VHE Gamma Ray Astronomy : A tool to study Very High Energy Universe

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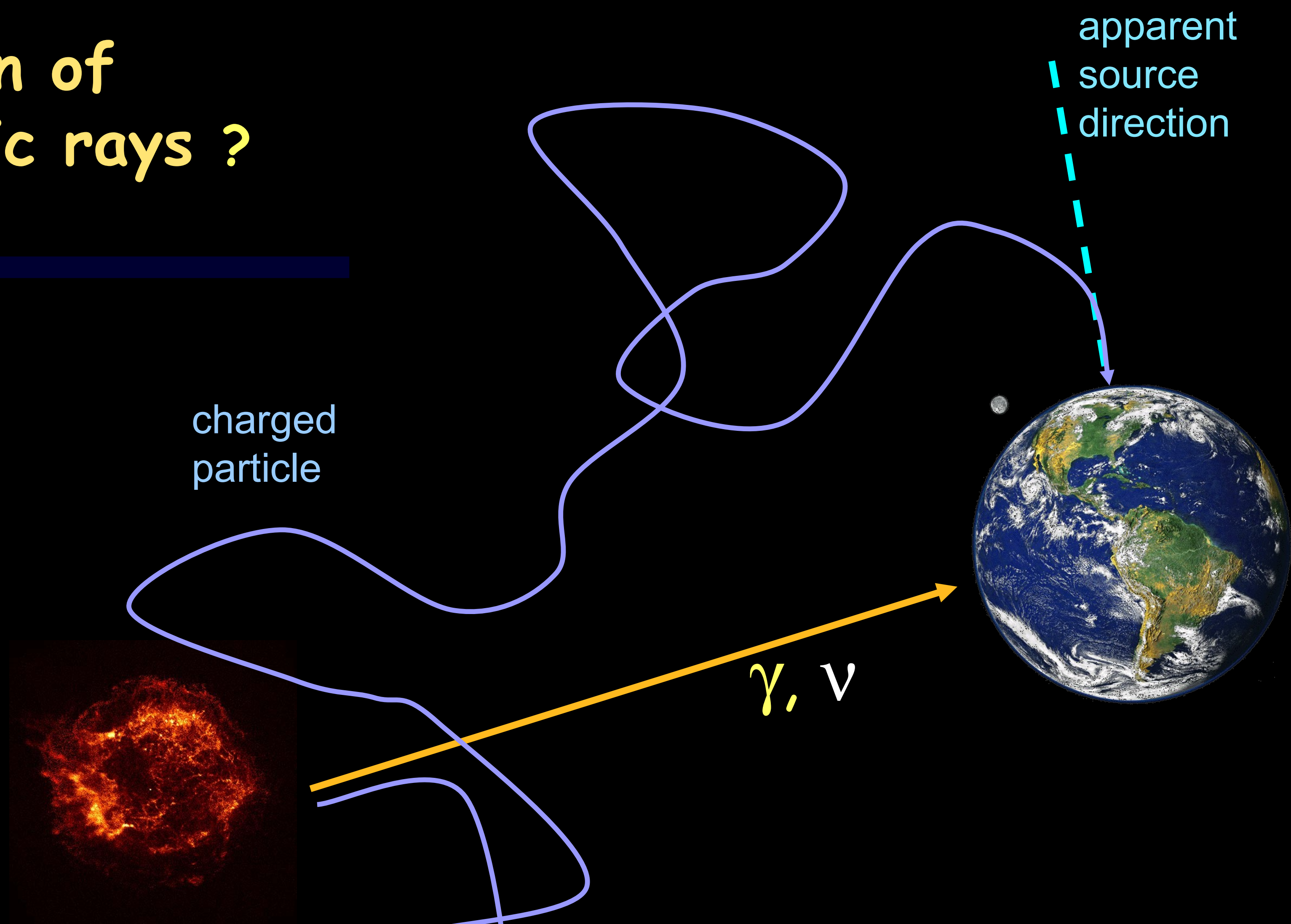
Outline:

- VHE Gamma Ray Astrophysics
- Atmospheric Cerenkov Techniques
- Connecting TeV gamma rays with Cosmology
- Indirect Dark Matter detection
- Tests of Violation of Lorentz Invariance
- Conclusions and Future directions

27th IARGRG, H.N.B. (Garhwal) University, March, 2013

Origin of cosmic rays ?



nucleus + X -> π + X'

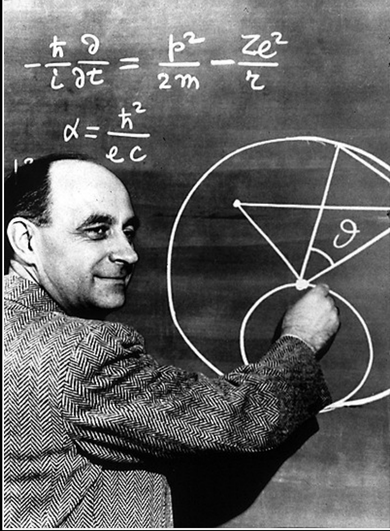
$\pi^0 \rightarrow \gamma\gamma$

$\pi^\pm \rightarrow \mu + \nu$

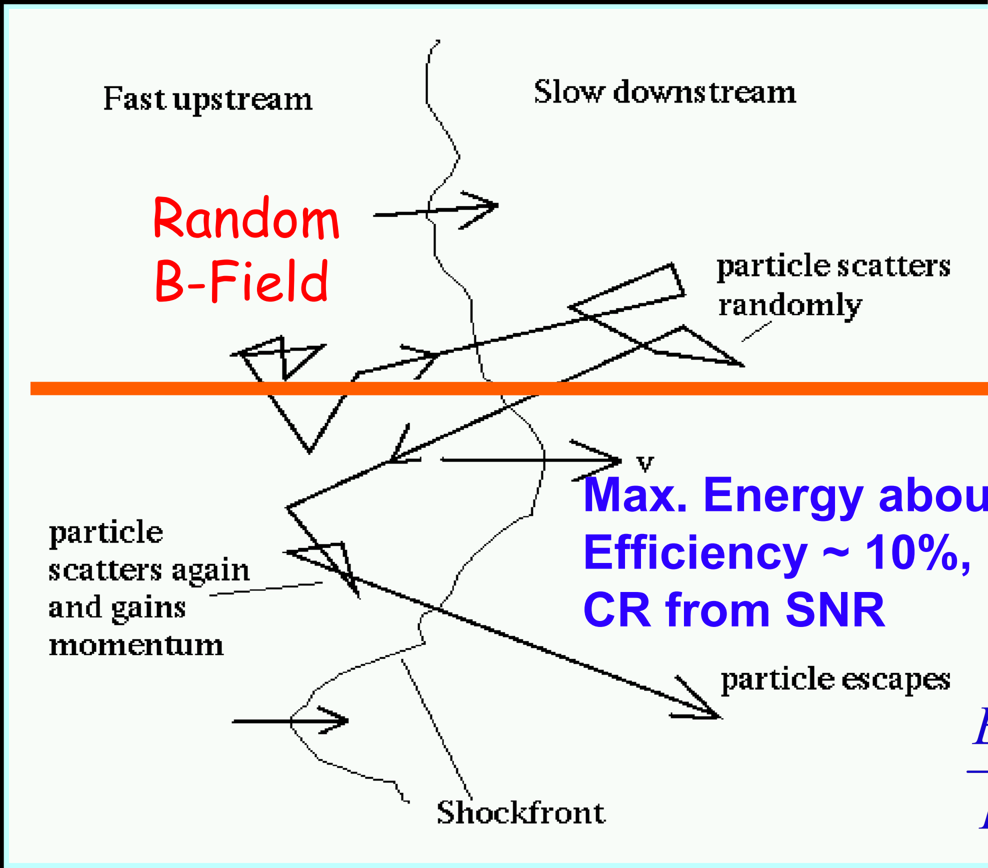
$\mu \rightarrow e + \nu\nu$

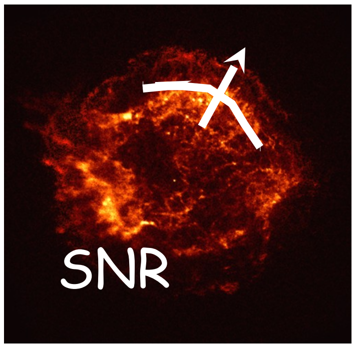
Shock acceleration mechanism

(by Enrico Fermi)



Particles (electrons and hadrons) get scattered many times in shock front and gain energy in each cycle (TeV energies → several 100 years)

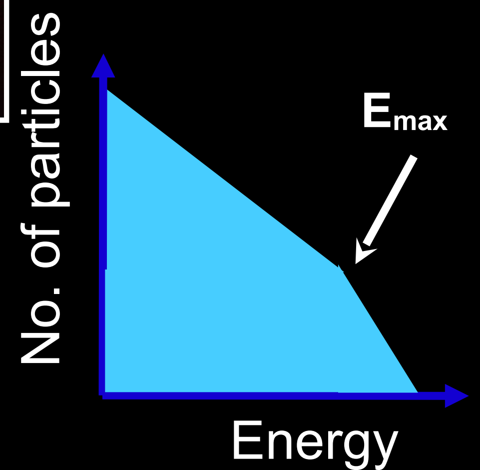




Max. Energy about 10^{15} eV
Efficiency ~ 10%, needed for CR from SNR

$$\frac{E_f}{E_i} = 1 + \frac{4}{3}\beta$$

Power law spectrum



Predicts a $E^{-2.0}$ spectrum

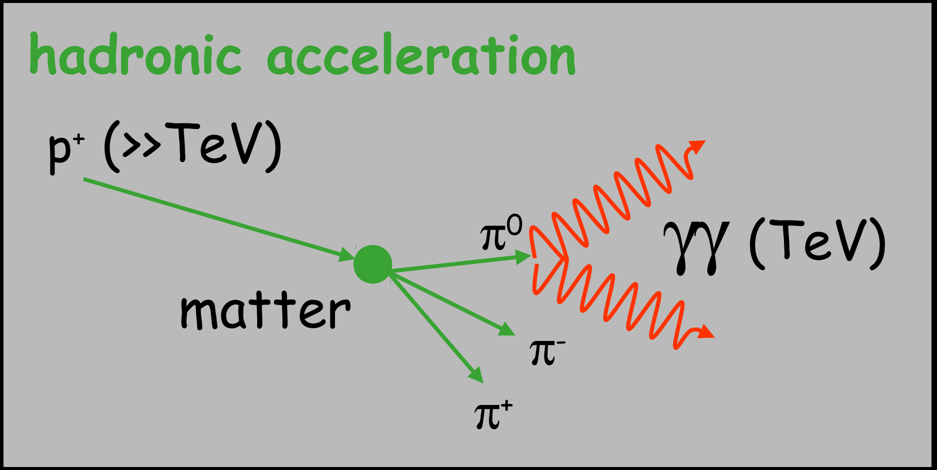
γ-ray astronomy and cosmic rays (CR)

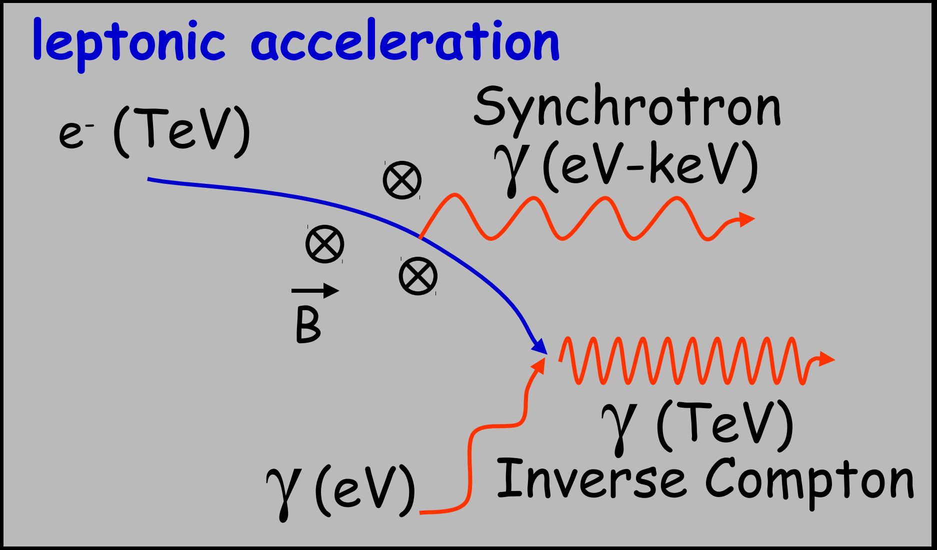
- Origin of CRs?
- (charged) CRs deflected by B-fields

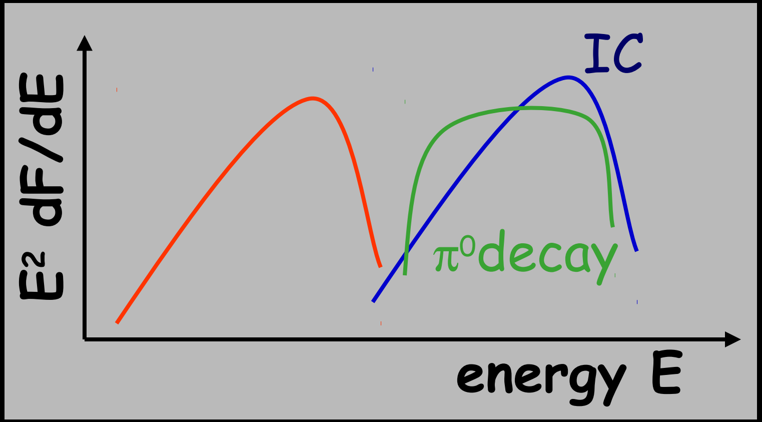
=> search for γ-rays produced by CRs close to source

- discriminate hadronic vs leptonic acceleration

=> shape of spectrum



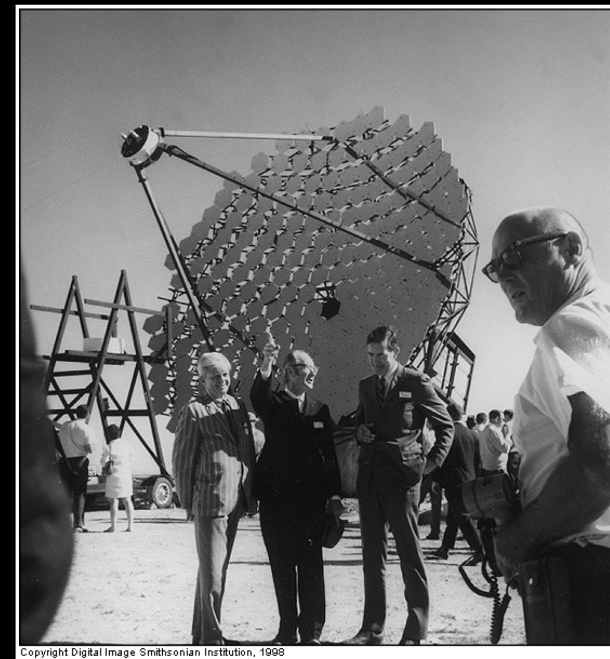




TeV Gamma-rays (10^{12}eV)

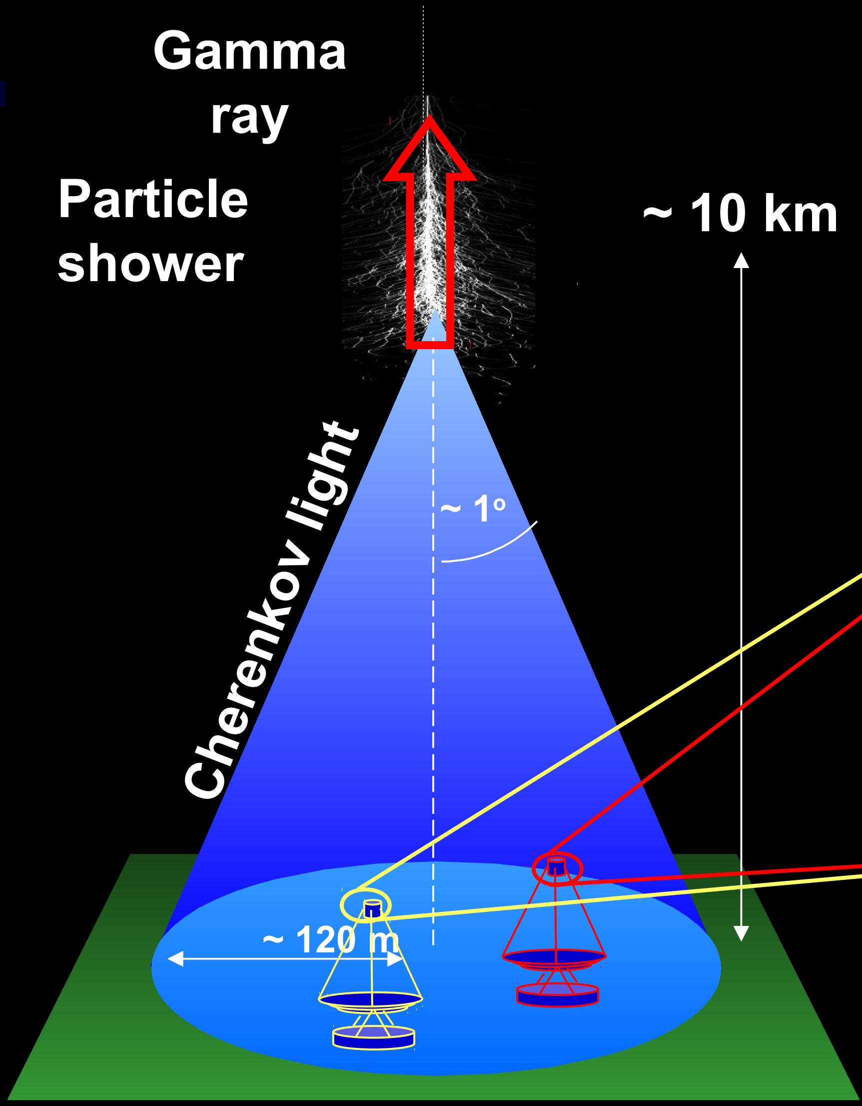
Very High Energy γ-ray Astronomy

- Youngest astronomic discipline
- First significant measurement of TeV γ-ray emission from Crab Nebula by Whipple telescope in 1989
- > 50 hrs for 9 sigma detection

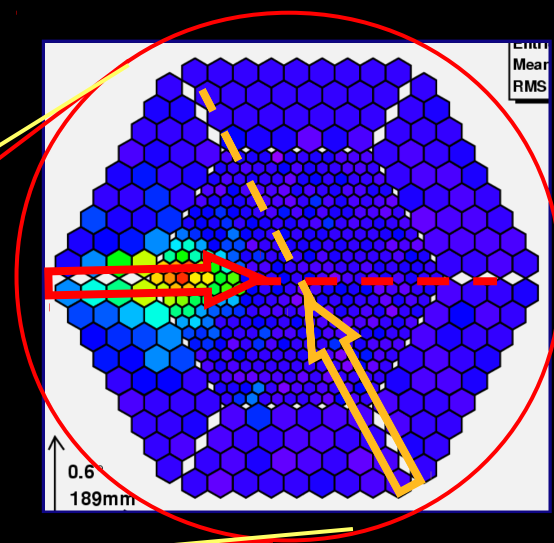


- Current generation since 2004
- 1% of Crab nebula flux
- You can now see TeV gamma rays from Crab nebula in < 2 mins

Imaging Air Cherenkov Telescopes

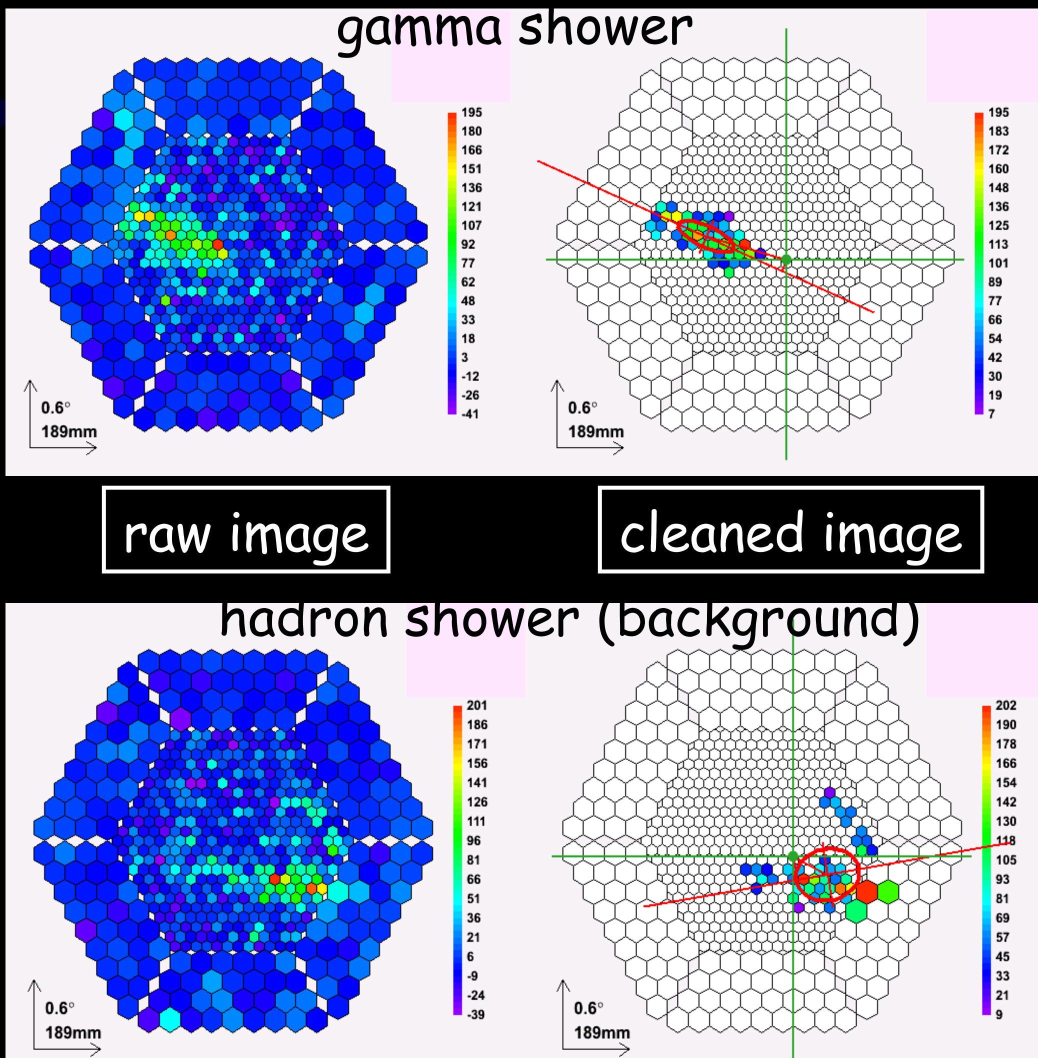


Cherenkov light Image of particle shower in telescope camera



reconstruct:
arrival direction, energy
have to reject hadron background

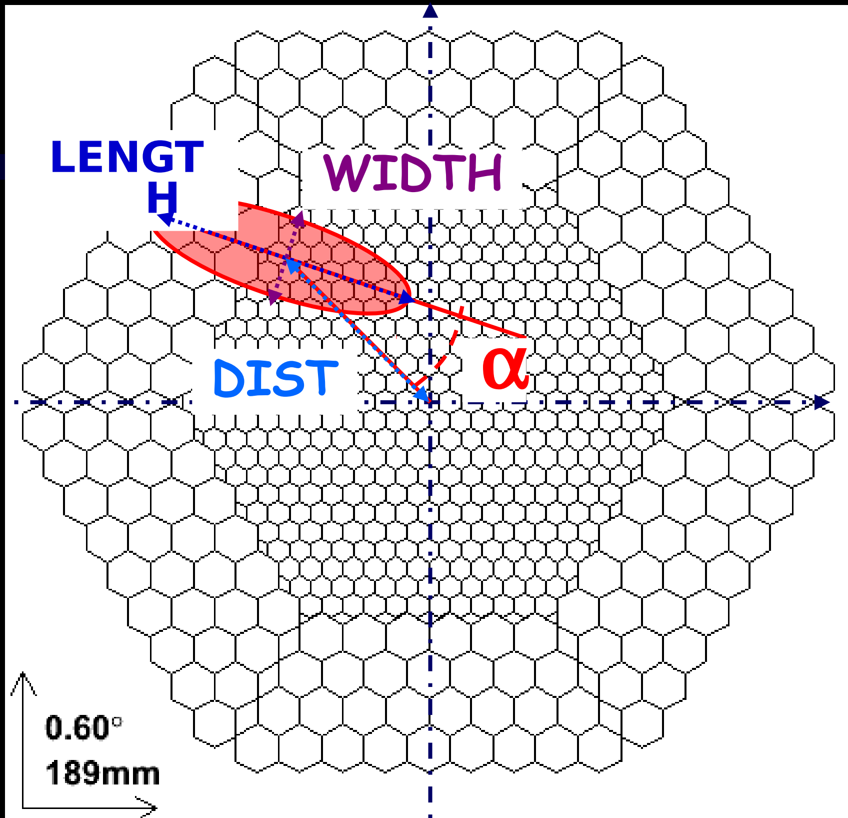
Background Rejection

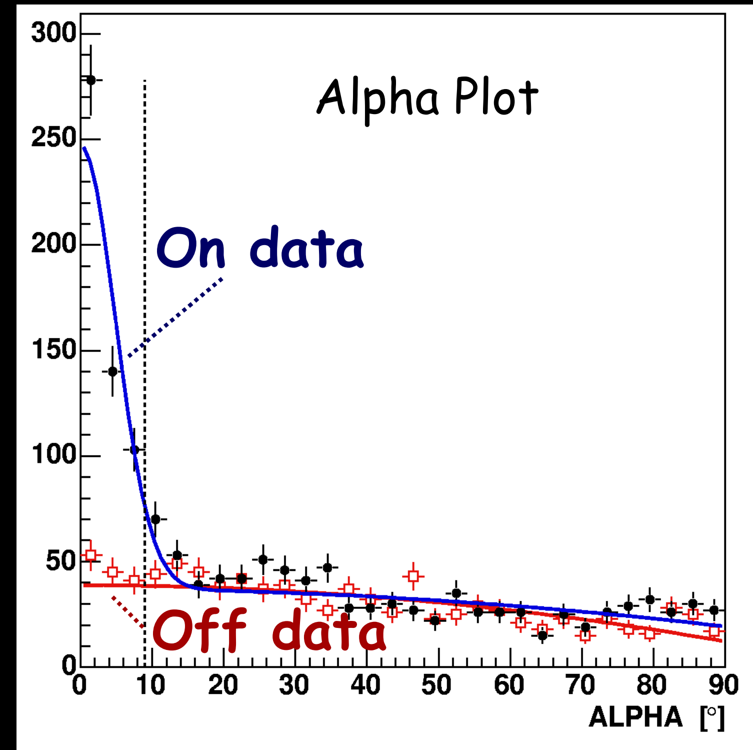


Main Background:

- **Cosmic Ray (hadron) showers**
- **$>10^4$ times more numerous than γ-ray showers**
- **Reject based on shower shape**

Standard "Hillas" Analysis





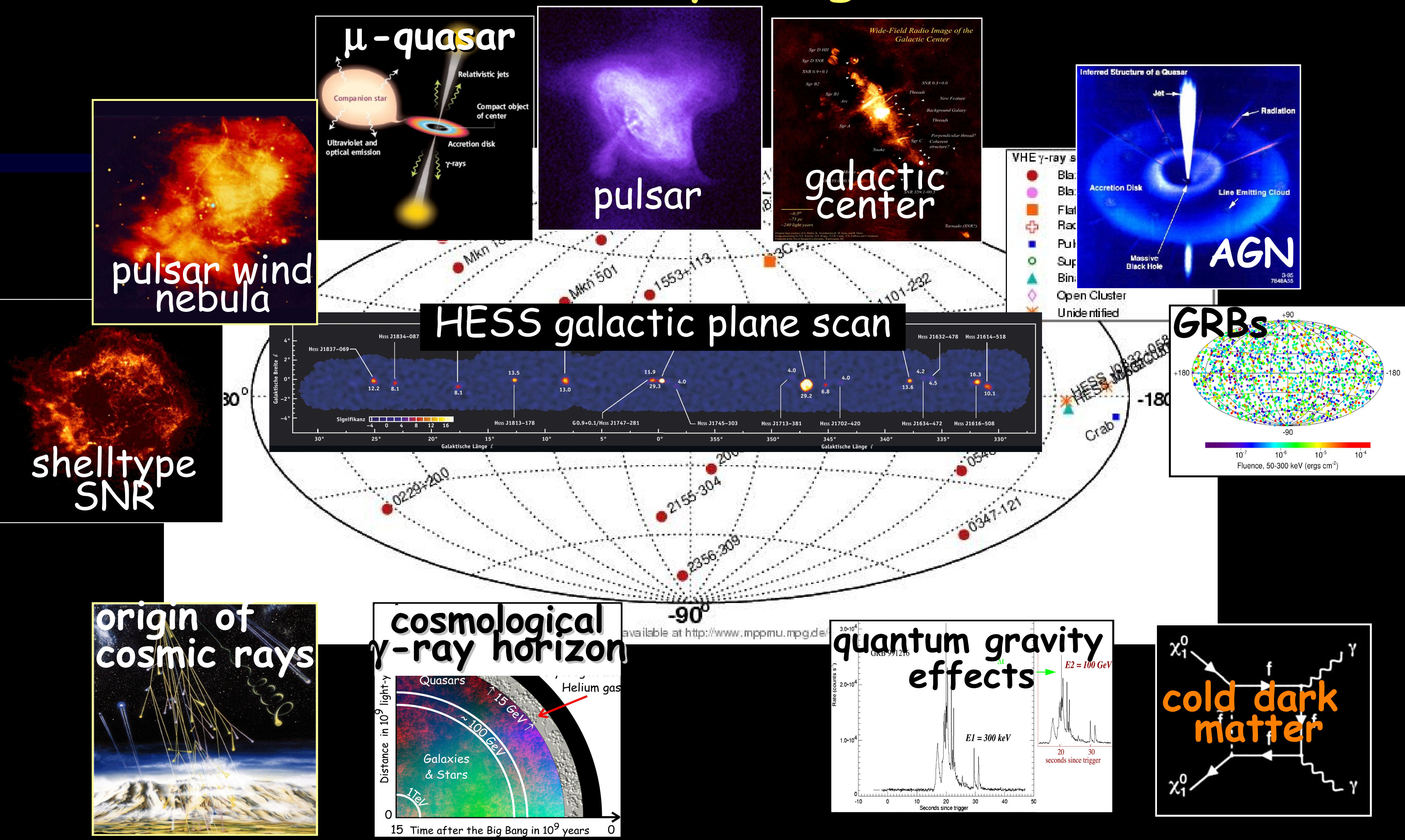
Background rejection with multidimensional cuts on Hillas parameters: Length, Width, Dist, Alpha, Size

Hadron background:
- isotrop arrival direction
- flat Alpha distribution

Gammas:
- excess in source direction

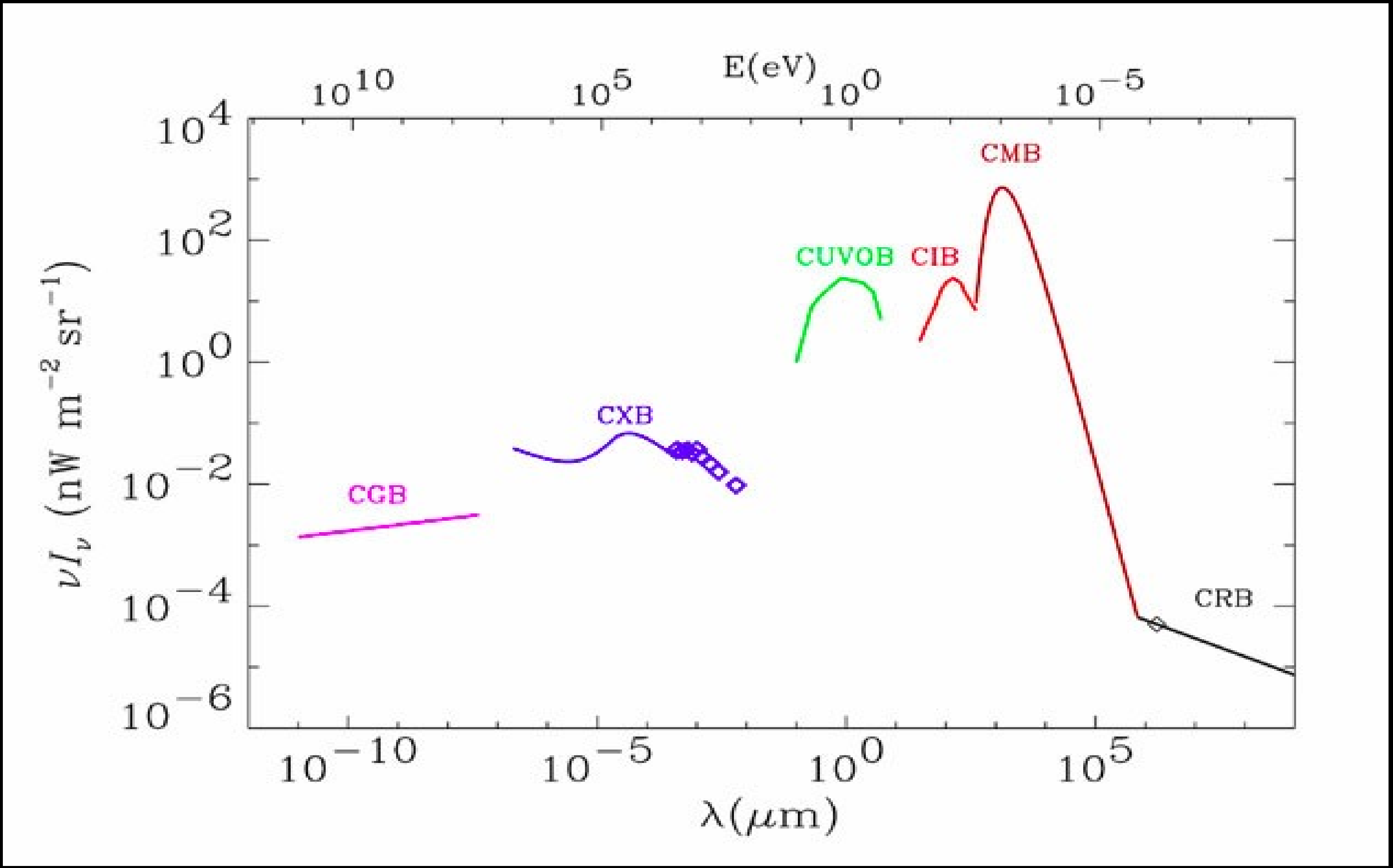
Current generation of IACTs

VHE γ-ray targets



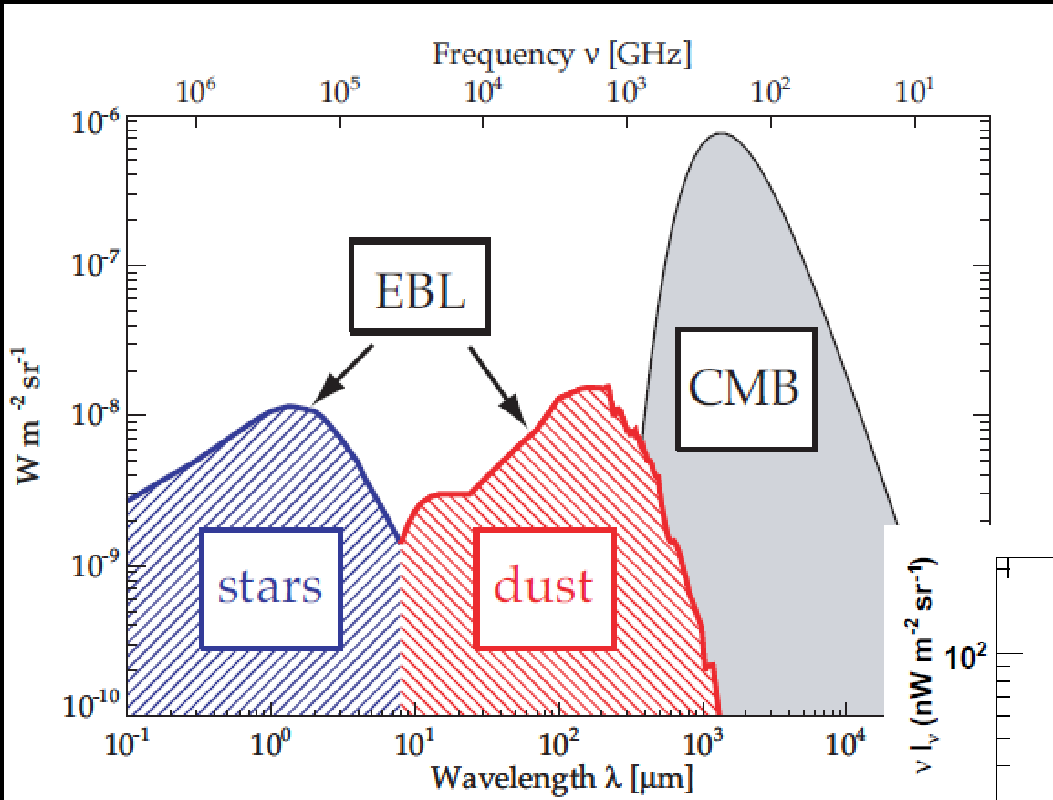
> 100 sources above 100 GeV, rapid growth in recent years

Photon Background in the universe



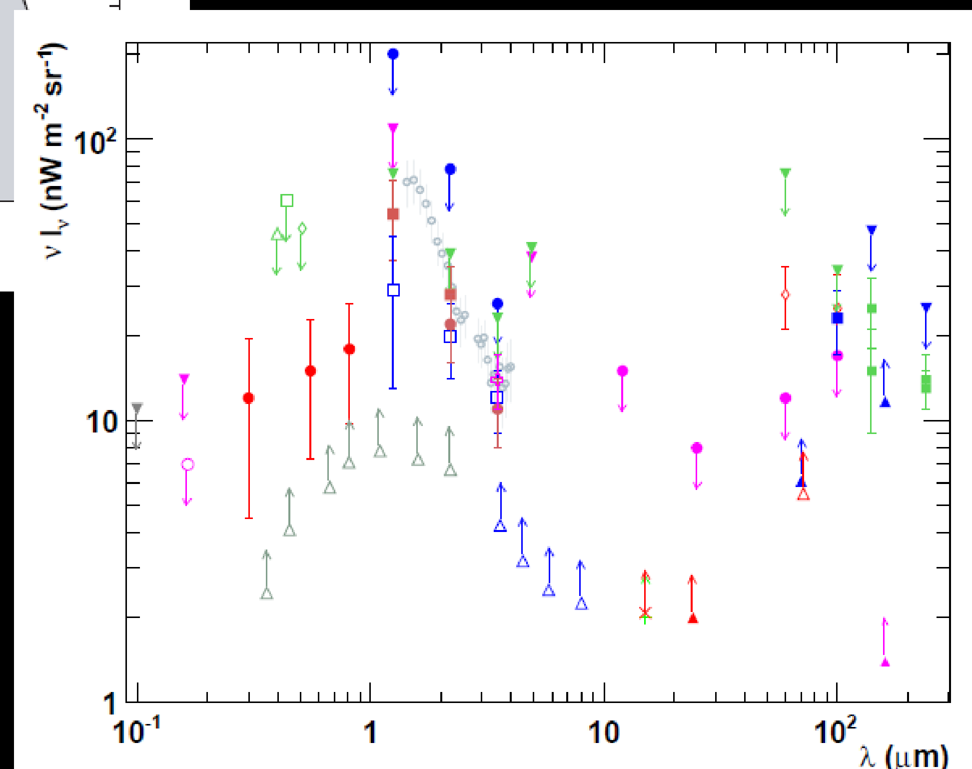
Relic of structure formation in the Universe
UV to far IR wavelengths (1 to 1000 microns) : EBL

Extragalactic Background Light



accumulated radiation in history of universe

Test of star formation and galaxy evolution

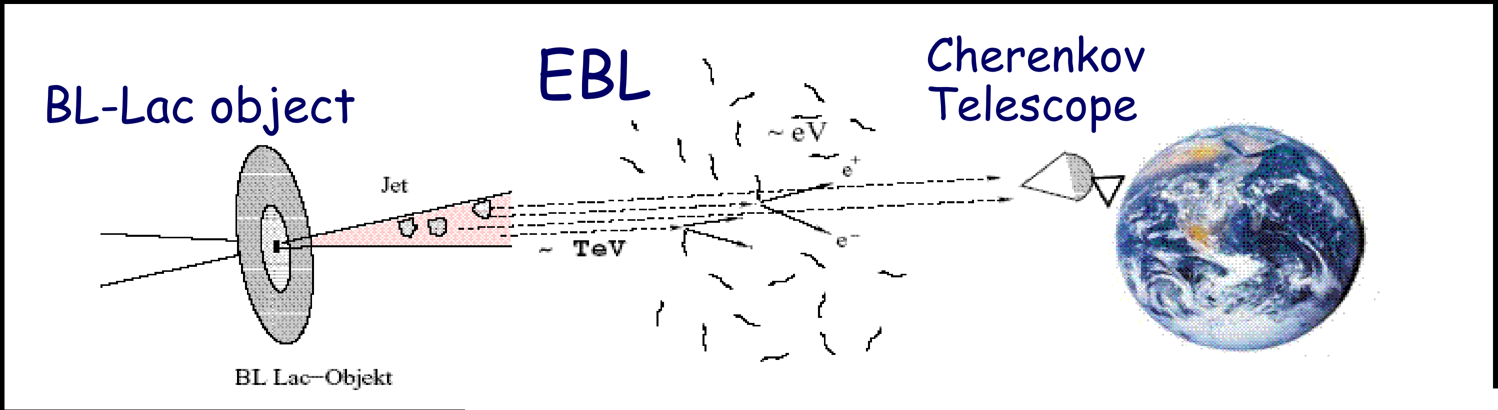


Direct and indirect measurements

Uncertainities due to strong foreground emission (zodiacal light)

Can TeV photons shed some light on it ?

Attenuation of VHE Gamma Rays



$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \longrightarrow e^+ + e^- \quad \text{with } E_{\gamma_{\mathrm{VHE}}} \cdot E_{\gamma_{\mathrm{EBL}}} > (m_e c^2)^2$$

$$\sigma_{\gamma\gamma}(E_\gamma,\ \epsilon,\ \mu) = \frac{3\sigma_{\mathrm{T}}}{16}(1-\beta^2) \times \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

$$\beta \equiv \sqrt{1 - \frac{\epsilon_{\mathrm{th}}}{\epsilon}},$$

$$\epsilon_{\mathrm{th}}(E_\gamma,\ \mu) = \frac{2\,(m_e c^2)^2}{E_\gamma\,(1-\mu)},$$

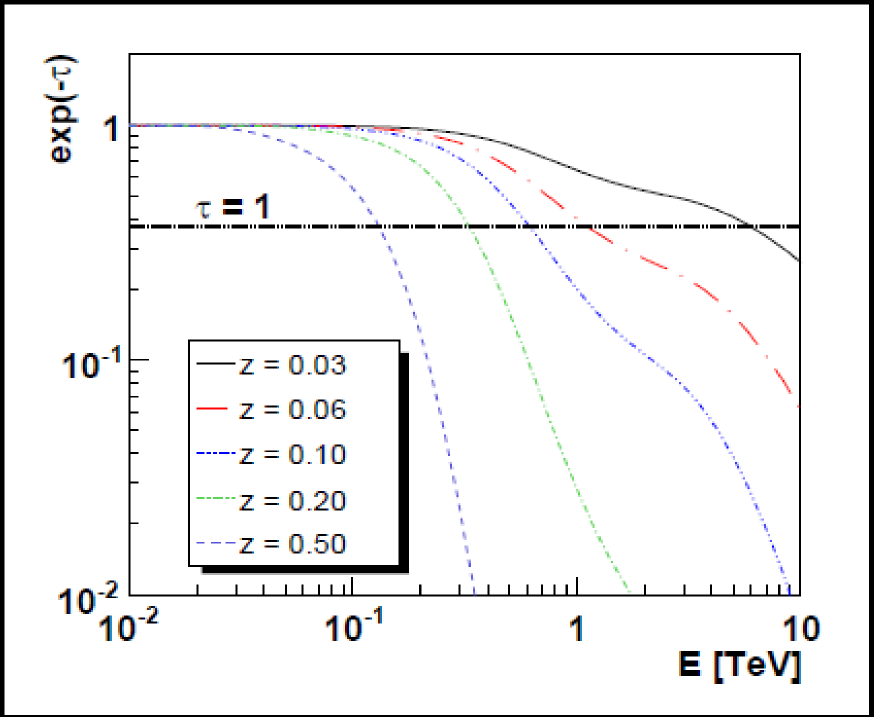
$$\left(\frac{dl}{dz}\right) = c\left(\frac{dt}{dz}\right) = \frac{R_H}{(1+z)E(z)}$$

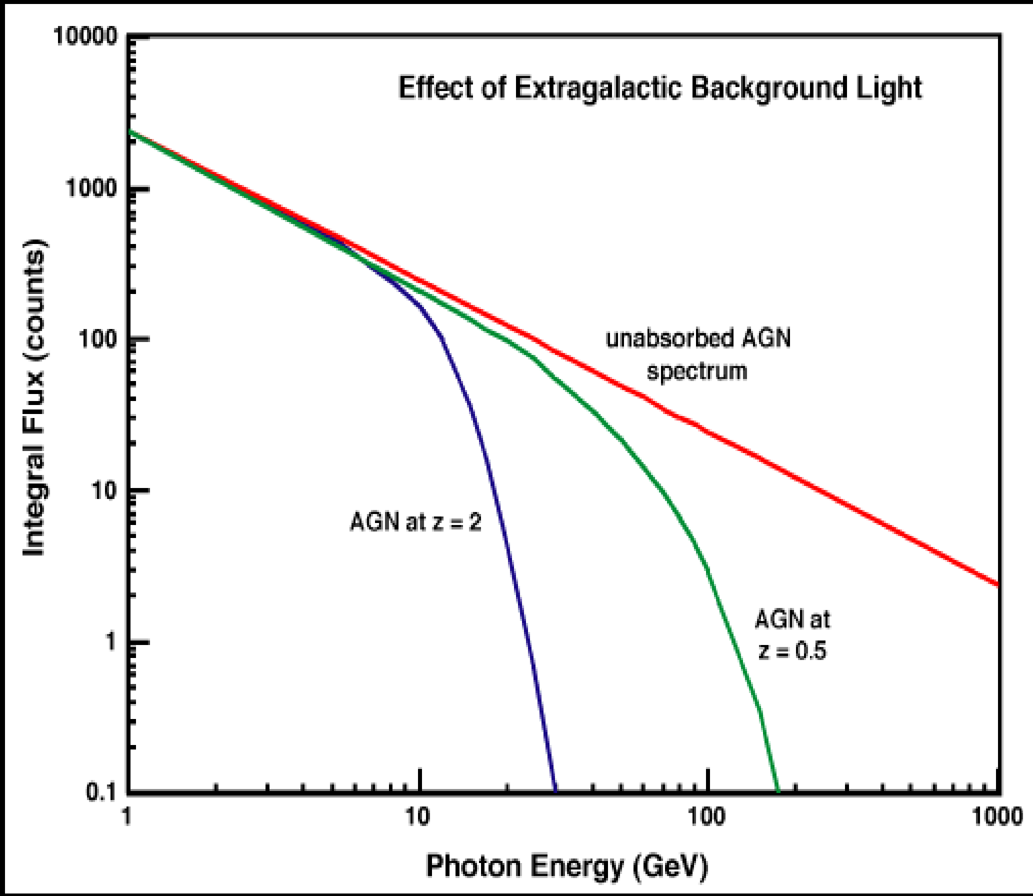
$$E(z) \equiv \left\{(1+z)^2(\Omega_m z + 1) + z(2+z)[(1+z)^2\Omega_r - \Omega_\Lambda]\right\}^{1/2}$$

The optical depth traversed by a photon observed at energy E_γ that was emitted by a source at redshift z is given by

$$\tau_\gamma(E_\gamma,\ z) = \int_0^z \left(\frac{dl}{dz'}\right) dz' \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{\mathrm{th}}}^{\infty} d\epsilon' n_\epsilon(\epsilon',\ z')\sigma_{\gamma\gamma}(E'_\gamma,\ \epsilon',\ \mu),$$

Effects of EBL Absorption



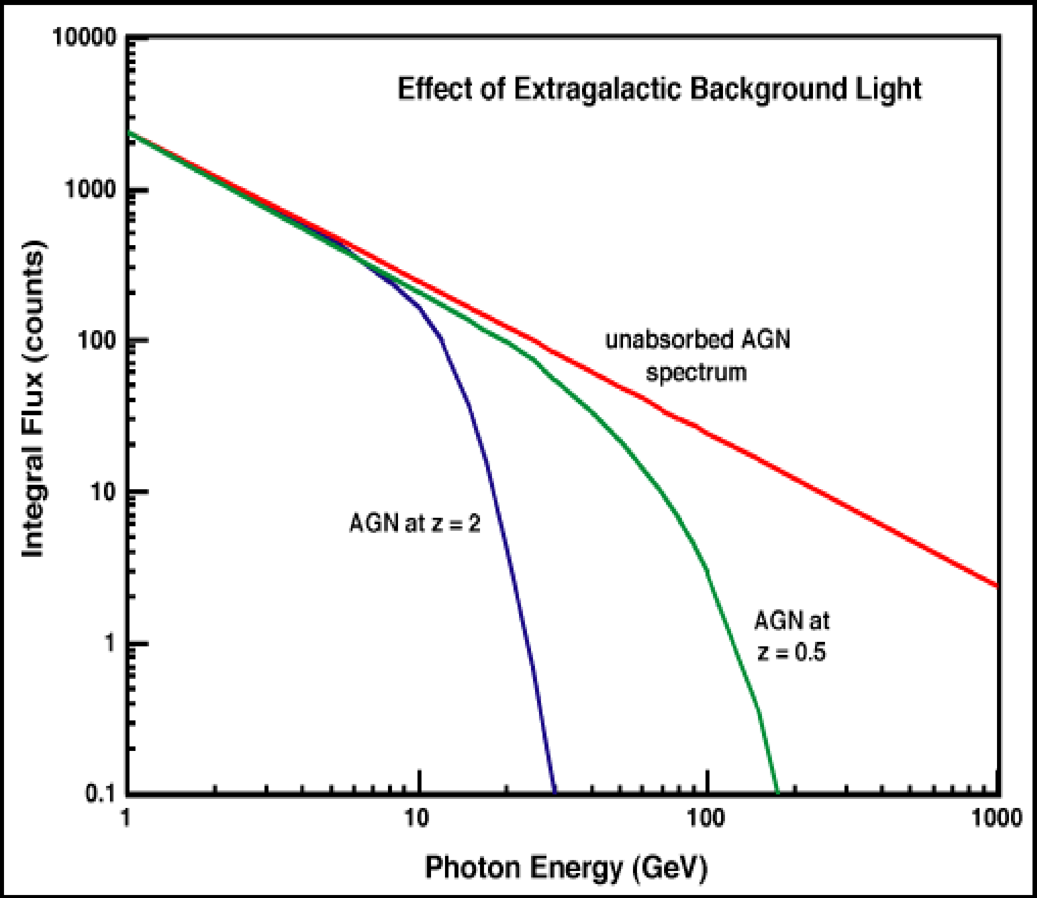


$$\frac{dN_{\mathrm{obs}}}{dE} = \frac{dN_{\mathrm{int}}}{dE} \times e^{-\tau_\gamma(E,z)}$$

Optical depth depends on z and energy of the photons emitted
Tau = 1 is the Gamma Ray Horizon

Assuming no cut off in intrinsic spectrum

Effects of EBL Absorption



- Absorption leads to cutoff in AGN spectrum
- Measurement of spectral features allows to constrain EBL Models
- A low threshold detector is required to see distant source

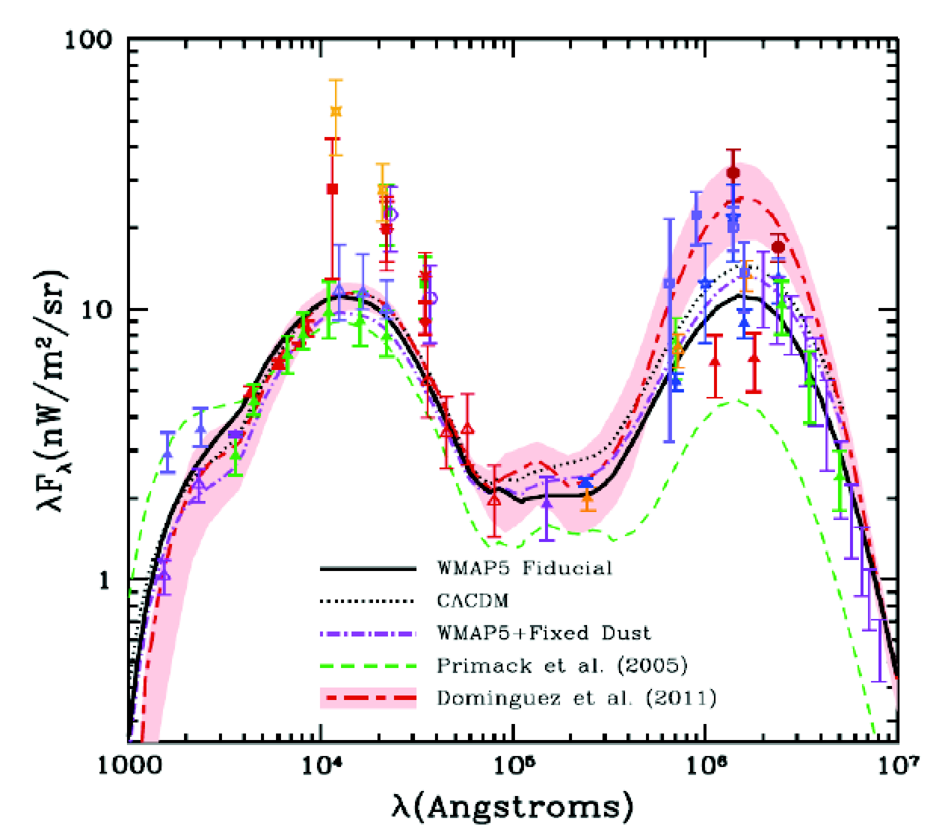
Extragalactic Background Light Models

- Backward Evolution : takes existing galaxy population, scales it backwards as power-law (1+z)

- Backward Evolution from Observations : Attempts to correct for changing luminosity functions and SEDs with redshift and galaxy types

- Evolution directly observed and Extrapolated based on MWL observations

- Forward Evolution : stars with cosmological initial conditions, takes into account formation of galaxies including stars and AGNs, stellar evolution , scattering, absorption, re-emission by dust



Gilmore et al MNRAS (2012), 422, 3189

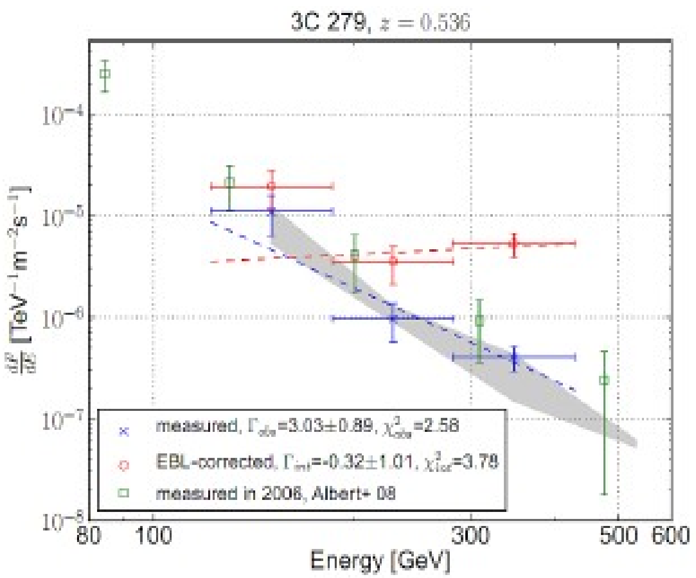
Observations of High red shift objects

3C 279 (z = 0.536)

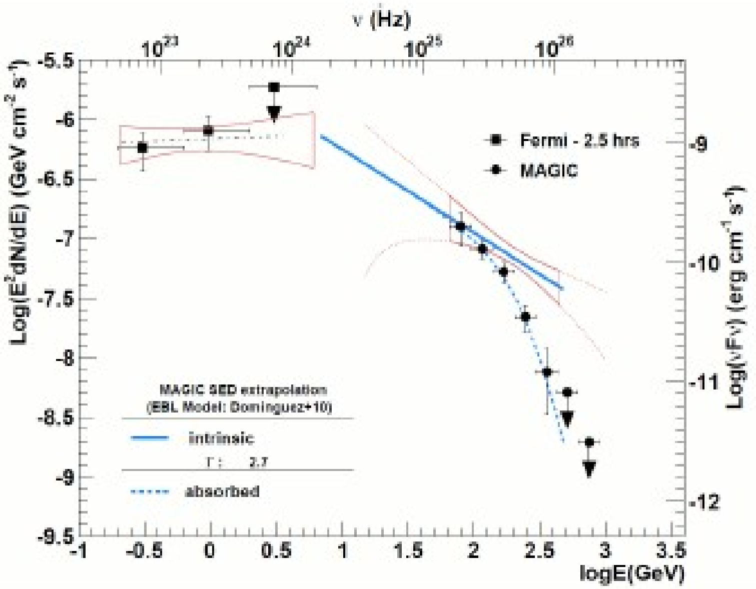
- discovered by MAGIC in 2006
  EBL constraints [Science 2008]
- re-observed 2007 and 2009

PKS 1222+21 (z = 0.432)

- MAGIC discovery during flare 2010
- fast variability

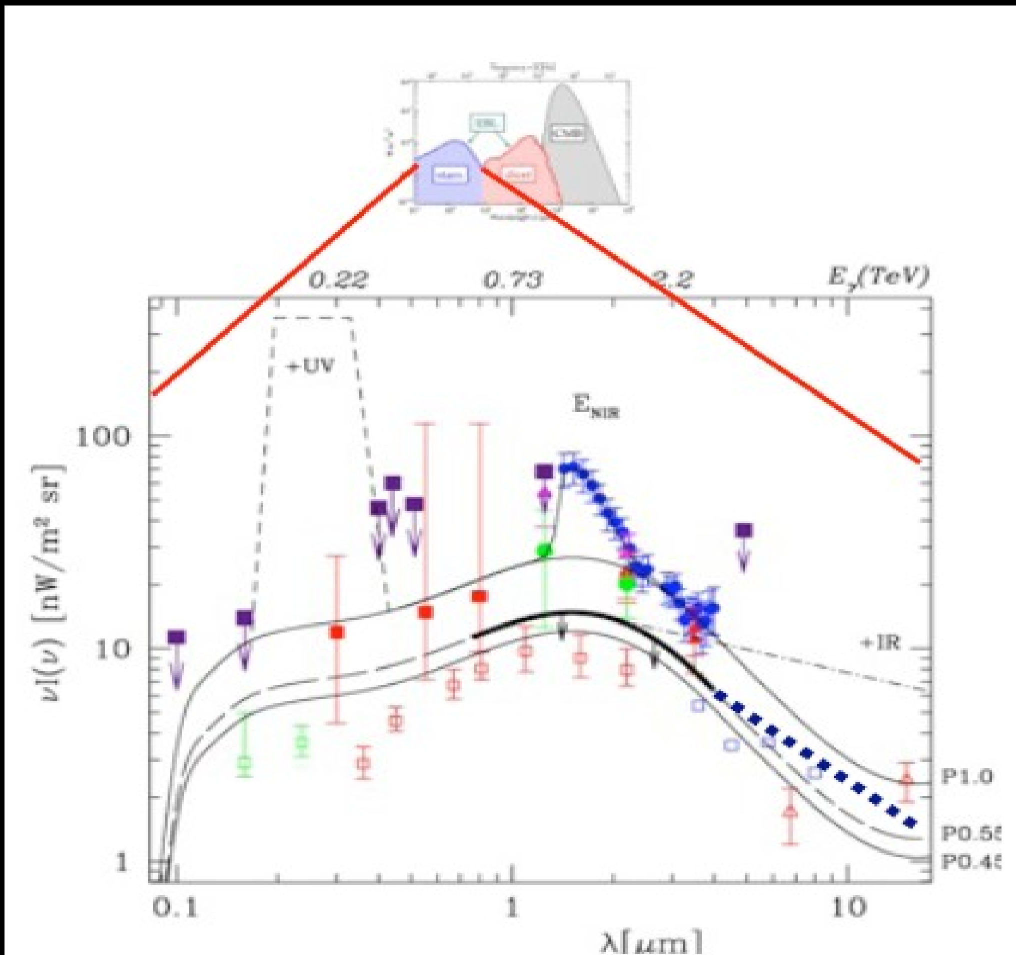


[A&A 2011]

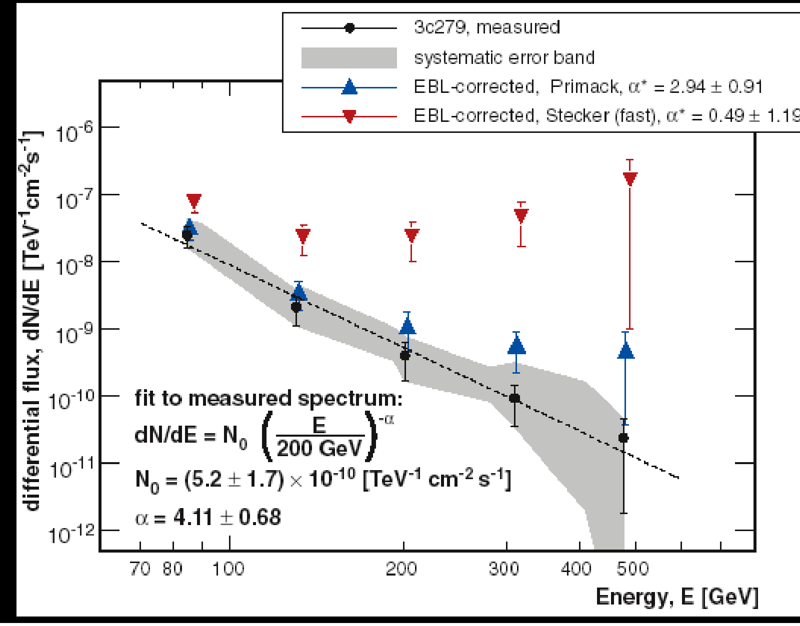


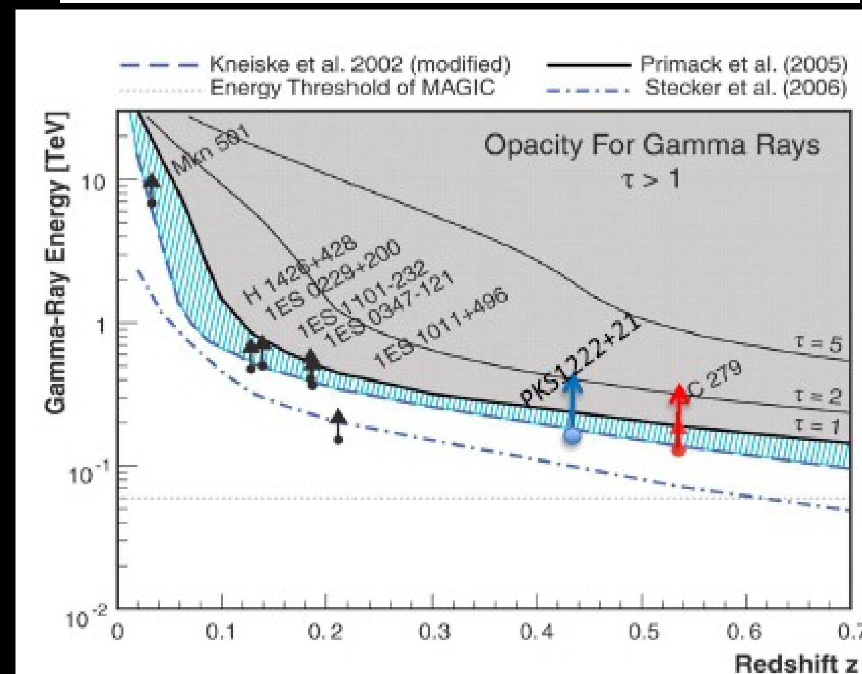
[ApJ Lett 2011]

Constraints from mid to high redshift objects (z ~ 0.1 to 0.5)



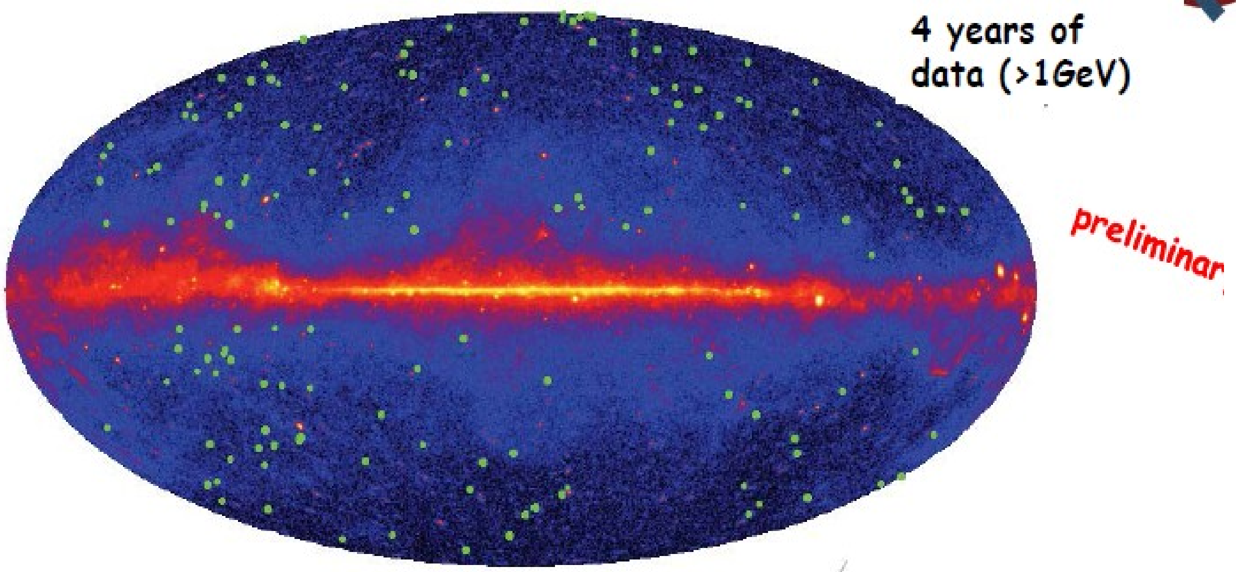
HESS, Nature 440 (2006) 1018-1021





MAGIC, Science (2008)

The extragalactic GeV sky



- 1017 TS>25, |b|>10° sources
- 886 AGNs in 'clean' sample
- Census:
  - 310 FSRQs
  - 395 BLLacs
  - 179 of unknown&other type

- subclasses assigned from ν_{syn}

LSP, ISP, HSP: low-, intermediate-, high-synchrotron peaked blazars, resp

- LSP: $\log(\nu_{syn}) < 14$
- ISP: $14 < \log(\nu_{syn}) < 15$
- HSP: $\log(\nu_{syn}) > 15$

with ν_{syn} in Hz

[2LAC: Ackermann et al. 2011 (The Fermi-LAT collaboration)]

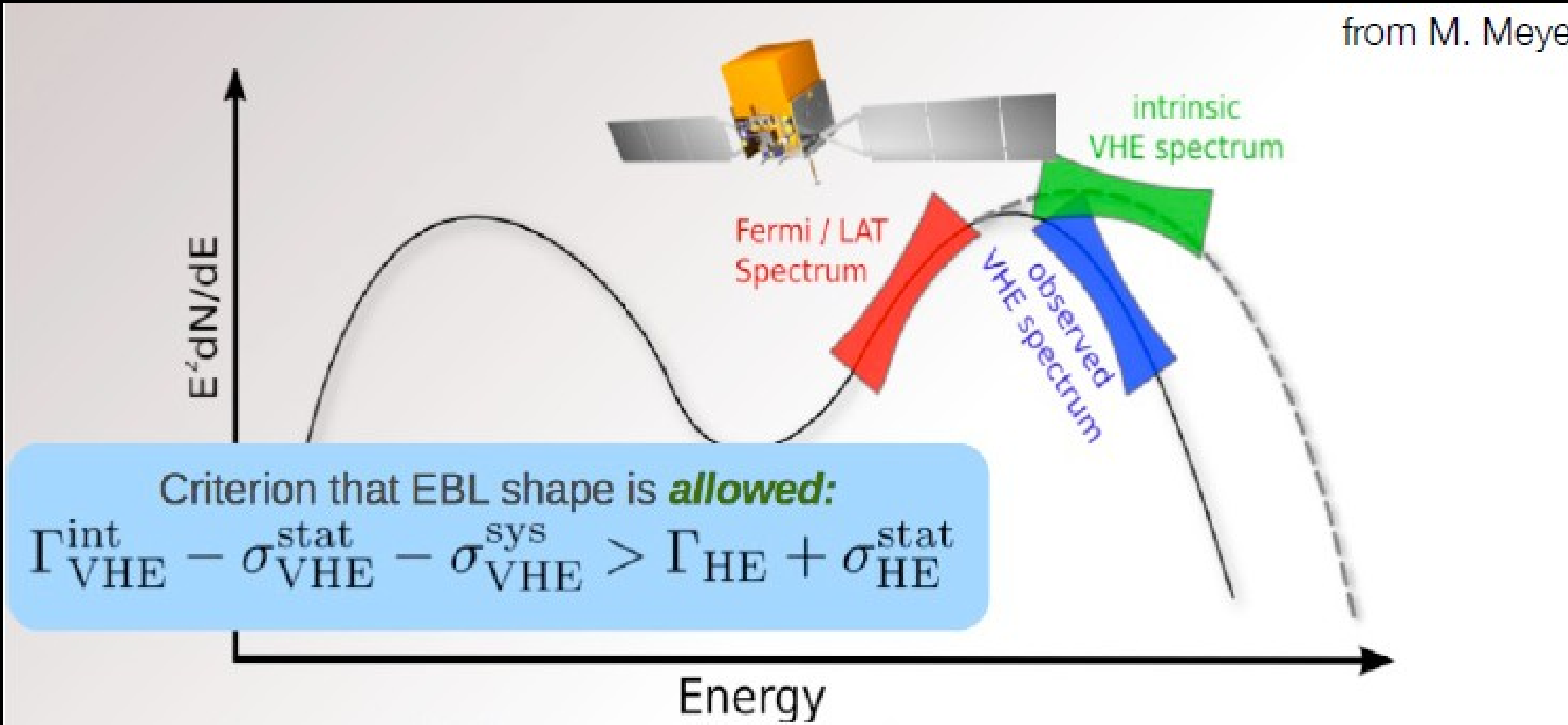
→ probes *opt/UV range* of EBL

→ probes *evolution* of EBL

→ adds *information on unabsorbed* part of source spectrum; lever arm!

LAT constrains opt./UV-EBL, z>0.2

Constraints from GeV-TeV data

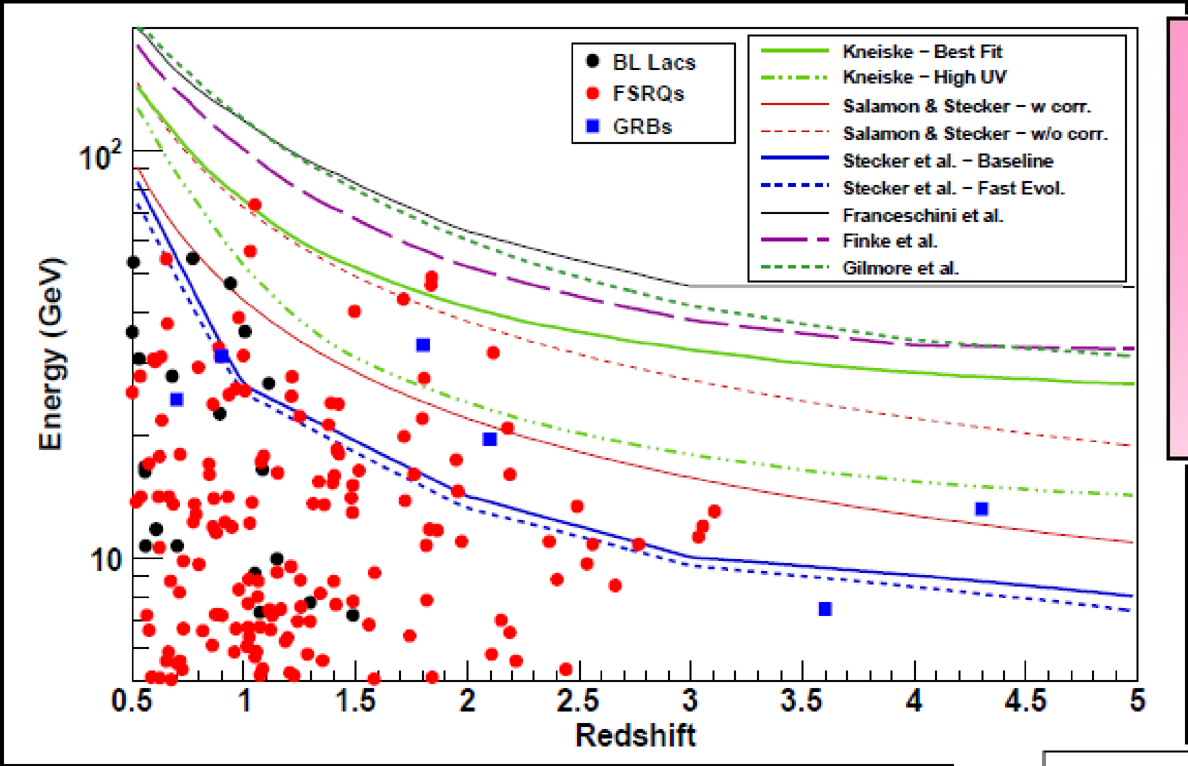


Criterion that EBL shape is ***allowed:***

$$\Gamma_{\mathrm{VHE}}^{\mathrm{int}} - \sigma_{\mathrm{VHE}}^{\mathrm{stat}} - \sigma_{\mathrm{VHE}}^{\mathrm{sys}} > \Gamma_{\mathrm{HE}} + \sigma_{\mathrm{HE}}^{\mathrm{stat}}$$

- ***Now: use spectral index measured by Fermi***
- Test if fitted spectrum has an spectral index softer than the index measured by Fermi / LAT ⇒ If so, EBL shape is allowed
- If spectrum shows break, compare ***only the first index*** to Fermi measurement
- Test if spectrum shows an exponential pile up ⇒ If so, EBL shape is excluded

Constraints from GeV data



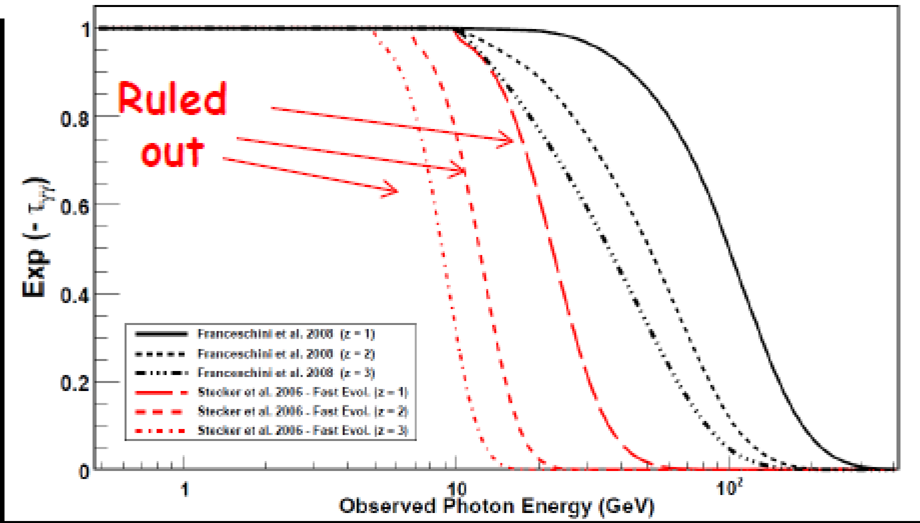
First Year of Fermi data:

reject with high significance [HEP: >8.9σ, LRT: >11.4σ]

EBL models that predict large opacities in the 20-50 GeV energy range for distant sources (z~1...4).

[Abdo et al, 2010, ApJ, 723, 1082]

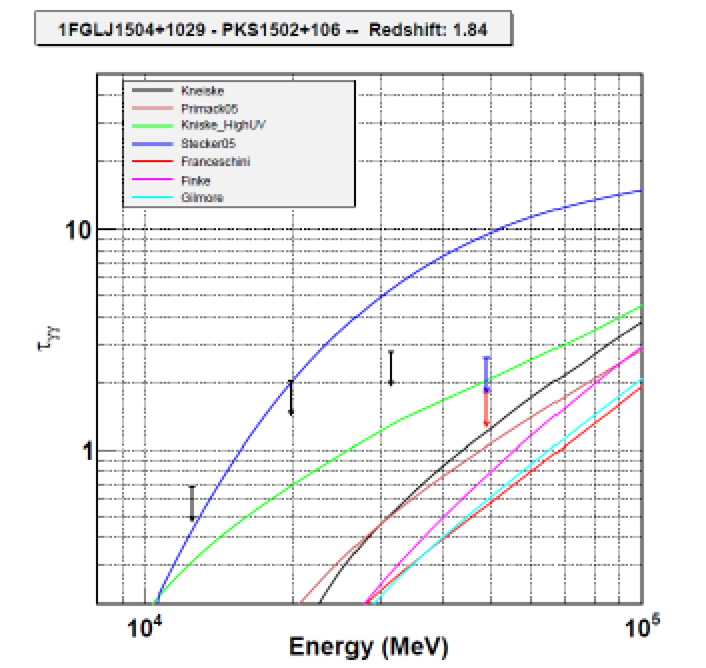
EBL absorption negligible at <15 GeV for z≲2



Constraints from GeV data

Source	z	E_{max}	$\tau_{UL}(z, E_{max})$
J1147-3812	1.05	73.7	1.33
J1504+1029	1.84	48.9	1.82
J0808-0751	1.84	46.8	2.03
J1016+0513	1.71	43.3	0.83
J0229-3643	2.11	31.9	0.97
J1012+2439	1.81	27.6	2.41

Robust upper limits



Proceeding beyond ULs

- 46-months of 1-500 GeV data

- blazars of BL Lac type
- 'non-variable' in 2LAC
- the "best" (>3σ in 3-10 GeV band) 150 BL Lacs from 2LAC
- sub-divided into 3 redshift bins (50 sources each):

z = 0 …. 0.2, 0.2 …..0.5, 0.5 …… 1.6

35 HSPs, 10 ISPs, 5 LSPs; 27 HSPs, 18 ISPs, 5 LSPs; 10 HSPs, 19 ISP, 21 LSPs

Test of EBL Models

Goal: *collective deviation of observed spectrum from its intrinsic one*

Assumption: intrinsic spectrum represented by LogParabola within LAT E-range

Procedure: *in each redshift bin…*

- fit spectra of all sources independently
- LogParabola-fit in [1GeV, E_{crit}] -> intrinsic spectrum & extrapolation to high energies
- Spectra of all sources modified by *common term* exp[-b τ(E,z)] [combine likelihoods]

$$F(E)_{obs} = F(E)_{intr} \exp[-b \cdot \tau(E,z)_{model}]$$

Test:

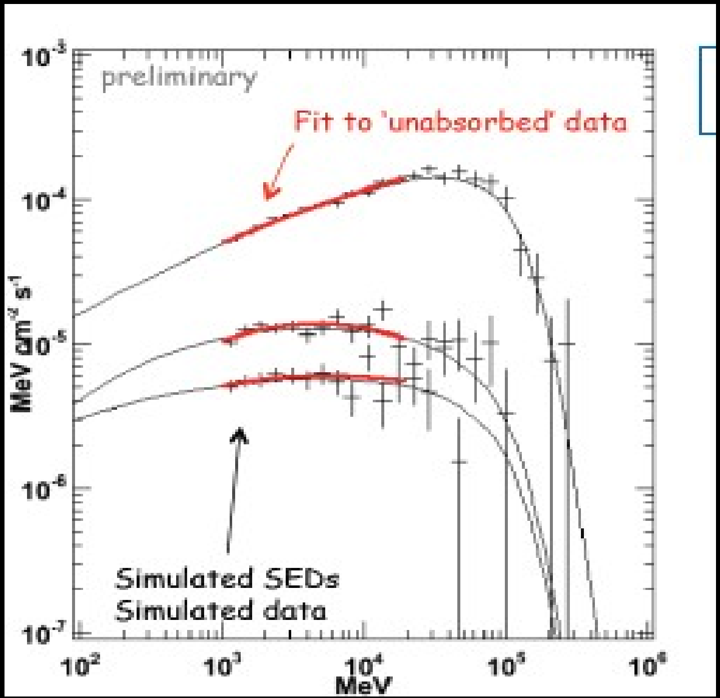
(1) No EBL:

Null Hypothesis b=0

(2) Model prediction correct:

Null hypothesis b=1

TS=2 [Log L(b) - Log L(b=0/1)]



Test of EBL Models

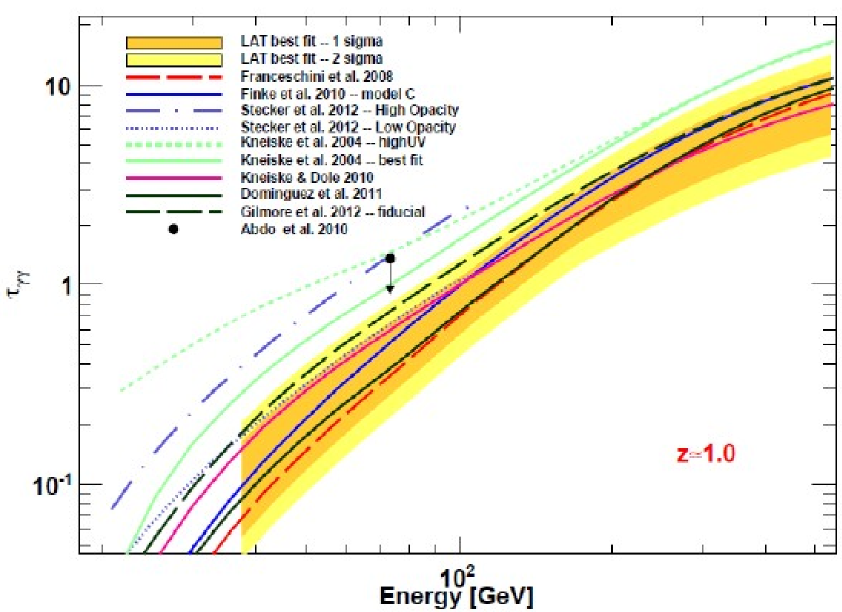
Many EBL models tested:

no EBL

model prediction correct

Model[a]	Significance of b=0 Rejection[b]	b[c]	Significance of b=1 Rejection[d]
Stecker et al. (2006) – fast evolution	4.6	0.10±0.02	17.1
Stecker et al. (2006) – baseline	4.6	0.12±0.03	15.1
Kneiske et al. (2004) – high UV	5.1	0.37±0.08	5.9
Kneiske et al. (2004) – best fit	5.8	0.53±0.12	3.2
Gilmore et al. (2012) – fiducial	5.6	0.67±0.14	1.9
Primack et al. (2005)	5.5	0.77±0.15	1.2
Dominguez et al. (2011)	5.9	1.02±0.23	1.1
Finke et al. (2010) – model C	5.8	0.86±0.23	1.0
Franceschini et al. (2008)	5.9	1.02±0.23	0.9
Gilmore et al. (2012) – fixed	5.8	1.02±0.22	0.7
Kneiske & Dole (2010)	5.7	0.90±0.19	0.6
Gilmore et al. (2009) – fiducial	5.8	0.99±0.22	0.6

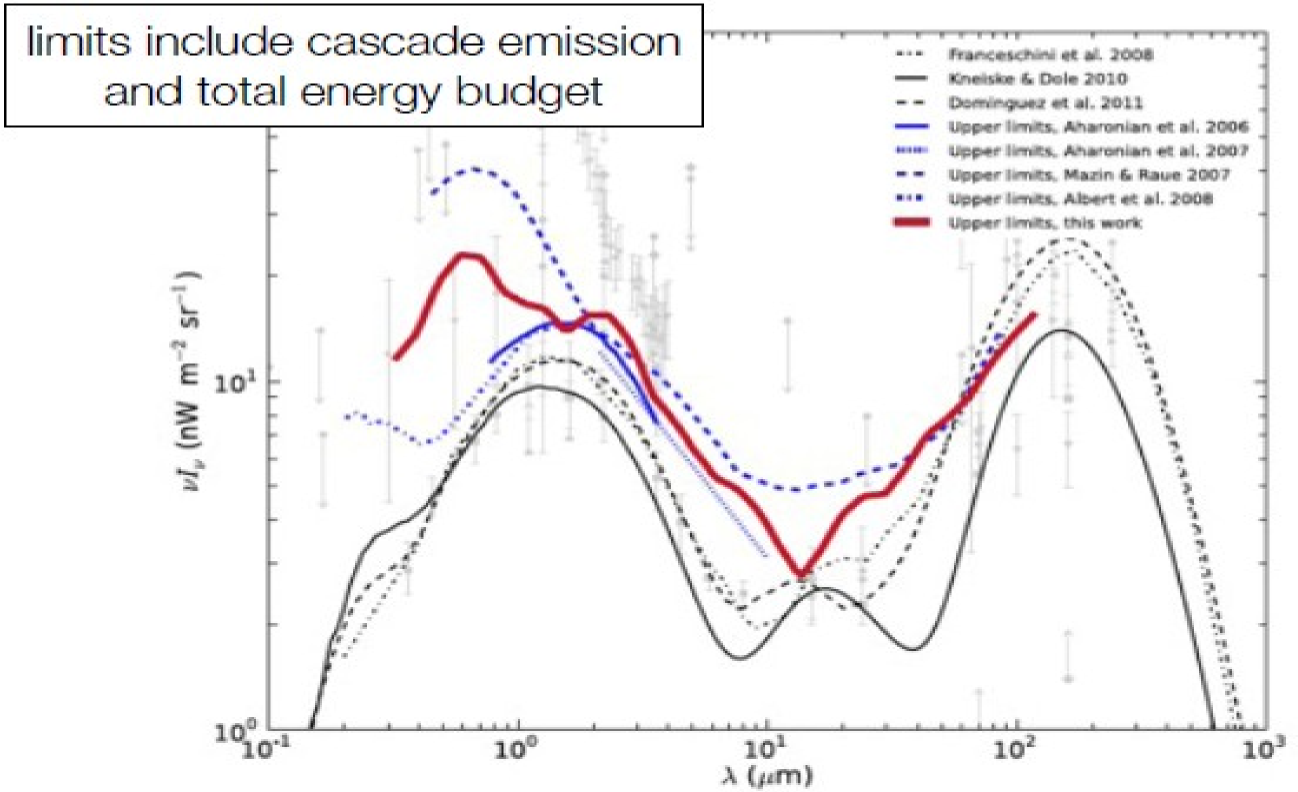
rejection $>3\sigma$



EBL flux level 3-4 times lower than previous estimates in the opt/UV

[Abdo etal. 2010] .

Combined GeV-TeV Constraints



Meyer, Raue, DM, Horns, A&A (2012) 542, A59

- Positive: Different methods lead to similar constraints
- Negative: Sometimes too strong assumptions (e.g. power law spectra)

Alternative Approaches to constrain EBL

The method (1)

Mankuzhiyil, MP, Tavecchio 2010
ApJL, 715, L16

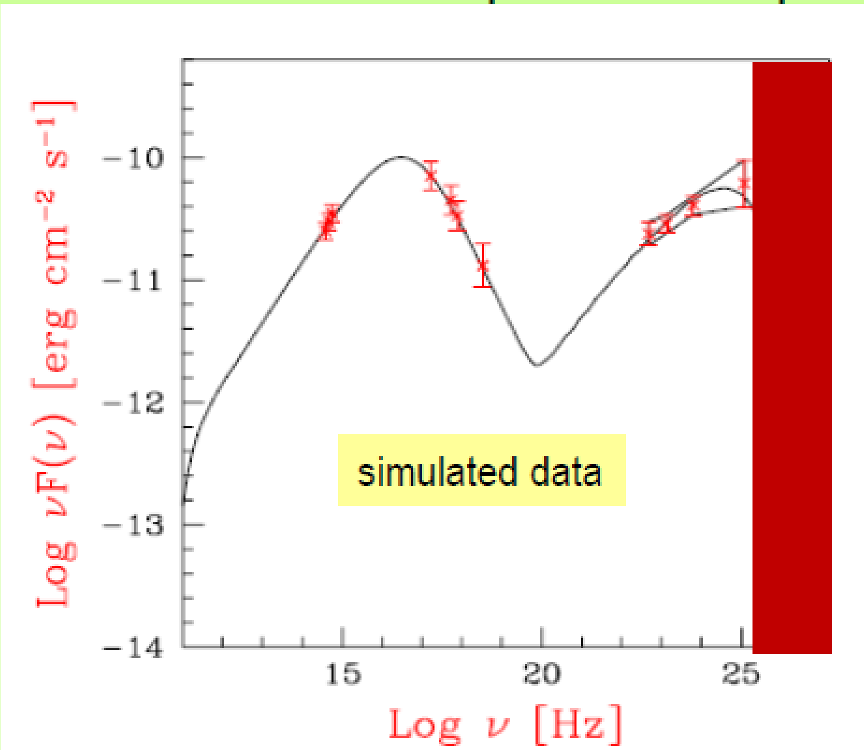
Simultaneous multi-ν obs's:

- optical + X-rays + HE γ-ray + VHE γ-ray

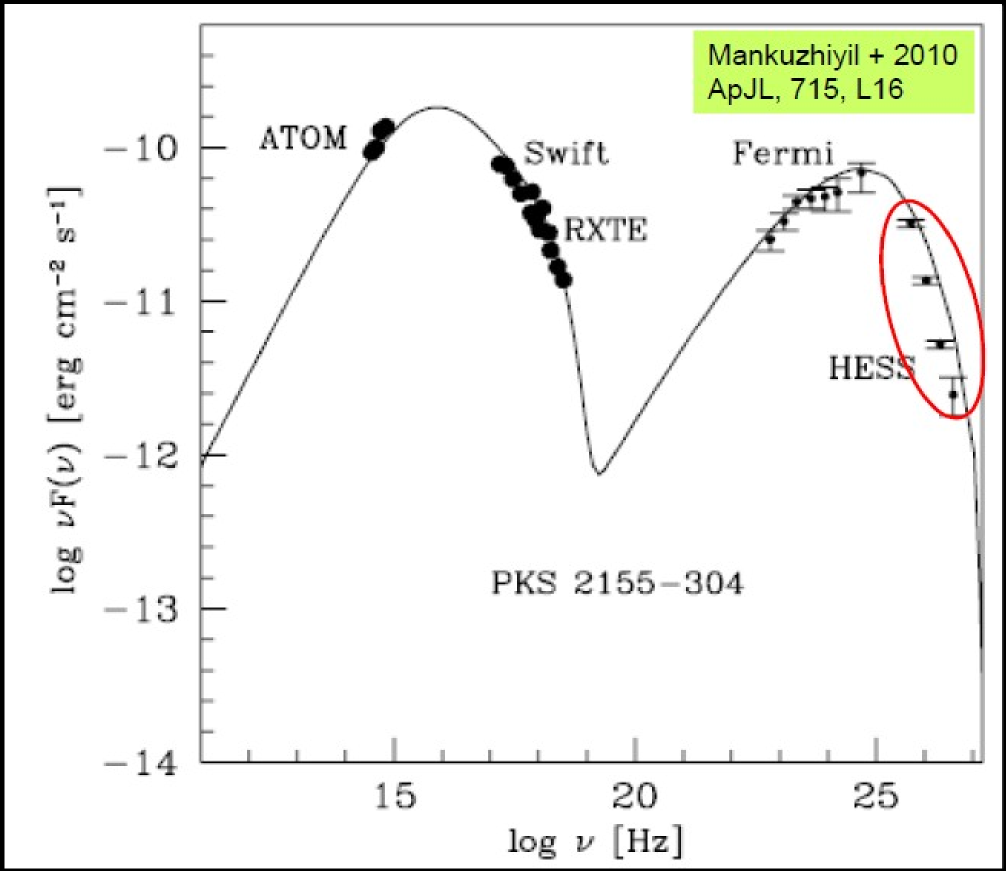
Model SED: use SED w/out (EBL-affected) VHE γ-ray data:

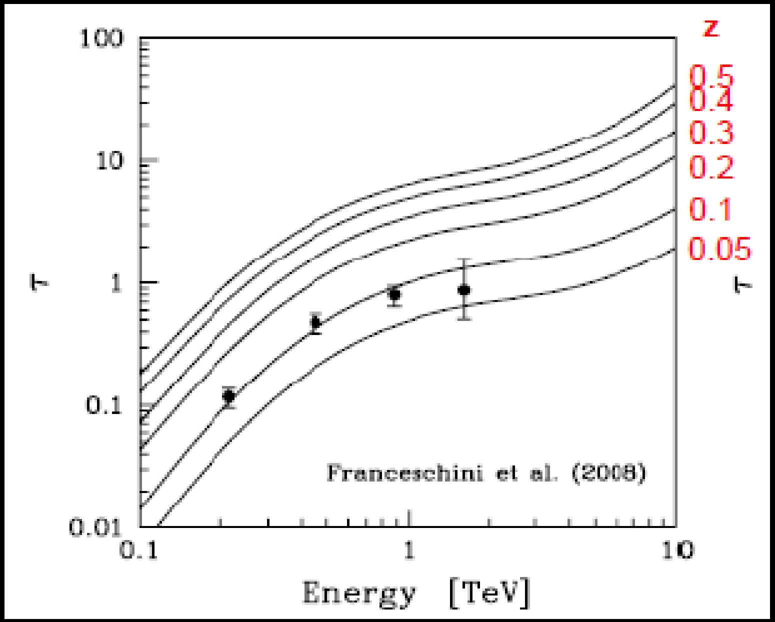
→ χ^2-minimization → SSC model

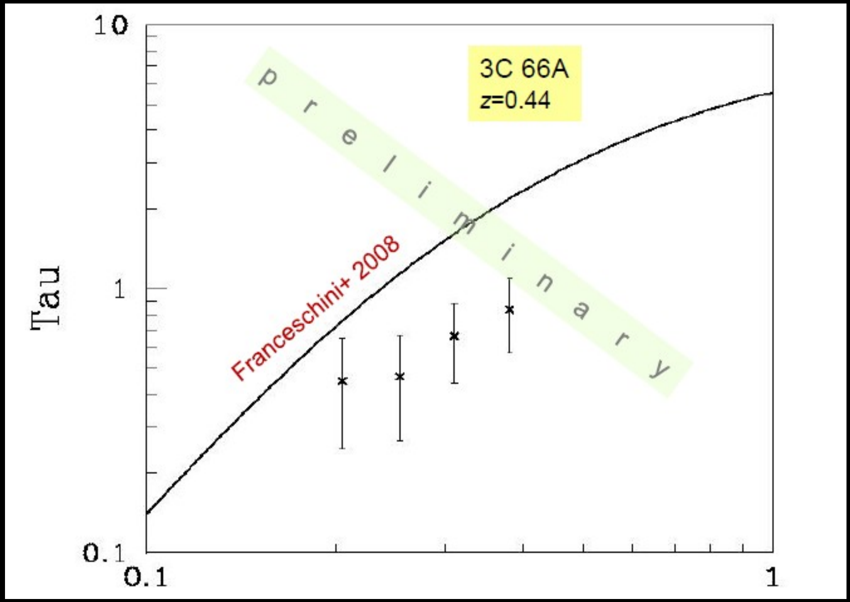
(check structure of multi-D parameter space)



Applications to a few sources

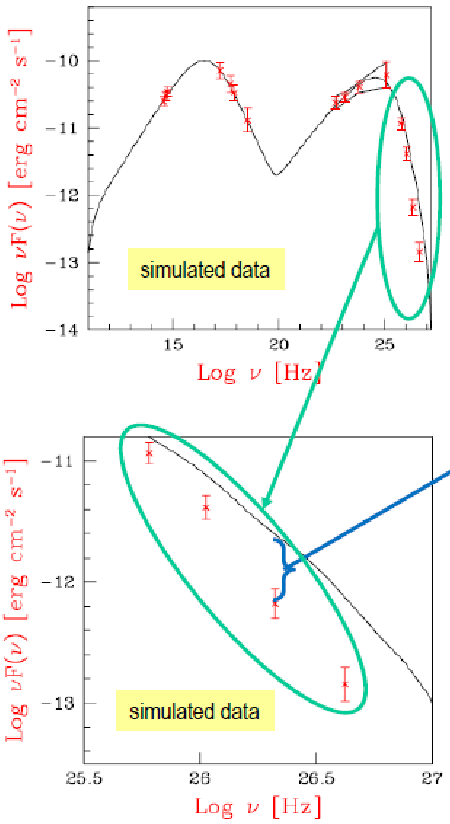






τ lower than predicted?
z uncertain?
ALPs?

...the method (2)



Extrapolate model SED into VHE regime
→ **"intrinsic" blazar VHE emission**

Observed vs "intrinsic" emission
→ $\tau_{\gamma\gamma}(E,z)$

Assume (concordance) cosmology
→ $n_{EBL}(\varepsilon, z_j)$ (parametric: $\sum a_{nj}\, \varepsilon^n$)

Cons:
- indirect measurement of EBL
- method depends on blazar model
- theoretical uncertainties (e.g., electron spectrum)

Pros:
- unbiased method
- no assumptions on EBL, blazar SED
- SSC well tested locally on different emission states

Motivation to search for Dark Matter

Current cosmological models suggest DM content ~ 25%

$(\Lambda\mathrm{CDM}\ \text{model},\ \Omega_{CDM}h^2 \approx 0.1)$

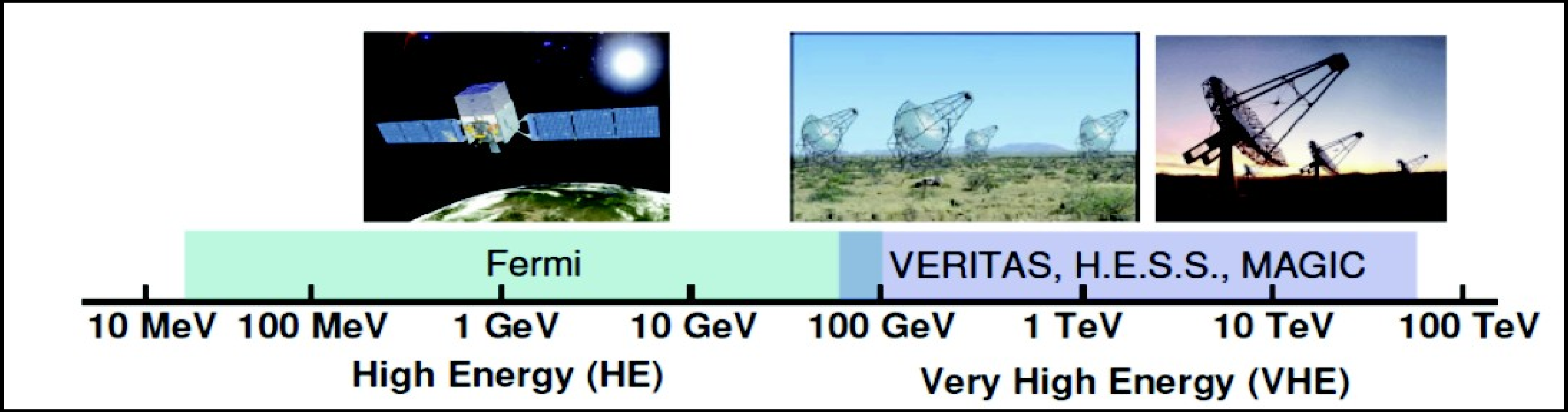
Mainly observed through gravitational lensing

Indirect detection possible if candidates are WIMPs (appear in extensions of standard model Particle Physics : SUSY)

$50\ \mathrm{GeV} \leq m_{WIMPs} \leq 10\ \mathrm{TeV}$

WIMPs can self-annihilate giving standard model particles :

Gamma ray lines from direct annihilation of photons
Gamma ray continuum from hadronization of annihilation products.



IACT Dark Matter Program

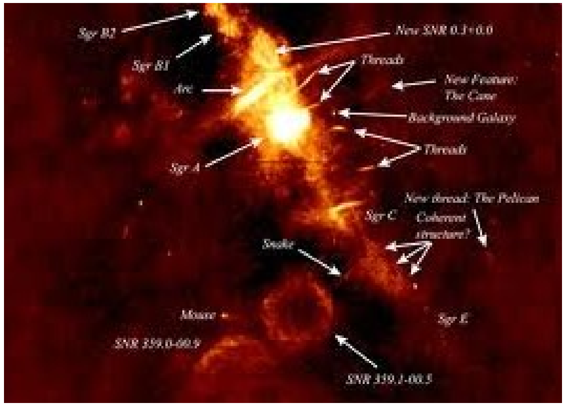
Galaxy Clusters : Lot of DM content, distant, possible astrophysical background

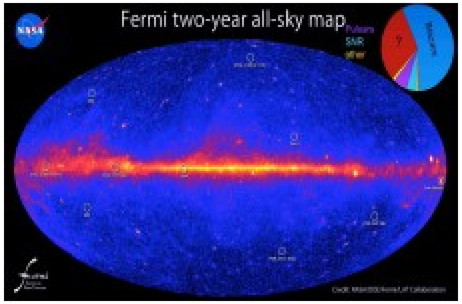
Galactic Center : Complex region, huge astrophysical background, nearby

Dwarf Galaxies : DM dominated, less astrophysical background, low flux

Unidentified HE sources from Fermi

Plan : Deep observations on a variety of source classes





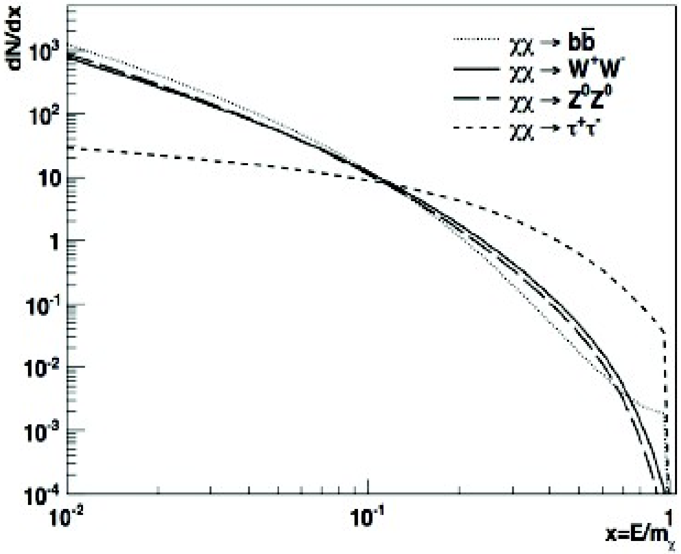
Observations on dSph, focus on Segue

Segue1 : 23 +/- 2 Kpc, discovered in 2006 in SDSS

Most DM dominated dSph known to date

Deep Exposure on Segue

No signal, flux UL limits calculated



Quantity/dSph	Draco	Ursa Minor	Boötes 1	Willman 1	Segue 1
Excess (counts)	-28.4	-30.4	28.5	-1.45	31.2
Significance[a]	-1.51	-1.77	1.35	-0.08	1.4
95% CL UL[b] (counts)	18.8	15.6	72.0	36.7	102.5
E_{TH} (GeV)	340	380	300	320	300
Flux UL 95% CL[c] (cm^{-2} s^{-1})	0.49×10^{-12}	0.40×10^{-12}	2.19×10^{-12}	1.17×10^{-12}	8×10^{-13}

Upper limits on Annihilation Crosssection

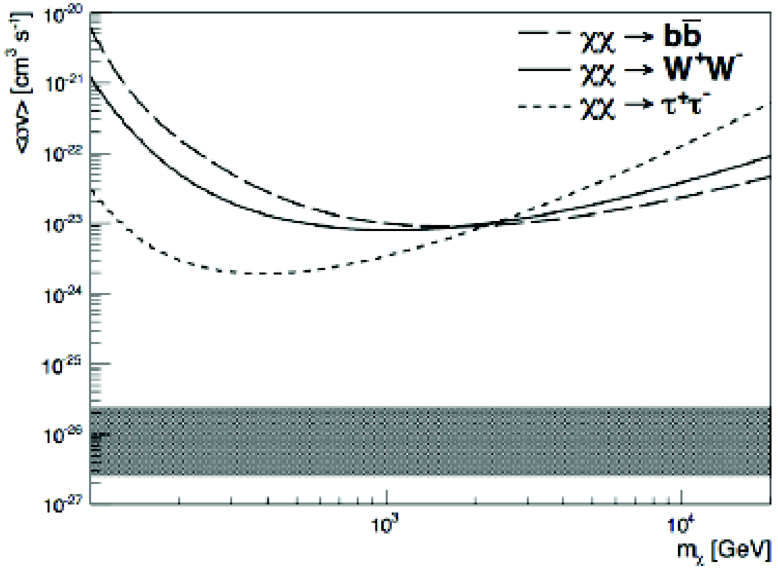
Differential gamma-ray flux from DM annihilation coming from a spherical DM halo:

$$\frac{d\phi}{dE}(\Delta\Omega, E) = \frac{<\sigma v>}{8\pi m_{DM}^2}\left(\frac{dN_\gamma}{dE}\right)_{DM} \boxed{< J(\Delta\Omega)) >}$$

Upper limits on the number of detected gamma-ray N_γ constrain the WIMP parameter space:

$$< \sigma v >^{95\%CL} = \frac{8\pi}{< J(\Delta\Omega) >} \times \frac{N_\gamma^{95\%CL} m_{DM}^2}{T_{OBS}\int_0^{m_{DM}} A_{eff}(E)\frac{d^3\Phi_\gamma}{dEdAdt}dE}$$

$$\langle J \rangle = \int_{\Delta\Omega} d\Omega \int dl\, \rho^2(r(l))$$



For Segue, Einasto profile has been chosen

Exclusion curves give us an idea on the several range of uncertainities from DM models on crosssections

VERITAS Coll, PRD, (2012)

Tests for Lorentz Invariance Violation

In standard relativistic QFT, space-time considered as a fixed arena in which physical processes take place

- Planck length $l_P \equiv \sqrt{\hbar G_N / c^3} \approx 1.6 \times 10^{-33} \mathrm{cm}$
- corresponds to $M_P \equiv \sqrt{\hbar c / G_N} \approx 1.2 \times 10^{19} \mathrm{GeV}$

gravity as non-renormalizable interaction
may leave distinctive imprint at energies $\ll$ Planck mass
if violating any fundamental symmetry

Foamy structure of quantum space-time:

- Space-time at large distances is "smooth" but, at very short distances it might show a very complex structure due to quantum fluctuations:

Manifestations

- Energy dependent dispersion of radiation can be manifested in arrival time of photons

Amelino-Camelia et al. (1998)

- Look for signatures for deviations from QFT, presumably suppressed by some power of Planck mass
- From a purely phenomenological point of view, the effect can be treated by a perturbative expansion: Assume $E \ll M_{Planck}$.

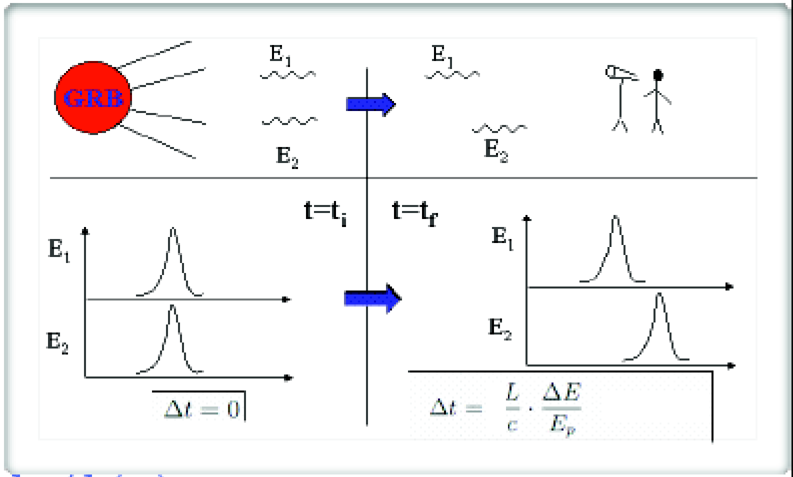
$$c^2 p^2 = E^2 \left(1 + \xi \left(\frac{E}{M_P}\right) + \mathcal{O}\left(\frac{E^2}{M_P^2}\right) + \ldots\right)$$

- explicit breaking of LI at Planck mass scale
- in critical string theory: quadratical deviation only

- Implies energy-dependent speed of light:

$$v = \frac{\partial E}{\partial p} \approx c\left(1 - \xi\left(\frac{E}{M_P}\right)\right)$$

Vacuum acquires non-trivial optical properties: refractive index v(E)=c/n(E)



$$\Delta T = \xi \frac{\Delta E}{M_{QG}} \times \frac{L}{c} = \xi \frac{\Delta E}{E_{QG}} \times H_0^{-1} \int dz/h(z)$$

Aldo Morselli

Scineghe 08

Phenomenological Approach

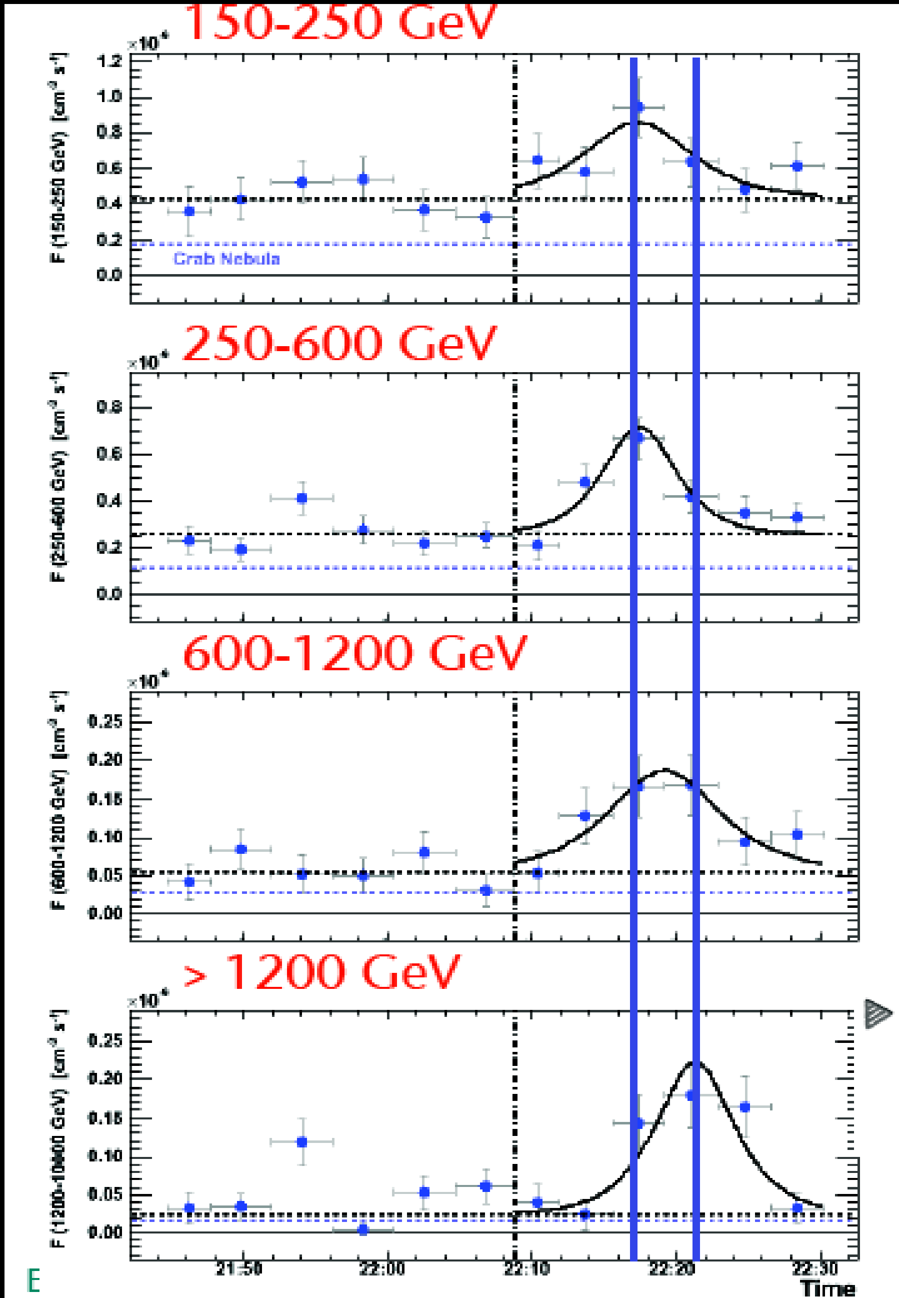
- Need very fast transient phenomena providing a “time stamp” for the simultaneous emission of different energy γ –rays.

Figure of merit for QG tests: $M_{\mathrm{QG}} = \xi \frac{LE}{c\Delta t}$

- *E*: the lever arm
  - for the instrument (*Instrumental limit*)
  - for the observed energies (*Observing a source*)
- t: the time resolution
  - time resolution of the instrument (*Instrumental limit*)
  - the binning time to have enough statistics (*Observing a source*)
- L: the typical distance of the sources

Taken from R.Wagner, Scineghe 2008

A large flare from Mrk 501



LCs for different energy ranges (4 min bins)

➡Flare is seen in all energy ranges

Time delay? between highest and lowest energy ranges

- First time in VHE regime

Photons emitted simultaneously at different energies?

- Delay found, no-delay probability P=2.6%.

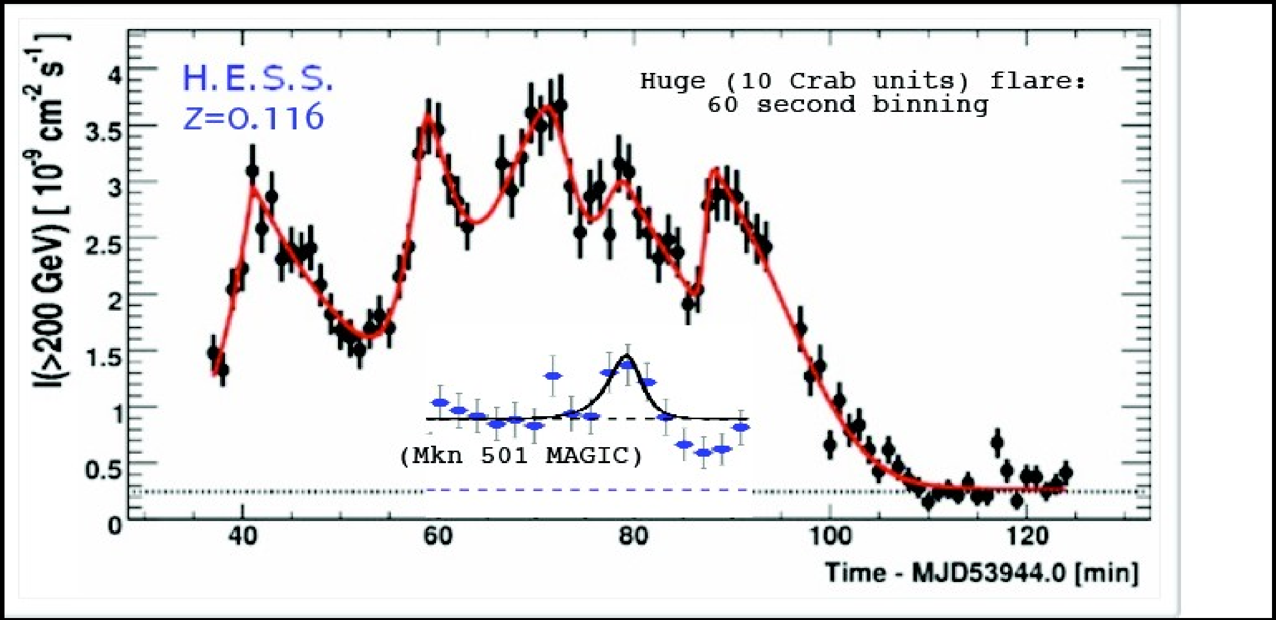
$$\tau = (0.030 \pm 0.012)\mathrm{s/GeV}$$
$$\tau_q = (3.71 \pm 2.57) \times 10^{-6}\mathrm{s/GeV}^2$$

- Establish lower limits:

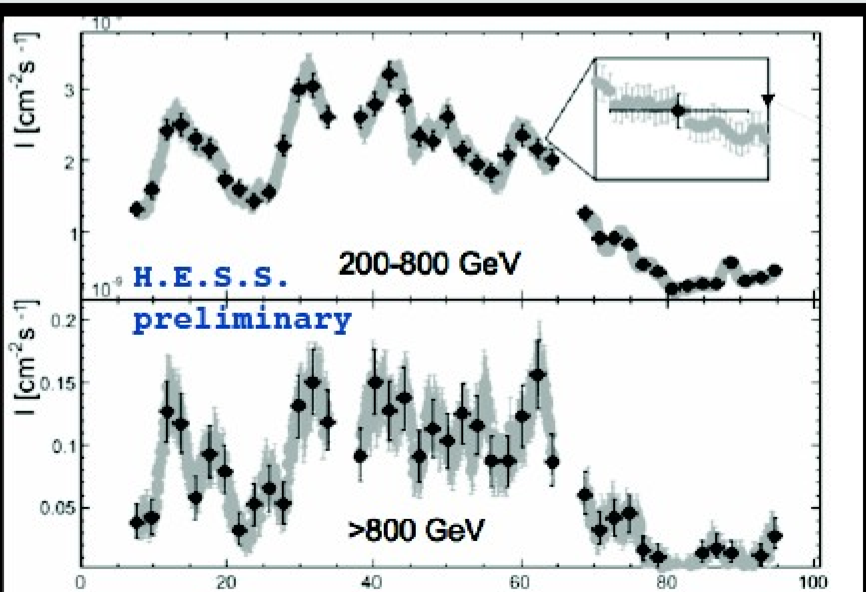
$$M_{\mathrm{QG1}} > 0.26 \times 10^{18}\mathrm{GeV}$$ linear dispers
$$M_{\mathrm{QG2}} > 0.27 \times 10^{11}\mathrm{GeV}$$ quadr. dispers

MAGIC Collab.
2008

A Large Flare from PKS 2155-304



HESS Collab. 2007



Bühler & Jacholowska (2008)

Methods: Oversampled light-curves, wavelets

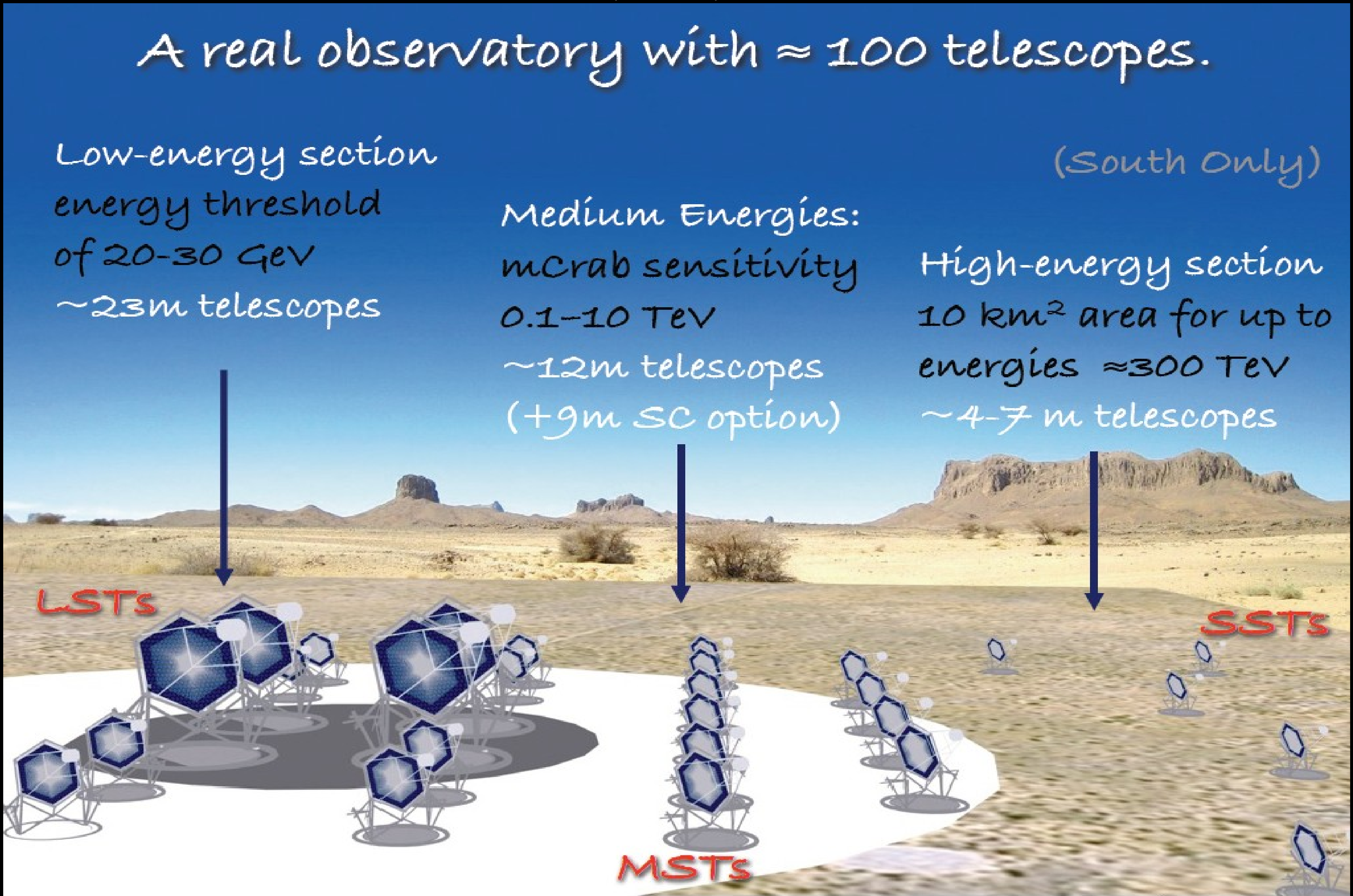
No significant time lag found Δt=20s; RMS=28s.

Assume source effect can be neglected: $\Delta t < 72\mathrm{s}$

$$\Delta E = \langle E_{>800\mathrm{GeV}} \rangle - \langle E_{200-800\mathrm{GeV}} \rangle \approx 1.02\mathrm{TeV}$$

$$M_{\mathrm{QG1}} > 0.62 \times 10^{18}\mathrm{GeV}$$

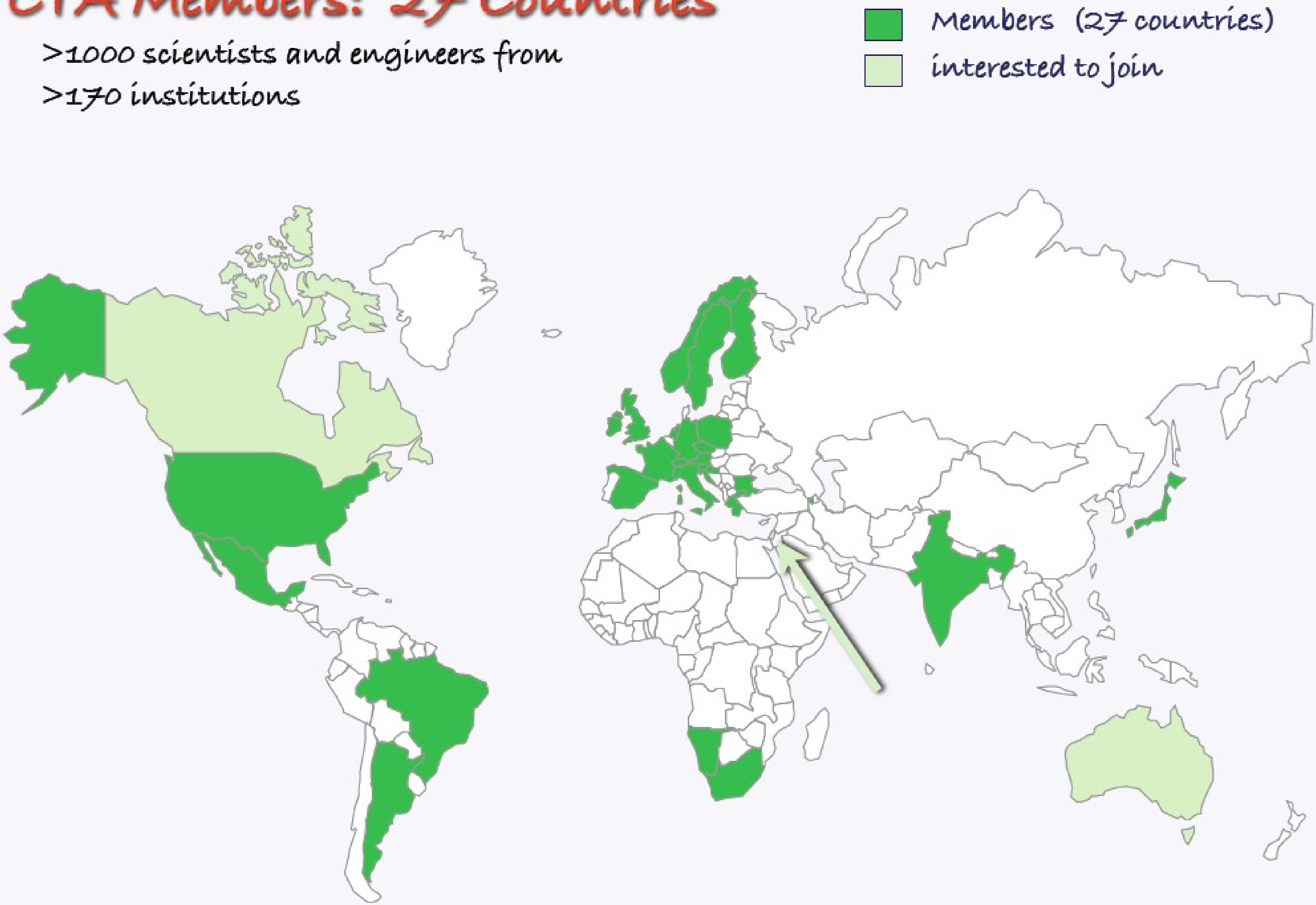
Perspectives for future Cerenkov Telescope Array (CTA)



CTA Members: 27 Countries

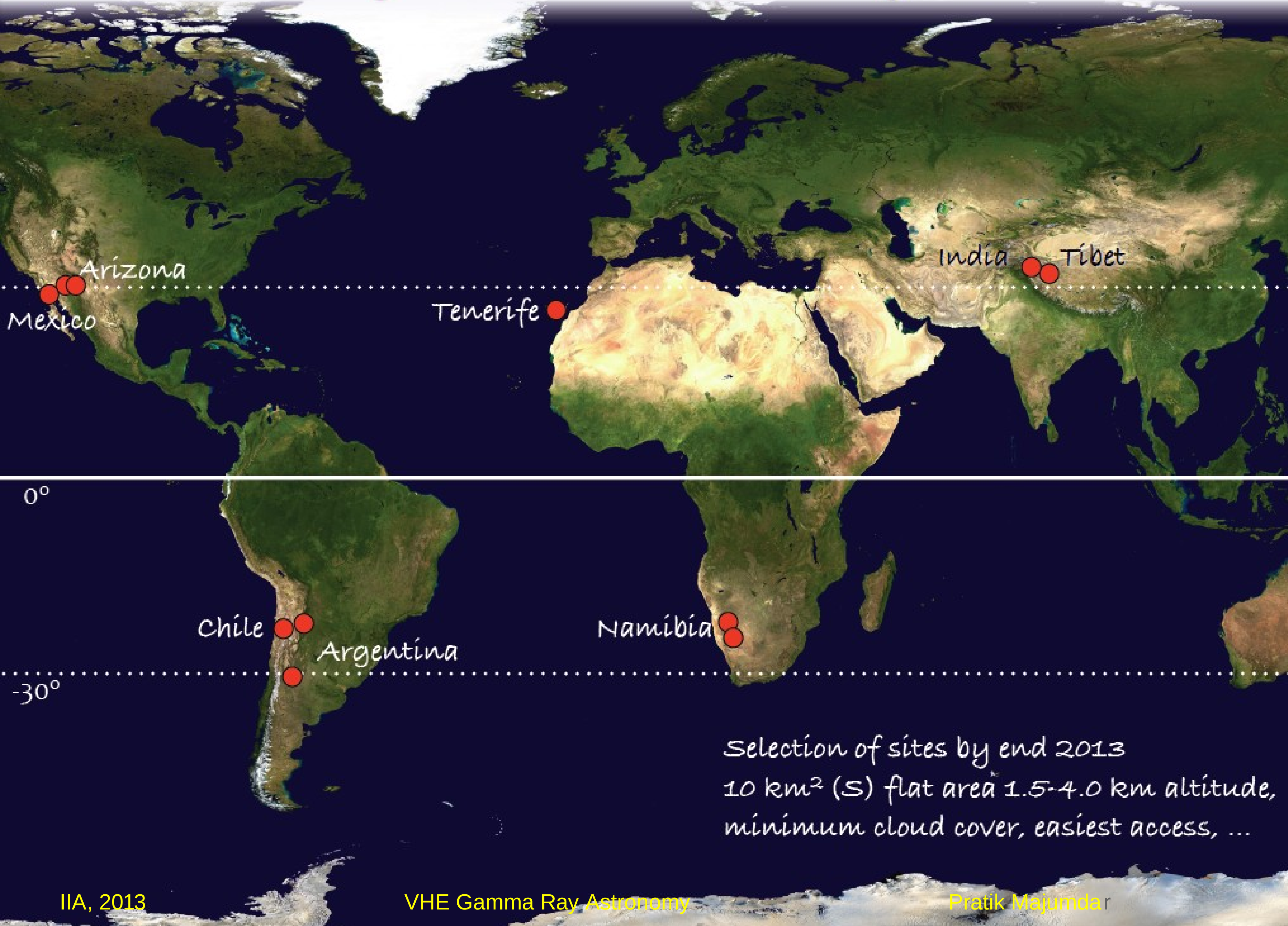
>1000 scientists and engineers from

>170 institutions



Argentina, Armenia, Austria, Brazil, Bulgaria, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, Sweden, Switzerland, UK, USA

One observatory with two sites - operated by one consortium



Selection of sites by end 2013
10 km² (S) flat area 1.5-4.0 km altitude,
minimum cloud cover, easiest access, ...

Indian Consortium in CTA (SINP, TIFR, IIA, BARC)

- Site Survey at Hanle (IIA/TIFR) : Proposal submitted to CTA Consortium
- Simulations for optimizing array configurations (SINP, BARC, TIFR) : Test production done at SINP
- Calibration for the camera of the prototype LST (SINP) : Technical responsibility under Pratik Majumdar
- Other tasks being identified and worked upon

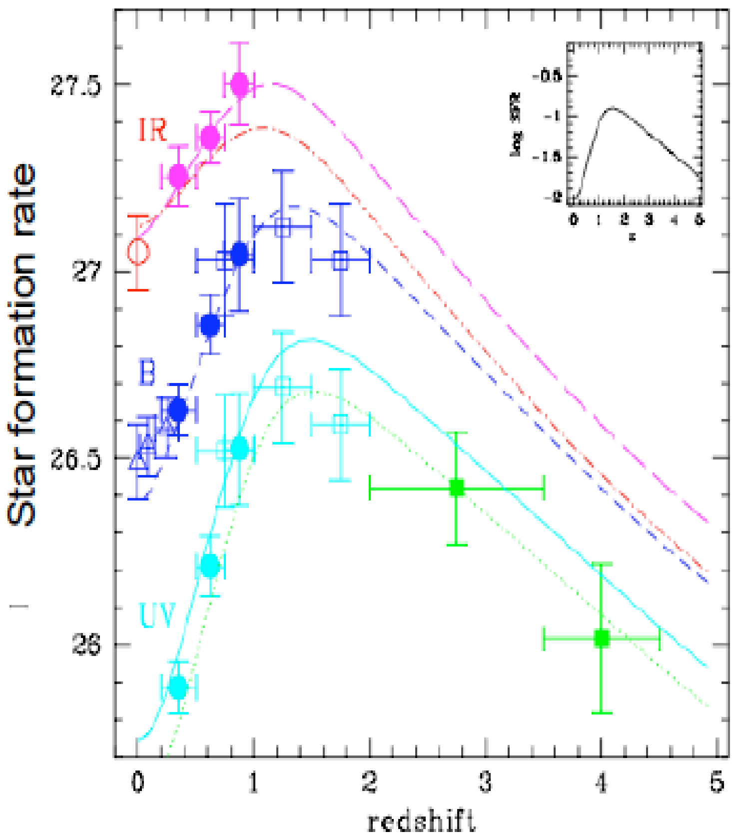
- Next major task is to identify areas of contribution, make a proper budget and submit the 4-institute proposal.

Major Goals to be accomplished

Simultaneous observation of intrinsic and absorbed parts of the spectrum

15 – 20% EBL resolution is possible : What about EBL evolution ?

- Star and galaxy evolution is largely unknown
- Fermi (CTA) can measure blazar spectra up to redshift **z ~ 1** (**z ~ 2**)
- Such sources are behind the main star formation epoch ➡ **beacons**
- Using the sources with **z**<1, the EBL evolution can be resolved!
- Need >100 sources
- Need to know intrinsic evolution of the sources (BH masses, internal radiation fields, see A. Reimer 07)

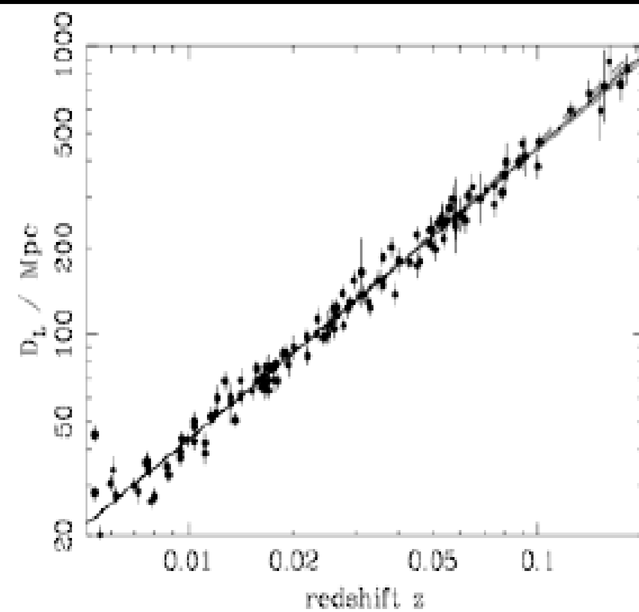


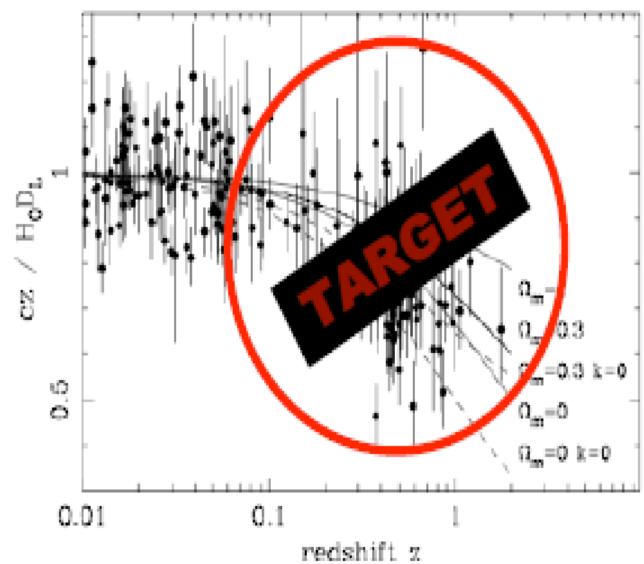
Madau, 1998

Cosmology with AGNs in GeV TeV gamma rays

Based on Blanch & Martinez, 2001

- If one knows
  - **Intrinsic AGN spectrum and**
  - **EBL density**
- determine distance to the sources using the EBL signature in the measured spectra
- Can cover range from z=0.004 to z > 2

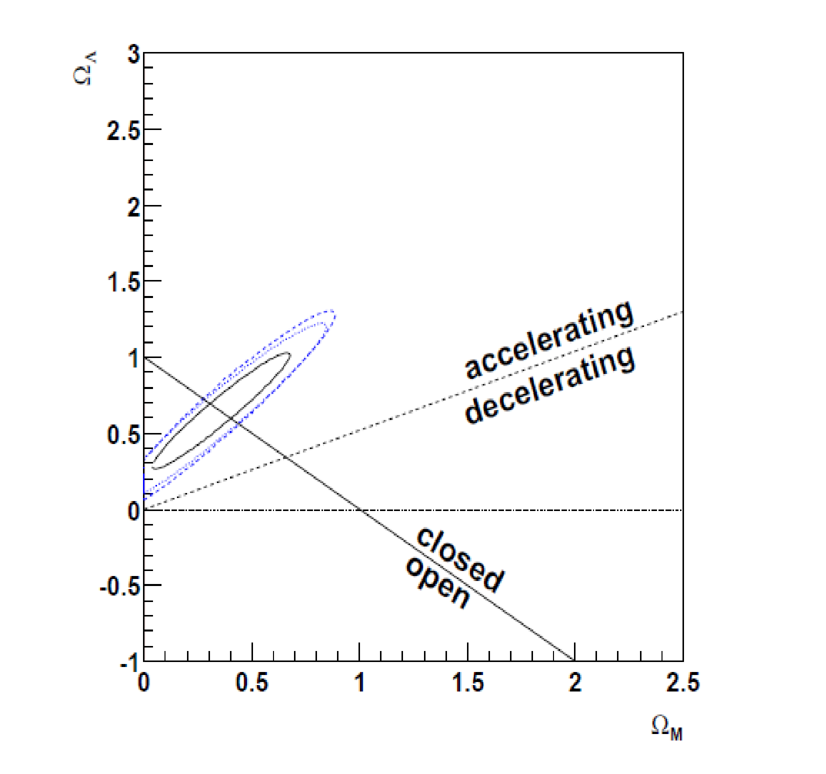




Cosmology with GeV-TeV gamma rays

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

The study of absorption spectra of AGN at different redshifts will open up the study of cosmological parameters



Independent and behaves differently than Luminosity-distance relation in SN 1A

Relies on existence of EBL which is assumed to be uniform and isotropic on cosmological scales.

AGNs as sources : high z

Blanch and Martinez 2004

Conclusions

EBL carries essential cosmological information : Blazars validated as probes of gamma ray horizon

GeV – TeV gamma rays can put strong constraints on density of EBL

With common sources between Fermi and TeV instruments we hope to disentangle internal absorption from EBL

UV/optical component of EBL at z ~ 1 by Fermi-LAT

Current understanding : EBL lower than what was thought before.

Upcoming Cerenkov Telescope Array (CTA) will give more insights to it

Specially measure mid to Far IR EBL to better accuracies

Indirect independent distance measurements : Hubble parameter, hope to do serious cosmology , Indirect detection of DM is quite feasible.

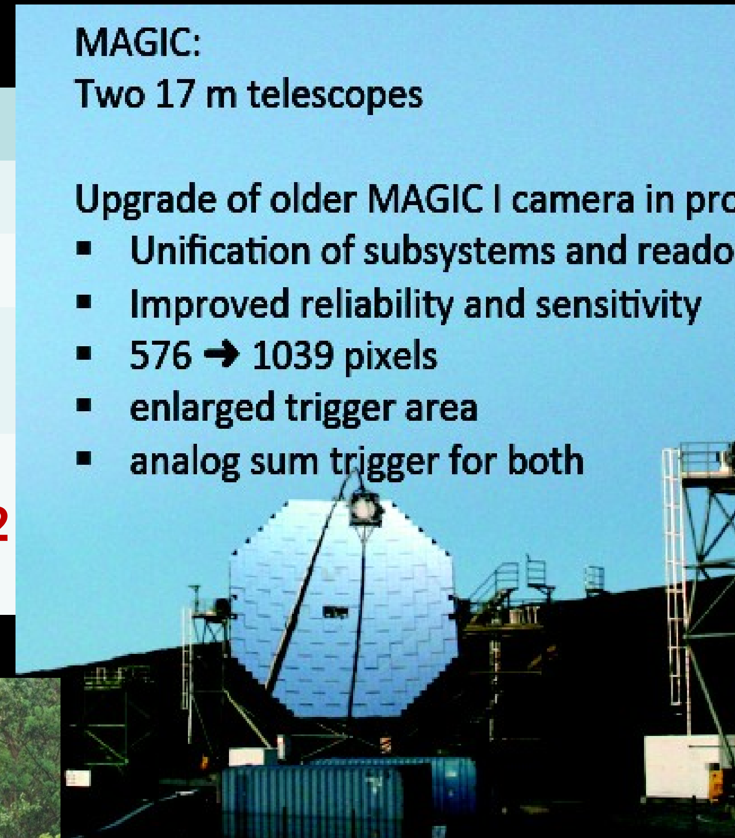
CTA will also probe fundamental physics questions : tests on LIV .

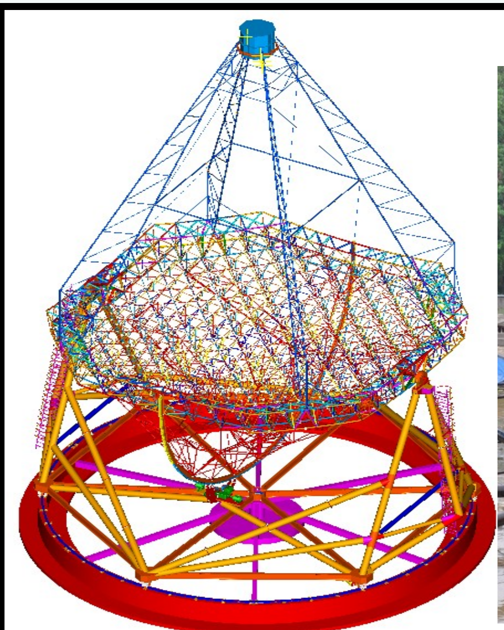
Backup Slides

Immediate Steps in future

VERITAS Upgrade

Year	Item	Status
2009	Relocation of Telescope 1	Complete
2010	Network Upgrade	Complete
2011	Trigger Upgrade: faster, more flexible telescope trigger.	Complete
2012	**Camera Upgrade: replacement of all 2,000 PMTs with high-QE devices.**	**Complete : Summer 2012**



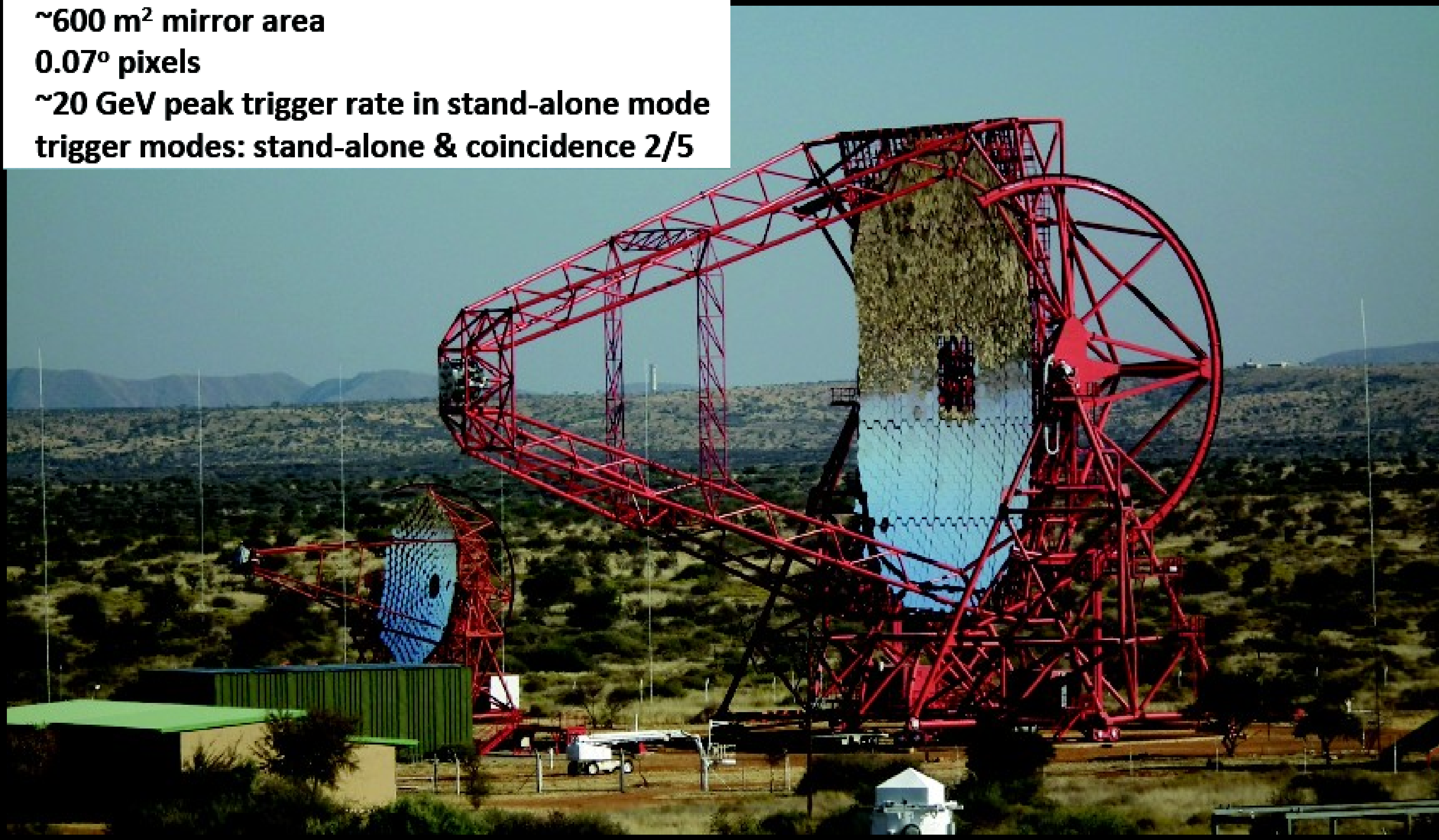


MACE @ HANLE

Hanle: 4200 m asl, 32.7N

Giant 28 mt telescope : H.E.S.S. II

~600 m^2 mirror area
0.07^o pixels
~20 GeV peak trigger rate in stand-alone mode
trigger modes: stand-alone & coincidence 2/5



How to do even better with Ch. telescopes ?

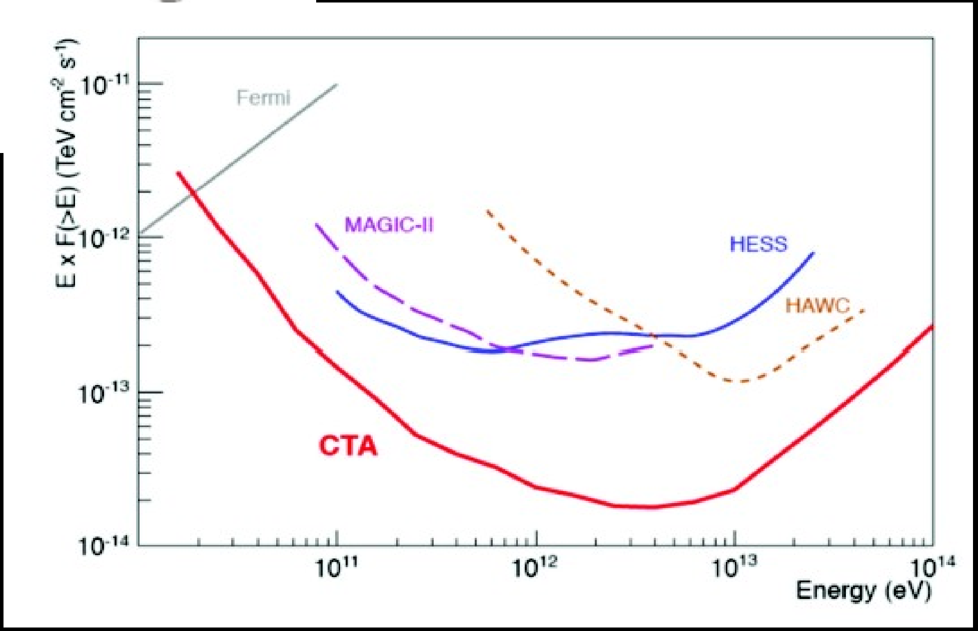
A future Cherenkov observatory needs:

for E > TeV:
bigger collection area
(i.e. large array of telescopes, wider FOV)

more events

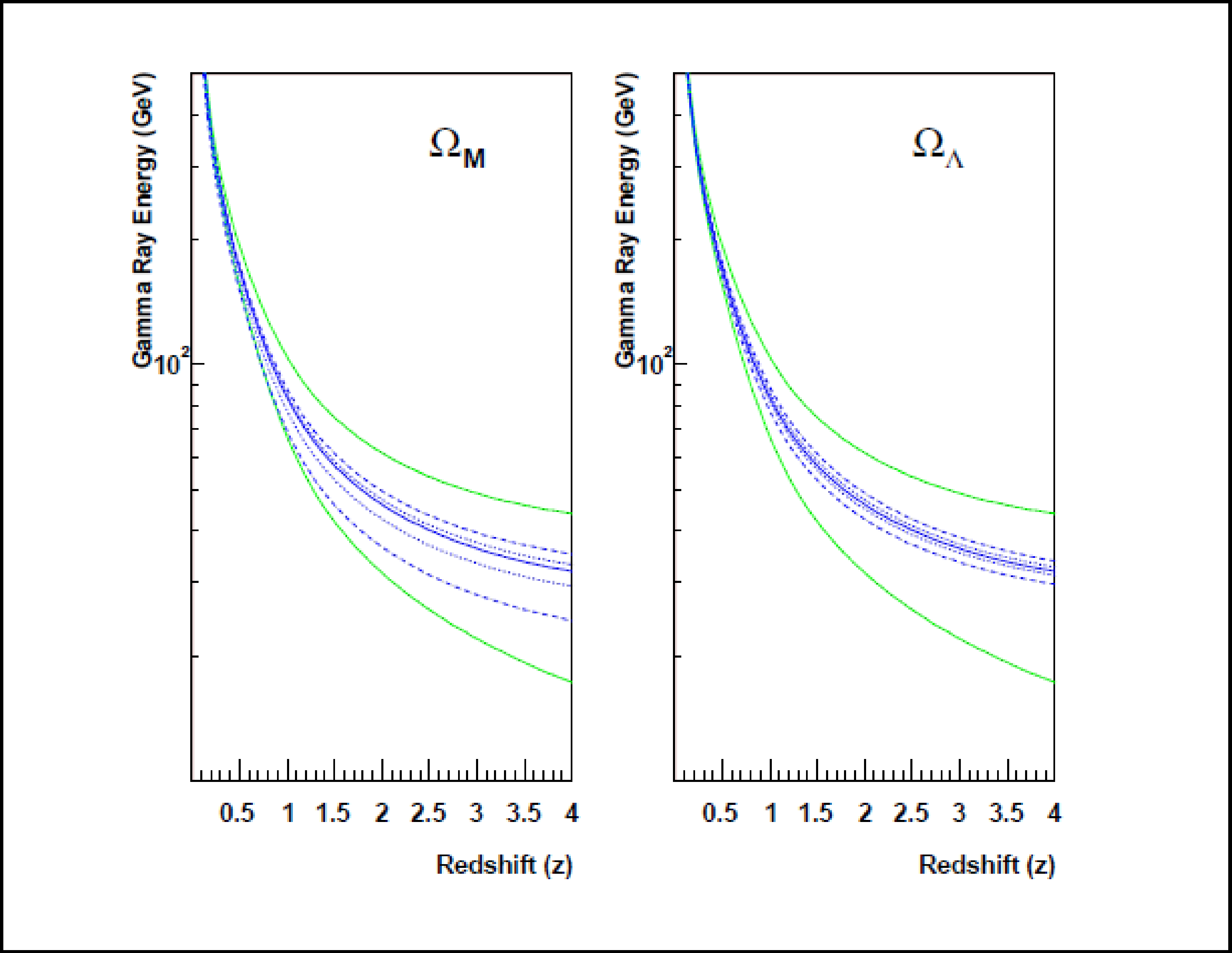
for E < TeV:
better background rejection
(i.e. large array of telescopes, wider FOV for multiple shower images)

better events



Wish list ~ at least 10 times better Sensitivity, ~ 5 angular resolution may be possible

Cosmology with TeV gamma rays.



Pair Conversion Telescopes

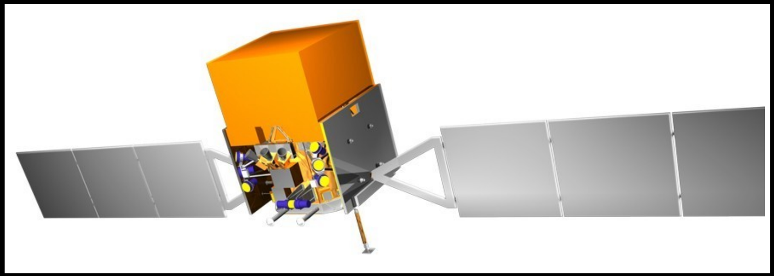
- EGRET (on Compton gamma ray observatory)

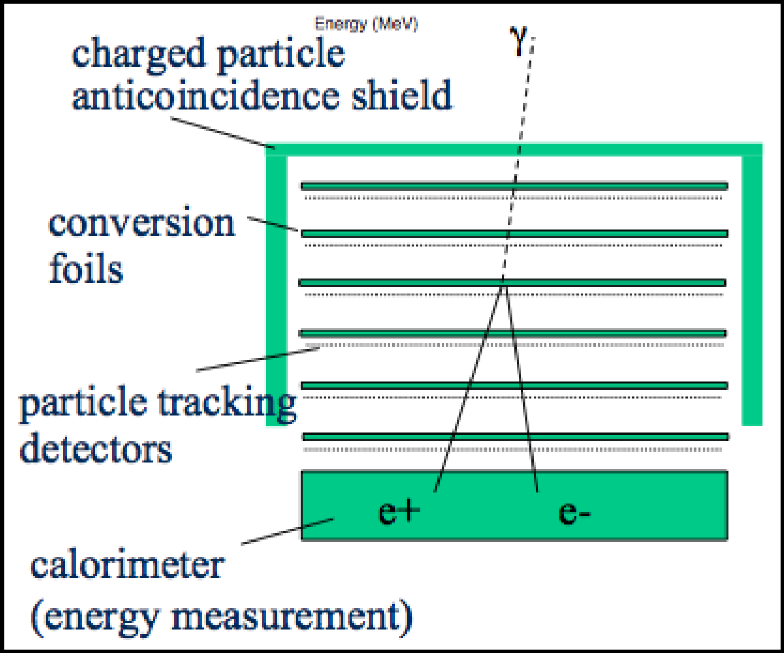
Three main parts:

A tracker to determine the trajectory of the $e^{\pm}$

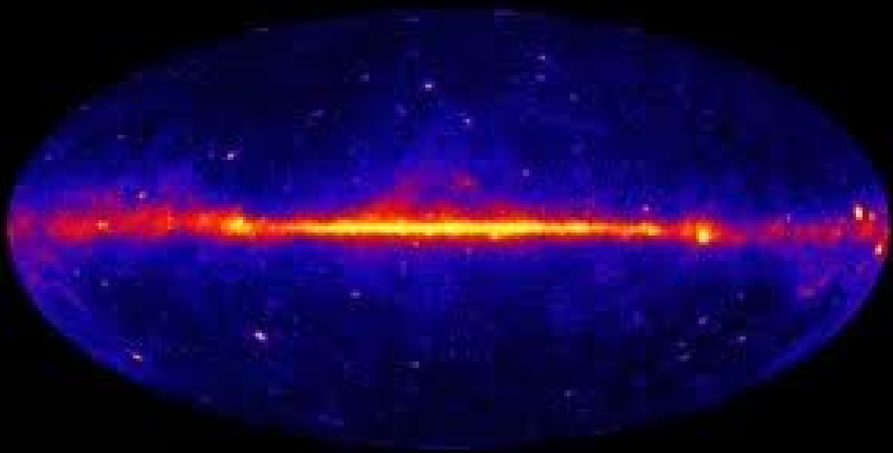
A calorimeter for measuring the energy

An "active shield" against charged cosmic rays (particle detector set in anti-coincidence)





- Skymap for first 2 years



- Launched successfully in 2008 June, delivering a wealth of data on gamma ray sources, > 1500 point sources

Fermi Acceleration

Stochastic Mechanism
Charged particles collide with clouds in ISM and are reflected from irregularities in galactic magnetic field
2^{nd} order

Charged particles can be accelerated to high energies in astrophysical shock fronts
1^{st} order acceleration