VHE cosmic γ rays and fundamental physics (with emphasis on photon propagation)

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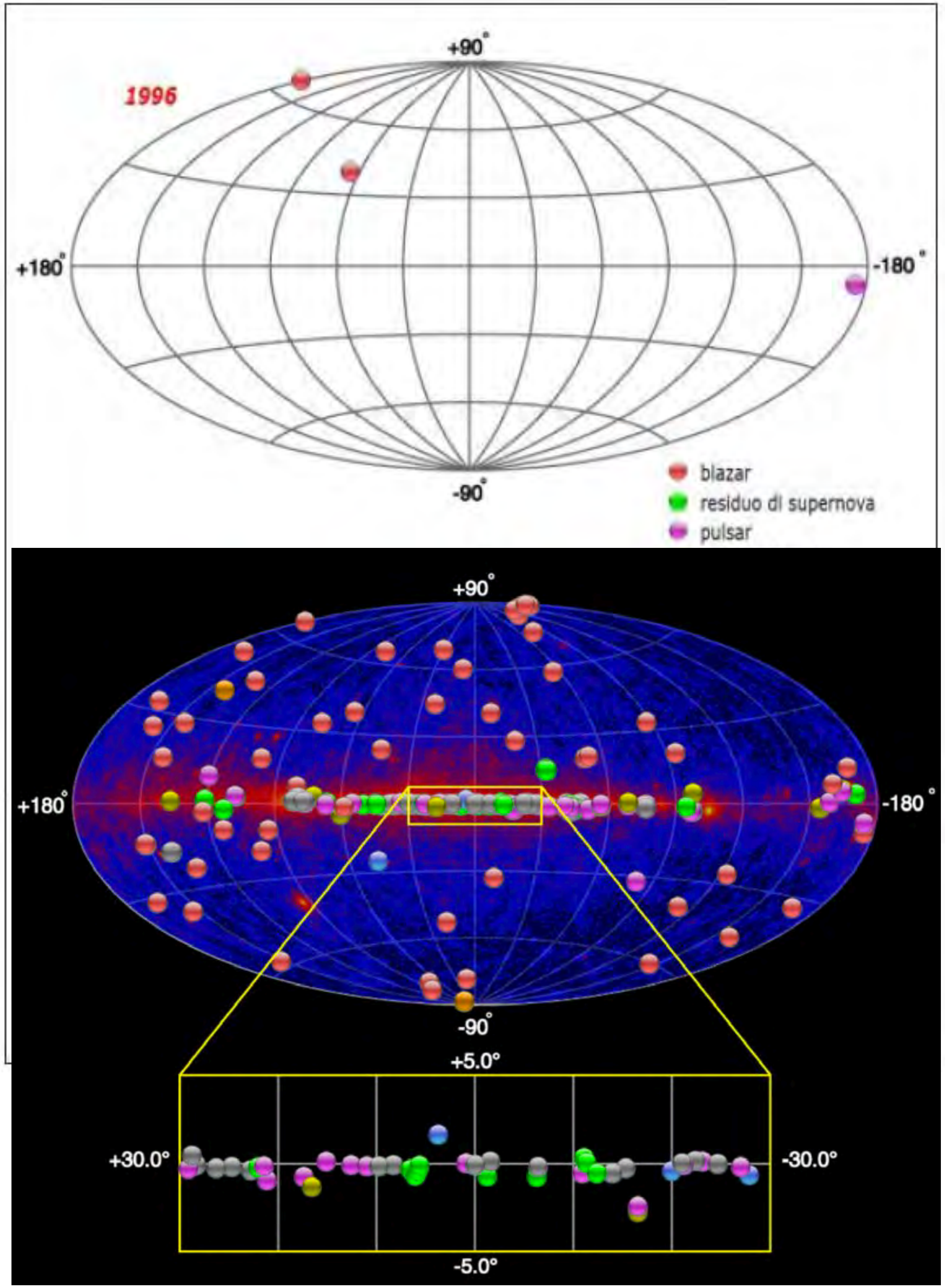
- Introduction: why gamma rays? How?
- Some results related to fundamental physics
- What's next

Roma, May 2013

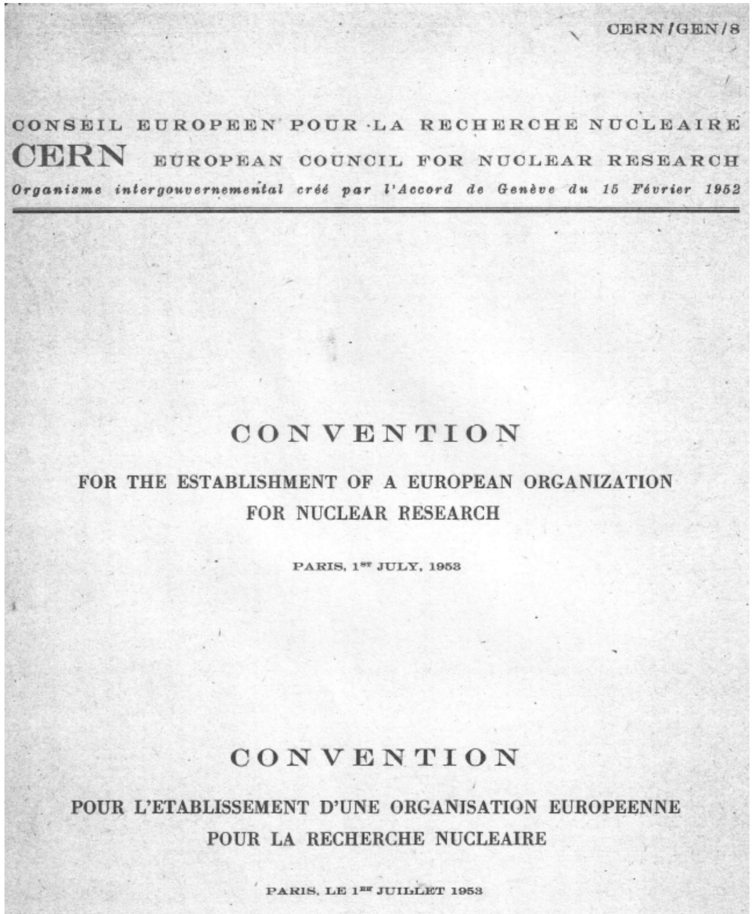
Highlight in γ-ray astrophysics (MAGIC, HESS, VERITAS)

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 1000 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 160 (and >200 papers) in the last years. ~500 sources above 10 GeV
  - And also a better knowledge of the diffuse gammas and electrons
- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources
- A new tool for cosmic-ray physics and fundamental physics



Main physics results and perspectives
(with emphasis on fundamental physics)

- *Cosmic Rays*
- *Search for "WIMP" Dark Matter*
- Photon propagation
  - Transparency of the Universe;
  - Energy of the vacuum;
  - Tests of Lorentz Invariance;
  - Cosmology



CERN/GEN/8

CONSEIL EUROPEEN POUR LA RECHERCHE NUCLEAIRE

CERN EUROPEAN COUNCIL FOR NUCLEAR RESEARCH

Organisme intergouvernemental créé par l'Accord de Genève du 15 Février 1952

CONVENTION

FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PARIS, 1ST JULY, 1953

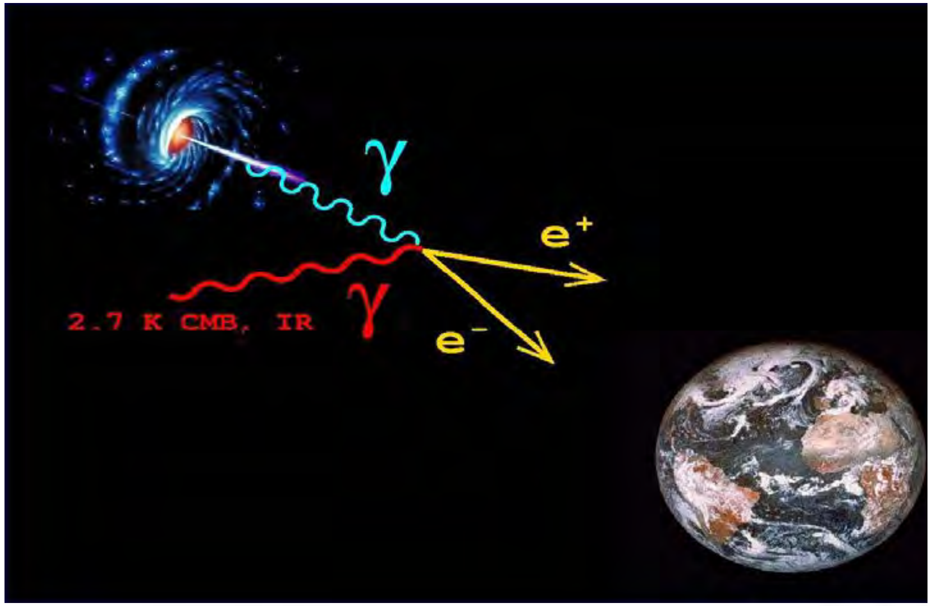
CONVENTION

POUR L'ETABLISSEMENT D'UNE ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

PARIS, LE 1ER JUILLET 1953

How do gamma rays reach us?

$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$



$$\epsilon > \epsilon_{\rm thr}(E,\varphi) \equiv \frac{2\, m_e^2\, c^4}{E\,(1-\cos\varphi)}$$

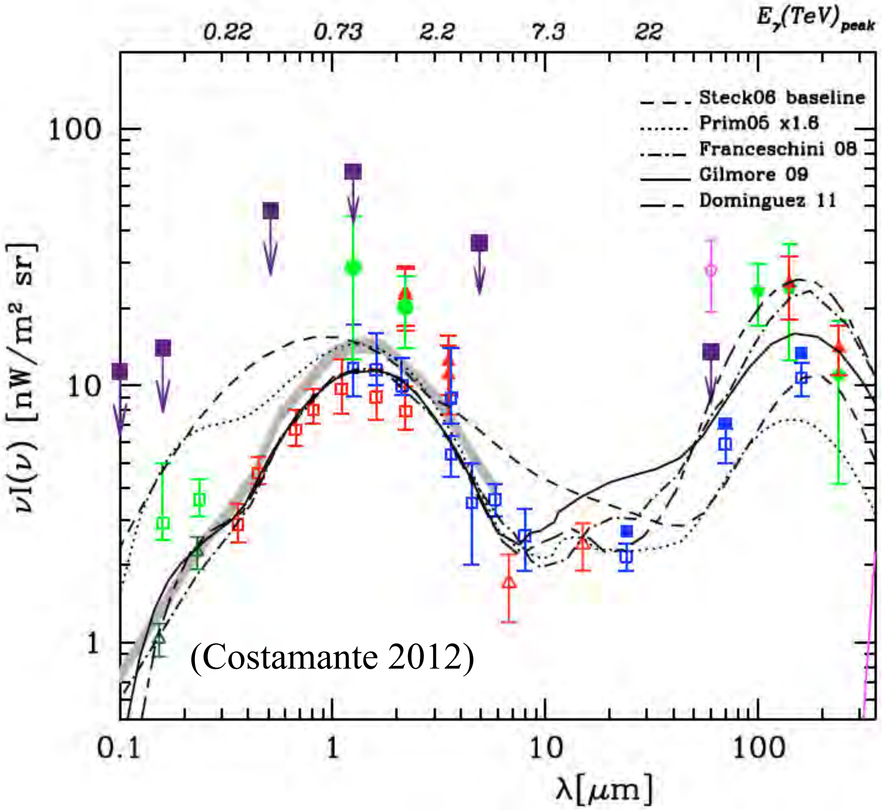
$$\sigma_{\gamma\gamma}(E,\epsilon,\varphi) = \frac{2\pi\alpha^2}{3m_e^2} W(\beta) \simeq 1.25\cdot 10^{-25}\, W(\beta)\,{\rm cm}^2\ ,$$

$$W(\beta) = \left(1-\beta^2\right)\left[2\beta\left(\beta^2-2\right)+\left(3-\beta^4\right)\,\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

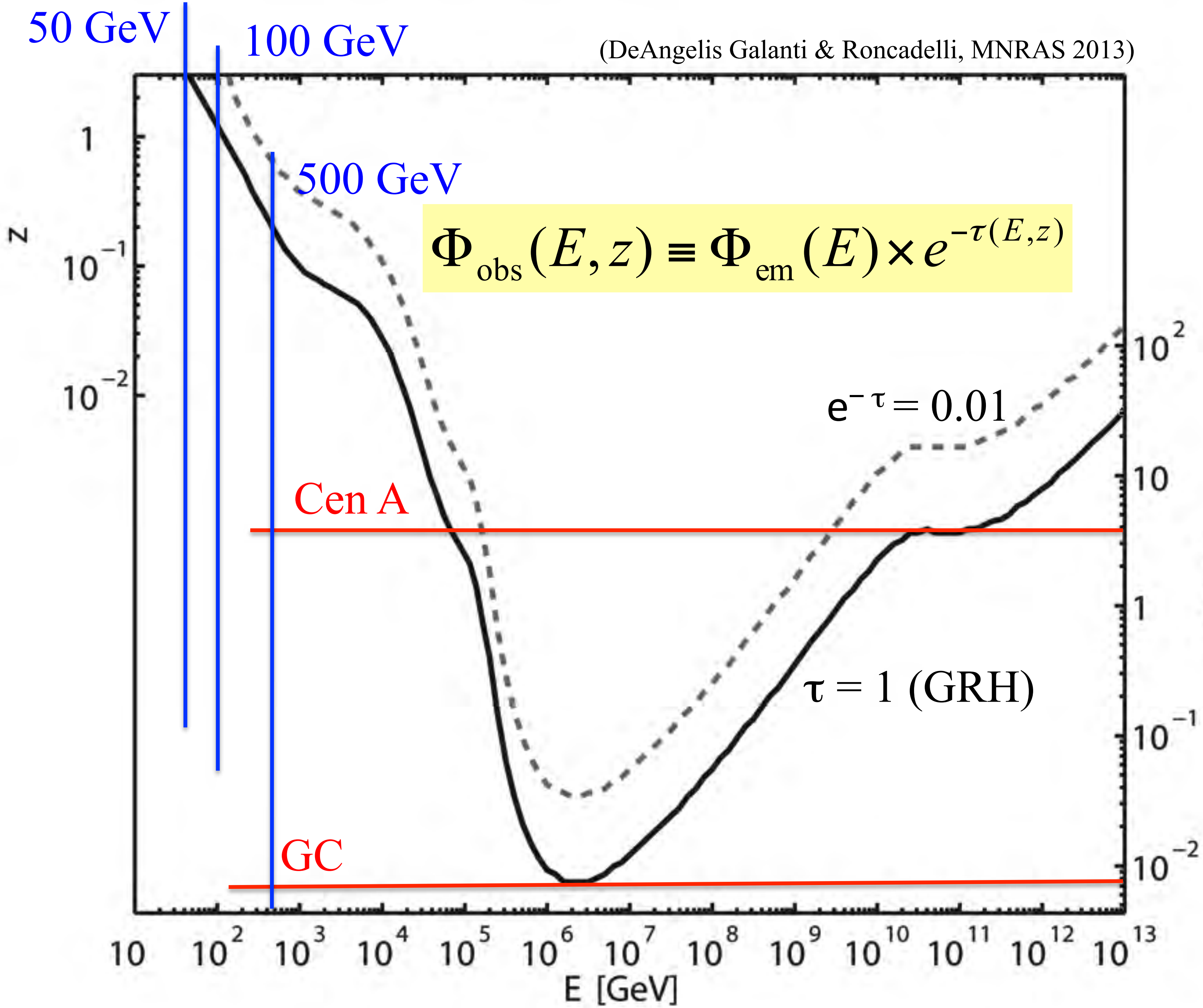
Maximum $\sigma_{\gamma\gamma}^{\rm max} \simeq 1.70\cdot 10^{-25}\ {\rm cm}^2$ for $\beta \simeq 0.70$.
For an isotropic background, it is maximized for

$$\epsilon(E) \simeq \left(\frac{900\ {\rm GeV}}{E}\right)\ {\rm eV}$$

Exercise 1



(Costamante 2012)



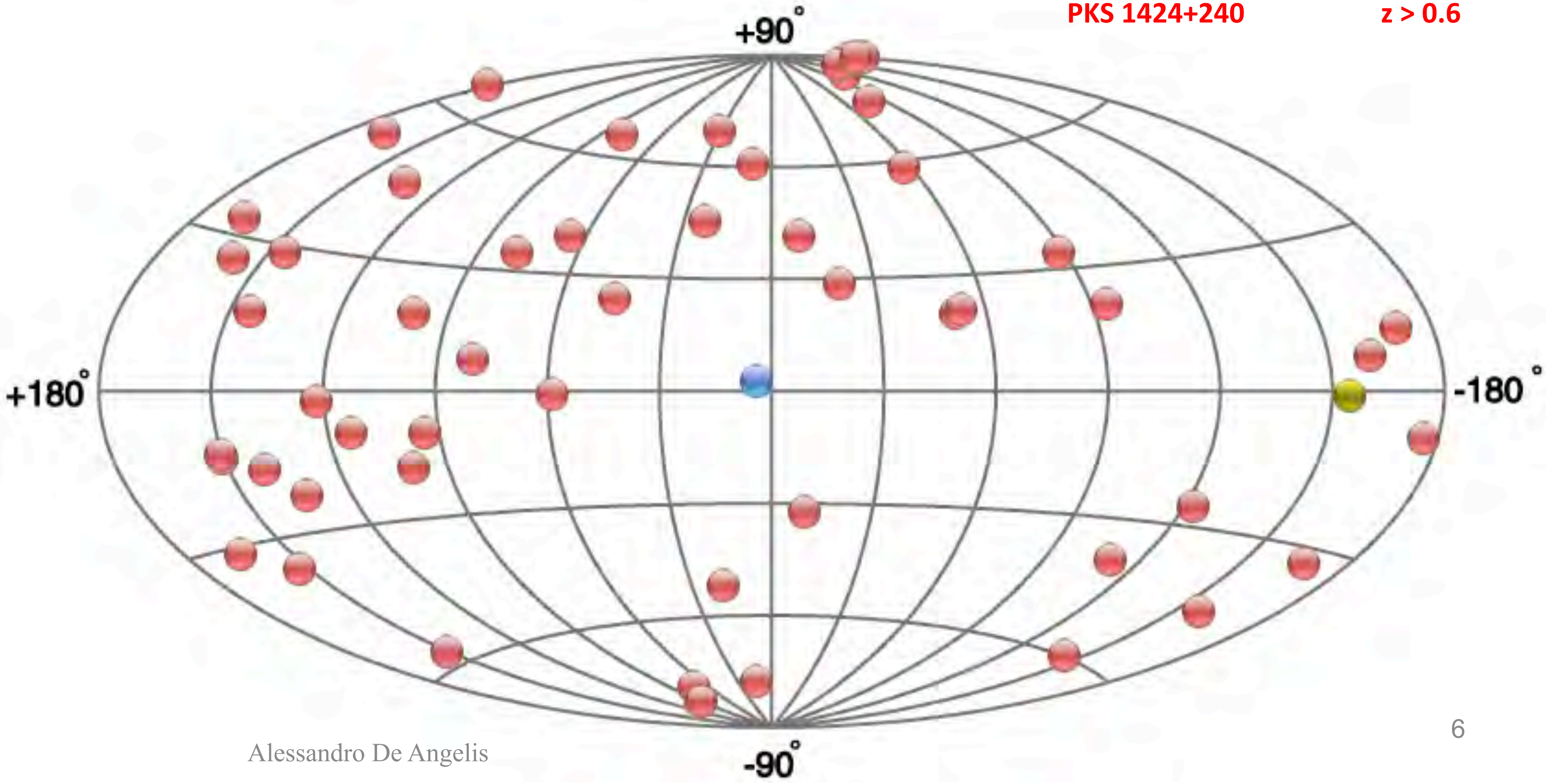
(DeAngelis Galanti & Roncadelli, MNRAS 2013)
50 GeV
100 GeV
500 GeV
$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$
$e^{-\tau} = 0.01$
$\tau = 1$ (GRH)
Cen A
GC
z
1
10^{-1}
10^{-2}
10^{2}
10
1
10^{-1}
10^{-2}
D [Mpc]
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
E [GeV]

Extragalactic Sources

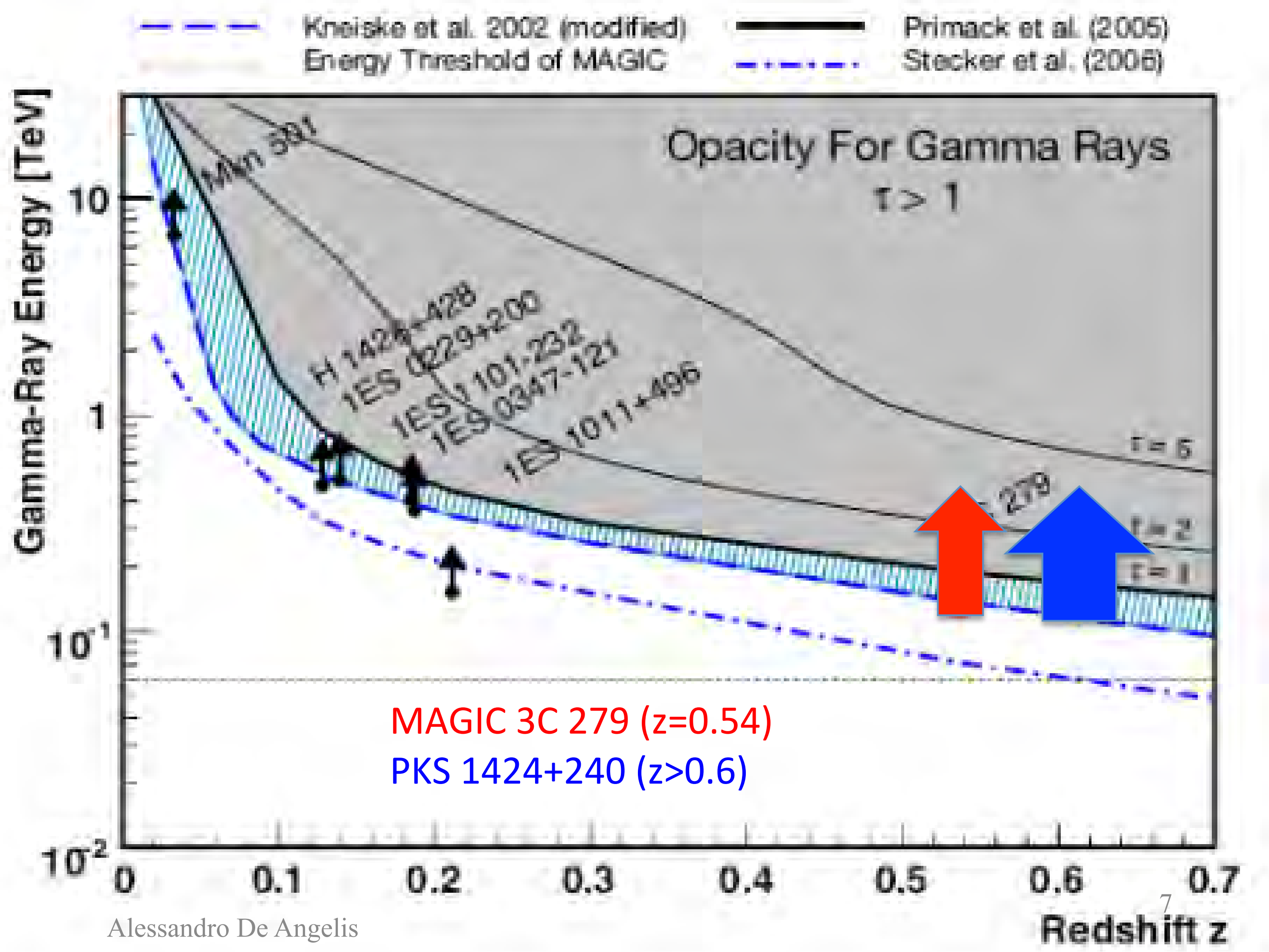
~50 Sources

...

1ES 1011+496	**z=0.21**
1ES 0414+009	z=0.29
S5 0716+71	**z=0.31±0.08**
1ES 0502+675	z=0.34
PKS 1510-089	z=0.36
4C +21.43	**z=0.43**
3C 66A	**z=0.44**
3C 279	**z=0.54**
PKS 1424+240	**z > 0.6**

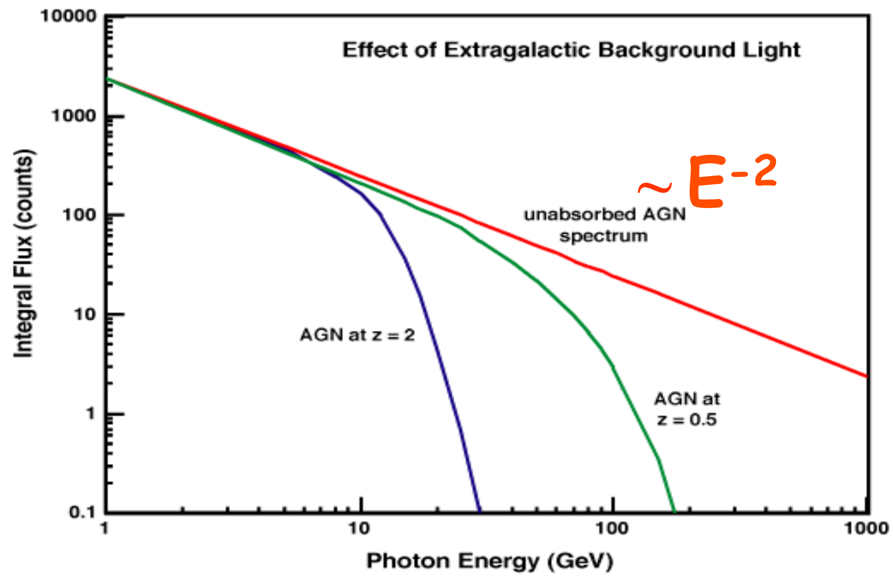


Are our AGN observations consistent with theory (1) ?

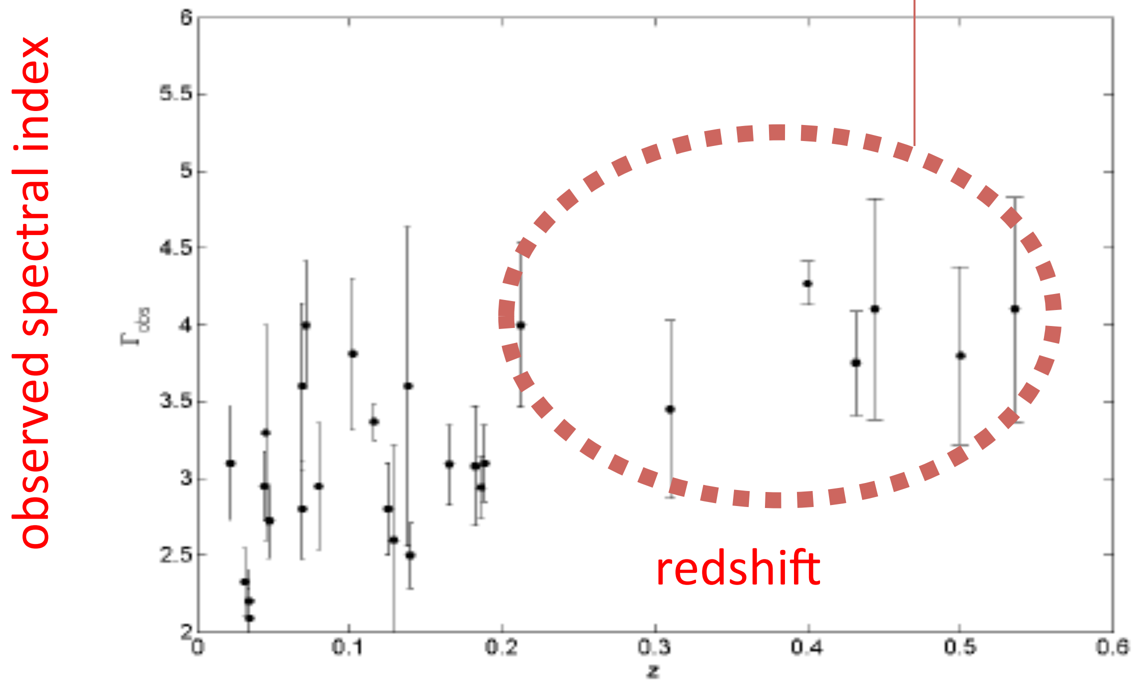


Are our AGN observations consistent with theory (2)?

Measured spectra affected by attenuation in the EBL:



Selection bias?
New physics ?



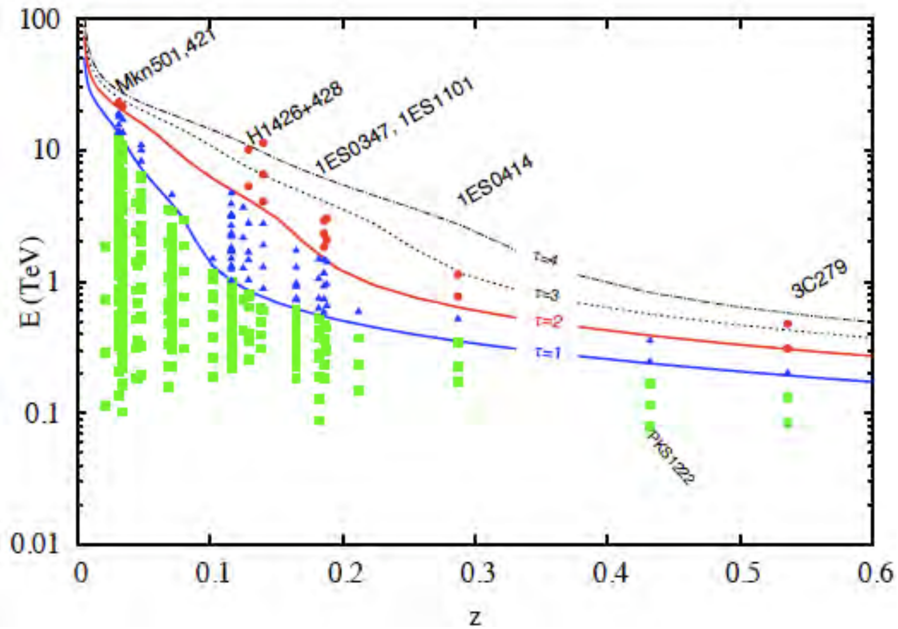
(DA, Galanti, Roncadelli; PRD 2011)

Attempts to quantify the problem overall

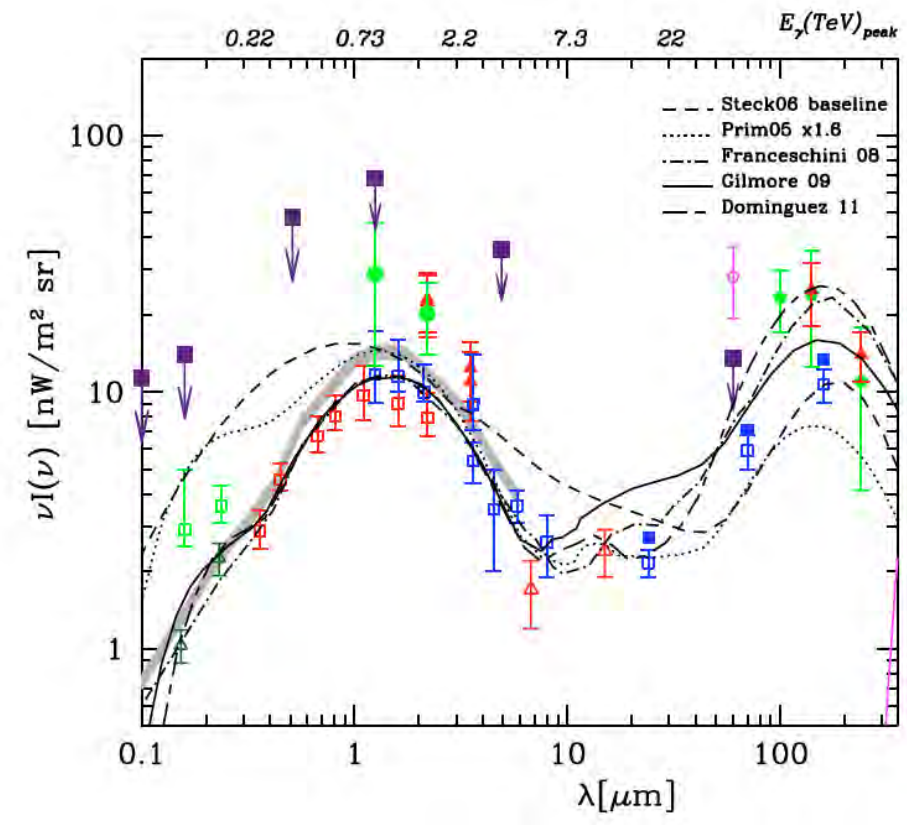
- Analysis of AGN
  - For each data point, a corresponding lower limit on the optical depth τ is calculated using a minimum EBL model
  - Nonparametric test of consistency
  - Disagreement with data: overall significance of 4.2 σ

=> <u>Understand experimentally the outliers</u>

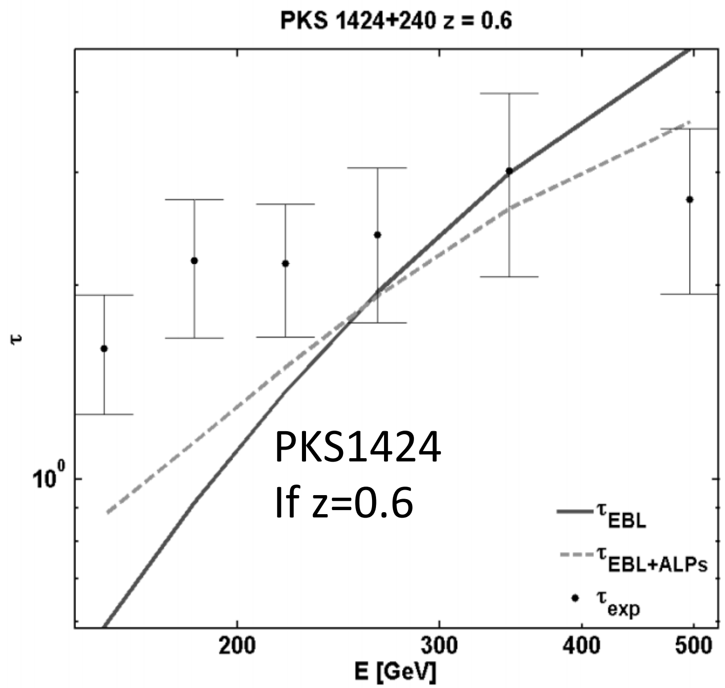
(Horns , Meyer 2011)

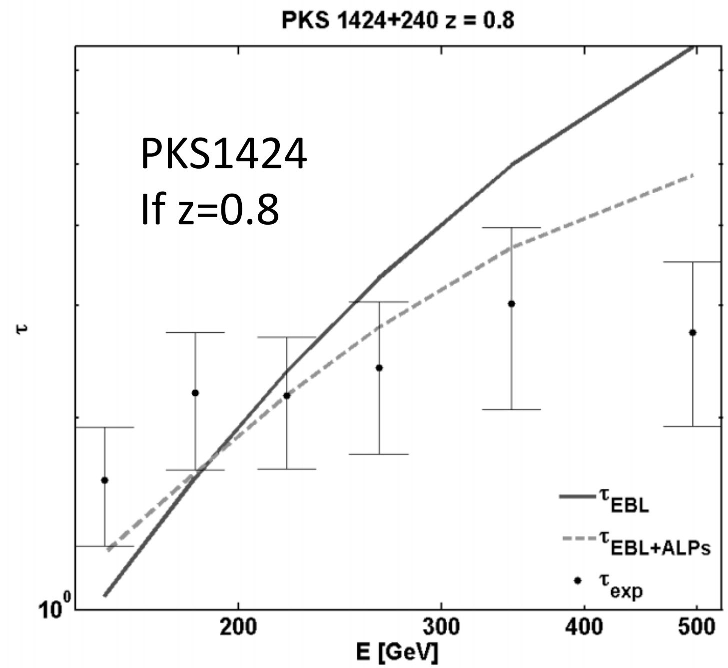


A reminder: EBL rather well constrained, and extrapolation from Fermi are possible

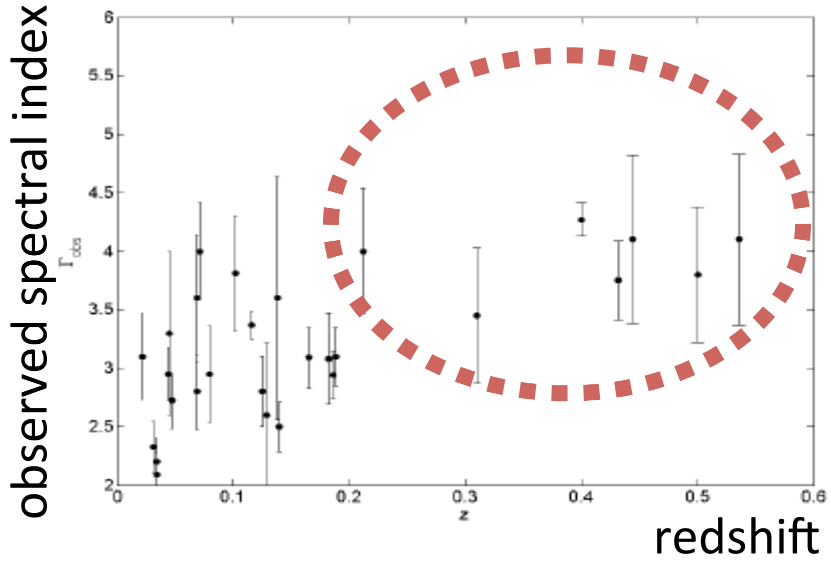


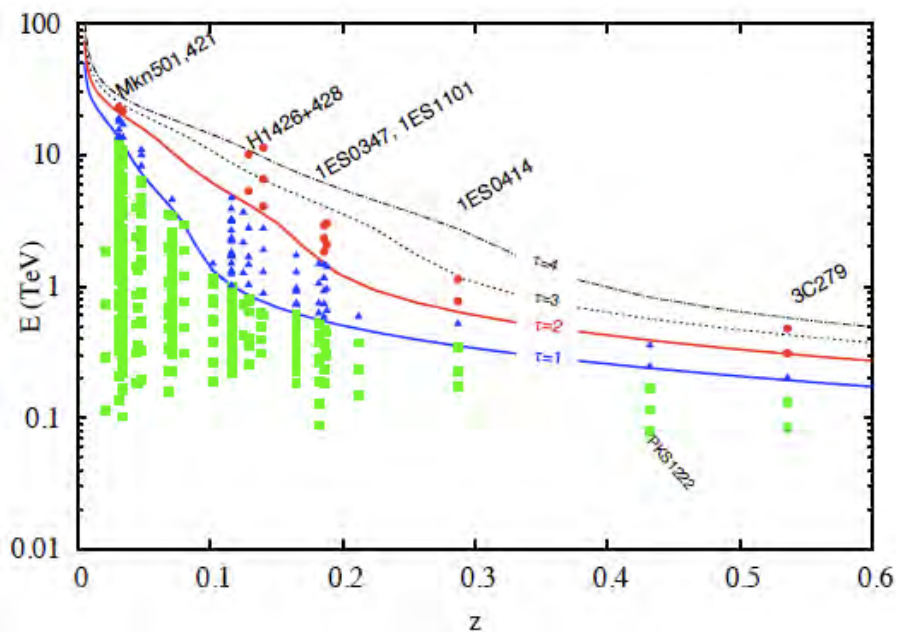
Alessandro De Angelis





If there is a problem





Explanations range from the standard ones

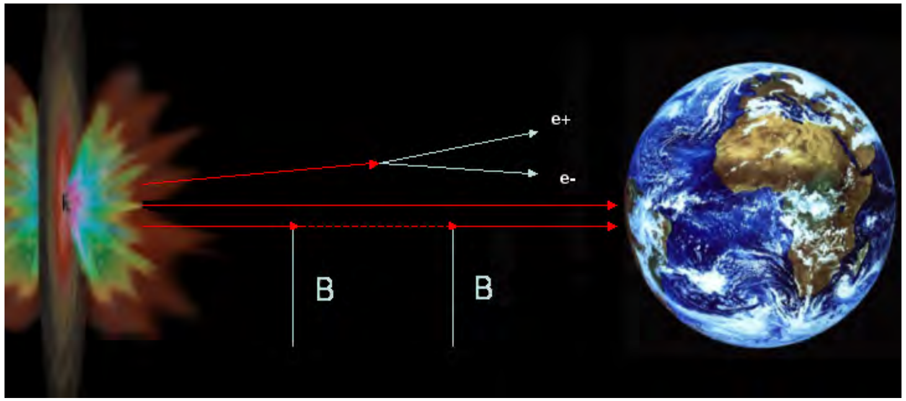
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of "wrong" outliers

to almost standard

- γ-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or ν from the same source

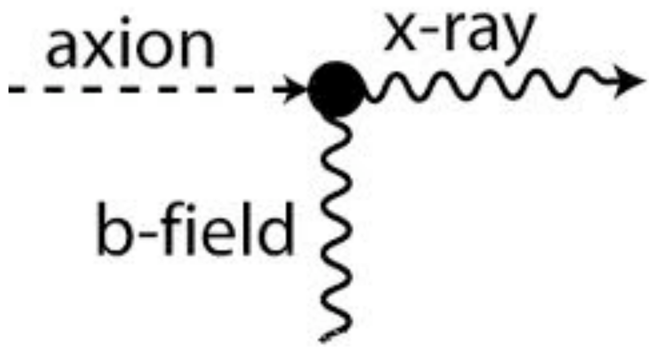
to possible evidence for new physics

- Oscillation to a light "axion"?
  - (DA, Roncadelli & MAnsutti [DARMA], PRD2007, PLB2008)
  - Axion emission (Simet+, PRD2008)
  - A combination of the above (Sanchez Conde et al. PRD 2009)
- Violation of the Lorentz invariance



Axions and ALPs

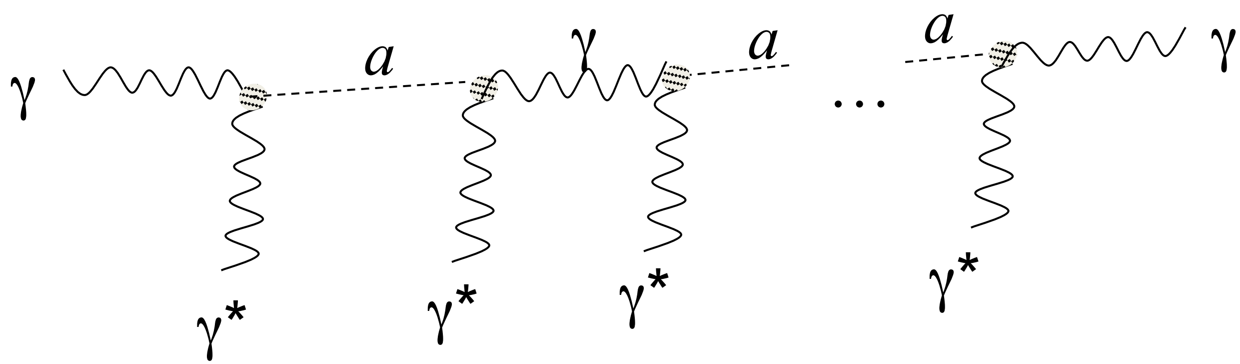
- The “strong CP problem”: CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the “axion” from the name of a cleaning product
  - Pseudoscalar, neutral, stable on cosmological scales, feeble interaction, couples to the photon
    - Can make light shine through a wall
  - The minimal (standard) axion coupling $g \propto m$; however, one can have an “ALP” in which $g = 1/M$ is free from m



$$\frac{m}{1\,\mathrm{eV}} \simeq \frac{1}{M/6\times 10^{6}\,\mathrm{GeV}}$$

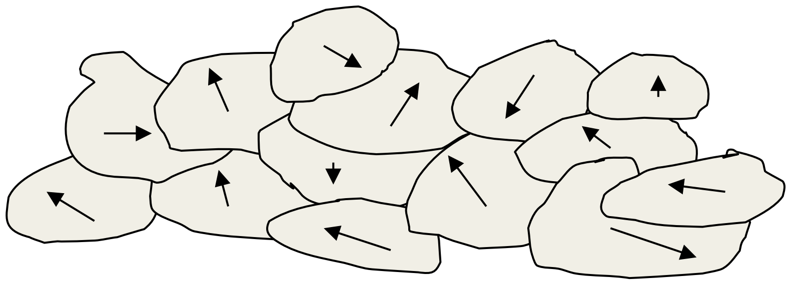
The photon-axion mixing mechanism

$$L_{a\gamma\gamma} = g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right)a$$



Propagation: Raffelt-Stodolsky 1987; Csaki-Kaloper-Terning 2002; DA Roncadelli MAnsutti 2007; Simet Hooper Serpico 2008

- Magnetic field 1 nG < B < 1aG (AGN halos). Cells of ~ 1 Mpc

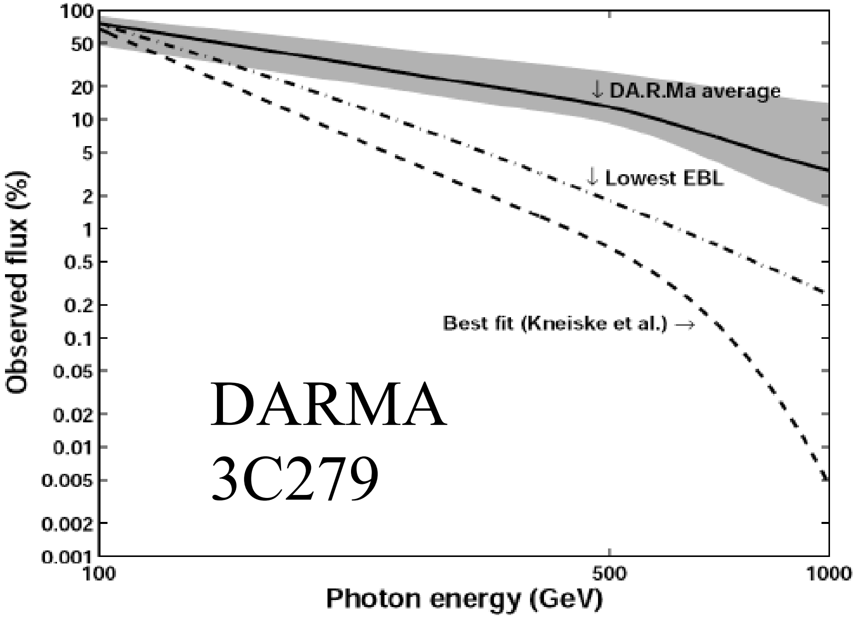


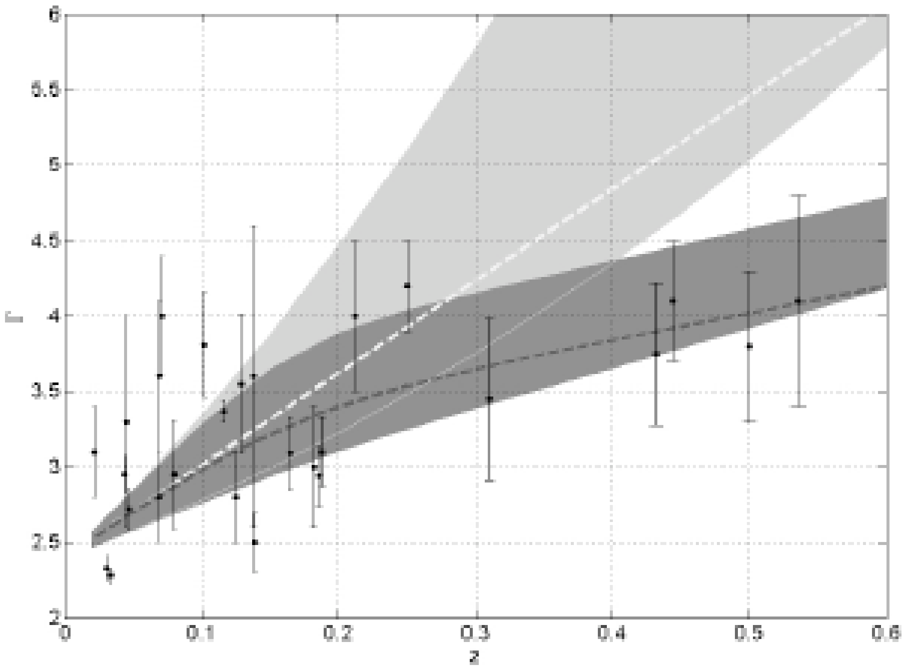
$$P_{\gamma\to a} \approx NP_1$$

$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times 10^{-3}\left(\frac{B_T}{1\text{nG}}\frac{s}{1\text{Mpc}}\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2$$

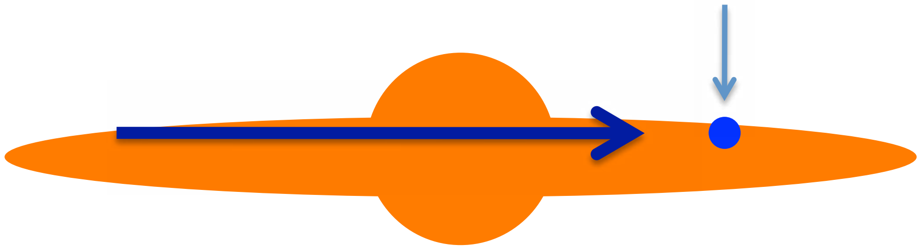
- $m_a < 0.02$ eV (direct searches)
- $g < 10^{-10}\,\text{GeV}^{-1}$ from astrophysical bounds

If B ~ 0.1–1 nG, λ ~ 1-10 Mpc, observations can be explained





Note: if conversion "a la Simet-Hooper-Serpico",
=> the effect could be directional



- Could also be something else:

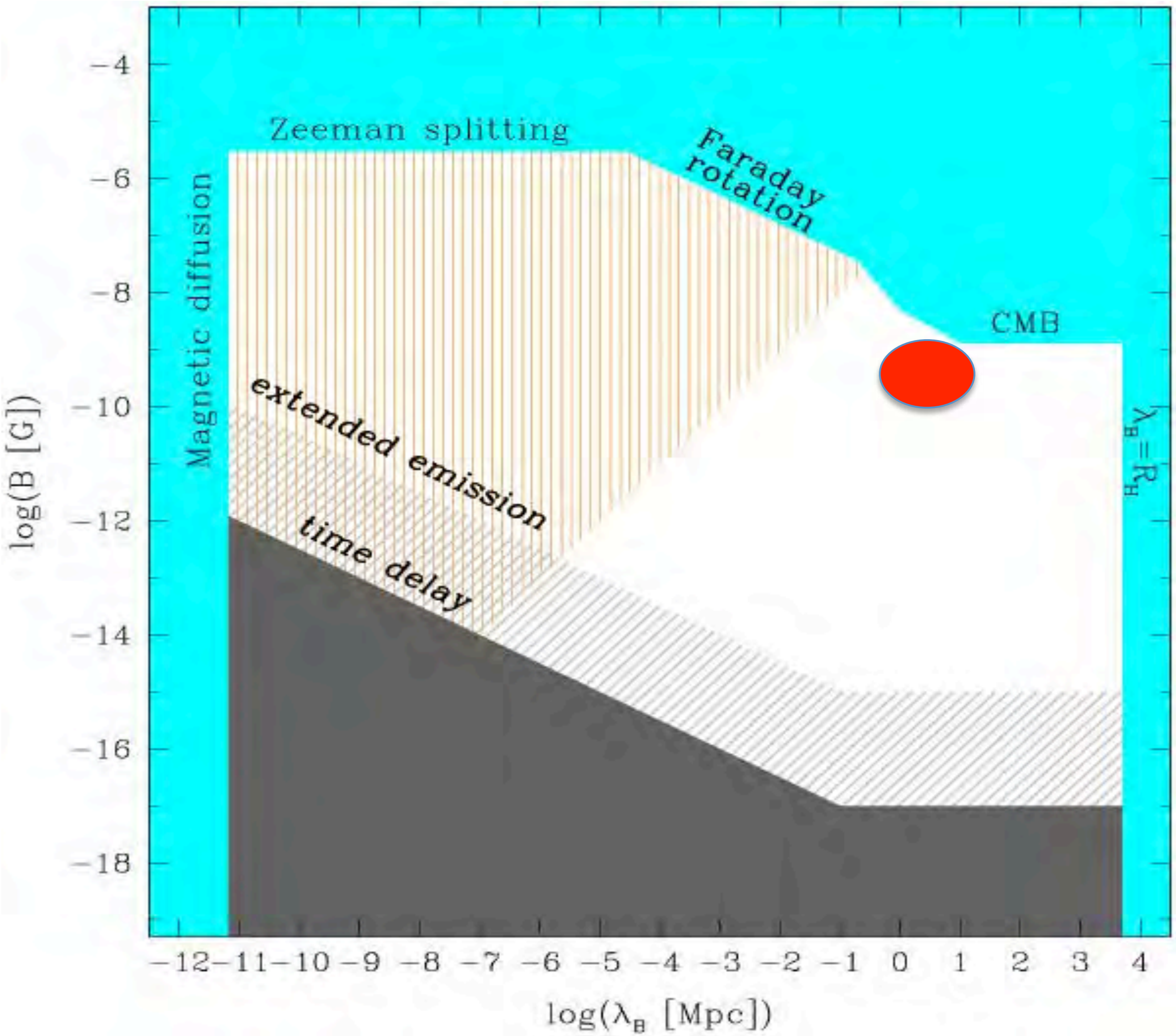
  Whatever (light and almost sterile) particle feebly coupling to the photon

  Exercise 2

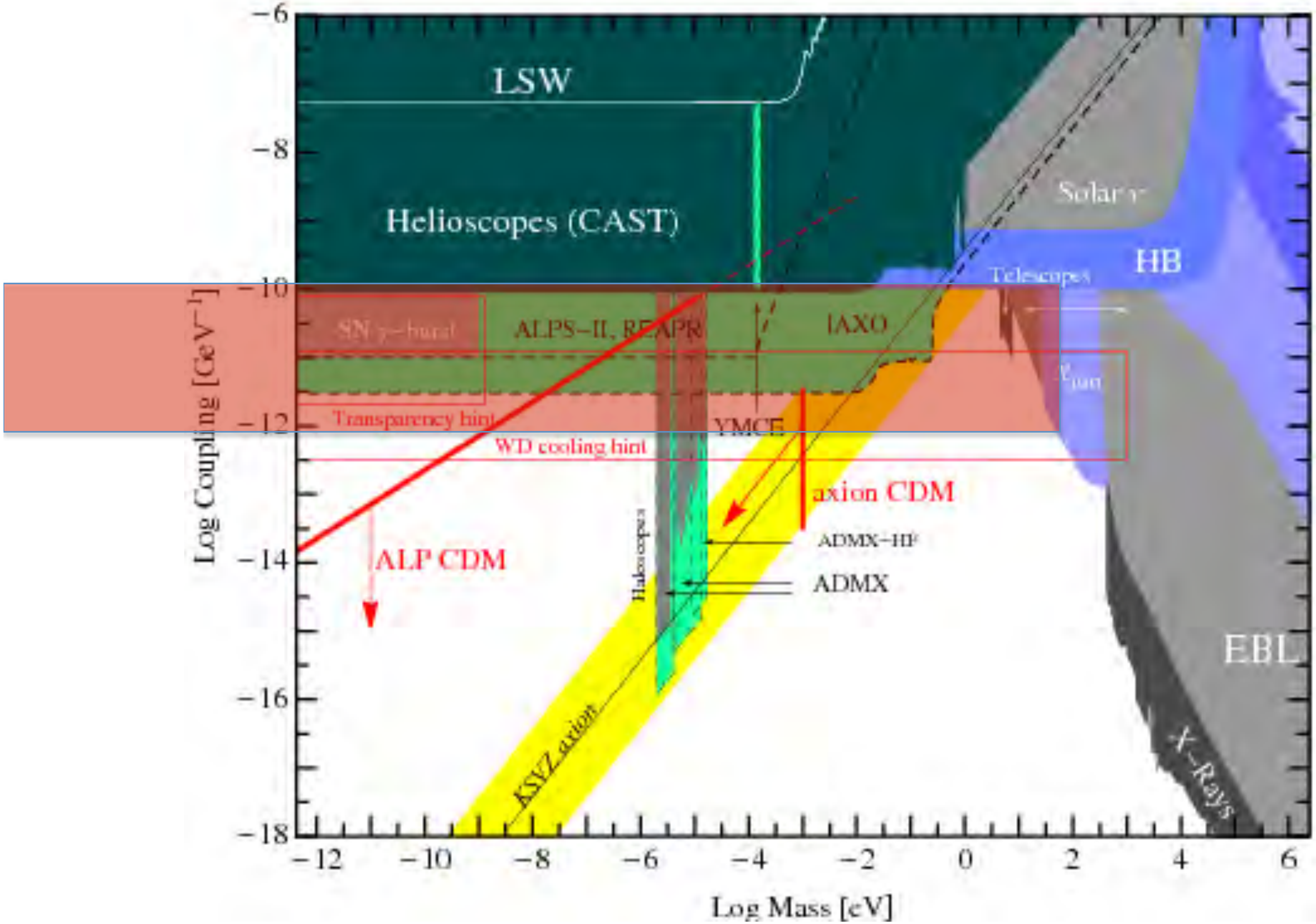
  – Paraphoton
    - Shadow photon

  – New millicharged particles

Intergalactic magnetic fields: indications from DARMA



Preferred values for m, g



Even more exotic explanations: is Lorentz invariance exact?

- For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  - Is there an aether? (Dirac 1951)
  - Many preprints, often unpublished (=refused) in the '90s

- Then the discussion was open
  - Trans-GZK events? (AGASA collaboration 1997-8)
  - LIV => high energy threshold phenomena: photon decay, vacuum Cherenkov, GZK cutoff (Coleman & Glashow 1997-8)
  - GRB and photon dispersion (Amelino-Camelia et al. 1997)
  - Framework for the violation (Colladay & Kostelecky 1998)
  - LIV and gamma-ray horizon (Kifune 1999)
  - ...

LIV? New form of relativity?

- Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} => Lorentz transformations with "some" invariant c (Galilei relativity is the limit $c \to \infty$)
- CMB is the aether: give away isotropy?
- QG motivation: give away linearity? (A new relativity with 2 invariants: "c" and E_P)

- In any case, let's sketch an effective theory…
  – Let's take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) as a perturbation of the Hamiltonian (Amelino-Camelia+)

A heuristic approach: modified dispersion relations (perturbation of the Hamiltonian)

- We expect the Planck mass to be the scale of the effect

$$E_P = \sqrt{hc/G} \cong 1.2 \times 10^{19}\,\mathrm{GeV}$$

$$H^2 = m^2 + p^2 \rightarrow H^2 = m^2 + p^2\left(1 + \xi\frac{E}{E_P} + \ldots\right)$$

$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi\frac{E}{2E_P} + \ldots\right)$$

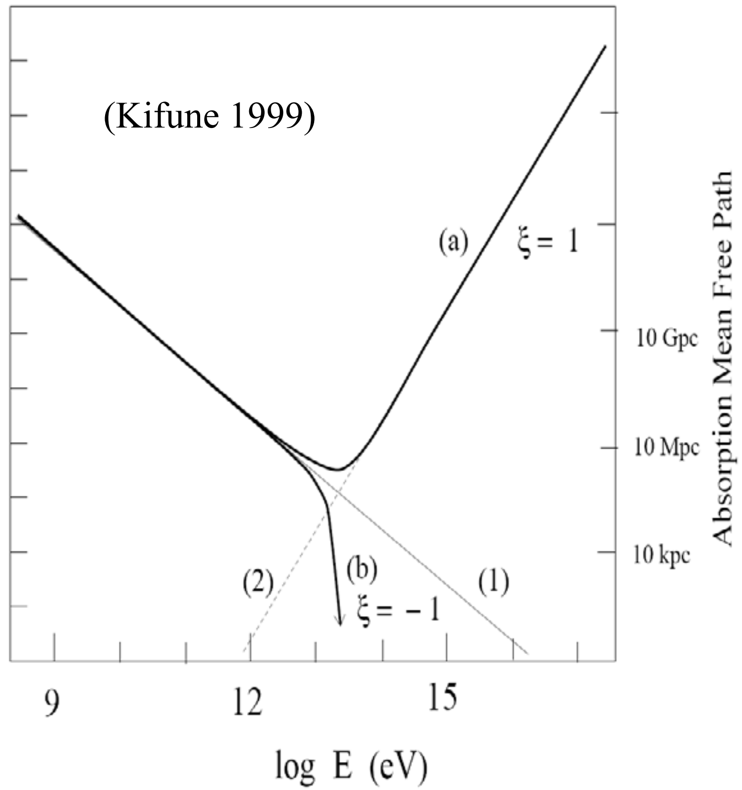
$$v = \frac{\partial H}{\partial p} \cong 1 - \frac{m^2}{2p^2} + \xi\frac{p}{E_P} \Rightarrow \boxed{v_\gamma \cong 1 + \xi\frac{E}{E_P}}$$

=> effect of dispersion relations at cosmological distances can be important at energies well below Planck scale:

$$\boxed{\Delta t_\gamma \cong T\Delta E\frac{\xi}{E_P}}$$

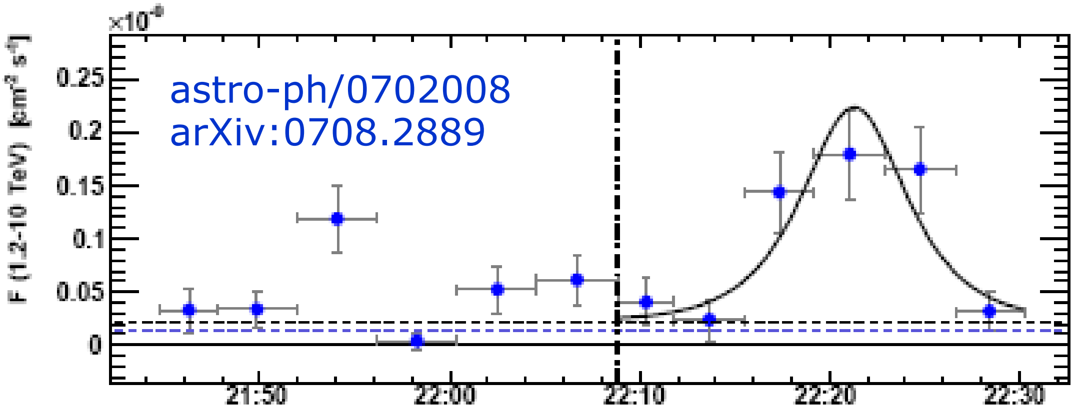
Also an effect on the cross sections

- Enhanced transparency of the Universe wrt QED

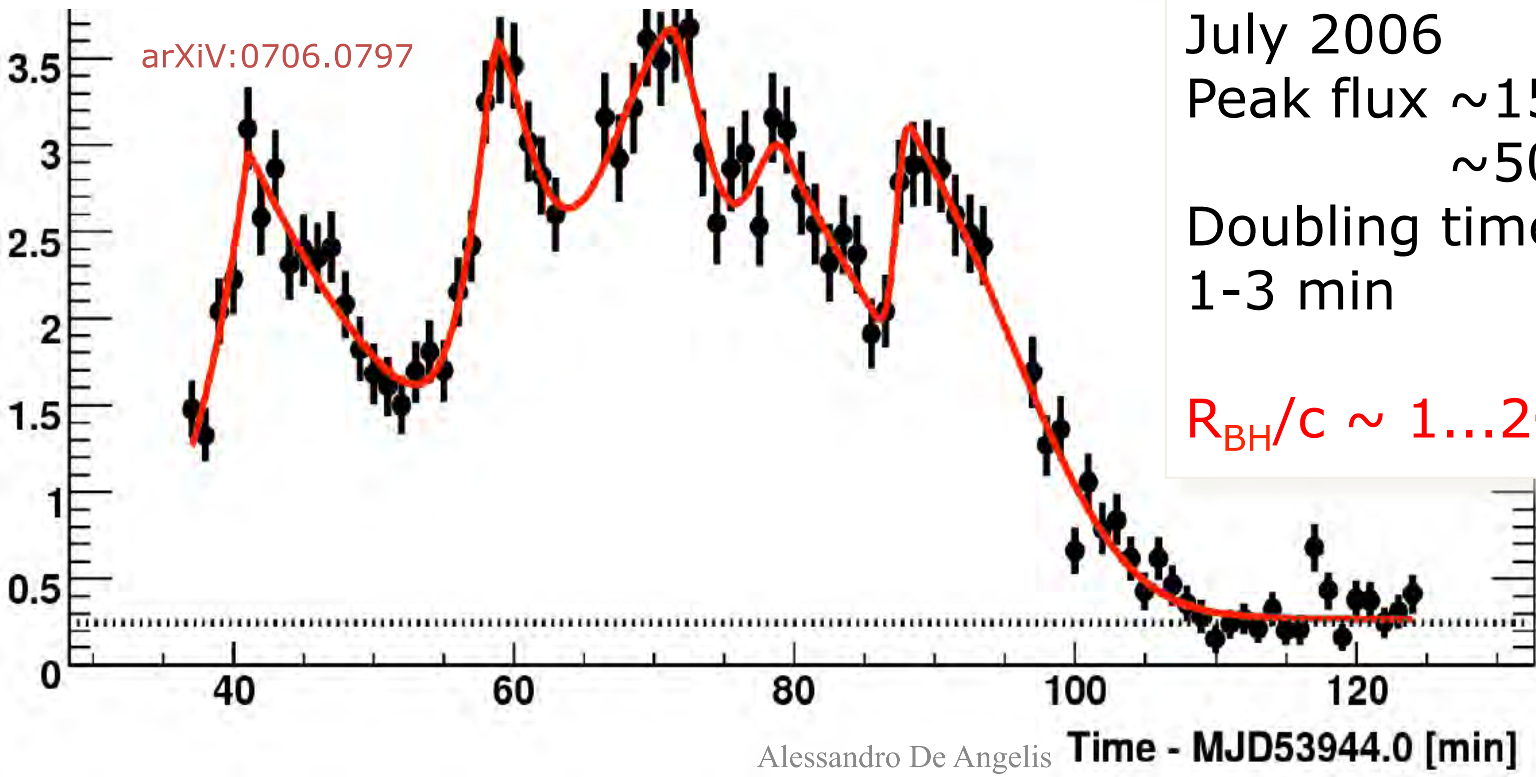


$$c^2 p^2 = E^2\left[1 + \xi\frac{E}{E_s} + O\left(\frac{E}{E_s}\right)^2\right]$$

Rapid variability, and the possible dispersion of the speed of light



MAGIC, Mkn 501
Doubling time ~ 2 min

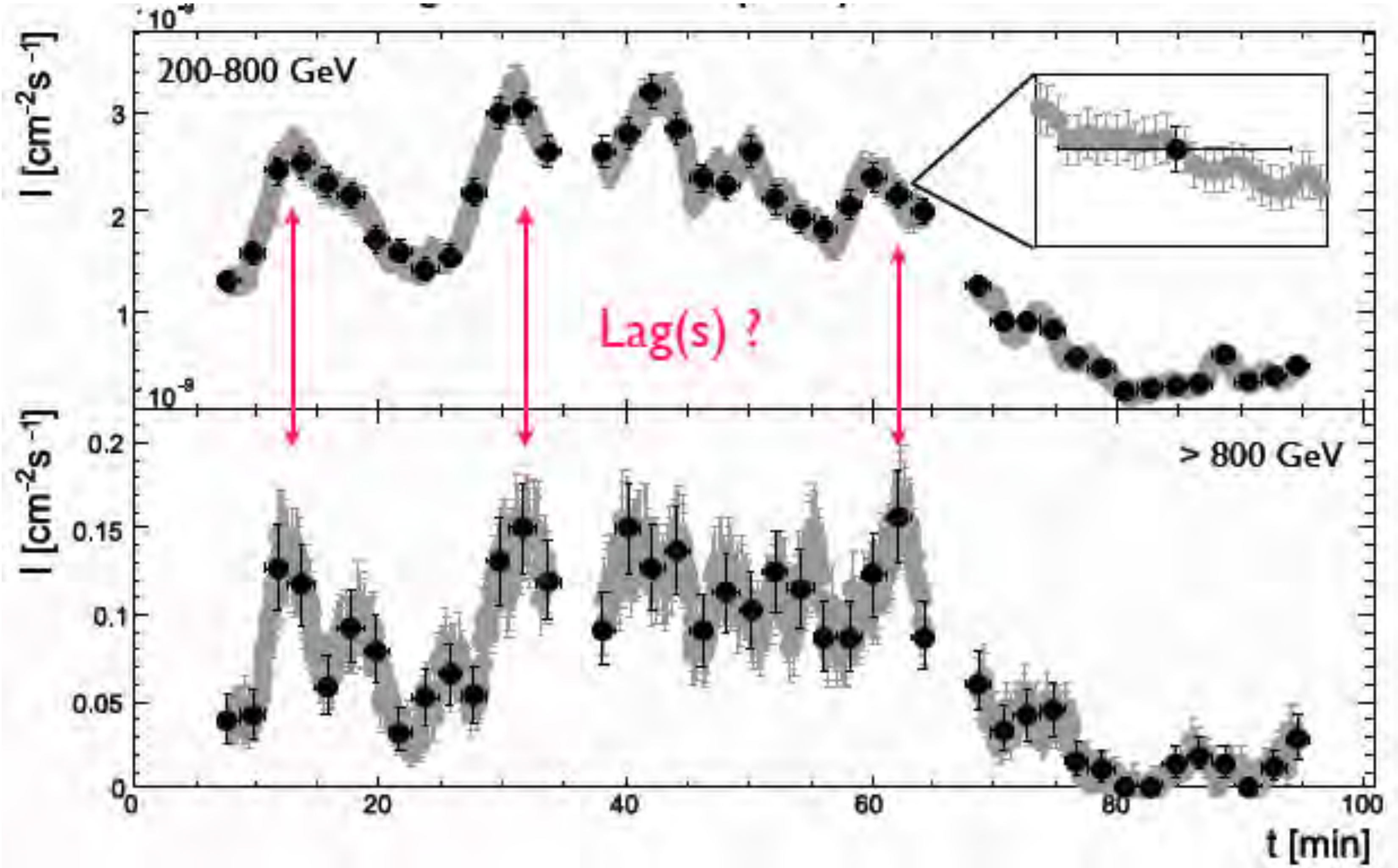


HESS PKS 2155
z = 0.116

July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min

$R_{BH}/c \sim 1 \ldots 2 \cdot 10^4$ s

Tests of Lorentz violation: the name of the game



HESS, PKS 2155

Present limits (Fermi's GRB, Vasileiou+ 2013)

- Linear: $\xi < 7.6$ (scale of violation $E_{s1} > 7.6\ E_P$)
- Quadratic: $E_{s2} > 1.3\ 10^{11}$ GeV

To decetct 2nd order effects, ground-based detectors (Cherenkov and HAWC) should rule

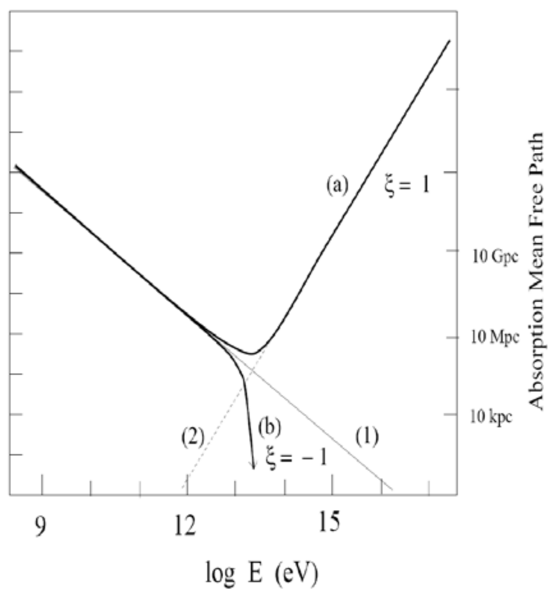
$$(\Delta t)_{obs} \cong \frac{3}{2}\left(\frac{\Delta E}{E_{s2}}\right)^2 H_0^{-1}\int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Two possible extraordinary claims

- *A possible relation between arrival time and energy*
- Signal from sources far away hardly compatible with EBL

$$c^2 p^2 = E^2 \left[1 + \xi \frac{E}{E_s} + O\left(\frac{E}{E_s} \right)^2 \right]$$

- We should keep in mind that
  - Extraordinary claims require extraordinary evidence
    - New Scientist, SciAm blog/news, …, and then?
  - Claims must be followed up
    - If we see this in such sources, what else do we expect?
    - Fundamental implications of unexpected findings?
    - Are we seeing a part of the same big picture?



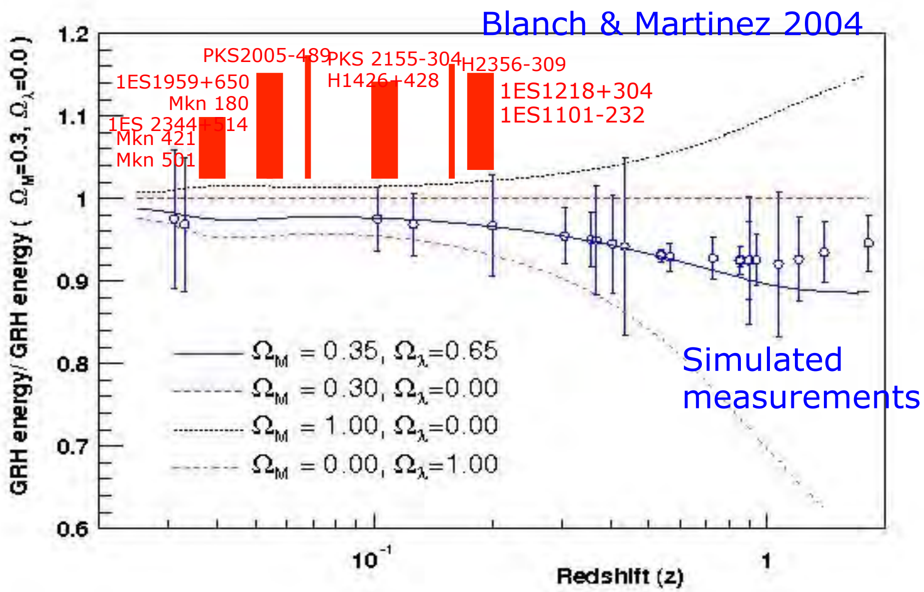
A no-loss situation: if propagation is standard, cosmology with AGN

GRH depends on the γ–ray path and there the **Hubble constant and the cosmological densities** enter => if EBL density is known, the GRH might be used as a **distance estimator**

$$\frac{dl}{dz} = c \cdot \frac{1/(1+z)}{H_0\left[\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\lambda\right]^{1/2}}$$

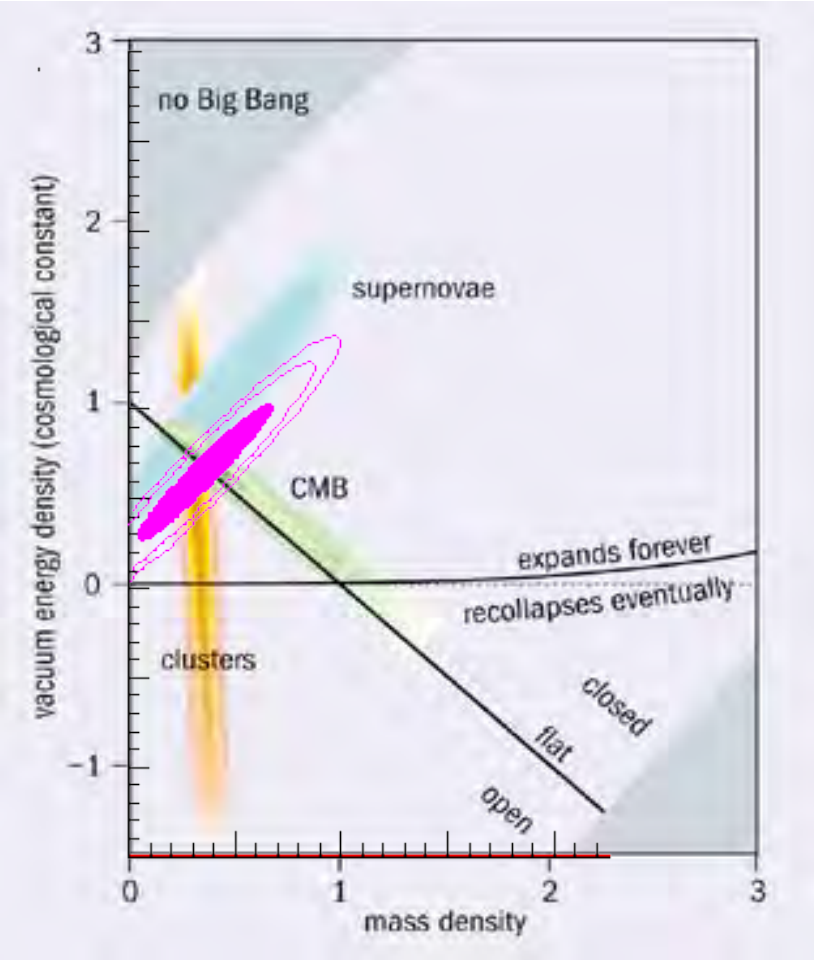
GRH behaves differently than other observables already used for cosmology measurements.

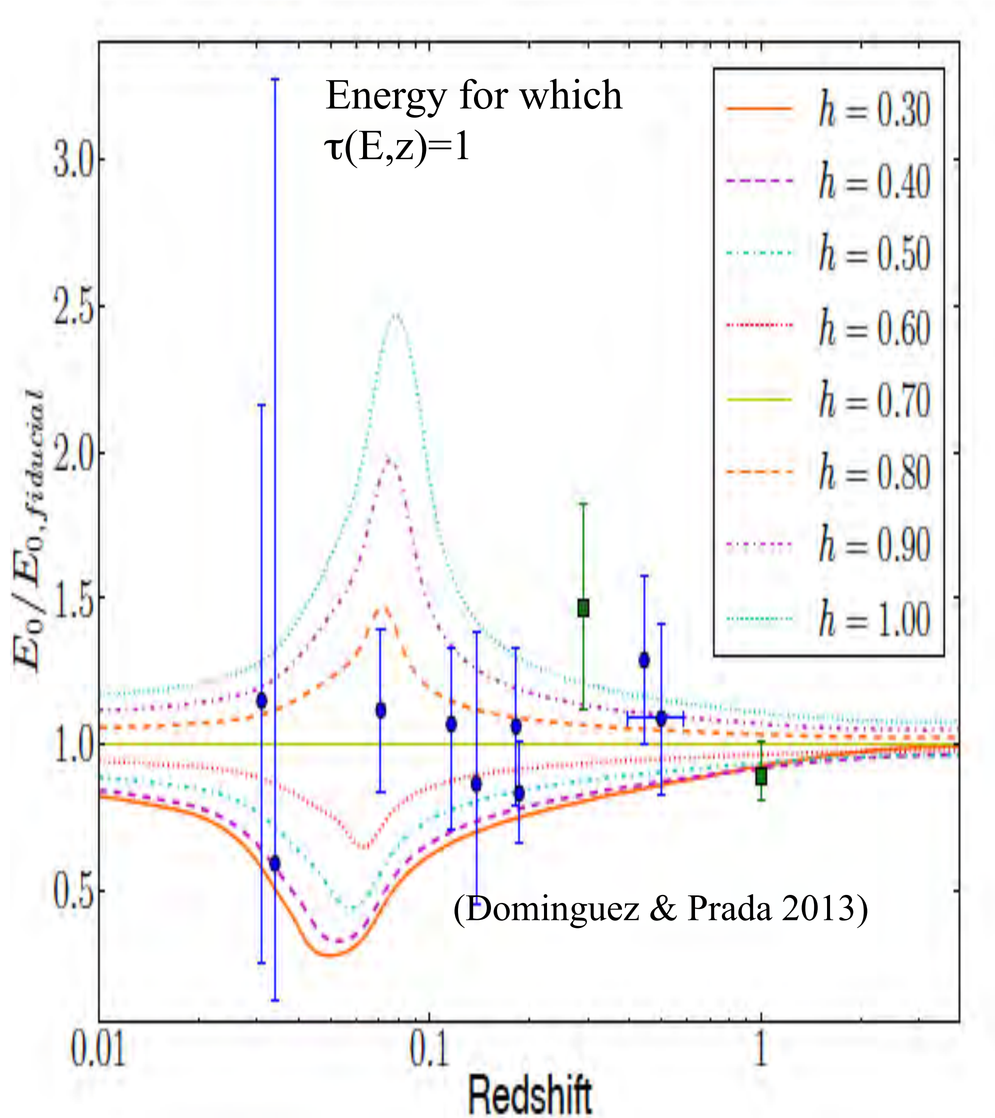
EBL constraints can pave the way for the use of AGNs to fit Ho, Ω_M and Ω_Λ …



Determination of H_0, Ω_M and Ω_Λ

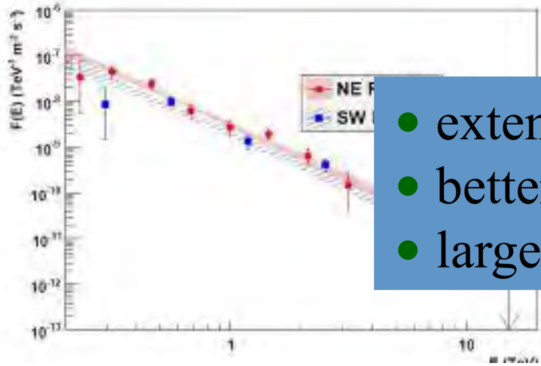
Using the foreseen precision on the GRH measurements of 20 extrapolated AGN, cosmological parameters can be fitted

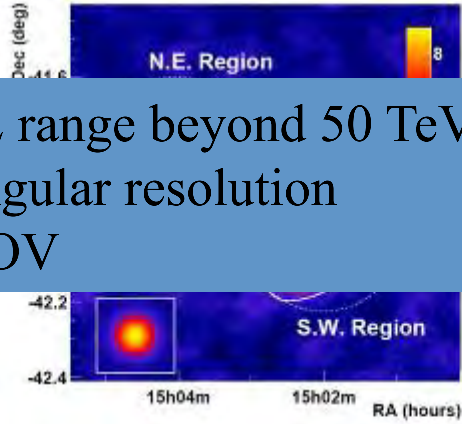




A wish list for the future

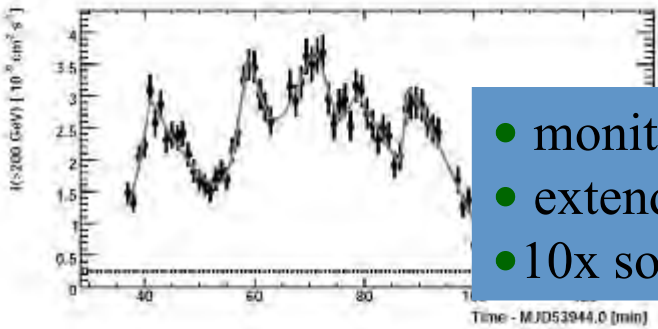
- Galactic sources & CR





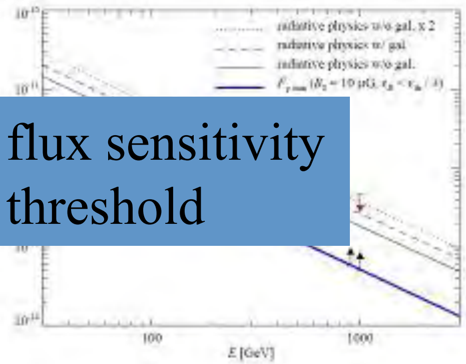
- extend E range beyond 50 TeV
- better angular resolution
- larger FOV

- AGN & gamma prop.



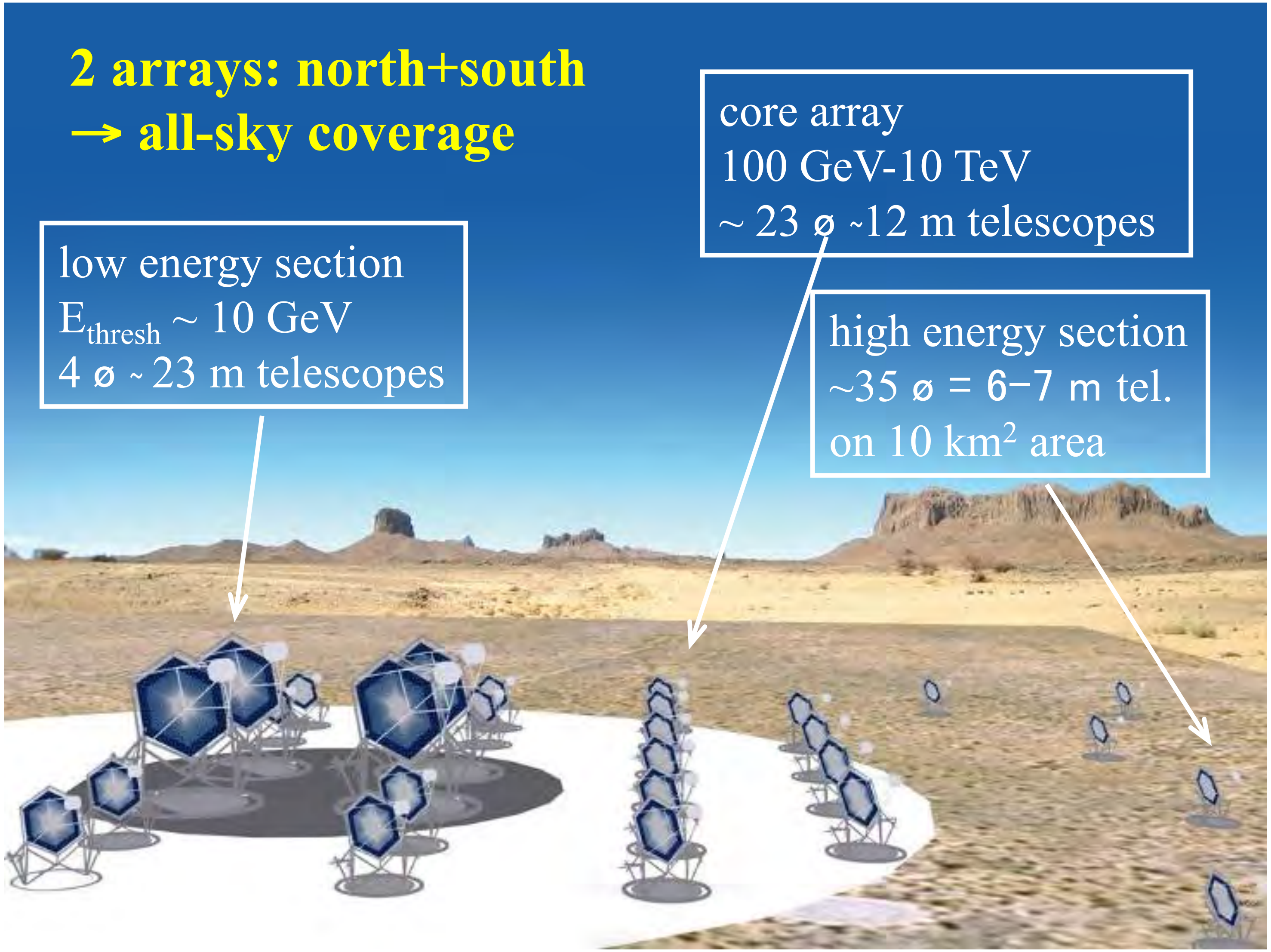
- monitor many objects simult.
- extend E range under 50 GeV
- 10x sources

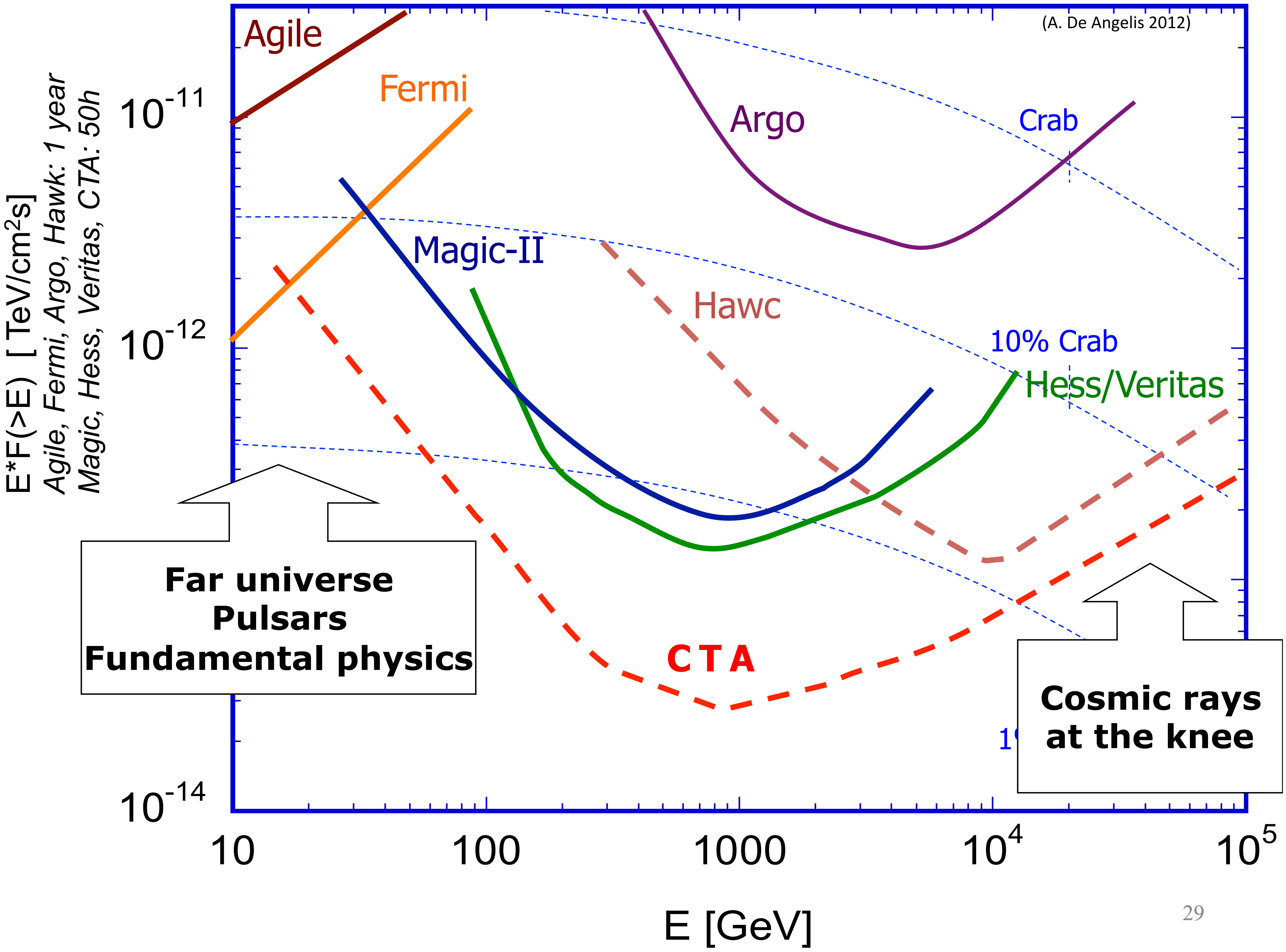
- New particles, new phenomena
  - dark matter and astroparticle physics



- better flux sensitivity
- lower threshold

The CTA concept (a possible design)




(A. De Angelis 2012)
Agile
Fermi
Argo
Crab
Magic-II
Hawc
10% Crab
Hess/Veritas
CTA
Far universe
Pulsars
Fundamental physics
Cosmic rays
at the knee
E*F(>E) [TeV/cm²s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h
10^-11
10^-12
10^-14
10
100
1000
10^4
10^5
E [GeV]

Summary

- Clear interplay between VHE (γ) astrophysics and fundamental physics; this model of cooperation has worked well, and can work well in the future
  - We are confident that this exchange between complementary worlds will be useful, as history of particle physics demonstrated
  - This is especially true for relativity and gravitation
- *Cosmic Rays:*
  - *SNR as galactic sources established*
    - *Astronomy with charged CR is difficult*
    - *Astronomy with neutrinos is not easy*
    - *VHE photons can be the pathfinder*
- *Still no detection of DM*
  - *The information from no detection is not as good as for accelerators*
- A few clouds might hide new physics
  - Photon propagation
- Rich fundamental science (and astronomy/astrophysics) from gamma rays
  - HEA is exploring regions beyond the reach of accelerators
  - A “simple” extension of present detectors is in progress: CTA