Highlights from MAGIC

and what's next in the MultiMessenger/CTA era

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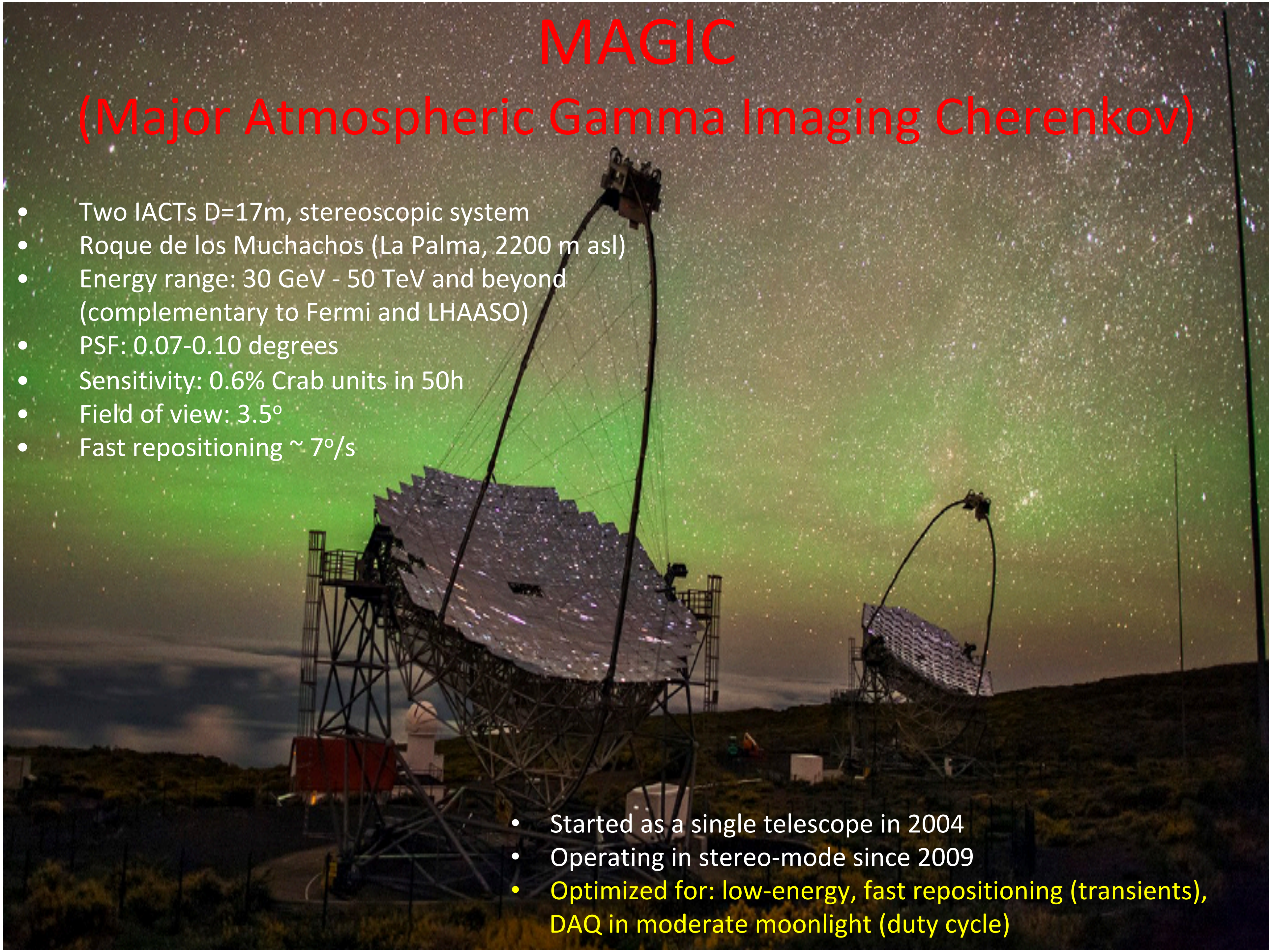
Roma, July 2020

Outline

- MAGIC
- Shortly, the highlight of last year
  - MAGIC and the search for transients
    - GRB190114C
    - Implications for fundamental physics, and prospects
- The future
  - Multimessenger
    - MM: lessons from the TXS 0506 +056 neutrino event
    - Neutrinos
  - Systematic studies
    - Sources
    - WIMPs
    - EBL
    - ALPs
  - La Palma: LST is on its (our) way

MAGIC

(Major Atmospheric Gamma Imaging Cherenkov)



- Two IACTs D=17m, stereoscopic system
- Roque de los Muchachos (La Palma, 2200 m asl)
- Energy range: 30 GeV - 50 TeV and beyond (complementary to Fermi and LHAASO)
- PSF: 0.07-0.10 degrees
- Sensitivity: 0.6% Crab units in 50h
- Field of view: 3.5°
- Fast repositioning ~ 7°/s

- Started as a single telescope in 2004
- Operating in stereo-mode since 2009
- Optimized for: low-energy, fast repositioning (transients), DAQ in moderate moonlight (duty cycle)

MAGIC: 180 Astro-Physicists From 12 Countries

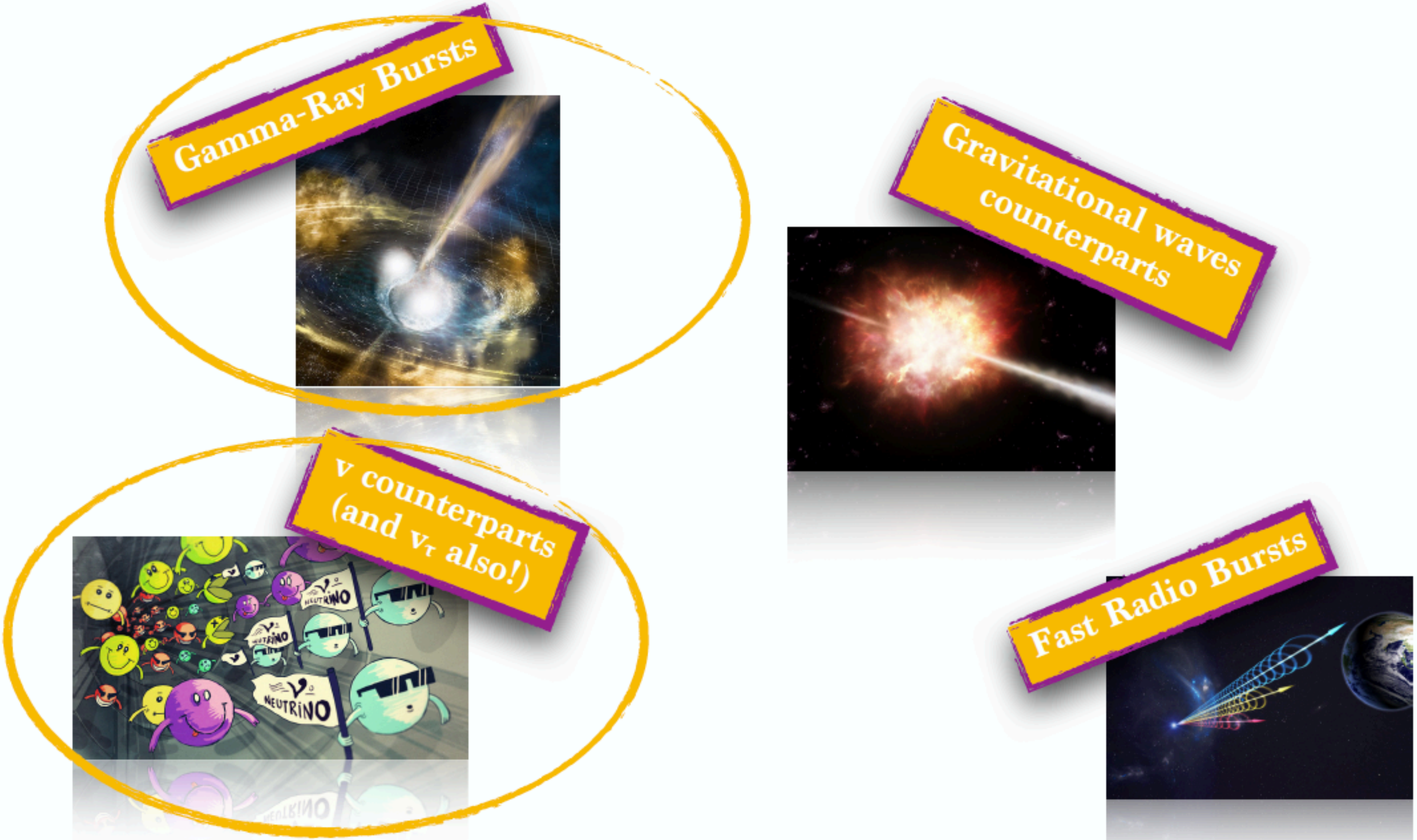
Armenia	ICRANet and Alikhanian Broth. Nat. Lab.
Bulgaria	Sofia nuclear Physics Institute
Brazil	CBPF Rio de Janeiro
Croatia	Consortium (Zagreb, +…)
Finland	Consortium (Tuorla, +…)
Germany	DESY Zeuthen, U. Dortmund, MPI Munich, U. Würzburg
Japan	Consortium (Kyoto, +…)
Italy	INFN & U. Padova, INFN Pisa & U. Siena, INFN Como/Milano Bicocca, INFN Udine/Trieste & U. Udine, INAF (Consortium: Rome, +…)
Poland	U. Lodz
Spain	U. Barcelona, UAB Barcelona, IEEC-CSIC Barcelona, IFAE Barcelona, IAA Granada, IAC Tenerife, U. Complutense Madrid, CIEMAT Madrid
Switzerland	ETH Zurich
India	Kolkata

Status of MAGIC: impact of COVID+

- The Roque de los Muchachos Observatory suffered in February an important storm with very strong winds (the largest at ORM in the last 20 years) and "calima" dust
  - Minor damages to mirrors/actuators
- At ~ the same time, the COVID storm
  - Fixings were a bit slowed down
  - Summer General Meeting (Padua) replaced with zoom
- We could restart data taking only in June

MAGIC and the search for transients

There is a very dense research program, each year about 15% of time invested on it



(M. Mallamaci)

Fast and smooth repointing (< 30 s)

A very sophisticated alert system, based on GCN and special agreements with IceCube, Ligo/Virgo, Fermi, …

- We can react ~20 s after a GCN trigger
- We can repoint the telescope within ~30 s

$\Rightarrow$ Latency < 1 min

System Basically operational since Aug 2005

TITLE: GCN GRB OBSERVATION REPORT
NUMBER: 3747
SUBJECT: GCN GRB observation 050713A
DATE: 05/08/03 19:30:58 GMT
FROM: Alessandro De Angelis at INFNandUdineU. <deangeli@fisica.uniud.it>

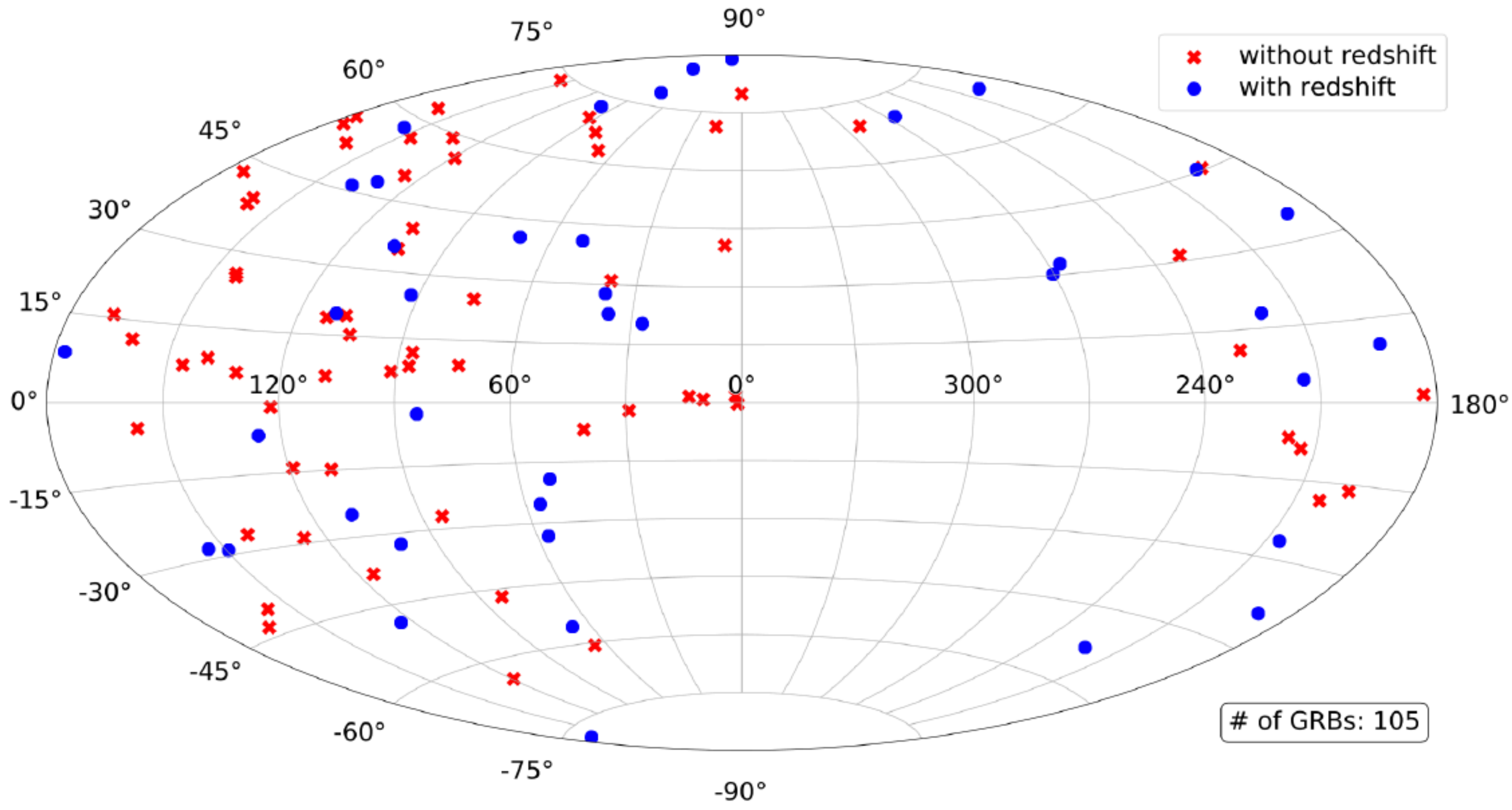
TITLE: GCN GRB OBSERVATION REPORT
SUBJECT: GRB 050713A: Observation at very high energy by MAGIC

N. Galante and Stamerra (INFN/Siena)
D. Bastieri, M. Fagiolini, M. Gaug, M. Garczarczyk, T. Lenisa, F. Longo,
K. Mannheim, S. Mizobuchi, A. Moralejo, R. Paoletti, L. Peruzzo, A Piccioli, S. Shore
on behalf of the MAGIC Collaboration:

"The MAGIC Cherenkov telescope in La Palma has observed GRB050713A 40s after T0.
This observation, started 20 seconds after the alert given
by Swift (Trigger #145675; Falcone et al., GCN Circ 3581), thanks to the
capability of fast pointing by MAGIC and to the prompt reaction by the operators; it
overlapped for around 30 seconds with Swift during the main burst,
and lasted 2400 s. The first look at the MAGIC data did not reveal strong gamma ray
emission above 175GeV. The flux limit derived at very
high energies by MAGIC is 2-3 orders of magnitude lower than the extrapolation from
the X band [1]. A detailed analysis is in progress. To our knowledge, this is the first
simultaneous observation of a GRB in the X band and in the HE gamma region."

[1] A. Falcone, private communication.

…and we have observed > 100 GRBs since Aug 2005



…until, after a few marginal signals, we got the big one

The Astronomer's Telegram

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

Offline analyses revealed signal > 50 σ

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to

nature

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

4366 Accesses | **493** Altmetric | Metrics

Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies (from radio waves to gigaelectronvolt γ-rays), which originates from synchrotron radiation generated by energetic electrons in the accompanying shock waves[3,4]. Although emission of γ-rays at even higher (teraelectronvolt) energies by other radiation mechanisms has been theoretically predicted[5,6,7,8], it has not been previously detected[7,8]. Here

nature

Article | Published: 20 November 2019

Observation of inverse Compton emission from a long γ-ray burst

MAGIC Collaboration, P. Veres, [...] D. R. Young

Nature **575**, 459–463(2019) | Cite this article

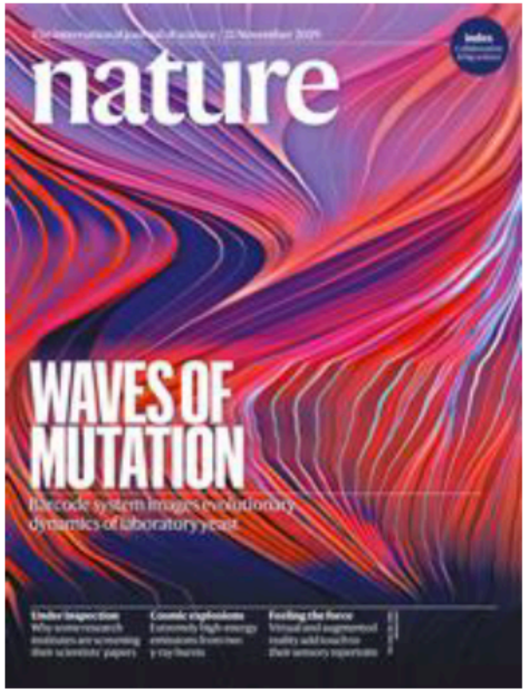
4707 Accesses | **758** Altmetric | Metrics

Abstract

Long-duration γ-ray bursts (GRBs) originate from ultra-relativistic jets launched from the collapsing cores of dying massive stars. They are characterized by an initial phase of bright and highly variable radiation in the kiloelectronvolt-to-megaelectronvolt band, which is probably produced within the jet and lasts from milliseconds to minutes, known as the prompt emission[1,2]. Subsequently, the interaction of the jet with the surrounding medium generates shock waves that are responsible for the afterglow emission, which lasts from days to months and occurs over a broad energy range from the radio to the gigaelectronvolt bands[1,2,3,4,5,6]. The afterglow emission is generally well explained as synchrotron radiation emitted by electrons accelerated by the external shock[7,8,9]. Recently, intense long-lasting emission between 0.2 and 1 teraelectronvolts was observed from GRB 190114C[10,11]. Here we report

MAGIC discovery paper: received 10 May 2019, accepted 2 September 2019

4 publications appeared in Nature in November 21st 2019 issue



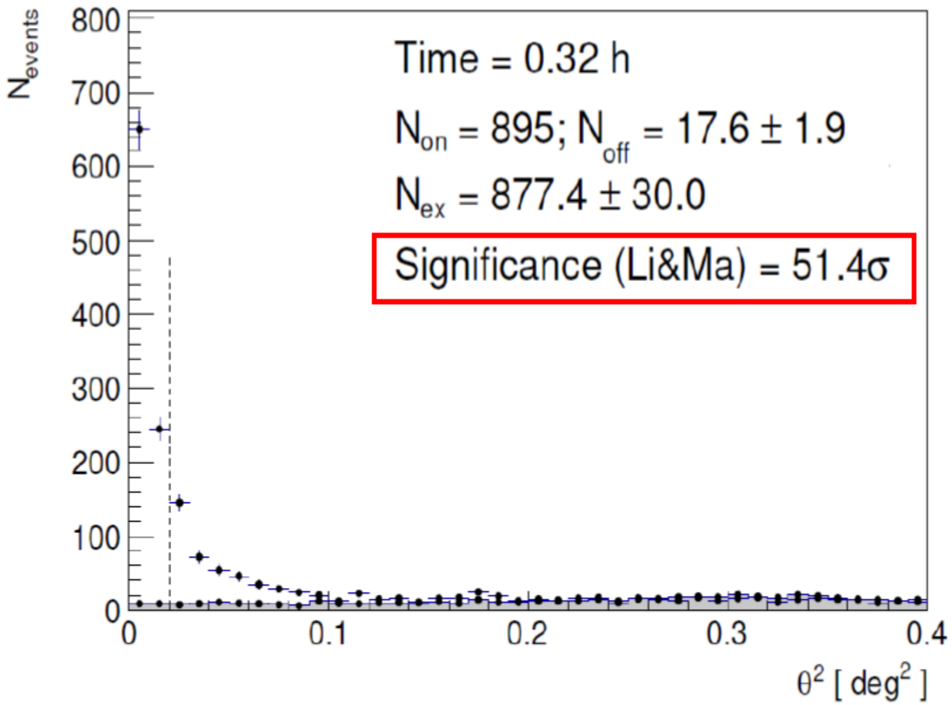
News & Views | 20 November 2019
Bing Zhang
Extreme emission seen from γ-ray bursts

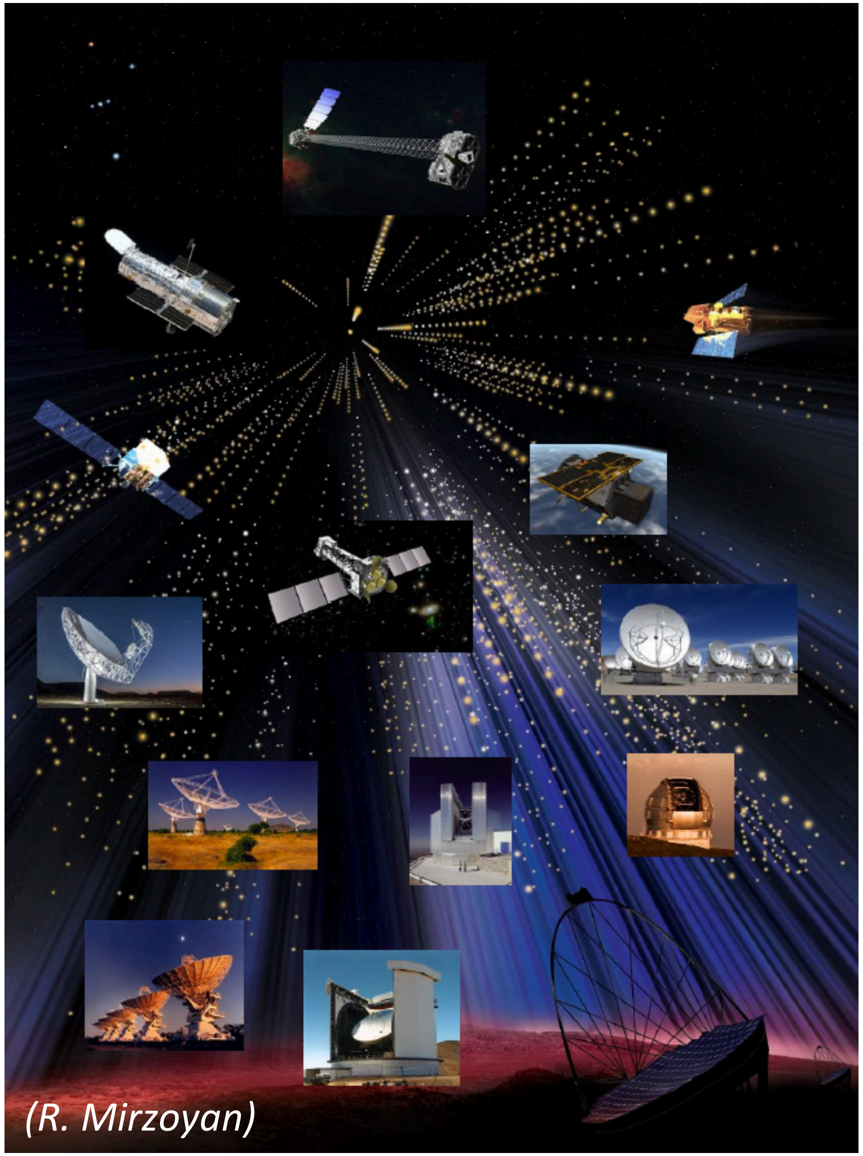
Teraelectronvolt emission from the γ-ray burst GRB 190114C
Acciari, et al., MAGIC Collaboration
Observations of teraelectronvolt-energy γ-rays starting about one minute after the γ-ray burst GRB 190114C reveal a distinct component of the afterglow emission with power comparable to the synchrotron emission.

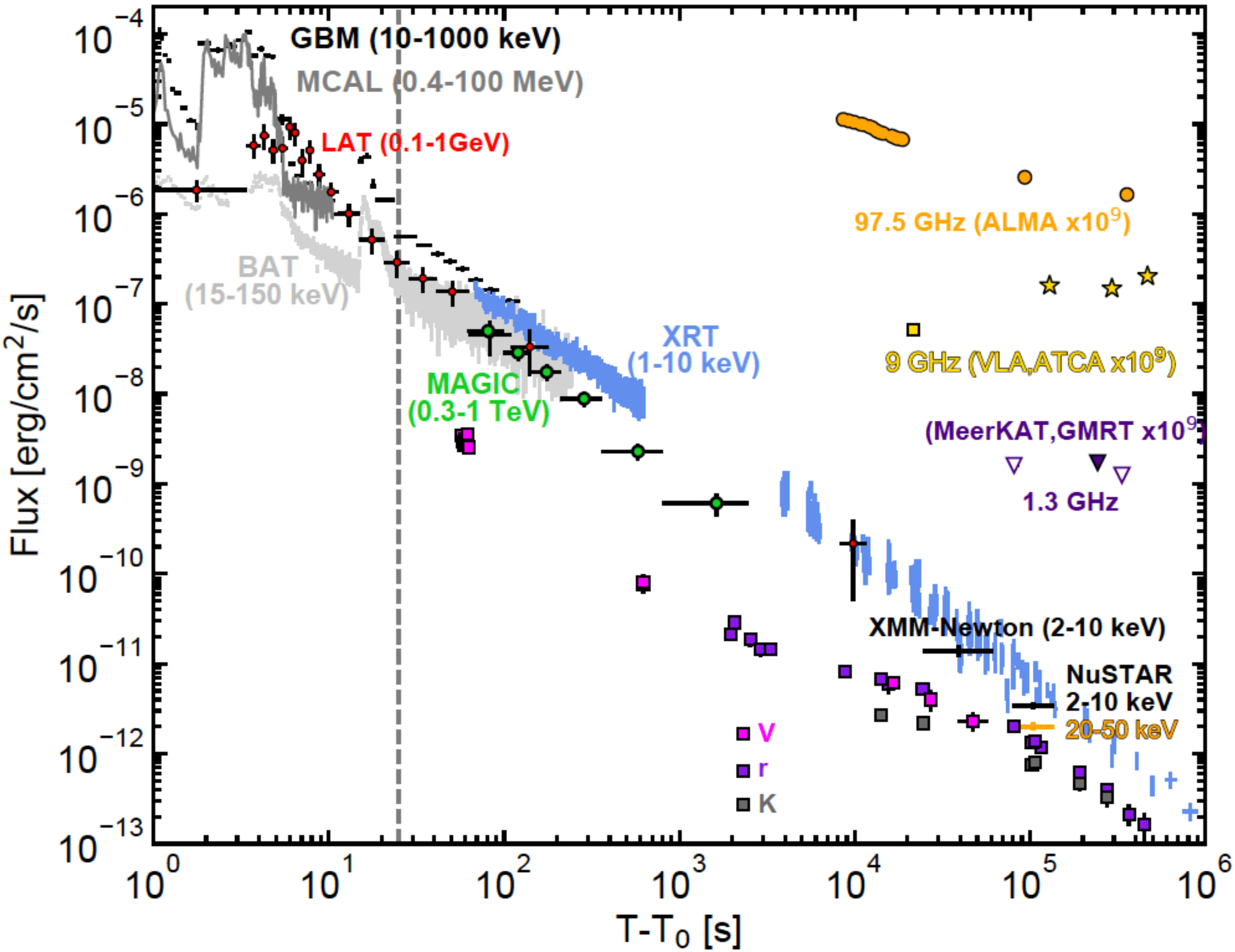
Observation of inverse Compton emission from a long γ-ray burst
MAGIC Collaboration, et al.,
A multi-frequency observing campaign of the γ-ray burst GRB 190114C reveals a broadband double-peaked spectral energy distribution, and the teraelectronvolt emission could be attributed to inverse Compton scattering.

A very-high-energy component deep in the γ-ray burst afterglow
Abdalla, et al., H.E.S.S. Collaboration
Very-high-energy γ-rays observed ten hours after the prompt emission of the γ-ray burst 180720B can be attributed to either an inverse Compton or an extreme synchrotron process.

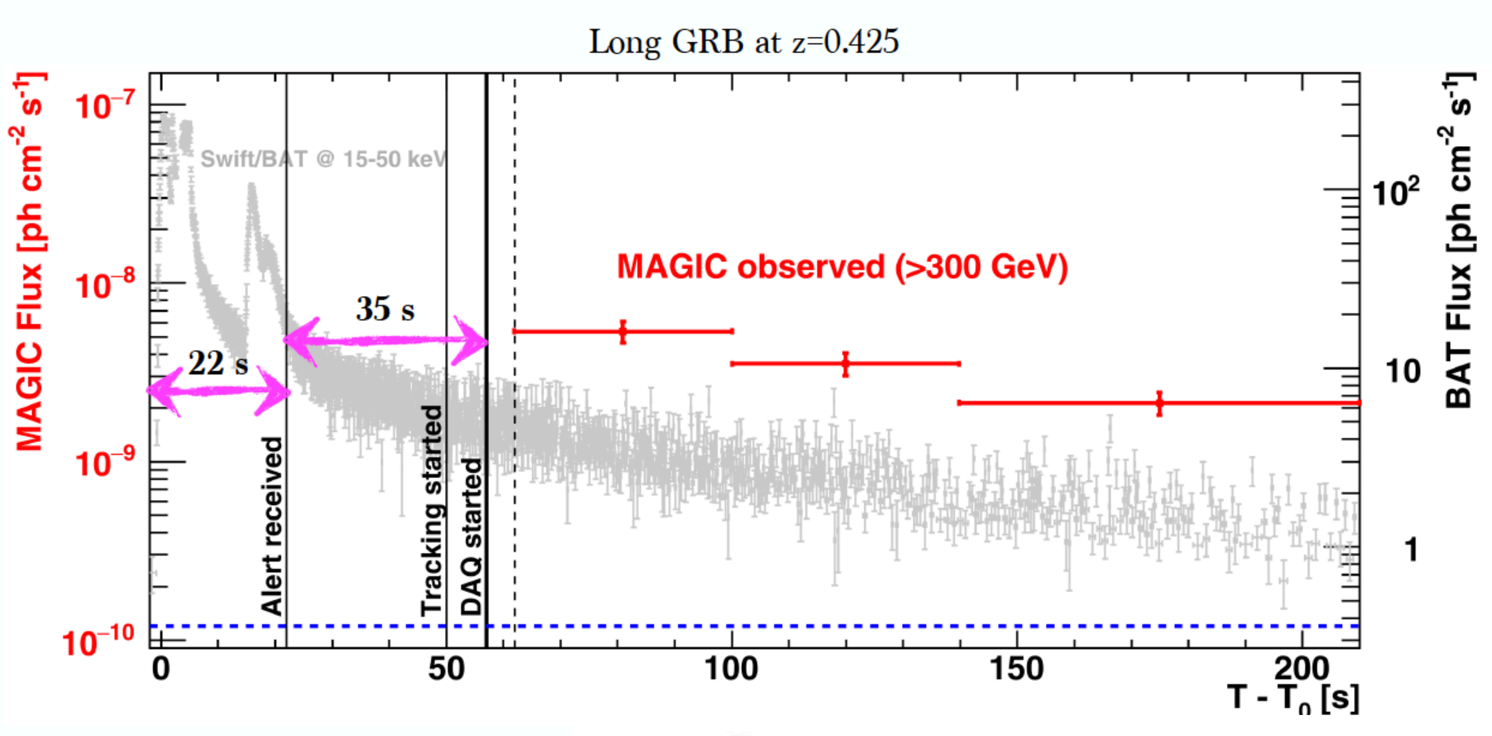
To give an idea, the signal in the first 30 s was ~130 Crab
Some shifters thought it was a fake alert
>30 σ quickly reached. But many detected it…

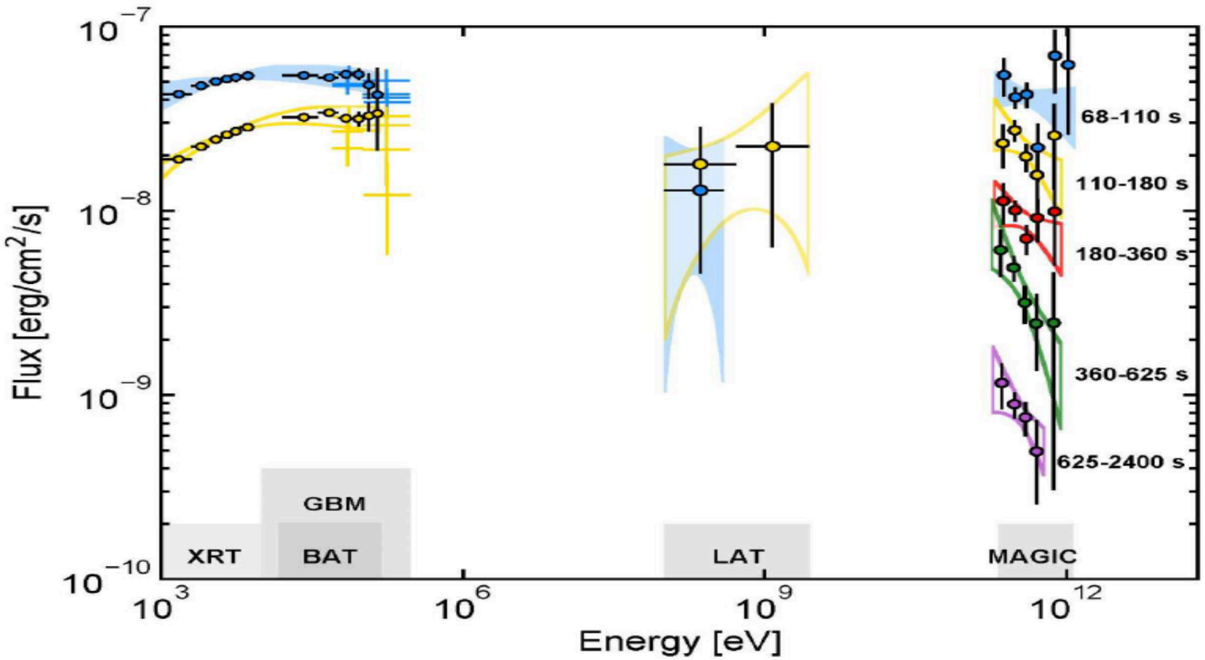




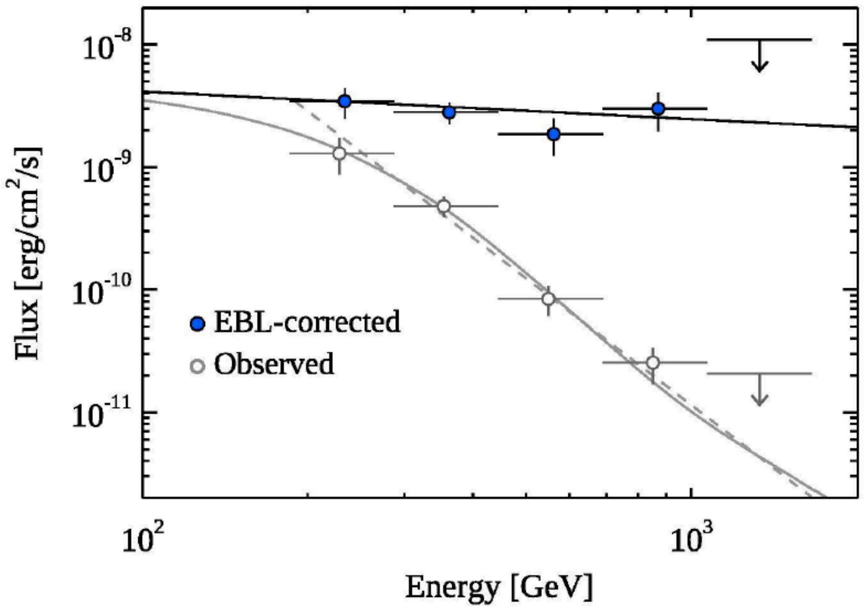


GBM (10-1000 keV)
MCAL (0.4-100 MeV)
LAT (0.1-1GeV)
BAT (15-150 keV)
XRT (1-10 keV)
MAGIC (0.3-1 TeV)
97.5 GHz (ALMA x10^9)
9 GHz (VLA,ATCA x10^9)
(MeerKAT,GMRT x10^9)
1.3 GHz
XMM-Newton (2-10 keV)
NuSTAR
2-10 keV
20-50 keV
V
r
K
Flux [erg/cm^2/s]
T-T0 [s]

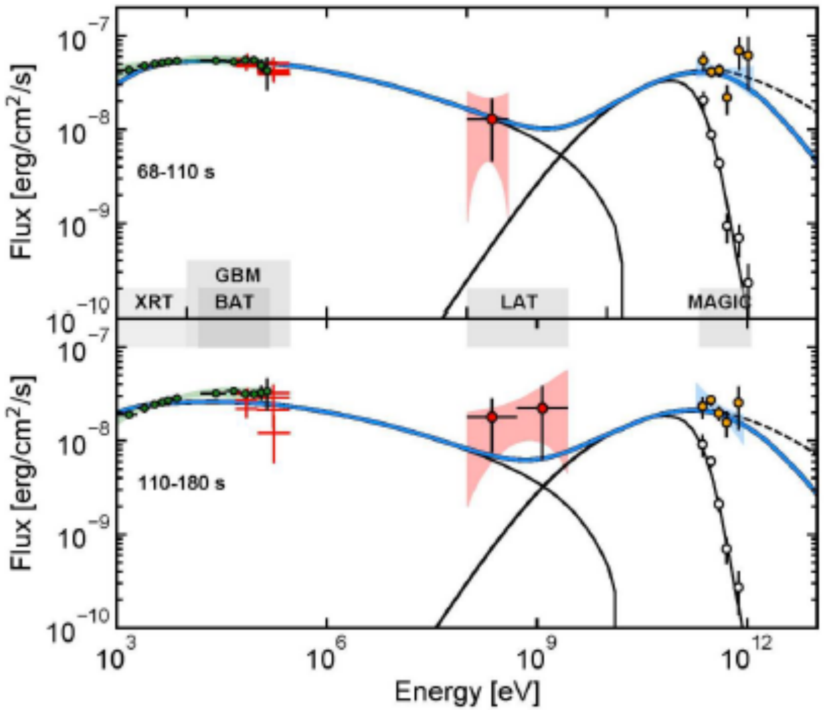

Long GRB at z=0.425
MAGIC Flux [ph cm^{-2} s^{-1}]
BAT Flux [ph cm^{-2} s^{-1}]
Swift/BAT @ 15-50 keV
MAGIC observed (>300 GeV)
22 s
35 s
Alert received
Tracking started
DAQ started
T - T$_0$ [s]


Flux [erg/cm^2/s]
Energy [eV]
68-110 s
110-180 s
180-360 s
360-625 s
625-2400 s
XRT
GBM
BAT
LAT
MAGIC

Spectrum above 0.2 TeV over the period between T0 + 62 s & T0 + 2454 s



- Note the double-peak structure, resembling the well-known pattern from blazars SED
- The energy in the Compton peak is comparable to the energy in synchrotron



Recently: GRB190114C used for constraining Lorentz-Invariance Violation (source far away, large E interval…)

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

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

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

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

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

1st order: $$\boxed{\Delta t_\gamma \cong T \Delta E \frac{\xi}{E_P}}$$

…and 2nd order IACTs (and LHAASO) rule!

$$E^2 \simeq p^2 \times \left[1 - \sum_{n=1}^{\infty} s \left(\frac{E}{E_{\rm QG,n}}\right)^n\right],$$

$$v_\gamma \simeq 1 - \sum_{n=1}^{\infty} s \frac{n+1}{2} \left(\frac{E}{E_{\rm QG,n}}\right)^n,$$

which can be subluminal or superluminal, for $s = +1$ or $s = -1$, respectively. This results in an energy-dependent time delay between photons. Taking into account only the leading LIV correction of order n, the time delay between photons of energy difference ΔE is

$$\Delta t = s \frac{n+1}{2} D_n(z) \left(\frac{\Delta E}{E_{\rm QG,n}}\right)^n,$$

$$D_n(z) = \frac{1}{H_0} \int_0^z \frac{(1+\zeta)^n}{\sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}} d\zeta,$$

Results, and possibilities

Phys. Rev. Lett. 125, 021301 (2020)

Source	Source type	Redshift	$E_{QG,1}$ $[10^{19}$ GeV$]$	$E_{QG,2}$ $[10^{10}$ GeV$]$	Instrument
GRB 090510	GRB	0.9	9.3	13	*Fermi*-LAT[1]
GRB 190114C_{Min}	GRB	0.42	0.28	7.3	MAGIC
GRB 190114C_{Th}	GRB	0.42	0.59	6.3	MAGIC
PKS 2155-304	AGN	0.116	0.21	6.4	H.E.S.S.[2]
Mrk 501	AGN	0.034	0.036	8.5	H.E.S.S.[3]
Mrk 501	AGN	0.034	0.021	2.6	MAGIC[4]
Mrk 421	AGN	0.031	pending	pending	MAGIC
Crab Pulsar	Pulsar	2.0 kpc	0.055	5.9	MAGIC[5]

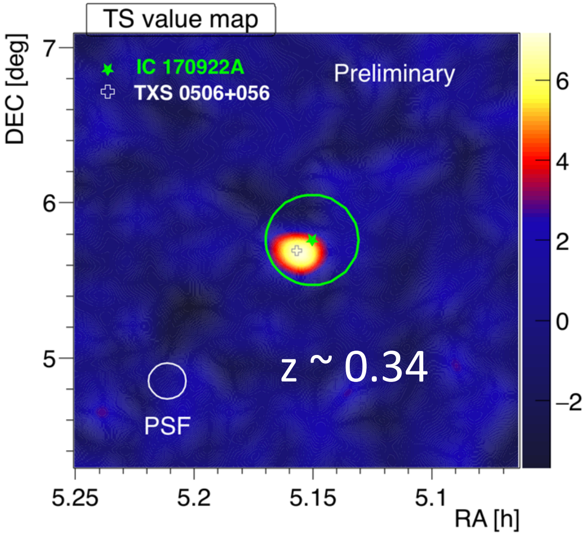
- 1st order violation: sensitivity of Fermi is out of reach
- 2nd order: limits comparable with HESS PKS 2155, MKN501

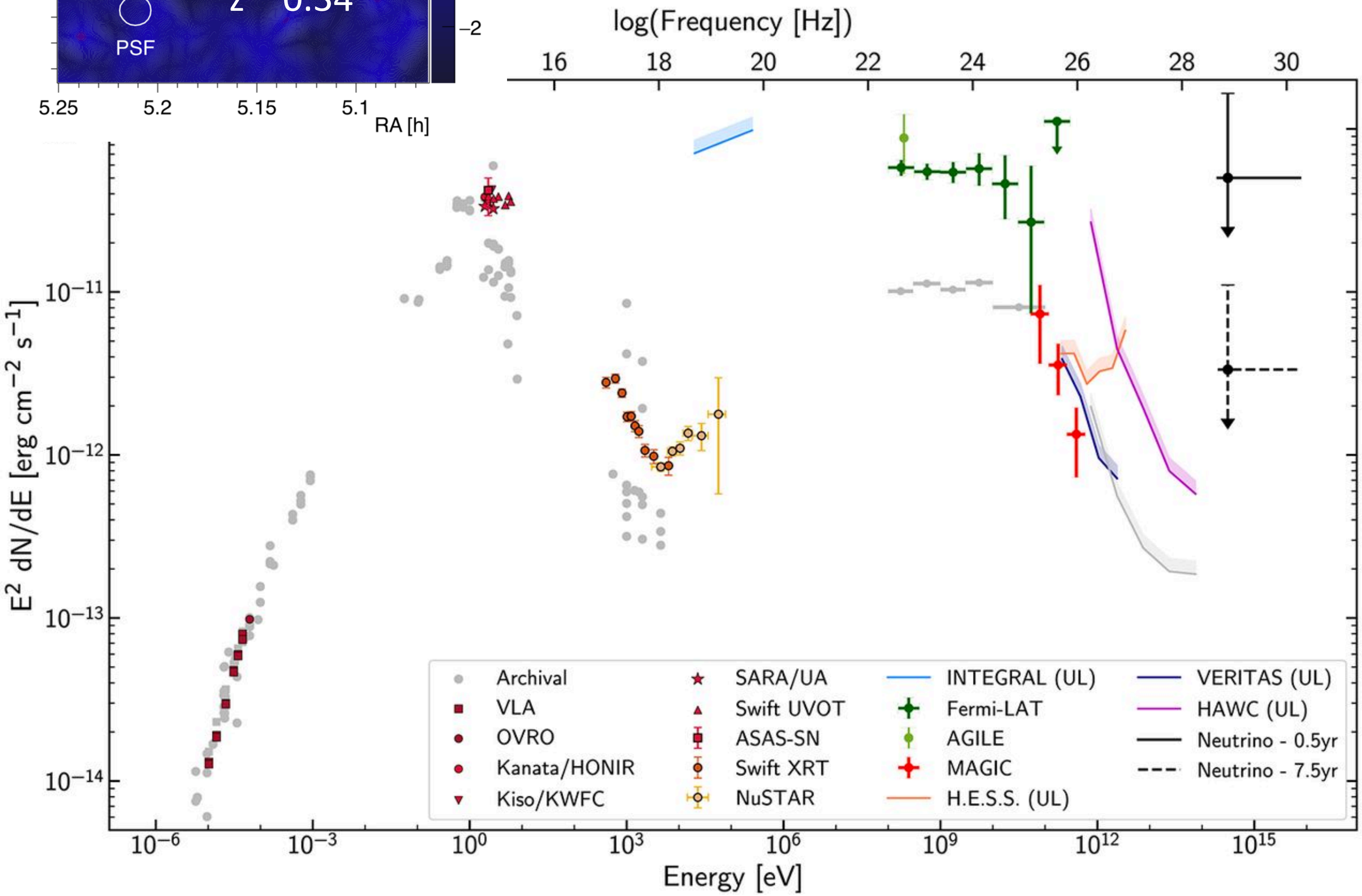
- Another analysis will possibly be performed (weighted bins, LIV & mean free path)
- But… Now we know we can detect GRBs

A few things going on in MAGIC
(with a bias for fundamental physics)

MM with neutrinos

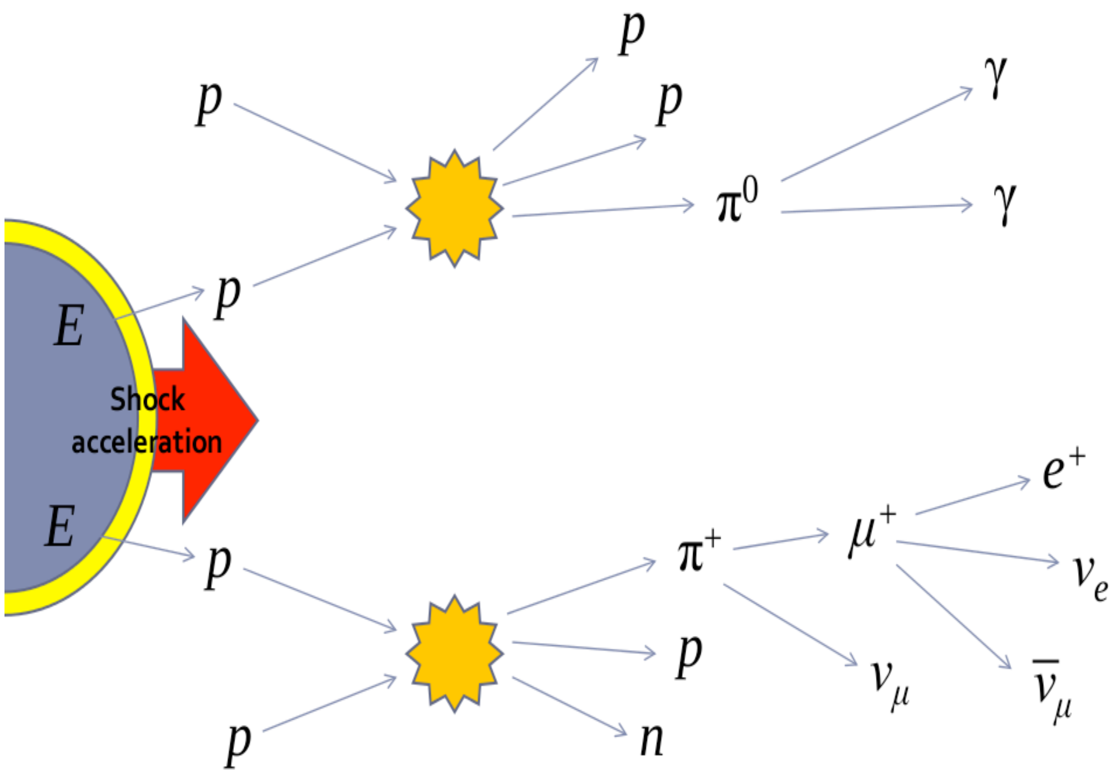
- The TXS0506 +056 event has opened a new window in MM astrophysics





γ and ν in cosmic accelerators:

hadronic mechanisms (pp, pγ) produce both



Neutral mesons decay in **photons**:

$\pi^o \rightarrow \gamma\gamma$

charged mesons decay in **neutrinos**:

$\pi^+ \rightarrow \nu_\mu + \mu+$

$\mu^+ \rightarrow \nu_\mu + \nu_e + e^+$

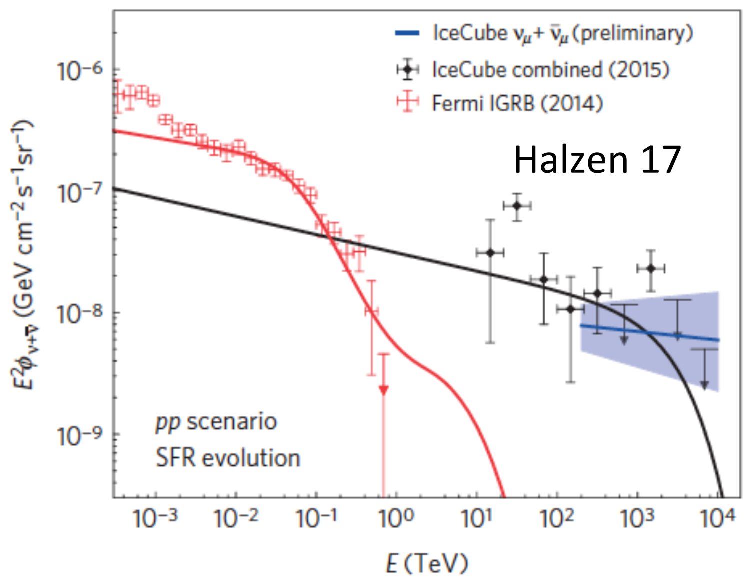
$\pi^- \rightarrow \nu_\mu + \mu^-$

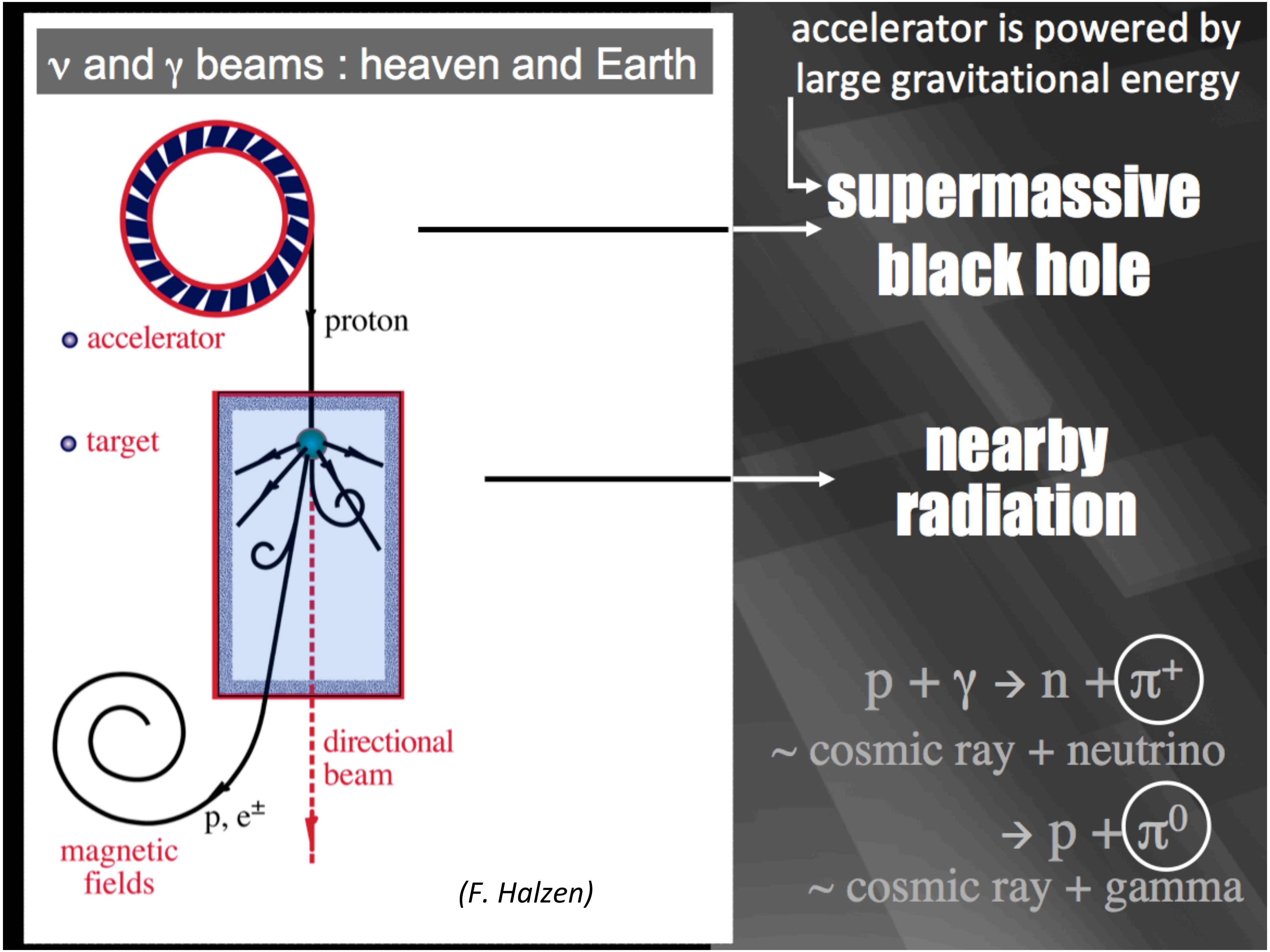
$\mu^- \rightarrow \nu_\mu + \nu_e + e^-$

Flux ν ~ Flux γ

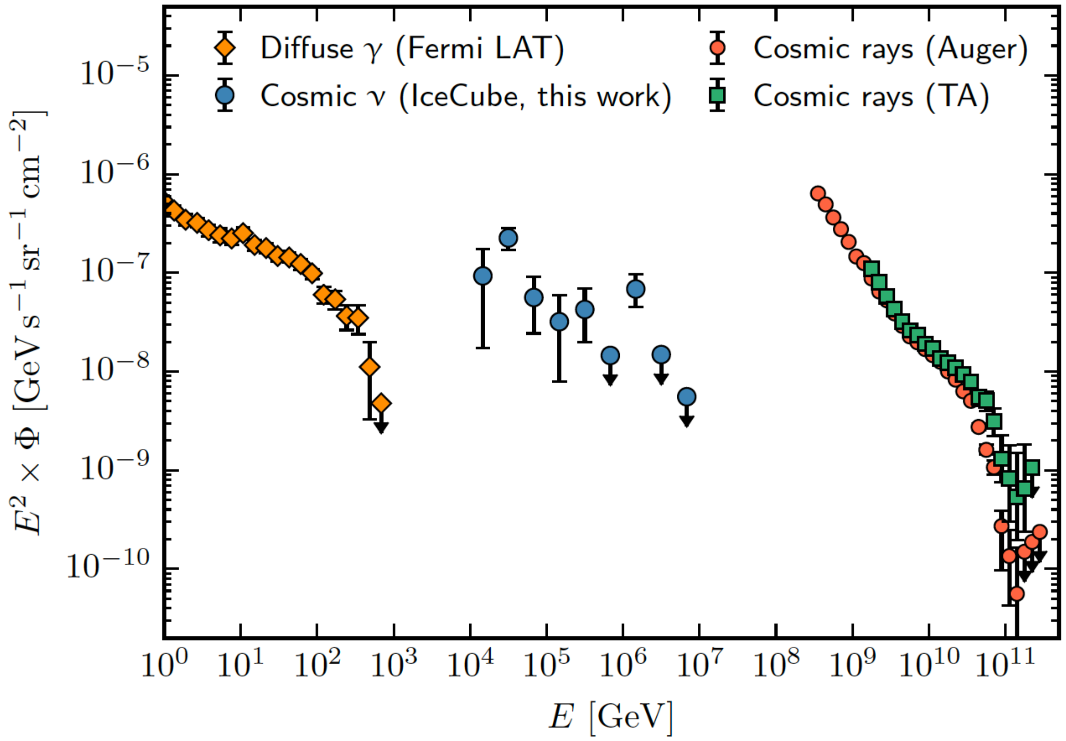
Diffuse flux of neutrinos

- Gamma rays are likely to be reprocessed in the target/ dump (photons? protons?), to shower and degrade they energy - this might explain the shift in the E distribution of the extragalactic background of γ vs. ν, as well as the energy difference between the MAGIC gamma rays and the IceCube neutrino




ν and γ beams : heaven and Earth
accelerator is powered by large gravitational energy
supermassive black hole
nearby radiation
accelerator
proton
target
directional beam
magnetic fields
p, e±
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma
(F. Halzen)

γ - ν connection



- Looking for clusters of neutrino events in the sky
  - Point source searches
  - Needs bigger neutrino detectors
- Looking for coincidences gamma rays/neutrinos (flaring sources)
  - Multimessenger search: requires space and time coincidences with other probes (GW, photons; in this last case time delays are possible)
  - If we see neutrinos and gammas from the same source, we can measure the “size” of the target (beam dump) by comparing their energy distributions

MoU with IceCube

public
- Follow-up of high-energy neutrinos from IceCube

private
- Follow-up of neutrino clusters from IceCube (catalogue-based + all-sky). Specific programs aimed at gamma-ray and optical telescopes.

→ MoU with Imaging Air Cherenkov Telescopes

Most of this real-time infrastructure has been developed for **Gamma-ray Follow-up** (GFU) pioneered by the collaboration with MAGIC.

2019 news from MAGIC

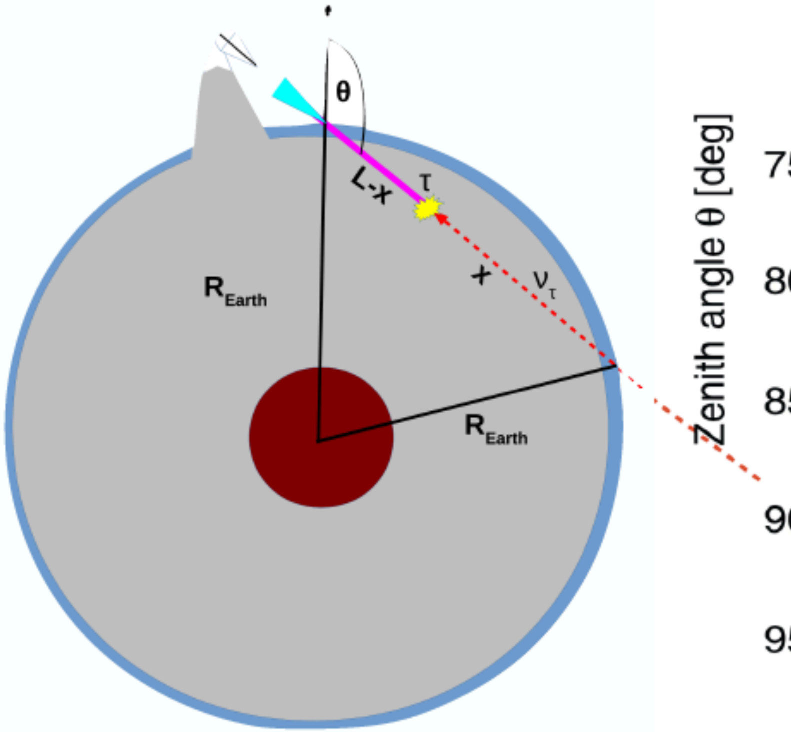
- Follow-up of 6 alerts for a total about 15 hours of observations
- The MAGIC Automatic Alert System is optimised and works for automatically repointing to gold alerts.

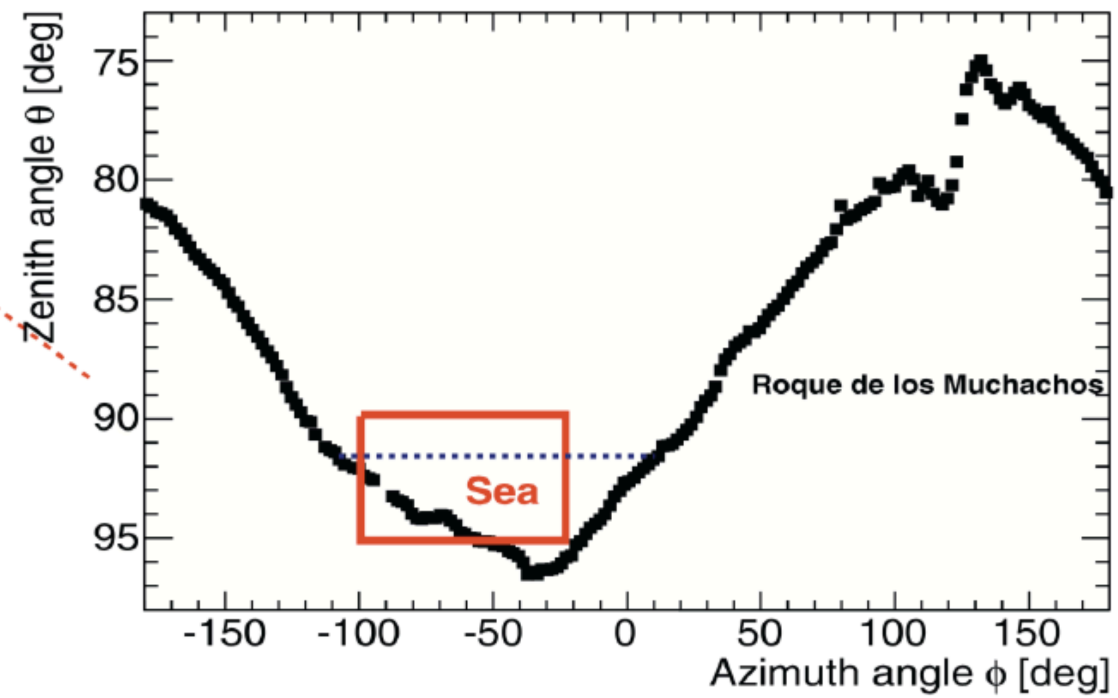
(M. Mallamaci)

Thanks to the possibility of pointing below the horizon, MAGIC can also be by itself a neutrino detector

Earth-skimming technique for the detection of high-energy τ-neutrinos

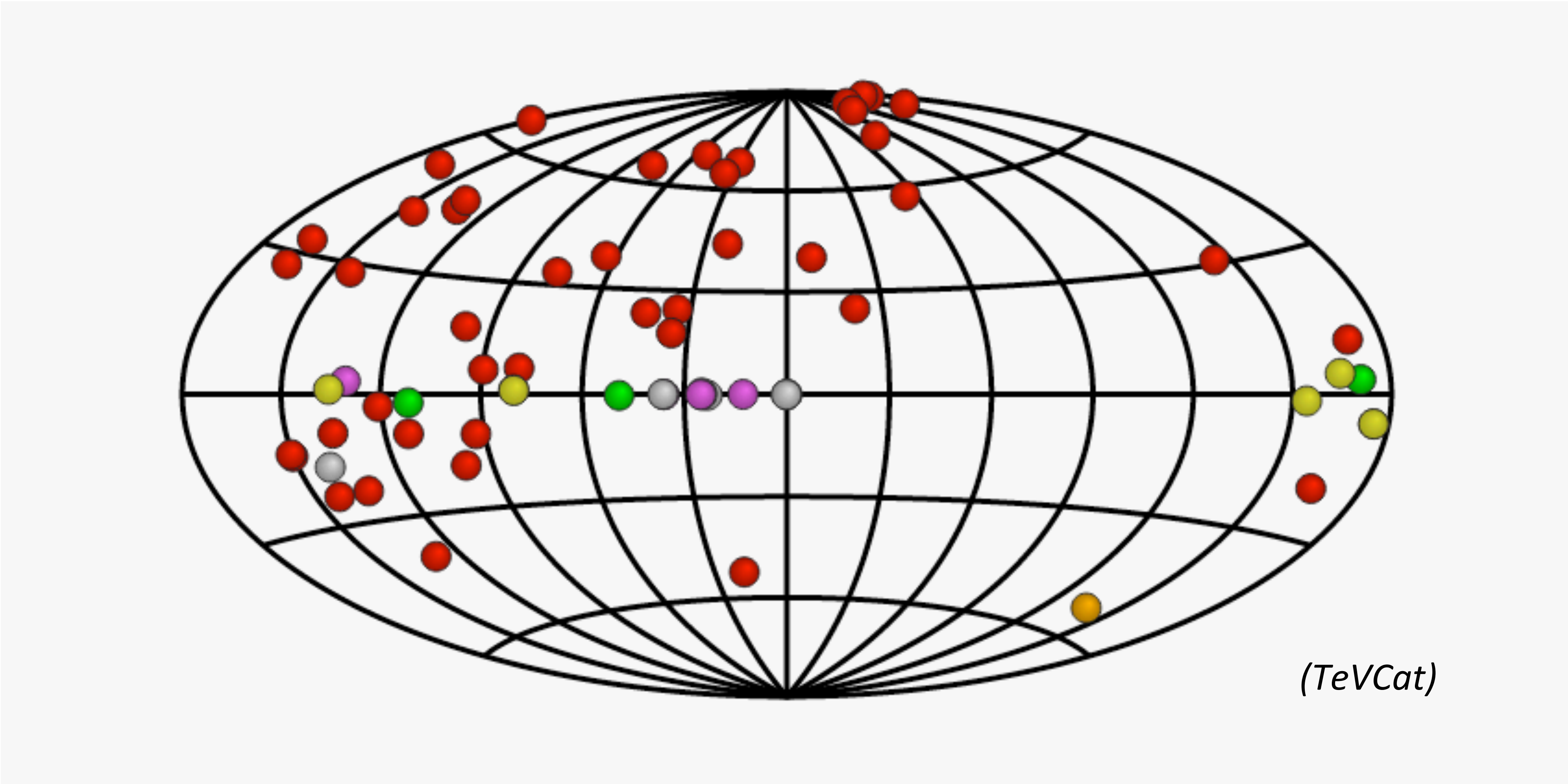
(M. Mallamaci)





MAGIC can observe τ-lepton showers deriving from PeV-EeV τ-neutrinos

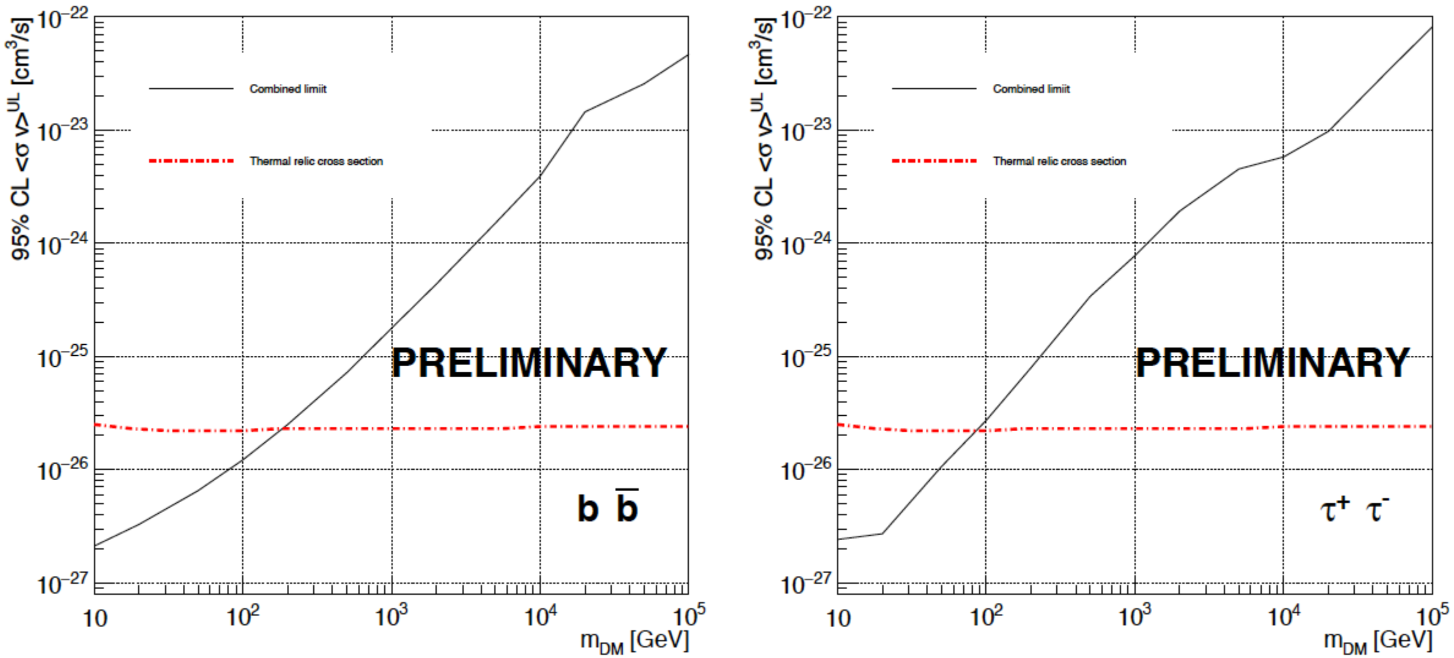
Sources



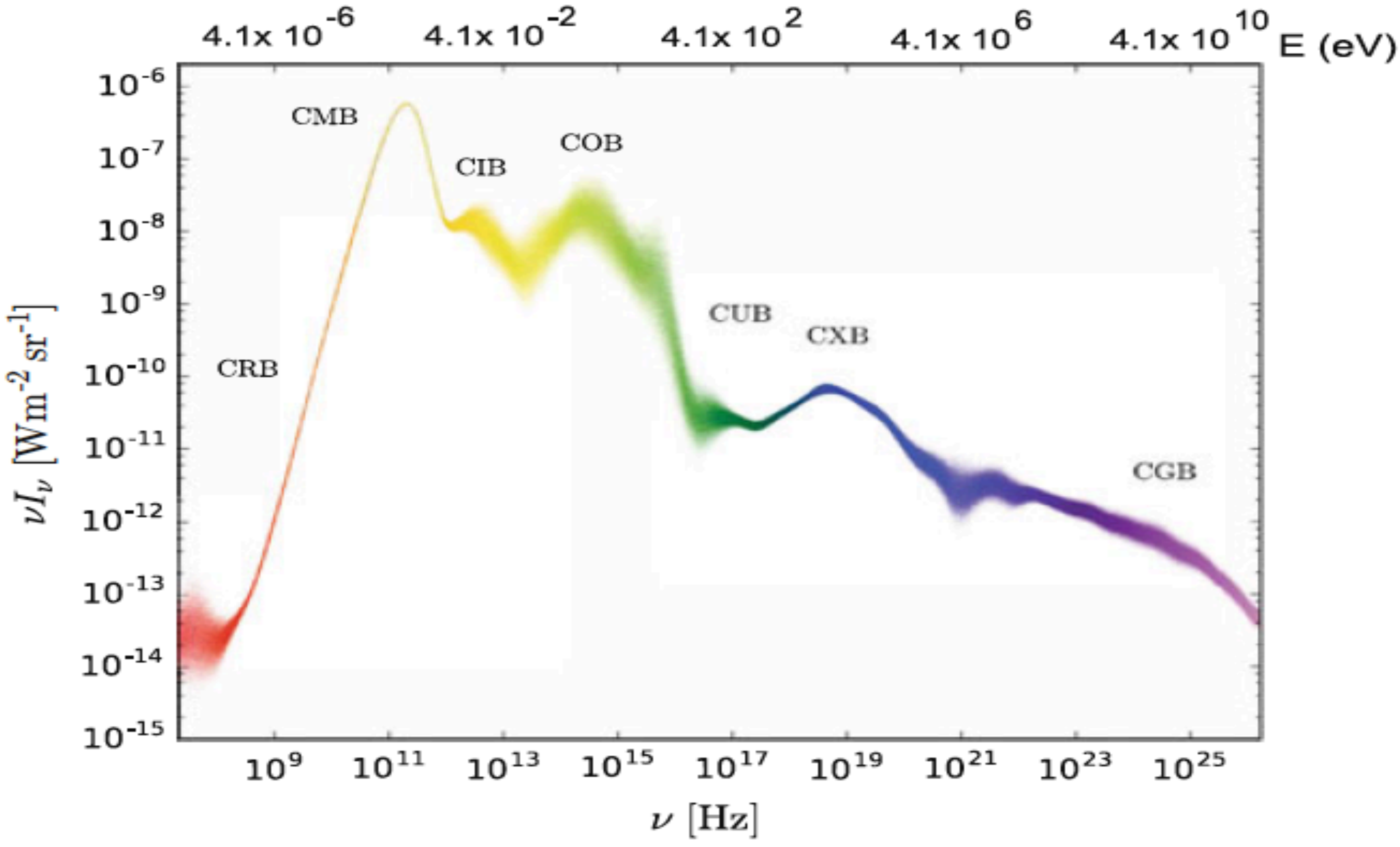
- Low threshold (down to 30 GeV with Sum Trigger, 40 GeV in normal data taking conditions) allows to increase source statistics (presently 68 sources)
- In particular pulsars and distant blazars can be the targets in which we are best

Indirect searches for WIMPs

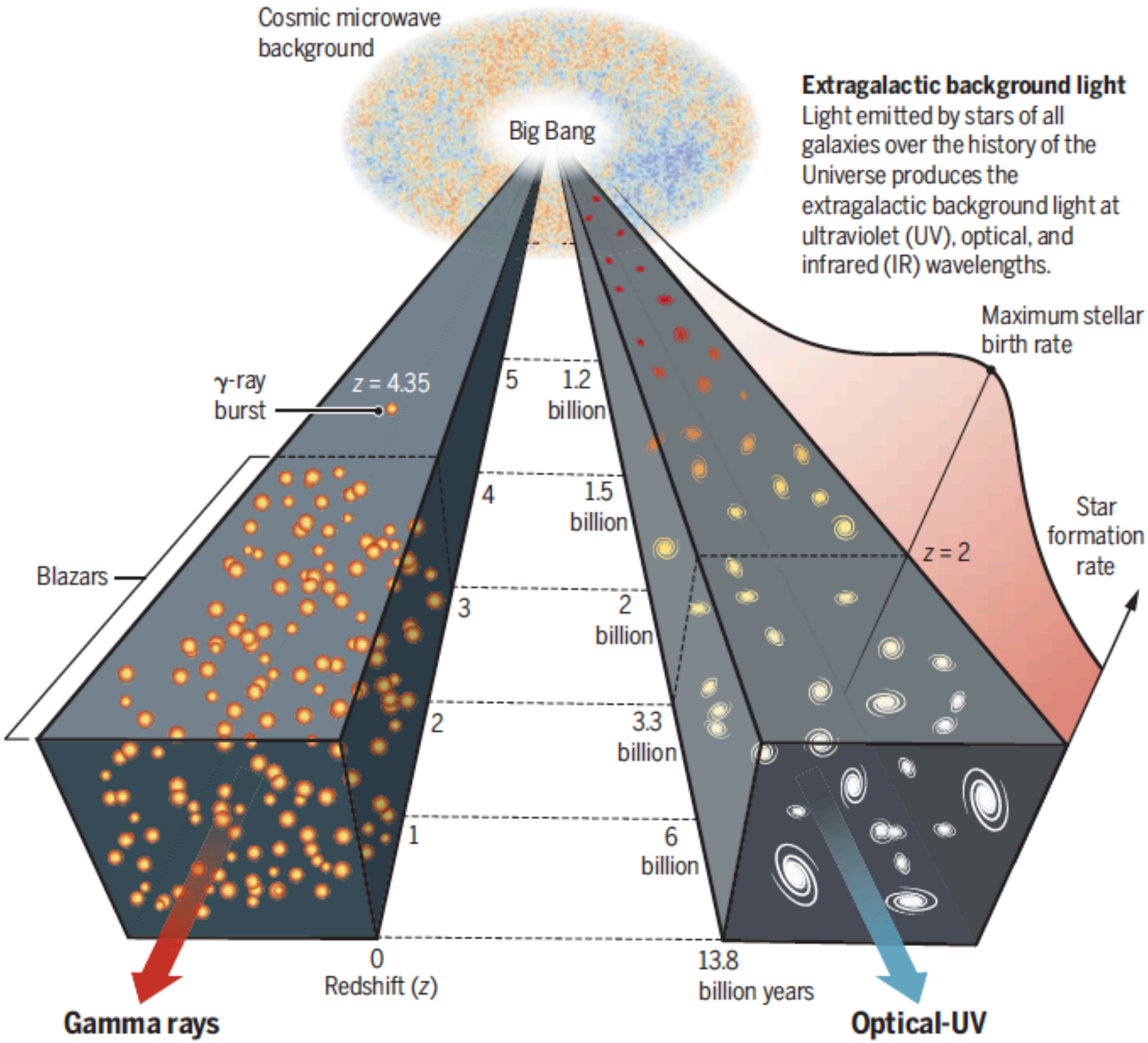
- The golden channel for IACTs: $\chi\chi \rightarrow \gamma\gamma$
- The golden targets
  1. dSPHs (uncertain signal, no background)
  2. The GC region (lot of signal expected, background difficult to model; Southern hemisphere is better)
- A common effort between IACTs, HAWC and Fermi makes sense, and is in progress (for the moment limited to point 1., …)
- MAGIC is competitive with Fermi above 20 (5) TeV in the bb ($\tau\tau$) decay channels



Gamma-ray background in the Universe



Extragalactic Background Light



(E. Prandini 2018)

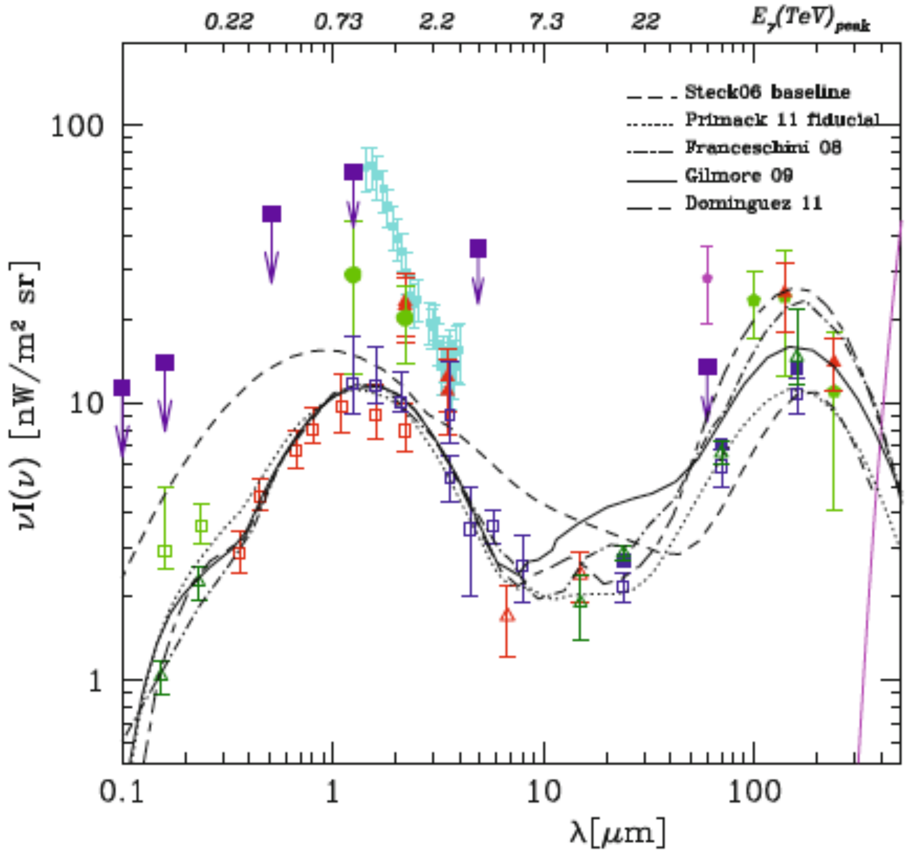
- This radiation covers a wavelength range between ~0.1 and 600 μm (consider the redshift and the reprocessing)
- After the CMB, the EBL is the second-most energetic diffuse background
- Understanding EBL is fundamental
  - To know the history of star formation
  - To model VHE photon propagation for 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.
- To determine EBL:
  - Galaxy count + diffuse model
  - Attenuation of sources

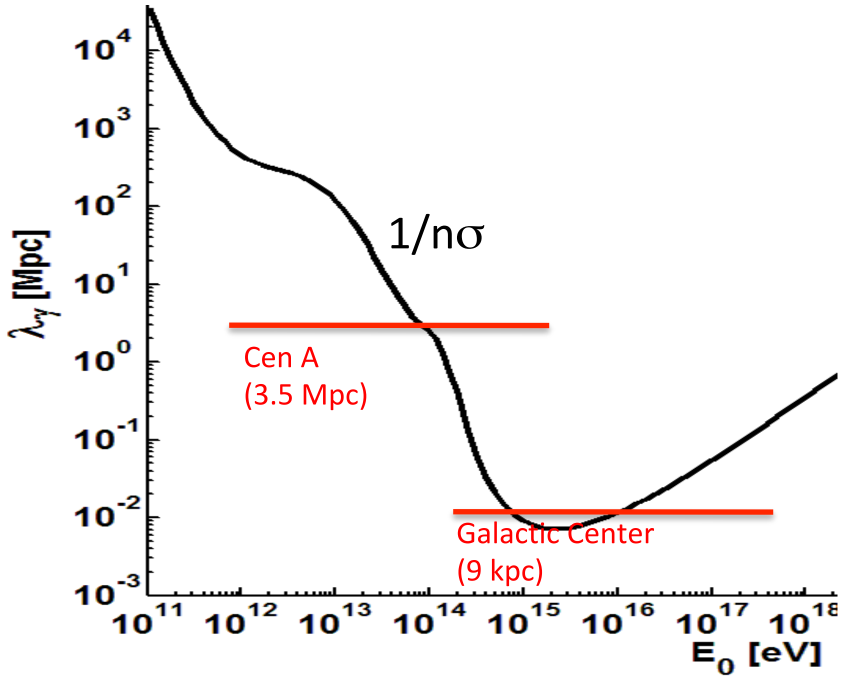
$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$

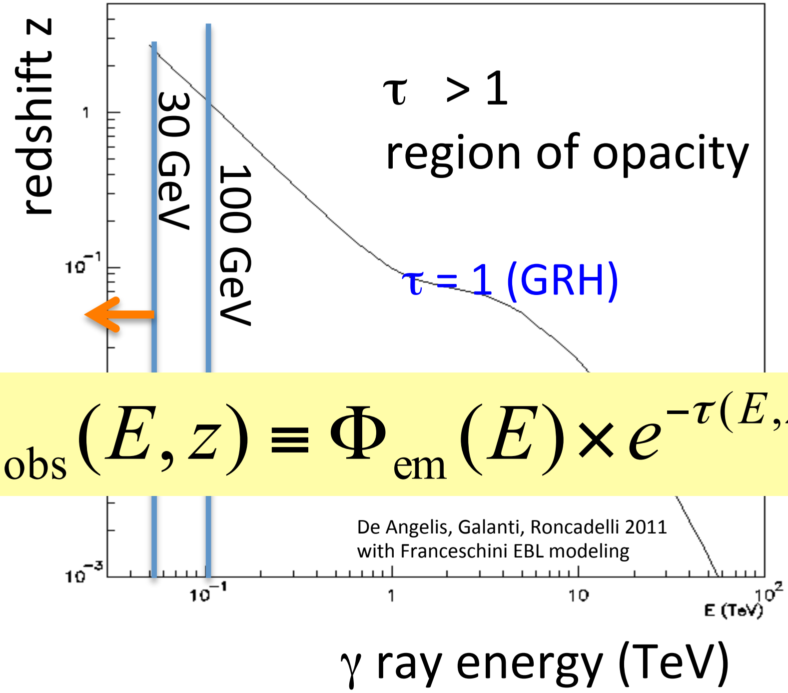
$$\sigma(\beta) \sim \frac{2\pi\alpha^2}{3m_e^2} W(\beta) \simeq 1.25 \cdot 10^{-25}\, W(\beta)\, \mathrm{cm}^2$$

$$W(\beta) = (1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

Max for: $\epsilon(E) \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}$



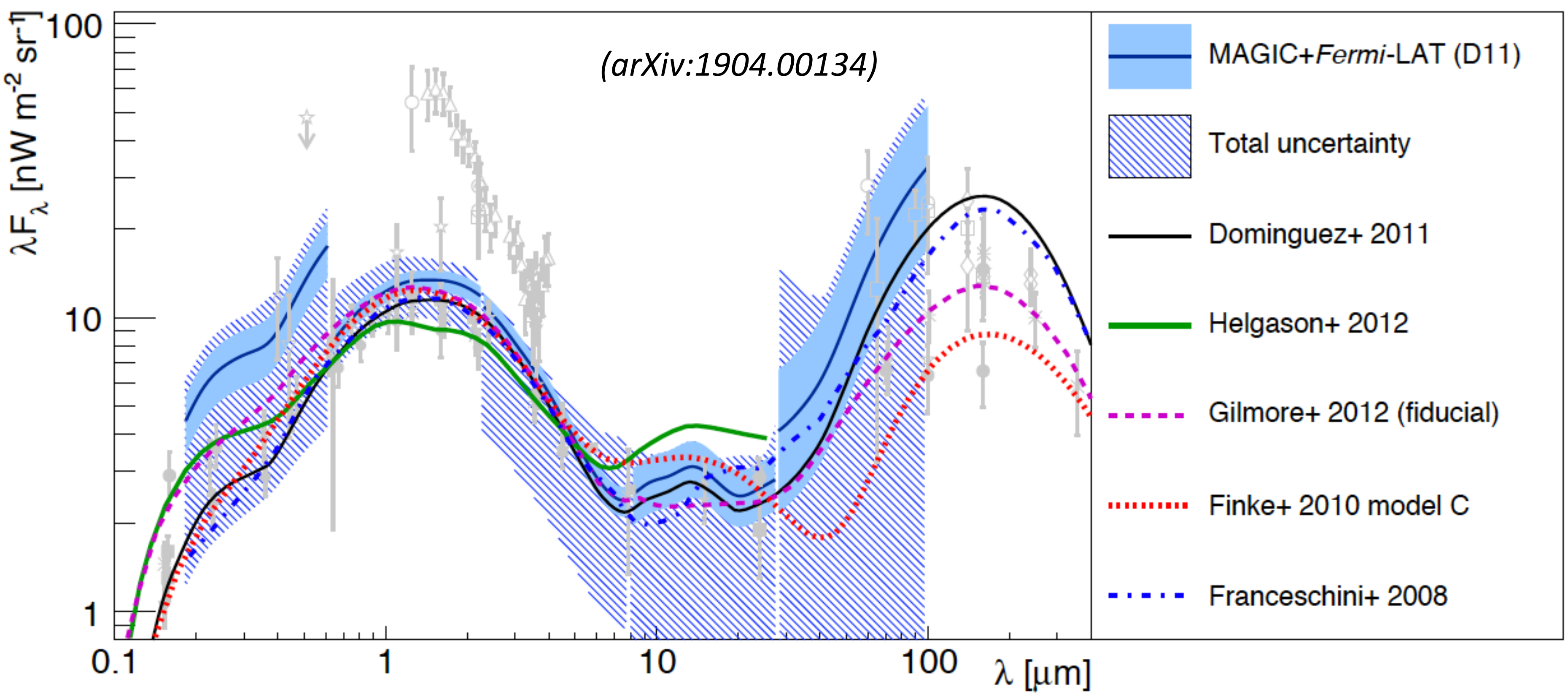




$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

Extragalactic Background Light: results

- Likelihood fit using 32 sources observed by Fermi LAT and MAGIC
- 5 bins of wavelength
- LAT energy band is not very much affected by absorption, and thus it is a robust lever arm

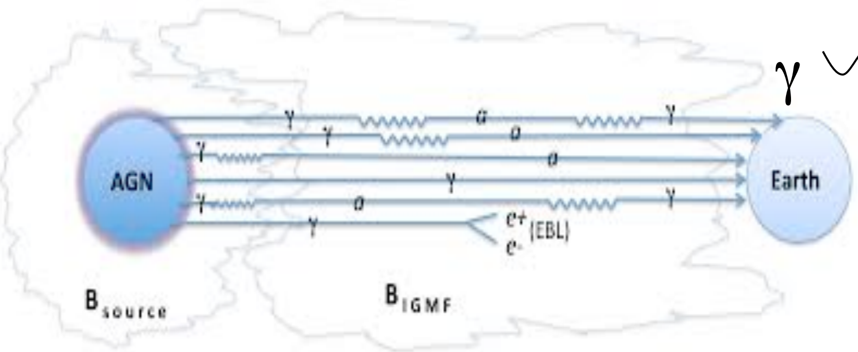


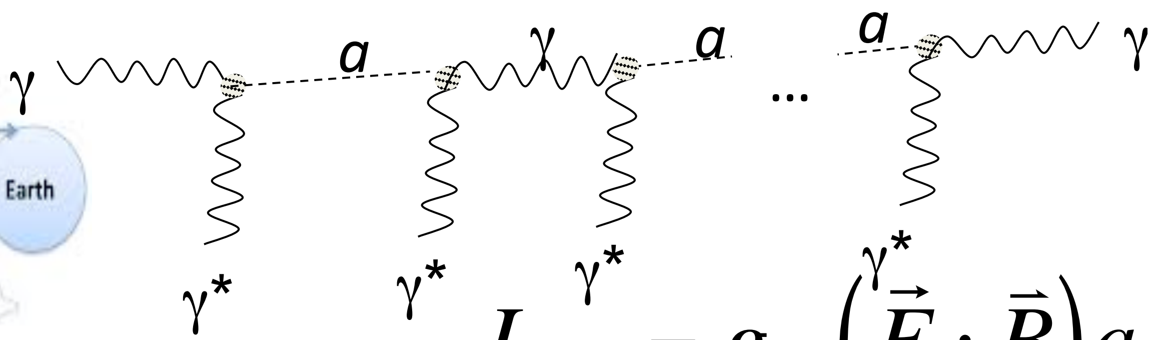
Anomalies in the propagation of photons?

- Too large flux of high energy photons with respect to EBL? (Horns & Meyer 2014, 4σ)
- Dependence of the de-convoluted spectral index on z (DA, Persic and Roncadelli 2014, Galanti, Roncadelli, DA and Bignami 2018)
- Other evidence from irregularities on spectral indices (several authors)

- A mechanism mixing photons with “sterile” particles (axions, dark photons, paraphotons) could solve the possible tensions in data

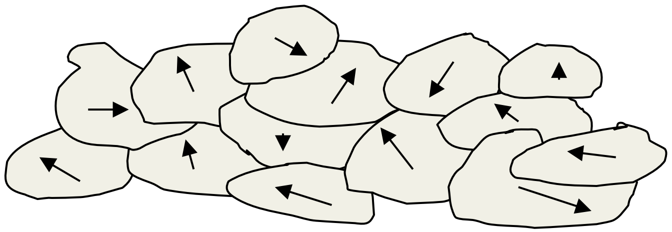
The photon-axion mixing mechanism





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

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



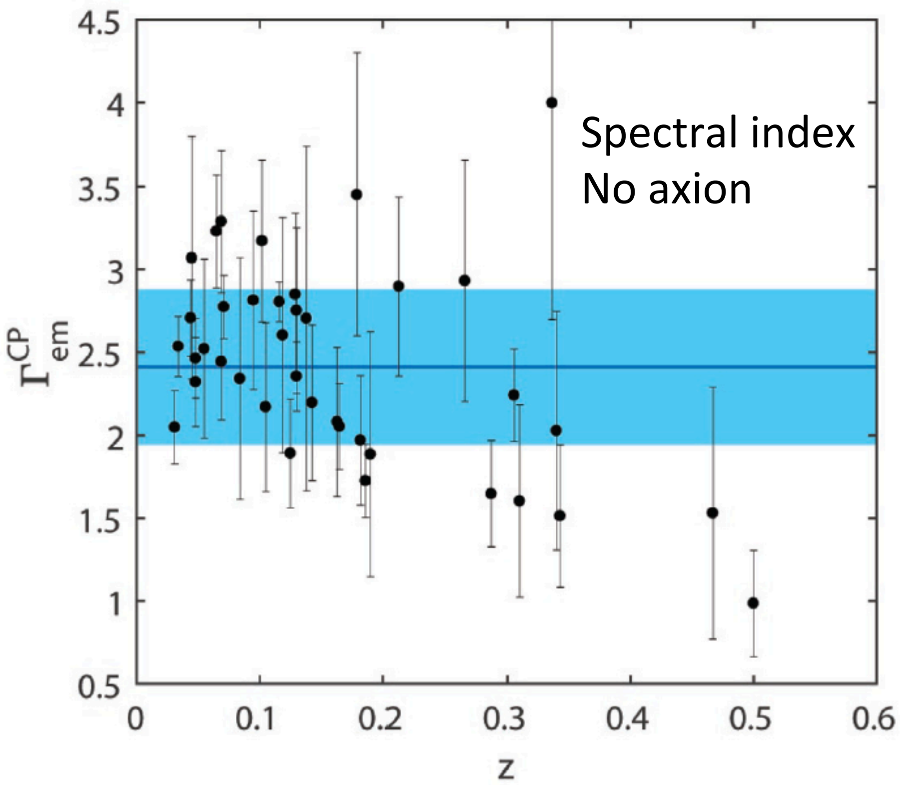
$$P_{\gamma\to a} \approx N P_1$$

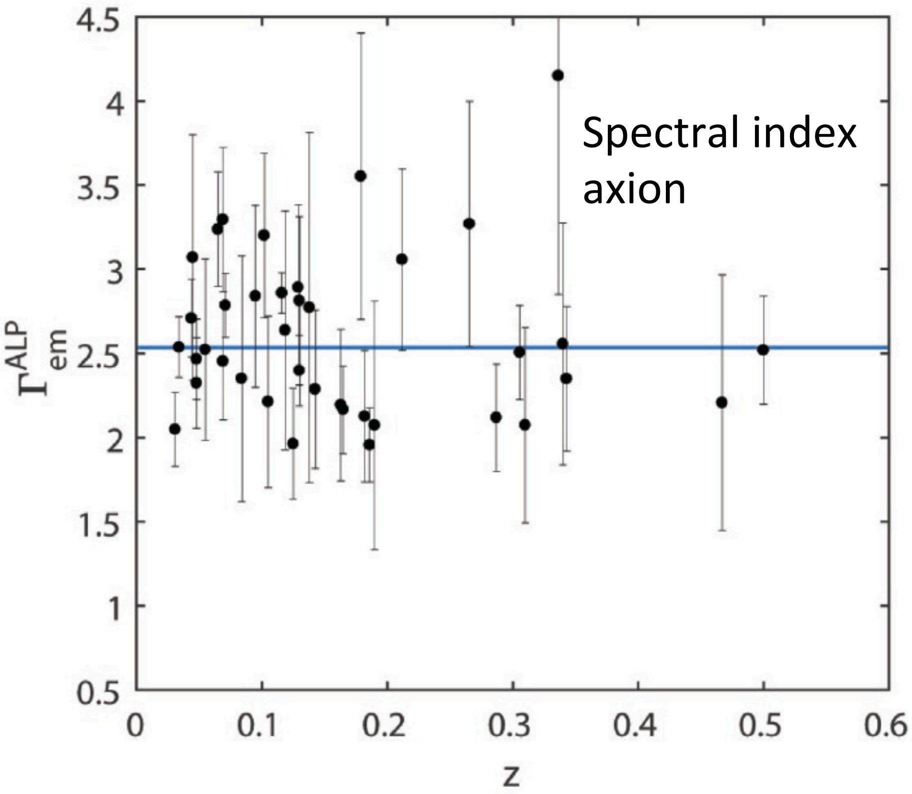
$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times 10^{-3}\left(\frac{B_T}{1\text{nG}}\frac{s}{1\text{Mpc}}\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2$$

- Photons-ALP mixing could enhance the transparency of the Universe:
  - Photon/ALP mixing in the intergalactic space (DA, Roncadelli & MAnsutti [DARMA], PRD2007)
  - Conversion into axion at the source, reconversion in the Milky Way (Hooper, Simet, Serpico 2008)
  - A combination of the above

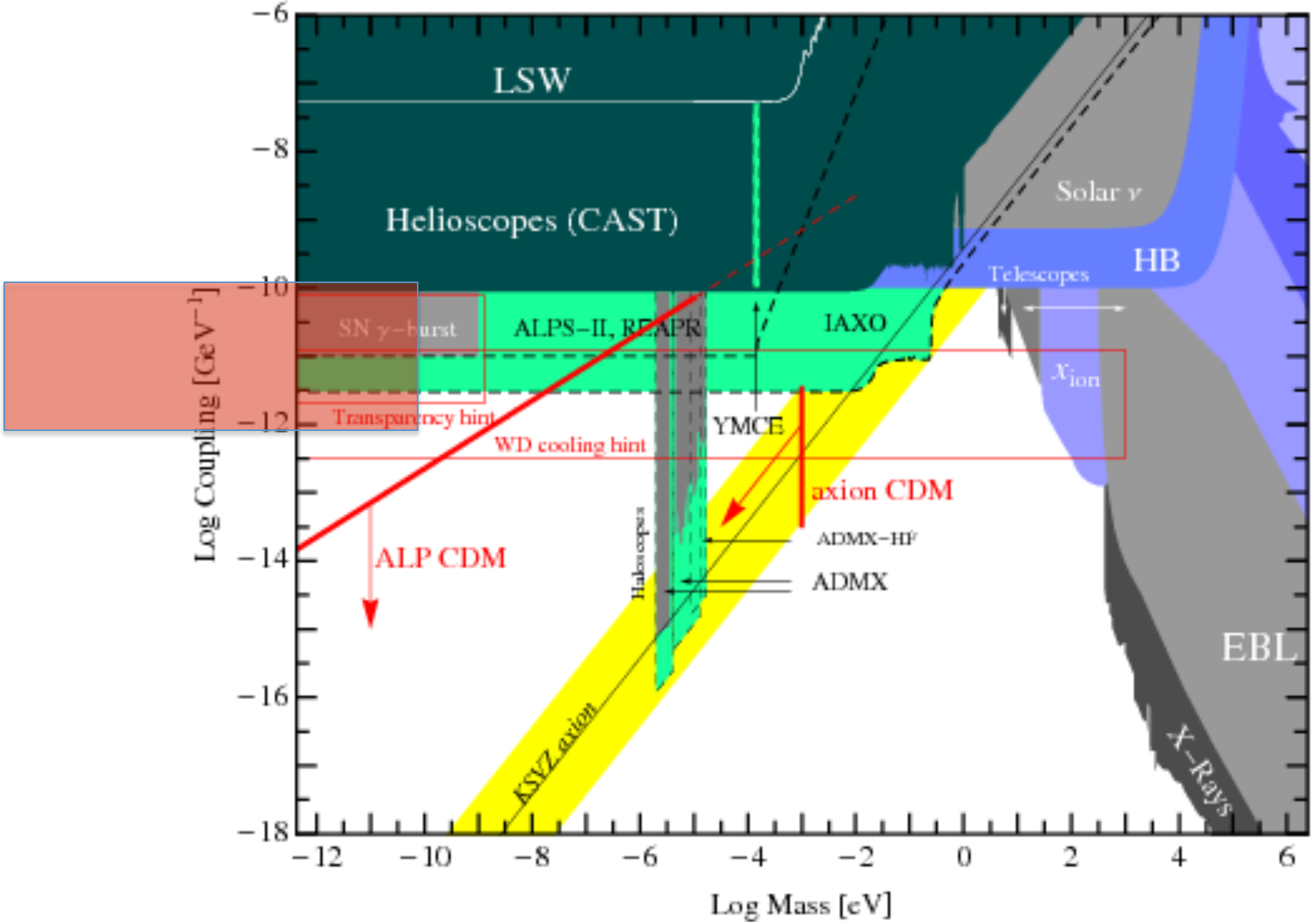
Spectral index vs. z

- Needs a good statistics of far-away sources





Preferred values for m, g (DARMA)



But warning: despite the statistics increases, the significance does not grow…

A new guy in town: the 23-m LST1 has come (see Teshima’s talk on Wed)

…and starts being competitive…

- Sensitivity ~2x MAGIC, but improving
- Crab Nebula, Crab Pulsar, + … observed

…and is going to be joined by his 3 twins soon
(2nd LST coming already in 2021)

Conclusions

- MAGIC is alive and well
- Its exclusive points can provide good values
  - Just discovered the first GRB at TeV energies, and fast repointing can pay again for transients
  - Low energy is also an asset
  - Possibility to look close to the horizon (high energies)
  - Possibility to look below the horizon (neutrinos)
  - PMTs working under moderate moon conditions
- For some features in common with the other IACTs, the phase of inter-IACT working groups (also with Fermi and HAWC) has started
- MultiMessenger activities are being tuned
- LST is coming fast, and we are thinking to the new era
- Proposals from external scientists are welcome