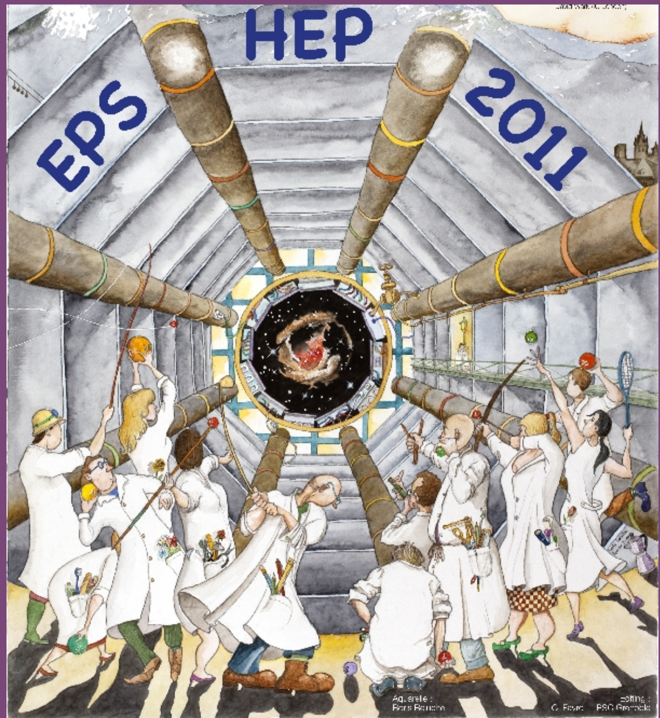

Gamma ray astronomy: implications for fundamental physics

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Disclaimer and acknowledgements

- Cover only gamma-rays (and not cosmic rays)
- Choice of "fundamentality" necessarily a bit personal
- Thanks to colleagues who have helped me and others whose material I use (I try to give proper credit throughout the talk)
- ICRC in 3 weeks will surely add more exciting results

OUTLINE

- Introduction: gamma-ray astronomy
  - Space: Fermi-LAT
  - Ground: HESS, VERITAS, MAGIC
- Gamma-rays and fundamental physics
  - The origin of Cosmic Rays
  - Cosmic-ray electron/positron
  - Extragalactic Background Light / Cosmology
  - Tests of Lorenz Invariance
  - Dark matter searches -> More this afternoon (T. Bringmann's review)

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INTRODUCTION: GAMMA RAY ASTRONOMY

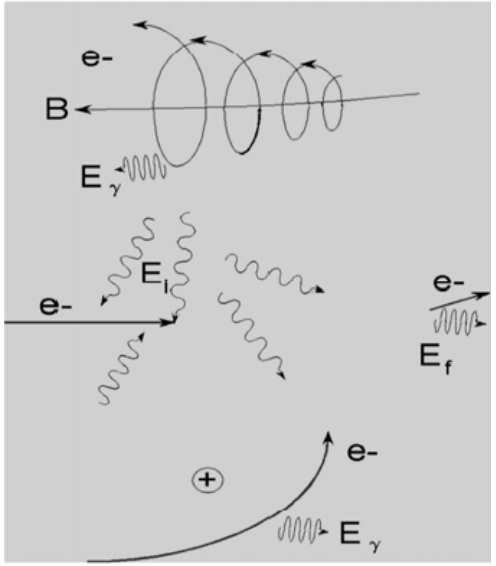
Processes

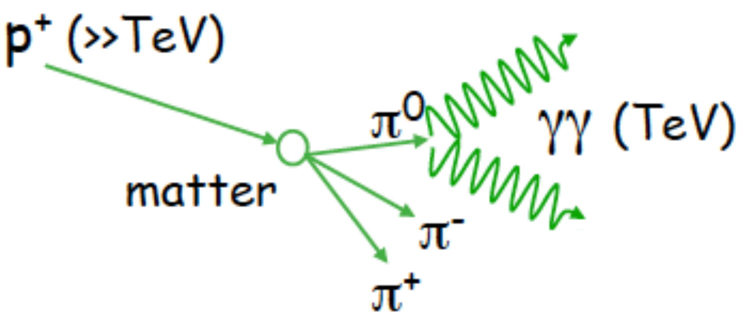
- High Energy (HE, 100 MeV – 100 GeV) and Very High Energy (VHE, 100 GeV – 100 TeV) astronomies study objects emitting in the highest energy range of electromagnetic spectrum

- Gamma-rays produced in non-thermal environments by radiation/ interaction of accelerated charged particles:

  - Electrons: synchrotron, inverse Compton scattering (off ambient or synchrotron photons), Bremmstrahlung

  - Protons: through π^0 decays from interactions with interstellar matter





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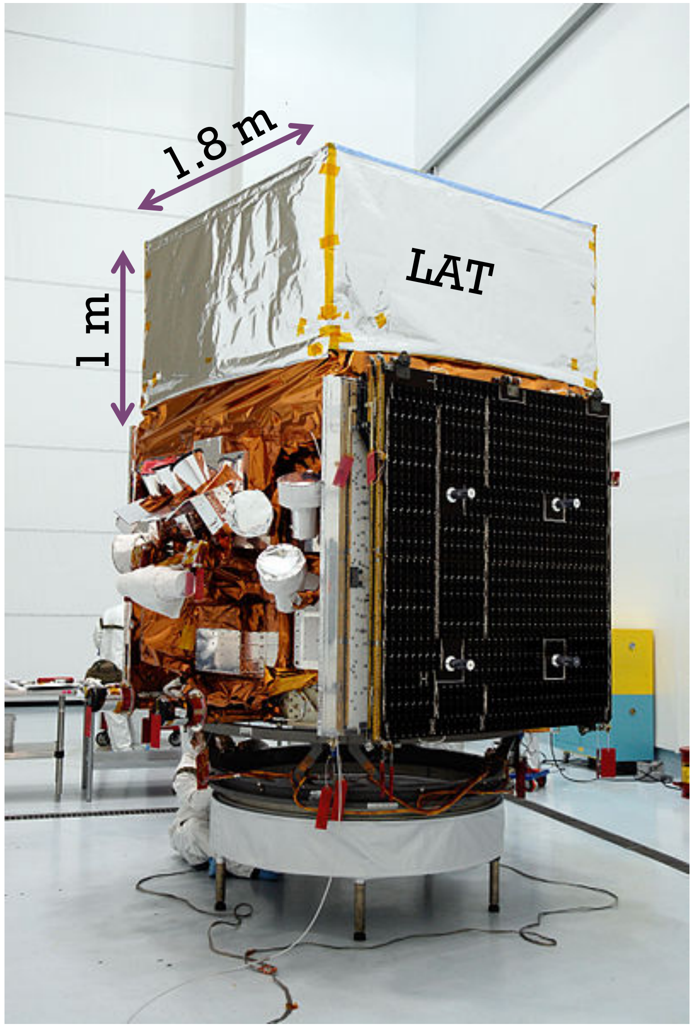
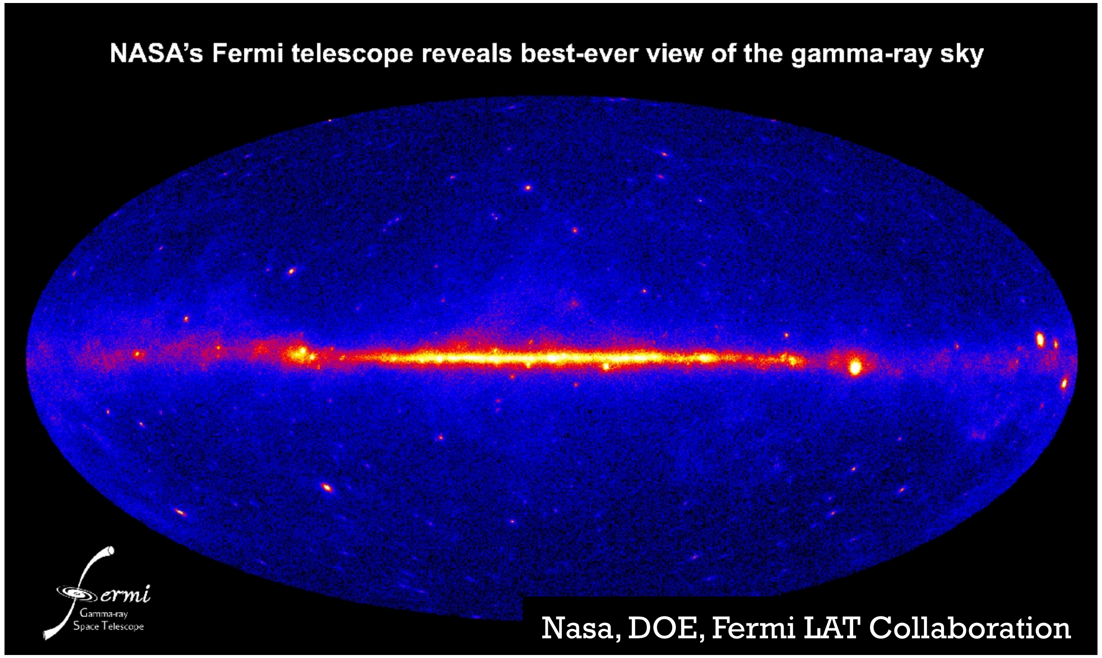
HE instruments: Fermi-LAT

- Space-borne detector. Anticoincidence shield + tracker + calorimeter (no magnet)
- Almost background free
- Energy range 30 MeV – 300 GeV
- Energy resolution 10-15%
- PSF ~1° (0.1°) at 1 (100) GeV
- Field of view 2.4 sr
- Survey mode: full sky every 2 orbits (three hours). Slew to keep ToO in FOV
- Operates since August 2008



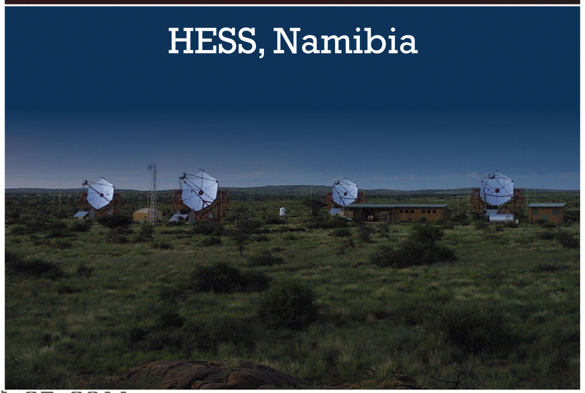
The HE sky

- 2-year catalog hot from the oven (July 11)
- 1873 sources, 127 firmly identified, 1174 reliably associated, 572 unidentified. 12 are extended (SNR, PWN and Centaurus A)
- Major breakthrough, up to 2008 only 270 sources (EGRET)



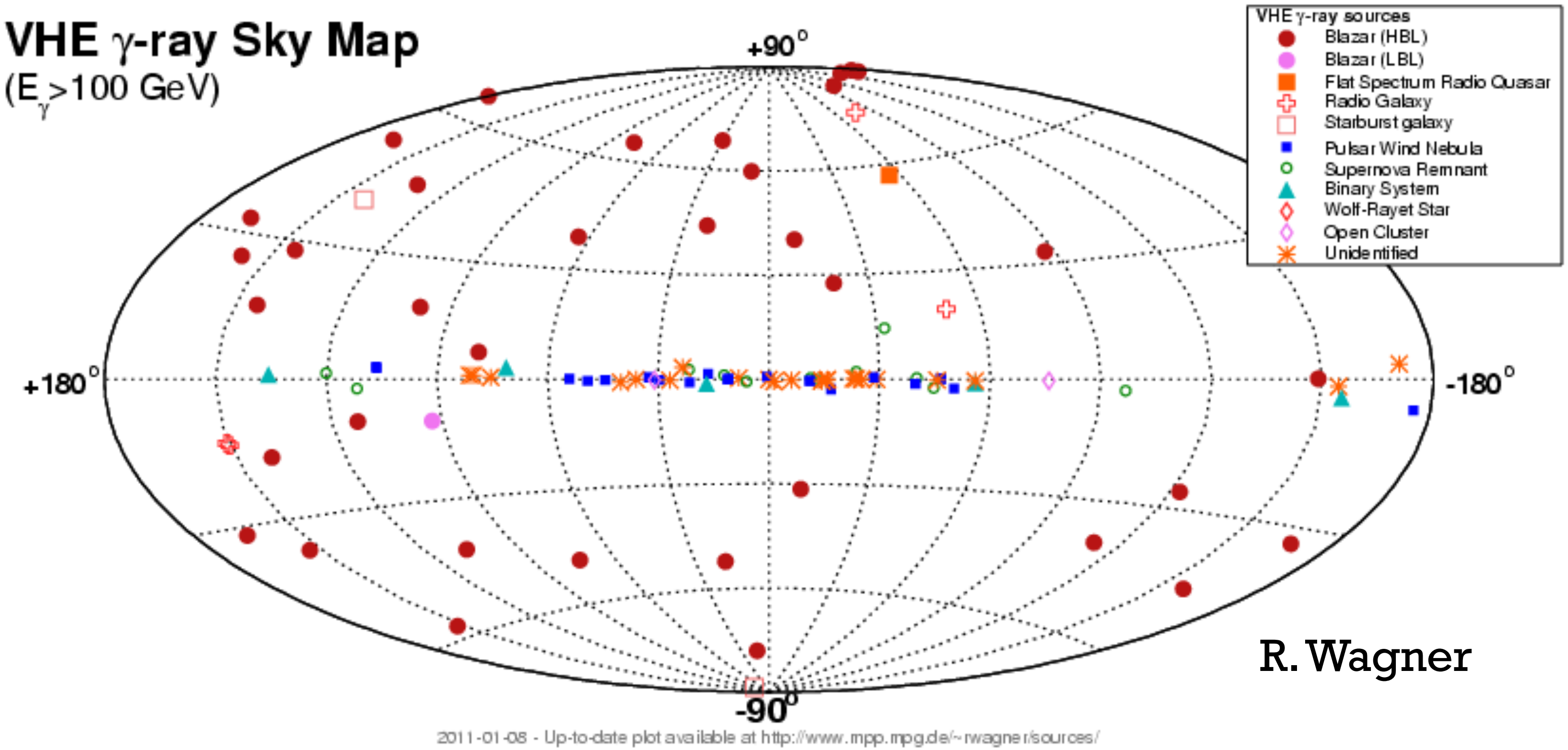
+ VHE instruments: Cherenkov telescopes

- Gamma-ray fluxes drop exponentially with energy ➔ for energies above ~100 GeV we need larger collection areas ➔ Cherenkov telescopes
- Huge CR background ➔ Imaging technique
- Energy range ~100 GeV – 100 TeV
- Energy resolution 10-15%
- PSF ~0.1° at 1 TeV
- Field of view 3-5 deg diameter (~0.005 sr)
- Pointed observations, systematic scans of limited regions
- Array of 4 (VERITAS, HESS) and 2 telescopes (MAGIC)
- Operating since 2003 (HESS), 2005 (MAGIC) and 2006 (VERITAS)



The VHE sky

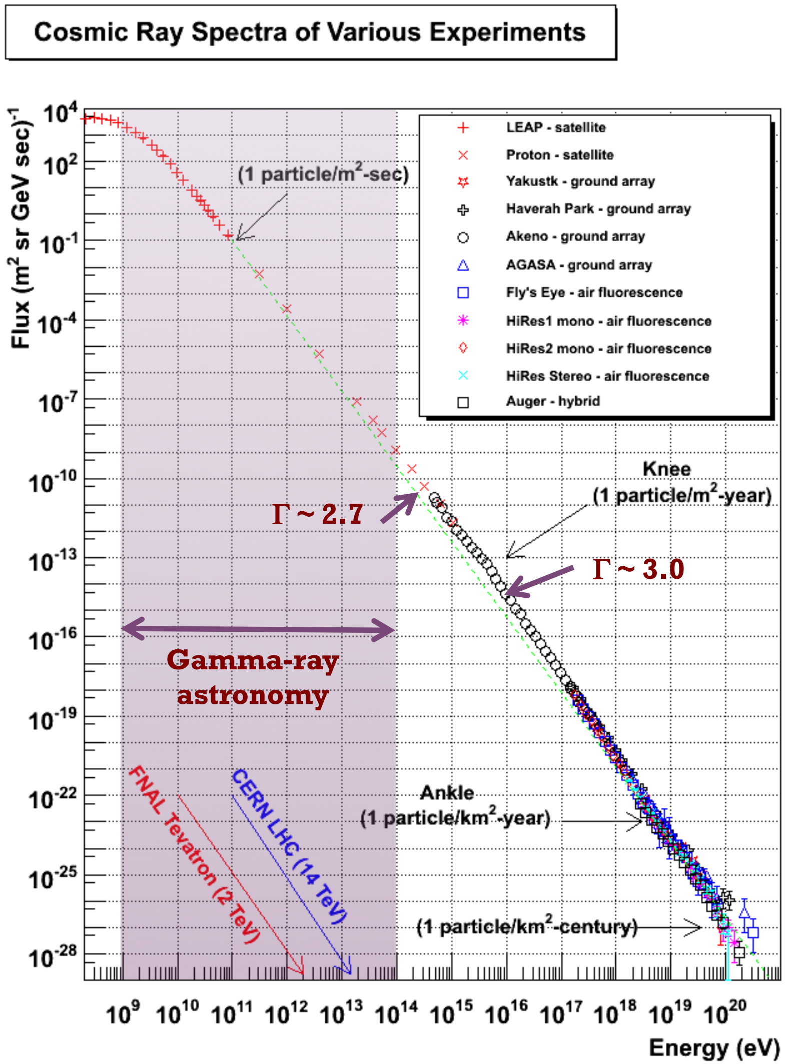
- Over 100 sources (vs. 14 until 2005), about ~25 unidentified
- Many by systematic scan of inner Galaxy (HESS)



R. Wagner

ORIGIN OF COSMIC RAYS

Cosmic Rays

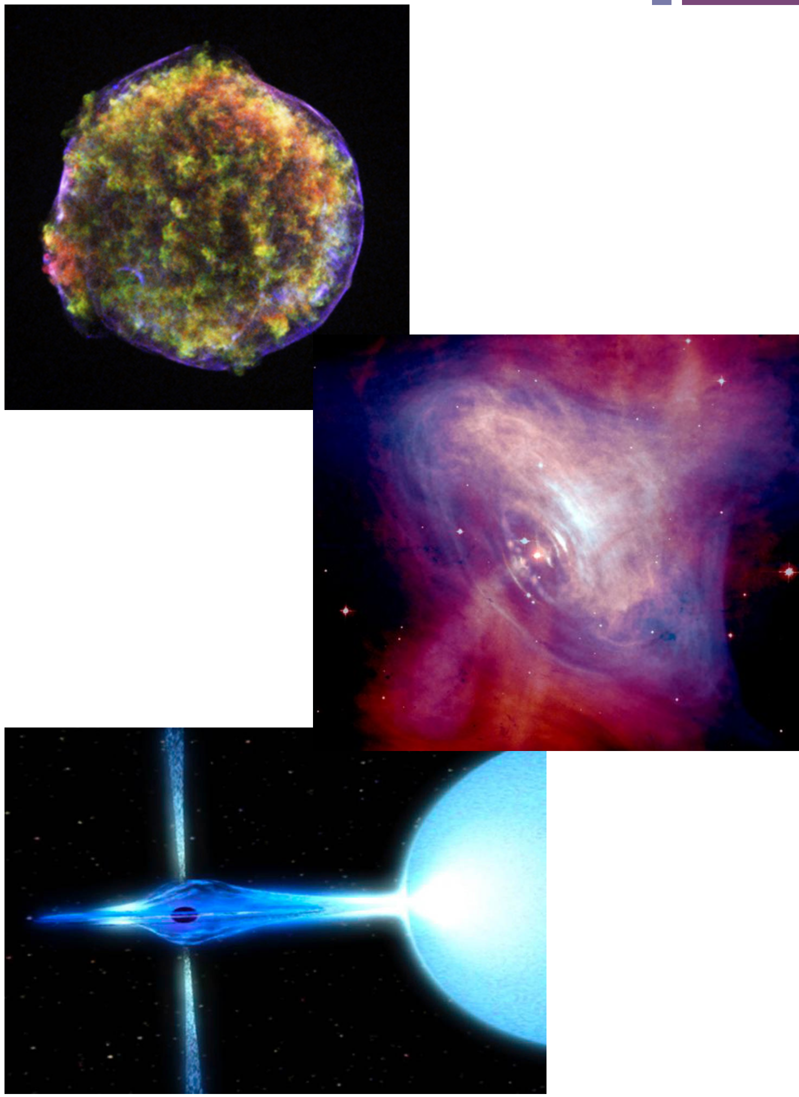


- Cosmic rays discovered 100 years ago
- Composed mainly of protons and heavier nuclei (plus electrons, gammas, neutrinos, anti-particles…)
- Isotropic distribution
- Spectrum covers ~13 decades in energy and ~30 orders of magnitude in flux
- Power-law reveals non-thermal origin
- Up to 10^{15}-10^{16} eV (the "knee") confined by Galactic magnetic fields ➔ Galactic origin

2011 Europhysics Conference on High Energy Physics, Grenoble, France, July 21-27, 2011.

Cosmic Rays, possible sources

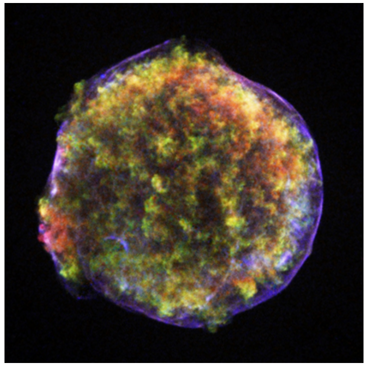
- Possible sources need to be able to accelerate particles up to the knee (~3×10^{15} eV)
- We know of several Galactic objects that could accelerate up to those energies by their detection at TeV energies, including: SNR's, pulsars and PWN, binary systems, star forming regions, supper-bubbles
- Extra evidence is gathered by observing starburst galaxies, with large number of these kind of objects



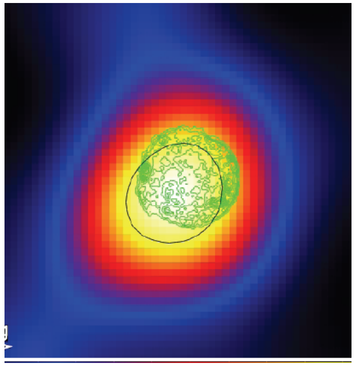
Supernova remnants

- After SN explosion the ejected material sweeps interstellar and circumstellar gas, forming a shock, which efficiently accelerate particles (non-linear process)
- Both e and p are accelerated:
  - e lose energy through synchrotron radiation (X-ray and radio) and IC (gamma)
  - p lose energy through pp interaction, producing gamma through π^0 decay, γ and p same spectral index, $E_\gamma^{max} \sim 0.1\ E_p^{max}$
- The energy budget (10^{51} ergs) and frequency (1 every ~50 years) enough if ~10% of energy used on acceleration
- The slow escape of CR from the shock can be speeded up by interaction with dense molecular clouds

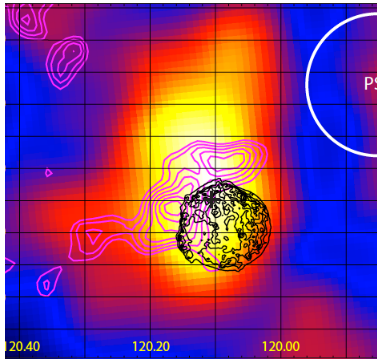
Young shell-type SNR: Tycho



X-ray Chandra



~GeV gamma-rays Fermi



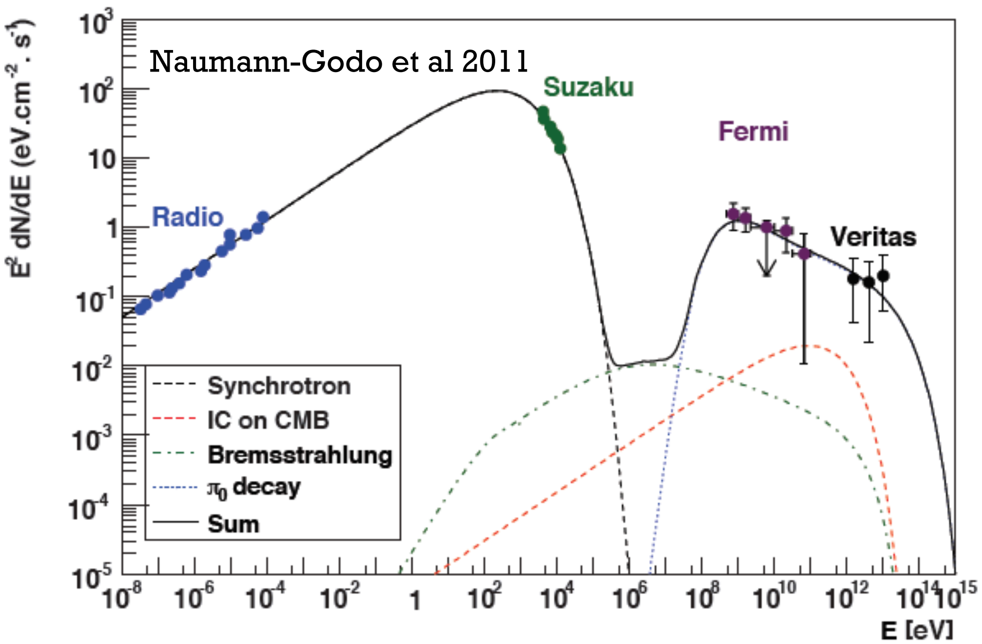
~TeV gamma-rays VERITAS

Type Ia

440 years

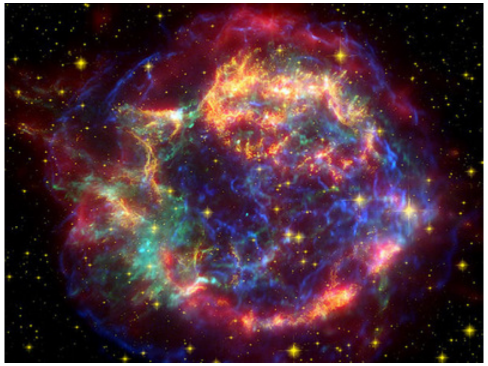
2-5 kpc

- Synchrotron flux + magnetic field 215μG determine the electron population (PL index 2.2-2.3 and cutoff 6-7 TeV)
- IC of e off CMB cannot reproduce gamma-ray flux (B should be lower, disfavored, and still fails at low energies). Bremmstahlung also not good
- Accelerated protons interacting with ambient medium producing gamma through π^0 decay reproduce the spectrum

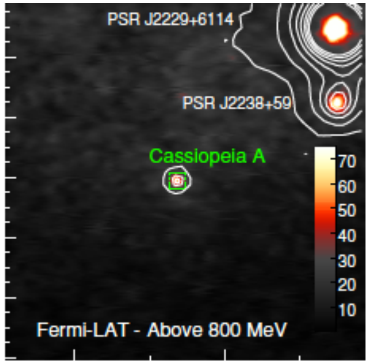


2011 Europhysics Conference on High Energy Physics, Grenoble, France, July 21-27, 2011.

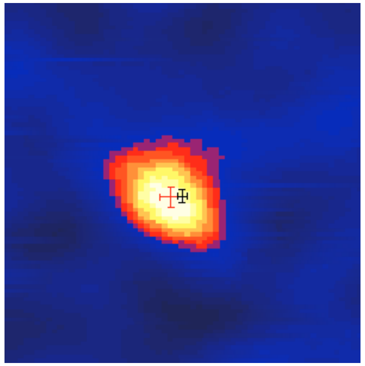
+ Young shell-type SNR: Cas A



IR Spizer, Opt Hubble,
X-ray Chandra



~GeV gamma-rays Fermi

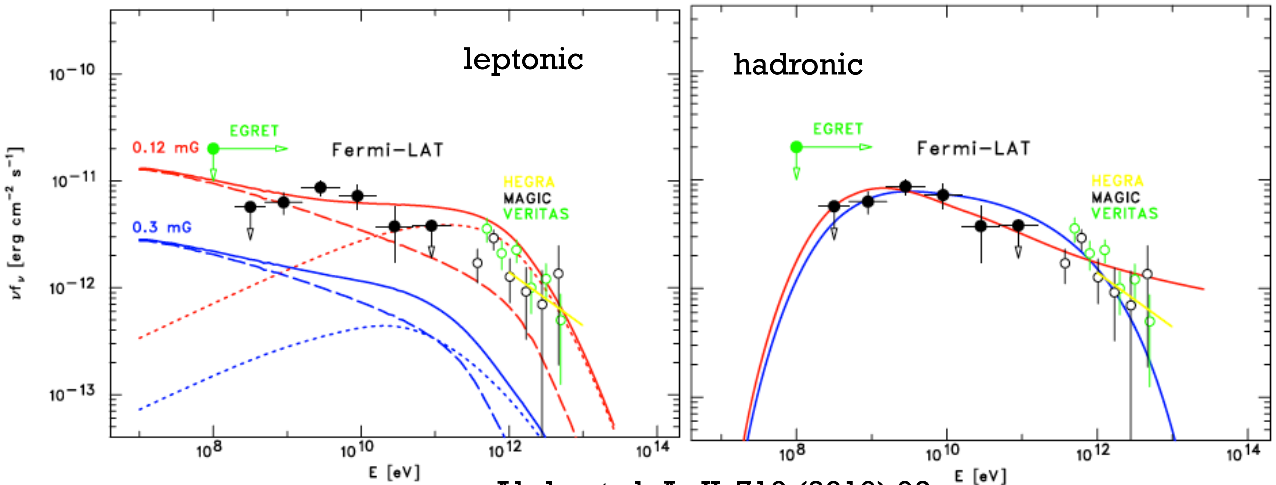


~TeV gamma-rays MAGIC
(also VERITAS, HEGRA)

Type II

300 years

3.4 kpc



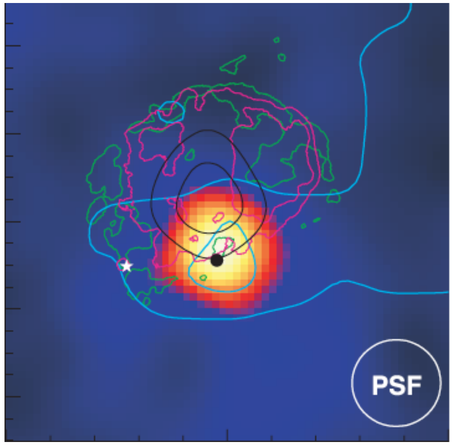
Abdo et al. ApJL 710 (2010) 92

- Emission from the shell favored wrt central compact object
- Emission can be explained both by accelerated leptons (bremmstrahlung +IC) or protons (π^0 decay)
- No clear cutoff

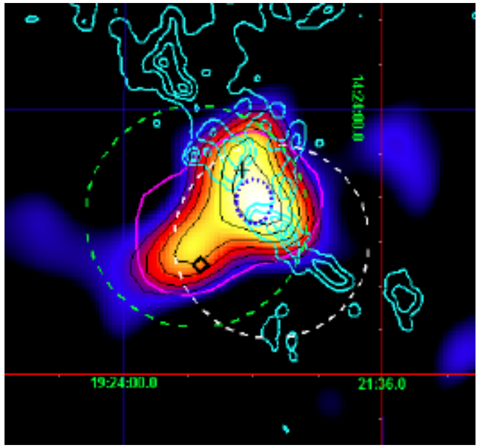
Other cases: J1713, Vela Jr., RCW86, SN 1006,… (HESS)

Old SNR: interaction with clouds

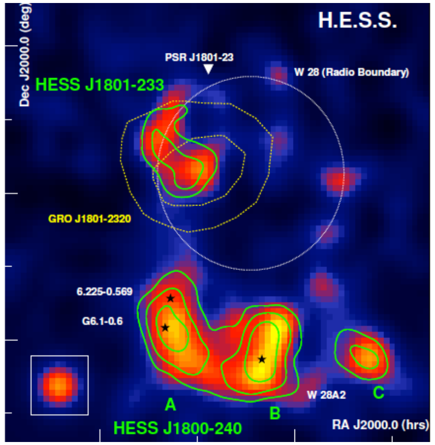
- If a CR source is close to a molecular cloud, the number of targets for pp collisions increases dramatically
- The gamma-ray emission on SNR-MC interaction region.
- Farther clouds get illuminated in gamma-rays with spectra with slopes 2.1-2.9, related to the CR escape flux
- Several known cases:



IC443 MAGIC (also VERITAS, Fermi)



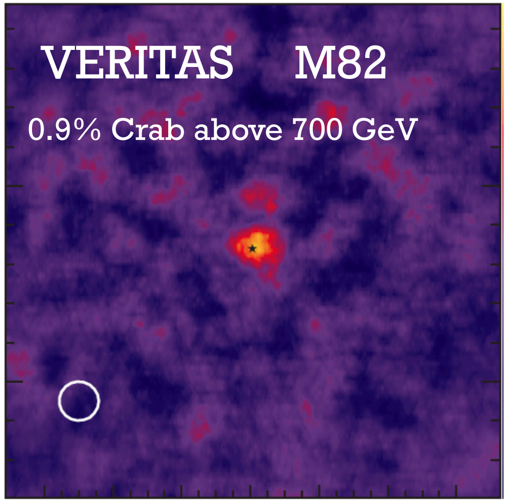
W51 MAGIC (also HESS, Fermi)



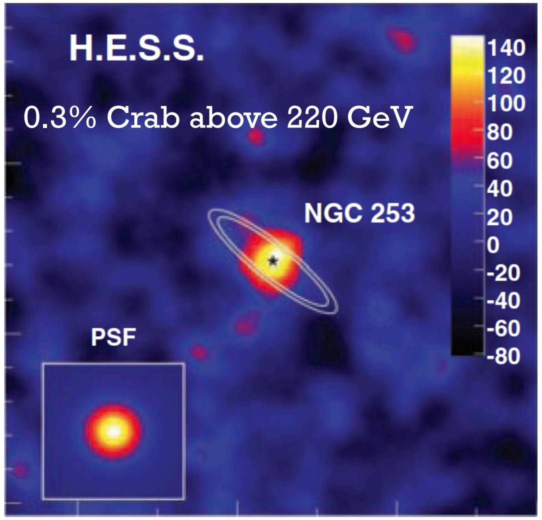
W28 HESS (also Fermi)

- Other similar cases: SNR G359.1-0.5 (HESS), CTB 37A (HESS, Fermi), W44(Fermi)

Starburst galaxies: M82 & NGC253



Acciari et al. Nature 462 (2009) 8557



Acero et al. Science 326 (2009) 1080

- Hypothesis: if CRs are accelerated at SNRs and/or massive star winds, starburst galaxies should contain higher densities of CRs, which in turn should illuminate them in gamma-rays, by their interactions with the interstellar gas and radiation
- The two most favorable cases have been detected at VHE gamma-rays by VERITAS (M82, 137 hrs) and HESS (NGC253, 119 hrs)
- and also at GeV gamma rays by Fermi shortly after
- Inferred CR density is 500 (2000) times larger in M82 (NGC253) than in our galaxy

Origin of cosmic rays summary

- SNR's have enough energy budget and frequency to account for all or big part of CR flux in the Galaxy
- Needed efficiencies (10%) in CR acceleration are at work
- Do the shocks accelerate particles up to the needed energies?
  - Certainly they do accelerate up to 10^{14}eV
  - Still in question whether energies up to the "knee" ($\sim 3\times 10^{15}$ eV) of CR spectrum are reached. Shock speed and magnetic field smaller for older SNR, so in principle only the young ones could contribute to the highest energies
- What is the ratio p/e in the particles accelerated in shocks?
- How do CR escape the shock? Magnetic turbulence damping in shock/molecular cloud interactions?
- Are SNR the only galactic CR accelerators?

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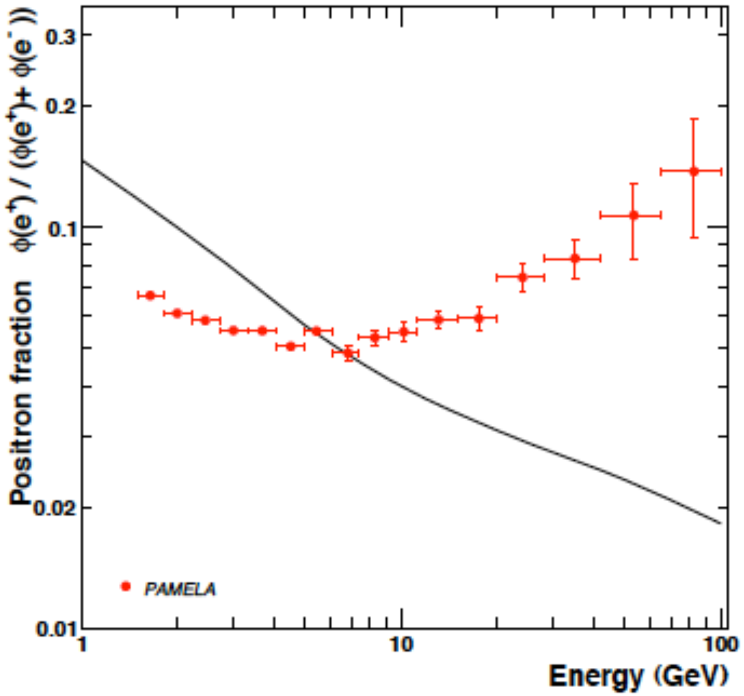
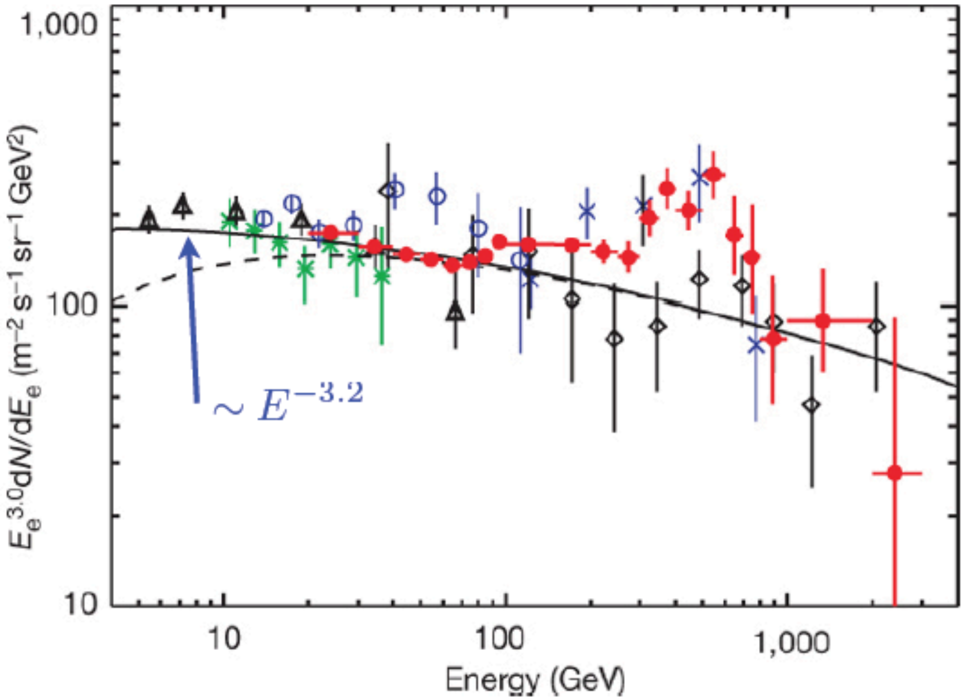
COSMIC RAY ELECTRONS

The cosmic ray electron and positron anomalies

- PAMELA and ATIC have found anomalies in the e^+ fraction (10-100 GeV) and the e^++e^- (100-1000 GeV) flux with respect to theoretical expectations of cosmic ray production and propagation in the Galaxy



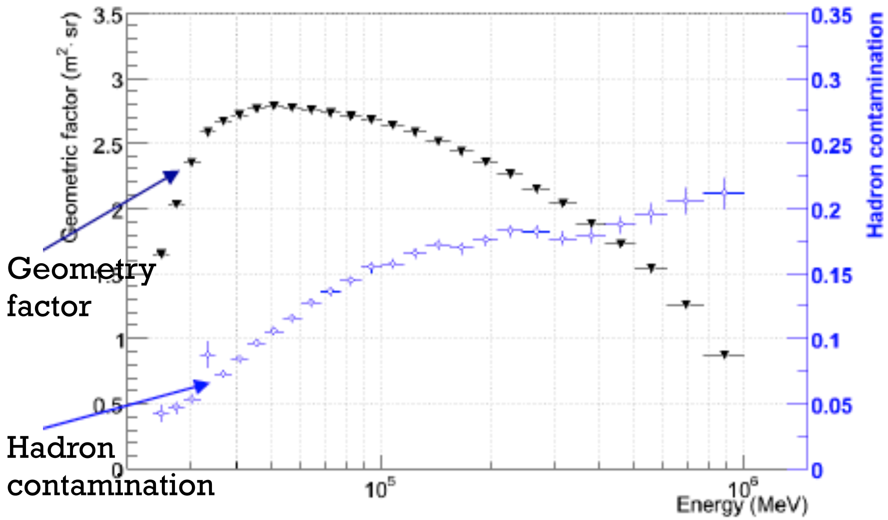
Adriani et al. Nature 458 (2009) 607

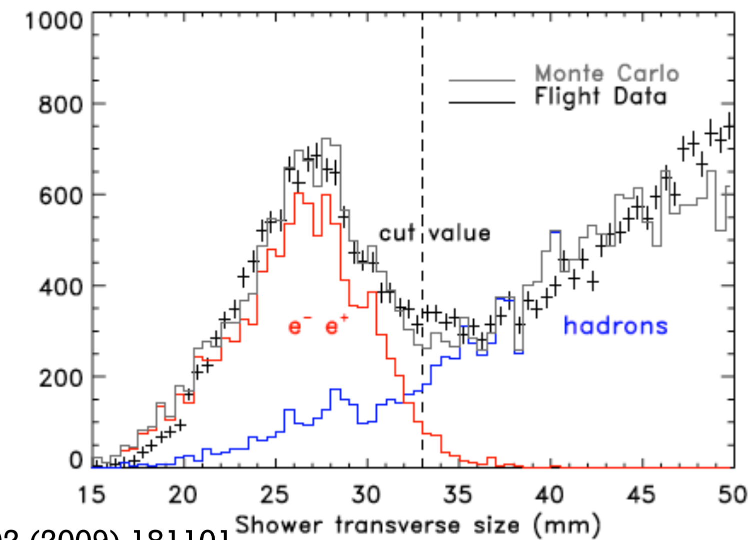


J. Chang *et al.* Nature **456** 362-365 (2008)

Measuring electrons with Fermi

- Challenging analysis:
  - Fermi is actually a fine electron spectrometer but there is hadron contamination
  - It records 10^7 electrons/positrons per year above 20 GeV
  - e/h separation relies on MC validated with beam tests and flight data
  - Extension of separation power and energy reconstruction from 300 GeV to 1 TeV relying on MC

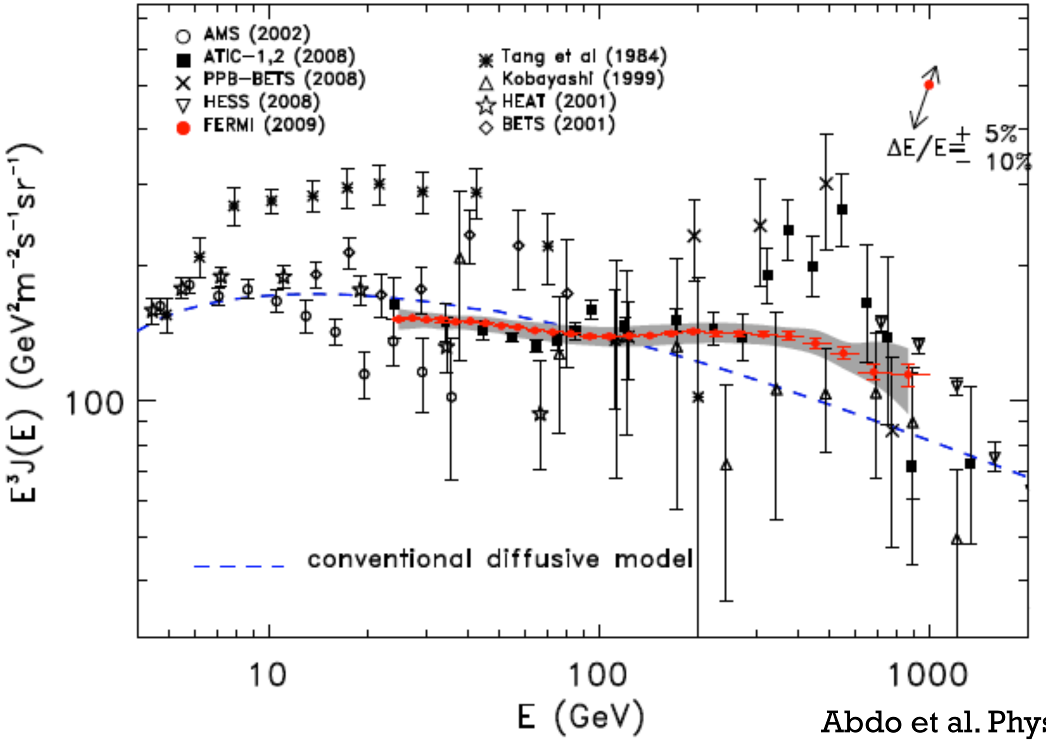




Abdo et al. Phys. Rev. Lett. 102 (2009) 181101

Electron spectrum measured by Fermi

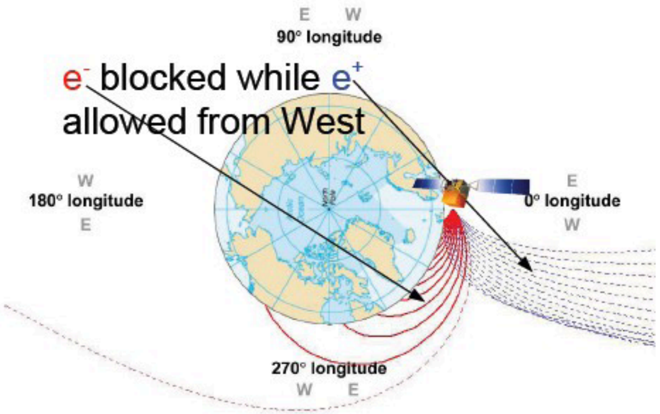
- The spectrum measured by Fermi does not show sharp features
- It can be fitted (considering systematic errors) with simple power law with index ~-3
- It deviates from the conventional diffusive model using Galprop

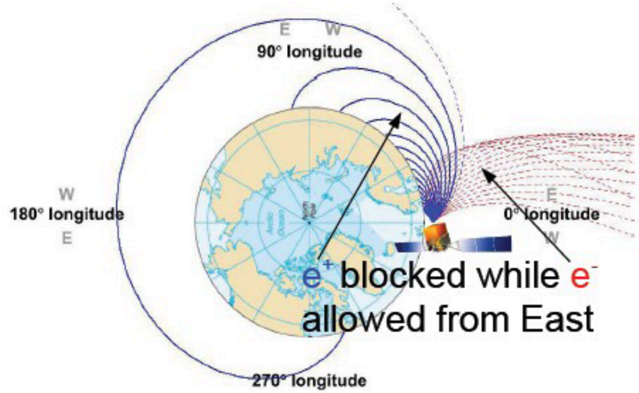


Abdo et al. Phys. Rev. Lett. 102 (2009) 181101

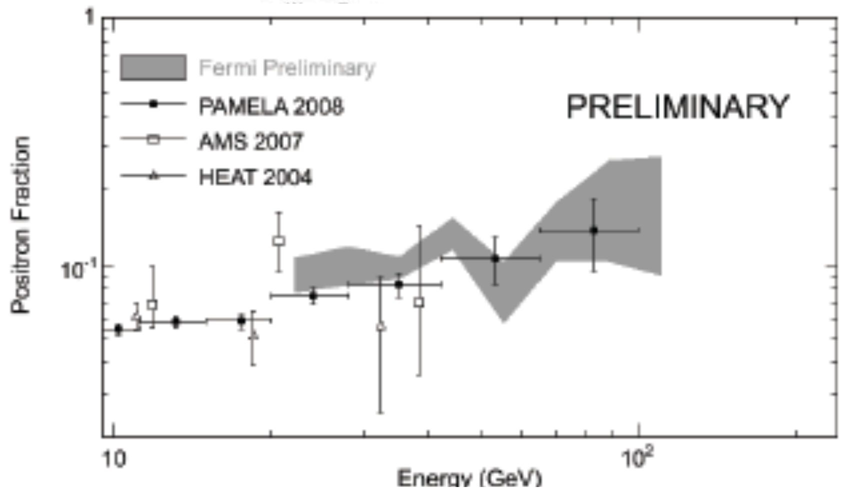
Positron fraction measured by Fermi

- Fermi has no magnet and cannot distinguish charge sign
- Depending on the detector pointing, particles from one or other charge sign get blocked by Earth





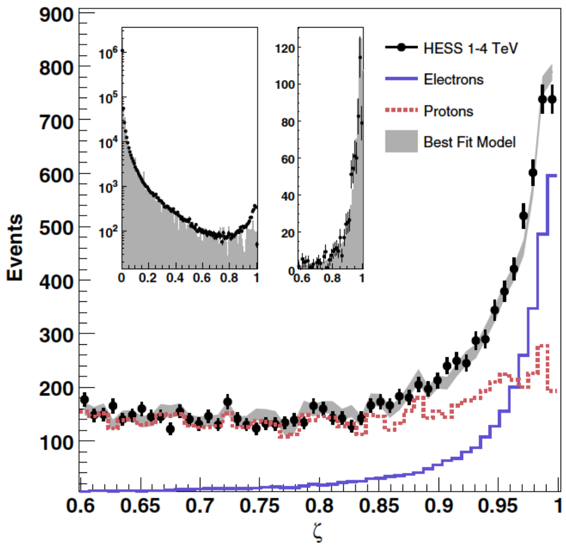
- Measured positron fraction in agreement with PAMELA result
- MAGIC has plans to measure e+ fraction up to ~1 TeV using similar technique with Moon shadow (Colin et al. ICRC 2009)

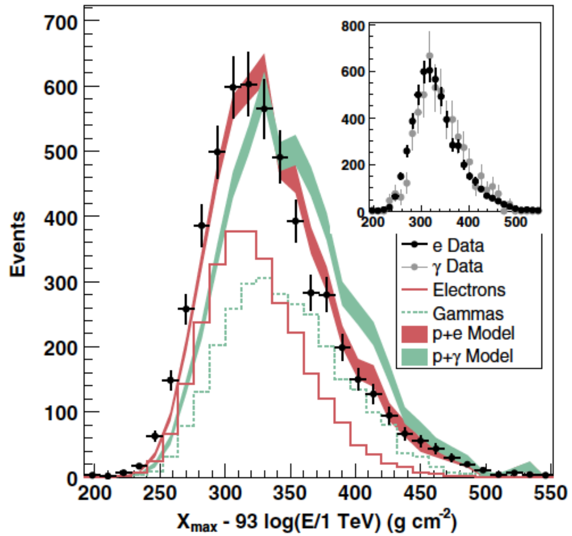


Fermi-LAT, 3rd Fermi Symp. 2011

Measuring electrons with HESS

- Challenging analysis:
  - Electrons and gammas look essentially identical for Cherenkov telescopes
  - Needs a very efficient gamma/hadron separation (achieved with Random Forest algorithm) ➔ Energy threshold increased up to ~350 GeV (600 GeV for first analysis)
  - Requires extensive and well understood MC simulations of hadronic and electrons showers
  - Uncertainty in the residual gamma-ray background

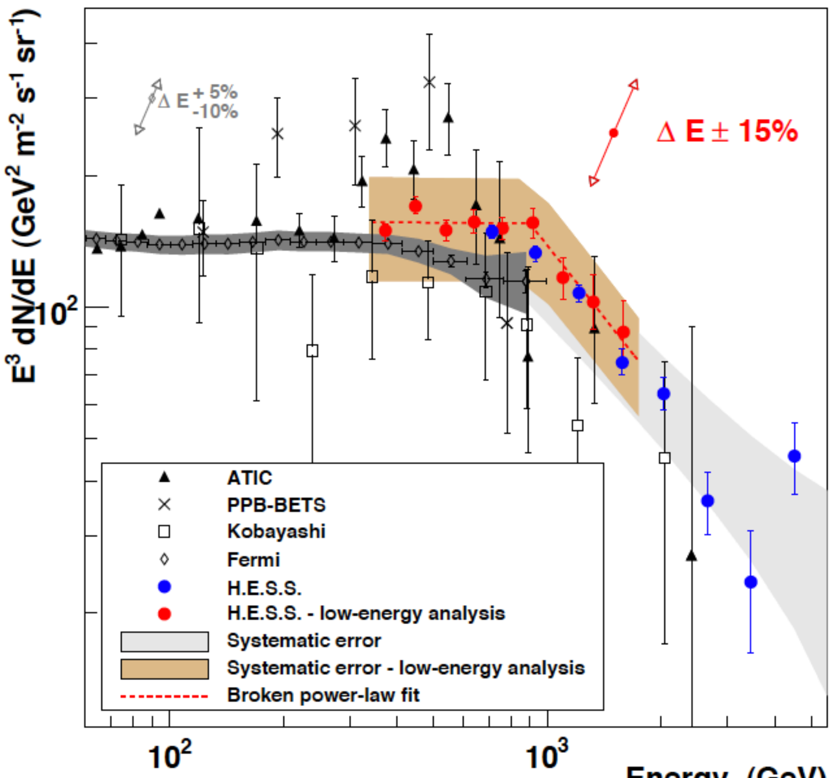




Aharonian et al. Phys. Rev. Lett. 101 (2008) 261104

Electron spectrum measured by HESS

- The spectrum measured by HESS does not show sharp features
- It can be fitted with power law with index -3 which steepens at 1 TeV
- General agreement with Fermi considering systematics



Aharonian et al. A&A 508 (2009) 561

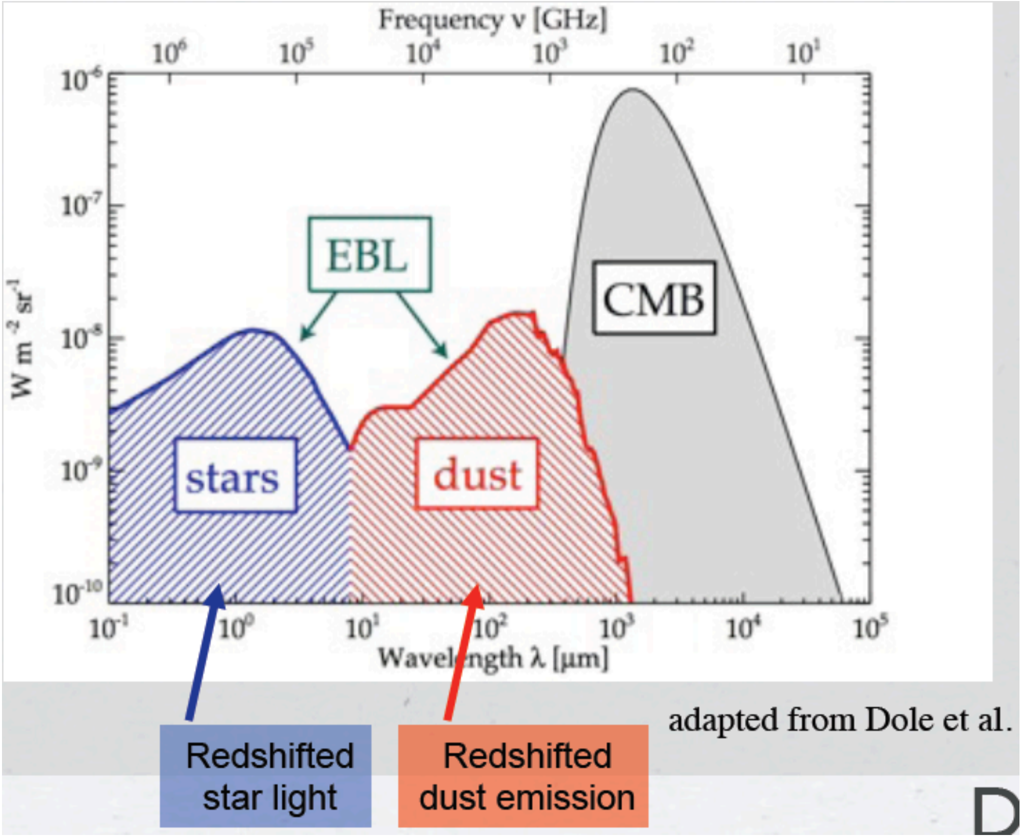
Electron spectrum summary

- Combined data Fermi/HESS contradicts the presence of the ATIC feature
- The harder spectrum explained by harder electrons in conventional production mechanisms
- Or by local source(s) (pulsars), which also explains PAMELA
- Others not excluded (e.g. Dark matter annihilation)

EXTRAGALACTIC BACKGROUND LIGHT

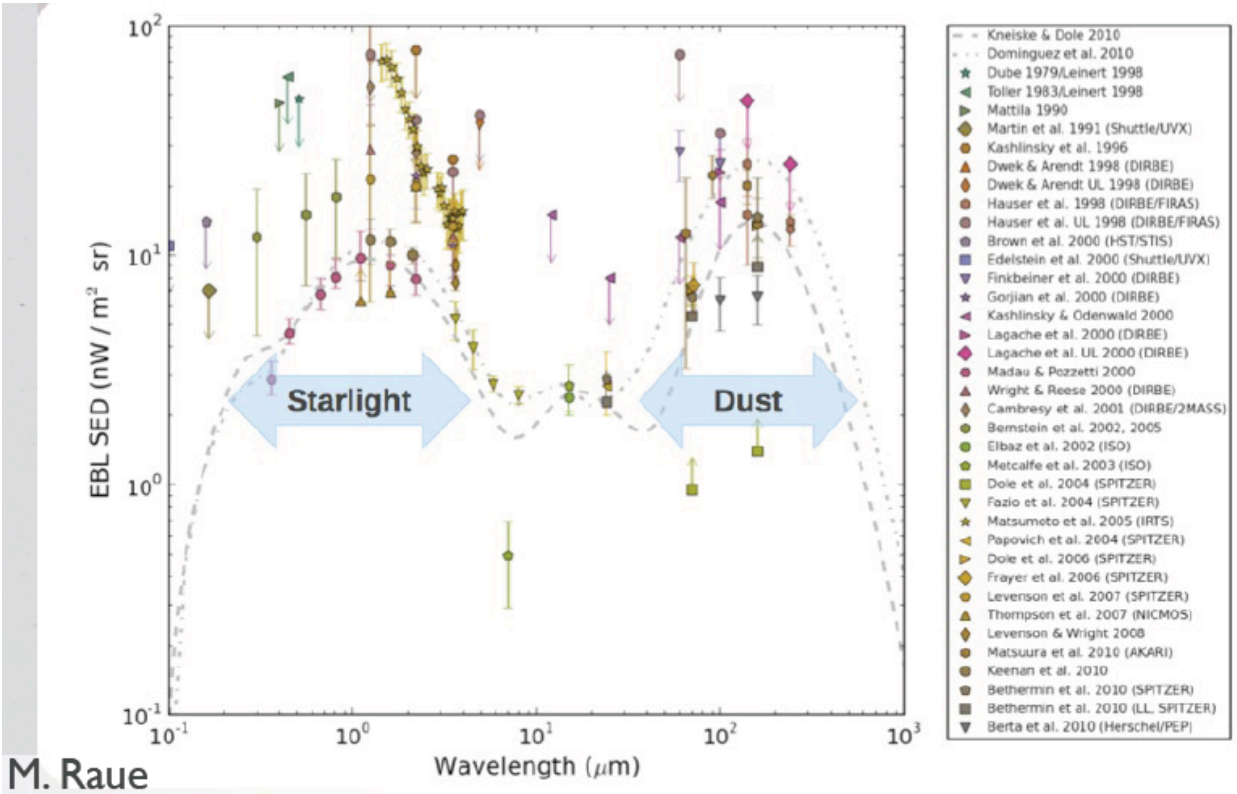
Extragalactic Background Light

- The EBL is the light emitted by all extragalactic sources along the history of the universe
- Isotropically distributed
- The EBL provides information about energy density of universe, and constrains models for star formation, galaxy evolution and cosmology
- 2 main components: redshifted light from stars and redshifted reprocessed light from dust emission



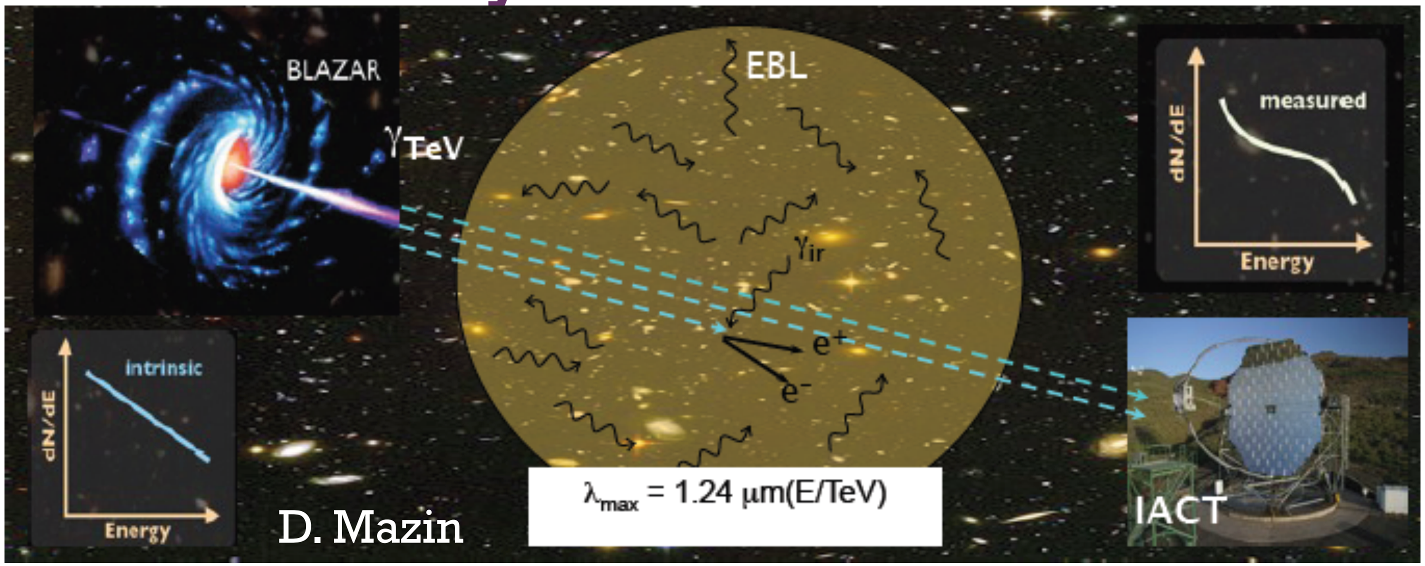
EBL: direct measurements

- Direct measurements using UV to FIR instruments
- Difficult measurements due to intense foreground (100 times larger in the whole range).
- Terrestrial, zodiacal and Galactic sources are dominant foreground
- Lower limits from Galaxy counts

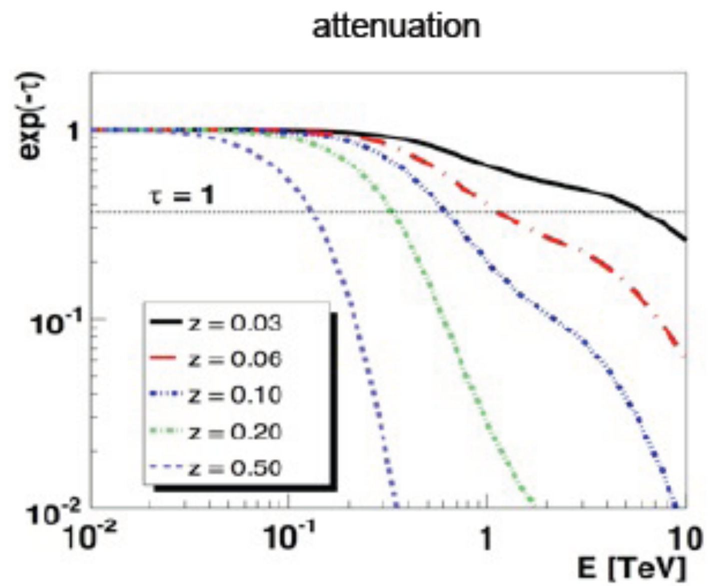


2011 Europhysics Conference on High Energy Physics, Grenoble, France, July 21-27, 2011.

Gamma rays interact with EBL

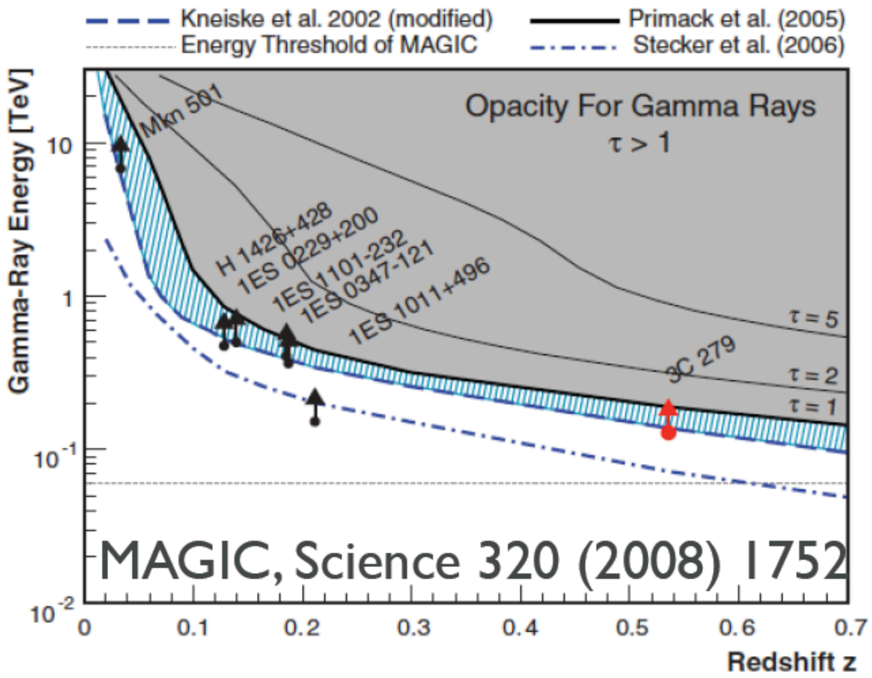


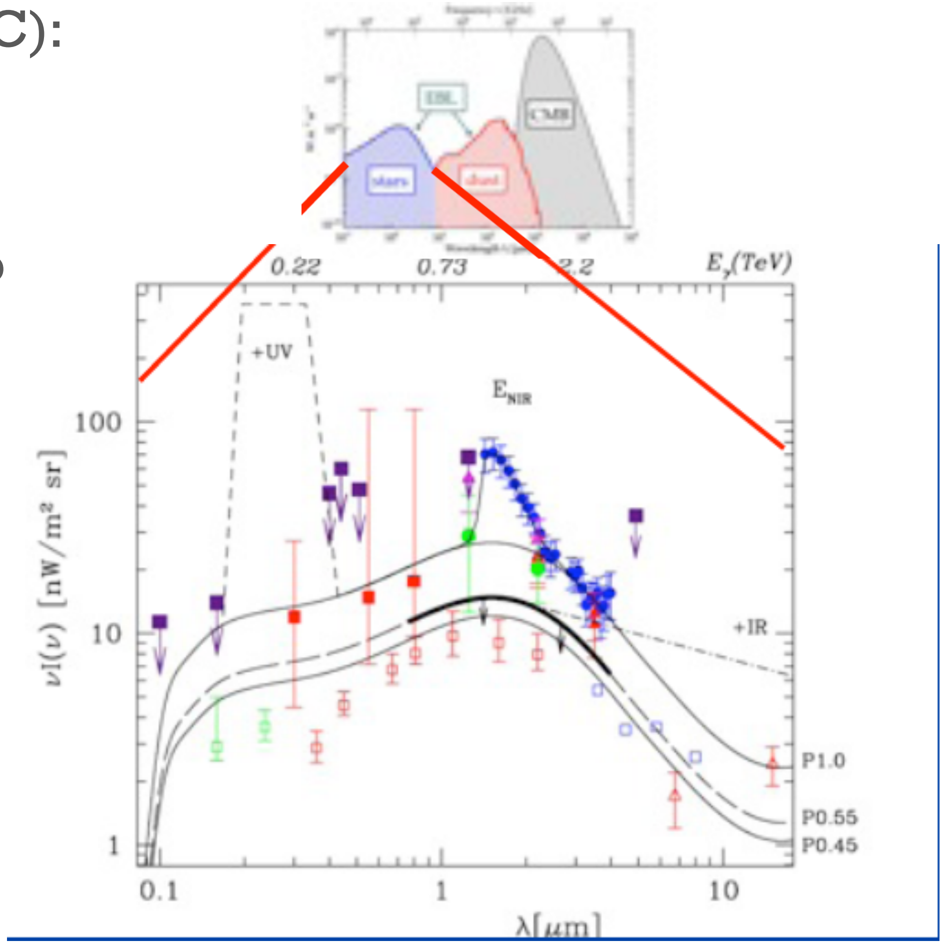
- Gamma rays from distant sources interact with EBL
- Measured spectrum modified by pair creation
- By measuring the distortion of the gamma-ray spectrum wrt intrinsic one we are measuring EBL



Constraints on EBL with Cherenkov Telescopes

- Two criteria to constrain EBL used by Cherenkov telescopes (HESS, MAGIC):
  - Spectrum cannot be too hard $\Gamma > 1.5$
  - There cannot be spectral pile up

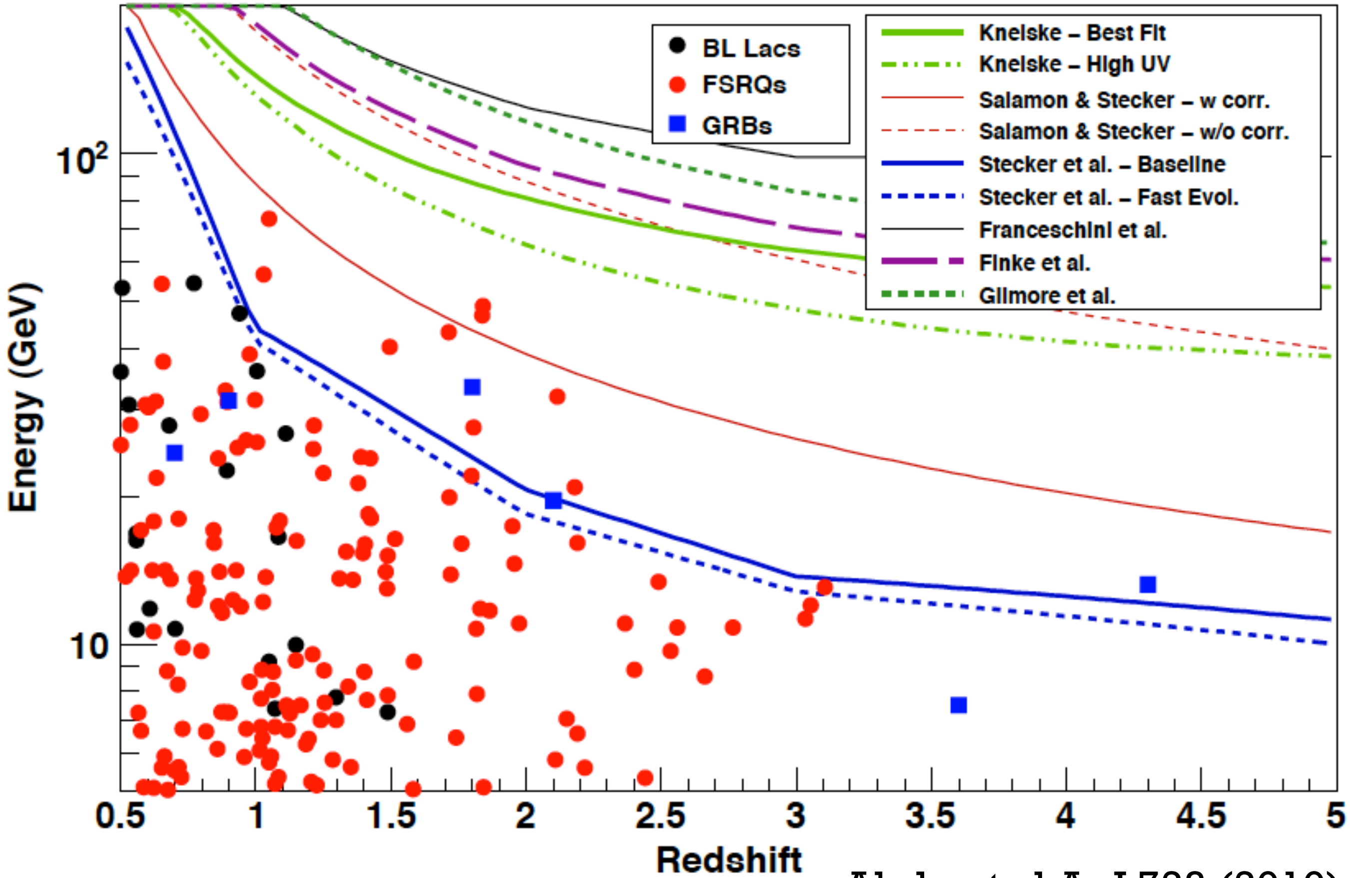




HESS, Nature 440 (2006) 1018

Constraints on EBL with Fermi

- Fermi exclude models for which the maximum-energy observed photon has a very small probability of being detected

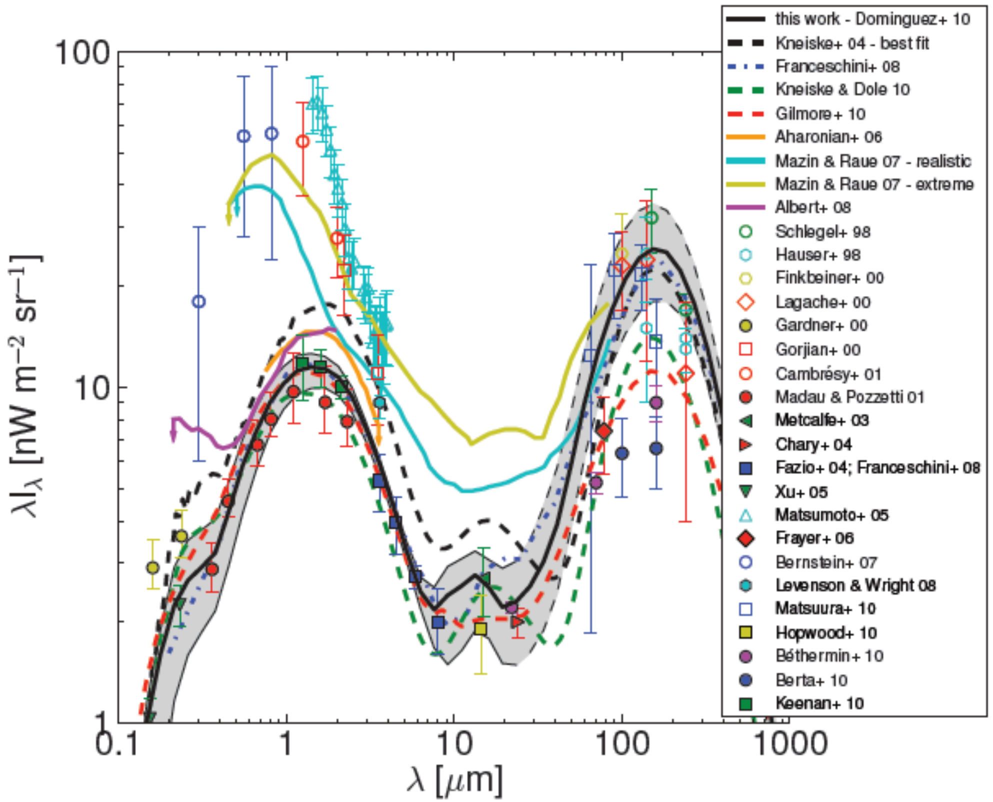


Lines represent the horizon of optical depth $\tau = 3$ predicted by different models

Abdo et al ApJ 723 (2010) 1082

EBL summary

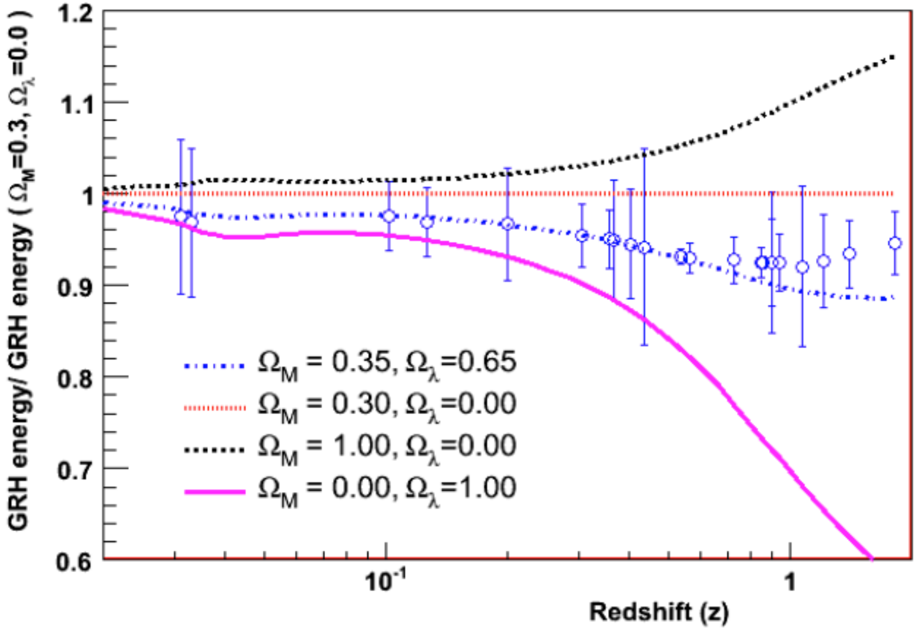
- Models with high EBL are excluded with high significance
- Recent models suggest actually levels close to lower limits



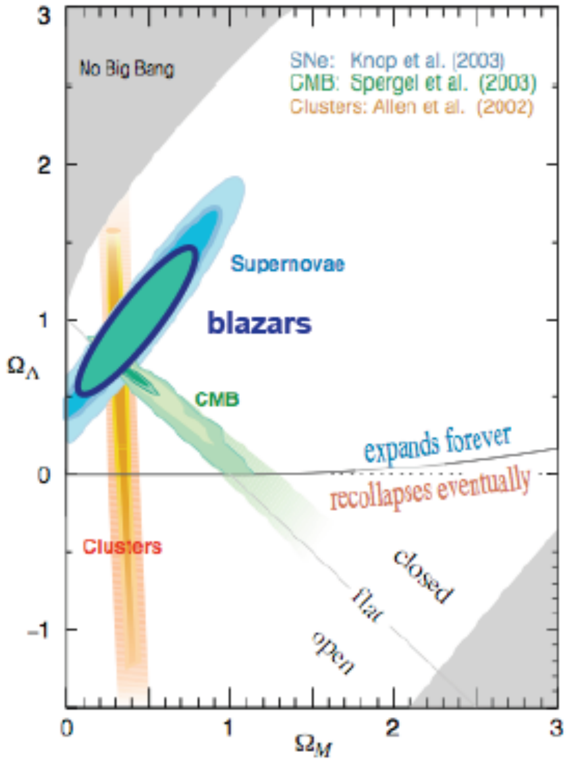
Dominguez et al, MNRAS, 410, 2556 (2010)

Measuring cosmological parameters

- Optical depth depends on cosmological parameters
- If EBL known with precision measuring AGN cutoffs vs. redshift can then provide an independent measurement
- Number of sources needed (>100, probably at reach only for CTA)



Blanch & Martínez Astropart. Phys. 23 (2005) 588



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TESTS OF LORENTZ INVARIANCE

Testing Lorentz Invariance with gamma-rays

- Energy dependence of speed of light
- Predicted by several Quantum Gravity theories:

  $v = c(1 \pm \xi(E/M_P) \pm \zeta(E/M_P)^2 + \ldots)$

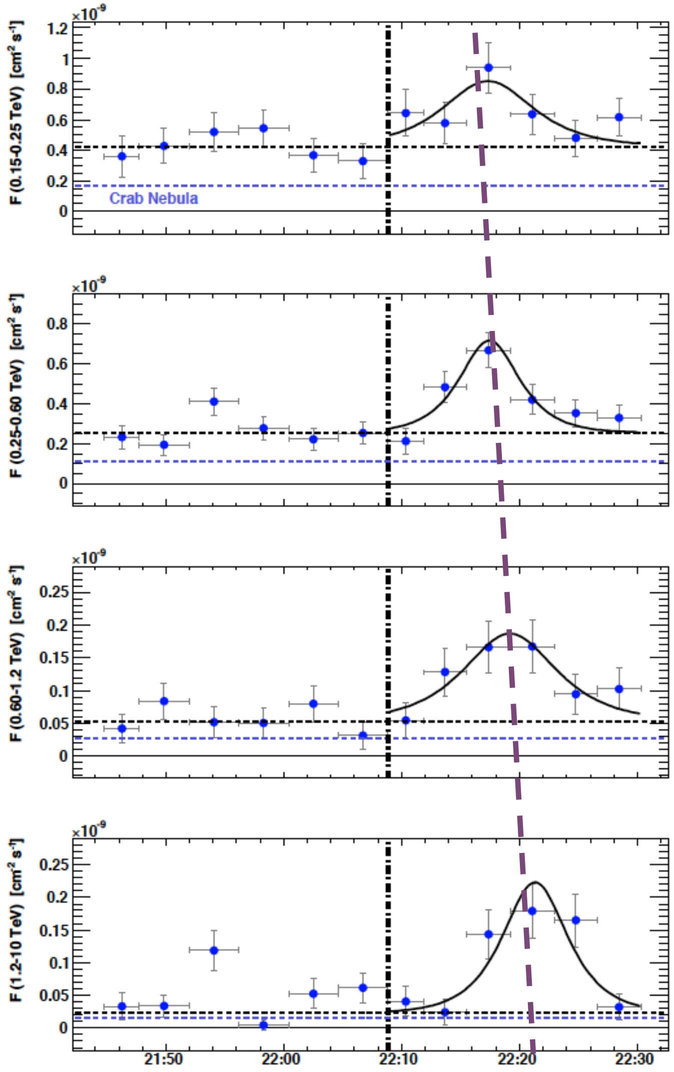
- Tiny effect expected since scale close to Planck Mass, but…
  - Measureable time delays are expected for photons from cosmological distances (AGN's, GRB's)…
  - … observed over a wide energy range

$$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_P H_0} \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2E_P^2 H_0} \int_0^z \frac{(1+z')^2 dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

- Fermi observes for larger redshifts (up to z~8) and shorter energy ranges (O(10 GeV))
- Cherenkov telescopes smaller redshifts (up to z~0.5 due to EBL) but larger energy range (O(1 TeV))

Testing Lorentz Invariance with MAGIC



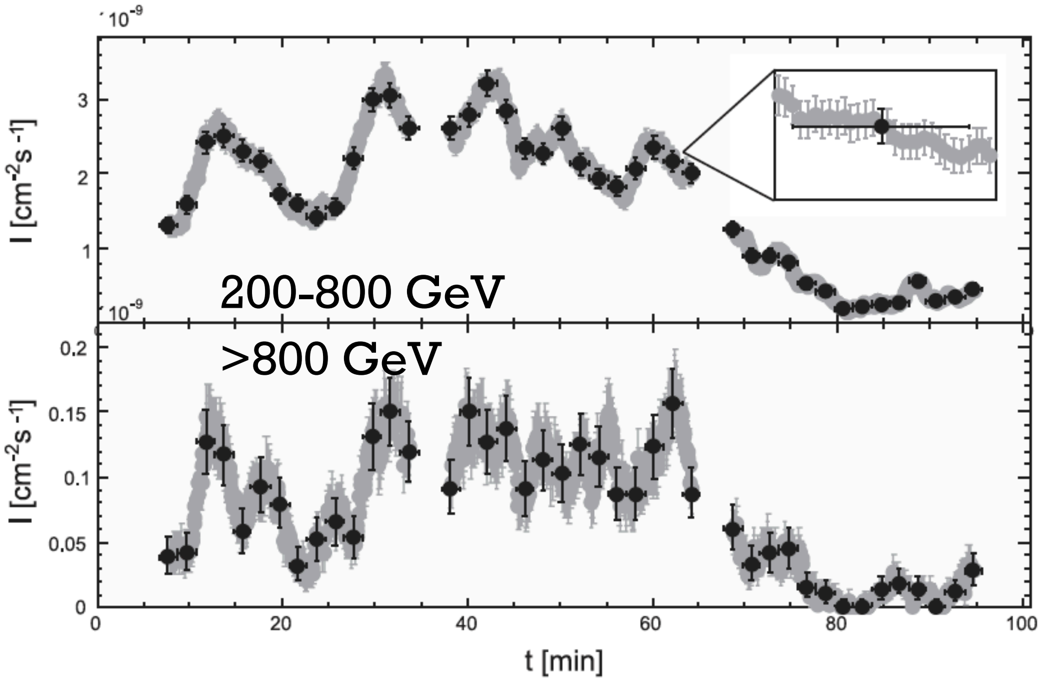
Albert et al., ApJ 669 (2007) 862

Albert et al. Phys. Lett. B 668 (2008) 253

- Use two flares of Mrk 501 ($z = 0.034$) on July 2005
- Variations of the flux of O(10) in the flares. Peak 4×Crab
- Doubling time: 1-2 minutes
- Energy range: 150 GeV – 10 TeV
- Delays in the time of arrival fitted using two different methods: Energy Cost Function and Likelihood
- Best fits: $\tau_l = (30\pm12)$ s/TeV
  $\tau_q = (3.71\pm2.57)$ s/TeV^2
- Delays at the source cannot be excluded
- Limits (95% CL): $M_{QGl} > 0.3\times10^{18}$ GeV
  $M_{QGq} > 5.7\times10^{10}$ GeV

Testing Lorentz Invariance with HESS

- Use exceptionally intense flare of PKS 2155-304 flares ($z = 0.116$) on July 28th 2006
- Peak flux: 15×Crab (40×average)
- Doubling time: 1-3 minutes

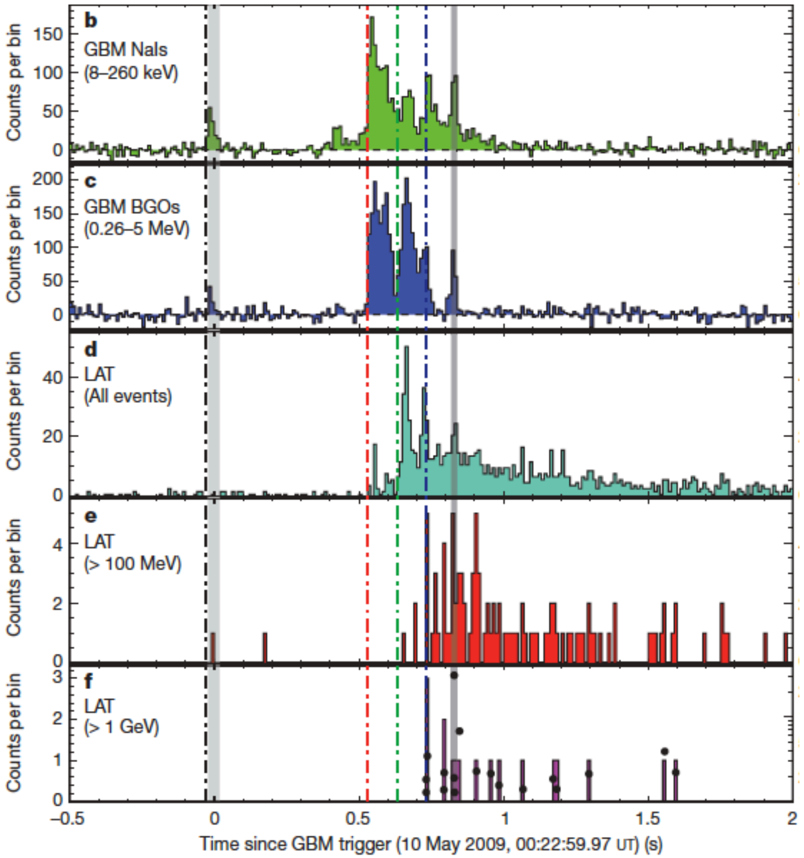


Aharonian et al. Phys. Rev. Lett. 101 (2008) 170402
Abramowski et al. Astroparticle Physics 34 (2011) 738

- Energy range: 200 GeV – 4 TeV
- Delays in the time of arrival fitted using Likelihood function:
  $\tau_l = (-5.5 \pm 10.9)$ s/TeV
  $\tau_q = (1.7 \pm 6.3)$ s/TeV^2
- Limits (95% CL):
  $M_{QGl} > 2.1 \times 10^{18}$ GeV
  $M_{QGq} > 6.4 \times 10^{10}$ GeV

Testing Lorentz Invariance with Fermi

- Use GRB 090510 ($z = 0.903$) on July 28^{th} 2006
- Duration: <1 second



Abdo et al. Nature 462 (2009) 331

- Energy range: 10 MeV – 30 GeV
- Delays in the time of arrival constrained with DisCan method (similar to Energy Cost Function):

  $\tau_1 < 30$ s/TeV

- Limits (95% CL):

  $M_{QGl} > 1.5\times10^{19}$ GeV

  $M_{QGq} > 3.0\times10^{10}$ GeV

- Limit to the scale mass for the linear term exceeds the Planck Mass!!

Lorentz Invariance Tests summary

Abramowski et al. Astroparticle Physics 34 (2011) 738

Source (*s*)	Experiment	Method	Results (95% CL limits)
GRB 021206	*RHESSI*	Fit + mean arrival time in a spike	$M^l_{QG} > 1.8 \times 10^{17}$ GeV
GRB 080916C	*Fermi* GBM + LAT	associating a 13 GeV photon with the trigger time	$M^l_{QG} > 1.3 \times 10^{18}$ GeV $M^q_{QG} > 0.8 \times 10^{10}$ GeV
GRB 090510	*Fermi* GBM + LAT	associating a 31 GeV photon with the start of any observed emission, DisCan	$M^l_{QG} > 1.5 \times 10^{19}$ GeV $M^q_{QG} > 3.0 \times 10^{10}$ GeV
9 GRBs	BATSE + OSSE	wavelets	$M^l_{QG} > 0.7 \times 10^{16}$ GeV $M^q_{QG} > 2.9 \times 10^{6}$ GeV
15 GRBs	*HETE-2*	wavelets	$M^l_{QG} > 0.4 \times 10^{16}$ GeV
17 GRBs	*INTEGRAL*	likelihood	$M^l_{QG} > 3.2 \times 10^{11}$ GeV
35 GRBs	BATSE + *HETE-2* + *Swift*	wavelets	$M^l_{QG} > 1.4 \times 10^{16}$ GeV
Mrk 421	Whipple	likelihood	$M^l_{QG} > 0.4 \times 10^{17}$ GeV
Mrk 501	MAGIC	ECF	$M^l_{QG} > 0.2 \times 10^{18}$ GeV $M^q_{QG} > 0.3 \times 10^{11}$ GeV
		likelihood	$M^l_{QG} > 0.3 \times 10^{18}$ GeV $M^q_{QG} > 5.7 \times 10^{10}$ GeV
PKS 2155-304	H.E.S.S.	MCCF	$M^l_{QG} > 7.2 \times 10^{17}$ GeV $M^q_{QG} > 1.4 \times 10^{9}$ GeV
		wavelets	$M^l_{QG} > 5.2 \times 10^{17}$ GeV
		likelihood	$M^l_{QG} > 2.1 \times 10^{18}$ GeV $M^q_{QG} > 6.4 \times 10^{10}$ GeV

- Models with linear term constrained by Fermi limit
- Quadratic term best constrained by Cherenkov telescopes due to the larger energy range

+

DARK MATTER SEARCHES

Indirect Dark Matter Searches with gamma-rays

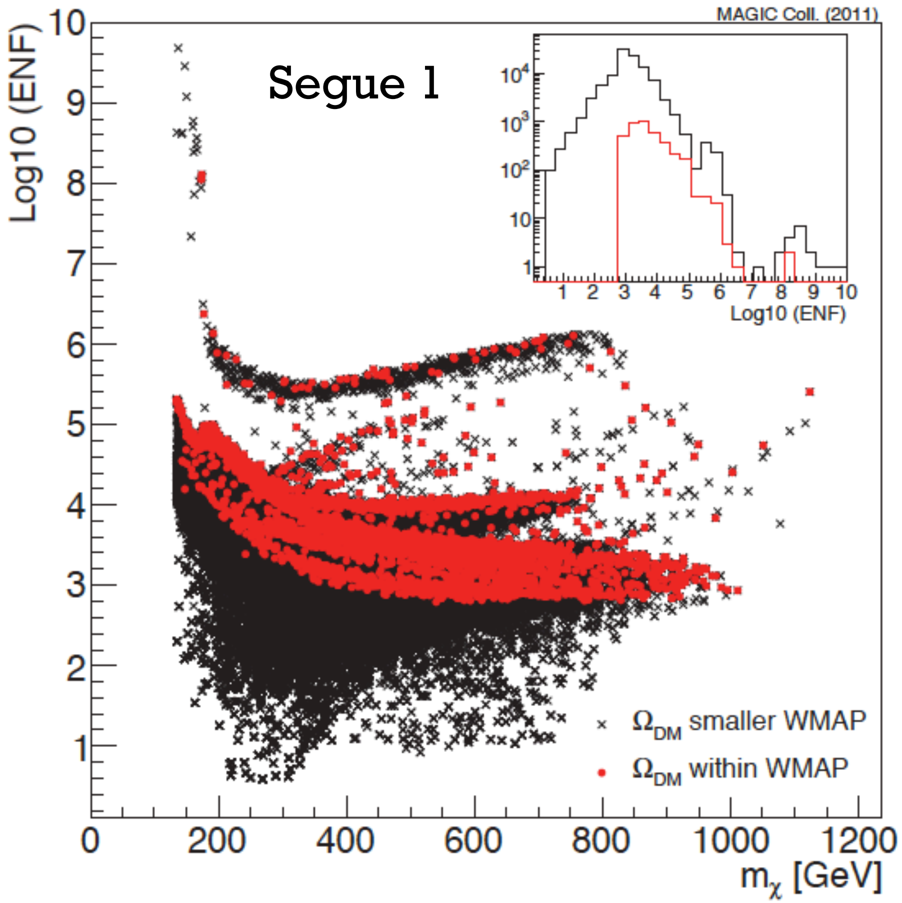
- Look for gamma-rays [secondary] product of the annihilation of dark matter particles
- Point telescopes at sites of dark matter over-densities

$$\Phi(E>E_0)=\underbrace{\frac{1}{4\pi}\frac{\langle\sigma_{ann}\upsilon\rangle}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_{i=1}^{n}B^i\frac{dN_\gamma^i}{dE}dE}_{(1)}\;\underbrace{\int_{\Delta\Omega}\int_{los}\rho^2(r(s,\Omega))\,ds\,d\Omega}_{(2)}$$

- (1): "Particle Physics" term:
  - Should be universal
  - May provide unique spectral features
  - For a given model we can constrain the average cross section
  - Energy resolution of instrument not included
- (2): "Astrophysical" term
  - Depends on the target (GC and halo, galaxy clusters, dwarf spheroidals, galactic sub haloes,…)
  - Large uncertainties from simulations
  - Angular resolution of instrument not included

Indirect Dark Matter Searches with MAGIC

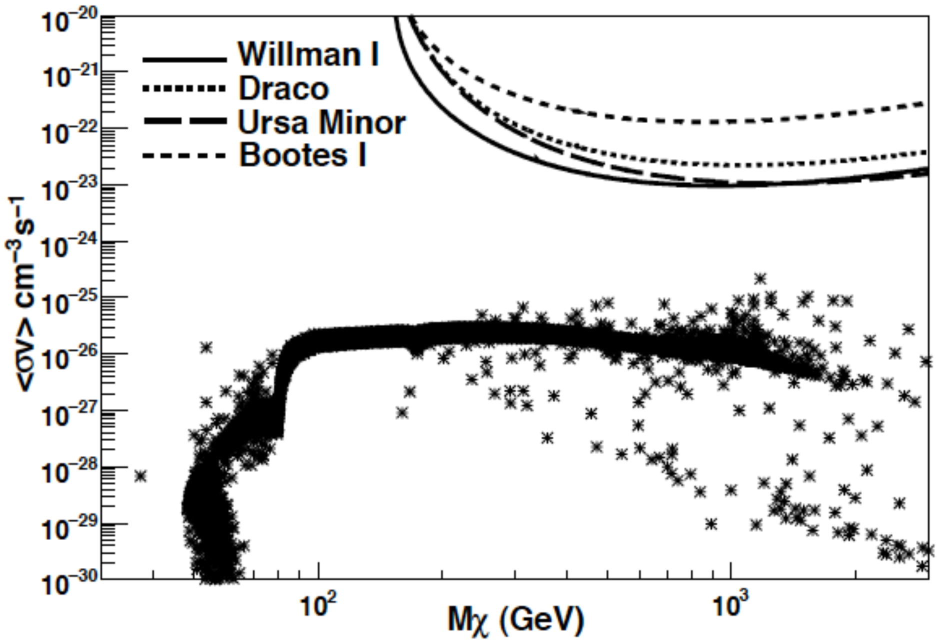
- Several promising targets pointed:
  - Dwarf Spheroidal Galaxies:
    - Draco (8 hrs)
    - Wilman I (15 hrs)
    - Segue 1 (30 hrs)
  - Perseus galaxy cluster (25 +20 hrs)
  - Galactic Center (17 hrs)
  - Mini-halo candidates (20 hrs)
- Enhancement factors needed at the order of 10^3 for WMAP allowed mSUGRA models
- See more this afternoon J. Aleksić talk



Aleksić et al. JCAP 06 (2011) 035

Indirect Dark Matter Searches with VERITAS

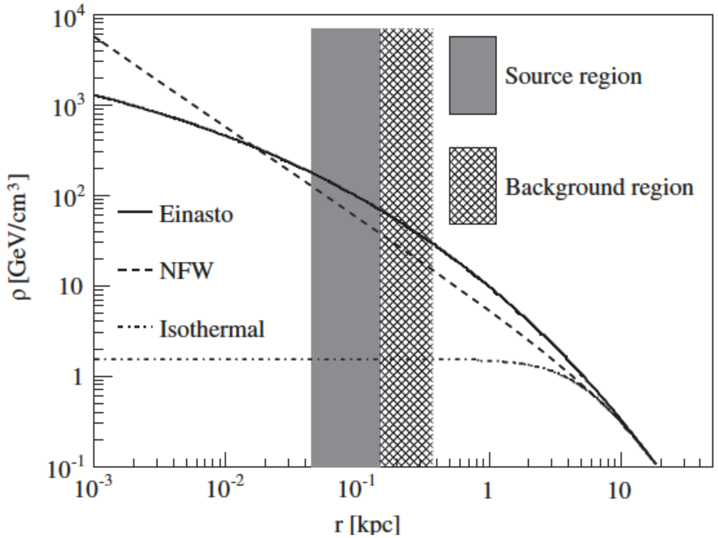
- Concentrated on dwarf Spheroidal Galaxies:
  - Draco (20 hrs)
  - Ursa Minor (20 hrs)
  - Boötes 1 (15 hrs)
  - Willman 1 (15 hrs)
  - Segue 1 (30 hrs)
- Also: Coma Cluster (20 hrs)
- Results similar to those obtained by MAGIC (similar objects and sensitivity)

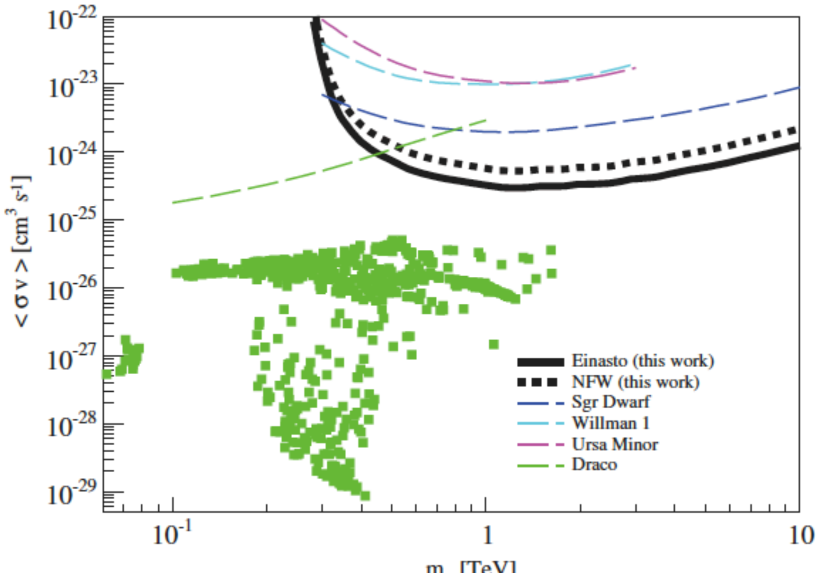


Acciari et al, ApJ 720 (2011) 1174

Indirect Dark Matter Searches with HESS

- Dwarf Spheroidals:
  - Sagittarius (10 hrs)
  - Carina (15 hrs)
  - Sculptor (12 hrs)
- Clusters of Galaxies:
  - Coma (8 h)
  - Abell 496 (15 h)
  - Abell 85 (33 h)
- Galactic Halo:
  - Galactic Center (150 hrs)
  - ★ Galactic Halo (112 hrs), high flux expected, no known astrophysical background, well understood profile. **Best limits** for Cherenkov telescopes. Still enhancements factors of order 100 needed

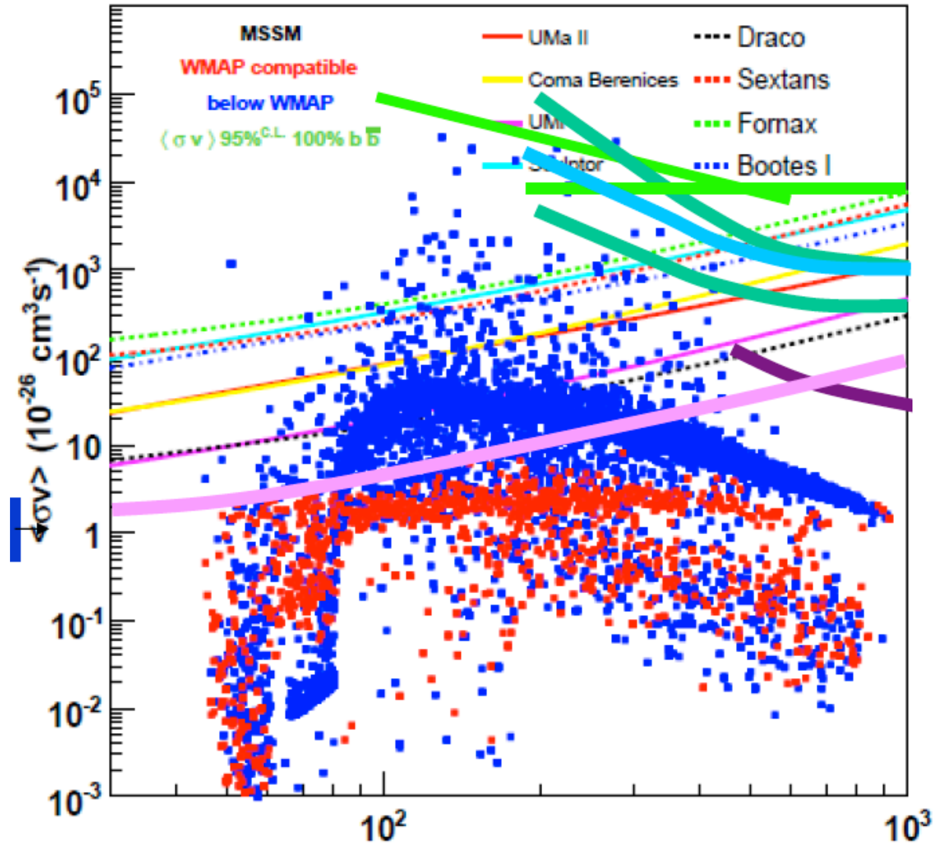




Abramowski et al. Phys. Rev. Lett 106 (2011) 161301

Indirect Dark Matter Searches with Fermi

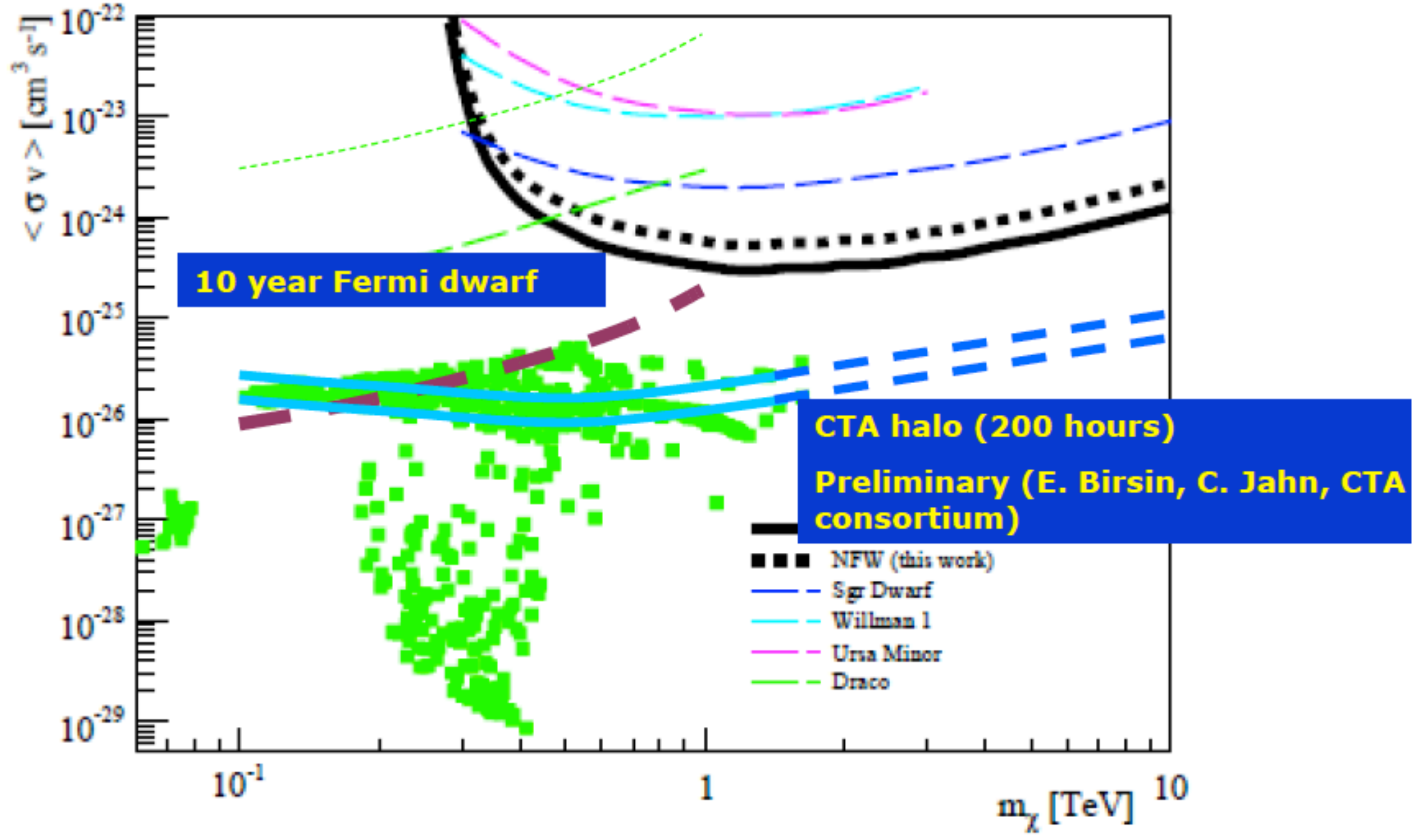
- All possible candidates are observed almost simultaneously
- Results from two years of observations
  - Galaxy Clusters (stacked)
  - Galactic Halo
  - Search for spectral lines
  - ★ Dwarf Spheroidals (stacked likelihood) ➔ **best limits** 10^{26} cm^3s^{-1} at reach after 10 years



Adapted by J. Conrad (IDMS 2011) from Abdo et al. ApJ 712 (2010) 147

Indirect Dark Matter Searches summary

- All known possible DM annihilation sites are being observed
- Sensitivity to SUSY DM still not reached by present generation of instruments
- Situation will improve in the following years



2011 Europhysics Conference on High Energy Physics, Grenoble, France, July 21-27, 2011.

CONCLUSIONS

- Gamma-ray instruments have been used to probe fundamental physics in several fronts:
  - Evidence on SNR's as the primordial sites of CR acceleration are being gathered
  - Cosmic-ray electrons/positrons measured between 30 GeV and 5 TeV, confirming a harder spectrum than previously thought
  - Models of Extragalactic Background Light constrained down almost to lower limits from galaxy counts
  - Quantum Gravity scale probed up to Planck Mass with Lorenz Invariance tests
  - Ongoing DM searches with no positive results so far. Expecting to start constraining models in the coming years