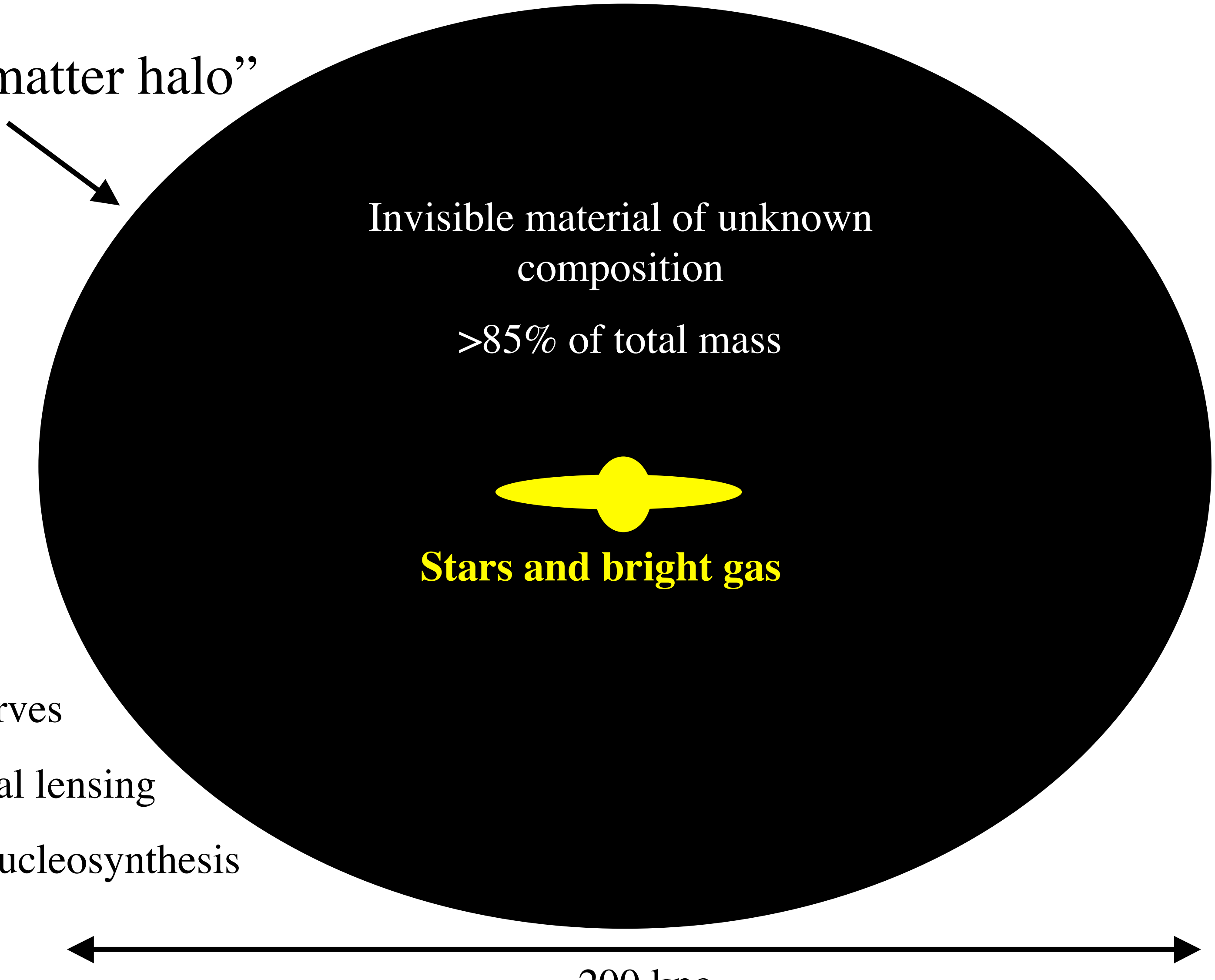
Cartoon of a Galaxy



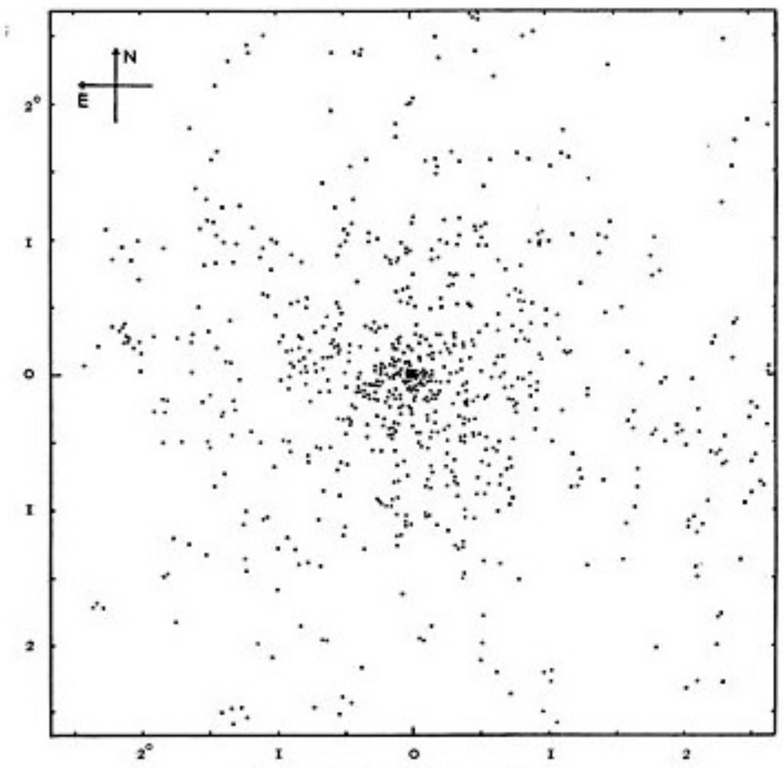
- rotation curves
- gravitational lensing
- Big bang nucleosynthesis
- CMB…

First Evidence for Large Amounts of Dark Matter: Zwicky's Estimate of Galaxy Cluster Masses (1933, 1937)

- Coma is a very big, nearby cluster with ~ 1000 galaxies, apparently dynamically relaxed.
- Relative velocities of cluster galaxies can be measured using Doppler shifts.
- Mass estimate was obtained using virial theorem:

1/2<potential energy> + <kinetic energy>=0 ➡ $M \approx \frac{2 < v^2 >< r >}{G} = 10^{13} M_{sun}$

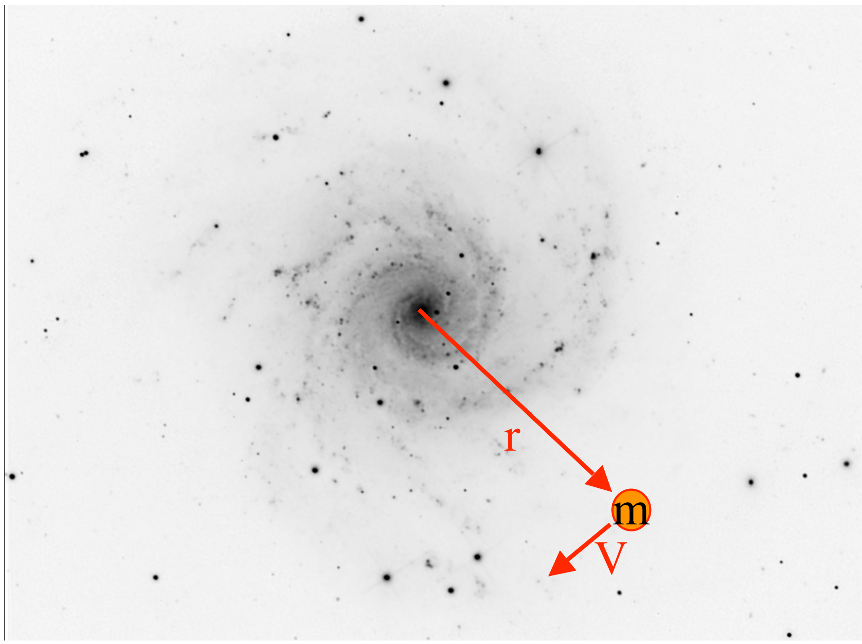
- Estimated mass was 500 times greater than expected based on galaxy counts and luminosity.



"If this is confirmed, we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter."

(Zwicky, 1933)

Rotation Curves of Spiral Galaxies



For test mass in orbit around a galaxy:

$$\frac{V^2(r)}{r} = \frac{GM(r)}{r^2}$$

Once **r** is big enough to be outside the galaxy,

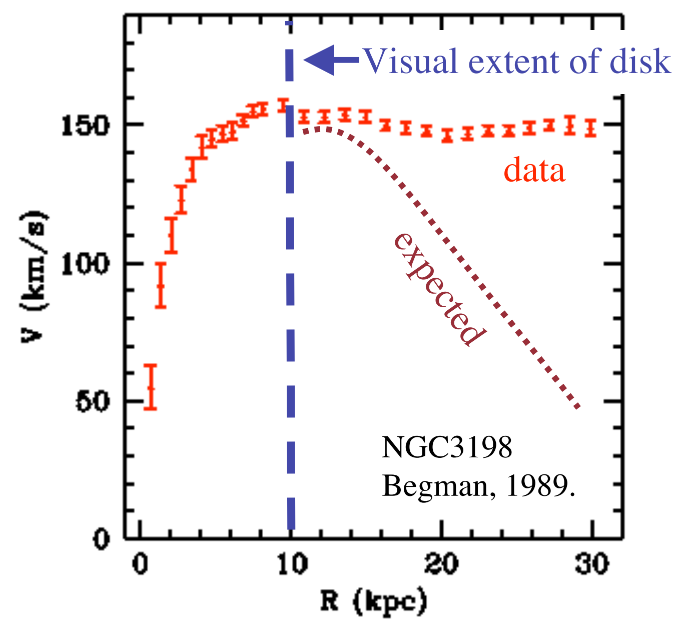
$$V(r) \propto \frac{1}{\sqrt{r}}$$

Q: What mass distribution is compatible with a flat rotation curve?

A: Spherically symmetric halo, with density

$$\rho(r) \propto \frac{1}{r^2}$$

This is the expected density for gravitationally bound ideal gas.



Dark Matter in 20th Century: a Synopsis

1933 Zwicky estimates Coma cluster mass using virial theorem and finds 500 times more than expected (but would have been only 40 times if he had used right value of Hubble constant)

1940-1970 Problem of "missing mass" largely ignored for 30 years…

Observation of galaxy rotation curves beyond optical radius show that rotation curve is still flat.

1970's Realization that the universe would not look right on large scales without dark matter.

1980s Could $\Omega_m=1$? (as required by inflation with no cosmological constant)

(definition: $\Omega_m=\rho_{matter}/\rho_{critical}$)

1990s "Golden Age of Cosmology" - vast quantities of data.

New mass estimators: strong and weak gravitational lensing.

COBE discoveres fluctuations in the cosmic microwave background (CMB).

Revolutionary discovery that cosmological constant not zero by observing supernovae.

First acoustic peak in CMB detected, confirms that universe is flat, so $\Omega_\Lambda+\Omega_m=1$.

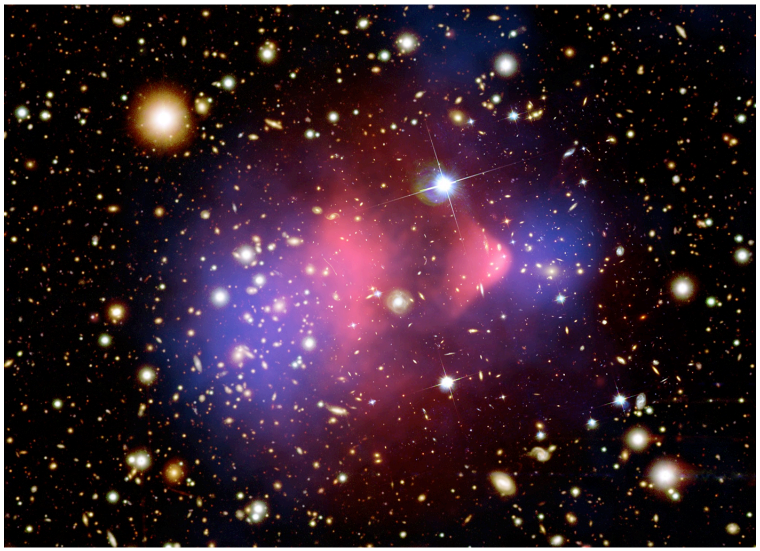
CMB + Supernovae: $\Omega_\Lambda= 0.7$ and $\Omega_m=0.3$.

Measurements of deuterium & CMB strongly constrain baryon density: $\Omega_{baryons}= 0.04$.

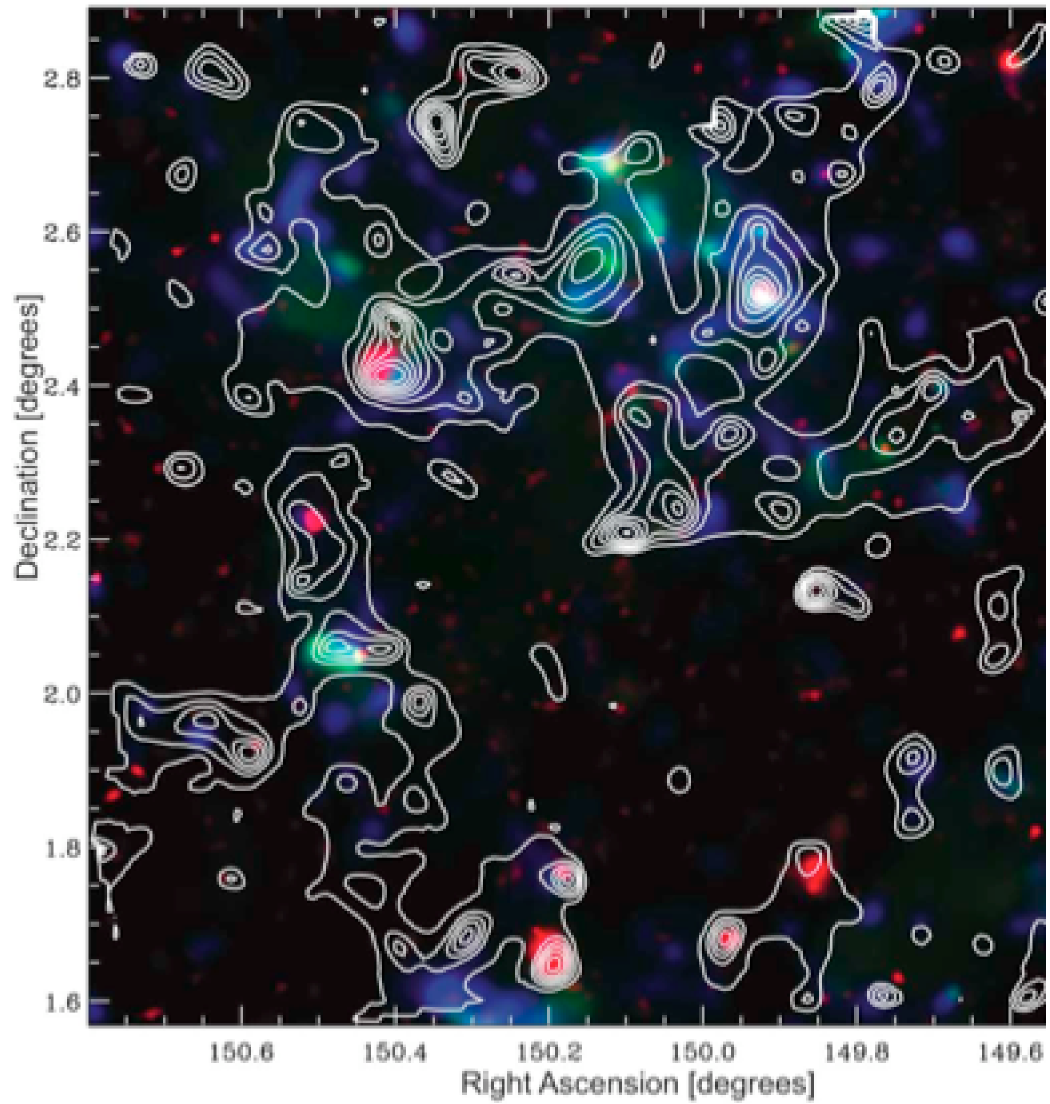
Need for non-baryonic dark matter firmly established.

2003 WMAP confirms consensus cosmological parameters.

Gravitational Lensing Maps Dark Matter



Markevitch et al., 2006



Massey et al., 2007

Dark Matter From Supersymmetry

Standard Model	MSSM Higgs	Superpartner flavor states	Superpartner mass states	
u,d,s,c,t,b		squarks		
e, μ, τ		sleptons		
ν_e,ν_μ,ν_τ		sneutrinos		
$W^\pm$		charged winos	$\chi^\pm{}_2$	Charginos
	$H^\pm$	charged higgsinos	$\chi^\pm{}_1$	
γ		photino	$\chi^0{}_4$	
Z^0		zino	$\chi^0{}_3$	Neutralinos
h	h	higgsino	$\chi^0{}_2$	
	H	higgsino	$\chi^0{}_1$	Mass: 30-1000 GeV
	A^0			
G		gravitino		

mixing

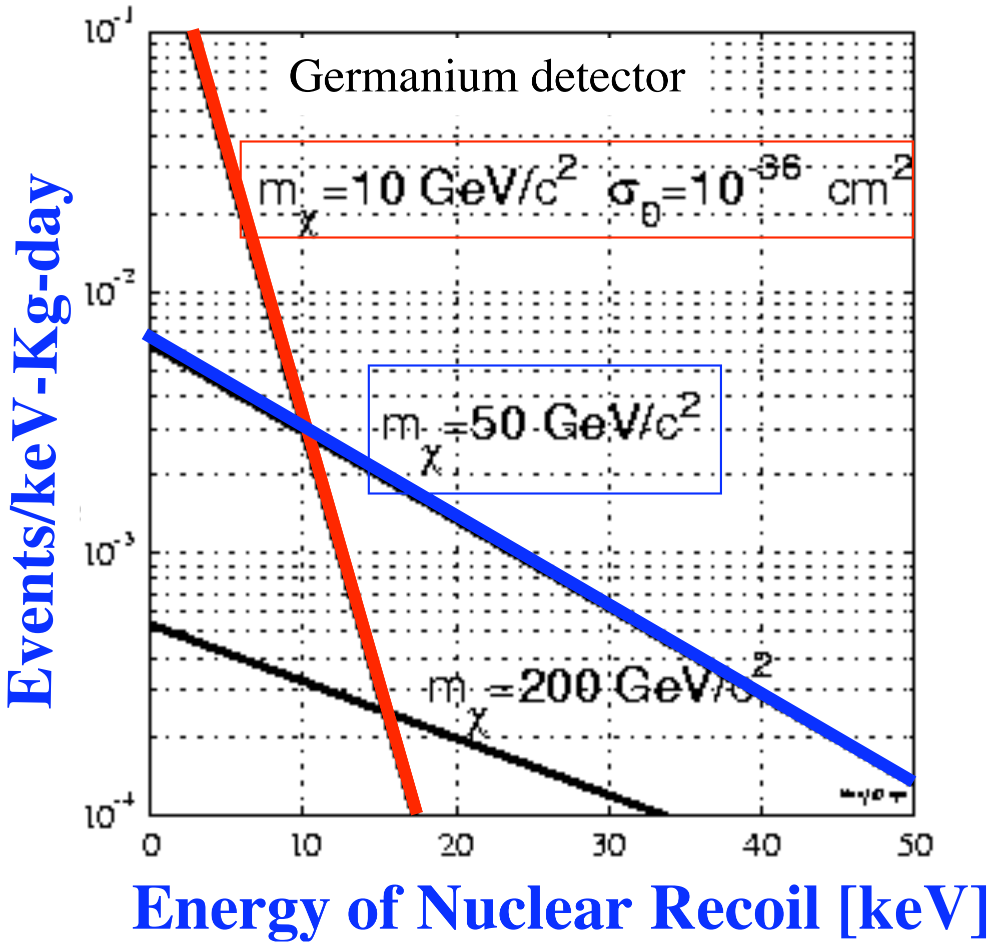
Lightest neutralino is dark matter?

Spectrum of WIMPs in a Detector on Earth

Based on simple assumptions:

- Particles are gravitationally bound to halo, with Maxwellian velocity distribution (V_{rms}=220 Km/s) and local density 0.3 GeV/cm^3
- WIMPs are heavy particles, 10 GeV< M_{WIMP}< 1 TeV.

⇨ Nuclear scattering can efficiently transfer energy to a nucleus, since $M_{nucleus}$~M_{wimp}.
The signal will be a nuclear recoil, with energy ~10 keV



- Scattering is non-relativistic.
- Shape of spectrum does not depend on particle physics inputs.
- Amplitude of spectrum depends on unknown supersymmetry parameters and some astrophysical uncertainties.

Spin-Dependent and Spin-Independent Interactions

• In non-relativistic limit, the axial vector, vector and scalar couplings become simply spin-dependent and spin-independent-- either the scattering amplitude flips sign when you flip a spin or it doesn't.

• Interaction coherent over target nucleus, because de Broglie wavelength of Wimp is big:

$$\lambda = \frac{h}{m_\chi v_\chi} = 0.9\ fm \left(\frac{100\ GeV}{m_\chi}\right)\left(\frac{220\ km/s}{v_\chi}\right)$$

• Nuclear shell model: nucleons in the nucleus are arranged in opposite spin pairs.

• Spin-dependent cross section is suppressed by cancellation of pairs of opposite spin nuclei, so coupling is effectively to net total nuclear spin.

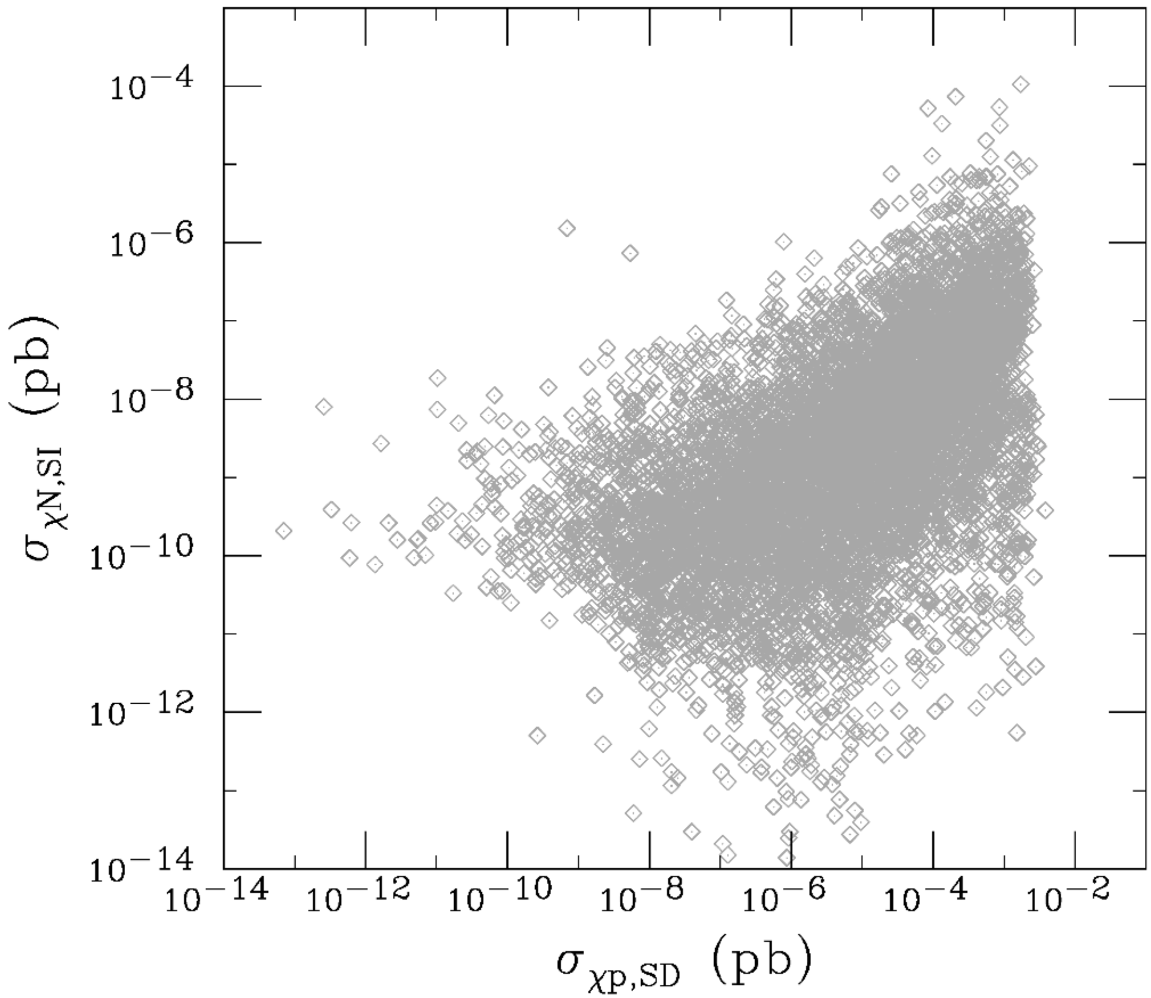
• For spin-independent coupling, cross section is proportional to A^2
(A = number of protons and neutrons).

• If the two couplings are similar in strength, detection via spin-independent scattering on a high- A nucleus is easier.

Parameter Scan of Spin-independent and Spin-dependent Couplings in MSSM

• The spin-dependent couplings tend to be larger, sometimes *much* larger.

• Therefore, experiments optimized for spin-dependent sensitivity play an important role, despite the A^2 boost in sensitivity for the spin-independent searches.

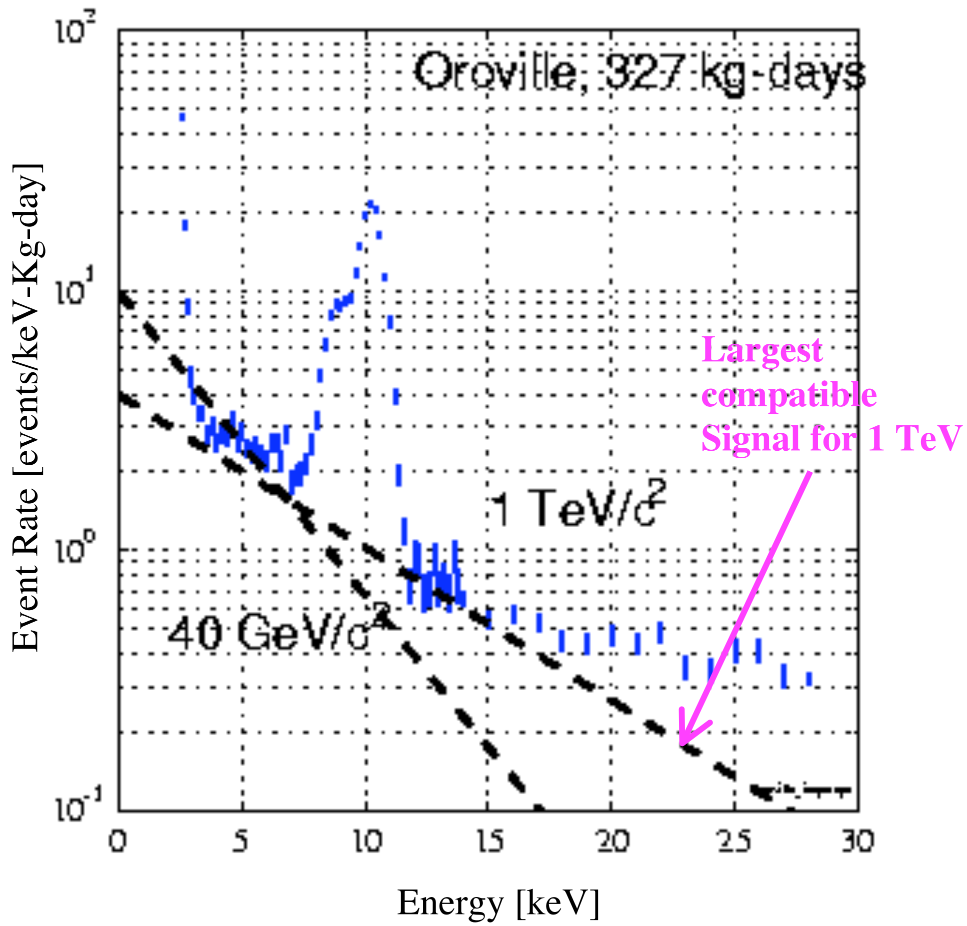


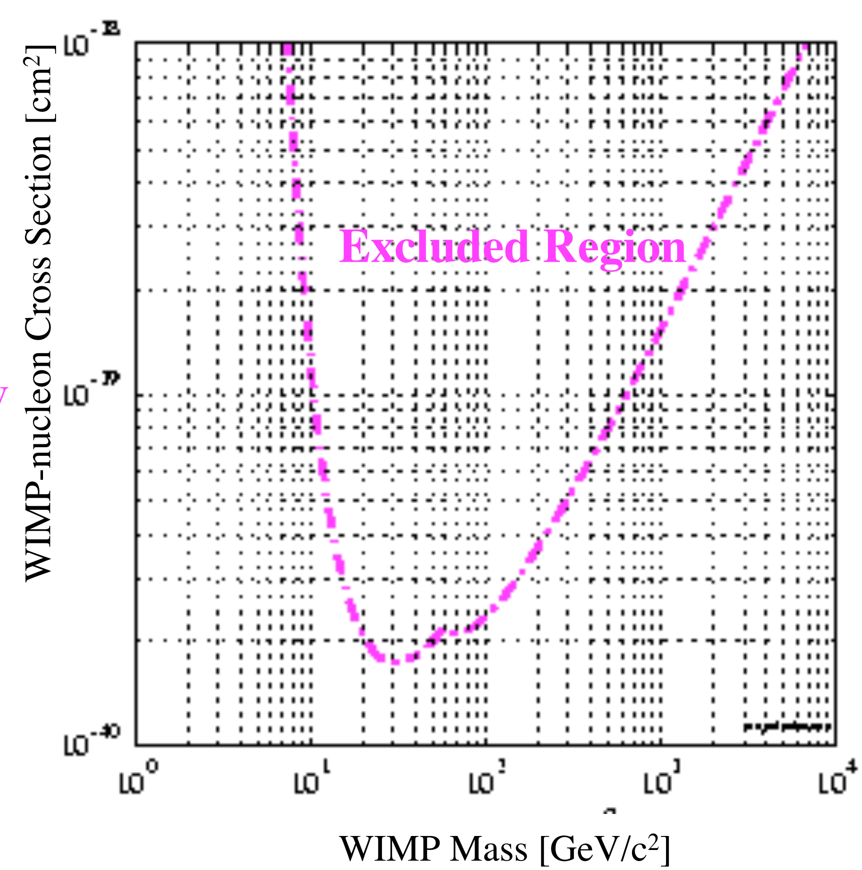
Halzen & Hooper, 2005

What Determines Sensitivity?

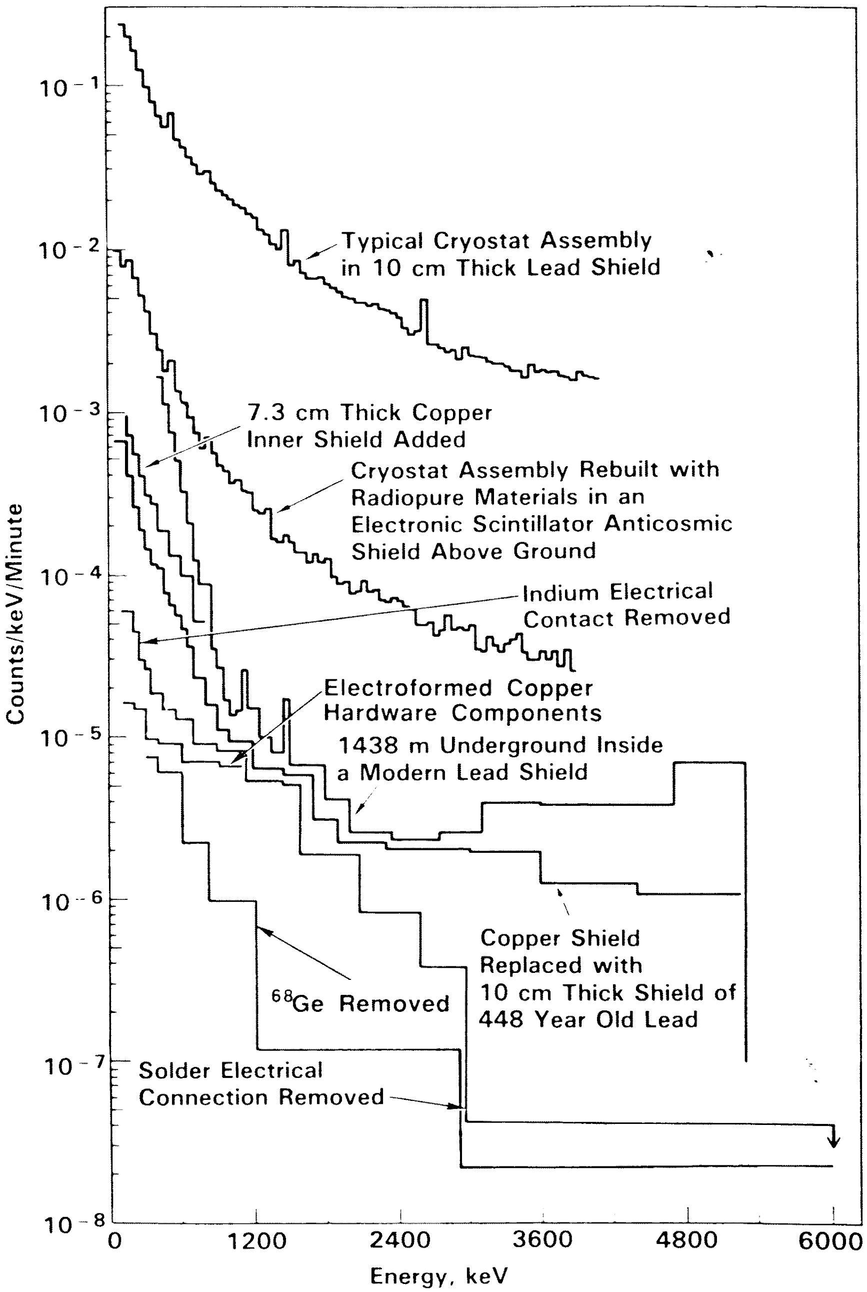
- Construction of sensitivity plot is illustrated with data from an early experiment.
- Environmental radioactivity limits sensitivity.

Assume halo density 0.3 GeV/cm^3





Backgrounds from Radioactivity and Cosmic Rays



- A long history of successful attempts to reduce by choosing special materials and shielding.

Gammas & betas

From primordial, cosmogenic, and manmade nuclei: (not an exhaustive list!)

^{238}U, ^{232}Th + daughters (incl. ^{222}Rn)

^{40}K, ^{14}C

^{85}Kr, ^{137}Cs, ^{3}H - nuclear tests

^{68}Ge, ^{60}Co - cosmogenic in detector setups

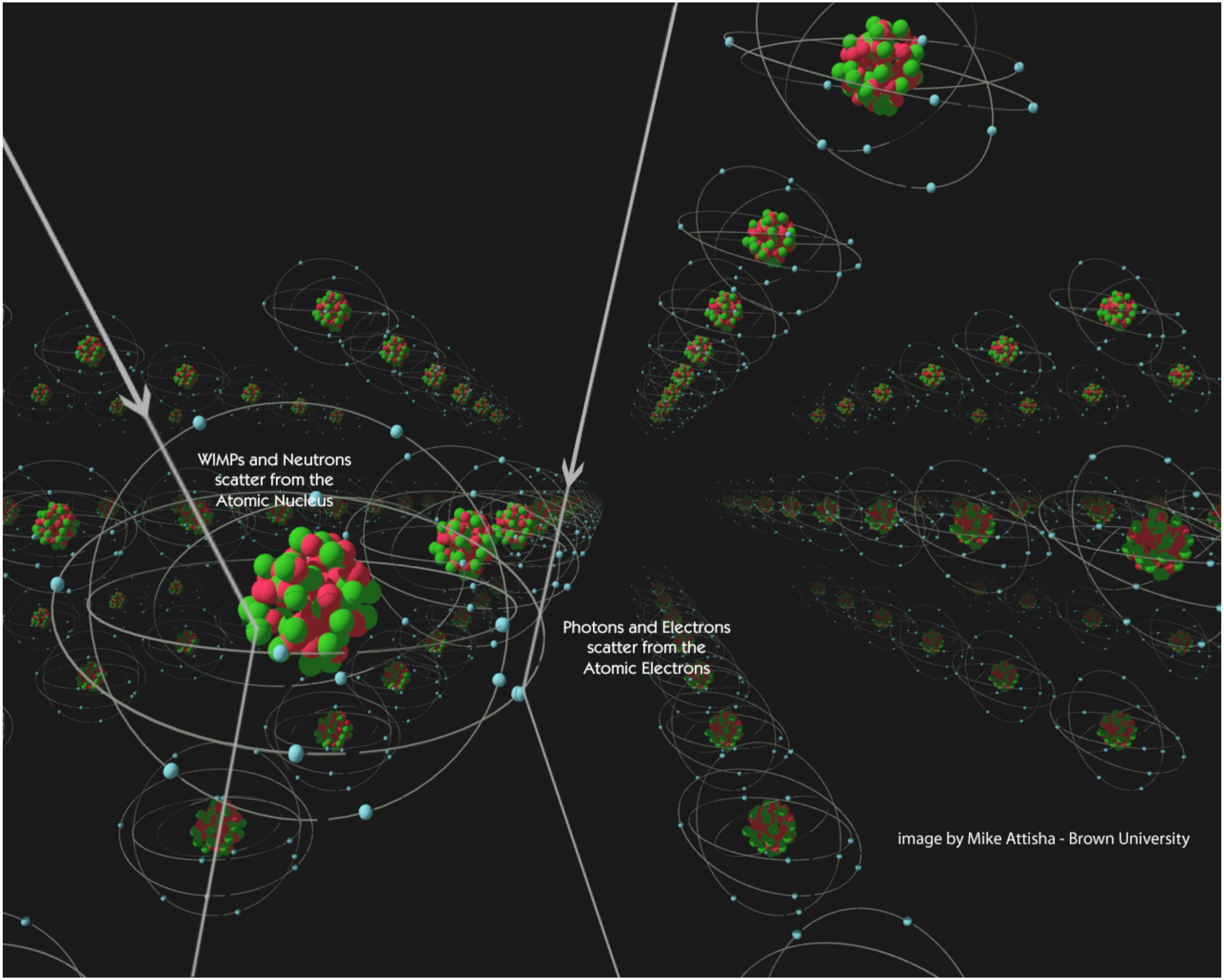
Cosmic Rays (p, π , μ, e…)

Can be reduced by going underground.
The μ's penetrate to great depth.

Neutrons

From μ spallation or (α, n) reactions in rocks, with alphas from U/Th chains. Can be shielded with moderator at low energies.

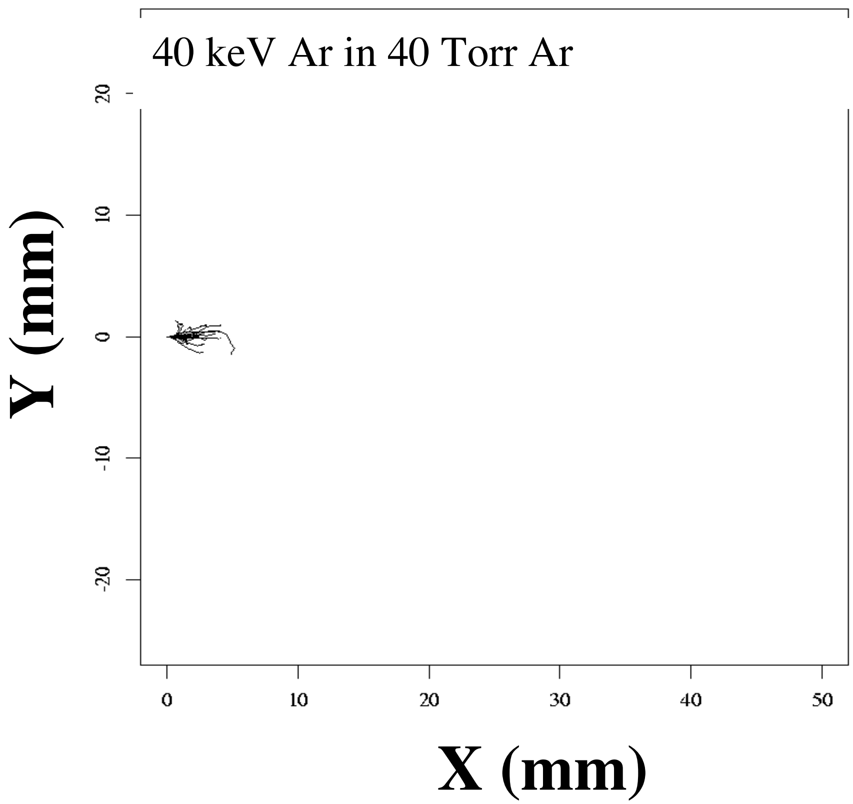
(figure from Brodzinski et al, Journal of Radioanalytical and Nuclear Chemistry, 193 (1) 1995 pp. 61-70)

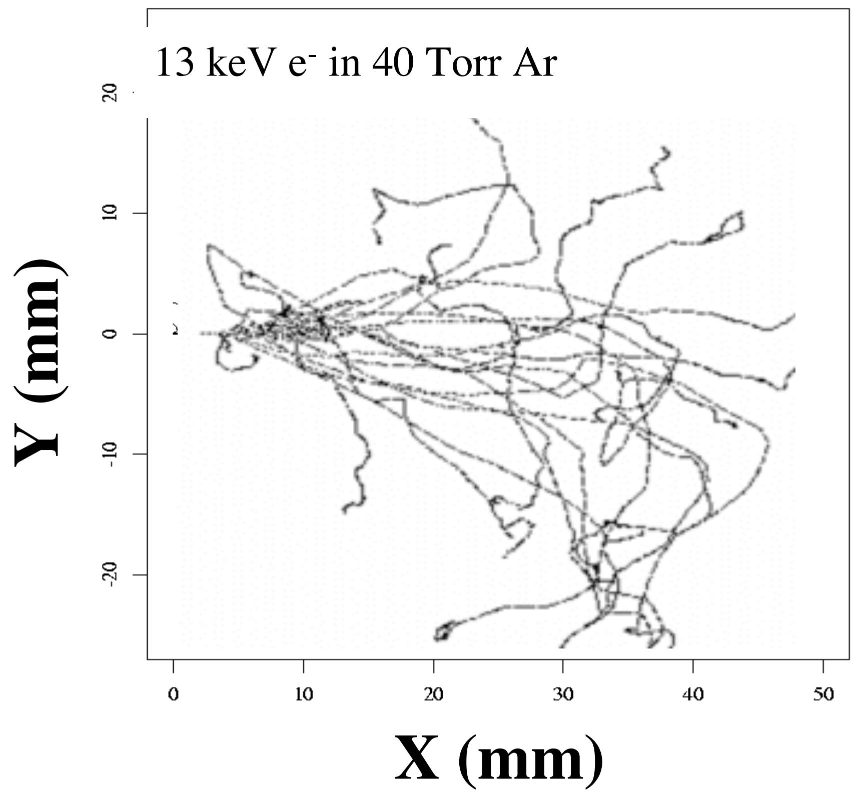

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons
image by Mike Attisha - Brown University

Discriminating Against Backgrounds

• WIMPs interact with the **nucleus**, while most backgrounds are due to **electron scattering** by gamma and beta rays.

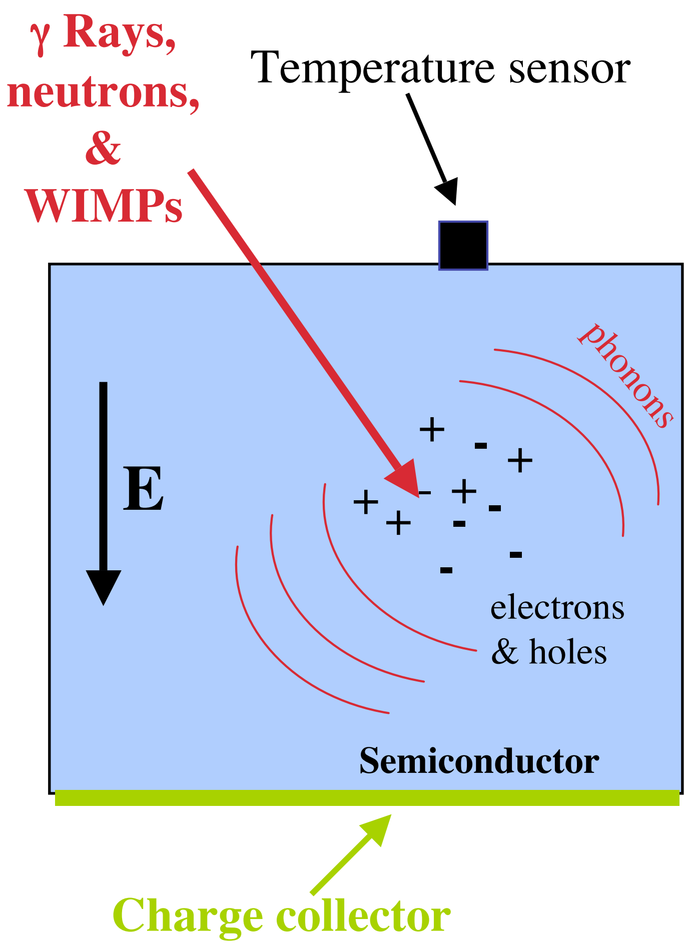
• The resulting spatial distributions of energy and charge are very different-- this is fundamental physical basis of most discrimination techniques.

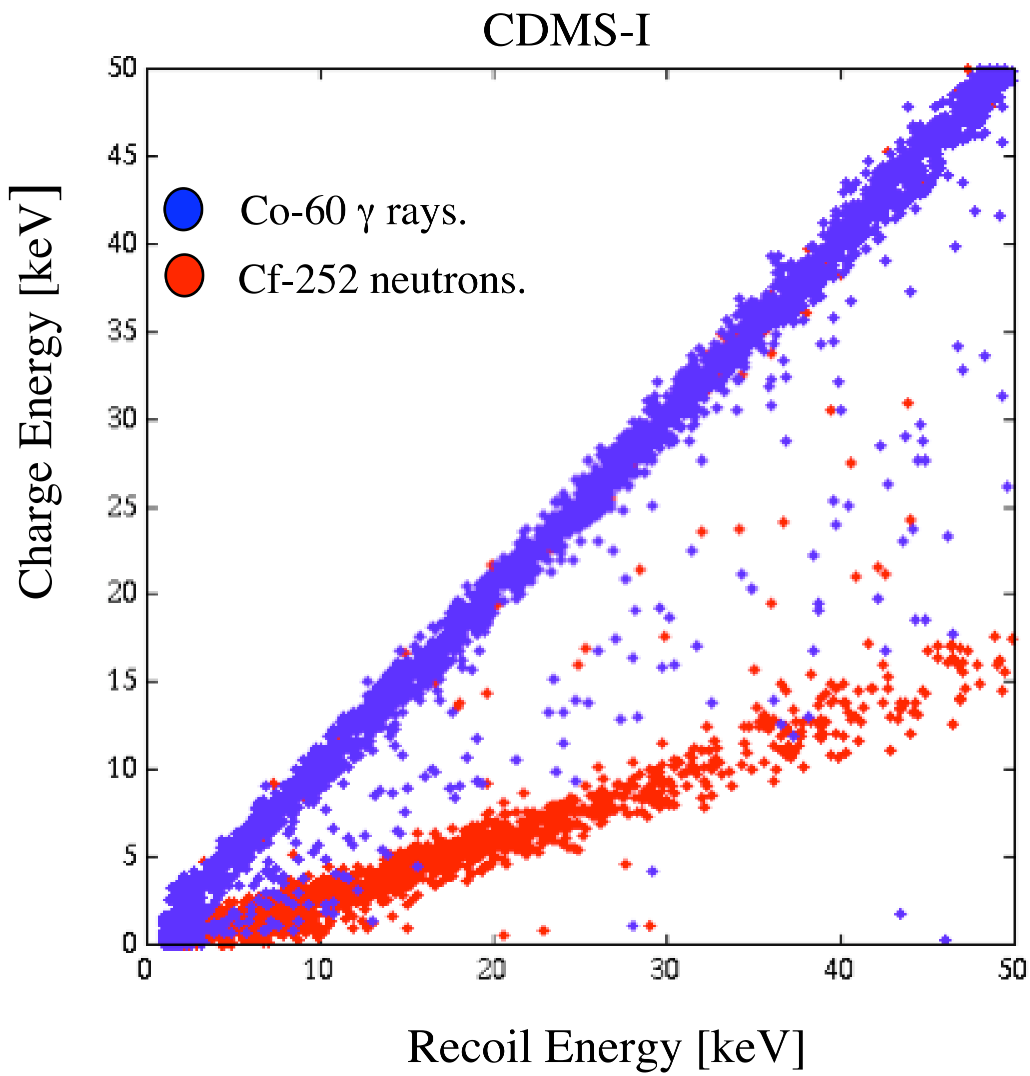




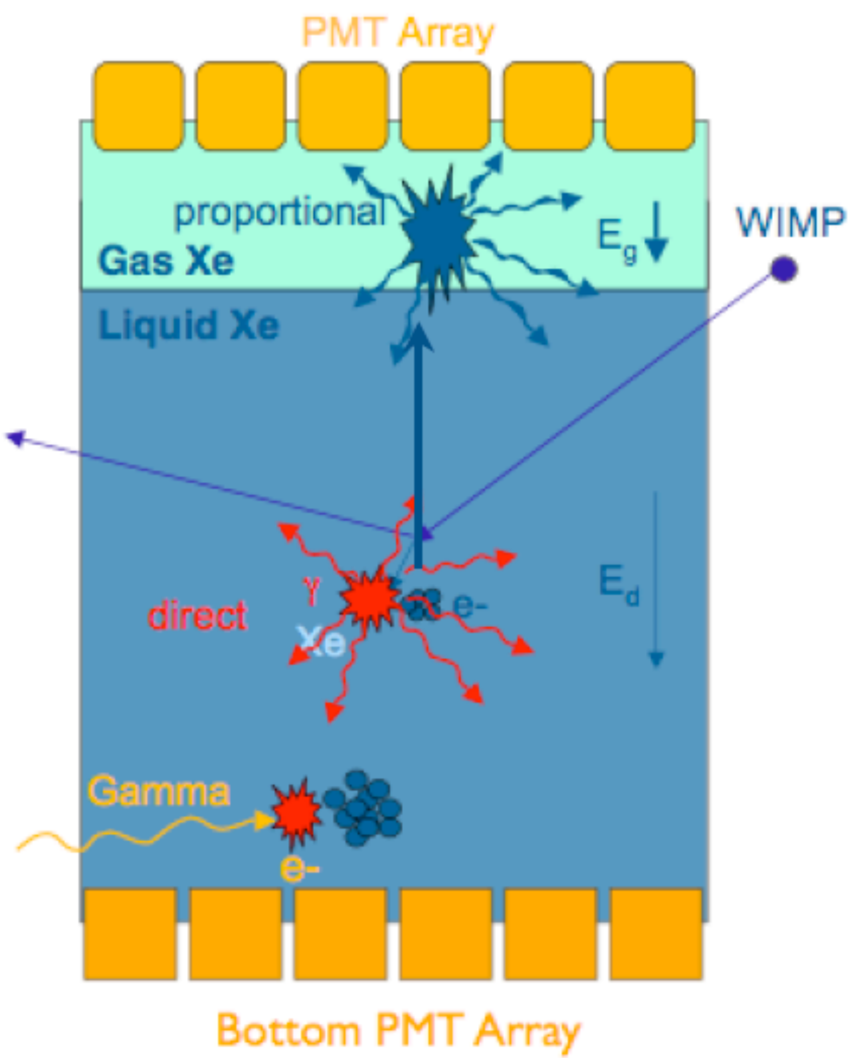
(Figures from DRIFT collaboration)

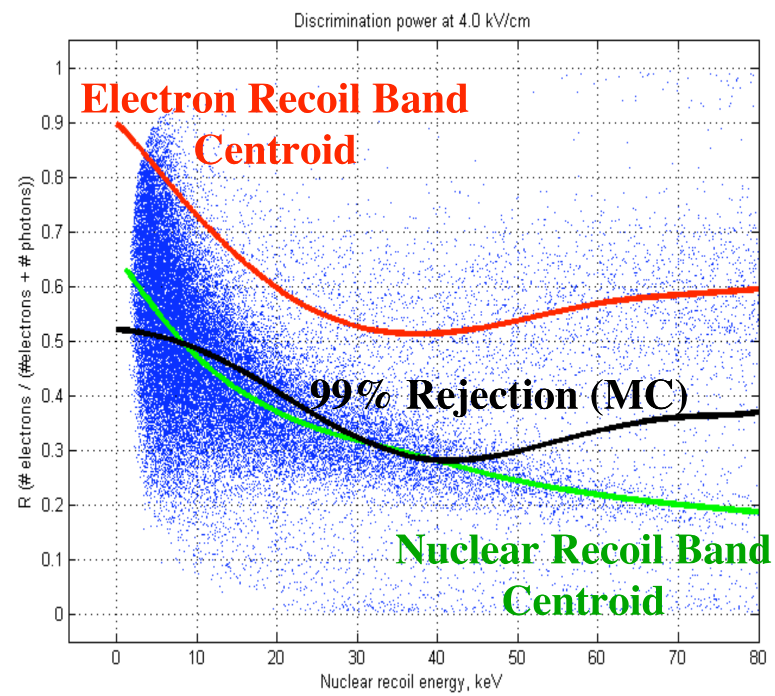
Background Discrimination With CDMS Cryogenic Detectors





Liquid Xenon

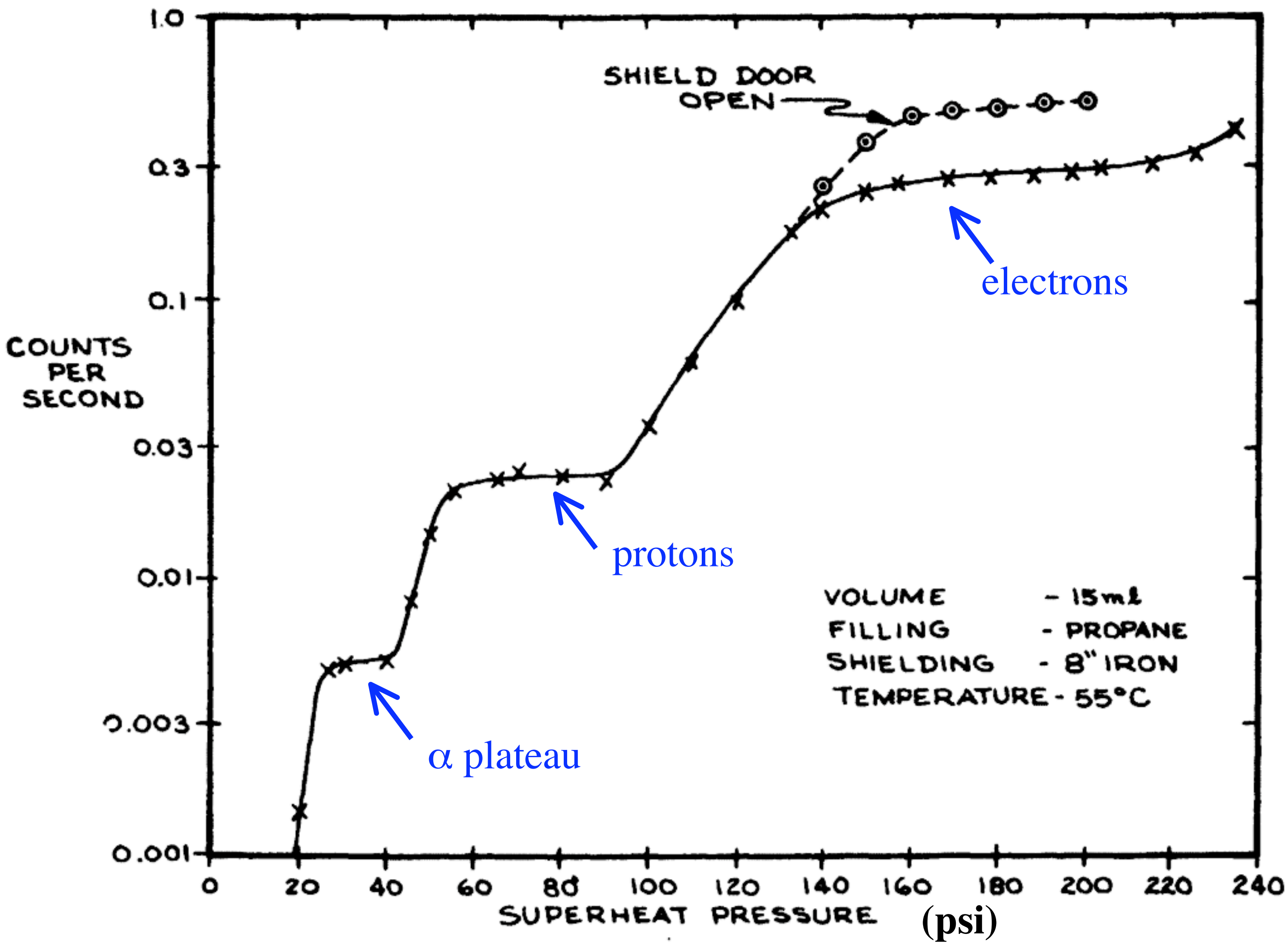




Observables Which Could be Used to Separate WIMP-nucleus Events from Backgrounds

- Spatial distribution of charge deposited in a low-pressure drift chamber.
- Ratio of ionization to deposited energy in a cryogenic detector (CDMS).
- Pulse shape discrimination in scintillating materials (organic & inorganic).
- Ratio of ionization to scintillation in liquid noble gases.
- Ratio of scintillation to deposited energy in a cryogenic detector.
- Annual modulation due to motion of Earth around the Sun.
- Daily modulation in direction of ion tracks in a low-pressure drift chamber, due to rotation of the Earth.
- **Efficiency for bubble formation in superheated liquids (bubble chambers).**

Background Discrimination in Bubble Chambers

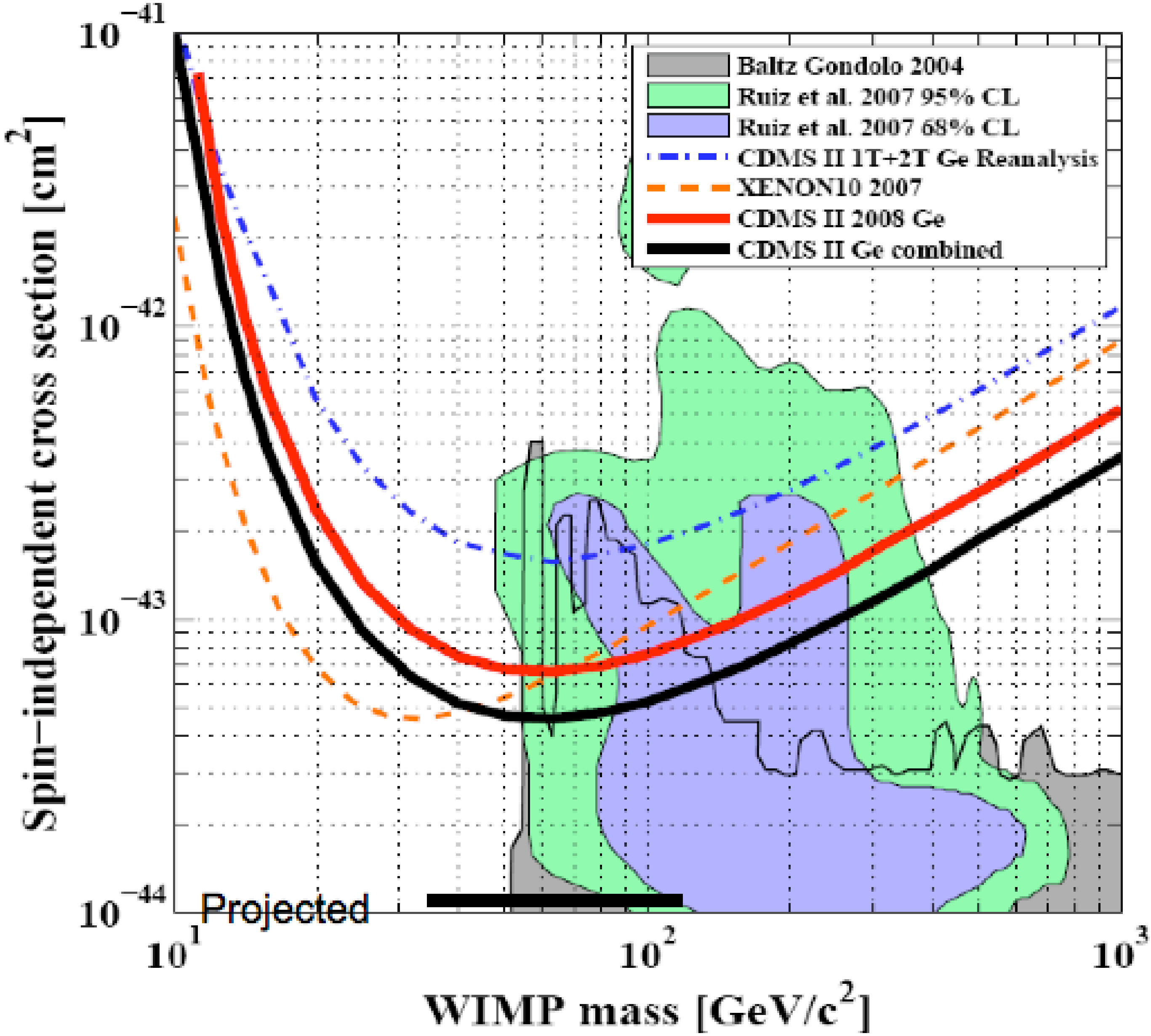


Waters, Petroff, and Koski, IEEE Trans. Nuc. Sci. 16(1) 398-401 (1969)

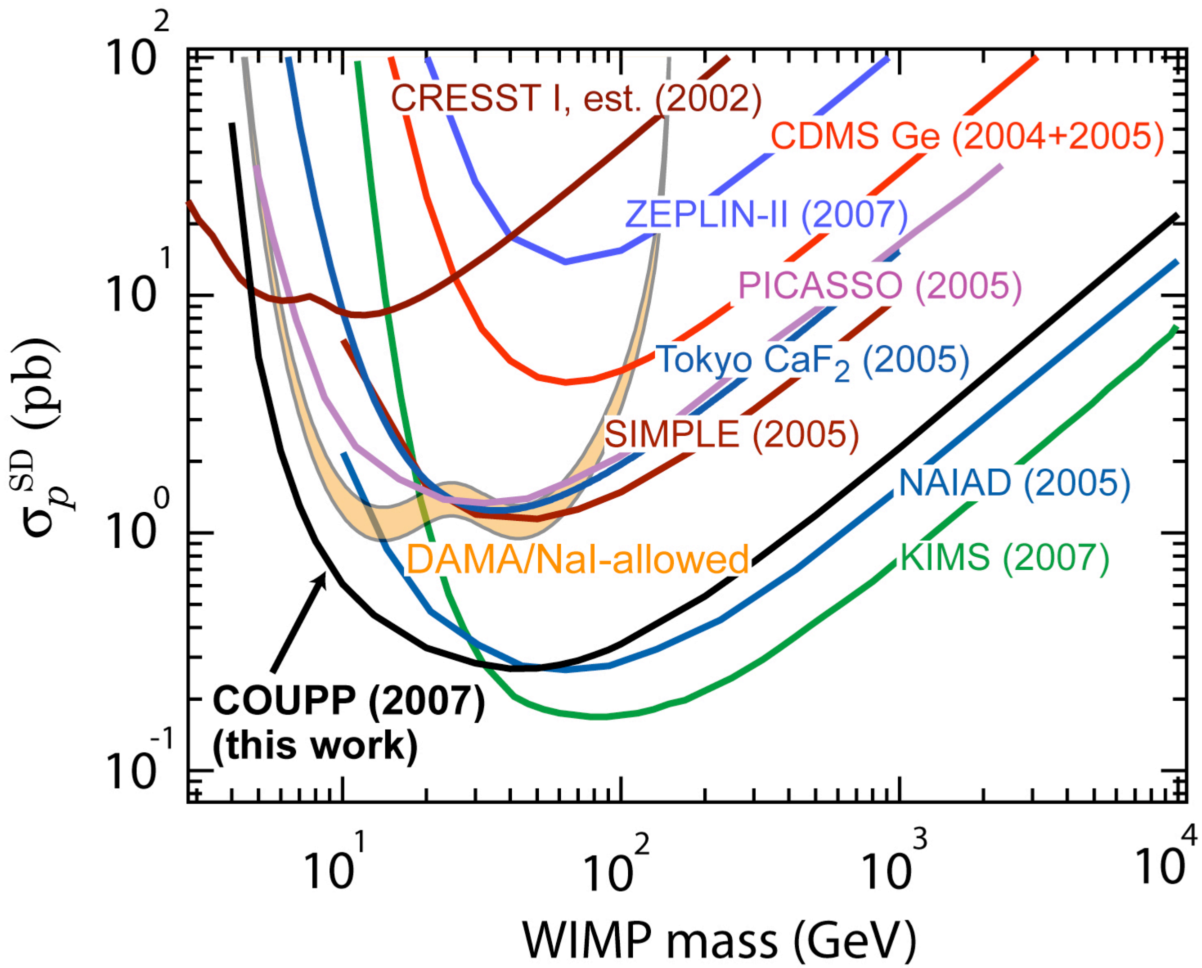
Technology Choices for Dark Matter Detection

<u>Technique</u>	**<u>Good features</u>**	**<u>Bad features</u>**
Cryogenic detectors CDMS, Edelweiss	Excellent to good (>99.9%) discrimination for alpha, beta, gamma	High cost, difficult to manufacture, scale up
Xenon TPC + Scintillation Xenon, Lux	Scalability, Easy cryogenics, high Z, good position resolution	Modest discrimination for beta, gamma (99%), expensive
Argon, scintillation only DEAP	Excellent discrimination for alpha, beta, gamma	Radioactivity of Ar-39
Argon TPC + Scintillation WARP, ARDM	Best discrimination	Radioactivity of Ar-39?
Bubble chamber **COUPP** PICASSO	Low cost, easy to scale best spin target (F) gamma discrimination	Alpha backgrounds
Drift chambers DRIFT	Directionality!	Small target mass

Spin-Independent Exclusion Limit



Spin-Dependent Sensitivity



Science, 319: 933–936 (2008).

Unique Role for Bubble Chambers

- Best spin-dependent sensitivity, due to efficient use of fluorine target.
  - No other technique very compelling for this.

- Potentially the best spin-independent sensitivity if alpha backgrounds can be low or additional discrimination methods are proven.
  - Solar neutrino experiments have demonstrated alpha backgrounds in liquid scintillator about 4 orders of magnitude lower than the published COUPP- 2 kg sensitivity.
  - Background reduction based on analysis of acoustic signals is extremely promising (Levine talk)
  - Scintillating bubble chambers also very promising, though work is needed to identify appropriate target liquids.

- Changing target liquids probes nature of WIMP-nucleon coupling.

- Lowest cost per kg of target material, by far.

  About 2 orders of magnitude lower than cryogenic detectors, 1 order of magnitude lower than liquid noble gases.