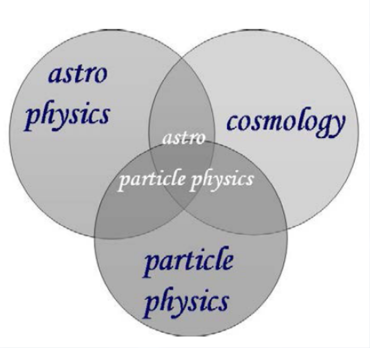
Astroparticle physics:
Connecting inner space & outer space

Subir Sarkar

University of Oxford
&
Niels Bohr Institute, Copenhagen



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)

ASPERA ad futurum, Brussels, 30 November 2012

Per Carlson (Physics Today, Feb 2012)

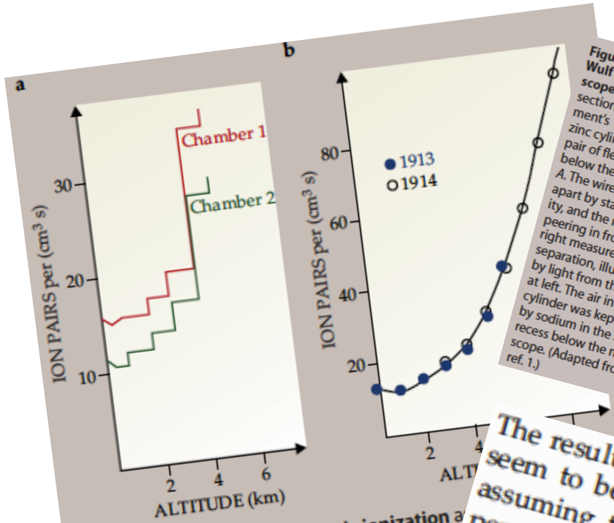
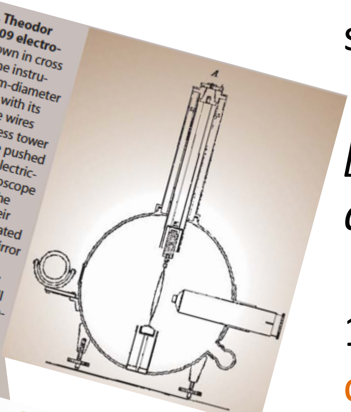


Figure 3. The rate of atmospheric ionization a as measured **(a)** by Victor Hess on 7 August 191 Kolhörster in 1913. (Adapted from ref. 2.)

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

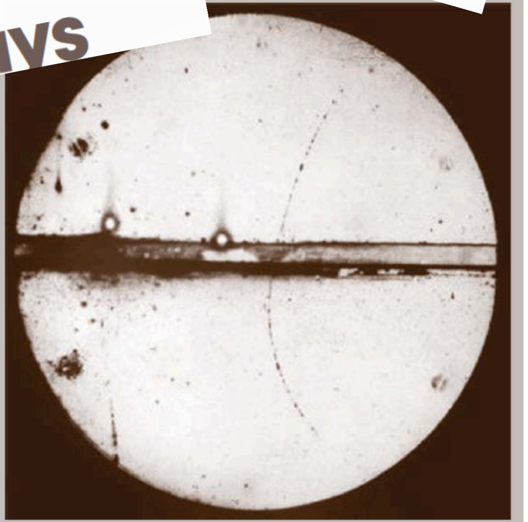


Figure 4. A historic cloud-chamber photograph taken by Carl Anderson in 1932 shows a positive particle, presumably from a cosmic-ray shower, entering from the top, curving in the chamber's transverse magnetic field, and losing energy in the lead plate. After traversing the plate, the track is much too 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 CTR Wilson - **Nobel Prize 1927**)*

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

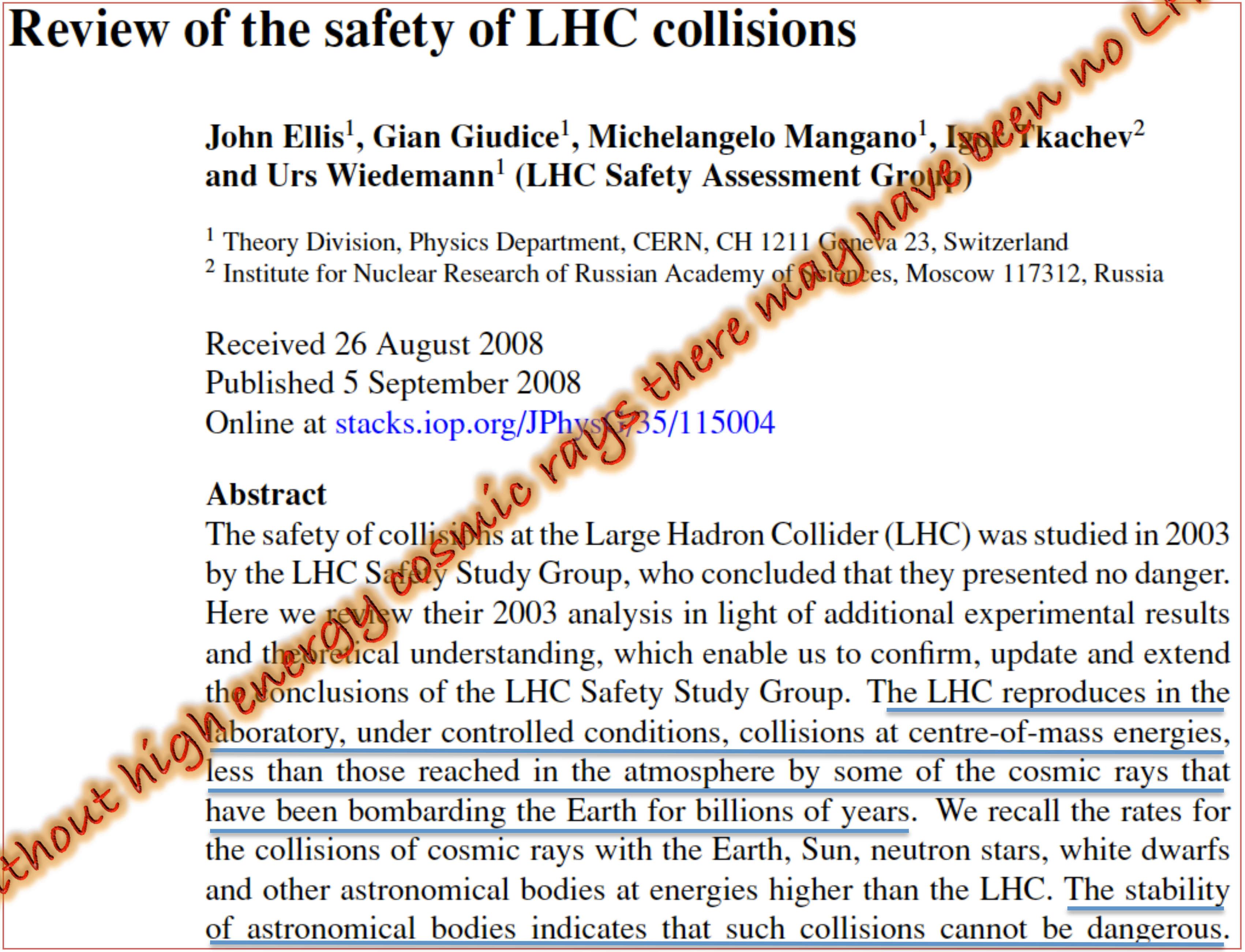
1937: Seth Neddermeyer & Carl Anderson discover the muon in cosmic rays

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

1947: George Rochester & Clifford Butler discover the kaon

*(Patrick Maynard Stuart Blackett awarded **Nobel Prize 1948** "for his development of the Wilson cloud chamber method and his discoveries therewith in the fields of nuclear physics & cosmic radiation")*

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)

[1] Theory Division, Physics Department, CERN, CH 1211 Geneva 23, Switzerland
[2] Institute for Nuclear Research of Russian Academy of Sciences, Moscow 117312, Russia

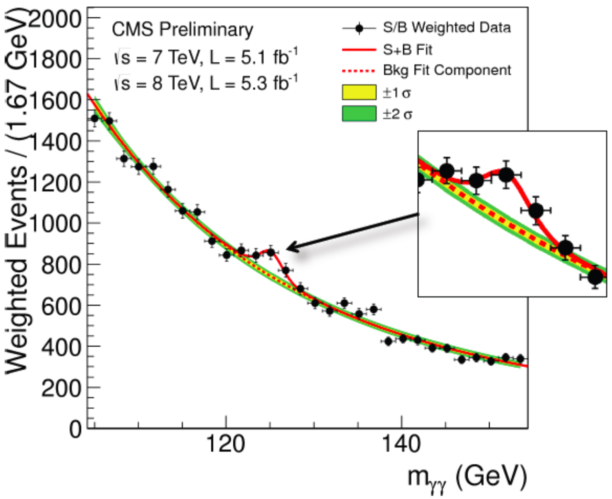
Received 26 August 2008
Published 5 September 2008
Online at stacks.iop.org/JPhysG/35/115004

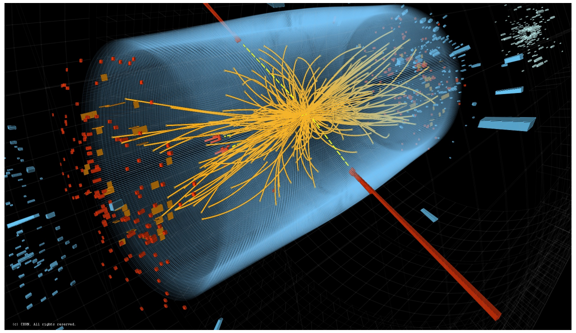
Abstract

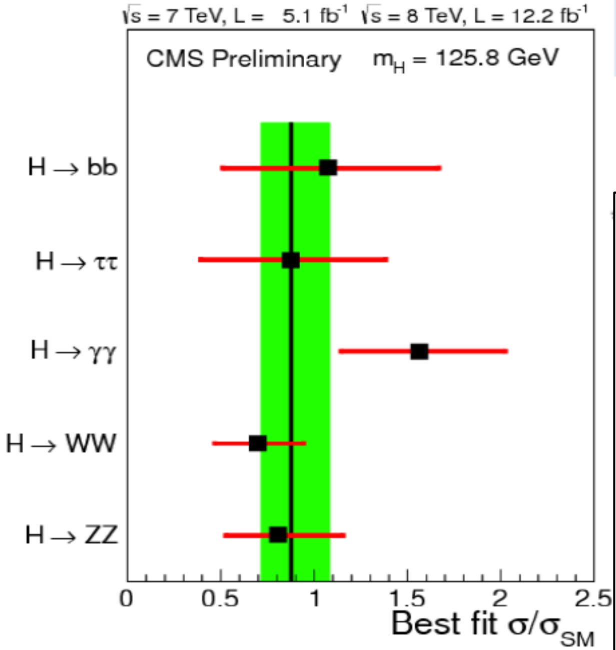
The safety of collisions at the Large Hadron Collider (LHC) was studied in 2003 by the LHC Safety Study Group, who concluded that they presented no danger. Here we review their 2003 analysis in light of additional experimental results and theoretical understanding, which enable us to confirm, update 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.

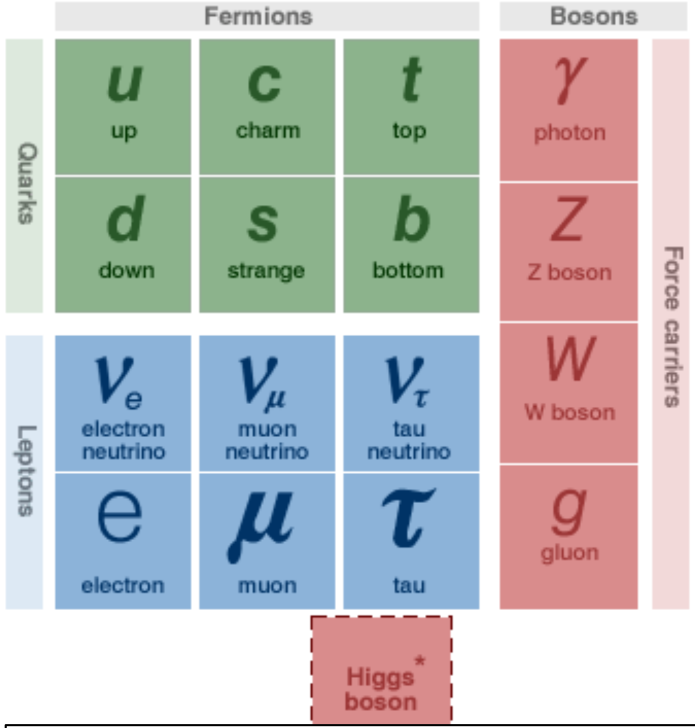
... without high energy cosmic rays there may have been no LHC!

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



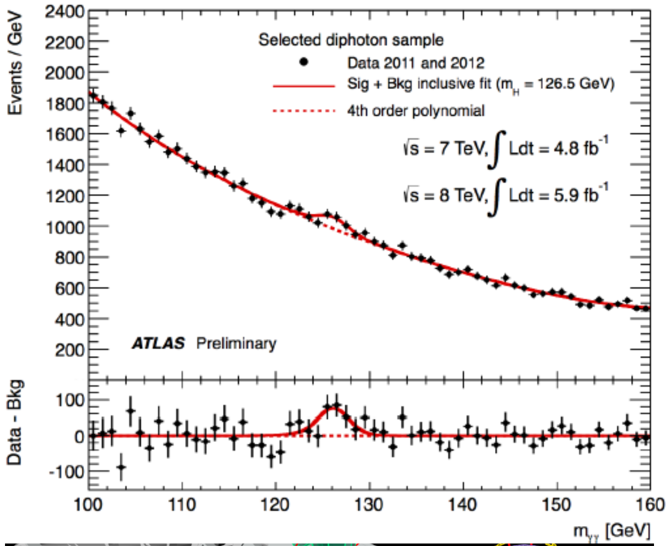


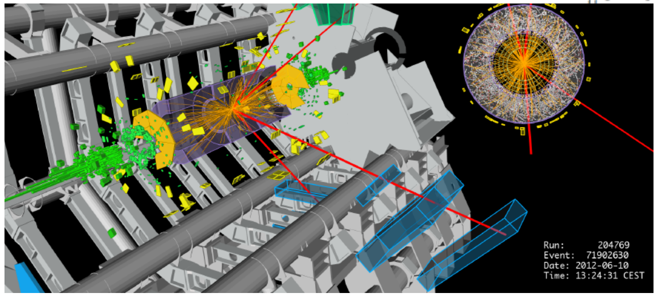


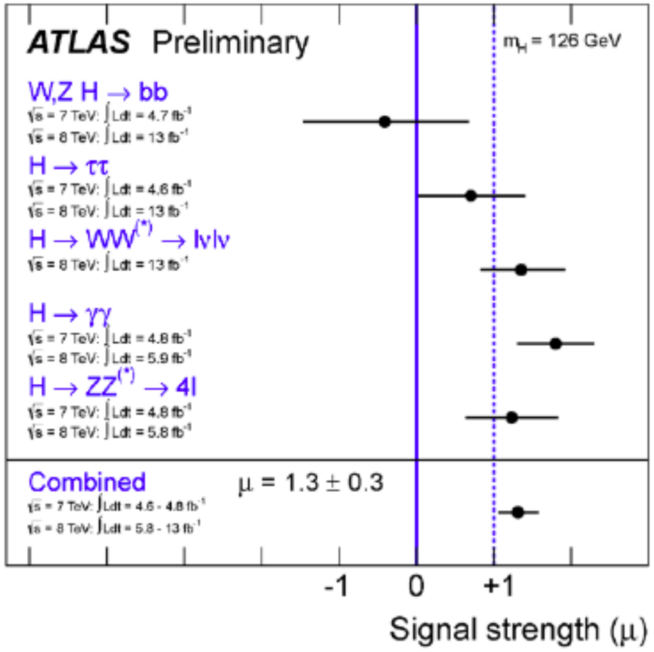


	Fermions			Bosons	
Quarks	**u** up	**c** charm	**t** top	**γ** photon	Force carriers
	d down	**s** strange	**b** bottom	**Z** Z boson	
Leptons	**ν_e** electron neutrino	**ν_μ** muon neutrino	**ν_τ** tau neutrino	**W** W boson	
	e electron	**μ** muon	**τ** tau	**g** gluon	

Higgs boson*







The triumph of the Standard Model ...

the Higgs boson is found!

The **Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model** provides an exact description of all *microphysics* (upto some cut-off M, when viewed as an effective field theory)

cosmological constant

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

Higgs mass divergence

super-renormalisable

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

renormalisable

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

non-renormalisable

neutrino mass

proton decay

New physics beyond the SM ⇒ **non-renormalisable operators** suppressed by M^n which 'decouple' as $M \to M_P$ (so **neutrino mass** is small, **proton decay** is slow ...)

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

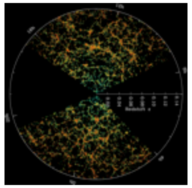
This provides possibilities for to baryogenesis as well as a candidate for **dark matter** – the lightest supersymmetric particle (typically the **neutralino** χ), if protected against decay by a conserved R-parity

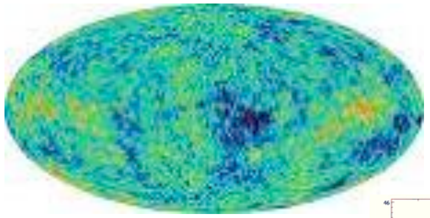
(But if the Higgs is composite as in **technicolour** models of $SU(2)_L \times U(1)_Y$ breaking then there is no need for supersymmetry ... and the lightest TC state can be dark matter)

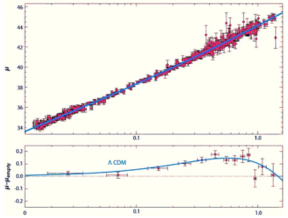
But the biggest 'fine tuning' problem arises when the SM is coupled to (classical) gravity ... because then the vacuum (dark) energy would be 10^{60} times bigger than is acceptable!

The world is indeed a strange place!

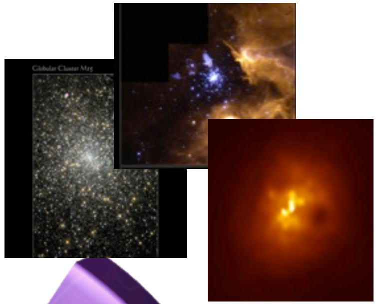
Mainly geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is inferred
from the 'cosmic sum rule':
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$

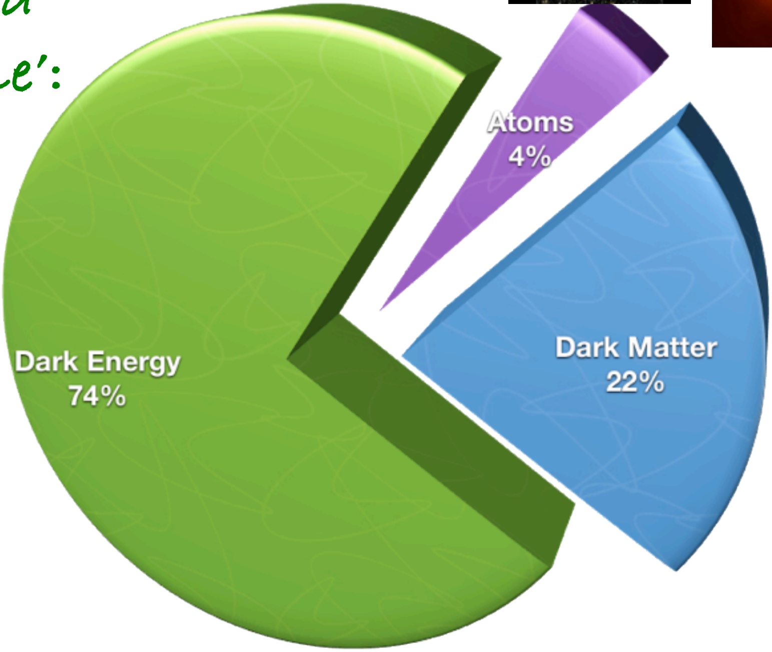




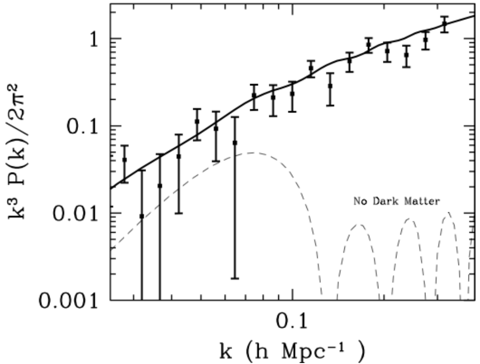


Baryons (but no antibaryons) …

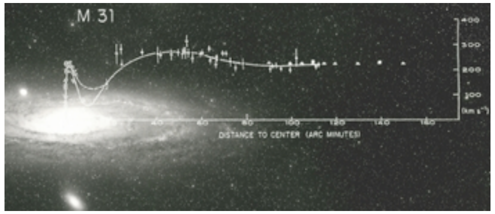


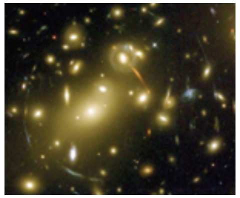


Both geometrical and dynamical evidence (if GR is valid on all scales)

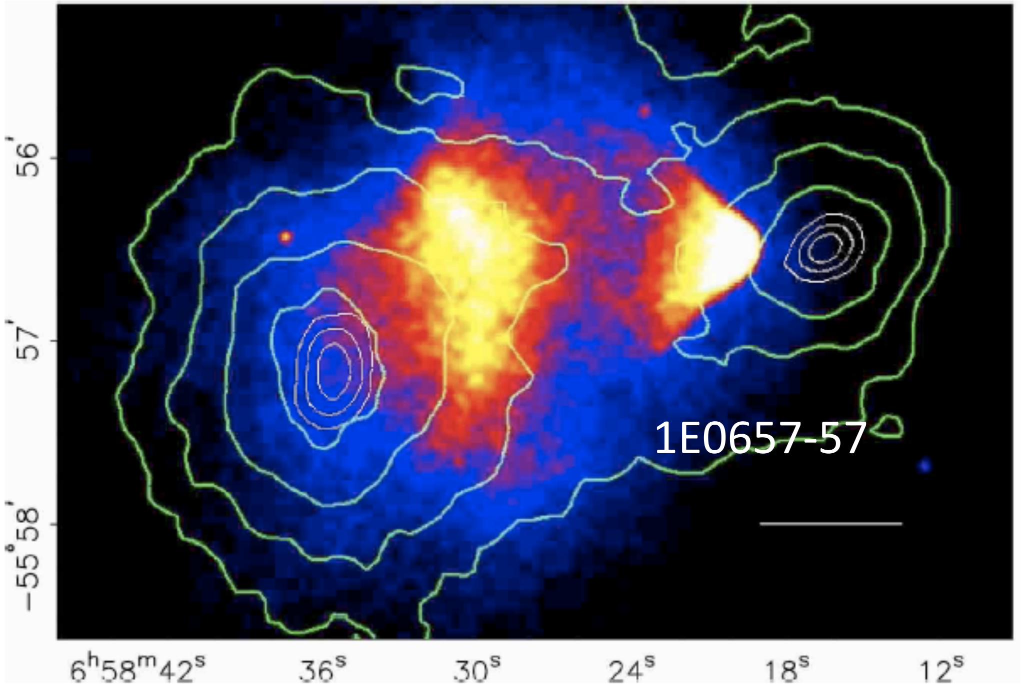


Both the baryon asymmetry and dark matter require new physics beyond the Standard $SU(3)_c\text{x}SU(2)_L\text{x}U(1)_Y$ Model of particle physics
… dark energy is even more mysterious (but as yet lacks compelling dynamical evidence)





Is dark matter really ~non-interacting?



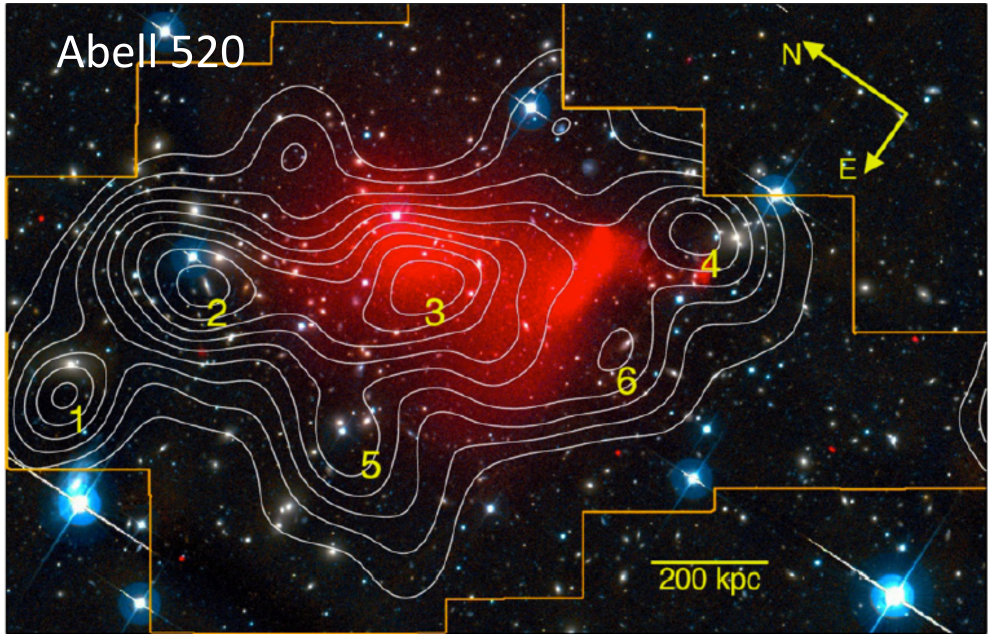
The 'Bullet Cluster' is often quoted as strong evidence for **collisionless dark matter** - in fact it sets a rather weak limit on self-interactions: $\sigma \lesssim 2\text{x}10^{-24}$ cm^2/GeV

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

Nine other such colliding clusters have been found … what are the odds of that?

In Abell 520, the dark core is coincident with the X-ray emitting gas implying that DM interacts with itself: $\sigma \approx (7 \pm 2) \times 10^{-24}$ cm^2/GeV

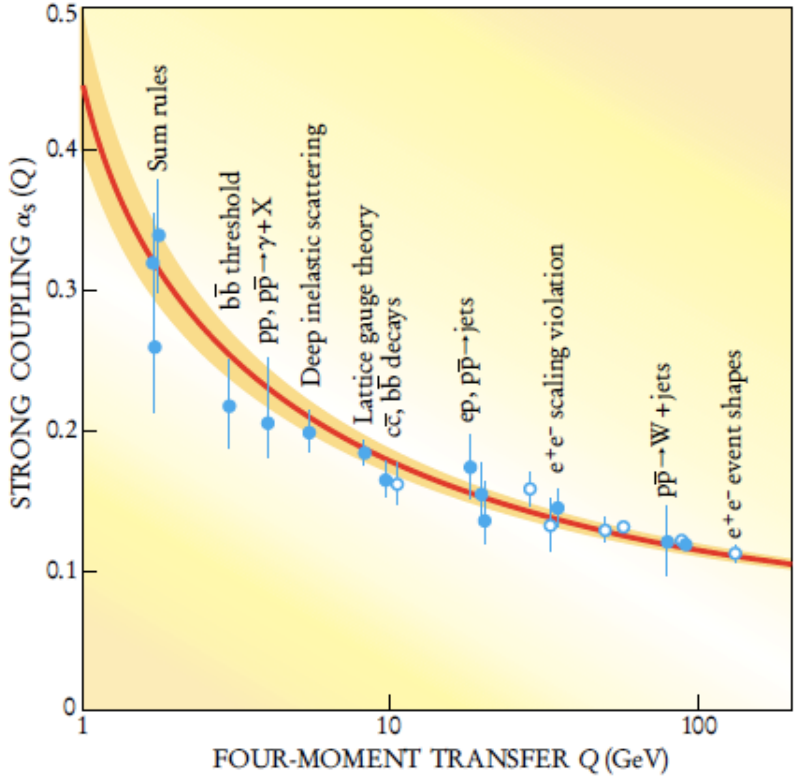
This result is contested … the implications for structure formation are currently under study through both galactic dynamics studies and computer simulations

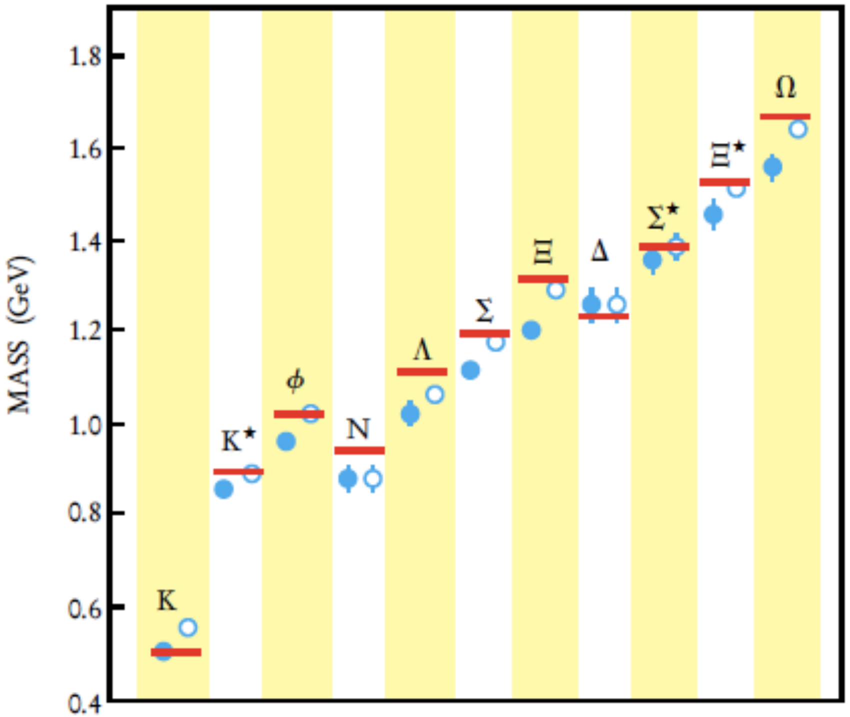


What should the world be made of?

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 theory – QCD - for why baryons are massive and stable



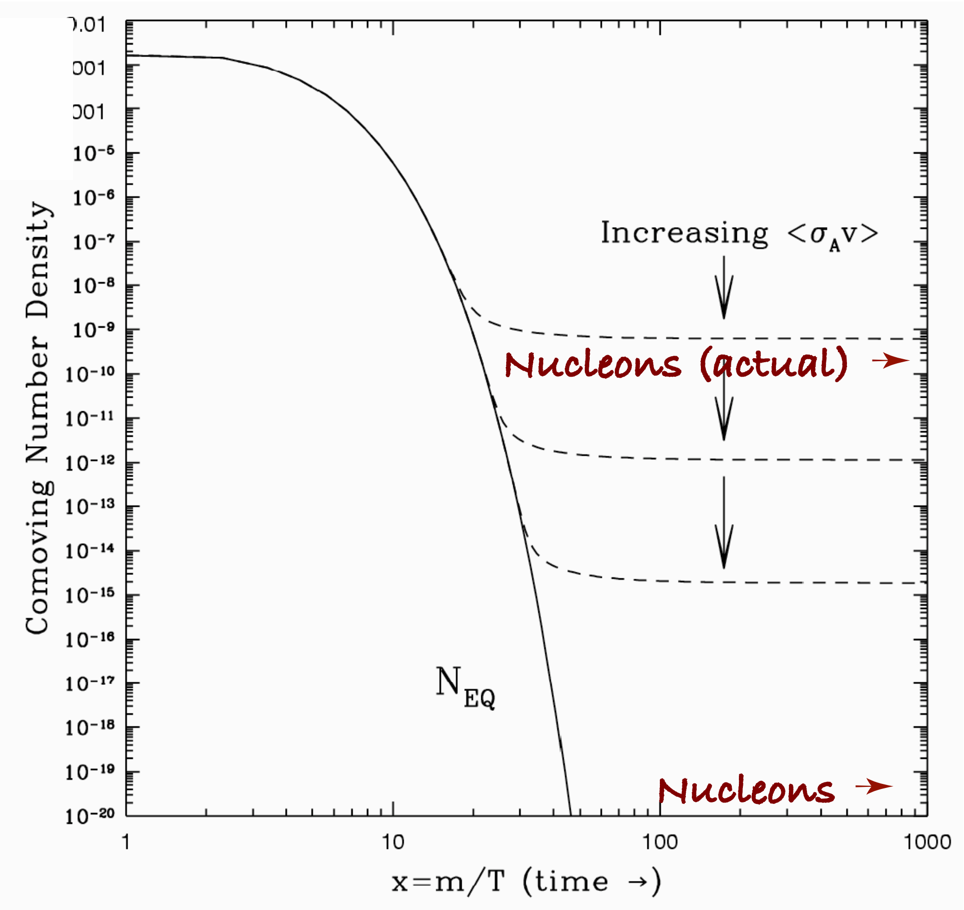


We understand the dynamics … and we can calculate the mass spectrum

But we get the expected relic abundance of baryons very 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:

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

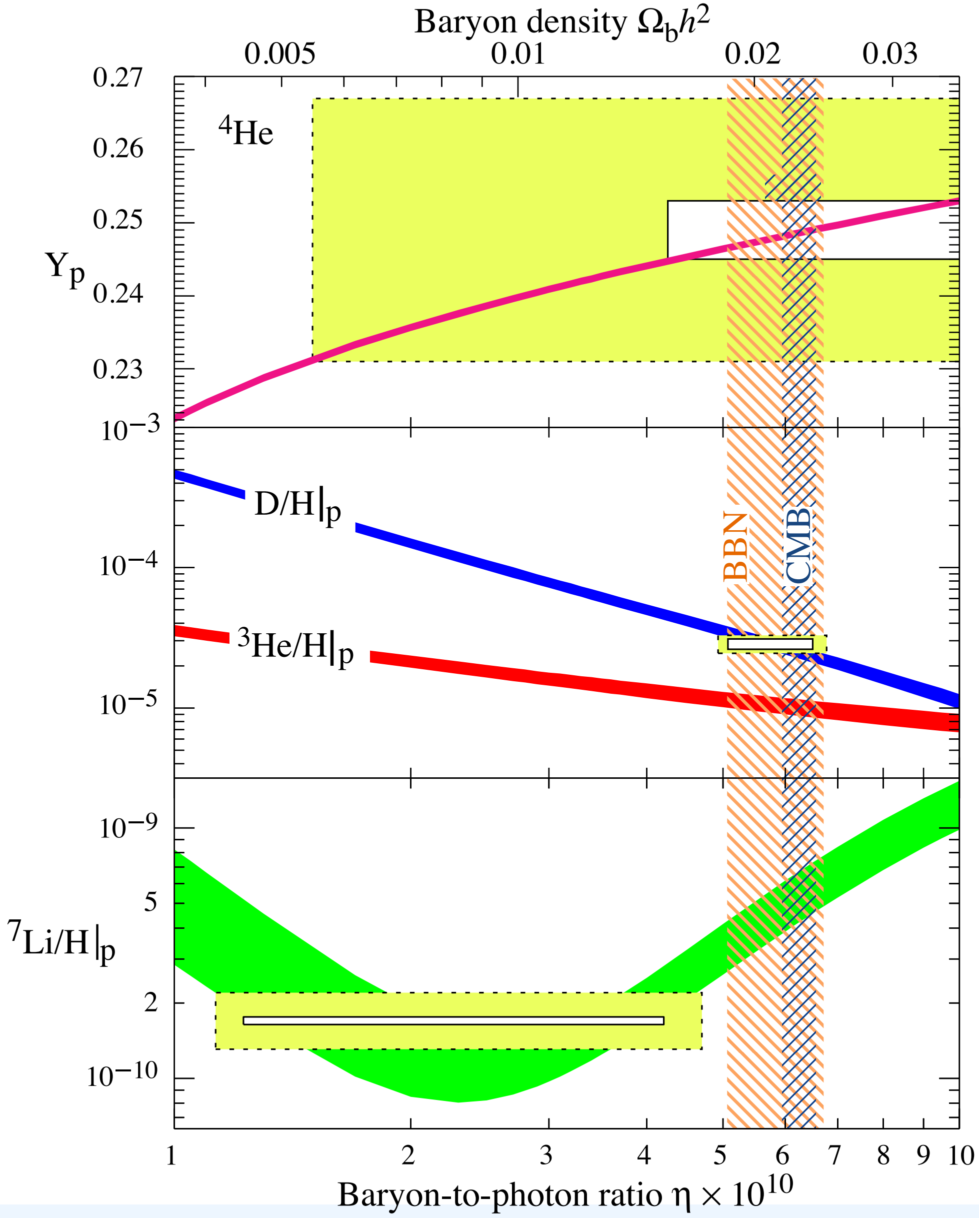
becomes comparable to the expansion rate

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

i.e. 'freeze-out' occurs at T ~ 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 are *no* antibaryons, so we must invoke an **initial asymmetry**: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

Although vastly *overabundant* compared to the natural expectation, baryons ***cannot*** close the universe (BBN ✚ CMB concordance)



Fields & Sarkar (Particle Data Group), 2012

... the dark matter must therefore be mainly *non-baryonic*

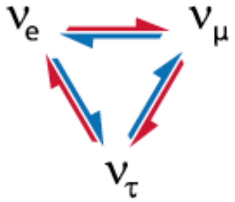
To make the baryon asymmetry requires a lot of new physics:

- 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 $SU(2)_L \times U(1)_Y$ breaking is not out-of-equilibrium

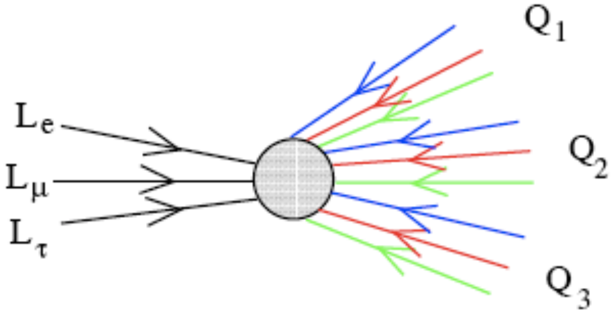
Hence the generation of the observed matter-antimatter asymmetry requires new BSM physics - can be related to the observed neutrino masses if these arise from lepton number **violation → leptogenesis**

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

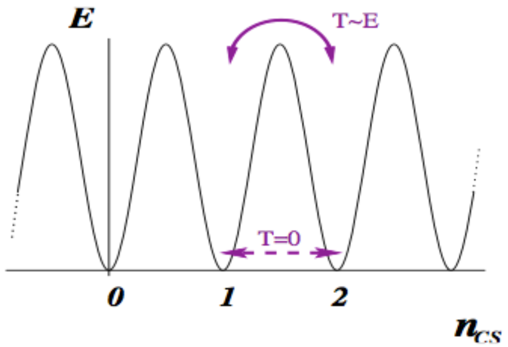


$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

Asymmetric baryonic matter



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



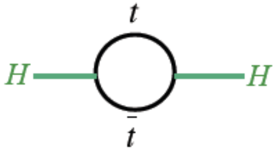
Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed N) would be redistributed by B+L violating processes (which conserve B-L) amongst all fermions – **in particular baryons** - which couple to the electroweak anomaly

An essential requirement for all this to work is that neutrino mass must be Majorana in nature (*not* Dirac) … can test experimentally by looking for neutrinoless double beta decay along with absolute neutrino mass scale measurement

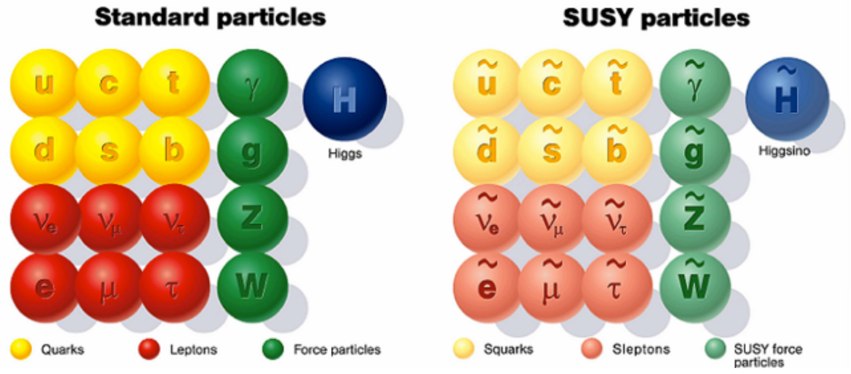
… in any case we accept that the only kind of matter which we are certain exists, originated **non-thermally** in the early universe

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~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	Violated? (matter parity adequate for p stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.25$



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

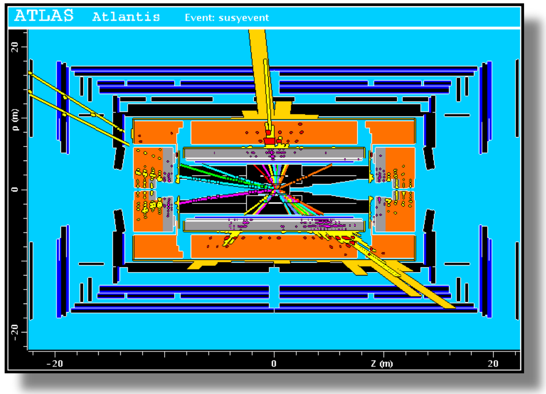


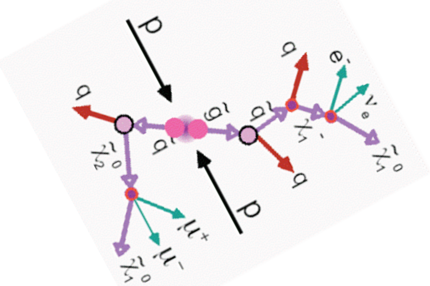
For (softly broken) supersymmetry we have the 'WIMP miracle':

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

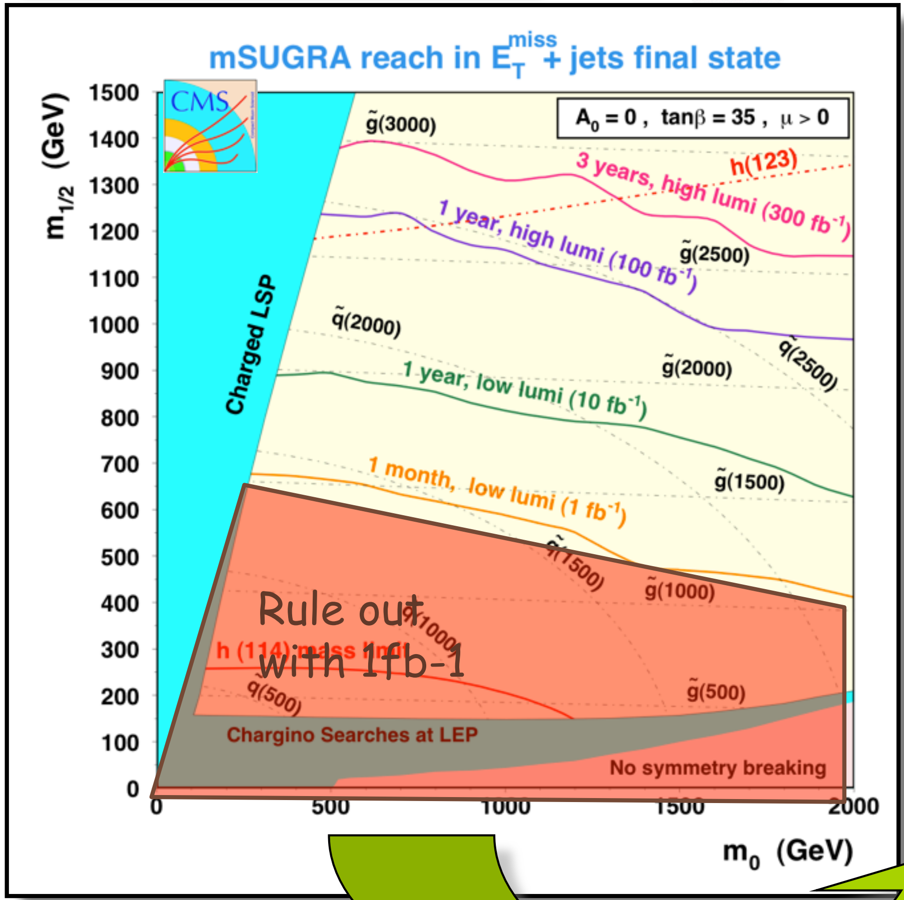
But why should a thermal relic have an abundance comparable to that of baryons?

LHC reach for SUSY dark matter

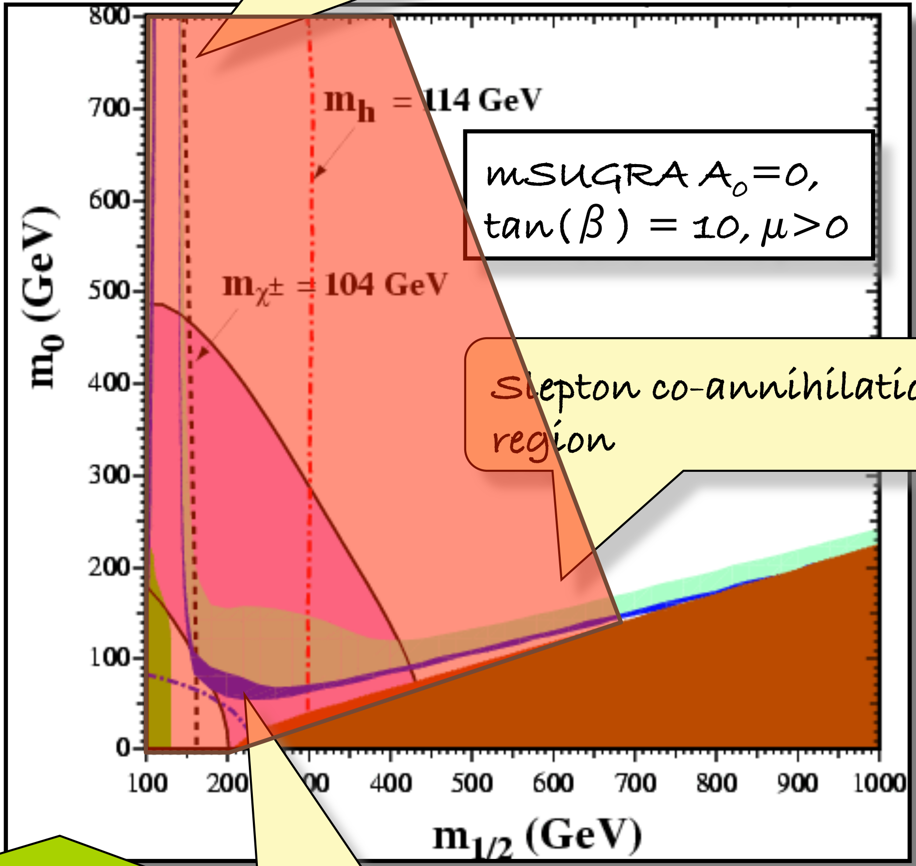




'Focus point' region:
annihilation to gauge bosons



Rule out with 1fb-1

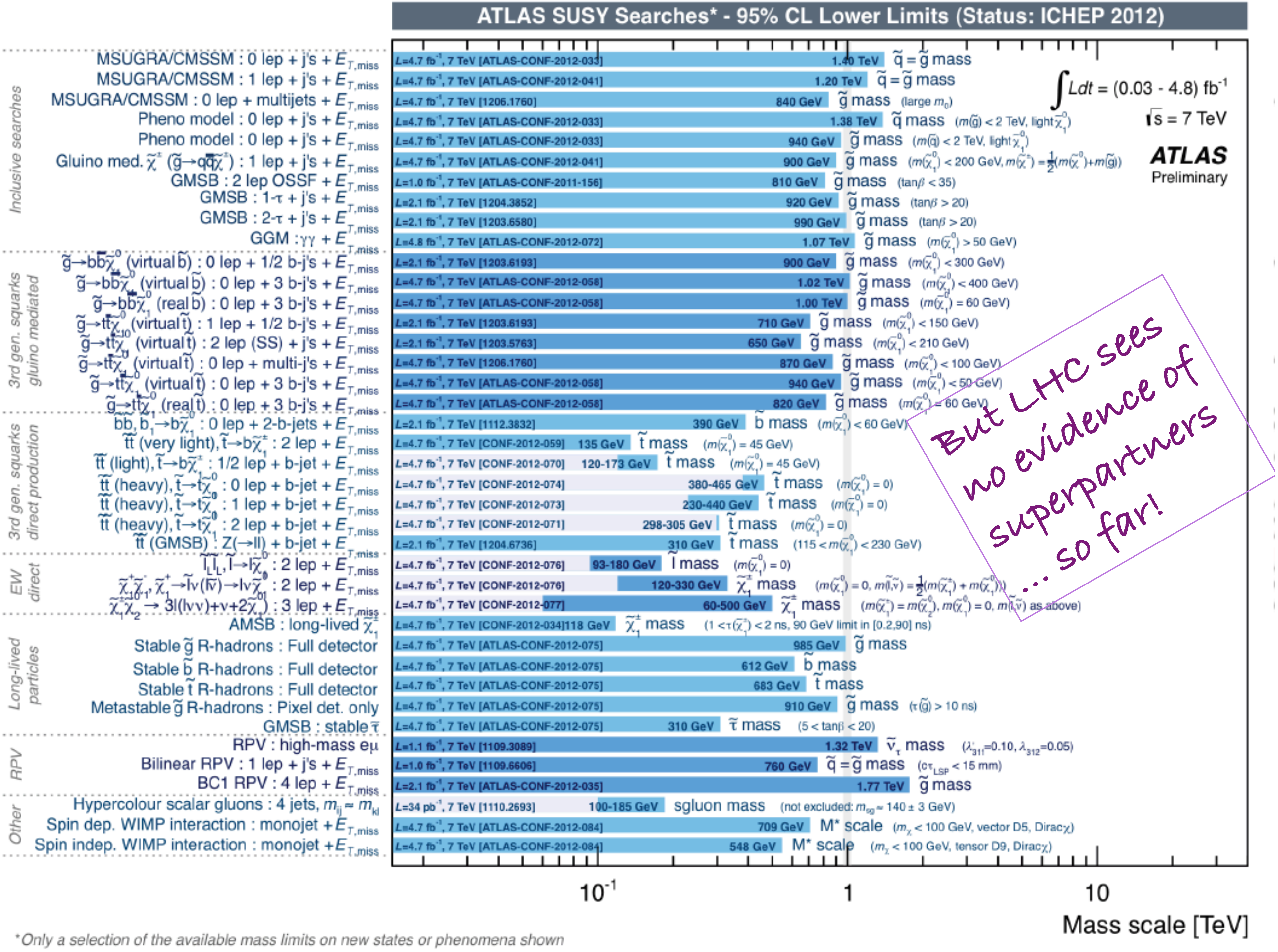


mSUGRA A_0=0, $\tan(\beta)$ = 10, μ>0

Slepton co-annihilation region

'Bulk' region:
t-channel slepton exchange

WMAP constraints



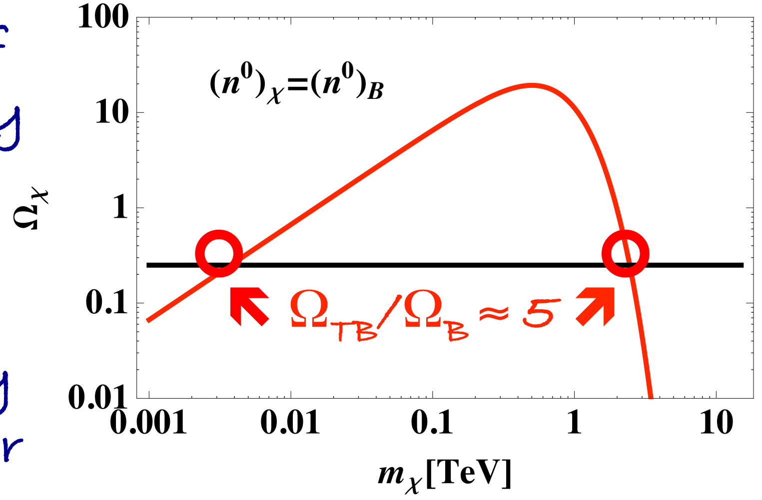
But LHC sees no evidence of superpartners … so far!

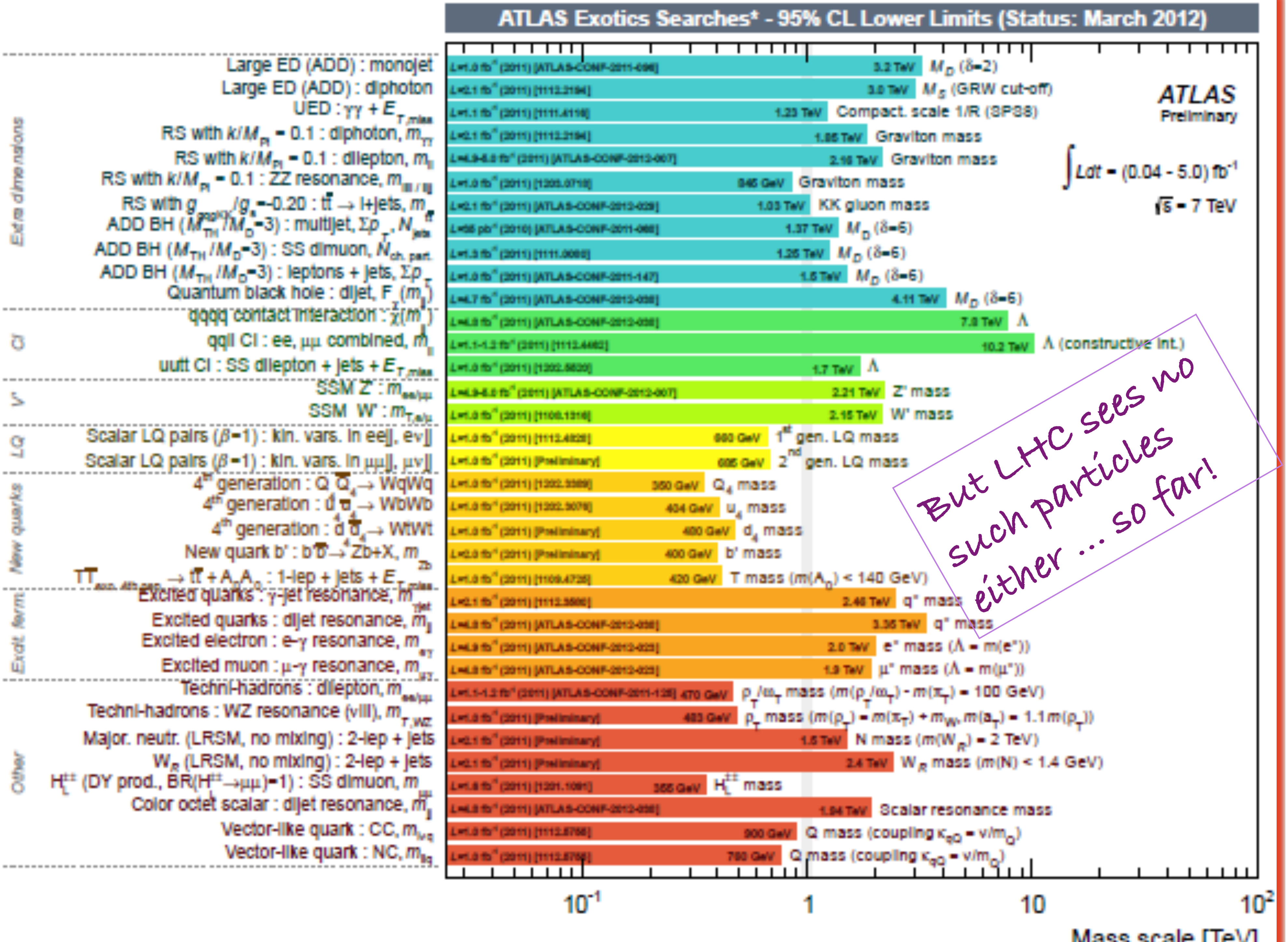
What should the world be made of ?

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	$U(1)_{DB}$	?	Asymmetric (like the observed baryons)	$\Omega_{DB} \sim 0.25$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.25$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?!	Asymmetric (like the observed baryons)	$\Omega_{TB} \sim 0.25$

A new particle can *share* in the B/L asymmetry if it is somehow linked with SU(2) gauge symmetry … **thus linking dark to baryonic matter!**

For example a TeV mass technibaryon can naturally be the dark matter … another possibility is a ~5 GeV mass 'dark baryon' in a hidden sector





*Only a selection of the available mass limits on new states or phenomena shown

But LHC sees no such particles either … so far!

Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr	~~'Freeze-out' from equilibrium~~ Asymmetric baryogenesis - how?	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	Dark baryon	$U(1)_{DB}$	?	Asymmetric (like observed baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Techni-colour	$\tau \sim 10^{18}$ yr	Asymmetric (like observed baryons)	$\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (very model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3?$
$\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	Neutrinos	Lepton number	Stable	Thermal (abund ~ CMB photons)	$\Omega_\nu > 0.003$
M_{string}/M_{Planck}	Kaluza-Klein states?	?	?	?	?
	Axions	Peccei-Quinn	stable	Field oscillations	$\Omega_a \gg 1!$

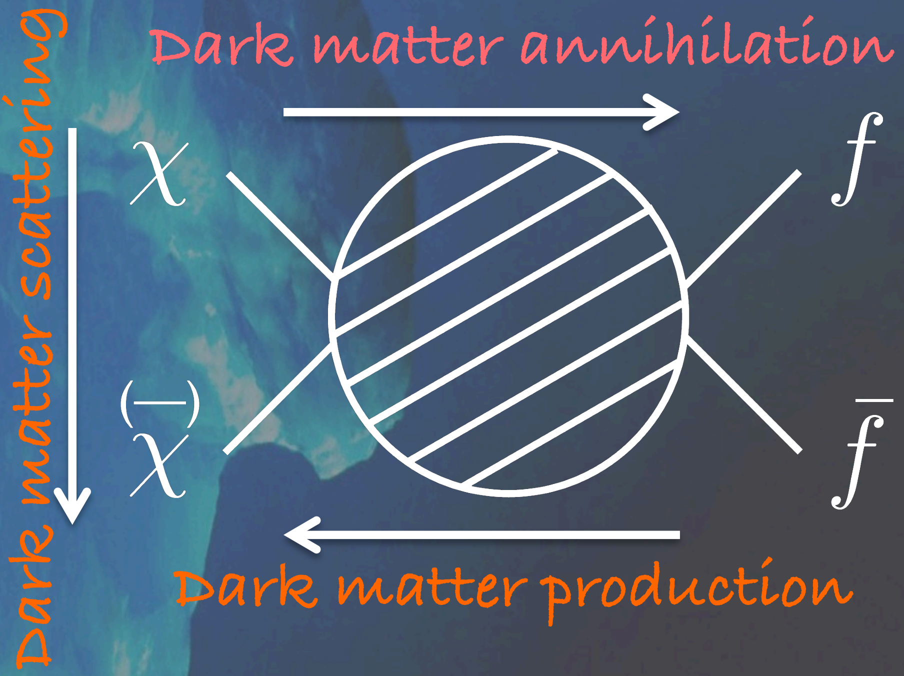
No definite indication from theory

must decide by experiment!

Detecting dark matter particles

➔Three complementary detection strategies:

- – Indirect detection
- – Direct detection
- – Collider experiments

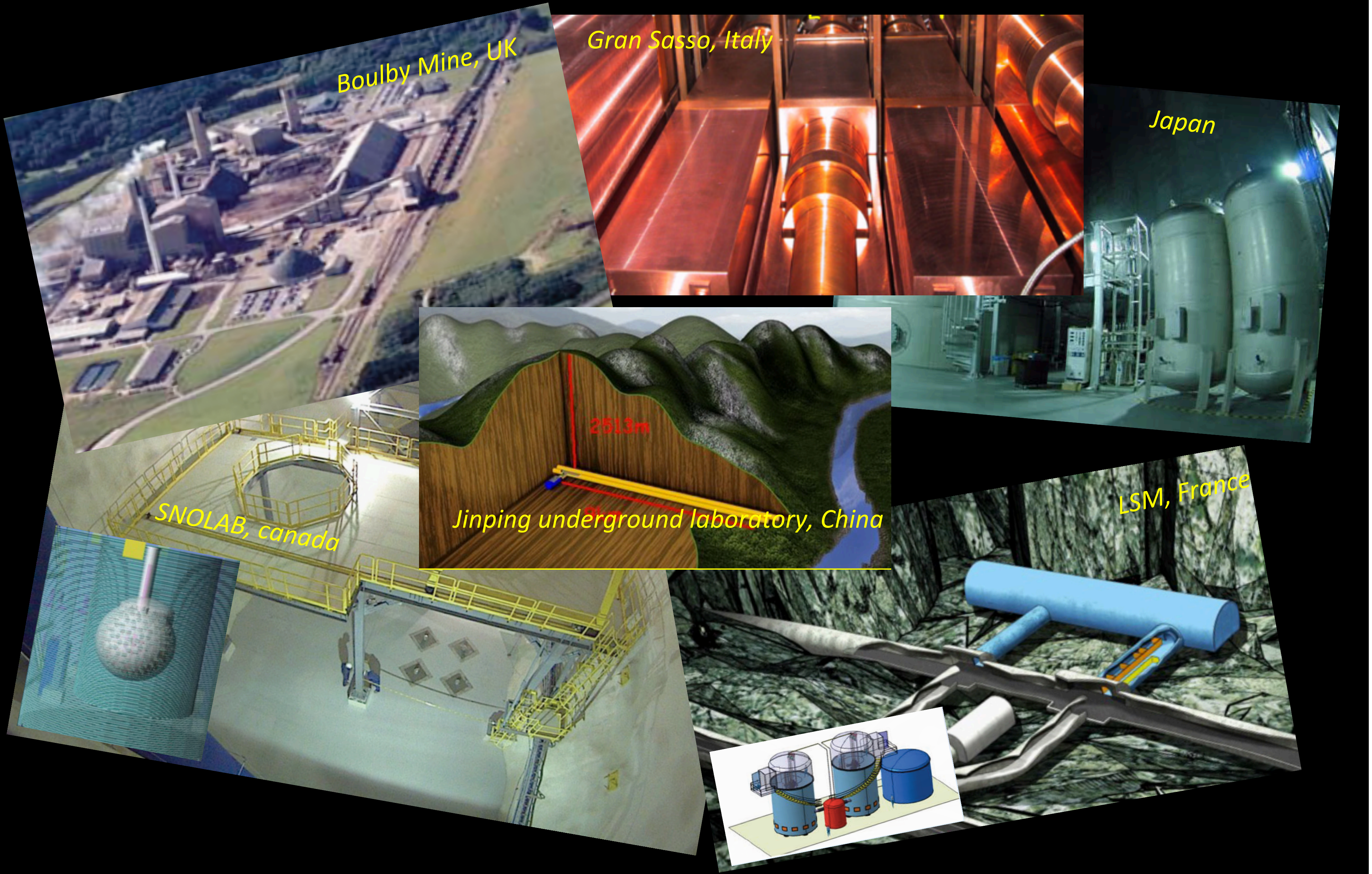


Dark matter annihilation

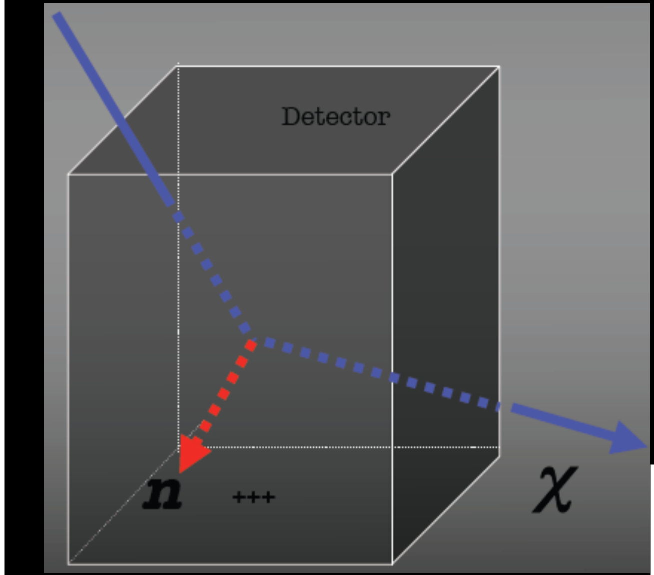
Dark matter scattering

Dark matter production

If dark matter is made of new particles then these are passing through us now!



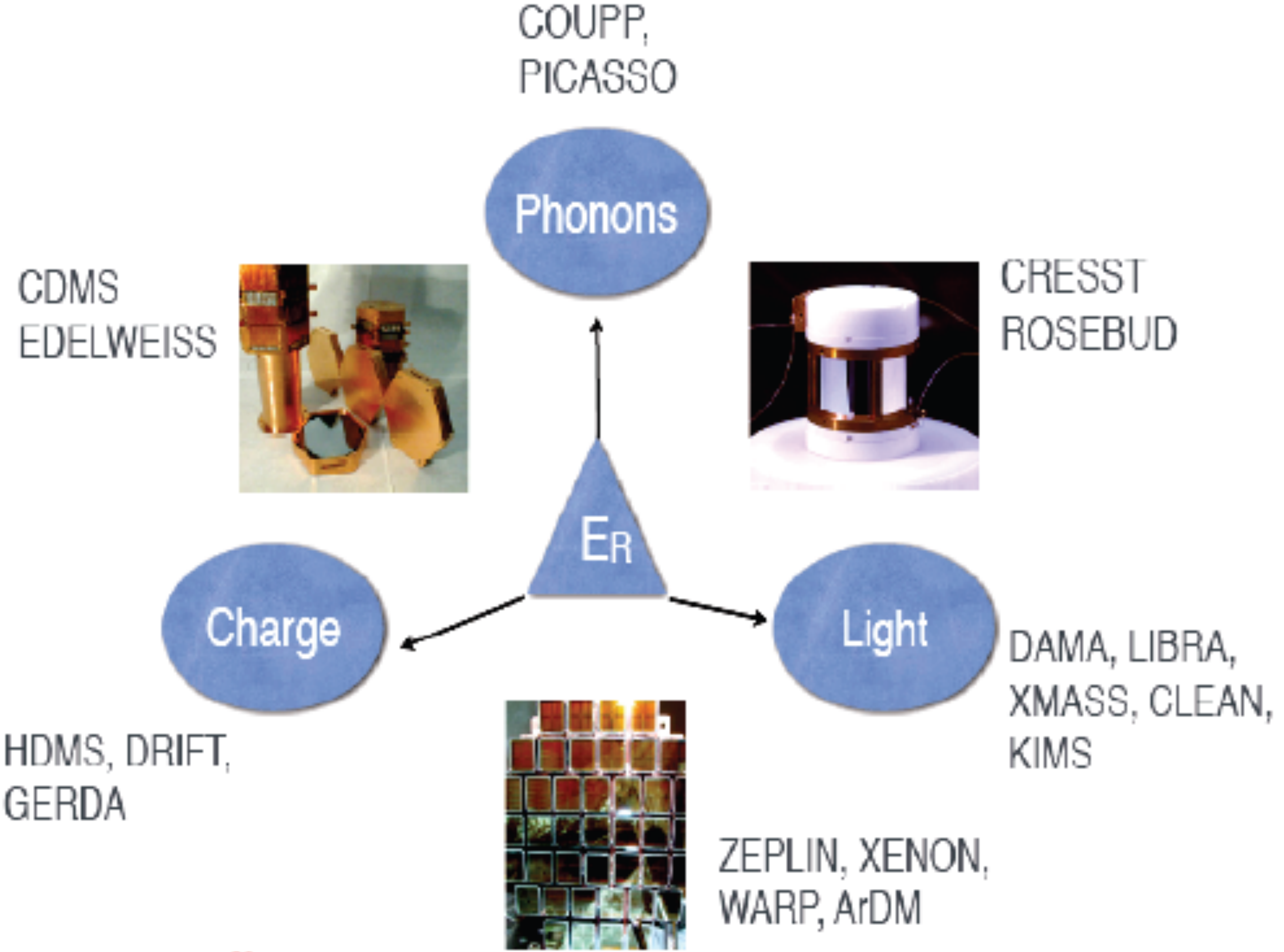
Many experiments worldwide are looking for such particles …



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

The recoil can be detected via the ionization (charge), scintillation (light), sound (phonons) and ultimately heat …

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



COUPP, PICASSO

Phonons

CDMS EDELWEISS

CRESST ROSEBUD

E_R

Charge

Light

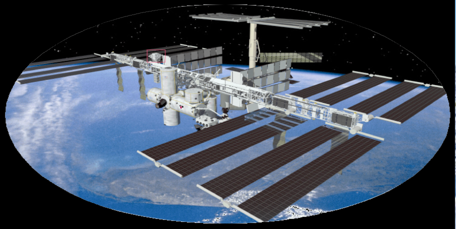
DAMA, LIBRA, XMASS, CLEAN, KIMS

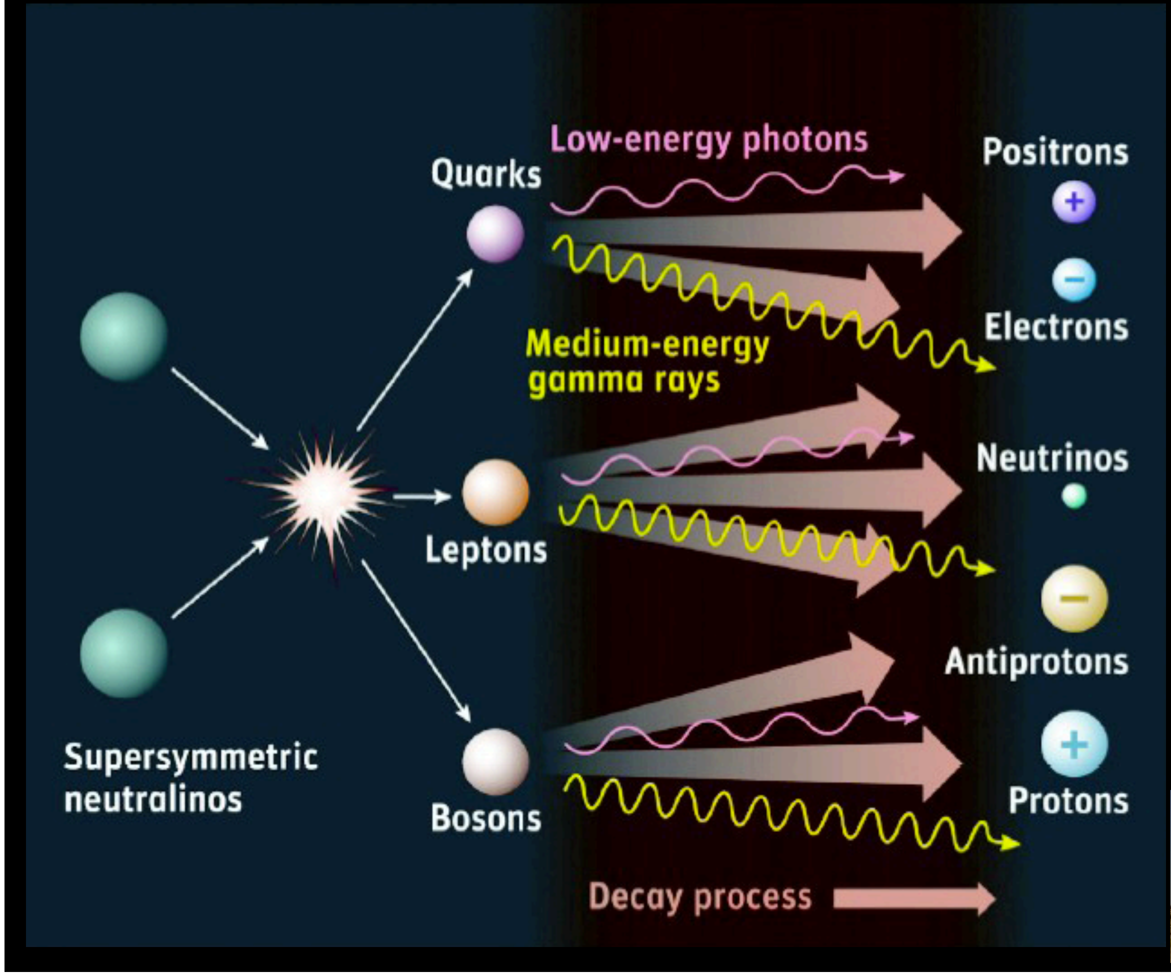
HDMS, DRIFT, GERDA

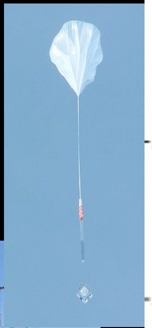
ZEPLIN, XENON, WARP, ArDM

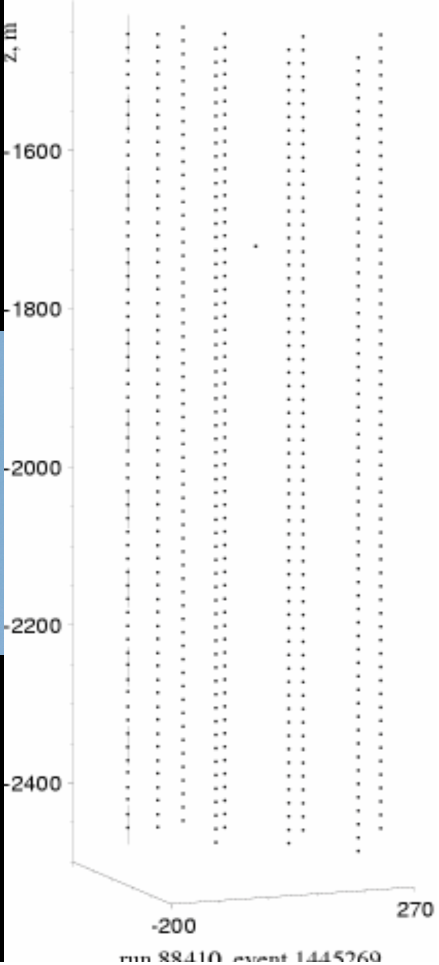
Dark matter particles in the Galaxy will occasionally annihilate, thus generating high energy γ-rays and small amounts of antimatter … look for this with balloon/satellite-borne instruments & ground-based telescopes

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

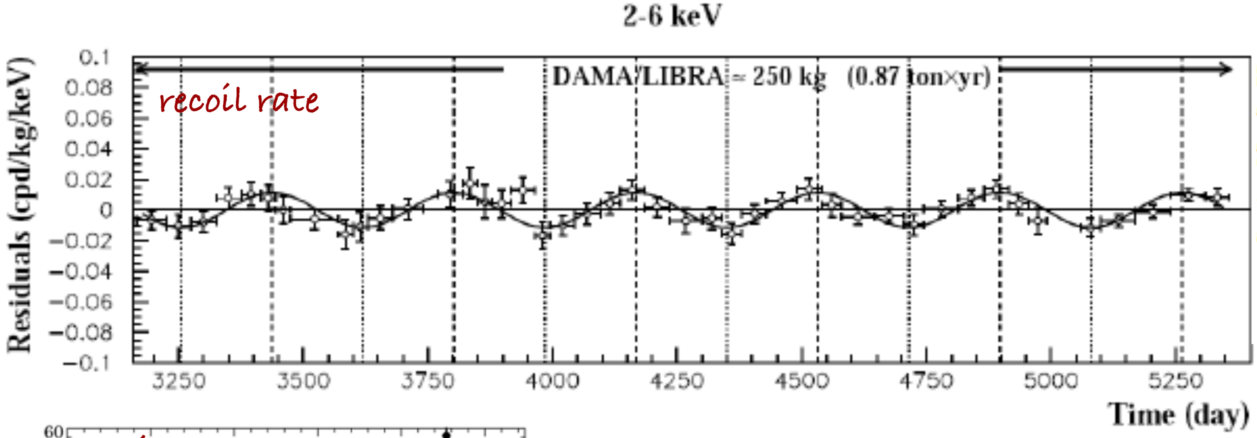


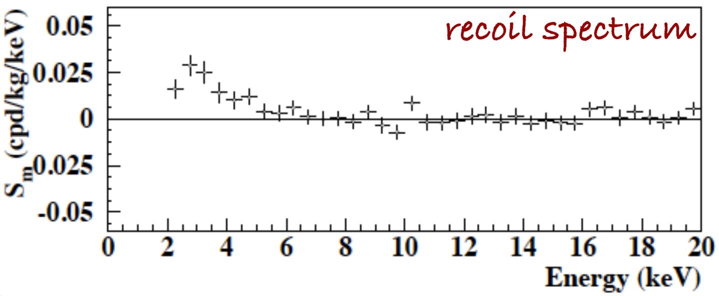




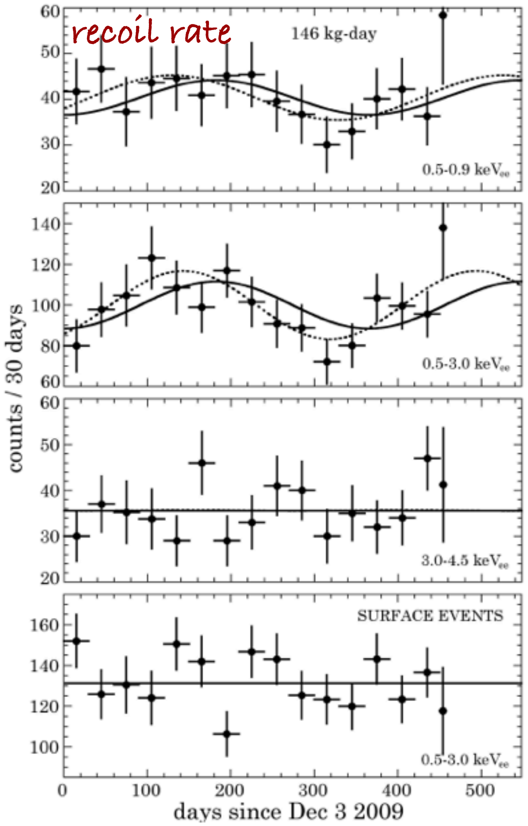


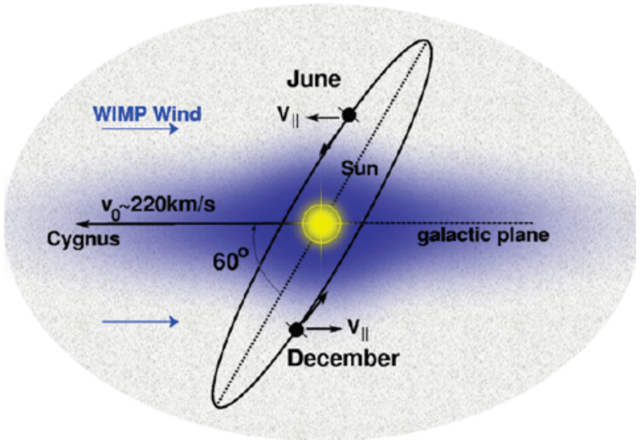
DAMA and **CoGeNT** have reported modulation signals consistent with ~5-10 GeV dark matter particles with $\sigma_{SI} \sim 10^{-40}$-$10^{-39}$ cm^2!

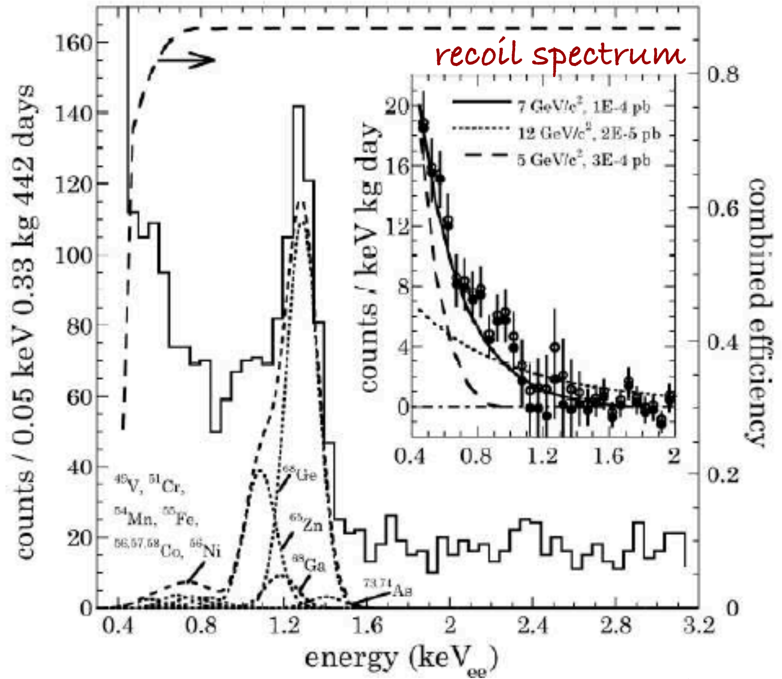




DAMA: Bernabei et al (2008, 2010)



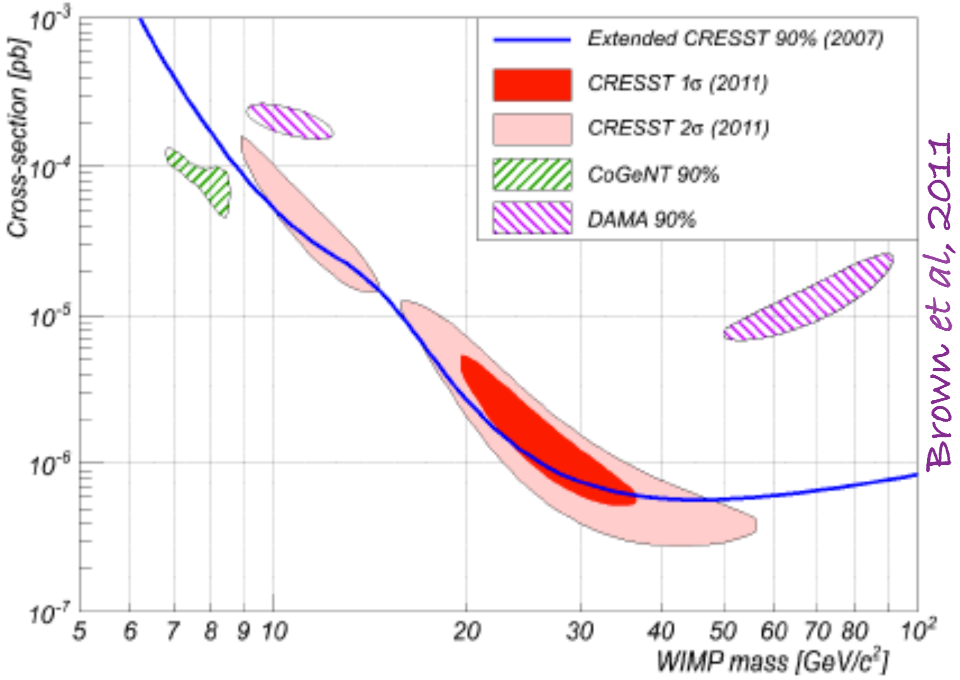




... as is expected due to the motion of the Earth through the DM 'wind'

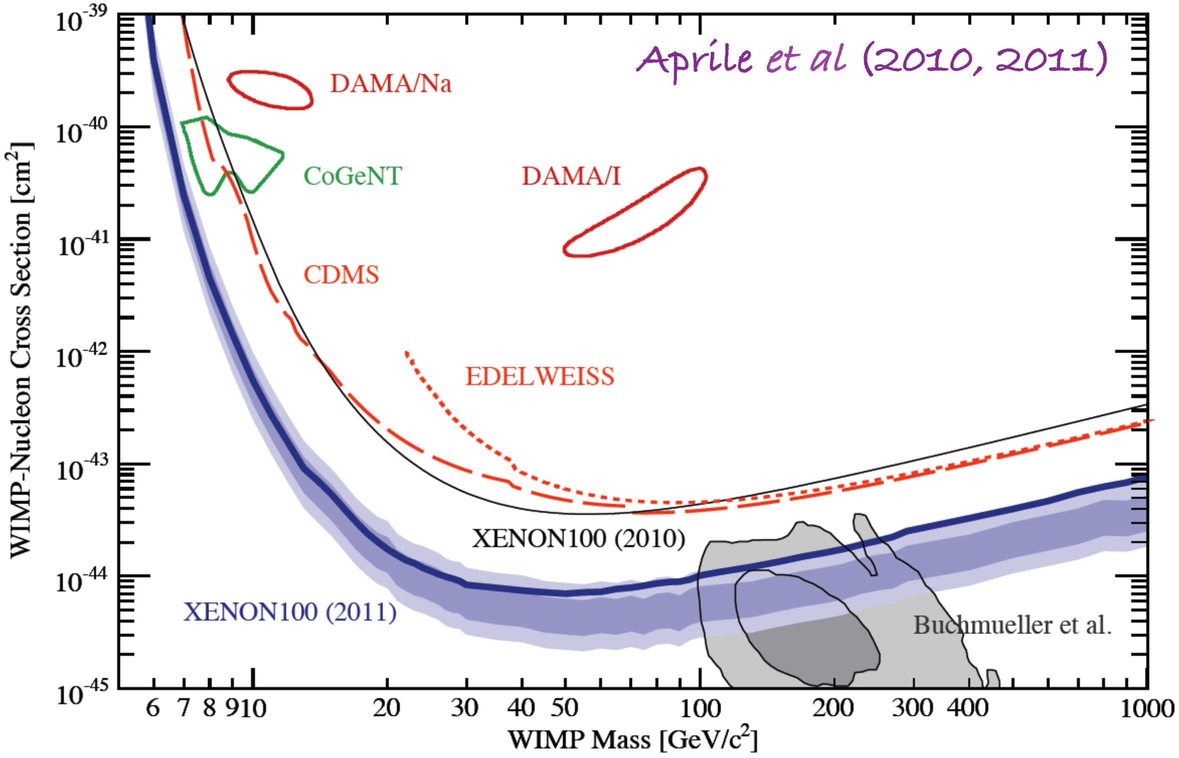
CoGeNT: Aalseth et al (2010, 2011)

CRESST too has reported recoil events consistent with such light dark matter ...



Brown et al, 2011

These signals can be consistent (if the velocity distribution for halo DM is *not* Maxwellian) … but seem to be ruled out by data from much bigger experiments like CDMS and XENON-100



Aprile et al (2010, 2011)

There are several sources of uncertainty in the measured recoil rate:

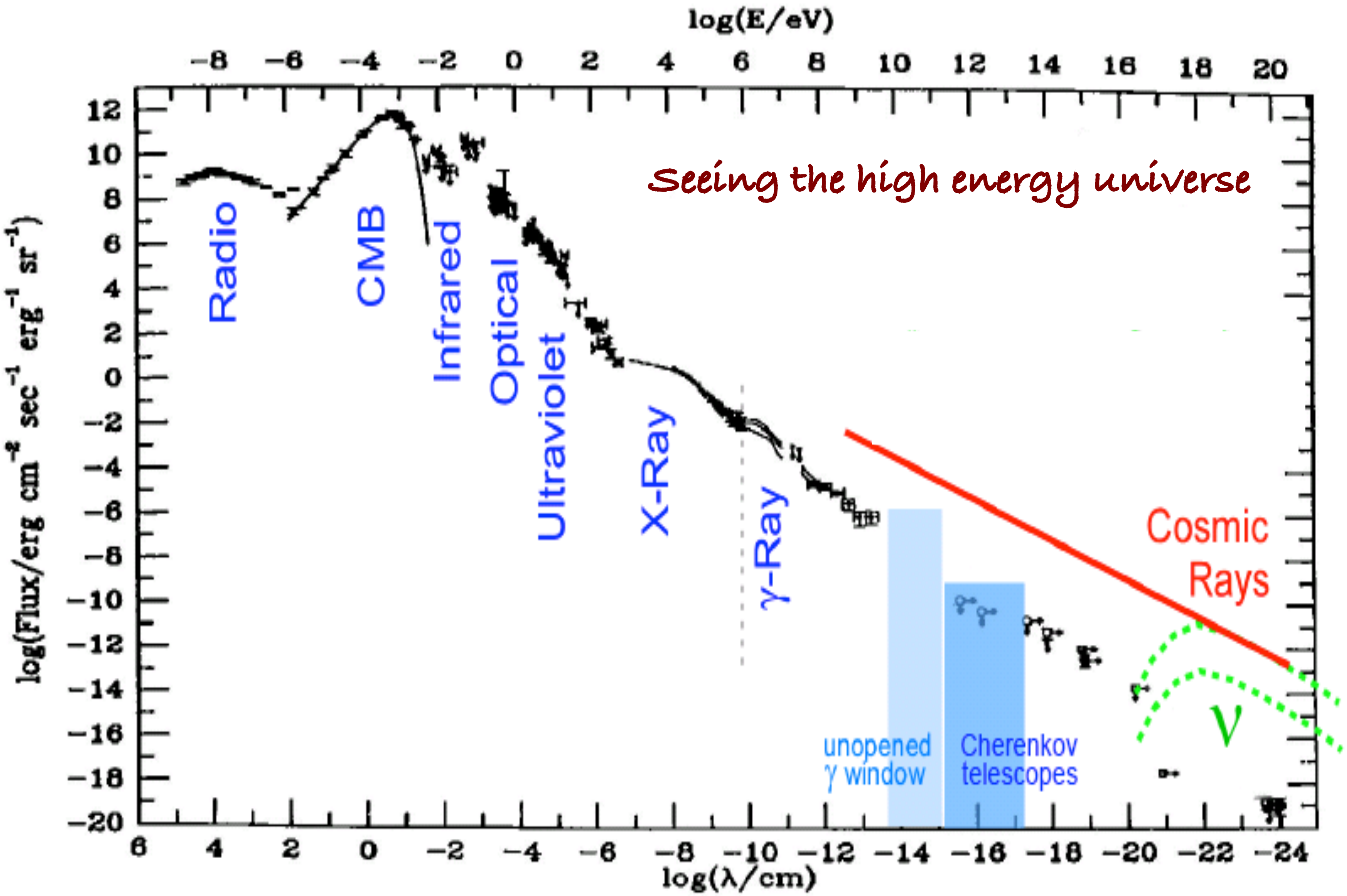
$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R,t) = M_{\rm tar}\frac{\boxed{\rho_\chi}}{2\,m_\chi\mu^2}\underbrace{\frac{(f_pZ+f_n(A-Z))^2}{f_n^2}\,\sigma_n}_{\text{Particle physics}}\underbrace{F^2(E_R)}_{\text{Nuclear physics}}\underbrace{\int_{v_{\rm min}}^{\infty}\mathrm{d}^3v\,\frac{f_{\rm local}(\vec{v},t)}{v}}_{\text{astrophysics}}$$

... so can attempt to reconcile the different results by considering whether dark matter might interact with neutrons and protons *differently* or have interactions that are mainly inelastic/momentum dependent/leptophilic/spin-dependent/electromagnetic ... or various combinations of these
⇒ *many* phenomenological studies over the past few years

Then there are experimental uncertainties (efficiencies, energy resolution, backgrounds ...) as well as uncertainties in translating measured energies into recoil energies (channelling, quenching ...)

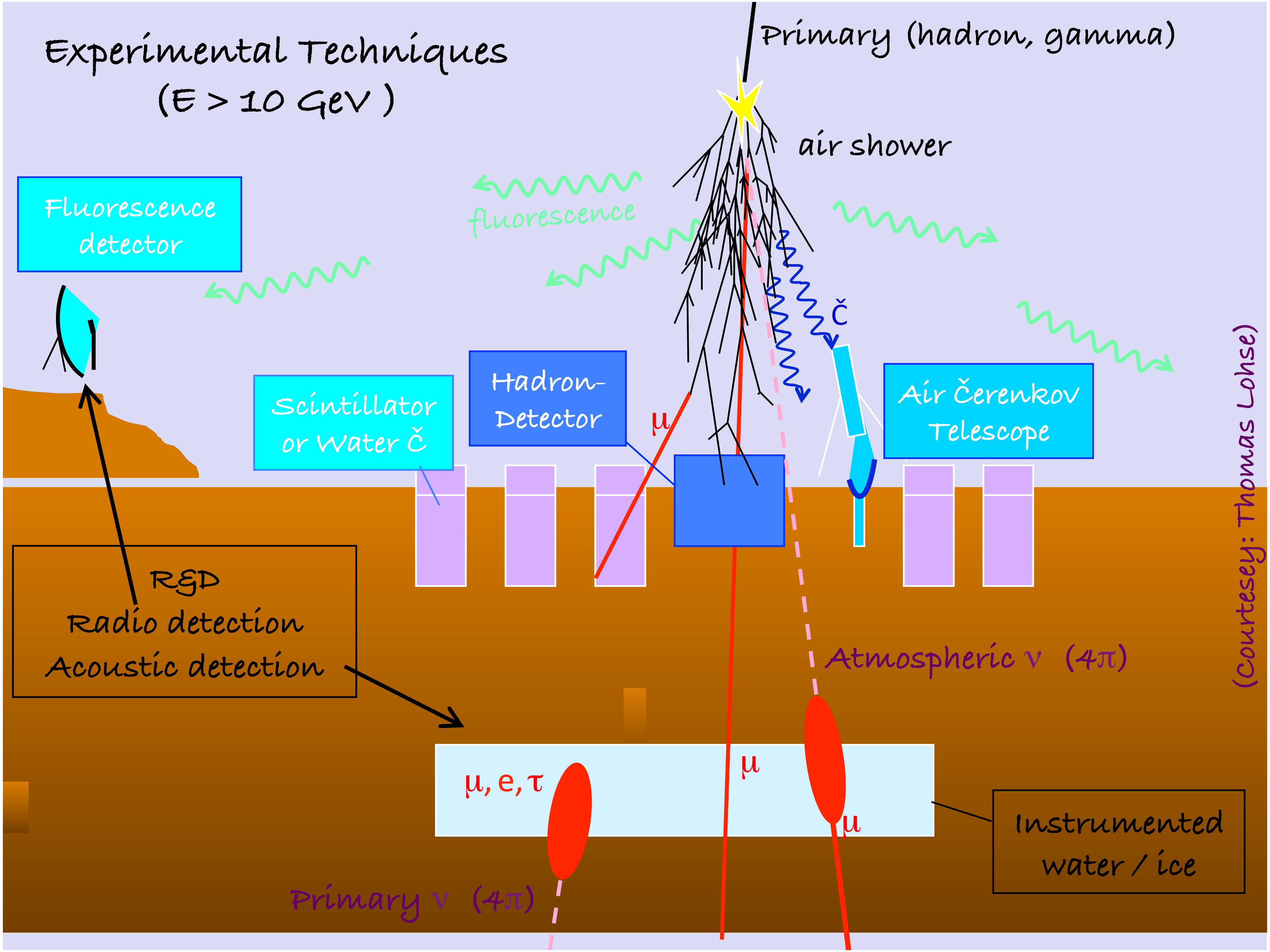
It is clear that new experiments (with low thresholds) are required

We can see the deep universe at energies of up to a few TeV, before photons get attenuated through $\gamma\gamma \rightarrow e^+e^-$ on cosmic radiation backgrounds



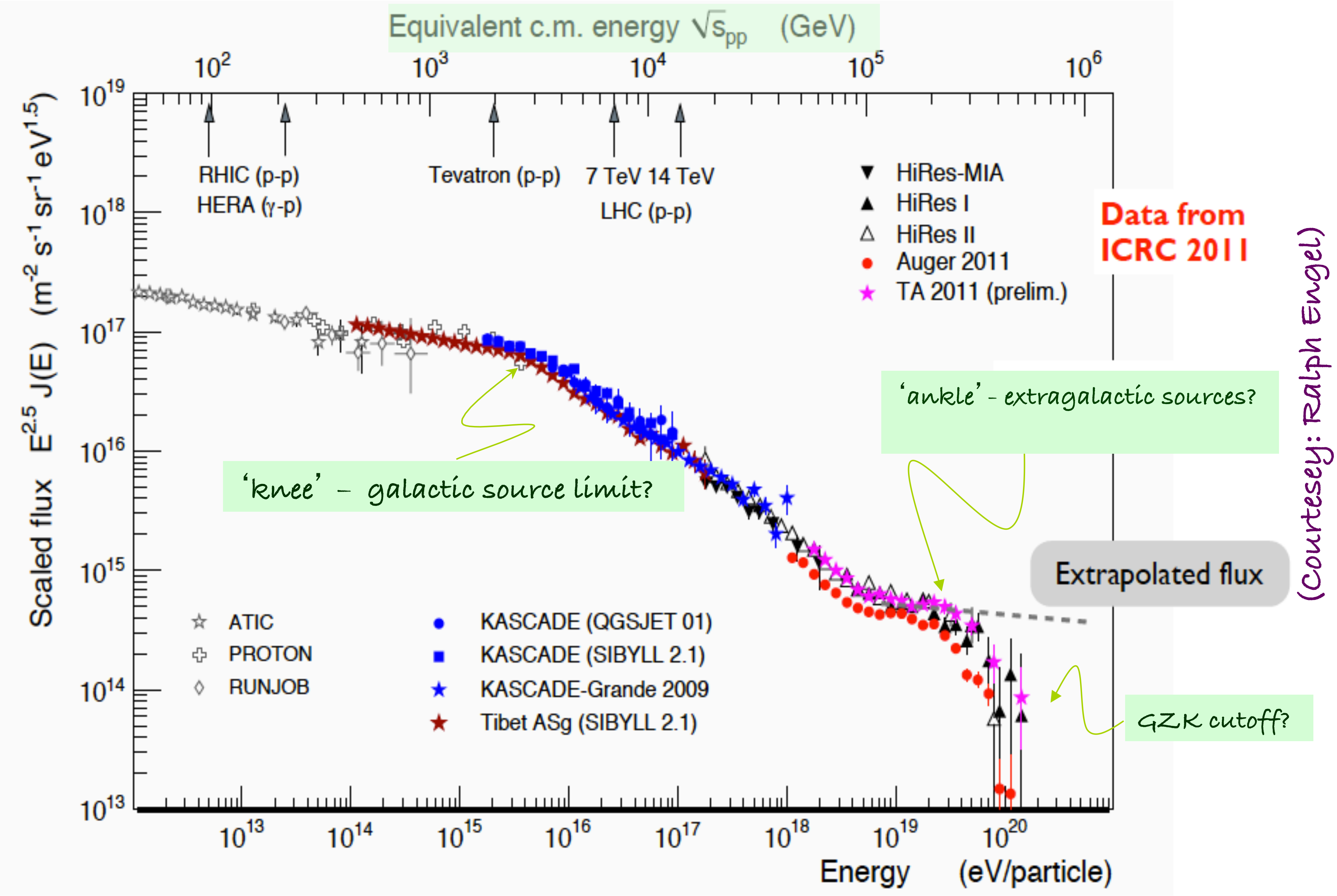
… and the universe is ~transparent to neutrinos at effectively *all* energies

Experimental Techniques
(E > 10 GeV)



(Courtesey: Thomas Lohse)

By studying cosmic ray (p, γ, μ, ν) interactions we also 'see' into the microscopic universe … well beyond the reach of terrestrial accelerators



'knee' – galactic source limit?

'ankle' - extragalactic sources?

GZK cutoff?

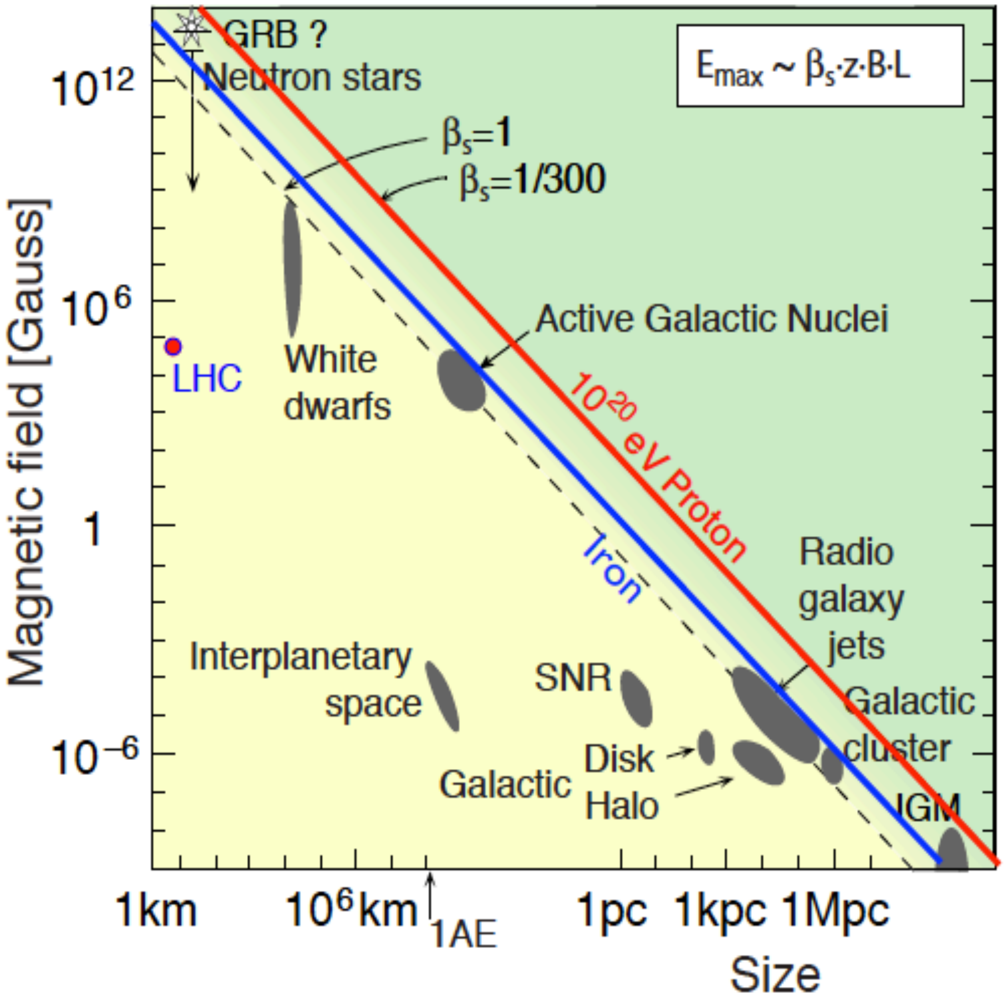
Extrapolated flux

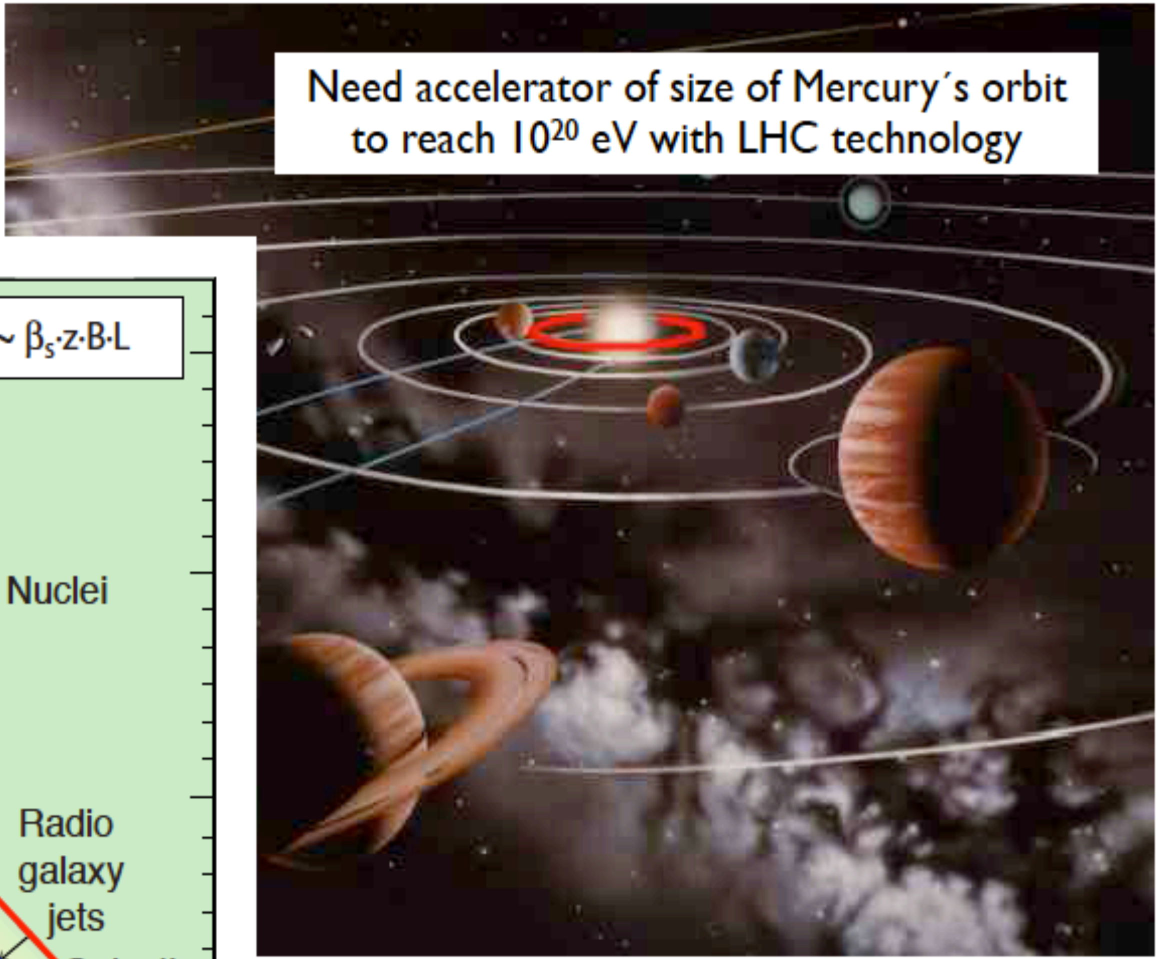
Data from ICRC 2011

(Courtesey: Ralph Engel)

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

Hillas plot (1984)





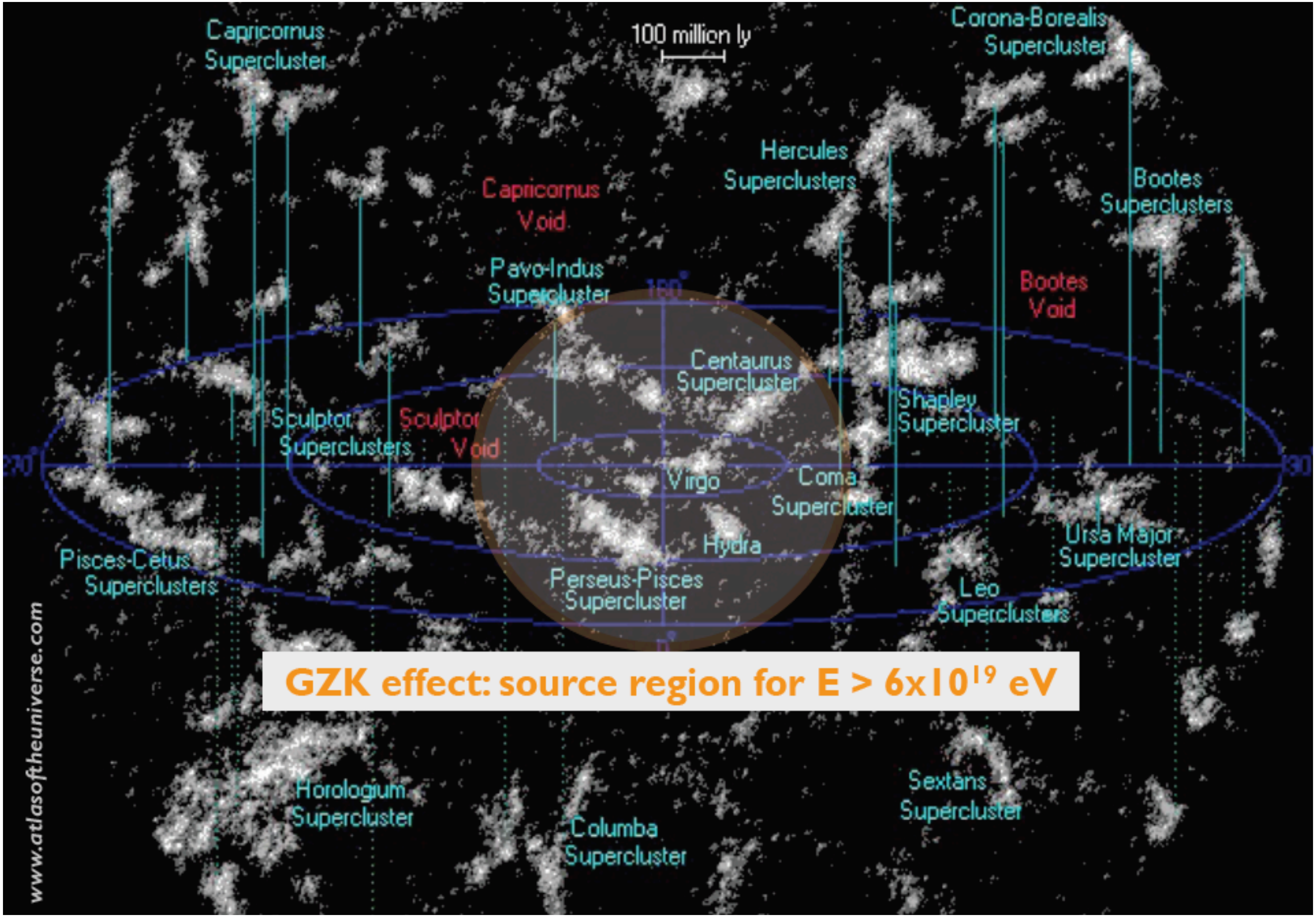
Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

Realistic constraints more severe

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

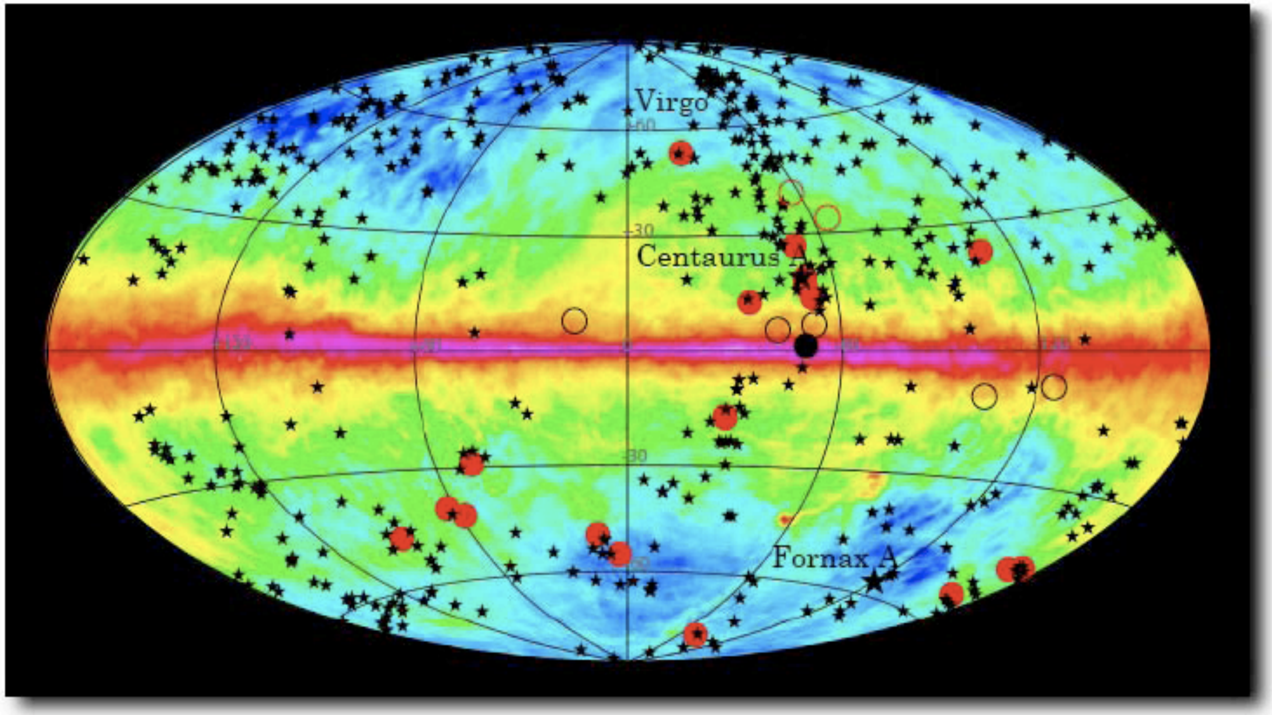
(Courtesey: Ralph Engel)

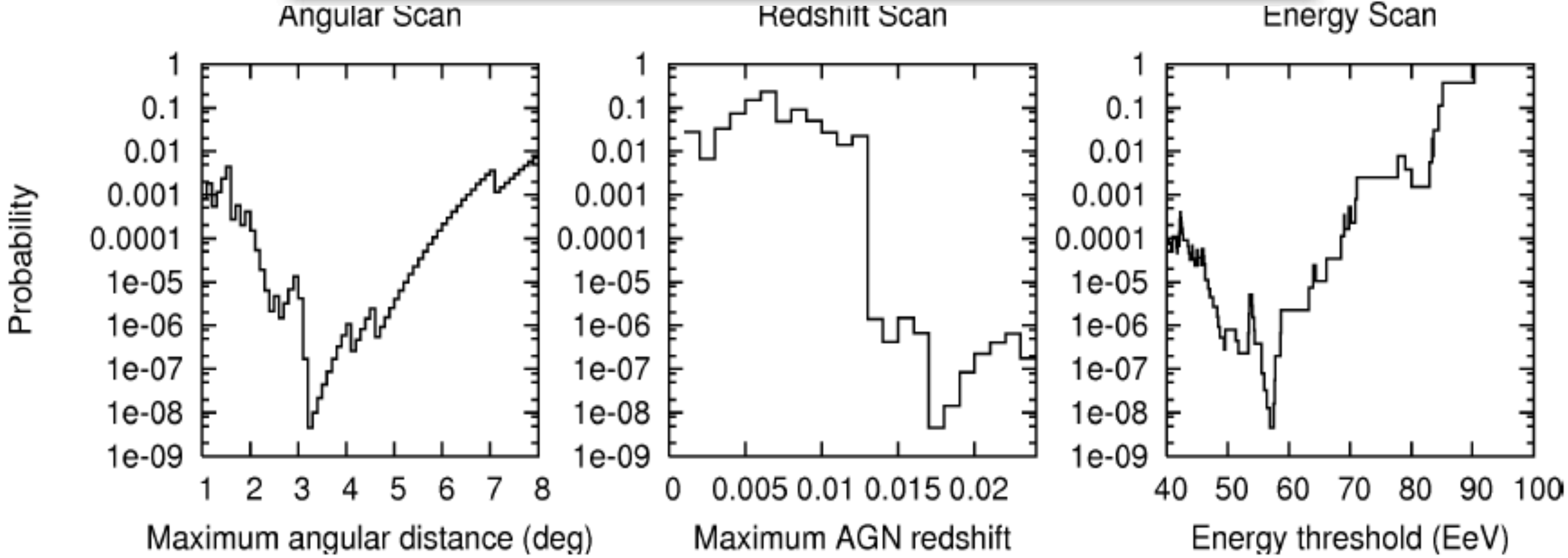
Because of the GZK cutoff, the UHECR sources must be within ~100 Mpc



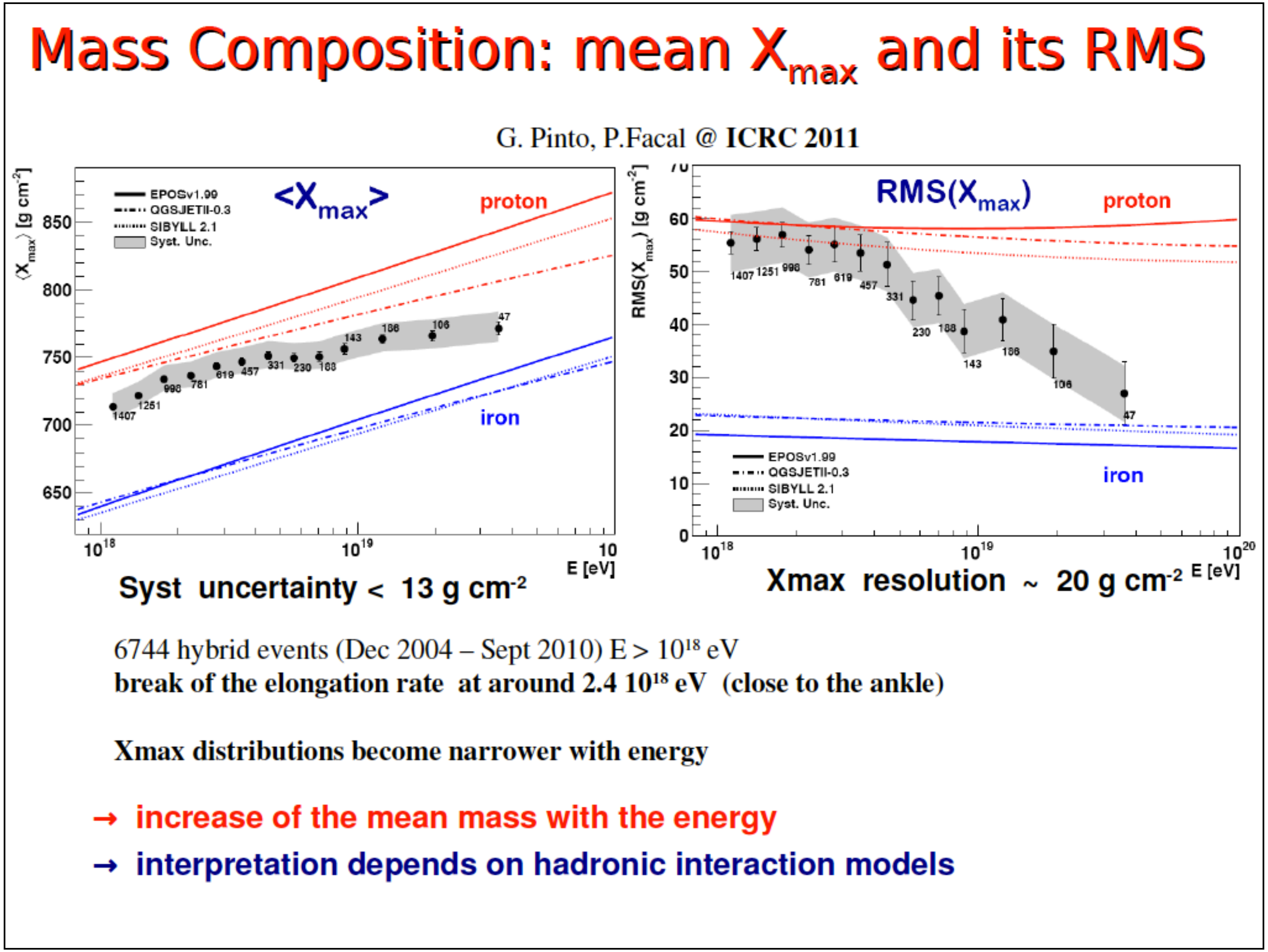
GZK effect: source region for E > 6×10^{19} eV

The arrival directions do correlate with nearby AGN (implying p primaries)





But Auger data on the depth of air shower maximum + fluctuations indicate in fact increasingly *heavier* composition at E > 10^{18} eV



Mass Composition: mean X_{max} and its RMS

G. Pinto, P.Facal @ **ICRC 2011**

Syst uncertainty < 13 g cm^{-2}

Xmax resolution ~ 20 g cm^{-2}

6744 hybrid events (Dec 2004 – Sept 2010) E > 10^{18} eV

break of the elongation rate at around 2.4 10^{18} eV (close to the ankle)

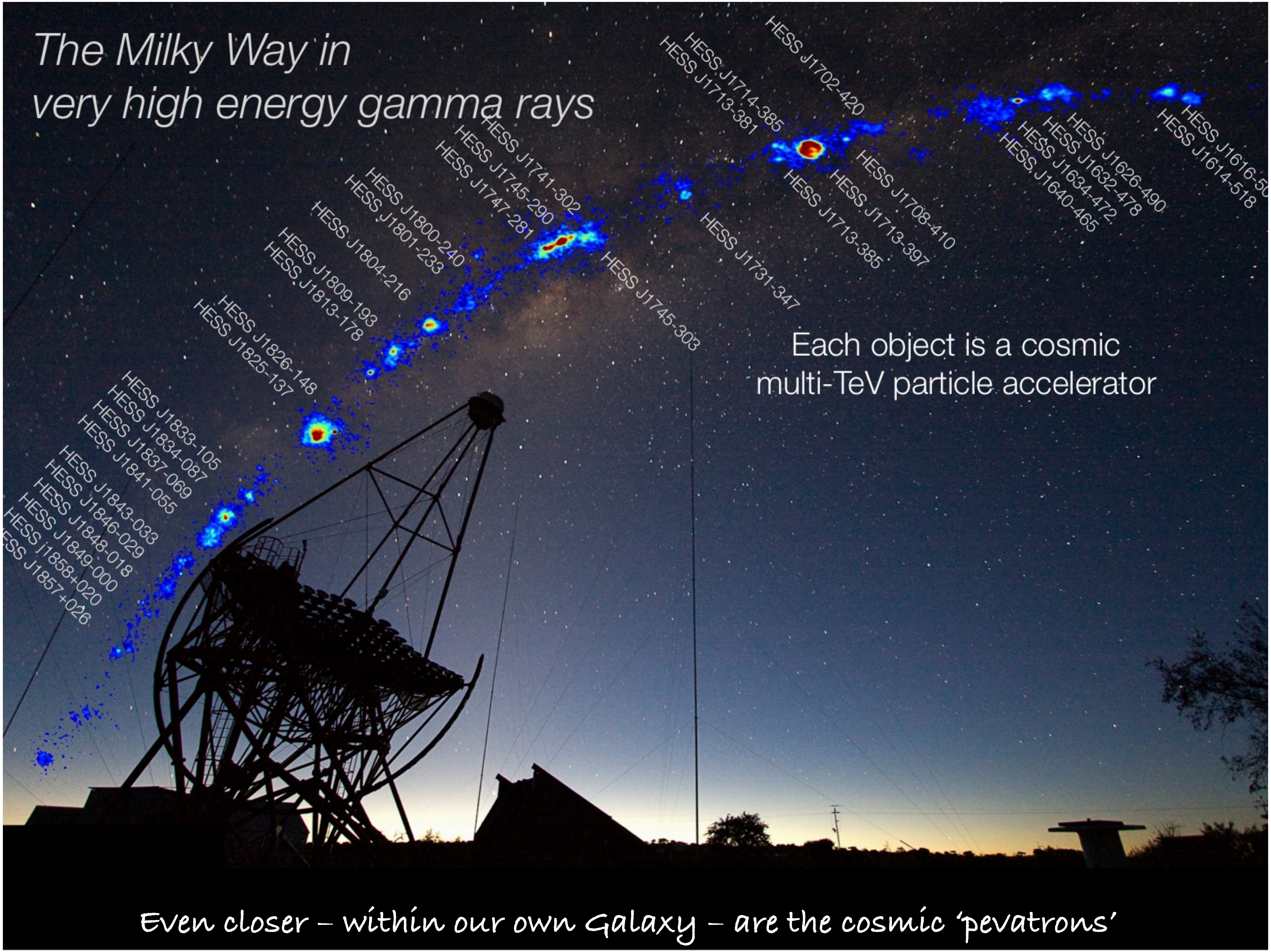
Xmax distributions become narrower with energy

→ **increase of the mean mass with the energy**

→ **interpretation depends on hadronic interaction models**

Conflict with results from HiRes/TA which are *consistent* with protons … need more data!

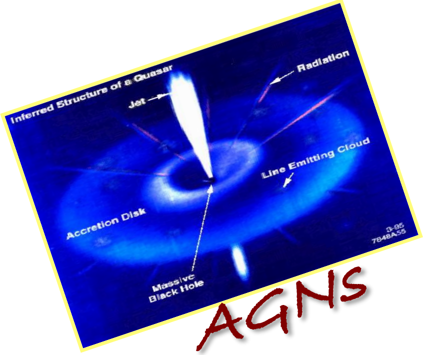
The Milky Way in very high energy gamma rays



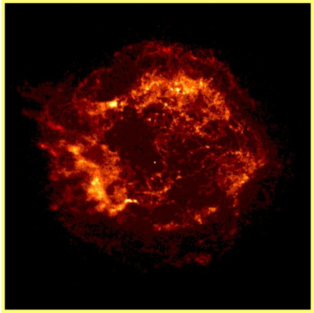
Each object is a cosmic multi-TeV particle accelerator

Even closer – within our own Galaxy – are the cosmic ‘pevatrons’

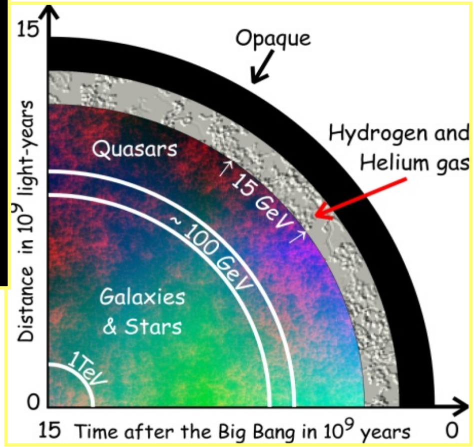
What can the TeV γ-ray window probe?



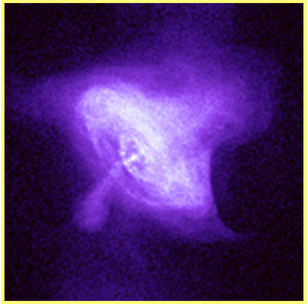
AGNs



SNRs



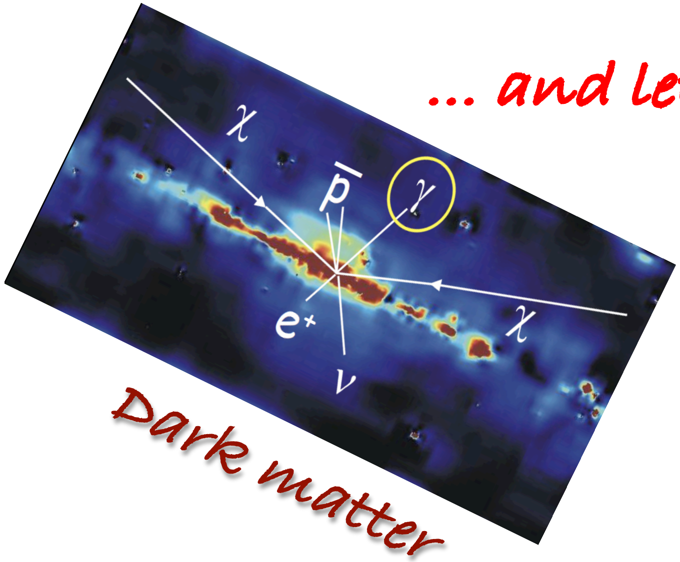
intergalactic space



Pulsars & PWN

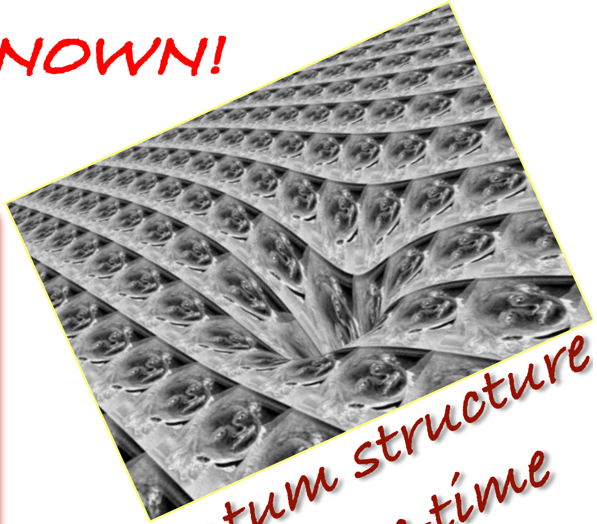
GRBs

... and let us not forget: the UNKNOWN!



Dark matter

> "In the fields of observation chance favors only the prepared mind"
>
> Louis Pasteur



quantum structure of space-time

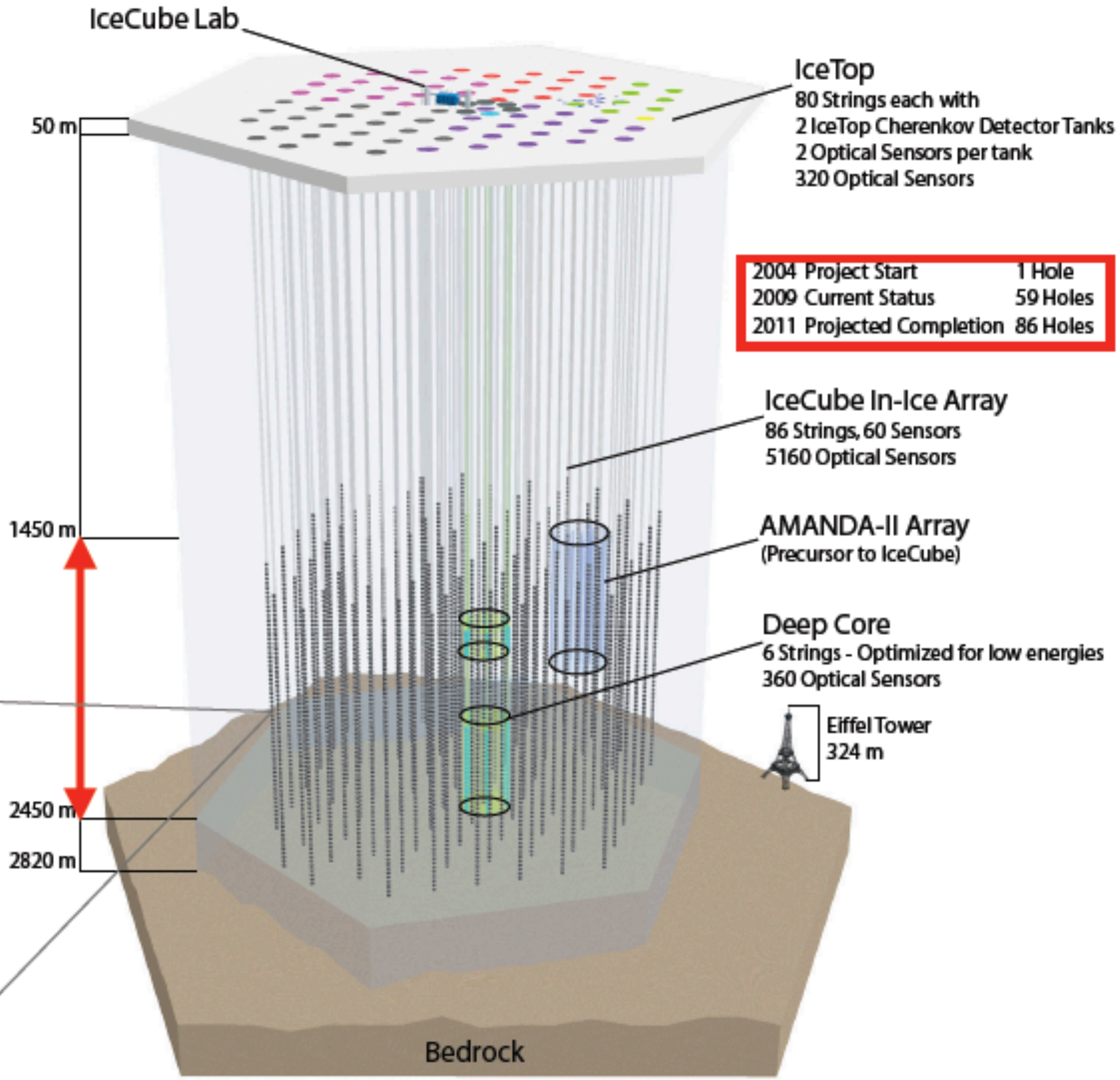
Recent science highlights with TeV γ-ray astronomy

- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars*: Science 322, 1221 (2008), Science 334, 69, (2011)
- *Supernova remnants:* Nature 432, 75 (2004)
- *The Galactic centre*: Nature 439, 695 (2006)
- *Galactic survey*: Science 307, 1839 (2005)
- *Starbursts*: Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN:* Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL:* Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark matter:* PRL 96, 221102 (2006) , PRL 106, 161301 (2011)
- *Test of Lorentz invariance*: PRL 101, 170402 (2008)
- *Cosmic ray electrons:* PRL 101, 261104 (2008)

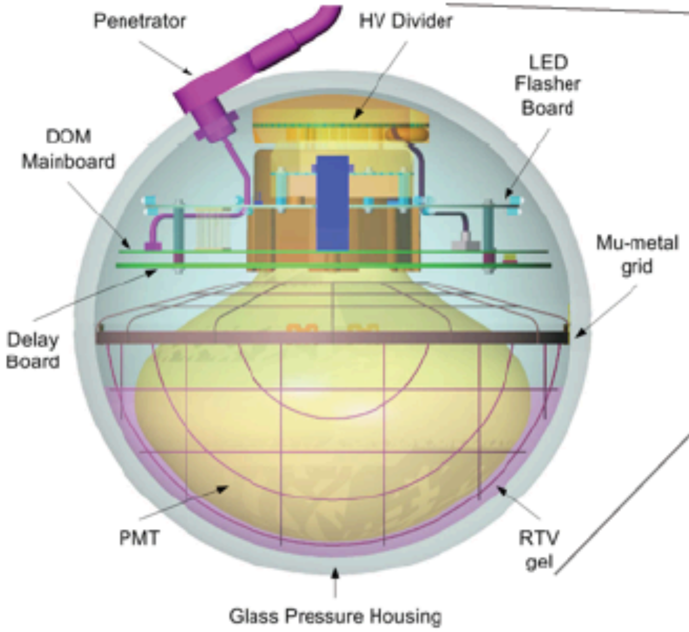
Results from **HESS, MAGIC** and **VERITAS**

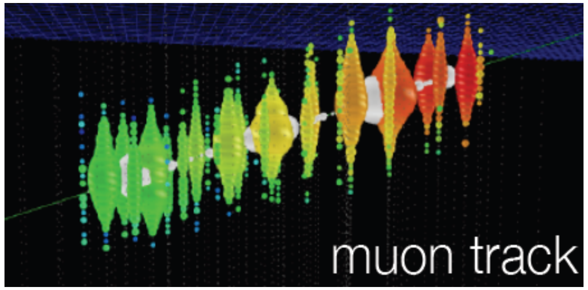
IceCube Observatory

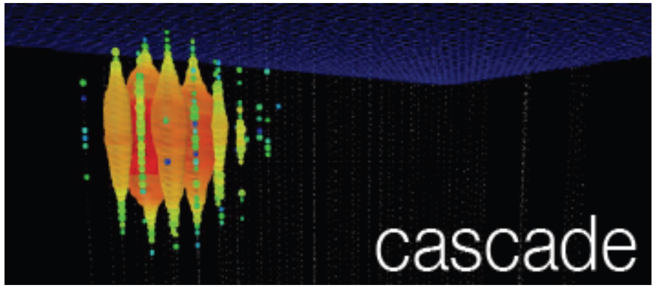
- 86 strings
- 5160 DOMs
- 17 m vertical spacing
- 125 m between strings



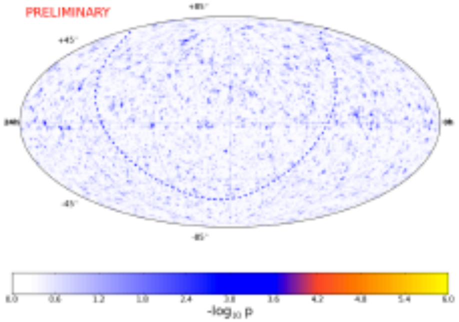
Digital Optical Module - DOM



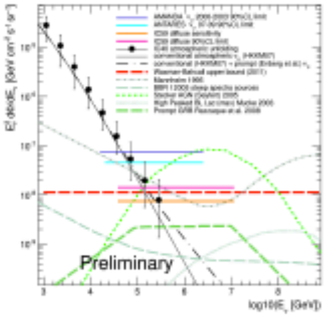




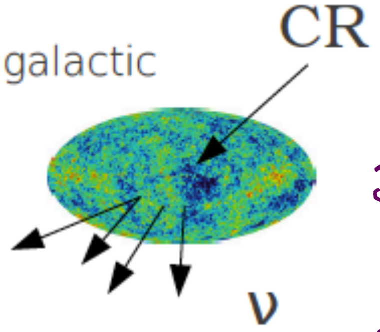
The IceCube physics program



Diffuse/ atmospheric

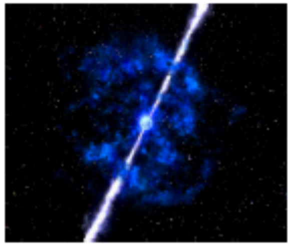


Search for an extragalactic neutrino signal



GZK neutrinos

Point source

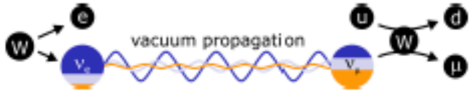


Search for point-like sources
→ galactic (e.g. SNR)
→ extragalactic (e.g. AGN)

Transient sources
→ GRB, flaring objects

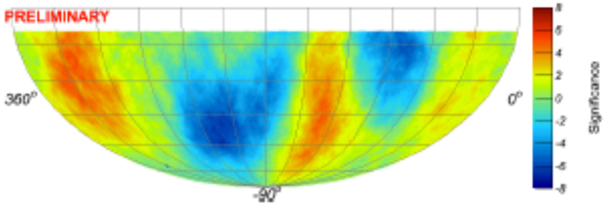
Optical follow-up programs

Prompt atms. neutrinos



Neutrino oscillations

Cosmic ray physics

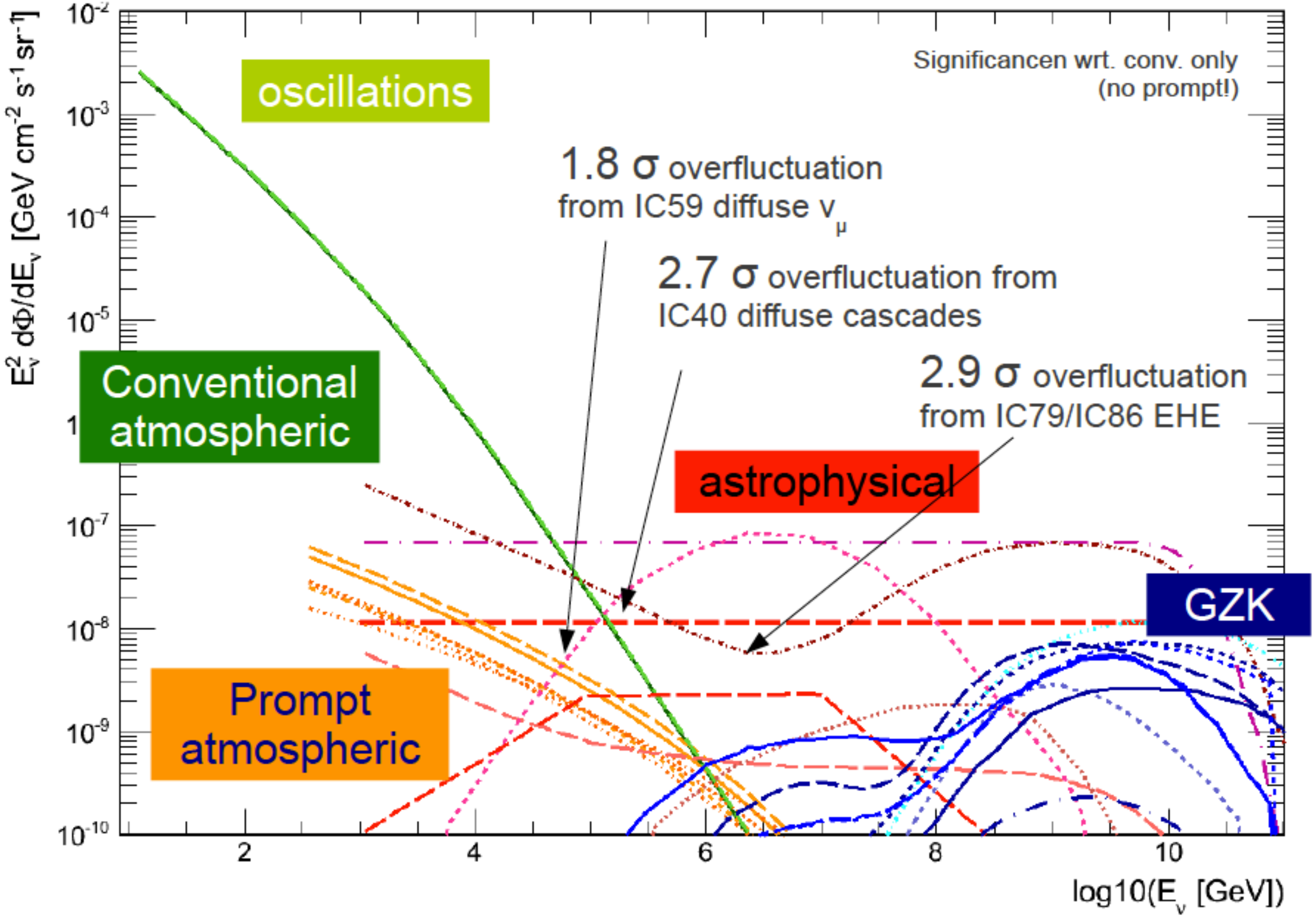


Dark Matter

Exotic particles

(Courtesey: Anne Schucraft)

Neutrino astronomy is hotting up ... several (marginal) indications of signals!



Significancen wrt. conv. only
(no prompt!)

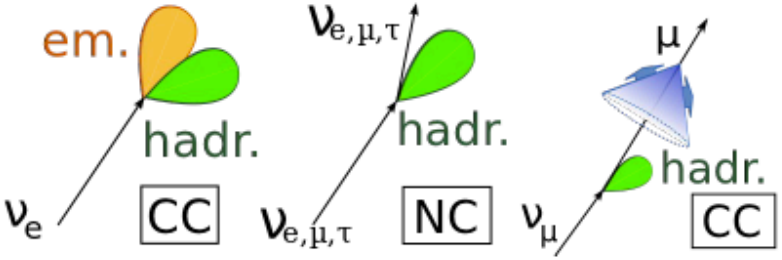
1.8 σ overfluctuation
from IC59 diffuse ν_μ

2.7 σ overfluctuation from
IC40 diffuse cascades

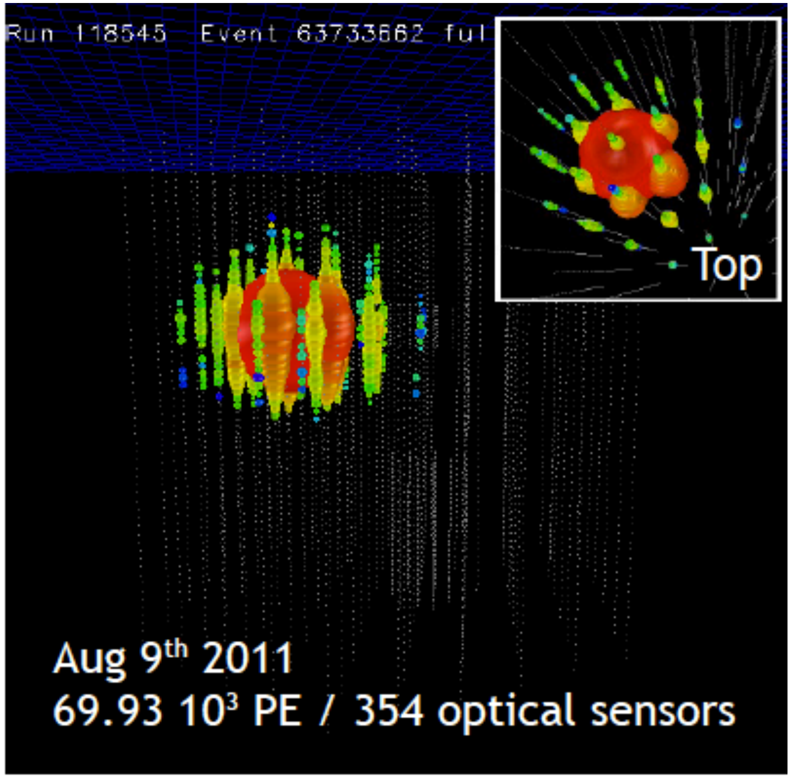
2.9 σ overfluctuation
from IC79/IC86 EHE

The first PeV (cosmic?) events in IceCube!

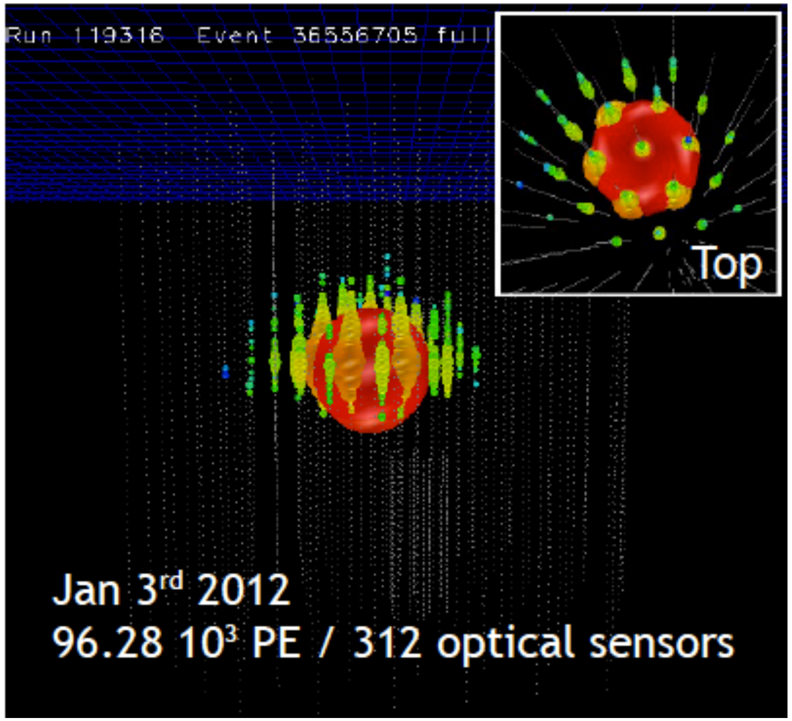
- 2 events / 672.7 days
  pass all selection criteria
- expected from atm. muon and conv.
  neutrino background: 0.14 events
- preliminary p-value: 0.0094 (2.36σ)
- cascade-like events:
  expected from CC & NC events with
  particle showers in the final state



If IceCube sees high energy cosmic neutrinos
then would strengthen case for Km3NeT ...



Aug 9th 2011
69.93 10^3 PE / 354 optical sensors



Jan 3rd 2012
96.28 10^3 PE / 312 optical sensors

Gravitational wave astronomy too may soon open a new window on the universe

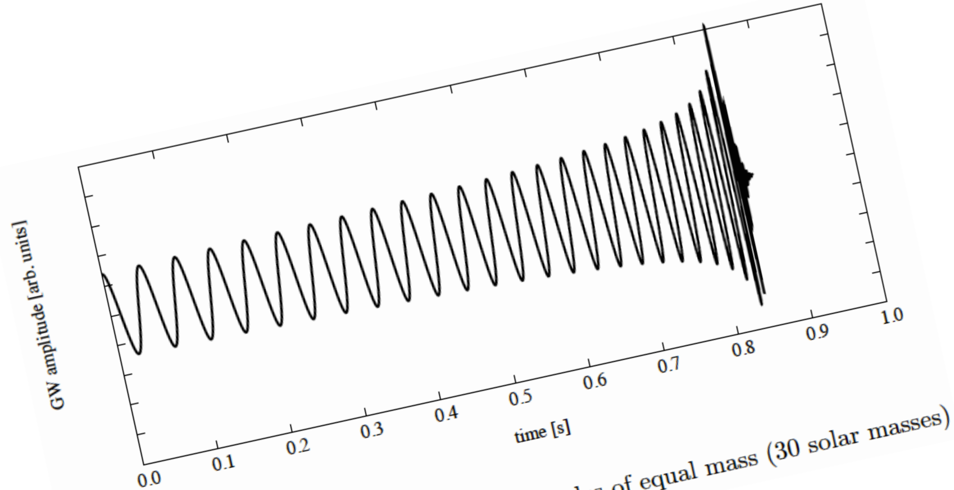
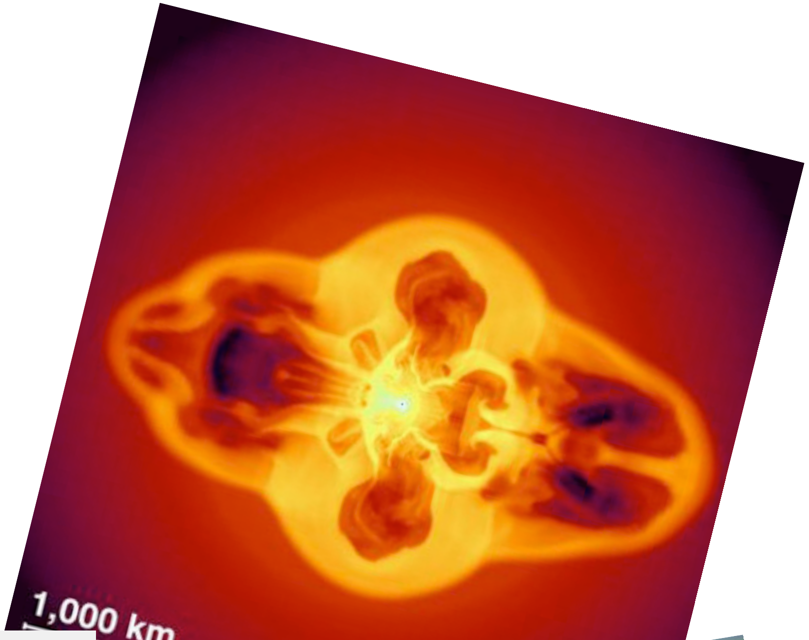
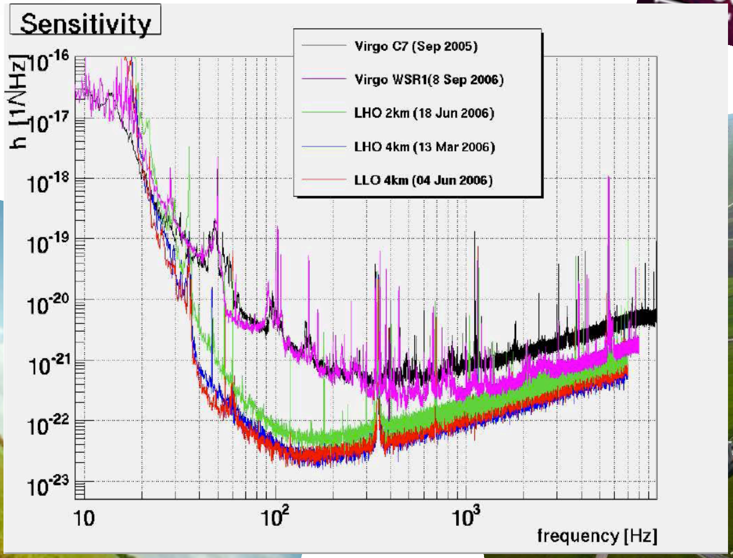


Figure 6: Coalescence signal for two black holes of equal mass (30 solar masses)





ET

Auger N

CTA

KM3NeT

1 ton
DM

1 ton
NM

Megaton
NNN

Common with Astrophysics

ASTRONET

Common with Particle Physics

CERN Strategy Group

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."
>
> Marcel Proust (*La Prisonnière, À la recherche du temps perdu, 1923*)