Dark Matter

Experiments

Wolfgang Rau, Queen’s University

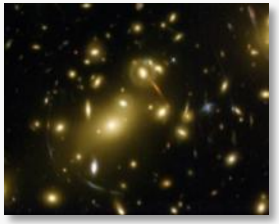
Overview

- Evidence for Dark Matter
- Dark Matter Candidates
- Indirect Searches
- Direct Searches
- Conclusions

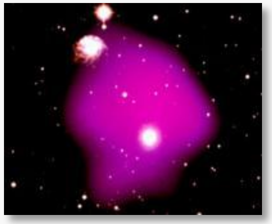
Evidence

Zwicky, 1930s
Coma cluster

Rubin-Cooper,
(1970s)
Rotation curves



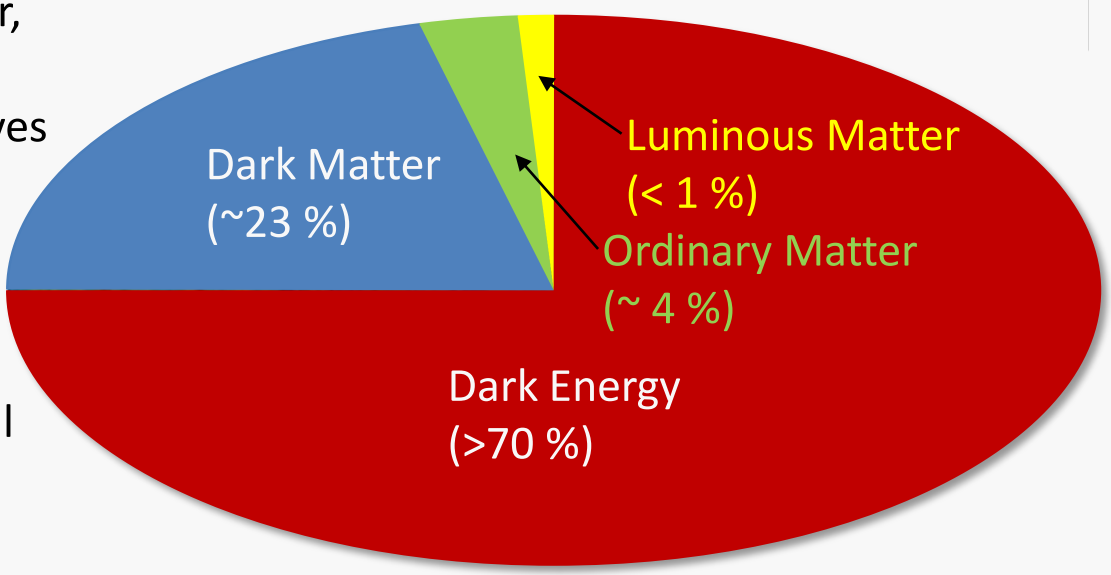
Gravitational
lensing



X-ray from
hot gas

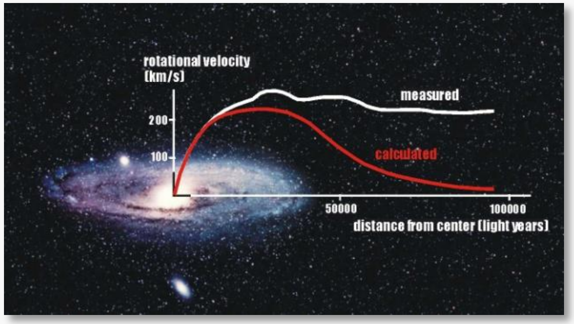
Bullet Cluster

Cosmic Microwave Background:
Global Energy/Matter Crisis



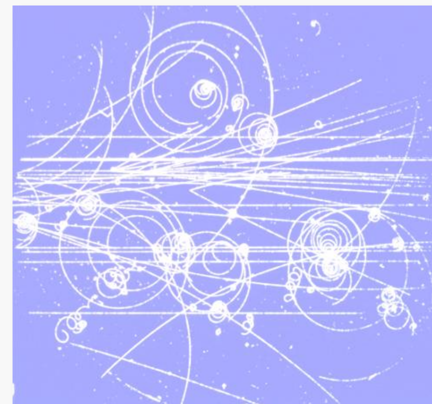
Overall geometry of space is flat ($\Omega = 1$)
Dark Matter / normal matter: ~5/1
Together with other observations:
~ ¾ of the Unvierse is not matter at all

Candidates

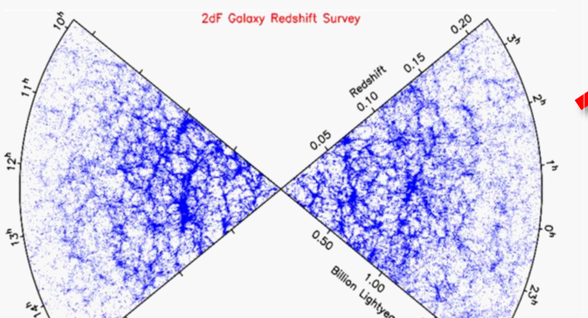


Here, but not yet observed in nature:
Weakly interacting

Not observed in accelerator experiments:
Heavy



Good candidate:
Weakly **I**nteracting **M**assive **P**article (**WIMP**)



Large scale structure of the Universe:
Slowly moving ('cold')

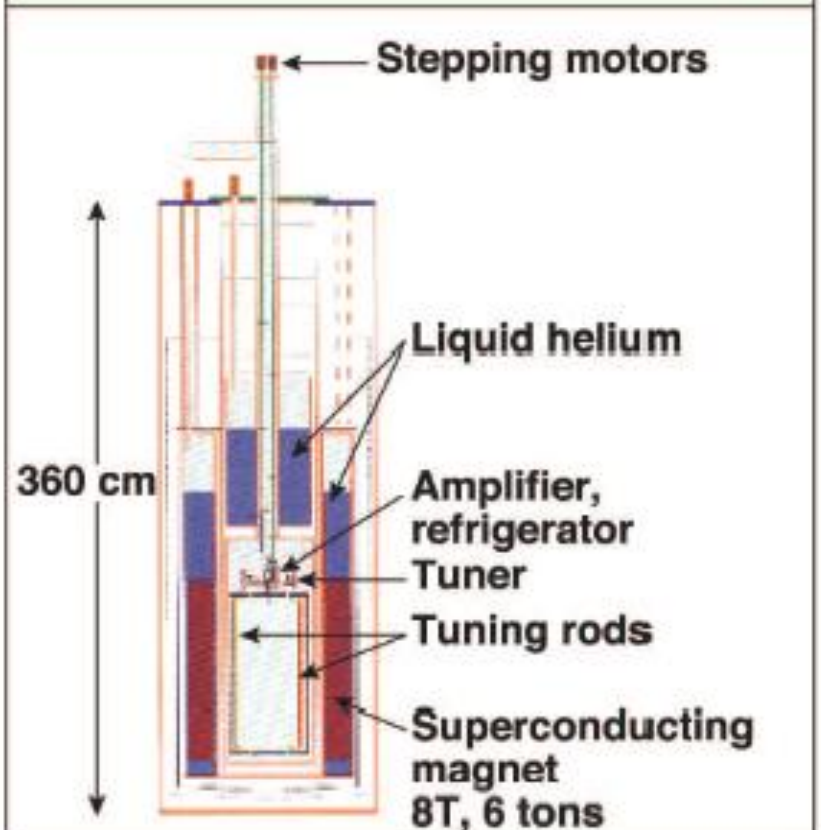
Predicted by SUSY:
Neutralino
Universal extra dimensions:
Kaluza-Klein particles

Others : e.g. Axions, Axinos, Gravitino, WIMPzillas…

Evidence
Candidates
Indirect Detection
Direct Detection
Conclusion

Candidates - Axions

Magnet with Insert (side view)



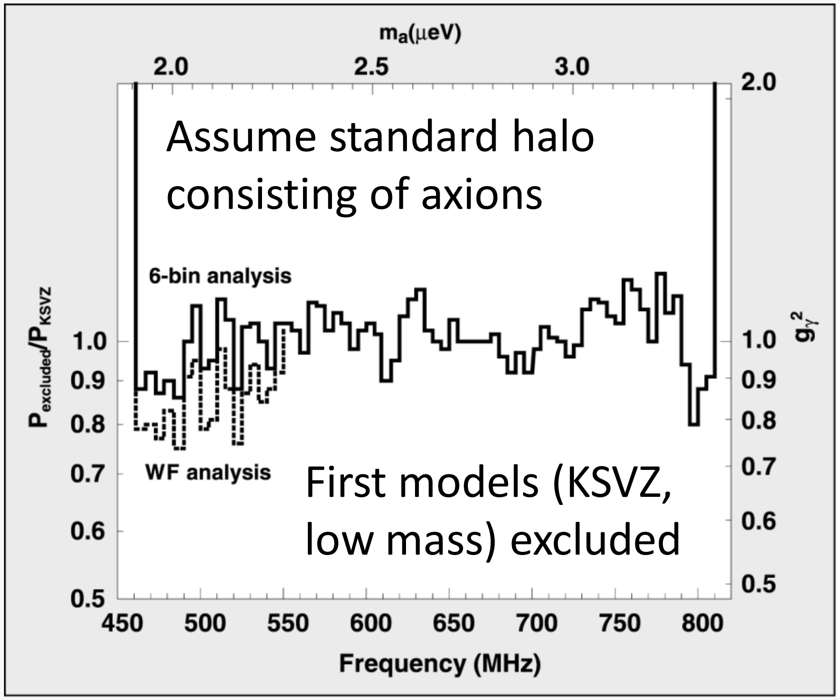
Pumped LHe → T ~ 1.5 k

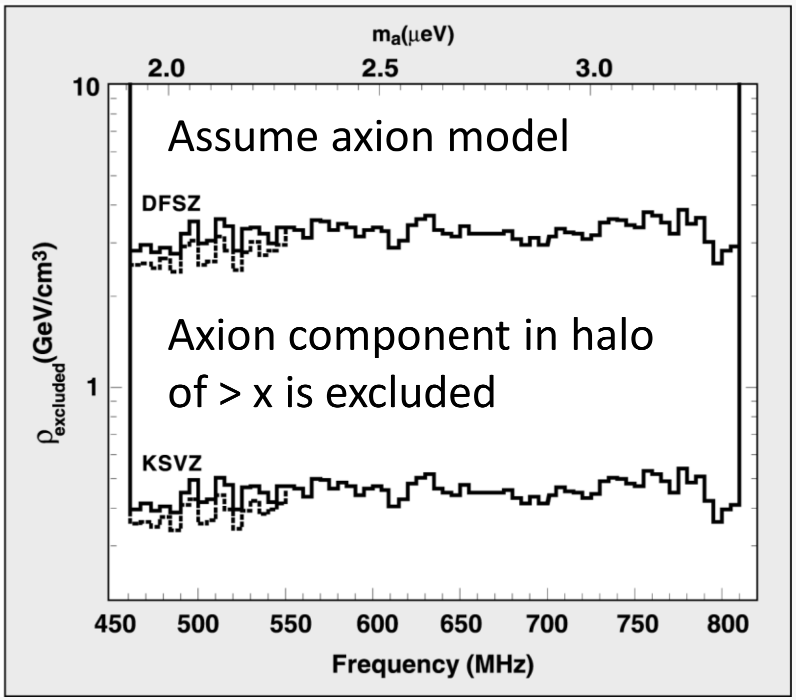
Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

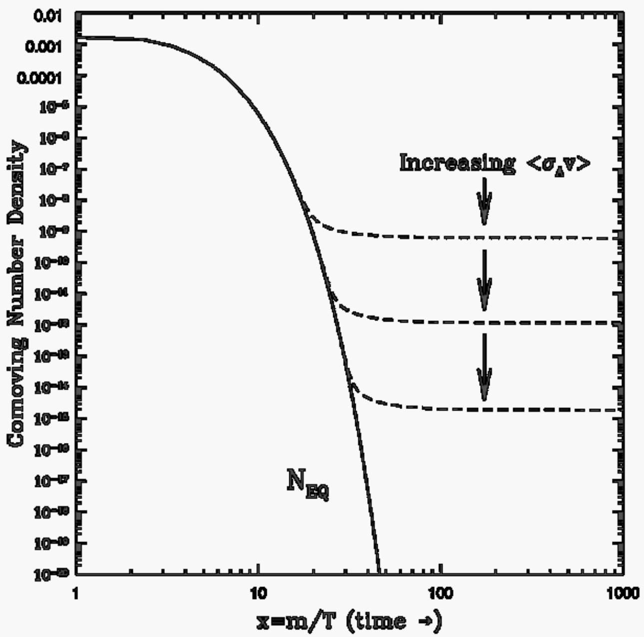
Candidates - Axions

Axions – Results





Candidates - WIMPs



Abundance of DM particles (χ)

Hot early universe, high density

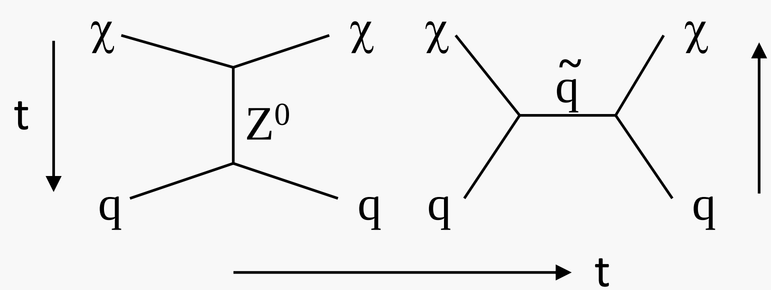
$T \gg m_\chi$: $\chi\bar{\chi} \leftrightarrow f\bar{f}$ – thermal equilibrium
$\rho_\chi \approx$ constant

$T < m_\chi$: $\chi\bar{\chi} \rightarrow f\bar{f}$ – only annihilation
ρ_χ decreases exponentially

Expansion – ρ_χ decreases, annihilation stops
$\rho_\chi \propto 1/\sigma_\chi$; n_χ stays constant
σ_χ is $\mathcal{O}$(weak interaction)

Example Neutralino (note: $\chi = \bar{\chi}$)

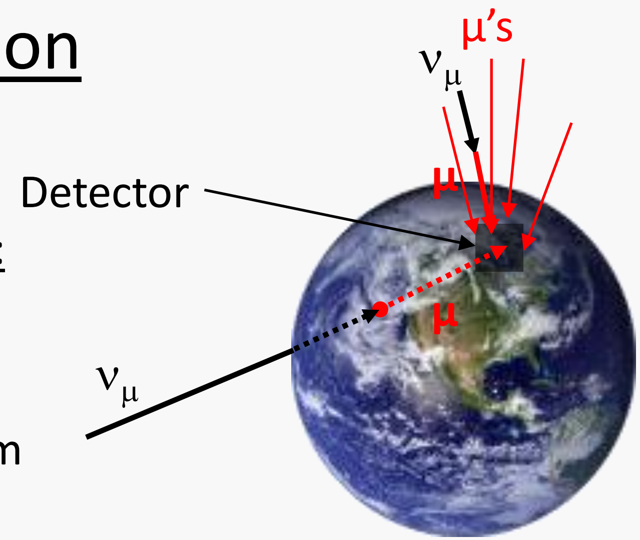
Indirect detection:
Search for products from annihilation



Production:
Early Universe, LHC

Direct detection:
Interactions with ordinary matter

Indirect Detection



Origin of indirect signal

- <u>SUSY WIMPs are Majorana particles:</u>

  WIMP-WIMP annihilation possible,
  annihilation rate depends on ρ_χ^2

  Search for annihilation products from regions with high WIMP density

  (decaying WIMPs also give indirect signal)

- <u>High WIMP density regions:</u>

  Center of the galaxy (Milky way, neighbours)

  Substructure of the halo, “subhalos”

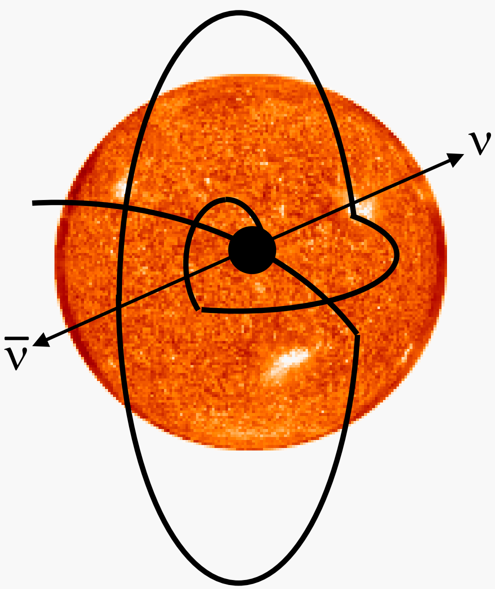
  Accumulation of WIMPs in sun/earth

- <u>What to look for:</u>

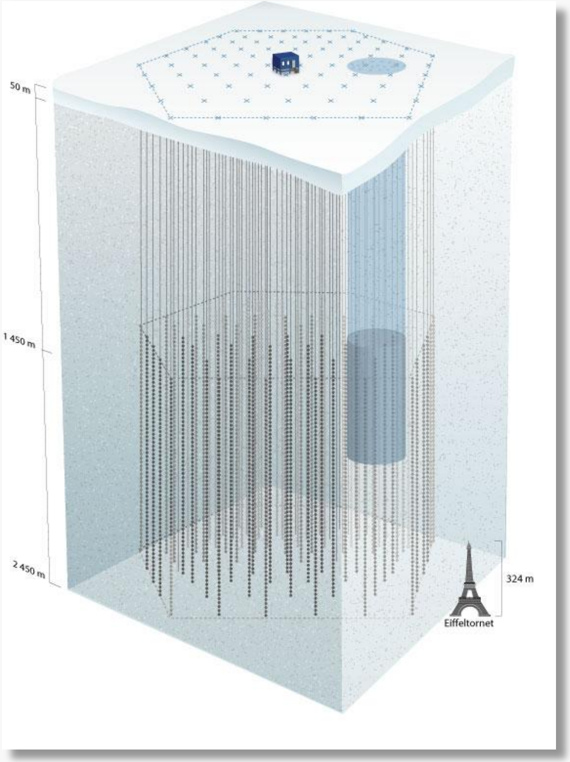
  neutrinos (center of sun/earth)

  gamma rays (center of galaxy, subhalos)

  exotic particles in cosmic radiation, e.g. positrons, anti-protons... (subhalos)



Indirect Detection - Neutrinos



SuperKamiokande

- 50 kt water Cherenkov detector
- Detects atmospheric/solar ν
- DM signal: high energy νs from center of sun/earth

Amanda/Icecube

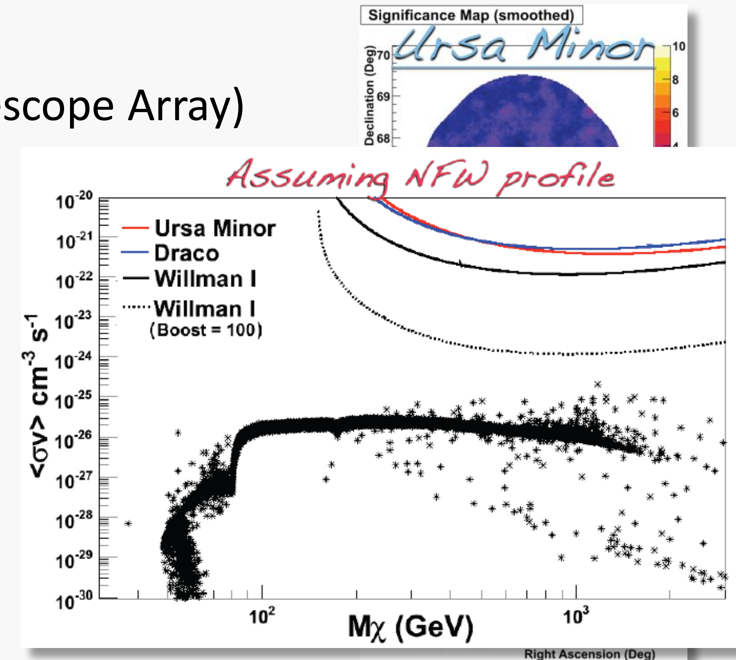
- Ice Cherenkov detector , south pole
- Searches for very high energy ν
- DM signal: “low” energy νs from center of sun/earth

Indirect Detection – Gamma rays

VERITAS – Ground based

(Very Energetic Radiation Imaging Telescope Array)

- 4 Cherenkov telescopes (12 m)
- Energy range ~150 GeV – >30 TeV
- Energy resolution 10-20 %
- Good angular resolution (~ 0.1°)



Looking for enhanced signal from dwarf galaxies

Nothing found so far

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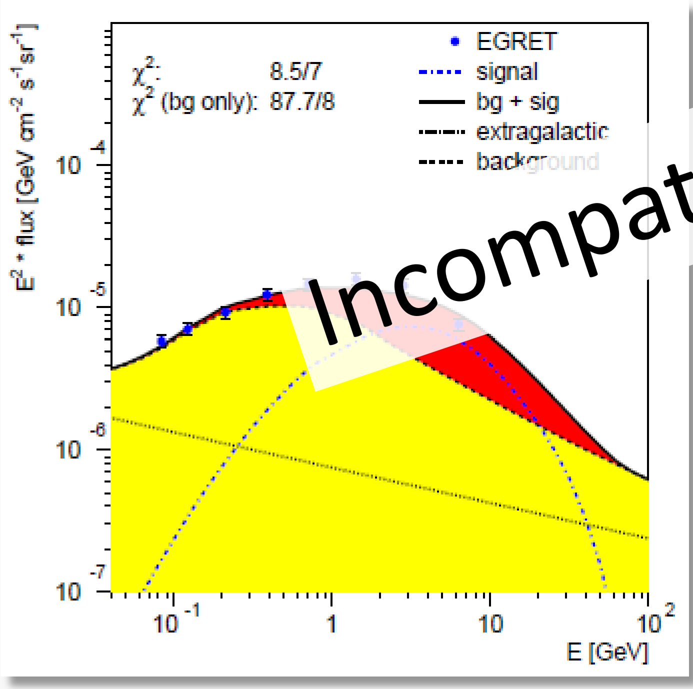
Indirect Detection – Gamma rays

EGRET - Satellite

(Energetic Gamma Ray Experiment Telescope)

- Part of the Compton Gamma Ray Observatory (NASA satellite; energy range 20 keV – 30 GeV)
- EGRET: 20 – 30 GeV (relevant range for WIMP signal)



De Boer, 2005

Incompatible with Fermi

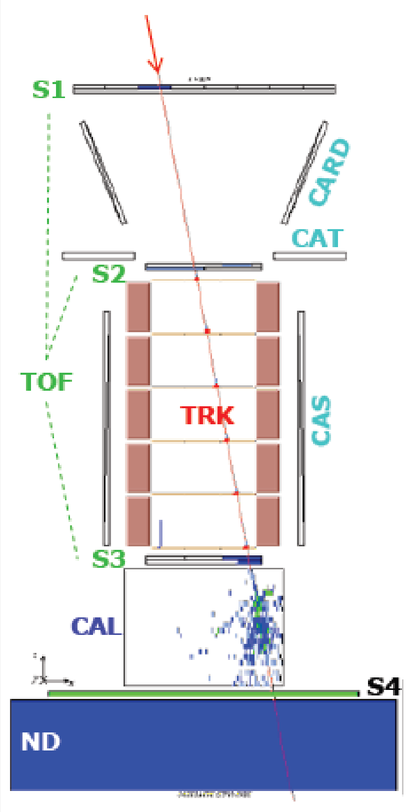
- Excess of gamma rays in the GeV range
- Could be explained with 50-150 GeV WIMP (rate very high though)
- Would require unexpected structure of DM halo (rings in the disk)
- Other 'conventional' explanations exist

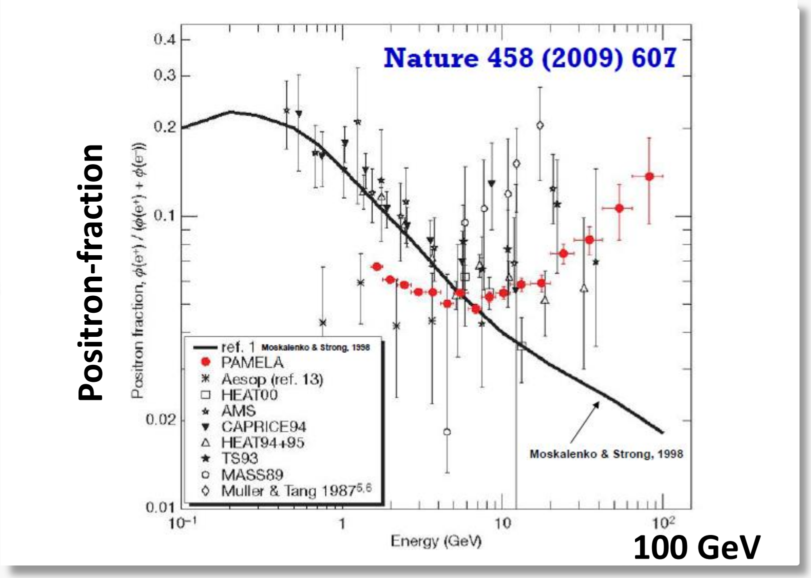
Indirect Detection - Positrons

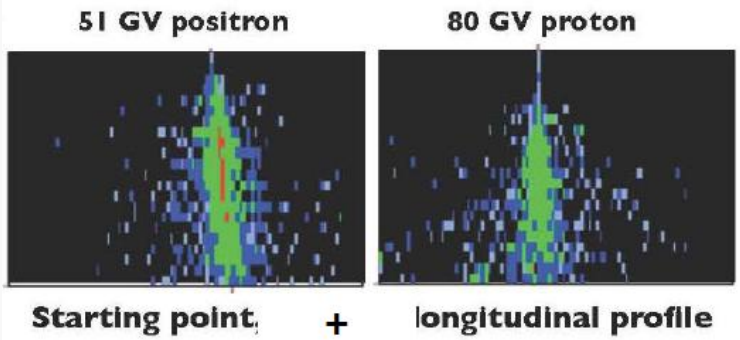
PAMELA – Satellite Experiment (2006-2011)
(Payload for Antimatter Matter Exploration and Light nuclei Astrophysics)

- ToF scintillator
- Gas tracker with Si detectors / magnetic field
- Calorimeter
- ^{3}He n counter to distinguish lepton/hadron showers

$\bar{p}$ 80-190 GeV, p up to 1 TeV
e^+ 50-300 GeV, e up to 500 GeV (2 TeV from calorimeter)
Light Nuclei (He, Be, C) up to 200 GeV/n, AntiNuclei search





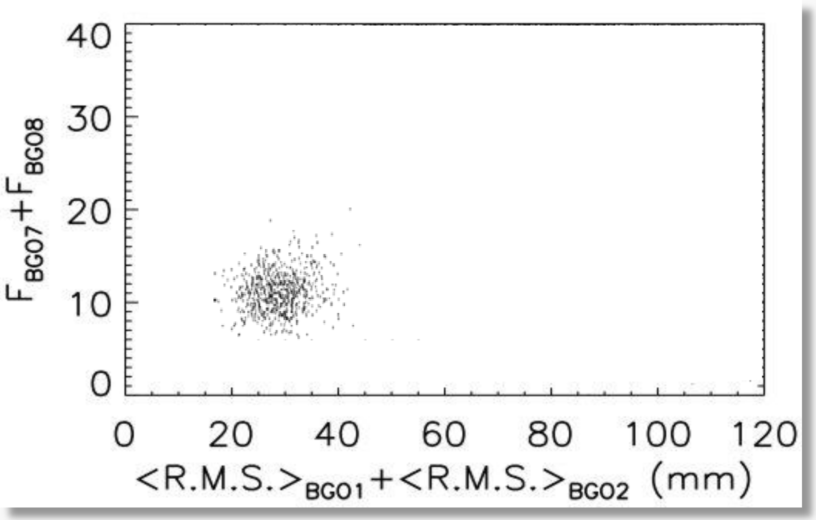


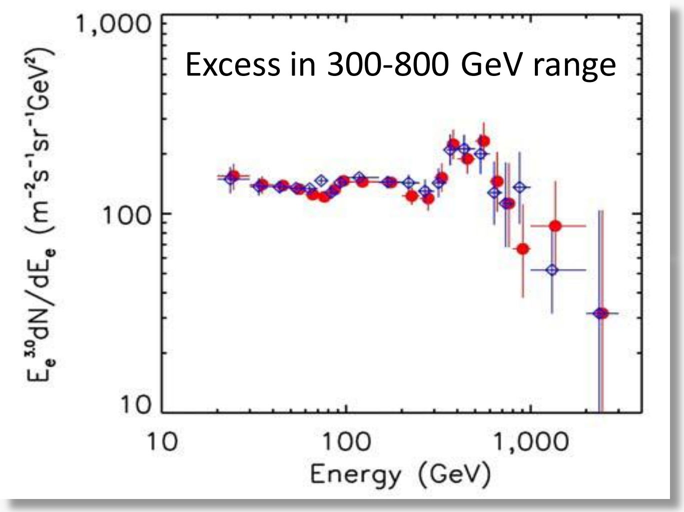
Indirect Detection – Electrons/Positrons

ATIC – Balloon Experiment
(Advanced Thin Ionization Calorimeter)

- Si pixel detector (charge)
- Passive graphite target w/ 3 scint. layers
- BGO calorimeter (8 layers, xy)

Separation between leptons and hadrons but not particle – antiparticle



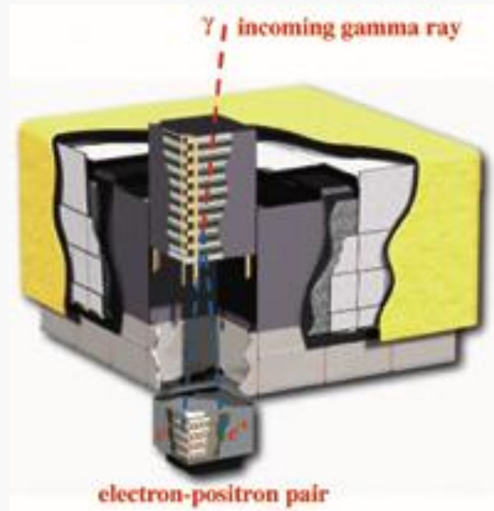


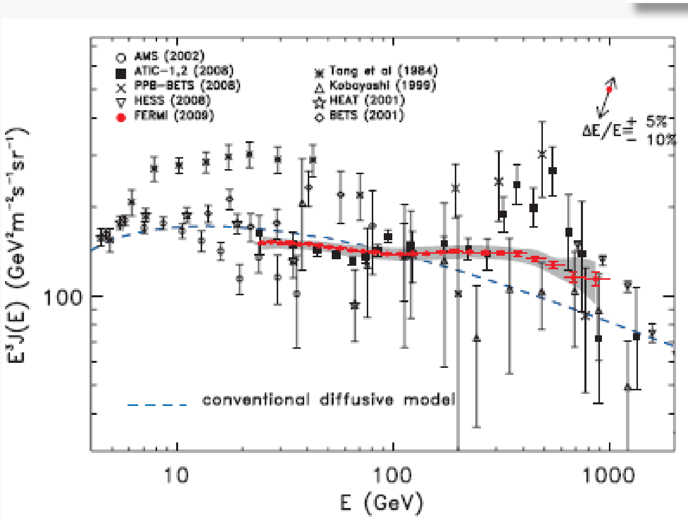
Indirect Detection – Electrons/Positrons

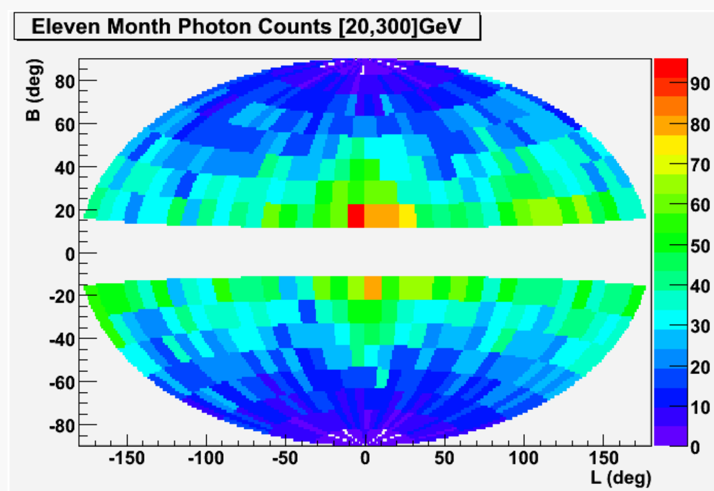
Fermi LAT – Satellite (Large Area Telescope)

- Gamma ray telescope, but also sensitive to electrons
- Energy range (e): 20-800 GeV
  $\Delta E \approx 10\%$ @ 100 GeV
- Angular resolution: ~ 0.1°

- Si/W tracker
- CsI calorimeter
- anti-coincidence plastic scintillator



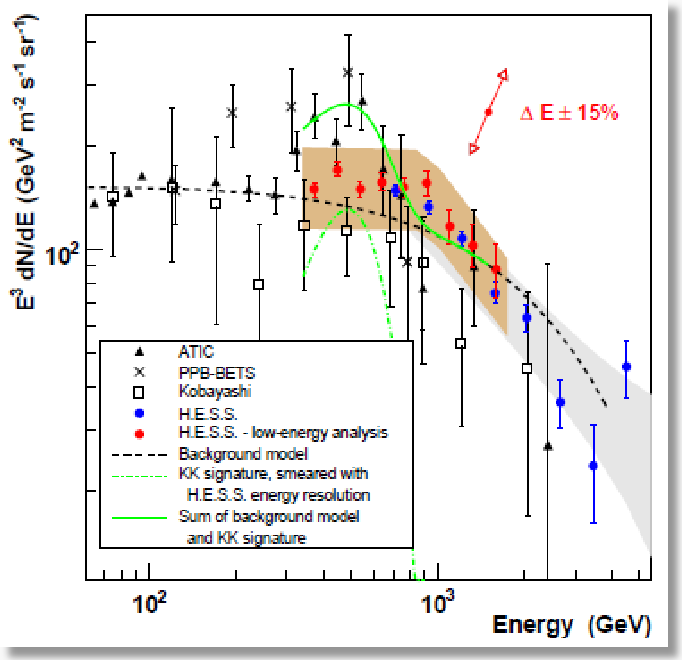




Indirect Detection – Electrons/Positrons

H.E.S.S. – Ground based
(High Energy Stereoscopic System)

- 4 Cherenkov telescopes (~ 12 m)
- Designed for high energy gamma rays but can also be used to measure electrons and hadrons
- Energy range (e^-) ~340 GeV – 5 TeV
- Energy resolution ~ 15 %

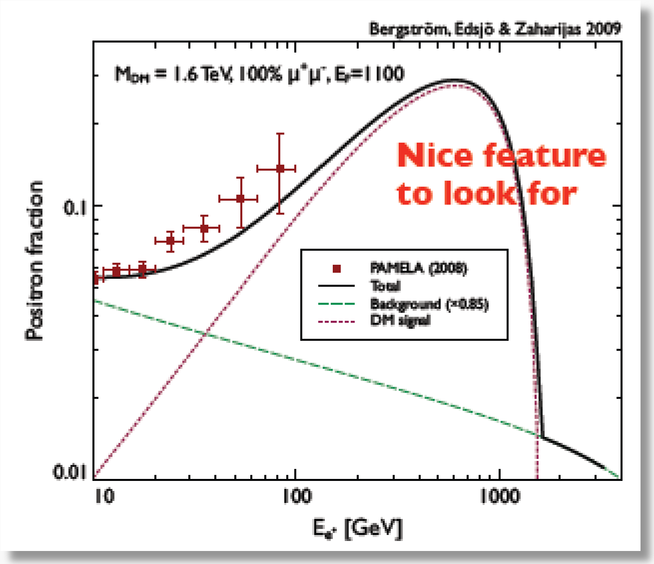


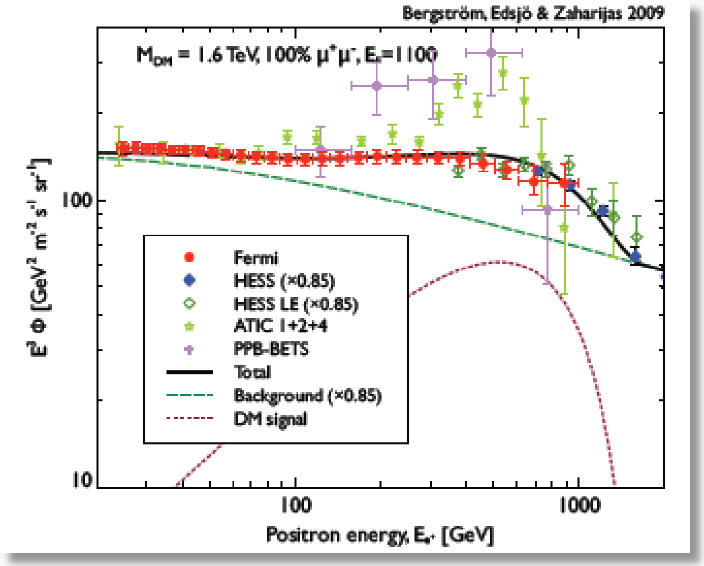
Indirect Detection – Electrons/Positrons

Attempt to fit PAMELA, HESS, Fermi data
(J. Edsjö, Stockholm, one of many attempts, just as example)

- ATIC data not really reproduced by Fermi/H.E.S.S. – but no contradiction (large error bars!), so ignore ATIC peak
- Example DM particle: 1.5 TeV, annihilation to $\mu^+\mu^-$

Problem:
need very high annihilation rate, does not fit simple DM halo models
→ Need enhancement factor ("boost factor") of order of 1000
substructure of halo (over densities enhance annihilation; x1000 unlikely)
particle physics, "Sommerfeld enhancement": increased σ at low velocity





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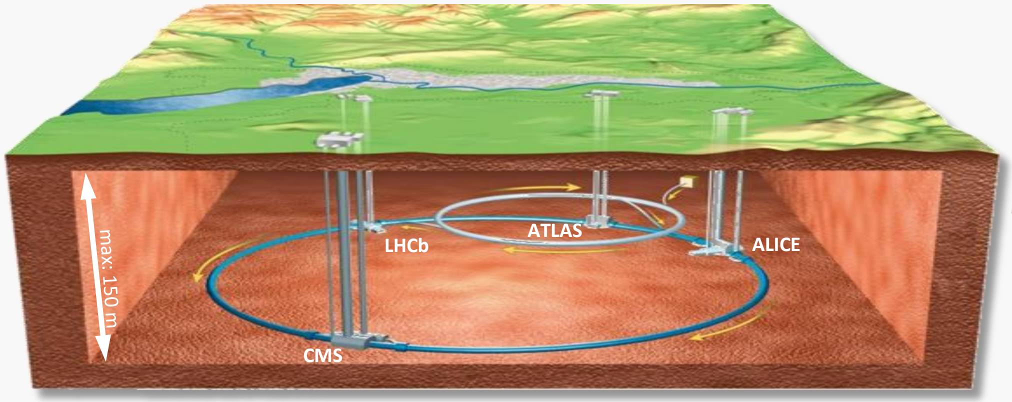
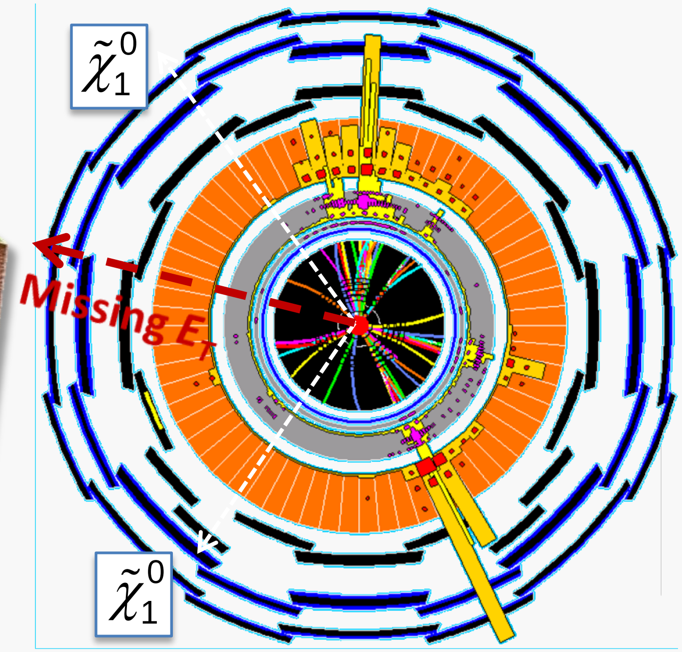
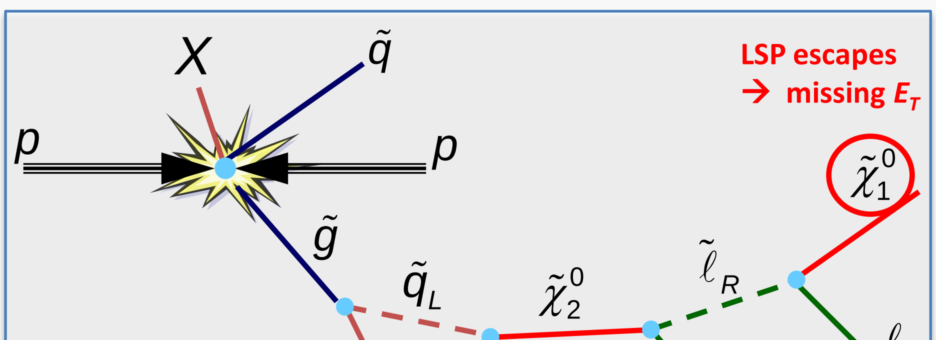
Indirect Detection – LHC (ATLAS)

LHC (Large Hadron Collider)

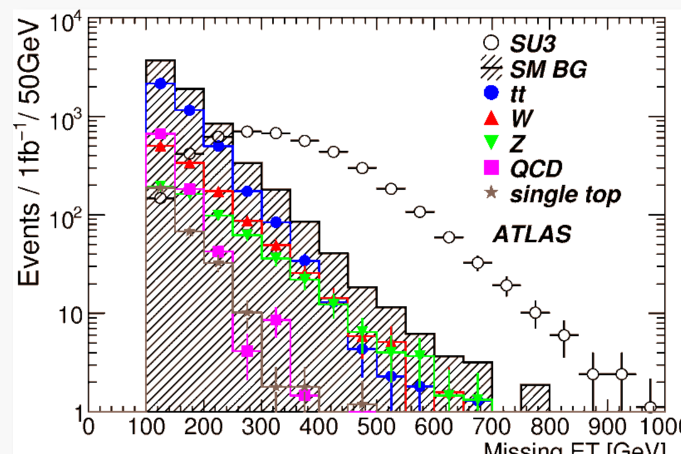




Produce new heavy particles in pp collisions
WIMP invisible (uncharged, does not decay)
Look for missing E, p; cannot confirm life time…



Typical SUSY cascade at a proton-proton collider



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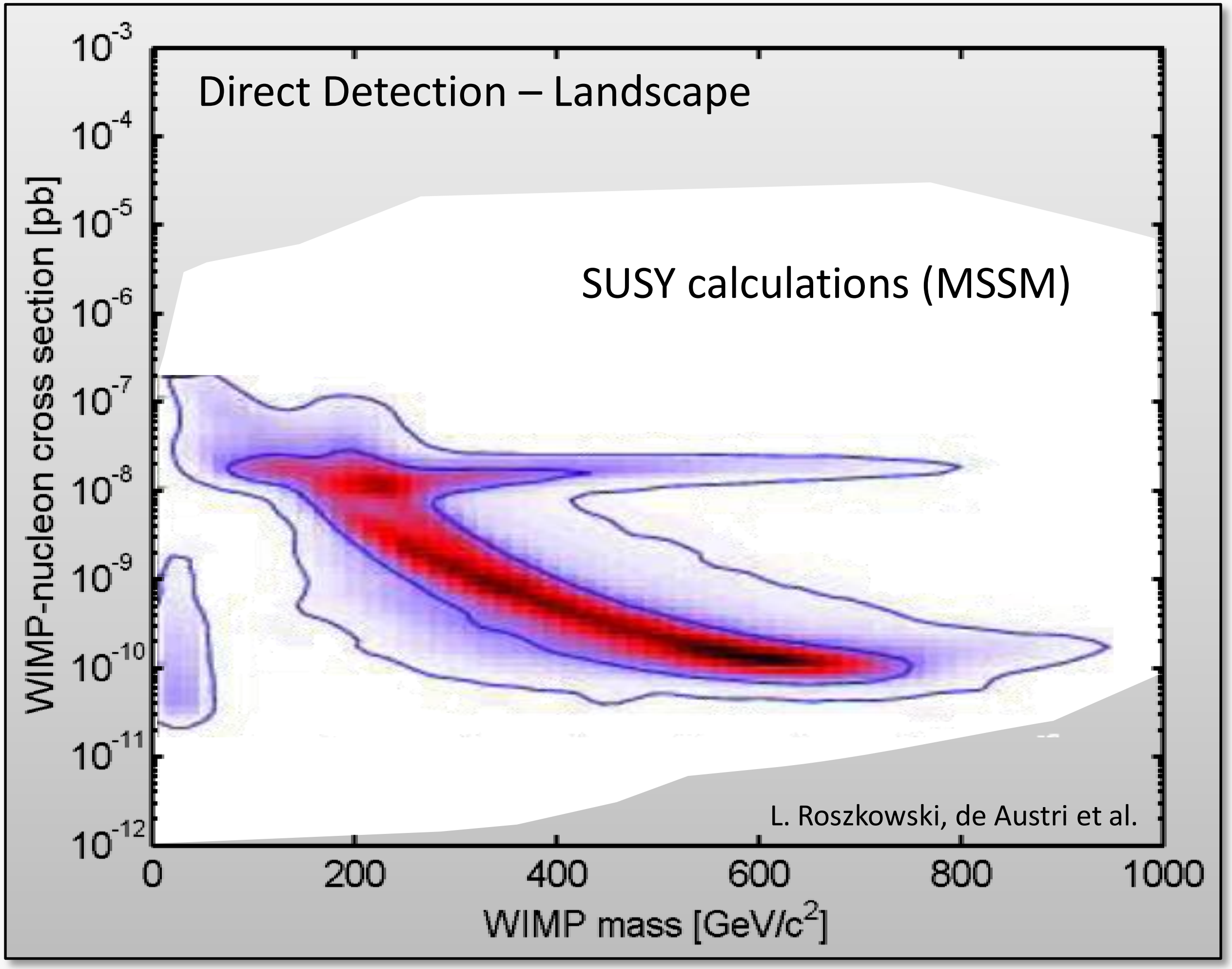
Direct Detection

Galactic Dark Matter WIMPs:

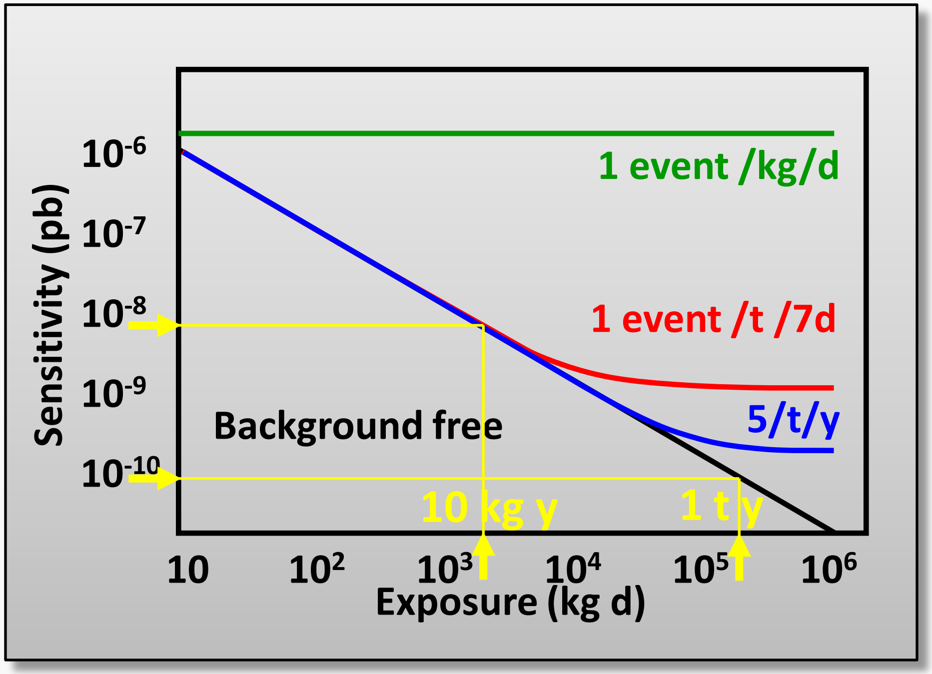
- Gravitationally bound
  $\rightarrow v_{WIMP} \leq v_{esc} \approx 600$ km/s = 2×10^{-3} c
  (typical v_{WIMP}: 270 km/s $\approx 10^{-3}$ c)
  $\rightarrow$ Significant energy transfer only for nuclear recoils
  (interact coherently with all nucleons $\rightarrow \sigma \propto A^2$)
- Typical WIMP mass: 10 – 1000 GeV/c^2
- WIMP density at the Earth: 0.3 GeV/c^2/cm^3
- Expected interaction cross section: can be estimated from total amount of DM (production in early universe): 10^{-9} – 10^{-10} pb, but large uncertainty (couple orders of magnitude)
  $\rightarrow$ Very rare interactions (< 0.1 evts/kg/d)
- Many more interactions from other sources (background): natural radioactivity (U, Th, K, …), cosmic radiation
  $\rightarrow$ Mostly ionizing: electron recoils

Corresponds to 5 $\text{WIMPs}^{60\ \text{GeV}}$ / litre
Or 150 g/earth
But 150 000/cm^2/s

WIMP Detection - Landscape



WIMP Detection - Background



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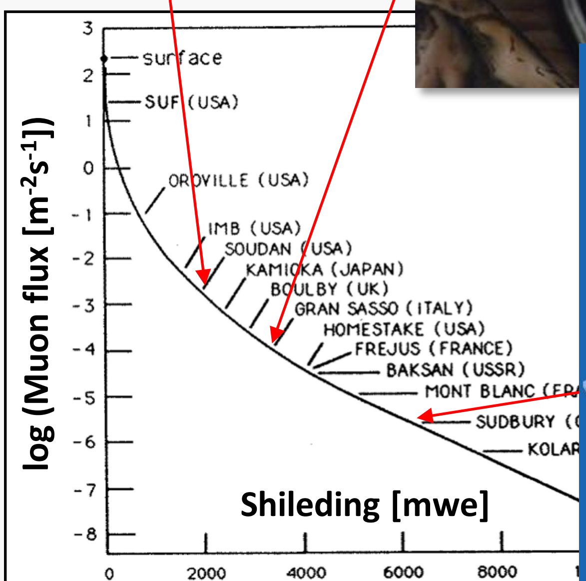
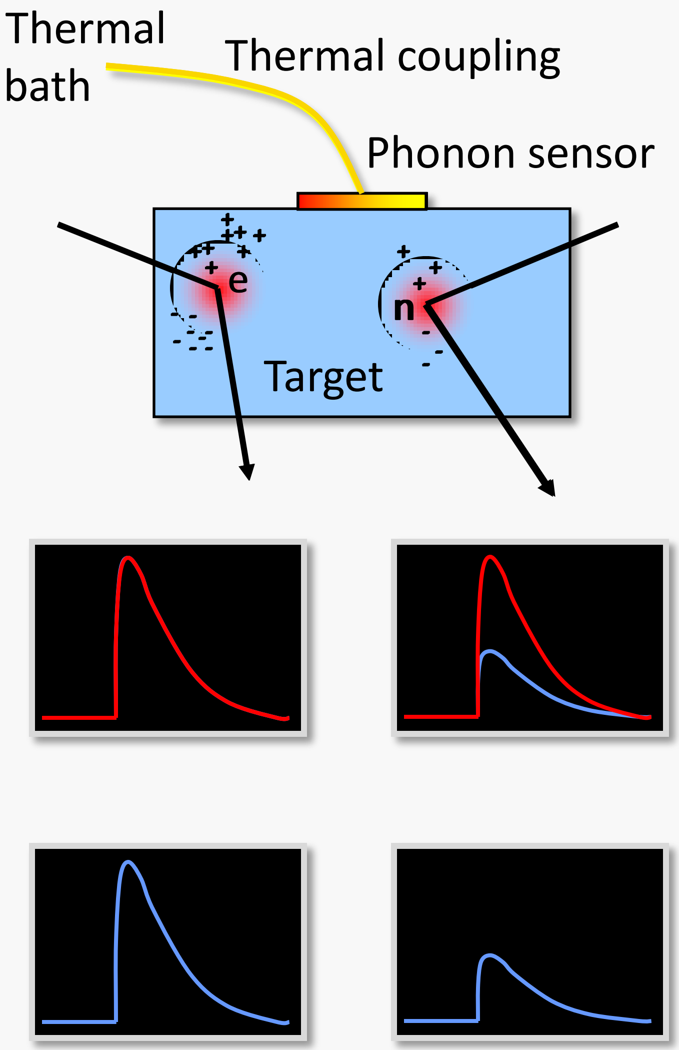
WIMP Detection - Underground

Underground Laboratories

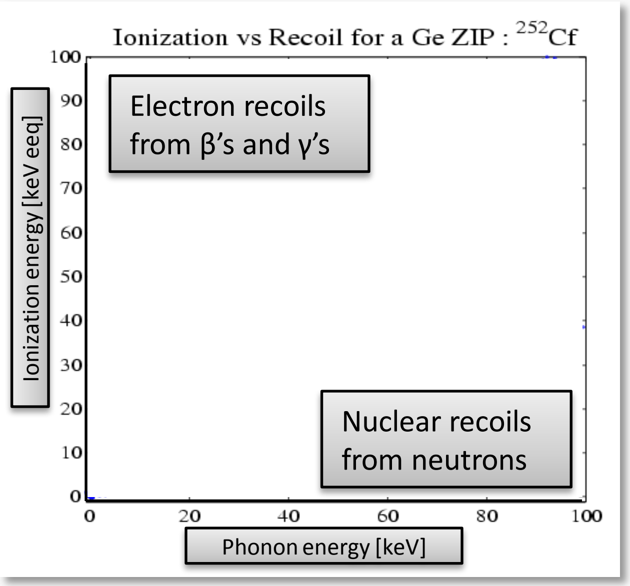
Soudan MN, USA – 2000 m w.e.
Canfranc, Spain – 2500 m w.e.
Kamioka, Japan – 2700 m w.e.
Bulby, UK – 3200 m w.e.
Gran Sasso, Italy – 3500 m w.e.
Baksan, Russia – 4500 m w.e.
Modane, France – 4800 m w.e.
SNOLAB, Canada – 6000 m w.e.



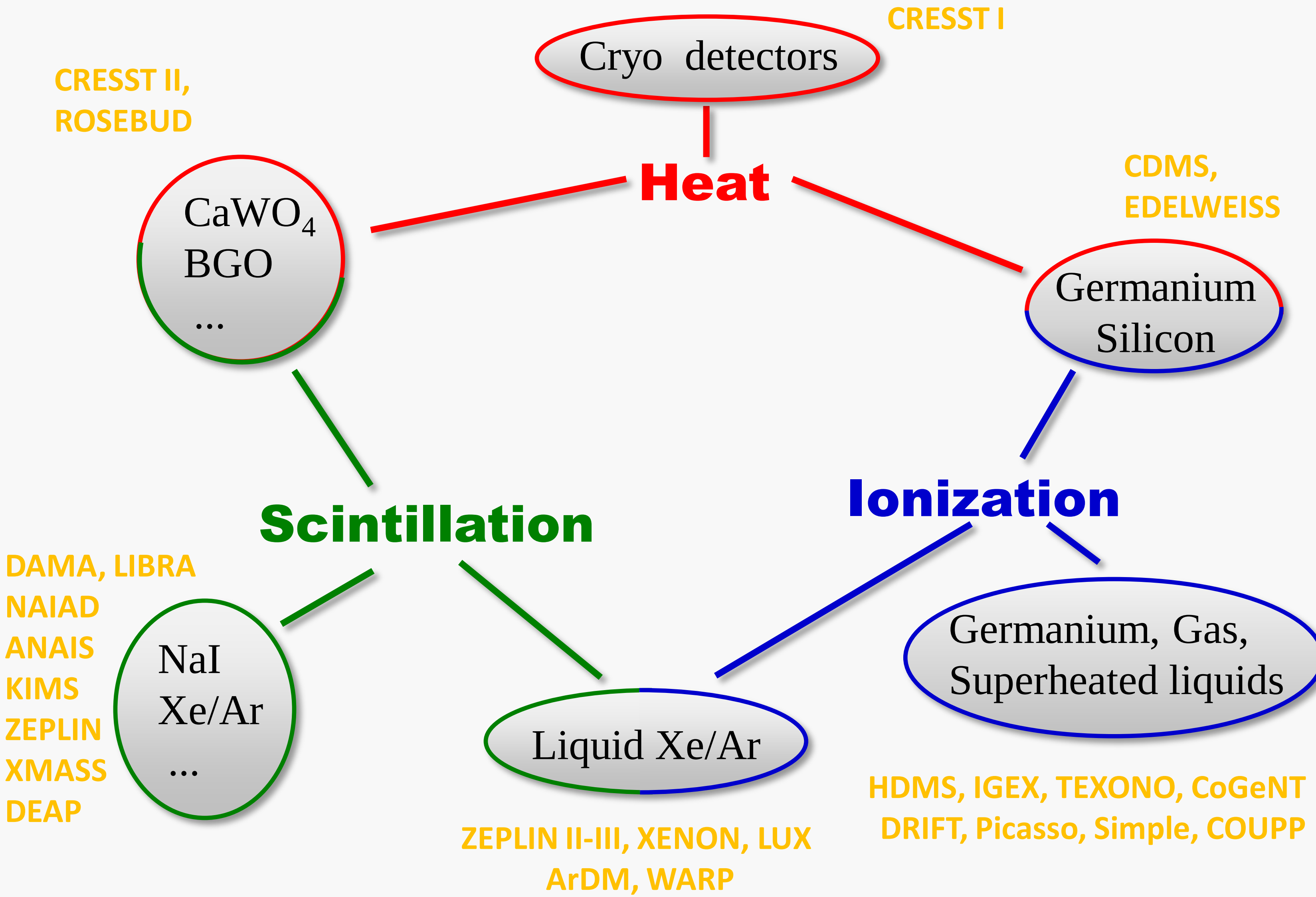
Direct Detection



- Conventional detectors (ionization, scintillation): signal reduction for nuclear recoils (quenching)
- Most energy converts to thermal energy (lattice vibrations – phonons)
- Measure thermal signal
- Combine with conventional technology: discrimination of BG



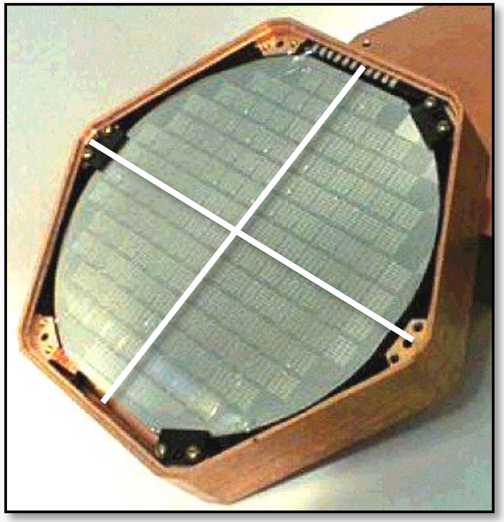
WIMP Detection - Experiments

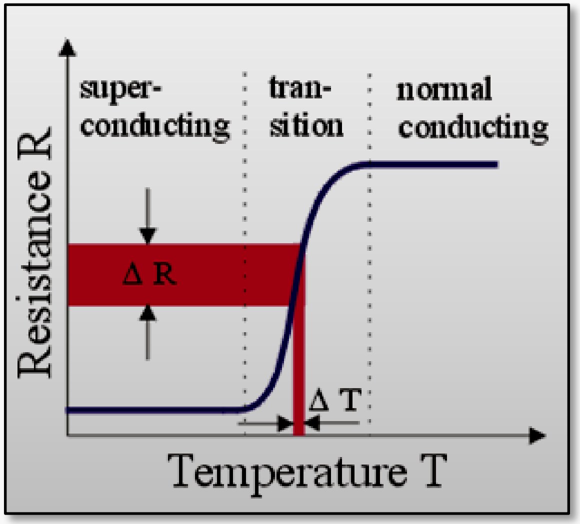


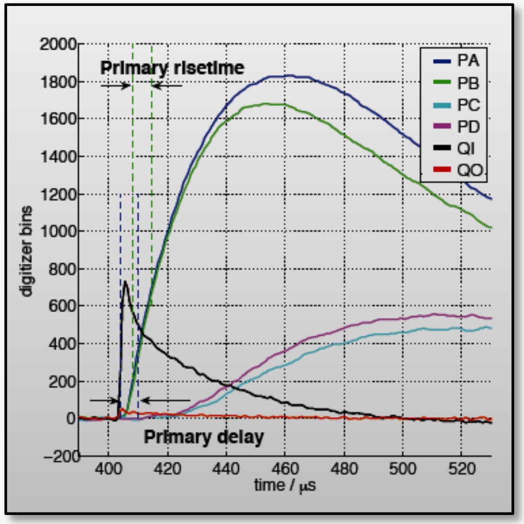
Cryogenic Dark Matter Search

Cryogenic ionization detectors, Ge (Si)

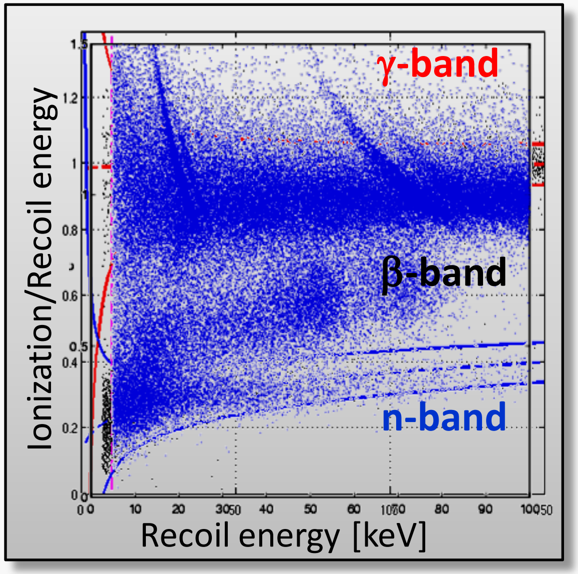
- ∅ = 7 cm, h = 1 cm, m = 250 g (100 g)
- Thermal readout: superconducting phase transition sensor (TES)
- Transition temperature: 50 – 100 mK
- 4 sensors/detector, fast signal (< ms)
- Charge readout: Al electrode, divided

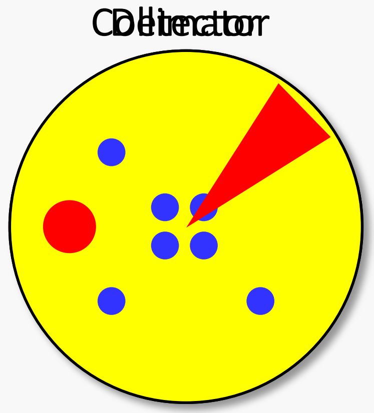


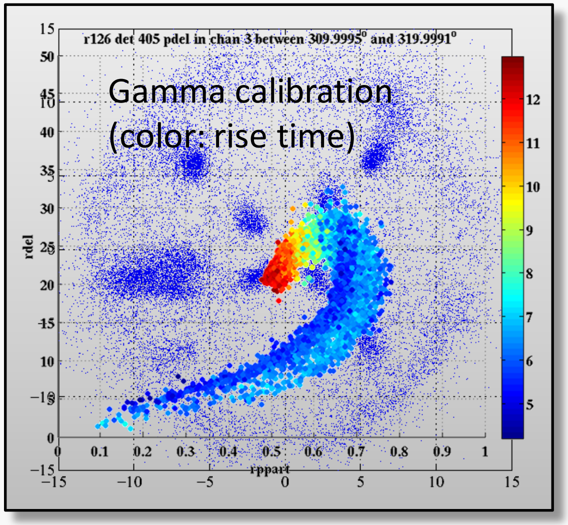




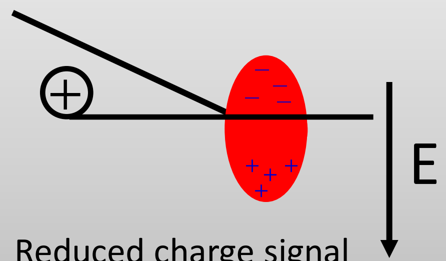
Cryogenic Dark Matter Search



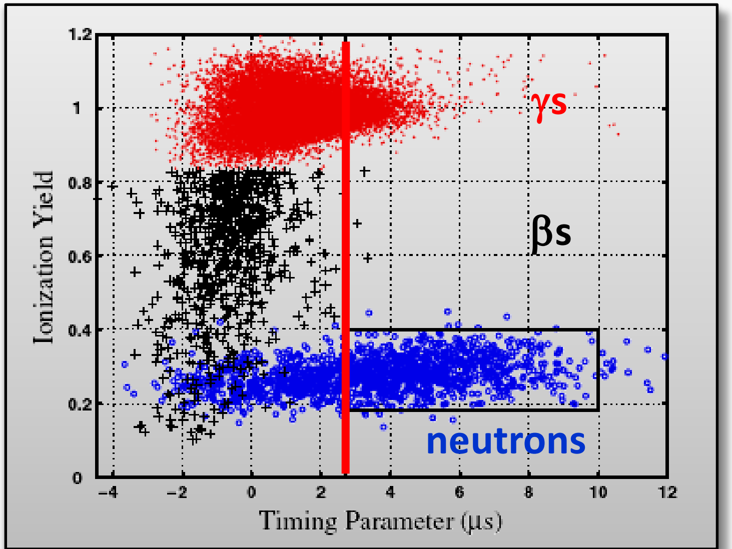




Surface effect



Reduced charge signal
but faster phonon signal



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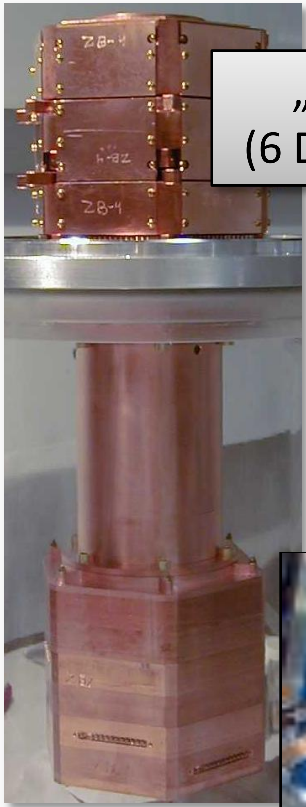
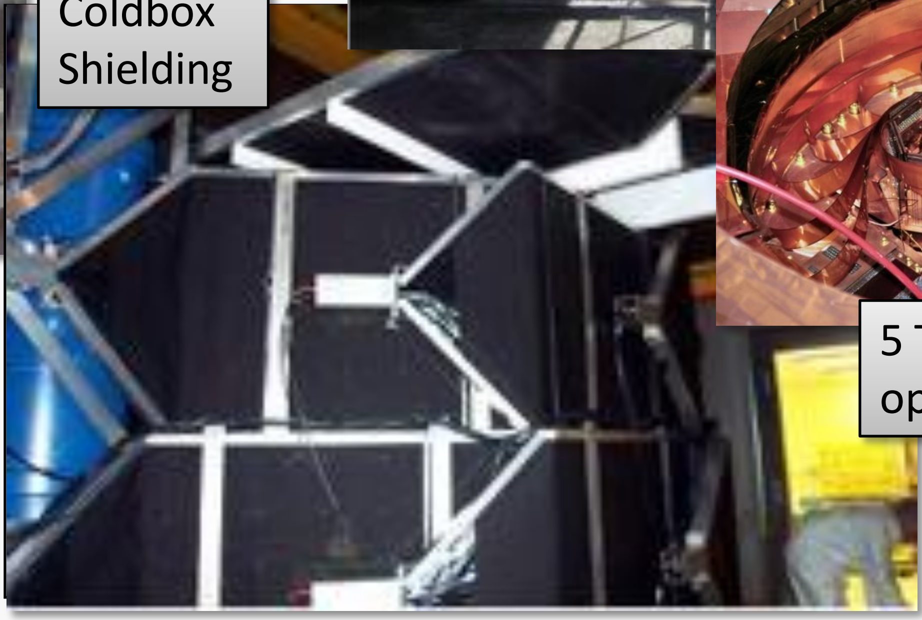
CDMS at Soudan

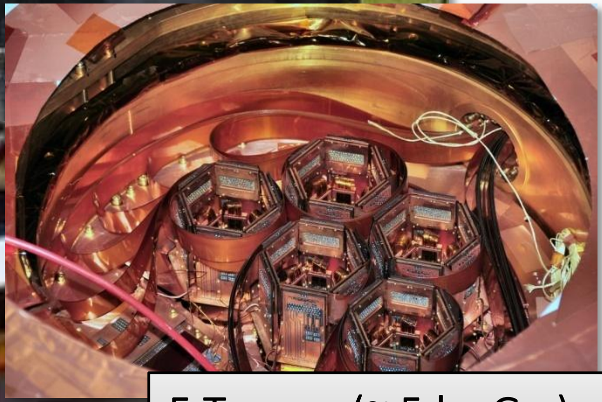


„Tower“
(6 Detectors)

Soudan
Underground lab

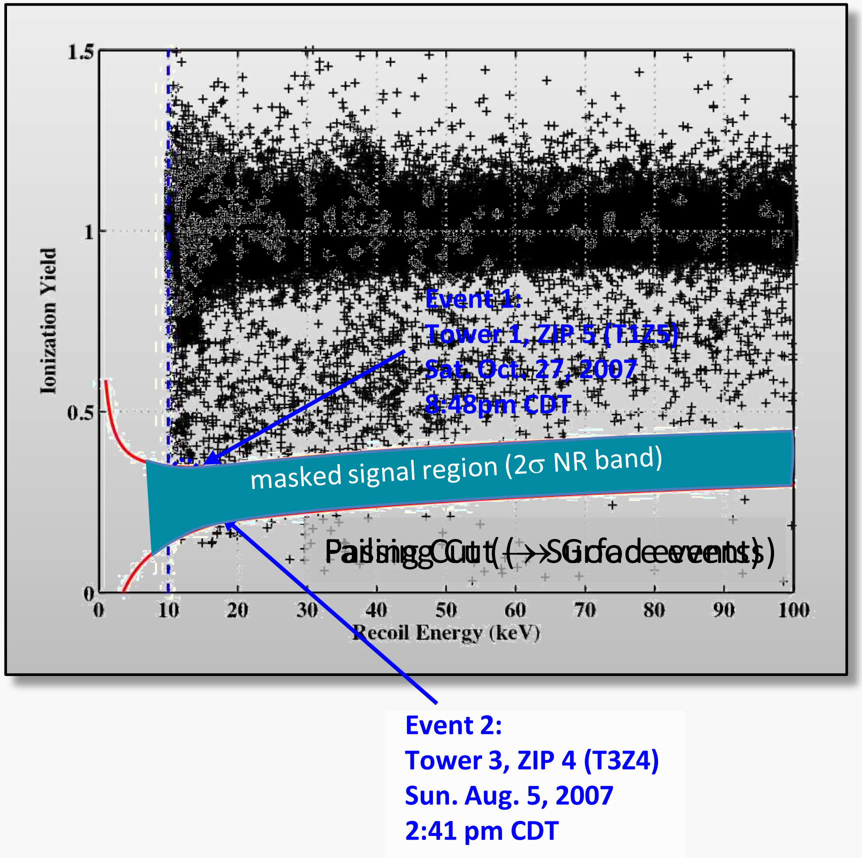


Cryostat,
Coldbox
Shielding



5 Towers (~ 5 kg Ge)
operated 2006 – 2008

CDMS Results



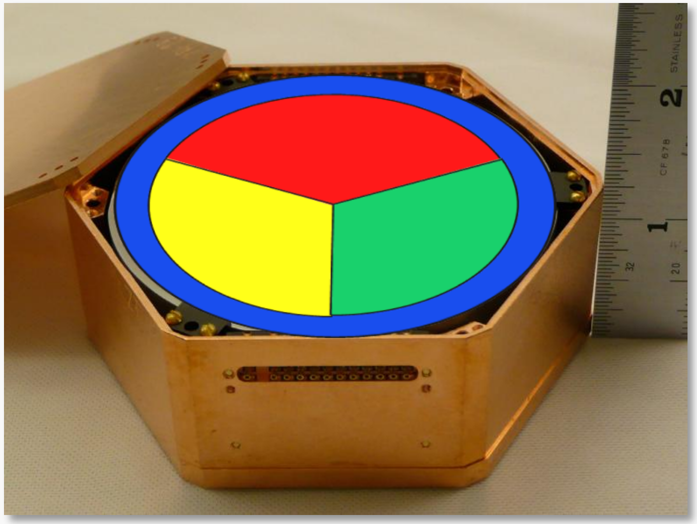
- Data from Jun. 2007 – end 2008
- Raw exposure: ~ 600 kg days
- Analysis threshold: 10 keV
- Main analysis steps:
  - Determine position dependent calibration/timing performance
  - Remove periods with bad detector performance
  - Remove multiple scatter & muon veto events
  - Remove surface events (timing)
  - Expected background: 0.8 (surface) events + 0.1 (neutrons)
- 120 kg days after cuts
- 2 events observed!

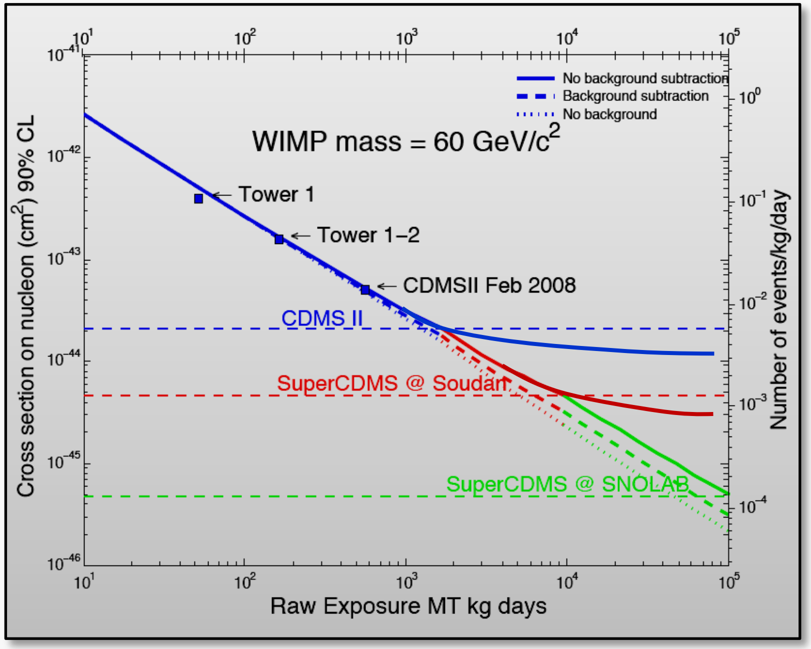
Poisson probability for 2[0.9]: 23 %
WIMP interaction cannot be excluded
BUT
NO significant evidence for WIMP signal

SuperCDMS at Soudan

- Increase thickness / mass of single module (1 cm, 230 g / module → 1 inch, ~ 630 g / module)
- New sensor designs
- First type (new phonon sensor design) tested at Soudan
- Second type (new electrode design) being installed for test
- Aiming for 10-15 kg total

→ Reduce background, increase exposure, gain x10 in sensitivity

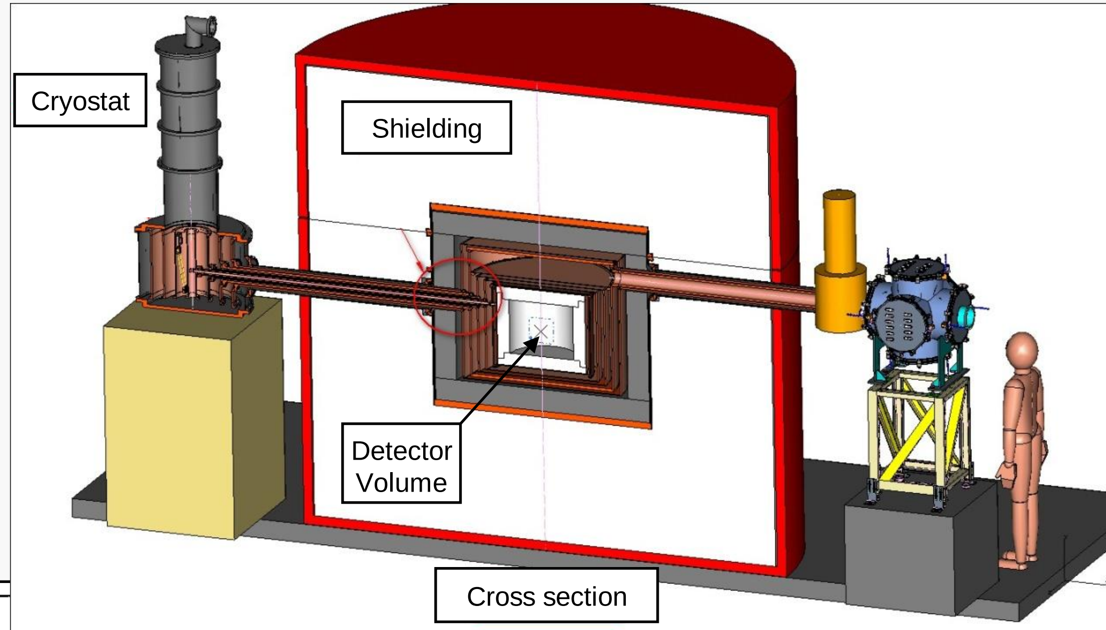


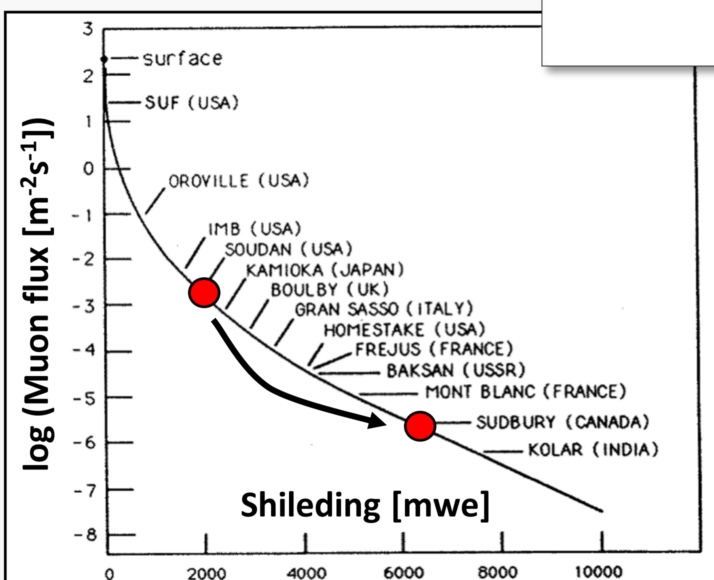


SuperCDMS at SNOLAB

Move to SNOLAB

- Less Cosmic radiation
- Cleaner environment
- Good infrastructure





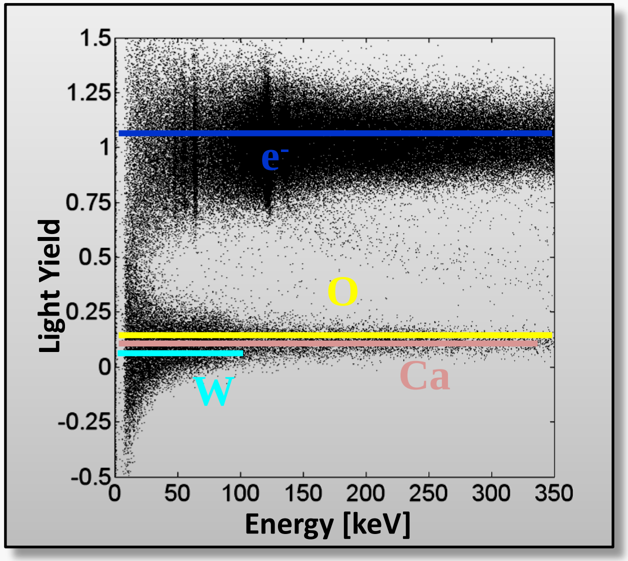
SuperCDMS Setup at SNOLAB (planned)

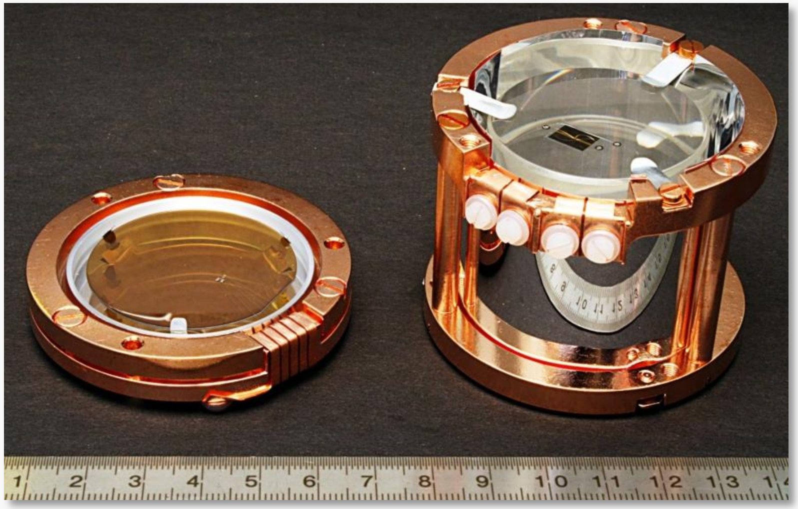
- Detector volume holds ~100 kg of active target
- Pb/Cu shielding against external radiation
- Increased PE shielding against neutrons
- Considering active neutron veto detector

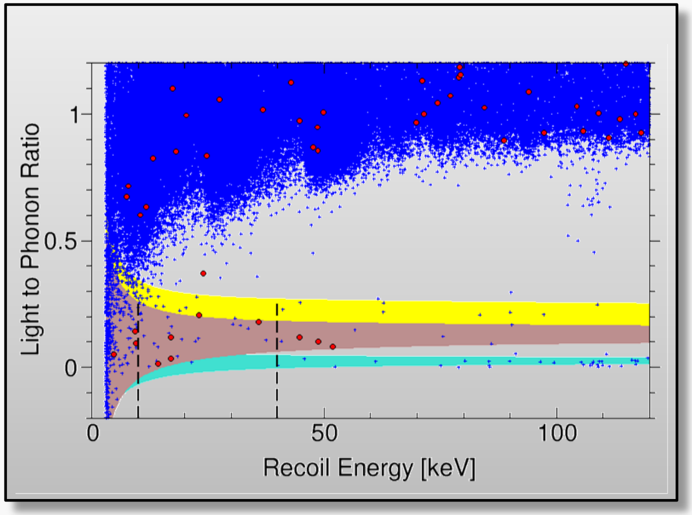
CRESST

Cryogenic scintillatior, $CaWO_4$ (Gran Sasso)

- ∅ = 4 cm, h = 4 cm, m = 300 g
- Thermal readout: TES
- Transition temperature: 7 – 15 mK
- Cryogenic light detector (Al_2O_3/Si)
- Reflective housing
- Setup holds up to 10 kg
- Presently 9 detectors (~ 3 kg) running, 120 kg d collected



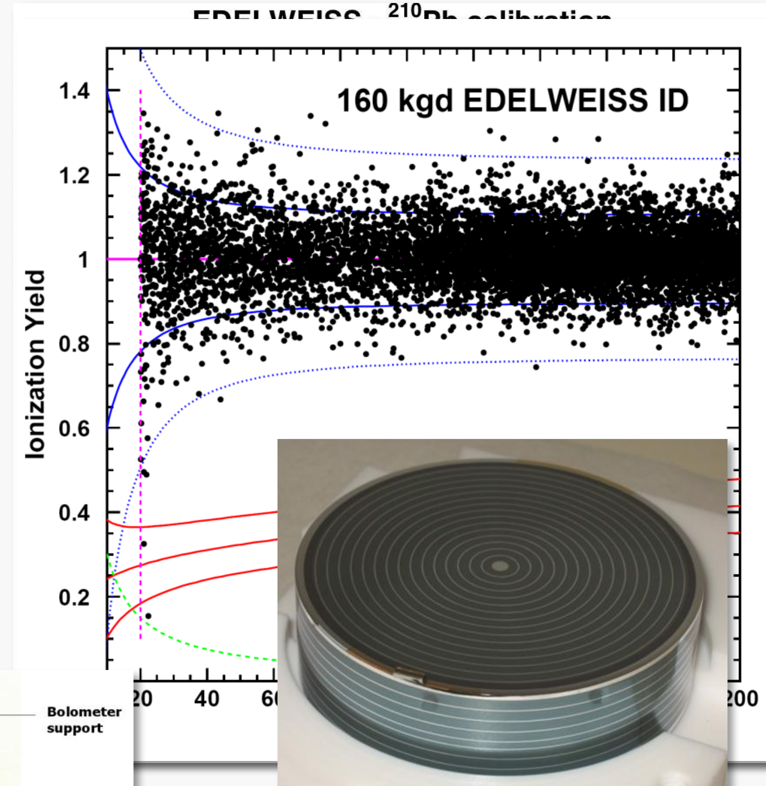


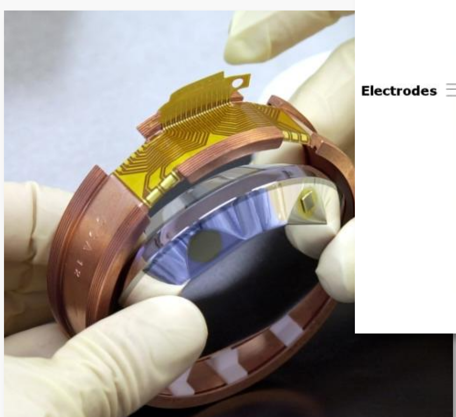


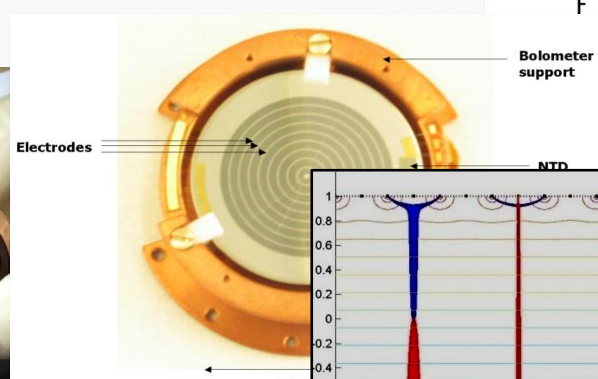
EDELWEISS

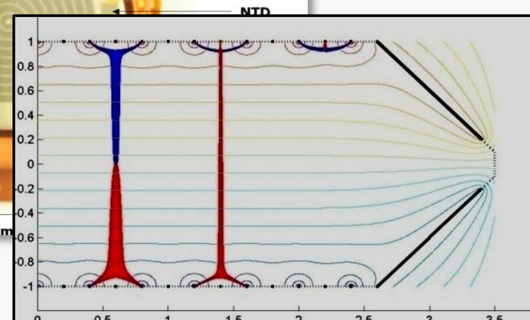
Cryogenic detectors, Ge (Modane)

- ∅ = 7 cm, h = 2 cm, m = 320 g
- Thermal readout: NTD
- Operation temperature: 15 – 20 mK
- 93 kg d, 3 background events
- New detectors with different electrode concept to remove surface events
- Very good performance
- Considerable improvement: 160 kg d, 1 event
- ~800 g detectors operational







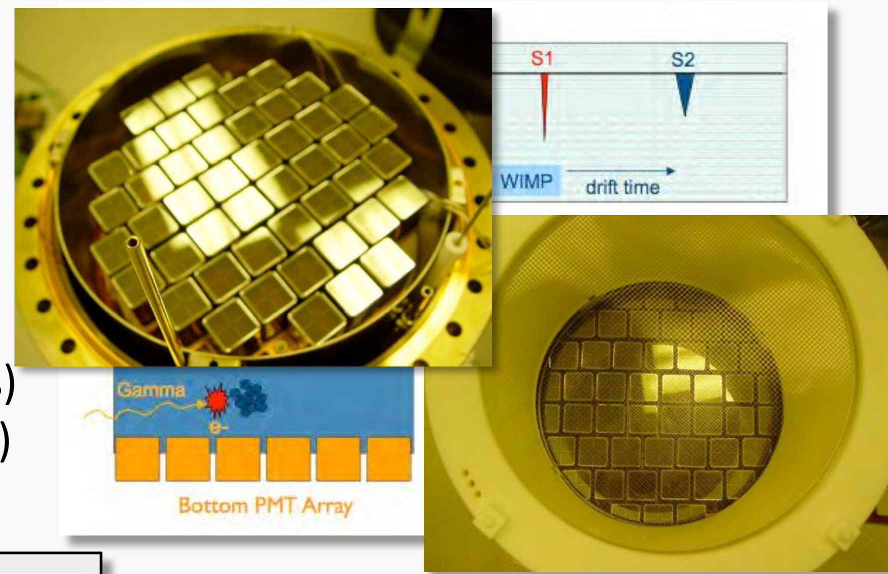


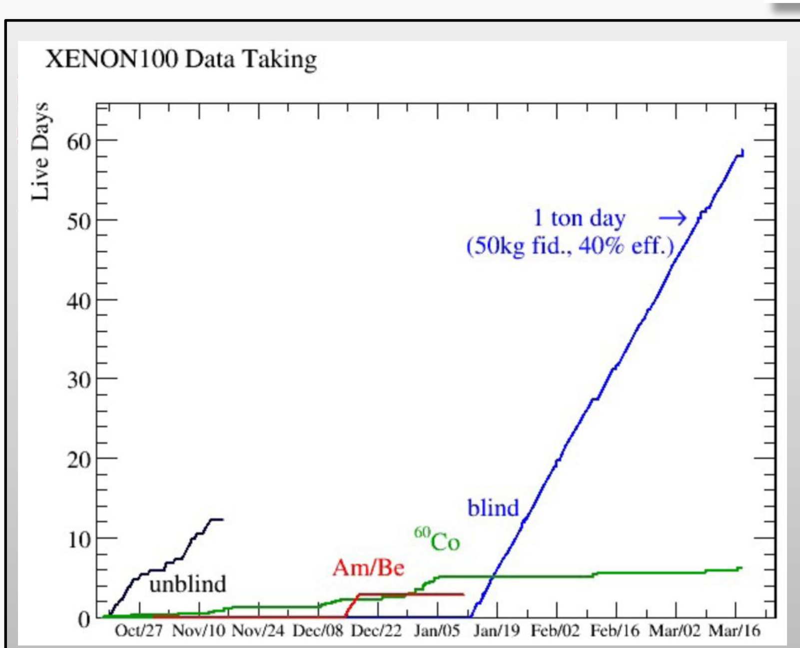
Evidence
Candidates
Indirect Detection
Direct Detection
Conclusion

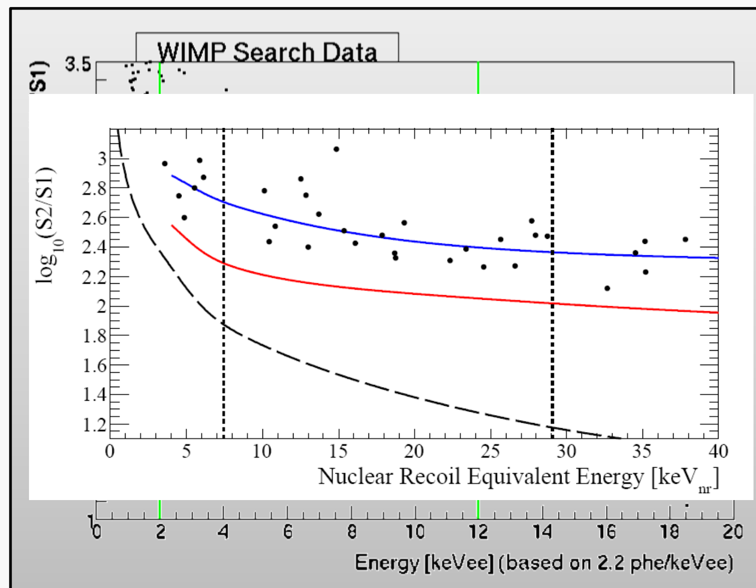
XENON

Liquid Xenon (Gran Sasso)

- Scintillation and ionization (drift electrons to surface, produce secondary scint. in gas phase)
- Good position reconstruction
- 1st phase: 10 kg (320 kg d, 10 evts)
  2nd phase: XENON100 (~50 kg fid)
  160 kg d, no events



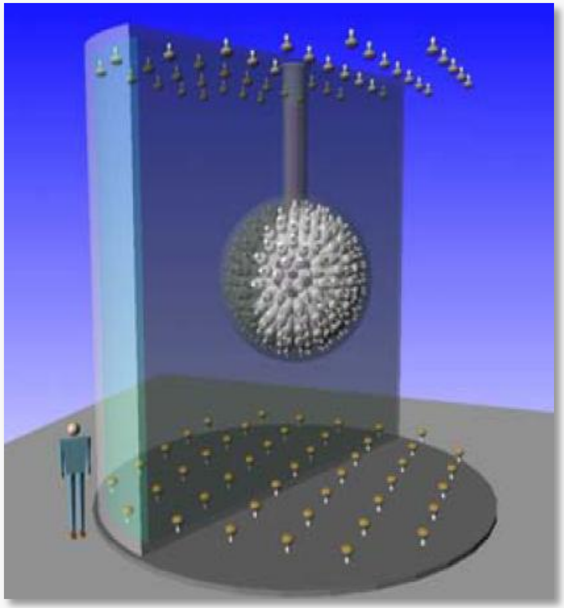


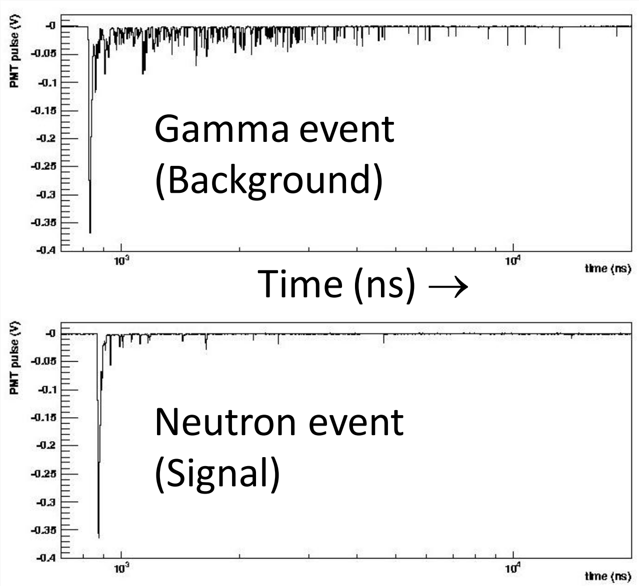


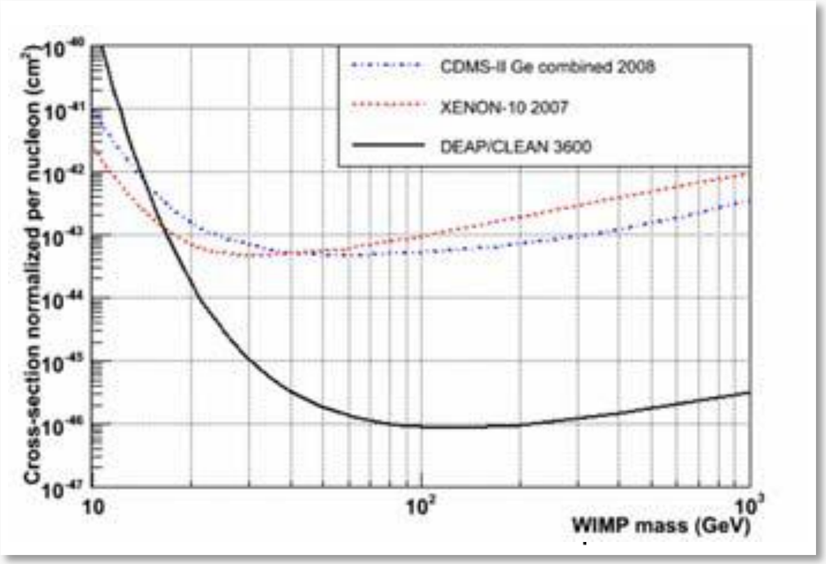
DEAP

Liquid Argon (SNOLAB)
(Dark matter Experiment with Ar using PSD)

- Total target mass 3600 kg (1000 kg fiducial)
- Pulse Shape analysis for background suppression
- 7 kg prototype operating
- Full scale is funded
- Installation at SNOLAB started in 2009
- Final sensitivity: ~10^{-10} pb





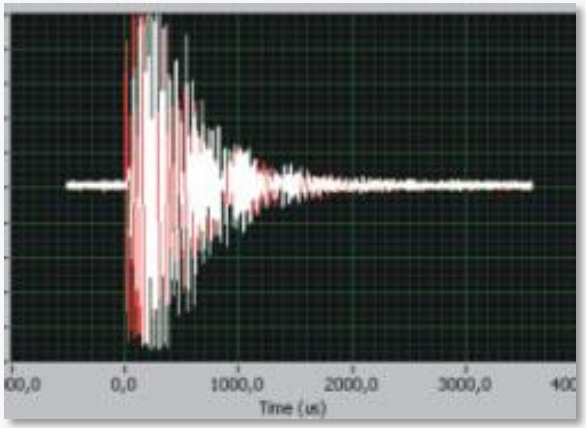


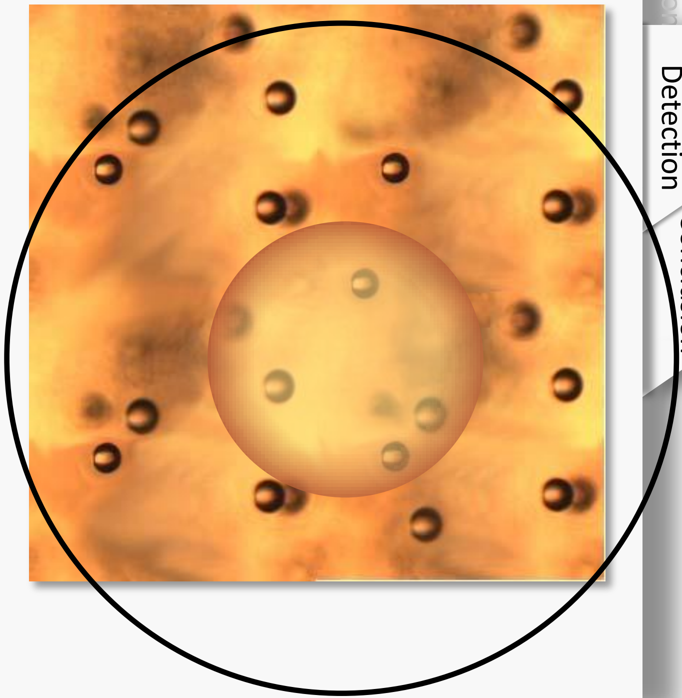
Evidence
Candidates
Indirect Detection
Direct Detection
Conclusion

PICASSO

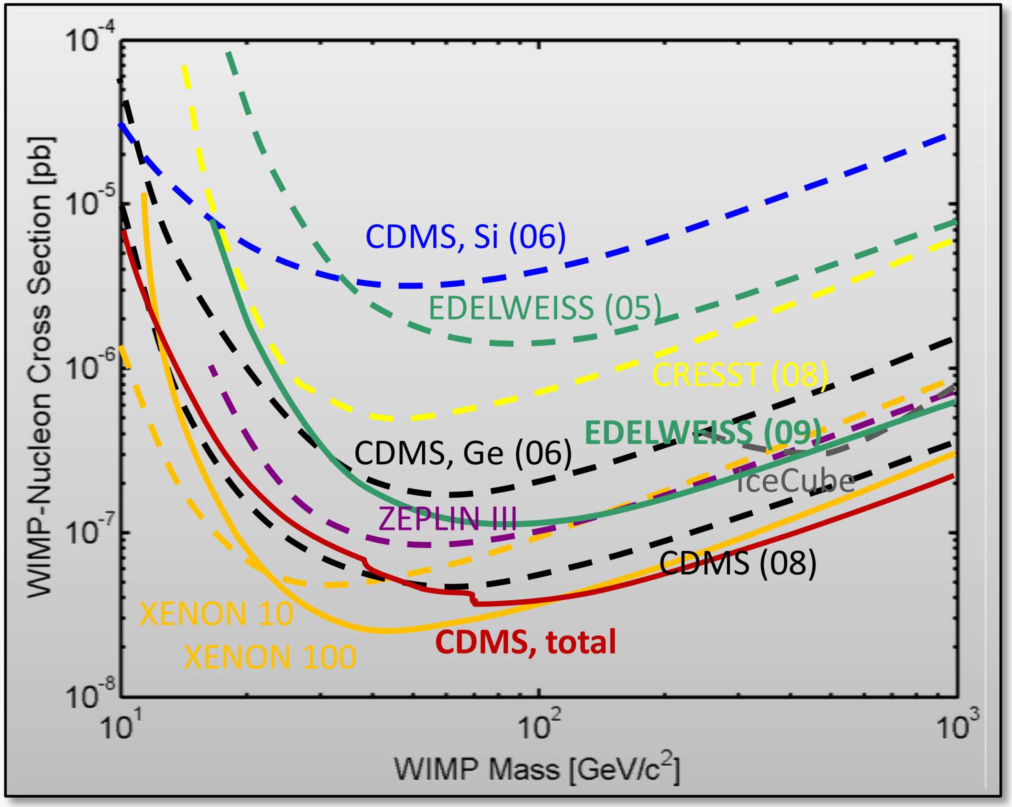
Superheated Freon (C_4F_{10}) droplets (SNOLAB) in a gel matrix; 2.6 kg (32 det)

- Droplets evaporate if energy is deposited
- Only nuclear recoils (and alphas) can evaporate droplets
- Acoustic readout
- Sensitive to spin-dependent interaction





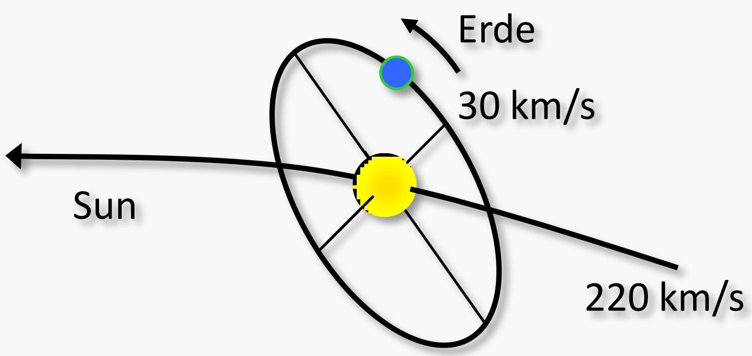
Results

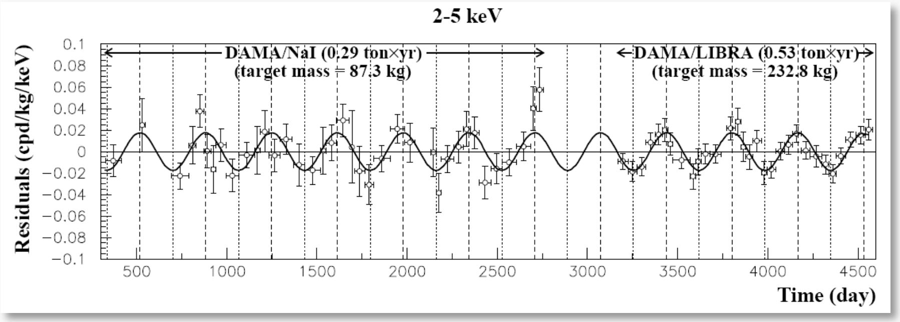

WIMP-Nucleon Cross Section [pb]
WIMP Mass [GeV/c^2]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^1
10^2
10^3
CDMS, Si (06)
EDELWEISS (05)
CRESST (08)
EDELWEISS (09)
CDMS, Ge (06)
IceCube
ZEPLIN III
CDMS (08)
XENON 10
XENON 100
CDMS, total

DAMA/LIBRA

NaI scintillator, 250 kg

- Gran Sasso
- Data: 7 years (1995-2002), 100 kg (DAMA)
  + 6 years (2003-2009), 250 kg (LIBRA) , 1.17 t y
- Obvious oscillation of the rate, correct phase
- Interpretation controversial

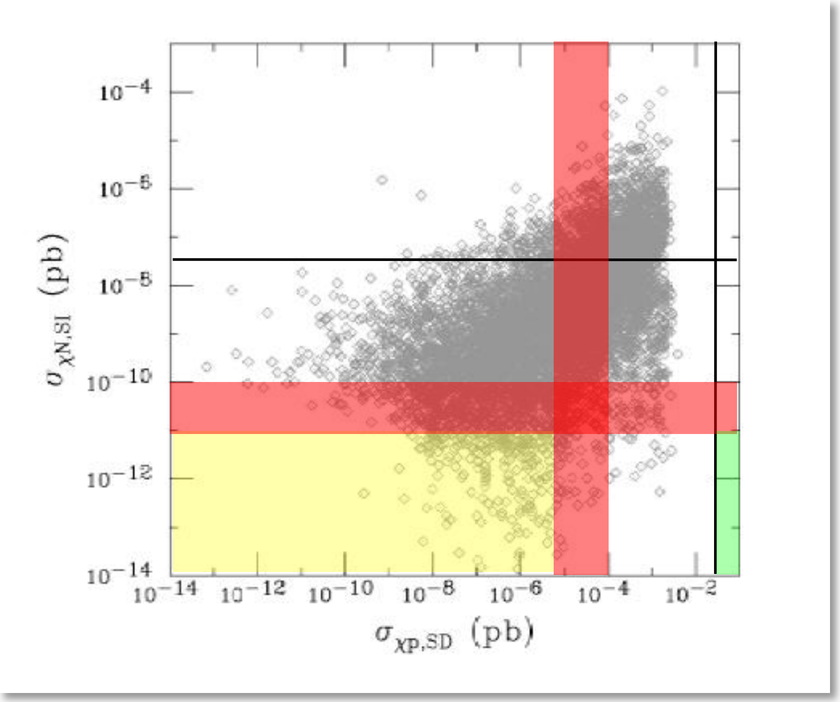




Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere	$<0.2\%\ S_m^{obs}$
TEMPERATURE	The installation is air-conditioned	$<0.5\%\ S_m^{obs}$
NOISE	Effective noise rejection	$<1\%\ S_m^{obs}$
ENERGY SCALE	Periodical calibrations + continuous monitoring of ^{210}Pb peak	$<1\%\ S_m^{obs}$
EFFICIENCIES	Regularly measured by dedicated calibrations	$<1\%\ S_m^{obs}$
BACKGROUND	No modulation observed above 6 keV; this limit includes possible effect of thermal and fast neutrons	$<0.5\%\ S_m^{obs}$
SIDE REACTIONS	Muon flux variation measured by MACRO	$<0.3\%\ S_m^{obs}$

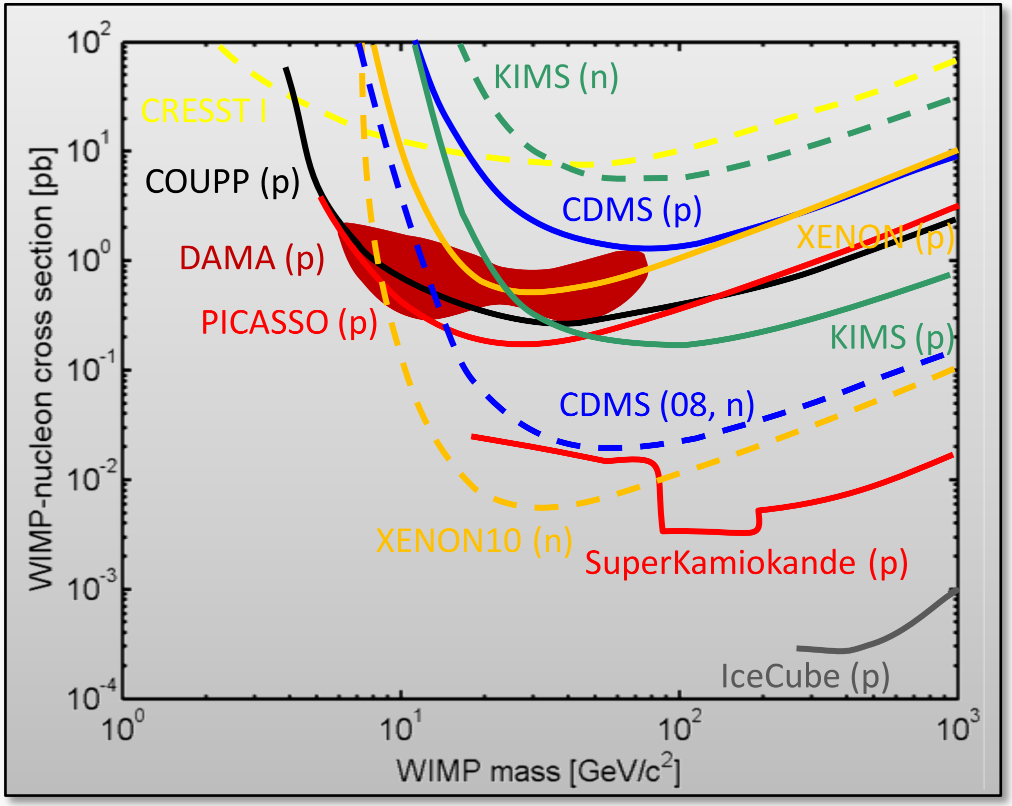
Results – Spin Dependent

Interaction cross section may depend on spin!



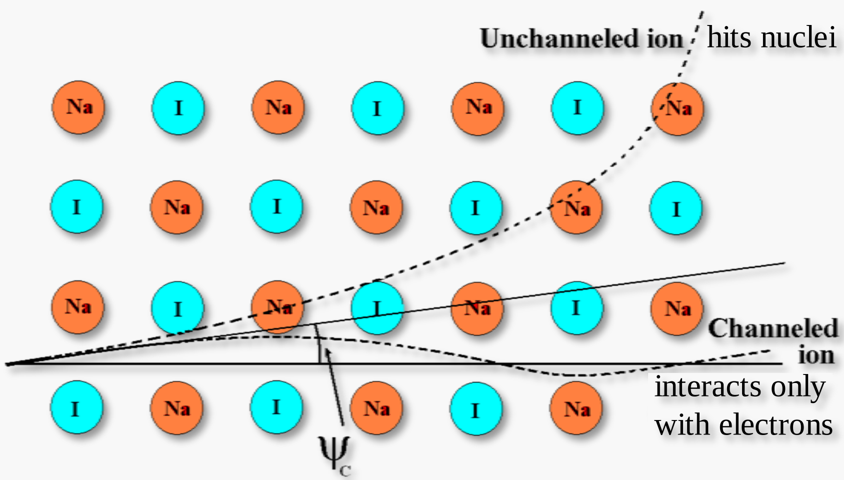
SUSY example

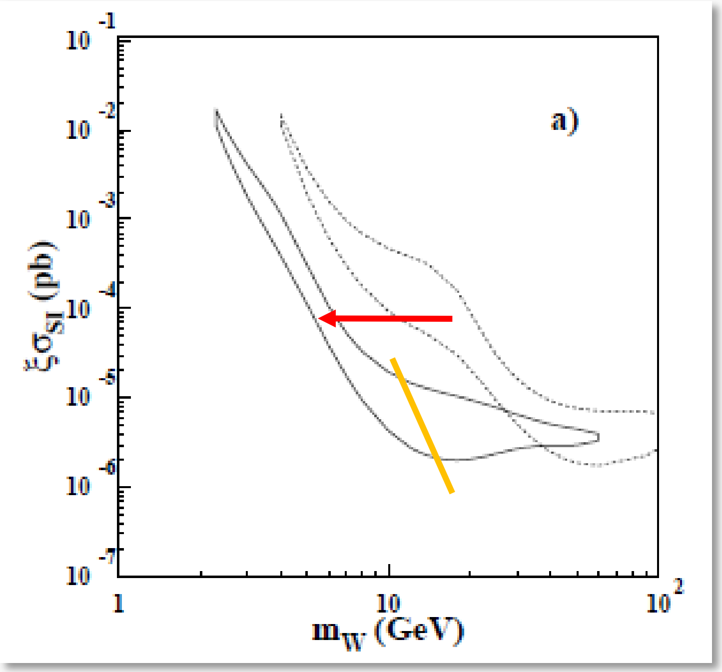
Results – Spin Dependent



Alternative Explanations

Channelling



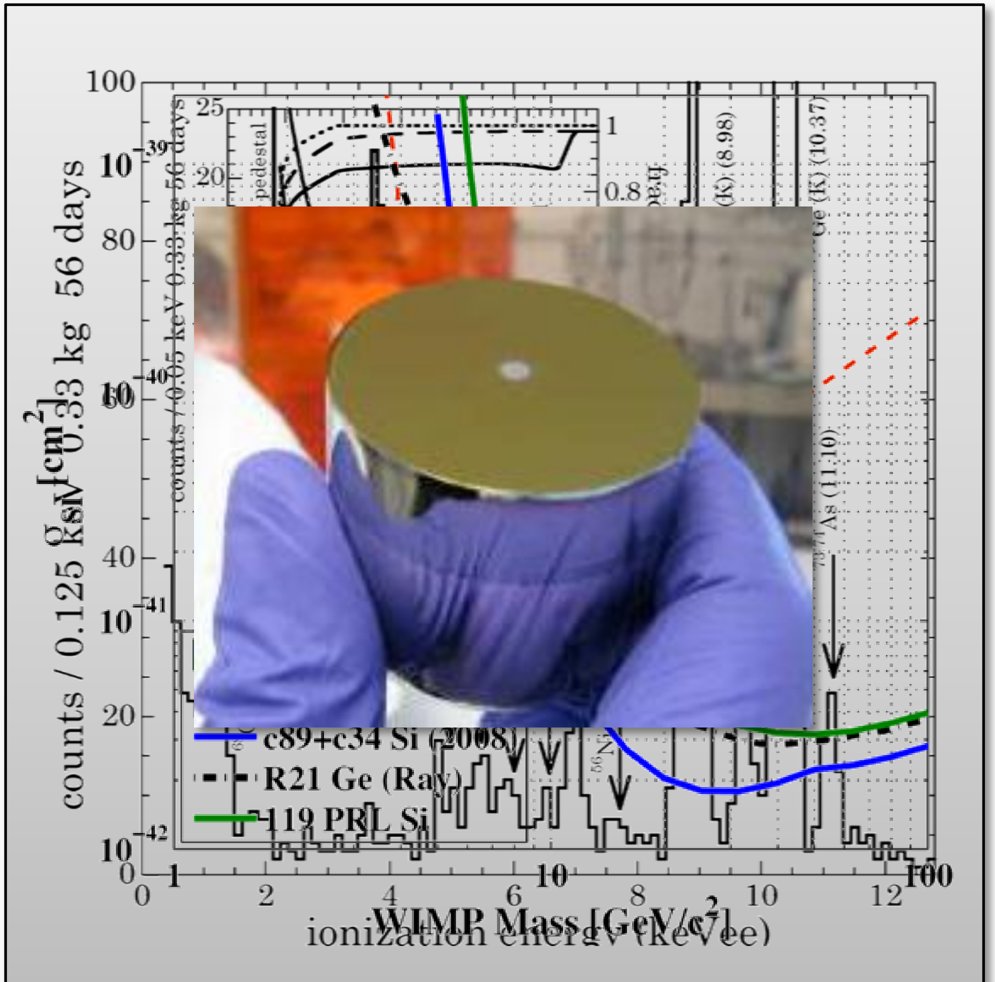


→ Channelled ions do not quench
→ Energy scale for NR equal to ER
→ Allowed signal region moves to lower masses

- Channelling model not fully worked out, effect probably (much?) smaller
- No indication for channelling in CDMS (needs more careful analysis!)
- Some experiments are starting to explore low mass region (CoGeNT, TEXONO, CDMS)

CoGeNT

Evidence for Dark Matter?

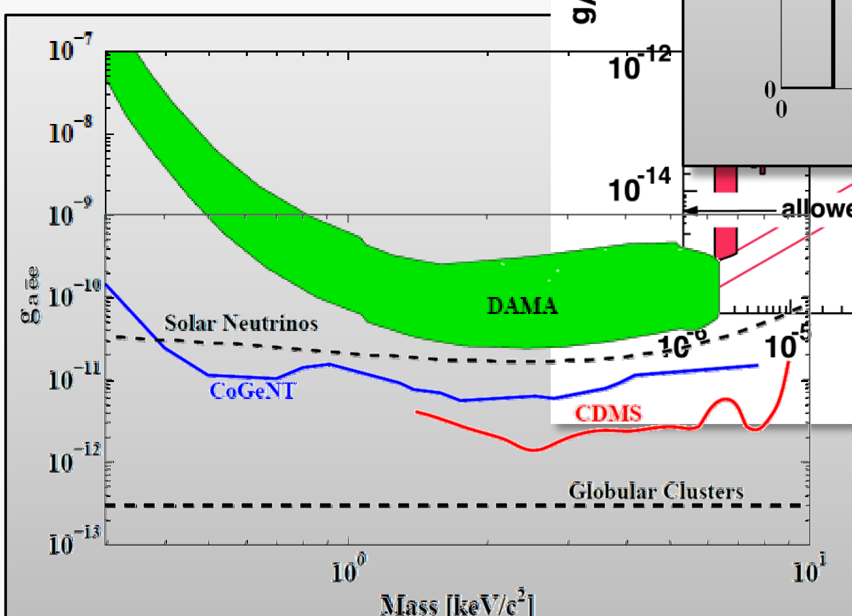


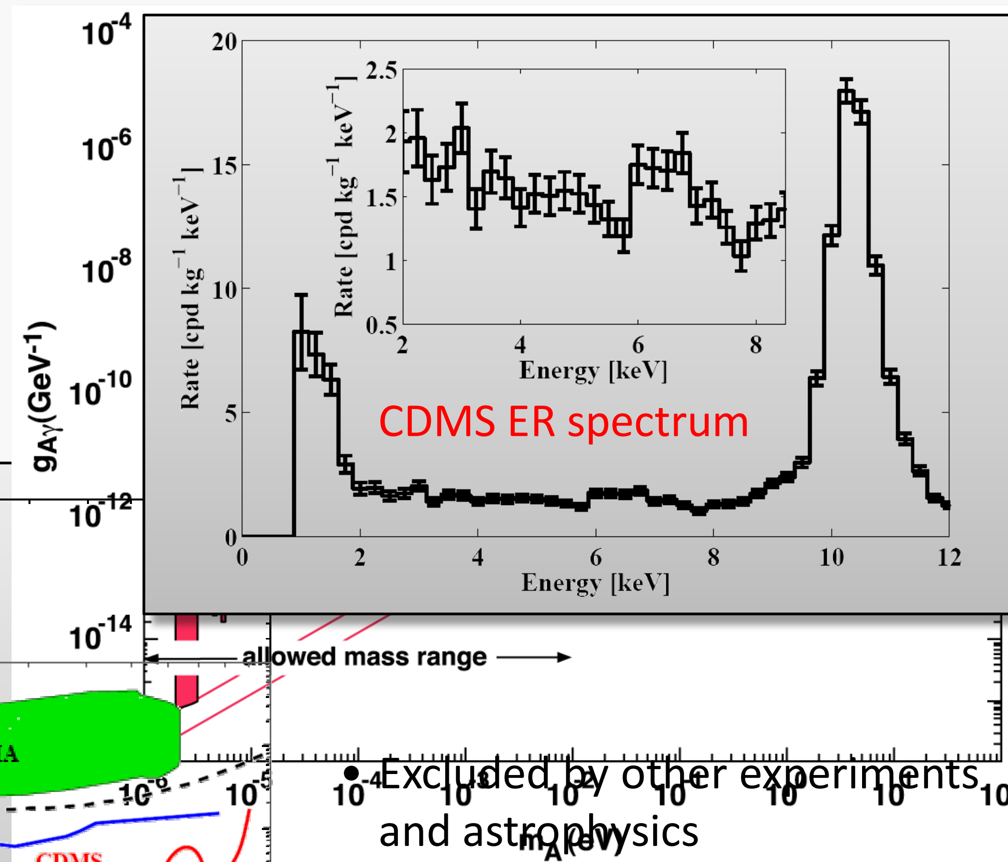
- Low threshold high resolution Ge detector
- Ultra low background
- No discrimination
- Observe rise in spectrum at low energy
- χ^2/dof for 'no WIMP' hypothesis: 20.4/20
- Claim that fit with WIMPs is better (give example for fit with χ^2/dof = 20.1/18)
- Show preferred region
- Tension with CDMS Si data (PhD thesis by J. Filippini, no paper published yet)

Alternative Explanations

Axion-like particles

- Axion-like particle could couple to electrons via the axio-electric effect
- Would see peak at Axion mass energy
- Best fit to DAMA data: 3.2 keV





- Excluded by other experiments and astrophysics
- Would not produce modulation (σ independent of velocity!)

Alternative Explanations

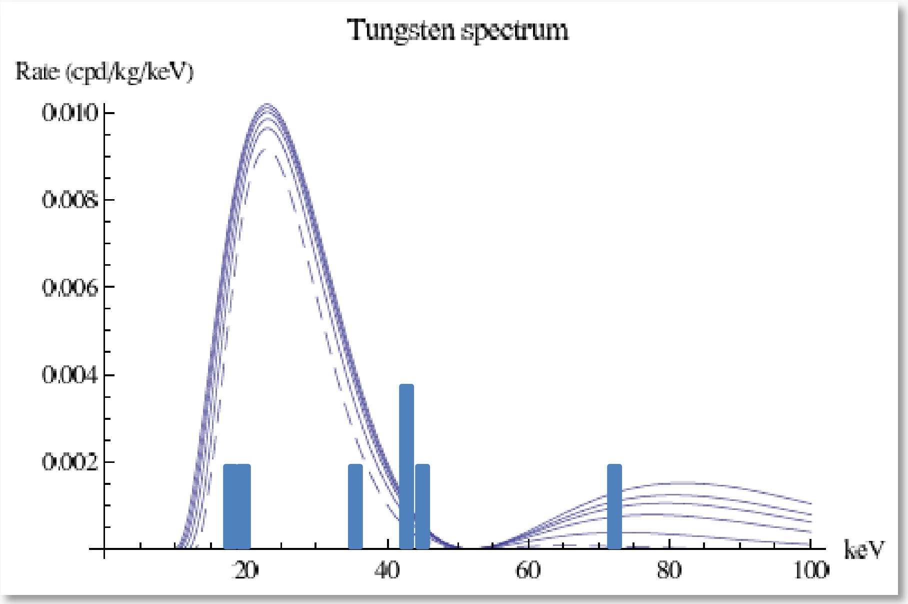
Electron-interacting dark matter

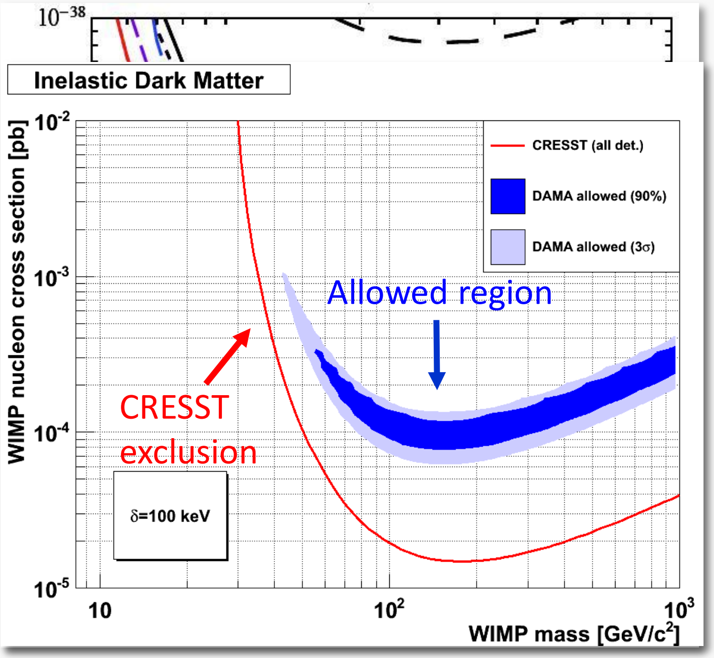
- Dark matter particle cannot transfer significant energy to electron at rest
- **BUT:** some electrons in atom have high momentum $\rightarrow$ keV energies possible
- Needs a more careful study of other experiments (CDMS has rather low ER background, but energy transfer in Ge might be lower than in Iodine)

Alternative Explanations

Inelastic dark matter

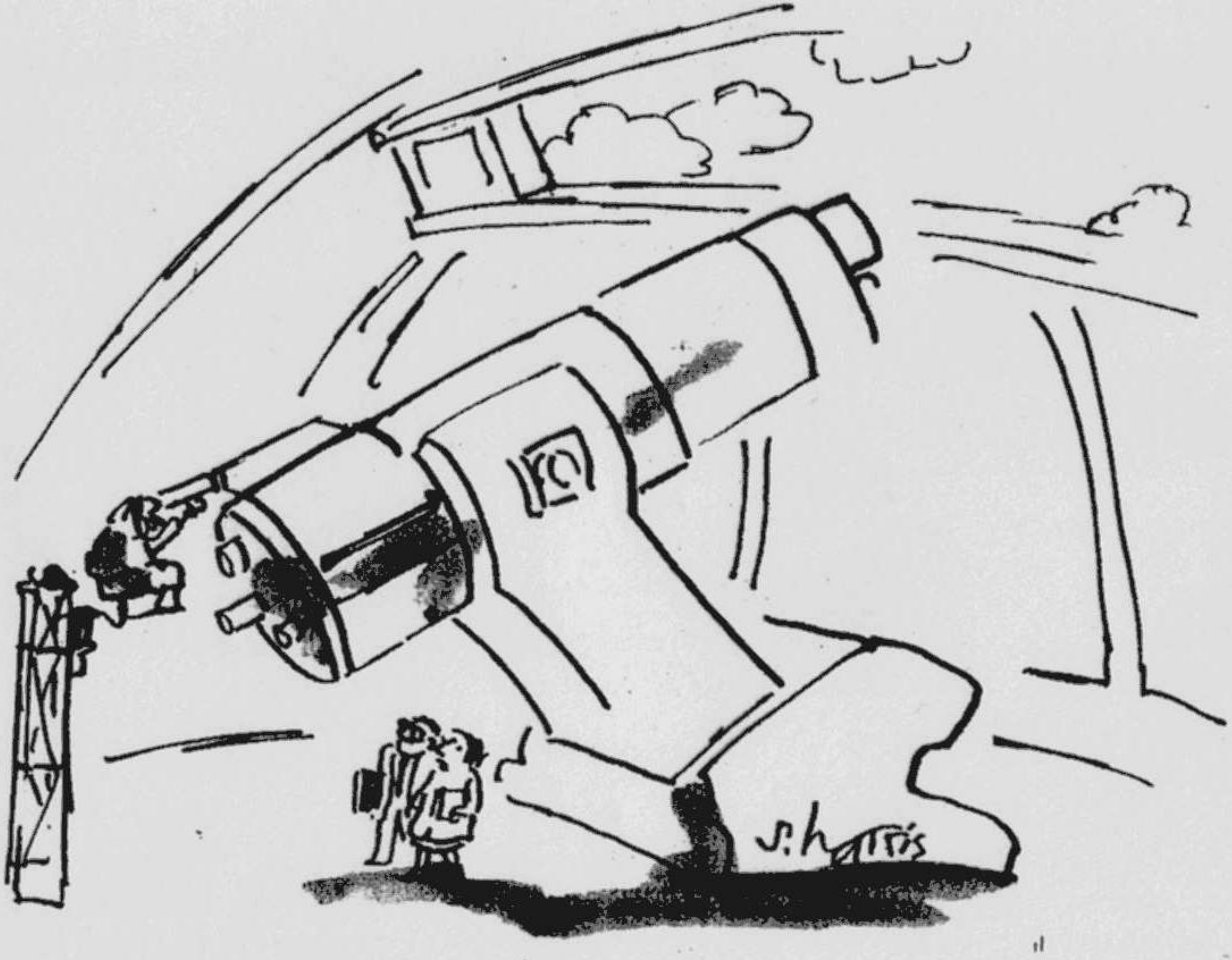
- WIMP has low energy (~100 keV) excited state
- Lead to large oscillation fraction (up to 100 % instead of only a few % for standard WIMP interactions
- Makes it more difficult for some other experiments to detect
- High mass nuclei are more sensitive, e.g. Win CRESST





Conclusion

- The Dark Matter problem is one of the most compelling problems in present day fundamental science
- Need to find what 85 % of the matter in the universe is
- WIMPs are prime candidates for Dark Matter
- Indirect detection via annihilation products from space
- Direct detection via nuclear recoils in terrestrial detectors
- Low rate expected – background reduction is essential
- Need to go underground
- No convincing signal has been found yet
- Controversial claim by DAMA/LIBRA (inconsistent with other experiments under most reasonably assumptions, some still need testing/analysis)
- Sensitivity of experiments is reaching interesting range
- First ton scale experiments are being build



"DR. GRUBER IS CONVINCED THAT IF DARK MATTER IS REALLY DARK, IT SHOULD BE VISIBLE IN THE DAYTIME."