Fundamental physics with (very) high energy γ rays

Alessandro De Angelis, INAF INFN/Univ. Udine & LIP/IST Milano 09

- Dark matter
- Rapid variability
  - Does c depend on the photon energy?
  - Anomalies in the propagation of photons
- 2 slides on Magic2

Fermi and Agile are delivering a wealth of results... Where do Cherenkov telescopes enter the game?

- Peak eff. area of Fermi: 0.8 m^2

  Strongest flare ever recorded of very high energy (VHE) γ-rays:

  1 photon / m^2 in 8 h above 200 GeV

  (PKS 2155, July 2006)

- The strongest *steady* sources are > 1 order of magnitude weaker!

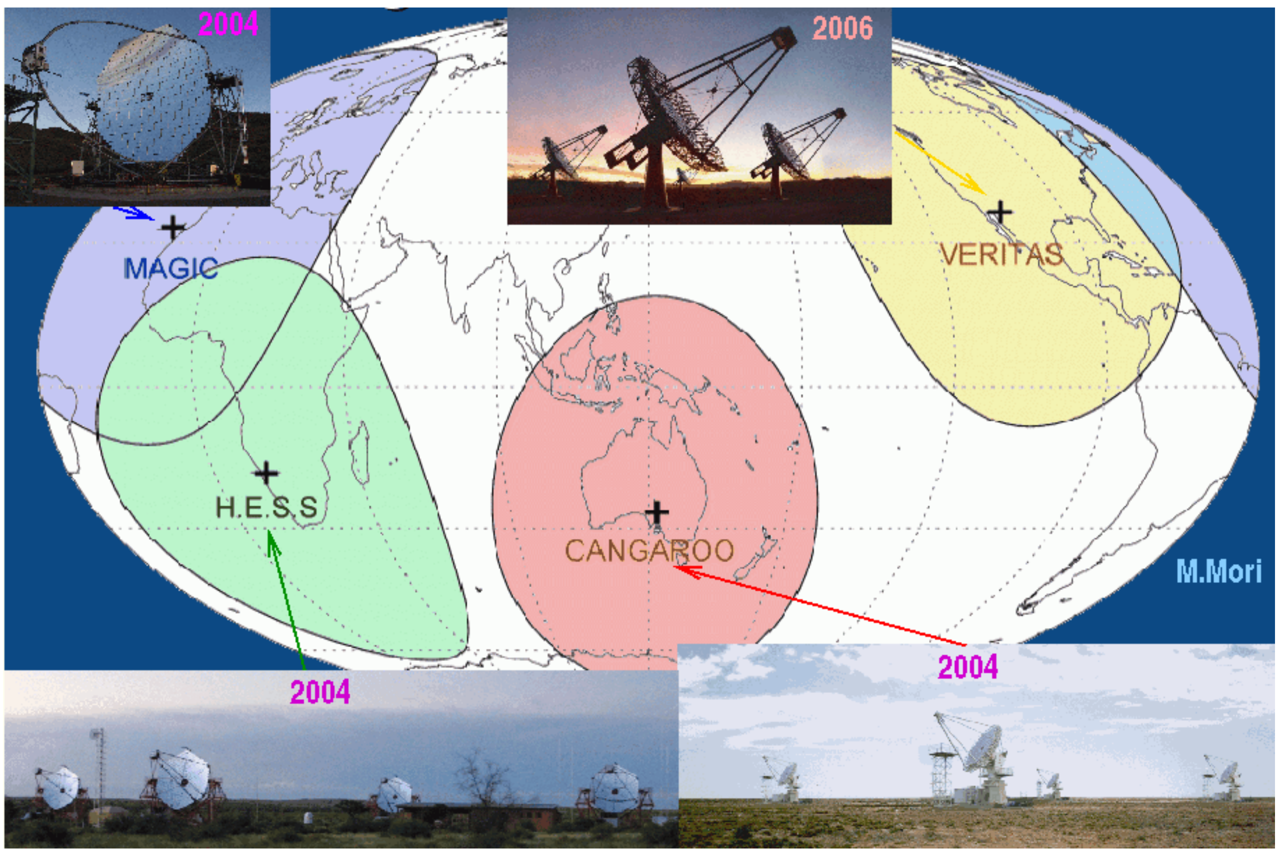
$\Rightarrow$ VHE astrophysics (in the energy region above 100 GeV) can be done only at ground

And what physics questions are answered using (also) VHE photons?

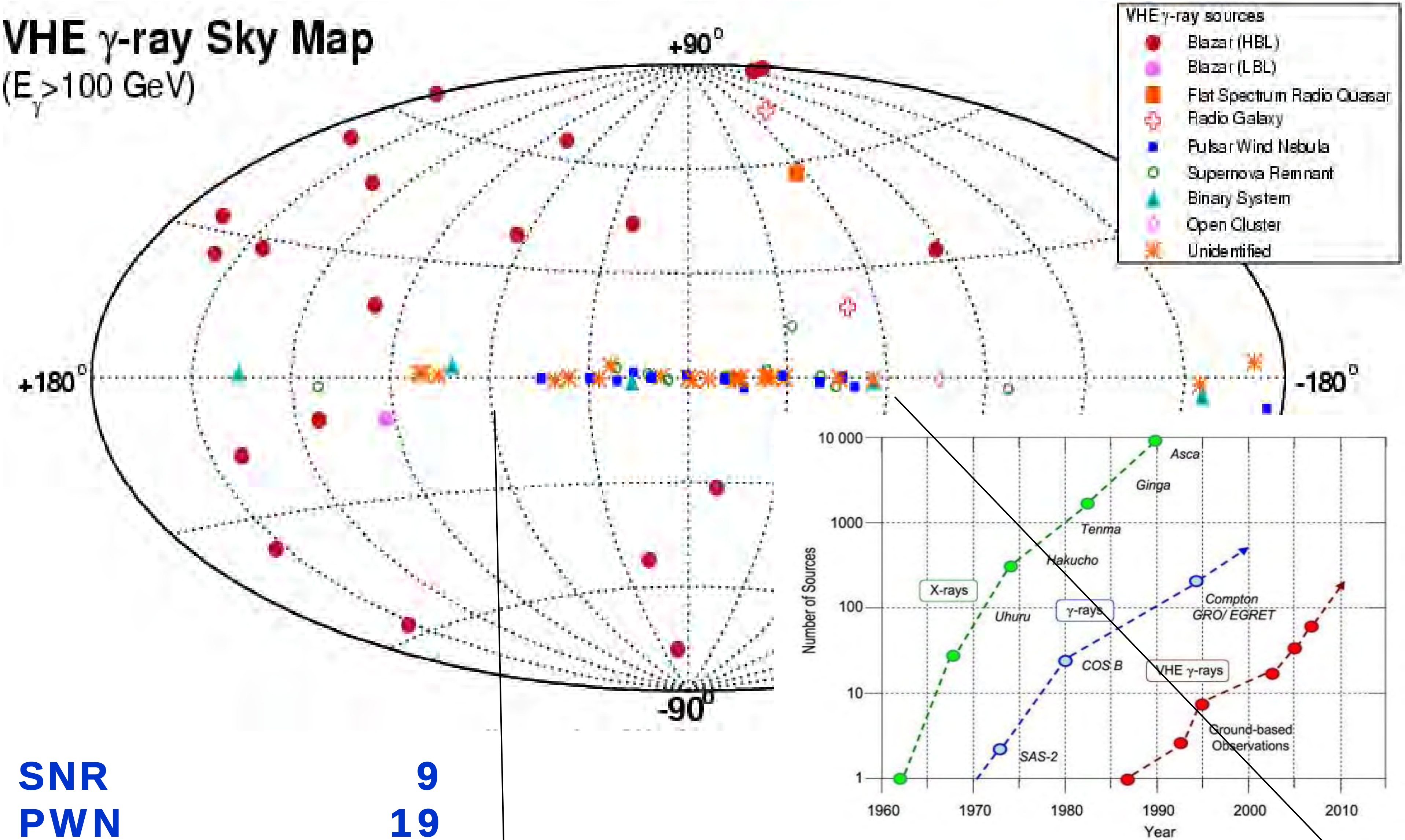
- Do emission processes continue at the highest energies?
- Photons produced in hadronic cascades can be a signature of protons at an energy 10 times larger

  => Cosmic Rays below the knee
- The highest energies can test fundamental physics in the most effective way
  - Tests of Lorentz invariance
  - Interaction with background particles in the vacuum
- ...

Instrument	Tels.	Tel. Area (m^2)	Total A. (m^2)	FoV (°)	Thresh. (TeV)	Sensitivity (% Crab)
H.E.S.S.	4	107	428	5	0.1	0.7
VERITAS	4	106	424	3.5	0.1	1
MAGIC	1 **(2)**	236	236 (472)(*)	3.5	0.05	1.6 (0.8)
CANGAROO-III	3	57.3	172	4	0.4	15



VHE γ-ray Sky Map
(E_γ>100 GeV)



SNR	**9**
PWN	**19**
Unid. gal.	**21**
GC	
Binary	**4**
AGN	**27**

Mar 2009: 81 sources > 100 GeV

DM search
(Majorana WIMPs)

$$\chi\chi \to q\bar{q} \to n \times \gamma$$

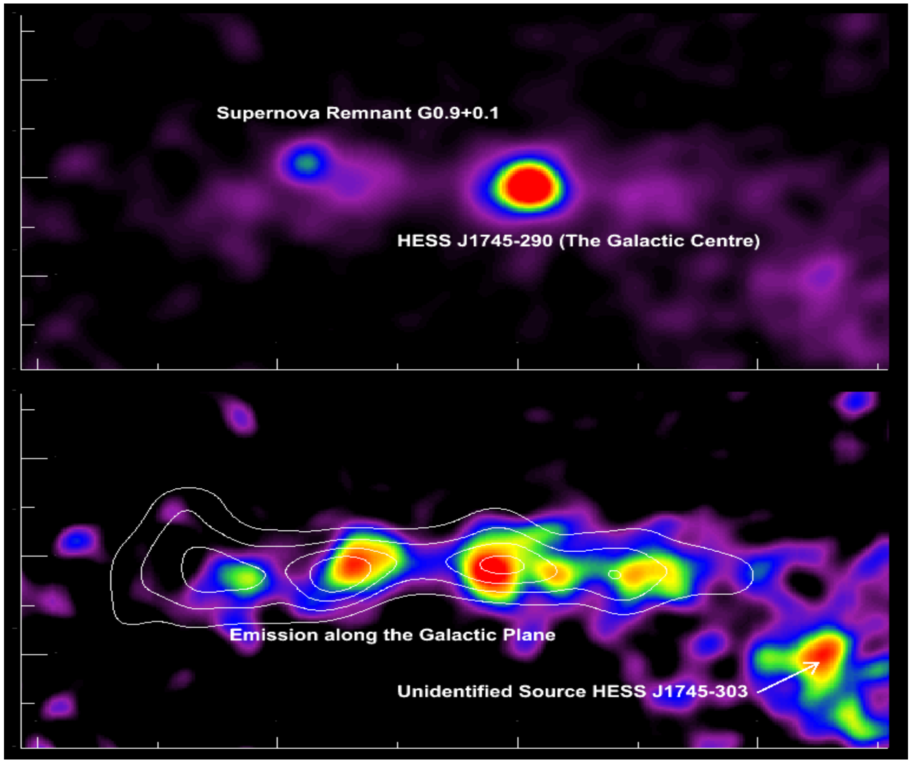
$$\chi\chi \to \gamma\gamma(Z)$$

$$\frac{dN}{dE} = \frac{1}{4\pi} \underbrace{\frac{\langle \sigma v \rangle}{m_{DM}^2} \frac{dN_\gamma}{dE}}_{Particle\ Physics} \times \underbrace{\int_{\Delta\Omega - los} dl(\Omega) \rho_{DM}^2}_{Astrophysics} \times \frac{1}{d^2}$$

Highest DM density candidate:
Galactic Center?
Close by (7.5 kpc)
Not extended

BUT:

- other γ-ray sources in the FoV
=> competing plausible scenarios
- halo core radius: extended vs point-like

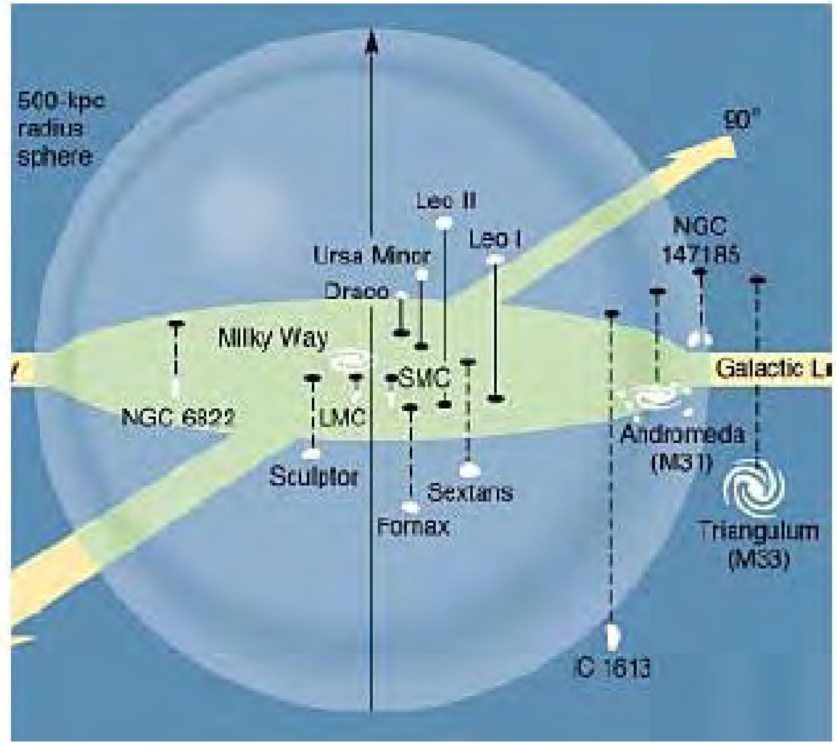


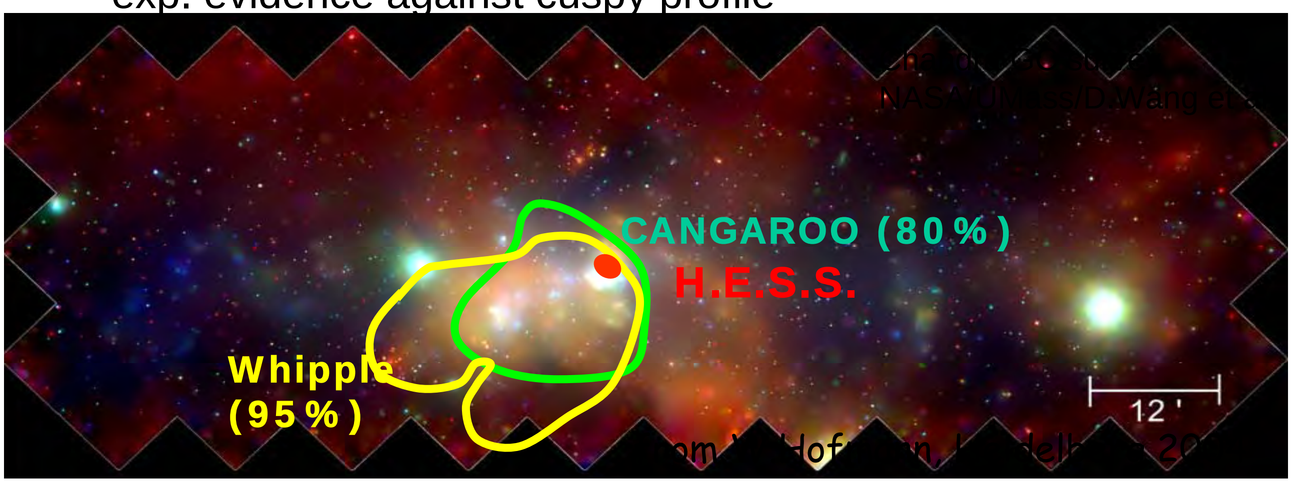
γ-ray detection from the Galactic Center

…and satellite galaxies

- detection of γ-rays from GC by Cangaroo Whipple, HESS, MAGIC
- σ_{source} < 3' (< 7 pc at GC)
  - hard $E^{-2.21\pm0.09}$ spectrum fit to χ-annihilation continuum spectrum leads to: M_χ > 14 TeV
  - other interpretations possible (probab

Galactic Center: very crowded sky region, stron exp. evidence against cuspy profile

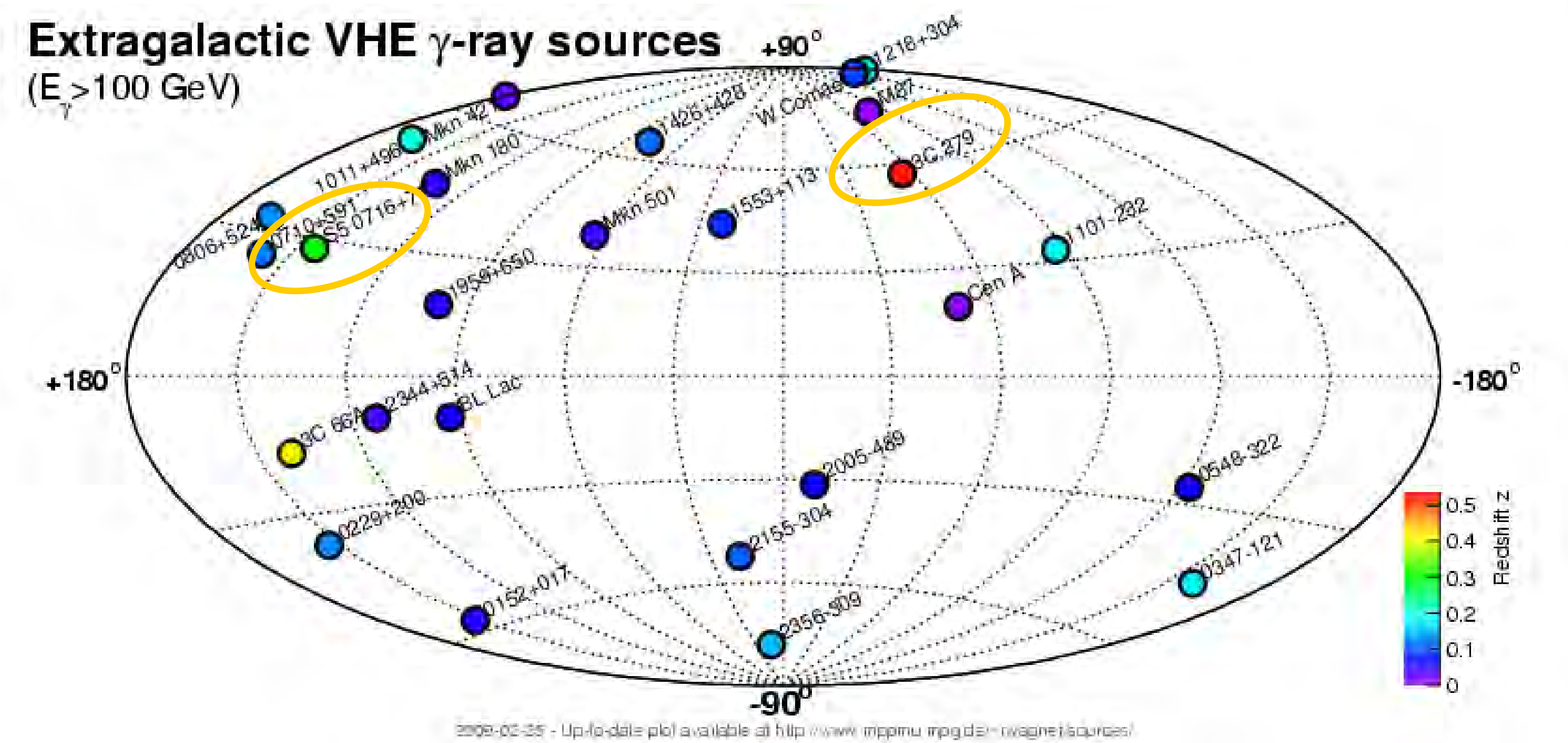




Milky Way satellites Sagittarius, Draco, Segue .Willman1, Perseus, …

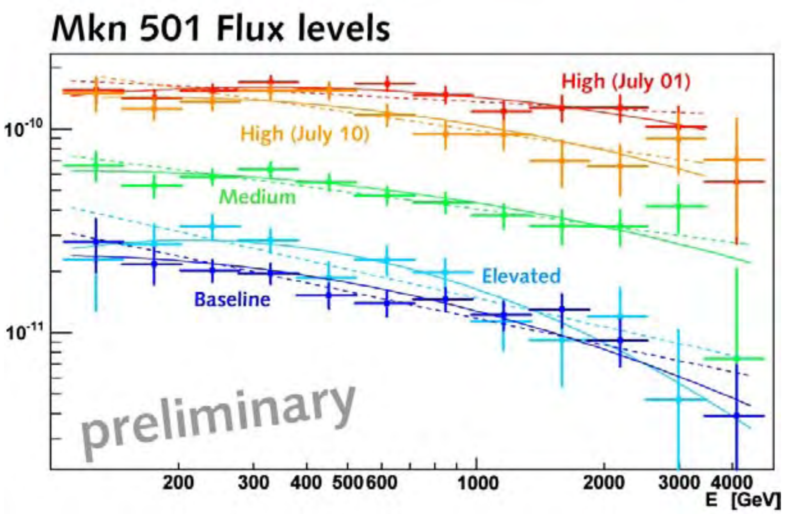
- proximity (< 100 kpc)
- low baryonic content, no central BH (which may change the DM cusp)
- large M/L ratio
- No signal for now…

Going far away…

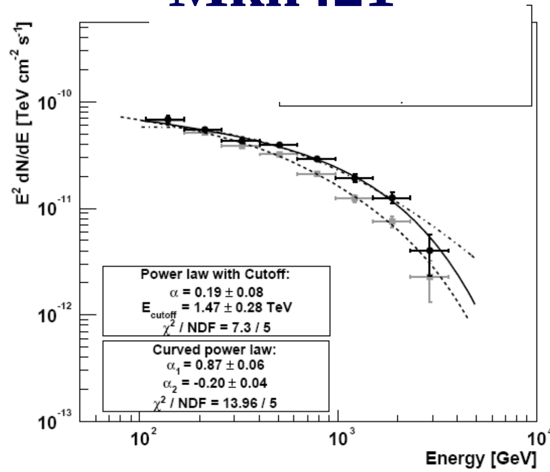


Variability: Mkn 421, Mkn501

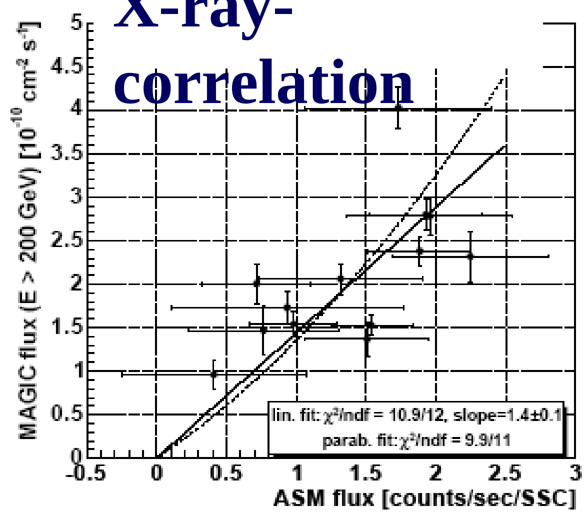
- Two very well studied sources, highly variable
  - Monitoring from Whipple, Magic...
  - TeV-X Correlation
    - No orphan flares...
      - See neutrino detectors



Mkn421

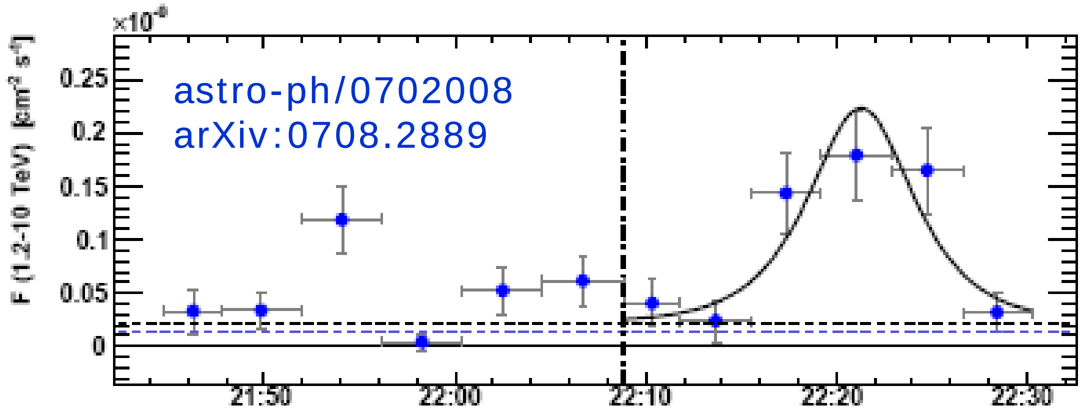


Mkn421 TeV-X-ray-correlation

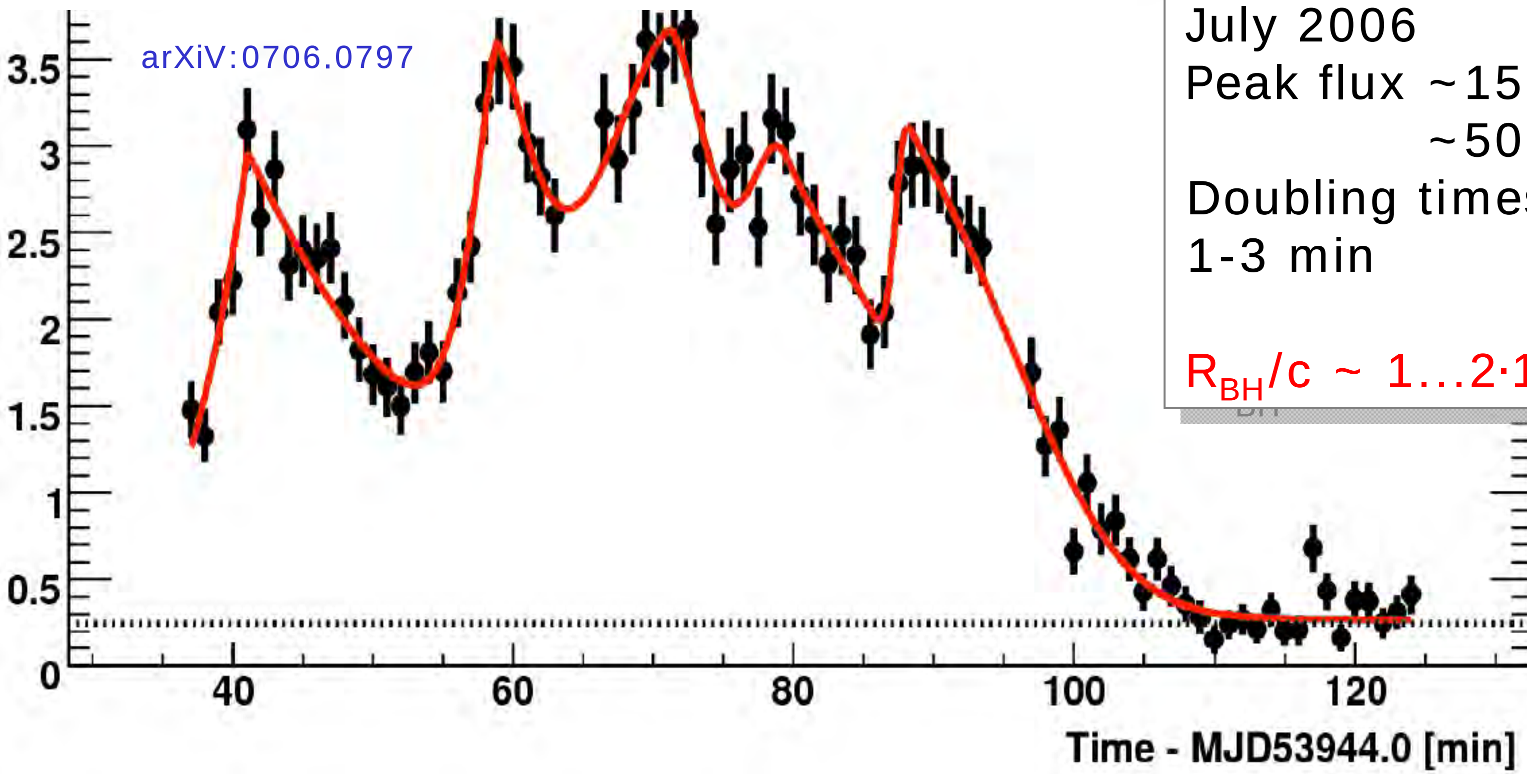


However, recently Fermi / HESS saw no correlation in PKS 2155

Rapid variability



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

Violation of the Lorentz Invariance?

Light dispersion expected in some QG models, but interesting "per-se"

$$V = c\,[1 \pm \xi\,(E/E_{s1}) - \xi_2\,(E/E_{s2})^2 \pm \ldots]$$

1st order $$(\Delta t)_{\rm obs} = \frac{\Delta E}{\mathbf{E_{s1}}} H_0^{-1} \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$$

MAGIC Mkn 501, PLB08

$E_{s1} \sim 0.03\ M_P$

$E_{s1} > 0.02\ M_P$

HESS PKS 2155, PRL08

$E_{s1} > 0.06\ M_P$

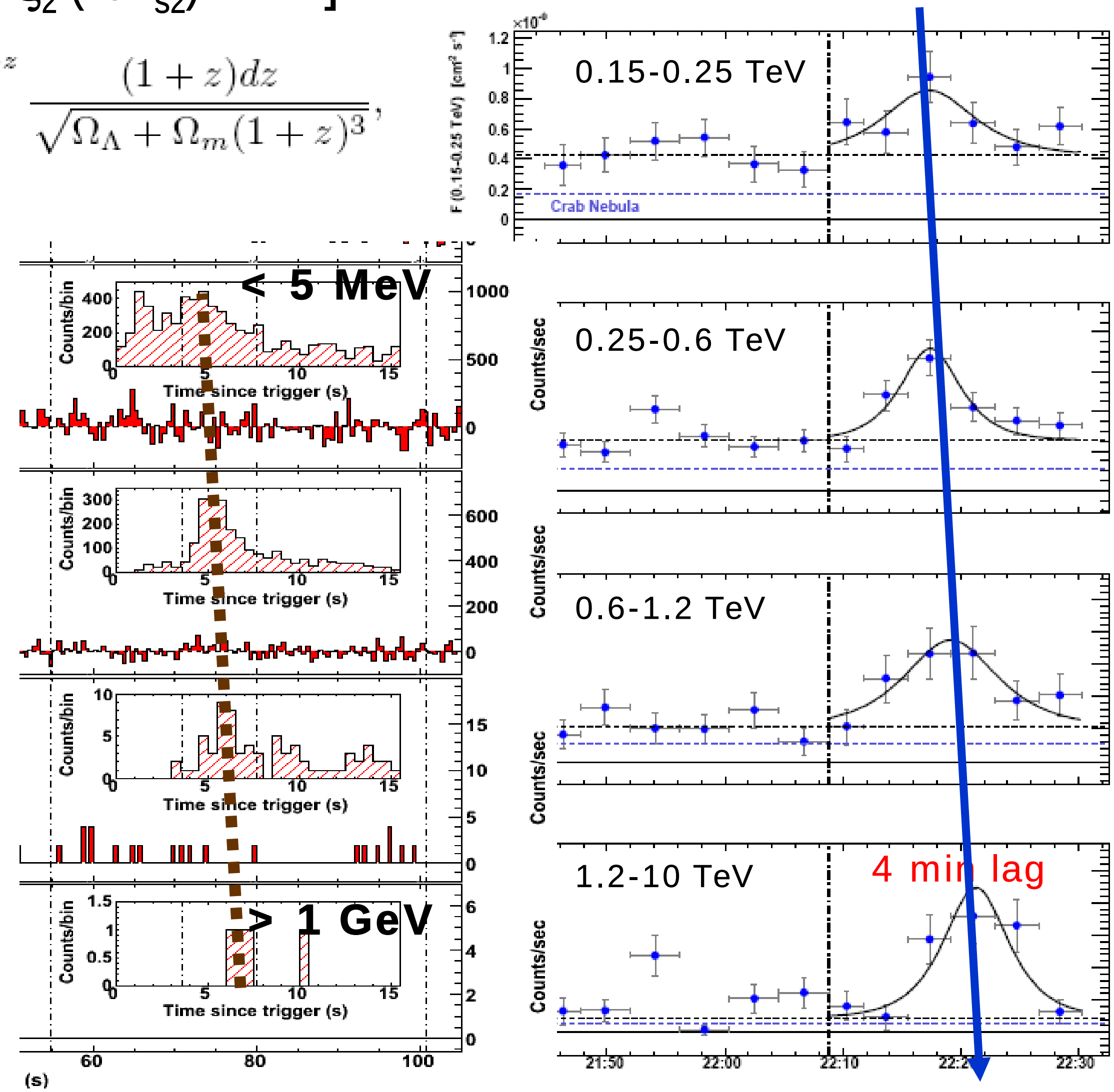
GRB X-ray limits:

$E_{s1} > 0.11\ M_P$ (Fermi, but…)

anyway in most scenarios

$\Delta t \sim (E/E_{s\alpha})^{\alpha},\ \alpha > 1$

- ▶ VHE gamma rays are the probe
- ▶ Mrk 501: $E_{s2} > 3 \cdot 10^{-9}\ M_P$, $\alpha = 2$



LIV in Fermi vs. MAGIC

- 13.2 GeV photon detected by Fermi **16.5 s** after GBM trigger. At 1st order

$$(\Delta t)_{\rm obs} = \frac{\Delta E}{\mathbf{E_{s1}}} \mathrm{H}_0^{-1} \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$$

- The MAGIC result for Mkn501 at z= 0.034 is Δt = (0.030 +- 0.012) s/GeV

Extrapolating, you get **(17 +- 7) s** (J. Ellis, Feb 2009)

or (49 +- 19) s (Alessandro)

SURPRISINGLY CONSISTENT:

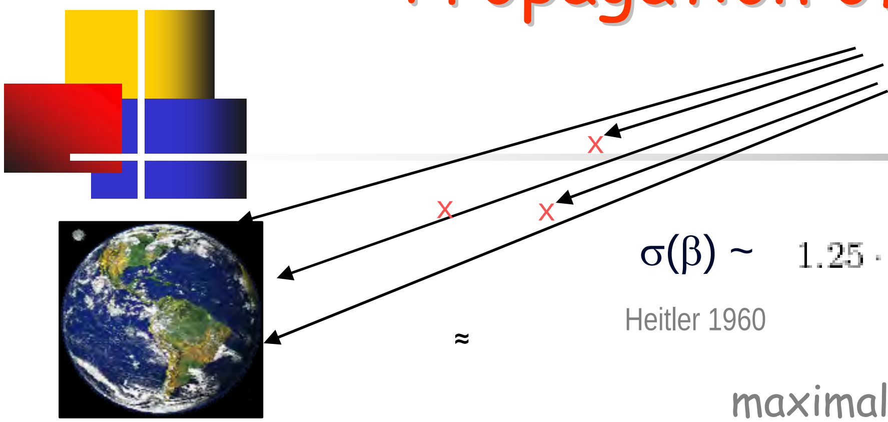
DIFFERENT ENERGY RANGE

DIFFERENT DISTANCE

However...

- The most likely interpretation is that the delay is due to physics at the source
  - A challenge for astrophysicists
- In any case:
  - Cherenkov telescopes are sensitive to effects at the Planck mass scale
  - More observations of flares will clarify the situation
  - And the bottomline: amazing to see light traveling for billions light years and keeping a ~ min delay

Propagation of γ-rays



dominant process for absorption:

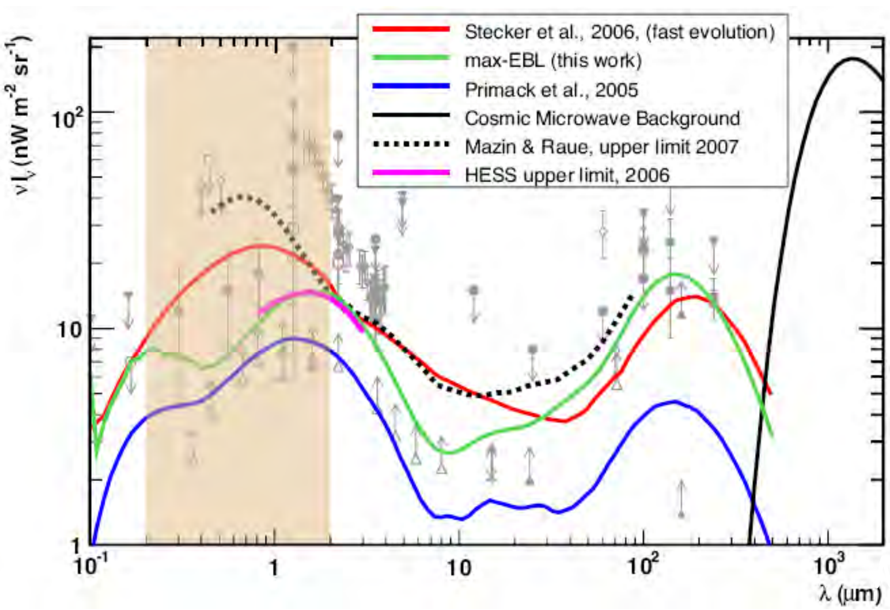
$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$

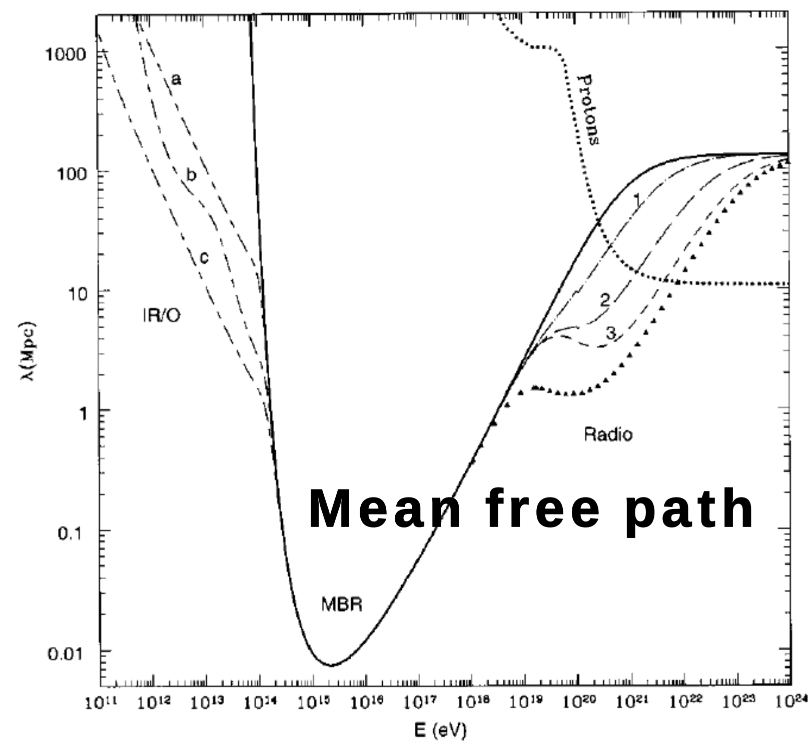
$$\sigma(\beta) \sim 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

Heitler 1960

maximal for: $\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right) \mathrm{eV}$

- For γ–rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation

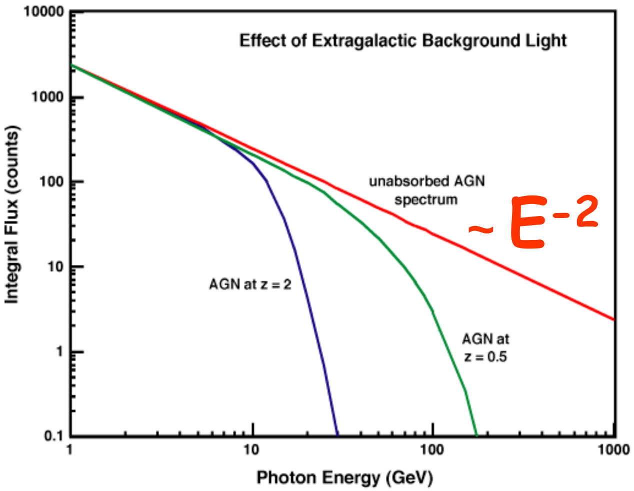


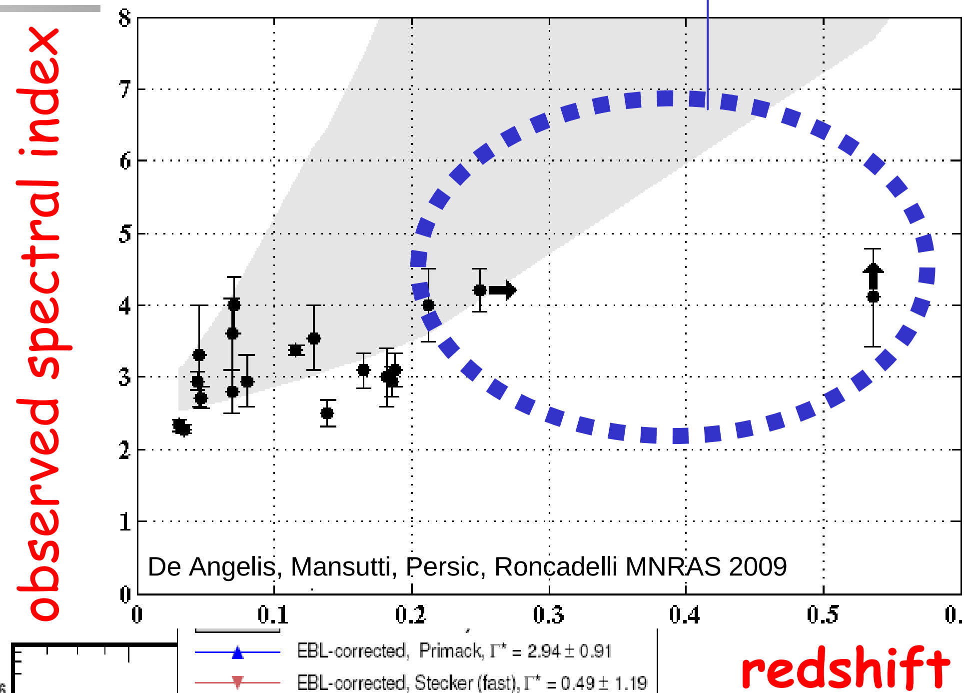


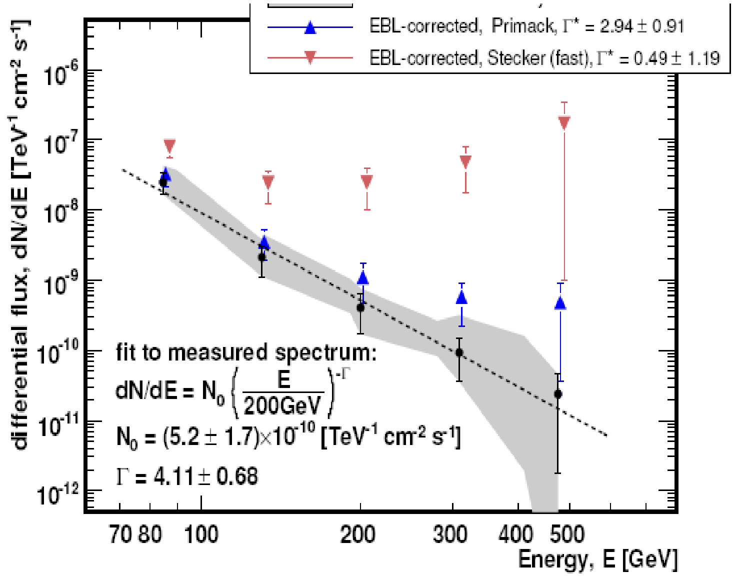
Are our AGN observations consistent with theory?

Selection bias?
New physics ?

Measured spectra affected by attenuation in the EBL:

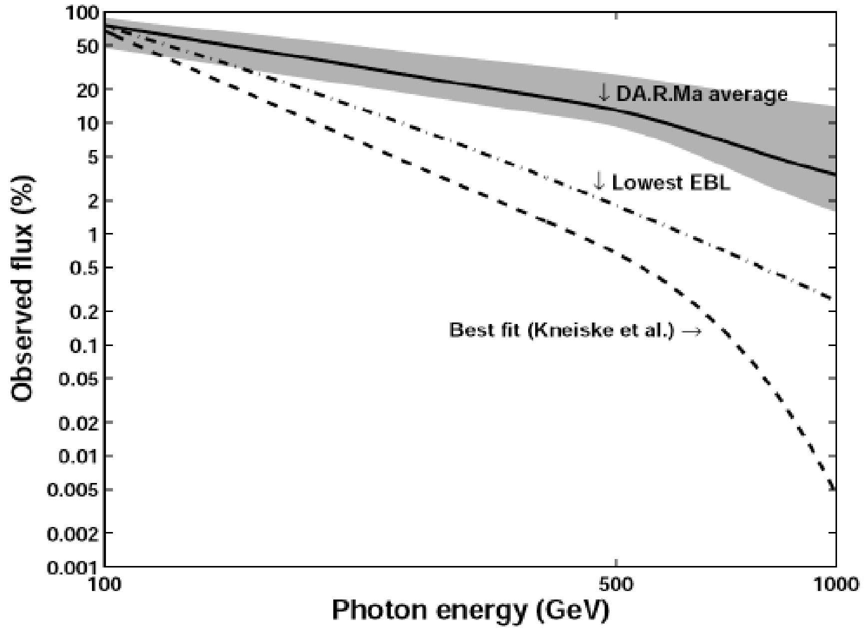


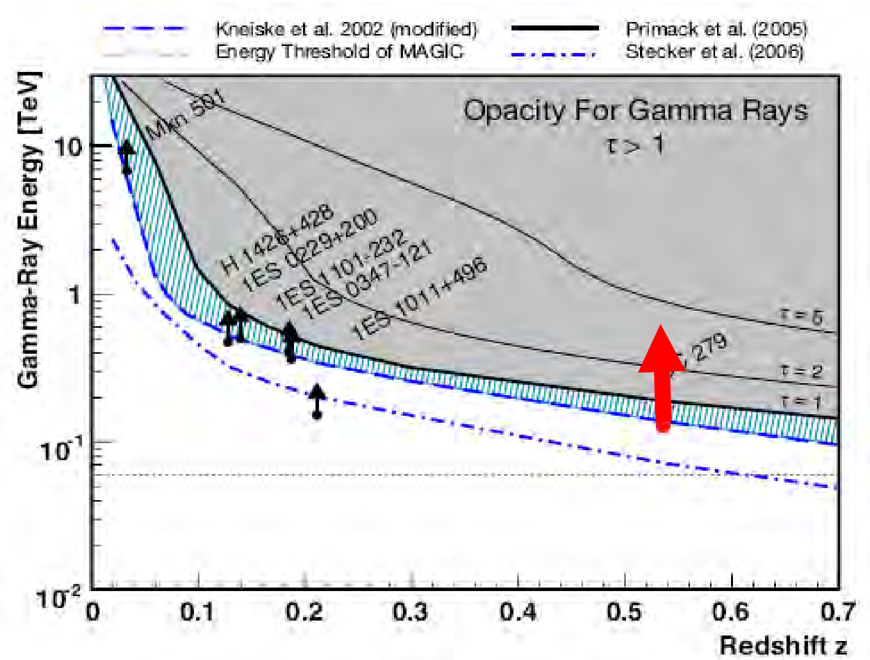




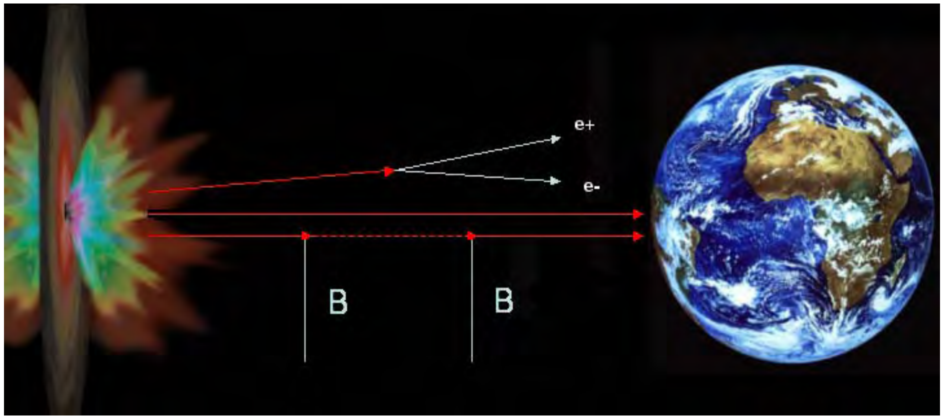
The most distant:
MAGIC 3C 279 (z=0.54)

Could it be seen?





- Explanations go from the standard ones
  - very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
  - Very low EBL
- to possible evidence for new physics
  - Interaction with a new light "axion"? (DA, Roncadelli & MAnsutti [DARMA], PLB2008, PRD2008)
    - Axion emission (Hooper et al., PRD2008)



We are (maybe) making two extraordinary claims

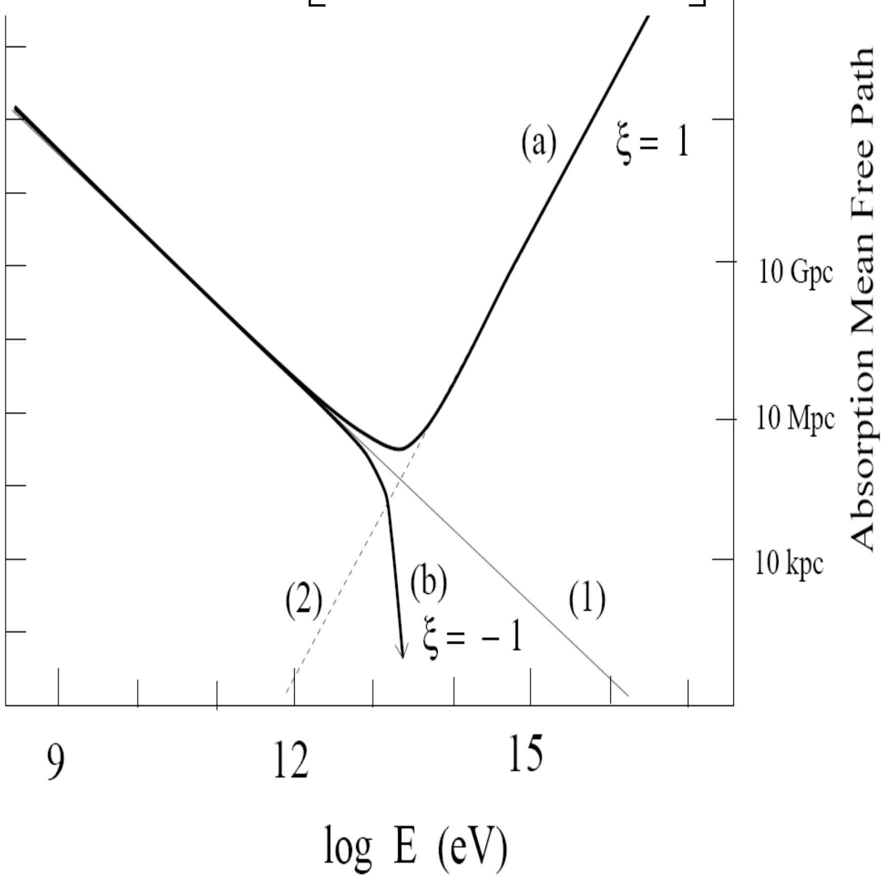
- A possible relation between arrival time and energy
- Signal from sources far away hardly compatible w/ EBL

- 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?

Can the unexpected transparency of the Universe be interpreted in the framework of LIV? It would be rather rather superluminal (Kifune 2000)

- Other mechanisms can be at work in the sector of LIV
- A full class of scenarios (Coleman-Glashow, Liberati-Sonego, Visser, etc.)
  - Room for phenomenology

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



What can we “observe” ?

SED(t) $\propto$ $SED_0(t) \otimes$

c(E) → LIV?

SED(E) $\propto$ $SED_0(E) \otimes$

ABSORPTION(E) [EBL, QED, Lorentz, Cosmology]

Galaxy formation
Astrophysics

New particles
Interacting w/ γs?

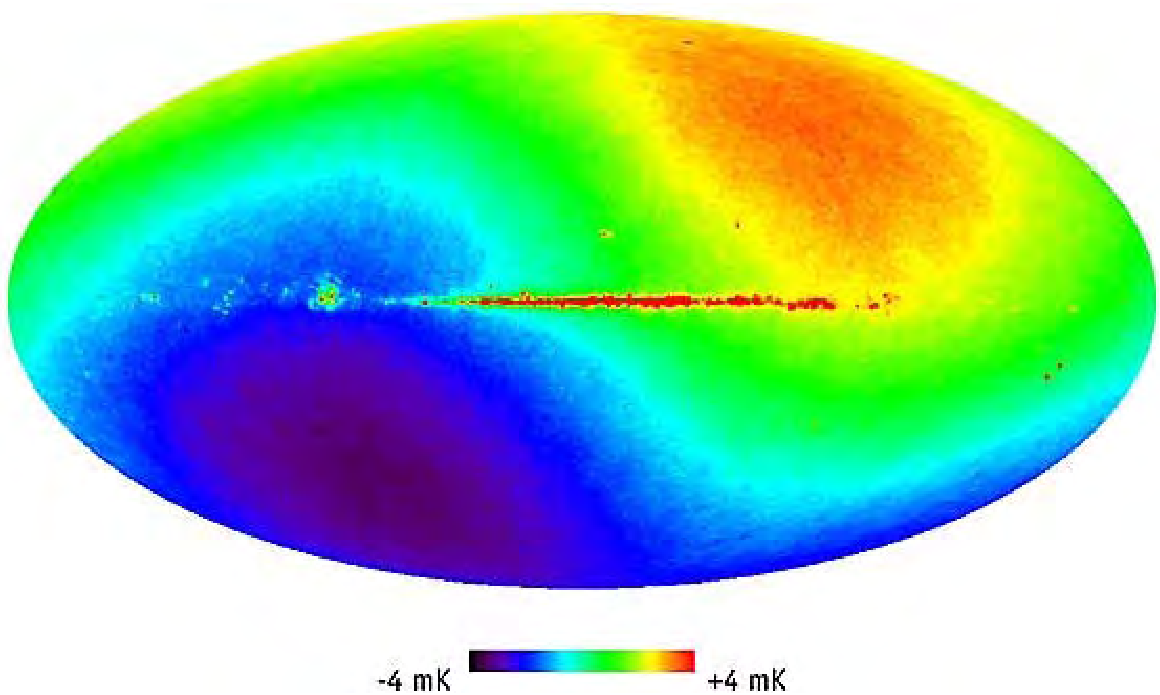
LIV?

Ω_m, Ω_Λ

THE GeV / TeV CONNECTION IS FUNDAMENTAL

We should have a statistics of flares (also from different sources)

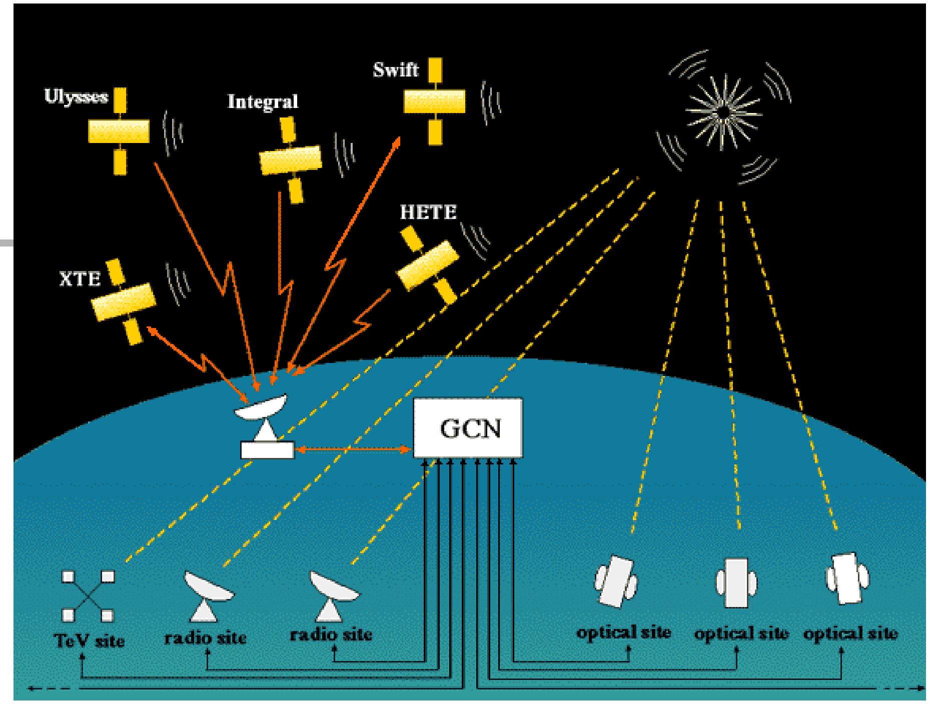
- Monitor different flares with an appropriate time analysis?
- Directionality?
  - Anisotropy of electrodynamics (Mansouri/Sexl, Kostelecky, Glashow, Consoli, Selleri, ...)

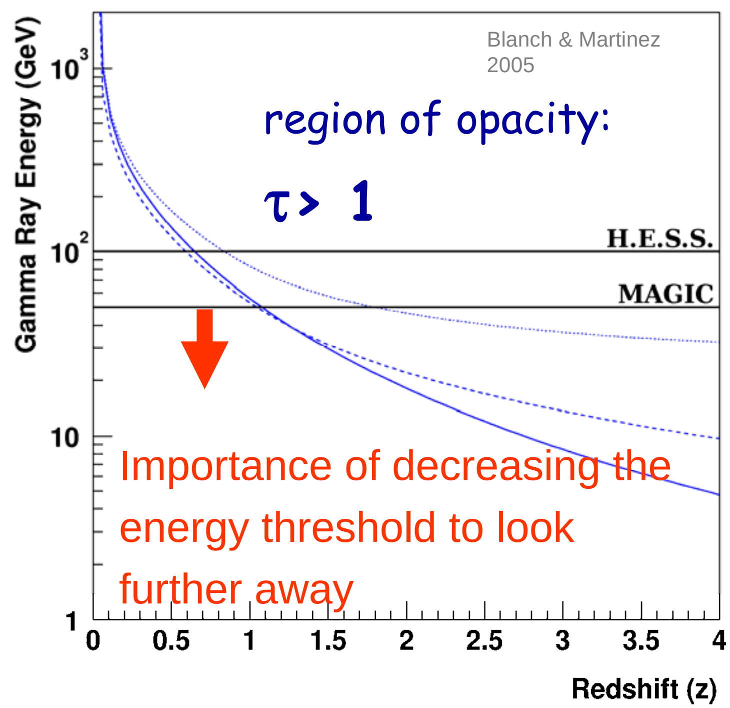


Building a consistent "big picture" for LIV and large transparency of the Universe will not be easy

GRBs
Another probe

- Interesting for astrophysical reasons, for propagation physics, for rapid variability-LIV
- MAGIC is the best instrument, due to its fast movement & low threshold
  - MAGIC is in the GCN Network
  - GRB alert active since Apr 2005





No VHE γ emission from GRB positively detected yet...
(all other observed GRB very short or at very high z)

Summary

High energy photons (often traveling through large distances) are a powerful probe of fundamental physics under extreme conditions, where nobody else can go

Possibility of digging into fundamental physics is real

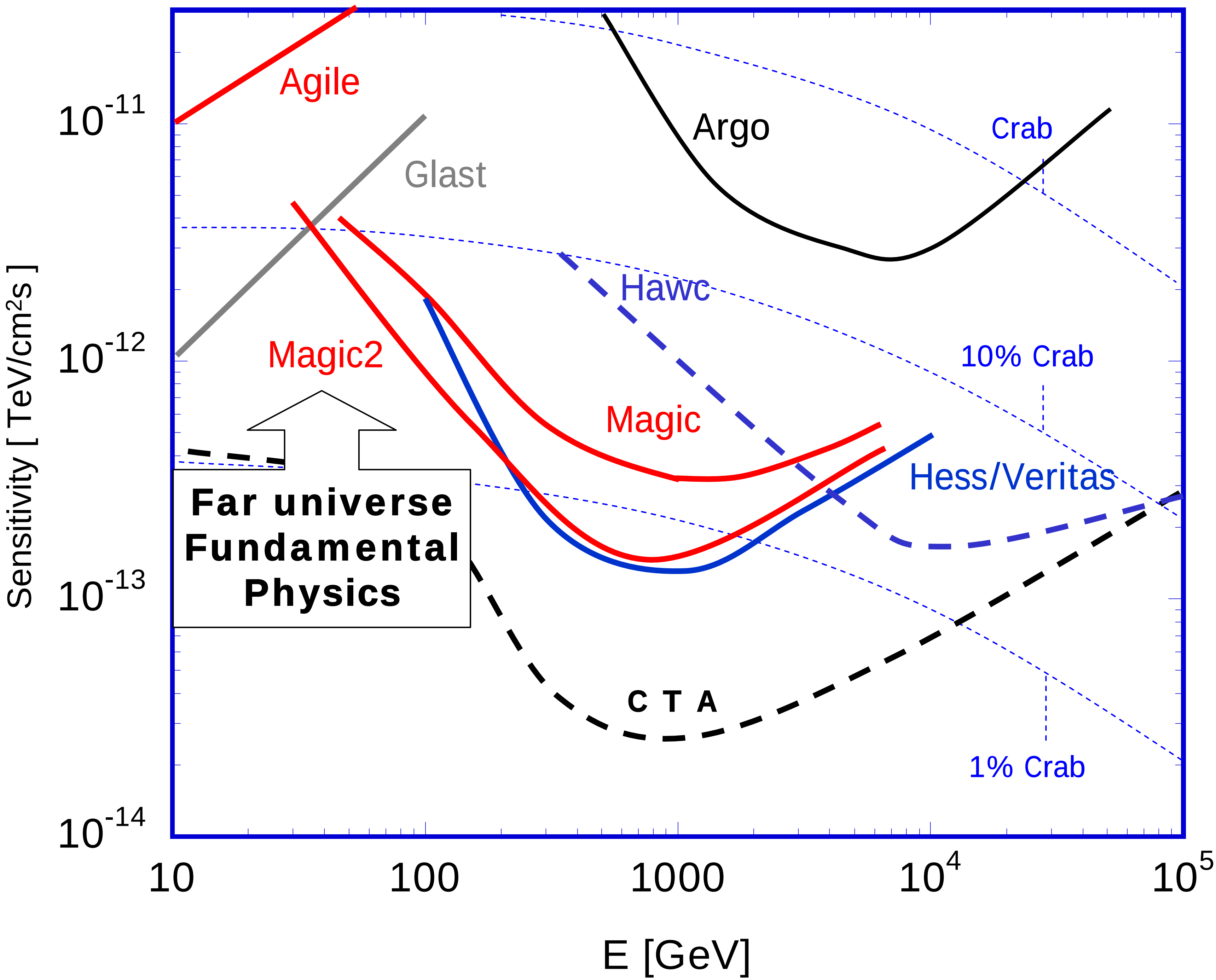
- What better than a crash test to break a theory?
- But… If we believe present claims, maybe it's already there…

⇒ Systematic studies of "strange behaviors"

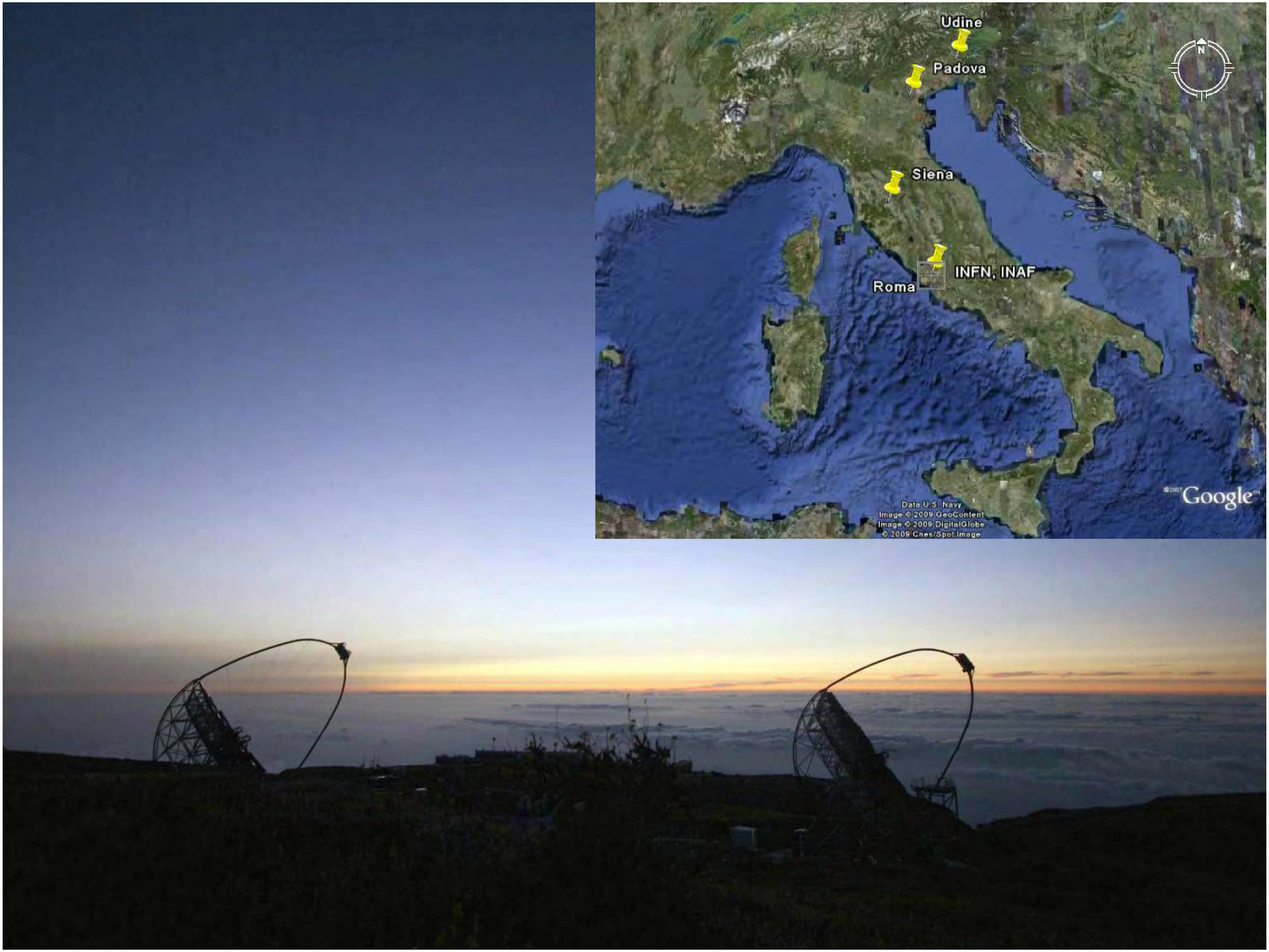
⇒ GRBs (high z, high energy, short timescales) -> Fermi, Agile

⇒ Deeper theoretical understanding

COMPARISONS HE-VHE



Agile
Glast
Argo
Crab
Hawc
Magic2
Magic
10% Crab
Hess/Veritas
Far universe
Fundamental
Physics
C T A
1% Crab
Sensitivity [TeV/cm²s]
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10
100
1000
10⁴
10⁵
E [GeV]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