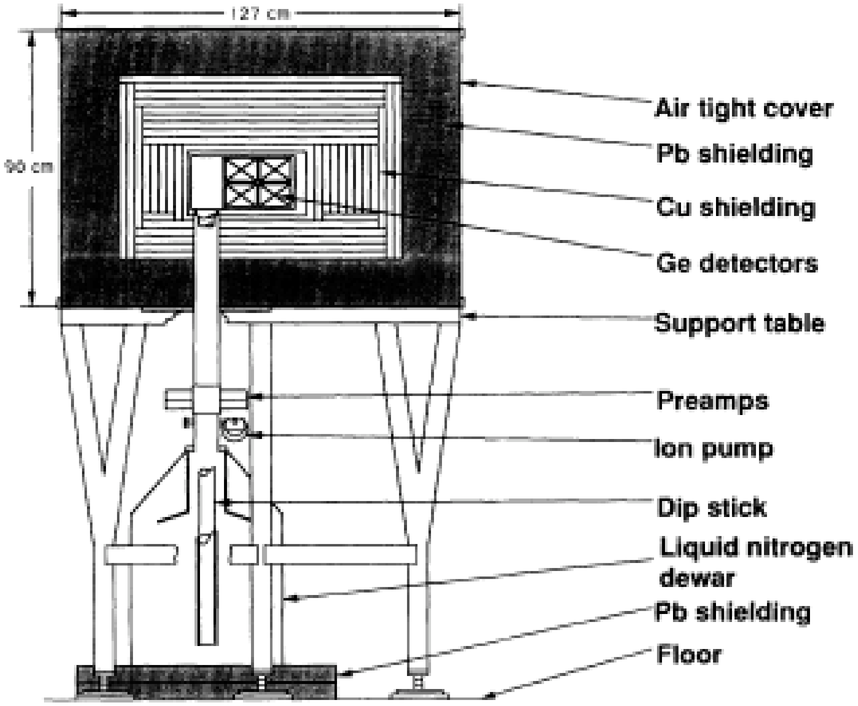


FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.

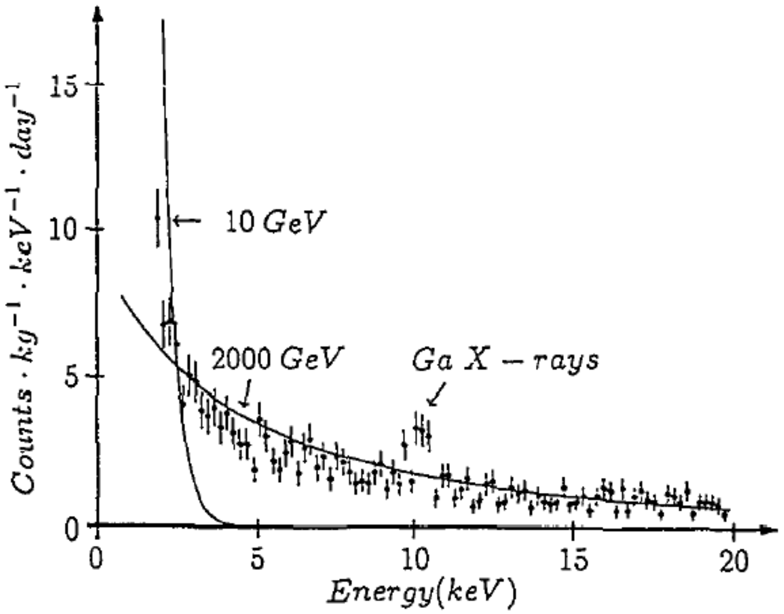


Figure 4: The low energy spectrum of our best crystal, from 1662 hours of data (live time, 51.6 kg days). The peak at 10.37 keV is due to Ga X-ray emission after electron capture in ^{68}Ge. Also shown are the expected recoil spectra for Dirac neutrinos of mass 10 and 2000 GeV.

Bangs and Bumps: looking for dark matter in our neighborhood

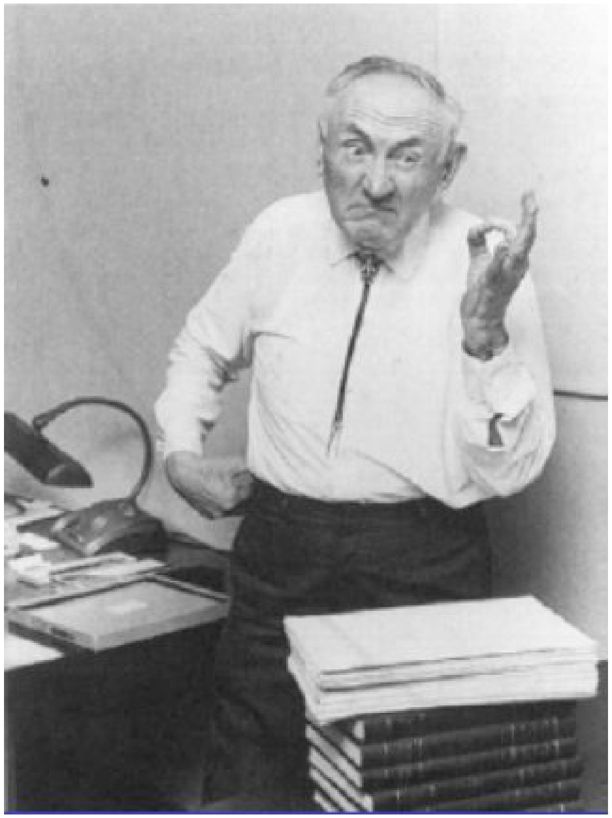
Peter Fisher

Aug. 17, 2006

Outline

- A word about “dark matter” and “relics” and an example particle
- Bumps: nuclear recoil
  - Cosmological relics - Example: Dirac neutrino
  - Spin dependent interactions - Example: Majorana neutrinos
- Bangs: annihilation
- Bumps and Bangs: terrestrial and solar capture

A word about "dark matter"…

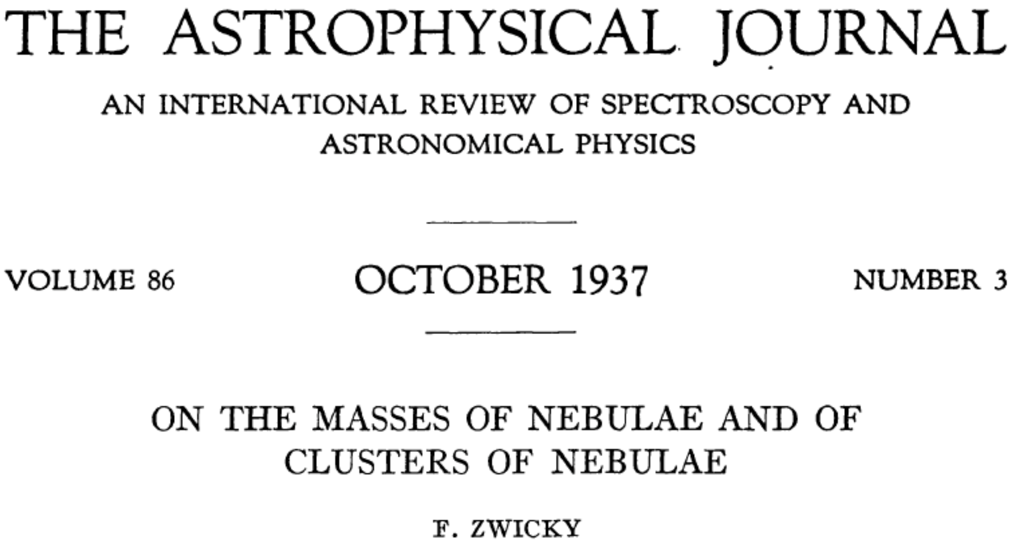


Fritz Zwicky (1933): Galactic dynamics

- Rotation curves
- Cluster infall velocities
- Perpendicular velocities
- Gravitational lensing

By "Dark Matter", I mean

- ρ_g=0.15-0.60 GeV/cm^3
- No strong or EM interactions
- V_o=250 km/s



THE ASTROPHYSICAL JOURNAL

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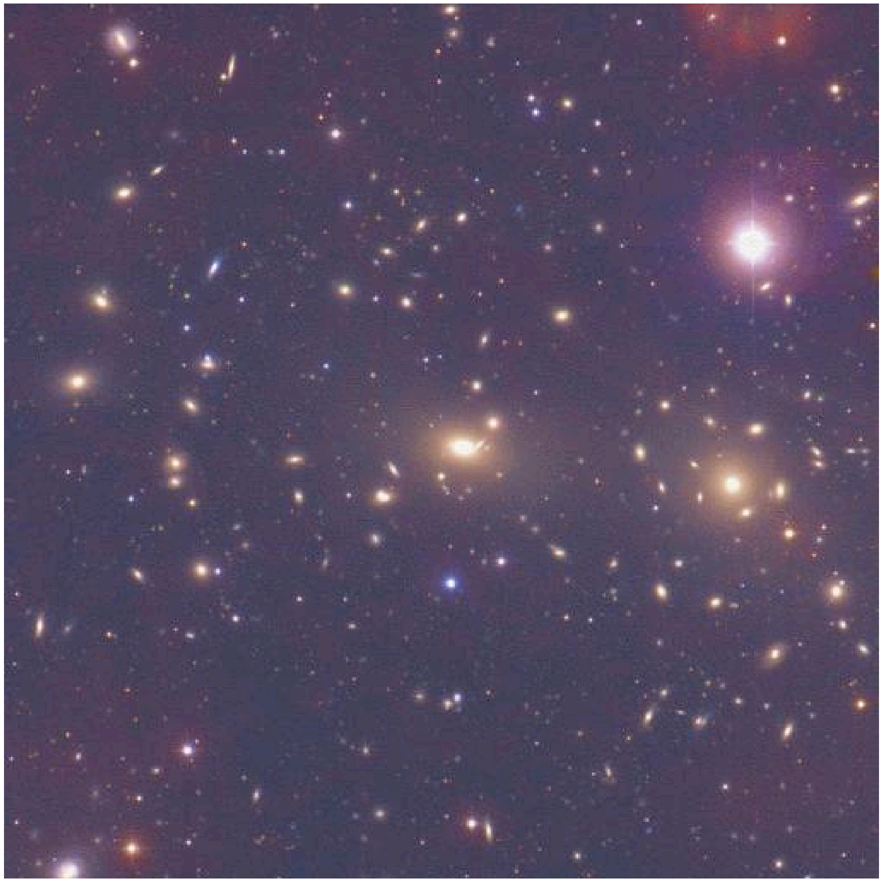
VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF
CLUSTERS OF NEBULAE

F. ZWICKY



Apply virial theorem to
Coma cluster of
"nebulae" (=galaxies) *i* :

$$G(t) = \sum_i \vec{p}_i \bullet \vec{r}_i$$

$$\left\langle \frac{dG(t)}{dt} \right\rangle = 0 = 2\langle T \rangle + \langle V \rangle$$

Apply to ~1000 galaxies of the Coma cluster:

$$M_{Coma} > \frac{3}{5}\frac{R\overline{\overline{v}}^2}{G}$$

R~600 kpc, characteristic radius

$v^2=5 \times 10^{15}\,cm^2/s^2$, time & space averaged velocity

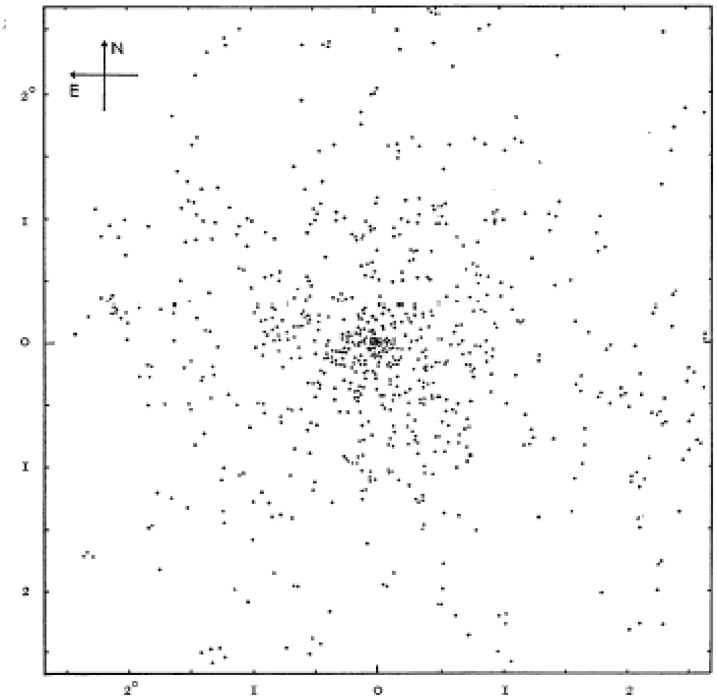
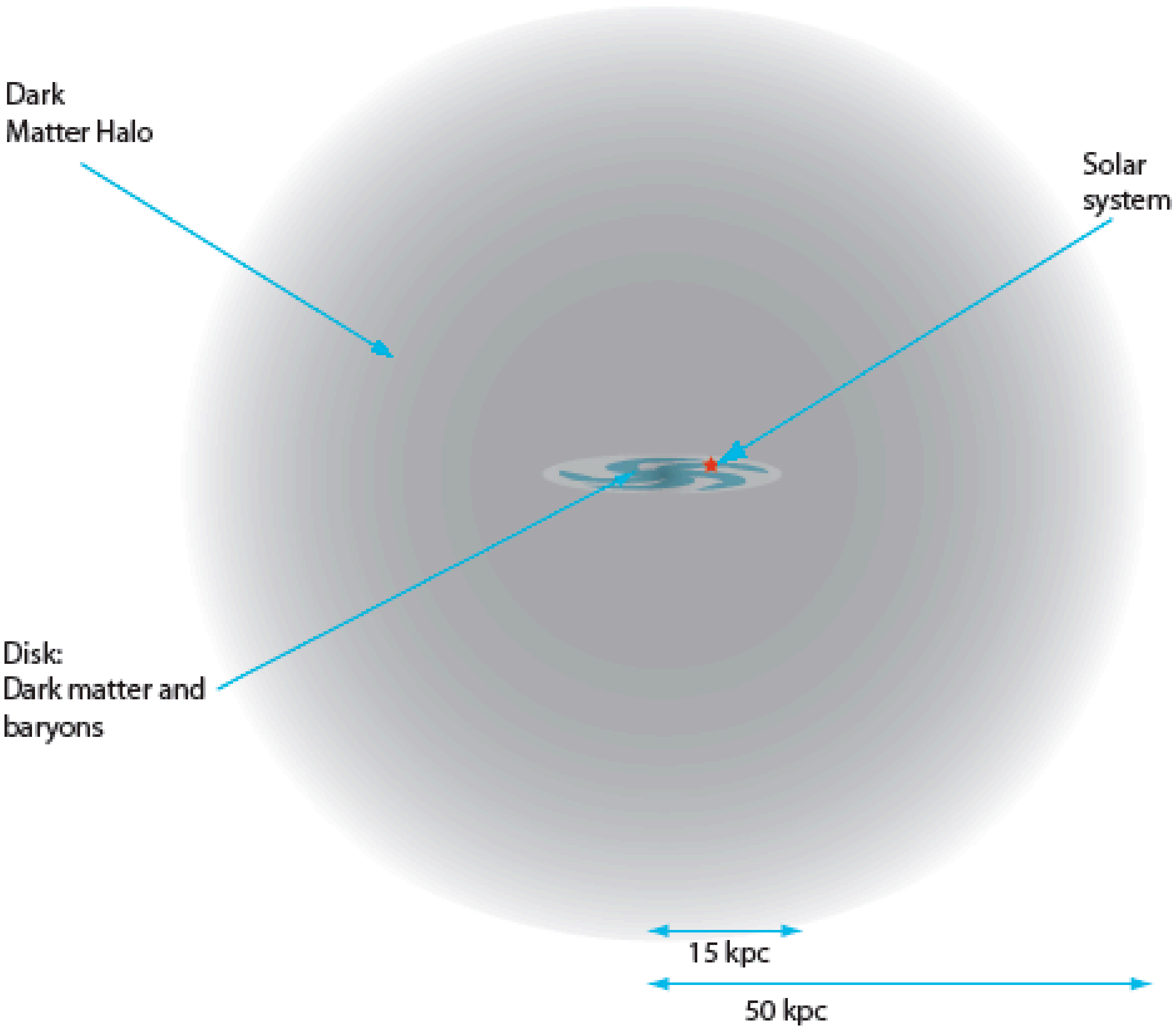


FIG. 3.—The Coma cluster of nebulae

$$\left.\begin{aligned} M_{galaxy} \sim \frac{M_{Coma}}{1000} = 4.5\times 10^{10}\,M_{Sun} \\ L \sim 8.5\times 10^{7}\,L_S \end{aligned}\right\} \rightarrow \gamma = 500$$

Luminosity conversion factor γ~3 for local stars



Contemporary picture:

Halo surrounding baryonic disk

- May be large variations of DM density
- May be bulk motion of DM in halo
- May be satellite halos

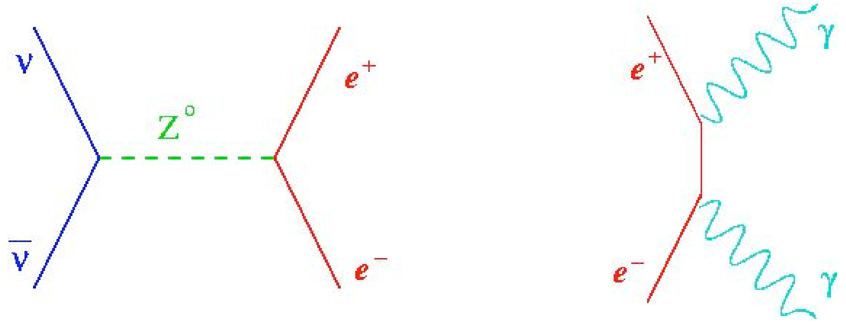
…and "relics"

Particles produced early in the Big Bang

- In equilibrium with photons when *T>>M*
- "Freeze out" (no change in total number of particles) when *T<<M*
- n_o depends on details of the theory
- Play no further role
- Known γ_{CMB}, ν_e, ν_μ and ν_τ
- Unknown *m*>1 GeV

Equilibrium between massive relics and photons before freeze out:

$$\nu + \bar{\nu} \leftrightarrow e^+ + e^- \leftrightarrow \gamma + \gamma$$



May be dark matter or part of dark matter

Example particle

For concreteness, will talk about fourth generation sequential neutrino and partner lepton

- Same couplings as ν_e, ν_μ and ν_τ
- MarkII/SLD/LEP measurements: $m_\nu > 45$ GeV
- Partner lepton heavier, $m_L > m_\nu$, neutrino stable
- Alternative: axions
  - Light, electromagnetic couplings

Relics

Estimates for stable relic particles (G.Borner, "The Early Universe: Facts and Fiction")

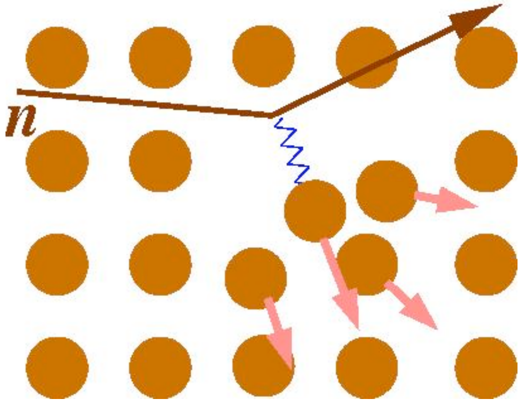
Particle	n_o (1/cm^3)	ρ_0 (GeV/cm^3)	T_f
Light ν	100	10^{-31} m(eV)	1 MeV
Heavy ν	10^{-4}GeV/m_ν^2	10^{-28} GeV/m_ν^2	0.05 m_ν
Charged leptons	10^{-10} GeV/m_L	10^{-34} GeV^2/m_L^2	0.03 m_L
Heavy hadrons	10^{-16} GeV/m_H	10^{-40}	0.02 m_H

Bumps: nuclear recoil experiments

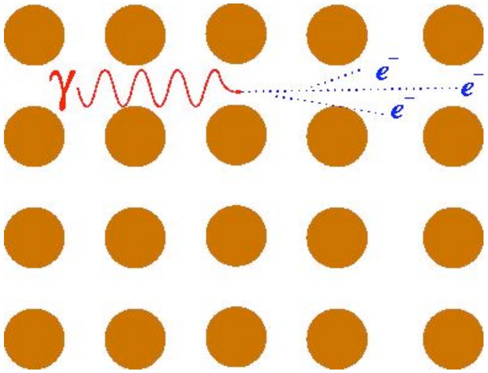
An extreme environment

Goal: create an instrumented region of matter free of terrestrial interactions.

Strong interactions



EM interactions

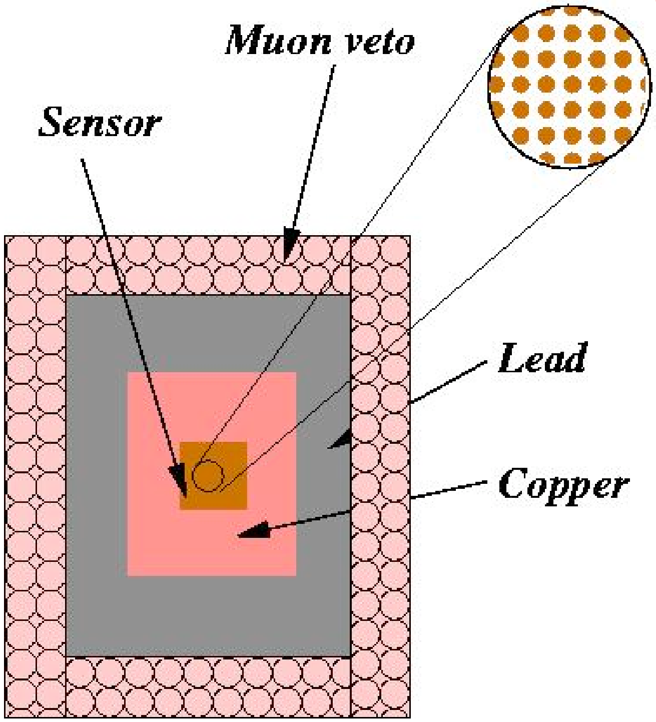


Example: crystal lattice.

Excitations:

- Ionization electrons, photons
- Phonons

Experiment

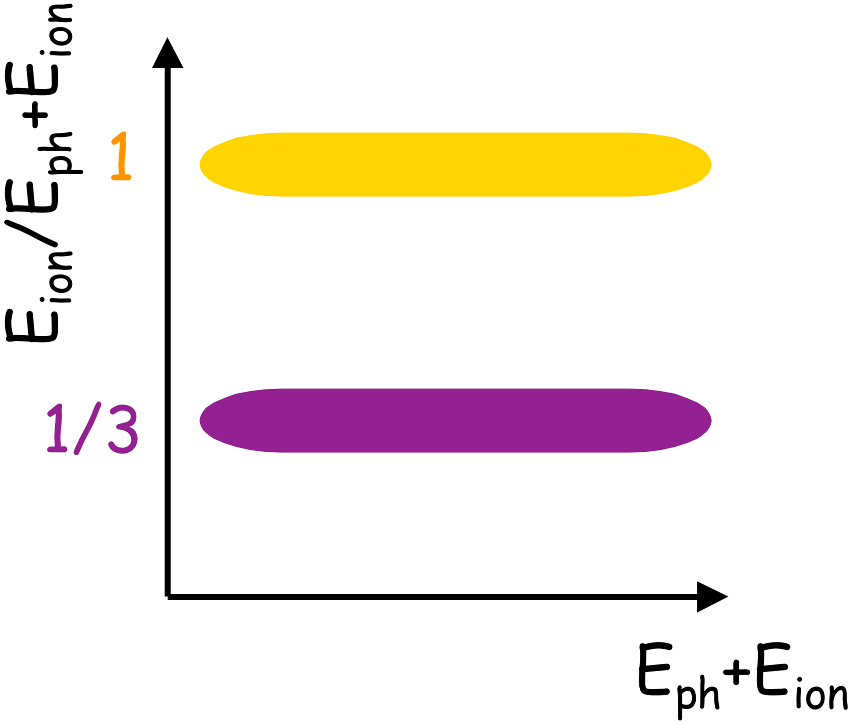


EM Shield:OHFC copper, Lead

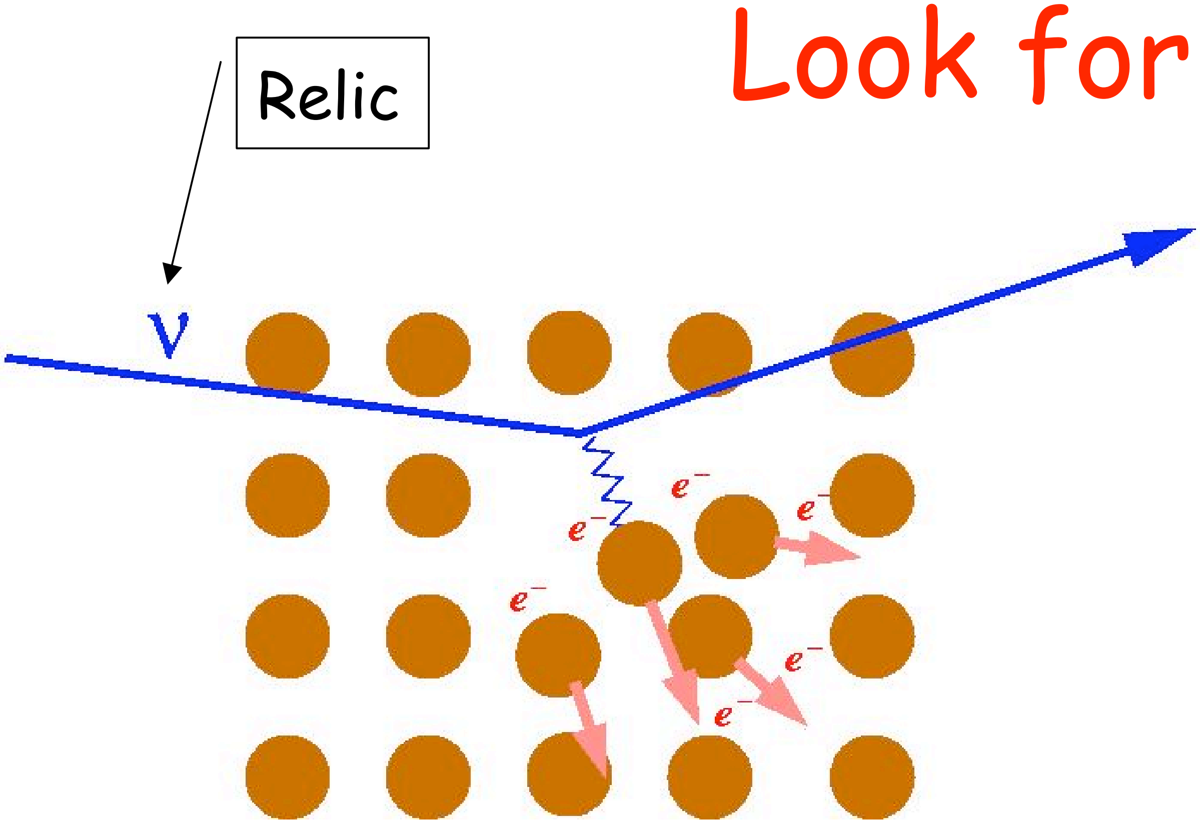
Neutron Shield: muon veto, Depth

Phonon shield : cold

Detection: discriminate between electrons, photons (EM only) and phonons (EM, strong)

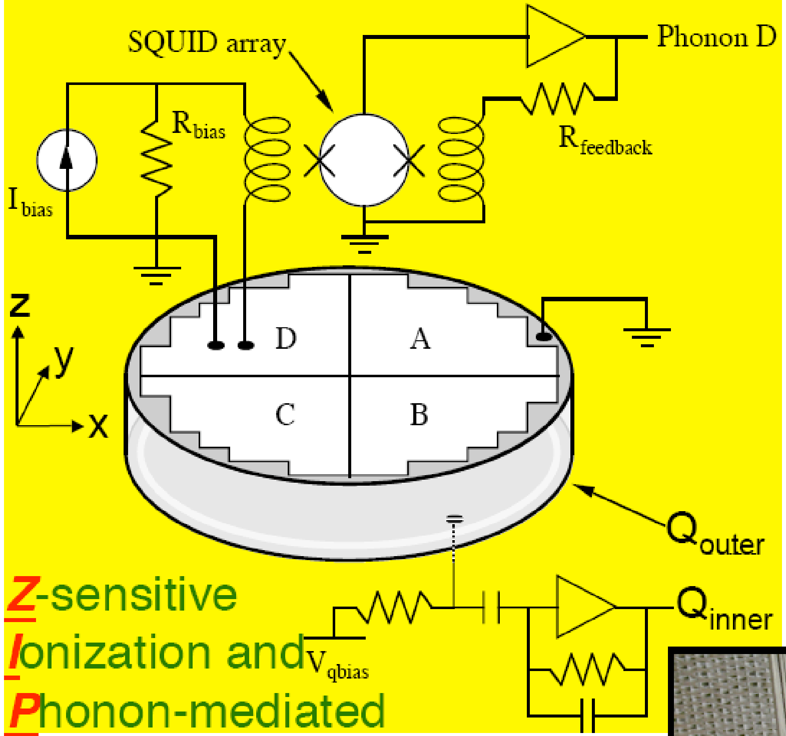


Look for



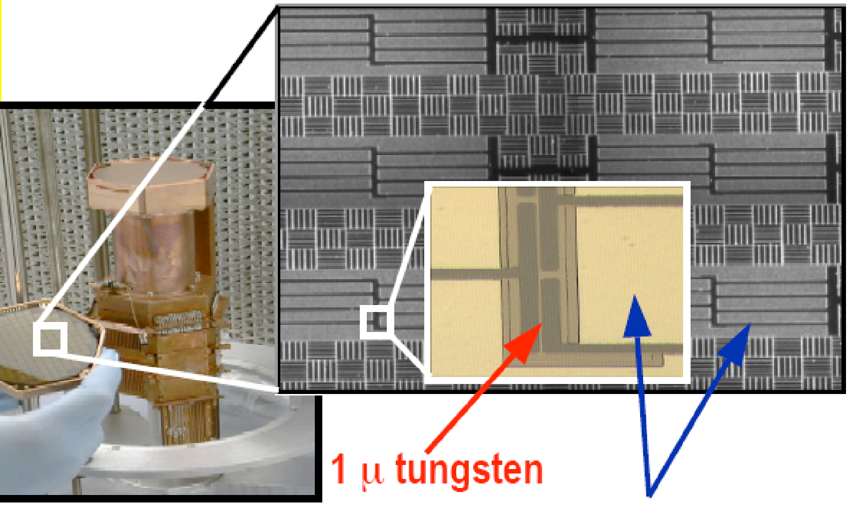
- M>50 GeV
- V_{ave}=250 km/s
- Maxwell-Boltzmann velocity distribution
- Spin?
- Coupling?
- Density?

CDMS (2004)



- 250 g Ge or 100 g Si crystal
- 1 cm thick x 7.5 cm diameter
- Photolithographic patterning
- Collect athermal phonons:
  - XY position imaging
  - Surface (Z) event veto based on pulse shape risetime

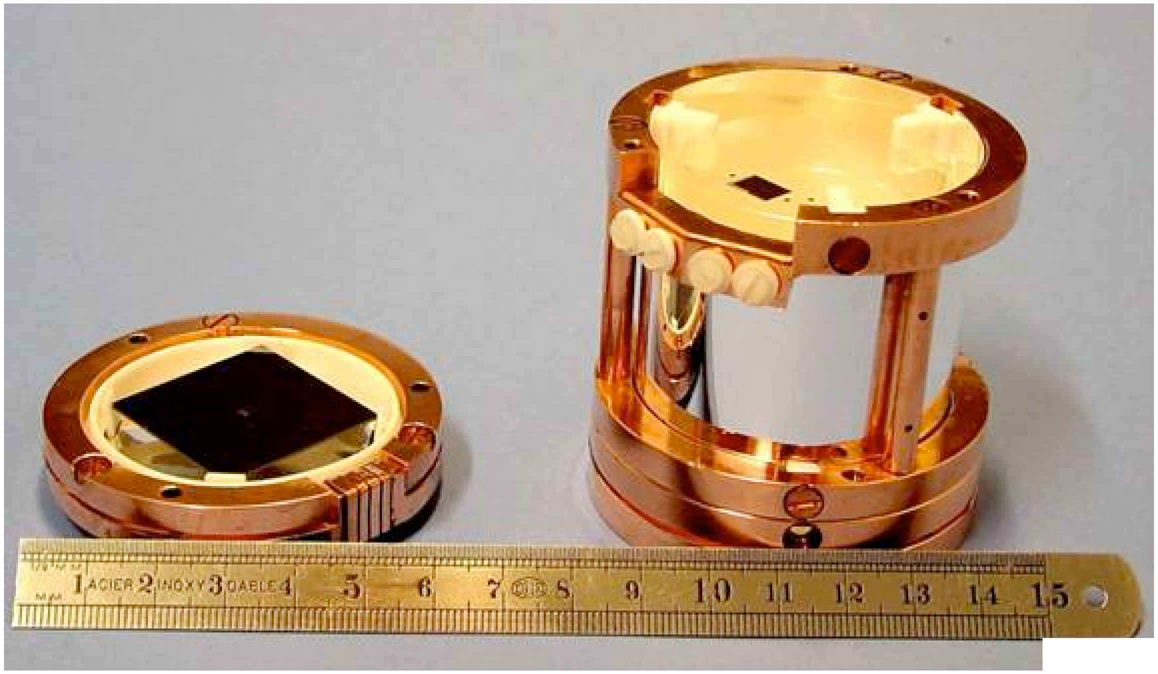
Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge



1 µ tungsten

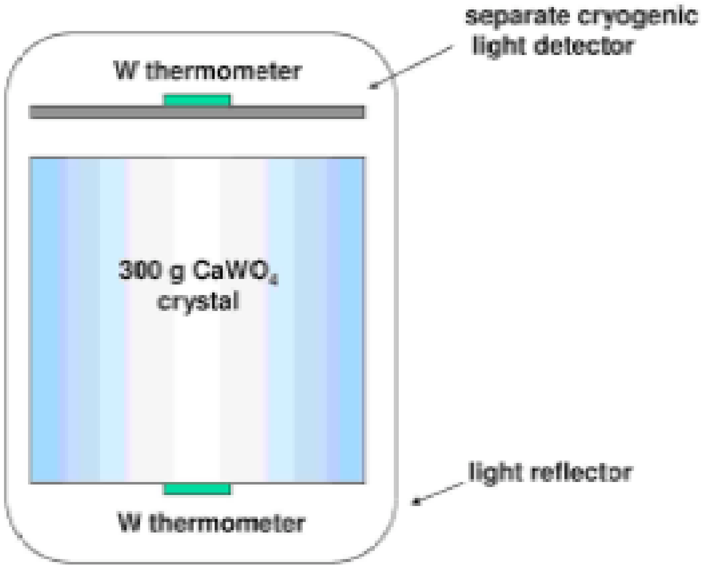
380µ x 60µ aluminum fins

CRESST

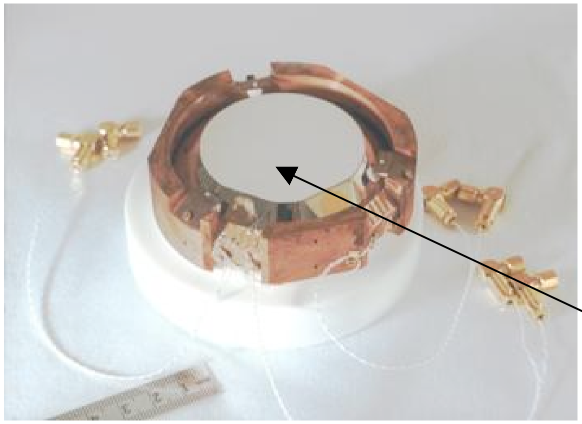


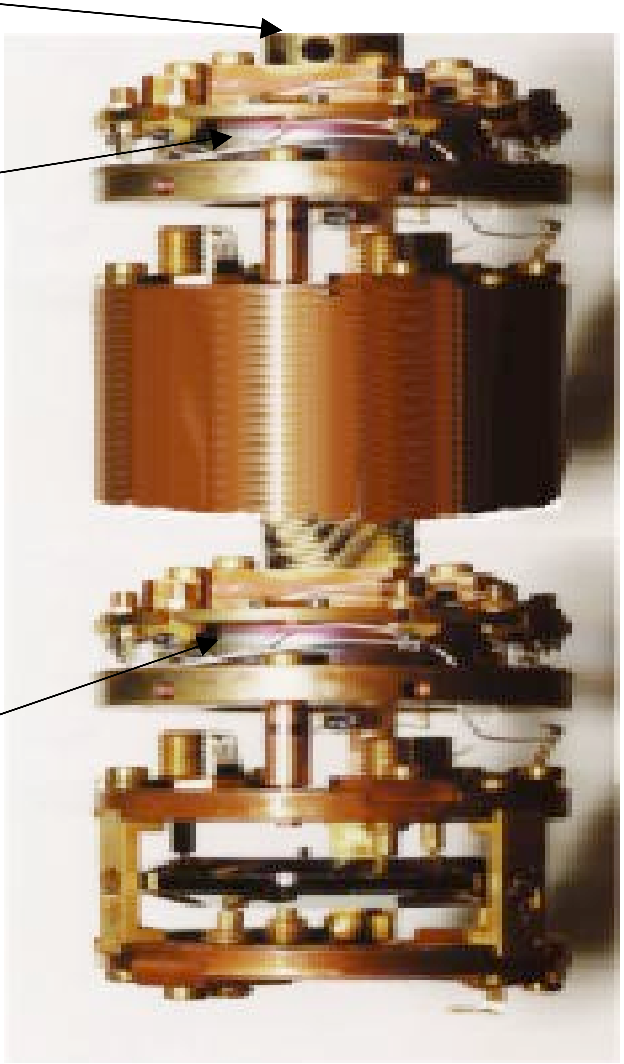
- Exposure of 19 kg-d
- Measure recoils of W target
- 2 300 g modules

Measure coincident thermal and light pulse from $CaWO_4$ target



Detectors (Edelweiss)





Cold finger

Ge sensor
(70 g)

Ge sensor
(70 g)

- Typical mass 70-250 g
- Si or Ge
- One side: ionization
- Other side: array of transition edge sensors

Signal…

- E_T<300 keV
- Recoil - E_{ion}~E_{phonon}/2

Then:

- Must be weak interaction (shielding)
- Slow (*p* small, coherent)
- Massive (nucleus~10-100 GeV recoils)

Kinematics:

$$T_R^{\max} = \frac{2\beta^{*2}}{1-\beta^{*2}} \qquad \beta^{*} = \frac{p}{E+M}$$

$$\rightarrow 2M\beta^{*2} \qquad \rightarrow \frac{\beta m_\nu}{M+m_\nu}$$

$$\frac{d\sigma}{dT_R} = \frac{G_F^2 M c^2}{8\pi v^2} N^2 \exp\left(-\frac{M T_R R^2}{3\hbar^2}\right)$$

Where *R*=nuclear radius

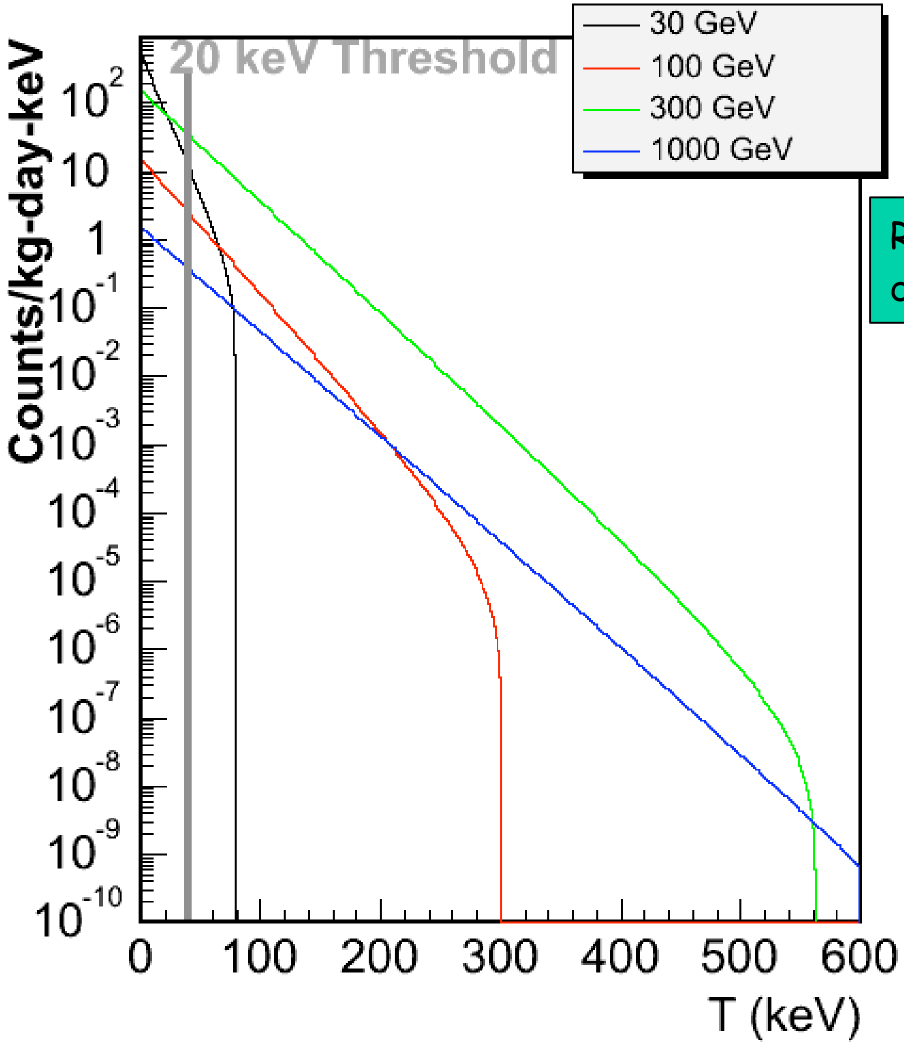
β*=CM velocity

Coherence: T_R<40 keV for typical nucleus

Can only be a relic from the Big Bang

Not necessarily dark matter

Recoil Energy Spectrum



$$\frac{dN}{dT} = n_\nu \frac{m_t}{A_t m_N} \tau \int \frac{d\sigma}{dT} v f(v) d^3 v$$

Relic density

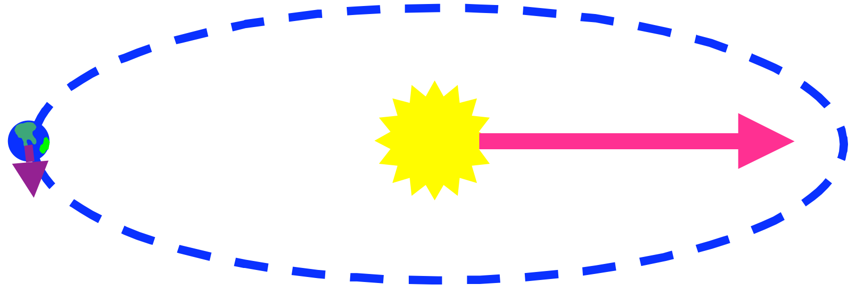
Number target nuclei

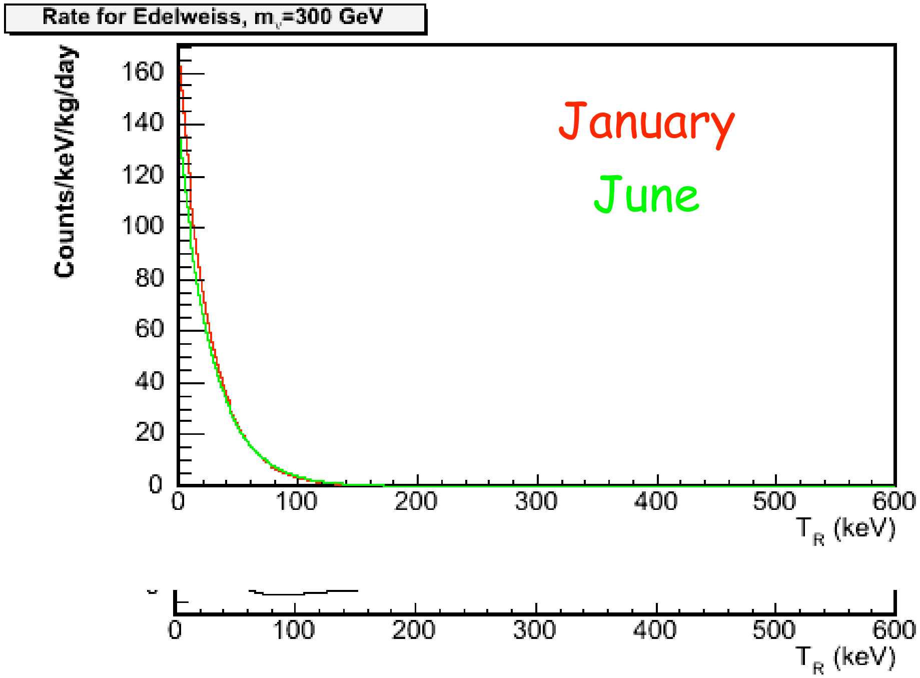
Measuring time

Velocity weighted scattering rate

- All the measurement is in the first bin, need to get threshold a low as possible
- Exposure time measured in kg-day
- f(v)=Maxwell-Boltzmann (best guess)

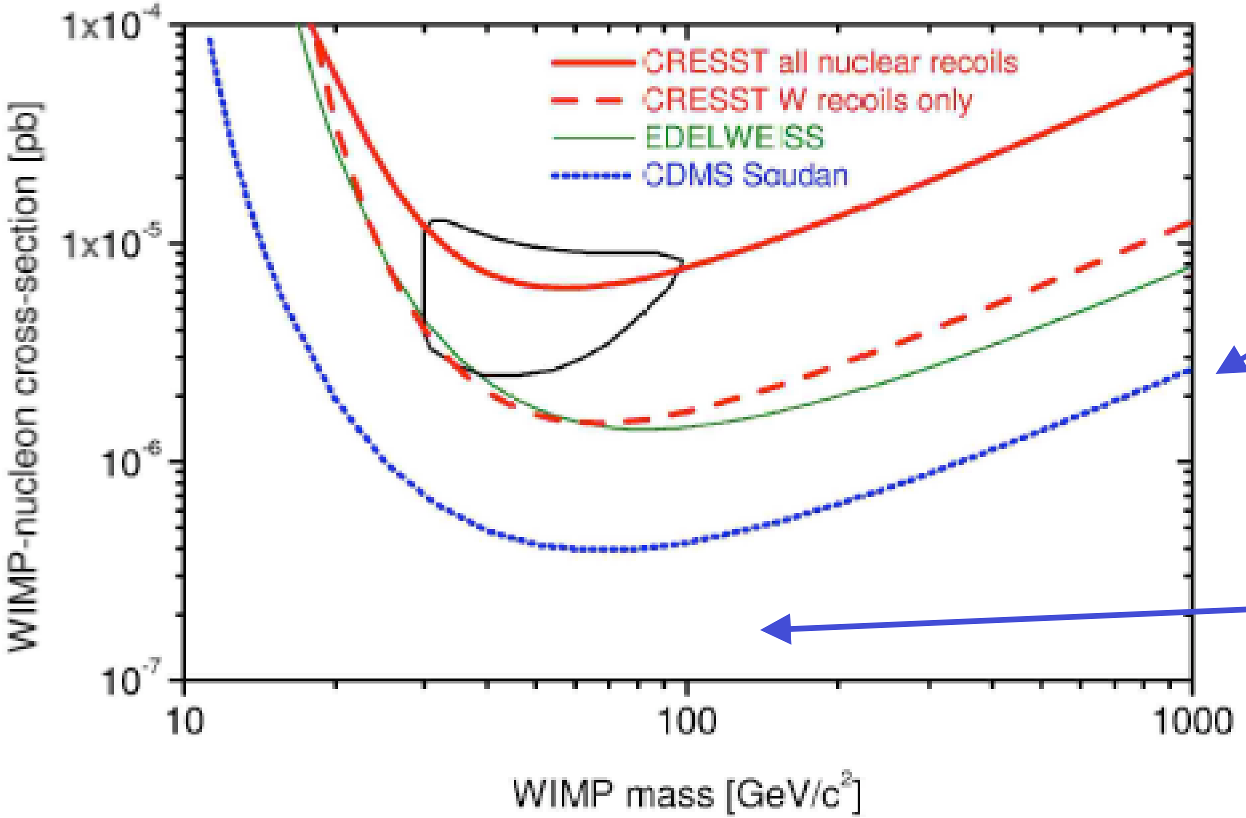
Annual variation in count rate





- Sun moves through galaxy rest frame ~250 km/s
- Earth moves around Sun at 30 km/s
- *Very* small effect
- Claimed observation by DAMA, rate measurements by others contradict

20 keV



Current state of play for SI interactions

CDMS 2004

Lots of models

ν_D as dark matter

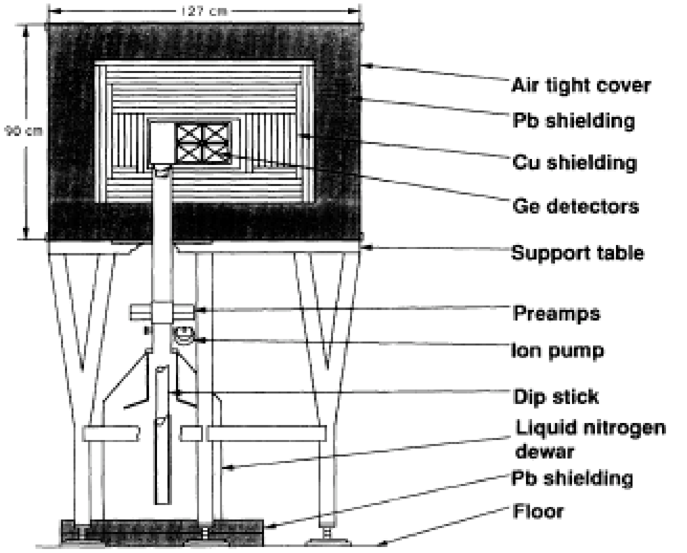


FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.

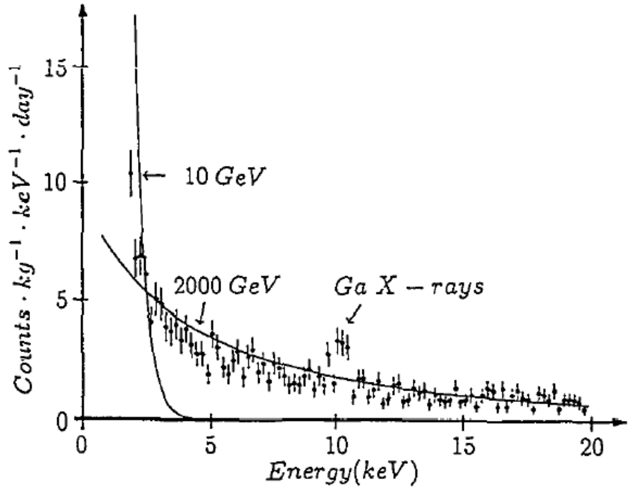


Figure 4: The low energy spectrum of our best crystal, from 1662 hours of data (live time, 51.6 kg days). The peak at 10.37 keV is due to Ga X-ray emission after electron capture in ^{68}Ge. Also shown are the expected recoil spectra for Dirac neutrinos of mass 10 and 2000 GeV.

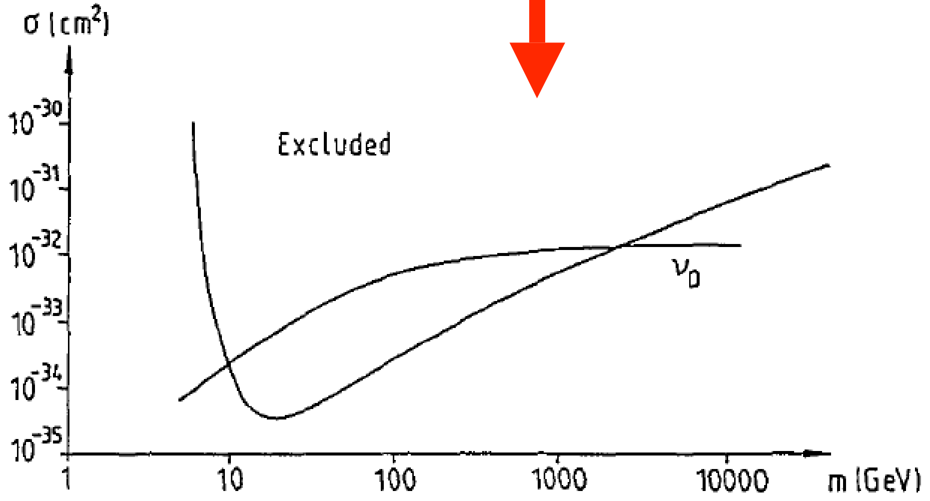


Figure 5: Exclusion plot for CDM from our experiment. CDM candidates with given mass m and interaction cross section σ above the curve are excluded. In particular Dirac neutrinos ν_D with standard coupling between 10 and 2400 GeV are ruled out.

First attempt (1988):

- Ionization only
- Assume ρ=0.3 GeV/cm^3
- Extract cross section limit assuming no signal

Dirac and Majorana Particles

$$\left.\begin{array}{ll} \psi_{\nu_D}(s)=\begin{pmatrix} \chi_s \\ \dfrac{\vec{\sigma}\bullet\vec{p}}{E+m_\nu}\chi_s \end{pmatrix} & \text{2 states} \\ \psi_{\bar{\nu}_D}(s)=\begin{pmatrix} -\dfrac{\vec{\sigma}\bullet\vec{p}}{\left|E\right|+m_\nu}\chi_s \\ \chi_s \end{pmatrix} & \text{2 states} \end{array}\right\}$$

Dirac states solutions to

$$\left(\gamma^{o}\frac{\partial}{\partial t}-\vec{\gamma}\bullet\frac{\partial}{\partial\vec{x}}-m\right)\psi=0$$

Fermion at rest

$$\begin{pmatrix}1\\0\\0\\0\end{pmatrix}\quad\begin{pmatrix}0\\1\\0\\0\end{pmatrix}\quad\begin{pmatrix}0\\0\\1\\0\end{pmatrix}\quad\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\qquad\text{Dirac}$$

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\i\\0\end{pmatrix}\quad\frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\0\\i\end{pmatrix}\qquad\text{Majorana}$$

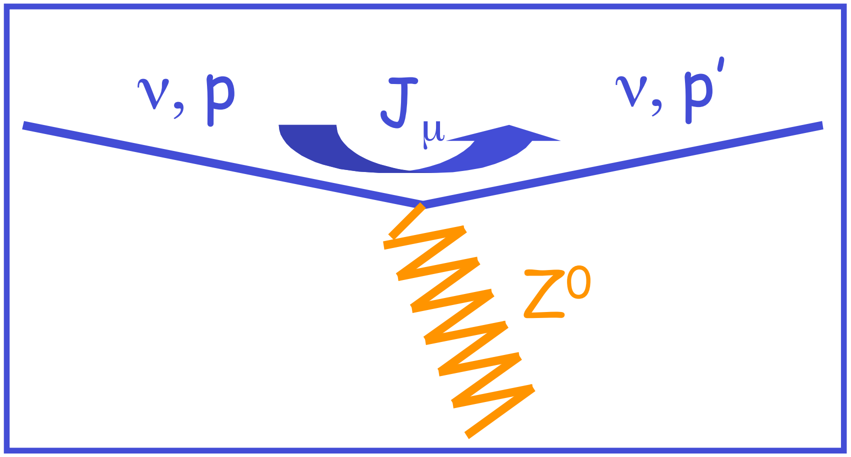
Since chargeless, can form:

$$\psi_{\nu_M}=\left(\psi_{\nu_D}+i\psi_{\nu_{\bar{D}}}\right)/\sqrt{2}$$

Consequences:

- Lepton number not conserved
- Entirely different coupling than Dirac neutrinos - no vector currents

ν neutral current interactions



Neutrino current:

$$J_\mu = \psi(p')(C_V\gamma_\mu - C_A\gamma_\mu\gamma_5)\psi(p)$$

Vector

Axial-vector

$$J_0 = C_V\psi(p')\psi(p)$$

$$\boxed{p \rightarrow 0}$$

$$\vec{J} = C_A\psi(p')\,\vec{S}\,\psi(p)$$

Dirac, scalar

$$\frac{d\sigma}{dT_R} = \frac{G_F^2 Mc^2}{8\pi v^2} N^2 \exp\left(-\frac{MT_R R^2}{3\hbar^2}\right)$$

Dirac,
Scalar
Majorana

$$\frac{d\sigma}{dT_R} = \frac{2G_F^2}{\pi\hbar^2 T_R^{\max}} \mu^2\lambda^2 J(J+1)\sum_q T_q^3 \Delta q$$

Nuclear physics

Nuclear spin

Quark content

ν neutral current interactions

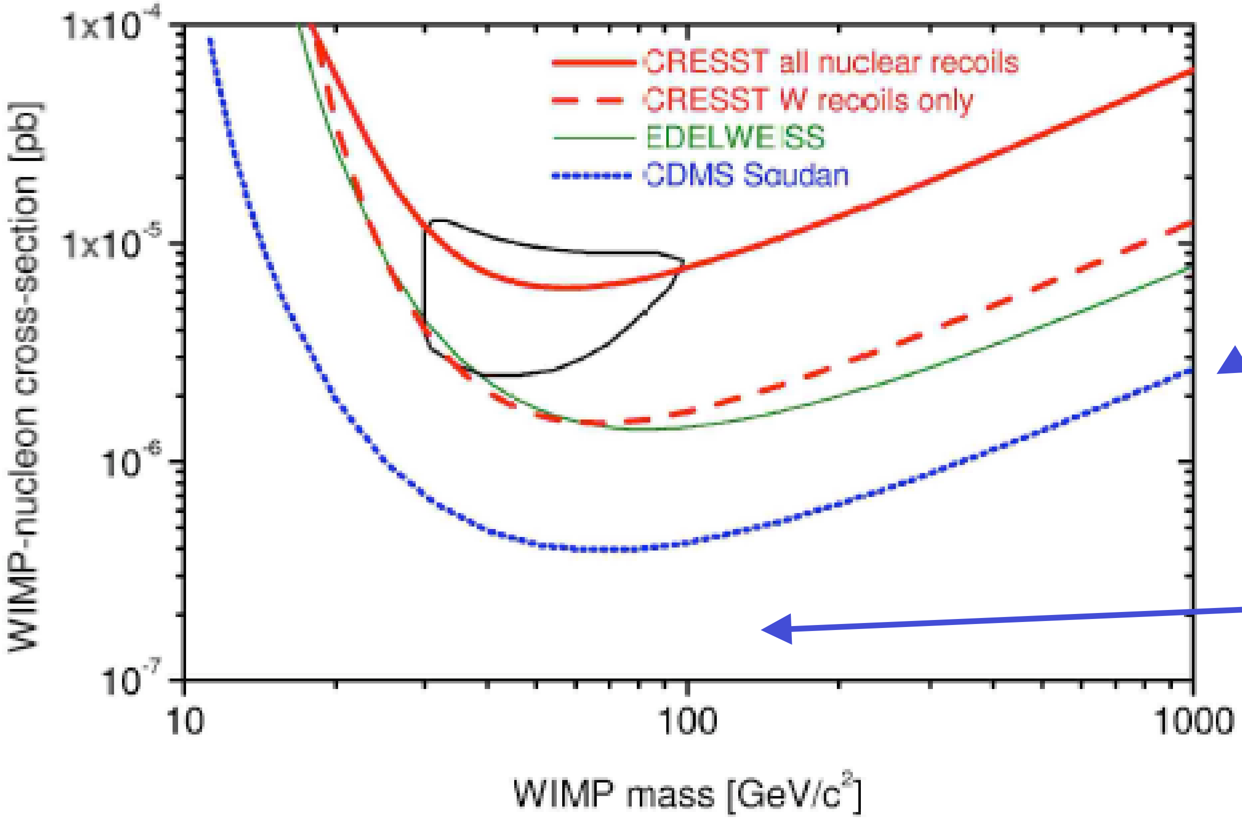
Dirac neutrinos (Spin Independent, SI)

- Cross section proportional to N^2 (~1600 for Ge)
- Independent of nuclear spin
- Simple nuclear physics

Majorana neutrinos (Spin Dependent, SD)

- No enhancement from coherence
- Proportional to J(J+1)
- Complicated nuclear physics, QCD

If a signal is observed, do not know if it is from SI or SD, $\sigma_{SI} \sim N^2 \sigma_{SD}$

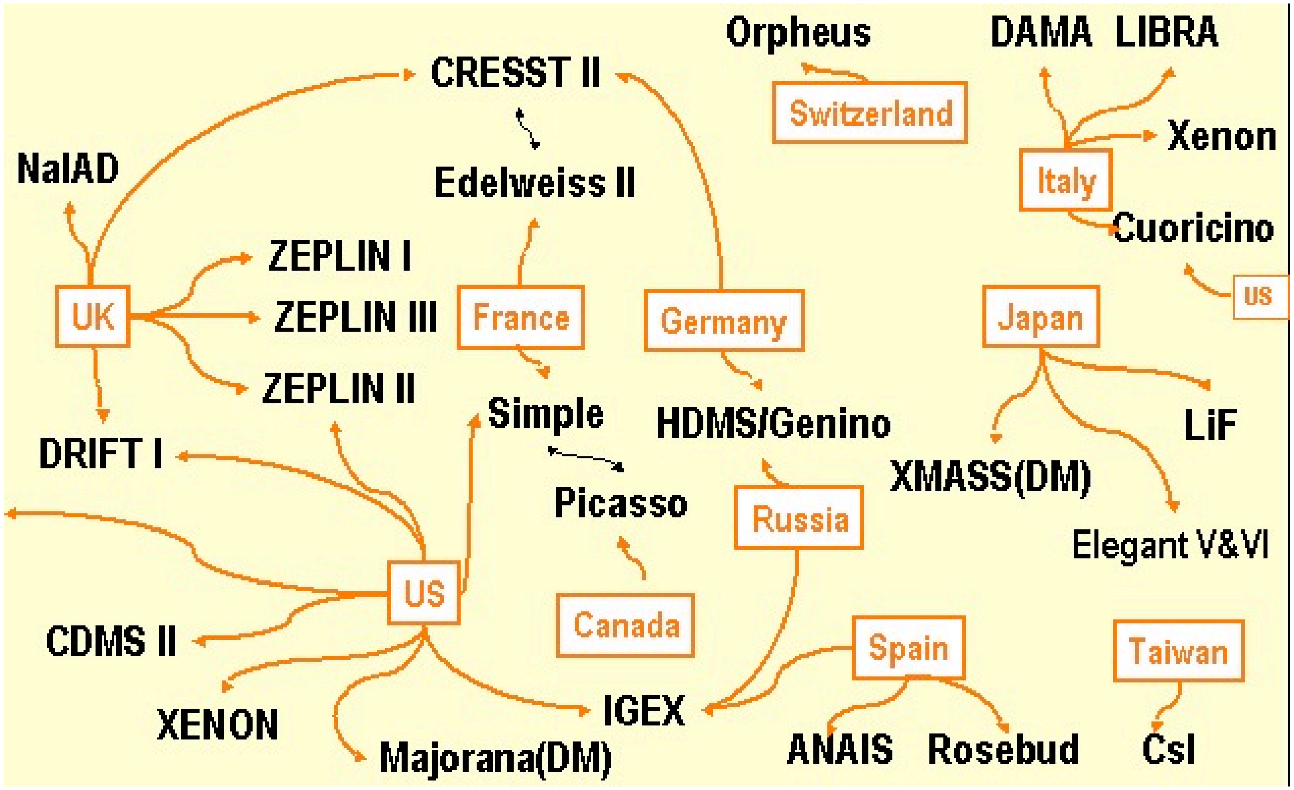


Current state of play for SI interactions

CDMS 2004

Lots of models

Where are we experimentally?



General focus on:

- Dark matter
- SUSY
- Spin independent interactions

Dark Matter recoil collaborations around the world

Candidate nuclei

- Need nuclei with lots of spin (i.e. *J* large)
- Few neutrons (as little SI interaction as possible)
- Favorable nuclear physics (i.e. λ large)
- Favorable experimental conditions
  - No long lived isotopes
  - Sensitive to recoils (phonons)
  - Easy to purify, handle

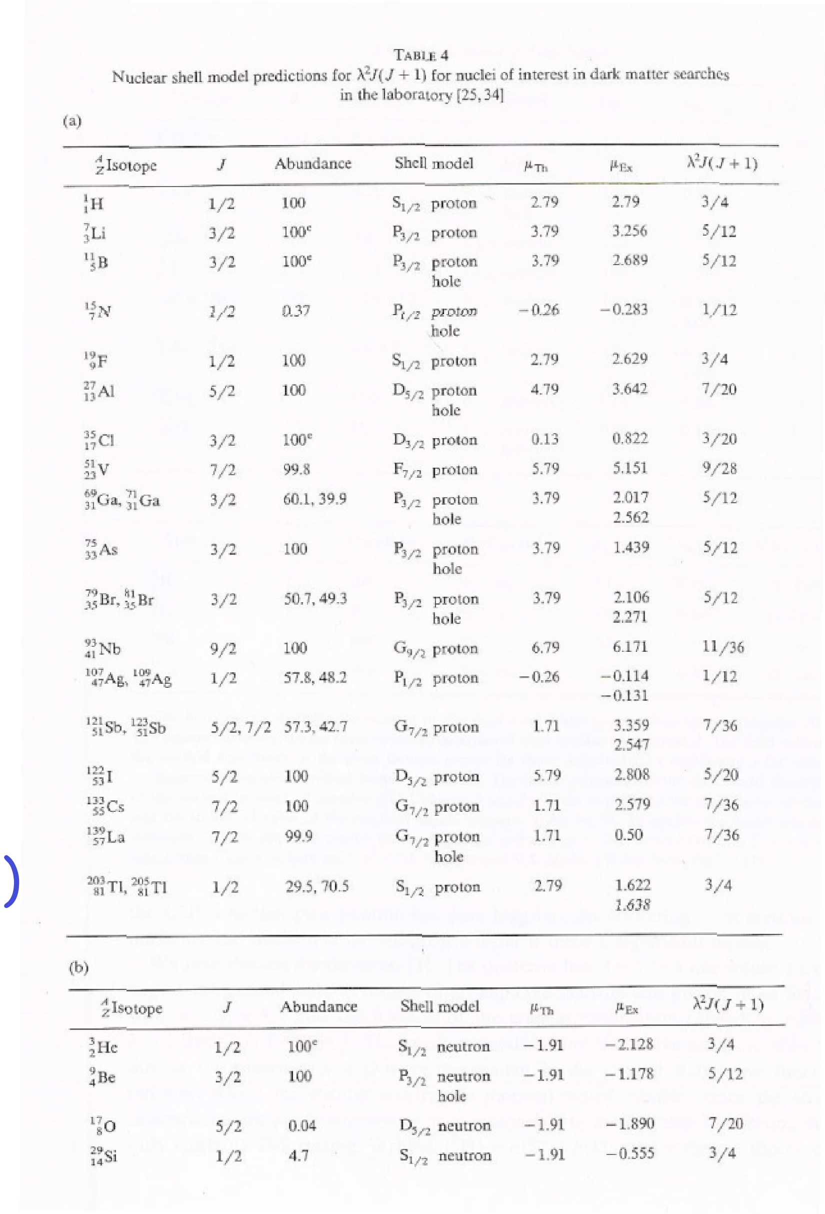


TABLE 4

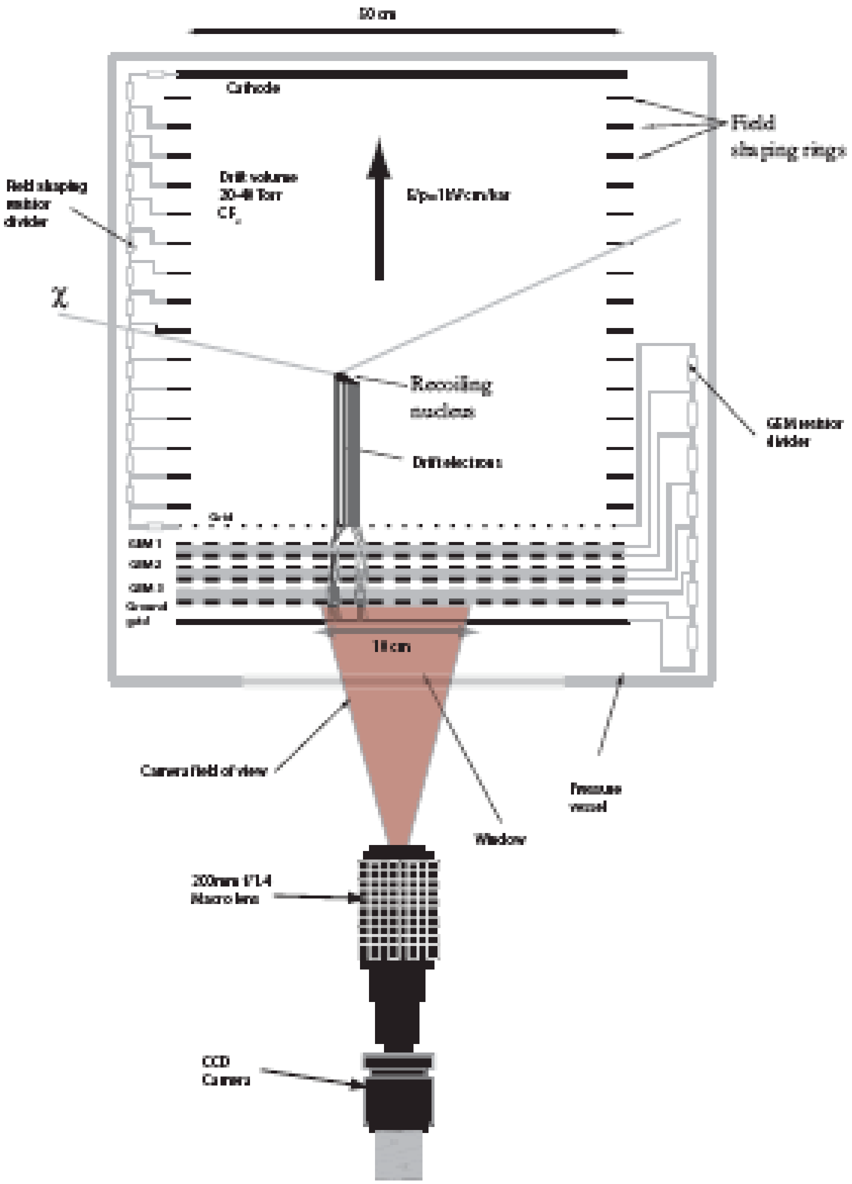
Nuclear shell model predictions for $\lambda^2 J(J+1)$ for nuclei of interest in dark matter searches in the laboratory [25, 34]

(a)

$^{A}_{Z}$Isotope	J	Abundance	Shell model	μ_{Th}	μ_{Ex}	$\lambda^2 J(J+1)$
$^{1}_{1}$H	1/2	100	$S_{1/2}$ proton	2.79	2.79	3/4
$^{7}_{3}$Li	3/2	100^e	$P_{3/2}$ proton	3.79	3.256	5/12
$^{11}_{5}$B	3/2	100^e	$P_{3/2}$ proton hole	3.79	2.689	5/12
$^{15}_{7}$N	1/2	0.37	$P_{1/2}$ proton hole	−0.26	−0.283	1/12
$^{19}_{9}$F	1/2	100	$S_{1/2}$ proton	2.79	2.629	3/4
$^{27}_{13}$Al	5/2	100	$D_{5/2}$ proton hole	4.79	3.642	7/20
$^{35}_{17}$Cl	3/2	100^e	$D_{3/2}$ proton	0.13	0.822	3/20
$^{51}_{23}$V	7/2	99.8	$F_{7/2}$ proton	5.79	5.151	9/28
$^{69}_{31}$Ga, $^{71}_{31}$Ga	3/2	60.1, 39.9	$P_{3/2}$ proton hole	3.79	2.017 2.562	5/12
$^{75}_{33}$As	3/2	100	$P_{3/2}$ proton hole	3.79	1.439	5/12
$^{79}_{35}$Br, $^{81}_{35}$Br	3/2	50.7, 49.3	$P_{3/2}$ proton hole	3.79	2.106 2.271	5/12
$^{93}_{41}$Nb	9/2	100	$G_{9/2}$ proton	6.79	6.171	11/36
$^{107}_{47}$Ag, $^{109}_{47}$Ag	1/2	57.8, 48.2	$P_{1/2}$ proton	−0.26	−0.114 −0.131	1/12
$^{121}_{51}$Sb, $^{123}_{51}$Sb	5/2, 7/2	57.3, 42.7	$G_{7/2}$ proton	1.71	3.359 2.547	7/36
$^{122}_{53}$I	5/2	100	$D_{5/2}$ proton	5.79	2.808	5/20
$^{133}_{55}$Cs	7/2	100	$G_{7/2}$ proton	1.71	2.579	7/36
$^{139}_{57}$La	7/2	99.9	$G_{7/2}$ proton hole	1.71	0.50	7/36
$^{203}_{81}$Tl, $^{205}_{81}$Tl	1/2	29.5, 70.5	$S_{1/2}$ proton	2.79	1.622 1.638	3/4

(b)

$^{A}_{Z}$Isotope	J	Abundance	Shell model	μ_{Th}	μ_{Ex}	$\lambda^2 J(J+1)$
$^{3}_{2}$He	1/2	100^e	$S_{1/2}$ neutron	−1.91	−2.128	3/4
$^{9}_{4}$Be	3/2	100	$P_{3/2}$ neutron hole	−1.91	−1.178	5/12
$^{17}_{8}$O	5/2	0.04	$D_{5/2}$ neutron	−1.91	−1.890	7/20
$^{29}_{14}$Si	1/2	4.7	$S_{1/2}$ neutron	−1.91	−0.555	3/4

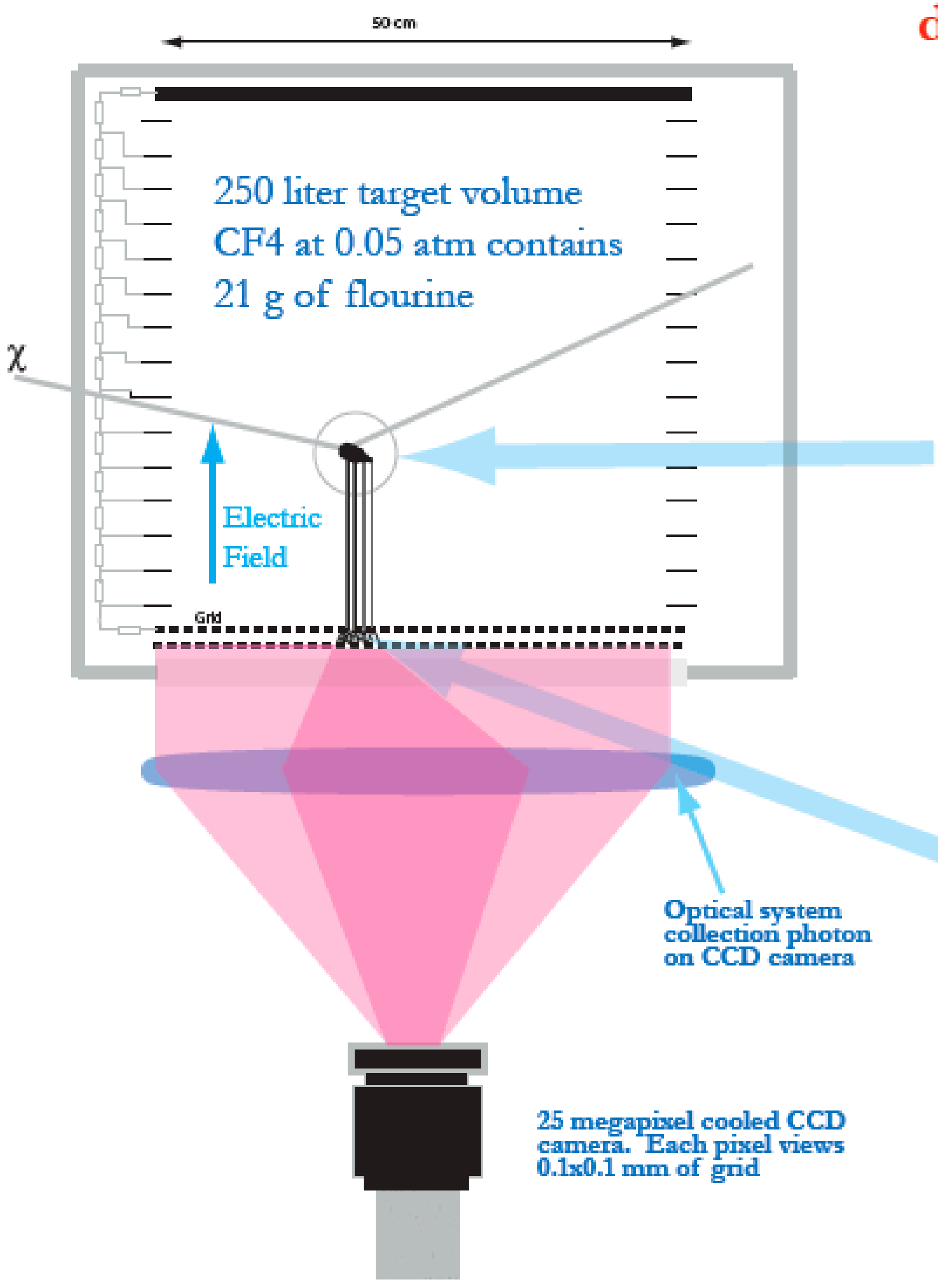


Some messing around: CF_4 low pressure (20-40 Torr) drift chamber

- 22 g flourine (spin 1/2)
- Nucleus recoils 1 mm, spread over ~10 GEM holes, 2D directionality, dE/dx
- Optical readout removes sensors from target region

A dark matter detector with directional sensitivity

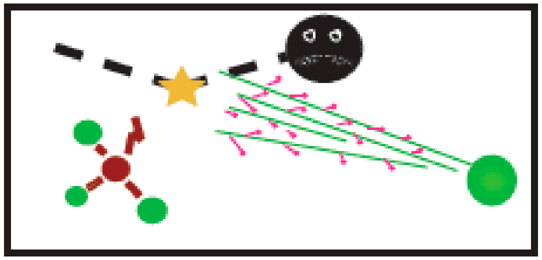
Unique features:
- direction of dark matter known
- spin dependent interactions
- very high background rejection
- low cost, simple construction



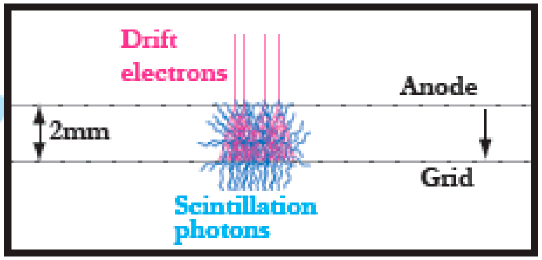
250 liter target volume
CF4 at 0.05 atm contains
21 g of flourine

Optical system collection photon on CCD camera

25 megapixel cooled CCD camera. Each pixel views 0.1x0.1 mm of grid



Flourine nucleus recoils after being struck by a dark matter particle. As the nucleus moves through the gas, it liberates electrons.



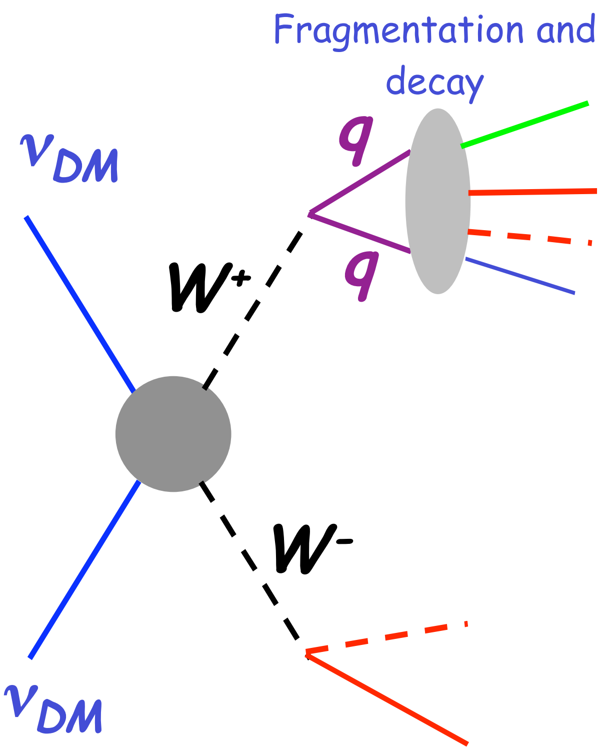
Drift electrons arrive at the grid and enter a high electric field. As each electron accelerates, it liberates other electrons and radiates visible light.

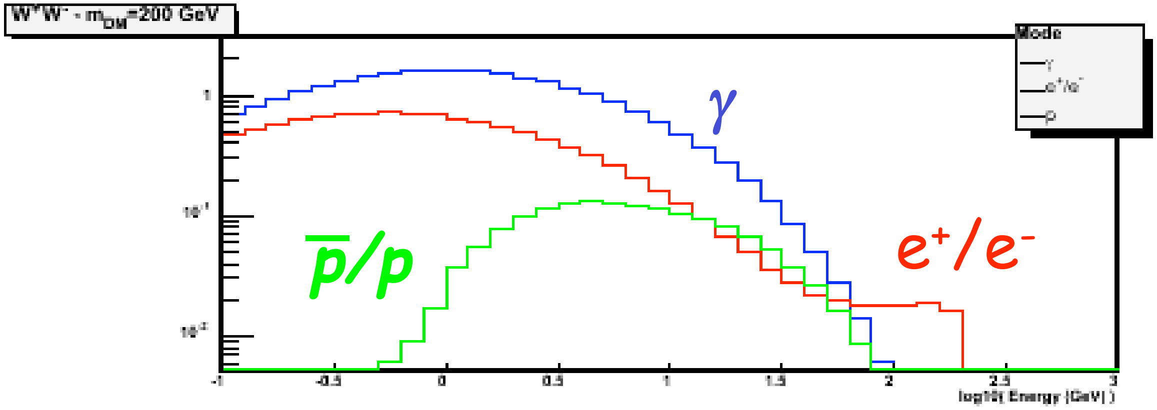
Peter Fisher (MIT), Steve Ahlen and Hidefume Tomita (BU)

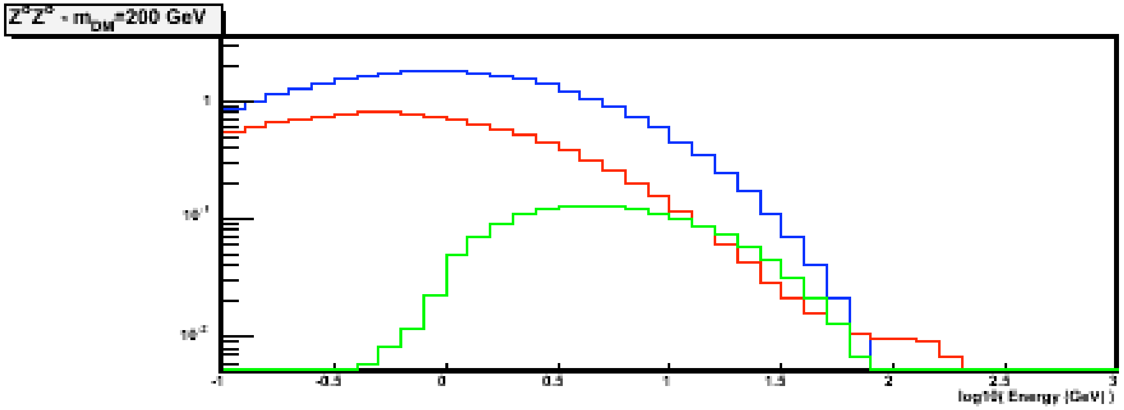
Supported by the MIT Kavli Institute and the Department of Energy

Bangs:

detection of products from dark matter annihilation





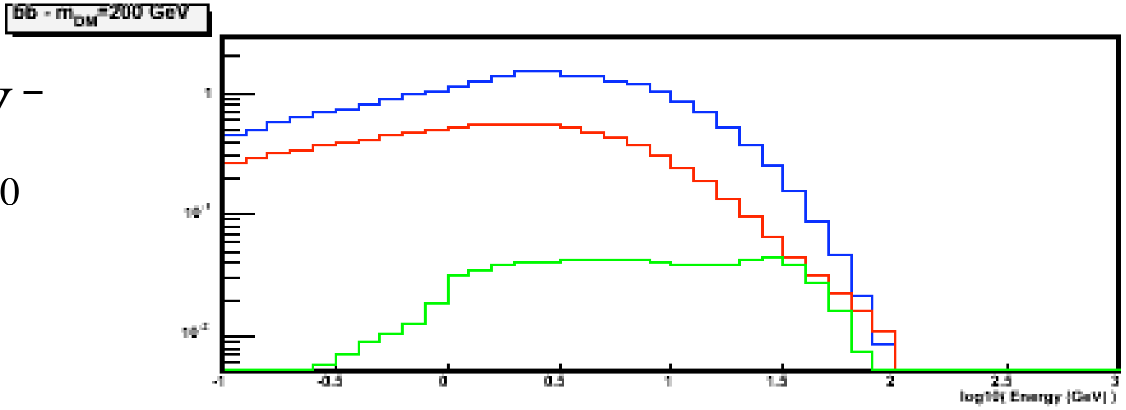


Typical processes:

$$\nu_{DM} + \nu_{DM} \rightarrow W^+ + W^-$$

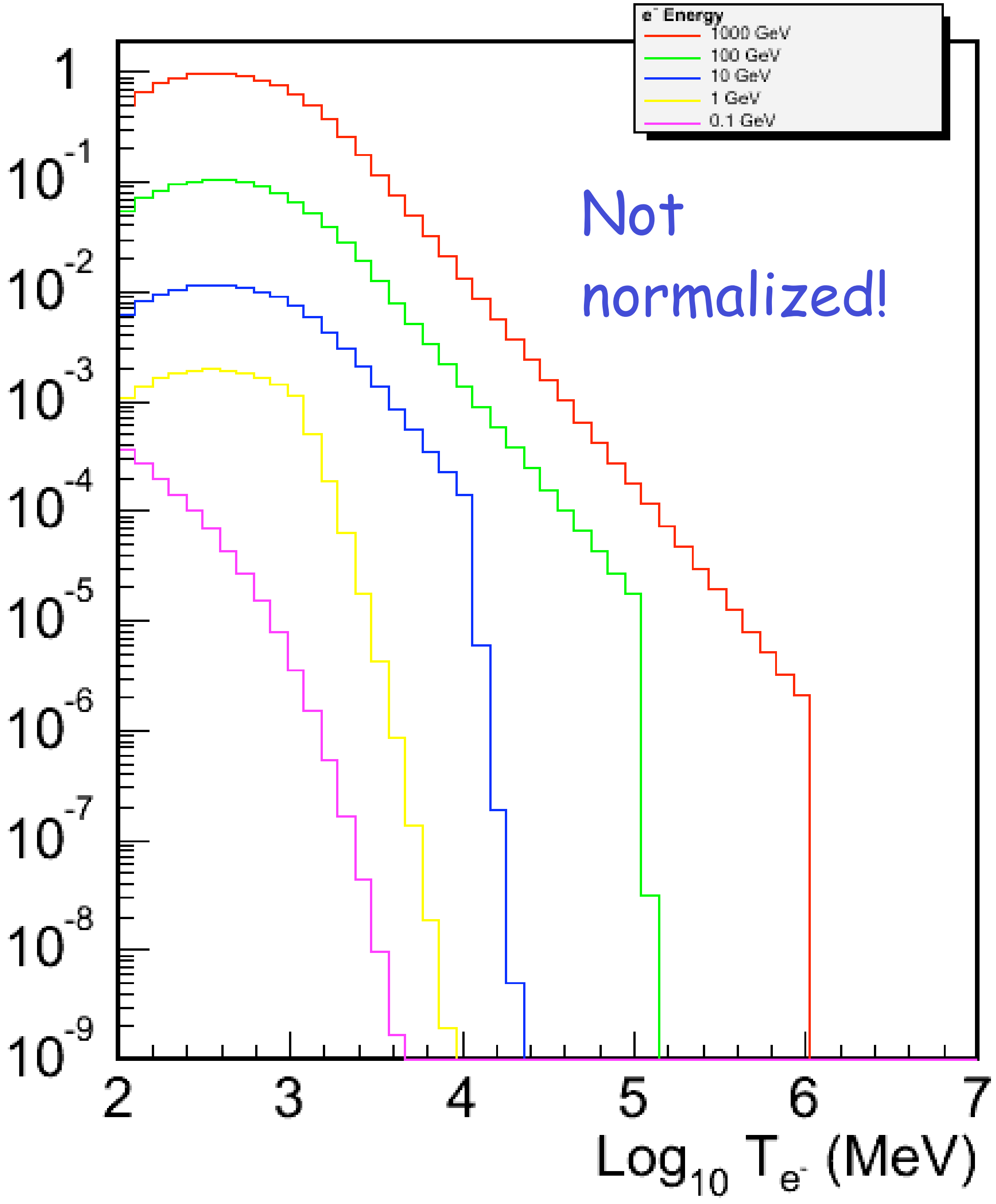
$$\nu_{DM} + \nu_{DM} \rightarrow Z^0 + Z^0$$

$$\nu_{DM} + \nu_{DM} \rightarrow b + \bar{b}$$

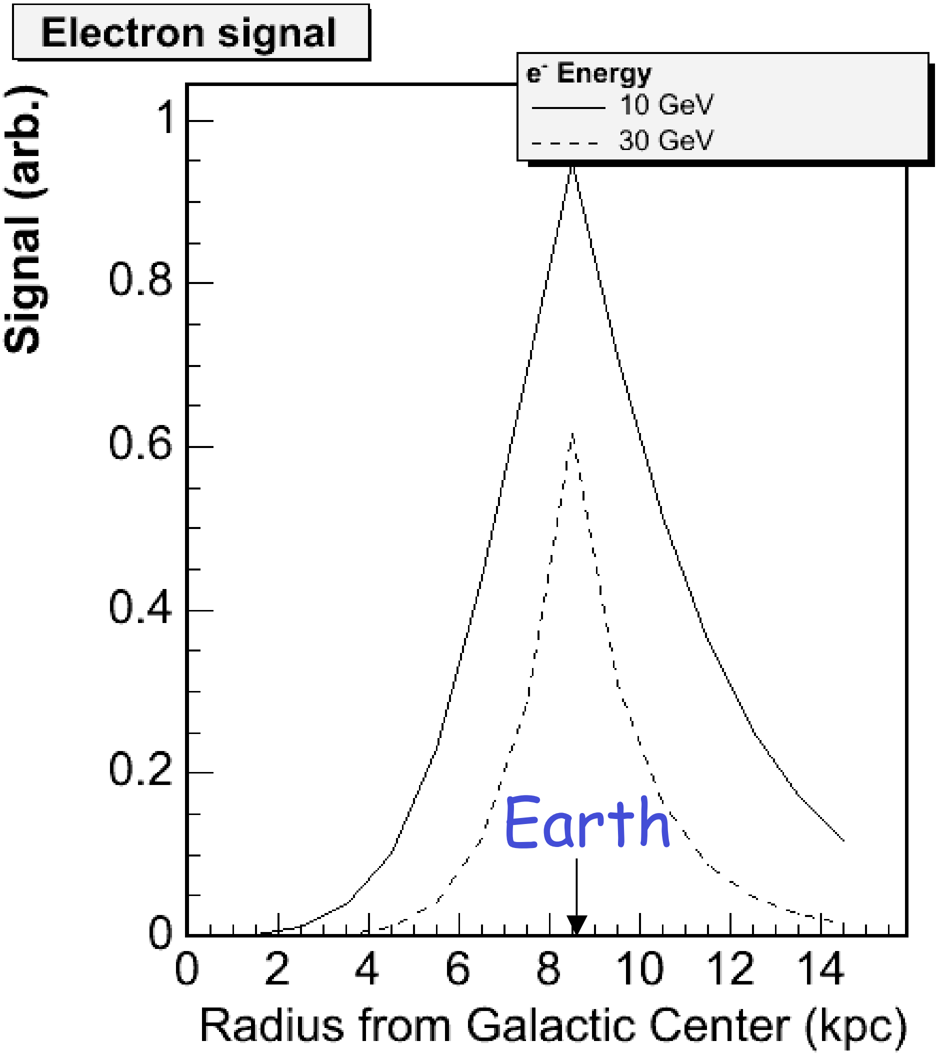


Galprop - I. Moskolenko and A. Strong - cosmic ray propagation problem fit to all known data

Green's functions - expected flux on Earth for uniform monoenergetic source of electrons

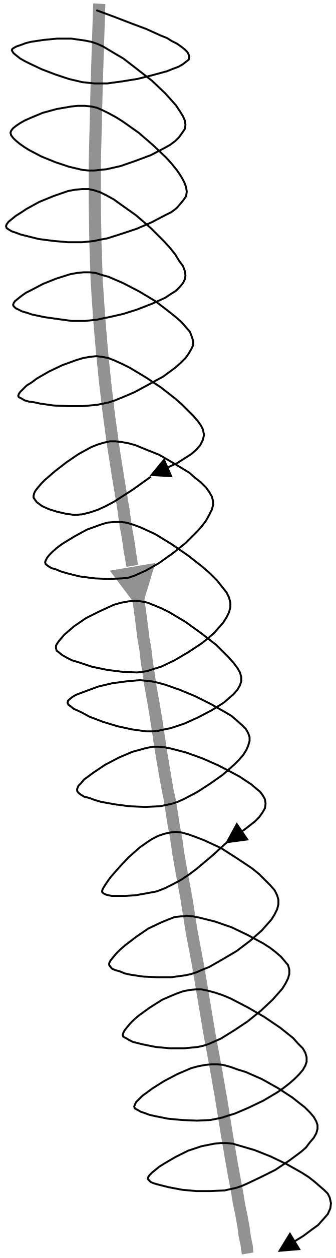


Not normalized!



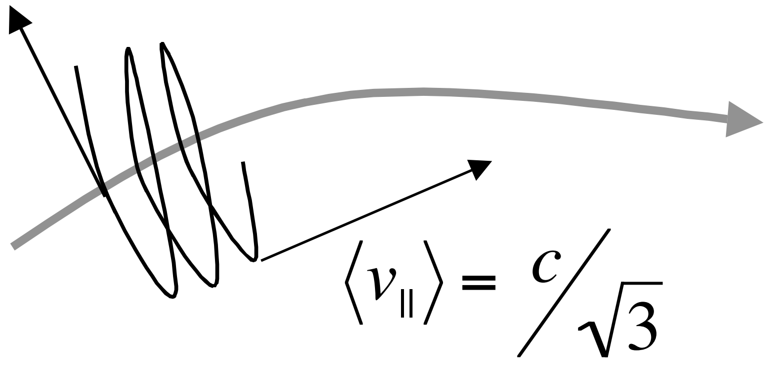
Integrated positron signal above 8 GeV for 100 GeV (solid line) and 30 GeV (dotted line). The Earth is located at 8.5 kpc radius.

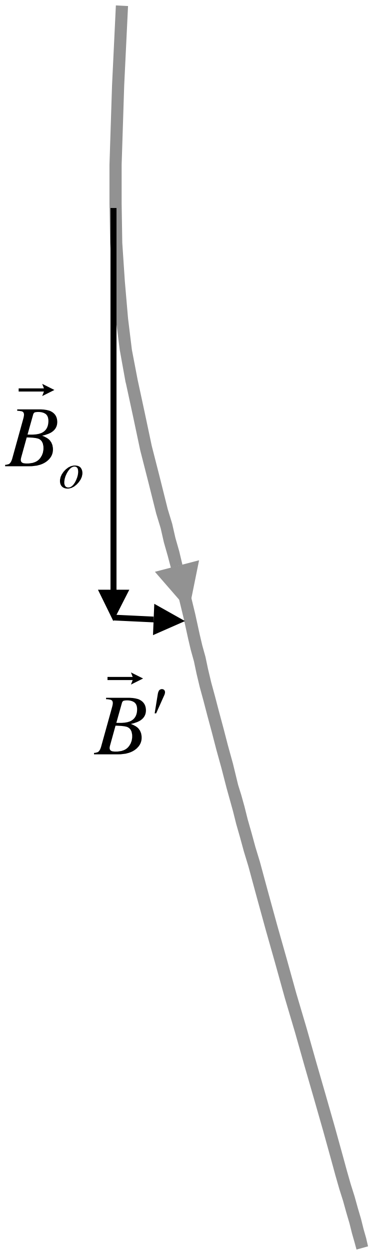
Contribution of DM outside of plane of galaxy difficult to understand - magnetic field structure not well known



Charged particles follow magnetic field lines

$$r_L = \frac{p}{0.3\,\frac{\mathrm{GeV}}{\mathrm{T-m}}\,B} \approx 7\,\mathrm{AU}$$



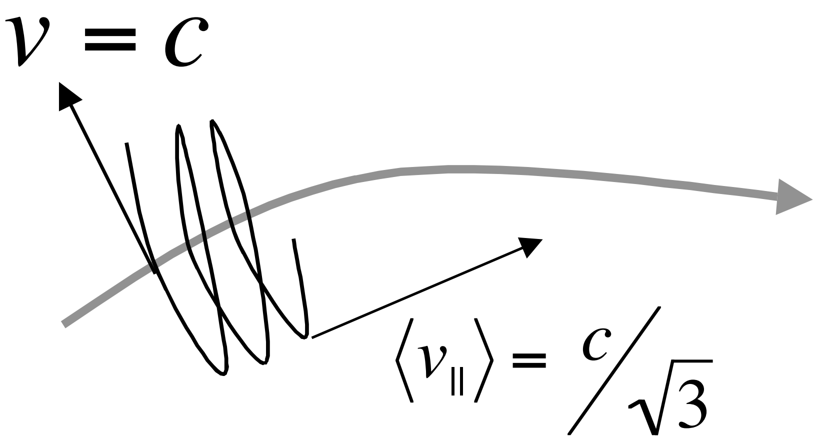


Magnetic turbulence - average variation of magnetic field:

$$\eta = \frac{\left\langle \vec{B}' \right\rangle}{\left\langle \vec{B}_o + \vec{B}' \right\rangle} \approx 10^{-4}$$

Mean time between scattering from inhomogenieties:

$$\tau_s = \frac{1}{\eta \omega_L} \approx 10\mathrm{y}$$



30 GeV electron: $v=c$, gives average velocity along field $c/3^{1/2}$

Electron lifetime determined by time τ_o to propagate one X_o=65 g/cm^2 in hydrogen

1 proton/cm^3 in ISM $\Longrightarrow$ X_o=1.3 x 10^{13} kpc

$\Longrightarrow$ τ_o=45 My

For electrons, synchrotron radiation loses at a similar rate.

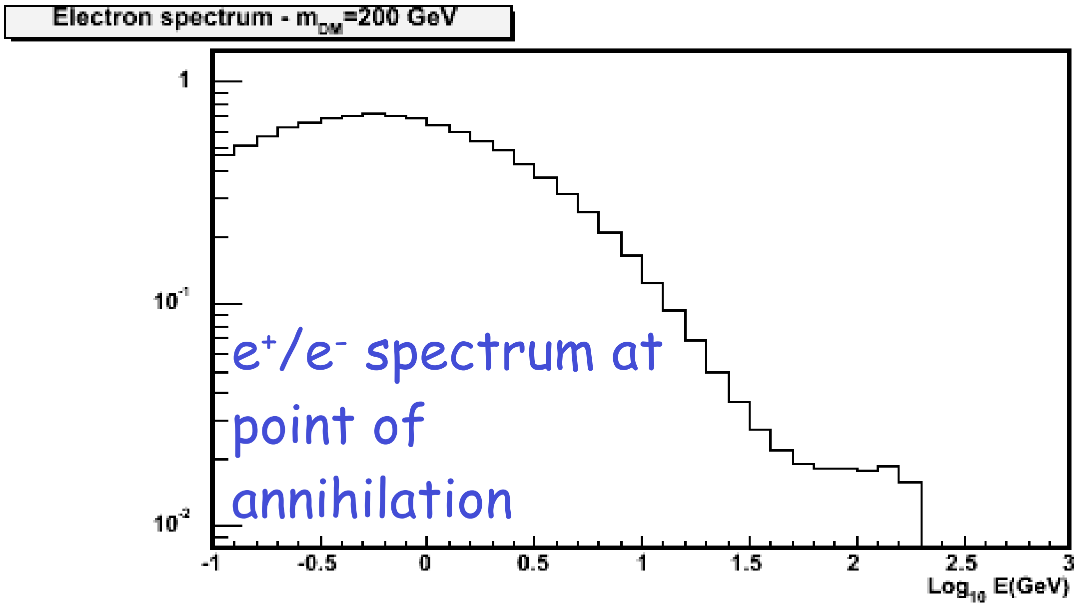
Number of scatterings: $N=\tau_o/\tau_s$

Random walk diffusion distance

$$d = \underbrace{\langle v_{\parallel} \rangle \boldsymbol{\tau}_s}_{\text{Advance each step}} \underbrace{\sqrt{N}}_{\text{RMS number of steps}} = \sqrt{\underbrace{\frac{1}{3} c^2 \boldsymbol{\tau}_s}_{\text{Diffusion coefficient}} \boldsymbol{\tau}_o} \approx 3\text{kpc}$$

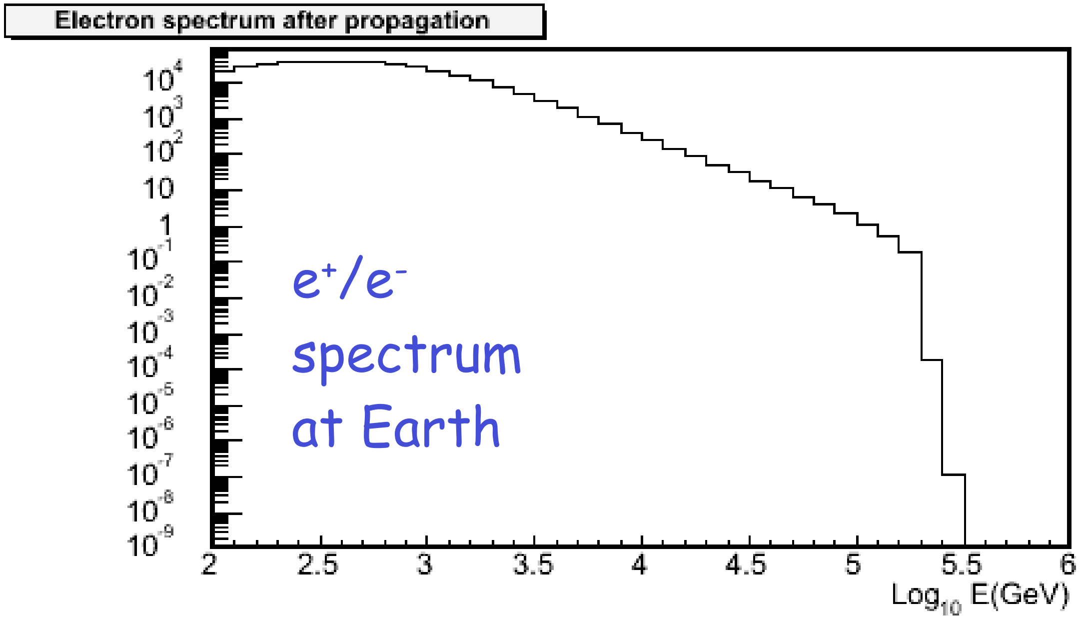
Propagation makes a mess!

During 3 kpc transit, DM annihilation products go through ~1 X_0 of material



Electron spectrum - m_{DM}=200 GeV

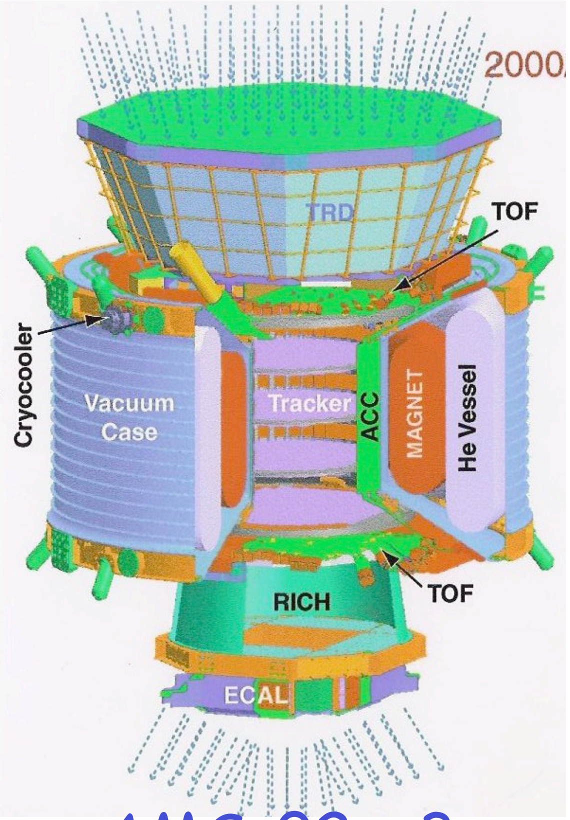
e^+/e^- spectrum at point of annihilation



Electron spectrum after propagation

e^+/e^- spectrum at Earth

Charged particle spectrometers



AMS-02 - 3 years on space station

In ~10 GeV region:

$p:e^-:e^+$

$10^3:10:0.1$

$p:\bar{p}$

$10^3:0.1$

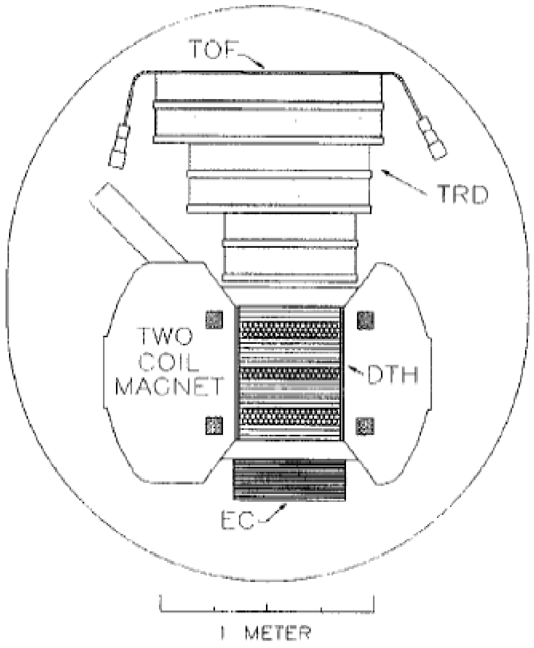
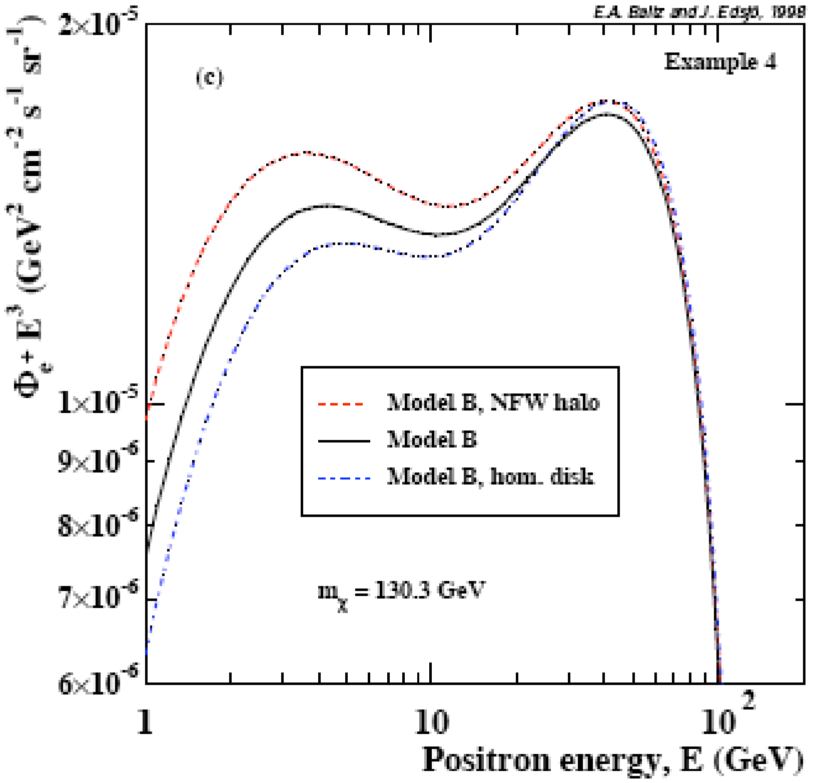
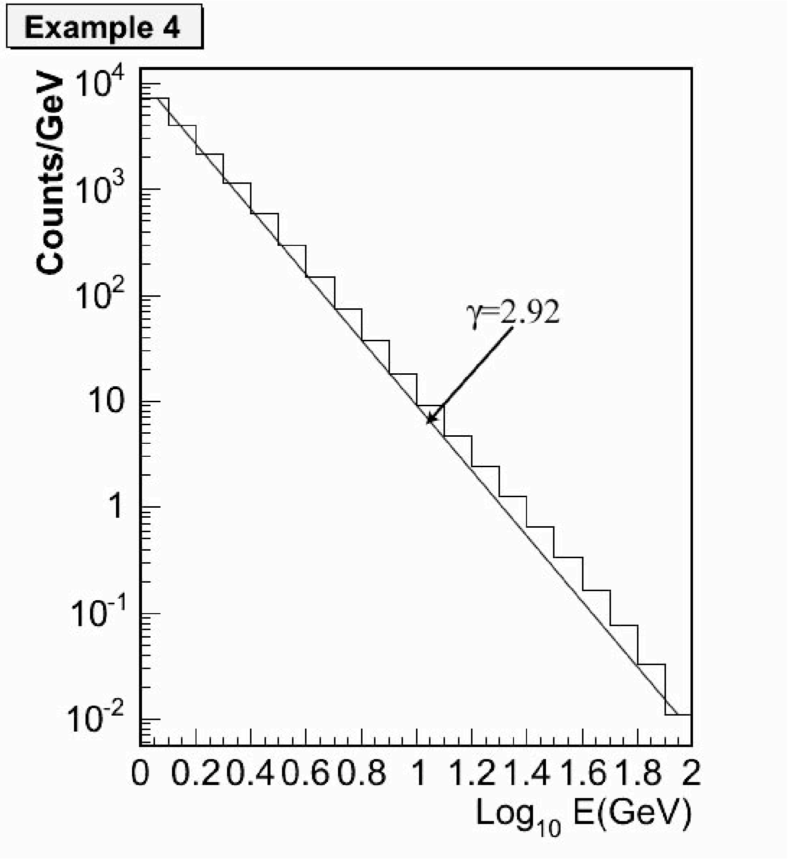


Fig. 1. Cross section drawing of the HEAT instrument.

High Energy Antimatter Telescope, ~50 h, balloon payload

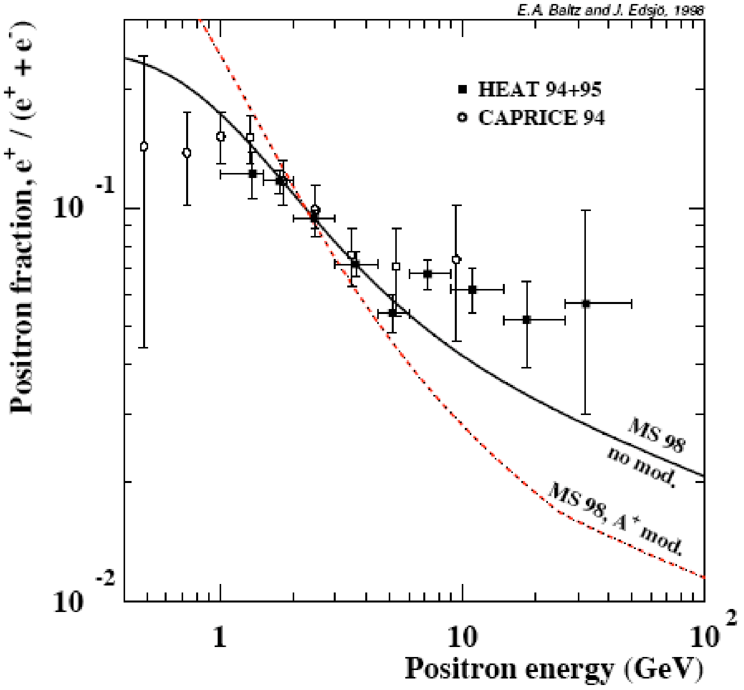
“Typical” signal - neutralino annihilation





Moral - in cosmic rays everything looks like

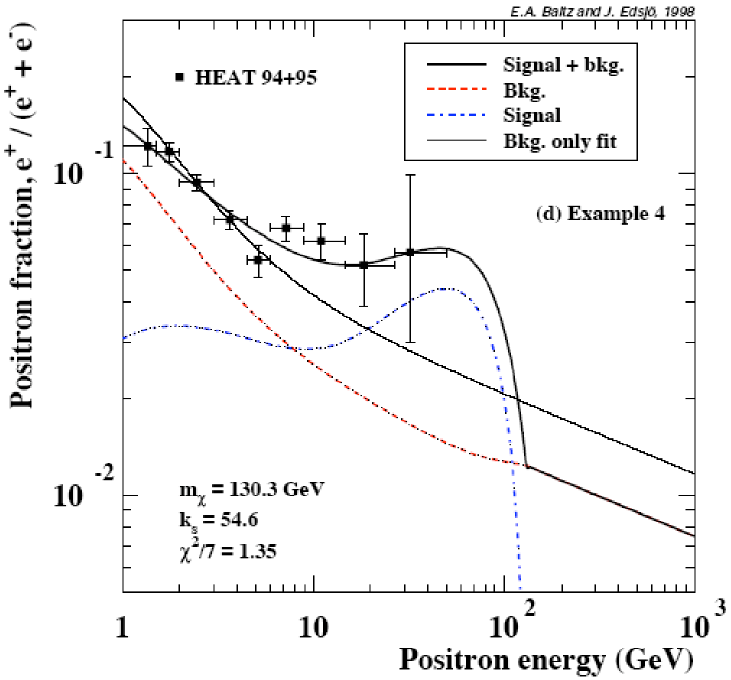
$$\frac{dN}{dE} \propto E^{-(2.5 \text{ to } 3.2)}$$



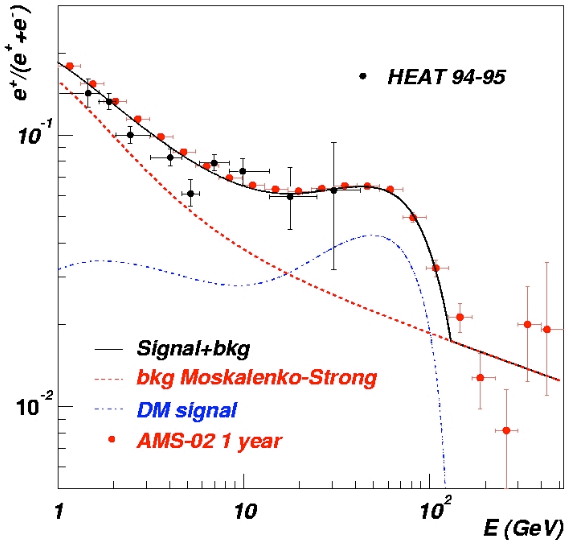
This first problem is that the propagation (especially solar modulation) is not well understood…

…the second is that HEAT runs out of sensitivity at ~50 GeV…

Fit with background (smooth) normalization with signal (bump) gives 55 times higher relic density than observed

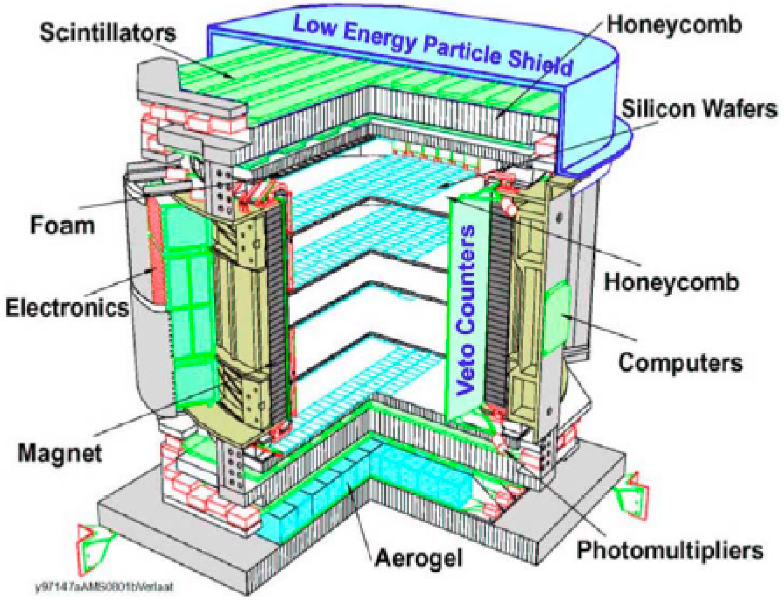


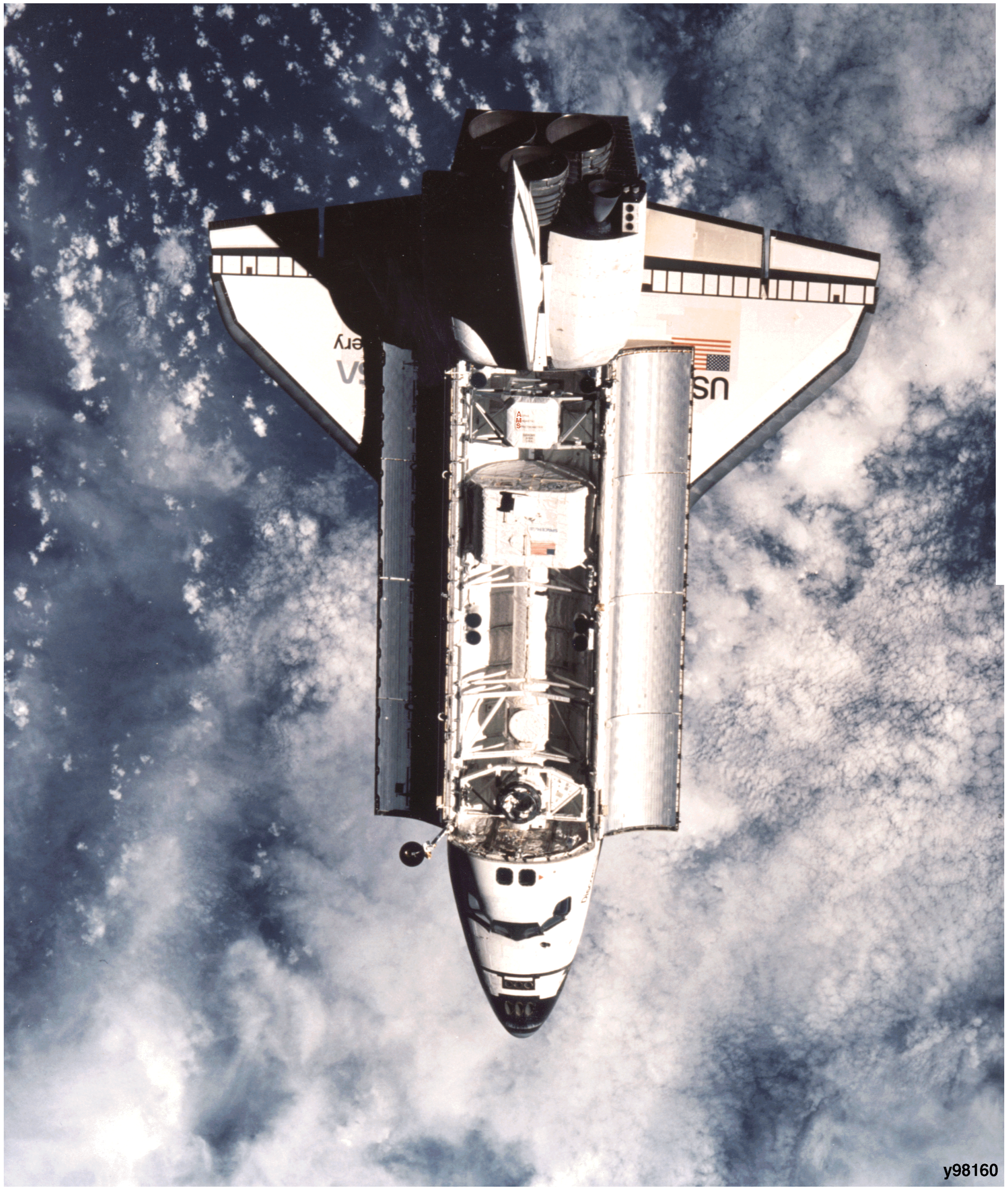
AMS-02 will just nail this

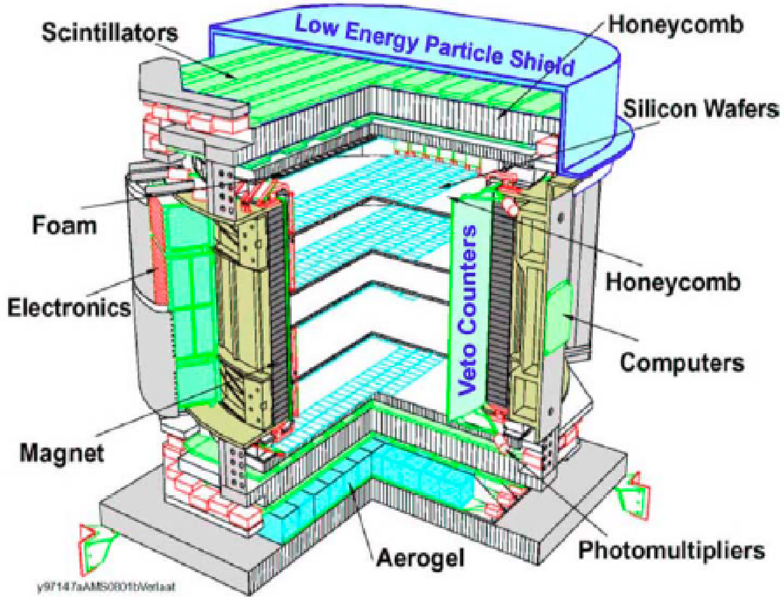


Questions

1. Why use $e^+/e^+ + e^-$? Solar modulation not important above 10 GeV.
2. Same signal appears in e^-, so why not use e^+, e^-,… in combined fit?
3. AMS-01 took LOTS of e- data (easy to ID, no $\bar{p}$!) Why not look at that?







AMS-01 - June 1998

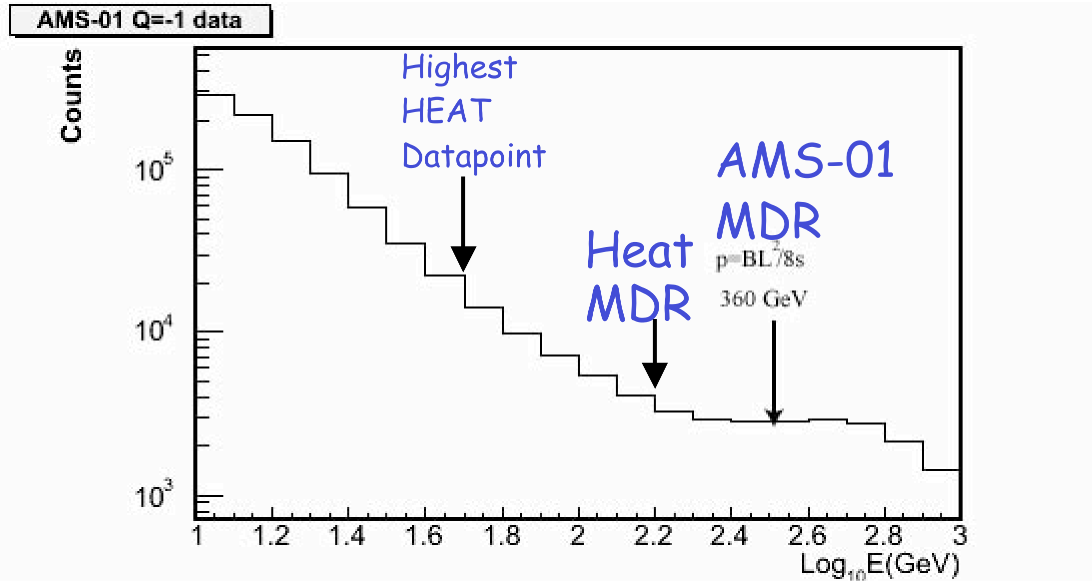
- ~100 h data taking at 400 km
- 200 M triggers

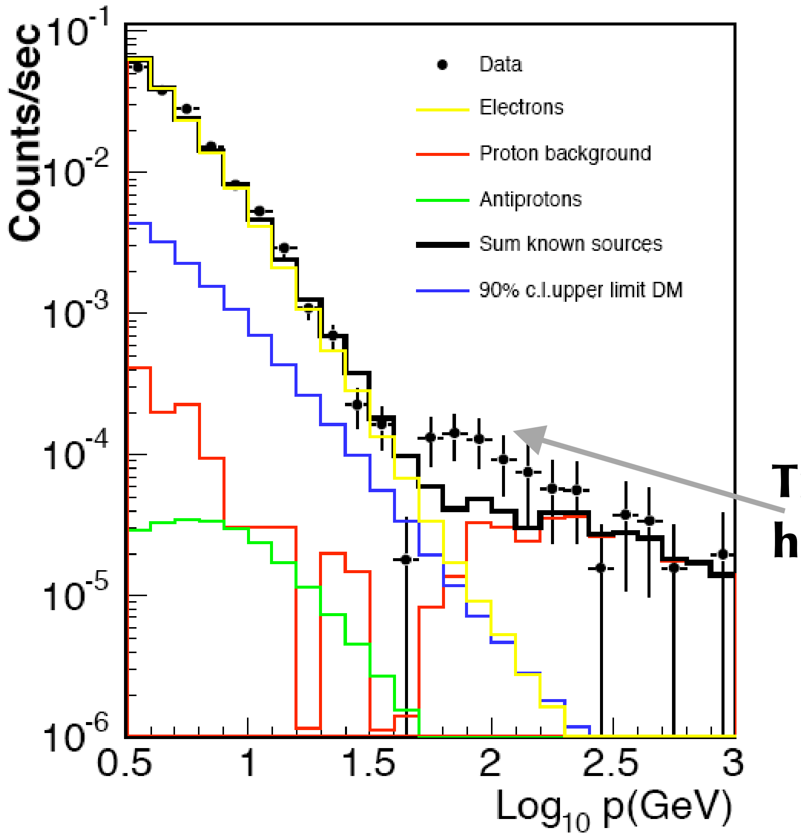
	HEAT	AMS-01	AMS-02
Aperture (m^2-str)	0.05	0.14	0.5
Exposure (h)	45	239	26,000
MDR (GV)	170	360	3,000
FOM for DM e^-	1	0.4-1.5	8-24
Status	Flew	Flew	Mar. 2008 (Hah!)

$$\mathrm{FOM} = \sqrt{(0.1 \text{ to } 0.01)\frac{\Omega}{0.05\mathrm{m}^2-\mathrm{str}}\frac{\tau}{45\mathrm{h}}}$$

Preliminary AMS-01 Z=-1 selection:

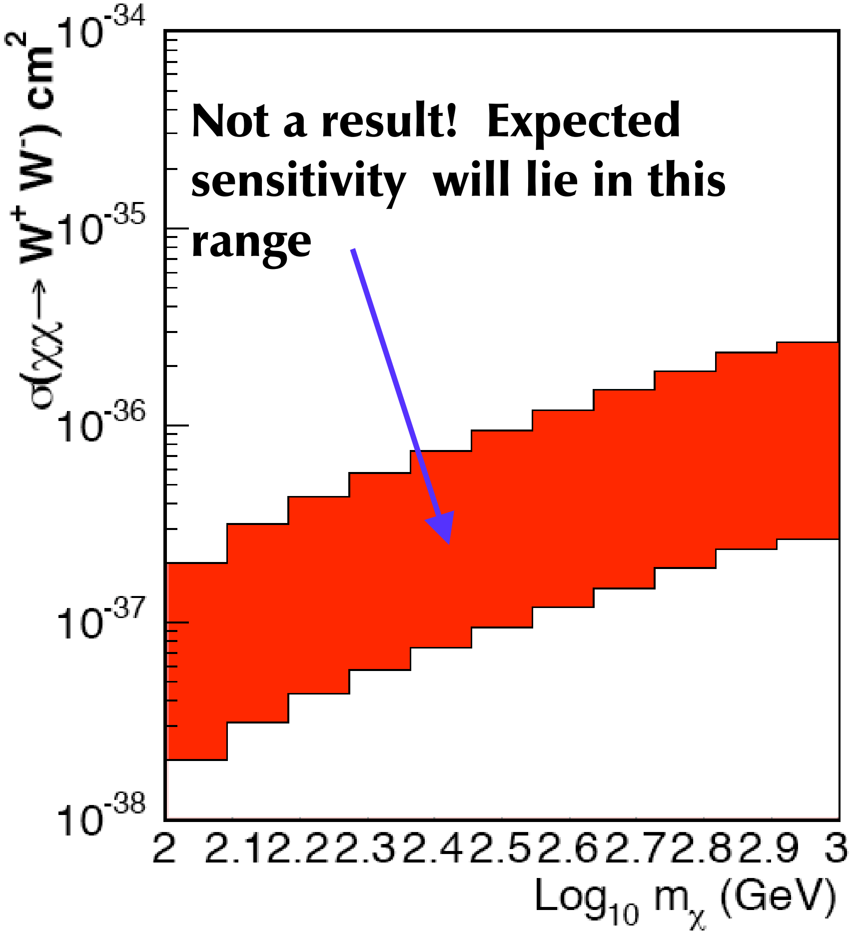
- Downward going
- |Q|=1 from both tracker and TOF
- Well fit track with 5 hits
- Not docked to MIR, not over SAA
- Good match between TOF and track





The primary background is mis-reconstructed protons (shown in red), which dominates for p>50 GeV. Owing to this, the fit is largely determined by the slope at lower energy rather than the spectral cutoff at higher energy.

Trouble here!



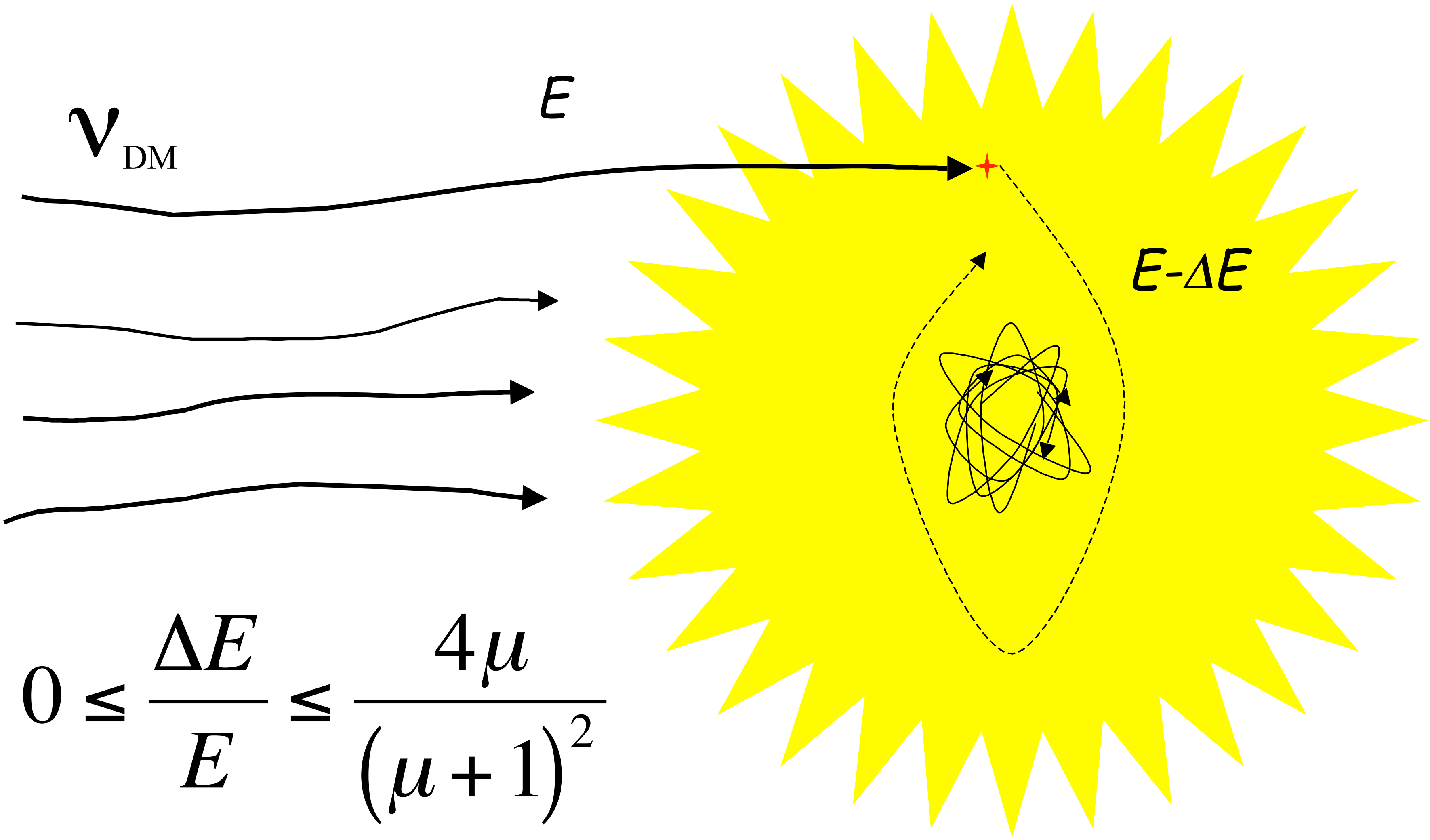
Not a result! Expected sensitivity will lie in this range

Fit for the normalization of

- **Expected electrons**
- **Expected antiprotons**
- **DM signal (electrons, antiproto from $W^{+}W^{-}$ fragmentation**

Bumps and Bangs:

Terrestrial and solar capture



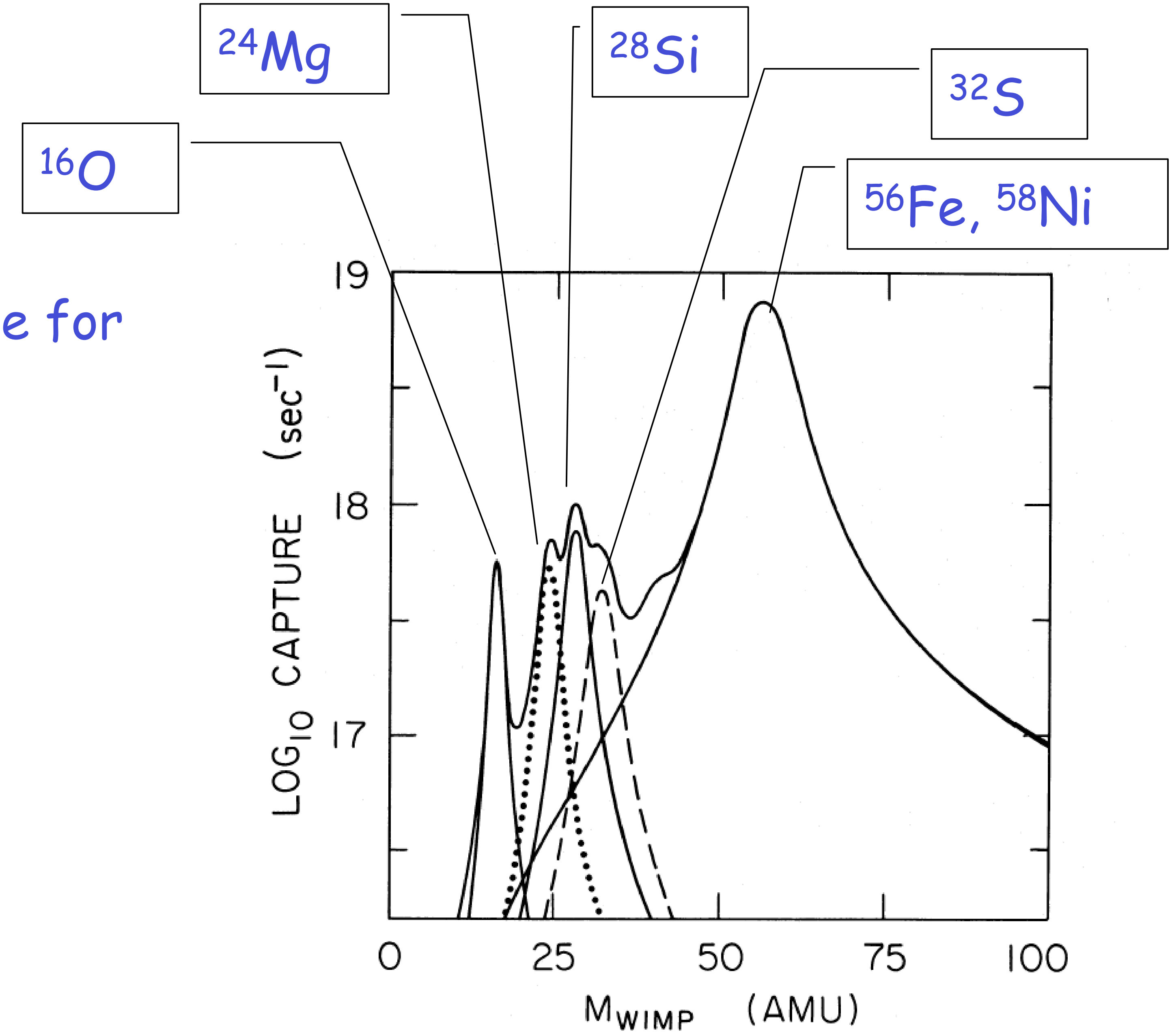
$$0 \leq \frac{\Delta E}{E} \leq \frac{4\mu}{(\mu+1)^2}$$

$$\mu = \frac{m_{DM}}{m_T}$$

Maximum when $\mu=1$, $E=\Delta E$

Most efficient energy transfer

Capture rate for Earth


^{16}O

^{24}Mg

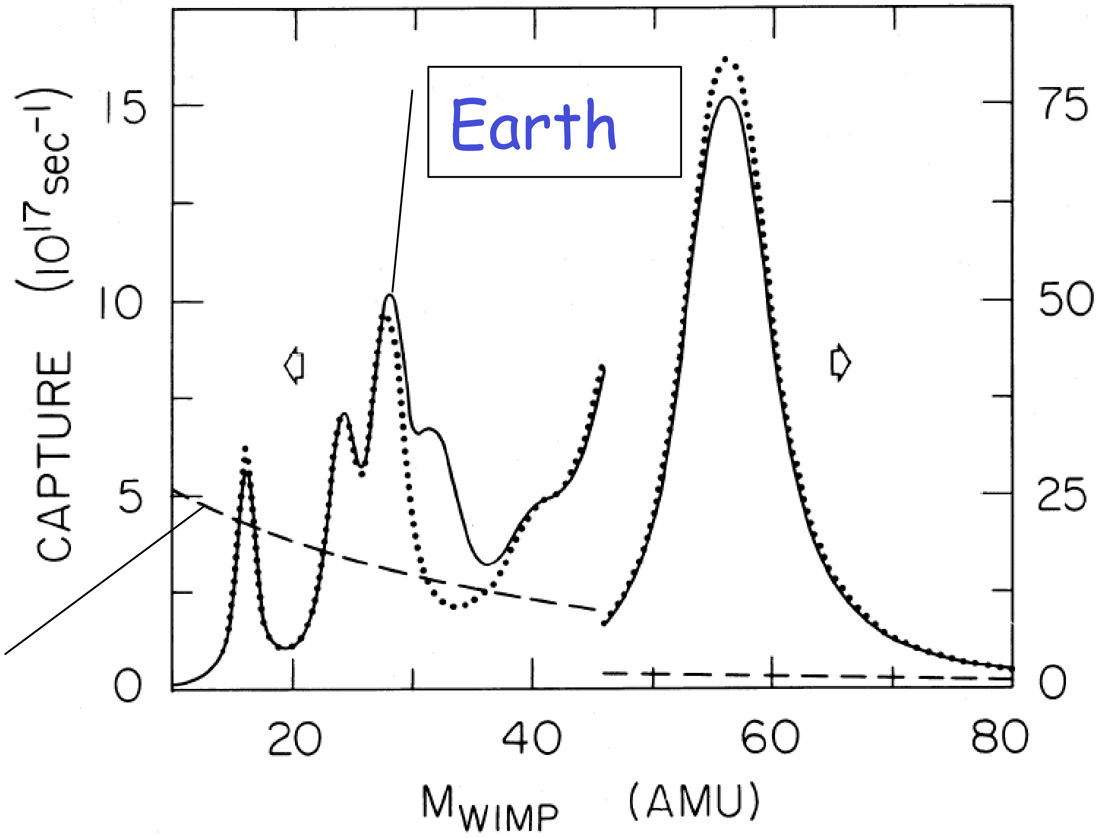
^{28}Si

^{32}S

^{56}Fe, ^{58}Ni

Capture rate for Sun is ~10^8 times higher.

Since Sun is mostly protons, no peaks and no strong suppression for Majorana type DM

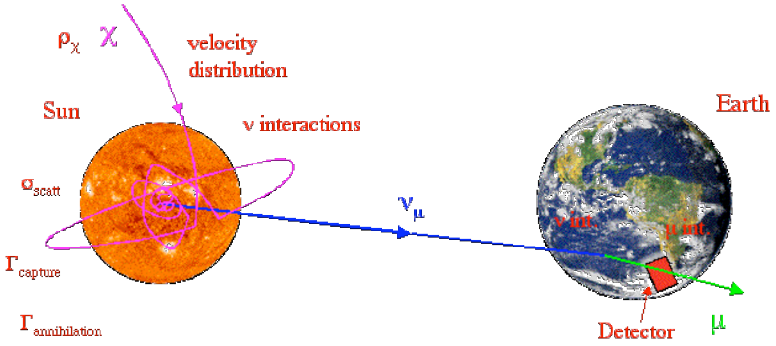


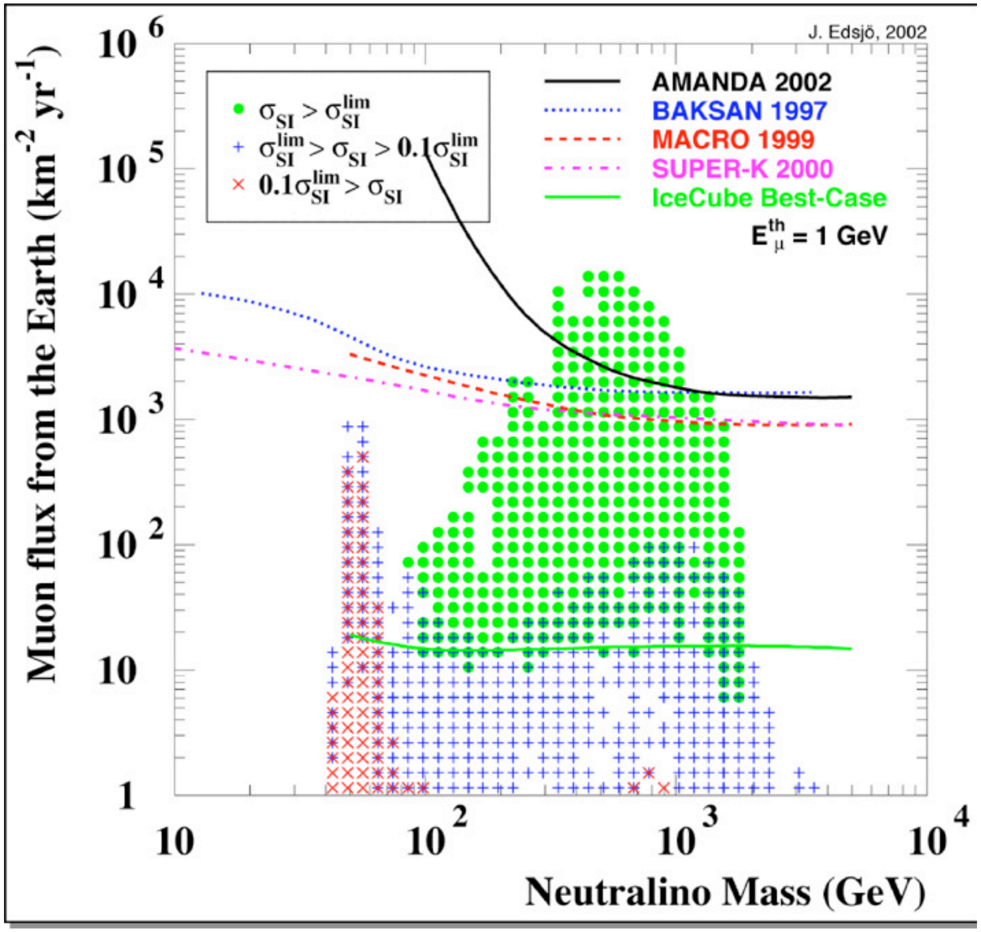
Earth

Sun (scaled by 5 10^8

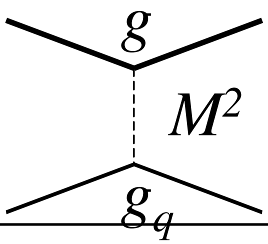
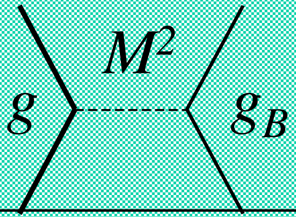
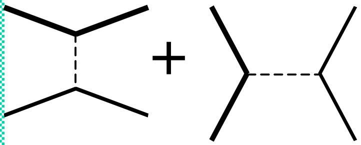
Signal is SM neutrino flux from

- The sun
- The Earth
- The center of the galaxy





Detectors: SuperK, AMANDA, ICECubed, ANTERES

	Scattering	Annihilation	Capture and Annihilation
Process			
Density	n	n^2	n^2
Rate	$g^2 g_q^2 / M^4$	$g^2 g_B^2 / M^4$	$\left(g^2 g_q^2 / M^4\right)\left(g^2 g_B^2 / M^4\right)$
Majorana/Dirac suppression	Majorana suppressed by N^2	Majorana not suppressed	Partial suppression for Majorana
Sampling	Flux at Earth now	Flux in local 3kpc now	Flux integrated over lifetime of galaxy
Experiments	CDMS CRESST ZEPLIN	AMS HEAT	SuperK AMANDA ICECube

Relics from the big bang may or may not be dark matter. The three main methods of searching for relics complement each other

- Different regions of galaxy
- Different timescales
- Different couplings

Emergence

- First clear hints will most likely come from direct detection experiments
- SD direct detection, cosmic ray and accelerator experiments will most likely elucidate distribution and species
- In absence of a discovery, galactic/solar/terrestrial capture will give the best limits.

So far, no one has seen anything.