MAGIC observations of distant Active Galactic Nuclei and their implications

Outline:

- Introduction: Very High Energy γ-rays from distant AGN as a tool for γ propagation studies
- The MAGIC stereo telescope system
- Some results and physics interpretations

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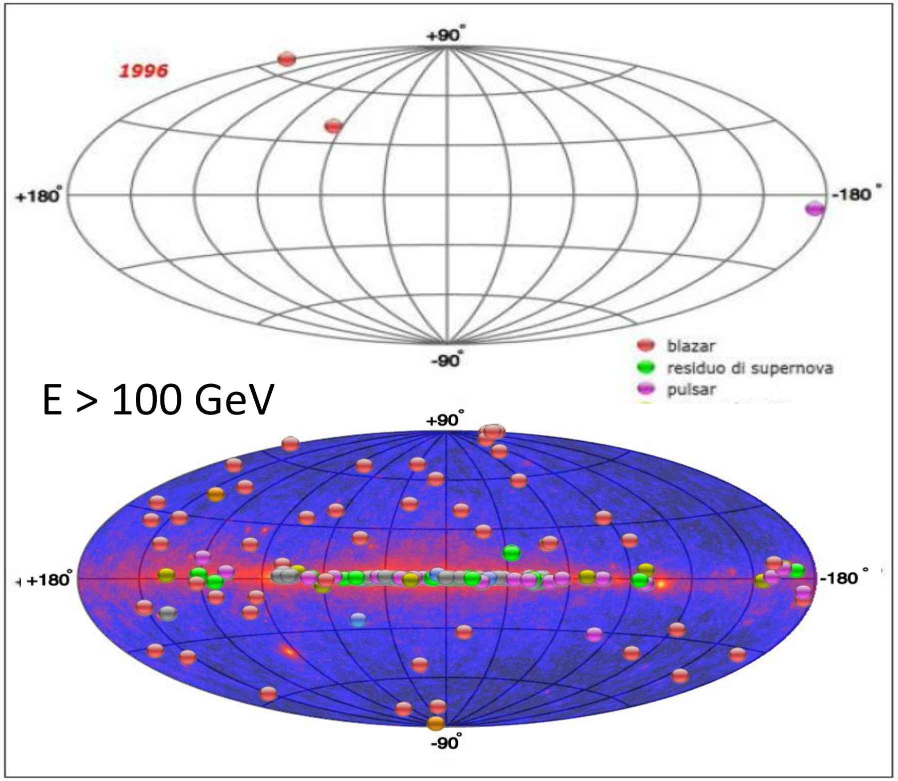
Very High Energy γ-rays as HEP tool

- Ideal carriers of information about **non thermal relativistic processes** in the Universe
- No deflection from magnetic field: point to the source
- Good detection efficiency
  (space-borne and ground based instruments)



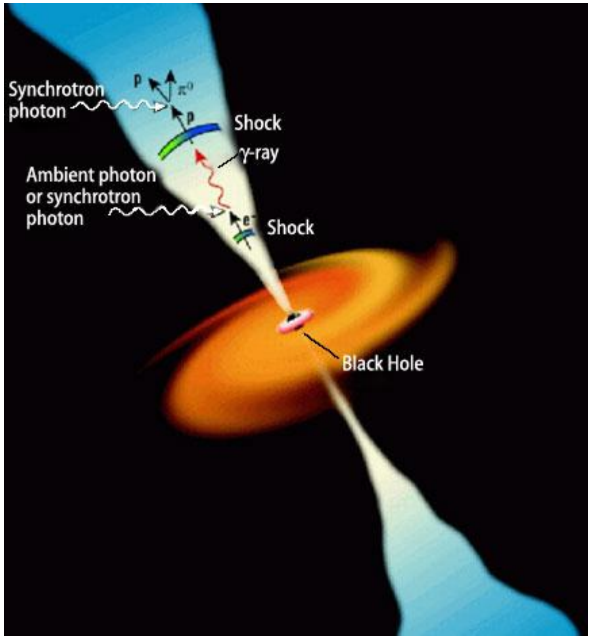
γ-rays are opening a new window on the Universe

Active Galactic Nuclei

Most of the extragalactic objects detected in VHE γ-rays

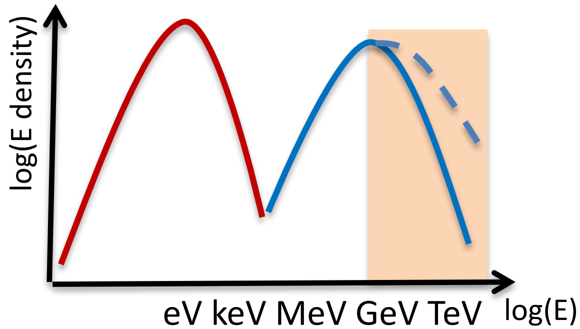
Powerful cosmic accelerators:

- Engine: supermassive black hole
- Rotating accretion disk
- Emission of collimated relativistic jets



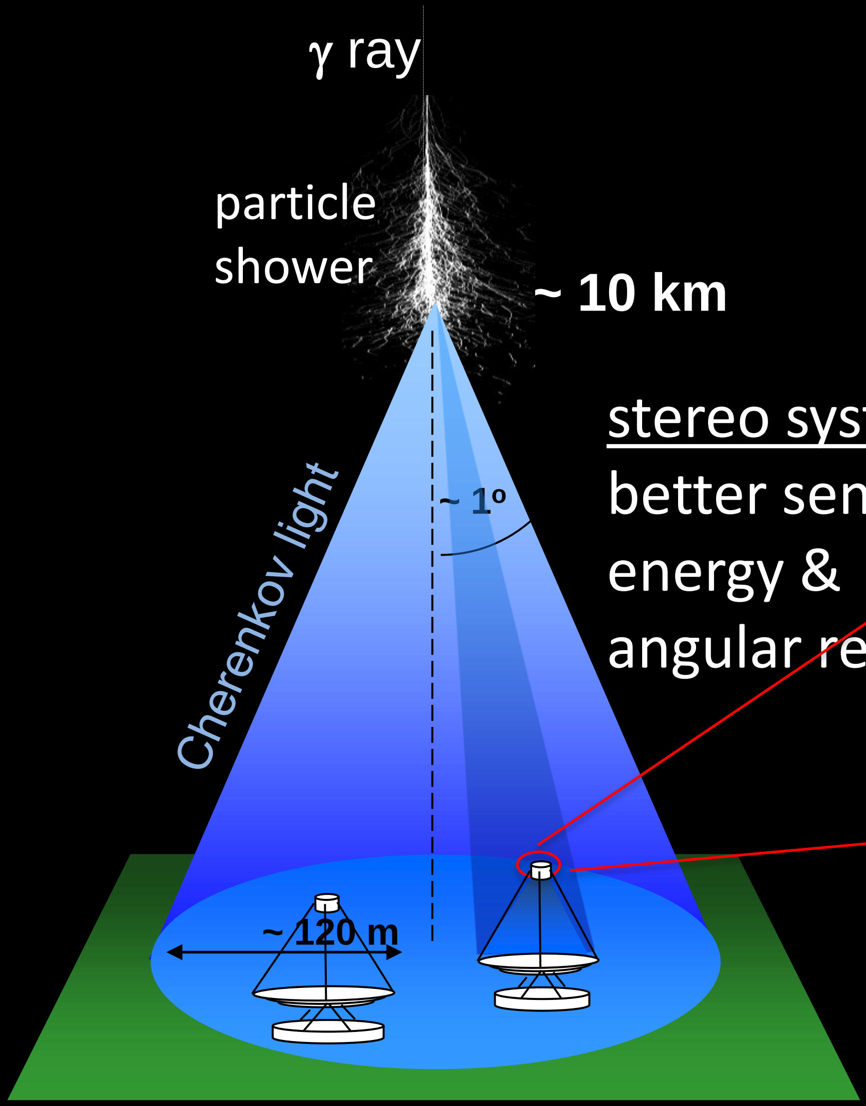
Blazar: jet pointing towards the observer

- Time variability at all frequencies
- Continuous Spectral Energy Distribution (SED) with two broad peaks:



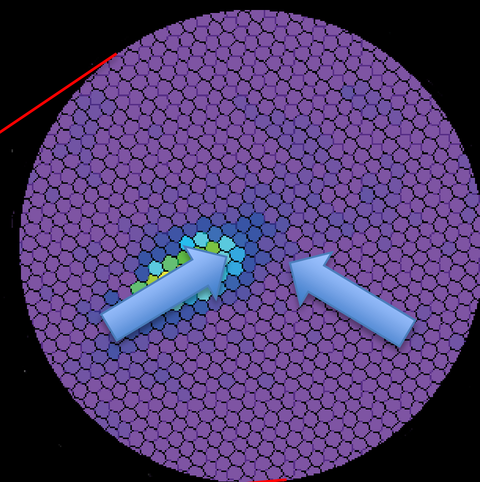
Cosmic background radiation
QED test
explore the deep Universe
new physics?
cosmology?

Imaging Air Cherenkov Technique



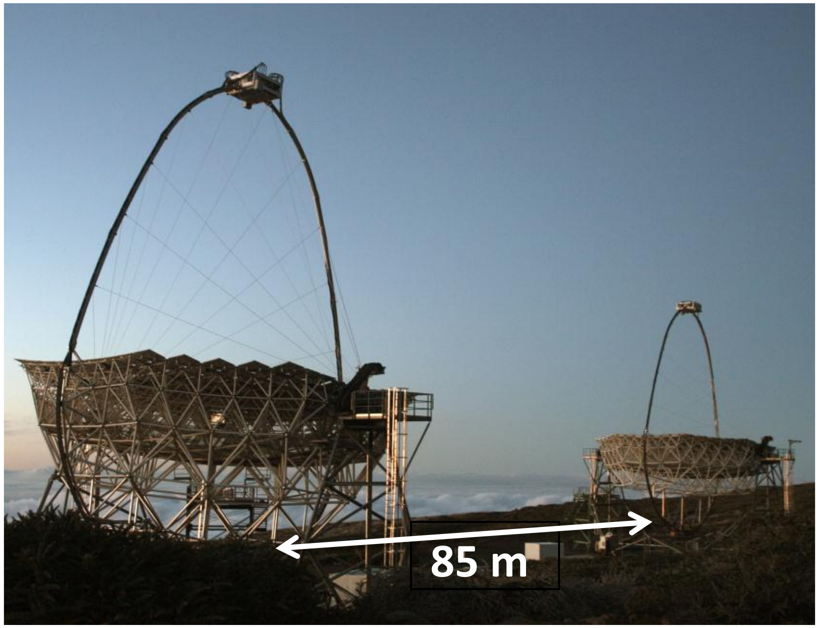
<u>stereo system</u>:
better sensitivity,
energy &
angular resolutions

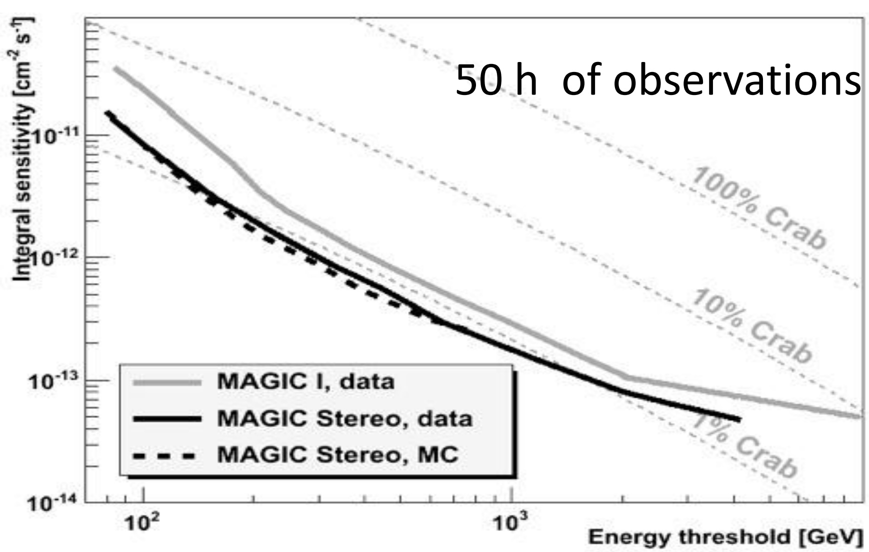
image of an air shower
in Cherenkov light
detected by the camera



- reconstruct: arrival direction, energy of primary γ
- reject hadron background in hardware as well as statistically in the analysis

MAGIC characteristics & stereo performance





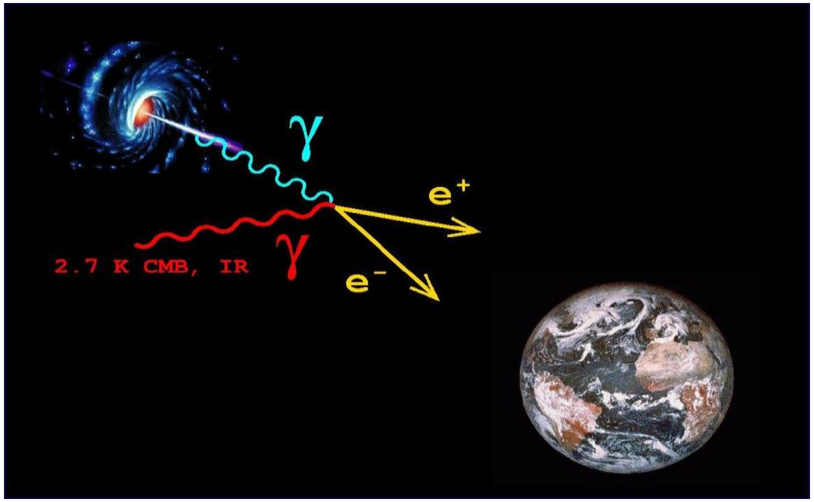
MAGIC-I in operation since 2004, MAGIC-II (stereo mode) since 2009

- 2 x 17 m ∅ dish (the largest mirror area for a single dish telescope)
- Light structure ➔ fast (< 20 s) re-positioning time
- Camera: low gain PMTs ➔ possible observations during moon time; field of view: 3.5°
- Fast readout 2 GSamples/s ➔ precise timing information
- Energy resolution: 20% @ 100 GeV ➔ 15% @ 1 TeV
- Angular resolution: 0.1 deg @ 100 GeV ➔ 0.05 deg @ 1 TeV
- Lowest energy threshold among IACTs: ~ 50 GeV (25 GeV with Sum Trigger)

Most sensitive observatory in the range 50-150 GeV

➢ Enhancement of the γ-ray horizon
➢ Cross calibration with Fermi
➢ Pulsar cutoff studies

Propagation of γ - rays



dominant process for absorption:

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

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

Heitler 1960

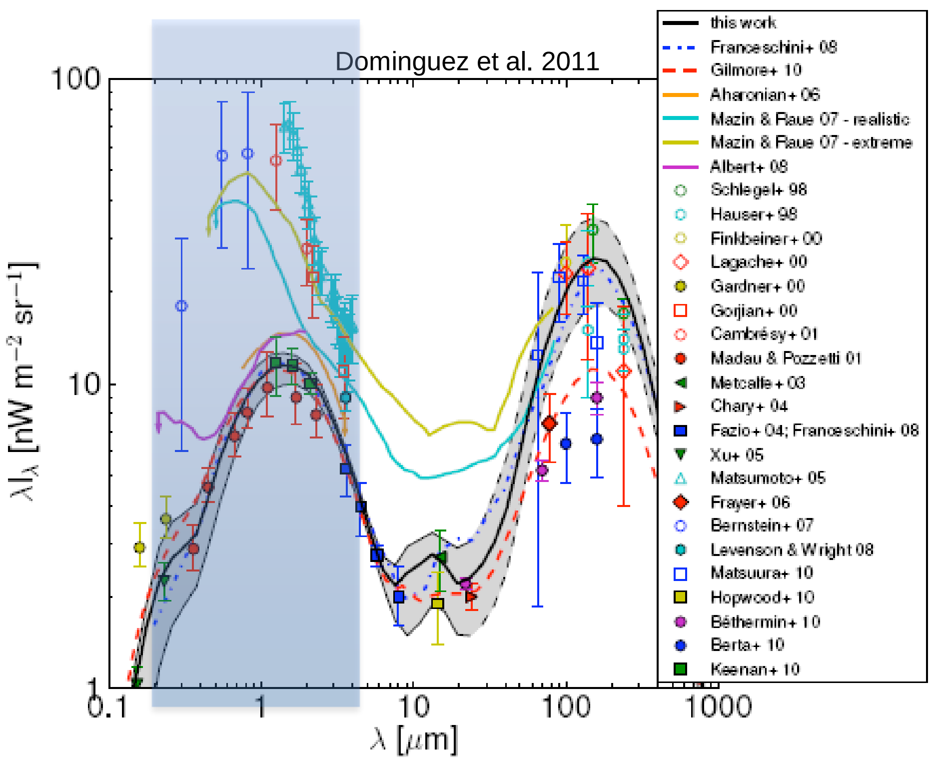
$$\beta = \sqrt{1-\frac{2m_e^2c^4}{E\varepsilon(1-\cos\theta)}}$$

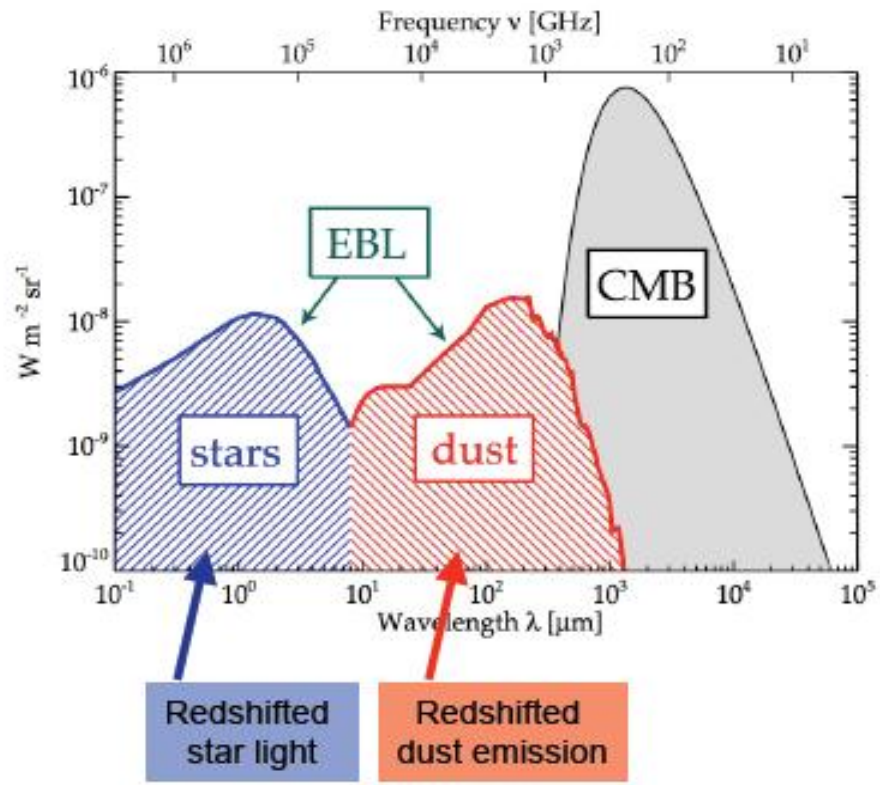
maximal for: $$\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right) \mathrm{eV}$$

- For VHE γ - rays, the relevant background component is optical/infrared (Extragalactic Background Light)

Extragalactic Background Light

- Thermal emission produced by all stars and partly absorbed/re-emitted by dust during the entire history of the Universe: two components ➔





- Several models try to describe the EBL Spectral Energy distribution: main differences depending on how the evolution in time and frequency is treated ➔ n(ε,z)

Attenuation

$$\Phi_{\rm obs}(E,z) \equiv \Phi_{\rm em}(E) \times e^{-\tau(E,z)}$$

τ optical depth

$$\tau(E,z) = \int_0^z dl(z) \int_{-1}^{1} d\cos\theta \frac{1-\cos\theta}{2} \int_{E_{thr(E,\theta)}}^{\infty} d\epsilon(z)\, n_\epsilon(\epsilon(z),z)\, \sigma(E(z),\epsilon(z),\theta)$$

n_ε (ε,z) spectral energy density of background photons (EBL)

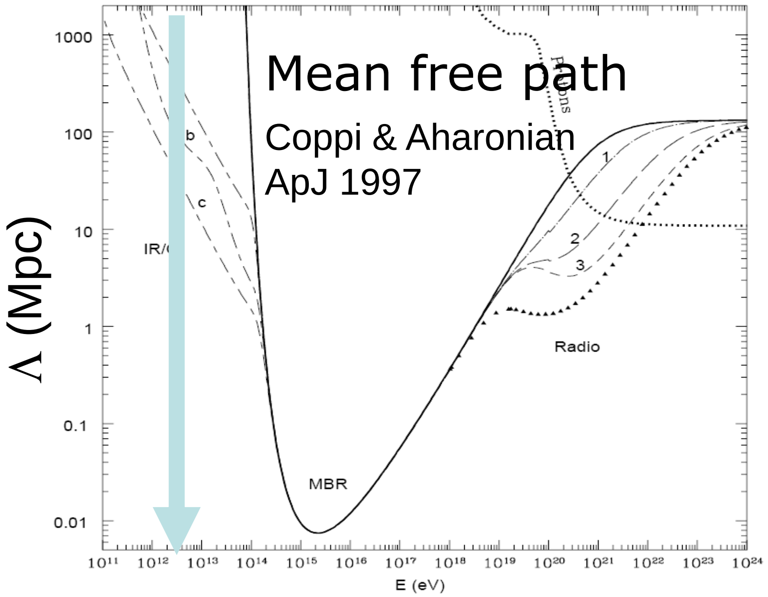
Neglecting evolutionary effects for simplicity:

$$\tau(E,D) \approx \frac{D}{\Lambda(E)} \qquad \left(\Lambda \propto \frac{1}{\sigma}\right)$$

$$\Phi_{\rm obs}(E,D) \approx \Phi_{\rm em}(E) \times e^{-\frac{D}{\Lambda(E)}}$$

For γ-rays energies above a few TeV

most of the VHE Universe is not visible to us

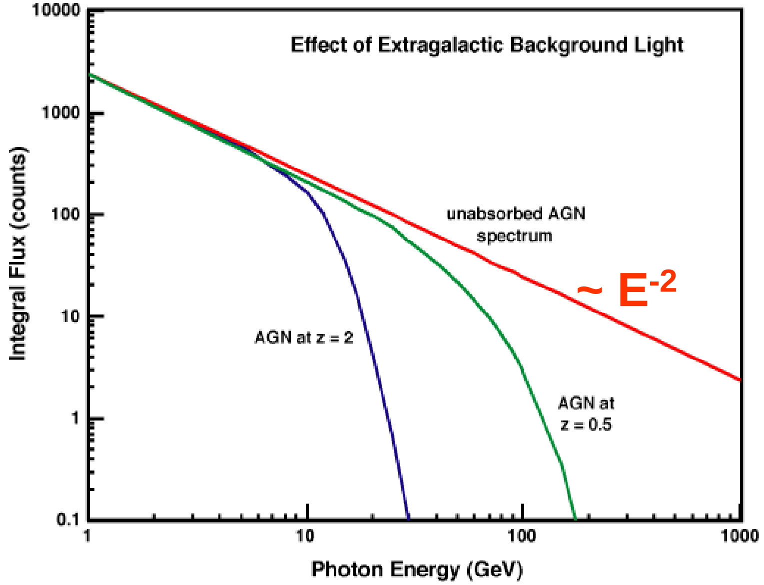


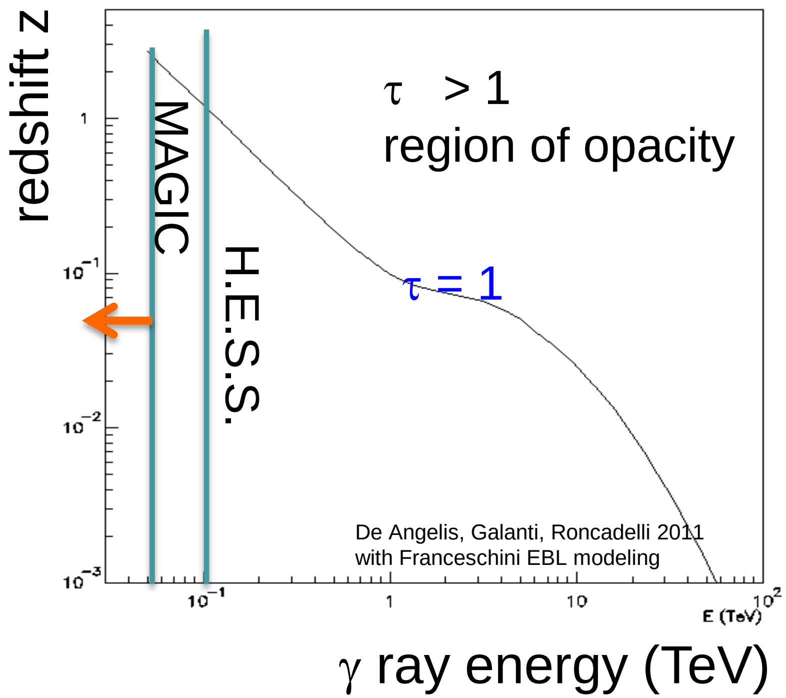
Consequences

- For E > 100 GeV:
  - The observed flux is exponentially suppressed at VHE
    ➔ the observed spectrum should be steeper than the emitted one.
  - The observed flux is exponentially suppressed at large distances
    ➔ very far-away sources should become invisible as energy increases

γ – ray horizon: τ(E,z) = 1

Fazio & Stecker 1970





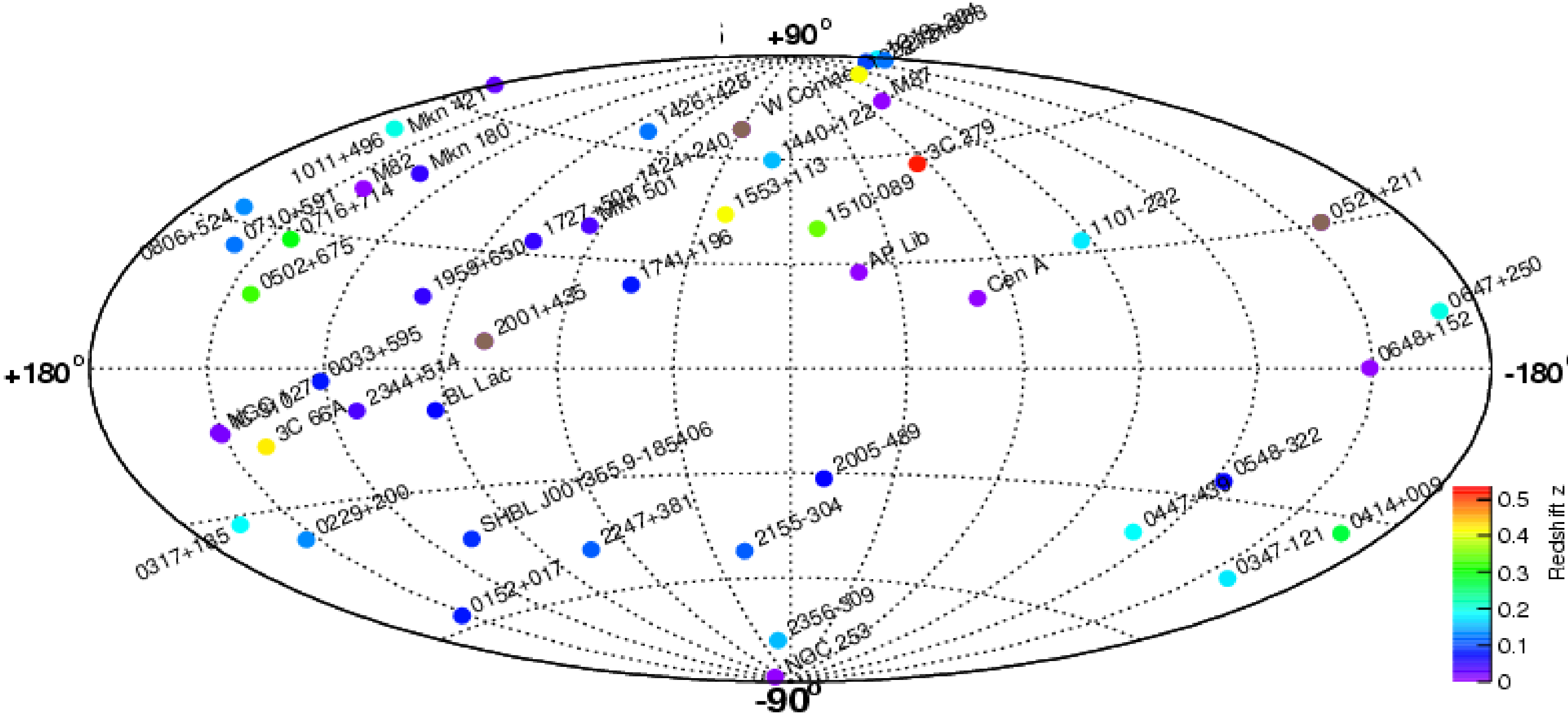
Extragalactic VHE γ-ray sources

~ 50 Sources

…

1ES 1011+496	**z=0.21**	**MAGIC 2007**
1ES 0414+009	z=0.29	HESS/Fermi 2009
S5 0716+71	**z=0.31**	**MAGIC 2009**
1ES 0502+675	z=0.34	VERITAS 2009
PKS 1510-089	z=0.36	HESS 2010
1ES 0647+250	**z=0.4**	**MAGIC 2011**
PKS1222+21	**z=0.43**	**MAGIC 2010**
3C 66A	**z=0.44**	**VERITAS 2009**
3C 279	**z=0.54**	**MAGIC 2008**

Thanks to its low energy threshold MAGIC is leader in detecting distant sources

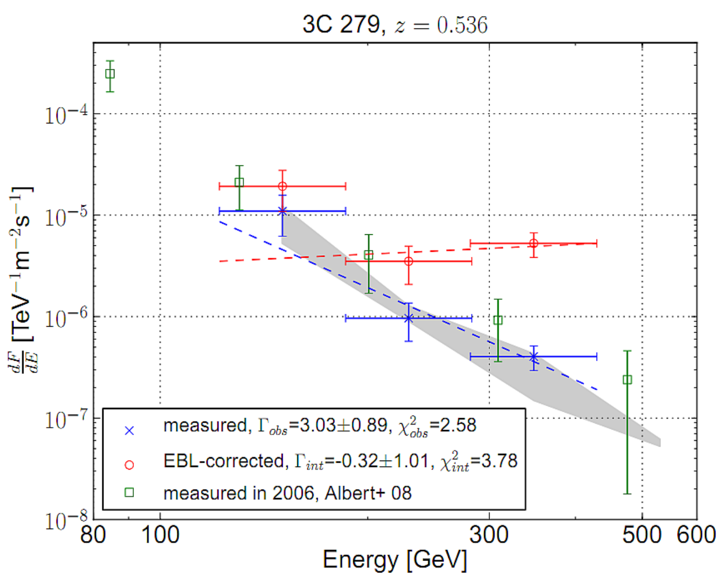


2011-11-20 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

MAGIC detection of the farthest VHE sources

3C 279 (z = 0.536)

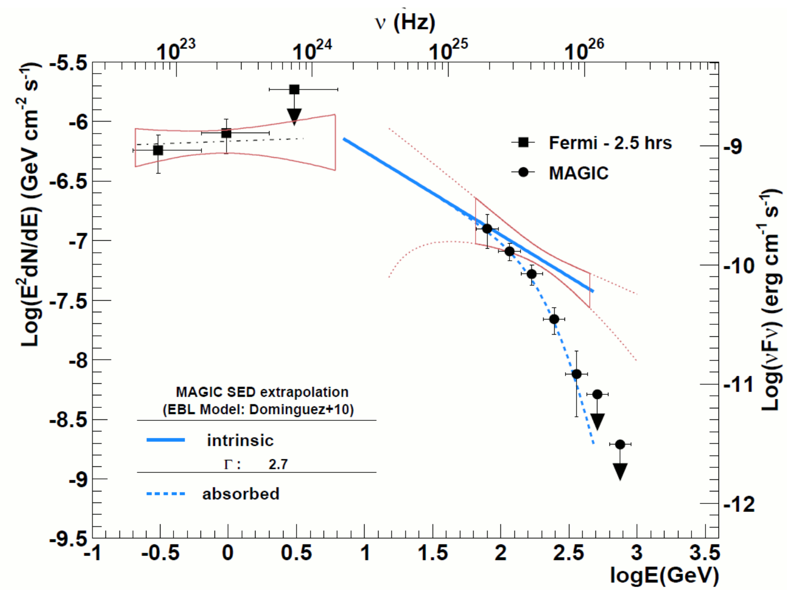
- discovered by MAGIC in 2006
  EBL constraints [Science 2008]
- re-observed 2007 and 2009



[A&A 2011]

PKS 1222+21 (z = 0.432)

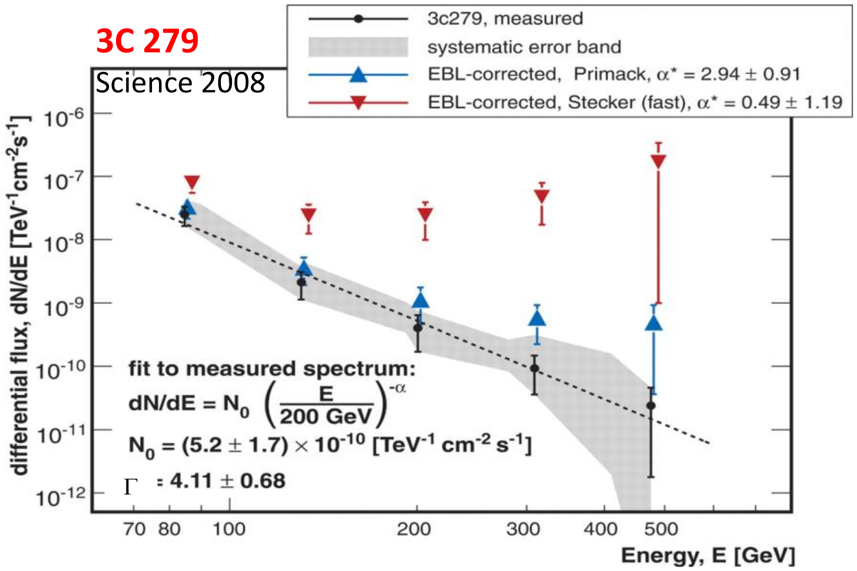
- MAGIC discovery during flare 2010
- fast variability

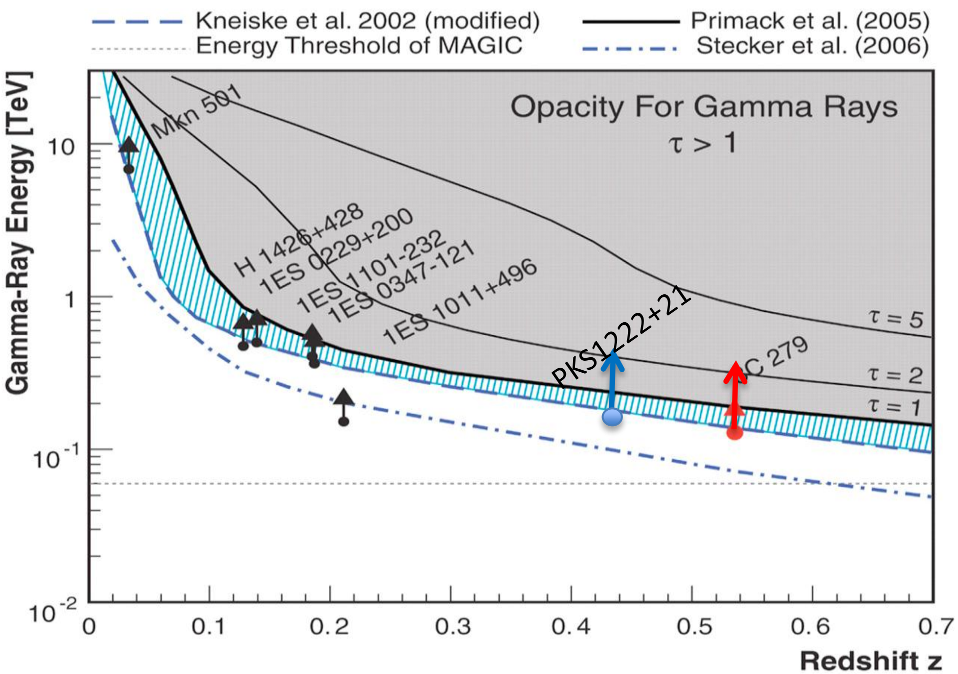


[ApJ Lett 2011]

Implications on Extragalactic Background Light

The measurement of spectral features allowed to place strong constraints EBL models





- Power law $\Gamma = 4.1 \pm 0.7$, measured up to 0.5 TeV ➔ spectrum sensitive to 0.2 - 2 μm
- Assuming minimum reasonable index $\Gamma_{em} = 1.5$ ➔ upper limit close to lower limit from galaxy count
- Results from PKS1222+21 confirm past claims on EBL

Emission harder than expected

➔ **Universe more transparent to γ-rays than expected**

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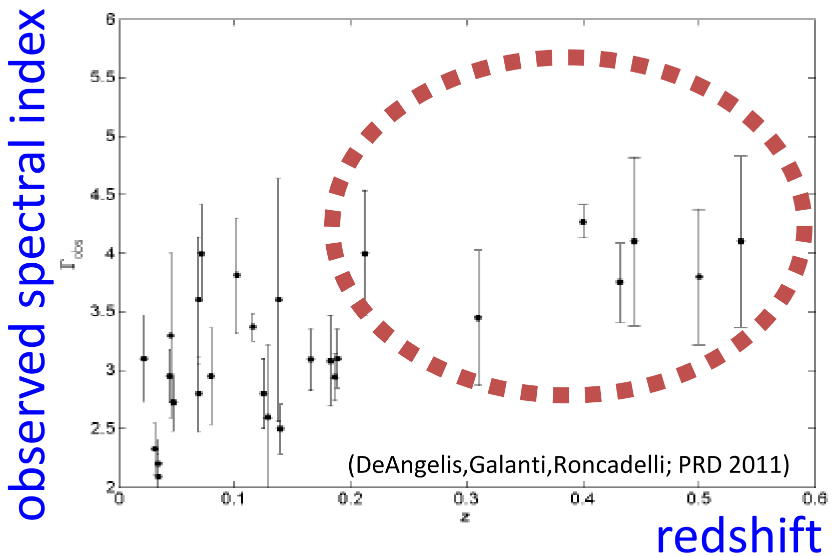
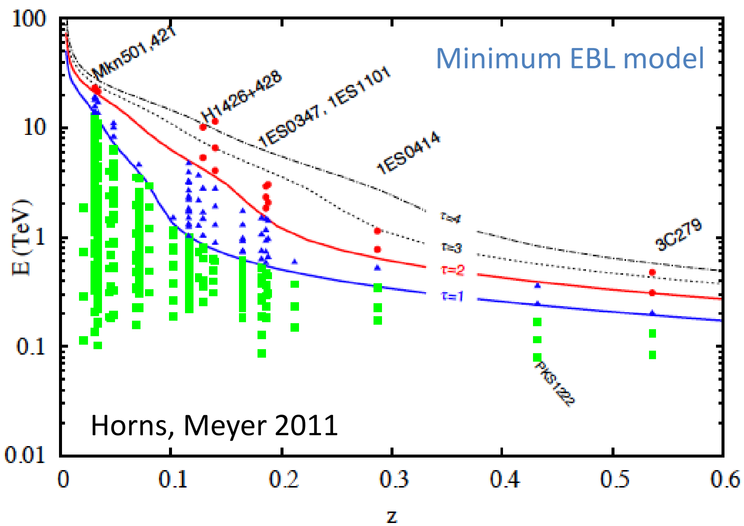
Are our AGN observations consistent with theory?





Explanations:

from the standard ones:

- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL (observational bias?)

to almost standard:

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

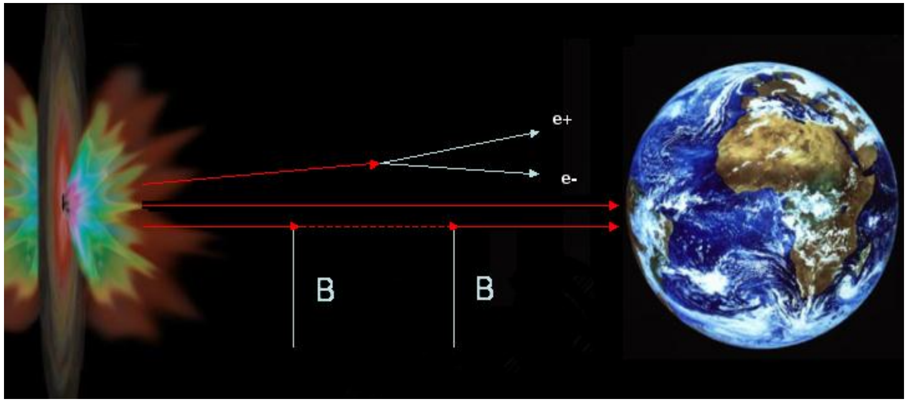
to more exotic ones:

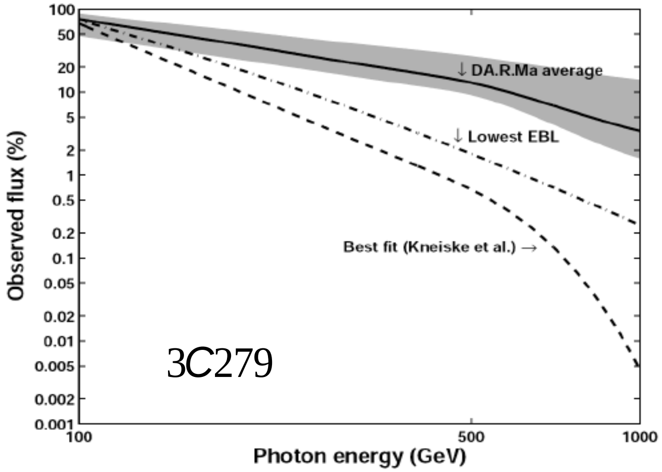
"given the broad range of energies and redshifts covered, source-intrinsic features are unlikely to explain the observed effect":

- possible evidence for new physics?

Oscillation to an Axion-Like Particle

Very light spin-zero bosons characterized by a $\gamma\gamma a$ coupling, predicted in many extensions of the SM. In the presence of external magnetic fields: photon-ALP oscillations.





Several interpretations:

- During the propagation in **the intergalactic medium**
  [DA.R.Ma, PLB2008, PRD2008]:
  small mass , small coupling (within limits) naturally explains the enhancement at large E

- Conversion **at the emission**
  [Simet, Hooper & Serpico, PRD 2008]:
  Milky Way acts as a converter to photons

- A combination of the above
  [Sanchez Conde et al. PRD 2009]

- Recently also used in modeling of rapidly varying VHE emission from PKS 1222+21
  [Tavecchio et al. MNRAS 2012]

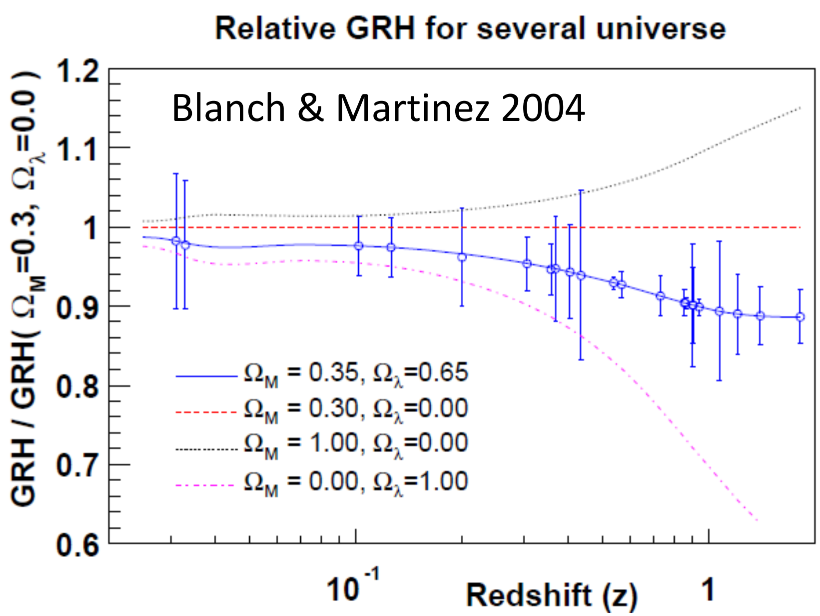
Cosmology with AGN

Gamma Ray Horizon depends on the γ–ray path and there the **Hubble constant and the cosmological densities** enter:

$$\frac{dl}{dz} = \frac{c}{H_o(1+z)} \frac{1}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$

➔ if **EBL density** and **intrinsic spectra** are known, the GRH might be used as a **distance estimator**

The study of the absorption of distant AGN γ – ray spectra may provide a complementary technique for the determination of the cosmological parameters.



Conclusions

- The MAGIC telescopes system is the worldwide most sensitive instrument in the energy range 50 – 150 GeV and has proven to be a powerful instrument in the study of distant AGN
- A new window is opening in VHE γ-ray astrophysics with implications in Fundamental Physics and Cosmology
- Further improvements and results expected with its upgrade and with the Cherenkov Telescope Array

Thank you

backup

Additional material:

- ALP limits
- Dark matter searches

The photon-axion mixing mechanism

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

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

Limits on:

- m_a < 0.02 eV (from direct searches (CAST))
- g < 10^{-10}GeV^{-1} from the non observation of γ-rays from the SN1987A, and direct searches

Indirect dark matter searches

DM annihilation/decay can produce VHE γ – rays

Self-annihilating WIMPs (as the neutralino in SUSY) can produce:

- Photon lines ($\gamma\gamma$, γZ)
- Photon excess at E < m from hadronization

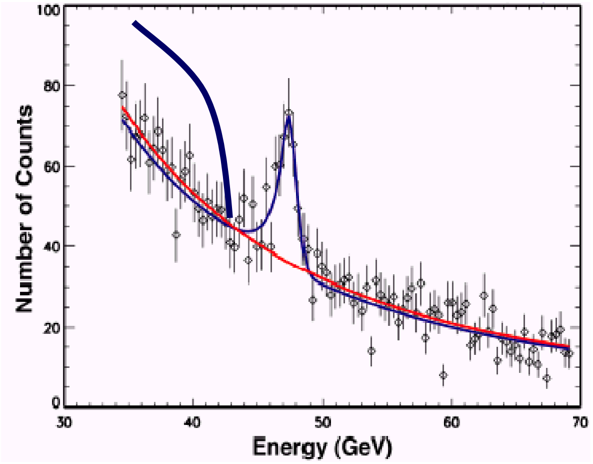
$$\Phi \propto \sigma \frac{\langle v \rangle}{m^2} \int_{los} \rho^2 \, dl$$

from particle physics

from astrophysics

Places to seek:

- Galaxy center (high flux, huge background)
- Dwarf galaxies (large M/L, low background, low flux)
- Galaxy clusters (huge DM content, large distance huge background)
- Unidentified HE γ-ray sources



Dwarf spheroidal galaxies

"spherical" collections of stars orbiting the Milky Way, (?) held together by DM (?)

- Large Optical Surveys (*eg.* SSDS, HST,...) has enabled astronomers to identify 20 or more such objects.
- Mass–to-Light ratio (indicative of DM content) often > 100 and some > 1000!
- Ideal locations to search indirect gamma rays signs from annihilation or decay of DM
- observed so far: Draco (ApJ 679, 428 (2008)), Willman-1 (ApJ 697, 1299 (2009)) and Segue-1 (JCAP 06 (2011) 035).

No significant excess.
Still a factor 600 above the mSUGRA models expectations.

- Stereo observations on dSph ongoing.