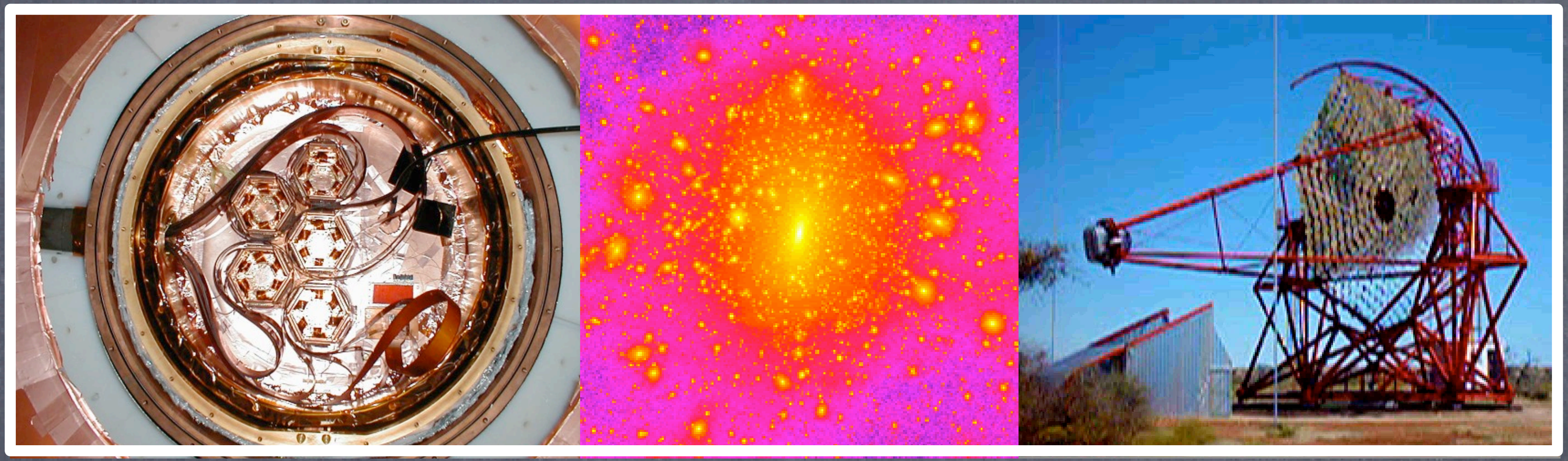
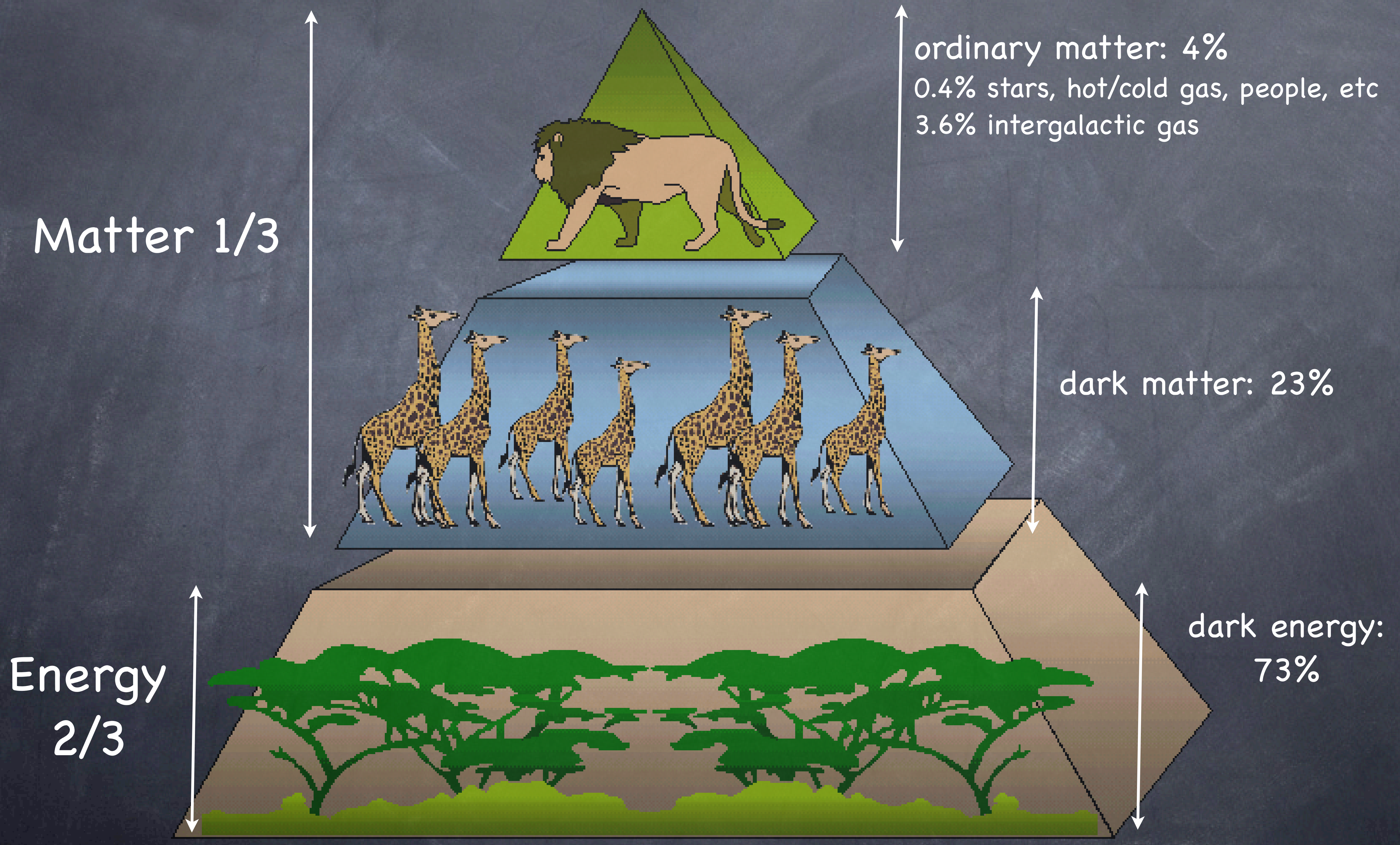
Searches for Cold Relics of the Early Universe



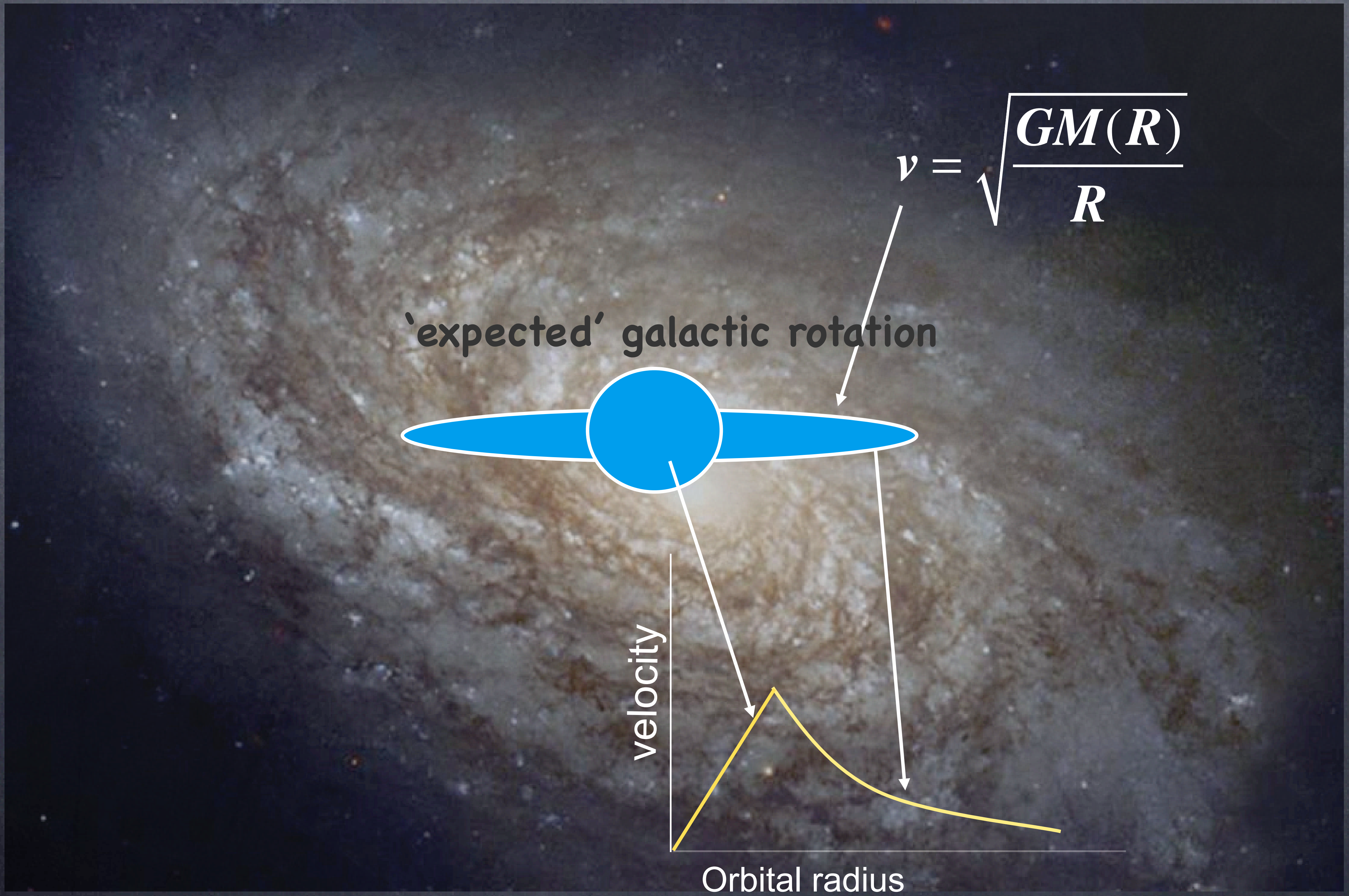
Laura Baudis
University of Florida
Toronto, January 26, 2006

The Cosmic Food Chain



Dark Matter in Galaxies

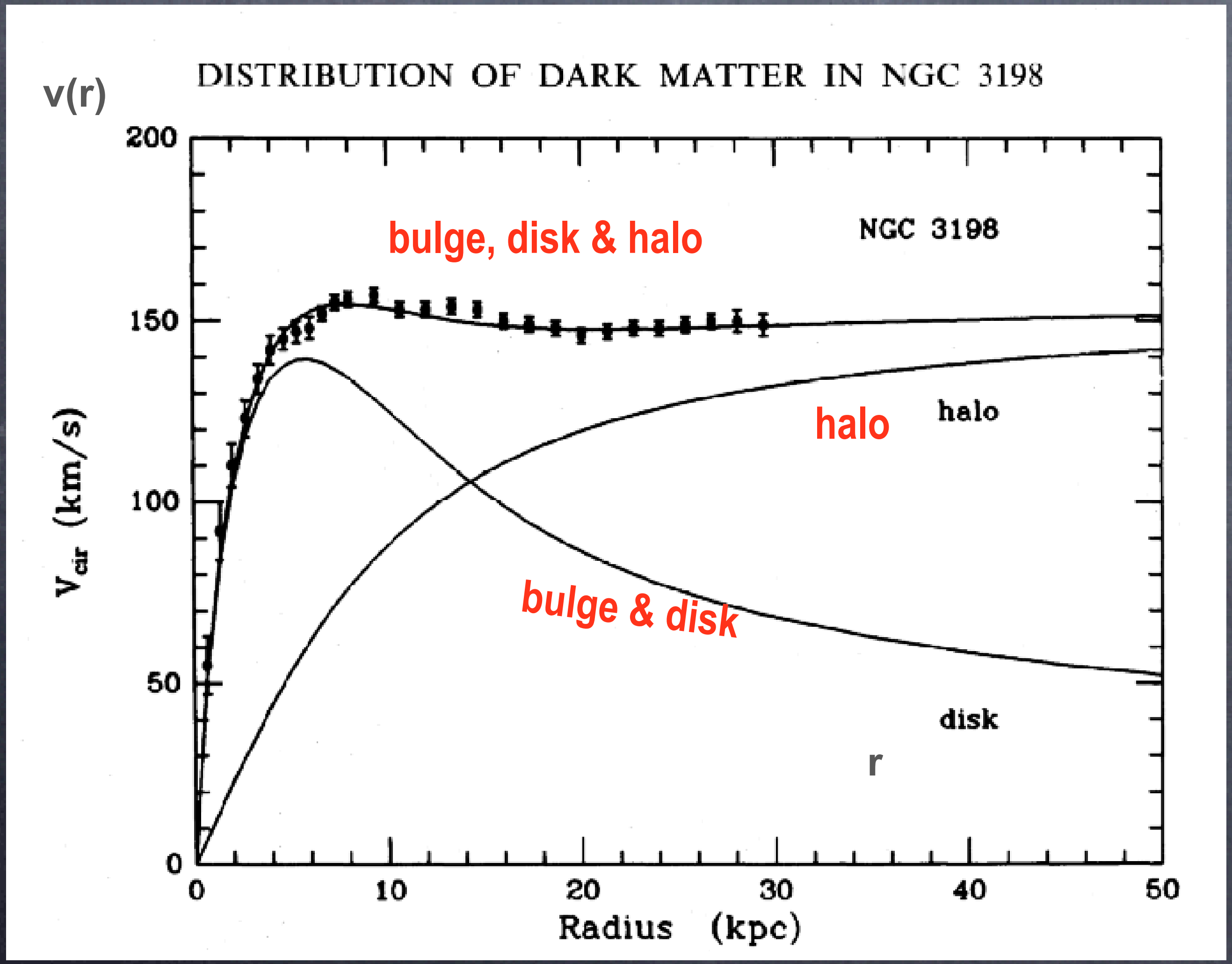
Star in central region: **M~r^3 => v∝r** Star outside: **M~ct => v∝1/√r**

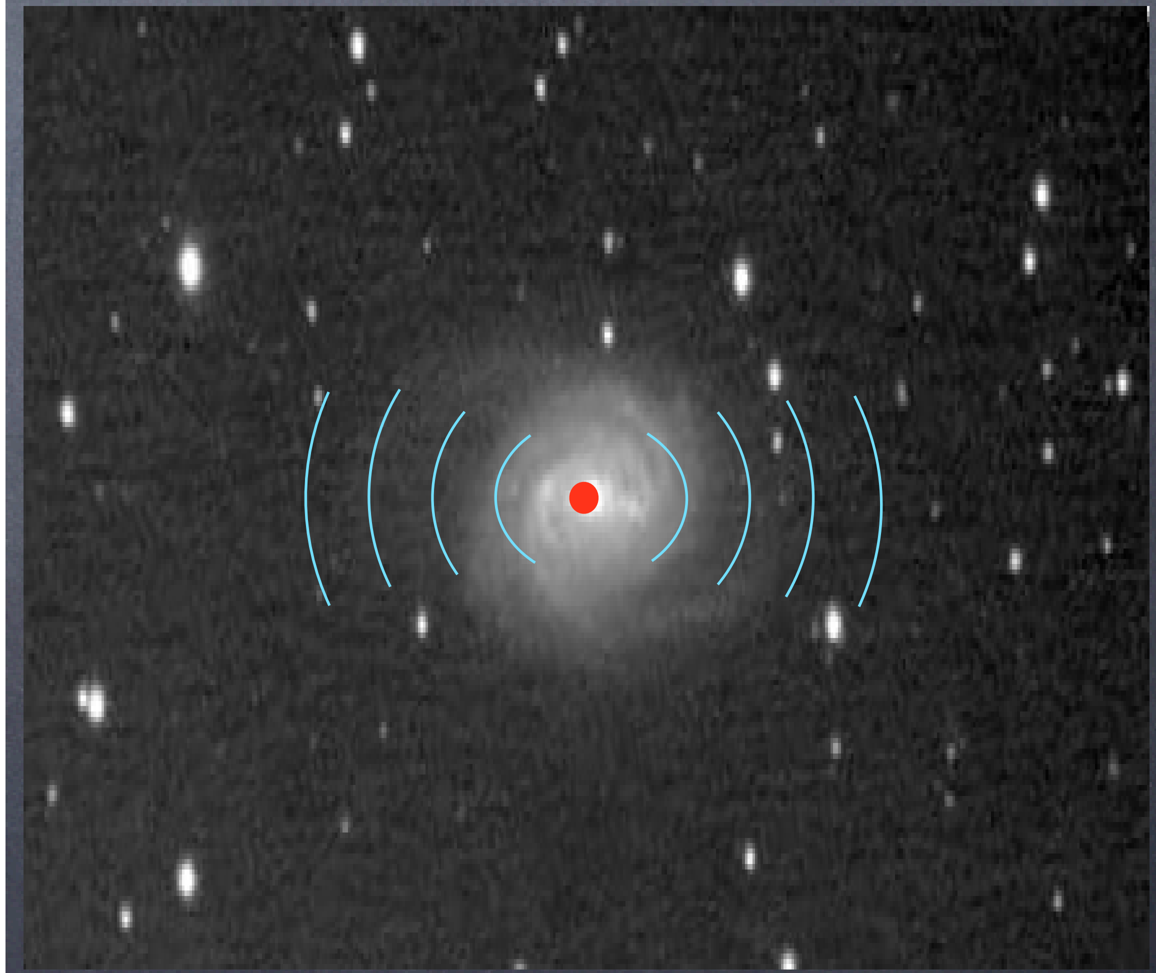


Dark Matter in Galaxies

Observations of interstellar gas a large radii => the rotation velocity is constant!

=> about 10 x more matter than can be directly seen ($\Omega_{Halo} \cong 0.1$)



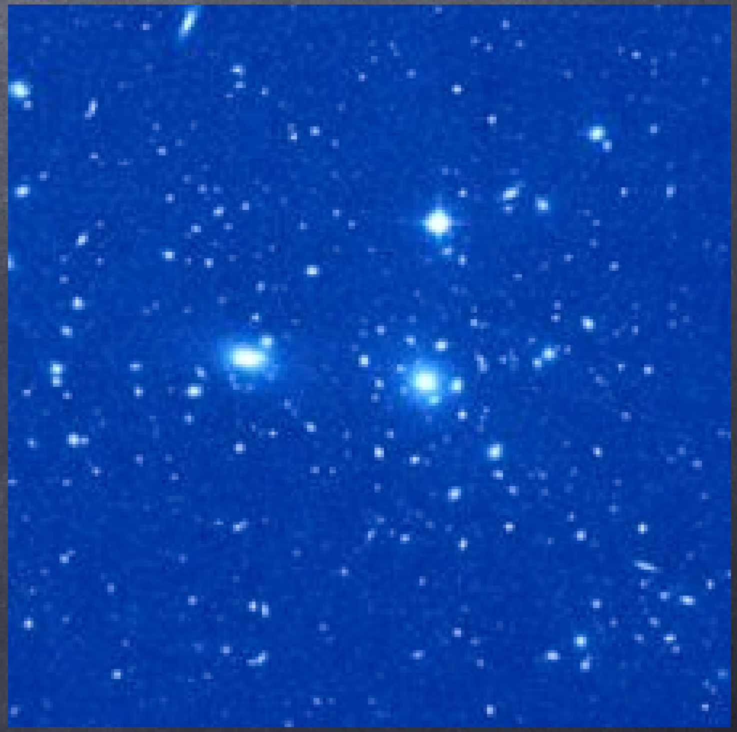


Dark Matter in Clusters

First observations - Fritz Zwicky 1933: measurements of the velocity dispersion of galaxies in the Coma cluster

-> by applying the virial theorem

$$M \approx \frac{2\langle r\rangle\langle v^2\rangle}{G}$$



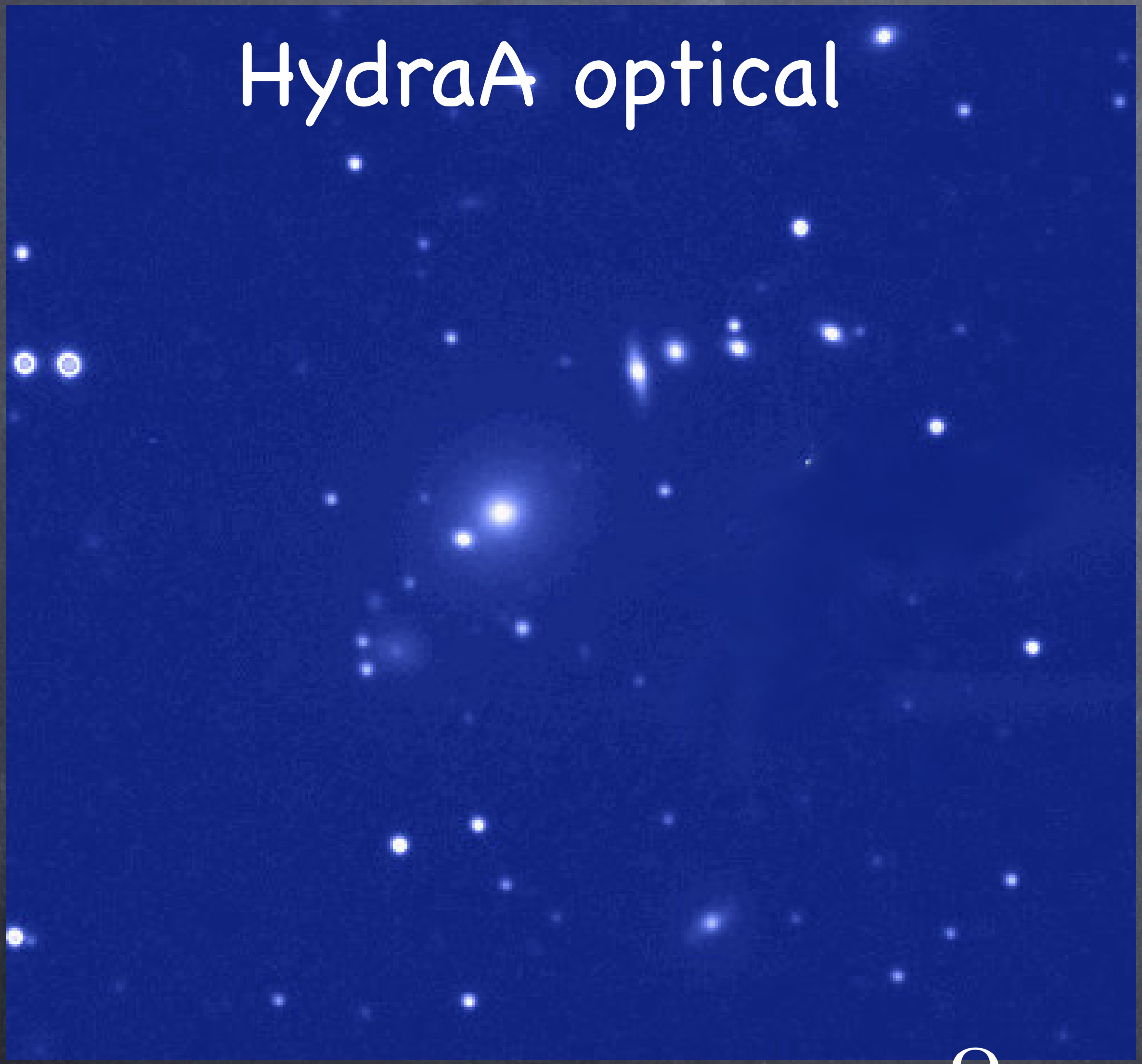
-> by measuring r and v $\Longrightarrow M$

For the Coma cluster:

$$\frac{M}{L} \approx 300 \frac{M_\odot}{L_\odot}$$

Dark Matter in Clusters

study of X-ray emission tracing the distribution of hot intra-cluster gas

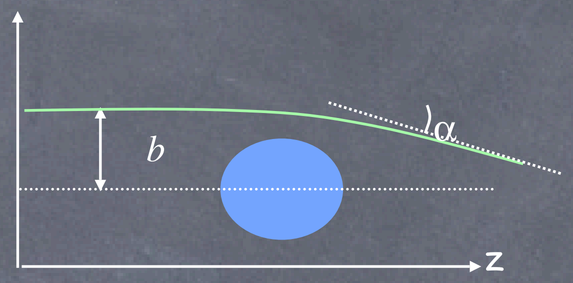


From Chandra observations:

$$\frac{\Omega_B}{\Omega_M} \simeq 0.065 h^{-3/2}$$

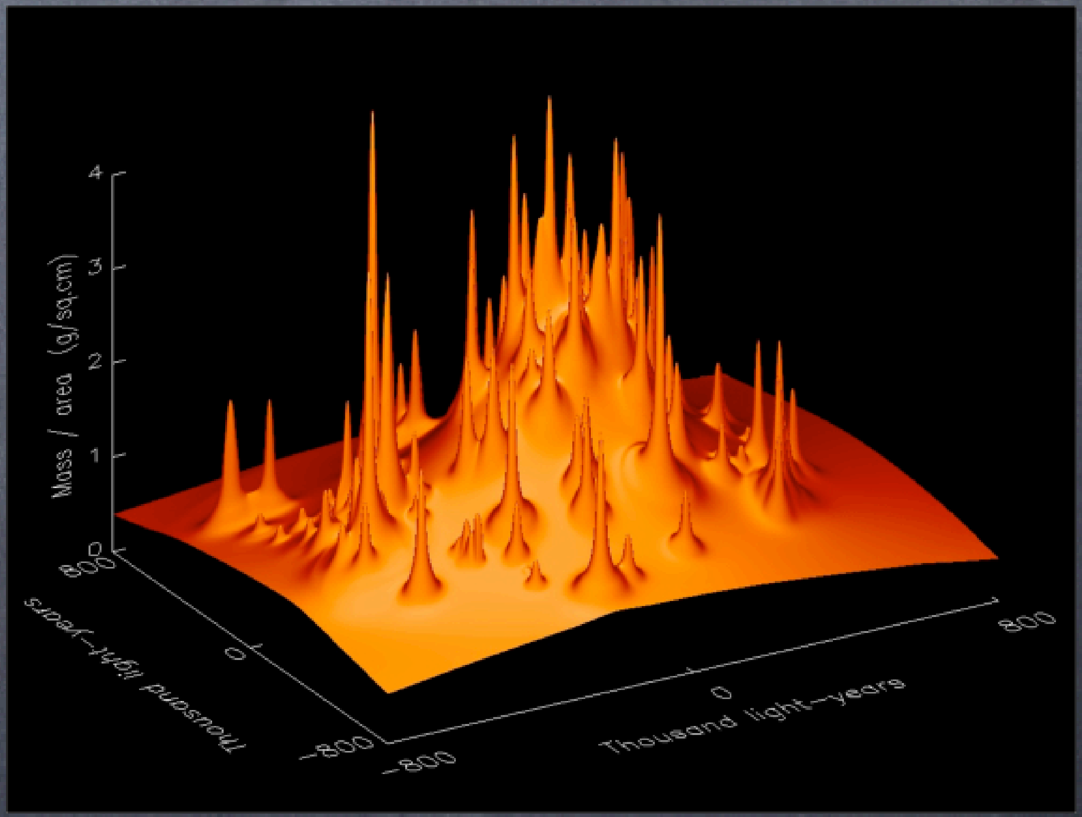
$$\Omega_M \simeq 0.3 h^{-1/2} \simeq 0.35$$

Dark Matter in Clusters



Gravitational lensing: light propagates along geodesics which deviate from straight lines when passing near intense grav fields => the distortion of images of background objects due to the grav mass of a cluster can be used to infer the mass of the cluster

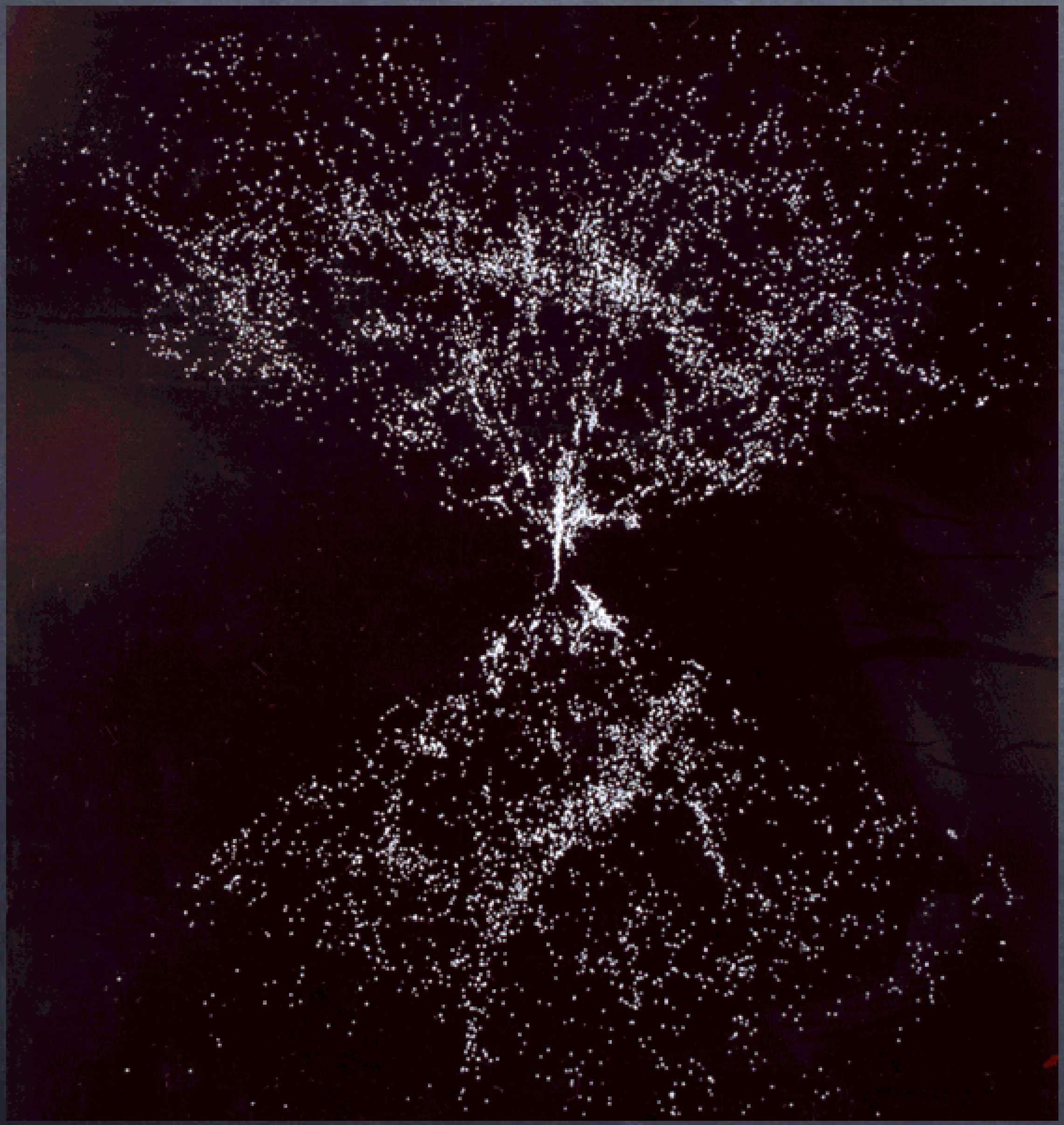
HST picture (1994)



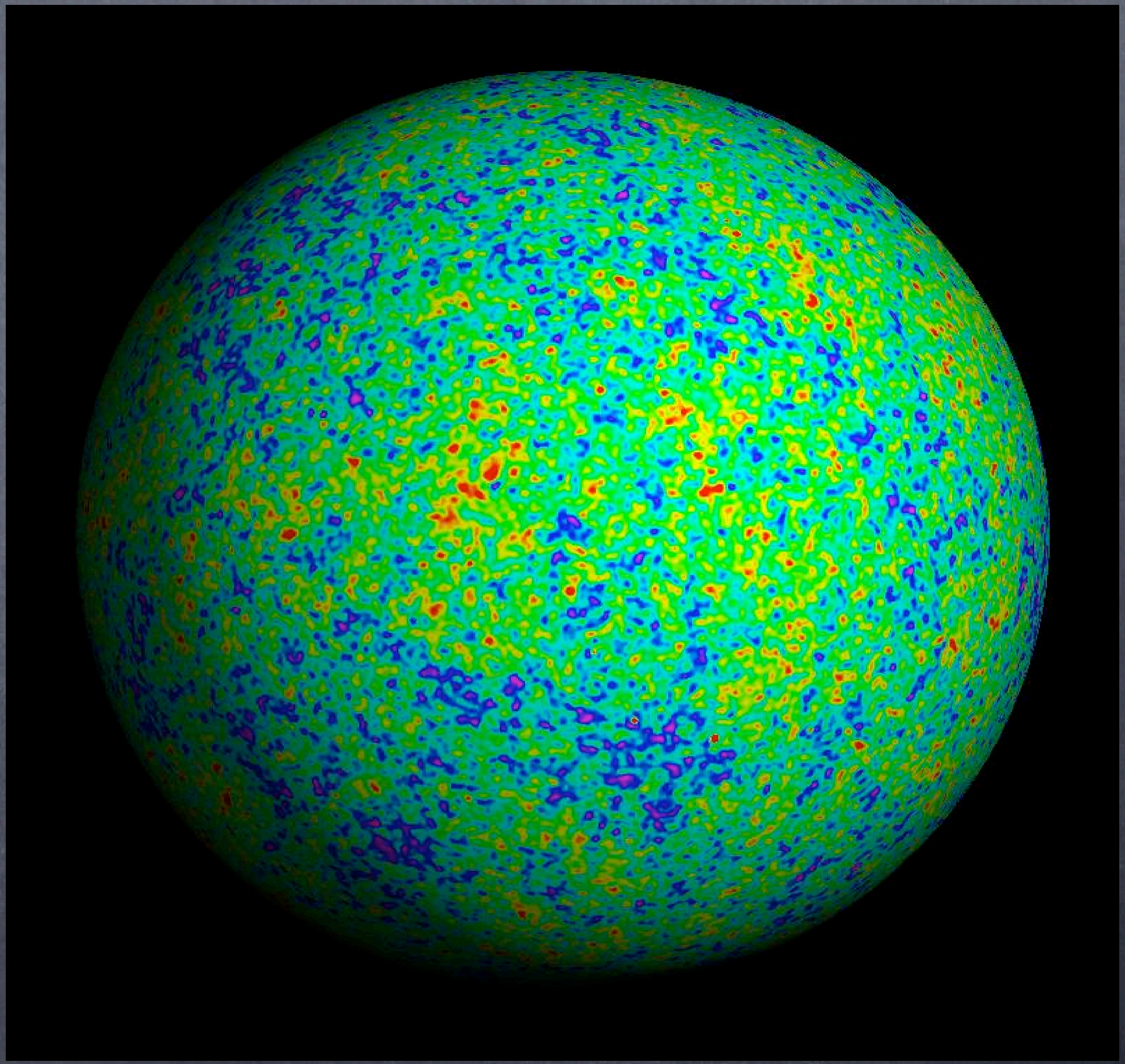
(Dark Matter) Mass reconstruction

Cosmological Scales

CfA survey of LSS
(each point = 1 galaxy)

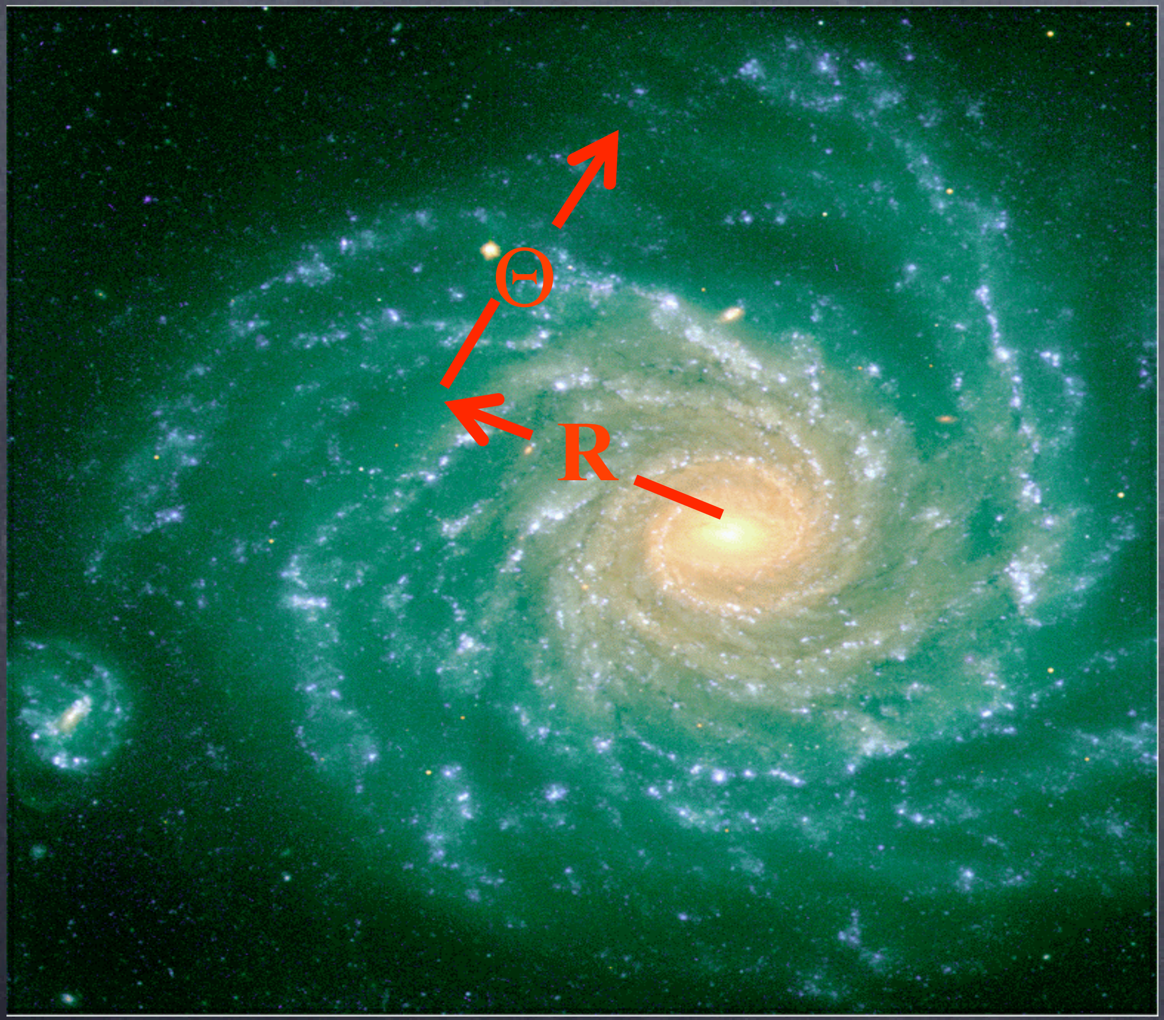


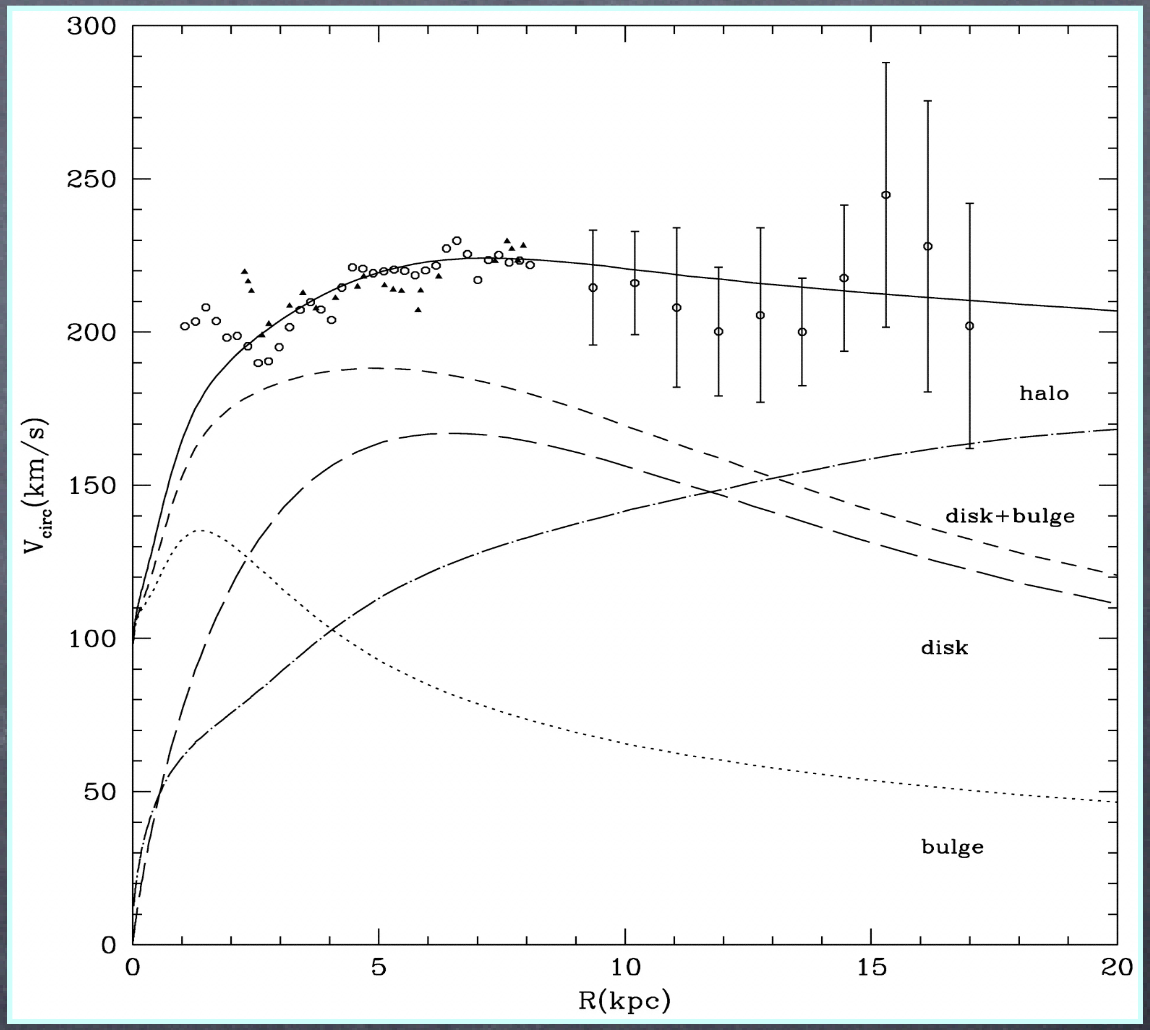
WMAP picture of the CMB sky



Local Dark Matter Density

Measured rotation curve of the Milky Way: flat out to ≈ 50 kpc





Acceptable range:
$\rho_0 = 0.2 - 0.8$ GeV/cm^3

(Klypin, Zhao & Somerville 2002)

Motivation from Particle Physics

Standard Model extremely successful … but incomplete!

Neutrinos change flavor -> are massive!

Hierarchy problem: 10^3 GeV << 10^{19} GeV

-> we expect new physics at the weak scale!

Popular extensions:

Supersymmetry (bosons <-> fermions)

LSP (neutralino)

Extra dimensions ($3 + \delta + 1$)

LKP (first KK excitation of the photon)

Cold Thermal Relics

If a massive, weakly interacting particle (WIMP) existed in the early Universe:

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

it was in equilibrium as long as its reaction

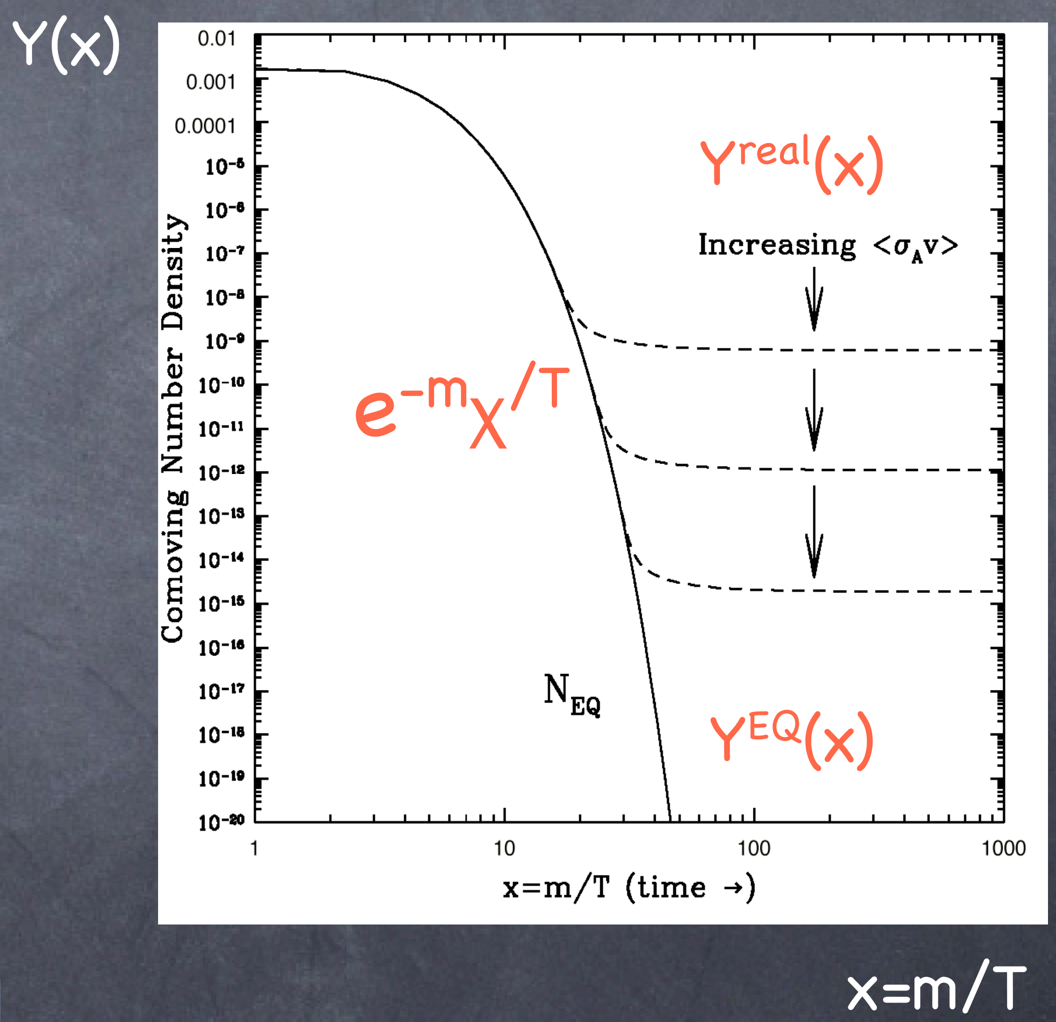
rate $\Gamma = n\sigma v$ was $\Gamma \gg H$

After the reaction rate drops below the

expansion rate H => 'freeze-out' and

we are left with a 'relic' density

$$\Omega_\chi h^2 \approx 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A |v| \rangle}$$



Cold Thermal Relics

$$\Omega_\chi h^2 \approx 3\times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A |v| \rangle}$$

If

$$\Omega_\chi \sim 0.2 \Rightarrow \langle \sigma_A v \rangle \sim 1 \text{ pb}$$

$$\sigma_\text{A} \sim \frac{\alpha^2}{m^2} \Rightarrow m \sim 100 \text{ GeV}$$

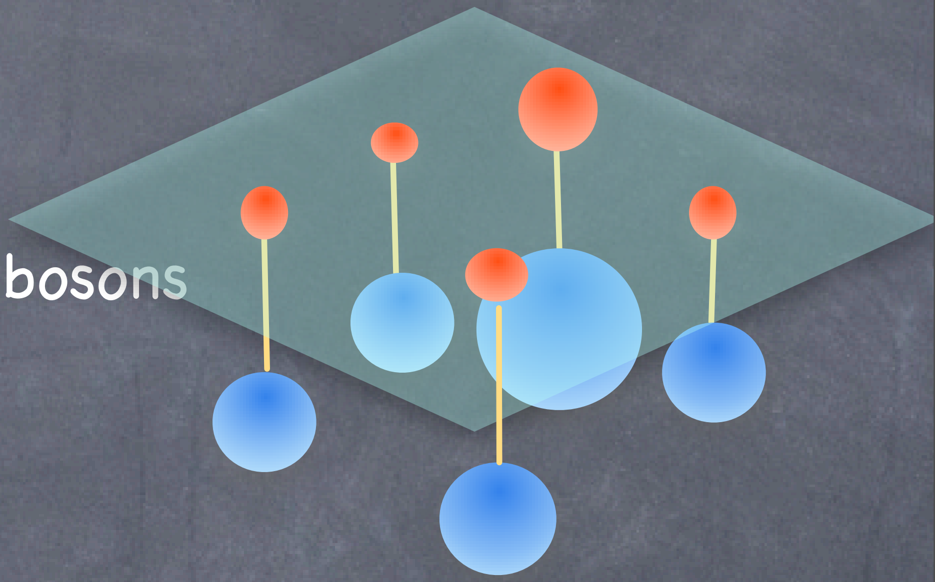
α=hypercharge fine structure constant
m=mass of DM particle

=> the relic density and mass point to the weak scale!

=> the new physics responsible for EWSB likely gives rise to a dark matter candidate (WIMP)

=> such a candidate can be explored in astrophysics experiments and in current + future accelerators

Supersymmetry



New fundamental space-time symmetry: fermions <=> bosons
=> SM particles get superpartners
(differ in spin by 1/2 and same quantum numbers)

To prevent rapid proton decay, a discrete symmetry (R-parity) is imposed

$R = (-1)^{3B+L+2S}$, B = baryon number, L = lepton number, S = spin

R = +1 for SM particles; R = - 1 for SUSY particles

=> Sparticles can only decay into an odd number of sparticles (+SM part.)

=> The lightest sparticle (LSP), R=-1, is stable and naturally becomes a dark matter candidate

$$\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0$$

Universal Extra Dimensions

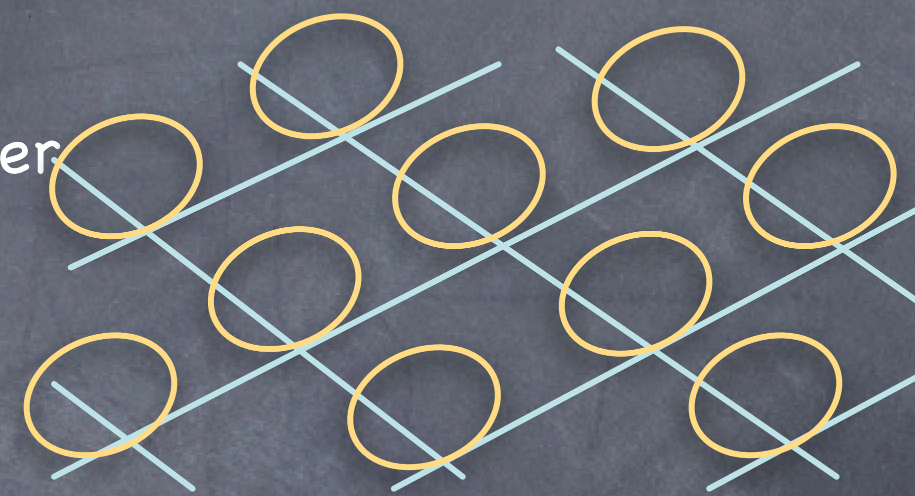
Appelquist, Cheng , Dobrescu, Phys.Rev. D64 (2001) 035002

All SM particles propagate into flat ED ($R^{-1} \sim$ TeV)

=> for each SM particle -> infinite tower of partner

states with the same quantum numbers

(n^2/R^2, n=0 are SM particles)

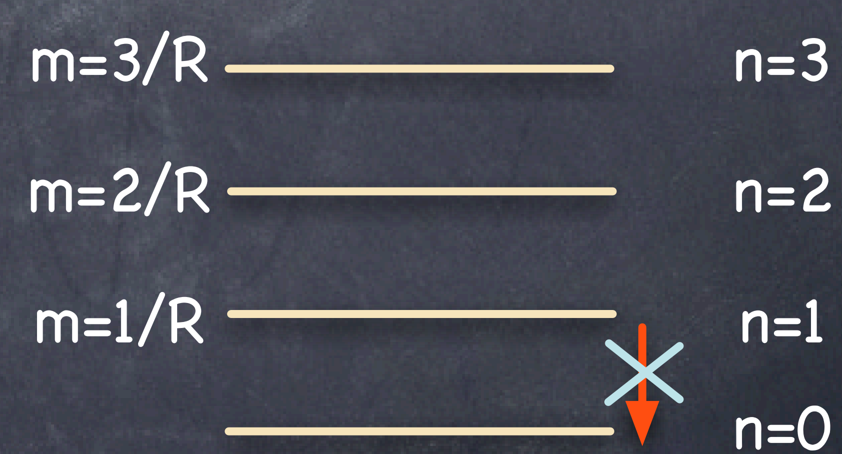


Translational invariance along the 5th dimension

=> discrete symmetry called Kaluza-Klein parity $P_{KK}=(-1)^n$

=> the lightest KK-mode is stable

=> the LKP excellent dark matter candidate



WIMPs:

10^6 per second through your thumb without being noticed!

10^{15} through a human body each day: only < 10 will interact, the rest is passing through unaffected!

If their interaction is so weak, how can we detect them?

Make them in Accelerators

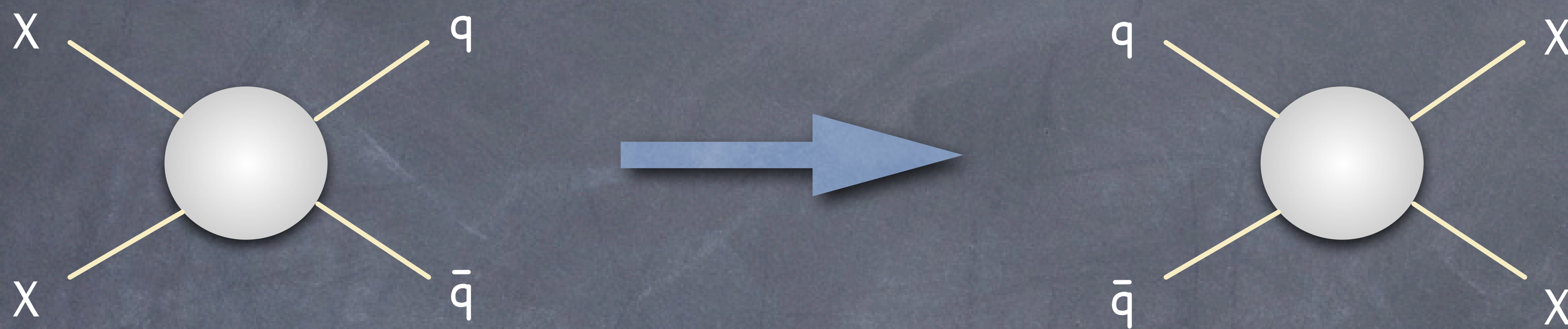
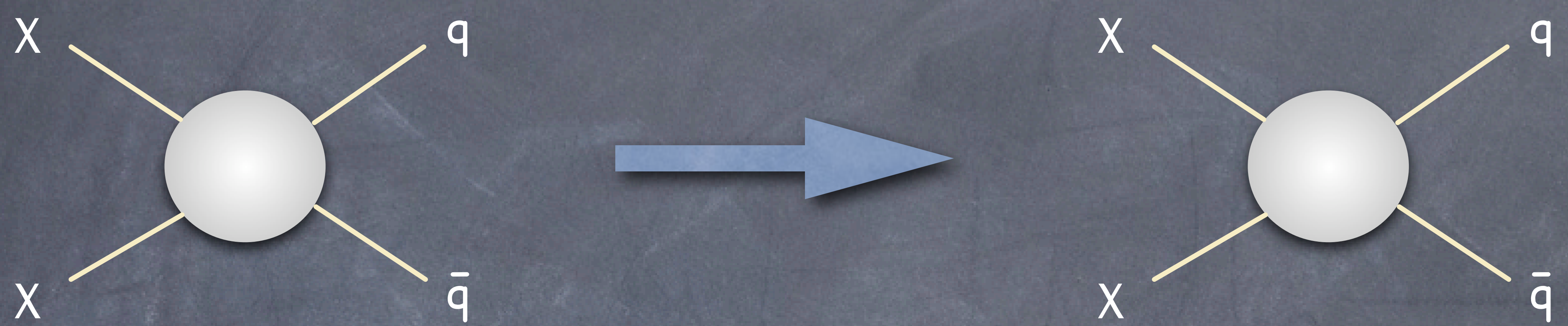
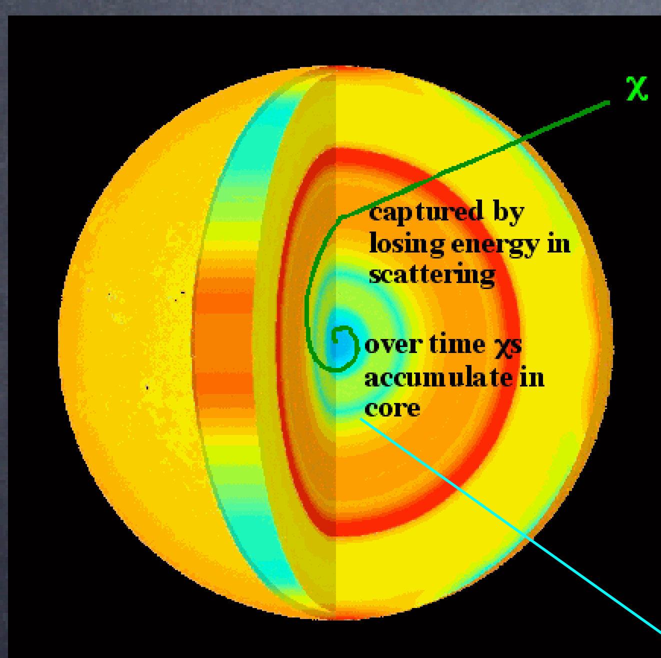
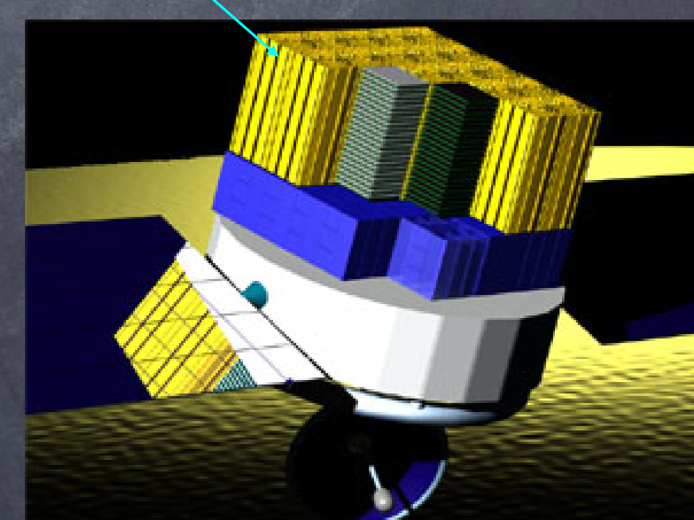


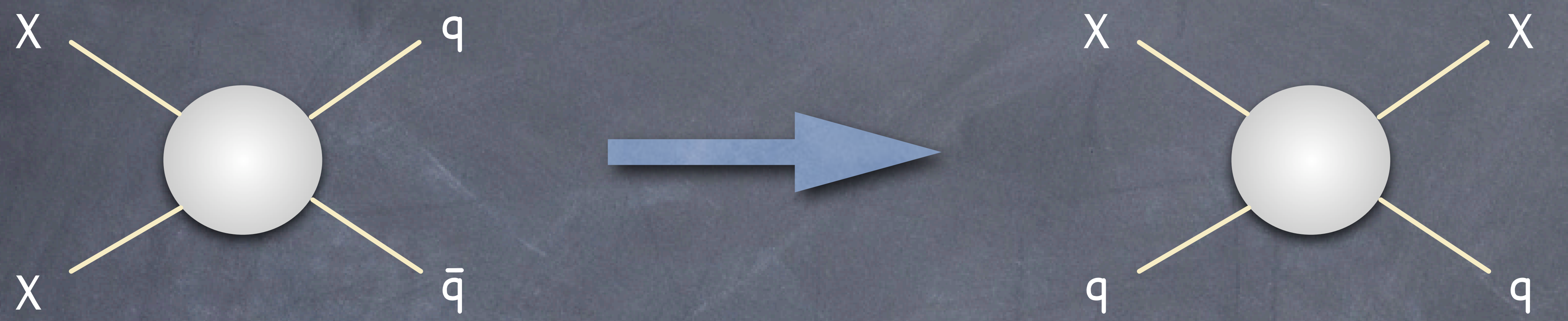
Image the Sun's Core, the Galactic Halo or Center

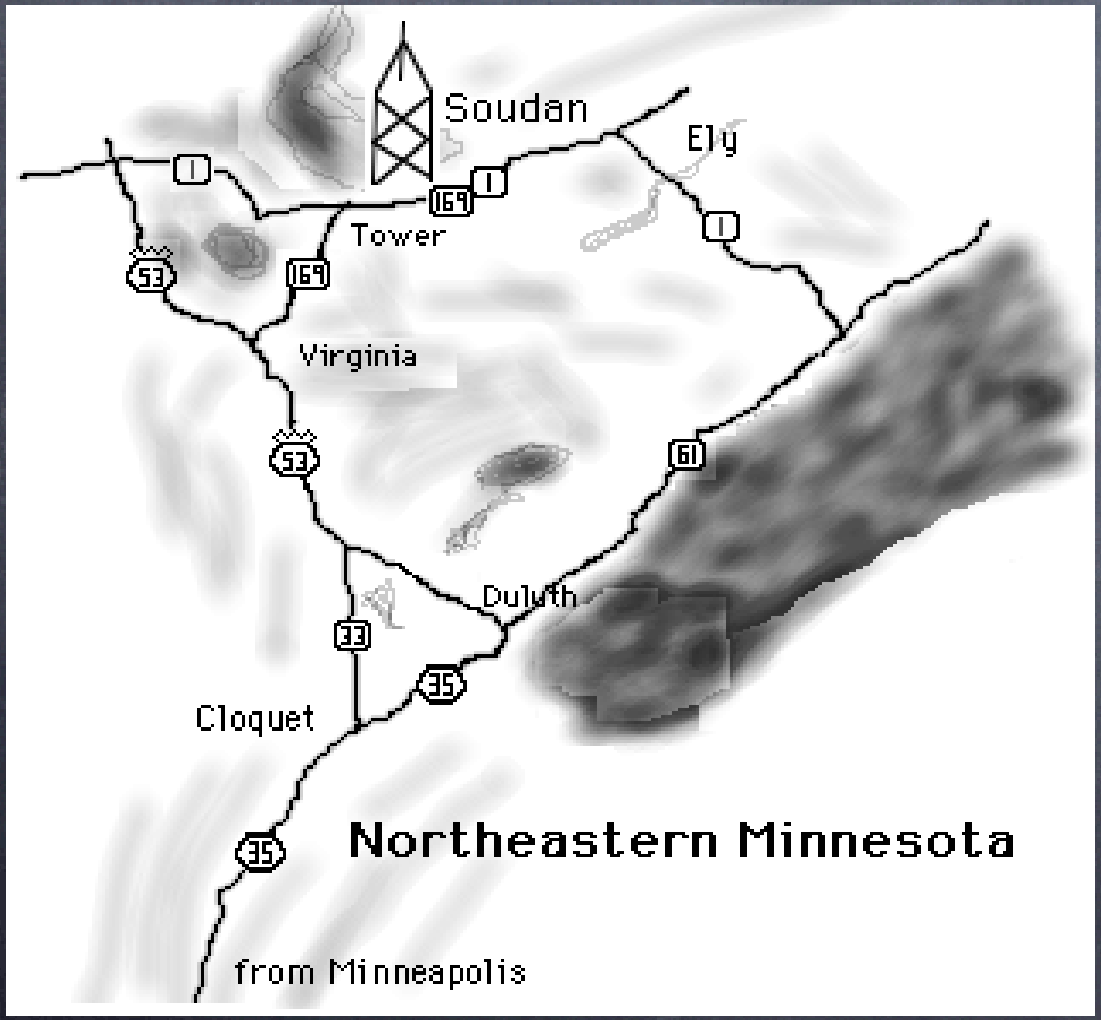




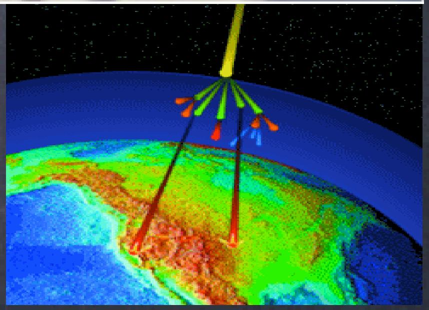


Or go to Minnesota



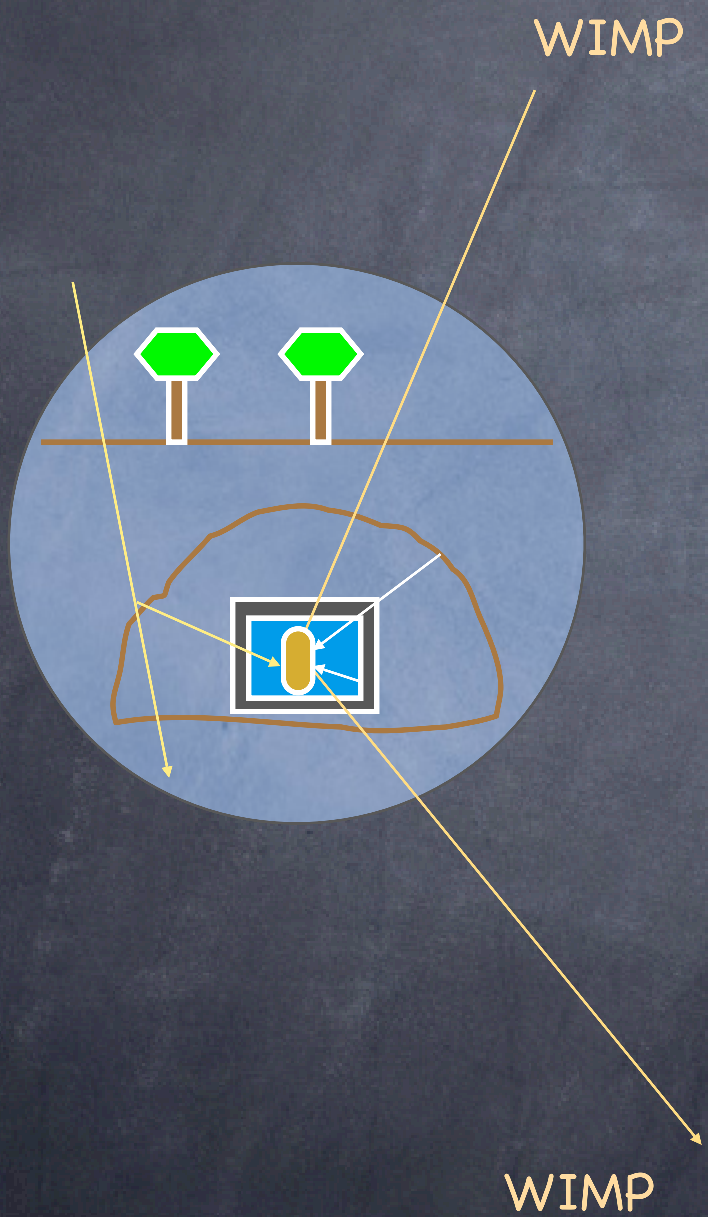


deep down an old iron mine…



… to get rid of
COSMIC RAYS

Direct WIMP Detection



Every liter if space:

10-100 WIMPs moving with $10^{-3}c$

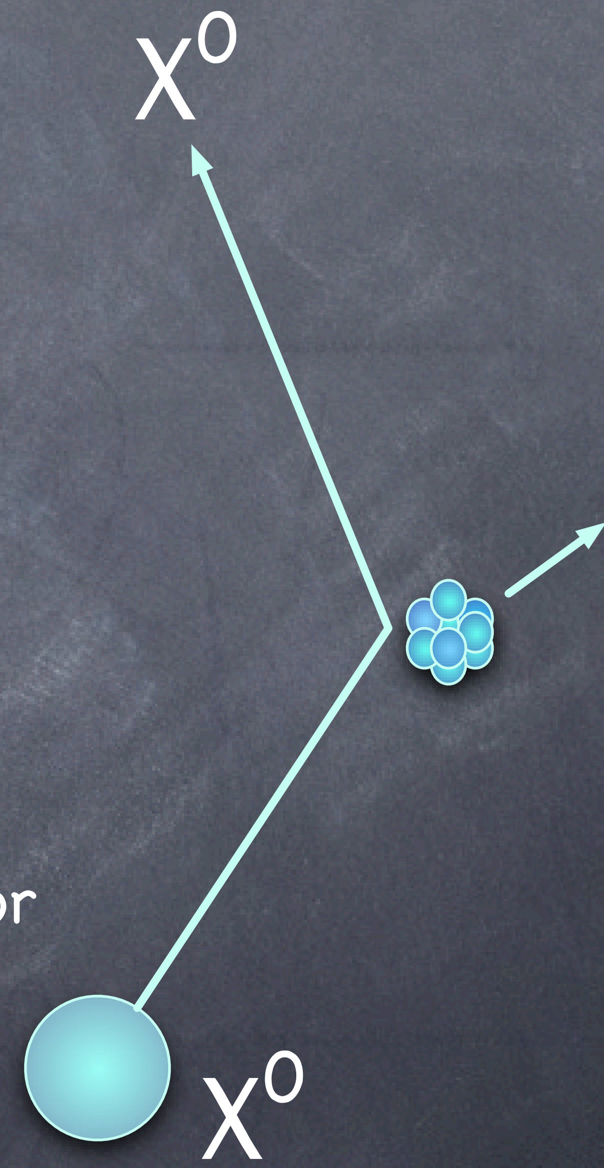
WIMPs scatter with nuclei:

$$\text{Rate} \sim N\, \rho_X / m_X \, \langle \sigma_{X\text{-}N} \rangle$$

N = number of target nuclei in detector

ρ_X = local WIMP density

$\langle \sigma_{X\text{-}N} \rangle$ = scattering cross section



Direct WIMP Detection

Elastic scattering: extreme NR limit

⇒ spin-spin interaction (coupling to the spin)

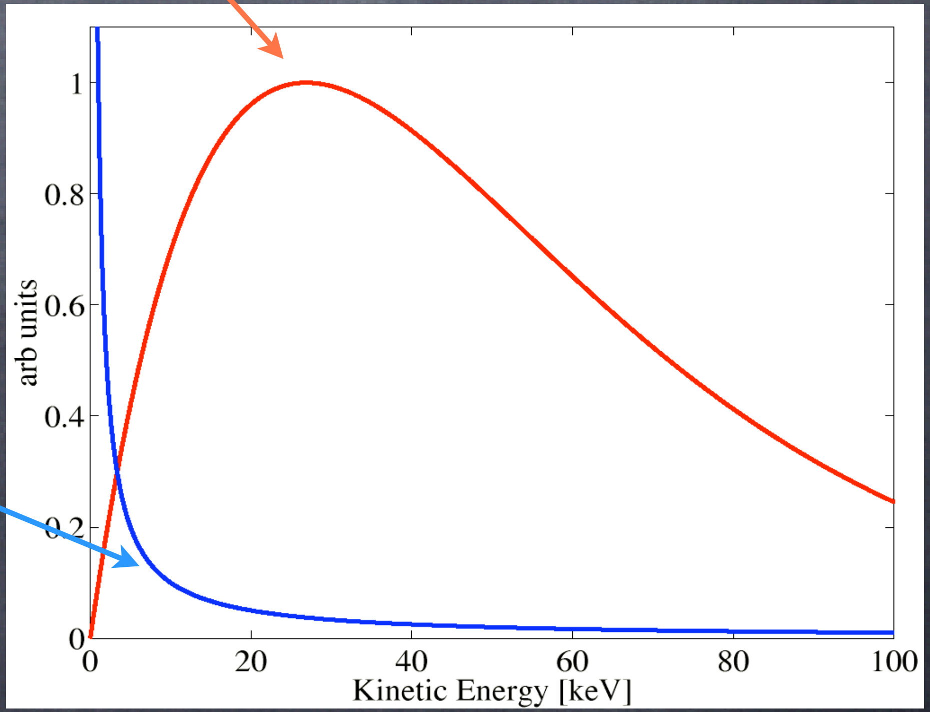
⇒ scalar interaction (coupling to the mass of the nucleus)

$$f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$

Event rate: depends on local WIMP

density and nucleus:

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi \mu^2} \exp\left(-\frac{Q m_N}{2\mu^2 v_0^2}\right) F^2(Q)$$

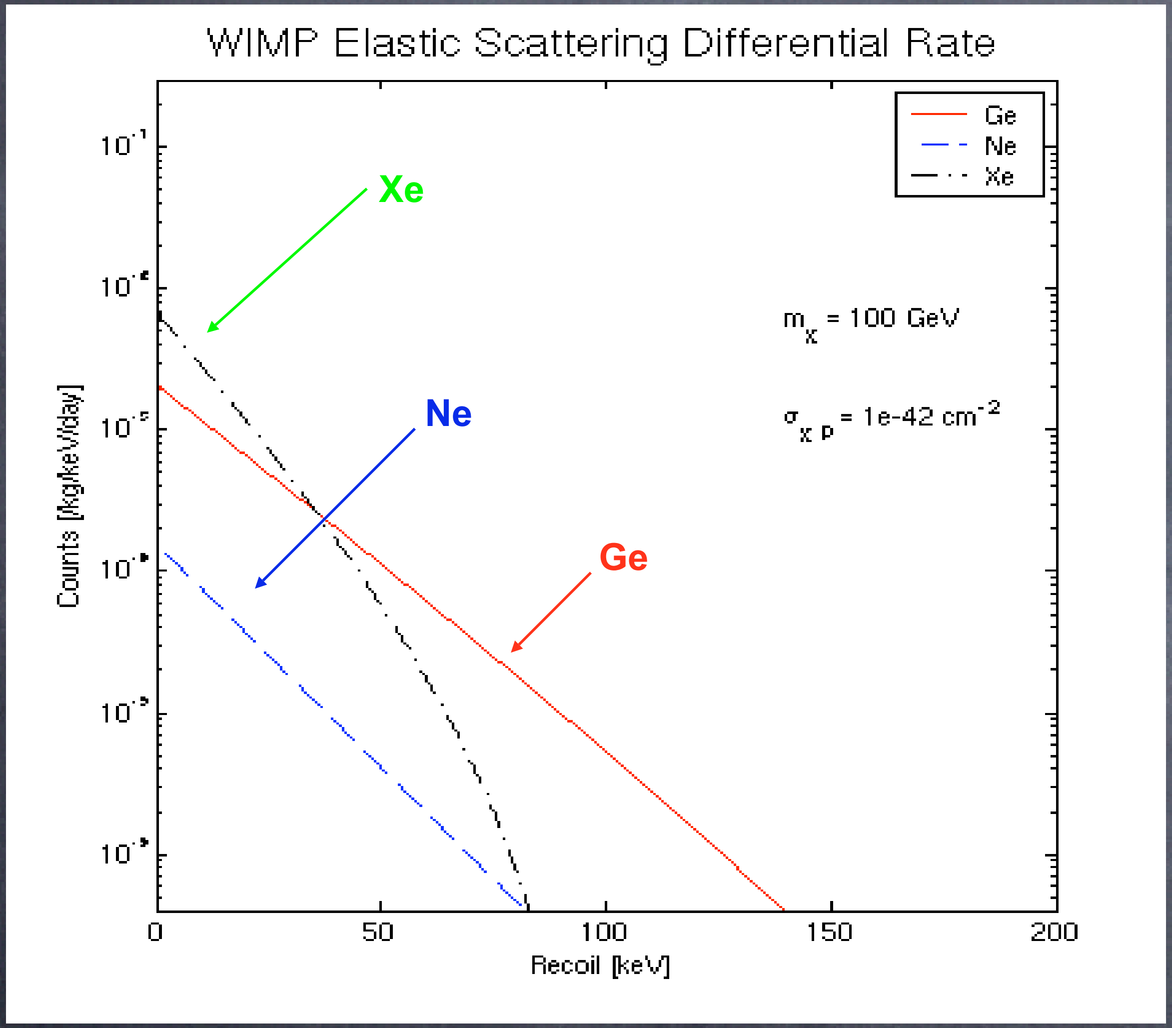


$$Q = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$

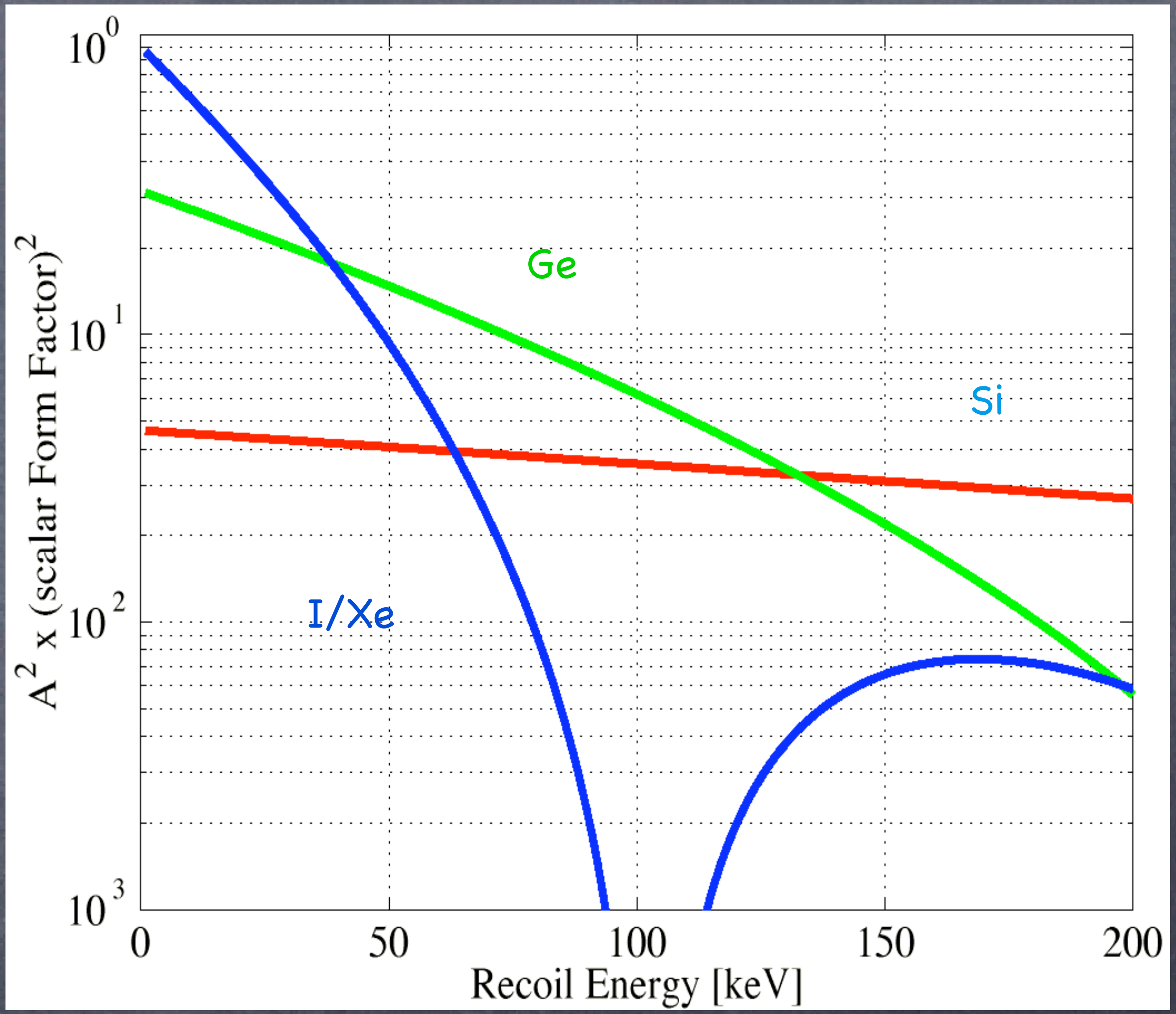
≤ 100 keV

Direct WIMP Detection

Differential rate



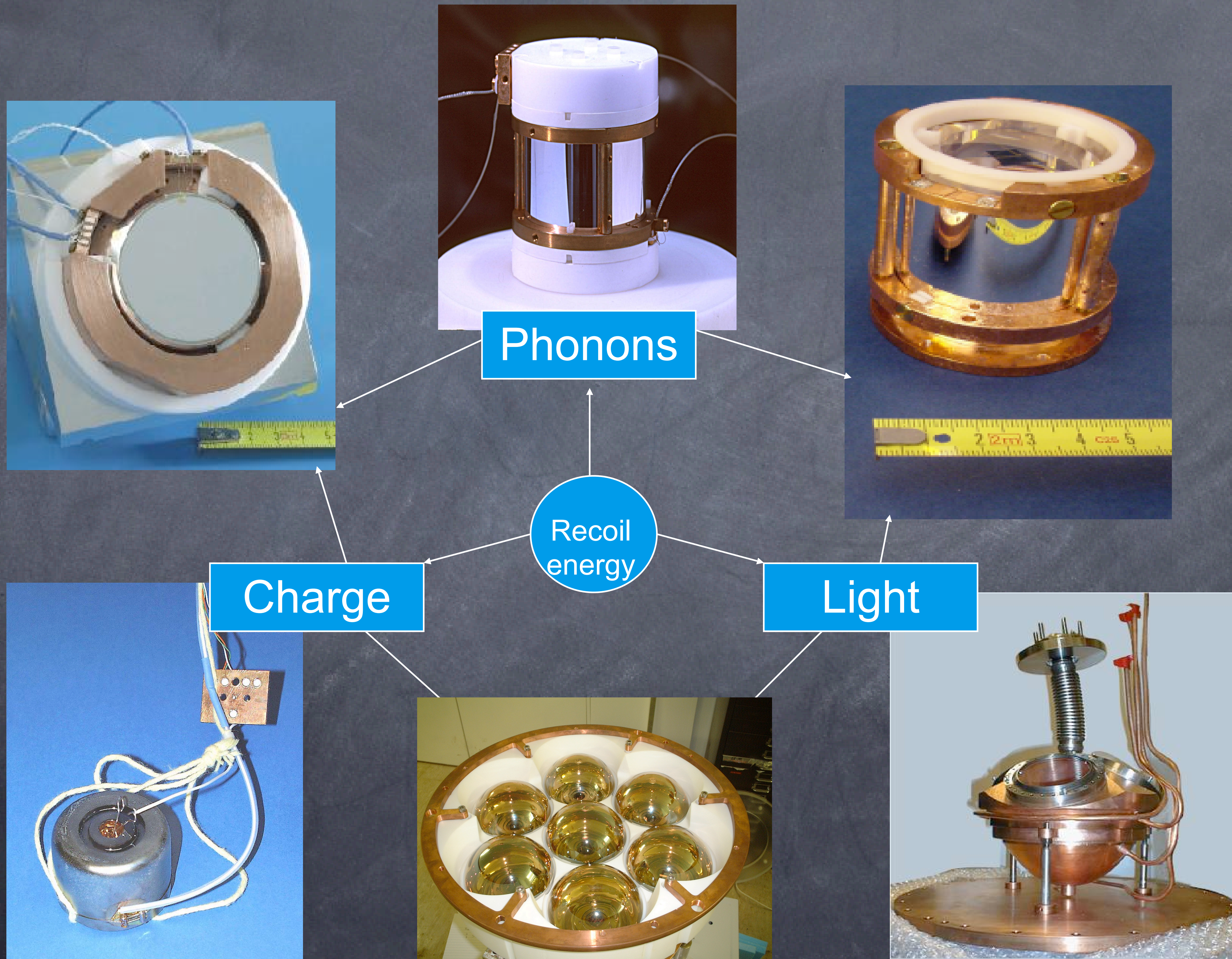
A^2 x Form Factor



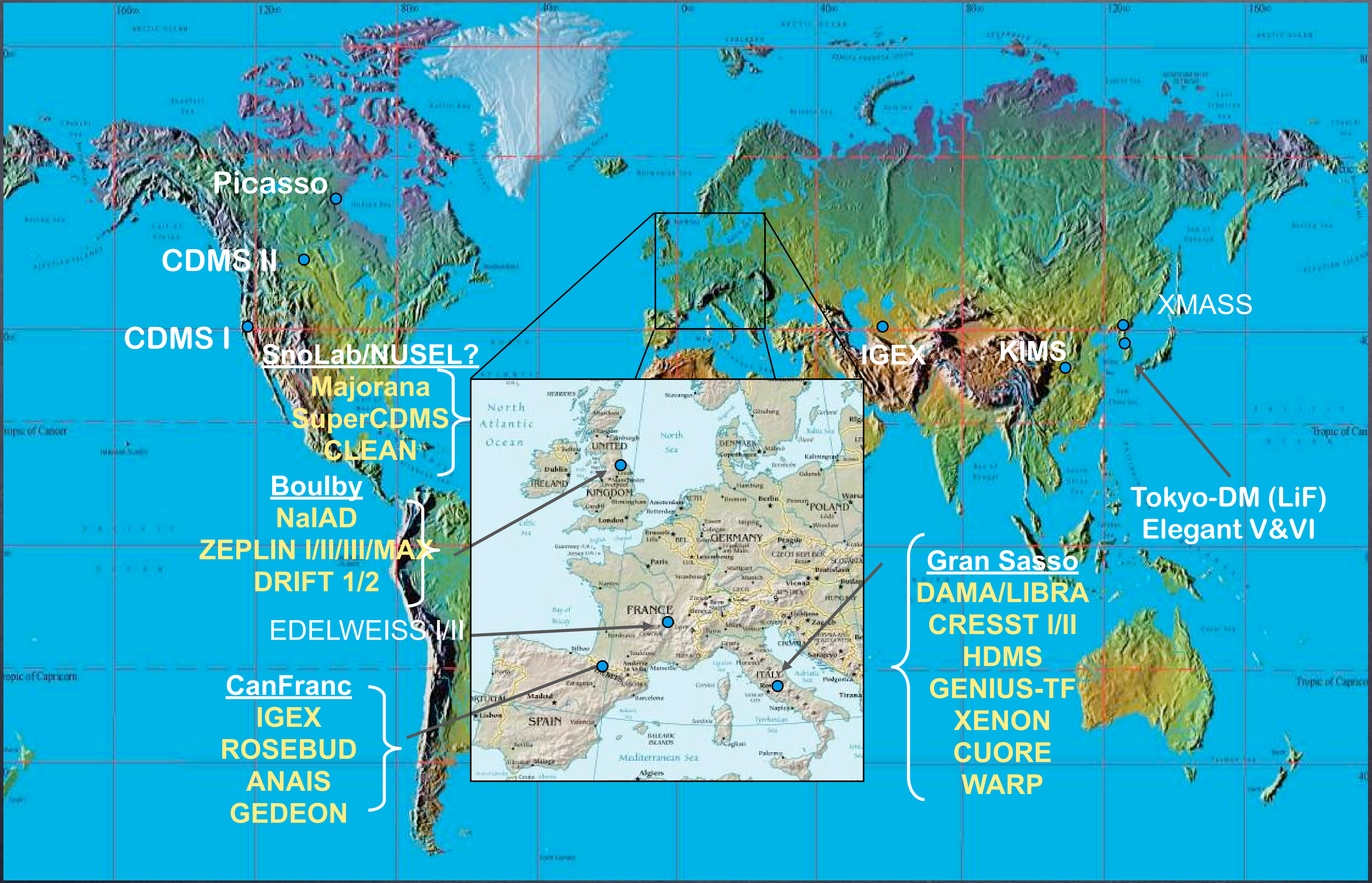
The form factor is the Fourier transform of the nucleon density (or of the 'scattering centers')

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

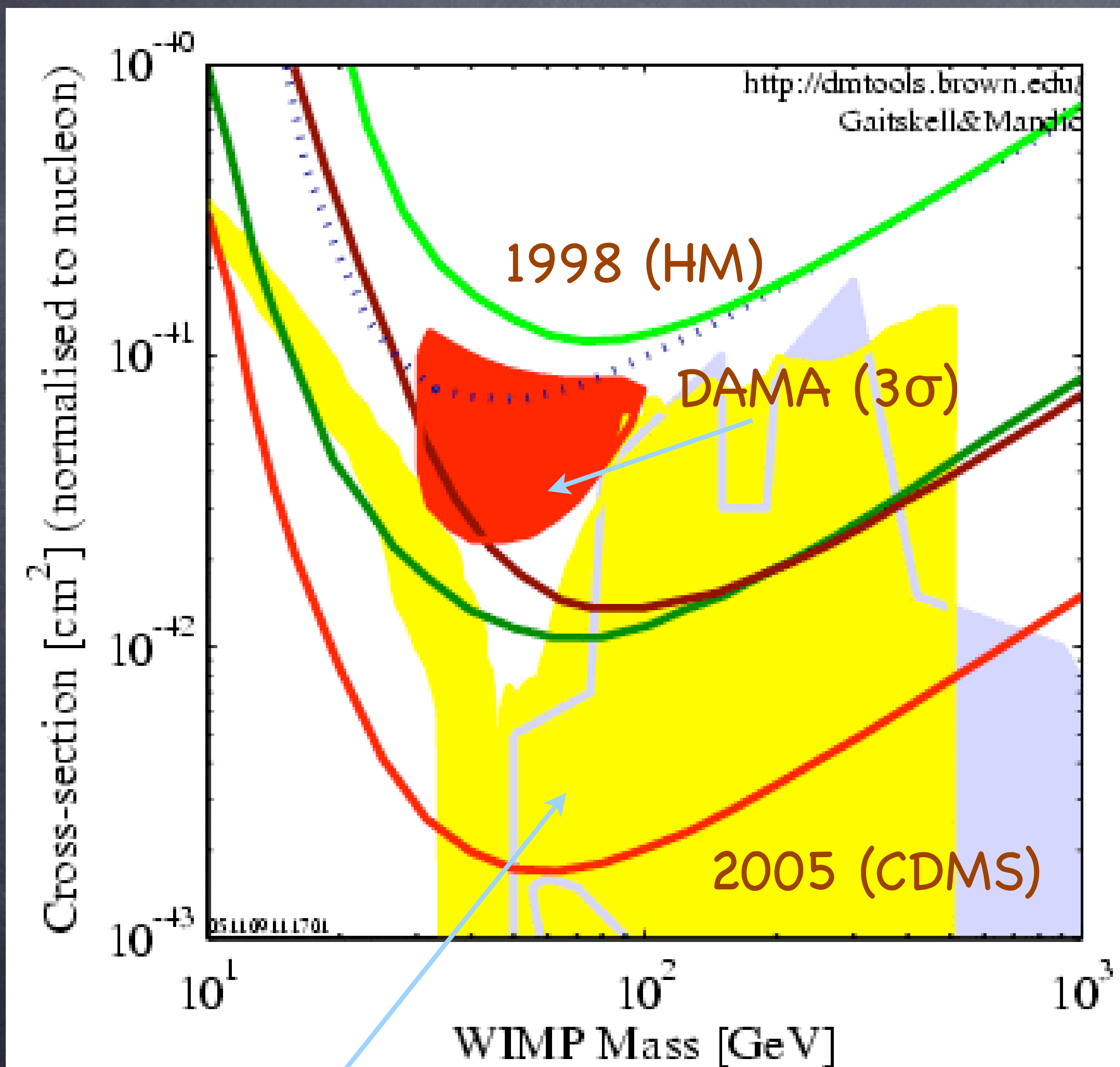
Direct detection techniques



World Wide WIMP Search



Where Do We Stand?



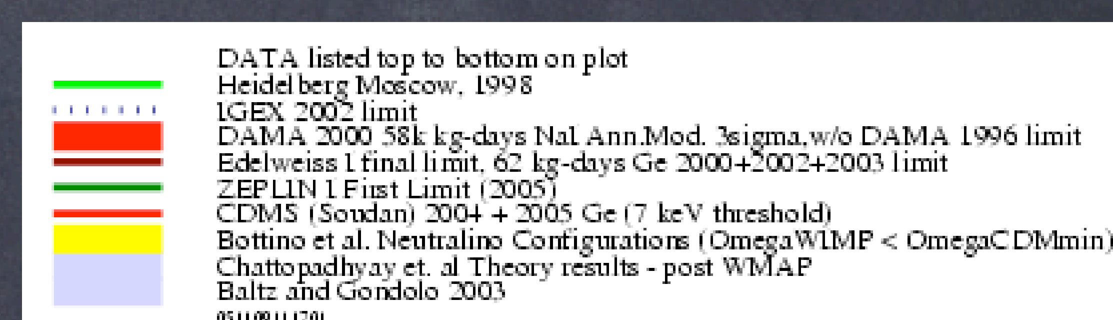
SUSY models

Current:
< 0.2 event/kg/day
or 2×10^{-7} pb (2×10^{-43} cm^2)

Most advanced experiments are testing the predicted SUSY parameter space

One evidence for a positive WIMP signal

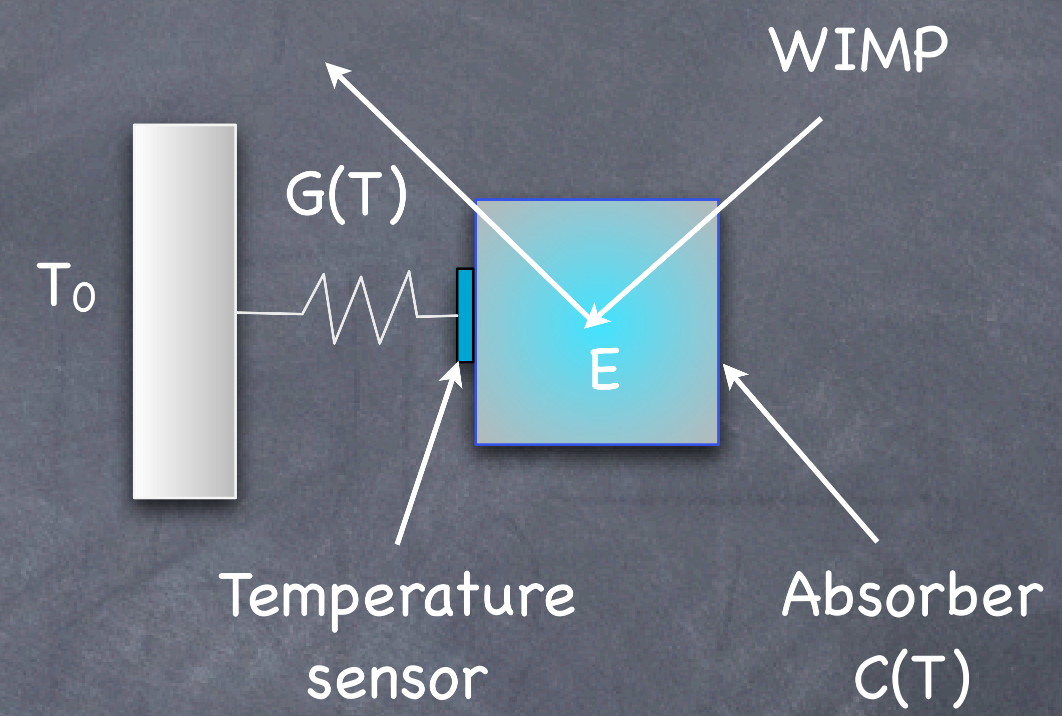
Not confirmed by other experiments



Cryogenic Experiments

Phonon mediated detectors:

detect thermal or fast phonons, after a WIMP interact in an absorber



A deposited energy => T-rise of absorber:

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}, \qquad \tau = \frac{C(T)}{G(T)}$$

C(T) = heat capacity

G(T)=thermal conductance link between the absorber and the reservoir at T_0

=> for pure dielectric crystals and superconductors at $T \ll T_c$:

$$C(T) \sim \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3 JK^{-1}$$

m = absorber mass, M = molecular weight

Θ_D = Debye temperature

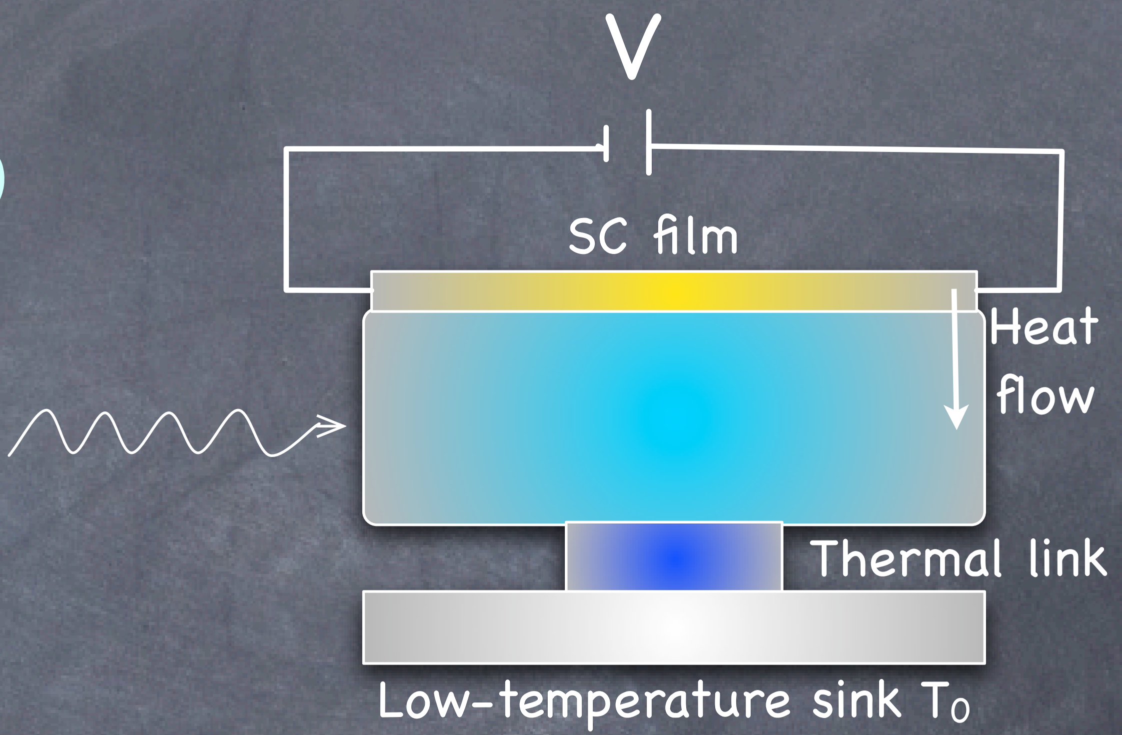
=> the lower the T, the larger ΔT per unit of absorbed energy

Transition Edge Sensors with Electrothermal Feedback

$T_0 \ll T_C$; V_B is placed across the film (TES)

=> equilibrium: when ohmic heating

balanced by heat flow into the absorber



When an excitation reaches the TES

=> R increases => I decreases by ΔI => P decreases

=> feedback signal = change in Joule power heating the film ($P=IV_B=V_B^2/R$)

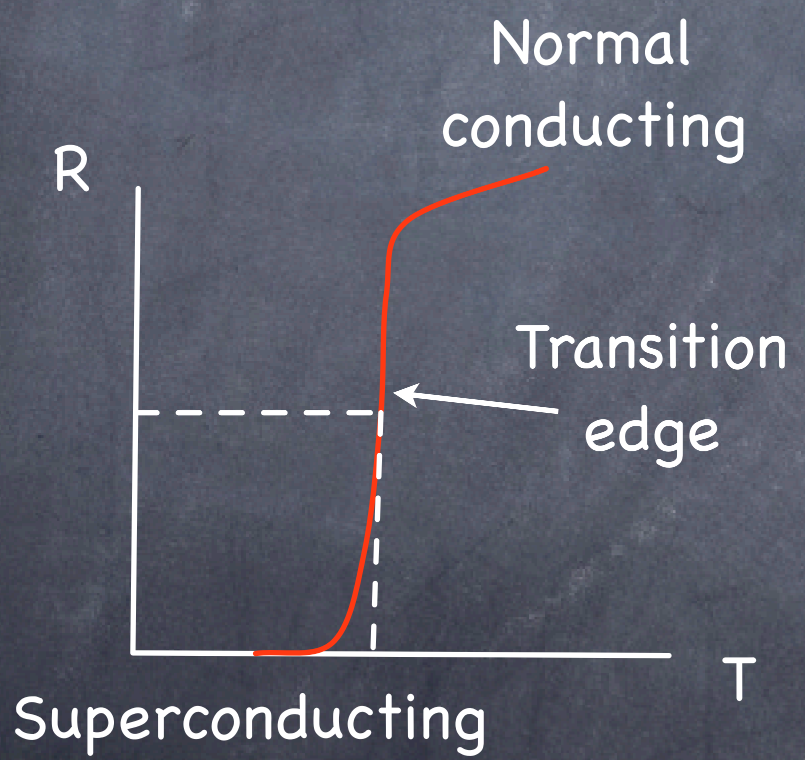
The deposited energy:

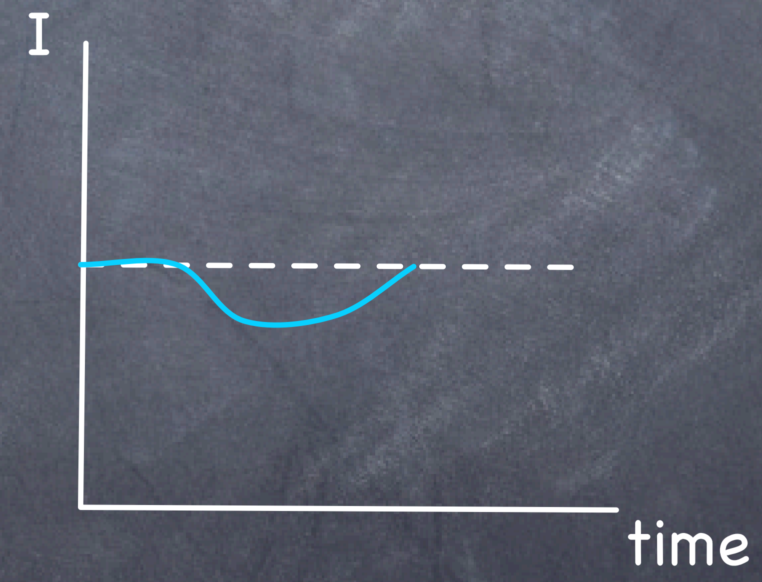
$$E = -V_B \int \Delta I(t)\,\mathrm{d}t$$

Transition Edge Sensors with Electrothermal Feedback

By choosing the voltage and the film resistivity properly

=> stable operating T on the steep portion of the transition edge





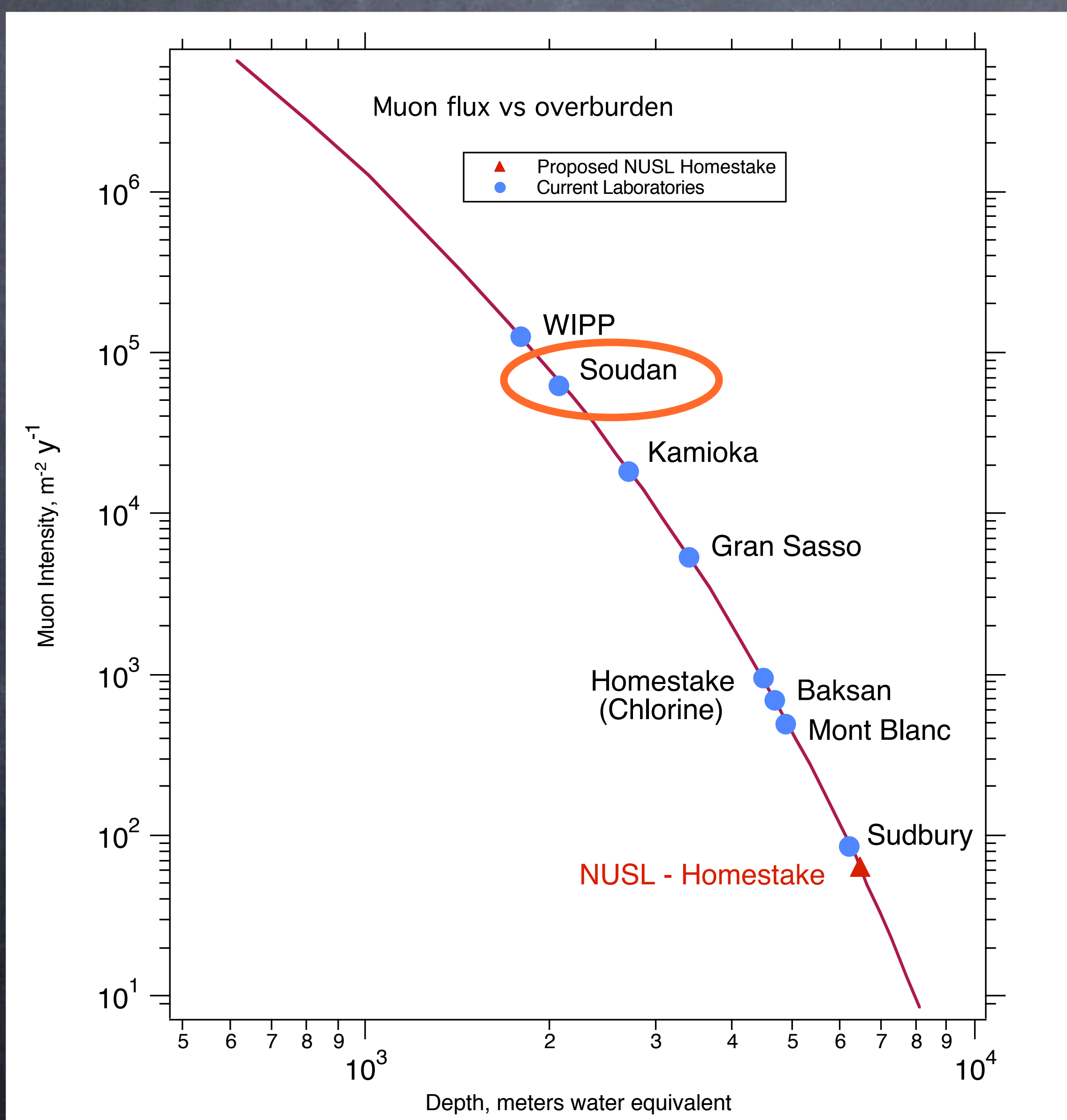
ET-feedback: leads to a thermal response time 10^2 faster than the thermal relaxation time + a large variety of absorbers can be used

The CDMS Experiment

At the Soudan lab in Minnesota, about 2090 mwe.

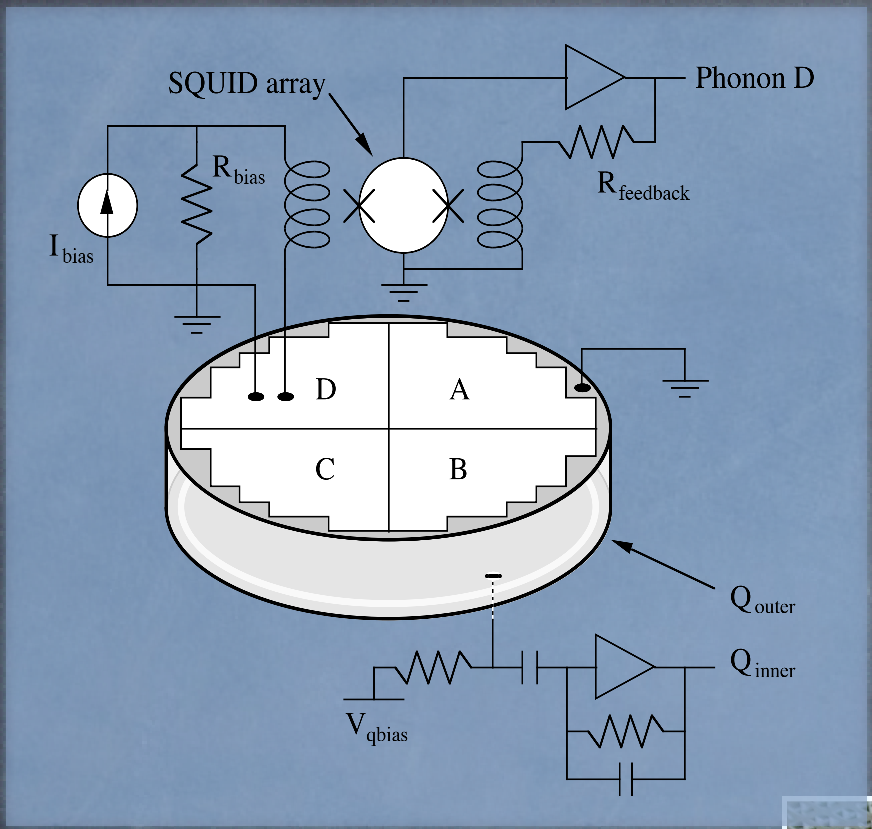
Neutron background reduced from 1/kg/day to 1/kg/year.

Muon Intensity [$m^{-2}y^{-1}$]



Depth [meters water equivalent]

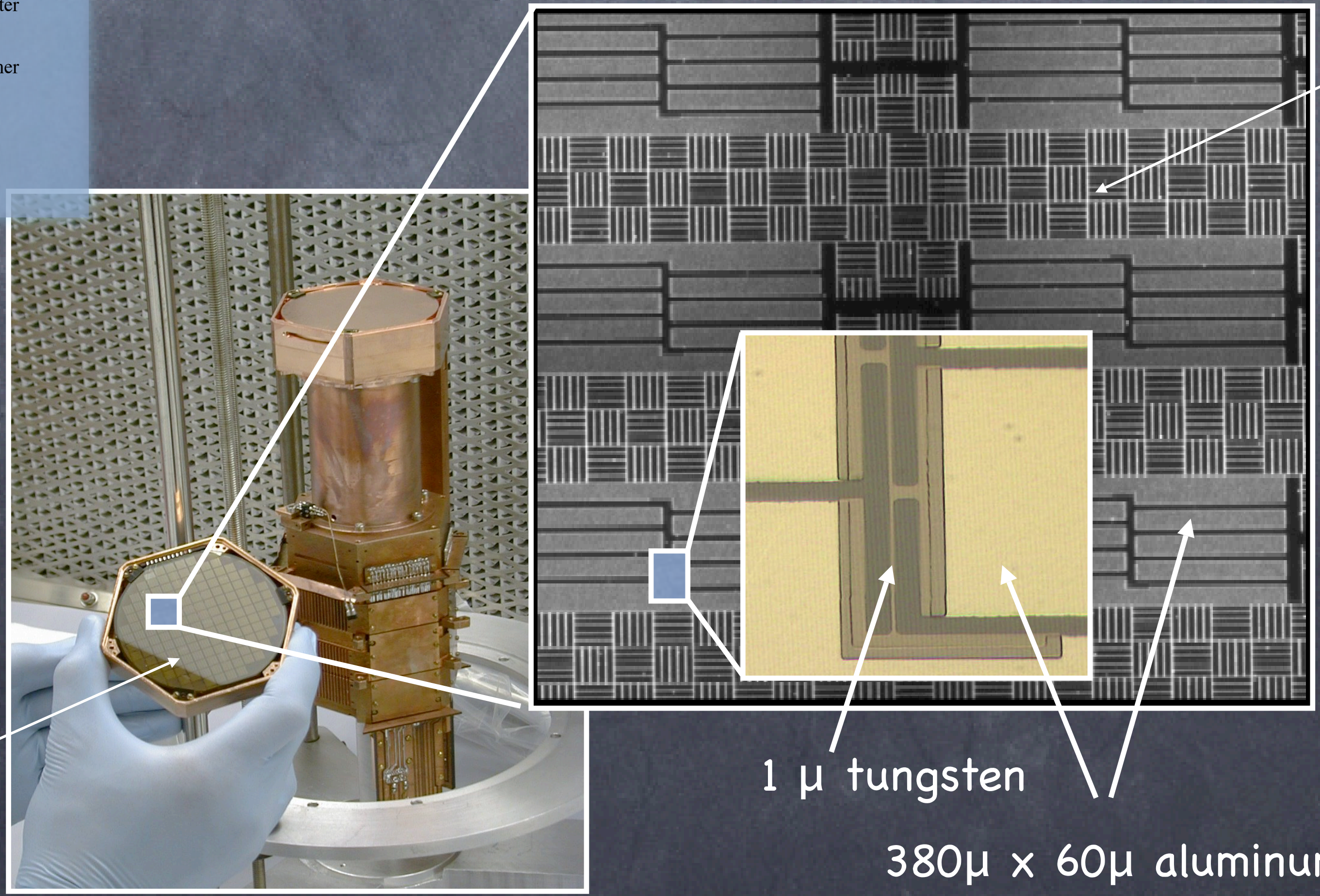
CDMS Detectors



Absorber:
250 g Ge or 100 g Si crystal
1 cm thick x 7.5 cm diameter
T-sensor:
photolithographic patterned thin Al+W films

Measure ionization in low-field (~volts/cm)

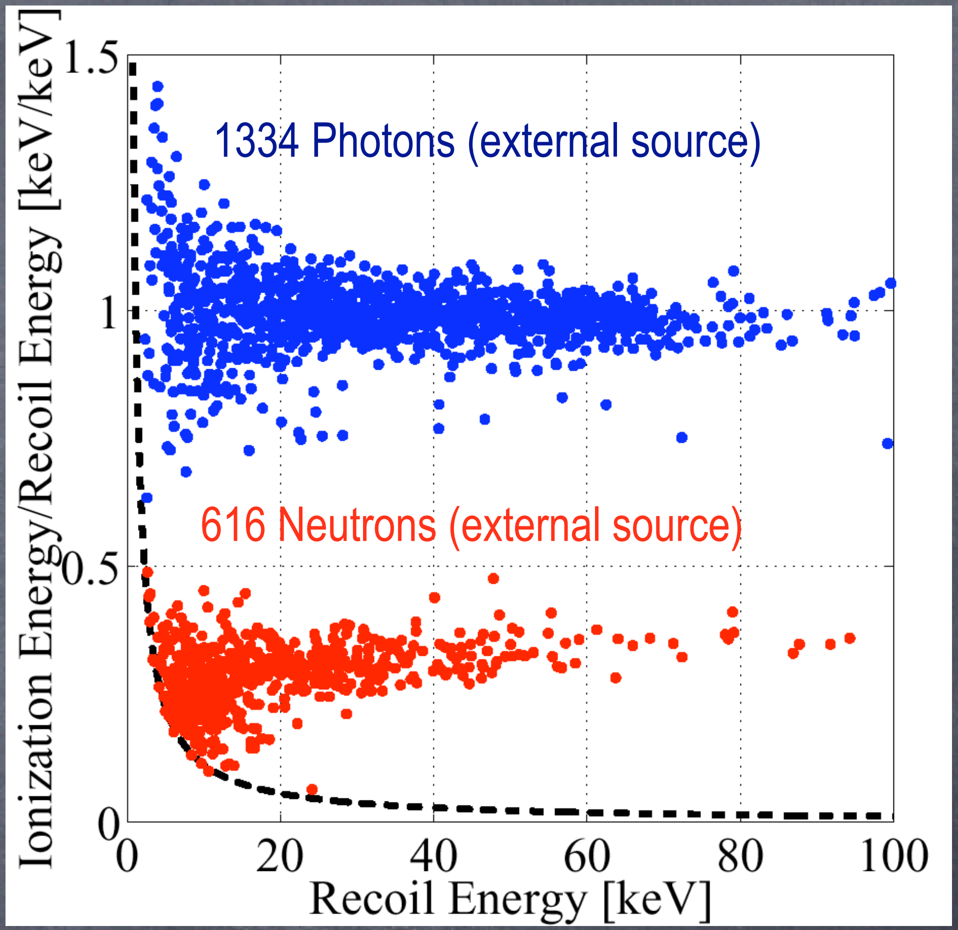
with segmented contacts to allow rejection of events near outer edge



CDMS Background Discrimination

The main contribution:

Use Ionization Yield (ionization energy per unit recoil energy) to reject the background

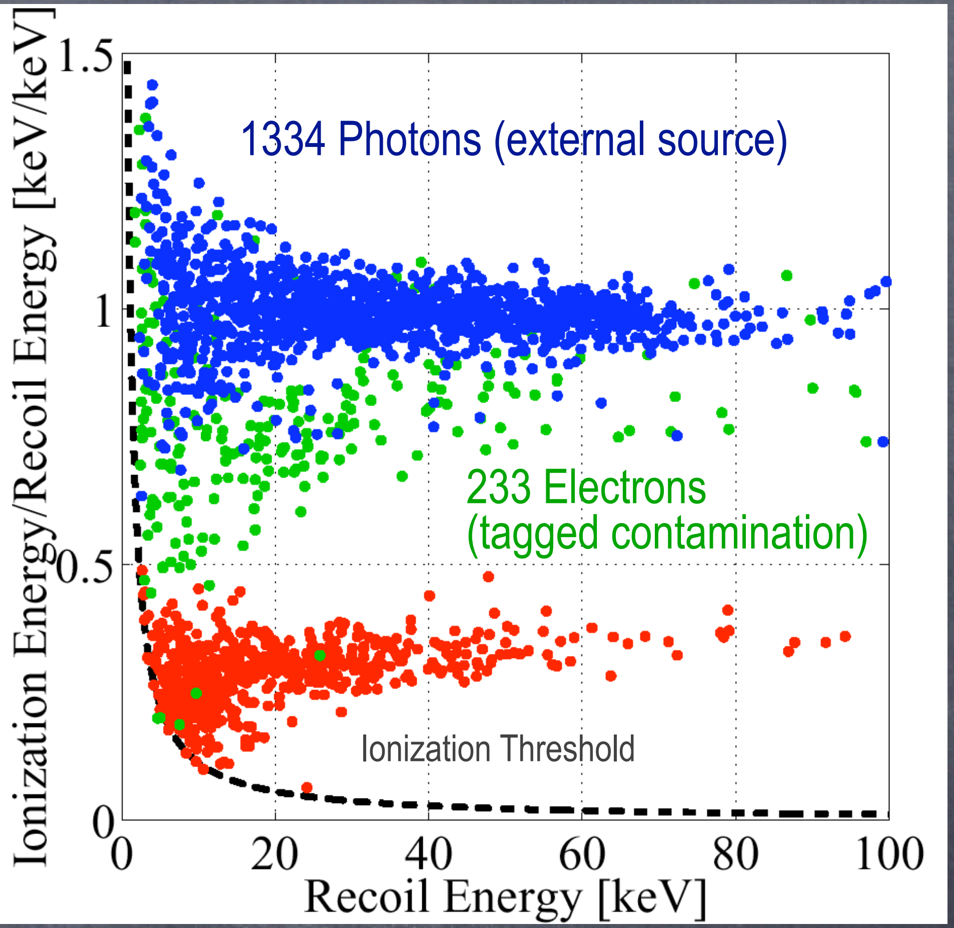


CDMS Background Discrimination

The main contribution:

Use Ionization Yield (ionization energy per unit recoil energy) to reject the background

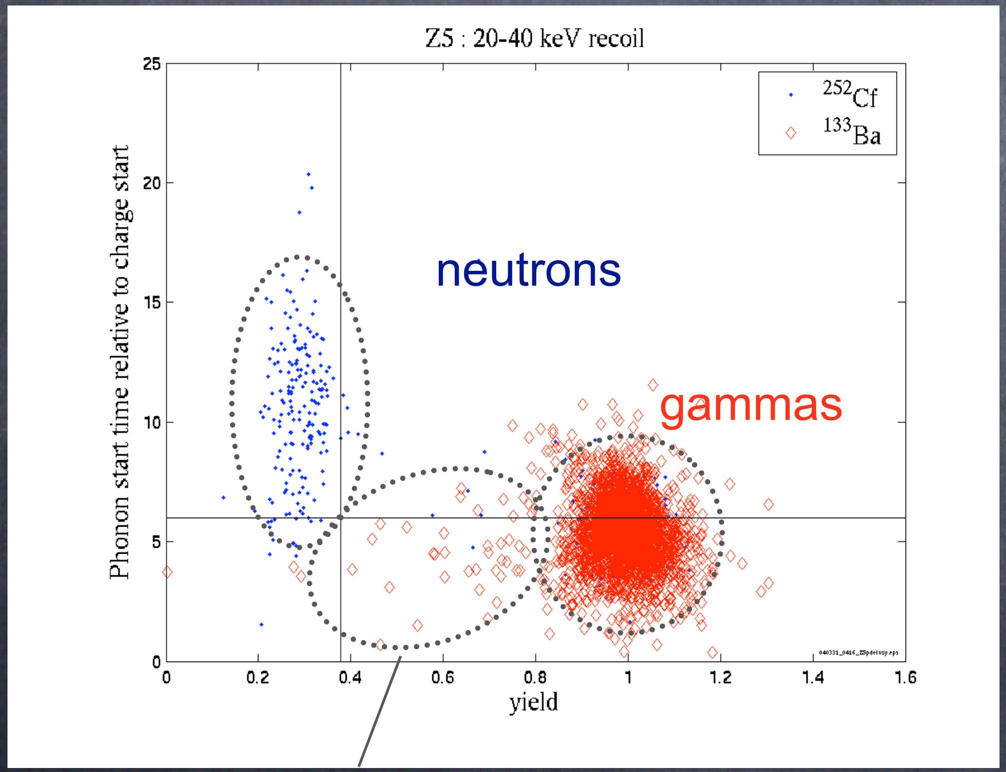
Particles (electrons) that interact in surface "dead layer" of detector result in reduced ionization yield



^{133}Ba and ^{252}Cf Calibrations

Use phonon risetime and charge to phonon delay for discrimination of surface events ("betas")

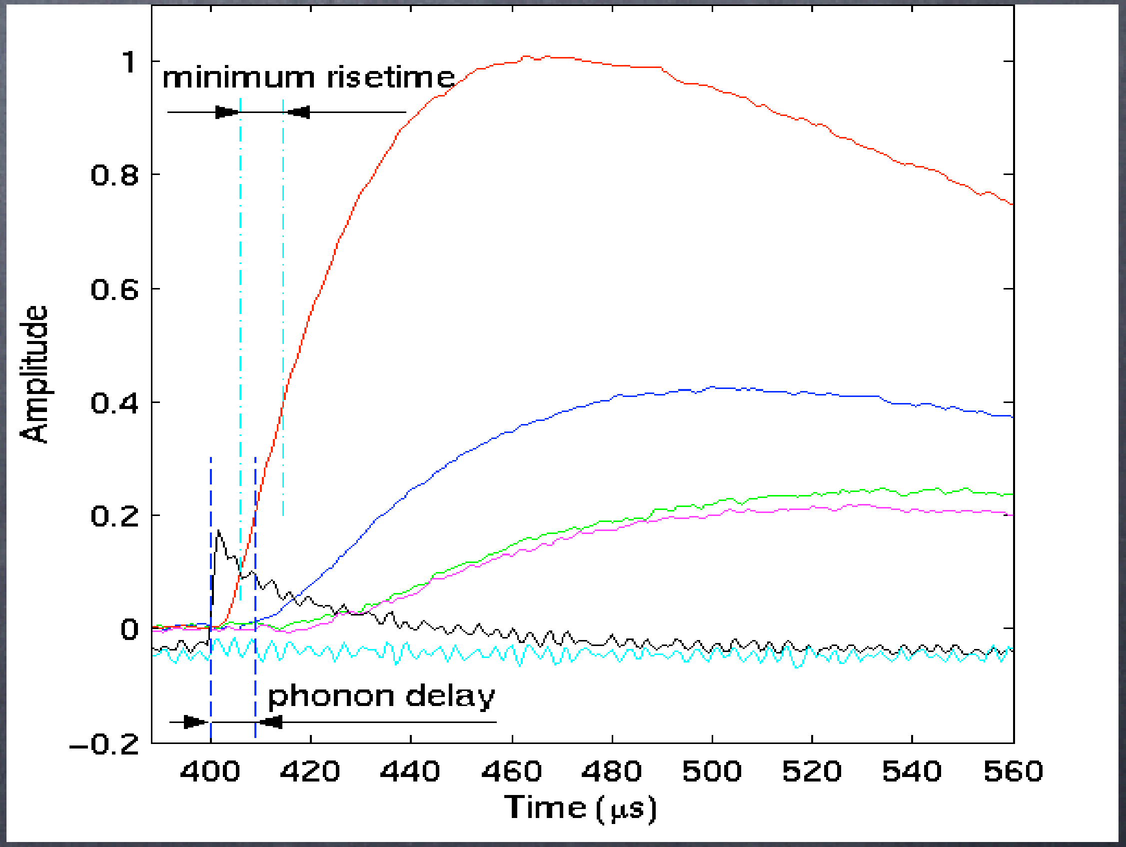
Ionization yield alone:	**Rejects >99.9% of gammas, >75% of betas**
Ionization+phonon timing:	**Rejects >99.9999% of gammas, >99% of betas**



Phonon delay [μs]

ejectrons

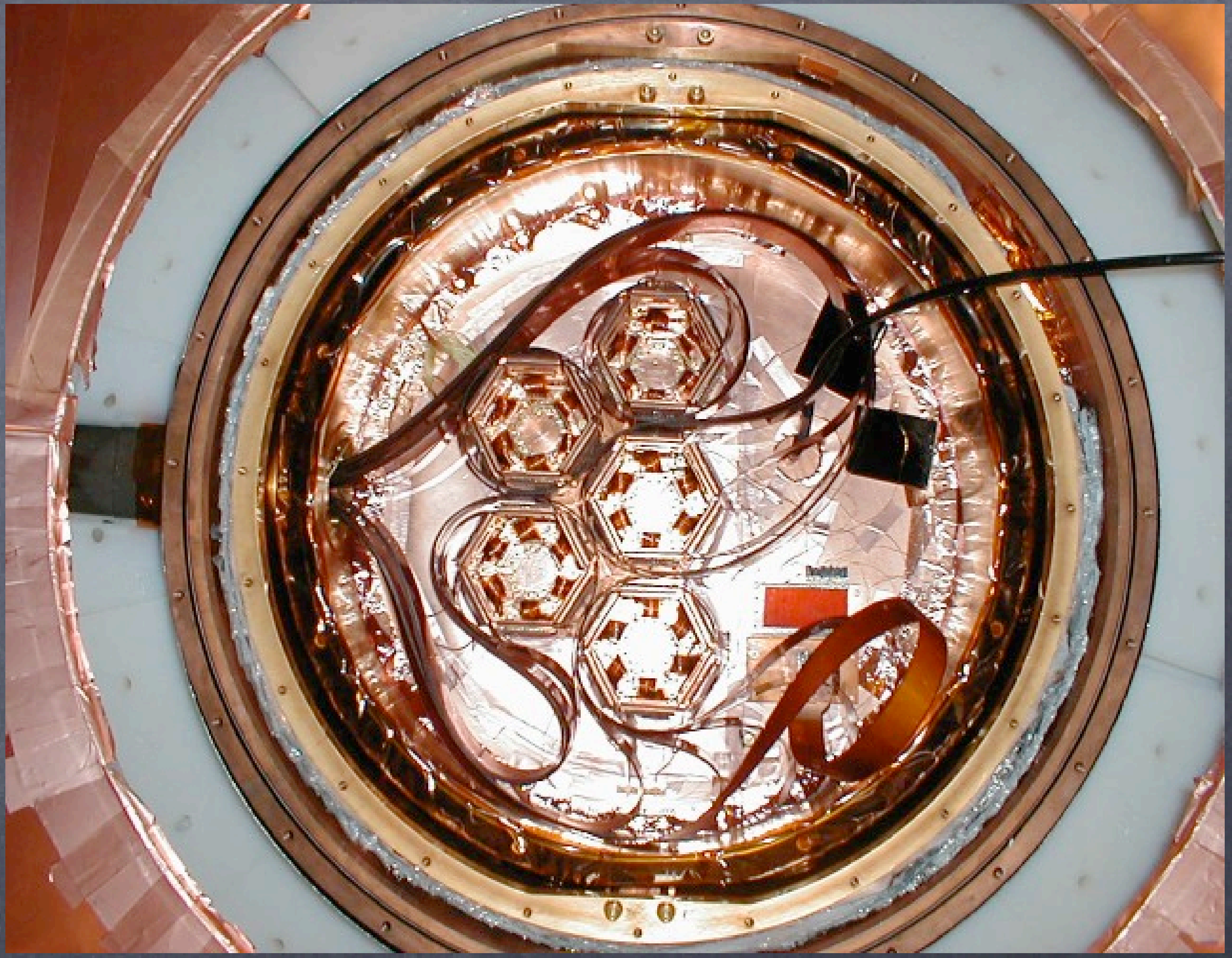
Ionization Yield



Amplitude

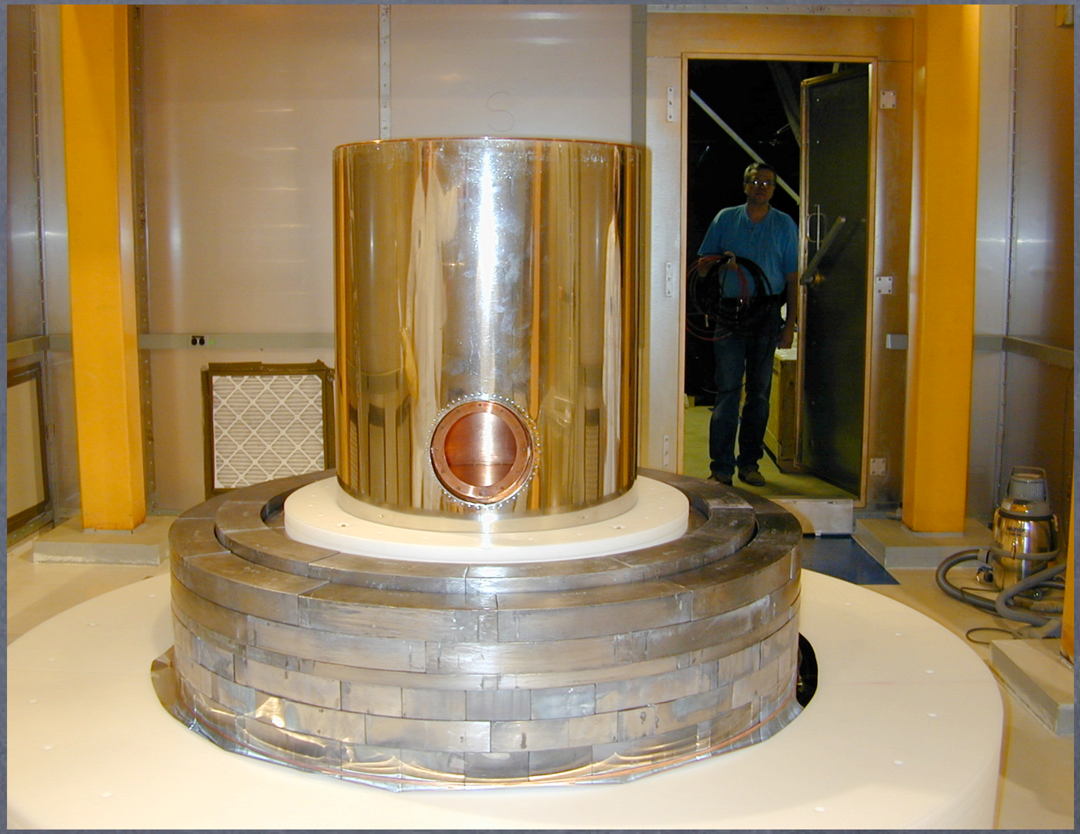
Time [μs]

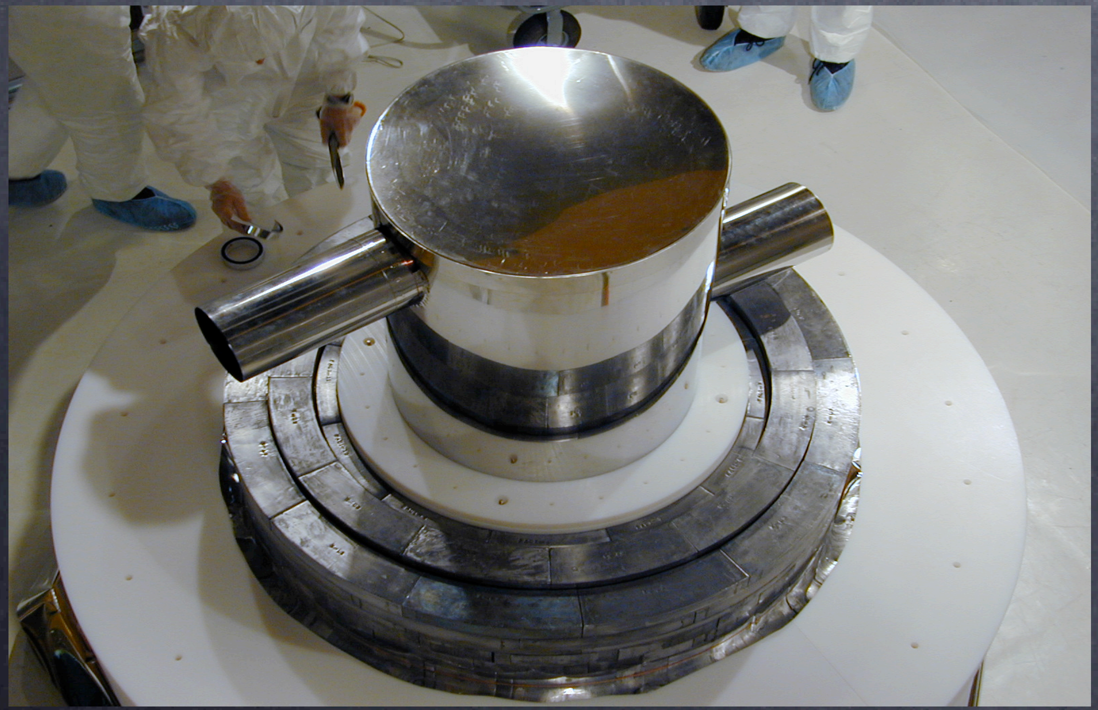
CDMS II at Soudan



5 towers in Soudan icebox:
19 Ge (4.75 kg) and 11 Si (1.1 kg) detectors

CDMS Icebox and Shield

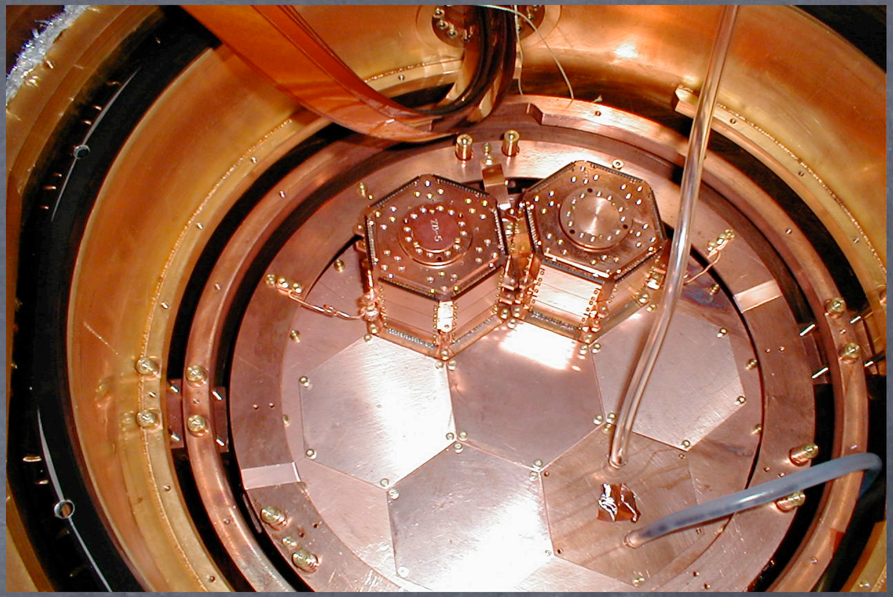




First Runs at Soudan

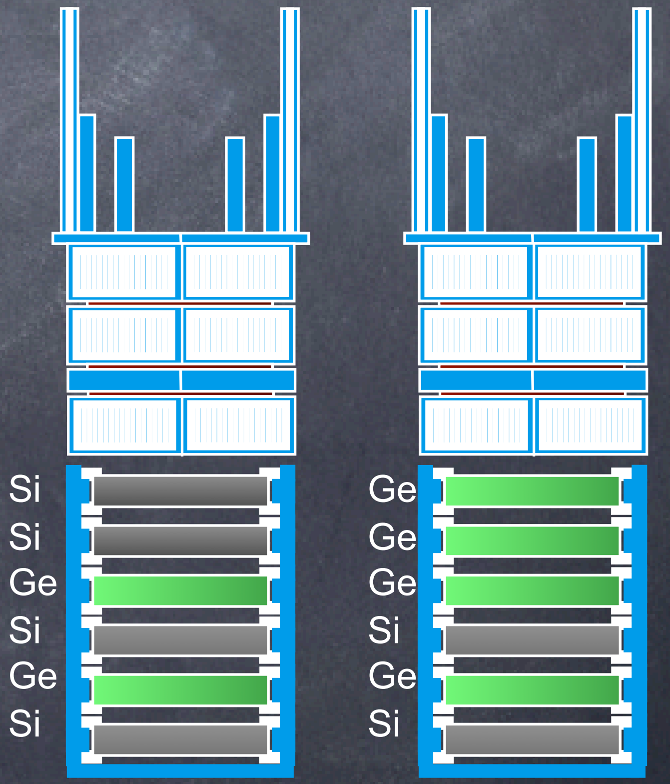
October 2003 - January 2004

- one tower = 4 Ge and 2 Si detectors
- 62 raw livedays, 53 after cuts of poor noise etc
- **22 kg d Ge exposure** (10-100 keV recoil)
- first results in 2004

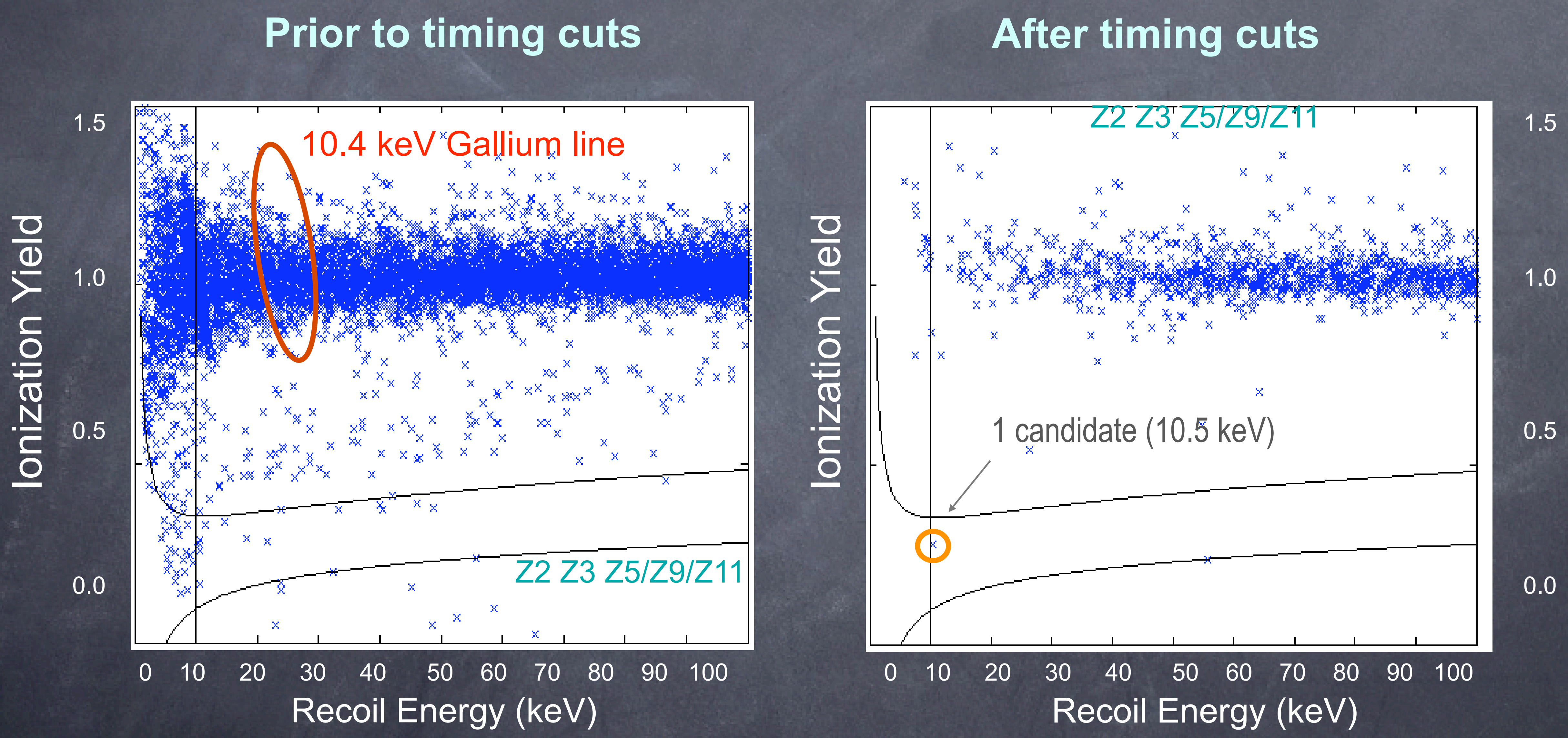


March 2004 - August 2004

- two towers = 6 Ge and 6 Si detectors
- 76 raw livedays, 74 after cuts of poor noise etc
- **38 kg d Ge exposure** (10 -100 keV recoil)
- first results in 2005



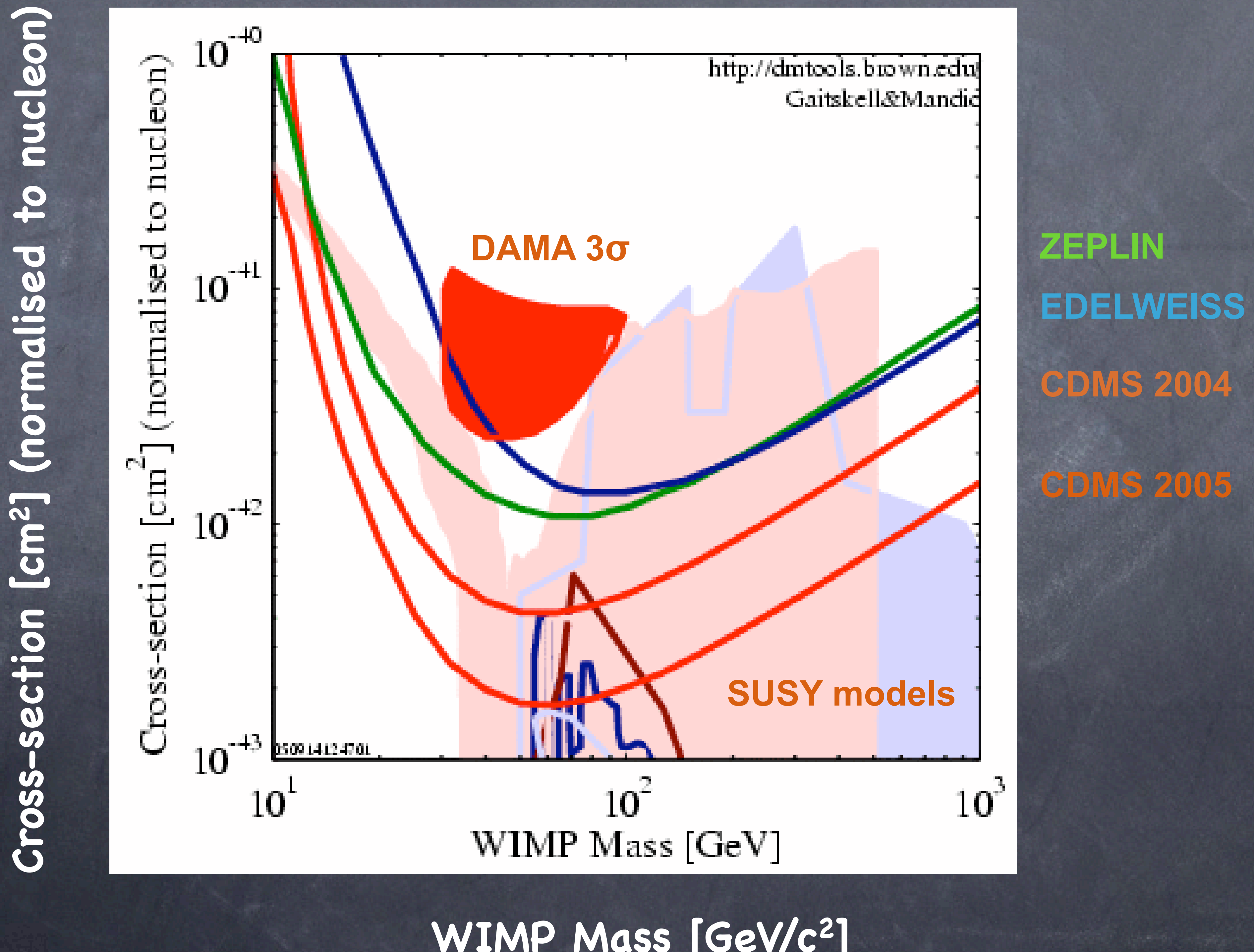
WIMP Search Data



0.4 ± 0.2 (stat) ± 0.2 (syst) Ge background expected -> 1 event seen

0.6 ± 0.2 (stat) ± 0.2 (syst) Si background expected -> 0 events seen

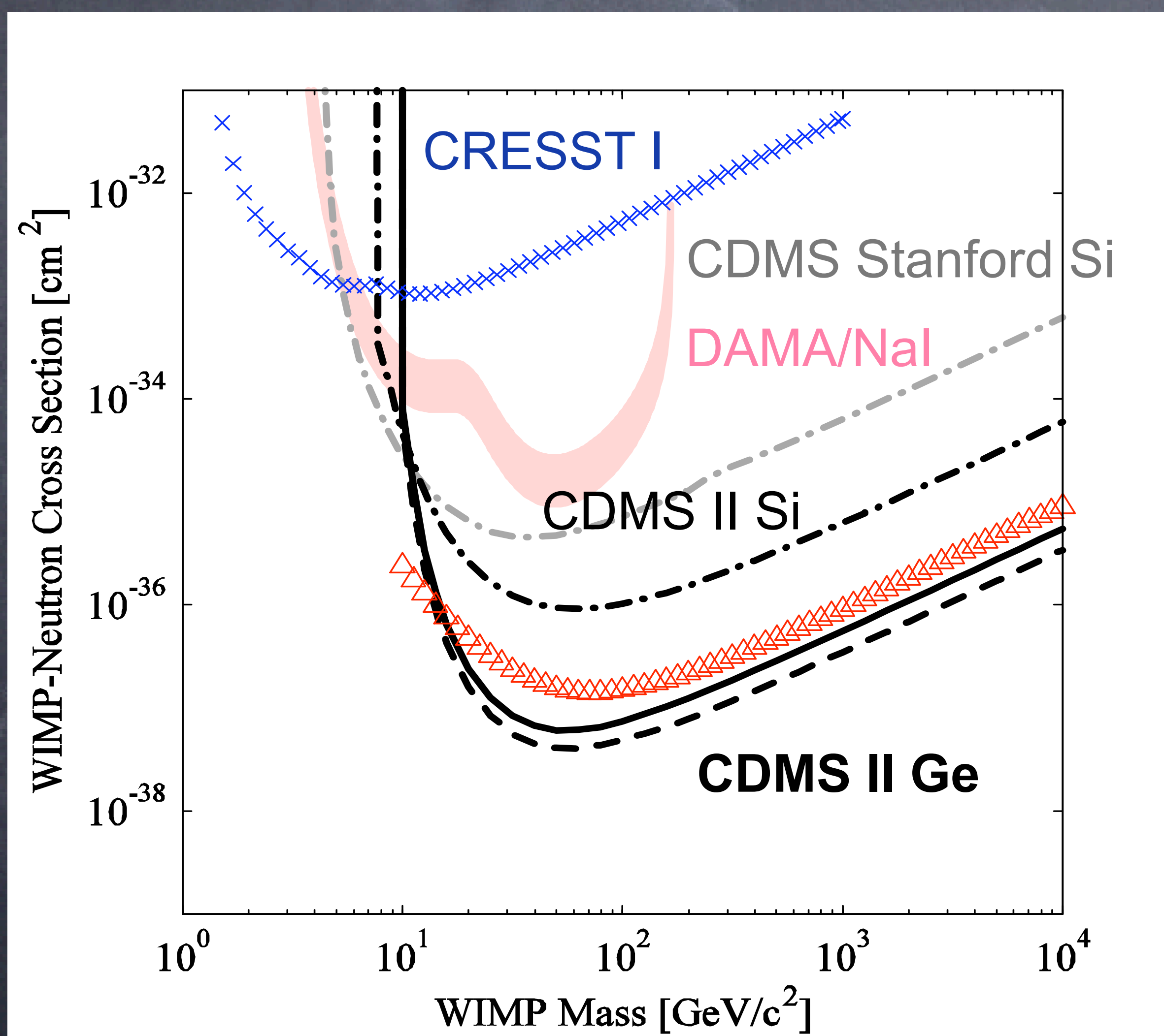
Spin-Independent Limits and SUSY Predictions



Spin-Dependent Limits

Pure neutron coupling

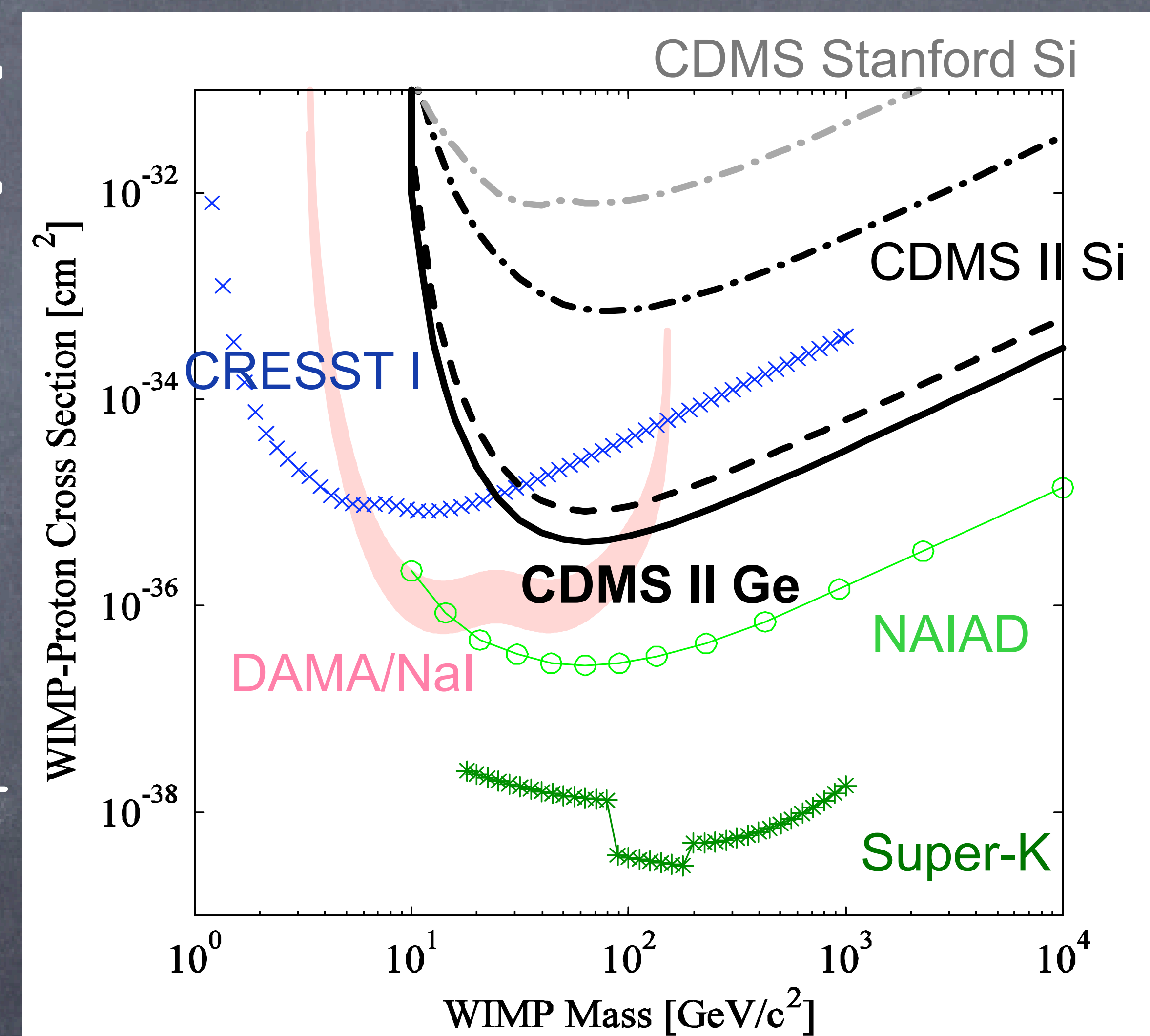
WIMP-neutron Cross-section [cm²]



WIMP Mass [GeV/c²]

Pure proton coupling

WIMP-proton Cross-section [cm²]

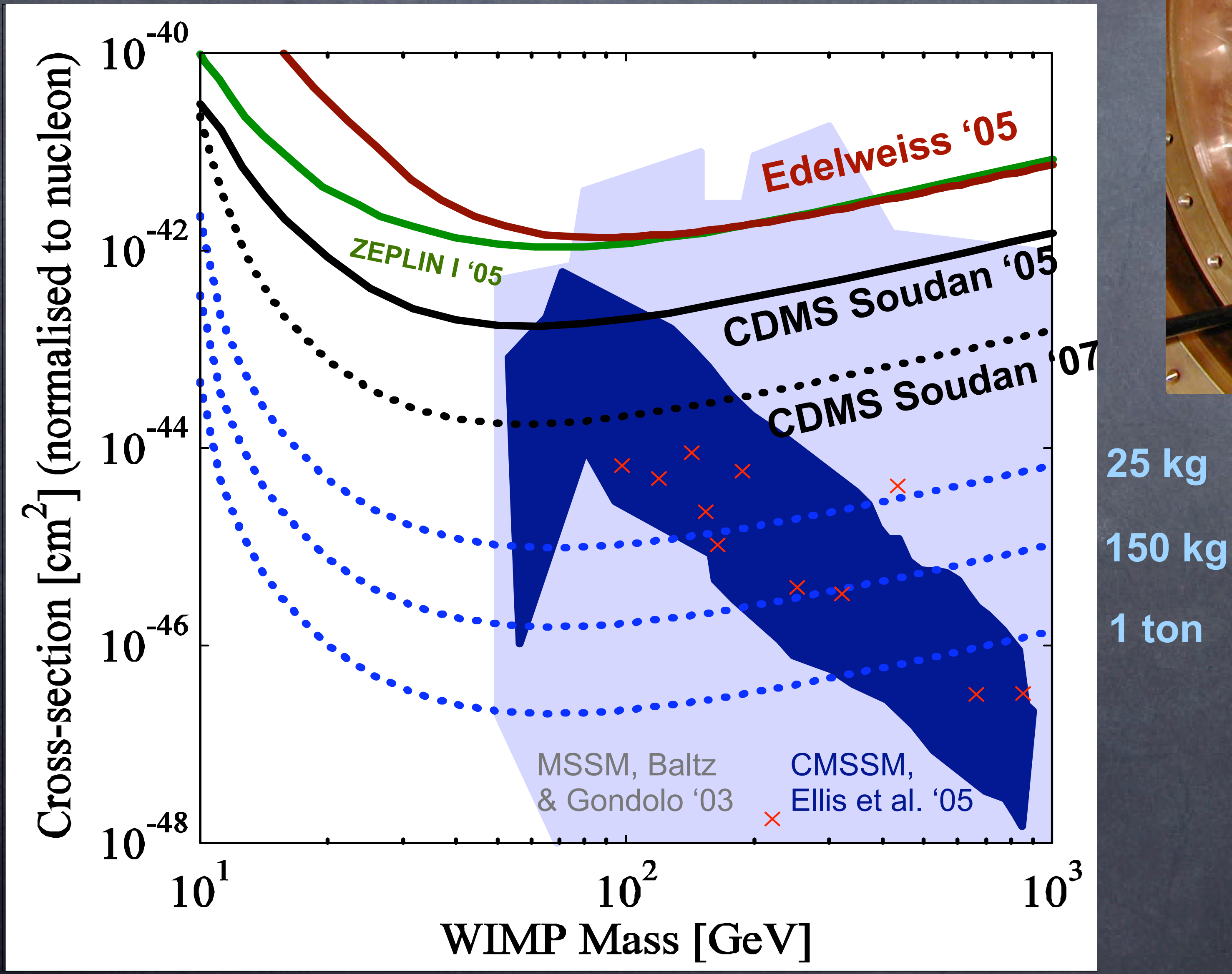


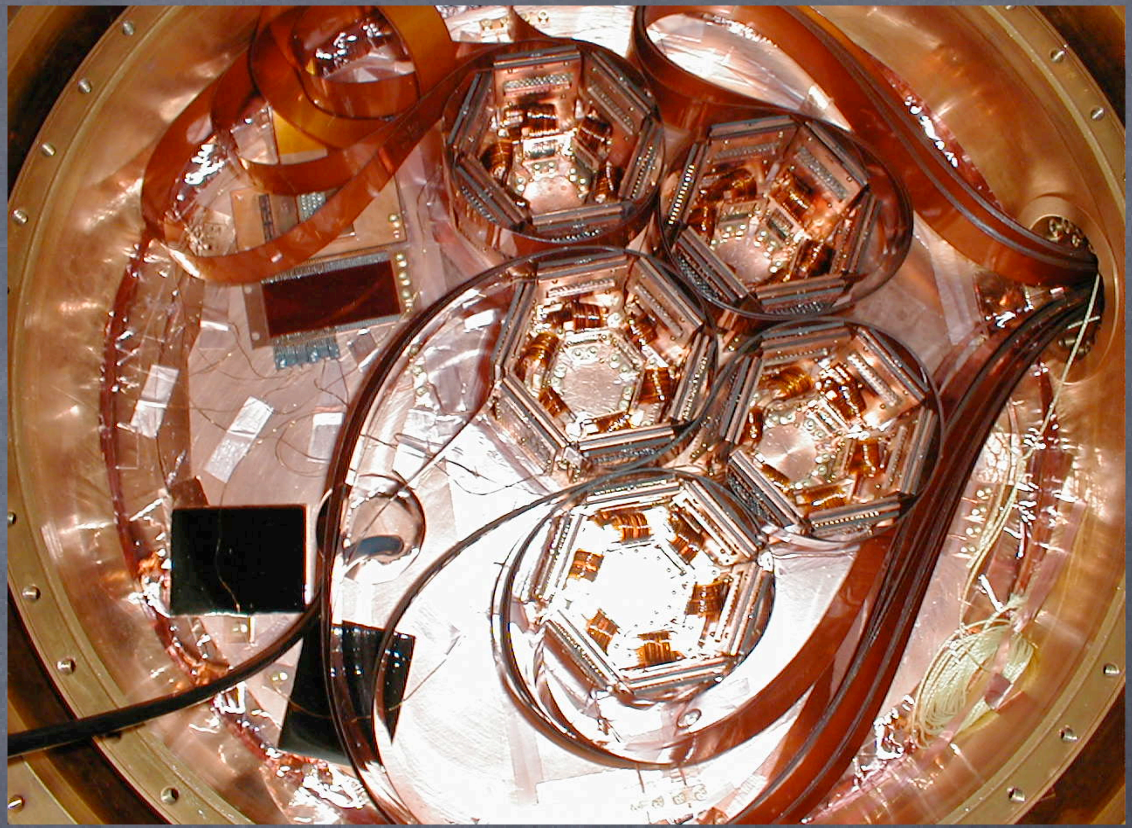
WIMP Mass [GeV/c²]

^{73}Ge, spin-9/2, 7.73%, ^{29}Si, spin-1/2, 4.68%; both single unpaired n

SUSY Reach with 5 Towers

Installed 3 additional towers:
30 detectors: 4.75 kg of Ge,
1.1 kg of Si

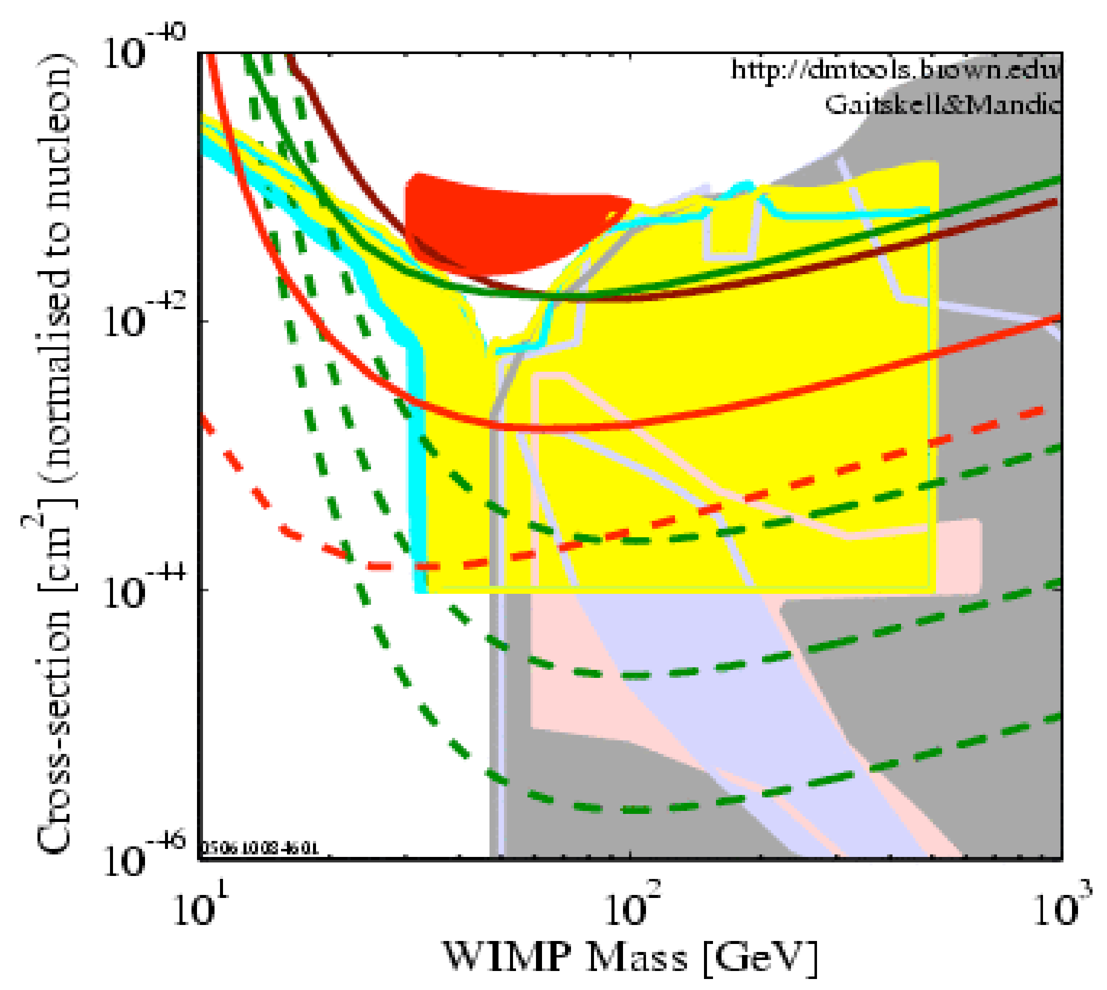




Other improvements:
cryogenics, backgrounds, DAQ

Currently commissioning:
=> run through 2006
=> improve sensitivity x10

Where Do We Stand?



Predictions: Bottino & al, Ellis & Olive, Baltz & Gondolo

1 event/kg d: EDELWEISS, CRESST, ZEPLIN

0.1 events/kg d: CDMS

1 event/kg yr: CDMSII, CRESSTII, EDELWEISSII, ZEPLINII

1 event/100 kg yr: future projects!

1 ton is needed in order to detect 10 events per year at $\sigma = 10^{-46}$ cm^2

Proposed Projects

Project	Discrimin	Type	Mass	Location
SuperCDMS	Yes	Ge/Si phonon/ioniz	1 ton	SNOLab
EUREKA	Yes	Ge, $CaWO_4$ phonon/ion/scint	100 kg - 1t	Gran Sasso?
ZEPLIN-MAX	Yes	LiXe ioniz/scint 2 phase	1 ton	Boulby
XENON	Yes	LiXe ioniz/scint 2 phase	1 ton (10 x 100 kg)	Gran Sasso
DRIFT3	Yes + direction	TPC (CS_2) negative ion	100 kg	Boulby
WARP/ArDM	Yes	LiAr ioniz/scint 2 phase	100 kg -1 ton	Gran Sasso
PICASSO	Yes	Superheated droplets (C_4F_{10}), ^{19}F	1 kg	SNOLab

Liquid Xenon

High atomic mass (A ~ 131): favorable for SI case ($\sigma \sim A^2$)

High atomic number (Z=54) and density (3 g/cm^3)

=> self-shielding, compact geometry

Available in large quantities at reasonable costs

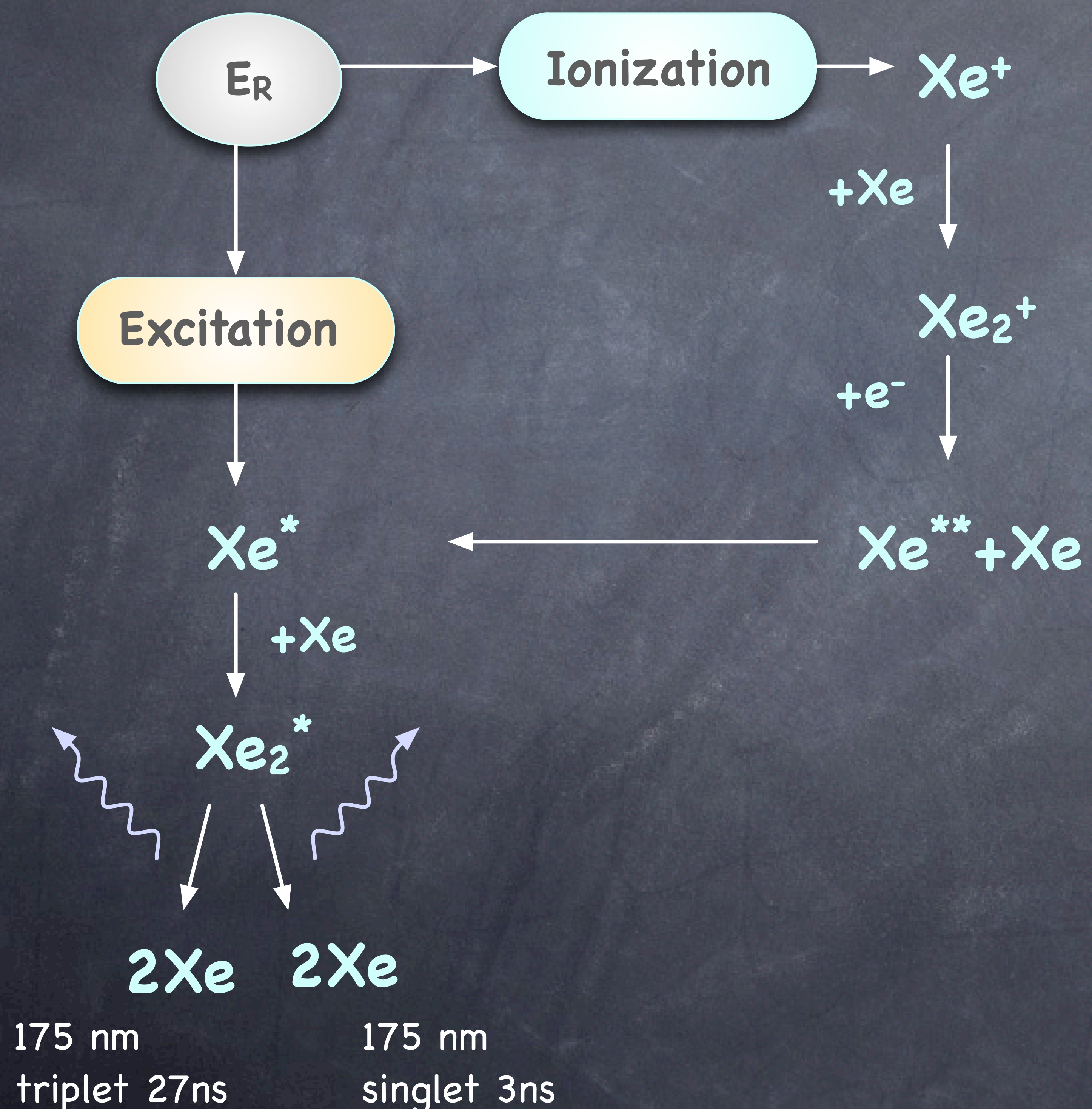
'Easy' cryogenics at -100 °C

No long lived radioactive Xe (except ^{136}Xe), can be easily purified

High photon yield (~NaI(Tl)) and high charge yield

Can separate spin/no spin isotopes: ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe, ^{134}Xe, ^{136}Xe

Basic Processes in LiXe

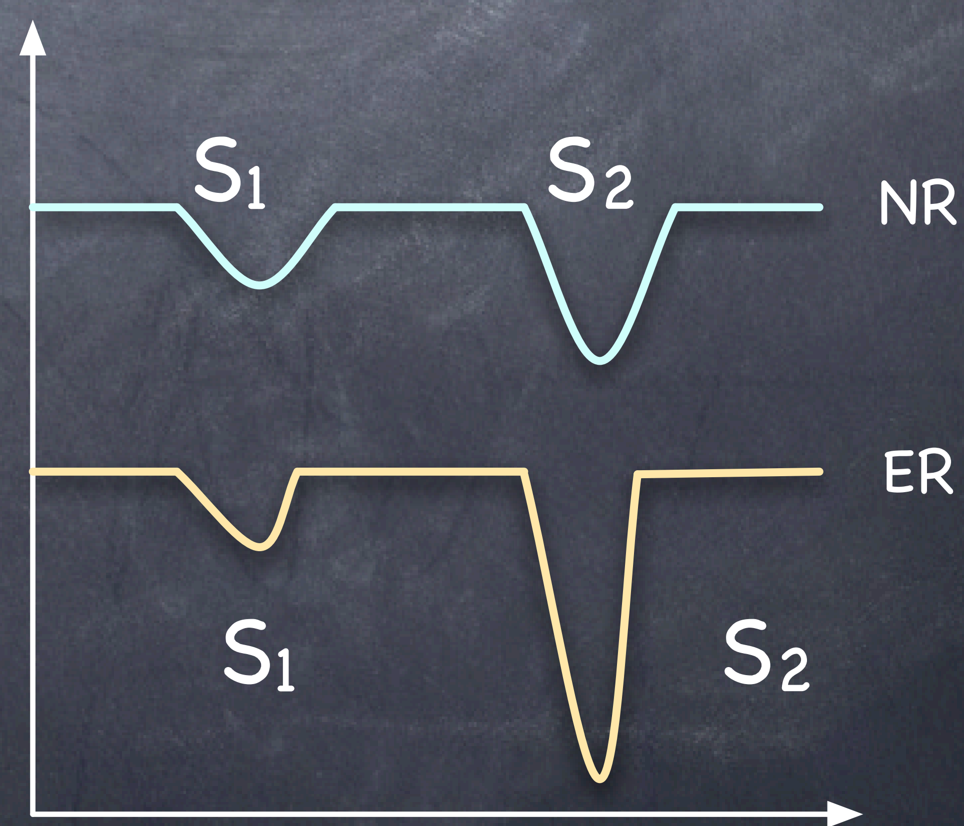


Excitation: 175 nm

singlet (3ns), triplet (27ns)

Ionisation:
recombinations 15 ns

NR: strong recombination
ER: good charge collection



A Two-Phase Liquid Xe Detector

n, WIMPs: slow nuclear recoils

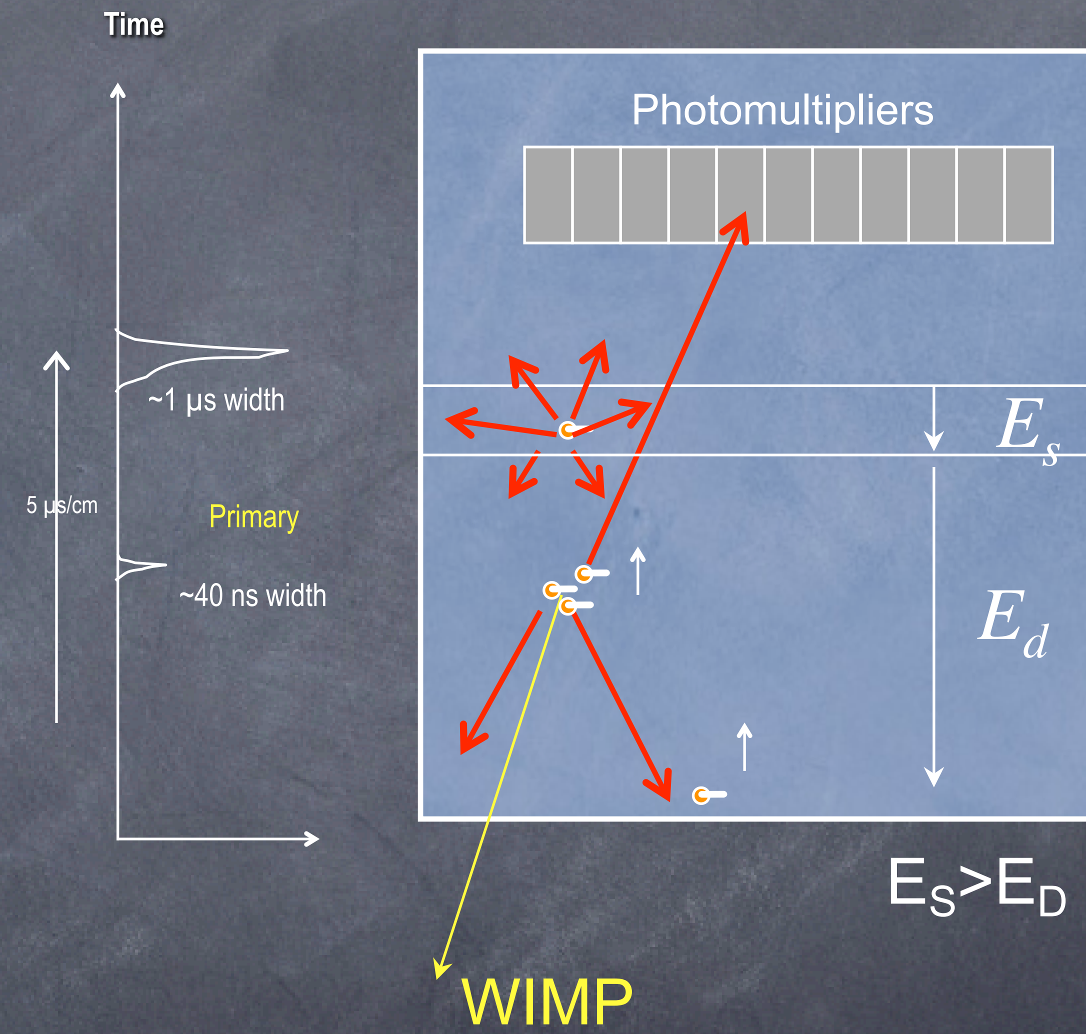
- Strong columnar recombination
- Ionization (S2) strongly suppressed

e^-, γ: fast electron recoils

- Stronger S2 signal

Ionization signal from nuclear recoils too small to be detected directly

- Extract charges from liquid to gas
- Detect proportional signal

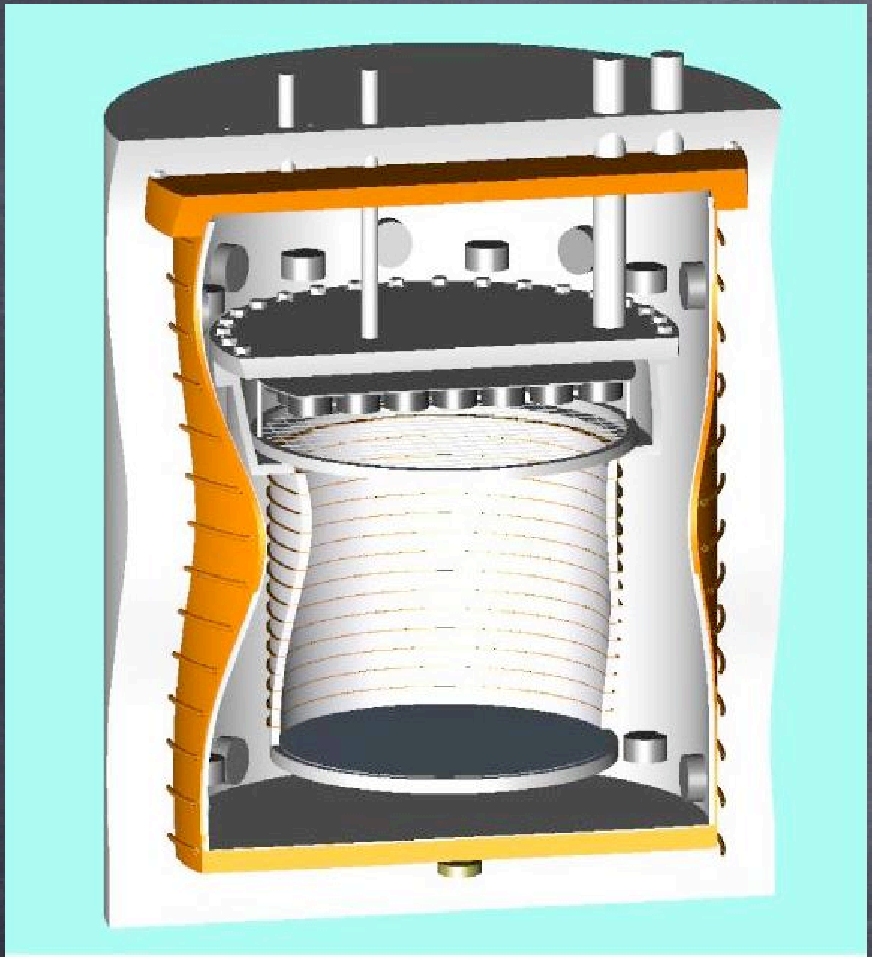


$(S2/S1)_{electron} >> (S2/S1)_{nuclear}$

→ event-by-event discrimination

Challenge: ultra-pure liquid and high drift field to preserve small electron signal (~ 20 electrons); efficient extraction into gas phase, efficient detection of small primary light signal (~ 200 photons) associated with 16 keV nuclear recoil energy

The XENON Proposal



Modular design: 1t active Xe target distributed in an array of 10 3D position sensitive dual-phase (liquid/gas) XeTPCs, actively shielded by 5 cm LXe veto.

R&D for XENON funded by NSF. Testing concept feasibility/capabilities with various prototypes. Construction and underground deployment of a 10 kg detector (XENON10) in 2006 approved.

1st 100 kg module (XENON100) to be ready for data taking by end of 2007. After 3 months at a background < 1×10^{-4} cts/keV/kg/day after rejection, the sensitivity of XENON-100 would be **$\sigma\sim2\times10^{-45}$ cm^2** .

10 kg Prototype for Gran Sasso

Goal: commission beginning 2006

10 kg, 3D dual-phase detector

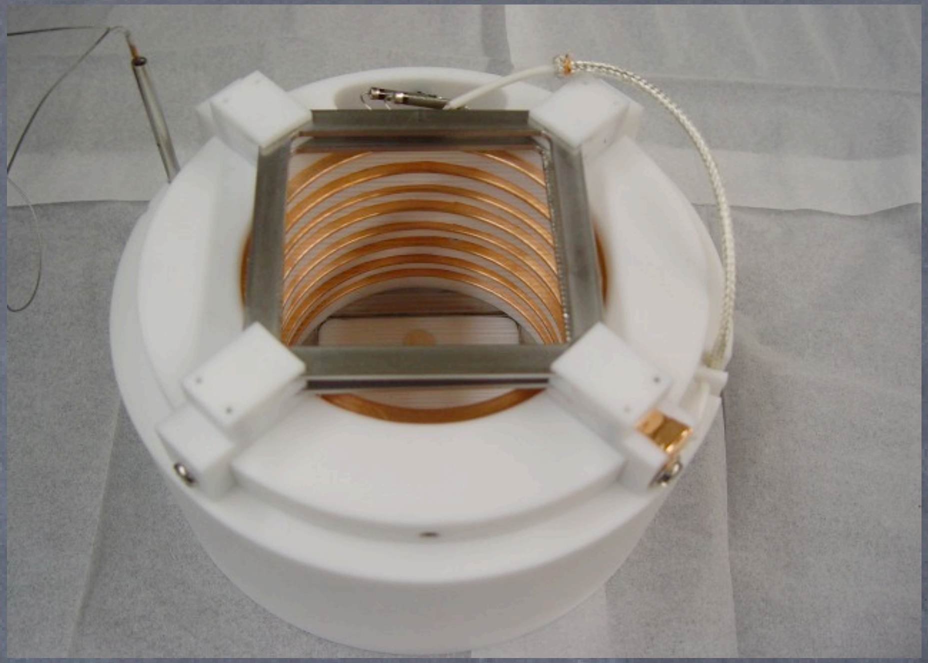
10 cm drift gap

Detector is being assembled now

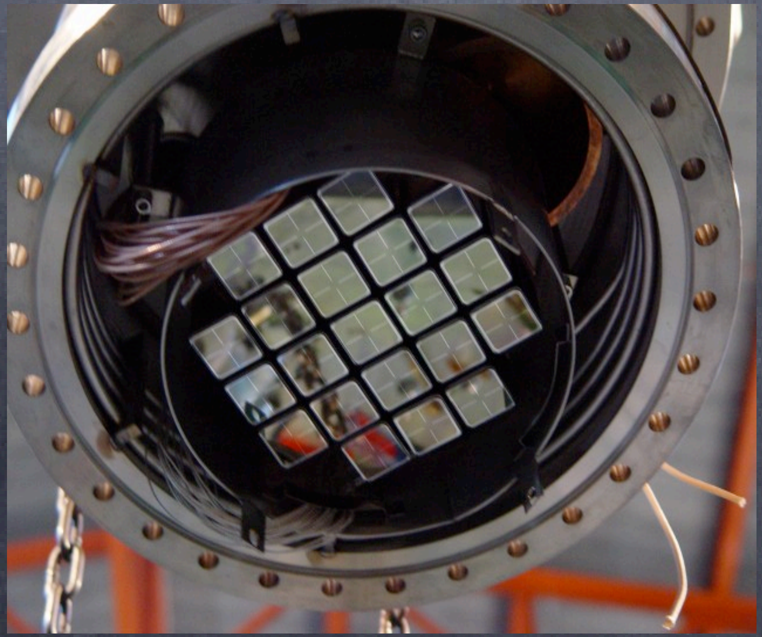
Gas purification/recirculation system exist

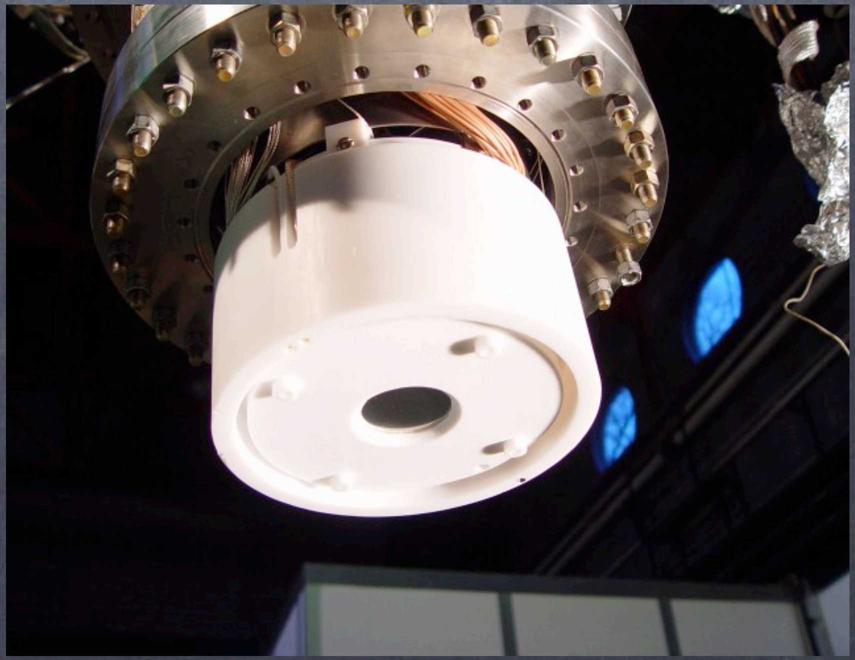
Shield in construction

DAQ: CAEN 8 channels FADCs

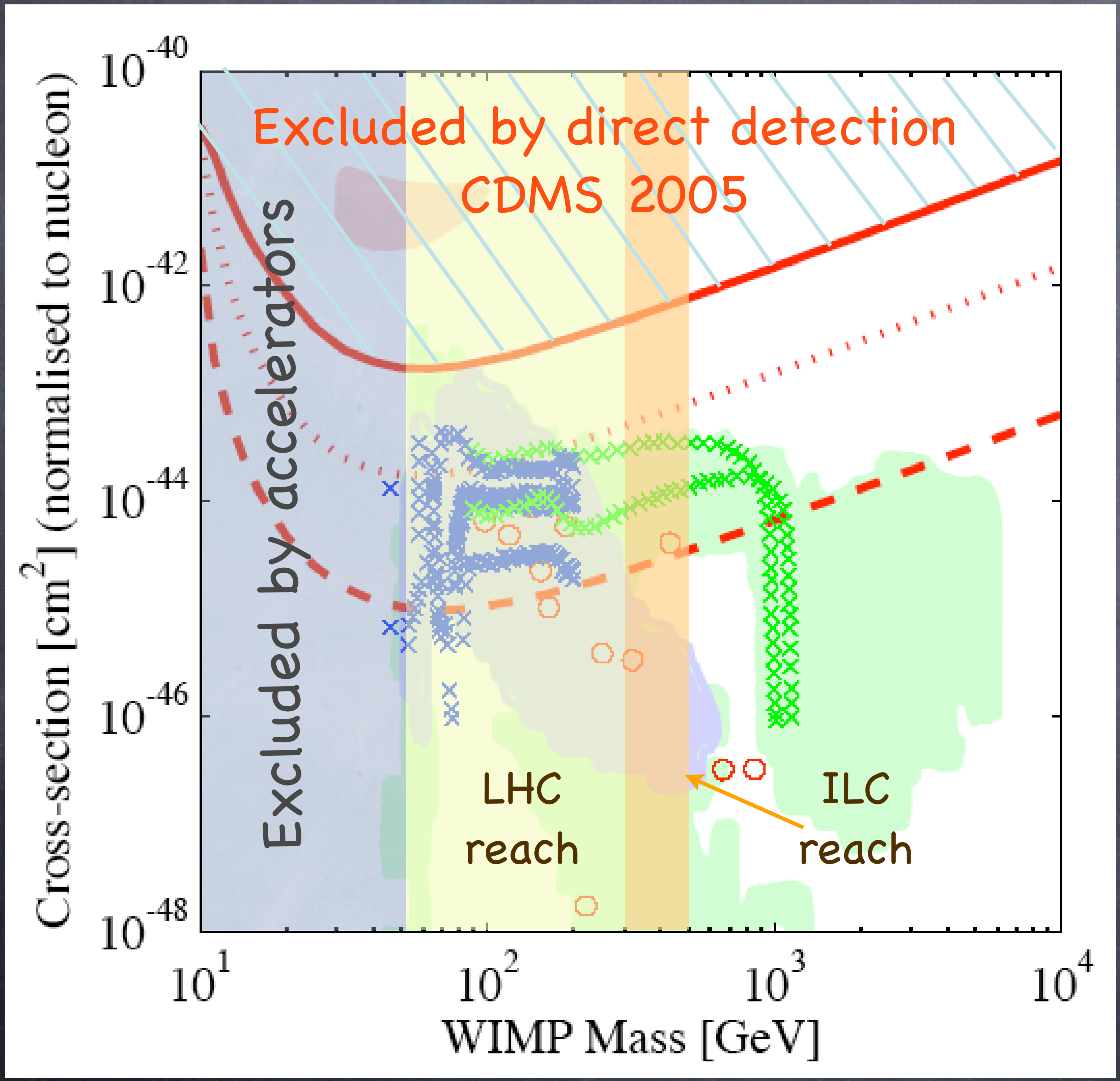


Hamamatsu R8520
QE>20% at 178 nm
U/Th = 13/3 mBq
Rb-Cs-Sb photocathode





Direct Detection and LHC/ILC



LHC: 2 TeV limit for gluino, squark, slepton
$m_\chi \sim 1/6\ m_c$ = 300 GeV
in most SUSY models

LHC: hard to tell the nature of the WIMP => **need ILC**
(Battaglia, Peskin hep-ph/0509135)

Direct detection: cross section limited, but can go to higher masses

=> complementarity between LHC/ILC and SuperCDMS/XENON

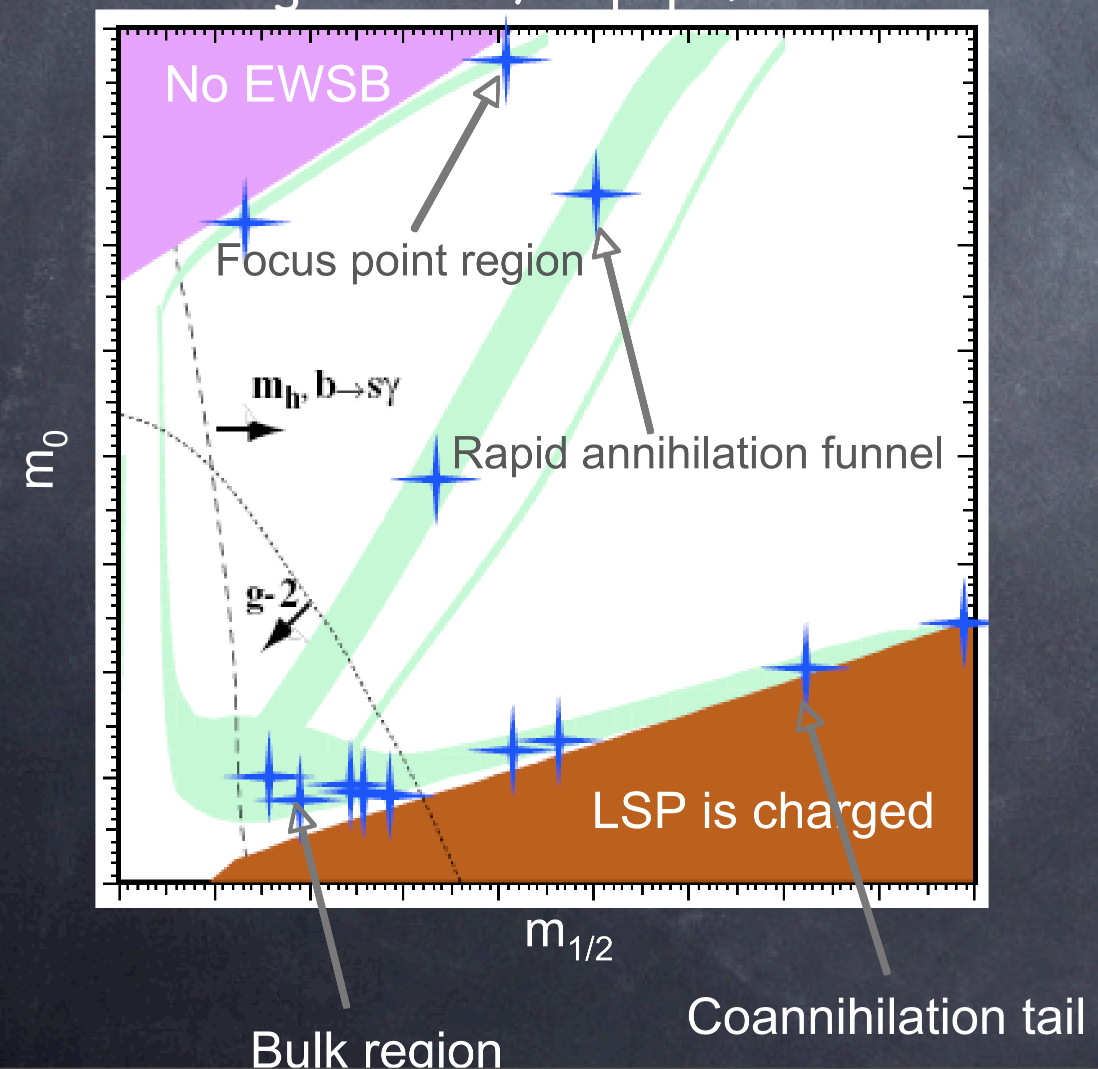
Direct Detection and LHC/ILC

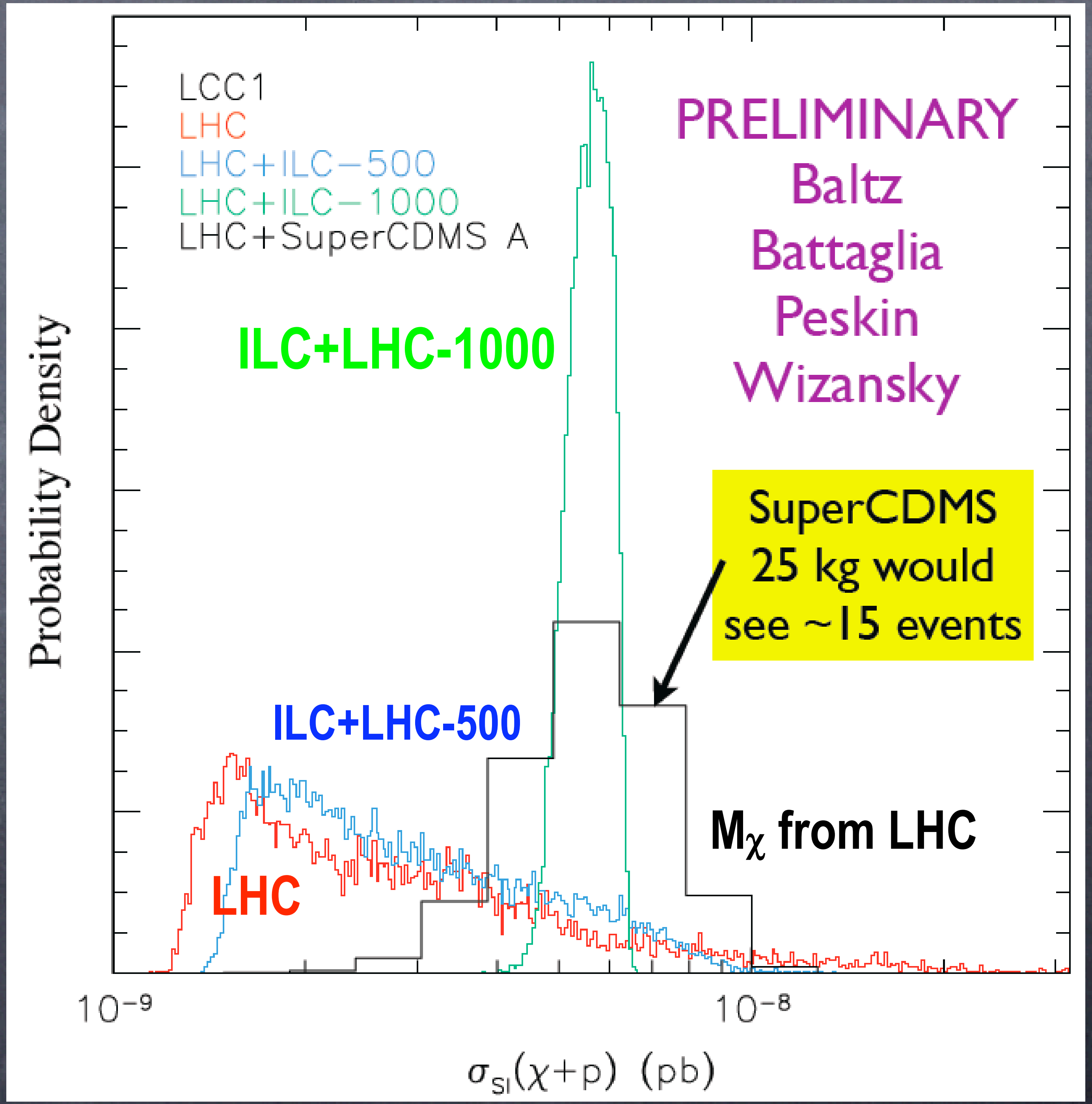
Take **SUSY benchmark model** (here LCC1 = mSUGRA bulk region) consist. Ω_{WMAP}

Explore range of models **compatible with accelerator data**

=> constrain secondary parameters

Battaglia et al., hep-ph/0106204





UED and Direct Detection

Cross section on quarks

depends on $\Delta_{q1}=(m_{q1}-m_{\gamma 1})/m_{\gamma 1}$

(LKP=γ_1)

Take Δ_{q1} as free parameter

=> translate direct detection

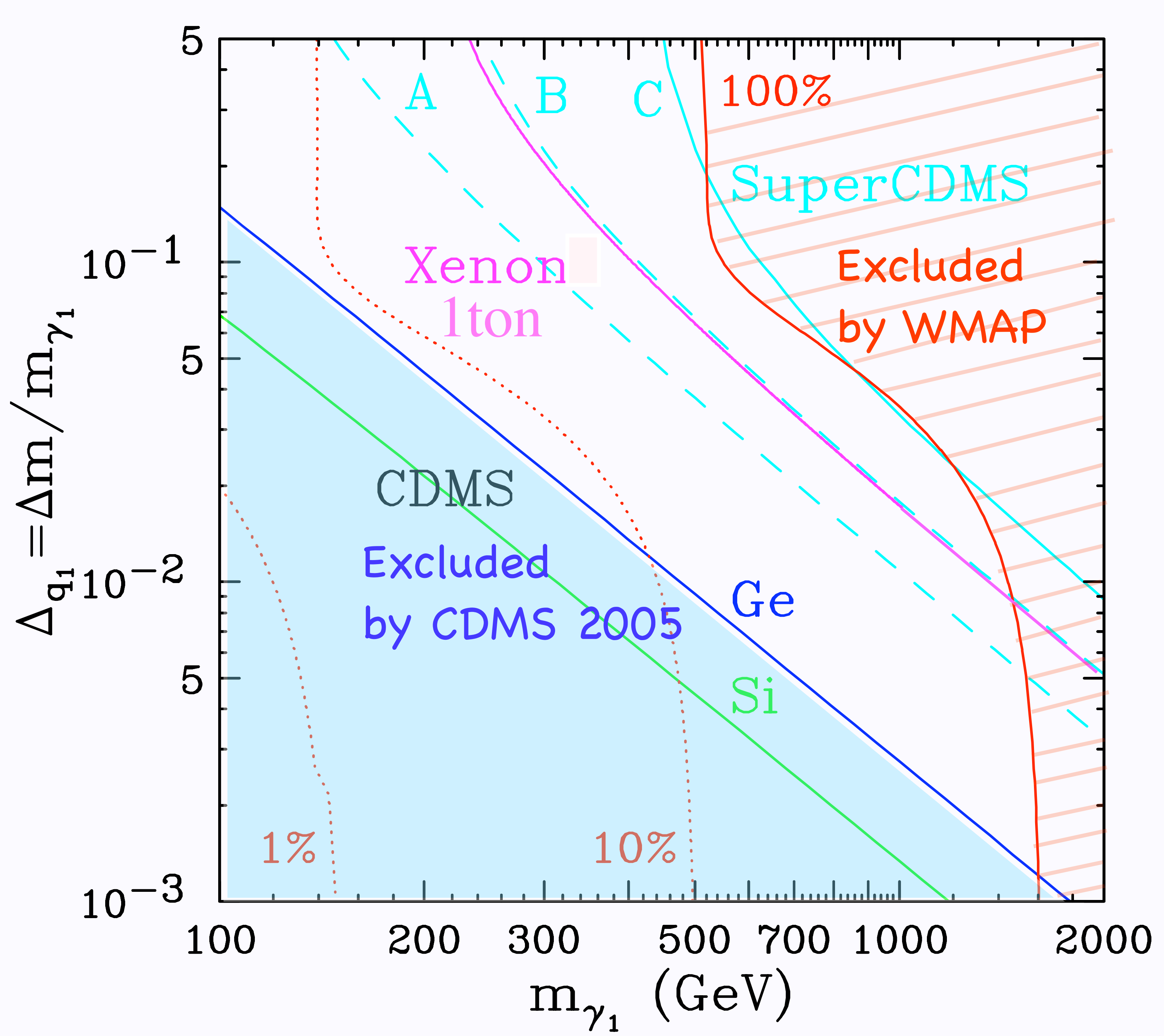
limits/predictions on cross

section into ($m_{\gamma 1}$-Δ_{q1})-plane

100% (red) curve corresponds to

$\Omega_{WIMP(\gamma 1)} \approx 0.27$ (from WMAP)

Spin-independent cross sections



Baudis, Kong, Matchev, 2005 preliminary

Indirect Detection

Observe the radiation produced in dark matter annihilation

The flux is proportional to the annihilation rate:

$$\Gamma_A = \rho_{DM}^2 \sigma_{ann} \mathrm{v}\, \mathrm{m}_\chi^{-2}$$

=> look at regions where large dark matter densities accumulate ('amplifiers')

in the galactic halo and center: $e^+, \bar{p}, \gamma$ and ν's

in the Sun, Earth core: high-energy ν's

Indirect Detection

$\chi\,\chi \rightarrow$ bb, WW, … $\rightarrow e^+, e^-, p, \bar{p}, \gamma$

$\chi\,\chi \rightarrow Z\gamma, \gamma\gamma$

$$\phi_{prod} \propto \langle\sigma_{ann}v\rangle\, \rho_\chi^2/m_\chi^2 \times g\,(\text{propagation})$$

particle physics parameters:

flux decreases with high χ mass

flux increases with σ_{ann}

astrophysics/cosmology:

dark halo profile

presence of clumps

propagation parameters

Gamma Ray Detection

Ground-based telescopes: detect Cerenkov light in atmosphere (ACTs):

HESS (2004), **MAGIC** (2003), **CANGAROO** (2004), **VERITAS** (2006),...

$E_{th} \approx$ 50-100 GeV

Space-based telescopes: detect gamma's via e^+e^- production

EGRET (on CGRO): 1991-2000, observed Universe from 30 MeV-30 GeV

GLAST: scheduled to launch in 2007, up to 100s of GeV

The Galactic Center

Excess of gamma rays from the galactic center region observed by:

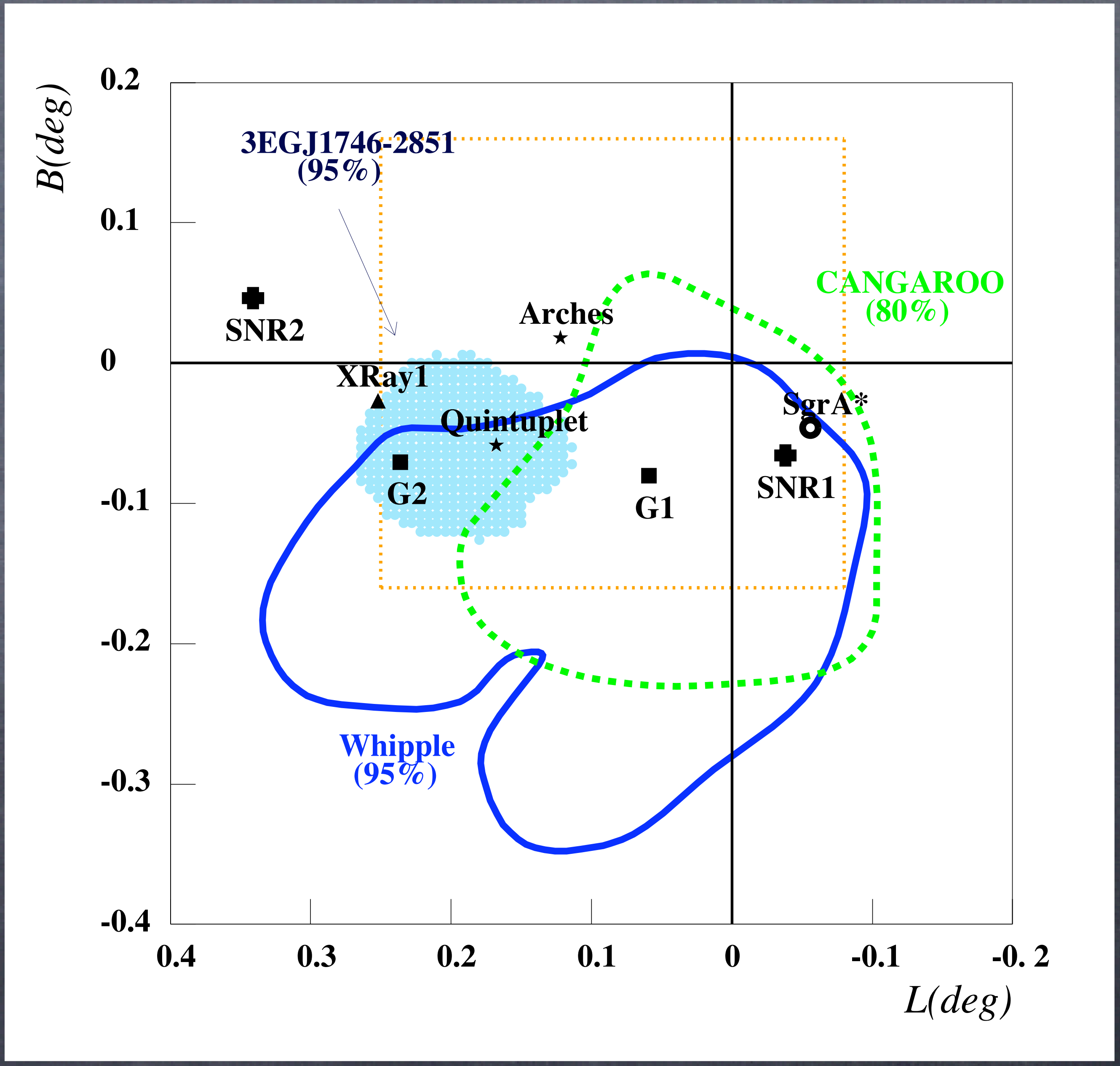
EGRET (3EG J1746-2851)

WHIPPLE

CANGAROO

HESS

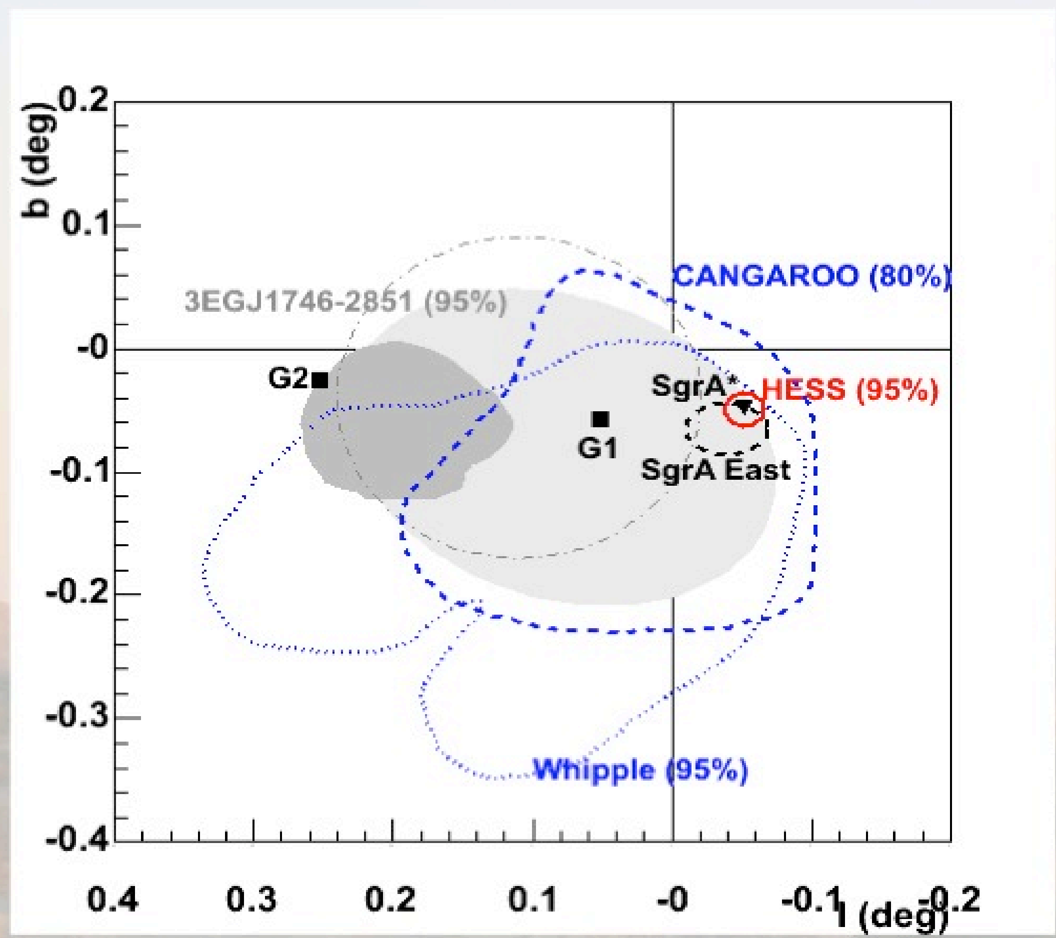
Before HESS:



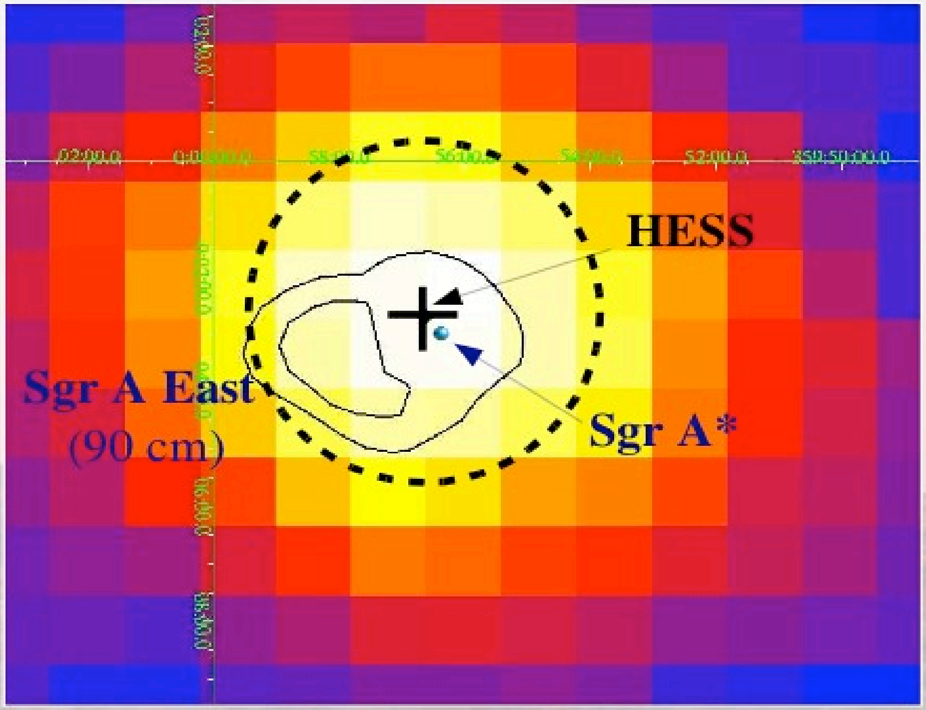
The Galactic Center

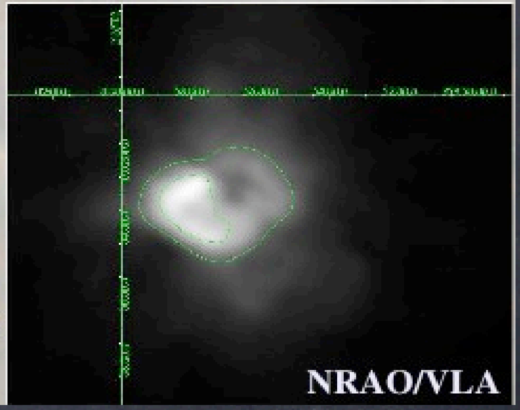
After HESS:

W. Hofmann, MPIK Heidelberg



Position: 14" ± 30" from Sgr A*
Extension: $\sigma < 3'$ (7 pc)



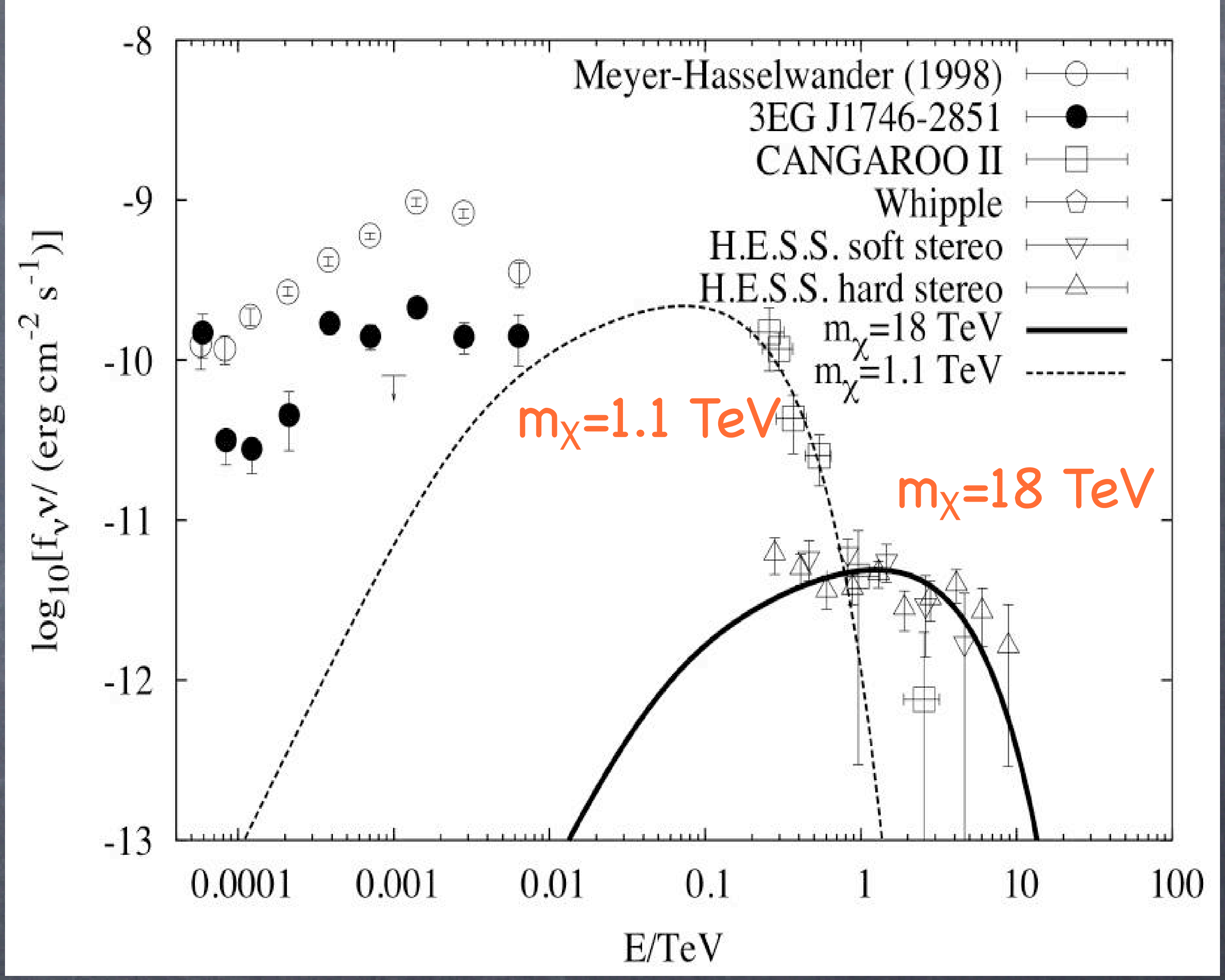


Sgr A East
(90 cm)

Could It Be Dark Matter?

D. Horns, Phys. Lett. B 625, 225, 2005

CANGAROO and **HESS** data:
could be fit by neutralinos
but very heavy ones in
the case of HESS: **M≈18 TeV**
(CANGAROO: **M≈1.1 TeV**)



Acceleration associated with SMBH
nearby SN can not be ruled out

Important to establish:

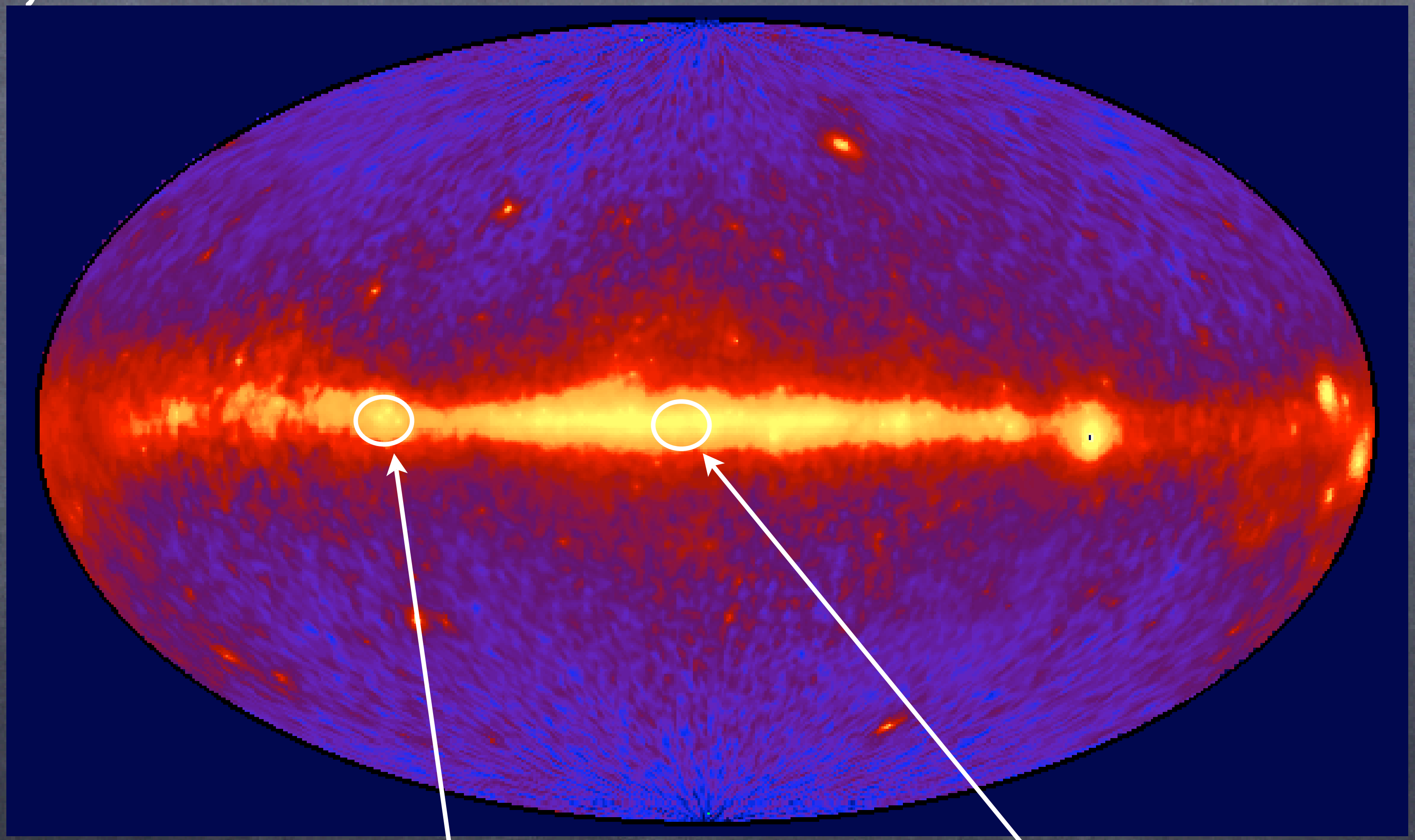
source location

time variability

energy spectrum

The Diffuse Gamma Ray Sky

EGRET: large catalogue of gamma ray sources above 100 MeV (~60% unidentified)



Galactic plane emission (Milagro)

Cygnus region (Milagro)

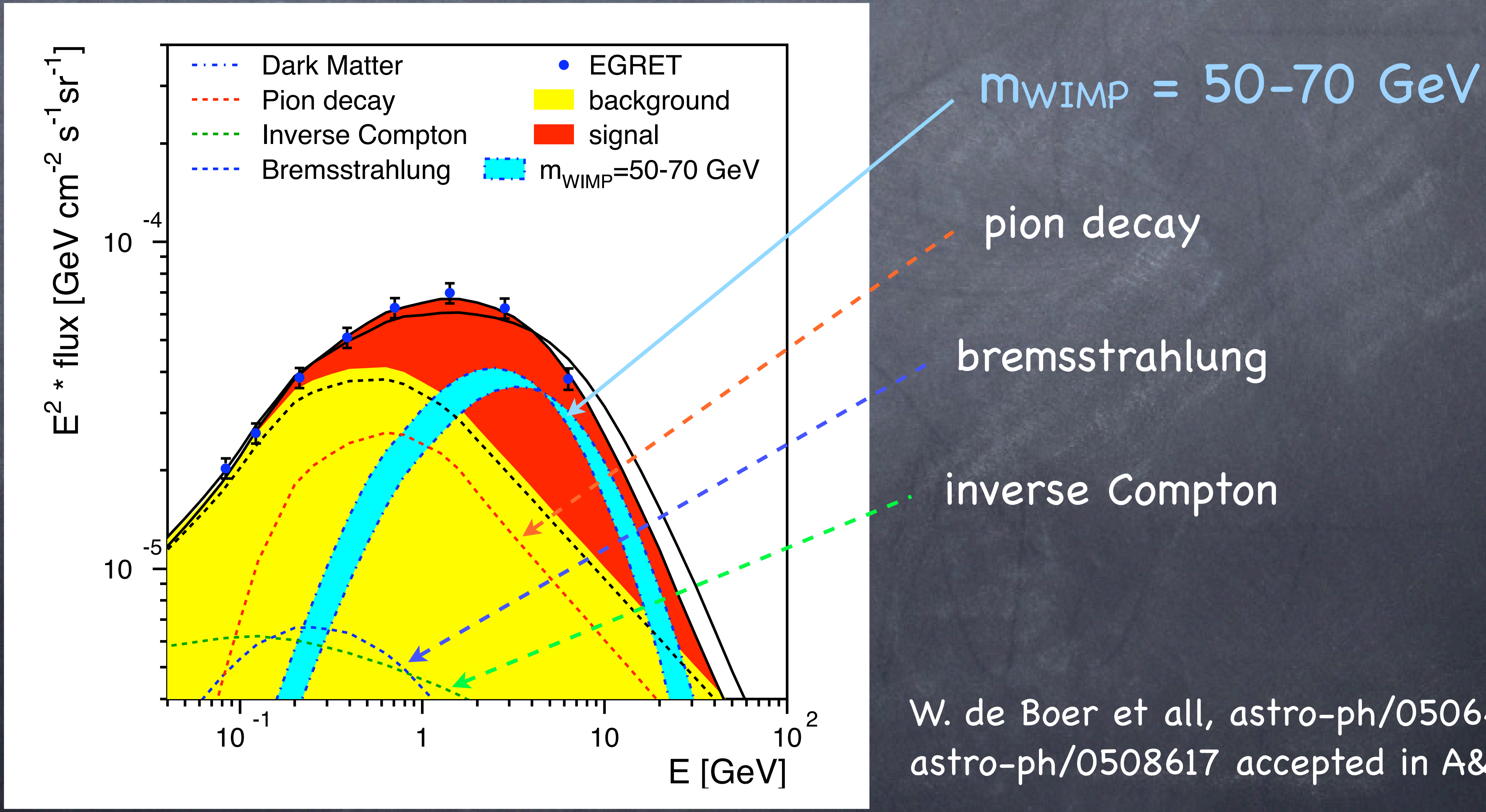
Galactic center region (HESS)

Rene Ong, 2005

EGRET Excess of Diffuse Gammas

Diffuse component: excess by **x2** above expected background

Interpreted as from **Dark Matter Annihilation** in the halo

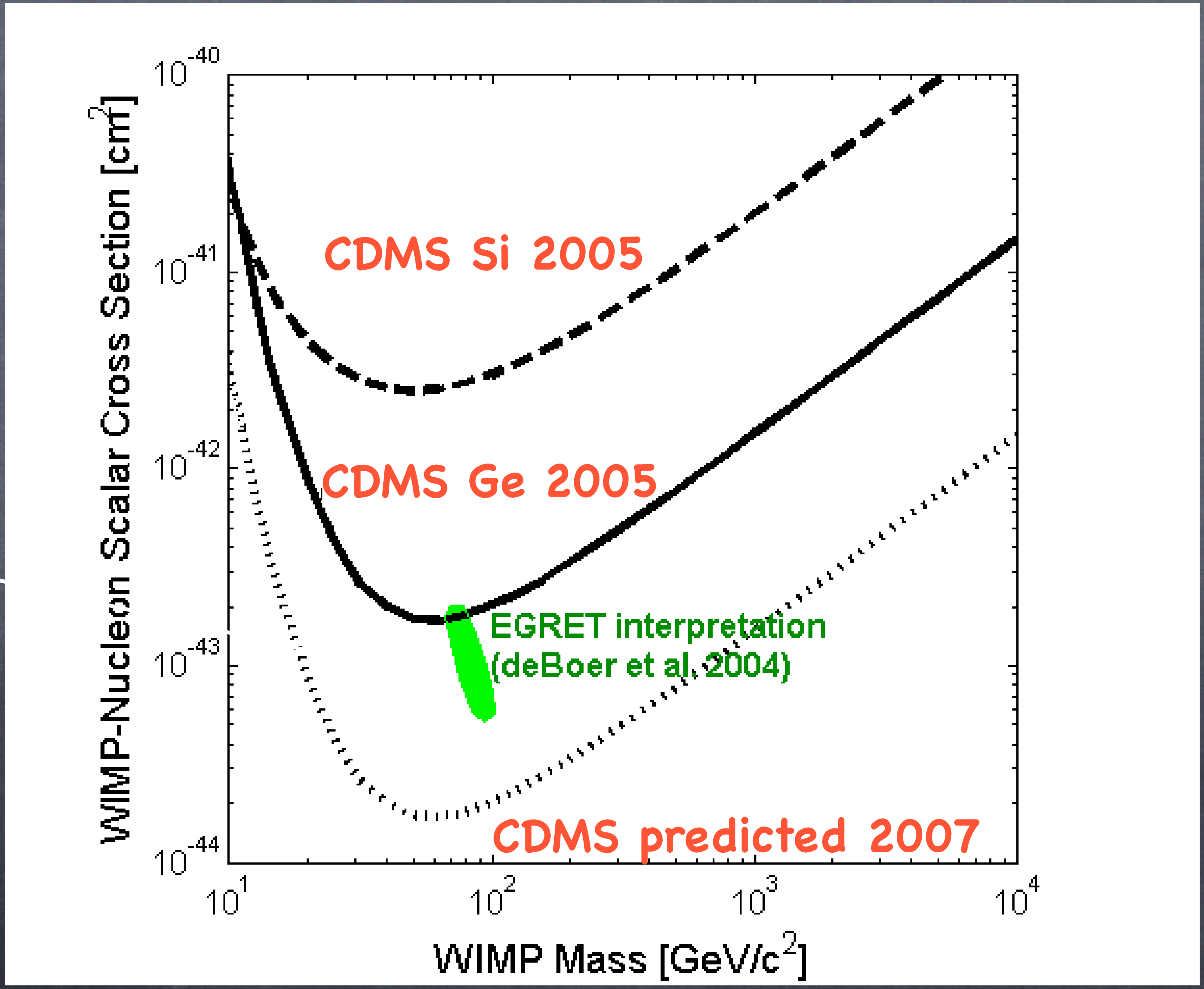


W. de Boer et all, astro-ph/0506447
astro-ph/0508617 accepted in A&A

Predicted EGRET Region and CDMS

EGRET gammas as DM annihilation

W. de Boer
astro-ph/0408272
astro-ph/0508617



WIMP annihilation in Sun/Earth

WIMPs will scatter with nuclei in the Sun and get trapped

when $v < v_{escape}$ => settle to the core => annihilate

Neutrinos ($\approx$ 1/3-1/2 m_{WIMP}) **can escape and be detected**

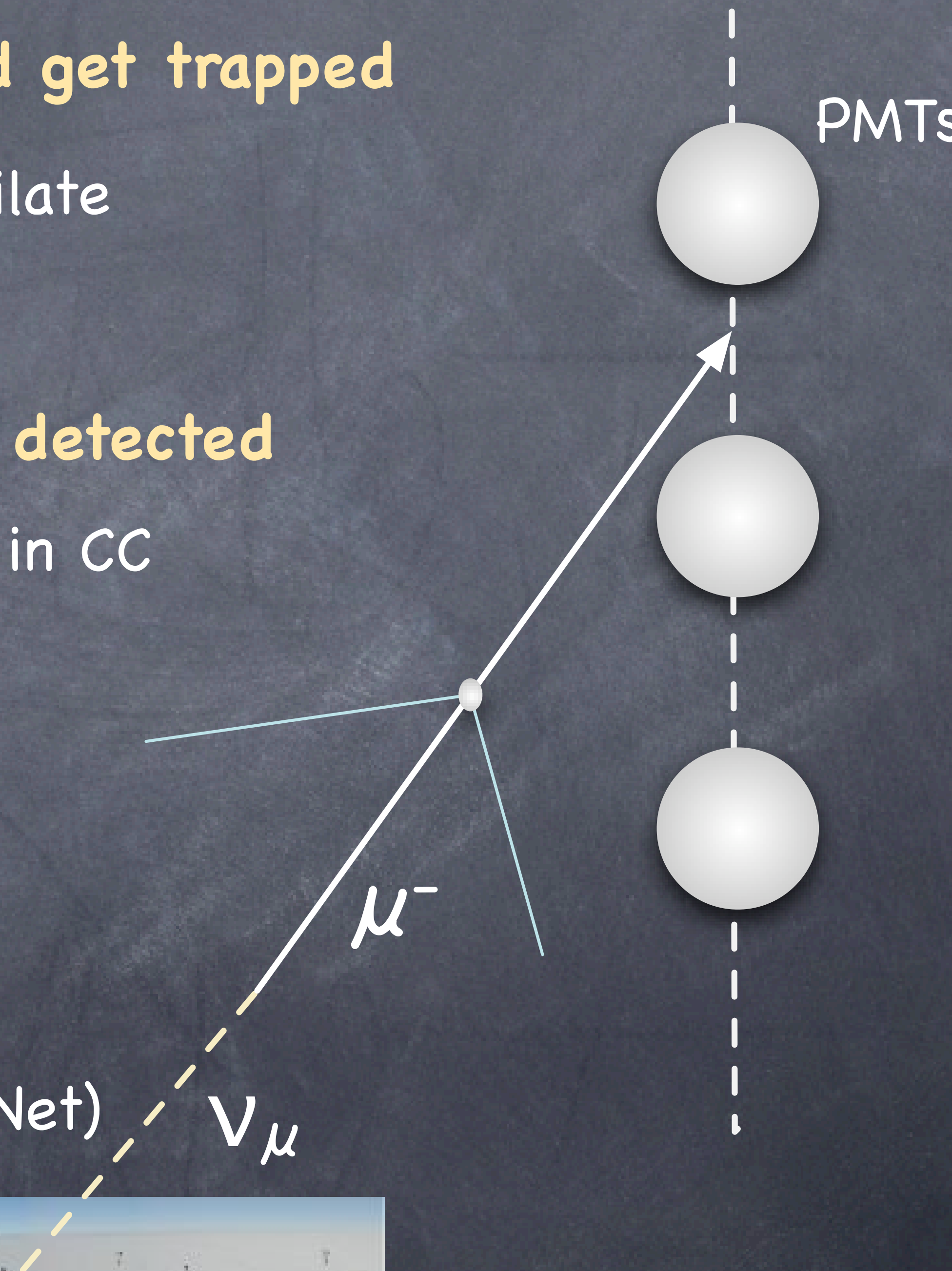
in neutrino telescopes via muon tracks produced in CC

interactions below the detector

Underground Detectors (MACRO, Super-K, ...)

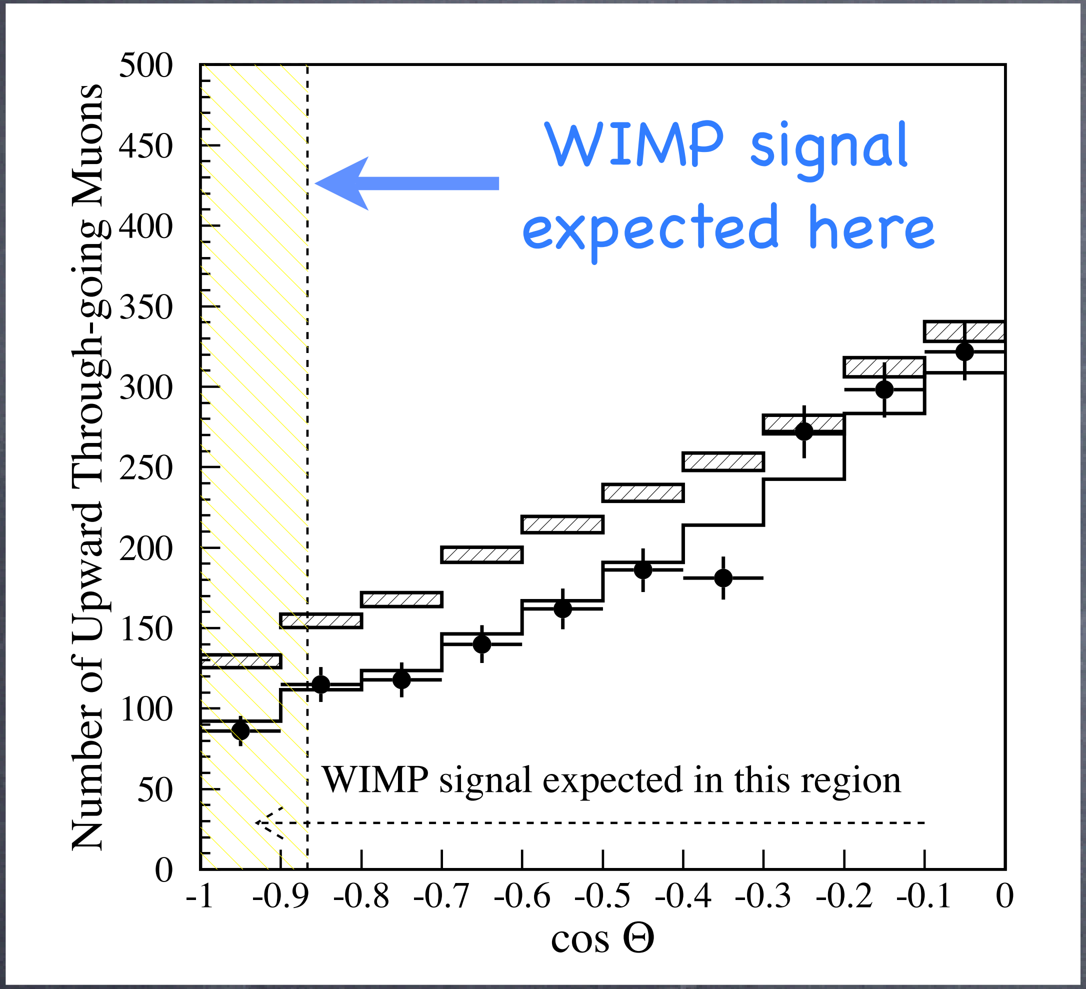
Arrays of PMTs deep in ice, lake, sea (AMANDA,

Baikal, ANTARES, NESTOR, NEMO, IceCube, Km3Net)



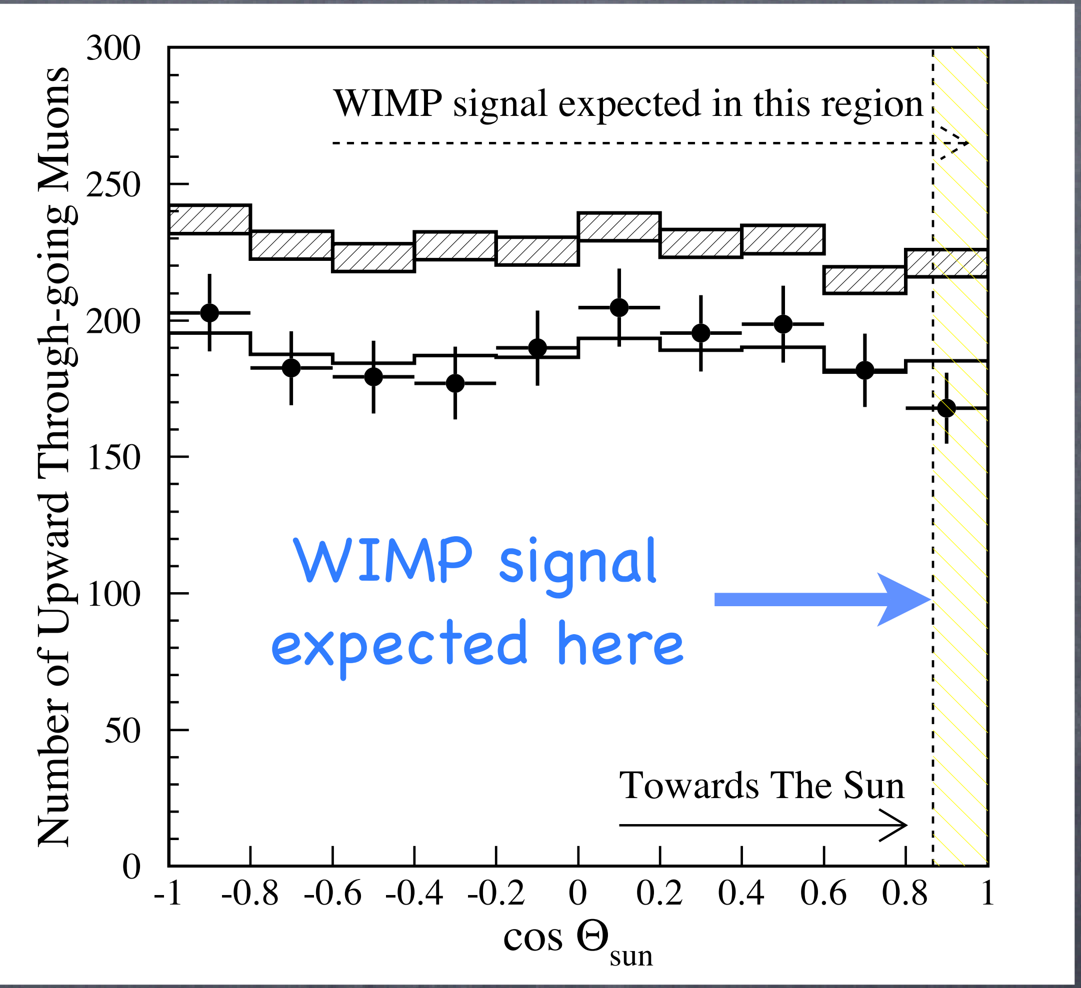
SuperK WIMP Search Results

Earth



Zenith distribution of upward-going μ's

Sun



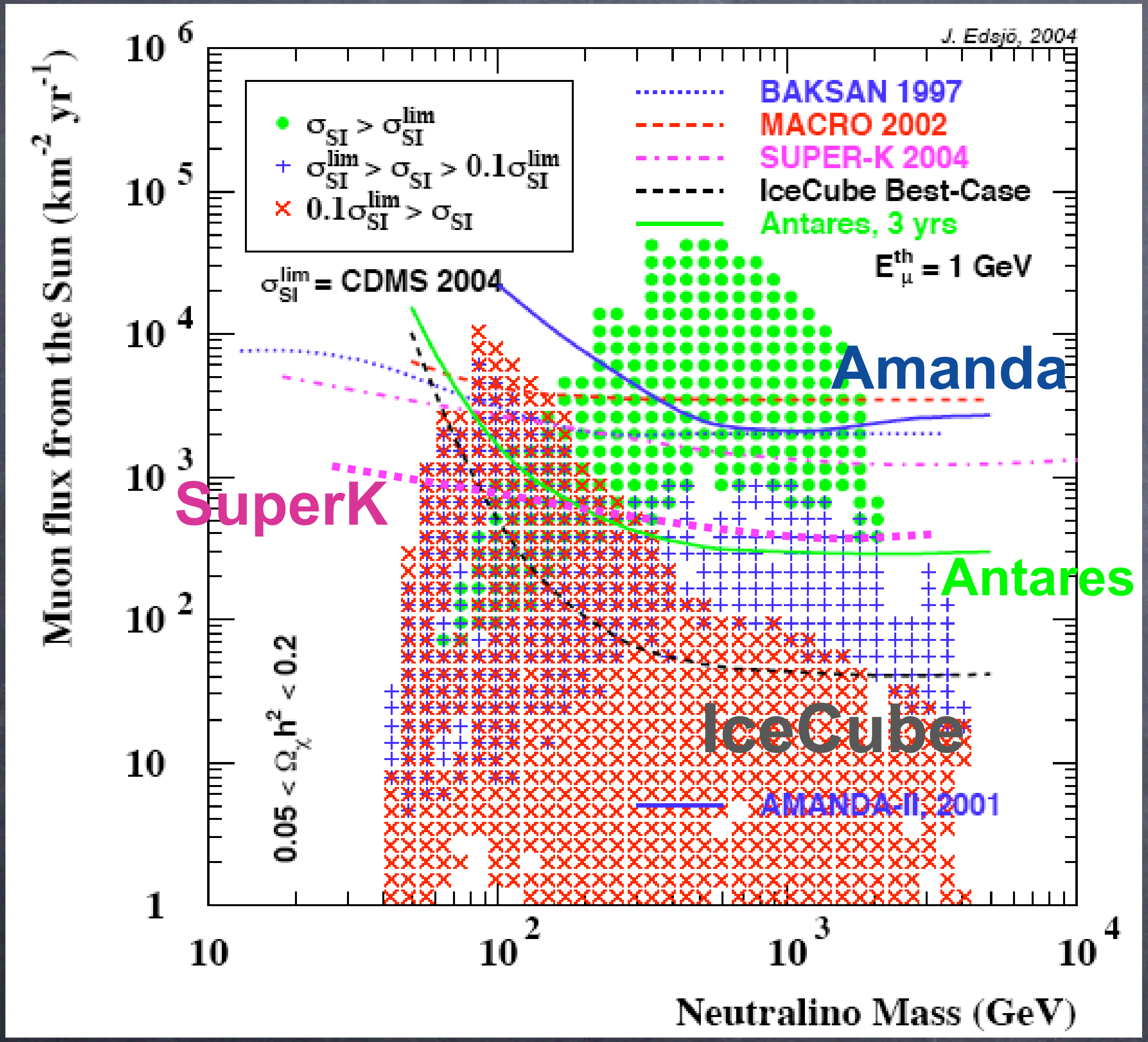
Angular distribution of upward-going μ's with respect to the Sun

No excess seen above atmospheric neutrino background

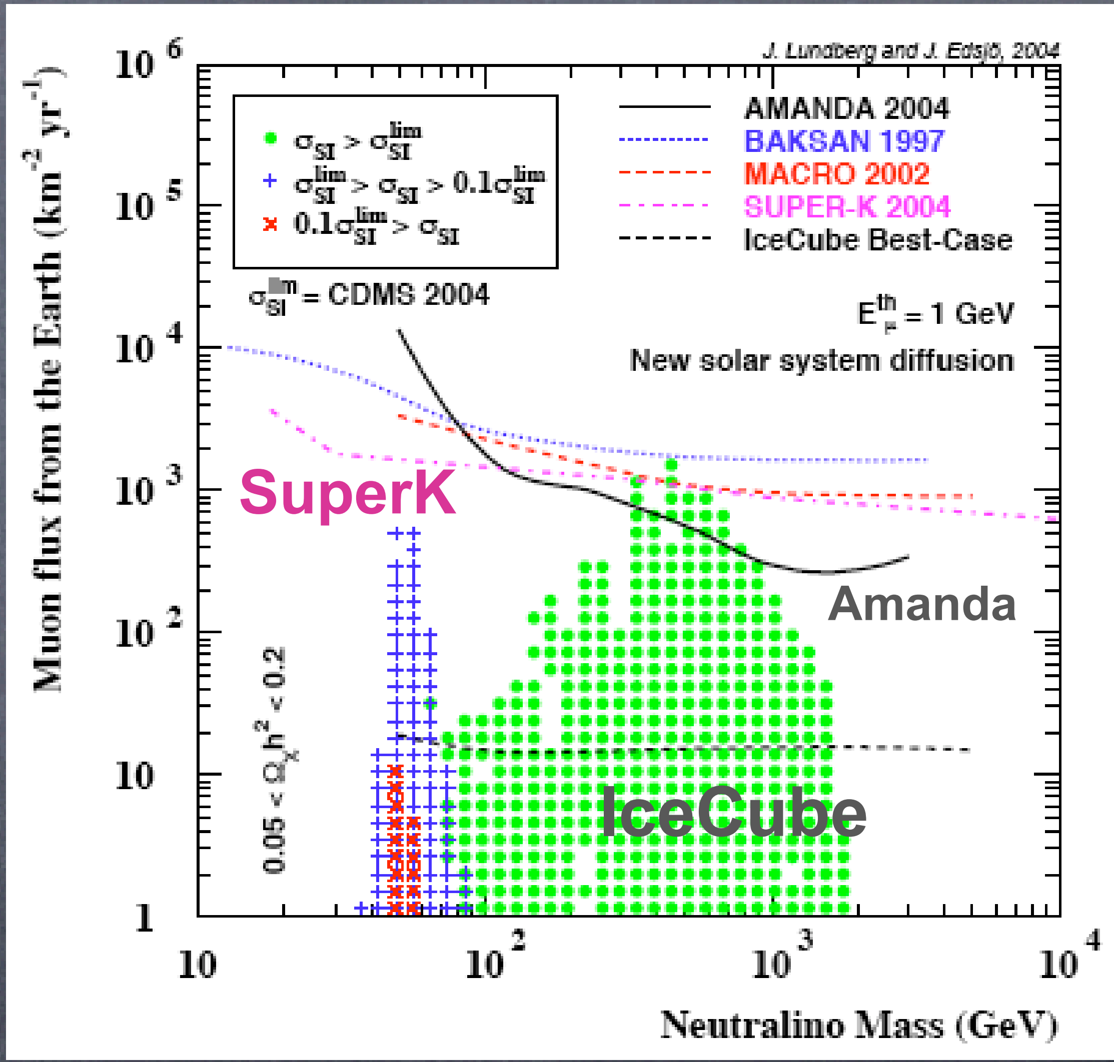
Phys. Rev. D70, 2004 SuperK Collaboration

Limits: Neutrinos from Sun/Earth

Sun



Earth



Green points: excluded CDMS 2004

J. Edsjö 2004, with DarkSusy

Summary

Direct detection

discover relic particle

constrain $(m, \rho \times \sigma)$

with input from LHC/ILC

determine ρ_{local}

Indirect detection

discover relic particle

constrain $(m^2, \sigma \times \int \rho^2)$

with input from LHC/ILC

determine $\rho_{GC/halo}$

LHC/ILC

discover new particles

determine physics model and m_{WIMP}

predict direct/indirect cross sections

Conclusions

Dark matter: very exciting field! Many ideas, many experiments...

Direct detection: 10^{-7} pb level reached for the first time (CDMS 2005)

=> test some SUSY and UED models

Indirect detection: several possible signals; predicted WIMP masses from 60 GeV - 18 TeV! (astrophysical uncertainties much higher)

LHC/ILC: will hopefully discover new particles and provide the microscopic properties of possible dark matter candidates.

GOAL: study the distribution of dark matter in the galaxy, understand how the galaxy formed

More slides...

Halo profile from N-body simulations

N-body simulations suggest a universal dark matter profile, with the same shape for all masses. The parameterisation for a dark matter halo density is:

$$\rho(r) = \rho_0 \left(\frac{r}{R}\right)^{\gamma-1} \left[1 + \frac{r}{R}\alpha\right]^{(\gamma-\beta)/\alpha}$$

different groups => different results for the spectral shape in the innermost regions of galaxies and clusters - namely for the parameter γ

	α	β	γ	R(kpc)
Kravtsov	2.0	3.0	0.4	10.0
NFW	1.0	3.0	1.0	20.0
Moore	1.5	3.0	1.5	28.0
Iso	2.0	2.0	0	3.5

The Density of Baryons

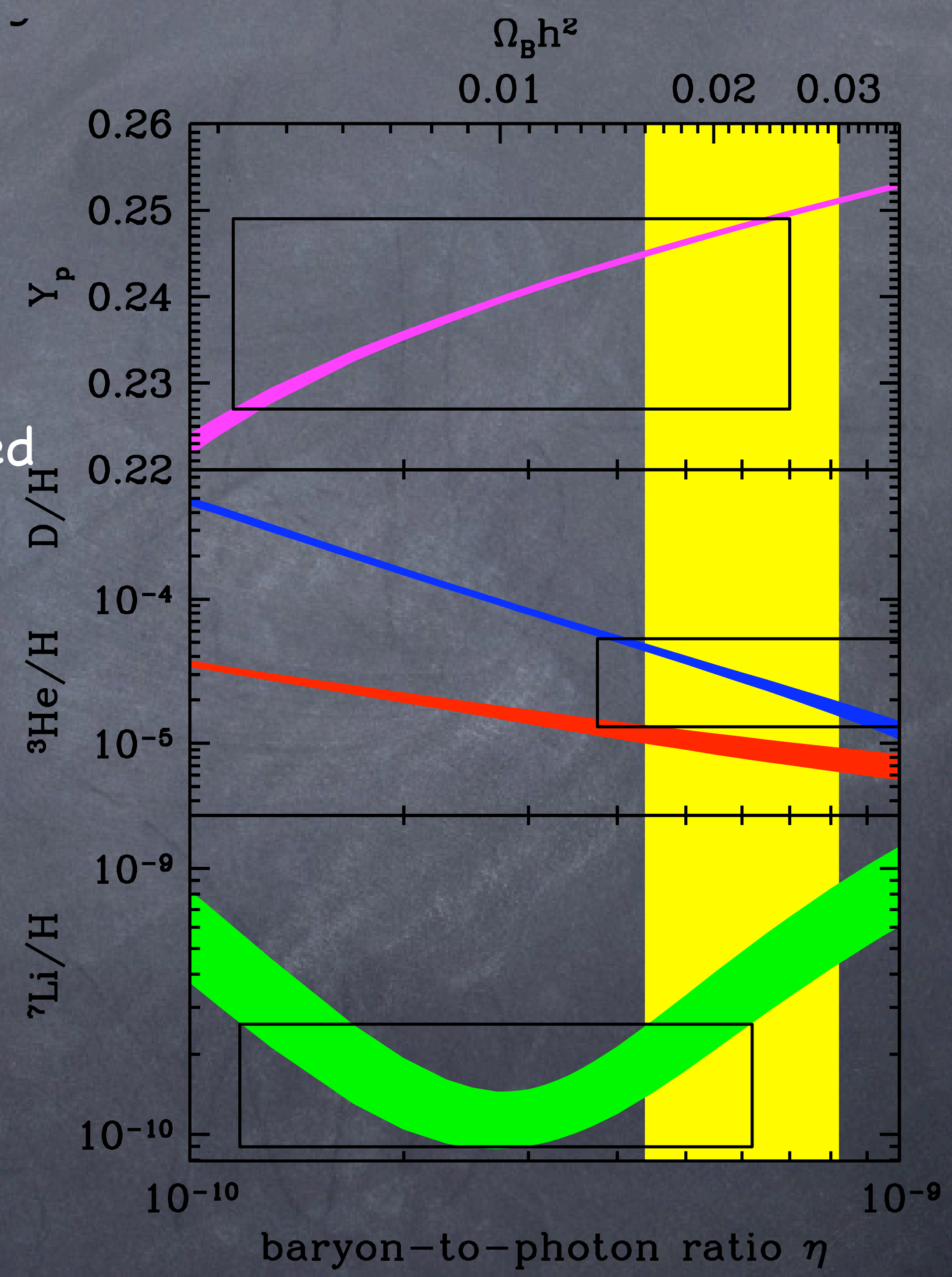
Strongest constraint comes from measurements of the D abundance by absorption of quasar light as it passes through gas clouds at high z

These absorption lines have been measured with the Keck telescope and the HST Since there are no known astrophysical sites producing D, all observed D is primordial

=> $0.016 \leq \Omega_B h^2 \leq 0.024$

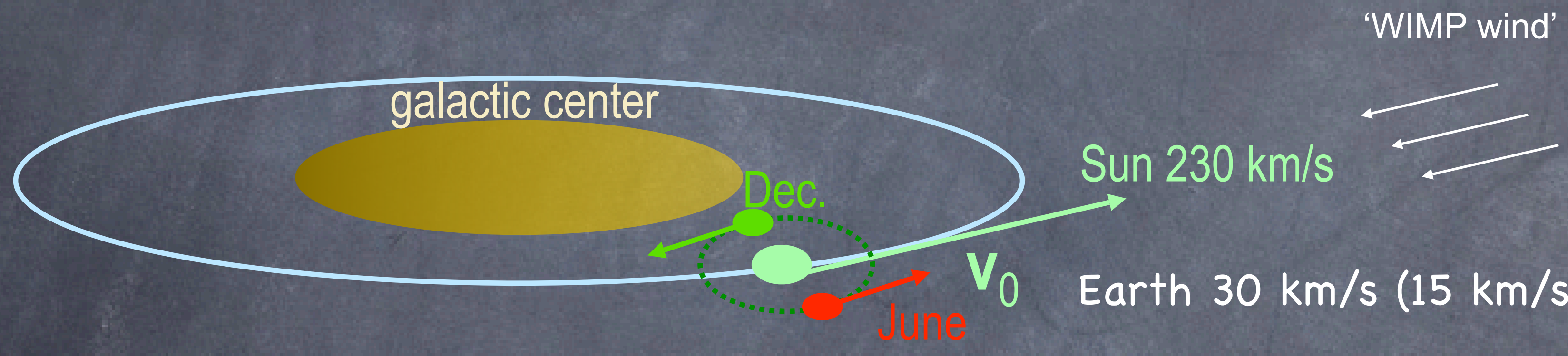
=> Strong support for non-baryonic dark matter!

(yellow = CMB)

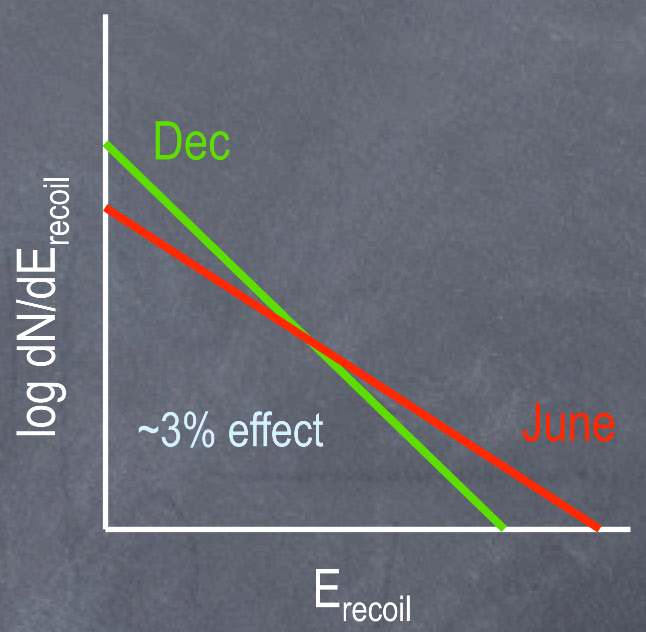


Predicted Signature: Annual Modulation

WIMP Isothermal Halo (assume no co-rotation) v_0~ 230 km/s



Earth 30 km/s (15 km/s in galactic plane)

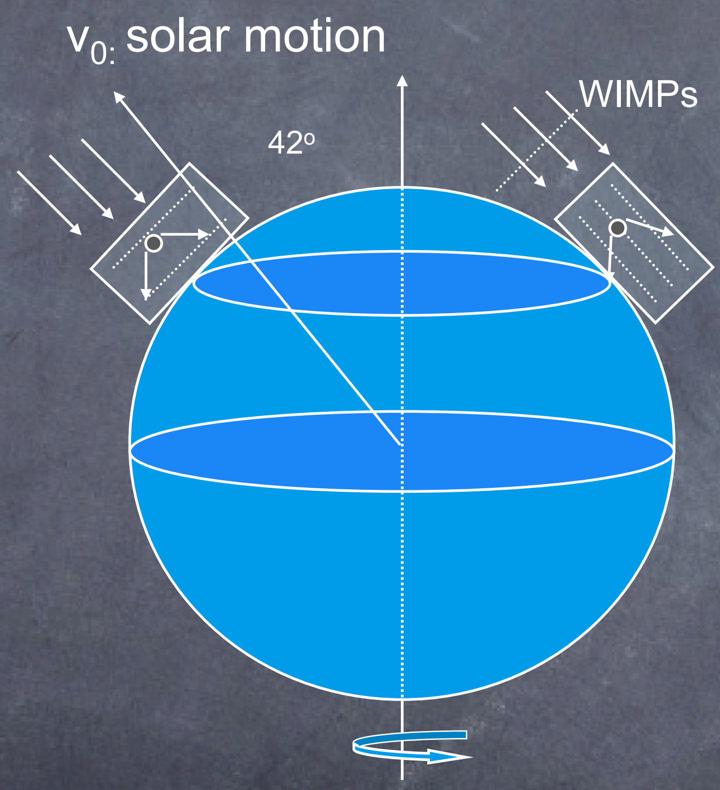


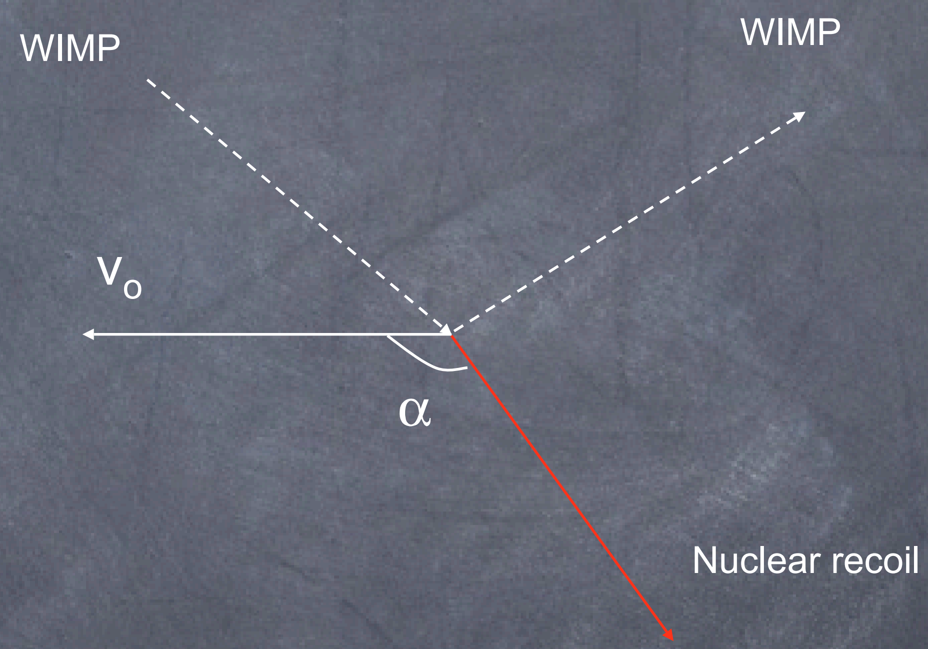
$$f(v)dv = \frac{vdv}{v_e v_0 \sqrt{\pi}} \left\{ \exp\left[-\frac{(v-v_e)^2}{v_0^2} \right] - \exp\left[-\frac{(v+v_e)^2}{v_0^2} \right] \right\}$$

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

The diurnal modulation

In direction:





The mean recoil direction rotates over one sidereal day

The distribution of the angle α between the solar motion and recoil directions: peaks at α=180°

Quenching Factor and Discrimination

WIMPs (and neutrons) scatter off nuclei

Most background noise sources (gammas, electrons) scatter off electrons

Detectors have a different response to nuclear recoils than to electron recoils!

Quenching factor = describes the difference in the amount of visible energy in a detector for these 2 classes of events

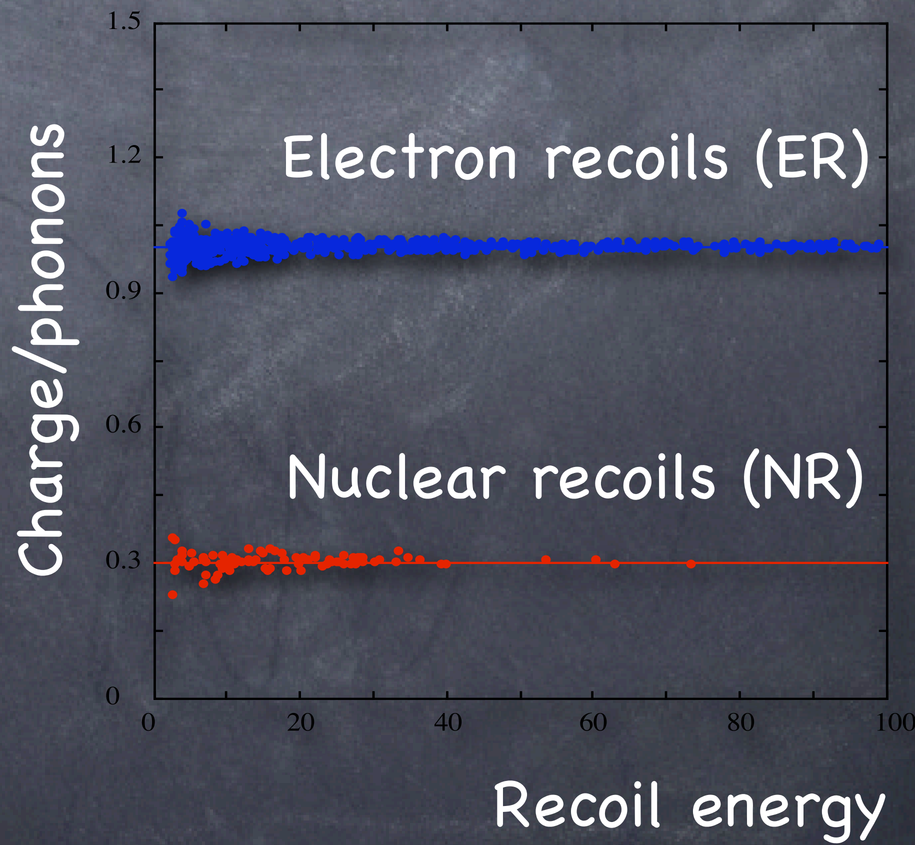
charge and phonons in Ge

$E_{visible}$ ~ 1/3 E_{recoil} for NR

(=> QF ~ 30% in Ge)

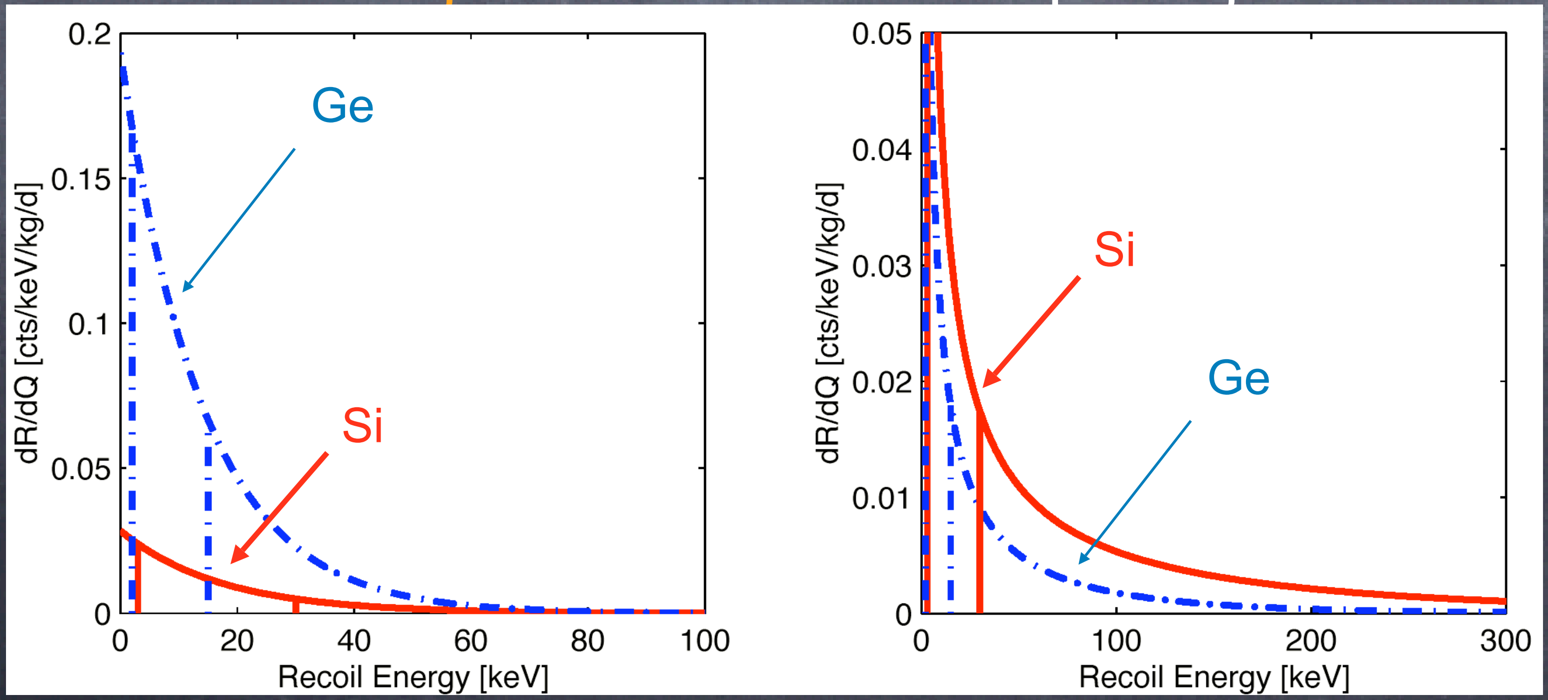
ER = background

NR = WIMPs or neutrons (background)



Neutron Background

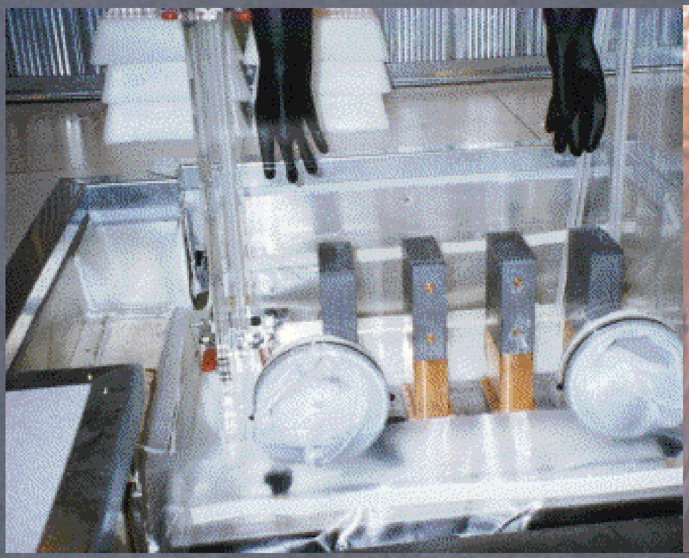
- neutrons generated by muon interactions in the shield: tagged by muon veto
- 'punch through' neutrons: HE n's produced by muon interactions in rock
    - look at ratio of multiple scatters vs single scatter
    - compare 2 different materials
- WIMPs: Ge has ~6x higher interaction rate per kg than Si
- neutrons: Si has ~2x higher interaction rate per kg than Ge



WIMPS 40 GeV

Background neutrons

The DAMA Experiment



At LNGS (3800 mwe)

9 x 9.7 kg low activity NaI crystals,

each viewed by 2 PMs (5-7 pe/keV)

QF on I: ~ 8%

background level: ~1-2 events/kg/d/keV

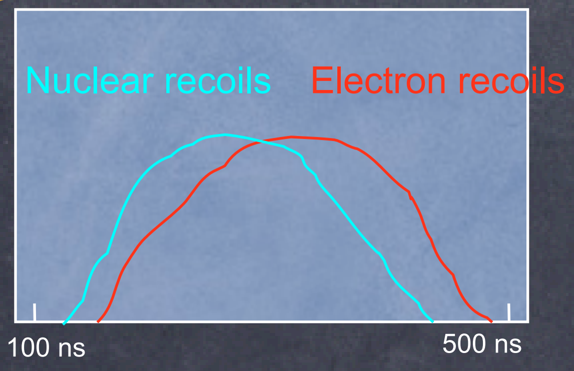
$E_{threshold} \approx 2\ keV_e \approx 25\ keV_r$

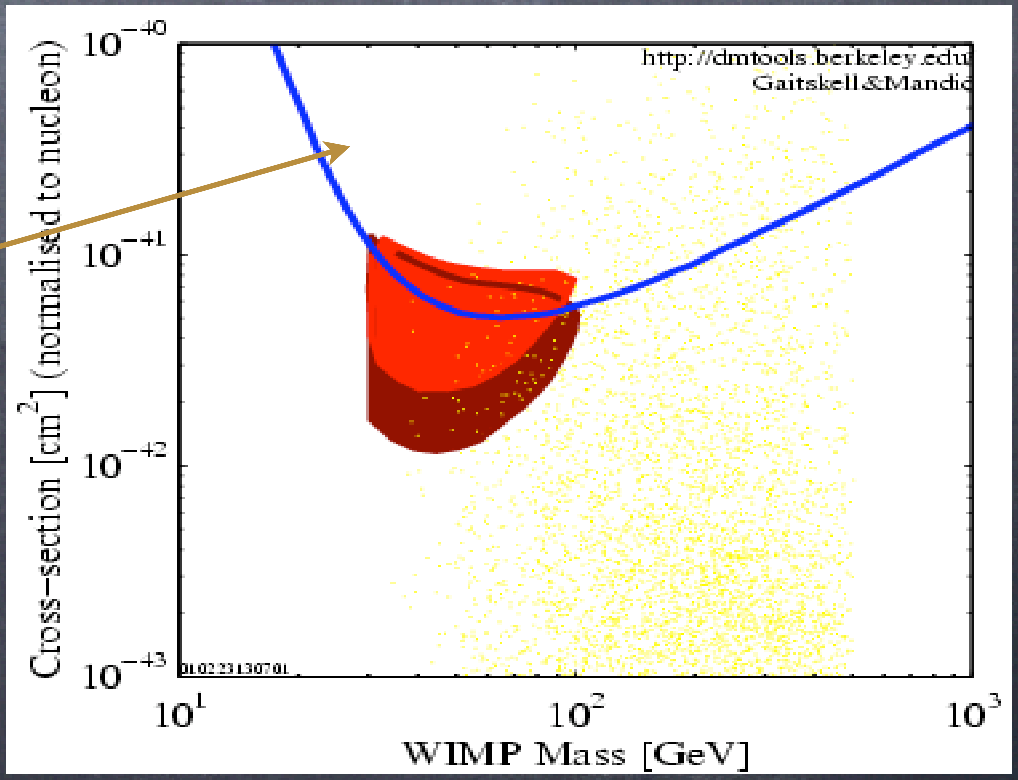
End of data taking 2002

PSD: statistical analysis of

pulse time constant

=> limit from 1996





PLB 509 (2001)

The DAMA Signal

astro-ph/0307403,
Riv. N. Cim. 26, 2003

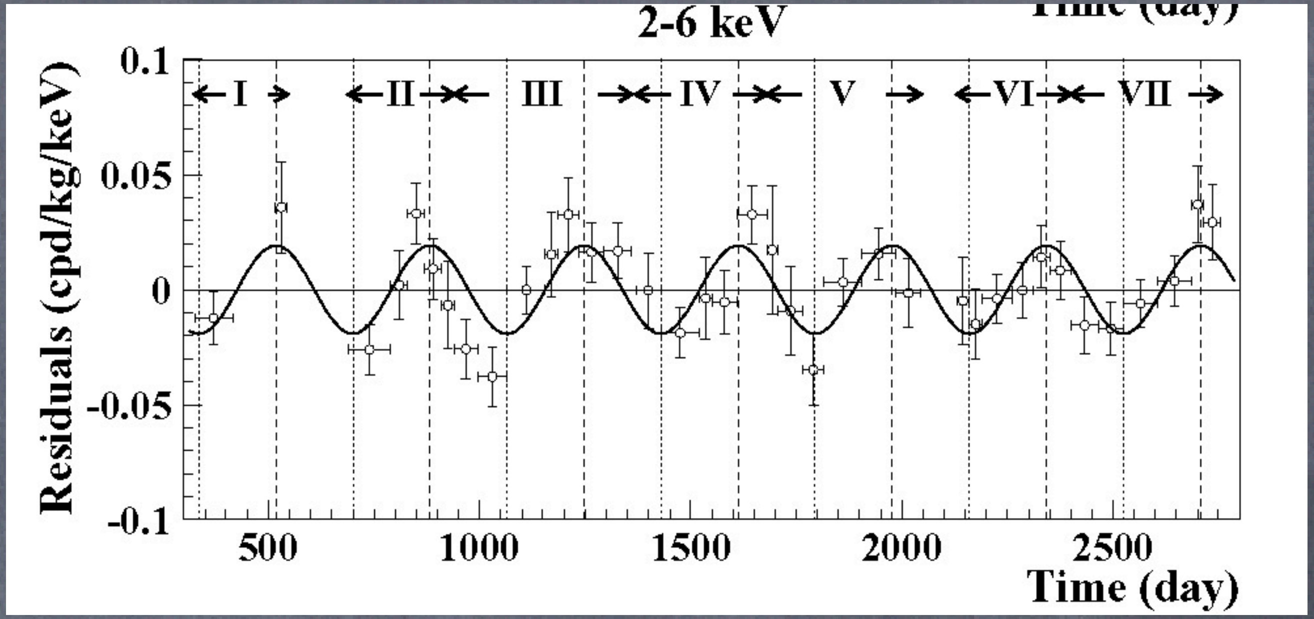
$A \cos [\omega(t-t_0)]$; t_0 = 152.5 d; T = 1yr

Annual modulation analysis:

-> 7 annual cycles:

107800 kg x days

-> positive signal (6.3 σ CL)



Day 1 = Jan 1, 1995; A = 0.0192 +/- 0.0031 c/d/kg/keV

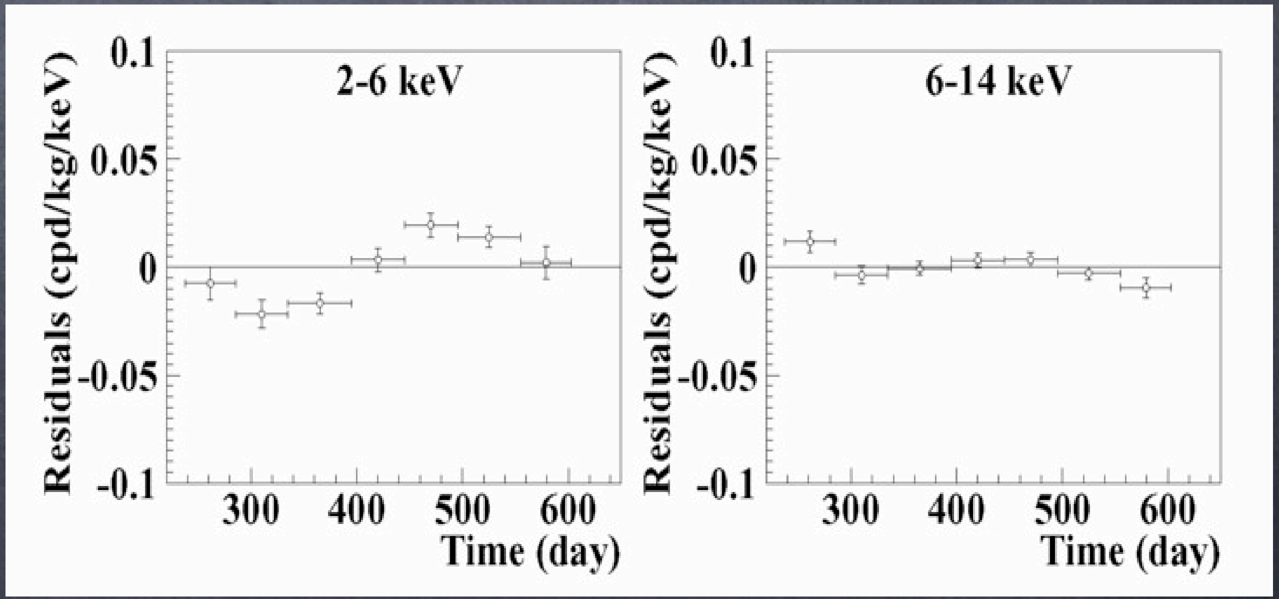
Studied variations of:

T, P(N_2), radon, noise,

energy scale, efficiencies,

n-background,

μ-background



A = 0.0195 +/- 0.031 ev/d/kg/keV

A = -0.0009 +/- 0.0019 ev/d/kg/keV

Technical questions on DAMA

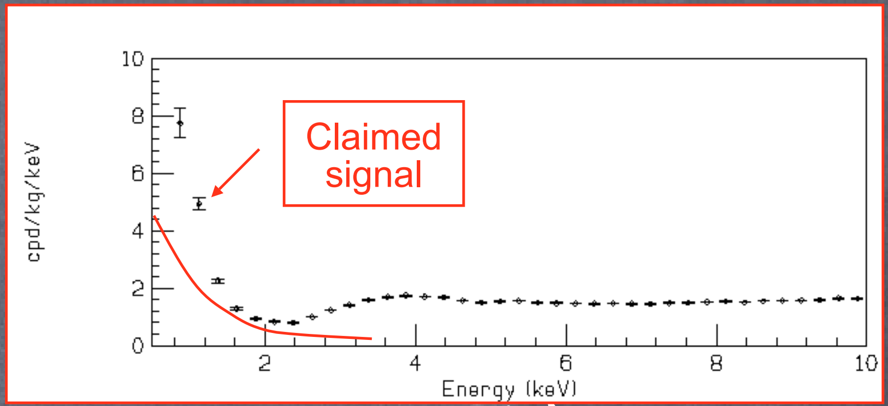
Efficiency?

the signal is in a region of sharply decreasing efficiency

method of determining and monitoring efficiency

local source

spectrum of gammas



Shape of the spectrum?

spectrum before cut

detailed explanation of shape (why does it decrease at threshold?)

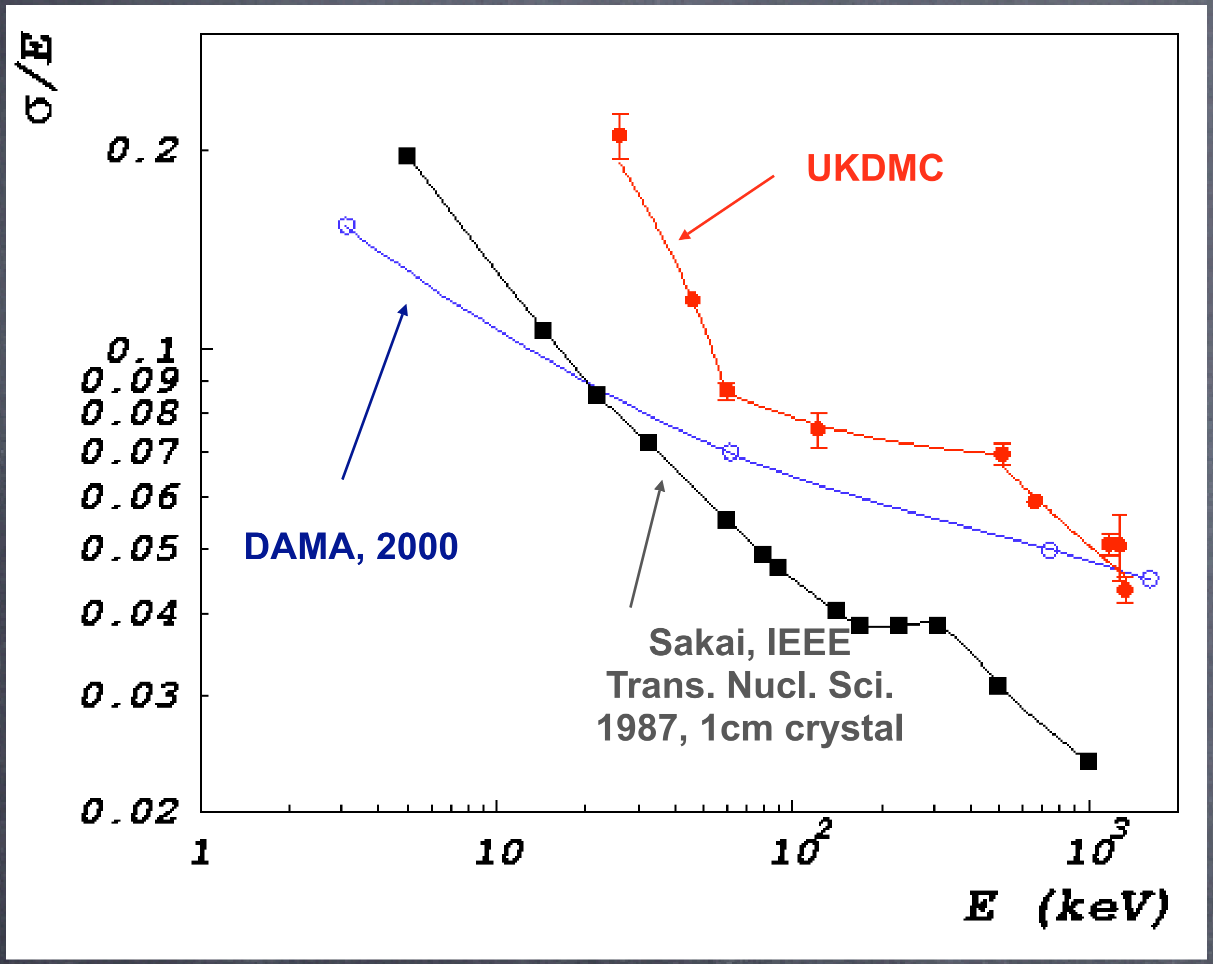
MC simulations of backgrounds

Stability?

is threshold stability sufficient (<1%)?

monitoring of other qualities (noise, etc)

DAMA energy calibration

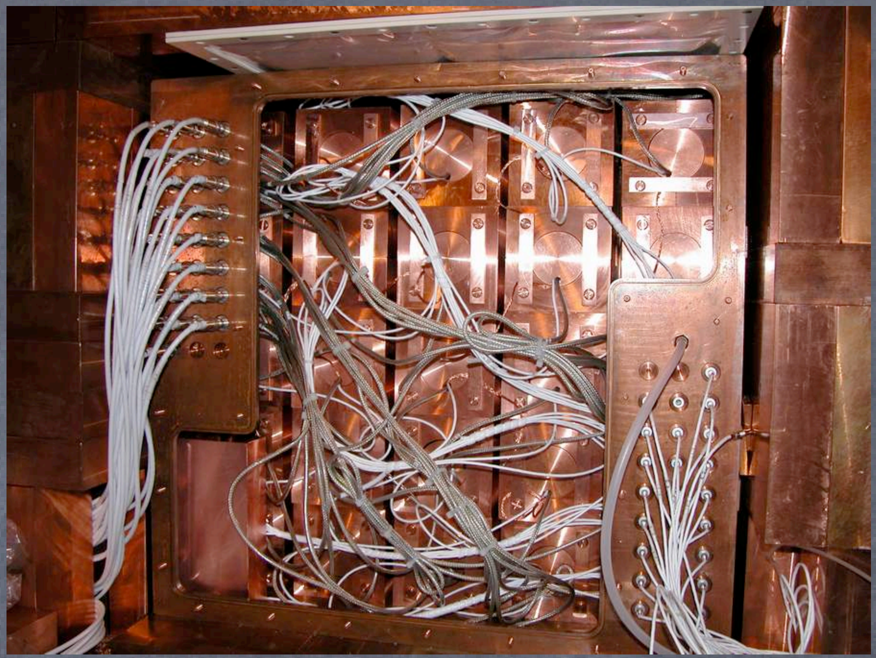


"DAMA energy resolution at low energies is better than the resolution measured for much smaller crystals and better than the poissonian limit with a light yield of 10 p.e./keV"

(UKDM, Robinson et al., 2002)

The LIBRA Experiment

update to LIBRA:



250 kg of radio-pure NaI

new electronics and DAQ

improved background (~few)

improved light yield

installation completed end 2002

runs since March 2003

Cryogenic Experiments

Principle: phonon mediated detectors

Motivation: increase the energy resolution + detect smaller energy depositions

Remember: $$\Delta E \sim \sqrt{\varepsilon E}$$

In Si: ϵ = 3.6 eV /electron-hole pair.

Max phonon energy = 60 meV
=> many more phonons than e-hole pairs will be produced!

As dark matter detectors

thermal phonon detectors (measure an increase in T)

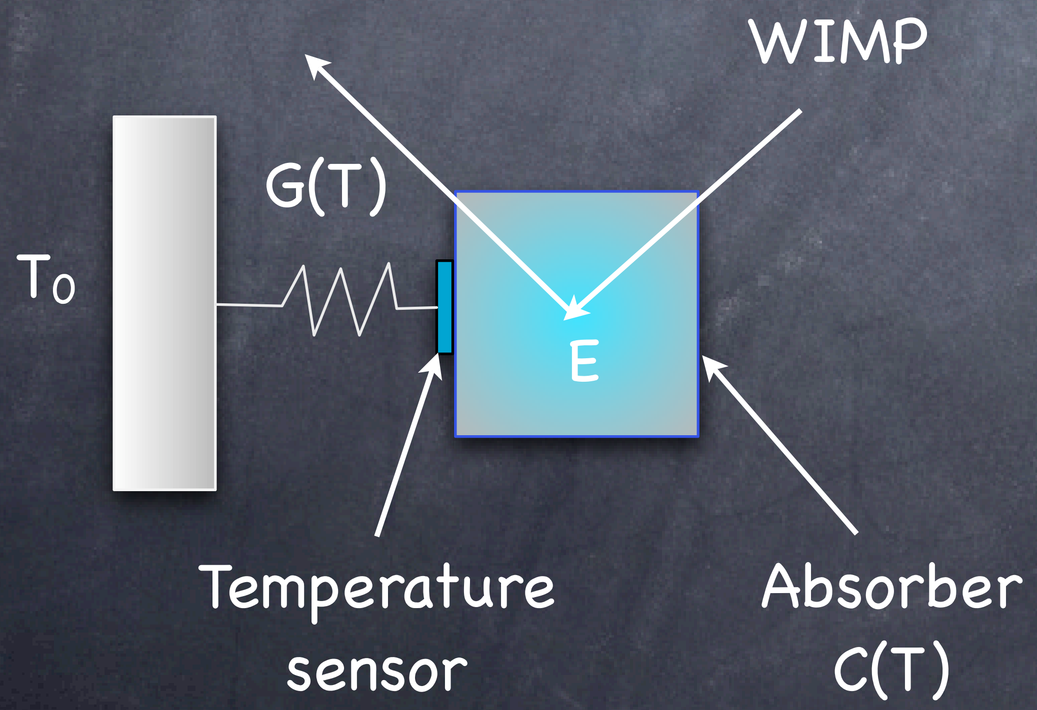
athermal phonon detectors (detect fast, nonequilibrium phonons)

Cryogenic Detectors

A deposited energy E will produce a temperature rise ΔT:

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}, \qquad \tau = \frac{C(T)}{G(T)}$$

C(T) = heat capacity
G(T)=thermal conductance link between the absorber and the reservoir at T_0



Normal metals: the electronic part of C(T) ~ T, and dominates C at low T

Superconductors: the electronic part is ~ exp($-T_c/T$), T_c = SC transition temperature

negligible compared to lattice contributions for $T \ll T_c$

Basic Principles

=> for pure dielectric crystals and superconductors at $T \ll T_c$:

$$C(T) \sim \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3 JK^{-1}$$

m = absorber mass, M = molecular weight
Θ_D = Debye temperature

=> the lower the T, the larger ΔT per unit of absorbed energy

=> in thermal detectors: E is measured as the temperature rise ΔT

Example: at T = 10 mK, a 1 keV energy deposition in a 100 g detector

$$W \approx 2.35\sqrt{k_B T^2 C(T)}$$

$C(T)/k_B$ = nr of phonon modes
$k_B T$ = mean energy per mode

Basic Principles

=> for pure dielectric crystals and superconductors at $T \ll T_c$:

$$C(T) \sim \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3 JK^{-1}$$

m = absorber mass, M = molecular weight
Θ_D = Debye temperature

=> the lower the T, the larger ΔT per unit of absorbed energy

=> in thermal detectors: E is measured as the temperature rise ΔT

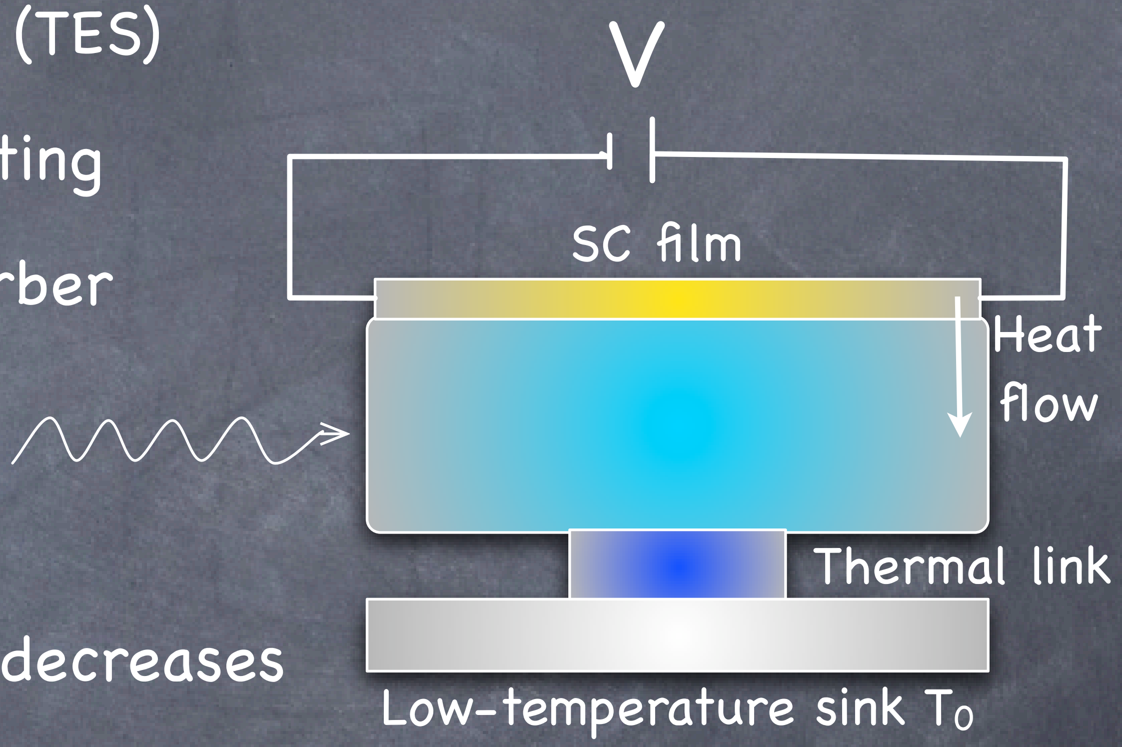
Example: at T = 10 mK, a 1 keV energy deposition in a 100 g detector increases the temperature $\Delta T \approx 1\ \mu K$ => can be measured!

$$W \approx 2.35\sqrt{k_B T^2 C(T)}$$

$C(T)/k_B$ = nr of phonon modes
$k_B T$ = mean energy per mode

TES with Electrothermal-Feedback

$T_0 \ll T_C$; a voltage is placed across the film (TES) and equilibrium is reached when ohmic heating is balanced by the heat flow into the absorber



When an excitation reaches the TES

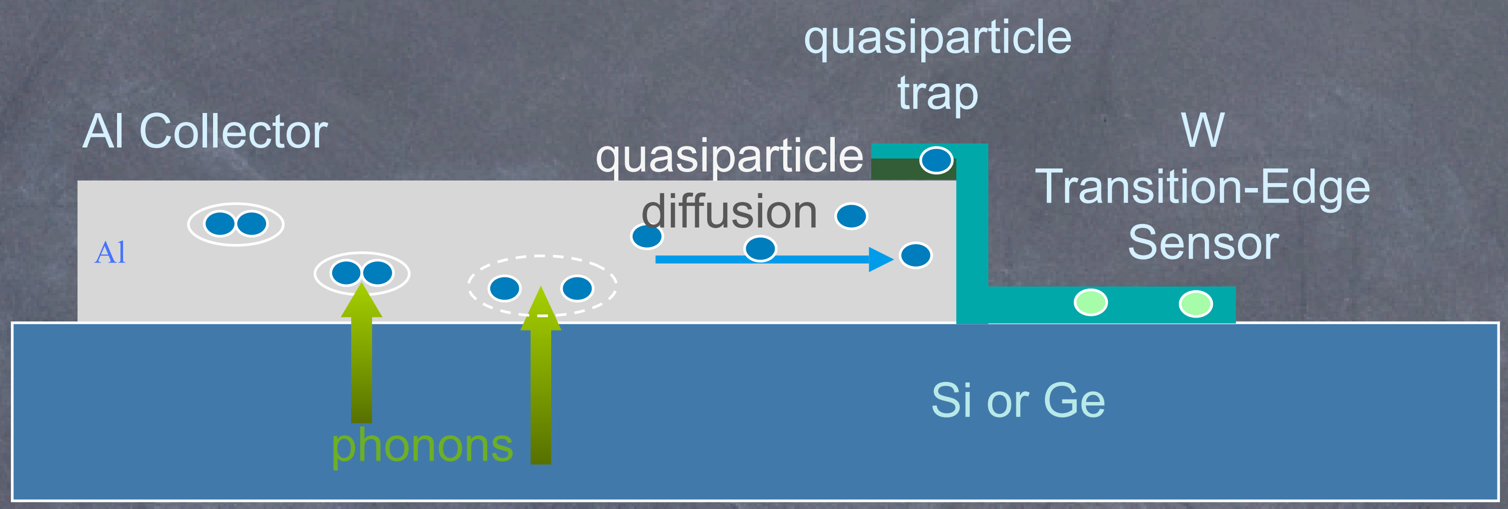
=> the resistance increases => the current decreases by ΔI, as well as the Joule heating

the feedback signal = the change in Joule power heating the film $P=IV=V^2/R$

the energy deposited is:

$$E = -V_B \int \Delta I(t)\,dt$$

The Phonon Signal



Interaction creates THz (~ 4meV) phonons

Phonons propagate to SC Al-fins on the surface, break Cooper pairs and create quasiparticles

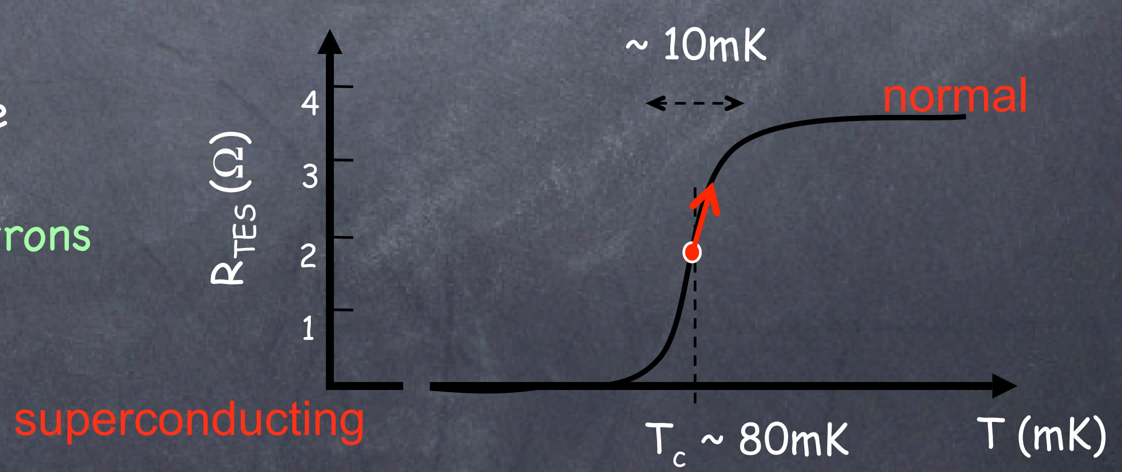
Quasiparticles diffuse in 10 μs through the Al-fins and are trapped in the W transition-edge sensors (TES) where they release their binding energy to the W electrons

The electron system T is raised increased R

The TES is voltage biased and operated in the Electro-Thermal Feedback (ETF) mode, $P_J = V_B^2/R$: when R increases, I decreases

Current change is measured by SQUIDs

W Transition-Edge Sensor: a really good thermometer



The Ionization Signal

An interaction breaks up the electron-hole pairs in the crystal

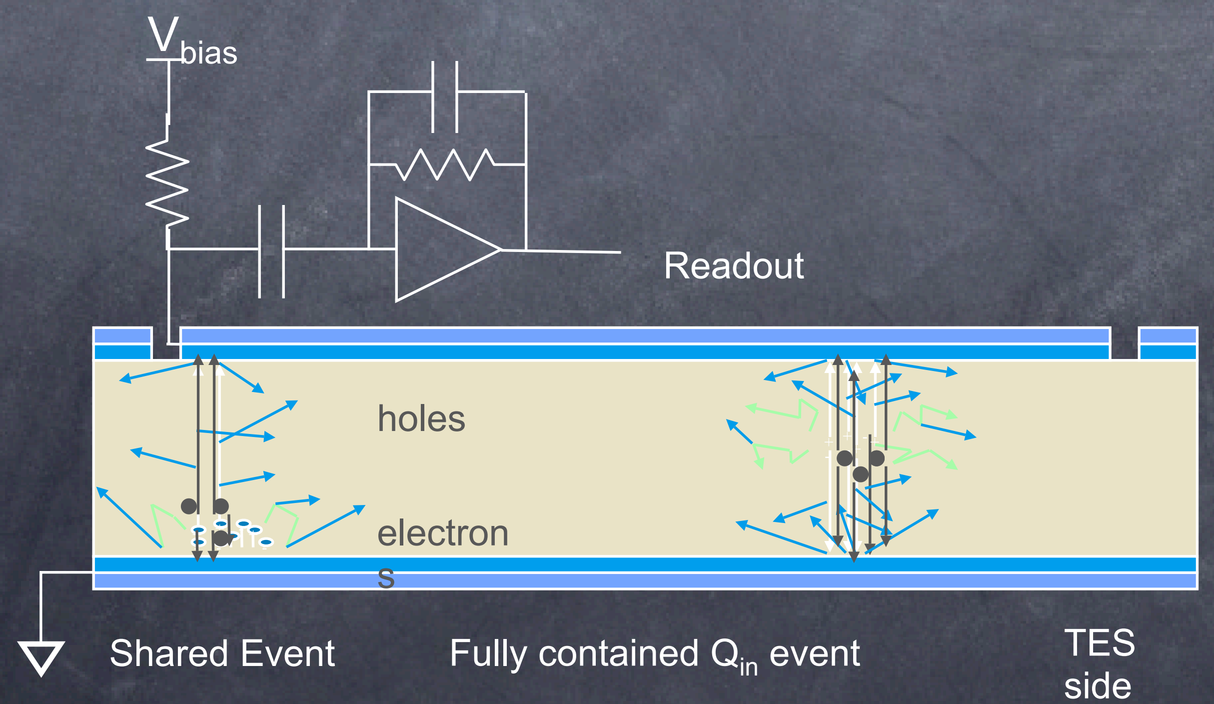
An electric field through the crystal separates the electrons and holes

The charge is collected by electrodes on the surface of the crystal

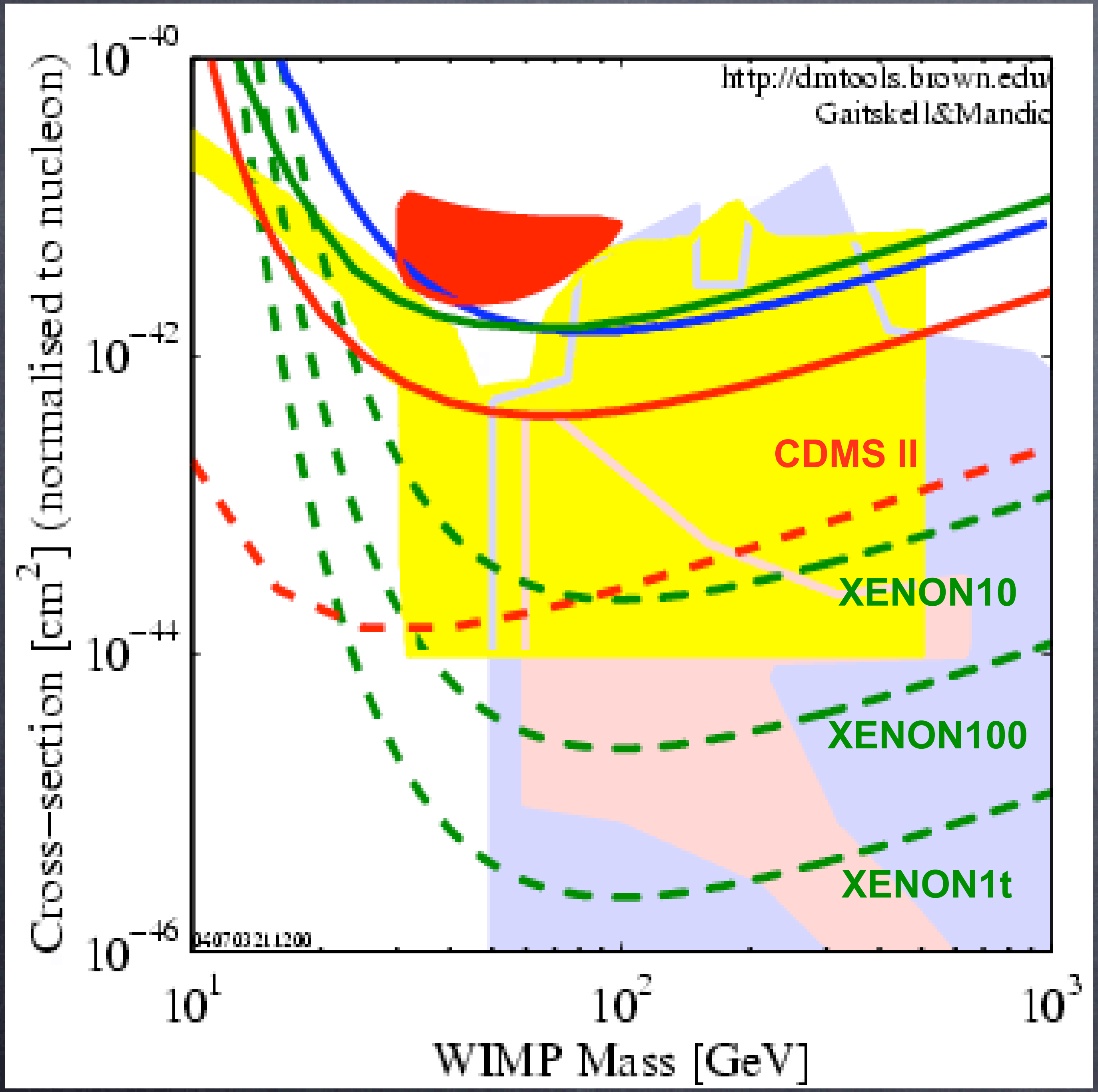
Two charge channels:

- Main electrode: a disk in the center of the crystal surface
- Second electrode: a ring at the edge of the crystal surface

Events within few μm of the surface: deficit charge collection ("dead layer")



Goal of XENON



1t liquid xenon experiment in the Gran Sasso lab/Italy:

XENON10: 10 kg prototype, in GS beginning of 2006

XENON100: first 100 kg module, in GS in 2007/2008

XENON1t: 1 ton (10 x 100 kg modules), in GS in 2010-2015

Test a large part of the predicted parameter space

Discover WIMPs!

The Extragalactic Spectrum

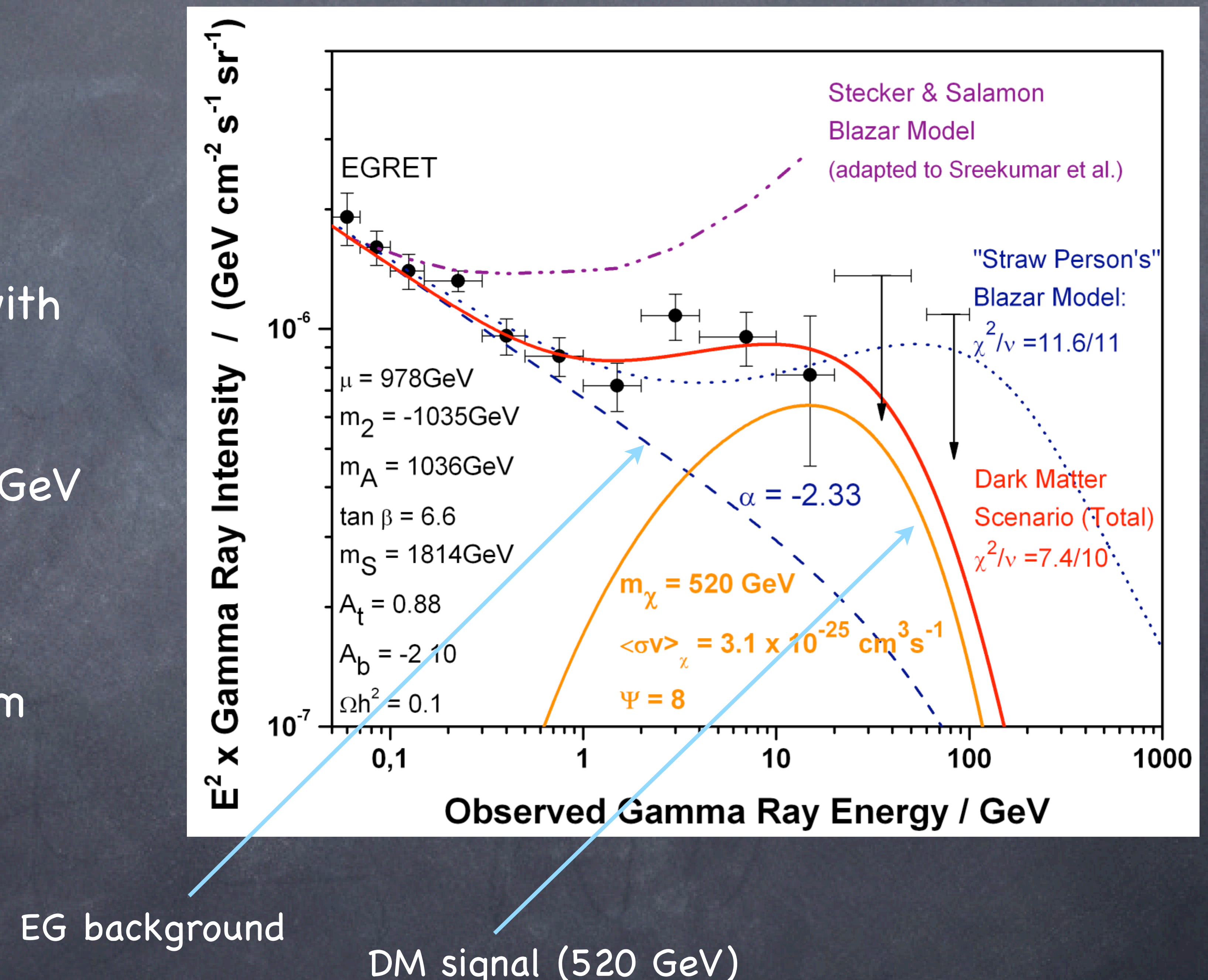
D. Elsaesser, K. Mannheim
Phys. Rev. Lett 94 (2005) 171302

EGRET EGB spectrum

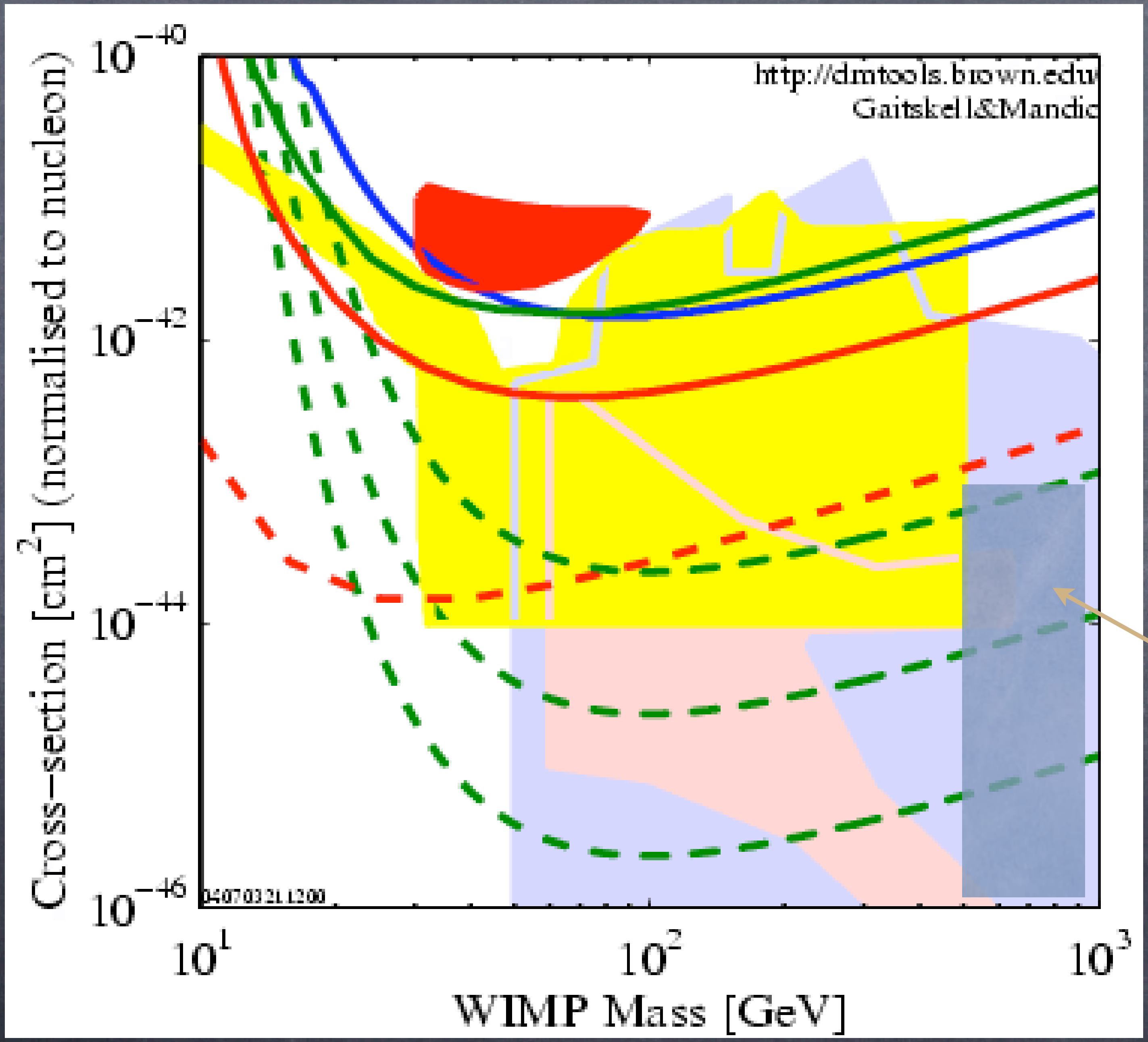
2 components:

- a steep-spectrum law with power index -2.33
- a strong bump at ~few GeV

BUMP: interpreted as from **WIMP annihilation** with m_{WIMP} ~ 500 GeV



EG WIMP Signal and Direct Detection



CDMS 2005

CDMS 2007

EG WIMP
M>500 GeV
$\sigma<10^{-7}$ pb

UED and Direct Detection

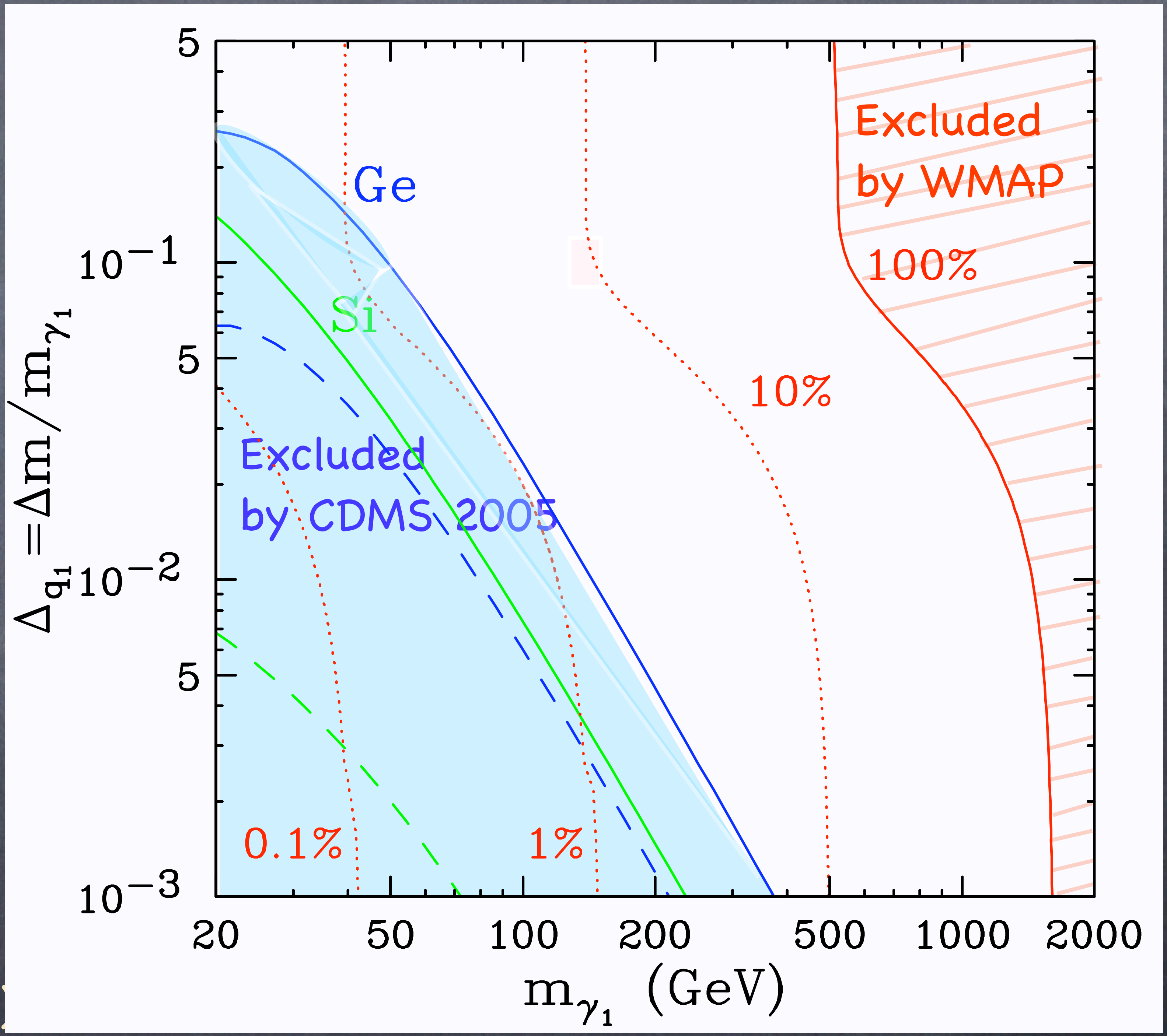
Cross section on quarks depends on $\Delta_{q1}=(m_{q1}-m_{\gamma 1})/m_{\gamma 1}$ (LKP=Υ_1)

Take Δ_{q1} as free parameter

=> translate direct detection limits/predictions on cross section into ($m_{\gamma 1}$-Δ_{q1})-plane

100% curve corresponds to $\Omega_{WIMP(\gamma 1)} \approx 0.27$ (from WMAP)

Spin-dependent cross sections



LB, Kong, Matchev, 2005 preliminary