

# Hot on the Tail of the Elusive WIMP : Dark Matter Searches in the 21<sup>st</sup> Century

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2006 MIT Astrophysics Colloquium

# Outline of Talk

Very Brief intro

- Cosmology Today

Principles of Detection

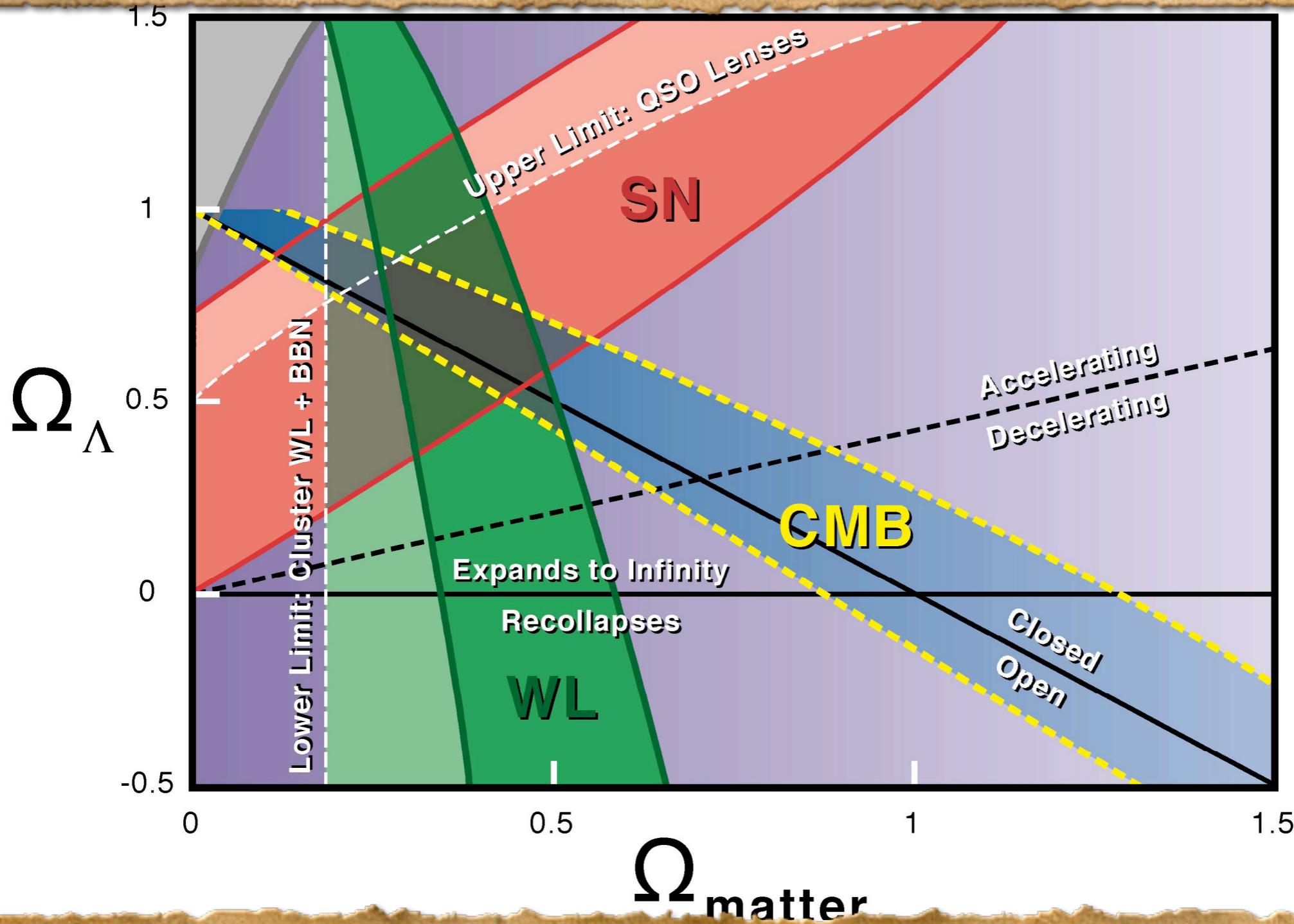
- Indirect Detection
- Direct Detection

Experimental implementations

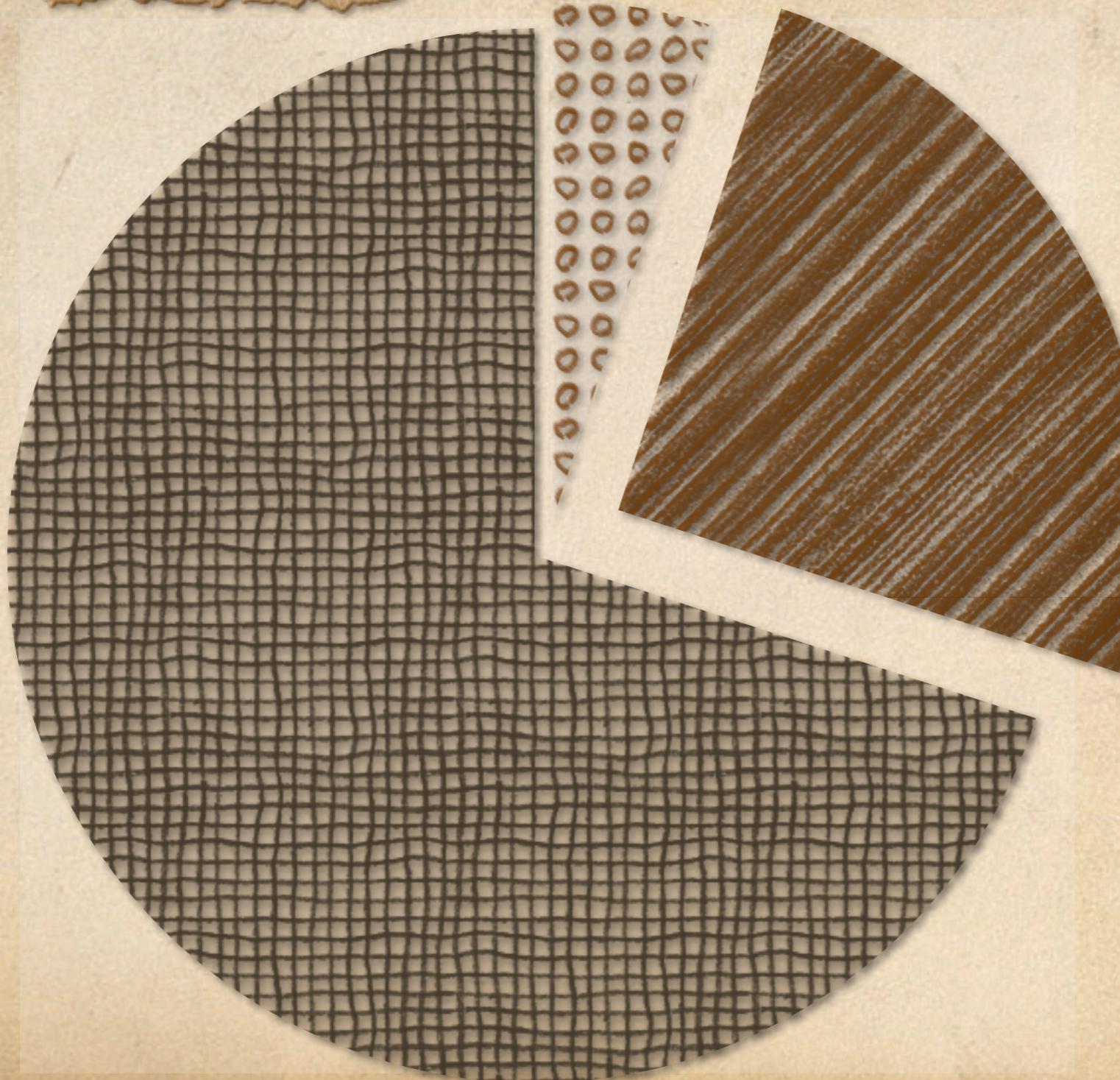
- CDMS, XENON, ...

Complementarity with  
Colliders : LHC / JLC

# Today's Cosmology



# Matter - Energy Budget



Weakly Interacting  
Massive Particles

- Baryons
- Dark Matter
- Dark Energy

$$\sum \Omega = 1$$

# Chasing the Neutralino

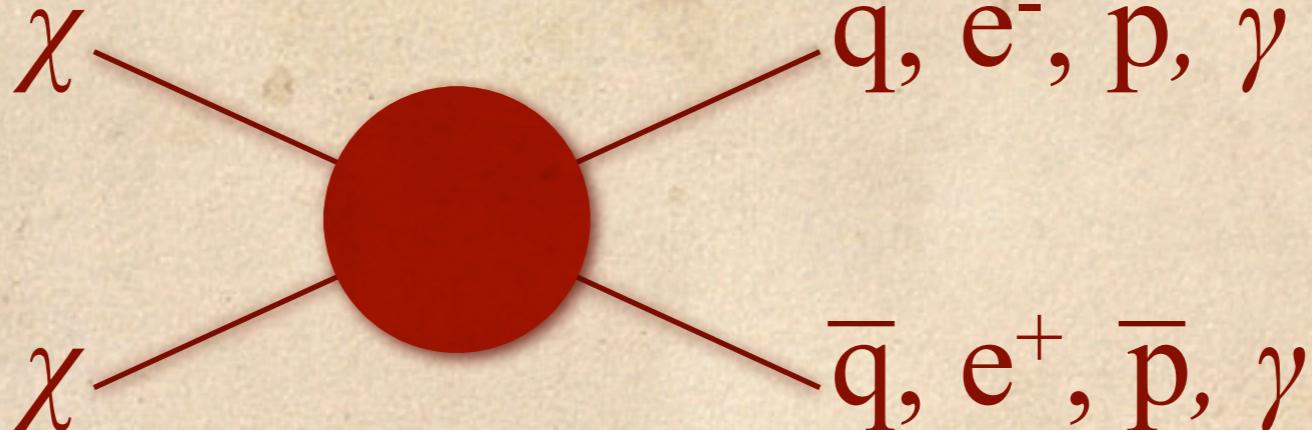
- We “know” that Dark Matter must
  - Have some mass
  - Have been non-relativistic early on in cosmological time
  - Has a certain annihilation cross section
- There exists several theoretical candidates for such a particle
- This talk will focus on one particular candidate
  - The lightest supersymmetric particle commonly referred to as the neutralino

$\chi$



# Principles of Indirect Detection

# Principles of Indirect Detection


$$\phi = \frac{\langle \sigma_{ann} v \rangle \rho_\chi^2}{m_\chi^2} g$$

Input from particle physics

$\sigma_{ann}$  : annihilation cross section

$m_\chi$  : WIMP mass

Input from Astrophysics

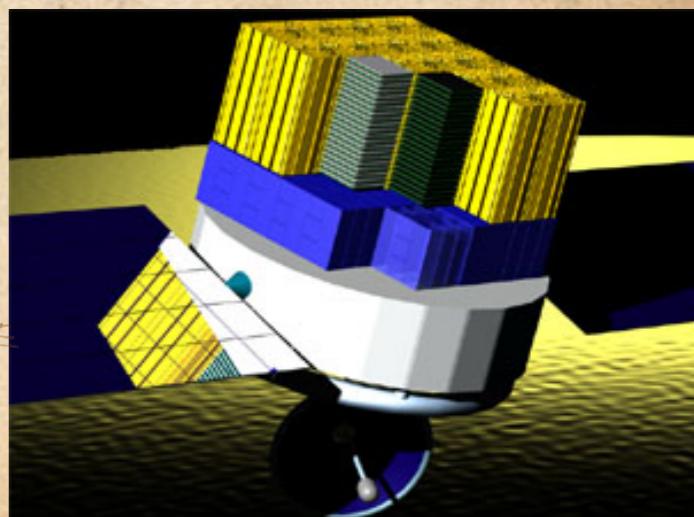
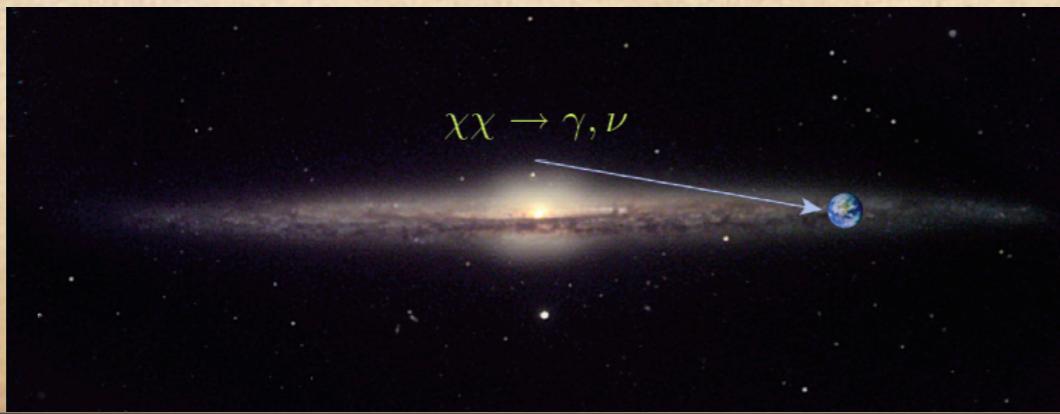
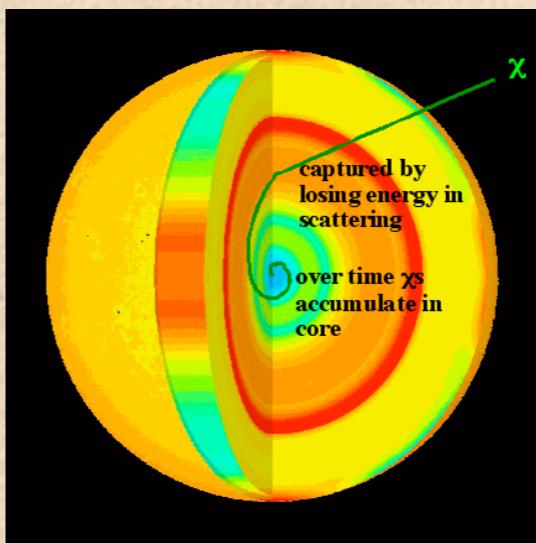
$\rho$  : WIMP density at source

$v$  : WIMP velocity at source

$g$  : Propagation factor to earth

# A couple of places to look

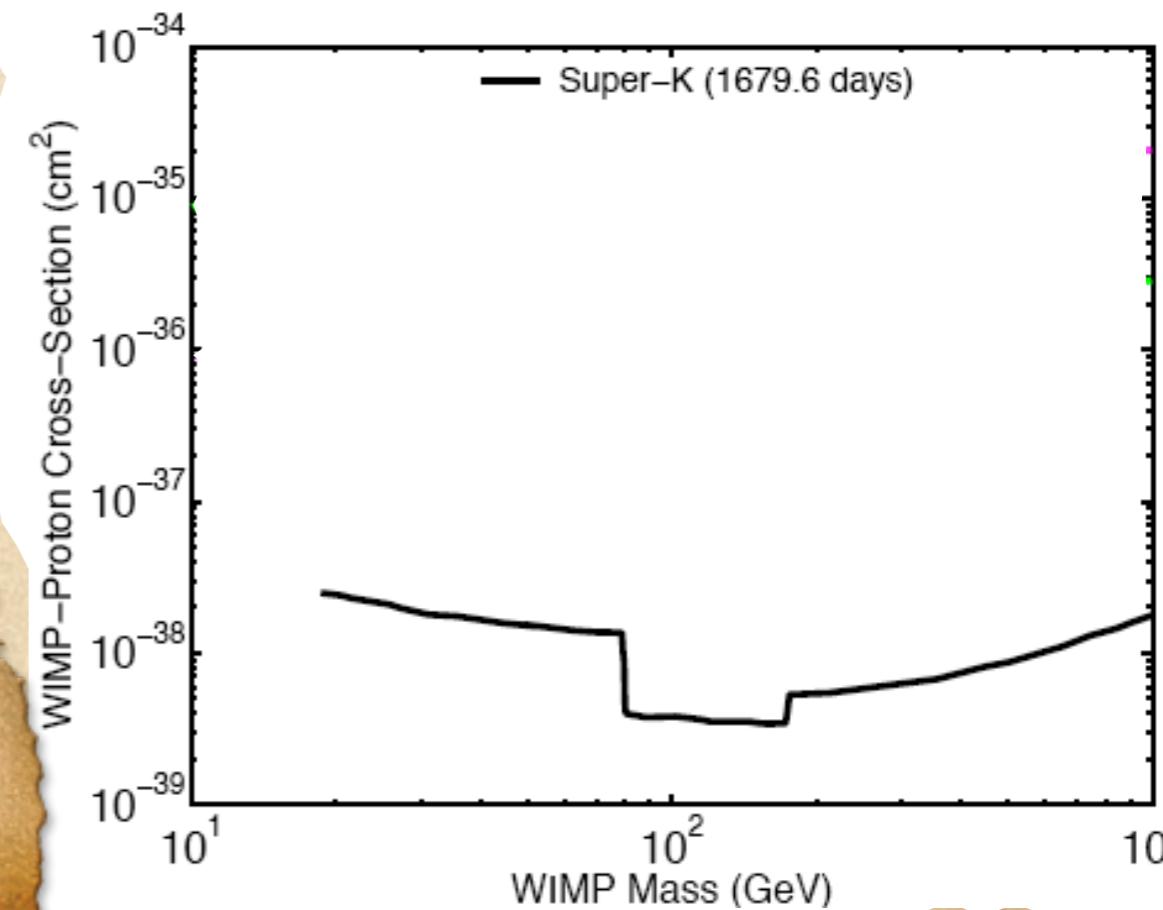
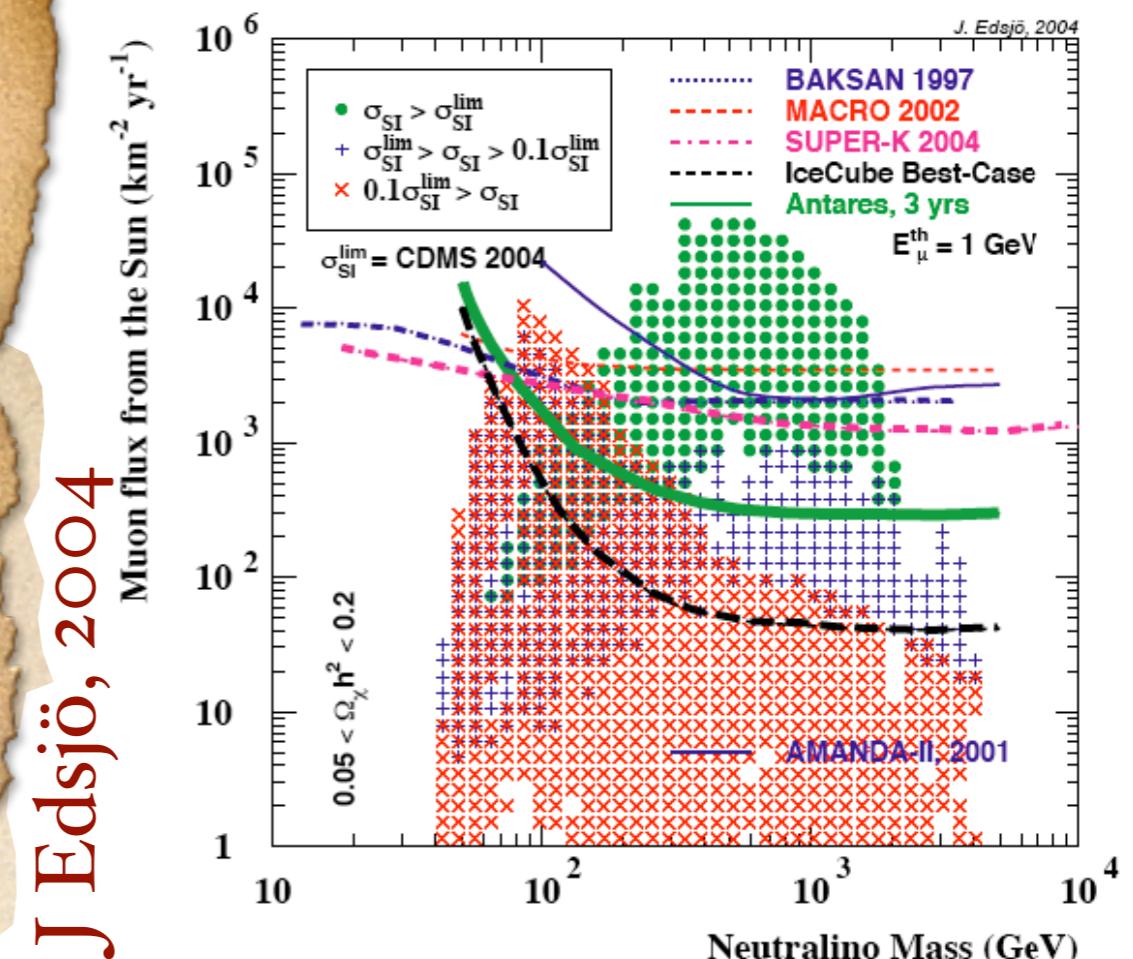
- ♦ Neutrinos from the Earth's & Sun's center
  - Super-K,
  - IceCube :
    - Looking for WIMPs in Antarctica
- ♦ Galactic and extra-galactic gammas
  - EGRET, GLAST

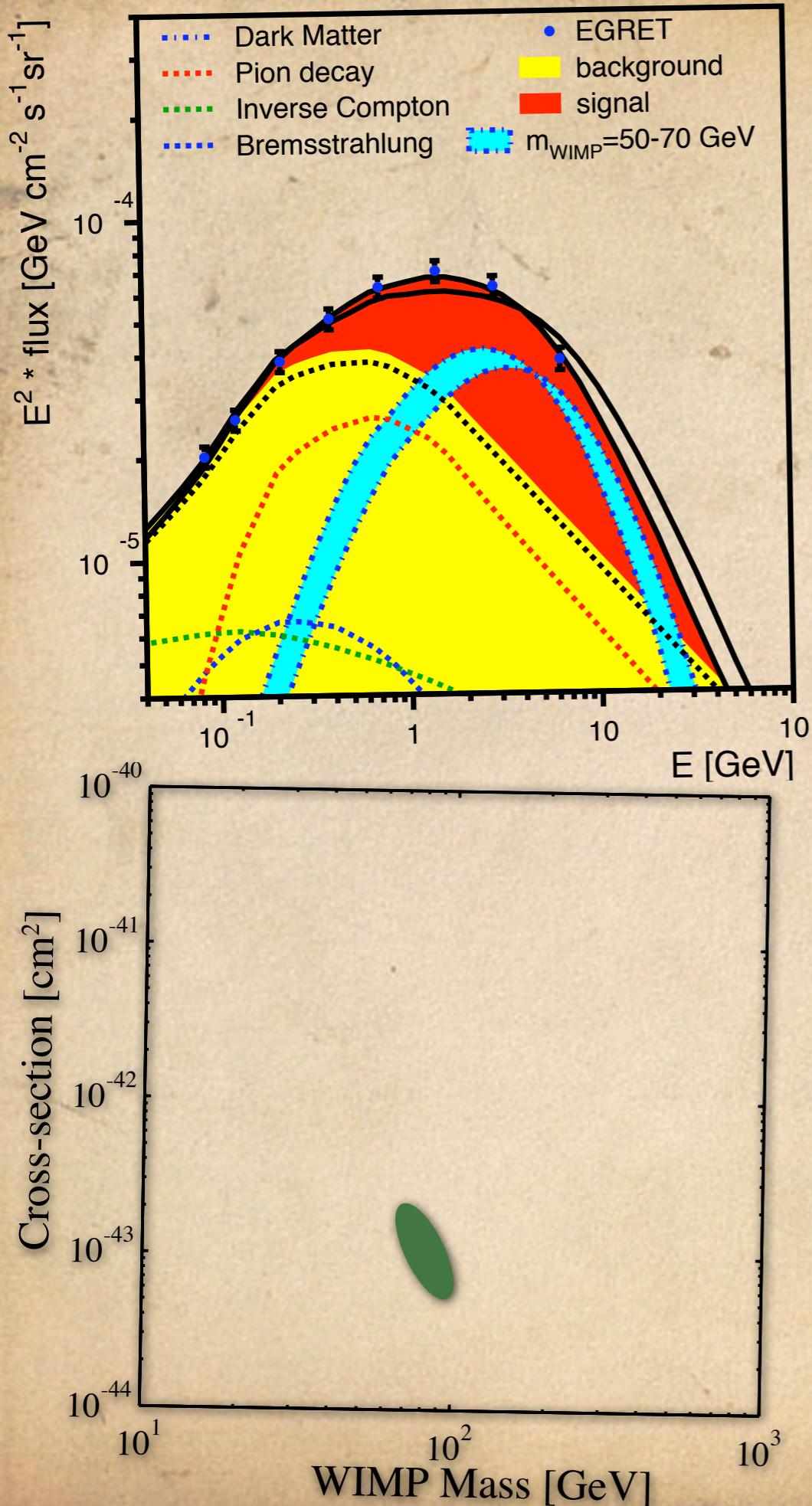


# WIMP

## Annihilation into Neutrinos

- Looking for excess  $\mu$ 's from the Sun's direction, above atmospheric background
- Upper limit on  $\mu$  flux translates into WIMP-proton cross section
  - Amanda Astropart. Phys. 24 2006
  - Super-K Phys. Rev D70 2004





# EGRET

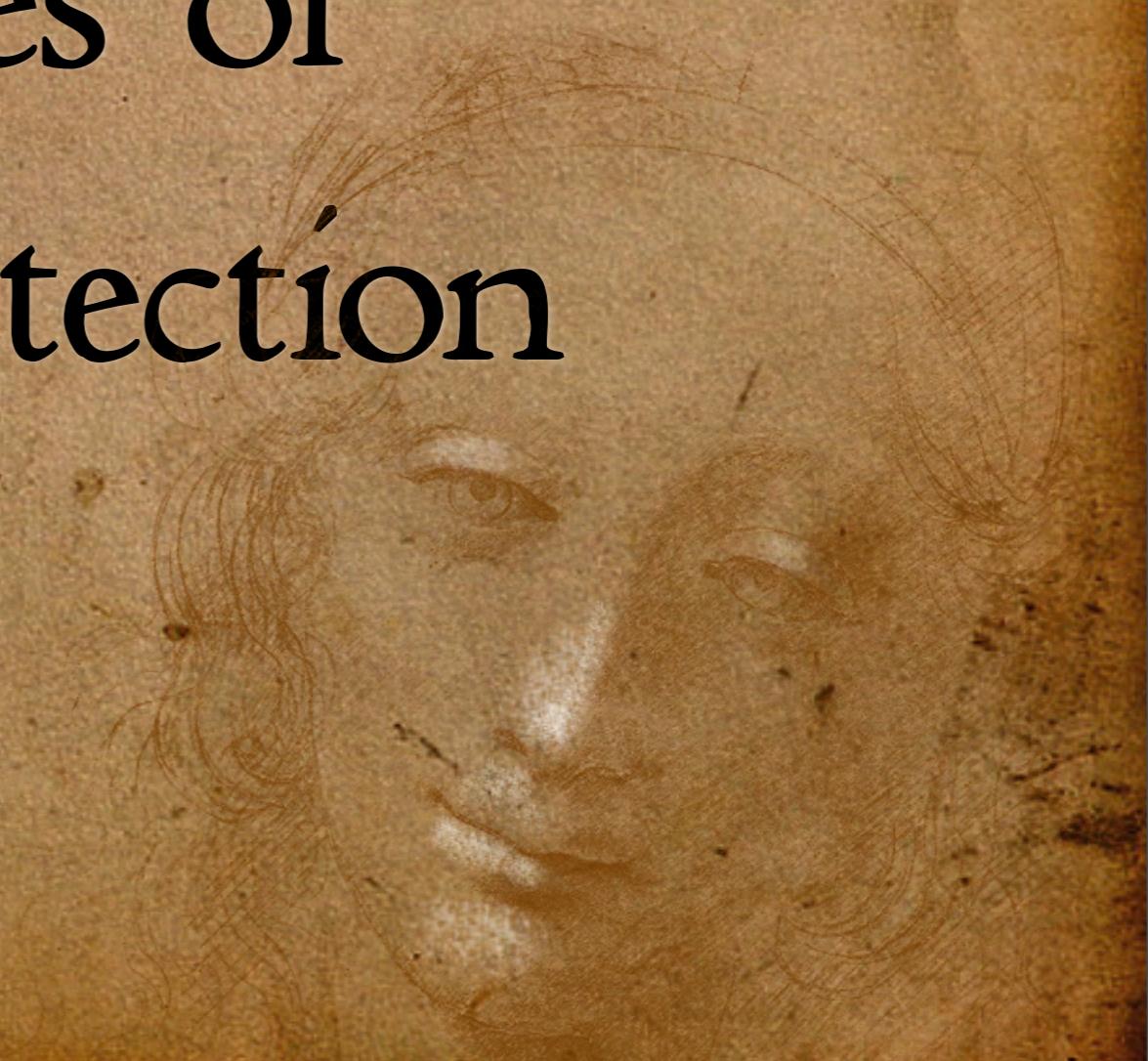
## Diffuse Galactic Gammas

- Diffuse galactic gamma component  $\sim 2x$  larger than the expected background

- Can be interpreted as arising from Dark Matter annihilation in the halo

- W. de Boer et al.  
[astro-ph/0506447](#) &  
[astro-ph/0508617](#)

# Principles of Direct Detection



# Principles of Direct Detection

*Input from Particle Physics*

$$\sigma_0 = \left( \frac{m_r}{m_{r-p}} \right)^2 A^2 \sigma_{\chi-p}$$

*Knowledge of Nuclear Structure*

$$F^2(Q) = \left[ \frac{3j_1(qR_1)}{qR_1} \right]^2 \exp(- (qs)^2)$$

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q)$$

*Our choice of Target Nucleus*

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

$$m_{r-p} = \frac{m_\chi m_p}{m_\chi + m_p}$$

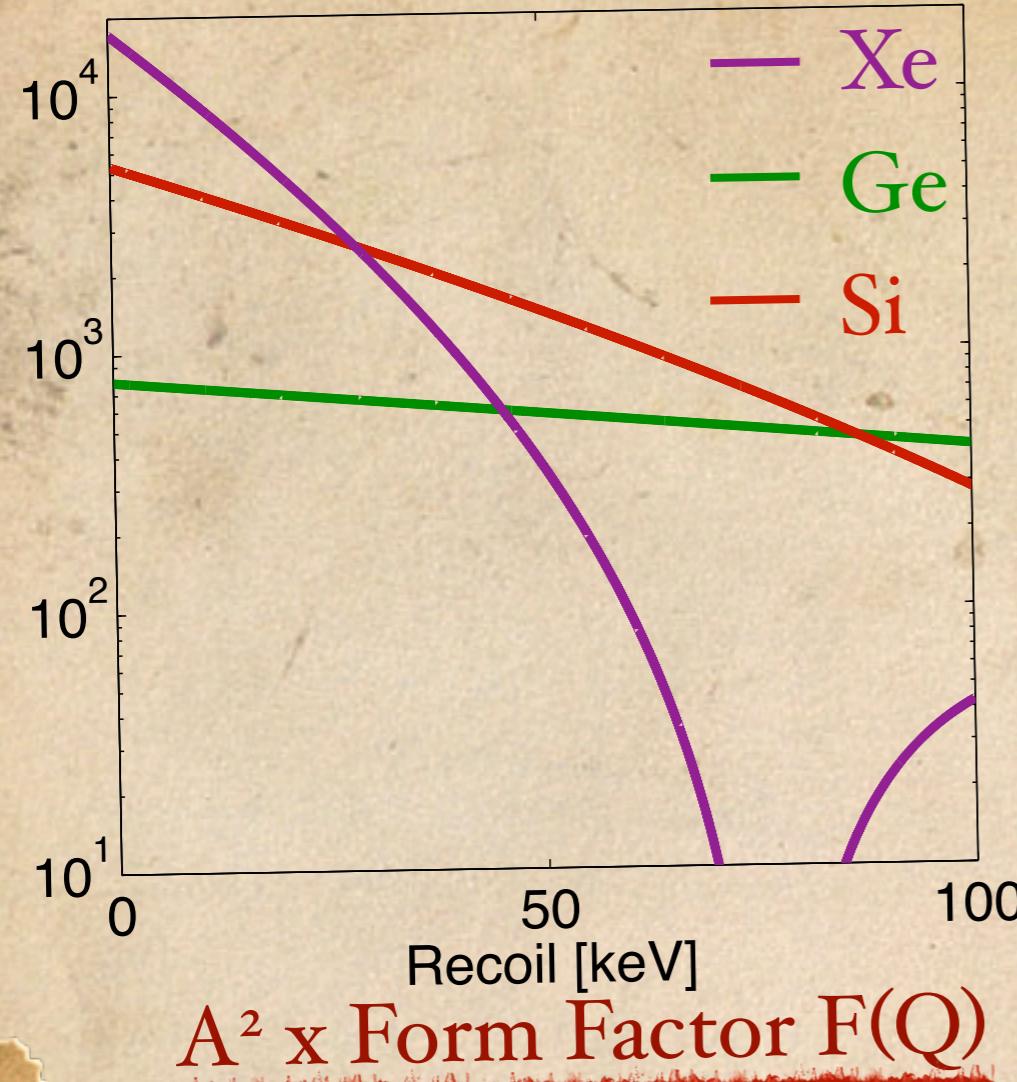
*Input from Astrophysics*

$$T(Q) = \exp(-v_{min}^2/v_0^2)$$

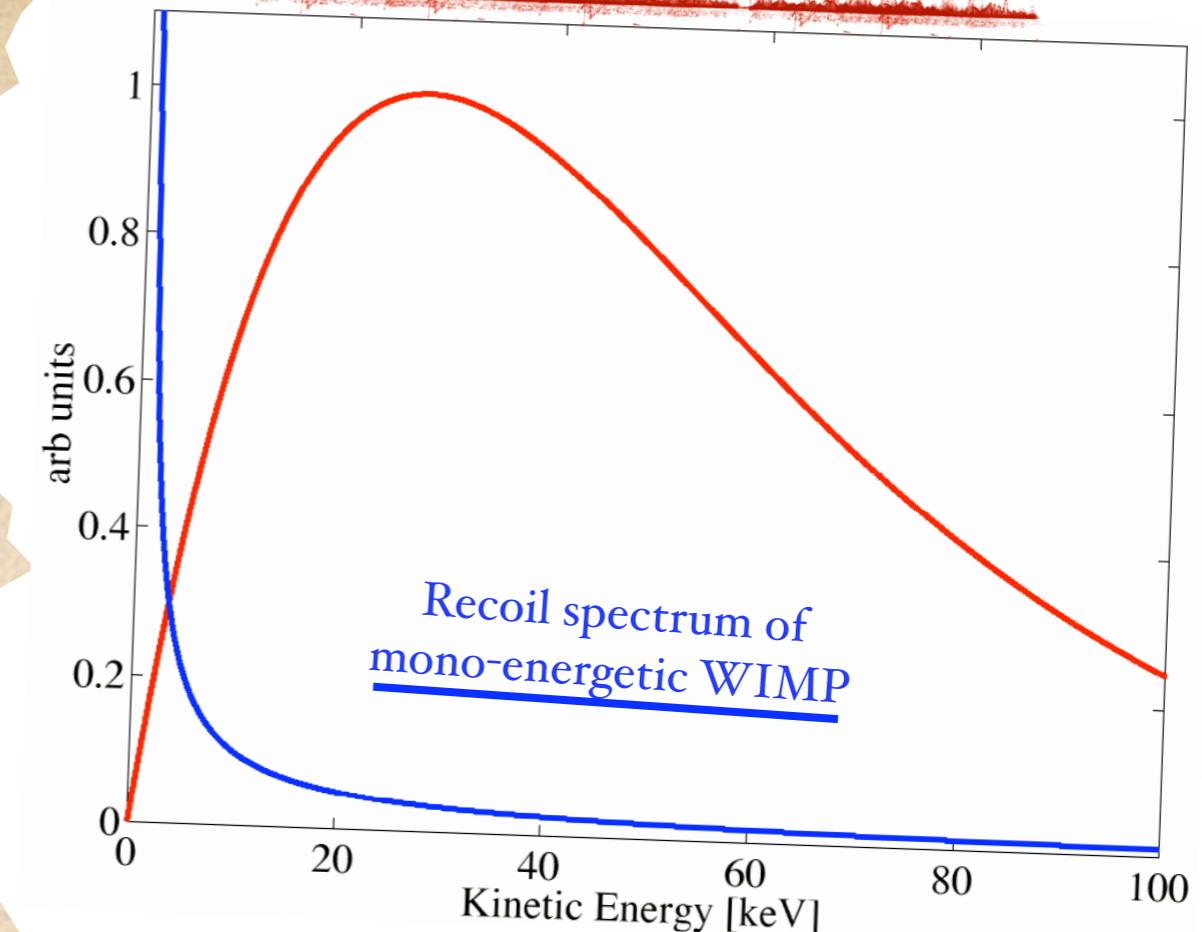
$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$

$$v_0 \approx 220 \text{ km/s}$$

# Woods-Saxon Form Factor



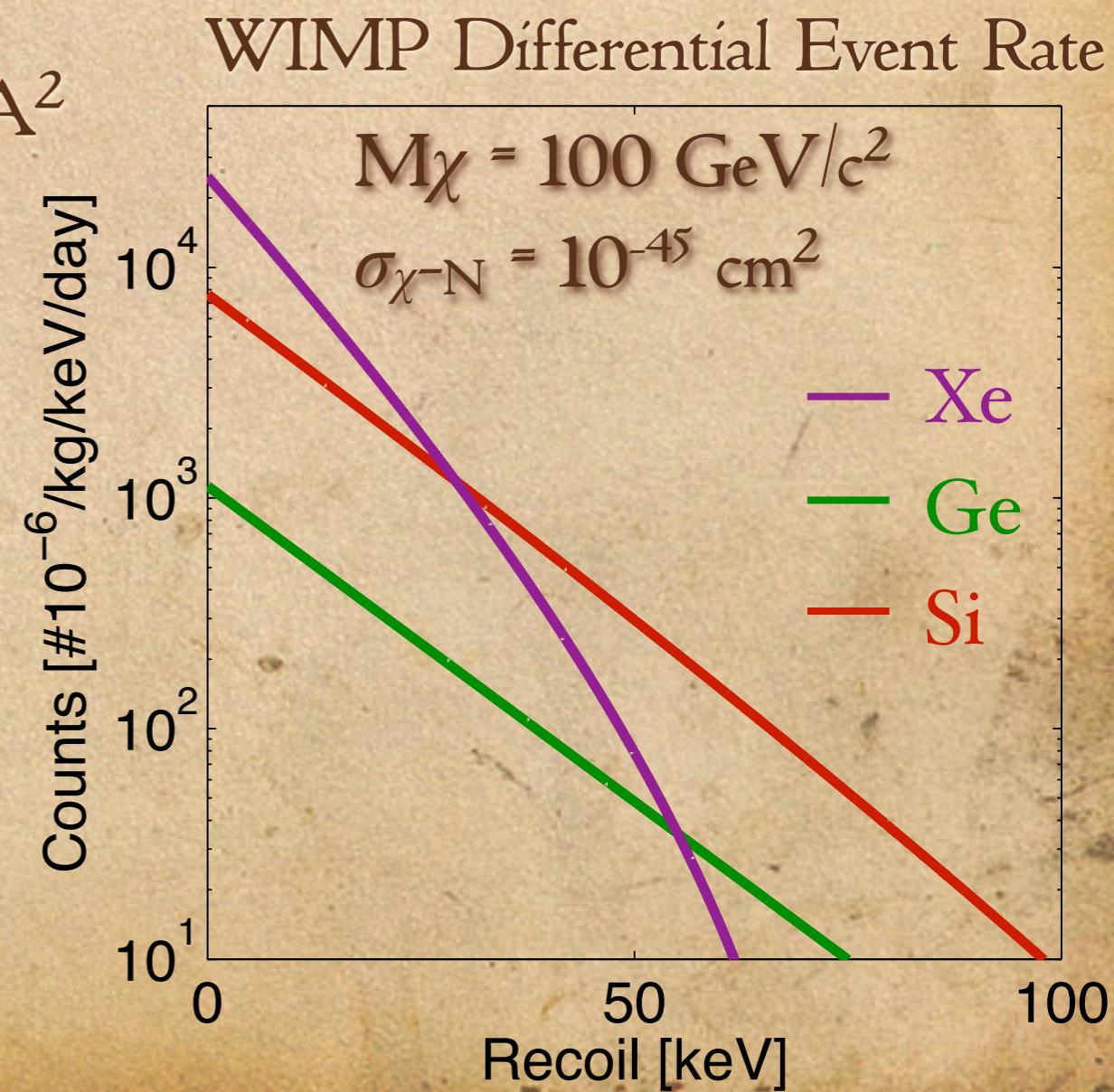
# WIMP velocity distribution



# Input Functions

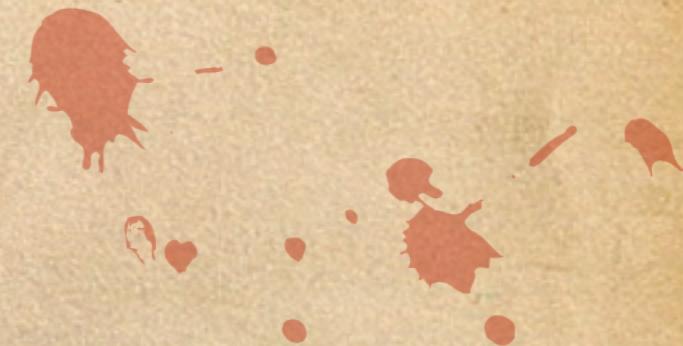
# Principles of Direct Detection

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy  $\sim \text{few} \times 10 \text{ keV}$
- For spin-indep. event rate scales as  $A^2$
- For spin-dep. event rates determined by the total spin of the nucleus
- Featureless exponential energy spectrum
  - no obvious peak, knee, break, ... that determines  $M_\chi$  or  $v_0$



# Principles of Direct Detection

- Various experimental methods exist for measuring such an energy deposition
  - Scintillation in crystals / liquids
  - Ionization in crystals / liquids
  - Thermal / athermal heating in crystals
  - Bubble formation in liquids / gels
- Easy in principle, hard in practice
  - Significant uncertainties/unknown in estimating DM event rates / energy spectrum
  - Background rates overwhelm the most optimistic DM scattering rates !!



# Looking for a very small needle in a big haystack



# Detector Physics to the Rescue

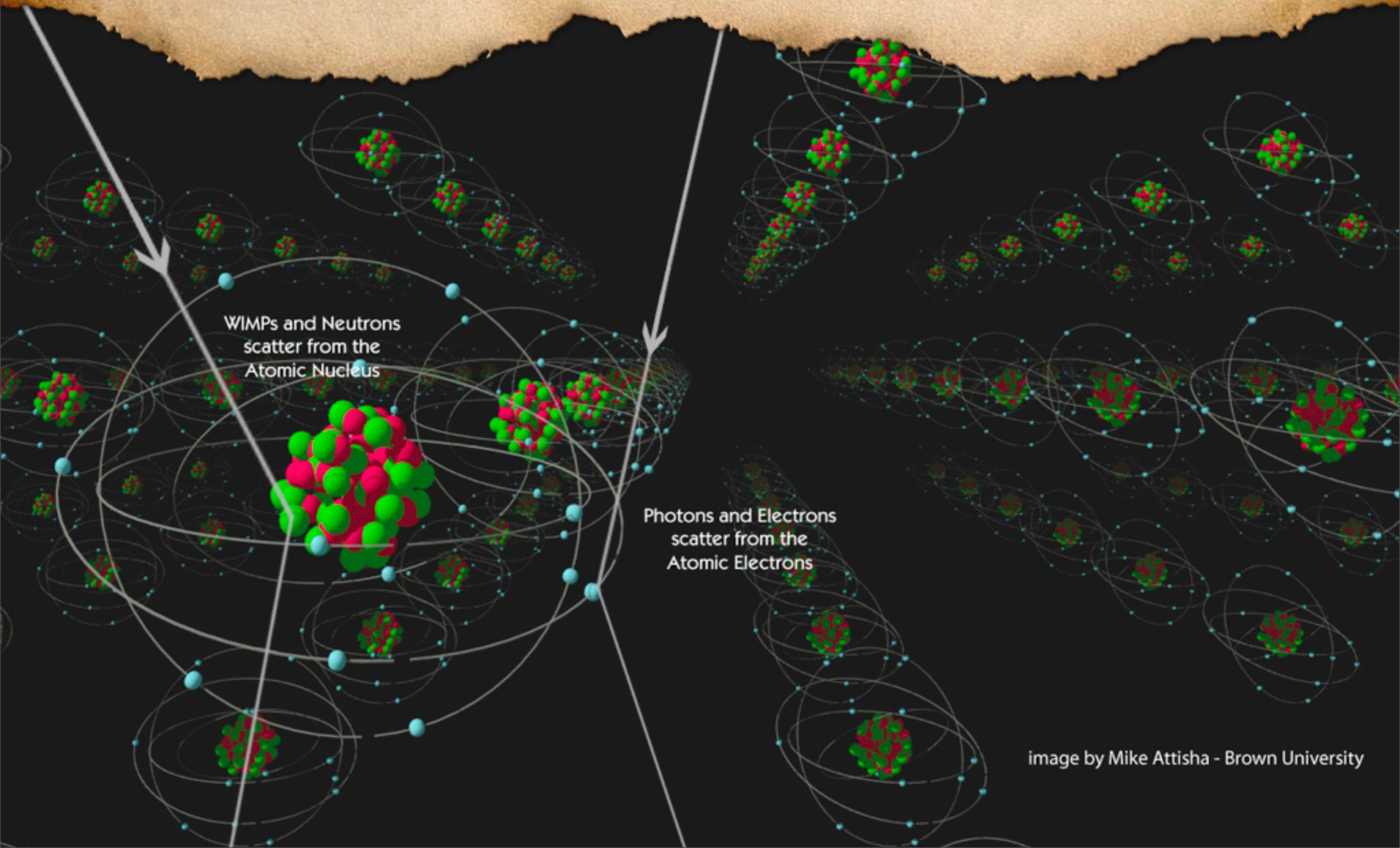


image by Mike Attisha - Brown University

# Event Discrimination (or Particle ID)

- Scattering from an atomic nucleus vs an atomic electron leads to different physical effects in most materials
- Sensitive to this effect effectively reduces background
- DM is expected to interact exclusively with the nucleus while backgrounds interact predominantly with the electrons

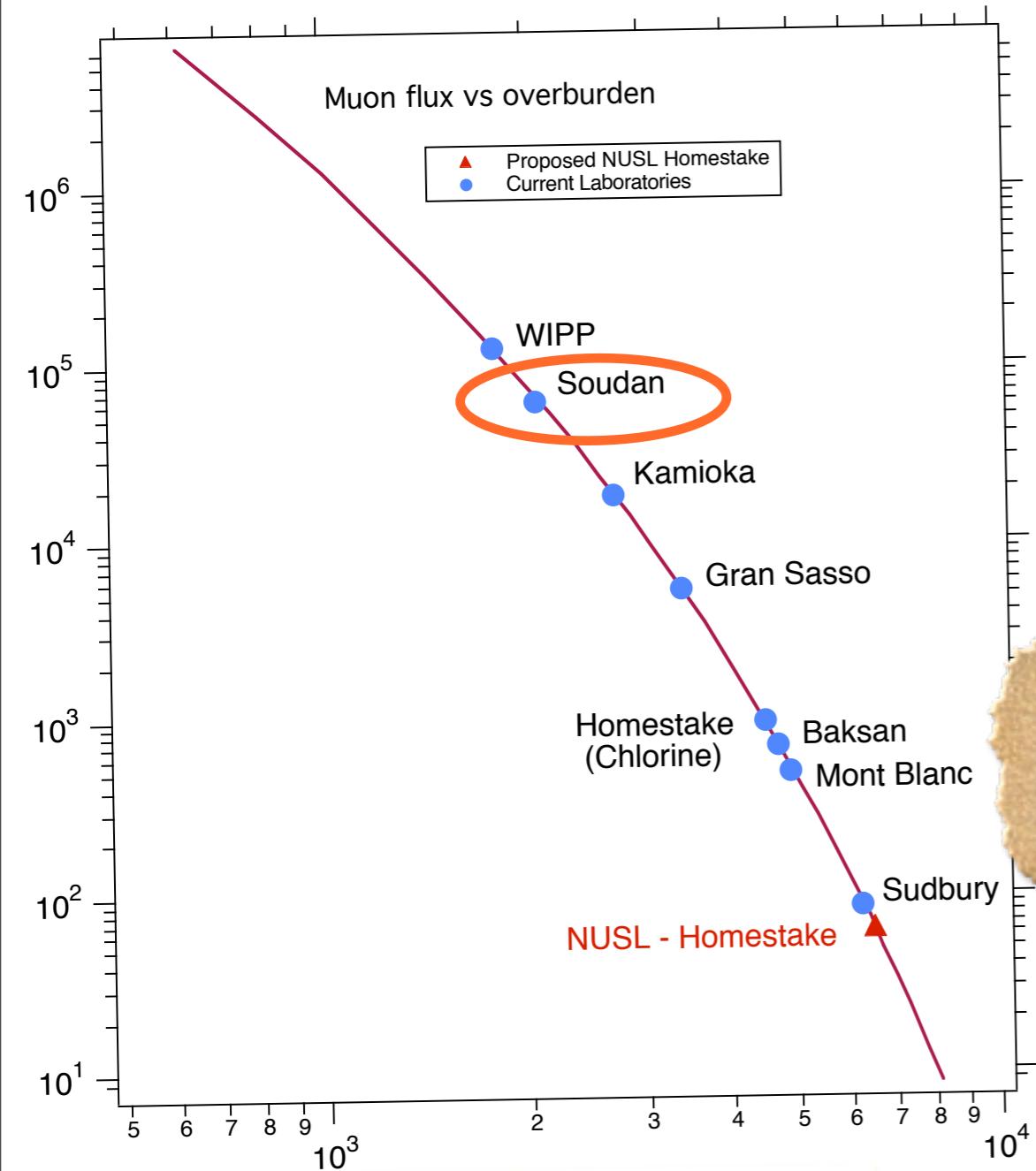
# Backgrounds can't be eliminated entirely



# Neutrons :

## Unrejected background

### Muon Flux vs Depth



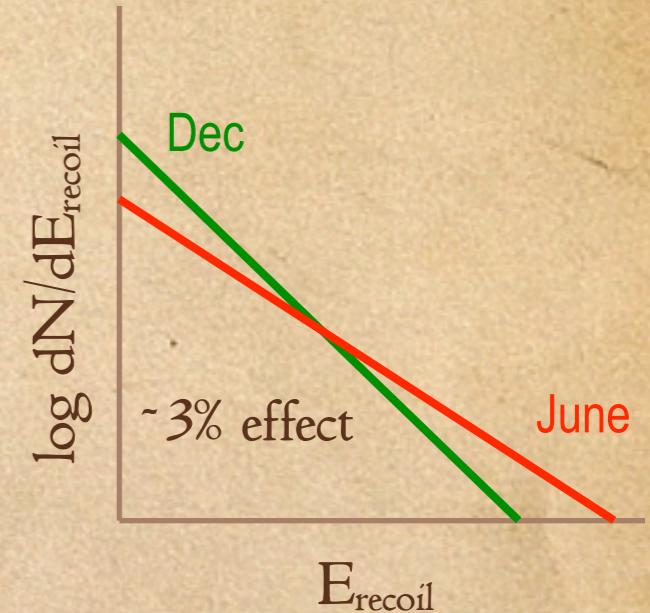
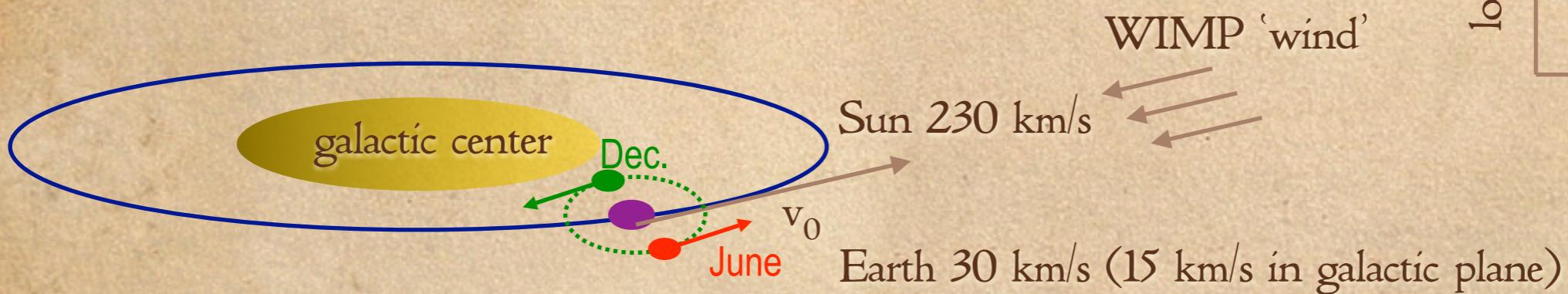
- Neutrons recoil off of atomic nuclei, thus appearing as **WIMPS**
- Neutrons come from
  - Environmental radioactivity
    - Can be addressed with shielding
  - Spallation due to cosmic muons
    - Must go deep underground to avoid

# Directional Signal

- Temporal variation of WIMP signal provides a means to distinguish it from background
  - Variation in
    - Energy spectrum
    - Event rate
    - Recoil direction
- all depend on direction of the earth through the WIMP “wind”

# Annual Modulation

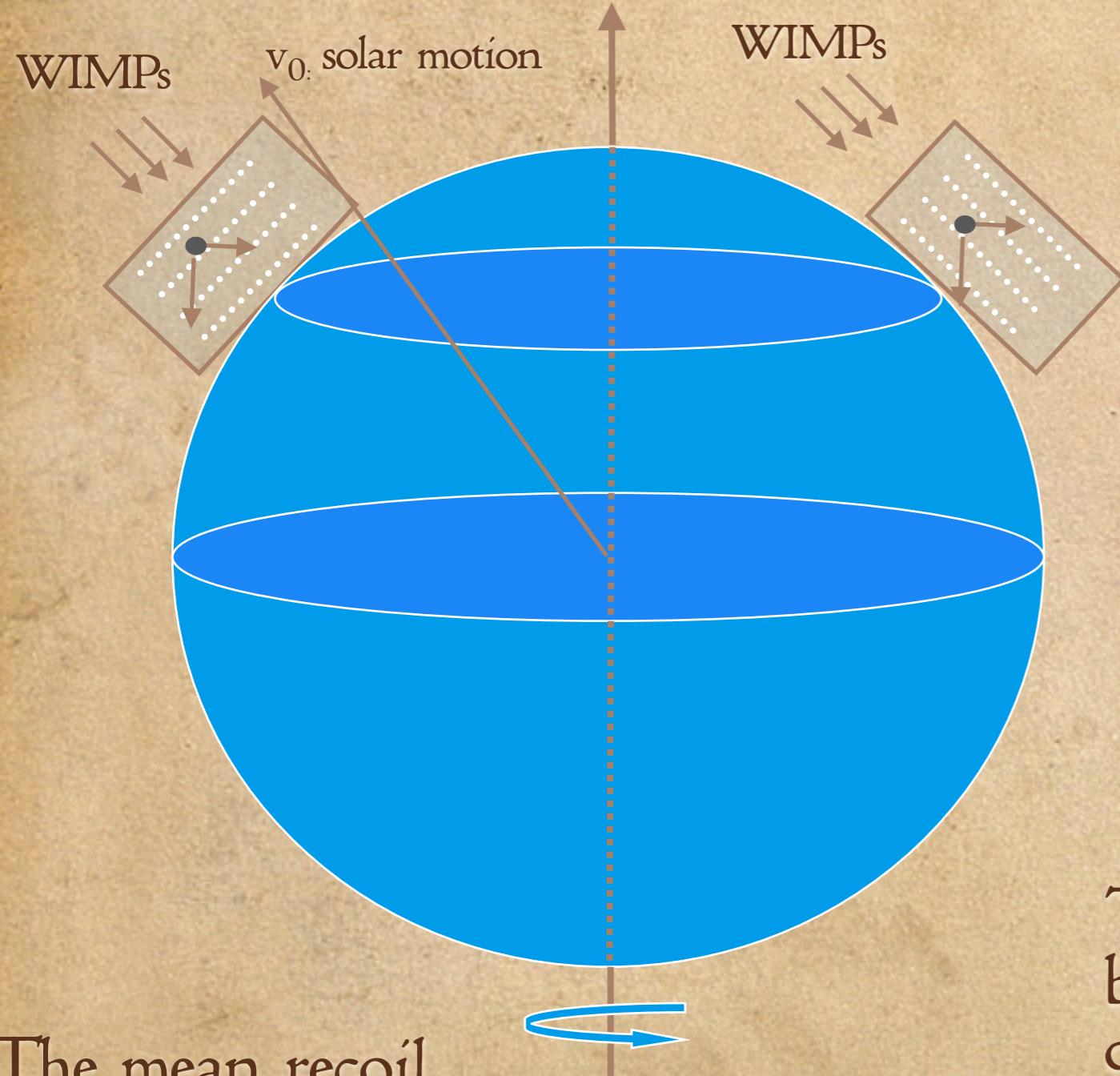
WIMP Isothermal Halo (assume no co-rotation)  $v_0 \sim 230$  km/s



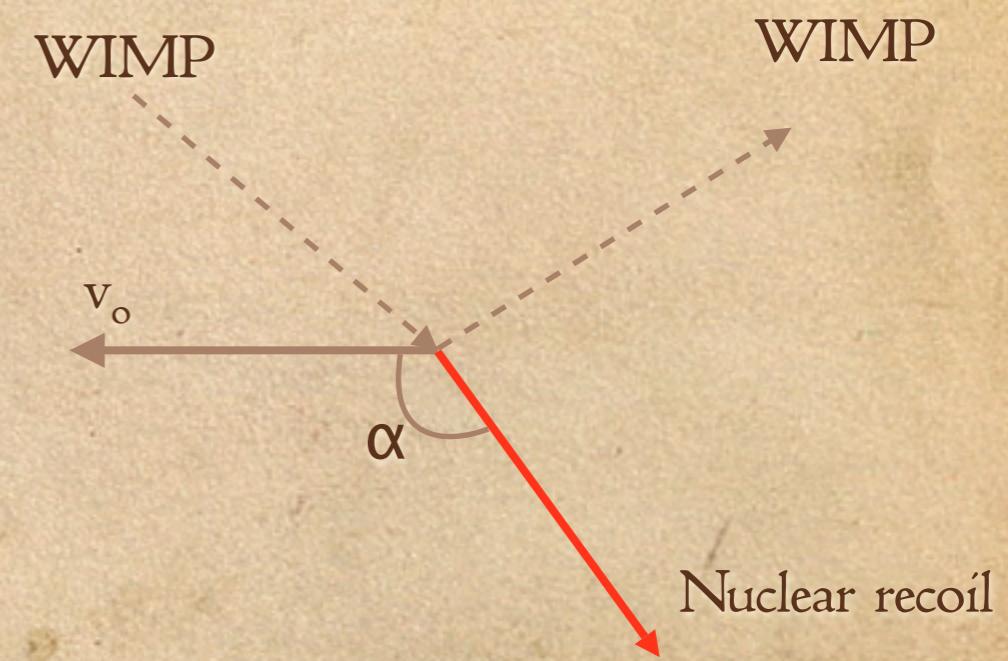
$$f(v)dv = \frac{vdv}{v_e v_0 \sqrt{\pi}} \left\{ \exp \left[ -\frac{(v - v_e)^2}{v_0^2} \right] - \exp \left[ -\frac{(v + v_e)^2}{v_0^2} \right] \right\}$$

$$T(Q) = \frac{\sqrt{\pi}}{2} v_0 \int_{v_{\min}}^{\infty} \frac{f(v)dv}{v} = \frac{\sqrt{\pi} v_0}{4 v_e} \left[ \text{erf} \left( \frac{v_{\min} + v_e}{v_0} \right) - \text{erf} \left( \frac{v_{\min} - v_e}{v_0} \right) \right]$$

# Diurnal Modulation



The mean recoil direction rotates over one sidereal day



The distribution of the angle  $\alpha$  between the solar motion and recoil directions: peaks at  $\alpha=180^\circ$



# Direct Detection Searches

# Dark Matter Searches

## Around the Globe





World Wide WIMP  
searches

# Current DM Searches

**TABLE 2** Current status of dark matter experiments (by technology)

From : DIRECT DETECTION OF DARK MATTER,  
R. J. Gaitskell, Annu. Rev. Nucl. Part. Sci. 2004. 54:315–59

Collaboration	Location	Readout	Target mass	Search dates
IGEX-DM	Baksan (Russia)	Ionization (77 K)	3 kg Ge	2001–
IGEX-DM	Canfranc (Spain)	Ionization (77 K)	2 kg Ge	2001–
GENIUS TF	Gran Sasso (Italy)	Ionization (77 K)	~5 kg Ge $\beta\beta$	2002–2005
NAIAD	Boulby (UK)	Scintillator ( $\sim$ 300 K)	~50 kg NaI array	2001–2005
LIBRA	Gran Sasso (Italy)	Scintillator ( $\sim$ 300 K)	$\leq$ 250 kg NaI array	2003–
ANALIS	Canfranc (Spain)	Scintillator ( $\sim$ 300 K)	11 kg NaI prototype	2000–2005
Rosebud	Canfranc (Spain)	Therm. phon. ( $\sim$ 20 mK)	$\leq$ 1 kg Ge, $\text{Al}_2\text{O}_3$	1995–
Rosebud	Canfranc (Spain)	Therm. phon. + scint. ( $\sim$ 20 mK)	~1 kg $\text{CaWO}_4$ , BGO	2000–
CDMS II	Soudan (USA)	Non-therm. phon. + ioniz. (<50 mK)	0.2–1.5 kg Si, 1–4.2 kg Ge	2001–2006
EDELWEISS II	Fréjus (France)	Therm. phon. + ioniz. ( $\sim$ 30 mK)	1 kg Ge	2000–2004
CRESST II	Gran Sasso (Italy)	Therm. phon. + scint. ( $\sim$ 10 mK)	1 kg $\text{CaWO}_4$	2000–2006
CUORICINO	Gran Sasso (Italy)	Therm. phon. ( $\sim$ 20 mK)	40 kg $\text{T}_2\text{O}_2$ $\beta\beta$	2002–
ORPHEUS	Bern (Switzerland)	Superconducting grains ( $\sim$ 4 K)	0.5 kg Sn	2001–
SIMPLE	Rustrel (France)	Superheated droplets ( $\sim$ 300 K)	Freon	1999–
PICASSO	Sudbury (Canada)	Superheated droplets ( $\sim$ 300 K)	~10 g–1 kg Freon	2001–
ZEPLIN I	Boulby (UK)	Scintillator PSD ( $\sim$ 150 K)	6 kg LXe	2002–2004
<b>Xenon</b>		<b>Scint. + Ioniz</b>	<b>10 kg</b>	<b>2006–</b>
XMASS-DM	Kamioka (Japan)	Scint. + ioniz. ( $\sim$ 150 K)	2 kg LXe	2002–2004
XMASS-DM	Kamioka (Japan)	Scint. + ioniz. ( $\sim$ 150 K)	14 kg LXe	2004–
DRIFT-I	Boulby (UK)	ioniz. NITPC (300 K)	0.167 kg $\text{CS}_2$	2002–2005
Bubble Chamber (Chicago)	Soudan (USA)	Superheated liquid ( $\sim$ 300 K)	1 kg Freons	2004–
(MACHe3)	Grenoble (France)— not underground	Exciton ( $\sim$ 20 mK)	0.02 g $\text{He}_3$	1998–

# PIBRA

- ♦ Large sodium Iodide Bulk for RAre processes
- ♦ Target : Room Temp Scintillator
  - NaI crystals
  - Naturally abundant odd-spin isotopes allow for some sensitivity to both spin dependent and spin independent interactions
- ♦ Detection Mechanism
  - Photomultiplier tubes detect scintillation photons
  - #scintillation photons proportional to recoil energy (roughly 6 photoelectrons per keV)

# PIBRA

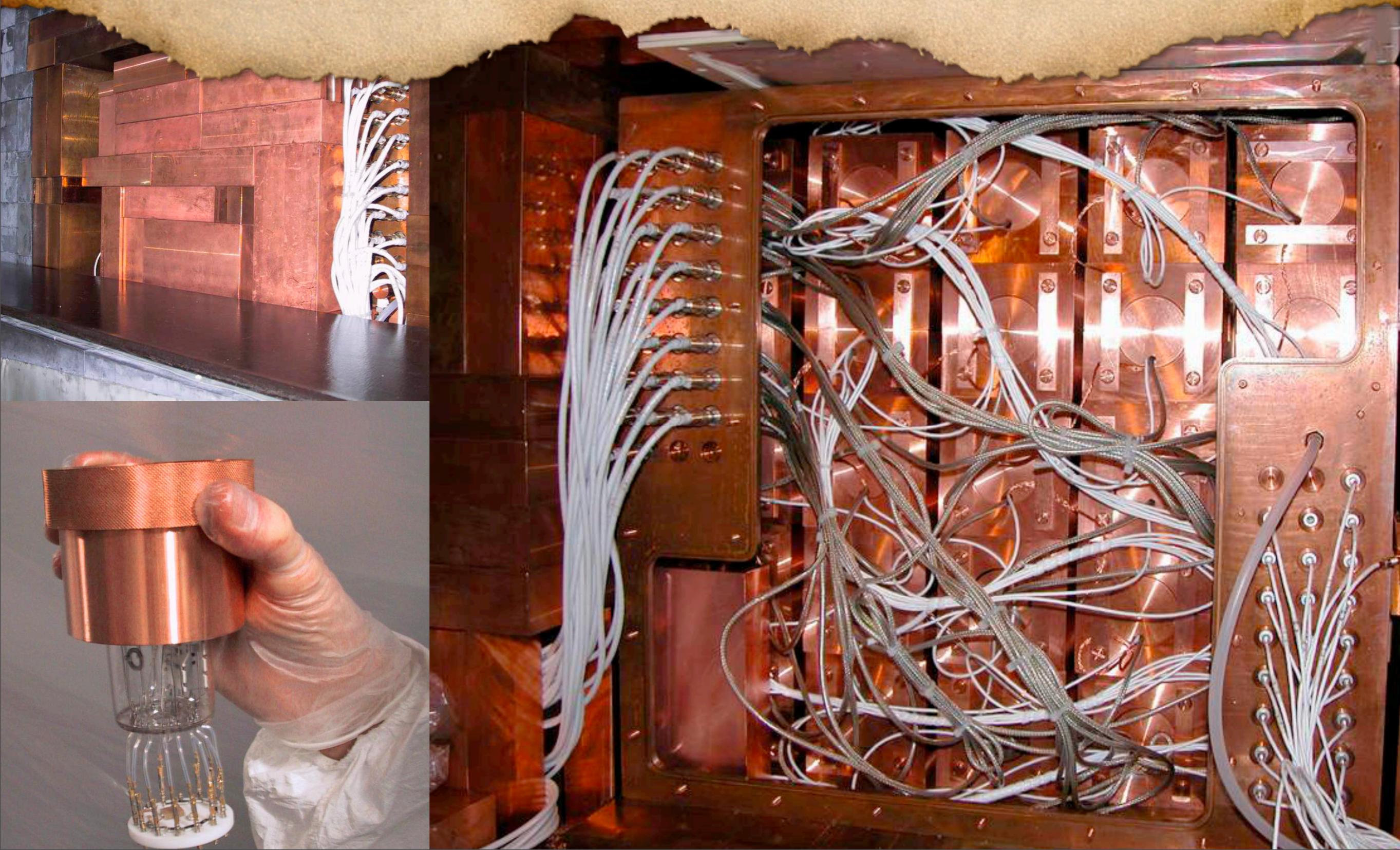
- ♦ **Background Discrimination :**

- Small difference in pulse shape between electron and nuclear recoils
- Insufficient for event by event discrimination, but can be used on a statistical basis

- ♦ **Mass / Exposure**

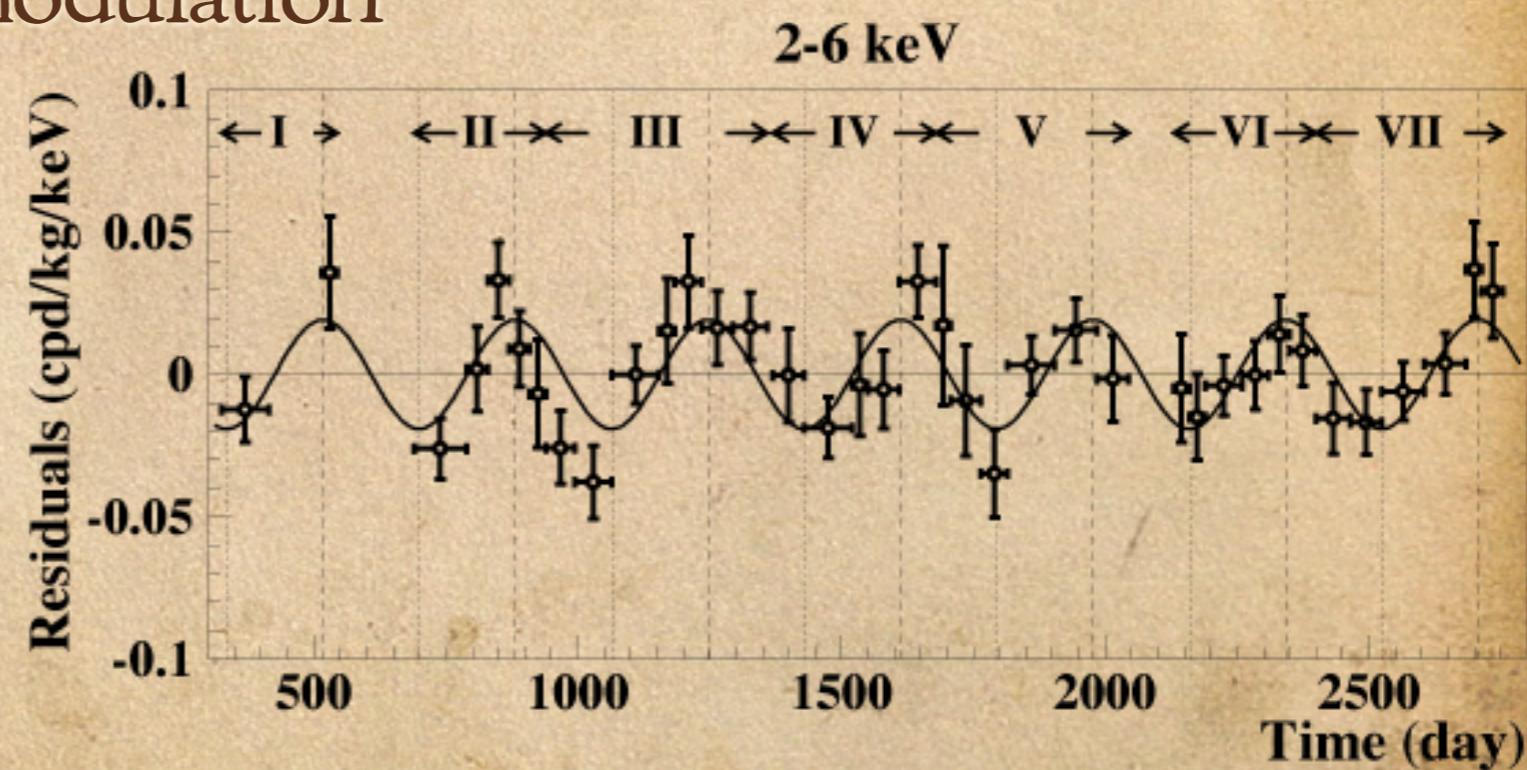
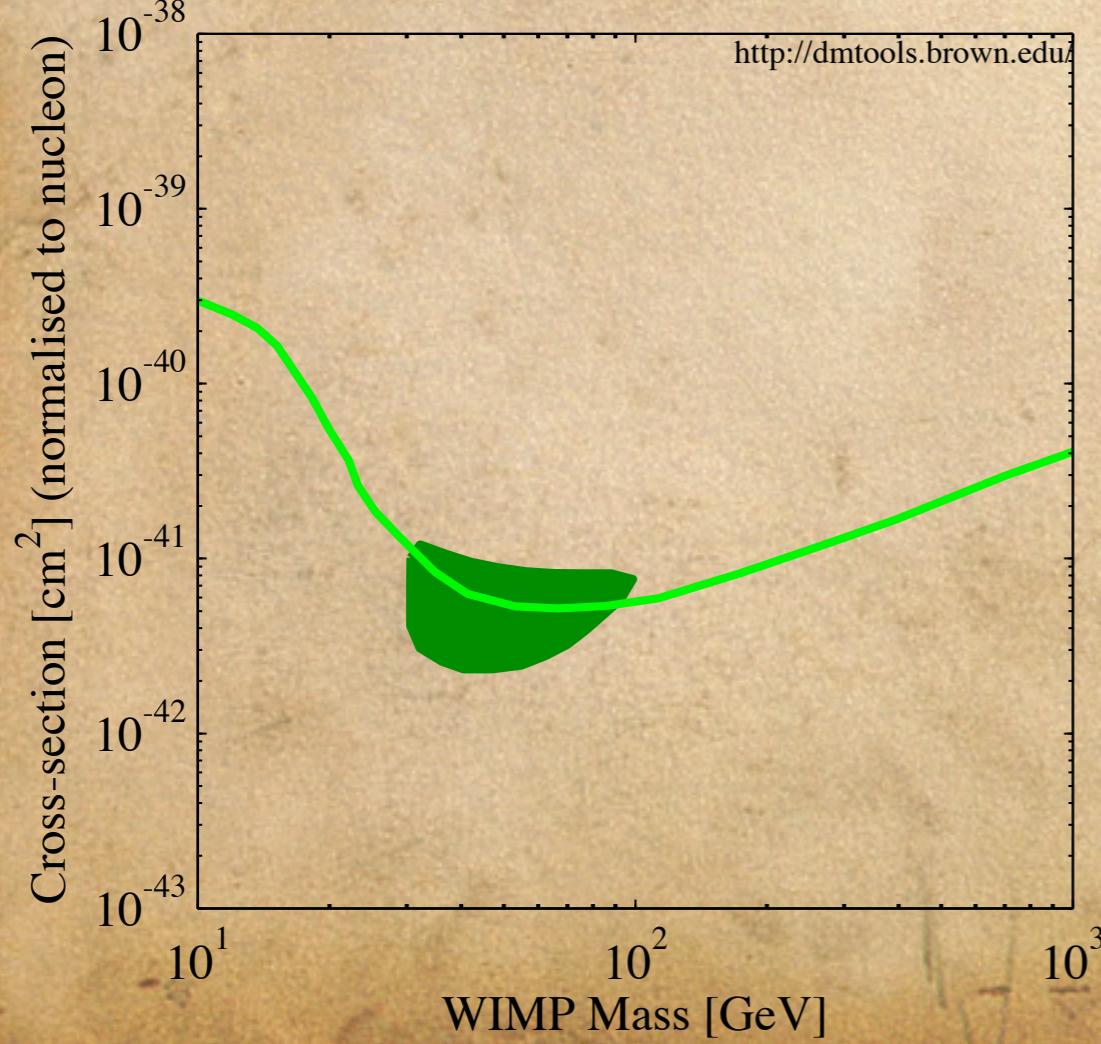
- Operating 250 kg of detectors at the Gran Sasso underground laboratory (~3000 mwe) since 2003
- Recently finished operating 100 kg of detectors for 7 years (DAMA)
- Background rate ~ 1 evt/kg/keV/day

# Inside LIBRA



# The DAMA Signal

- Observed a modulating signal in the lowest energy bins
  - Amplitude and phase of modulation consistent with standard WIMP halo model



# DRIFT

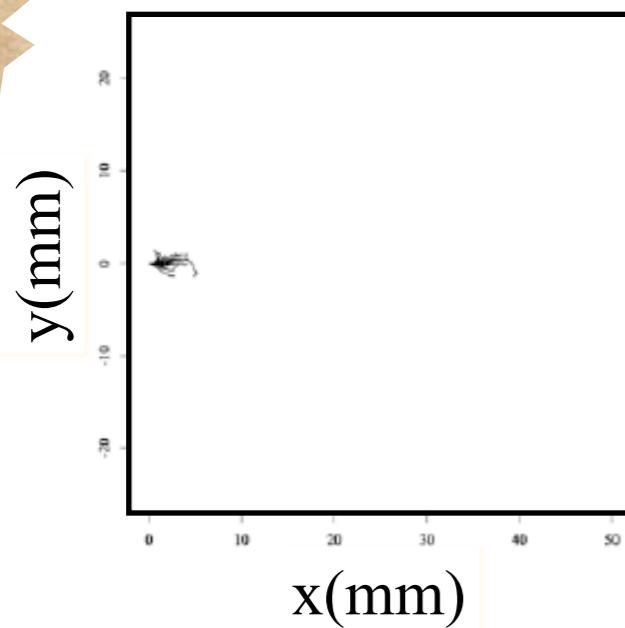
- ♦ Directional Recoil Identification From Tracks
- ♦ Target :
  - $\text{CS}_2$  gas
  - Sensitivity to spin independent interactions
- ♦ Detection Mechanism
  - Time projection chamber
  - Length/shape of track dependent on energy density of recoiling particle

# DRIFT

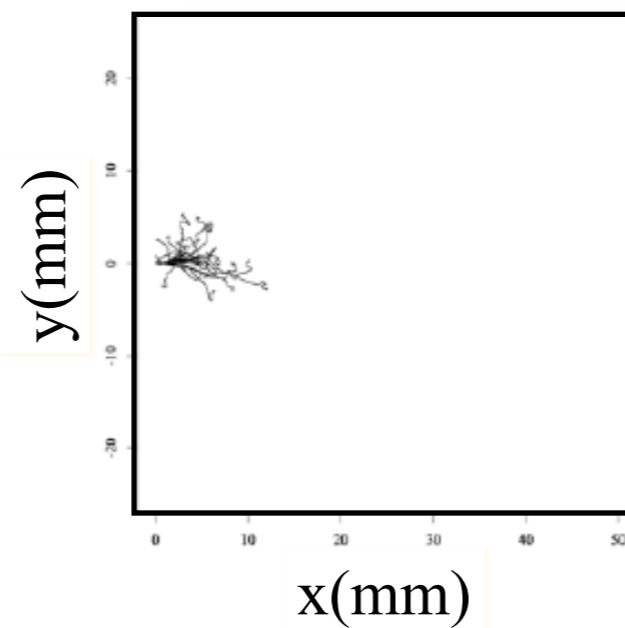
## ♦ Background Discrimination :

- ♦ Track shape
- ♦ Recoil directional

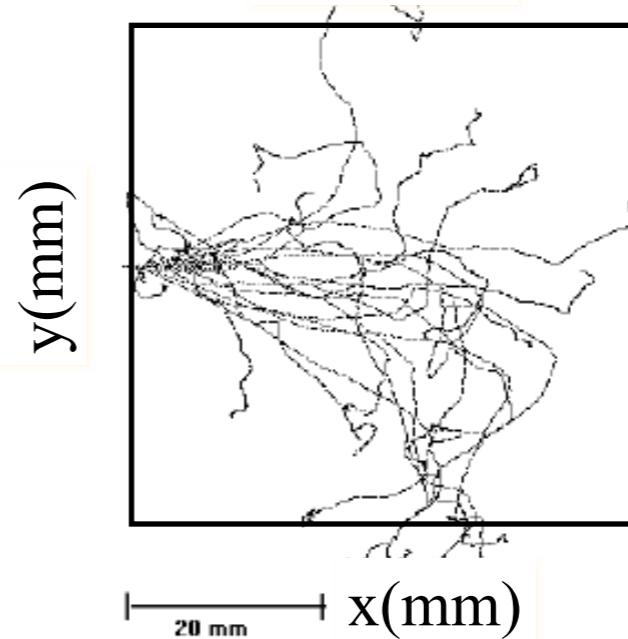
Ar Nuclear Recoils



$\alpha$  particle Recoils



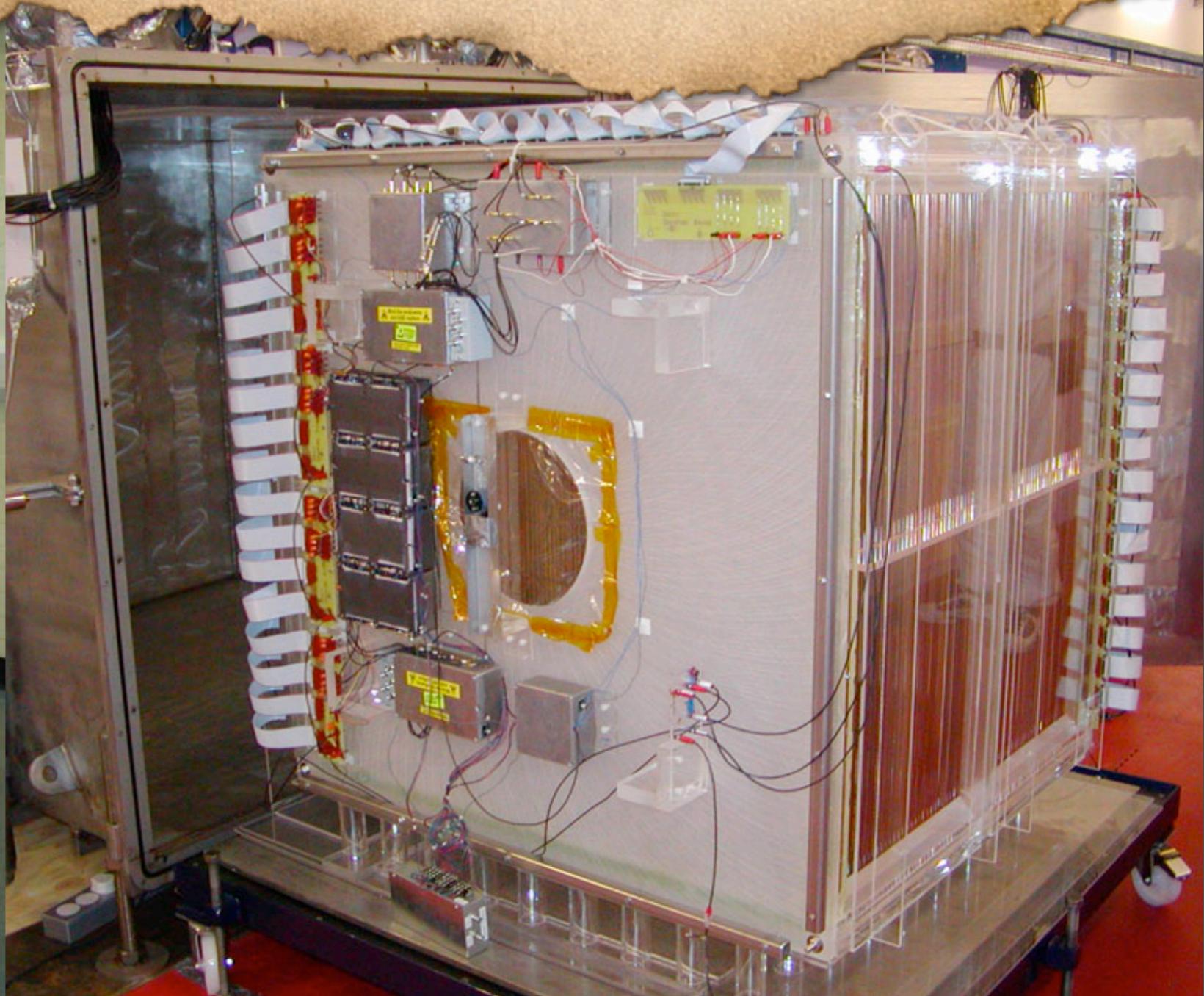
$\beta$  Recoils



## ♦ Mass / Exposure

- ♦ DRIFT-II : 10 kg-day data accumulated
- ♦ DRIFT-III : 100 kg target mass

# Inside DRIFT



# COUPP

- Chicagoland Observatory for Underground Particle Physics
- Target : Halocarbon liquids
  - $\text{CF}_3\text{Br}$ ,  $\text{CF}_3\text{I}$ , ... (even Xe)
  - Sensitive to both spin dependent AND spin independent interactions
- Detection Mechanism
  - Bubble formation in superheated liquid
  - Pressure sensor detects formation of bubble, triggers imaging camera
  - Sensitive to events with recoil energy above a specific tunable threshold

# COUPP

## ♦ Background Discrimination :

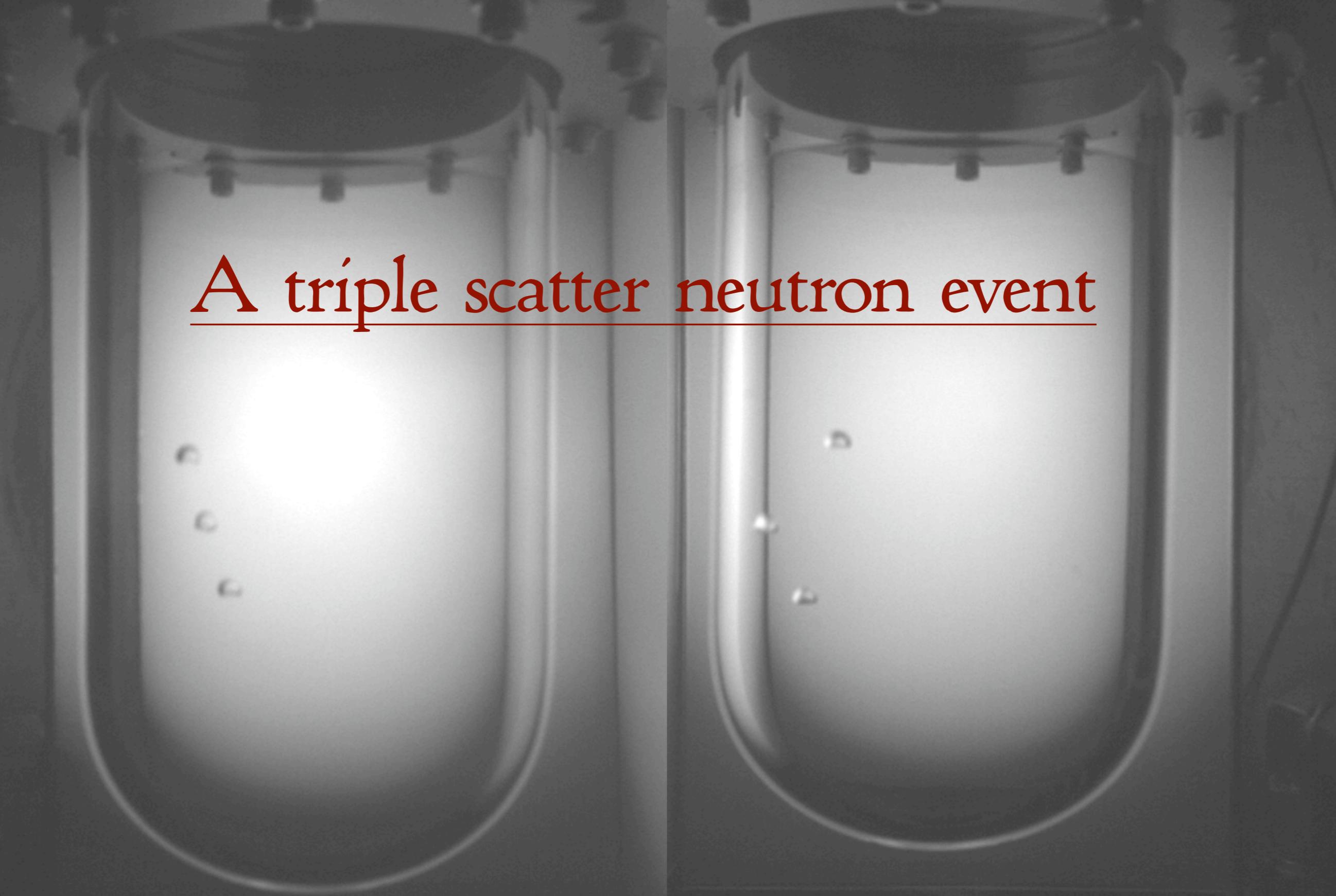
- Insensitive to electron recoils (deposited energy density insufficient to create bubble)
- By selecting operating pressure can reduce fraction of electron recoils resulting in bubble to  $\sim 10^{-9}$

## ♦ Mass / Exposure

- Currently operating 2 kg of detector at Fermilab underground site ( $\sim 300$  mwe)
- Clear path towards expanding to larger masses
- Expect background rate  $\sim 10^{-5}$  evt/kg/keV/day

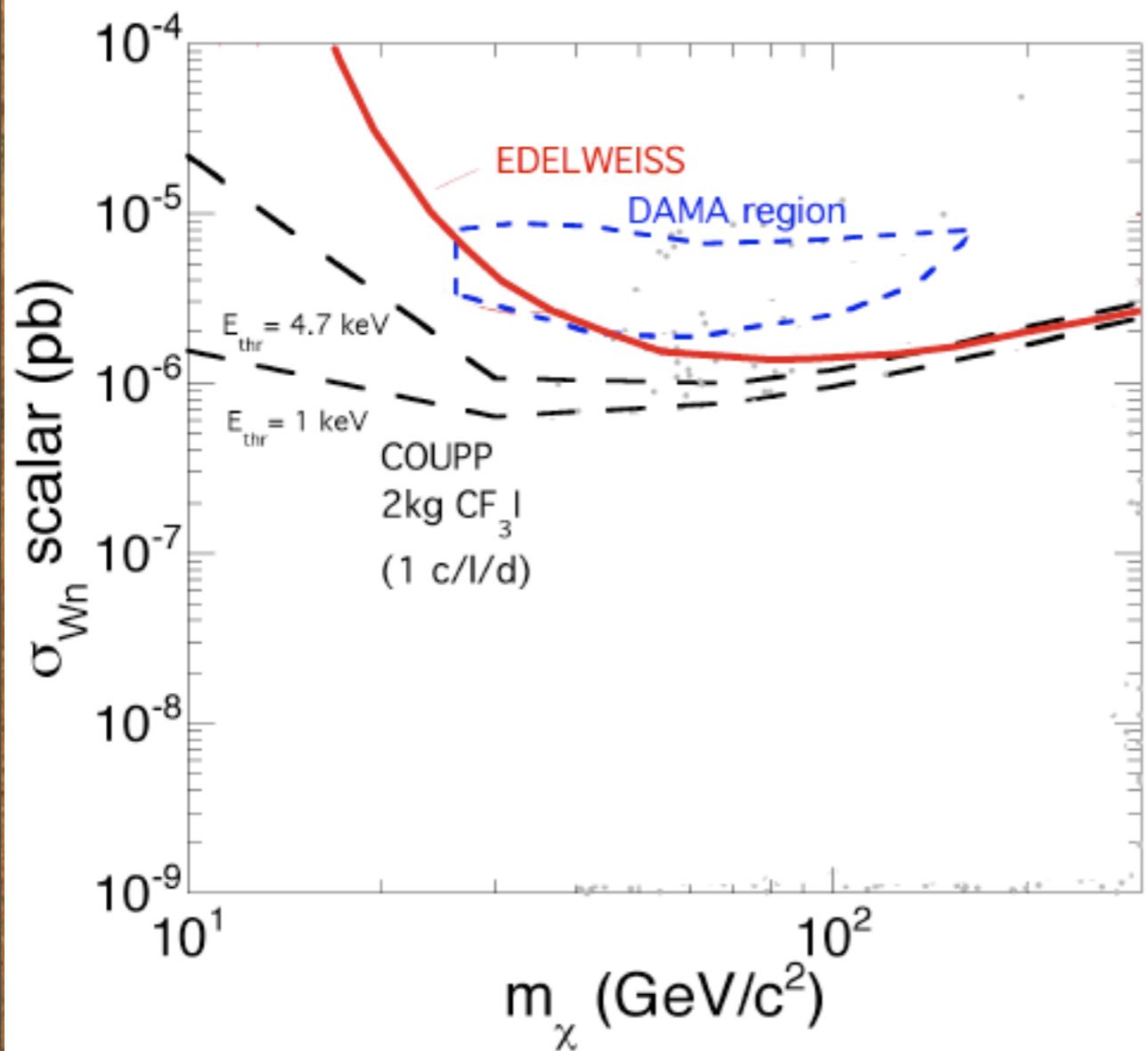
# COUPP in Action

A triple scatter neutron event

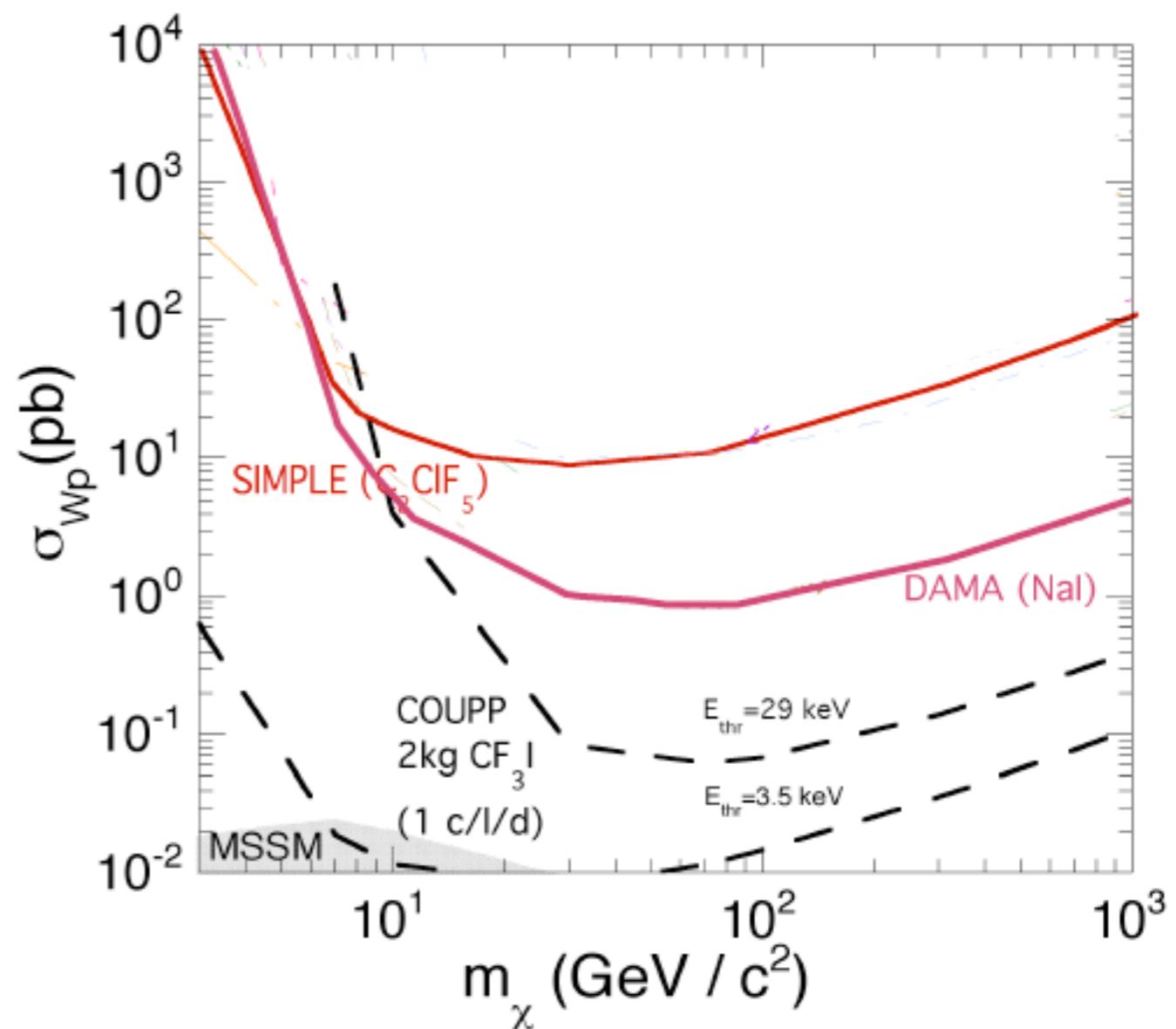


# Expected Reach of 2 kg Experiment

Spin Independent



Spin Dependent



# XENON

- ◆ Target : Liquid Xenon

- A = 131
- Large sensitivity to spin independent interactions
- Sensitive to spin dependent interaction through  $^{129}\text{Xe}$ ,  $^{131}\text{Xe}$  isotopes

- ◆ Detection Mechanism

- Scintillation in LXe : detected by photomultiplier tubes above the liquid (prompt signal)
- Ionization in LXe : Electrons drifted through the liquid by an electric field. Result in scintillation in Xe vapor above the liquid (delayed signal ~ 150  $\mu\text{s}$ )
- #scintillation photons / ionization electrons proportional to recoil energy (roughly 200 photons for a 16 keV recoil)

# XENON

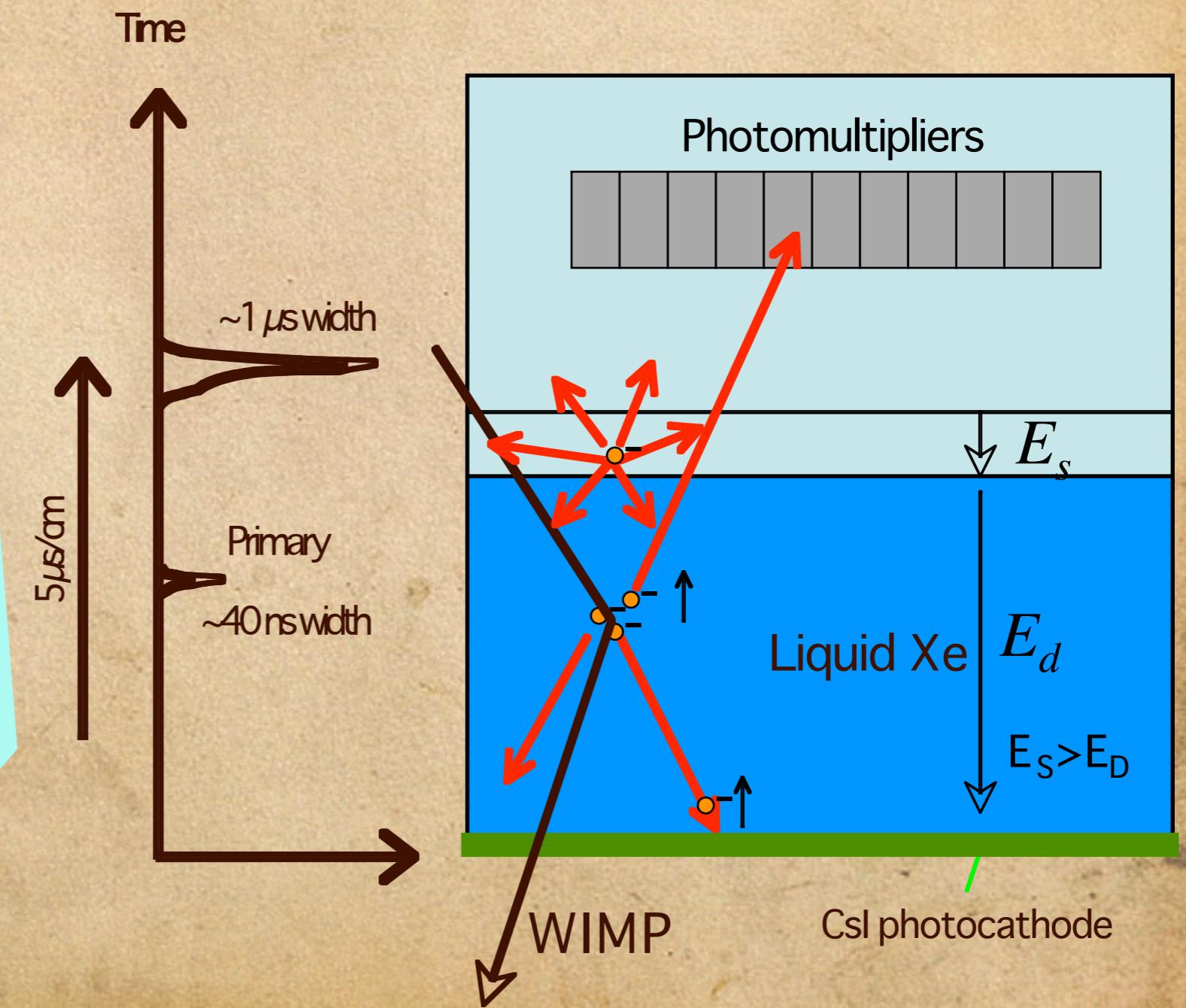
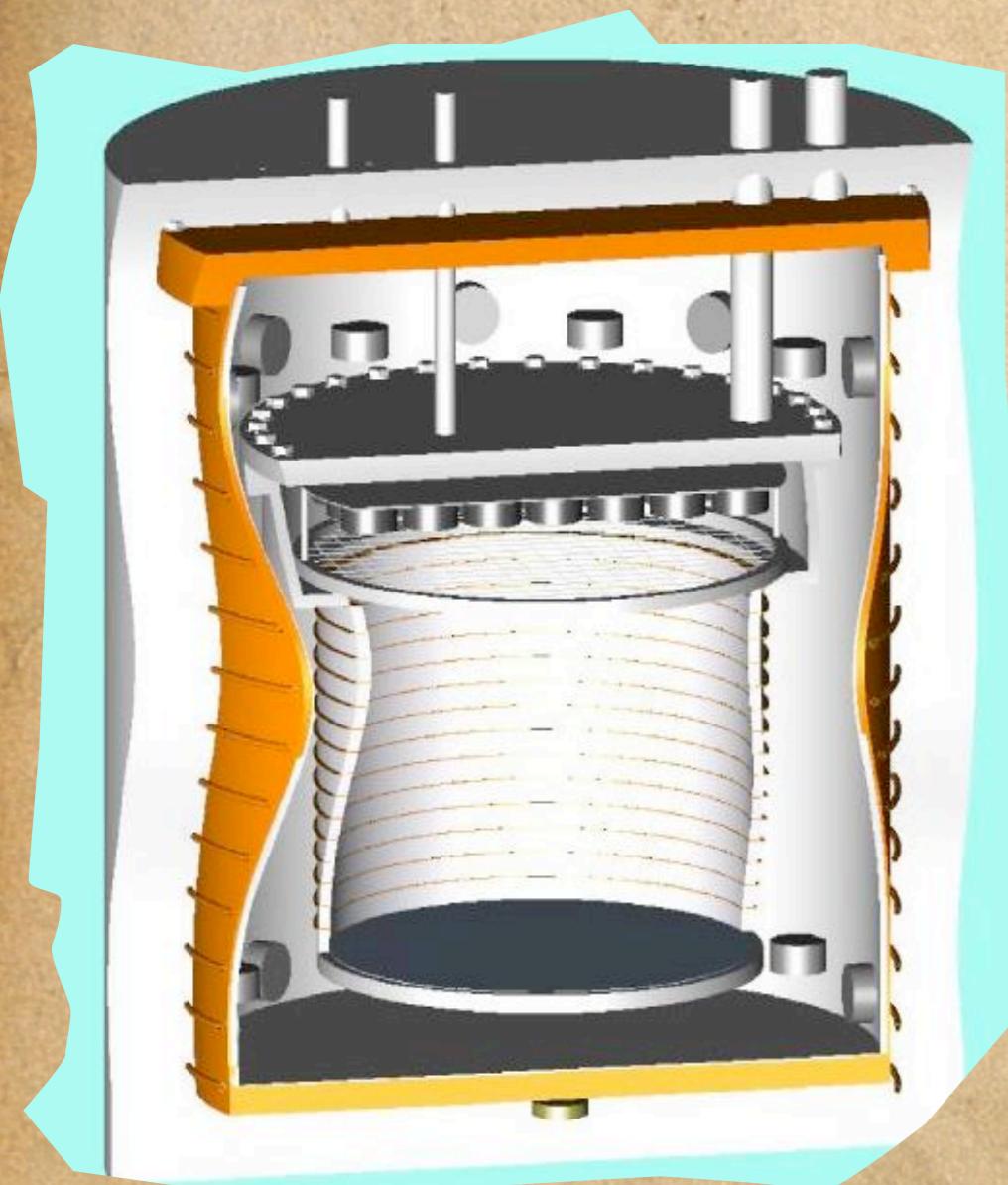
- **Background Discrimination :**

- Higher ratio of scintillation to ionization signal for nuclear recoils compared to electron recoils
- Able to achieve event by event discrimination at 99 %

- **Mass / Exposure**

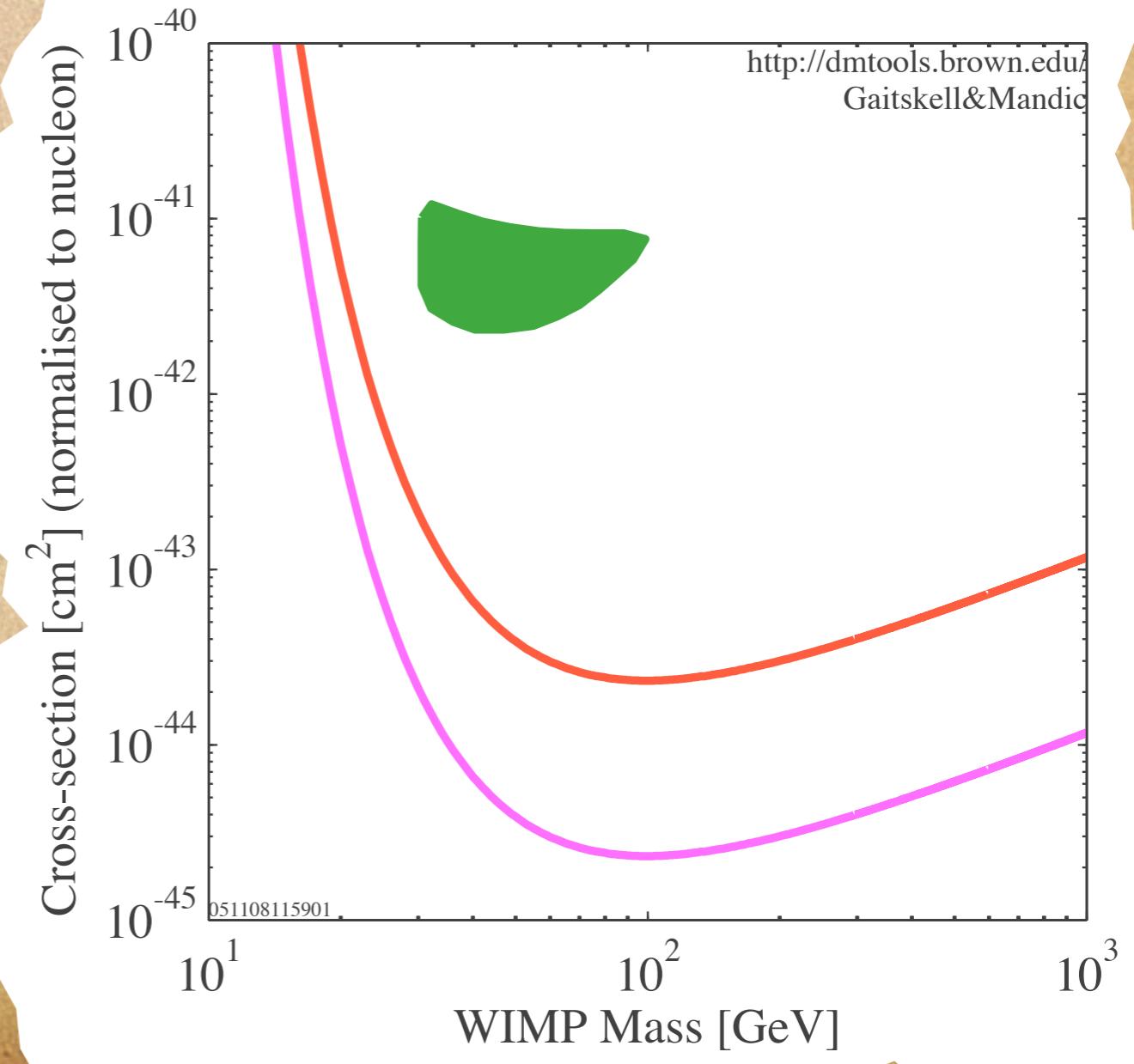
- Plan to operate a 10 kg of detector at the Gran Sasso underground laboratory (~3000 mwe)
- Clear path towards expanding to larger masses

# The XENON Design



# Expected Reach of 10 / 100 kg Experiment

— 10 kg  
— 100 kg  
— DAMA modulation  
region for reference





- ♦ Cryogenic Dark Matter Search
- ♦ Target : Semiconductor crystals
  - ♦ Ge / Si
  - ♦ Largely sensitive to spin independent interactions, although presence of some naturally abundant odd spin isotopes allows for some spin dependent sensitivity
- ♦ Detection Mechanism
  - ♦ Athermal phonons in crystal : provide a calorimetric measure of the recoil energy
  - ♦ Ionization signal : Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy



## • Background Discrimination :

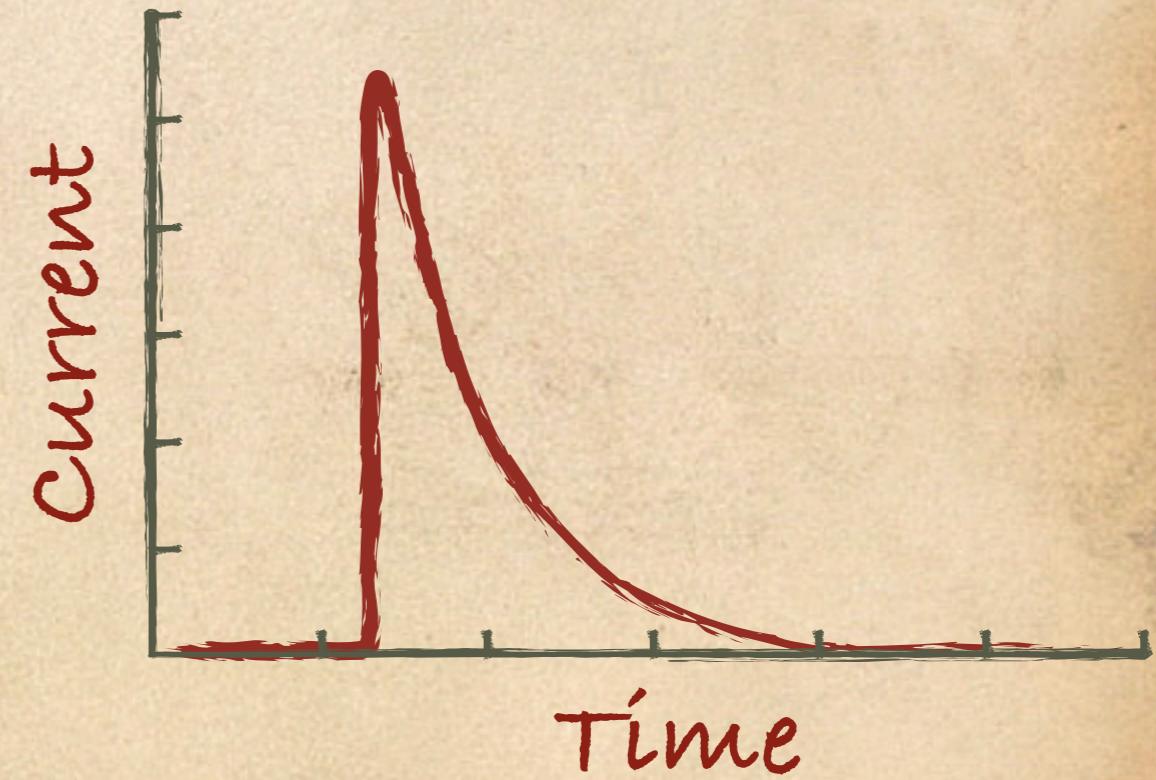
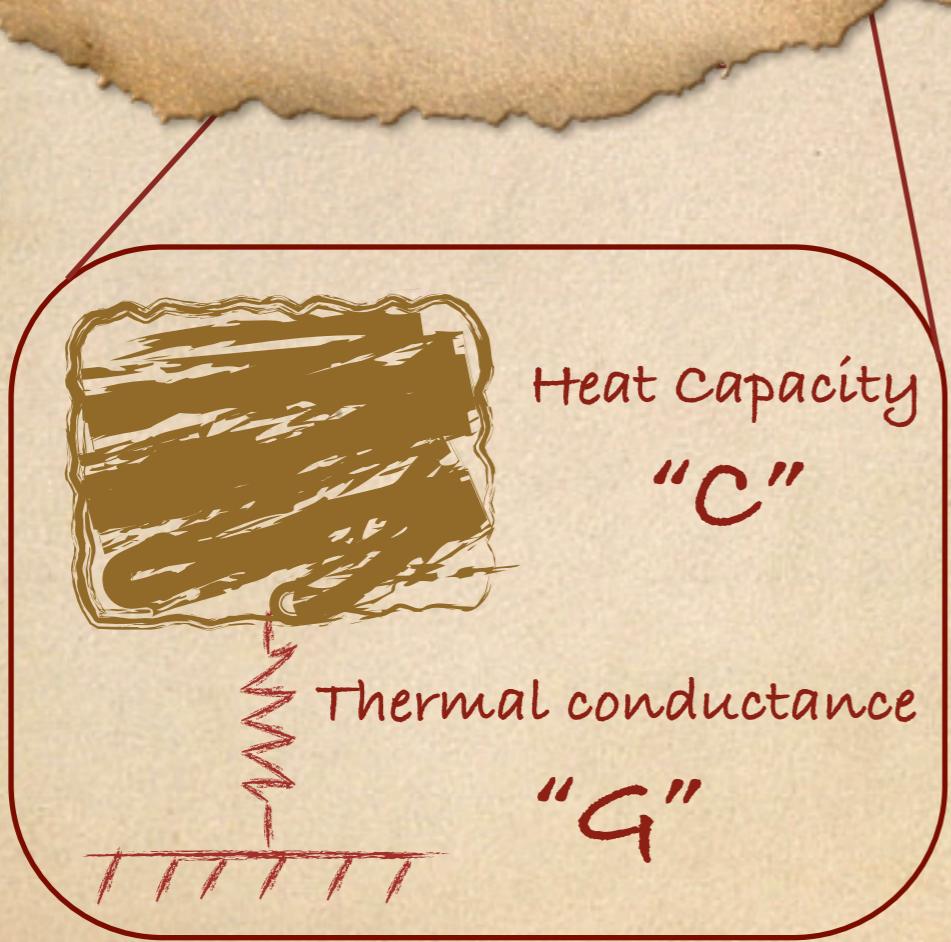
- Higher ratio of ionization to athermal signals for electron recoils
- Able to reject bulk electron recoils at the 1 in  $10^6$  level

## • Mass / Exposure

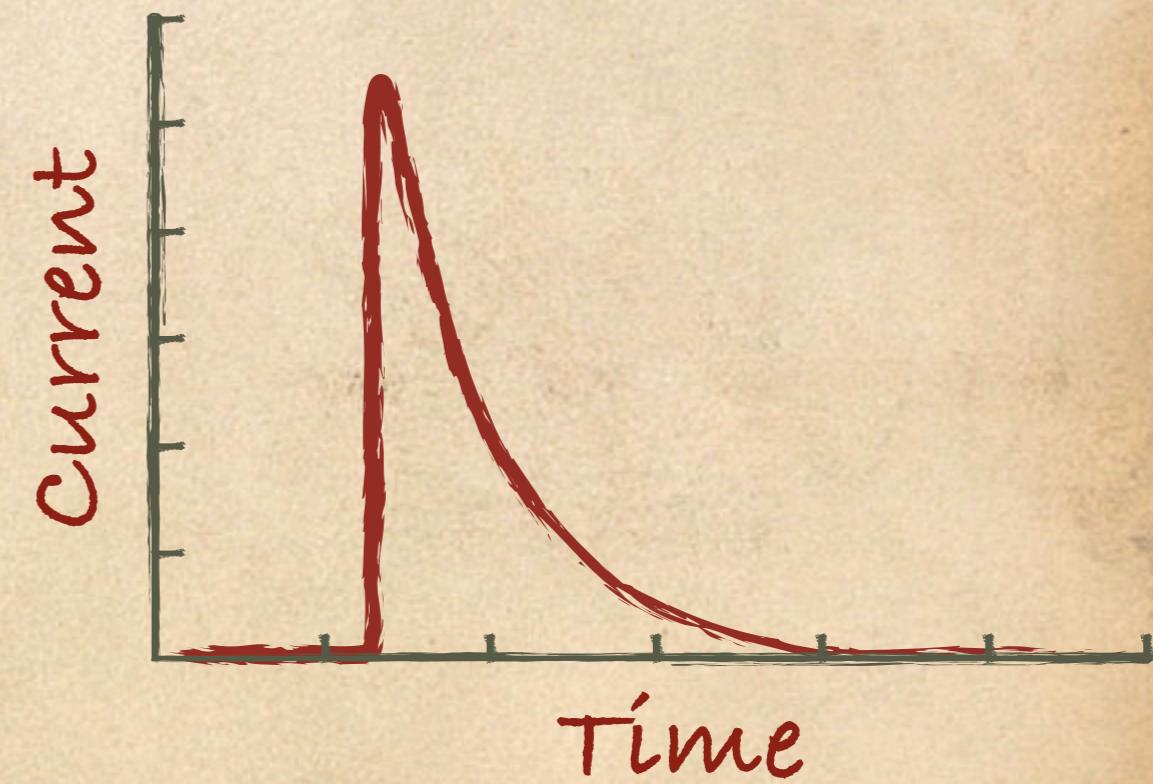
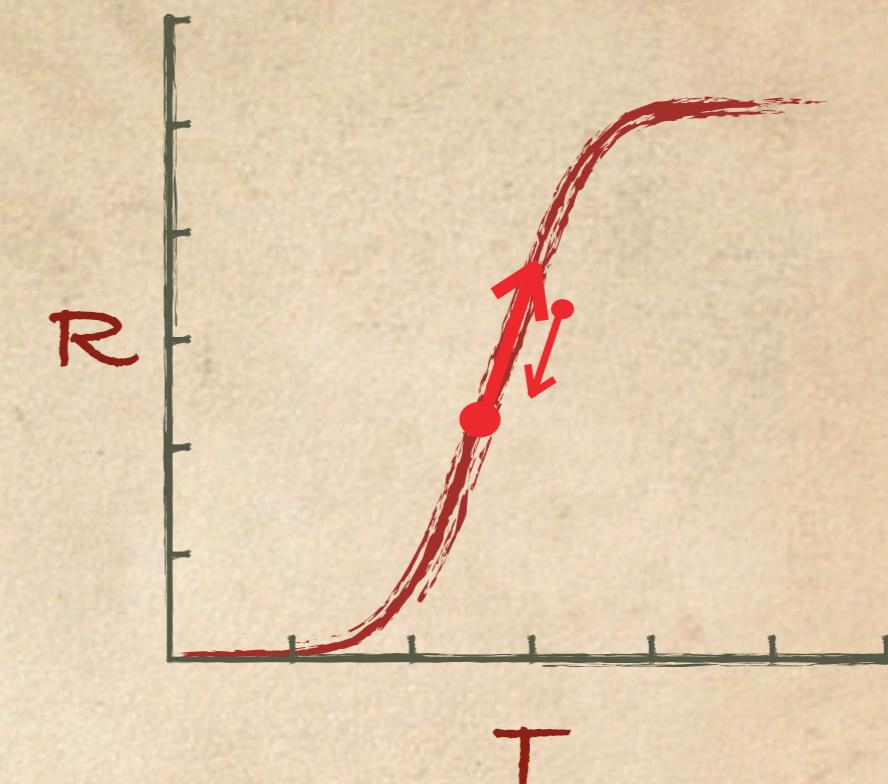
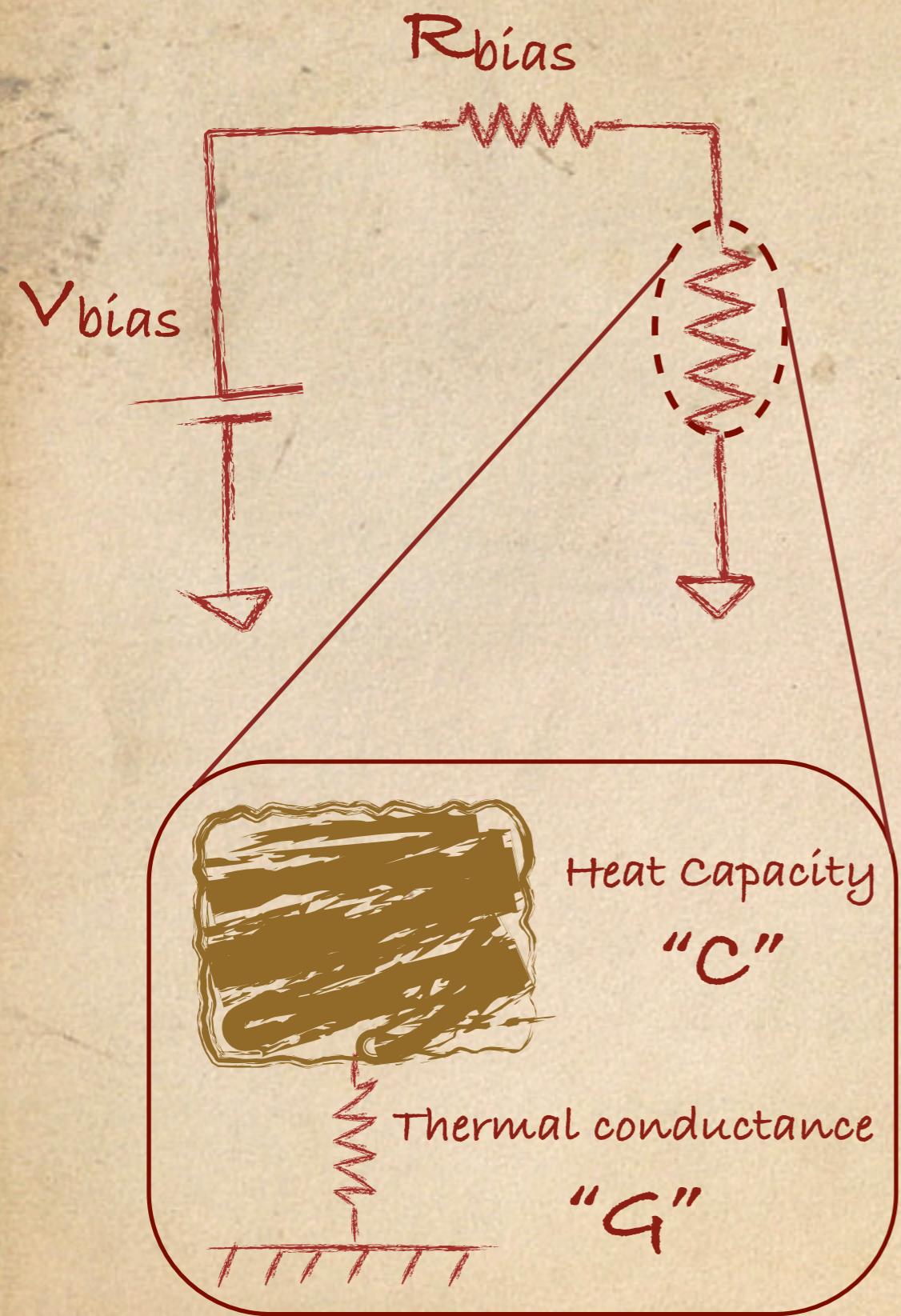
- Preparing to operate 5 kg of detectors at the Soudan underground laboratory (~2000 mwe)
- Background rate ~ 1 evt/kg/keV/day
- Planning upgrade in detector mass to 25 kg (SuperCDMS)

# CDMS Detectors

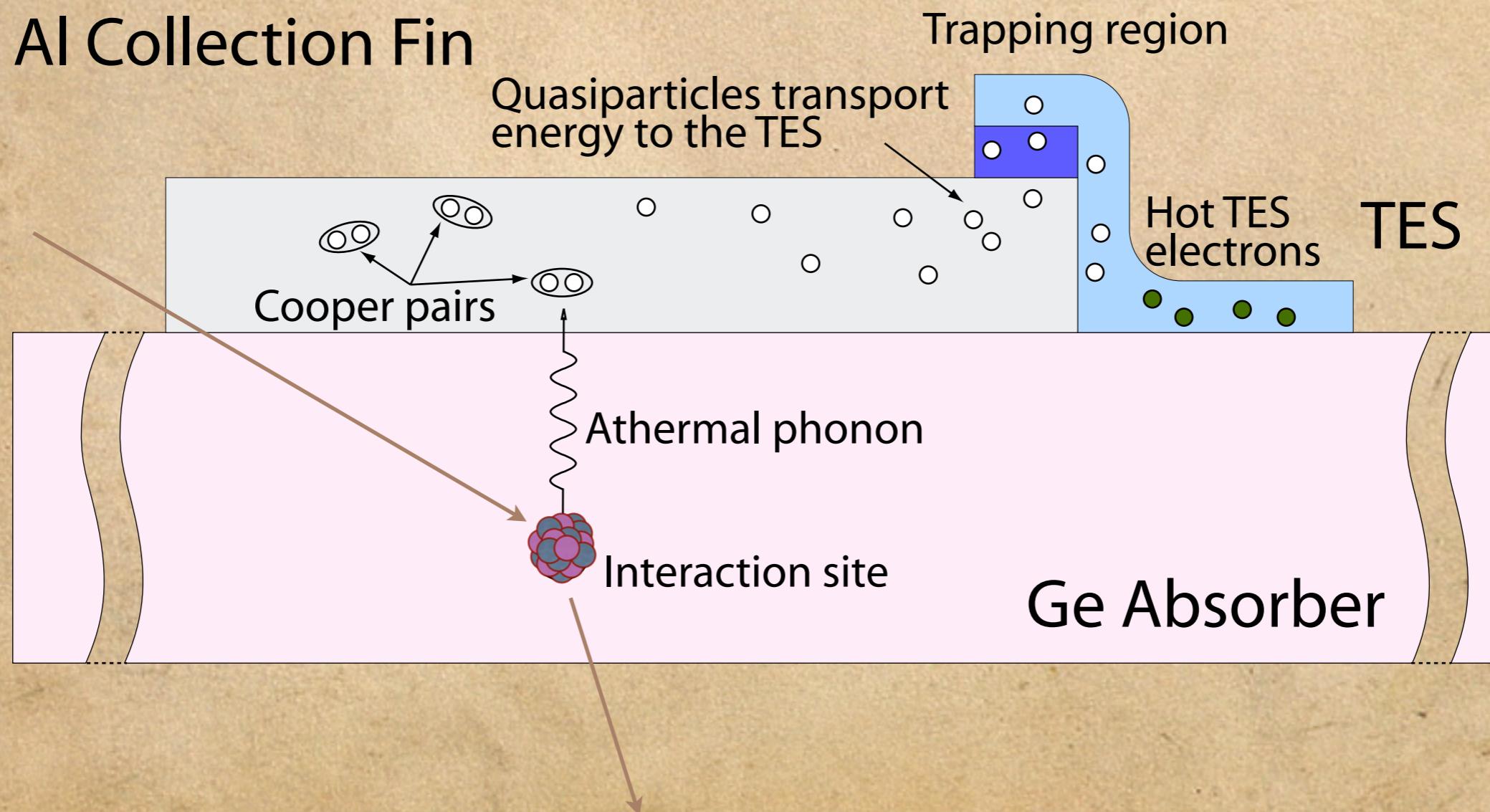
A brief detour ...



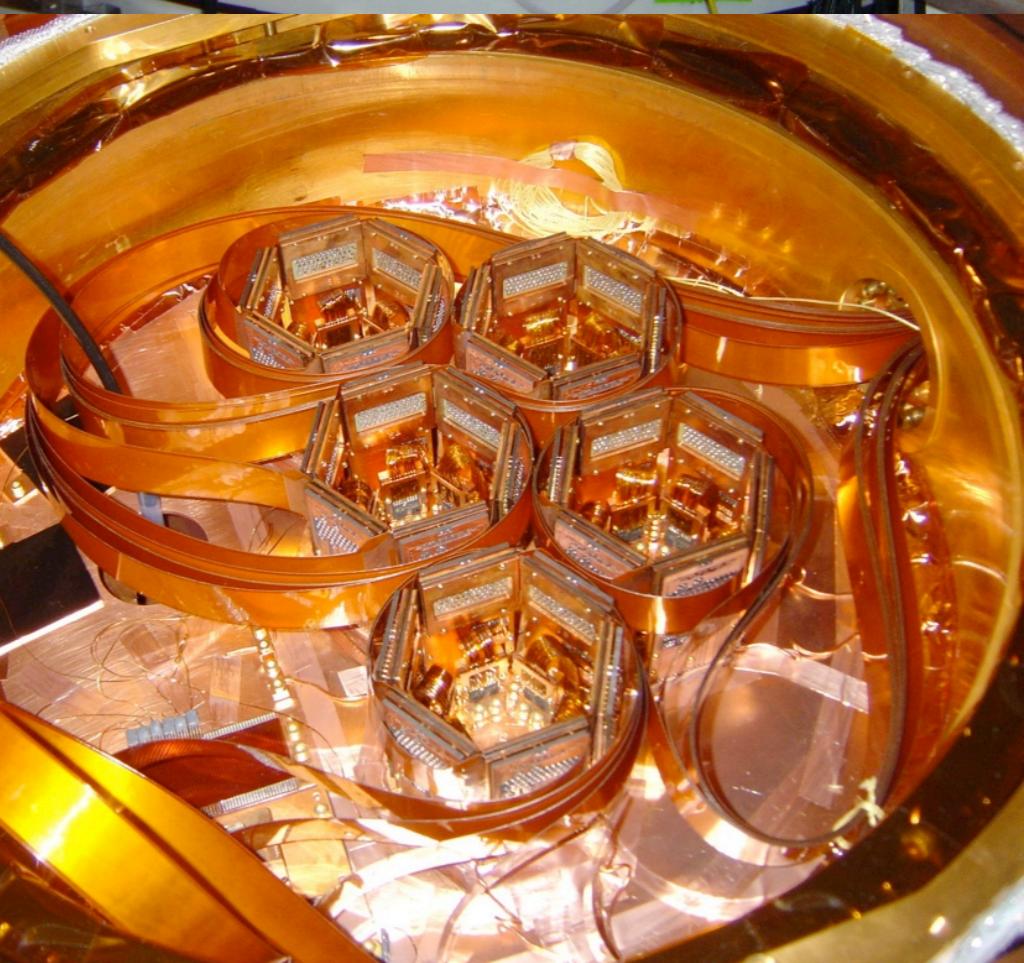
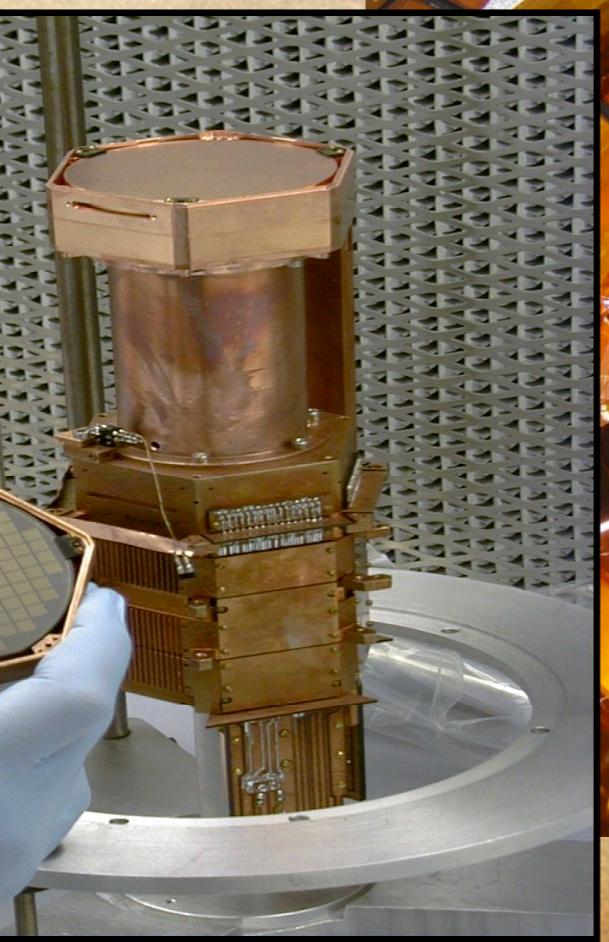
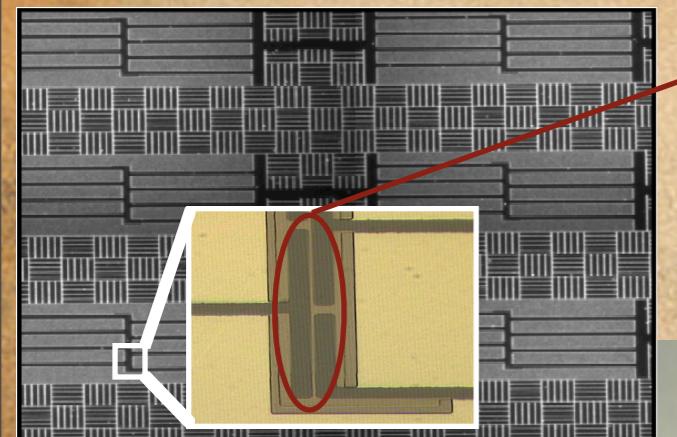
Consider the following electrical circuit :



# Getting the Energy to the Sensors

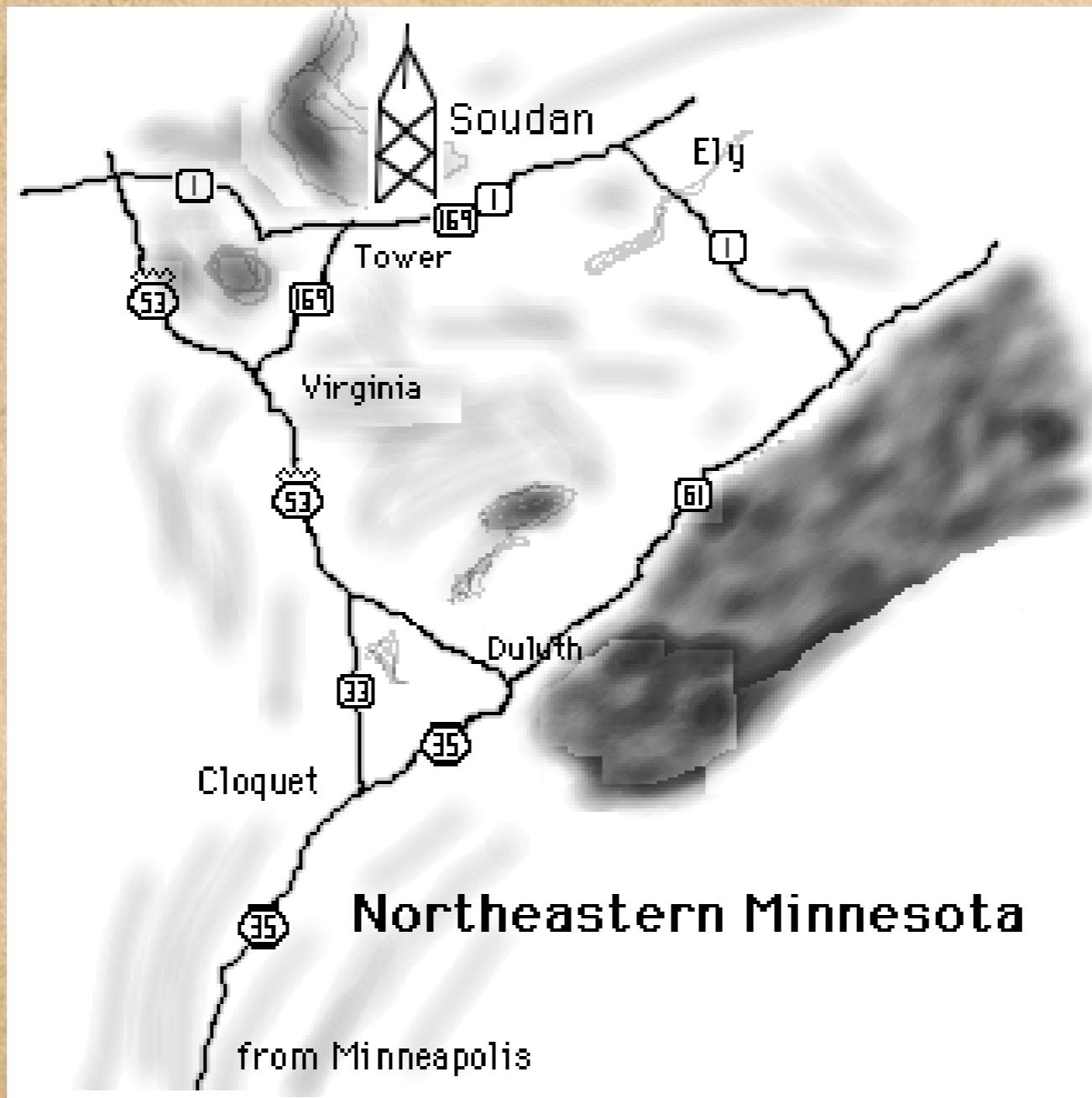


This is the  
superconducting  
thermometer  
 $1 \times 250 \mu\text{m}$



*Box it all up and go to Northern Minnesota*

*4 hours drive North on Minneapolis*



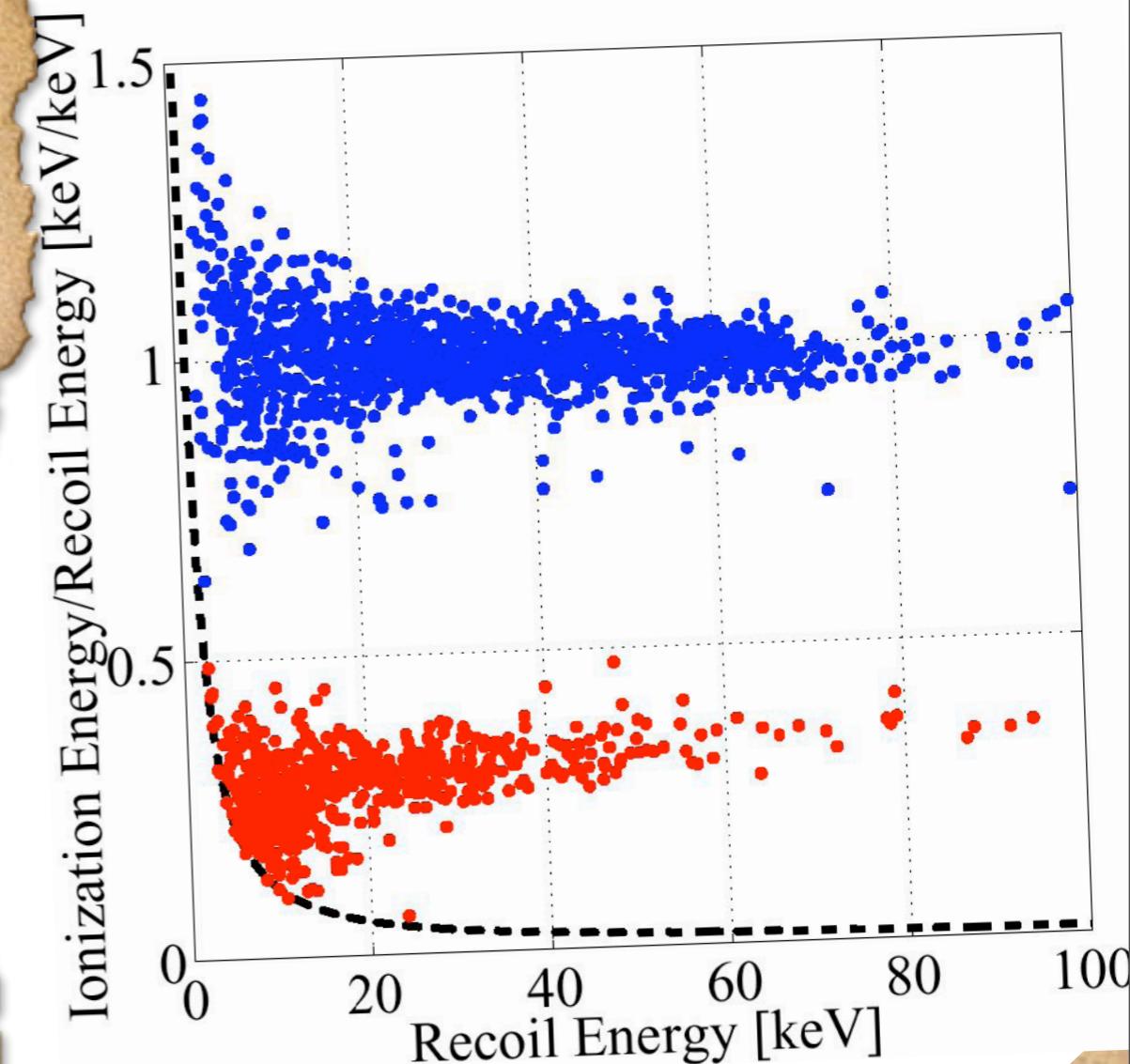




# CDMS Background

## Discrimination in Action

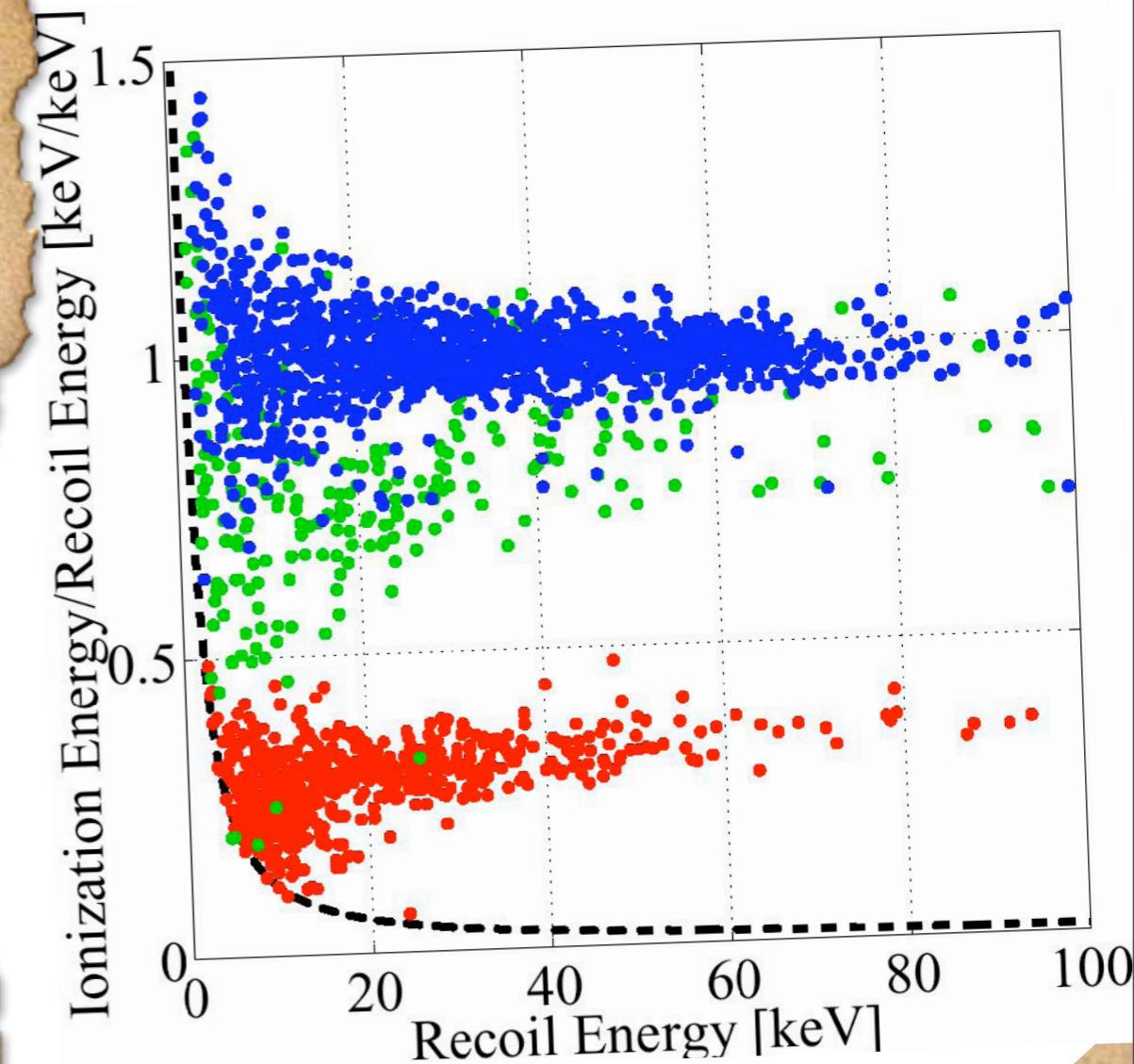
- Calibration with  $^{60}\text{Co}$  ( $\gamma$ ) source results in the blue (high yield) electron recoils
- Calibration with  $^{252}\text{Cf}$  ( $n$ ) source results in the red (low yield) nuclear recoils
- Can identify/eliminate the electron recoils better than 1 in  $10^6$
- ... BUT ...



# CDMS Background

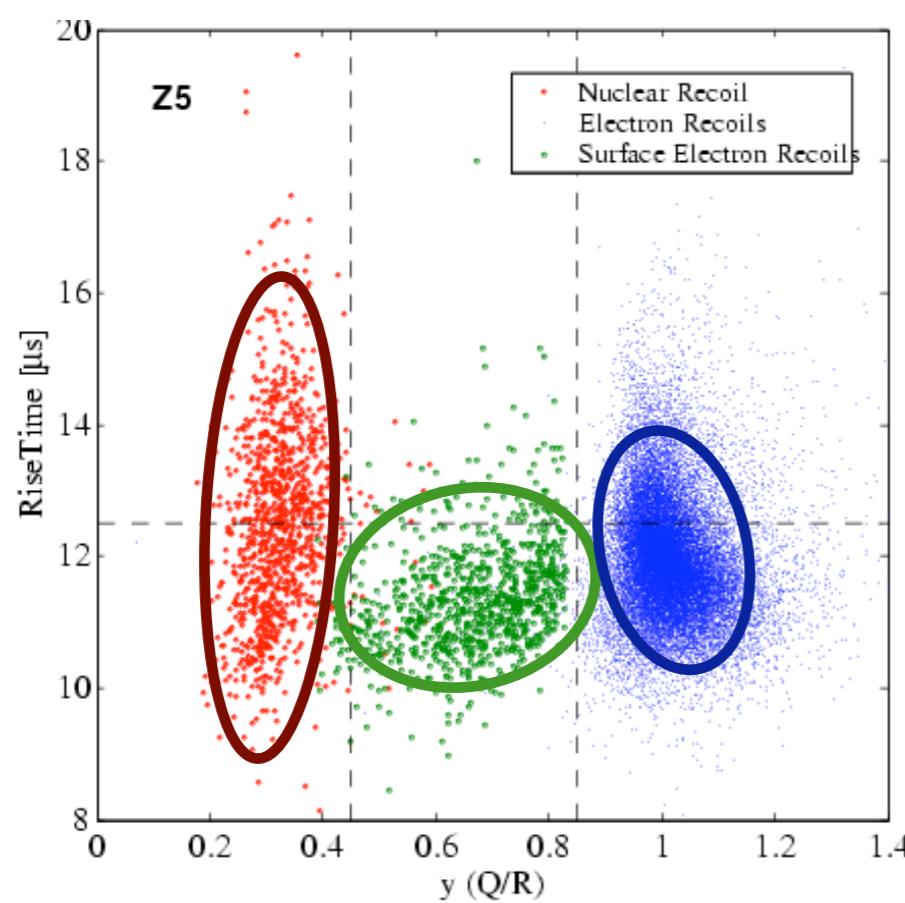
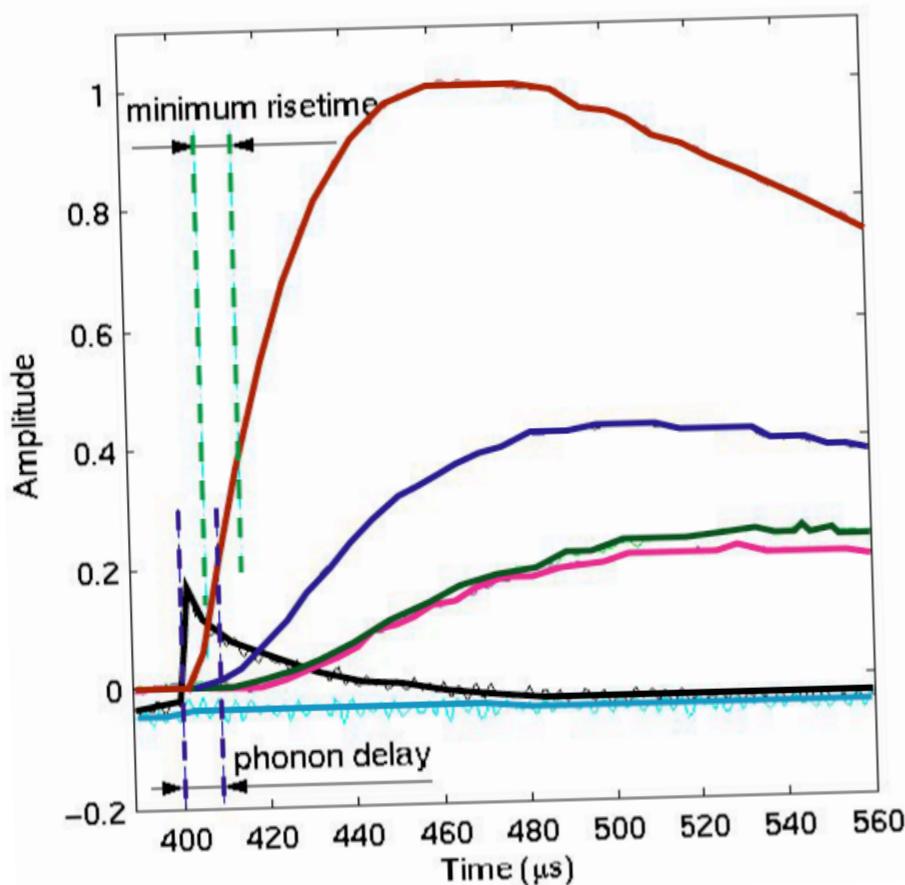
## Achilles' Heel

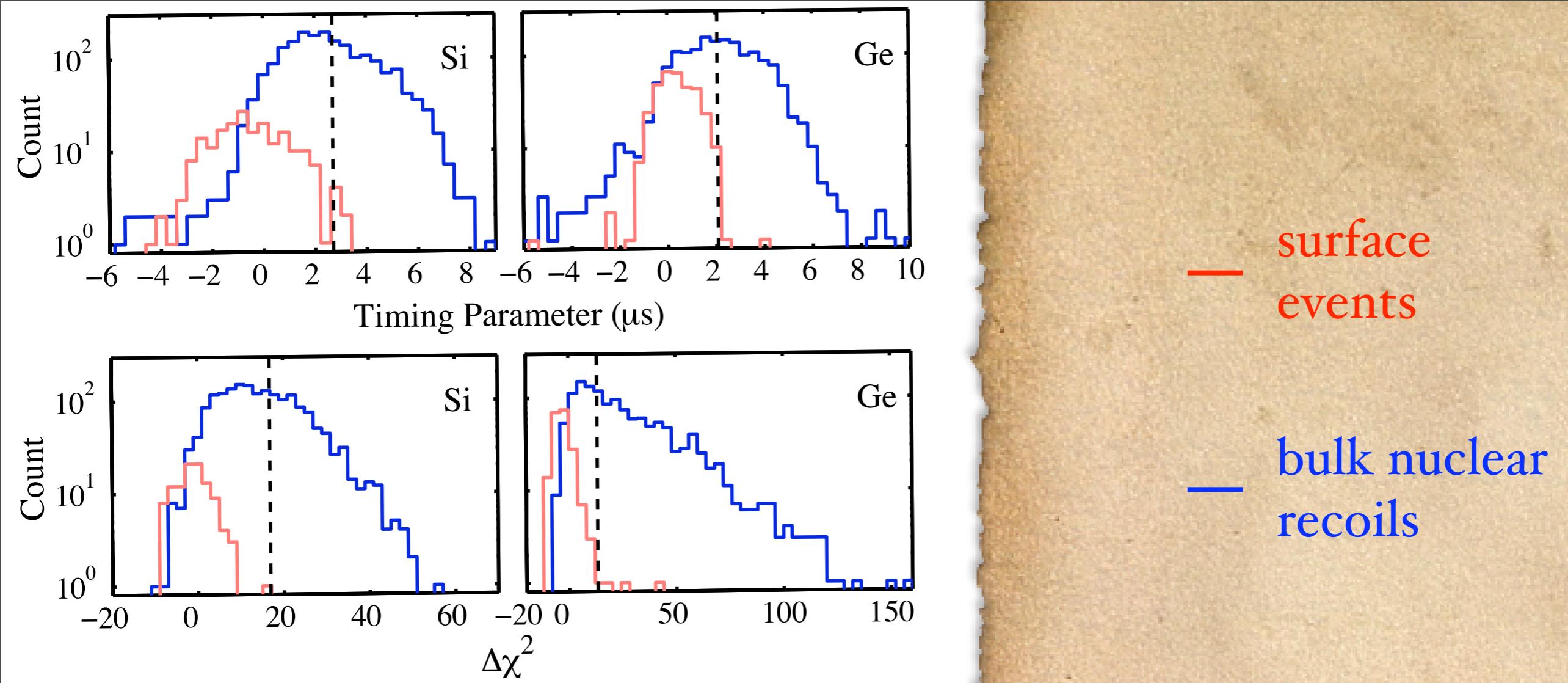
- Calibration with  $^{60}\text{Co}$  ( $\gamma$ ) source also results in the *green* (mid yield) electron recoils
- Events are due to electrons that interact near the surface (dead layer) of the detector
- Can be mis-identified as nuclear recoils



# Timing to The Rescue

- Analysis of pulse shapes / timing parameters further separates the event populations



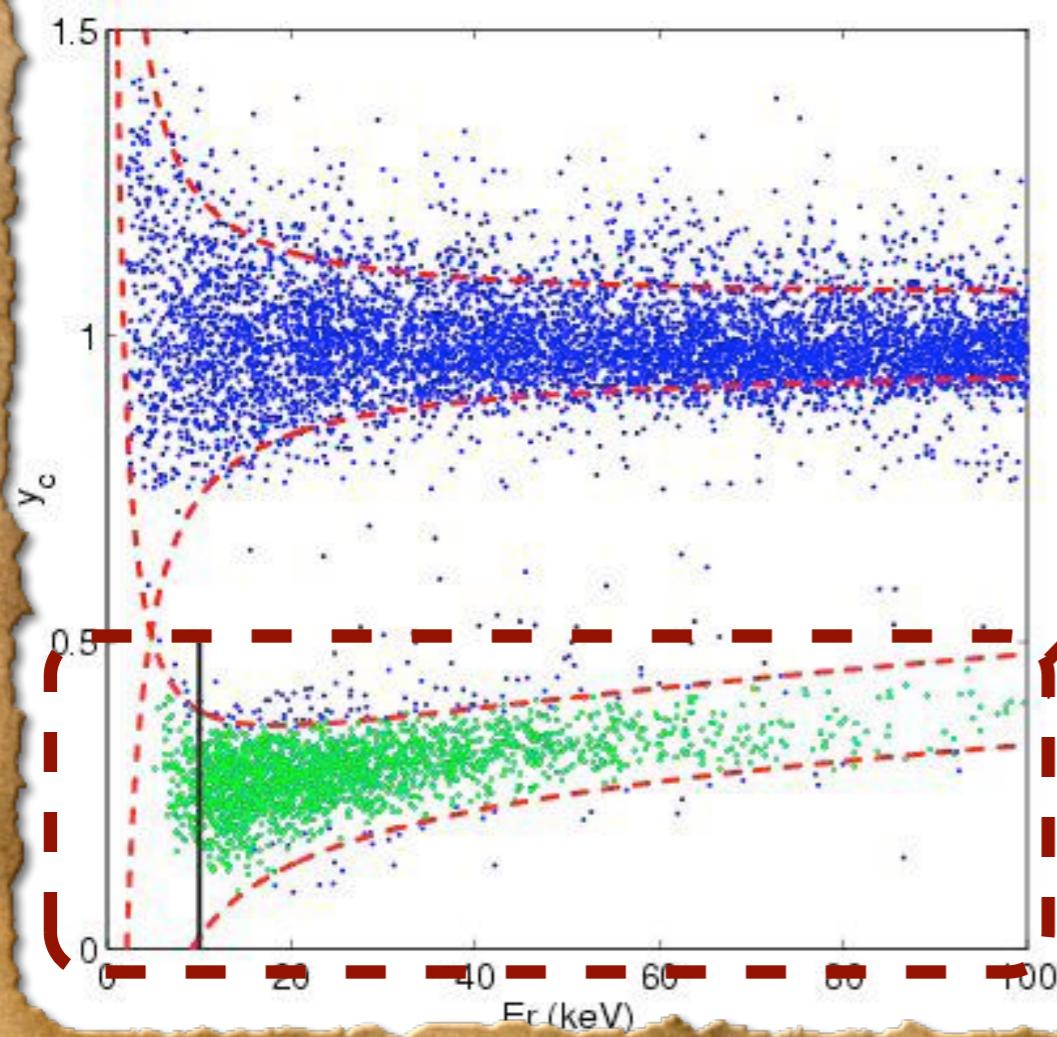


# Applying the Binning Cut

# CDMS in Action

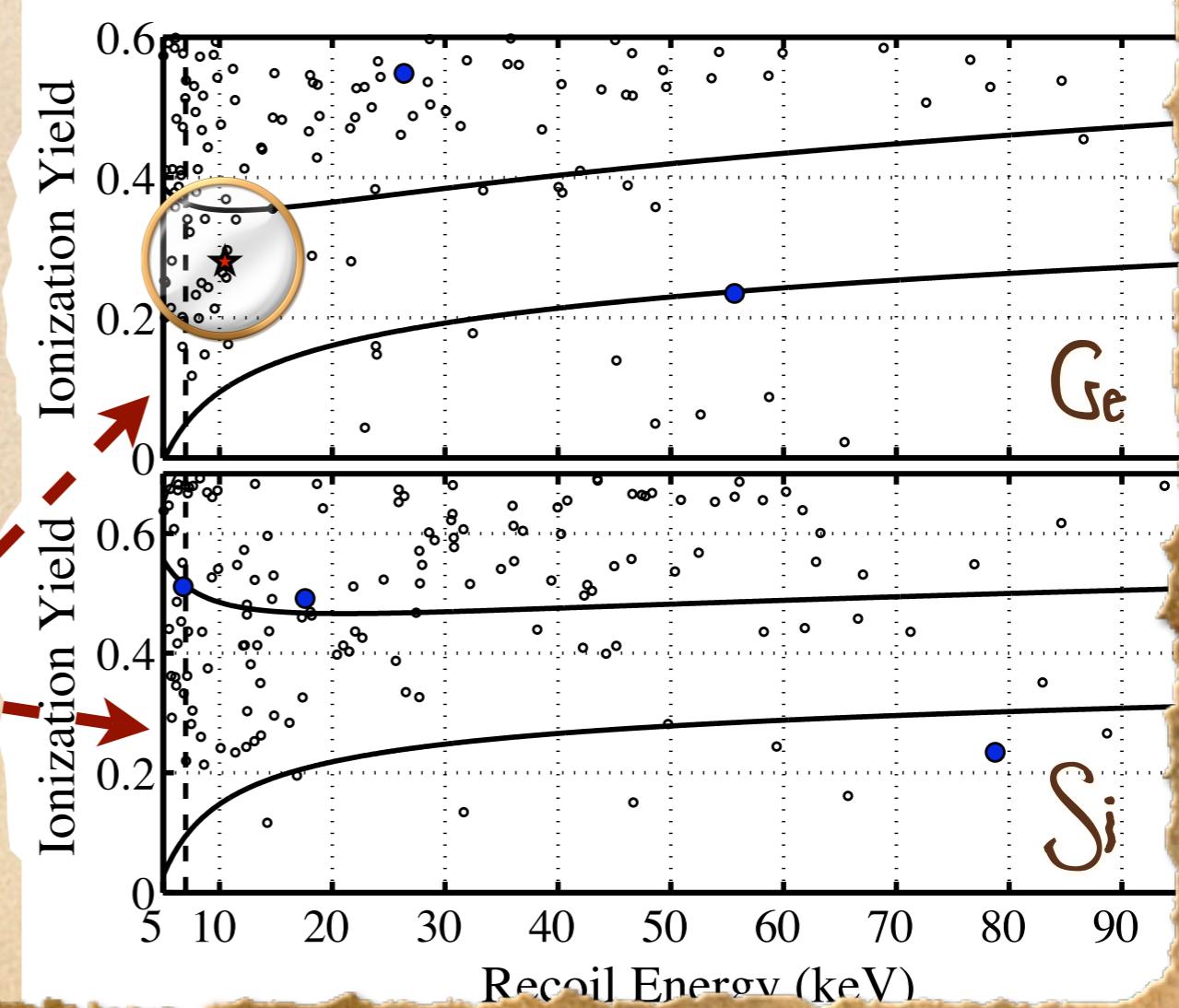
## Calibration data

- Electron recoils : blue
- Nuclear recoils : green

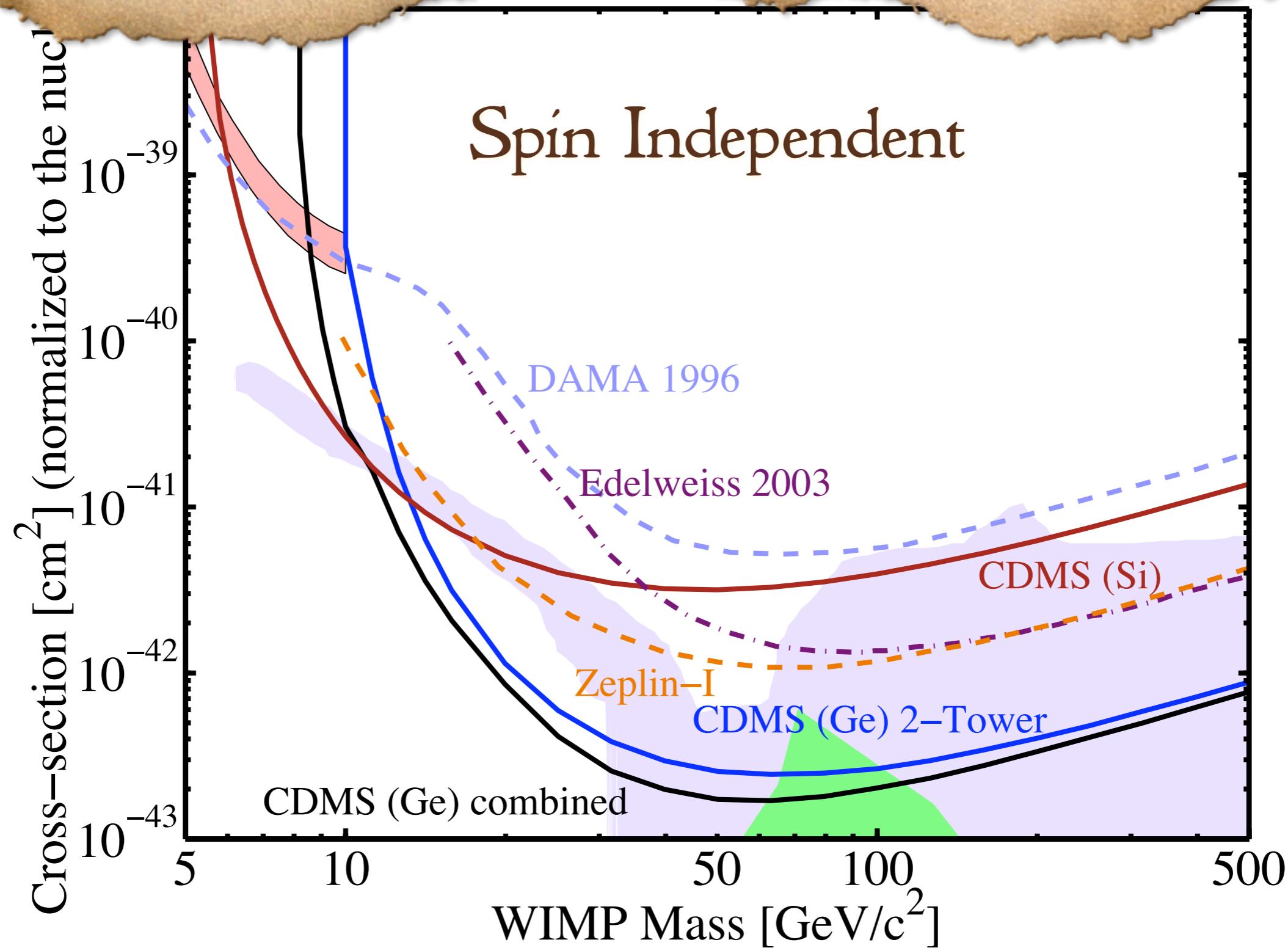


## Dark Matter data

- Only one event passes all background rejection cuts



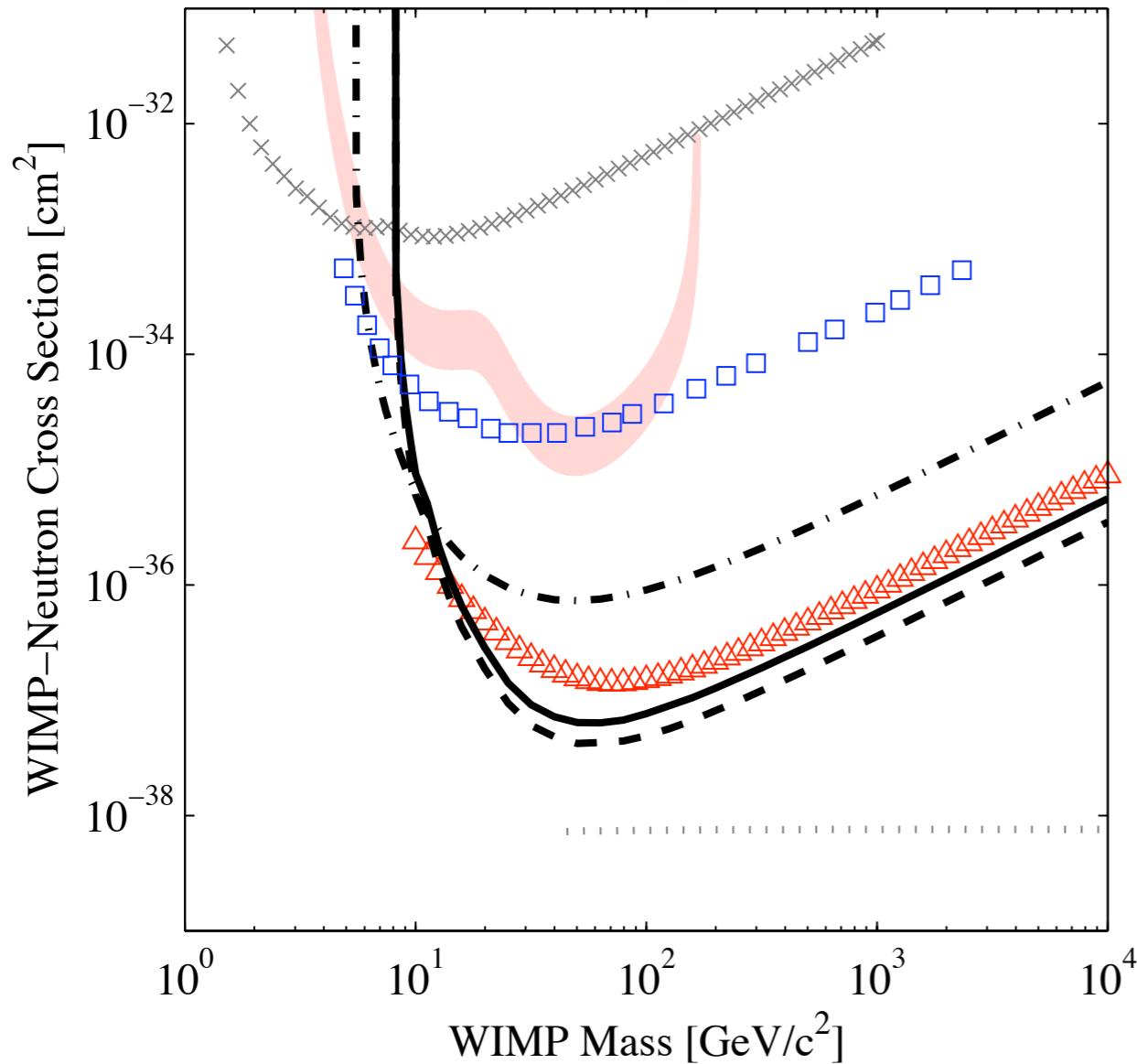
# CDMS Limits



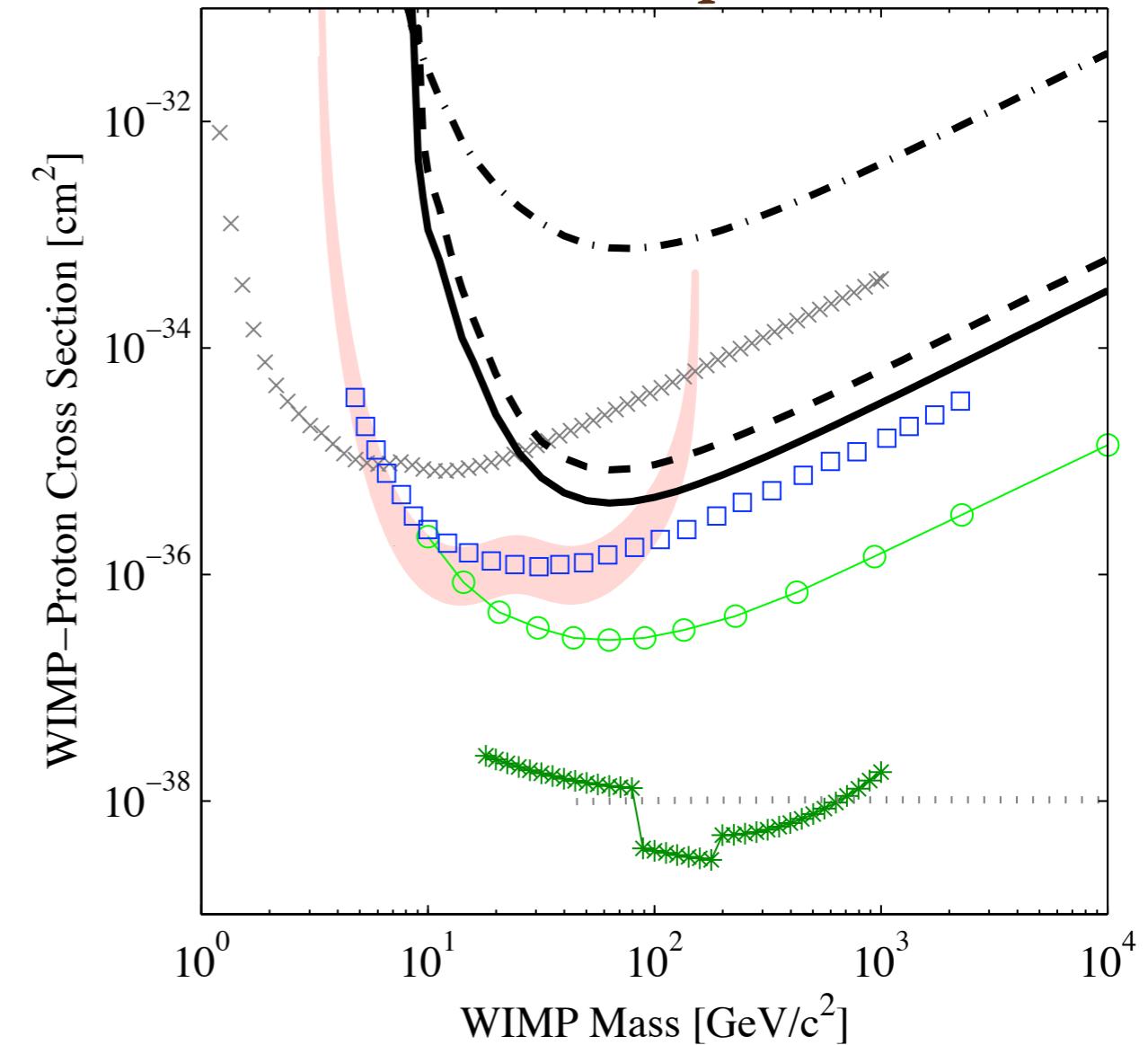
# CDMS Limits

## Spin Dependent

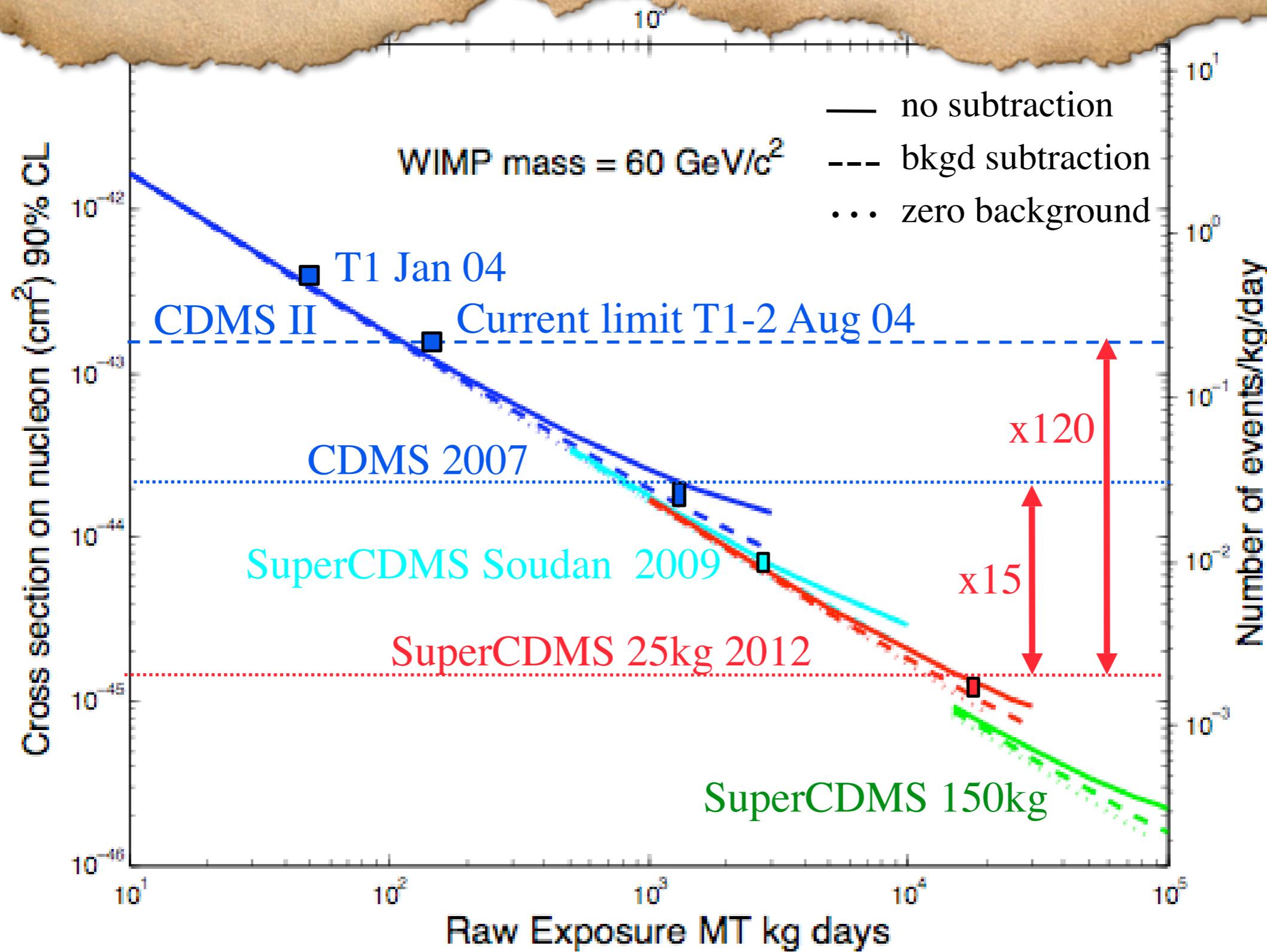
— Wimp-Neutron



— Wimp-Proton



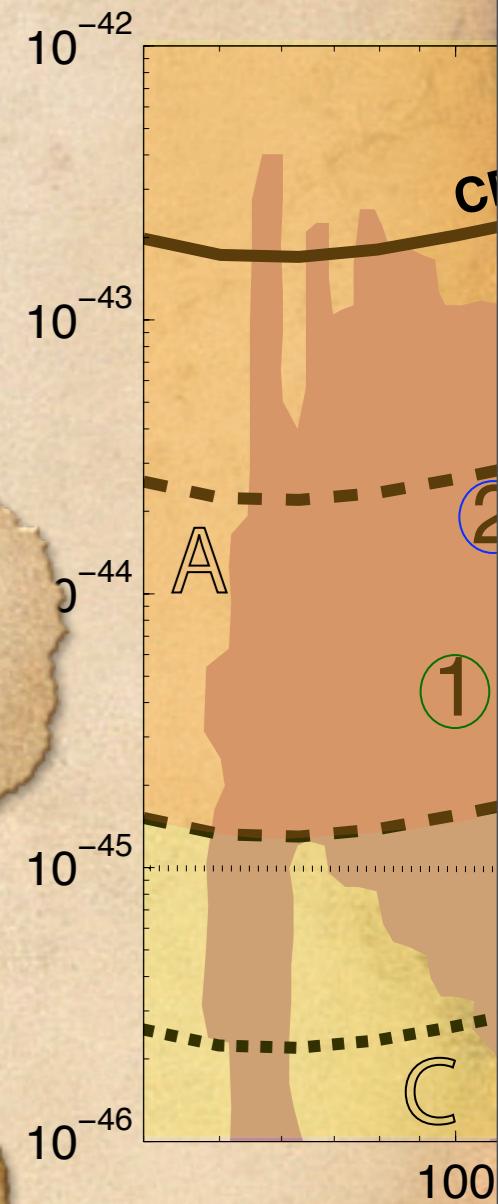
# The SuperCDMS Program



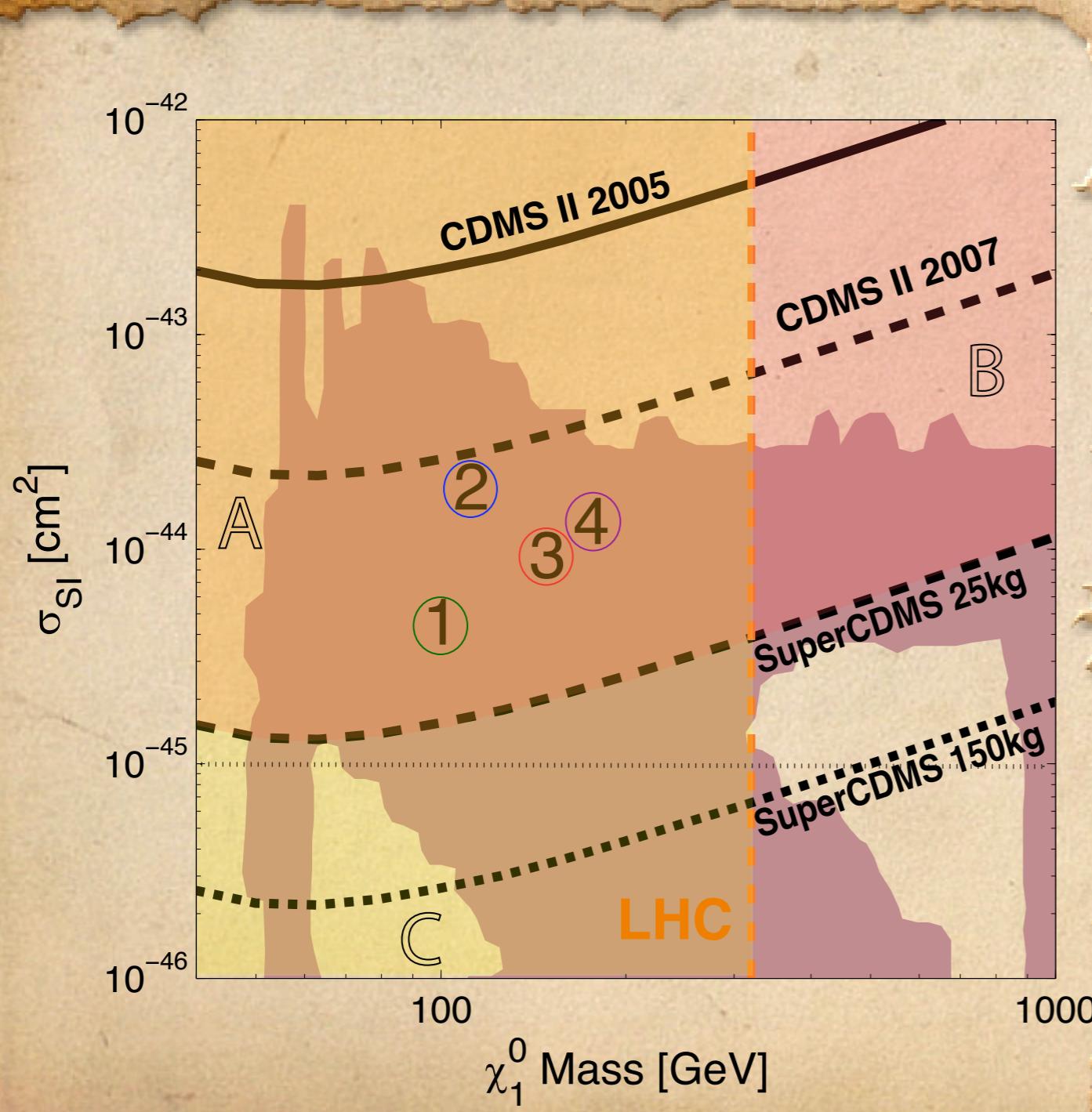
# Complementarity with Colliders

# SuperCDMS and the LHC

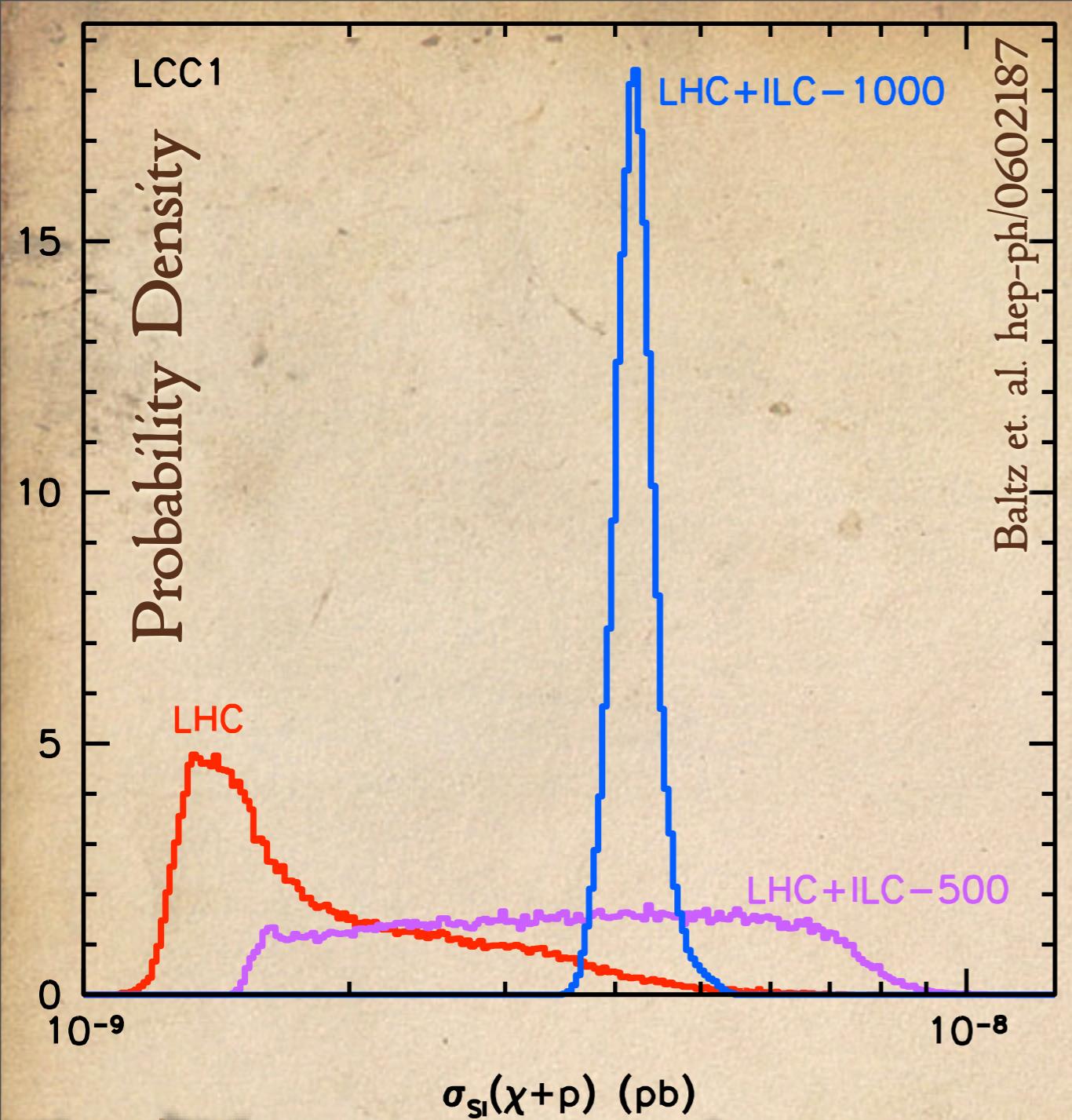
- For most generic WIMP candidates information from both accelerators and direct detection experiments is required to fully identify and understand the particle
  - e.g. It is hoped / expected that the LHC will be able to produce the Lightest Supersymmetric Particle, however, it will not be able to identify it as the cosmological Dark Matter



# SuperCDMS and the LHC

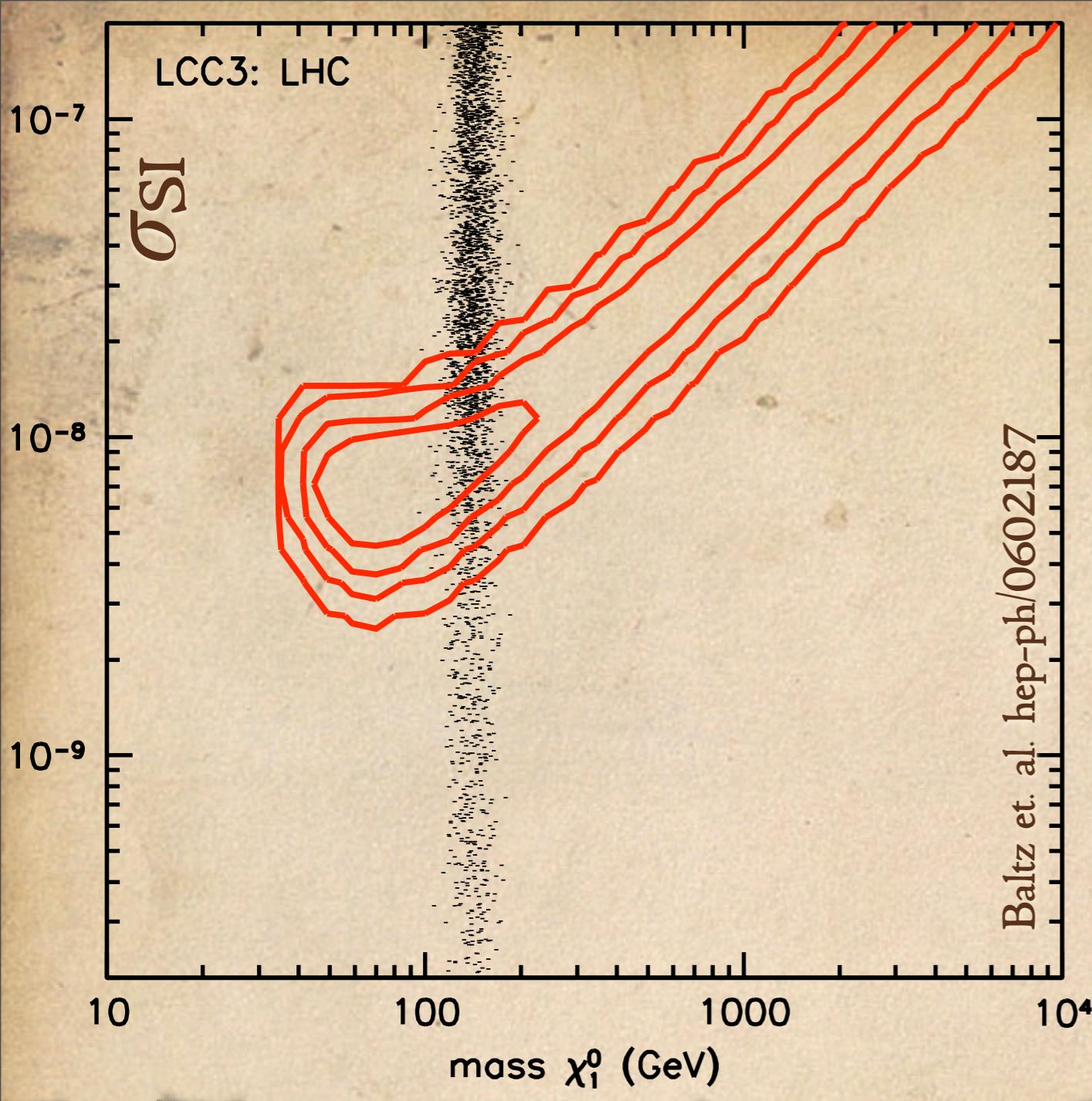


- Direct detection and collider experiments measure different aspects of the WIMP
- 4 points in SUSY parameter space where chosen such that :
  - Different WIMP annihilation channels
  - Particles are accessible to LHC/ILC



- If SUSY is described by point #1
  - LHC and ILC-500 GeV will not determine the elastic scattering cross-section  $\sigma_{\text{SI}}$
  - SuperCDMS 25kg would see  $\sim 15$  events and constrain  $\sigma_{\text{SI}}$  comparable to ILC-1000

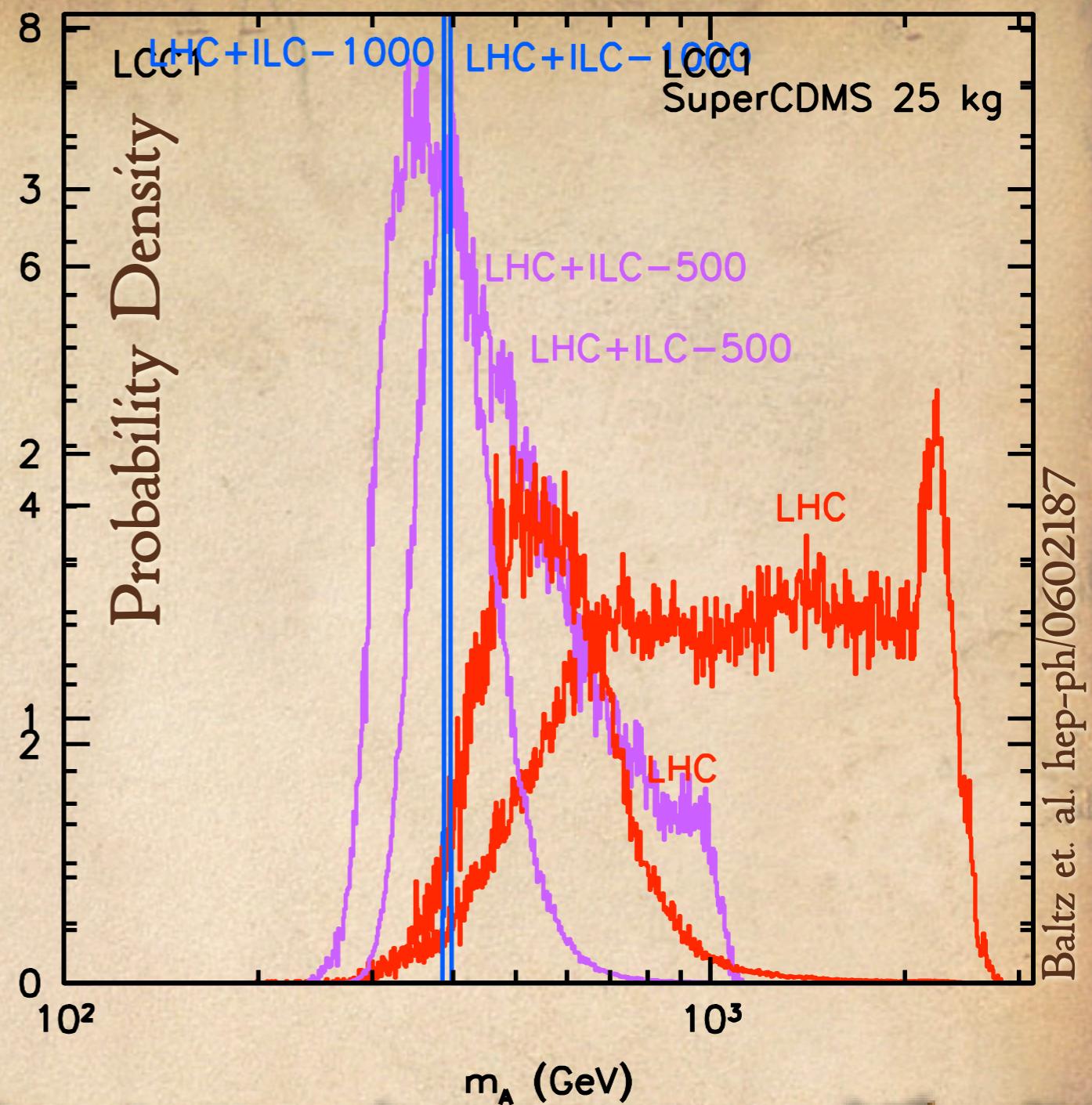
# $\chi$ Mass-Cross Section Complimentarity



- If SUSY is described by point #3
  - LHC can constrain mass to  $\sim 20\%$
  - SuperCDMS 2yr data will constrain the elastic scattering cross-section  $\sigma_{\text{SI}}$

# $\chi$ Mass-Cross Section Complimentarity

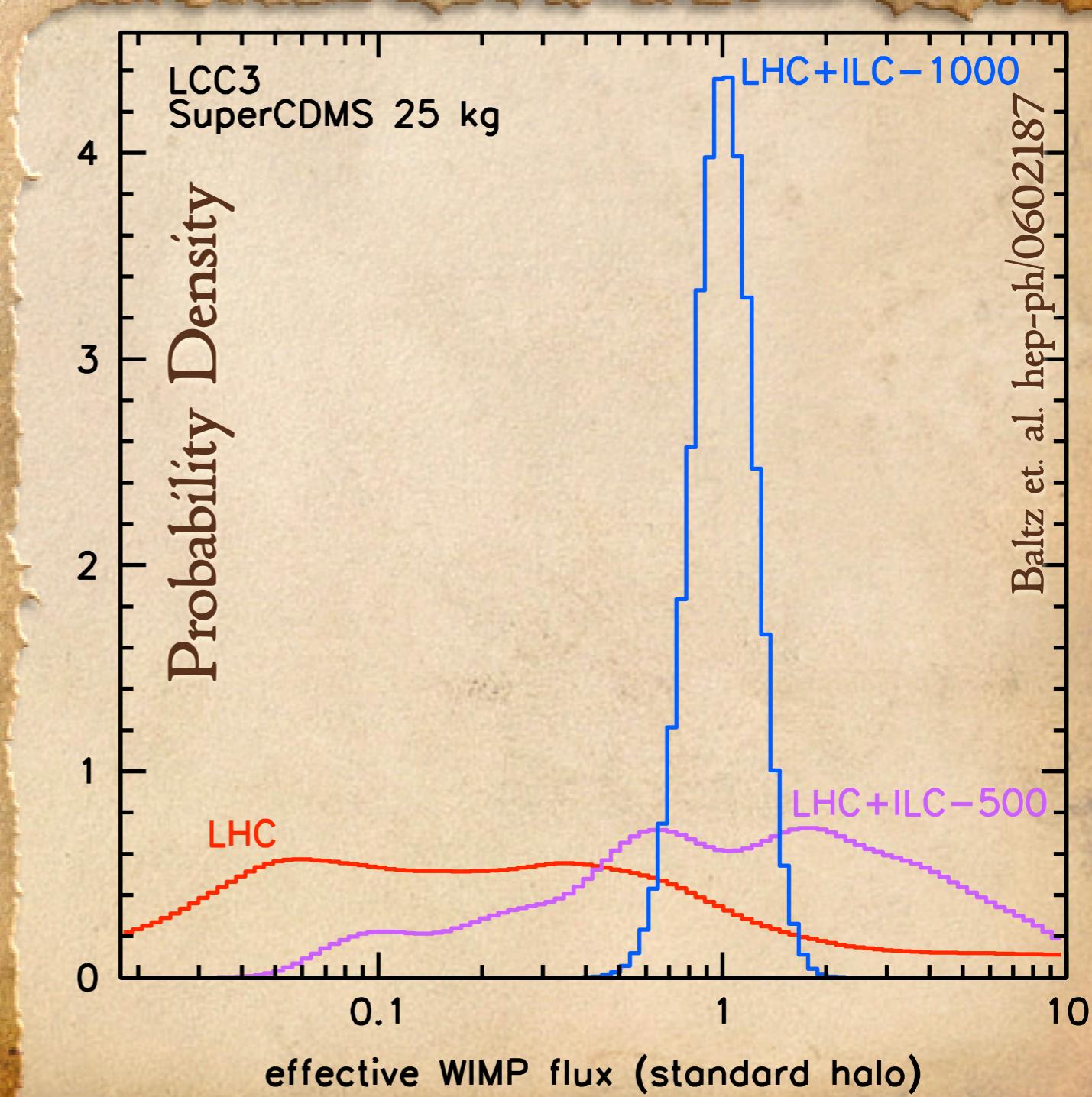
- Large uncertainties associated with the mass of the heavy Higgs :  $m_A$
- Until it is produced in the ILC-1000
- SuperCDMS 2yr data will help improve LHC value



# Determining the Mass of the Heavy Higgs $m_A$

# The Local Halo Density

- ♦ Neutralino relic density  $\Omega_\chi h^2$  can be calculated with SUSY parameters from LHC/ILC
  - In combination with direct detection rate measurement can determine local halo  $\chi$  density
  - Relevant for questions of WIMP clumping on a galactic scale



# Final Words On Complementarity

## Direct Detection

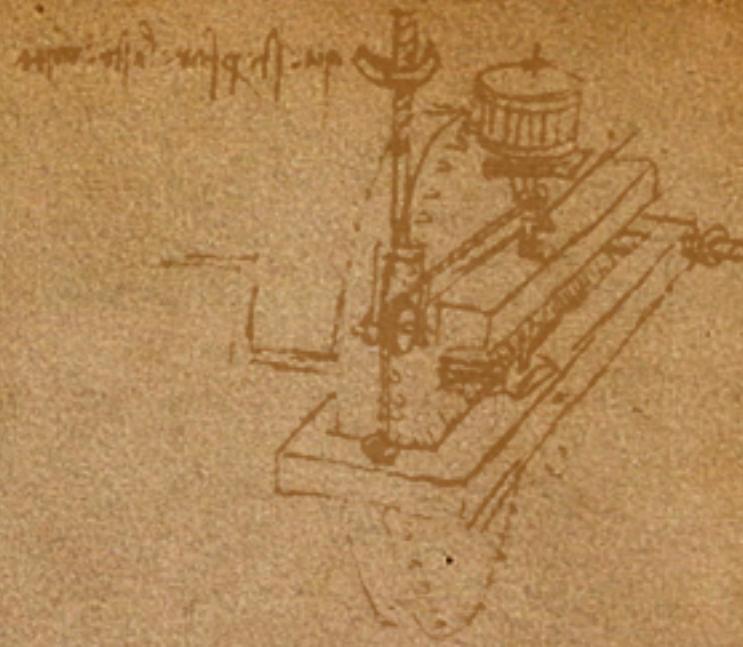
- Discover relic particle
- Constrain  $m_\chi, \rho \sigma_{\text{dir}}$
- With LHC/ILC input

## Indirect Detection

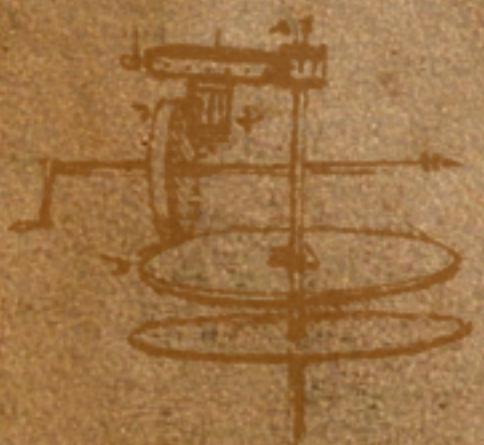
- Discover relic particle
  - Constrain  $m_\chi^2, \sigma_{\text{in}} \int \rho^2$
  - With LHC/ILC input
- determine  $\rho_{\text{halo}}$  (or GC)

## Collider Production

- Discover supersymmetric particles
- Determine physics model behind  $m_\chi$
- Predict  $\sigma_{(\text{in-})\text{direct}}$

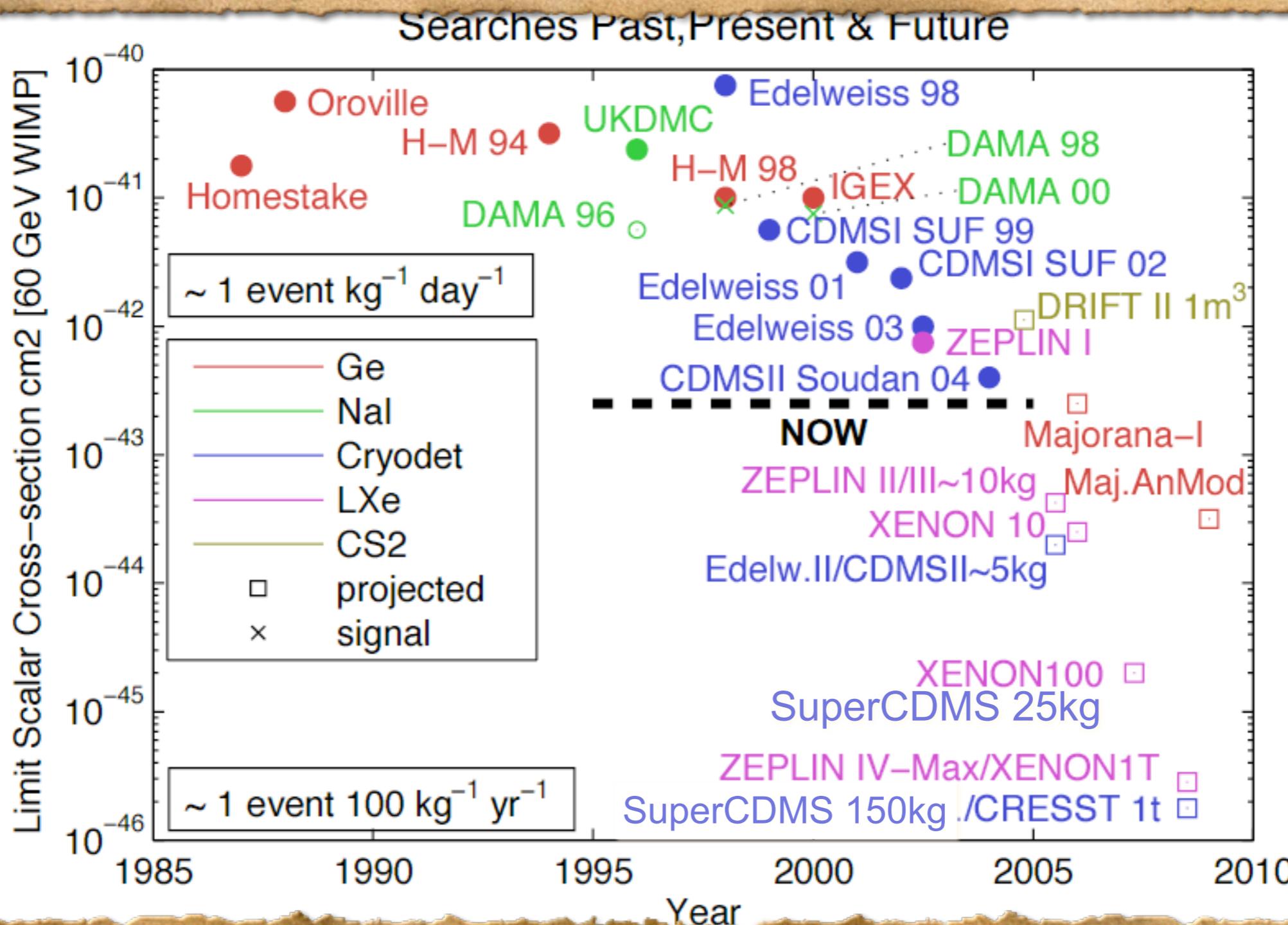


# Conclusion



# DM Searches in the 21<sup>st</sup> Century

## Ready to Take on Theory ;)



**H**ot on the **T**ail of  
the **E**lusive **WIMP** :  
**D**ark **M**atter **S**earches  
in the **21<sup>st</sup>** **C**entury

تarek Saab

2006 MIT Astrophysics Colloquium