Gamma-ray astronomy and fundamental physics

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- Introduction: why gamma rays? How?
- Some results related to fundamental physics
- What's next

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CERN/GEN/8

CONSEIL EUROPEEN POUR LA RECHERCHE NUCLEAIRE

CERN EUROPEAN COUNCIL FOR NUCLEAR RESEARCH

Organisme intergouvernemental créé par l'Accord de Genève du 15 Février 1952

CONVENTION

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PARIS, 1ST JULY, 1953

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POUR L'ETABLISSEMENT D'UNE ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

PARIS, LE 1ER JUILLET 1953

Research on cosmic rays is in CERN's constitution

3. The basic programme of the Organization shall comprise:

(...)

(c) The organization and sponsoring of international co-operation in nuclear research, including co-operation outside the Laboratory. This co-operation may include in particular:

- (i) work in the field of theoretical nuclear physics;
- (ii) the promotion of contacts between, and the interchange of, scientists, the dissemination of information, and the provision of advanced training for research workers;
- (iii) collaboration with and advising of national research institutions;
- (iv) work in the field of cosmic rays.

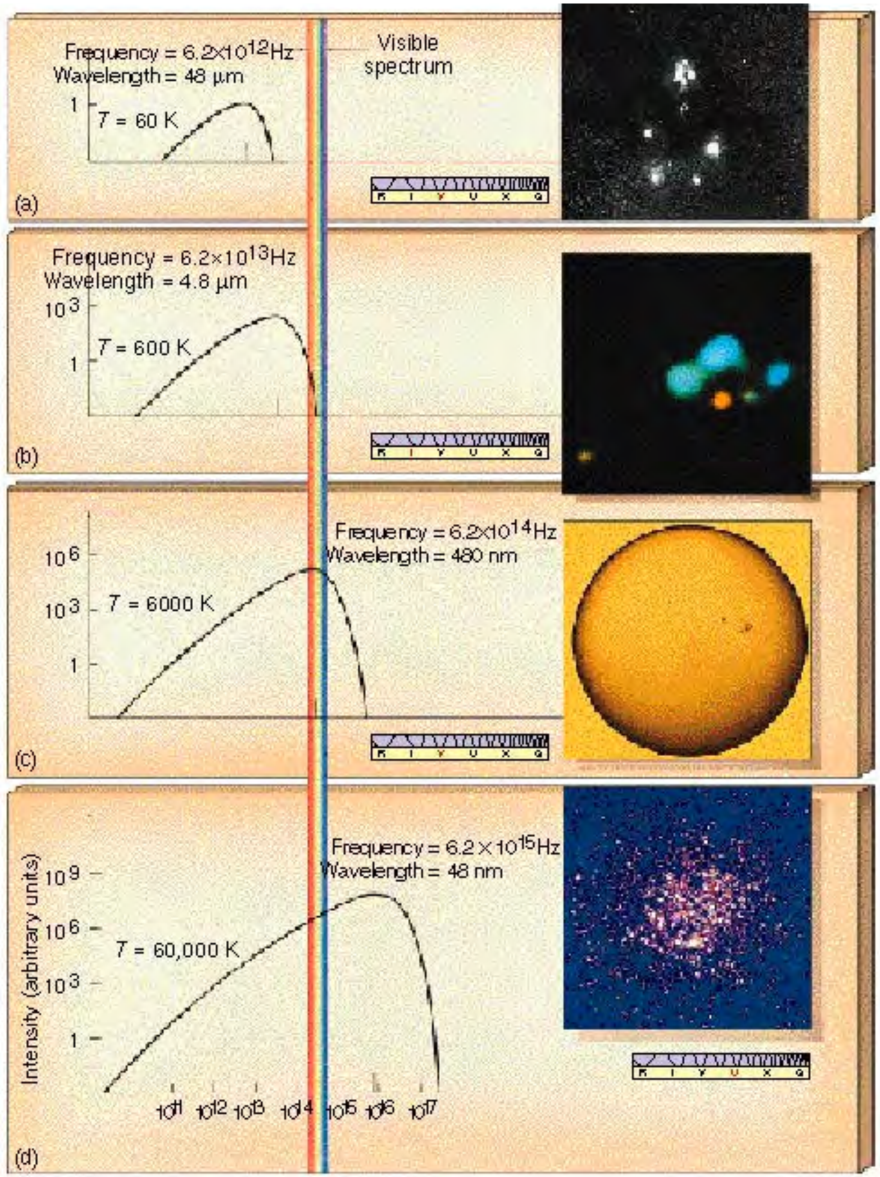
Thermal Radiation: Black Body Spectrum

A Galactic gas cloud
called Rho Ophiuchi:
60 K

Dim star near the
center of the Orion Nebula:
600 K

Our star – the Sun:
6000 K

Cluster of very bright stars, Omega Centauri,
as observed from the space:
60,000 K



Accretion Disks can reach
temperatures >> 10^5 K

But this is still
~1 keV, in the
X-Ray band!

High Energy γ rays: non-thermal Universe

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, …; Intergalactic Magnetic Fields, …
- Gamma rays traveling to us!
  - HE: 30 MeV to 30 GeV
  - VHE: 30 GeV to 30 TeV

Plus: "new" particles (e.g. Dark Matter)

- No deflection from magnetic fields, gammas point ~ to the sources
  - Magnetic field in the galaxy: ~ 1μG
    R (pc) = 0.01p (TeV) / B (μG)
    => for p of 300 PeV @ GC the directional information is lost

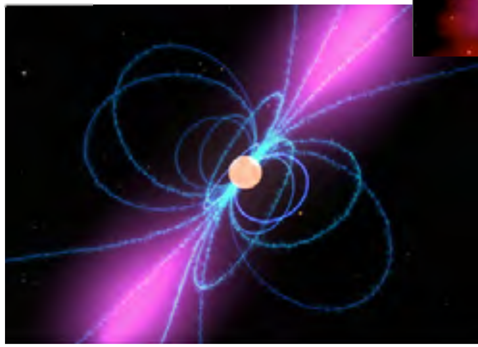
  $\Rightarrow$ Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

Studying Gamma Rays allows us to see these aspects of the Universe

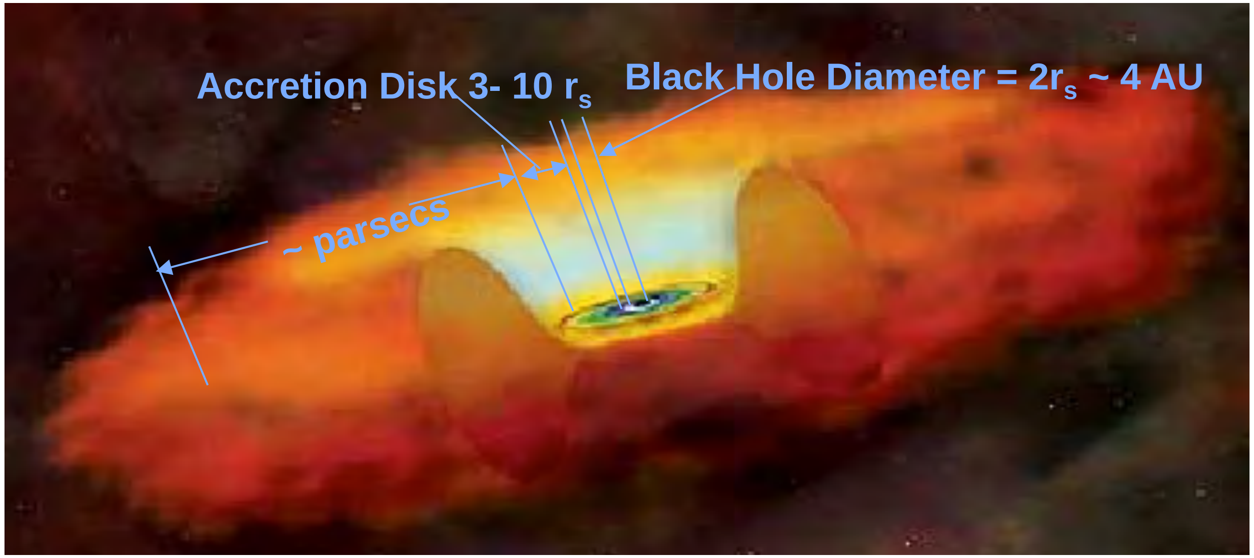
Examples of known extreme environments

GRB

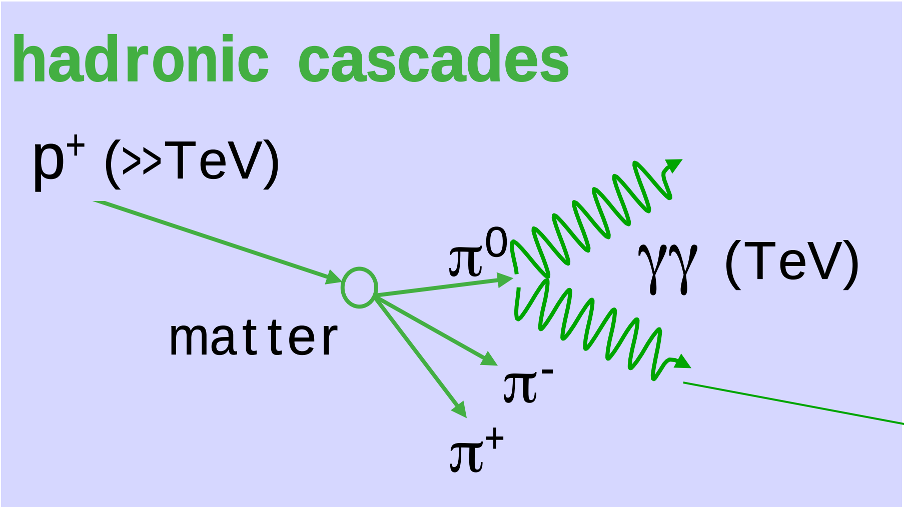
SuperNova Remnants
Pulsars

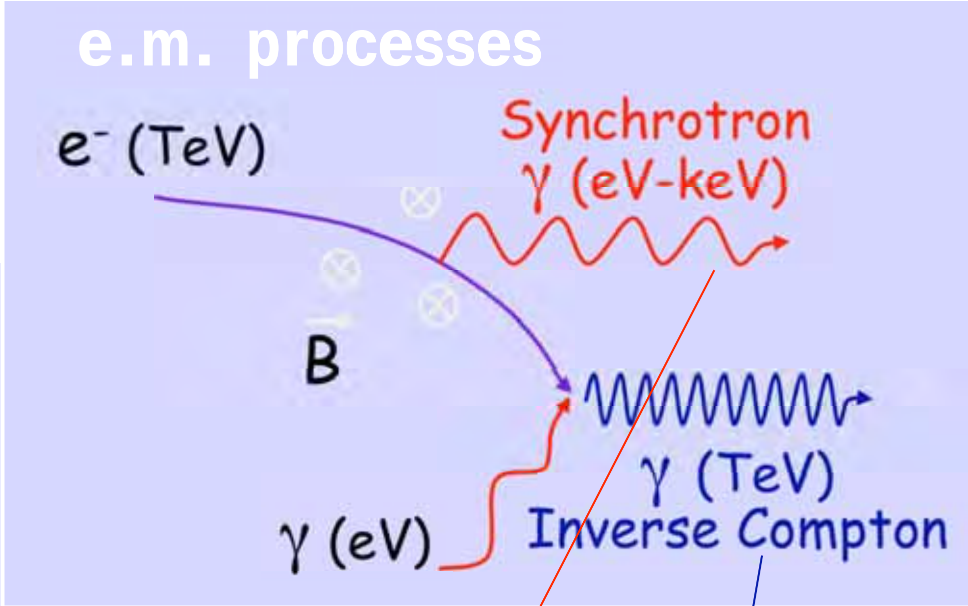


Active Galactic Nuclei



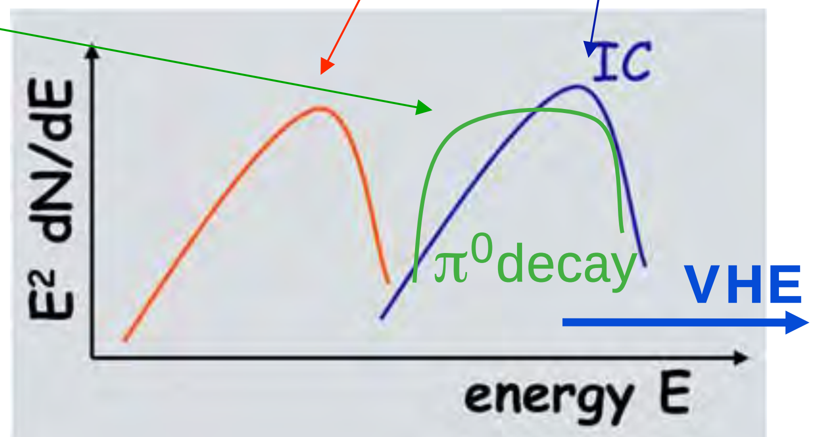
Cosmic γ rays: different production mechanisms expected to be at work



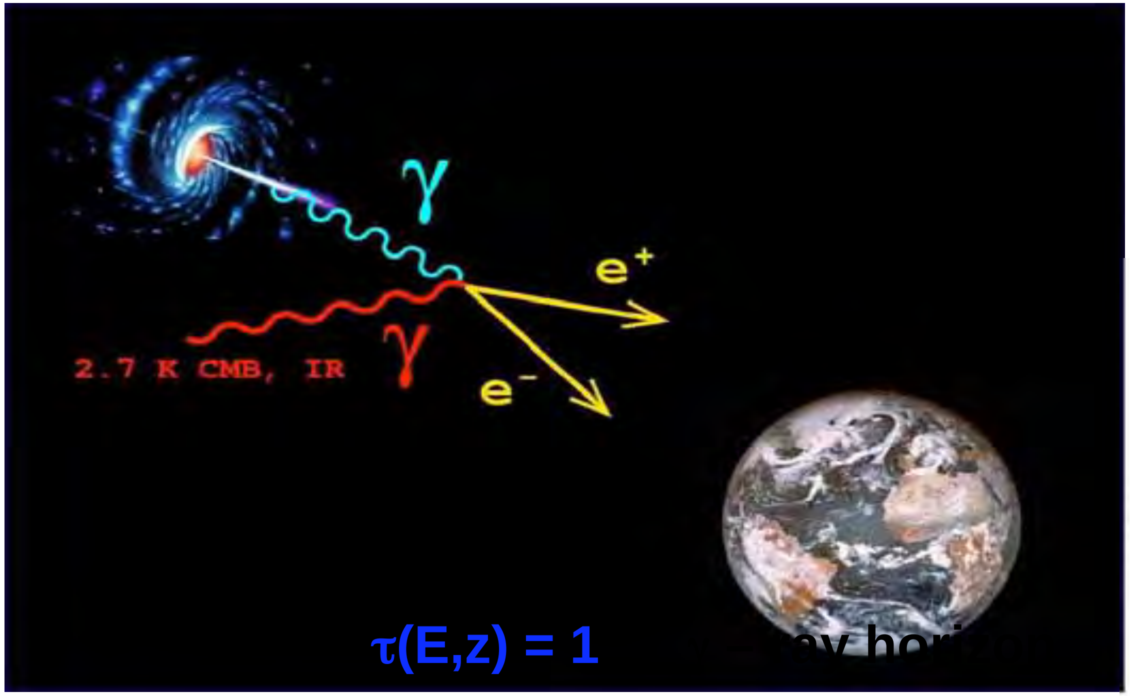


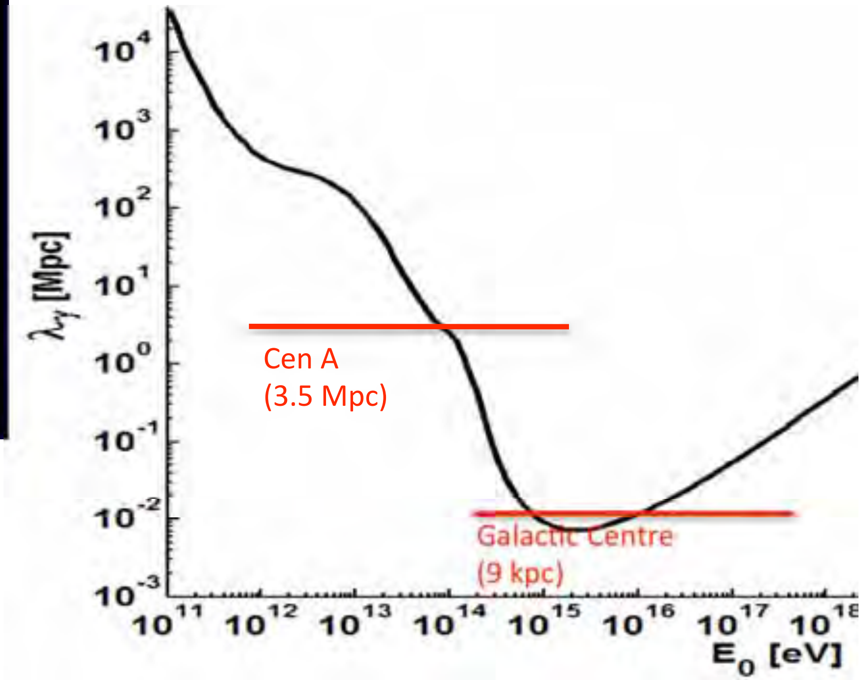
In the VHE region,
$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

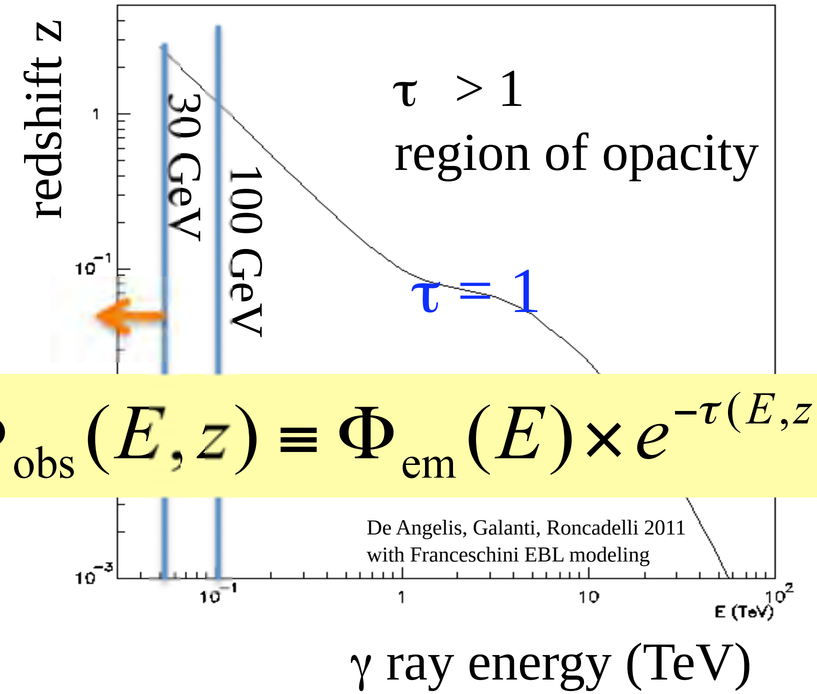
To distinguish between had/leptonic origin study Spectral Energy Distribution (SED): (differential flux) · E^2



How do gamma rays reach us?







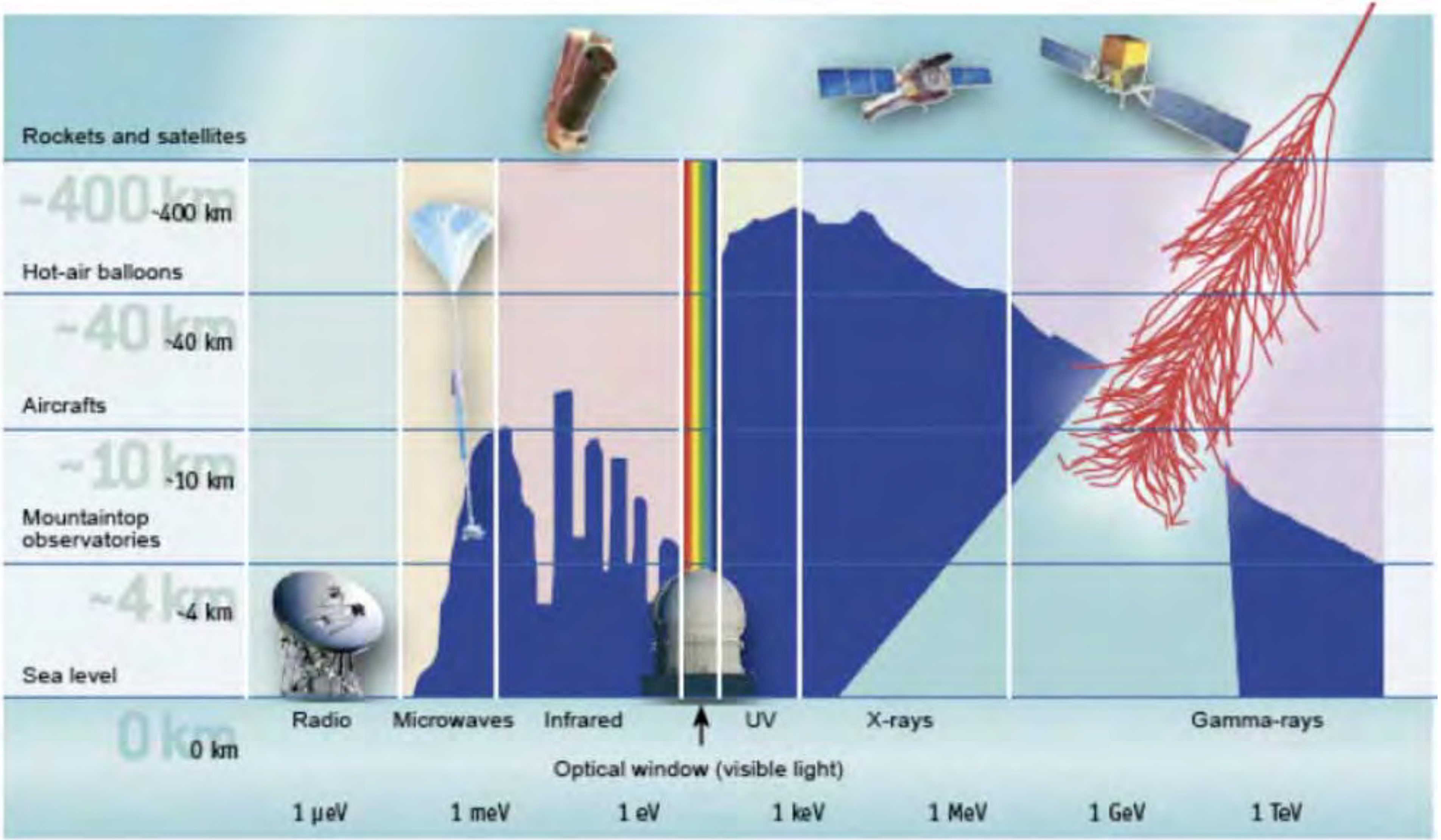
$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+ e^-$$

$$\sigma(\beta) \sim 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

Max for: $\boxed{\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\,\mathrm{GeV}}{E}\right)\mathrm{eV}}$

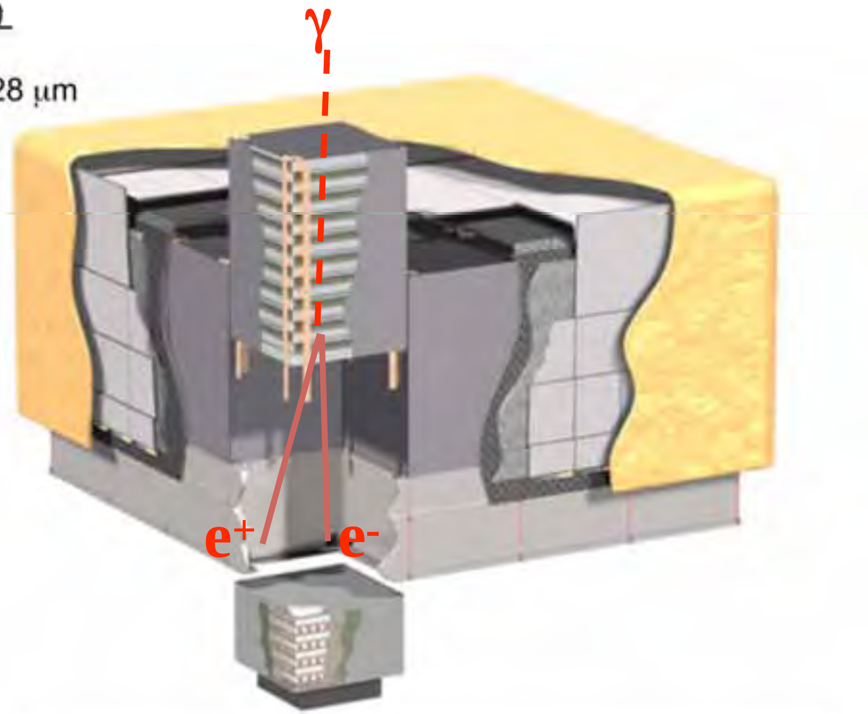
Gamma rays interact with the atmosphere



=> GeV (HE) detection requires satellites; TeV (VHE) can be done at ground

Detectors

Precision Si-strip Tracker (TKR)
18 XY tracking planes
Single-sided silicon strip detectors 228 μm pitch, 8.8 10^5 channels
Measure the photon direction

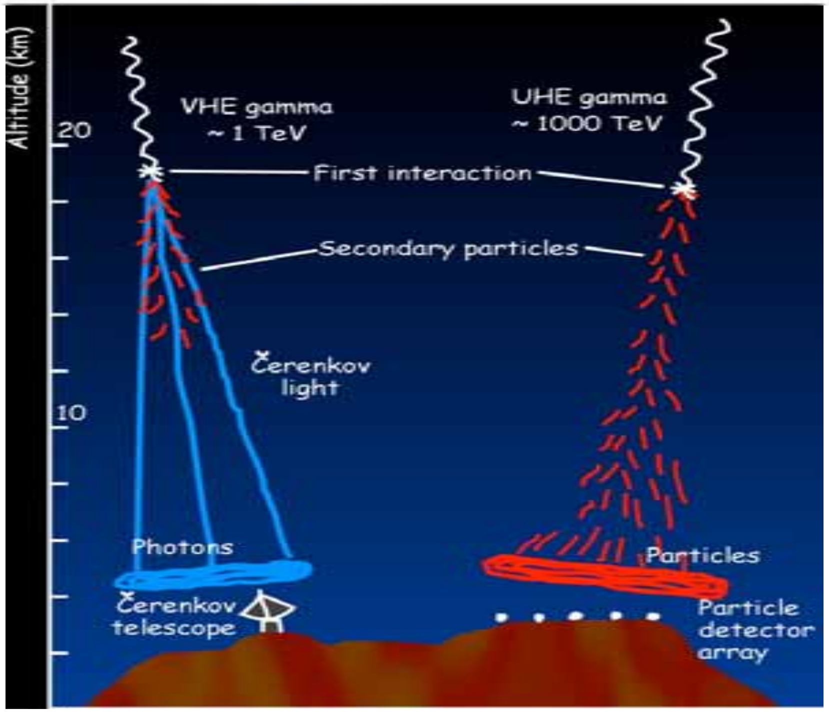


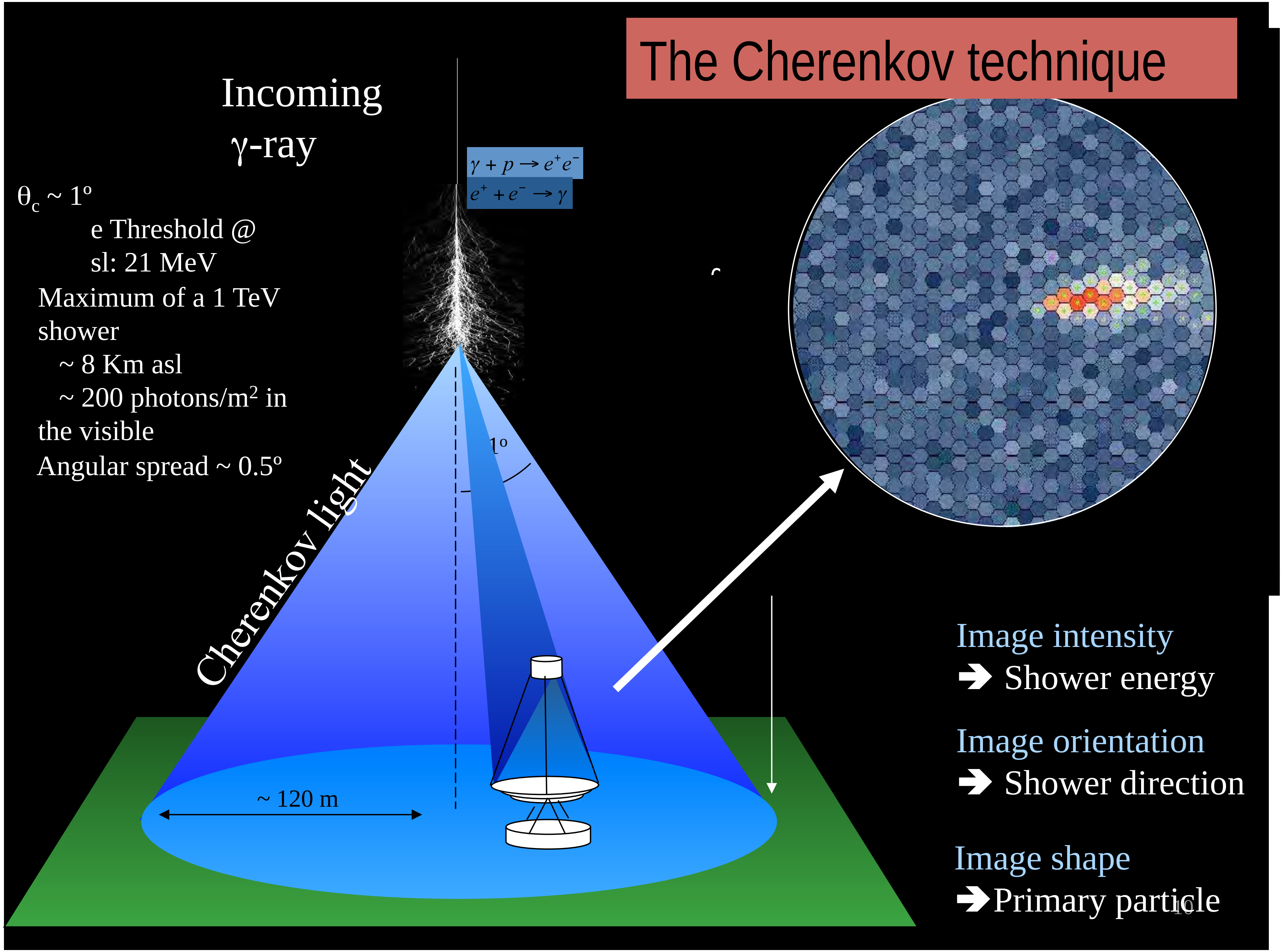
- Satellites (AGILE, Fermi)
  - Silicon tracker (+calorimeter)

- Cherenkov telescopes (HESS, MAGIC, VERITAS)

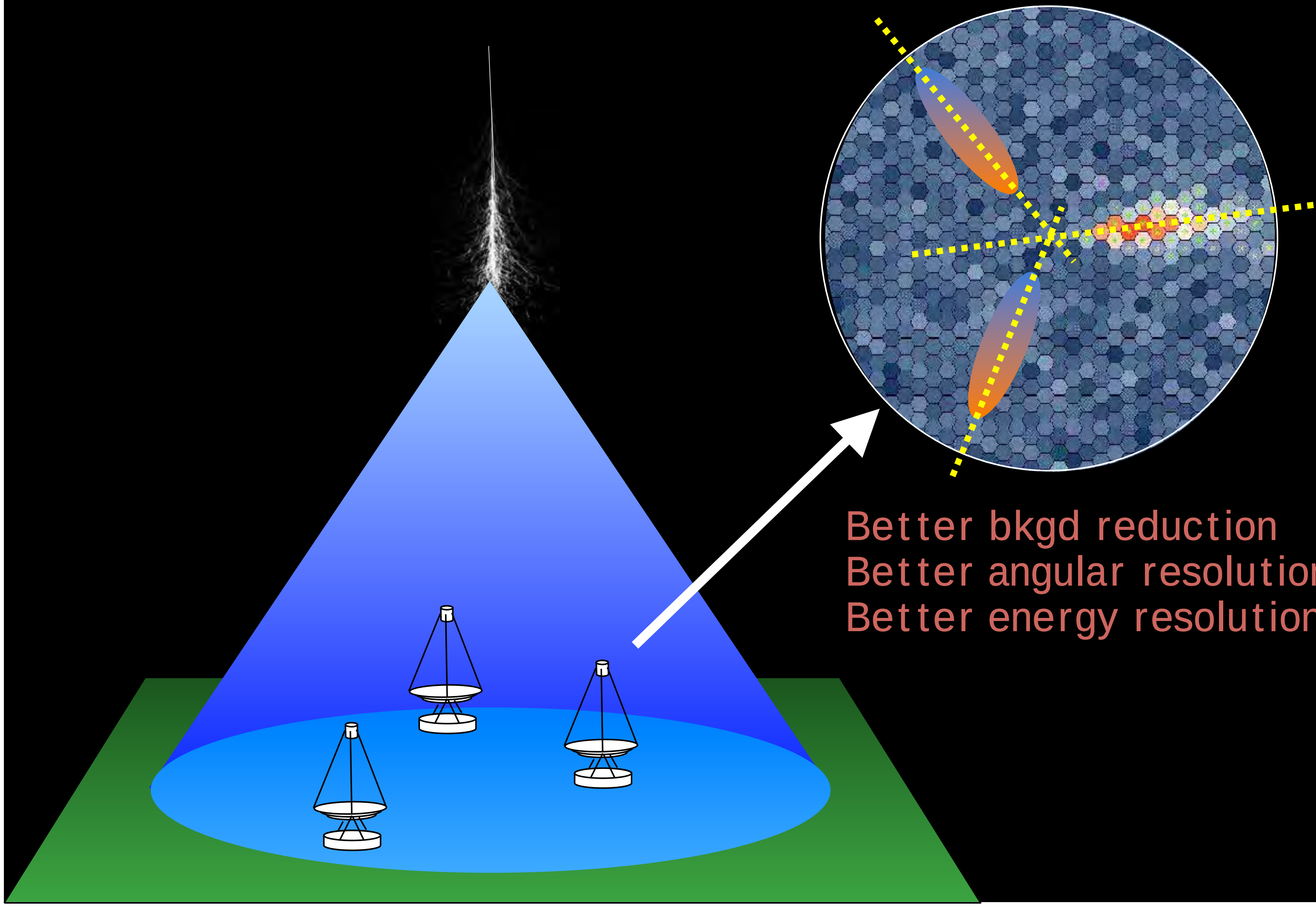
- Extensive Air Shower det. (ARGO): RPC, scintillators

HEP detectors!



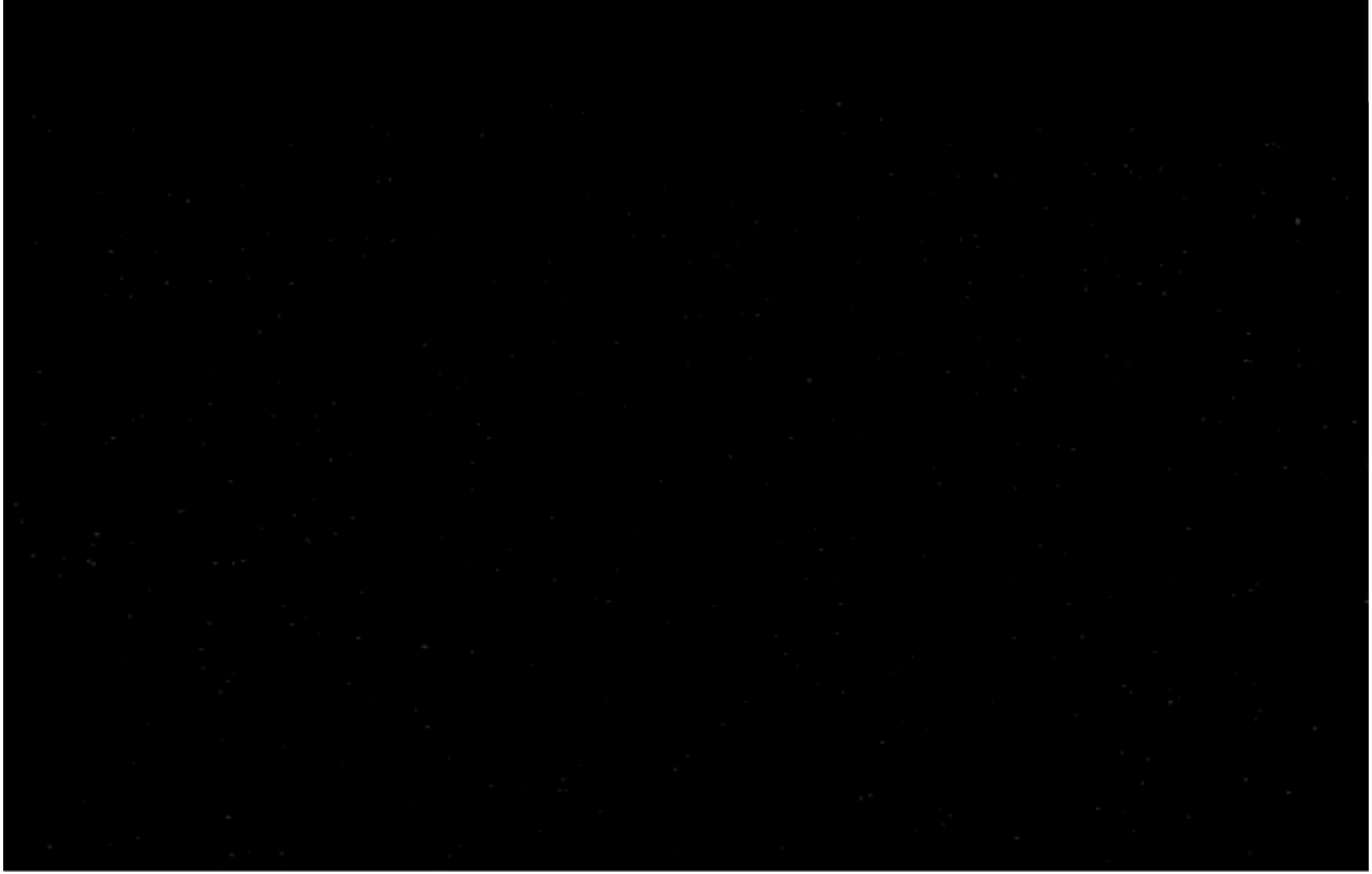

The Cherenkov technique
Incoming
γ-ray
$\gamma + p \rightarrow e^{+}e^{-}$
$e^{+} + e^{-} \rightarrow \gamma$
$\theta_c \sim 1^o$
e Threshold @
sl: 21 MeV
Maximum of a 1 TeV shower
~ 8 Km asl
~ 200 photons/m^2 in the visible
Angular spread ~ 0.5^o
Cherenkov light
1^o
~ 120 m
Image intensity
➔ Shower energy
Image orientation
➔ Shower direction
Image shape
➔ Primary particle

Systems of Cherenkov telescopes



Better bkgd reduction
Better angular resolution
Better energy resolution

Signal duration: ~ 3ns



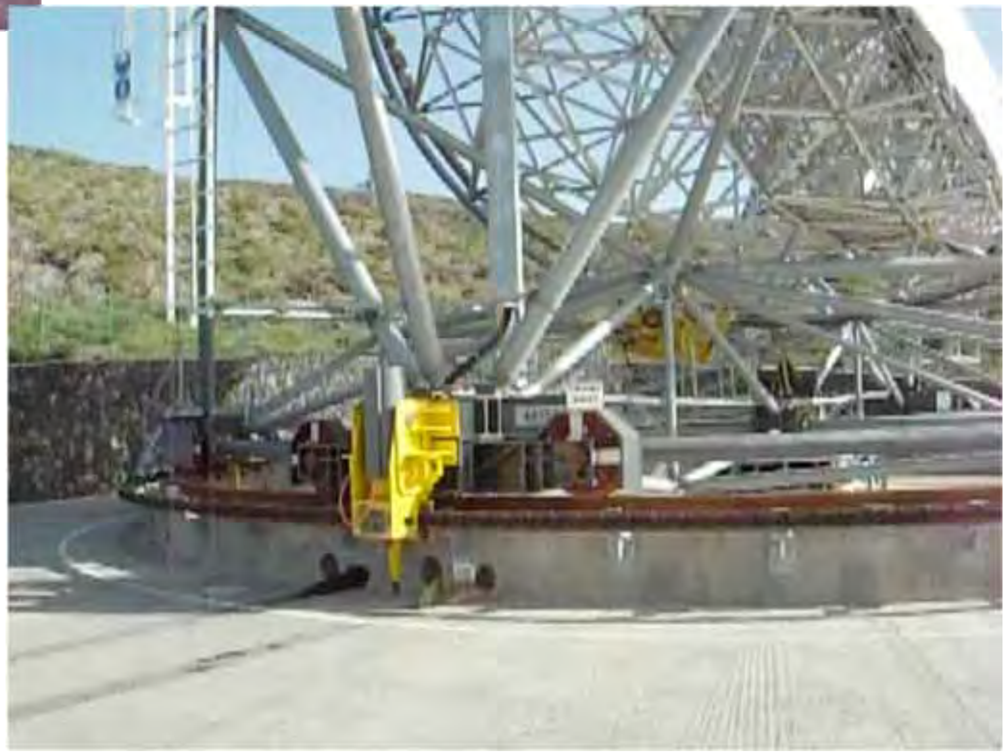
MAGIC at La Palma

the largest reflector in the world
(2 x 17 meters diameter telescopes)

An international collaboration of 160 scientists from institutes in Germany, Italy, Spain, Japan, Switzerland, Finland, Poland, Bulgaria, Croatia

Commissioned as a stereo system since May 2010

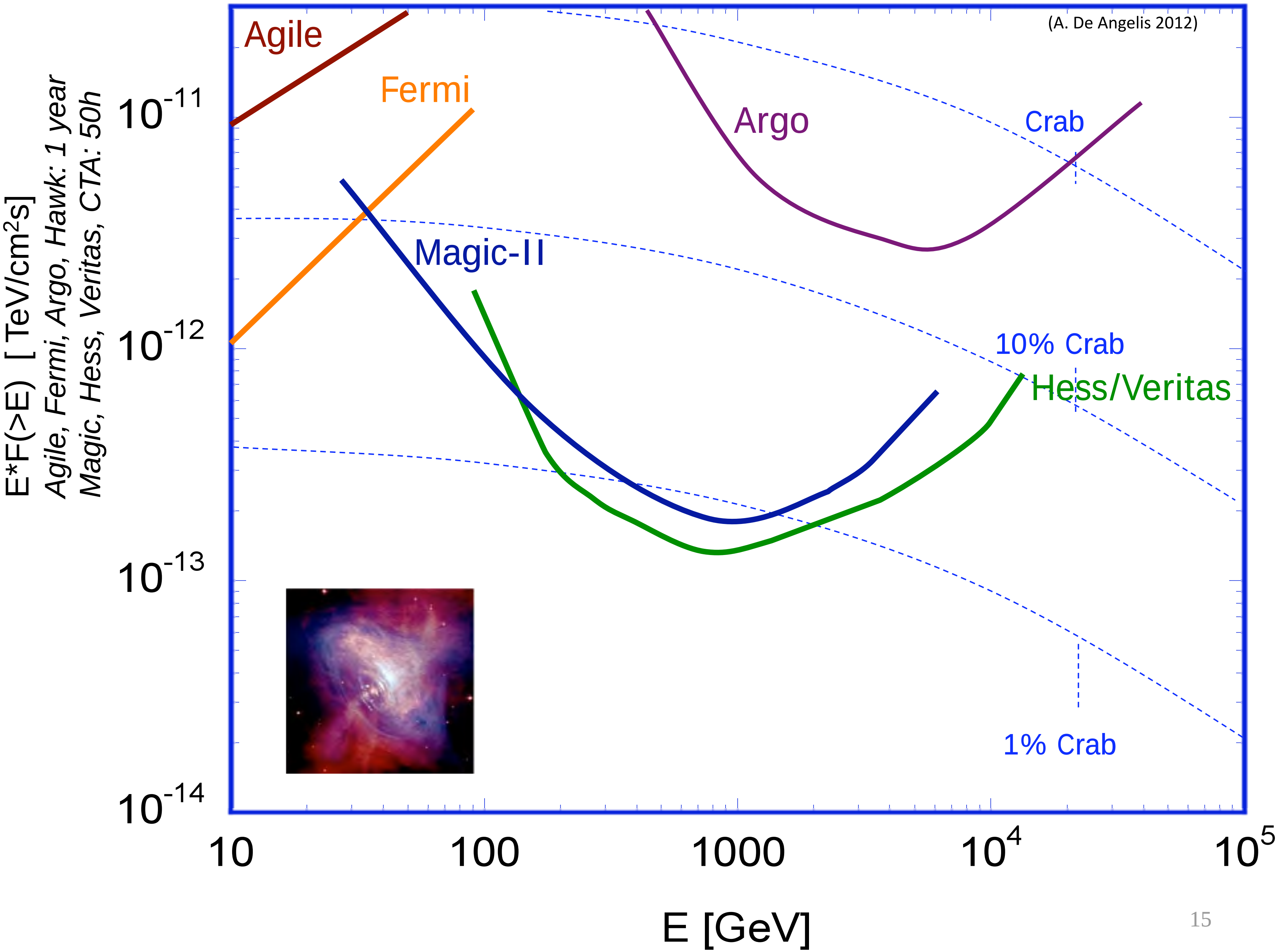
(was mono since 2004)



Instr.	Tels. #	Tel. A (m^2)	FoV (°)	Tot A (m^2)	Thresh. (TeV)	PSF (°)	Sens. (%Crab)
H.E.S.S.	4	107	5	428	0.1	0.06	0.7
MAGIC	2	236	3.5	472	0.05(0.03)	0.06	0.8
VERITAS	4	106	4	424	0.1	0.07	0.7

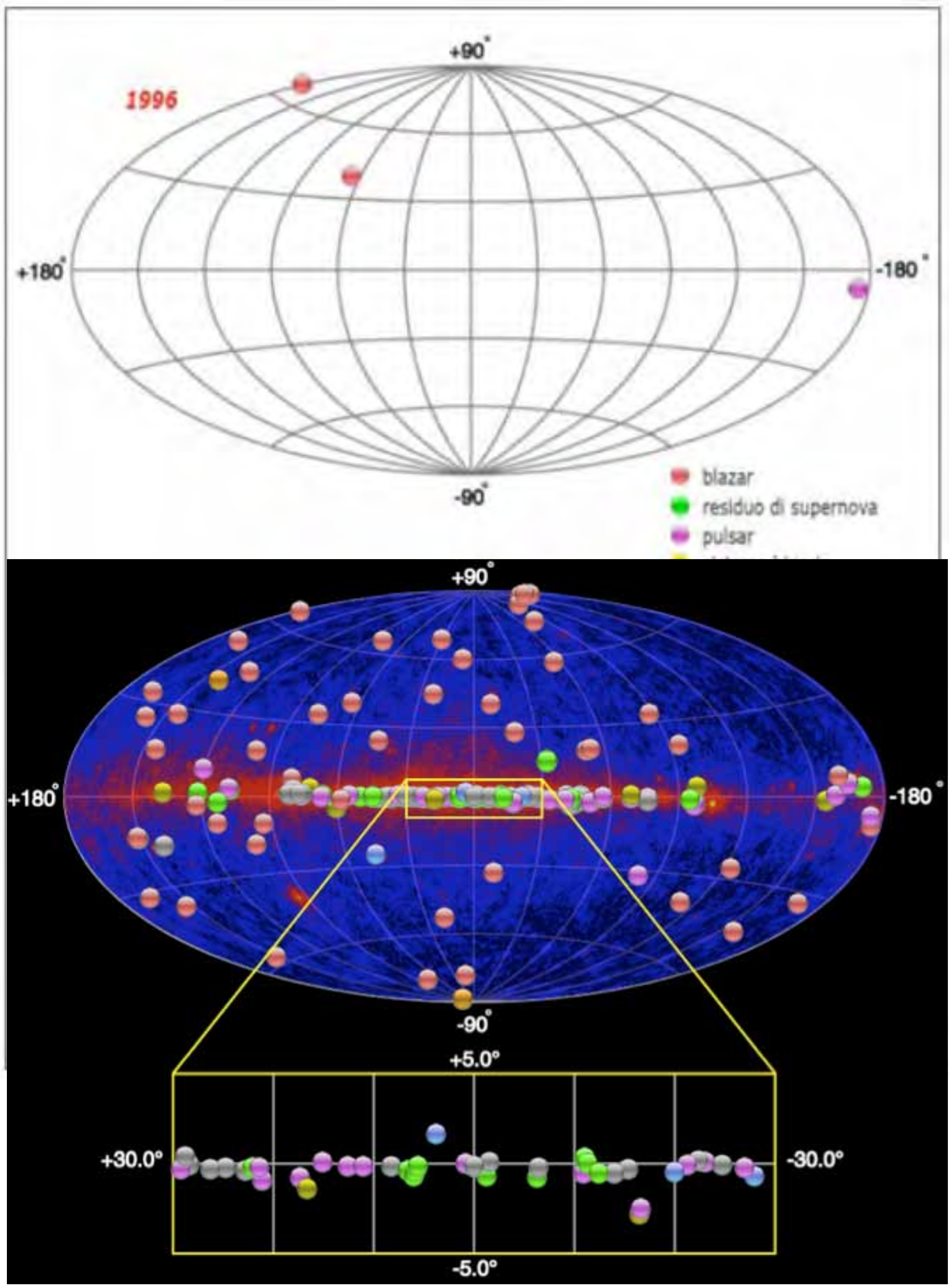
VERITAS: 4 telescopes (~12m) in Arizona operational since 2006

H.E.S.S.: 4 telescopes (~12m) in Namibia operational since 2003


(A. De Angelis 2012)
Agile
Fermi
Argo
Crab
Magic-II
10% Crab
Hess/Veritas
1% Crab
10-11
10-12
10-13
10-14
10
100
1000
10^4
10^5
E [GeV]
E*F(>E) [TeV/cm2s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h

Highlight in γ-ray astrophysics (MAGIC, HESS, VERITAS)

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 130 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 150 (and >200 papers) in the last 7 years
  - And also a better knowledge of the diffuse gammas and electrons
- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources
- A new tool for cosmic-ray physics and fundamental physics

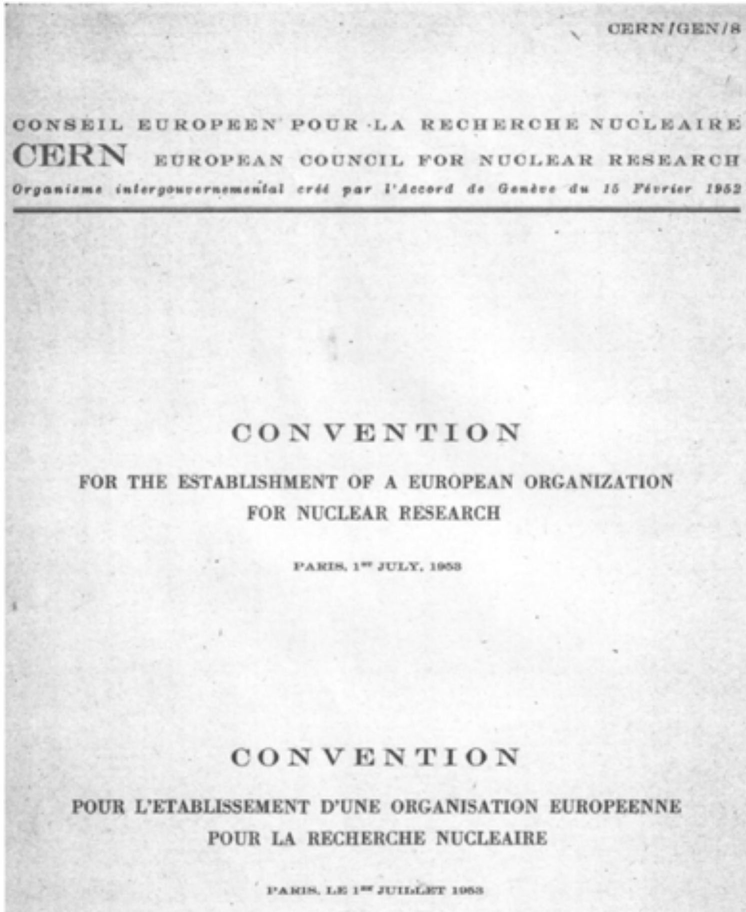


Main physics results and perspectives
(with emphasis on fundamental physics)

- *Cosmic Rays*

- Transparency of the Universe;
  Tests of Lorentz Invariance;
  Axion-Like Particles

- Search for “WIMP” Dark Matter



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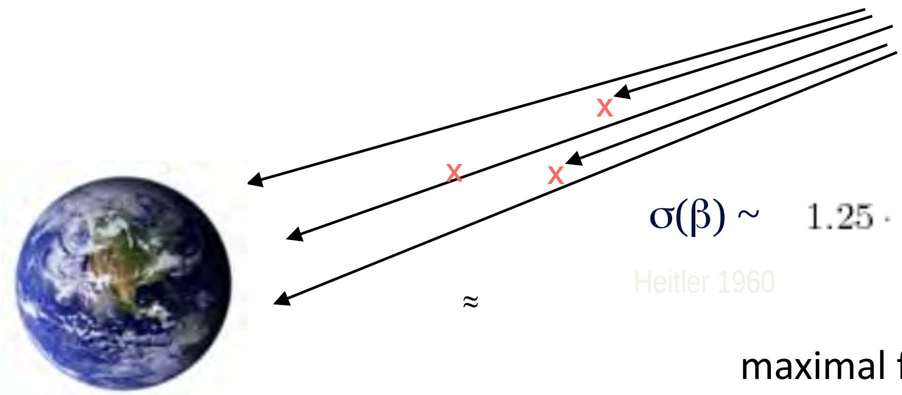
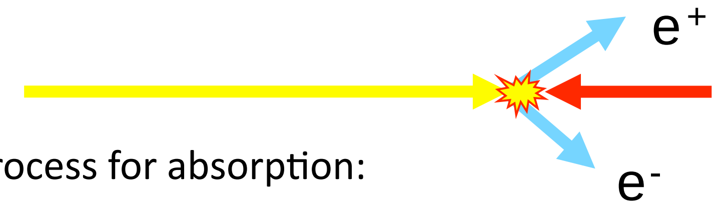
Propagation of γ-rays





dominant process for absorption:

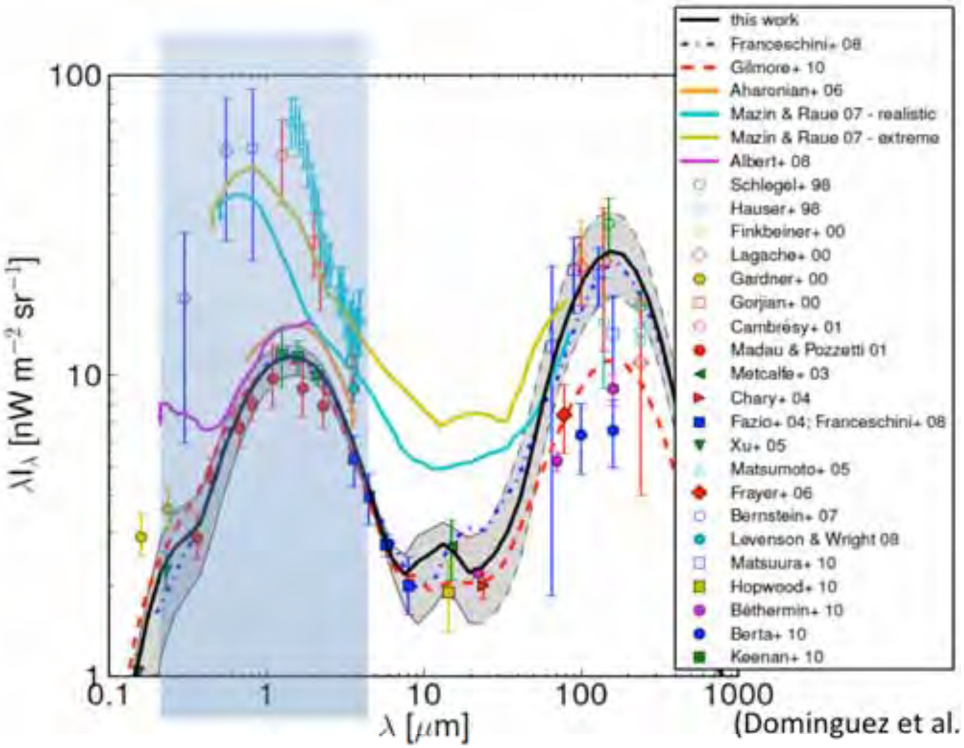
$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$$

$$\sigma(\beta) \sim 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

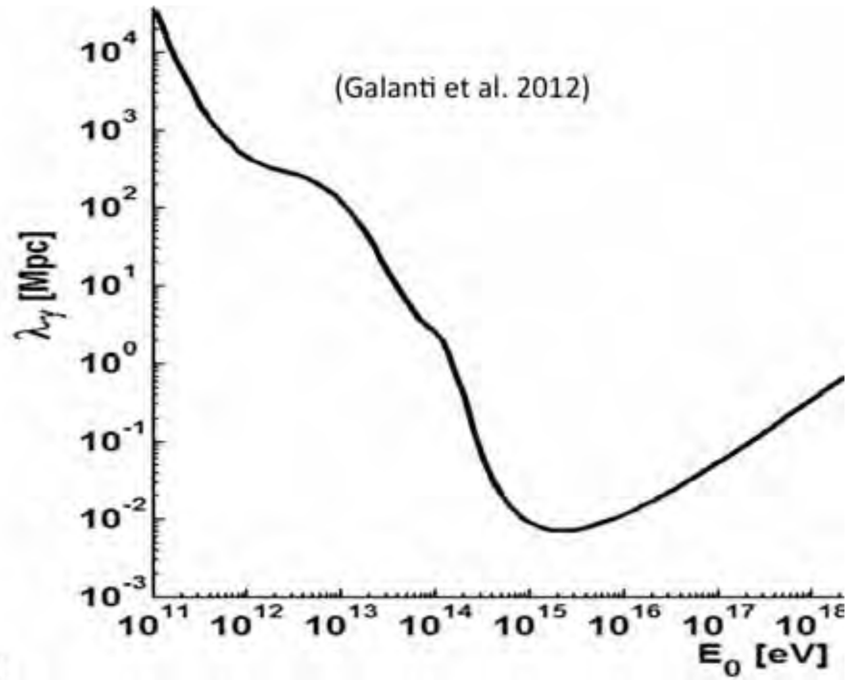
Heitler 1960

maximal for: $\boxed{\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right) \mathrm{eV}}$

- For gamma rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation



(Dominguez et al. 2011)

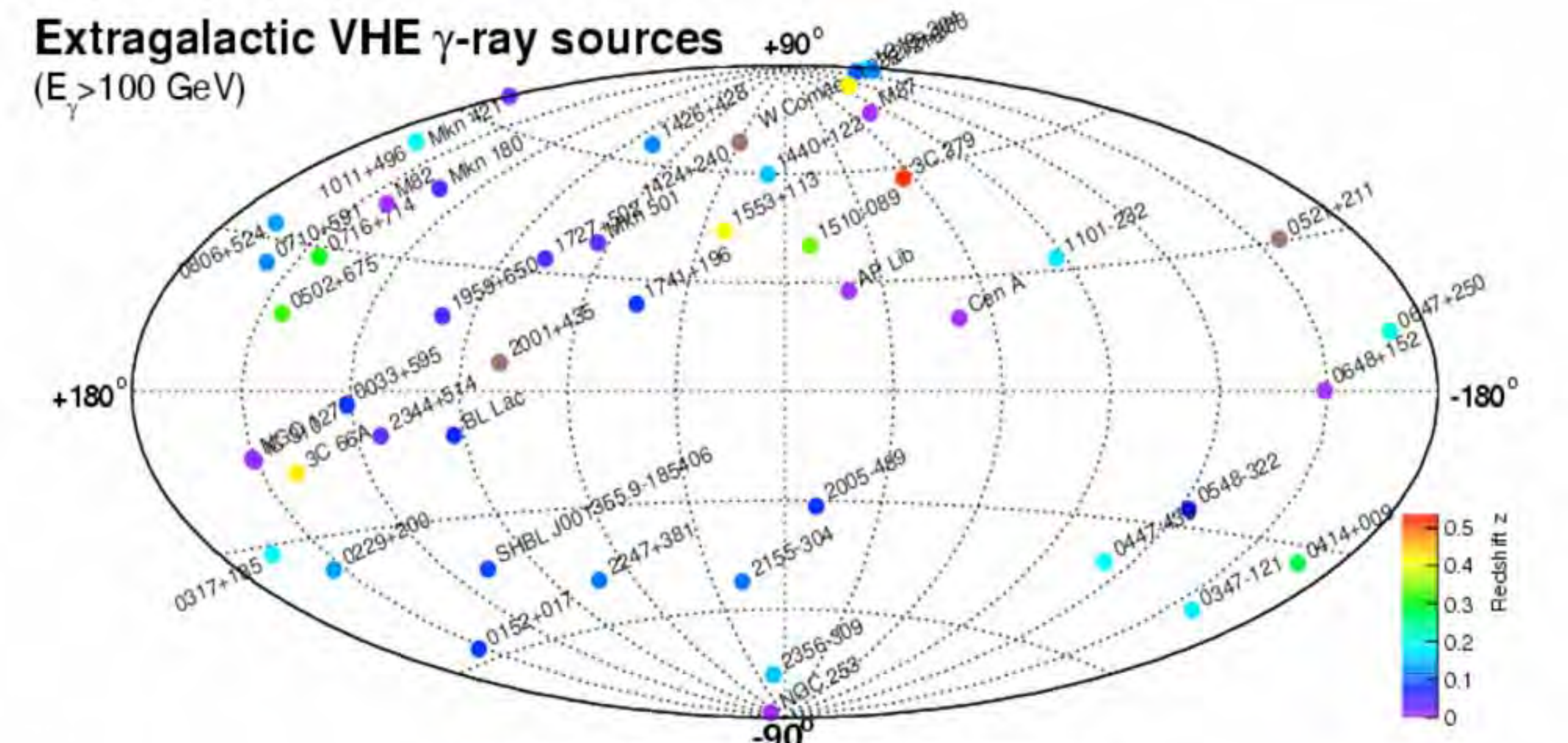


Extragalactic Sources

~50 Sources

…

1ES 1011+496	**z=0.21**	**MAGIC 2007**
1ES 0414+009	z=0.29	HESS/Fermi 2009
S5 0716+71	**z=0.31±0.08**	**MAGIC 2009**
1ES 0502+675	z=0.34	VERITAS 2009
PKS 1510-089	z=0.36	HESS 2010
4C +21.43	**z=0.43**	**MAGIC 2010**
3C 66A	**z=0.44**	**VERITAS 2009**
3C 279	**z=0.54**	**MAGIC 2008**



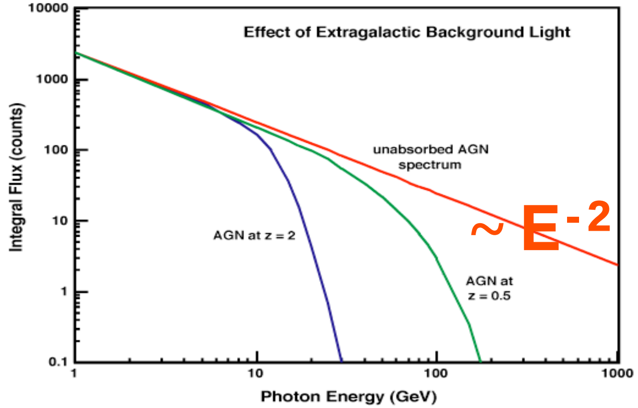
Alessandro De Angelis

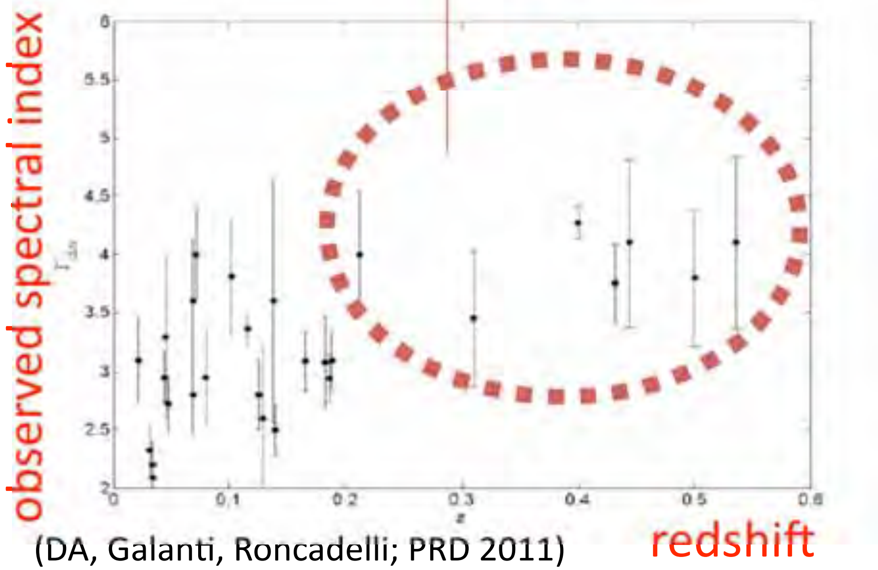
2011-11-20 - Up-to-date plot available at http://www.mppmu.mpg.de/~rwagner/sources/

Are our AGN observations consistent with theory?

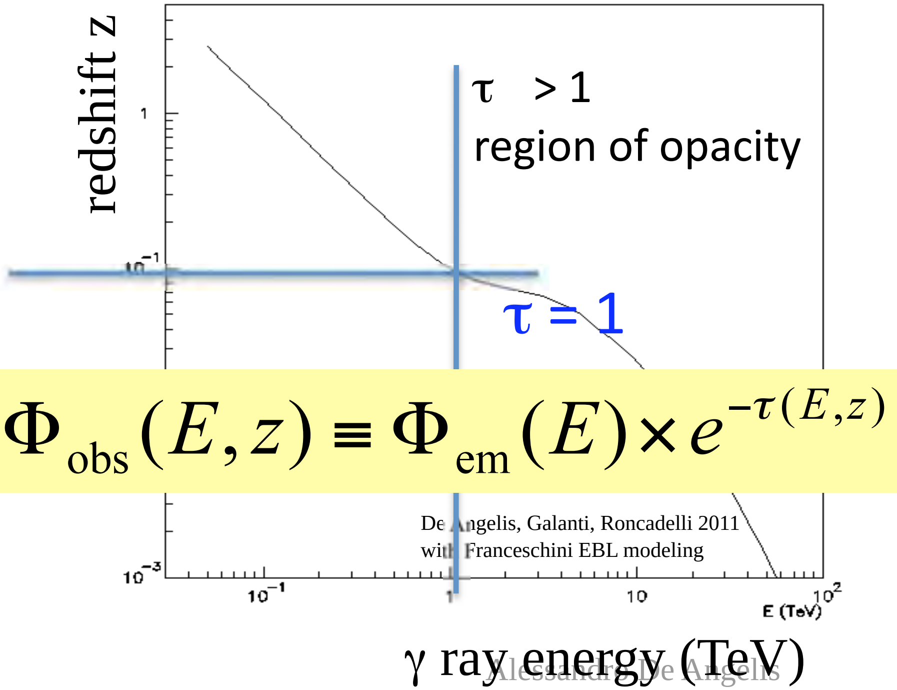
Selection bias?
New physics ?

Measured spectra affected by attenuation in the EBL:

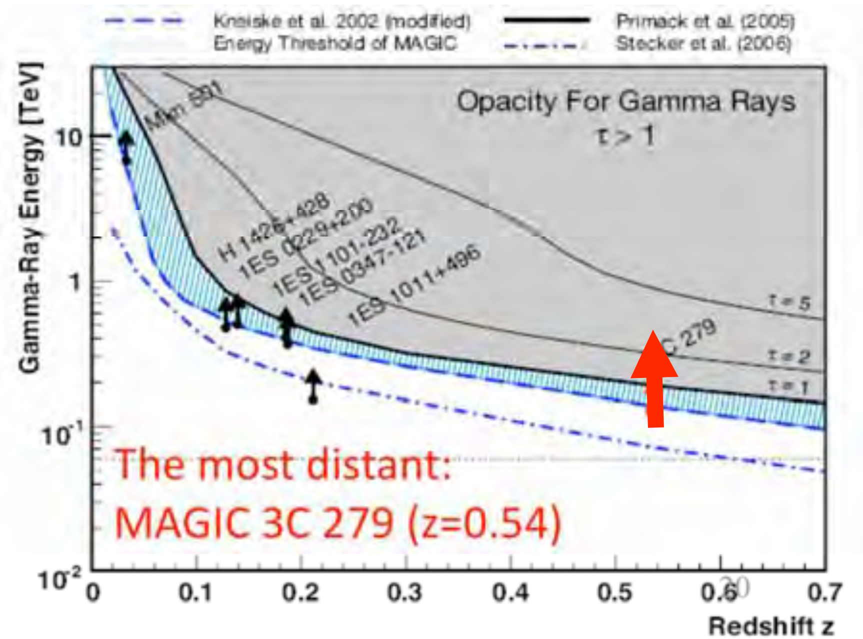




(DA, Galanti, Roncadelli; PRD 2011)



$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

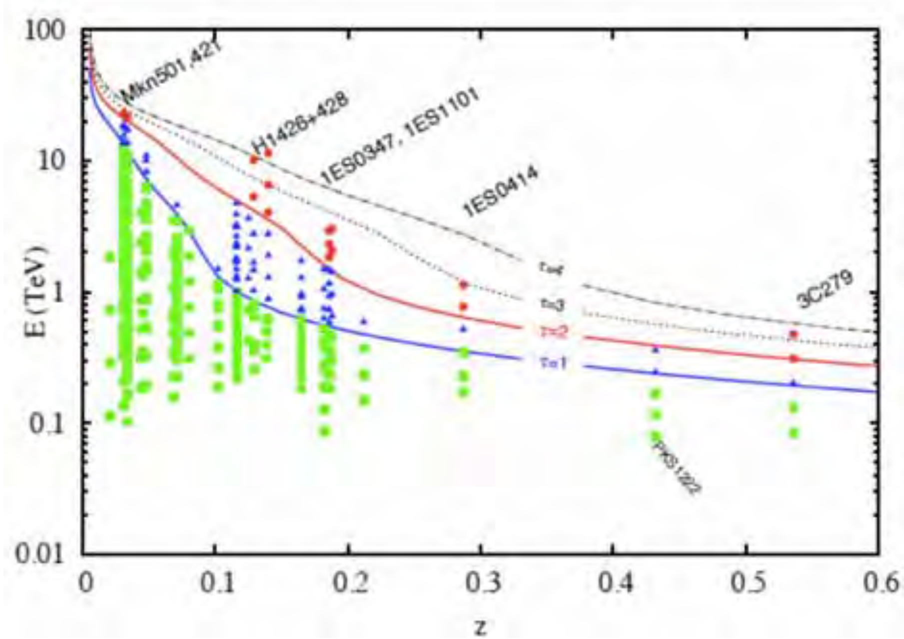


Attempts to quantify the problem overall

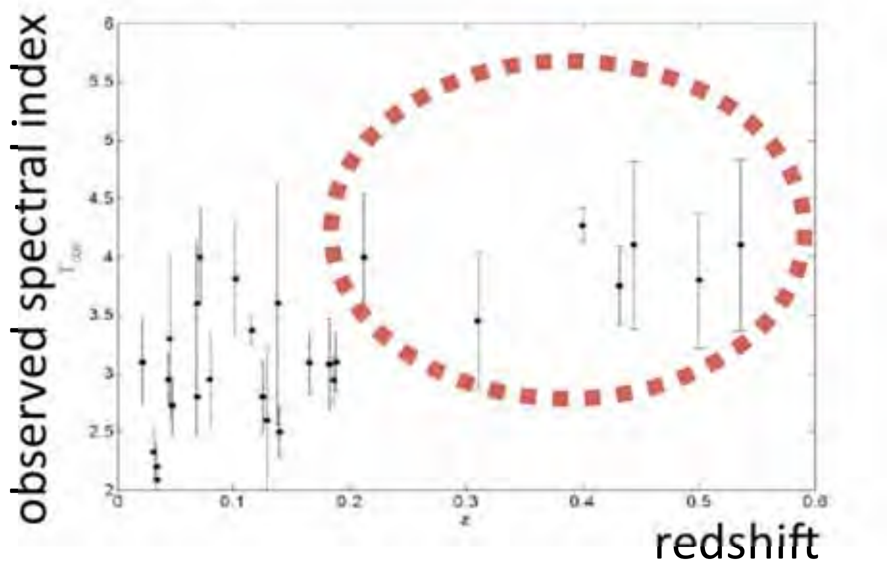
- Analysis of AGN
  - For each data point, a corresponding lower limit on the optical depth τ is calculated using a minimum EBL model
  - Nonparametric test of consistency
  - Disagreement with data: overall significance of 4.2 σ

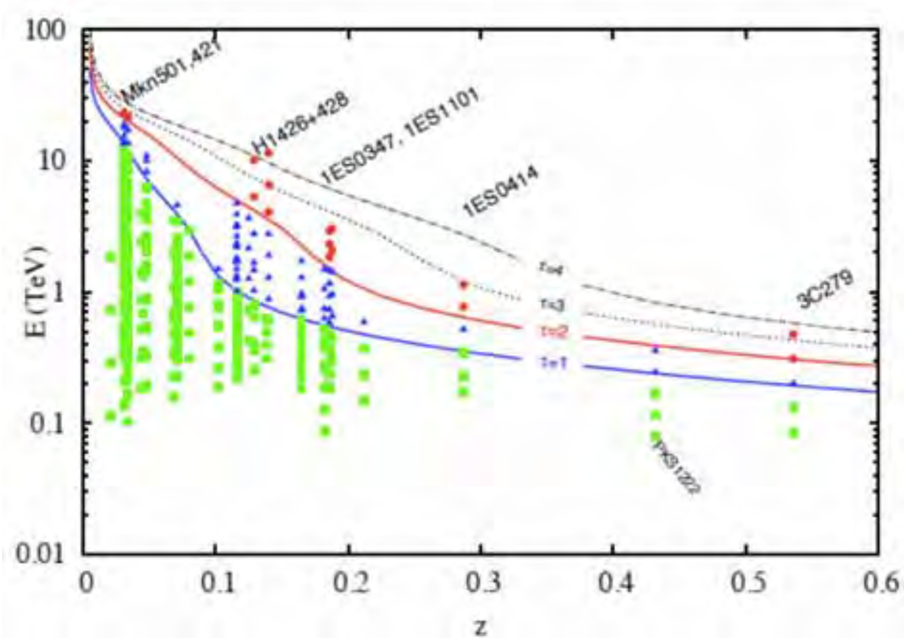
=> <u>Understand experimentally the outliers</u>

(Horns , Meyer 2011)



If there is a problem





Explanations from the standard ones

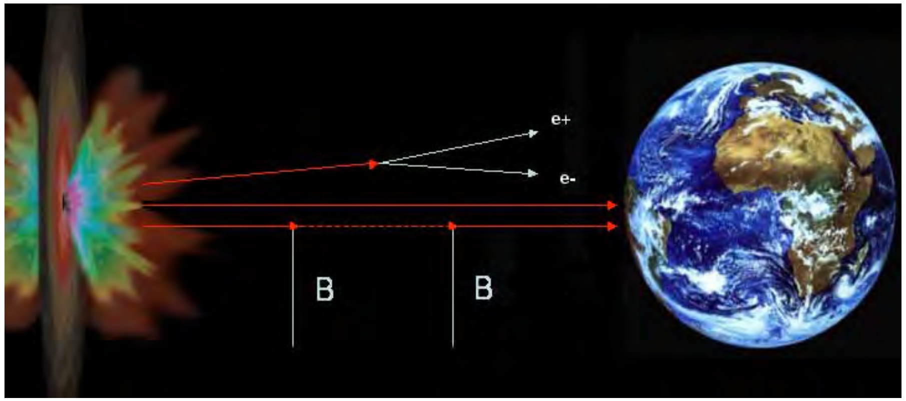
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of "wrong" outliers

to almost standard

- γ-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or ν from the same source

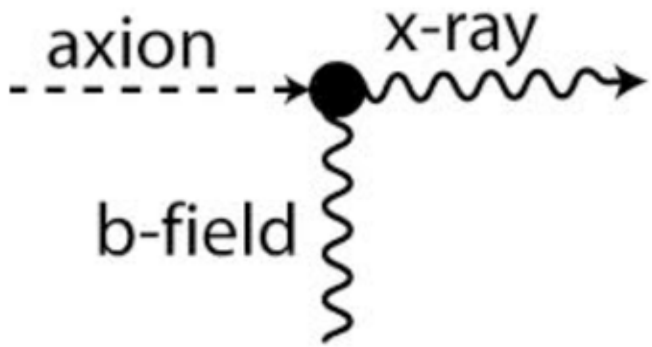
to possible evidence for new physics

- Oscillation to a light "axion"? (DA, Roncadelli & MAnsutti [DARMA], PRD2007, PLB2008)
- Axion emission (Simet+, PRD2008)
- A combination of the above (Sanchez Conde et al. PRD 2009)



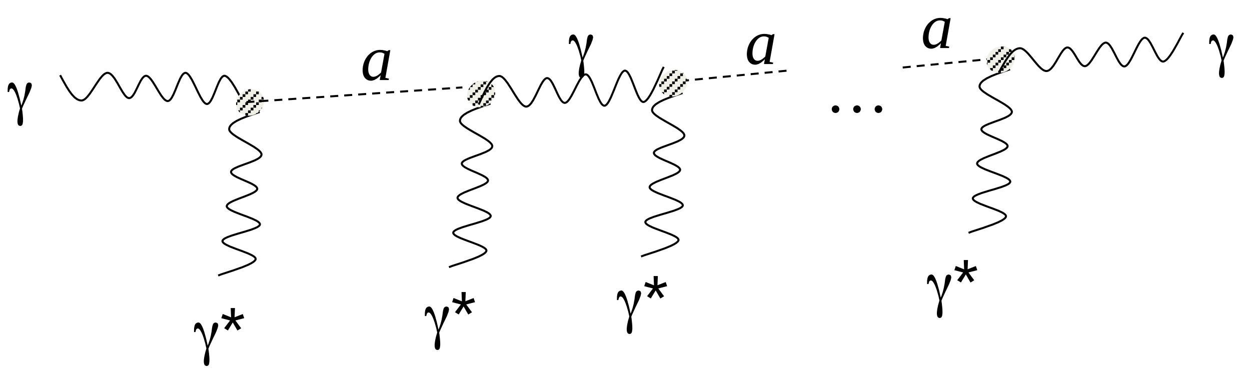
Axions

- The "strong CP problem": CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the "axion" from the name of a cleaning product
  - Pseudoscalar, neutral, stable on cosmological scales, feeble interaction, couples to the photon
    - Can make light shine through a wall
  - The minimal (standard) axion coupling $g \propto 1/m$; however, one can have an "ALP" in which $g = 1/M$ is free from m



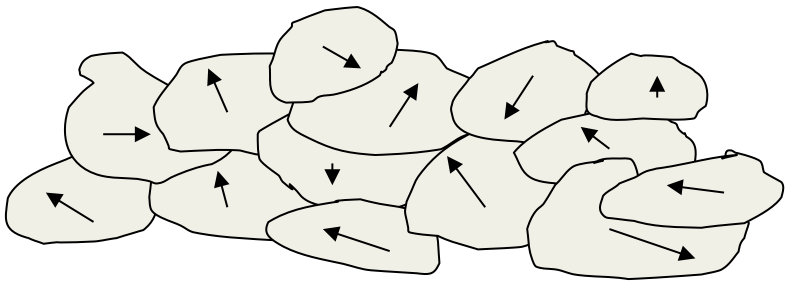
The photon-axion mixing mechanism

$$L_{a\gamma\gamma} = g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right)a$$



Propagation: Raffelt-Stodolsky 1987; Csaki-Kaloper-Terning 2002; DA Roncadelli MAnsutti 2007; Simet Hooper Serpico 2008

- Magnetic field 1 nG < B < 1aG (AGN halos). Cells of ~ 1 Mpc

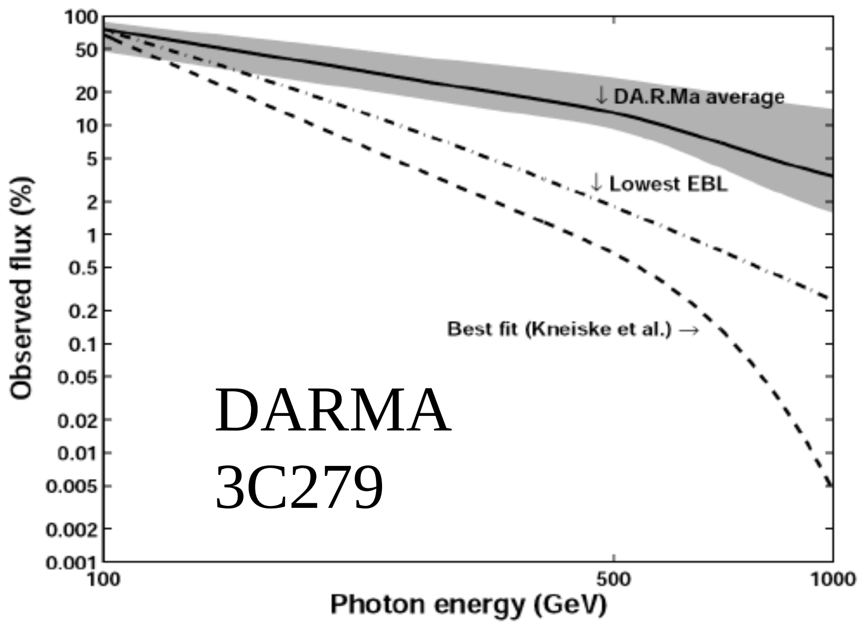


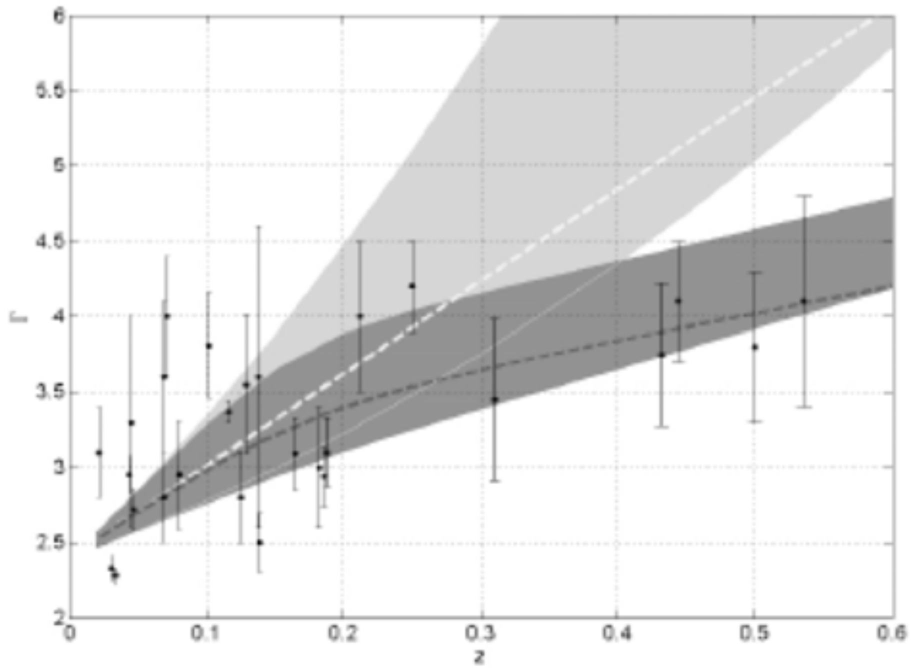
$$P_{\gamma\to a} \approx NP_1$$

$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times 10^{-3}\left(\frac{B_T}{1\mathrm{nG}}\frac{s}{1\mathrm{Mpc}}\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2$$

- $m_a < 0.02$ eV (direct searches)
- $g < 10^{-10}\mathrm{GeV}^{-1}$ from the non observation of γ-rays from the SN1987A, and direct searches

If B ~ 0.1 – 1 nG, observations can be explained





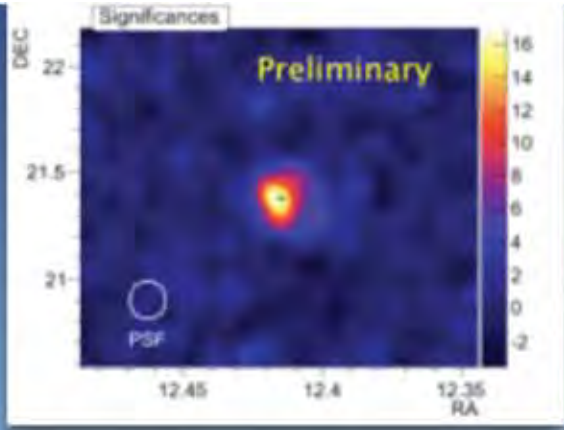
Note: if conversion "a la Simet-Hooper-Serpico", => the effect could be directional

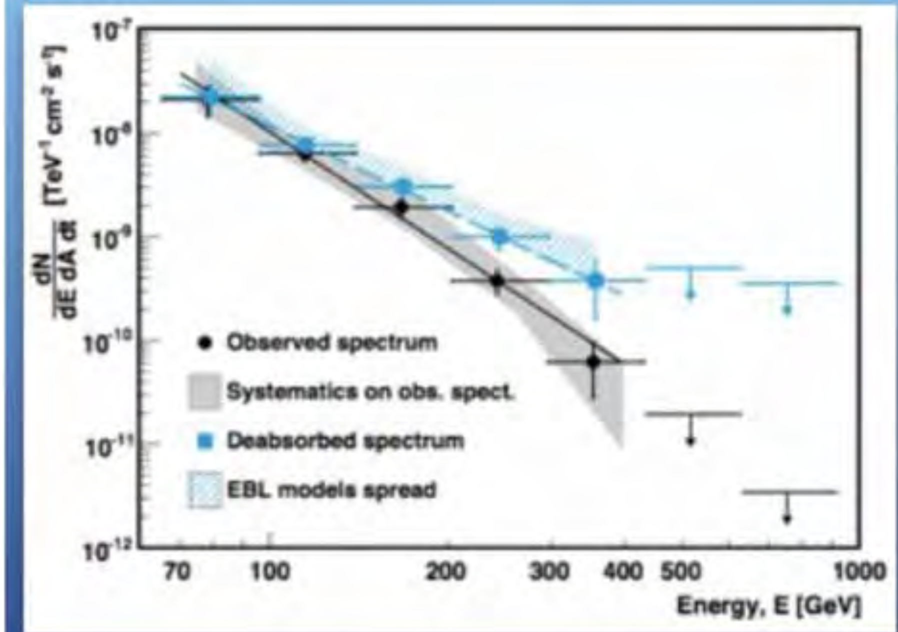
- Could also be something else:

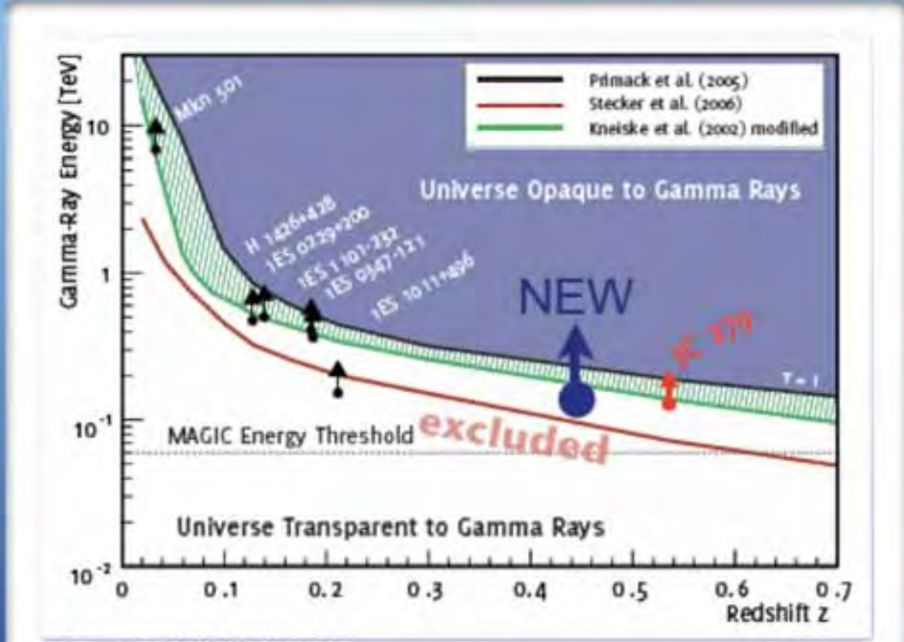
  Whatever (light and almost sterile) particle feebly coupling to the photon
  - Paraphoton
    - Shadow photon
  - New millicharged particles...

Recent confirmation: something not understood

- 2010 June 17, flare state
- PKS 1222+21 (4C +21.35) is a high redshift (z=0.43) FSRQ
  - (only 3C279, PKS1510-089 so far)
- Observations triggered by a high state reported by Fermi-LAT
- Can be used for EBL studies



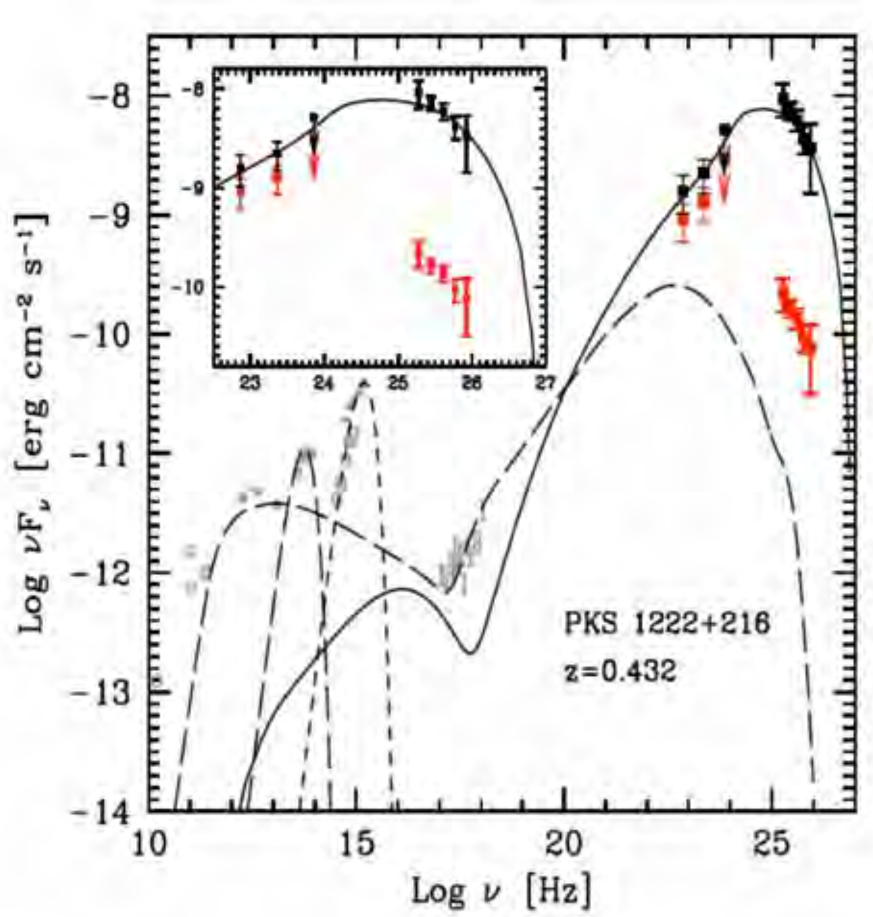




Science 320 (2008) 1752

PKS1222: an alternative discussion of the problem

- Tavecchio, Roncadelli, Galanti, Bonnoli 2012:
  - the $\gamma \rightarrow a$ conversion occurs before most of the photons reach the BLR. Accordingly, ALPs traverse this region unimpeded and
  - Outside, the re-conversion $a \rightarrow \gamma$ takes place either in the same magnetic field of the source or in that of the host galaxy
  - Resulting parameters of the ALP needed to fit the data consistent with DARMA



Summarizing: if the expected photon yield at VHE is different from what we think, what might be wrong?

- Emission models are more complicated than we think (but only for sources far away: nearby sources behave well)

- VHE photons are generated on the way (interaction of cosmic rays, neutrinos and photons with intergalactic medium: Sigl, Essey, Kusenko, …)

- Something is wrong in the $\gamma\gamma$ -> e+e- rate calculation
  - Vacuum energy (new sterile particles coupling to the photons): DARMA, …
    - For example an ALP: consistent values for m, g=(1/M) in a range not experimentally excluded ("Se non e' vero e' ben pensato")
  - $\gamma\gamma$ -> e+e- cross section

    QED calculations appears to be in a safe region; then it must be
    - the boost (Lorentz transformations; relativity)

Is Lorentz invariance exact?

- For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  - Is there an aether? (Dirac 1951)
  - Many preprints, often unpublished (=refused) in the '90s
    - Gonzales-Mestres, ADA, Jacobson, …

- Then the discussion was open
  - Trans-GZK events? (AGASA collaboration 1997-8)
  - LIV => high energy threshold phenomena: photon decay, vacuum Cherenkov, GZK cutoff (Coleman & Glashow 1997-8)
  - GRB and photon dispersion (Amelino-Camelia et al. 1997)
  - Framework for the violation (Colladay & Kostelecky 1998)
  - LIV and gamma-ray horizon (Kifune 1999)
  - …

LIV? New form of relativity?

- Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} => Lorentz transformations with "some" invariant c (Galilei relativity is the limit c $\rightarrow\infty$)
- CMB is the aether: give away isotropy?
- QG motivation: give away linearity? (A new relativity with 2 invariants: "c" and E_P)

- In any case, let's sketch an effective theory…
  - Let's take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) as a perturbation of the Hamiltonian (Amelino-Camelia+)

A heuristic approach: modified dispersion relations (perturbation of the Hamiltonian)

- We expect the Planck mass to be the scale of the effect

$$E_P = \sqrt{hc/G} \cong 1.2 \times 10^{19}\,\mathrm{GeV}$$

$$H^2 = m^2 + p^2 \rightarrow H^2 = m^2 + p^2\left(1 + \xi \frac{E}{E_P} + \ldots\right)$$

$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi \frac{p}{2E_P} + \ldots\right)$$

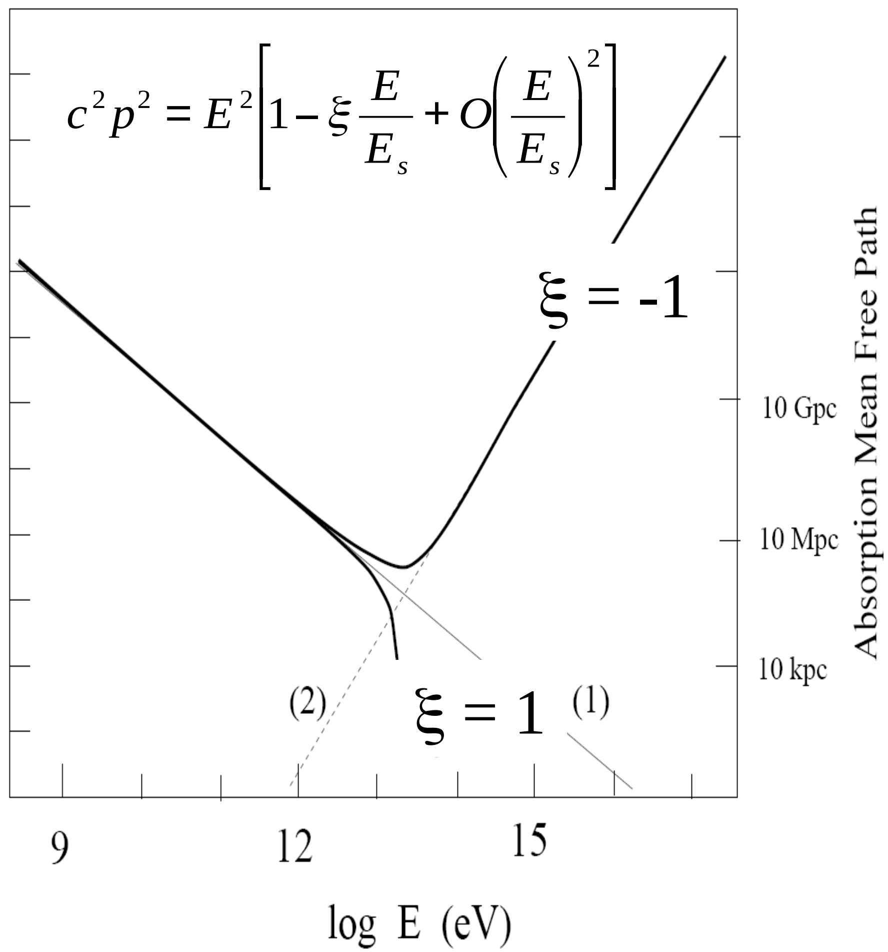
$$v = \frac{\partial H}{\partial p} \cong 1 - \frac{m^2}{2p^2} + \xi \frac{p}{E_P} \Rightarrow \boxed{v_\gamma \cong 1 + \xi \frac{E}{E_P}}$$

=> effect of dispersion relations at cosmological distances can be important at energies well below Planck scale: $\boxed{\Delta t_\gamma \cong T \Delta E \frac{\xi}{E_P}}$

Other effects of LIV: modified thresholds (Coleman-Glashow); transparency (Kifune 99)

$$v = \frac{\partial H}{\partial p} \cong 1 - \frac{m^2}{2p^2} + \xi \frac{p}{E_P}$$

- $\xi < 0$:
  - Increased transparency (threshold $\gamma\gamma$ -> ee moves forward)



$c_e = c_\gamma(1+\delta)$, $0 < abs(\delta) << 1$ Coleman & Glashow; Stecker and Glashow

1. If $\delta<0 \Rightarrow c_e < c_\gamma \Rightarrow$ decay $\gamma \to e^+e^-$ kinematically allowed for gamma with energies above

$$E_{max} = m_e \, sqrt(2/abs(\delta))$$

- $E_\gamma > 100$ TeV => $abs(\delta) < 5 \times 10^{-17}$

2. If $\delta>0 \Rightarrow c_e > c_\gamma \Rightarrow$ electrons become superluminal for energies larger than $E_{max}/sqrt(2)$ => Vacuum Cherenkov Radiation.

- $E_e > 2$ TeV from cosmic electron radiation => $abs(\delta) < 2 \times 10^{-14}$
- Modification of $\gamma \gamma \to e+e-$ threshold. Using Mkn 501 and Mkn 421 spectra observations up to $E_g > 20$ TeV
=> $abs(\delta) < 1.3 \times 10^{-15}$

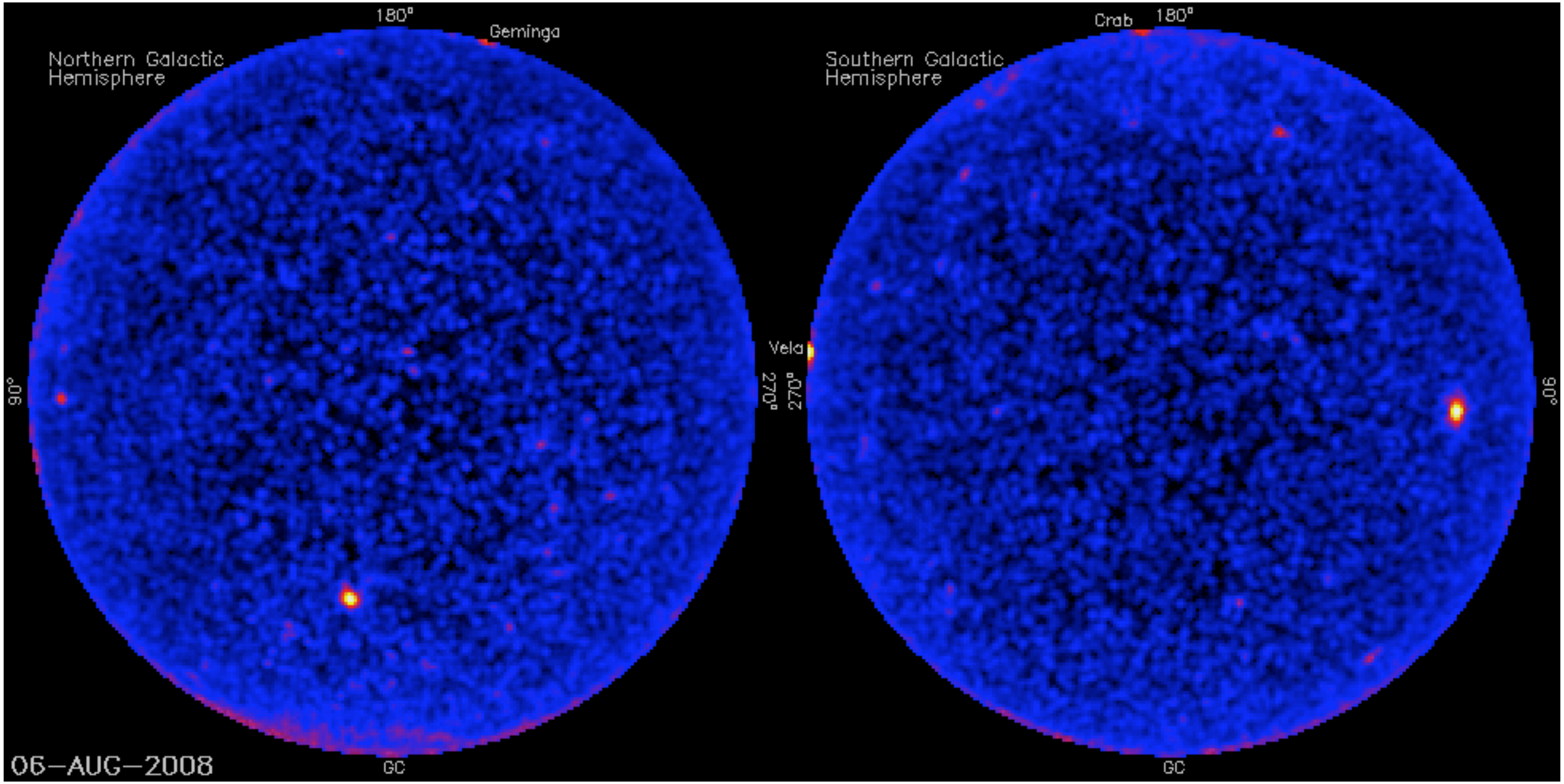
From MAGIC Mkn501 (taken as a LIV signal): $|\delta| \sim 2\ 10^{-15}$

Astrophysical constraints: time of flight

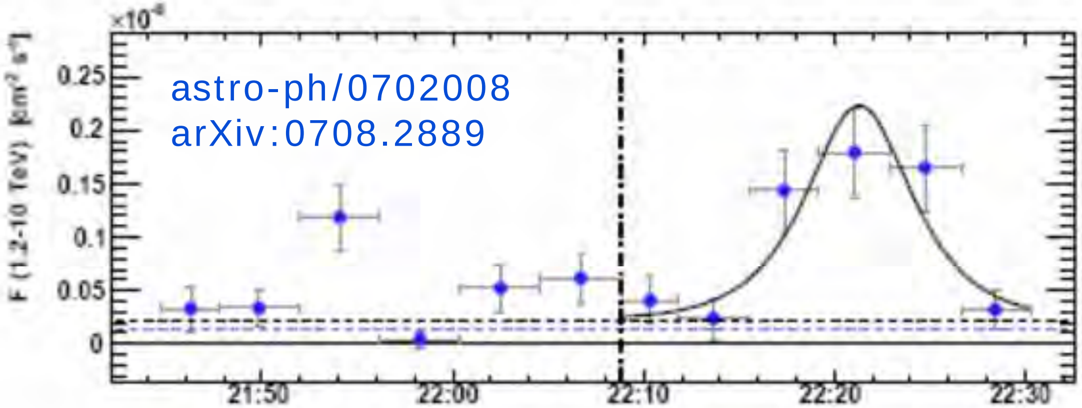
- Effect of dispersion relations at cosmological distances can be important at energies well below Planck scale:

$$v_\gamma \cong 1 + \xi \frac{E}{E_P} \Rightarrow \boxed{\Delta t_\gamma \cong T \Delta E \frac{\xi}{E_P}}$$

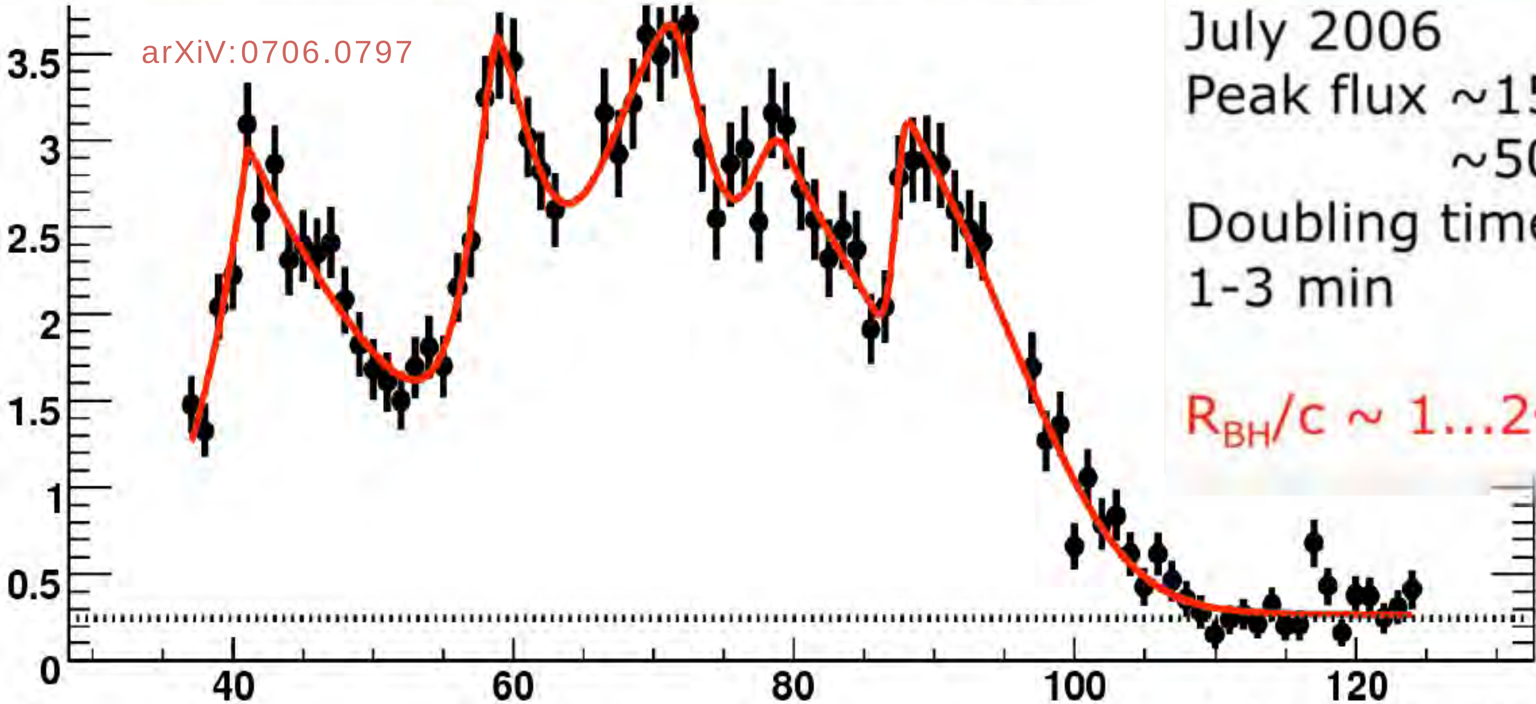
Variability



Rapid variability



MAGIC, Mkn 501
Doubling time ~ 2 min

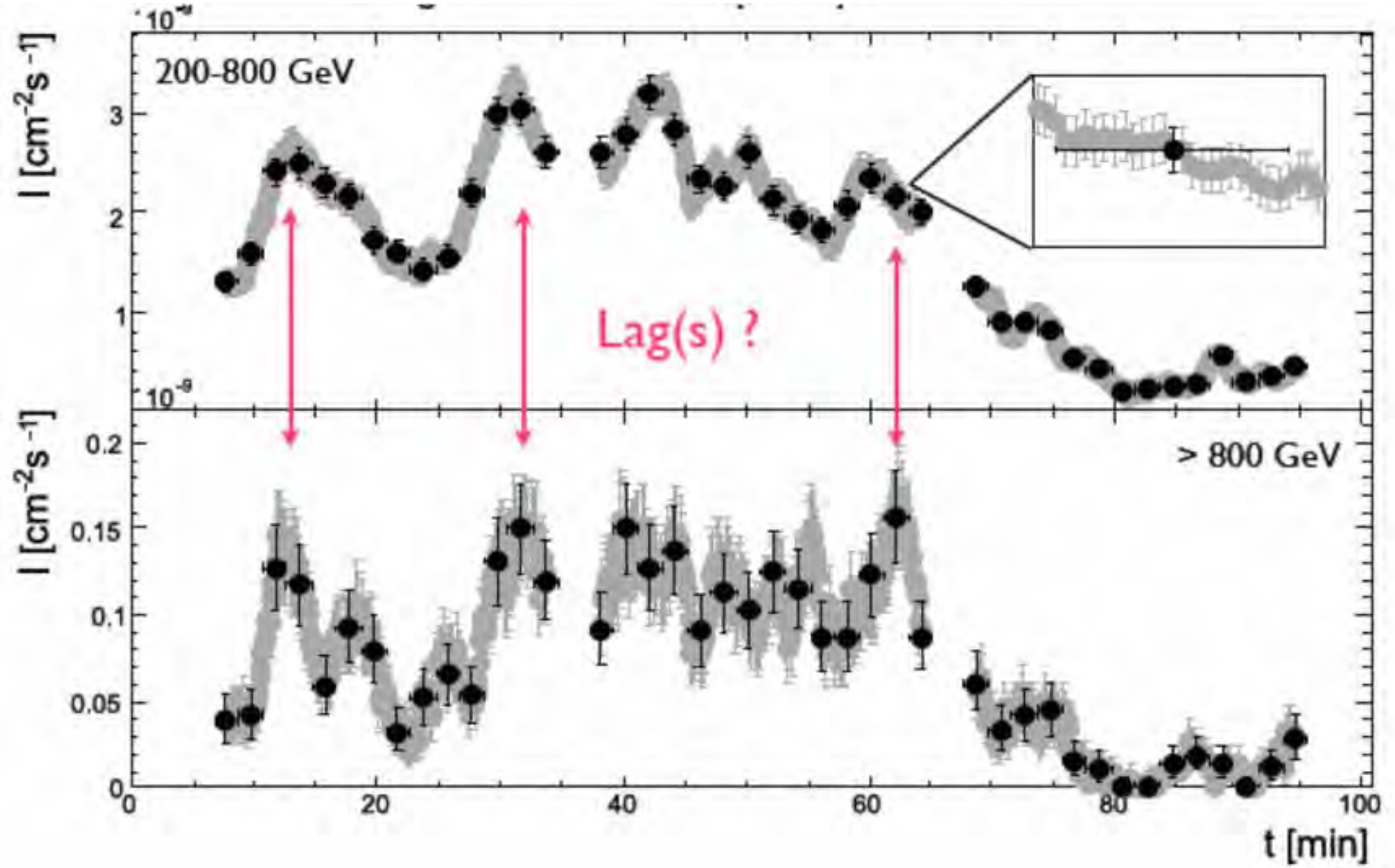


HESS PKS 2155
z = 0.116

July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min

$R_{BH}/c \sim 1...2 \cdot 10^4$ s

Tests of Lorentz violation: the name of the game



HESS, PKS 2155

Quite some interest on Mkn 501 flare by MAGIC…

$$v_\gamma \cong c\left(1+\xi\frac{E}{M_P}+\xi_2^2\frac{E}{M_P^2}+\ldots\right)$$

1st order

$$(\Delta t)_{obs} \cong \left(\frac{\Delta E}{E_{s1}}\right) H_0^{-1}\int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

MAGIC Mkn 501, PLB08
(with J. Ellis et al.)

$E_{s1} \sim 0.04\ M_P$ ($\xi \sim -25$)

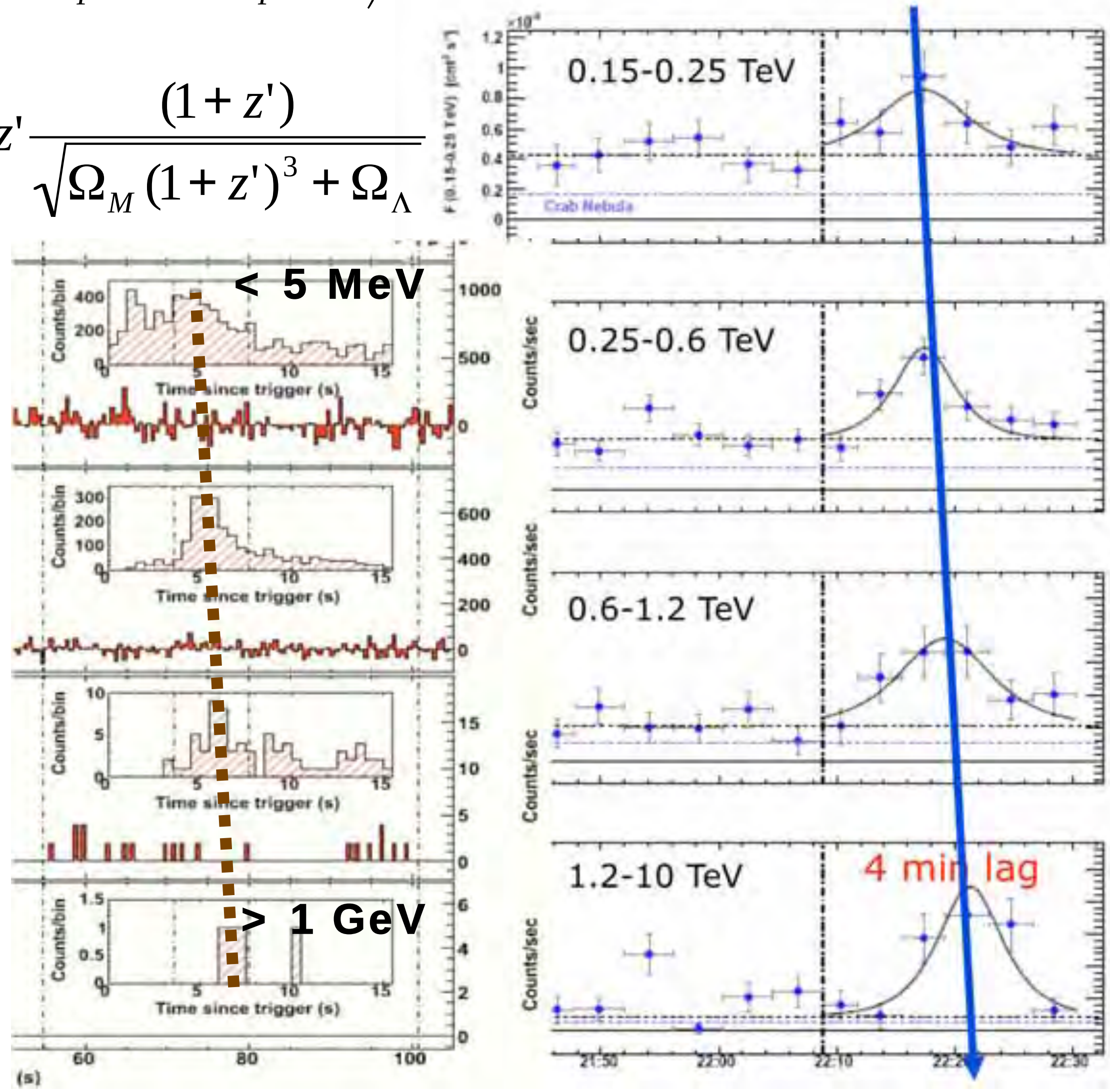
$E_{s1} > 0.02\ M_P$

HESS PKS 2155, PRL08

$E_{s1} > 0.06\ M_P$

GRB X-ray limits:

$E_{s1} > 0.11\ M_P$ (Fermi, but…)



LIV in Fermi vs. MAGIC+HESS

- GRB080916C at **z~4.2** : 13.2 GeV photon detected by Fermi **16.5 s** after GBM trigger. At 1st order

$$(\Delta t)_{obs} \cong \left(\frac{\Delta E}{E_{s1}}\right) H_0^{-1} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}} \quad K(z) \sim z$$

- The MAGIC result for Mkn501 at z= 0.034 is Δt = (0.030 +- 0.012) s/GeV; for HESS at z~0.116, according to Ellis et al., Feb 09, Δt = (0.030 +- 0.027) s/GeV
- Δt ~ (0.43 ± 0.19) K(z) s/GeV

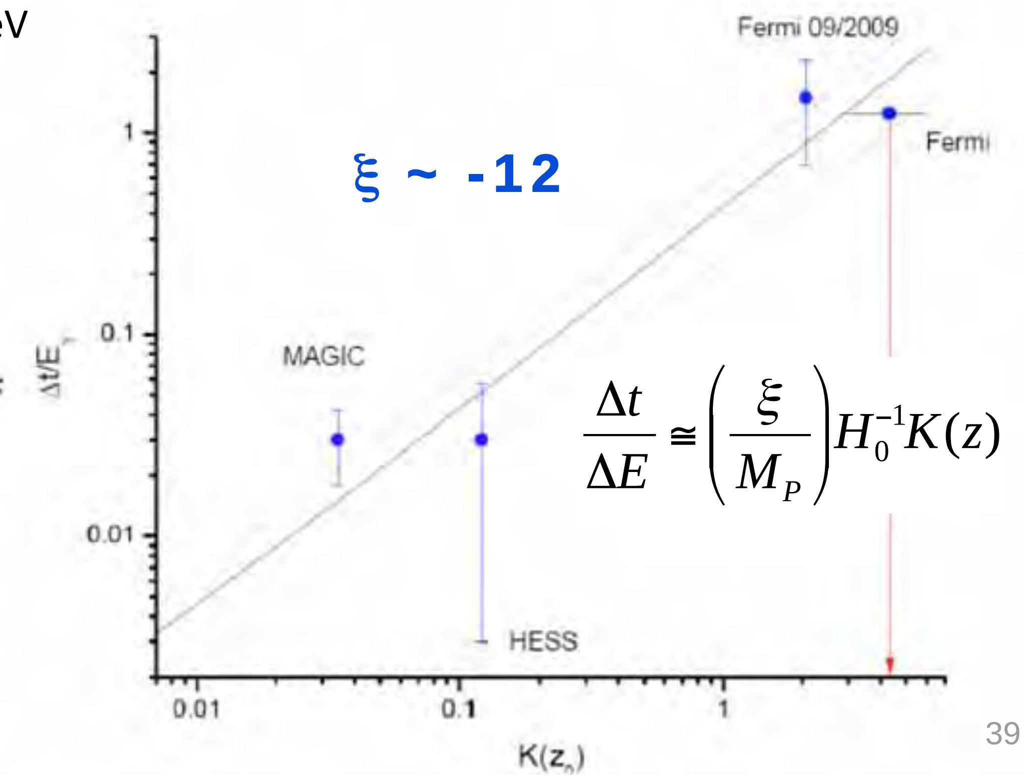
Extrapolating, you get from Fermi **(26 +- 11) s**

(J. Ellis et al., Feb 2009)

SURPRISINGLY CONSISTENT:

DIFFERENT ENERGY RANGE

DIFFERENT DISTANCE



$$\frac{\Delta t}{\Delta E} \cong \left(\frac{\xi}{M_P}\right) H_0^{-1} K(z)$$

BUT: Fermi GRB 090510 GRB 090902

- $z = 0.903 \pm 0.003$
- prompt spectrum detected, significant deviation from Band function at high E
- High energy photon detected: 31 GeV at T_o + 0.83 s [expected from Ellis & al. (12 ± 5) s]
- tight constraint on Lorentz Invariance Violation:
  - $E_{s1} = M_{QG} >$ several M_{Planck}

- $z = 1.8 \pm 0.4$
- one of the brightest GRBs observed by LAT
- after prompt phase, power-low emission persists in the LAT data as late as 1 ks post trigger: highest E photon so far detected: 33.4 GeV, 82 s after GBM trigger [expected from Ellis & al. (26 ± 13) s]
- much weaker constraints on LIV E_s

=> Fermi rules, and 1st order violations appear unlikely

2^{nd} order? Cherenkov rules!

$$(\Delta t)_{obs} \cong \frac{3}{2}\left(\frac{\Delta E}{E_{s2}}\right)^2 H_0^{-1}\int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}}$$

$E_{s2} > 6\ 10^{10}$ GeV ($\sim 10^{-9}\ M_P$) (HESS, MAGIC)

A no-loss situation:

if propagation is standard, cosmology with AGN

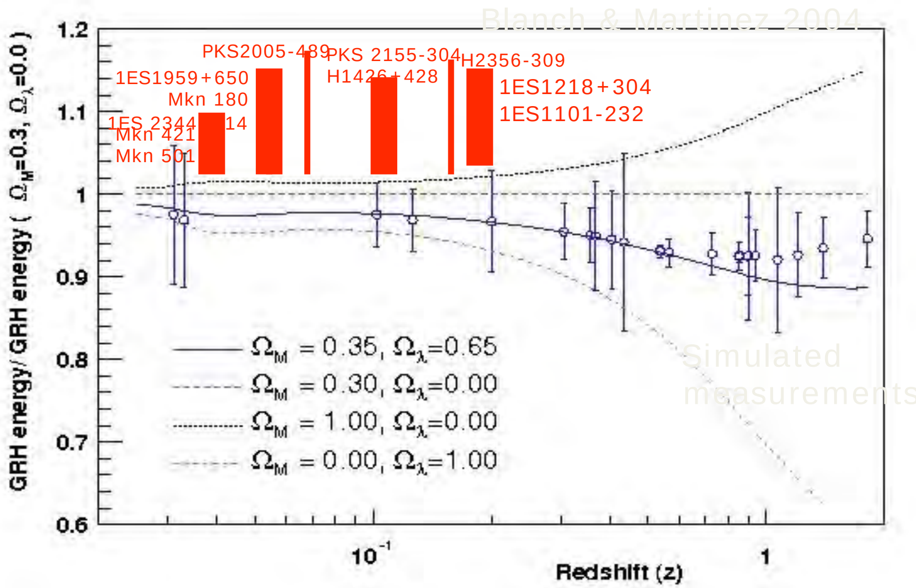
If propagation is standard, cosmology with AGN

GRH depends on the γ–ray path and there the **Hubble constant and the cosmological densities** enter => if EBL density and intrinsic spectra are known, the GRH might be used as a **distance estimator**

$$\frac{dl}{dz} = \frac{c}{H_0} \frac{1}{(1+z)\left[(1+z)^2(\Omega_M\, z+1) - \Omega_\Lambda\, z(z+2)\right]^{\frac{1}{2}}}$$

GRH behaves differently than other observables already used for cosmology measurements.

EBL constraints are paving the way for the use of AGN to fit Ω_M and Ω_Λ …

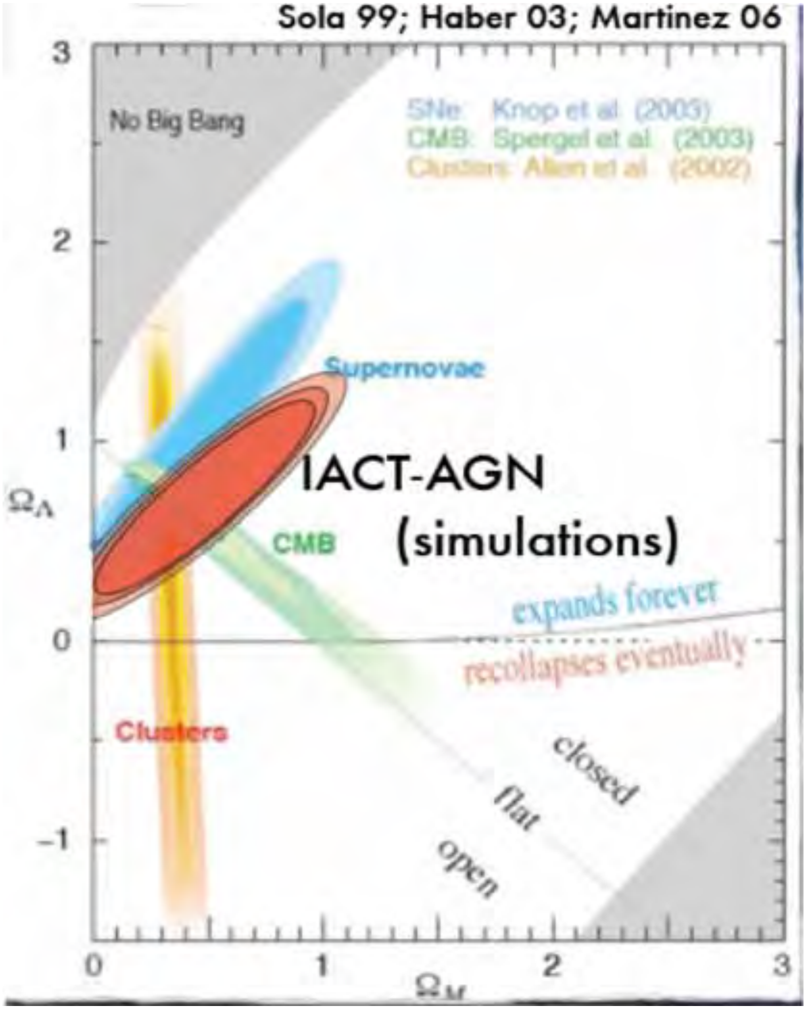


Determination of H_0, Ω_M , Ω_L

$$\tau(E,z) = \int_0^z dz' \frac{dl}{dz'} \int_0^2 dx \frac{x}{2} \int_{\frac{2m^2c^2}{Ex(1+z)^2}}^{\infty} d\varepsilon \cdot n(\varepsilon, z') \sigma\left[2xE\varepsilon(1+z)^2\right]$$

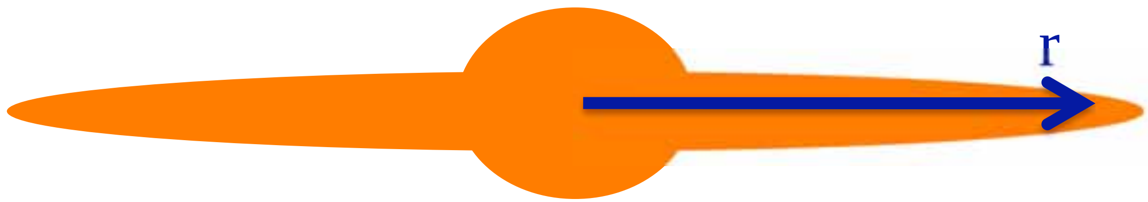
Using the foreseen precision on the GRH (distance at which $\tau(E,z)=1$) measurements of 20 extrapolated AGN at z>0.2, cosmological parameters can be fitted.

=> The $\Delta\chi^2$=2.3 2-parameter contour might improve by a factor 2 the 2004' Supernovae combined result !

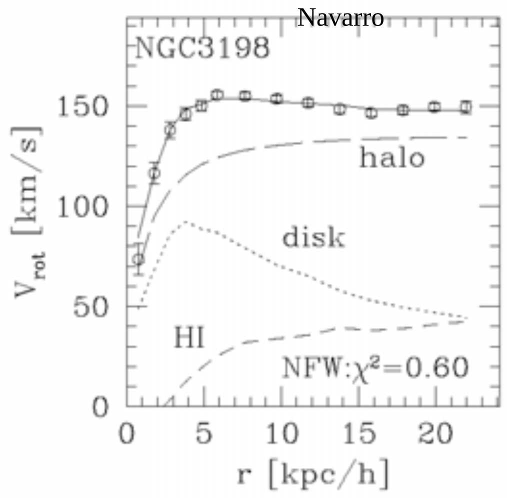


The Dark Matter Problem

Measure rotation curves for galaxies:



Begelman/
Navarro

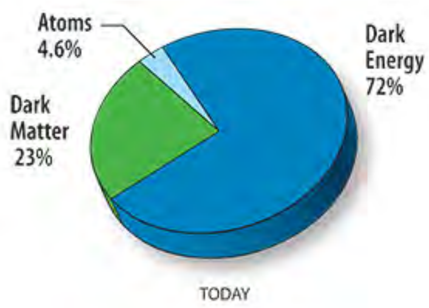


For large r, we expect:

$$G\frac{M}{r^2} = \frac{v^2(r)}{r} \quad \Rightarrow \quad v(r) \sim \frac{1}{\sqrt{r}}$$

we see: flat or rising rotation curves

Hypothesized solution: the visible galaxy is embedded in a much larger halo of Dark Matter (neutral; weakly interacting; mix of particles and antiparticles - in SUSY Majorana)



Famous Bullet Cluster

Which signatures for gamma detectors?

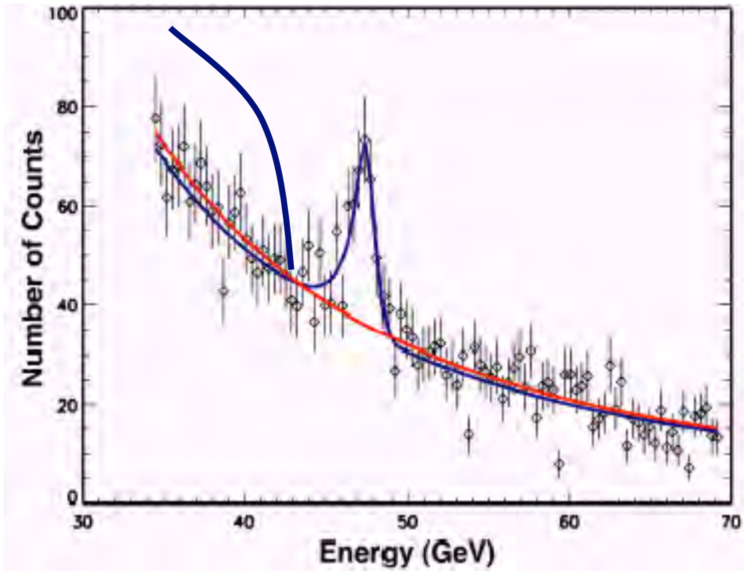
- Self-annihilating WIMPs, if Majorana (as the neutralino in SUSY), can produce:
  - Photon lines ($\gamma\gamma$, γZ)
  - Photon excess at E < m from hadronization
- Excess of antimatter (annihilation/decay)
- Excess of electrons, if unstable

$$\Phi \propto \sigma \frac{\langle v \rangle}{m^2} \int_{los} \rho^2 \, dl$$

from particle physics

from astrophysics

Look to the closest point with M <<L



Many Places to Seek DM!

Galactic Center

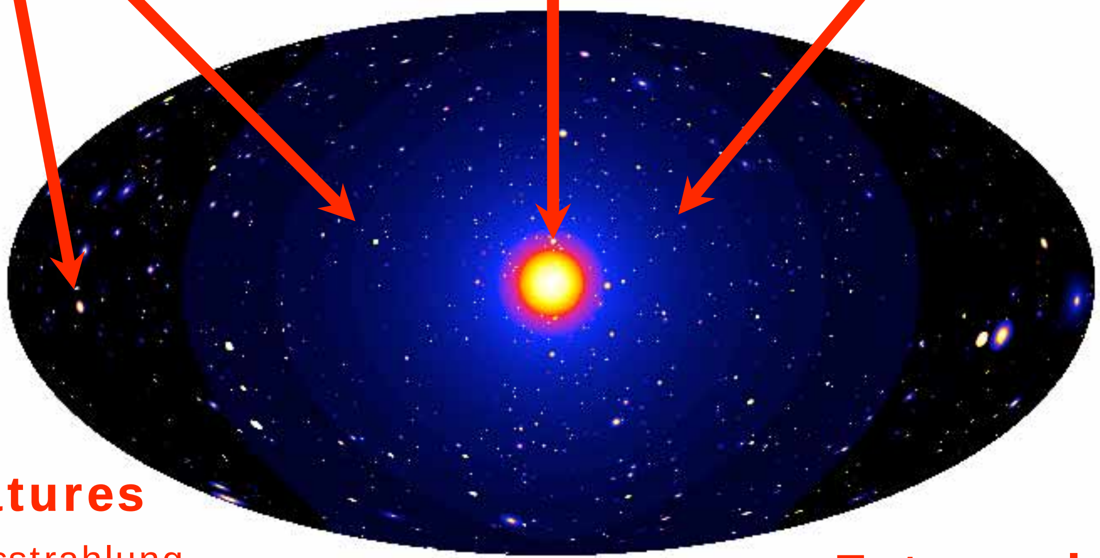
Good statistics but source confusion/diffuse background

Satellites

Low background and good source id, but low statistics, astrophysical background

Milky Way Halo

Large statistics but diffuse background



All-sky map of simulated gamma ray signal from DM annihilation (Pieri et al 2006)

Spectral Features

Lines, endpoint Bremsstrahlung,...

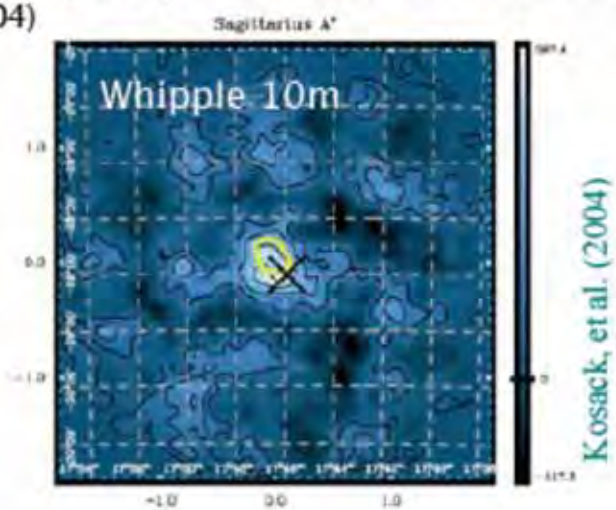
No astrophysical uncertainties, good source Id, but low sensitivity because of expected small BR

Extra-galactic

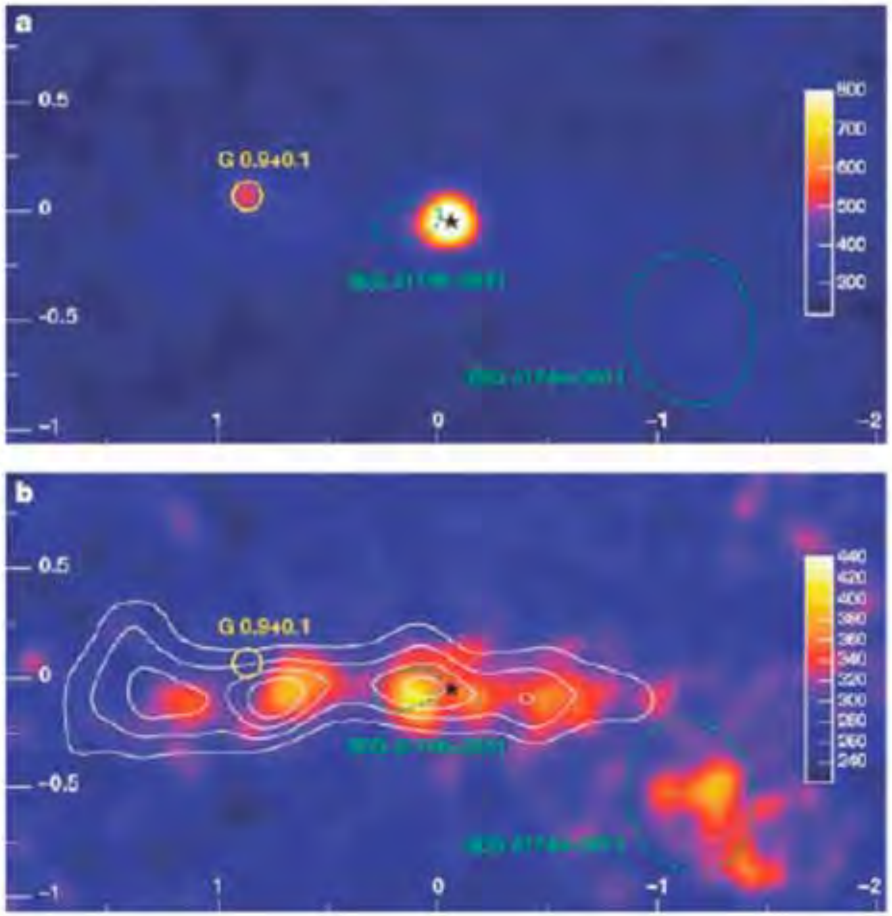
Large statistics, but astrophysics, galactic diffuse backgrounds

Results from GC

- **EGRET:** 3EG J1746-2851 (Hartman et al. 1999)
- **Whipple 10m (1995-2003, LZA)** - Evidence for GC at 3.7 std. dev., flat spectrum source (Kosack et al. ApJ, 608, L97 2004)



- **CANGAROO-II (2001-2002)** - steep spectrum source ($dN/dE \sim E^{-4.6}$) - not same as Whipple/HESS source (Tsuchiya et al., 2004, ApJ, 606)
- **H.E.S.S. (2004-2006)** - Now >60 std. dev, $dN/dE \sim E^{-2.1}$ cutoff ~15 TeV, no variability, within 15 arcsec Sgr A*?, PWN? diffuse emission from molec. clouds $dN/dE \sim E^{-2.3}$ (Aharonian et al., 2004, A&A, 425, L13; 2006, Nature, 439, 695)
- **MAGIC (2004-2005, LZA, 25hr)** - 7.3 std. dev, conf. HESS spectrum (Albert et al., 2006, 638, L101)

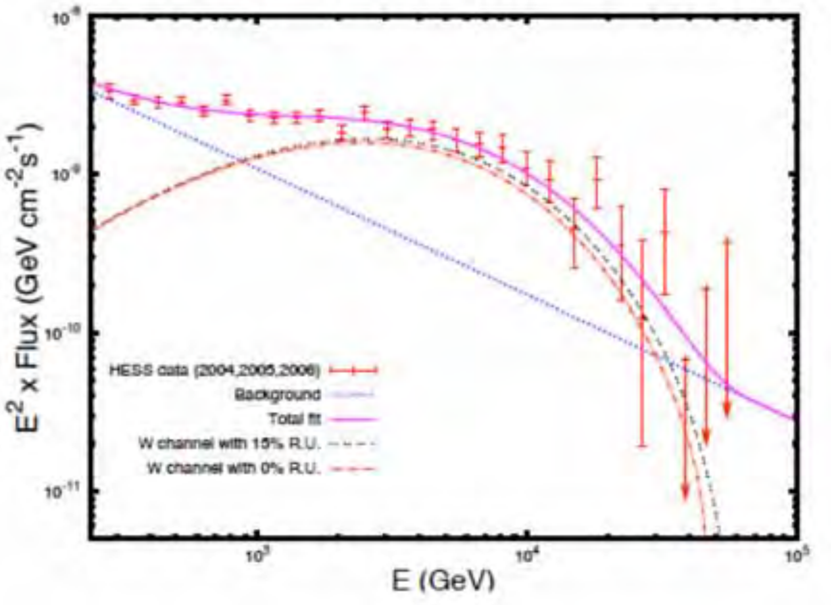


HESS GC region (Aharonian et al., 2006, Nature 439, 695)

Large Astrophysical Backgrounds for DM Search!

(Buckley 2011)

γ-ray detection from the GC



- detection of γ-rays from GC by Cangaroo, Whipple, HESS, MAGIC

- hard $E^{-2.2}$ spectrum
  fit to χ-annihilation continuum
  spectrum leads to: M_χ > 14 TeV

  - other interpretations possible (probable)

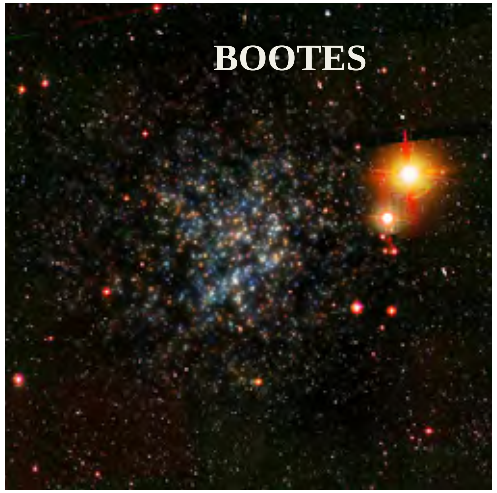
  Galactic Center: very crowded sky region, strong exp. evidence against cuspy profile

no real indication of DM…

The spectrum is featurless!!!

One of the focuses: dwarf Spheroidals

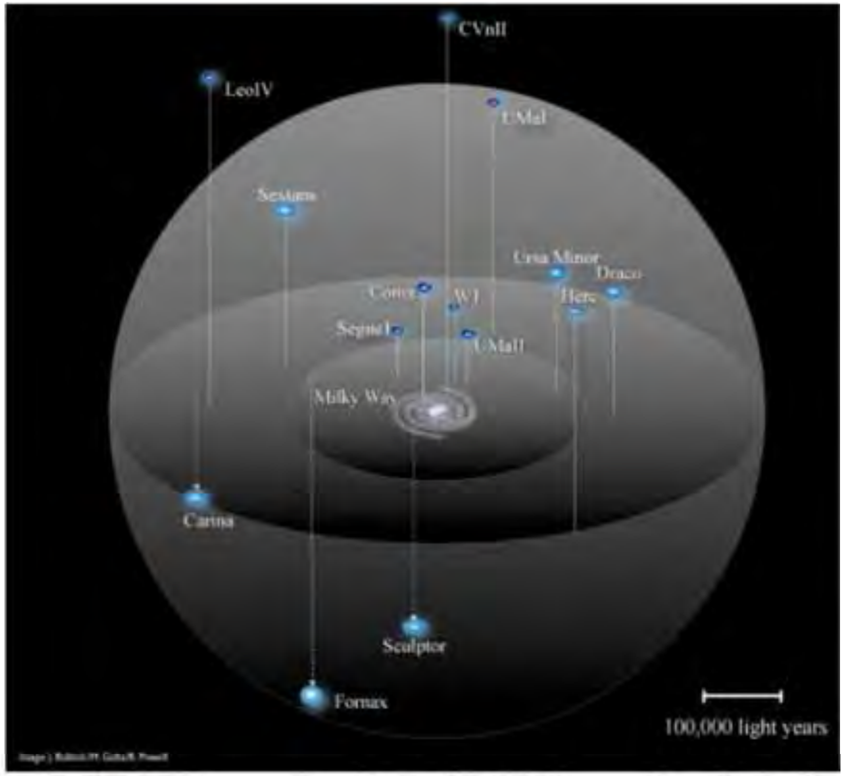
- Dwarf Spheriodal Galaxies (dSphs) are approx. “spherical” collections of stars orbiting the Milky Way, (?) held together by DM (?)
- Large Optical Surveys (*eg.* SSDS, HST,...) has enabled astronomers to identify 20 or more such objects.
- Mass–to-Light ratio (indicative of DM content) often > 100 and some > 1000!
- Ideal locations to search indirect gamma rays signs from Annihilation or Decay of DM



dSph

Milky Way satellites Sagittarius, Draco, Segue1, Willman1, Perseus, …

- proximity (< 100 kpc)
- no central BH (which may change the DM cusp)
- large M/L ratio (low baryonic content)
- **No signal for now…**



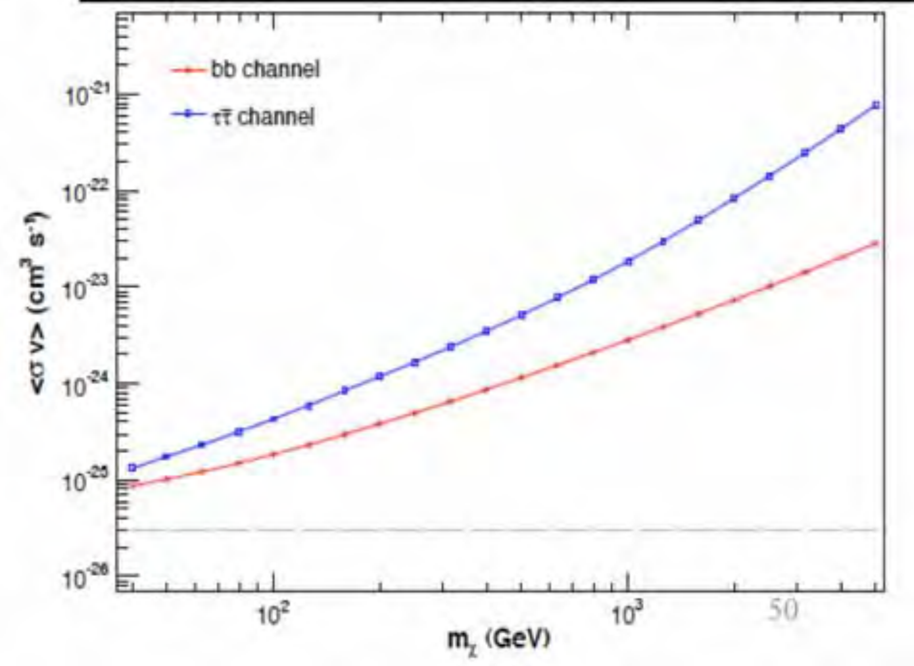
Results dominated by Fermi observations of Segue1

in the Leo constellation at ~23 kpc from the Sun

luminosity is ~300x the Sun, M/L ~3400

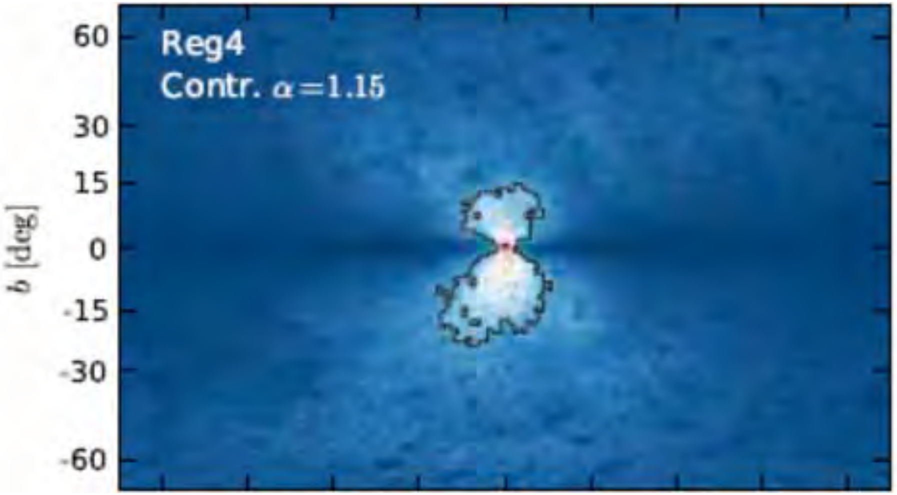
small improvement by stacking

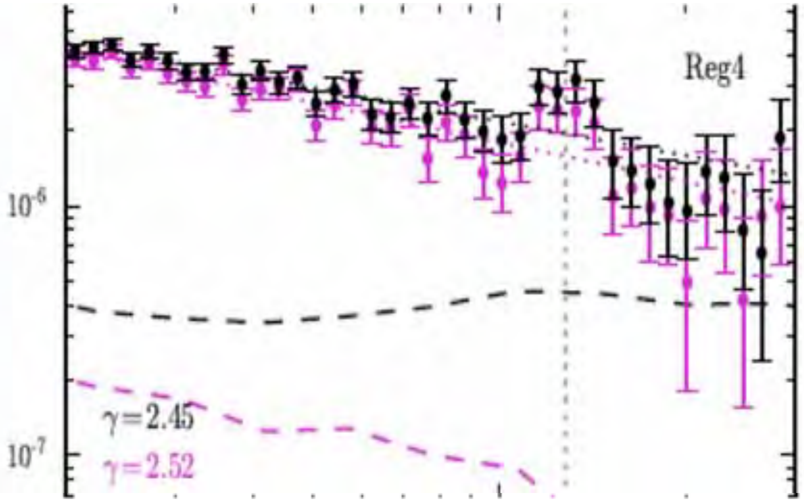
- Still a factor of >4 larger than a possible signal, even at low mass and in the most favorable assumptions
  - Majorana WIMP, DM profiles
- What could improve it?
  - A “boost” of ρ^2 given by an anomalous DM concentration in subhalos
  - At 100 GeV, an improvement by a factor of 30 in sensitivity



Data-driven line searches (1)

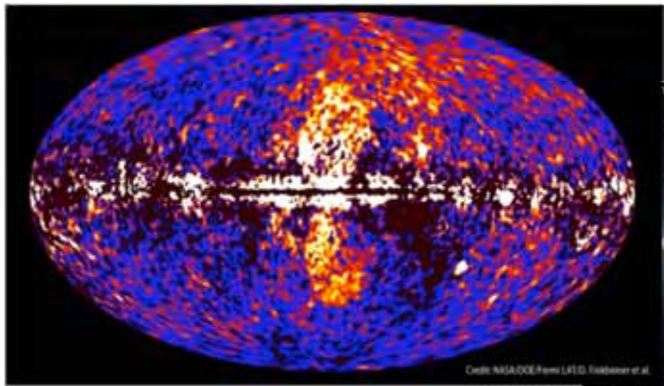
- Very recently, one paper claims a positive signal (a ~4σ photon excess at ~130 GeV from Fermi data)
  - C. Weniger, arXiv:1204.2797

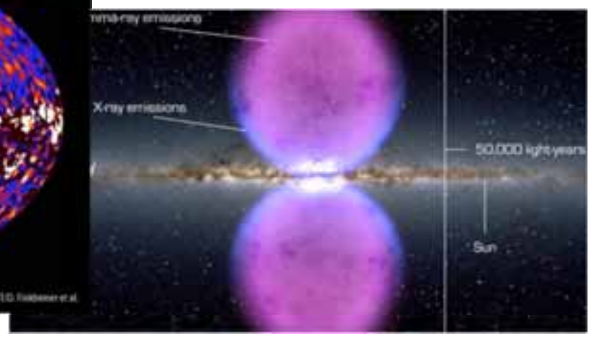




Selection of the region b(i)ased on data

Large overlapping with The Fermi "bubbles"





Data-driven line searches (2)

- Confirmed by an independent analysis
  - Tempel+, arXiv:1205.1045

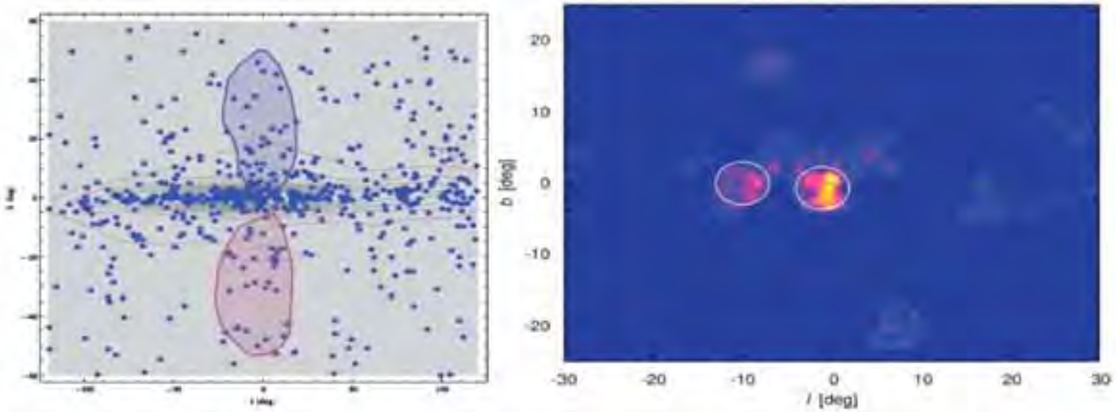
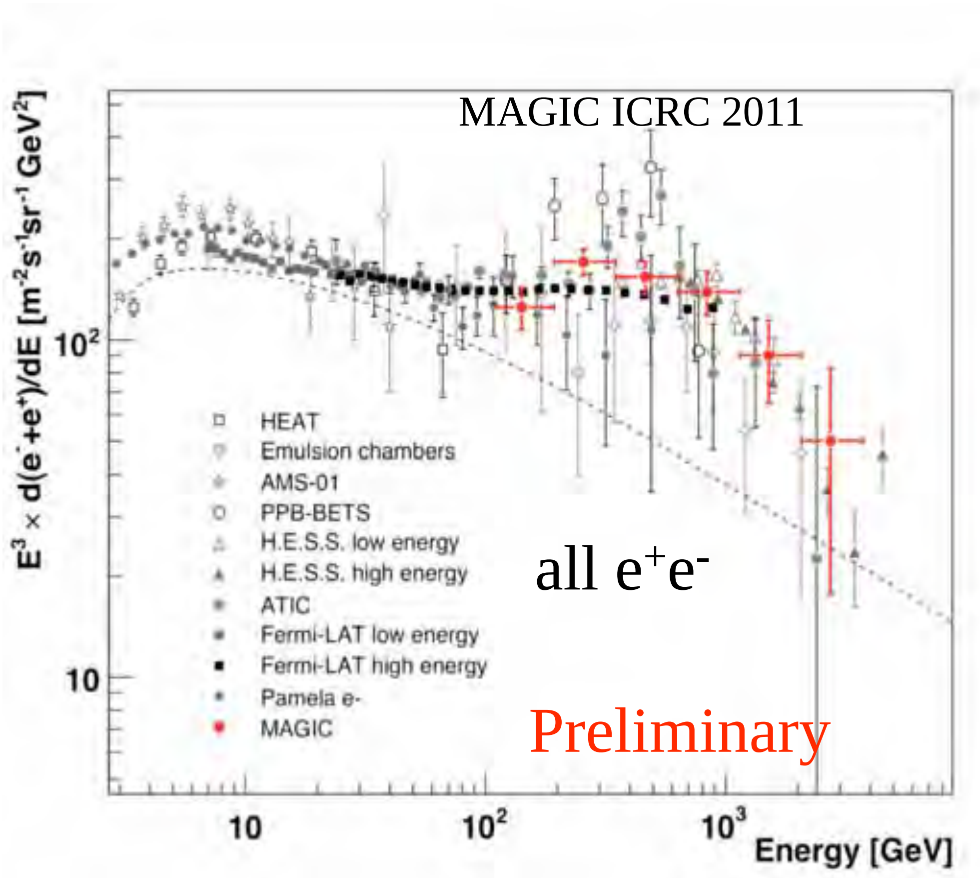


Figure 2: *Left: a Fermi "photograph" of our Galaxy in gamma-rays with the energy* 120 GeV $< E_\gamma <$ 140 *GeV. Fermi data is shown with blue dots. Fermi bubbles are also shown for illustration. Right: intensity of the* 120 GeV $< E_\gamma <$ 140 *GeV photons in the Galaxy. The white circles denote the signal regions that provide the excess with highest statistical significance; grey circles denote other regions showed in Table 1; green dot mark the assumed centre of the Galaxy.*

Not confirmed by a "blind" line search by the official Fermi team on May 14 (But warning: it's a different thing)

- Perspects from IACT: bad. Fermi: wait several years. LHC?

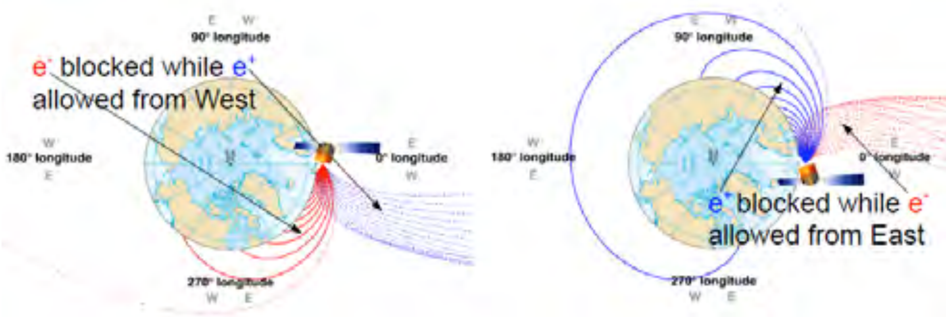
Cosmic rays: the ATIC anomaly



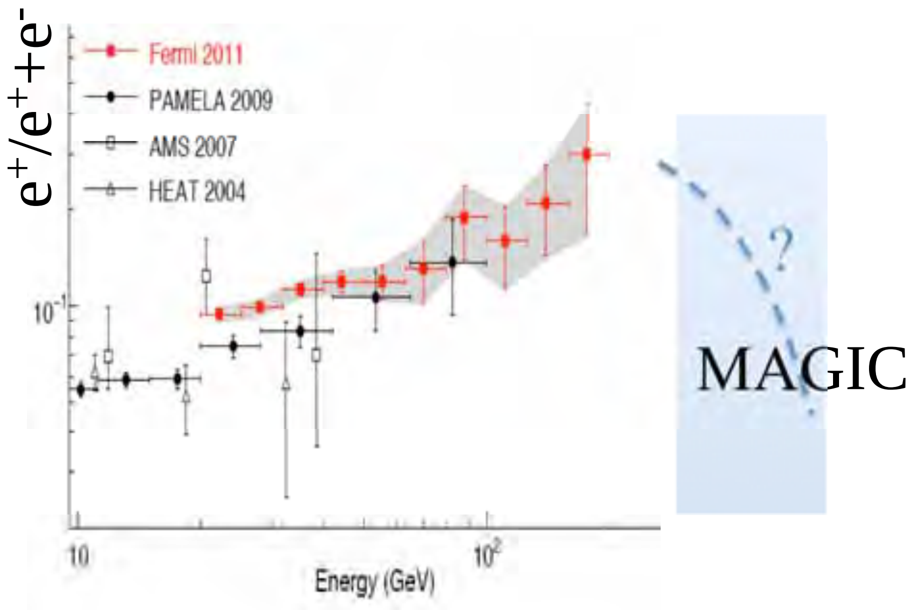
No peaks;

a possible excess might have standard/astrophysical explanations

Cosmic rays: the PAMELA anomaly



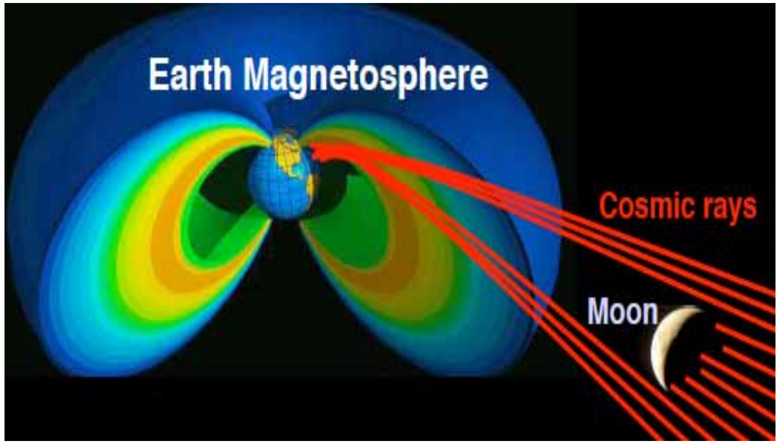
Unexpected increase in e^+/e^- ratio (PAMELA) confirmed by Fermi @ ICRC 2011:



Moon shadow observation mode developed for the MAGIC telescopes [MAGIC ICRC 2011]

probe e+/e- ratio at 300-700 GeV

sensitivity (50h): 300-700GeV: ~4.4% Crab measurement possible in few years



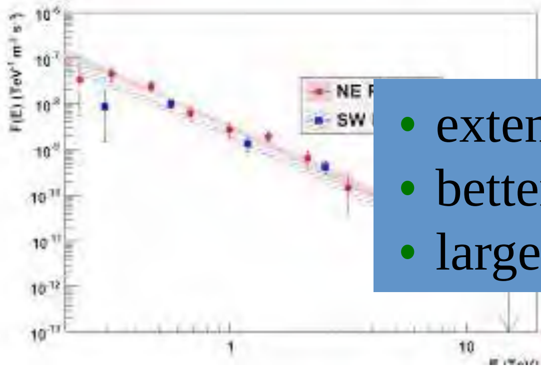
DM: interplay with accelerators

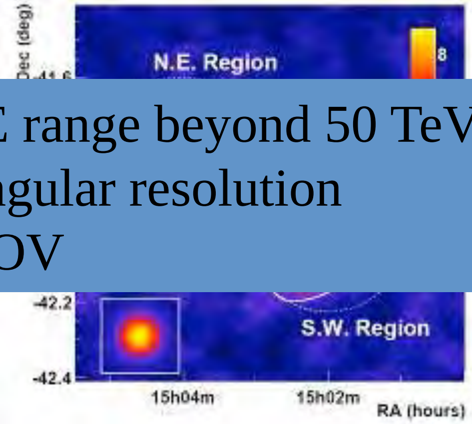
- LHC may find candidates but cannot prove that they are the observed Dark Matter, nor localize it
- *Direct searches (nuclear recoil) may recognize local halo WIMPs but cannot prove the nature and composition of Dark Matter in the sky*

- LHC reach limited to some 200-600 GeV; IACT sensitivity starts at some ~200 GeV (should improve)

A wish list for the future

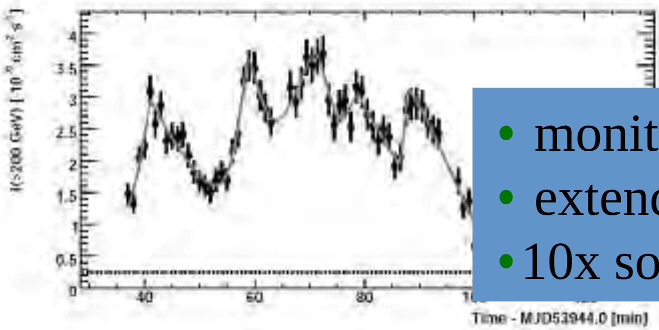
- Galactic sources & CR





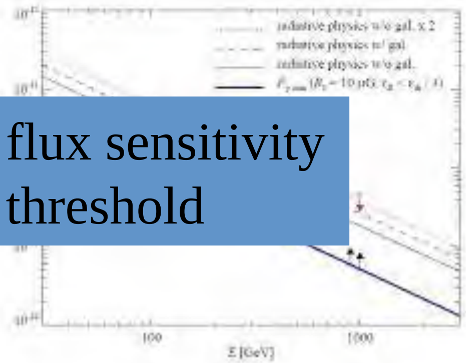
- extend E range beyond 50 TeV
- better angular resolution
- larger FOV

- AGN & gamma prop.



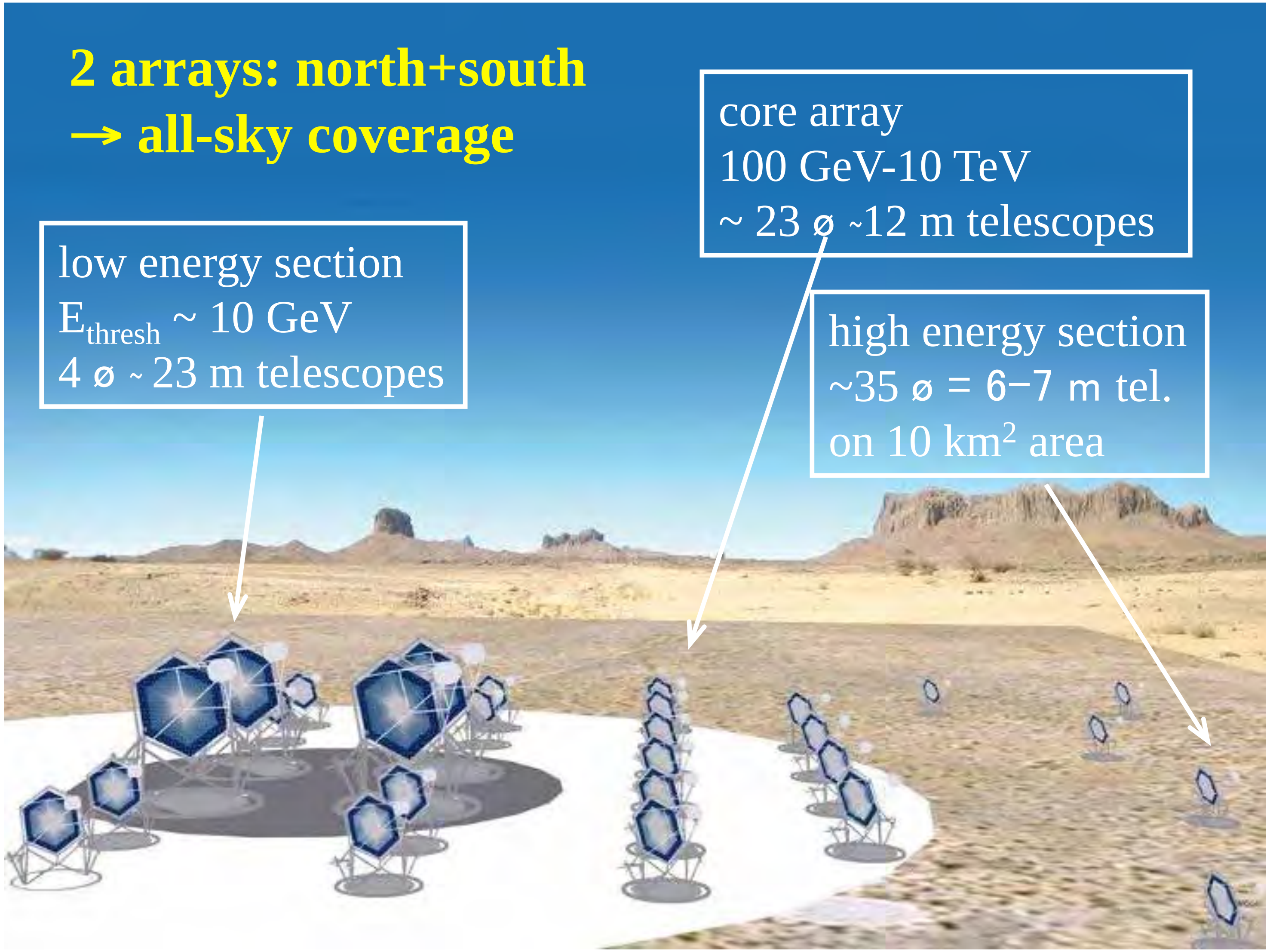
- monitor many objects simult.
- extend E range under 50 GeV
- 10x sources

- New particles, new phenomena
  - dark matter and astroparticle physics

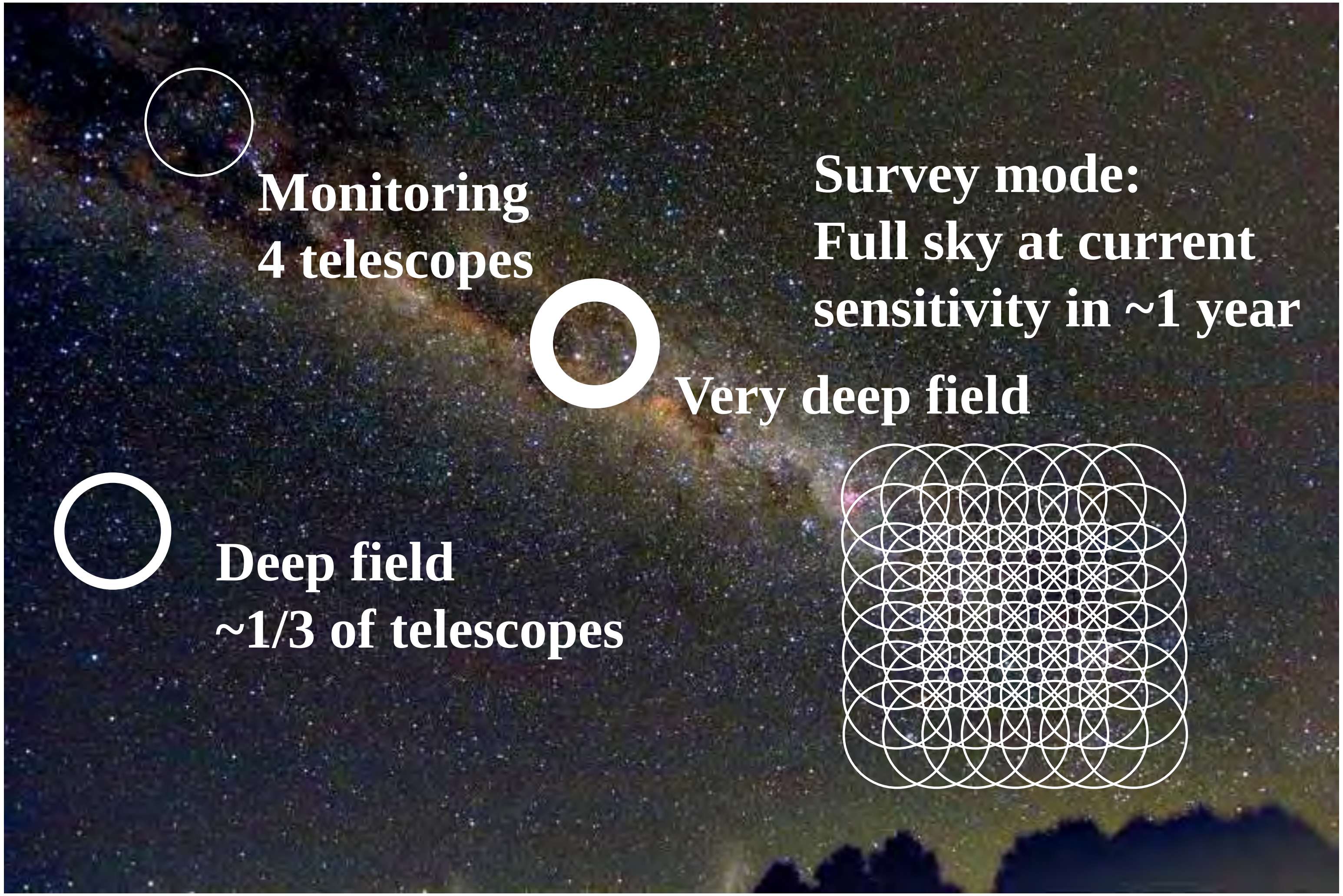


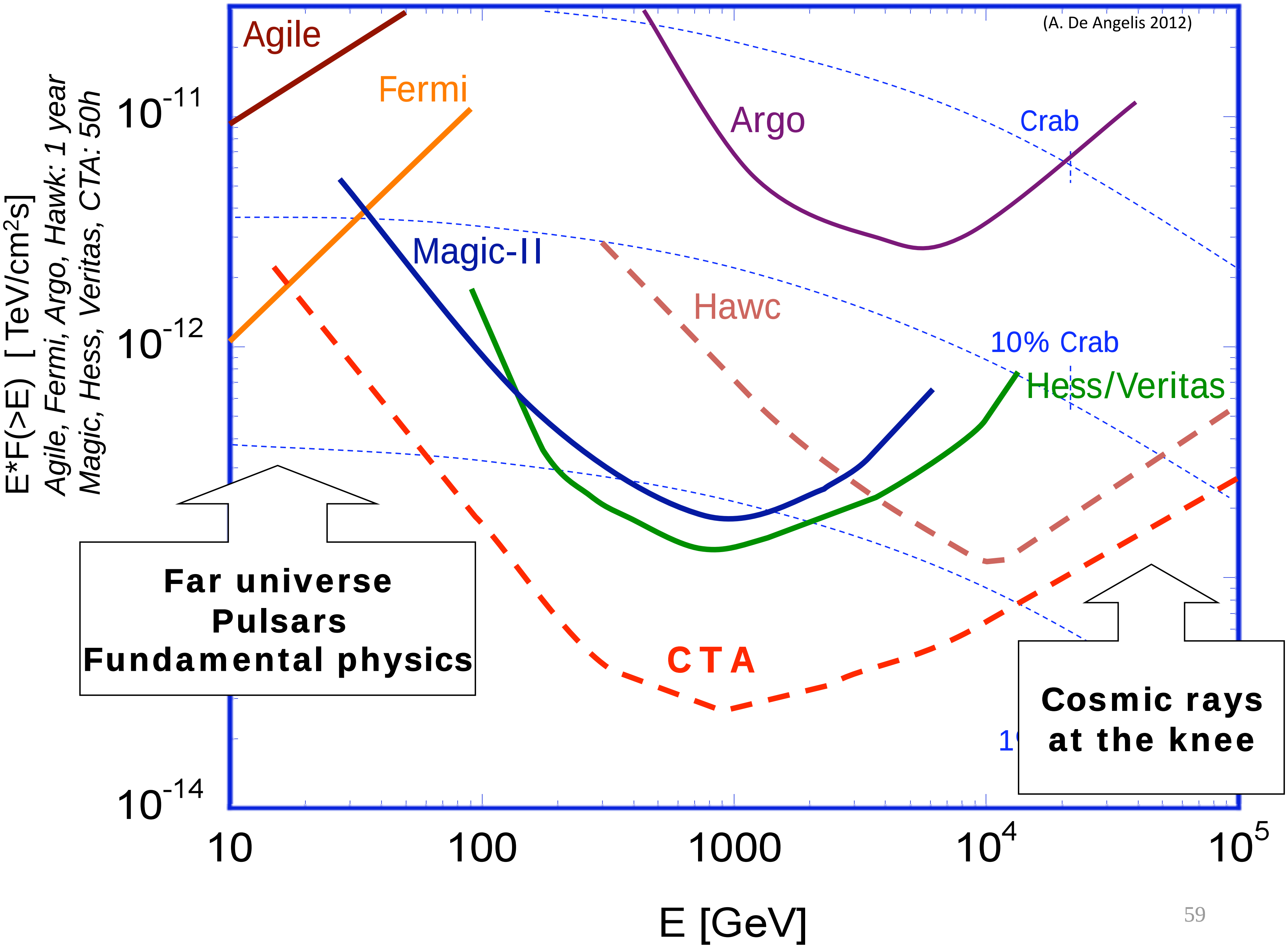
- better flux sensitivity
- lower threshold

The CTA concept (a possible design)



CTA operation modes





(A. De Angelis 2012)
Agile
Fermi
Argo
Crab
Magic-II
Hawc
10% Crab
Hess/Veritas
CTA
Far universe
Pulsars
Fundamental physics
Cosmic rays
at the knee
E*F(>E) [TeV/cm²s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h
10^{-11}
10^{-12}
10^{-14}
10
100
1000
10^4
10^5
E [GeV]

Relevance to high energy physics

- Physics
  - Energy: TeV energy scale (particle acceleration, elementary processes in the Universe)
  - Evolution of the Universe
  - Fundamental physics
    - Search for cosmological Dark Matter
    - Axion-like particles and new particles
    - Probe Quantum gravity (space time structure of vacuum) – close to the Planck Scale
  - Hadronic interactions (Gamma / Hadron separation)
  - Synergy with neutrino detectors

- Cutting edge technologies developed in HE physics
  - High QE advanced photodetectors, HPDs, SiPMs
  - Analogue signal transmission via optical fibers
  - Readout system 2GHz ultra fast analogue ring sampler
  - Ultra fast trigger system
  - Large data flow, massive computing (GRID computing)

Summary

- Clear interplay between VHE (γ) astrophysics and fundamental physics; this model of cooperation has worked well, and can work well in the future
  – We are confident that this exchange between complementary worlds will be useful, as history of particle physics demonstrated
- *Cosmic Rays:*
  – *SNR as galactic sources established*
    - *Astronomy with charged CR is difficult*
    - *Astronomy with neutrinos will be difficult*
    - *VHE photons can be the pathfinder*
- Still no detection of DM
  – The information from no detection is not as good as for accelerators
- A few clouds might hide new physics
  – Photon propagation
- Rich fundamental science (and astronomy/astrophysics) from gamma rays
  – HEA is exploring regions beyond the reach of accelerators
  – A “simple” extension of present detectors is in progress: CTA

BACKUP

Origin of V(HE) Cosmic Rays

- Supernovae may be source of particles up to $>10^{15}$ eV
  - Nuclei receive energy from the shock wave of the supernova explosion
- The sources for ultrahigh cosmic rays are extragalactic: probably, AGN (and GRB?)
- Galactic (~1000 nG) and extragalactic (~0.1 nG?) fields make it difficult to observe directly the sources of CR
  - Gamma rays?

Marvel 1961

- Remember: despite the opinion of the Fantastic 4, only ~1%-0.1% of the cosmic rays are gammas…
- (In 1998, the Human Torch called his son "Cosmic Ray" in memory of that event)

Connection gamma/CR

- Study of target-accelerator systems: pinpointing sources of cosmic rays up to the knee
  - New "fresh" cosmic rays interacting with matter near the source OR…
- pp -> nπ^0 -> 2nγ

  Secondary γ -rays have ~ 1/10 of the energy of the primary p

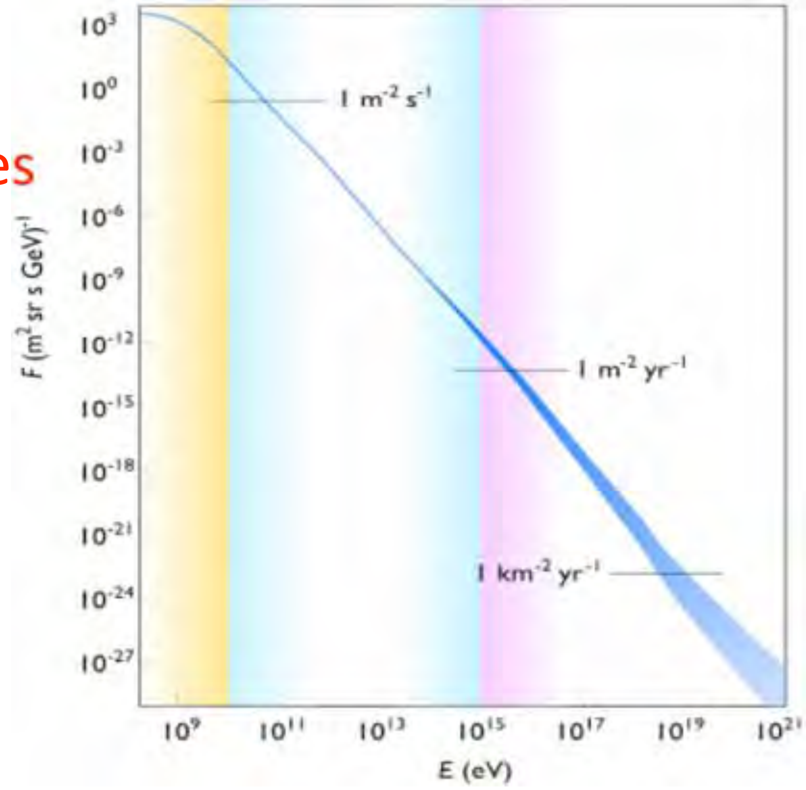
$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{dN_p}{dE_p} \otimes D\left(x = \frac{E_\gamma}{E_p}\right)$$

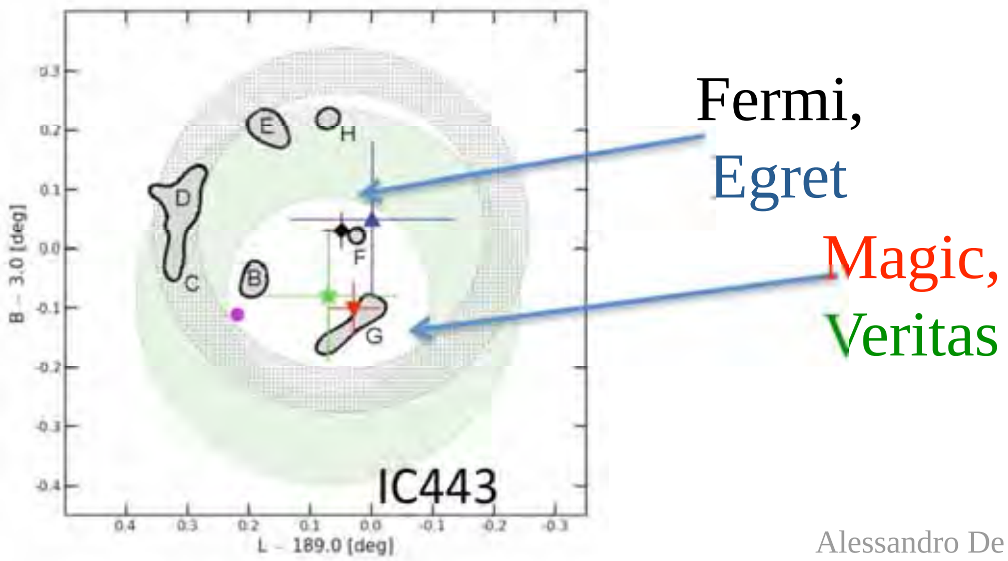
- For a power-law proton distribution the γ -ray distribution is again a power law with the same spectral index
  - This property should not be misinterpreted in the sense of a delta-function approximation: in general the γ -ray spectrum at energy Eγ does not trace the proton spectrum at energy Ep/f.
    - any feature in the proton spectrum will reappear smoothed in the γ -ray spectrum (e.g., an exponential cutoff in the proton spectrum, exp(−Ep/E_{cut}), is transformed into a sub-exponential, exp[−(16Eγ /E_{cut})$^{1/2}$]

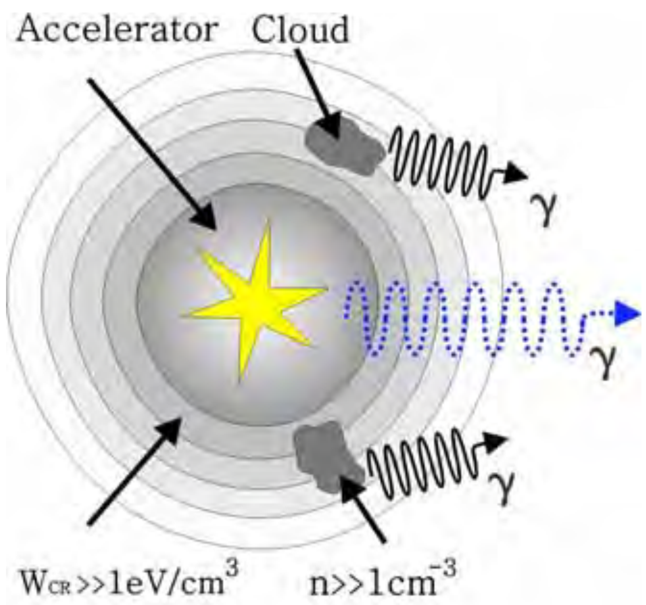
Sources of CR up to the knee

Cherenkov telescopes & gamma satellites

- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004)
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)

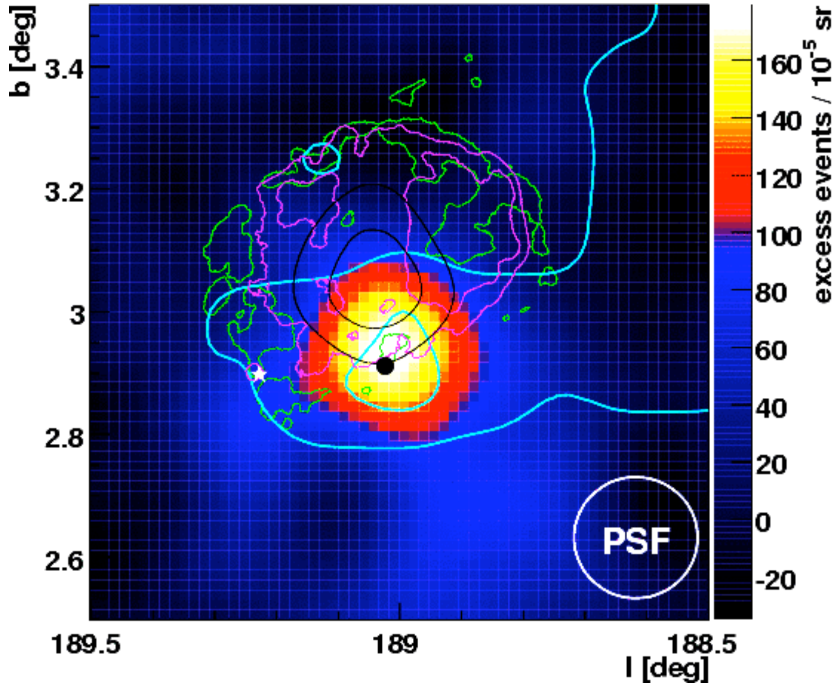


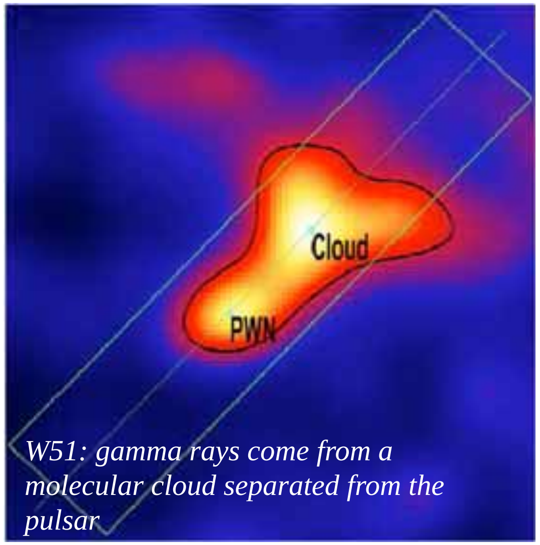




Molecular clouds close to IC 443, W51

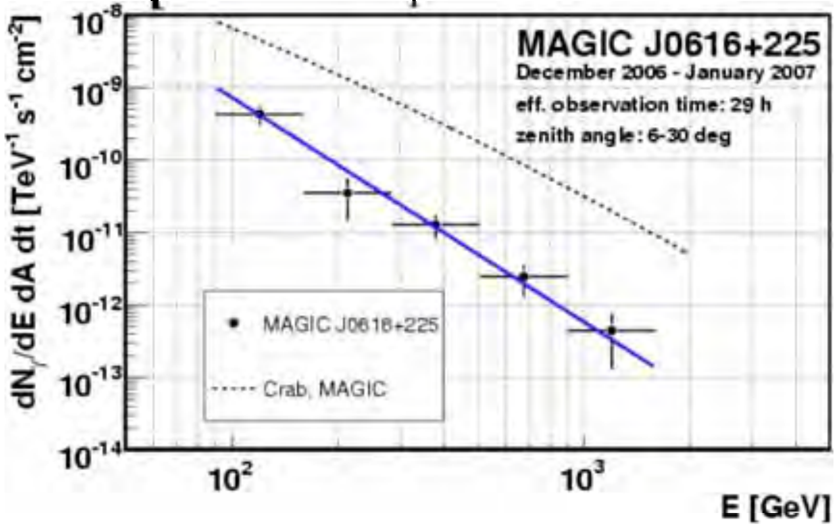
- ^{12}CO emission line 2001 (cyan line)
- contours of 20 cm VLA radio data from Condon et al. (1998) (green)
- 1720 MHz OH maser indication for a shock in a high matter density environment (black point)
- X-ray contours from Rosat (purple) (Asaoka & Aschenbach 1994)
- Gamma –ray contours from EGRET (Hartman et al. 1999) (black)
- g-ray excess coincides with cloud





W51: gamma rays come from a molecular cloud separated from the pulsar

[Albert et al. ApJ 664L 87A 2007

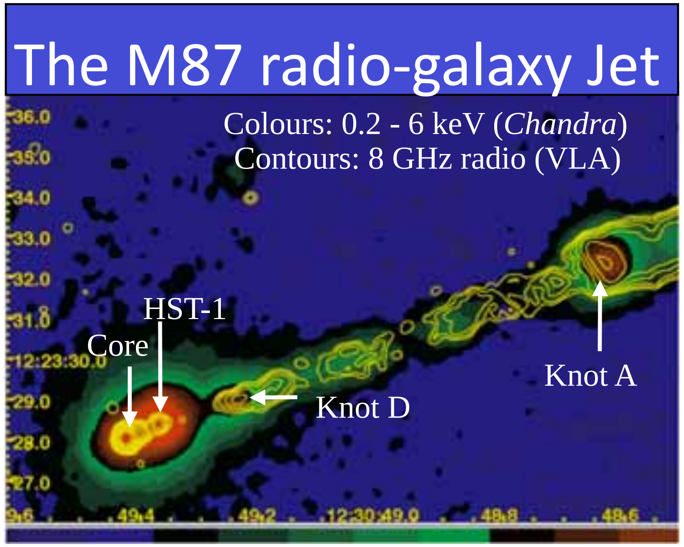


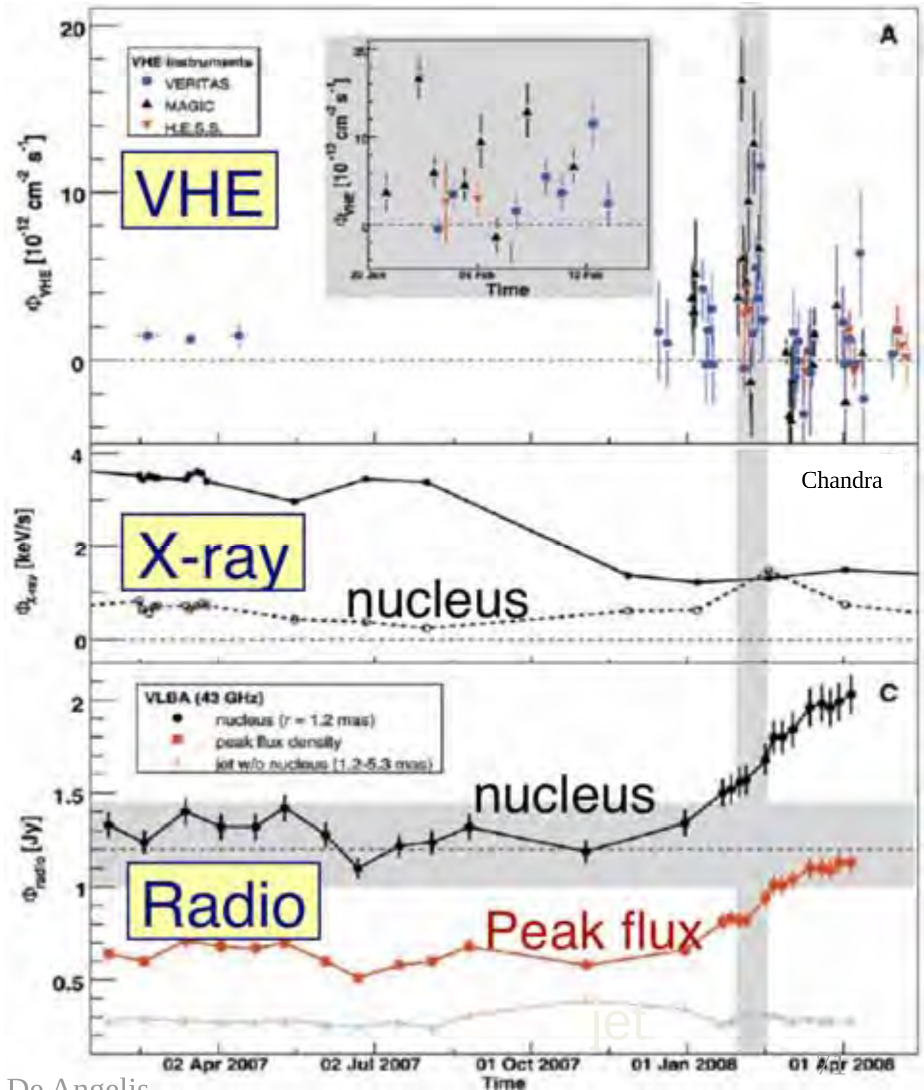
More on morphology

More on SED

Orphan flares?

Extragalactic sources: situation less clear (Auger?)
Joint HESS-MAGIC-VERITAS campaign on M87 (Science 2009)

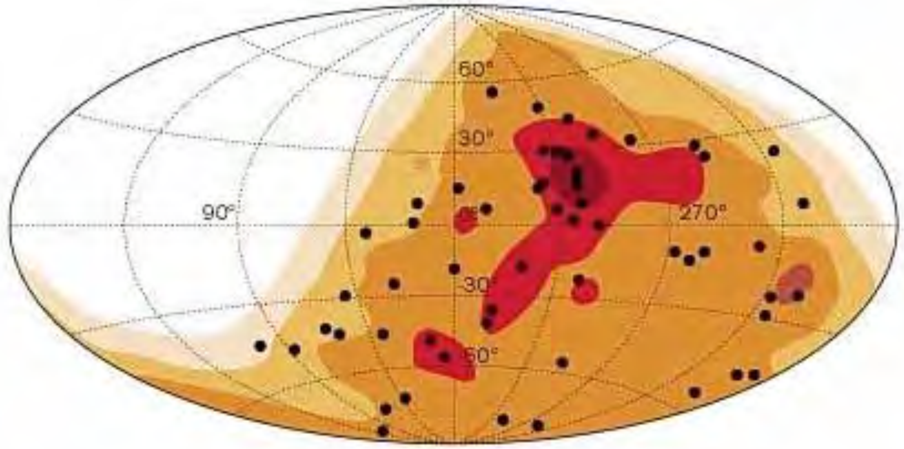


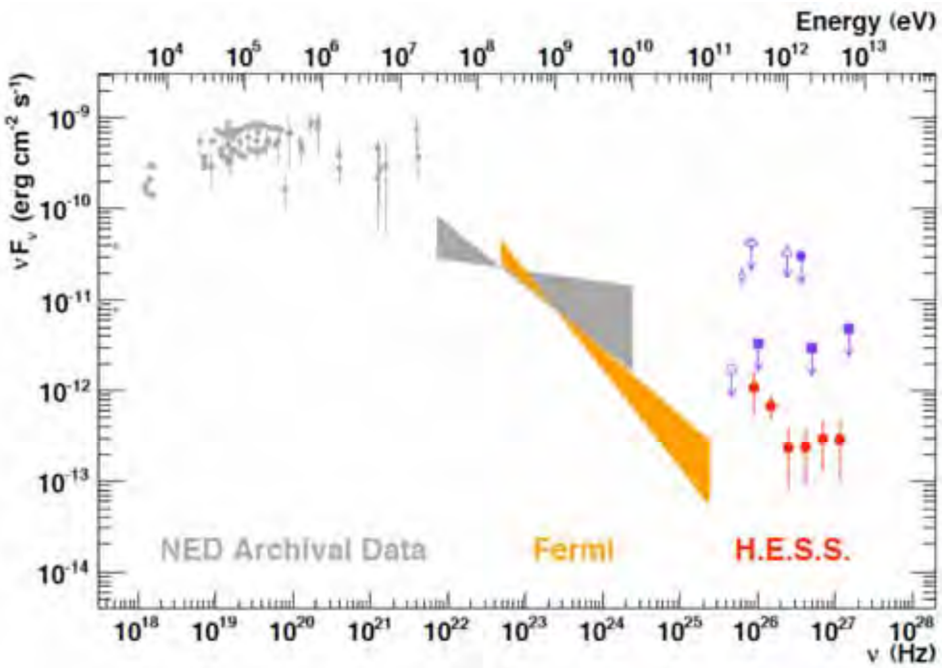


- Al ~60 Mly
- Shared monitoring HESS, MAGIC VERITAS
- Confirmation of day-scale VHE variability
- Correlation with the nucleus in X & Radio.
- Evidence of central origin of the VHE emission (60 Rs to the BH)

Cen A

- Located at a distance of ~13 Mly, the best candidate as a CR emitter from Auger
- Very faint VHE gamma-ray emitter (HESS 2009)





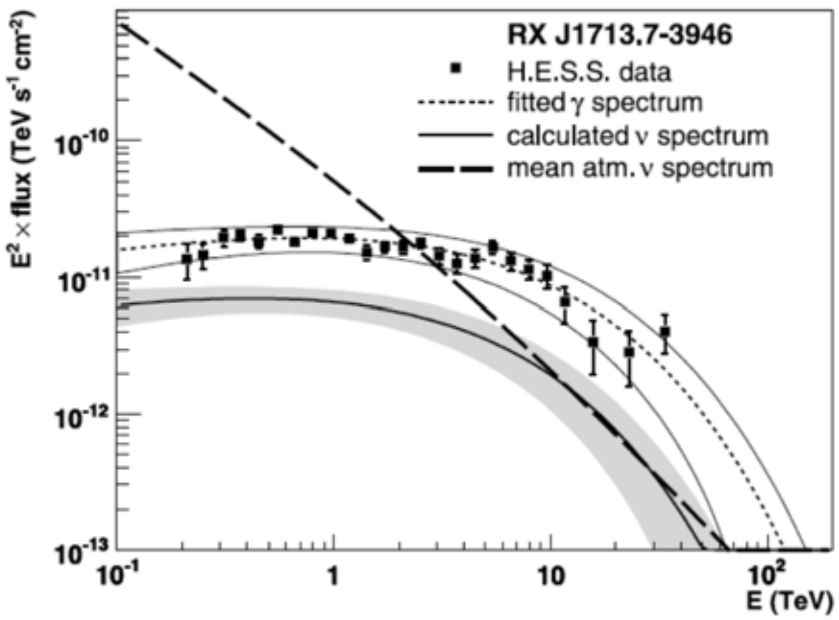
CR: clear synergy with neutrino detectors

- Smoking gun would be a correlation of VHE CR (difficult: magnetic fields) or a neutrino signal
- Many model uncertainties present in the gamma/p relation disappear when studying gamma/neutrino

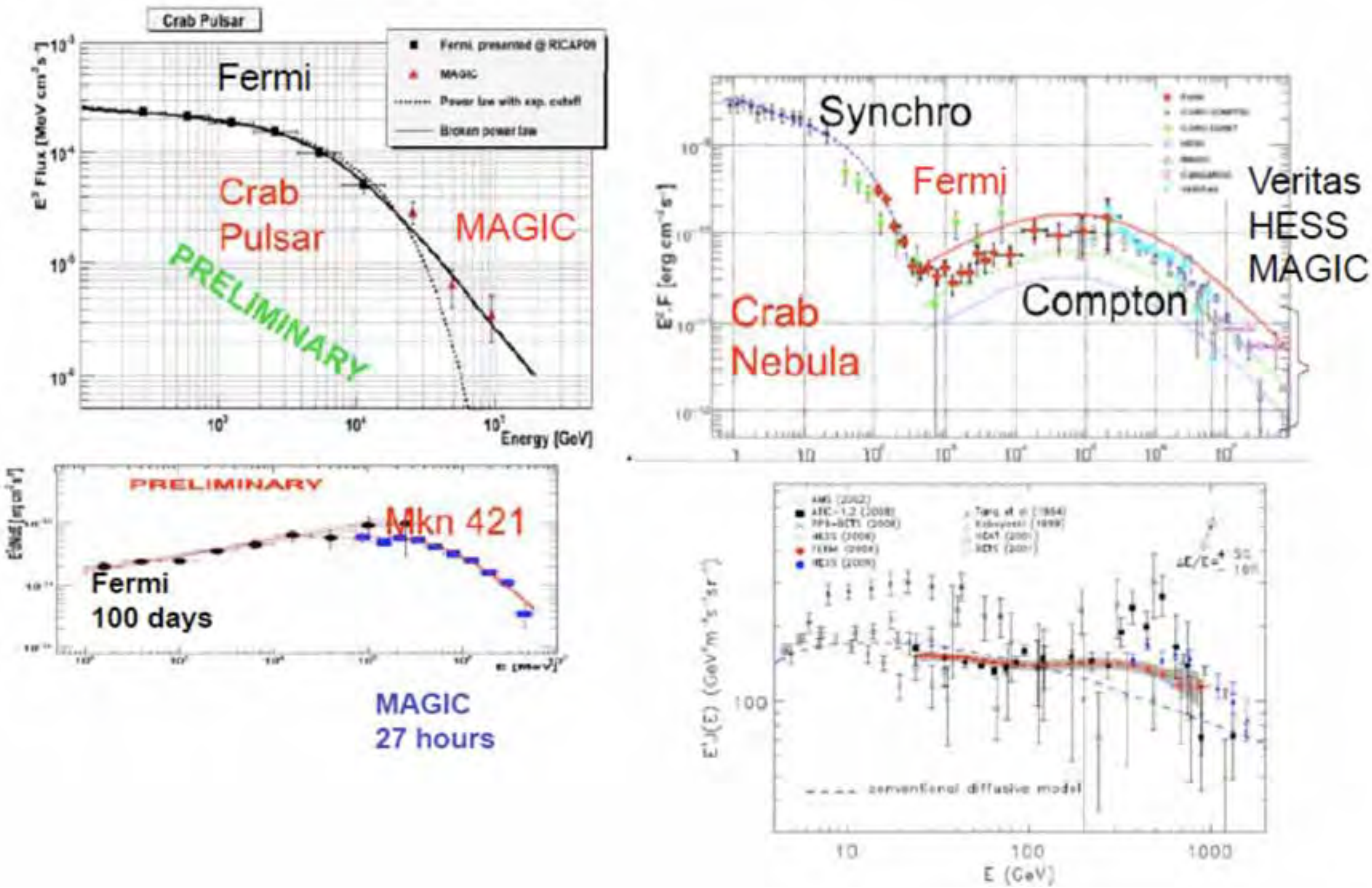
$$\frac{dN_\nu}{dE} \approx \frac{1}{2}\frac{dN_\gamma}{dE}$$

(reflects the fact that pions decay into gamma rays and neutrinos that carry 1/2 and 1/4 of the energy of the parent. This assumes that the four leptons in the charged pion decay equally share the charged pion's energy)

$\Rightarrow$Very accurate input for neutrino detectors

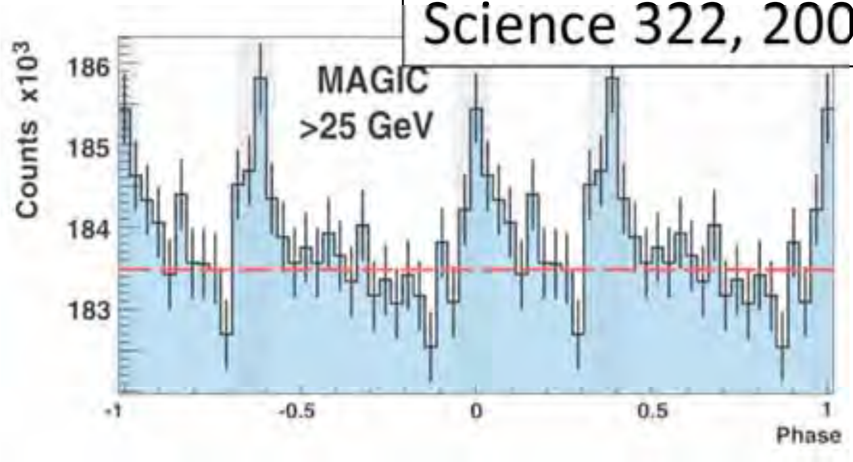


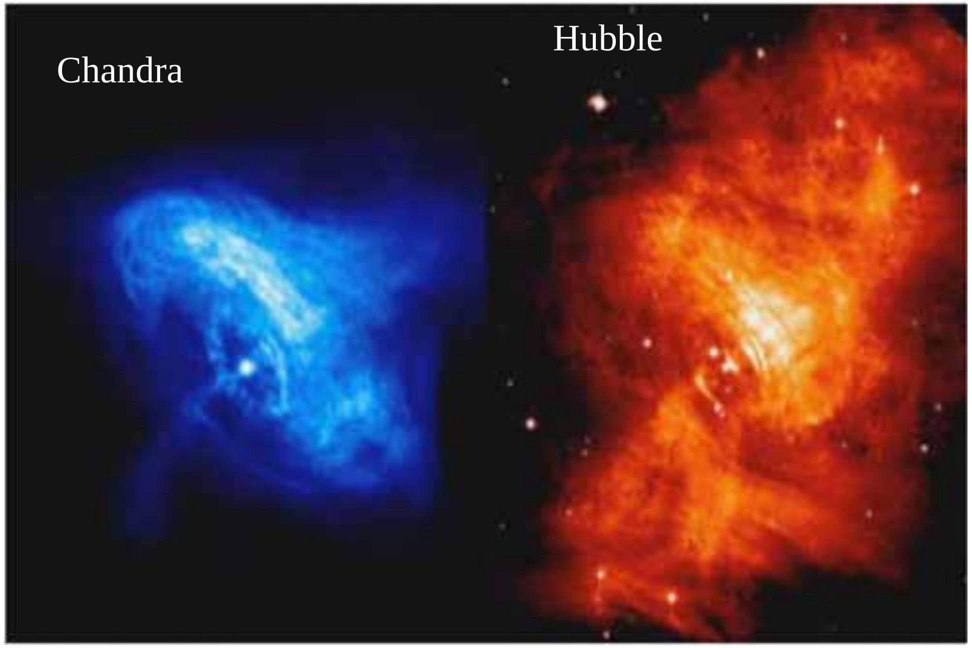
Complementarity to Fermi



Crab pulsar

Science 322, 2008





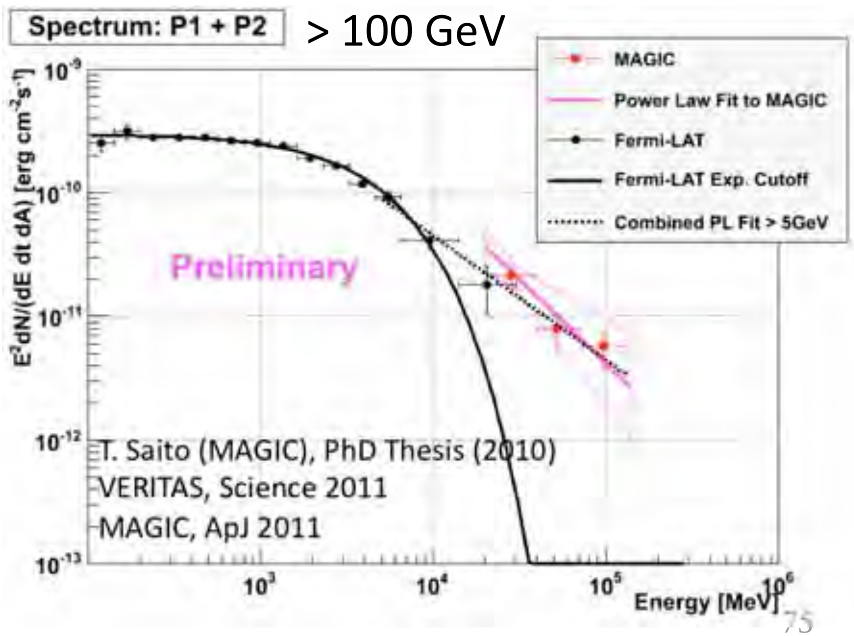
First detection of a pulsar above 25 GeV with special “sum” trigger

+ T. Saito thesis 2010, VERITAS 2011, MAGIC2011:

Extension of spectrum to 400 GeV:

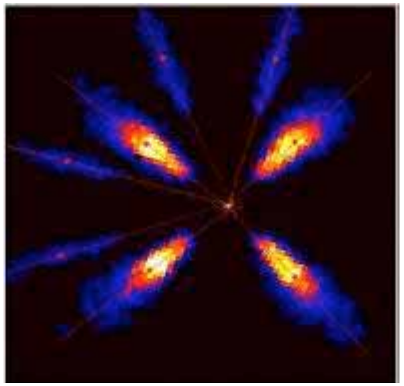
inconsistent with the exponential
+ cutoff extrapolation (>5σ)

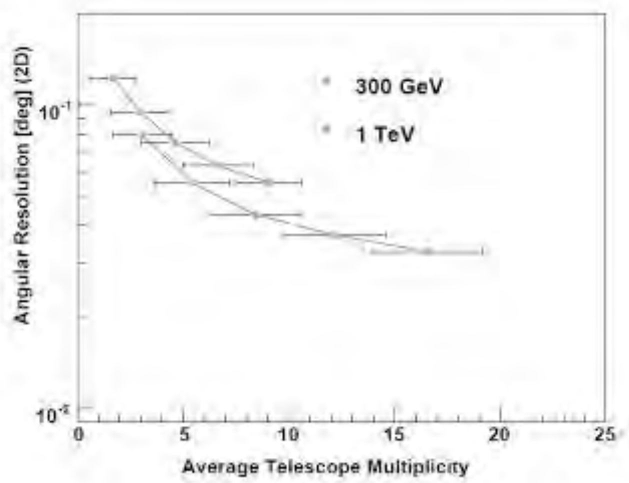
Challenging result for pulsar models



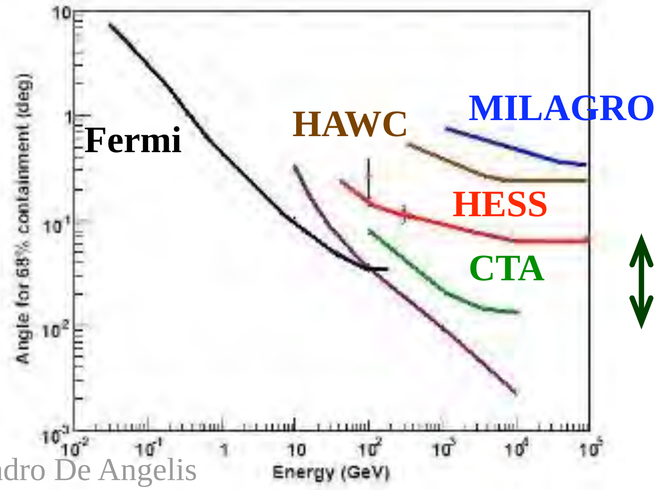
CTA performance: angular resolution

- Angular resolution improves as more telescopes used in reconstrution



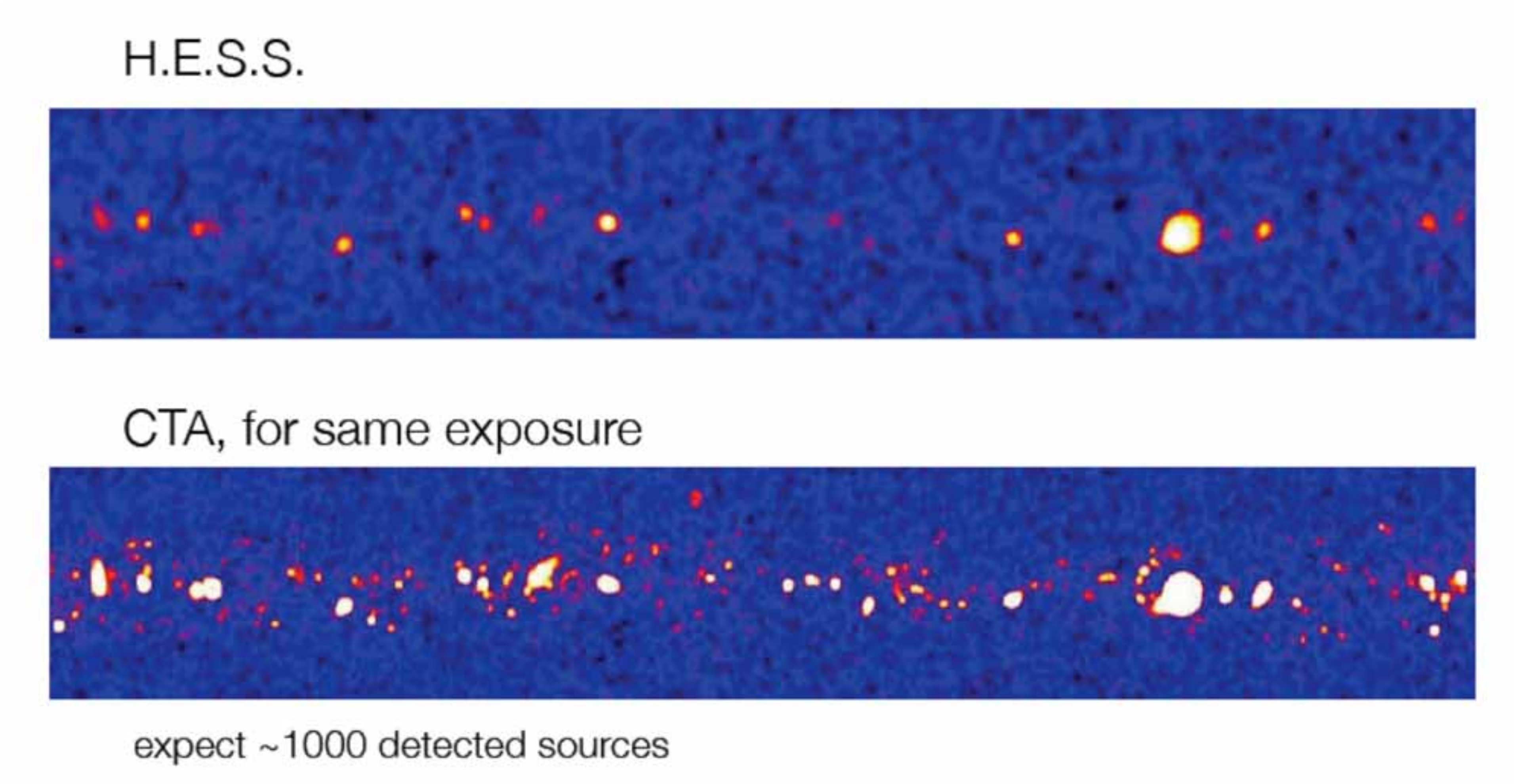


- Angular resolution closer to theoretical limit



factor **3** improvement

CTA: Expectations for Galactic plane survey



CTA schedule (optimistic)