Connecting inner space & outer space: LHC and the Universe

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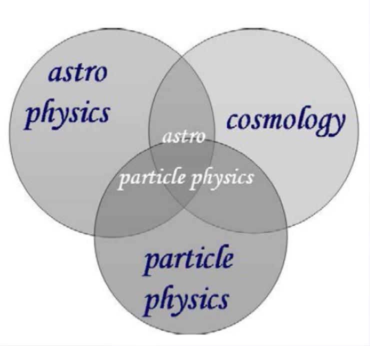


> It is likely that further research into "showers" and "bursts" of the cosmic rays may possibly lead to the discovery of still more elementary particles, neutrinos and negative protons, of which the existence has been postulated by some theoretical physicists in recent years.

Victor Hess (1936)

The Latsis Symposium: *Nature at the Energy Frontier*, ETH Zurich, 3-6 June 2013

The birth of astroparticle physics

Per Carlson, *Physics Today*, Feb 2012

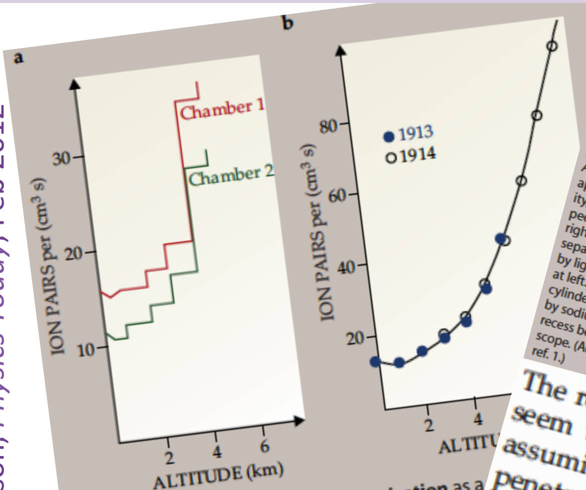
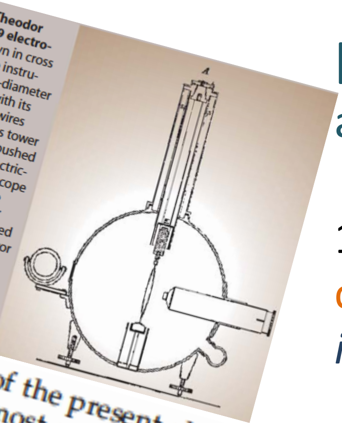


Figure 3. The rate of atmospheric ionization as a as measured **(a)** by Victor Hess on 7 August 1912, Kolhörster in 1913. (Adapted from ref. 2.)

Figure 2. Theodor Wulf's 1909 electroscope. *Shown in cross section is the instrument's 17-cm-diameter zinc cylinder with its pair of flexible wires below the access tower A. The wires are pushed apart by static electricity, and the microscope peering in from the right measures their separation, illuminated by light from the mirror at left. The air in the cylinder was kept dry by sodium in the small recess below the microscope. (Adapted from ref. 1.)*



The results of the present observations seem to be most readily explained by assuming that radiation of very high penetrating power enters the atmosphere from above, and can still produce a part of the ionization observed in closed vessels at the lowest altitudes.[4]

A century of **cosmic rays**

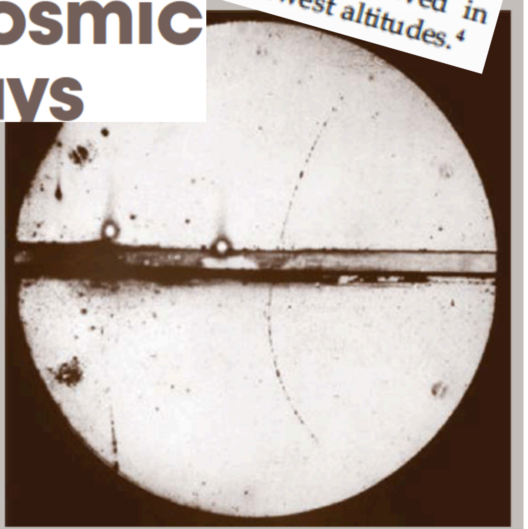


Figure 4. A historic cloud-chamber photograph taken by Carl Anderson in 1932 shows a positive particle, presumably from a cosmic-ray shower, entering from the top, curving in the chamber's transverse magnetic field, and losing energy in the lead plate. After traversing the plate, the track is much too long for a proton of that curvature. Also, the weak ionization density along the track indicated a particle much lighter than the proton. This was the first sighting of the positron proposed by Paul Dirac in 1928. (Adapted from ref. 10.)

1912: Victor Hess discovers cosmic rays (named so in 1927 by Millikan) – **Nobel Prize 1936**

[1928: Paul Dirac predicts the existence of anti-particles – **Nobel Prize 1933**]

1932: Carl Anderson discovers the positron in cosmic rays **- Nobel Prize 1936** *(cloud chamber invented by C T R Wilson - **Nobel Prize 1927**)*

[1935: Hideki Yukawa predicts the existence of mesons – **Nobel Prize 1949**]

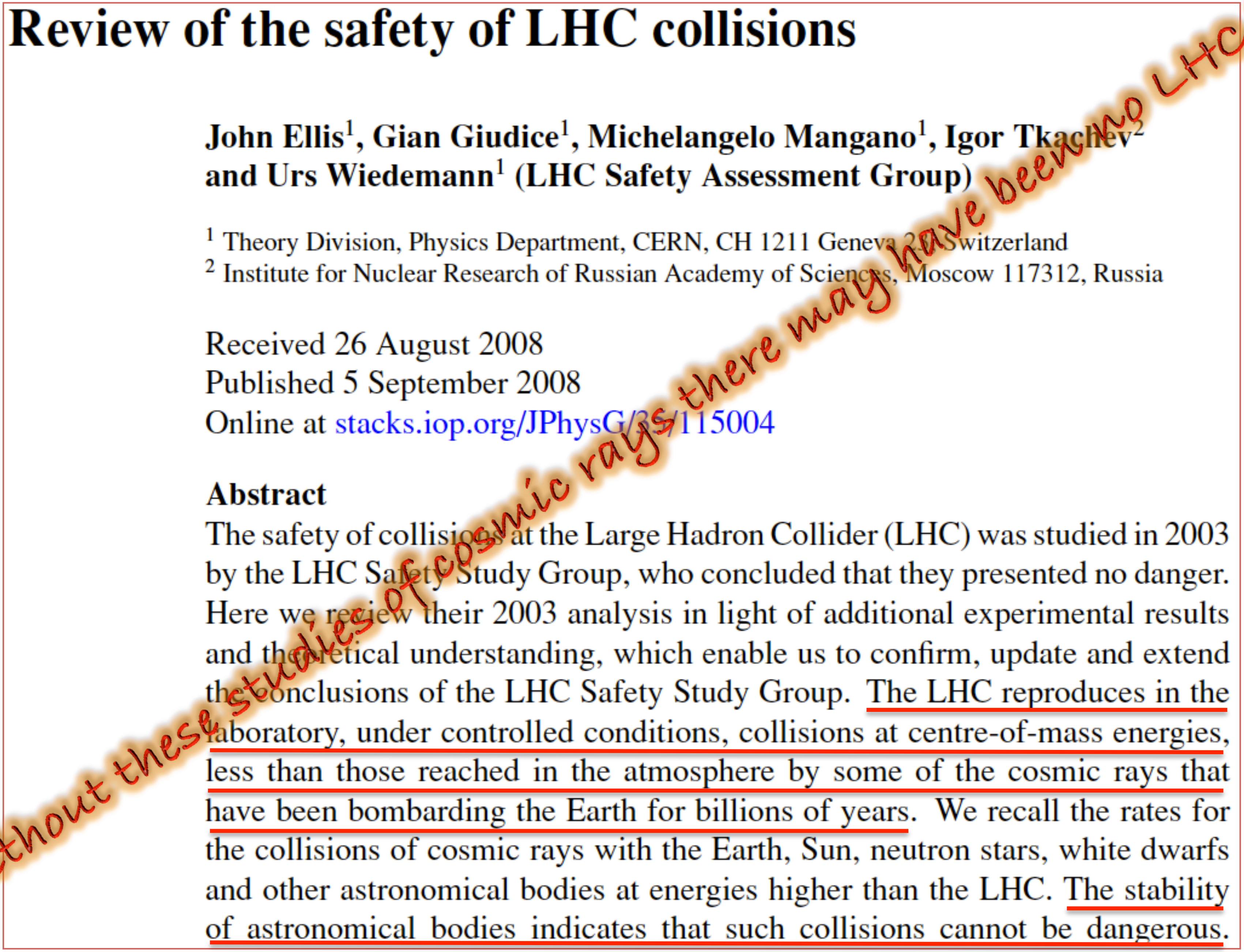
1937: Seth Neddermeyer & Carl Anderson discover the muon in cosmic rays

1947: Cecil Powell discovers the pion in cosmic rays **– Nobel Prize 1950**

1947: George Rochester & Clifford Butler discover the kaon

*(Patrick Blackett awarded **Nobel Prize 1948** "for his development of the Wilson cloud chamber method …")*

So there were indeed more fundamental discoveries in cosmic rays – until accelerators took over the show in the ’60s … but what have cosmic rays done for high energy physics since then?



Review of the safety of LHC collisions

John Ellis[1], Gian Giudice[1], Michelangelo Mangano[1], Igor Tkachev[2] and Urs Wiedemann[1] (LHC Safety Assessment Group)

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Abstract

The safety of collisions at the Large Hadron Collider (LHC) was studied in 2003 by the LHC Safety Study Group, who concluded that they presented no danger. Here we review their 2003 analysis in light of additional experimental results and theoretical understanding, which enable us to confirm, update and extend the conclusions of the LHC Safety Study Group. The LHC reproduces in the laboratory, under controlled conditions, collisions at centre-of-mass energies, less than those reached in the atmosphere by some of the cosmic rays that have been bombarding the Earth for billions of years. We recall the rates for the collisions of cosmic rays with the Earth, Sun, neutron stars, white dwarfs and other astronomical bodies at energies higher than the LHC. The stability of astronomical bodies indicates that such collisions cannot be dangerous.

… without these studies of cosmic rays there may have been no LHC !

European Organization for Nuclear Research

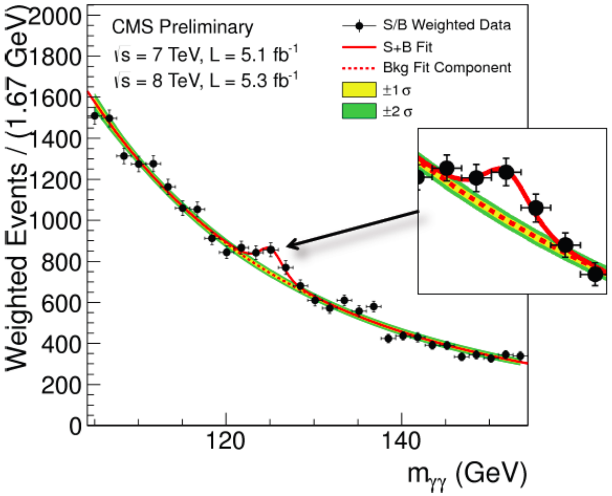
The safety of the LHC

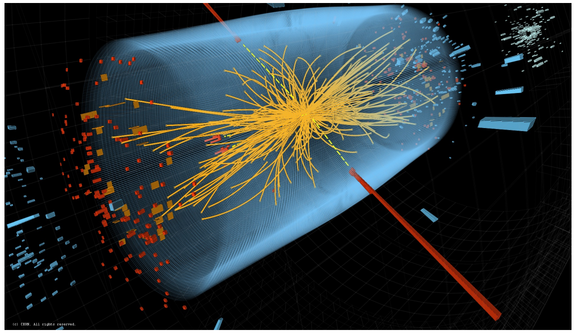
The Large Hadron Collider (LHC) can achieve an energy that no other particle accelerators have reached before, but Nature routinely produces higher energies in cosmic-ray collisions. Concerns about the safety of whatever may be created in such high-energy particle collisions have been addressed for many years. In the light of new experimental data and theoretical understanding, the LHC Safety Assessment Group (LSAG) has updated a review of the analysis made in 2003 by the LHC Safety Study Group, a group of independent scientists.

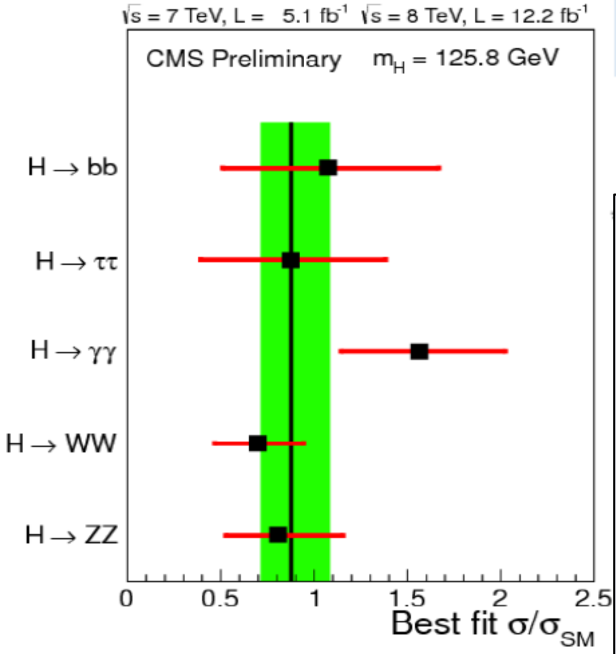
The experiments that we will do with the LHC have been done billions of times by cosmic rays hitting the Earth ... They're being done continuously by cosmic rays hitting our astronomical bodies, like the moon, the sun, like Jupiter and so on and so forth. And the Earth's still here, the sun's still here, the moon's still here. LHC collisions are not going to destroy the planet.

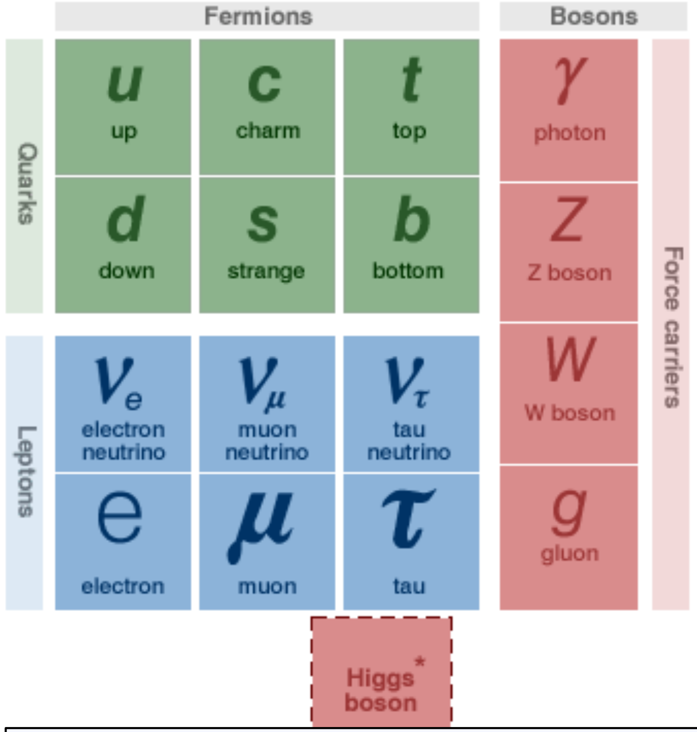
John Ellis

… and without the LHC we could not have made further progress in particle physics









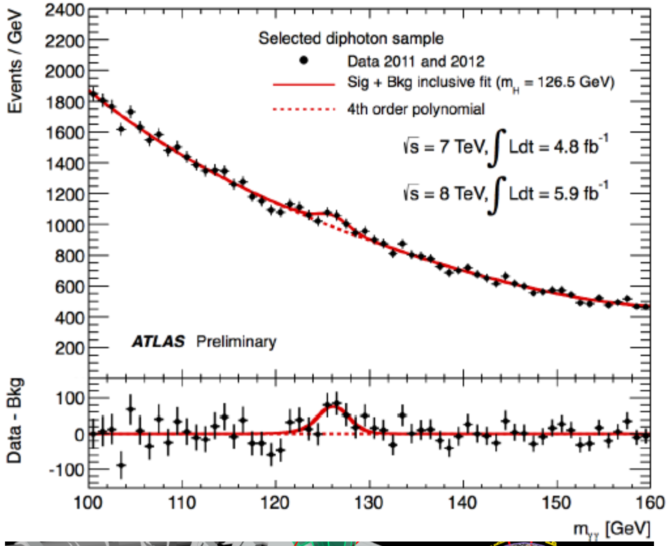
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

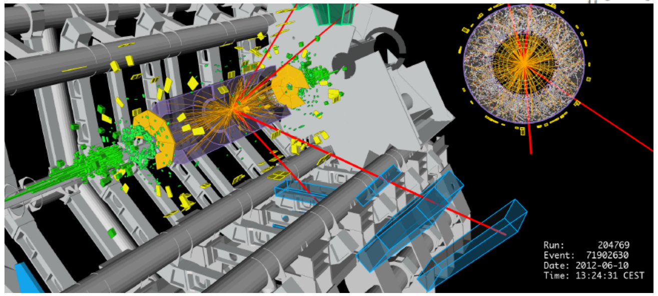
Higgs* boson

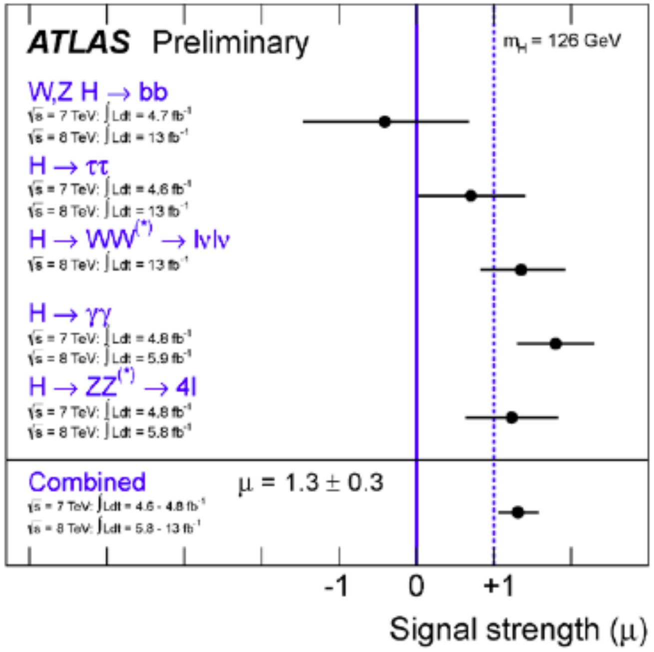
The triumph of the Standard Model …

Higgs is found!

Talks by: **Myers**, **Virdee**, **Gross**







The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** (viewed as an effective field theory up to some high energy cut-off scale ***M***) accurately describes *all* microphysics

Talk by: **Ratazzi**

$$+M^4 + M^2\Phi^2 \qquad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

hierarchy problem

super-renormalisable

$$\mathcal{L}_{\mathrm{eff}} = F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + \Phi^2$$

renormalisable

$$+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \dots$$

neutrino mass

proton decay

non-renormalisable

New physics beyond the SM ⇒ **non-renormalisable operators** suppressed by M^n which 'decouple' as $M \longrightarrow M_{\mathrm{P}}$ (… so **neutrino mass** is small, **proton decay** is slow *etc*)

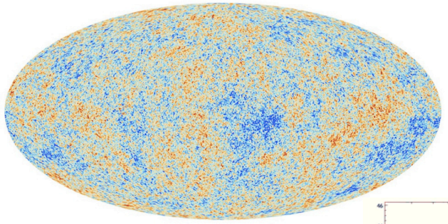
But as *M* is raised, the effects of the **super-renormalisable operators** are *exacerbated*
One solution for Higgs mass divergence ⟶ 'softly broken' supersymmetry at $M \sim$ 1 TeV

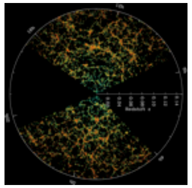
This provides new possibilities for baryogenesis as well as a good candidate for **dark matter** – the **lightest supersymmetric particle** (typically the neutralino χ), *if* it is cosmologically *stable* because of a conserved quantum number (R-parity)

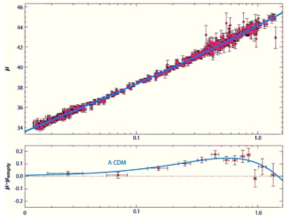
This has been the target of *most* dark matter searches, whether using nuclear recoil detectors or looking for cosmic annihilation products, or missing E_{T} signals at colliders

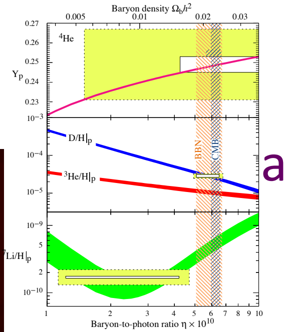
The world is indeed a strange place!

Mainly geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is *inferred* from the ‘cosmic sum rule’:
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$

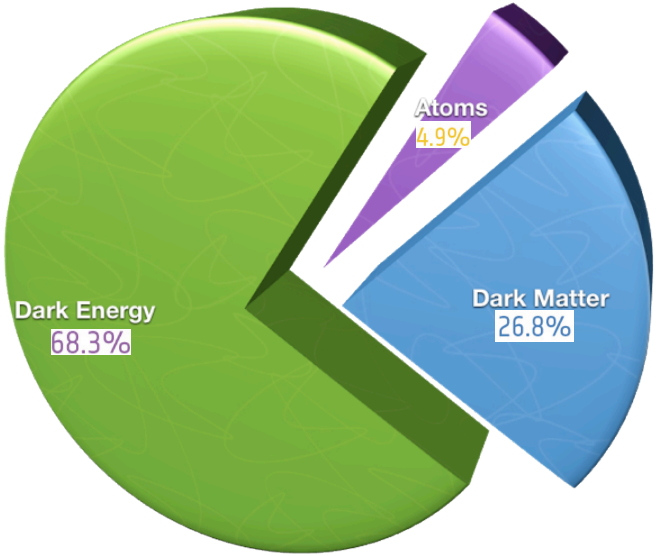




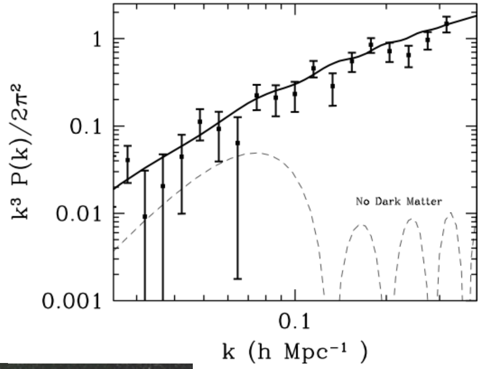




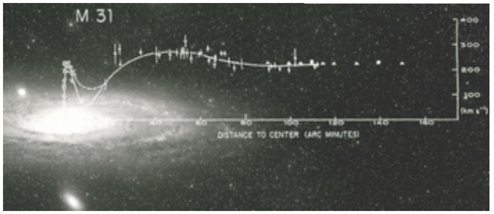
Baryons (*no* anti-baryons)

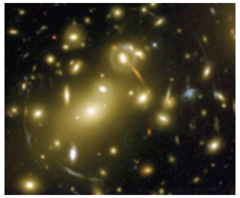


Both geometrical and dynamical evidence (if GR is valid on all scales)

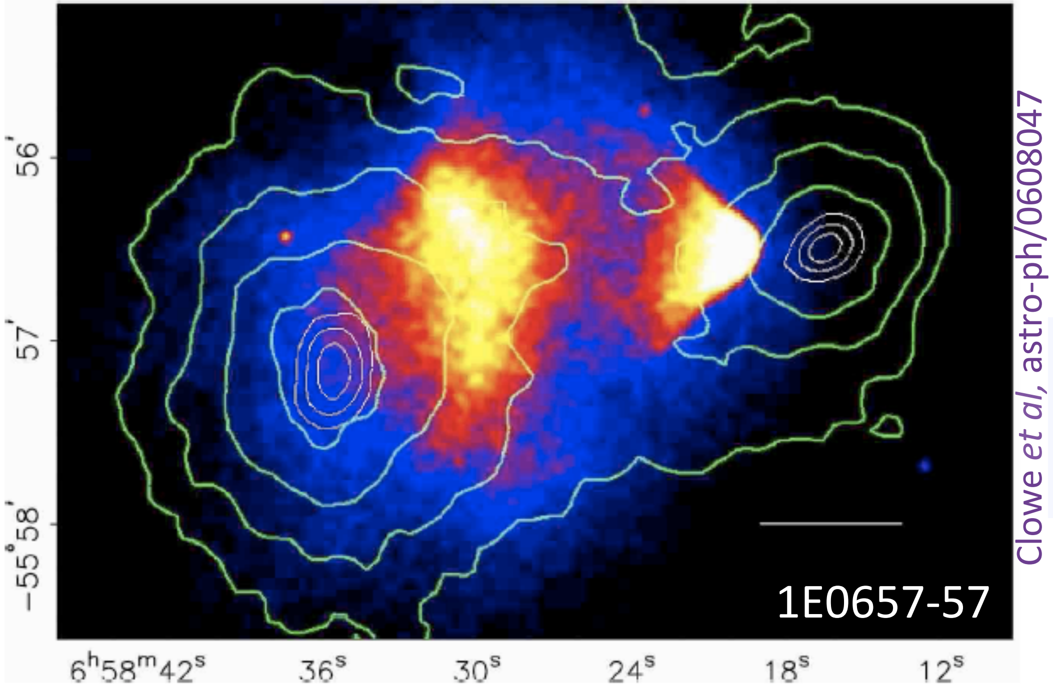


Both the baryon asymmetry and dark matter require that there be *new* physics beyond the Standard $SU(3)_c \mathrm{x} SU(2)_L \mathrm{x} U(1)_Y$ Model
… dark energy is even more mysterious (but as yet lacks compelling dynamical evidence)





What can astrophysics tell us about dark matter interactions?



Clowe *et al*, astro-ph/0608047

The 'Bullet Cluster' is often cited as evidence for **collisionless dark matter** … in fact it sets a very *weak* limit on self-interactions: $\sigma \lesssim 2\text{x}10^{-24}$ cm^2/GeV

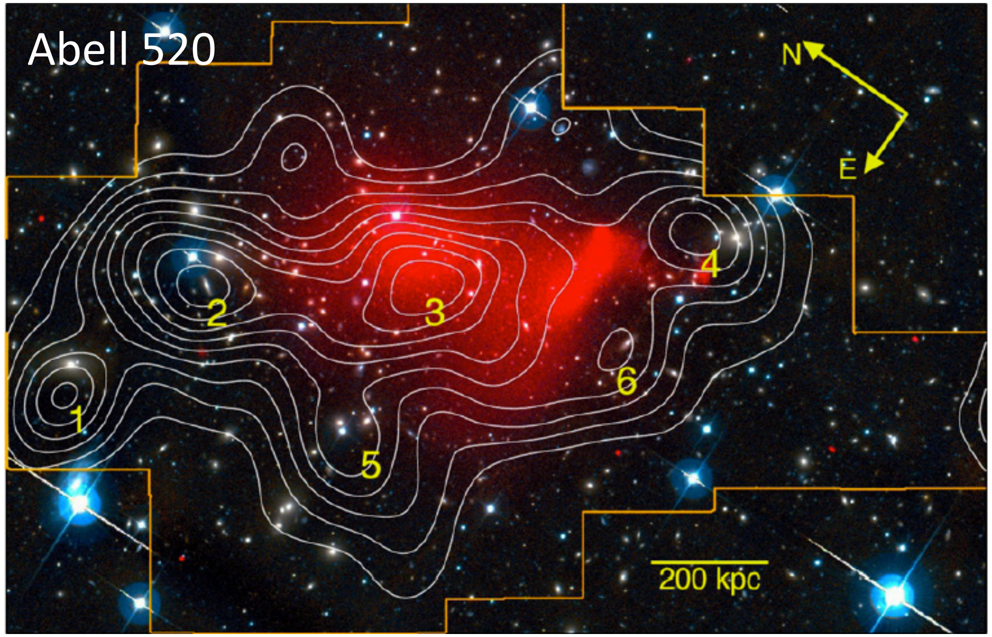
Moreover it poses a *challenge* for ΛCDM cosmology: why is the relative velocity so high (>3000 km/s on a scale of 5 Mpc)?

9 other colliding clusters have been found … odds are *tiny* in a gaussian density field!

Moreover In Abell 520, the inferred dark matter concentration is partly *coincident* with the X-ray emitting gas implying that DM is *self-interacting* with: $\sigma \sim 8 \pm 2 \text{ x}10^{-24}$ cm^2/GeV

This result is contested … the implications for structure formation are currently under study
➞ $\sigma \approx 2\text{x}10^{-24}$ cm^2/GeV *may* be consistent with both systems (Frandsen *et al*, in preparation)

This has the potential to solve several problems of CDM cosmology *and* discriminate between various particle candidates for dark matter

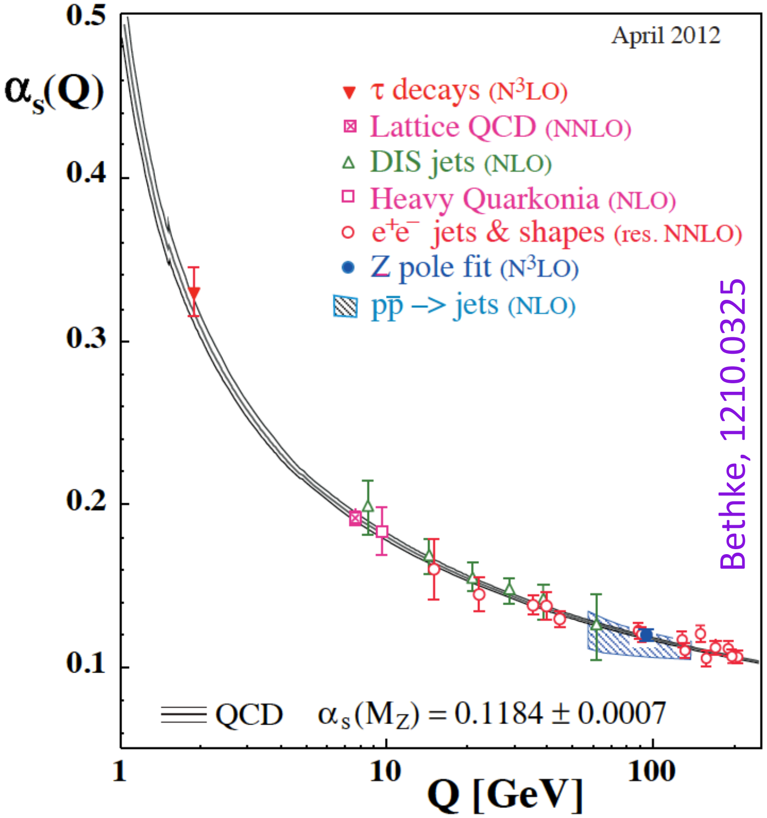


Jee *et al*, 1202.6368

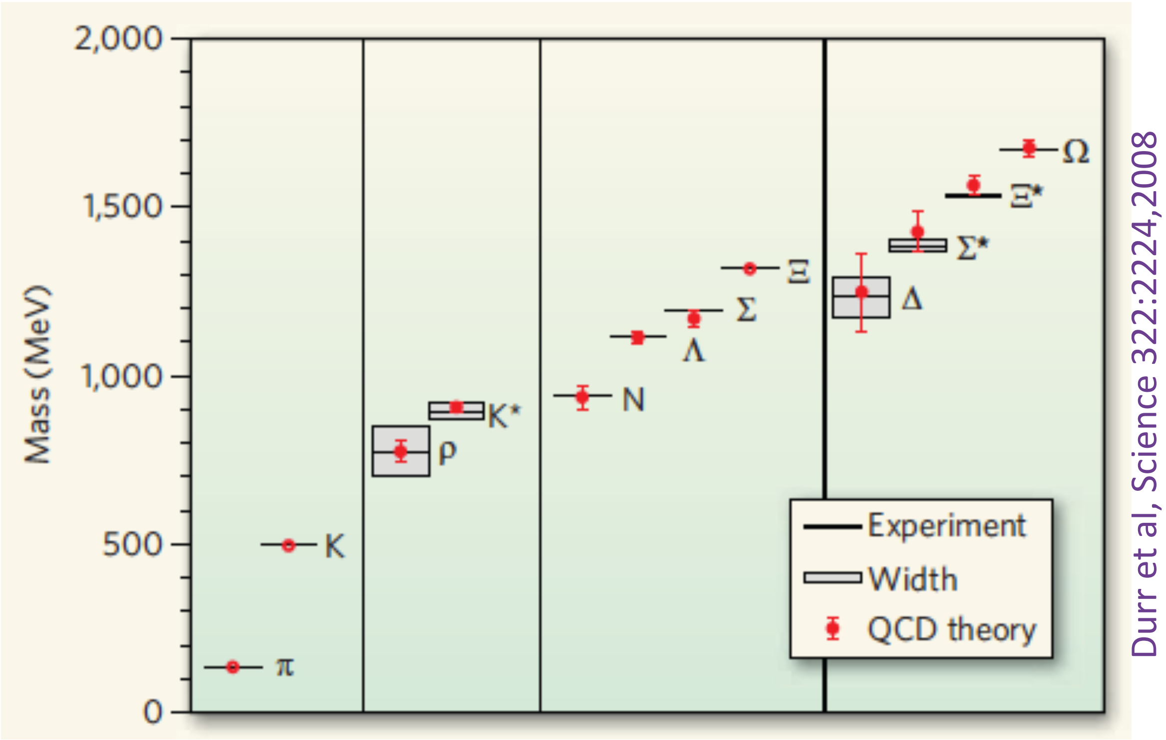
What should the world be made of?

Mass scale	**Particle**	**Symmetry/ Quantum #**	**Stability**	**Production**	**Abundance**
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

We have a good theoretical explanation for why baryons are massive and stable



Bethke, 1210.0325



Durr et al, Science 322:2224,2008

We understand the dynamics of QCD … and can calculate the mass spectrum

Nevertheless we get the cosmology of baryons *badly* wrong!

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{\mathrm{T}}^2)$$

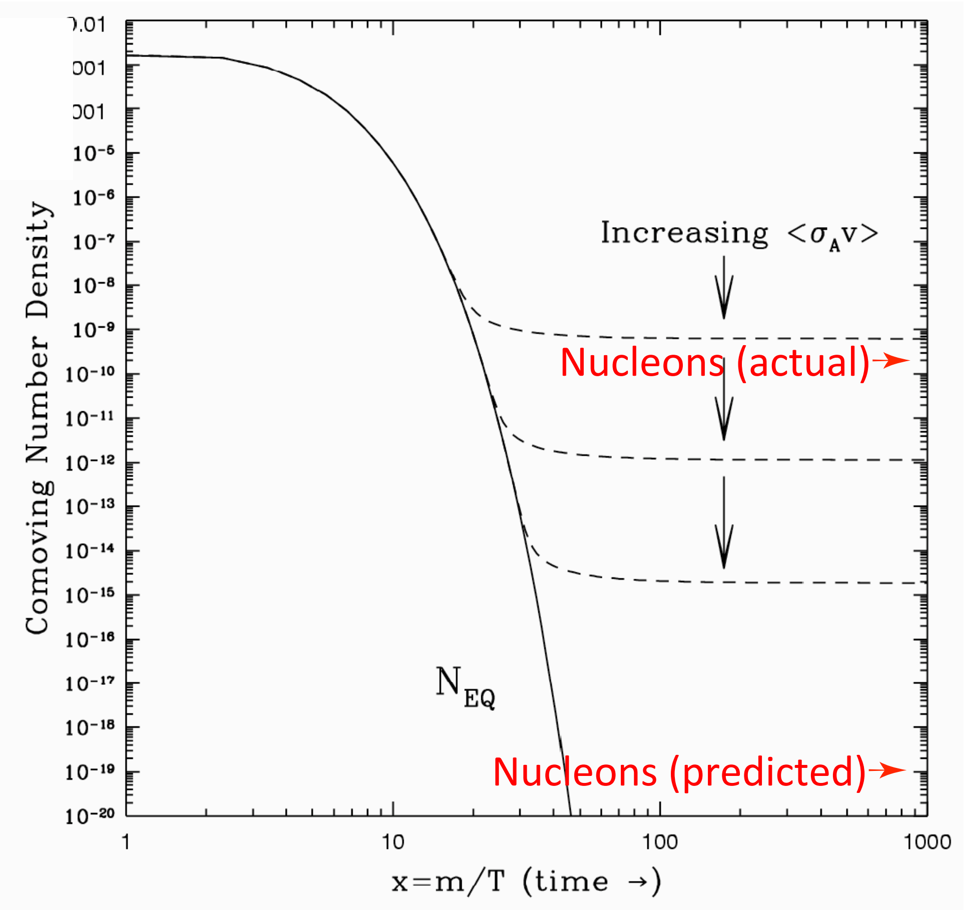
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

‘Freeze-out’ occurs when annihilation rate:

$$\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$$

becomes comparable to the expansion rate

$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}}$ where $g \sim$ # relativistic species



Nucleons (actual)→

Nucleons (predicted)→

i.e. ‘freeze-out’ occurs at $T \sim m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

However the observed ratio is 10^9 **times *bigger* for baryons**, and there seem to be ***no* antibaryons**, so we must invoke an **initial asymmetry**: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

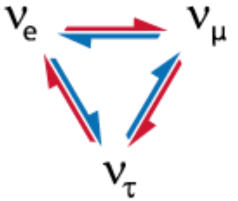
To make the baryon asymmetry requires a lot of new physics:

- *B*-number violation
- *CP* violation
- Departure for thermal equilibrium

The SM does allow *B*-number violation (through non-perturbative – 'sphaleron'-mediated – processes) … but *CP*-violation is too weak and $SU(2)_L$ x $U(1)_Y$ breaking is *not* a 1st order phase transition

Hence the generation of the observed matter-antimatter asymmetry requires *new* BSM physics - can be related to the observed neutrino masses if these arise from *lepton number* violation → **leptogenesis**

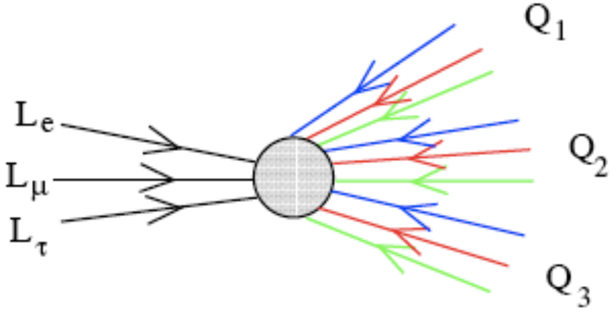
'See-saw': $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\overline{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N^c_J$ $\quad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$



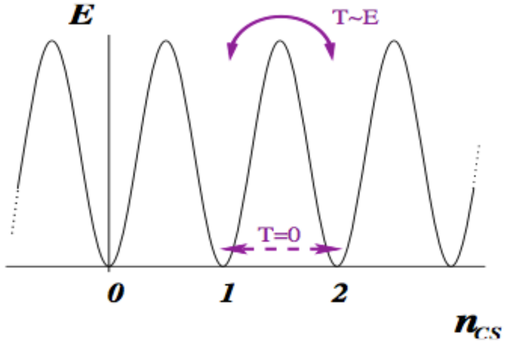
Talk by: **Smirnov**

$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

Asymmetric baryonic matter

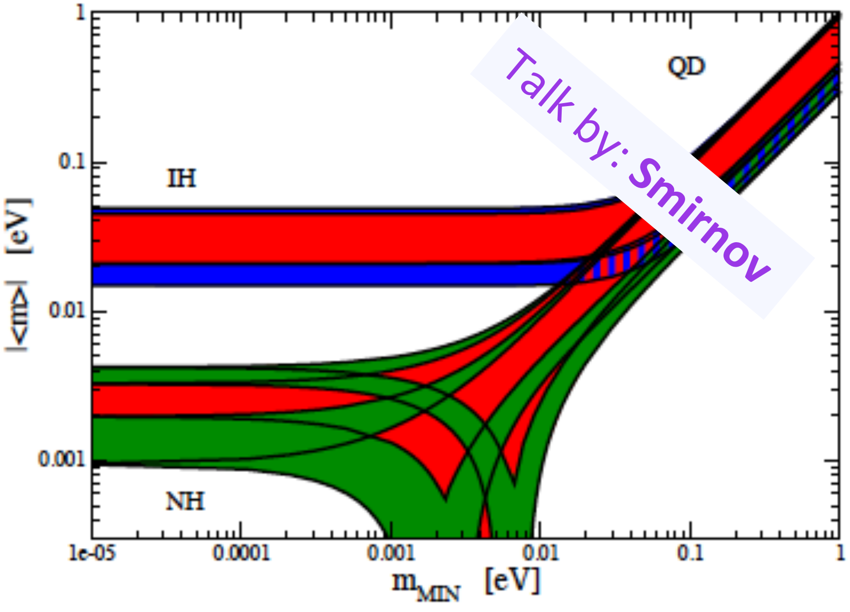


$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed N) would be redistributed by B+L violating processes (which conserve B-L) amongst *all fermions* which couple to the electroweak anomaly – in particular **baryons**

An essential requirement is that neutrino mass must be Majorana (*not* Dirac) … test experimentally by looking for neutrinoless double beta decay, along with measurement of the absolute neutrino mass scale



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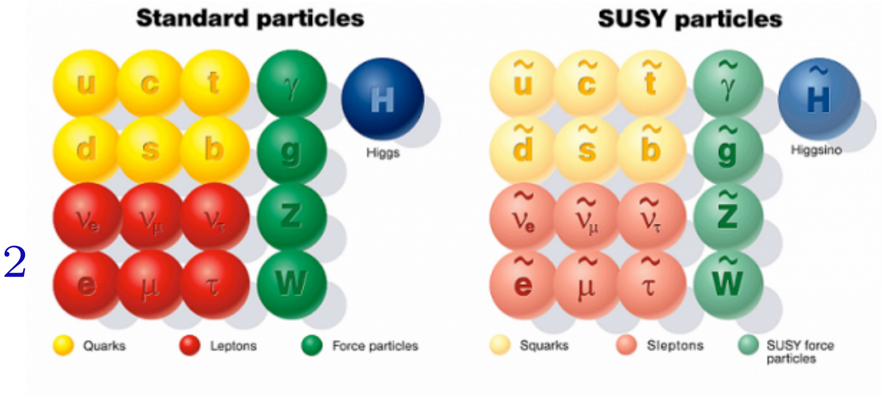
$\Lambda_{\mathrm{Fermi}} \sim G_{\mathrm{F}}^{-1/2}$	Neutralino?	*R*-parity?	Violated? (matter parity *adequate* to ensure *p* stability)	'freeze-out' from thermal equilibrium	$\Omega_{\mathrm{LSP}} \sim 0.3$



$$\mathcal{L}_{\mathrm{eff}} \supset M_A A_\mu A^\mu + m_{\mathrm{f}} \bar{f}_{\mathrm{L}} f_{\mathrm{R}} + m_H^2 |H|^2$$

For (softly broken) **supersymmetry** we have the 'WIMP miracle':

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle_{T=T_{\mathrm{f}}}} \simeq 0.1 \quad \text{, since } \langle \sigma_{\mathrm{ann}} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

But why should a *thermal* relic have an abundance comparable to non thermal relic baryons?

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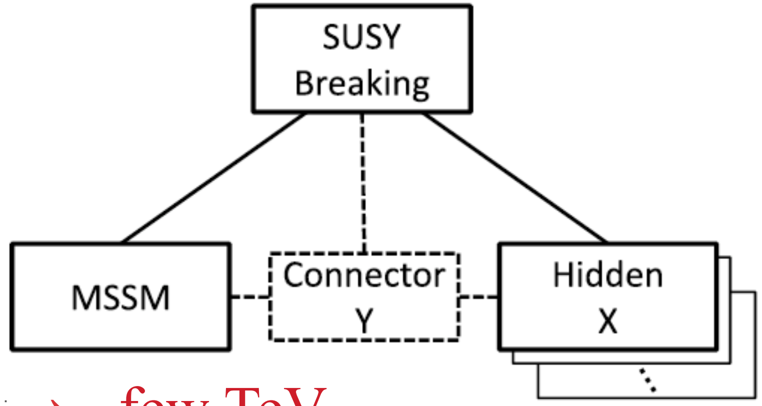


(GMSB) Hidden sector matter also provides the '*WIMPless* miracle' (Feng & Kumar, 0803.4196)

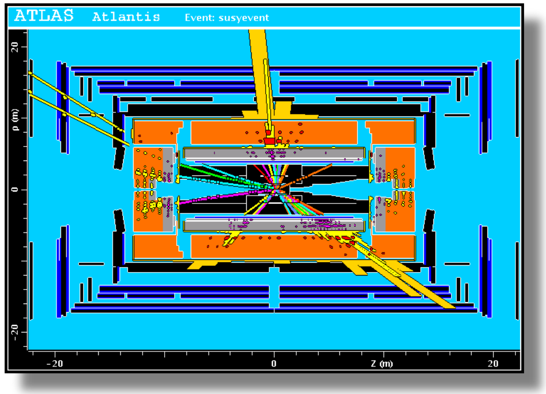
… because: $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$

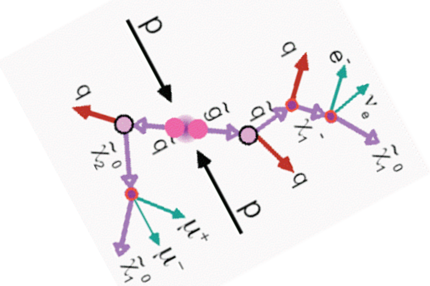
Such dark matter can have *any* mass: ~0.1 GeV → ~few TeV

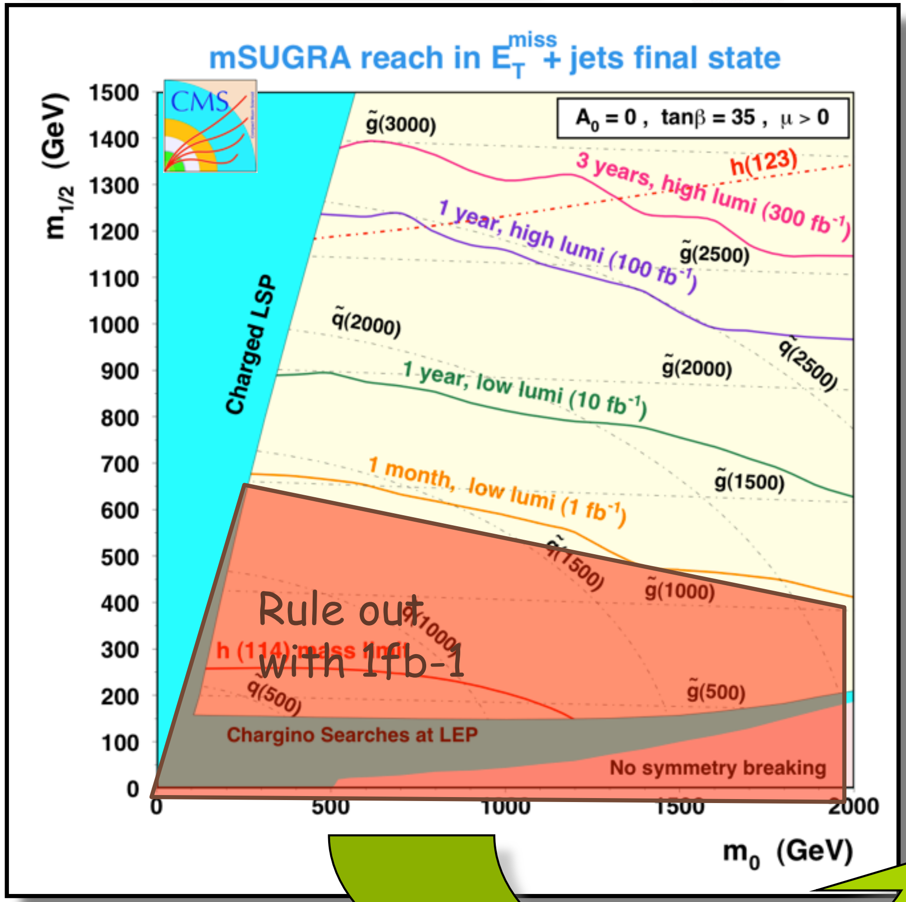
$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle_{T=T_{\mathrm{f}}}} \simeq 0.1 \quad , \text{since } \langle\sigma_{\mathrm{ann}} v\rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$

But why should a *thermal* relic have an abundance comparable to non-thermal relic baryons?

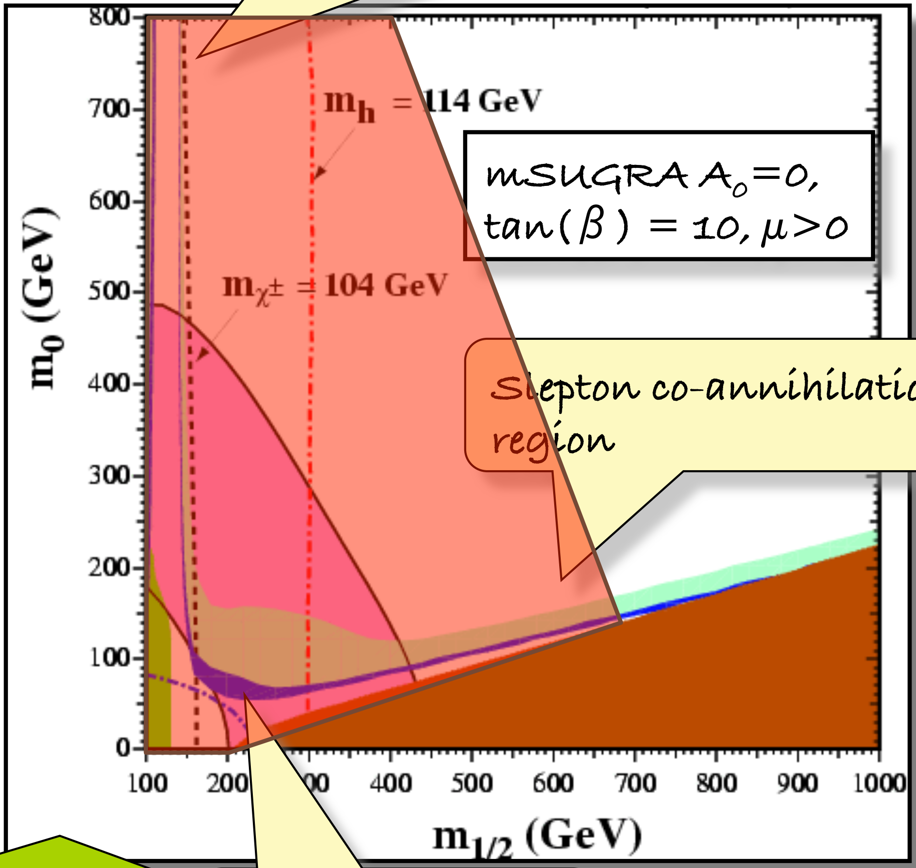
LHC reach for SUSY dark matter







Rule out with 1fb-1



mSUGRA $A_0 = 0$, $\tan(\beta) = 10$, $\mu > 0$

'Focus point' region: annihilation to gauge bosons

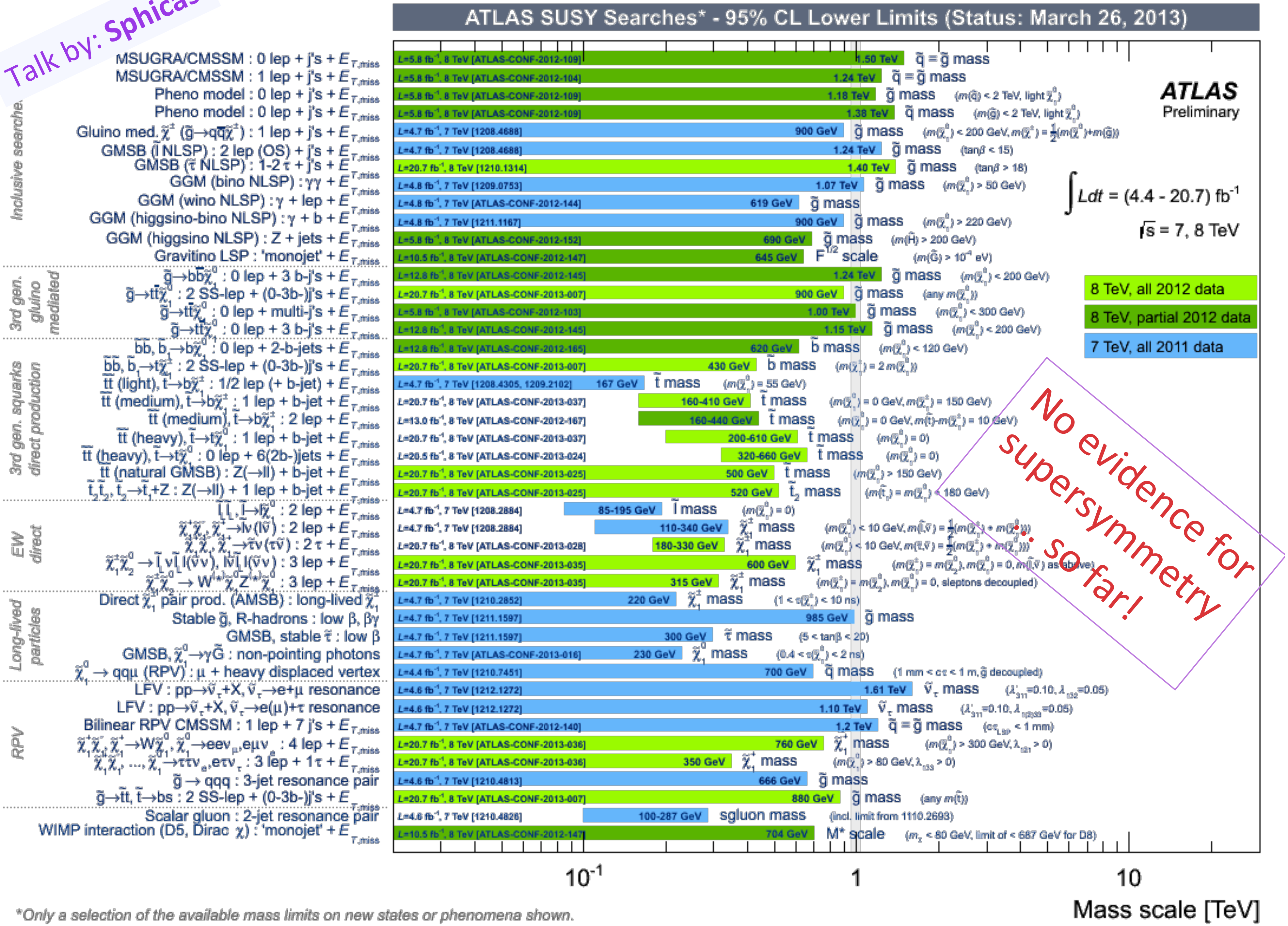
Slepton co-annihilation region

'Bulk' region: t-channel slepton exchange

WMAP constraints

(Courtesey: Alan Barr)

Talk by: Sphicas



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)

*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

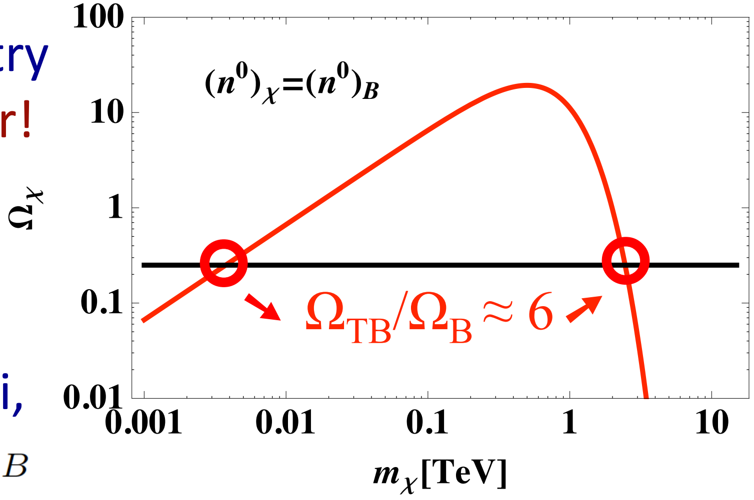
No evidence for supersymmetry ∴ so far!

What should the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'Freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like the *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?	Asymmetric (like the *observed* baryons)	$\Omega_{TB} \sim 0.3$

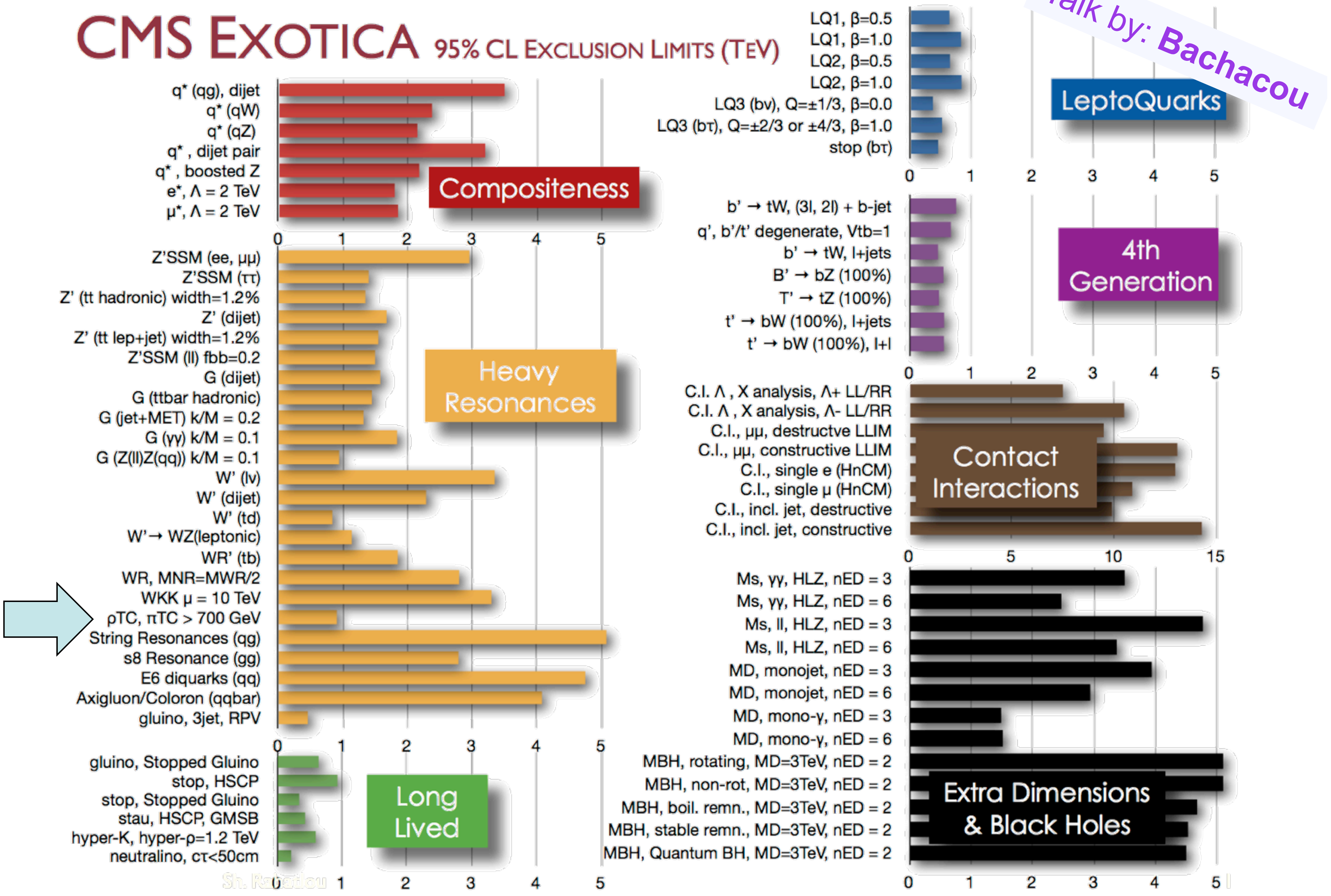
A new particle can naturally *share* in the *B/L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

For example a *O*(TeV) mass **technibaryon** can be the dark matter (Nussinov 1985) … another possibility is a ~6 GeV mass **'dark baryon'** in a *hidden sector* (Gelmini, Hall & Lin 1986, Kaplan 1992): $\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B)\Omega_B$

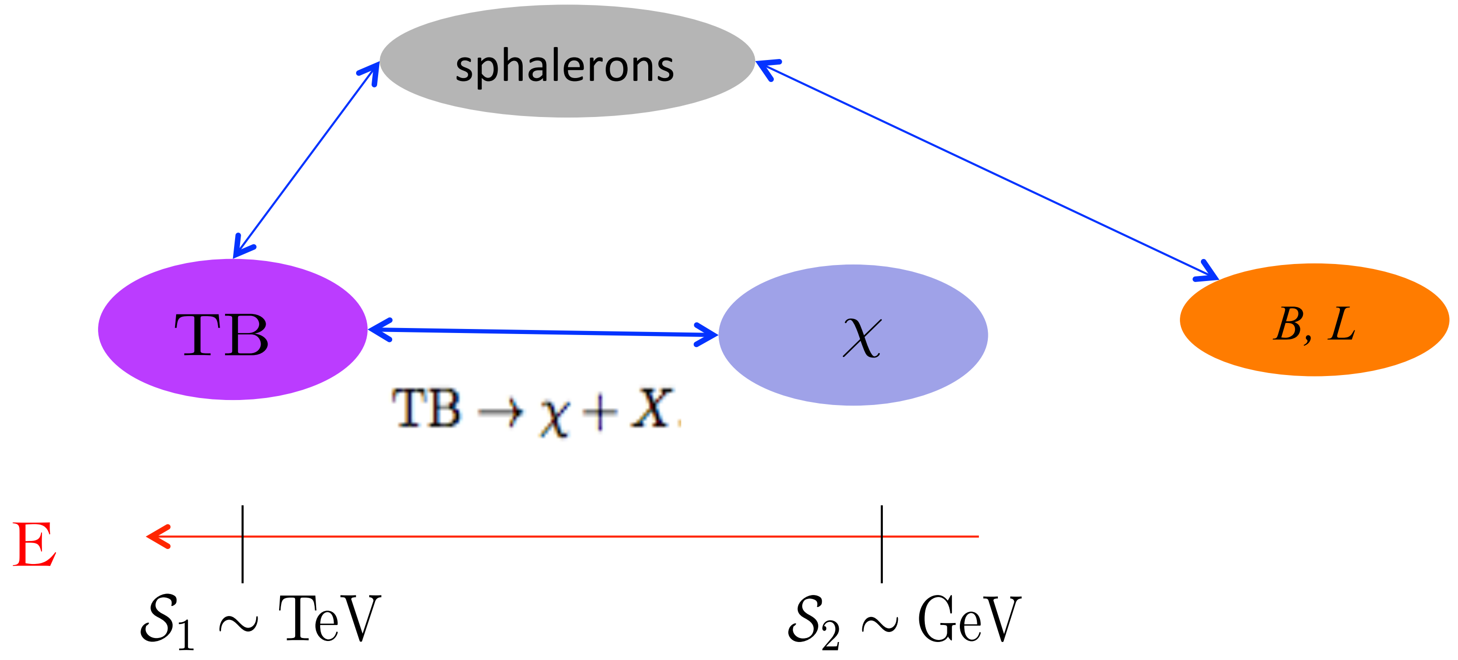


But LHC sees no such particles either … so far!

Talk by: **Bachacou**



Why have we not seen these particles yet?



S_1 States (constituents) carry weak charges and are connected to sphalerons

S_2 States are SM singlets (in a hidden sector/hidden valley) but directly connected to the S_1 sector (with scale separation – TeV ➔ GeV – because of different β-function)

$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\mathrm{sph}}$, then χ decouples and becomes DM

The S_1 states do couple to the SM (so should show up at LHC14!

Frandsen, Sarkar, Schmidt-Hoberg, 1103.4350

Axion dark matter

Talk by: **Ratazzi**

$$\begin{aligned}\mathcal{L}_{\rm eff} &= M^4 + M^2\Phi^2 && \text{super-renormalisable}\\ &+ (D\Phi)^2 + \bar\Psi \not{D}\Psi + F^2 + \bar\Psi\Psi\Phi + \Phi^2 \boxed{+\theta_{\rm QCD} F\tilde F} && \text{renormalisable}\\ &+ \frac{\bar\Psi\Psi\Phi\Phi}{M} + \frac{\bar\Psi\Psi\bar\Psi\Psi}{M^2} + \dots && \text{non-renormalisable}\end{aligned}$$

Talk by: **Hertzog**

The SM admits a term which would lead to CP violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons → requires $\theta_{\rm QCD} < 10^{-6}$

To achieve this without fine-tuning, $\theta_{\rm QCD}$ must be made a dynamical parameter, through the introduction of a new $U(1)_{\text{Peccei-Quinn}}$ symmetry which must be broken … the resulting (pseudo) Nambu-Goldstone boson is the **axion** which acquires a small mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi\, (f_\pi/f_{\rm PQ})$

The coherent oscillations of relic axions contain energy density *that behaves like CDM* with $\Omega_a h^2 \sim 10^{11}\ \text{GeV}/f_{\rm PQ}$ … however the *natural* P-Q scale is probably $f_{\rm PQ} \sim 10^{18}$ GeV

Hence axion dark matter would typically need to be significantly diluted i.e. its relic abundance is *not* predictable (or seek anthropic explanation for why $\theta_{\rm QCD}$ is small?)

What should the world be made of?

Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
$\boldsymbol{\Lambda_{QCD}}$	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	~~'Freeze-out' from equilibrium~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 6\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\boldsymbol{\Lambda_{Fermi}}$ $\sim G_F^{-1/2}$	Neutralino?	R-parity	violated?	'freeze-out' from equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr	Asymmetric (like observed baryons)	$\Omega_{TB} \sim 0.3$
$\boldsymbol{\Lambda_{hidden\ sector}}$ $\sim (\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (very model dependent)	$\tau \sim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3?$
$\boldsymbol{\Lambda_{see\text{-}saw}}$ $\sim \Lambda_{Fermi}^2/\Lambda_{B\text{-}L}$	**Neutrinos**	Lepton number	Stable	Thermal (abundance ~ CMB photons)	$\Omega_\nu > 0.003$
$\boldsymbol{M_{string}/M_{Planck}}$	Kaluza-Klein states? Axions	? Peccei-Quinn	? stable	? Field oscillations	? $\Omega_a \gg 1$!

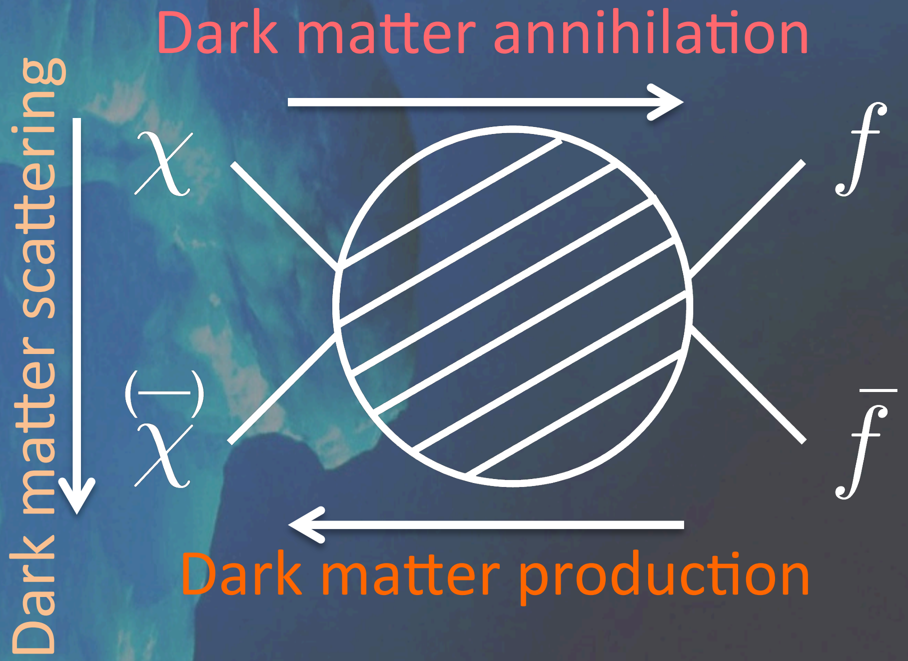
No definite 'indication from theory

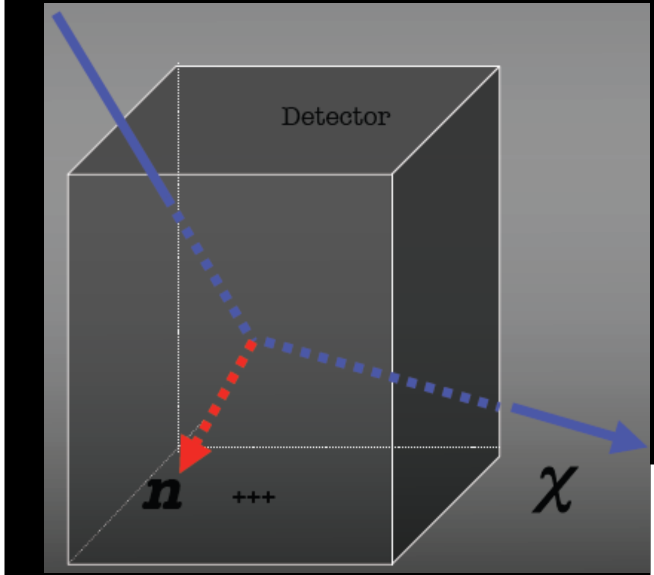
must decide by experiment!

Detecting dark matter particles

⇛ Three complementary detection strategies:

- ➢ Indirect detection
- ➢ Direct detection
- ➢ Collider experiments



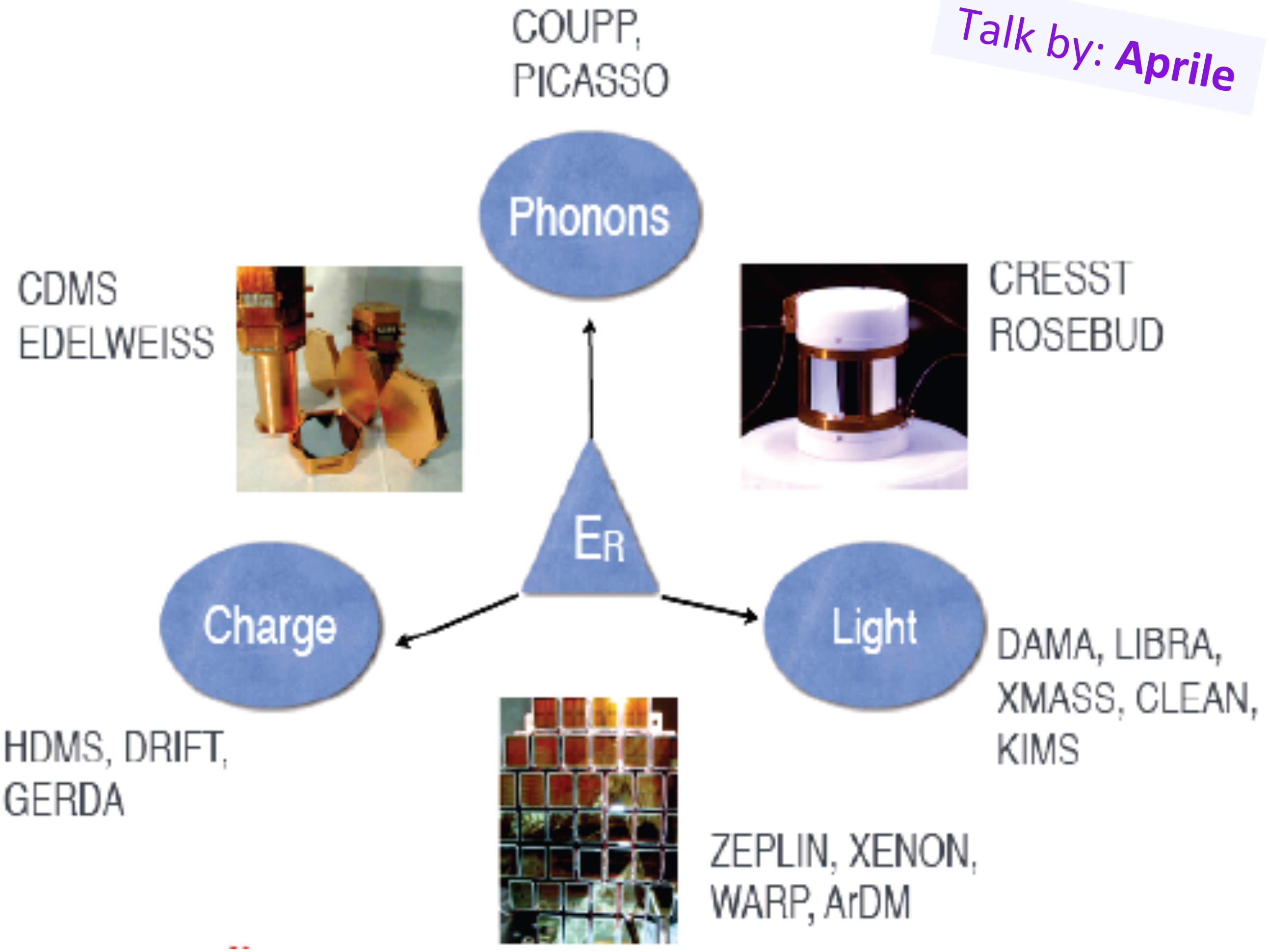


A passing dark matter particle orbiting in the Galaxy (at ~300 km/s) can scatter off a nucleus in an underground detector … the expected rate is *very* low (<< 1 event/kg/yr)

The recoil is detected via the ionization (charge), scintillation (light), and sound (phonons) ➛ heat

Experiments usually measure more than one channel to discriminate against the much bigger electron recoil background

(Very different techniques required to detect axions)



COUPP, PICASSO

CDMS EDELWEISS

CRESST ROSEBUD

HDMS, DRIFT, GERDA

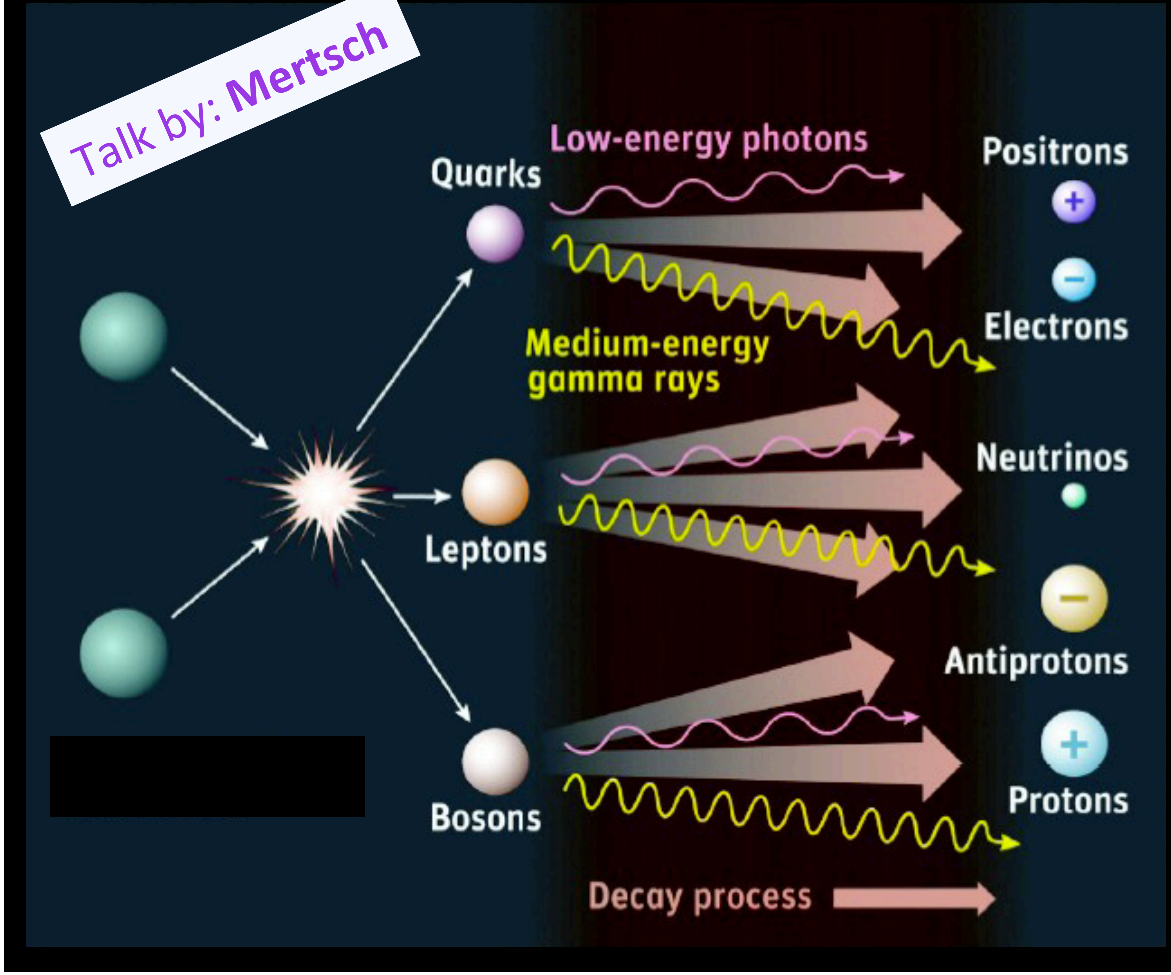
DAMA, LIBRA, XMASS, CLEAN, KIMS

ZEPLIN, XENON, WARP, ArDM

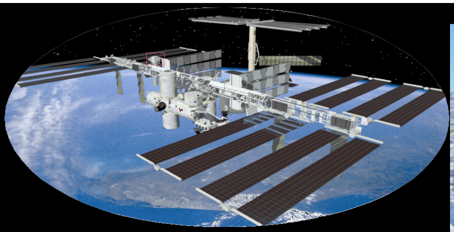
Talk by: **Aprile**

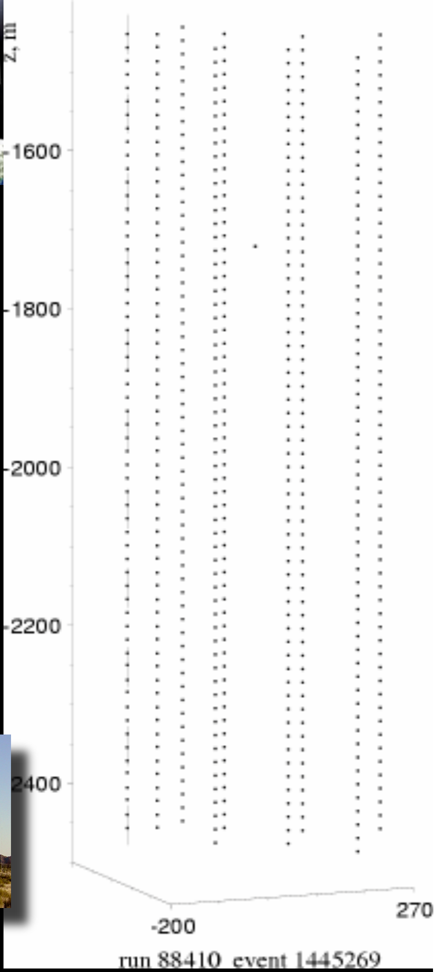
Dark matter particles in the Galaxy will occasionally annihilate (especially in dense clumps e.g. the Galactic Centre or dwarf satellite galaxies), thus generating high energy γ-rays and traces of antimatter … search with balloon/satellite-borne instruments as well as ground-based telescopes

➛ Main issue is reliable estimation of expected fluxes, as well as astrophysical backgrounds


Talk by: **Mertsch**

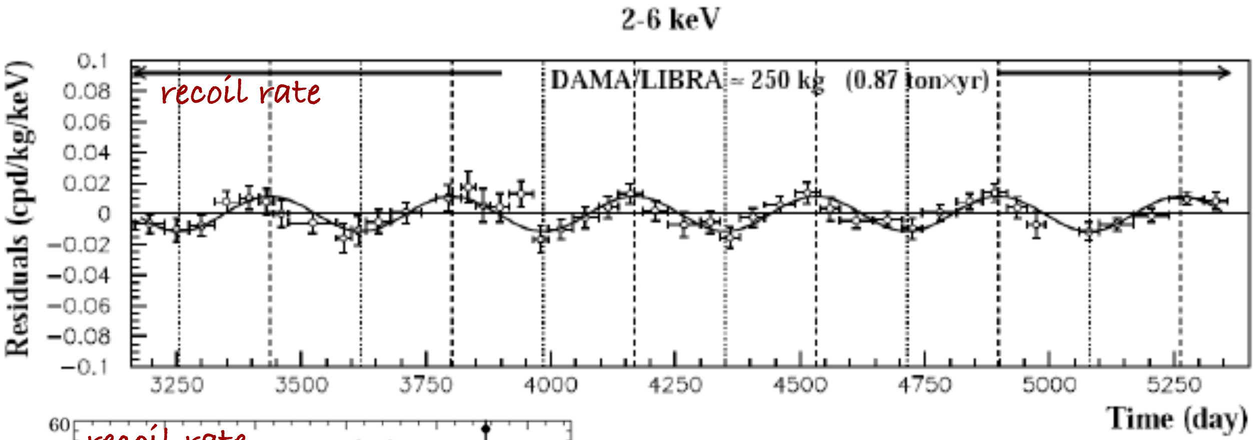
[redacted]

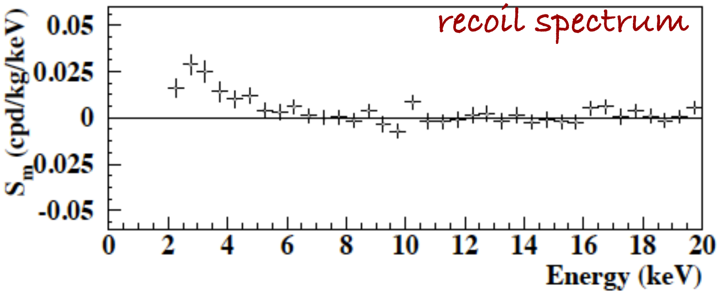




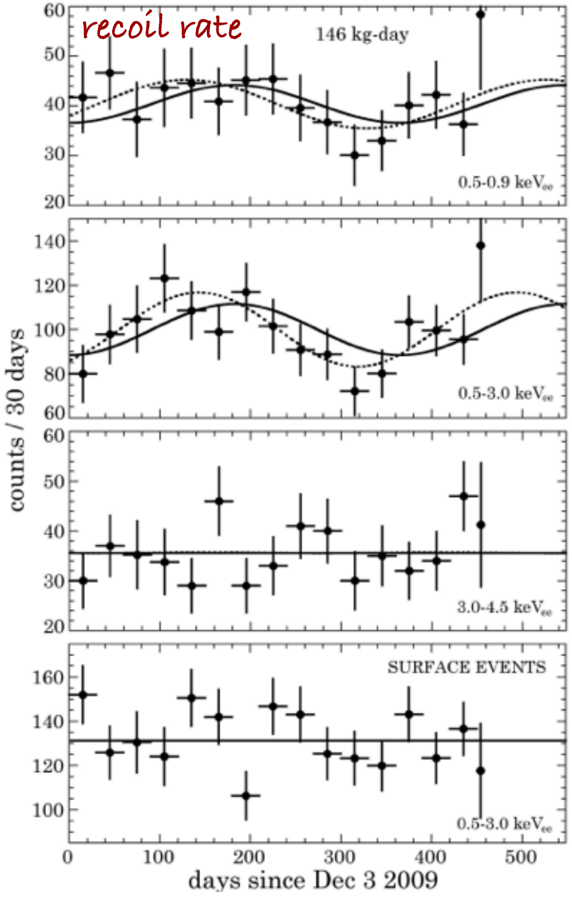
Can also look for neutrinos from annihilations of dark matter particles in e.g. the Sun or Earth

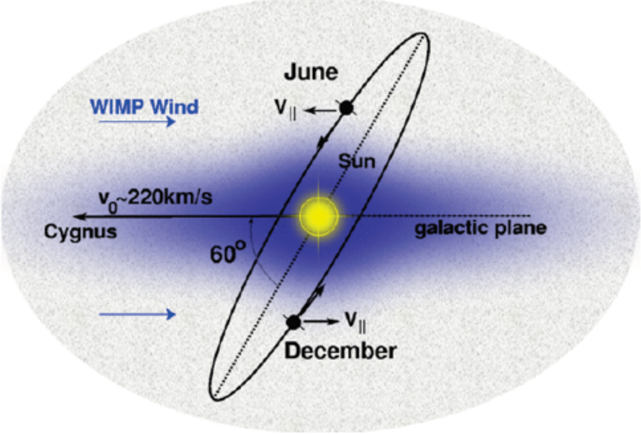
DAMA and **CoGeNT** have reported modulation signals consistent with ~5-15 GeV particles with $\sigma_{SI} \sim 10^{-40}$-$10^{-39}$ cm^2 (**CRESST** too has reported possible recoil events)





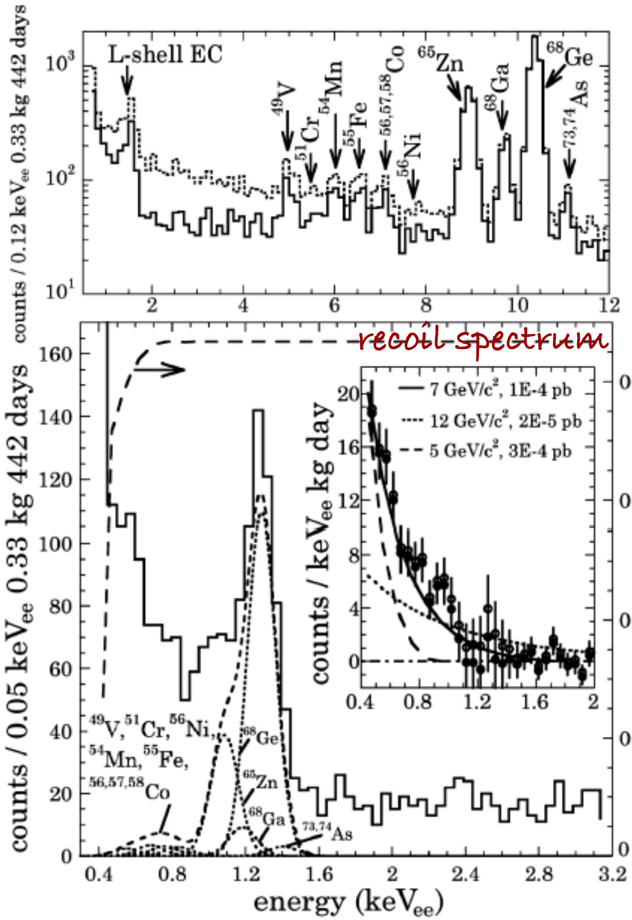
DAMA: 1002.1028





… as expected due to the Earth's motion through the DM 'wind'

However these seem to be all ruled out by stringent limits set by the CDMS and XENON expts



COGeNT: 1106.0650

However CDMS-Si [1304.4279] has detected 3 events ⇒ 8.7 GeV mass DM with $\sigma_{\rm SI} \sim 2 \times 10^{-41}$cm^2

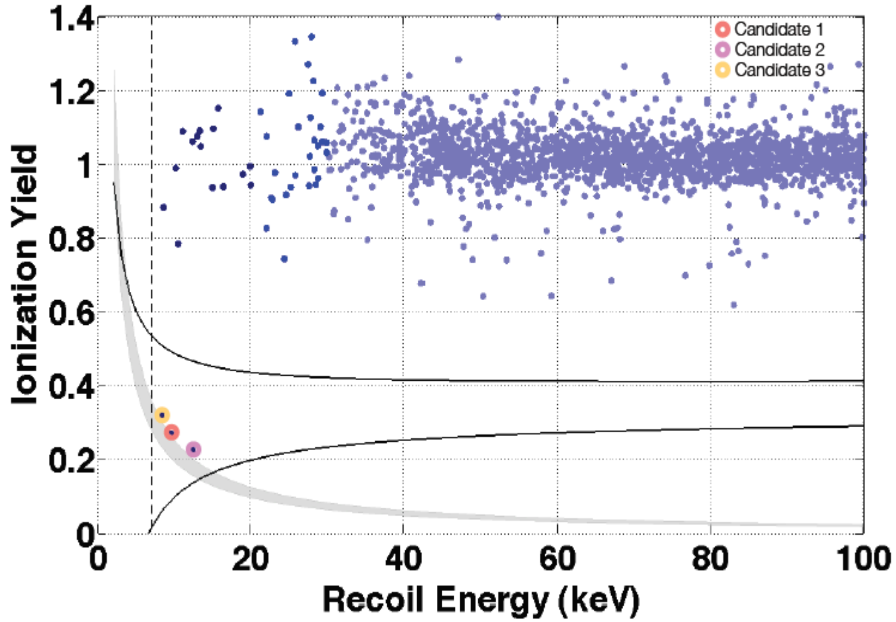
BBC NEWS

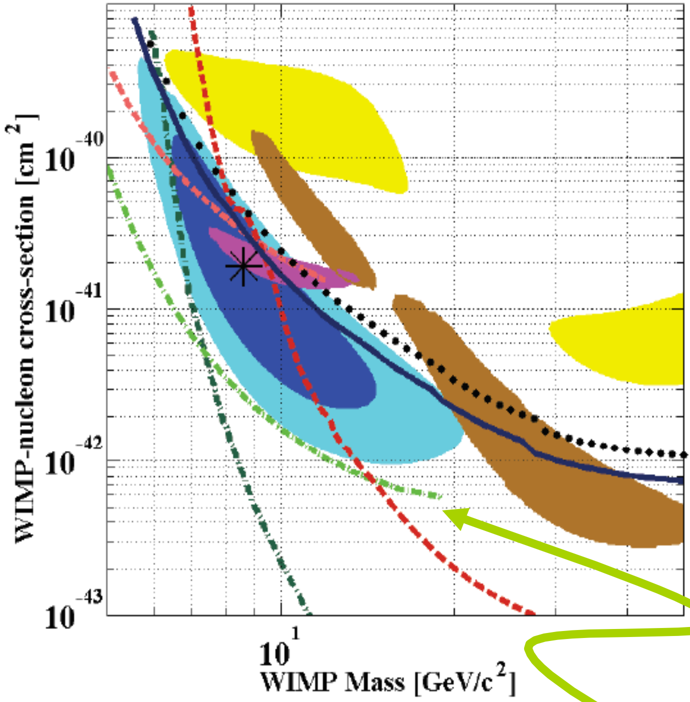
SCIENCE & ENVIRONMENT

15 April 2013 Last updated at 21:08

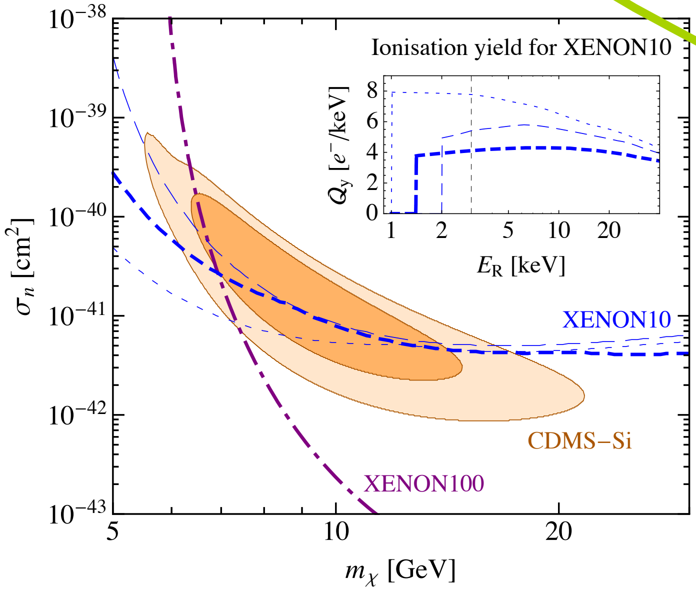
Dark matter experiment CDMS sees three tentative clues

Unblinding Results - after timing cut





- A profile likelihood analysis favors a WIMP+background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level (~3σ, p-value: 0.19%).
- We do not believe this result rises to the level of a discovery, but does call for further investigation.
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9x10^{-41}cm^2.



This limit is too stringent by a factor of ~5-10 (XENON10 erratum, 1104.3088)

Contrary to appearance, these events *are* consistent @90% CL with XENON10 (Frandsen *et al*, 1304.6066)

There are many ambiguities in interpreting the measured recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R,t) = M_{\mathrm{tar}}\frac{\rho_\chi}{2\,m_\chi\mu^2}\frac{(f_pZ+f_n(A-Z))^2}{f_n^2}\sigma_n F^2(E_R)\int_{v_{\mathrm{min}}}^{\infty}\mathrm{d}^3v\,\frac{f_{\mathrm{local}}(\vec{v},t)}{v}$$

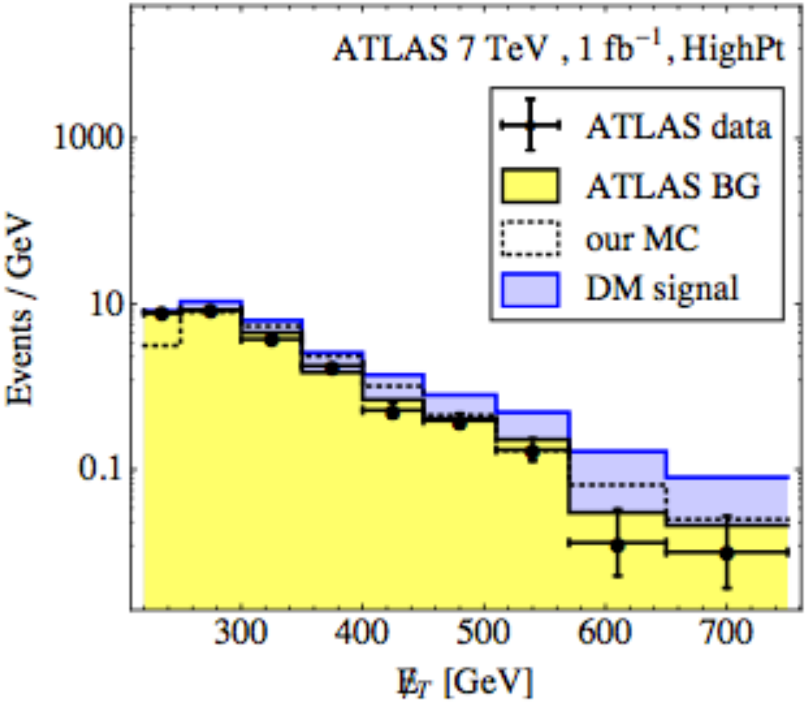
Nuclear physics

Particle physics

astrophysics

- ➢ Dark matter may *interact differently* with neutrons & protons (e.g. Frandsen *et al,* 1107.2118), or have interactions that are mainly *inelastic* or *momentum-dependent* or *spin-dependent* or even *electromagnetic* …
- ➢ Moreover different experiments are sensitive to different regions of the (uncertain) dark matter velocity distribution, hence apparently inconsistent results (e.g. CoGeNT and CRESST) can easily be reconciled by departing from the *assumed* isotropic Maxwellian form (e.g. Frandsen *et al,* 1111.0292)
- ➢ Then there are experimental uncertainties (efficiencies, energy resolution, backgrounds) as well as uncertainties in translating measured energies into recoil energies (channelling, quenching) plus nuclear form factors …

No *single* experiment can either confirm or rule out dark matter
(… also *not* a good strategy to look just under the supersymmetric lamp post!)



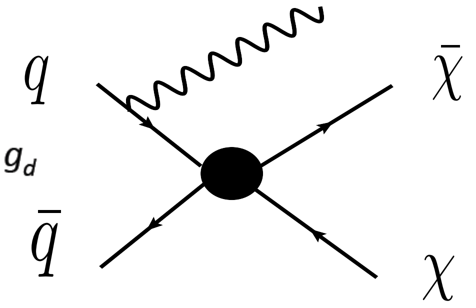
'Monojet' events at colliders directly measure the coupling of dark matter to SM,

e.g. $\mathcal{L}^{\text{eff}}_{\chi} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$

→ $\sigma_p^{\text{SI}} = \frac{f^2\mu_{\chi n}^2}{\pi\Lambda^4}$, where $f = 3$ for $g_u = g_d$

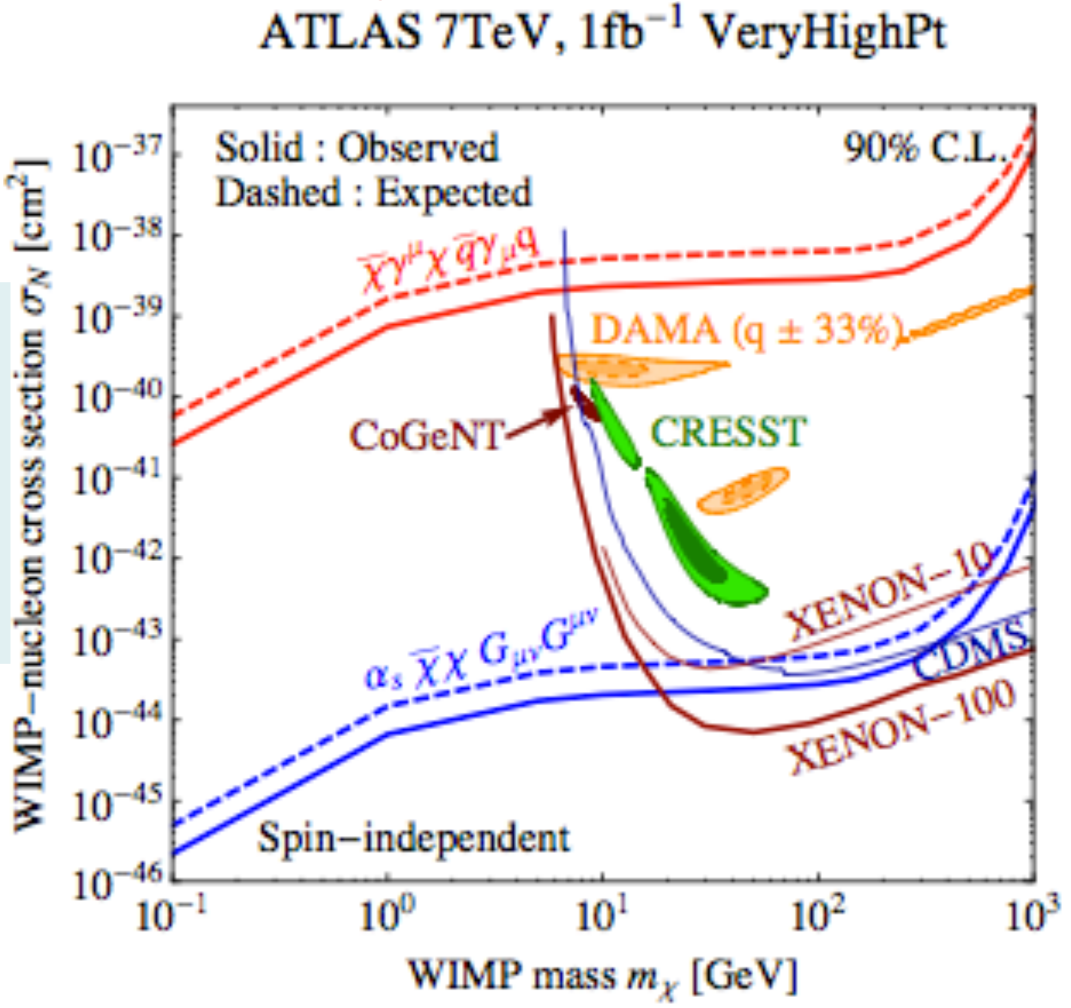
$\Lambda = m_R/\sqrt{g_q g_\chi}$

→ $\sigma\,(j + \text{MET}) \sim 1/\Lambda^4 \sim \sigma_p$

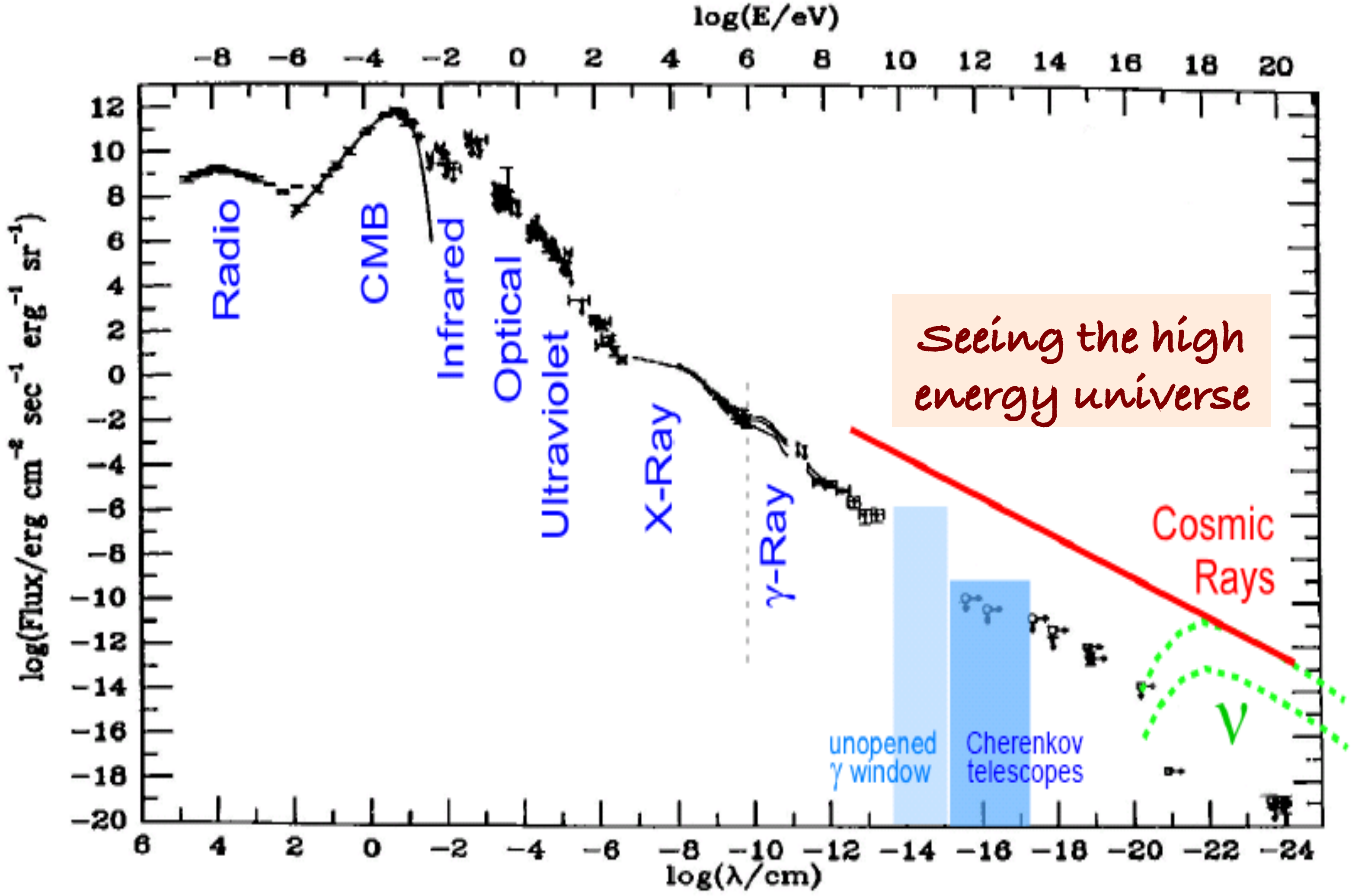


However these bounds require the scale Λ of the effective operator to exceed ~0.7 TeV, while perturbative unitarity requires g_q, $g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV … so for higher energy collisions *cannot* rely on effective operator description (Fox *et al* 1203.1662)

For scalar-mediated processes, heavy quark loops can significantly enhance the monojet cross-section (Haisch, Kahlhoefer, Unwin, 1208.4605) – sensitive probe!



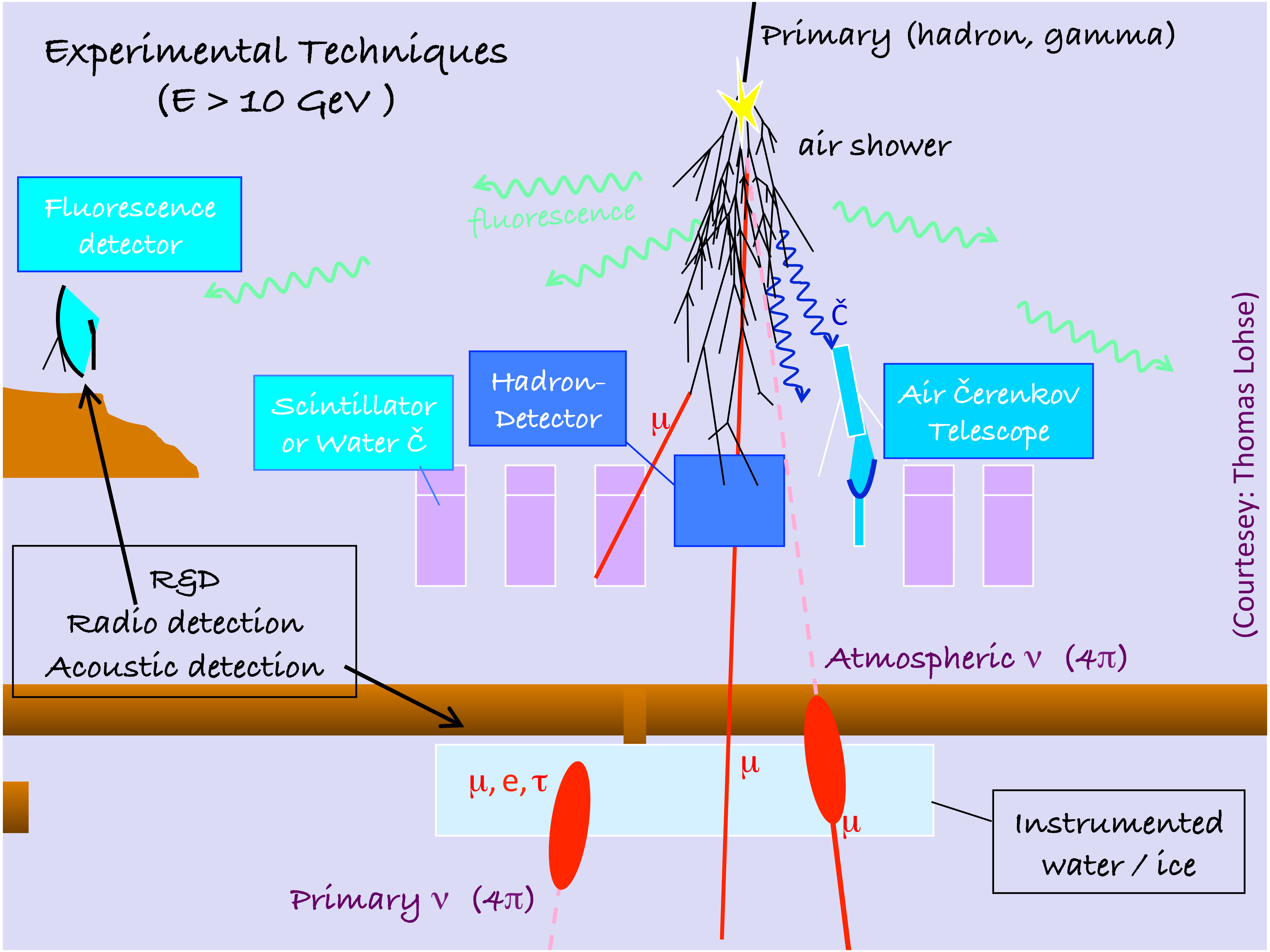
We can *see* the universe directly with **photons** up to a few TeV … beyond this they are attenuated, $\gamma\gamma \rightarrow e^{+}e^{-}$, on the CIB/CMB



Using cosmic rays we should be able to 'see' up to ~6 x10^{10} GeV (before they get attenuated by $p\gamma \rightarrow \Delta^{+} \rightarrow n\pi^{+}, p\pi^{0}$, on the CMB)

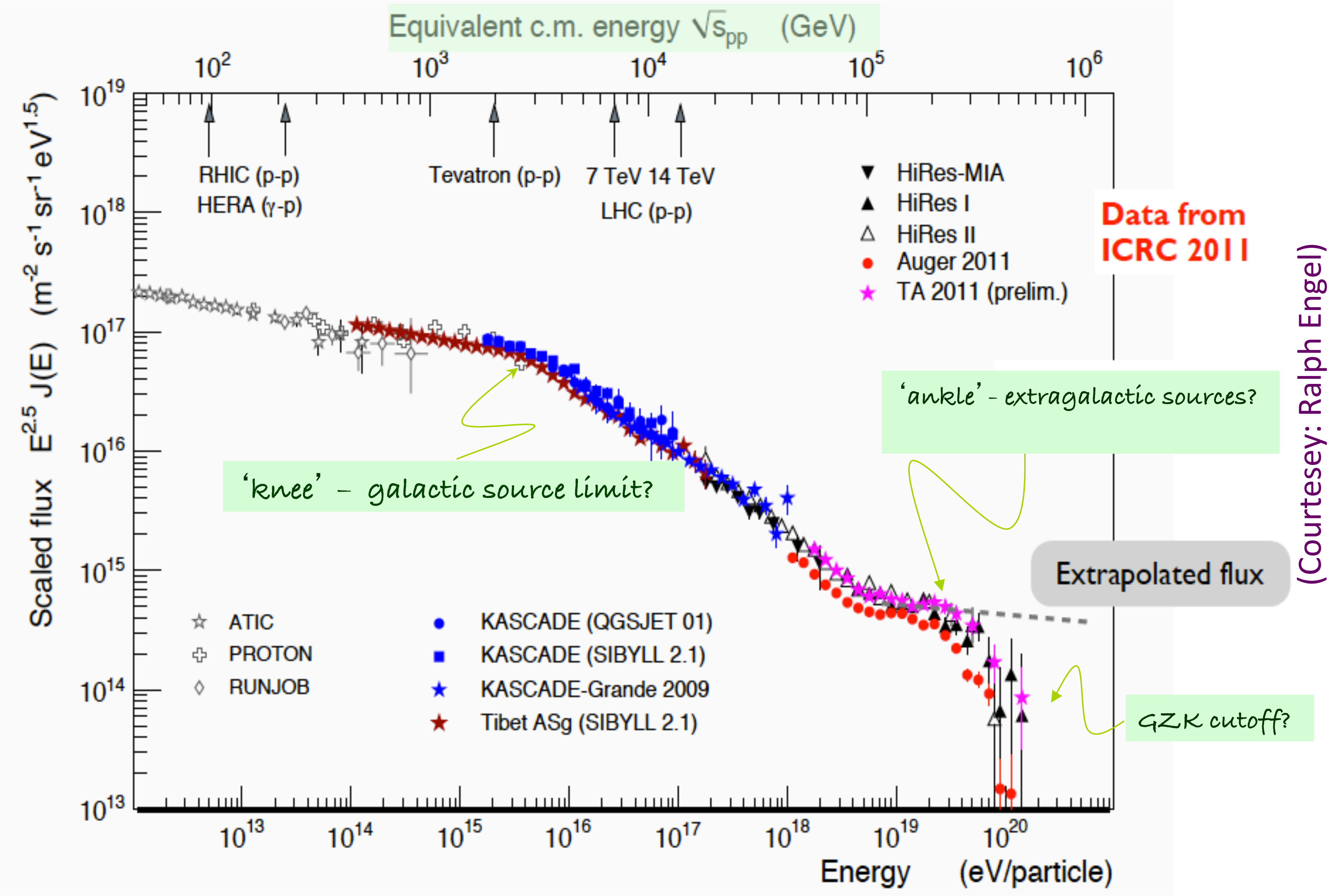
… and the universe is transparent to **neutrinos** at nearly *all* energies

Experimental Techniques
(E > 10 GeV)



(Courtesey: Thomas Lohse)

By studying cosmic ray (p, γ, ν) interactions, we can probe cms energies up to *O*(100) TeV … well beyond the reach of terrestrial accelerators



Data from ICRC 2011

'knee' – galactic source limit?

'ankle' – extragalactic sources?

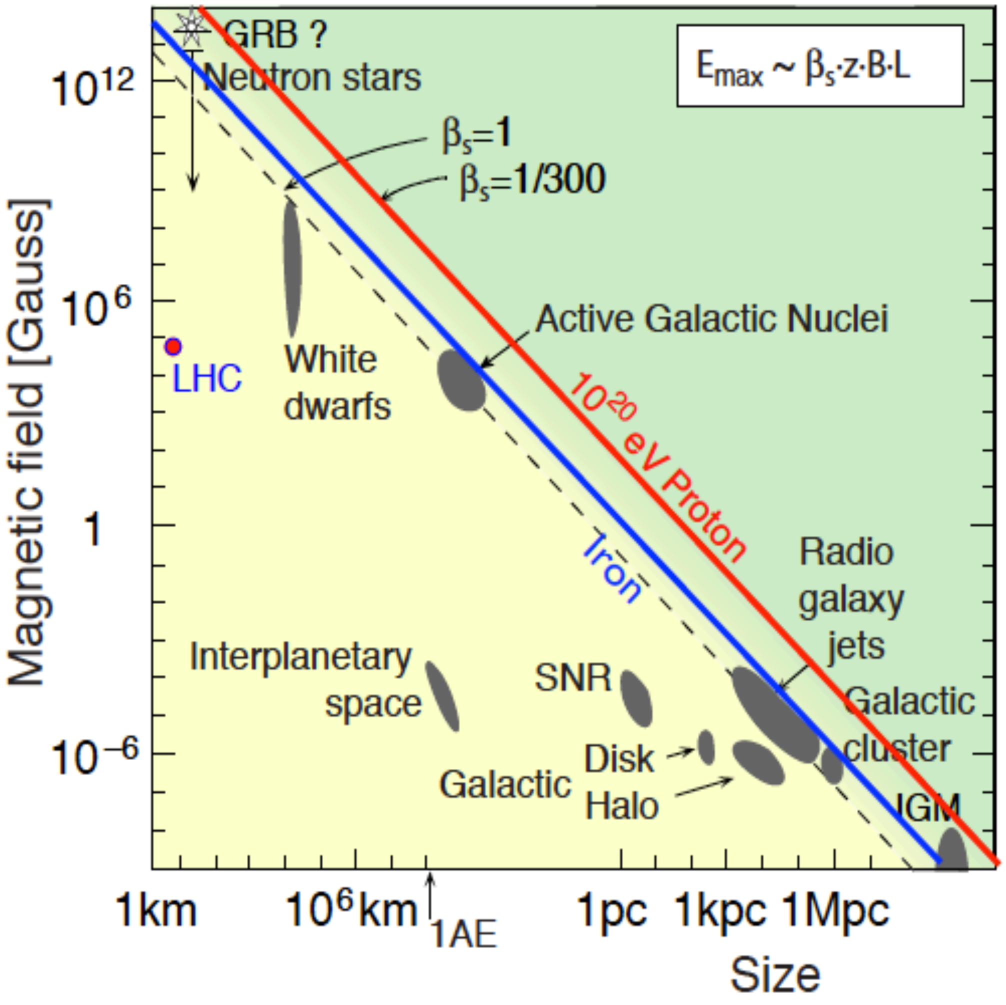
Extrapolated flux

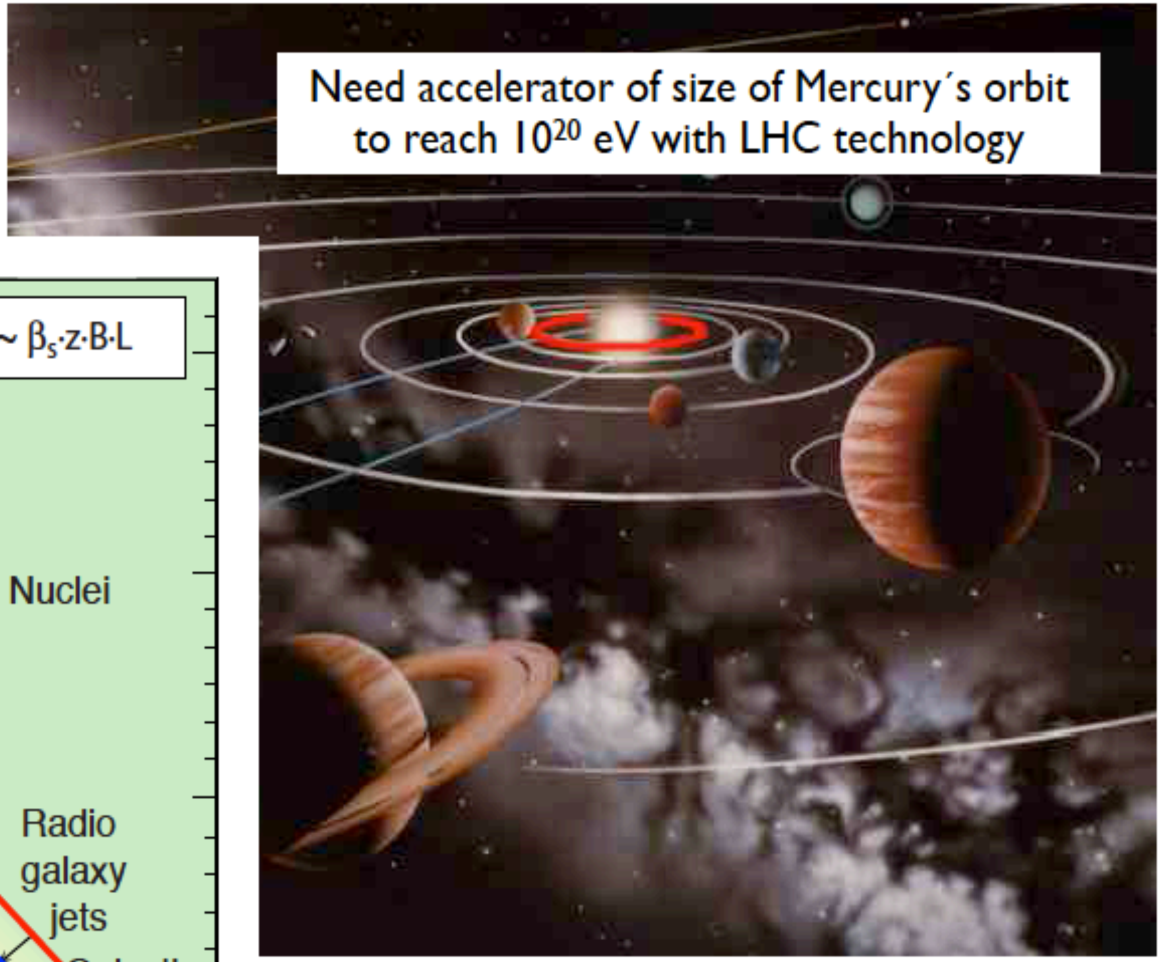
GZK cutoff?

(Courtesey: Ralph Engel)

How does Nature manage to accelerate particles to ~ZeV energies?

Hillas plot (1984)



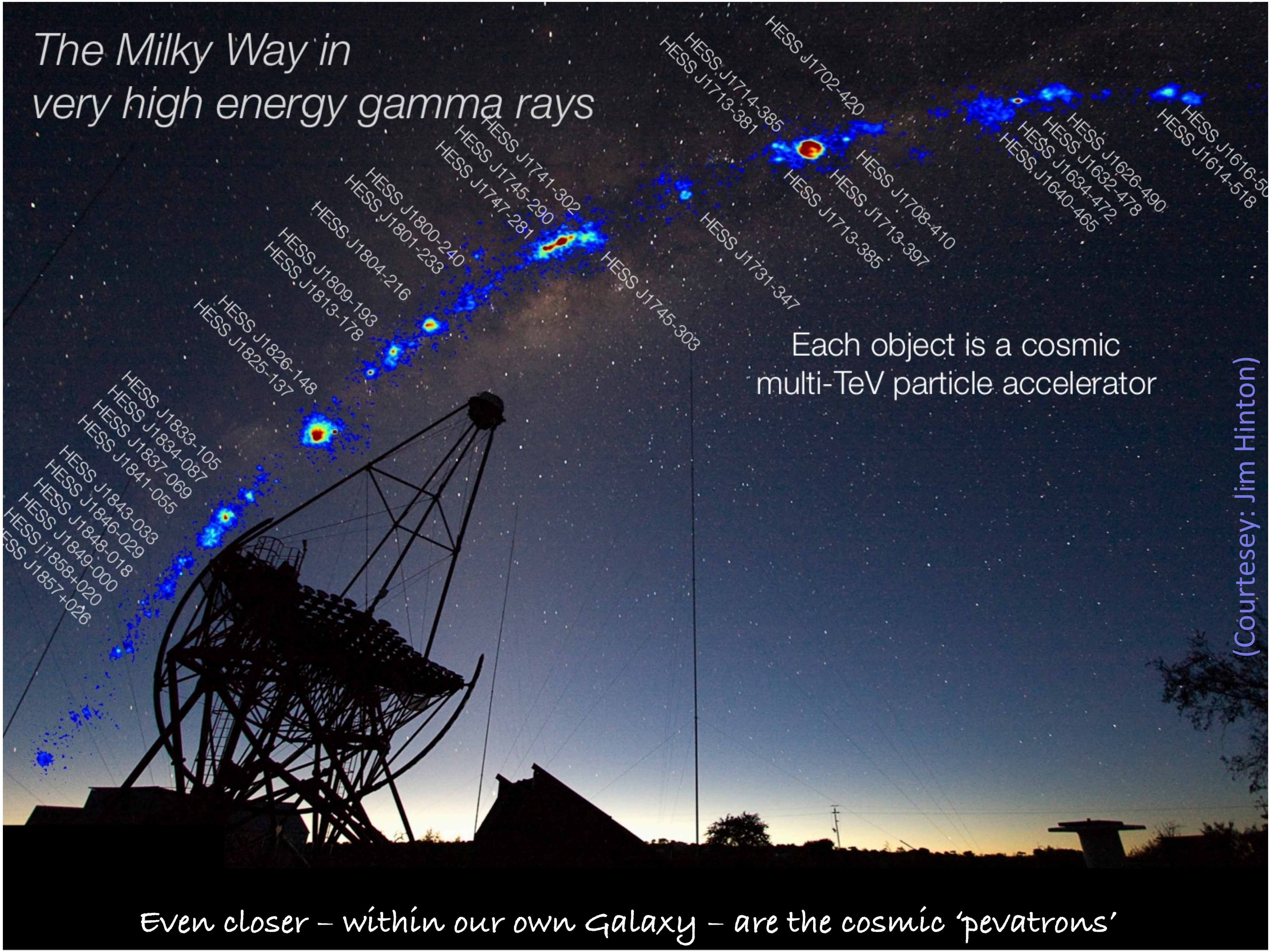


Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

(Courtesey: Ralph Engel)



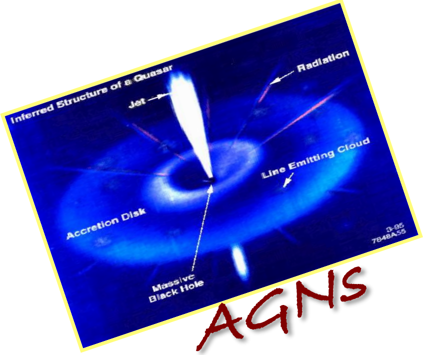
The Milky Way in very high energy gamma rays

Each object is a cosmic multi-TeV particle accelerator

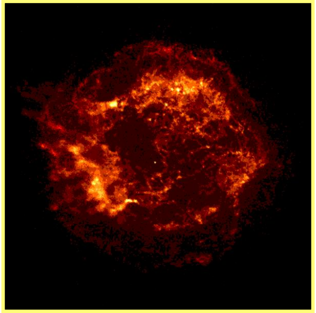
(Courtesey: Jim Hinton)

Even closer – within our own Galaxy – are the cosmic 'pevatrons'

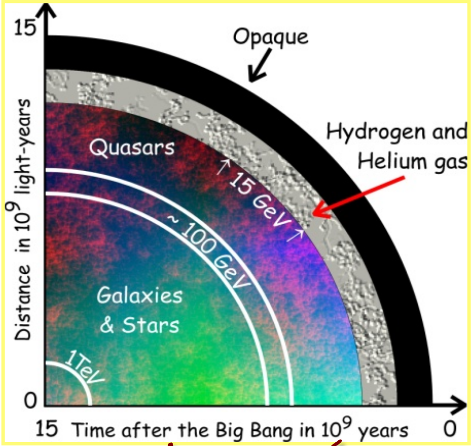
What can the TeV γ-ray window probe?



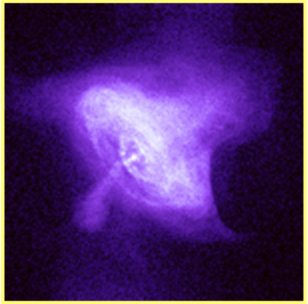
AGNs



SNRs



Cosmology (EBL)



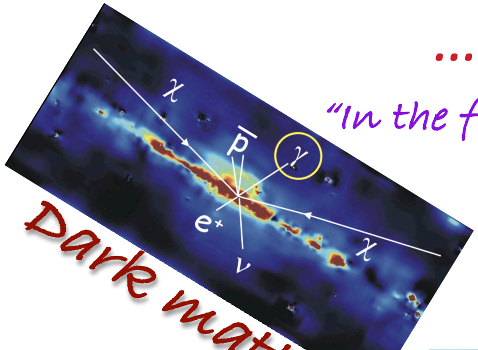
Pulsars & PWN

GRBs

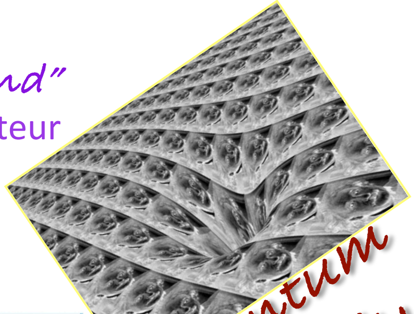
… and let us not forget: the ***unknown****!*

"In the fields of observation chance favors only the prepared mind"

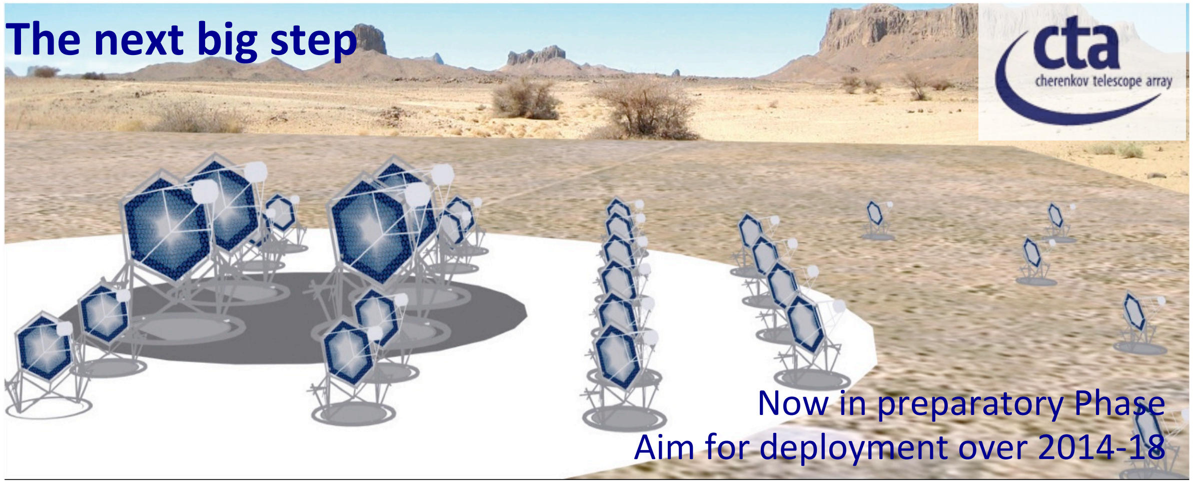
Louis Pasteur



Dark matter



quantum gravity

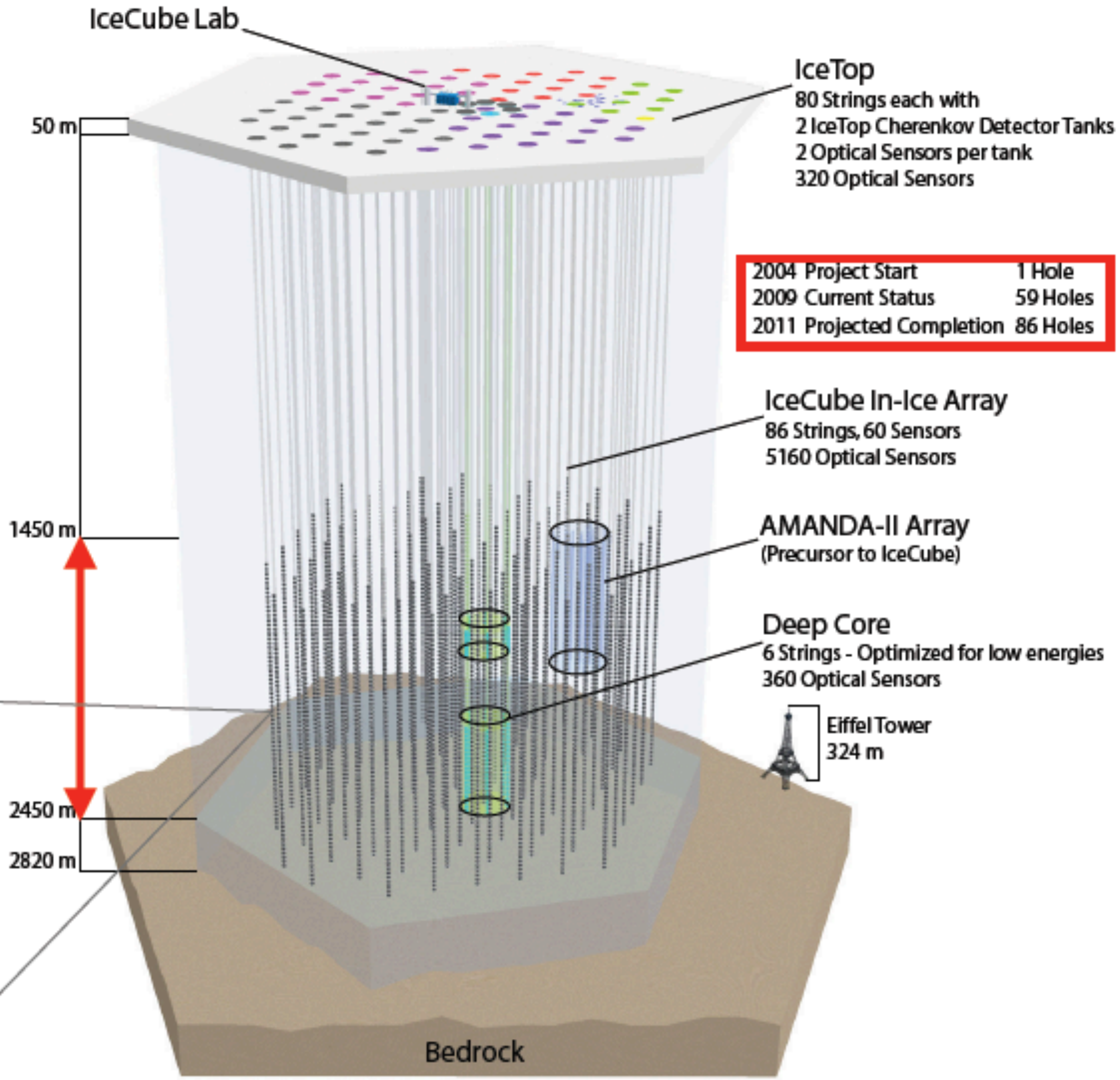


The next big step

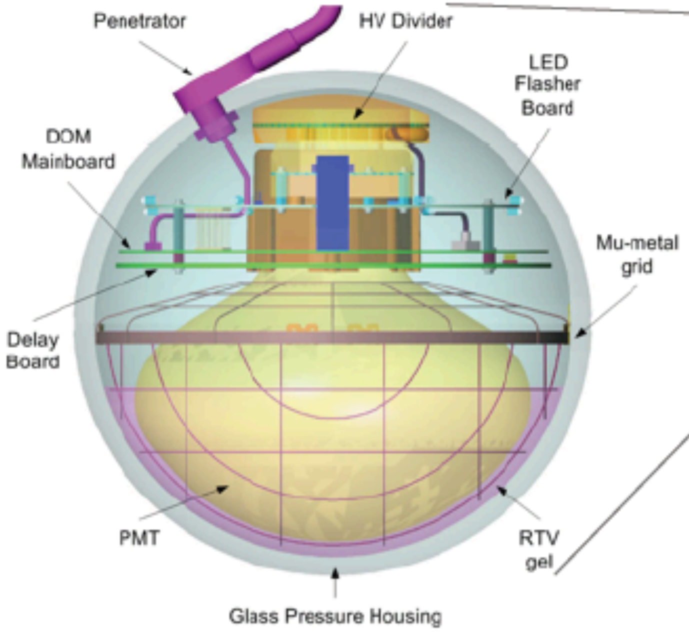
Now in preparatory Phase
Aim for deployment over 2014-18

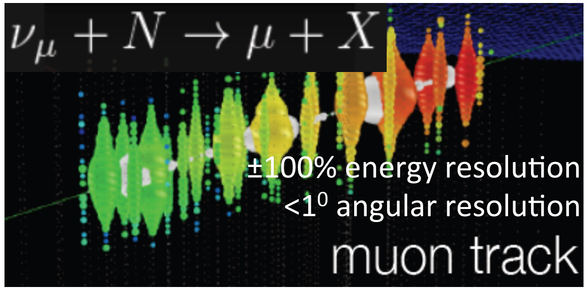
IceCube Observatory

- 86 strings
- 5160 DOMs
- 17 m vertical spacing
- 125 m between strings



Digital Optical Module - DOM



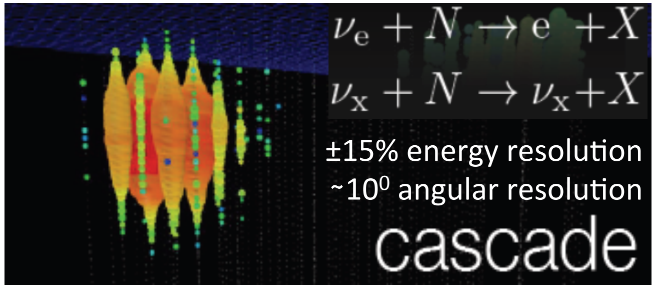


$\nu_\mu + N \rightarrow \mu + X$

±100% energy resolution

<1^0 angular resolution

muon track



$\nu_e + N \rightarrow e + X$

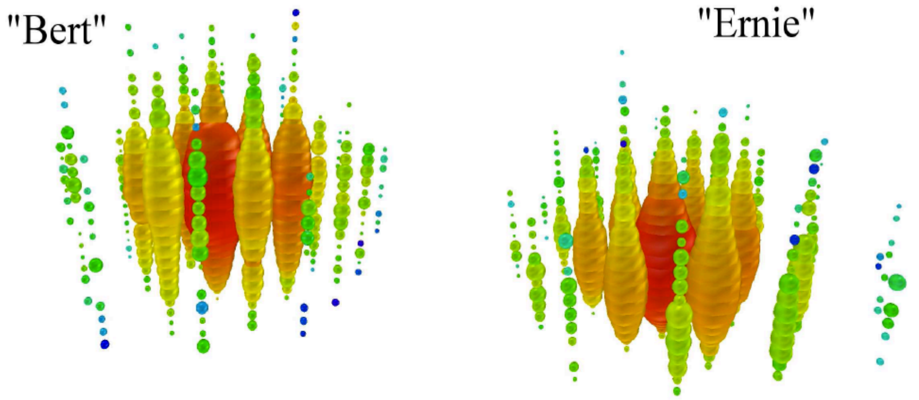
$\nu_x + N \rightarrow \nu_x + X$

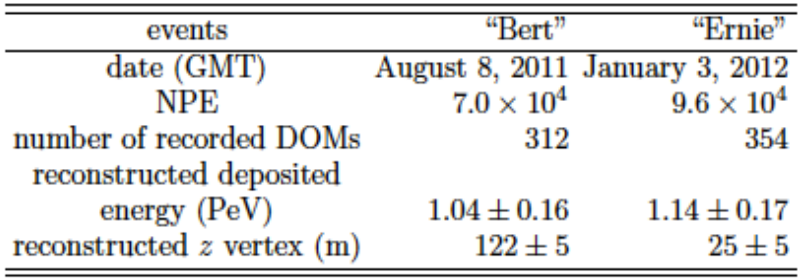
±15% energy resolution

~10^0 angular resolution

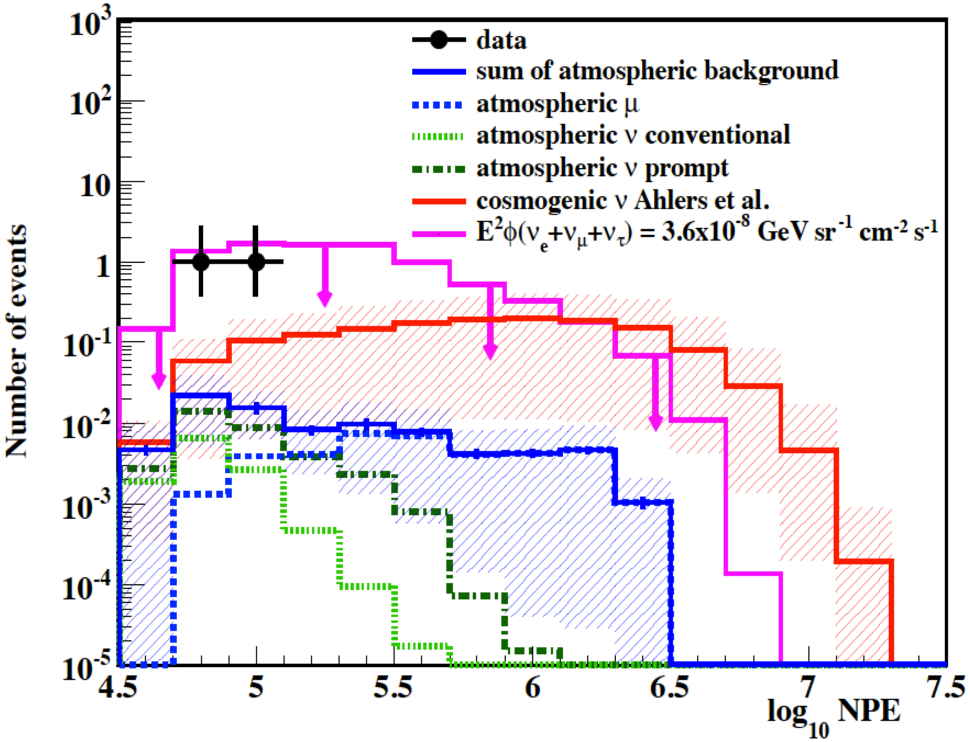
cascade

First observation of PeV-energy neutrinos with IceCube [1304.5356]

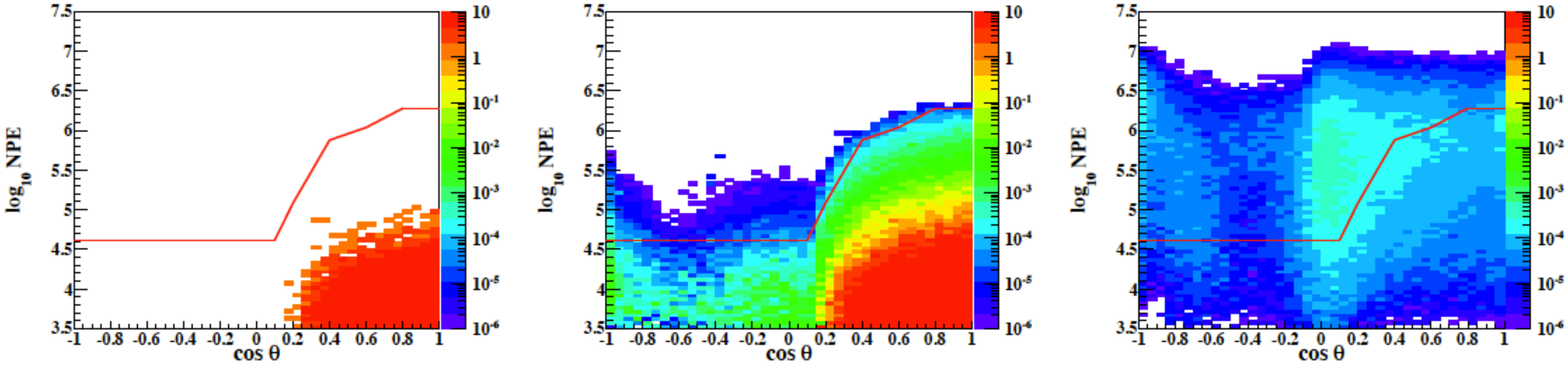




events	“Bert”	“Ernie”
date (GMT)	August 8, 2011	January 3, 2012
NPE	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed deposited energy (PeV)	1.04 ± 0.16	1.14 ± 0.17
reconstructed z vertex (m)	122 ± 5	25 ± 5



Expected atmospheric neutrino background: 0.082 ± 0.004 ± 0.05 ⇒ *p*-value: 2.9×10^{-3} (2.8σ)



ET

Auger N

CTA

KM3NeT

ASPERA

1 ton DM

1 ton NM

Megaton NNN

Common with Astrophysics

ASTRONET

Common with Particle Physics

CERN

CERN Strategy Group

(Courtesey: Stavros Katsanevas)

The European Strategy for Particle Physics

Prepared for the special European Strategy Session of Council in Brussels on 30 May 2013

A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.*

Summary

Astroparticle physics addresses some of the most fundamental and interesting questions concerning the universe … to find the answers will require a new generation of ambitious experiments and a *global* effort

> *"The only true voyage of discovery, the only fountain of Eternal Youth, would be not to visit strange lands but to possess other eyes, to behold the universe through the eyes of another, of a hundred others, to behold the hundred universes that each of them beholds, that each of them is."*
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> Marcel Proust (*La Prisonnière, À la recherche du temps perdu*, 1923)