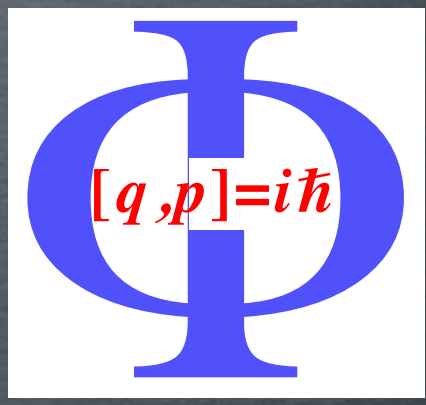
The 2014 CERN Summer Student Programme

Astroparticle Physics (3/3)

Laura Covi

Institute for Theoretical Physics
Georg-August-University Gottingen



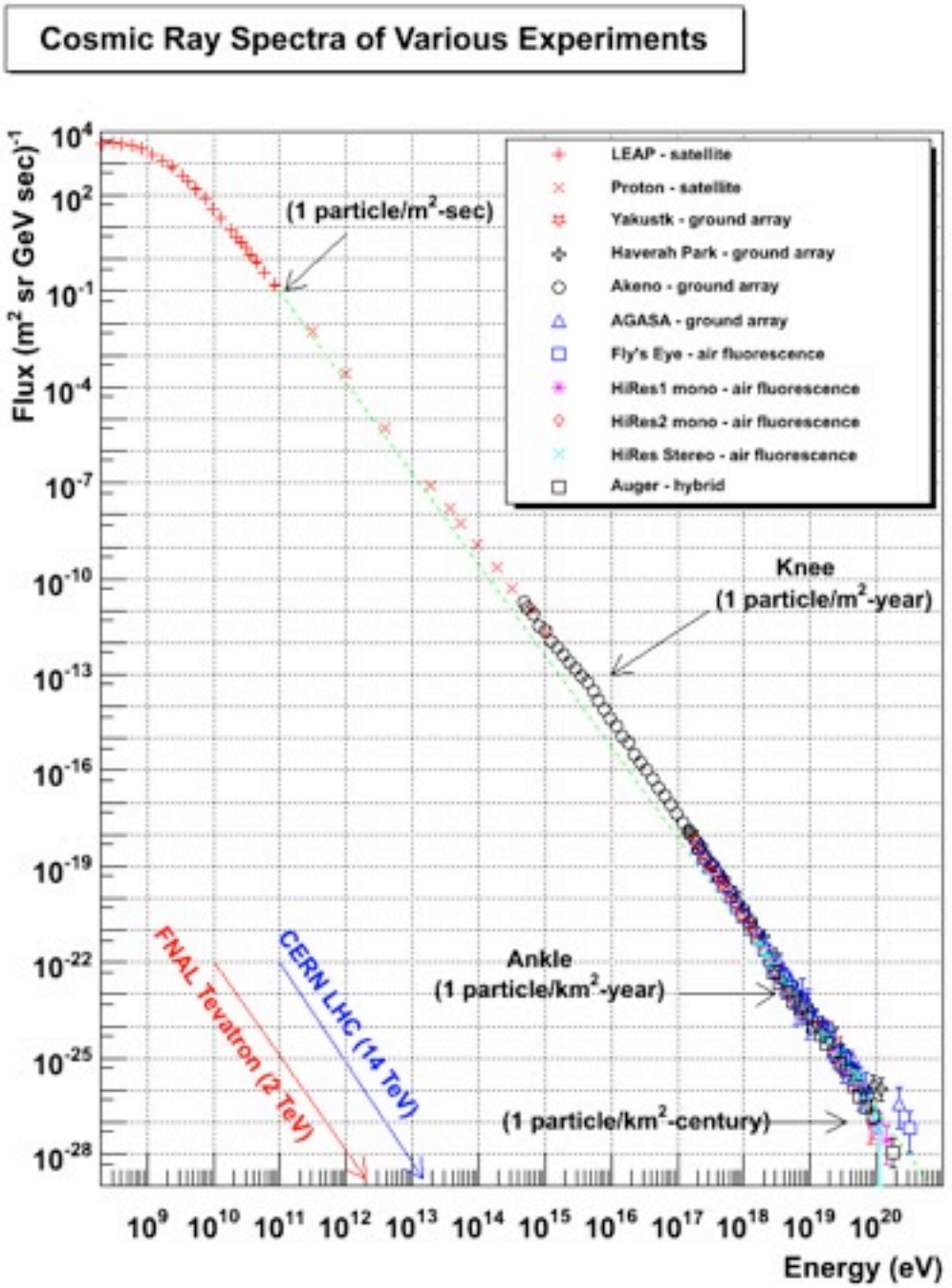
inVisibles
neutrinos, dark matter & dark energy physics

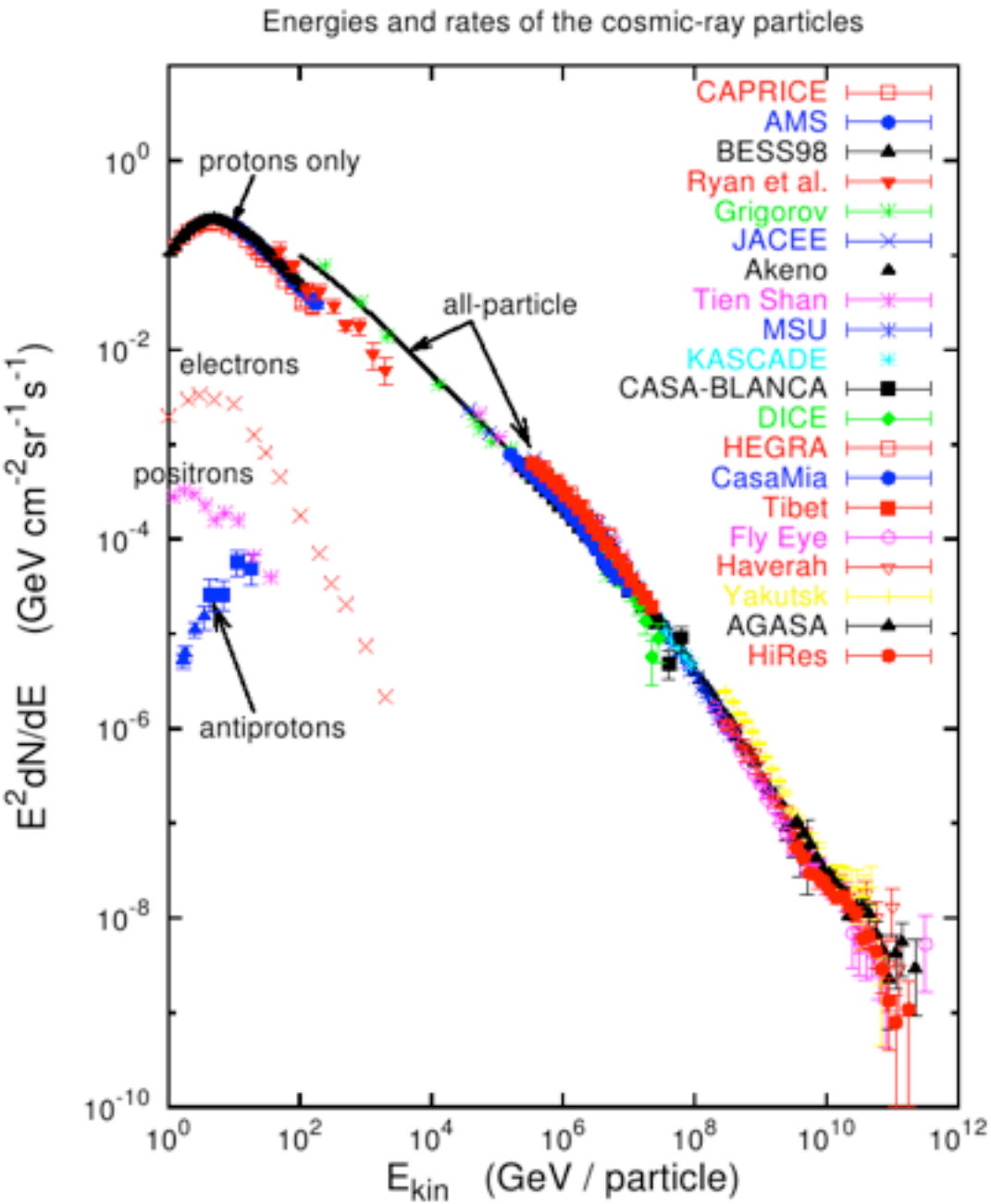
Outline

- Introduction:
  - The beginnings: 100+ years of cosmic rays
  - Basic concepts
- Dark Matter: a multi-particle and multi-wavelength/signal search
- Recent Data in cosmic rays and neutrino astronomy
- Outlook

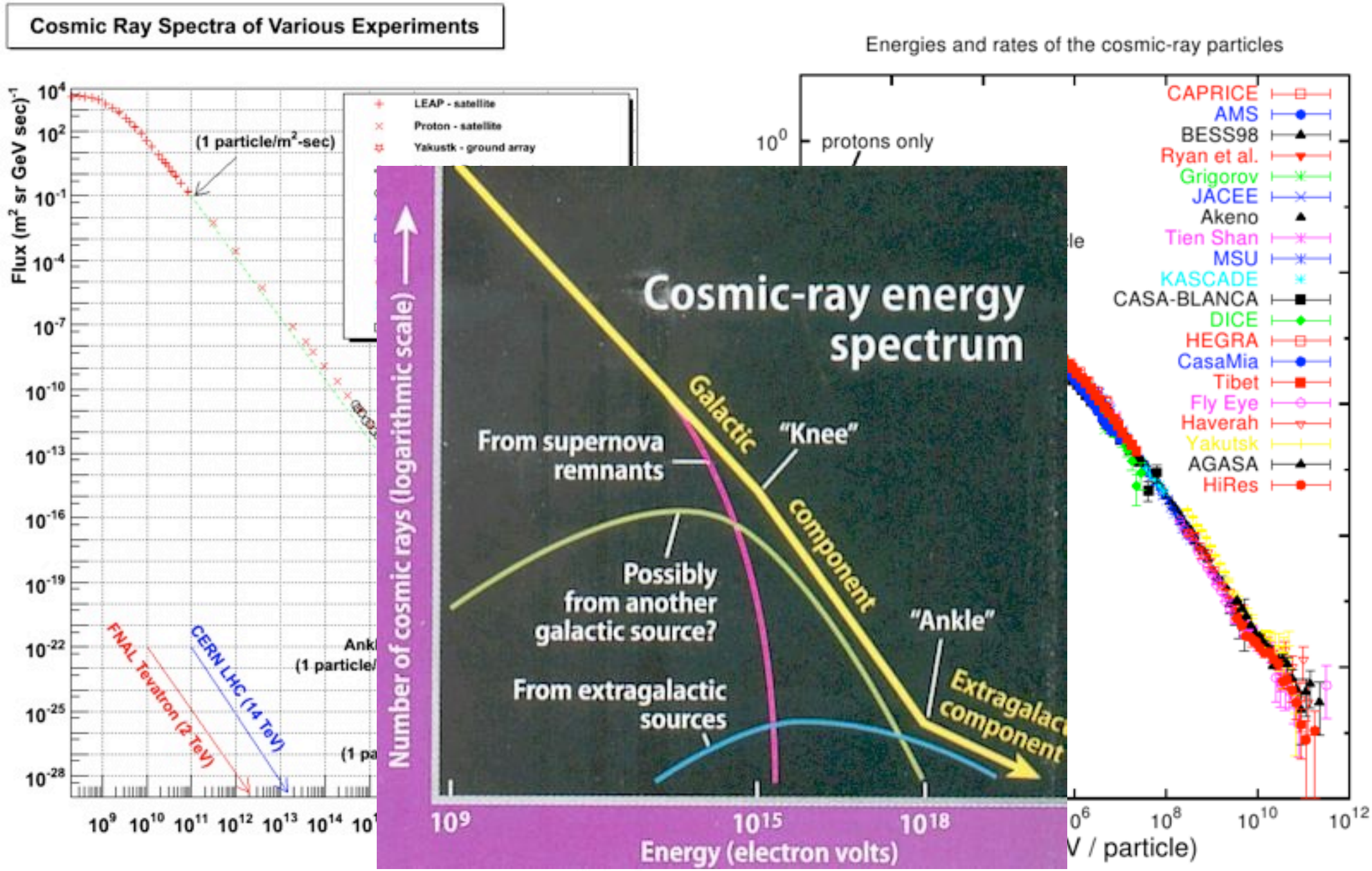
Cosmic Rays data

Cosmic Rays spectrum



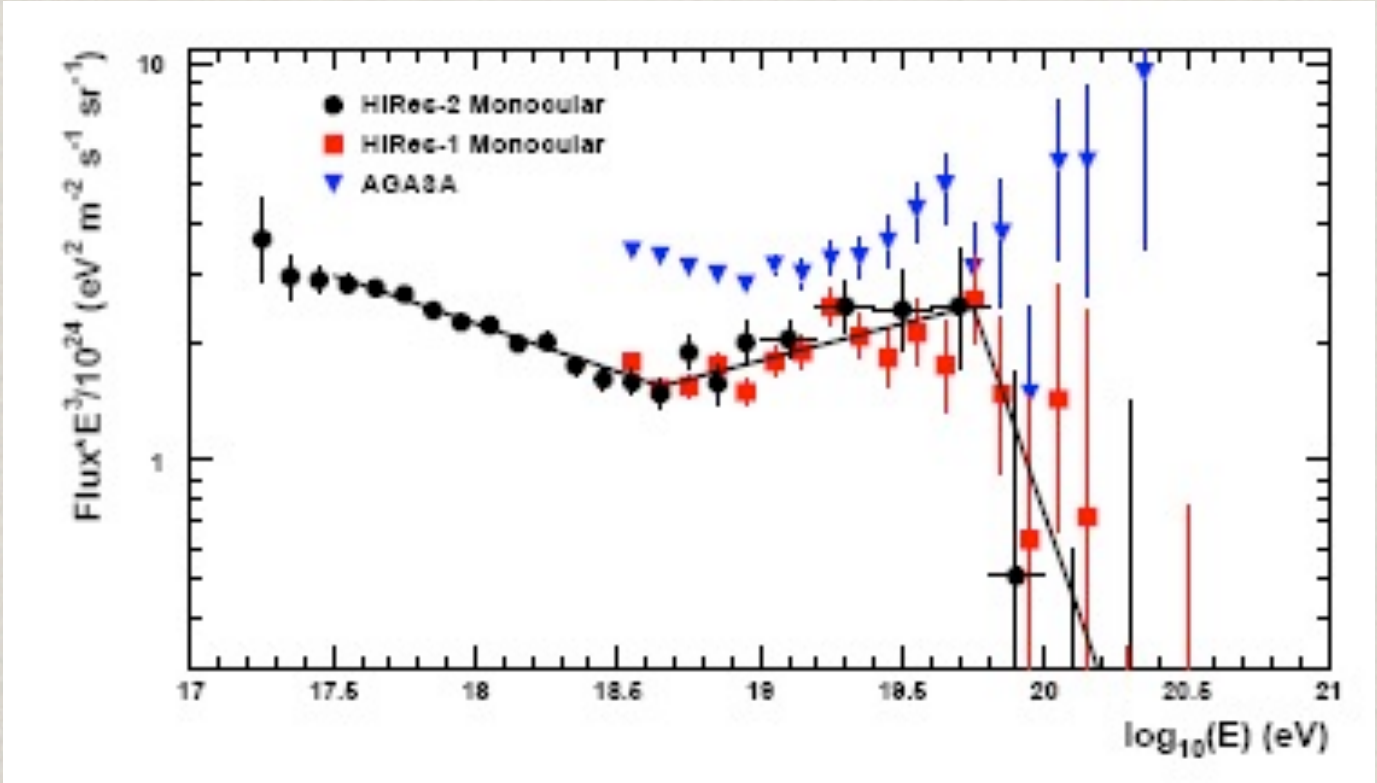


Cosmic Rays spectrum



UHECR & THE GZK CUT-OFF

Long controversy between AGASA and Hires experiments:
is there a GZK cut-off or not ???

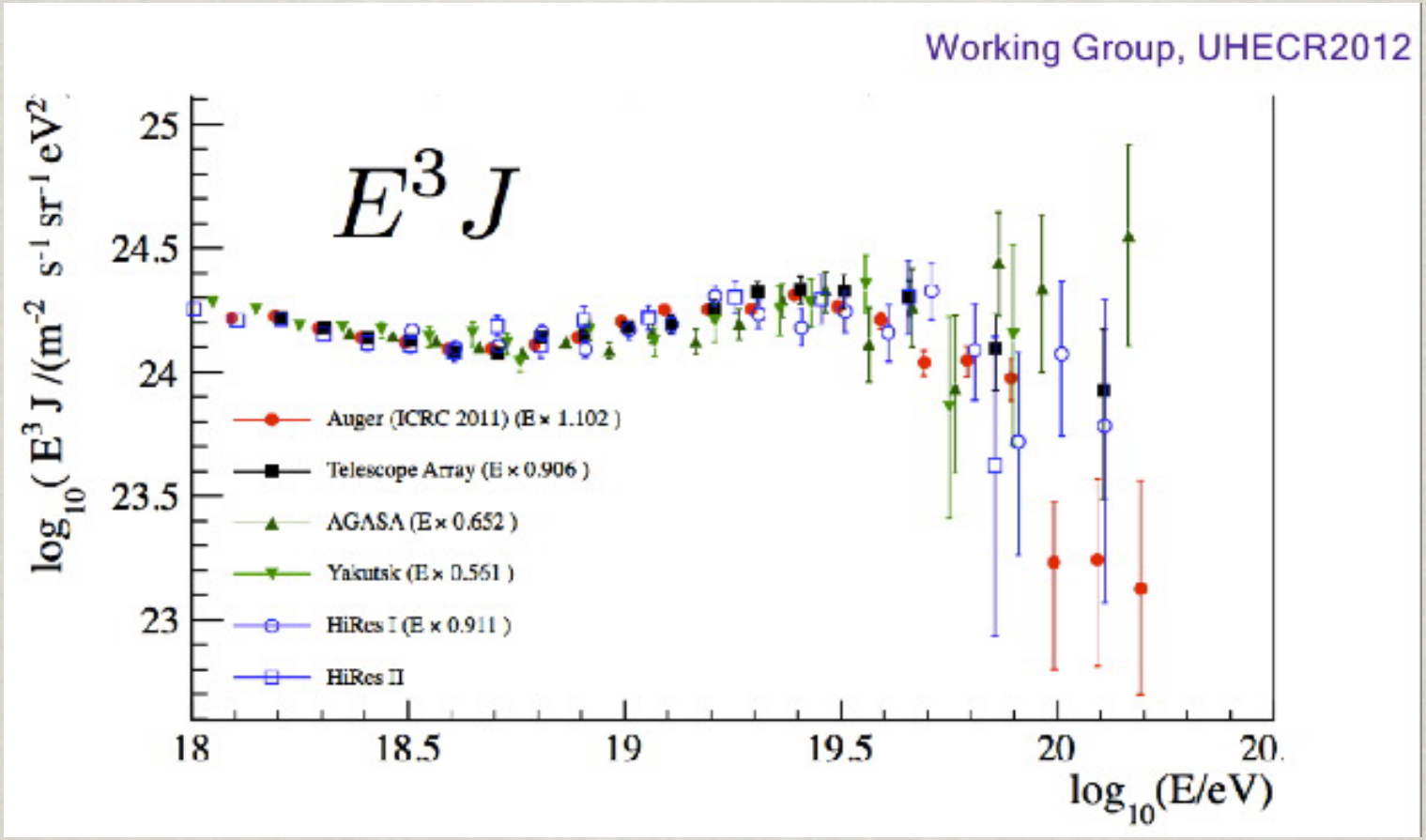


NO

YES

But they are not using the same technique: AGASA is a surface array (SA), while HIRes a fluorescence detector (FD)...

Auger & the GZK cut-off

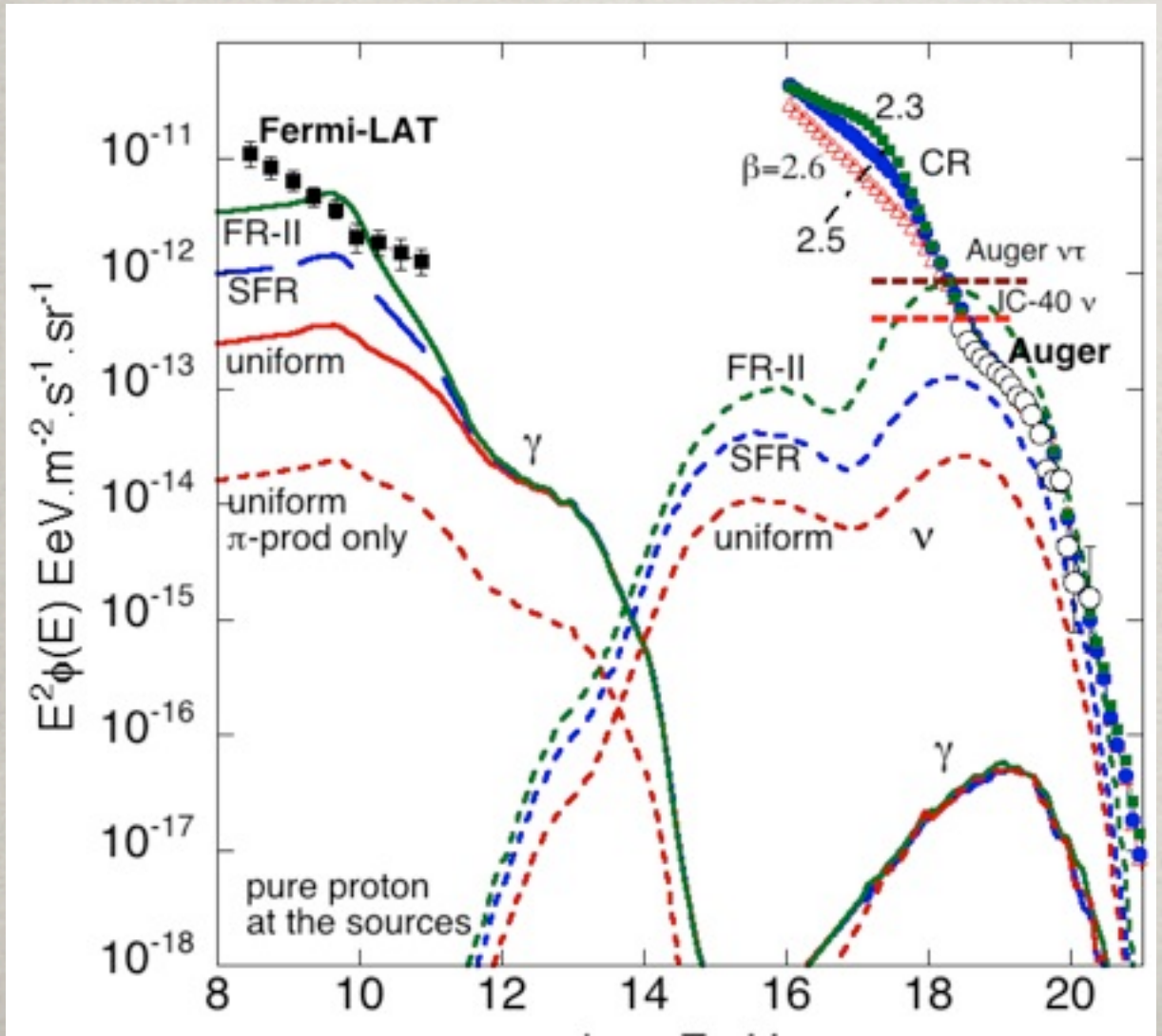


Controversy now solved by AUGER & TA , hybrid detectors with both SA and FD: the energy measured by the two methods differ ! Calibrating SA with FD one obtains good agreement between the experiments and sees a cut-off...

But absolute energy scale is still unclear !

But is it the GZK cut-off ?

Still not proved if the suppression of the flux is really due to the GZK process... It may also be the rarity of such high energy accelerators (recall the Hillas plot !).



How is it possible to disentangle the two ?

With neutrinos and gammas !

In fact the GZK pions decay and produce either neutrinos or gammas.

At the moment no neutrinos found yet...

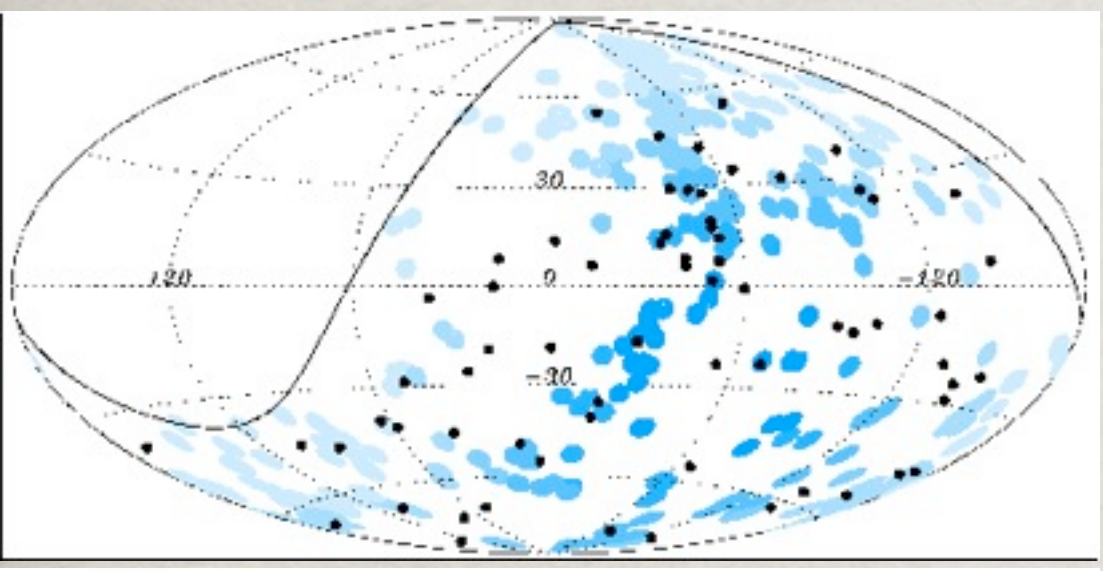
Sources of UHECR ?

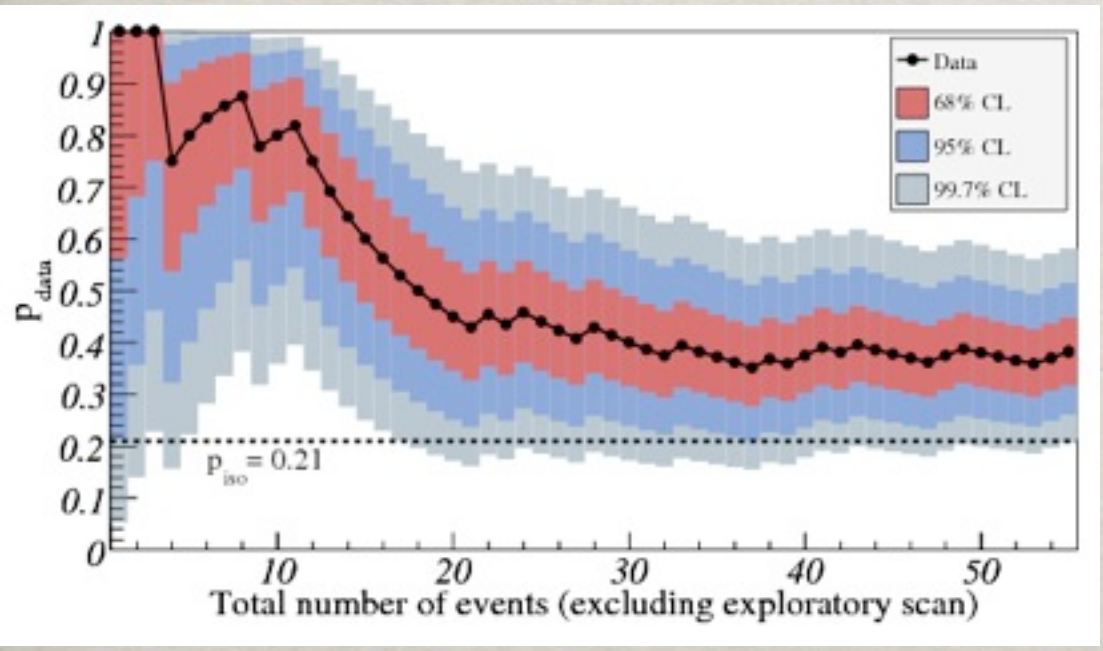
We have seen that different astrophysical object are candidates for the UHECR acceleration. Two informations could help to pinpoint the sources:

- Directional information: is the arrival direction of UHECR correlated with a particular type of source ? For so large energies protons are only weakly deflected by the magnetic fields, especially for nearby sources !

- Composition: are the UHECR protons (H) or heavier nuclei like iron (Fe) instead ? The depth of the first interaction in the atmosphere allows to distinguish (Fe interacts earlier than H but with large fluctuations !)

Correlation with AGNs



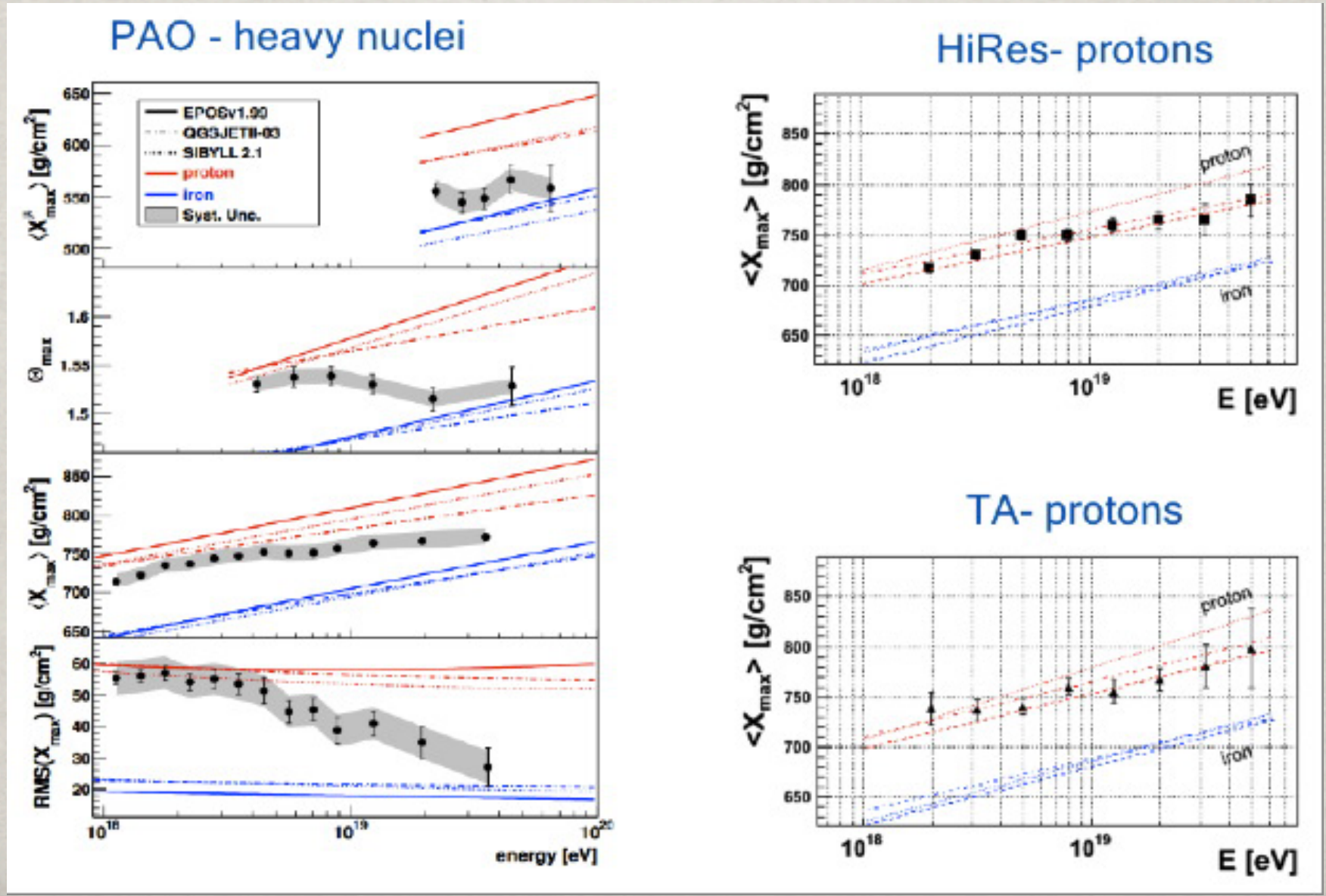


AUGER announced already in 2007 the detection of a possible correlation between UHECR and AGNs. Unfortunately the statistics became worse in the later years, but the signal is not completely lost... $\sim 3\sigma$ But is the correlation with AGNs or only with large scale structure ?

[Auger, arXiv:1009.1855 [astro-ph.HE]

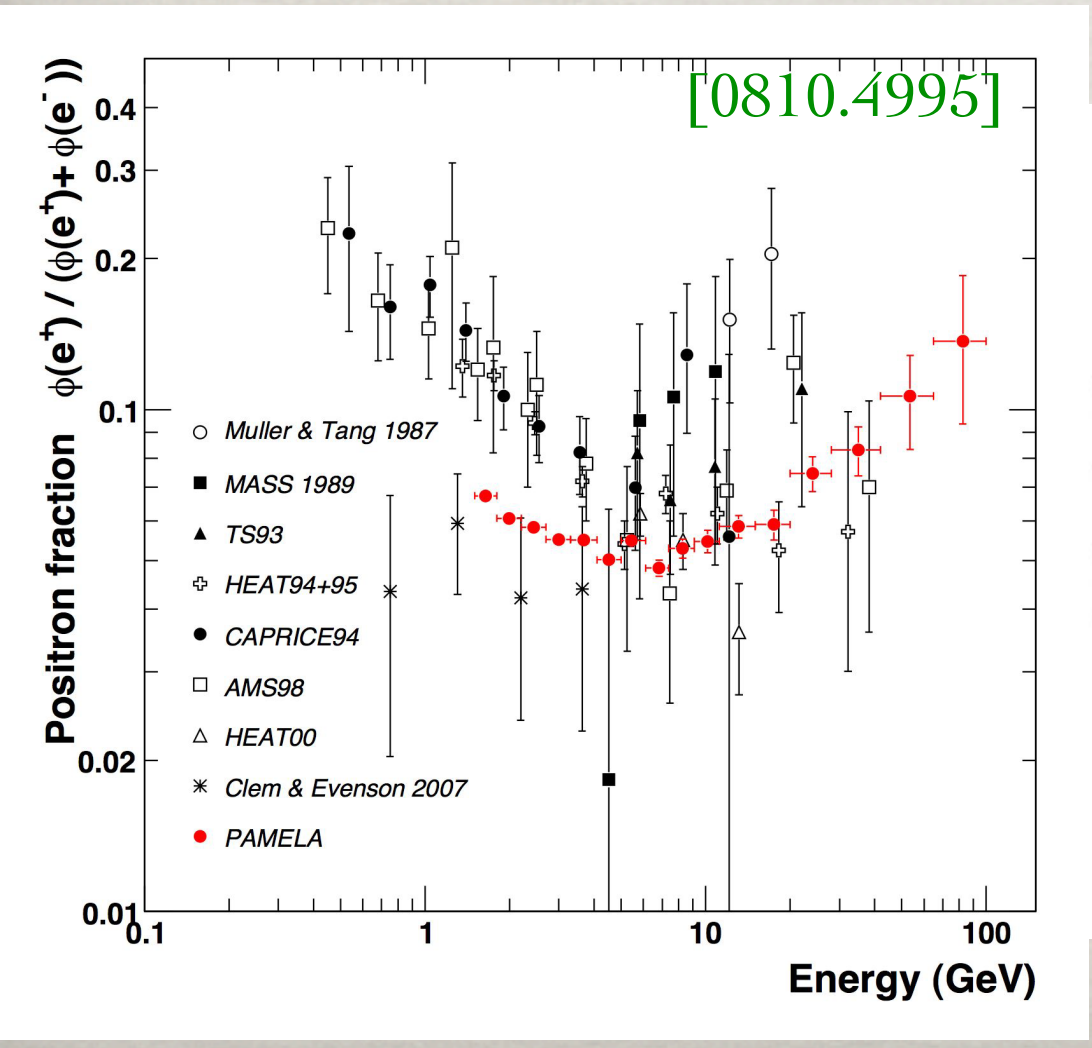
UHECR COMPOSITION

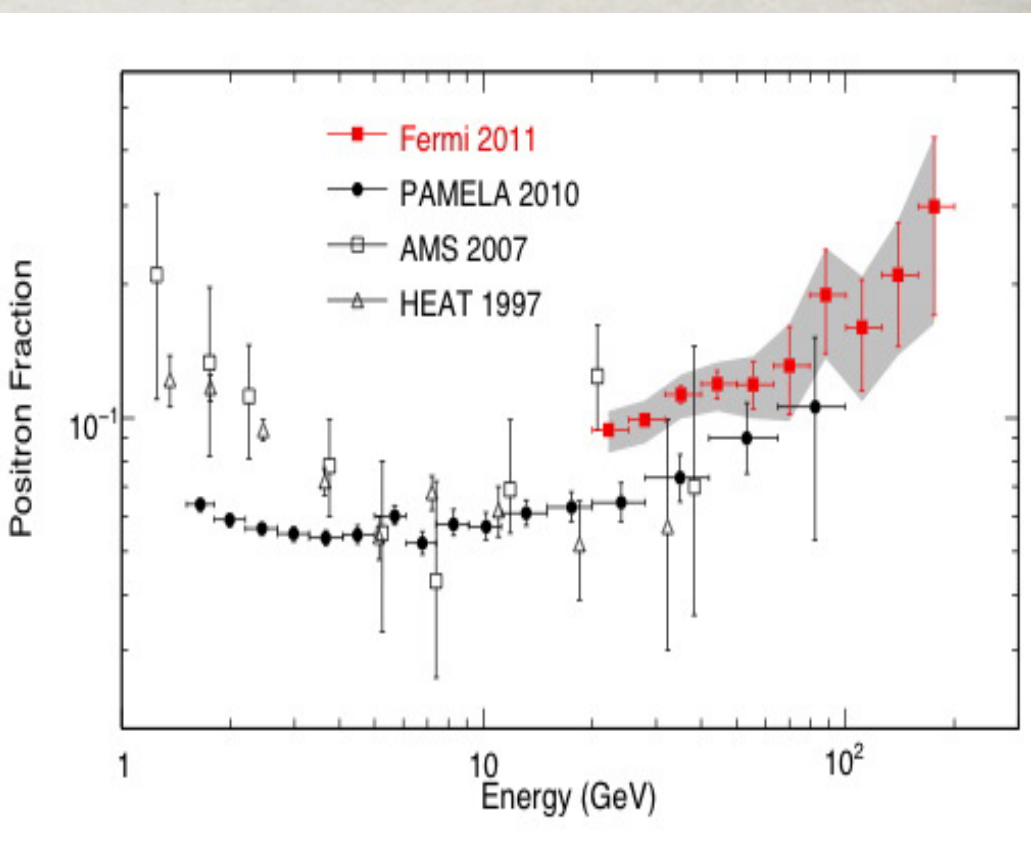
Open question: the different experiments are not in agreement...



Antimatter in CR: positrons

In 2008 PAMELA observes a rising positron fraction, later confirmed by FERMI (exploiting Earth magnetic field !):





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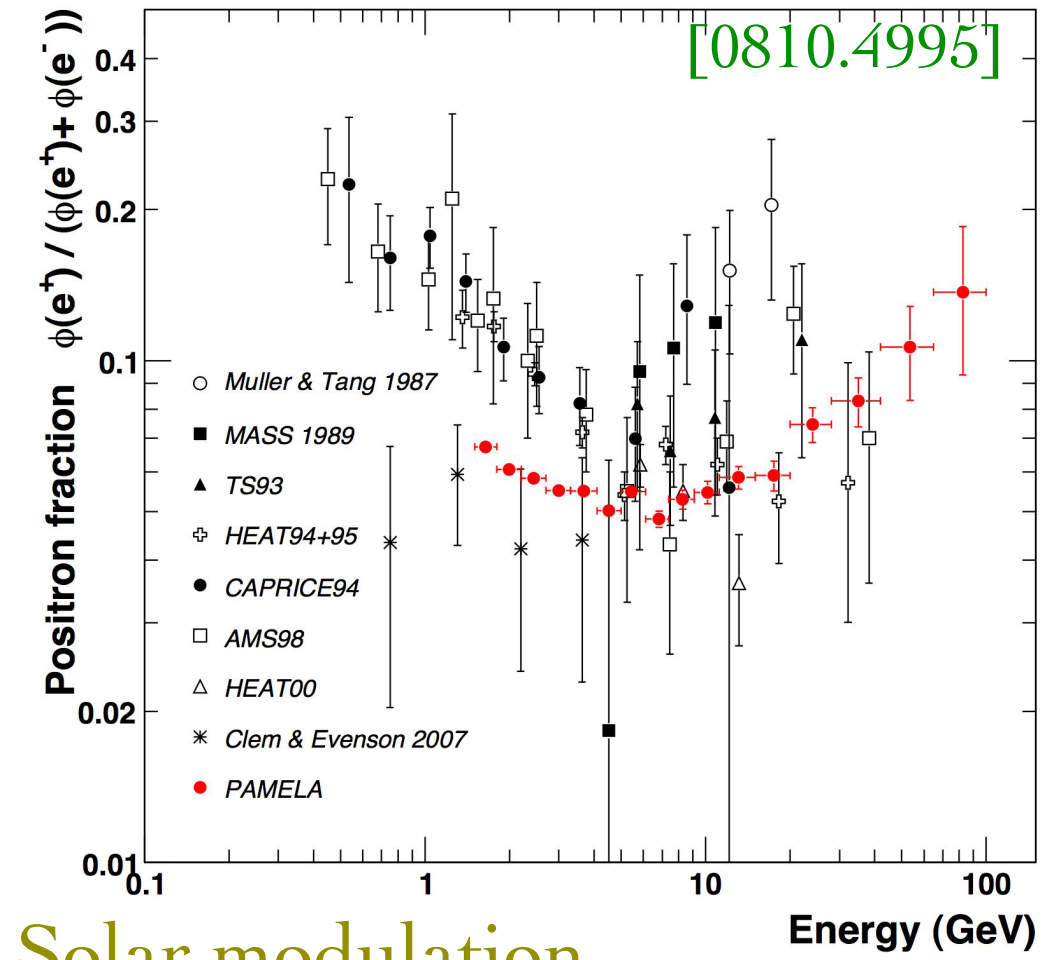
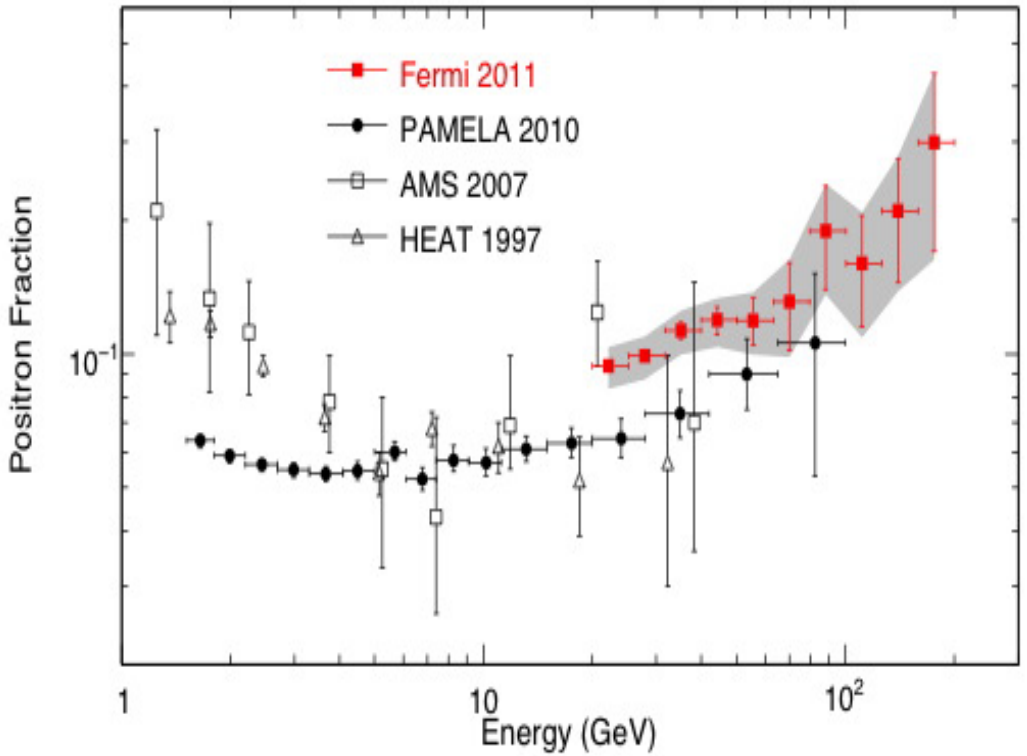


Solar modulation



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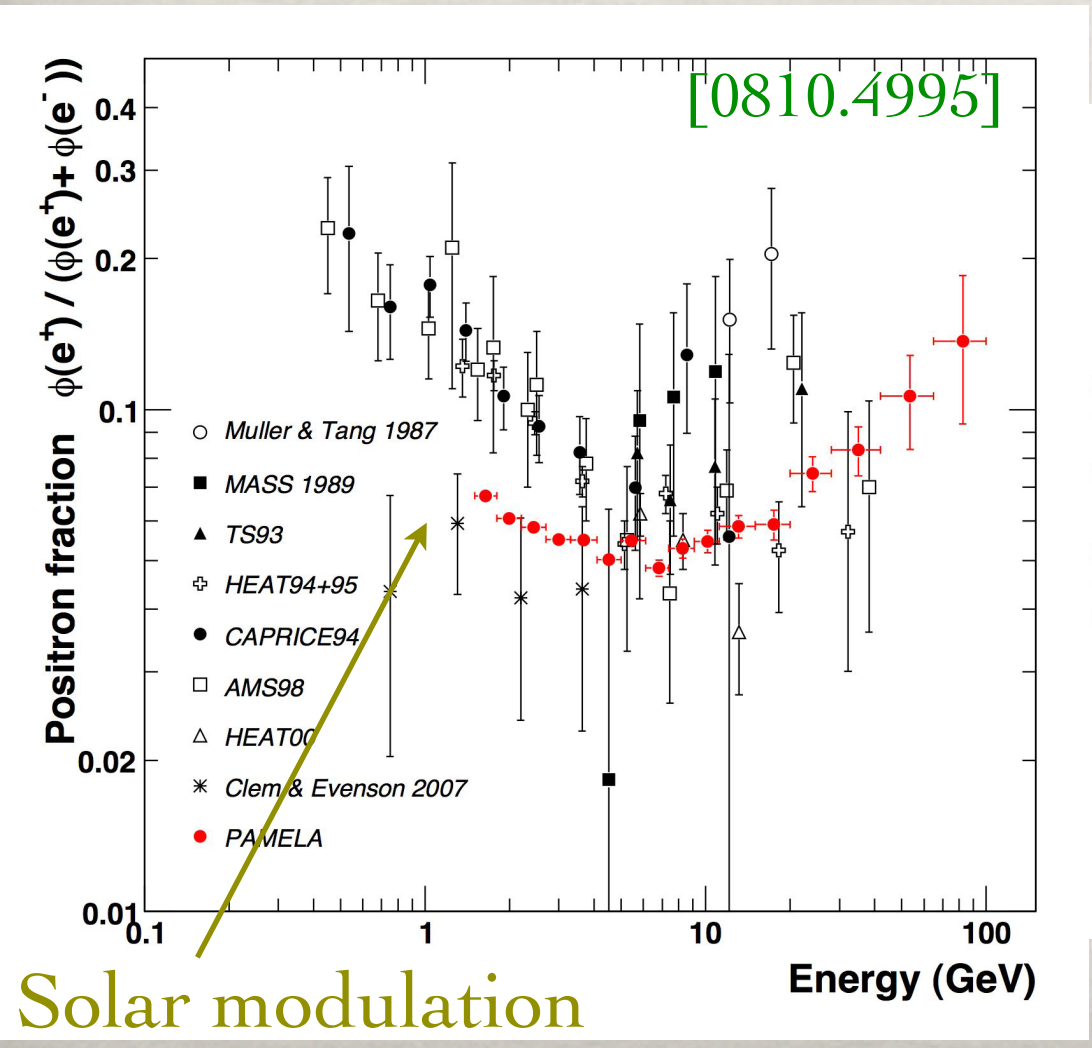
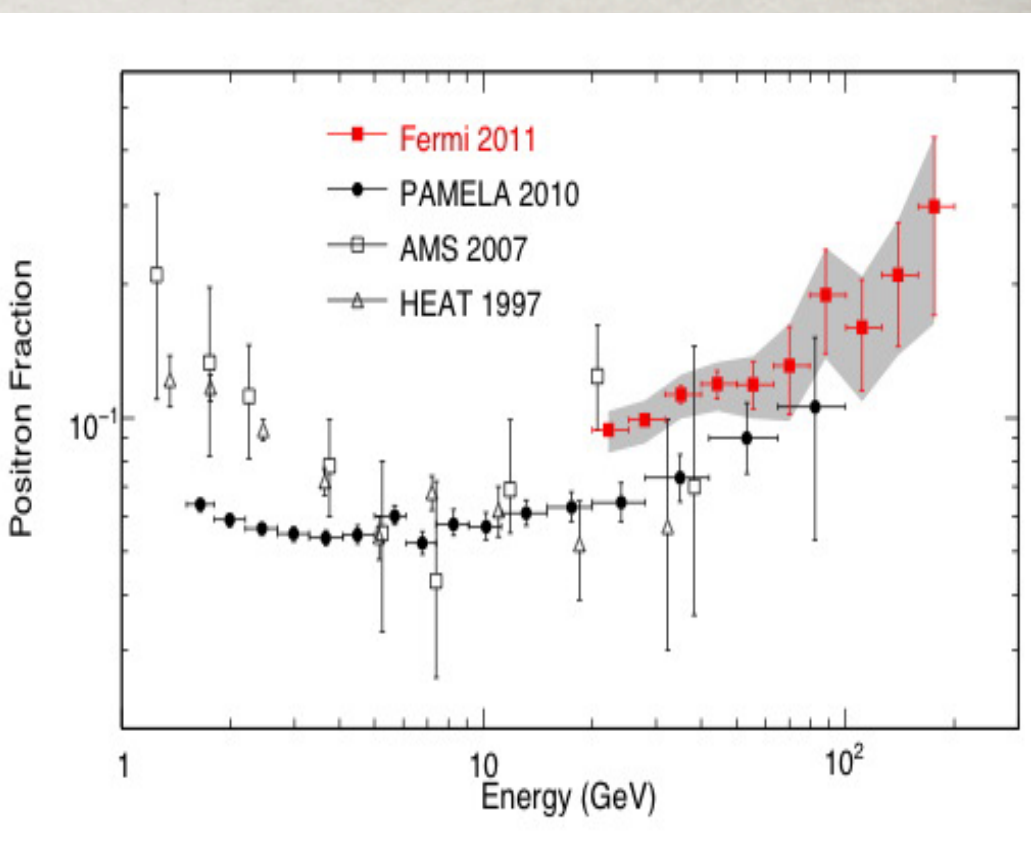
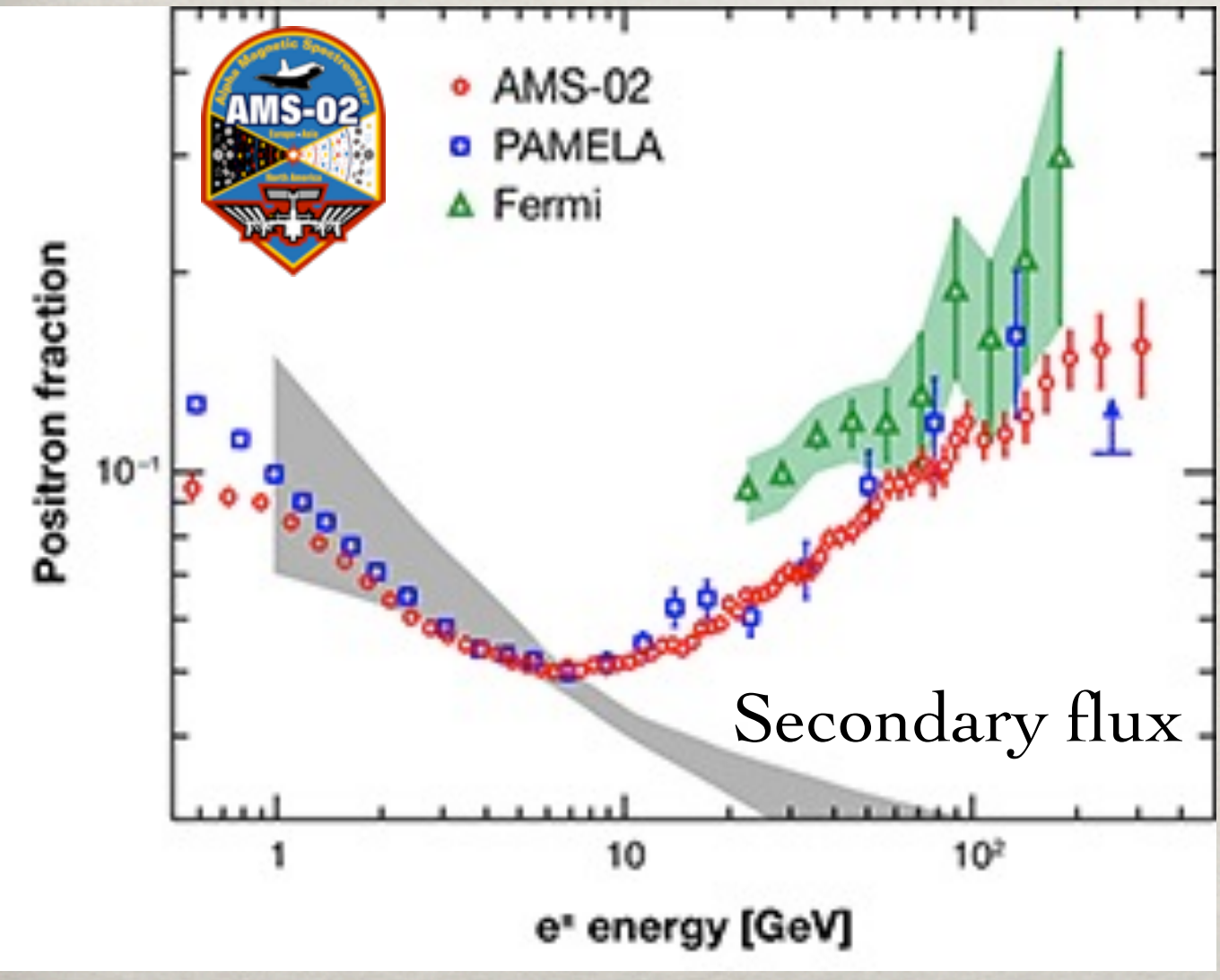




Antimatter in CR: positrons

AMS-02 confirms PAMELA and FERMI !



Such a rising spectrum is not explainable by "secondary" positrons produced by CR propagation !

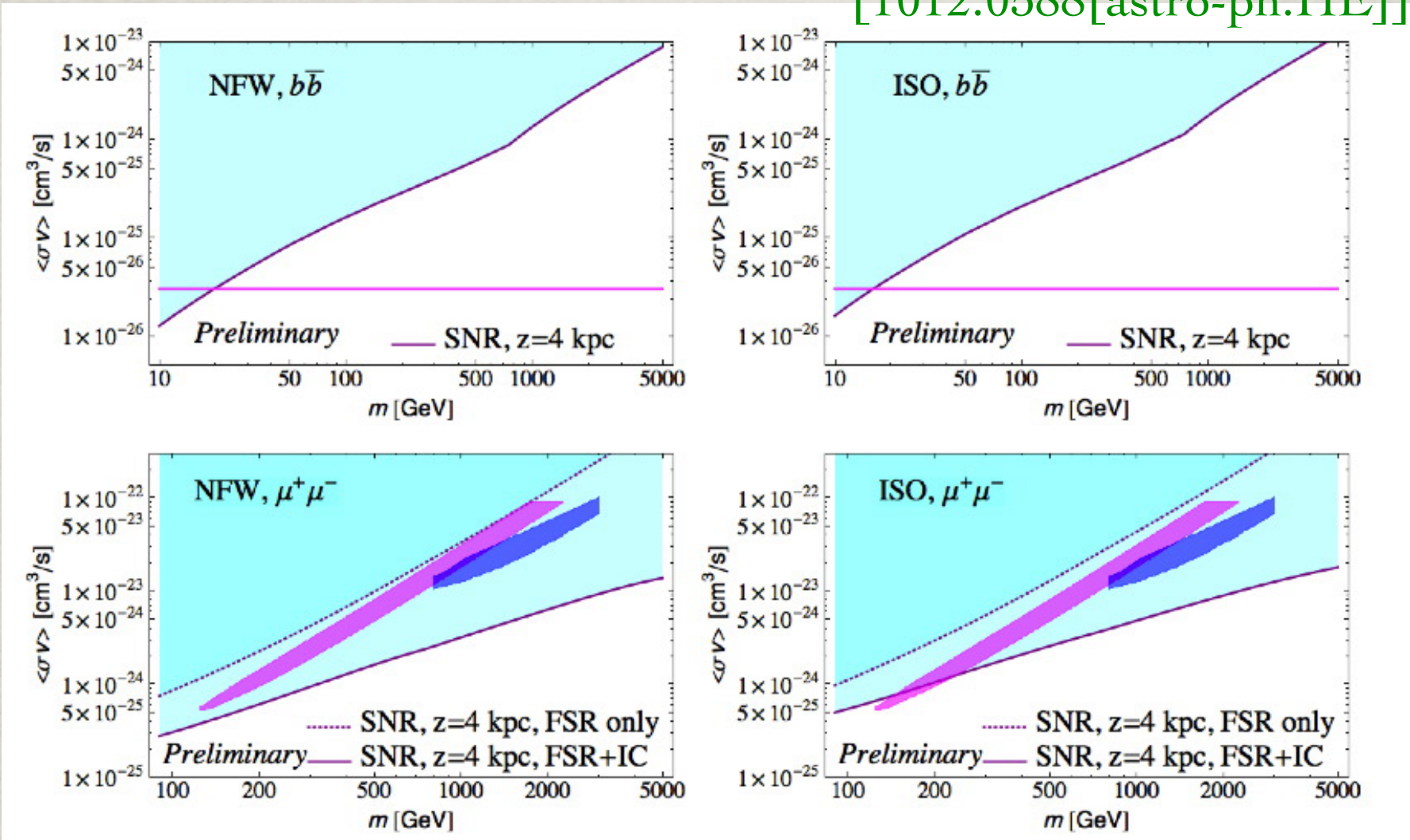
Need a positron source and not too far away...

Dark Matter or astrophysics ?

WIMP ANNIHILATION ???

The FERMI galactic flux gives bounds on the annihilation cross-section, depending on the channels/DM profile:

[1012.0588[astro-ph.HE]]

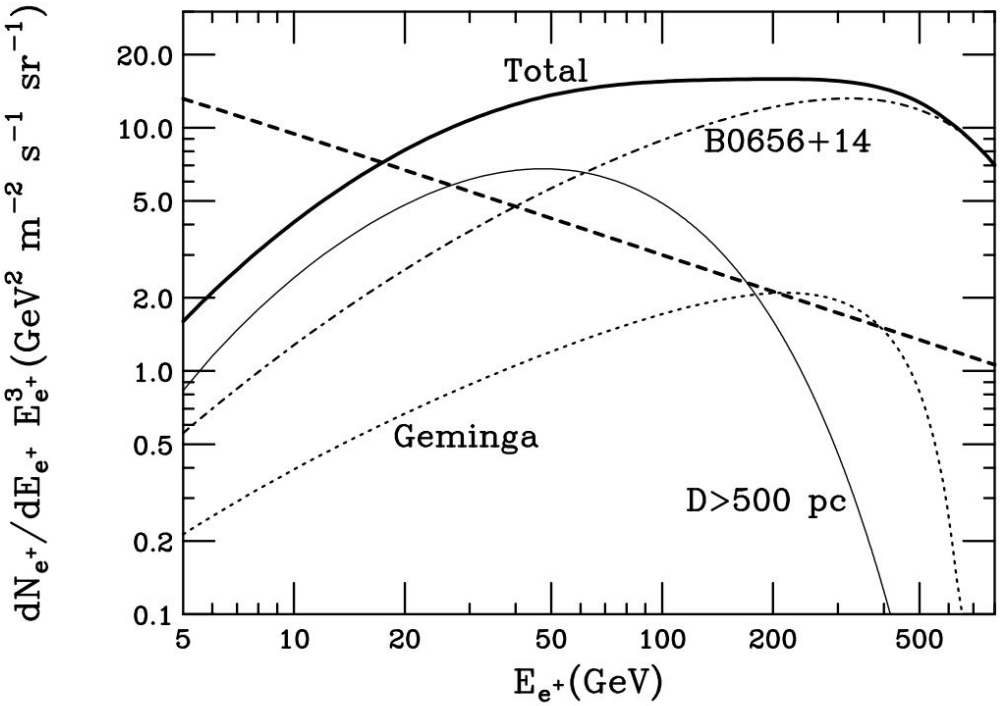


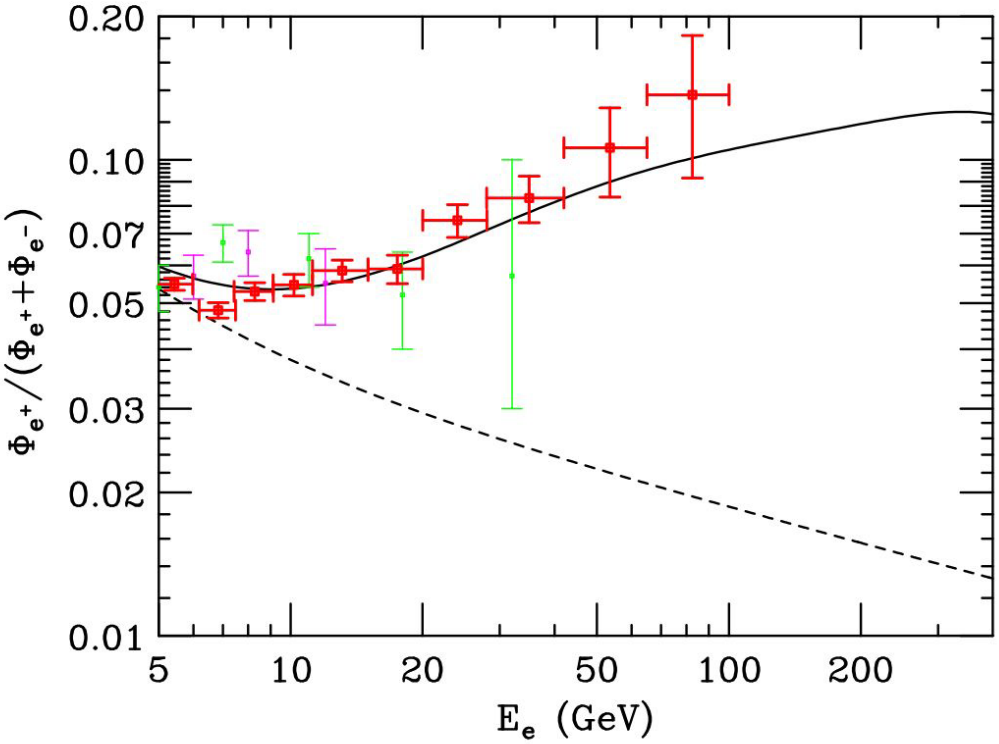
Weaker bounds from other targets: Dwarf galaxies, extragal, ...

Maybe it is a pulsar

One or more local pulsars may also be a source of positrons, producting e^+e^- pairs from their energetic gammas

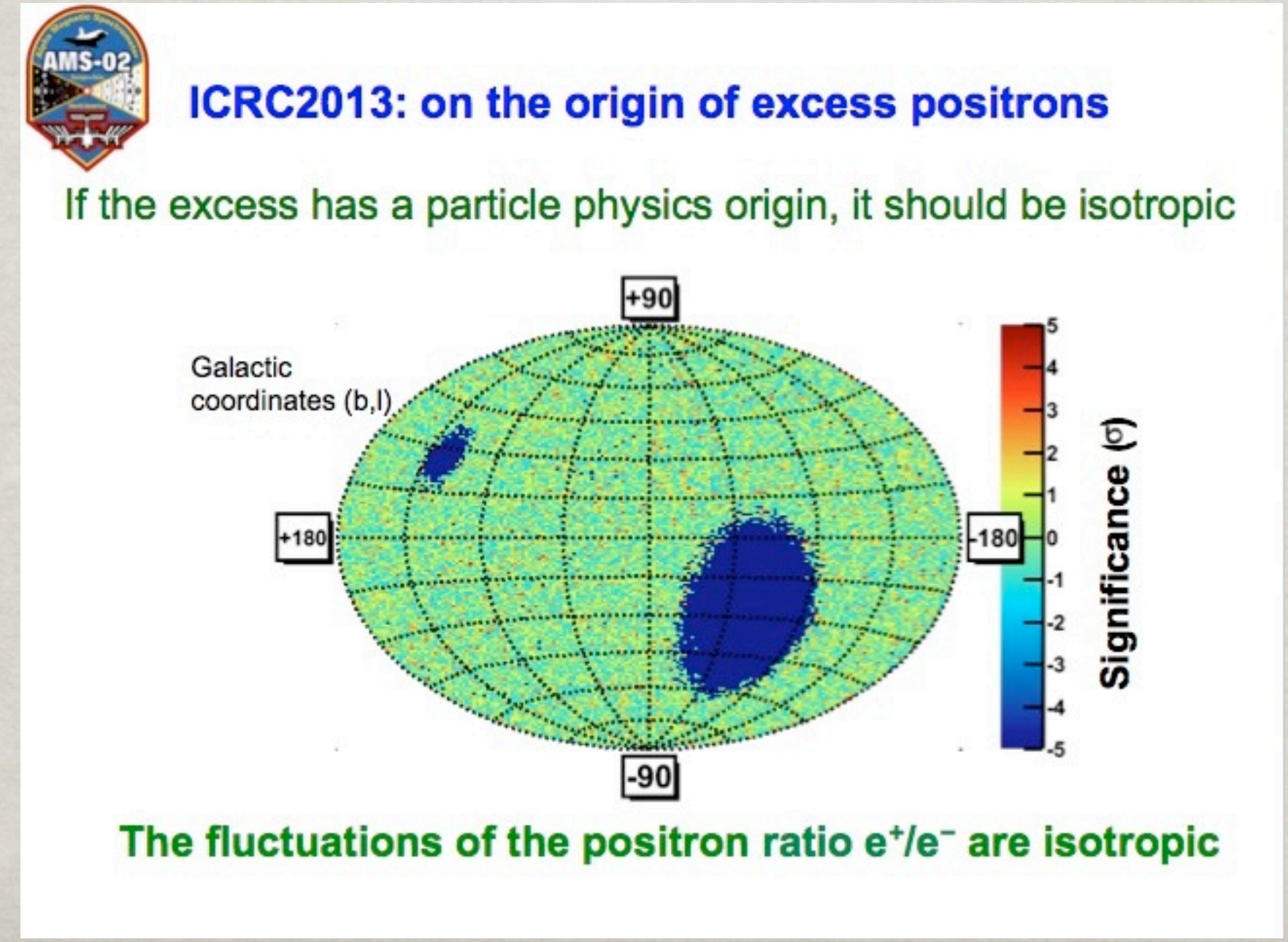
[Hooper, Blasi & Serpico 08]





Differences from DM signal: exponential cut-off and some small anisotropy, but of the order 0.05-0.1 %

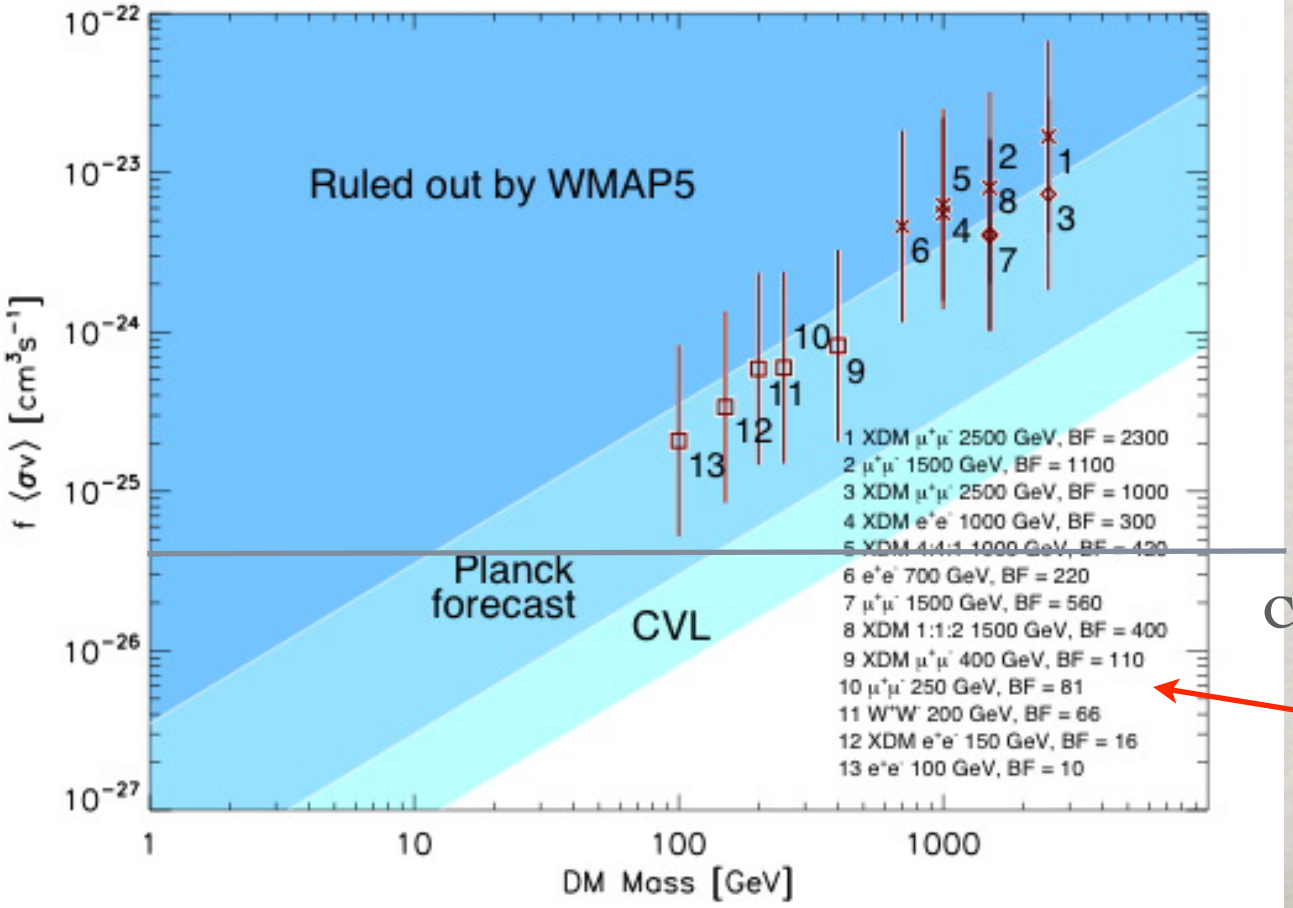
Anisotropy in positrons



PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leave imprints into the CMB ! WMAP already puts some constraints, but Planck will reach cross sections needed by PAMELA

[Slatyer, Padmanabhan& Finkbeiner 0906.1197]



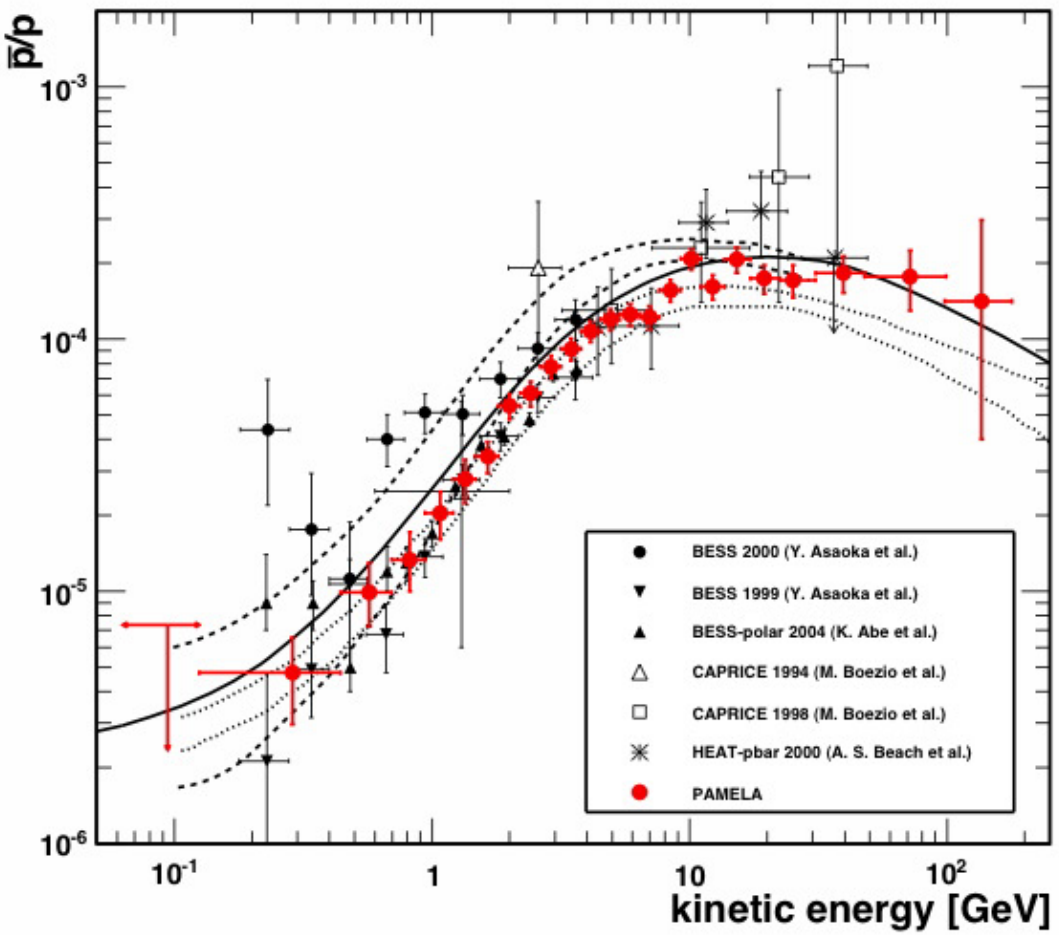
But, without polarization data the limit is weaker than WMAP limit !

Thermal cross-section

Pamela-inspired DM models

Antimatter in CR: antiprotons

[PAMELA, 1007.0821]

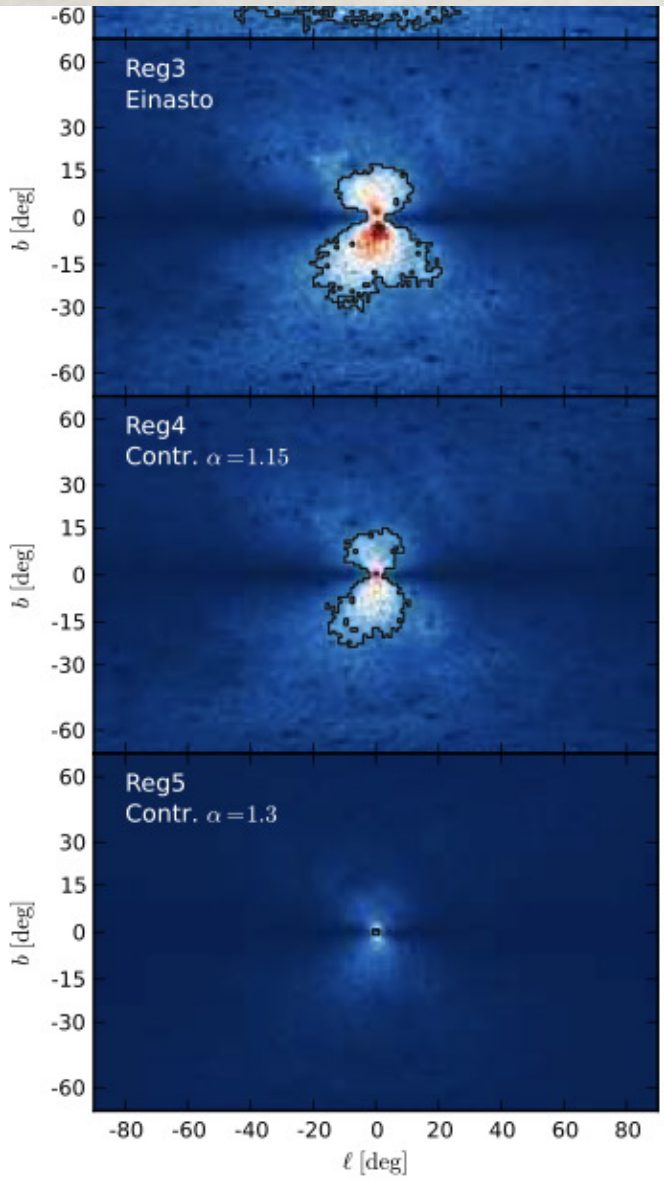


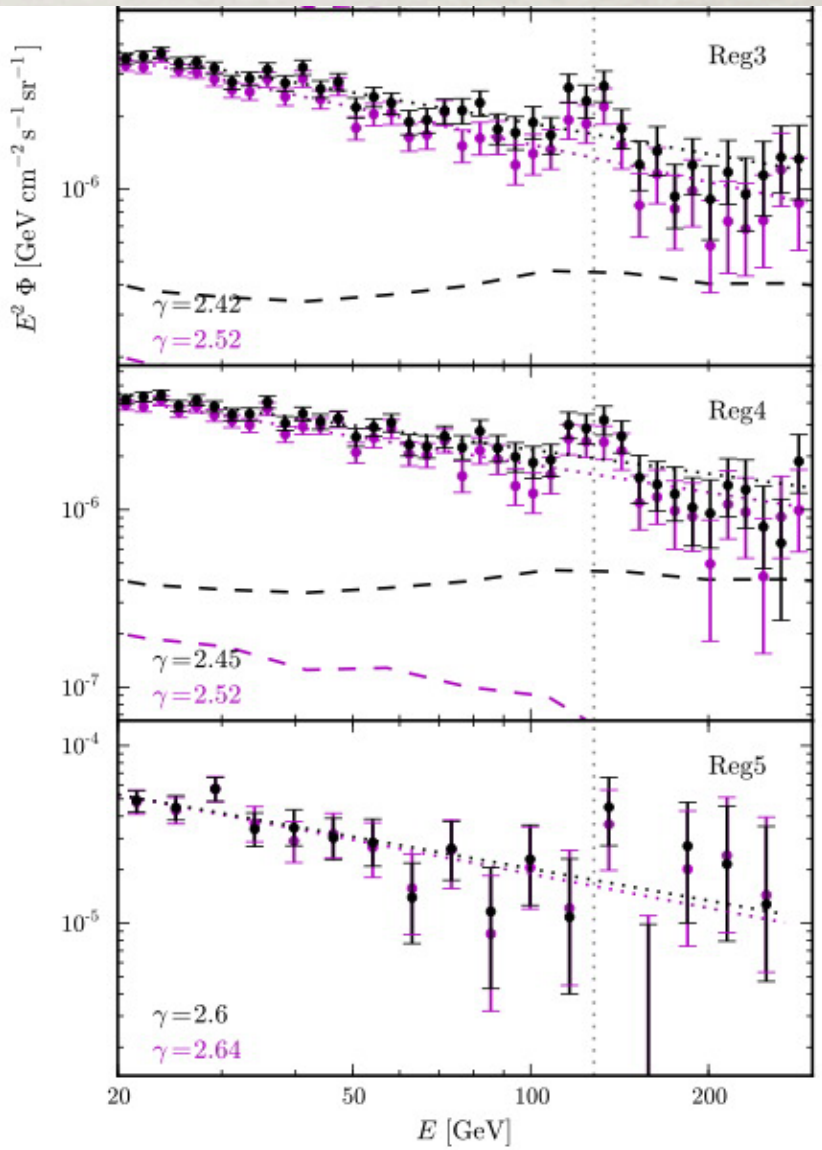
Antiproton fraction is instead consistent with spallation production from cosmic rays...
We are waiting for the AMS-02 data!

News from the sky

Possible line hidden in the FERMI data ?

Choose optimized regions in the sky: [Ch. Weniger, 1204.2797]

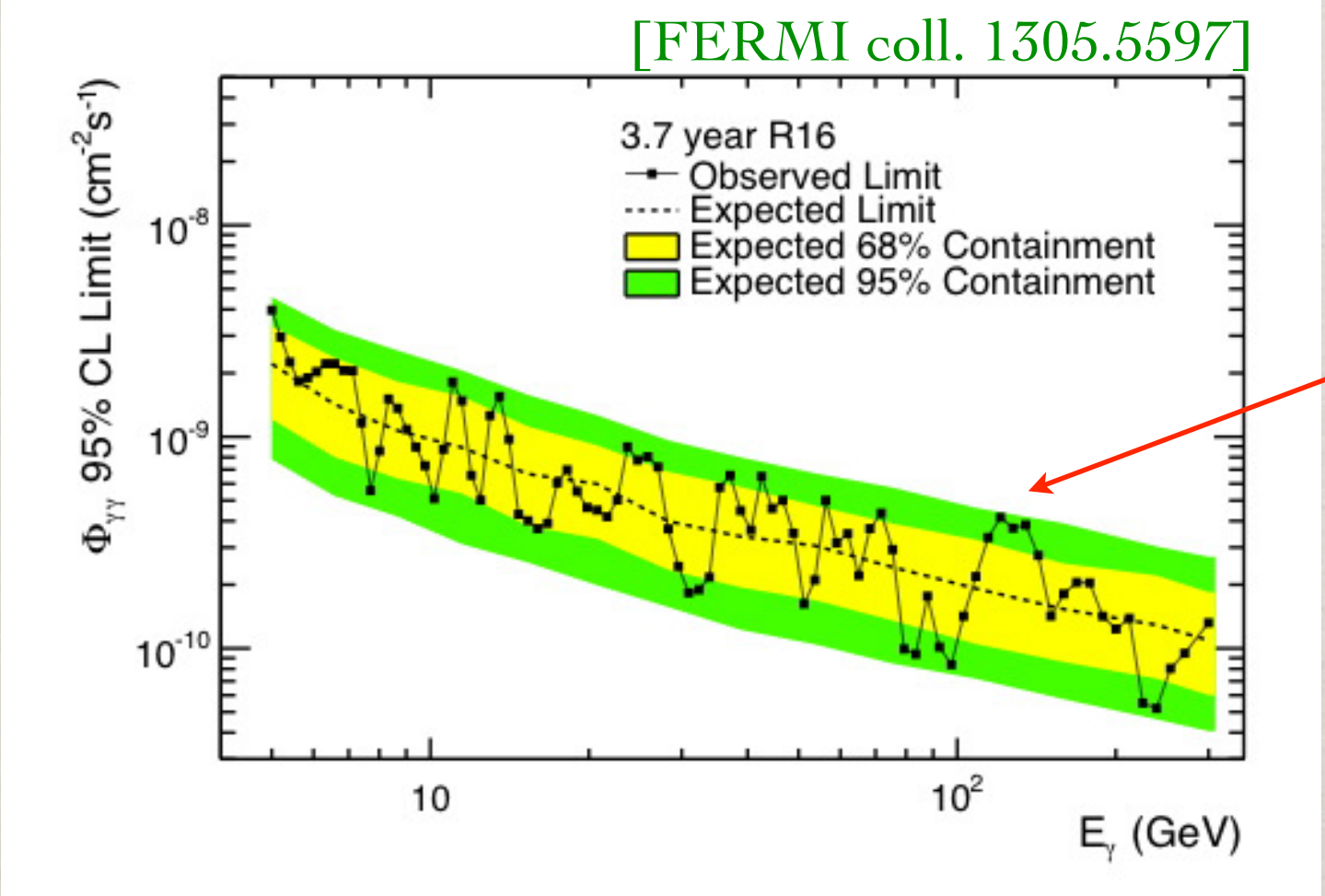




FERMI LINE

New analysis by the FERMI collaboration sees only an excess of $3.2\,\sigma$ (local) and $1.5\,\sigma$ (global)

[FERMI coll. 1305.5597]

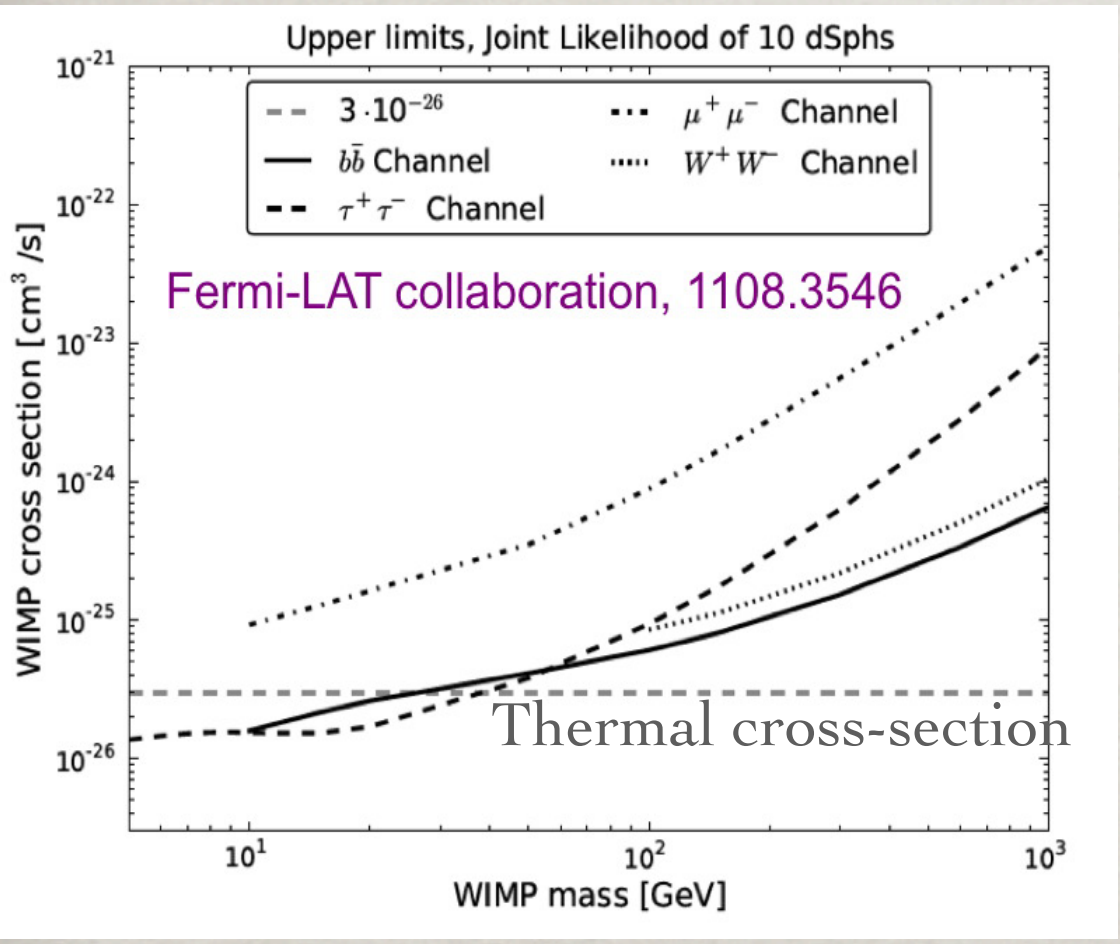


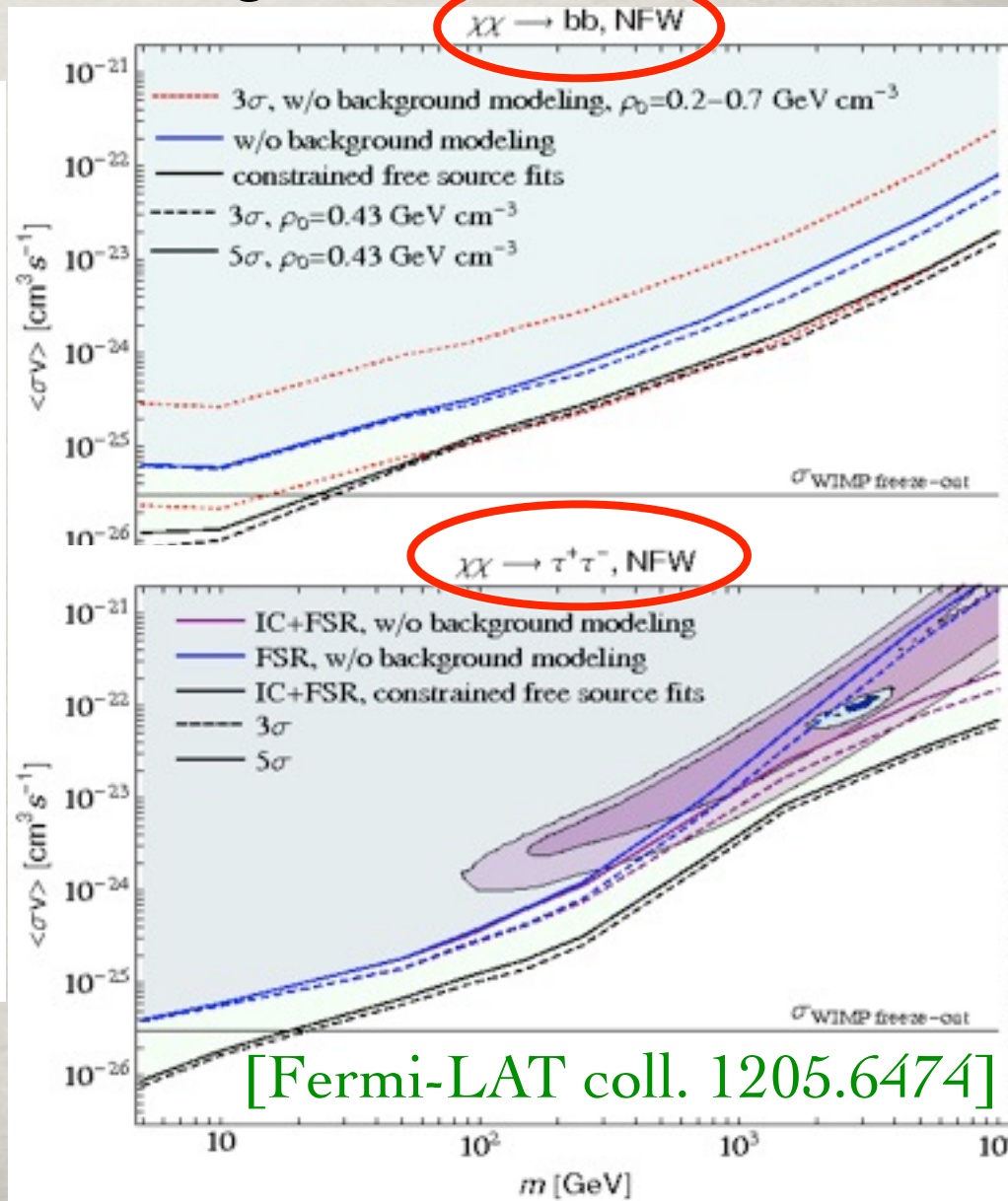
Line

Possibly a statistical fluctuation...

Bounds on the continuum

FERMI gives bounds on the gamma-ray emissions from satellite dwarf-galaxies and the galactic centre



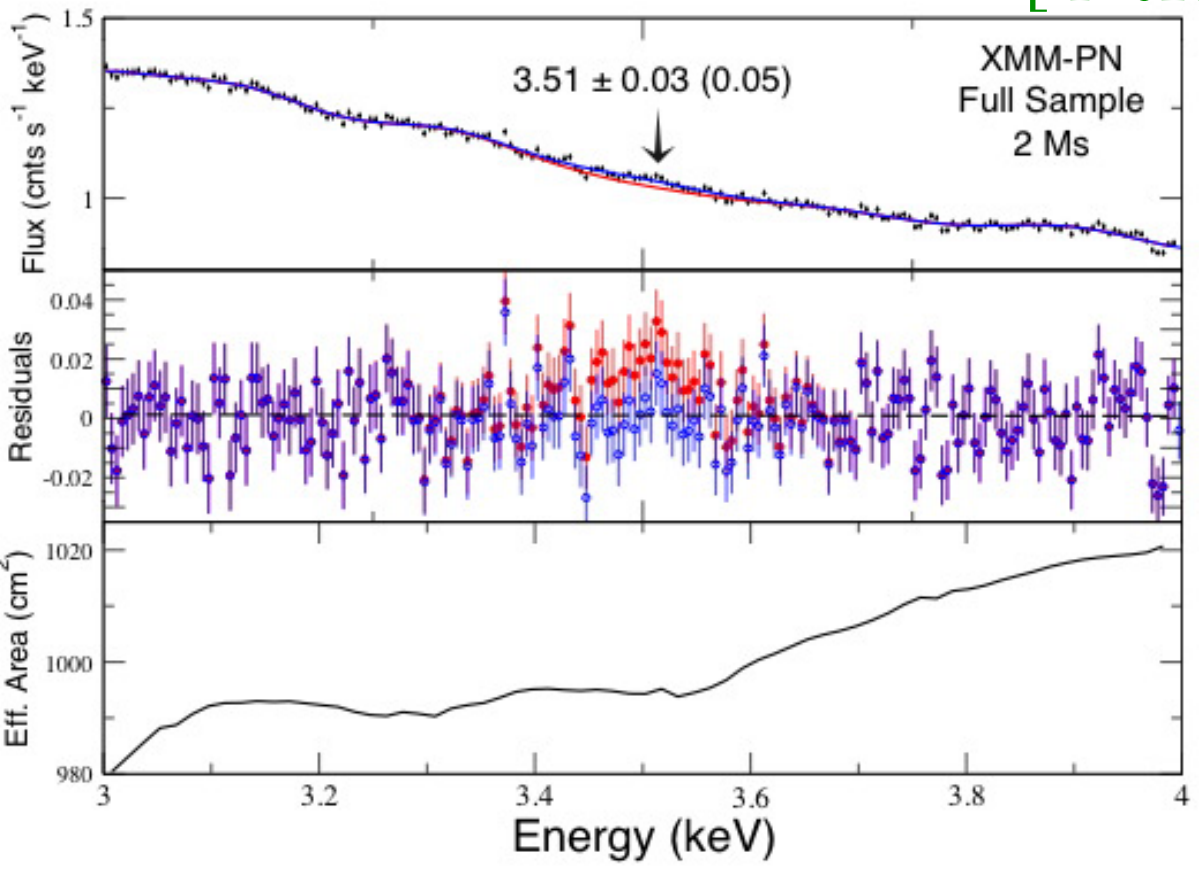


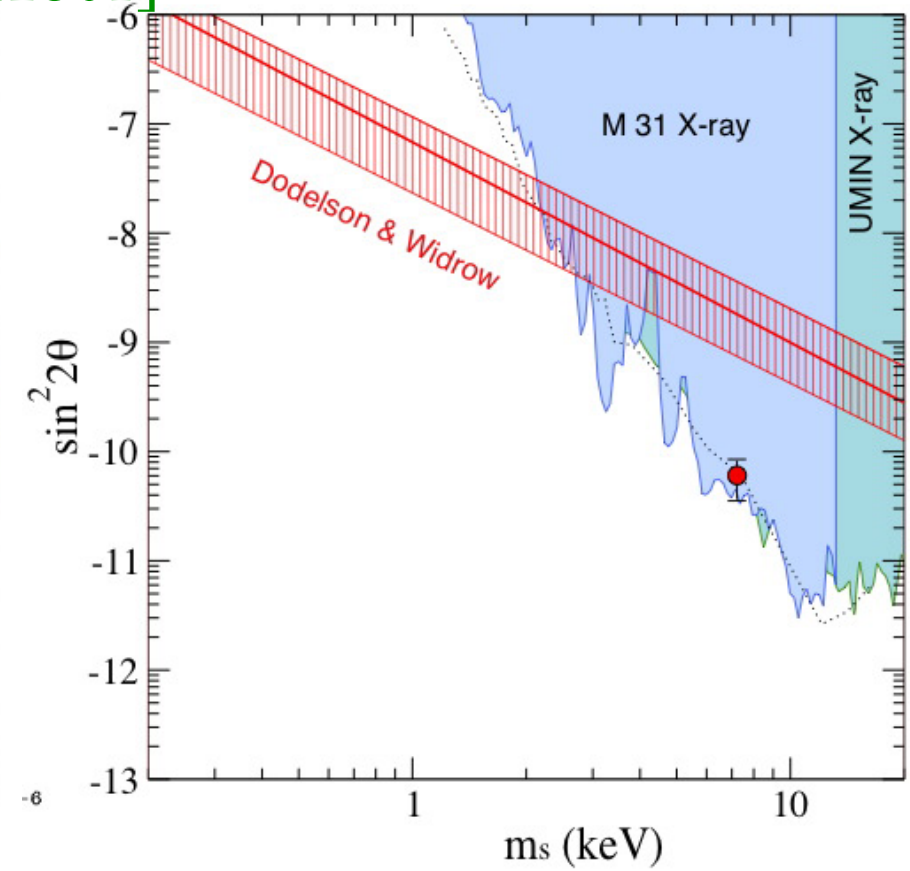
ν EWS FROM THE SKY

Possible new line in X-ray data at about 3.5 keV !
Seen both in stacked clusters and in Andromeda/Perseus.
[1402.2301, 1402.4119]

Not seen in Virgo or centre of Milky Way... [1405.7943]

[1402.2301]





Neutrinos

Atmospheric Neutrinos

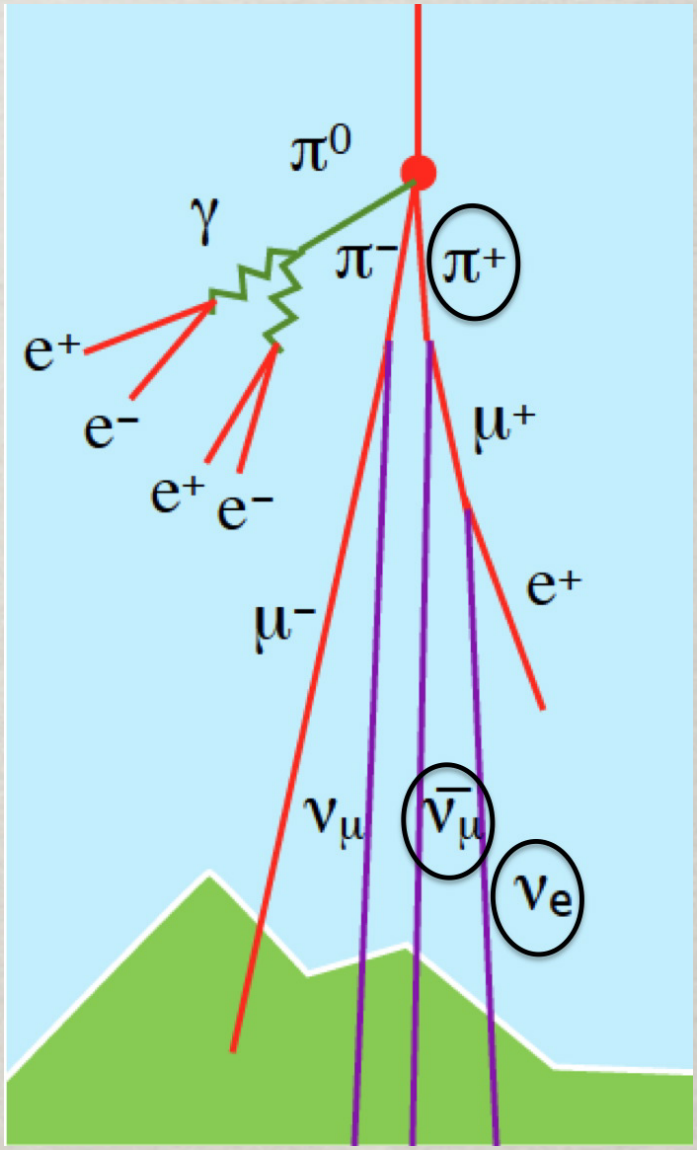
Cosmic rays interacting in the atmosphere produce as usual pions and therefore neutrinos in the ratio

$$\nu_\mu : \nu_e = 2$$

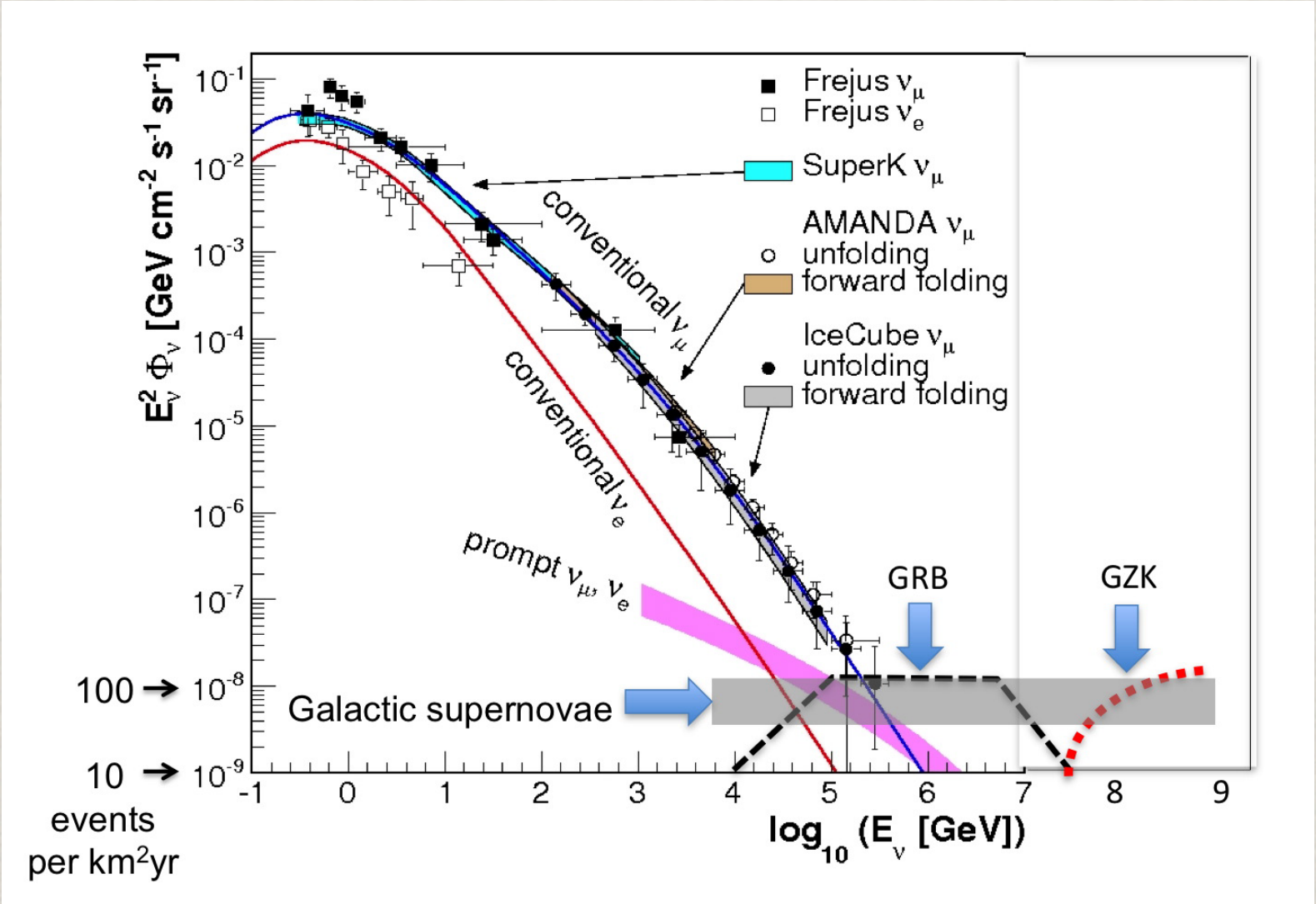
Lower ratio is measured:
neutrino flavour oscillation

→ Neutrino lectures by B. Kayser

For us they are background...

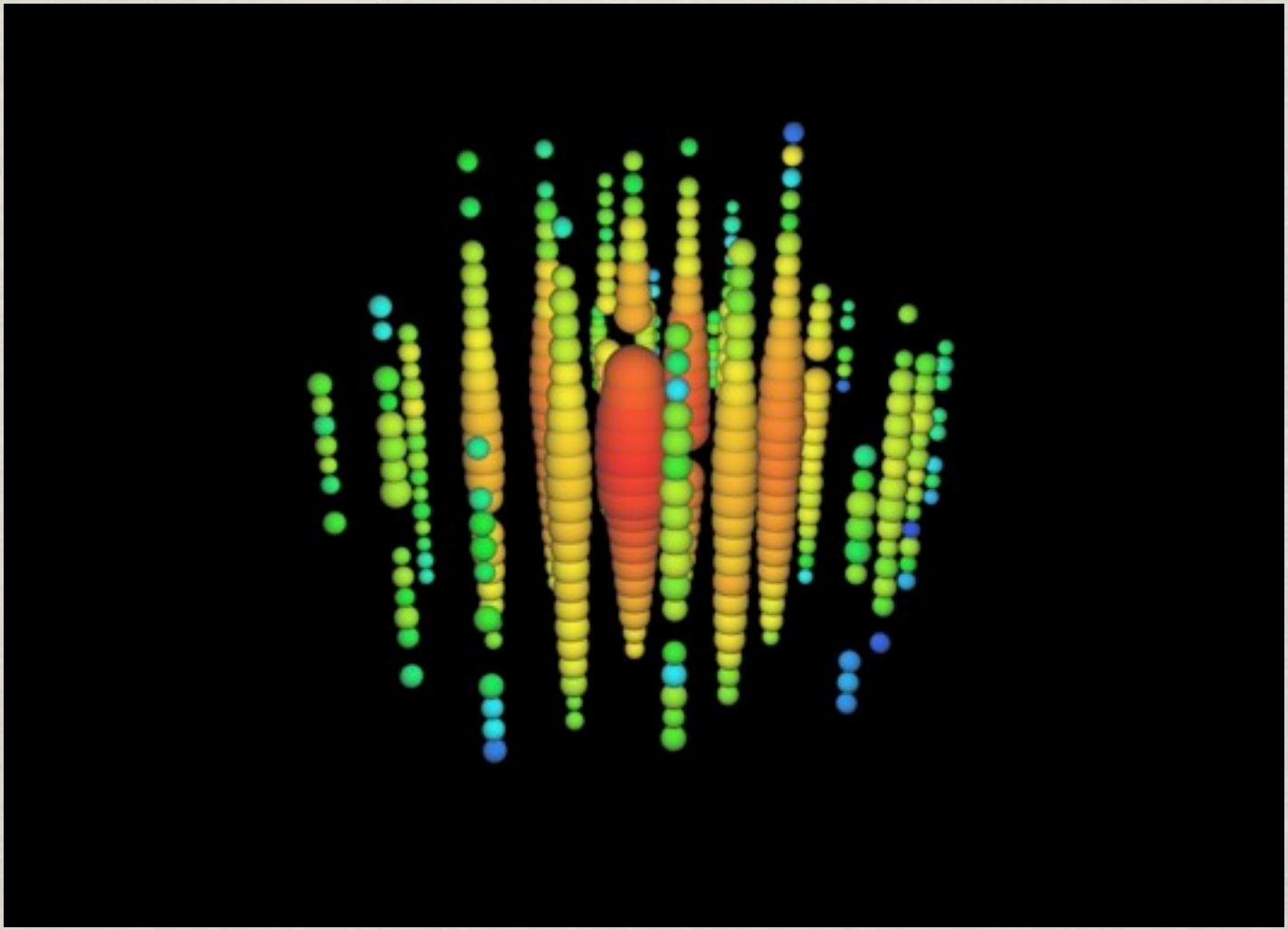


Neutrino Flux



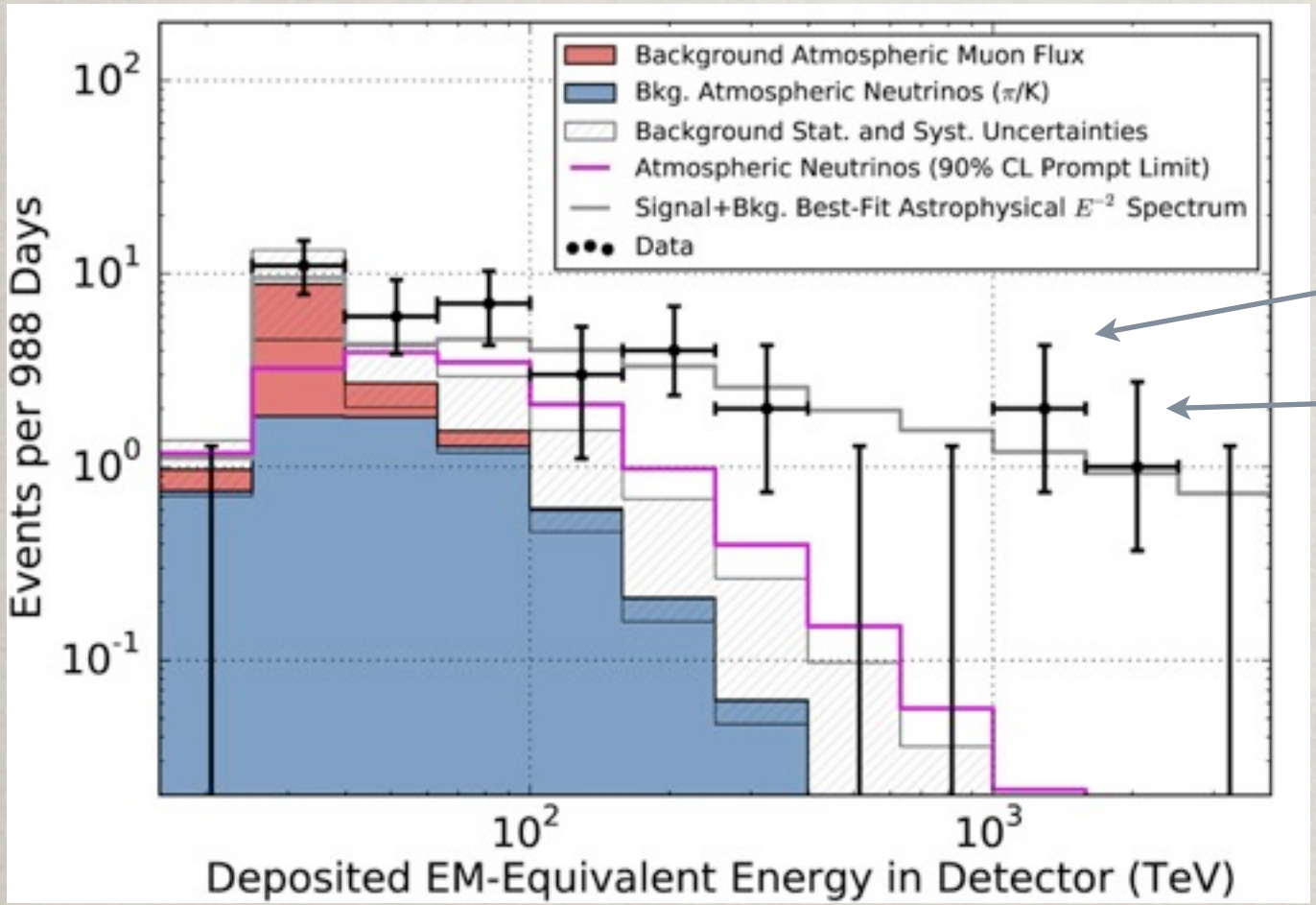
Low Energy part dominated by atmospheric neutrinos, at higher energy different signals are expected...

Neutrino News



First events in PeV energies announced last year !

Neutrino News



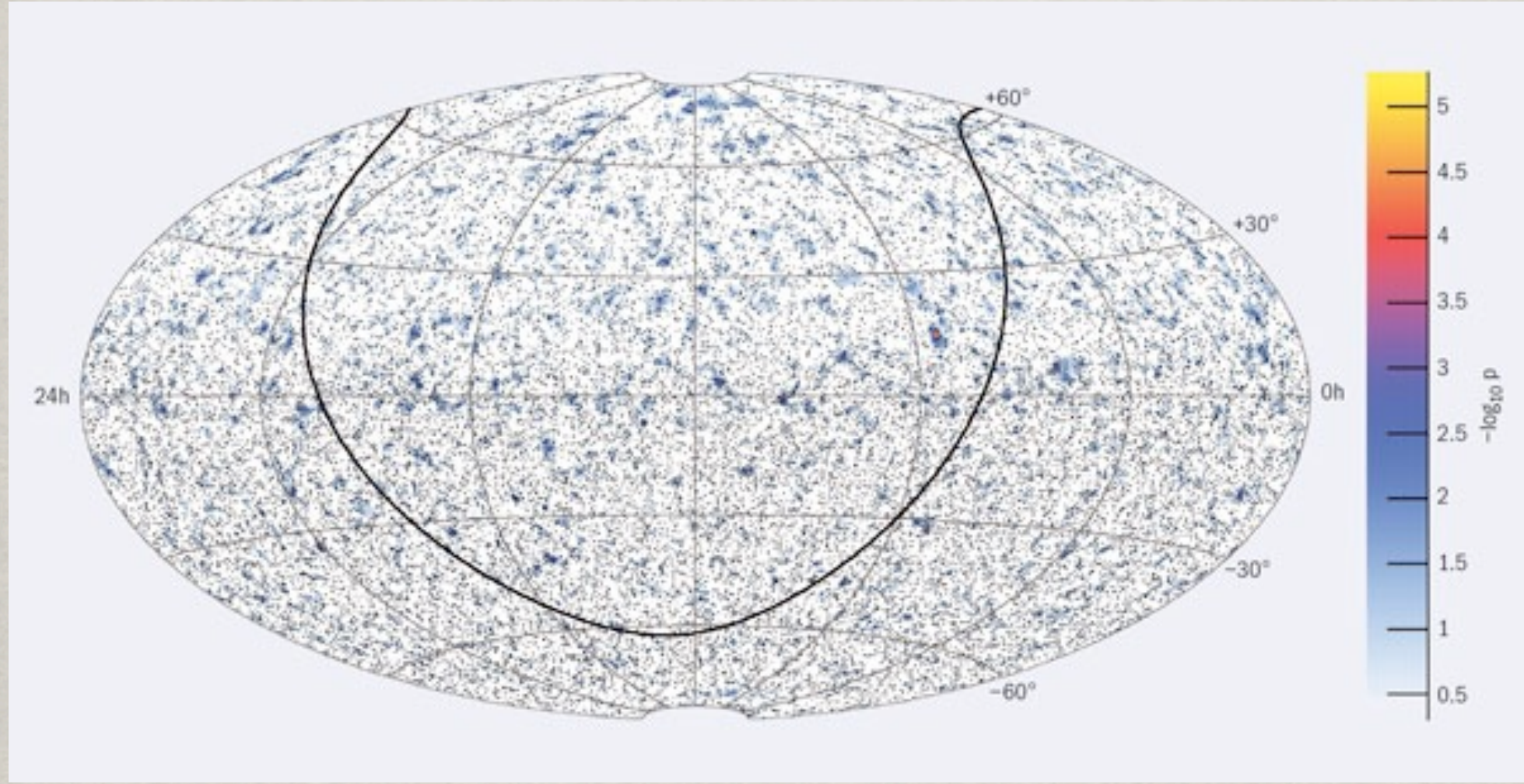
Bert & Ernie

Big Bird

Another event seen above 100 TeV !

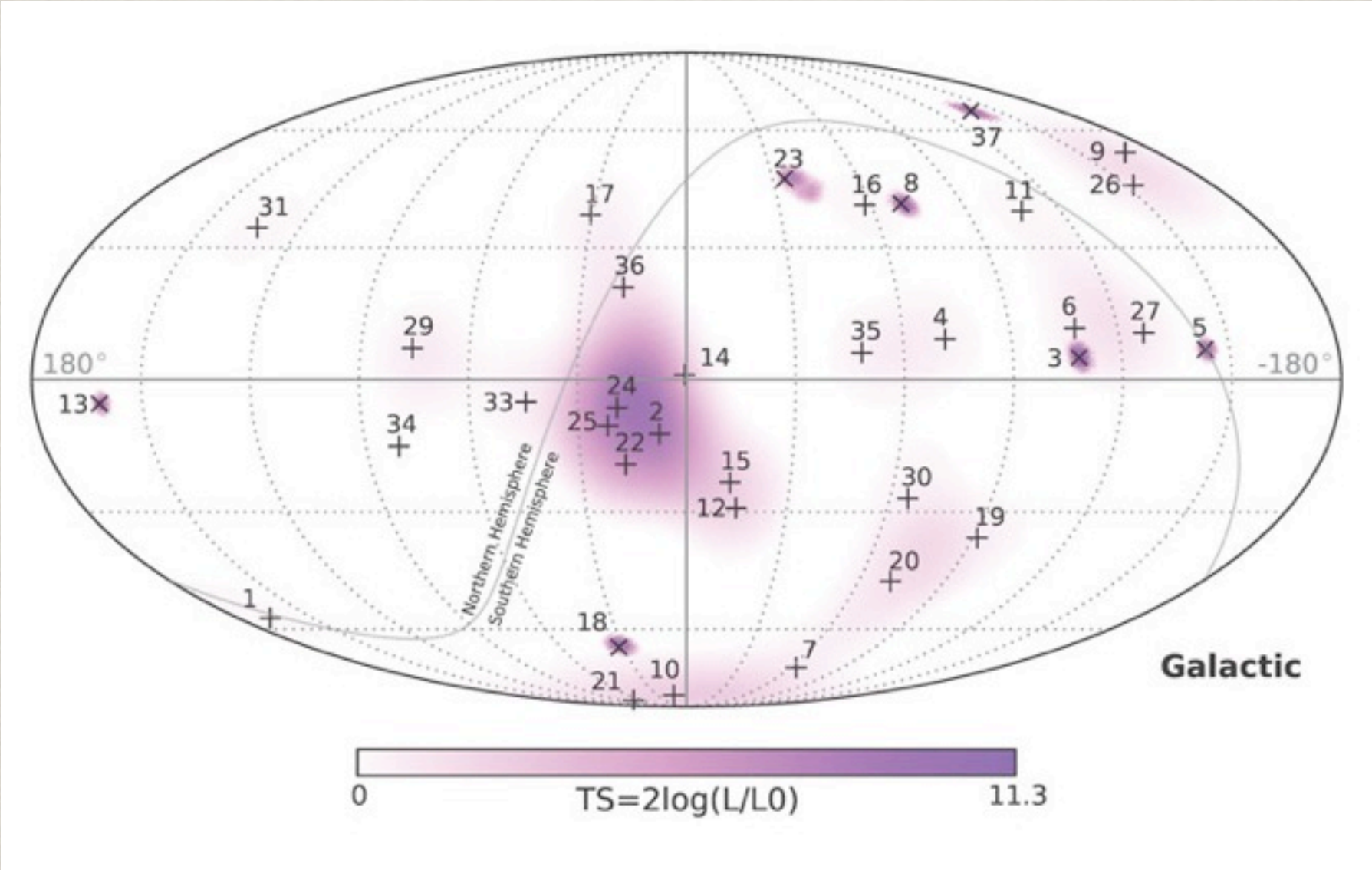
Not compatible with atmospheric neutrino background, but too low energy for the GZK neutrinos...

Neutrino Astronomy



Neutrino sky map so far... The hope is to obtain the same for high energy neutrino and find correlation with sources...
No deflection on magnetic field for neutrinos !

Neutrino Astronomy



No statistically significant correlation so far ... Many events away from the galactic plane, possibly extragalactic origin.

Baryogenesis

Baryogenesis

- The CMB data and BBN both require $\Omega_B \sim 0.05$
- Can it be a relic of thermal decoupling from a symmetric state ? NO ! Decoupling "a la WIMP" give a value $\Omega_B \sim 10^{-10}$, way too small...
- Are we living in a matter patch ??? No evidence of boundaries between matter/antimatter in gammas or antinuclei in cosmic rays... Our patch is as large as the observable Universe !
- No known mechanism can create such separation... The Universe is asymmetric !

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: actually need B-L violation since B+L is violated by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate

- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Baryogenesis via Leptogenesis

[Fukugita & Yanagida '86]

Produce the baryon asymmetry from an initial lepton asymmetry reprocessed by the sphaleron transitions. Naturally possible in the case of see-saw mechanism for generating the neutrino masses.

$$W = Y_\nu L H N + \frac{1}{2} M_R N N \quad \rightarrow \quad \text{see-saw}$$

Moreover the RH Majorana neutrino can generate a lepton asymmetry via decay if the rate also violates CP

$$N \to \ell\, H \quad N \to \bar{\ell}\, H^\star$$

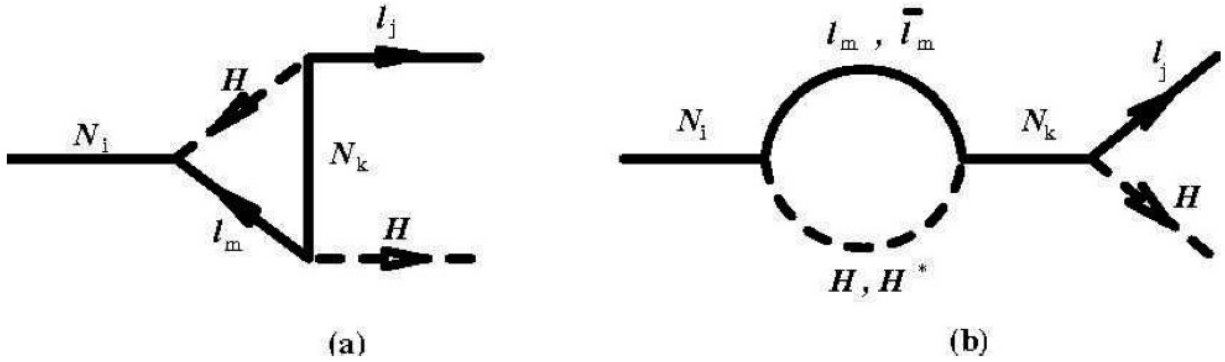
Both channel are possible due Majorana nature of N !

Thermal Leptogenesis

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{ for } M_i \ll M_j$$

It is bounded !

→relation to neutrino masses via Y_ν...

$$\epsilon \leq 10^{-6} \left(\frac{M_1}{10^{10}\ \text{GeV}} \right) \frac{m_{atm}}{m_1 + m_3}$$

[Davidson & Ibarra 02]

Thermal Leptogenesis

The "back of the envelope" computation:

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

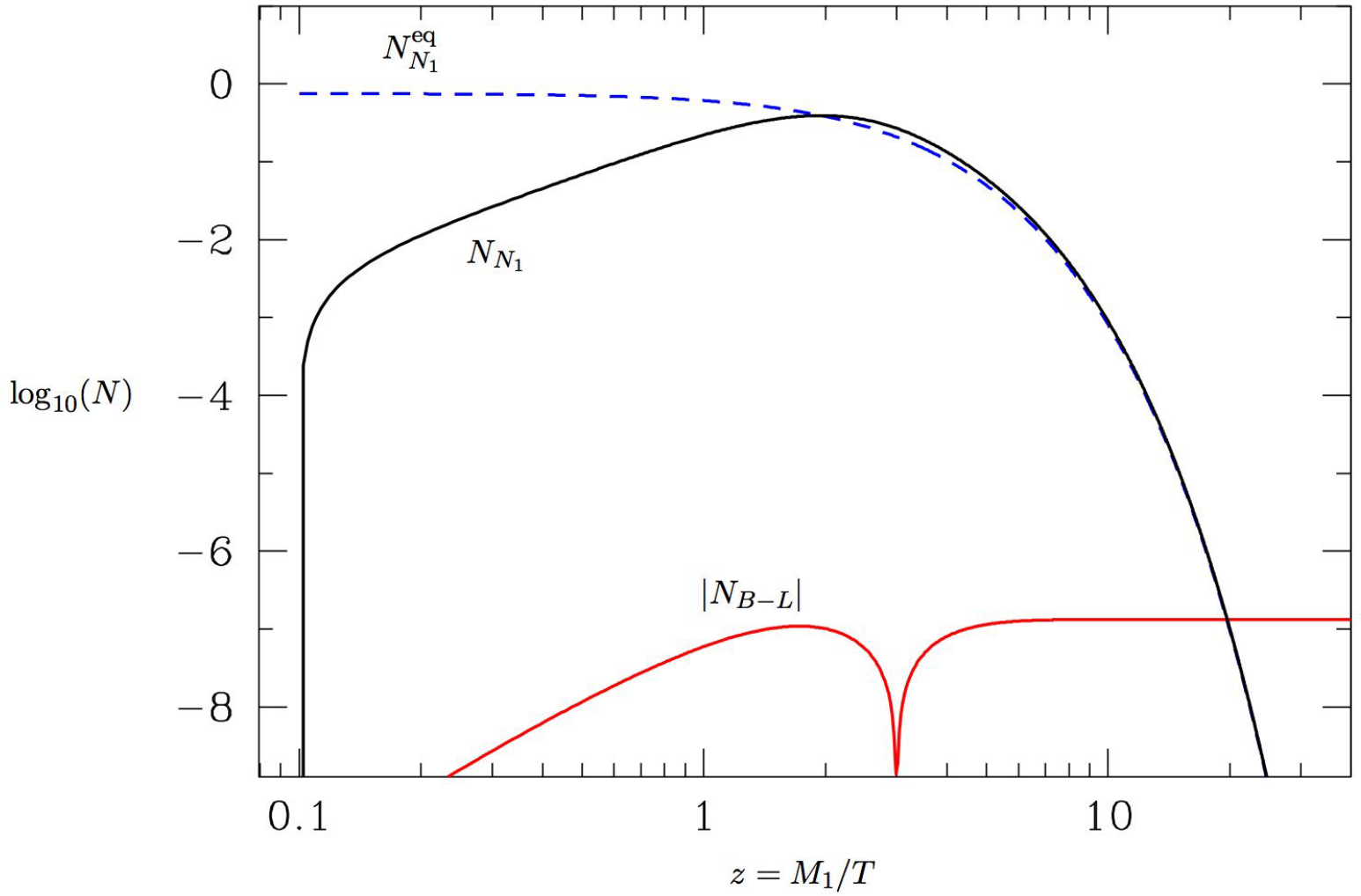
$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3) g}{8\pi^4 g_S} \epsilon_1 \simeq 4 \times 10^{-3} \epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3} \epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

[Buchmüller, Di Bari & Plümacher '04]



Outlook

Outlook

- Origin of UltraHigh-Energy Cosmic Rays still unclear, but a cut-off in the spectrum is now found: is it the GZK cut-off ?
- Dark Matter is a WIMP, we should see it at colliders, in direct detection experiments and in indirect detection... There are tantalizing hints in Indirect Detection and Direct Detection, more data are expected soon !
- Astroparticle physics offers lots of data and open questions: still lots to do !

References

- Reviews on cosmic rays:
  - A. Olinto Phys.Rept 333 (2000) 329 (astro-ph/0002006)
  - G. Sigl arXiv:1202.0466

- Reviews on Dark Matter, especially Indirect Detection:
  - G. Bertone, D. Hooper, J. Silk Phys.Rept. 405 (2005) 279 (hep-ph/9404175)
  - A. Ibarra, D. Tran, C. Weniger arXiv:1307.6434

- Recent results:
  Talks at the ICRC2013 conference, see http://www.cbpf.br/~icrc2013/