Listening for the Dark

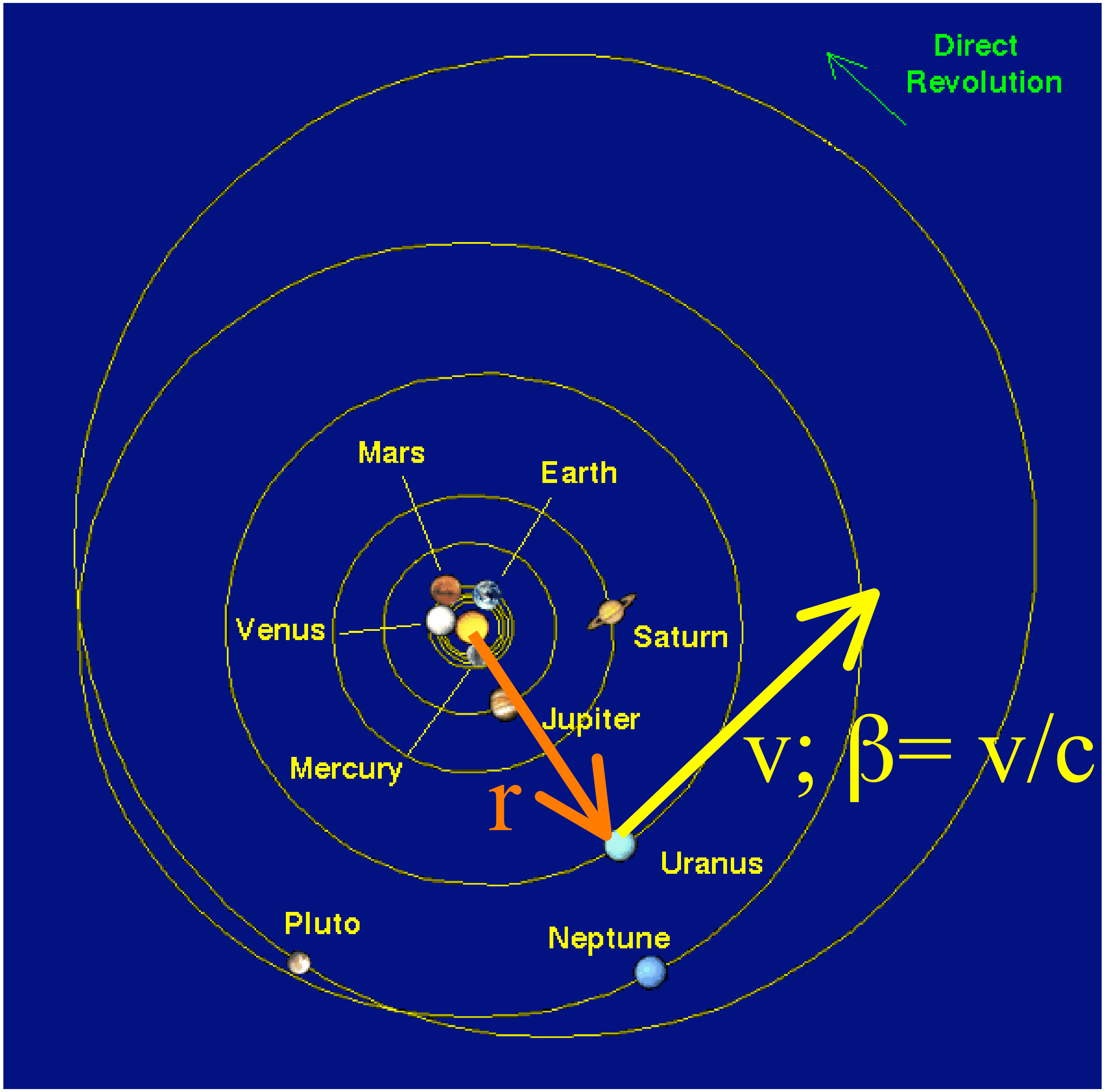
Harry Nelson
UCSB

Plan

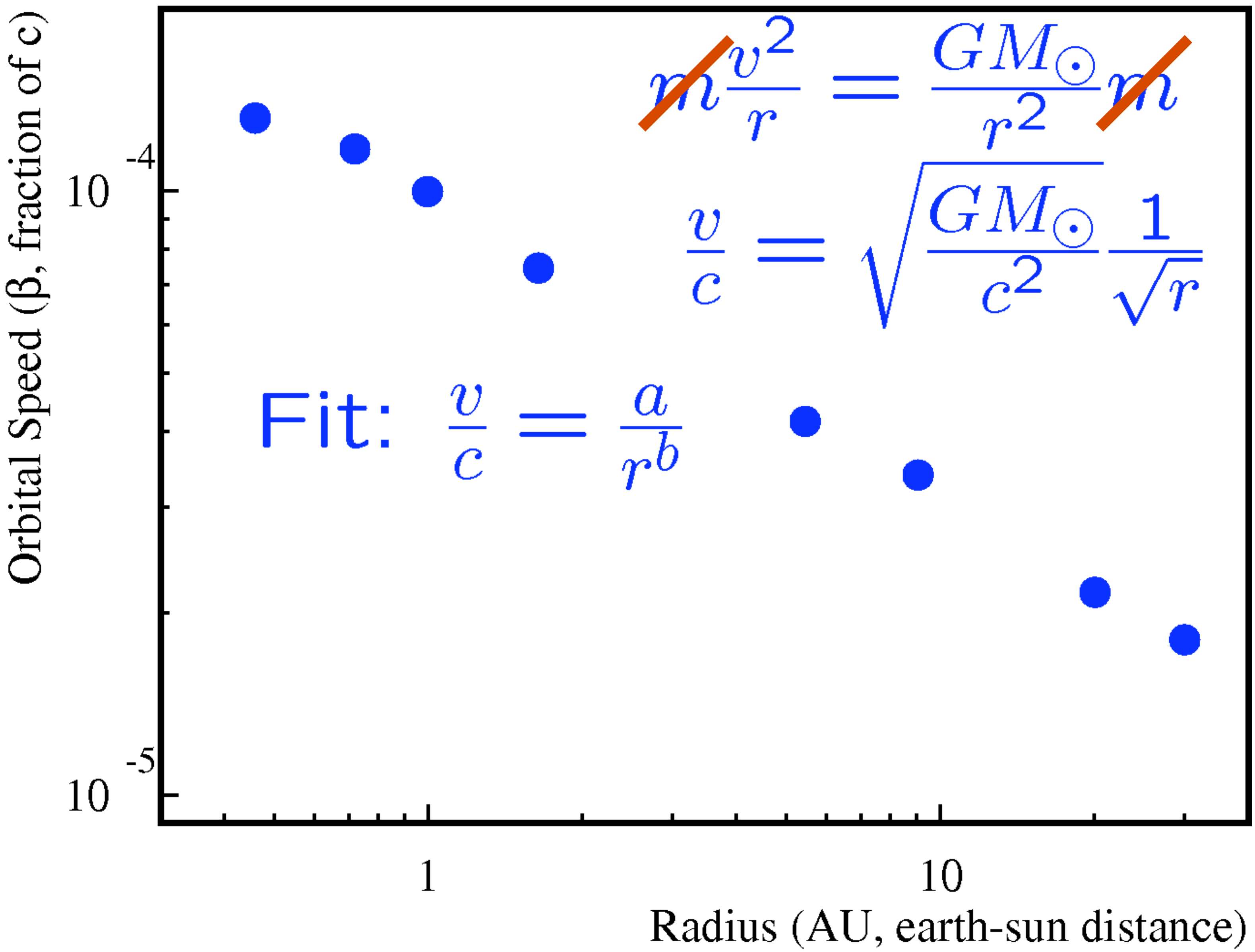
- Massive Dark Matter
- Direct Detection
- Xenon
- CDMS
- Future

`We Declare a New Order'

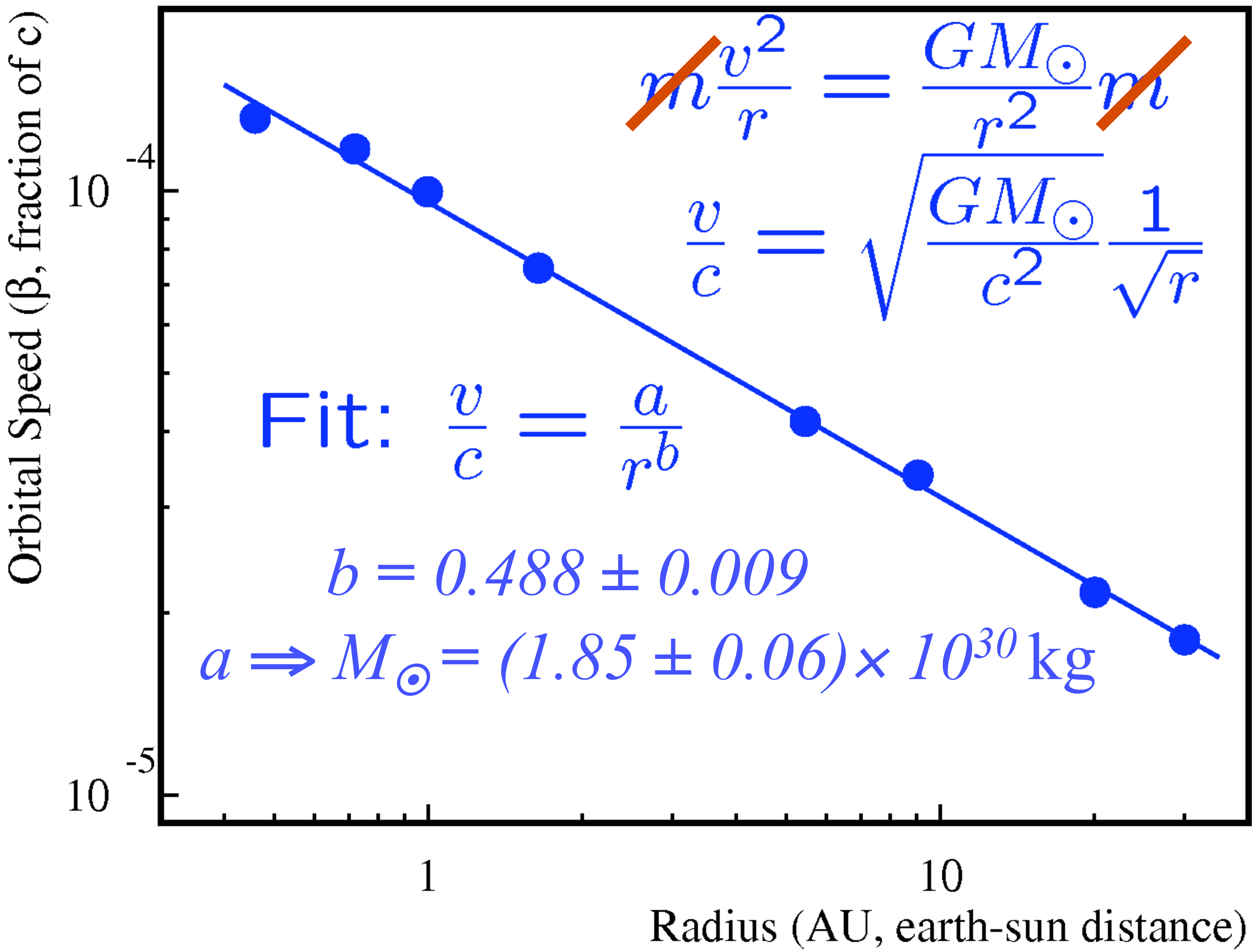
(Joel Primack)


Direct
Revolution
Mars
Earth
Venus
Saturn
Jupiter
Mercury
r
v; β= v/c
Uranus
Pluto
Neptune

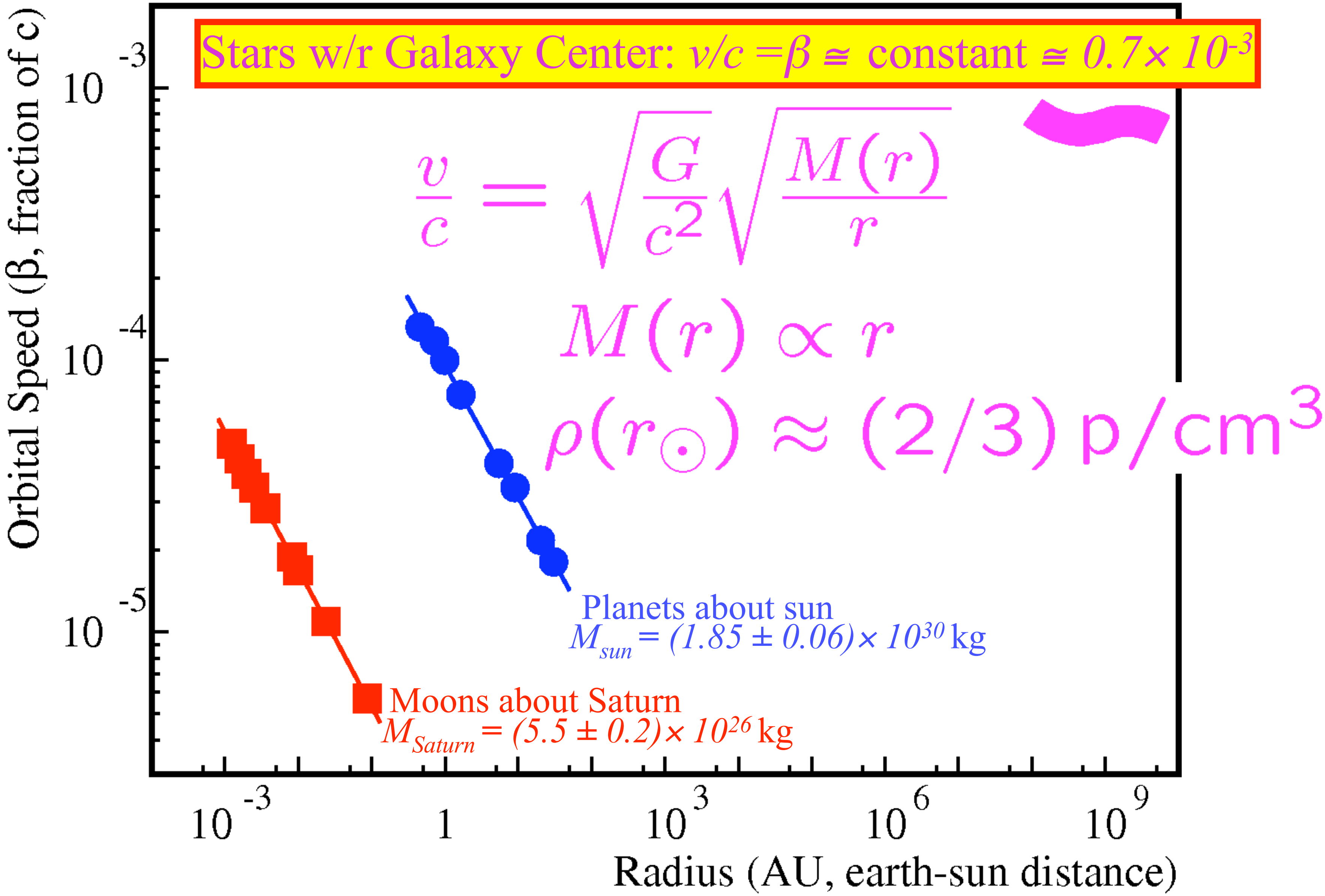
Rotation Curves



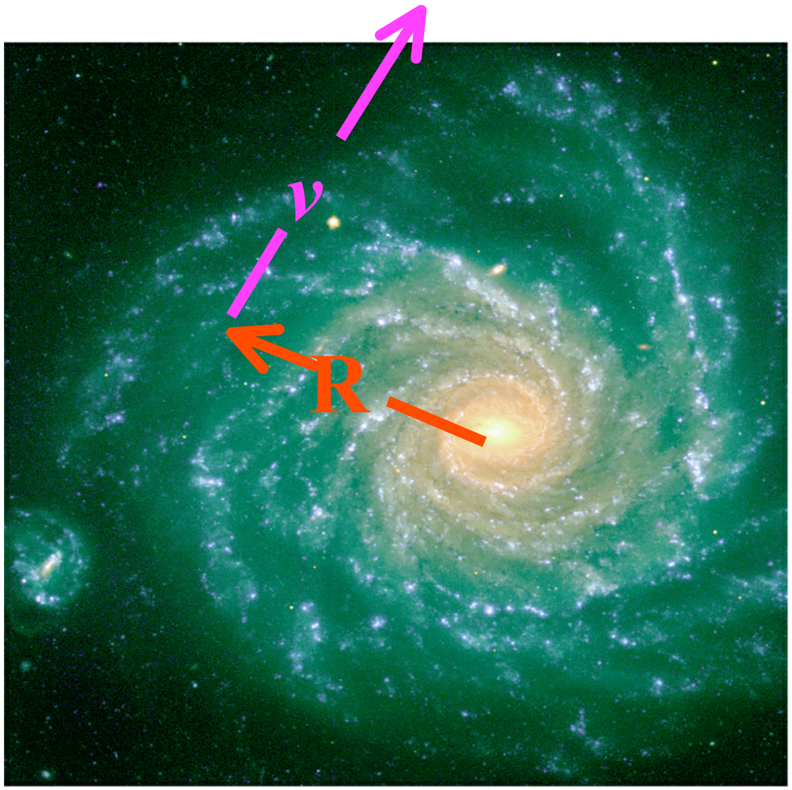
Rotation Curves



Rotation Curves

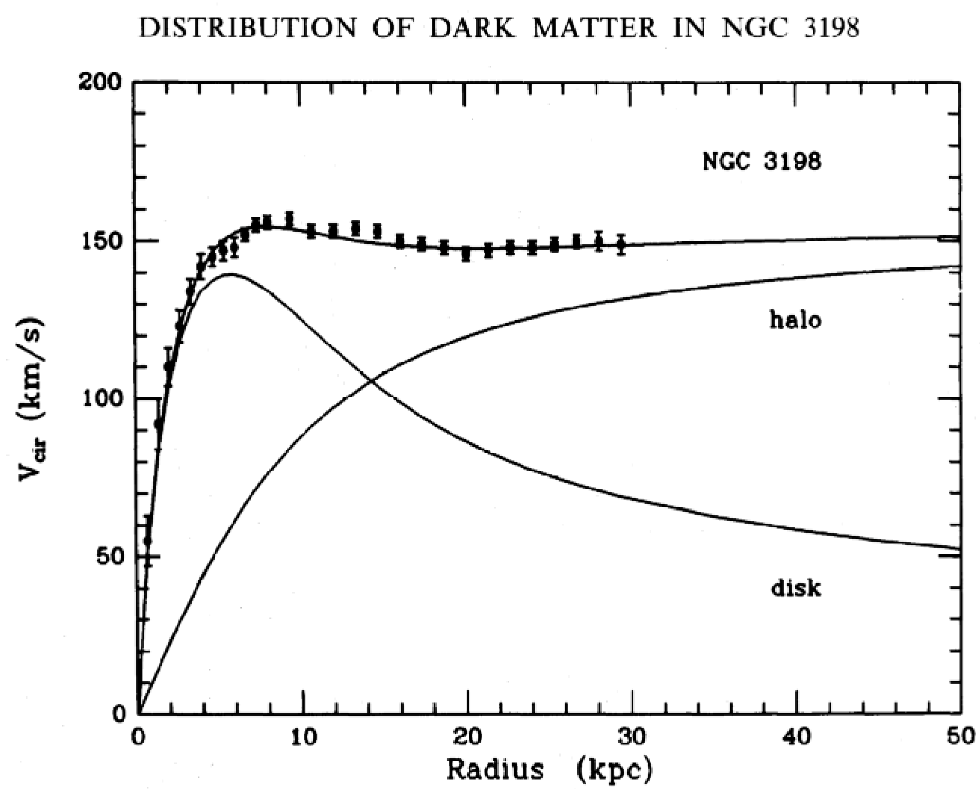


Galactic Dark Matter



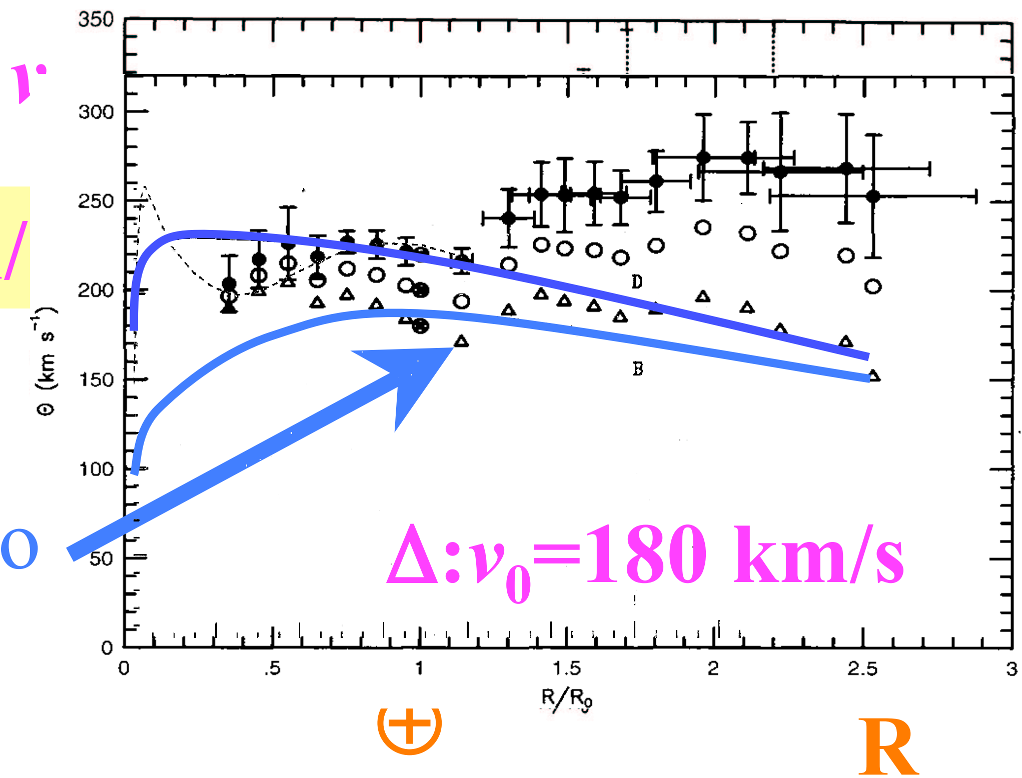
R is the distance from center

v is the speed (tangential)



What about our home galaxy (Milky Way)?

Honma and Sofue, 1996



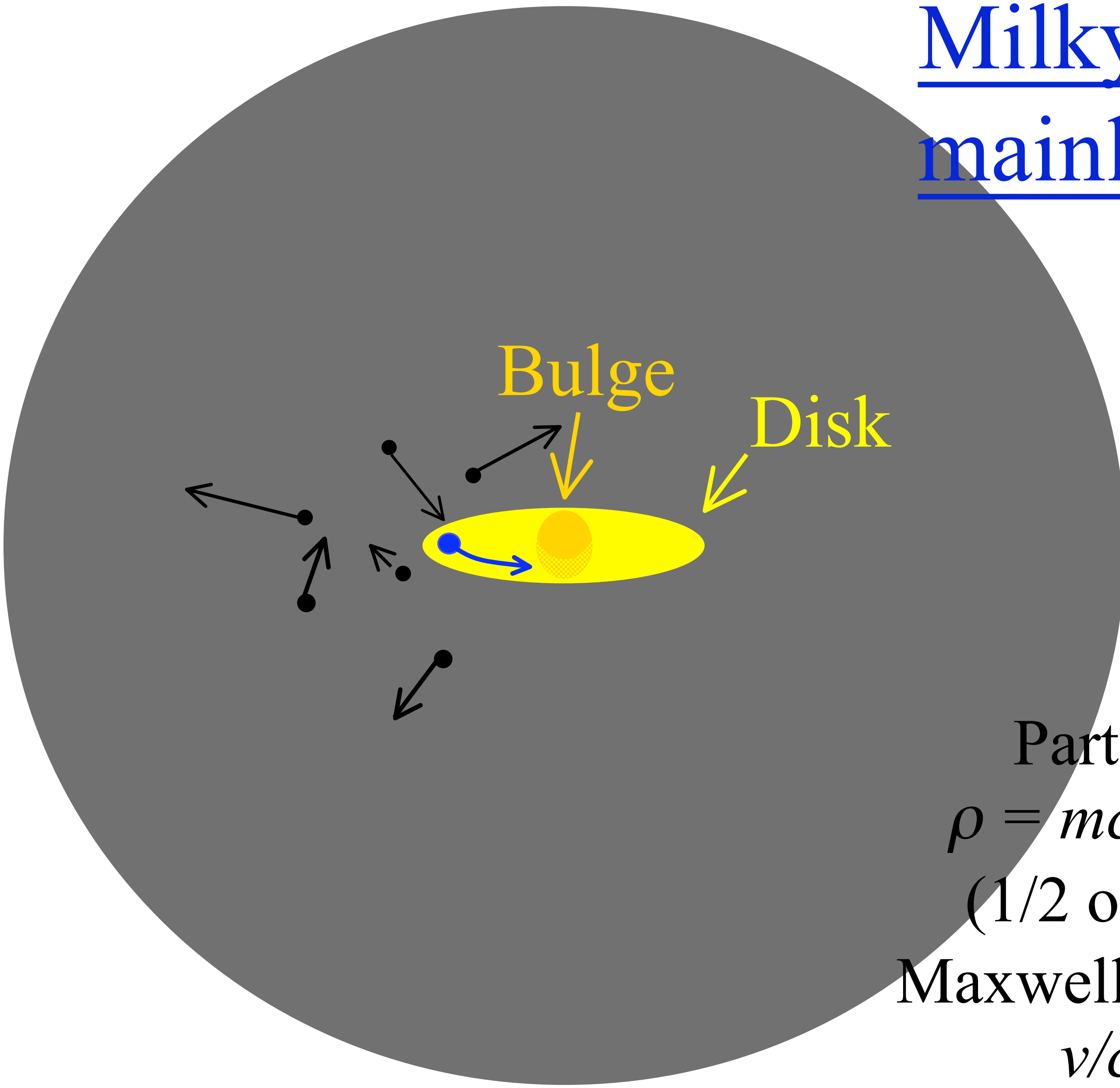
220 km/

Δ:v_0=180 km/s

Without the Dark Halo

(Binney & Tremaine)

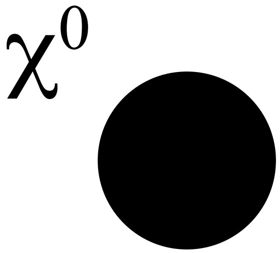
Milky Way: mainly a dark cloud

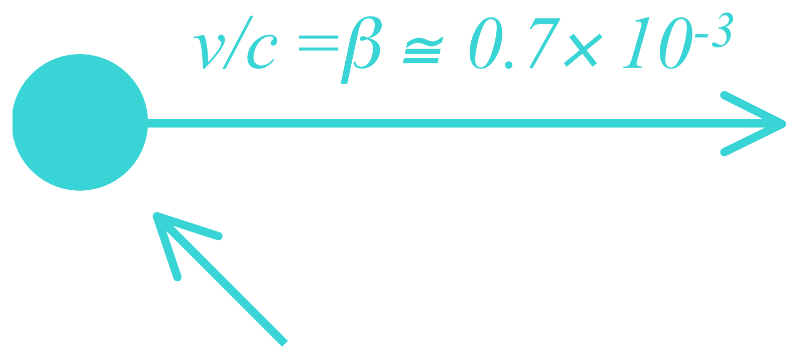


Sun: moves in plane of disk
$v/c = \beta \cong 0.7 \times 10^{-3}$

Particles in `halo': 3-d
$\rho = mc^2 \times n \cong 1/3\ GeV/cm^3$
(1/2 of total mass density)
Maxwellian/Gaussian (simple)
$v/c = \beta \cong 0.7 \times 10^{-3}$

Design a Particle and an Experiment





Neutral: cool particles neutral – γ, n, ν, K^0, Z^0, H^0…

We use Germanium, A=73, mc^2=67.6 GeV; others: Si, S, I, Xe, W

Massive: $M_\chi c^2 \approx 100$ GeV hinted at by accelerator data

`Weak Scale'

$E_R \approx$ _ $m_{Ge}c^2\,\beta^2$

$\approx$ _ 68 GeV × _ × 10^{-6}

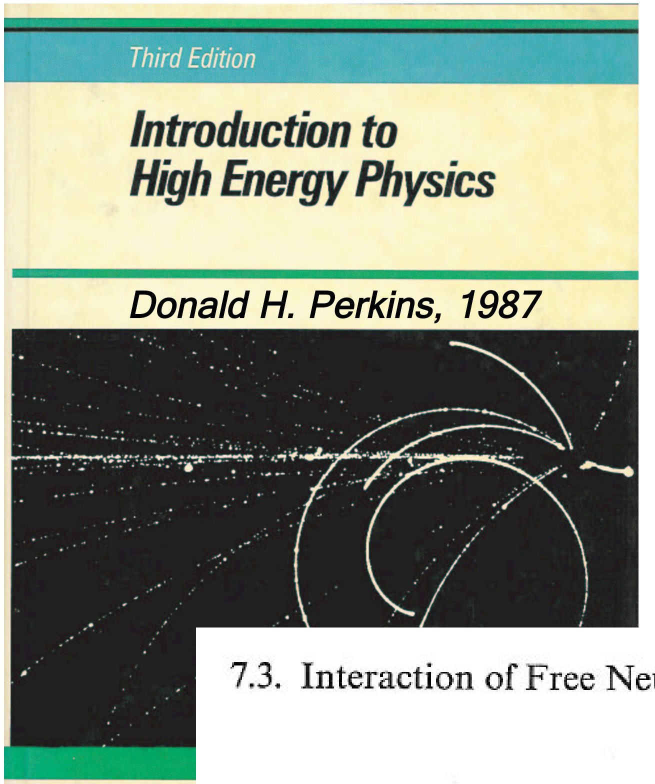
$\approx$ 20 keV

$\approx$ x-ray energy ! Easy!

Arguments for σ characteristic of weak interaction

1. Particle physics… chose $M_\chi c^2 \approx 100$ GeV, `Weak Scale'
2. Big Bang… independently implies weak cross section as well…
   Coincidence(s)… or Clues ???

What is the weak interaction cross section?



7.3. INTERACTION OF FREE NEUTRINOS: INVERSE β-DECAY

The cross-section for the inverse reaction (7.3) of free antineutrinos on protons can be calculated from (7.8). In this case, there are only two particles in the final state, so that using (4.6) we obtain (in units $\hbar = c = 1$)

$$\sigma(\bar{\nu}_e p \to n e^+) = \frac{W}{v_i} = \frac{G^2}{\pi} |M|^2 \frac{p^2}{v_i v_f}, \qquad (7.13)$$

where v_i, v_f are the relative velocities of the particles in the initial and final states ($v_i = v_f \simeq c$) and p is the numerical value of the CMS momentum of the neutron and positron. We are dealing with a mixed transition, with $M_F^2 = 1$ for the Fermi contribution ($\Delta J = 0$) and $M_{GT}^2 \simeq 3$ for the spin-multiplicity factor for the Gamow-Teller contribution ($\Delta J = 1$). Thus,

$$\sigma = \frac{M_F^2 + M_{GT}^2}{\pi} G^2 p^2 \simeq \frac{4G^2p^2}{\pi}. \qquad (7.14)$$

For neutrinos in the MeV energy range, incident on a fixed nucleon target, the CMS momentum and laboratory neutrino energy above threshold ($Q = 1.8$ MeV) are related by $p \simeq (E_\nu - Q)/c$. For $pc \simeq 1$ MeV and G from

7.3. Interaction of Free Neutrinos: Inverse β-Decay 213

(7.12) we obtain therefore

$$\sigma = \frac{4}{\pi} \times 10^{-10} \left(\frac{\hbar}{M_p c}\right)^2 \left(\frac{p}{M_p c}\right)^2 \simeq 10^{-43}\ \text{cm}^2. \qquad (7.15)$$

This corresponds to a mean free path for antineutrino absorption in water of 10^{20} cm or 100 light years. The first observation of such interactions was made by Reines and Cowan in 1959. They employed a reactor as the

Rate governed by scattering cross section, σ

$$\text{Rate} = N[\frac{\text{atoms}}{\text{kg}}] \times \phi[\frac{1}{\text{cm}^2\text{day}}] \times \sigma[\frac{\text{cm}^2}{\text{atom}}]$$

$$N = \frac{M}{A} \times N_A = \frac{1000\ \ [\text{g}]}{72.61\ \ [\text{g/mole}]} \times 6.02 \cdot 10^{23}\ [\text{atoms/mole}]$$

$$N = 8.3 \times 10^{24}\ \ [\frac{\text{Ge atoms}}{\text{kg}}]$$

$$\phi = \frac{\rho}{M_\chi c^2} vT = \frac{1/3\ \ [\text{GeV/cm}^3]}{100[\text{GeV}]} \times 0.7 \cdot 10^{-3} \times 3 \cdot 10^{10} [\text{cm/s}] \times 86400[\text{s/day}]$$

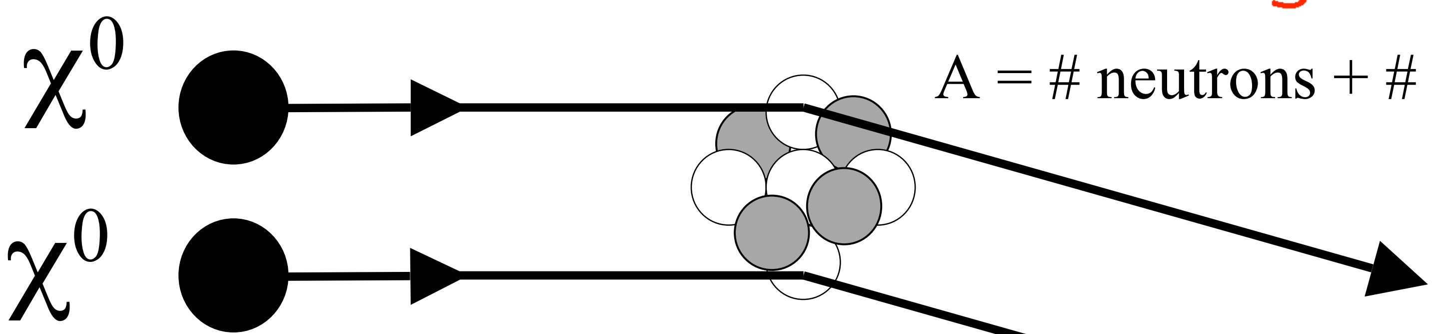
$$\phi = 6.1 \times 10^9 [\frac{1}{\text{cm}^2\text{day}}]$$

$$\text{Rate} = 5.0 \times 10^{34} \sigma[\text{cm}^2]\ [\frac{1}{\text{kg-d}}]$$

Coherence, density of states enormous bonus!

Scattering off a proton….

$\text{Rate(proton)} = 5.0 \times 10^{-9}[\frac{1}{\text{kg-d}}]$ …. Hopeless!



A = # neutrons + # protons

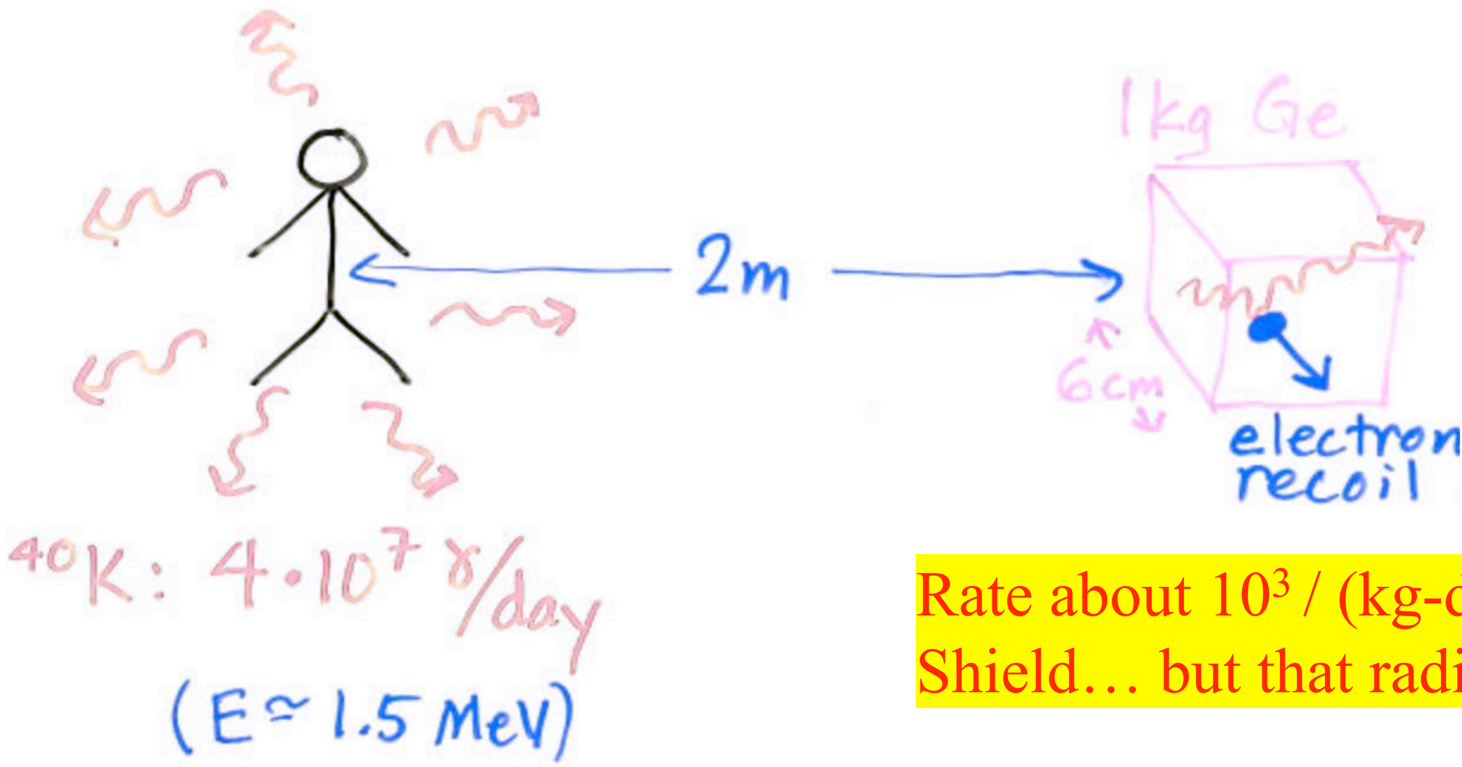
Indistinguishable

Density of States: $\propto p^2 \propto A^2 v^2$

$|M_{if}|^2 \propto A^2$

$\text{Rate(Ge)} = (72^4) \cdot 5.0 \times 10^{-9} \approx 0.14[\frac{1}{\text{kg-d}}]$

Rate of Main Background

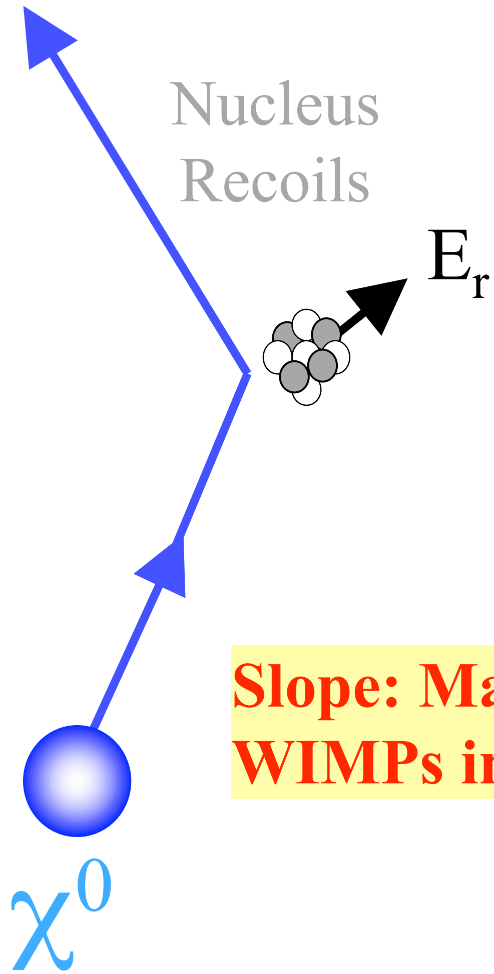


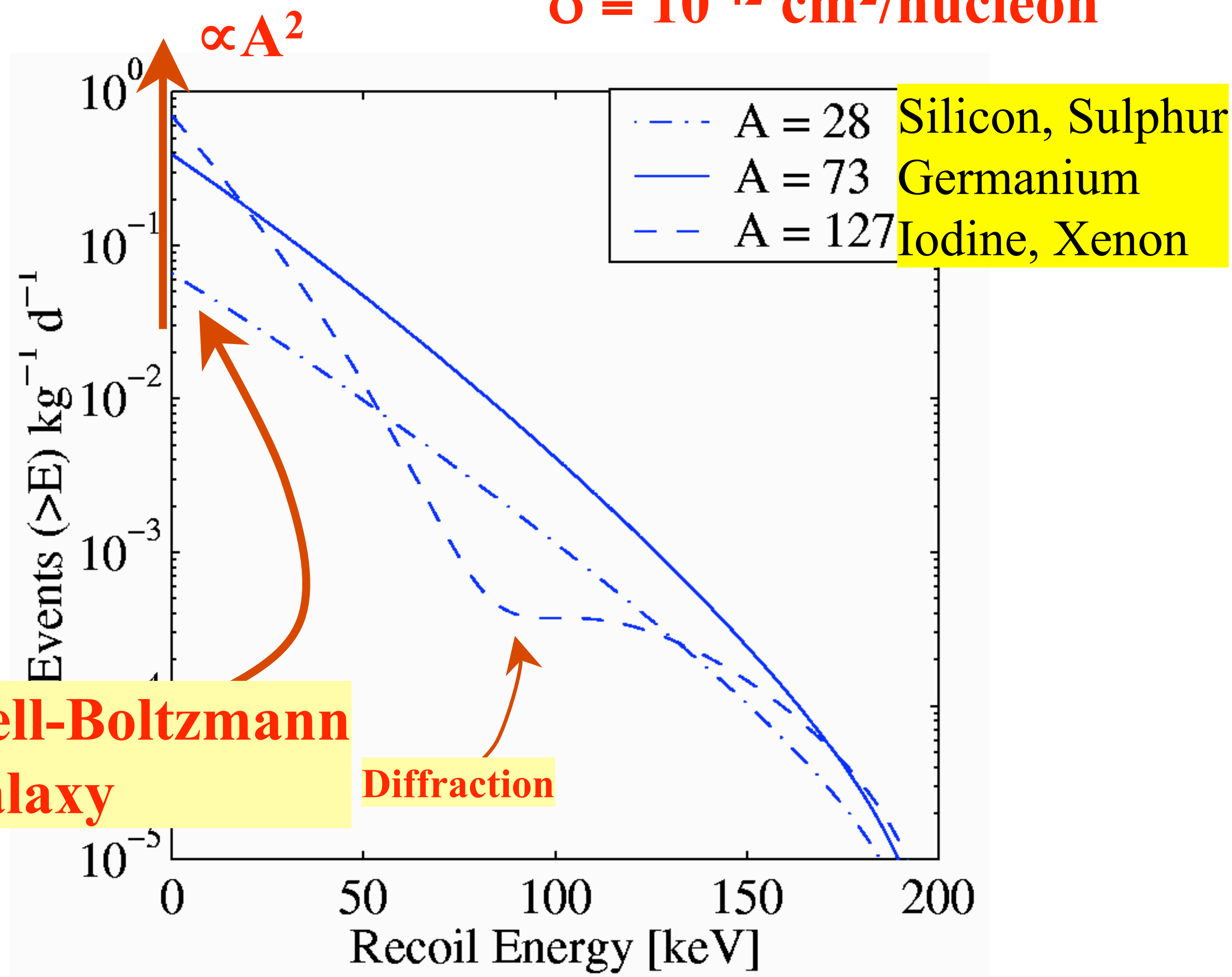
Rate about 10^3 / (kg-day) !!!
Shield… but that radioactive too

Strategies: DAMA… huge target mass (100 kg),
look for astrophysical modulation
CDMS… small target mass (few kg)
distinguish electron from nucl. recoil

Signal Shape

M_{WIMP}=100 GeV
$\sigma = 10^{-42}$ cm^2/nucleon





Catalog of Direct Detection Experiments

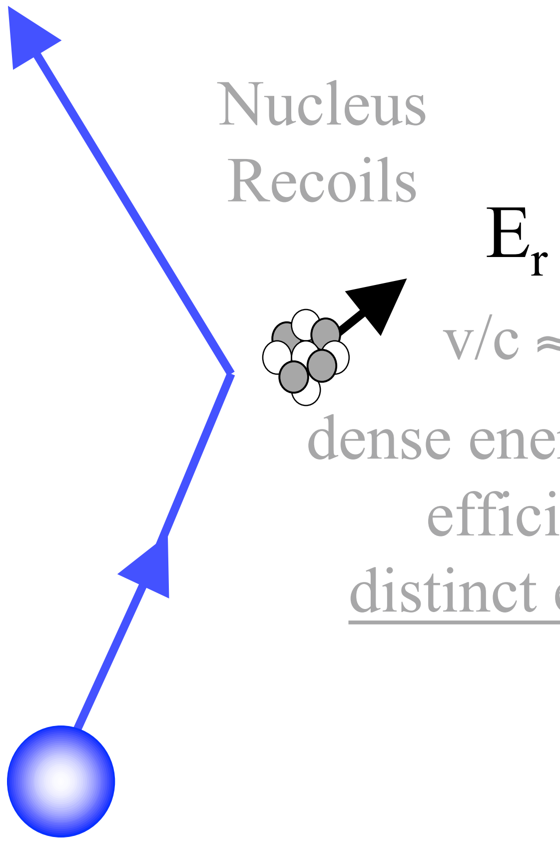
Site	Experiment	Technique	Target	Status
Baksan (Russia)	IGEX	Ionisation	3kg Ge	Operational
Bern (Switzerland)	ORPHEUS	SSD	0.5kg Sn	Operational
Boulby (UK)	NaI NaIAD ZEPLIN I ZEPLIN II/III ZEPLIN-MAX DRIFT-I DRIFT-10	Scintillator Scintillator Scintillator Scintillator/Ionisation Scintillator/Ionisation TPC TPC	5kg NaI 50kg NaI 5kg Lxe 30kg/7kg Xe 1000kg Xe 0.2kg CS_2 2kg CS_2	Completed Operational Operational Construction Planned Operational Planned
Canfranc (Spain)	COSME IGEX ANAIS ROSEBUD	Ionisation Ionisation Scintillator Thermal	0.2kg Ge 2.1kg Ge 107kg NaI Al_2O_3,Ge,$CaWO_4$	Completed Operational Constrcution Operational
Frejus (France)	Saclay-NaI EDELWEISS I EDELWEISS II	Scintillation Thermal/Ionisation Thermal/Ionisation	10kg NaI 0.07kg Ge 1.3 kg Ge	Completed Completed Operational
Gran Sasso (Italy)	Hdlberg/Mscw HDMS Genius DAMA LIBRA Xenon CRESST-I CRESST-II CUORICINO CUORE	Ionisation Ionisation Ionisation Scintillation Scintillation Scintillation Thermal Thermal/Scintillation Thermal Thermal	2.7kg Ge 0.2kg Ge 100kg Ge 100kg NaI 250kg NaI 6kg Xe 1kg Al_2O_3 10kg $CaWO_4$ 40kg TeO_2 760kg TeO_2	Completed Operational Planned Operational Construction Operational Operational Construction Construction Planned
Kamioke (Japan)	XMAS	Scintillator/Ionisation	3 kg Xe 1000 kg Xe	Operational Planned
Otto-Cosmo (Japan)	Elegants V Elegants VI LiF	Scintillation Scintillation Thermal	NaI CaF_2 LiF	Operational Operational Operational
Rustrel (France)	SIMPLE	SDD	Freon	Operational
Stanford (USA)	CDMS-1	Thermal/Ionisation	0.1kg Si, 1kg Ge	Completed
Soudan (USA)	CDMS-II CryoArray	Phonons/Ionisation	0.3ks Si, 0.75kg Ge 2 kg Si, 7 kg Ge 100-1000 kg Ge	Construction Construction Planned
??? (USA)	XENON	Scintillator/Ionisation	1000 kg Xe	Planned
Sudbury (Canada)	PICASSO	SDD	1g Freon	Operational

Indirect Detection:
Super-Kamiokande, Amanda, Ice-Cube, HEAT, GLAST, Egret…

Look for astrophysical neutrinos, gammas From WIMP annihilation

Direct Detection: Signal and Main Background

Signal

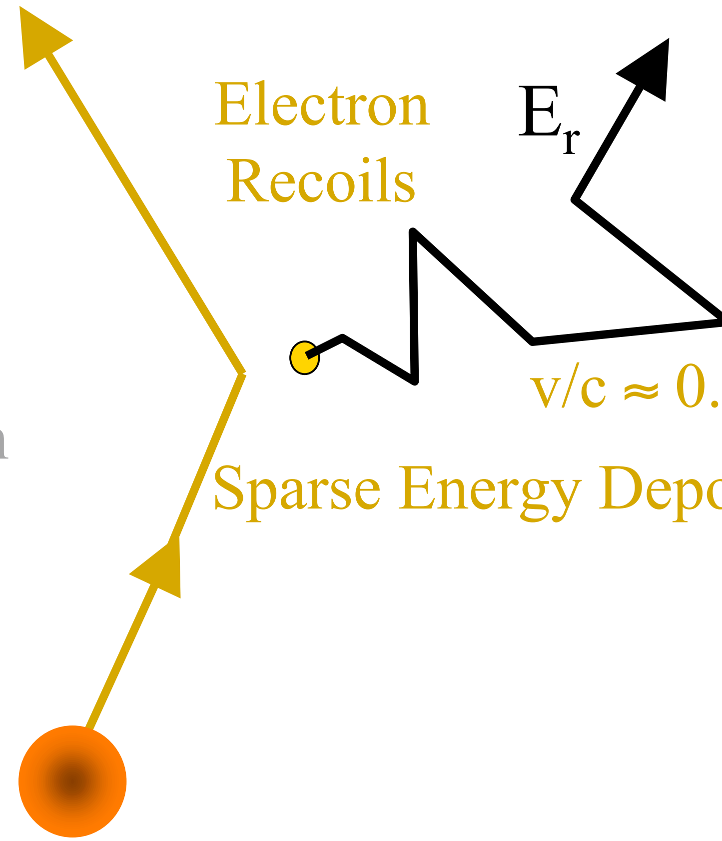


$v/c \approx 7\times10^{-4}$

dense energy deposition
efficiency low
distinct energy scale

χ^0 (calibrate: neutron)

Background

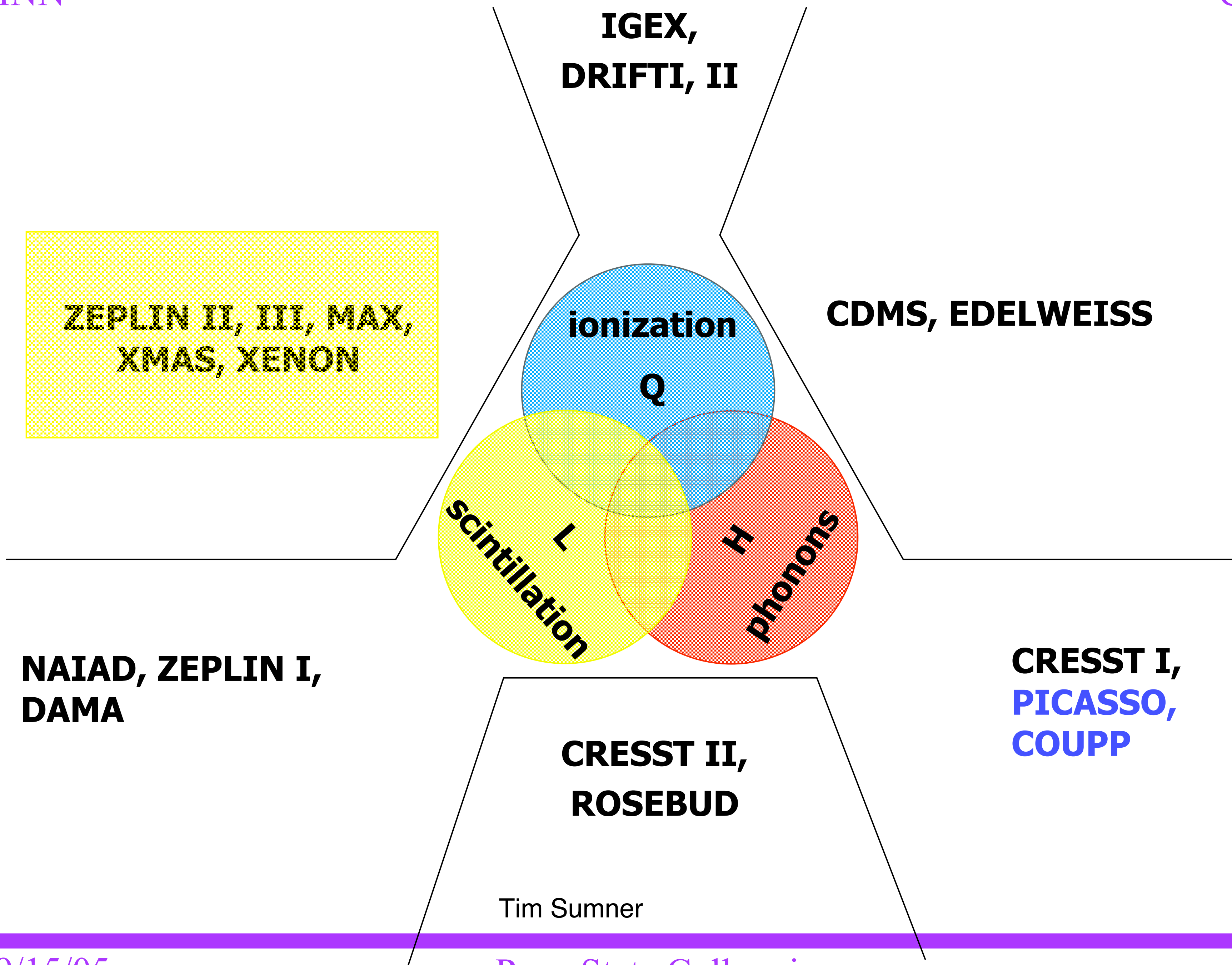


$v/c \approx 0.3$

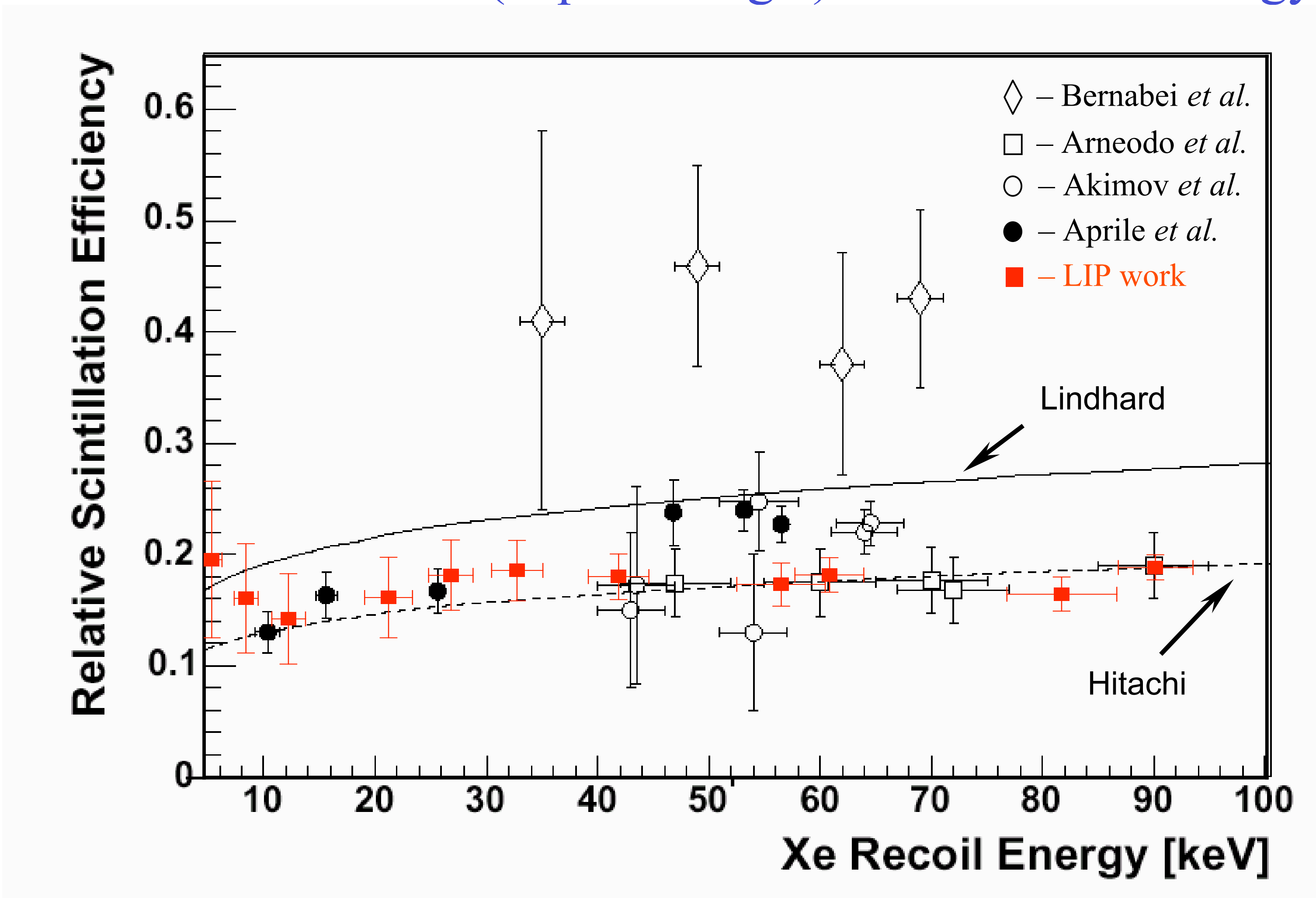
Sparse Energy Deposition

γ

Differences the Basis of Particle ID


IGEX,
DRIFTI, II
ZEPLIN II, III, MAX,
XMAS, XENON
ionization
Q
CDMS, EDELWEISS
scintillation
L
H
phonons
NAIAD, ZEPLIN I,
DAMA
CRESST I,
PICASSO,
COUPP
CRESST II,
ROSEBUD
Tim Sumner

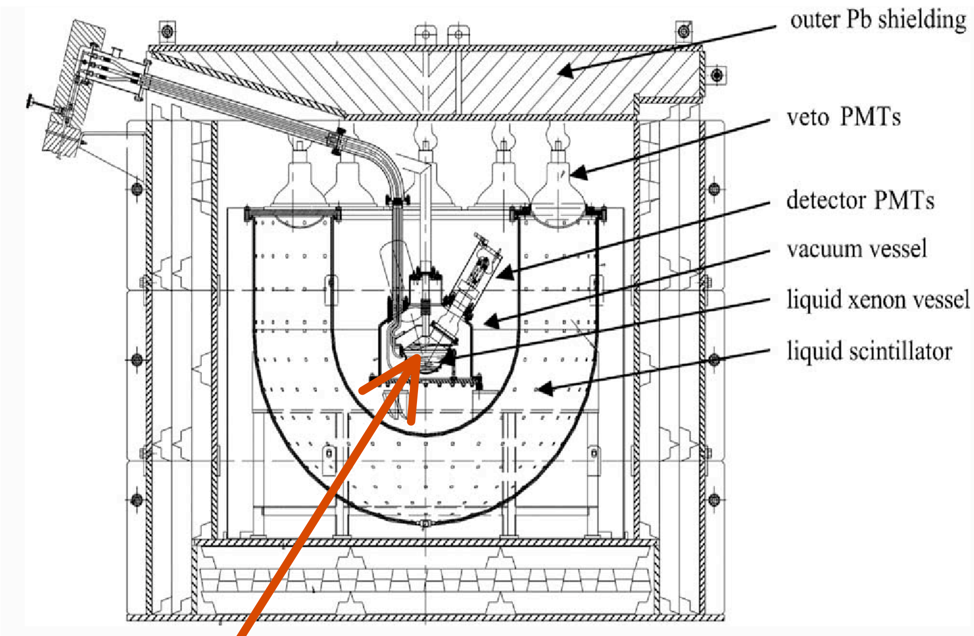
Xenon – nuclear recoils give 1/7 scintillation/energy, compared to electron recoils (``quenching'')…. Sets recoil energy scale



E. Aprile *et al.*, arXiv:astro-ph/0503621

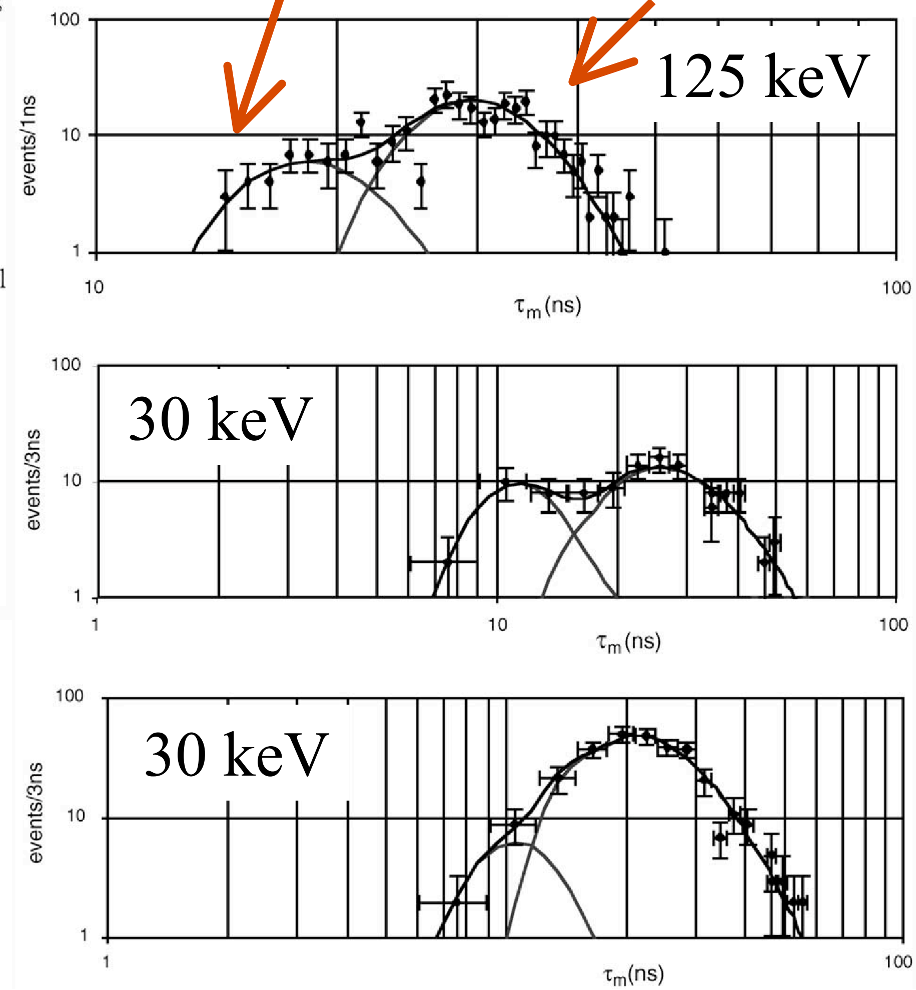
Tim Sumner

Zeplin 1 – Scintillation Alone



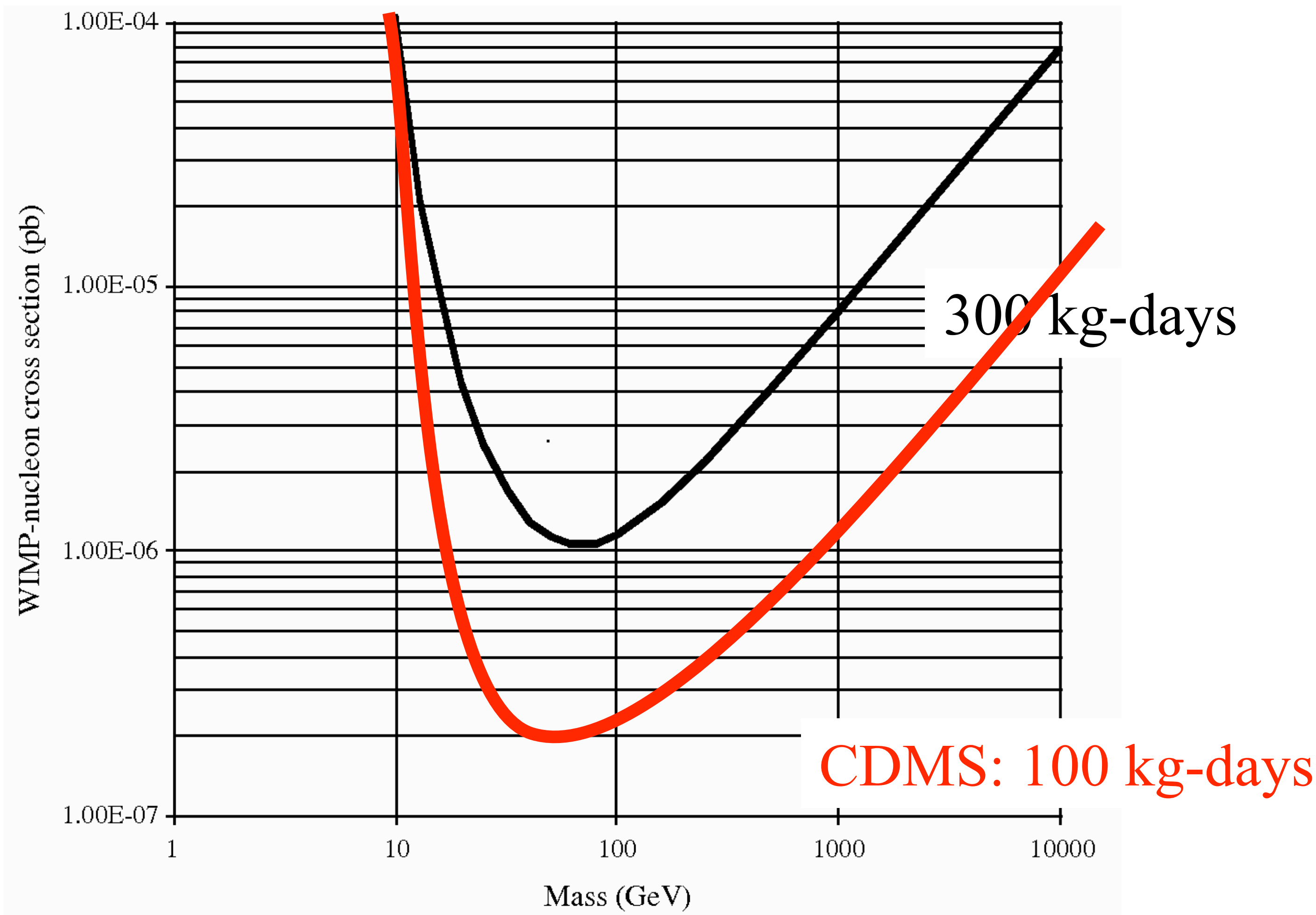
3.2 kg Xe

Nuclear Recoils – Faster Risetime…

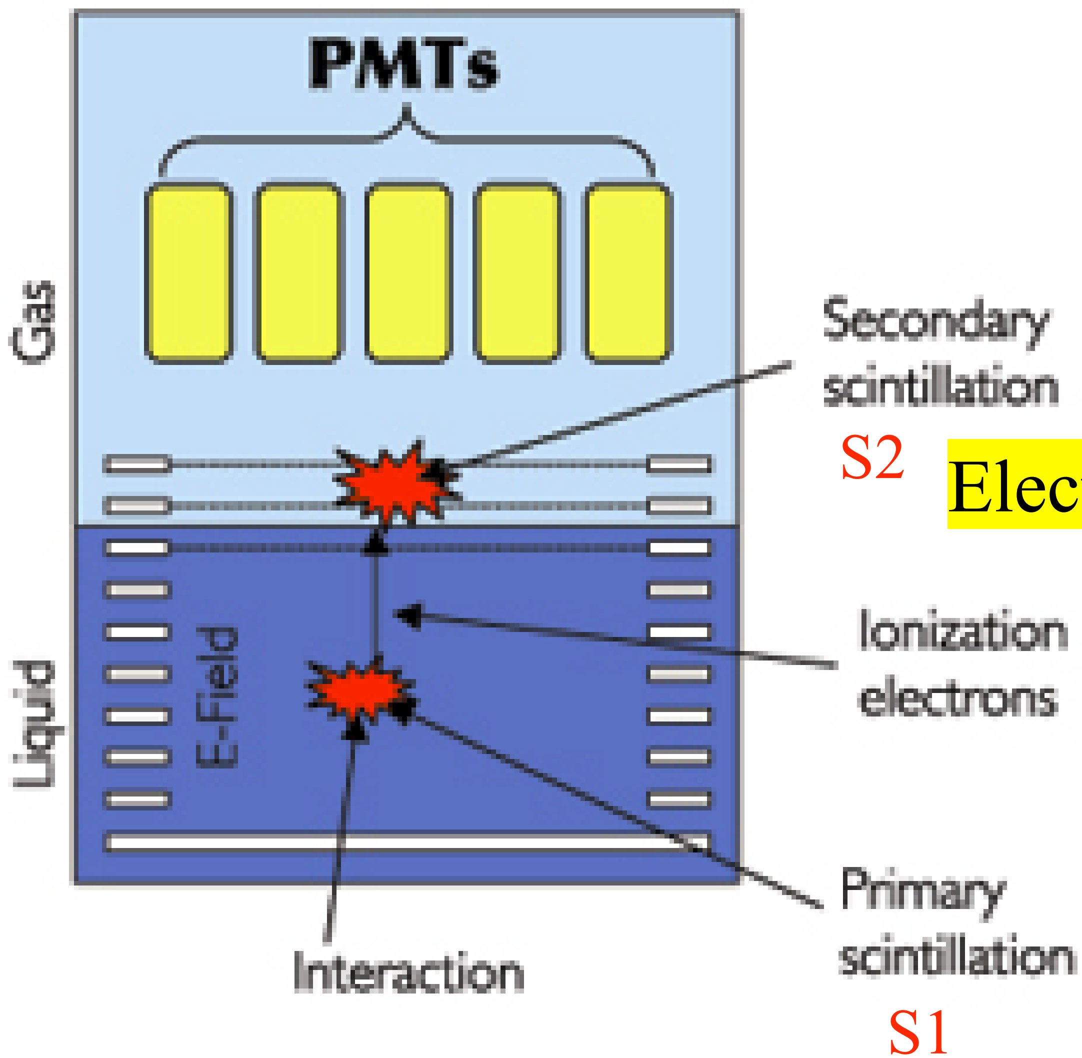


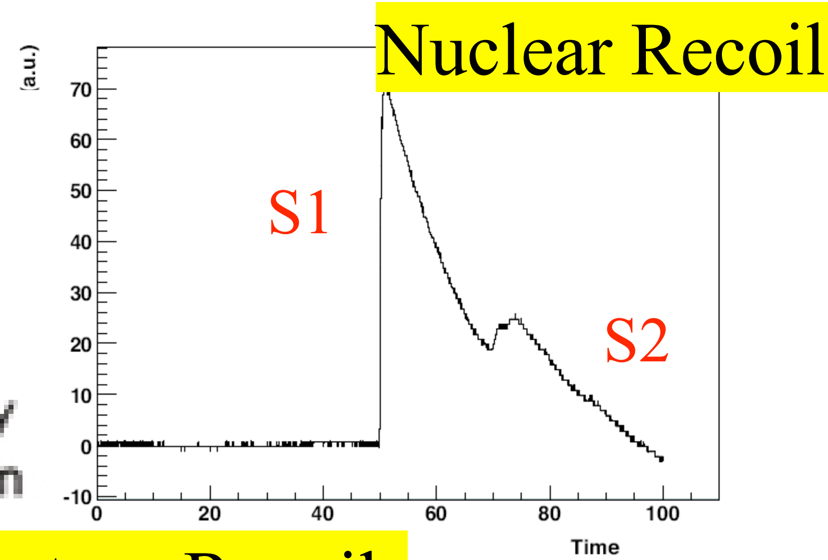
Zeplin-I Limit- Background Weakens

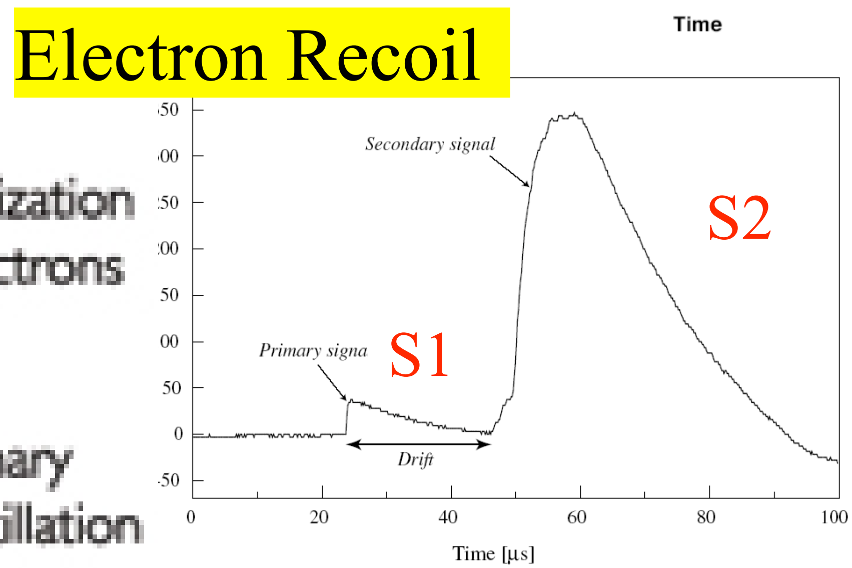
10^{-42} cm^2

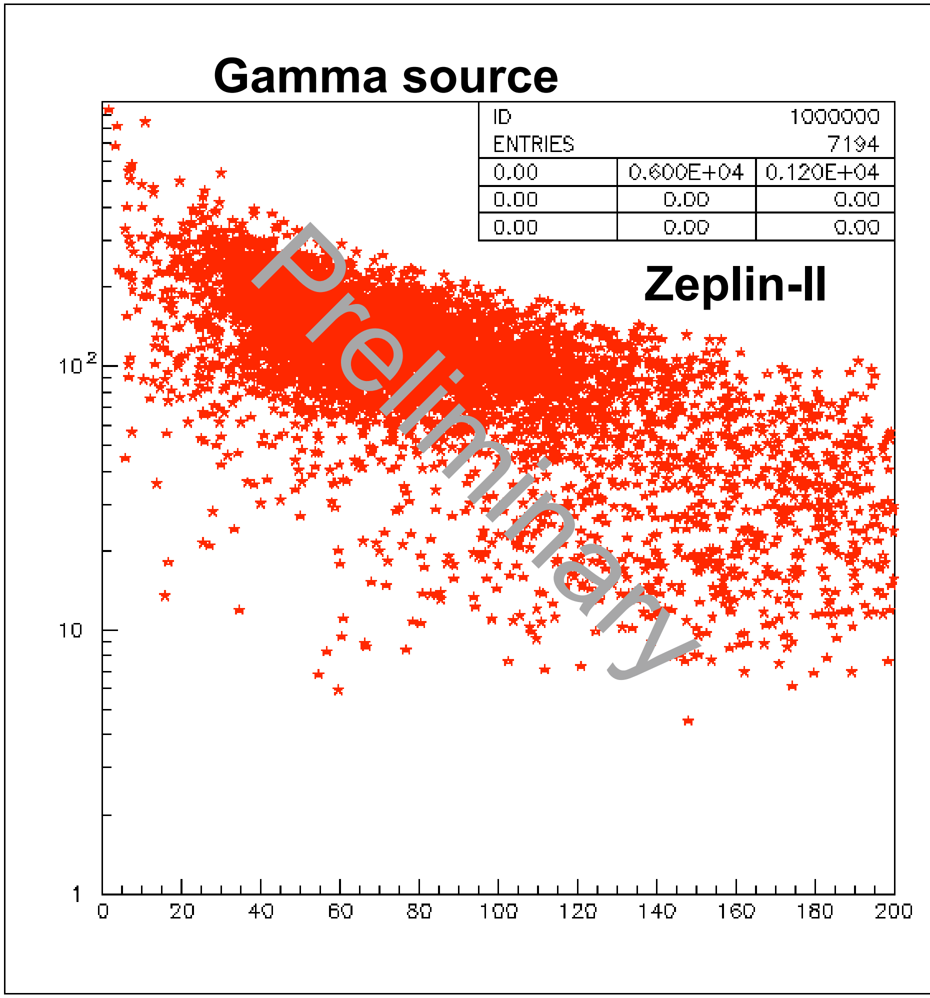


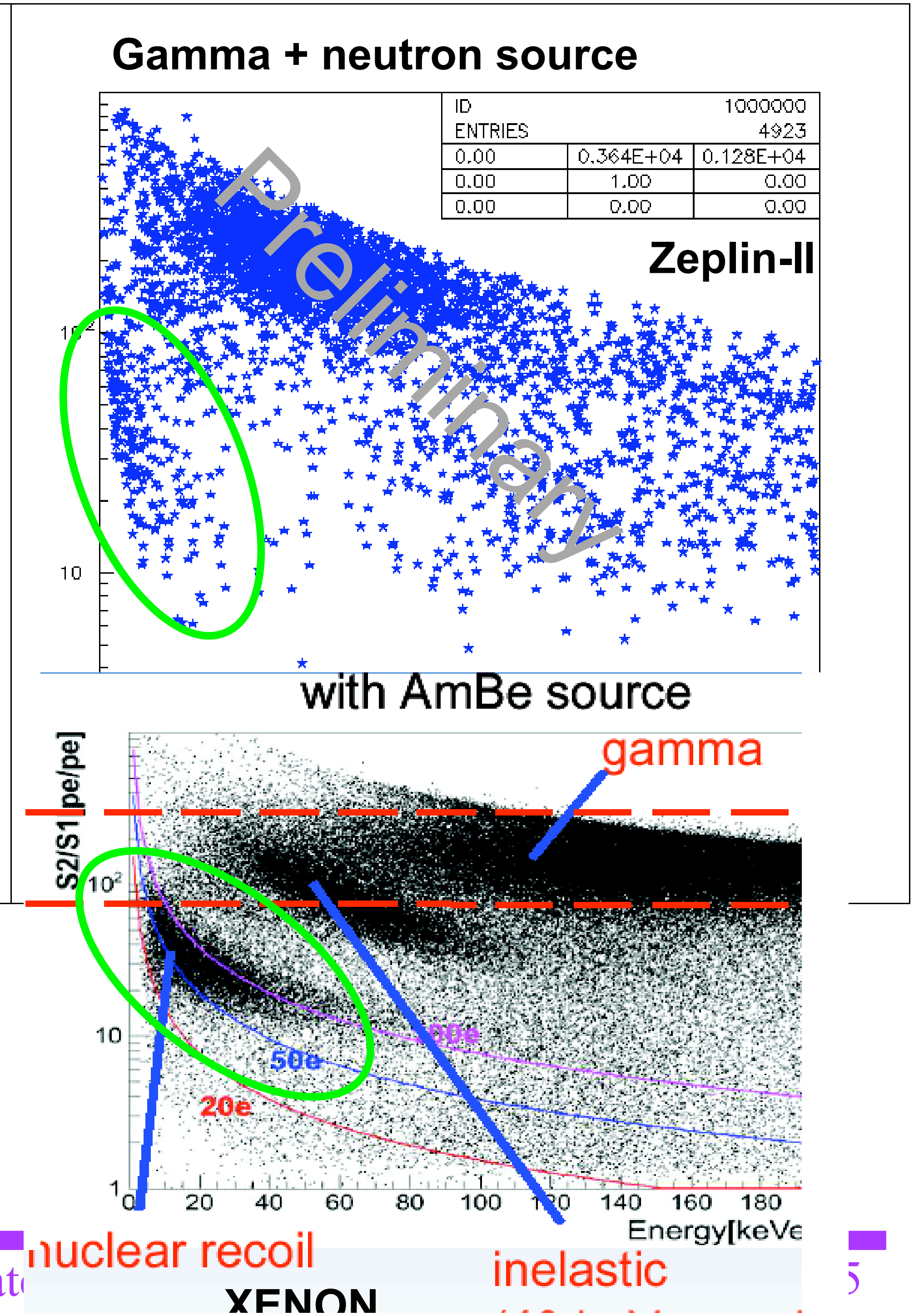
2-Phase (Liquid/Gas) Noble … Ar or Xe







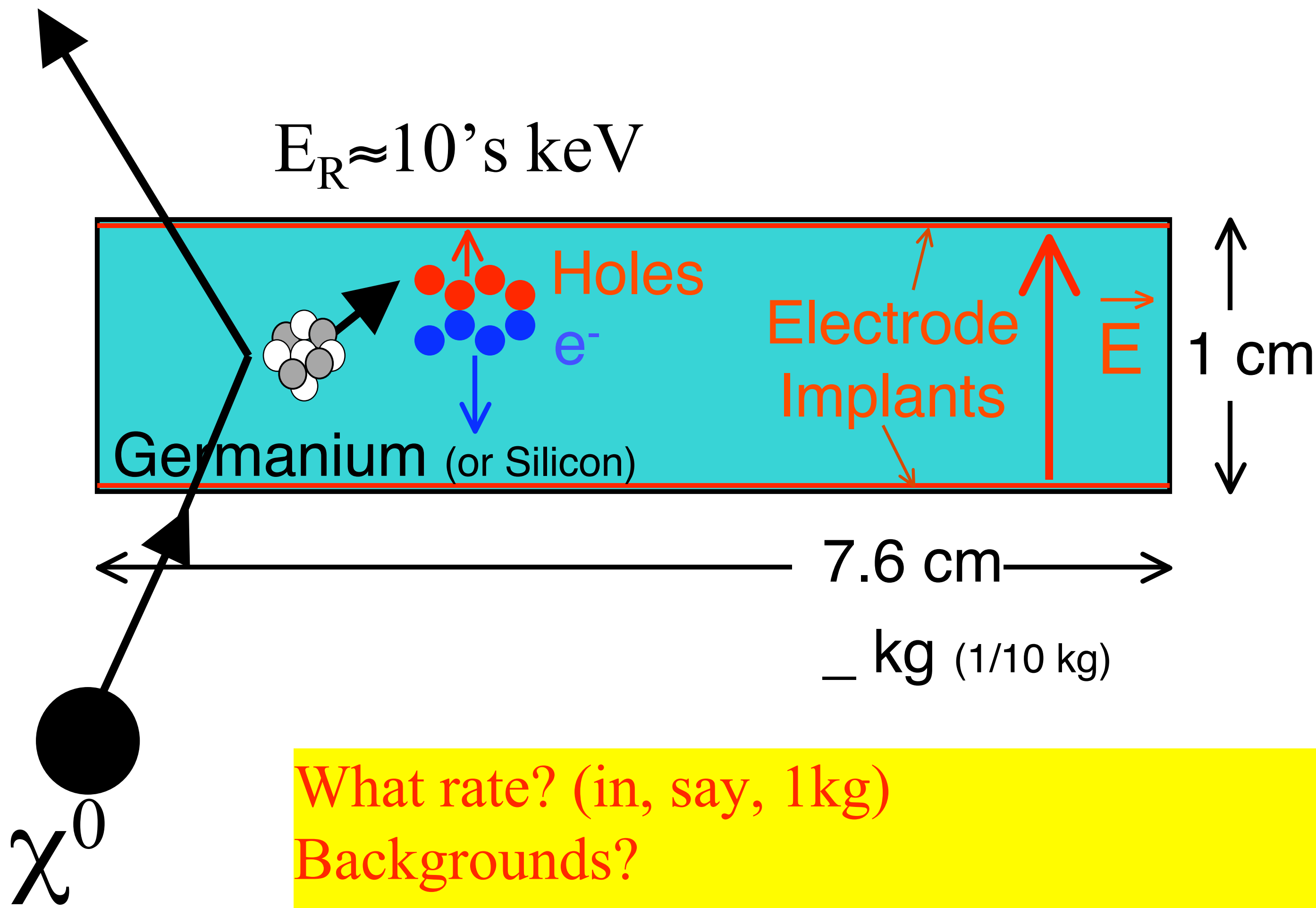

Gamma source
ID 1000000
ENTRIES 7194
0.00 | 0.600E+04 | 0.120E+04
0.00 | 0.00 | 0.00
0.00 | 0.00 | 0.00
Zeplin-II
Preliminary
0 20 40 60 80 100 120 140 160 180 200


Gamma + neutron source
ID 1000000
ENTRIES 4923
0.00 | 0.364E+04 | 0.128E+04
0.00 | 1.00 | 0.00
0.00 | 0.00 | 0.00
Zeplin-II
Preliminary
with AmBe source
gamma
S2/S1 [pe/pe]
50e
20e
0 20 40 60 80 100 120 140 160 180
Energy[keVe
nuclear recoil
inelastic
XENON

Analysis….

- Appears scalable
- However, unforeseen backgrounds are the rule as sensitivity increases
- Promising… ZEPLIN-II and Xenon-10 soon deployed in deep sites

CDMS: Adapt Traditional Ionization Detector

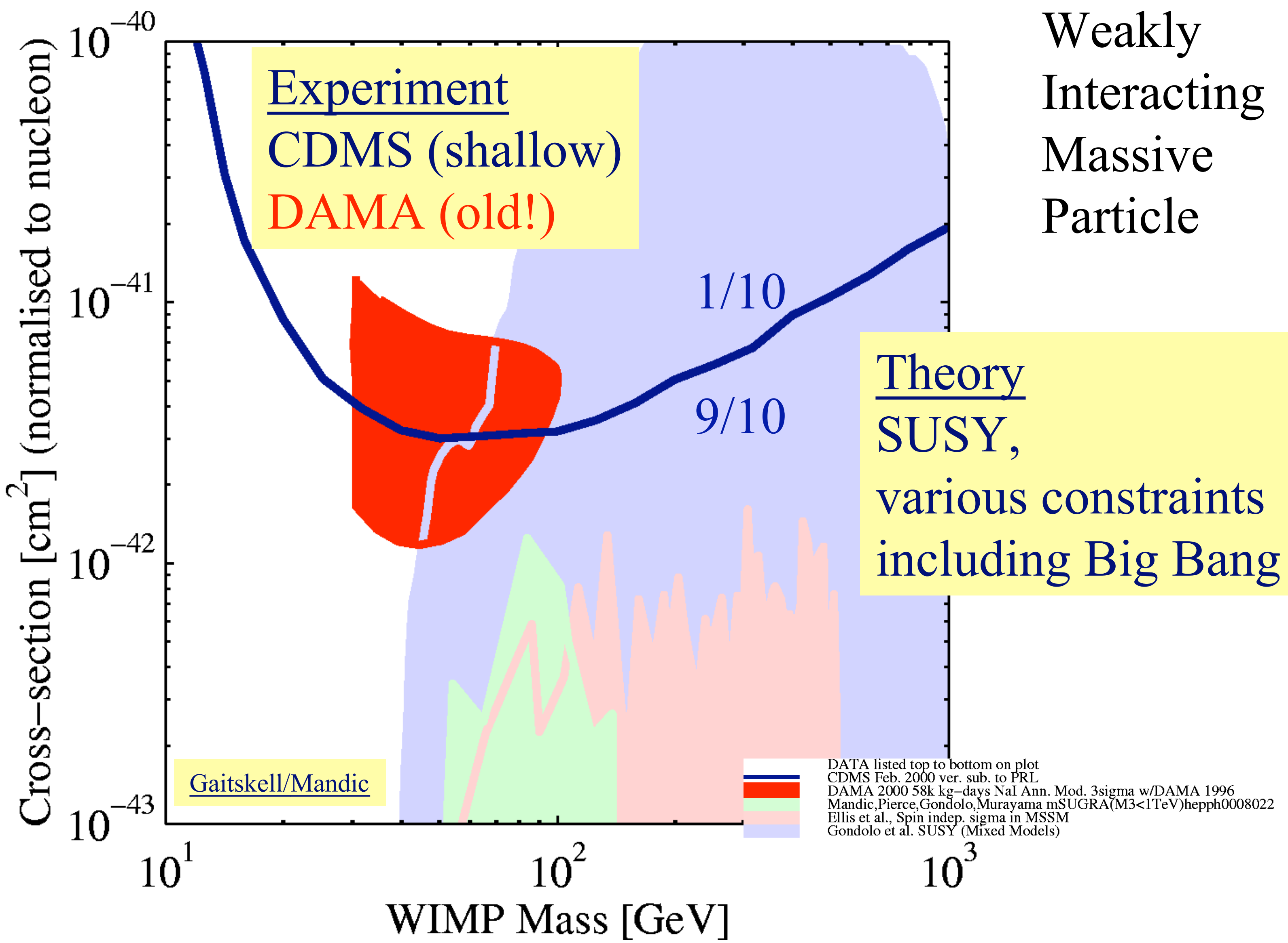


What rate? (in, say, 1kg)

Backgrounds?

…….. Gamma rays, neutrons, surface beta-decay

Our Hunting Ground

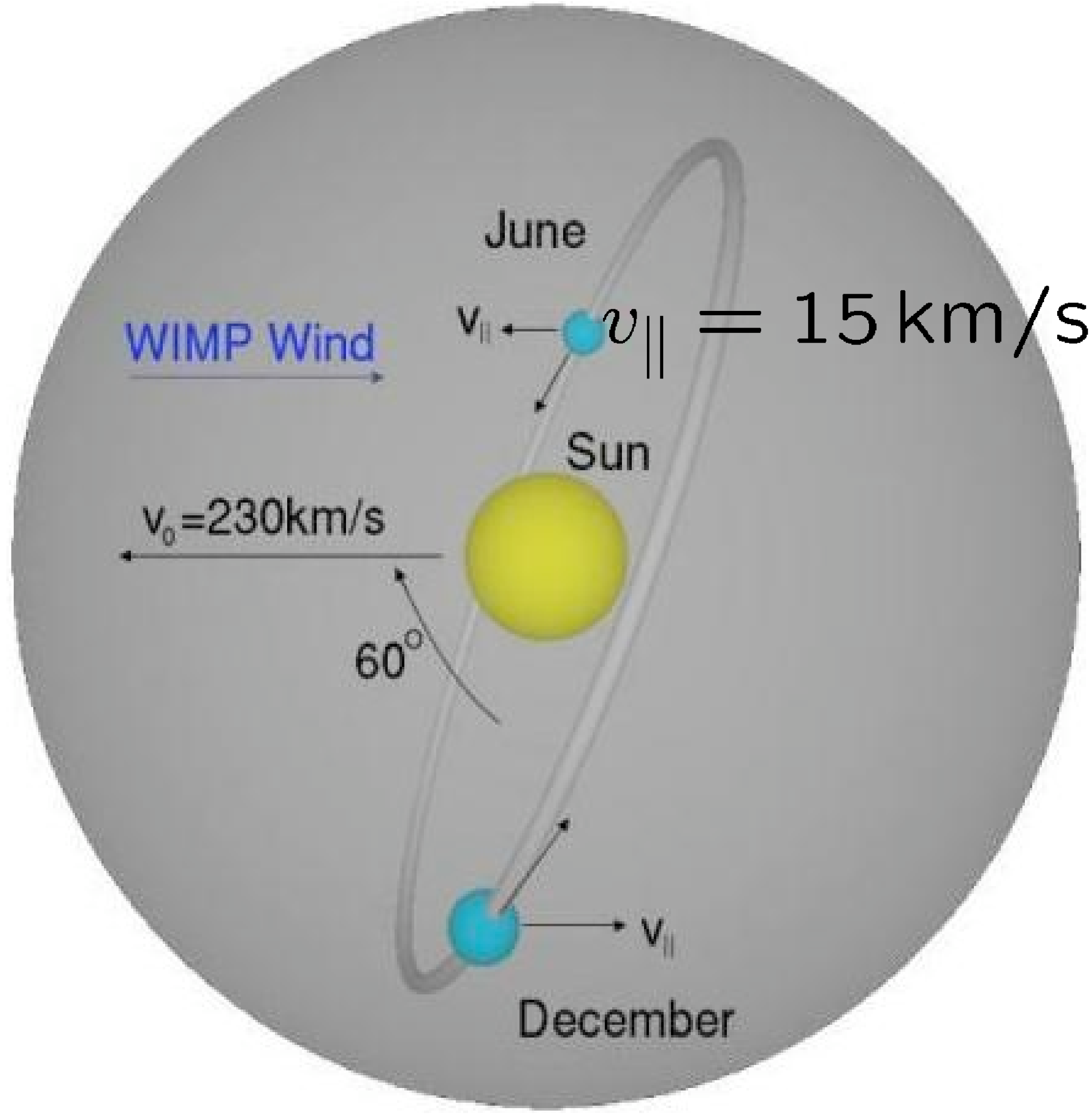


Weakly
Interacting
Massive
Particle

DAMA – Exploit Annual Modulation

Signal: higher rate in June,
lower in December

Background: constant in time



CDMS Collaboration (Mar. 2002)

CDMS Collaboration

Cryogenic
Dark
Matter
Search

Brown University

M.J. Attisha, **R.J. Gaitskell**, J-P. F. Thompson

Case Western Reserve University

D.S. Akerib, P. Brusov, C. Bailey, M.R. Dragowsky, D.D.Driscoll, S.Kamat, A.G. Manalaysay, T.A. Perera, R.W.Schnee, G.Wang

University of Colorado at Denver

M. E. Huber

Fermi National Accelerator Laboratory

D.A. Bauer, R. Choate, M.B. Crisler, R. Dixon, M. Haldeman, D. Holmgren, B. Johnson, W.Johnson, M. Kozlovsky, D. Kubik, L. Kula, B. Lambin, B. Merkel, S. Morrison, S. Orr, E.Ramberg, R.L. Schmitt, J. Williams, J. Yoo

Lawrence Berkeley National Laboratory

J.H Emes, R. McDonald, R.R. Ross, A. Smith

Santa Clara University

B.A. Young

Stanford University

P.L. Brink, **B. Cabrera**, J.P. Castle, C.L. Chang, J. Cooley, M. Kurylowicz, L. Novak, R. W. Ogburn, M. Pyle, T. Saab, A. Tomada

University of California, Berkeley

J. Alvaro-Dean, M.S. Armel, M. Daal, J. Fillipini, A. Lu, V. Mandic, P.Meunier, N. Mirabolfathi, M.C.Perillo Isaac, W. Rau, **B. Sadoulet**, D.N.Seitz, B. Serfass, G. Smith, A. Spadafora, K. Sundqvist

University of California, Santa Barbara

R. Bunker, S. Burke, D.O. Caldwell, D. Callahan, R.Ferril, D. Hale, S. Kyre, R. Mahapatra, J.May, **H. Nelson**, R. Nelson, J. Sander, C.Savage, S.Yellin

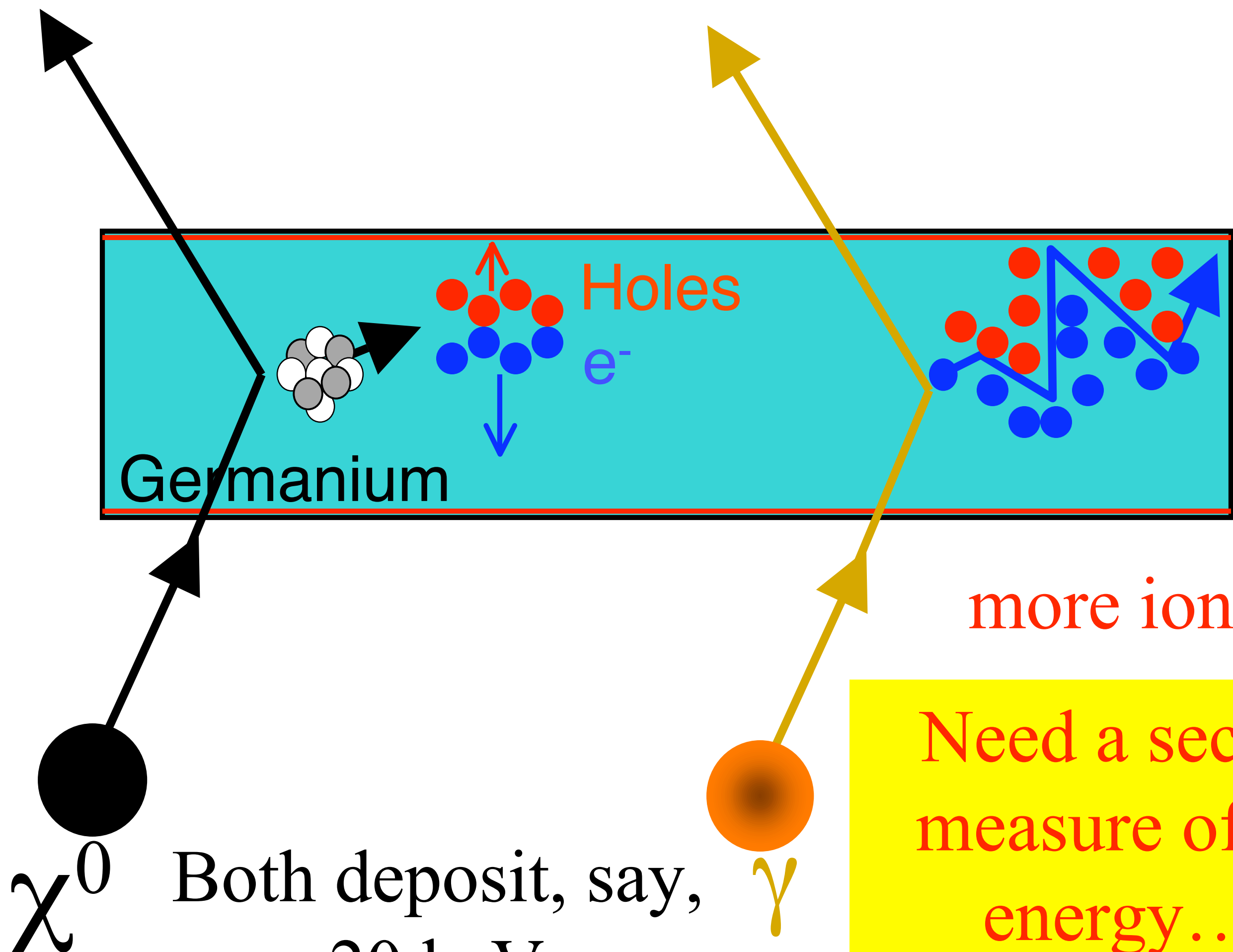
University of Florida

L. Baudis, S. Leclerq

University of Minnesota

J. Beaty, **P. Cushman**, L. Duong, A. Reisetter

Nuclear Recoil bad at making Ionization

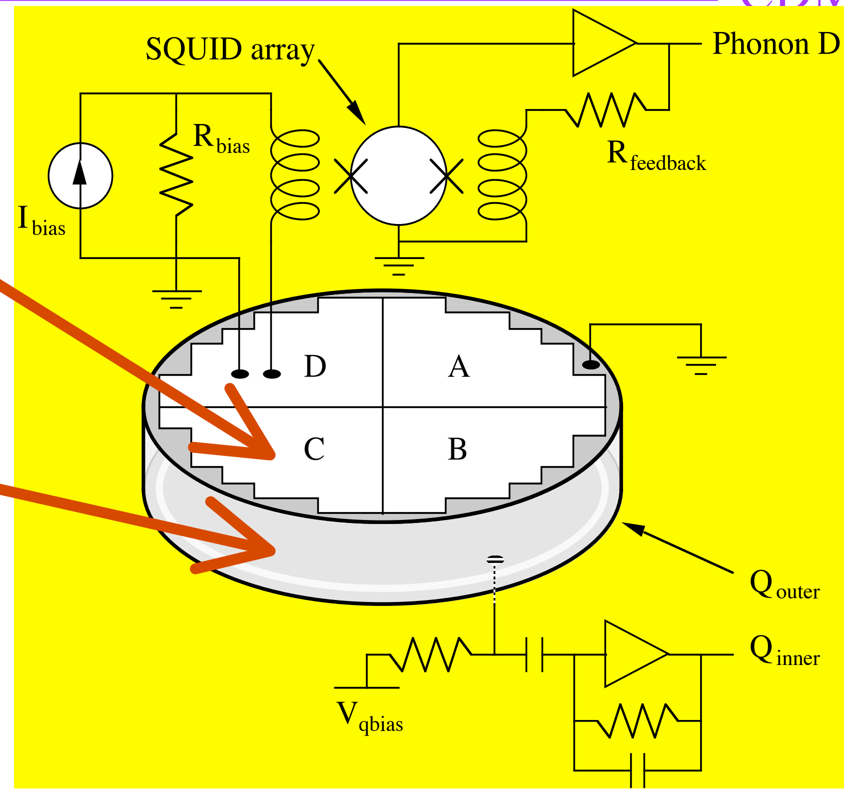


more ionization!

Both deposit, say, 20 keV

Need a second, `fair' measure of deposited energy… sound!

Our Detectors



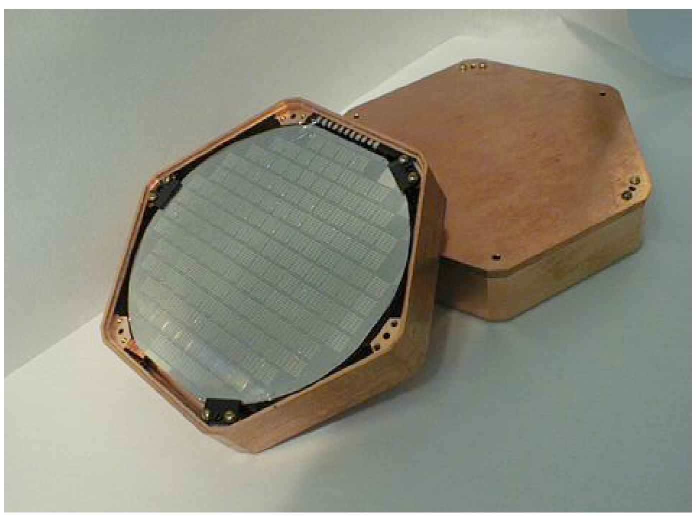
`Phonon sensor (4)' (TES)

Array of Transition Edge Sensors

Ionization Electrodes (2)

x-y-z imaging:

from timing, sharing

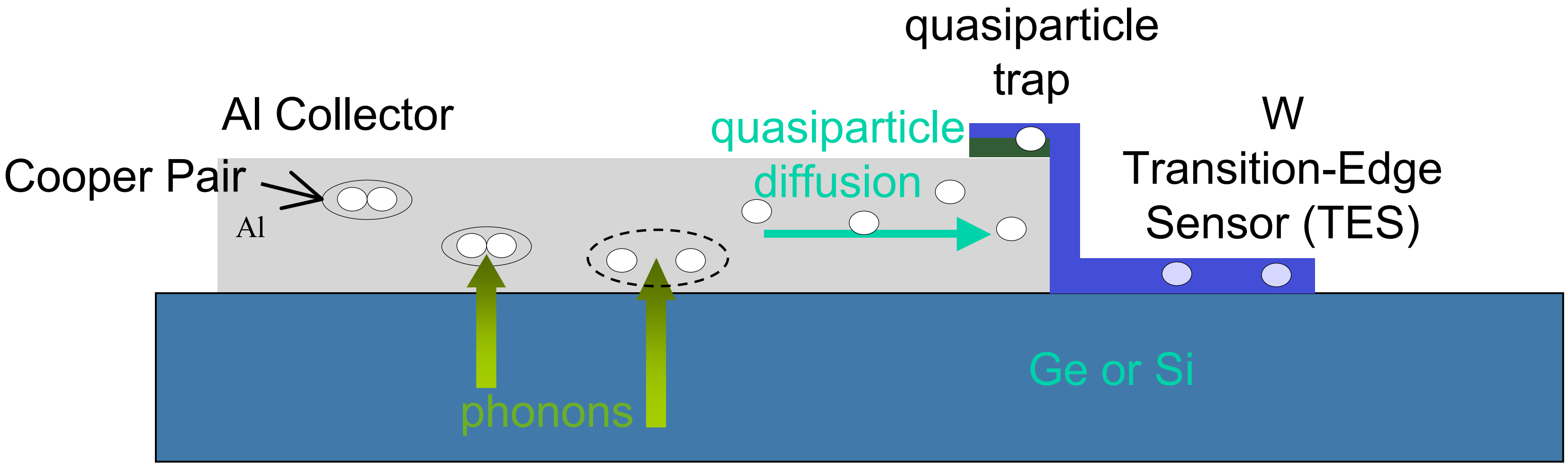


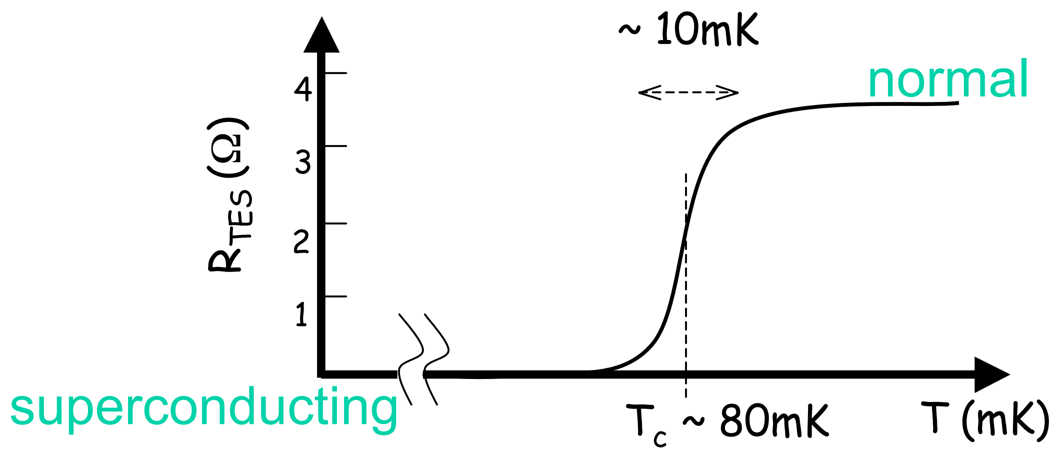
Z-coordinate, Ionization, Phonons

ZIP

Operate at 0.050 Kelvin

The Phonon Sensor



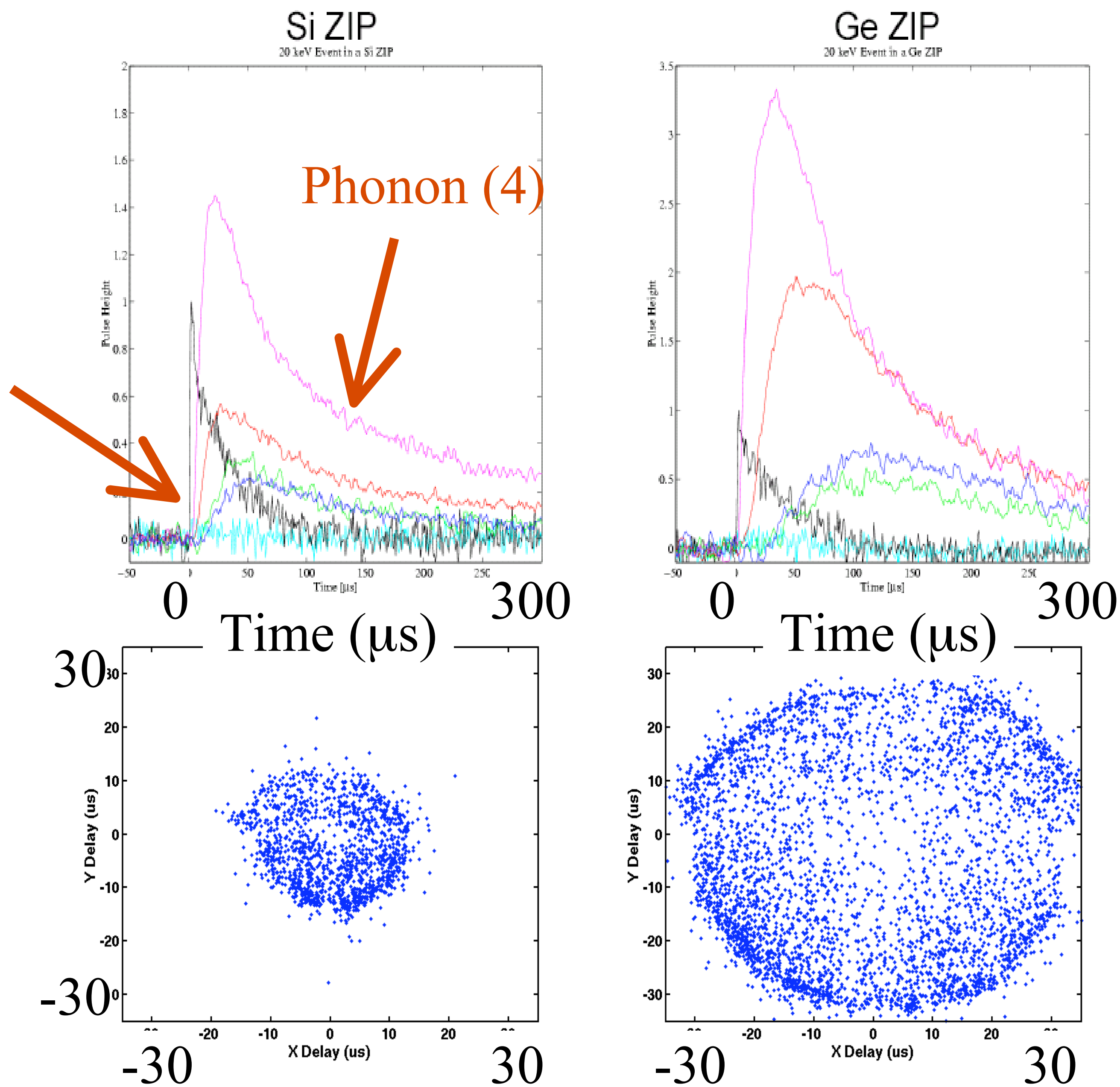


R. Schnee

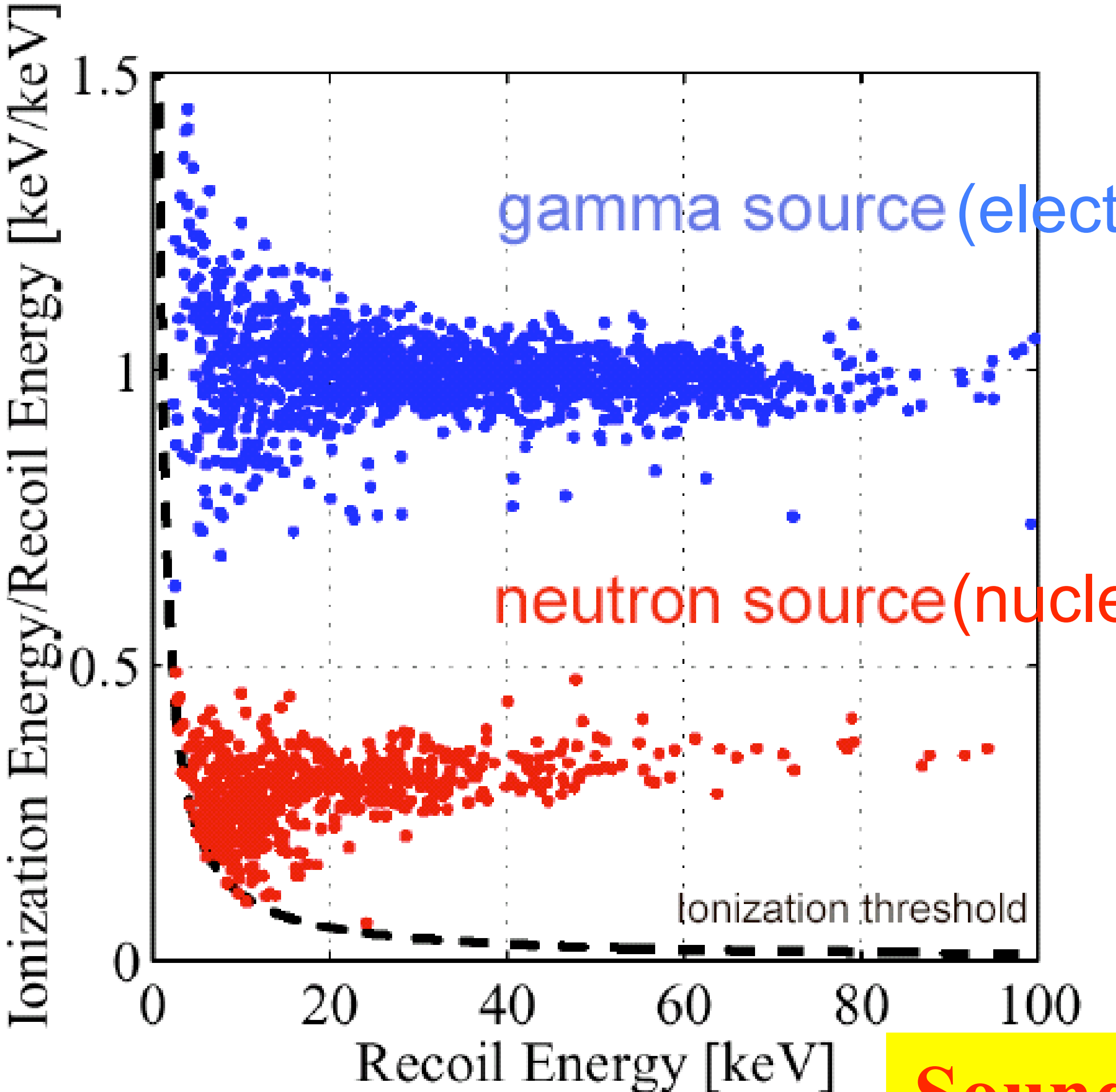
Pulses

20 KeV

Charge (2)



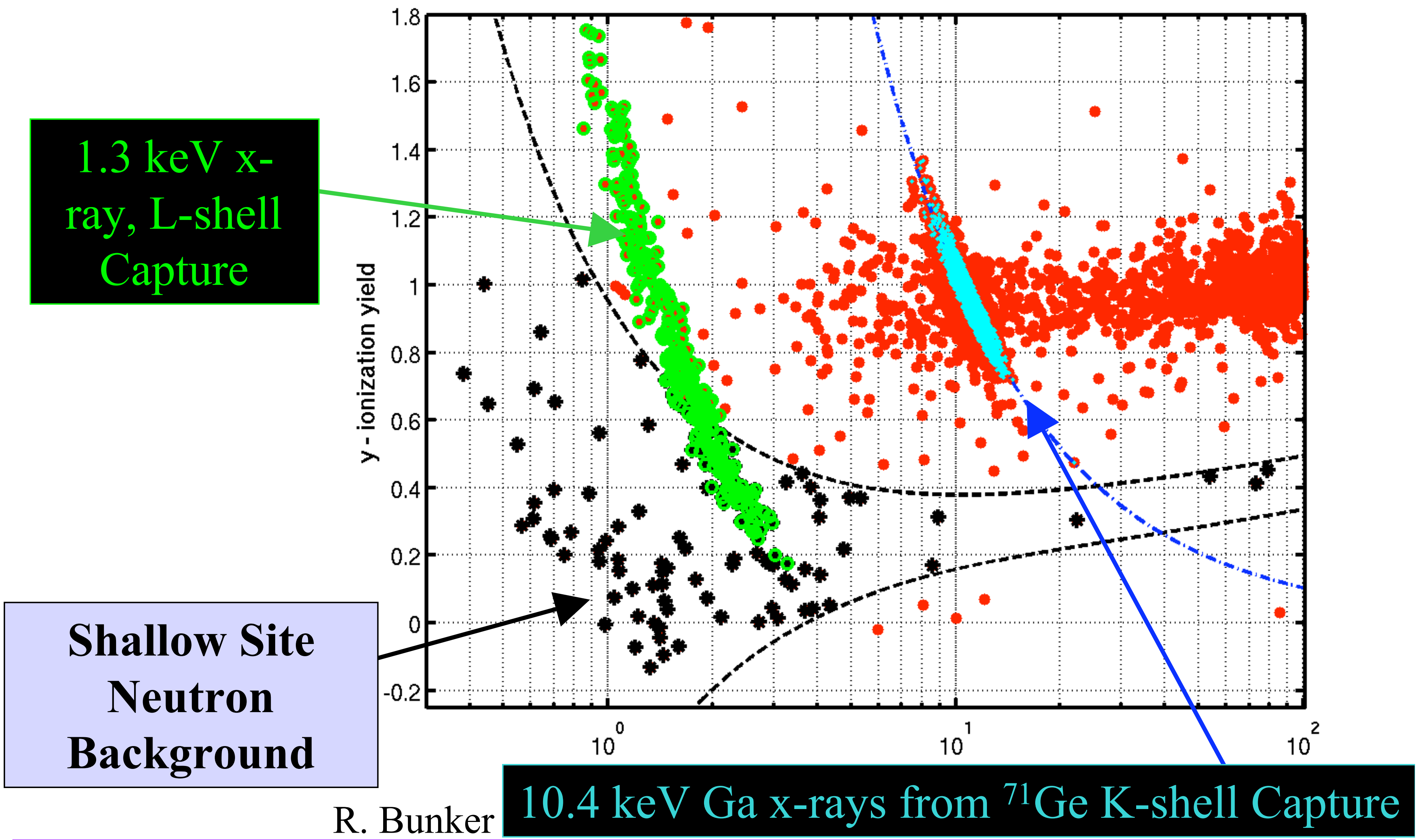
Separation of the types of recoils



Neutrons cause nuclear recoils too! Another background…

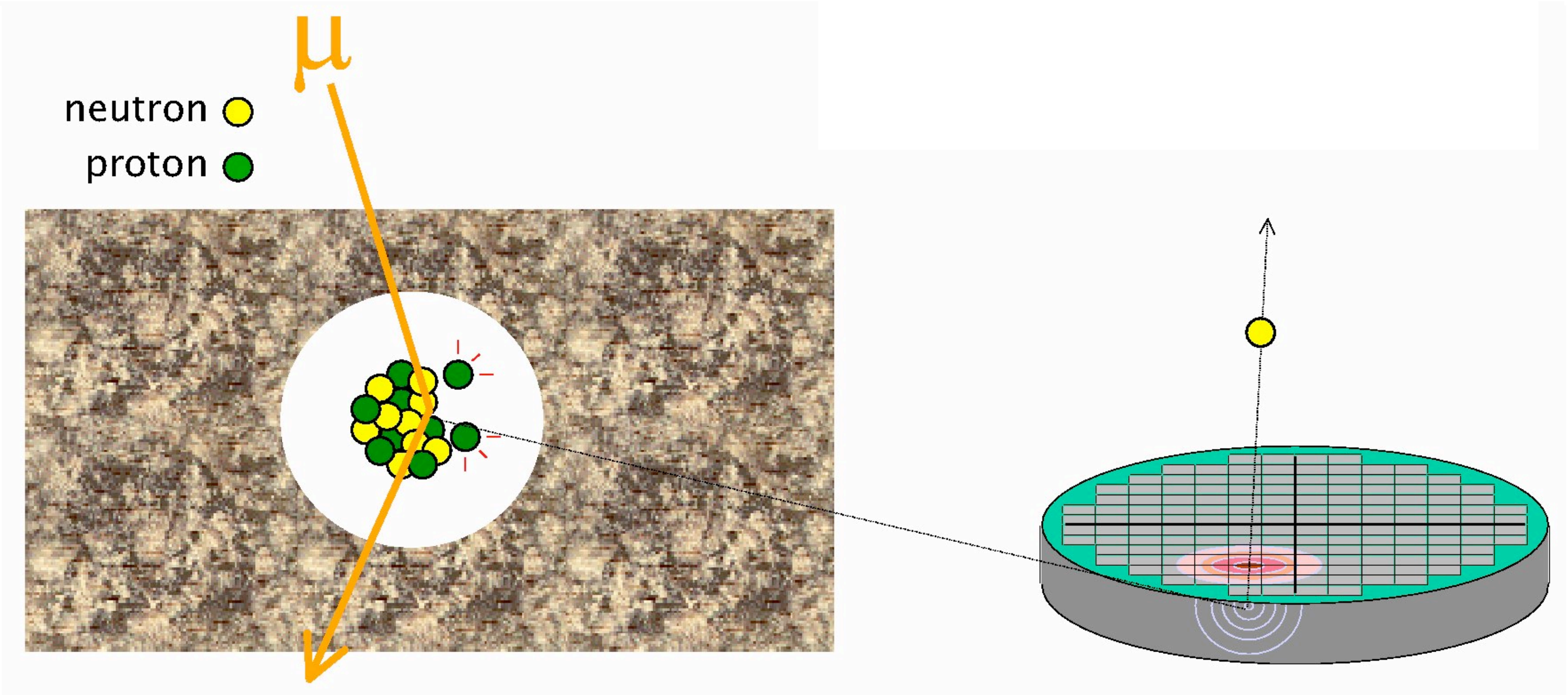
Sound

SUF Run 21 Germanium – Low Threshold



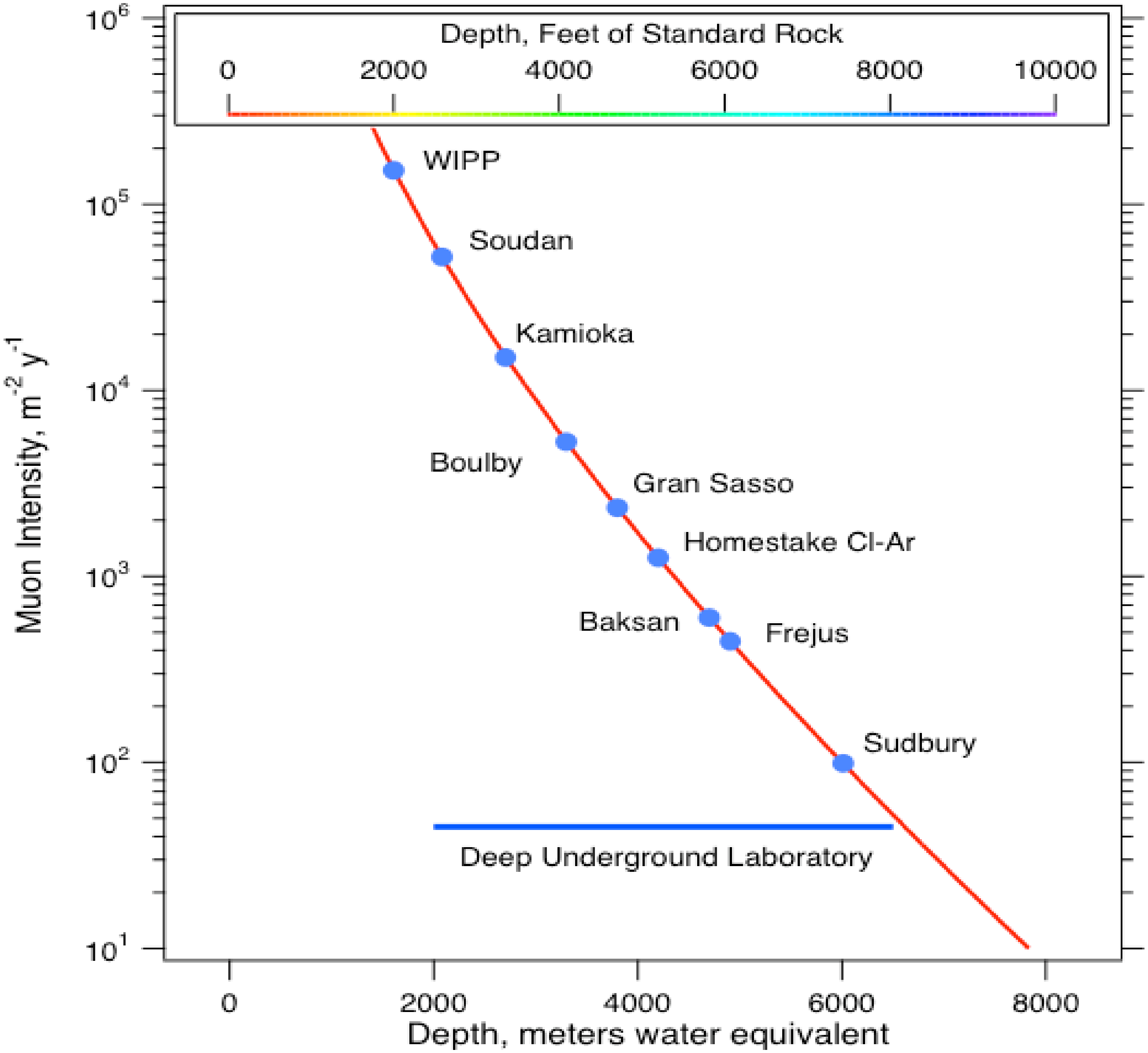
R. Bunker

Background Neutrons from Cosmic Ray Muons

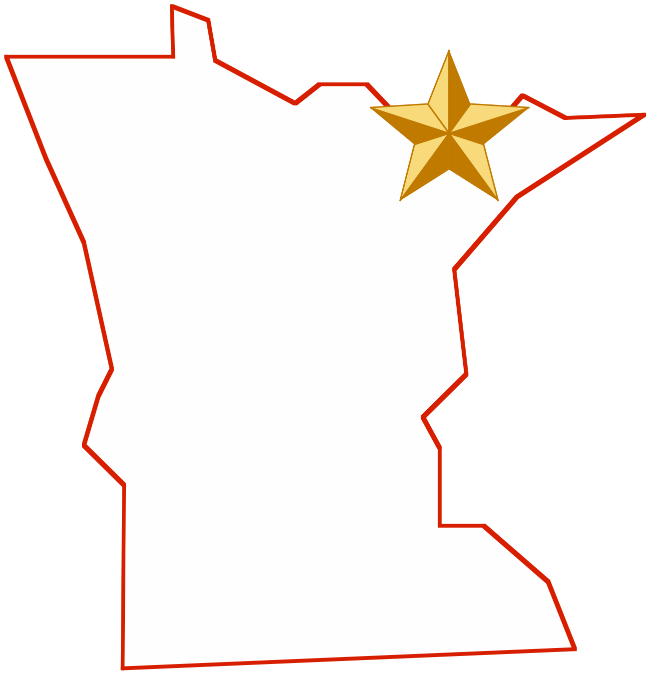


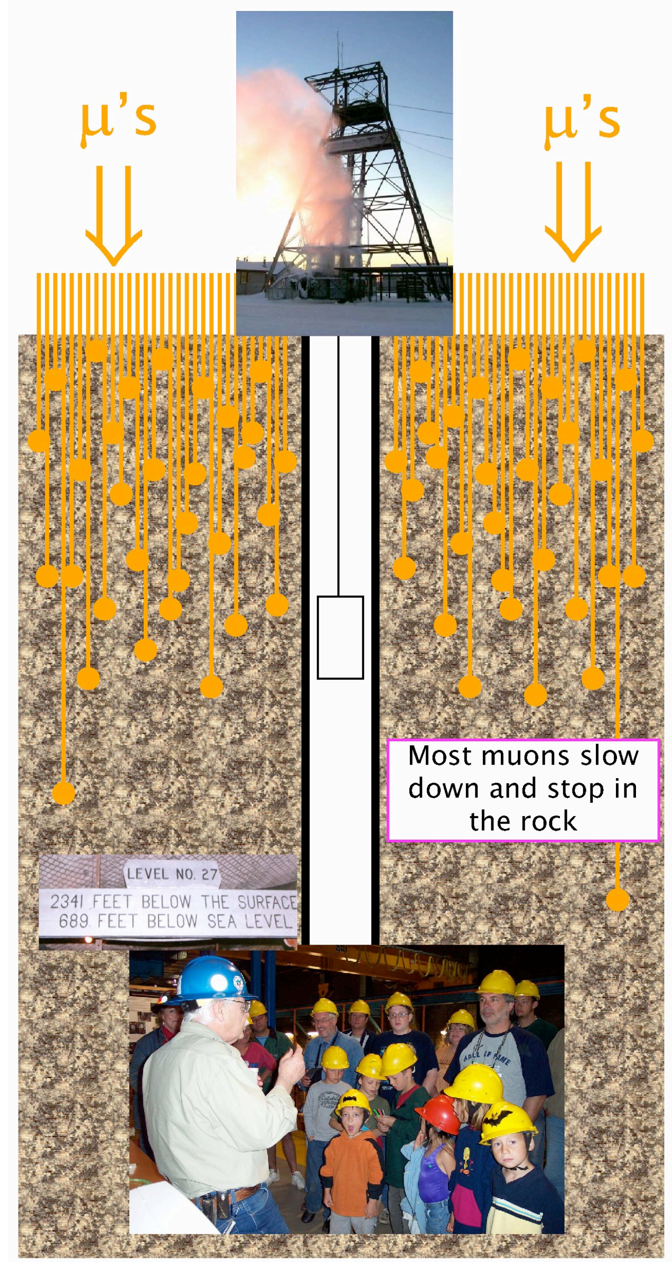
Limited our earlier results…moved to a deep mine

Go Deep Underground to Evade Muons



Deep Facility





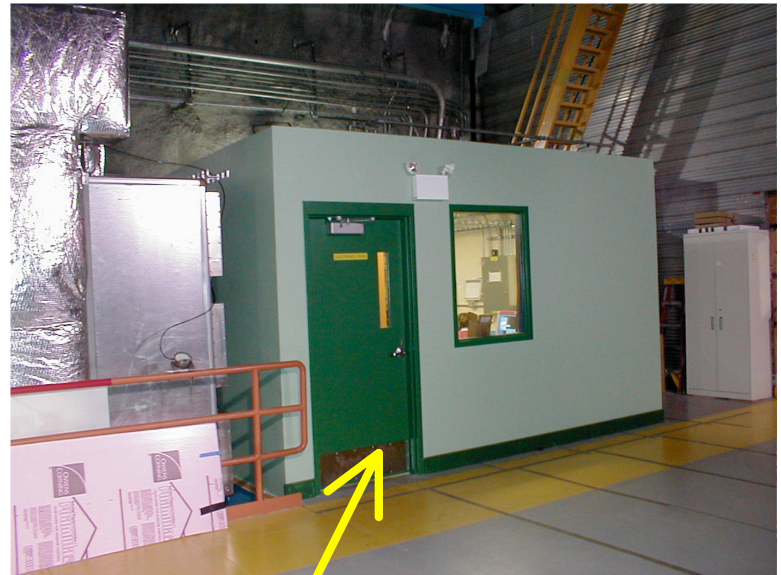
Soudan Mine

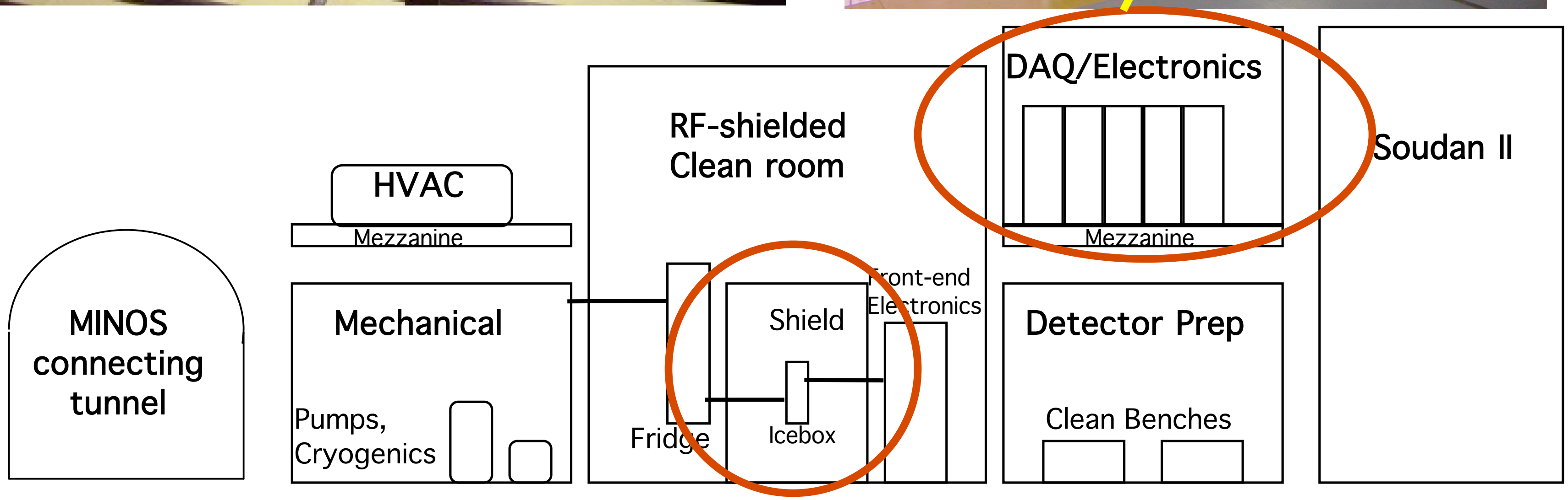
Hosts: State of Minn., U Minn., Fermilab

690 meters underground

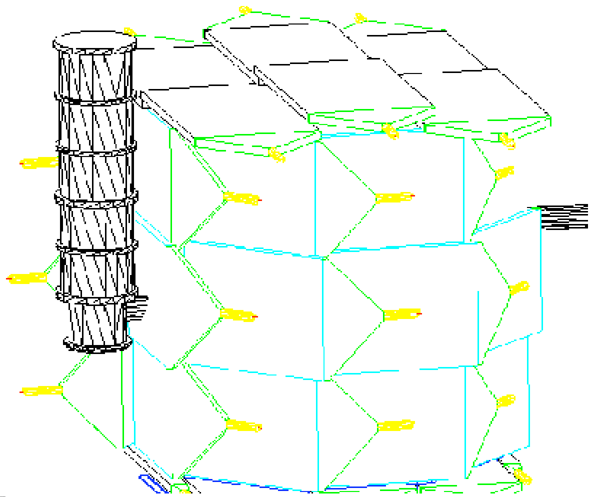
2090 meters water equivalent

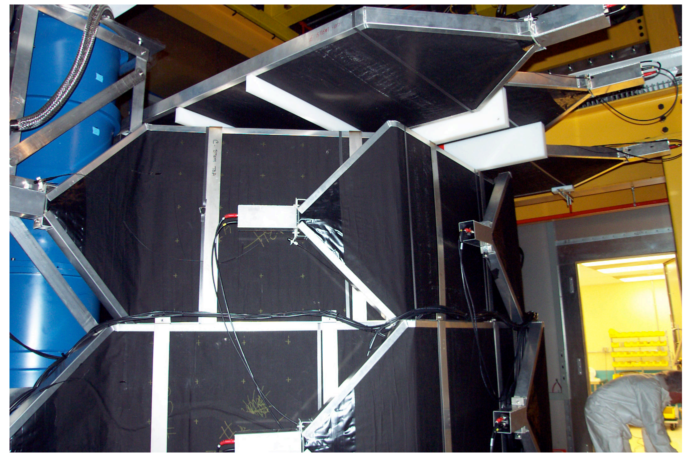
Down deep in the Soudan mine

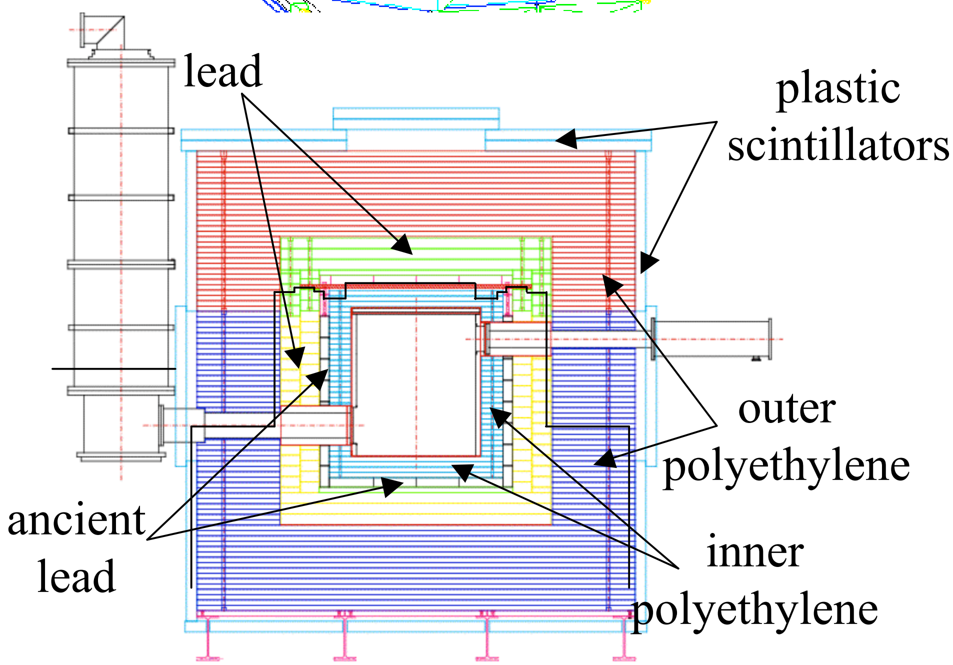




Outside In

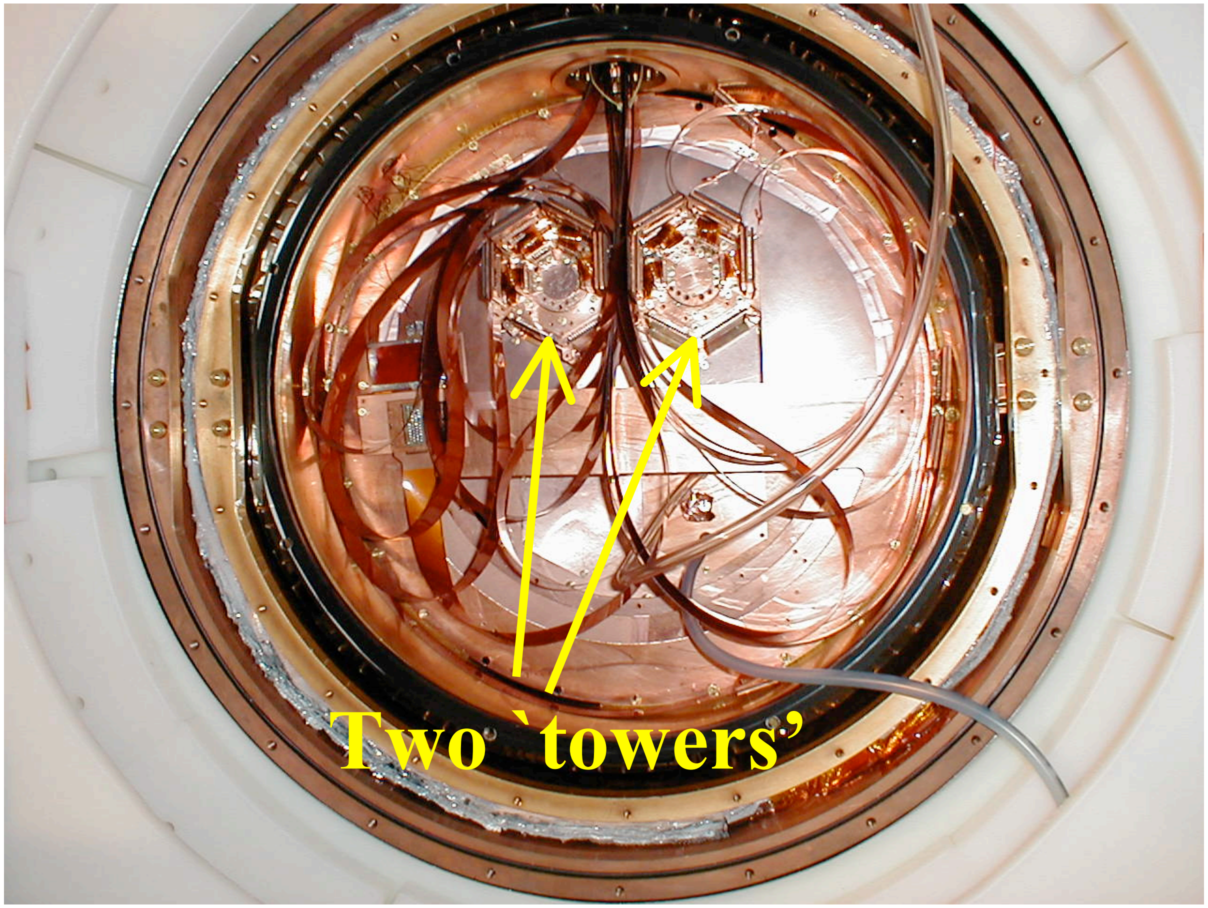


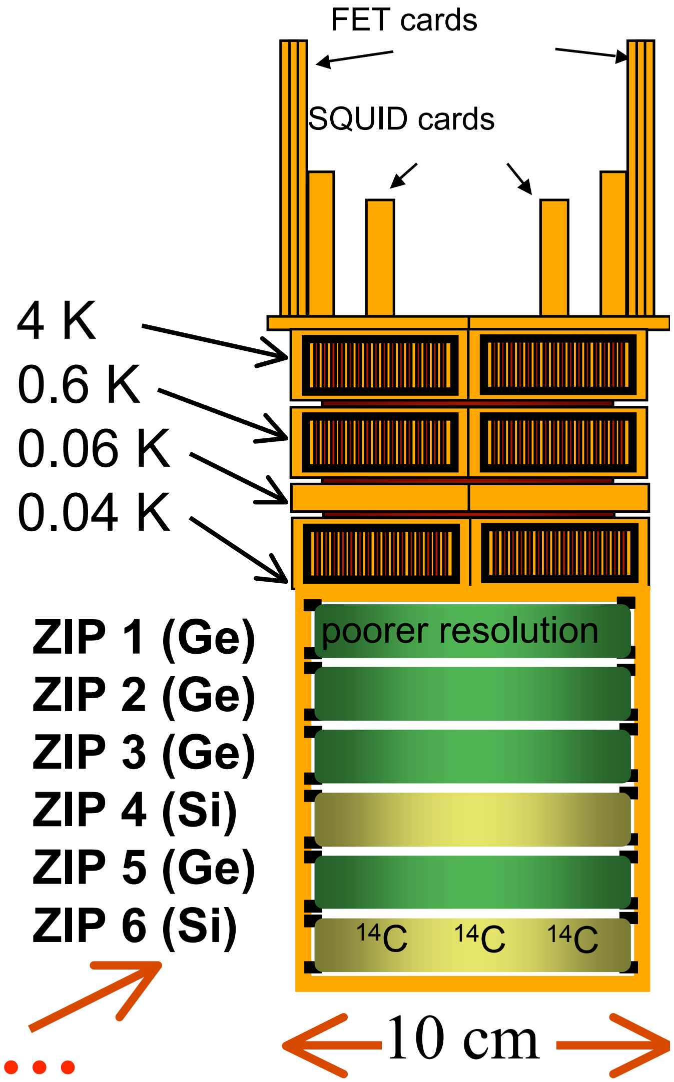



lead
plastic scintillators
outer polyethylene
inner polyethylene
ancient lead

A Cold Heart

Results from first…

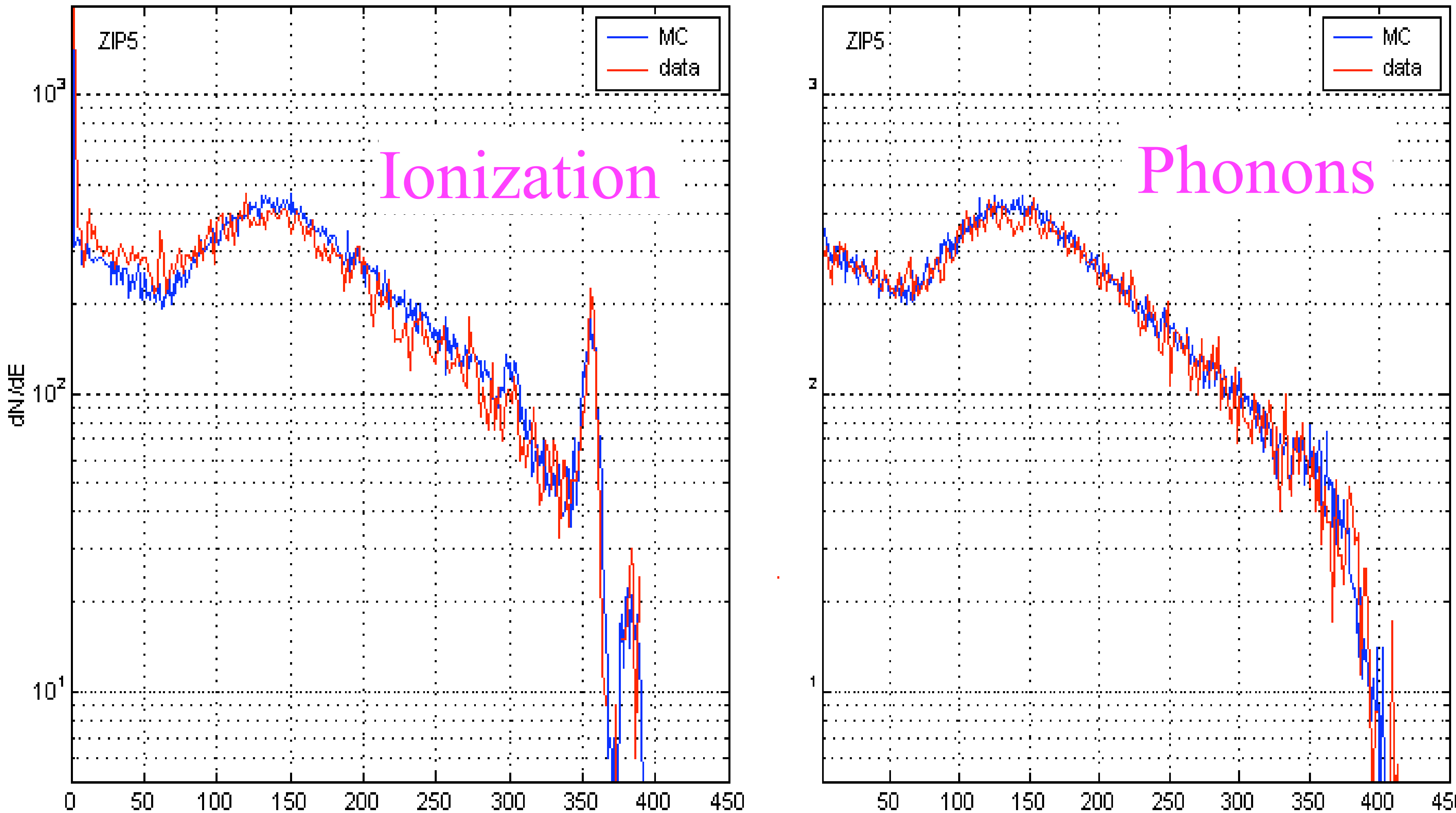




6 detectors…

4 Germanium (0.25 kg each), 2 Silicon (0.1 kg each)

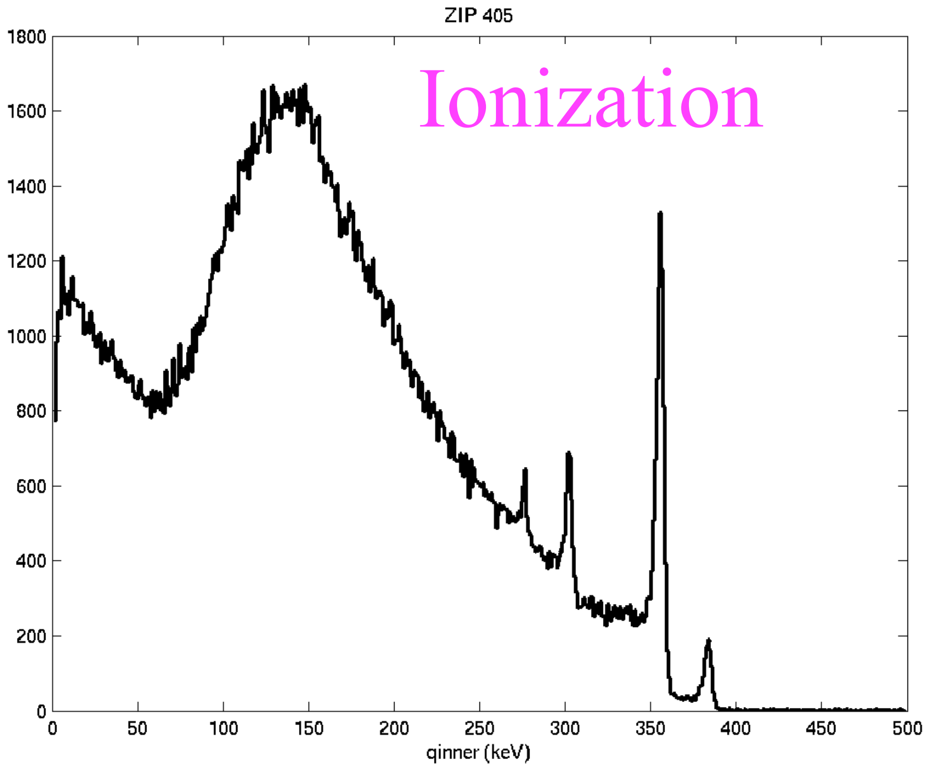
γ Calibration (^{133}Barium) (e^- recoils)

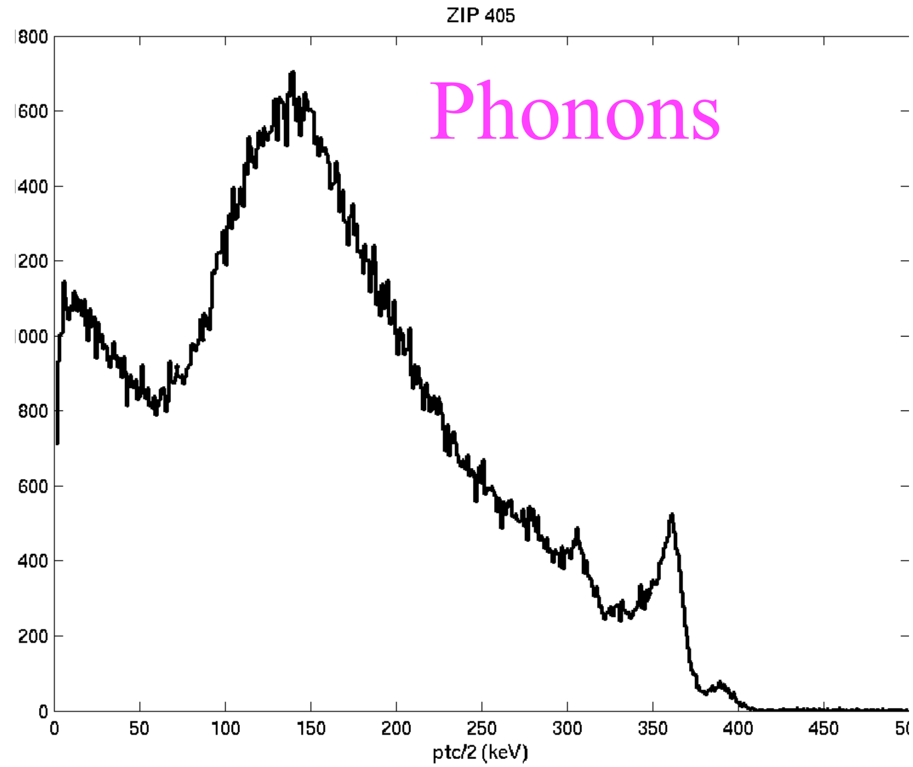


L. Baudis

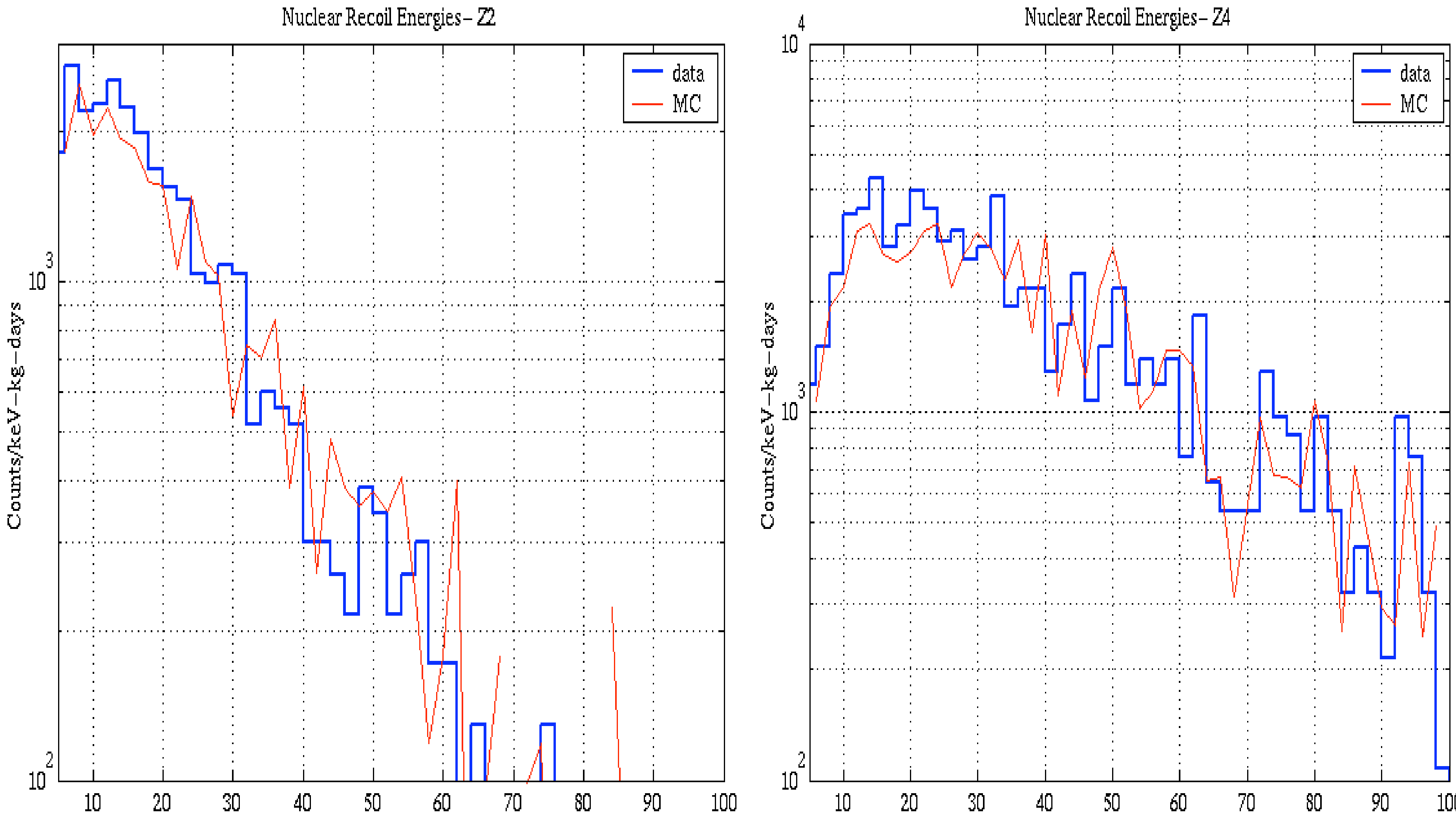
Energy, KeV

Better Source, Calibration





n Calib. (^{252}Californium) (nuclear recoils)



S. Kamat

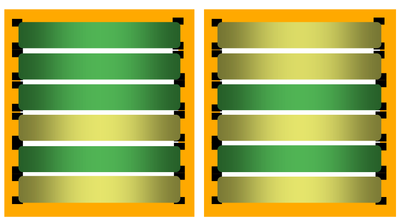
Reconstructed recoil energy, KeV

Soudan Data

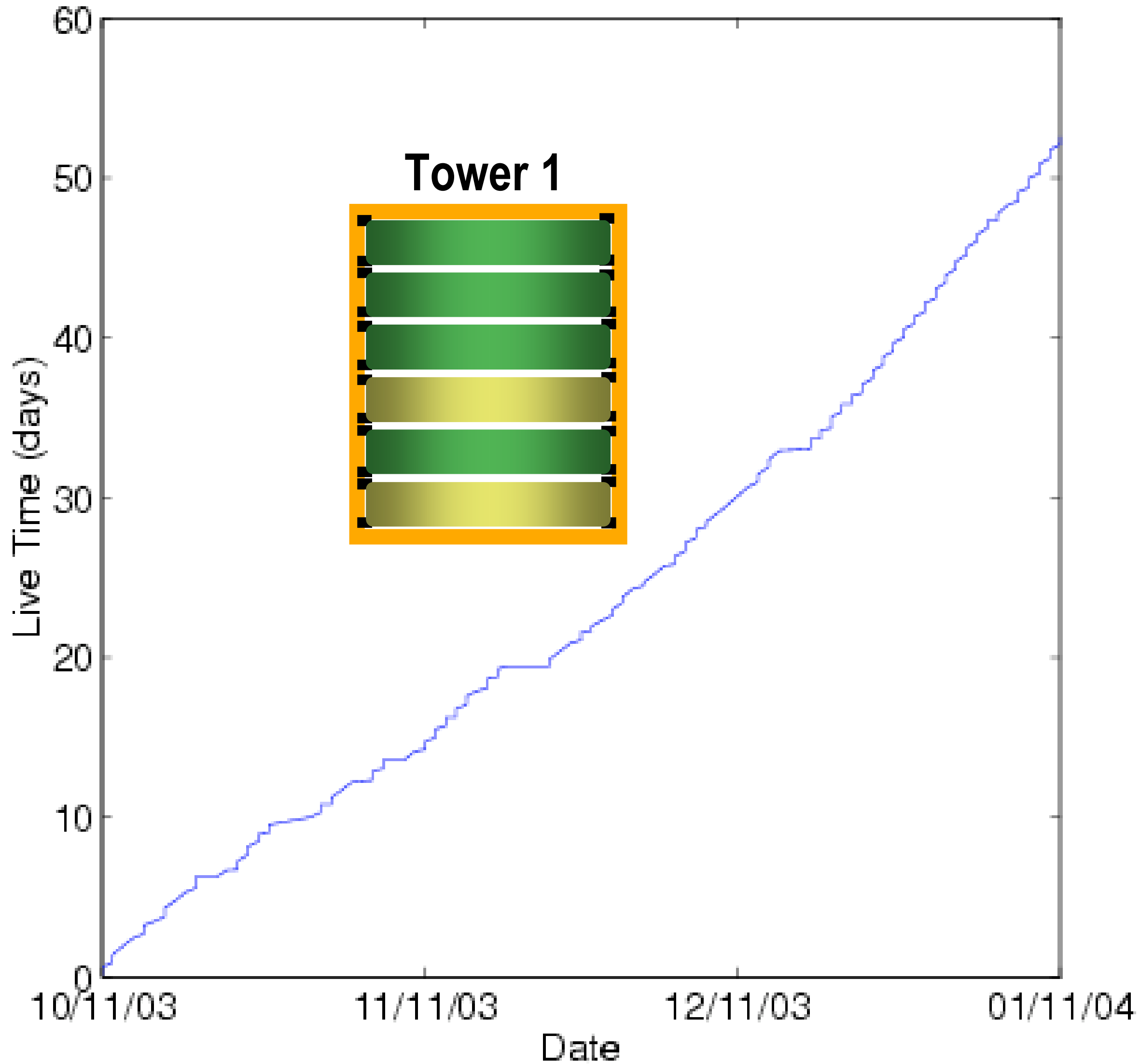
First Run

- 92 calendar days
- 53 live days,
  1 kg Germanium

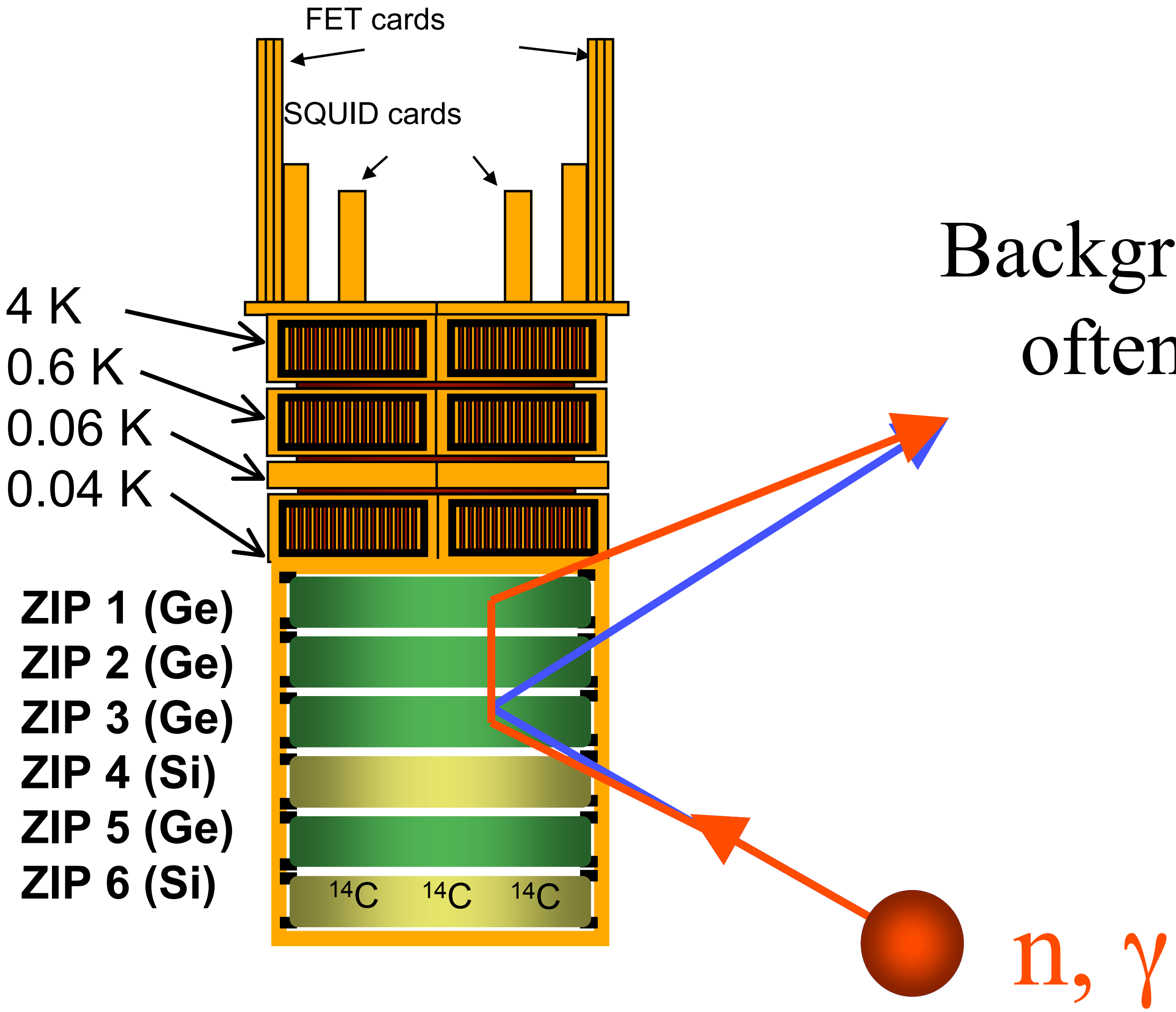
Second Run



- 140 calendar days
- 74 live days,
  1.5 kg Germanium
  0.6 kg Silicon
- Double `Exposure'



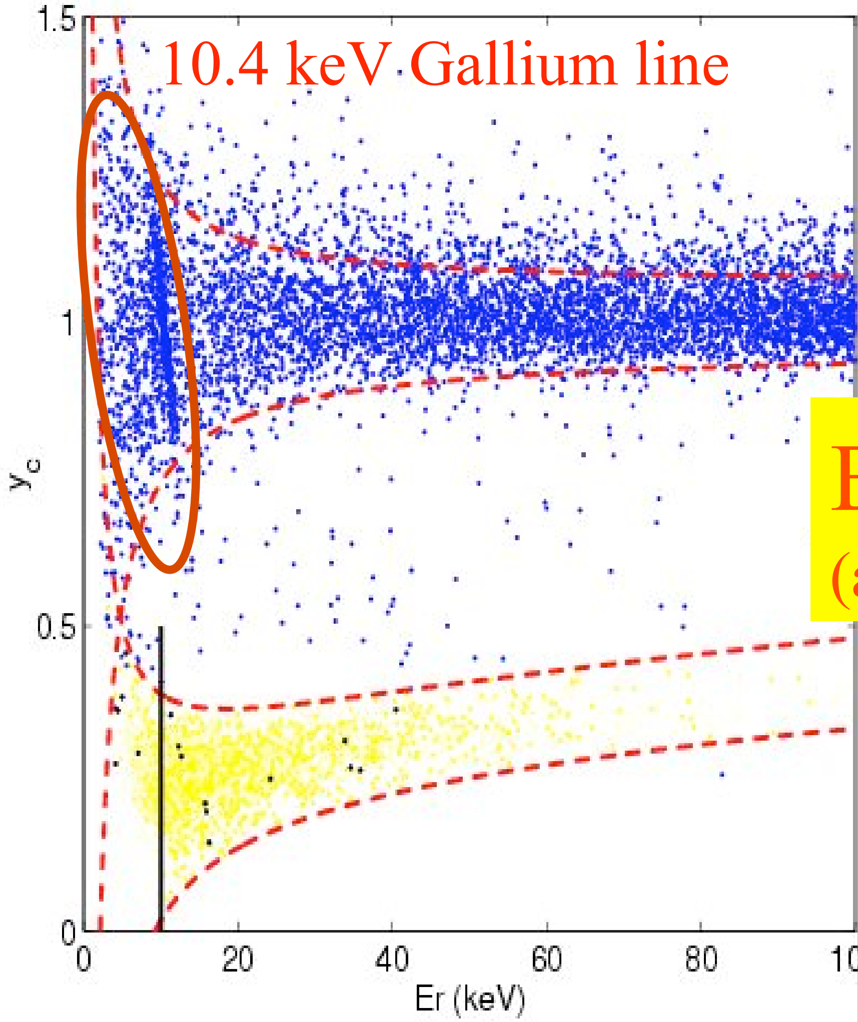
Reject Multiple Interactions

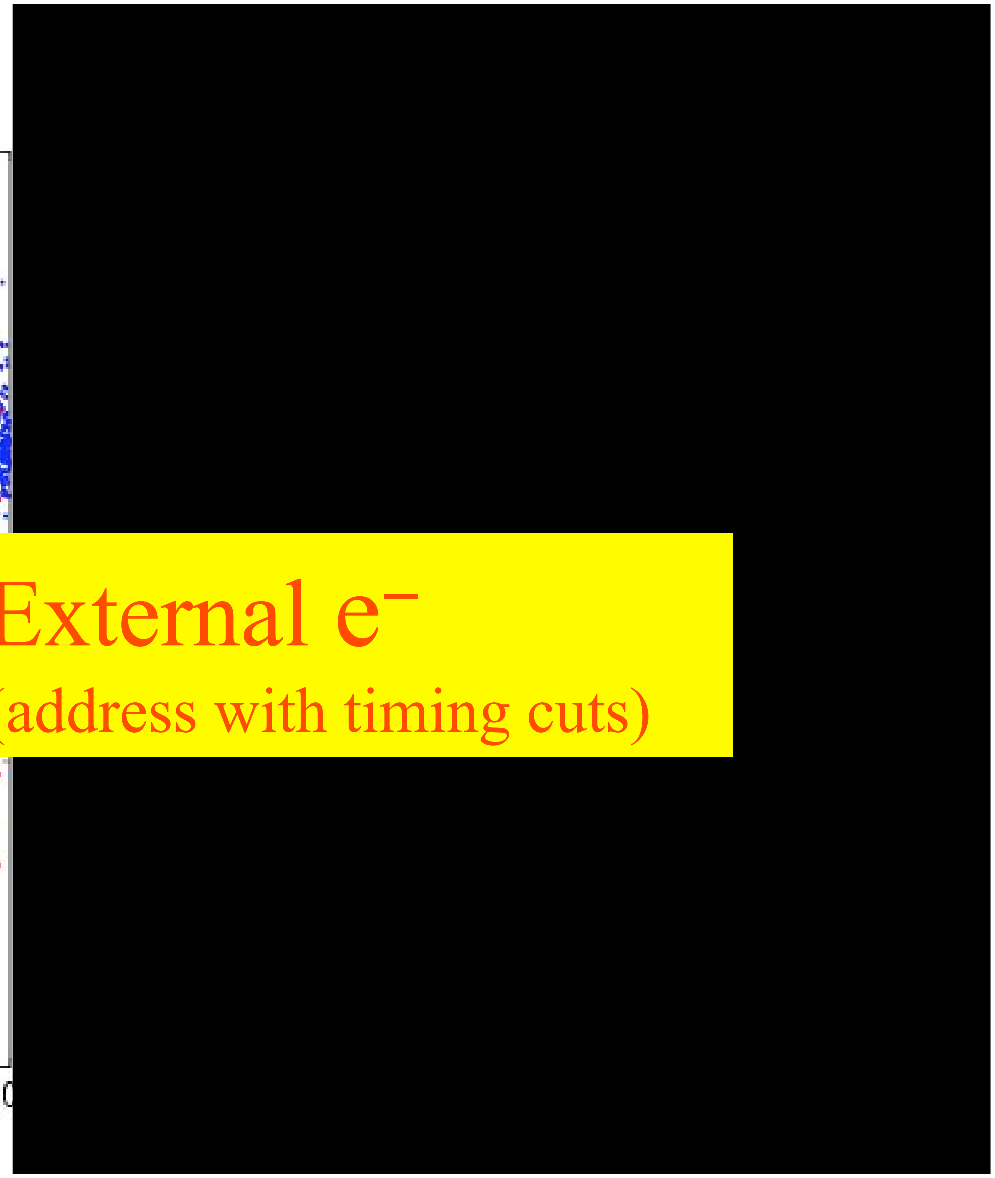


Backgrounds often do

First Run

Prior to timing cuts



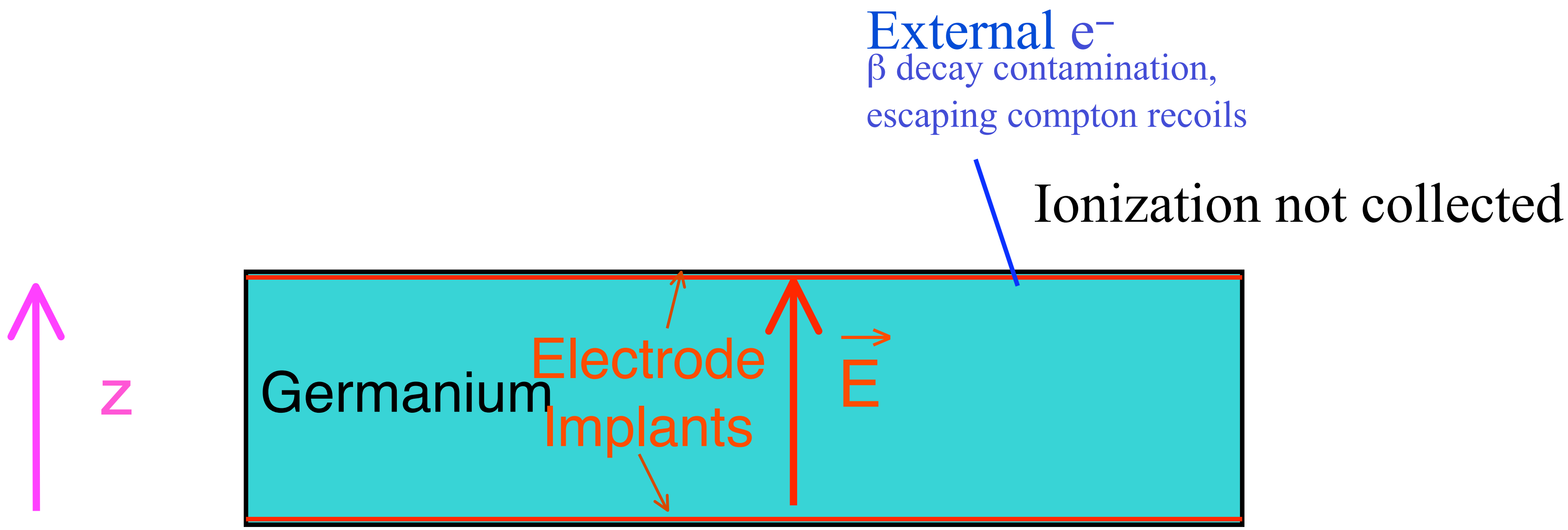


External e⁻

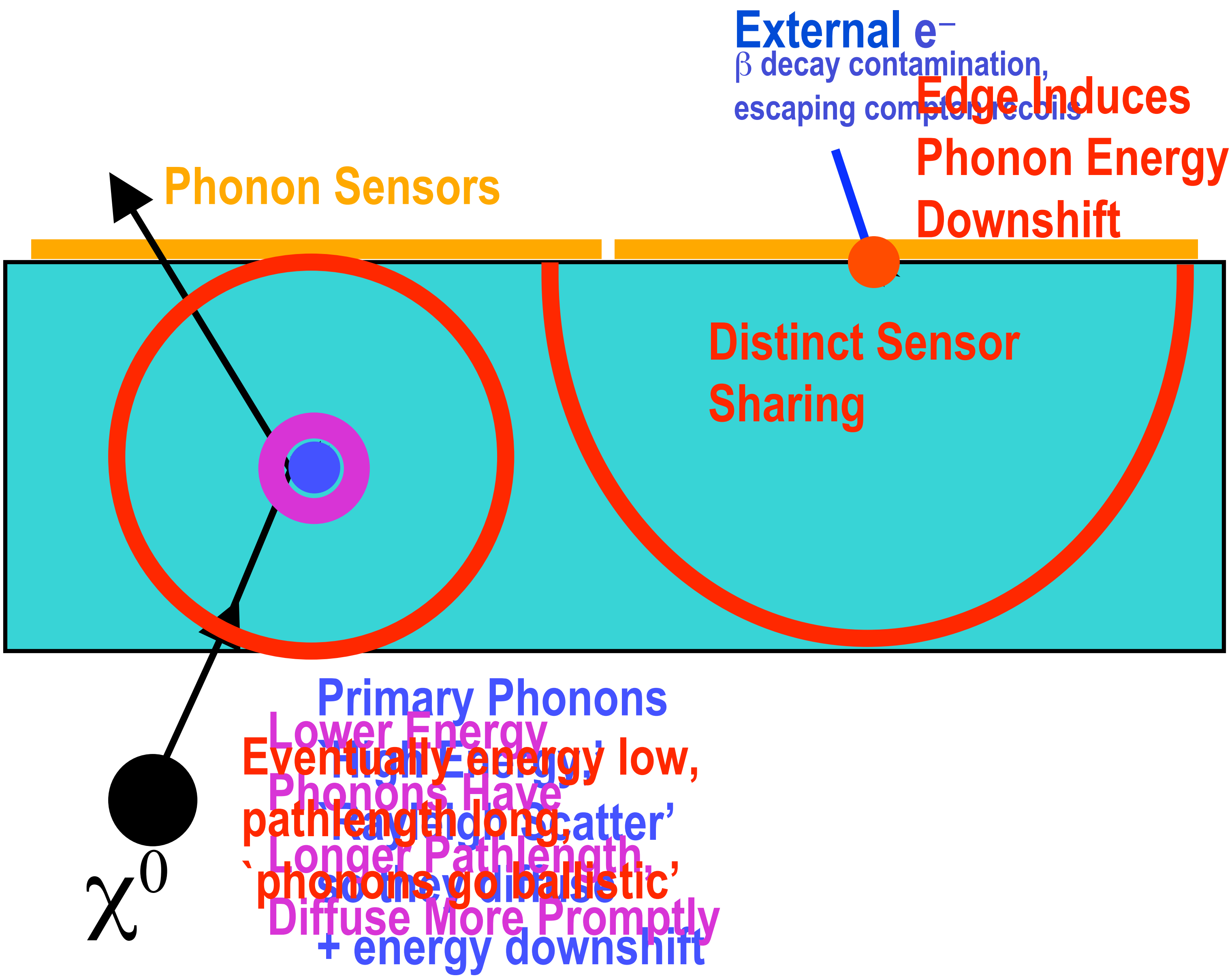
(address with timing cuts)

Nuclear Recoils induced by a neutron source

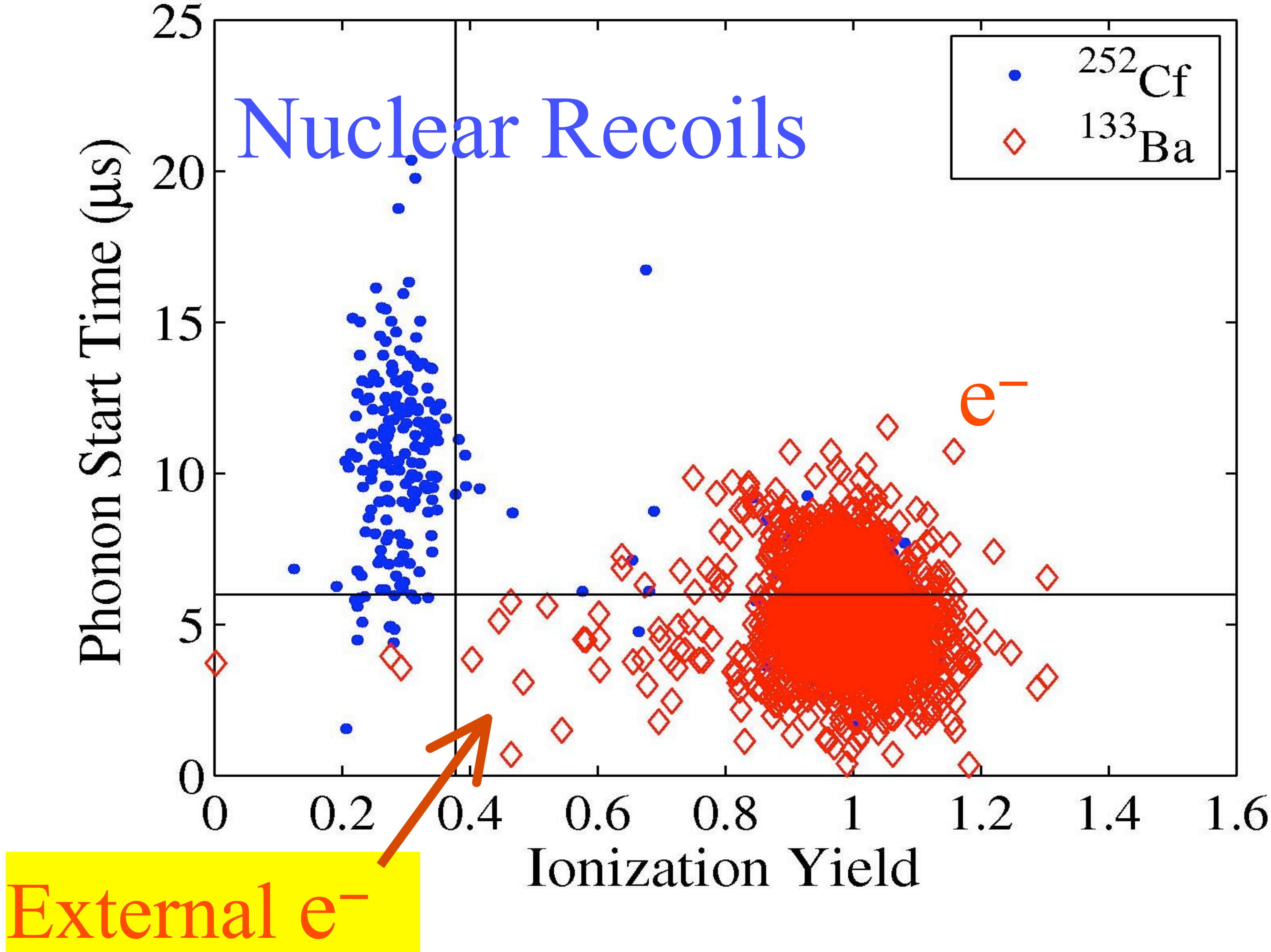
External e⁻ : surface events, ionization missed



`ZIP' : `reconstruct' z with start time, risetime


External e⁻
β decay contamination,
escaping compton recoils
Edge Induces
Phonon Energy
Downshift
Phonon Sensors
Distinct Sensor
Sharing
Primary Phonons
High Energy,
`Rayleigh Scatter'
so they diffuse
+ energy downshift
Lower Energy
Phonons Have
Longer Pathlength,
Diffuse More Promptly
Eventually energy low,
pathlength long,
`phonons go ballistic'
χ0

Timing rejects surface/external e⁻

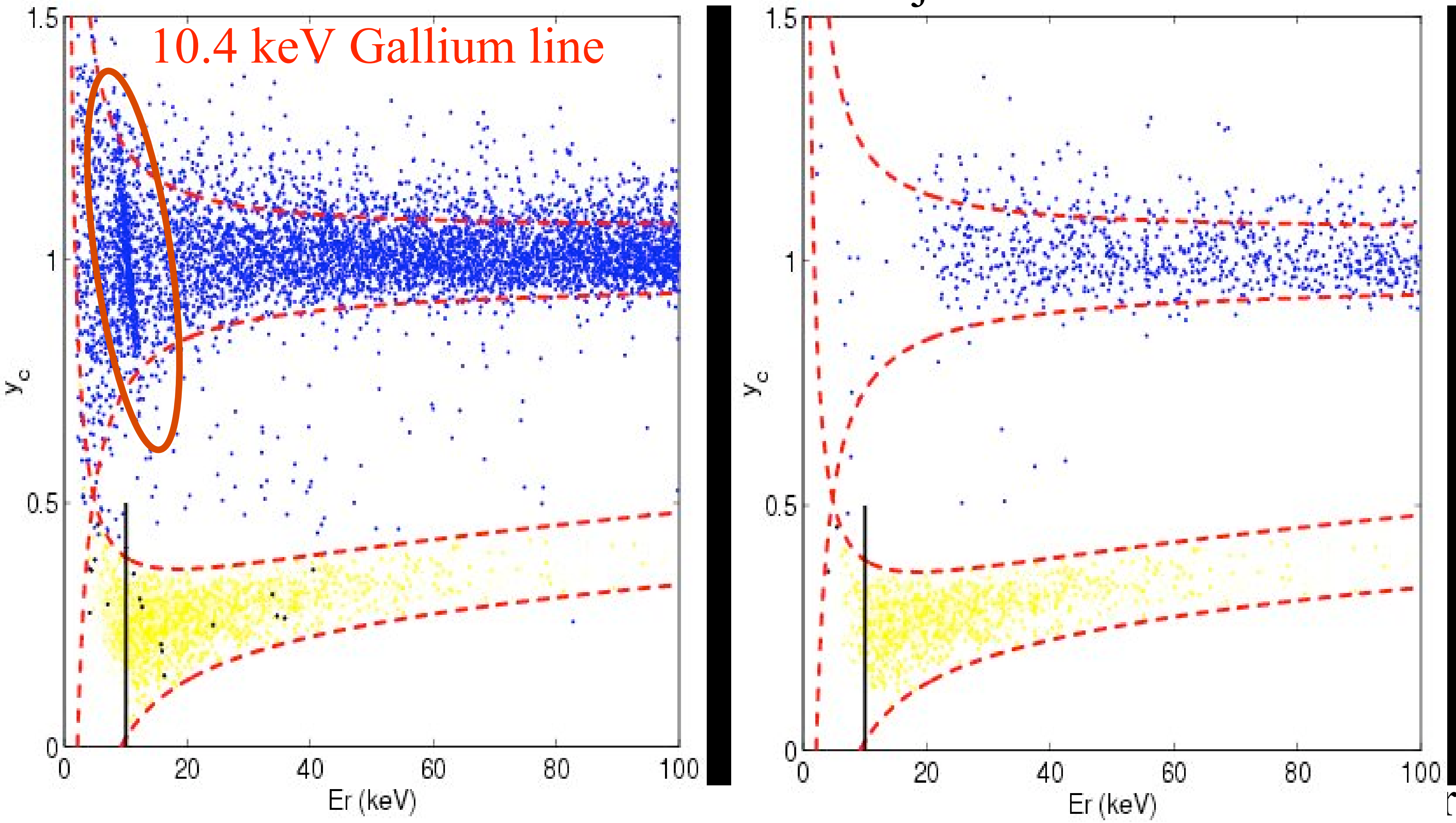


WIMP search data with Ge detectors

Z2, Z3, Z5

Prior to timing cuts

After timing cuts, which reject external electrons

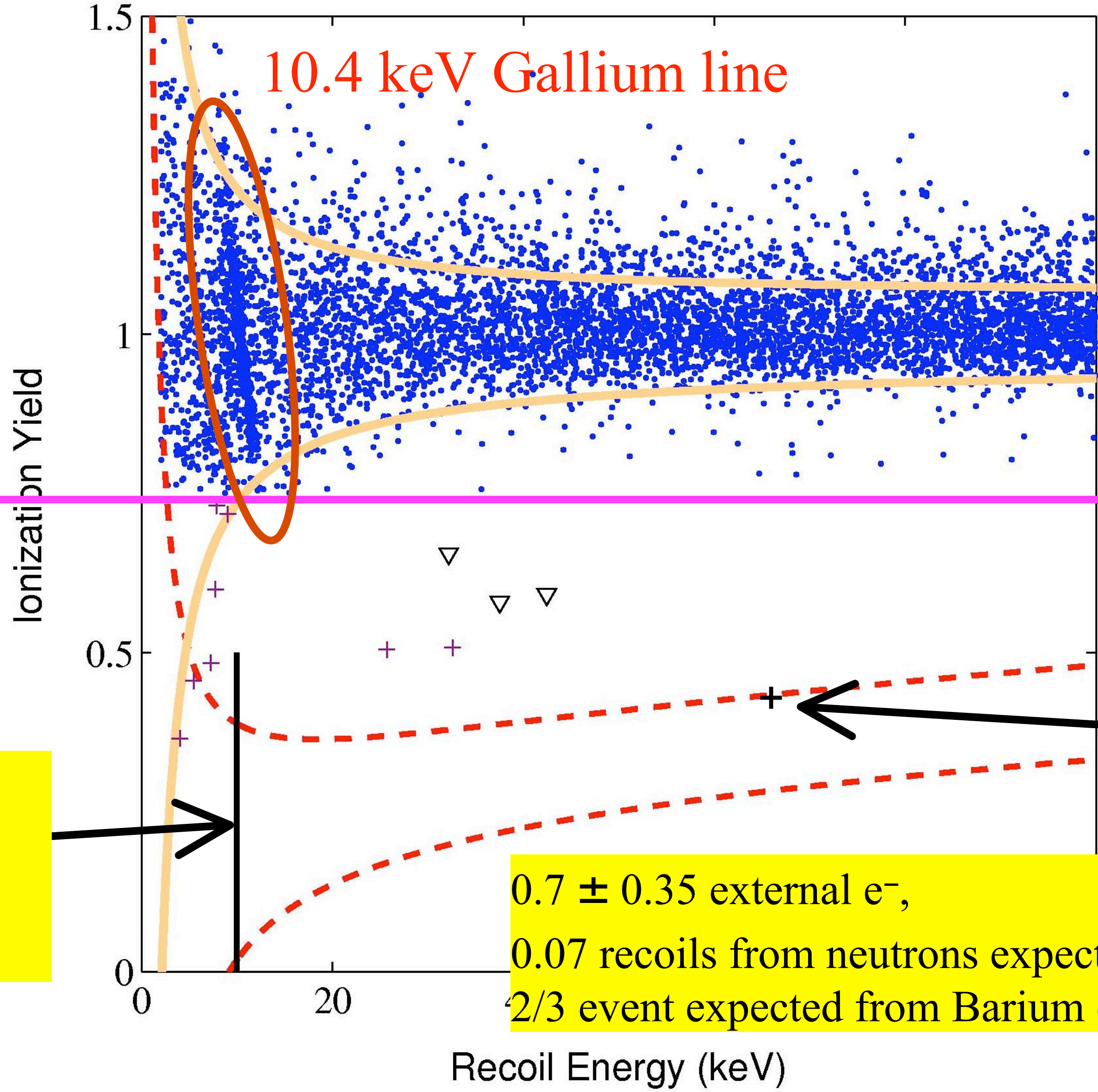


ra

Nuclear Recoils induced by a neutron source

All the features on one plot

Z2, Z3, Z5



Surface Rejection:

Omitted

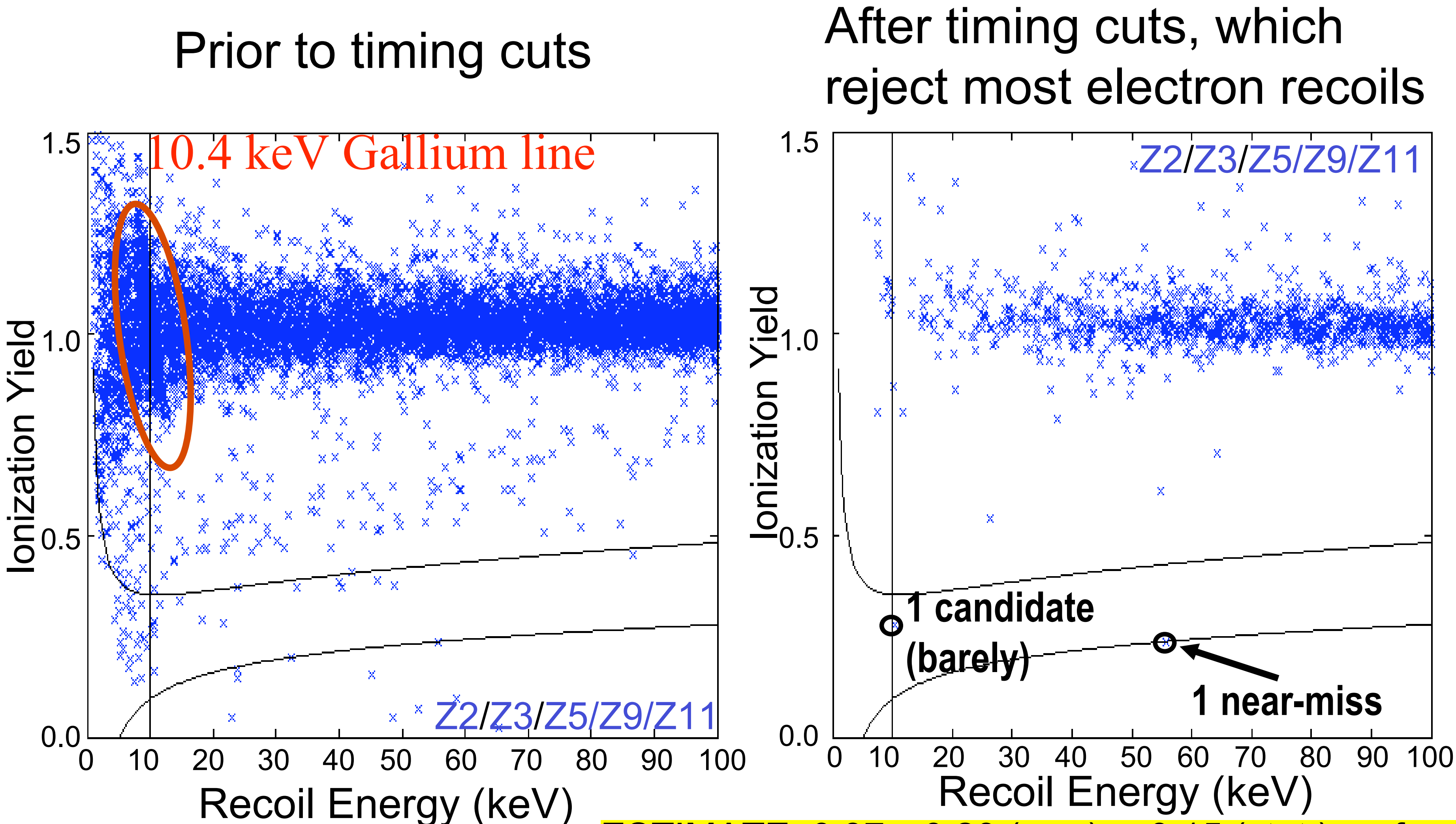
Applied

10 keV threshold (1 20 keV)

Energy Estimate Corrected (non-blind)

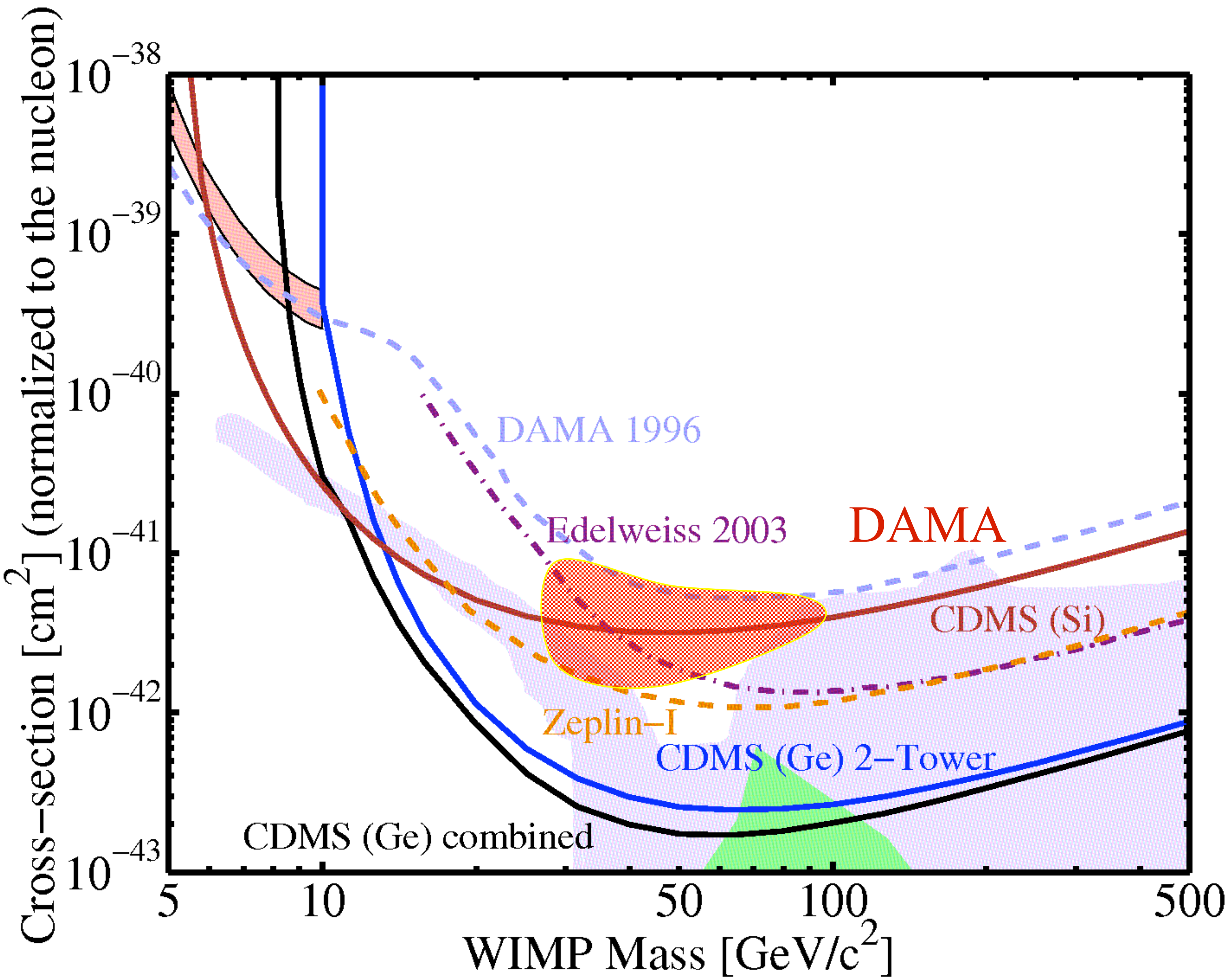
0.7 ± 0.35 external e⁻,
0.07 recoils from neutrons expected
2/3 event expected from Barium calib

Second Run – twice the exposure



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

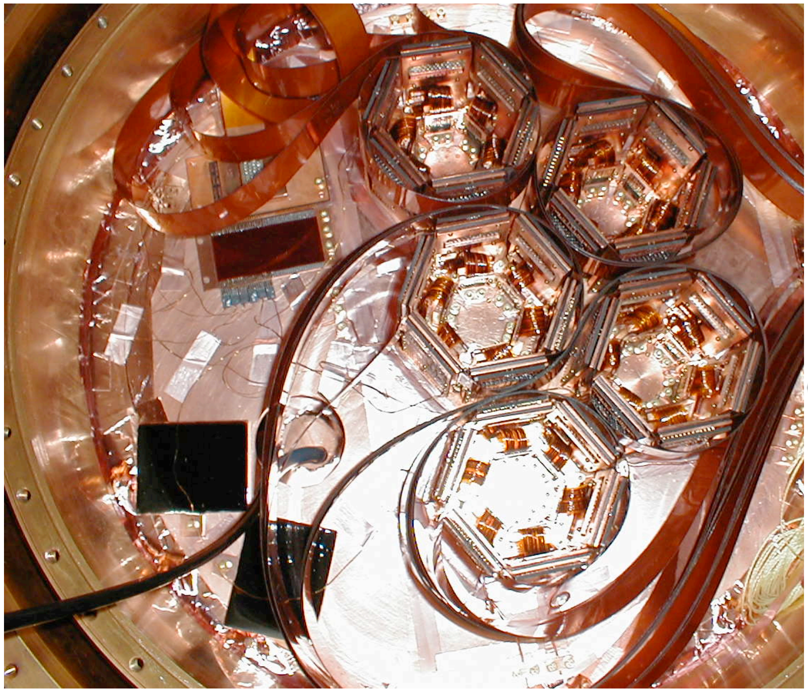
Limits

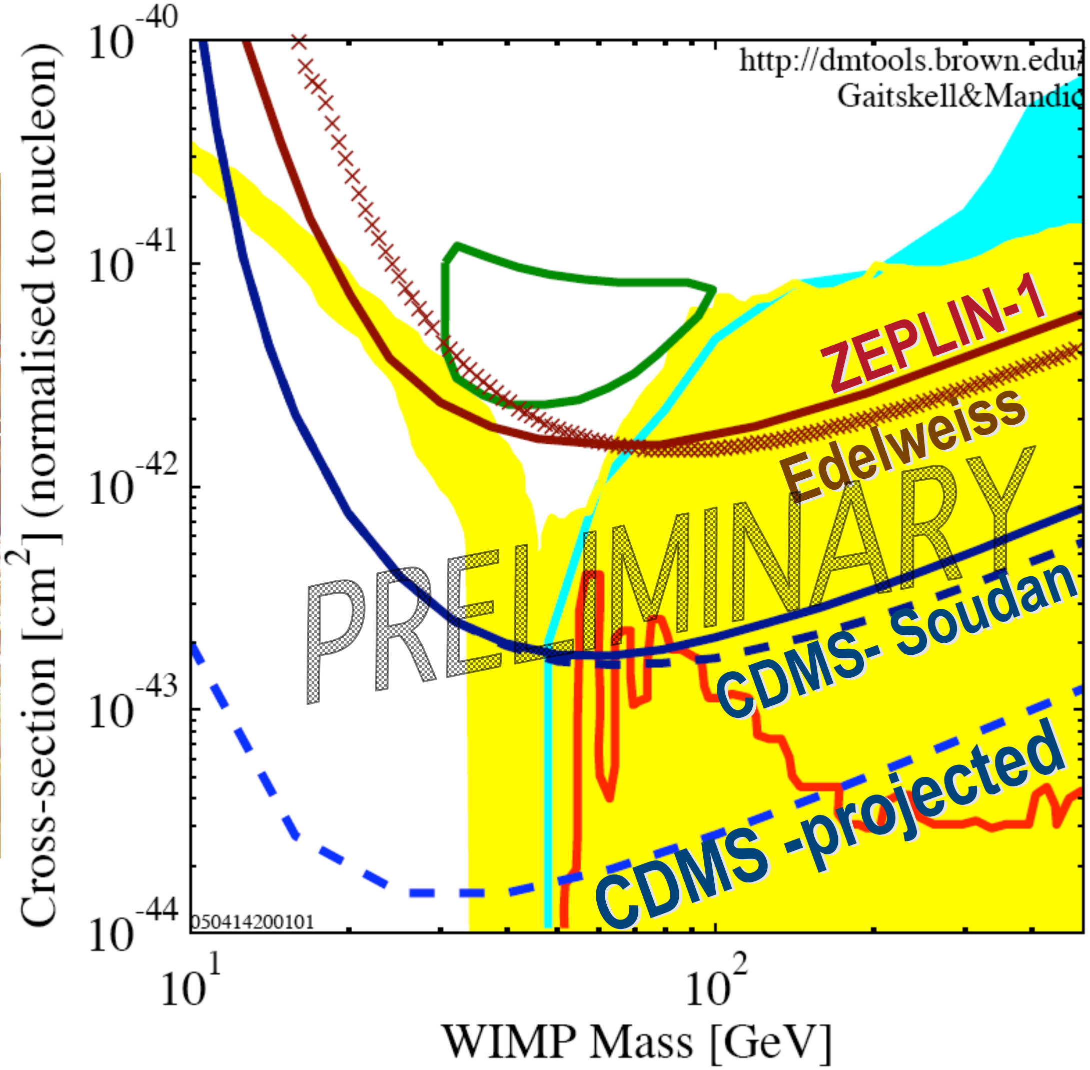


Cross−section [cm^2] (normalized to the nucleon)
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
5
10
50
100
500
WIMP Mass [GeV/c^2]
DAMA 1996
Edelweiss 2003
DAMA
CDMS (Si)
Zeplin−I
CDMS (Ge) 2−Tower
CDMS (Ge) combined

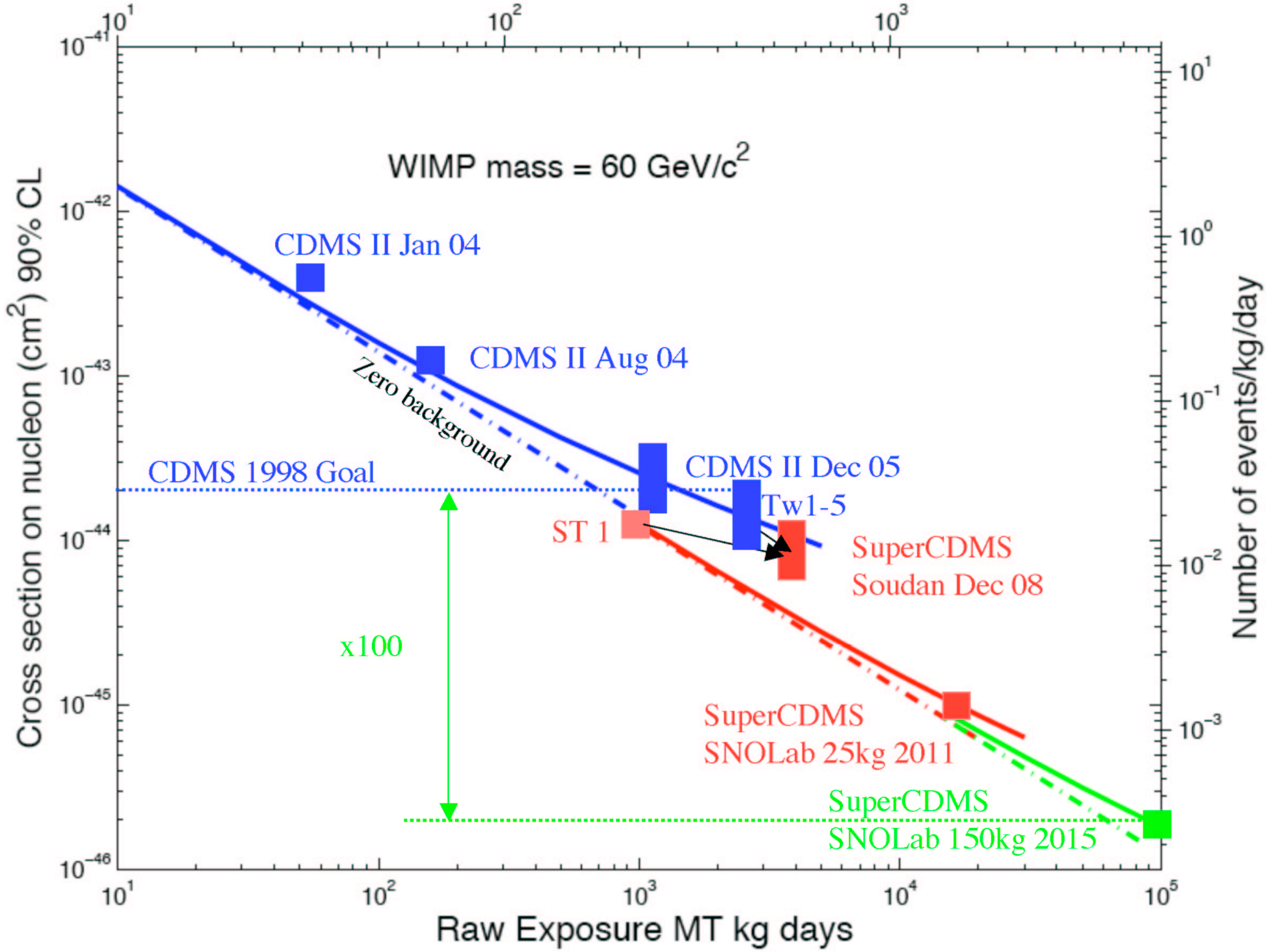
The Near Future

Installed 3 additional towers November 2004

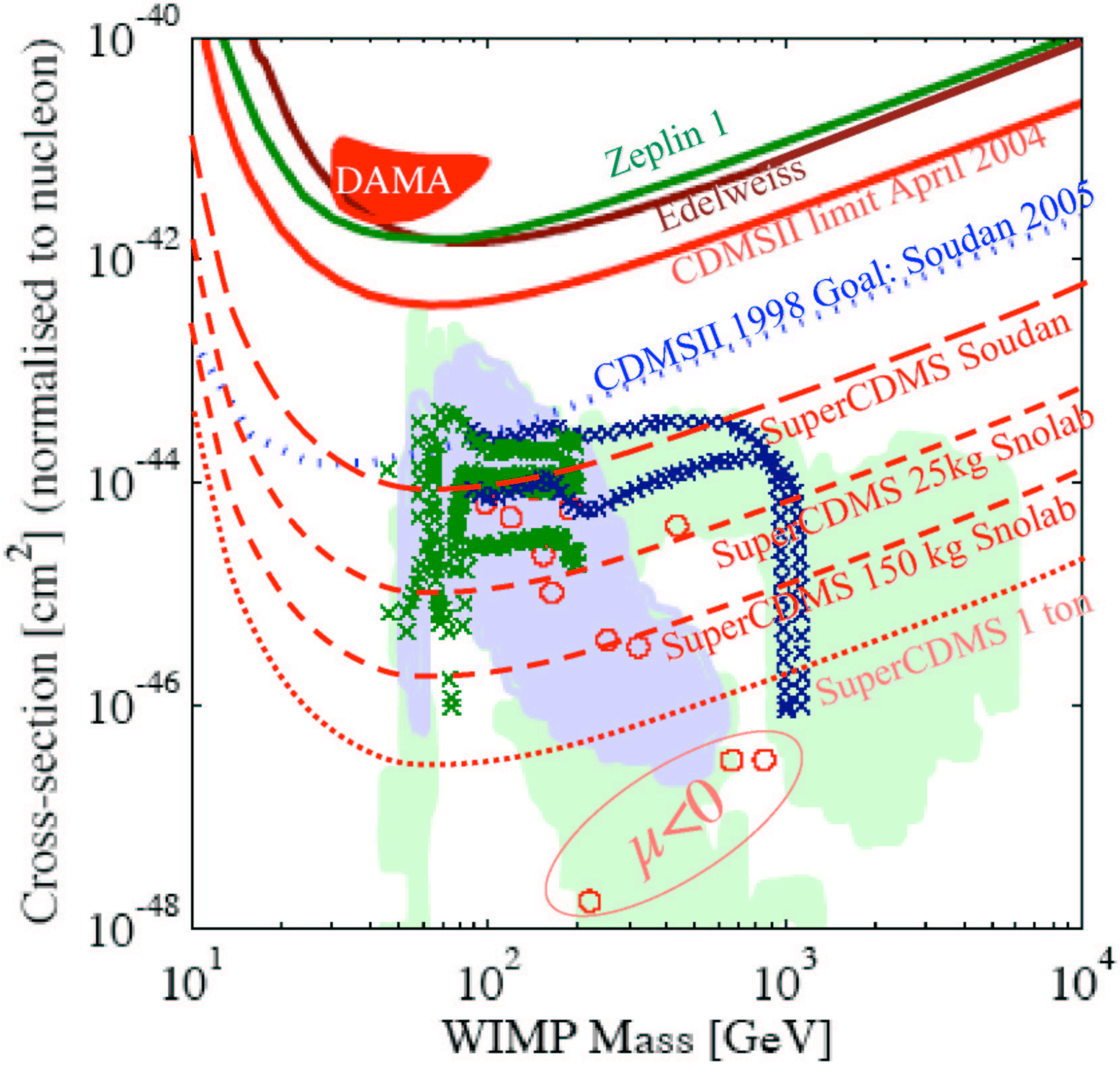




Sensitivity Expectations: Distant Future

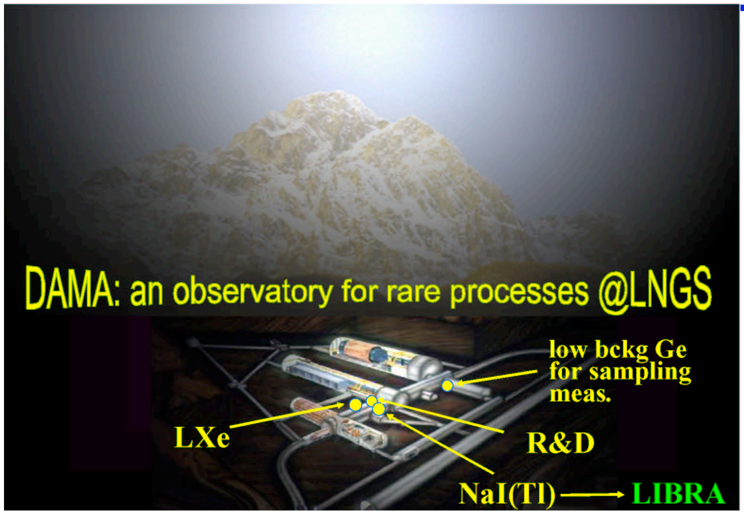


Projected Sensitivies



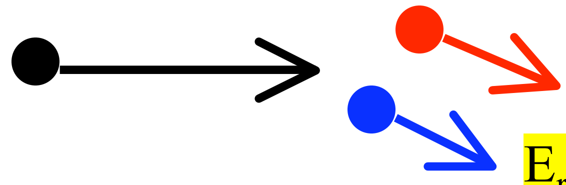
CDMS Collaboration(March 2002)

DAMA – 100 kg of NaI



Sodium, A=23

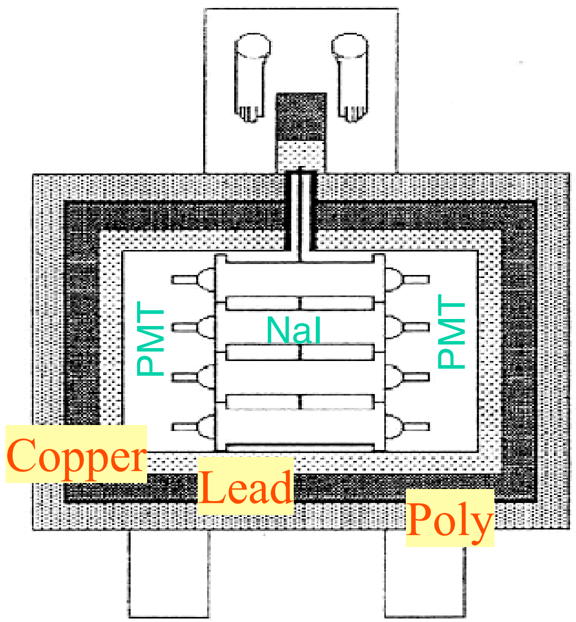
$E_{obs}(KeV_{ee}) \approx 0.25\ E_{recoil}\,(KeV)$

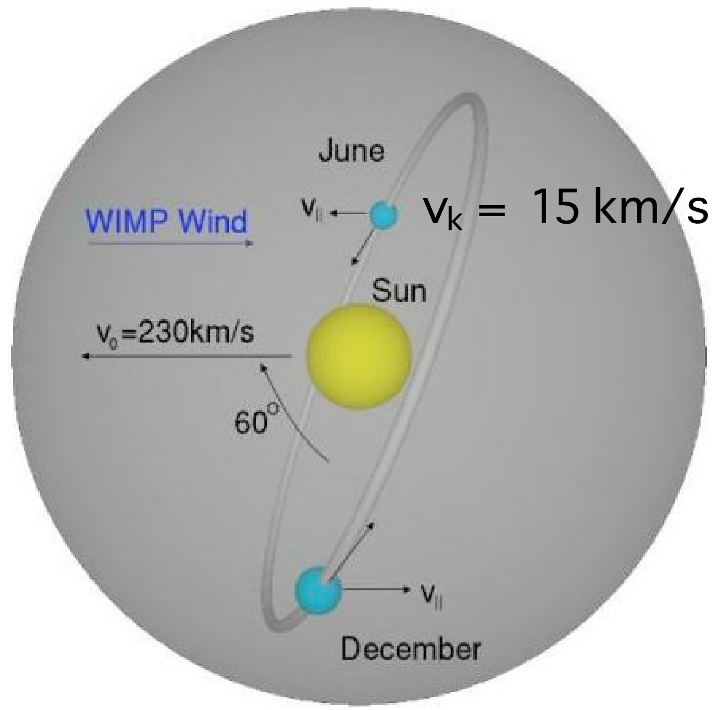


$E_{recoil} \rightarrow$ Light

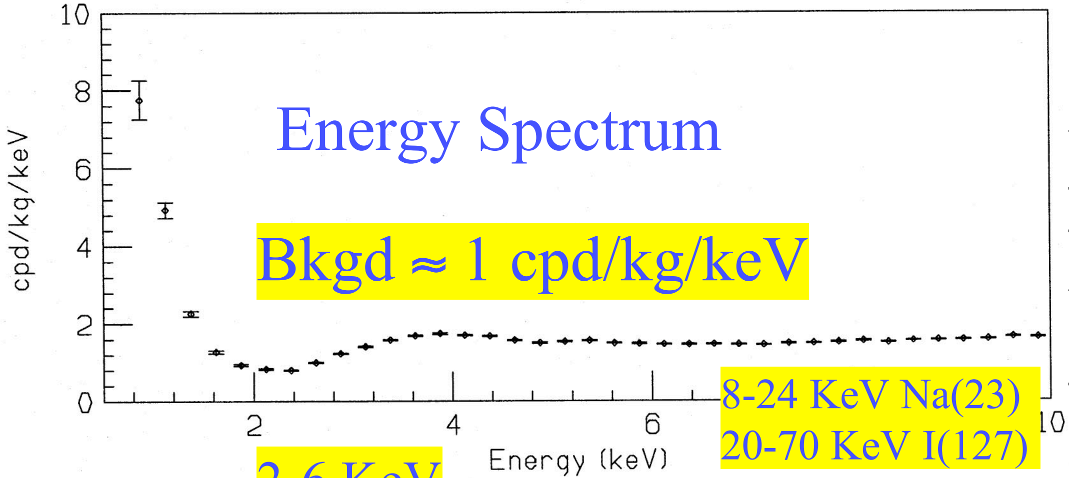
Iodine, A=127

$E_{obs}(KeV_{ee}) \approx 0.09\ E_{recoil}\,(KeV)$





DAMA Background and Signal



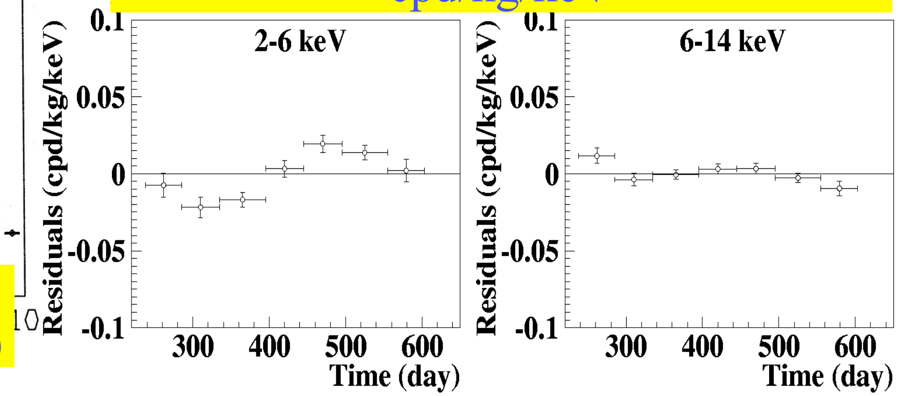
Energy Spectrum

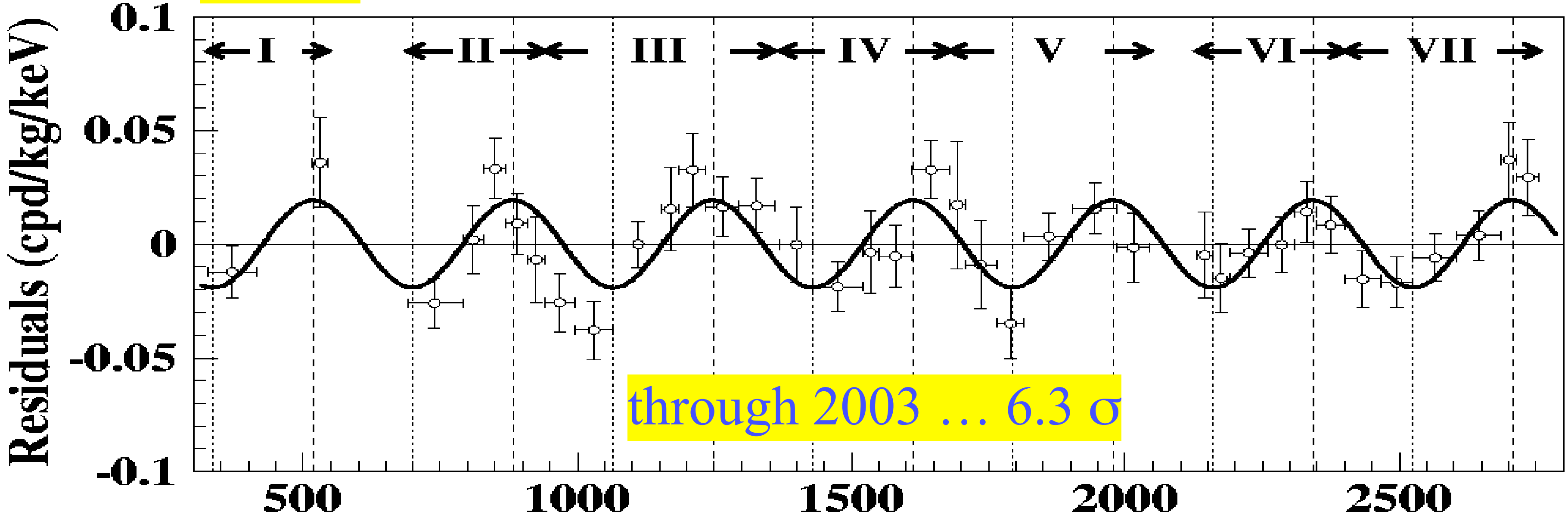
Bkgd ≈ 1 cpd/kg/keV

8-24 KeV Na(23)
20-70 KeV I(127)

2-6 KeV

0.0195±0.031 -0.0001±0.019
cpd/kg/keV

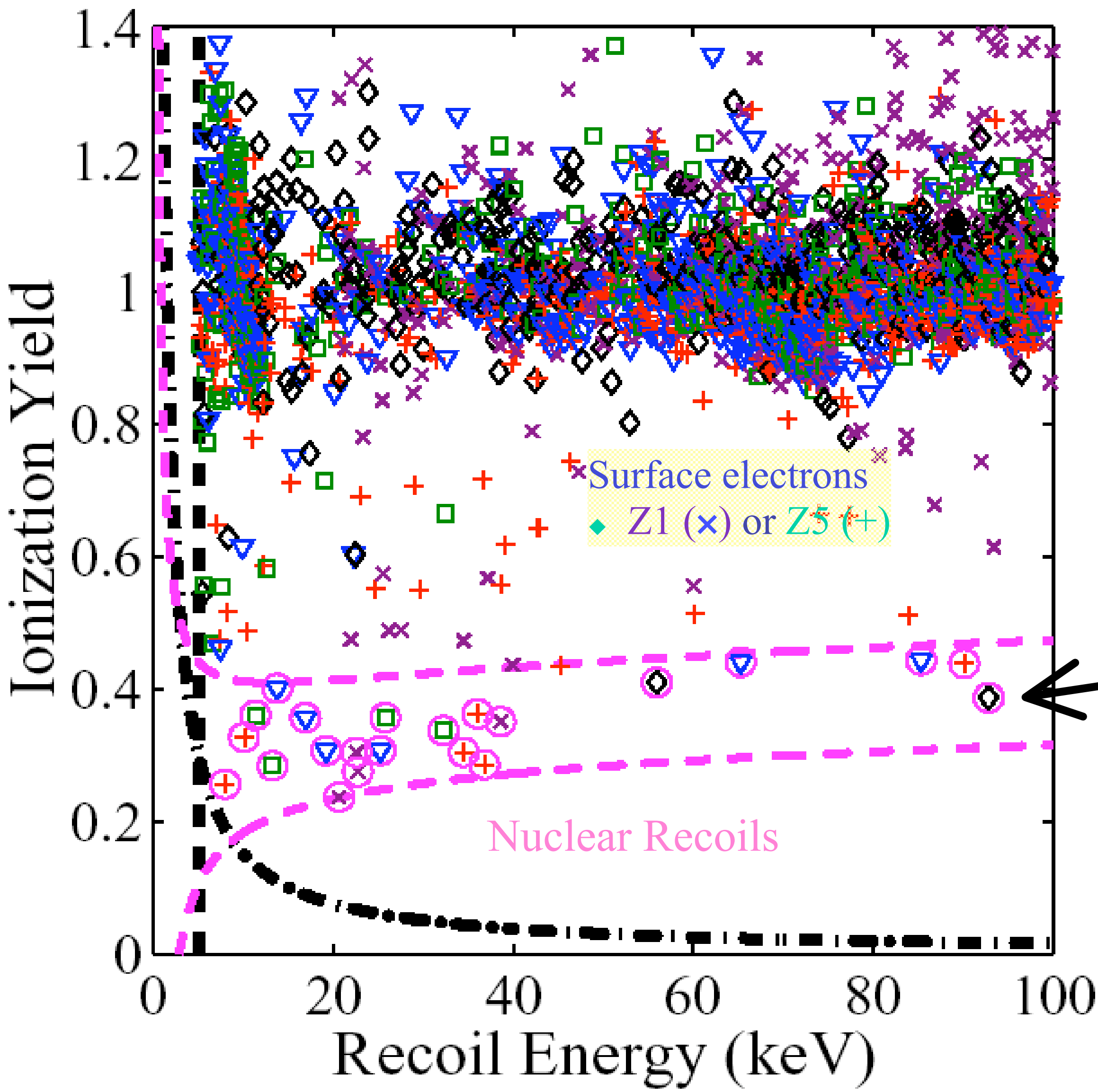




through 2003 … 6.3 σ

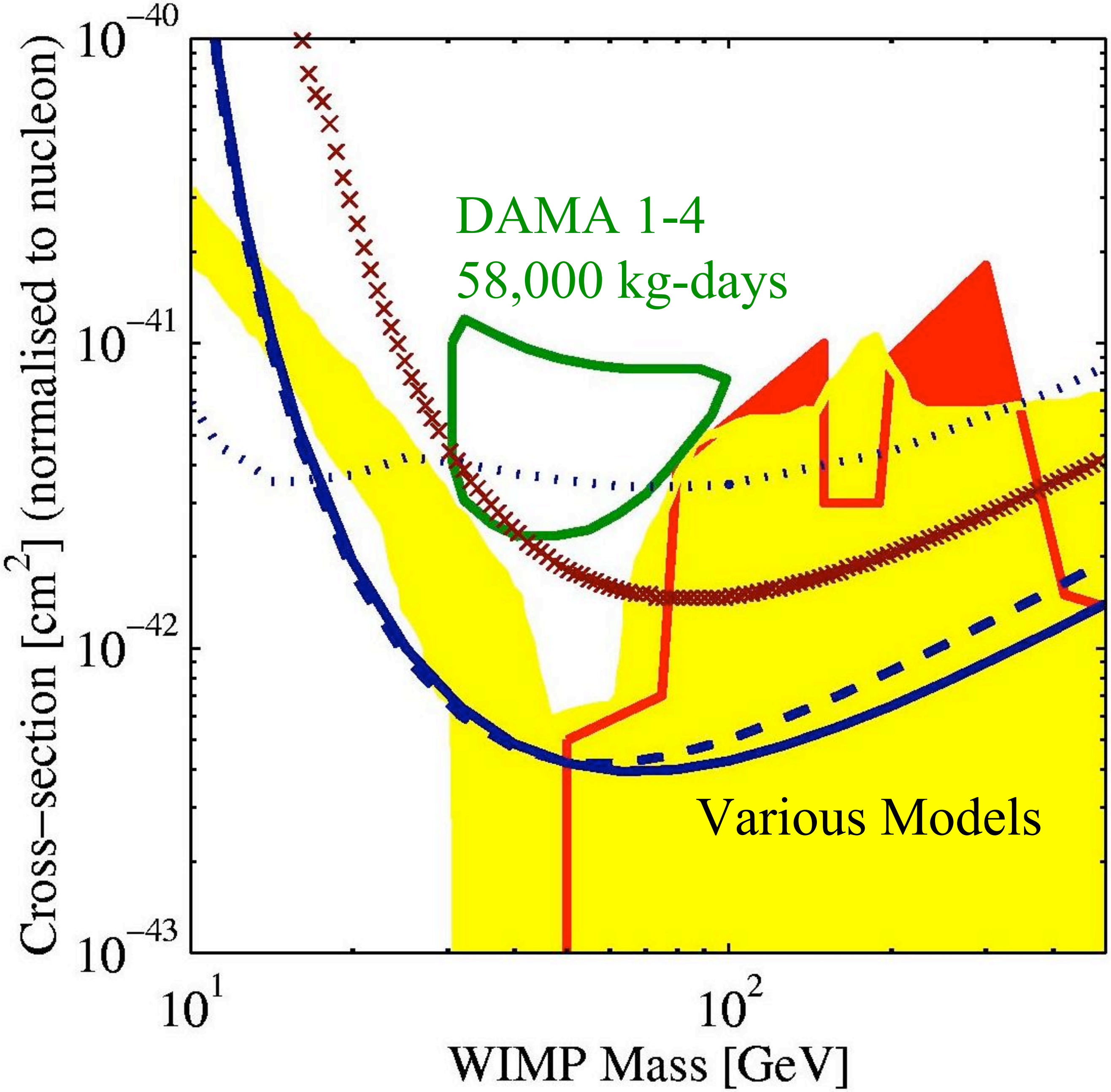
Bernabei et al., astro-ph/0307403

Similar Exposure… Stanford Site



Neutrons!! Soudan rock filters the muons that make them (but not WIMPS)

Limits



CDMS Stanford

Edelweiss

Non-blind

blind

(10's of kg-days)