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Strategies for the Detection of Dark Matter

What do we know?

What have we achieved so far?

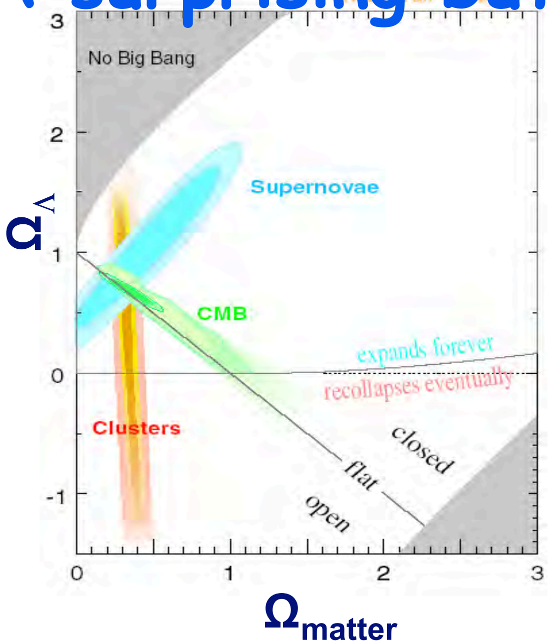
Entering interesting domain

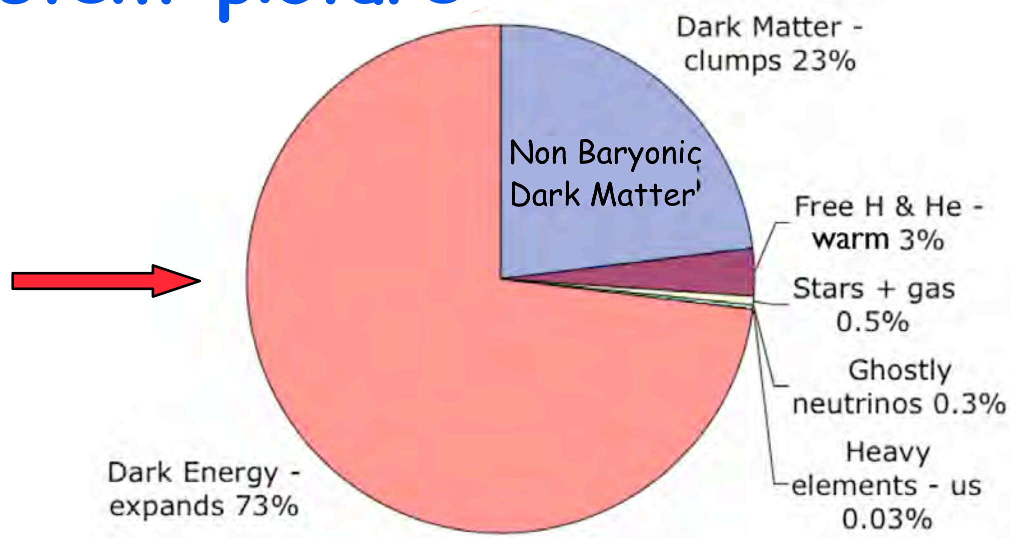
Strategies for the future

Exciting new technologies

Standard Model of Cosmology

A surprising but consistent picture





Not ordinary matter (Baryons)

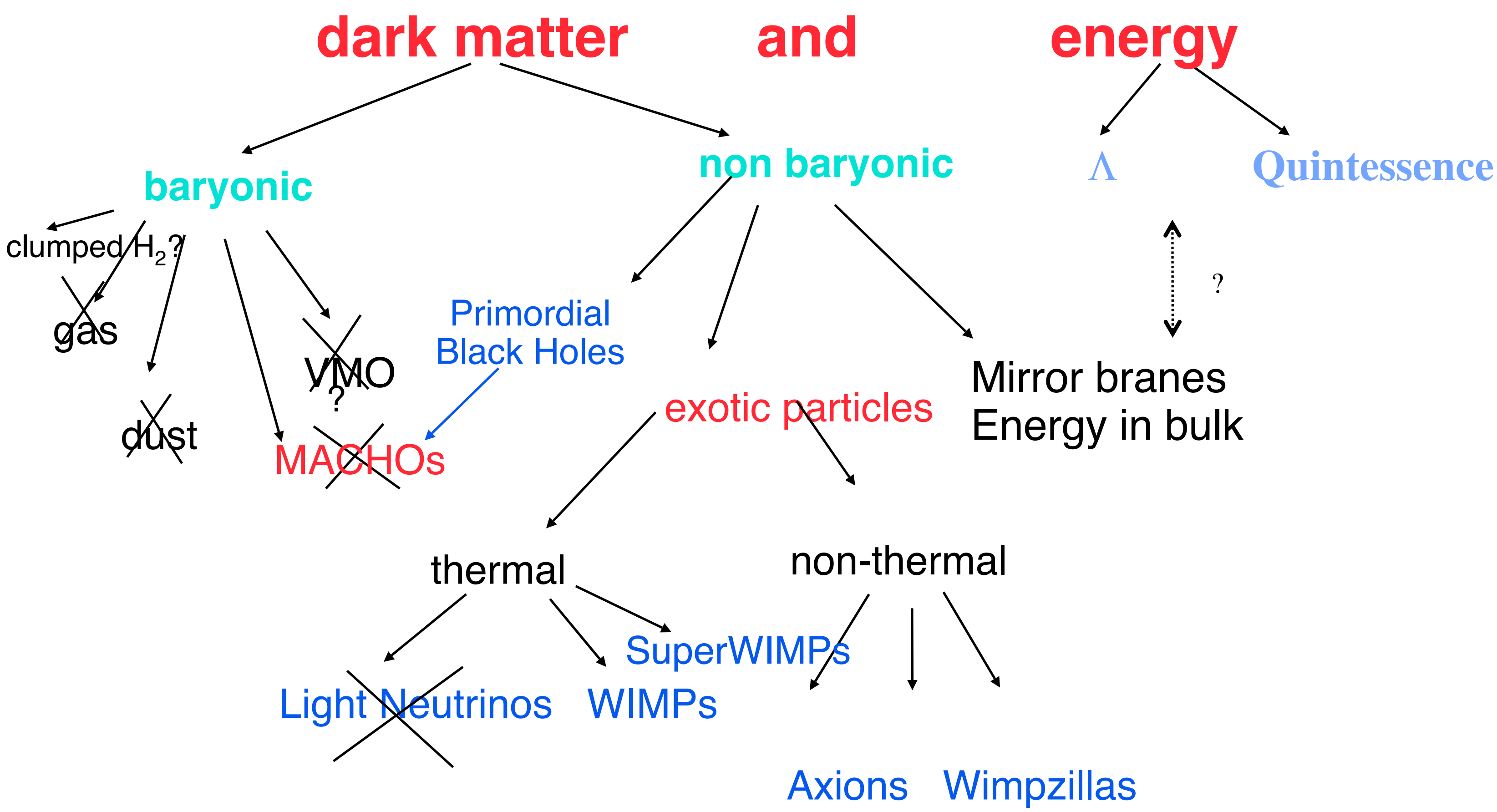
$\Omega_m >> \Omega_b = 0.047 \pm 0.006$ from | Nucleosynthesis / WMAP

+ internally to WMAP $\Omega_m h^2 \neq \Omega_b h^2$ How many σ's?

Mostly cold: Not light neutrinos ≠ small scale structure

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

Ongoing Systematic Mapping

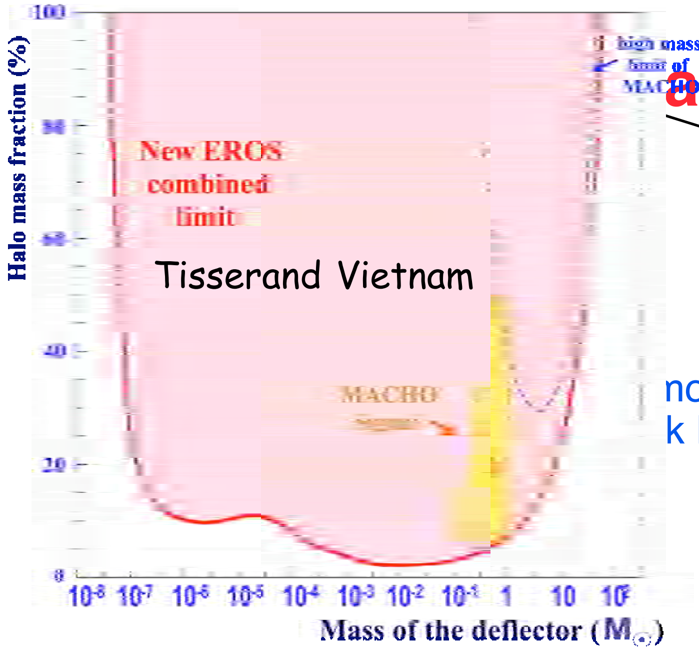


Most baryonic forms excluded (independently of BBN, CMB)

Particles: well defined if thermal **(difficult when athermal)**

Additional dimensions?

Ongoing Systematic Mapping



atter and energy

non baryonic

Λ Quintessence

nordial
k Holes

exotic particles

Mirror branes
Energy in bulk

?

thermal

non-thermal

~~Light Neutrinos~~ WIMPs SuperWIMPs

Axions Wimpzillas

Most baryonic forms excluded (independently of BBN, CMB)

Particles: well defined if thermal (difficult when athermal)

Additional dimensions?

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

Dynamic stabilization by a Peccei-Quinn axion?

New result by PVLAS (Zavattini et al.) 1-1.5 10^{-3} eV M_{PQ}≈ 2-6 10^{5} GeV very low!

would need a way to escape horizontal branch limits

Gravity is not included and we do not understand vacuum energy

Always the danger of a failure of General Relativity

Particle Cosmology

Bringing both fields together: a remarkable concidence

Particles in thermal equilibrium
+ decoupling when nonrelativistic

Freeze out when annihilation rate ≈ expansion rate

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

Generic

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

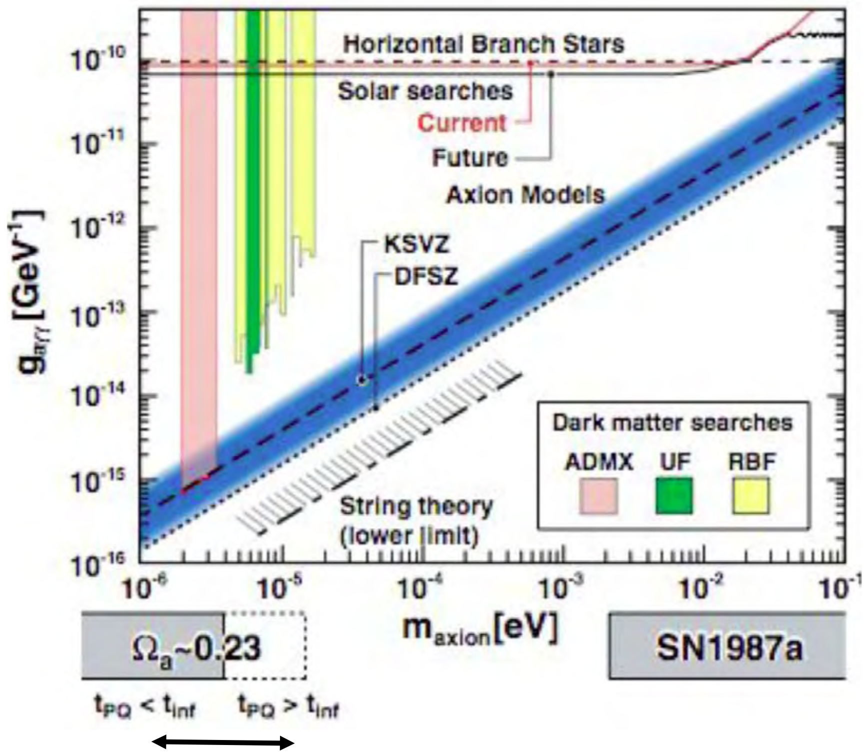
2 generic methods:

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

Axions

ADMX



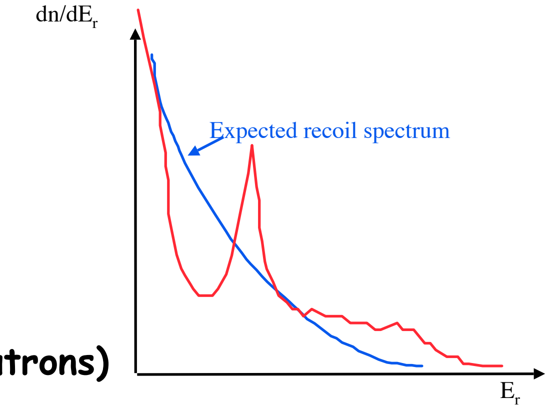
Region of mass where axions are a significant component of dark matter

- Completing phase I construction.
  - 1-2 years to cover 10^{-6} - 10^{-5} eV down to KSVZ
- Phase II to cover same range down to DFSZ
  - Requires dilution refrigerator to go from 1.7 to 0.2 K
- Beyond Phase II, they hope to develop cavities and SQUIDs making it possible to operate in the 10-100 GHz range, extending the mass range of the search.

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

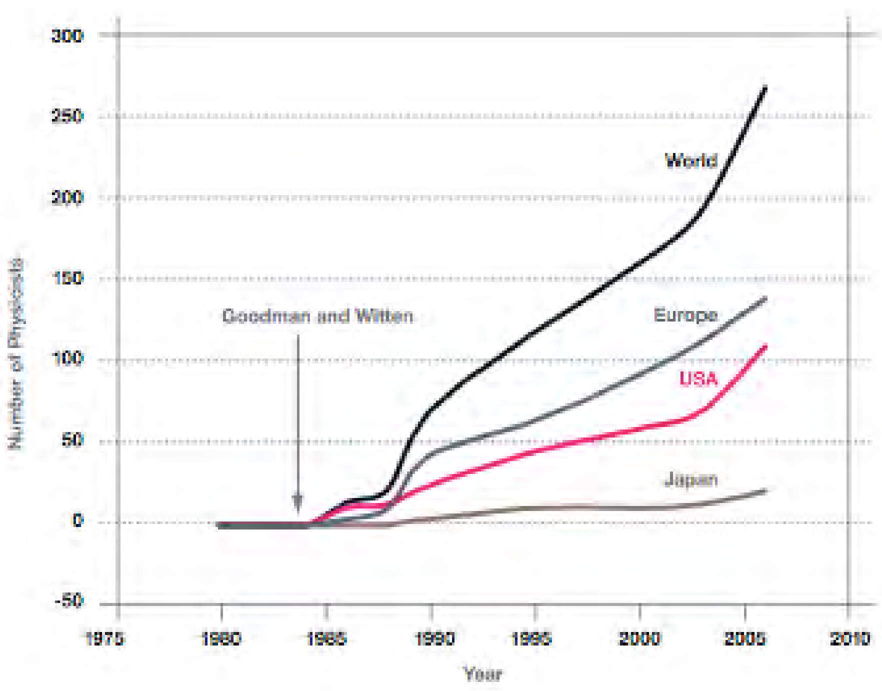
Linked to galaxy

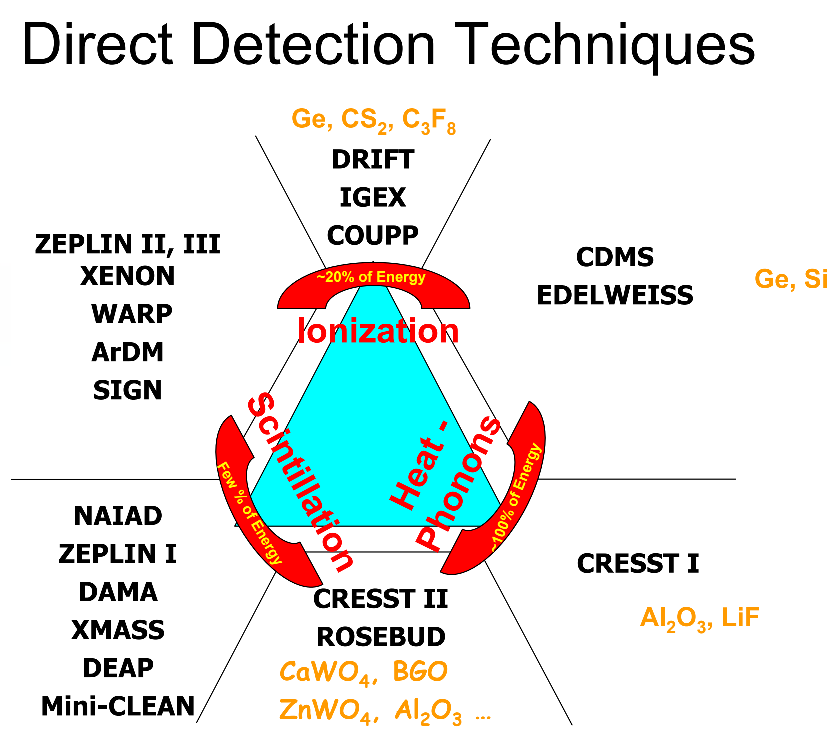
- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)

Significant progress

Phonon mediated detectors: example of CDMS: best sensitivity
New technologies: Noble gas, high pressure gas

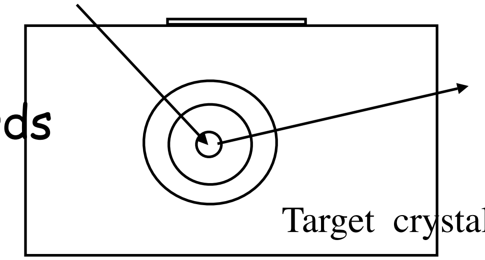
A Blooming Field





In U.S. , Dark Matter Science Assessment Group (cf. Dark Energy Task Force)
+ HEPAP P5 prioritization

Phonon Mediated Detectors



Principle: Detect lower energy excitations

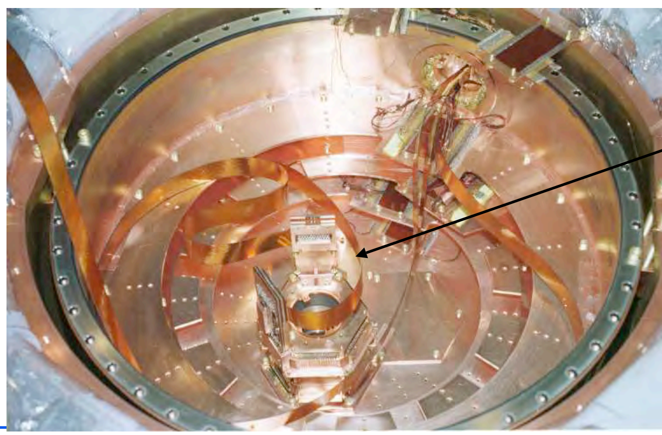
15 keV large by condensed matter physics standards

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
    - e.g. CDMS I and II
    - EDELWEISS
  - or photon (CRESST II)

But: operation at very low temperature!

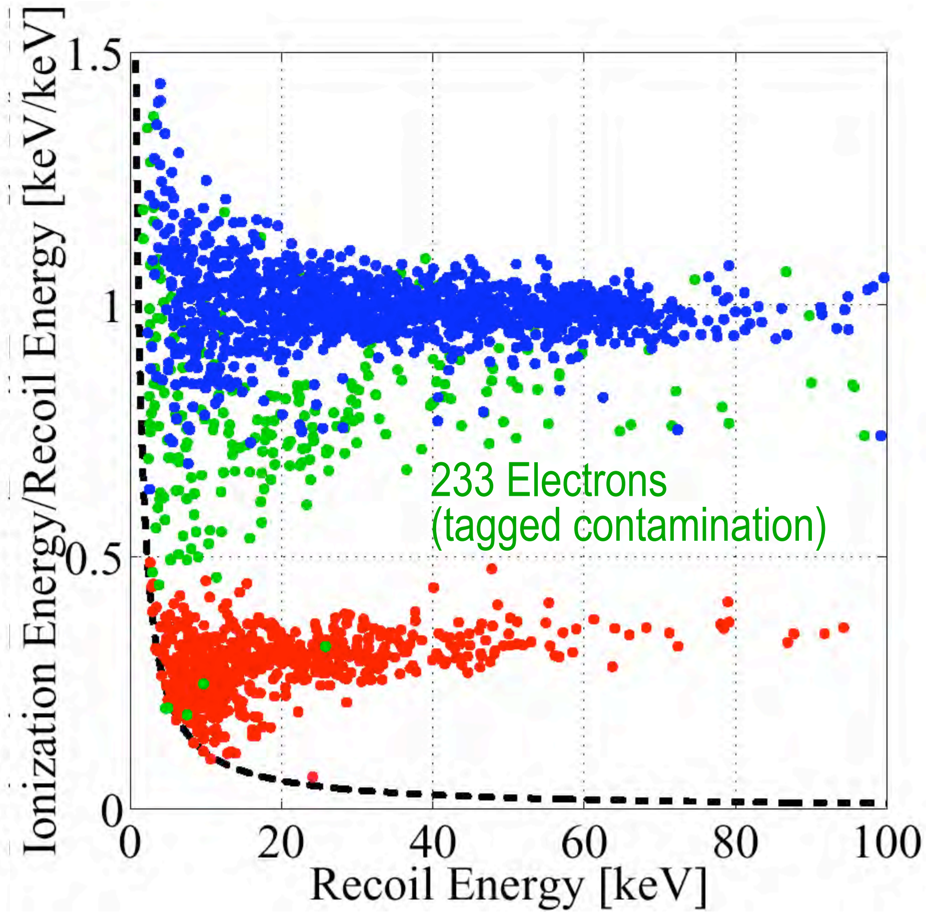
ex: CDMS I
1999



CDMS Background Discrimination

It works!

Use Ionization Yield (ionization energy per unit recoil energy) to reject the background



But

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

CDMS II

The CDMS Collaboration

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University of Minnesota
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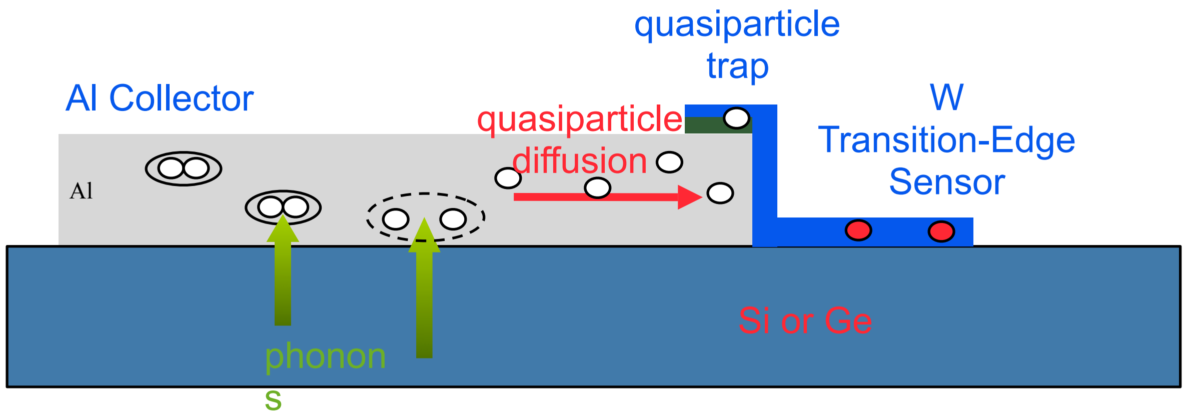
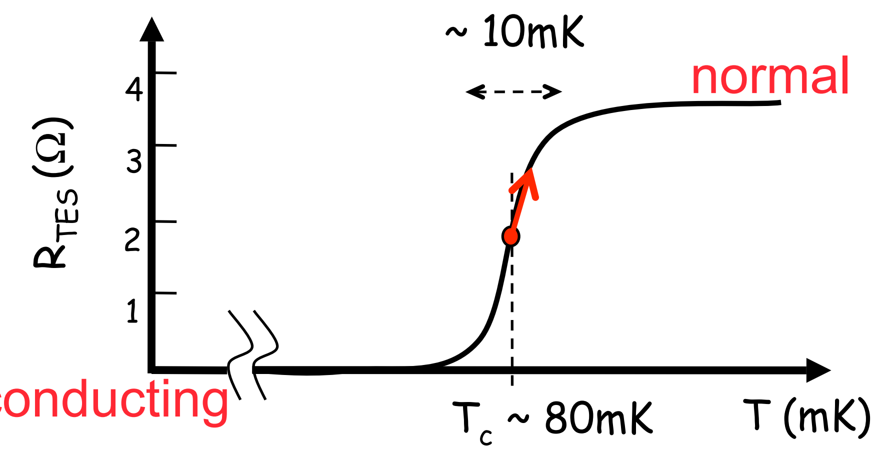
Funded by NSF and DOE

Athermal Phonon Sensor Technology



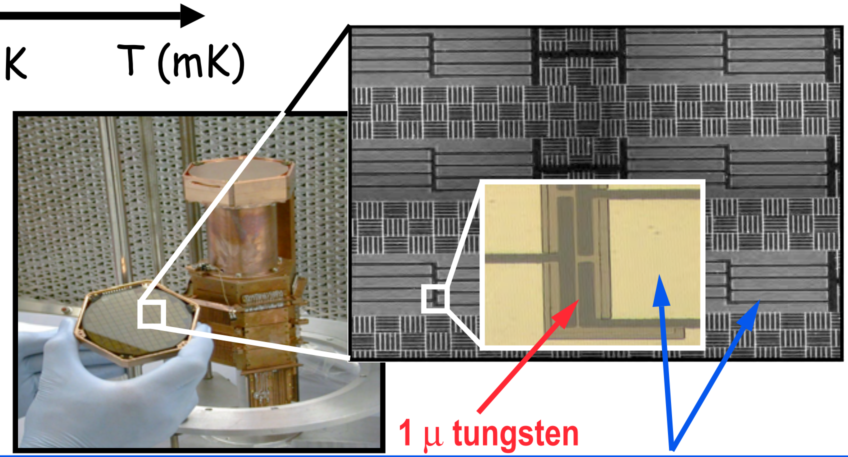
Measurement of athermal phonon signals maximizes information



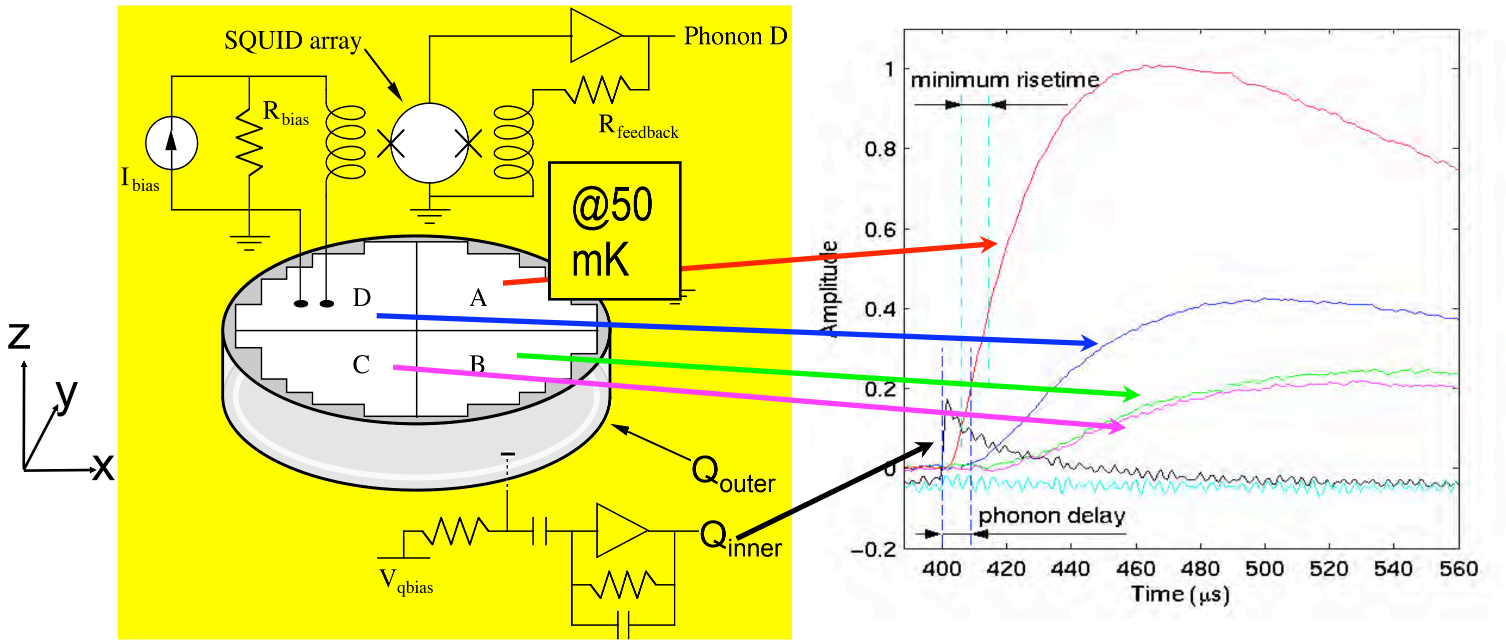
Voltage biased W Transition-Edge Sensor

1µ photolythography

3"Ø, 1cm thick



Large Amount of information



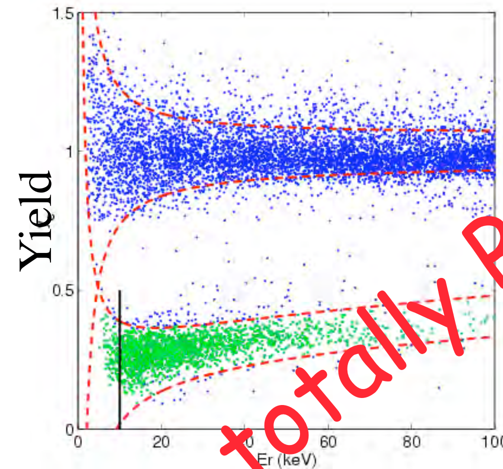
2 ionization signals (inner detector, guard)

4 phonons: Risetime and delay with respect ionization

gives information about the 3D position of the event, in particular the proximity to the surface

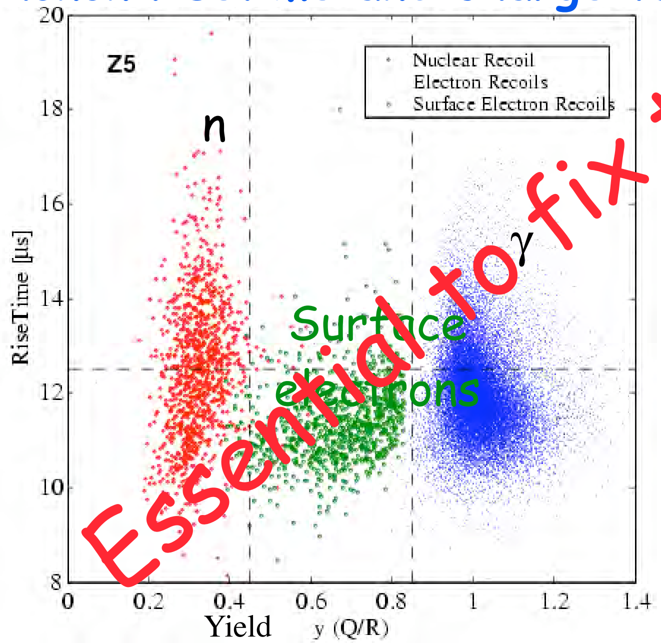
Athermal Phonon Advantage

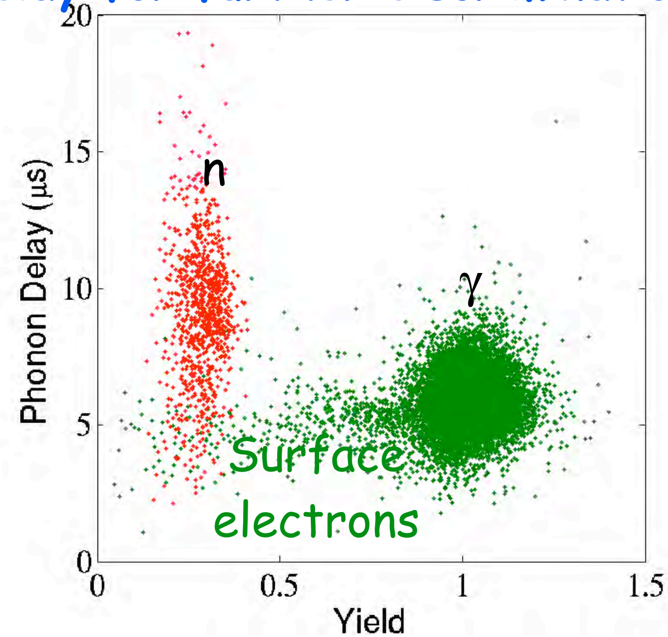
In addition to ionization yield



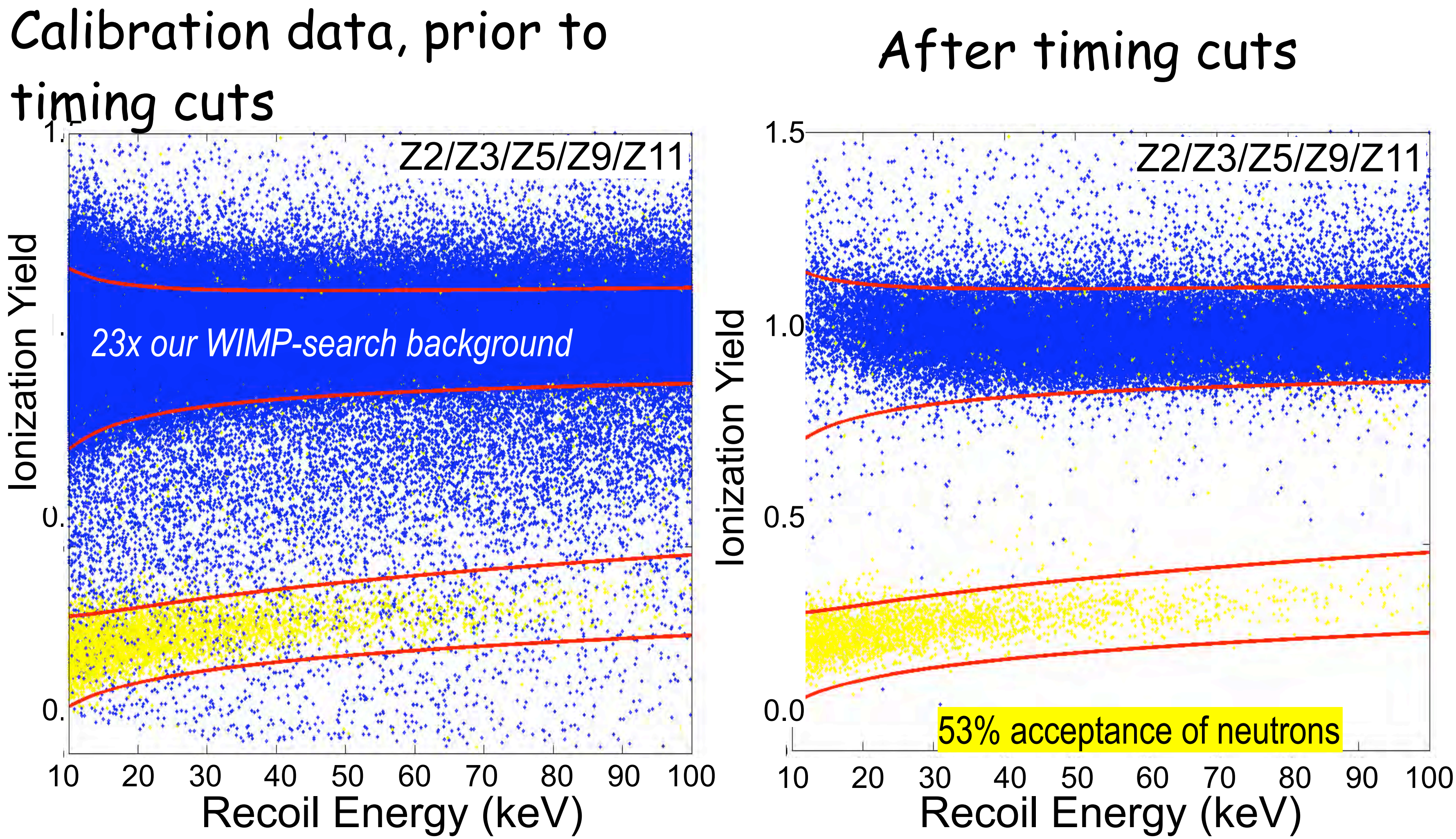
Essential to fix the cuts totally Blind

Use phonon risetime and charge to phonon delay for further discrimination





In Situ Calibrations

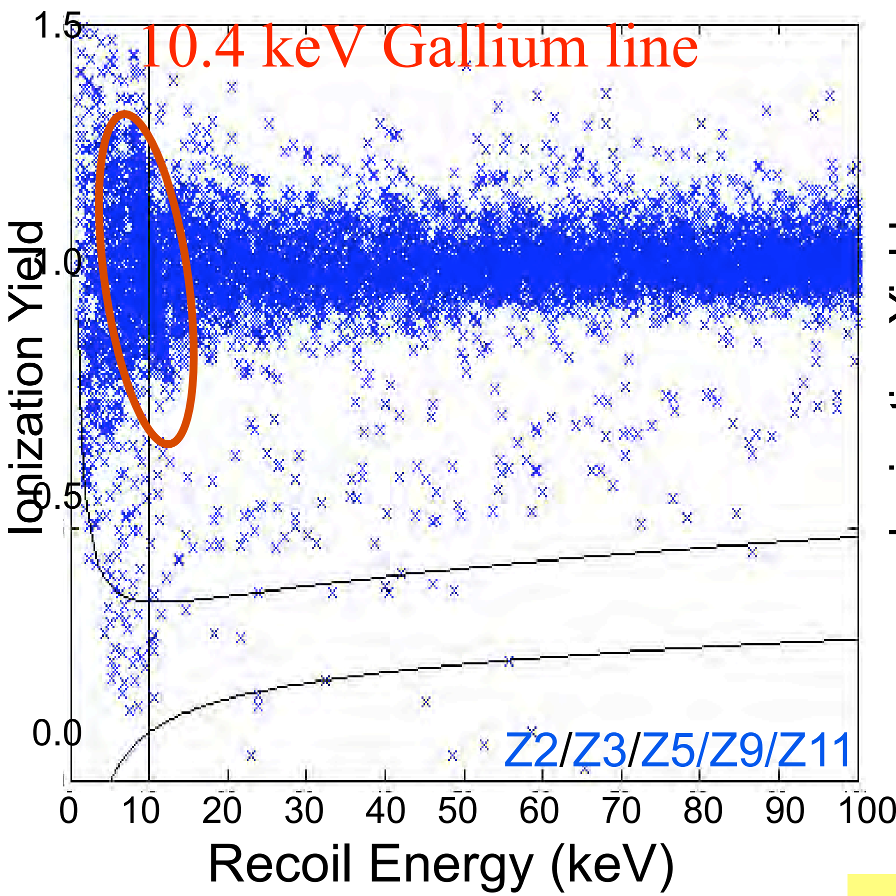


Blue points: electron recoils induced by a ^{133}Ba γ source

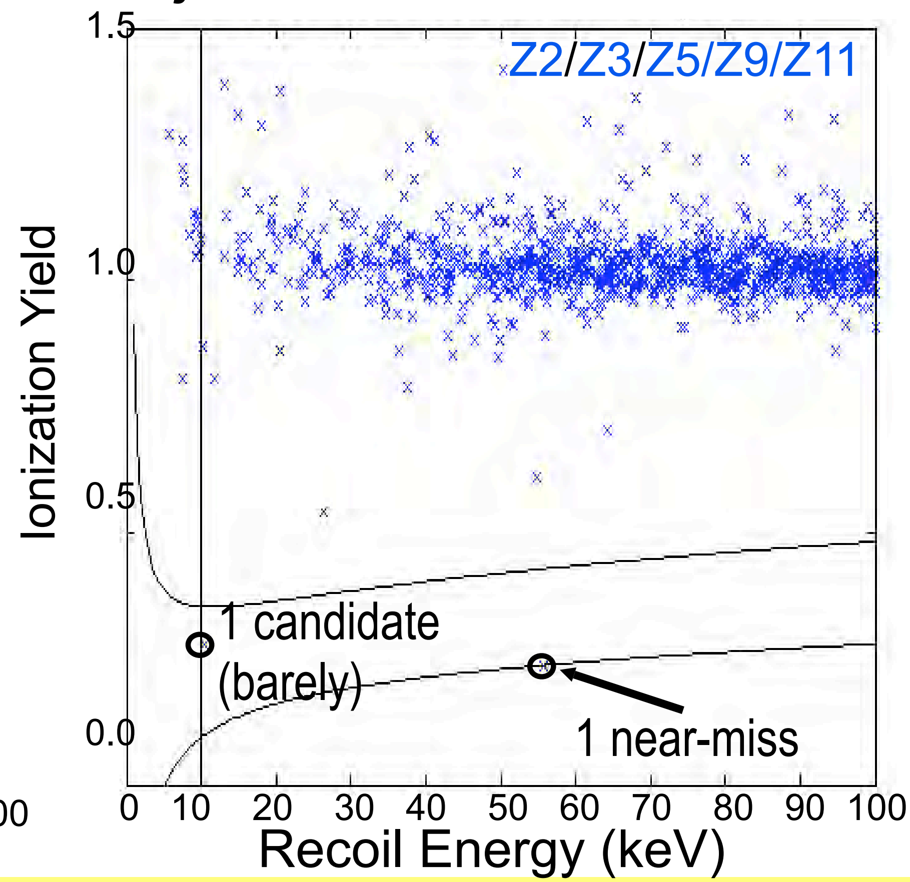
Yellow points: nuclear recoils induced by a ^{252}Cf neutron source

WIMP-search data

Prior to timing cuts



After timing cuts, which reject most electron recoils

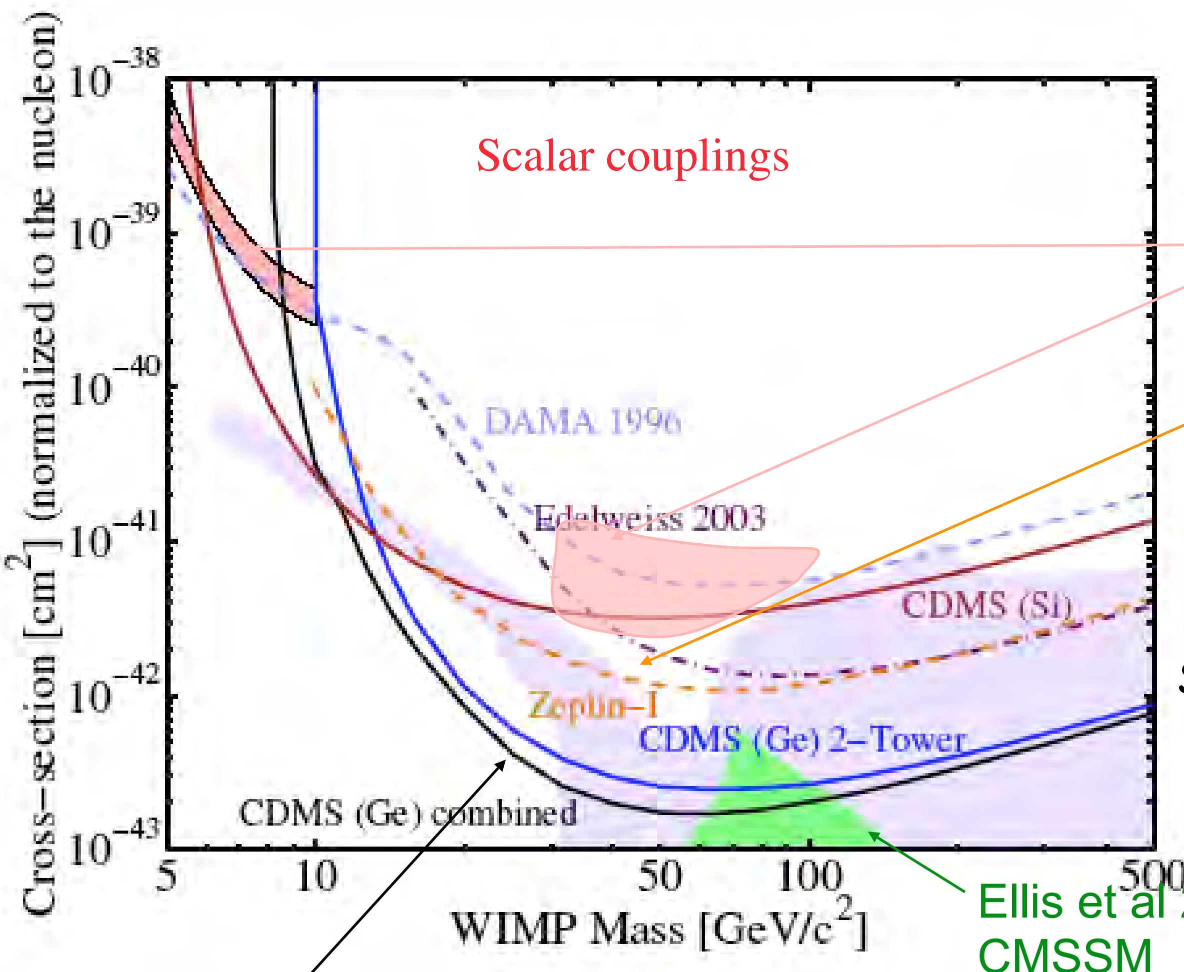


90 kg.days

34kg.days after cuts

ESTIMATE: 0.37 ±0.15(stat.) ± 0.20(sys.) electron recoils,
0.05 recoils from neutrons expected

CDMS II (2005)



10 times more sensitive than any other experiment

Increasing tension with DAMA who claims a signal (NaI)

Zeplin-I result in doubt astro-ph/0512120

See PRL 96 (2006) 011302

Ellis et al 2005 CMSSM

Entering in interesting territory

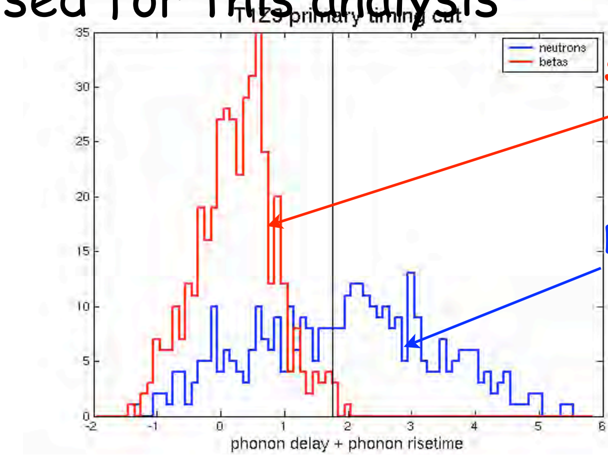
Adding 1st Soudan run, 53kg.day-> 19kg.day after cut

Total 53 kg.day after cut

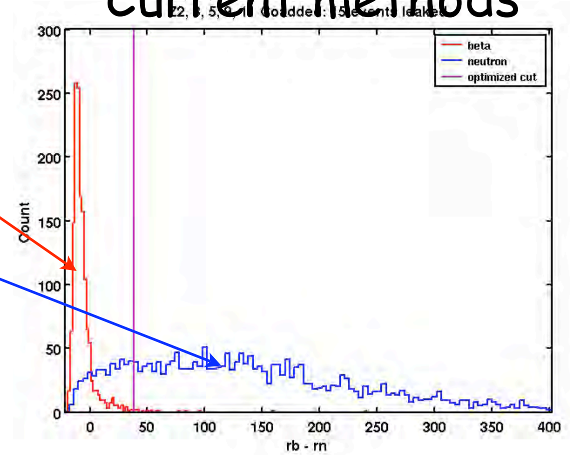
CDMS II Reach

Large background rejection margin

Used for this analysis



Current methods



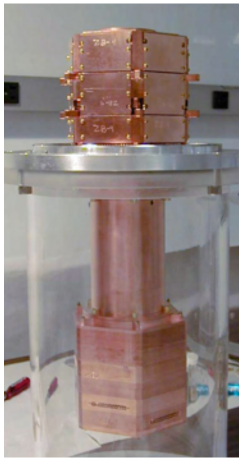
Surface events

Nuclear recoils

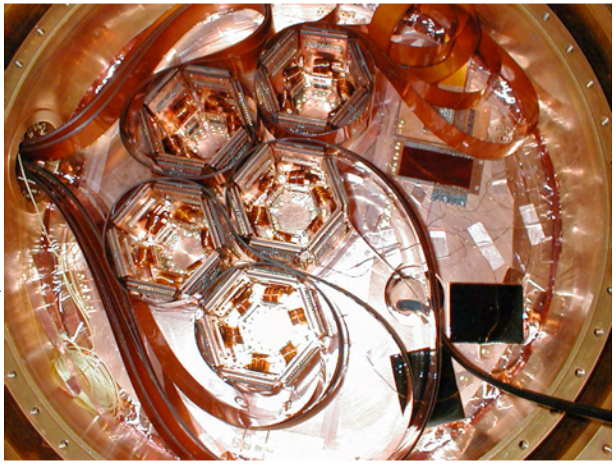
5 Towers

5 Kg Ge, 2kg Si

5x



⇒



Run through December 2007

=> X 10 further 2 10^{-44} cm^2 @ 60GeV/c^2

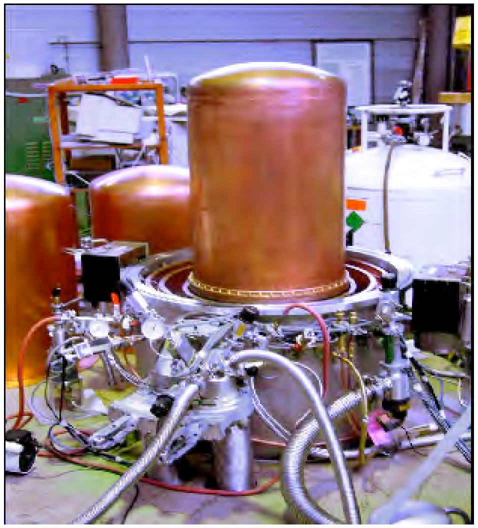
Other Phonon Mediated Detectors

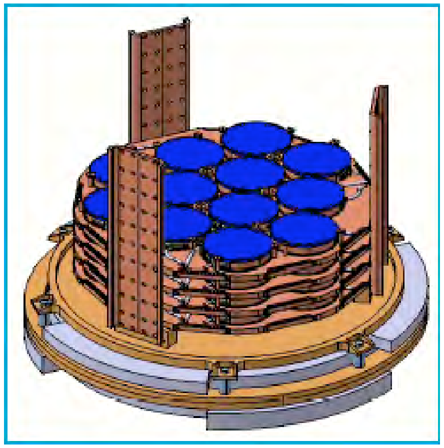
EDELWEISS II

Mounting 21x350g Ge +NTD detectors in new cryostat

Most detectors: no athermal phonon rejection of surface events

7x350g Nb/Ge fast phonon





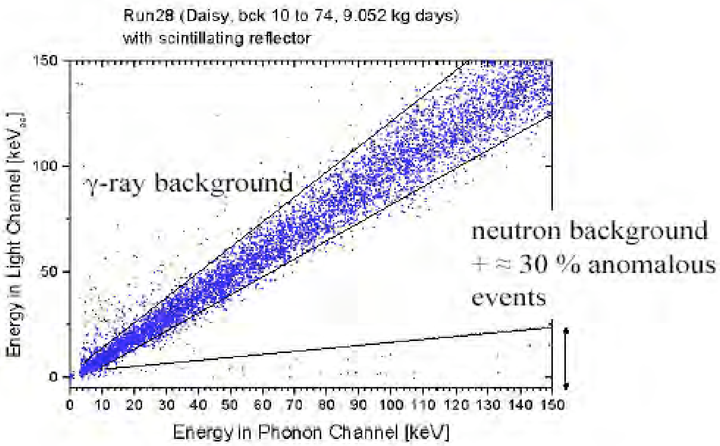
CRESST II

$CaWO_4$

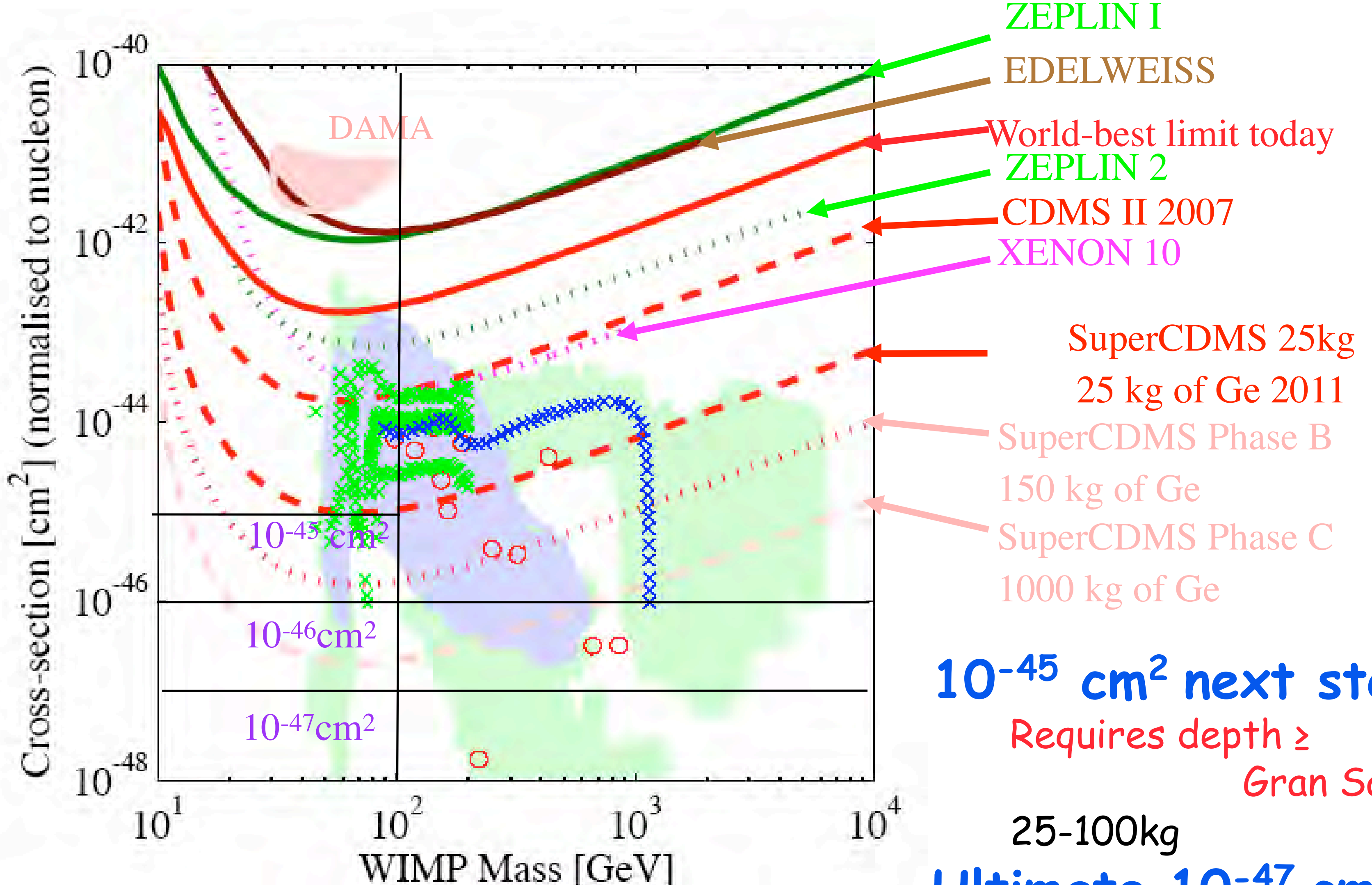
Scintillation + phonons

Excellent rejection, no dead layer

Insensitive to W recoil scintillation



Goals: Cover Supersymmetry



10^{-45} cm^2 next step

Requires depth ≥ Gran Sasso

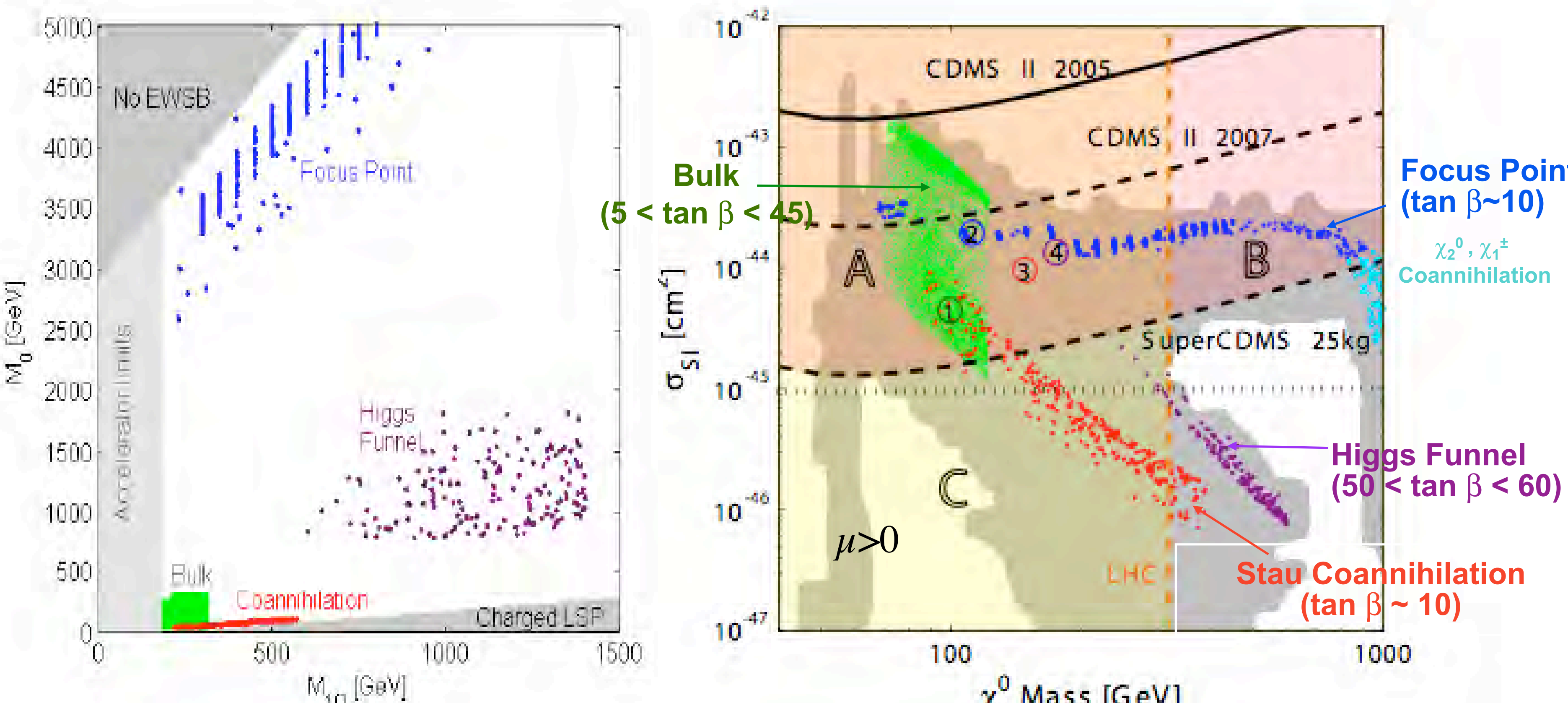
25-100kg

Ultimate 10^{-47} cm^2

2-8 tons

≈ No background!

Why 1 Zeptobarn ≡ 10^{-45} cm^2



Low cross sections correspond to fine tuning

The Higgs funnel and stau coannihilation are fine tuned to enhance annihilation

The lower the elastic cross section, the finer the tuning!

10^{-45}cm^2 is a natural scale

Complementarity with LHC: Rich physics in region of overlap

Elastic scattering: Larger mass range

Strategies for the Future

Lessons from CDMS & Edelweiss

Search for rare events requires maximum amount of information

Large signal/noise => identification of background

≠ threshold detectors (Simple, Picasso, COUPP)

Active discrimination of the background event by event:

-> zero background

≠ Statistical methods (cf. DAMA, ZEPLIN1)

≥ 2 promising technologies

Phonon mediated detectors: demonstrated, but need to master complexity

Liquid Noble Gases: graceful scaling but need to demonstrate threshold and master complex phenomenology

Other ideas: high pressure gas

Several experiments with different technologies/targets

Beware: "A background may hide another one" R&D at real scale

Importance of the physics requires cross checks

Interesting science in target comparison $\approx A^2$

Phonon mediated detectors

Current technology capable to go to 25kg region

Super CDMS 25kg -> 10^{-45}cm^2

EDELWEISS II, CRESST II -> EURECA

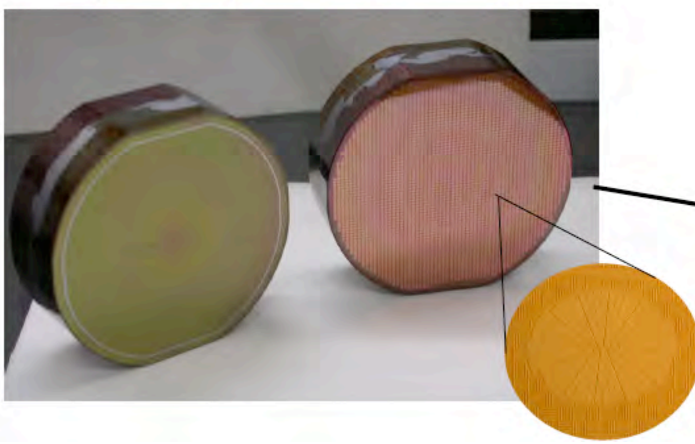
Baseline detector for SuperCDMS

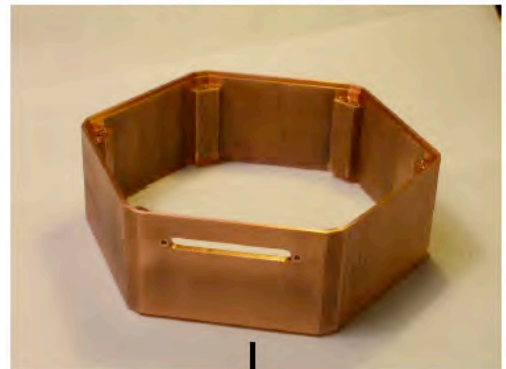
CDMS-II ZIPs:
3" dia x 1 cm => 0.25 kg of Ge

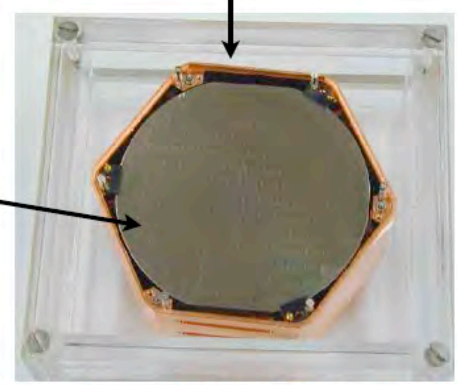
Existing ZIPs

SuperCDMS ZIPs:
3" dia x 1" => 0.64 kg of Ge

ZIPs for SuperCDMS







Completed 1" thick Si ZIP

Significant change of production testing methods -> 1 Ton

Noble Liquids 1

Single-Phase Techniques

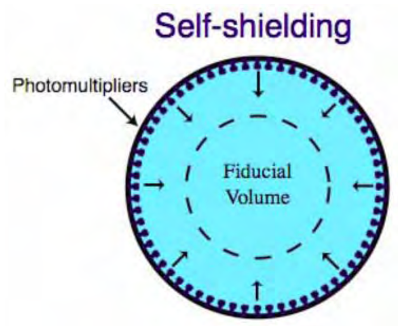
DEAP, Mini-CLEAN, XMASS

- Pulse shape discrimination to discriminate electrons from nuclear recoils.

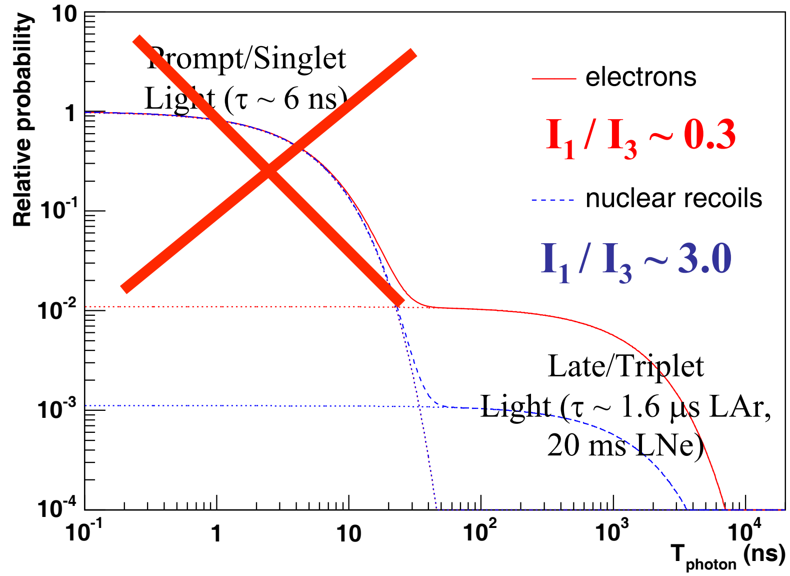
Recent breakthrough

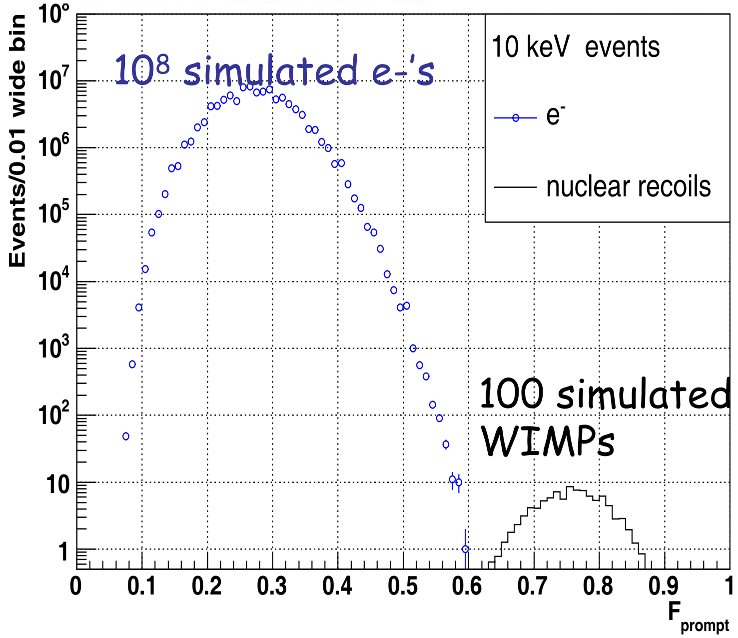
Singlet killed in nuclear recoils

+



Gets better as size increases.





M.G.Boulay and A.Hime, Astroparticle Physics 25, 179 (2006)

but ^{39}Ar, radial resolution (Rayleigh scattering +few photons)

Liquid Noble Gases 2

Another breakthrough: extraction of electrons from liquid

Argon :WARP, ArDM: can use ionization + scintillation +pulse shape

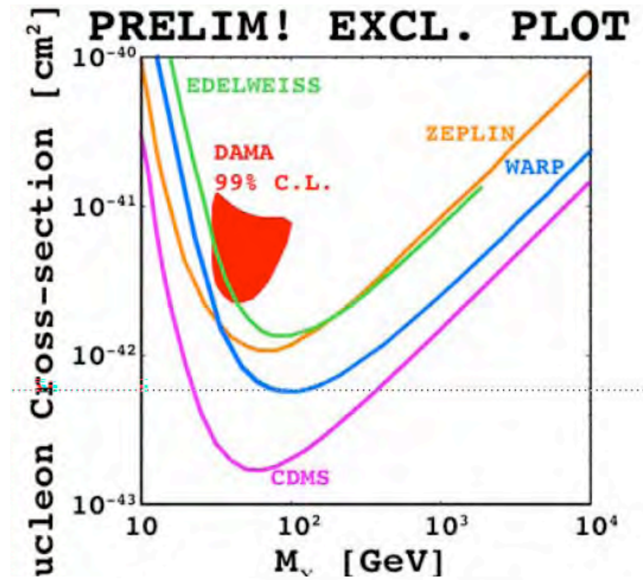
Hot out of the press: Liq.Ar

WARP prototype 97kg days
Ionization + Scintillation
including pulse shape
No event above 40 keV
Soft neutrons below?

But energy scale?

Why scintillation yield is 80%

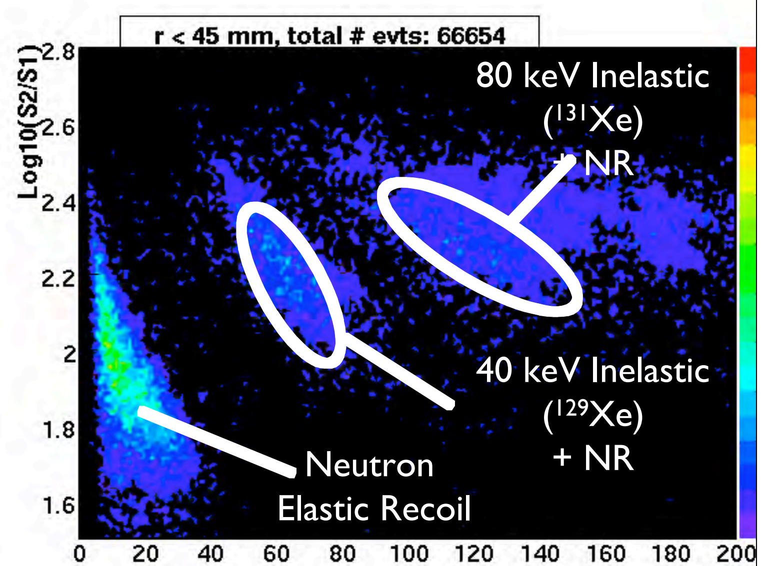
180kg module in fabrication



Xenon: ZEPLIN II, Xenon ionization + scintillation

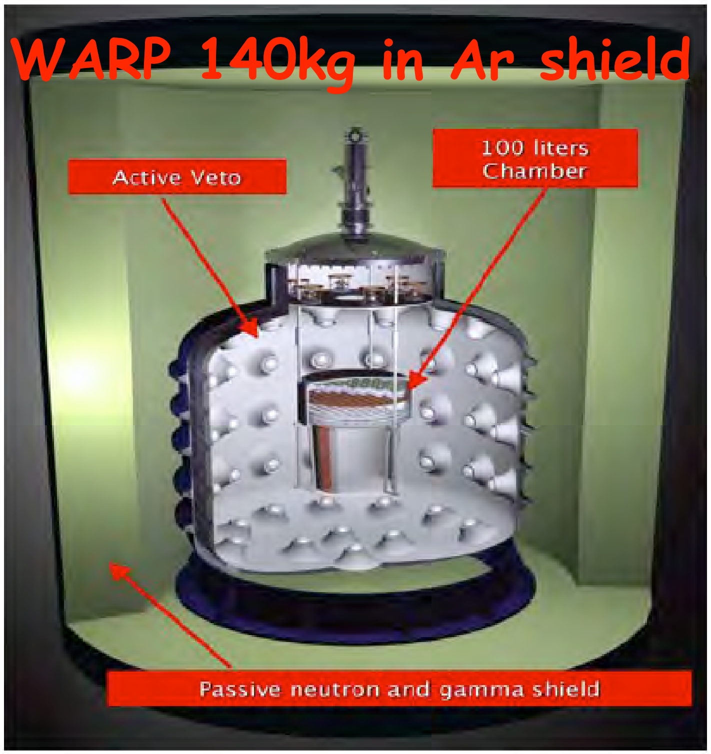
≈ 10kg taking data: results soon!

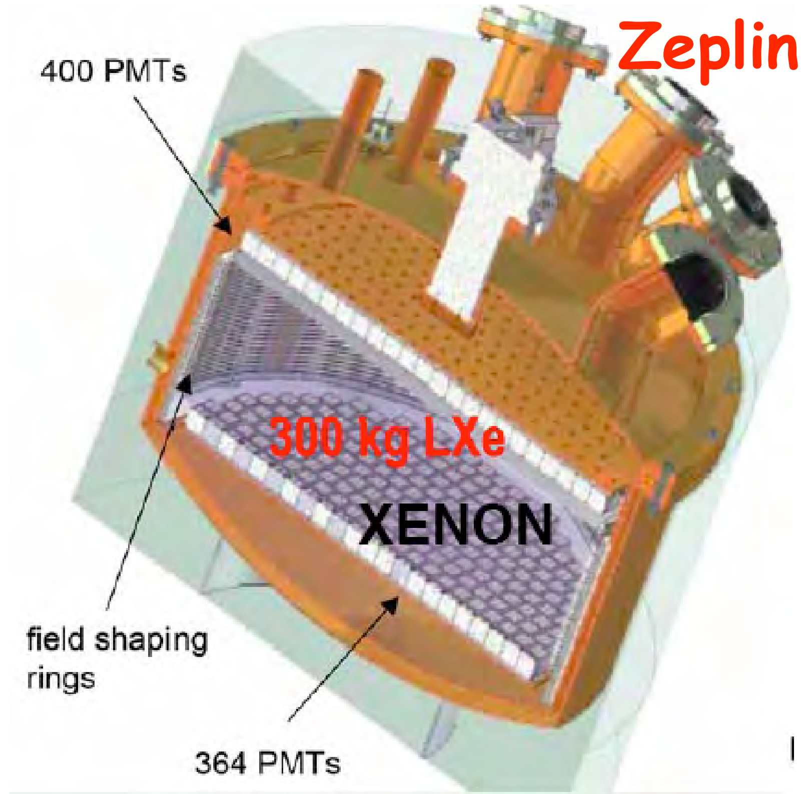
Complex phenomenology



=>Very Large masses

Hope: "easily" scalable to >1 ton





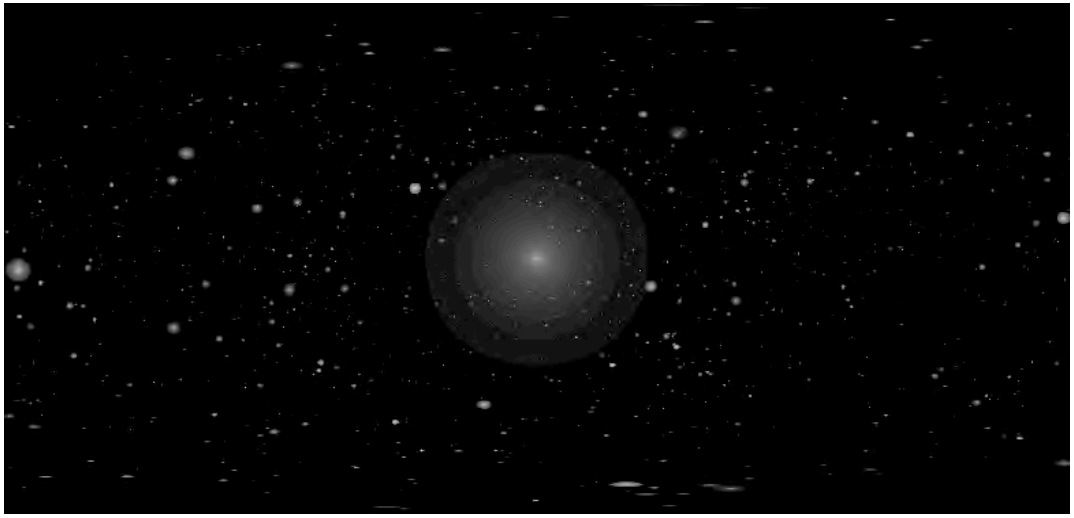
But: Have to Master complex phenomenology

Demonstrate discrimination close to threshold

Obtain good spatial reconstruction against edges

Exclude ^{39}Ar, ^{85}Kr

Gamma Rays: A smoking gun?

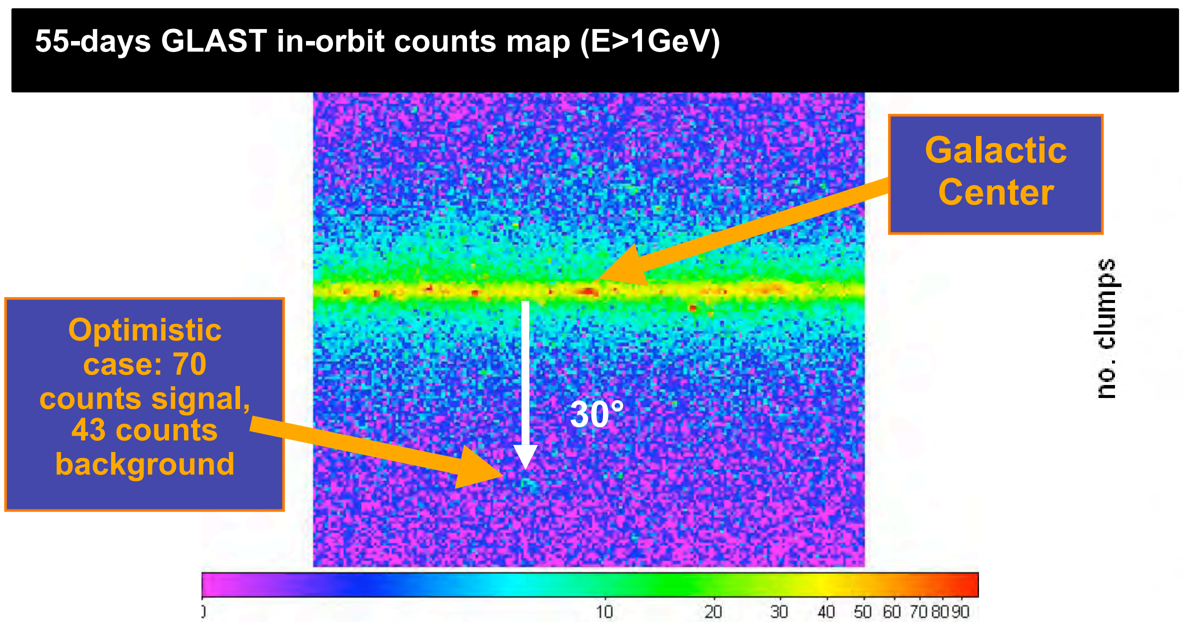


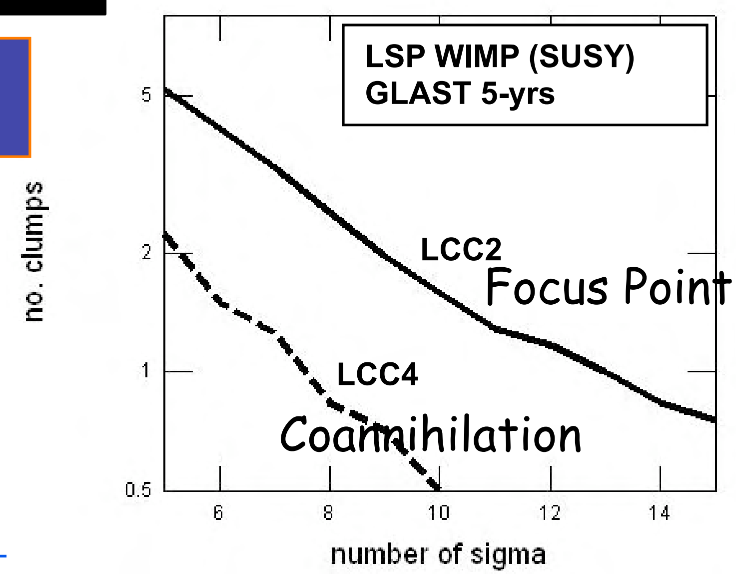
Simulation of the γ ray sky from Dark Matter annihilation

Ted Baltz 2006 (Taylor/ Babul 2005)

SUSY: often maximal σ

Hierarchical clustering





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

Interesting alignment between Cosmology and Particle Physics

Well defined roadmap for WIMP searches

Elastic scattering

- $10^{-45}cm^2$ identifying event by event nuclear recoil
  Phonon mediated detectors can do it (e.g.SCDMS 25kg) +tests Noble Gas
- $10^{-46-47}cm^2$ Need large mass, 0 background technologies
  Liquid noble gases appears to be best complement to phonon mediated det,

When we have a discovery: link to galaxy (low pressure TPC≈5000 m^3)

Interesting role of indirect detection

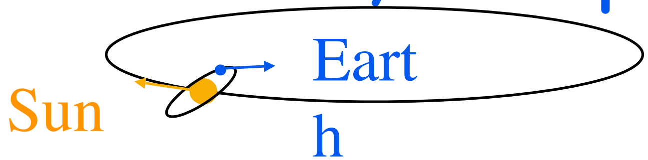
GLAST could be an interesting smoking gun:
High energy neutrino from sun as probe of p spin dependent

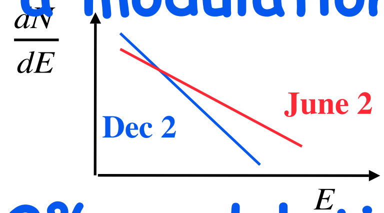
Importance

Instrumentation (high information content)
≥2 technologies (Technical risk, Cross check, A^2 dependence)
Take full advantage of complementary information (LHC,GLAST,HE solar ν's)

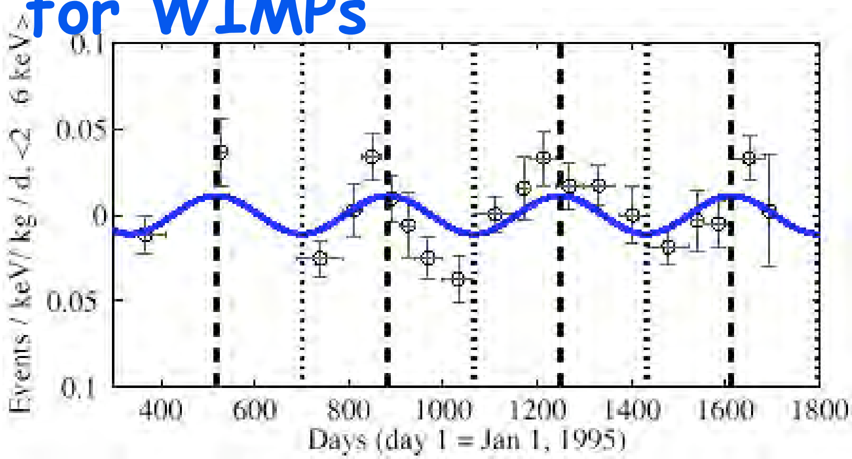
Danger of statistical methods DAMA

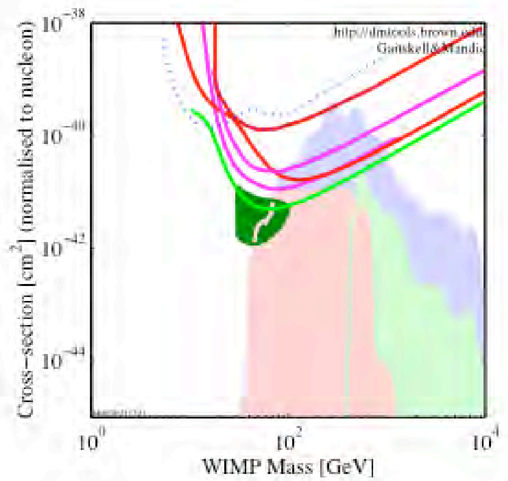
If WIMPs exist, we expect a modulation in event rate



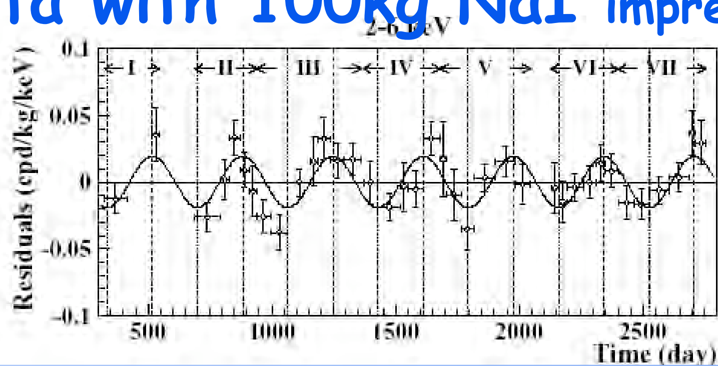


2000: DAMA interprets a ±2% modulation as evidence for WIMPs





Now 7 years data with 100kg NaI impressive modulation



Source DAMA
Astro-ph/0307403

Essentially excluded by other experiments

Technical Questions about DAMA

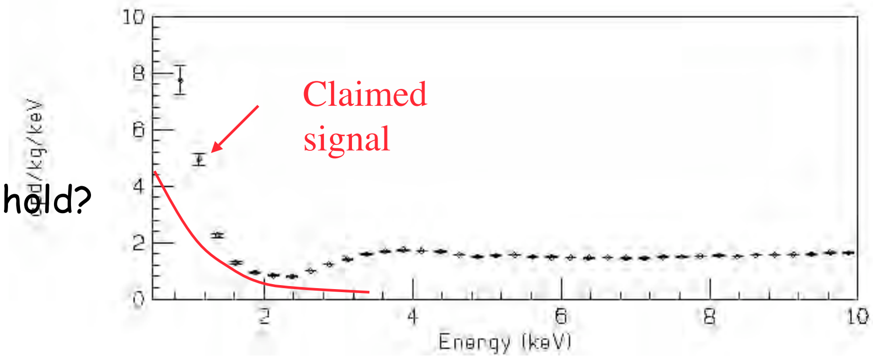
Efficiency?

The signal is a a region of sharply increasing efficiency

Method of determining and monitoring efficiency
Local source
Spectrum of gammas

Shape of the spectrum?

Spectrum before cut?
Detailed explanation of shape:
e.g. why does it decrease at threshold?



Stability?

Is threshold stability sufficient? (<1%)
DAMA: No modulation of multiples
Monitoring of other quantities (noise etc…)

Threshold Detectors

Similar concern: little information, spectrum by weeping threshold

Superconducting granules (Bern)

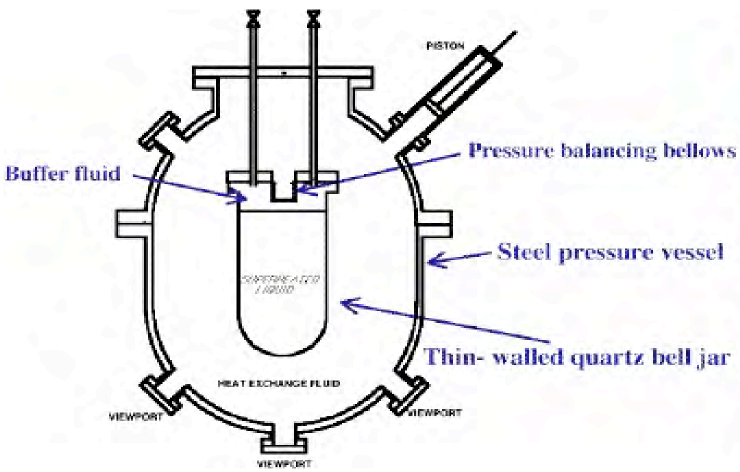
Metastable droplets Simple, Picasso

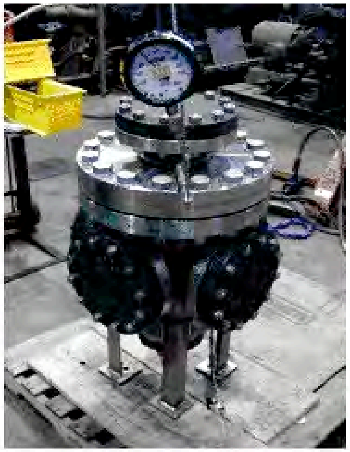
COUPP: Bubble chamber

Long duration metastable state broken by large ionization events

nuclear recoil or nuclear recoil from alpha (purity level ≈ Borexino)

2.5 kg prototype CF_3I bubble chamber at Fermilab (300 mwe)





Likely to be an excellent way to lower upper limit.

Much more difficult to get a convincing positive signal

Directional Detectors

DRIFT: Low pressure TPC

(Temple U.), Occidental Coll. + U.K.

Sensitive to axis of nuclear recoil provided low enough pressure

⇒Link to galaxy

1m^3 prototype at Boulby with some (non fundamental) technical difficulties. De-emphasis by U.K.

Challenge: mass

e.g. CS_2 (40 Torr) 1 m^3, 0.167 kg,

20 micron diameter wires 2 mm pitch.

Need 5000m^3 to be in to region

Develop technology

Note high pressure + high density of information works

Wait for discovery before a major detector

Overlap region: Rich Physics

If both seen at LHC and in Direct Detection

If observed at the same mass, direct detection provides ultimate proof that it is dark matter: stable and here in the galaxy

≠ SuperWIMP e.g sleptons -> gravitinos

Eventually Complete Self consistency

≠ Non minimal supersymmetry, or more complex particle physics models

≠ Non standard cosmology:not tested above T$\gtrsim$1GeV

In the initial stages, when incomplete information

direct detection can bring additional information

At formal level: no right to apply cosmological relic density unless we detect dark matter particles

By giving an idea of the mass (if not too high): help unravel the decay chain

Initially likely to be multiple solutions: help choose the right one

Before ILC 2x500 GeV, even if low masses, many quantities are not available

Direct detection brings unique information

mass of Heavy Higgs

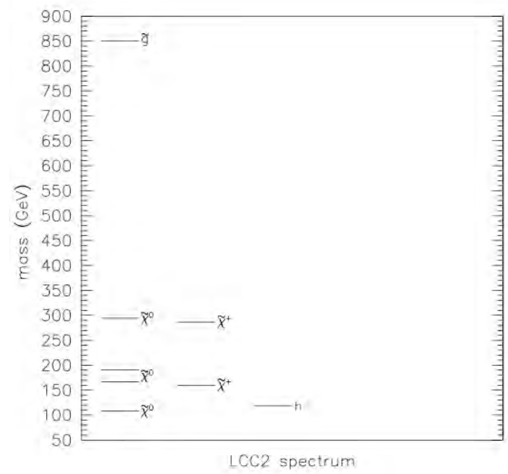
mixing of neutralinos

tan ß

Multiple solutions

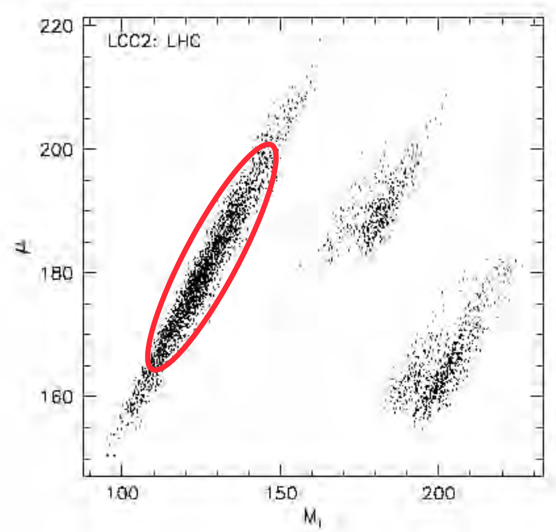
Even after full study at LHC

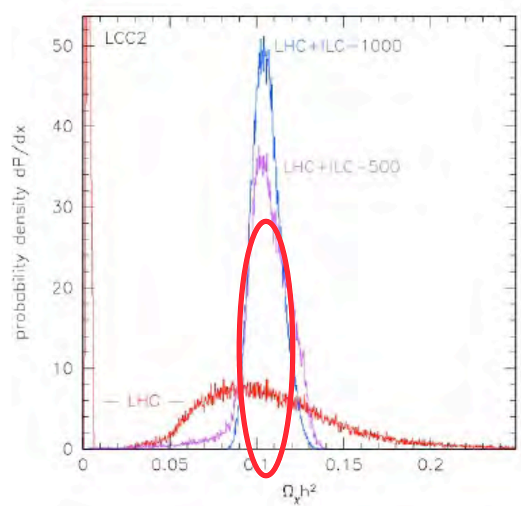
Some masses are too large
e.g. LCC2: Baltz et al.

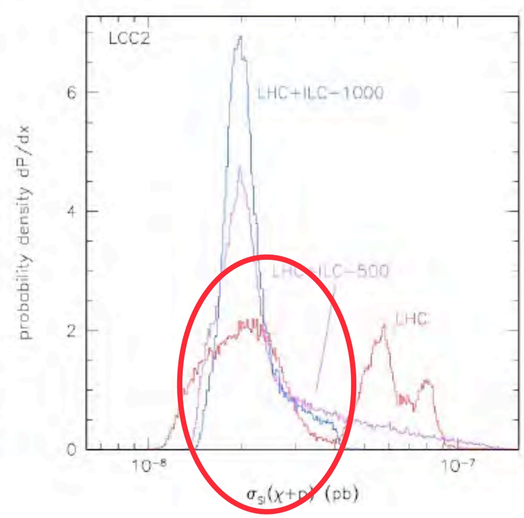


Reconstruction by LHC -> several solutions

Direct Detection/Relic density chooses the right solution



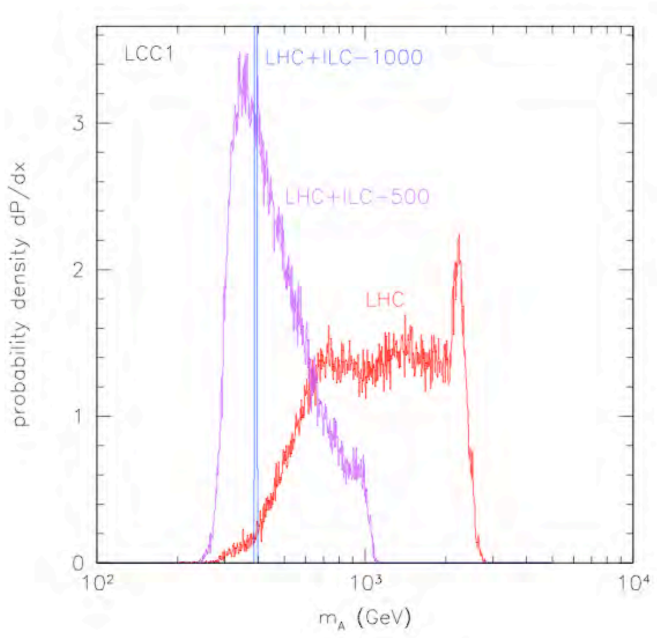


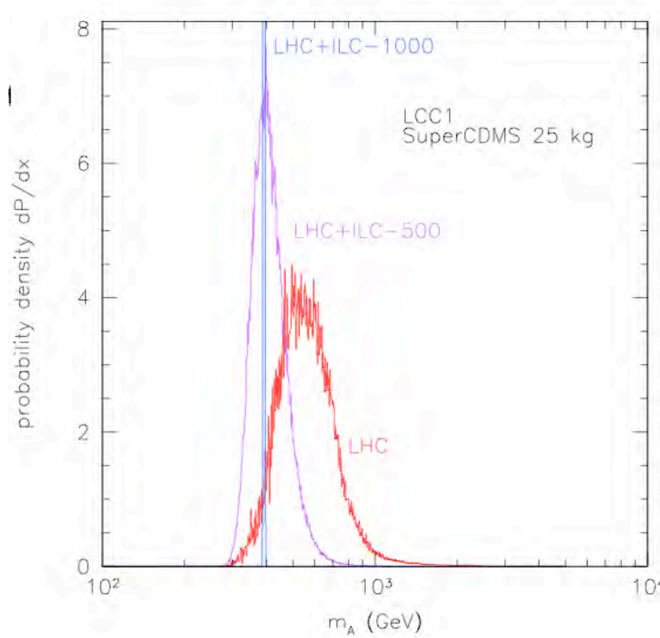


Complementary Information Example

Direct Detection provides unique information
Mass of axial higgs

LCC1 (favorable to LHC)

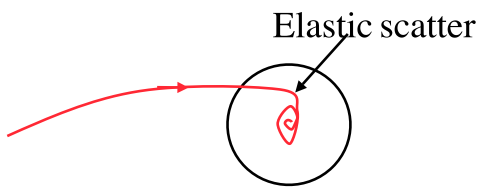




Neutrinos from Sun/Earth

Capture by sun & earth

Trapped
=> annihilation in center



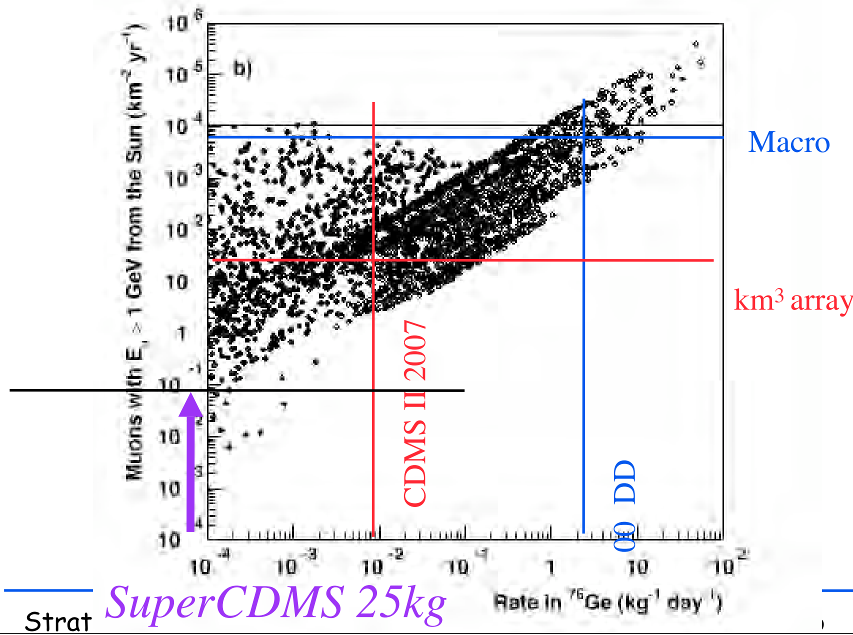
Observable: high energy neutrino

$$\frac{dn}{dt} = \Gamma_{elast} n - \Gamma_{ann} n^2 \quad \Rightarrow \text{in equilibrium } \Gamma_{ann} n^2 = \Gamma_{elast} n$$

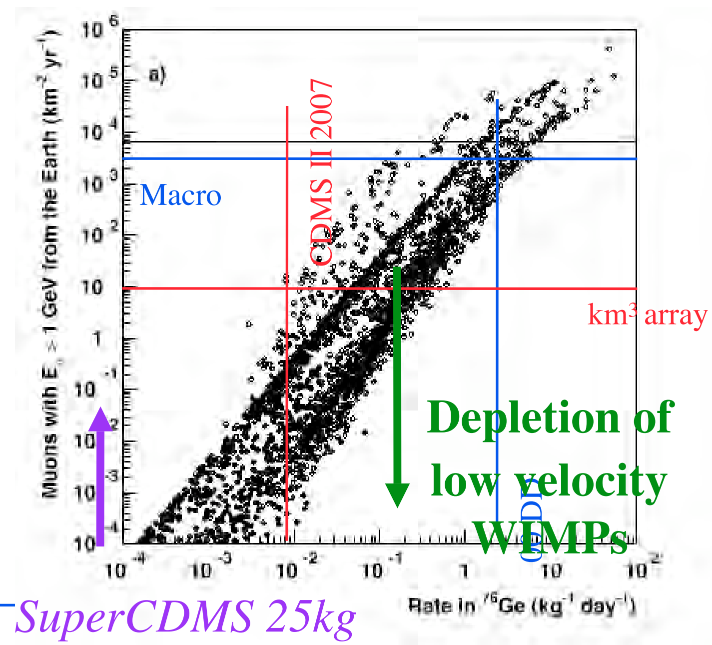
$\Rightarrow$ measure elastic scattering

More or less proportional

Sun (also spin dependent)



Earth



Neutrinos from annihilation in Sun

WIMPs captured in Sun, eventually annihilate-> Neutrinos

In general

Not competitive with direct detection for scaler (spin independent) coupling

Important input for spin dependent **(Sun is made of p!)**

"n" scattering "p" scattering