Cosmology with GeV-TeV Gamma Rays

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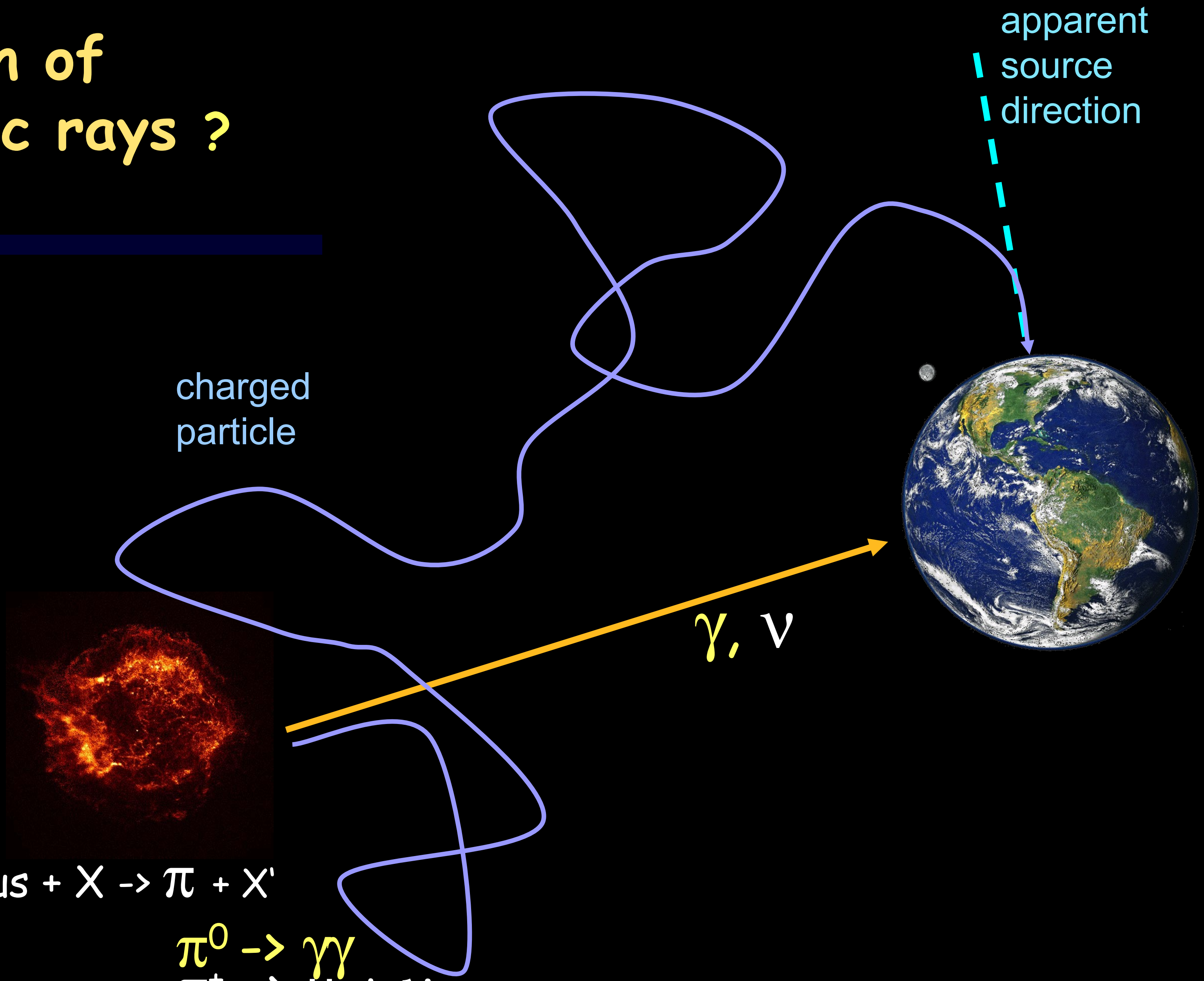
Outline:

- VHE Gamma Ray Astrophysics
- Atmospheric Cerenkov and Satellite Detectors
- Probing Cosmology with GeV-TeV gamma rays
- Conclusions and Future directions

Saha Theory Workshop : Cosmology at the Interface
January 28, 2015

Origin of cosmic rays ?



apparent
source
direction

charged
particle

γ, ν

nucleus + X -> π + X'

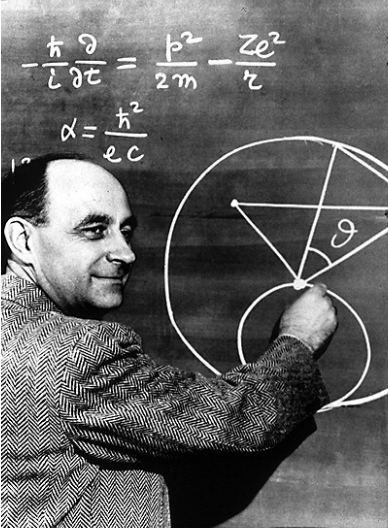
$\pi^0 \rightarrow \gamma\gamma$

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

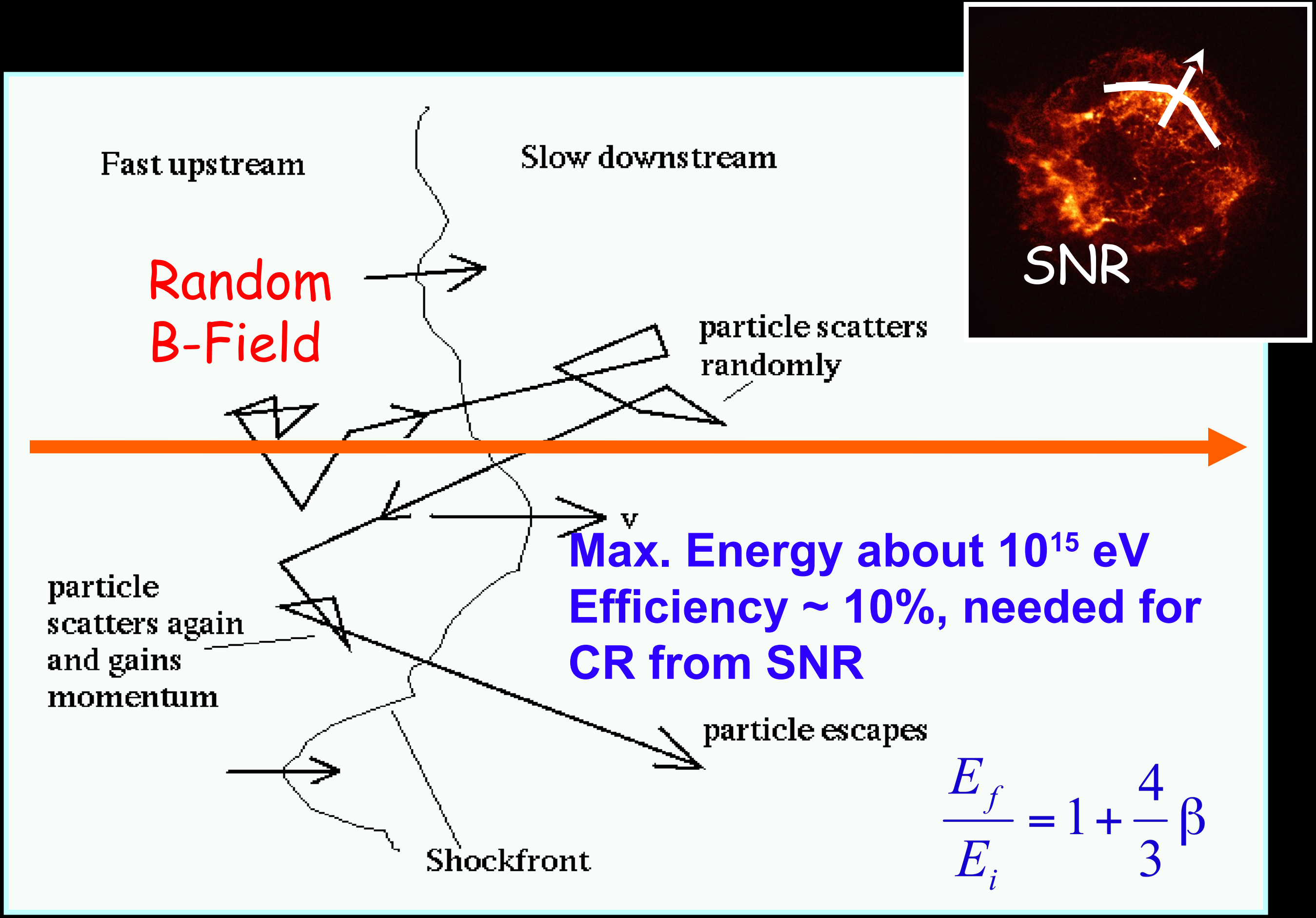
$\mu \rightarrow e + \nu\nu$

Shock acceleration mechanism

(by Enrico Fermi)



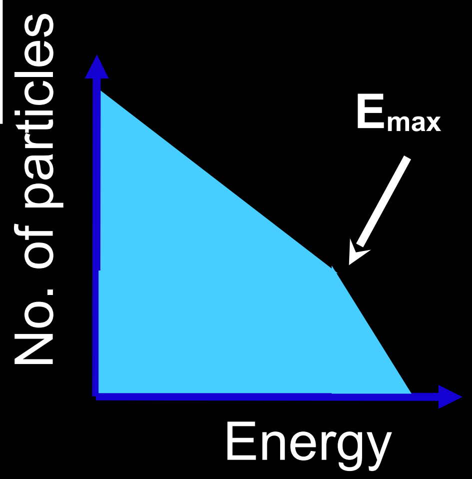
Particles (electrons and hadrons) get scattered many times in shock front and gain energy in each cycle (TeV energies → several 100 years)



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

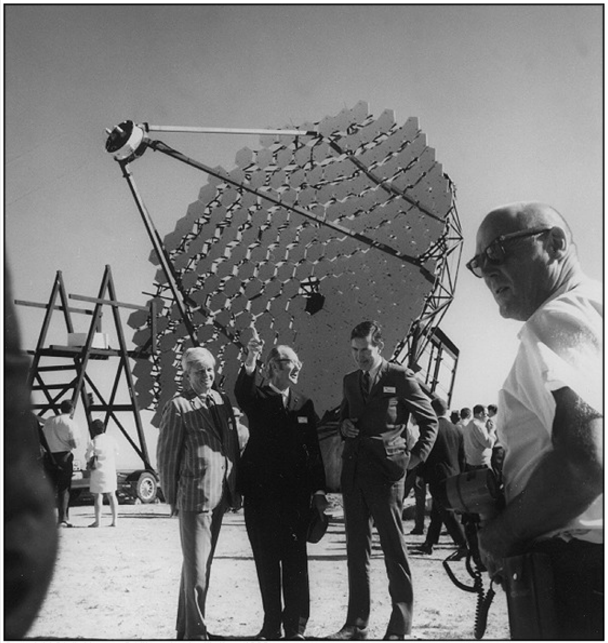


Predicts a $E^{-2.0}$ spectrum

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

Very High Energy γ-ray Astronomy

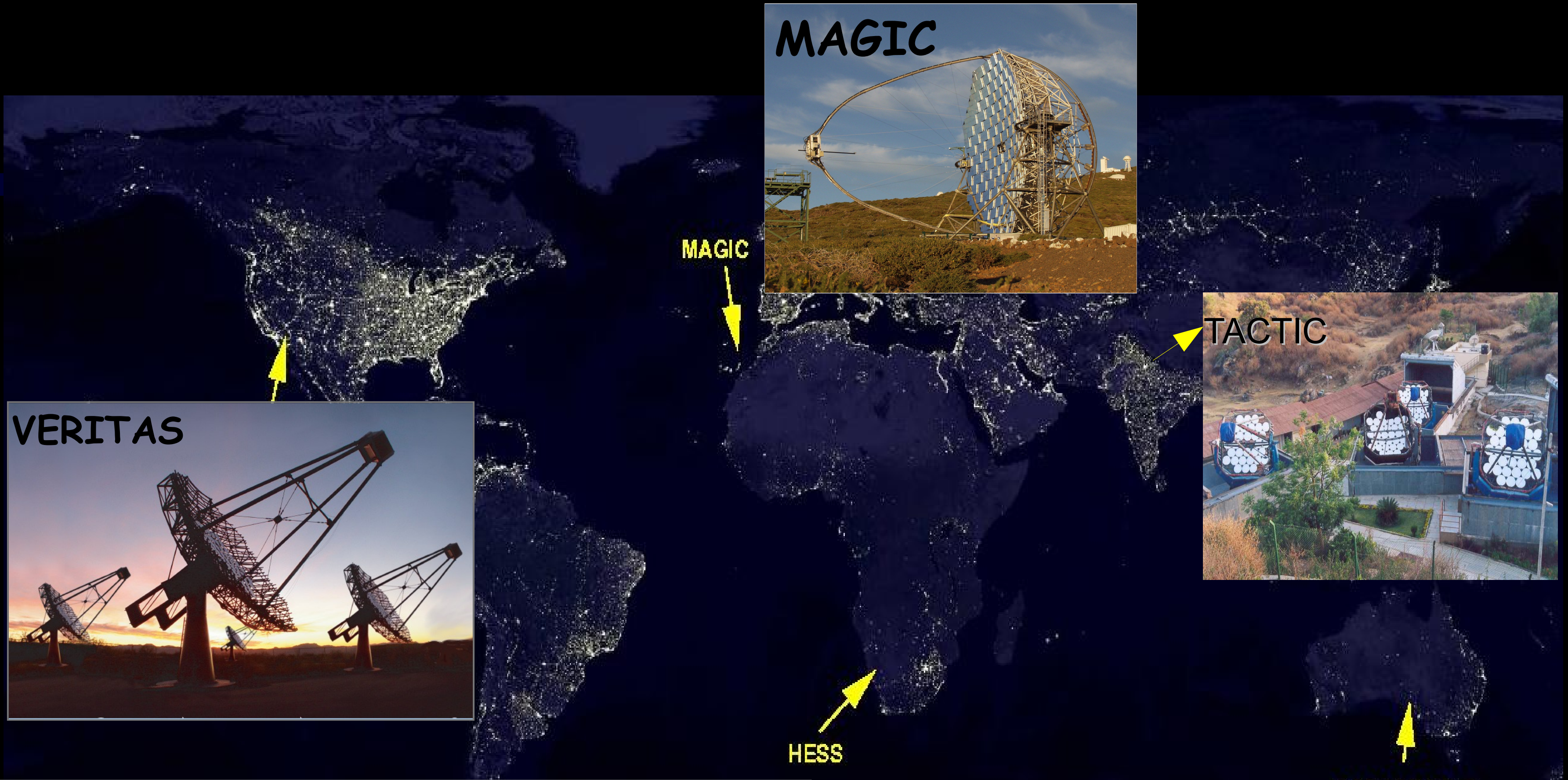
- Youngest astronomic discipline
- First significant measurement of TeV γ-ray emission from Crab Nebula by Whipple telescope in 1989
- > 50 hrs for 9 sigma detection



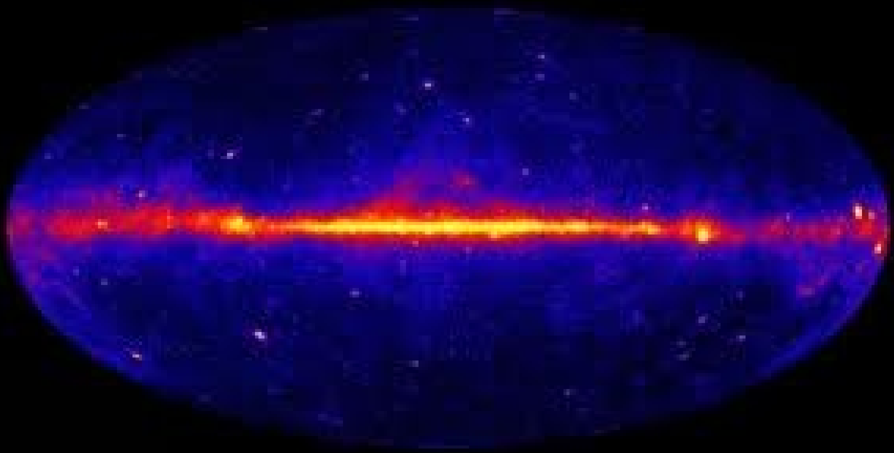
Copyright Digital Image Smithsonian Institution, 1998

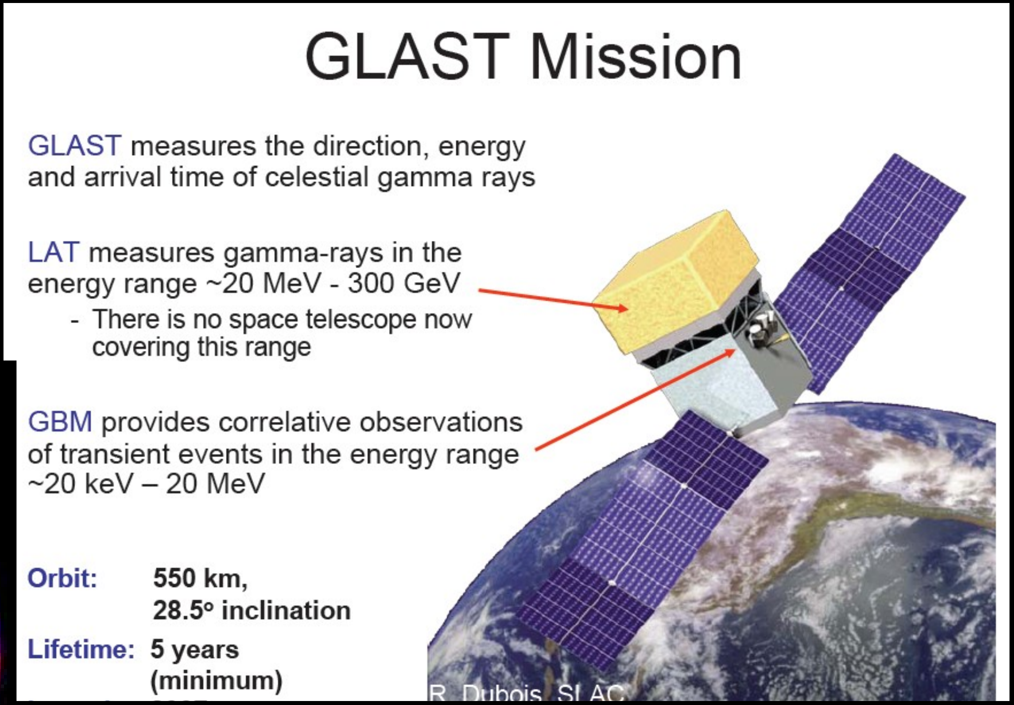
- Current generation since 2004
- 1% of Crab nebula flux
- You can now see TeV gamma rays from Crab nebula in < 2 mins

Current generation of IACTs



- Skymap for first 2 years





GLAST Mission

GLAST measures the direction, energy and arrival time of celestial gamma rays

LAT measures gamma-rays in the energy range ~20 MeV - 300 GeV

- There is no space telescope now covering this range

GBM provides correlative observations of transient events in the energy range ~20 keV – 20 MeV

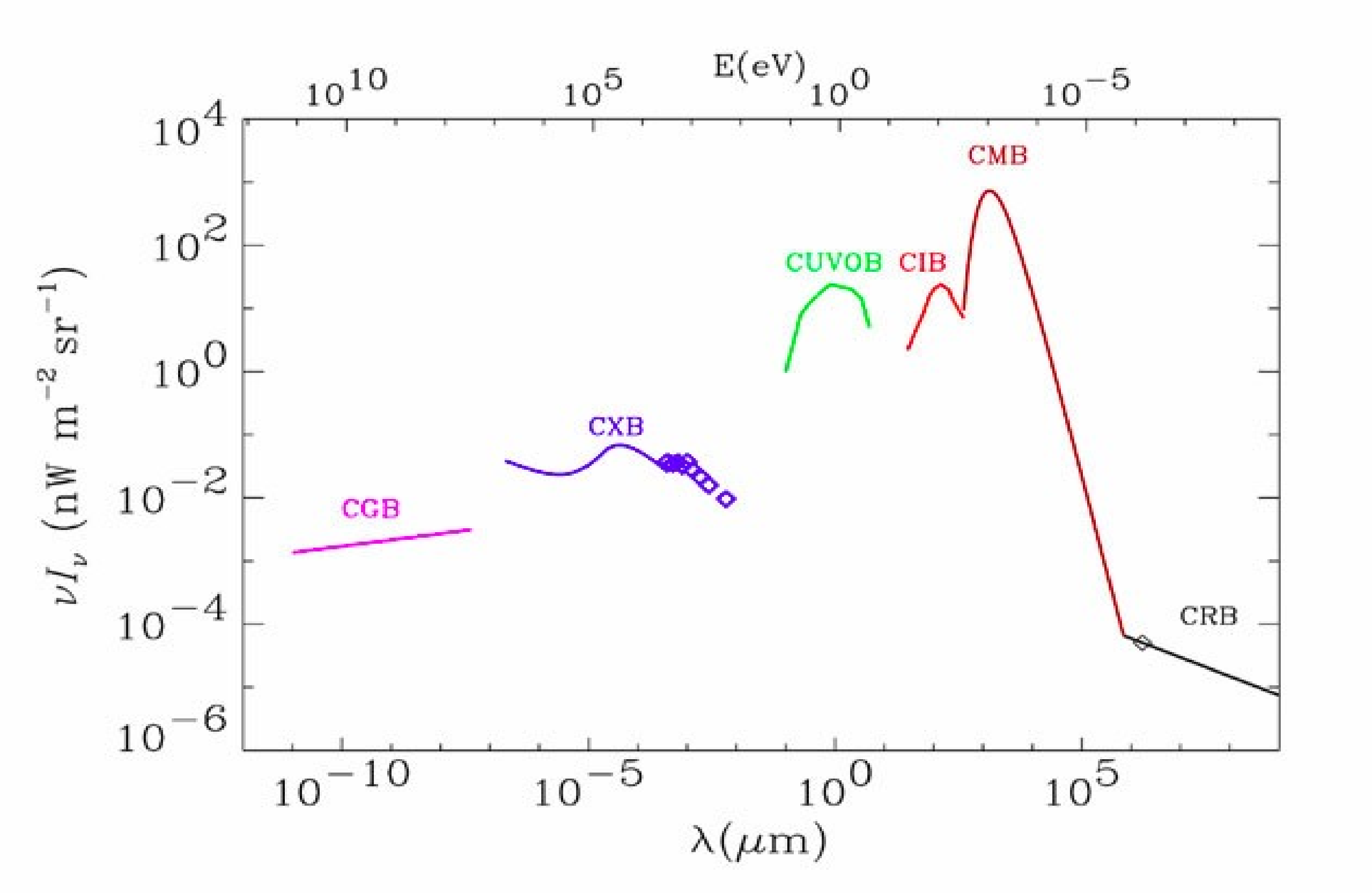
Orbit: 550 km,
28.5° inclination

Lifetime: 5 years
(minimum)

R. Dubois, SLAC

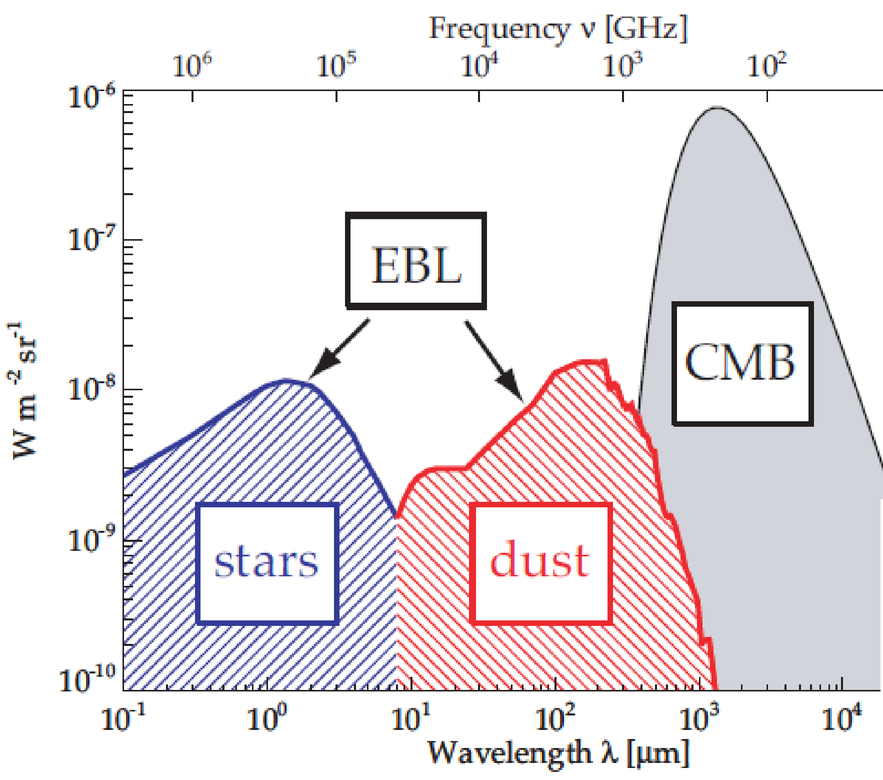
- Launched successfully in 2008 June, delivering a wealth of data on gamma ray sources, > 1500 point sources

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



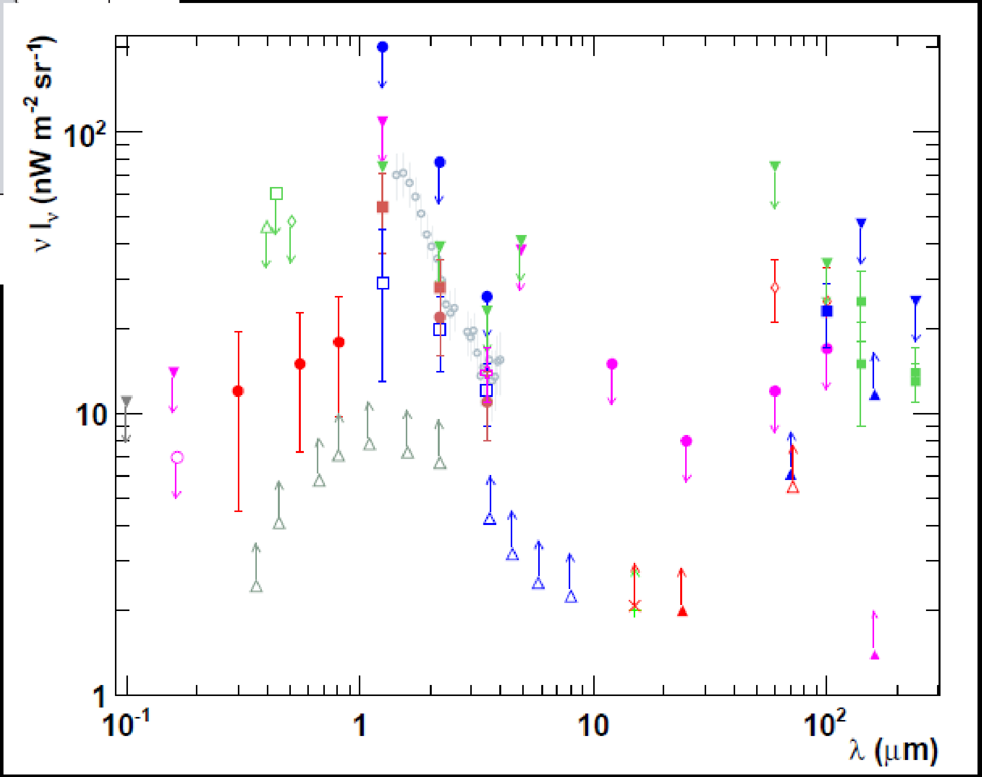
accumulated radiation in history of universe

Test of star formation and galaxy evolution

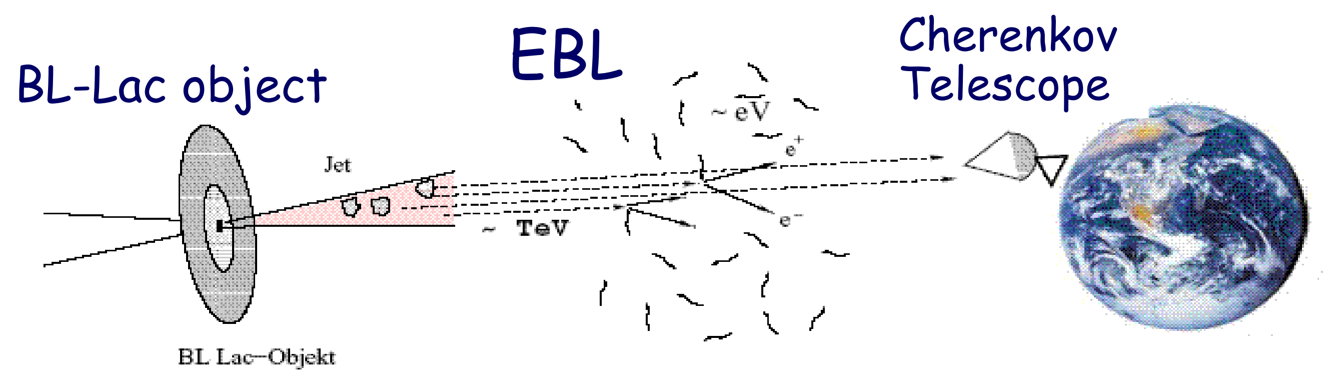
Direct and indirect measurements

Uncertainities due to strong foreground emission (zodiacal light)

Can TeV photons shed some light on it ?



Attenuation of VHE Gamma Rays



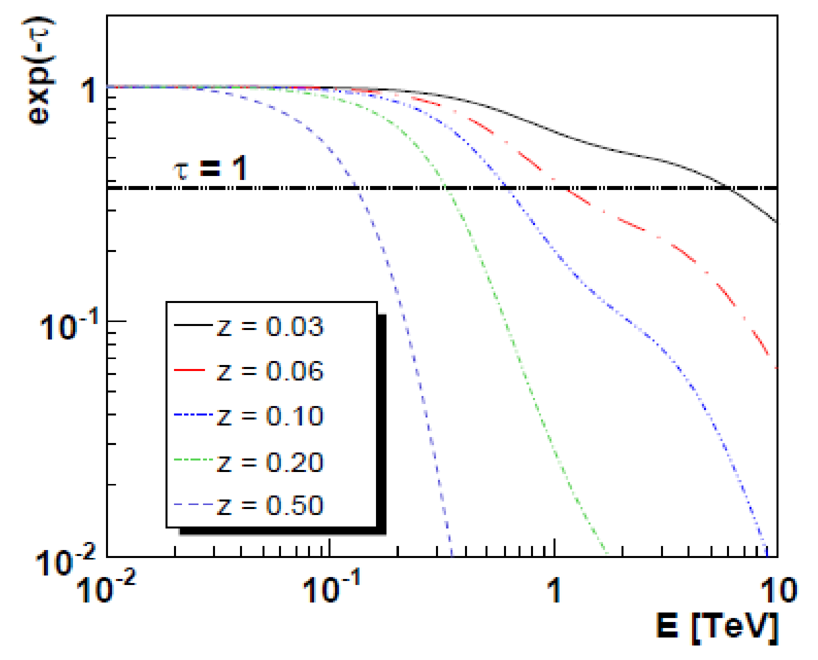
$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \longrightarrow e^+ + e^- \quad \text{with } E_{\gamma_{\mathrm{VHE}}} \cdot E_{\gamma_{\mathrm{EBL}}} > (m_e c^2)^2 \tag{1}$$

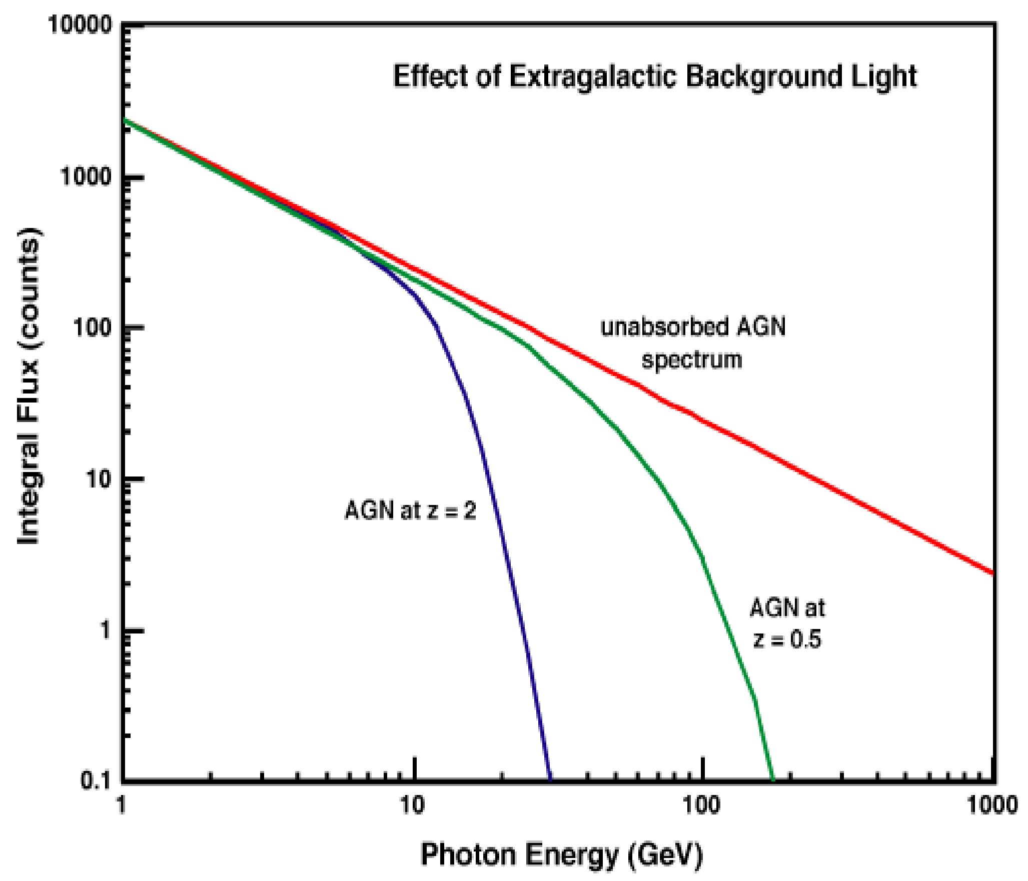
The optical depth of the VHE γ-rays, $\tau(E)$, emitted at the redshift z, can be then calculated solving the three-fold integral (see also [15]):

$$\tau(E_\gamma, z) = \int_0^z \mathrm{d}\ell(\mathrm{z}') \int_{-1}^{1} d\mu \, \frac{1-\mu}{2} \int_{\varepsilon'_{th}}^{\infty} d\varepsilon' \, n(\varepsilon', z') \, \sigma_{\gamma\gamma}(\varepsilon', E', \mu) \tag{2}$$

$$\begin{aligned} \mu &:= \cos\theta \\ n(\varepsilon) &:= \text{EBL energy density} \\ \mathrm{d}\ell(\mathrm{z}) &:= \text{distance element} \end{aligned}$$

Effects of EBL Absorption



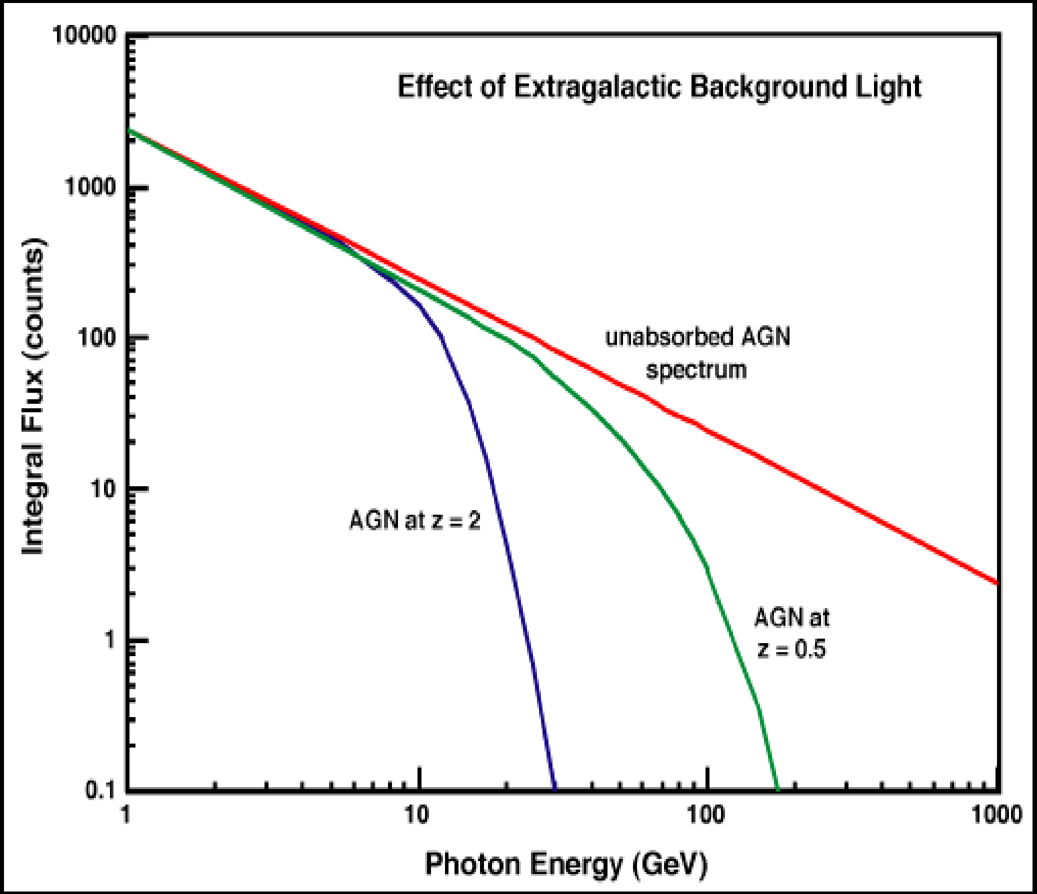


$$\frac{\mathrm{d}N_{\mathrm{obs}}}{\mathrm{d}E} = \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} \times e^{-\tau_\gamma(E,z)}$$

Optical depth depends on z and energy of the photons emitted

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*

Cosmic Gamma Ray Horizon => fundamental quantity in cosmology

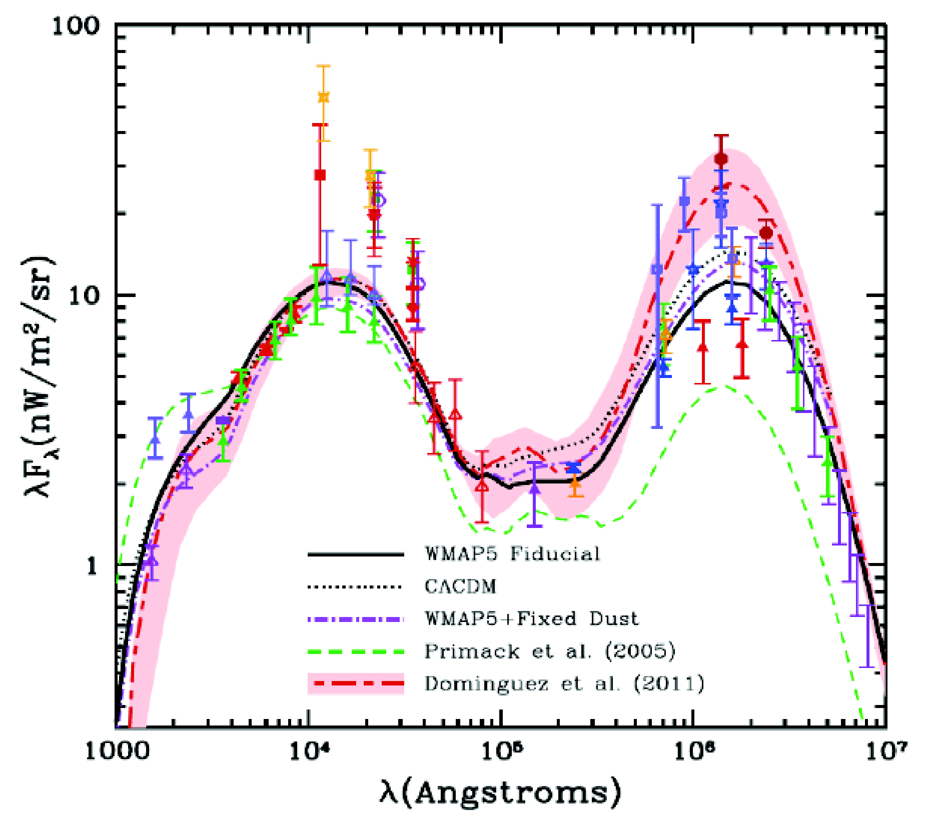
Extragalactic Background Light Models

- 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

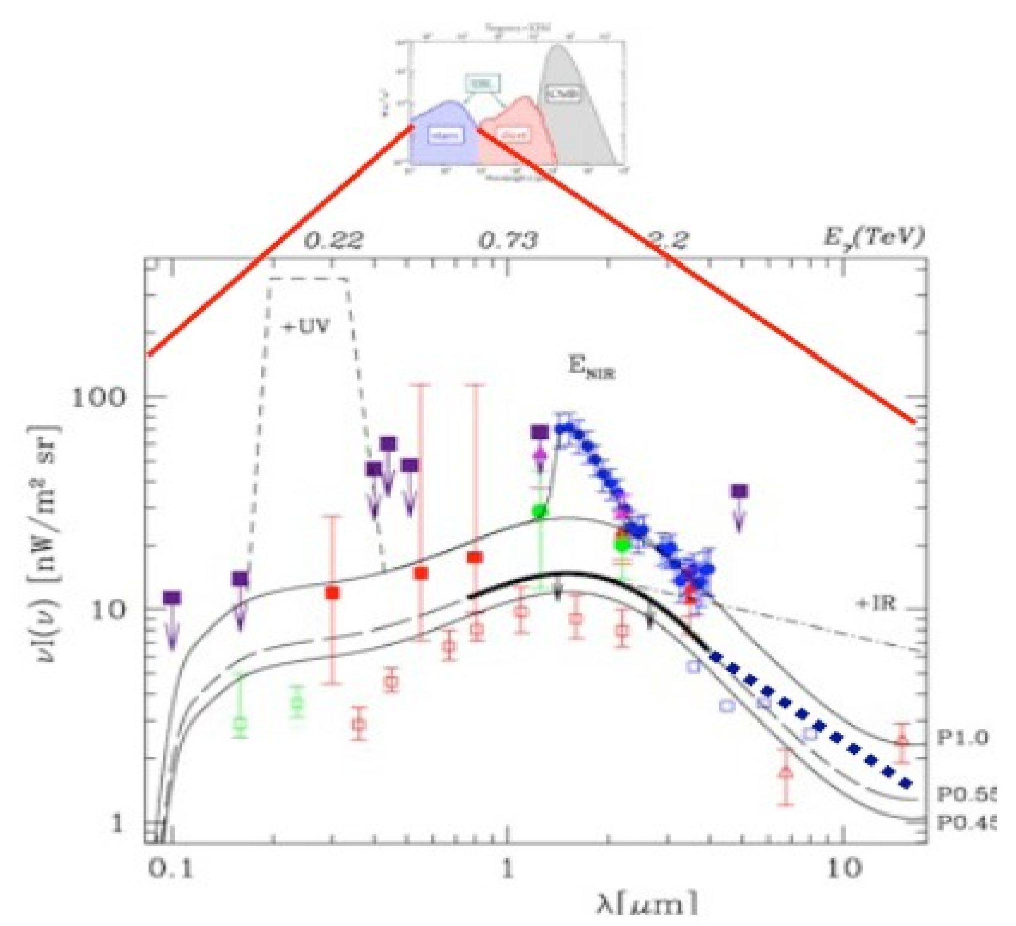
- Evolution directly observed and Extrapolated based on MWL observations

- 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

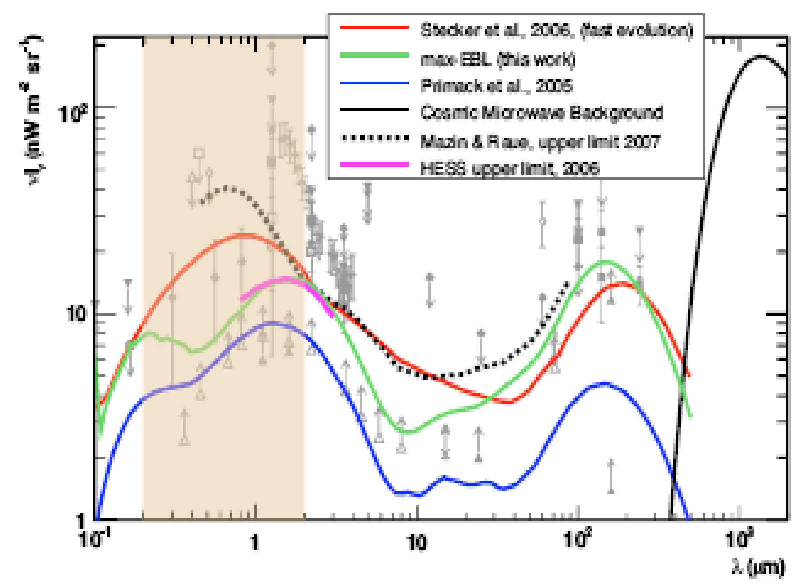


Gilmore et al MNRAS (2012), 422, 3189

Detections of mid redshift objects (z ~ 0.1 to 0.25) : Probe mid-IR



HESS, Nature 440 (2006) 1018-1021



High z (<1)probes optical and near-IR

z>1 probes UV radiation,from young stellar objects ==> global star formation rates

Observations of High red shift objects

3C 279 (z = 0.536)

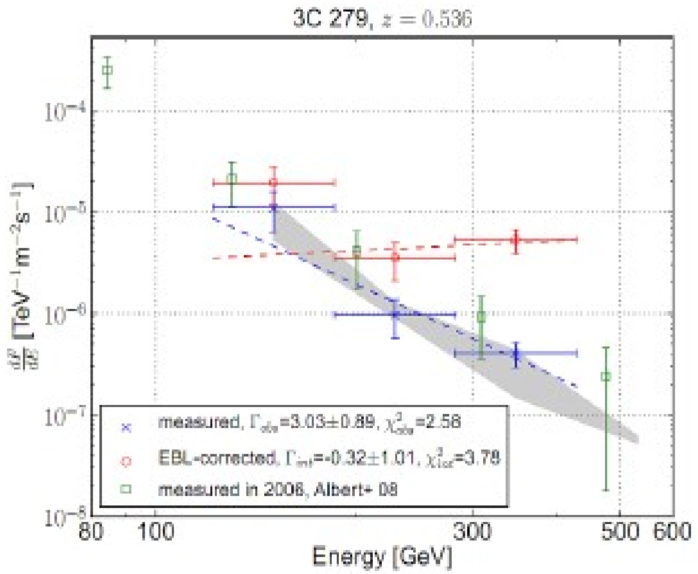
- discovered by MAGIC in 2006

  EBL constraints [Science 2008]

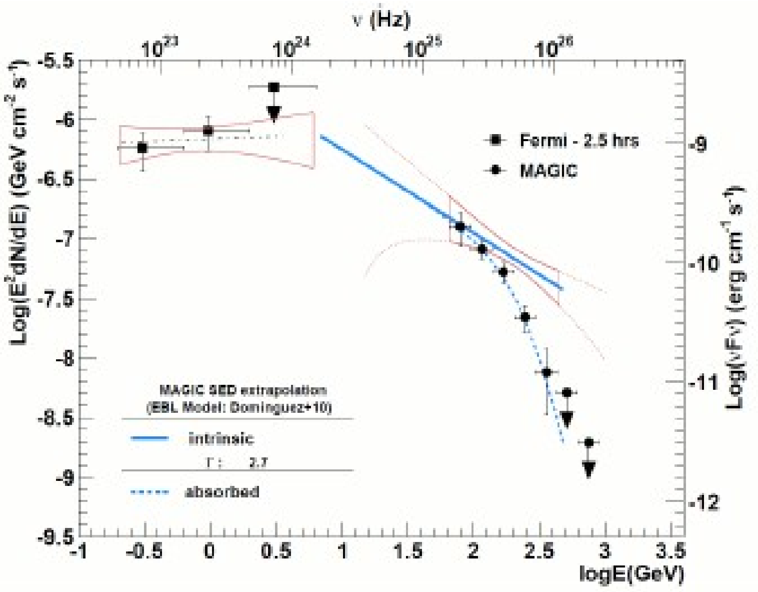
- re-observed 2007 and 2009

PKS 1222+21 (z = 0.432)

- MAGIC discovery during flare 2010
- fast variability



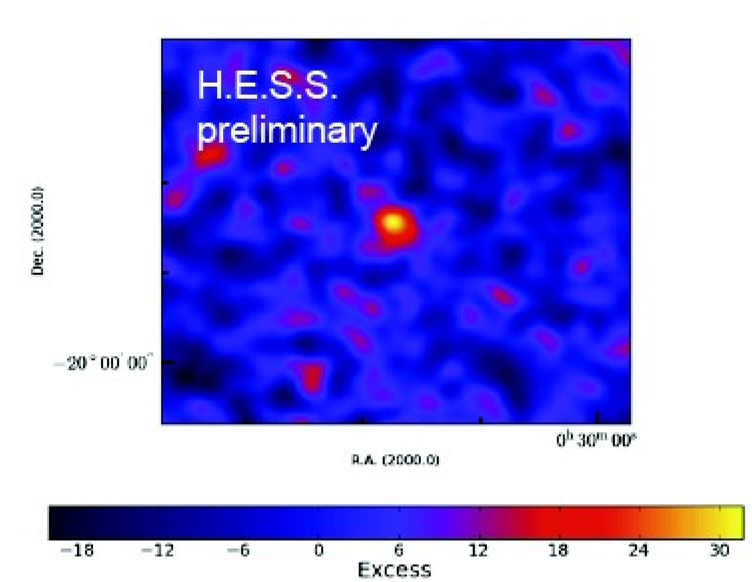
[A&A 2011]

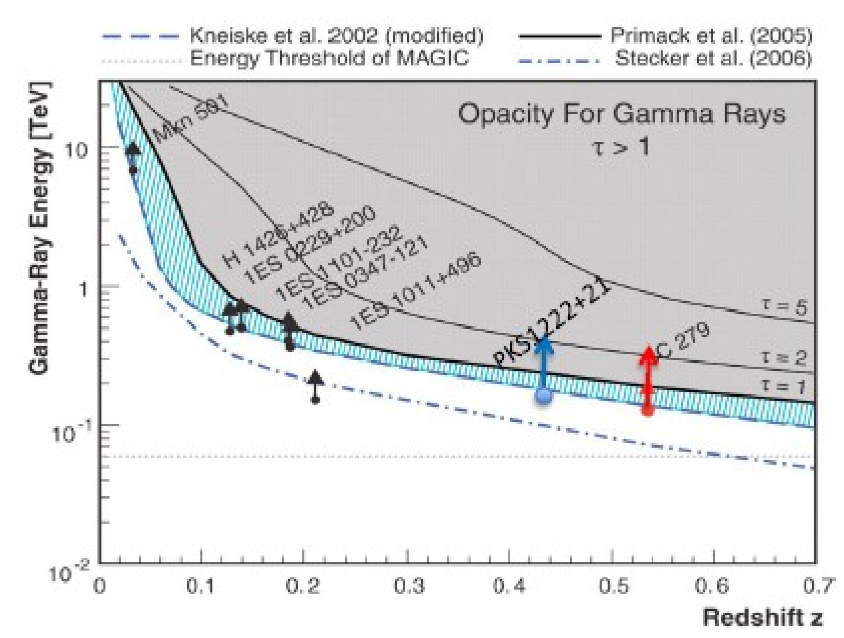


[ApJ Lett 2011]

Discovery of KUV 00311-1938

- Very distant blazar (z ~ 0.61)
- H.E.S.S. observations
  - 52.5 h of good-quality data
  - 5.1σ (152 excess events)



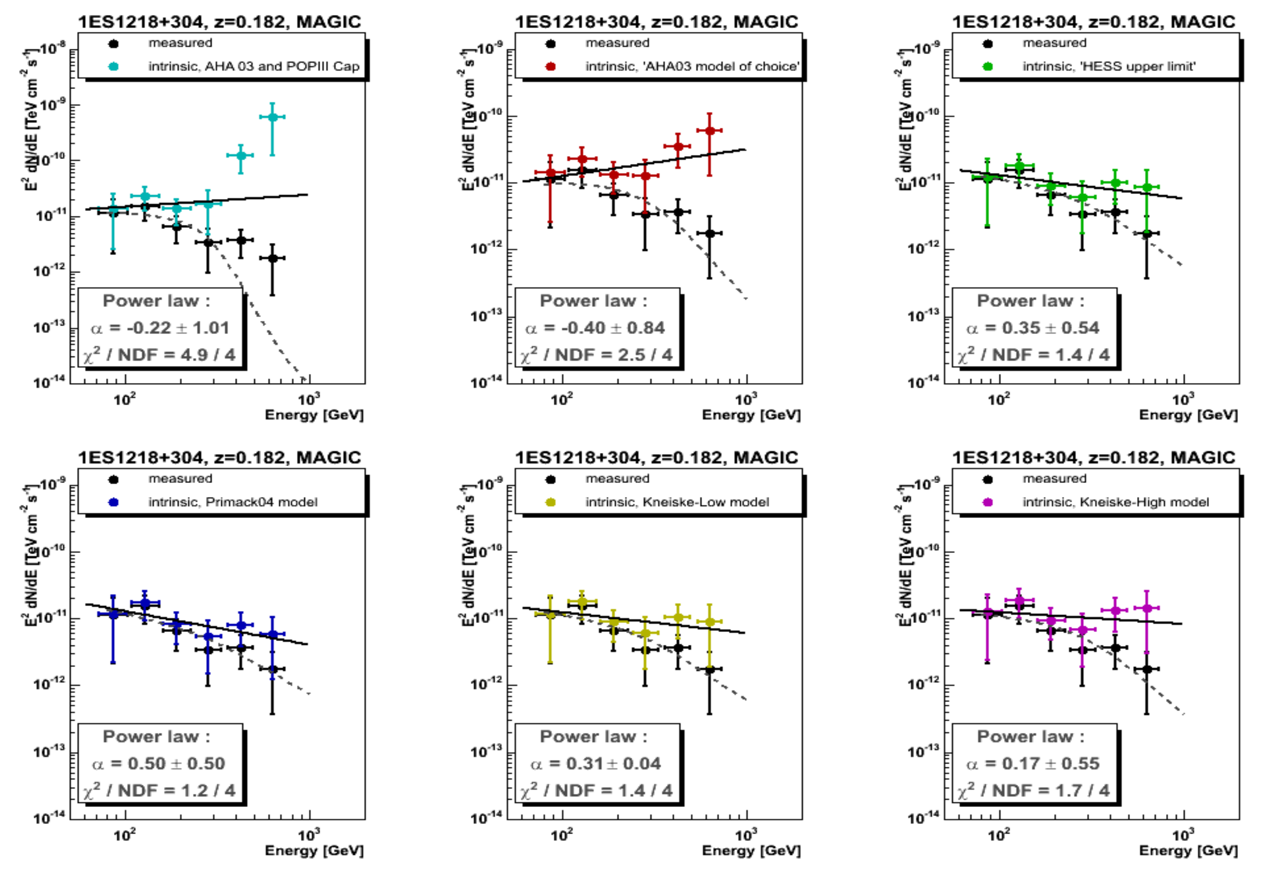


Strong limits on EBL can be imposed through these detections

Universe more transparent to gamma rays than expected

EBL Constraints from TeV data

- Is it possible to derive EBL constraints from the 1ES1218 spectrum?
- Assuming 6 different EBL realizations, all reconstructed de-absorbed spectra do not contradict the rising slope $dN/dE \sim E^{-\Gamma}$, $\Gamma > 1.5$



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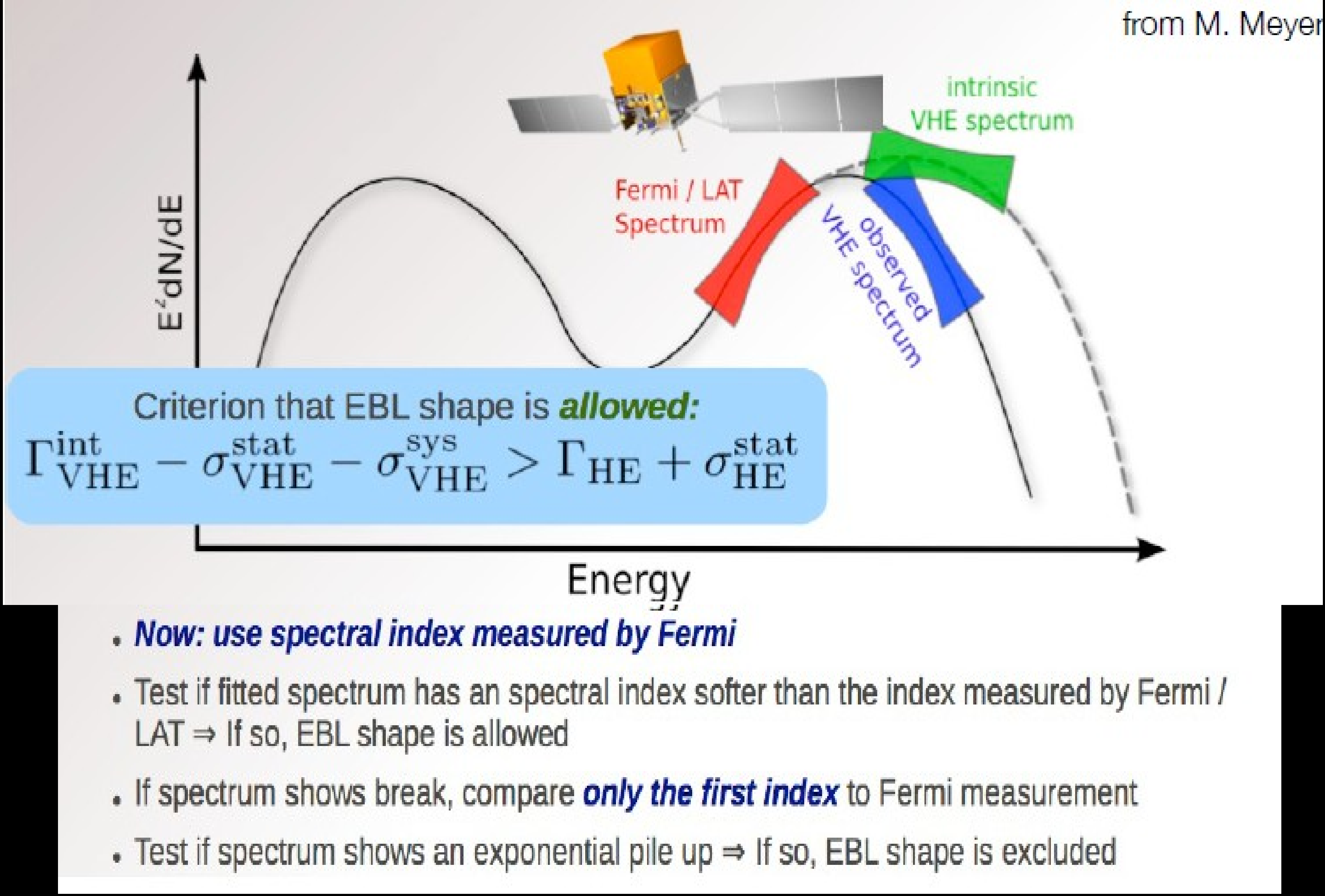
Constraints from GeV-TeV data

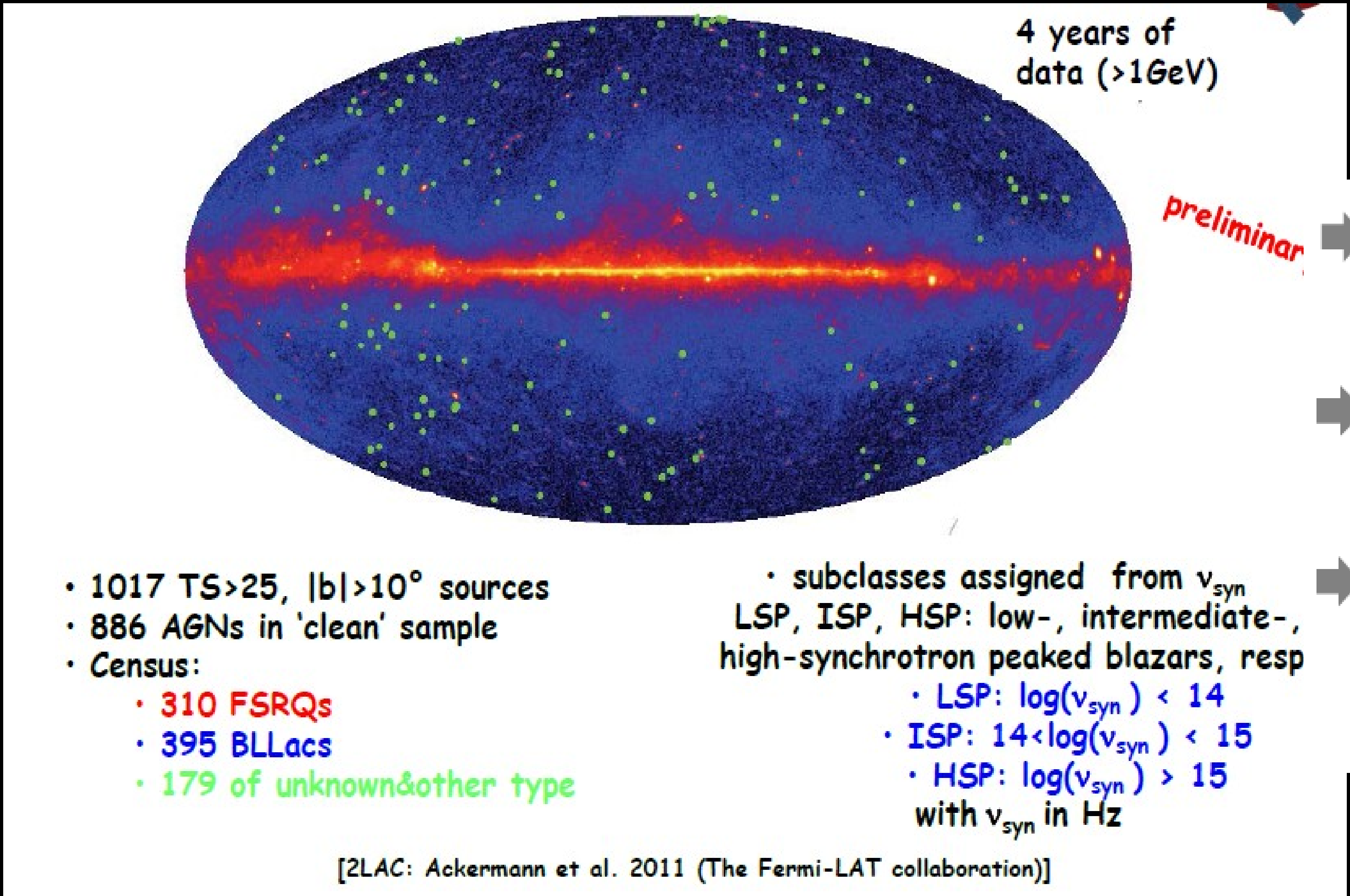


Criterion that EBL shape is ***allowed:***

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

- ***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

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)]

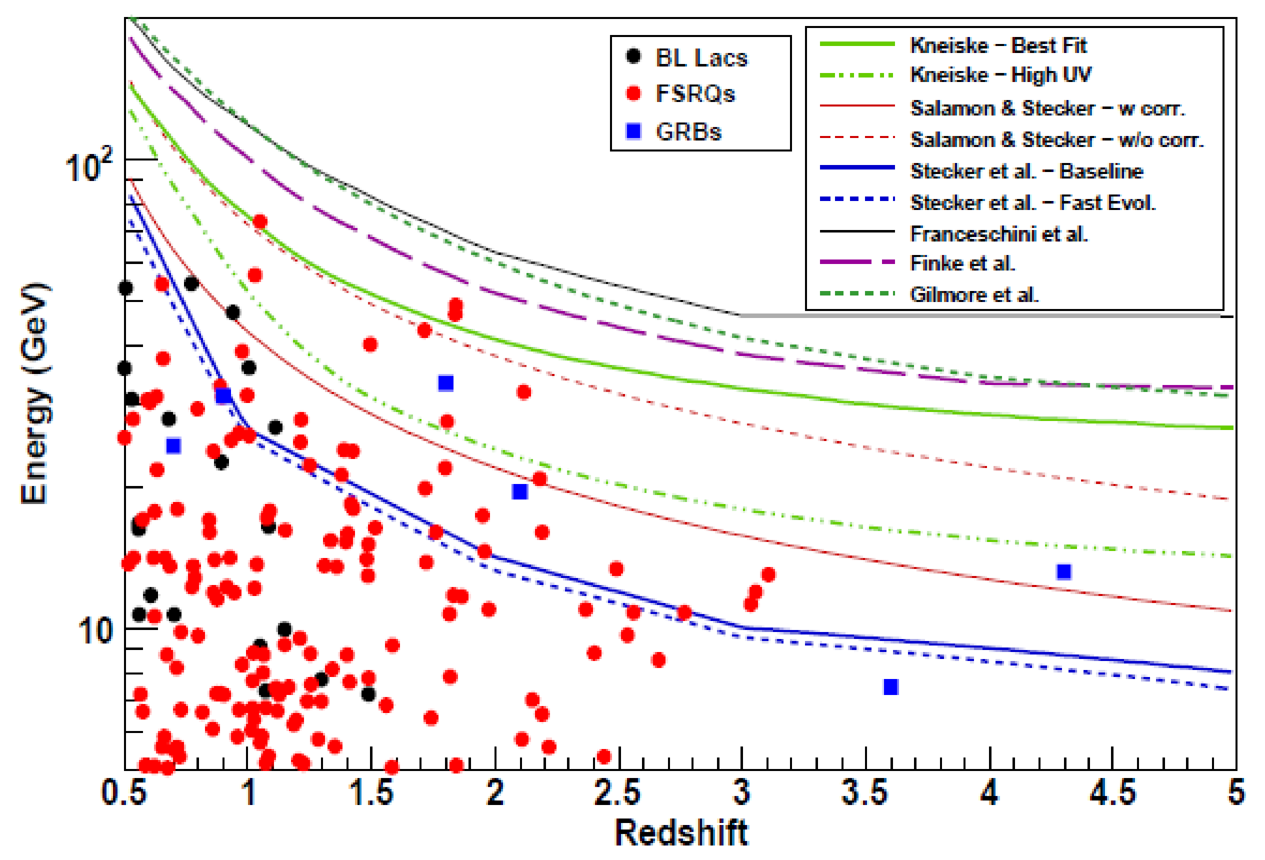
➡ probes *opt/UV range* of EBL

➡ 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 data

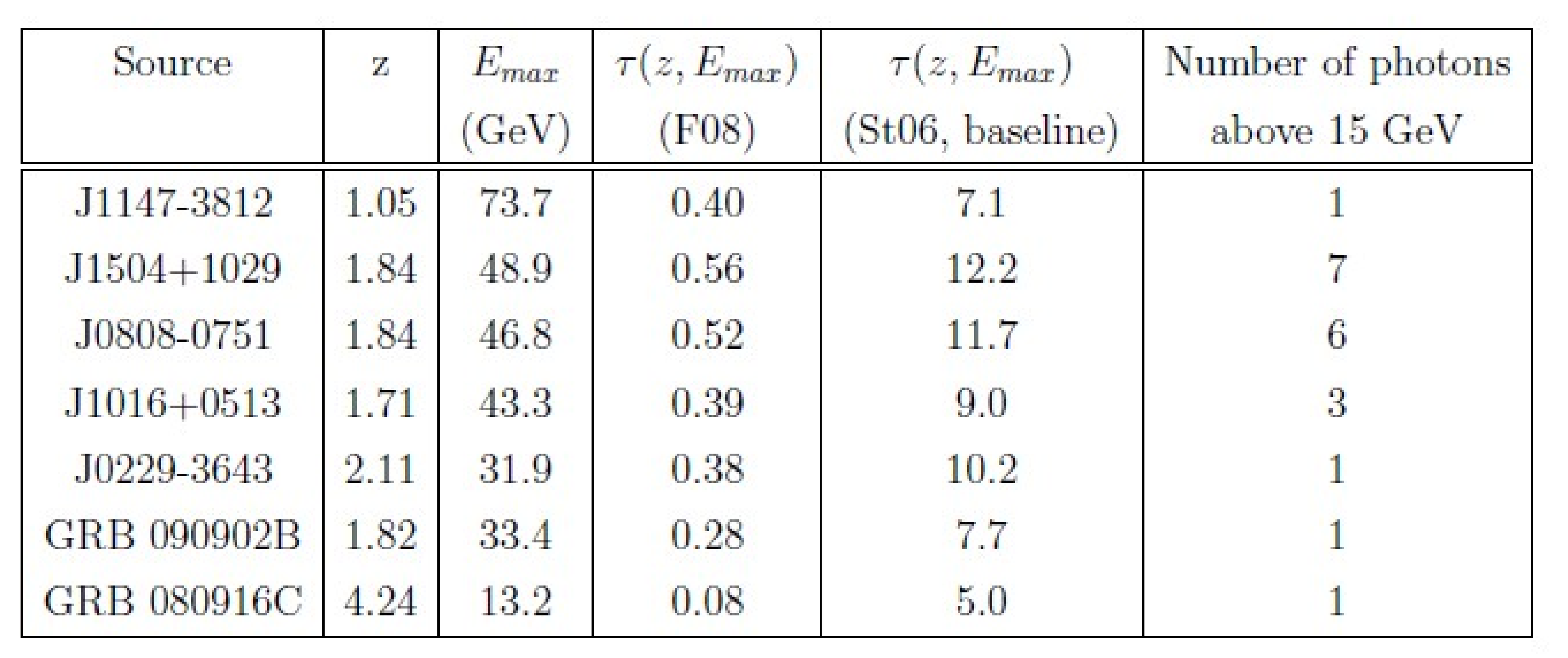


Rule out the EBL
models
based on a large
sample of
AGNs and GRBs

Highest Energy Photon method
Chance Probability the HEP events are
not real is small using MC

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

Constraints from GeV data

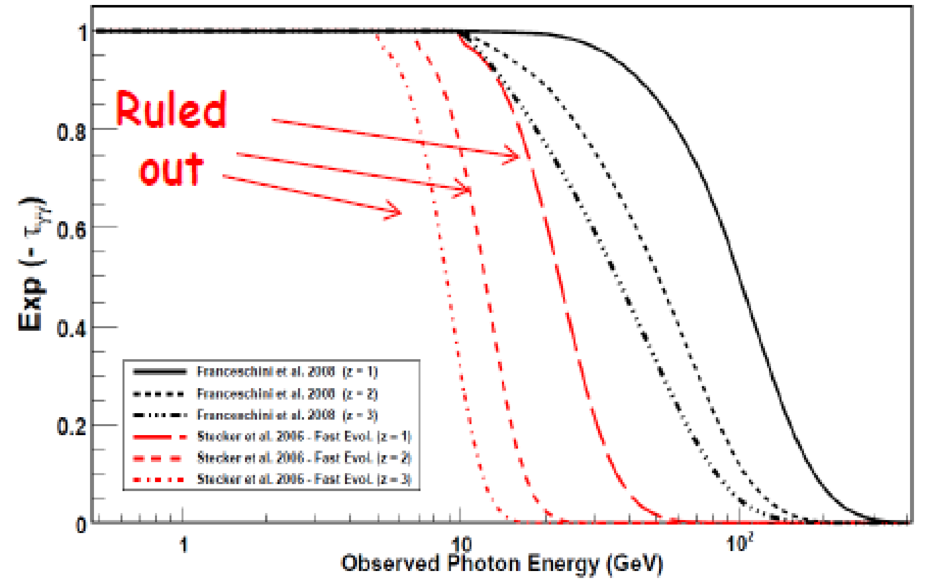


Source	z	E_{max} (GeV)	$\tau(z, E_{max})$ (F08)	$\tau(z, E_{max})$ (St06, baseline)	Number of photons above 15 GeV
J1147-3812	1.05	73.7	0.40	7.1	1
J1504+1029	1.84	48.9	0.56	12.2	7
J0808-0751	1.84	46.8	0.52	11.7	6
J1016+0513	1.71	43.3	0.39	9.0	3
J0229-3643	2.11	31.9	0.38	10.2	1
GRB 090902B	1.82	33.4	0.28	7.7	1
GRB 080916C	4.24	13.2	0.08	5.0	1

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).



Constraints from GeV data

- 46-months of 1-500 GeV data

Likelihood Ratio Test

- 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

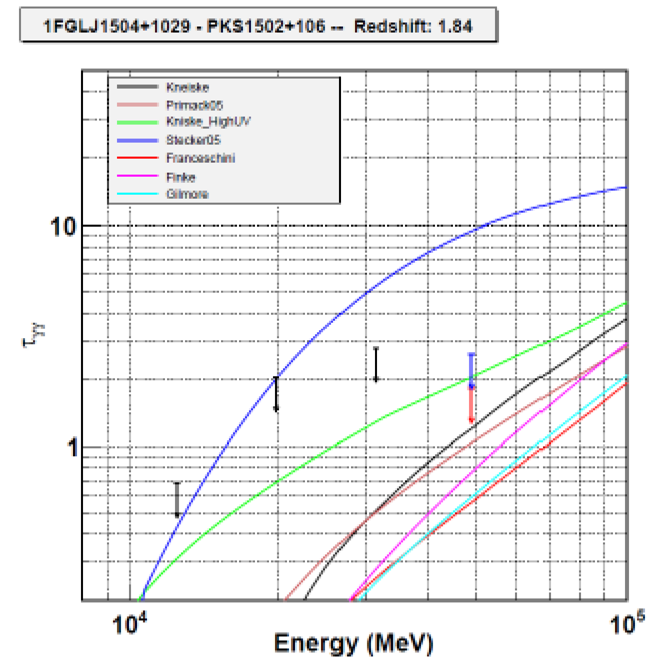
Compares the likelihood of a null hypothesis model (L0) to best represent the data with the likelihood of a competitive model (L1)

$$TS = -2 \times (log(L_0) - log(L_1))$$

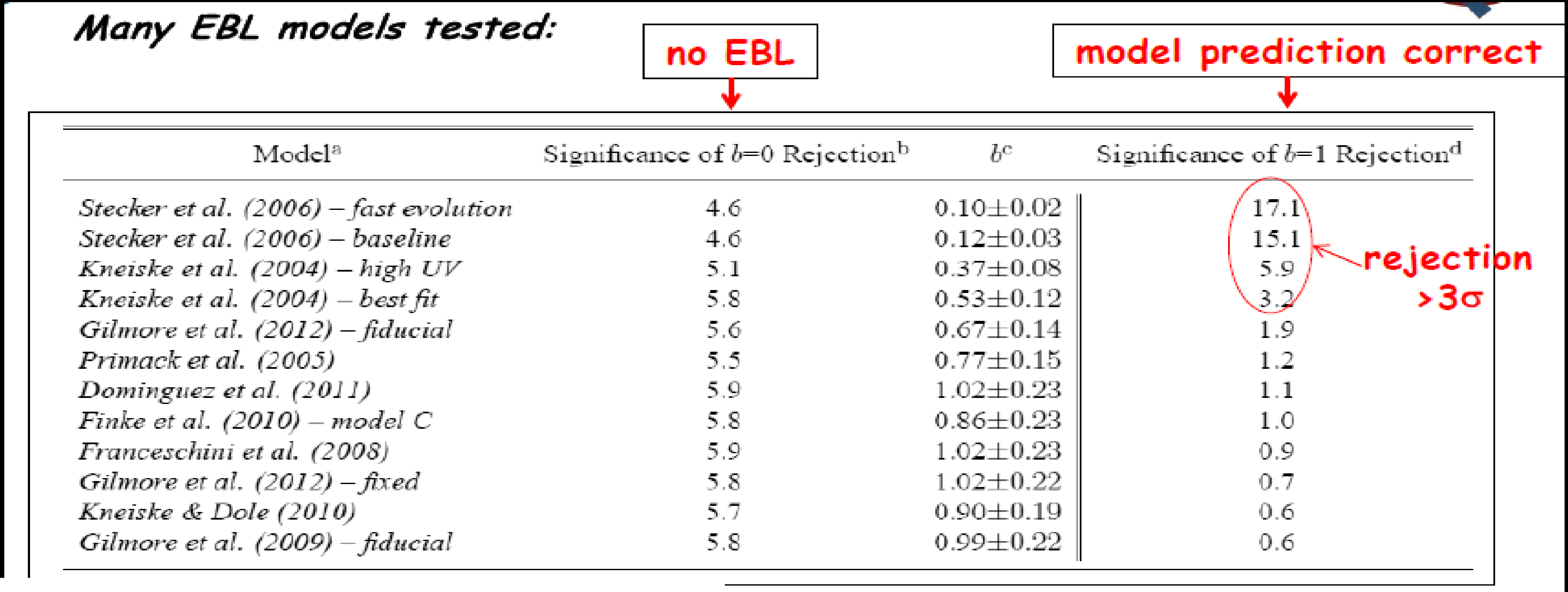
Observed spectrum $\exp[-\alpha\tau_{mod}(E,z)]F_{unabs}(E)$

$$\tau_{\gamma\gamma}(E,z) = b \times \tau^{model}_{\gamma\gamma}(E,z)$$

$$\tau_{\gamma\gamma}(E,z) = \ln[F_{unabs}(E)/F_{obs}(E)].$$



Test of EBL Models



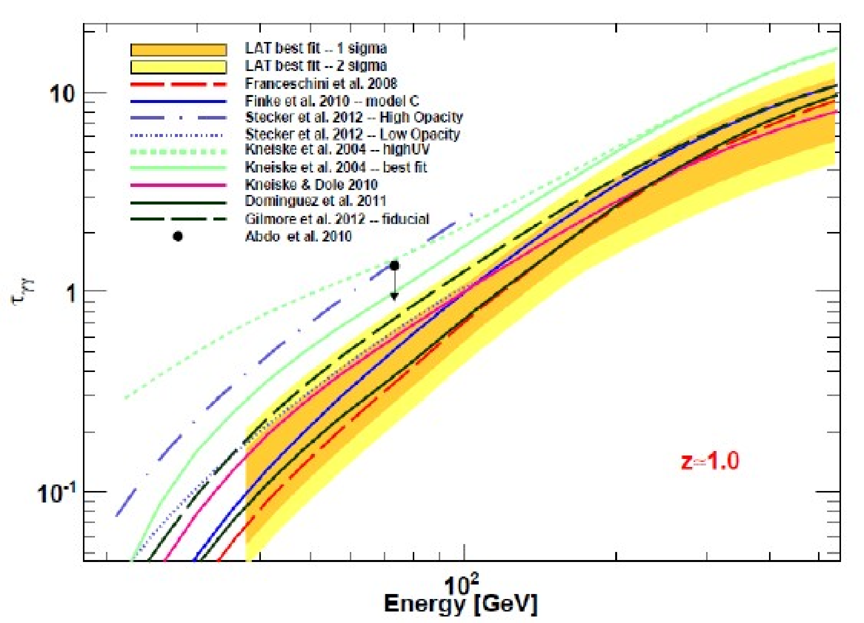
Many EBL models tested:

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

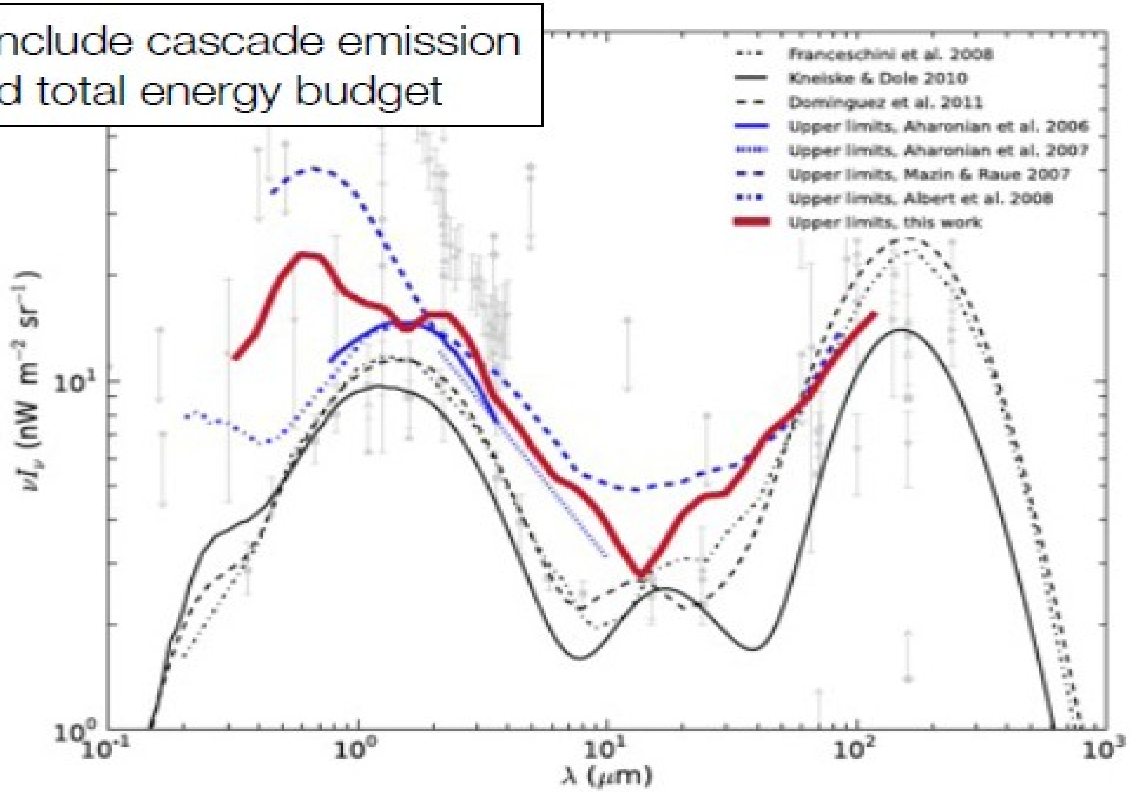
rejection >3σ



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

[Abdo etal. 2010] .

Combined GeV-TeV Constraints



limits include cascade emission and total energy budget

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

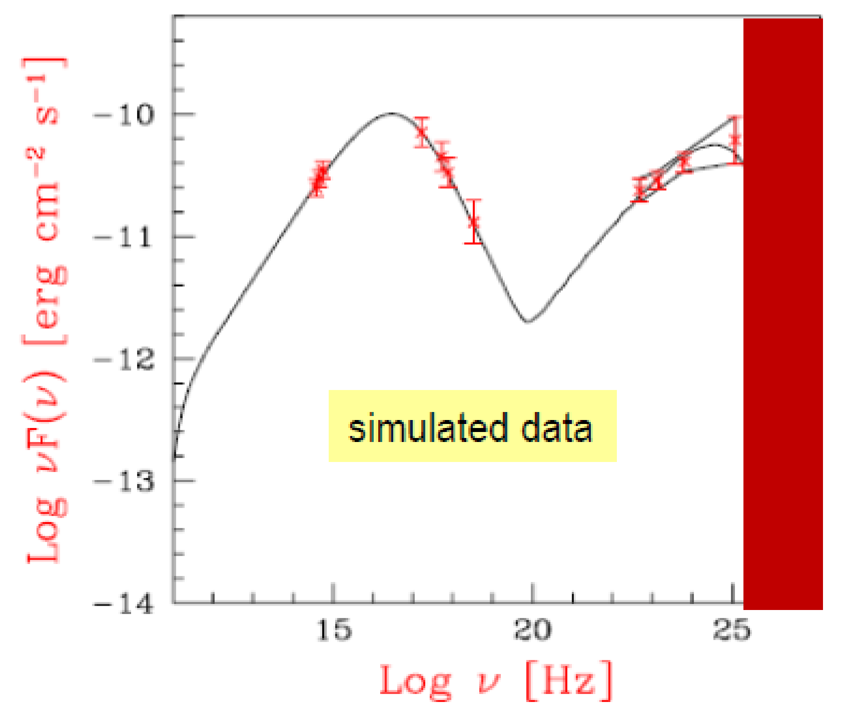
Simultaneous multi-ν obs's:

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

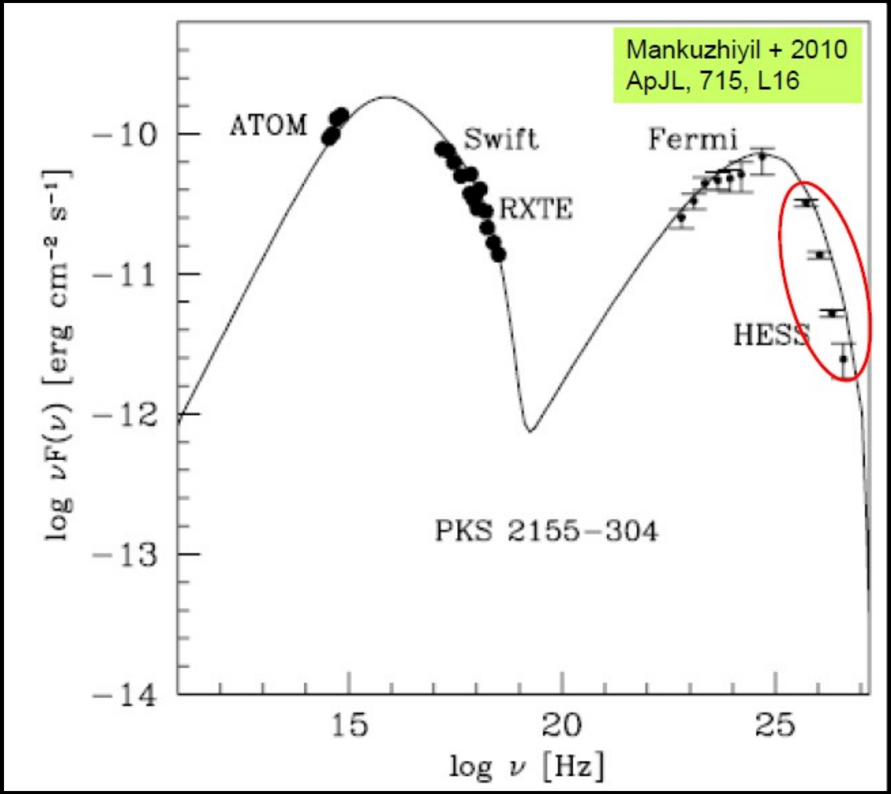
Model SED: use SED w/out (EBL-affected) VHE γ-ray data:

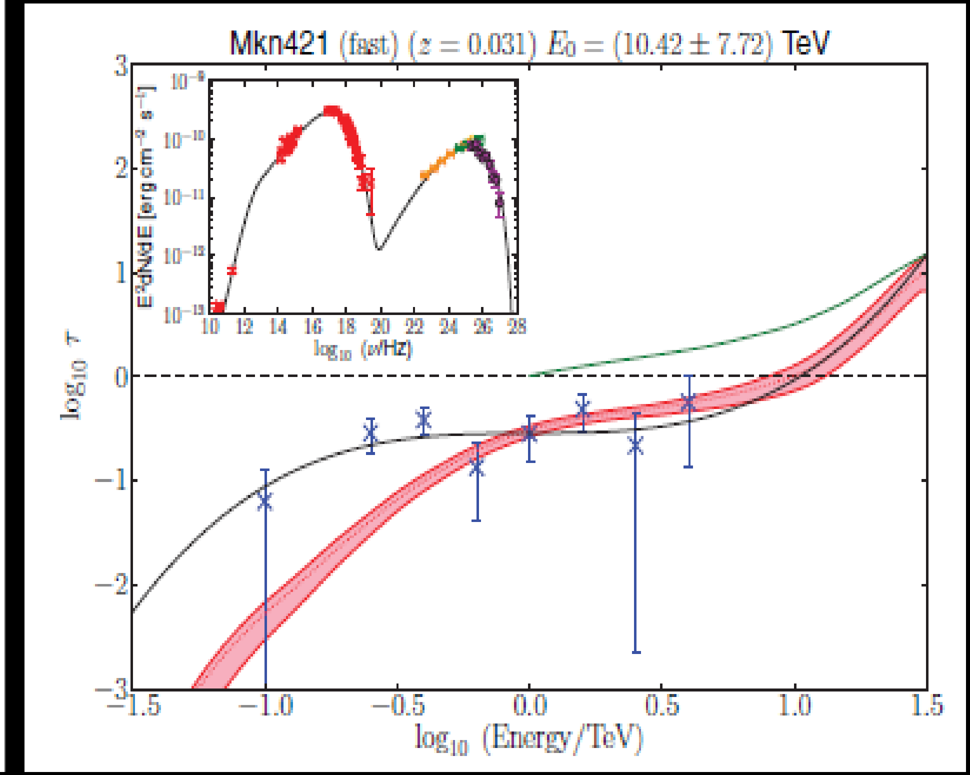
→ χ^2-minimization → SSC model

(check structure of multi-D parameter space)



Applications to a few sources





15 well studied blazars in Fermi in quiescent state

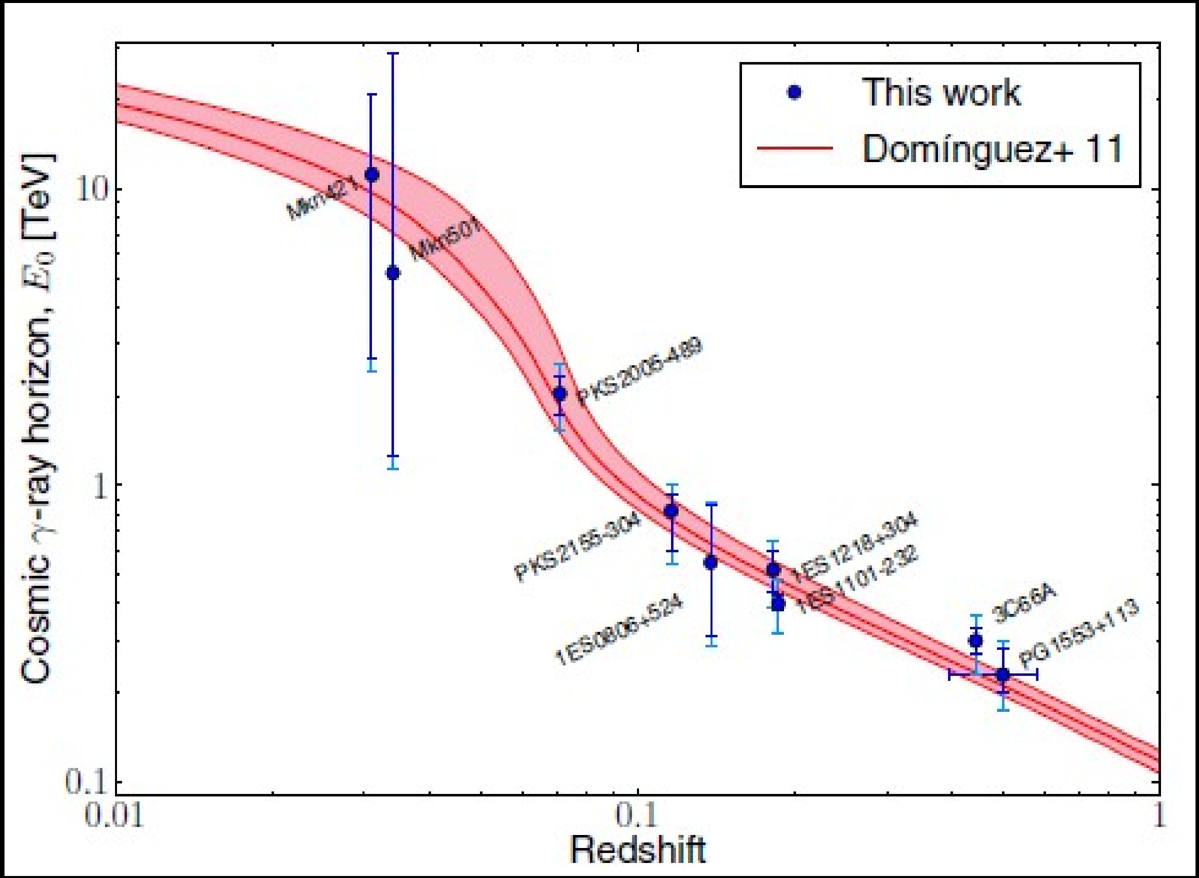
TeV data not used in the SSC fits to exclude EBL effects

Calculate optical depth, compare with model predictions

Dominguez et al, ApJ 770 (2013)

$$\tau(E,z) = \ln\left(\frac{dF}{dE}\Big|_{\rm int} \Big/ \frac{dF}{dE}\Big|_{\rm obs}\right)$$

Cosmic Gamma Ray Horizon

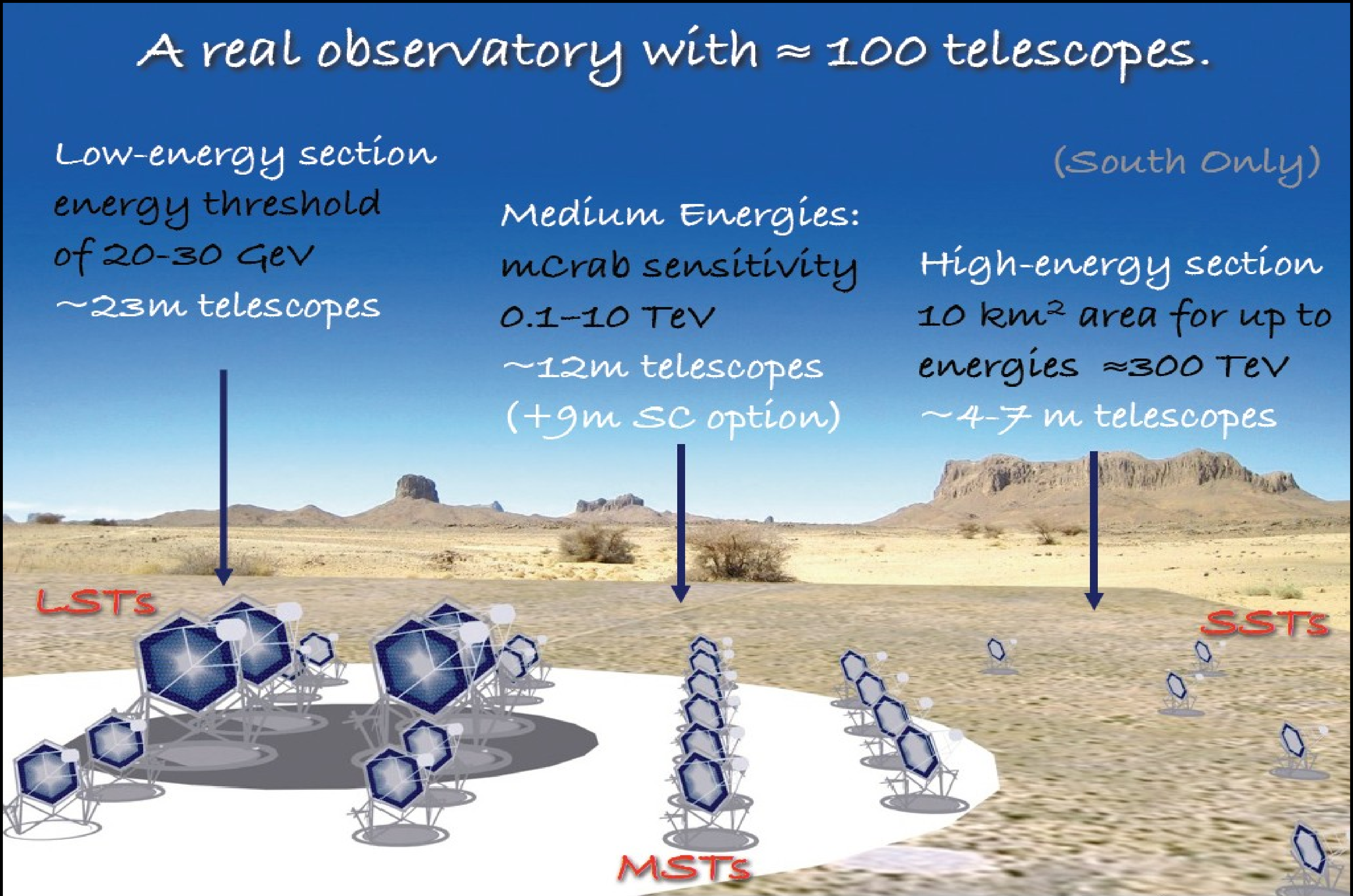


Calculate CGRH : energy at which optical depth = 1

Uncertainities higher for closest objects because of less power for current IACTs to observe highest energies (~ tens of TeV)

Dominguez et al, ApJ 770 (2013)

Perspectives for future Cerenkov Telescope Array (CTA)



A real observatory with ≈ 100 telescopes.

Low-energy section
energy threshold
of 20-30 GeV
~23m telescopes

Medium Energies:
mCrab sensitivity
0.1–10 TeV
~12m telescopes
(+9m SC option)

(South Only)

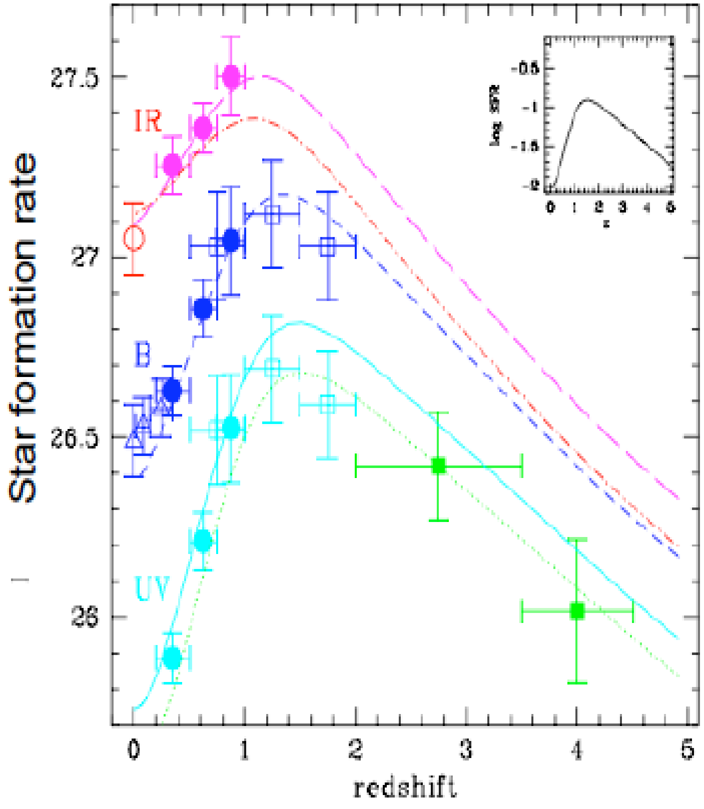
High-energy section
10 km² area for up to
energies ≈300 TeV
~4-7 m telescopes

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)

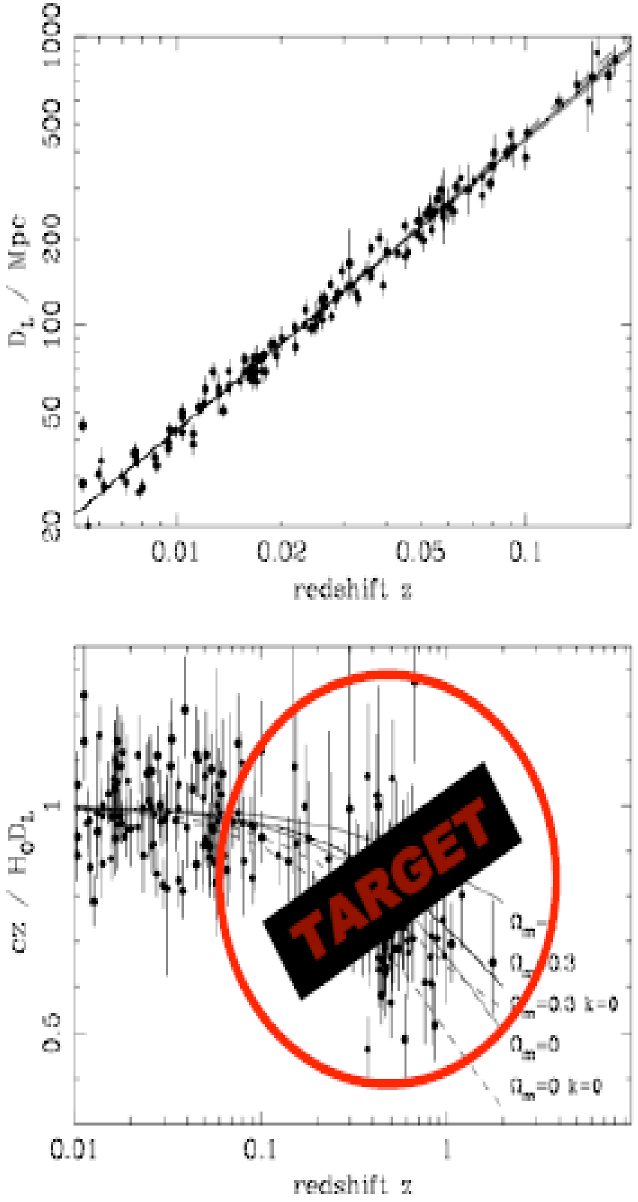


Madau, 1998

Cosmology with AGNs in GeV TeV regime

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



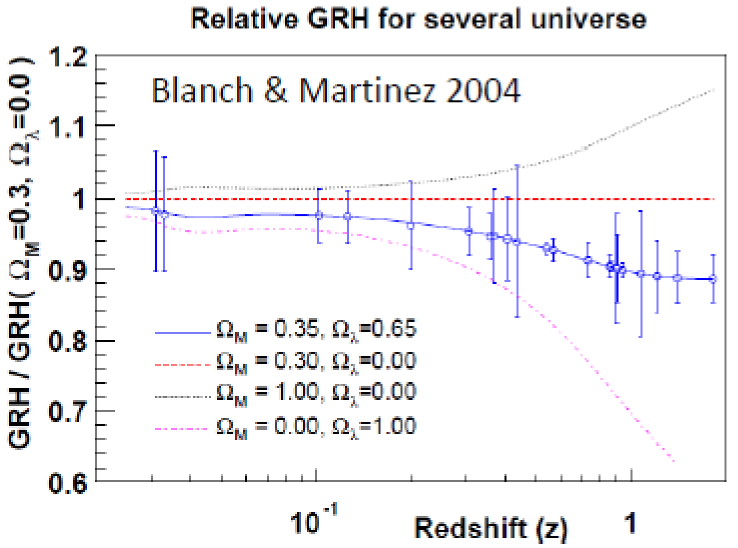
Cosmology with GeV-TeV gamma rays

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.



Relative GRH for several universe

Blanch & Martinez 2004

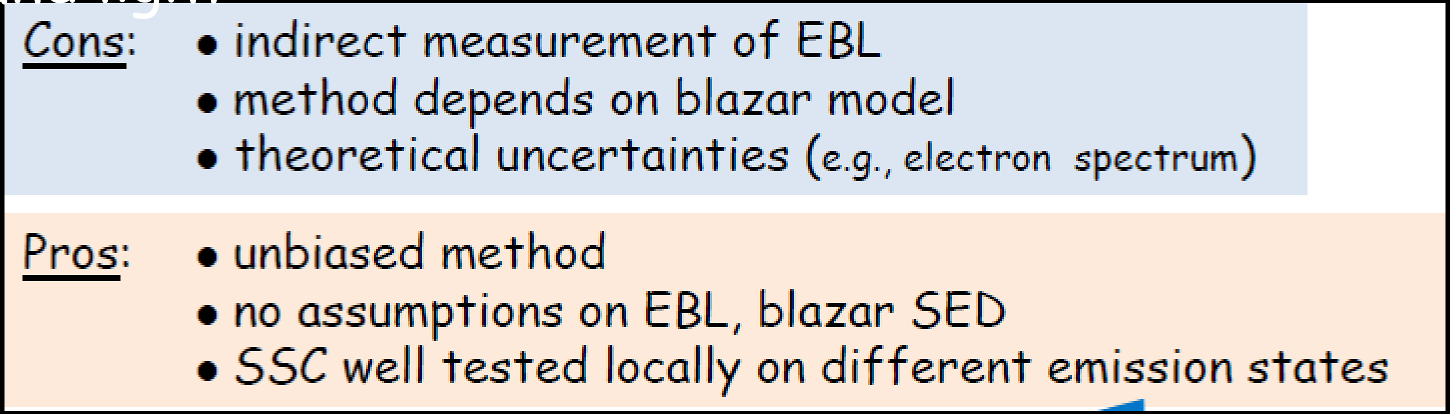
Independent and behaves differently than Luminosity-distance relation in SN 1A

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

AGNs as sources : high z

Conclusions

- TeV Gamma rays can be a good probe of Extragalactic Background light



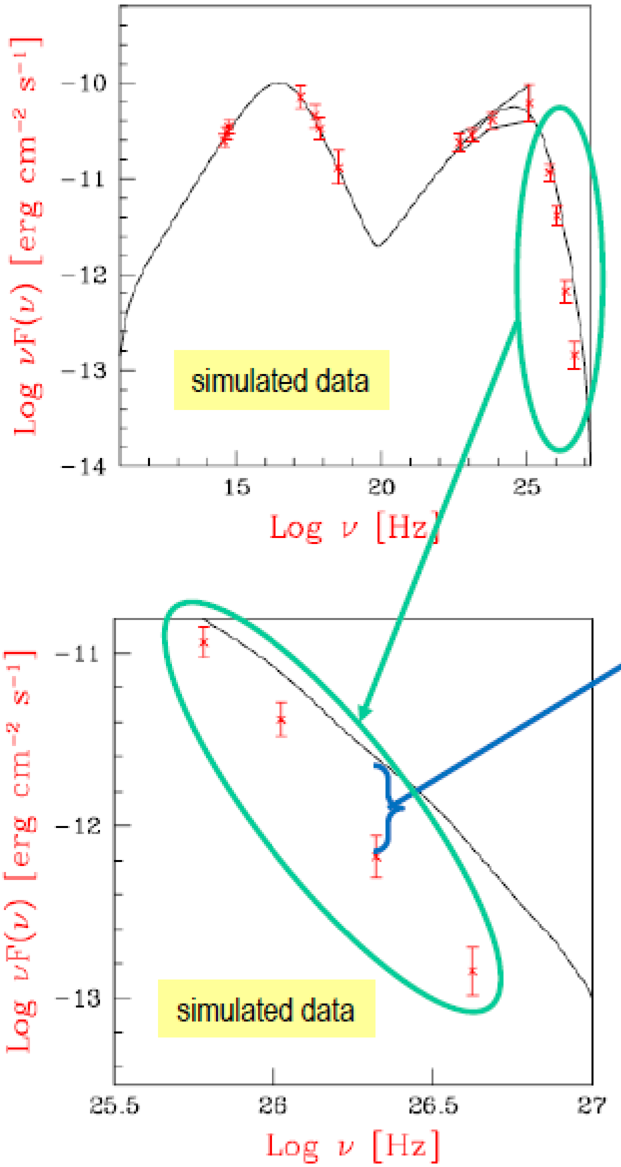
Cons:
- indirect measurement of EBL
- method depends on blazar model
- theoretical uncertainties (e.g., electron spectrum)

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

- Determination of CGRH is an important quantity in cosmology
- Already, new generation of detectors providing wealth of data to constraint EBL
- Furture with more data from Fermi-LAT and upcoming CTA looks bright.

Backup Slides

...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: $\sum a_{nj}\,\varepsilon^n$)

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:

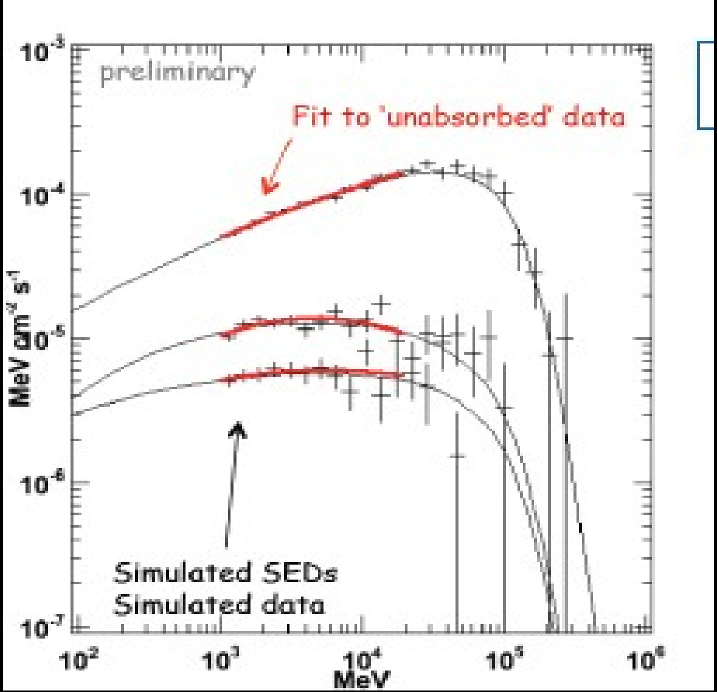
(1) No EBL:

Null Hypothesis b=0

(2) Model prediction correct:

Null hypothesis b=1

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



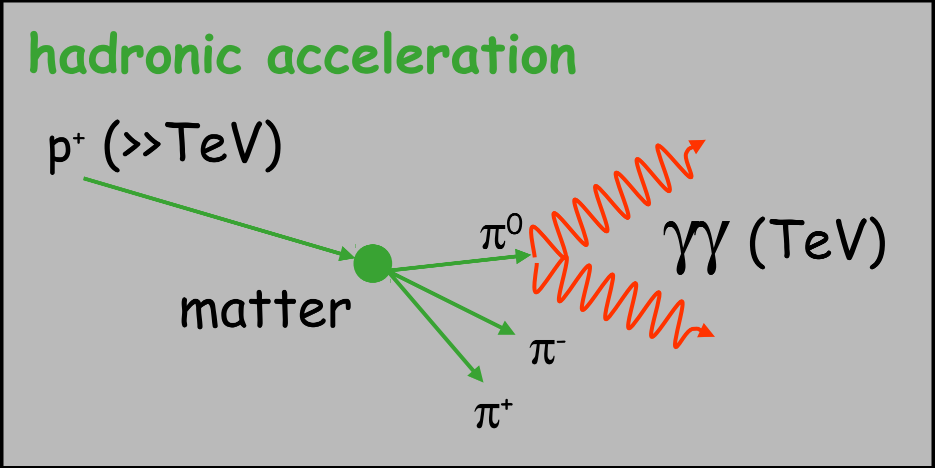
γ-ray astronomy and cosmic rays (CR)

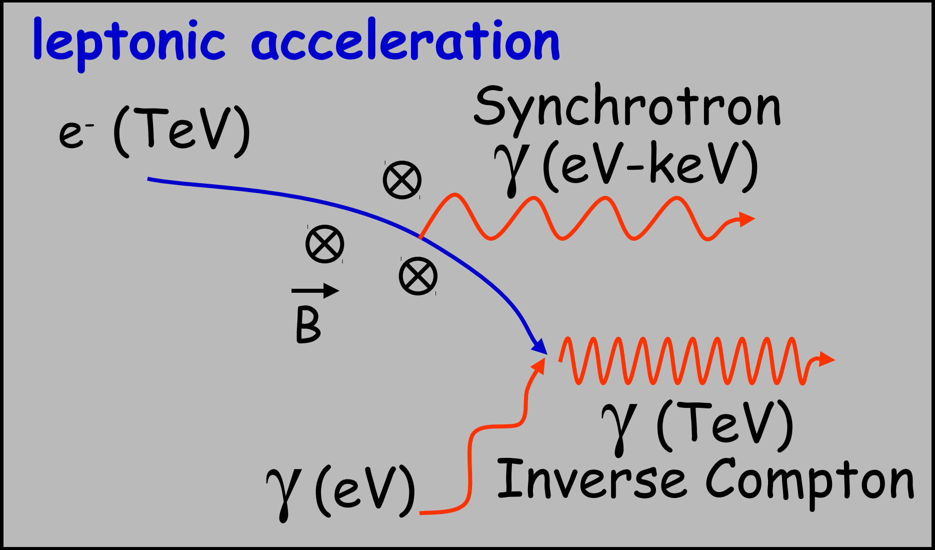
- Origin of CRs?
- (charged) CRs deflected by B-fields

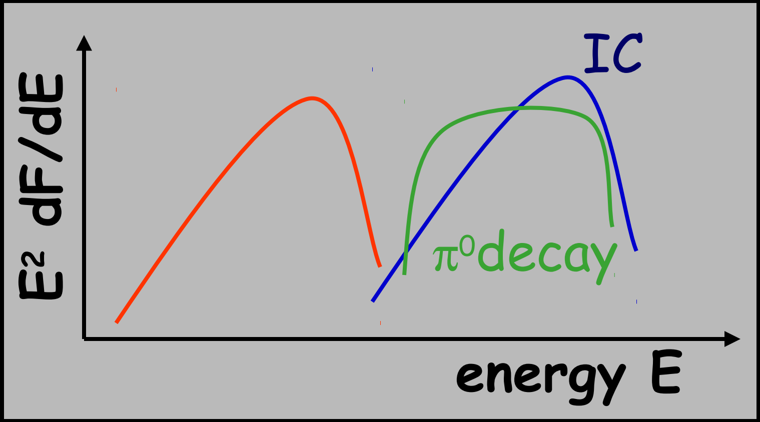
=> search for γ-rays produced by CRs close to source

- discriminate hadronic vs leptonic acceleration

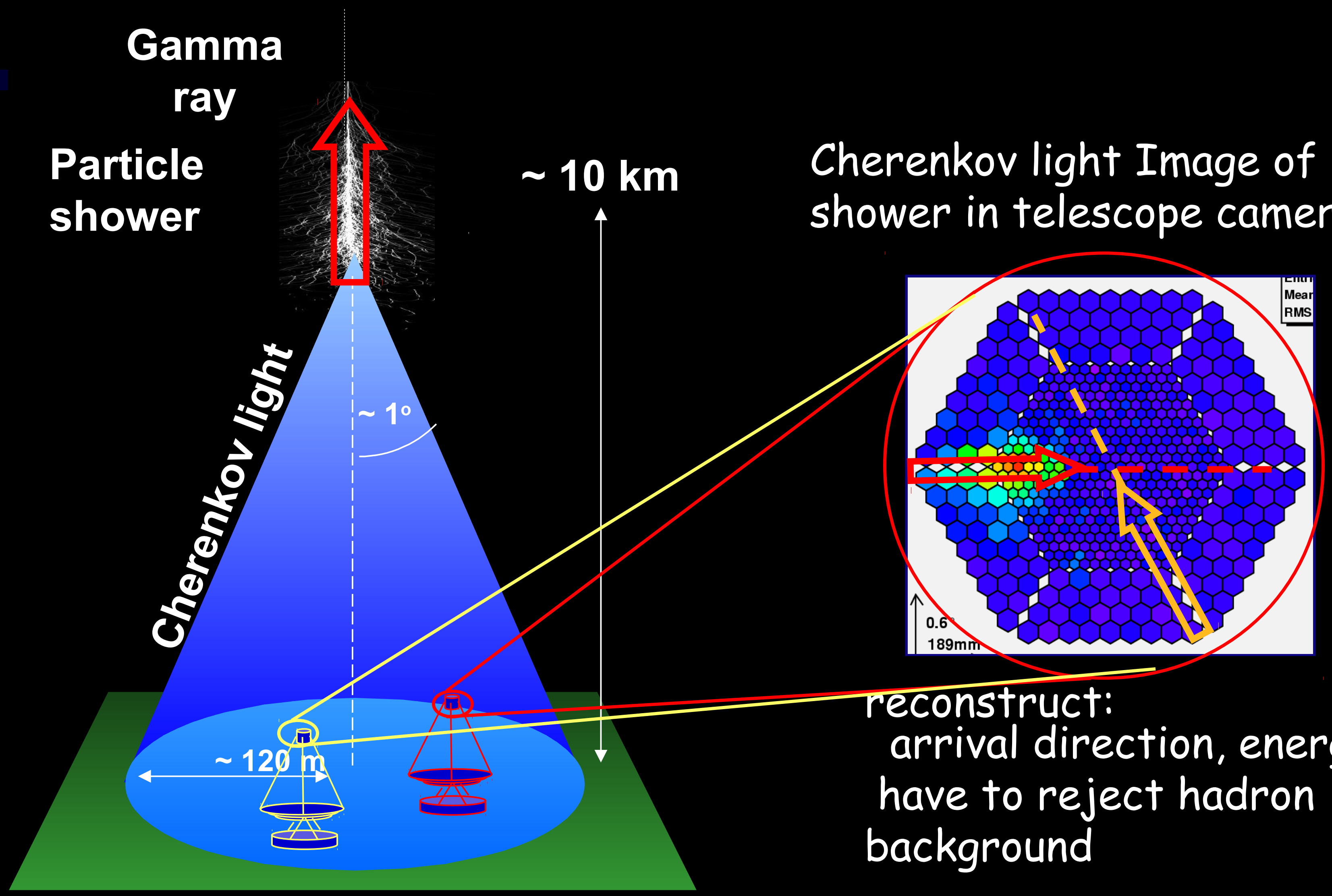
=> *shape of spectrum*







Imaging Air Cherenkov Telescopes



Cherenkov light Image of particle shower in telescope camera

reconstruct:
arrival direction, energy
have to reject hadron background