

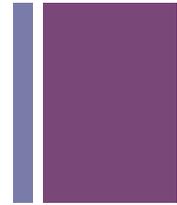


## Gamma ray astronomy: implications for fundamental physics

**Javier Rico**  
**ICREA/IFAE**



# + Disclaimer and acknowledgements

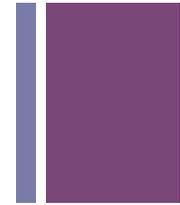


- VERY wide physics program → chose to talk only about results on fundamental physics
- Choice of “fundamentality” necessarily a bit personal
- Thanks to colleagues who have helped me and others whose material I use (I try to give proper credit throughout the talk)
- Also thanks to the organization for the invitation to participate in this very interesting conference



# OUTLINE

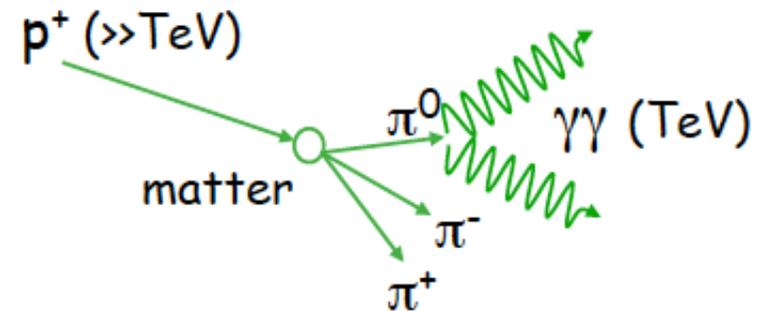
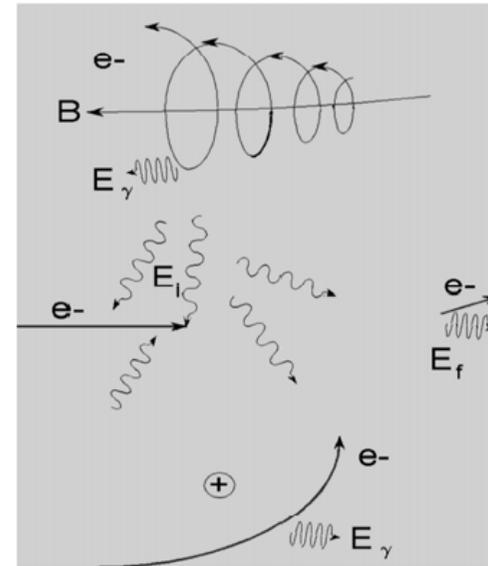
- Introduction: gamma-ray astronomy
  - Space: Fermi-LAT
  - Ground: HESS, VERITAS, MAGIC
  
- Gamma-rays and fundamental physics
  - The origin of Cosmic Rays
  - Cosmic-ray electron/positron
  - Extragalactic Background Light / Cosmology
  - Tests of Lorentz Invariance
  - Dark matter searches



# INTRODUCTION: GAMMA RAY ASTRONOMY

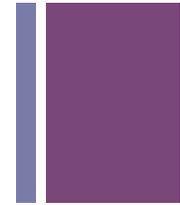
# + Processes

- High Energy (HE, 100 MeV – 100 GeV) and Very High Energy (VHE, 100 GeV – 100 TeV) astronomy 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), Bremsstrahlung
  - Protons: through  $\pi^0$  decays from interactions with interstellar matter

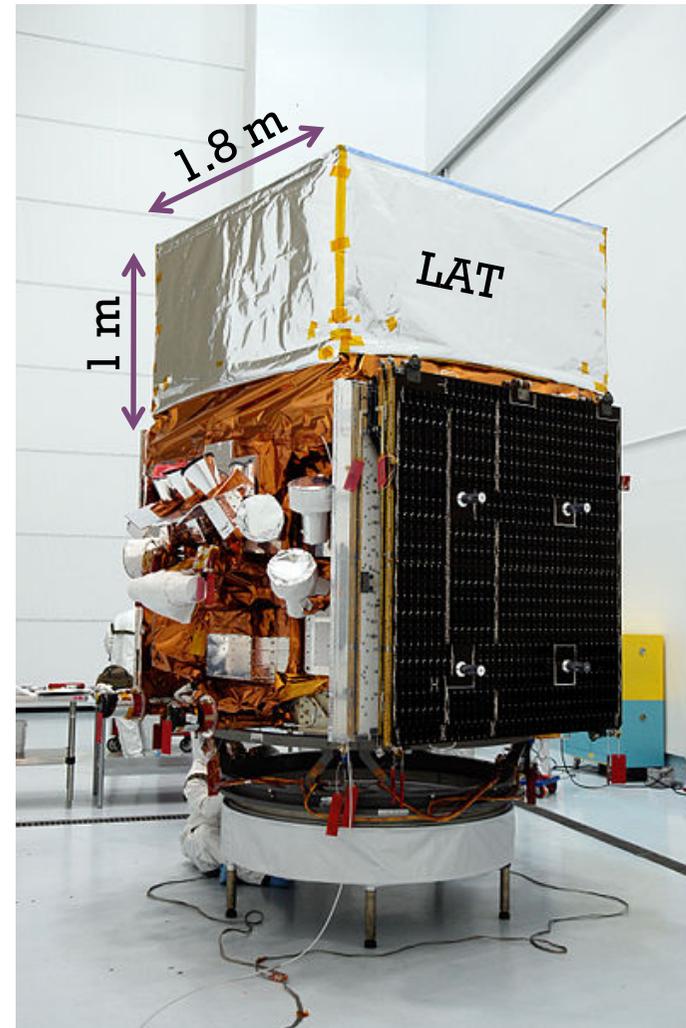




# HE instruments: Fermi-LAT

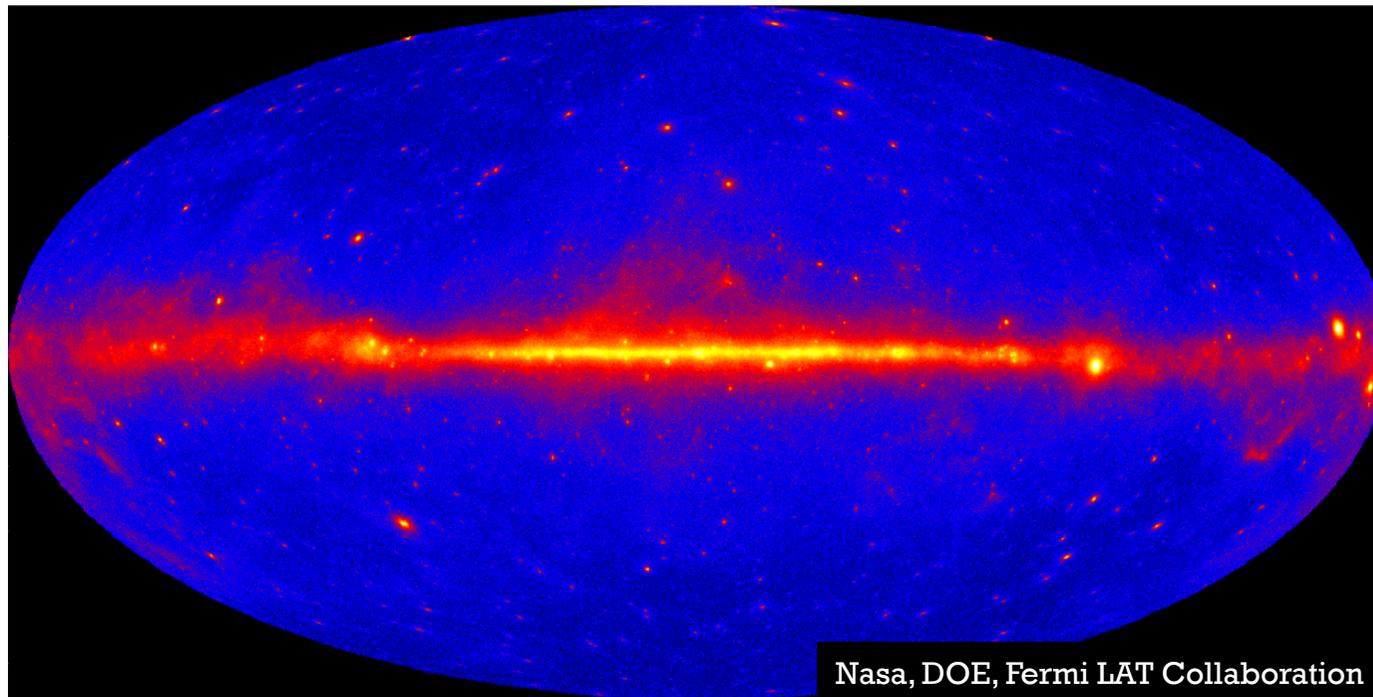


- Space-borne detector.  
Anticoincidence shield + tracker + calorimeter (no magnet)
- Almost background free
- Energy range 30 MeV – 300 GeV
- Energy resolution 10-15%
- PSF  $\sim 1^\circ$  ( $0.1^\circ$ ) at 1 (100) GeV
- Field of view 2.4 sr
- Survey mode: full sky every 2 orbits (three hours). Slew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



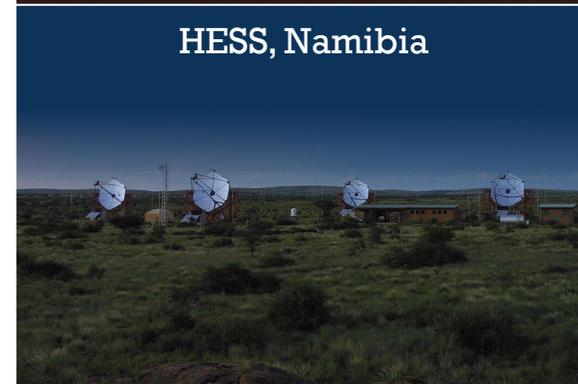
# + The HE sky

- 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

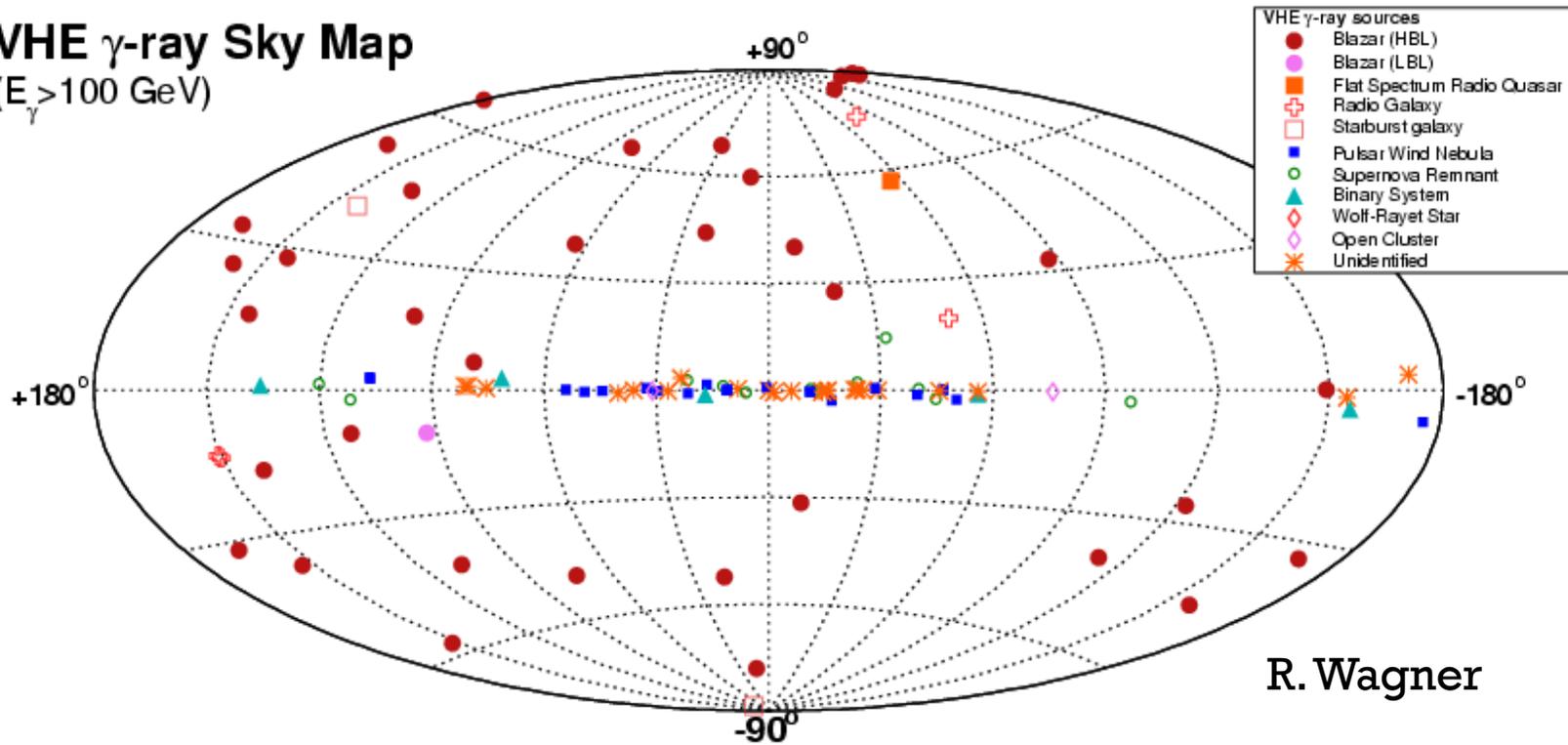
- Gamma-ray fluxes drop exponentially with energy → for energies above  $\sim 100$  GeV we need larger collection areas → Cherenkov telescopes
- Huge CR background → Imaging technique
- Energy range  $\sim 100$  GeV – 100 TeV
- Energy resolution 10-15%
- PSF  $\sim 0.1^\circ$  at 1 TeV
- Field of view 3-5 deg diameter ( $\sim 0.005$  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

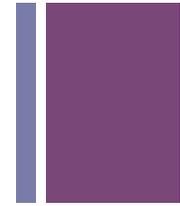
- Over 100 sources (vs. 14 until 2005), about ~25 unidentified
- Many by systematic scan of inner Galaxy (HESS)

**VHE  $\gamma$ -ray Sky Map**  
( $E_\gamma > 100$  GeV)



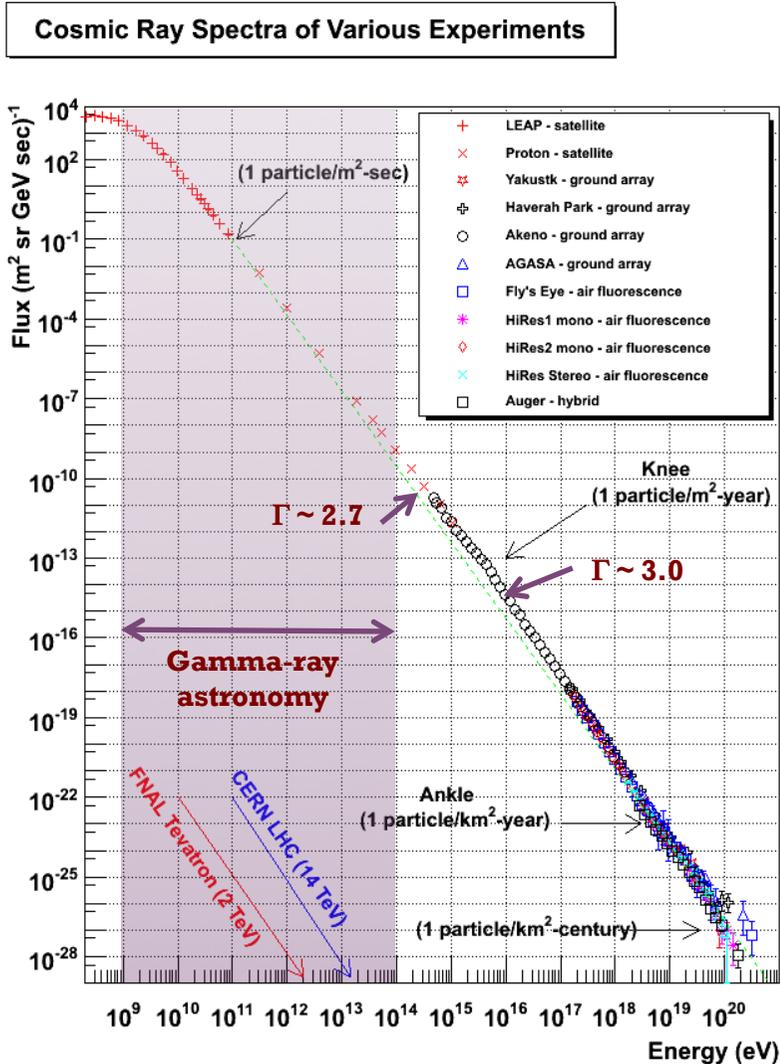
R. Wagner

2011-01-08 - Up-to-date plot available at <http://www.mpp.mpg.de/~rwagner/sources/>



# ORIGIN OF COSMIC RAYS

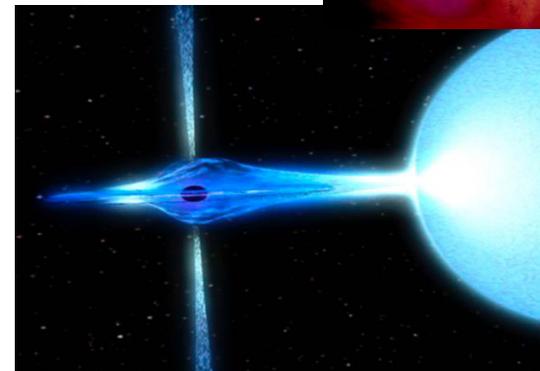
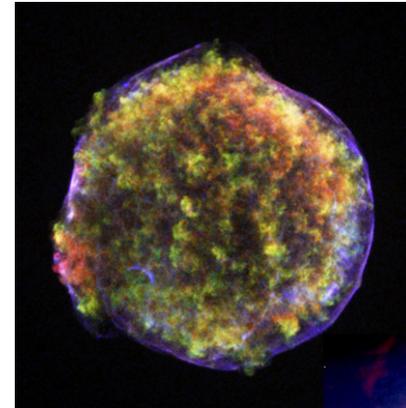
# + Cosmic Rays



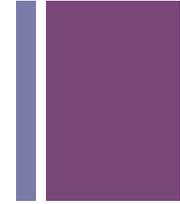
- Cosmic rays discovered 100 years ago
- Composed mainly of protons and heavier nuclei (plus electrons, gammas, neutrinos, anti-particles...)
- Isotropic distribution
- Spectrum covers  $\sim 13$  decades in energy and  $\sim 30$  orders of magnitude in flux
- Power-law reveals non-thermal origin
- Up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

# + Cosmic Rays, possible sources

- Possible sources need to be able to accelerate particles up to the knee ( $\sim 3 \times 10^{15}$  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, super-bubbles
- Extra evidence is gathered by observing starburst galaxies, with large number of these kind of objects

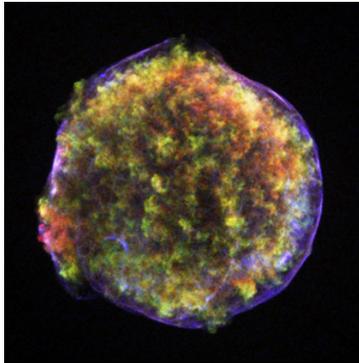
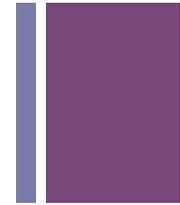


# + Supernova remnants

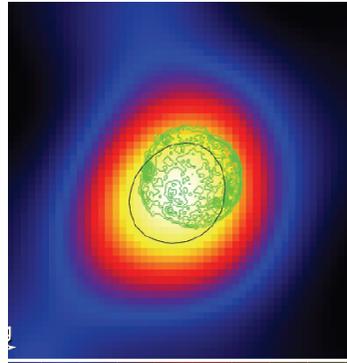


- After SN explosion the ejected material sweeps interstellar and circumstellar gas, forming a shock, which efficiently accelerates particles (non-linear process)
- Both e and p are accelerated:
  - e lose energy through synchrotron radiation (X-ray and radio) and IC (gamma)
  - p lose energy through pp interaction, producing gamma through  $\pi^0$  decay,  $\gamma$  and p same spectral index,  $E_\gamma^{\max} \sim 0.1 E_p^{\max}$
- The energy budget ( $10^{51}$  ergs) and frequency (1 every  $\sim 50$  years) enough if  $\sim 10\%$  of energy used on acceleration

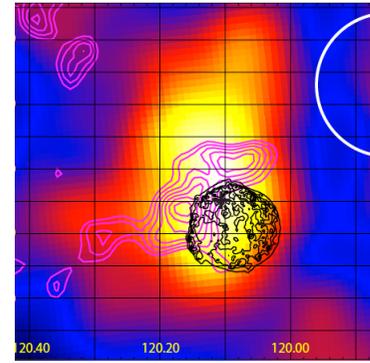
# + Young shell-type SNR: Tycho



X-ray Chandra



~GeV gamma-rays Fermi



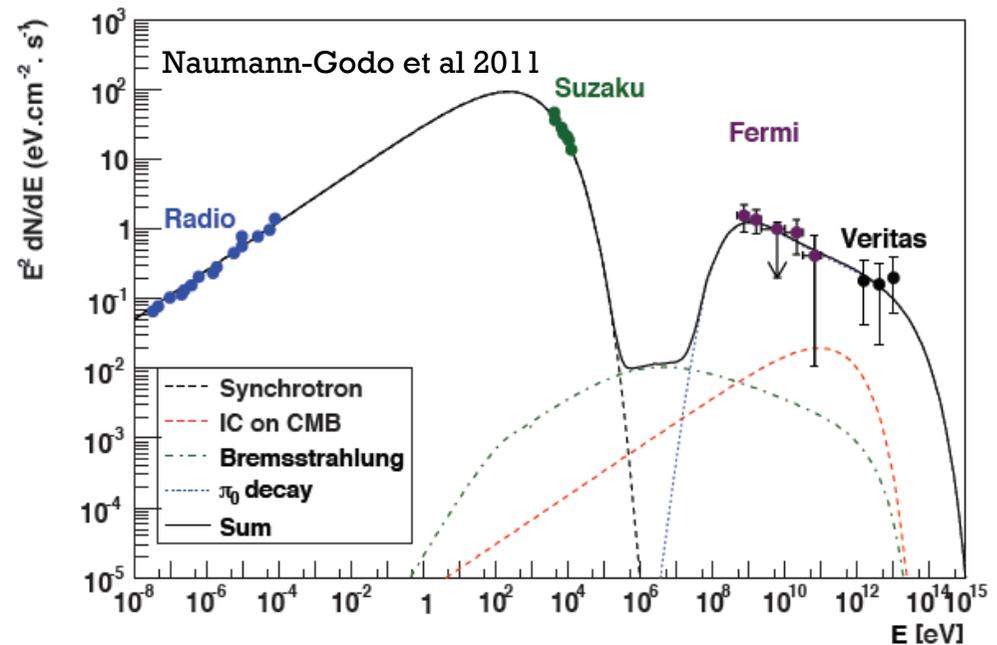
~TeV gamma-rays VERITAS

Type Ia

440 years

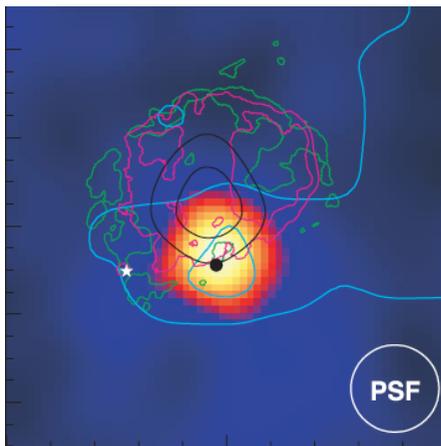
2-5 kpc

- Synchrotron flux + magnetic field  $215\mu\text{G}$  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). Bremsstrahlung also not good
- Accelerated protons interacting with ambient medium producing gamma through  $\pi^0$  decay reproduce the spectrum

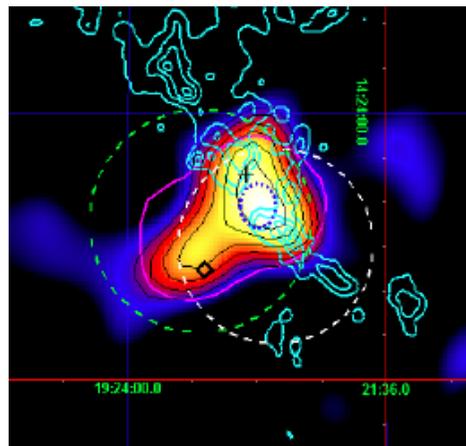


# + Old SNR: interaction with clouds

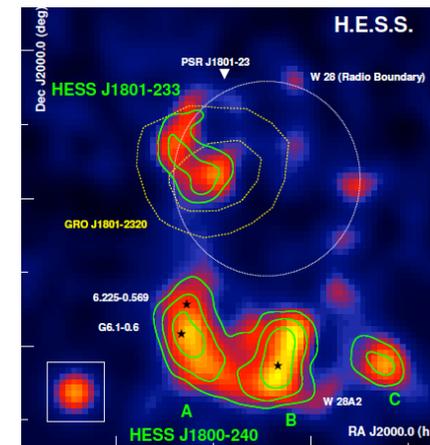
- If a CR source is close to a molecular cloud, the number of targets for pp collisions increases dramatically
- The gamma-ray emission on SNR-MC interaction region.
- Farther clouds get illuminated in gamma-rays with spectra with slopes 2.1-2.9, related to the CR escape flux
- Several known cases:



**IC443** MAGIC (also VERITAS, Fermi)



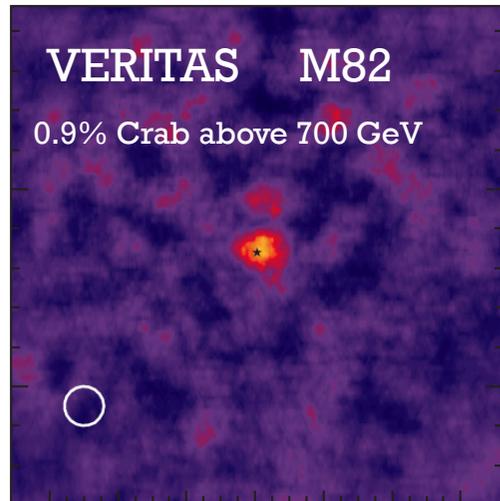
**W51** MAGIC (also HESS, Fermi)



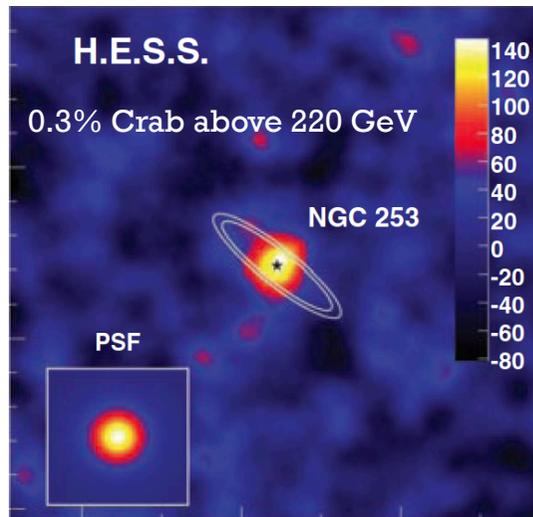
**W28** HESS (also Fermi)

- 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

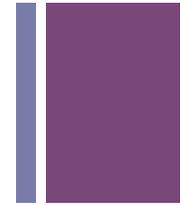


Acero et al. Science 326 (2009) 1080

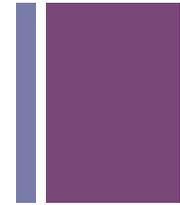
- Hypothesis: if CRs are accelerated at SNRs and/or massive star winds, starburst galaxies should contain higher densities of CRs, which in turn should illuminate them in gamma-rays, by their interactions with the interstellar gas and radiation
- The two most favorable cases have been detected at VHE 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



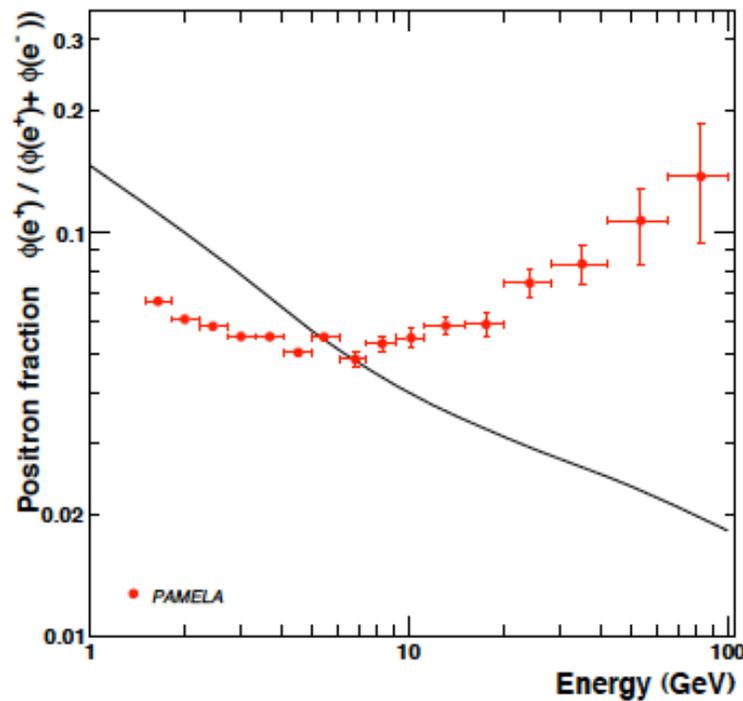
- SNR's have enough energy budget and frequency to account for all or big part of CR flux in the Galaxy
- Needed efficiencies (10%) in CR acceleration are at work
- Do the shocks accelerate particles up to the needed energies?
  - Certainly they do accelerate up to  $10^{14}$ eV
  - Still in question 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? High energy CRs escape during the Sedov phase. Do interactions with clouds help accelerate high energy particle escape?
- Are SNR the only galactic CR accelerators?



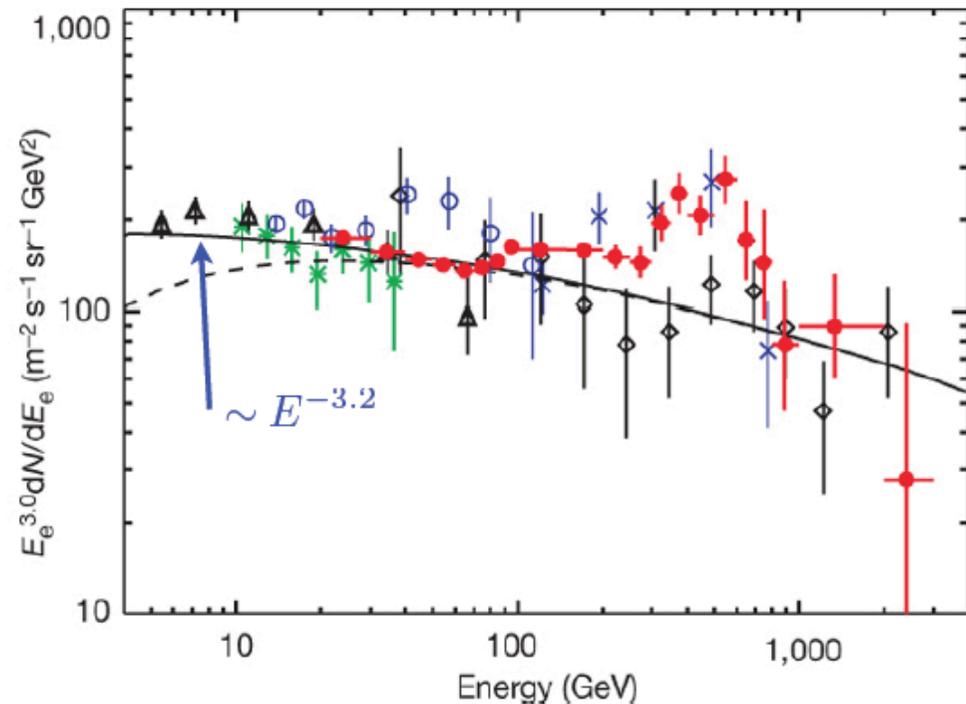
# COSMIC RAY ELECTRONS

# + 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

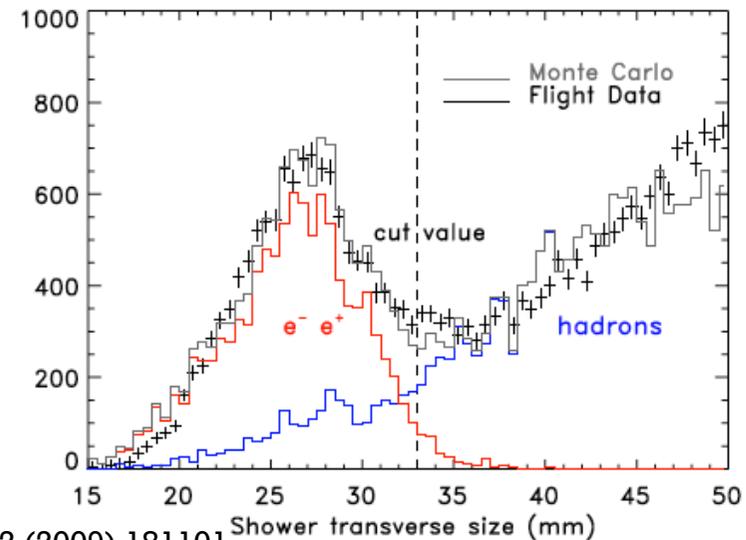
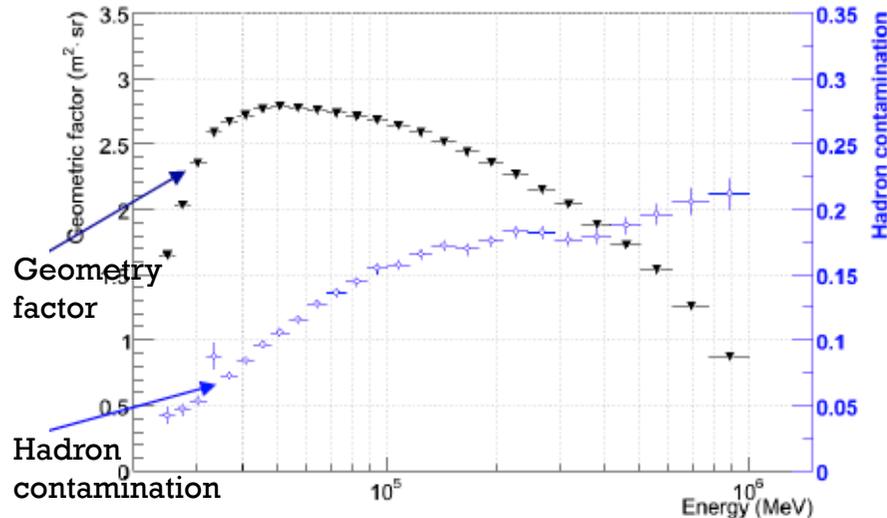


J. Chang et al. Nature 456 362-365 (2008)

# + Measuring electrons with Fermi

## ■ Challenging analysis:

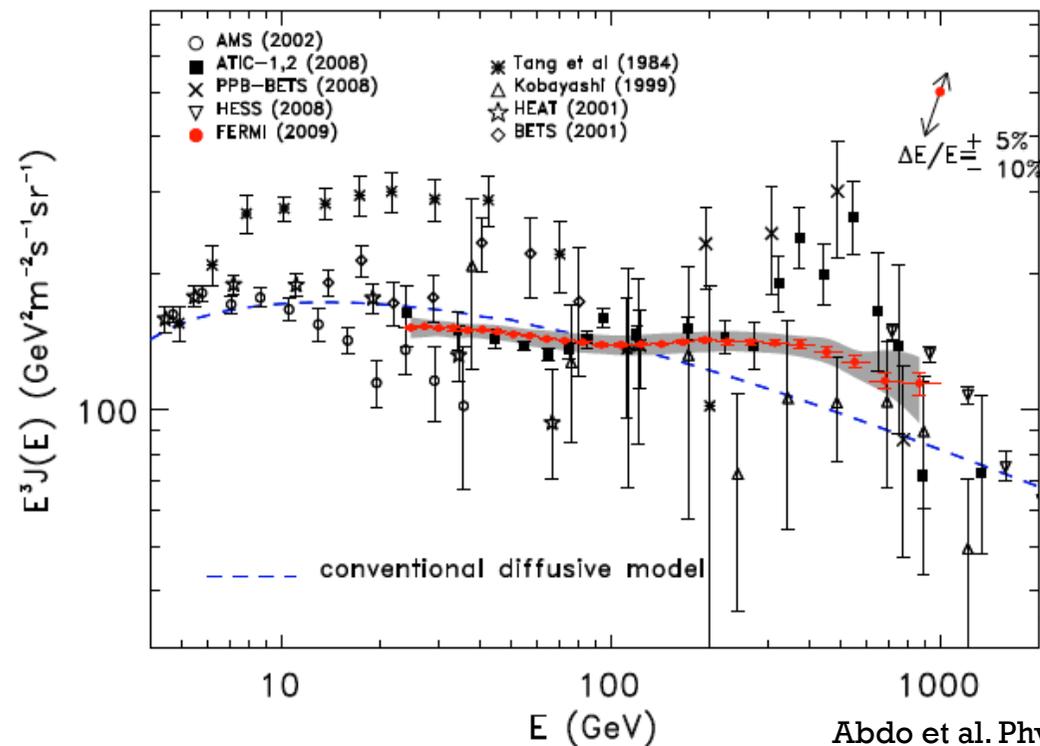
- Fermi is actually a fine electron spectrometer but there is hadron contamination
- It records  $10^7$  electrons/positrons per year above 20 GeV
- e/h separation relies on MC validated with beam tests and flight data
- Extension of separation power and energy reconstruction from 300 GeV to 1 TeV relying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



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

# + Electron spectrum measured by Fermi

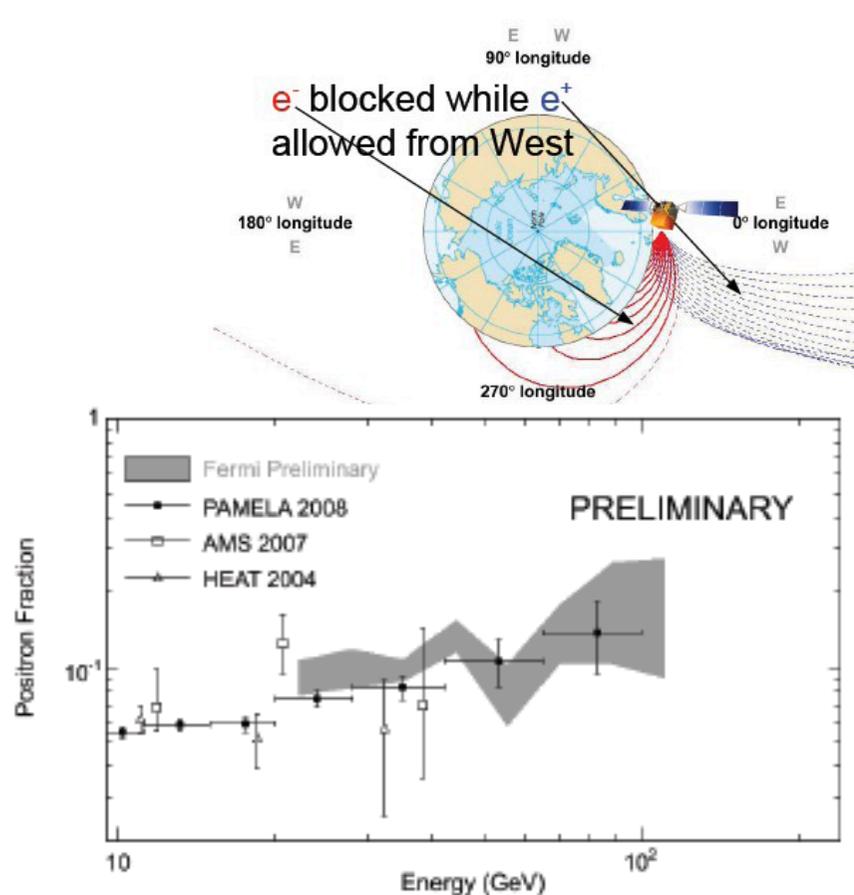
- The spectrum measured by Fermi does not show sharp features
- It can be fitted (considering systematic errors) with simple power law with index  $\sim -3$
- It deviates from the conventional diffusive model using Galprop



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

# + Positron fraction measured by Fermi

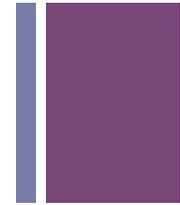
- Fermi has no magnet and cannot distinguish charge sign
- BUT... depending on the detector pointing, particles from one or other charge sign get blocked by Earth



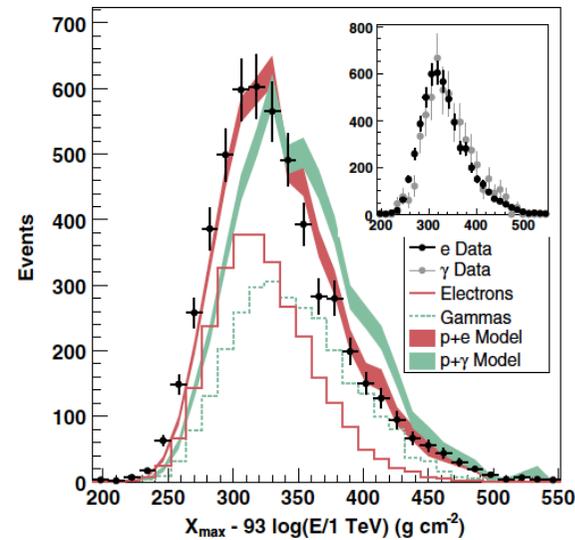
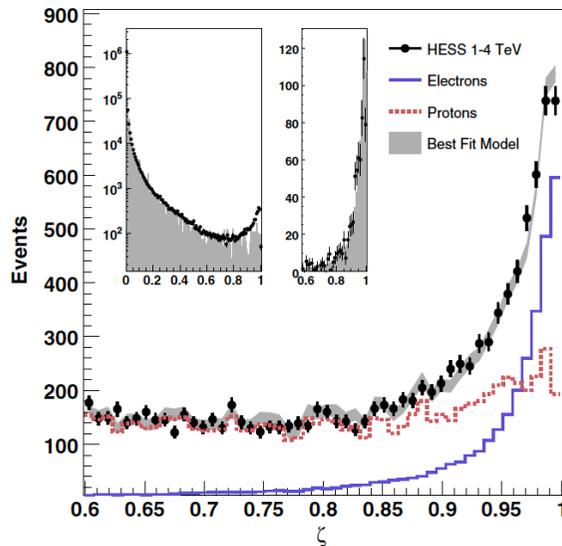
- Measured positron fraction in agreement with PAMELA result
- MAGIC is measuring e<sup>+</sup> fraction up to ~1 TeV using similar technique with Moon shadow (Colin et al. ICRC 2011)



# Measuring electrons with HESS

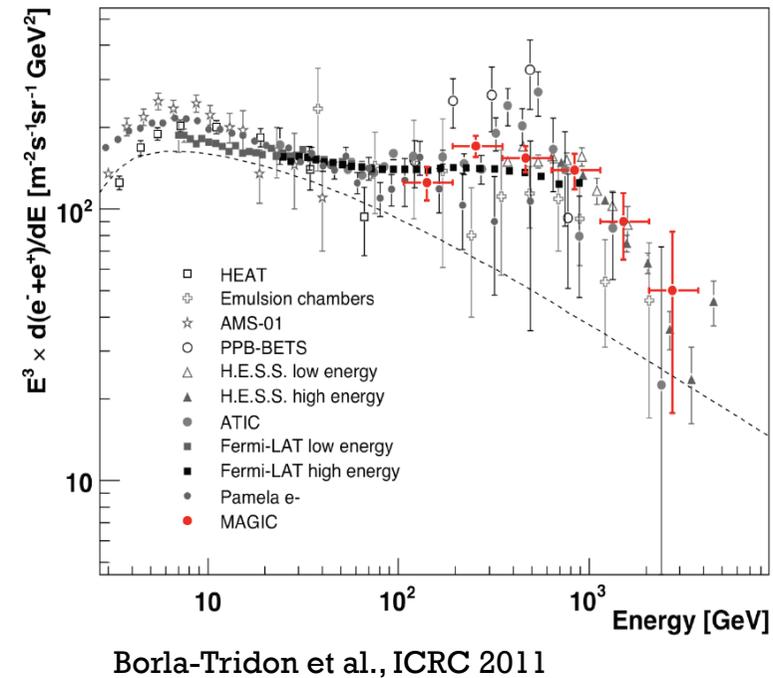
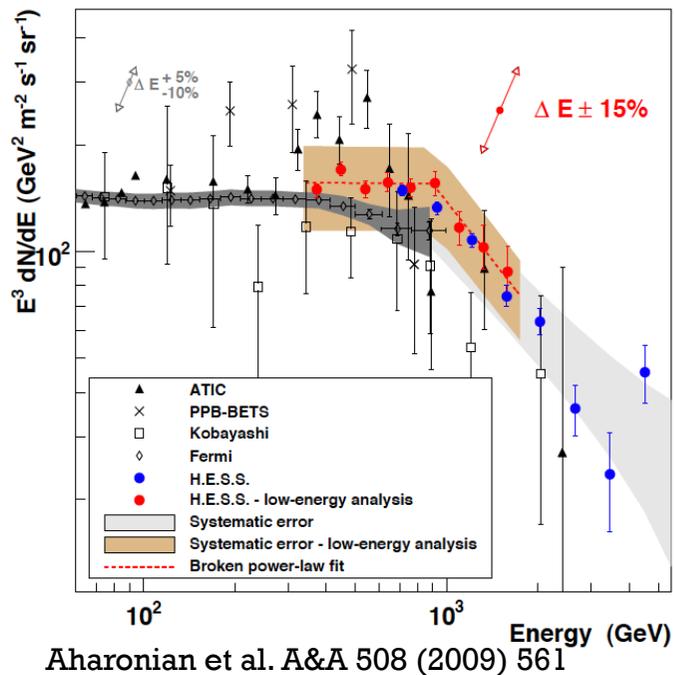


- Challenging analysis:
  - Electrons and gammas look essentially identical for Cherenkov telescopes
  - Needs a very efficient gamma/hadron separation (achieved with Random Forest algorithm) → Energy threshold increased up to ~350 GeV (600 GeV for first analysis)
  - Requires extensive and well understood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

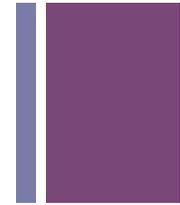


# + Electron spectrum measured by HESS and MAGIC

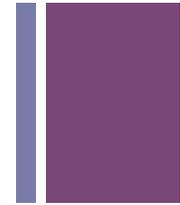
- The spectrum measured by HESS does not show sharp features
- It can be fitted with power law with index -3 which steepens at 1 TeV
- General agreement with Fermi considering systematics
- Recent results by MAGIC (similar technique) confirm HESS/Fermi



# + Electron spectrum summary



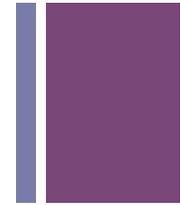
- Combined data Fermi/HESS/MAGIC contradicts the presence of the ATIC feature
- The harder spectrum explained by harder electrons in conventional production mechanisms
- Or by local source(s) (pulsars), which also explains PAMELA
- Others not excluded (e.g. Dark matter annihilation)



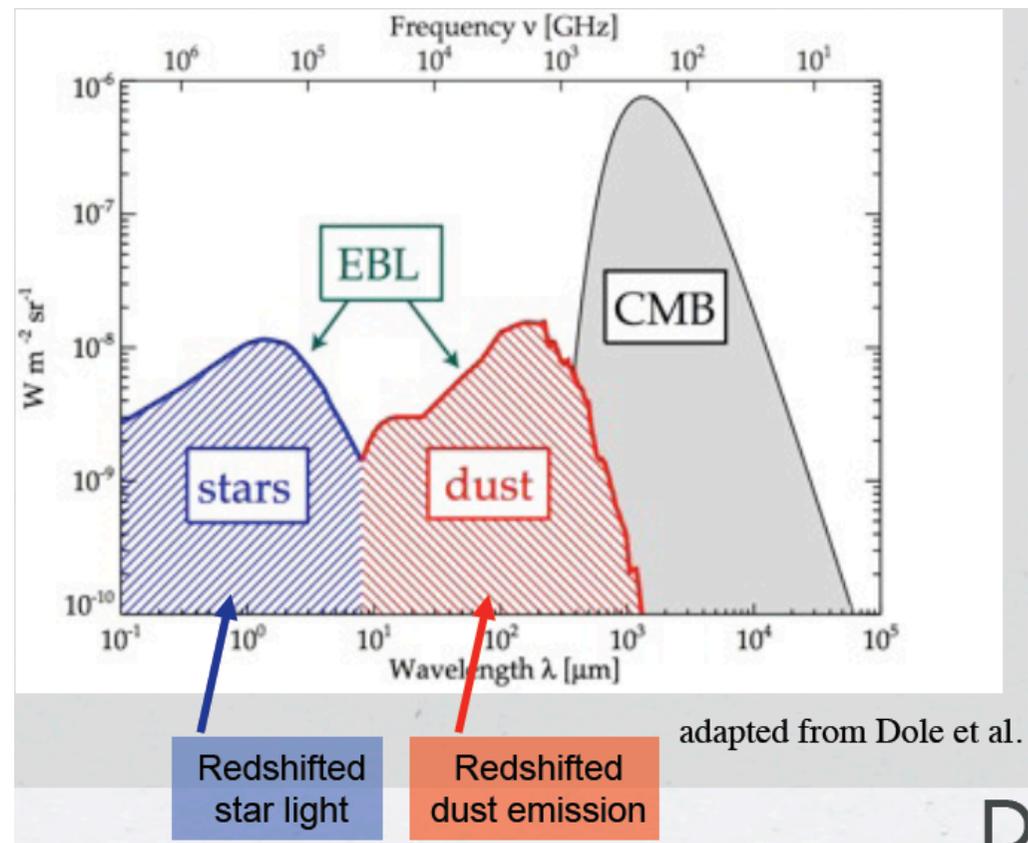
# EXTRAGALACTIC BACKGROUND LIGHT



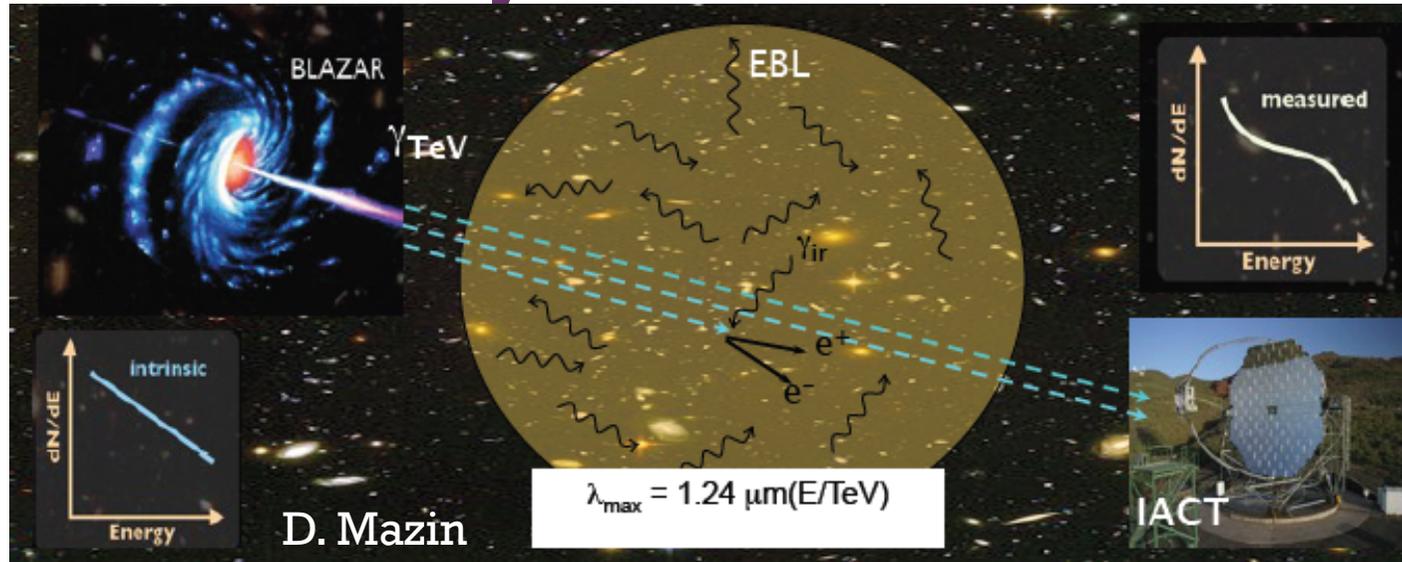
# Extragalactic Background Light



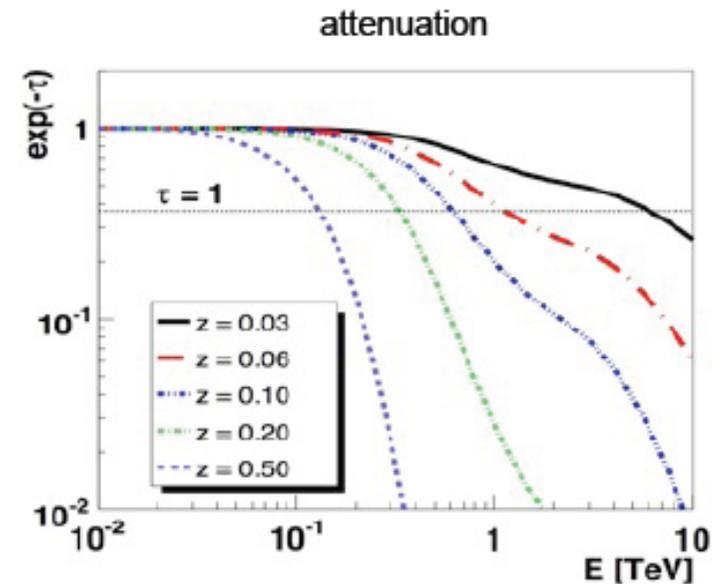
- The EBL is the light emitted by all extragalactic sources along the history of the universe
- Isotropically distributed
- The EBL provides information about energy density of universe, and constrains models for star formation, galaxy evolution and cosmology
- 2 main components: redshifted light from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



# + Gamma rays interact with EBL

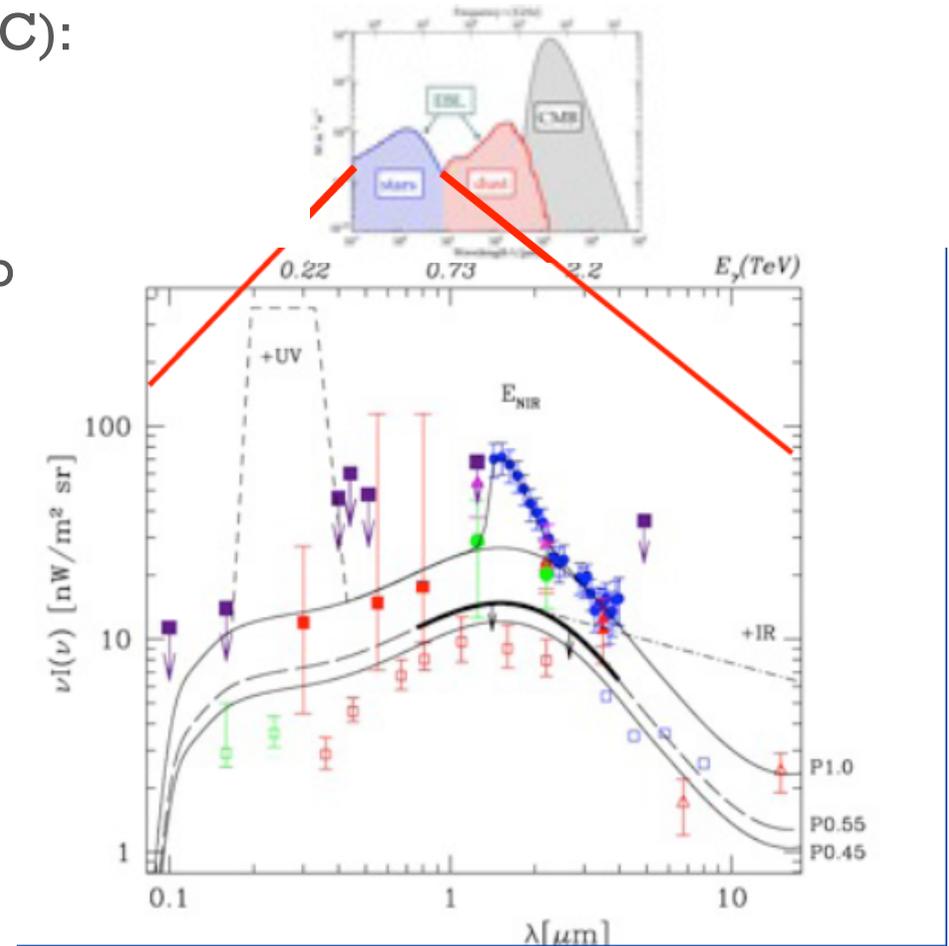
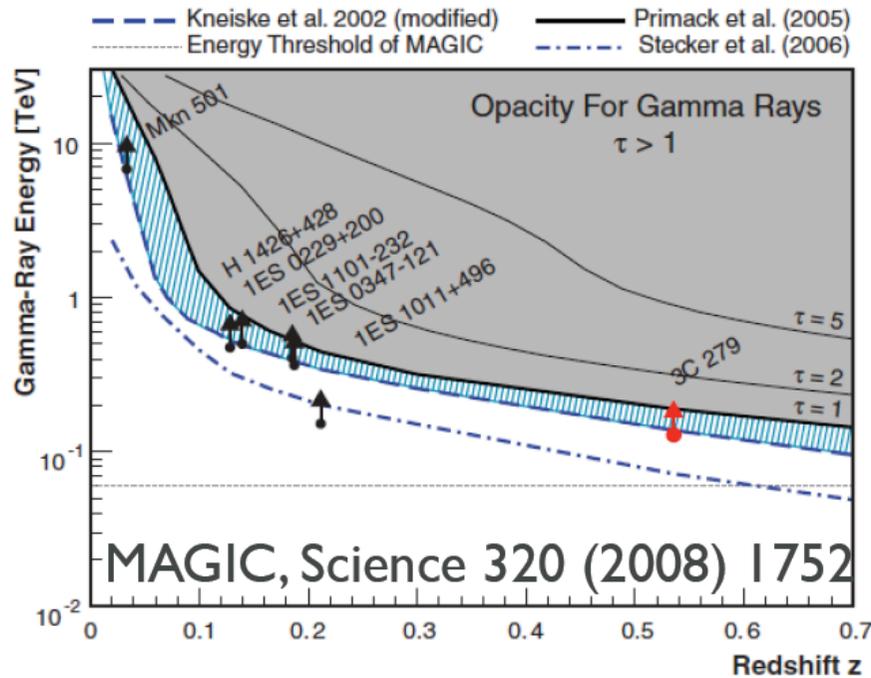


- Gamma rays from distant sources interact with EBL
- Measured spectrum modified by pair creation
- By measuring the distortion of the gamma-ray spectrum wrt intrinsic one we are measuring EBL



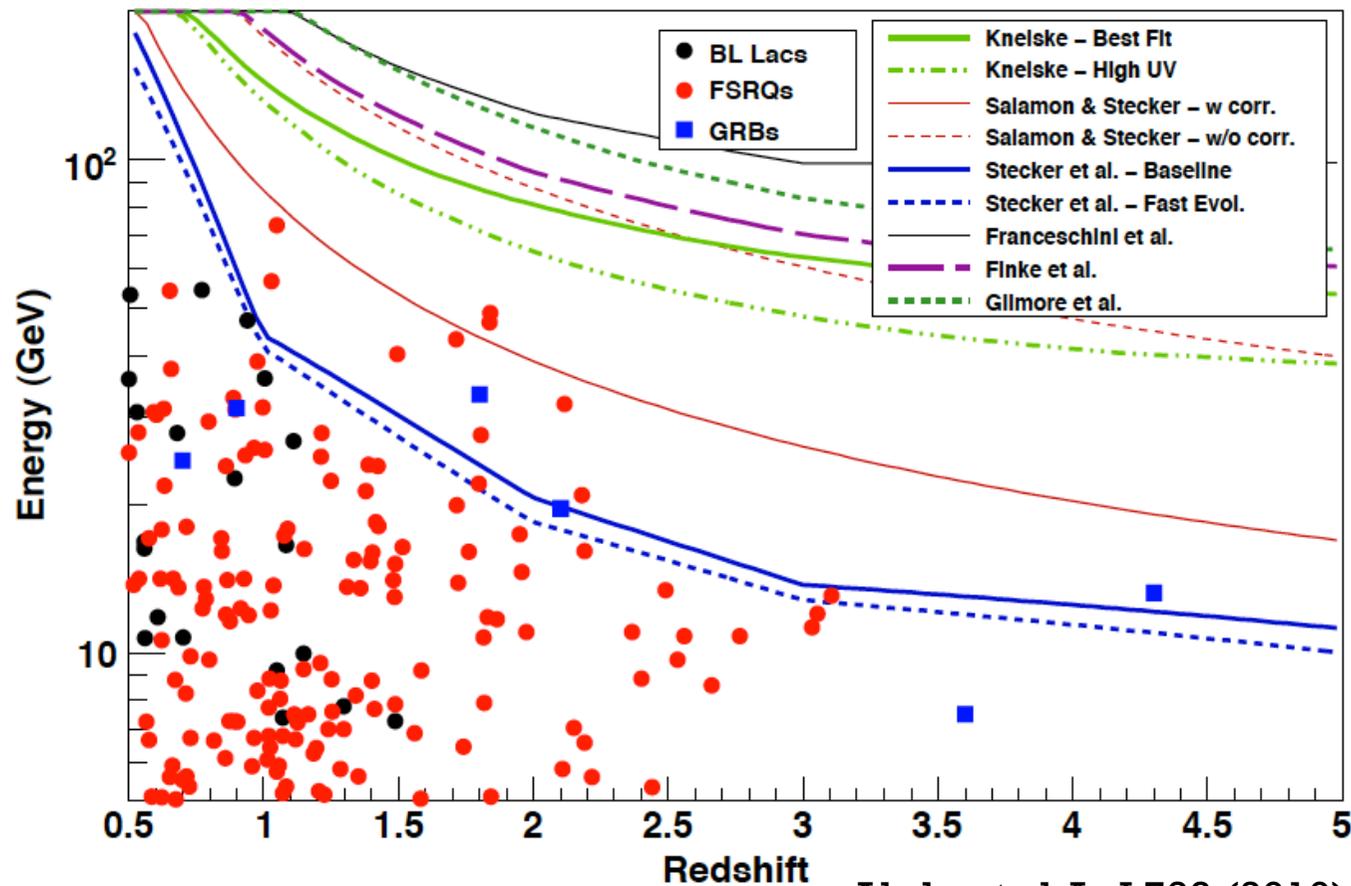
# + Constraints on EBL with Cherenkov Telescopes

- 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



# + Constraints on EBL with Fermi

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

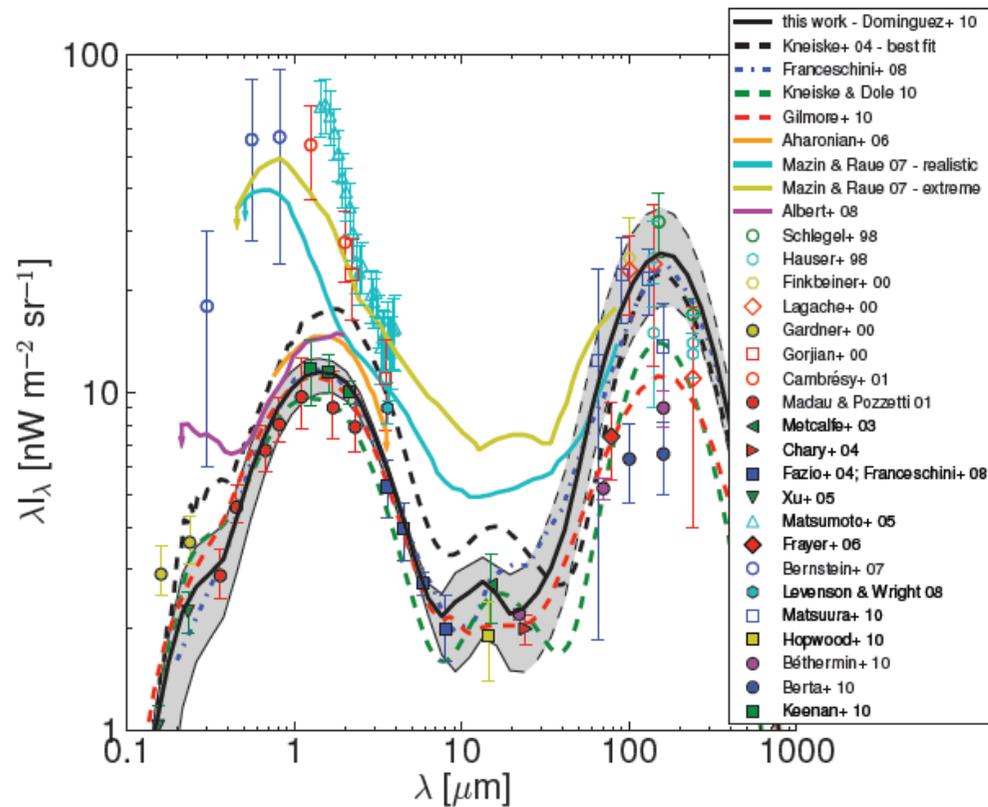


Lines represent the horizon of optical depth  $\tau = 3$  predicted by different models

Abdo et al ApJ 723 (2010) 1082

# + EBL summary

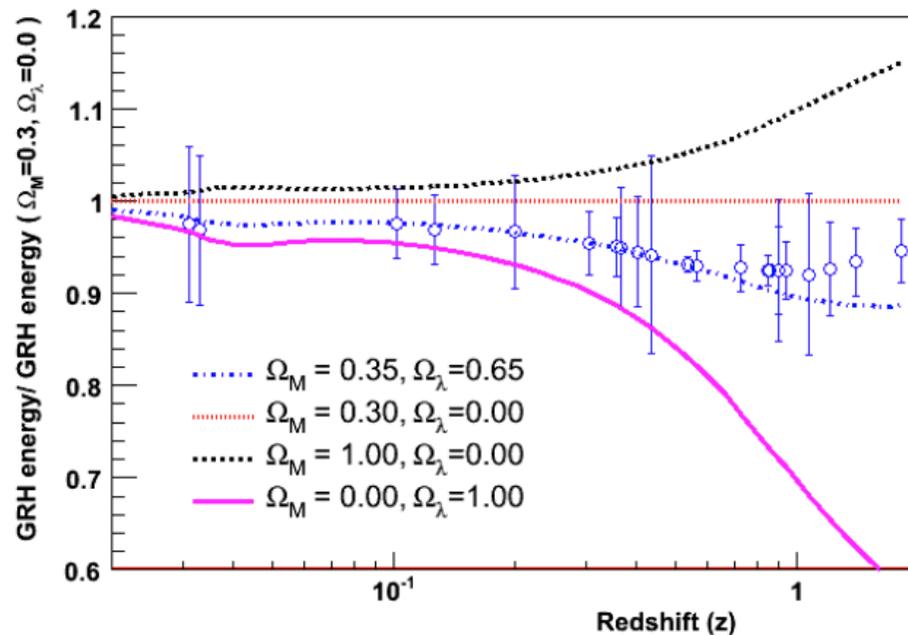
- Models with high EBL are excluded with high significance
- Recent models suggest actually levels close to lower limits



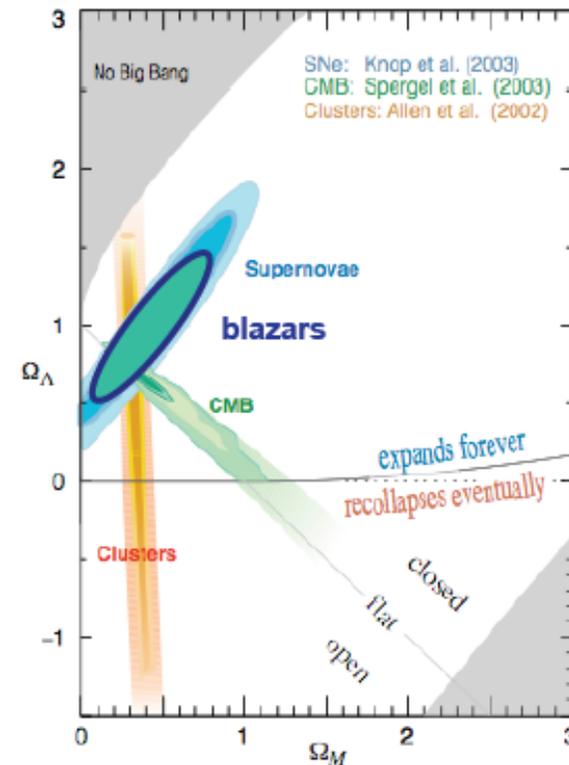
Dominguez et al, MNRAS, 410, 2556 (2010)

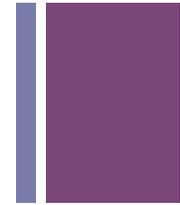
# + Measuring cosmological parameters

- 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





# TESTS OF LORENTZ INVARIANCE

# + Testing Lorentz Invariance with gamma-rays

- Energy dependence of speed of light
- Predicted by several Quantum Gravity theories:  
$$v = c(1 \pm \xi(E/M_p) \pm \zeta(E/M_p)^2 + \dots)$$
- 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

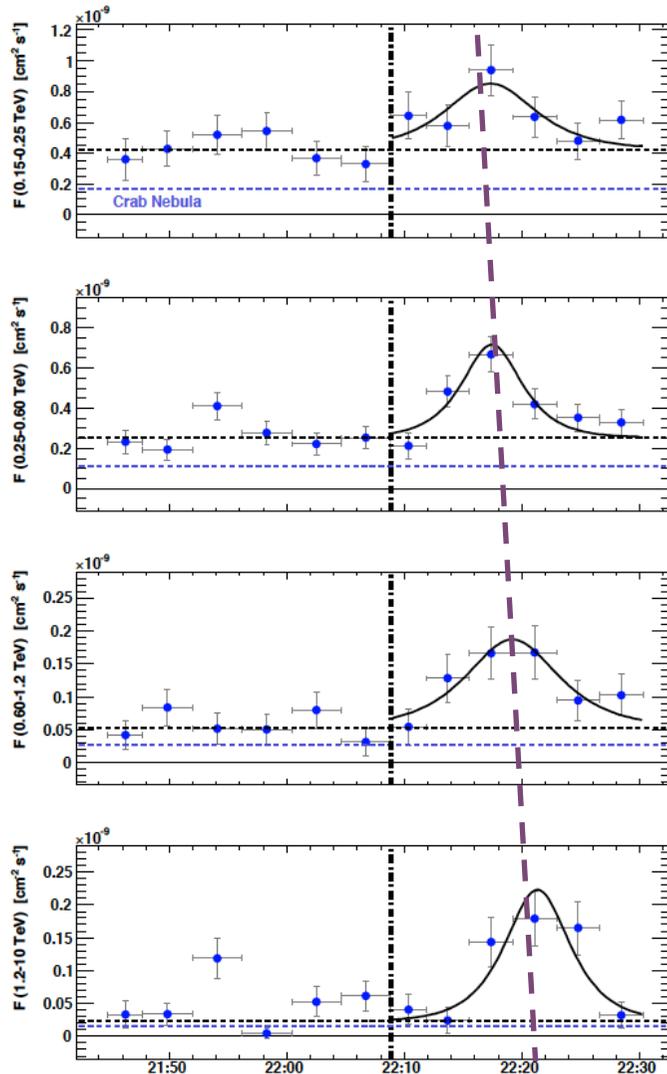
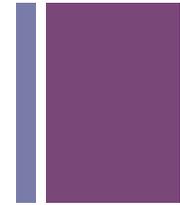
$$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_p H_0} \int_0^z \frac{(1+z') dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

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

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



# Testing Lorentz Invariance with MAGIC



Albert et al., ApJ 669 (2007) 862

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

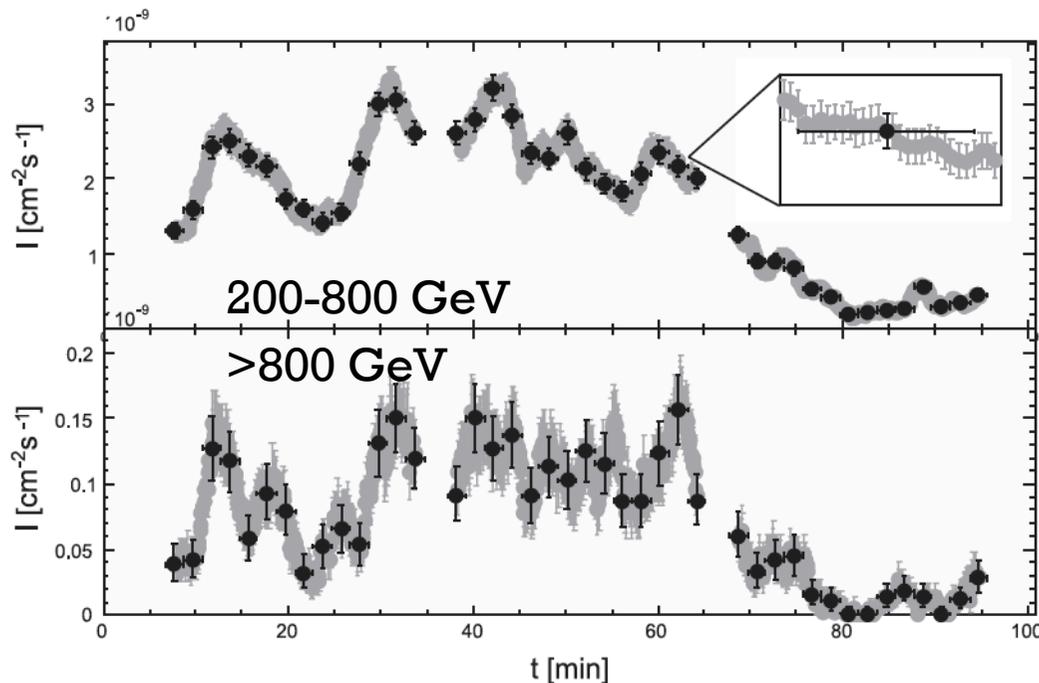
XXXI Physics in Collision. Vancouver (Canada) 28 Aug-1 Sep 2011

- Use two flares of Mrk 501 ( $z = 0.034$ ) on July 2005
- Variations of the flux of O(10) in the flares. Peak  $4\times$ 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:  $\tau_1 = (30 \pm 12) \text{ s/TeV}$   
 $\tau_q = (3.71 \pm 2.57) \text{ s/TeV}^2$
- Delays at the source cannot be excluded
- Limits (95% CL):  $M_{\text{QGI}} > 0.3 \times 10^{18} \text{ GeV}$   
 $M_{\text{QGq}} > 5.7 \times 10^{10} \text{ GeV}$

Javier Rico ICREA/IFAE

# + Testing Lorentz Invariance with HESS

- Use exceptionally intense flare of PKS 2155-304 flares ( $z = 0.116$ ) on July 28<sup>th</sup> 2006
- Peak flux:  $15 \times \text{Crab}$  ( $40 \times \text{average}$ )
- Doubling time: 1-3 minutes



- Energy range: 200 GeV – 4 TeV
- Delays in the time of arrival fitted using Likelihood function:  
 $\tau_1 = (-5.5 \pm 10.9) \text{ s/TeV}$   
 $\tau_q = (1.7 \pm 6.3) \text{ s/TeV}^2$

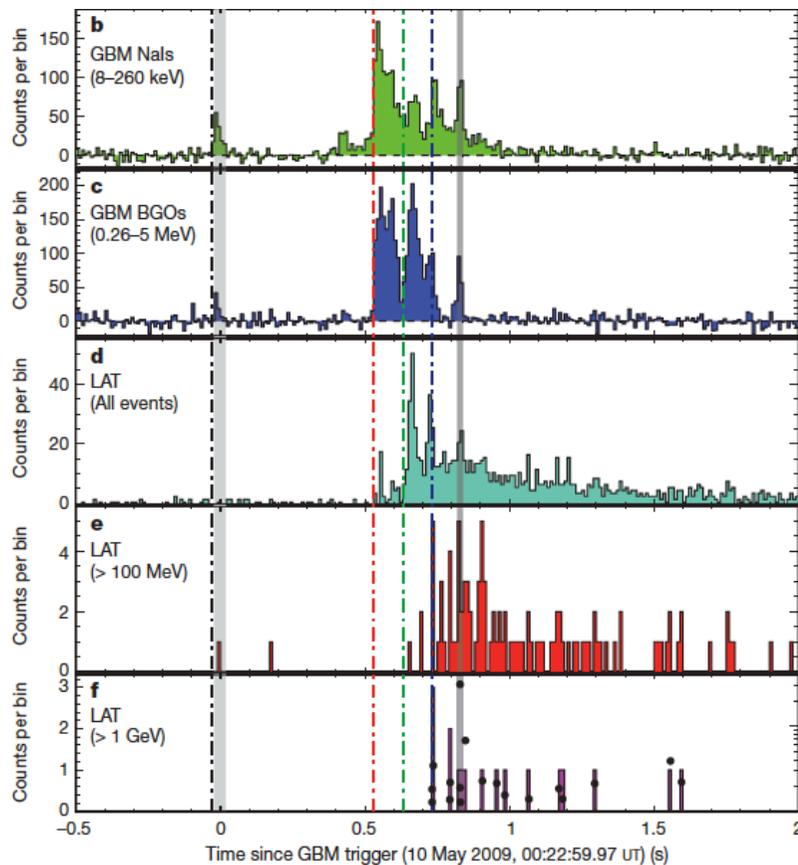
- Limits (95% CL):  
 $M_{\text{QG1}} > 2.1 \times 10^{18} \text{ GeV}$   
 $M_{\text{QGq}} > 6.4 \times 10^{10} \text{ GeV}$

Aharonian et al. Phys. Rev. Lett. 101 (2008) 170402

Abramowski et al. Astroparticle Physics 34 (2011) 738

# + Testing Lorentz Invariance with Fermi

- Use GRB 090510 ( $z = 0.903$ ) on July 28<sup>th</sup> 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):  
 $\tau_1 < 30 \text{ s/TeV}$
- Limits (95% CL):  
 $M_{\text{QG}l} > 1.5 \times 10^{19} \text{ GeV}$   
 $M_{\text{QG}q} > 3.0 \times 10^{10} \text{ GeV}$
- Limit to the scale mass for the linear term exceeds the Planck Mass!!

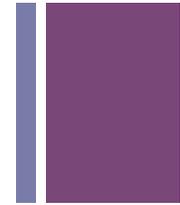


# Lorentz Invariance Tests summary

Abramowski et al. *Astroparticle Physics* 34 (2011) 738

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

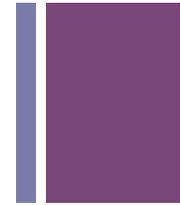
- Look for gamma-rays [secondary] product of the annihilation of dark matter particles
- Point telescopes at sites of dark matter over-densities

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

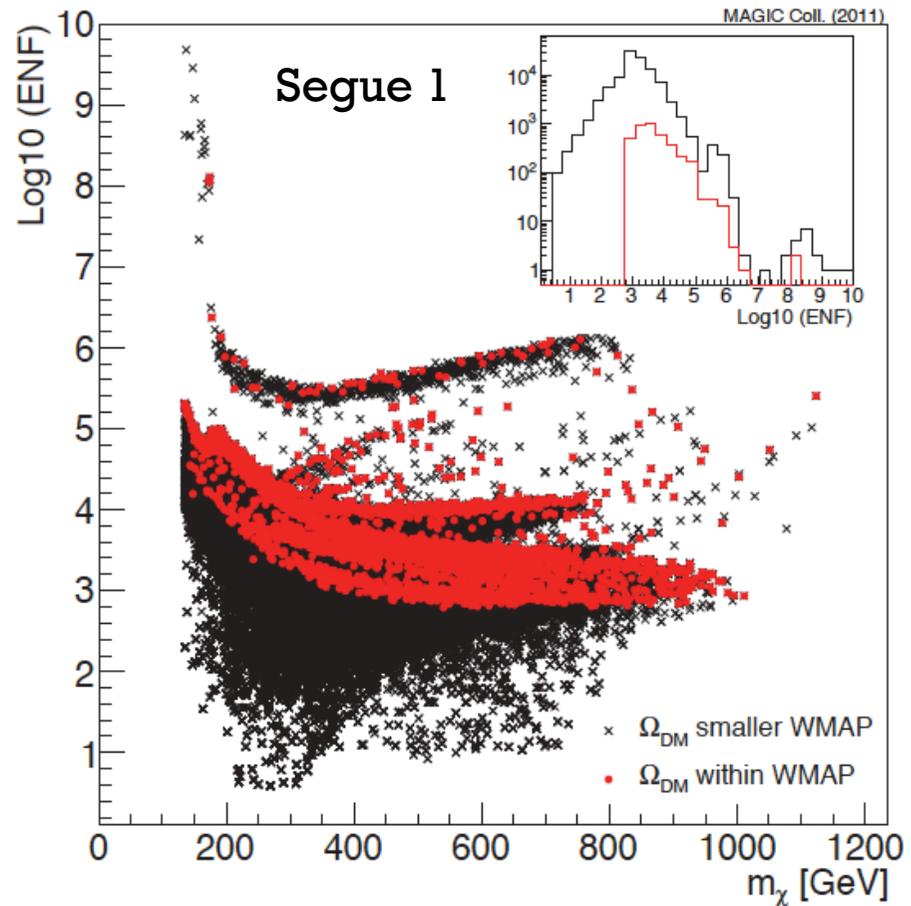
- (1): “Particle Physics” term:
  - Should be universal
  - May provide unique spectral features
  - For a given model we can constrain the average cross section
  - Energy resolution of instrument not included
- (2): “Astrophysical” term
  - Depends on the target (GC and halo, galaxy clusters, dwarf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



# Indirect Dark Matter Searches with MAGIC



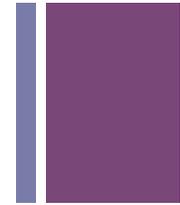
- Several promising targets pointed:
  - Dwarf Spheroidal Galaxies:
    - Draco (8 hrs)
    - Wilman I (15 hrs)
    - Segue 1 (30 hrs)
  - Perseus galaxy cluster (25 +20 hrs)
  - Galactic Center (17 hrs)
  - Mini-halo candidates (20 hrs)
- Enhancement factors needed at the order of  $10^3$  for WMAP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



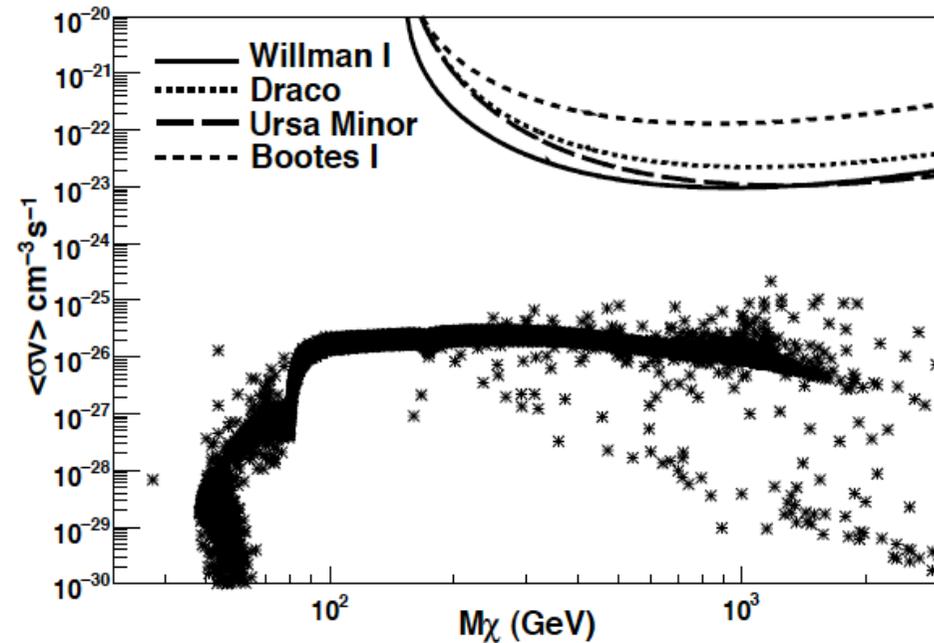
Aleksić et al. JCAP 06 (2011) 035



# Indirect Dark Matter Searches with VERITAS



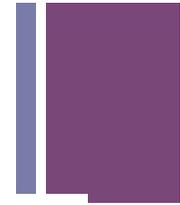
- Concentrated on dwarf Spheroidal Galaxies:
  - Draco (20 hrs)
  - Ursa Minor (20 hrs)
  - Boötes 1 (15 hrs)
  - Willman 1 (15 hrs)
  - Segue 1 (30 hrs)
- Also: Coma Cluster (20 hrs)
- Results similar to those obtained by MAGIC (similar objects and sensitivity)



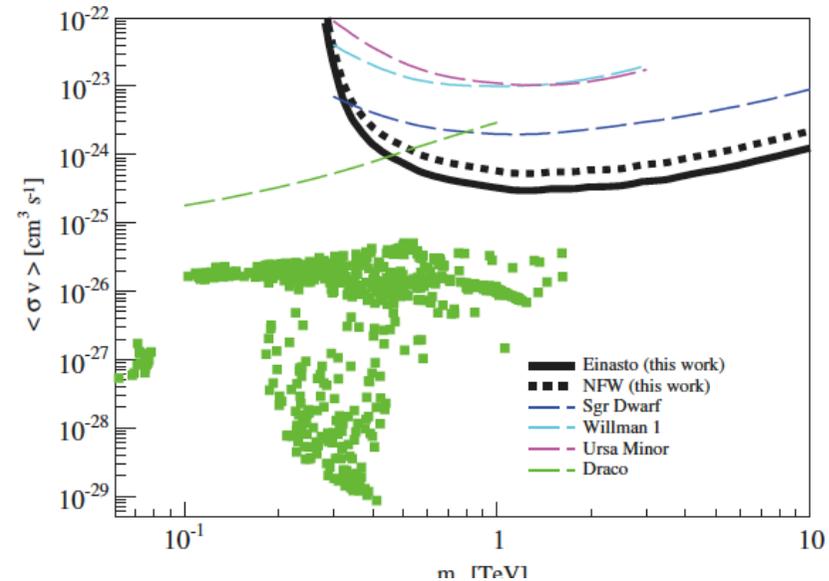
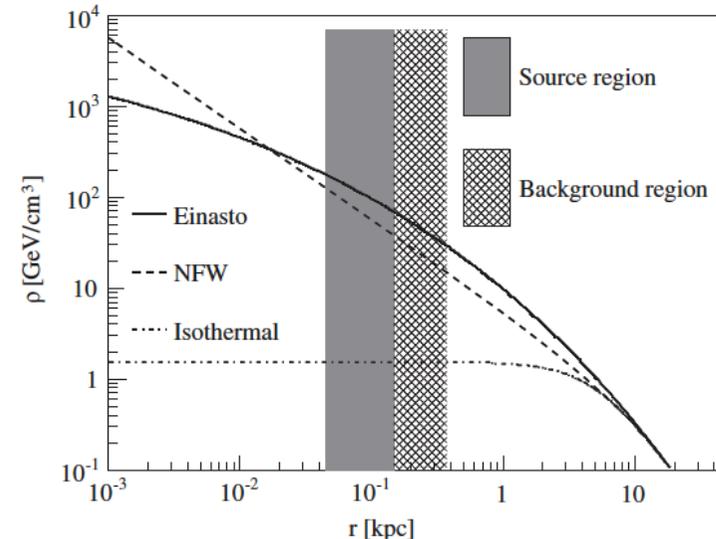
Acciari et al, ApJ 720 (2011) 1174



# Indirect Dark Matter Searches with HESS

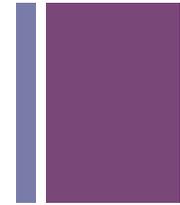


- Dwarf Spheroidals:
  - Sagittarius (10 hrs)
  - Carina (15 hrs)
  - Sculptor (12 hrs)
- Clusters of Galaxies:
  - Coma (8 h)
  - Abell 496 (15 h)
  - Abell 85 (33 h)
- Galactic Halo:
  - Galactic Center (150 hrs)
  - ★ Galactic Halo (112 hrs), high flux expected, no known astrophysical background,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

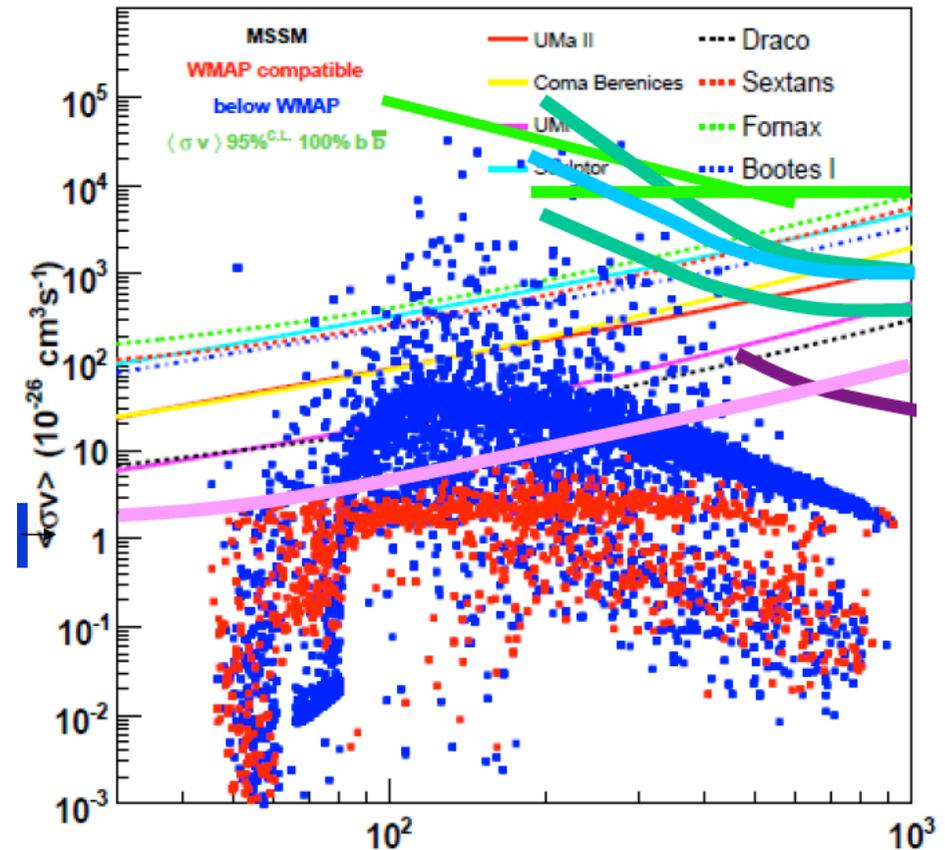




# Indirect Dark Matter Searches with Fermi



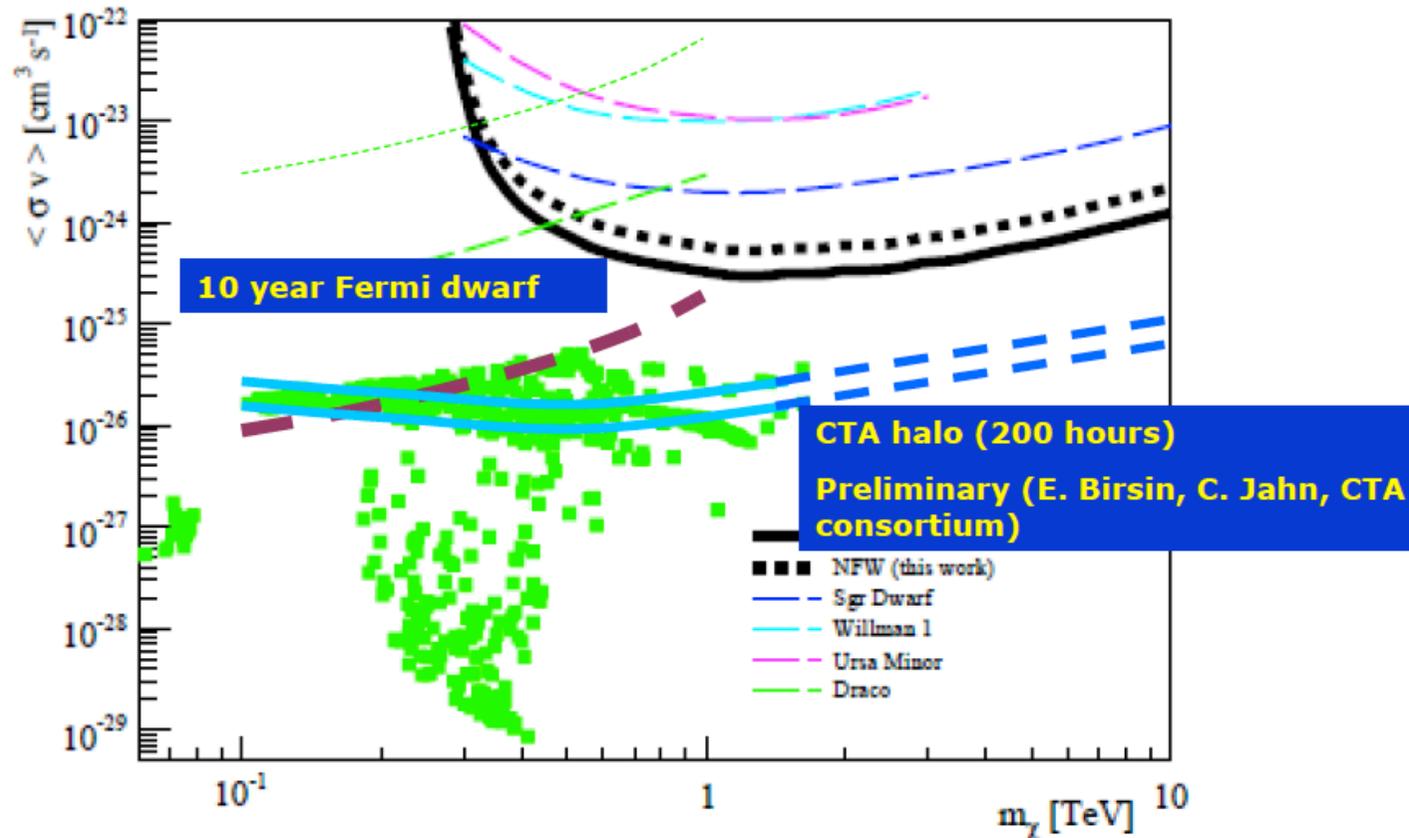
- All possible candidates are observed almost simultaneously
- Results from two years of observations
  - Galaxy Clusters (stacked)
  - Galactic Halo
  - Search for spectral lines
  - ★ Dwarf Spheroidals (stacked likelihood) → **best limits**  
 $10^{26} \text{ cm}^3 \text{ s}^{-1}$  at reach after 10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



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

# + Indirect Dark Matter Searches summary

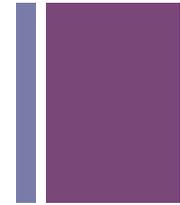
- All known possible DM annihilation sites are being observed
- Sensitivity to SUSY DM still not reached by present generation of instruments
- Situation will improve in the following years





## 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



# BACKUP

# Imaging technique

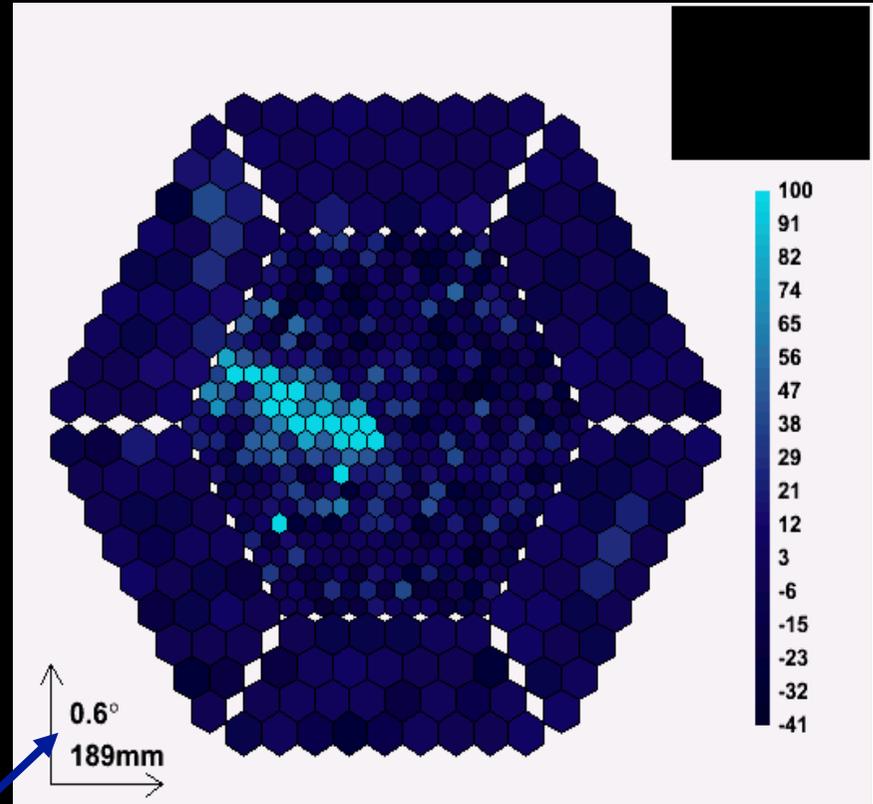
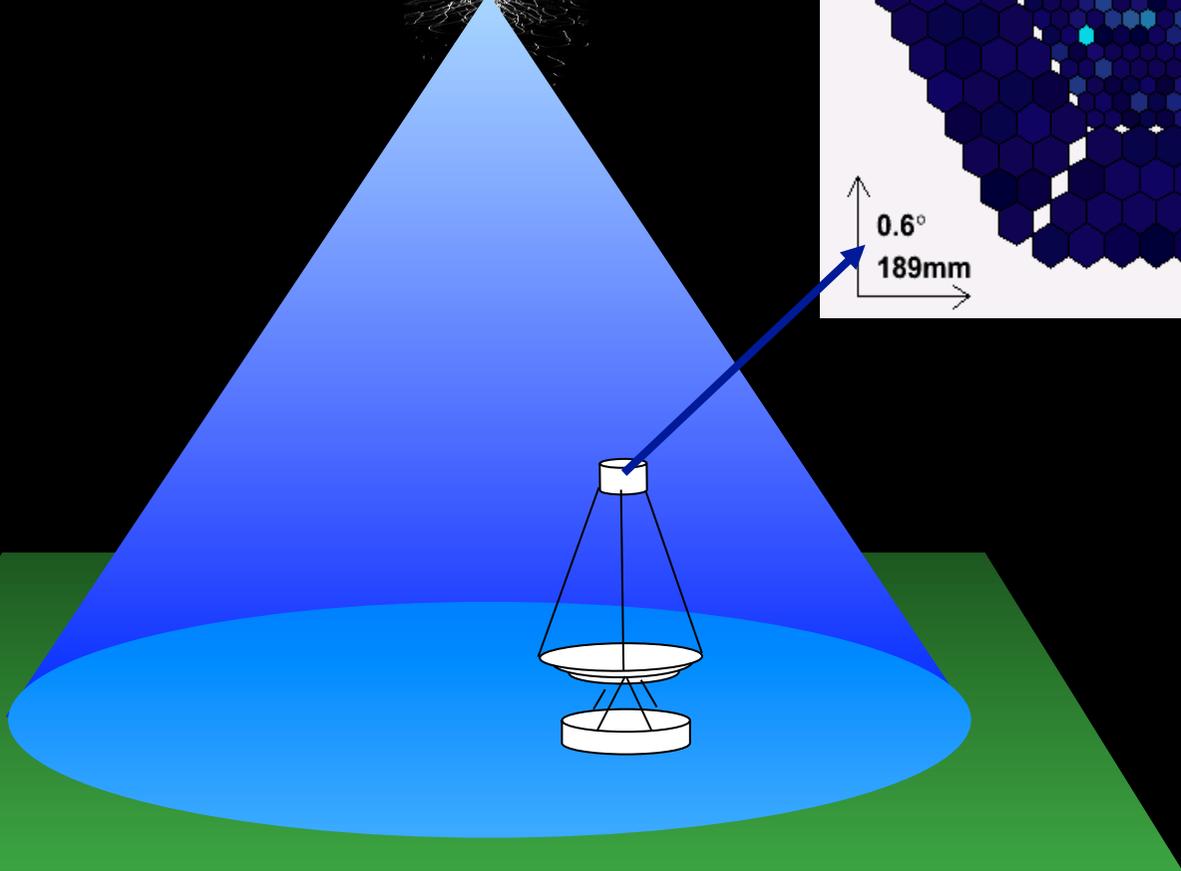
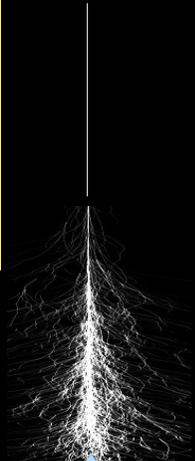
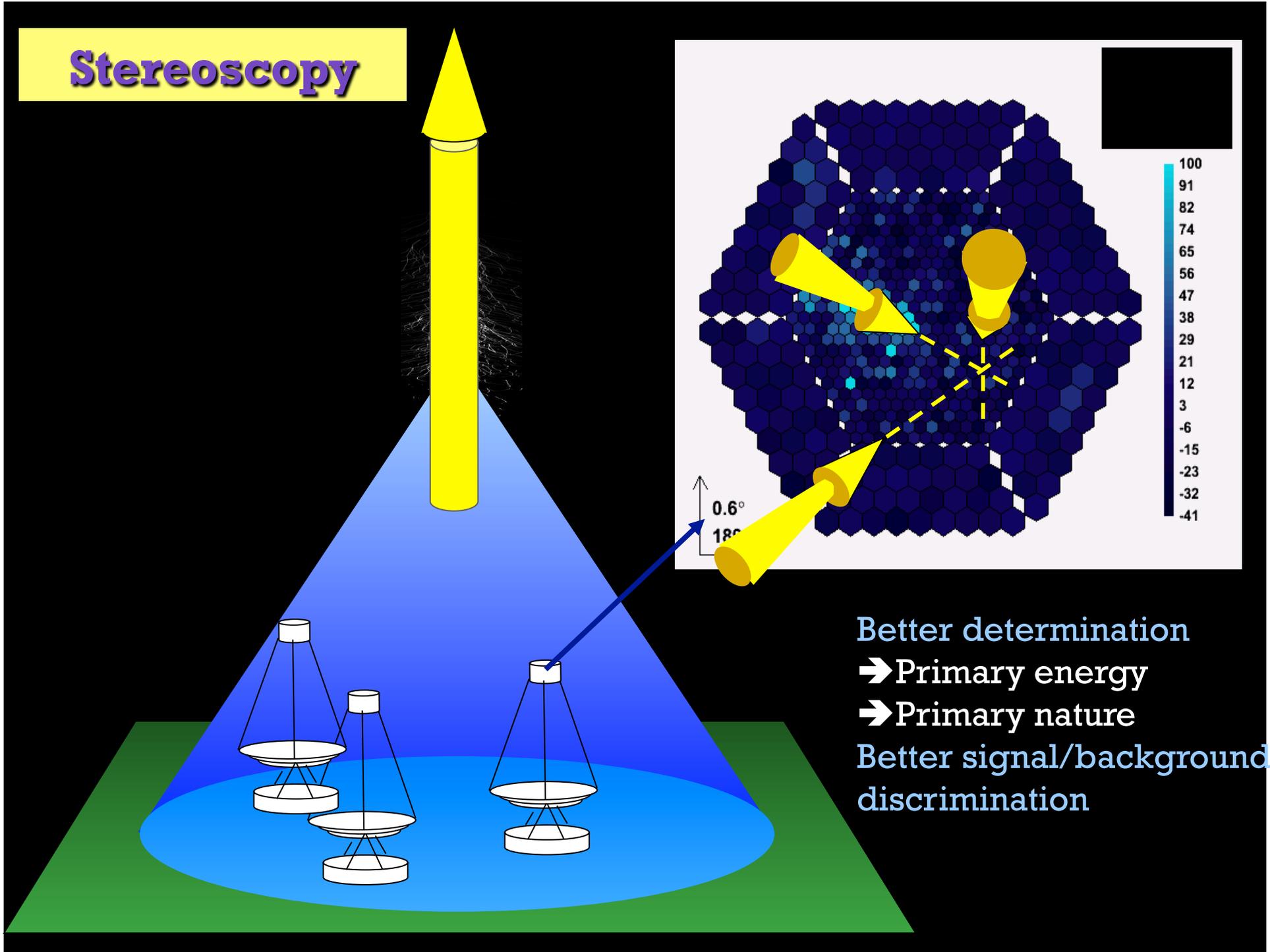


Image intensity  
→ Primary energy

Image orientation  
→ Prim. direction

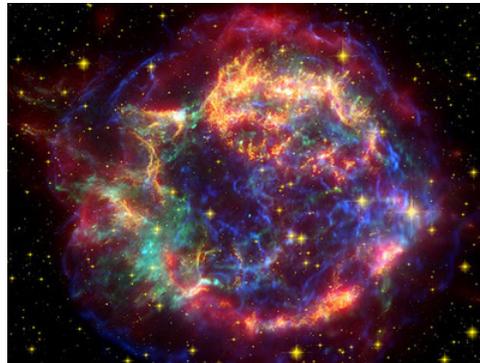
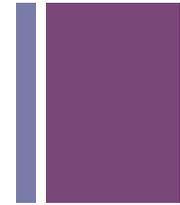
Image shape  
→ Primary nature

# Stereoscopy

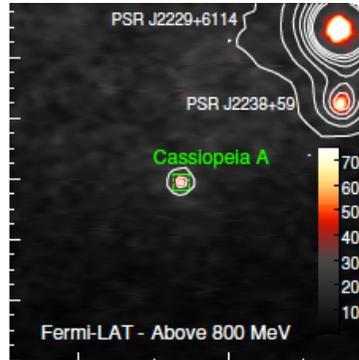


Better determination  
→ Primary energy  
→ Primary nature  
Better signal/background  
discrimination

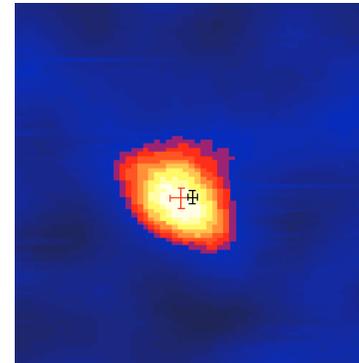
# + Young shell-type SNR: Cas A



IR Spitzer, Opt Hubble,  
X-ray Chandra



~GeV gamma-rays Fermi

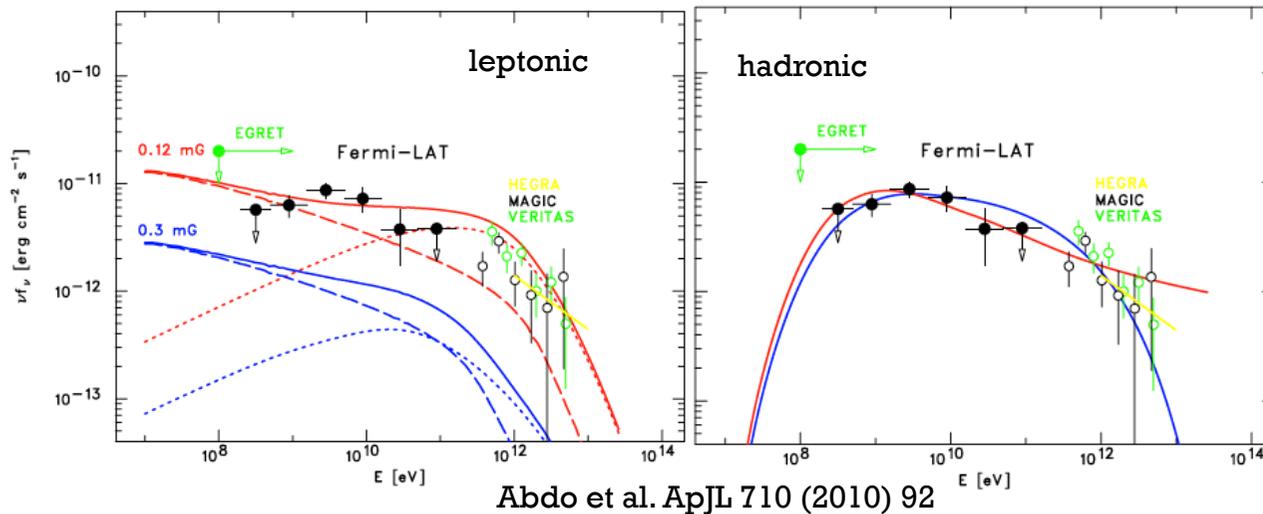


~TeV gamma-rays MAGIC  
(also VERITAS, HEGRA)

Type II

300 years

3.4 kpc



- Emission from the shell favored wrt central compact object
- Emission can be explained both by accelerated leptons (bremsstrahlung + IC) or protons ( $\pi^0$  decay)

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

- No clear cutoff

# + 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

