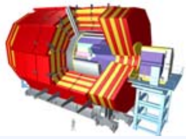
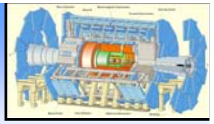




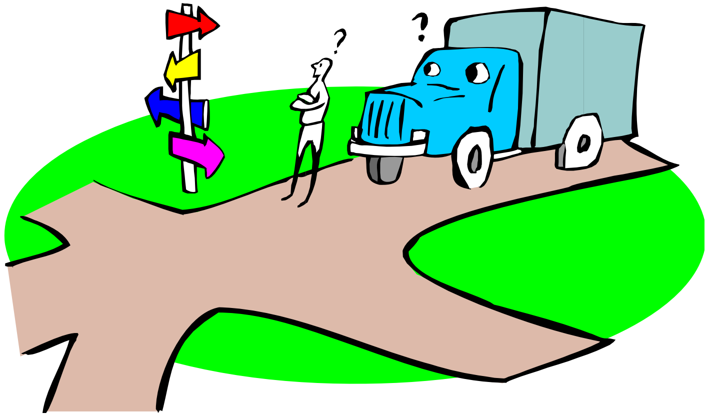
The Road to Discovery

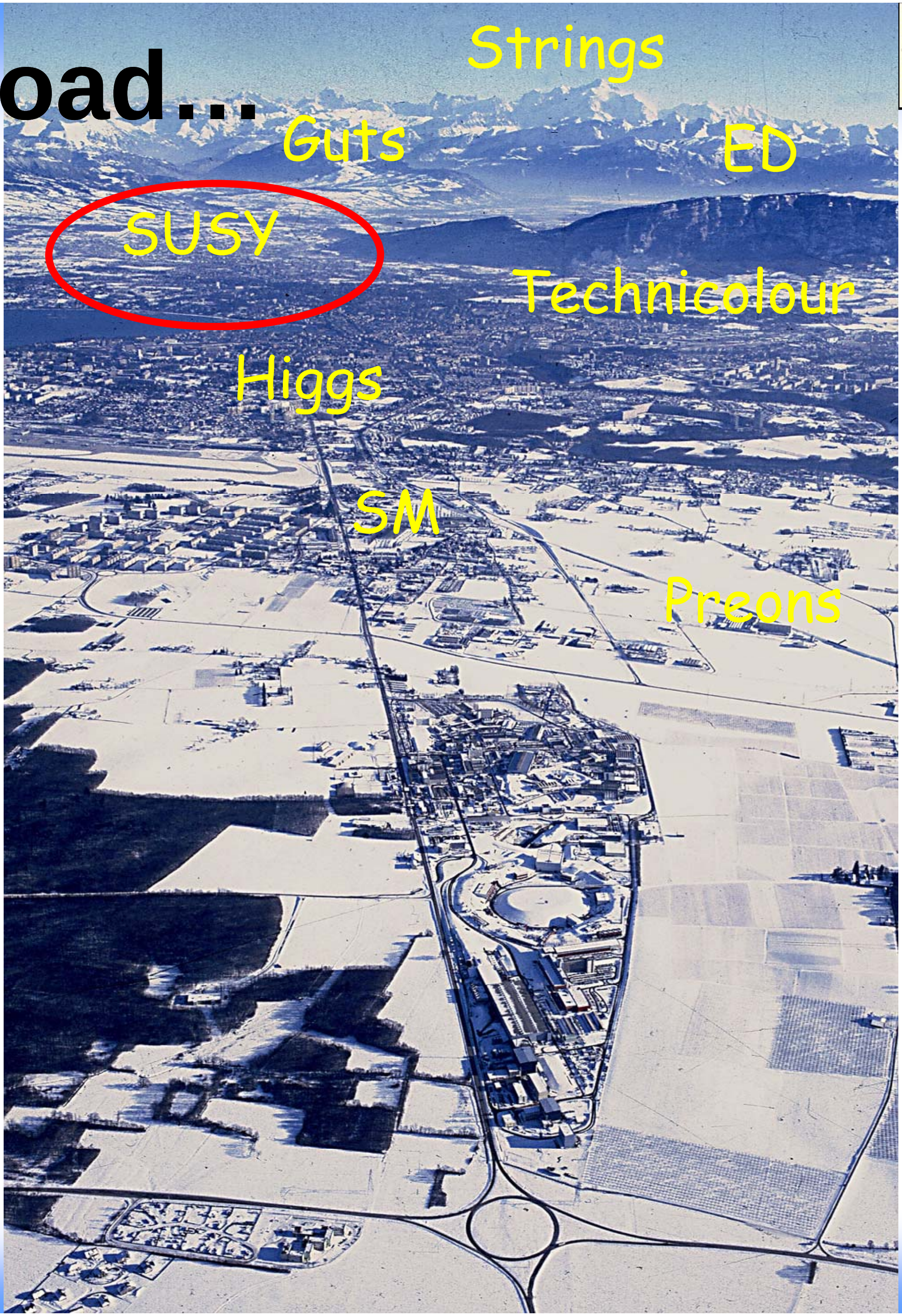
Andy Parker

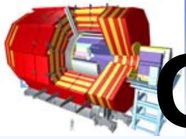
Cambridge University

Along the road…

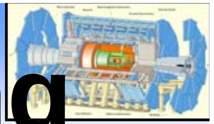
Even more
SUSY choices…







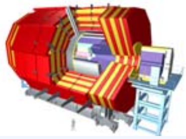
Gauge Mediated SUSY Breaking



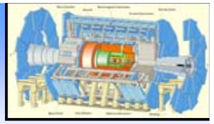
- Mechanism for SUSY breaking in a separate sector, communicated to MSSM particles via SU(3)xSU(2)xU(1) at scale $M_m \ll M_P$
- Gravitino LSP with m « 1GeV
- NLSP is neutralino or slepton which can have long lifetime
- ➔ $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma \quad \tilde{\ell}_R \rightarrow \tilde{G}\ell$
- Decays may occur outside detector

Parameters of GMSB models

$F_m \ll (10^{10}\ \mathrm{GeV})^2$	SUSY breaking scale
M_m	Messenger scale
$\Lambda \equiv F_m / M_m$	
N_5	Number of messenger 5-plets
tan(β)	
sgn(μ)	
C_{grav}	Fixes lifetime of decays into gravitinos



Searches for GMSB

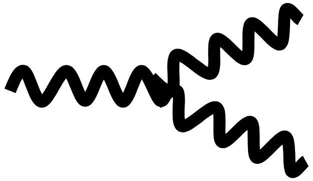


In these models the gravitino is the lightest SUSY particle (LSP). The available signatures depend on which particle is the next lightest (NLSP), and the strength of decays to the gravitino.

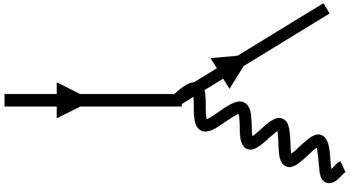
We consider 4 cases: NLSP either neutranlino or slepton, and $C_{grav}=1$, giving a fast decay, or $C_{grav}>>1$, giving a slow decay of the NLSP to gravitinos.

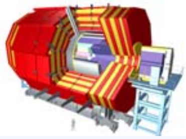
The decay modes are:

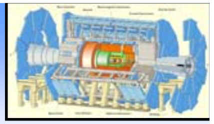
$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$



$$\tilde{\ell}_R \rightarrow \tilde{G}\ell$$

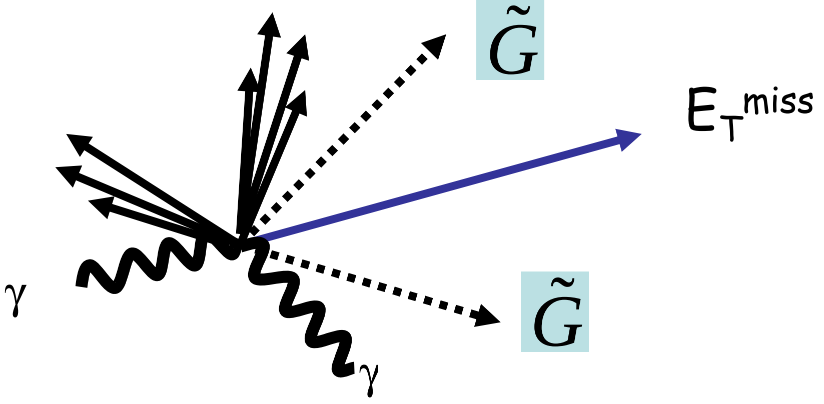






Case 1: C_{grav}=1 Fast decay

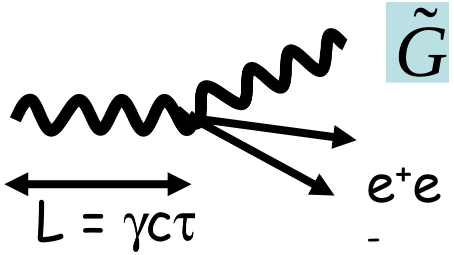
$\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$



2 high energy photons in every event, with jets, leptons and missing energy - very small SM background

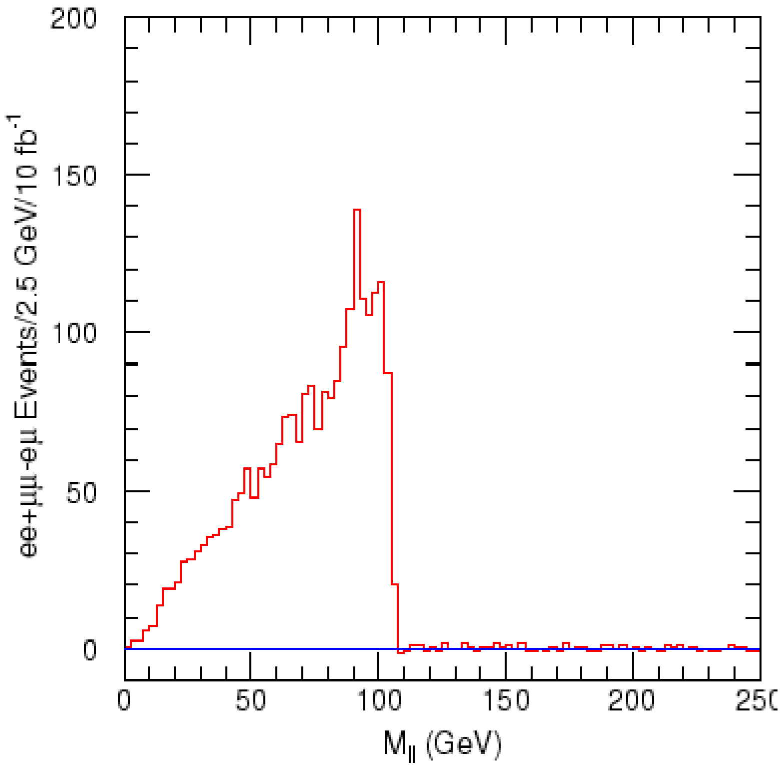
-> easy to discover!

2% of decays are $\tilde{\chi}_1^0 \to \tilde{G} e^+ e^-$



Measure lifetime and hence C_{grav}

Look for similar decay chain as before:

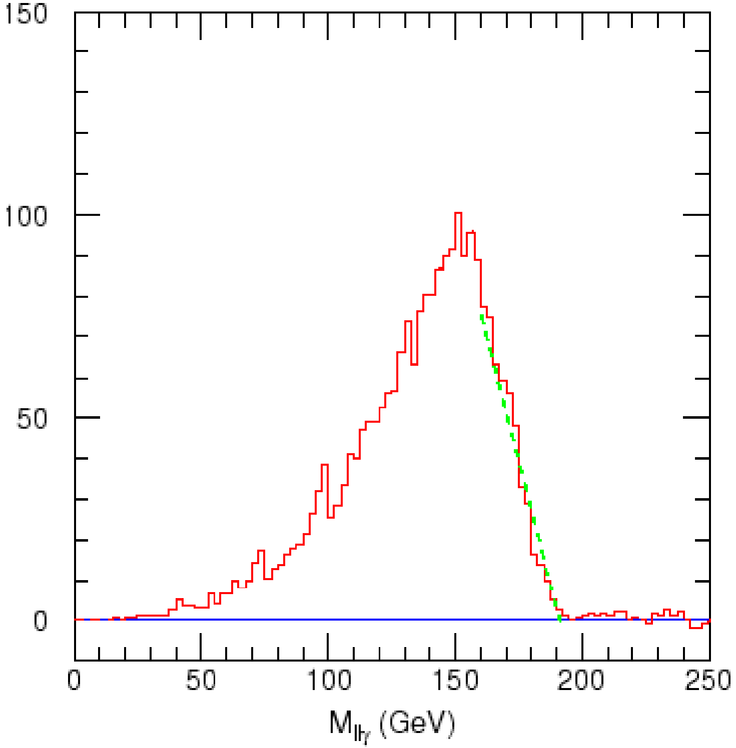


$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+\ell^- \rightarrow \tilde{G}\ell^+\ell^-\gamma$$

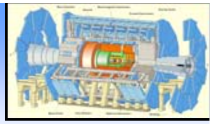
Get edge in dilepton mass distribution as before at

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

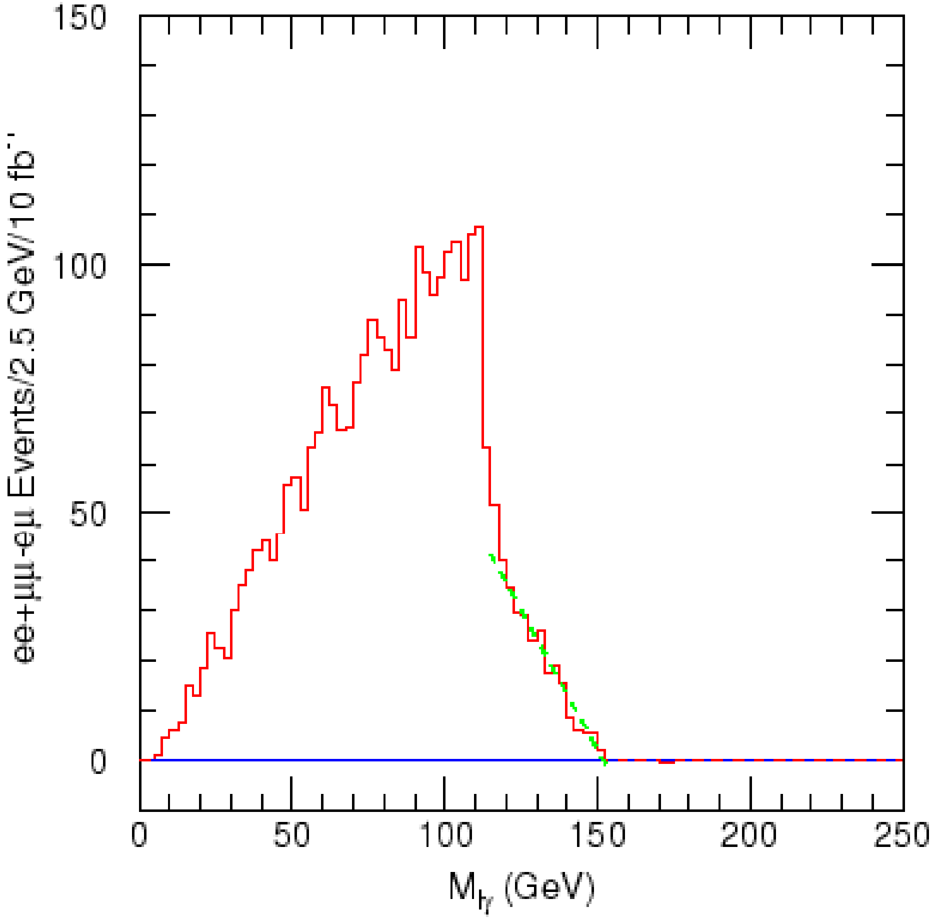
There is also a maximum value for the llγ mass - but we don't know which γ was produced in this chain - so use photon which produces smallest mass - this must be ≤ max value.



$$M_{ll\gamma}^{\max} = \sqrt{M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2}$$

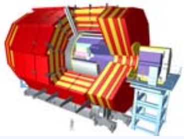


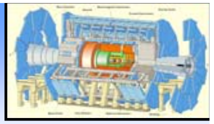
The photon can make invariant masses with each lepton, leading to two edges:



$$M_{\ell\gamma}^{(1)} = \sqrt{M_{\tilde{\ell}_R}^2 - M_{\tilde{\chi}_1^0}^2} = 112.7\,\mathrm{GeV}$$

$$M_{\ell\gamma}^{(2)} = \sqrt{M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}_R}^2} = 152.6\,\mathrm{GeV}$$





If we assume that the gravitino mass is small, these measurements determine the three unknown SUSY masses:

$$M^2_{\tilde{\ell}_R} = \frac{(M^{(1)}_{\ell\gamma})^2 (M^{(2)}_{\ell\gamma})^2}{(M^{\max}_{\ell\ell})^2}$$

$$M^2_{\tilde{\chi}^0_1} = M^2_{\tilde{\ell}_R} - (M^{(1)}_{\ell\gamma})^2$$

$$M^2_{\tilde{\chi}^0_2} = M^2_{\tilde{\ell}_R} + (M^{(2)}_{\ell\gamma})^2$$

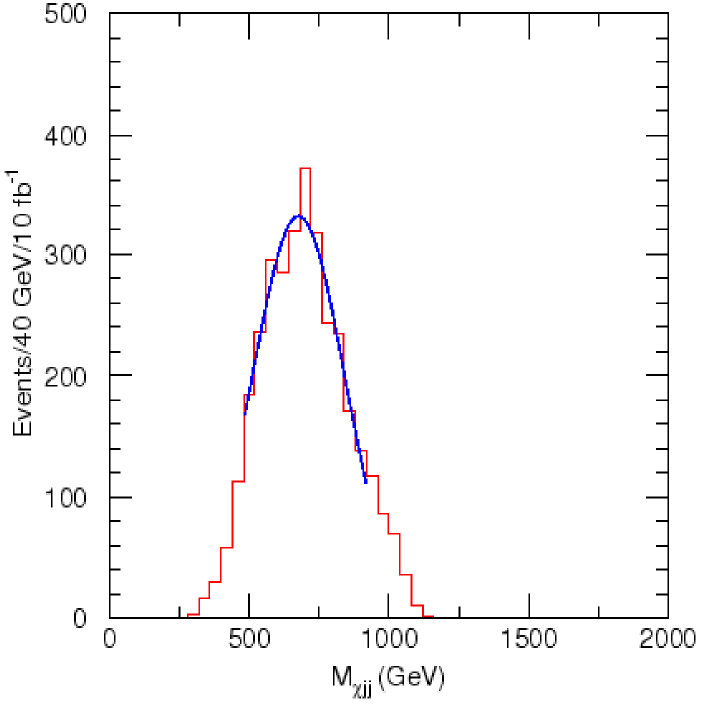
where we have the constraint :

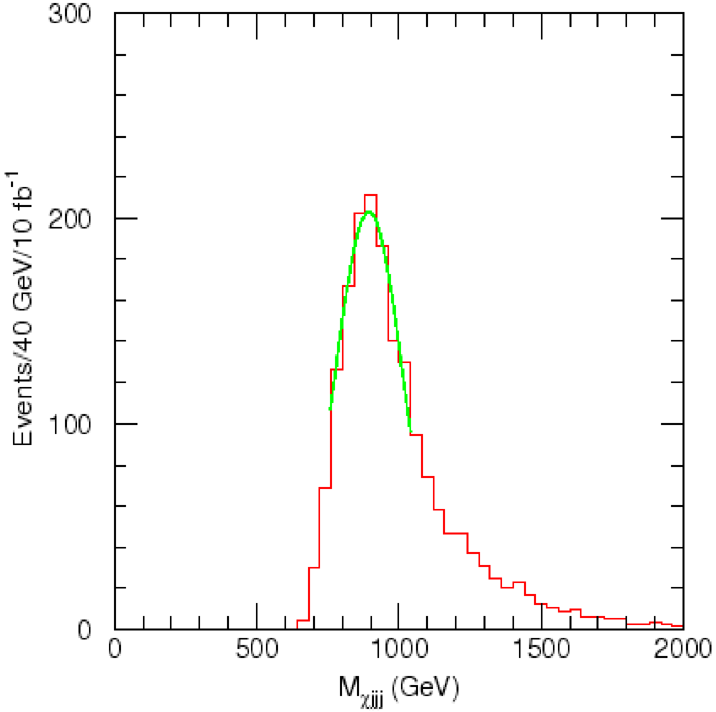
$$(M^{\max}_{\ell\ell\gamma})^2 = (M^{(1)}_{\ell\gamma})^2 + (M^{(2)}_{\ell\gamma})^2$$

So for this case, all the important parameters can be determined.

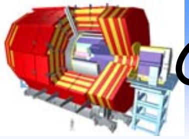
Gluino and squark masses at GMSB 1a

$$\tilde{q} \rightarrow \tilde{g}q \rightarrow \tilde{\chi}_2^0 q\bar{q}q$$



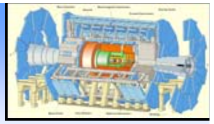


- Require two reconstructed χ^0_2. Combine each with 2 of hardest 4 jets for gluino mass, and then with third jet for squark mass



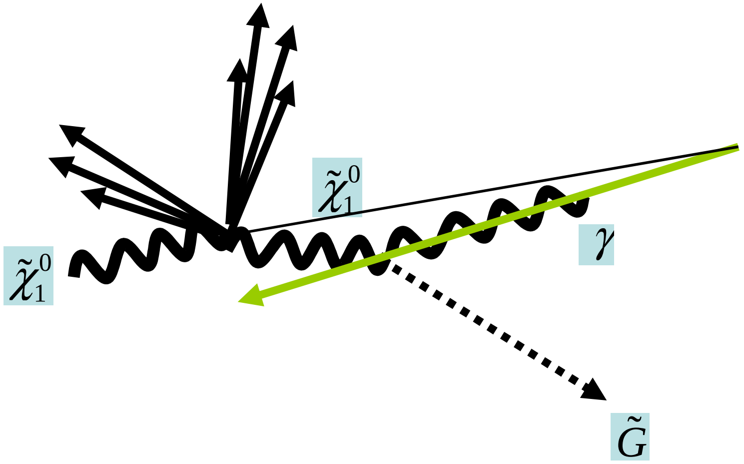
Case 2: C_{grav}>>1 Slow decay

$\tilde{\chi}_1^0 \rightarrow \tilde{G}\,\gamma$



In this case, the decay of the neutralino to the gravitino happens very slowly. For $C_{grav}=10^3$, $c\tau=1.1$ km.

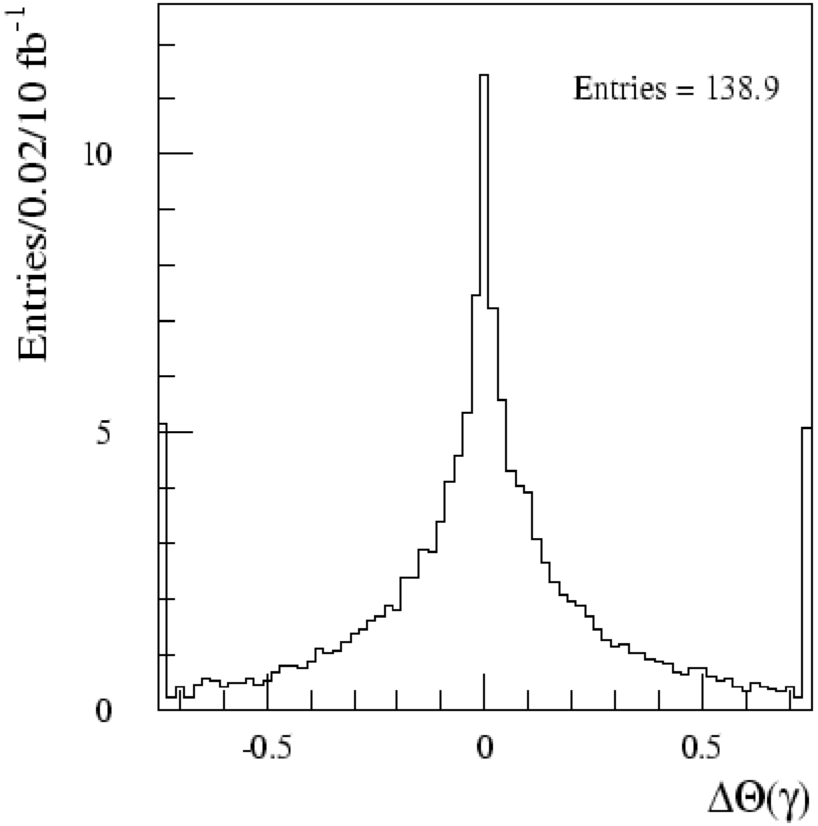
The signatures are then essentially the same as for SUGRA, except that in many events, high energy photons will be detected which do not point to the vertex, coming from neutralinos decaying while leaving the detector.



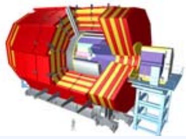
Calorimeter must measure γ pointing angle very well

Can detect $C_{grav} \leq 10^8$

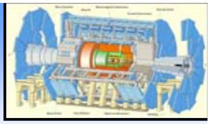
GMSB: Long lived neutralinos

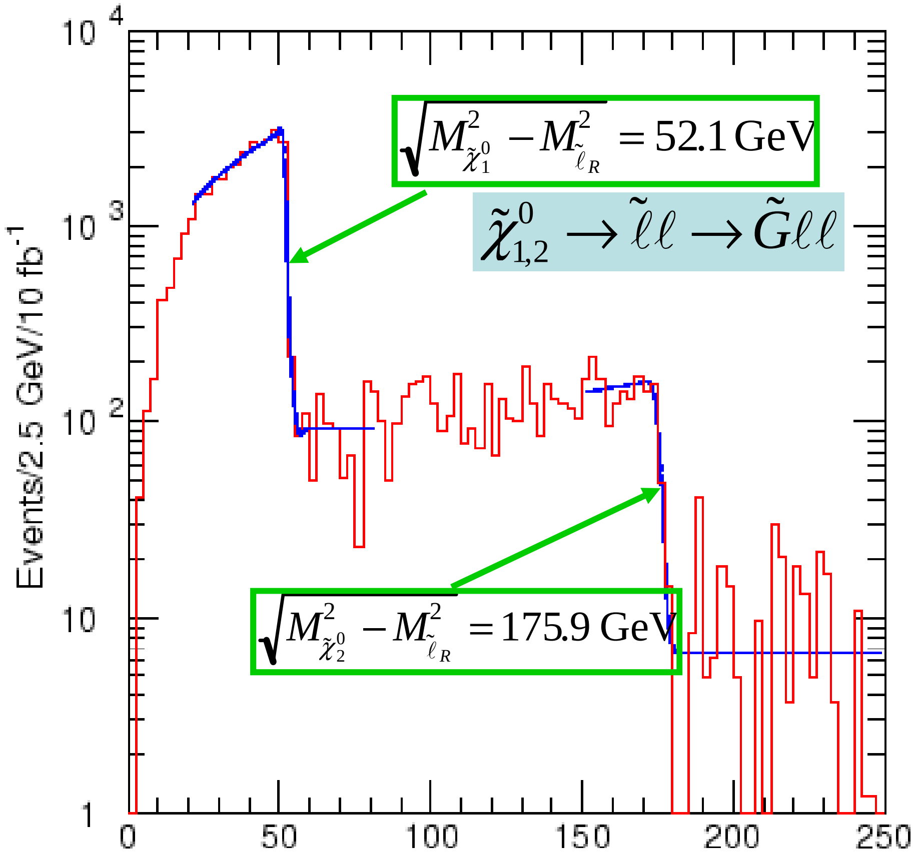


- ATLAS measures angle with EM calo (can also measure time delay)
- 5σ significant non-pointing gives 82% efficiency.
- Requiring p_T>20GeV, isolated photons gives overall signal efficiency of 52%
- For $30pb^{-1}$, get $c\tau$>100km at 95%CL and C_{grav}>10^8
- Corresponds to Λ>10^4



Case 3: C_{grav}=1 Fast decay $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1 \to \ell \tilde{G}$





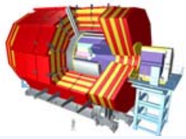
$$\sqrt{M^2_{\tilde{\chi}^0_1} - M^2_{\tilde{\ell}_R}} = 52.1\,\text{GeV}$$

$$\tilde{\chi}^0_{1,2} \to \tilde{\ell}\ell \to \tilde{G}\ell\ell$$

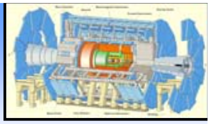
$$\sqrt{M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_R}} = 175.9\,\text{GeV}$$

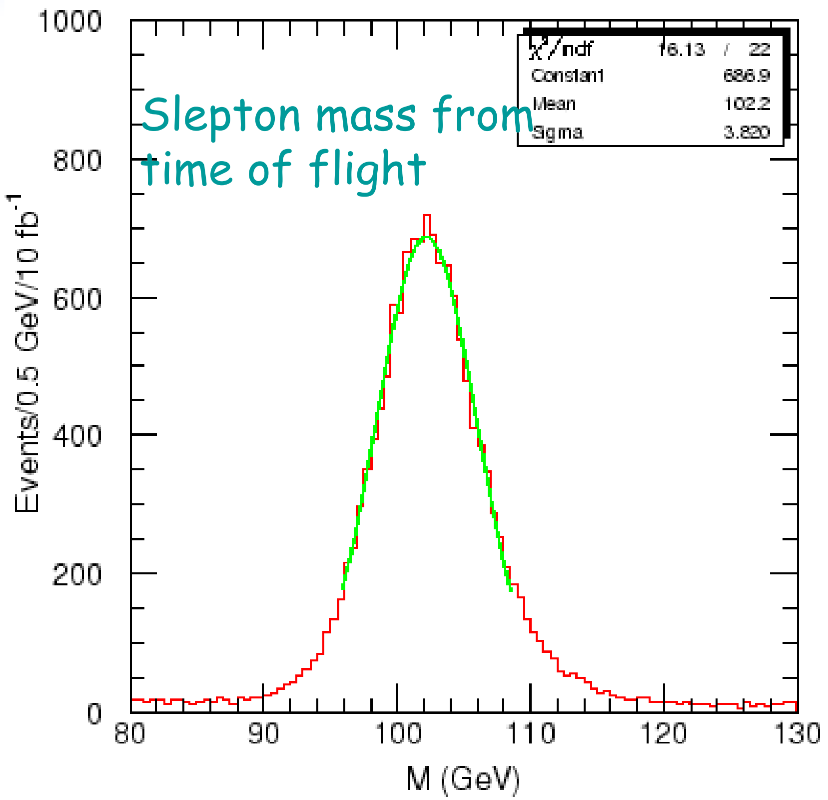
Dilepon mass spectrum

- If N_5>1, NLSP's are right-handed sleptons, which decay immediately to gravitinos.
- Large production cross section possible => 23pb
- ➲ Many signatures with leptons and p_T^{miss}
- Clear signal in this case
- Many mass measurements possible



Case 4: C_{grav} >> 1 Slow decay $\tilde{\tau}_1 \rightarrow \tau\tilde{G}$





Slepton mass from time of flight

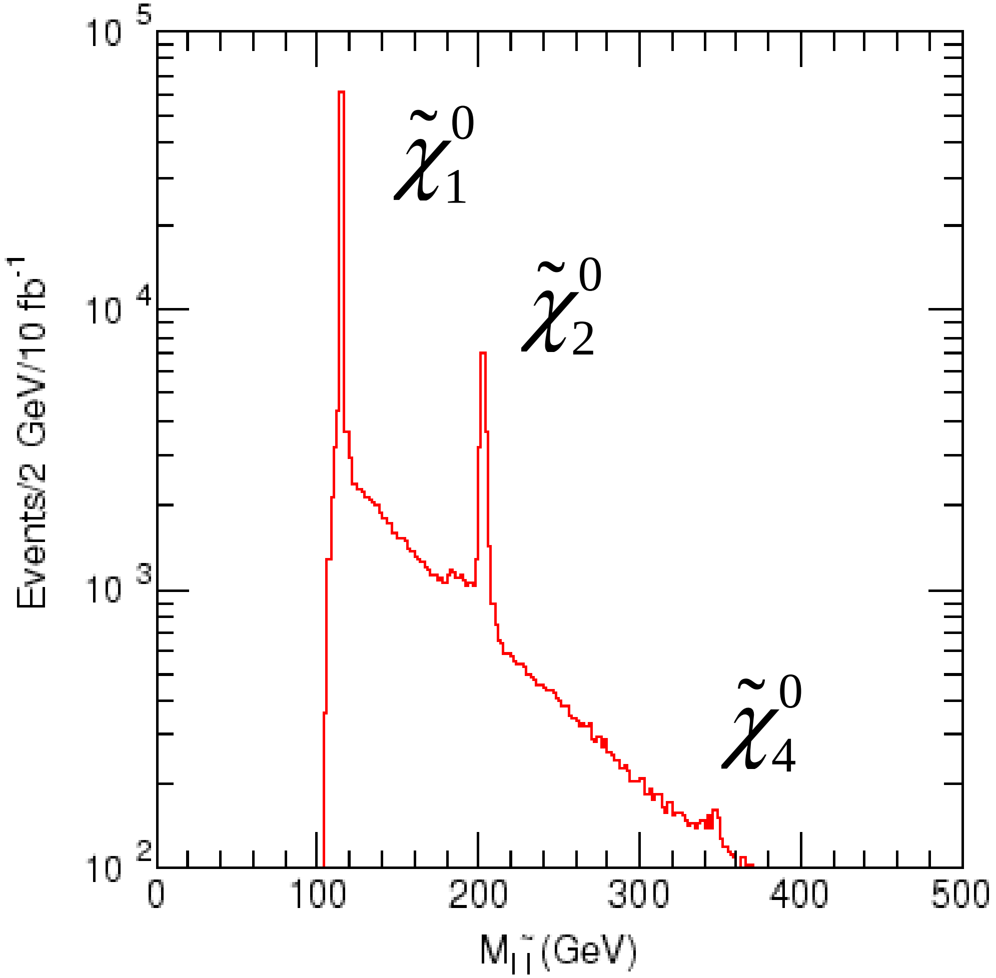
Slepton mass = 102.2 GeV.

Flight time to muon system is about 30ns for 10m path. Time resolution = 1ns

Trigger?

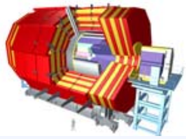
- Stau lifetime is now long, giving ct=1km
- ➲ Signature is two heavy quasistable particles in each event.
- Detect in muon system by time of flight! Staus arrive late - need excellent time resolution

Reconstruction of neutralino masses (Case 4)

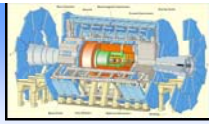


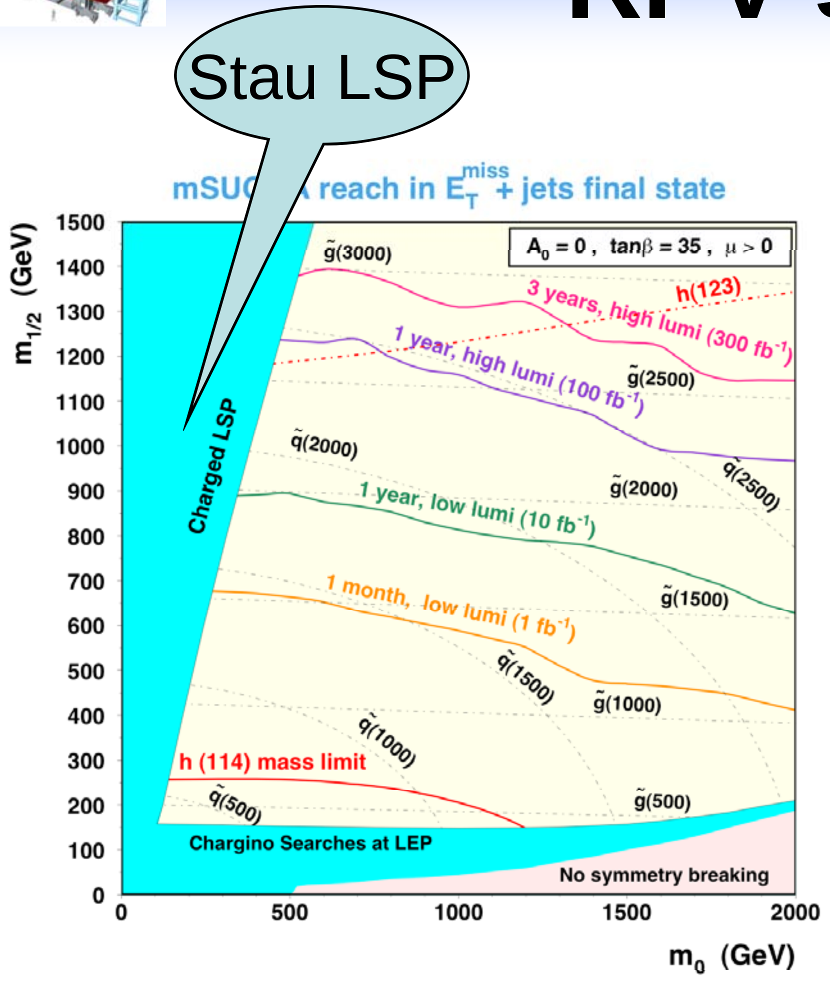
$$\tilde{\chi}_i^0 \rightarrow \tilde{\ell}_R \ell$$

- Neutralino decays can be fully reconstructed.
- Events with at least 3 (s)lepton candidates.
- Combine sleptons with leptons (p_T>10 GeV)
- SM background negligible.



RPV scenarios





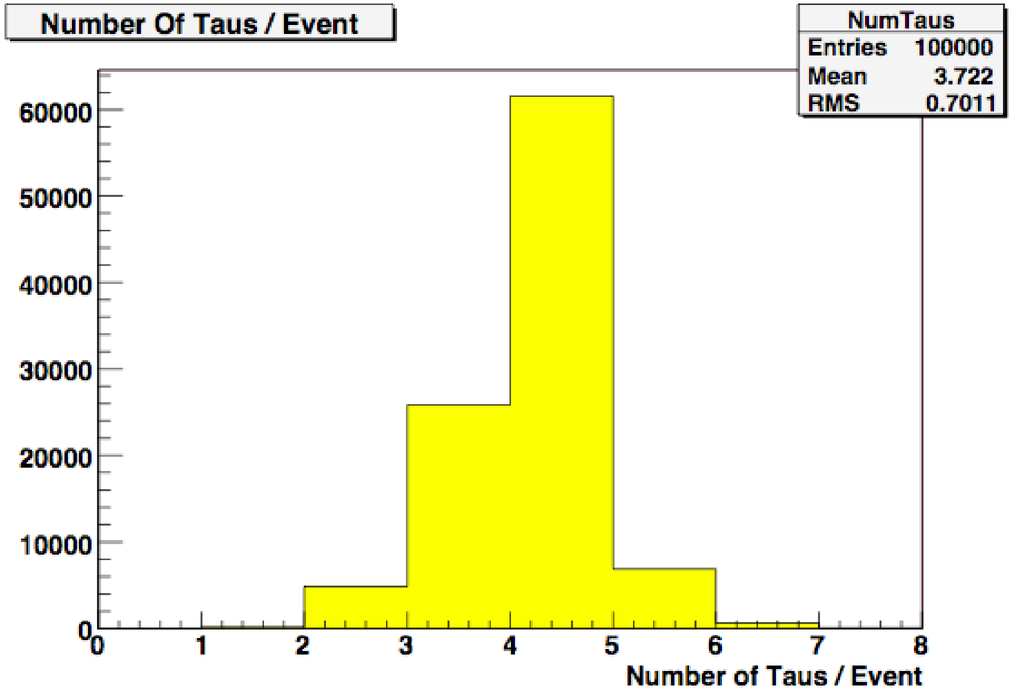
Stau LSP

RPV has less missing Et

Neutralino -> stau tau

stau -> tau mu qq

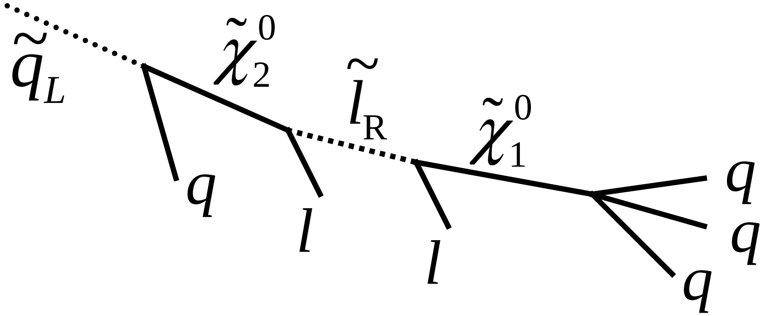
Large rate of taus - smoking gun



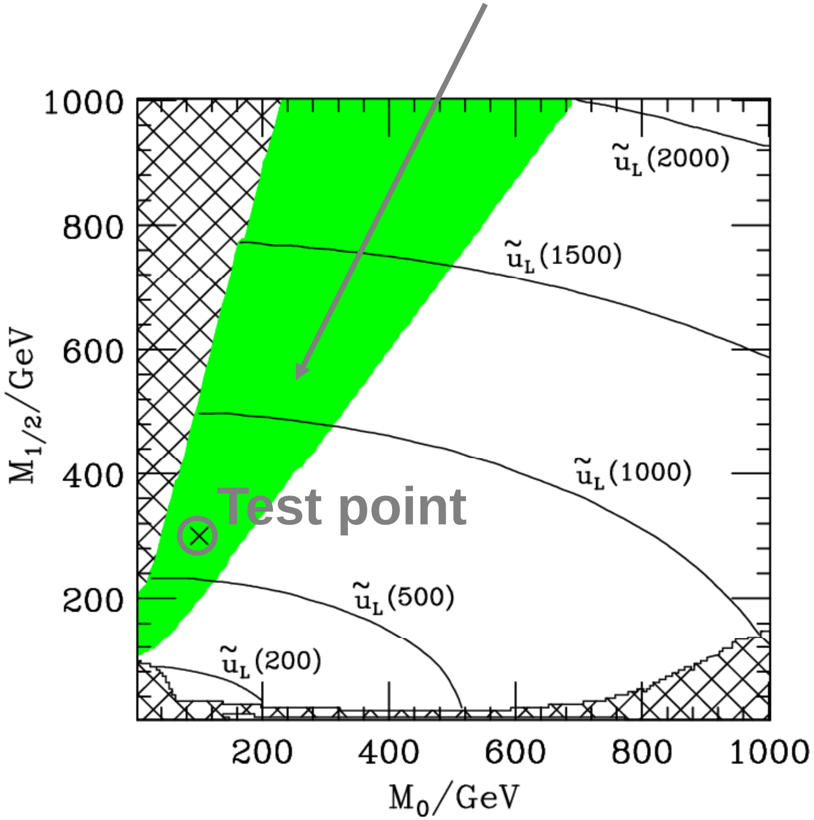
Phillips - Cambridge

R-Parity Violation

- **Use extra information from leptons to decrease background.**
- **Sequential decay of $\tilde{q}_L$ to $\tilde{\chi}_1^0$ through $\tilde{\chi}_2^0$ and $\tilde{l}_R$ producing Opposite Sign, Same Family (OSSF) leptons**



Decay via $\tilde{l}_R$ allowed where $m(\tilde{\chi}_2^0) > m(\tilde{l}_R)$



Looks like SUSY…?

Extra dimensions create excited states with TeV masses and same couplings as SM partners

Looks just like SUSY!

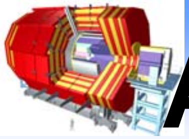
Ultimately must measure spin.

Can claim BSM Physics but not SUSY after 1 year…

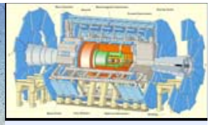
Conclusions on SUSY

- Can find signals for light SUSY with 1 fb^{-1} of data
- Need "model independent" search in inclusive variables
- Do not be misled by theory
- Check for anomalies:
  - Photons -> GMSB
  - Taus -> RPV
  - Strange top events -> Stop

- Don't jump to conclusions!
  The world may be stranger
  than we think…

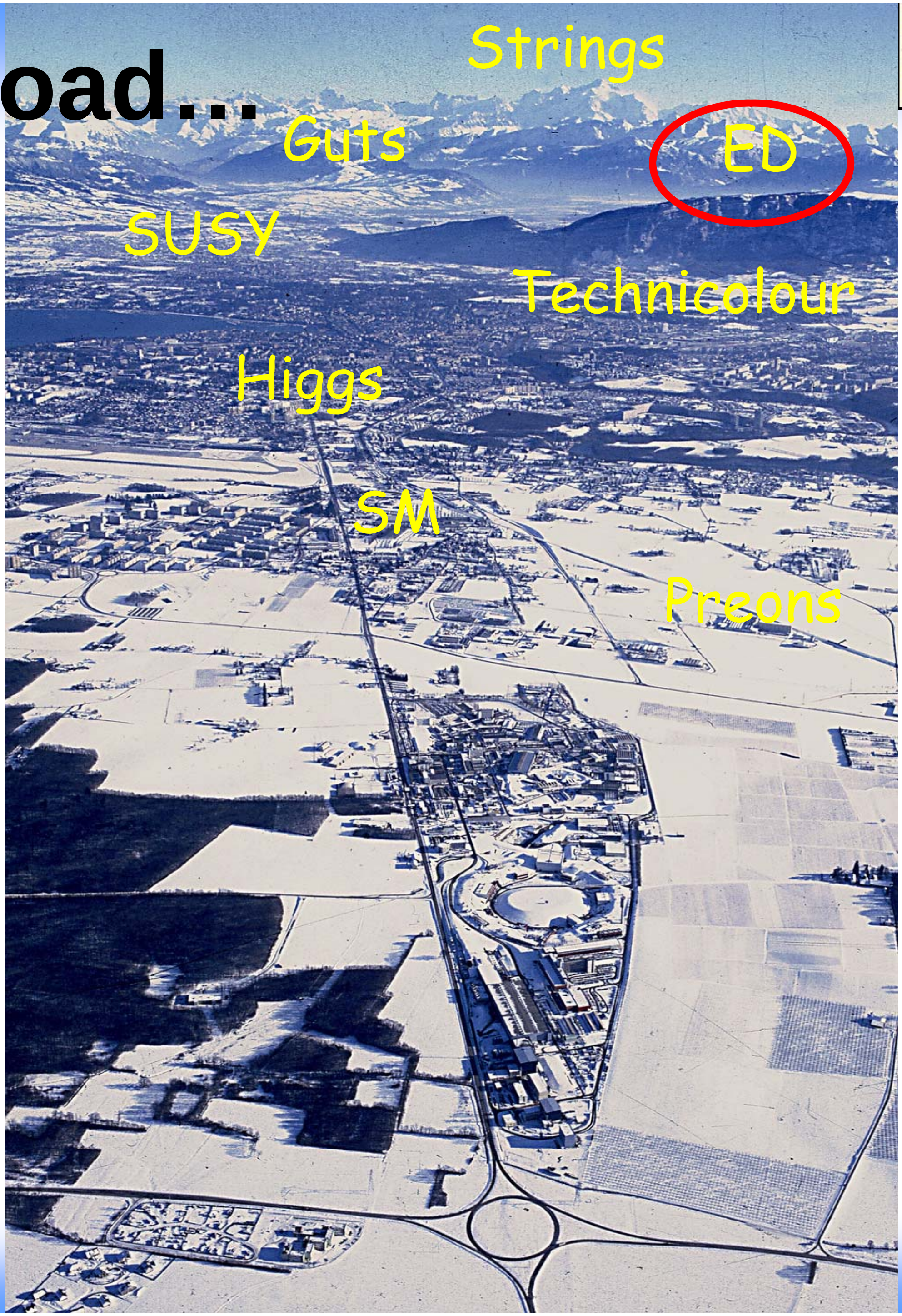


Along the road…

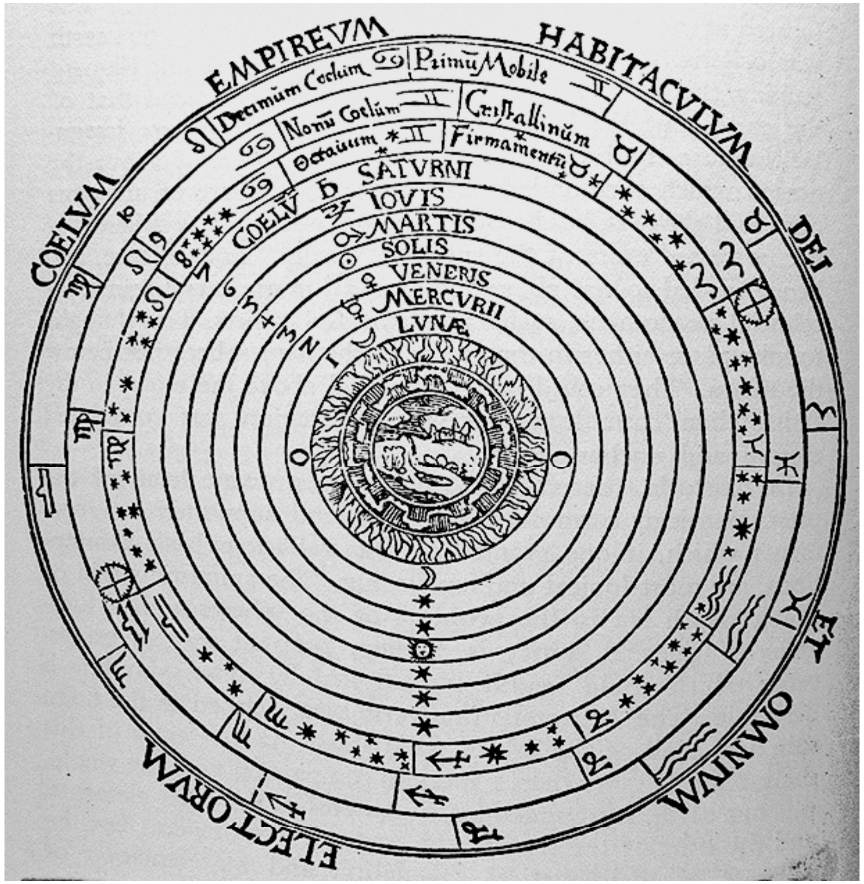


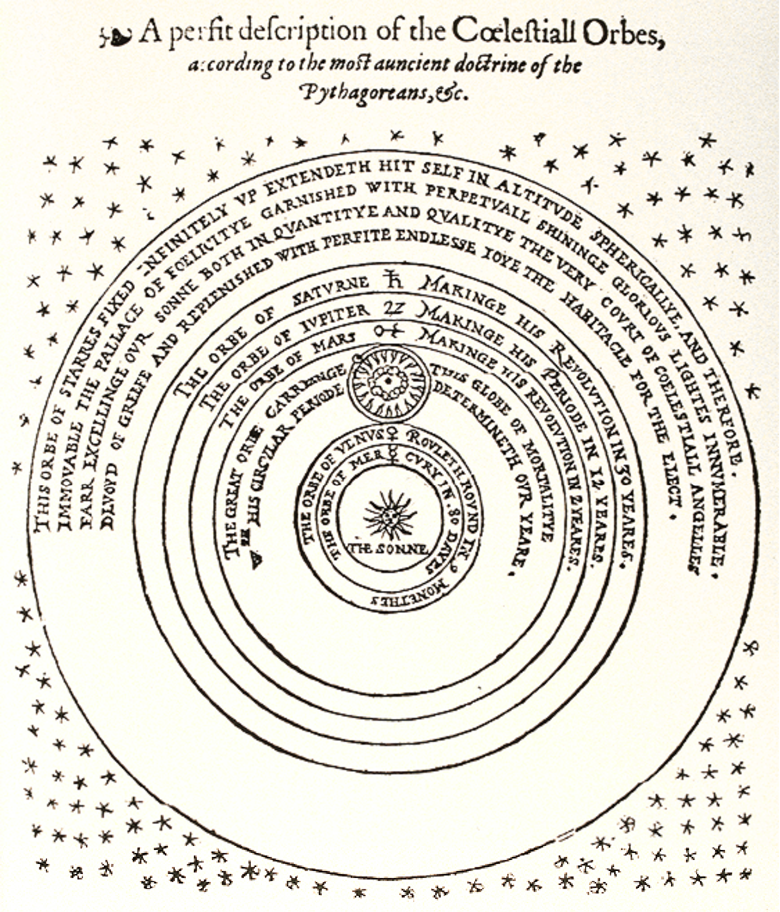
Beyond
infinity..

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Two views of the world….





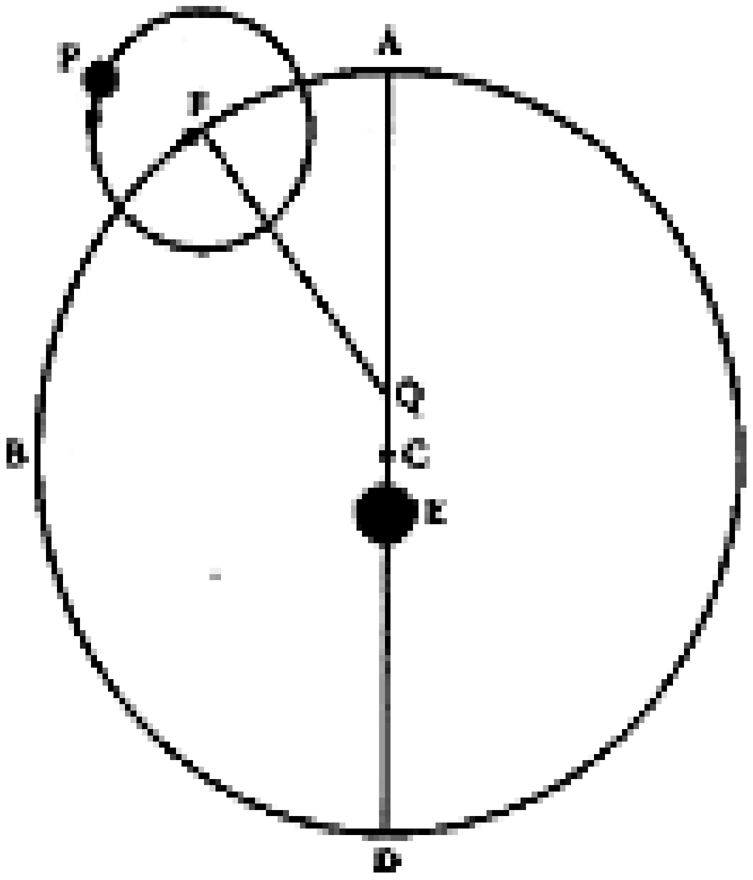
- Supersymmetry ….

….hidden perfection

Extra dimensions….

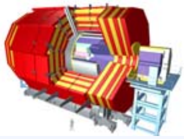
…different scales

Epicycles

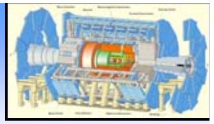


From Michael J. Crowe,
Theories of the World from Antiquity
to the Copernican Revolution.

- Typical Ptolemaic planetary model
- Symmetry is assumed: all orbits are based on circles
- But the Earth is not at the centre of the circle (*the eccentric*)
- The planet moves on an *epicycle*
- The epicycle moves around the *equant*



SUSY



- Conventional method to fix Higgs mass:

- Invoke SUSY
- Double the number of states in model
- Invoke SUSY breaking
- Fermion/boson loops cancel (GIM)
    - Higgs mass stabilised!
- 105 new parameters (MSSM)
- +48 more free parameters if R_P not conserved

=> SUSY is a good pension plan for experimentalists!

Extra dimensions

Hypothesize that there are extra space dimensions

Volume of bulk space >> volume of 3-D space

Hypothesize that gravity operates throughout the bulk

SM fields confined to 3-D

Then unified field will have "diluted" gravity, as seen in 3-D

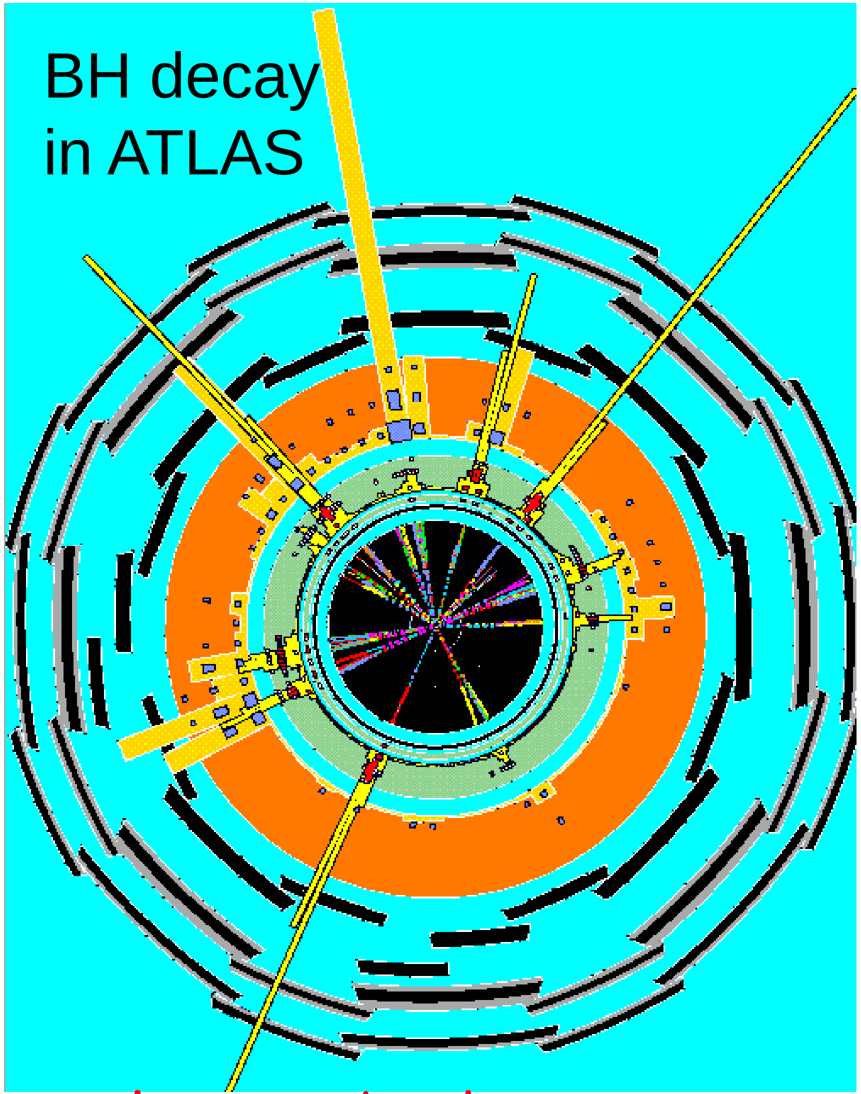
With n-D gravity mass scale=weak mass scale -> no hierarchy problem!

Can experimentally access quantum gravity!

- Missing energy signatures
- Black hole production

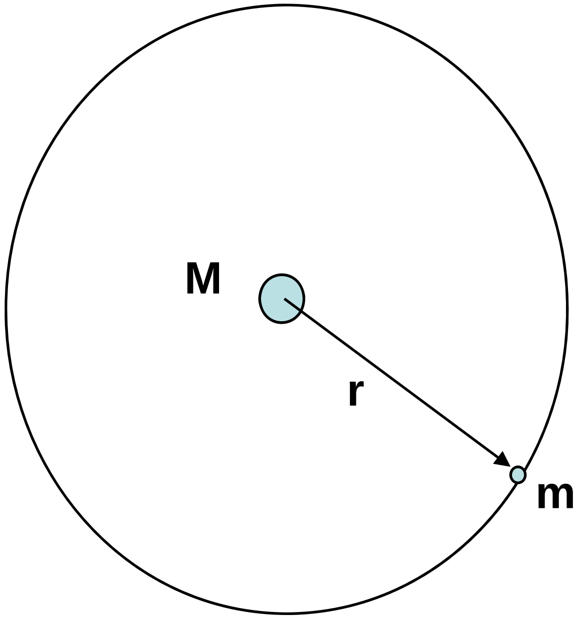
But extra dimension is different length scale from "normal" ones

-> new scale to explain



Extra dimensions are more like a lottery bet!

Gravity in 3-D space



Gauss's theorem:

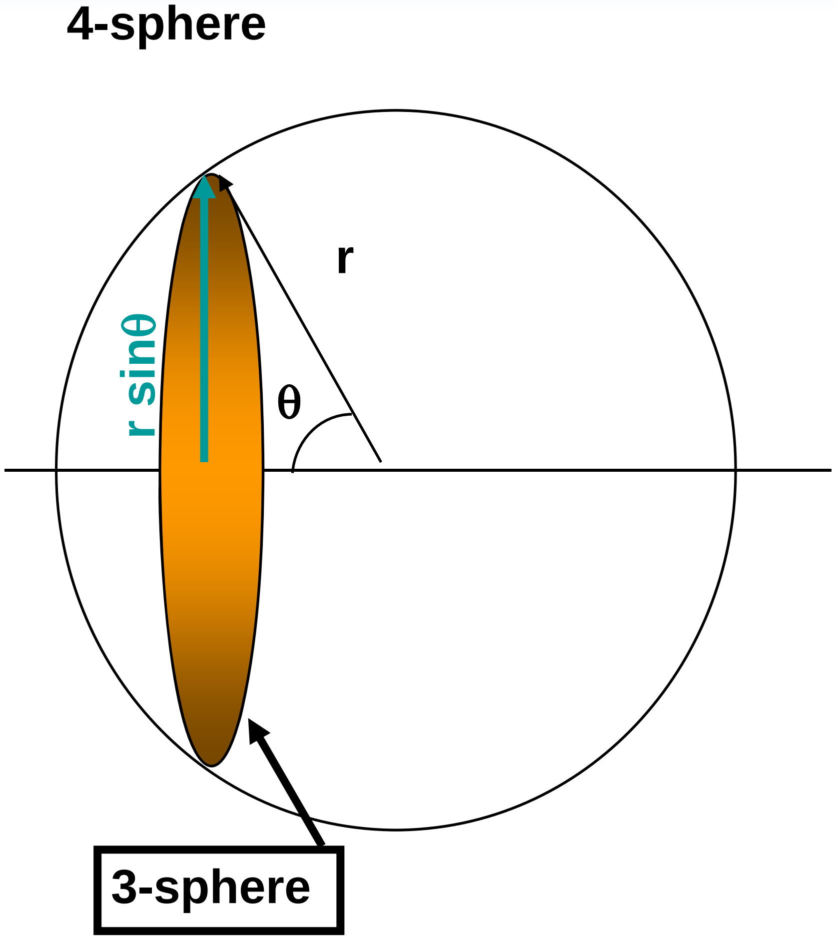
Field at r given by

$$\oint \vec{F}/m \, d\vec{S} = 4\pi GM$$

$$F/m \, 4\pi r^2 = 4\pi GM$$

$$\boxed{F = GMm/r^2}$$

Gravity in 4-D space



- Compute volume of 4-sphere

$$V_4(r) = \int_0^{\pi} V_3(r\sin\theta)\, r\sin\theta\, d\theta$$

$$= \int_0^{\pi} \tfrac{4\pi}{3} r^4 \sin^4\theta\, d\theta$$

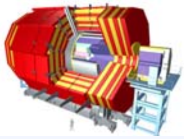
$$= \tfrac{1}{2}\pi^2 r^4$$

$$S_4 = \frac{d}{dr} V_4 = 2\pi^2 r^3$$

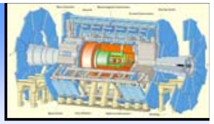
$$F/m\, S_4 = 4\pi G M$$

$$\boxed{F = \frac{2GMm}{\pi r^3}}$$

$$\boxed{G = 8\pi R^n M_D^{-(2+n)}}$$



The Planck Mass



Planck mass is point at which gravity becomes strong:

Consider two masses M_{PL} separated by their reduced Compton wavelength

$$\bar{\lambda} = \frac{\hbar}{M_{PL}c}$$

Set their PE e eir rest mass:

$$M_{PL}c^2 = \frac{GM_{PL}^2}{\bar{\lambda}} = \frac{GM_{PL}^3 c}{\hbar}$$

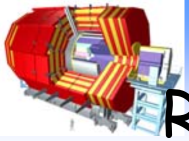
$$M_{PL} = \sqrt{\frac{\hbar c}{G}}$$

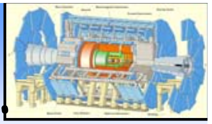
Define $\overline{M}_{PL} = \dfrac{M_{PL}}{\sqrt{8\pi}}$

$G=6.67\times10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$

$M_{PL}=2.2\times10^{-8}$ kg = 1.2×10^{19} GeV/c^2

$\overline{M}_{PL}=2.4\times10^{18}$ GeV/c^2





Relate the gravitational coupling in 3D to that in 4D:

$$F = \frac{2G_3Mm}{\pi r^3} \qquad \text{Let } G_* = \frac{G_3}{\pi}$$

$$V(r) = \frac{G_*Mm}{r^2} \qquad r < R$$

$$V(r) = \frac{G_*Mm}{rR} \qquad r > R$$

$$\frac{GMm}{r} = \frac{G_*Mm}{rR}$$

$$G = \frac{G_*}{R}$$

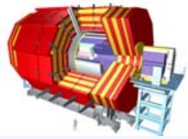
$$\overline{M}_{PL}^2 = M_*^3R$$

Separation can't exceed R in ED

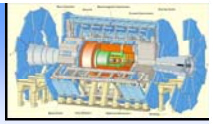
Generalise to n extra dimensions

$$\boxed{\overline{M}_{Pl}^2 = R^n M_*^{(2+n)}}$$

where M* is the bulk Planck mass in n+4 dimensions, and R is the radius of the extra dimensions.



Scale of extra dimensions



- For 4+n space-time dimensions

$$M_{Pl}^{2} \approx M_{Pl(4+n)}^{2+n} R^{n}$$

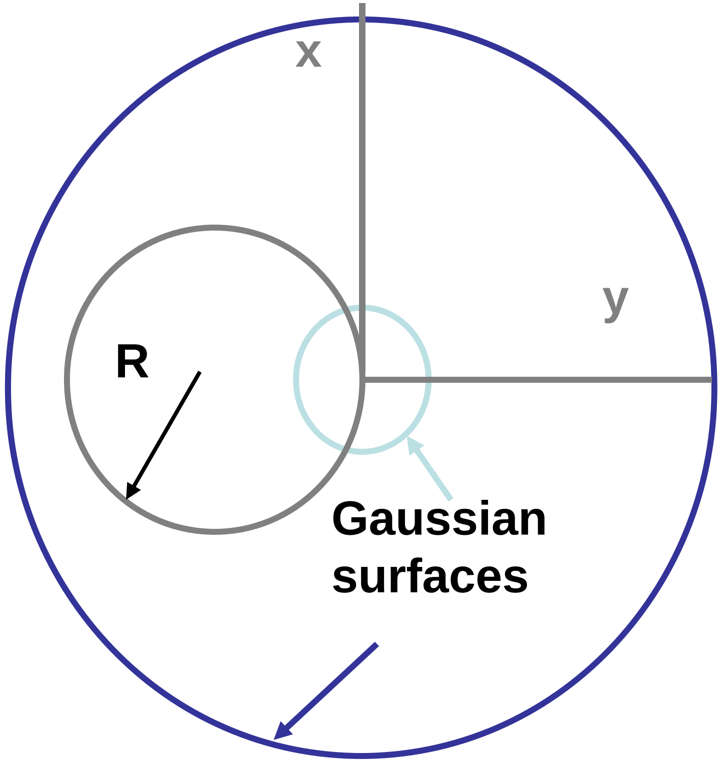
- For $M_{Pl(4+n)}$ ~ O(TeV)

$$R \approx 10^{30/n-17}\ cm \left(\frac{1TeV}{M_{Pl(4+n)}} \right)^{1+2/n}$$

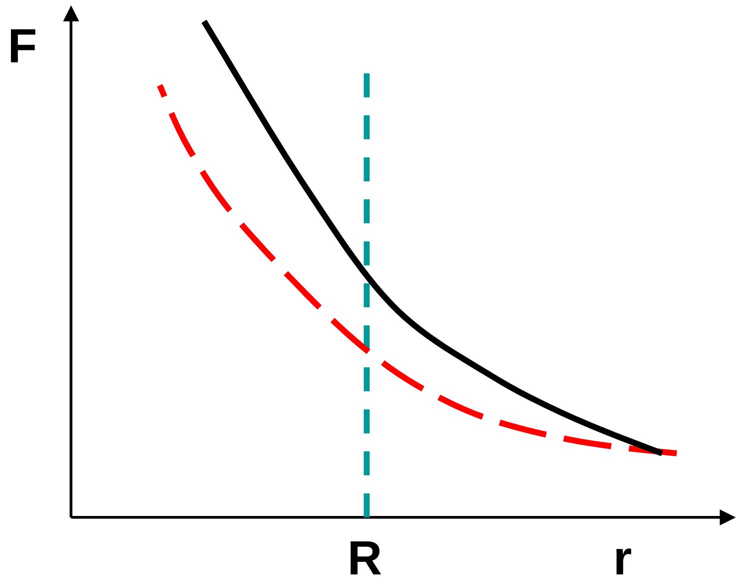
- n=1, R=10^{13} cm - ruled out by planetary orbits
- n=2, R~100 μm-1mm - OK (see later)

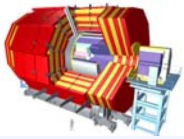
- -> Conclude extra dimensions must be compactified at <1mm

ED signature in gravity experiments

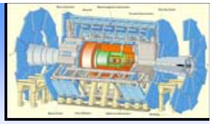


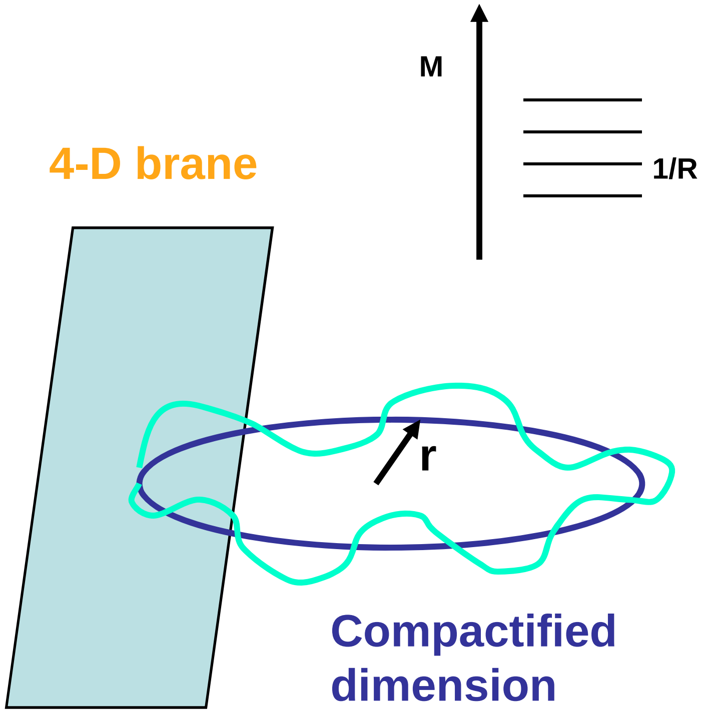
- r > R Get 3-D result
- r < R Get 4-D result





Kaluza Klein modes



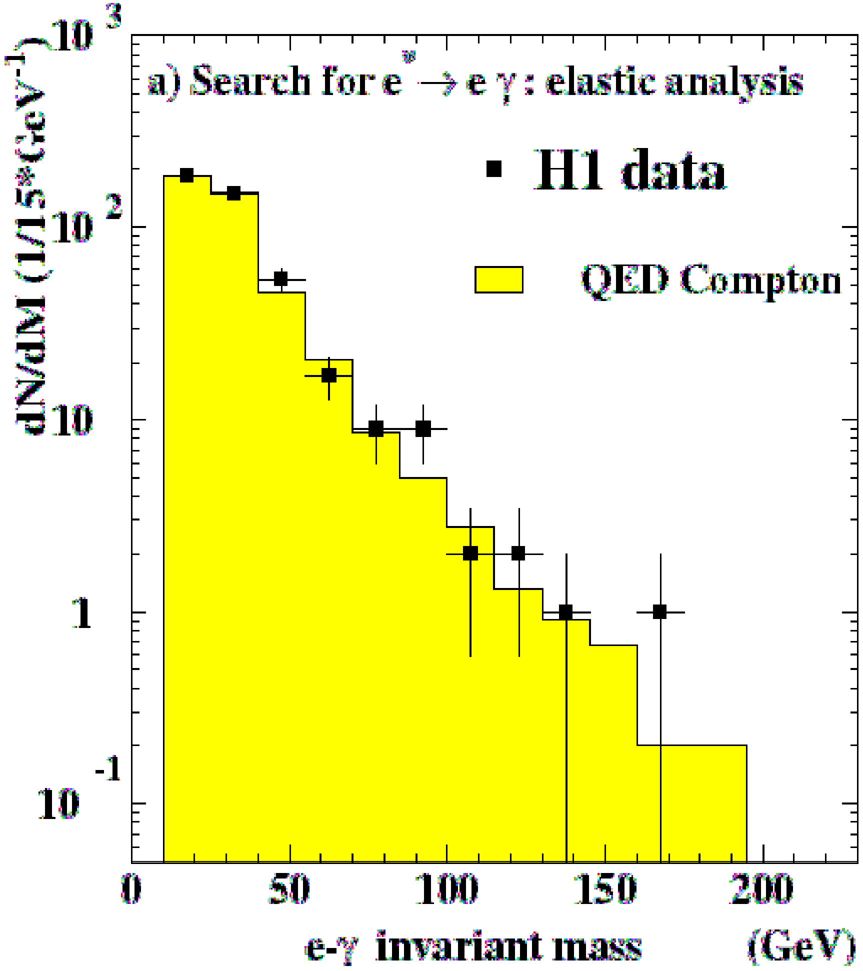


$$p = \hbar / \lambda, \qquad \hbar c = 0.2 GeV fm$$

$$\lambda = 1 mm, \qquad p = 0.2 / 10^{12} = 2.10^{-13} GeV$$

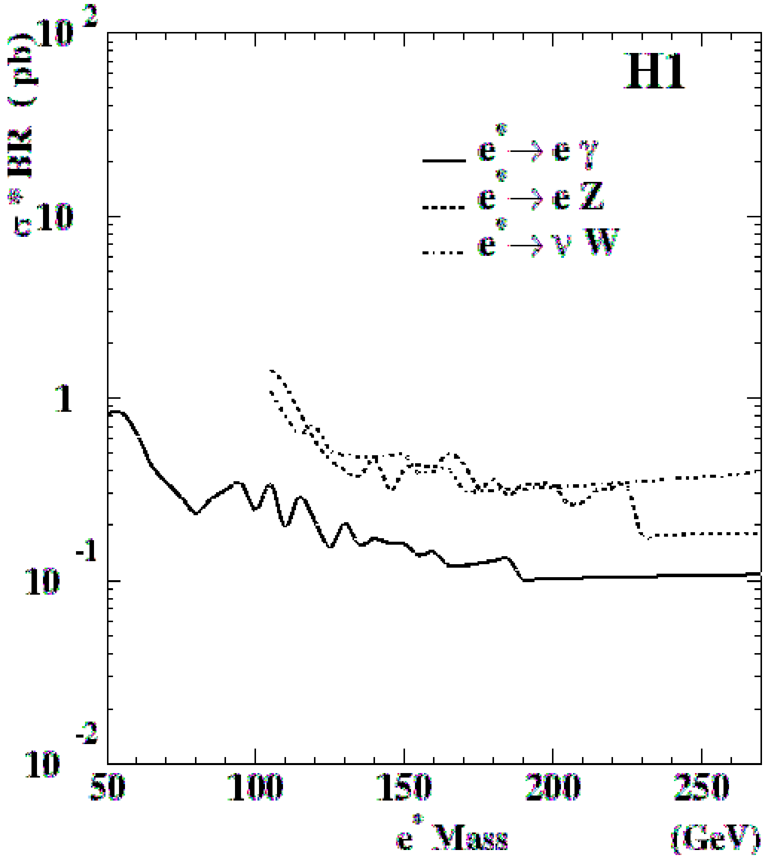
- Particles in compact ED:
- Wavelength set by periodic boundary condition
- States will be evenly spaced in mass
  - "tower of Kaluza-Klein modes"
- Spacing depends on scale of ED
  - For large ED (order of mm) spacing is very small - use density of states
  - For small ED, spacing can be very large.

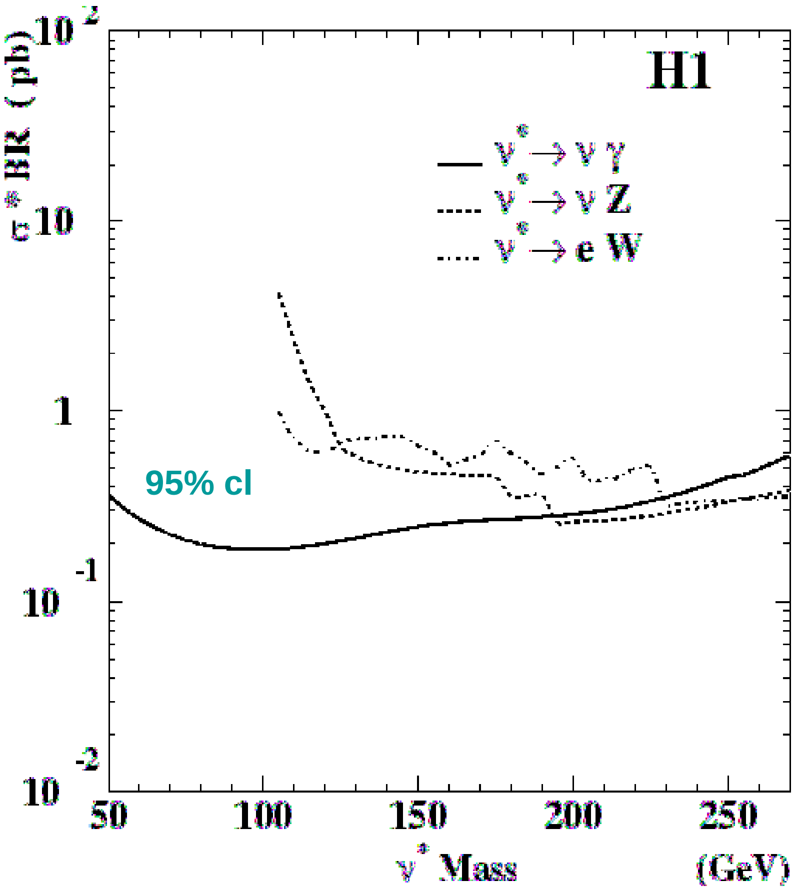
SM KK modes



- Interactions of SM fields measured to very high precision at scales of 10^{-18} m
- If gauge forces acted in bulk, deviations would have been measured
- KK modes would exist for SM particles
- For large ED, mass splitting would be small.

Excited fermion limits





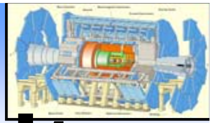
- Many channels examined: no evidence for f*.

Measuring Gravity in the lab

- Torsion balance
- Henry Cavendish 1778 (apparatus by Michell)
- Measured mean density of Earth (no definition of the unit of force).

- Sir Charles Boys inferred $G=6.664\times10^{-11}\,\mathrm{Nm^2/kg^2}$ from Cavendish's data a century later.

- Modern value
- $G = (6.6726 \pm 0.0001)\times10^{-11}\ \mathrm{Nm^2/kg^2}$.



Deviations from Newtonian Gravity

Gravity experiments present results in terms of Yukawa interaction of form

$$V(r) = -\int dr_1 \int dr_2 \frac{G\rho_1(r_1)\rho_2(r_2)}{r_{12}}[1 + \alpha e^{-r_{12}/\lambda}]$$

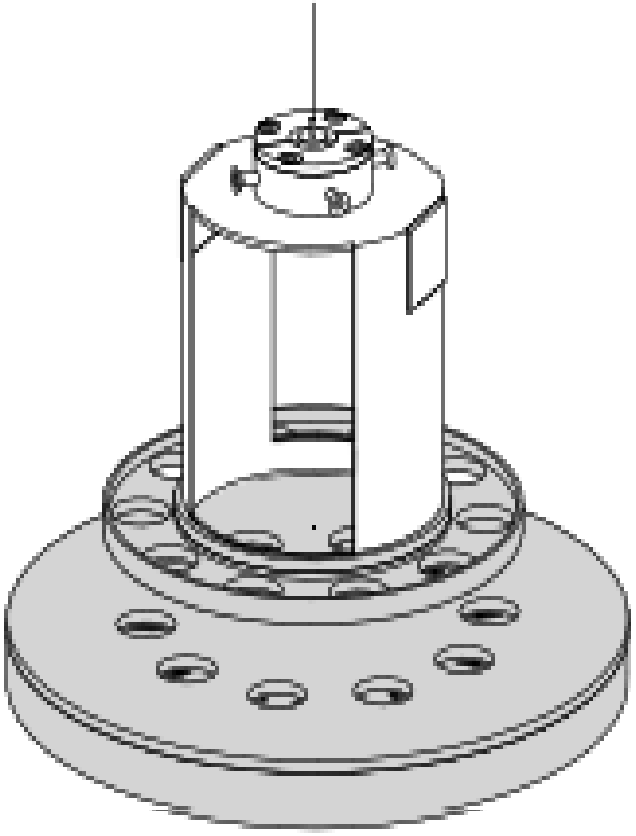
λ gives range of force

α gives strength relative to Newtonian gravity.

α depends on geometry of extra dimensions

Sensitive to forces of 4×10^{-14} N

Eot-Wash experiment



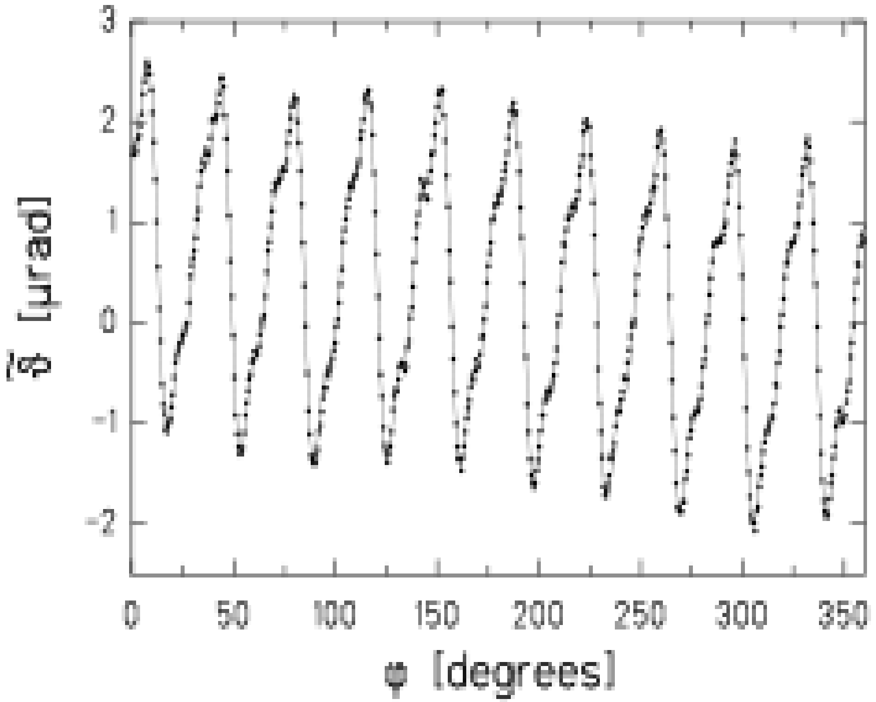
PRD 70(2004) 042004

- Torsion pendulum experiment
- "Masses" are 10 holes in each ring
- Lower attractor has two rings with displaced holes, rotates slowly
- Geometry designed to suppress long range signals without affecting shortrange ones

- Membrane shields EM forces
- All surfaces gold plated.

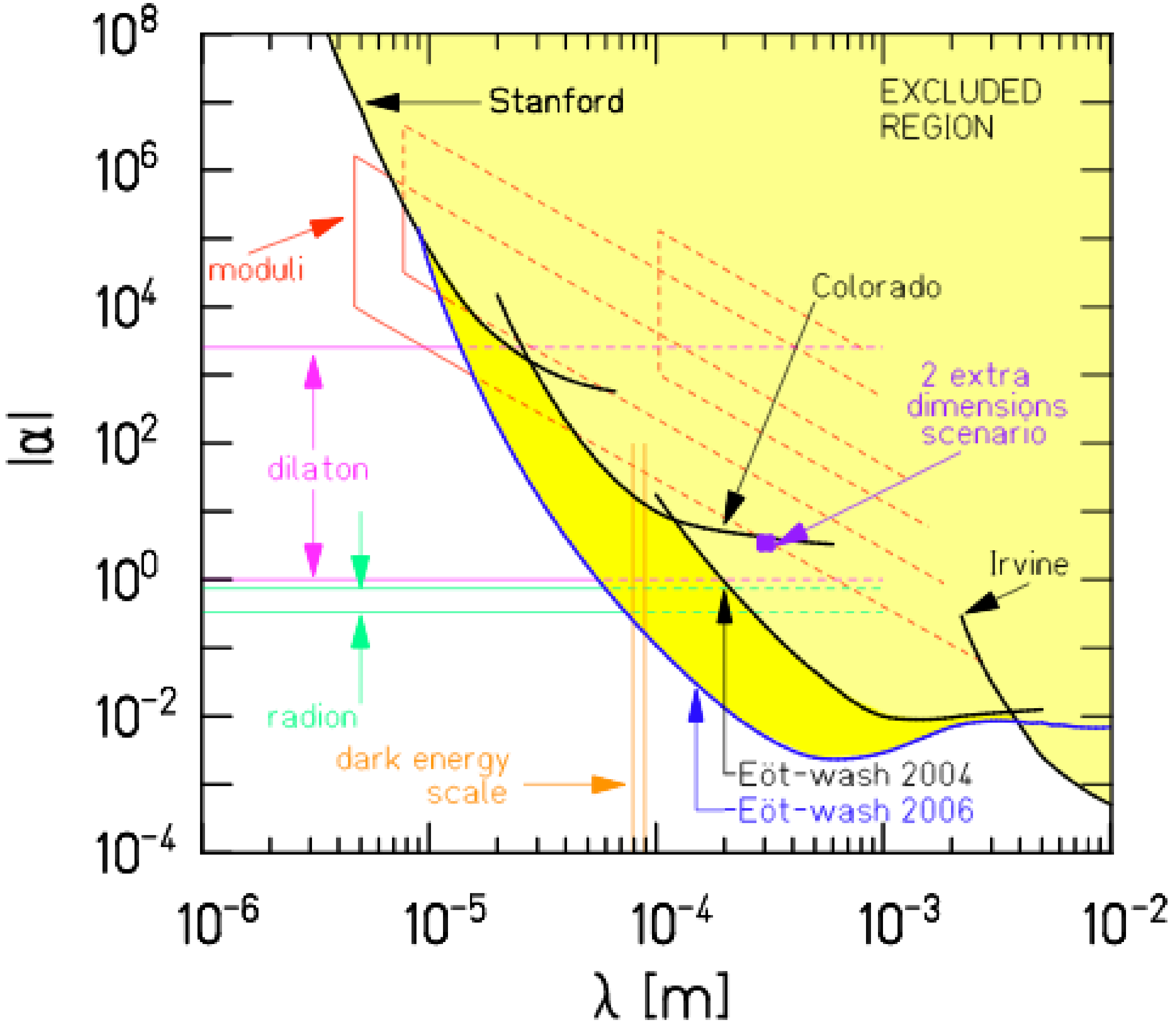
- Separation down to 137μm

Torsion pendulum data



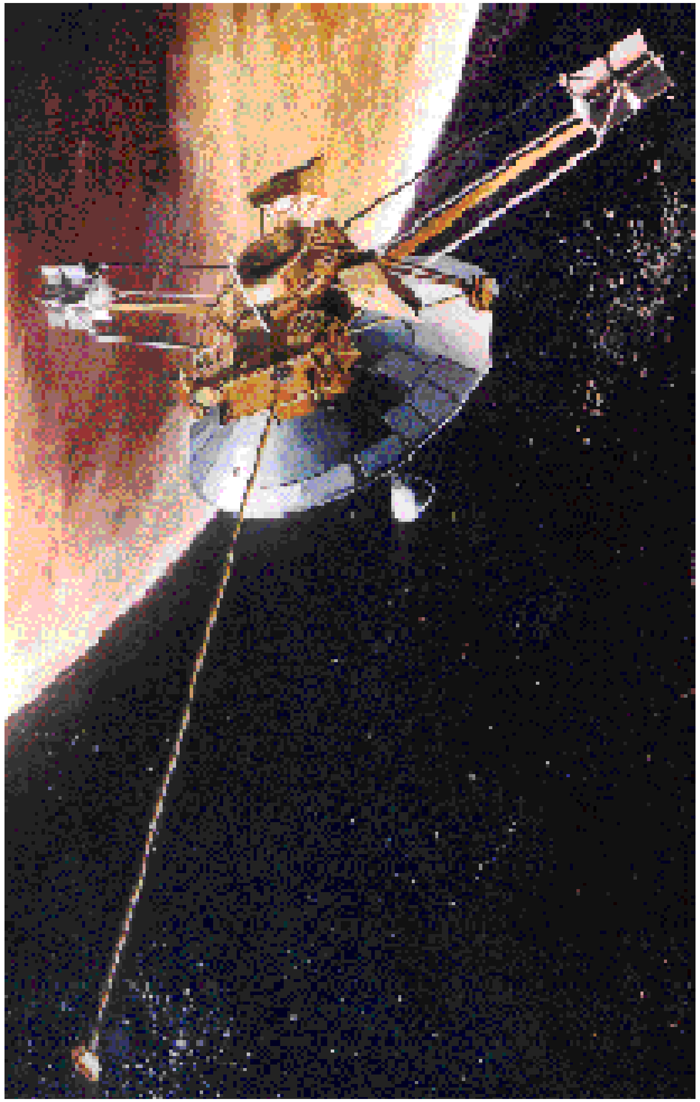
- Data from one turn of base plate, with fitted expected curve
- Angular precision 8nrad
- Signal would have higher harmonic content and different dependence on distance.

Eot-Wash results

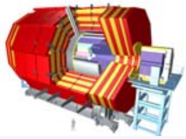


- 2006 results
- R< 44 μm for 1 ED larger than others.
- M*>3.2 TeV for 2 equal sized ED

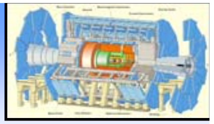
Pioneer 10

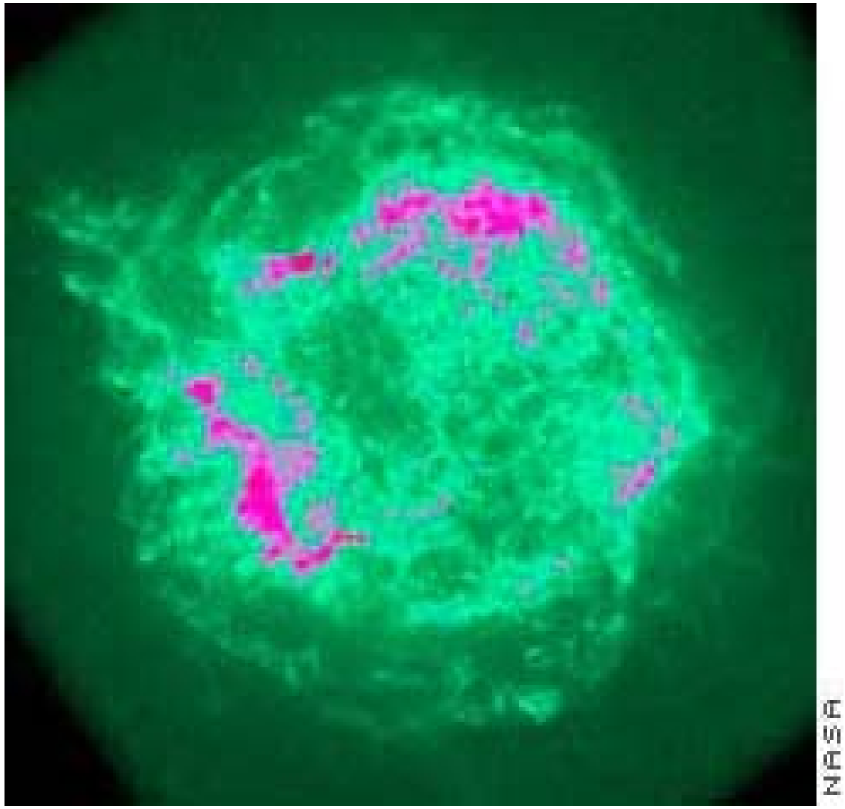


- Pioneer 10 is leaving the solar system after 30 years in flight.
- Orbit shows deccelaration from force of 10^{-10} g
- Radiation pressure?
  - Solar?
  - Antenna?
  - Heat?
  - Gas leaks
- Time dependence?



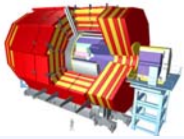
Astrophysical constraints



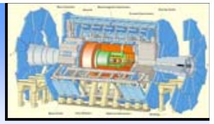


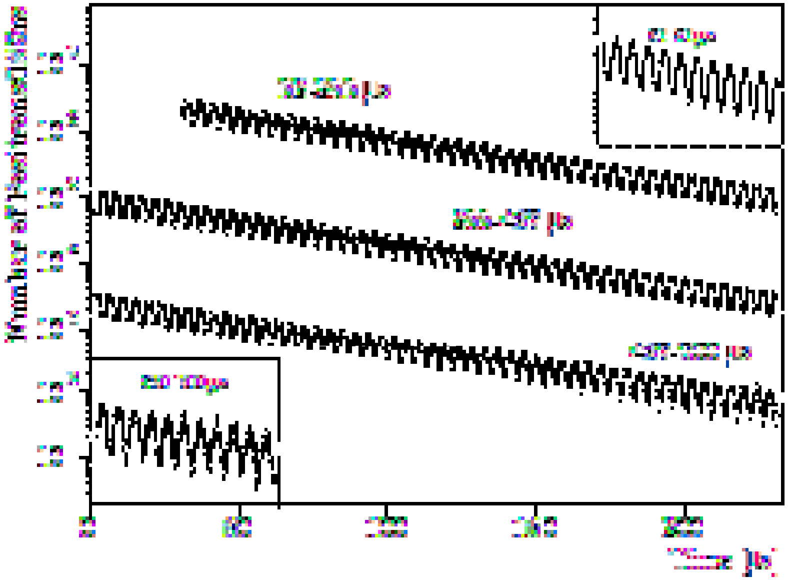
- Supernova remnants lose energy into ED, but production of KK states restricted to O(10MeV)
- Remnant cools faster

- Data from SN1987A implies
- M_D > 50 TeV for n=2
- PRL 83(1999)268



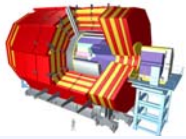
Limits from g-2



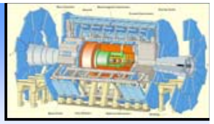


- g-2 is best measured number in physics:
- Theory: $a^{SM} = (g-2)/2$
- $= 11659159.7(6.7)\times10^{-10}$
- Experiment (PDG):
- $= 11659160(6)\times10^{-10}$

- LED can give contributions from KK excitations of W, Z, g, $O(10^{-10})$ (Cirelli, Moriond)
- Brookhaven experiment: hep-ph/0105077

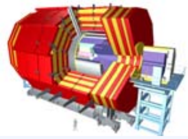


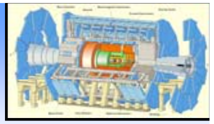
Neutrino oscillations



- Neutrino oscillations could occur into sterile neutrinos
- KK excitations of SM fermion singlets can mix with neutrinos to form sterile states
- Oscillation data (SNO, Super-Kamiokande…) are well fitted by oscillations into standard neutrino states
- -> little room for sterile states
- -> bound on ED models
- -> model dependent limits on parameters

- Eg LBNL-49369 gives R<0.82 μm





BACK-UP SLIDES