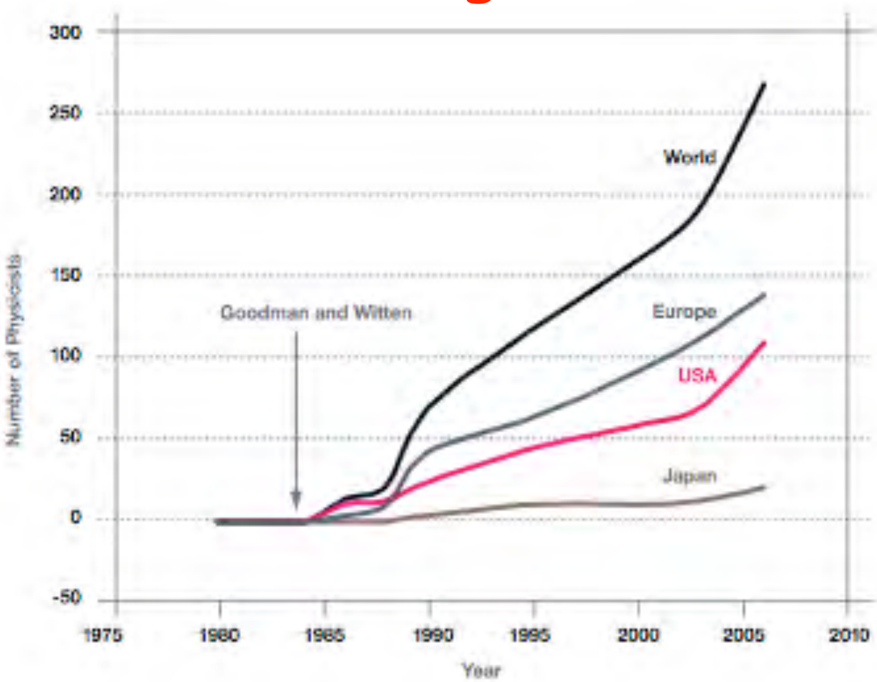
- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

Linked to galaxy

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

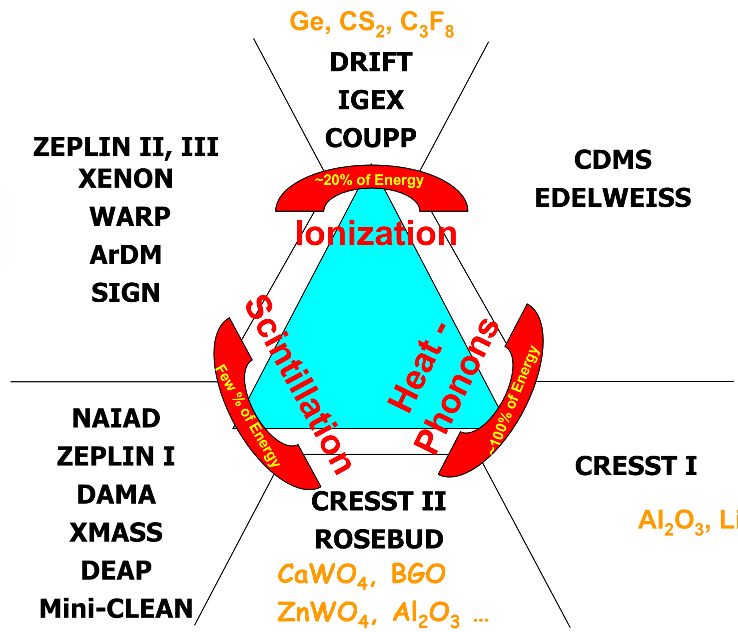
Experimental Approaches

A blooming field



As large an amount of information and a signal to noise ratio as possible

Direct Detection Techniques



At least two pieces of information in order to

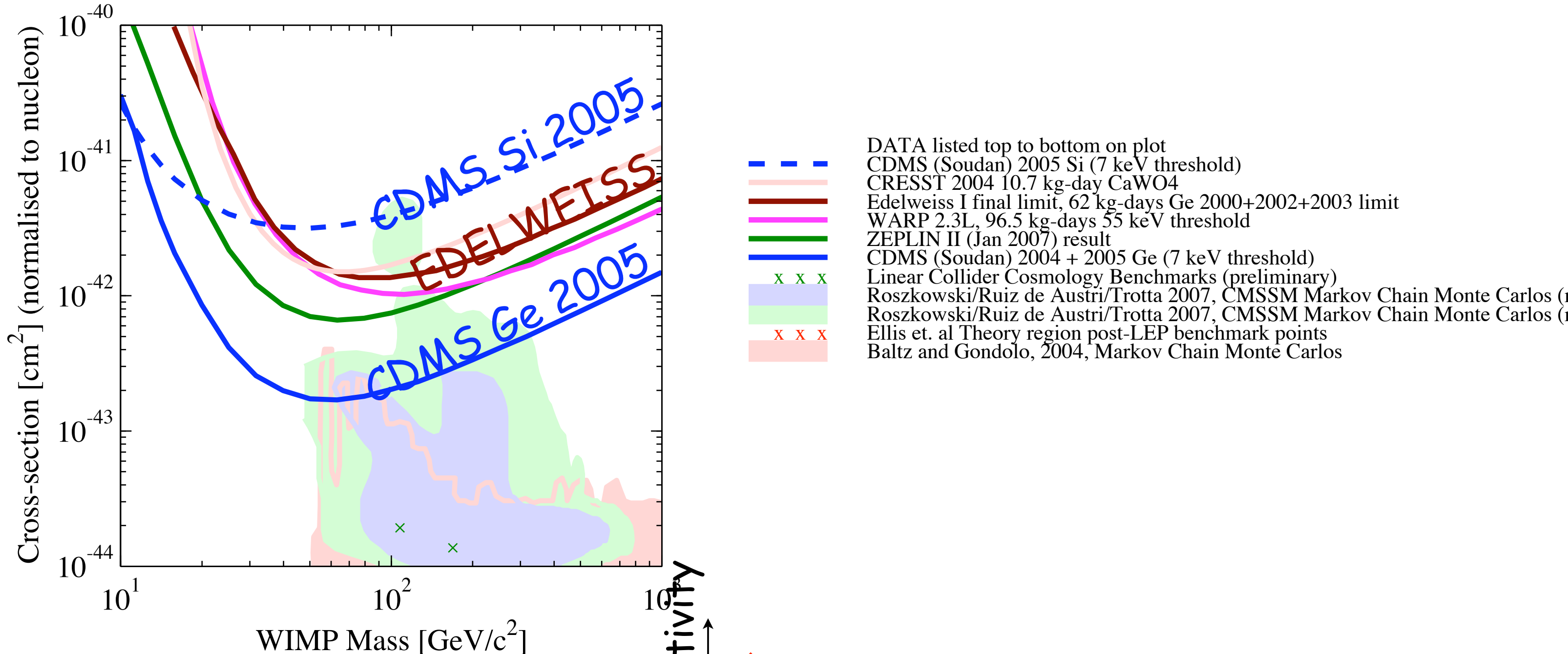
recognize nuclear recoil

extract rare events from background (self consistency)

+ fiducial cuts (self shielding, bad regions)

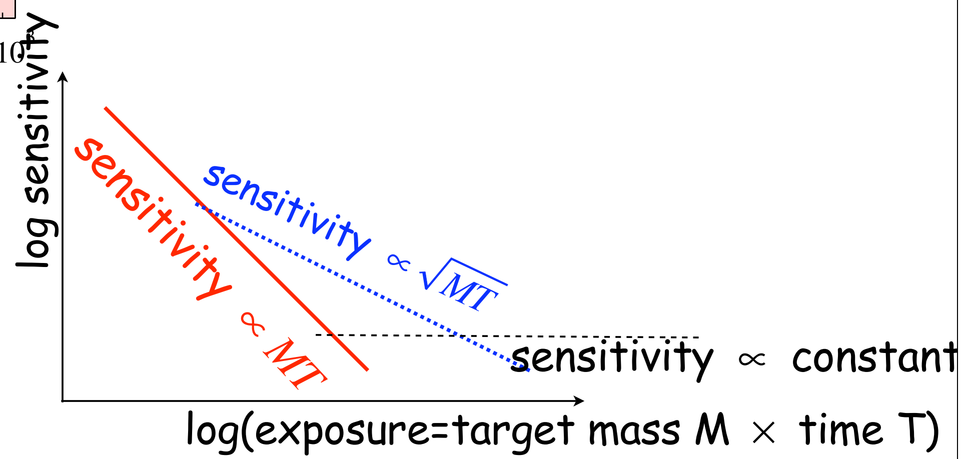
Status early 2007

Scalar coherent interaction ≈A^2



Three Challenges

- Understand/Calibrate detectors
- Be background free
  much more sensitive than
  background subtraction
  eventually limited by systematics
- Increase mass while staying background free



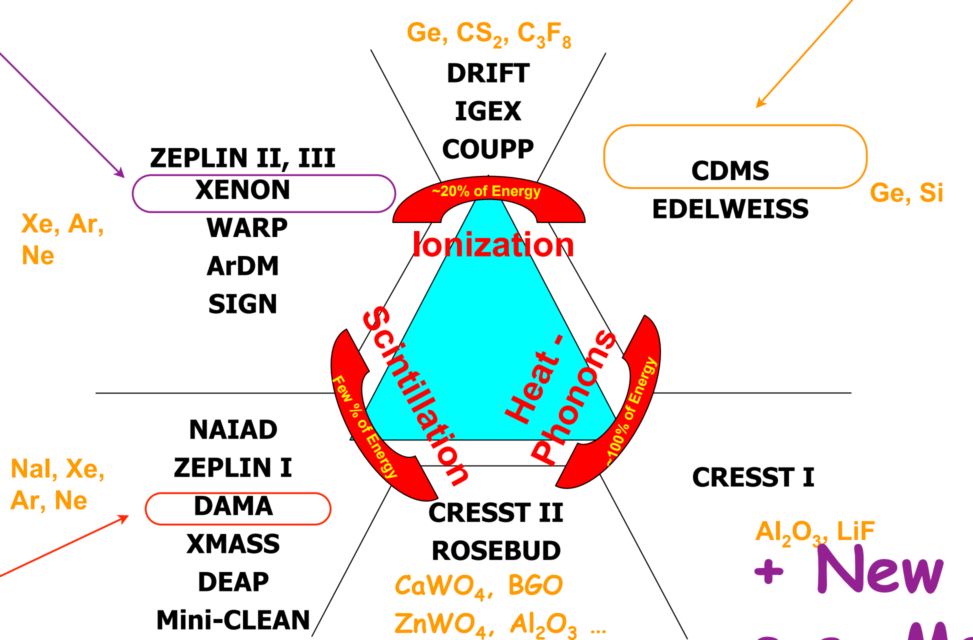
Current results

3 examples in more details

Xenon 10 as generic for
ZEPLIN II ,WARP, ArDM

CDMS as generic for
EDELWEISS & CRESST

Direct Detection Techniques



DAMA/Libra
new modulation result

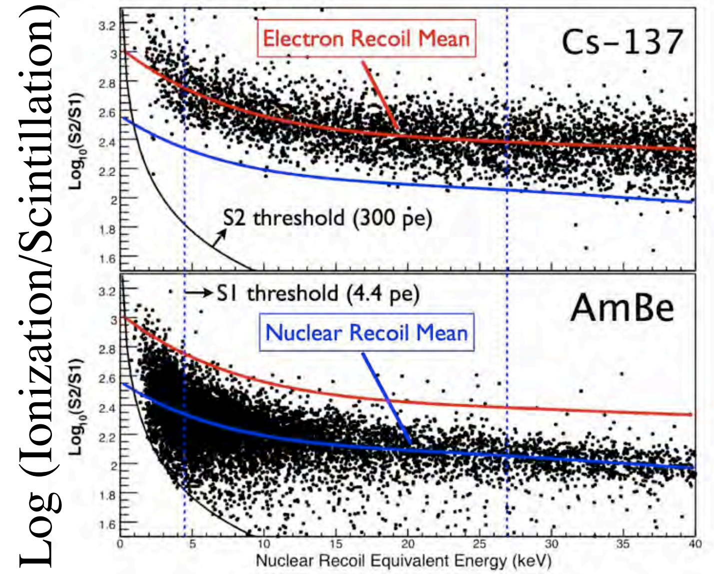
+ New ideas
e.g. Monroe Nygren

The Noble Liquid Revolution

Noble liquids are both excellent scintillators and ionization collectors
=> get to large mass while maintaining excellent background by self shielding and discrimination

Liquid Xenon

Ionization + scintillation



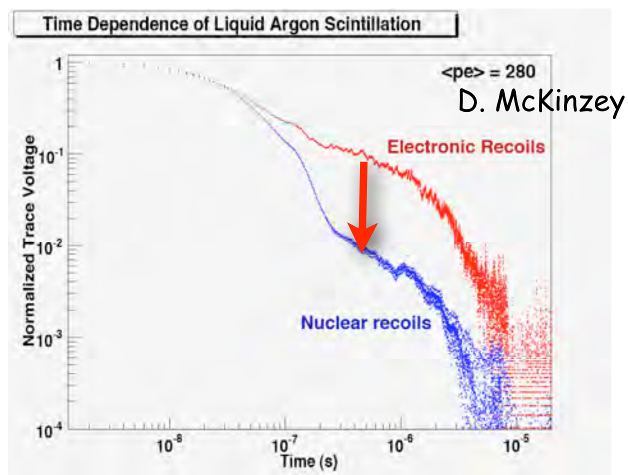
2 breakthroughs:

- ✳ Extraction of electrons from the liquid to the gas
- ✳ At low energy, separation between electron recoils and nuclear recoils increases

=> work down to ≈4.5 photo electrons with 99% electron rejection efficiency with 50% nuclear recoil efficiency

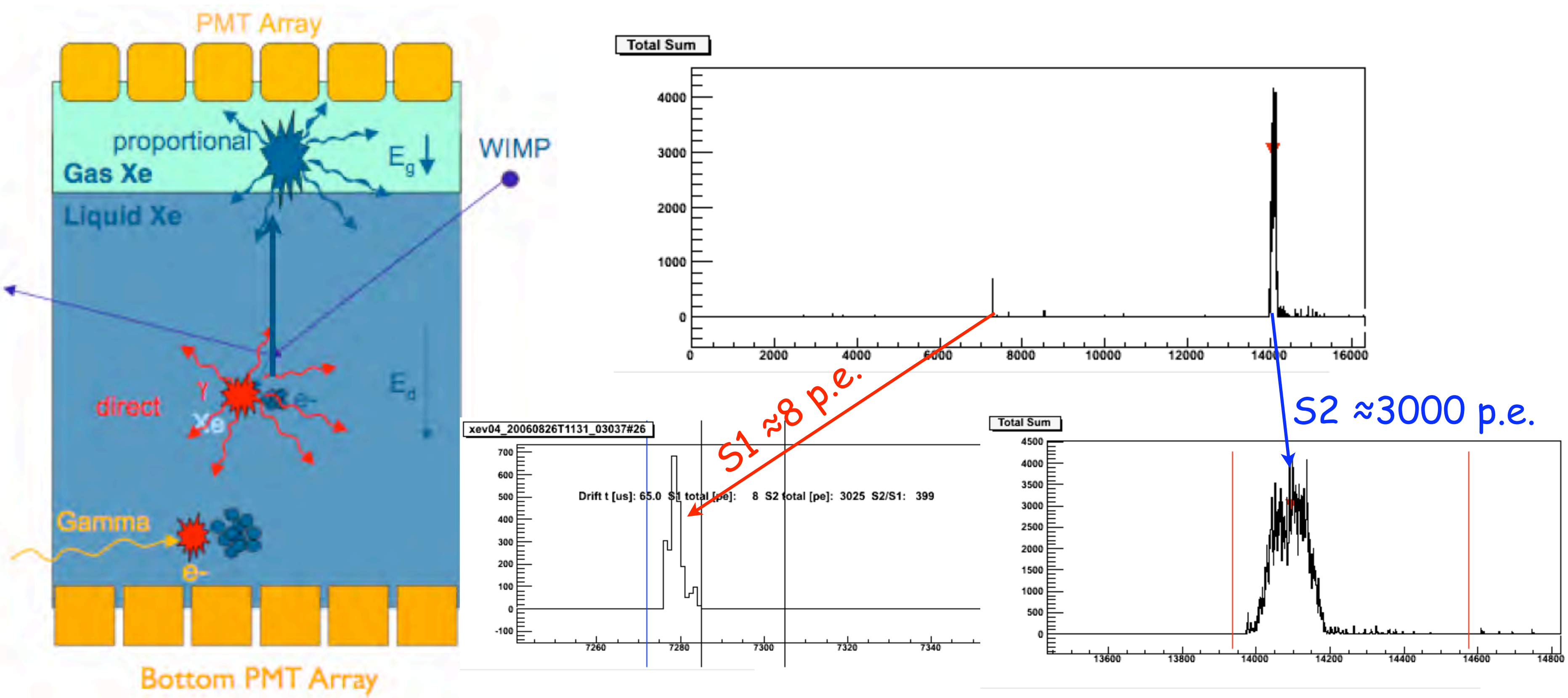
Liquid Argon (or Neon)

For light liquids, one additional handle : rise time
Triplet (long decay time) killed by nuclear recoil



Essential to reject ^{39}Ar (1 Bq/kg)
Underground argon depleted in ^{39}Ar

Xenon 10



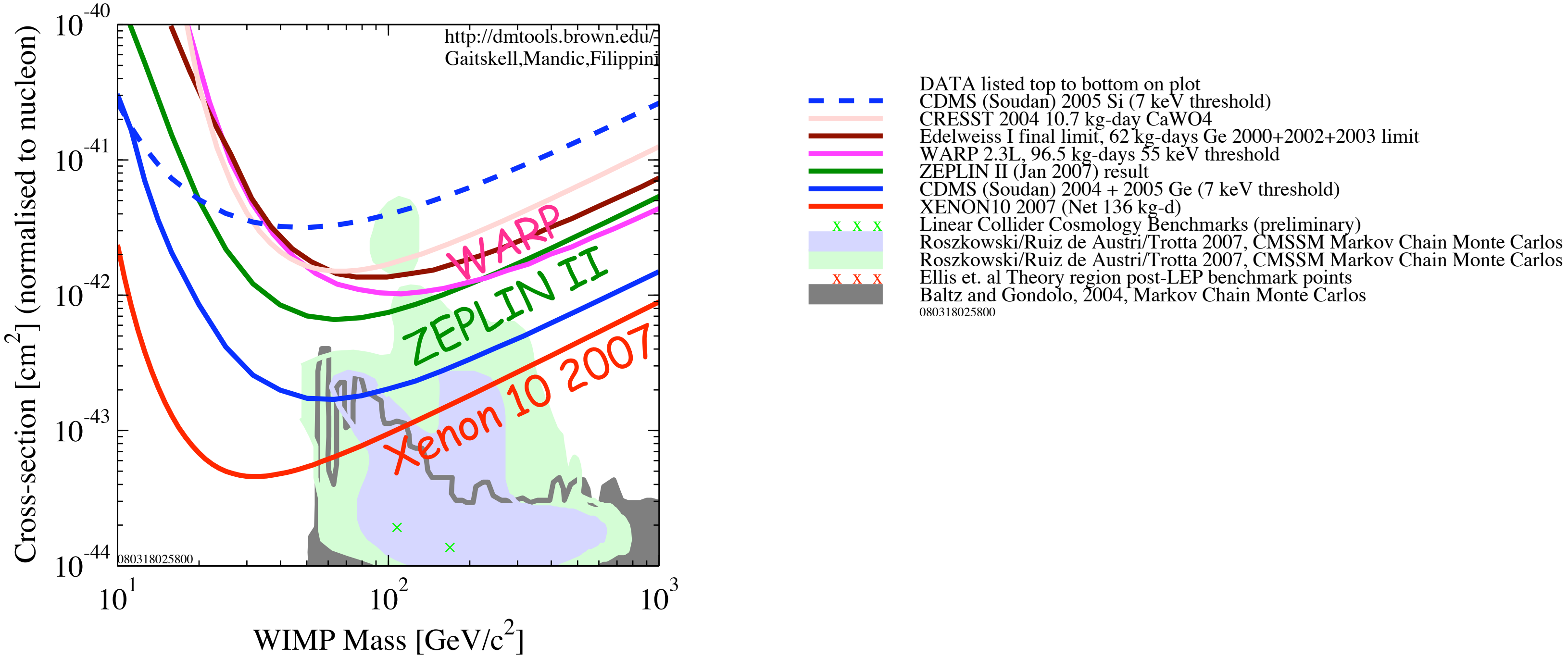
Liquid Xenon: Scintillation + ionization

two photon pulses => depth

Main differences with Zeplin II: Smaller Photomultipliers
Photomultipliers in liquid

Noble Liquids

Great progress!



What about our 3 challenges

?
- Understand/Calibrate detectors

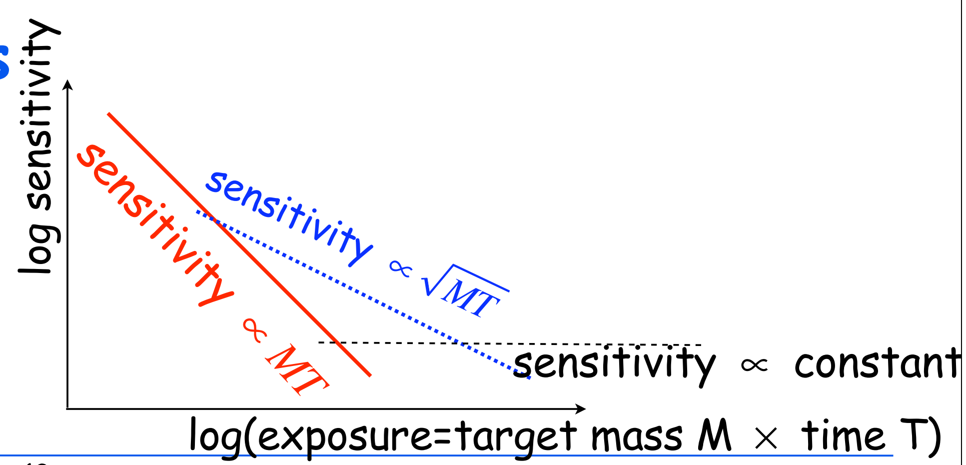
?
- Be background free

  much more sensitive than

  background subtraction

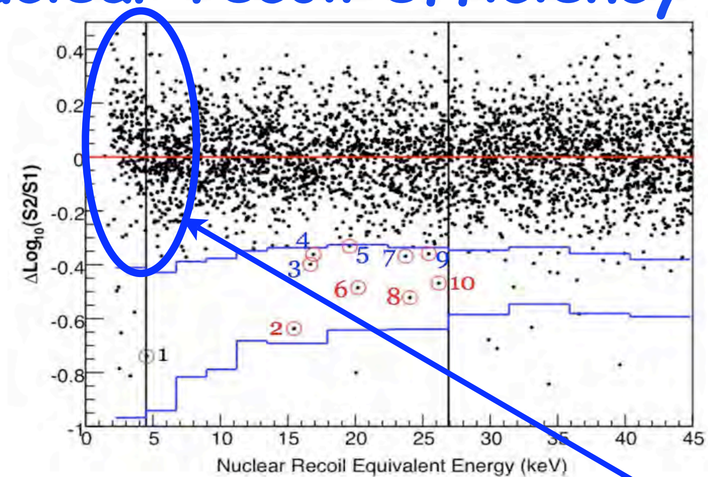
  eventually limited by systematics

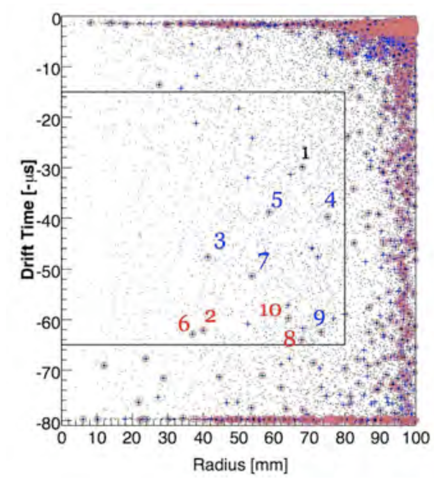
√
- Increase mass



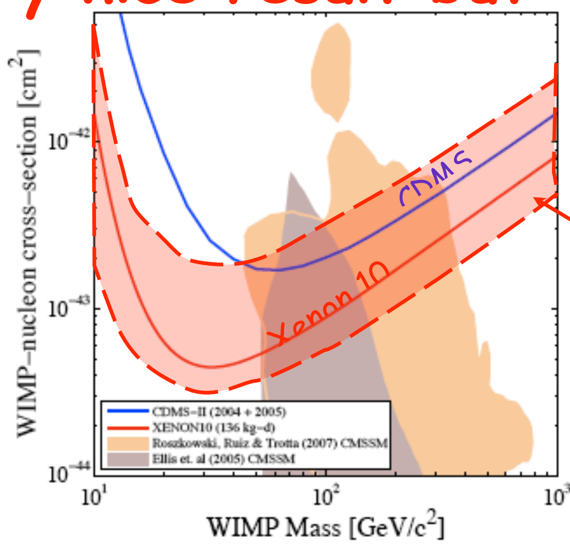
e.g. Xenon 10

After pattern recognition, 10 background events with 50% nuclear recoil efficiency





Very nice result but:



Large gap at small energy

Could it be disguised threshold

Why no flaring of electron at low S1?

Detector used in a region with no calibration

Large uncertainty

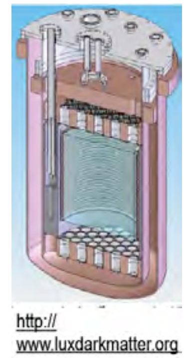
CDMS estimate July 2007

Noble Liquids: Current Plans

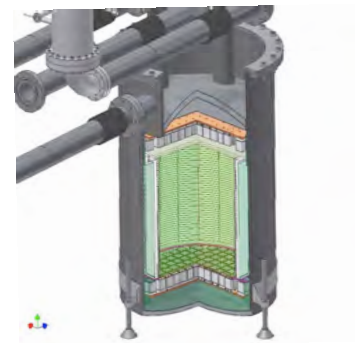
Single phase detectors

Xenon: Rely on self shielding + position reconstruction: XMASS 800kg
Argon: Rely on pulse shape discrimination: DEAP/Mini Clean

Lux 300kg



Xenon 100kg



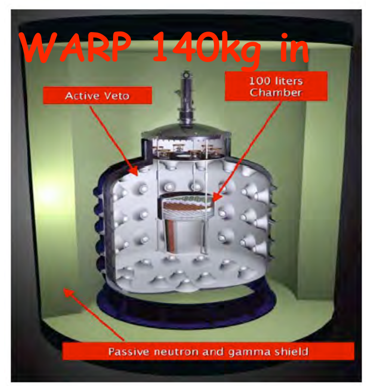
Dual phase Xenon

Xenon 100 : Assembly being finished in Gran Sasso (170kg- 50kg fiducual)
LUX 300kg : SUSEL (Homestake) Summer 09

Dual phase Argon

WARP 140kg: Assembly nearly finished
ArDM: Being assembled

WARP



ArDM

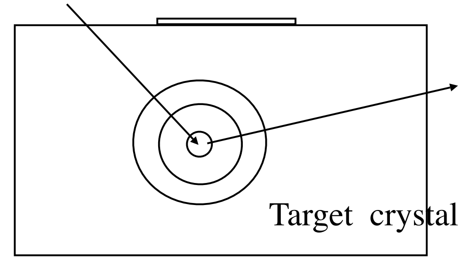
A clear danger

"My detector is bigger than yours!"
Not the whole story: Detailed understanding of the phenomenology
Zero background!

Phonon Mediated Detectors

Principle: Detect lower energy excitations

15 keV large by condensed matter physics standards

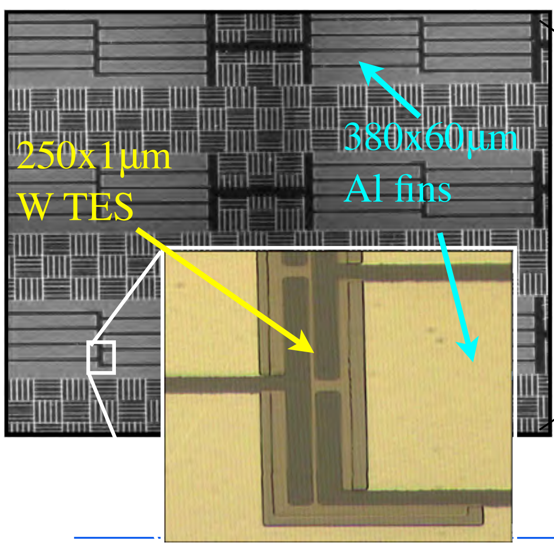


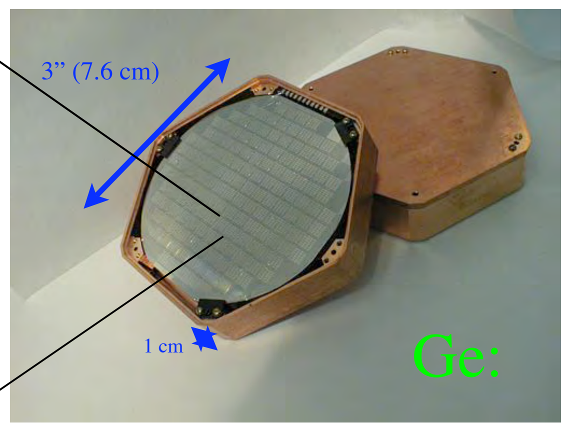
Goals

- Sensitivity down to low energy
  Phonons measure the full energy
- Active rejection of background: recognition of nuclear recoil
  Combine with low field ionization measurement CDMS EDELWEISS
  or scintillation (CRESST II)

But: operation at very low temperature!

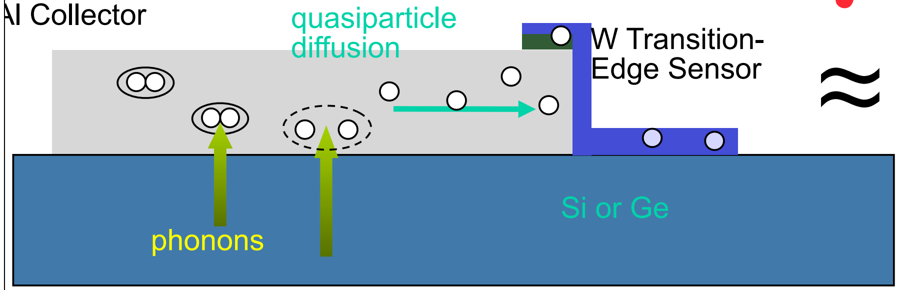
e.g. CDMS II: 40mK



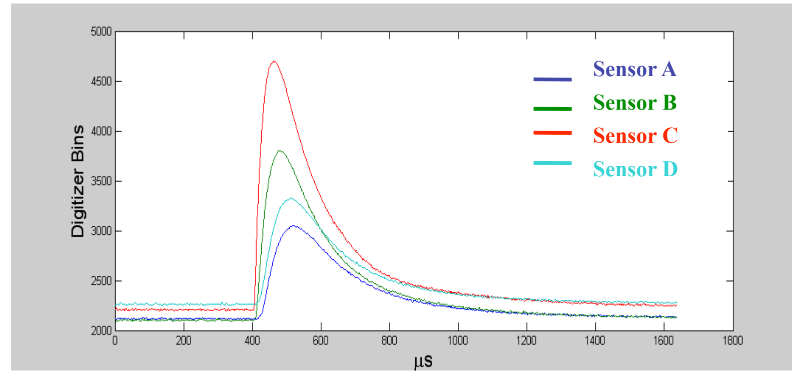


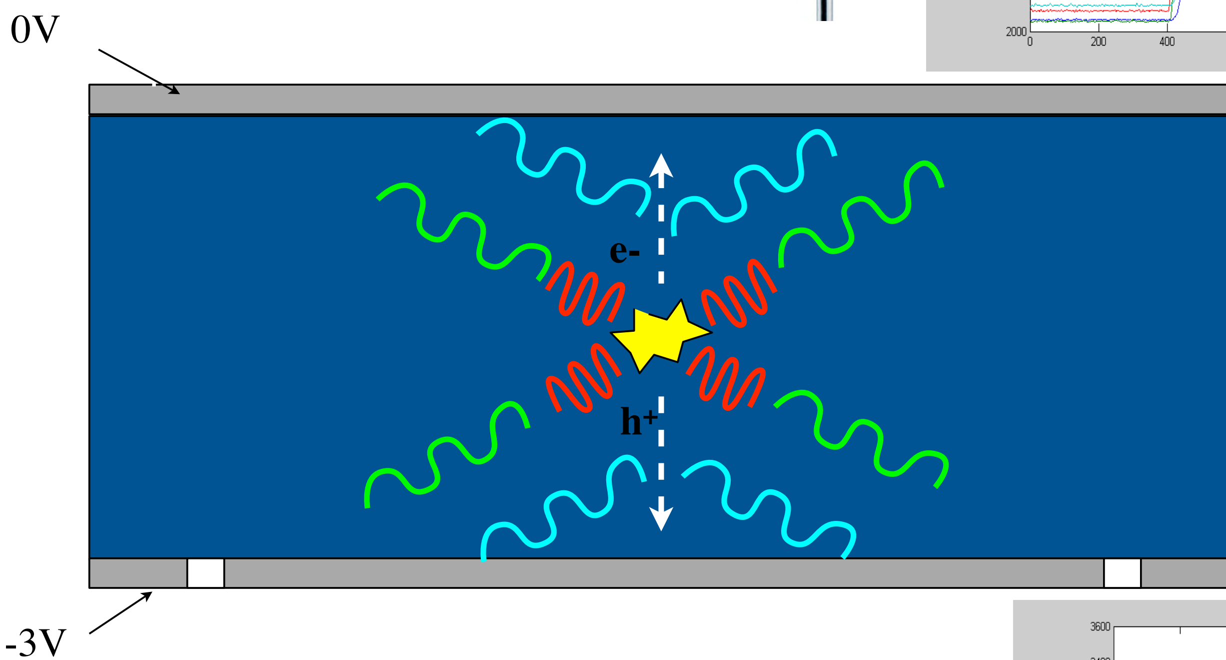
x 30= 5 towers of 6

Anatomy of an event



≈



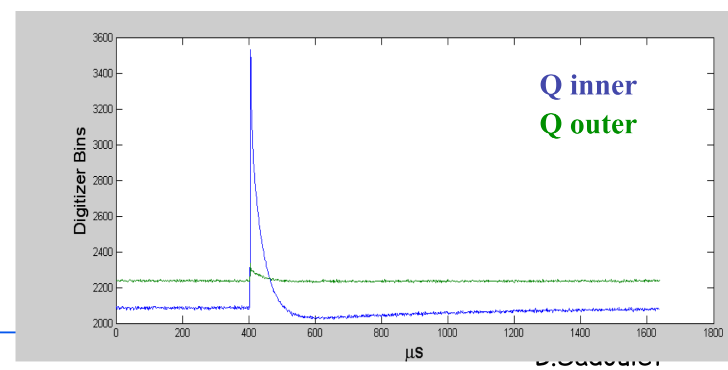


Hot charge carriers (3eV/pair)

Quasi-diffusive THz phonons

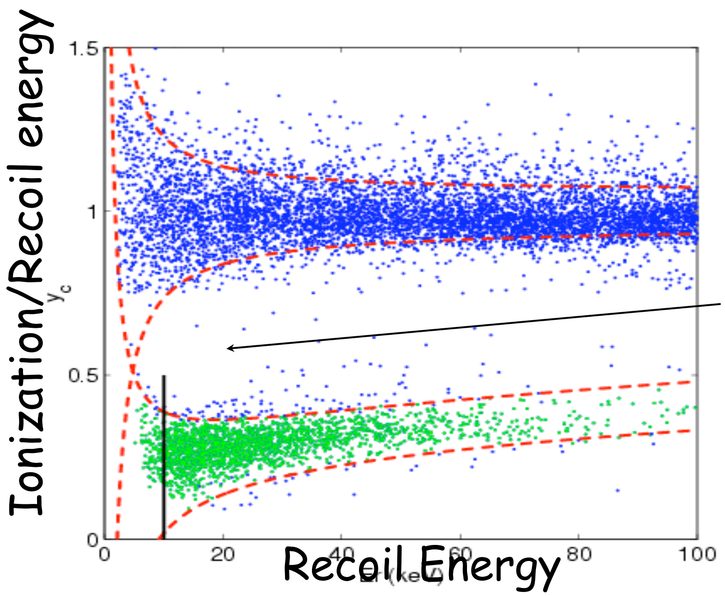
Quasi-Ballistic Neganov-Luke phonons

Quasi-Ballistic low-frequency phonons

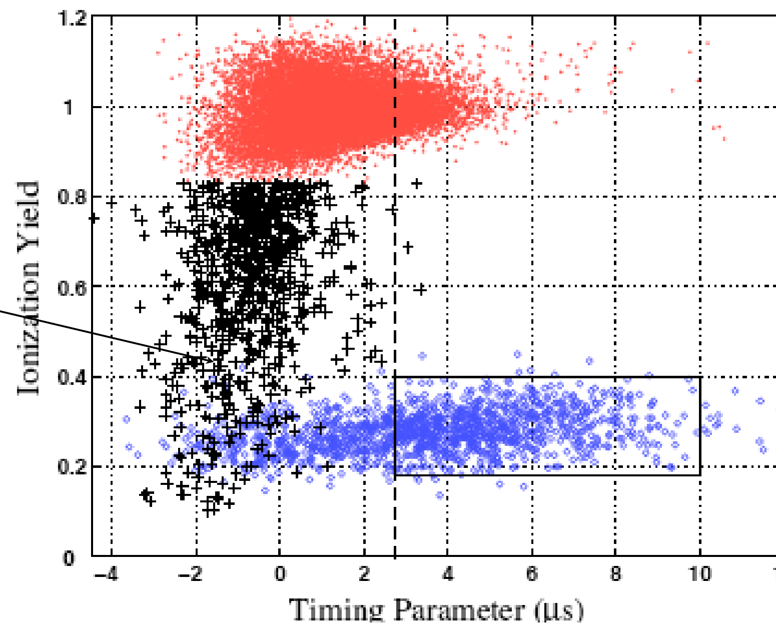


Multidimensional Discrimination

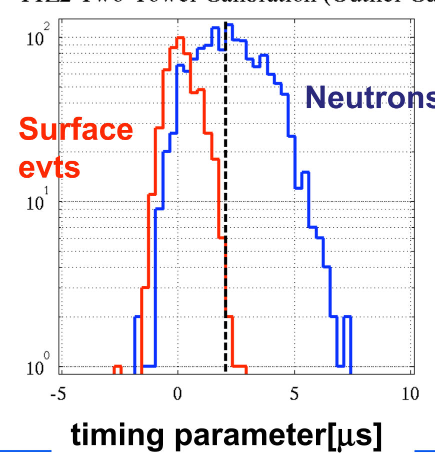
Ionization yield



Timing -> surface discrimination



T1Z2 Two-Tower Calibration (Outlier Cut)



Fix cuts blind (with calibration sources)

to get ≈0.5 events background

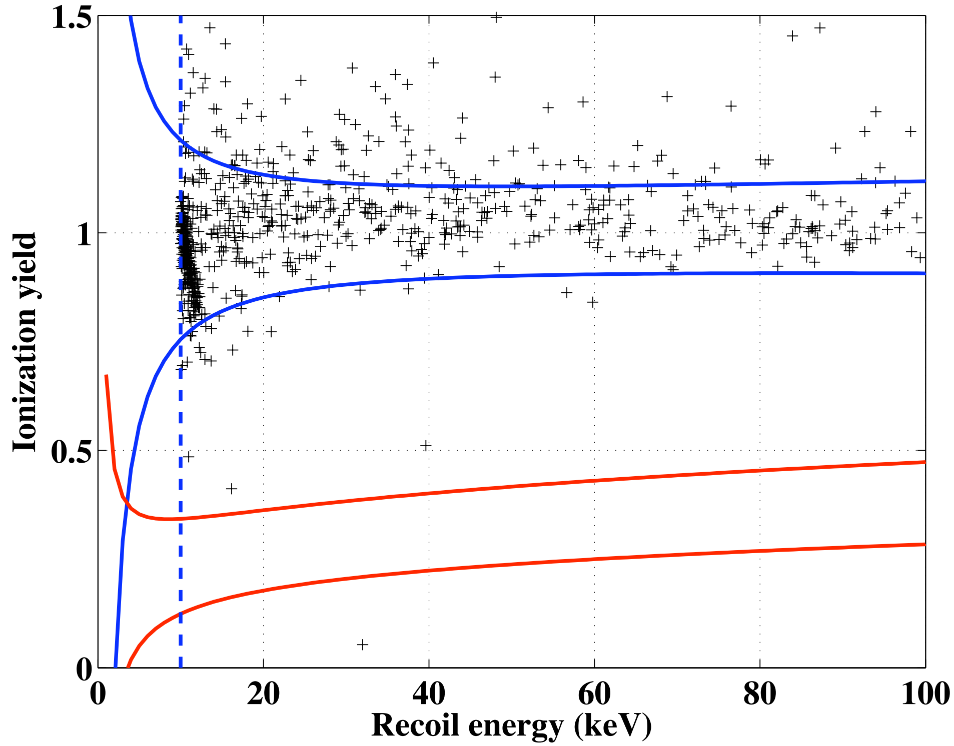
Opening the Box

Box opened Monday, February 4 for 15 Ge ZIPs
Remaining 8 Si and 1 Ge undergoing further leakage characterization

3σ region masked
=> Hide unvetoed singles

Lift the mask, see 97
singles failing timing cut

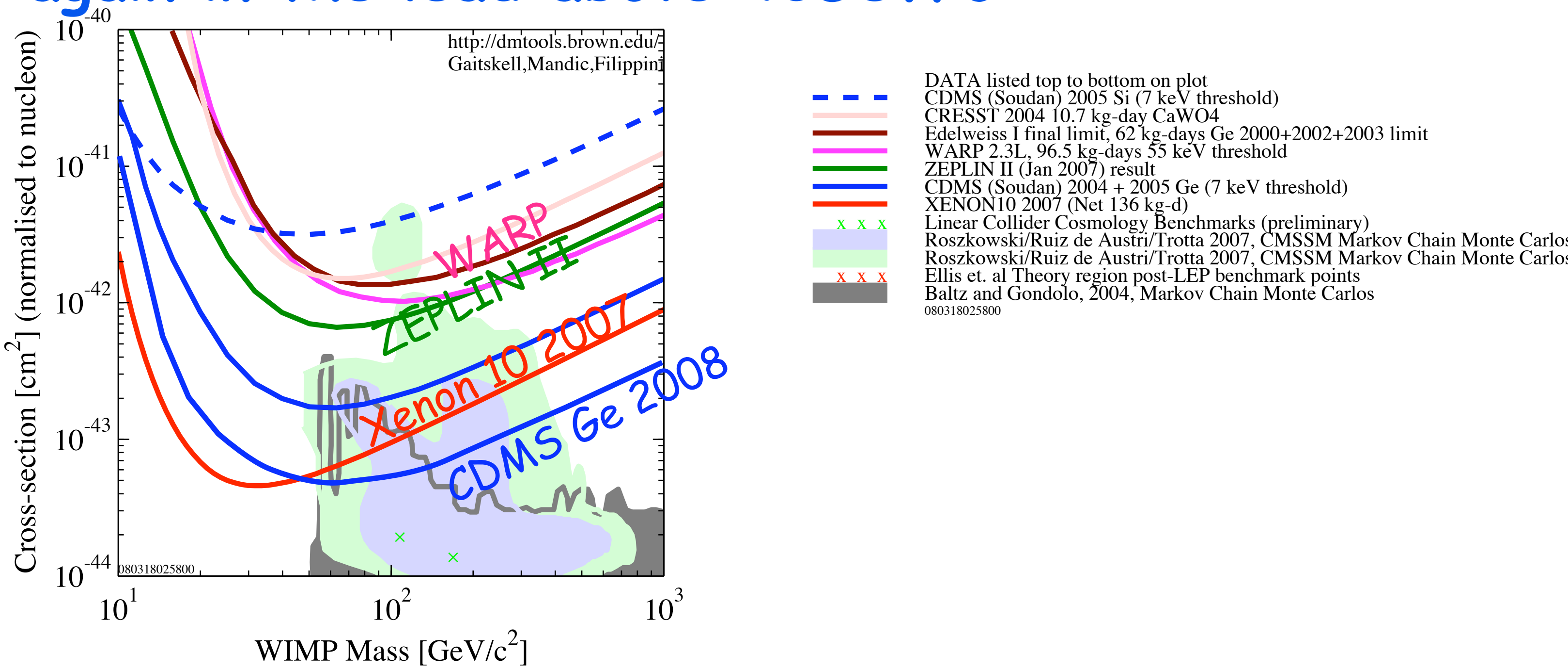
Apply the timing cut,
count the ~~candidates~~



No events observed

Current WIMP Limits

CDMS again in the lead above 40GeV/c^2



Preprint at:
- http://cdms.berkeley.edu
- arXiv:0802.3530

Immediate Future (cryogenic)

CDMS: run till ≈ December 08 ≈2000kg days

sensitivity ≈10^{-44} cm^2/nucleon

stay background free: - new towers 3 lower back grounds
- better discrimination tools

Edelweiss-> 10^{-43} cm

21 330g Ge detectors with NTD

+ 7 400g Nb Si (athermal phonons)

first commissioning run April -May 07 encouraging

no event > 30keV for eight NTD detectors (19 kg day) (cf 3 in EdelI)

first underground test of two 200g Nb Si

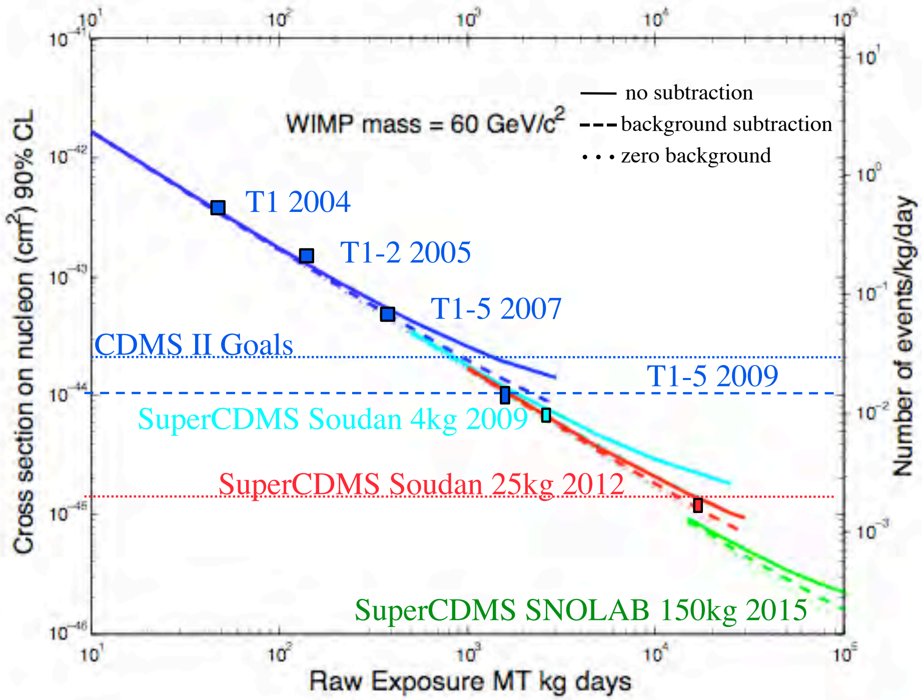
Interdigitated detectors

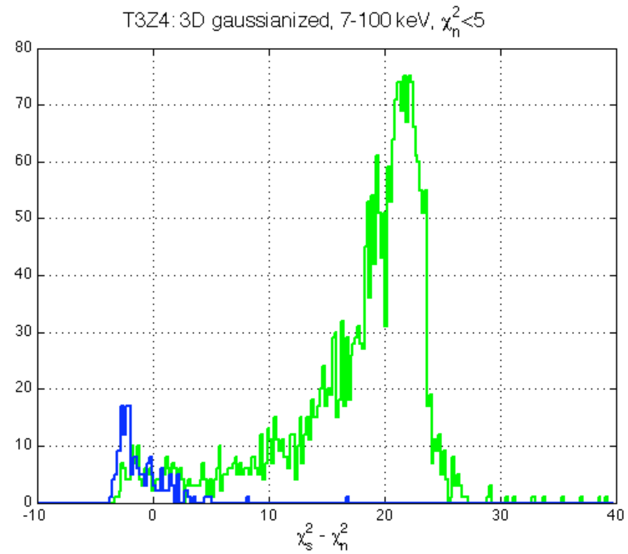
CRESST II-> 10^{-43} cm

Major upgrade 66 SQUIDs for 33 detectors + neutron shield

Three detectors running since 4/07.

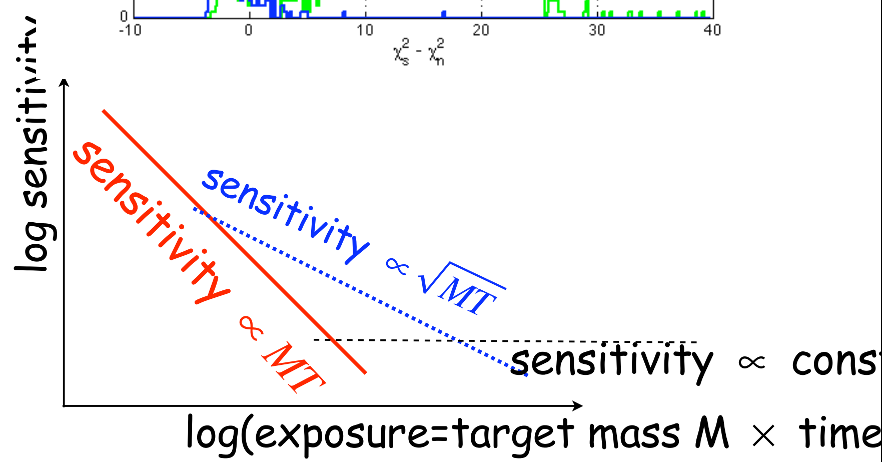
Low Temperature Detector Future





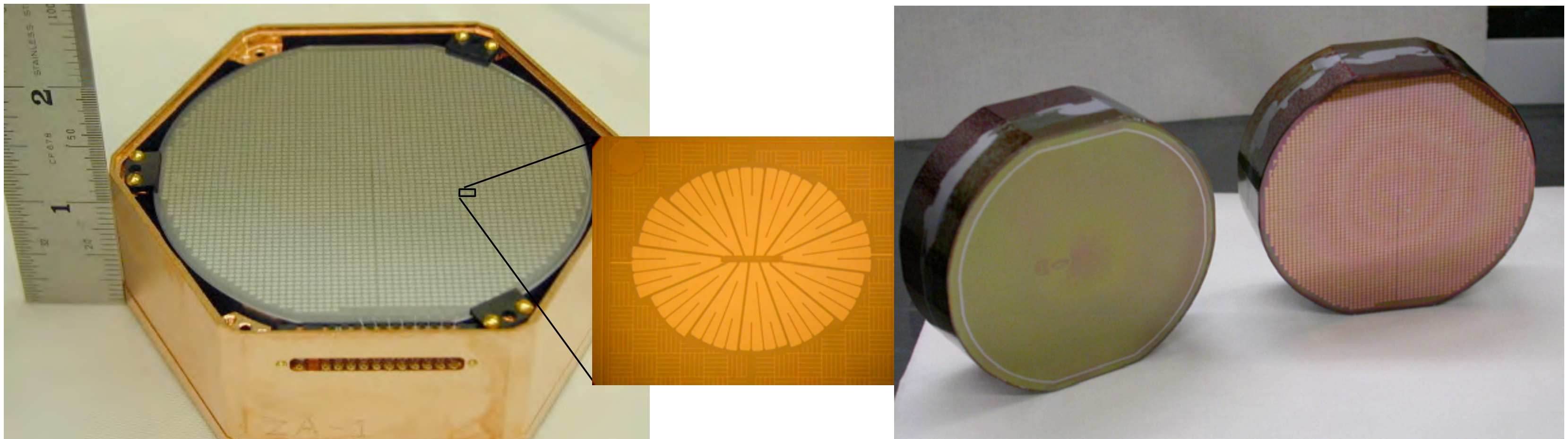
Three General Challenges

- Understand/Calibrate detectors
- Be background free
  much more sensitive than background subtraction
  eventually limited by systematics
- Increase mass while staying background free



Larger Detector Mass

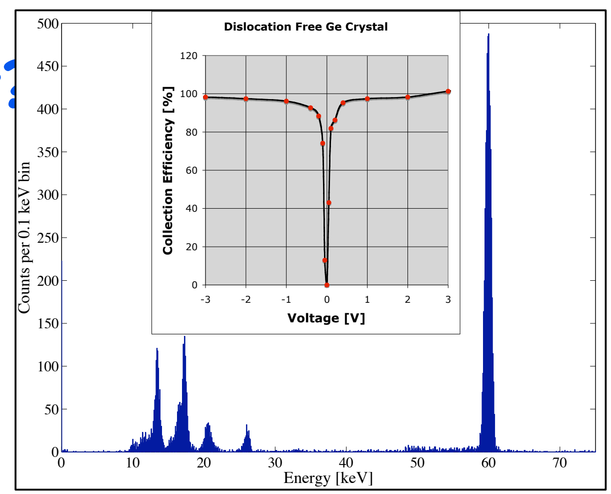
SuperCDMS 25 kg detectors: 1cm-> 1" 250g ->635 g



First tests encouraging (we need to add a radial measurement)
Double face 35% -> 70%?

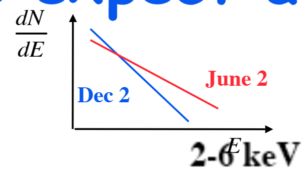
Much larger detectors -> 1ton expt?

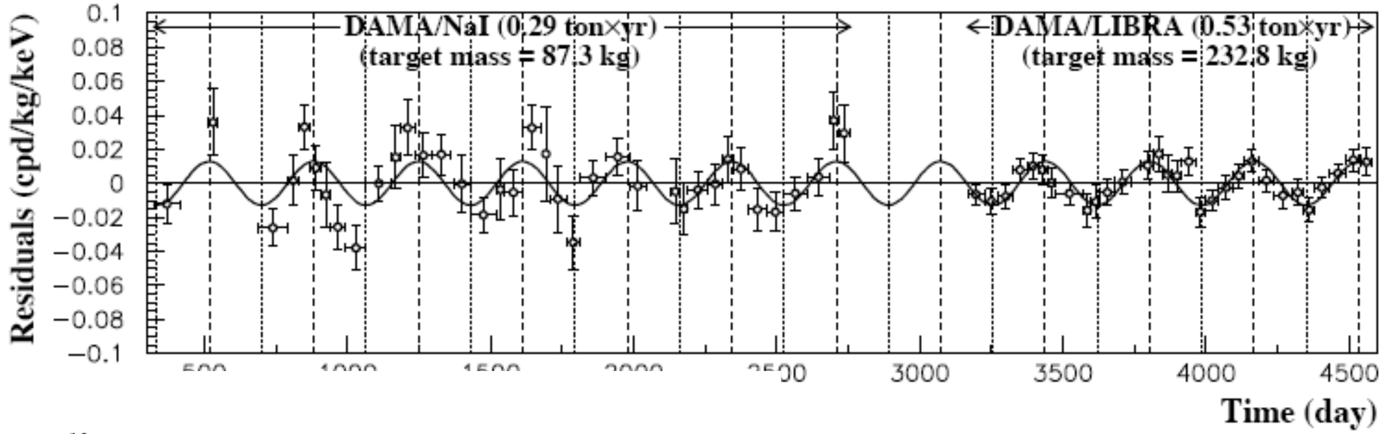
Liquid N2 Ge crystals limited to 3"
 ≈ 100 dislocation/cm^3
But we showed recently that dislocation free
 works at low temperature!
 Umicore grows (doped) 8" crystal
6"x2" or 8"x1" ≈ 5kg + Multiplexing

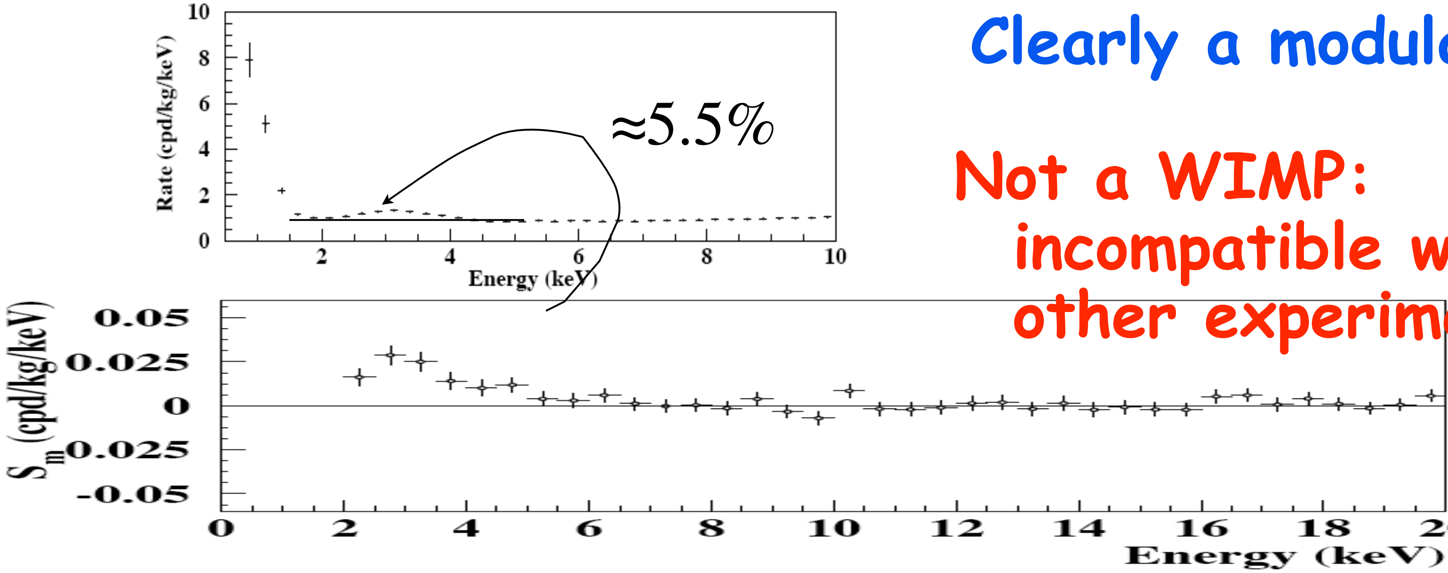


DAMA Claim April 2008

If WIMPs exist, we expect a modulation in event rate





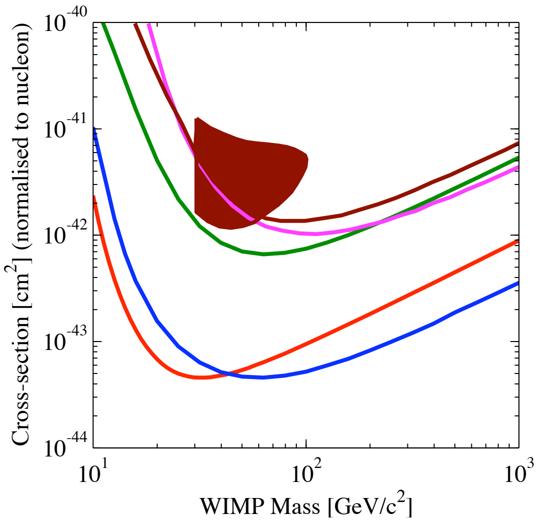


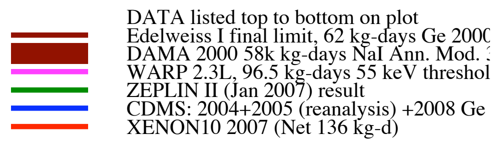
Clearly a modulation

Not a WIMP: incompatible with other experiments

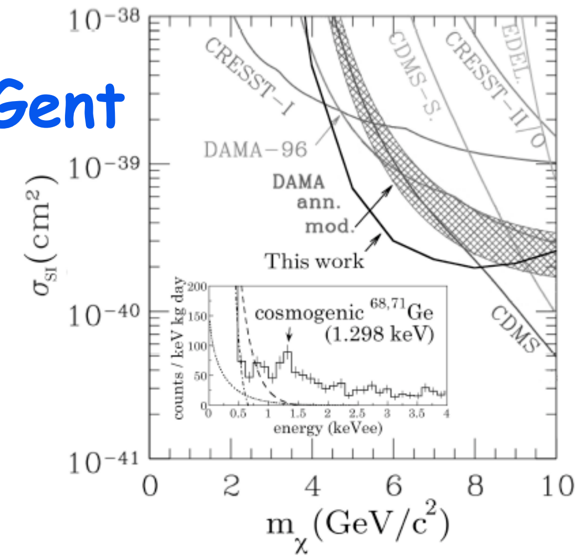
Tension with Other Expt.

Spin independent interactions



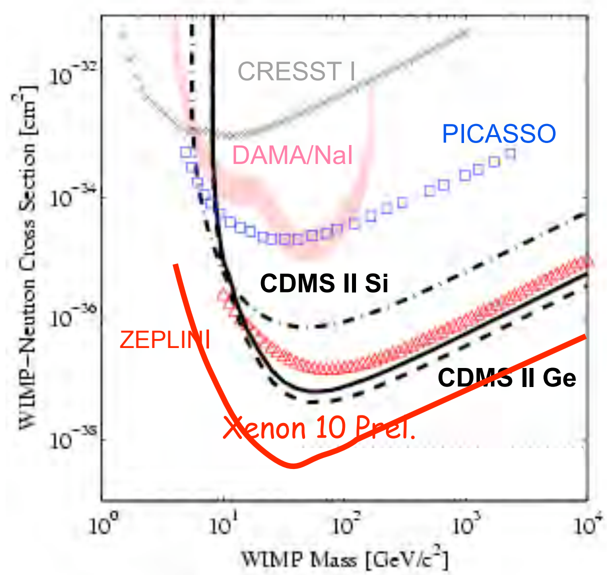


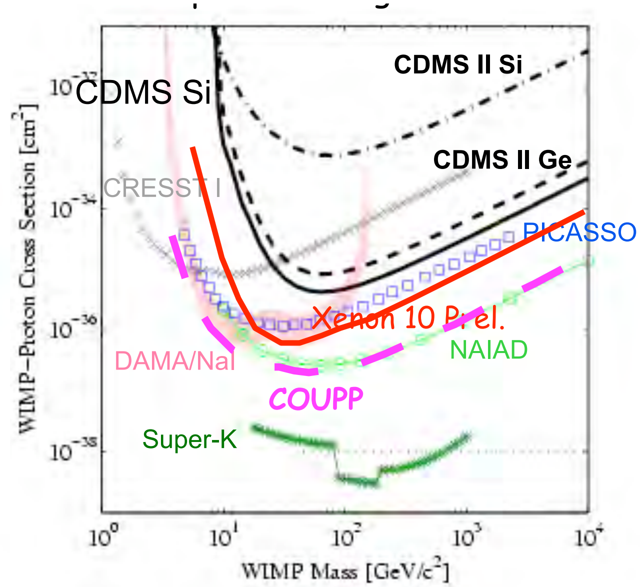
CoGent



Spin dependent

“n” scattering





What could it be?

An axionic type particle of 3 keV converting its mass into electromagnetic energy in detector

- Modulation by flux
- Predict electron recoil line at 3 keV
- Can be in principle checked by other detectors: being done by CDMS!

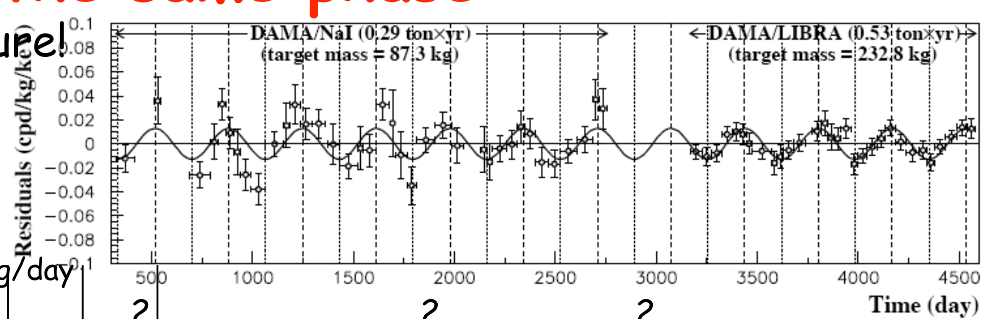
An Instrumental effect?

- e.g. Unstable threshold (DAMA claims that they checked!)

Not blind analysis!

An effect related to well known modulation of muon flux, which has exactly the same phase

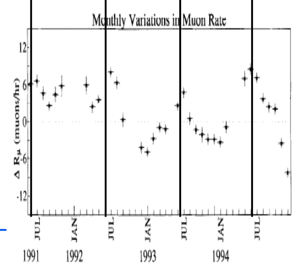
- Decay path change with temperature!



2 2 2 2

Not neutrons! effect too small

Interaction in scintillator too small 0.02/kg/day



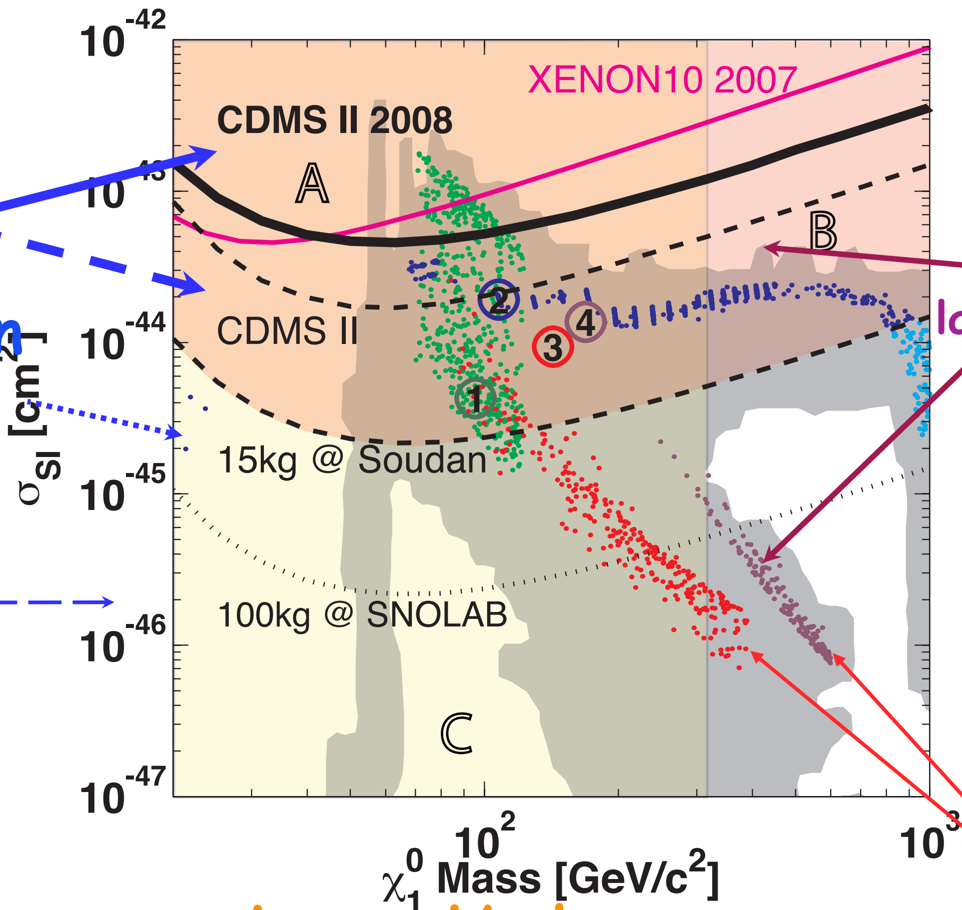
Measurement by MACRO

The overall picture

Current WIMP searches

Next generation

1 generation beyond



GLAST launched 11 June 08

Large Hadron Collider Jul 08

Finer and finer tuning to get right density!

Conclusions

Essential to detect Dark Matter

A key ingredient of the standard model of cosmology

At least show it is not an epicycle!

WIMPs is the generic Thermal model

The field of direct detection is very active, many ideas

We should reach $10^{-44}cm^2$/nucleon very soon (2009)

$10^{-45}cm^2$/nucleon should be reachable by

- phonon mediated detectors
- Liquid Xenon 2 phase
- Liquid Ar 2 phases+pulse shape

maybe other simpler technologies (XMASS, MiniCLEAN, COUPP)

$10^{-46-47}cm^2$/nucleon considerable challenge (≈ evt/ton/yr)

When we have a discovery: link to galaxy

(low pressure TPC≈5000 m^3)

Complementarity with accelerators and indirect detection

Large Hadron Collider may probe the same physics

GLAST could be smoking gun (Dark Matter + Hierarchical merging) + ICE Cube

We may well be at the brink of discovery!

B.Sadoulet, Science 315 (2007) 61

The US Deep Underground Science and Engineering Laboratory

A long series of studies

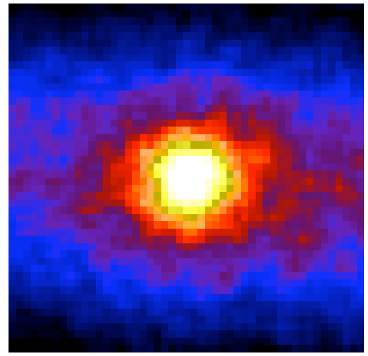
2000 Bahcall/Lesko committee
Series of workshops

2004-2006 Community wide cross disciplinary
S1 study

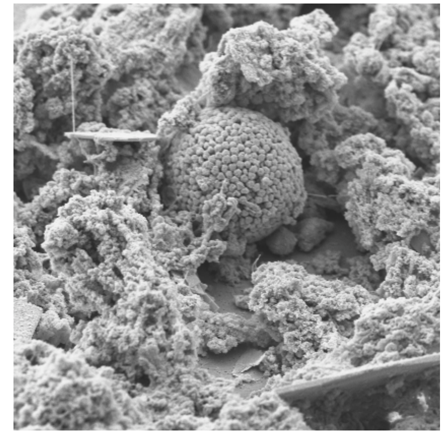
www.dusel.org

Dark Matter/Double beta decay

Neutrino picture of the Sun

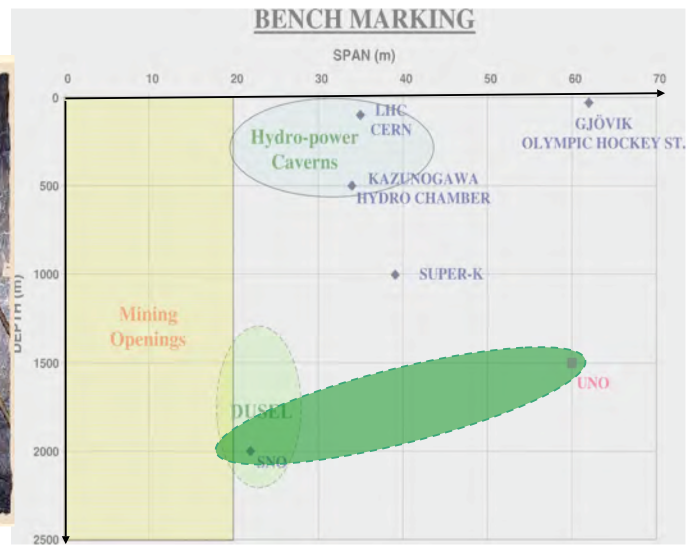


Geo-microbes



Deep Science

Large Block Geo Experiment Coupled Processes



Size of cavity vs depth

Undergraduates in South Africa mine

Scientific Motivation

Extraordinary increase of interest in underground science and engineering

3 Fundamental Questions that uniquely require a deep laboratory

- What is the universe made of? What is the nature of dark matter? What is dark energy? What happened to the antimatter? What are neutrinos telling us?
  Particle/Nuclear Physics: Neutrinos, proton decay
  Astrophysics: Dark Matter, Solar/Supernovae neutrinos

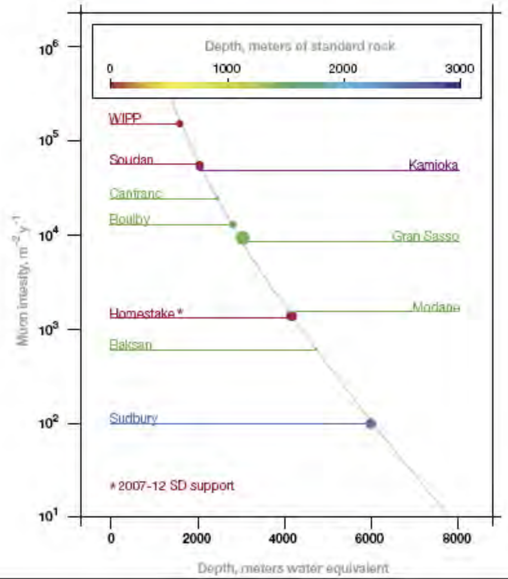
- How deeply in the earth does life extend? What makes life successful at extreme depth and temperature? What can life underground teach us about how life evolve on earth and about life on other planets?
  Unprecedented opportunity for long term in situ observations

- How rock mass strength depends on length and time scales? Can we understand slippage mechanisms in high stress environment, in conditions as close as possible tectonic faults/earthquakes?
  Earth Sciences: Mechanisms behind the constant earth evolution
  Engineering: rock mechanics at large scales, interplay with hydrology/chemistry/biology

The Frontier is at Large Depth!

Physics

- Neutron and activation of materials
  - Neutrinoless double beta decay
  - Dark Matter
  - Neutral current/ elastic scattering solar neutrino
  - New ideas (e.g. related to dark energy)
- Neutron active shielding (300MeV) is difficult and risky
- Rejection of cosmogenic activity is challenging



Biology

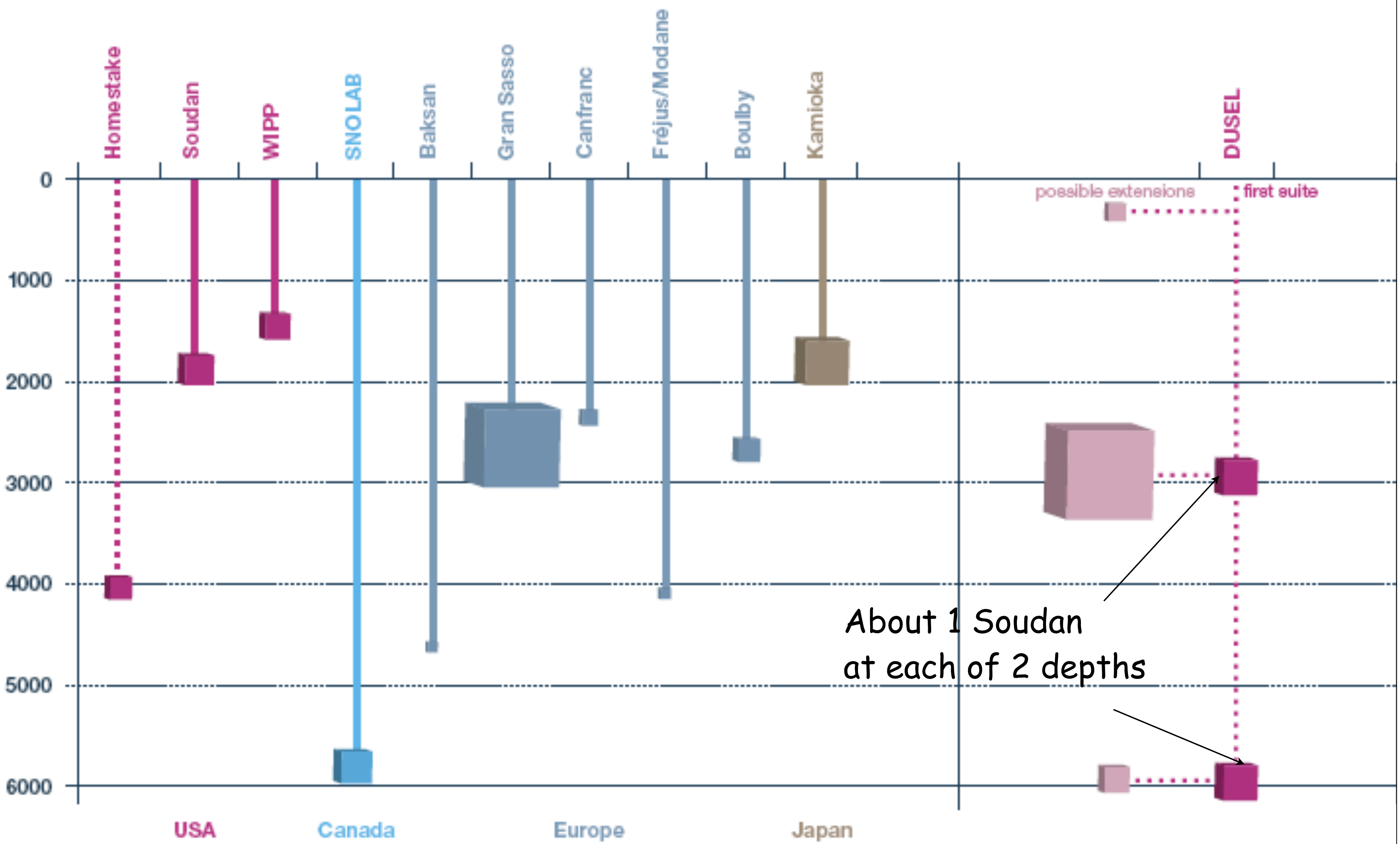
- DUSEL = aseptic environment at depth
- Study microbes in situ (at constant pressure, microbial activity at low respiration rate)
- Deep campus: Platform to drill deeper -> 12000ft (120°C)

Earth science/ Engineering

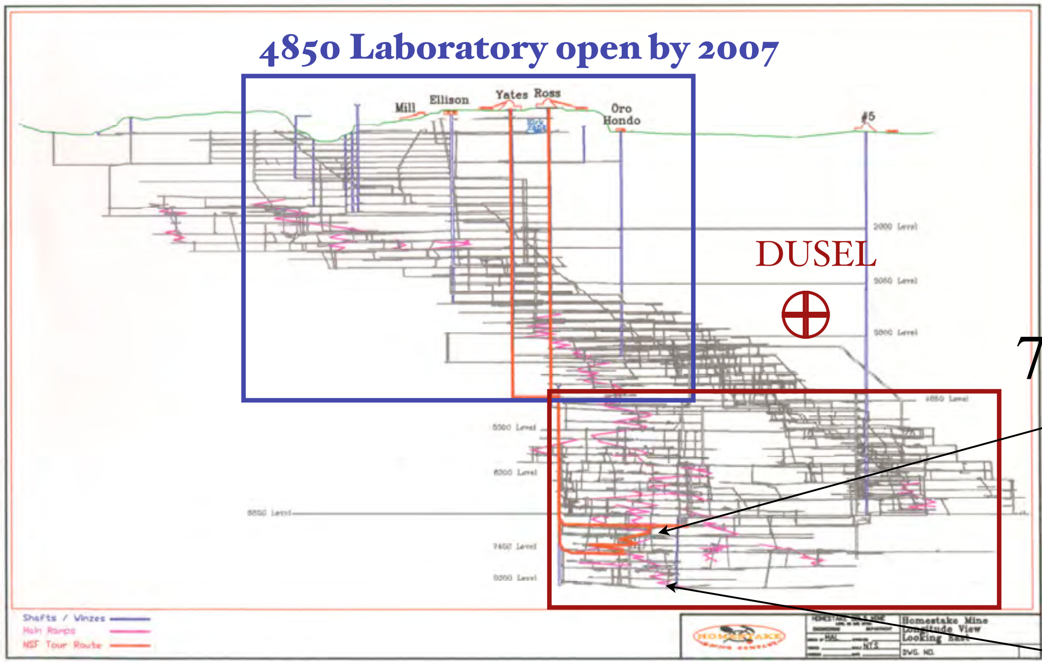
- Get closer to conditions of earthquakes
- Scale/stress
- Complementary to other facilities

DUSEL

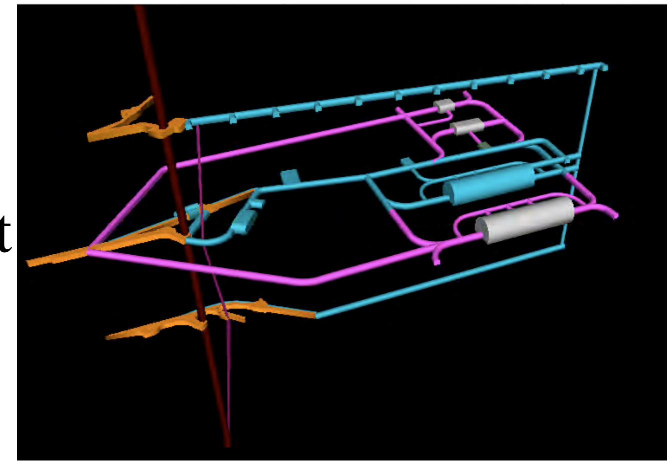
Underground facilities



Homestake Chosen Spring 2007

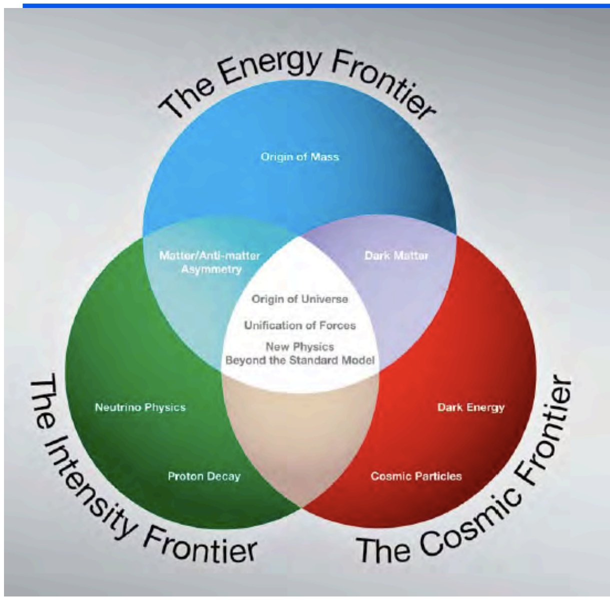


7400ft



- Well-Characterized Site with miles of tunnels
  - Varied, Interesting, and Suitable Geology
  - Extensive Experience to > 8000 feet below ground. Low risk
- Phased Approach to Developing the Facility
  - Ability to host near-term R&D and Experimental Opportunities: interim lab
  - Phased entry into the Initial Suite of Experiments
- Success in Securing Independent Funding for Interim Lab
  - Exceptional Local and Regional Support for DUSEL Goals
- Dedicated Facility without Competition for Access,Resources, or Priorities

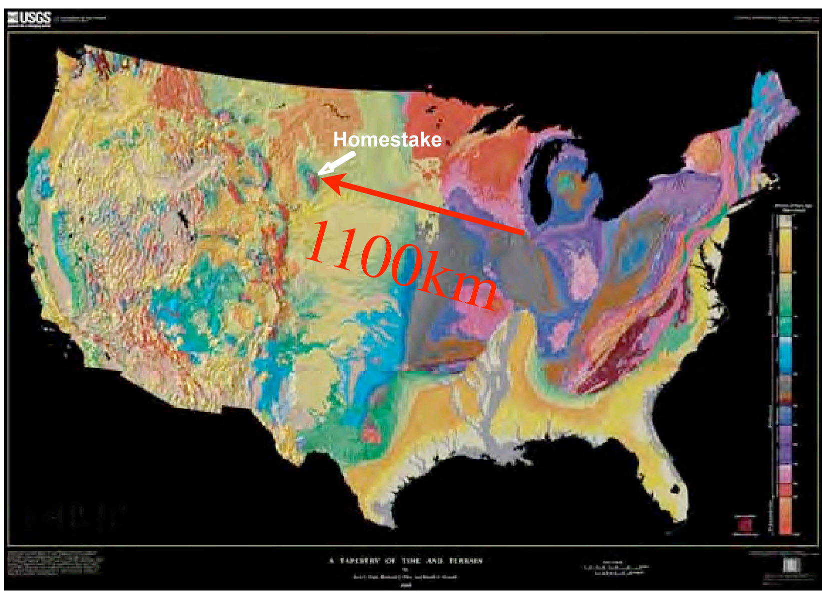
A Momentous Event: P5 Report



May 29, 2008 Priorities for HEP

in view of the time scale and cost of ILC
fiscal realities in the US

The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.



Reach of 700 kW beam
with first 100ktonne detector in DUSEL (50% of δ_{CP} range):
-- $\sin^2\theta_{13}$ ~ 0.009 (3σ)
-- mass hierarchy: $\sin^2\theta_{13}$ ~ 0.015 (2σ)

Alignment between DOE and NSF

Increased likelihood of DUSEL

Towards a real project

Facility studies (S3) ≈$250M

First Suite of Experiments ≈ $250M NSF + 250? DOE

2 competitions

S4: Engineering studies Fall 2008?

S5: Choice of experiments Spring 2009?

=> MREFC proposal ≥ December 2009

If everything goes well, beginning of construction ≥2012

Physics in ≥2014 (4850ft) ≥2016 (7400ft)

Conclusions

Frontier Science: we need the depth (and ≥30 yrs access)

DUSEL well justified from a global multidisciplinary perspective

- Alignment with many of NSF interests + DOE interest

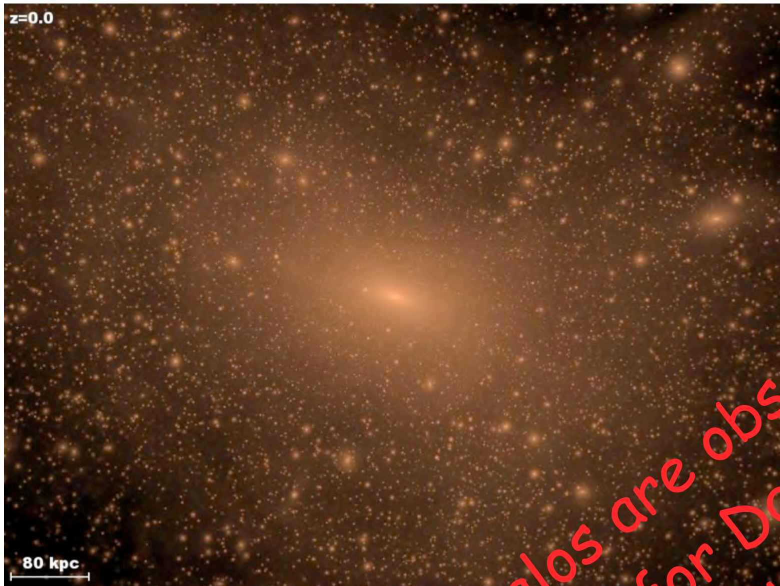
Significant chance to obtain necessary resources

DUSEL will benefit the International Physics Community

- Widens the underground frontier
  - Home for the most important experiments we foresee now
  - Flexible space for new unexpected ideas
- Multidisciplinary intellectual atmosphere, e.g. neutrino tomography!
  - Technical support
  - Long term R&D (instrumentation, low background)
  - Focus and coordination
  - E&O
- MREFC costs are initially not borne by community
  - But beware of large operating costs

Time scale is long: start now!

Gamma Rays: A smoking gun?



Via Lactea simulation

Diemand,Kuhlen,Madau

Piero Madau's talk

No gas in simulation

If subhalos are observed

Smoking gun for Dark Matter

Hierarchical merging

Simulated Glast

<= Via Lactea

$\langle\sigma v\rangle = 5\times10^{-26}$ cm^3 s^{-1}

M_χ = 46 GeV

2 years