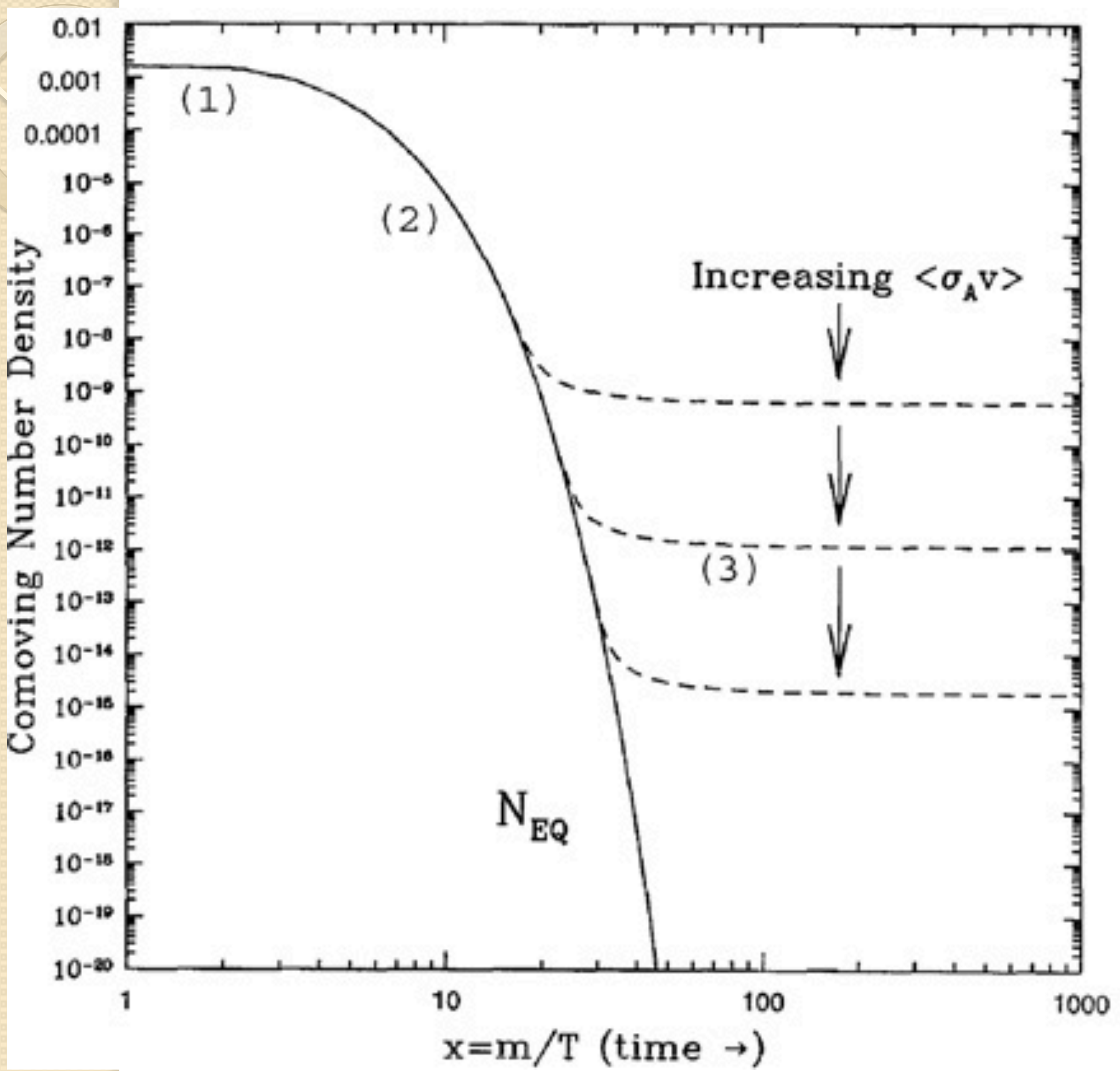
The Matter Content of the Universe II

- Searches for Dark Matter
  - Direct searches
  - Cosmological constraints
  - LHC searches for SUSY DM

WIMP Dark Matter

- Weakly interacting massive particles are the most favoured DM candidate
- Occur in many models, including a wide range of supersymmetric scenarios
- For CDM, freeze-out occurs when particles are non-relativistic. Expect DM in Galaxy to be moving at same speed as baryons – about 220 kms^{-1}

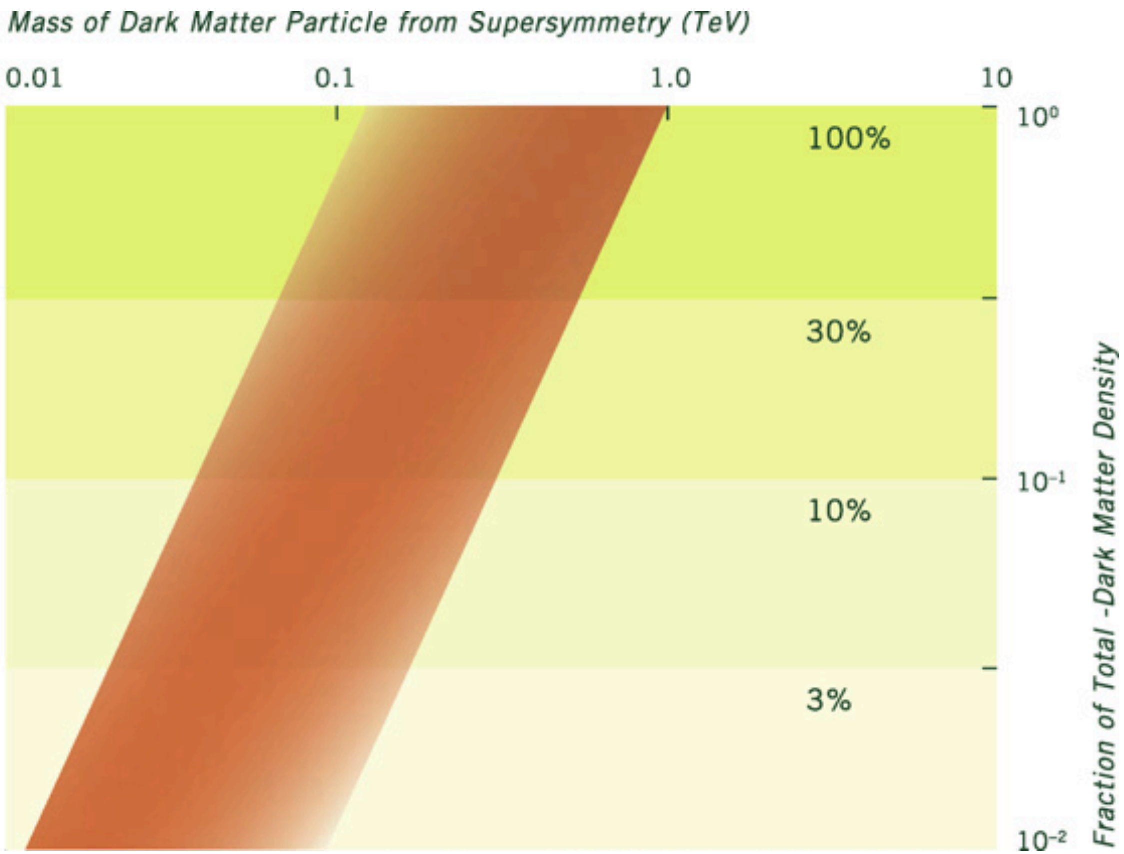
The "WIMP miracle"



Freezeout of dark matter depends on mass and annihilation cross-section.

Consider case for massive WIMP, (non-rel) with weak interaction cross-section

WIMP masses in range 100 GeV-1 TeV, with normal weak interactions, naturally give dark matter densities in the required range. These are exactly what are predicted by supersymmetry models, and other BSM scenarios.



For calculation of particle densities at freezeout see Kolb and Turner, section 5.2

HEPAP LHC*/ILC-subpanel Discovering the Quantum Universe http://www.linearcollider.org*

Signals for dark matter

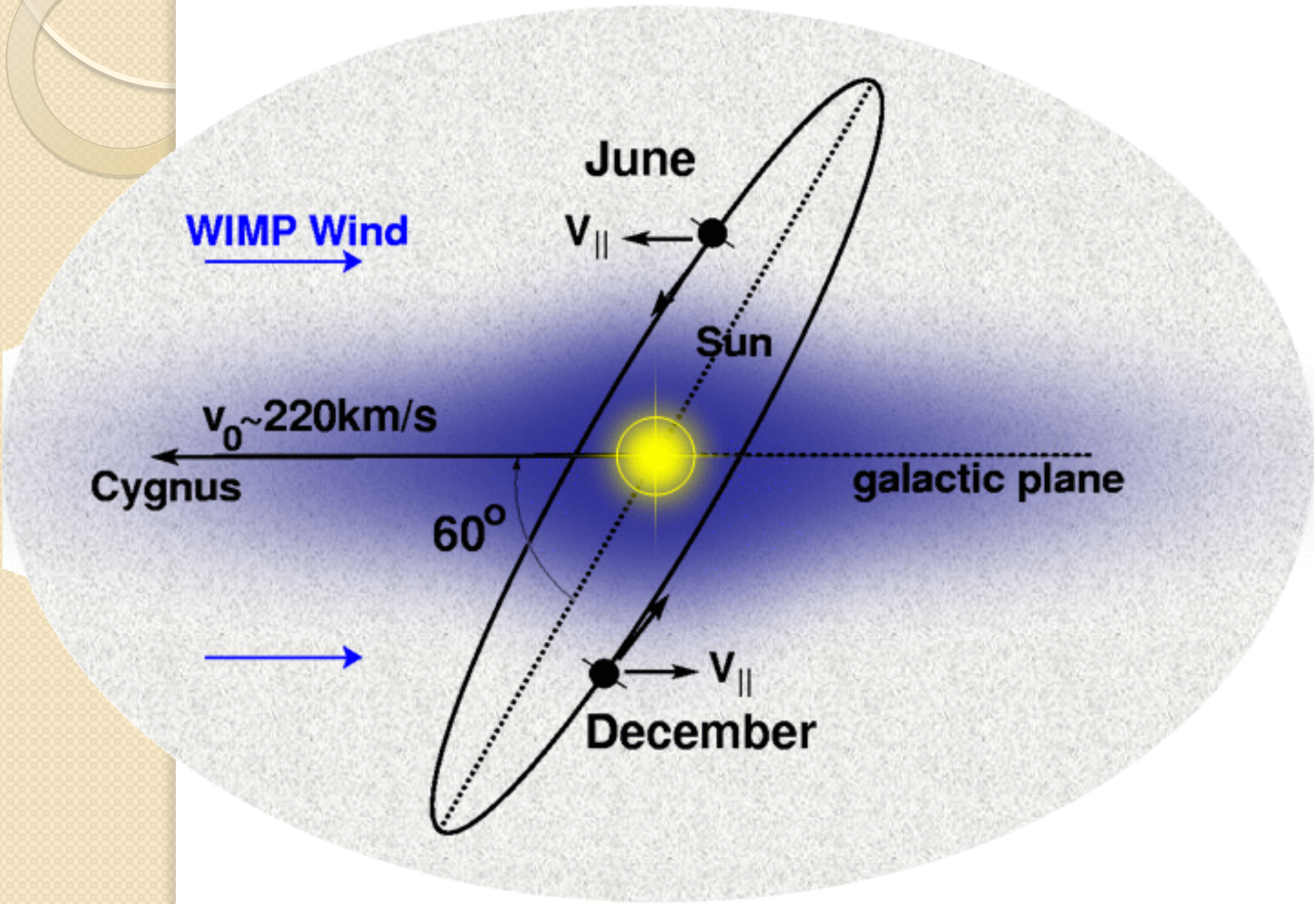
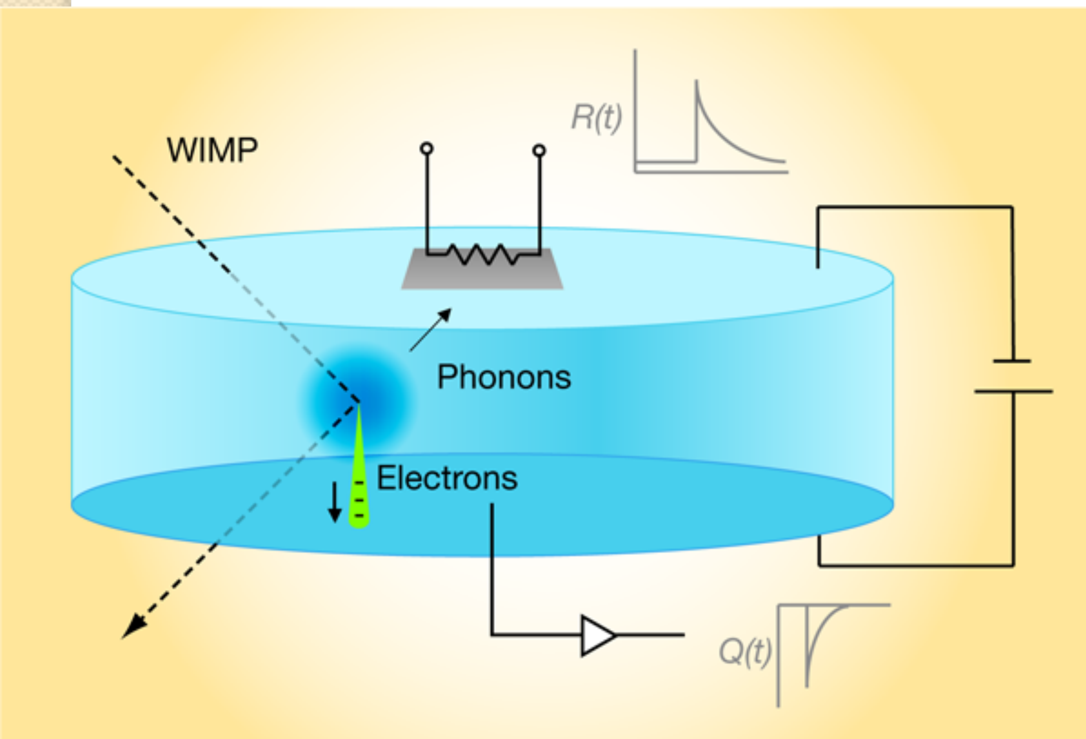


Figure from Sheffield HEP group

Earth passing through DM wind with seasonal modulation of velocity

Look for collisions between DM particles and detectors

DM detection principles



Measure recoil energy as phonons and ionization created in collision between WIMP and detector material.

Since v<<c, energy release is small -> require high sensitivity/ low noise detectors: normally use cryogenic temperatures to limit noise.

Coherent scattering:

$$\sigma \propto A \text{ for spin 0 target}$$

$$\propto \text{ J for spin J}$$

Expect O(1) DM particles/litre near Earth -> interaction rate expected to be <1/year/kg of target.

Work deep underground to shield from cosmic rays.

DM Backgrounds

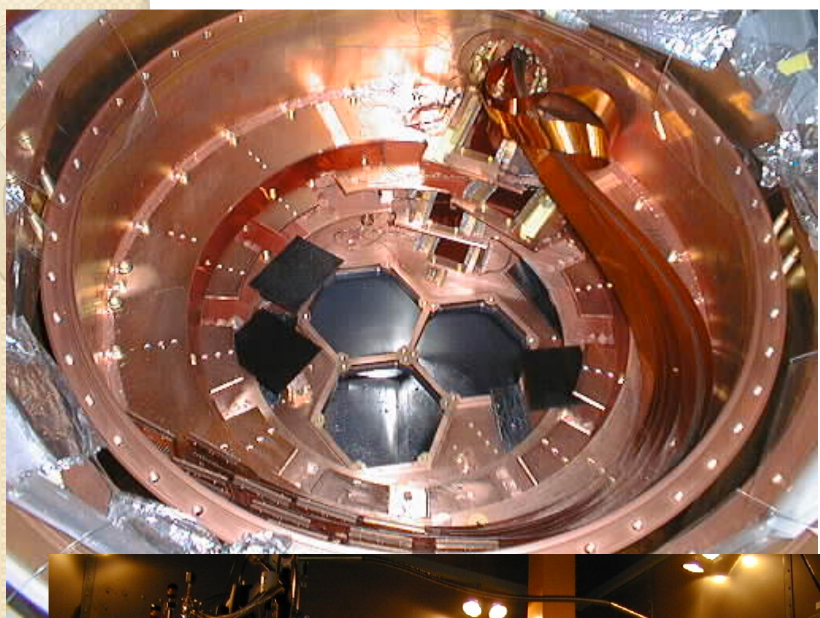
- Electrons and photons from environment, especially nuclear beta decays, gives different ratio of ionization/phonons than WIMPs
- Neutrons from cosmic ray showers and nuclear fission – scattering same as for WIMPs, but can shield and veto.

CDMS detector, Soudan, USA

Stacks of segmented germanium detectors (230 gm):
-detect ionization by drifting charge to surface in electric field
- Phonons break Cooper pairs in superconducting Al layer on surface. Resulting heat changes resistance, which is then measured as a current pulse.

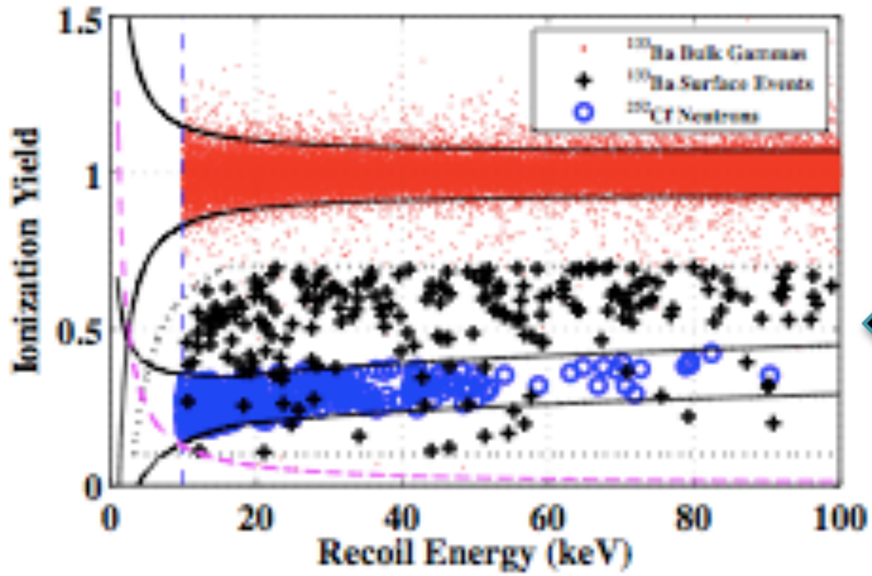
Segmentation allows time of arrival of the two signals to be measured, locating the region of detector which was hit. Outer ring of detector read out separately to veto events near edges. "Surface events" give reduced ionization but faster phonon pulse.

CDMS



10 mK crysostat constructed of radiopure copper to avoid background. Lead shield from ballast of 18th century French ship. Polyethelyne shield to moderate neutrons. Active muon shield.

CDMS calibration data

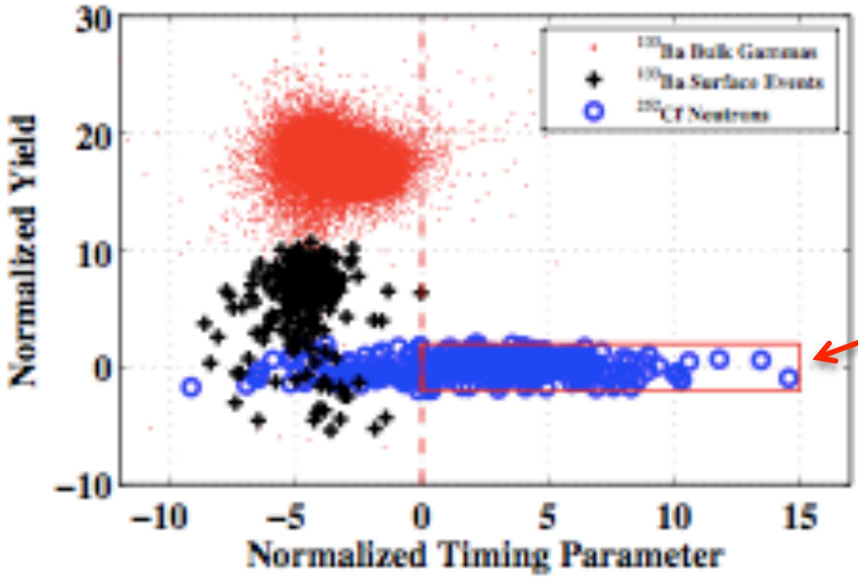


- Calibration data from radioactive sources

Electron scatters

Surface events

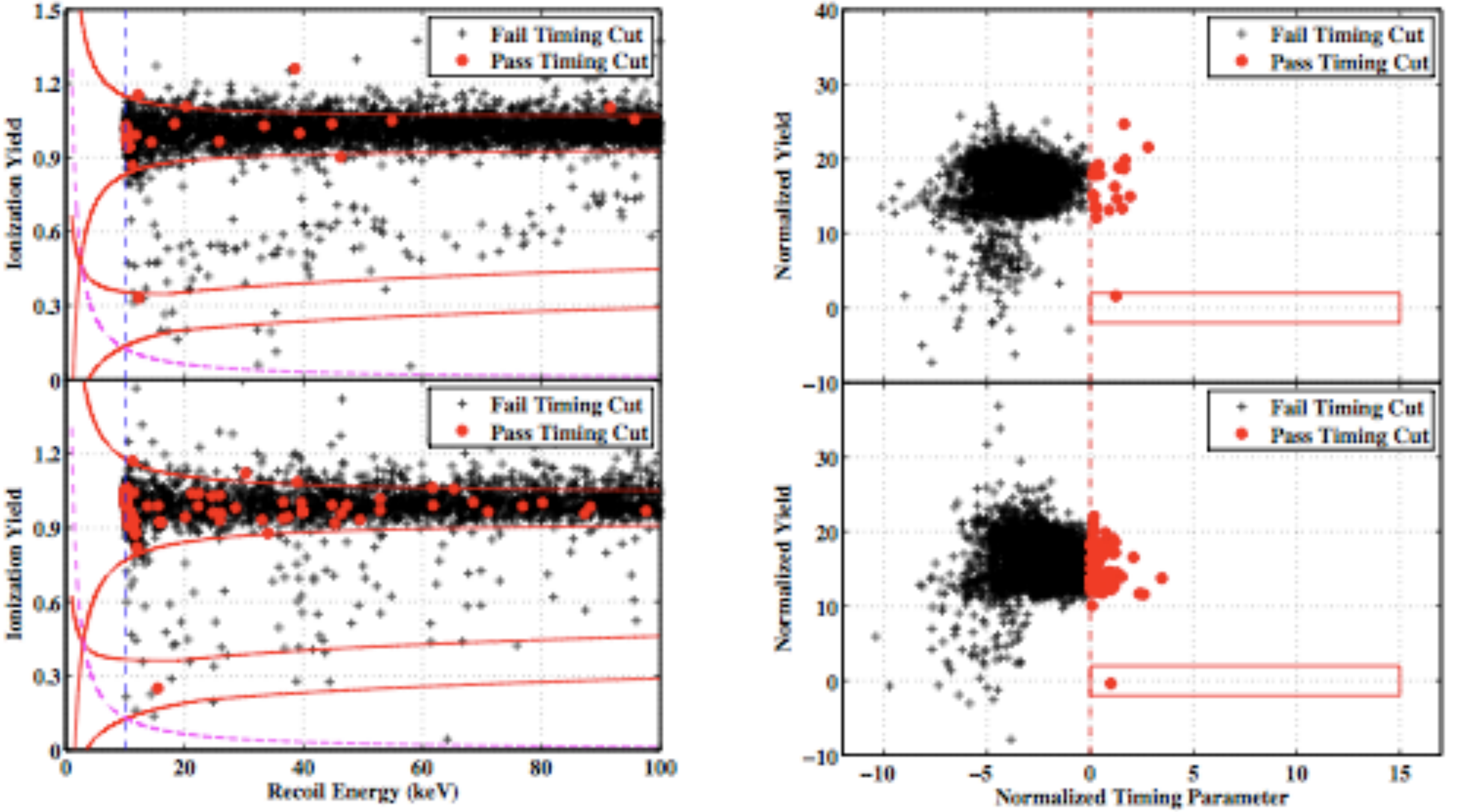
Neutron scatters



Timing of pulse shape removes surface events – but still dominant background, estimated at 0.6+- 0.1 events

Signal region

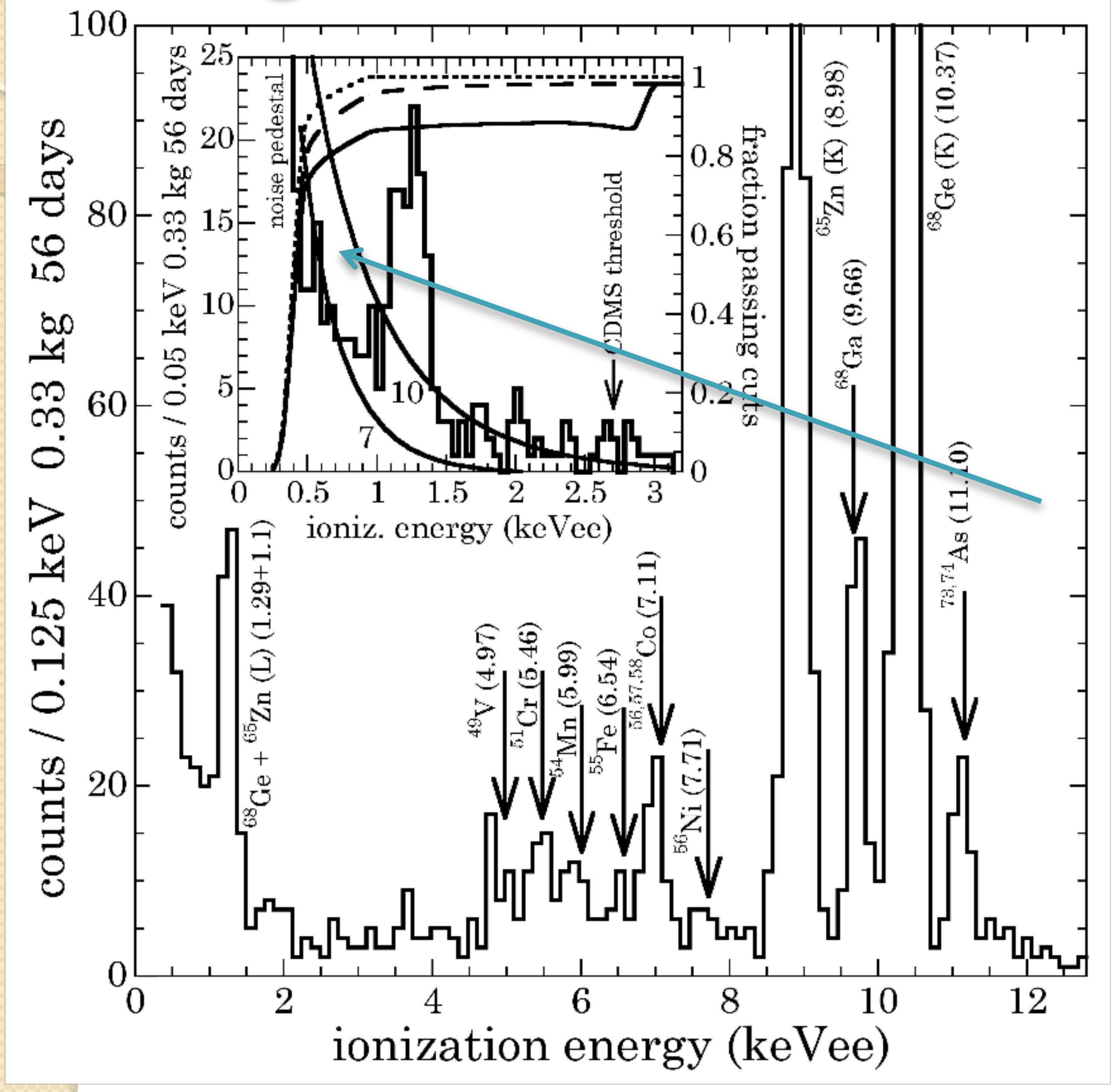
CDMS data



Data from two different detectors: two signal events observed, but not sufficient to claim signal. Used to set limit on DM cross-section.

http://cdms.berkeley.edu/0912.3592v1.pdf

Signal from CoGeNT detector

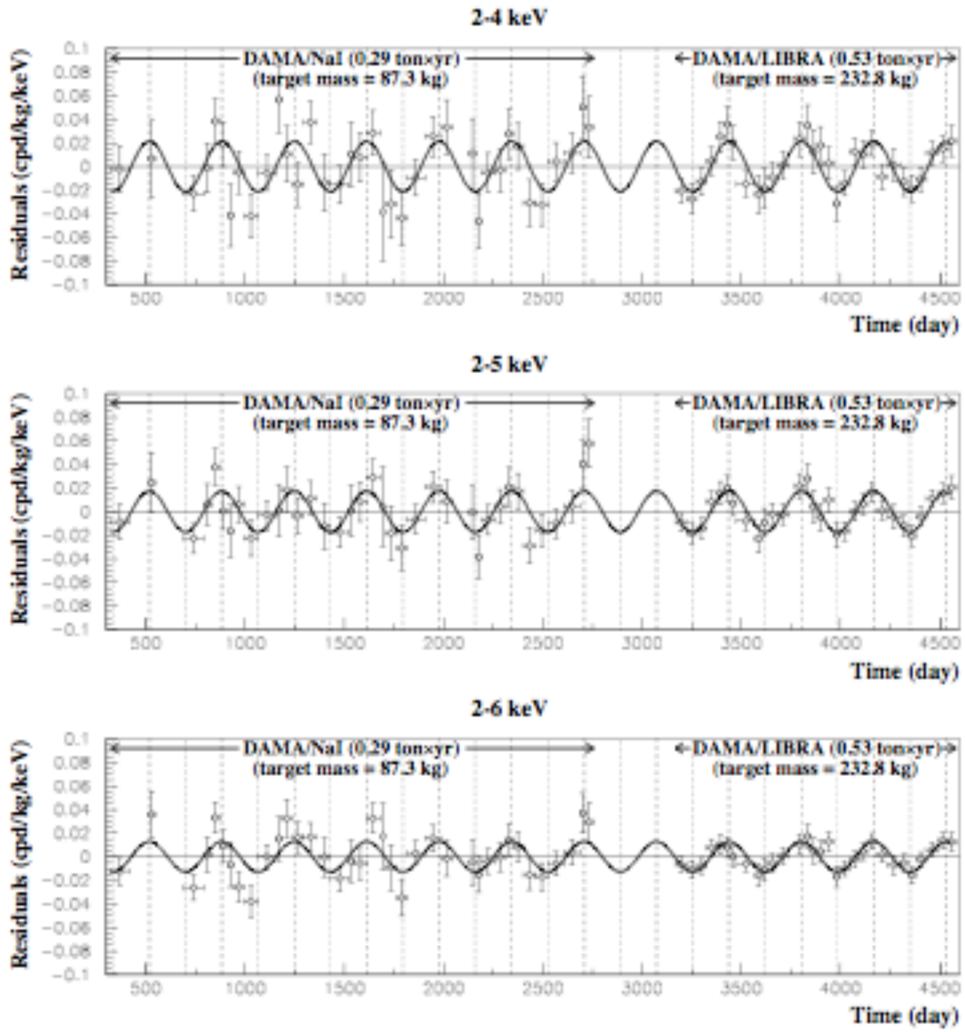


Single Ge crystal operating with much lower threshold than CDMS.

Arrows show expected nuclear levels.

Rise in rate below 1 keV matches signal expected for Wimp signal with a mass of 7 GeV/c^2

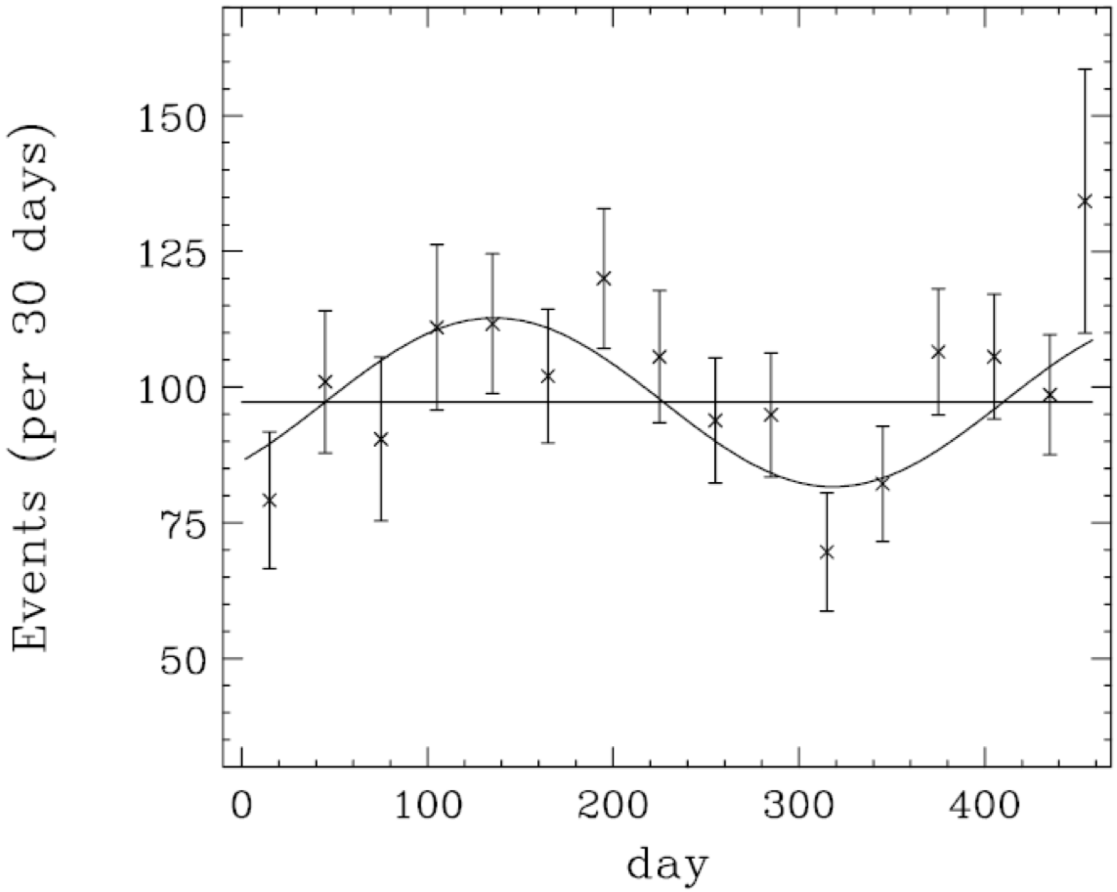
DAMA/Libra results



arXiv:astro-ph/0307403v1

- Uses 100 kg scintillator crystals to look for annual modulation of event rate. No background subtraction. 11 years of data. 8.2 sigma effect.
- Model independent method.
- Result claimed to be incompatible with expected dark matter rate – see eg http://arxiv.org/pdf/0807.0879v4
- >55 papers on arxiv proposing explanations!

Modulation of CoGeNT data



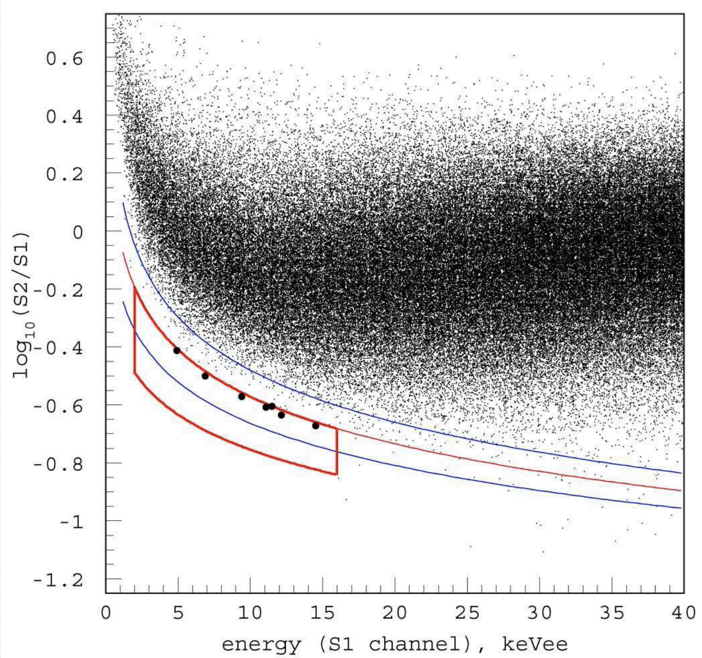
CoGeNT data shows annual modulation similar to DAMA, about 1 month earlier, but within errors.

DAMA data has expected phase for DM signal.

Xenon detectors

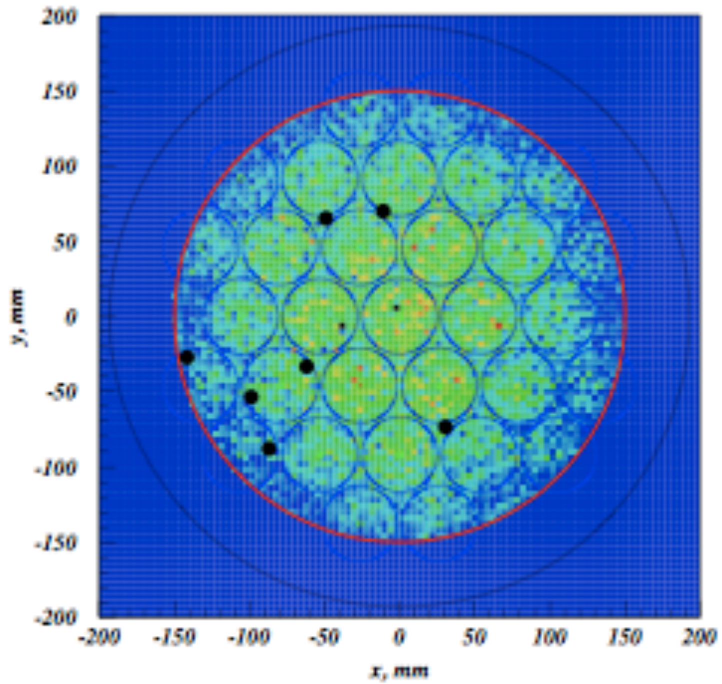
- XENON10 and ZEPLIN detectors use Xe liquid as detectors, producing scintillation light and ionization signals. Can locate interaction point in liquid -> no surface events. Competitive with CDMS but easier to scale up to large masses?

Ratio of signals



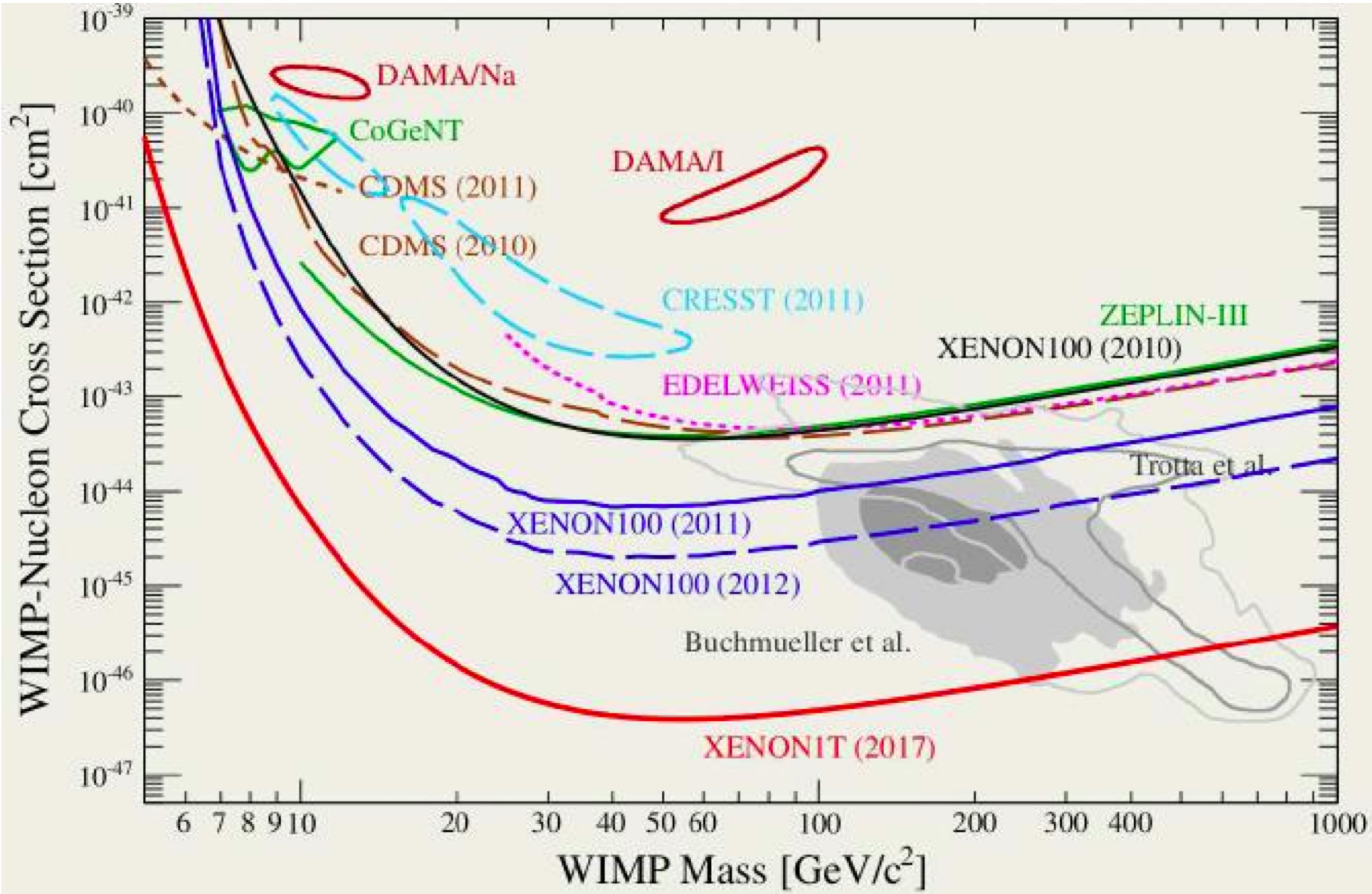
Energy

Events observed by ZEPLIN III

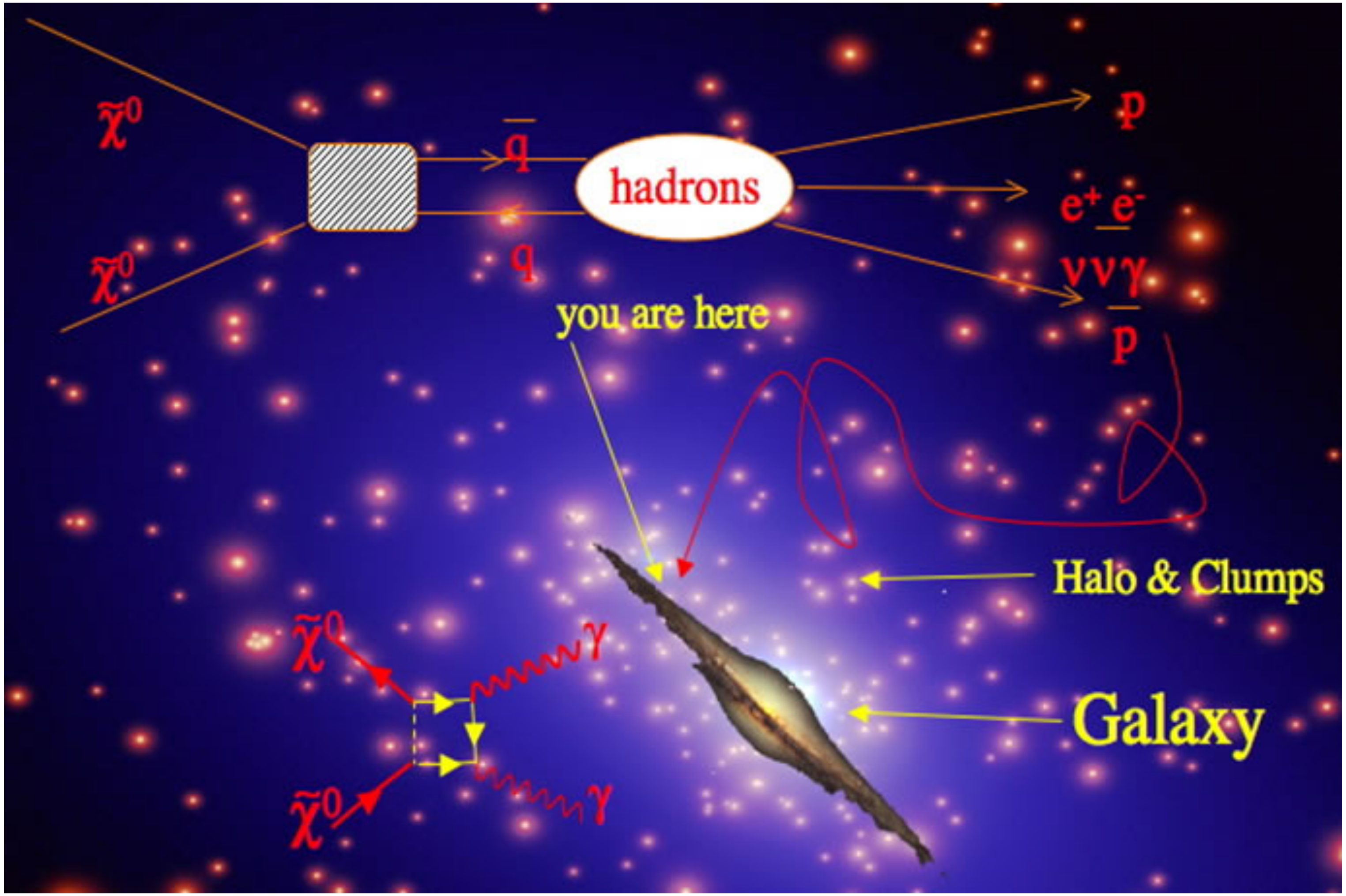


View of events in Xe from photomultipliers

Summary of direct DM searches

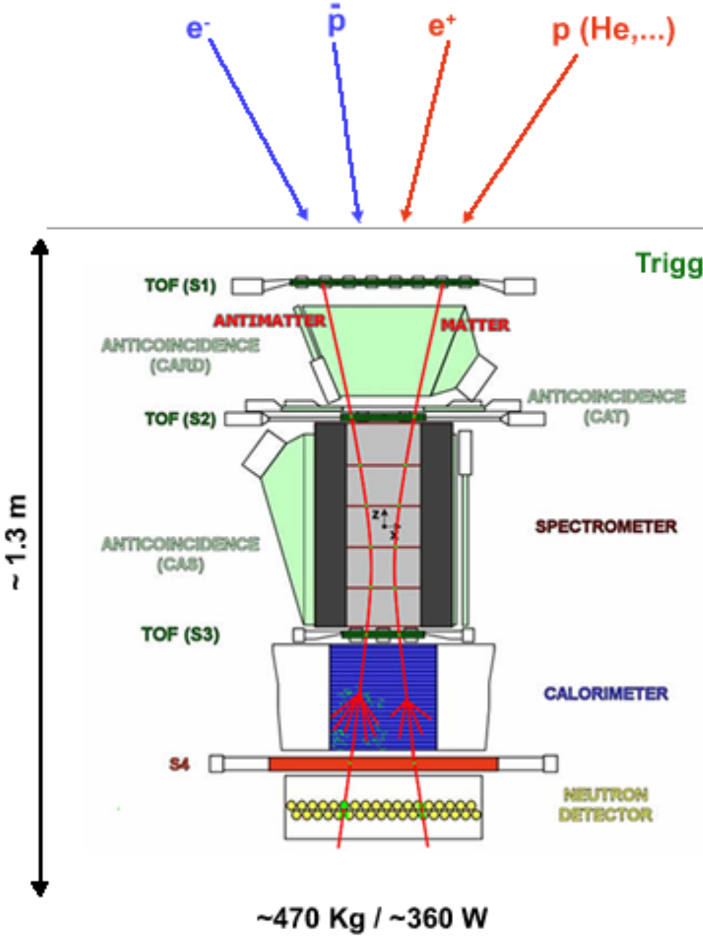


Pamela antimatter search



Look for antimatter flux from WIMP annihilation

PAMELA telescope



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

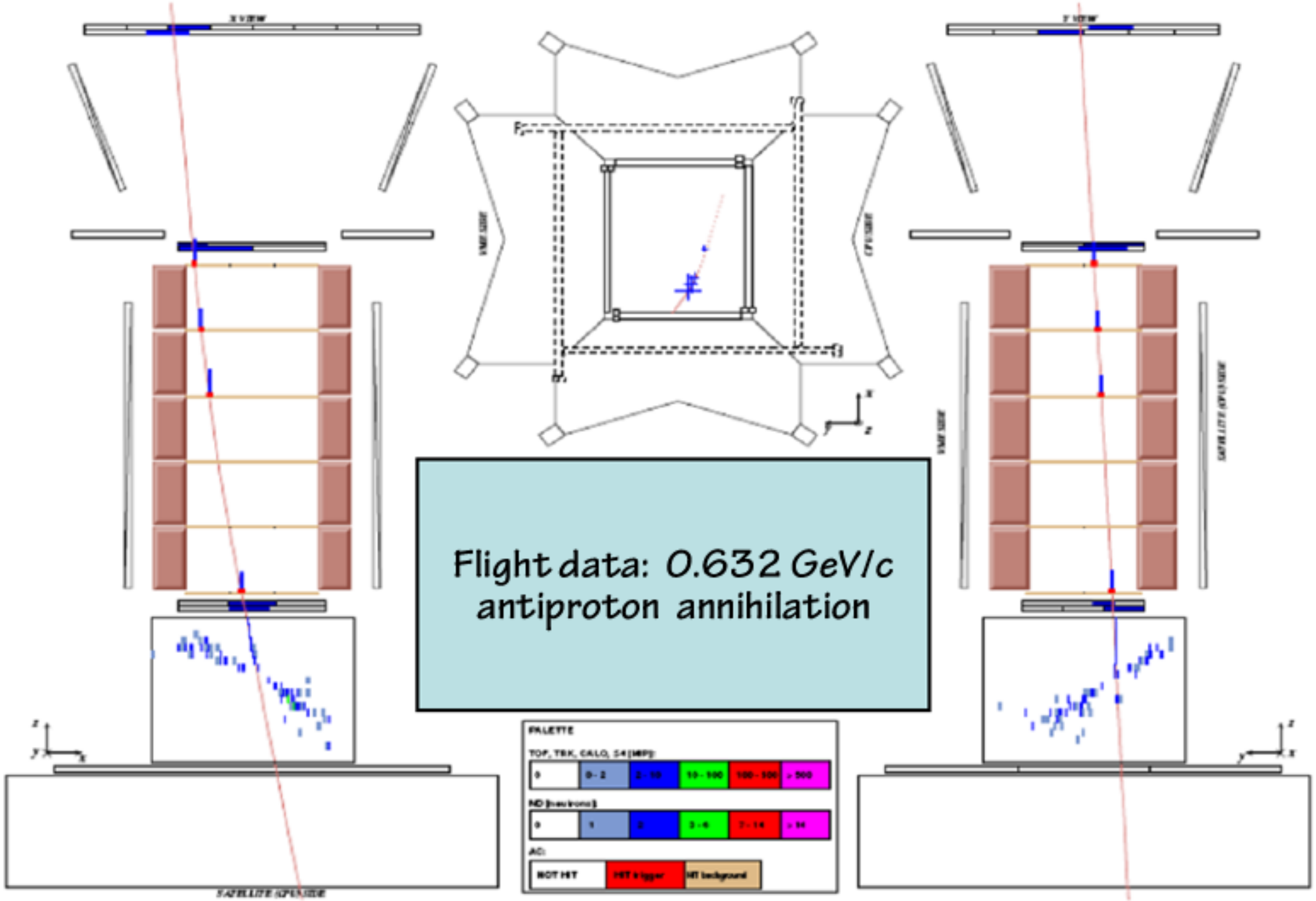
- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

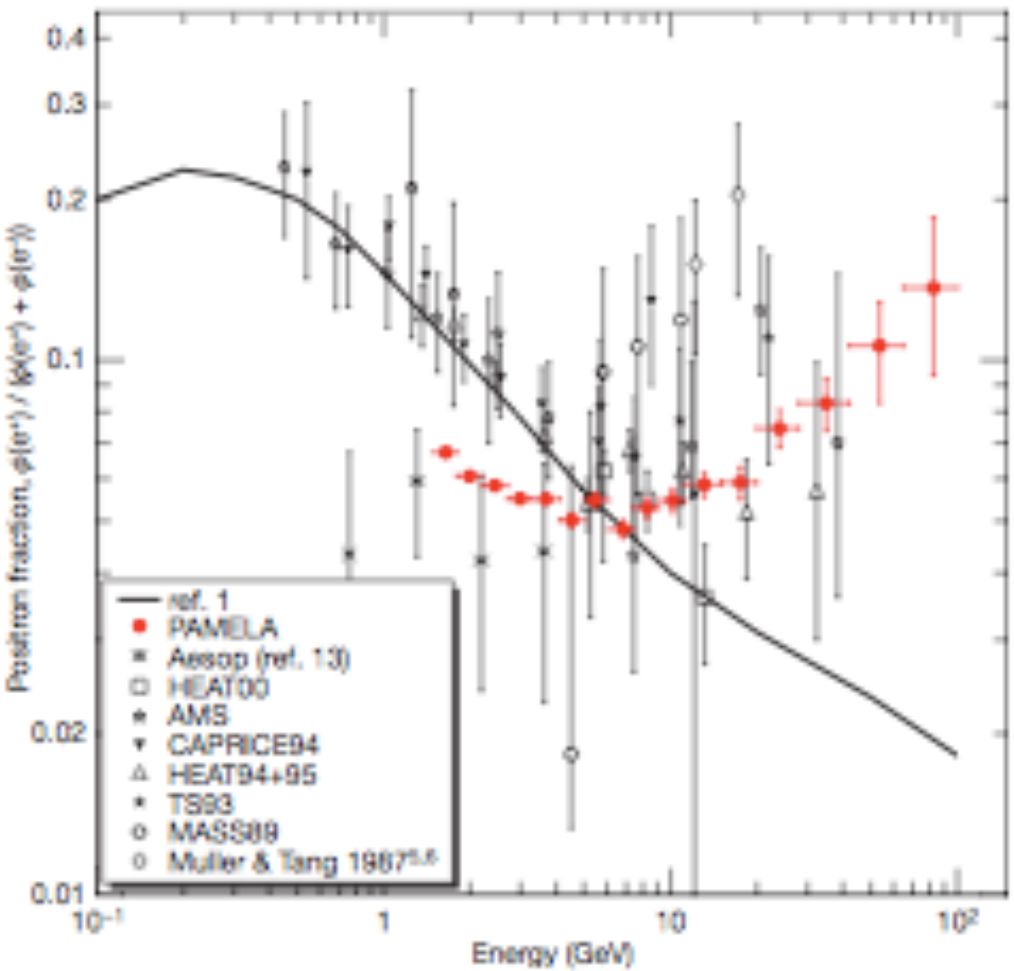
- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

Pamela events

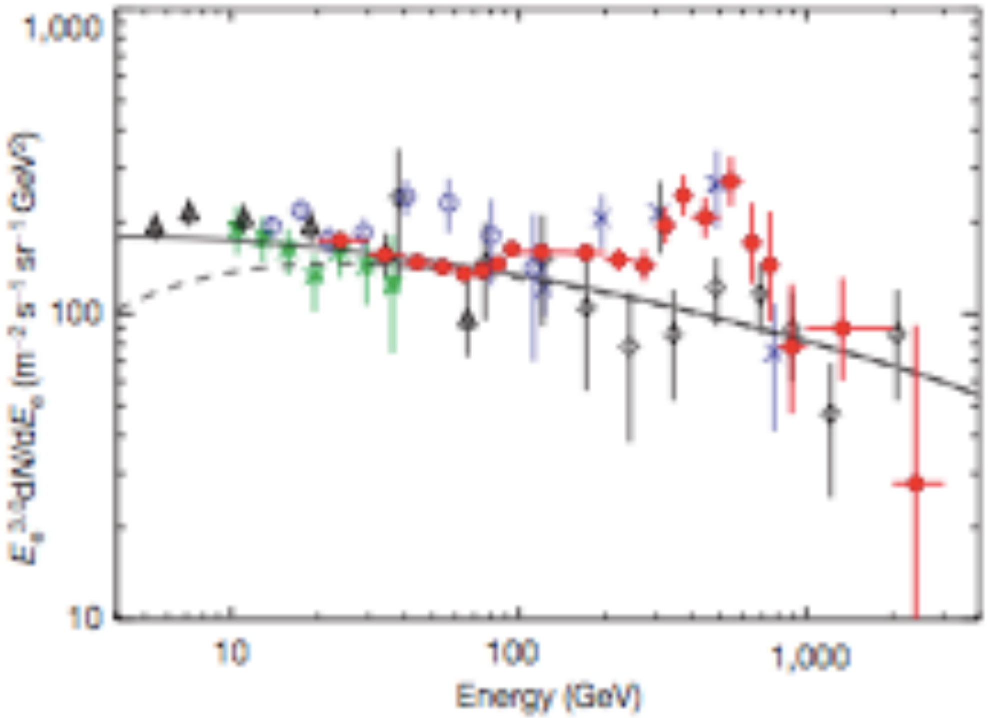


Pamela signal



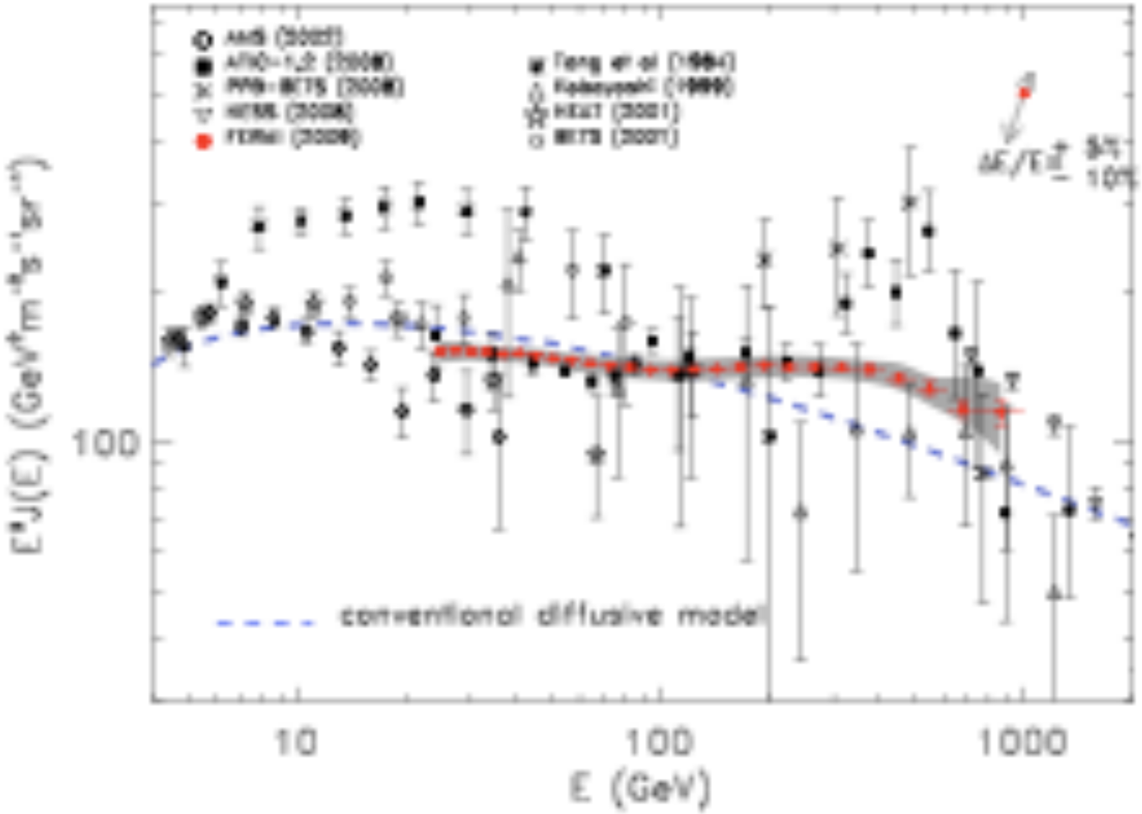
- Excess of positrons observed: dark matter or local activity (eg pulsars)?

ATIC signal



Excess of electrons at high energy observed by balloon experiment over Antartica. Rate 200x expected from WMAP DM density.

Fermi data



- Fermi large area telescope does not confirm ATIC result.

SUSY at the LHC

Multiplet name		Spin 0	Spin 1/2
Quarks/ squarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
Leptons/ sleptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$
Higgs/ higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$

The Minimal Supersymmetric Standard Model

$$R_P = (-1)^{3(B-L)+2s}$$

$= +1$ SM

$= -1$ SUSY

	Spin 1/2	Spin 1
Gluino/gluon	$\tilde{g}$	g
Winos, W's	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
Bino, B	$\tilde{B}^0$	B^0

R-parity

R-parity conservation has important consequences for experimental searches:

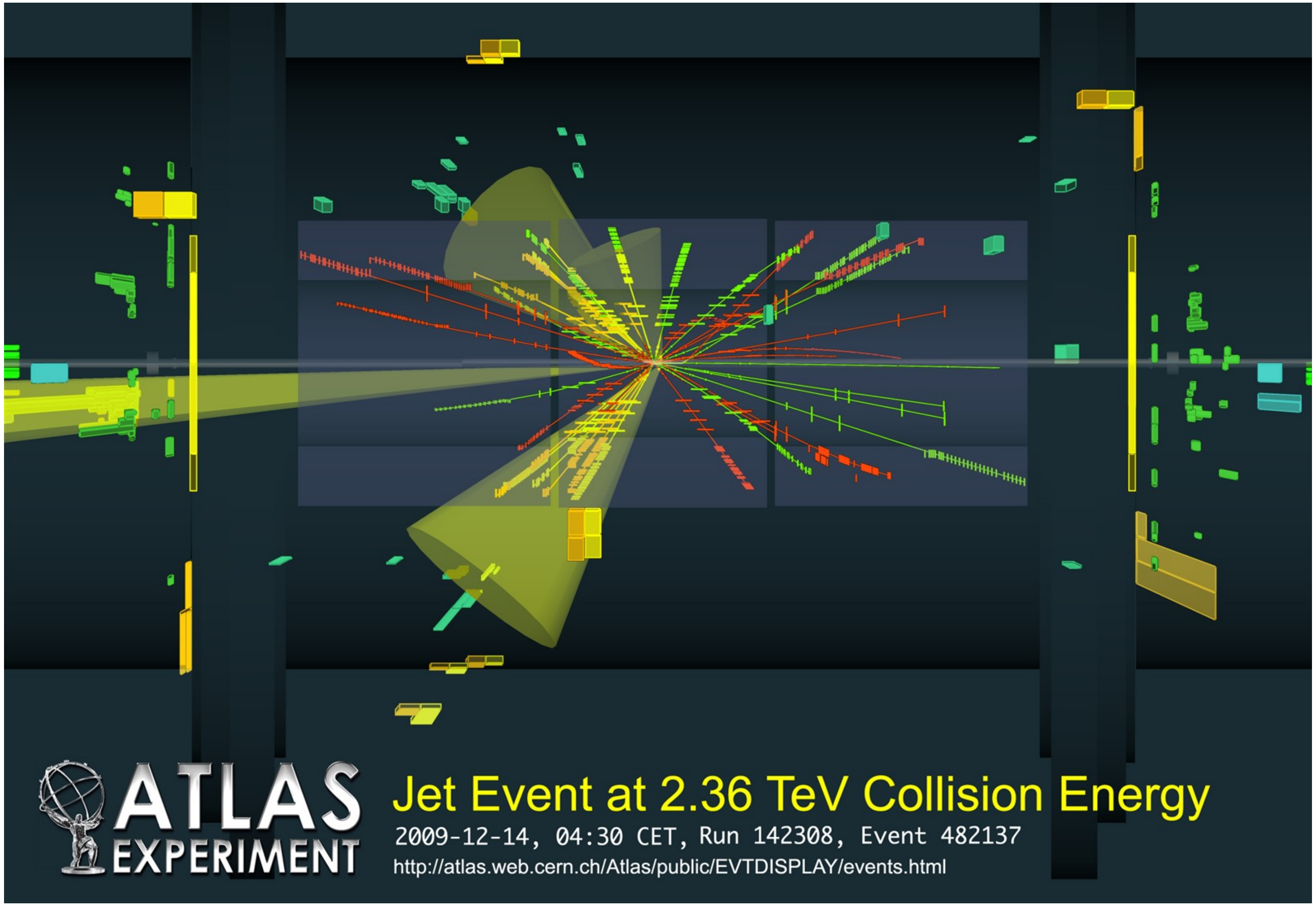
• any initial state must have $R_P = +1$, so SUSY particles must be produced in pairs. This requires energies of twice the SUSY mass.

•Any SUSY particle decay must be to a state with $R_P = -1$, and so each final state contains another SUSY particle.

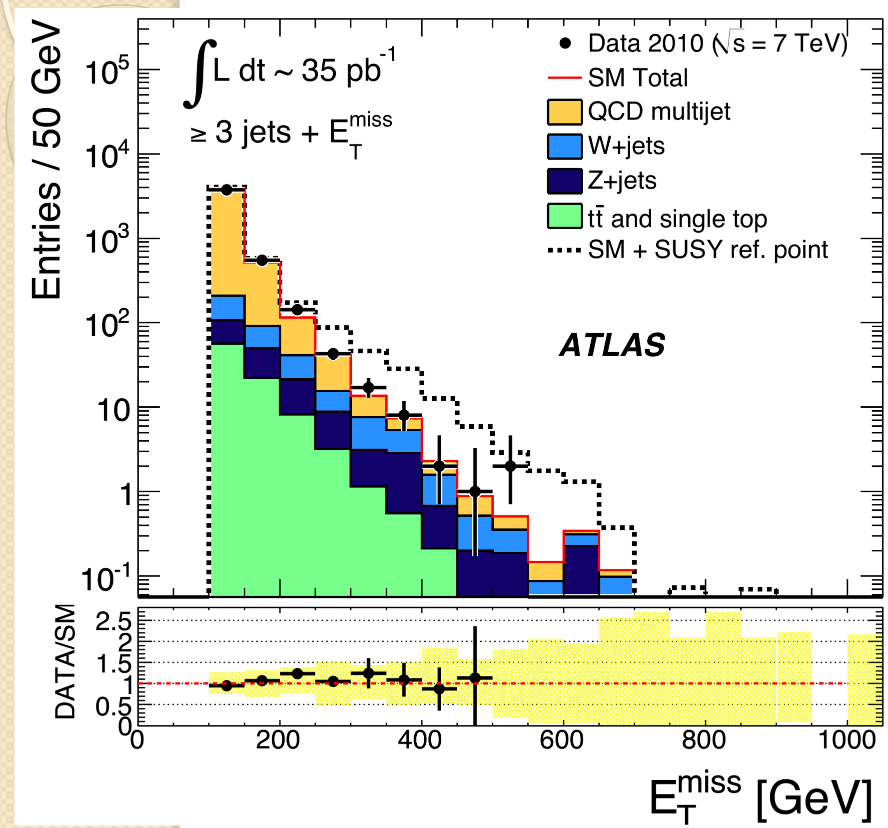
•The lightest SUSY particle (the LSP) must be stable.

•A stable LSP (unless very heavy) must be electrically neutral and weakly interacting to have escaped detection. This is just what is required for dark matter.

ATLAS studies at the LHC



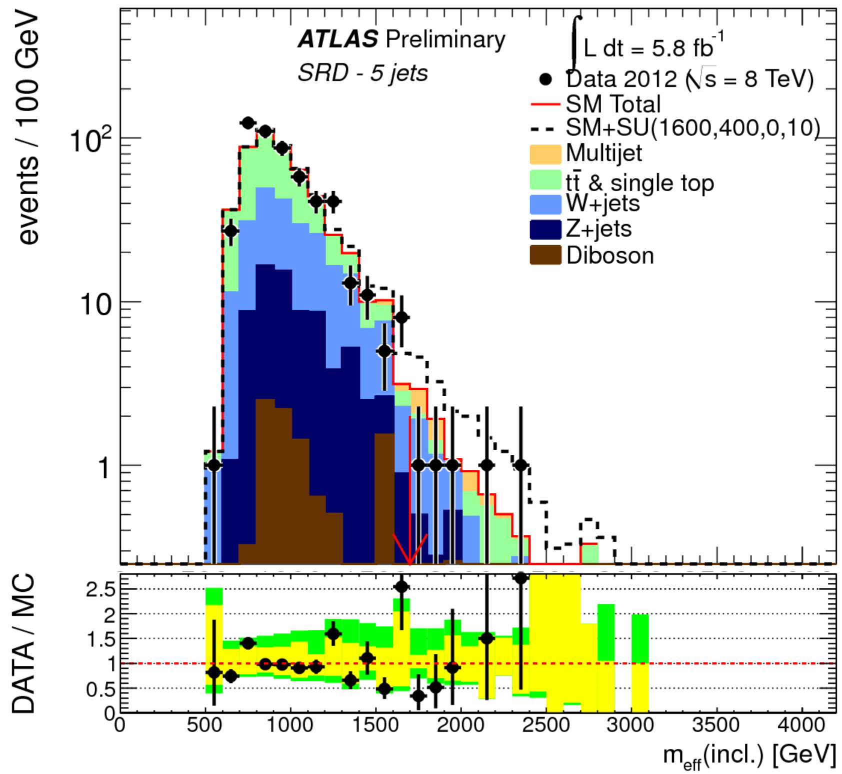
Look for large missing energy



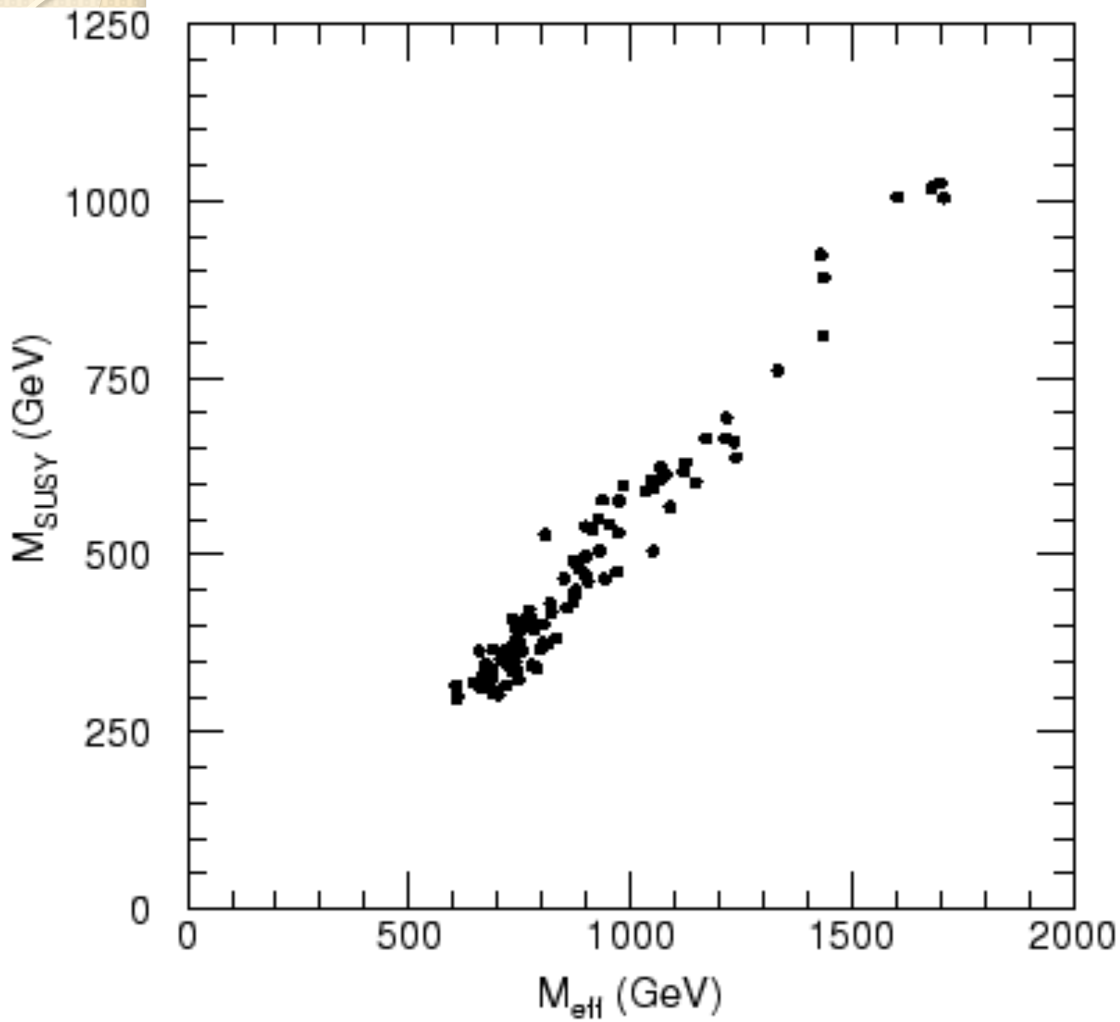
Define an effective mass for inclusive processes:

$$M_{eff} = E_T^{miss} + \sum_{i=1,4} p_T^i$$

Scalar sum over 4 highest p_T jets or leptons and include missing transverse energy.



More events expected at high M_{eff} with SUSY



$$M_{eff} = E_T^{miss} + \sum_{i=1,4} p_T^i$$

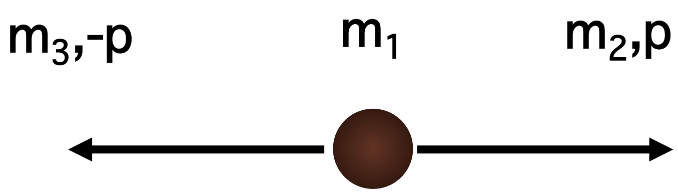
Peak of M_{eff} distribution vs the SUSY mass scale for a set of 100 minimal SUGRA model parameters.

- M_{SUSY} is mass of the lighter of gluino or u_R.
- Strong correlation -> spread of only 10%

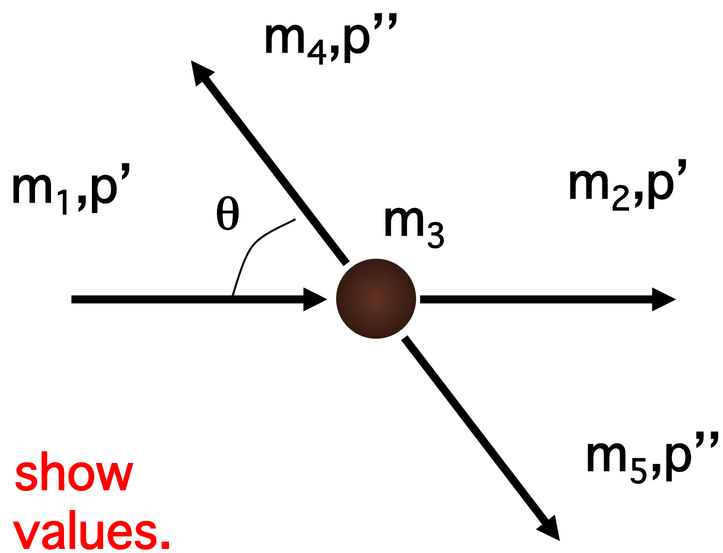
$$\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+ \ell^-$$

Each step in the chain is a two body decay.

The momentum of the outgoing particles is fixed in the rest frame of the parent, and is only a function of the 3 masses.



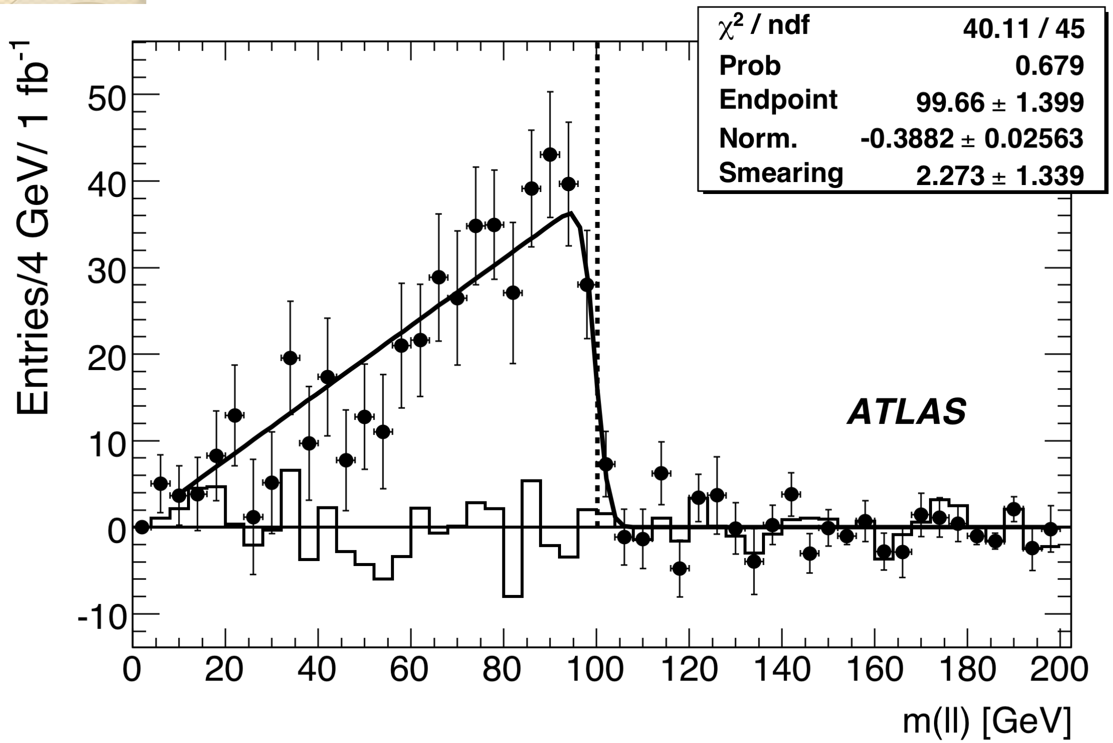
Consider two successive 2-body decays in the rest frame of particle 3:



Invariant masses of pairs of particles given by masses and θ only

Invariant mass distributions will show "edges" at max and min allowed values.

$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R^{\pm} \ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$



The position of the edge depends on the masses of the slepton and the two neutralinos.

$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1 - \frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

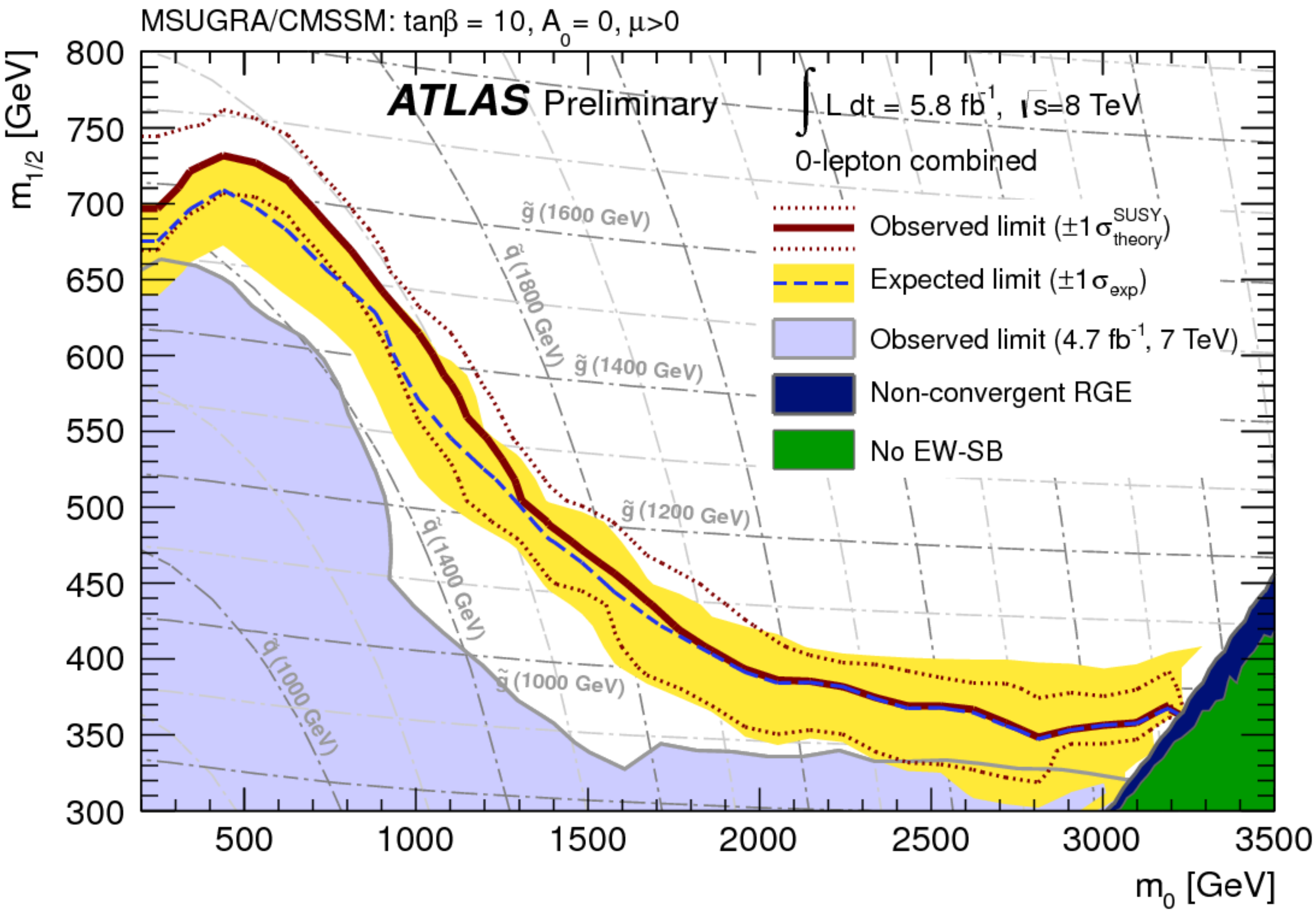
Plot invariant mass of lepton pairs

The leptons in the signal must be of opposite sign and from the same family, since the slepton carries the family information down the chain. Most background comes from processes with unrelated leptons.

eg: WW, or chargino pairs create equal numbers of μμ, ee, eμ and μe events.

Hence most background can be subtracted using opposite sign eμ pairs.

ATLAS limits on MSSM SUSY models – 2012 data



LHC constraints on DM

- With mass constraints of this form, can estimate mass of missing neutralino.
- Infer dark matter density from LHC measurements of mass and coupling strength: compare to astro data.

$$\boxed{\text{Error on } \Omega_\chi h^2 \approx 3-9\% \text{ with } 300\text{fb}^{-1} \text{ of data}}$$

Cf Estimated error from Planck of ~0.42%
(both estimates are model dependent)

Summary

- Dark matter experiments are starting to produce constraints on particle physics models.
- First hints of signals, still controversial.
- LHC will explore large areas of SUSY parameters.
- Require concordance between direct observations, and cosmology before we can claim to understand.