The 2016 CERN Summer Student Lectures

Astroparticle Physics (3/3)

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elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

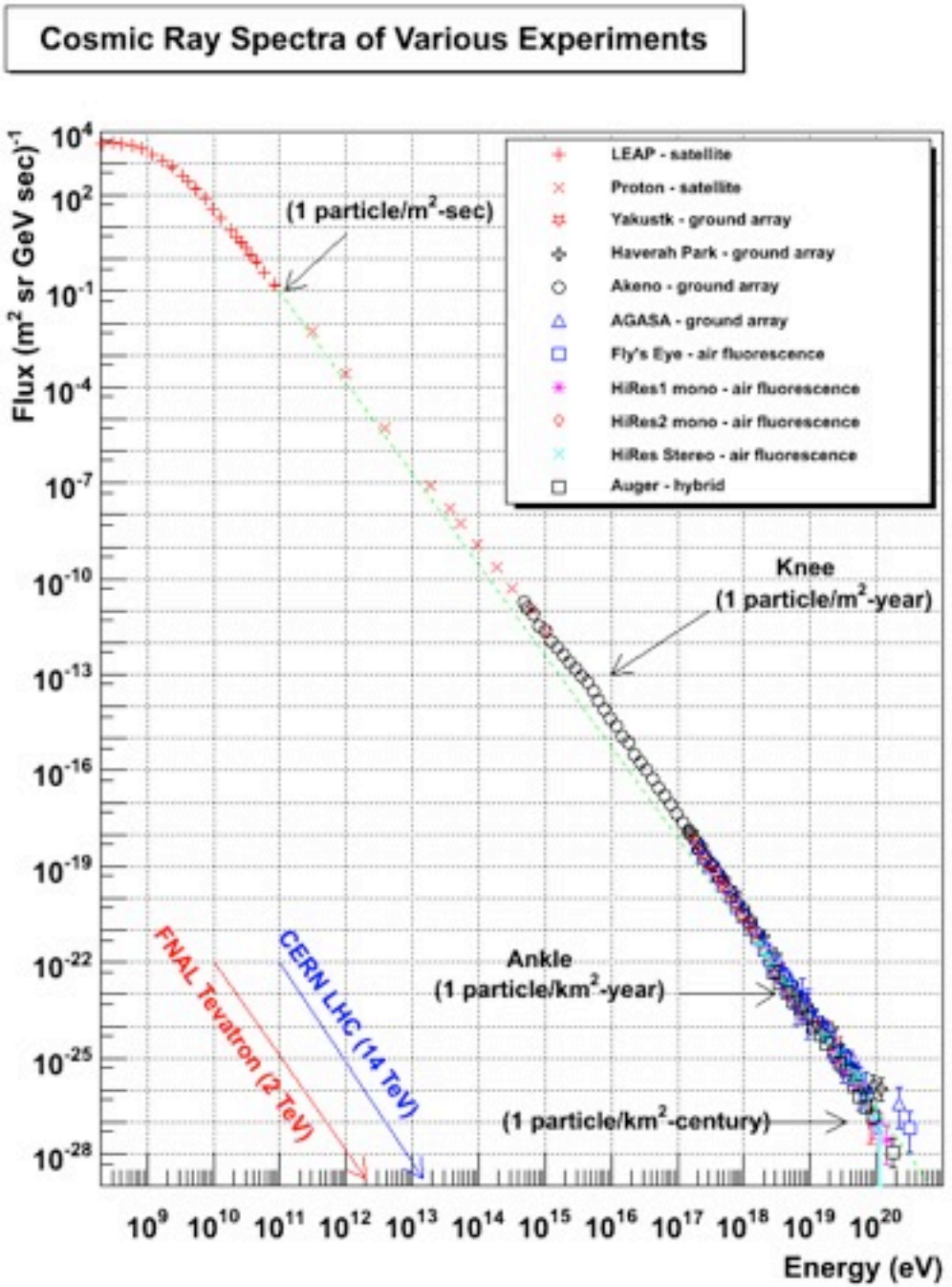
MARIE CURIE ACTIONS

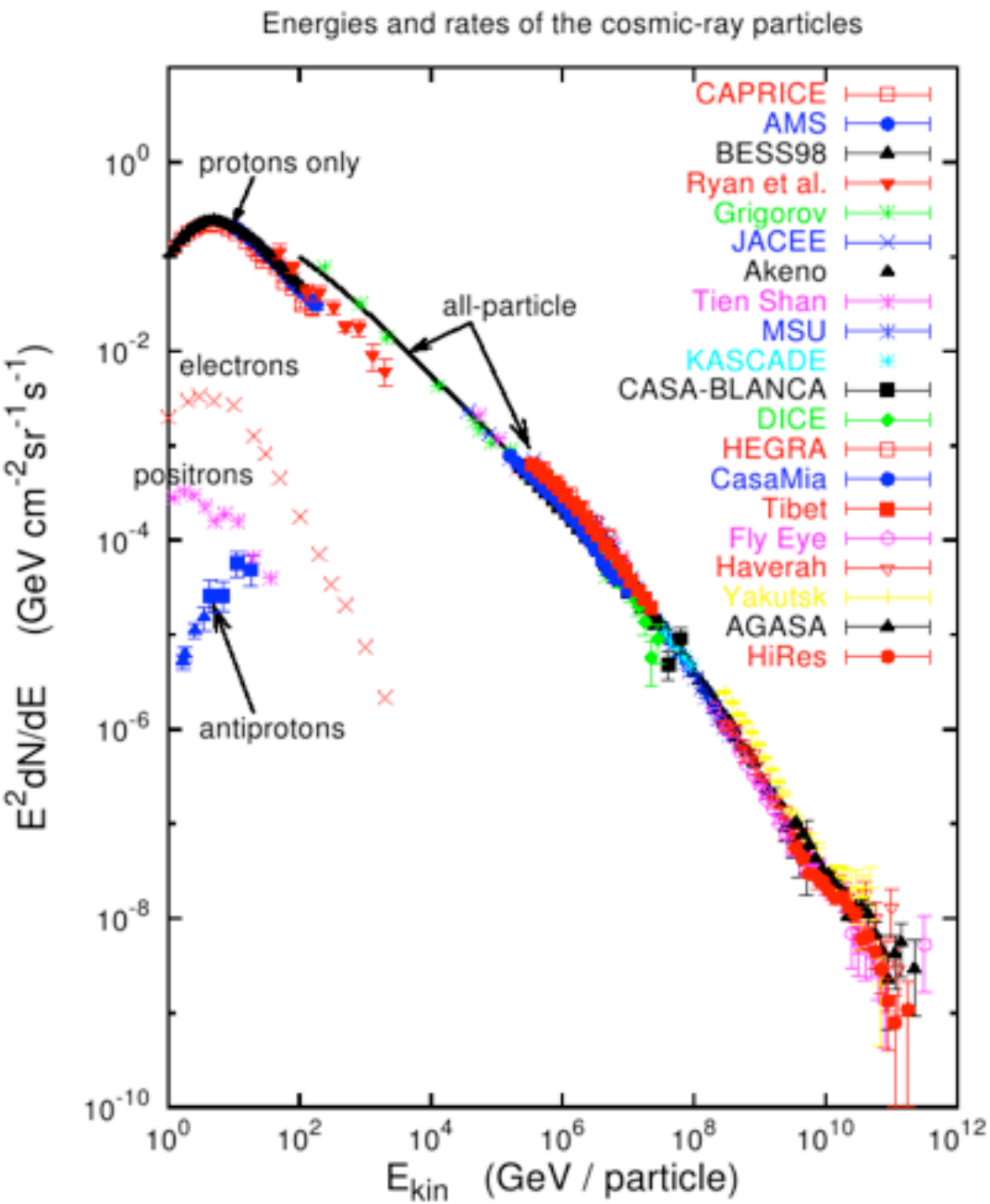
Outline

- 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, neutrino astronomy and gravitational waves
- Outlook

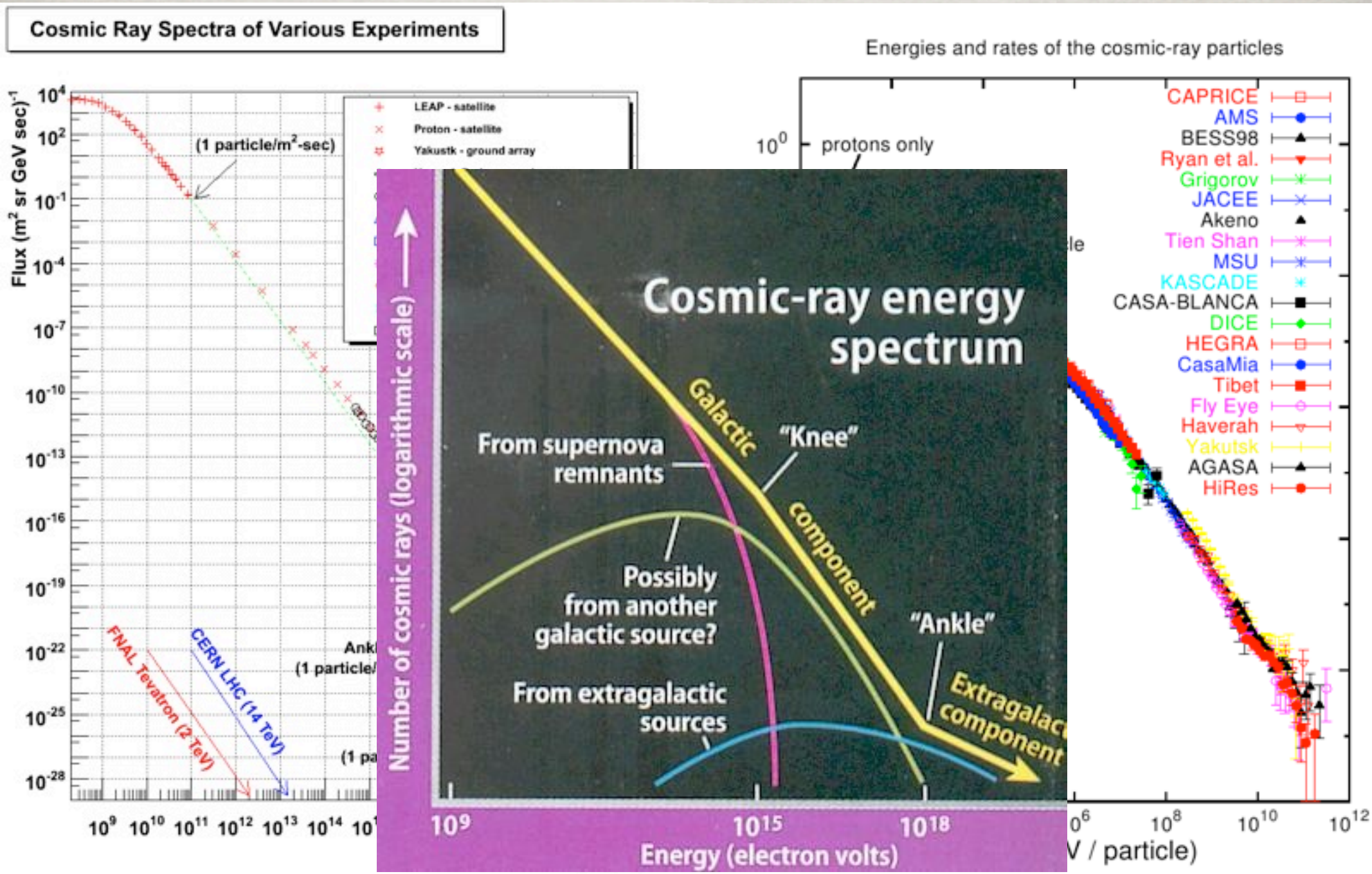
Cosmic Rays data

Cosmic Rays spectrum



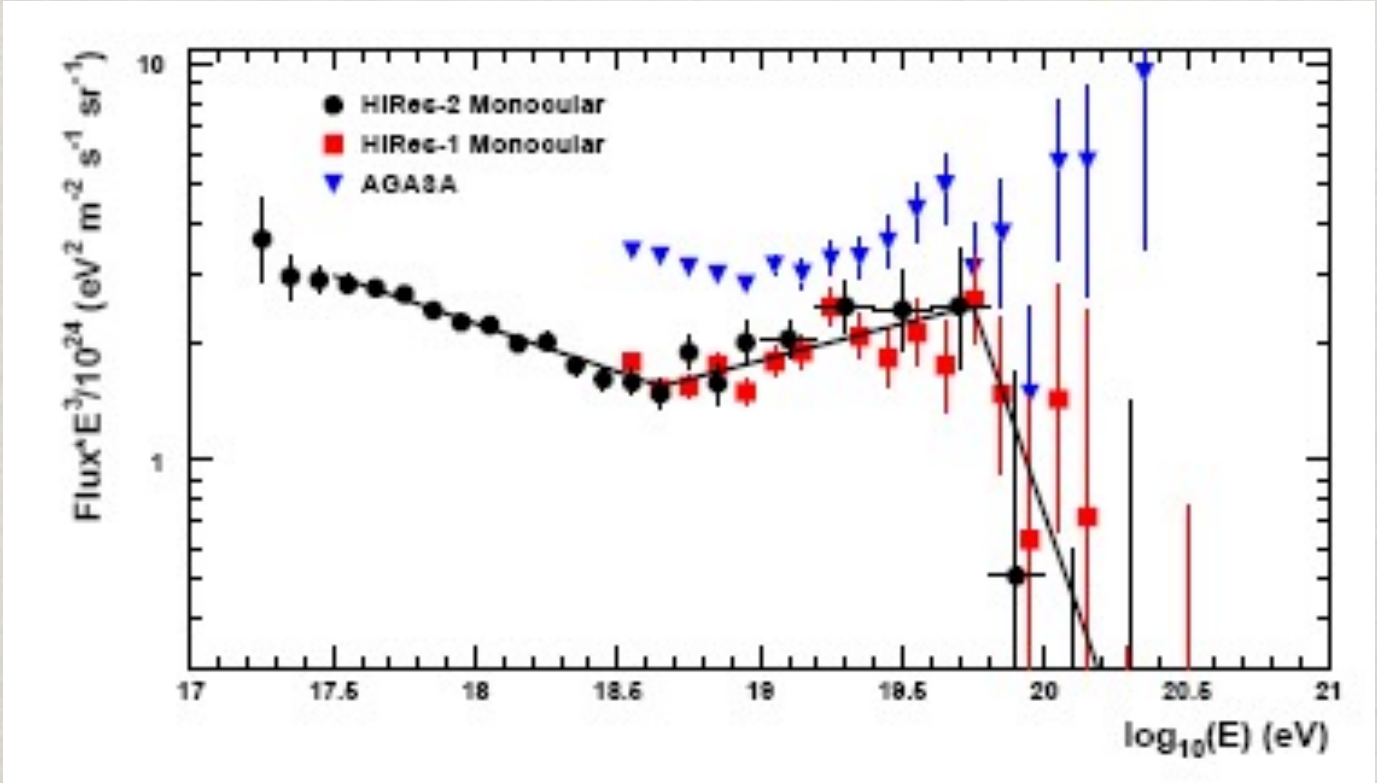


Cosmic Rays spectrum



UHECR & THE GZK CUT-OFF

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

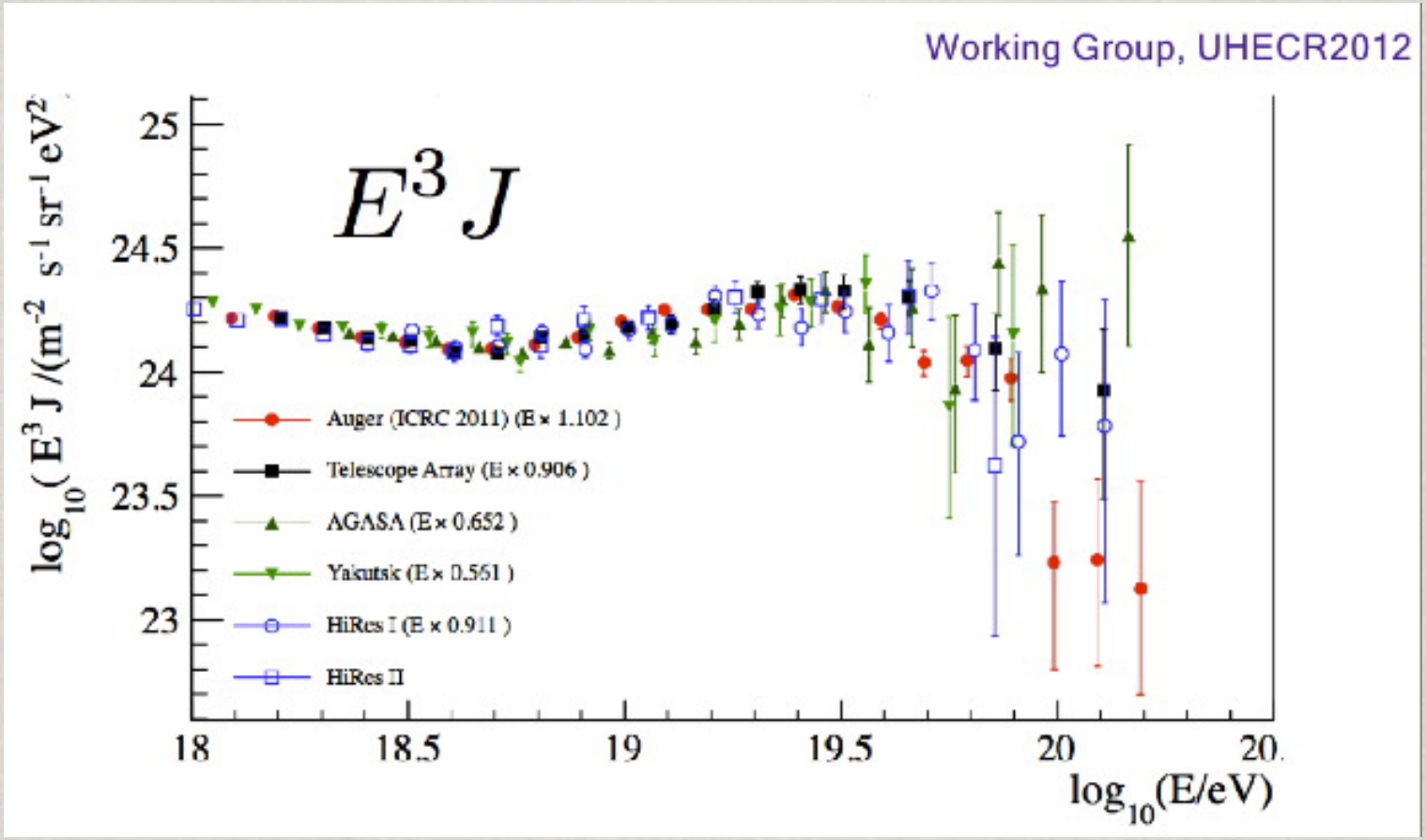


NO

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

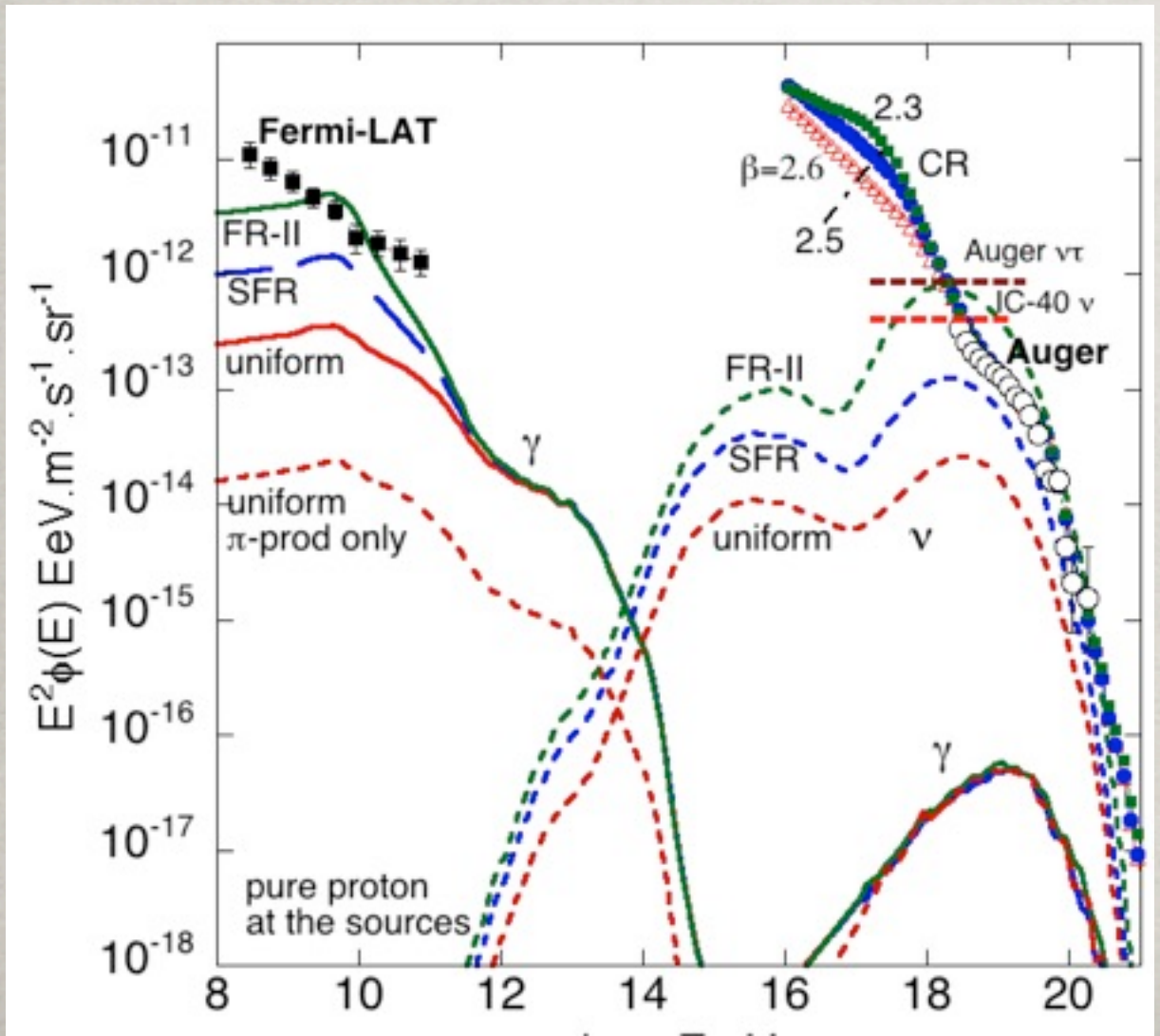


Controversy now solved by AUGER & TA , hybrid detectors with both SA and FD: the energy measured by the two methods differ ! Calibrating SA with FD one obtains good agreement between the experiments and sees a cut-off...

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...

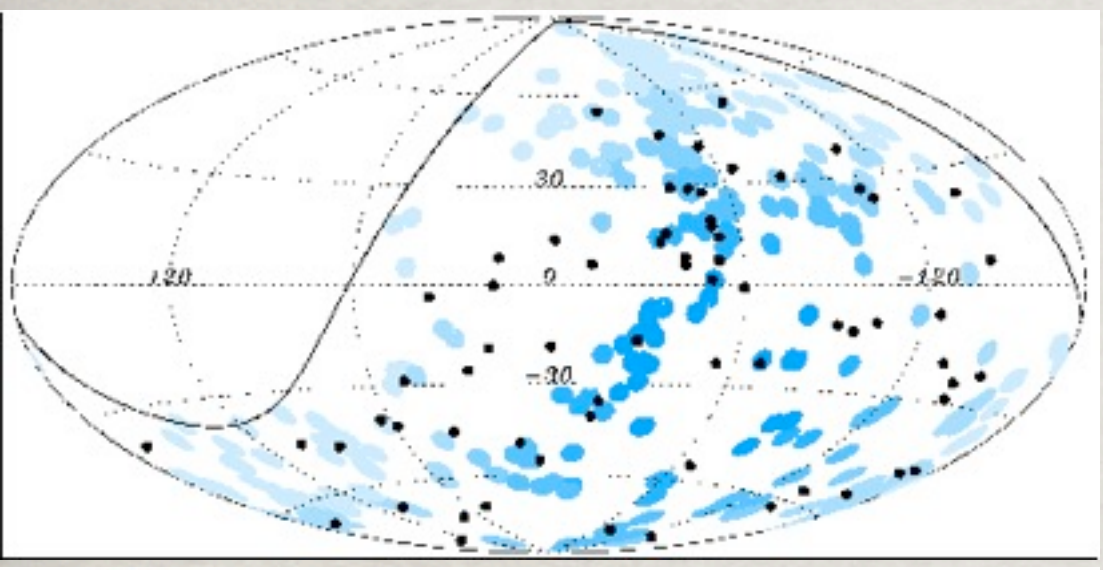
Sources of UHECR ?

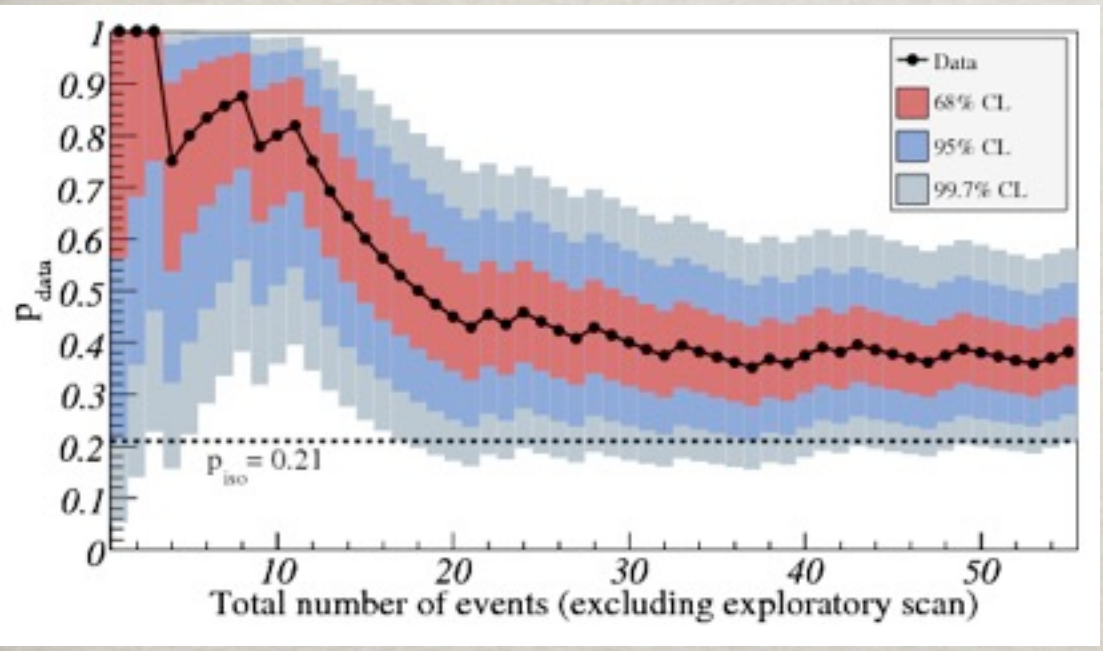
We have seen that different astrophysical object are candidates for the UHECR acceleration. Two informations could help to pinpoint the sources:

- 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

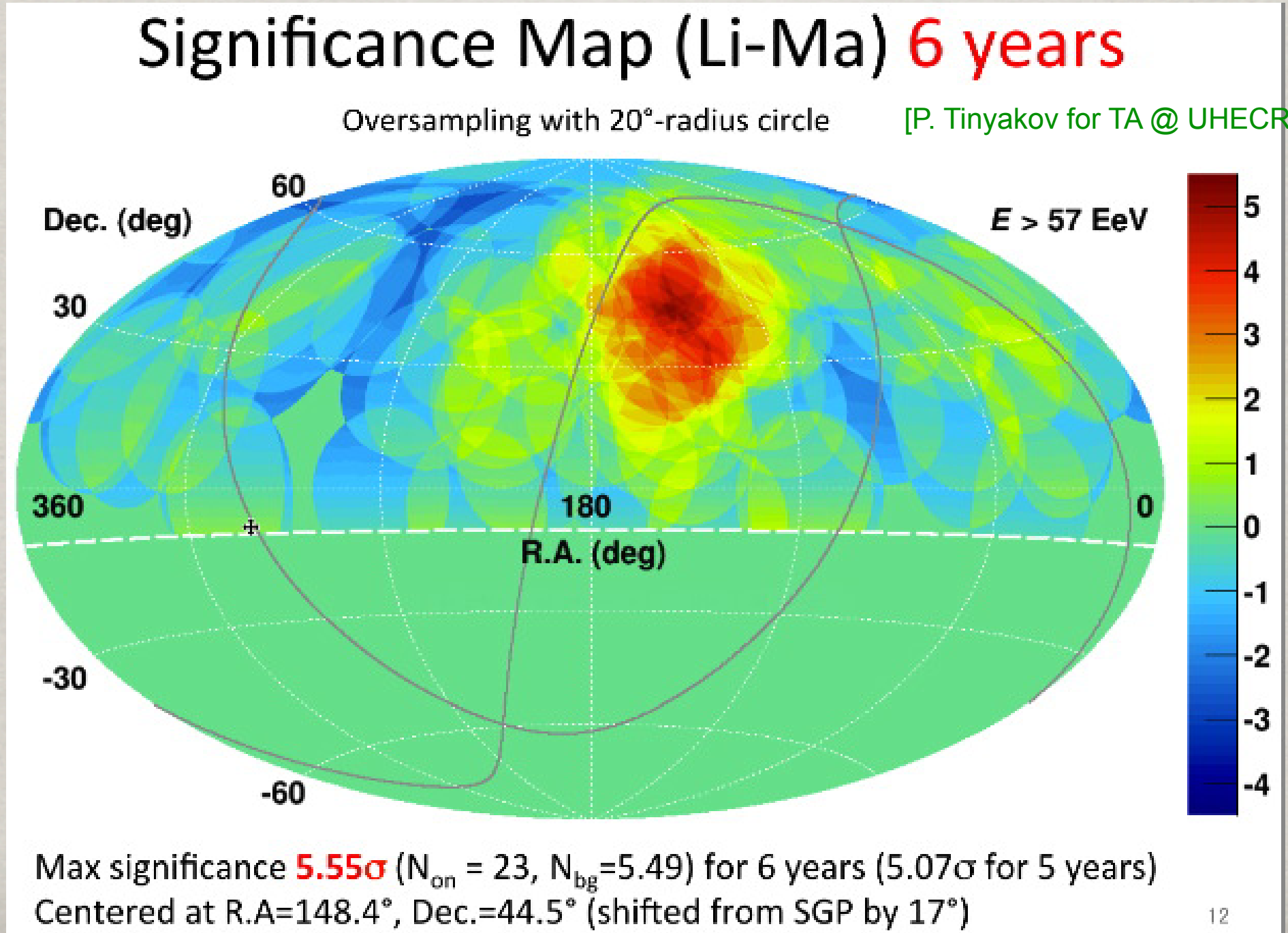




[Auger, arXiv:1009.1855 [astro-ph.HE]

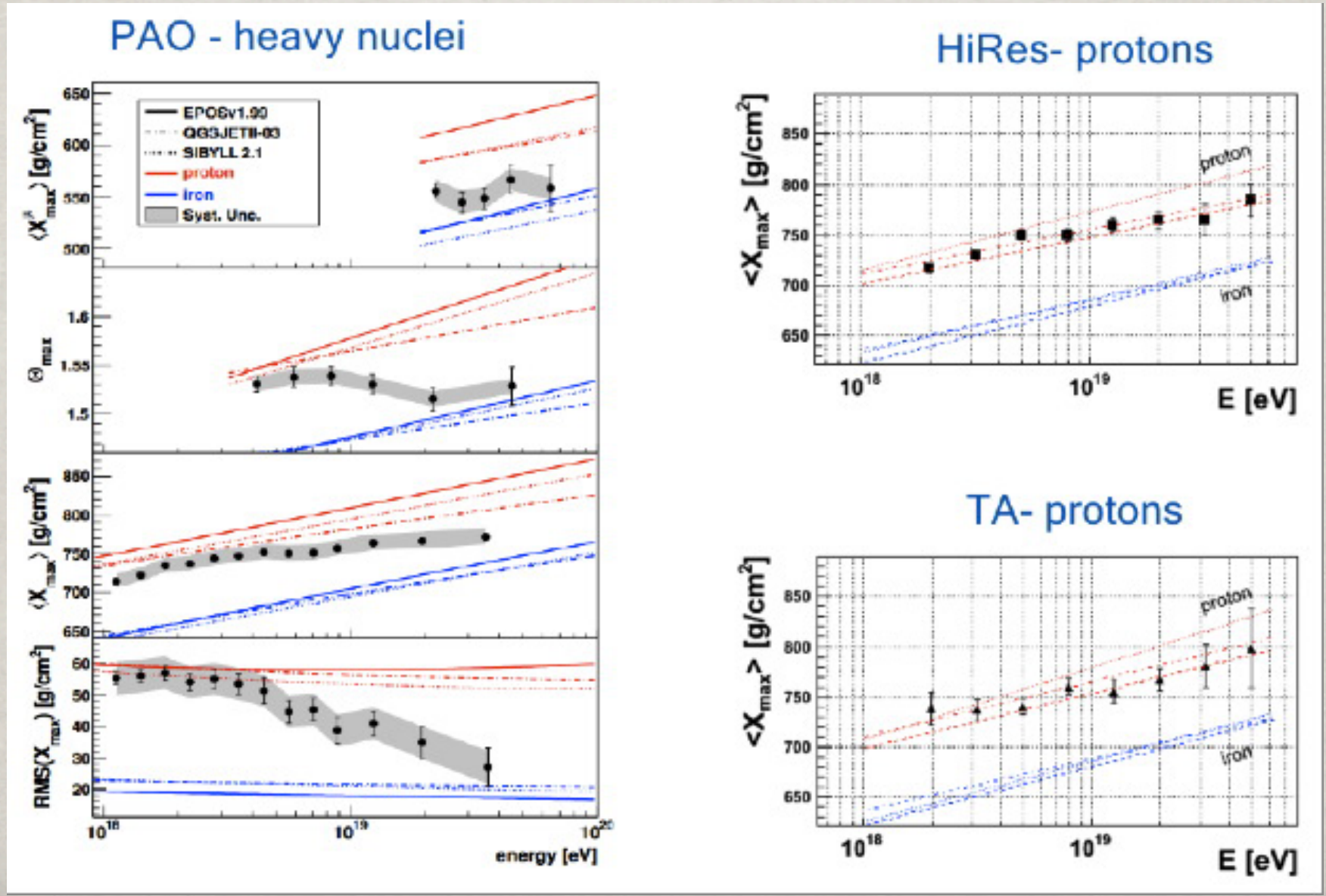
AUGER announced already in 2007 the detection of a possible correlation between UHECR and AGNs. Unfortunately the statistics became worse in the later years, but the signal is not completely lost... $\sim 3\sigma$ But is the correlation with AGNs or only with large scale structure ?

Hot Spot seen by TA



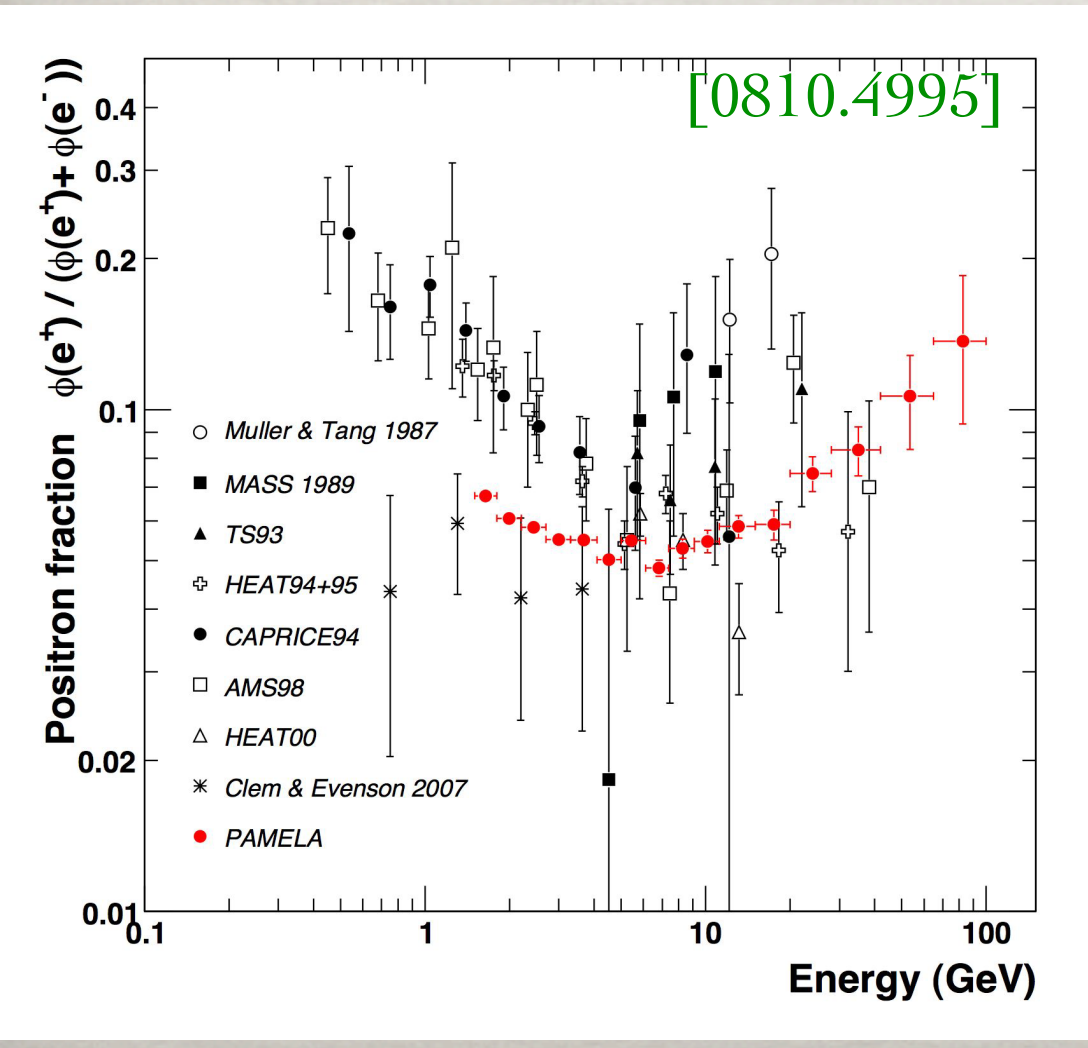
UHECR COMPOSITION

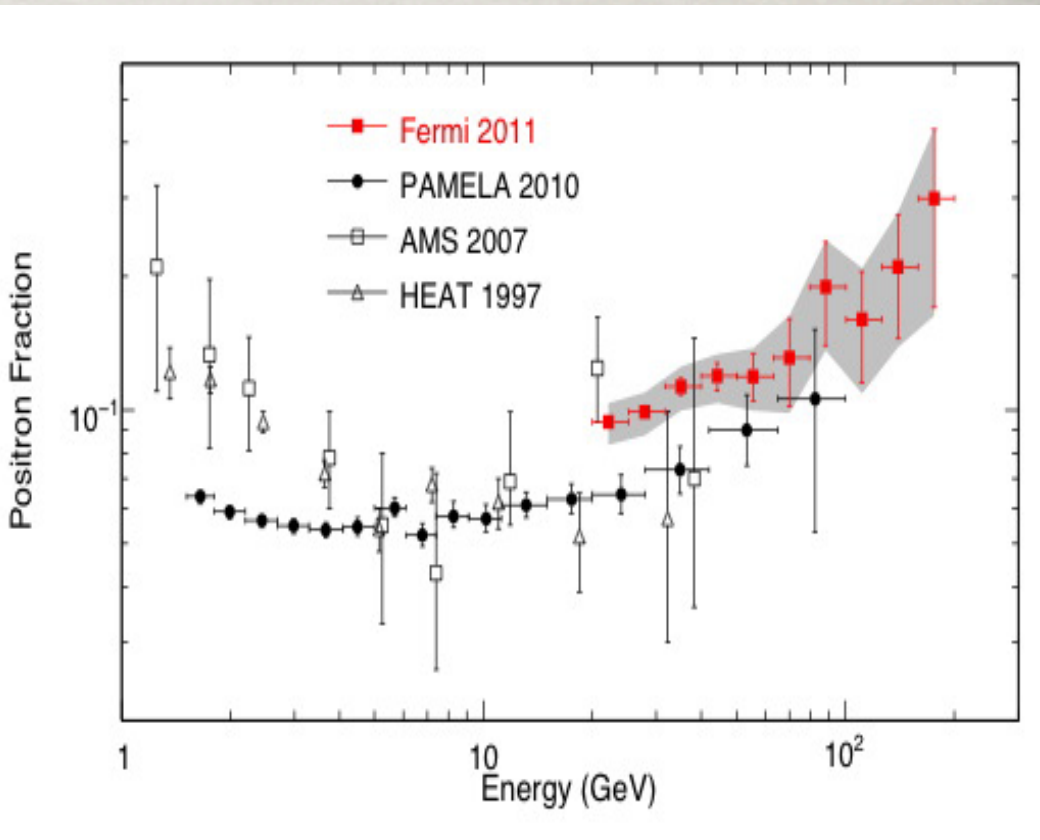
Open question: the different experiments are not in agreement...



Antimatter in CR: positrons

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





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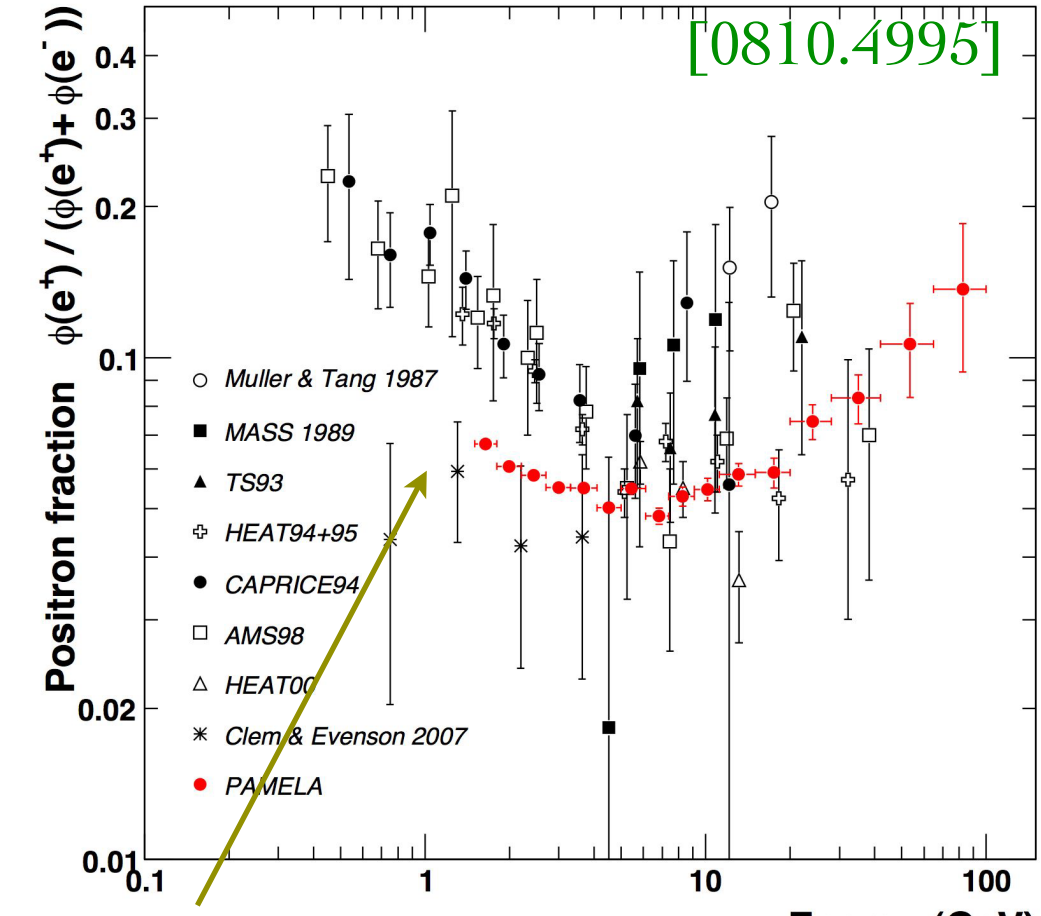
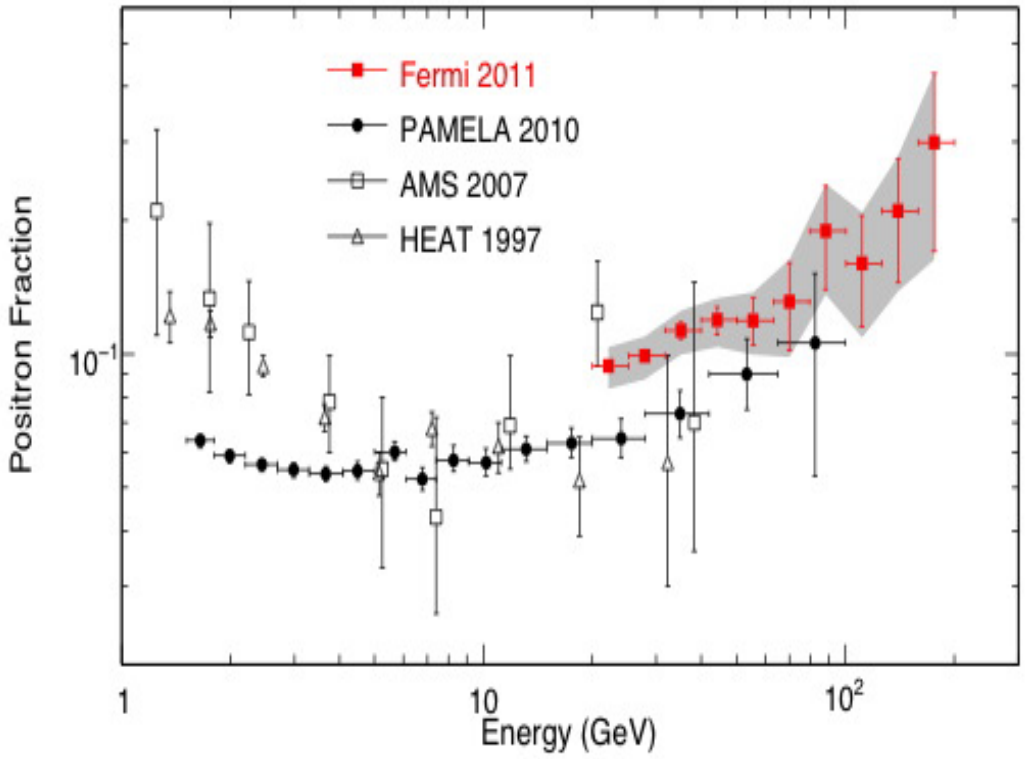
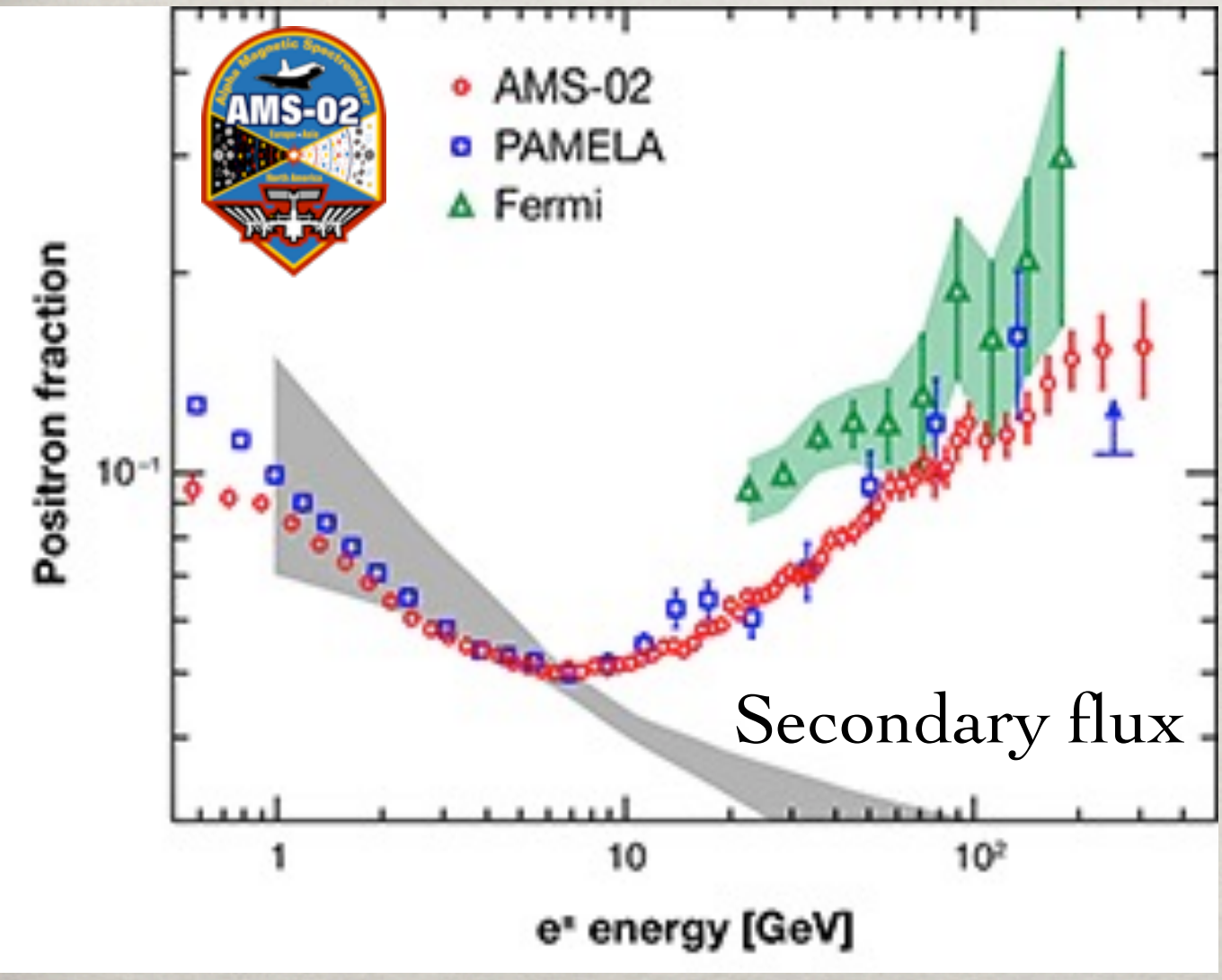




Antimatter in CR: positrons

AMS-02 confirms PAMELA and FERMI !



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

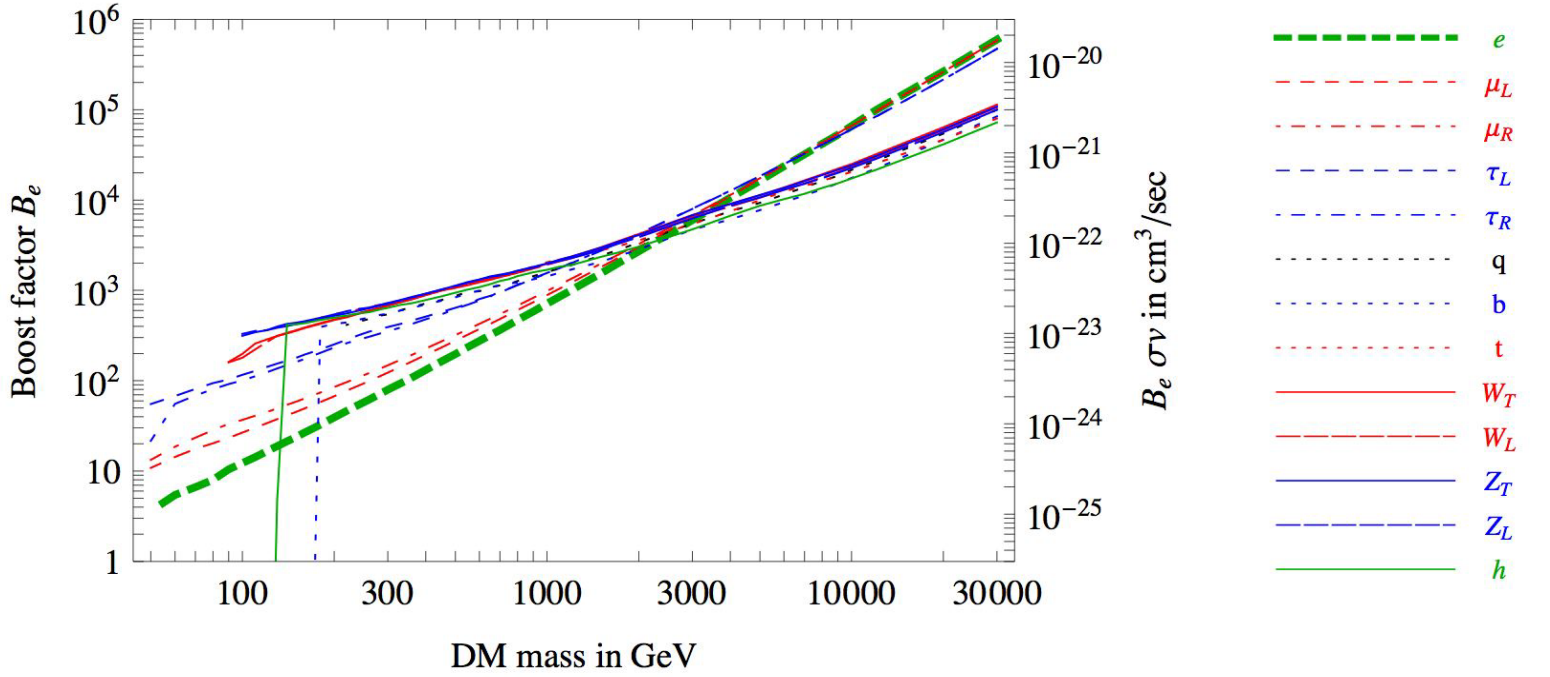
Need a positron source and not too far away...

Dark Matter or astrophysics ?

WIMP ANNIHILATION ?

Need a large boost factor or an enhancement of the annihilation cross-section to be consistent with the WIMP mechanism.

[Cirelli et al. 08]



Thermal relic annihilation cross-section corresponds to B=1...

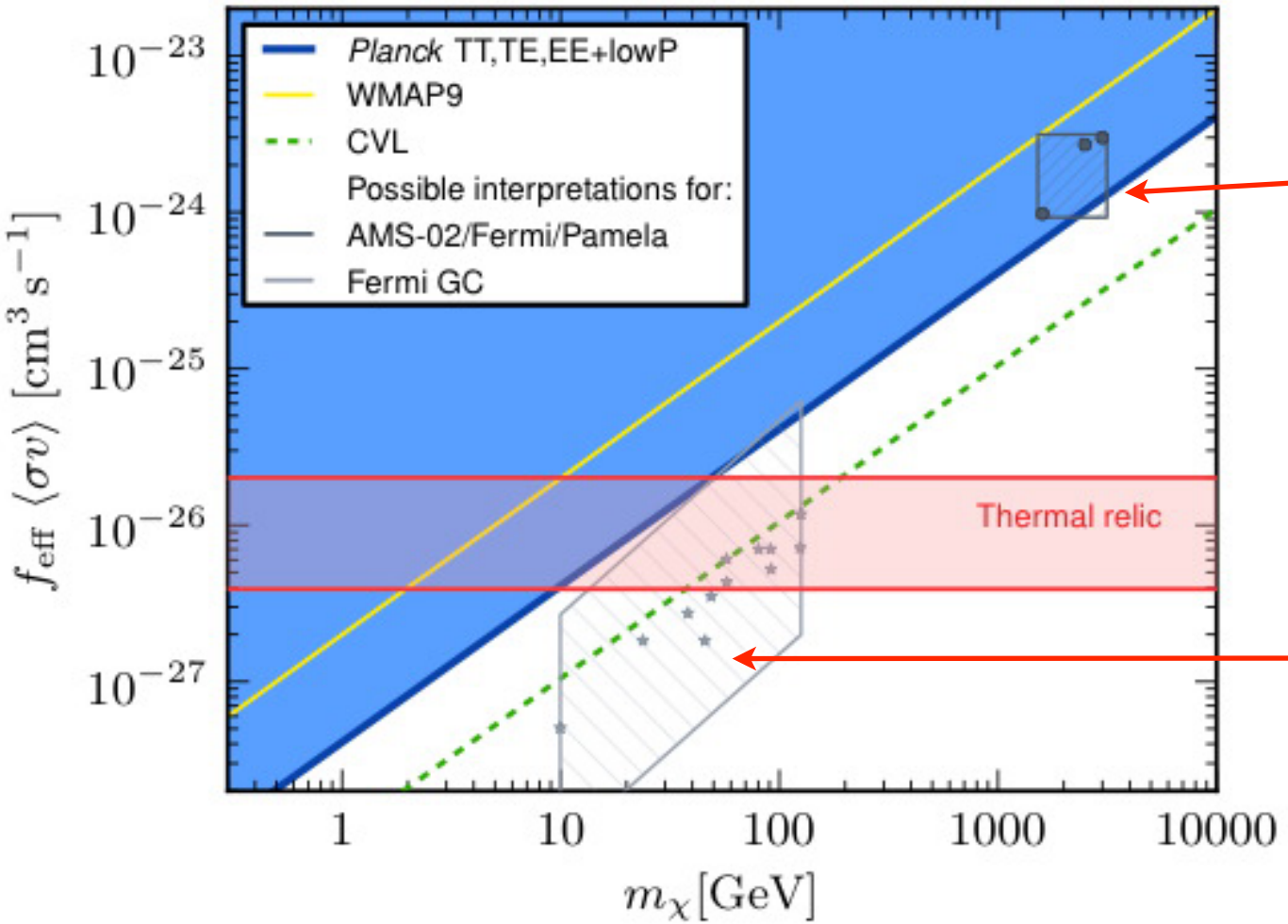
Difficult to obtain B > 10-100 from halo models...

Perhaps easier to enhance the annihilation cross-section ?

PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leaves imprints into the CMB ! Planck can now exclude cross-sections as those needed by PAMELA and AMS-02:

[Planck 1502.01589]



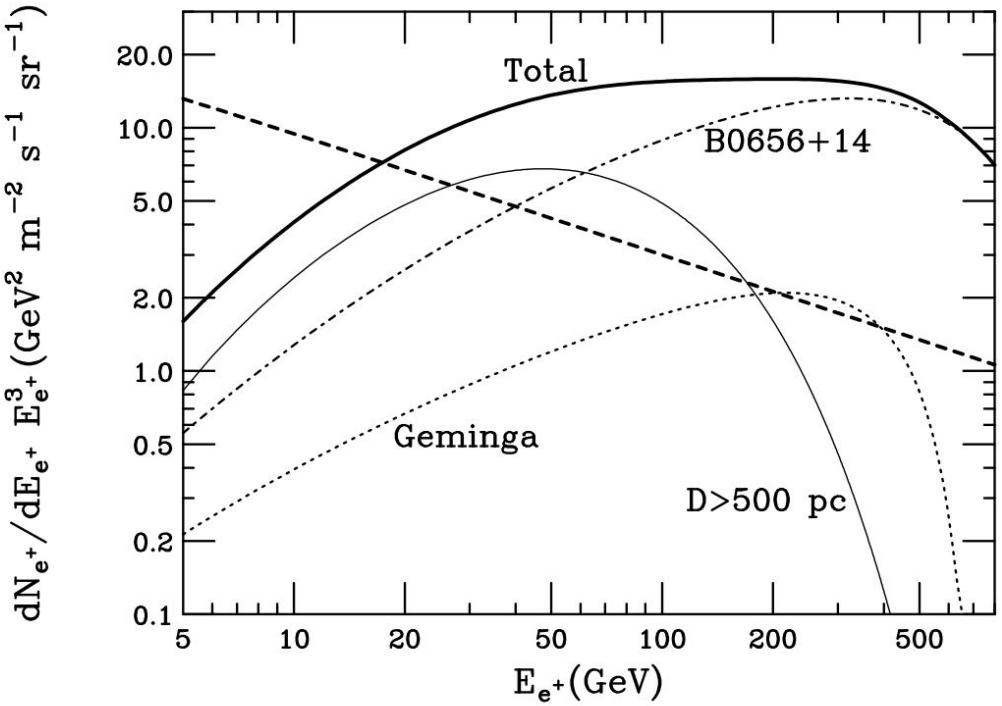
Pamela-inspired DM models

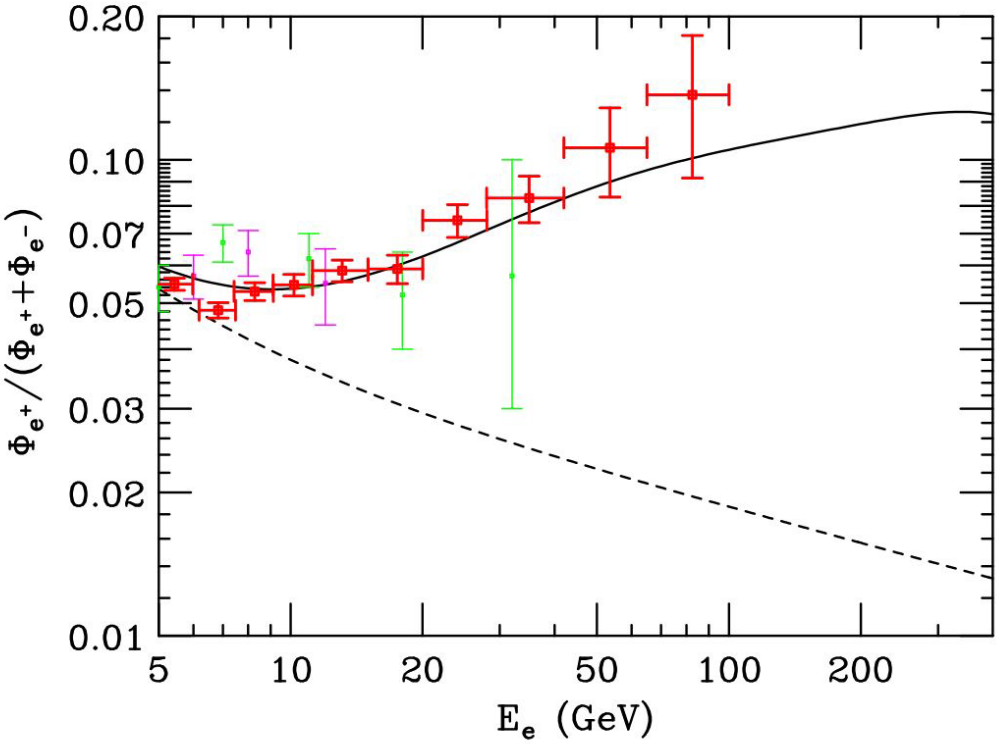
Galactic centre excess

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

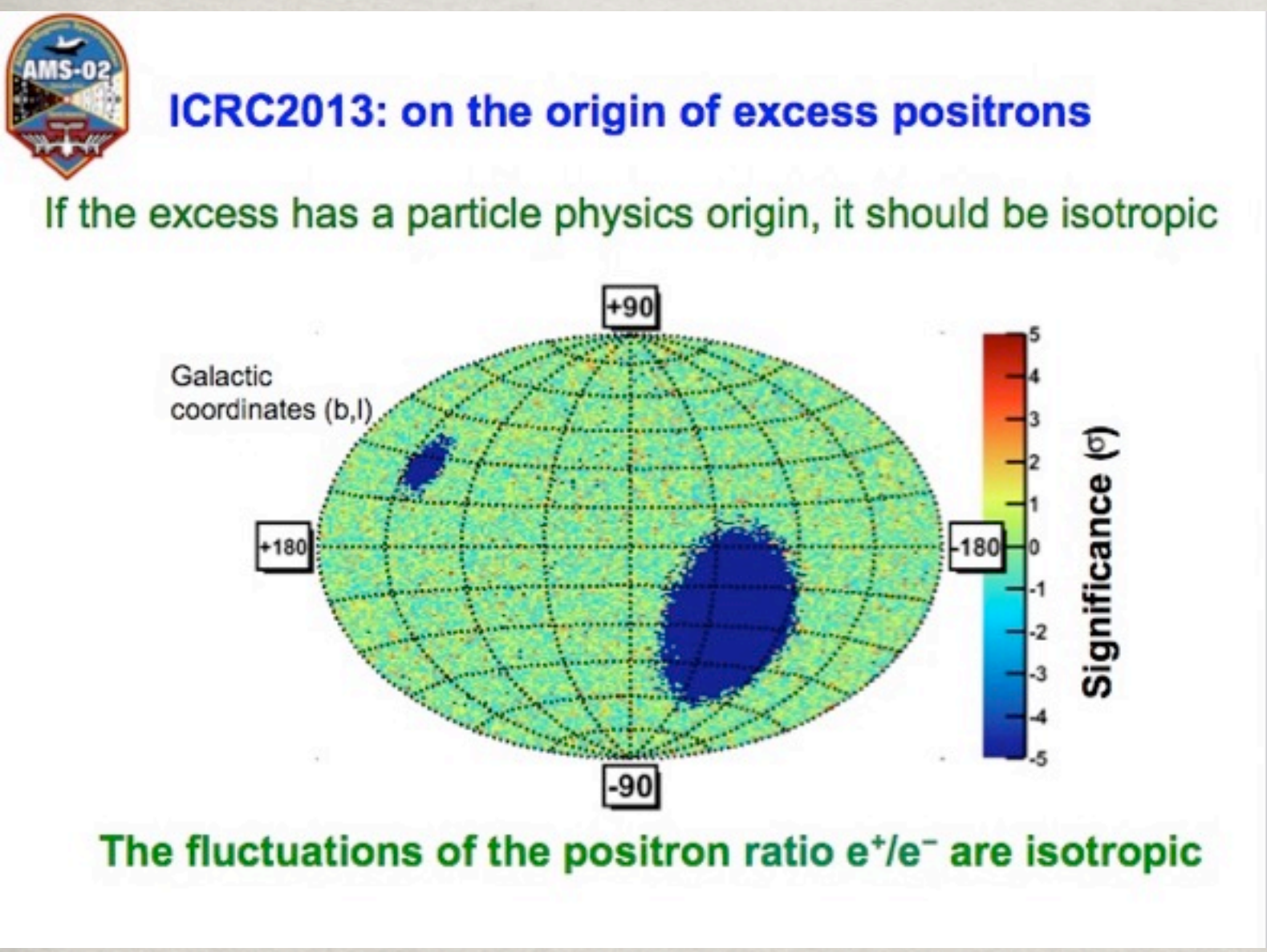
[Hooper, Blasi & Serpico 08]





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

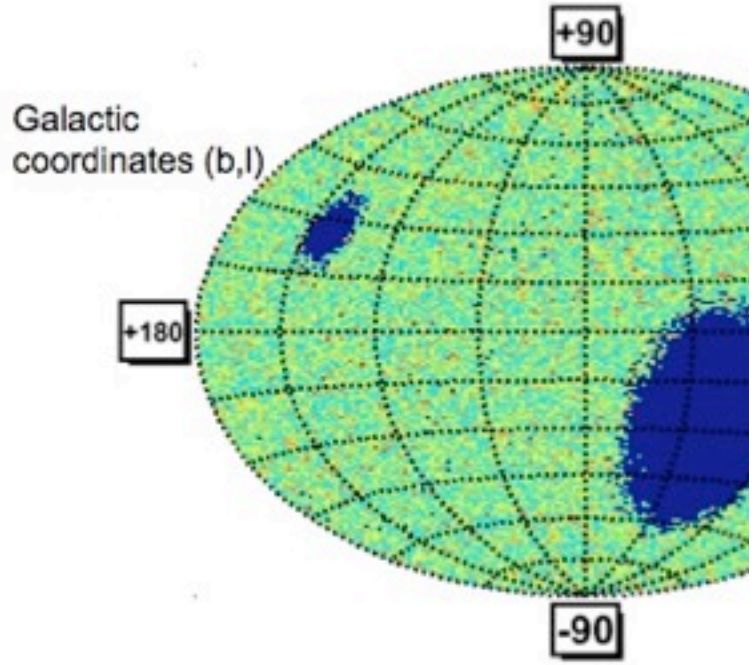
Anisotropy in positrons



Anisotropy in positrons

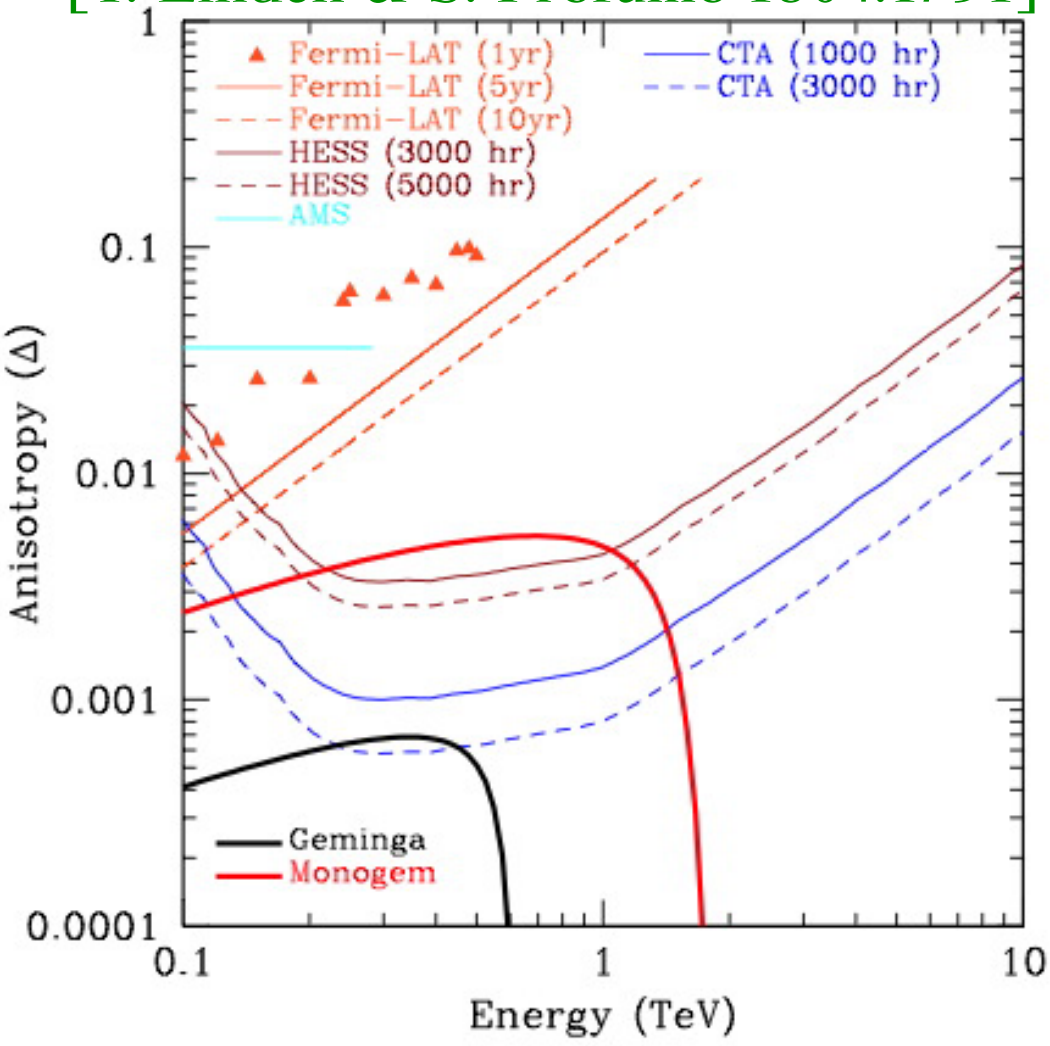
ICRC2013: on the origin of excess positrons

If the excess has a particle physics origin, it should be isotropic



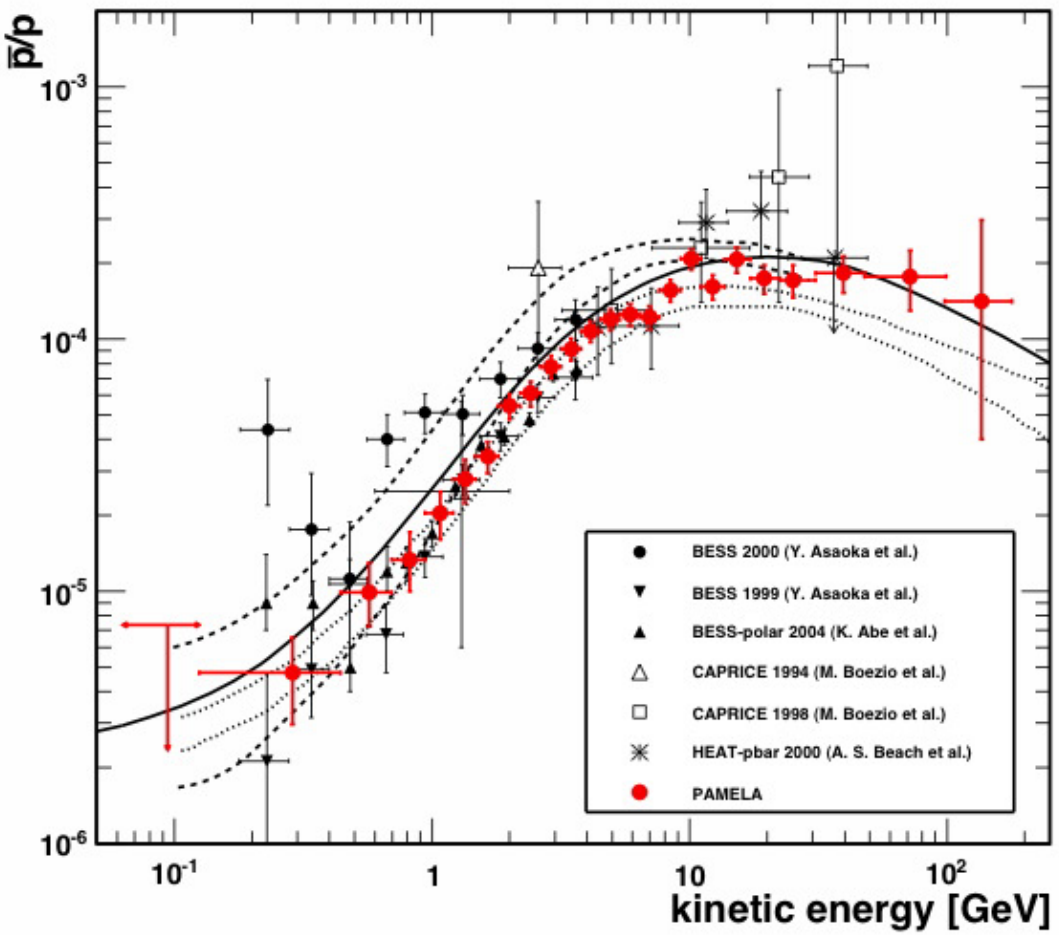
The fluctuations of the positron r

[T. Linden & S. Profumo 1304.1791]



Antimatter in CR: antiprotons

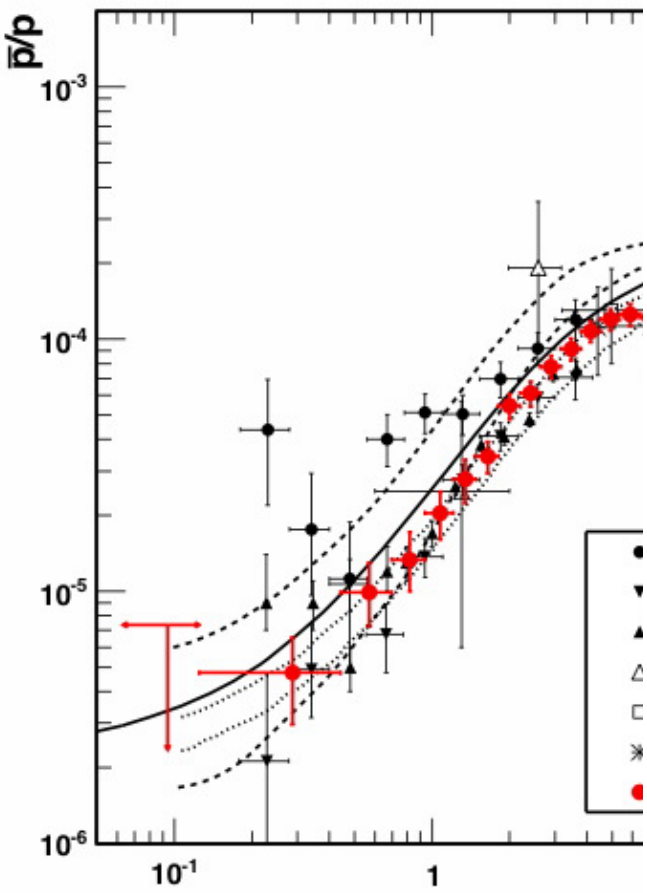
[PAMELA, 1007.0821]



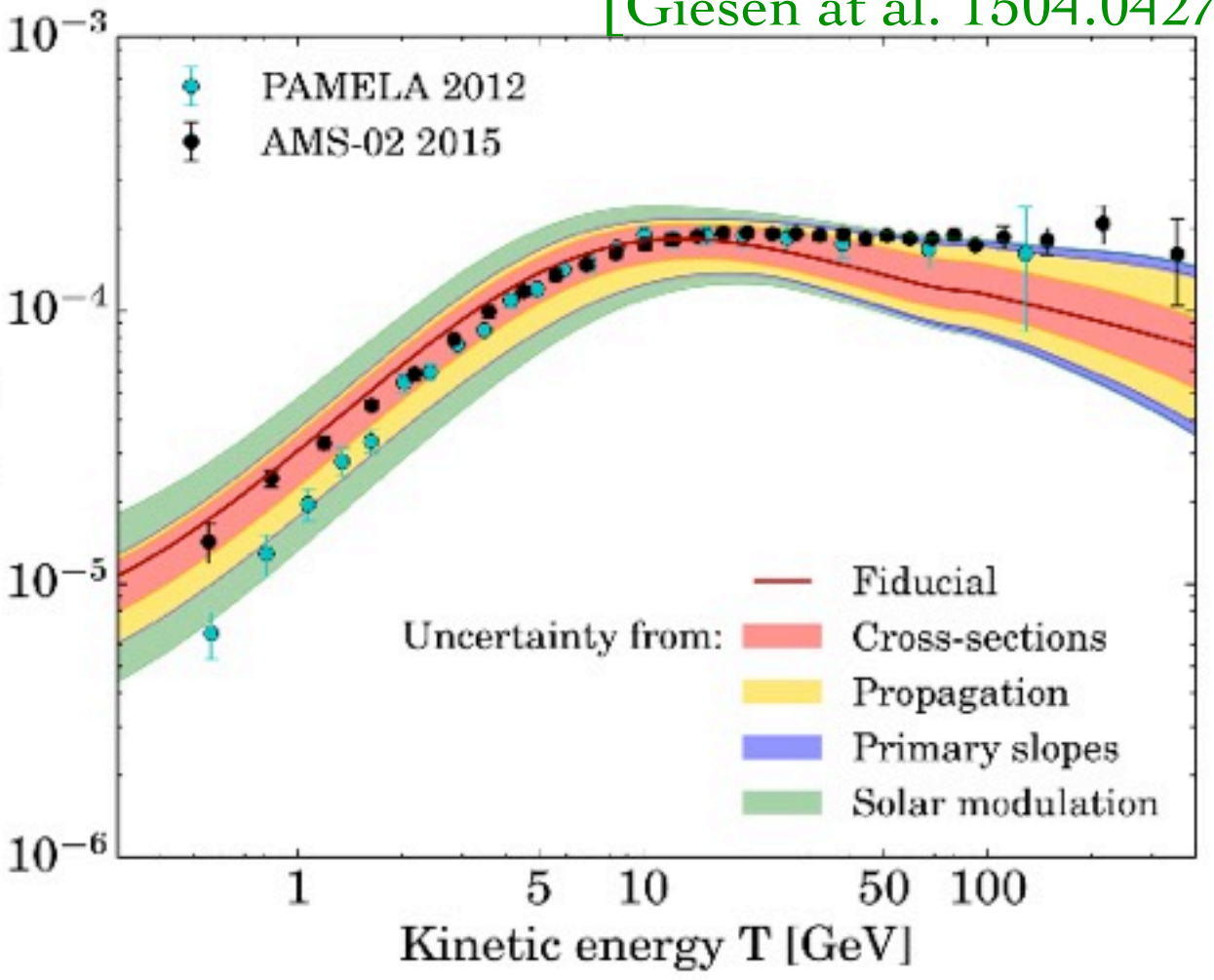
Antiproton fraction looked instead consistent with spallation production from cosmic rays... What about the new AMS-02 data?

Antimatter in CR: antiprotons

[PAMELA, 1007.0821]



[Giesen at al. 1504.04276]



Gamma rays observations

Search Strategies

Galactic center:

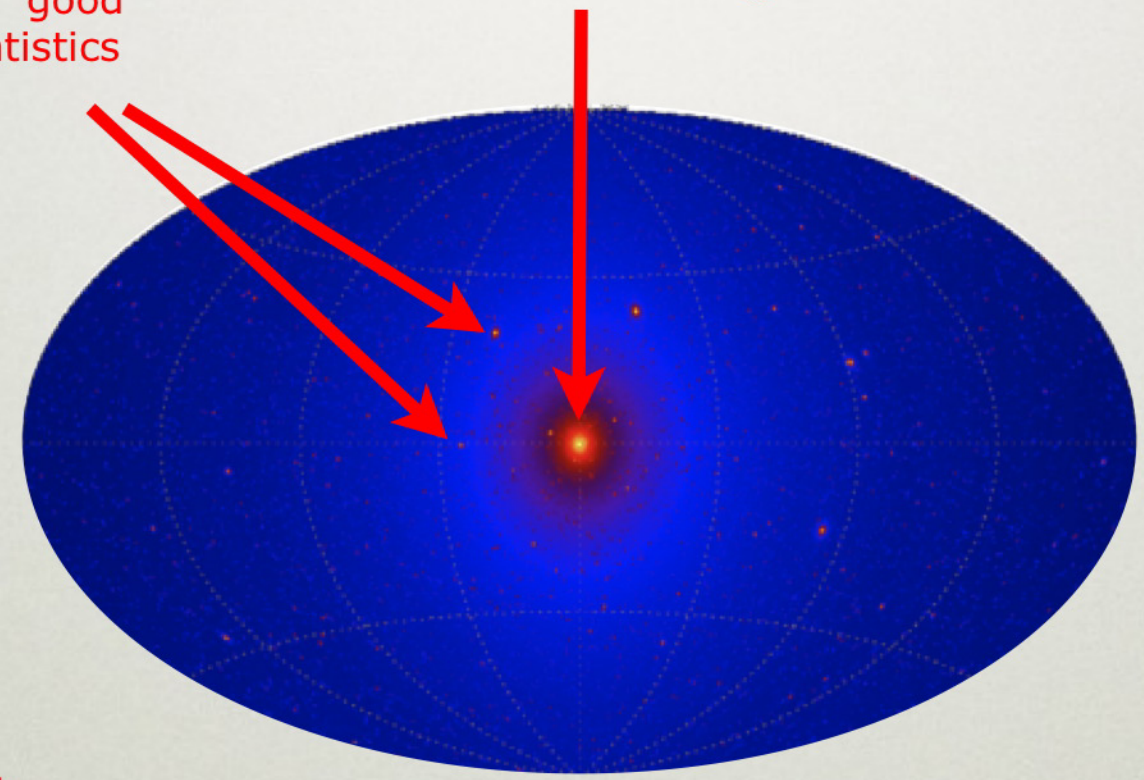
Good statistics but source confusion/diffuse background

Satellites:

Low background and good source ID, but low statistics

Milky Way halo:

Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

+Electrons!

Anisotropies

Spectral lines:

No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:

Low background but low statistics

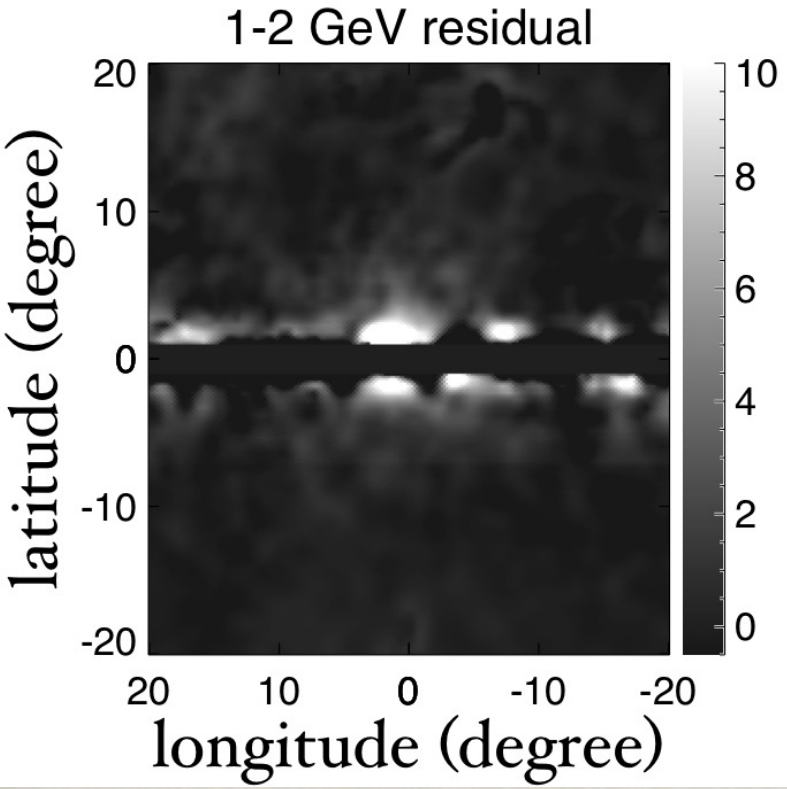
Extragalactic:

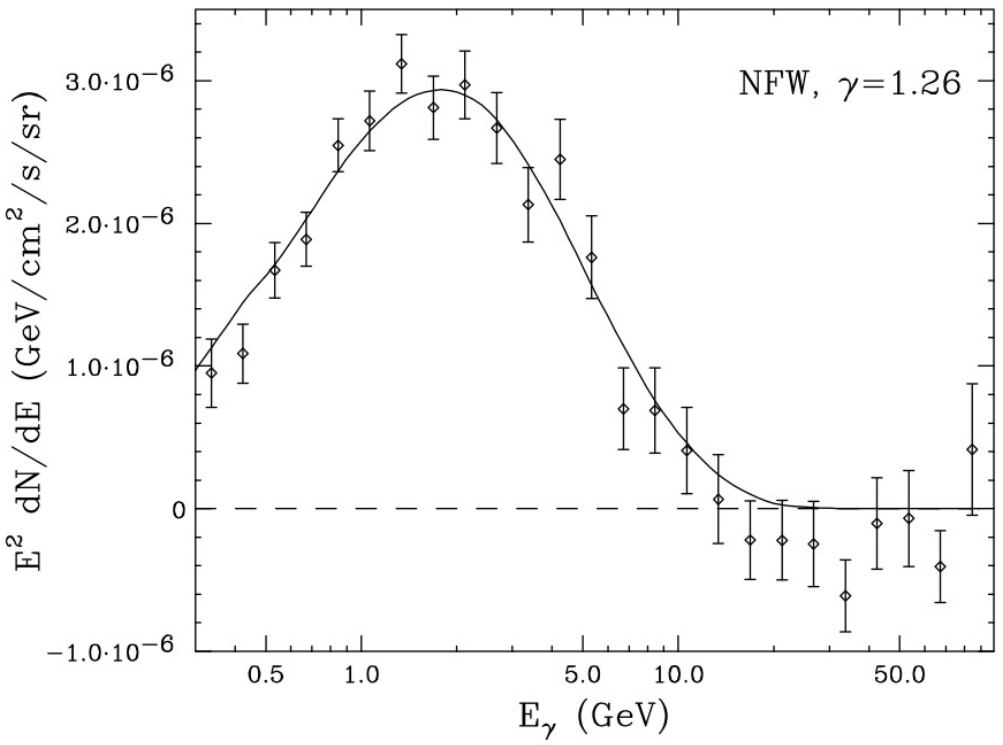
Large statistics, but astrophysics, Galactic diffuse background

Galactic centre excess

An excess has been found since some years in the FERMI-lat data by Hooper & al. in the direction of the Galactic centre:

[Daylan & al 1402.6703]



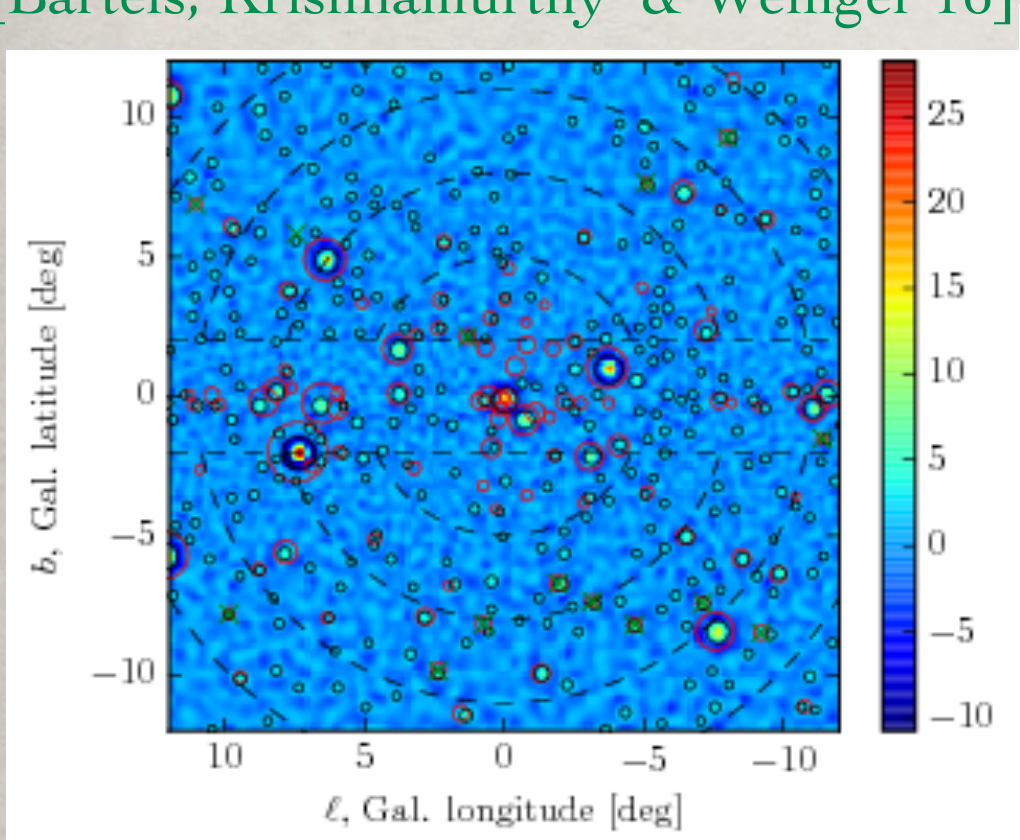


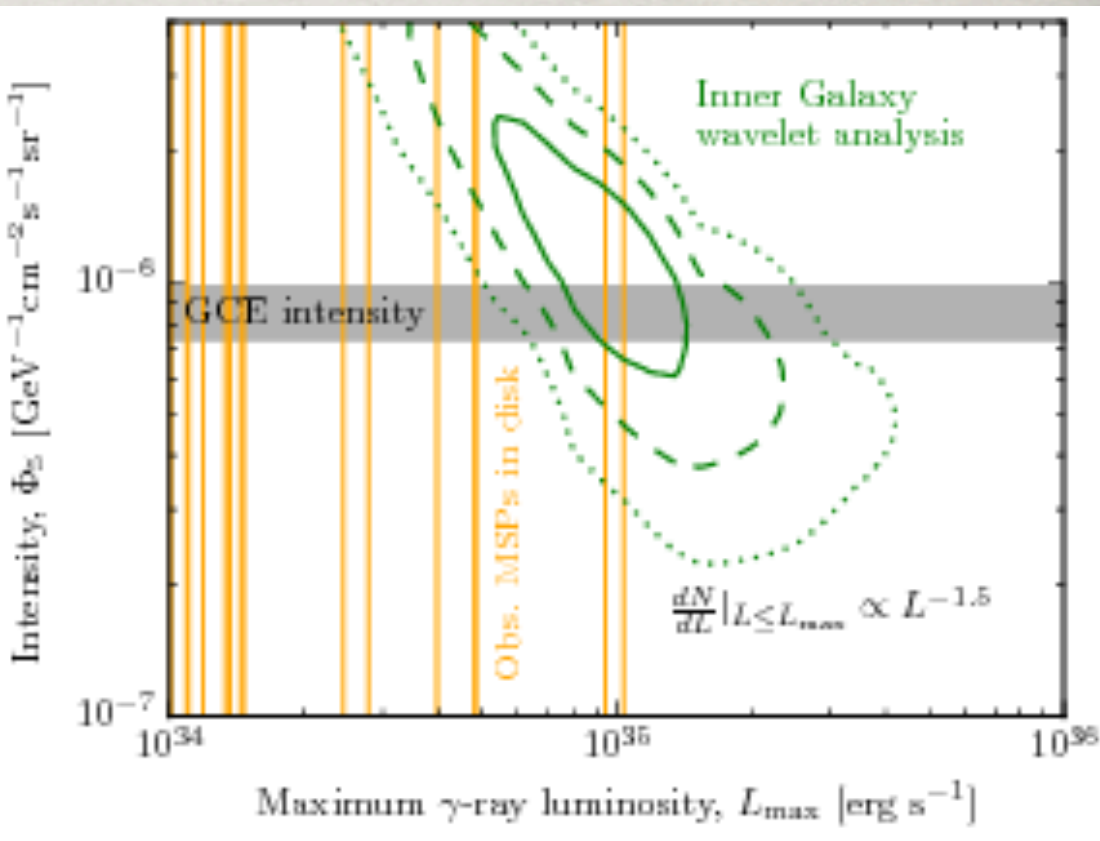
Compatible with a thermal relic annihilating into $b\,\bar{b}, \tau^+\,\tau^-$

Maybe due to millipulsar

A large population of millipulsars at the centre of the galaxy may be below the threshold for point-source detection:

[Bartels, Krishnamurthy & Weniger 16]

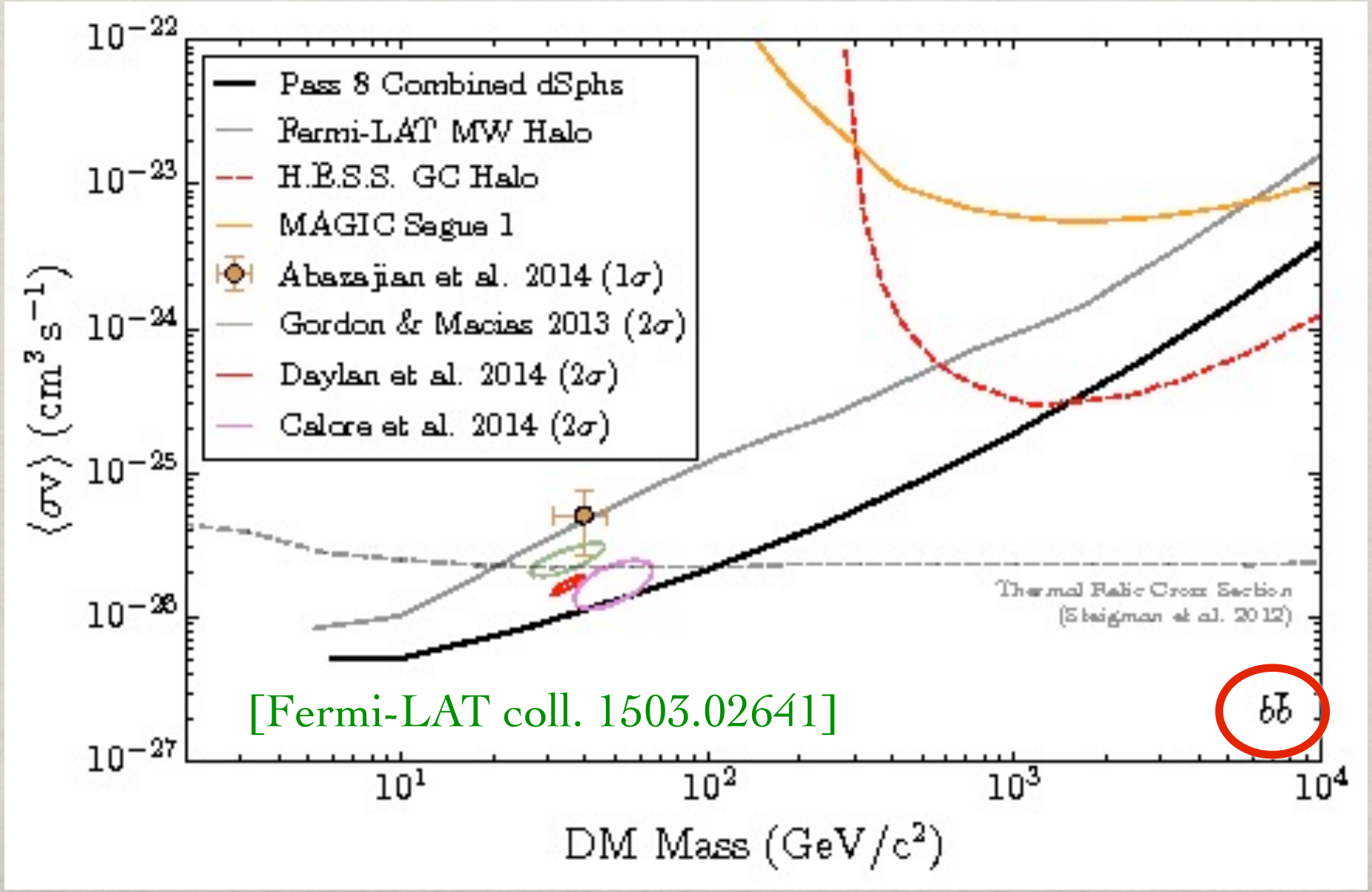




Wavelet analysis seems to find a substantial contribution...

Bounds on the continuum

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



[Fermi-LAT coll. 1503.02641]

Neutrinos

Atmospheric Neutrinos

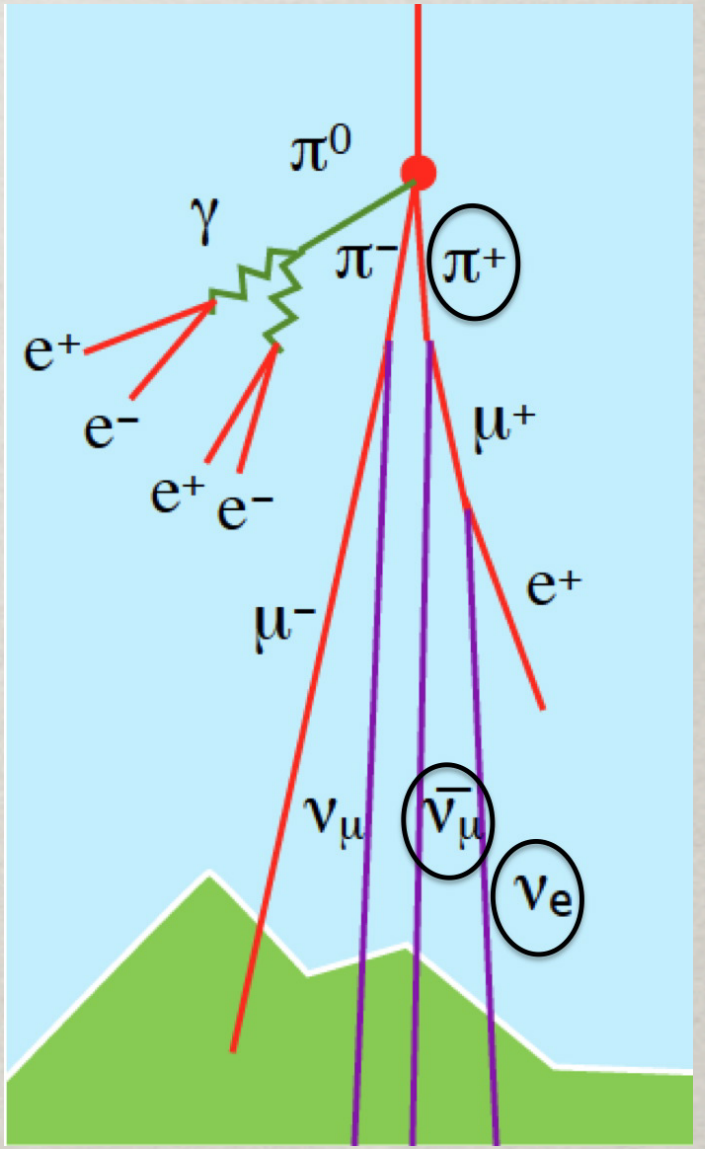
Cosmic rays interacting in the atmosphere produce as usual pions and therefore neutrinos in the ratio

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

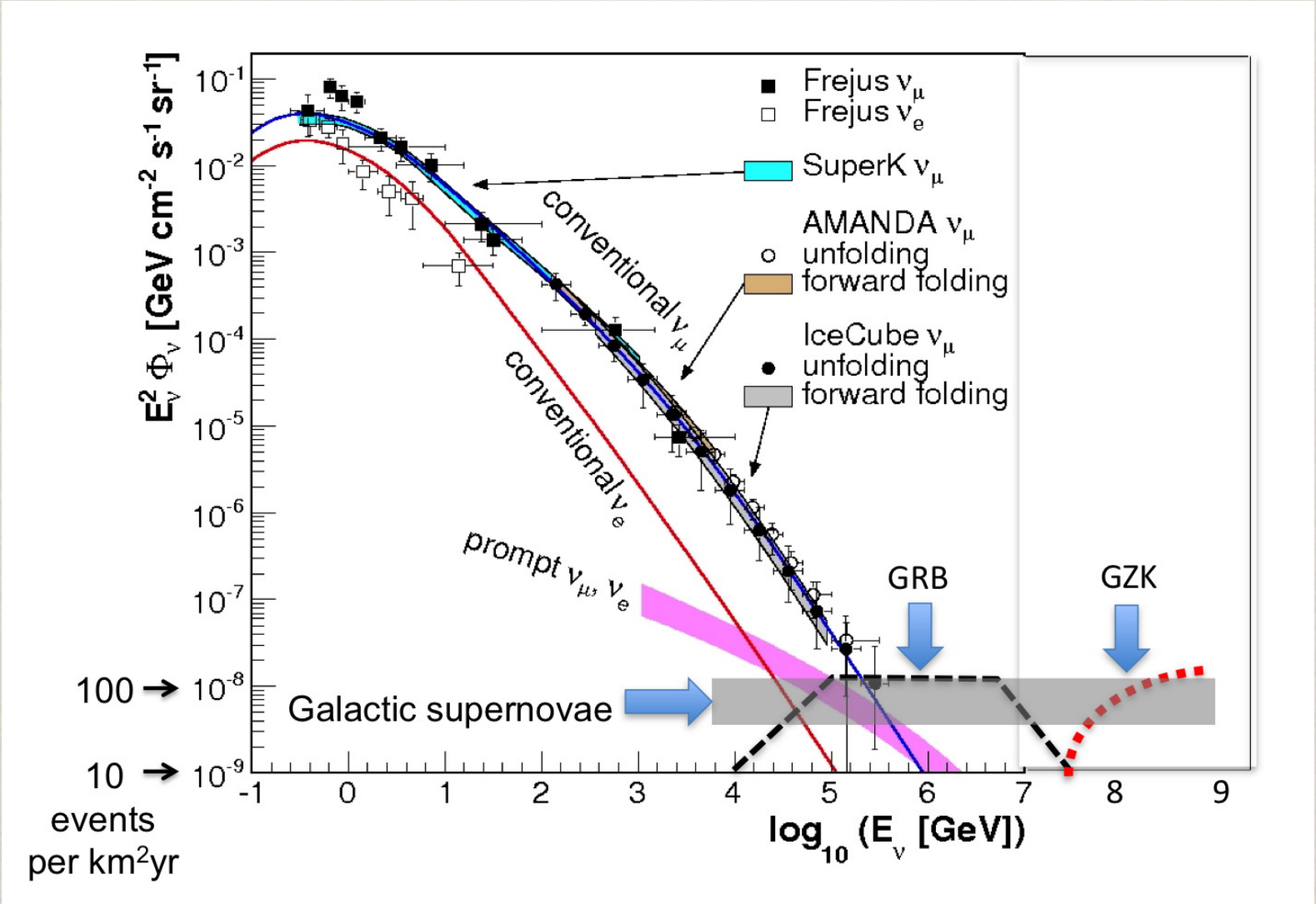
Lower ratio is measured:
neutrino flavour oscillation

→ Neutrino lectures by P. Hernandez

For us they are background...

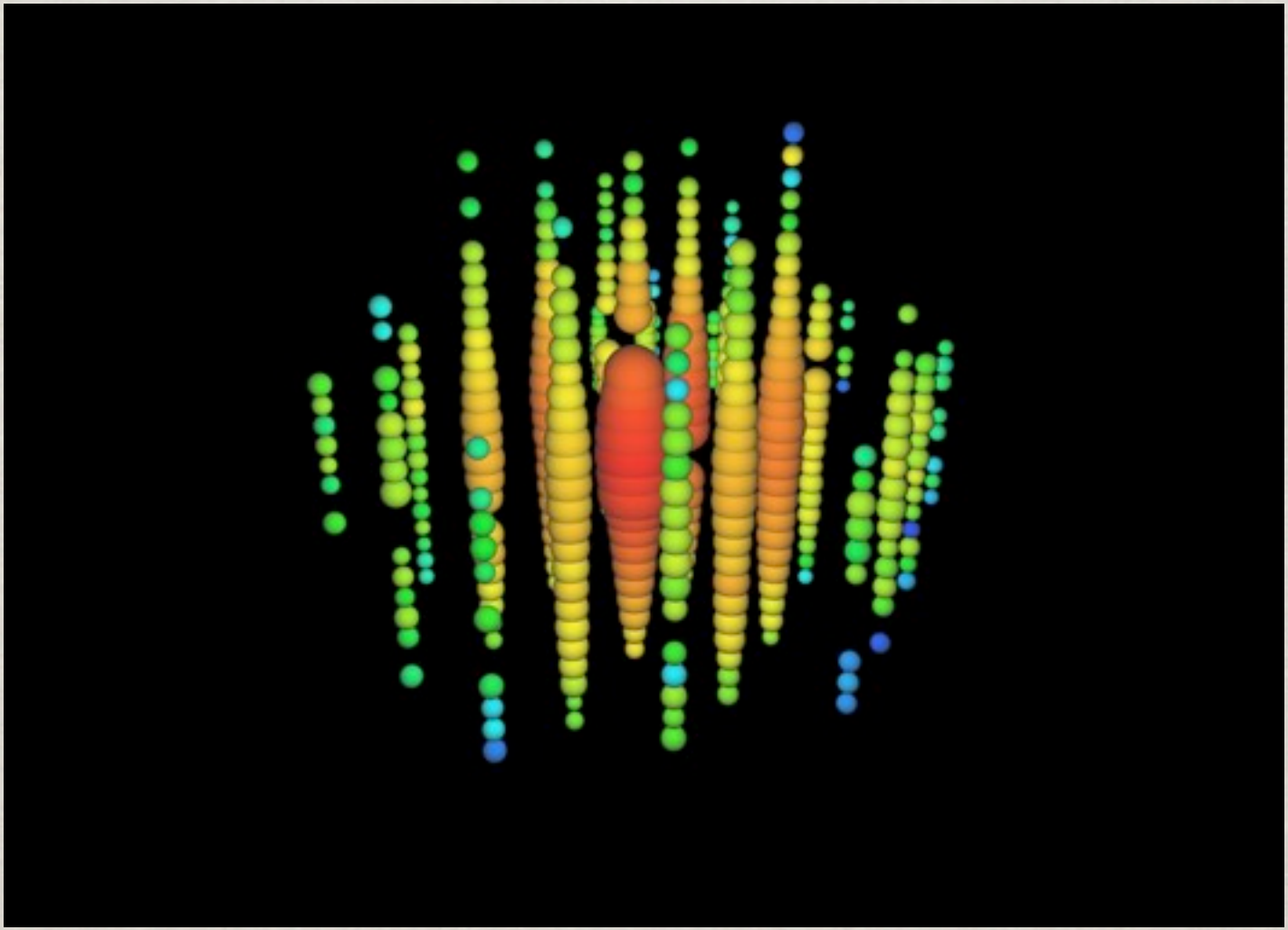


Neutrino Flux



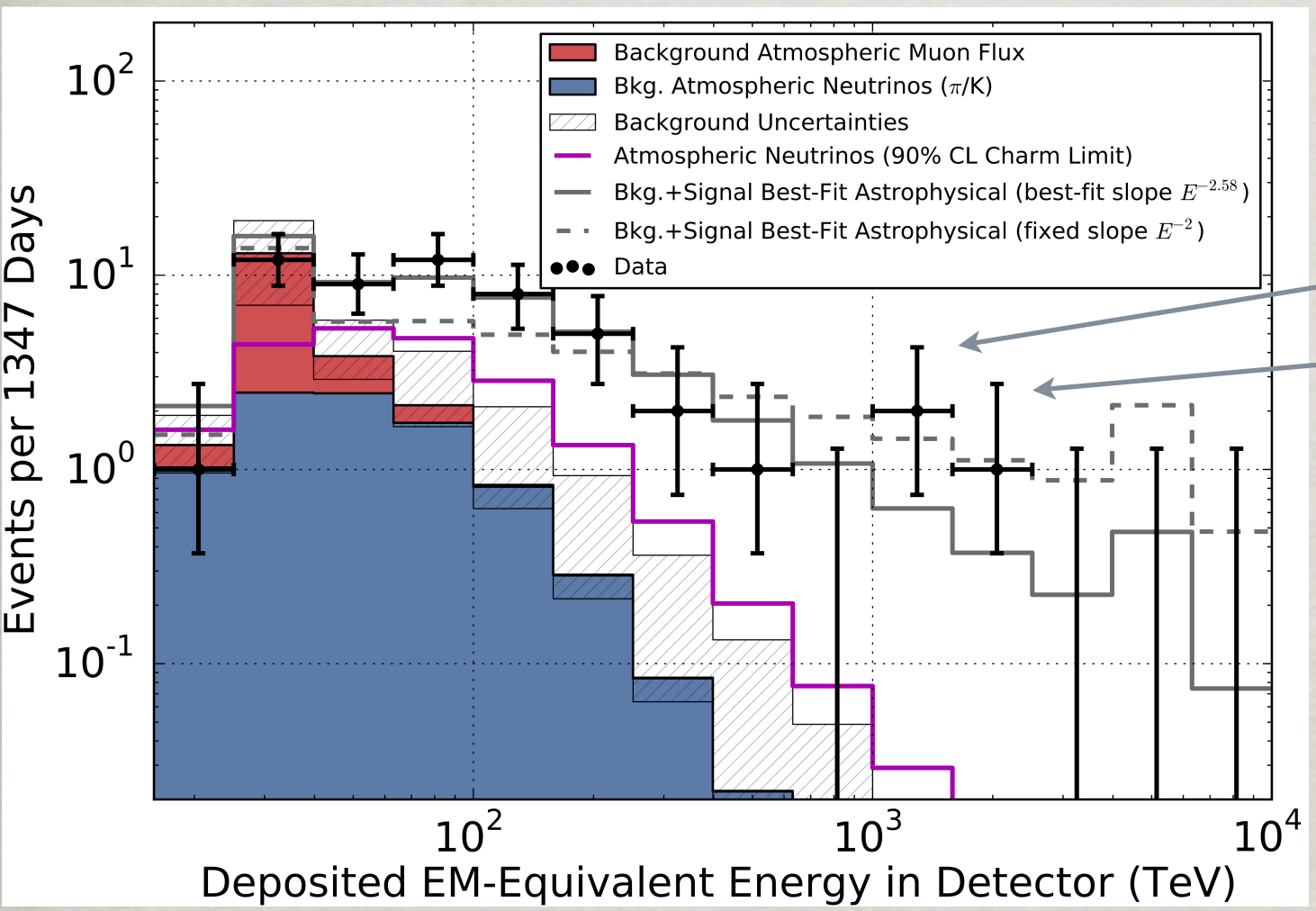
Low Energy part dominated by atmospheric neutrinos, at higher energy different signals are expected...

Neutrino News



Few events in PeV energies found !

Neutrino News



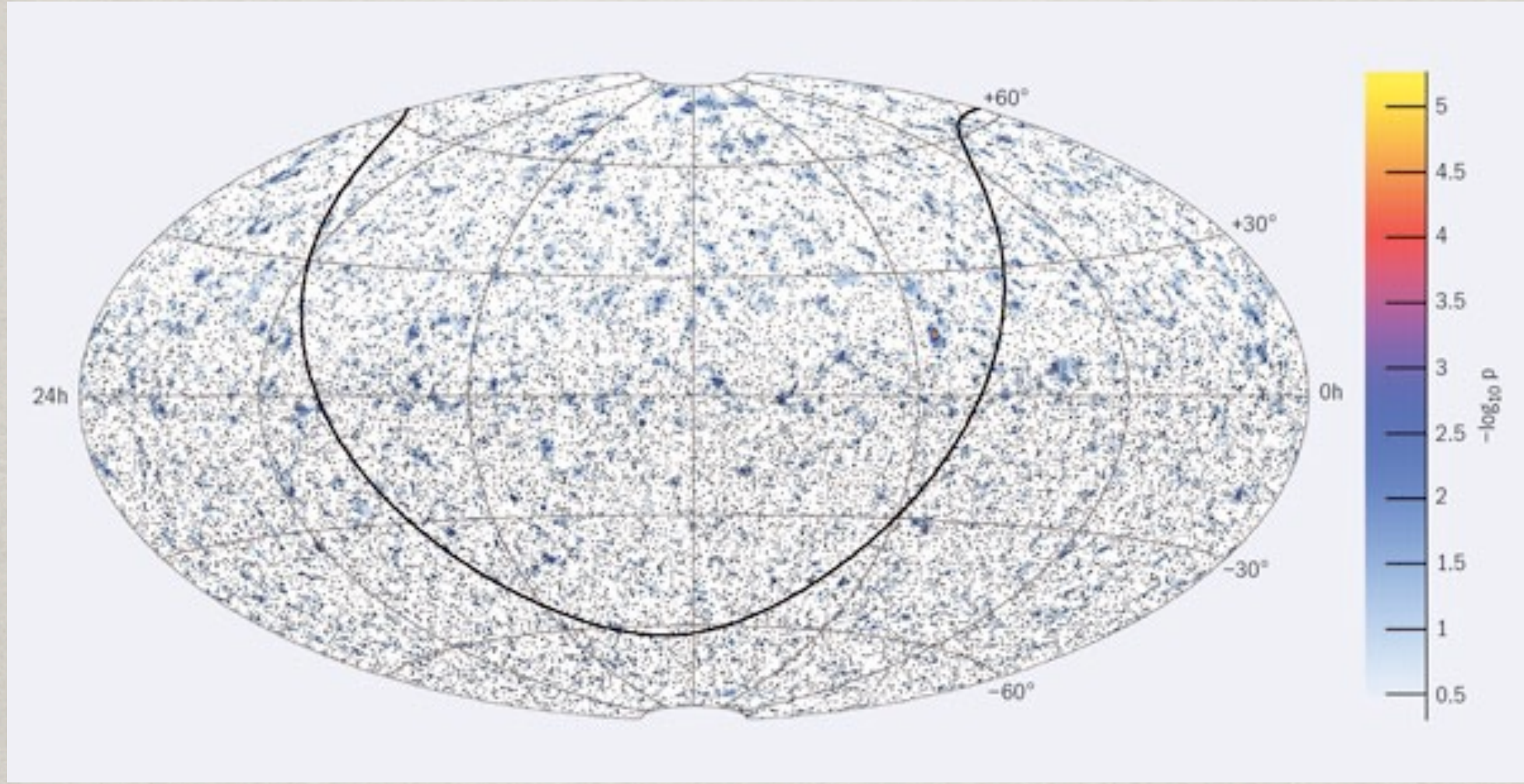
Bert & Ernie

Big Bird

More events seen in the PeV region !

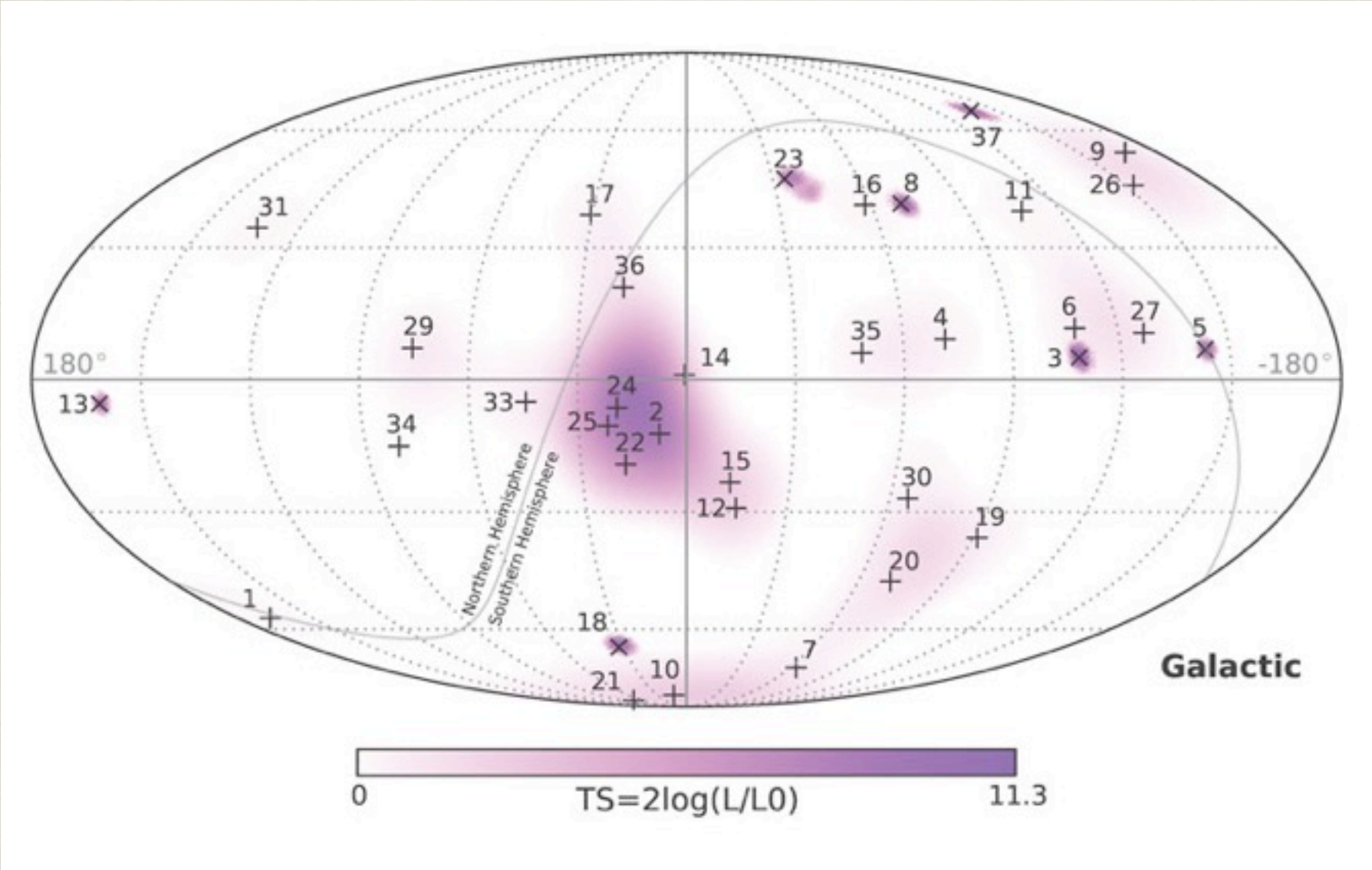
Not compatible with atmospheric neutrino background, but too low energy for the GZK neutrinos...

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 !

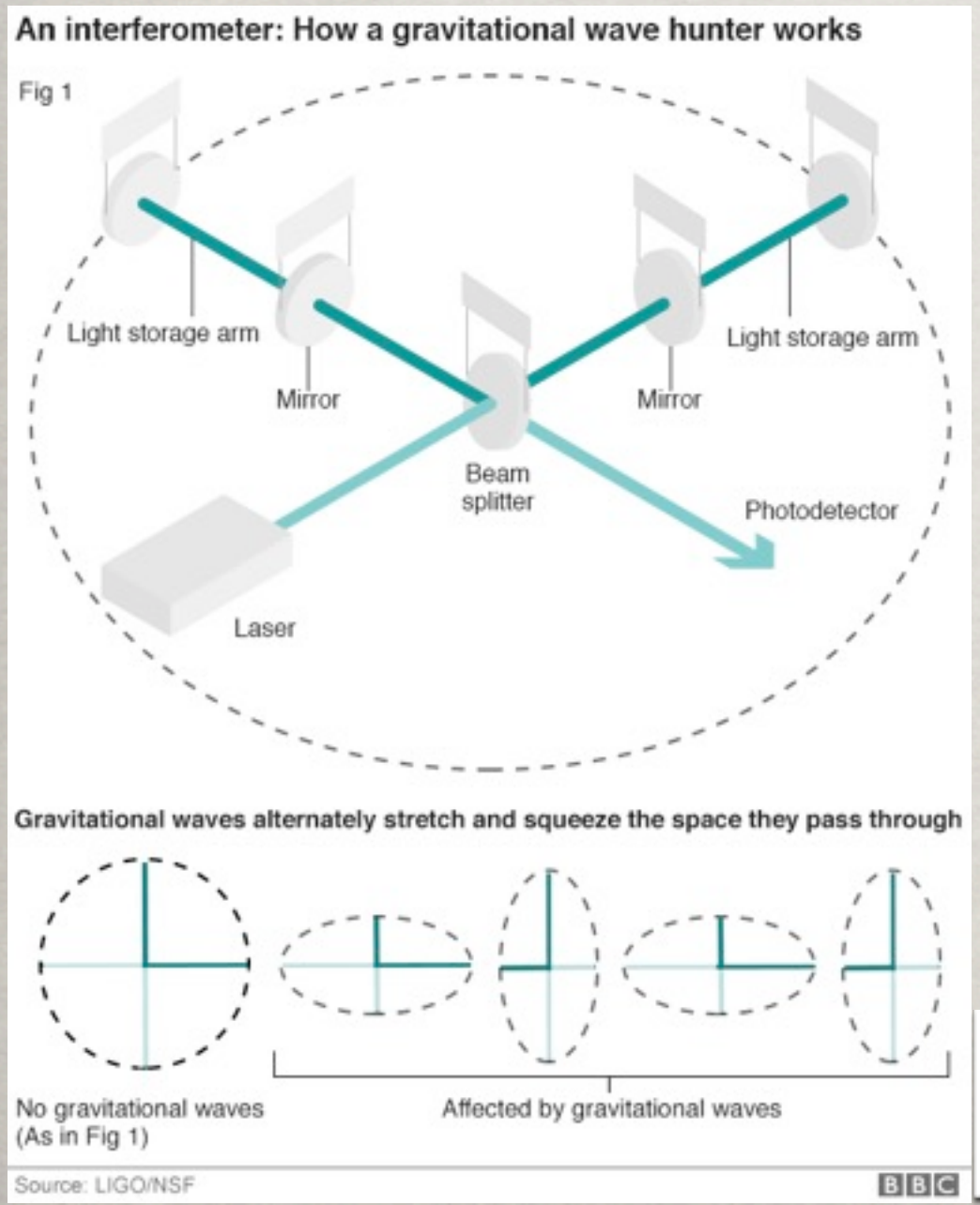
Neutrino Astronomy



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

Gravitational waves

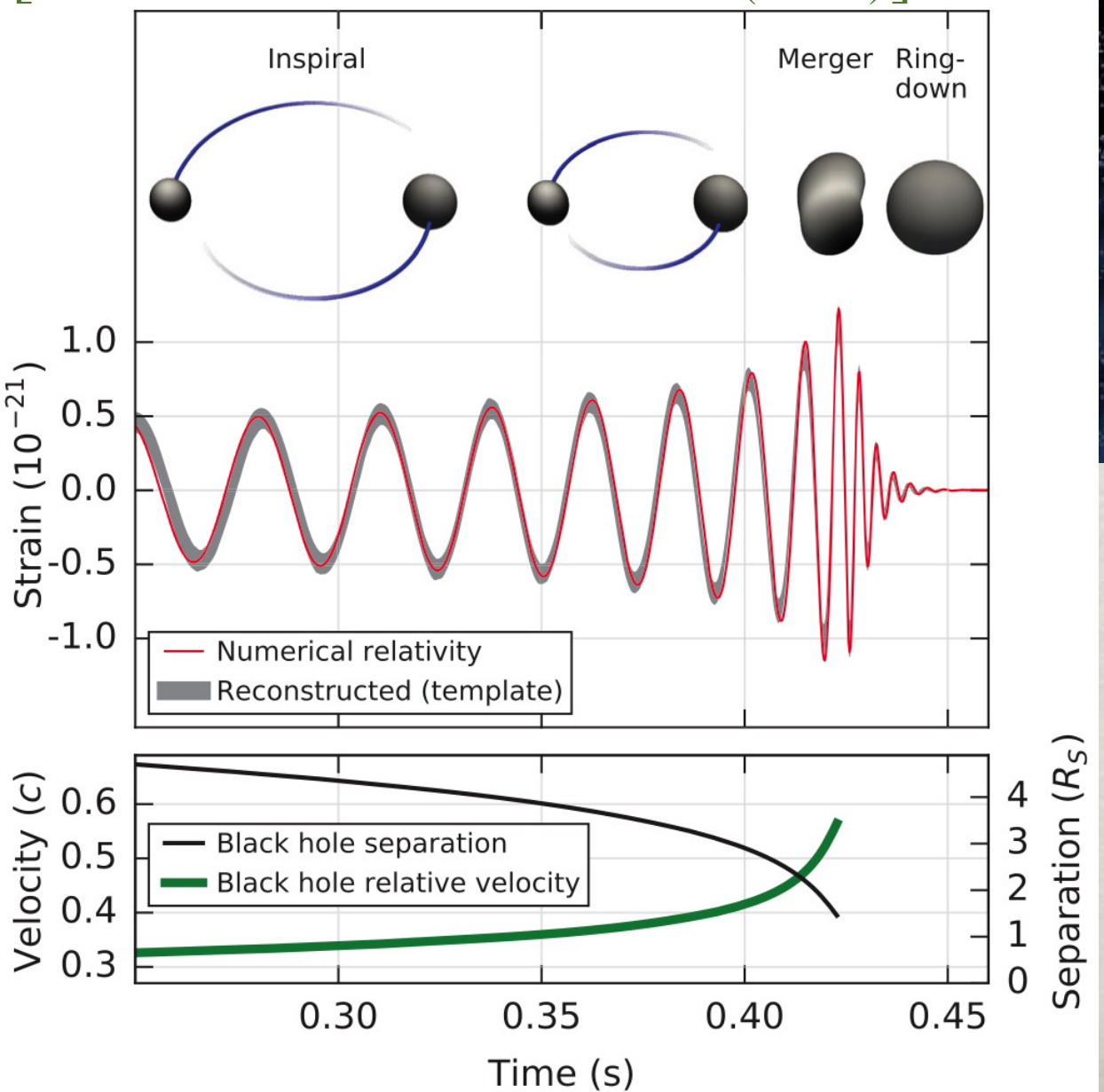
Breaking News: Gravitational waves

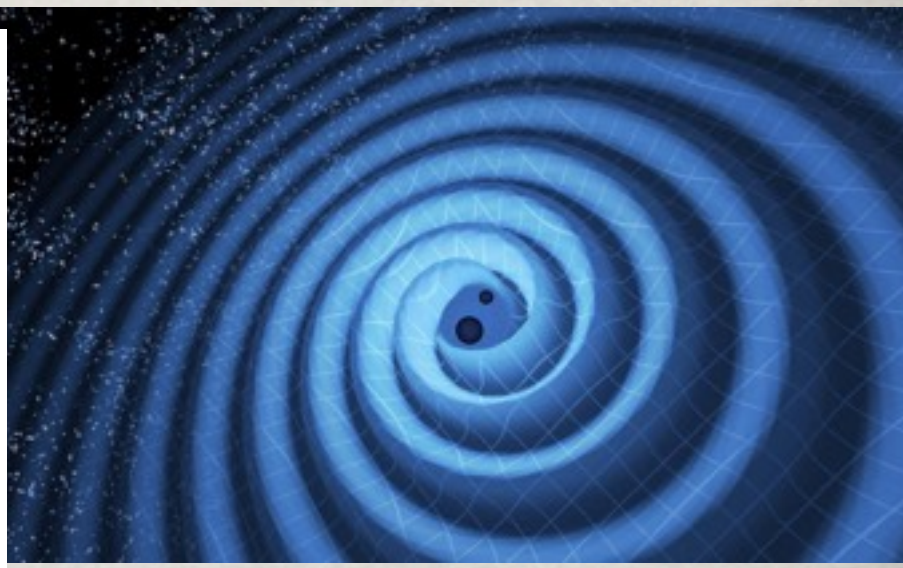


Advanced LIGO: Two Interferometers, 4 km arms

Breaking News: Gravitational waves

[aLIGO cn. PRL 116, 061102 (2016)]

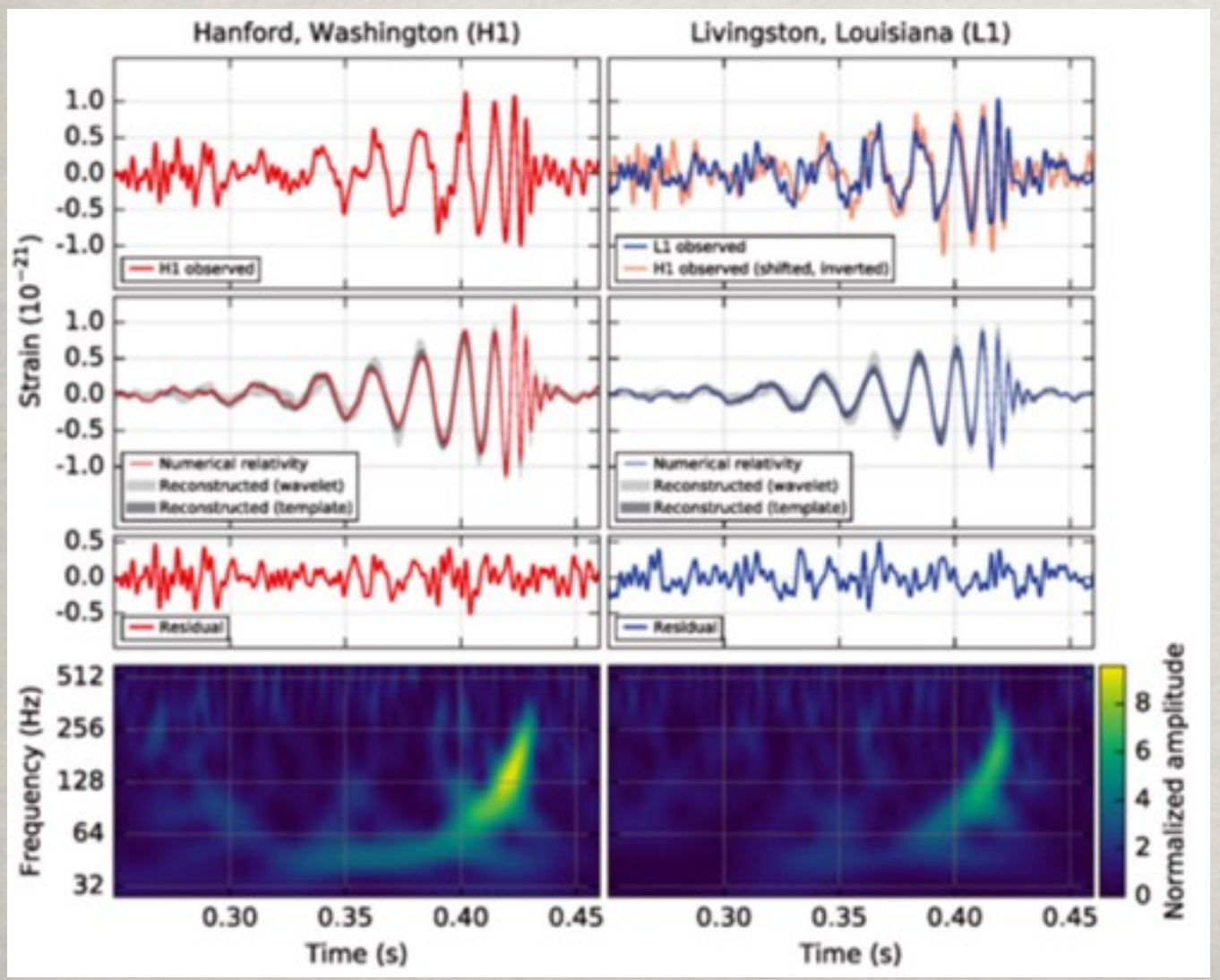




Numerical General Relativity gives predictions for the expected GW signal from two merging black holes

Breaking News: Gravitational waves

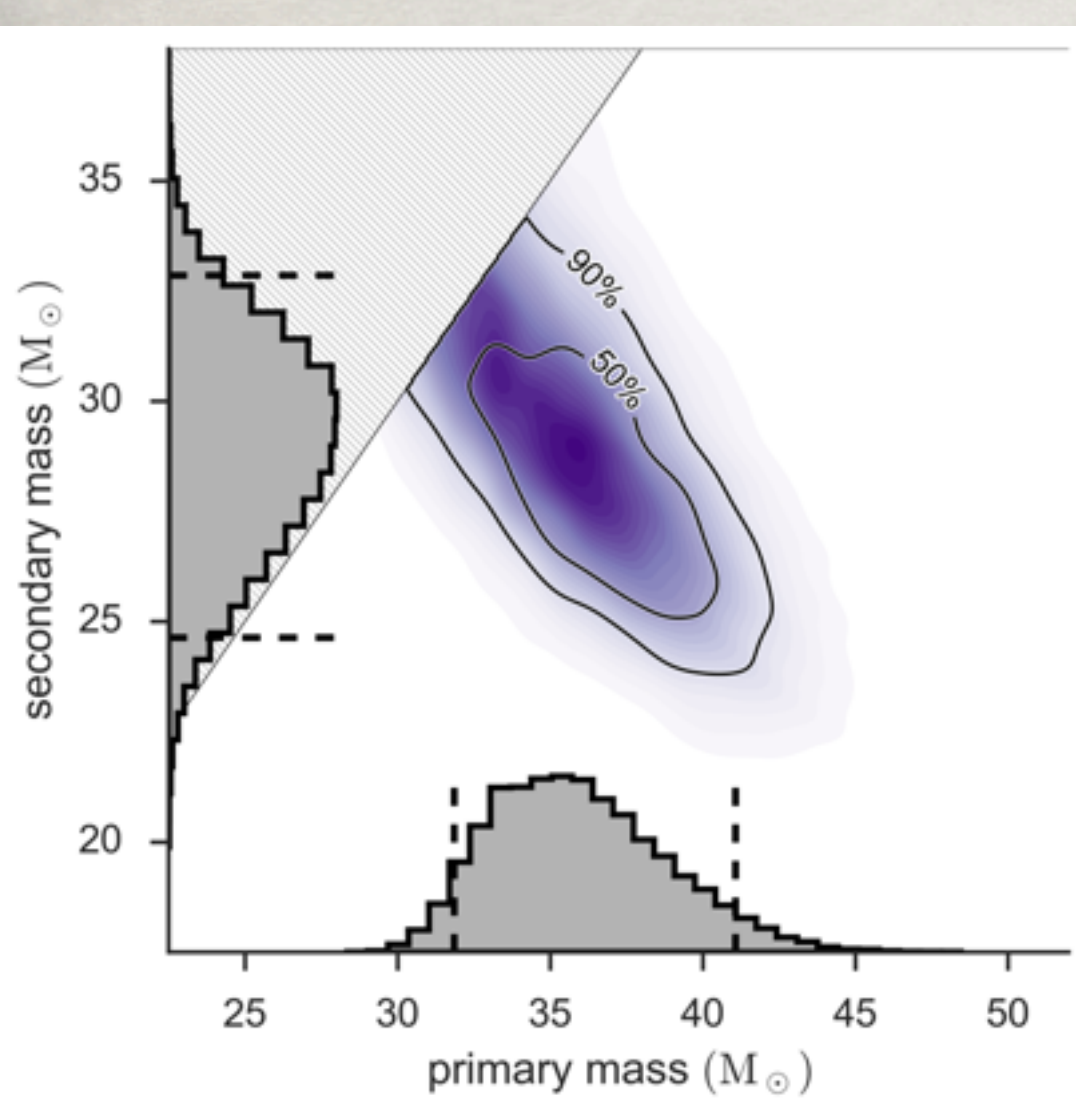
[aLIGO cn. PRL 116, 061102 (2016)]

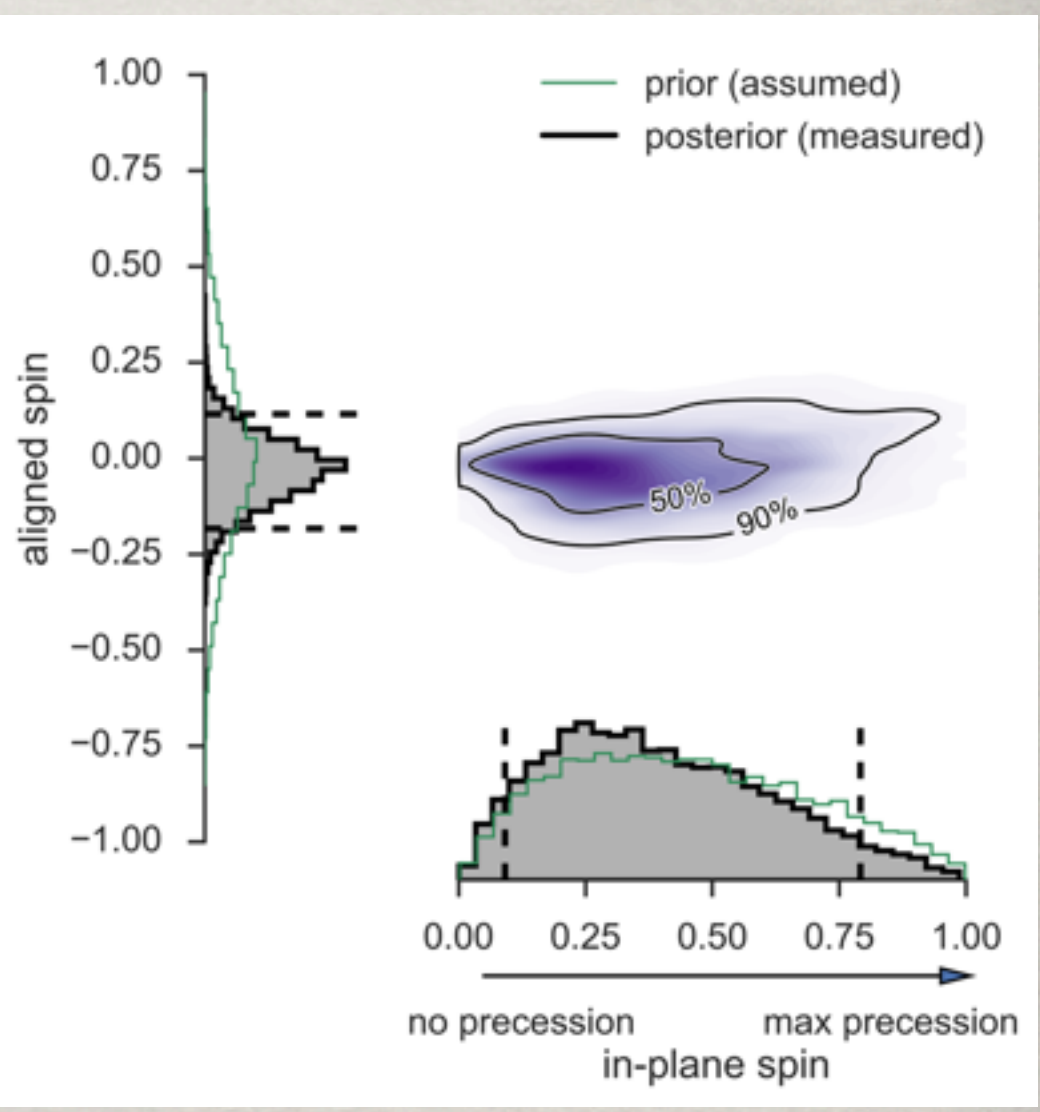


First detection of a GW signal on September 14 2015: GW150914

Same signal in both detector well in agreement with template from numerical GR

Breaking News: Gravitational waves

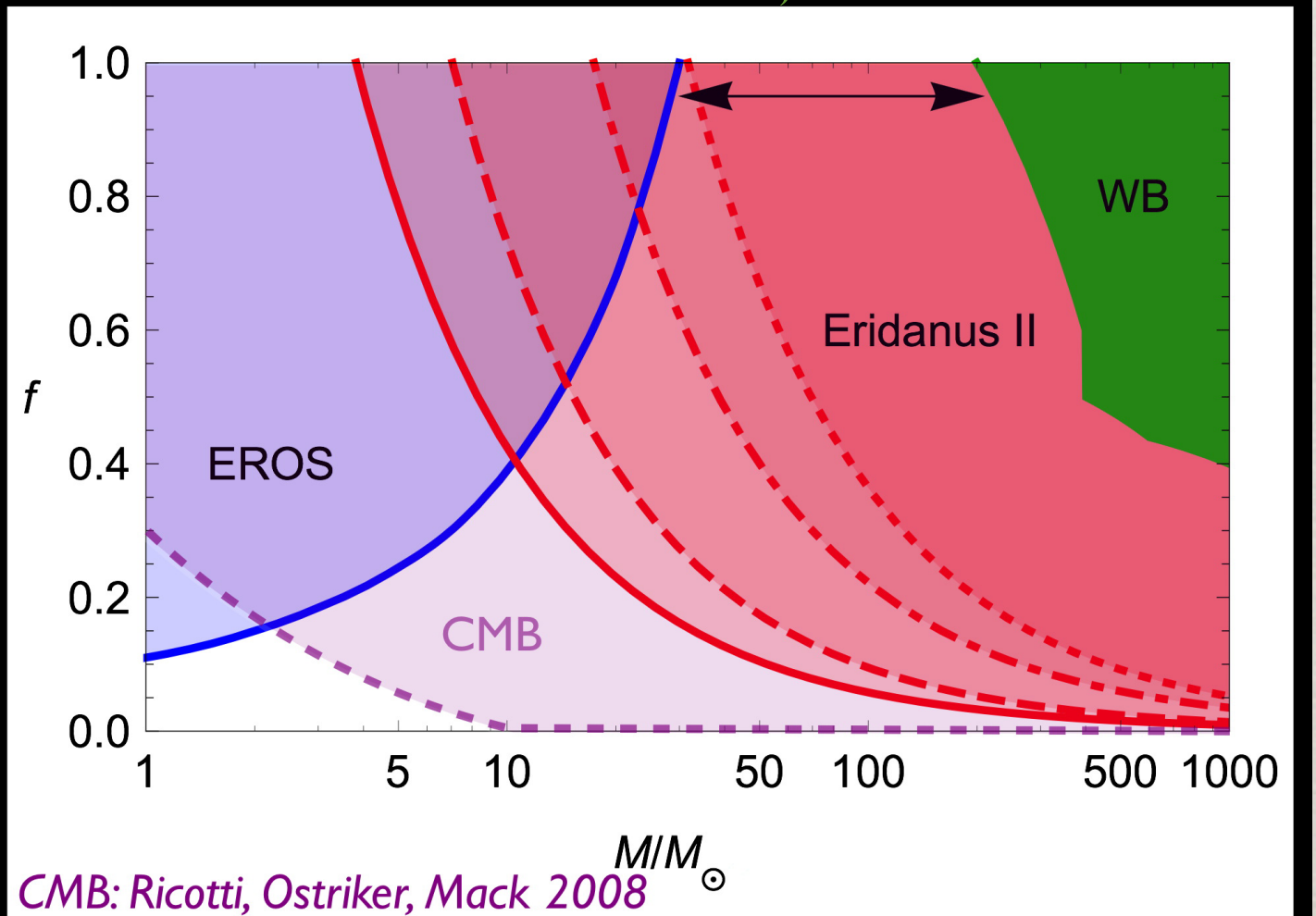




Good determination of mass of the merging BH and more...

Are BH the Dark Matter ?

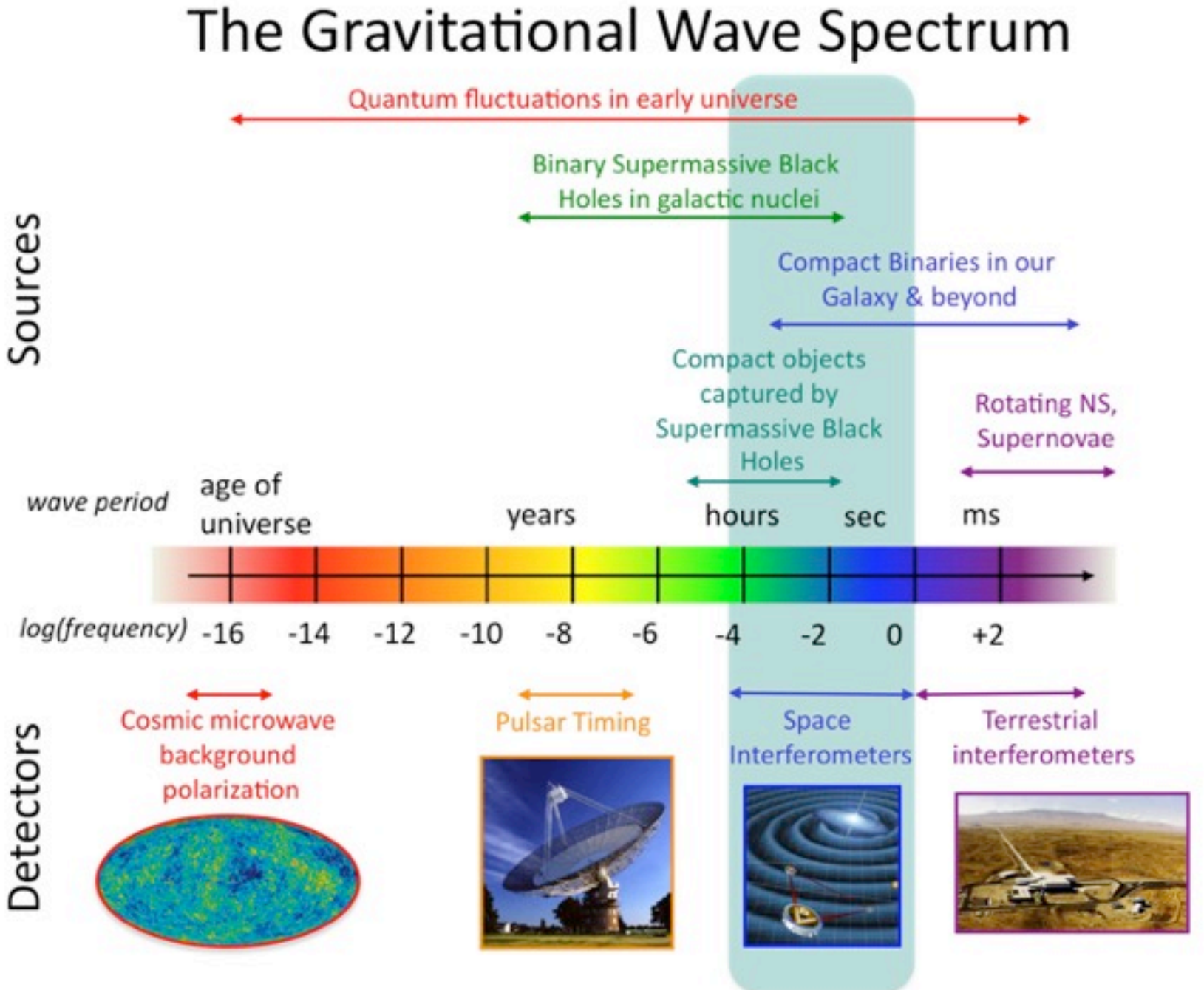
P. Gondolo, Talk @ DSU2016



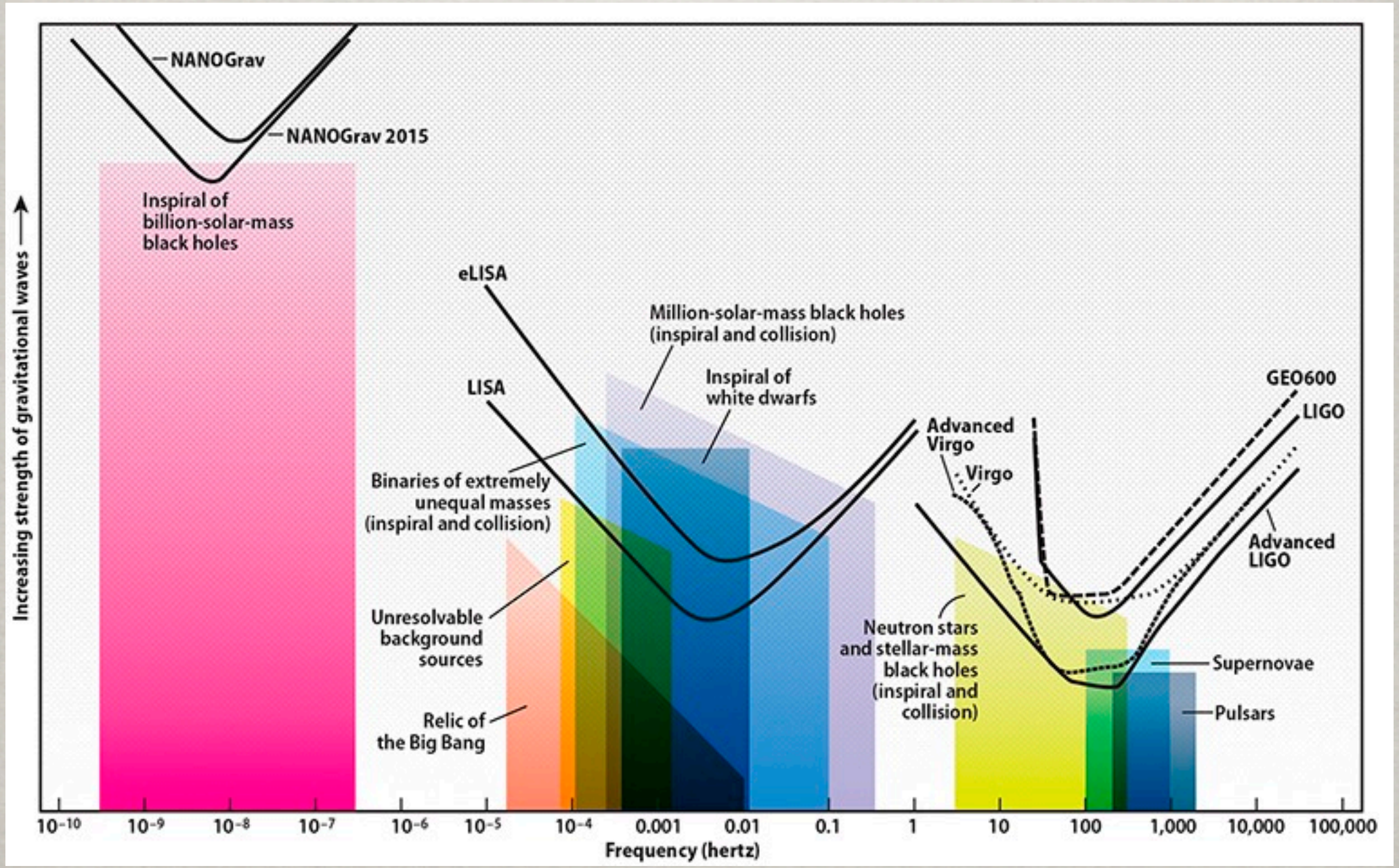
Carr, Kühnel, Sandstad 2016

Difficult to have all DM in a single mass window, but possible with an extended distribution.

Future of GW detection



Future of GW detection



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 new data, e.g. GW, and open questions: still lots to do !

References I

- Reviews on cosmic rays:
  - K. Kotera & A. V. Olinto Annu.Rev.Astron.Astrophys. 49 (2011) 119-153 (arXiv:1101.4256)

  - G. Sigl arXiv:1202.0466

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- Advanced LIGO results, see:
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  Animations: check Gravitational Waves Explained on
  http://youtube.com