Physics with Very High Energy Cosmic Gamma Rays

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Outline:

- Introduction
- Detection
- Physics
- Outlook

Introduction

Cosmic Gamma rays:

highest energy electromagnetic radiation from our Universe

Presently: Particle Physics domain (E_{γ} > few GeV):

* INSTRUMENTS: Particle detectors

* TECHNIQUES: Experimental particle physics analysis

* PHYSICS: Address questions on the frontiers of our fundamental physics knowledge.

Introduction

Very High Energy Cosmic Gamma rays:
Presently Highest energy messengers detectable from our universe which:

- Are stable particles

- Are not deflected by cosmic magnetic fields

=> allow to pinpoint and identify the source:

GAMMA-RAY ASTRONOMY

Introduction

1) Study the source: production mechanisms

VHE gamma rays are produced in the most energetic and violent phenomena in the universe:

a) Through conversion of the strongest gravitational potential energies into particle accelerations near compact objects (Black Holes, Neutron Stars,..)

=> Unique LAB to study extreme GRAVITATIONAL INTERATION

Introduction

b) In big explosions in compact object formation (supernovae, hipernovae, collapses,…)

=> Acceleration in shock waves in ultrarelativisic plasma

c) Through the annihilation or decay of very massive or energetic objects:
dark matter, very massive particles at unification scales, relics of universe phase transitions, primordial black holes,…

=> Tool to search for new, massive, particles and objects.

→ Genuine messengers of the very-high-energy, ultrarelativistic, non-thermal population of our universe.

Analysis of source information in Astrophysics

'It' happened…
Far, far away
Long, long time ago

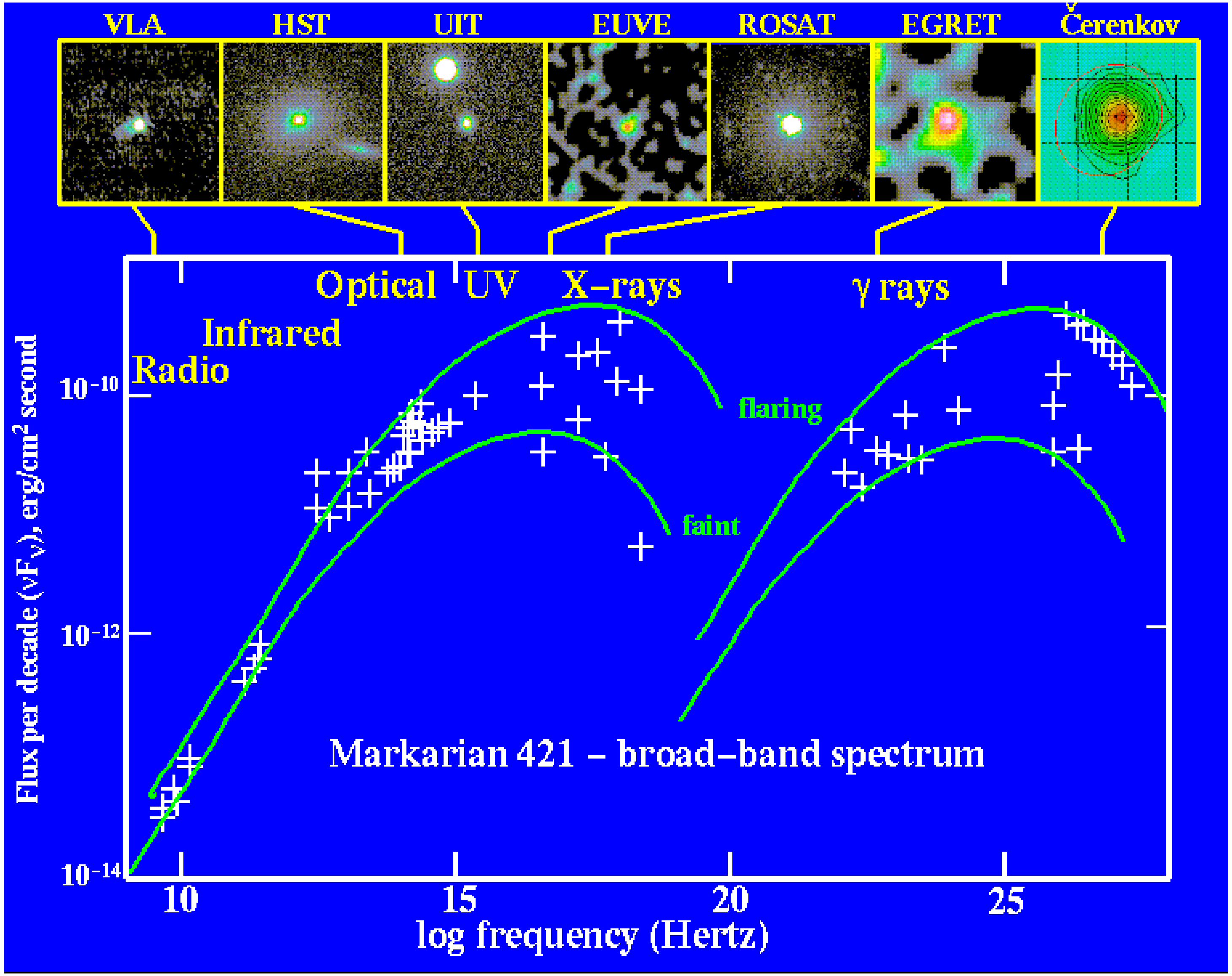
Messengers

Waves:
Radio, IR, visible,
UV, X, gravitational…

Counterparts very important

Particles:
Nuclei, Protons
Neutrinos
Gammas

Multiwavelength Spectrum



Introduction

2) Study the propagation in the cosmic medium:

VHE gamma rays are, so far, the most energetic messengers reaching us through a determinable path: explore the structure of space-time:

- at long distances: produced in sources at cosmological distances from us

- at the shortest distances: they explore space-time at the highest energies

=> they may allow us to address important questions in fundamental physics and cosmology

Introduction

An exciting and very promising field of

fundamental research

just starting

and mostly observation driven at present

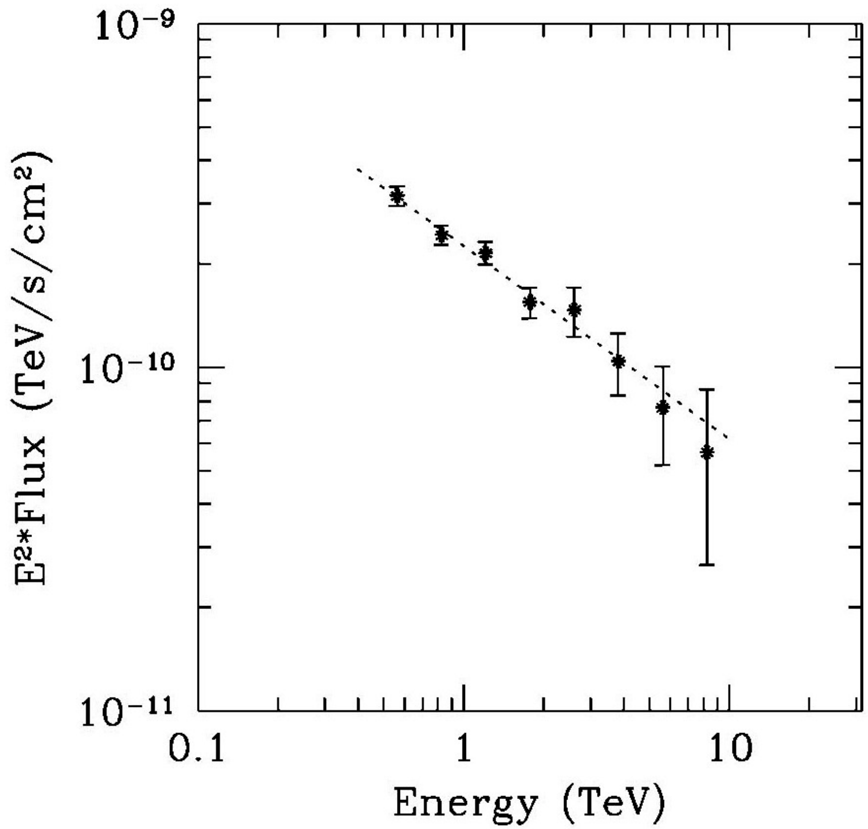
Detection

Gamma Ray Sources show typically in the VHE domain:

-Sharp Power Law spectra

$d\phi /dE = A E^{-\text{♋}}$

with ♋ = O(2.3-2.7)



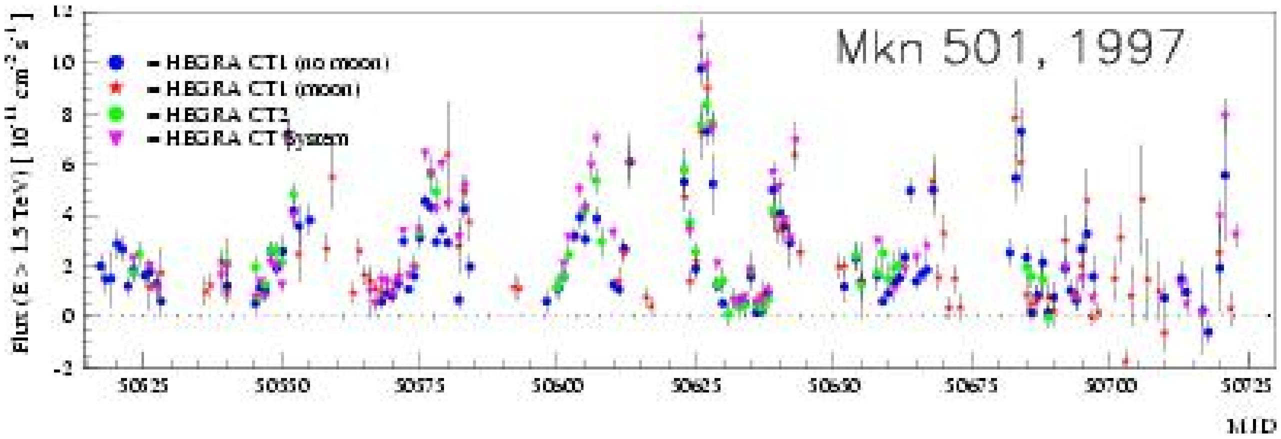
Mkn421 High State. WHIPPLE

Detection

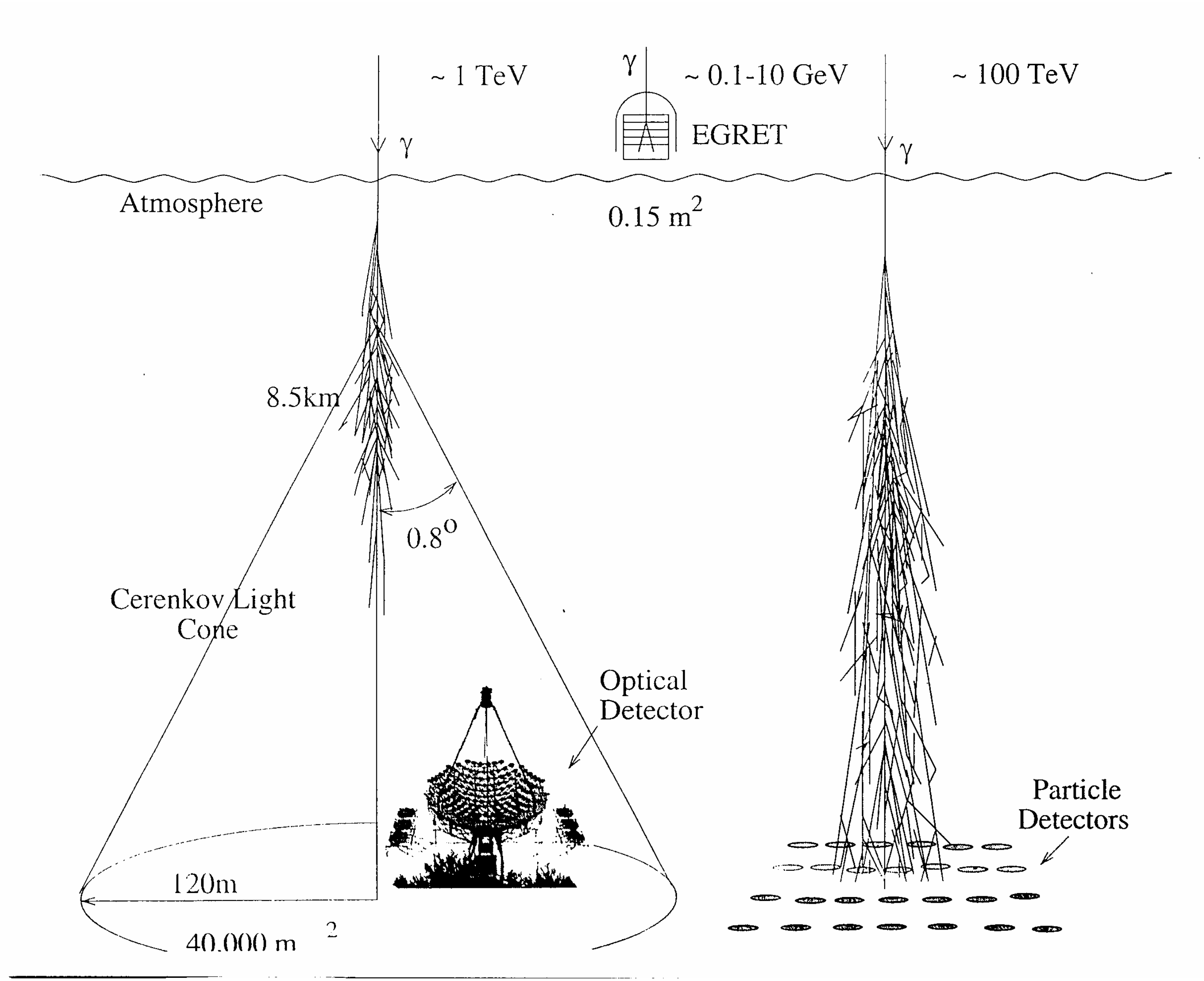
-Strong and fast time variations

=> very low fluxes at high energies

Need for large effective areas
and/or long exposures



Detection



~ 1 TeV
γ
γ
~ 0.1-10 GeV
EGRET
~ 100 TeV
γ
Atmosphere
0.15 m²
8.5km
0.8°
Cerenkov Light Cone
Optical Detector
Particle Detectors
120m
40.000 m²

Detection

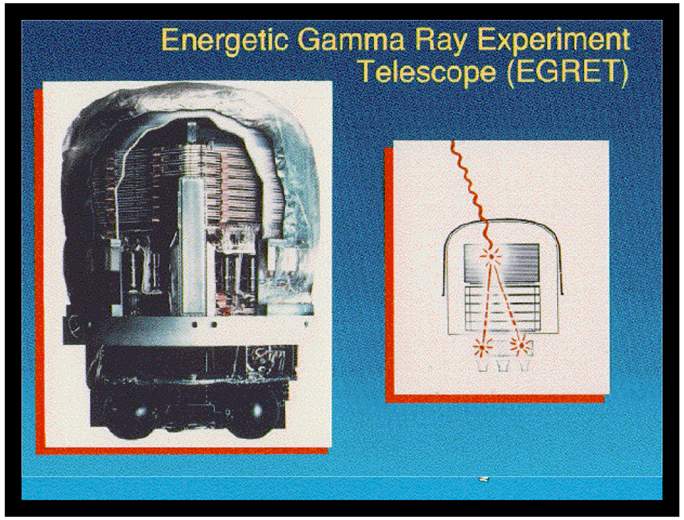
Satellites

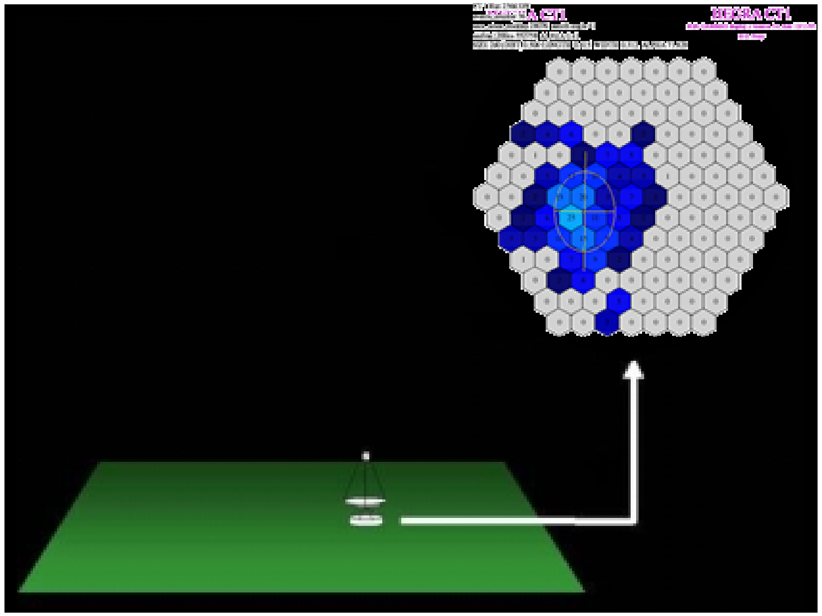
- **Primary detection**
- Small Effective Area < $1m^2$
- No background
- Energy<30GeV

Ground Detectors (IACTs)

- **Secondary detection**
- Huge Effective Area ~ 10^4m^2
- Enormous background
- Energy>300GeV

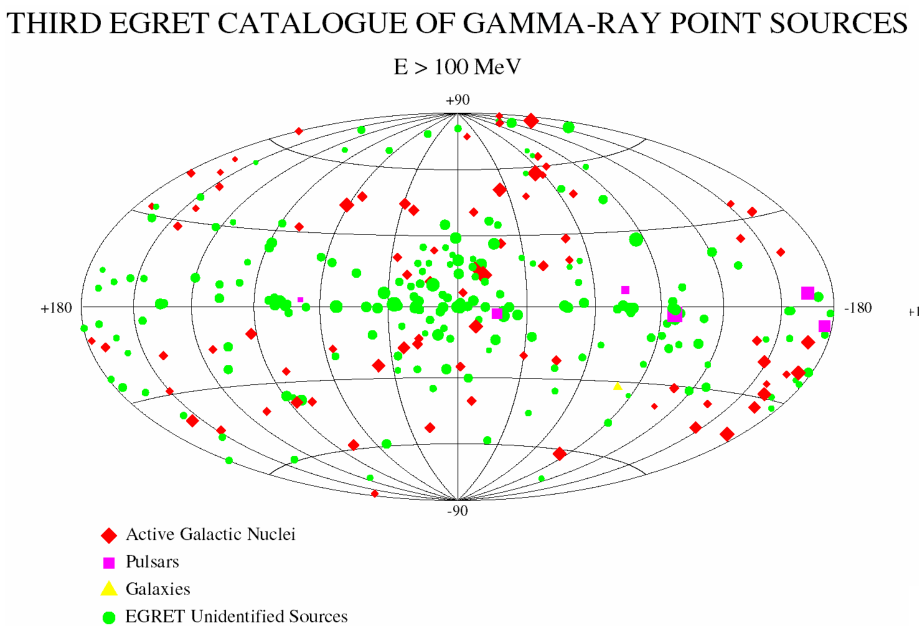
Unexplored Gap 30-300 GeV

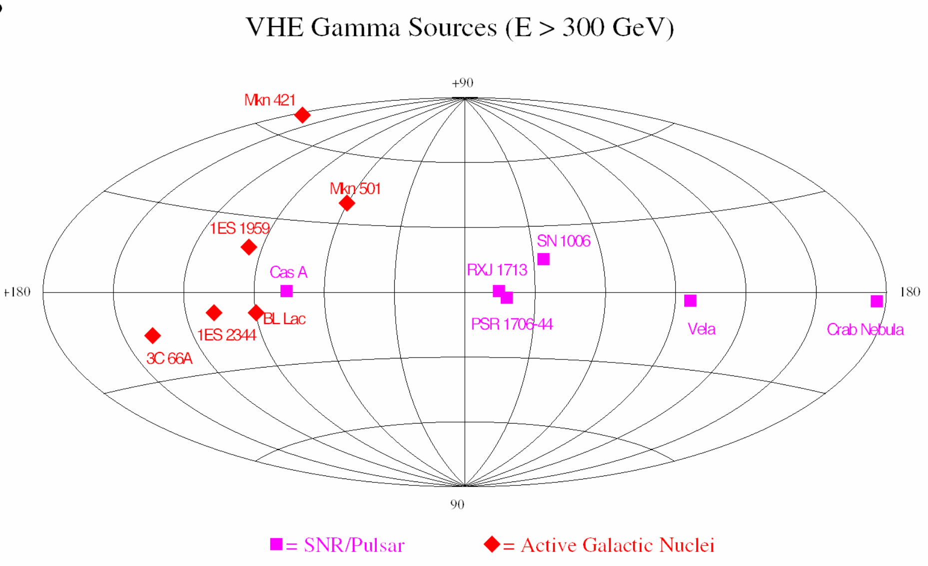




Detection

The unexplored spectrum gap





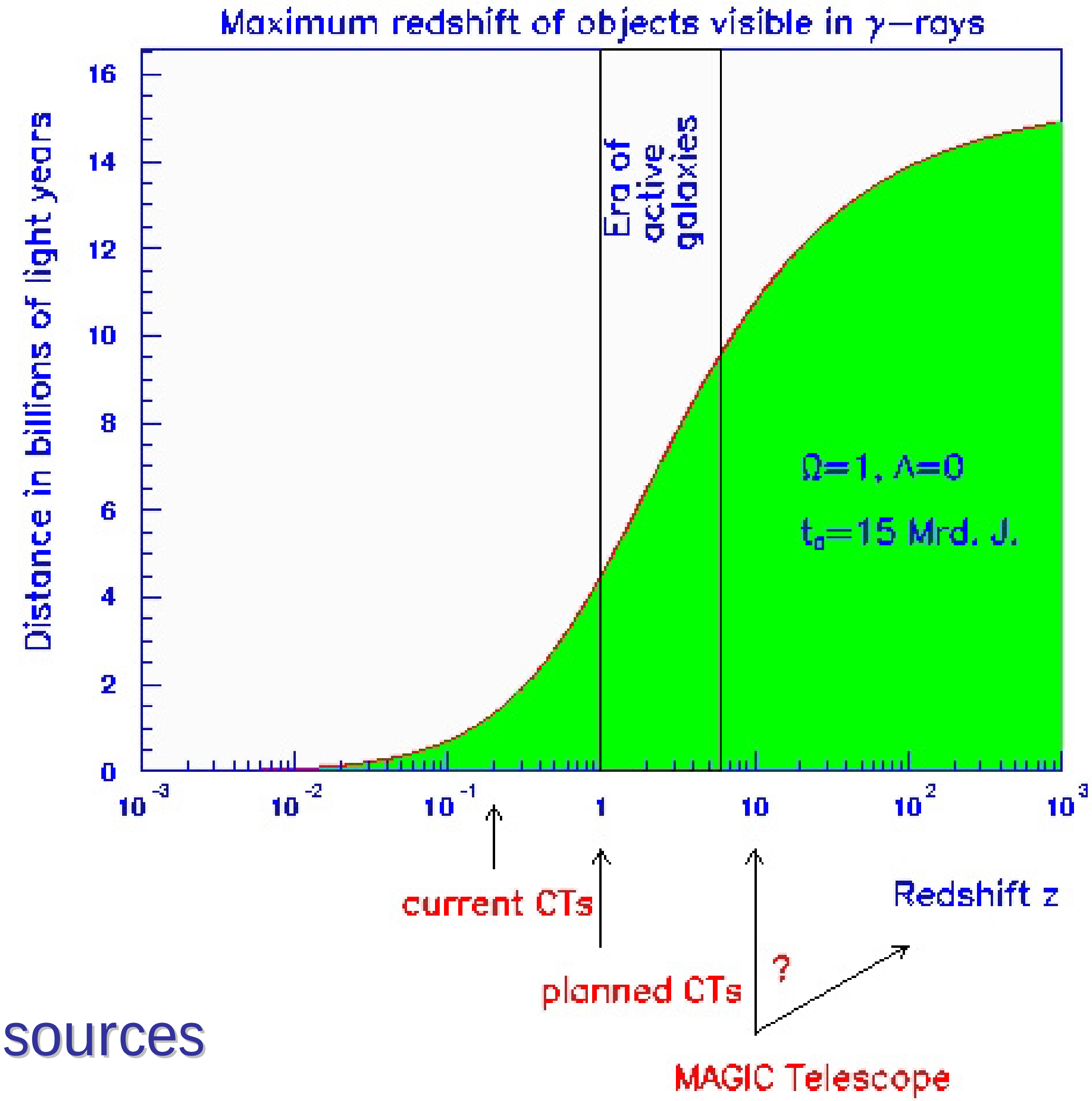
The cosmological γ-ray horizon

High energy γ-rays are absorbed in IR background.

$\gamma_{HE}\, \gamma_{IR} \rightarrow e^+ e^-$

Precisely in the "observation gap" the universe changes from opaque to transparent

A low threshold IACT shall see the bulk of the cosmological AGNs



Many new extragalactic sources could be discovered

Detection

NEXT SATELLITE:

GLAST mission

Improvement in one order of magnitude over EGRET

Launch 2007

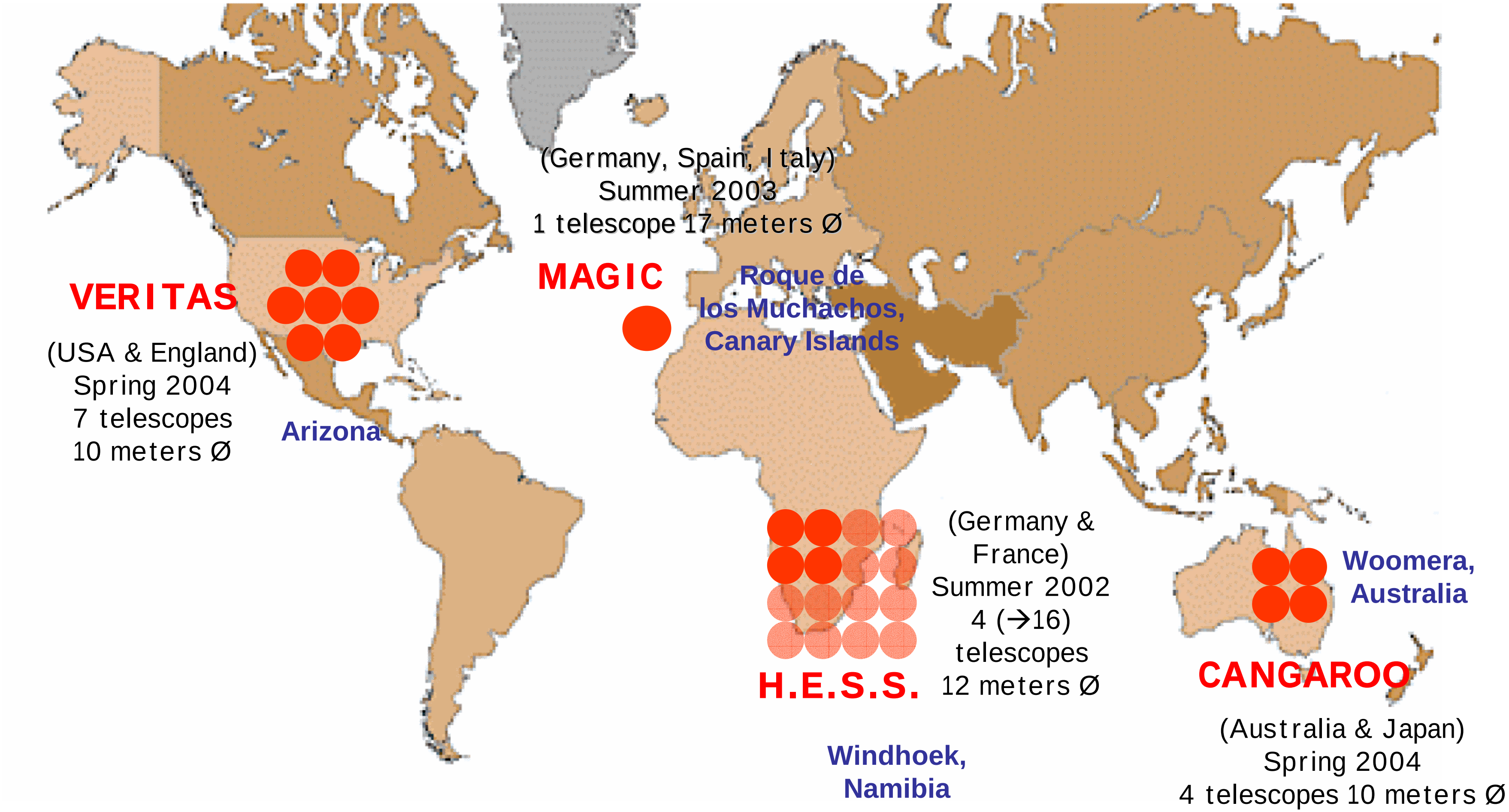
- All-sky survey
- Long-exposure

=> very good catalogue with thousands of sources

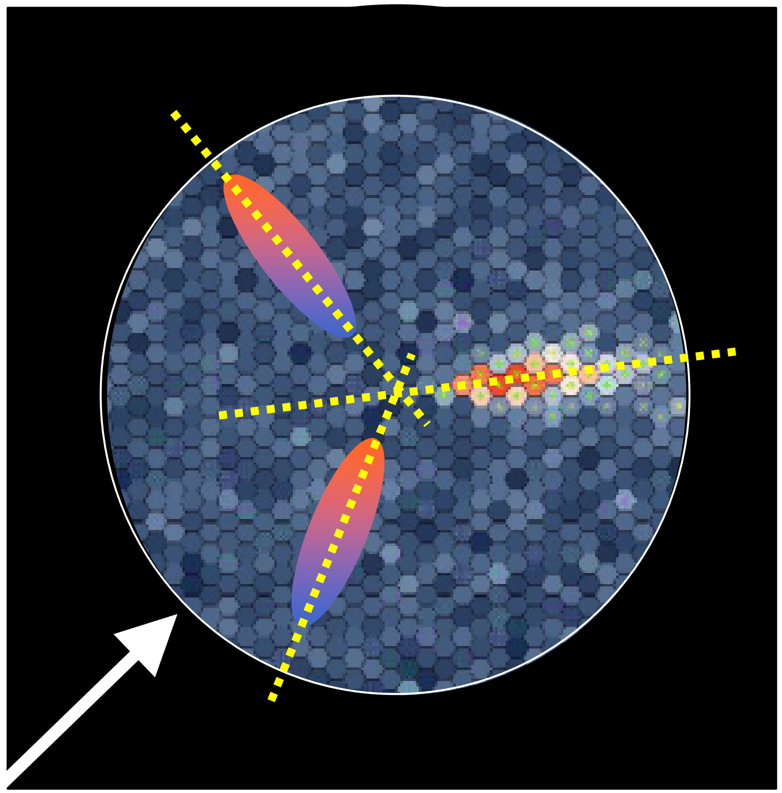
Credit: Hytec

Detection

The "Big" Four



Systems of Cherenkov telescopes and stereoscopy



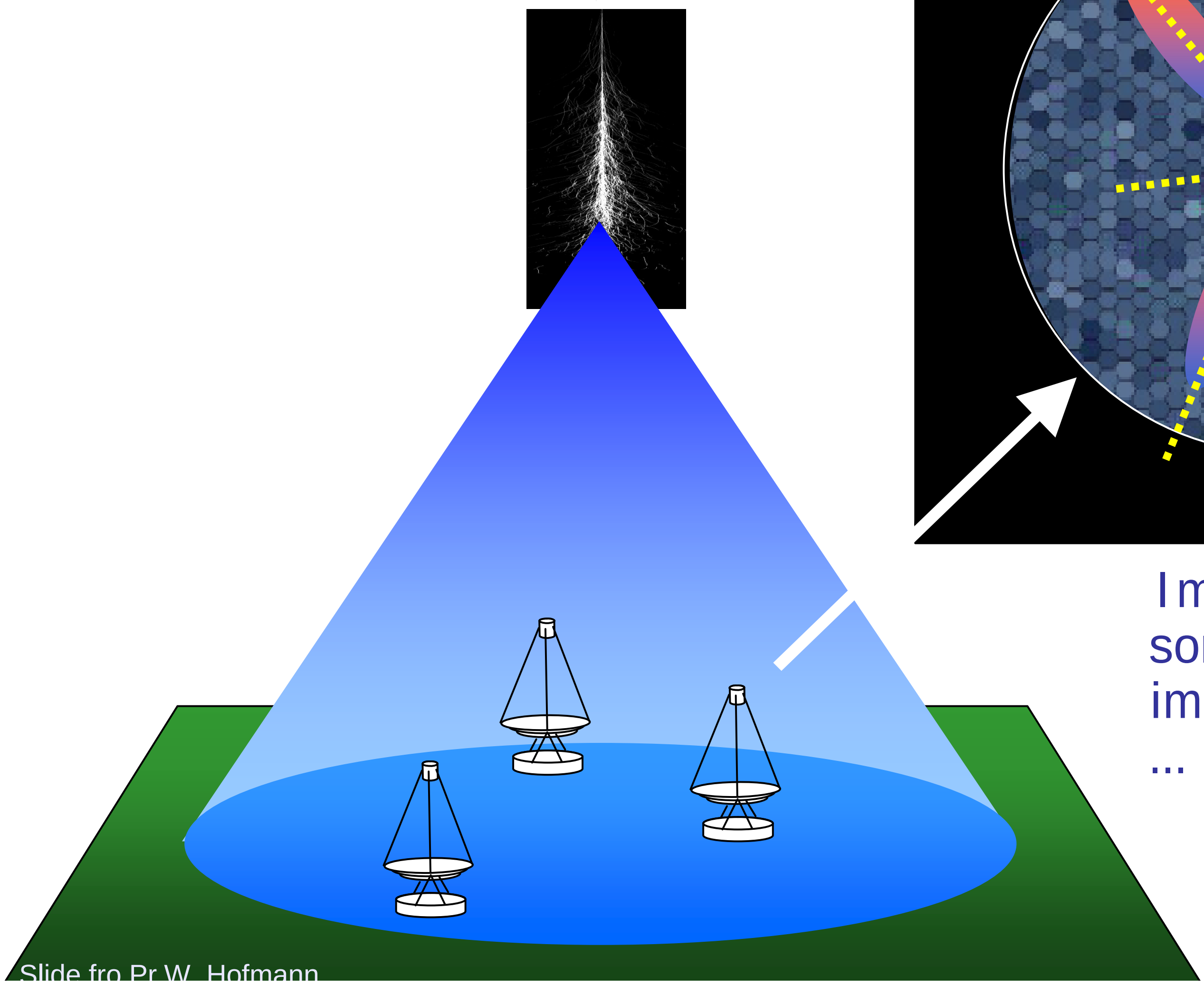


Image of source is somewere along image of shower axis ...

Use more views to locate source!

Detection: telescope array v.s. single large telescope

TELESCOPE ARRAY:

-Stereoscopic view at large energies:

=>Better energy resolution

⇒Better angular resolution

⇒Better background rejection

SINGLE LARGE TELESCOPE:

-No coincidence requirement:
=> Larger effective area

-Large light collection area:
=> Lower gamma energy threshold

MAGIC

Major Atmospheric Gamma Imaging Cherenkov Telescope

- Largest and more sensitive Cherenkov Telescope ever build.
- Design optimised for:

  - low threshold $E\gamma < 30$ GeV

  - fast repositioning $t_R < 30$ s.

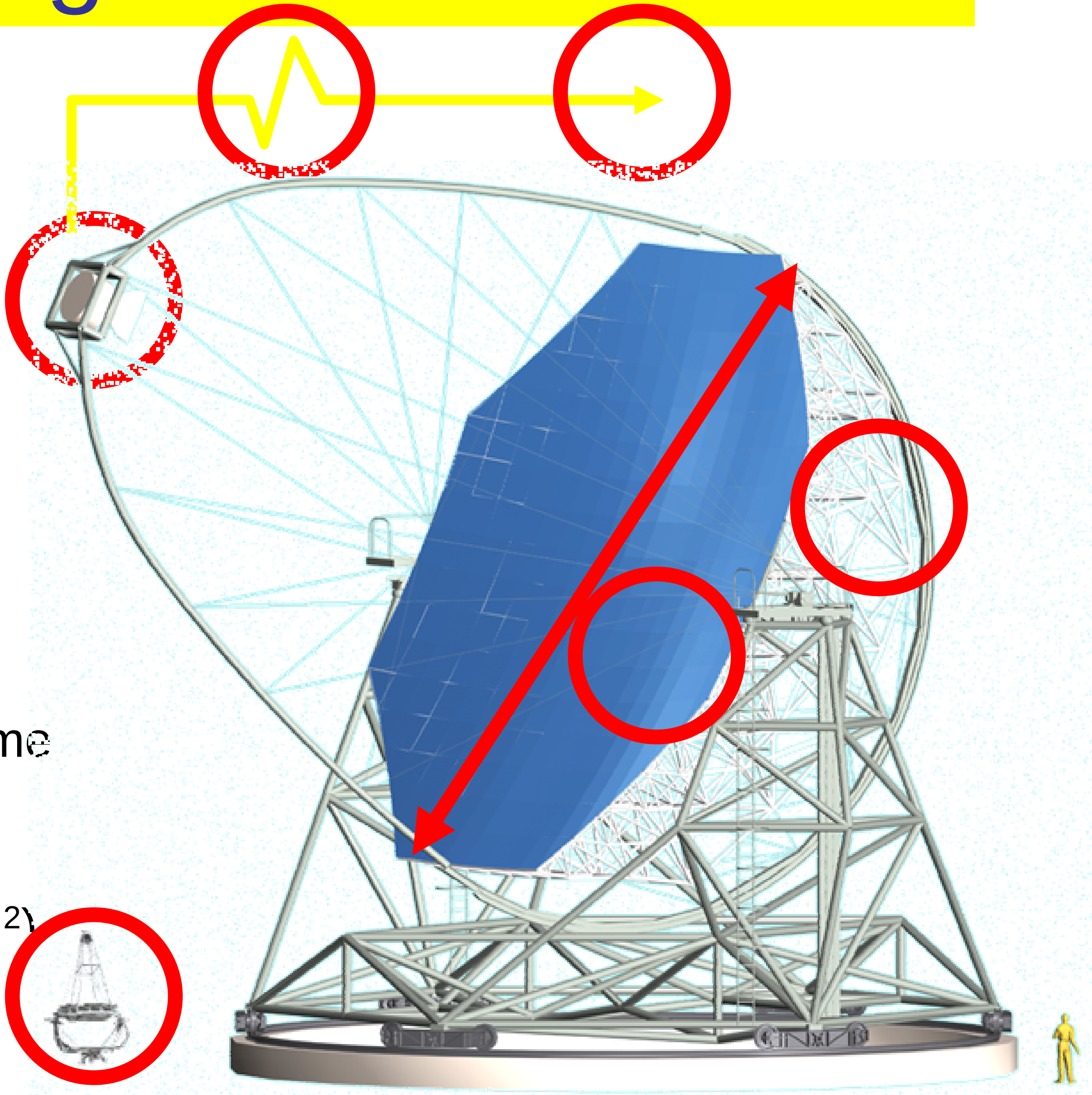
- Many new technological elements

Technological Innovations

- 577 pixels, enhanced QE PMT, 3.9 deg FOV camera
- Analog optical signal transport
- 2-level advanced trigger system
- Fast pulse sampling:

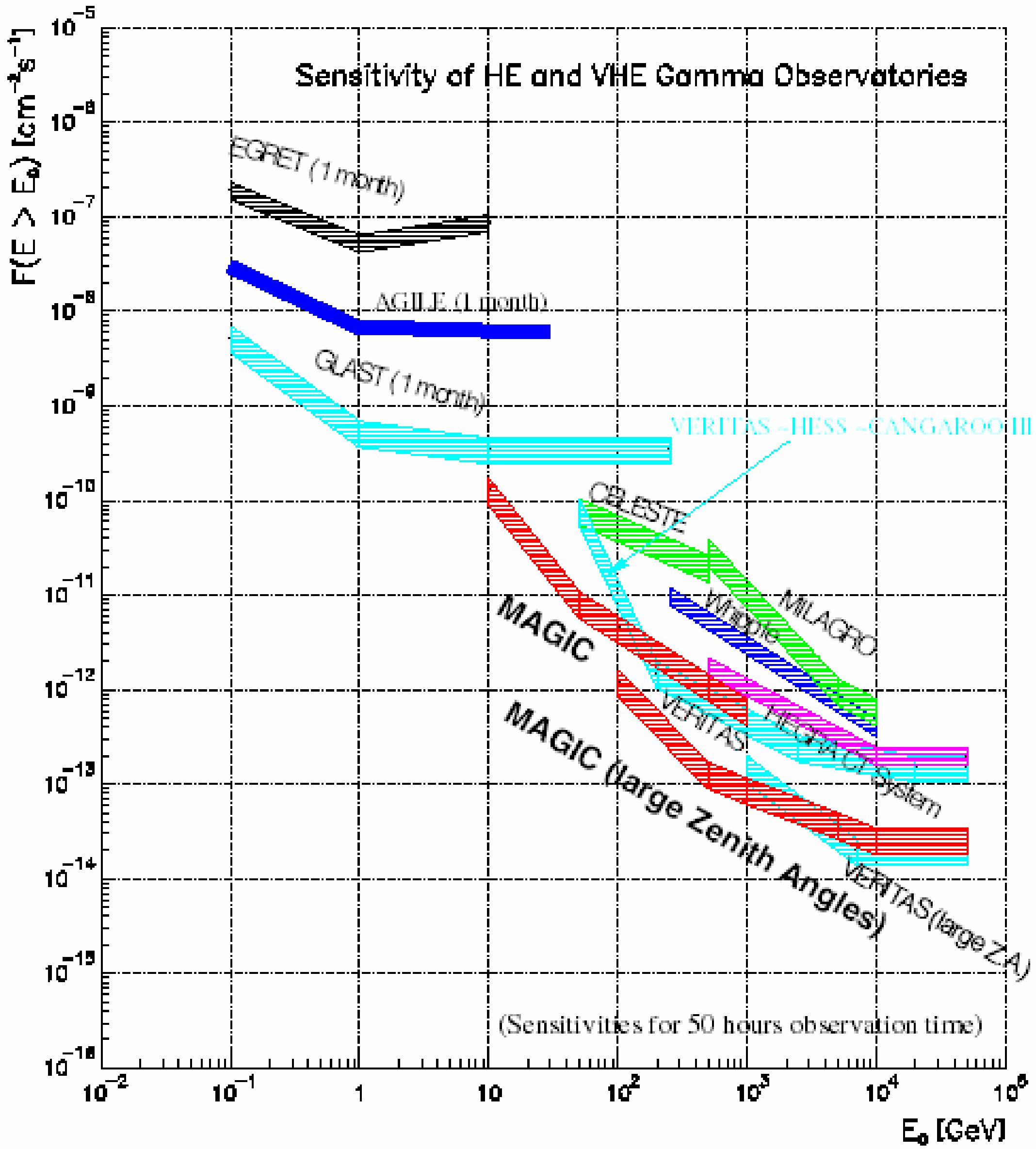
  300MHz-1GHz FADCs
- Ultra light carbon fibre frame
- 17 m diameter segmented

  aluminum reflector (240 m^2)
- Active mirror control
- LIDAR

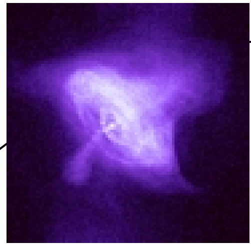


Expected Flux Sensitivities

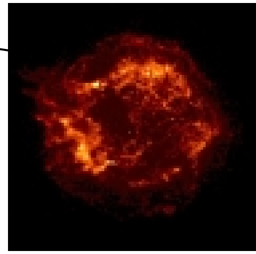
- New installations should close the observation gap.
- IACT technique will overlap with satellite detectors



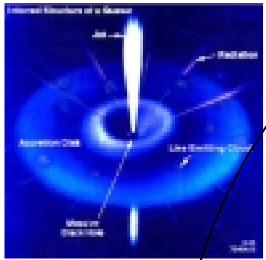
PHYSICS: SCIENTIFIC GOALS



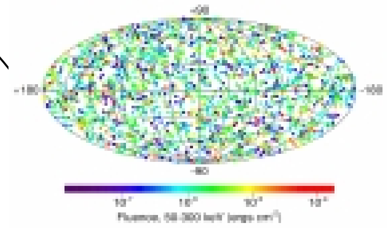
- Pulsars



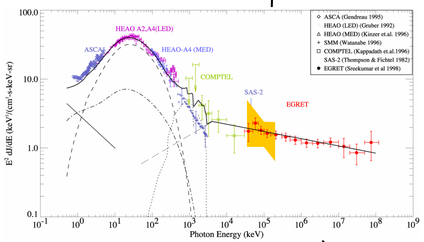
- SNRs



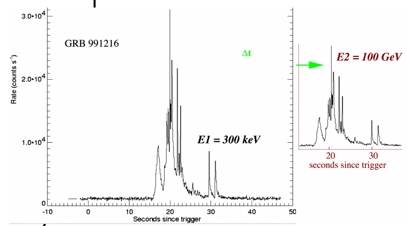
- AGNs



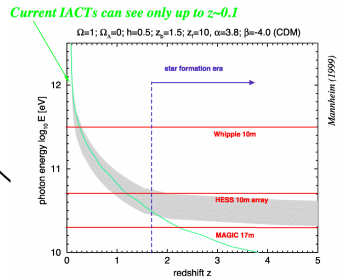
- GRBs



- Diffuse γ background



- Tests of Quantum Gravity



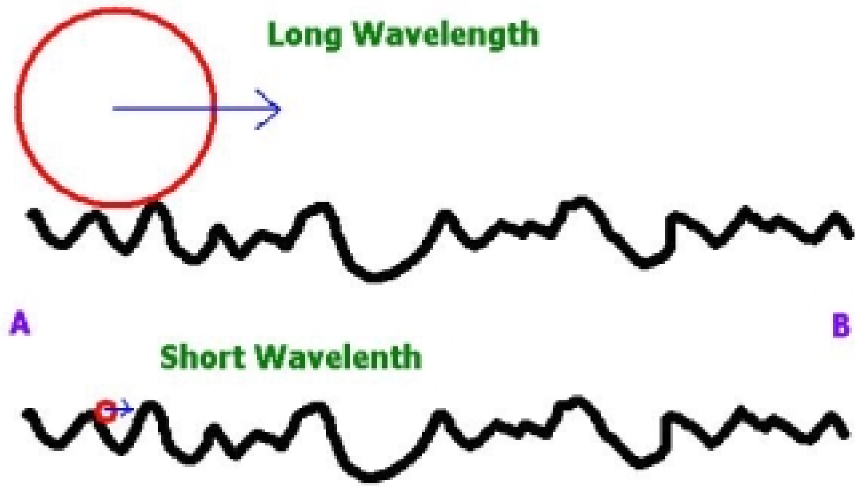
- Cosmological γ horizon

- Cold Dark matter

Tests of Quantum Gravity effects.

• Space-time at large distances is "smooth" but, if Gravity is a quantum theory, at very short distances it should show a very complex ("foamy") structure due to Quantum fluctuations.

• A consequence of these fluctuations is the fact that the speed of light in vacuum becomes energy dependent.



• The energy scale at which gravity is expected to behave as a quantum theory is the Planck Mass

$$E_{QG} = O(M_P) = O(10^{19})\ \mathrm{GeV}$$

Tests of Quantum Gravity effects.

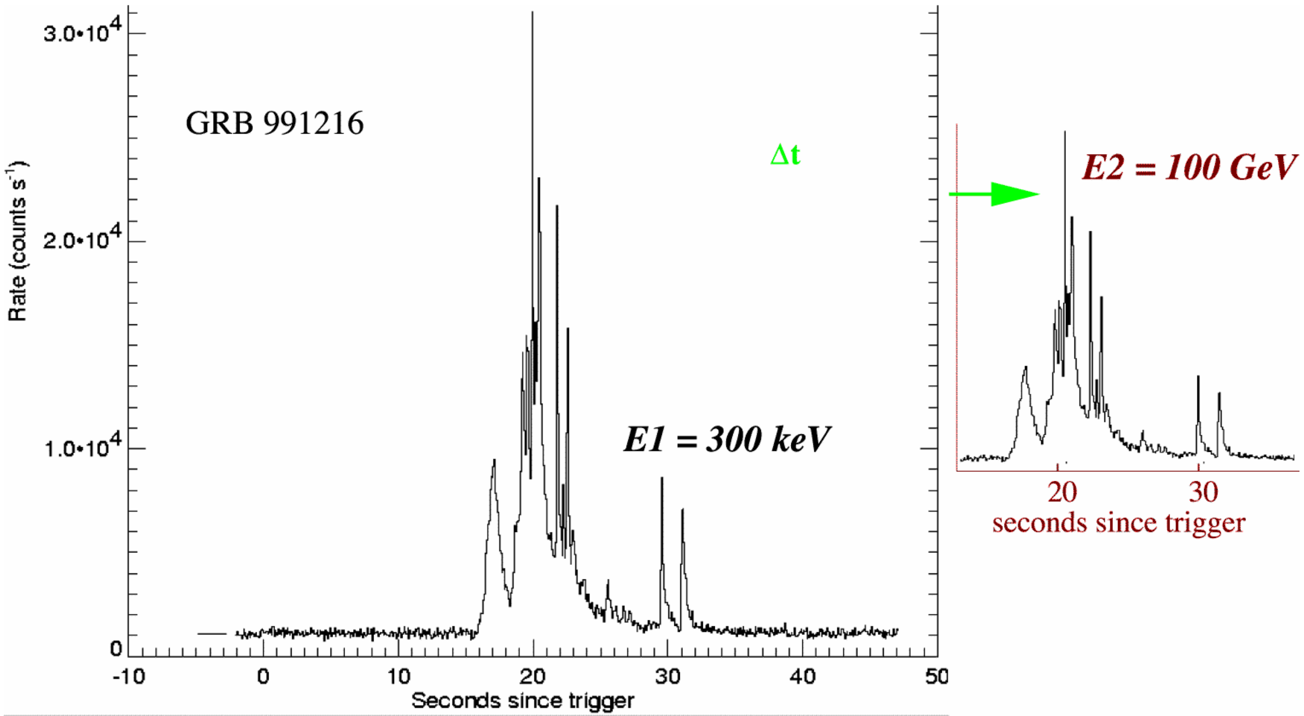
- From a phenomenological point of view, the effect can be studied with a perturbative expansion. In first order, the arrival delay of γ–rays emitted simultaneously from a distant source should be proportional to their energy difference 👎E and the path L to the source:

$$\Delta t \sim \frac{\Delta E}{E_{QG}} \frac{L}{c}$$

- The expected delay is very small and to make it measurable one needs to observe very high energy γ-rays coming from sources at cosmological distances.

- In addition one needs very fast transient fenomena providing a “time stamp” for the “simultaneous” emission of different energy γ –rays.

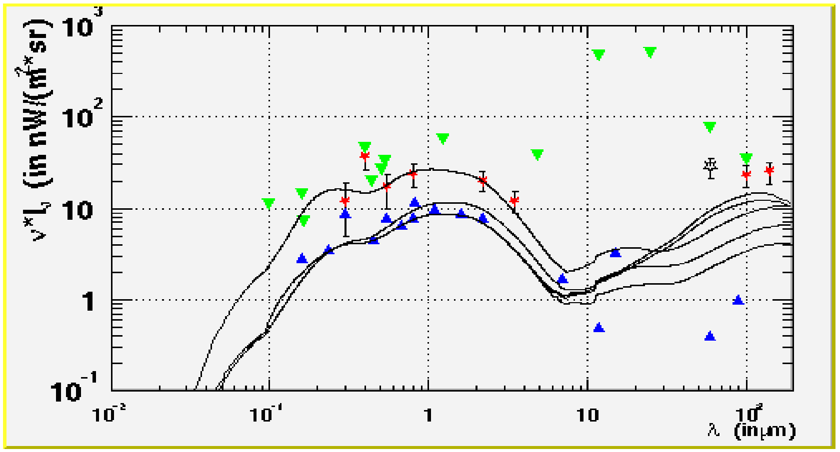
- Good source candidates are:
  - Very distant Blazars showing fast flares
  - Gamma-Ray-Bursts (GBR)



Cosmological GRH

High energy **γ-rays traversing cosmological distances** are expected to be absorbed through their interactions with the **EBL** by:

$$\gamma_{HE}\,\gamma_{IR} \longrightarrow e^{+}e^{-}$$

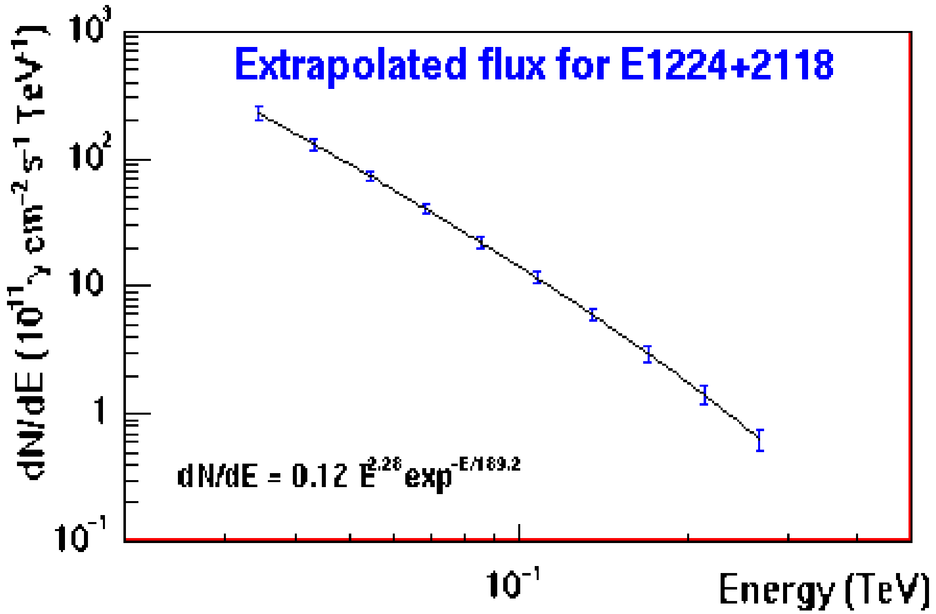


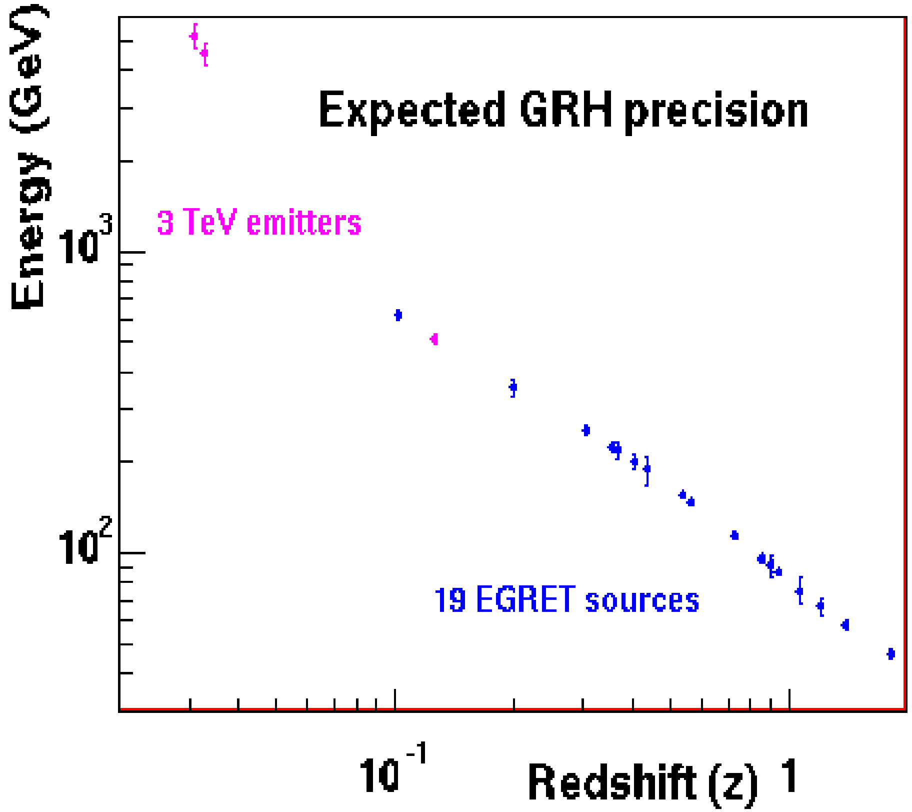
$$\Phi = \Phi_0 \cdot e^{-\tau(E,z)}$$

$\tau(E,z) = 1$ =>
Gamma Ray Horizon (GRH).

GRH Measurement expectation

Extrapolate HEGRA and EGRET AGNs to the **MAGIC energies**.



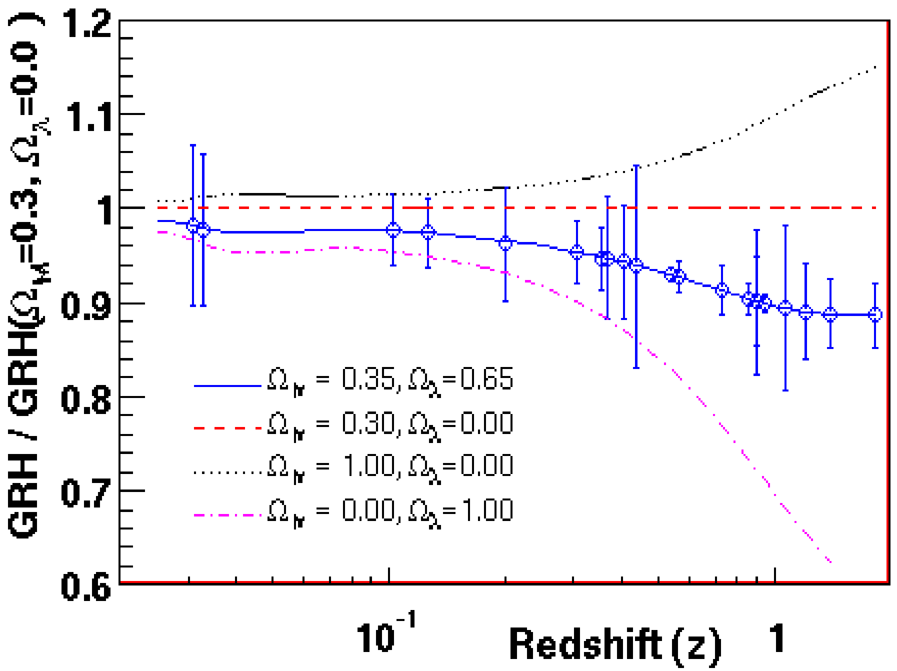


Expectations for **50 hours observation**

Cosmological Parameters

GRH => distance estimator based on the absorption over the gamma-ray path => cosmological parameters

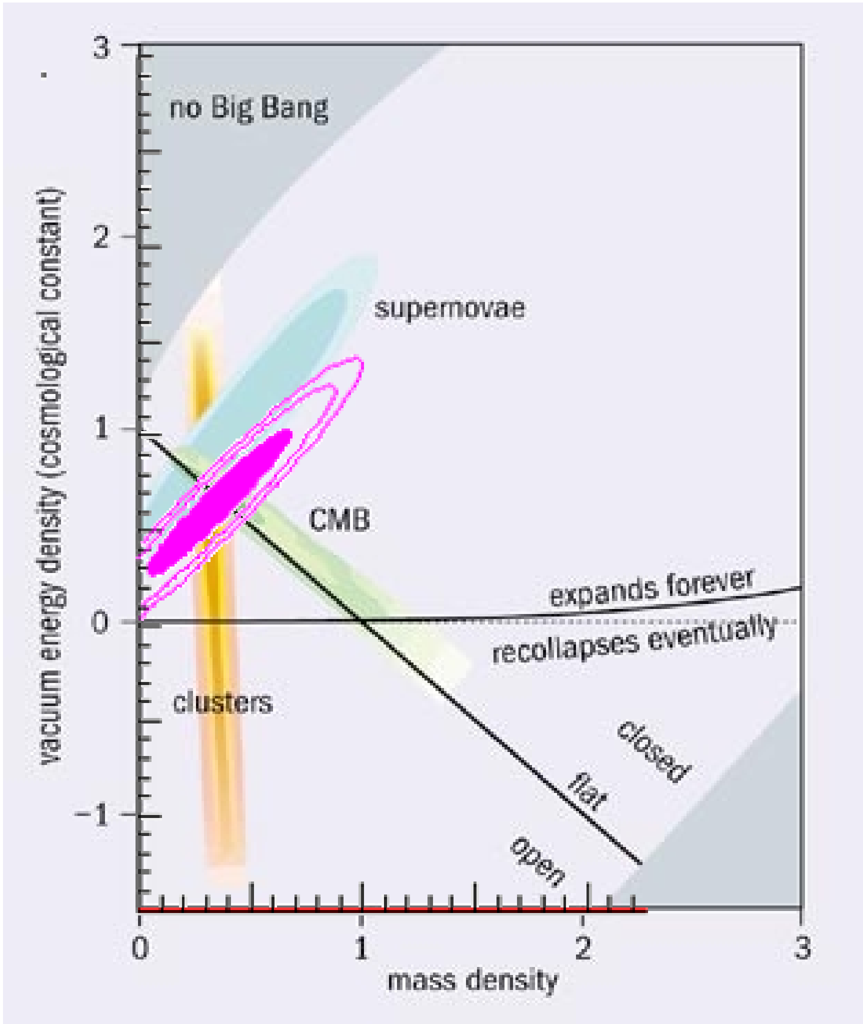
$$\frac{dl}{dz} = c \cdot \frac{1/(1+z)}{H_0 \left[\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\lambda\right]^{1/2}}$$



Determination of H_0, Ω_M and Ω_λ

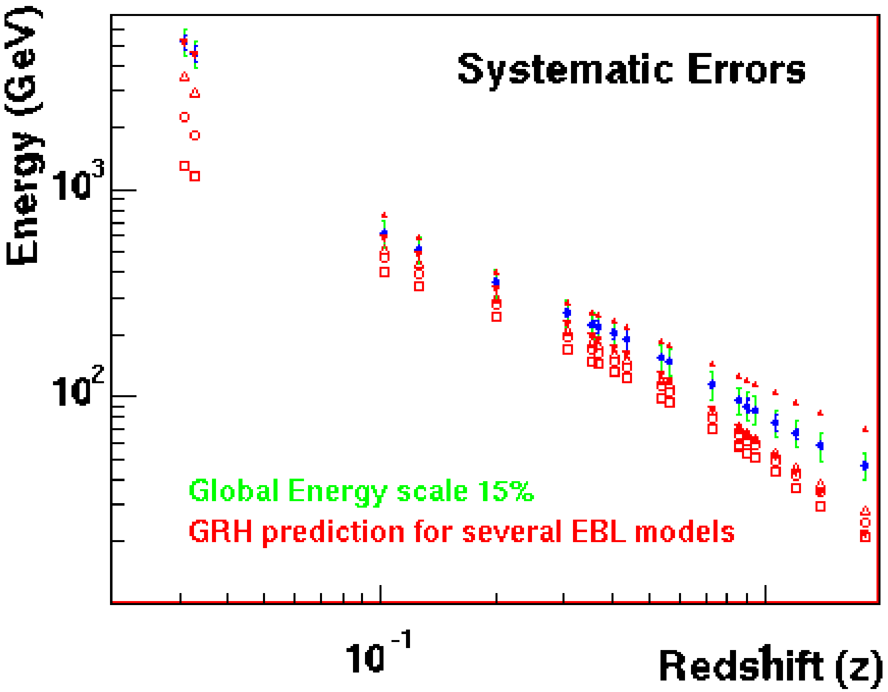
$$H_0 = 68.5 + 1.6 - 1.6\, km/s\, Mpc$$
$$\Omega_M = 0.35 + 0.21 - 0.20$$
$$\Omega_\lambda = 0.65 + 0.24 - 0.25$$

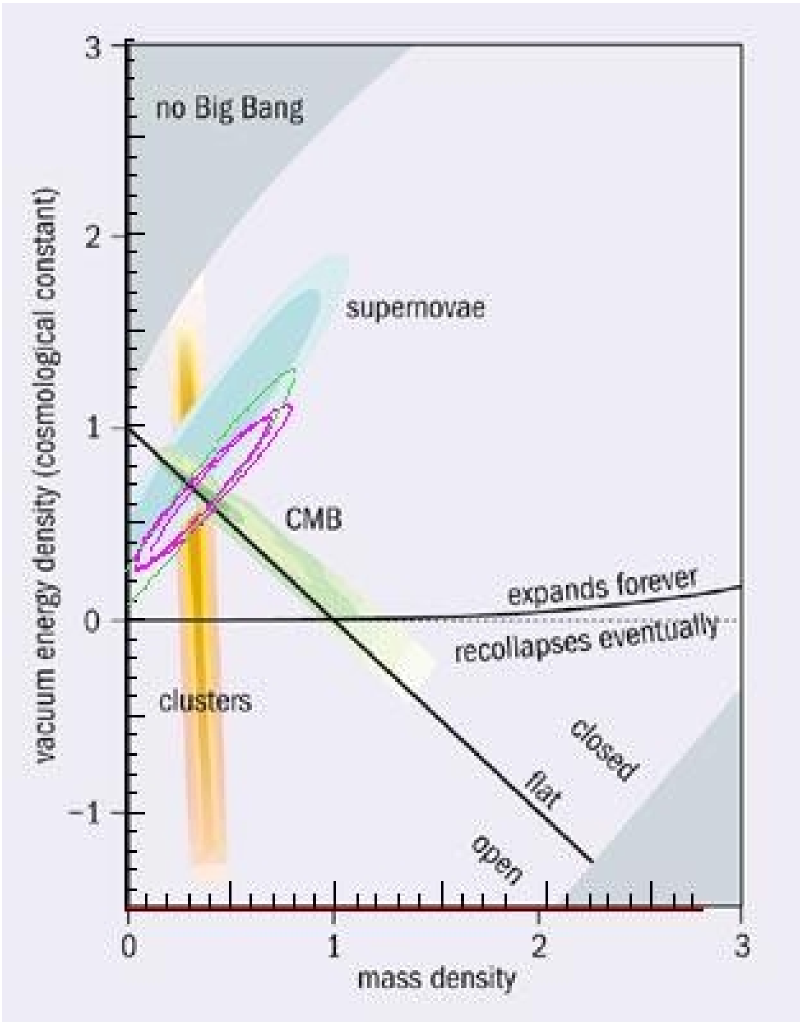
MINOS



=> The expected results improve by over a factor 2 the present Supernovae combined result !

Systematic Error Estimation





Measurement of Cosmological Parameters:

- A low-threshold telescope such as MAGIC shall be able to **measure the GRH** for sources in a large redshift range at a **few %** level.

- GRH => determination of COSMOLOGICAL PARAMETERS:

  - **independent on the current ones**

  - not rely on the existence of "standard universal candles"

  - **complementary to the Supernovae 1a** because it explores a different univers expansion epoch: uses AGN as sources **(medium to high redshift)**

- **Relevant constraints** on the cosmological densities for an amount of sources that could be observed during the **first and second years** of MAGIC operation.

Cold Dark Matter search

- *Observational cosmology* => more than 25% of universe's
- is non-barionic Dark Matter.

Understanding its nature is a big challenge for

FUNDAMENTAL PHYSICS

- In Standard Cosmology Cold Dark Matter is favoured

  ⇒Weakly Interacting Massive Particles (WIMPs)

  ⇒ No good candidate within the Standard Model

- Most plausible candidates for WIMPS-neutralinos χ

- Particle physics lower limit for $m\chi$>60-100 GeV

Neutralino annihilation signatures

- Indirect detection through annihilation into γ :

$\chi\chi \to \gamma\gamma$ (one loop)

=> line at $E\gamma = M\chi$

-> clean signature at high gamma energies but low flux

$\chi\chi \to \gamma$ **Z** (one-loop)

=> line at $E\gamma = M\chi - M_Z^2/(4 M\chi)$

-> clean signature at high gamma energies but low flux

$\chi\chi$ -> q bar(q) -> **jets** -> n γ (tree level)

=> continuum of "low-energy" gammas from cascade decays

-> difficult signature but large flux at low gamma energies

- Key issue within CMSSM: χ composition fraction:
  - higgsino-like -> important γ-line cross sections
  - gaugino-like -> low γ-line cross section

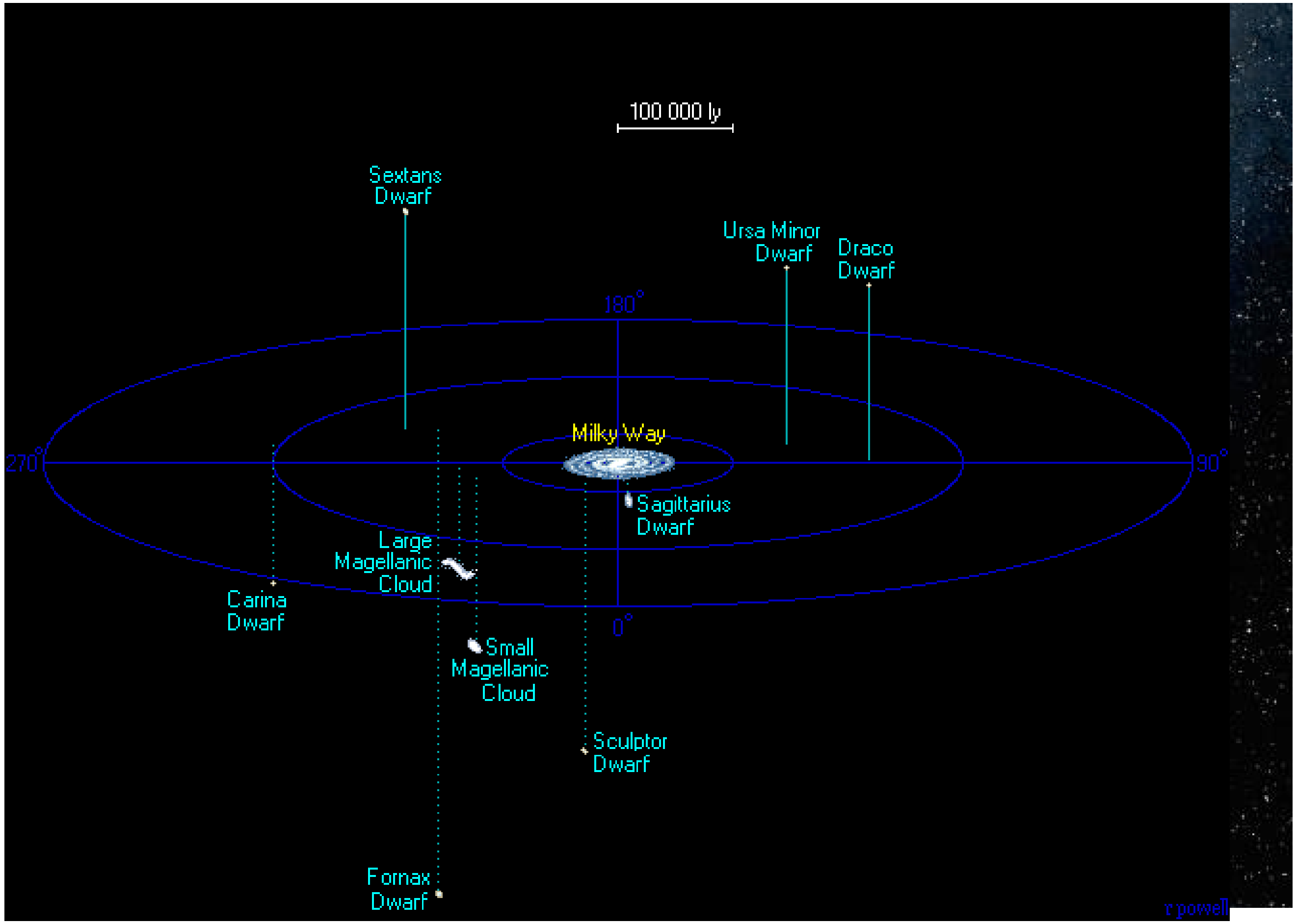
Where to look for Cold Dark Matter in our neibourghood ?

Neutralinos would constitute the galactic halo and would concentrate at

- the galaxy center

- visible satellites

- invisible satellites.



Cold dark matter

- Best signature: annihilation line in the center of our Galaxy:

  $\chi\chi \rightarrow \gamma\gamma$

=> good target for IACTs in the southern hemisphere

(huge collection area at La Palma - ZA= 70^0!

but

higher threshold E>300 GeV)

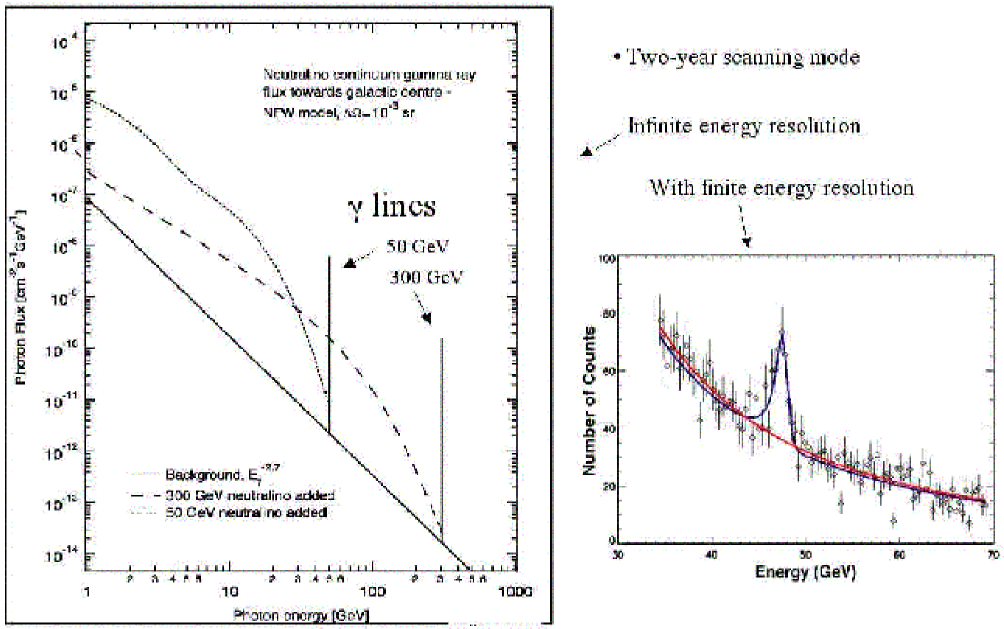
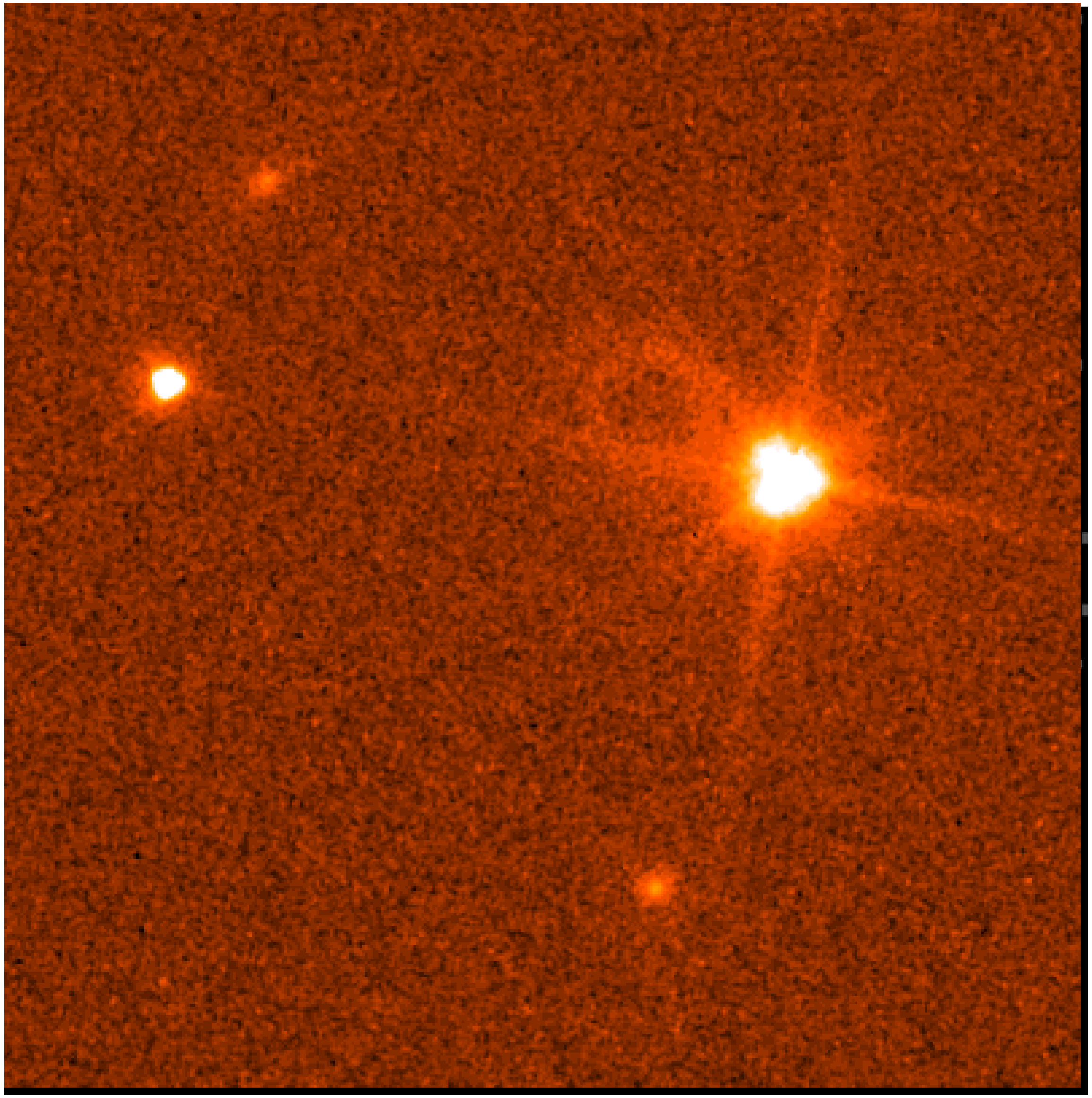
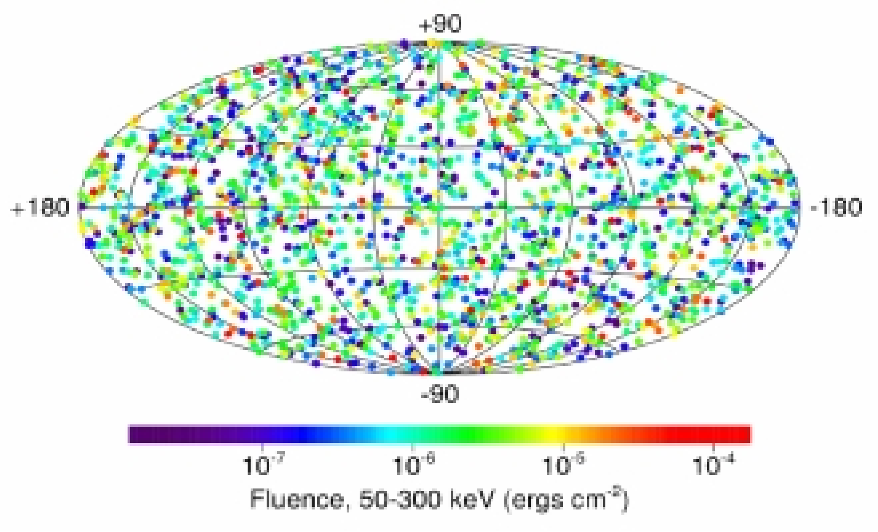


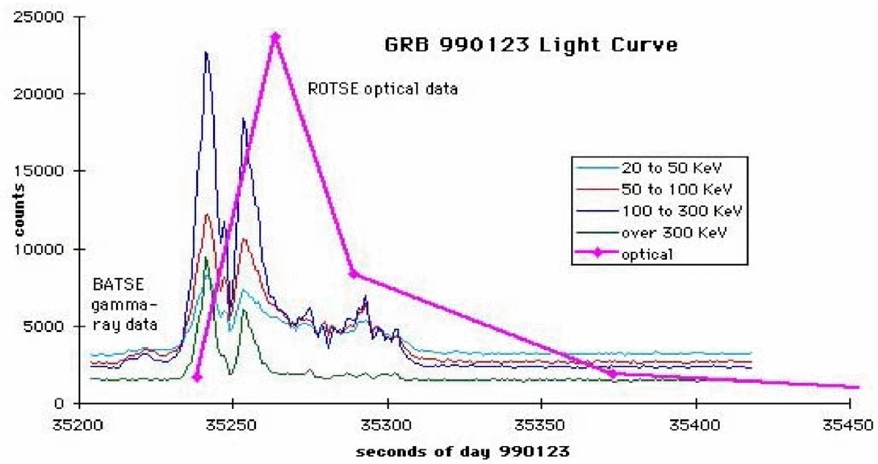
Figure 10: *Total photon spectrum from the galactic center from $\chi\chi$ annihilation (on the left), and number of photons expected in GLAST for $\chi\chi \rightarrow \gamma\gamma$ from a 1-sr cone near the galactic center with a 1.5 % energy resolution (on the right)*

Gamma Ray Bursts

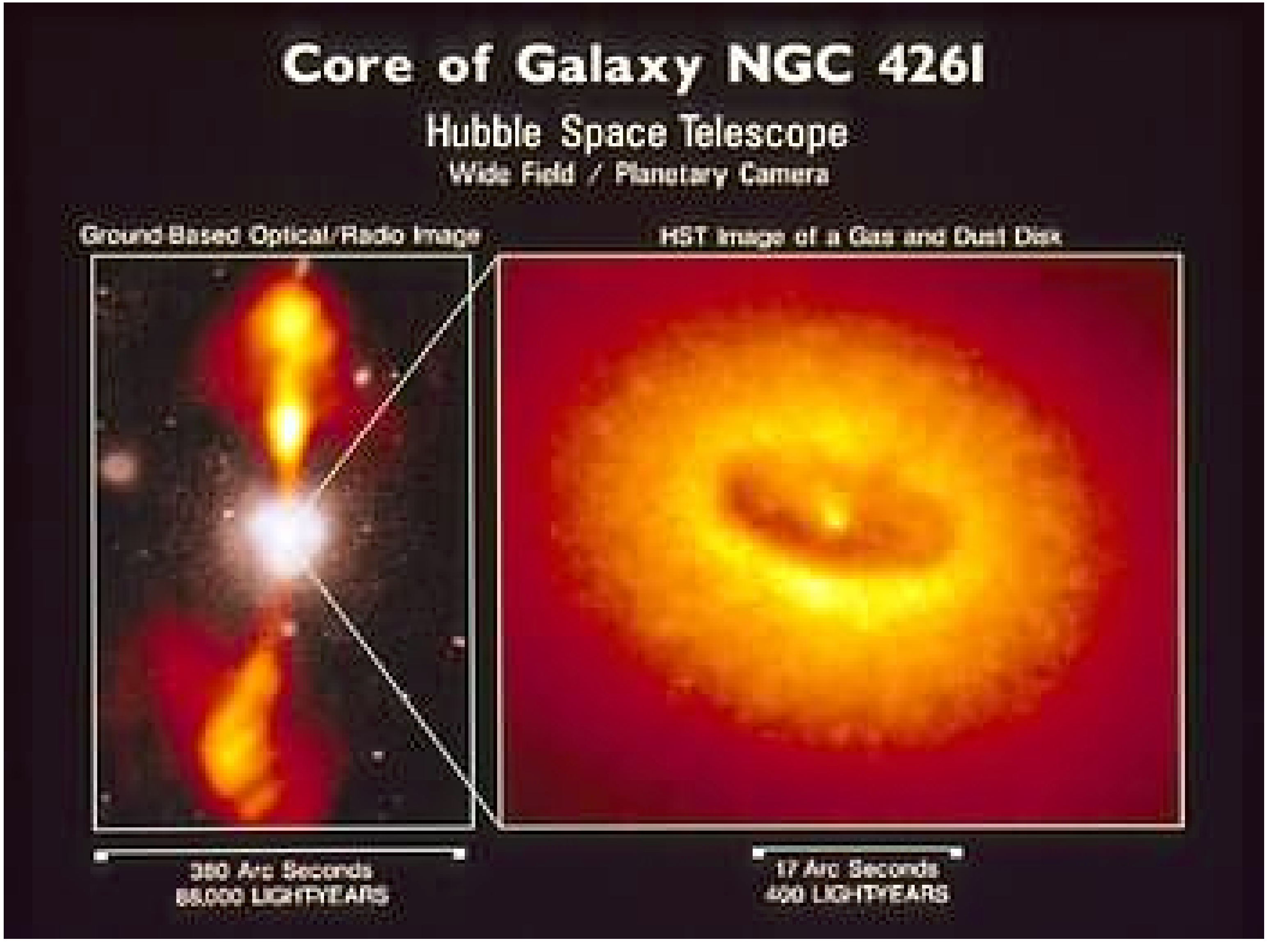


- Cosmological origin
- Lots of data at lower energies
- Mechanism not yet fully resolved.
- MAGIC take advantage:
  - Huge collection area
  - Low threshold
  - Fast repositioning.

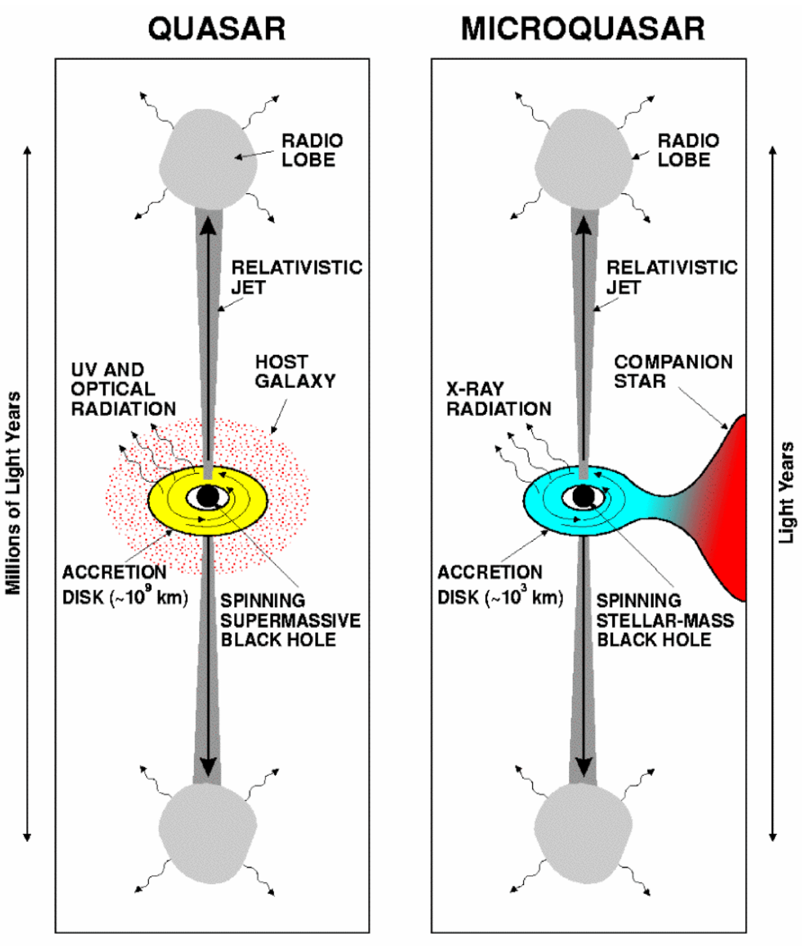


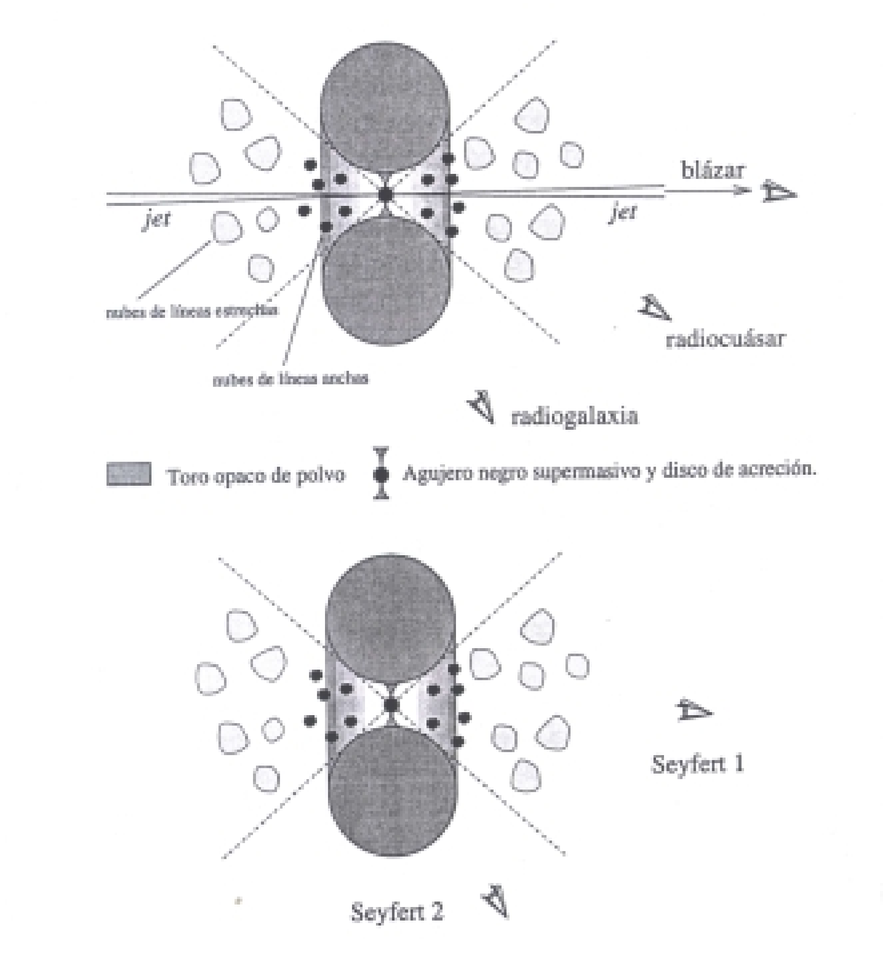


Active Galactic Nuclei



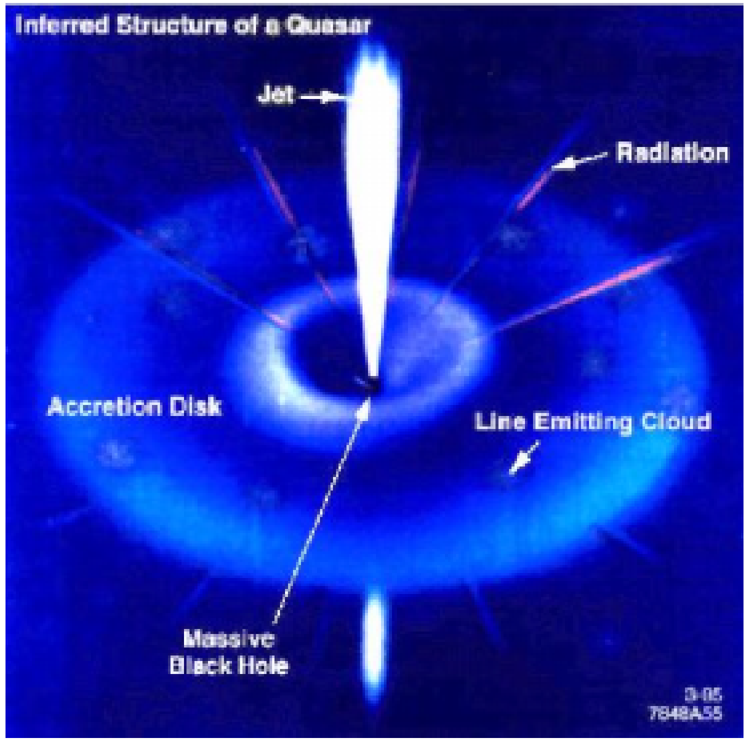
Active Galactic Nuclei

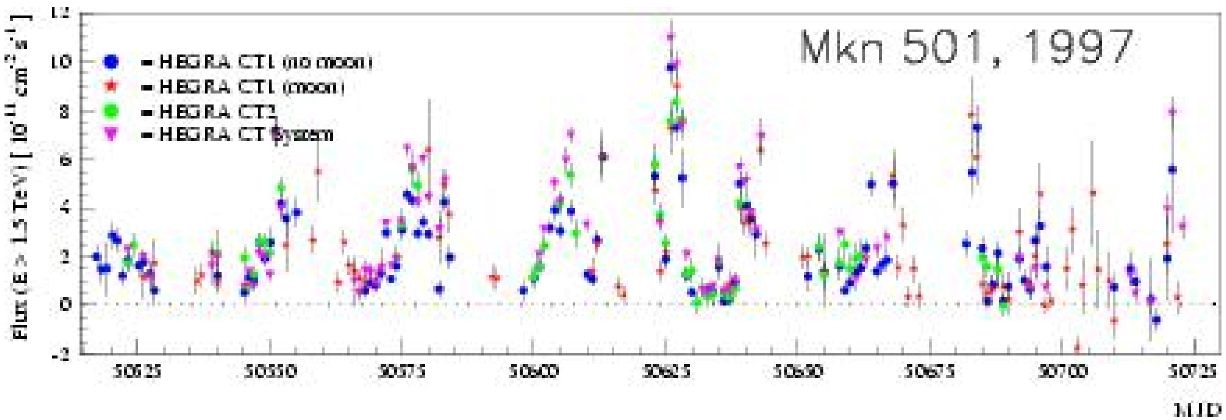




Active Galactic Nuclei

- Highest variability in X-ray and γ rays
- Closest to supermassive BH at Very High Energies



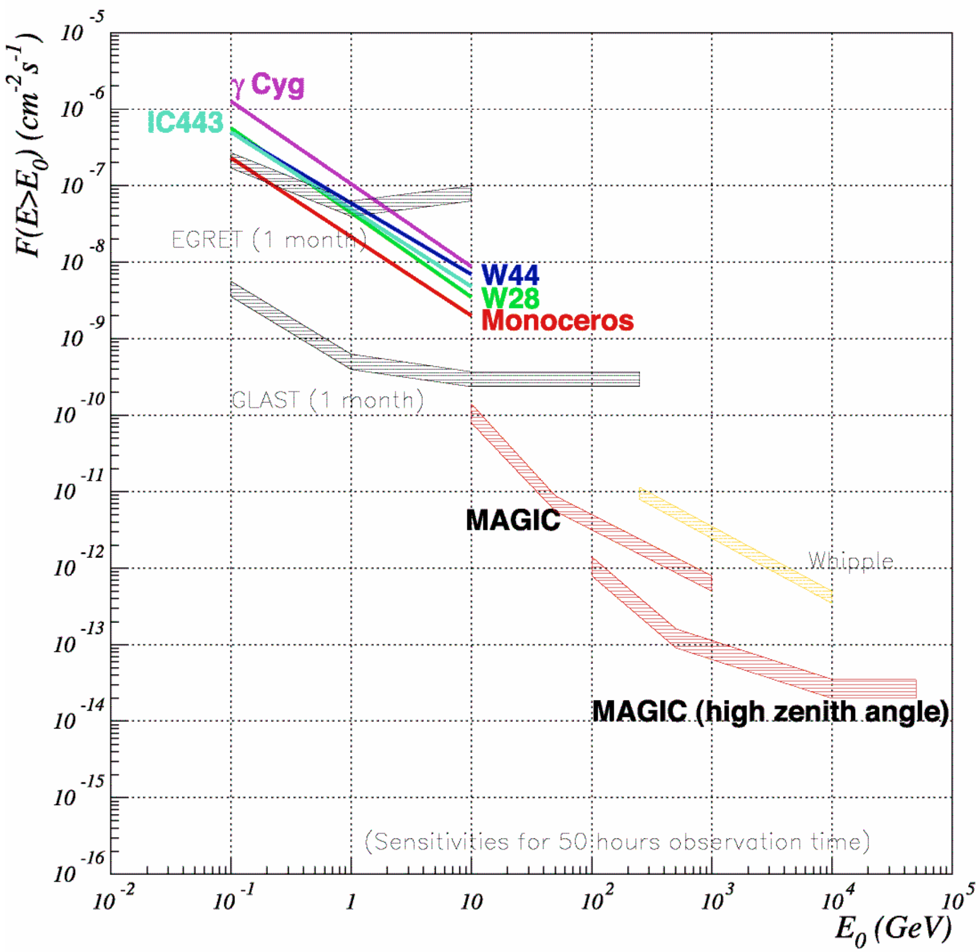


The origin of CRs. Shell-type SNRs

- Widely believed CRs produced in SRN blast shocks. X-rays & γ-rays are essential probes.
- Good evidence of electron acceleration
  - Syncroton X-rays
  - Inverse Compton in SN-1006
- No evidence of hadron acceleration yet

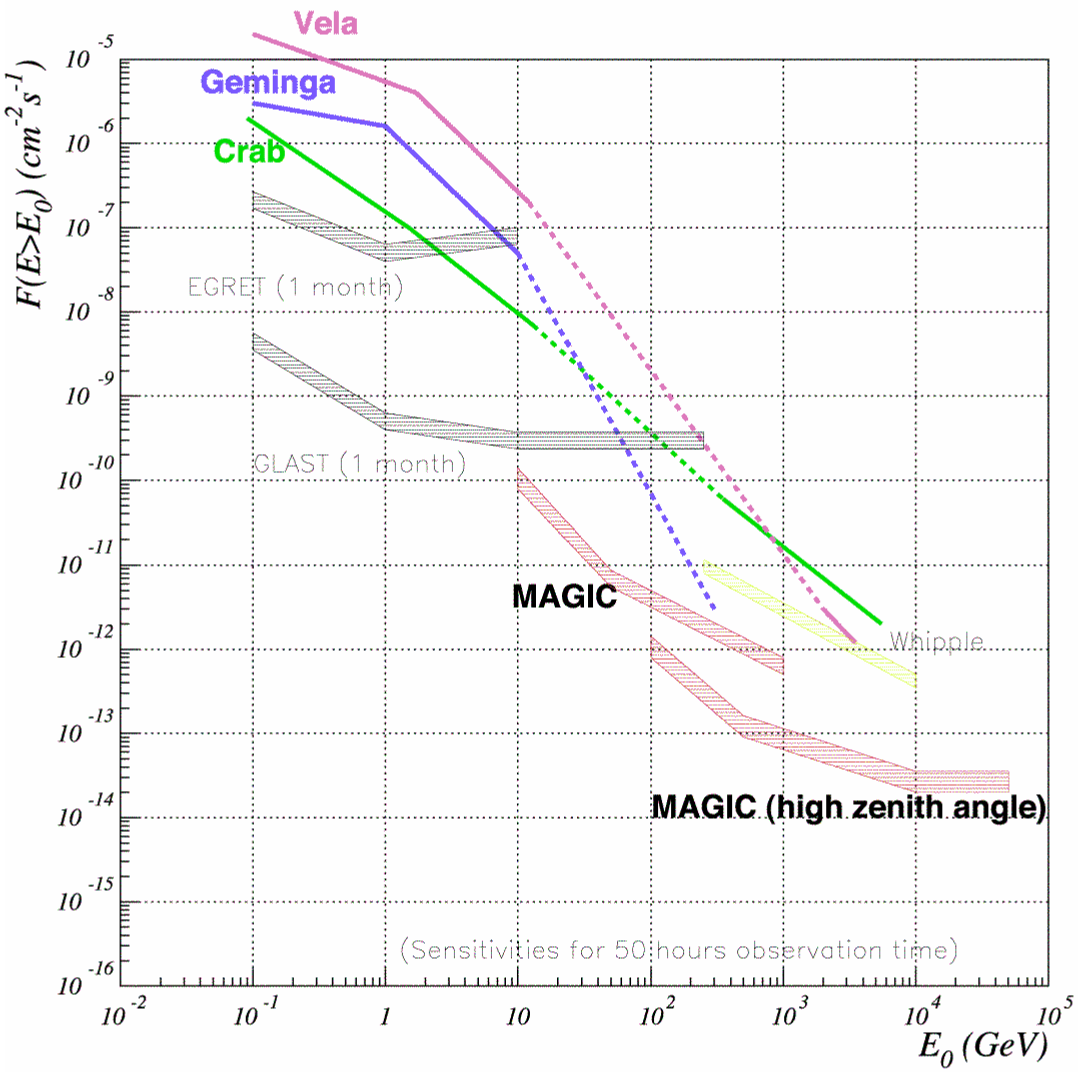
$$P,Fe+N \rightarrow \pi\text{'s} \quad \text{and} \quad \pi^0 \rightarrow \gamma\gamma$$

- **Look for π^0 emission coincident with dense clouds**



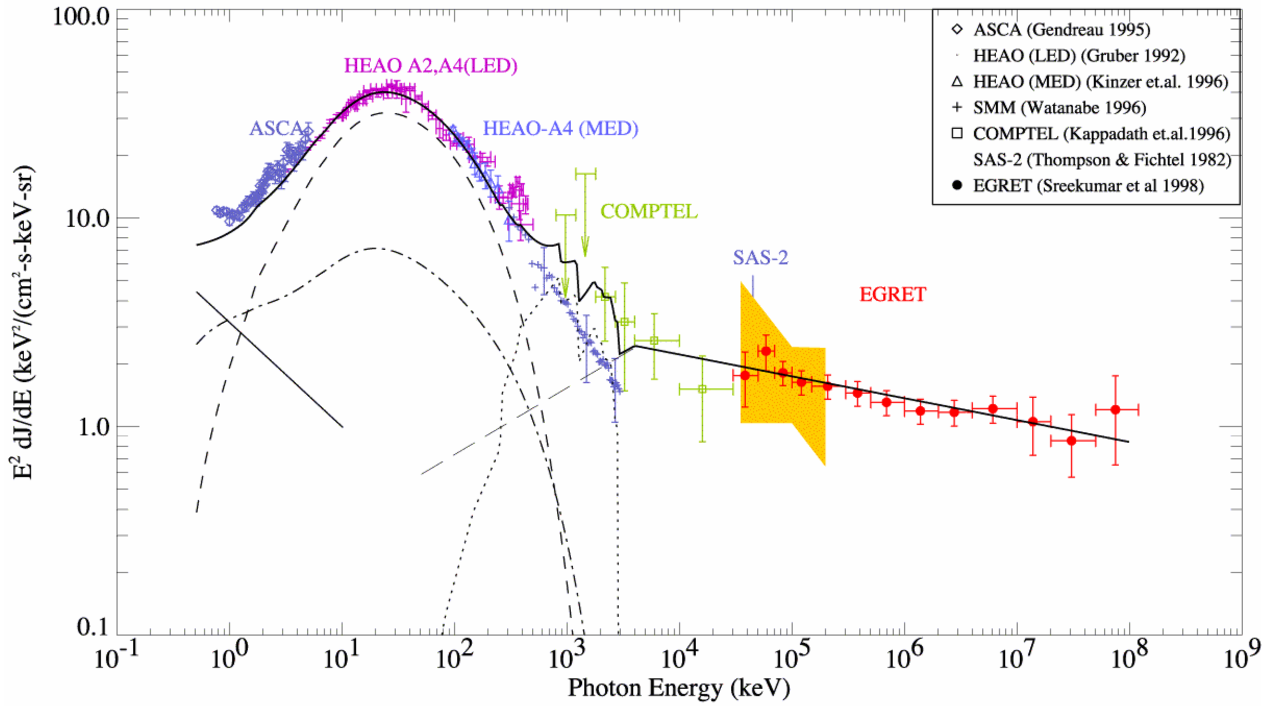
Pulsars

- 7 γ-ray pulsars seen by EGRET. Many of the ~170 EGRET unindentified sources may be pulsars. We can tell through the pulse emission.
- None by CT's ⇒ spectral cutoff
- Where do γ-rays come from? Outer gap or polar cap?



The diffuse extragalatic γ-ray background

- EGRET has measured background up to 100 GeV. General opinion: Due to AGNs?
- BUT Chiang and Mukherjee have shown AGNs only contribute 25% above 100 MeV
- **Where does the remaining background come from?**



Outlook

- VHE cosmic gamma ray physics consolidating as a new research field in the frontier of High Energy Astrophysics and Particle Physics.
- Many new installations starting or in progress for the near future.
- Hundreds of new sources expected to be discovered => High Energy Gamma-Ray Astronomy.
- There is a broad and exciting program of High Energy Astrophysics and Fundamental Physics studies just around the corner…