Particle Dark Matter : Evidence, Candidates and Experiments

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Most of the Experimental Input
from recent talks by
D.Bauer, B Sadoulet, L. Baudis,
B. Cabrera and G. Chardin

Outline

- Evidence for Dark Matter

- Dark Matter Candidates:
  ==> a motivation for New Physics

- Experimental Searches

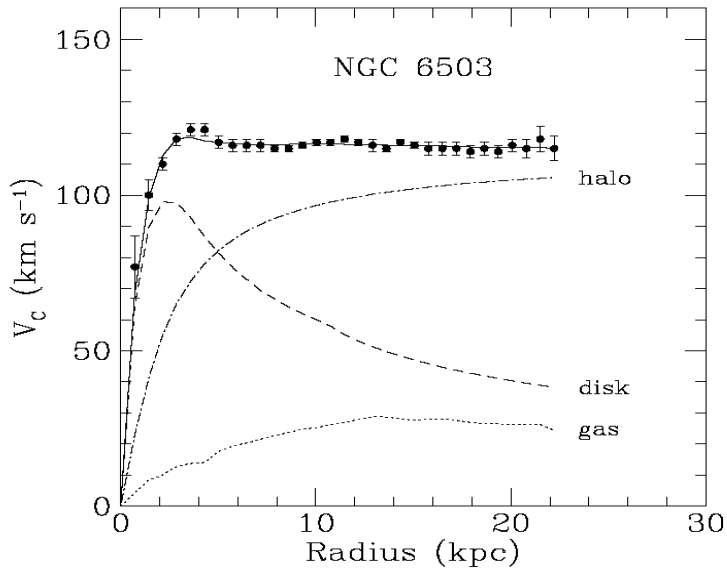
  -- Direct dark matter detection
  -- Indirect detection
  -- The interplay between high energy colliders and astrophysical DM measurements

- Comparison of DM detection technologies (?)

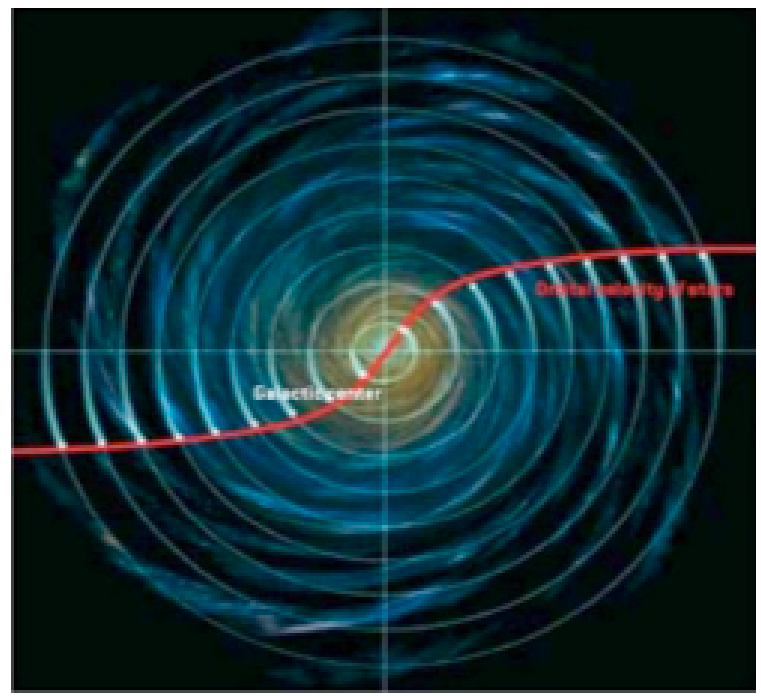
- Outlook

Evidence for Dark Matter:

- Rotation curves from Galaxies.



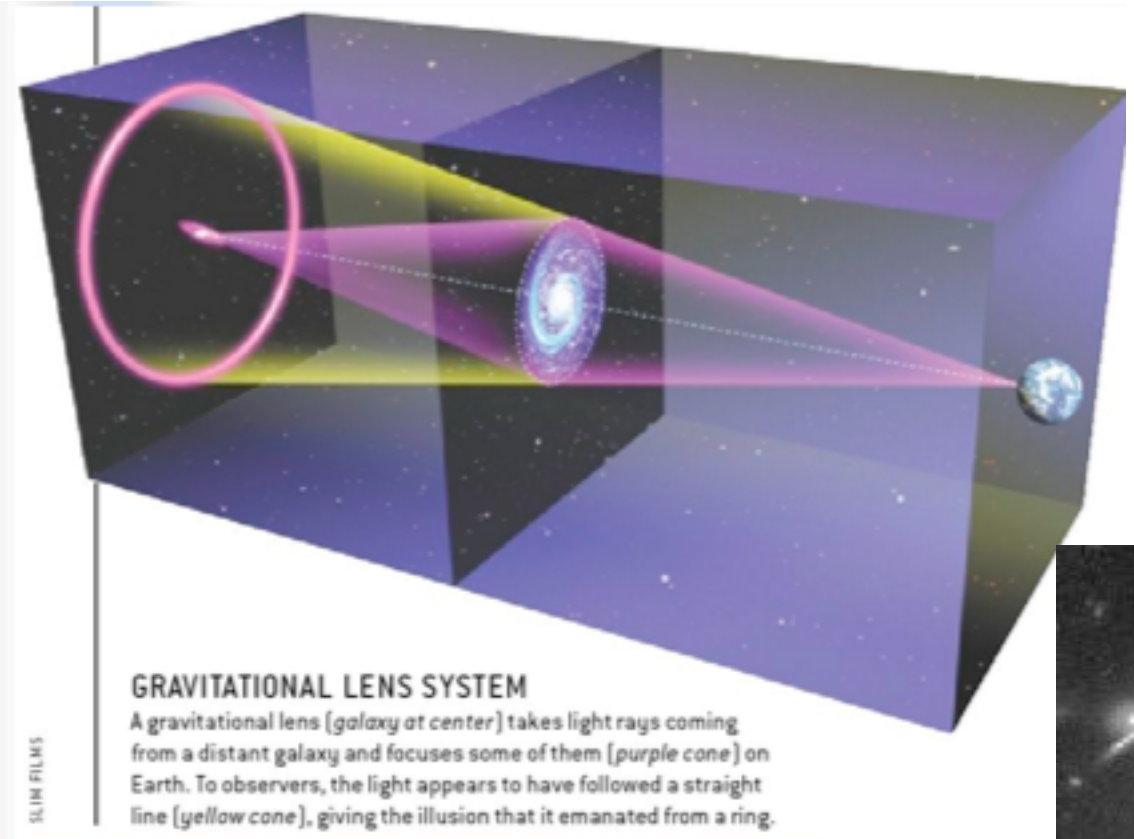
Gravity Prediction: $\frac{v^2}{r} = G_N \frac{M(r)}{r^2} \Rightarrow v^2 \propto \frac{1}{r}$

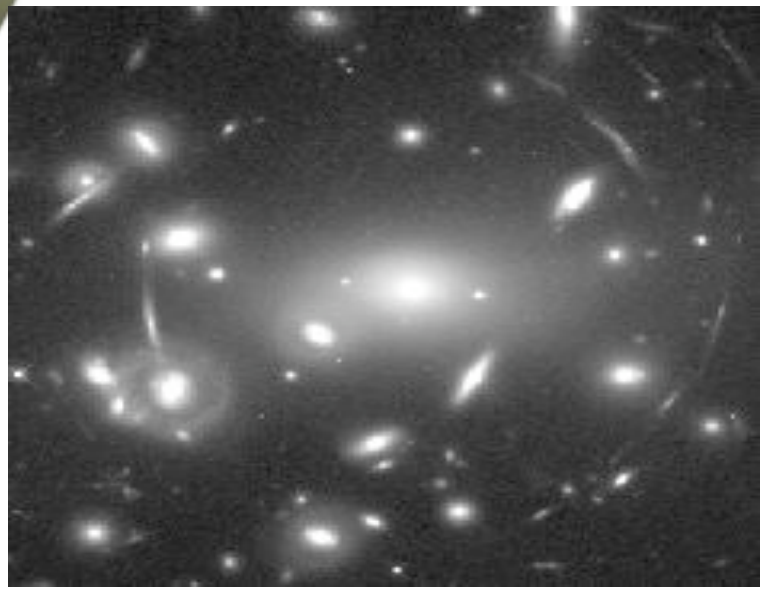


Luminous matter does not account for enough mass to explain rotational velocities of galaxies

==> Dark Matter halo around the galaxies

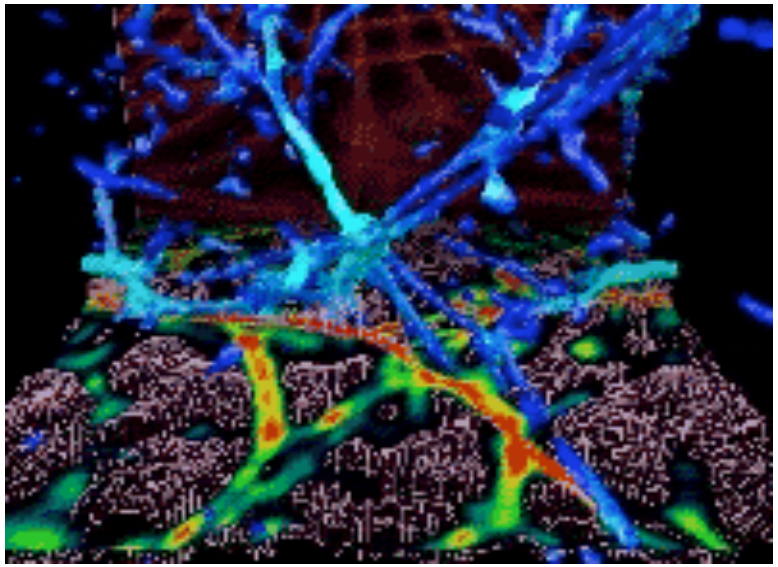
- Gravitational lensing effects

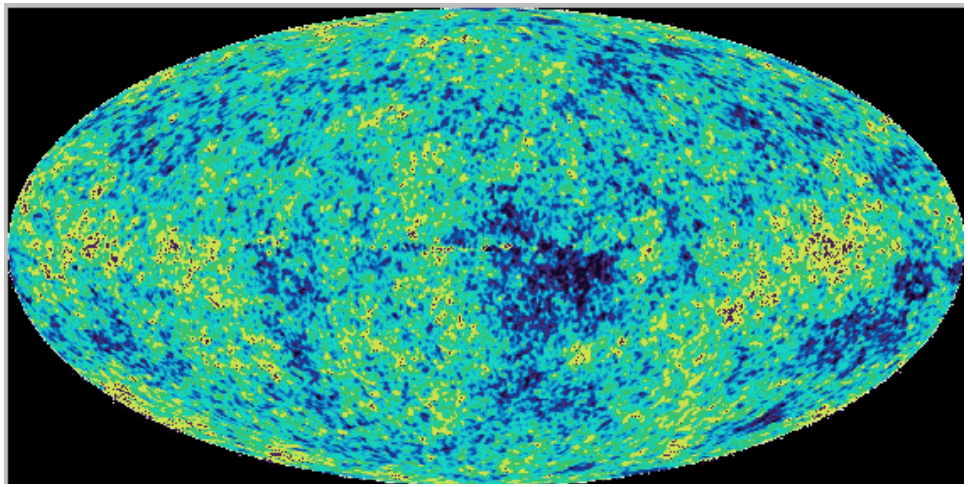




Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies

•Simulations of structure formation:
Large scale structure and CMB Anisotropies





The manner in which structure grows depends on the amount and type of dark matter present. All viable models are dominated by cold dark matter.

Baryon Abundance in the Universe

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

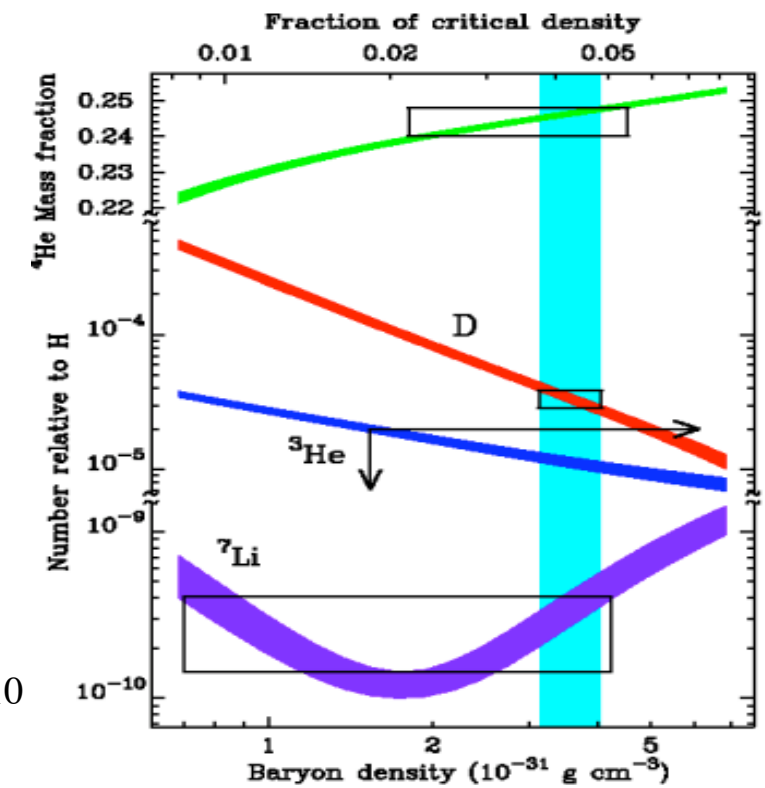
$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$

- CMBR, tell us

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

There is a simple relation between These two quantities

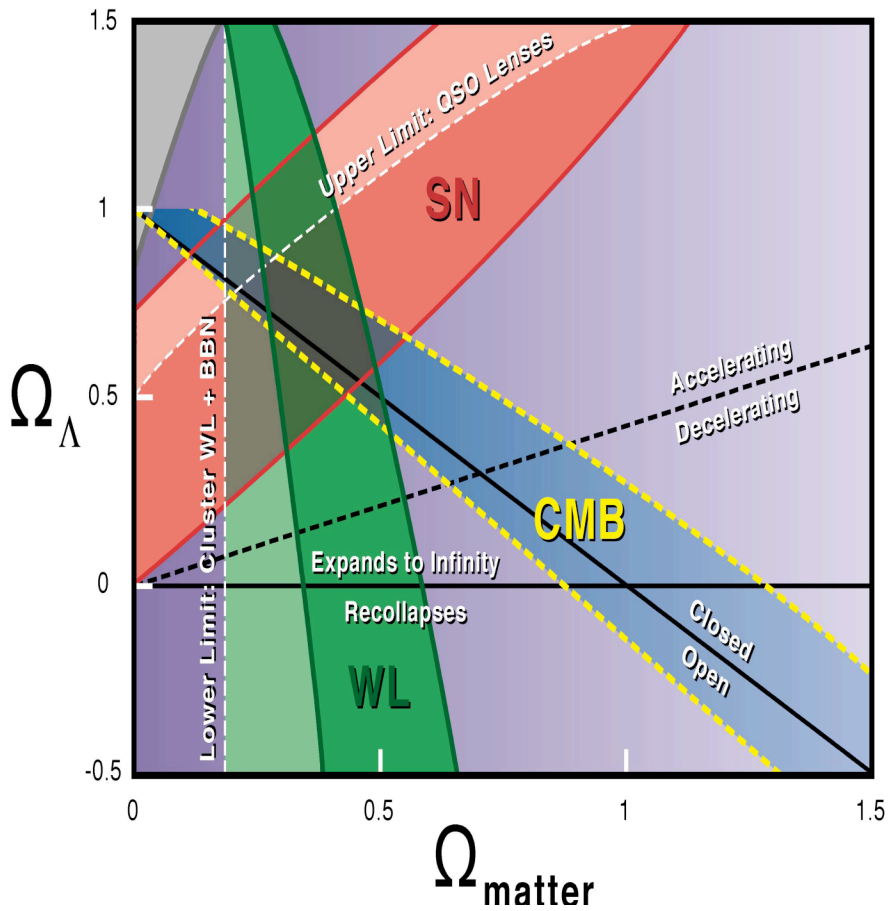
$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8} \Omega_B h^2 \approx 6\ 10^{-10}$$

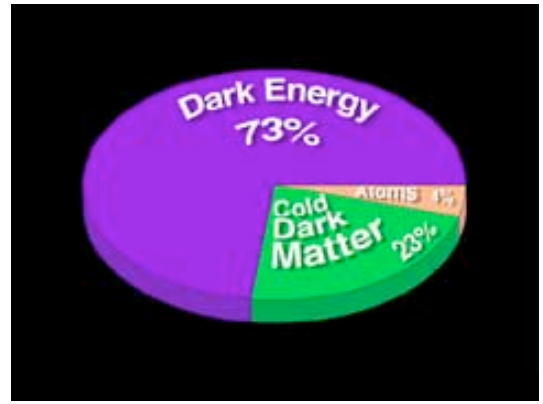


$$1\ GeV = 1.6\ 10^{-24}\ g$$

- Baryon Number abundance is only a tiny fraction of other relativistic species

From all the information we have ==> Precision Cosmology





$\Omega_M h^2 = 0.135 \pm 0.009$

$\Omega_B h^2 = 0.0224 \pm 0.0009$

$h = 0.71 \pm 0.04$

difference gives CDM energy density:

$$\Omega_{\mathrm{CDM}}\, h^2 = 0.1126 \pm^{0.0161}_{0.0181}$$

Evolution of the Dark Matter Density

- Produced in big bang, but also annihilate with each other.
- Annihilation stops when number density drops to the point that

$$H > \Gamma_A \approx n_\chi < \sigma_A v >$$

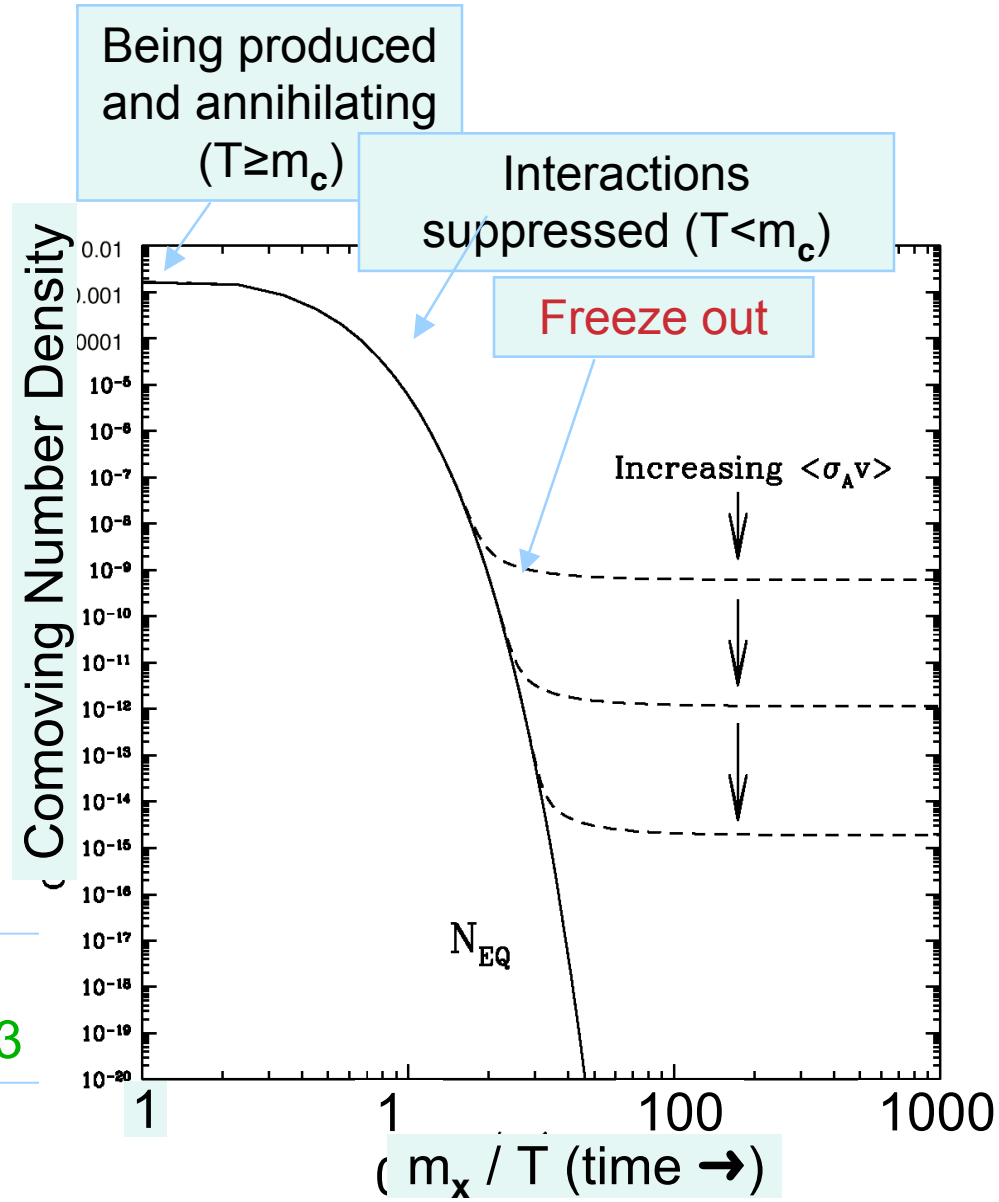
- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

- Leaves a relic abundance:

$$\Omega_\chi h^2 \approx 10^{-27} cm^3 s^{-1} / < \sigma_A v >_{fr}$$

if m_x and σ_A determined by electroweak physics, then $\Omega_x \sim 0.3$

$$\sigma_{ann.} \approx \text{a few pb} \approx \alpha_W^2 / M_W^2$$



What is Dark Matter? ==> Neutral and Stable Particle/s

- Baryonic and hot DM ==> experiments agree that can only be a tiny part of the total Dark Matter
- Cold Dark Matter: many well motivated candidates in particle physics, but none of them within the Standard Model

The SM has no suitable candidates:

- leptons, hadrons: too little photons: $\Omega_{rad.} \approx 10^{-4}$
- neutrinos: too light W/Z bosons: not stable

Most suitable candidates beyond the Standard Model:

- Axions
- Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

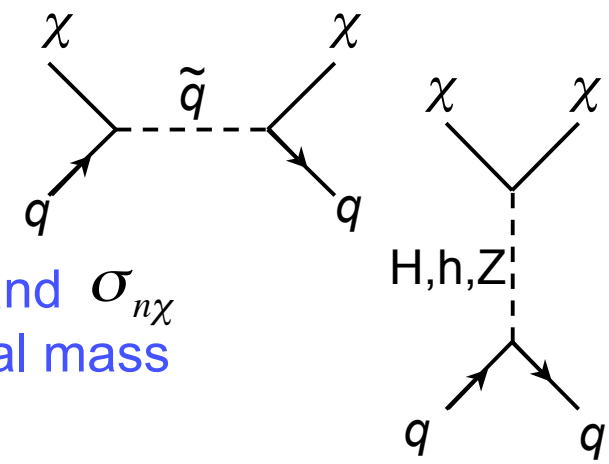
Most models of EWSB ==> add an extra discrete symmetry ==> the lightest newly introduced particle is stable: "Models of EWSB predict a WIMP"

WIMP prototypes:

LSP ==> lightest SUSY particle, neutralino, with R-parity conservation.
LKP ==> Extra dimensional KK U(1) gauge boson w/ KK parity conserved.
LTP ==> T-odd heavy photon in Little Higgs models w/ T-parity conserved.

Direct Detection of WIMPs

- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils ==> $\sigma_{n\chi}$



Main Ingredients to calculate signal:
Local density & velocity distribution of WIMPs and $\sigma_{n\chi}$
==> rate per unit time, per unit detector material mass

$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$

Scattering Cross section off nuclei averaged over the relative WIMP velocity

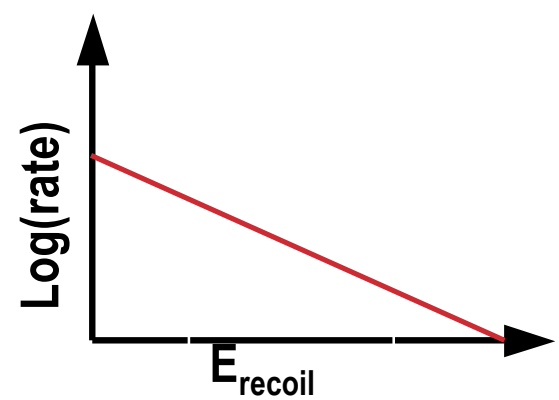
Number of target nuclei in the detector prop.to Detector mass/Atomic mass

local WIMP density = $\eta_\chi \approx 0.3$ GeV / cm^3 Wimp (Energy Density/ mass)

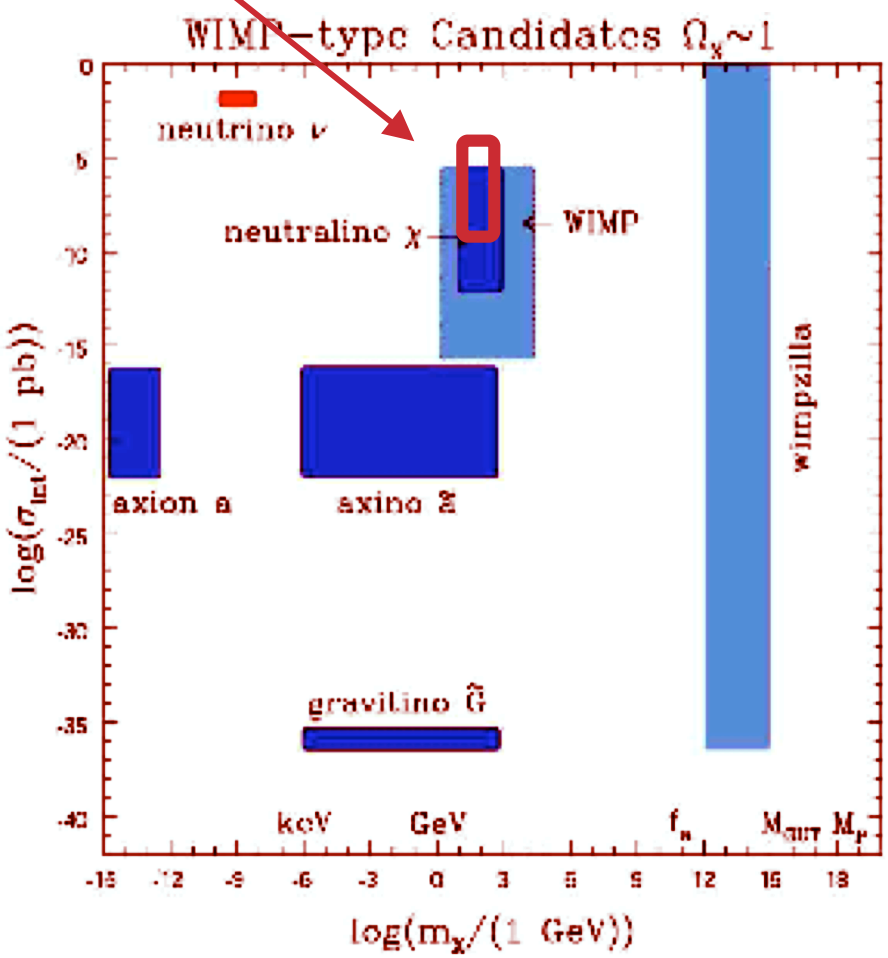
- Energy spectrum of recoils is featureless but depends on the WIMP and target nucleus mass:

$$E_R \approx 2\mathrm{v}^2 \left[\mathrm{m_T} / (1 + \mathrm{m_T} / m_\chi)^2 \right]$$

- Due to very weak interaction with ordinary matter, R is smaller than 1 event per kg material per day



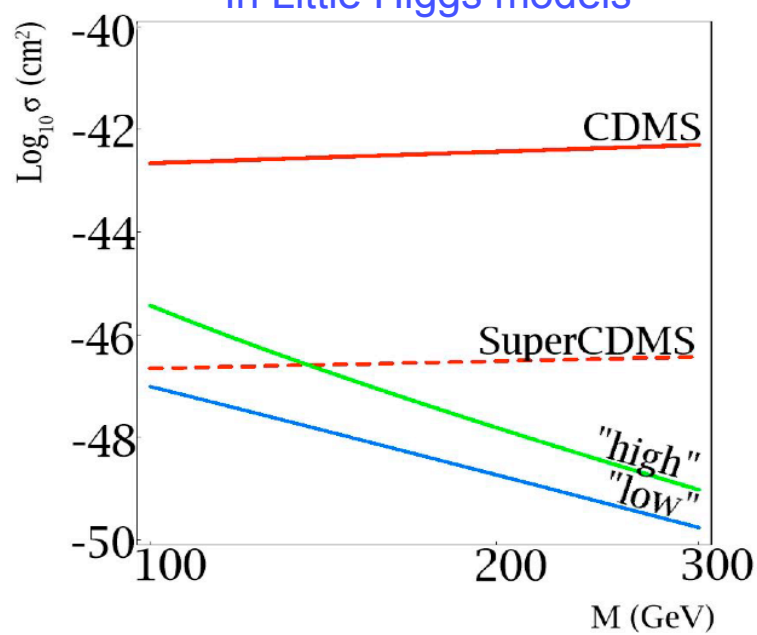
Current Experiments can only probe a small range of elastic scattering cross sections off nuclei for some of the many DM candidates



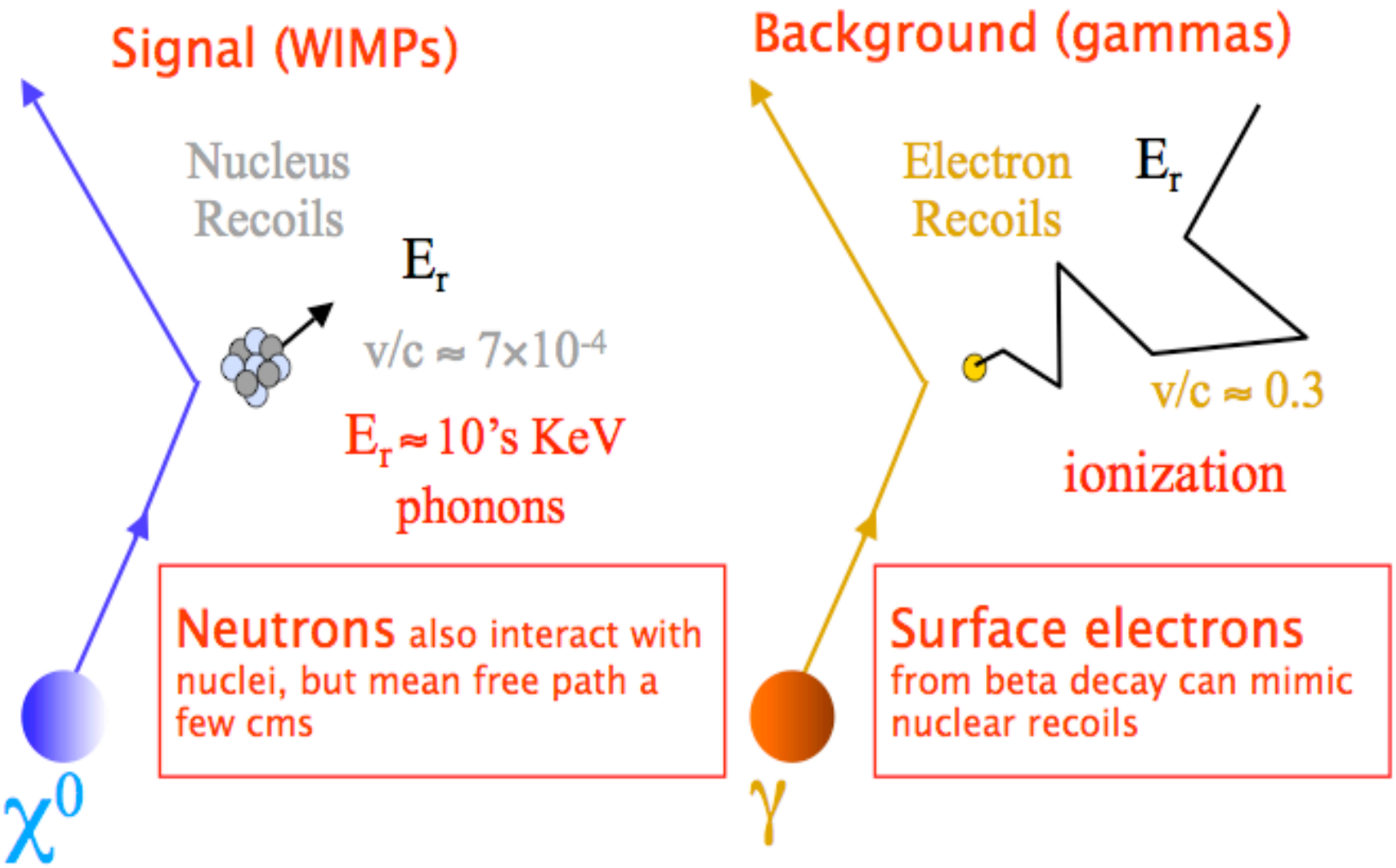
- In UED, the vector like, lightest particle with mass between 400-900 GeV could be probed by next generation of experiments

$$\sigma_{n\chi}^{si} \approx 10^{-46} cm^2$$

- DM heavy T-odd photon In Little Higgs models



The Signal and Backgrounds



Experimental Requirements for Direct Detection of WIMPs

- Detect tiny energy deposits ==>Nuclear recoils deposit only 10's of keV

- Background suppression
  - Deep sites to reduce cosmic ray flux

  Cosmic rays produce neutrons, which interact like WIMPs
  - Passive/active shielding

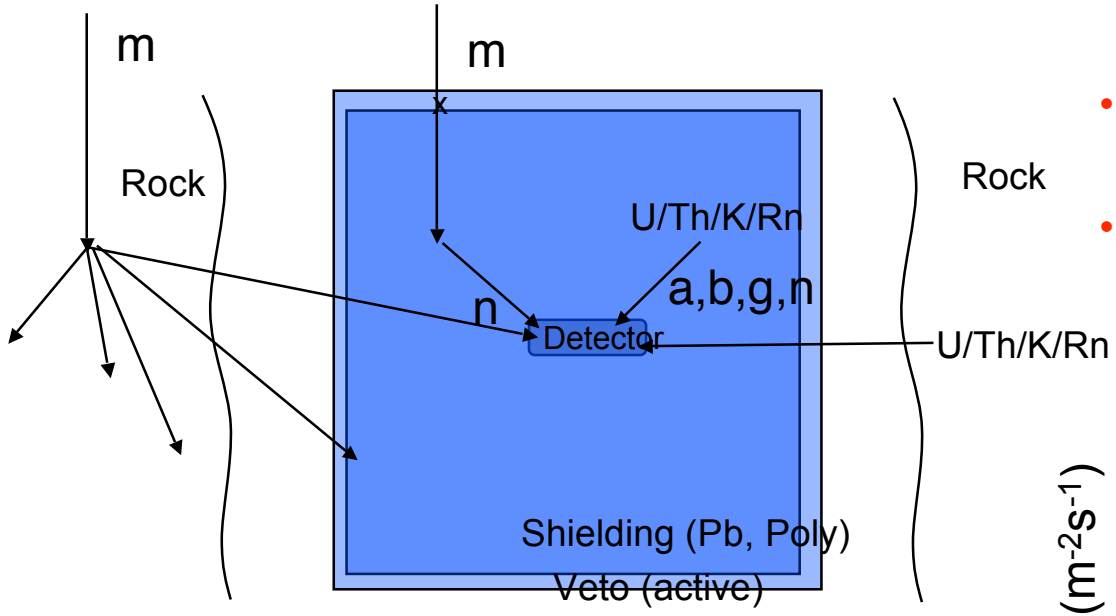
  To reduce overwhelming background from radioactivity
  - Careful choice and preparation of material

  Radioactive impurities $\propto$ surface area
- Residual background rejection
  - Recognize and reject electron recoils

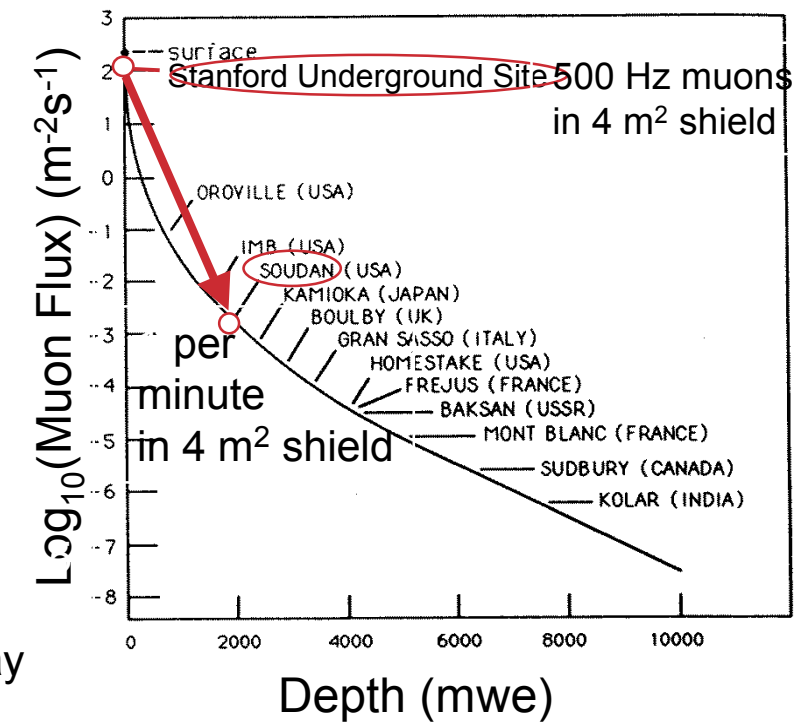
- Large Target Mass
  - WIMP interaction rate very low, so need lots of detectors

- Some signal unique to WIMPs
  - Specific features ==> interesting differences among experiments

Backgrounds for Direct Detection Experiments



- Pb shielding to reduce EM backgrounds from radioactivity
- Polyethylene contains hydrogen needed to moderate neutrons from radioactivity

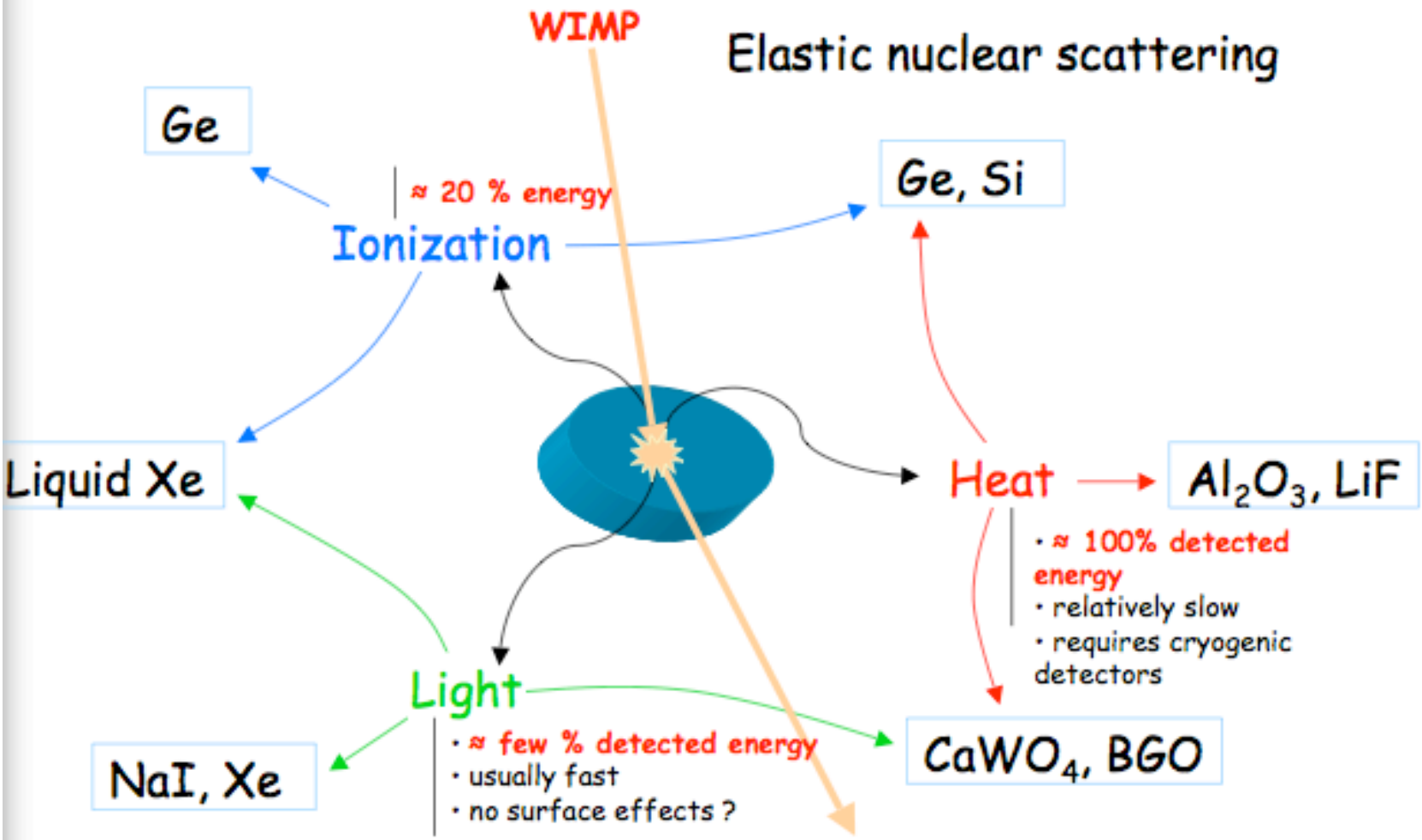


Depth is necessary to reduce flux of fast neutrons from cosmic ray interactions
(although active veto may partially substitute for depth)

Depth reduces neutron background to ~1 / kg / year

WIMP sensitivity goal is 0.01 events / kg / kev / day
CDMS goal (~ 20 WIMPS/year)

Direct detection techniques



The recoil energy of the scattered nucleus is transformed into a measurable signal: charge, scintillation light or phonons.

Observing more than one signal simultaneously yields a powerful discrimination against backgrounds, mostly electrons

Different techniques (cont'd)

- Ge Ionization experiments: HDMS, …

  -- limited by irreducible electromagnetic backgrounds close to crystals or by radioactive isotopes in the crystals by cosmic ray induced spallation

  -- next generation projects based on High Purity Ge (HPGe) ionization detectors ==> GERDA, GENIUS and Majorana

  expect to reduce background in 10^3 and compensate for the inability to discern electrons from neutrons on an event-by event basis

- Solid Scintillators at room temperature: NaI exp. as DAMA, NAIAD

  -- fast, can discern electrons from neutrons recoils on statistical basis using timing parameters of the signal pulse shape.

- Cryogenic Experiments at subKelvin Temperatures:

  -- leading the field with sensitivities

- Liquid noble element detectors:

  rapidly developing technology; promising avenue towards constructing ton-scale or even multi-ton detectors!

Current direct detection experiments

Discrim.	Name	Location	Technique	Target	Status
None	CUORICINO	Gran Sasso	Heat	41 kg TeO2	running
	GENIUS-TF	Gran Sasso	Ionization	42 kg Ge in liq. N_2	running
	HDMS	Gran Sasso	Ionization	0.2 kg Ge diode	stopped
	IGEX	Canfranc	Ionization	2 kg Ge Diodes	stopped
Statistical	DAMA	Gran Sasso	Light	100 kg NaI	stopped
	LIBRA	Gran Sasso	Light	250 kg NaI	running
	NaIAD	Boulby mine	Light	65 kg NaI	running
	ZEPLIN-I	Boulby mine	Light	4 kg Liquid Xe	stopped
Event-by-event	CDMS-I	Stanford	Heat + Ionization	1 kg Ge + 0.2 kg Si	stopped
	CDMS-II	Soudan mine	Heat + Ionization	5 kg Ge + 1 kg Si	running
	CRESST-II	Gran Sasso	Heat + Light	10 kg CaWO4	starting
	EDELWEISS-I	Modane	Heat + Ionization	1 kg Ge	stopped
	EDELWEISS-II	Modane	Heat + Ionization	10 kg Ge	starting
	XENON-10	Gran Sasso	Ionization + Light	10 kg Xe	starting
	WARP	Gran Sasso	Ionization + Light	3 kg Ar	running

Cryogenic detectors at mK temperatures

- Crucial characteristics:

-- Low energy threshold (< 10 KeV)

-- excellent energy resolution (<1% at 10 keV)

-- ability to differentiate electron from neutron recoil on an event-by-event basis

CDMS → Cool very pure Ge and Si crystals to < 50 mK, to detect heat from individual particle interactions

Active Background Rejection ==> Detect both heat and charge

Nuclear recoils produce less charge for the same heat as electron recoils

Shielding ==> Prevent radioactive decay products from reaching detector

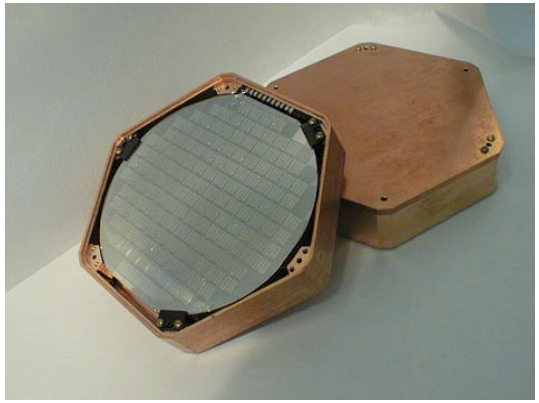
CDMS Specific: detectors collect athermal phonons providing information about location of event ==> reject events near outer surface caused by electron recoil

- Superconducting transition edge sensors photolitographically patterned onto one of the crystal surfaces detect the a-thermal phonons from particle interactions
- Charge electrodes are used for ionization measurements

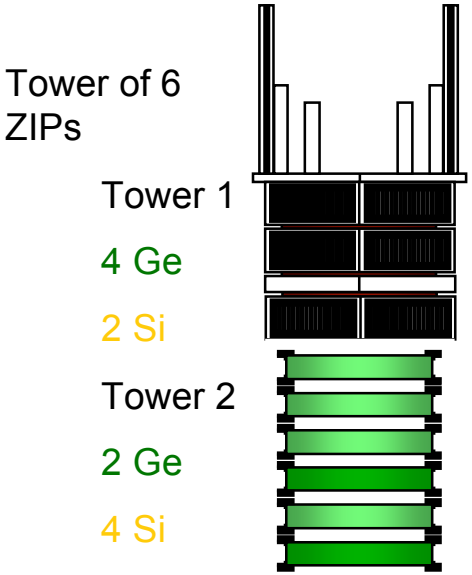
CDMS Active Background Rejection

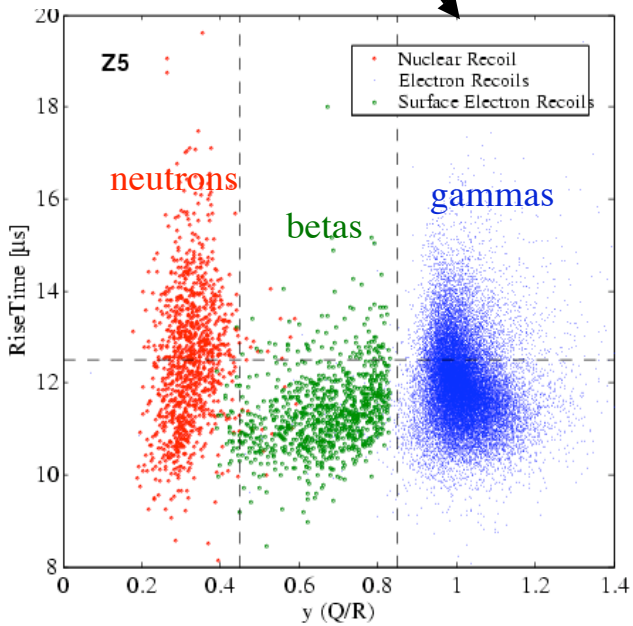
Detectors with excellent event-by-event background rejection

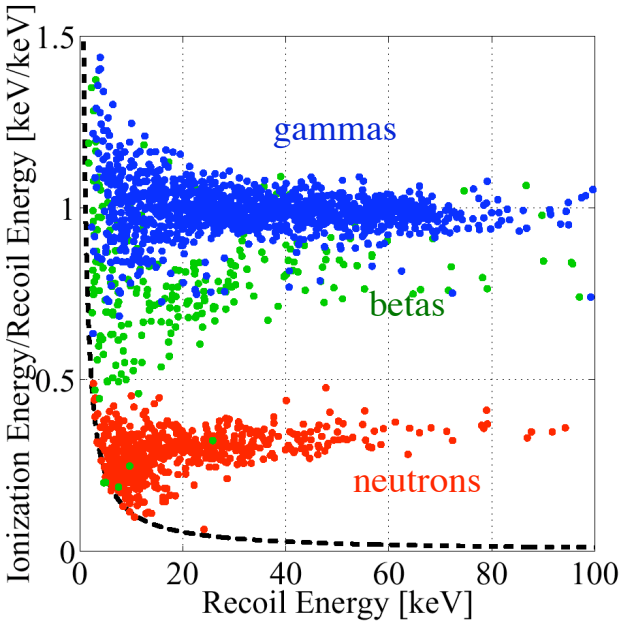
- Measured background rejection:
- 99.995% for EM backgrounds using charge/heat
- 99.4% for b's using pulse risetime as well



Much better than expected in CDMS II proposal!

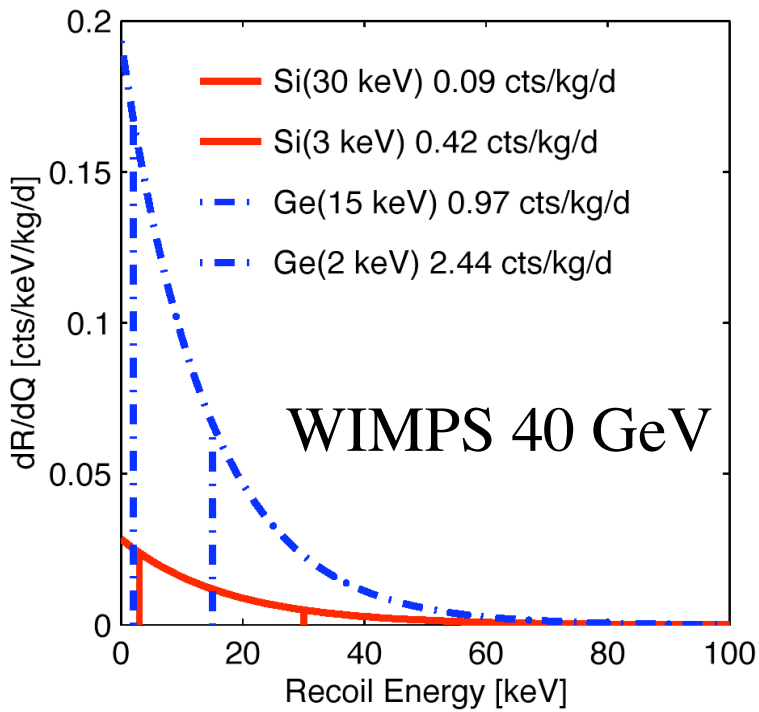


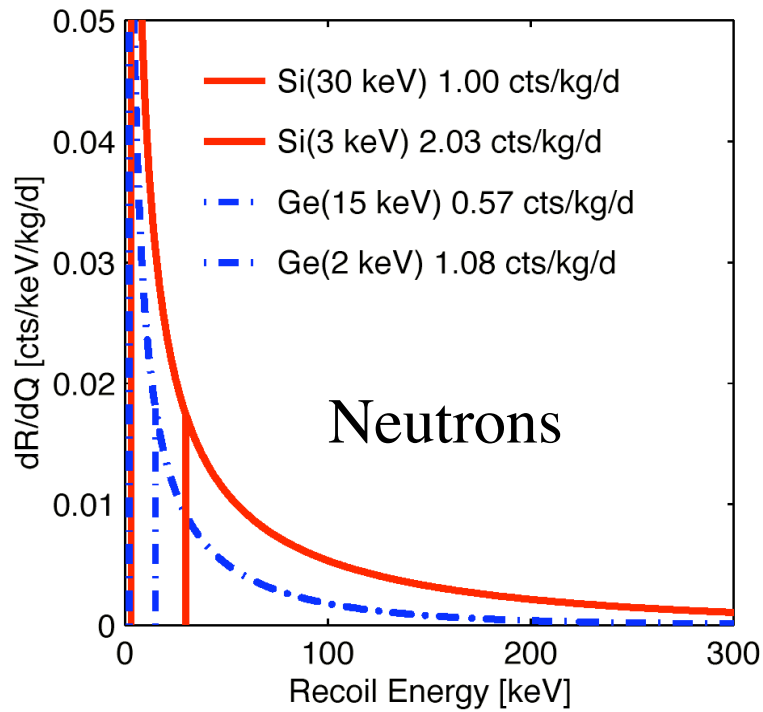




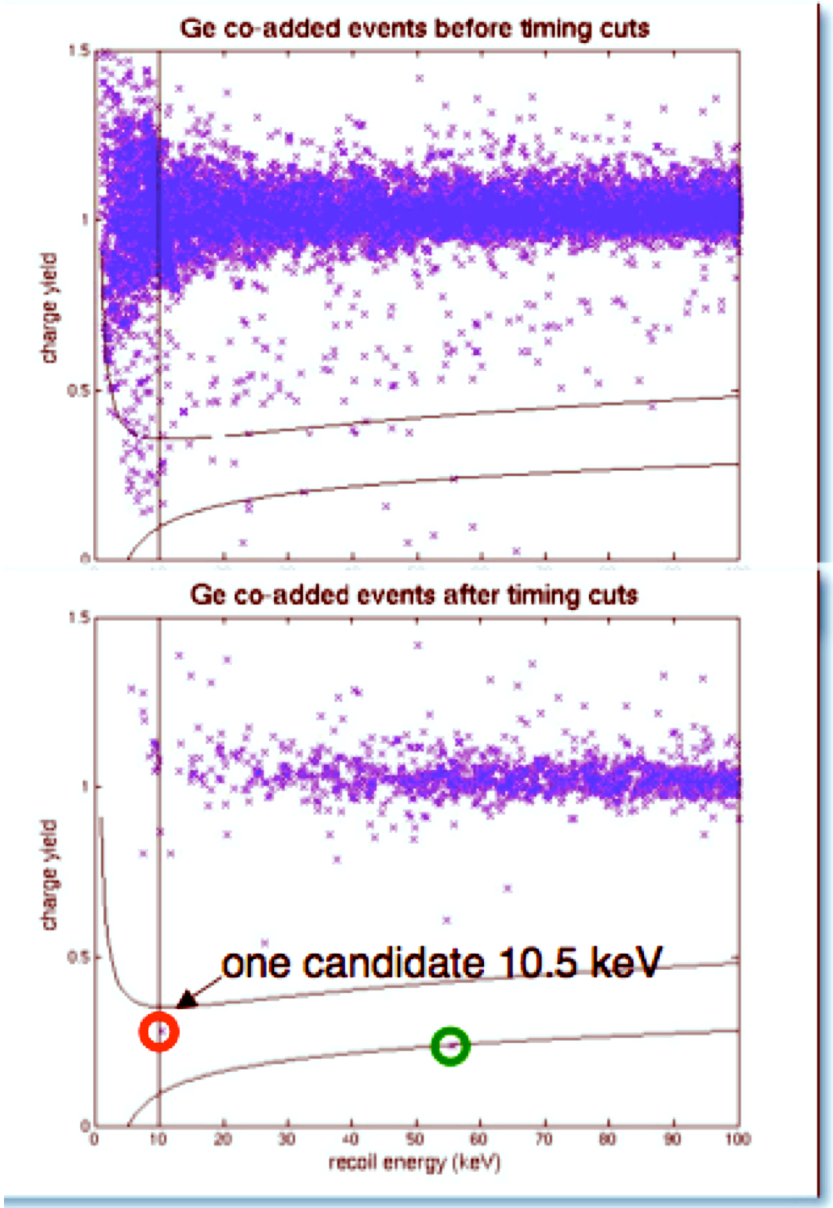
The advantage of multiple targets

- The 2 different materials used to distinguish between WIMPs and neutron interactions
  - For neutrons 50 keV - 10 MeV
    Si has ~2x higher interaction rate per kg than Ge
  - For WIMPs
    Si has ~6x lower interaction rate per kg than Ge
  - If nuclear recoils appear in Ge, and not in Si, they are WIMPs!





2-tower CDMS-II run @ Soudan



- 1 event after cuts and blind analysis
- **present benchmark**
- ≈ factor 5 increase in sensitivity expected within next two years
- powerful rejection of surface events using charge/phonon risetime
- Now start run with 5 towers

Other Phonon mediated detectors

Edelweiss: Similar to CDMS. CDMS has better technology and (easy to loose) time advantage

Edelweiss II @ Modane (4800 m w.e.)

- Aim for sensitivity improvement x 100 (competitive with CDMS II) (10^{-8} pb)
- Installation started 04/04 – expected to finish summer 05 (?)
- 1st phase: 21 NTD detectors (~7 kg total), 7 NbSi detectors (~3 kg total)
  - Only NbSi competitive in background rejection with CDMS II

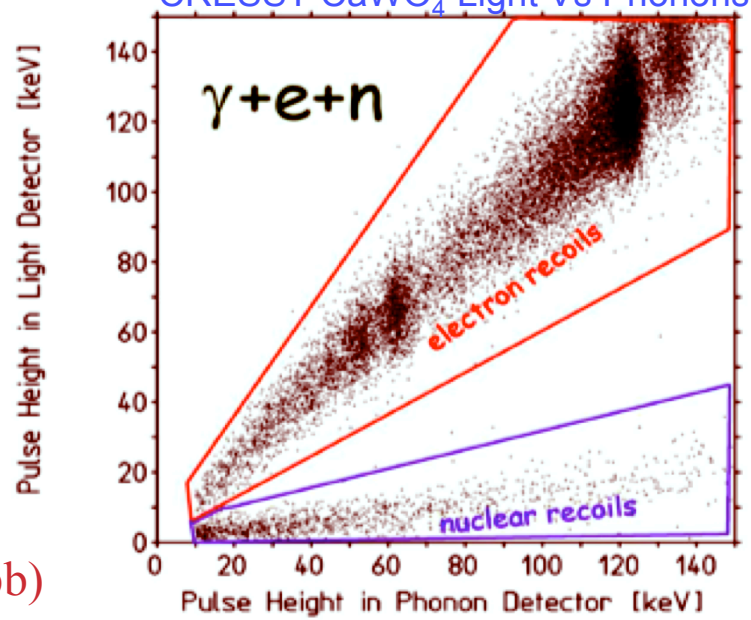
CRESST: Phonons plus Scintillation

- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron can be distinguished from nuclear recoils (WIMPs, neutrons) .

+ low energy threshold in phonon signal
+ no light yield degradation for surface events
- Very small scintillation signal
Scintillation threshold will determine minimum recoil energy

Running in Gran Sasso , 2005 Sensitivity Goal: (10^{-8} pb)

CRESST $CaWO_4$ Light Vs Phonons

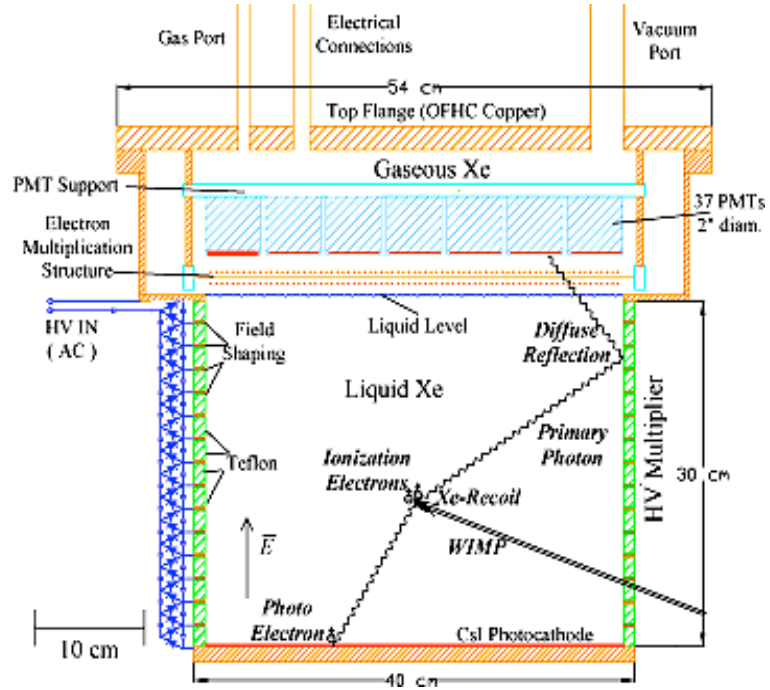


Long term: Eureca: Combination of 2 experiments? EU collaboration

Liquid Xenon Detectors:

Compromise between large mass and background rejection

- Potential to challenge cryogenic detectors
  - Background rejection
    - Pulse shape discrimination now
    - R&D towards scintillation + ionization
  - May scale more readily to high mass
- Challenges
  - Implementing "dual-phase" to improve scintillation signal near threshold
  - Ionization signal/noise poor near threshold
  - Must show 16 keV threshold to be competitive
- Several programs
  - XMASS (Japan)
  - ==> 100 kg within few years
  - Zeplin Series(UK/UCLA et al)
    Aiming for 6-30 kg deployment by 2006
  - US XENON project (Columbia et al)
    R&D on dual-phase experiment;
    10 kg prototype underway at Gran Sasso (2 x 10^{-8} pb)



Goal: 1 ton scale; 16 keV thr.;
99.5% background discrimination
reach a few 10^{-10} pb in 3 years

Also groups pursuing Argon (WARP/ArDM), Helium (HERON), Neon (CLEAN)

More specialized detectors need special discussion

- COUPP (Heavy liquid Bubble Chamber)

  Superheated heavy liquid (e.g. CF_3I)

  – Idea arose from superheated droplet experiments (SIMPLE/PICASSO)
  – Get more target mass from heavy liquid bubble chamber
  – Only high-ionization energy density tracks from nuclear recoils sufficient to cause nucleation (Insensitive to gammas, betas, & minimum ionizing particles

- DAMA: search for annual modulation ==> KIMS (with CsI)

  Huge target mass, no background rejection

  100 kg of NaI crystals read out by phototubes

  WIMP signal: 6σ annual modulation is observed in the rate.

  KIMS: Located at 700 mwe underground in Korea

  Test DAMA data with similar crystal detector containing Iodine.

  → should be helpful to confirm or deny claimed signal

- DRIFT: look for diurnal Modulation
  – Sensitive to axis of nuclear recoil provided low enough pressure

  DRIFT II extension to 10 kg module proposed (??)

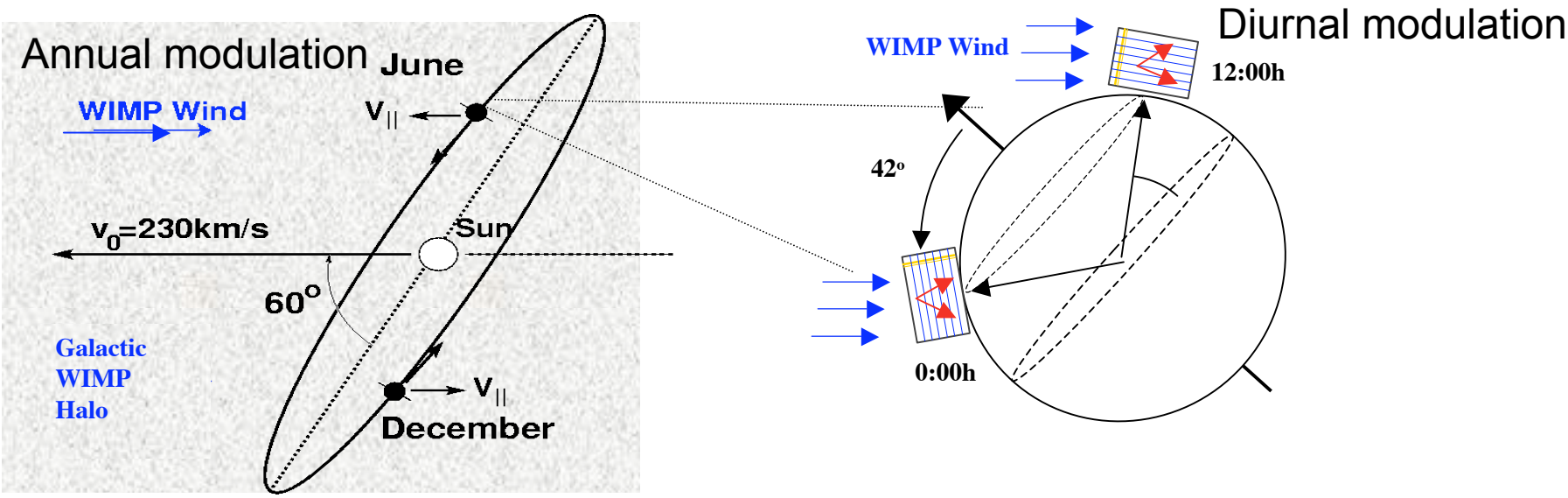
Directionality: Can we detect a WIMP wind?

Look for variation in WIMP flux with time of year (annual)

Requires long exposure and large mass to measure small effect (~5%)

Look for directionality of WIMP nuclear recoils on a daily basis (diurnal)

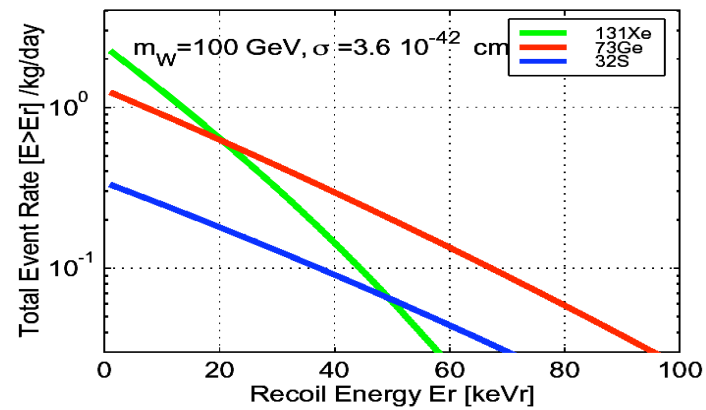
Requires detectors which can reconstruct direction of recoil with reasonable precision



Comparing different detectors

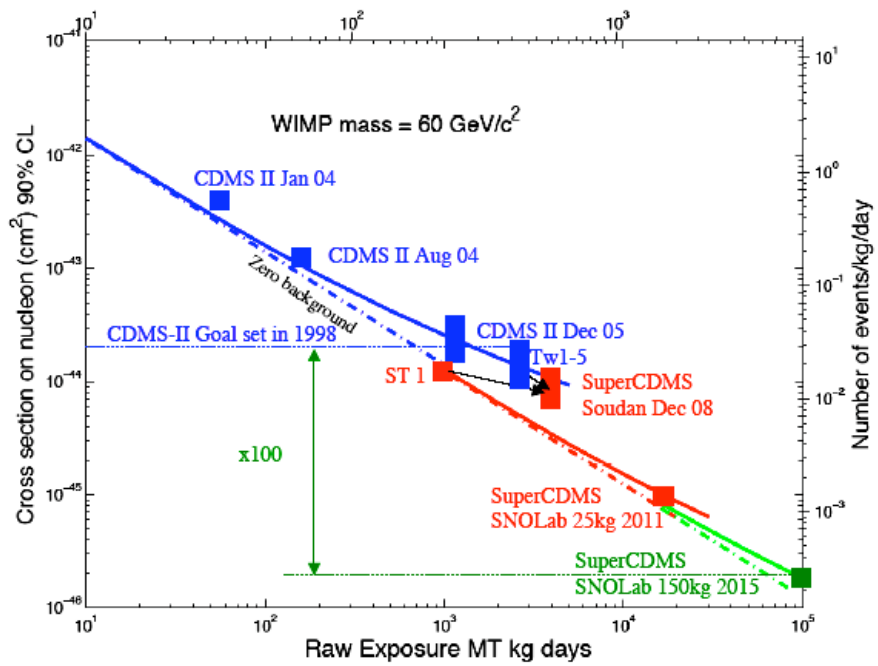
- Thresholds
  - Assuming scalar interactions (spin independent)

Larger rates at smaller recoil Energies
==> better reach for lighter WIMP candidates

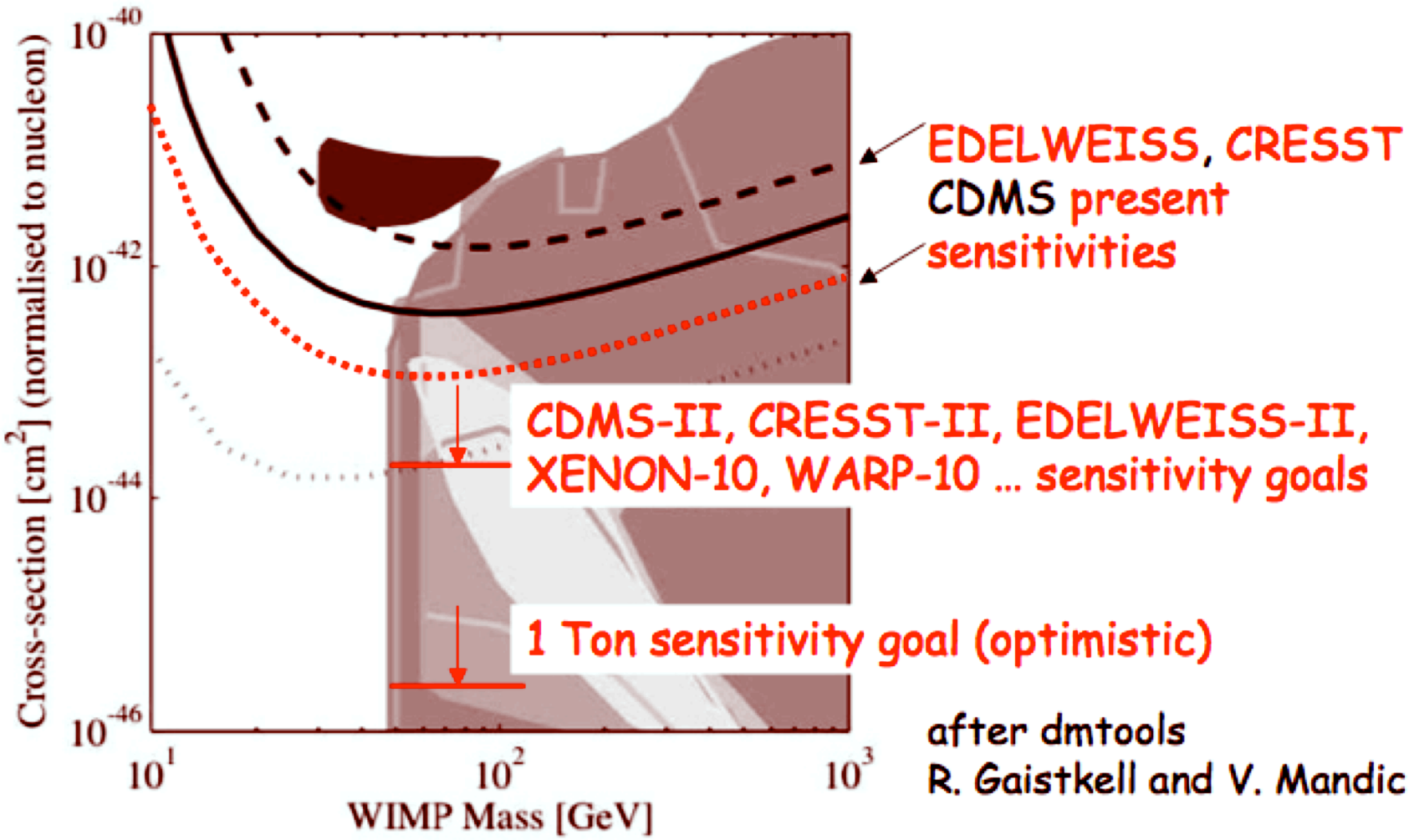


- Rejection
  - Need to be ≈background free
    - Sensitivity ≈1/MT
  - Background subtraction
    - Sensitivity ≈1/√ (MT)

The future: Run longer (T),
with more detectors (M)
and less background

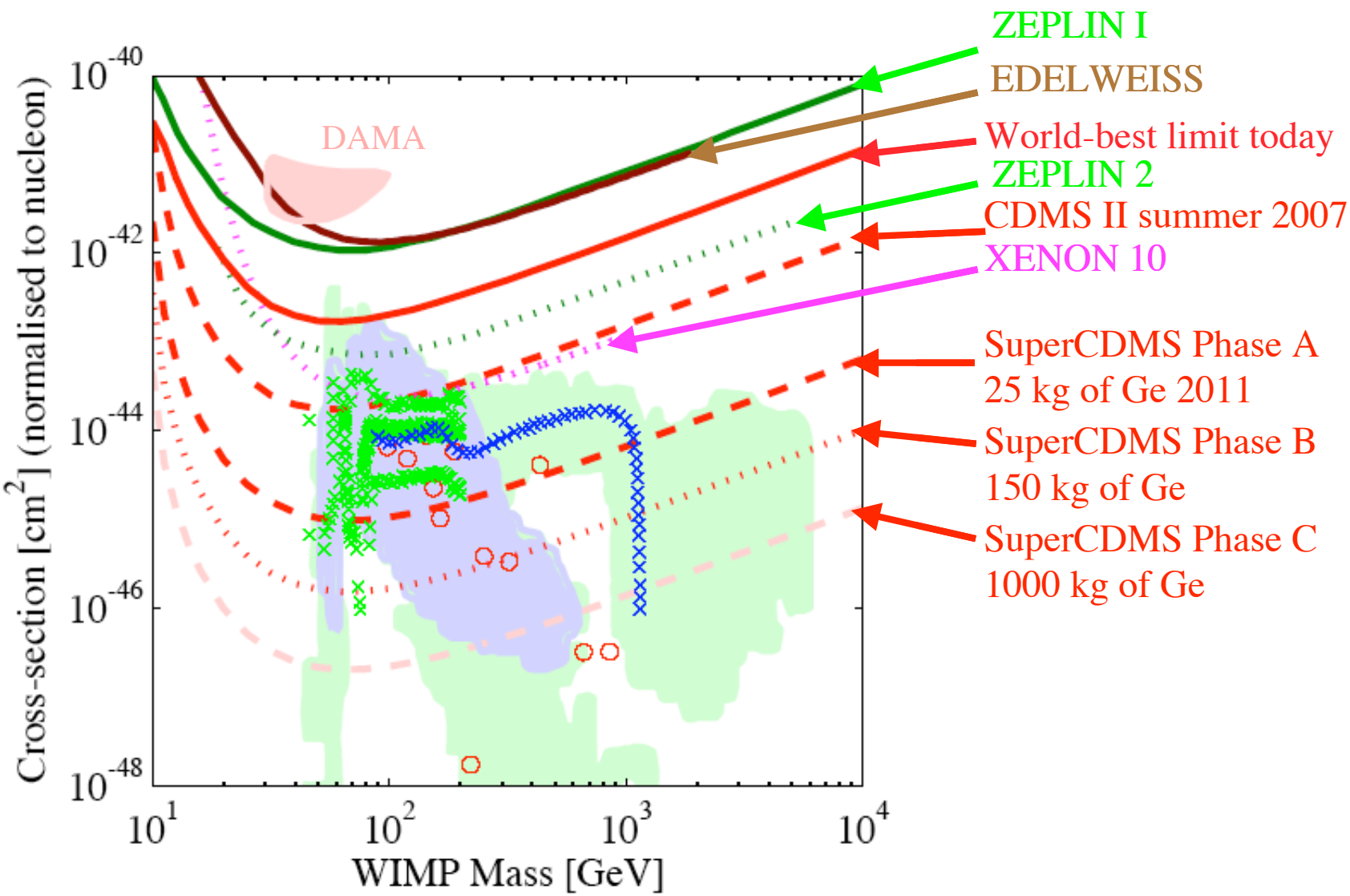


A bold look to the future



after dmtools
R. Gaistkell and V. Mandic

CDMS: a bold look to the future



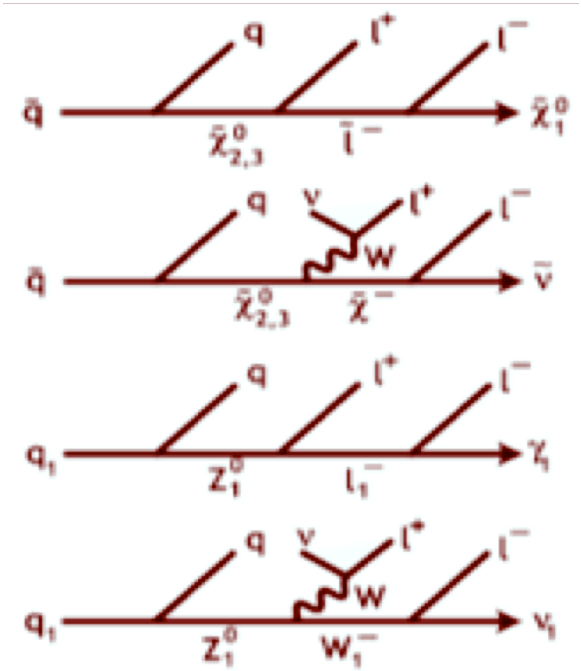
What can colliders say about DM?

The missing energy signature

Models of EWSB ==> predicts new heavy QCD interacting particles

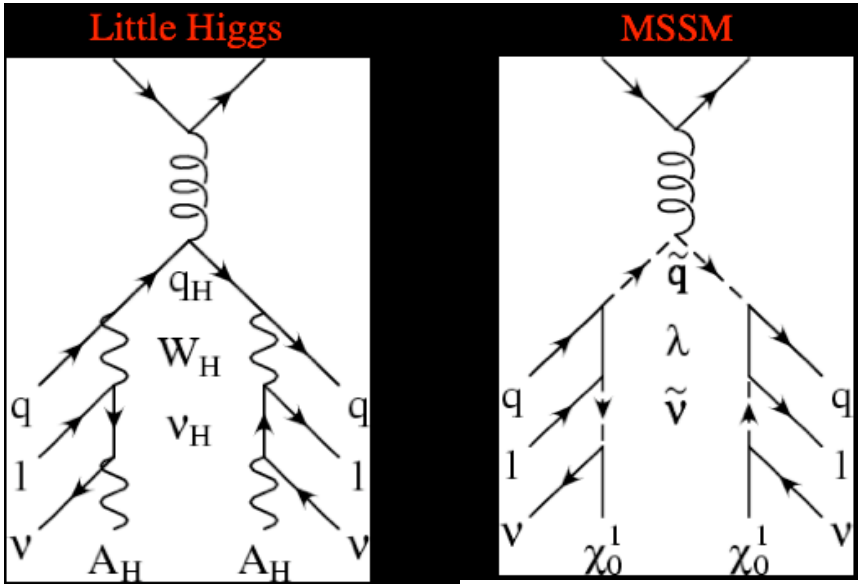
↓

Jets + leptons + $\not{E}_T$ at hadron colliders



- It is likely that the LHC will find evidence of DM, but it is unlikely that we will be able to reveal the precise identity of the WIMP (spin, quantum numbers)

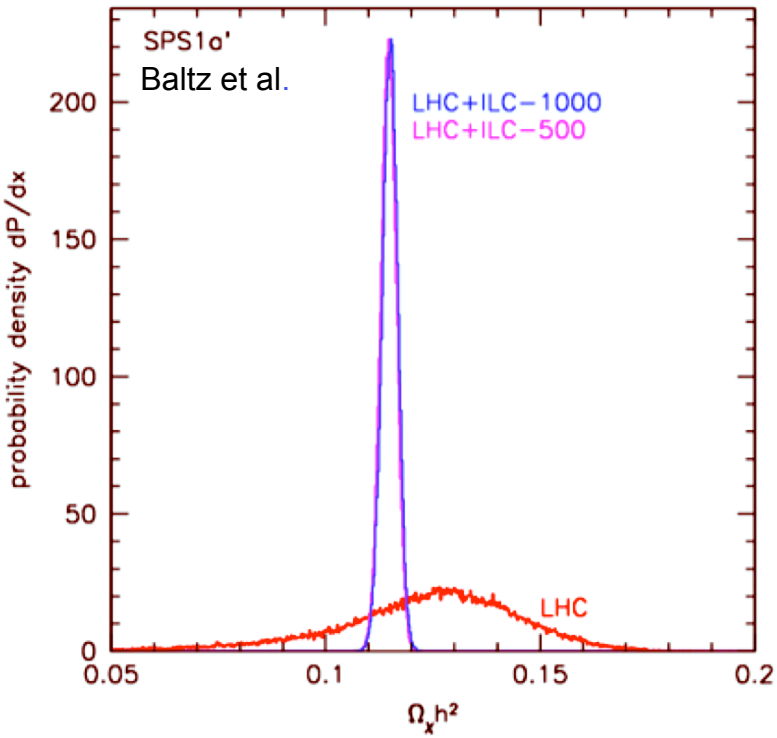
- The ILC via angular distributions and threshold shape of the reaction can give information of the underlying theory.



Connection of Collider Physics and Cosmology

- Knowledge of new physics particle masses and charges allows to compute the dark matter annihilation cross sections and the spin-independent dark matter-nucleon cross section.

- Use these results to compare with relic density CMB determinations from WMAP/Planck ==> crucial info about the new physics model



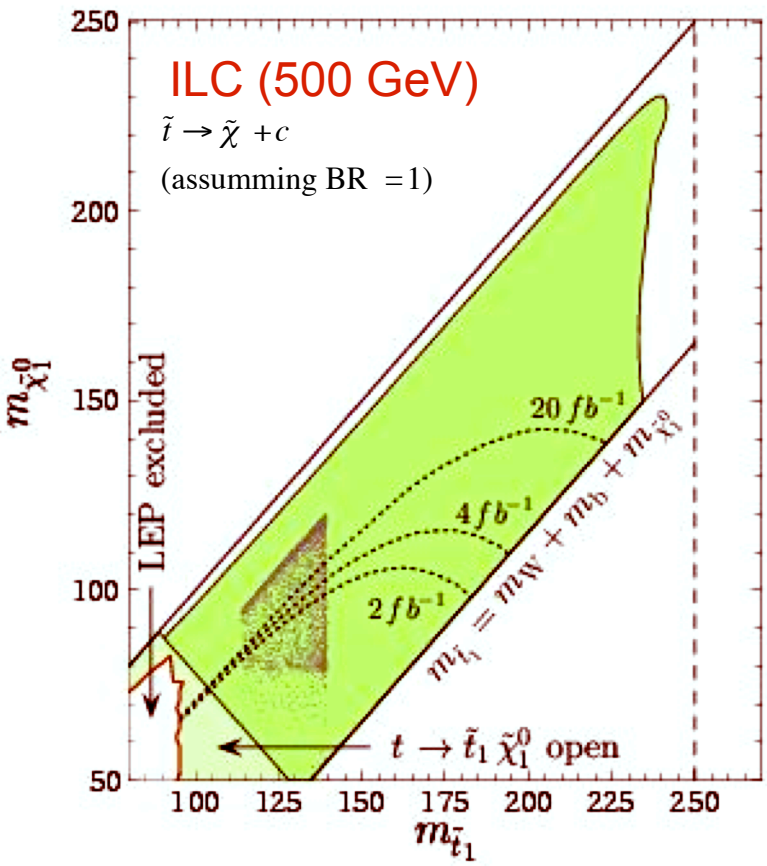
- For the success of this program, precision measurements will be necessary, as well as the determination of all the particles which interact with the WIMP.

The LHC will be helpful, but the ILC will be essential to obtain accurate results

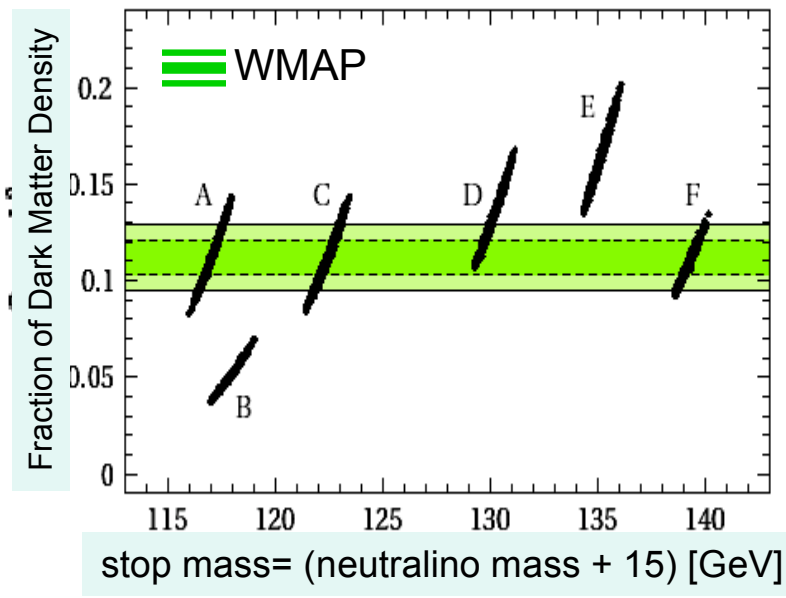
Dark Matter at Colliders: a challenging example

The LHC will probably find evidence of DM particles through missing momentum and missing energy analyses

The ILC will determine its properties with extreme detail, allowing to compute which fraction of the total DM density of the universe it makes



ILC sensitivity to DM density



SUSY models which explain DM and Matter-Antimatter Asymmetry

A particle physics understanding of cosmological questions!

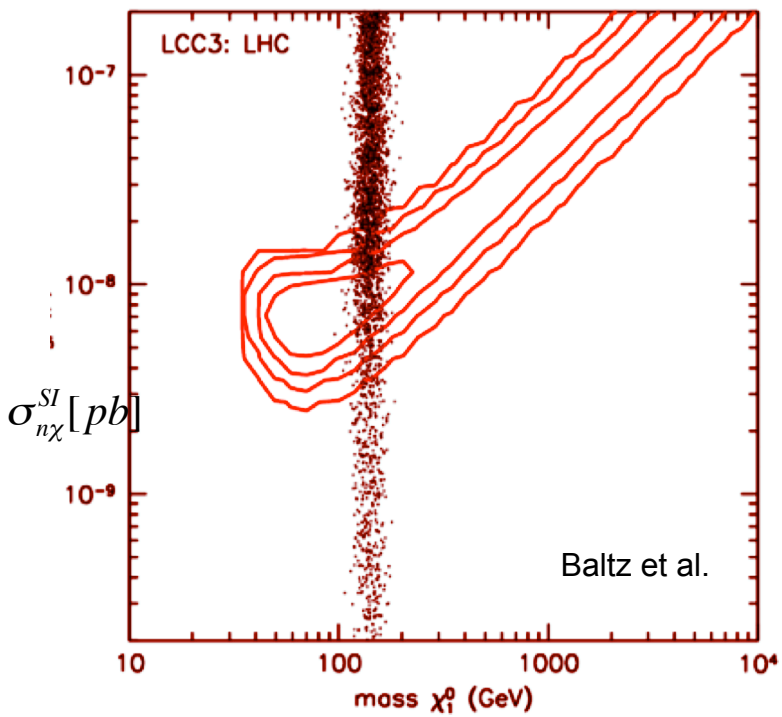
Collider measurements and Direct plus Indirect DM detection experiments

- If we see a signal at LHC and at superCDMS

Determination of the neutralino mass with accuracies of about

-- 10% (LHC, from kinematic of events with squark production and decay chain)

-- 25-30% (superCDMS, from recoil energy mass dependence, assuming 10% uncertainty in the velocity distribution)



Direct detection has two big uncertainties:

The local halo density, inferred by fitting to models of galactic halo:

assumed to be ≈ 0.3 GeV/cm3

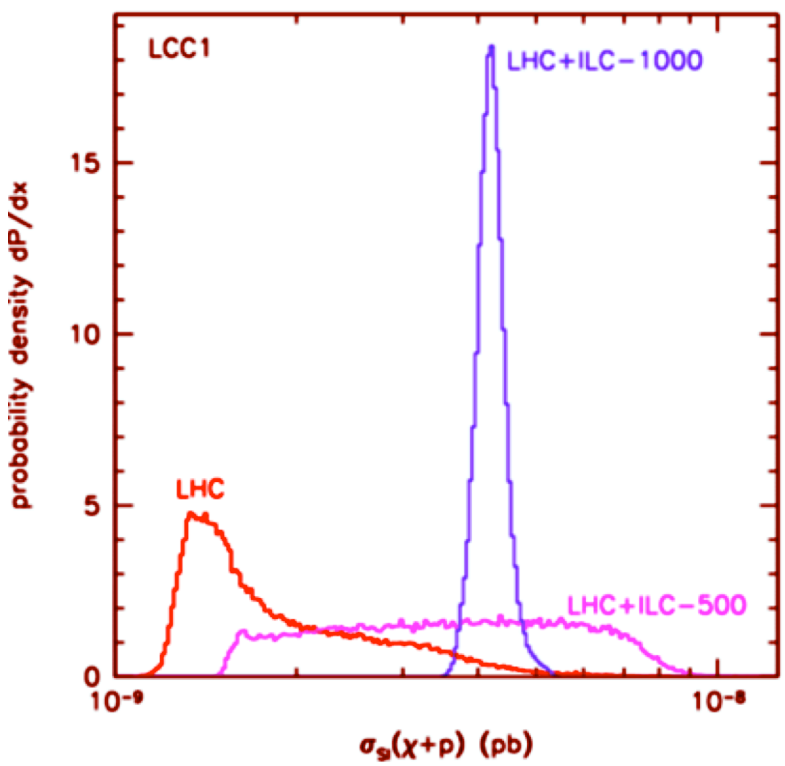
The galactic rotation velocity

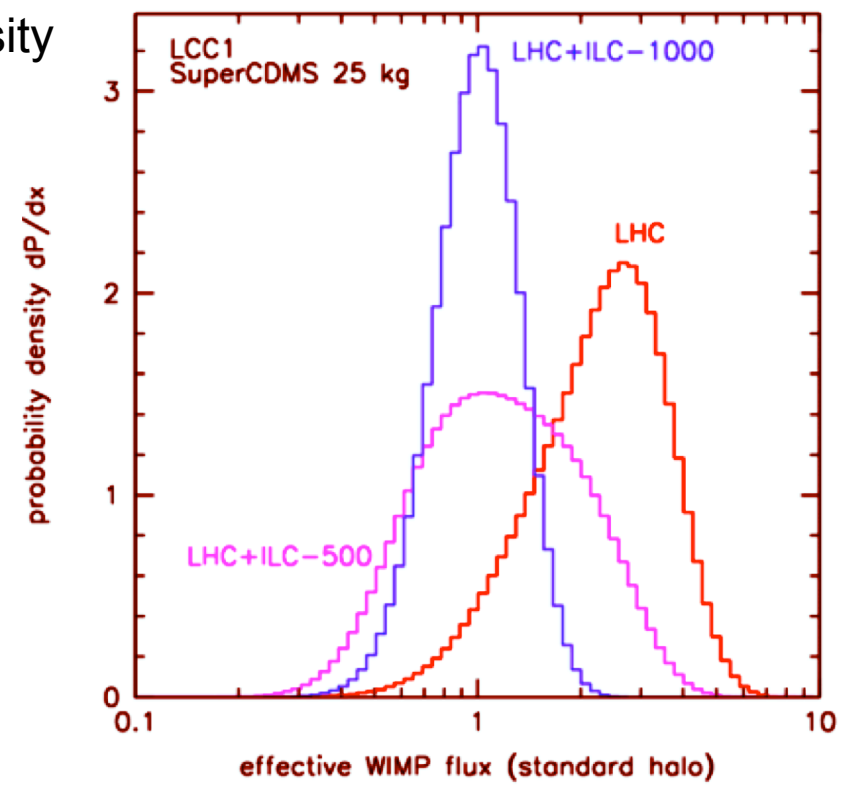
≈ (230 +- 20) km/sec

→ If big discrepancies were observed, it could point towards questioning our understanding of velocity distributions or the neutralino local flux

• Direct Dark Matter detection alone cannot constrain the neutralino-nucleon elastic scattering cross section,
but if it is computed from particle physics, then measuring the rate at SuperCDMS one can derived the value of the local flux of WIMP DM

If no direct DM detection and a $\not{E}_T$ signal at LHC
==> strong upper bound on local WIMP density

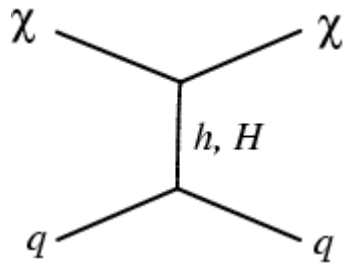




More about this in Baltz's talk at Fermilab

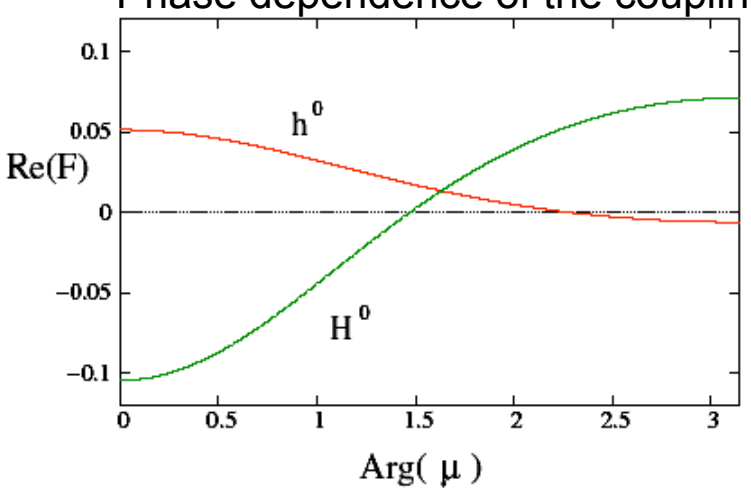
CP violation effects on Direct Dark Matter detection

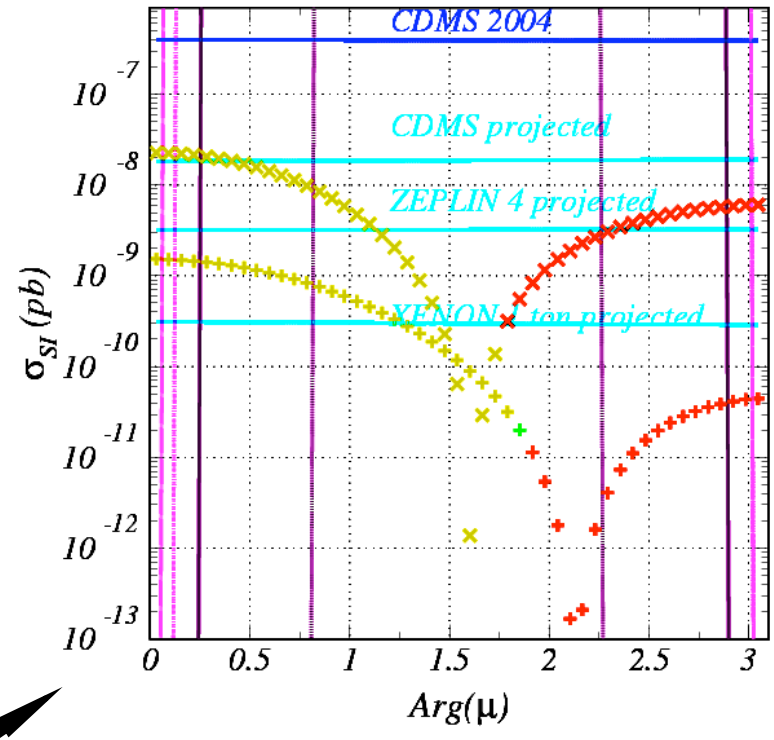
✳ CP violating phases compatible with EDM's and necessary for electroweak Baryogenesis can yield suppressions to $\sigma^{SI}_{n\chi}[pb]$



Only scalar (real) part of $\tilde{\chi}^0\tilde{\chi}^0 h/H$ couplings relevant

Phase dependence of the couplings





$\Omega h^2 > 0.129$

$\Omega h^2 < 0.095$

$0.095 < \Omega h^2 < 0.129$

$(|\mu|, M_1) = (300,60)\text{GeV}$

× $m_A = 200$ GeV:

$d_e =$ 8E-28 1E-27 e cm

+ $m_A = 1000$ GeV:

$d_e =$ 3E-28 9E-28 e cm

Balazs, MC, Menon, Morrissey, Wagner '04

Some comparisons we need to understand better

- **Cryogenic detectors**
  - CDMS seems to have better technology than EDELWEISS II

    What about time scales?

  -- CRESST II: aiming to same sensitivity as CDMS II and Edelweiss II

  The future: (reach of a few 10^{-10} pb)

  SuperCDMS (by 2015) and EURECA (I do not know enough about it)

  Experts think EURECA may be a significant competitor if too much delay in U.S.
- **Liquid Xenon**
  - Most serious competition is the XENON dark matter project (strongly US)
  - XENON-10 underway at Gran Sasso, aiming to same sensitivity as CDMS II
    - Starts to understand the complex phenomenology
    - "Dual phase" to better understand signal near threshold
    - Serious construction program ⟷ big push of UK on Zeplin II !!
  - ZEPLIN Max ==> R&D project at Boulby for a ton-scale experiment
  - XMASS: Competitive??
- **Very large mass Liquid Argon** (ton-scale)

  A realistic program they may be a serious competitor for SuperCDMS/Xenon/Zeplin (??)

Do we need more than one high mass technology? (experts think so)

Outlook

- Dark Matter: one of the fundamental questions of particle physics and cosmology
  ==> it demands new physics and it may be intimately related to the question of electroweak symmetry breaking

- The present generation of discriminating experiments: CDMS-II, CRESST-II, EDELWEISS-II, WARP, XENON-10… with sensitivities of ≈ few 10^{-8} pb are underway and will probe interesting regions of SUSY models

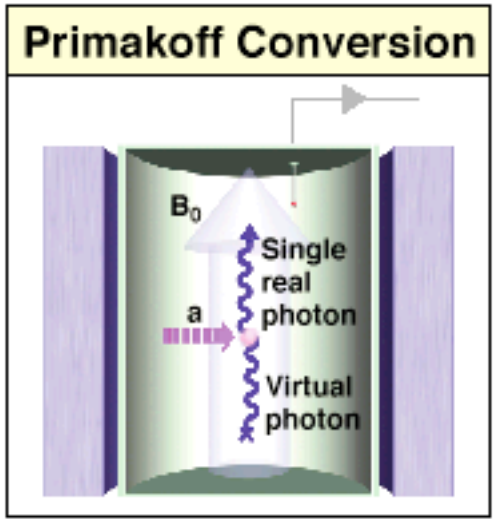
- The future generation of experiments: one-ton range and further improvements in background rejection like **EURECA, SuperCDMS, Xenon**,…
  ==> reach sensitivities of 10^{-10} pb and probe the bulk of SUSY parameters and other models of Dark Matter: UED, Little Higgs,…

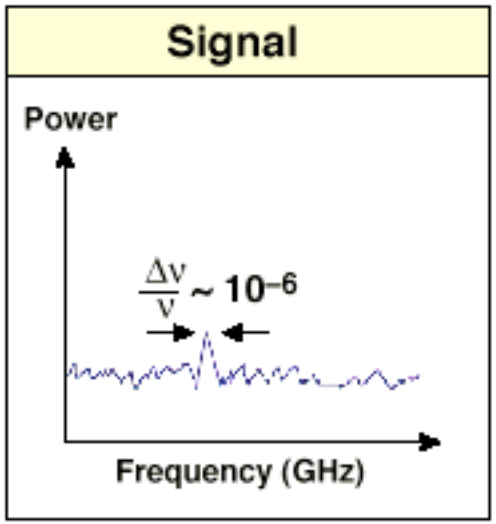
- Collider experiments: LHC/ILC can only detect DM through $\not{E}_T$ signals.
  ==> Can help understand the underlying physics model sufficiently by measuring properties of other new particles with precision
  ==> help to predict the mass and interactions of the WIMPs:
  -- compute the DM density and check model of new physics
  -- compute precisely quantities that enter in direct and indirect DM detection
  ==> Ultimately provide information about cosmological quantities: The local flux of WIMPs and the WIMP velocity distribution

EXTRAS

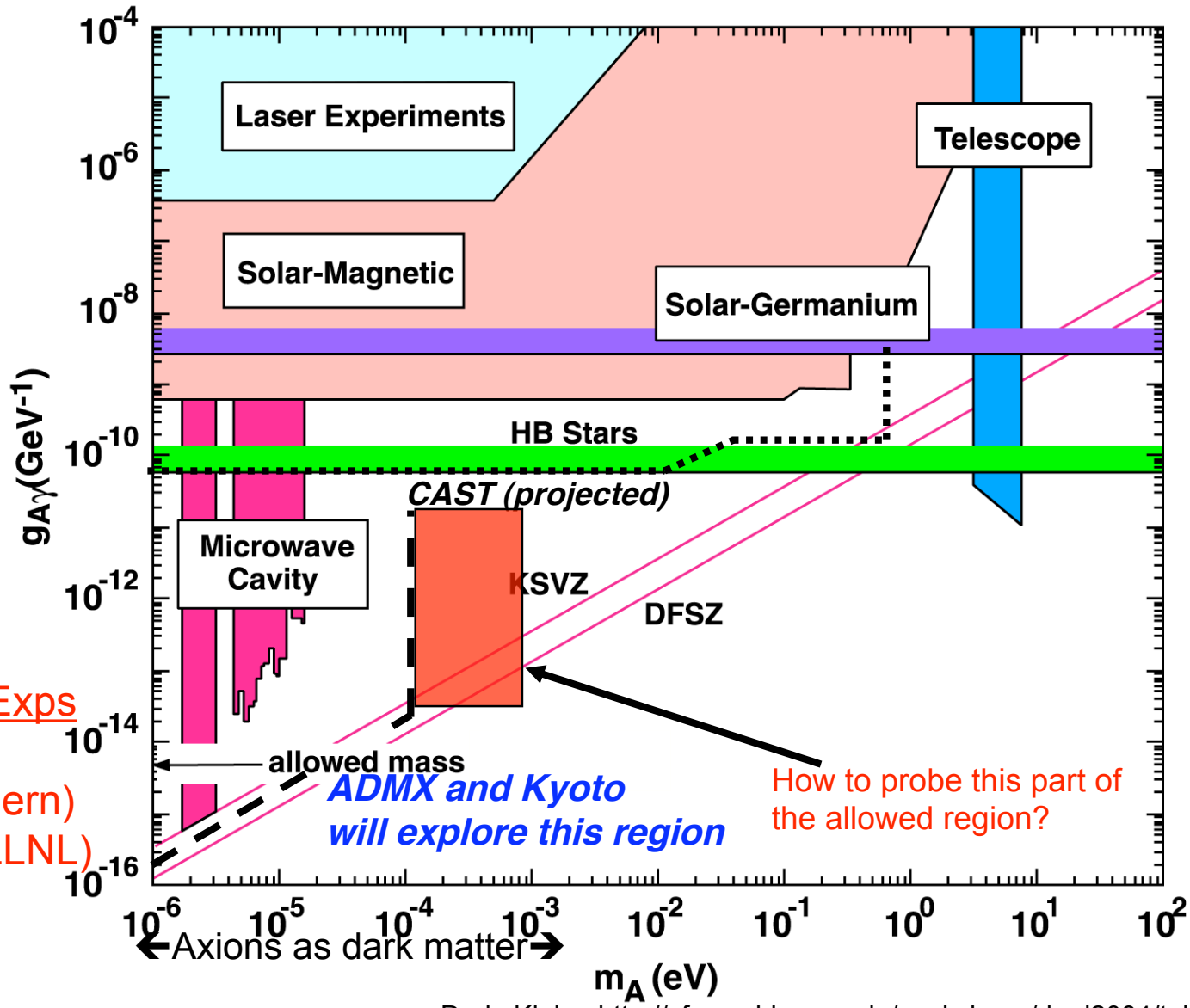
Axion Searches

- Axions invented to save QCD from strong CP violation
  - QCD contains CP violating term which would lead to large neutron electric dipole moment; experiments suggest otherwise
  - Axions would naturally suppress this term
- Couplings and masses
  - Mass window of relevance to dark matter: 10^{-6}-10^{-3} eV
  - Theoretical discussions of interaction rate ongoing
  - (KSVZ vs. DFSZ models)
- Method of detection
  - Primakoff conversion, followed by detection of photon





Summary of axion exclusion regions

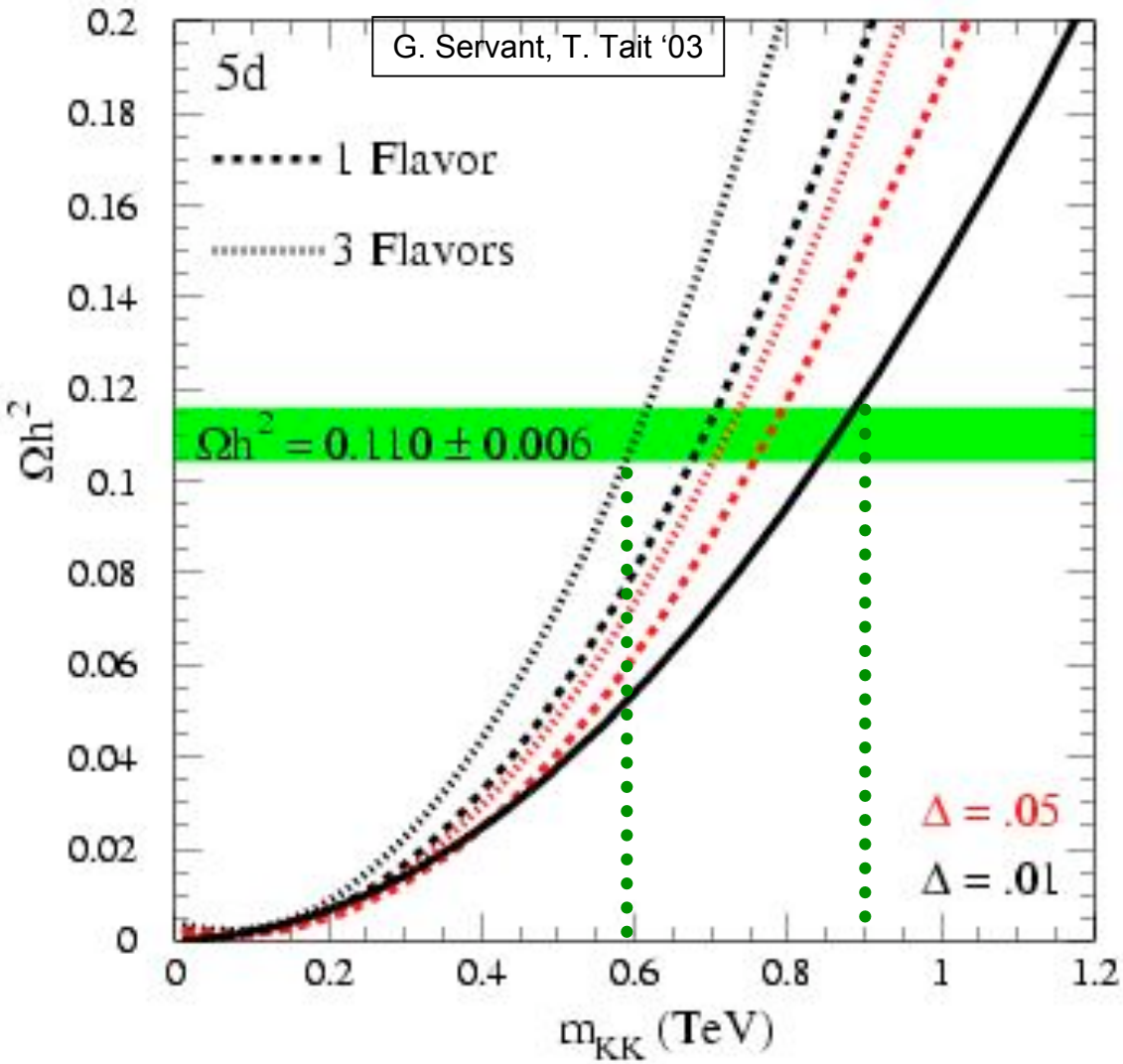


Current Exps
Kyoto
CAST (Cern)
ADMX (LLNL)

←Axions as dark matter→

Darin Kinion http://cfcp.uchicago.edu/workshops/dmd2004/talks/kinion.ppt

Relic Density in UED



D is the splitting between the $B^{(1)}$ and $e^{(1)}_R$ masses.

$$\Delta \equiv \frac{m_{e_R^{(1)}} - m_{B^{(1)}}}{m_{B^{(1)}}}$$

Coannihilation favors the 5d range **600-900 GeV**.

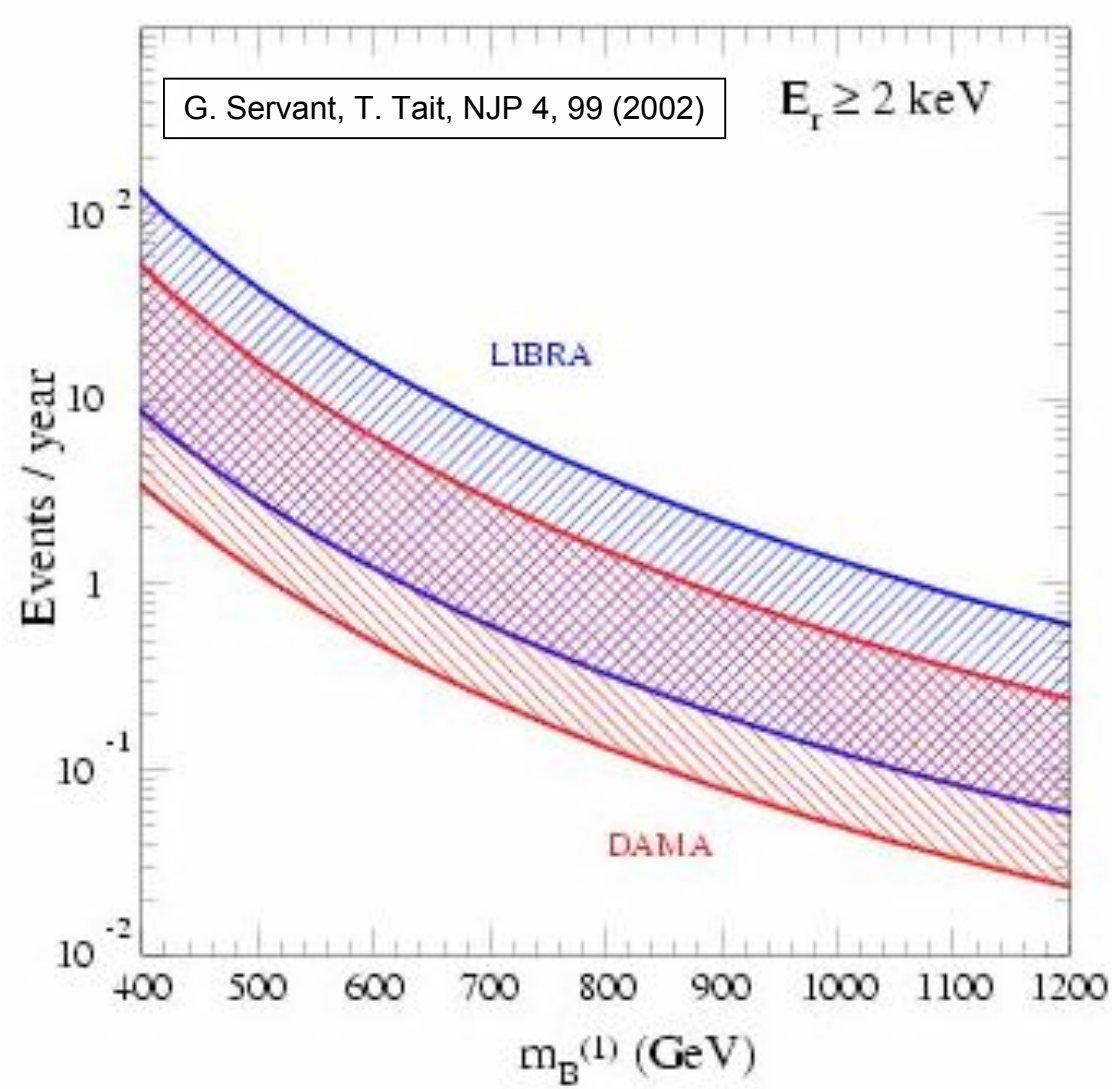
The 6d range is **425-625 GeV**.

NaI Detectors

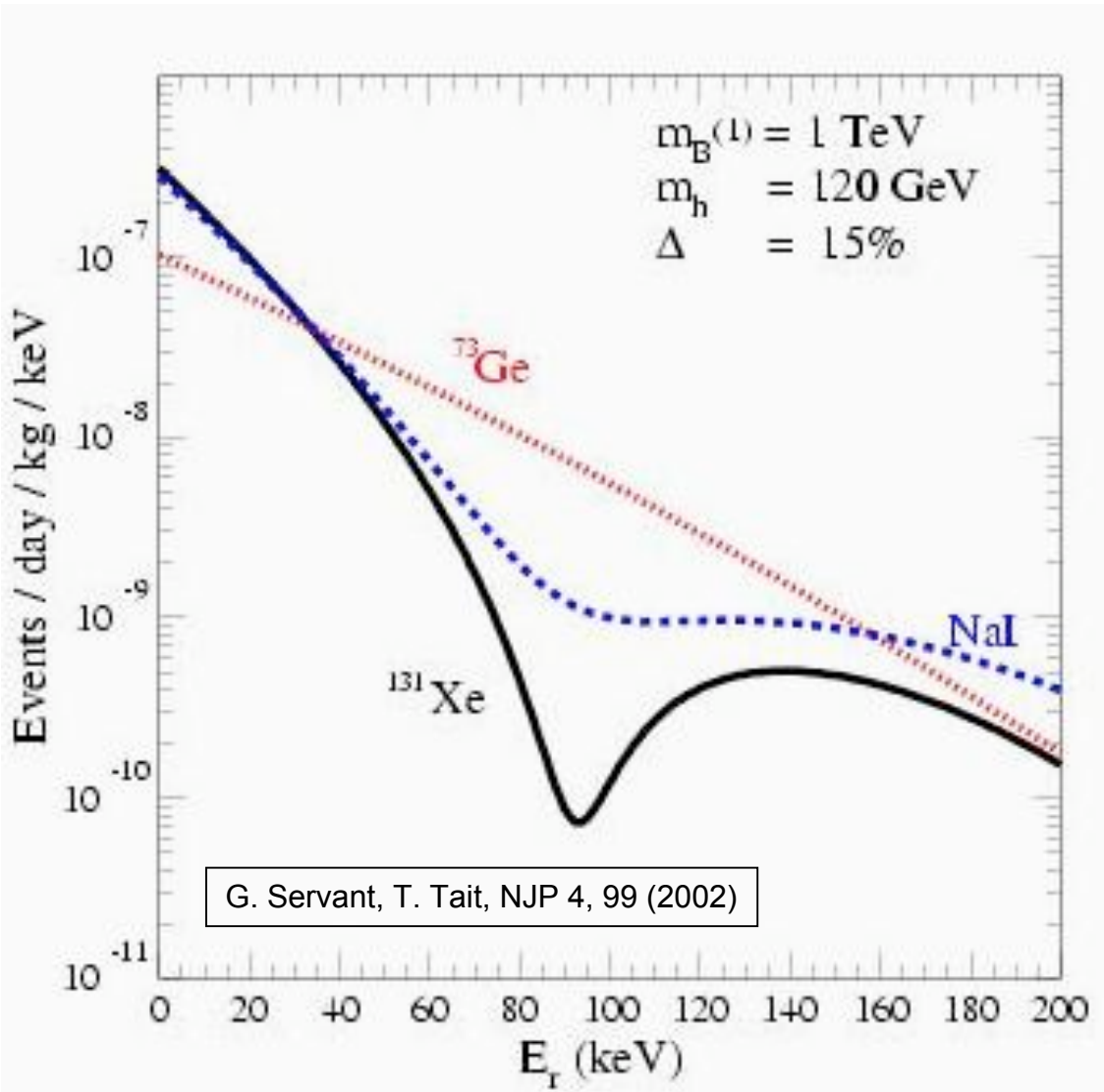
Search strategy is to see an annual modulation of events as the earth revolves around the sun.

DAMA: 100 kg NaI

LIBRA: 250 kg NaI



Differential Rates in E_r



Differential rates depend on nuclear form factors. They are important in order to correctly model experimental sensitivity.

Two form factors dominate for Non-relativistic scattering:

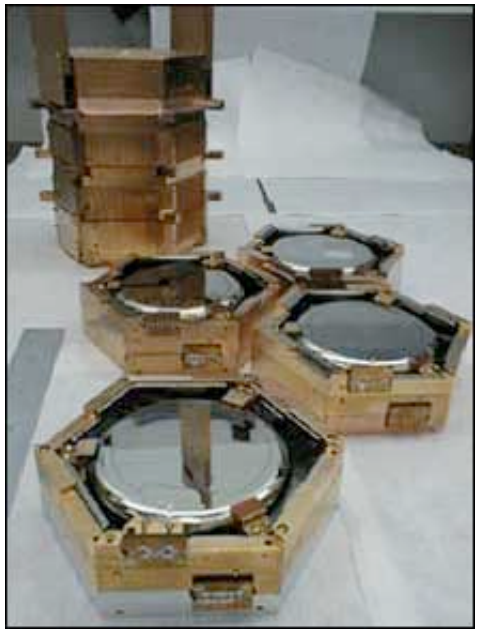
Scalar:

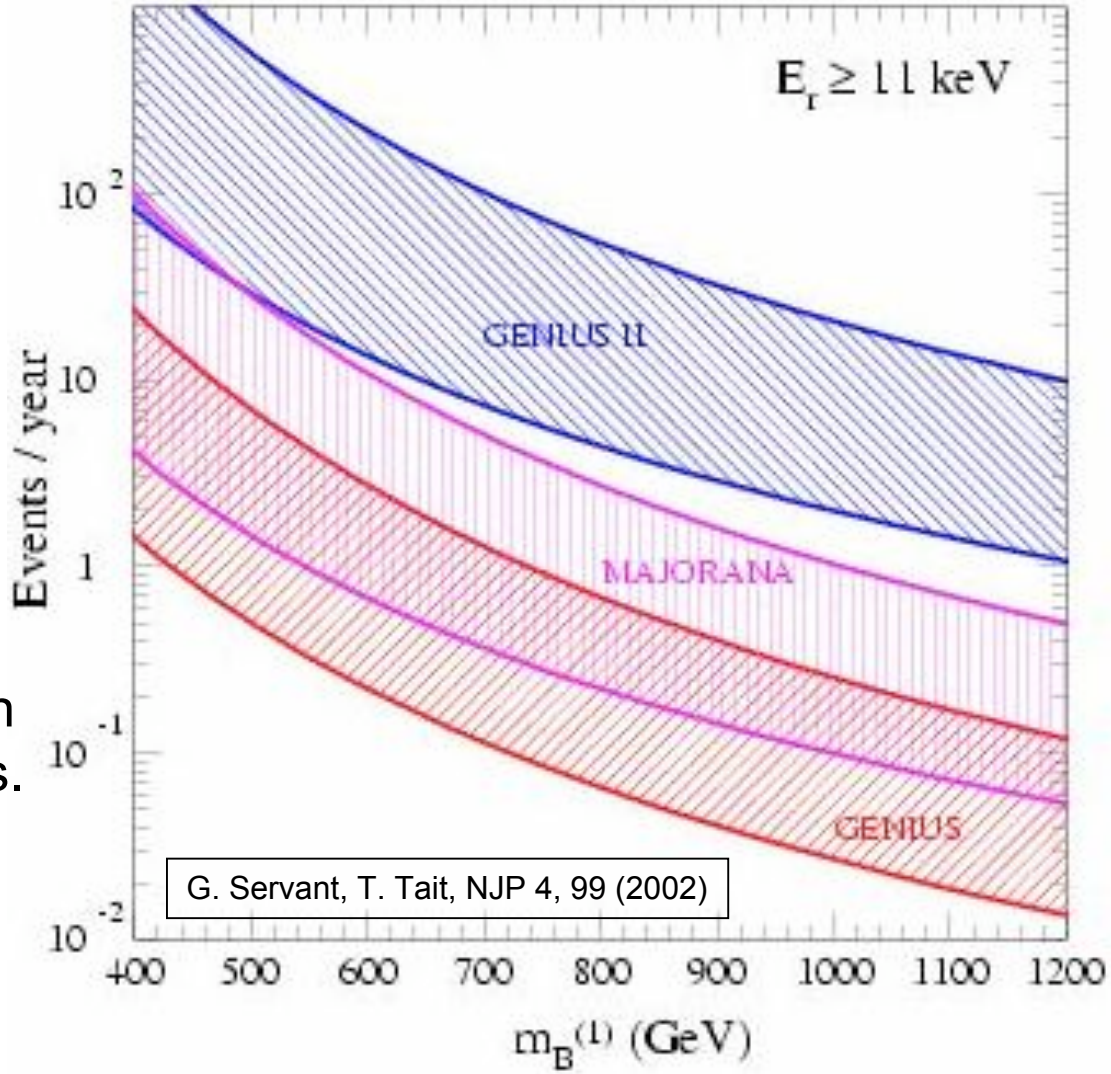
$$B_\mu^{(1)} B_{(1)}^\mu \left\langle \bar{q}q \right\rangle \propto A_N^{\ 2}$$

Spin-dependent:

$$B_i^{(1)} B_j^{(1)} \varepsilon^{ijk} \left\langle \bar{q}\gamma_k\gamma_5 q \right\rangle \propto \vec{S}^2_N$$

Germanium Detectors





G. Servant, T. Tait, NJP 4, 99 (2002)

Very precise calorimeter, in order to see a clear excess.

GENIUS : 100 kg ^{73}Ge
GENIUS-2 : 10^4 kg ^{76}Ge
MAJORANA : 500 kg ^{76}Ge

Evolution of the Relic Density

- **To estimate WIMPs relic density, assume it was in thermal equilibrium in the early universe:**

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} Exp\left[-m/T\right]$$

Interactions with the relativistic plasma are efficient, and the WIMPs follow a Maxwell-Boltzmann distribution.

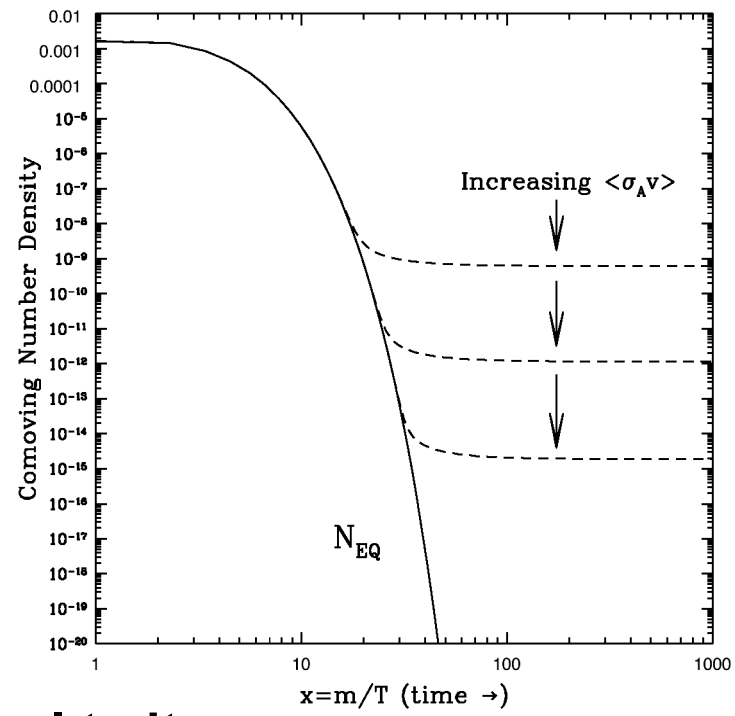
•However, the universe is expanding, and once the density is small enough, they can no longer interact with one another, and fall out of equilibrium.

Below the freeze–out temperature, the WIMPs density per co-moving volume is fixed

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle}{H\,x}\, s\left(Y^2 - Y_{eq}^2\right)$$

with Y = n/s and x = m/T

The key ingredient is the thermally averaged annihilation cross section:



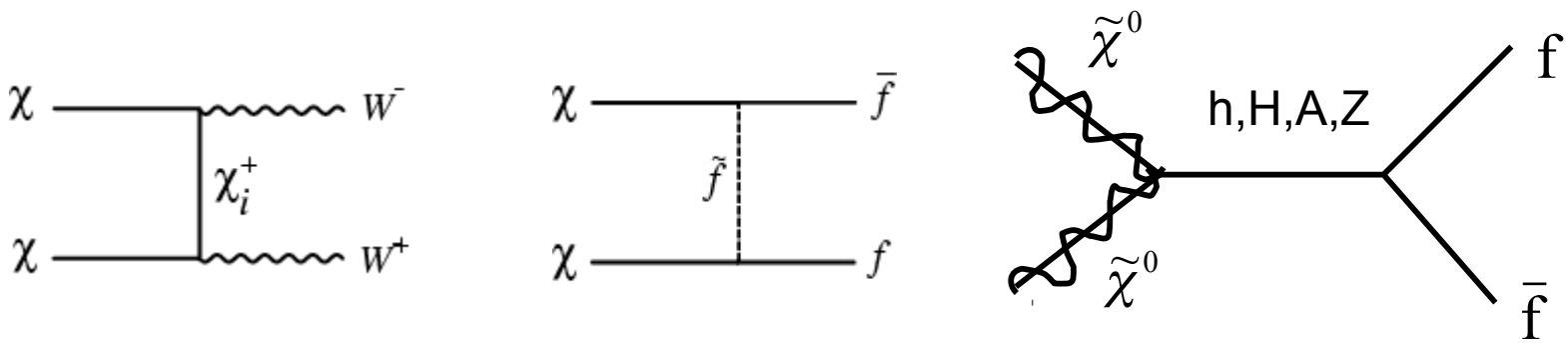
The relic density is inversely proportional to it.

Kolb and Turner

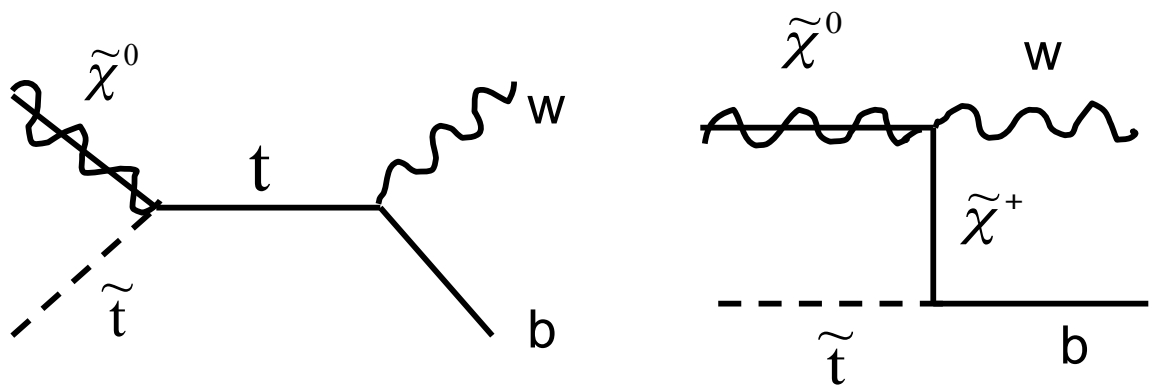
Supersymmetry:

with R parity discrete symmetry conserved $R_P = (-1)^{3B+L+2S}$
naturally provides a stable, neutral, dark matter candidate: the lightest neutralino $\tilde{\chi}^0$

Many processes contribute to the neutralino annihilation cross section



If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation



if stops NLSP

neutralino-stop

co-annihilation

Possible funding profile for SuperCDMS

Year	DOE(M$)	NSF(M$)	Total(M$)	Comments
2007	2	4	6	Includes 2M$ NSF MRI
2008	5	5	10	Sufficient for SuperCDMS 25 kg

			$16M	
2009	2	2	4	R&D towards 150/1000 kg
2010	2	2	4	R&D towards 150/1000 kg; CDR produced.
2011	2	2	4	R&D towards 150/1000 kg; TDR produced.
2012	4	4	8	Begin construction of 150/1000 kg
2013	5	5	10	Continue 150/1000 kg construction
2014	5	5	10	Continue 150/1000 kg construction
2015	5	5	10	Begin 150 kg operation

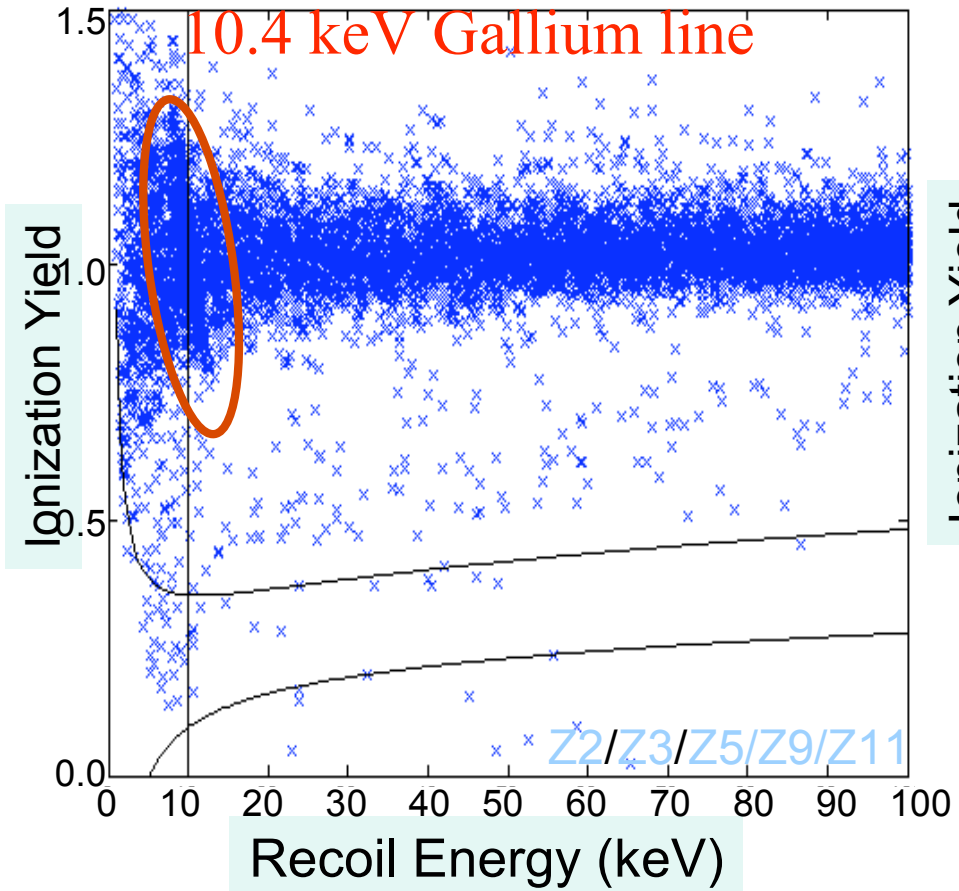
			$50M	

2016-2020 Continue funding at $10M per year to build detectors for 1000 kg, for additional subtotal of $50M. Operation of 1000 kg in 2020.

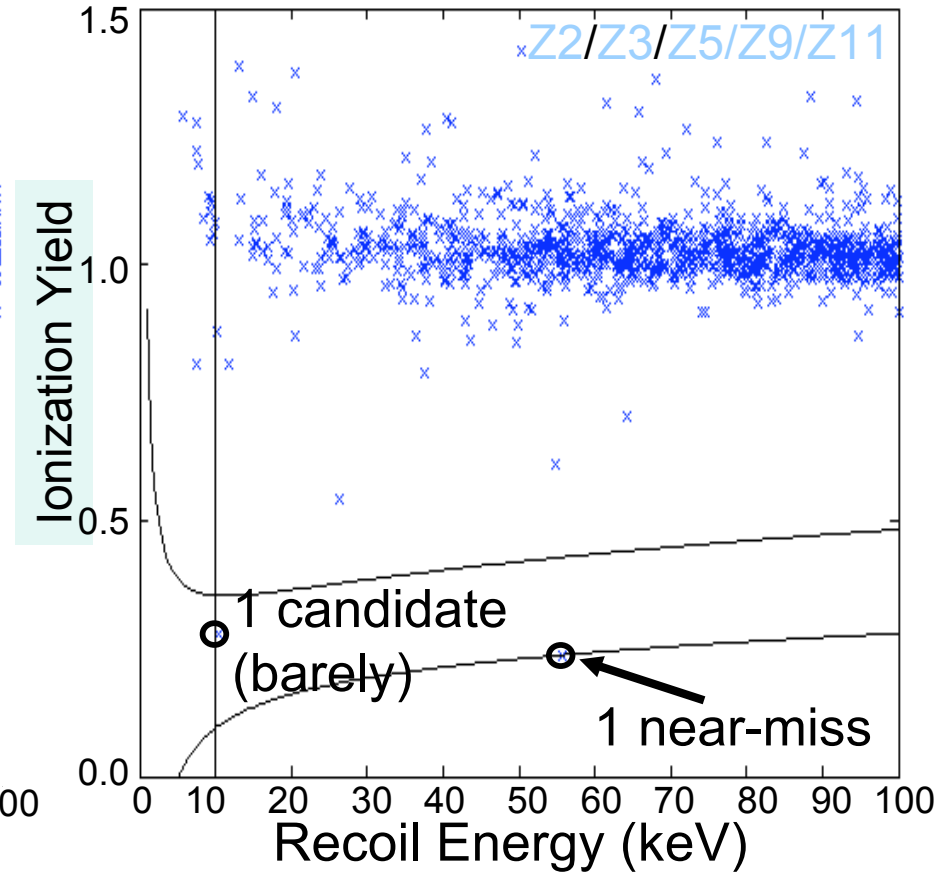
Note: In addition to the project money, we need about $1M/year total for each year we are operating at either Soudan or SNOLAB.

CDMS II: Preliminary New Results from Two Towers

Prior to timing cuts



After timing cuts, which reject most electron recoils



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