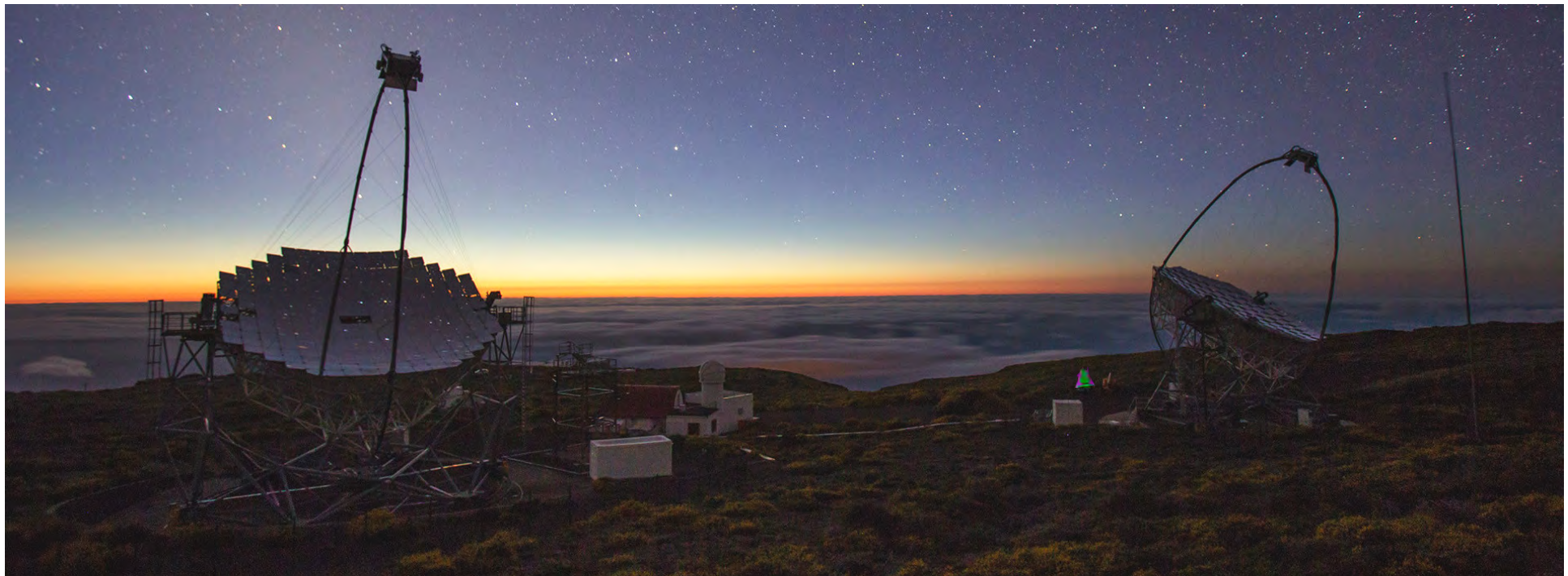# The MAGIC Telescopes
Status and recent results

CRIS 2016, Ischia

Alessandro De Angelis
INFN Padova & LIP/IST Lisboa

Thanks to O. Blanch, D. Elsasser, D. Glawion, A. Moralejo, M. Will

The MAGIC Telescopes

La Palma

Canary Islands   Africa

Roque de Los Muchachos Altitud 2426 m
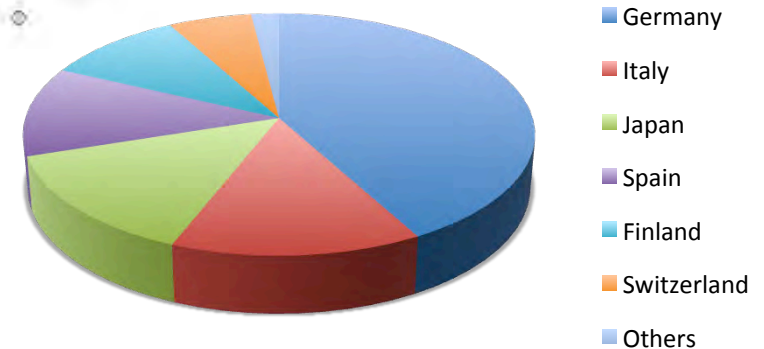
ORM

M. Bergmann

MAGIC Telescopes

- Stereoscopic System
  - 2 Imaging Atmospheric Cherenkov Telescopes
  - 17 m diameter, 240 m^2 each

- Operated for 12 years (7 years in stereo mode)
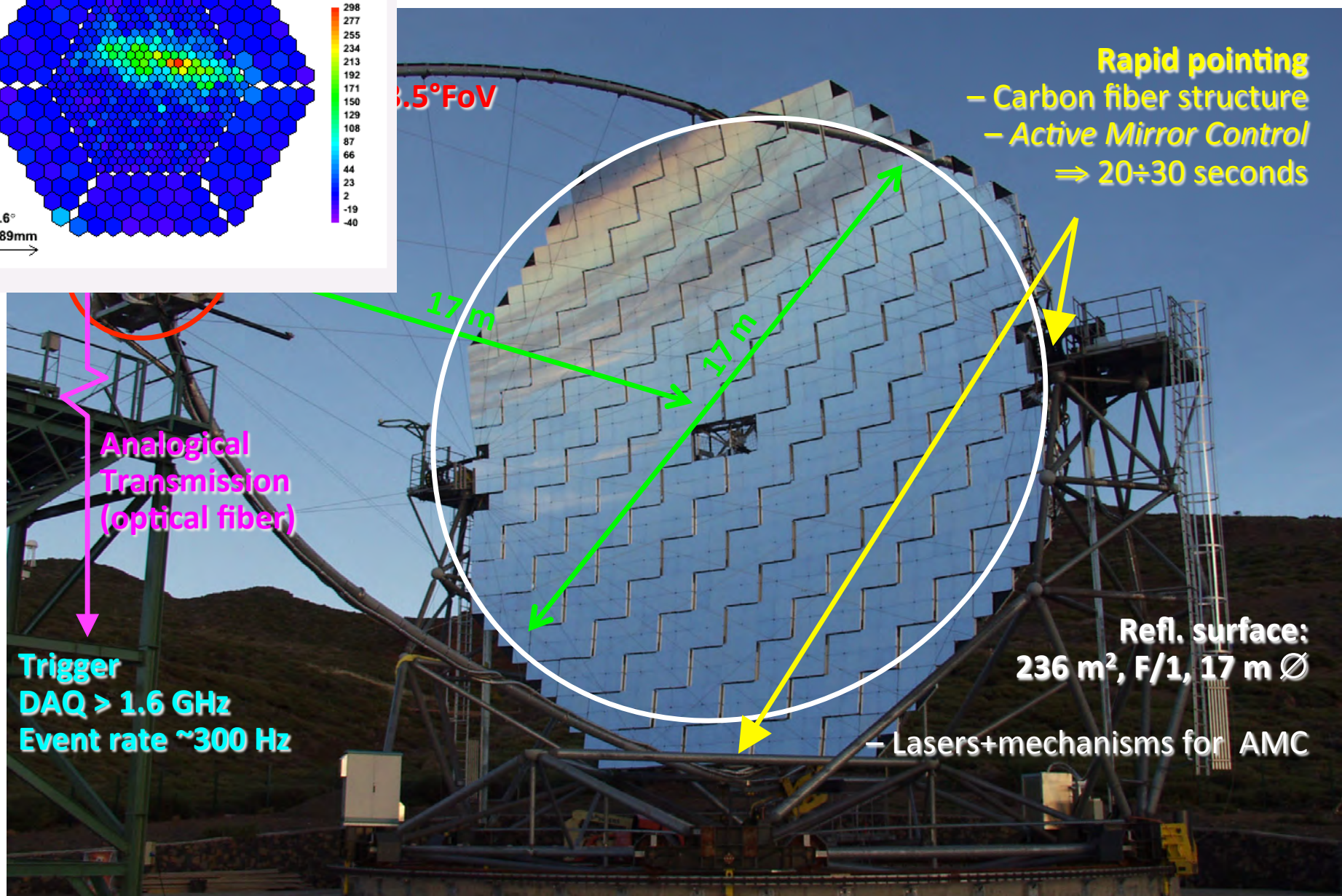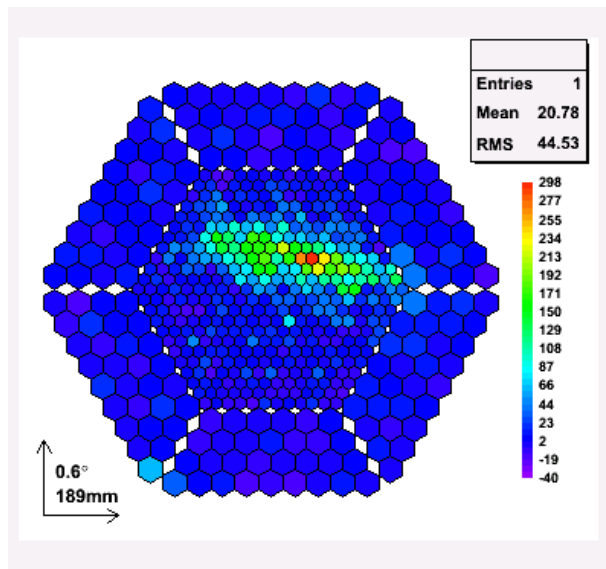
The MAGIC Collaboration

~170 scientists working in institutes from countries across the world:
Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain, Switzerland
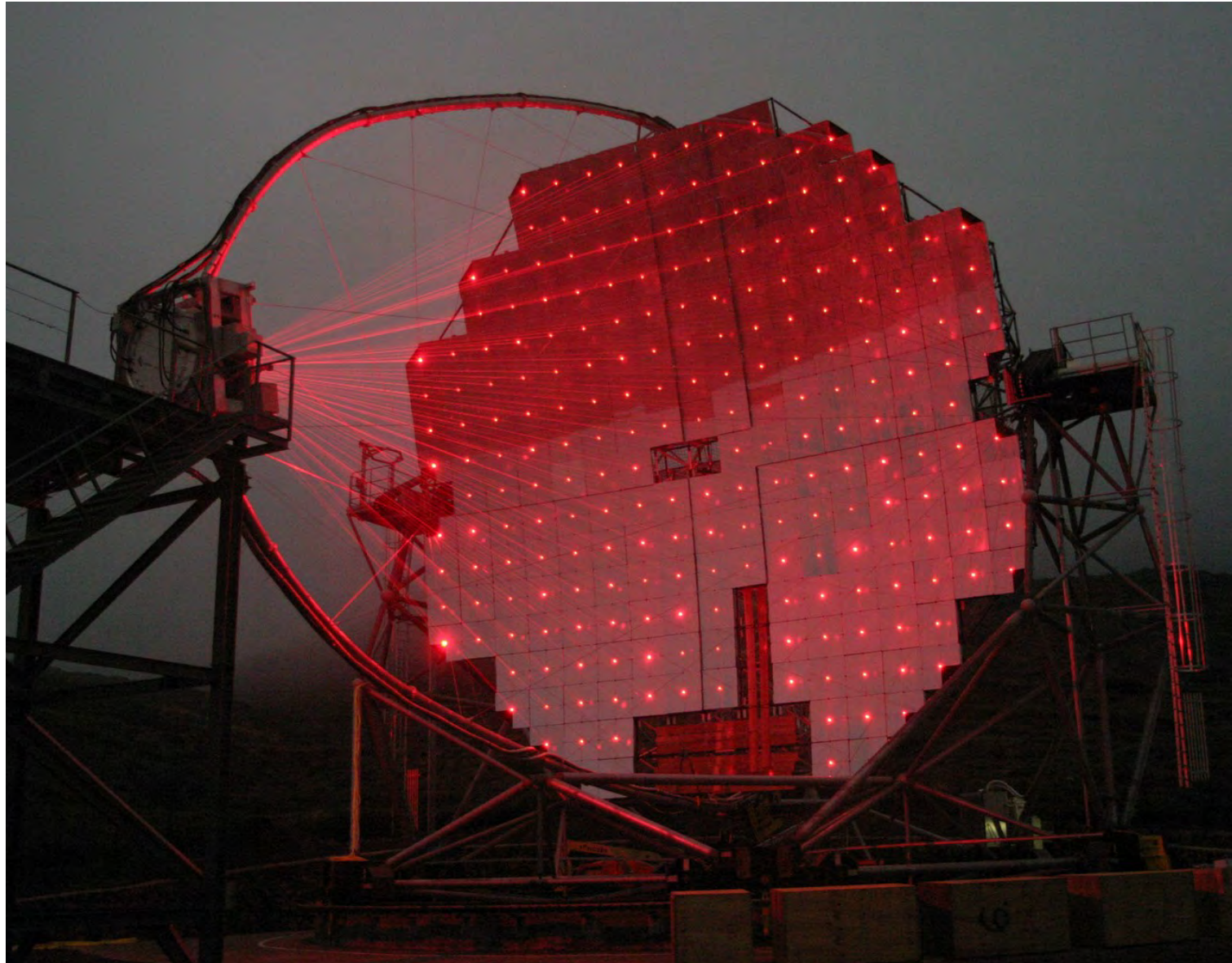
MAGIC: very fast movement (30s)

Fast DAQ

Entries 1
Mean 20.78
RMS 44.53

298
277
255
234
213
192
171
150
129
108
87
66
44
23
2
-19
-40

0.6°
189mm

3.5°FoV

Rapid pointing
– Carbon fiber structure
– *Active Mirror Control*
⇒ 20÷30 seconds

17 m

17 m

Analogical Transmission (optical fiber)

Refl. surface:
236 m², F/1, 17 m ∅

Trigger
DAQ > 1.6 GHz
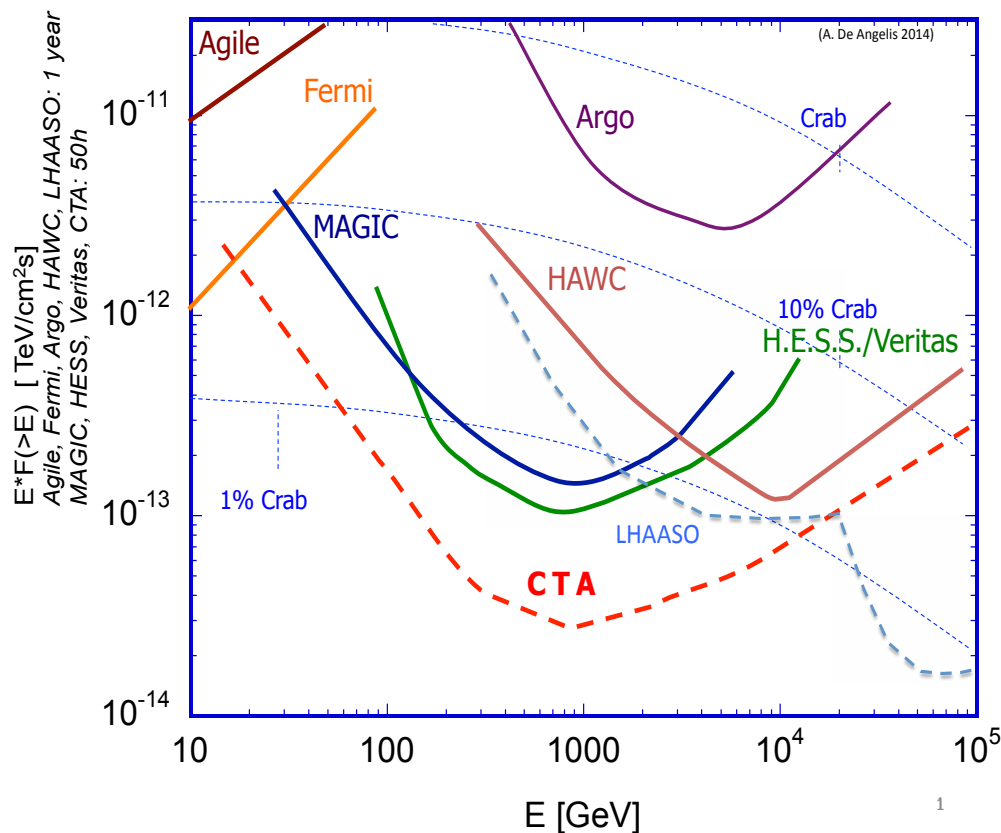**Event rate ~300 Hz**

– Lasers+mechanisms for AMC

An AMC System

All AMC Lasers switched on during foggy night

(nice propaganda picture; does never look like that during operation ...)

Performance of MAGIC in a nutshell

Energy range:

   50 GeV (30 GeV Sum-Trigger)
   Up to 50 TeV

Energy resolution:

   15% (@ 1 TeV) – 20% (@100 GeV)

Angular resolution:

   0.06° @ 1 TeV ,   0.1° @ 100 GeV

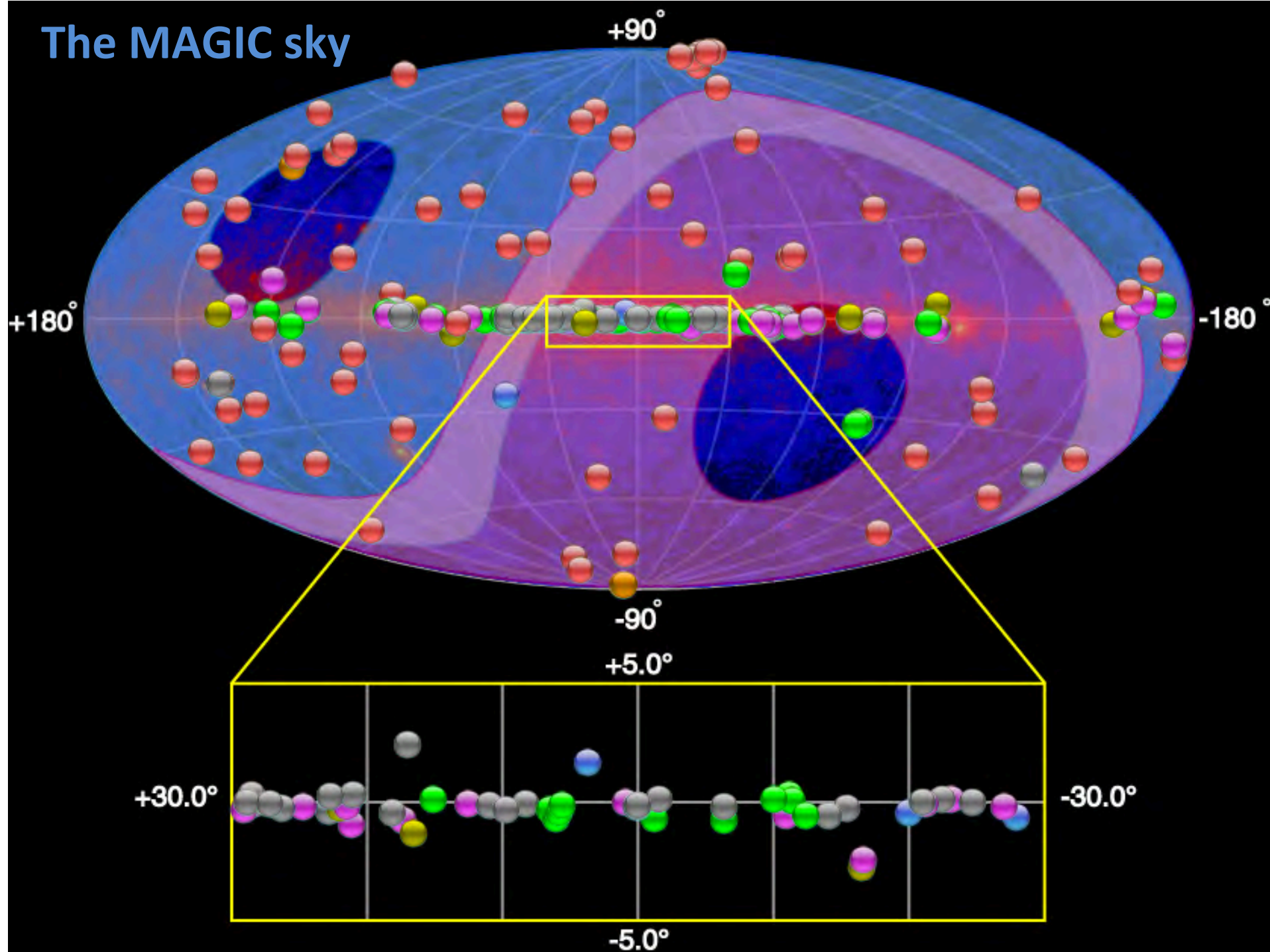**Sensitivity (5σ in 50h)**:

   0.7% Crab

Best in the world for:
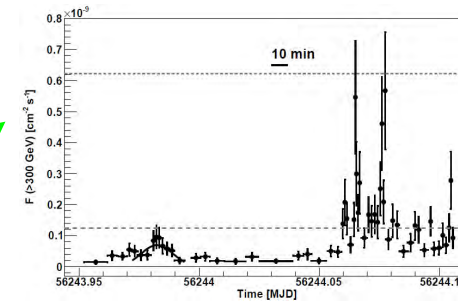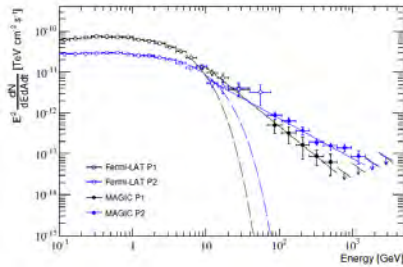
   Low threshold (looking far away)
   Prompt response to transients

The MAGIC sky

Galactic sources:
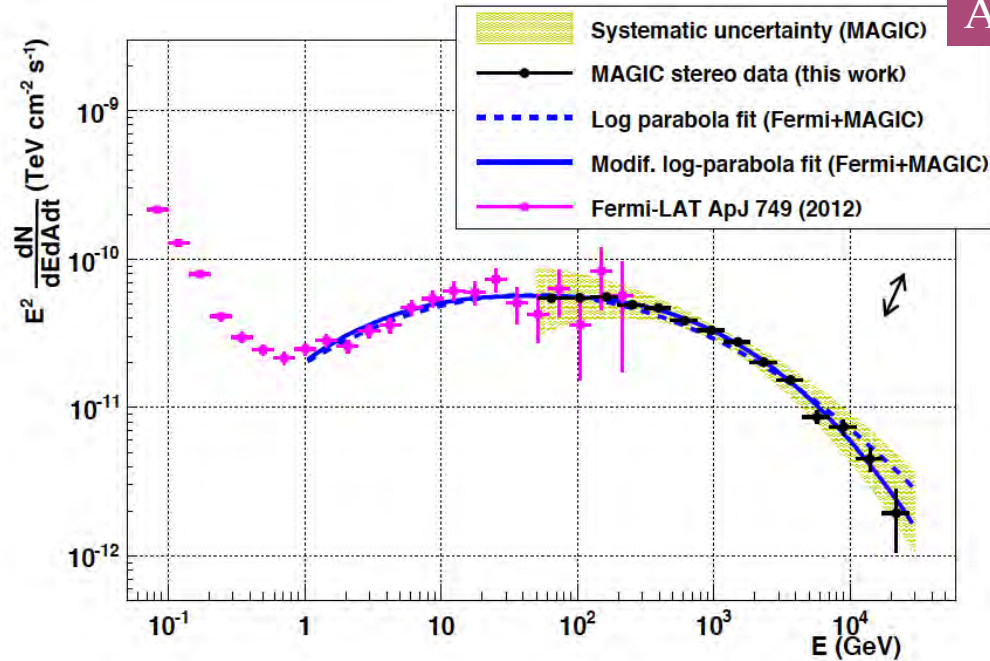Pulsars, PWN, SNR, Binaries, ?

AGN

Fundamental physics:
Dark matter, LIV, EBL, IGMF & cosmology

Galactic Physics with MAGIC
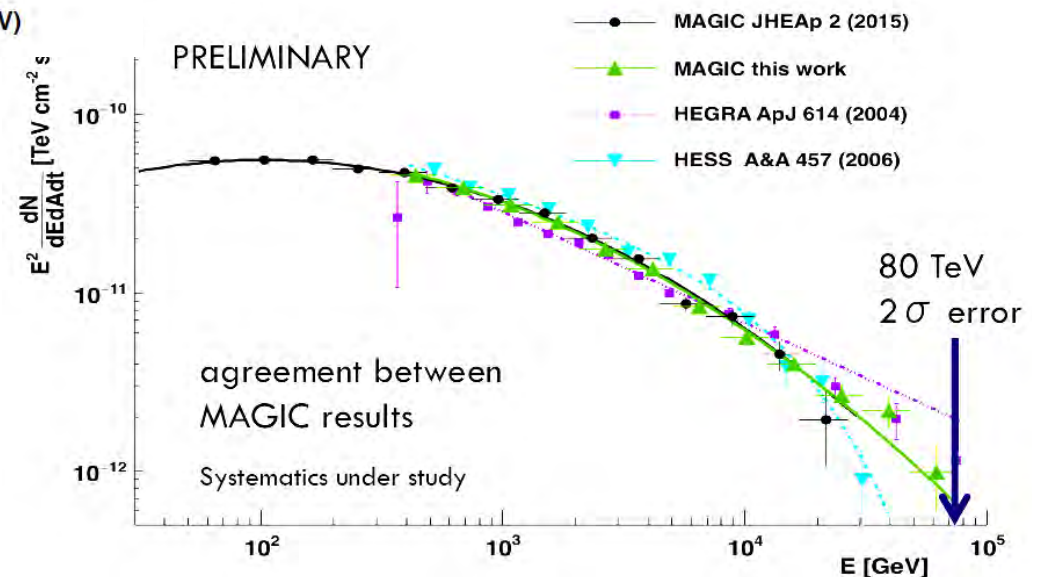
Crab Nebula: from SR to IC to...

Aleksić et al. (MAGIC) JHEAP, 5, 2015

Legend (top left plot):
- Systematic uncertainty (MAGIC)
- MAGIC stereo data (this work)
- Log parabola fit (Fermi+MAGIC)
- Modif. log-parabola fit (Fermi+MAGIC)
- Fermi-LAT ApJ 749 (2012)

- Spectrum from 30 GeV to 30 TeV

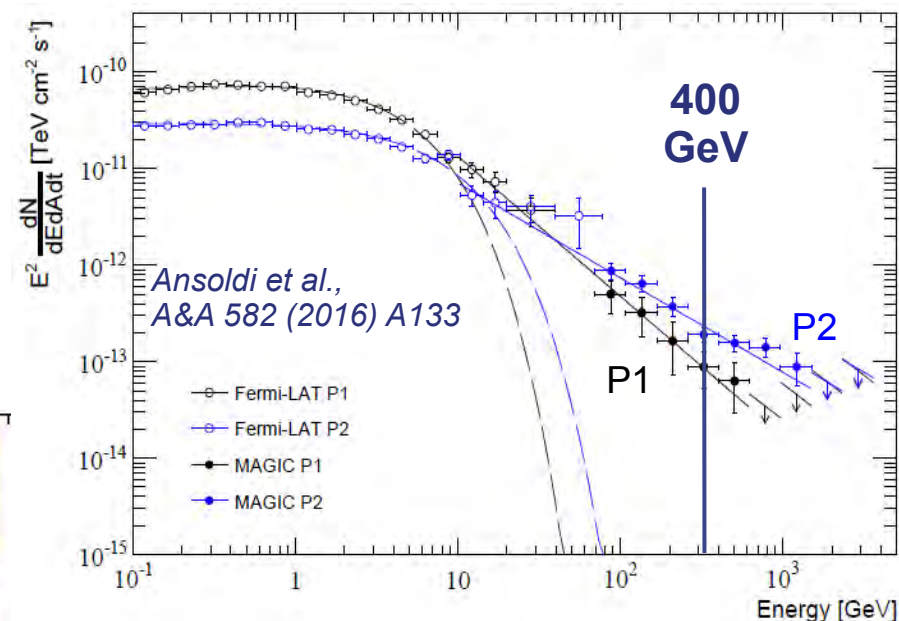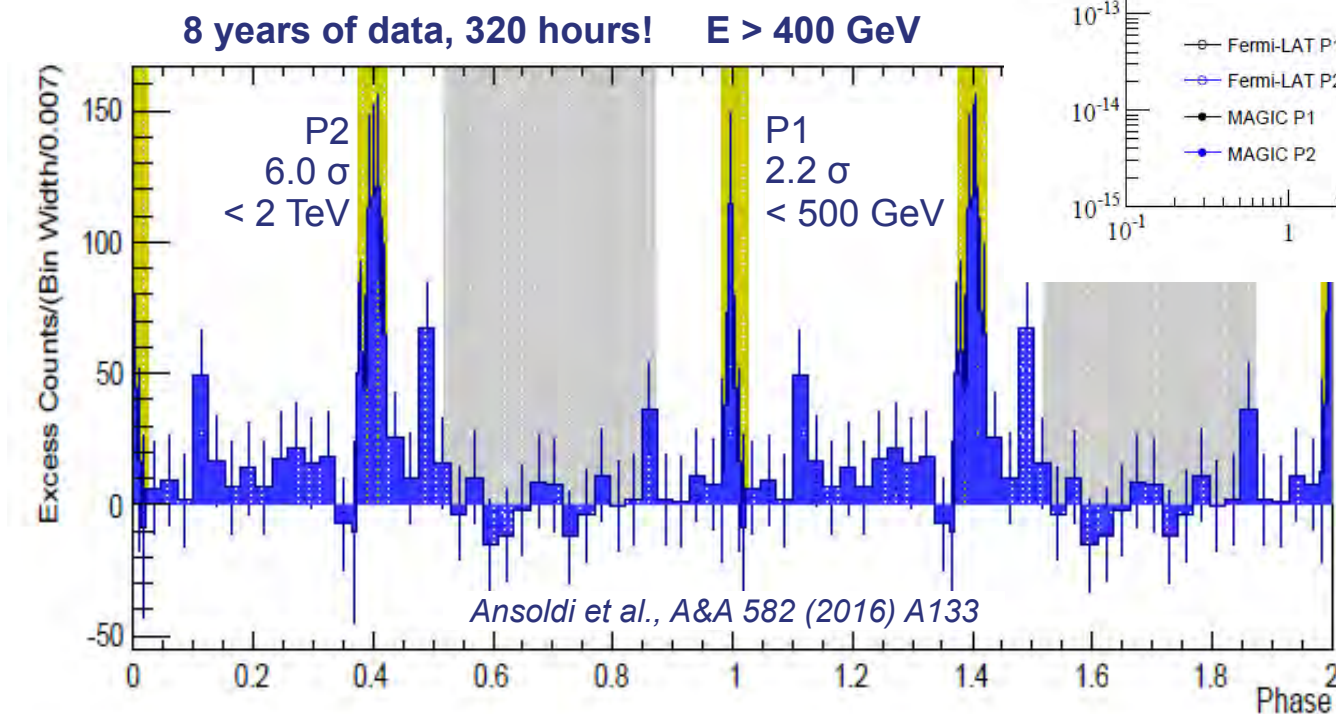- Together with *Fermi*-LAT, good coverage of the IC peak
  - Cross-calibration

- Large zenith angle observations to explore range → ~80 TeV

A deeper insight on the most studied source at VHE

Legend (bottom right plot):
- MAGIC JHEAp 2 (2015)
- MAGIC this work
- HEGRA ApJ 614 (2004)
- HESS A&A 457 (2006)

PRELIMINARY

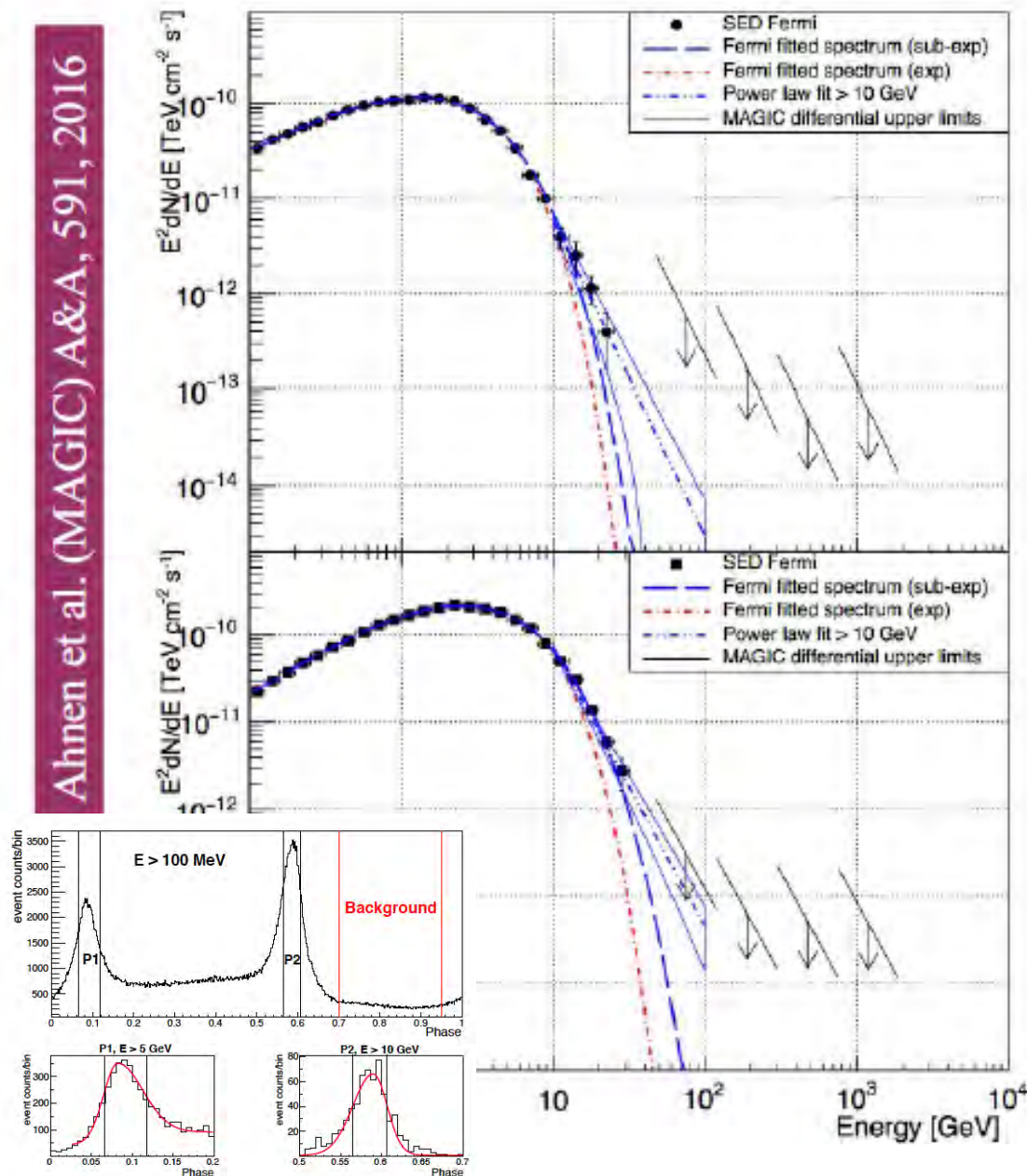agreement between MAGIC results

Systematics under study

80 TeV
2σ error

Crab Pulsar at TeV Energies

■ Implications for emission

► Inverse Compton
► Synchrotron-curvature ruled out
► Strong constraints to models

Ansoldi et al., A&A 582 (2016) A133

400 GeV

P1

P2

Fermi-LAT P1
Fermi-LAT P2
MAGIC P1
MAGIC P2

8 years of data, 320 hours!   **E > 400 GeV**

P2
6.0 σ
< 2 TeV

P1
2.2 σ
< 500 GeV

Ansoldi et al., A&A 582 (2016) A133

A look to the Geminga pulsar

Ahnen et al. (MAGIC) A&A, 591, 2016

- *Fermi*-LAT data:
  - ➢ Spectra extends to tens of GeV
  - ➢ Fits better to sub-exponential cut-off, even a broke power-law is possible (α~ 5, above 10 GeV)
  - ➢ No obvious mechanism to produce GeV emission

- VHE emission?
  - ➢ MAGIC UL in ~60 hours
  - ➢ Improved sensitivity below 100 GeV → detection or discrimination between power-law and cut-off
    (CTA in 50 hours)
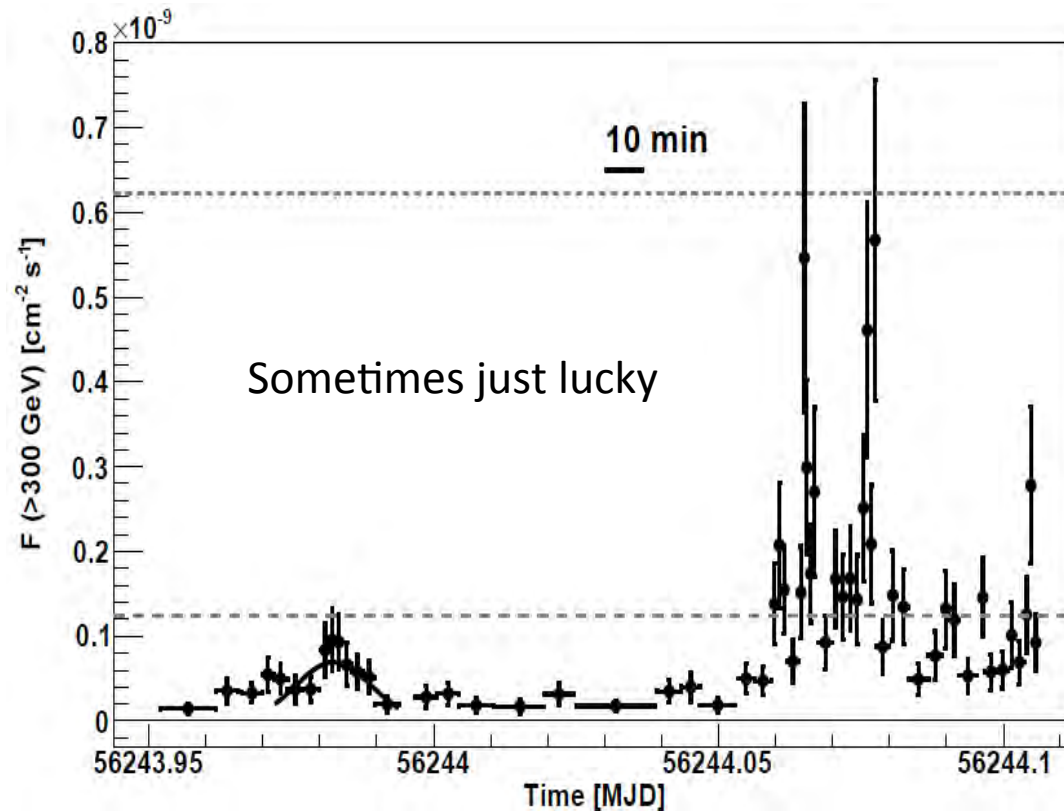
Is there also a VHE tail?

AGN Physics with MAGIC

AGN studies: a cooperative effort

Usually, VHE pointings on flaring objects triggered by Fermi
or by X-ray instruments

Aleksić et al. (MAGIC) Science 346, 2014

MAGIC-ATELs

- 13/06/2016 → 1ES 1959+650
- 01/06/2016 → PKS 1510-089
- 10/04/2016 → 1ES 1959+650
- 26/07/2016 → S2 0109+22
- 18/06/2015 → BL Lacertae
- 04/06/2015 → PKS 1510-089

  ...

- 16/11/2012 → IC 310

  ...
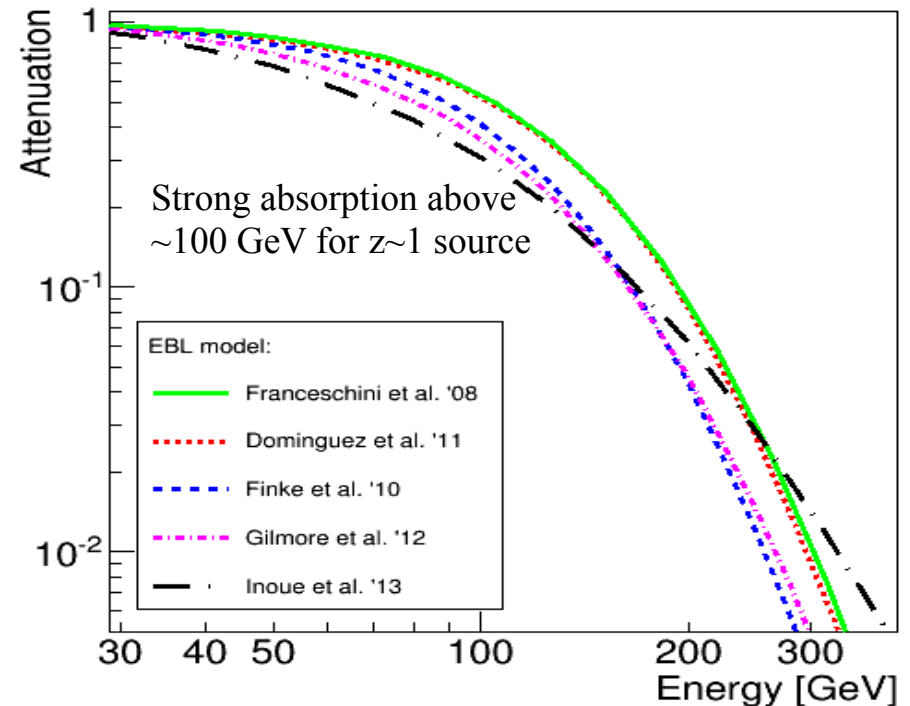
MAGIC expands the known VHE gamma-ray Universe

Lowest threshold: furthest AGN detected

For distant sources sub-TeV gamma-rays are absorbed in extragalactic background light

Strong absorption above ~100 GeV for z~1 source

FSRQ	Redshift	First VHE detection by:	Year
3C 279	0.536	**MAGIC**	2006
PKS 1510-089	0.361	HESS	2009
PKS 1222+216 (4C +21.35)	0.432	**MAGIC**	2010
B0218+35	**0.944**	**MAGIC**	**2014**
PKS 1441+25	**0.939**	**MAGIC**	**2015**
S4 0954+65*	0.368	**MAGIC**	**2015**

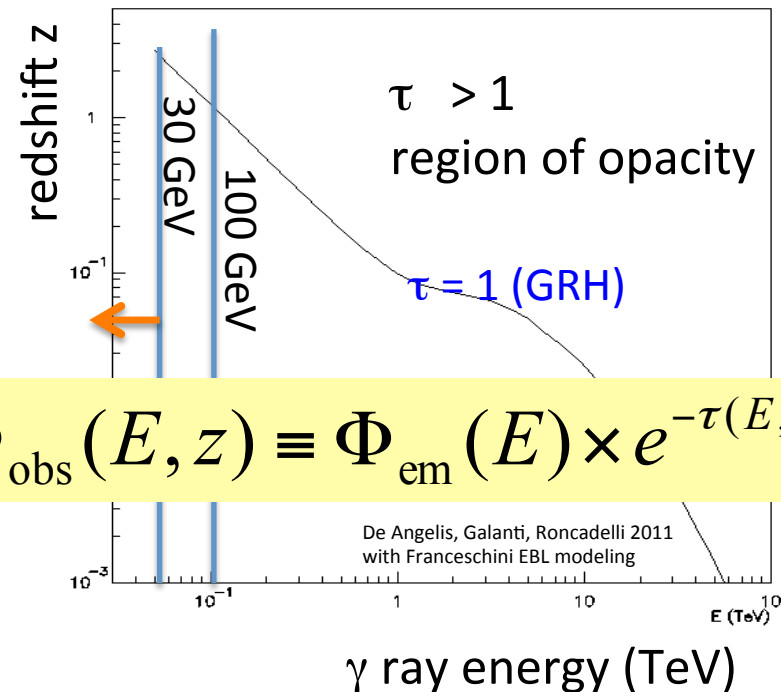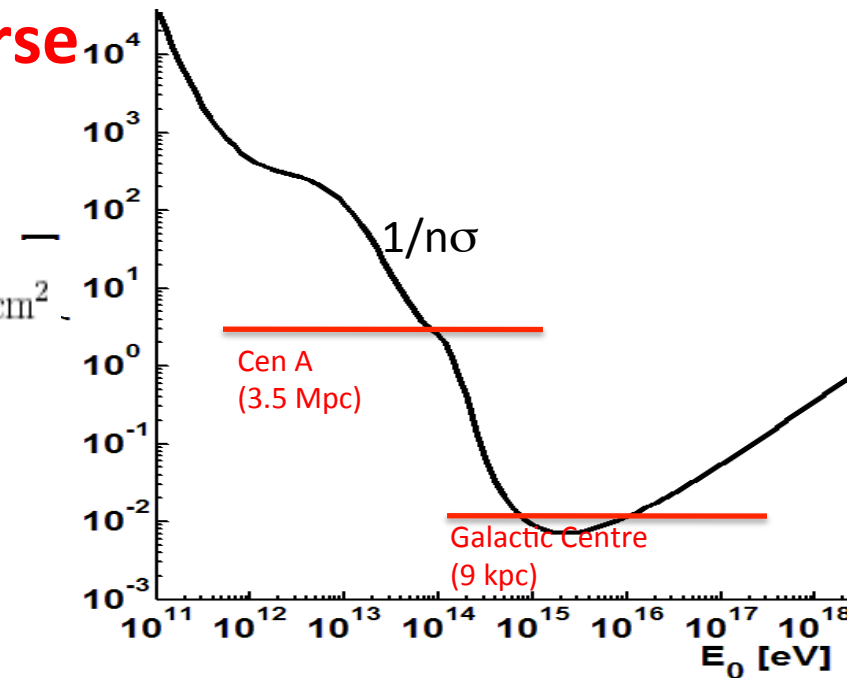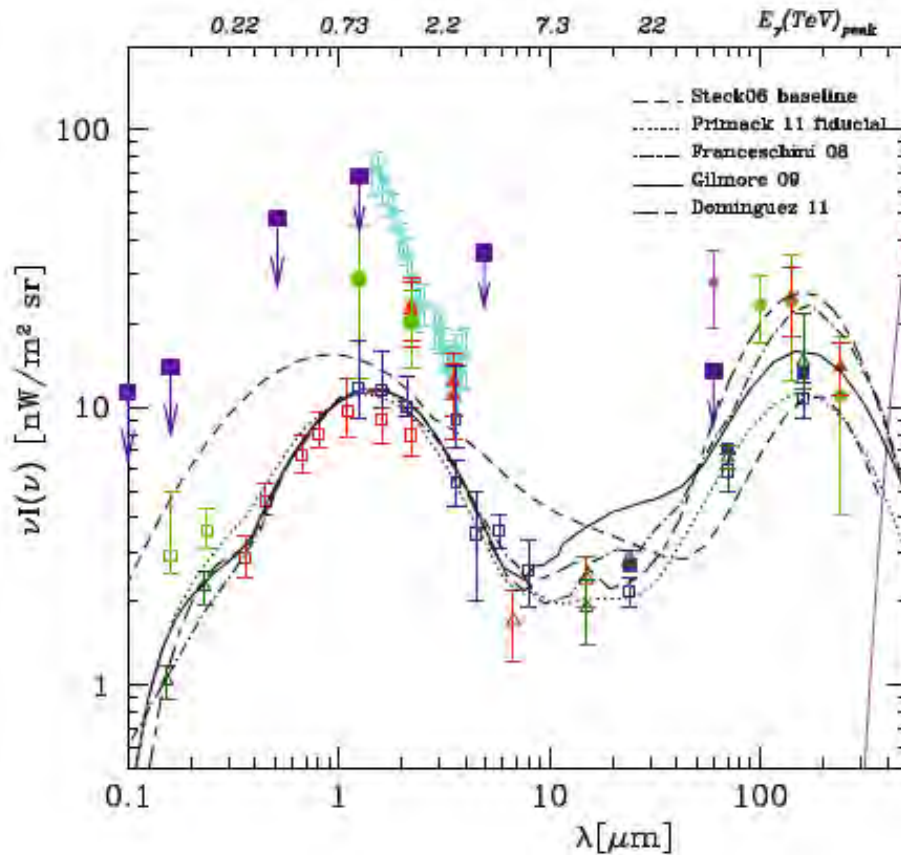# Our ennemy: opacity of the Universe

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

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

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

1/nσ

Cen A
(3.5 Mpc)

Galactic Centre
(9 kpc)

E_0 [eV]

Steck06 baseline
Primack 11 fiducial
Franceschini 08
Gilmore 09
Dominguez 11

$\nu I(\nu)$ [nW/m² sr]

$\lambda[\mu m]$

$E_\gamma(TeV)_{peak}$

redshift z

30 GeV

100 GeV

$\tau > 1$
region of opacity

$\tau = 1$ (GRH)
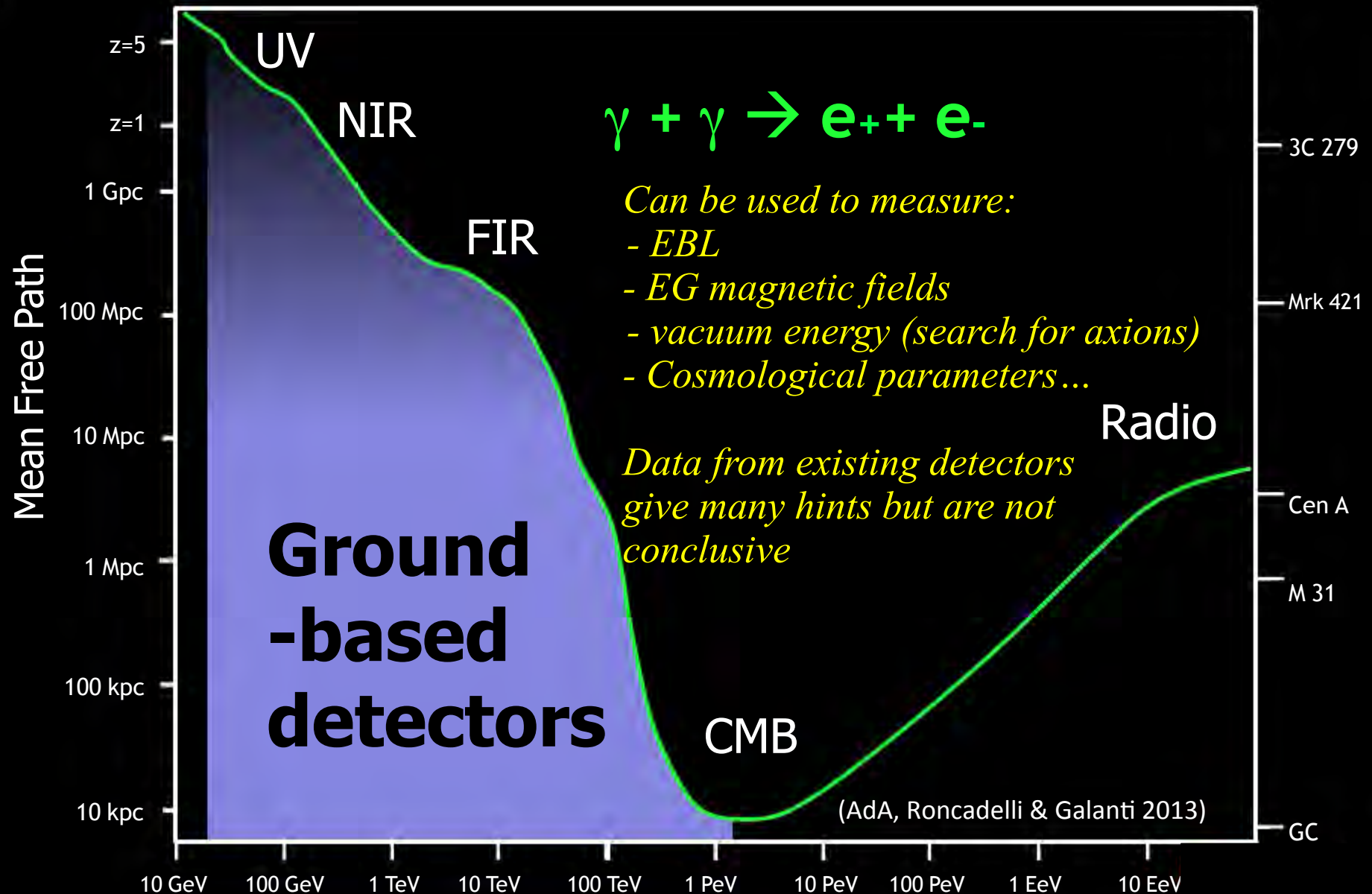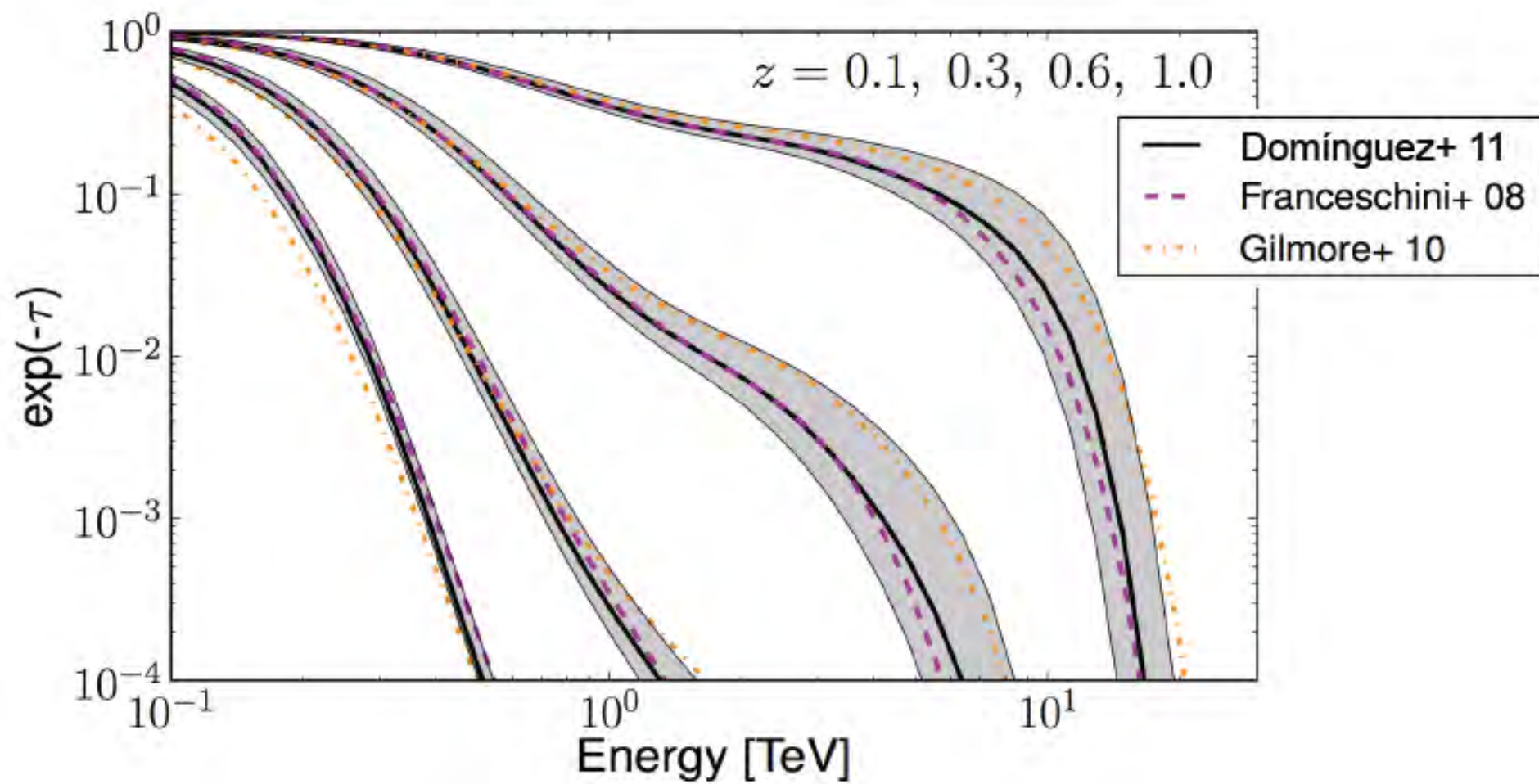
$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

De Angelis, Galanti, Roncadelli 2011
with Franceschini EBL modeling
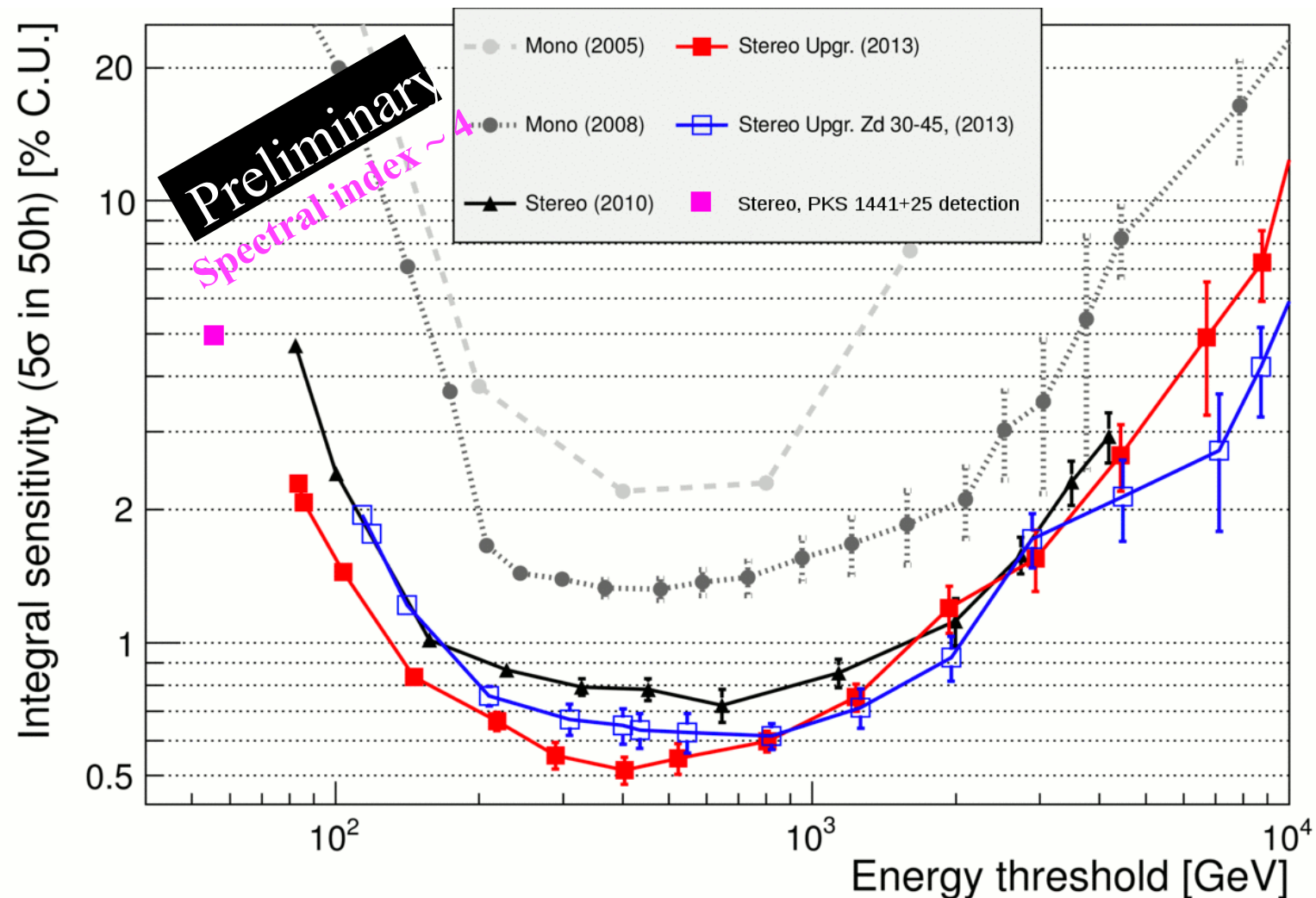
γ ray energy (TeV)

E (TeV)

- The diffuse extragalactic background light (EBL) is all the accumulated radiation in the Universe due essentially to star formation processes
- This radiation covers a wavelength range between ~0.1 and 600 µm (consider the redshift and the reprocessing)
- After the CMB, the EBL is the second-most energetic diffuse background
- The understanding of the EBL is fundamental
  - To know the history of star formation
  - To model VHE photon propagation for extragalactic VHE astronomy. VHE photons coming from cosmological distances are attenuated by pair production with EBL photons. This interaction is dependent on the SED of the EBL.
- Therefore, it is necessary to know the SED of the EBL in order to study intrinsic properties of the emission in the VHE sources

- The lowest-E threshold telescopes (MAGIC, in the future the CTA LST) can do it better
- EBL and the γ-ray horizon are one of the key programs of MAGIC [18]

The γ horizon: nuisance and resource

$$\gamma + \gamma \rightarrow e_+ + e_-$$

Can be used to measure:
- EBL
- EG magnetic fields
- vacuum energy (search for axions)
- Cosmological parameters…

Data from existing detectors give many hints but are not conclusive

(AdA, Roncadelli & Galanti 2013)

$z = 0.1,\ 0.3,\ 0.6,\ 1.0$

Domínguez+ 11
Franceschini+ 08
Gilmore+ 10

MAGIC keeps improving

- 2004 – MAGIC-I built
- 2007 – upgraded MAGIC-I readout
- 2009 – MAGIC-II built
- 2011-2012 – upgrade of readout systems and MAGIC-I trigger and camera

FSRQ at redshift ~ 1: S3 0218+35

- Gravitationally lensed blazars at $z = 0.944$ (lens at $z = 0.684$)

- Flare observed by *Fermi*-LAT in mid of July 2014 (full moon)

- MAGIC detection of delayed emission $\sim 12\,d$ after $\rightarrow$ ATel #6349

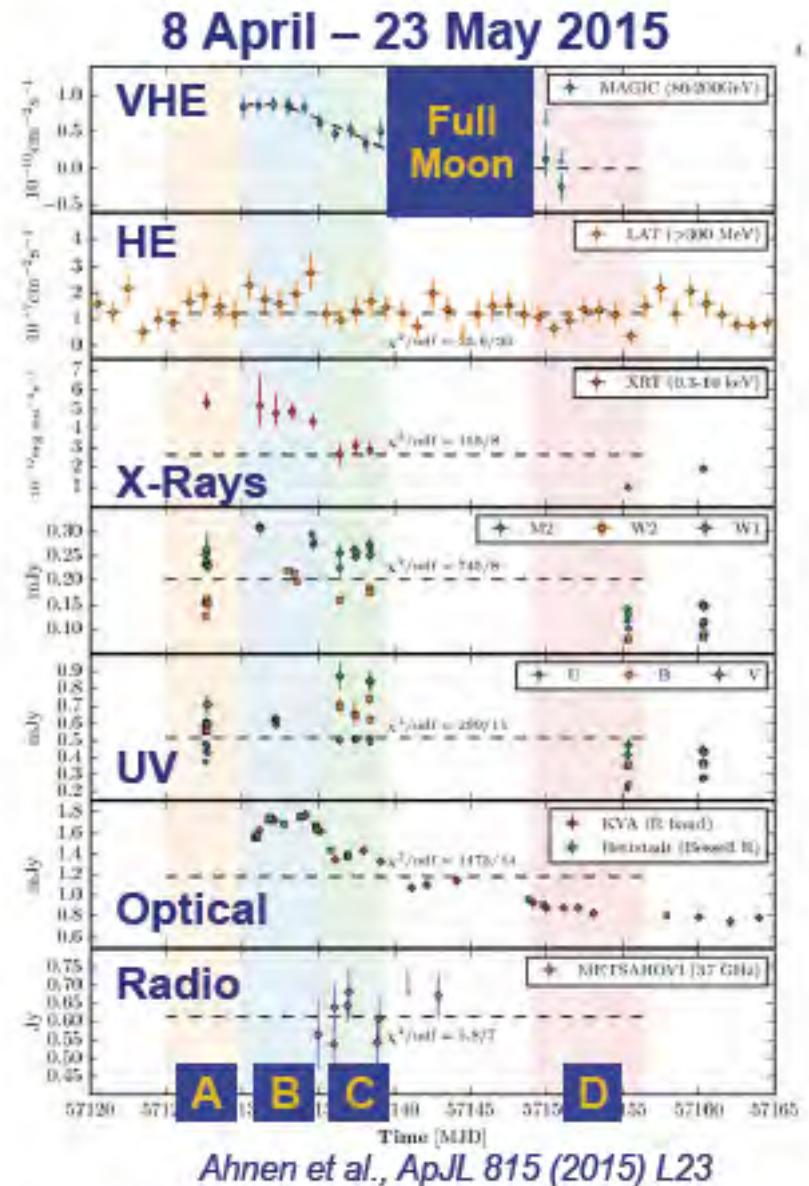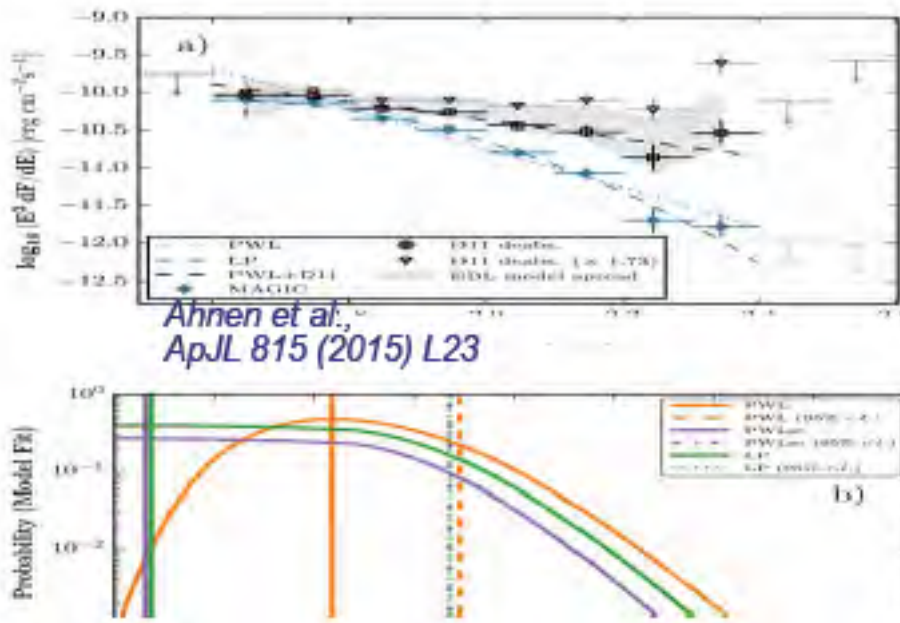- **Unprecedented distance scale for ground-based gamma-ray astronomy**
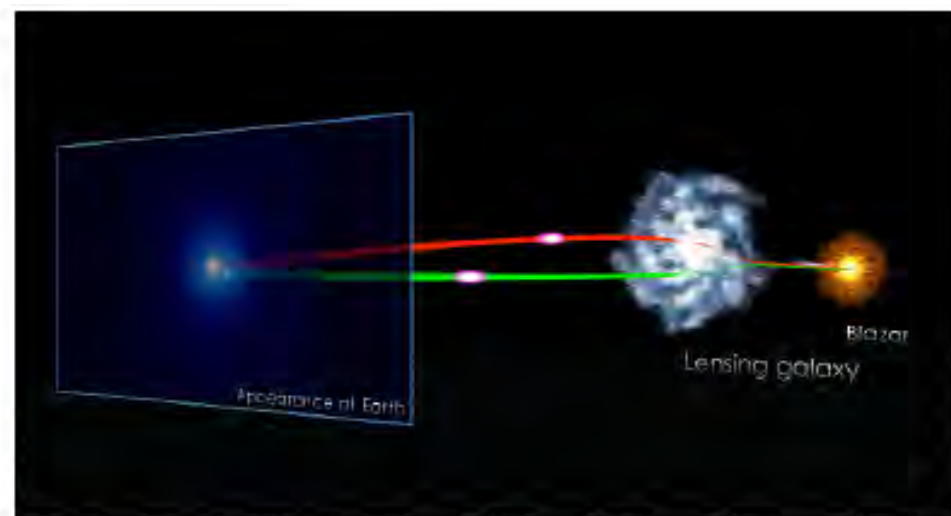
Credit: NASA/ESA, Hubble Legacy Archive
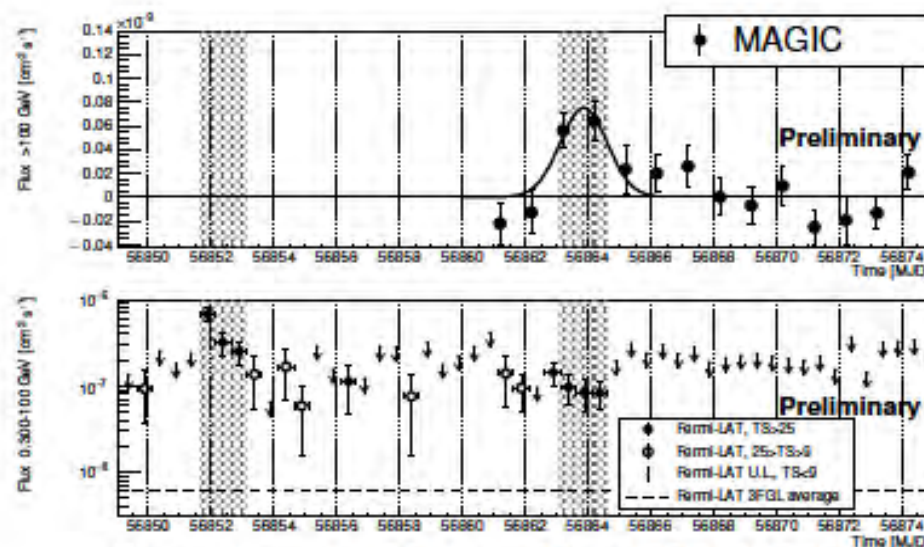
Sitarek et al. 2015. arXiv:1508.04580
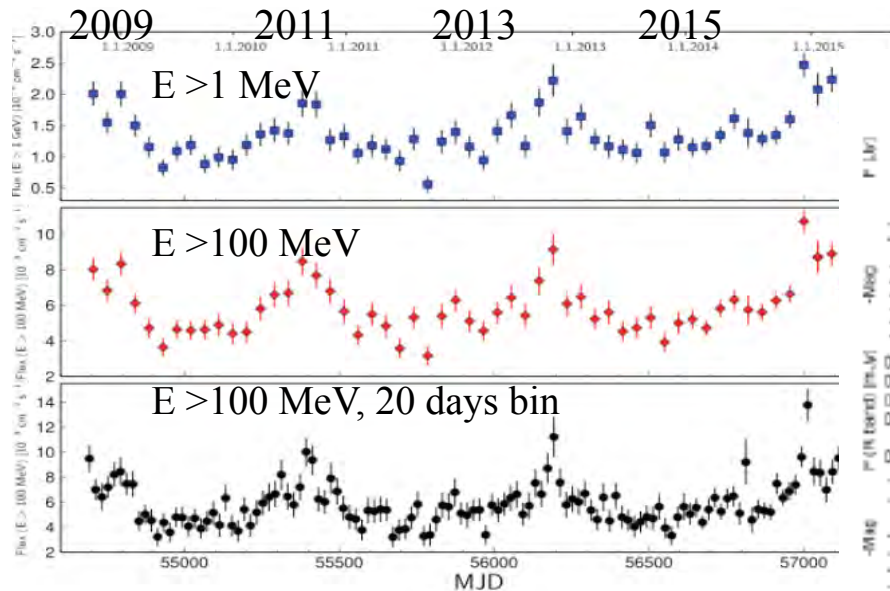
FSRQ at redshift ~ 1 : PKS 1441+25

- FSRQ at z = 0.939

- Flare in April 2015 → **Discovery**

- Spectrum consistent with current EBL models

Ahnen et al., ApJL 815 (2015) L23

8 April – 23 May 2015

Ahnen et al., ApJL 815 (2015) L23

Periodic signal from PG 1553+113 (z~0.5)?
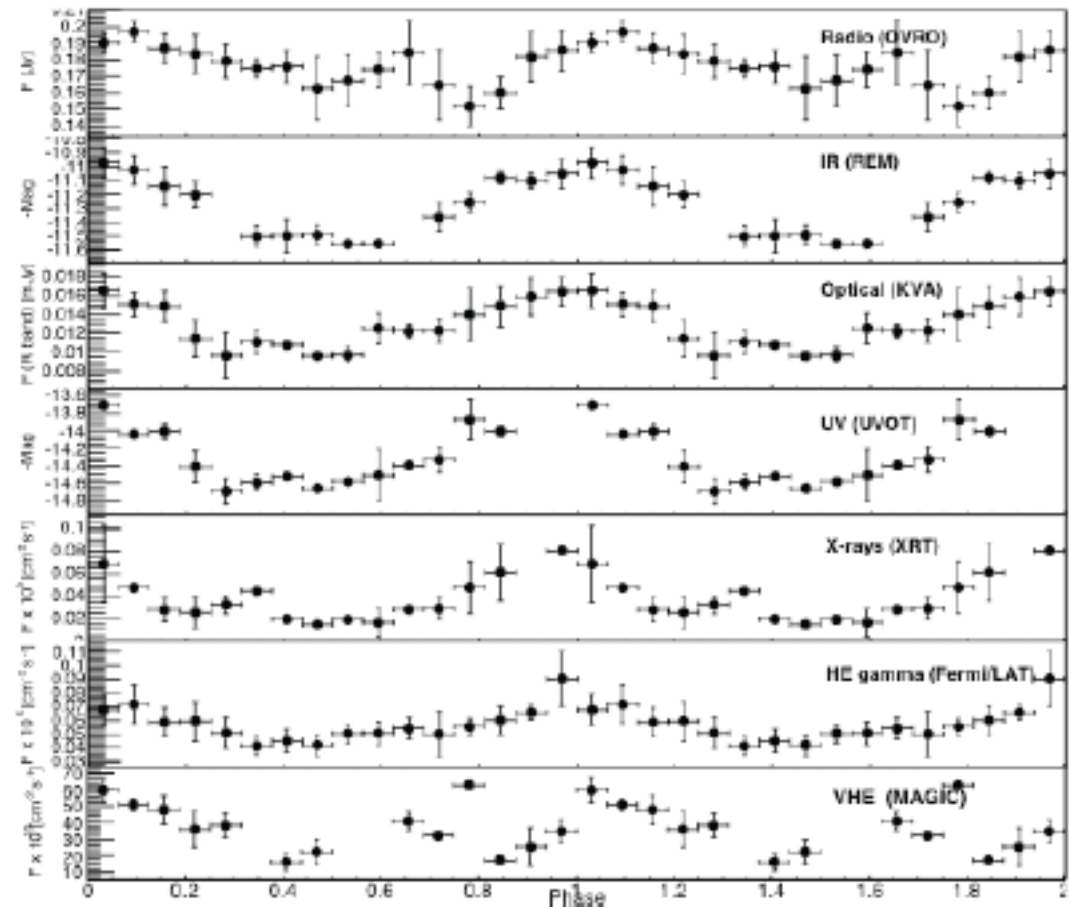
Ackermann et al., ApJL 813, 2015

MWL Light Curves

Fermi Collaboration has reported the detection of periodic signal (T=798 d)

Since 2014, intense MWL campaign
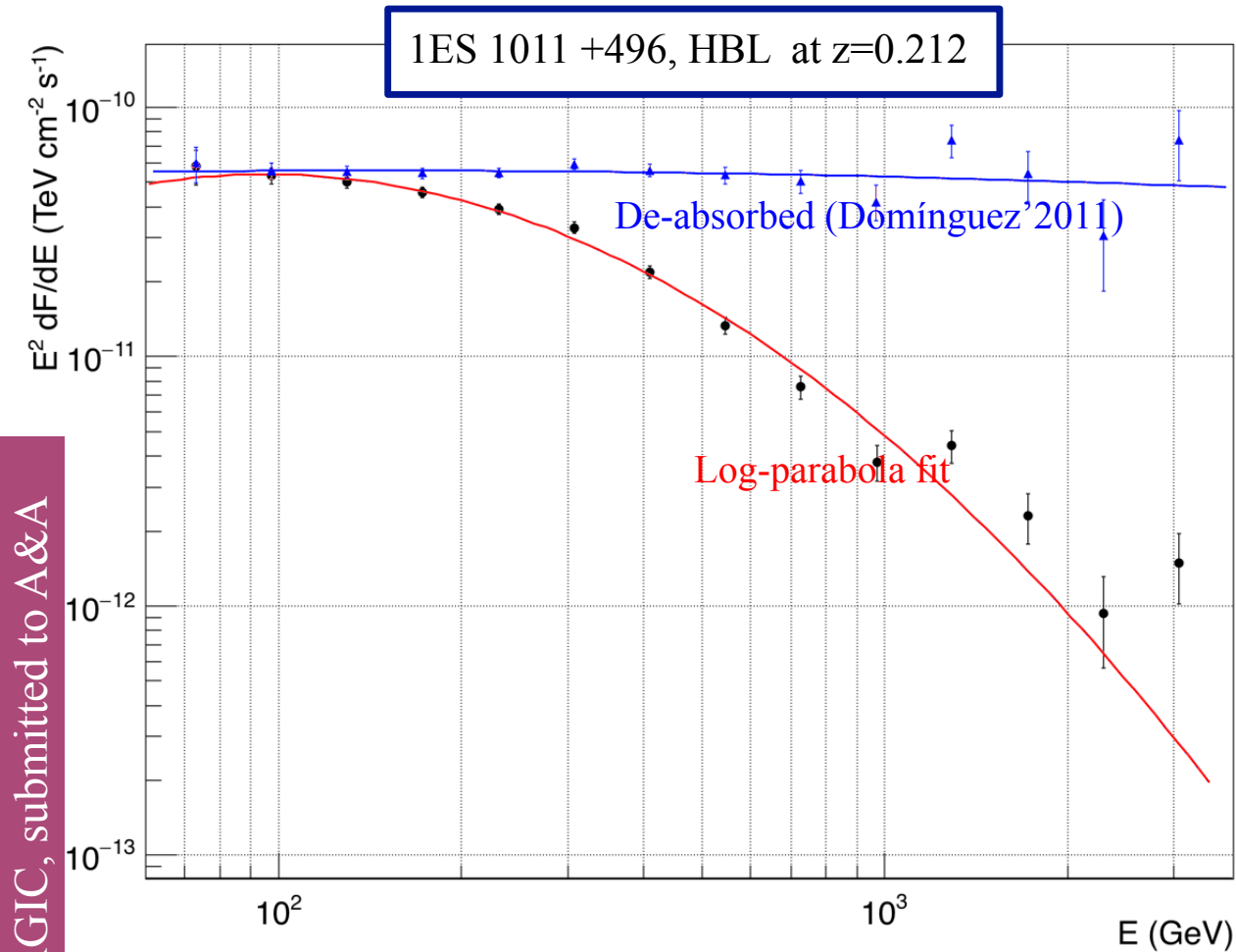
Well known at VHE, sparse sampling since 2005

VHE data with MWL coverage may shed light on the underlying mechanism

Constraints on EBL (a KOP for MAGIC)

- Take a template EBL model $\Rightarrow$ $\tau(E, z)$
- Model the observed spectra as:

$$dF_{obs}/dE = e^{-\alpha\, \tau(E, z)}\, dF_{intr}/dE$$

- α is a scaling parameter for the optical depth, i.e.
  - $\alpha = 0$: no EBL
  - $\alpha = 1$: the template EBL
- dF_{intr}/dE parametrized as
  - Log parabola (in case of Fermi paper)
  - Best fit among power-law, log parabola and other 3 reasonable functions with up to 4 parameters (HESS)
- A *joint likelihood* is computed using all the spectra simultaneously $\Rightarrow$ obtain best-fit value of α
  - if not compatible with $\alpha = 0$ $\Rightarrow$ EBL detection

Constraints on EBL

1ES 1011 +496, HBL at z=0.212

$E^2\, dF/dE$ (TeV cm^{-2} s^{-1})
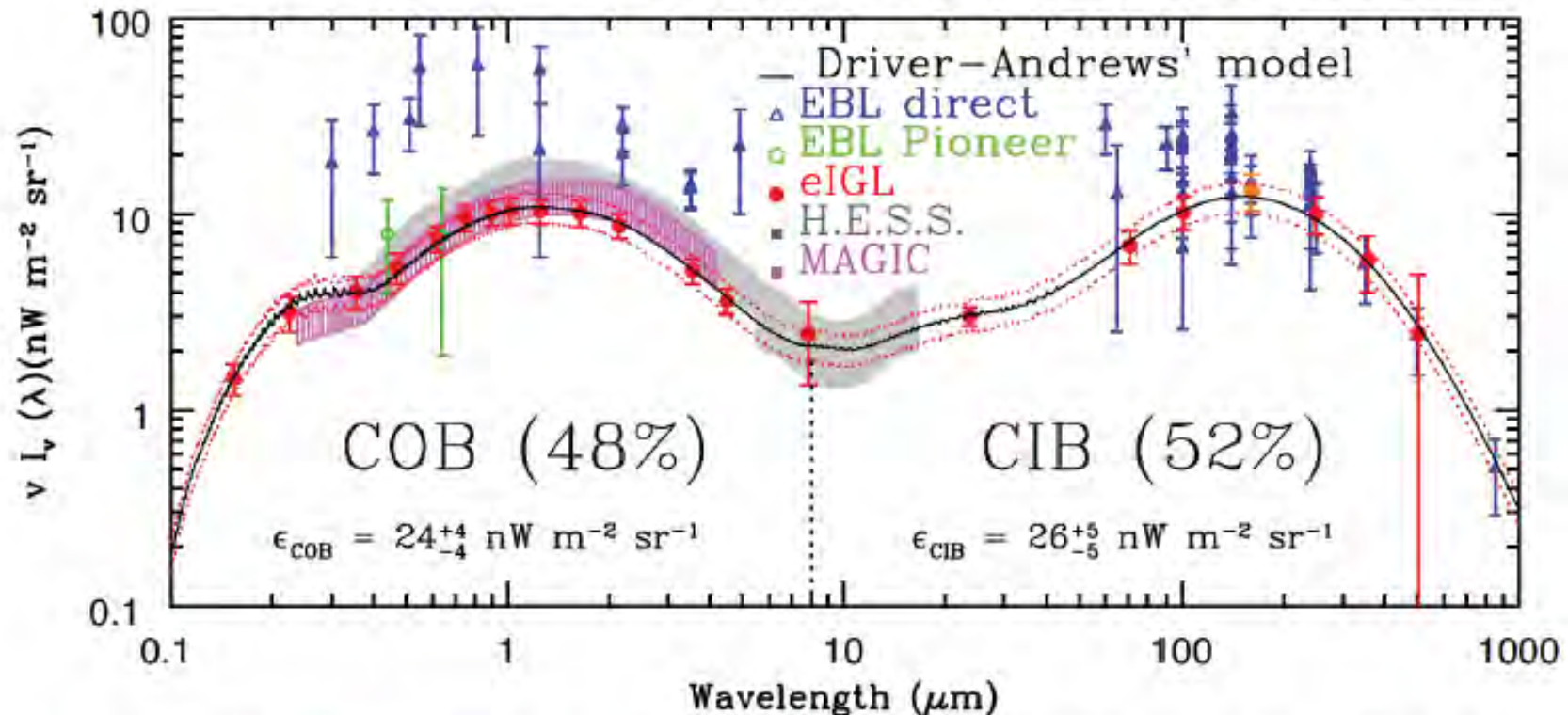
De-absorbed (Domínguez'2011)

Log-parabola fit

E (GeV)

MAGIC, submitted to A&A

12 hours of good data,
Spectral points up to optical depth τ=4
EBL scaling factor = 1.07(+0.24-0.20)$_{sta+sys}$

No EBL

Energy [GeV]

Best-fit EBL

Energy [GeV]
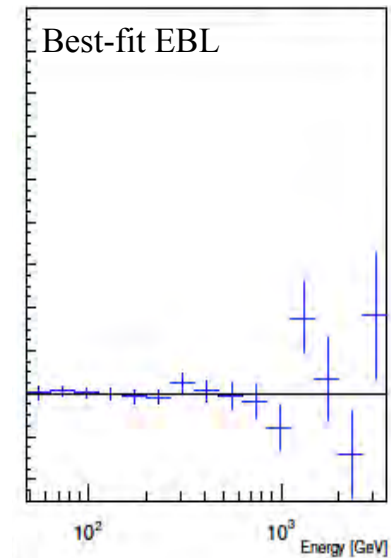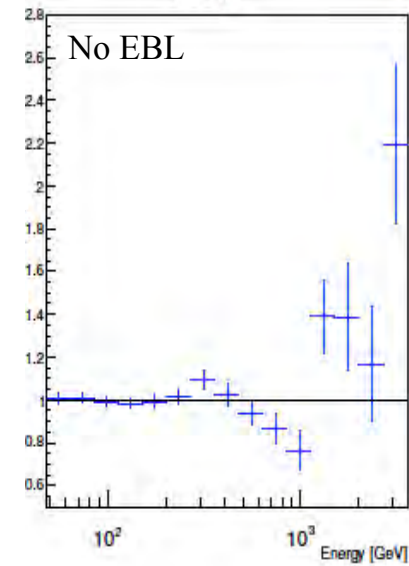
Summary of results on EBL

Driver+ arXiv:1605.01523v1 (2016)

- HESS and MAGIC results compatible with EBL models and also with the *extrapolated Integrated Galaxy Light* (same as galaxy counts but adding an extrapolation for the truncated luminosity functions)
- Both well below some of the direct EBL measurements
- Results not yet good enough to distinguish among state-of-the-art EBL models

Possible tension with data?

- Although overall EBL ~OK, there are some (marginal) indications of possible distortions ofthe spectra from far AGN

- Conversions of γs into Axion-Like Particles might reduce the opacity of the universe in particular energy ranges
  - 2007: De Angelis, Roncadelli, Mansutti (PL B659, PR D76)
  - 2007: Hooper & Serpico (PR D77), Mirizzi et al (Phys.Rev.D76)
 - 2008: Sanchez-Conde et al (PR D79)
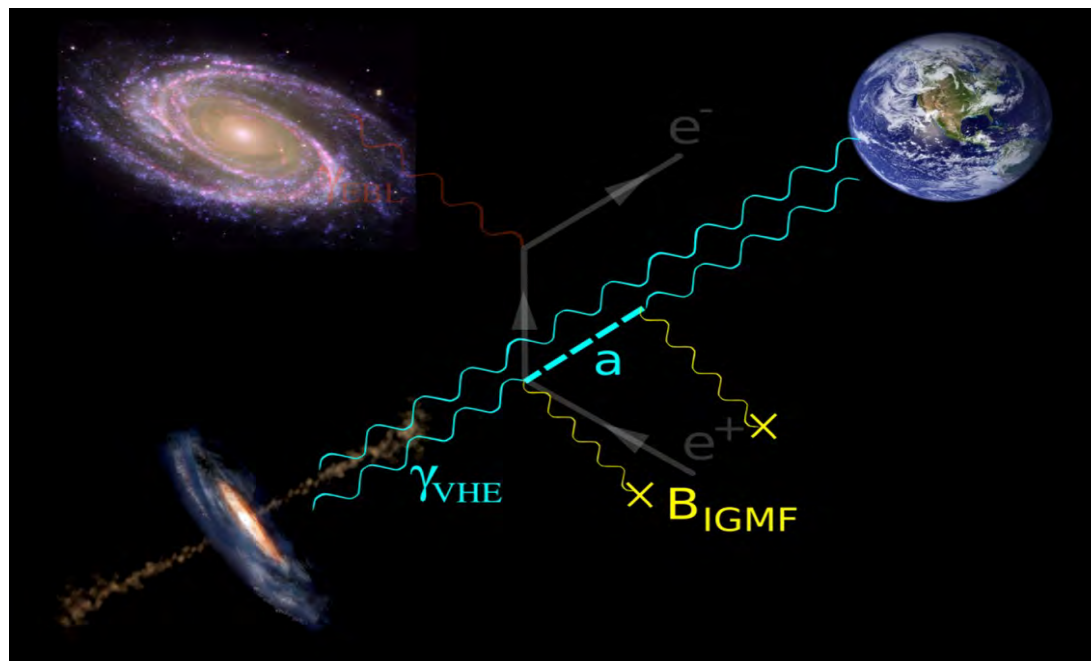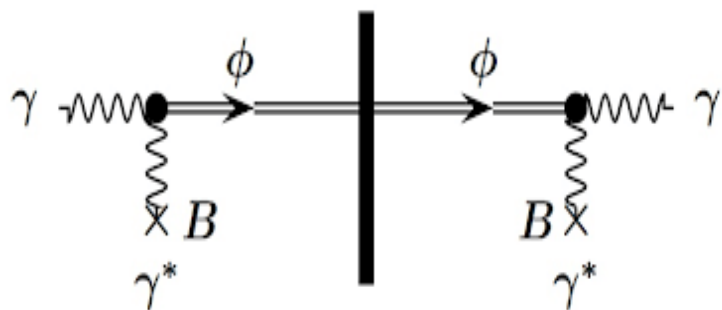
- Can this effect be detected also using anisotropies?

A win-win game: if no anomalous physics, determination of cosmological parameters

- Fluxes of VHE photons reaching the Earth have been attenuated due to the EBL density from observed spectra

$\Rightarrow$ Determine cosmological constants from observed HE spectra vs. fitted from lower energy

(Blanch & Martinez 2005; Dominguez & Prada 2013)
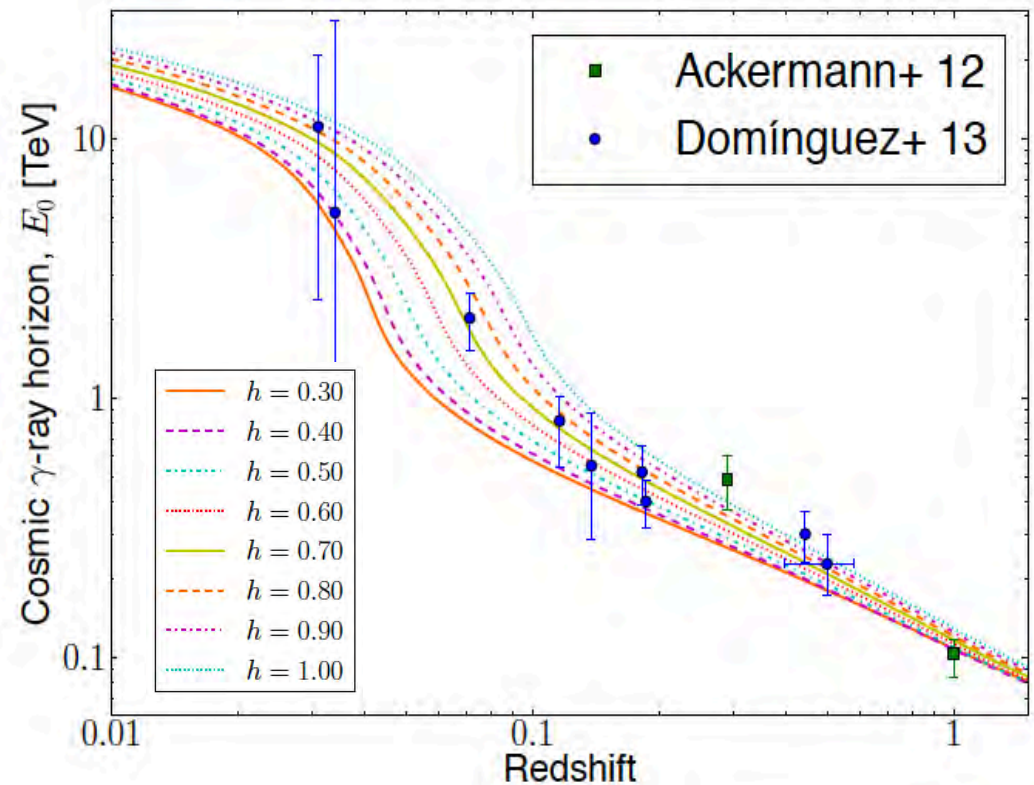
Cosmology

$$\tau(E,z) = \int_0^z \left(\frac{dl}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{th}}^\infty d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon',z')$$
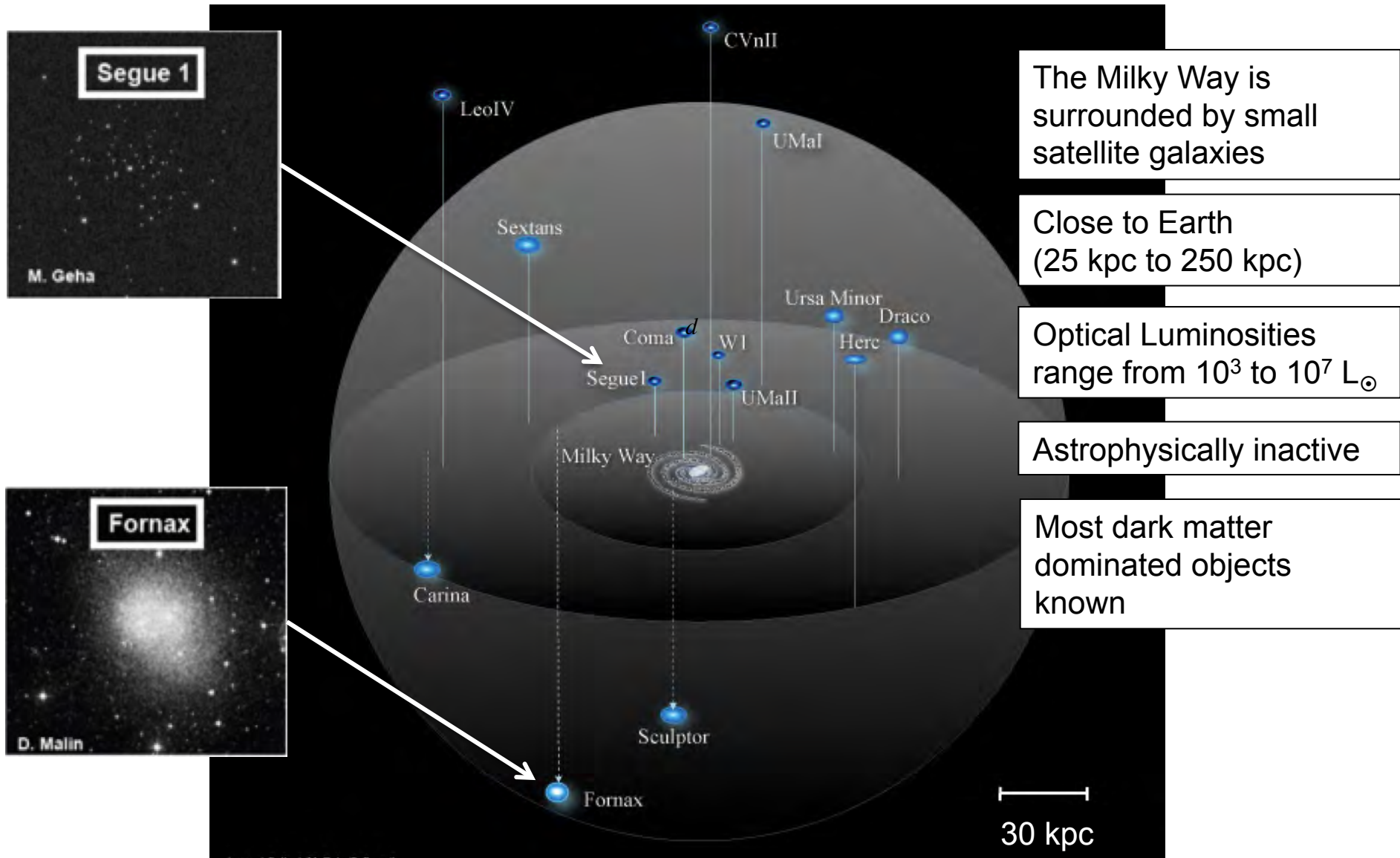
$$\left|\frac{dt}{dz'}\right| = \frac{1}{H_0(1+z')E(z')}$$

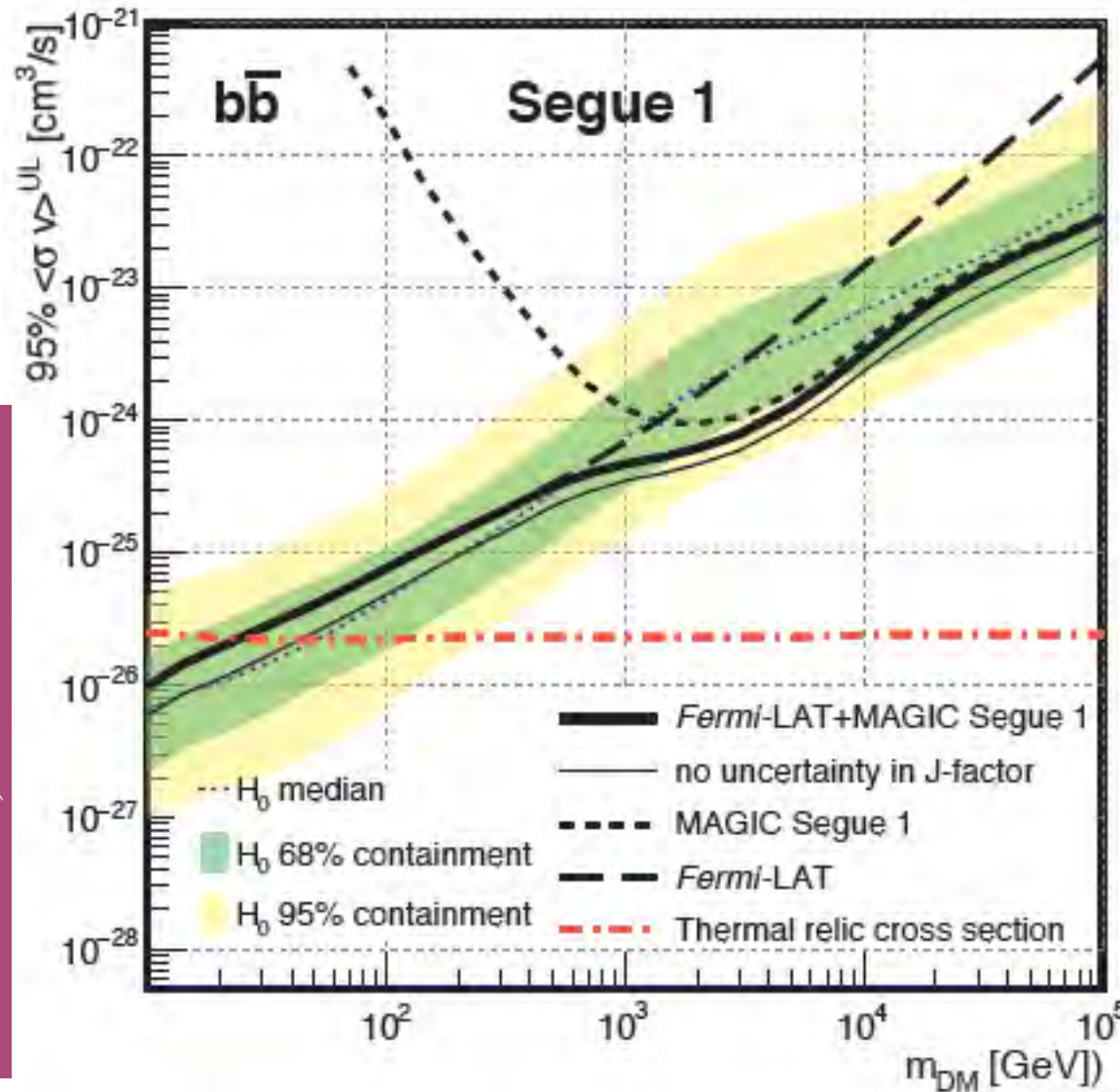$$E(z') \equiv \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

Dark matter searches

$$\frac{d\Phi}{dE} \propto \frac{<\sigma v>}{m^2} \sum_{BF} BF_i \left(\frac{dN_\gamma}{dE}\right)_i \int_{l.o.s.} \rho_{DM}^2\, d\ell$$

The Milky Way is surrounded by small satellite galaxies

Close to Earth
(25 kpc to 250 kpc)

Optical Luminosities range from 10^3 to 10^7 $L_\odot$

Astrophysically inactive

Most dark matter dominated objects known
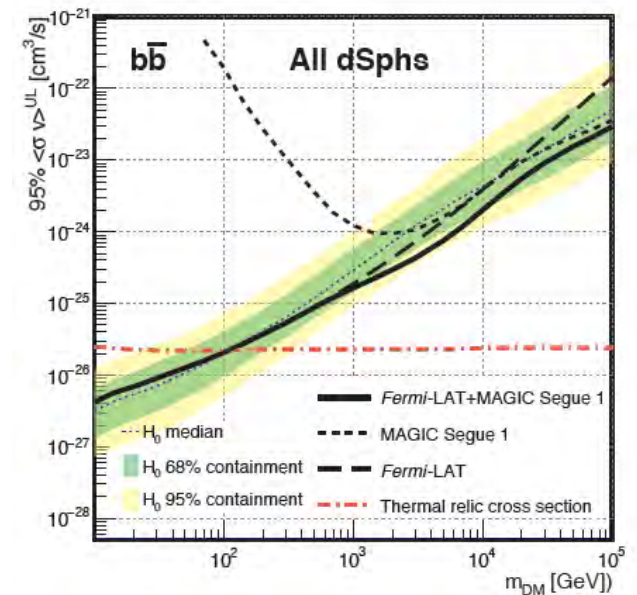
30 kpc

Dark matter searches: results

Large exposure (158h) of Segue 1 dSph galaxy

Result acknowledged by PDG

Combining MAGIC with Fermi data to further improve the limits

New inclusive analysis approach that is able to combine data from other detectors

MAGIC et al., JCAP2016

Summary

- 11 successful years of scientific operation (and counting)
  - 32 new VHE detections (24 AGNs; the farthest objects);
  - > 110 peer reviewed papers, 5 in Science

- MAGIC is at its most productive time in terms of physics (also best sensitivity)
  - → Acceleration mechanisms in pulsars
  - → Detailed broadband studies of Crab Nebula up to the highest energies
  - → Long term behaviour of binary systems and AGN
  - → Ultra fast variability in AGNs (minute scale)
  - → Increasing the accessible volume of the Universe with sources at z~1; measurements the EBL density at different redshifts
  - → Dark matter searches: best sensitivity on dark matter cross-section from dSph

- Collaboration efforts with Fermi, VERITAS, HESS, HAWC; follow-ups of GW and neutrinos

γ-ray detection: signal vs. background

- Is Crab Nebula easy to detect?

- Suppose to have a 100 x 100 m^2 detector with a resolution of 1 square degree:

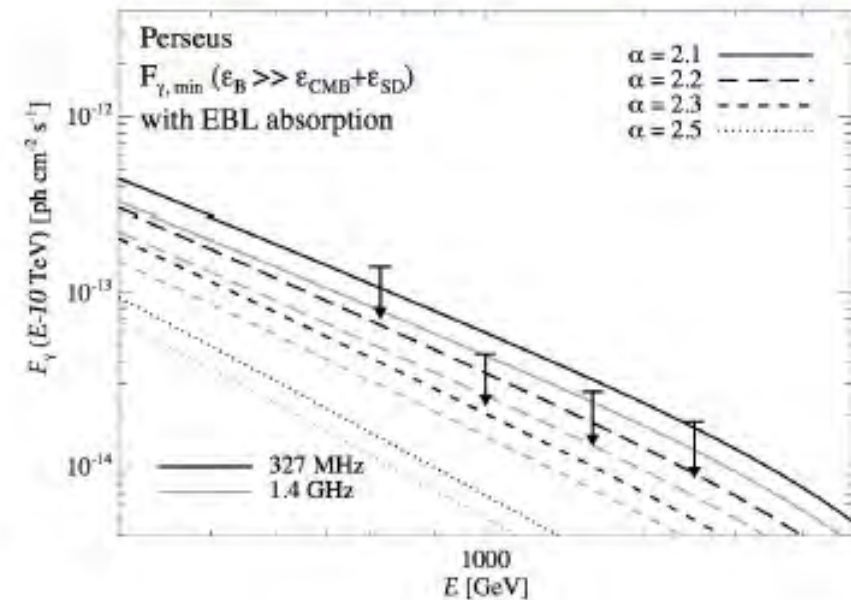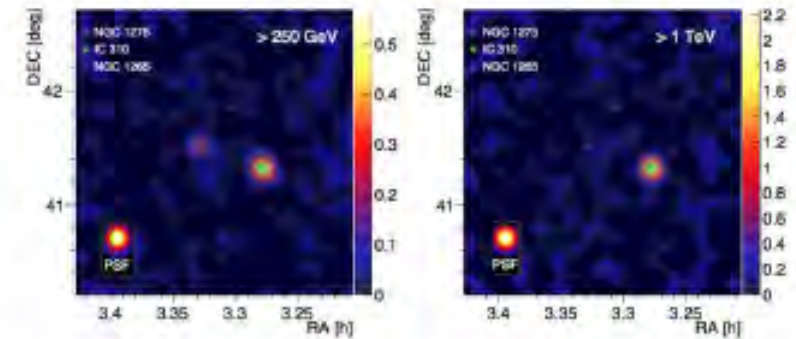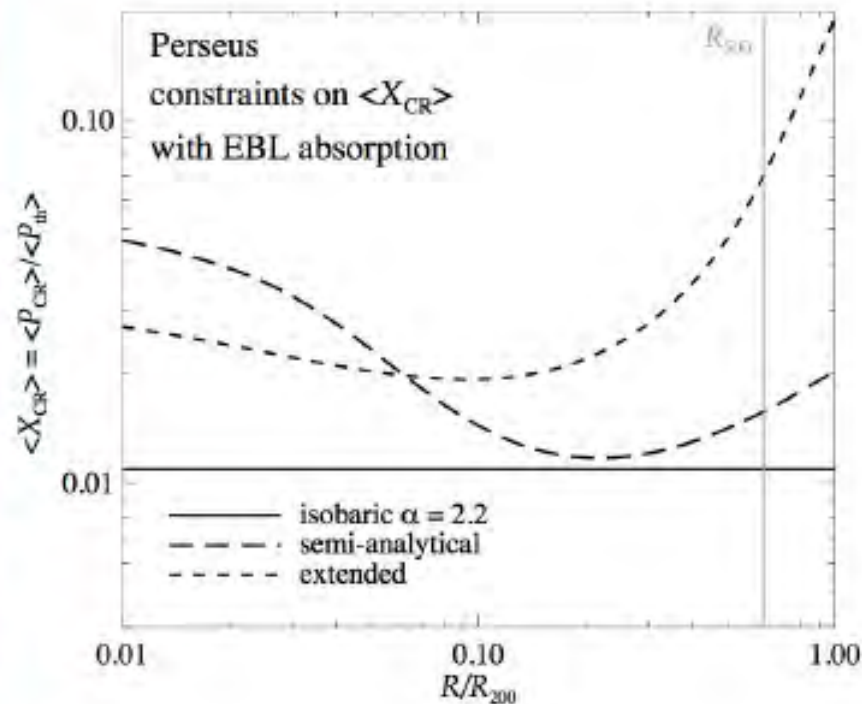Conceicao, De Angelis, Tome+ 2016)
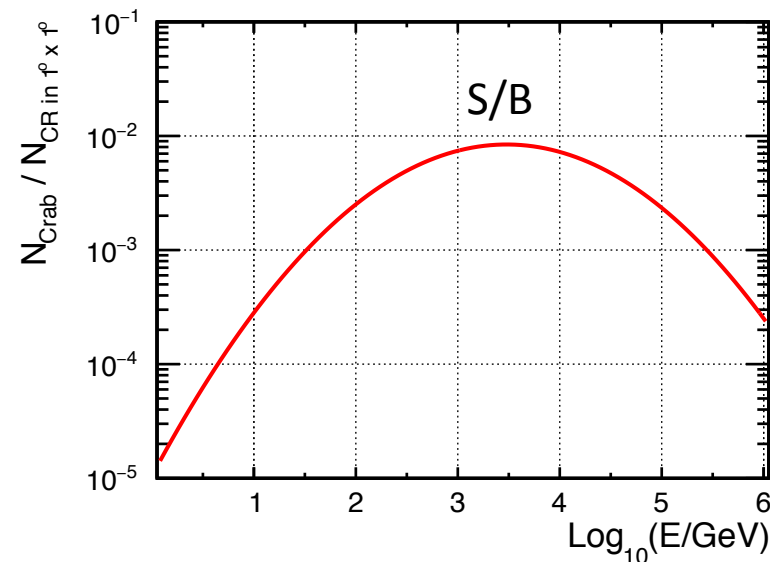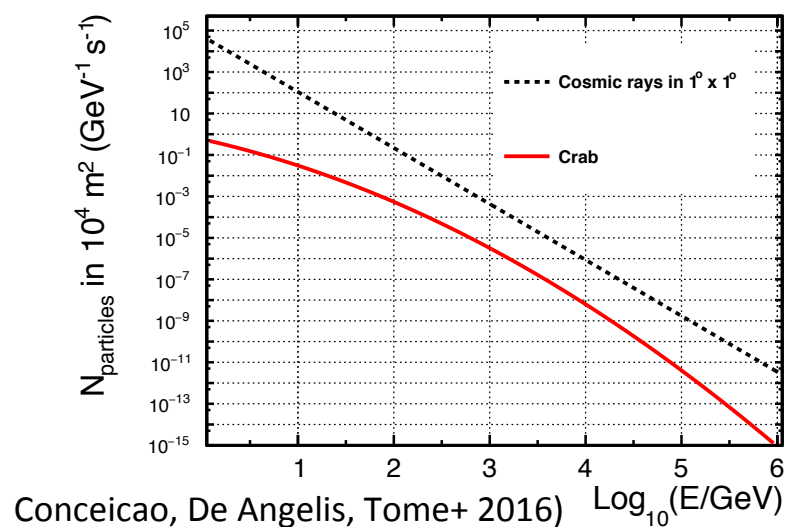
Conclusion: you need large effective area, good angular resolution, proton rejection

Diffuse gamma-rays from Cosmic Rays

Galaxy Clusters are expected to be a reservoir of CR → diffuse γ-rays from interaction with intrA-cluster medium

Ratio CR-to-thermal pressure < 1-2% (no extended) and CR spectral index > 2.1 (mini-halo by secondary e+)