Antonio Stamerra (INAF- Osservatorio Astronomico di Roma)
on behalf of the MAGIC collaboration

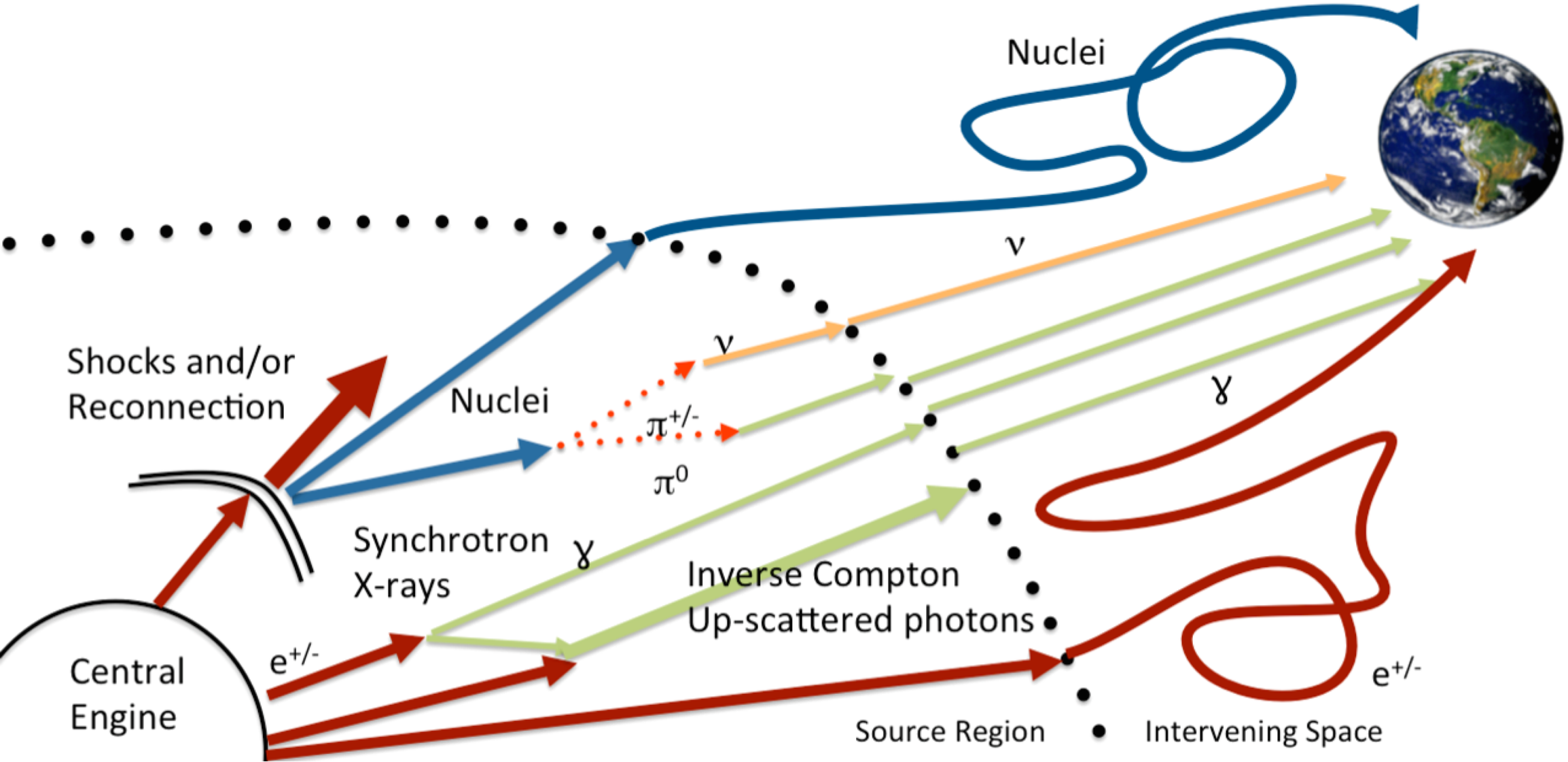
The transient sky at very-high energies: the MAGIC observations in a multi-messenger context

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

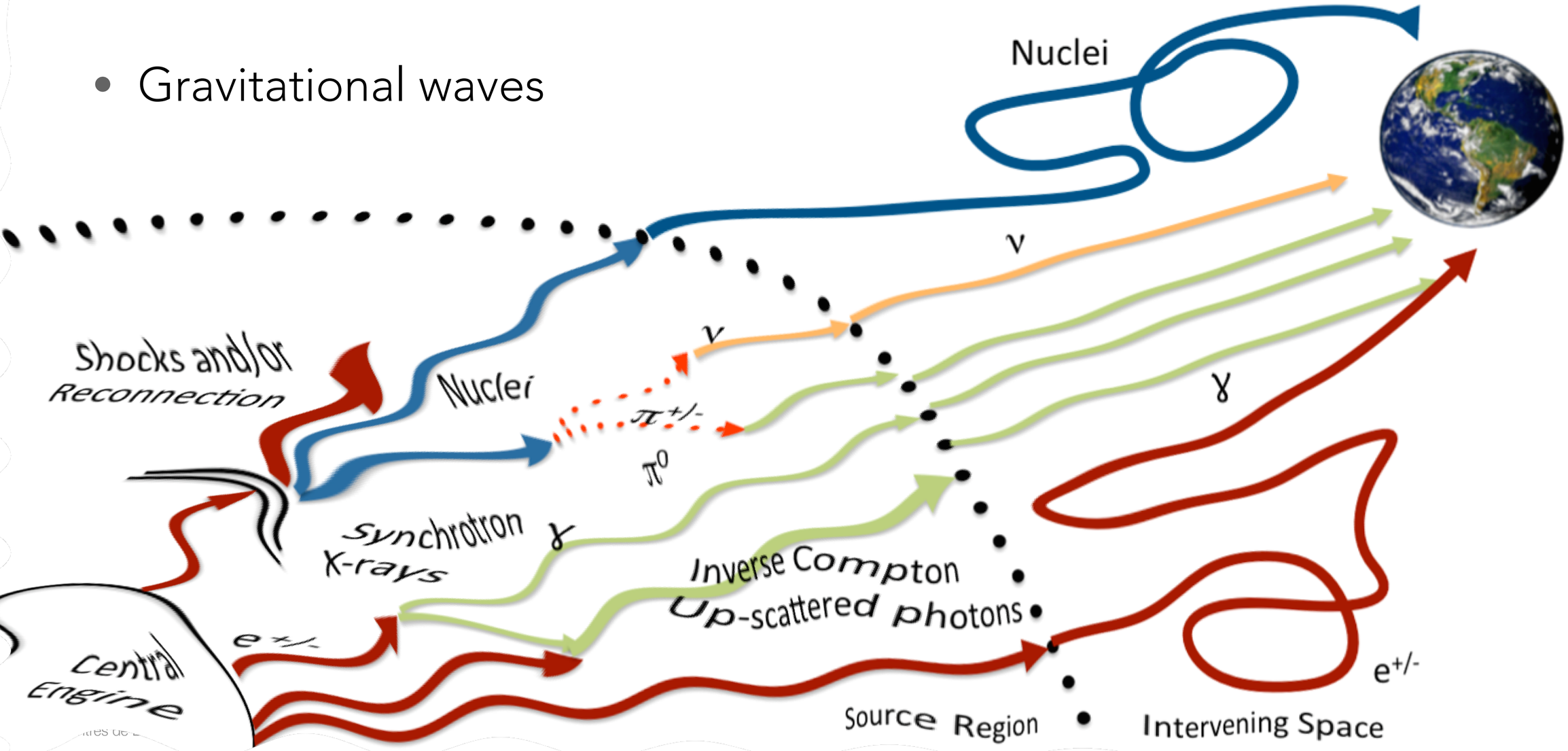
OAR

MULTIMESSENGER ASTROPHYSICS



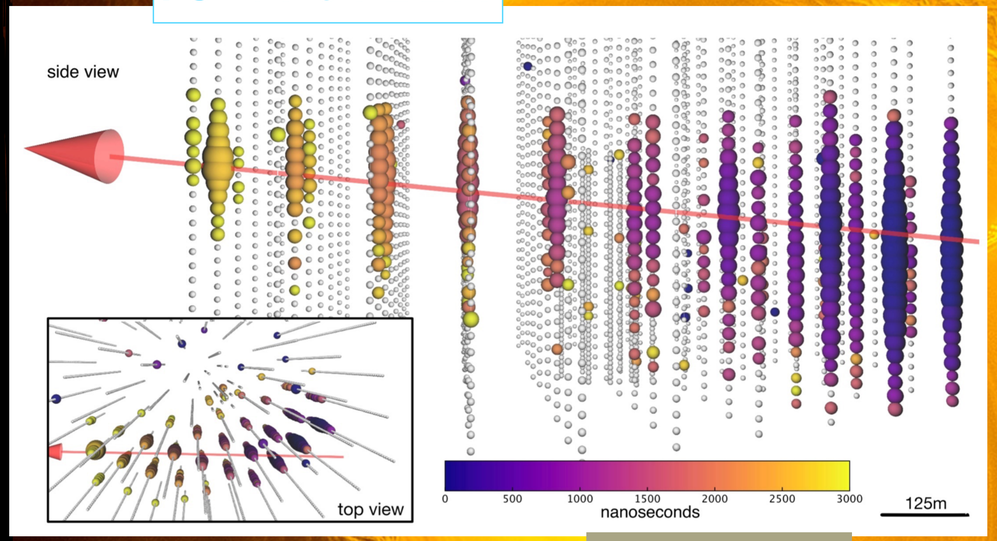
MULTIMESSENGER ASTROPHYSICS

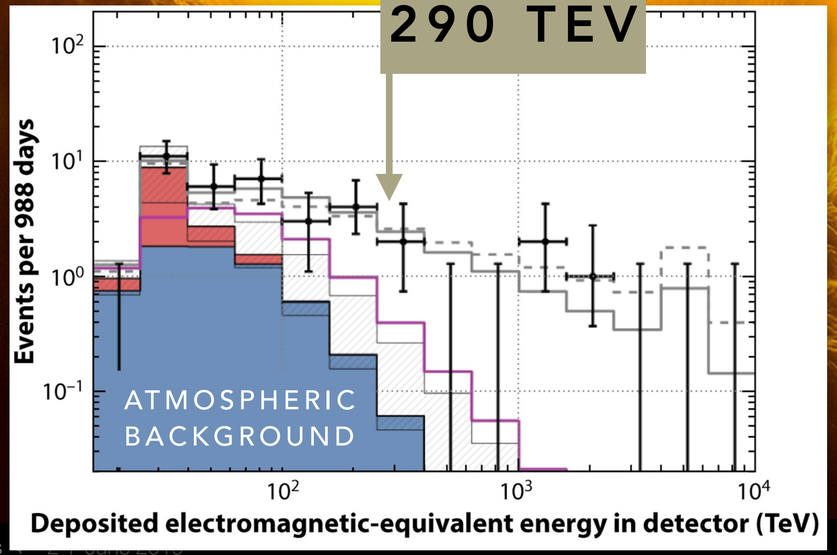
- Gravitational waves



VHE ASTRONOMY IN THE MULTI-MESSENGER DOMAIN: THE BLAZAR-NEUTRINO CONNECTION

IC-170922A





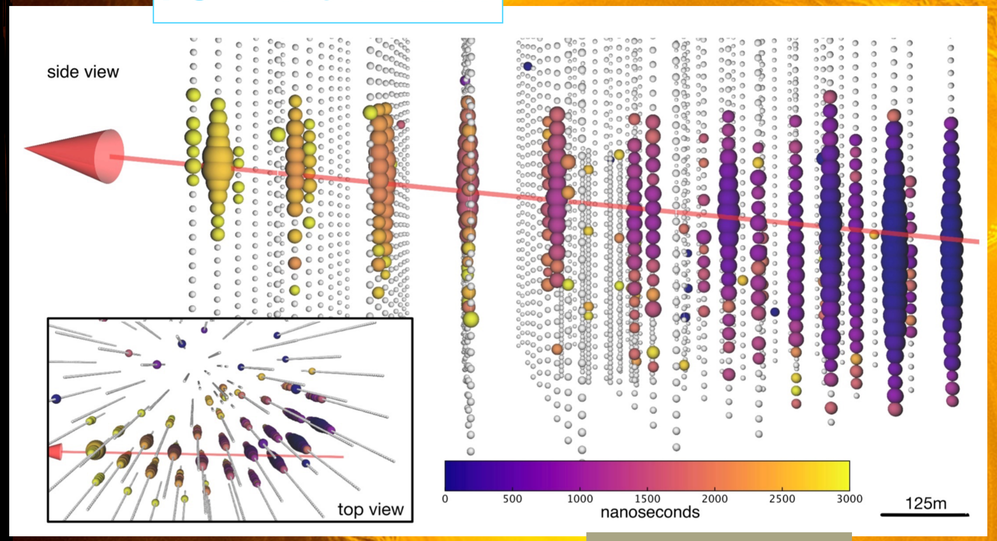
22 September 2017

High energy neutrino event

Uncertainties on direction < 1 deg

VHE ASTRONOMY IN THE MULTI-MESSENGER DOMAIN: THE BLAZAR-NEUTRINO CONNECTION

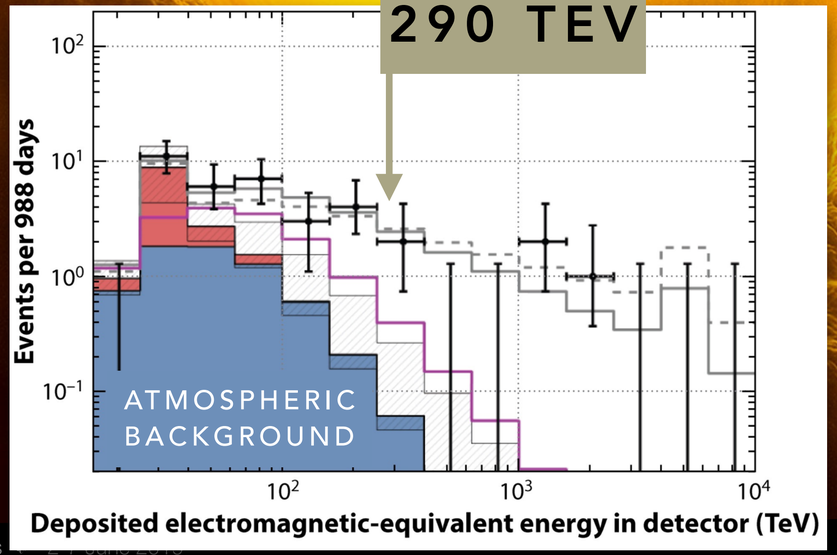
IC-170922A



Gamma-ray Flare of TXS0506+056
In coincidence with the neutrino

- Low/intermediate peaked blazar (synch peak ~10^{14} Hz)
- z=0.3365 (Paiano+2018)

290 TEV



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration on 28 Sep 2017; 10:10 UT*

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration: on 28 Sep 2017; 11:57 UT*
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)*

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.*

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration on 4 Oct 2017; 17:17 UT*

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

#10845; *D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)*

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, N. Isobe, R. Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, M. Shidatsu, F. Yatabe, Y. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Yoshii, Y. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, M. Serino, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi, T. Yoneyama (Osaka U.), M. Nakajima, T. Kawase, A. Sakamaki (Nihon U.), Y. Ueda, T. Hori, A.*

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR) on 17 Oct 2017; 14:08 UT*

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942, 12260

Tweet

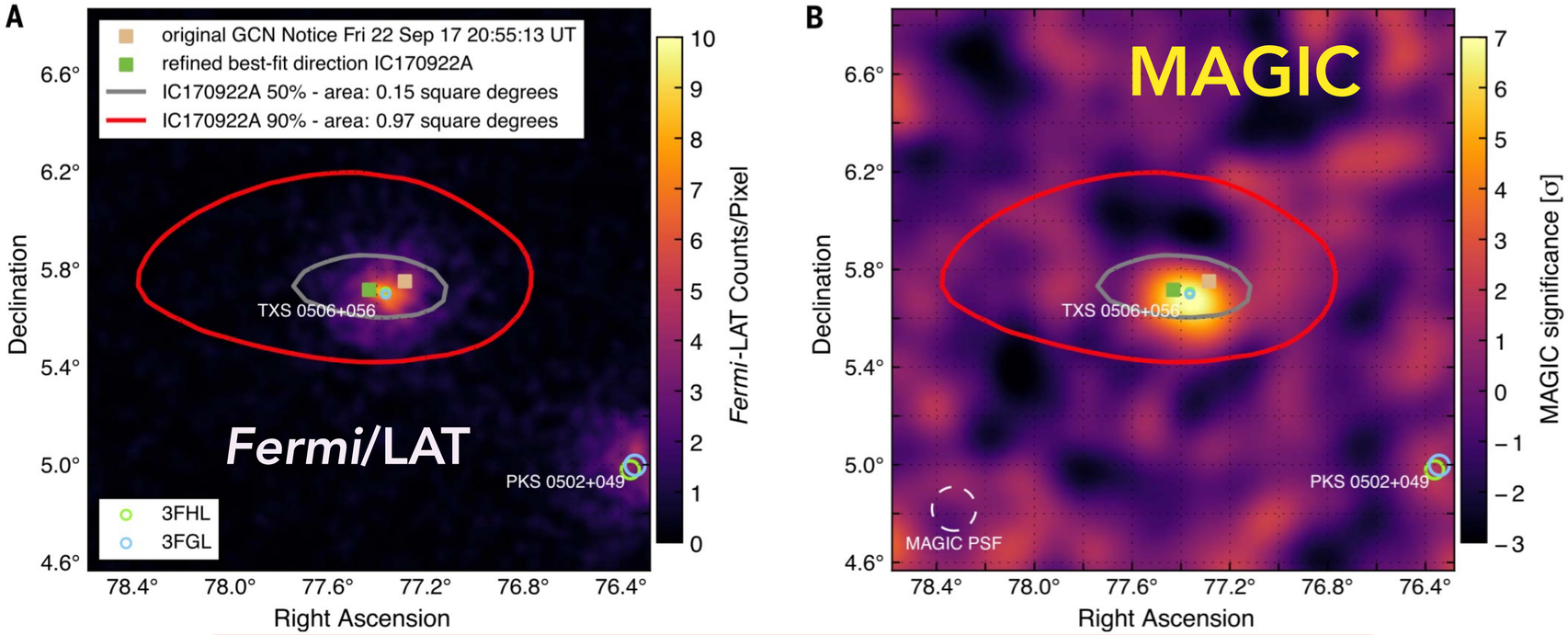
After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a syste of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory R de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamm astronomy in the energy range from 50 GeV to greater than 50 TeV.

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

THE γ-ν CONNECTION IN TXS 0506+056

- ✦Relatively small angular uncertainty of the HESE ν event
- ✦The blazar TXS 0506+056 only plausible candidate
- ✦Time correlation: TXS 0506+065 in γ high-state

Science 361, eaat1378 (2018)



CHANCE COINCIDENCE REJECTED AT 3σ LEVEL

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- ✦Relatively small angular uncertainty of the HESE ν event
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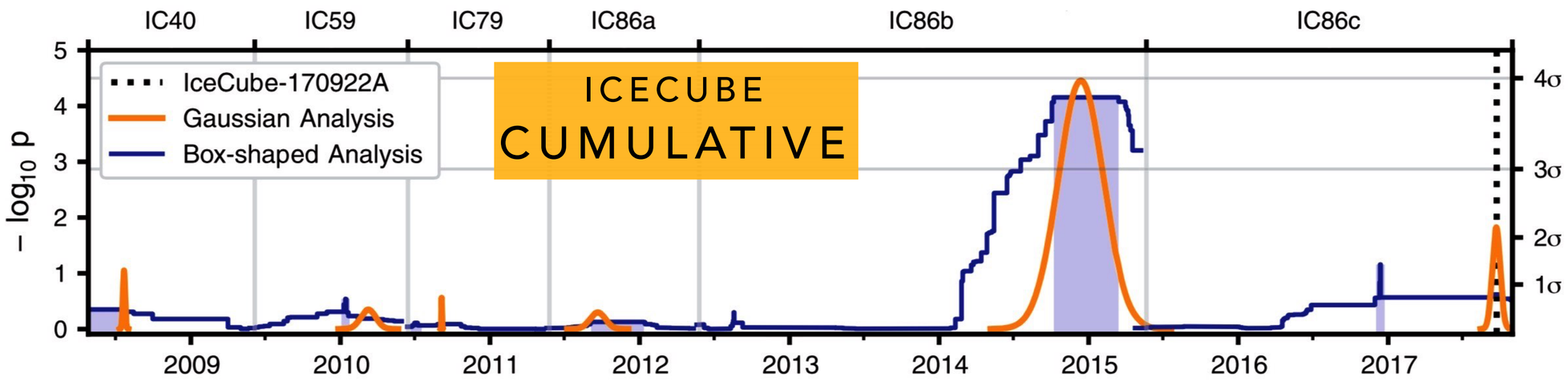
- ✦Time correlation: TXS 0506+065 in γ high-state
- ✦Archival analysis in IceCube reveals an excess in 2015, from the same direction!



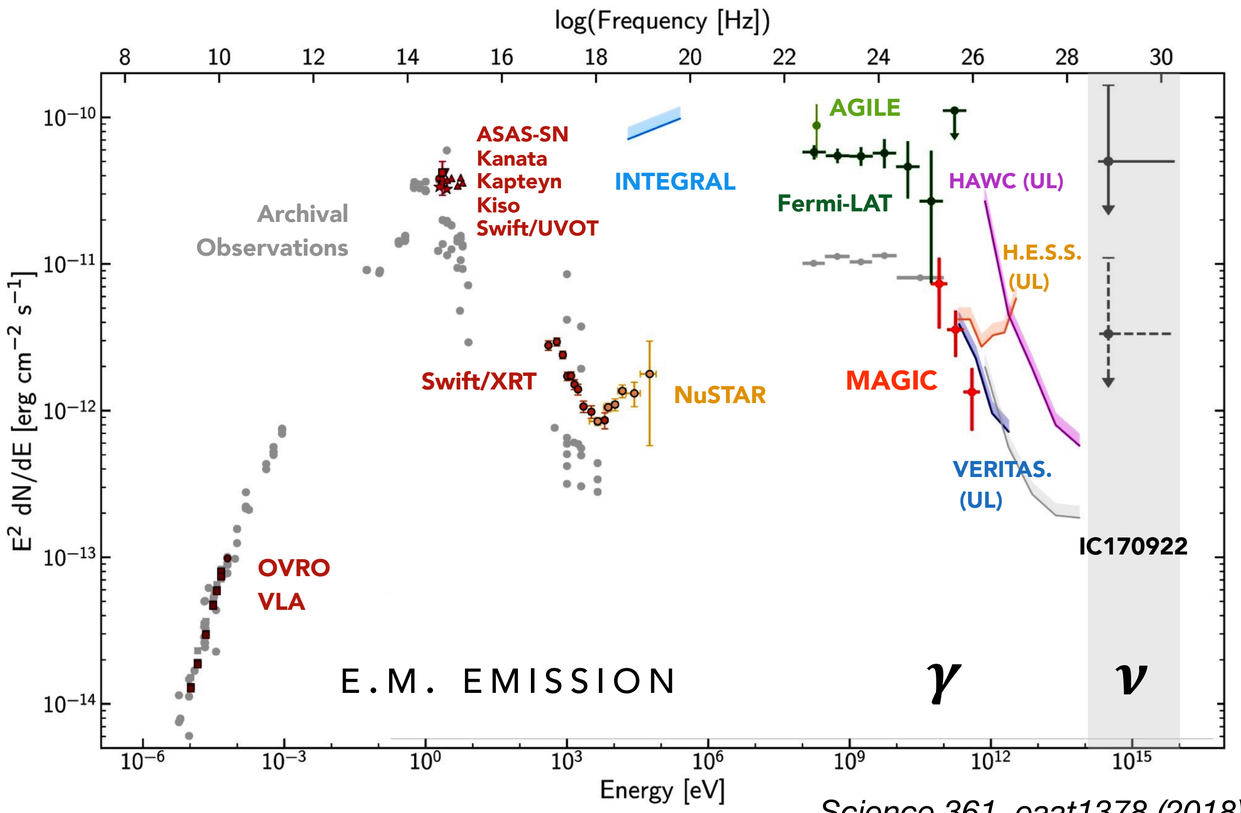
Science 13 Jul. 2018: Vol. 361, Issue 6398

THE γ-ν CONNECTION IN TXS 0506+056

✓ **association to the EHE170922A at the level of 3σ: the blazar TXS0506+056 is a good candidate as counterpart of the neutrino event EHE170922A detected by IceCube.**

- Which processes can produce the observed E>100 TeV neutrino and justify the observed gamma-ray emission?
- Which is the interplay between the gamma-ray emission processes, the hadron acceleration, the jet components and structure, the external radiation fields, the environment?
- The VHE gamma-ray observations can set limits on the maximum energy of accelerated protons?
- The correlation is compatible with the observed neutrino diffuse emission and the limits set on the contribution by blazars?

SED (Spectral energy distribution) of TXS 0506+56



Science 361, eaat1378 (2018)

One of the most luminous blazars known. Is it special?

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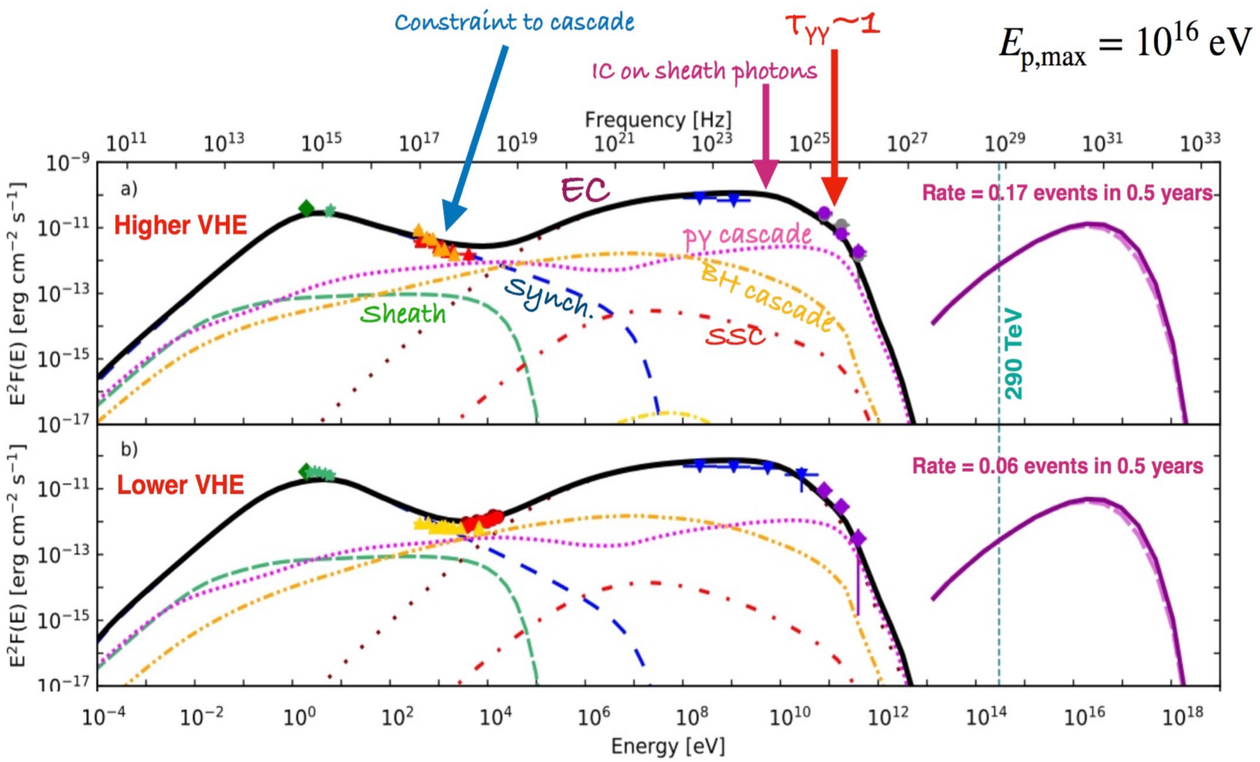

MAGIC-COLL., 2018, APJL - ARXIV:1803.04300

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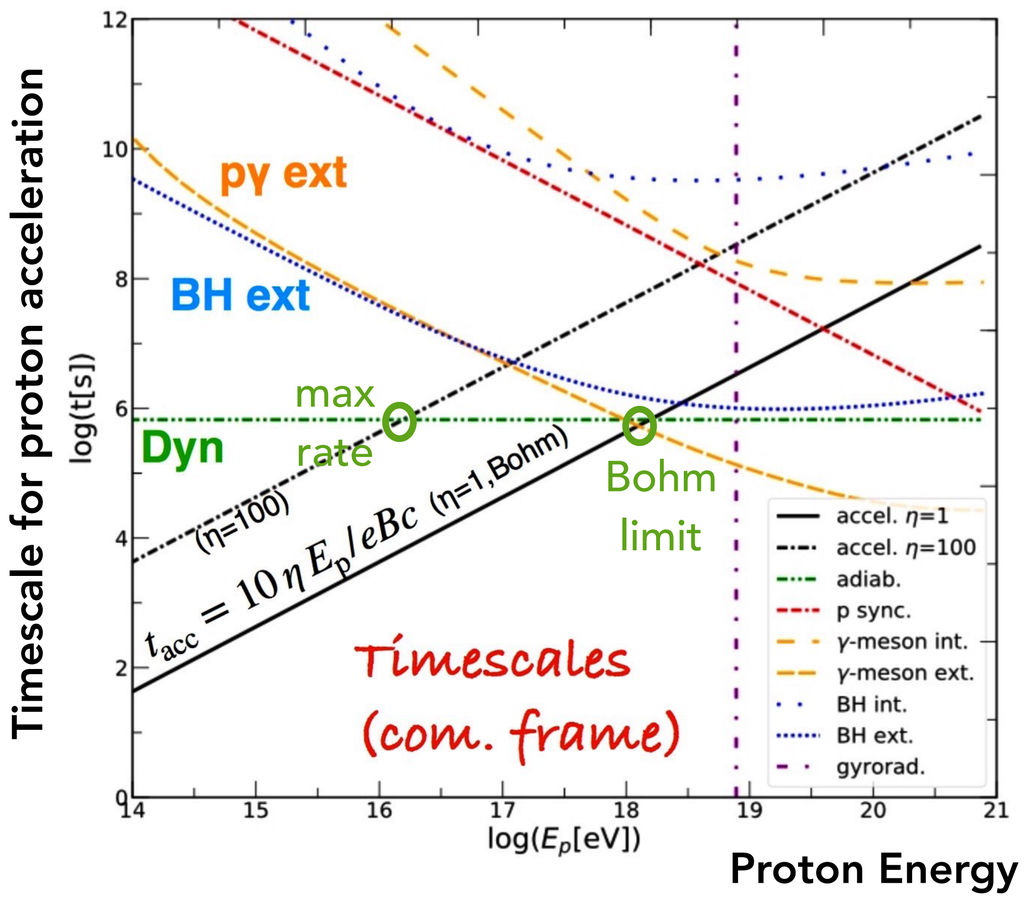

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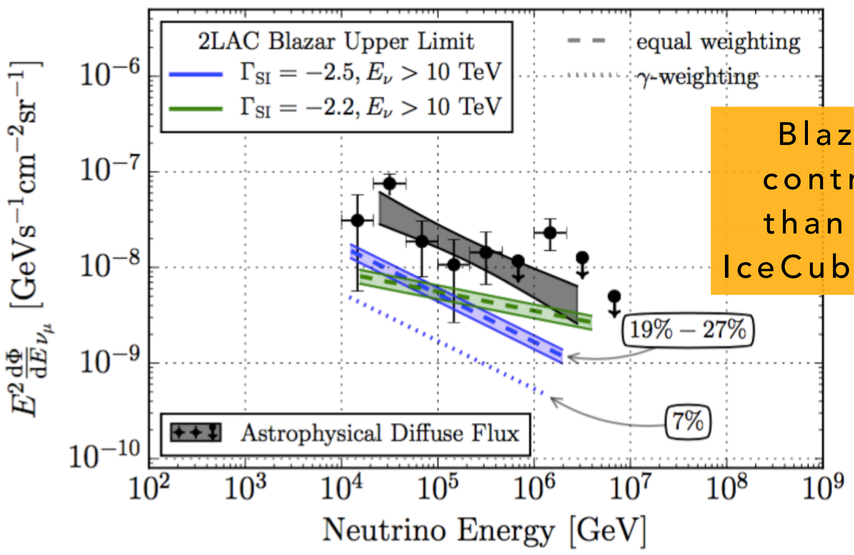
Aartsen et al. 2017



Blazars cannot contribute more than 30% to the IceCube diffuse flux

diffuse ν_μ flux — TXS luminosity

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{c}{H_0}\xi_z L_\nu \rho \mathcal{F} \frac{\Delta t}{T}$$

3×10^{-11} TeVcm^{-2}s^{-1}sr^{-1} — density of blazars

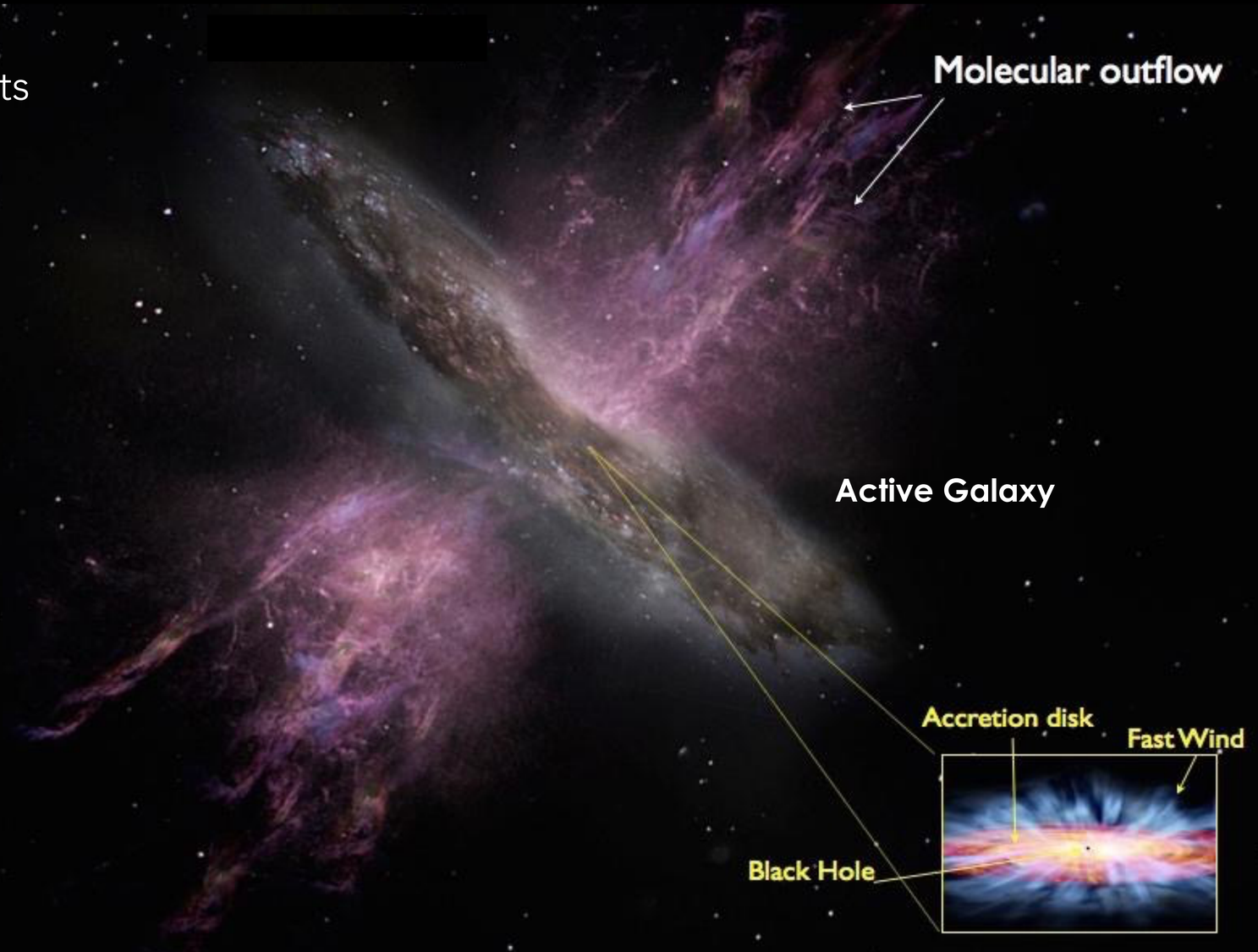
IceCube diffuse flux compatible with a sub-class (~5%) of TXS-like blazars flaring ~110-days once every 10 years

Halzen+2018, arXiV:1811.07439

LONGING FOR THE NEXT ν-γ EMITTING BLAZAR...

CHASING THE ASTROPHYSICAL SOURCES OF NEUTRINOS AND COSMIC RAYS

- Other classes of sources and environments producing high-energy neutrinos
- Jets, blazars
- Starburst galaxies
  - CR formation from SN explosions and interaction with ISM
- **Galactic Winds**
  - mildy relativistic
  - molecular outflow
  - CR interactions and cascades

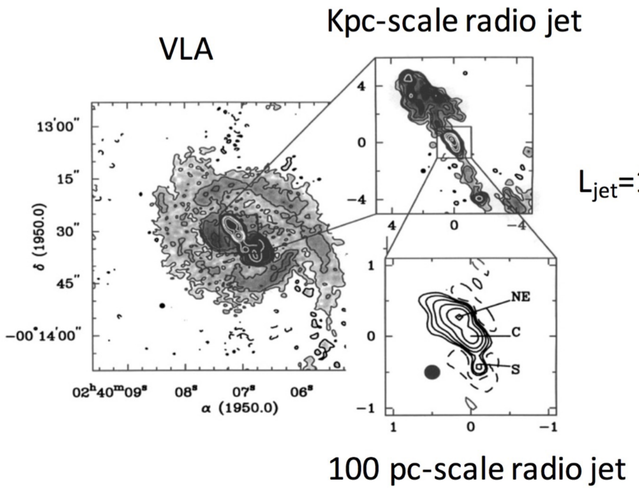


CHASING THE ASTROPHYSICAL SOURCES OF NEUTRINOS AND COSMIC RAYS

NGC1068 as neutrino emitter? *Lamastra+2016*

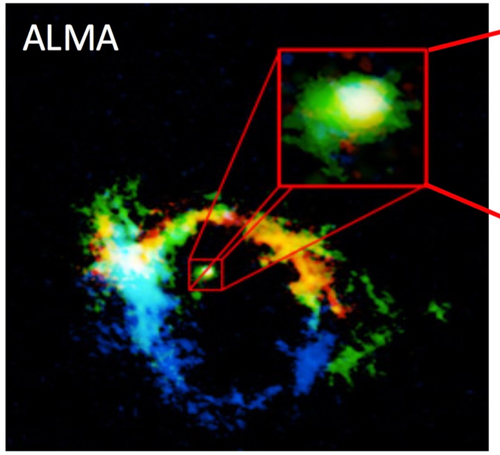
prototypical Seyfert-II galaxy

- distance D=14.4 Mpc
- composite starburst/AGN galaxy ($M_{BH}\approx10^{7}M_{sun}$)
- Luminous infrared galaxy $L_{IR}=2.8\times10^{11}L_{sun}$
- High luminosity ($L_{AGN}=10^{44}$-10^{45} erg/s)
  high obscured ($N_H>10^{24}$ cm^{-2}) AGN

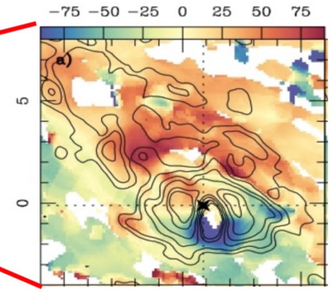


$L_{jet}=10^{43}$ erg/s

Molecular AGN-driven wind



CO velocity map



outflow velocity: $v_{out}\approx(100\text{-}\ 200)$ km/s

outflow size: $R_{out}\approx100$ pc

mass outflow rate: $dM_{out}/dt\approx108\ M_{\odot}$/yr

kinetic luminosity: $L_{kin}\approx1.5\times10^{42}$ erg/s

Credits:A. Lamastra

CHASING THE ASTROPHYSICAL SOURCES OF NEUTRINOS AND COSMIC RAYS

NGC1068 as neutrino emitter?

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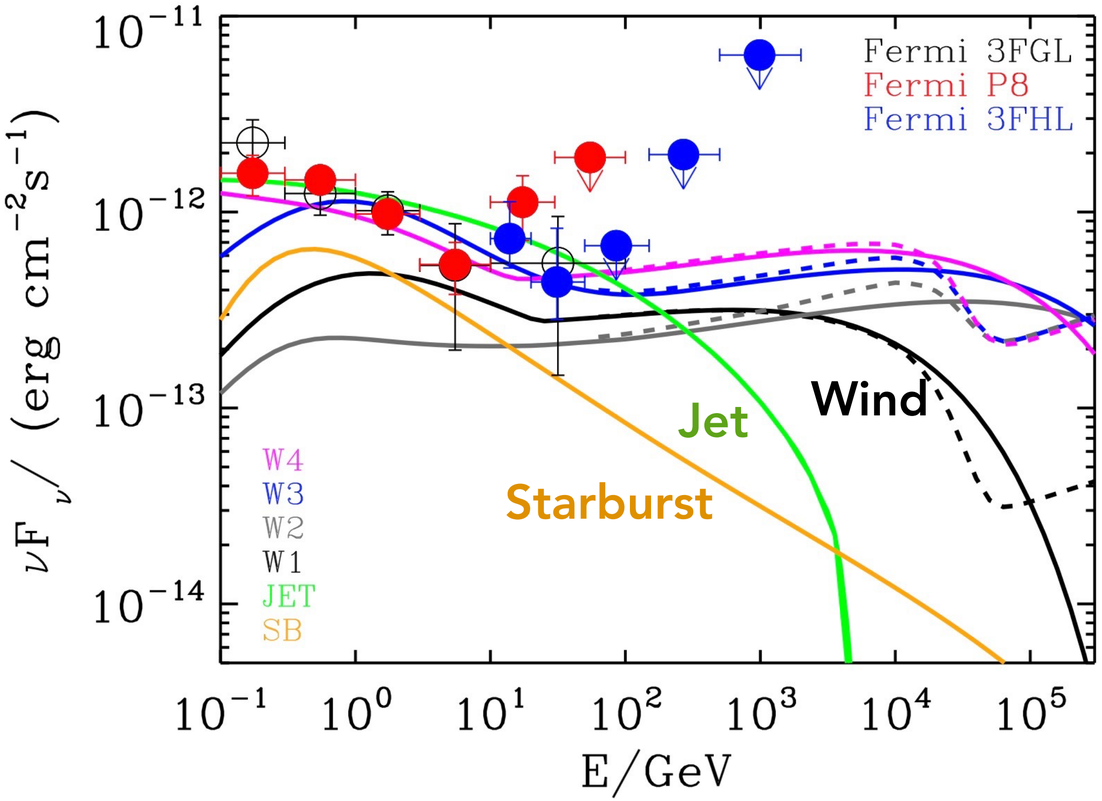

Lamastra+ 2016, 2019

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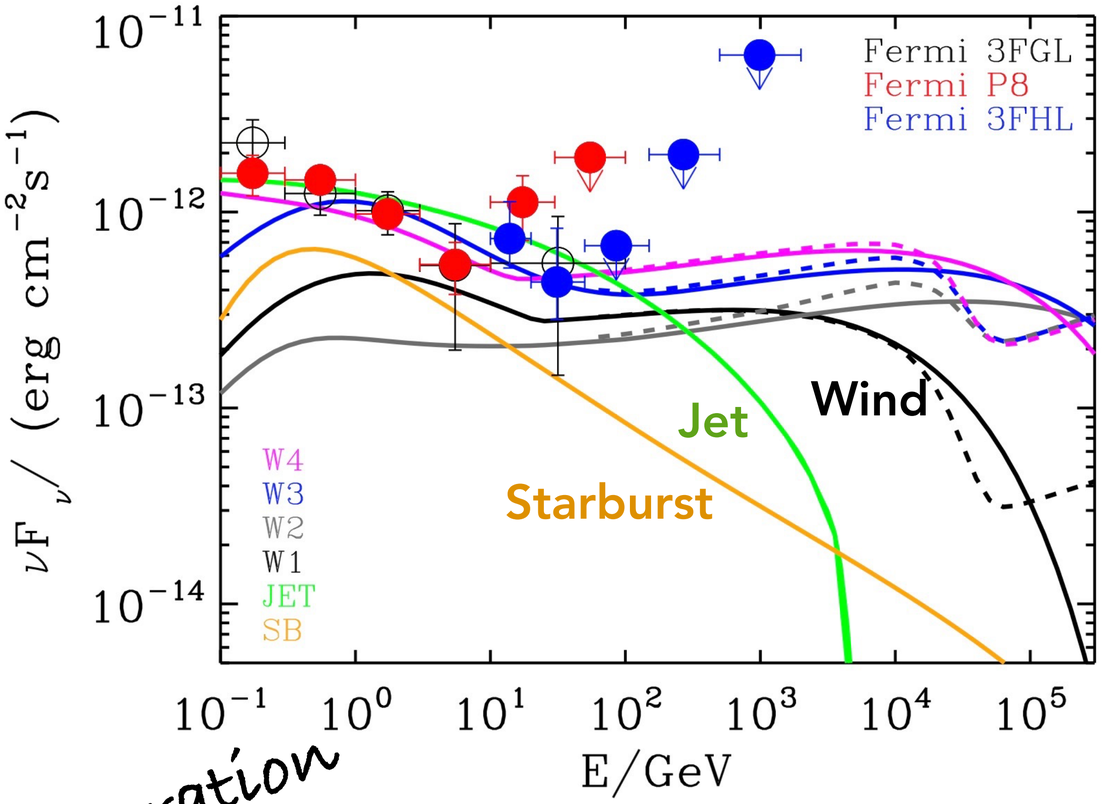
125 HOURS OF OBSERVATIONS WITH MAGIC FROM JANUARY 2016 TO JANUARY 2019



paper in preparation

Lamastra+ 2016, 2019

Credits:A. Lamastra

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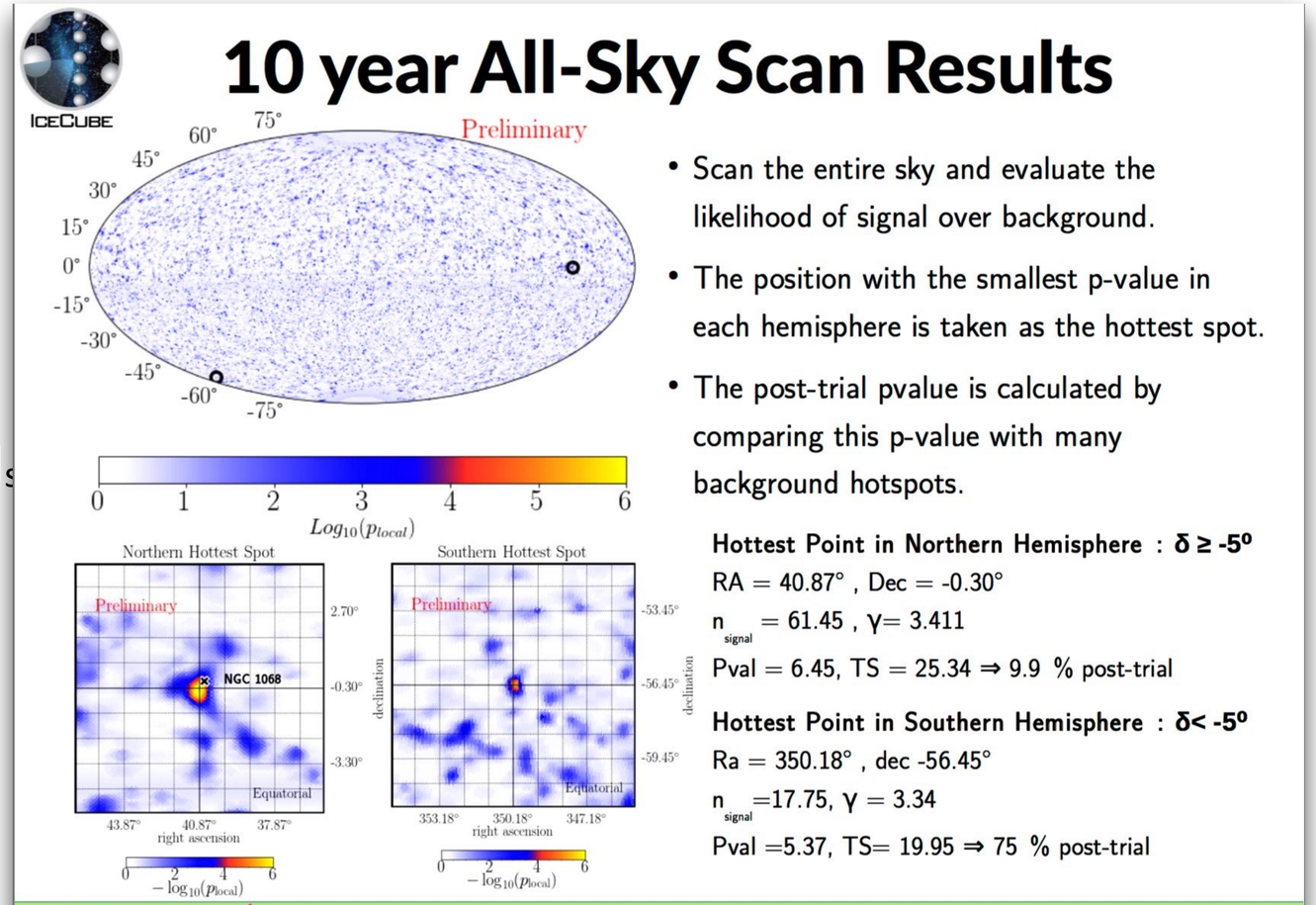

Credits: Tessa Carver (Workshop on Neutrino Telescopes) Francis Halzen (CTA 1st Science Symposium)

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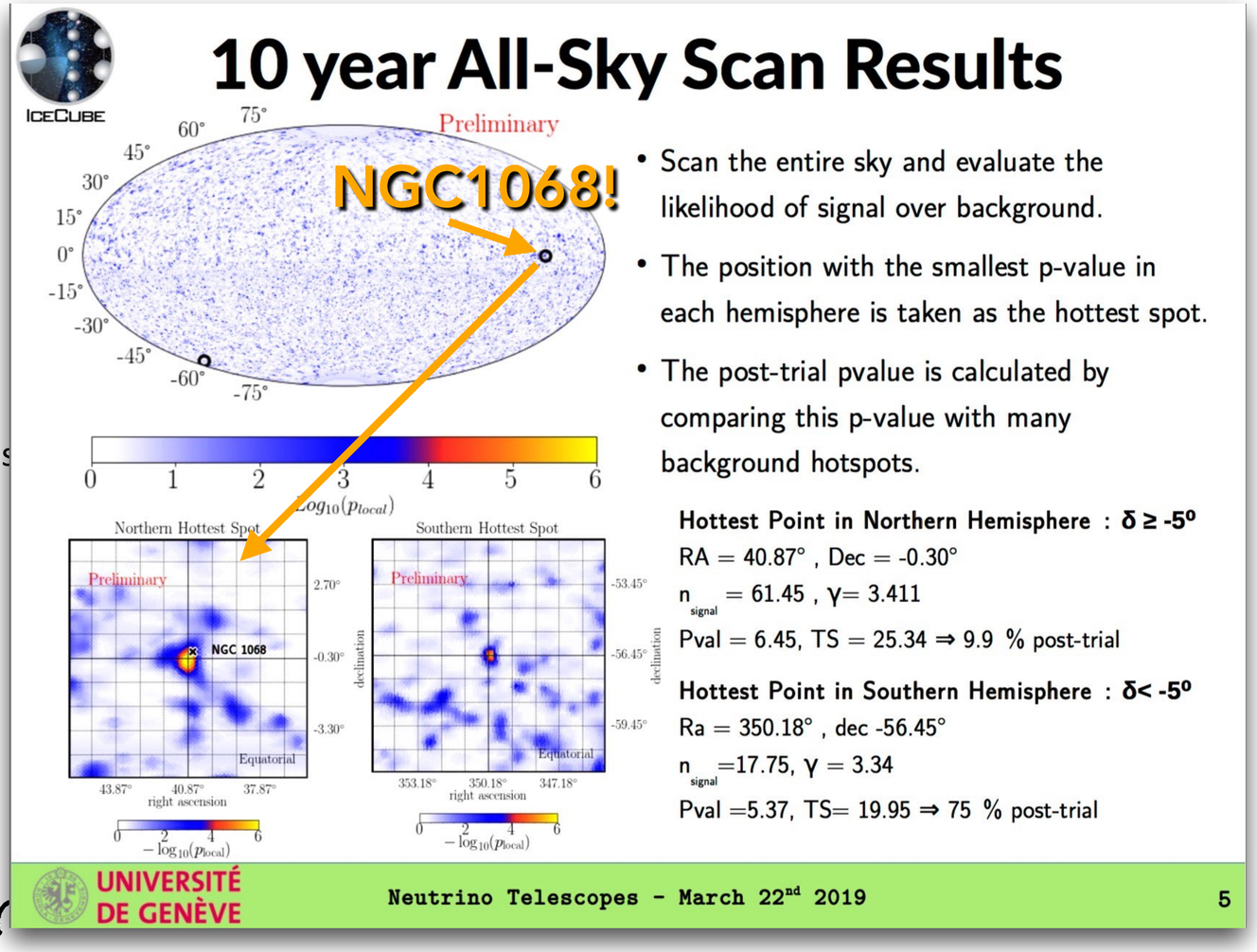

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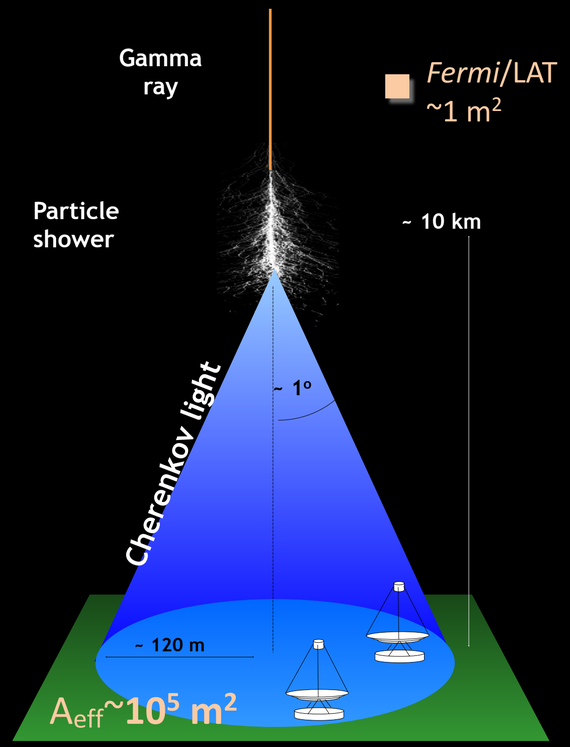
THE MAGIC TELESCOPES: A TRANSIENT FACTORY

TeV TRANSIENTS WITH **MAGIC**

Haunting transients: MAGIC has the required performances

- **Low energy** threshold
- pointing **speed** ~7 deg/s with *automatic* repointing on valid GCNs
- Observations in **moon-time**
- **Big effective area** ➠ photon statistics



Active since 2004
In stereo configuration since 2009
At least 5 more years foreseen

Energy threshold (trigger): ~50 GeV
Angular resolution: 0.1°@ 100 GeV; 0.05°@ 1 TeV
Sensitivity: ~0.5 % Crab Nebula in 50h observations
Light-weight construction, only ~70 T
Fast re-positioning to any coordinates in the sky: 7 deg/s
Producing ~ 1 TB data per observation night

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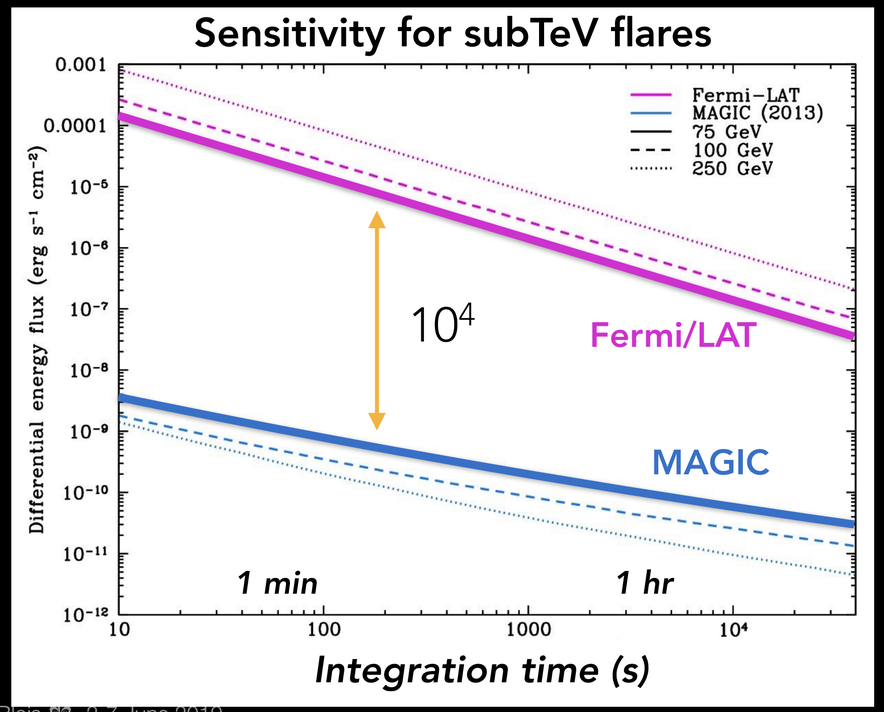

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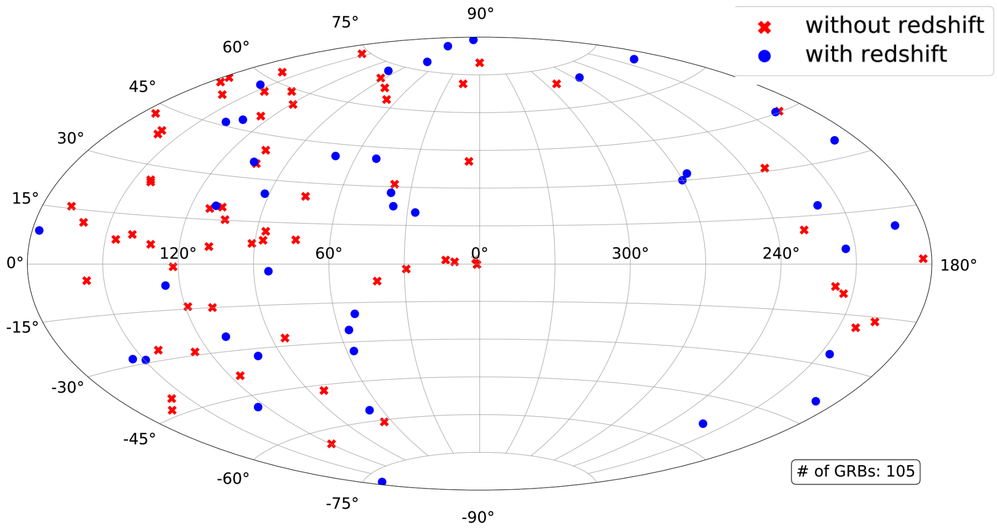
Large observing program on **GRB**, **Fast radio burst**, **neutrinos**, **GW alerts**

- ~8 **GRBs**/yr (105 GRBs observed since 2005)

GRB observed by MAGIC



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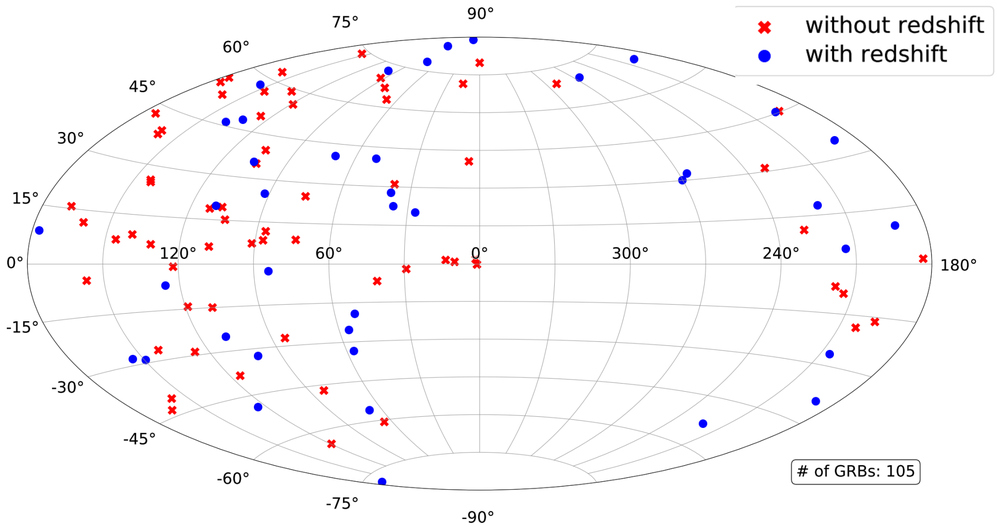
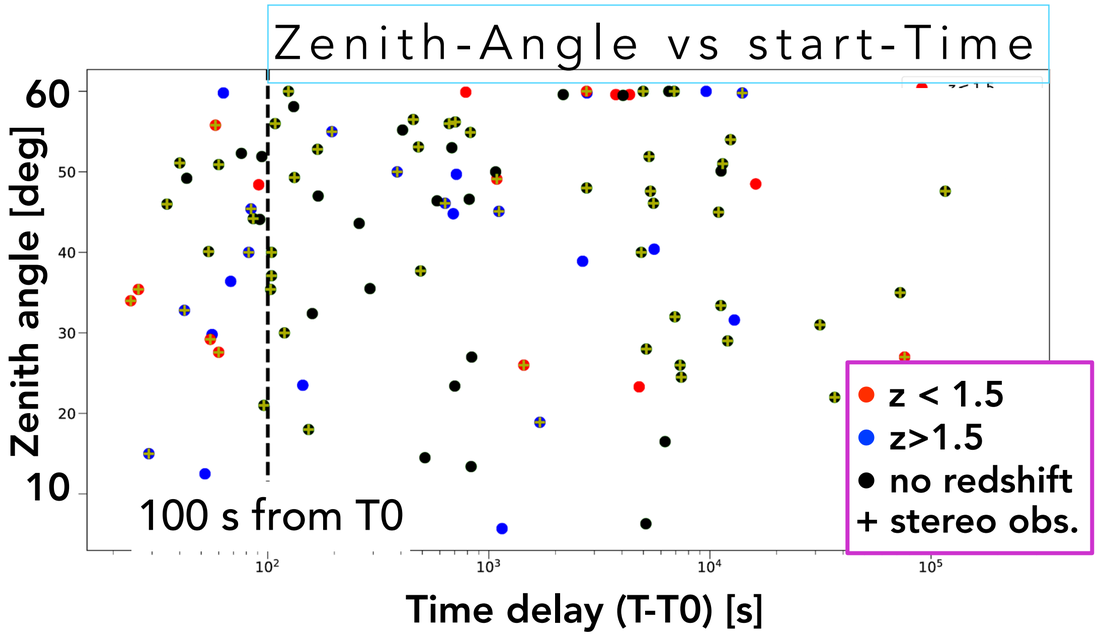
  - 24 within 100 s from T0

GRB observed by MAGIC





TeV TRANSIENTS WITH MAGIC

Large observing program on **GRB**, **Fast radio burst**, **neutrinos**, **GW alerts**

- ~8 **GRBs**/yr (105 GRBs observed since 2005)
  - 24 within 100 s from T0
- Pioneer ToO program on **IceCube neutrinos** *JINST, 11, P11009 (2016)*
  - 4 real-time alerts + 2 HESE (archival) + 2 PeV track (HET)
  - 30 hours of observations with MAGIC

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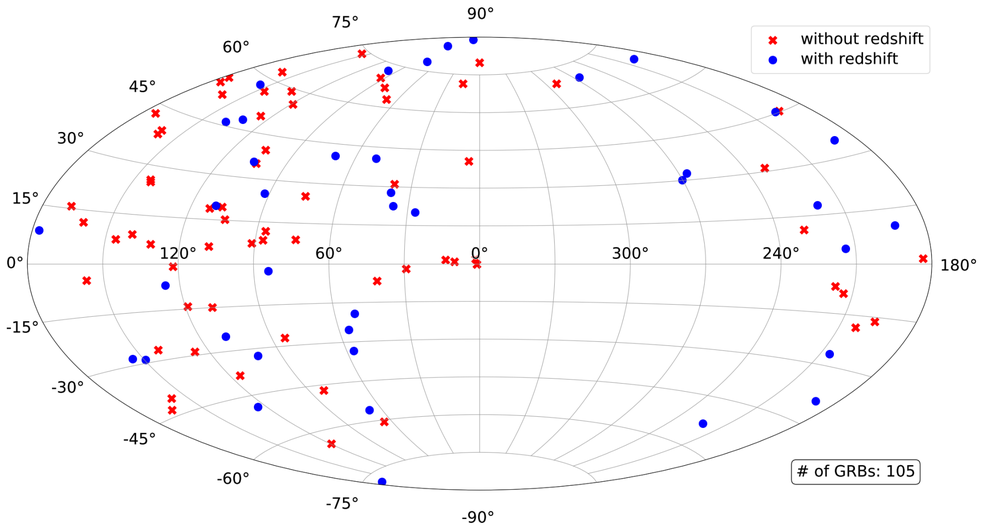
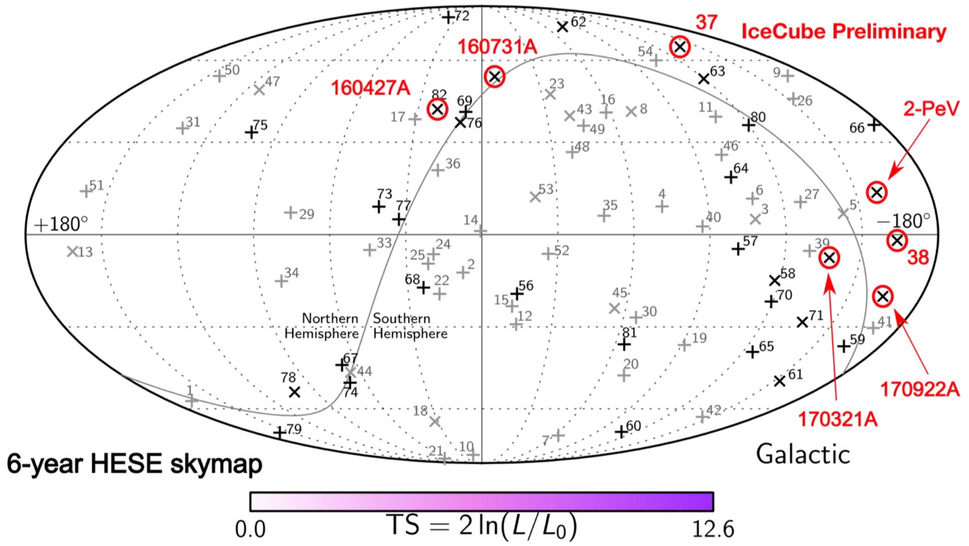


ν (HESE, EHE) observed by MAGIC



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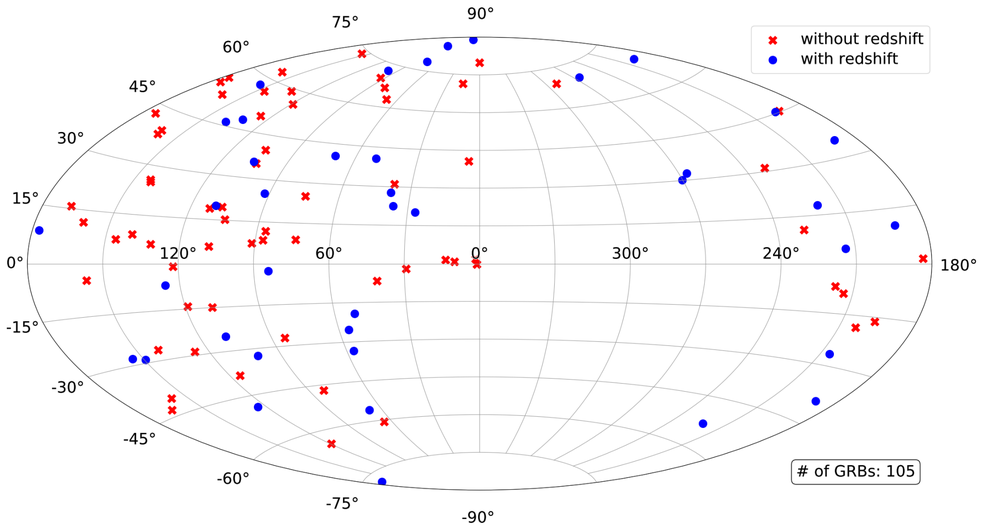
  - 30 hours of observations with MAGIC
- Observations of repetitive **FRB** 121102
- Follow-up of **GW alerts**
  - First IACT to provide a followup of optical candidates on GW151226 *De Lotto et al., Proc., IAU Symposium 324 (2016)*

GRB observed by MAGIC



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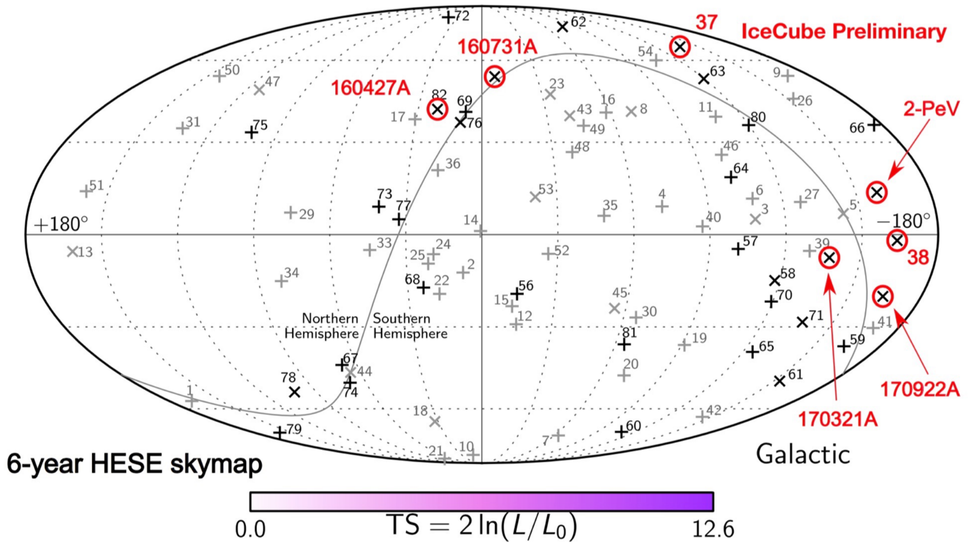


The first TeV GRB: GRB190114C

Large observing program on **GRB**, **Fast radio burst, neutrinos, GW alerts**

- ~8 **GRBs**/yr (105 GRBs observed since 2005)
  - 24 within 100 s from T0
- Pioneer ToO program on **IceCube neutrinos** *JINST, 11, P11009 (2016)*
  - 4 real-time alerts + 2 HESE (archival) + 2 PeV track (HET)

TeV Detection of GRB 190114C!
first GRB detected at the teraelectronvolt energies

es on GW151226 *De Lotto et al., Proc., IAU Symposium 324 (2016)*

GCN reporting the detection by MAGIC of GRB190114C

```
TITLE:   GCN CIRCULAR
NUMBER:  23701
SUBJECT: MAGIC detects the GRB 190114C in the TeV energy domain
DATE:    19/01/15 01:56:36 GMT
FROM:    Razmik Mirzoyan at MPI/MAGIC  <Razmik.Mirzoyan@mpp.mpg.de>

R. Mirzoyan (MPP Munich), K. Noda (ICRR University of Tokyo),

E. Moretti (IFAE Barcelona), A. Berti (University and INFN Torino),

C. Nigro (DESY Zeuthen), J. Hoang (UCM Madrid), S. Micanovic

(University of Rijeka), M. Takahashi (ICRR University of Tokyo),

Y. Chai (MPP Munich), A. Moralejo (IFAE Barcelona) and the MAGIC

Collaboration report:


On January 14, 2019, the MAGIC telescopes located at the Observatorio

Roque de los Muchachos on the Canary island of La Palma, detected

very-high-energy gamma-ray emission from GRB 190114C (Gropp et al.,

GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN

23692, Lipunov et al. GCN 23693, J. Selsing et al. GCN 23695).
The observation was triggered by the Swift-BAT alert and it started about

50s after the Swift T0: 20:57:03.19.

The GRB data of MAGIC shows a clear excess of gamma-ray events with the

significance >20 sigma in the first 20 min (starting at T0+50s) for energies


>300GeV. The relatively high detection threshold is due to the large zenith

angle of observations (~60 deg.) and the presence of partial moon. After

the first bright flash the source is quickly fading.

The MAGIC point of contact for this burst is R. Mirzoyan
(Razmik.Mirzoyan@mpp.mpg.de).

Burst Advocate for this burst is K. Noda ( <mailto:nodak@icrr.u-tokyo.ac.jp>
nodak@icrr.u-tokyo.ac.jp)
```

GRB190114C WITH MAGIC

Alert form Fermi/GBM and Swift/BAT *T0*=20:57:03 UT; coordinates sent by Swift BAT at *T-T0*=22 s

- ➜ MAGIC automatic repointing
- ➜ Start data taking at T-T0 ~50 s
- ➜ High-Zenith angle ~60 deg;
- ➜ Moon light conditions
  - ✓ very strong signal > 20σ !

Follow-up and data collected by many observatories:

- Gamma-rays: *Fermi-LAT, Fermi-GBM, AGILE*
- X-ray: *Swift-XRT, XMM, NUSTAR, INTEGRAL....*
- Optical: *Swift-UVOT, NOT, GTC, VLT, LT, Pan-STARRS, NTT, GROND, REM, HST, ...*
- Radio: *VLA, ALMA, ATCA, RT-22, MeerKAT, GMRT*

ATel reporting the detection by MAGIC of GRB190114C

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, 12475

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 greater than 50 TeV.

GRB190114C WITH MAGIC

Basic properties of the GRB190114C

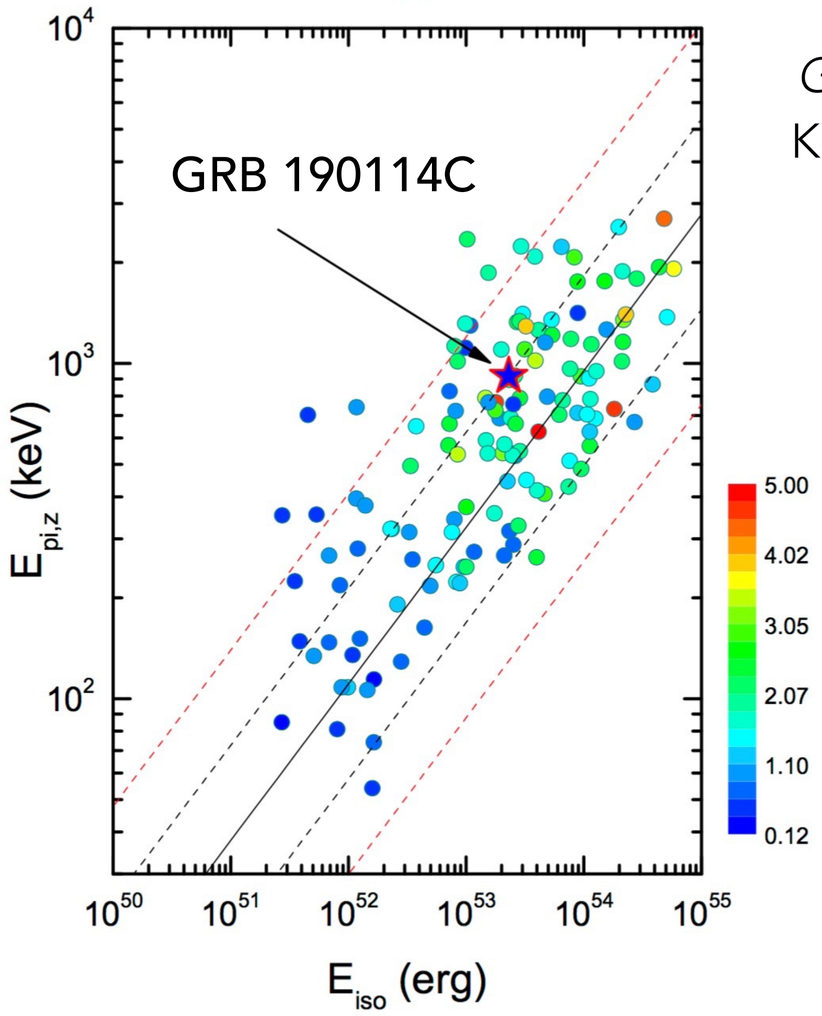
Redshift z=0.4245 *GCN23708*

Average properties of long-GRBs in a dense environment

➜ *http://tevcat.uchicago.edu/?mode=1&showsrc=324*

GRB 190114C SIMBAD

Canonical Name:	GRB 190114C
TeVCat Name:	TeV J0338-269
Other Names:	
Source Type:	GRB
R.A.:	03 38 01.17 (hh mm ss)
Dec.:	-26 56 46.73 (dd mm ss)
Gal Long:	222.47 (deg)
Gal Lat:	-53.08 (deg)
Distance:	z=0.4245
Flux:	(Crab Units)
Energy Threshold:	300 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2019-01
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced



GCN 23737
Konus-Wind

colore code: redshift

GRB190114C WITH MAGIC

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Average properties of long-GRBs in a dense environment

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Detection of TeV emission poses new questions:

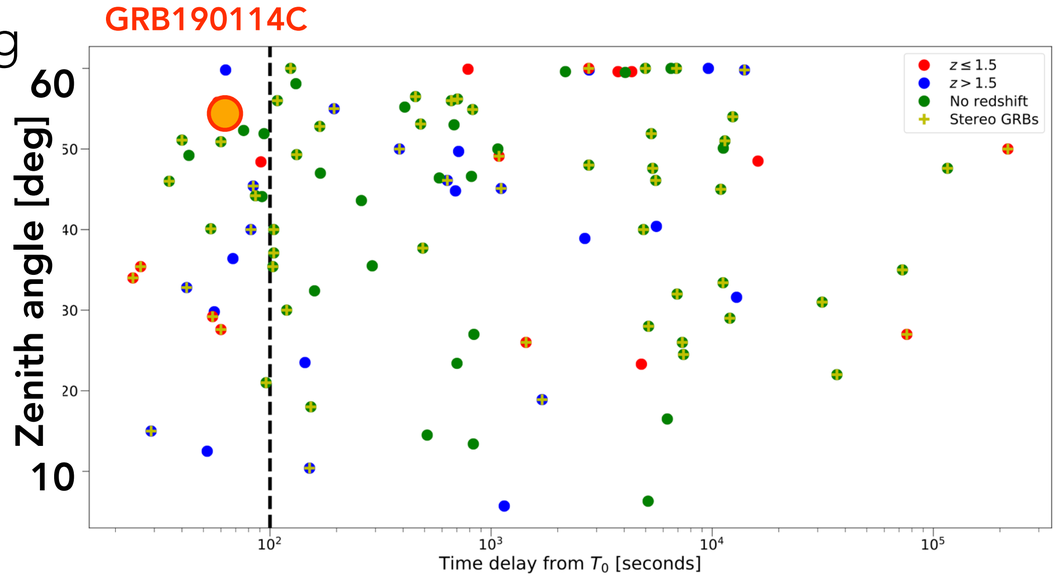
- Do all GRBs have a TeV component?
- Which processes are responsible?
- How does this connect to the usual GRB paradigm?

TeV observations with MAGIC provide the answer to those questions.

Stay tuned for the upcoming publication!

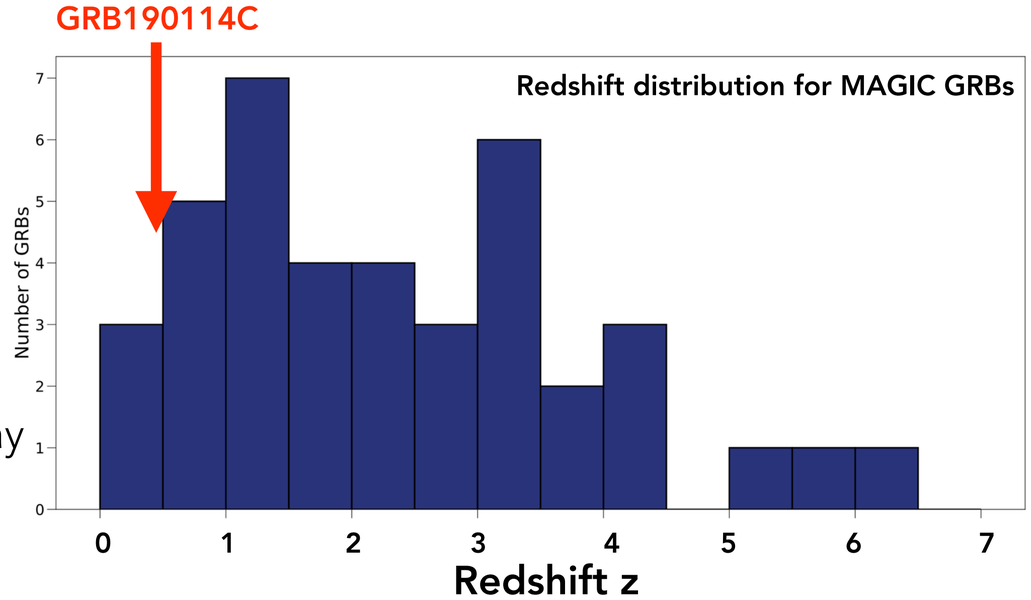
Fast Repointing

Afterglow typically decays as $t^{-1.5}$



Redshift

Within the gamma-ray horizon due to EBL



The era of GRB in the TeV domain is started!

- **First clear and strong detection of a GRB in the TeV!**
  - Photon statistics better than any GRB previously detected in the >GeV range

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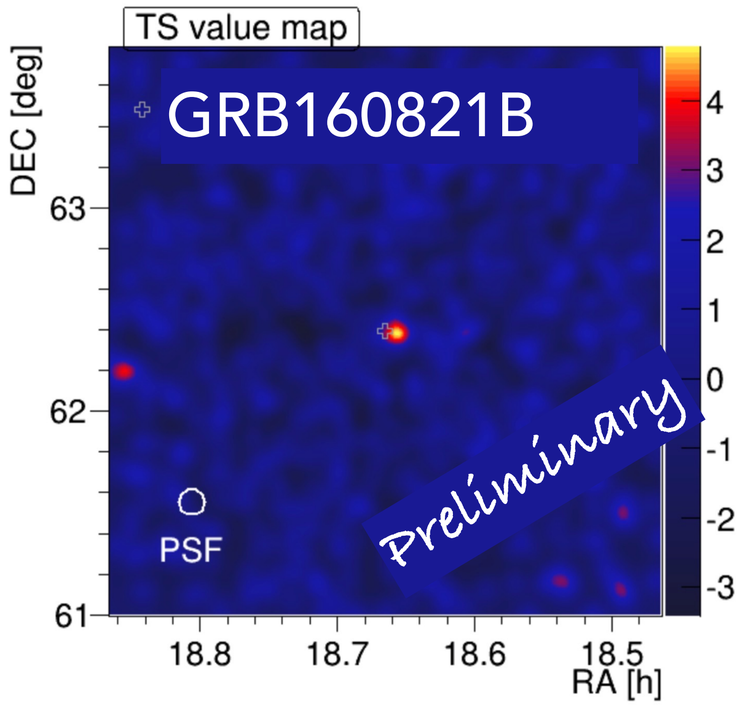
  (S. Inoue, ICRC 2017; K. Noda, Texas Symposium 2017; Berti et al., 2019, Proc. MG15)
  - z=0.16; recently associated to a kilonova
    Lamb et al. 2019 arXiV:1905.02159, Troja et al. arXiV:1905.01290

COMPELLING FOR FUTURE TEV-DETECTION OF GW COUNTERPARTS!

K. Noda, Texas Symposium 2017



4 h data, $> 4\sigma$ pre-trial, 3.1σ post-trial above 600-800 GeV: **detection hint** (3 independent analyzers)

new analysis in progress!

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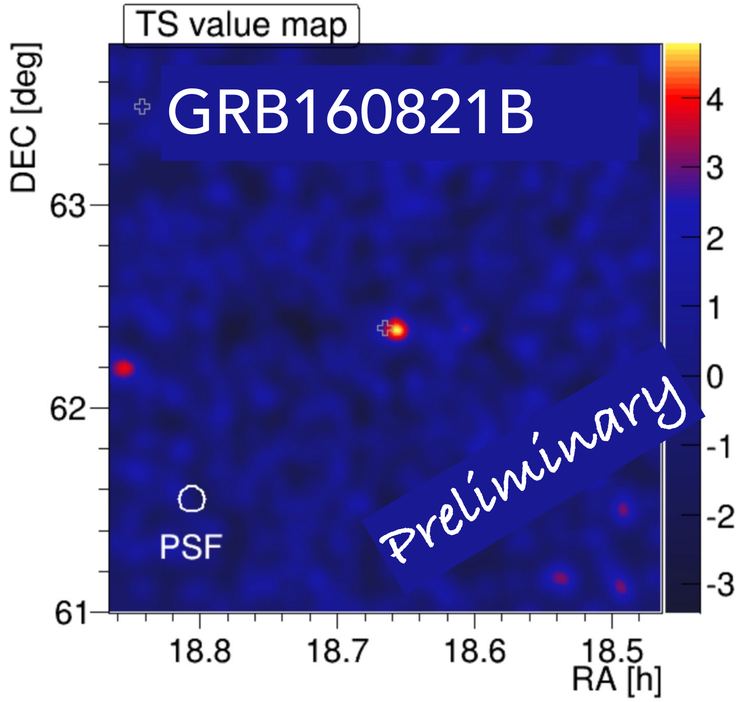
    Lamb et al. 2019 arXiV:1905.02159, Troja et al. arXiV:1905.01290
- Report of a possible late-afterglow emission from GRB180720B by H.E.S.S. (announced at CTA-symposium, 05/19)
  - 2nd brightest GRB; detection 10 hours after T0

K. Noda, Texas Symposium 2017



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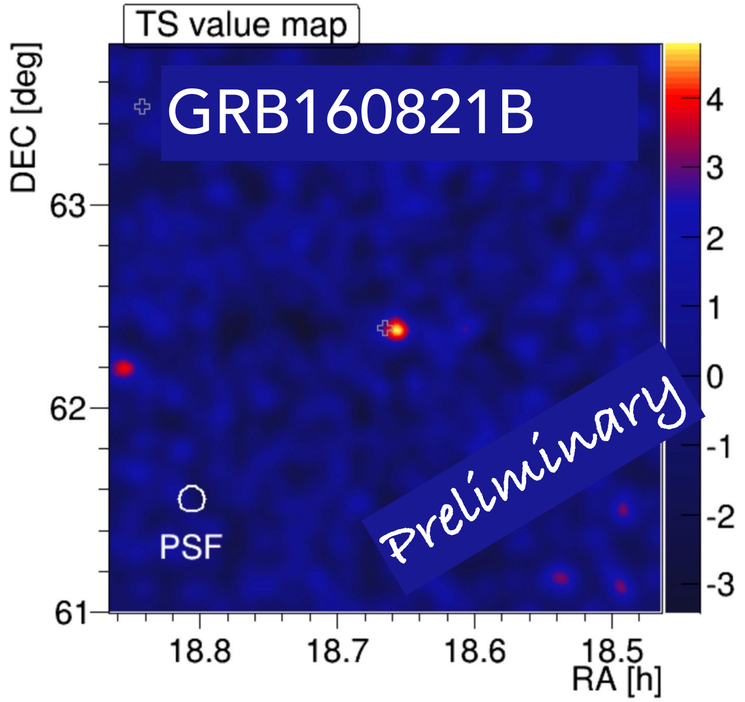
    Lamb et al. 2019 arXiV:1905.02159, Troja et al. arXiV:1905.01290

NEXT (DREAMED) FRONTIERS:

DETECTION OF A γ-RAY COUNTERPART OF A GW EVENT

SIMULTANEOUS DETECTION OF NEUTRINOS, GRAVITATIONAL WAVES AND γ-RAY FROM A NS-NS OR NS-BH MERGER!

K. Noda, Texas Symposium 2017



4 h data, > 4σ pre-trial, 3.1σ post-trial above 600-800 GeV: **detection hint** (3 independent analyzers)

new analysis in progress!

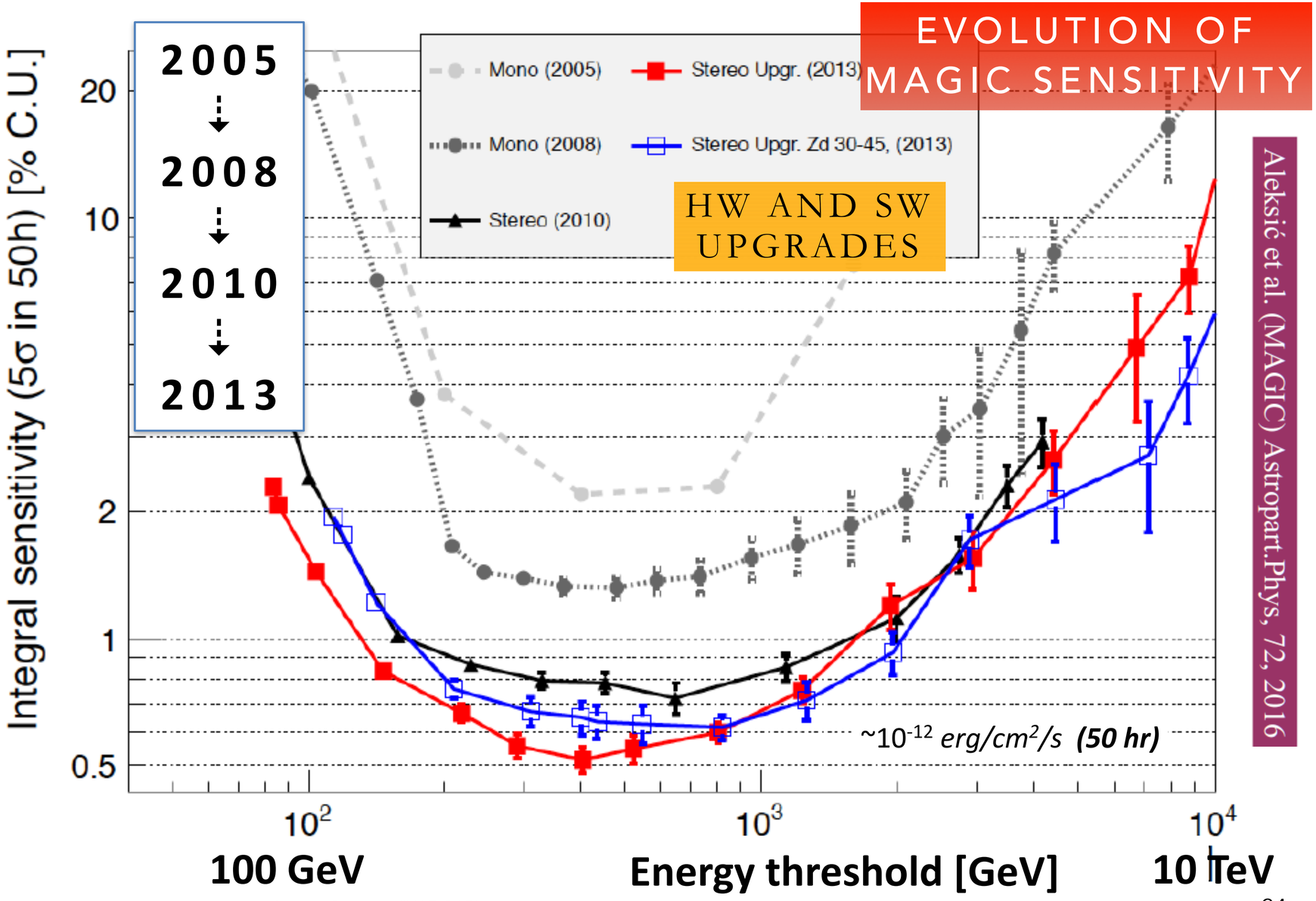
TAKE HOME MESSAGES

- γ-ray observations are key in the search for the sources of HE neutrinos
- AGN are plausible nu-sources and thus accelerators of UHE-CR
  - looking for next nu-blazar event!
- galactic winds, and AGN-driven winds looks as promising environments for CR acceleration and neutrino production

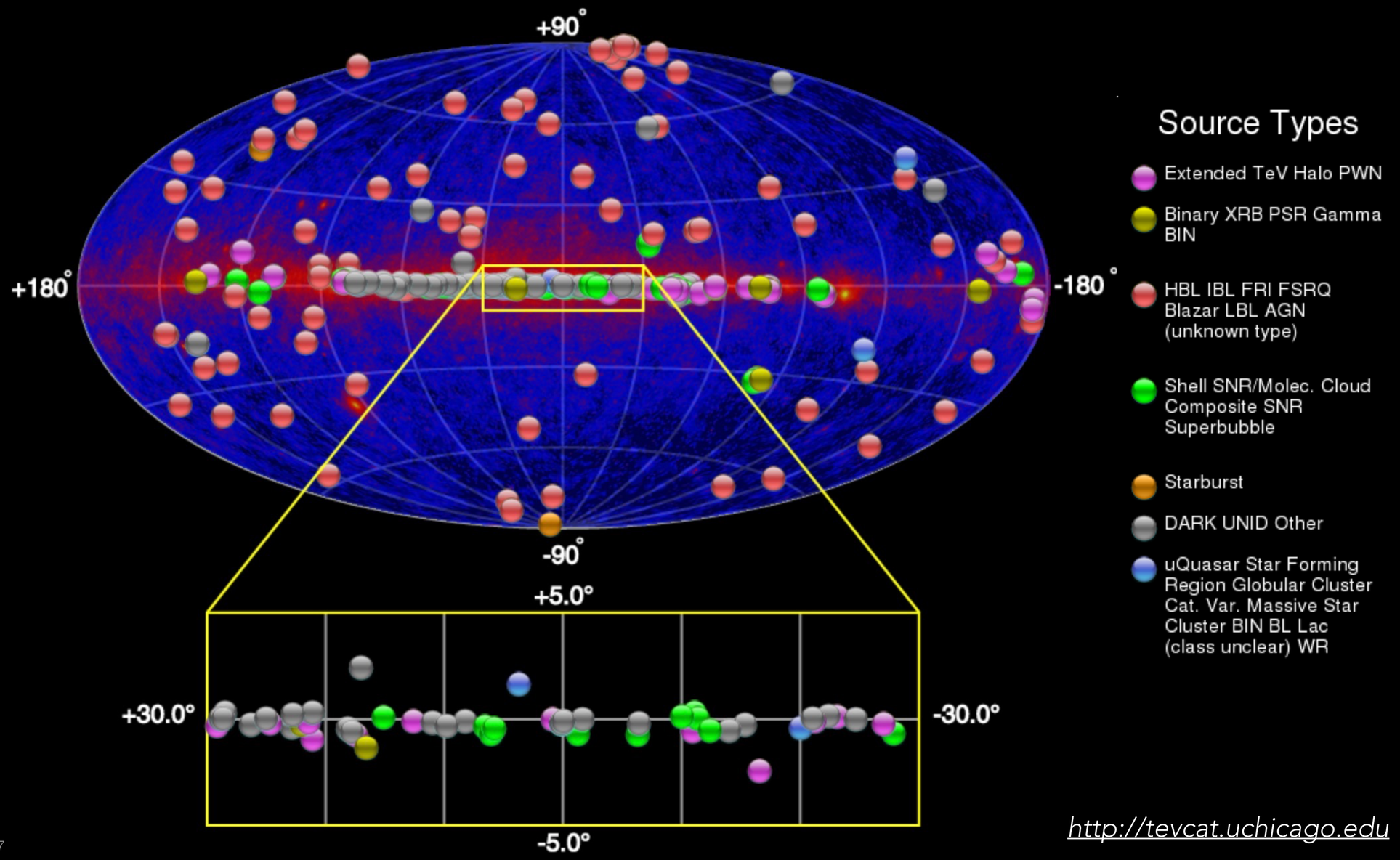
- Cherenkov telescope are ideal transient factories
- The GRB paradigm is amplified and revolutionised by the detection of TeV emission on GRB170114C
- Compelling clue that GRBs (long and short) are ubiquitous TeV emitters

FROM EXPERIMENT TO OBSERVATORY

- A constant increase of performance:
  - improved readout systems; mirror maintenance and upgrades; sum-Trigger system
  - Improved analysis: timing, better calibration and g/h algorithms
  - Study of systematics
- Development of strategies to observe in: moonlight and (very)large zenith angle conditions
- Stability and reliability of automatic repointing, and fast acquisition procedures



THE VHE GAMMA-RAY SKY



http://tevcat.uchicago.edu

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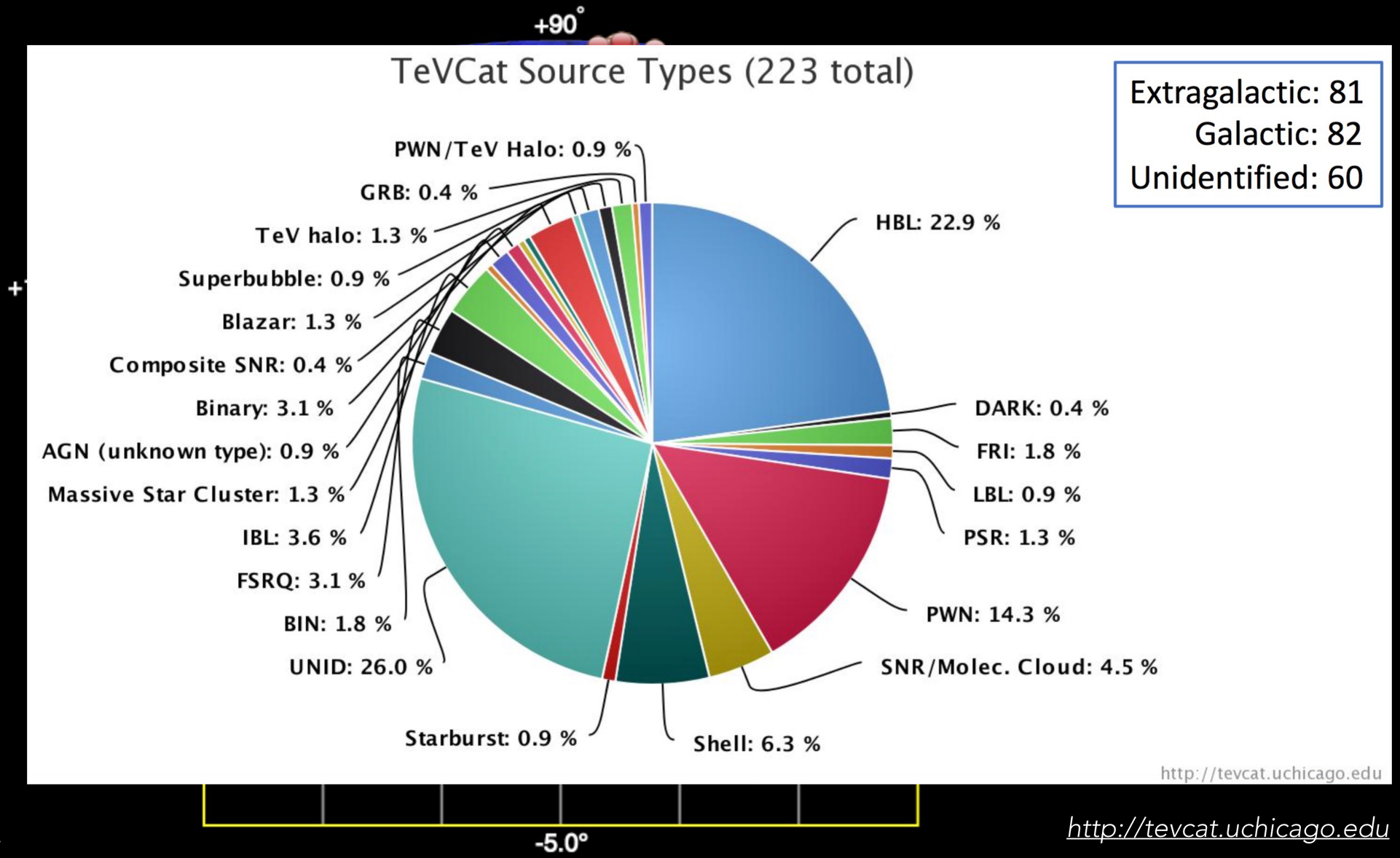

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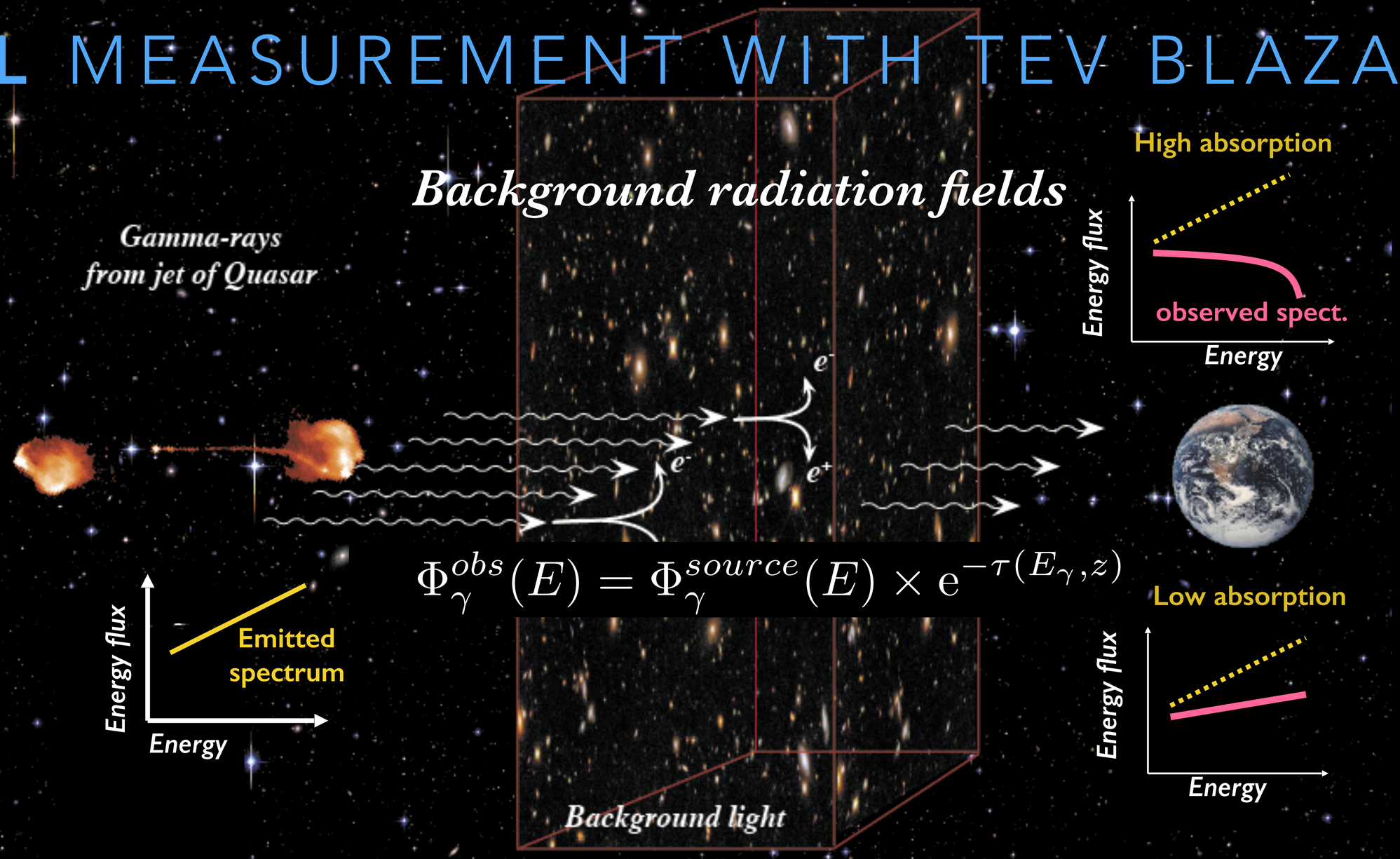
EBL MEASUREMENT WITH TEV BLAZARS



$$\Phi_\gamma^{obs}(E) = \Phi_\gamma^{source}(E) \times \mathrm{e}^{-\tau(E_\gamma, z)}$$

EBL: extragalactic Background Light

PRECISION AND STATISTICS: EBL MEASUREMENT

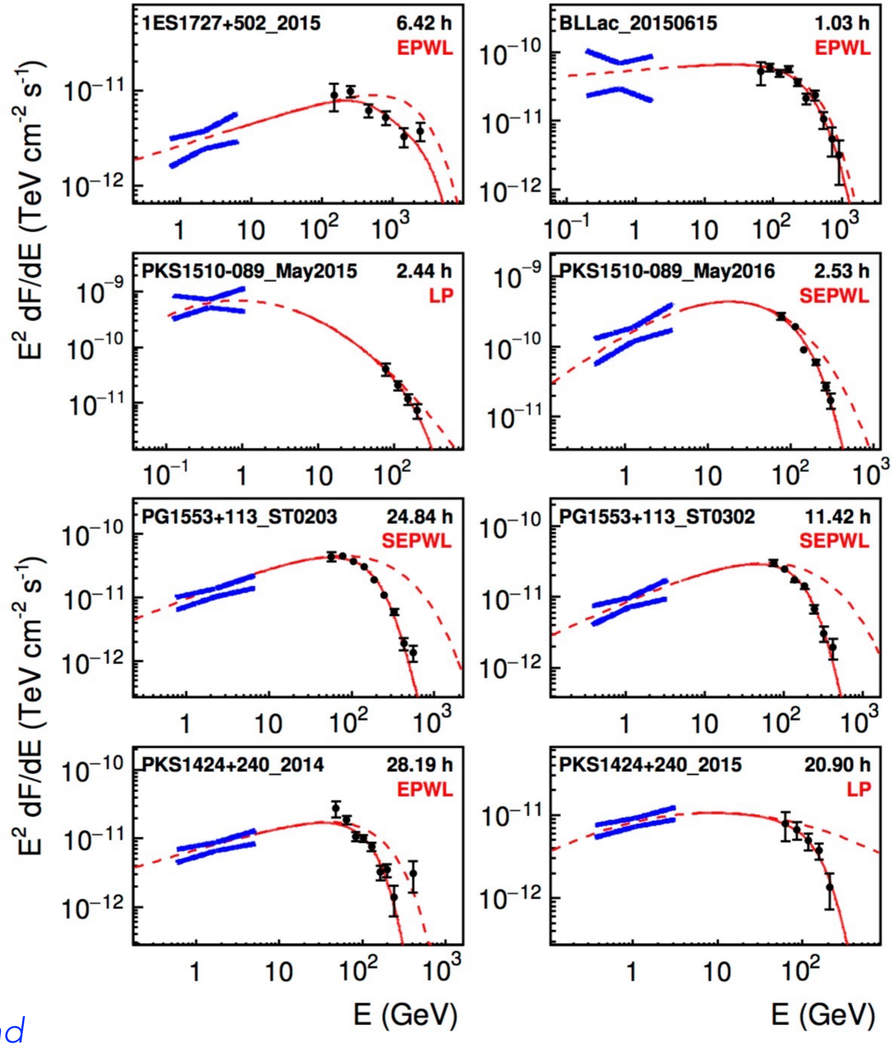
- Sum contribution of 32 spectra of blazars
- Combined spectrum of Fermi/LAT and MAGIC
- Different intrinsic spectral models

PWL: $F_0\,(E/E_0)^{-\Gamma}$ EPWL: $F_0\,(E/E_0)^{-\Gamma}\,e^{-E/E_c}$

LP: $F_0\,(E/E_0)^{-\Gamma-b\log(E/E_0)}$

ELP: $F_0\,(E/E_0)^{-\Gamma-b\log(E/E_0)}\,e^{-E/E_c}$

SEPWL: $F_0\,(E/E_0)^{-\Gamma}\,e^{-(E/E_c)^d}$



MAGIC coll., MNRAS acc., Measurement of the Extragalactic Background Light using MAGIC and Fermi-LAT gamma-ray observations of blazars up to z = 1 https://arxiv.org/abs/1904.00134

PRECISION AND STATISTICS: EBL MEASUREMENT

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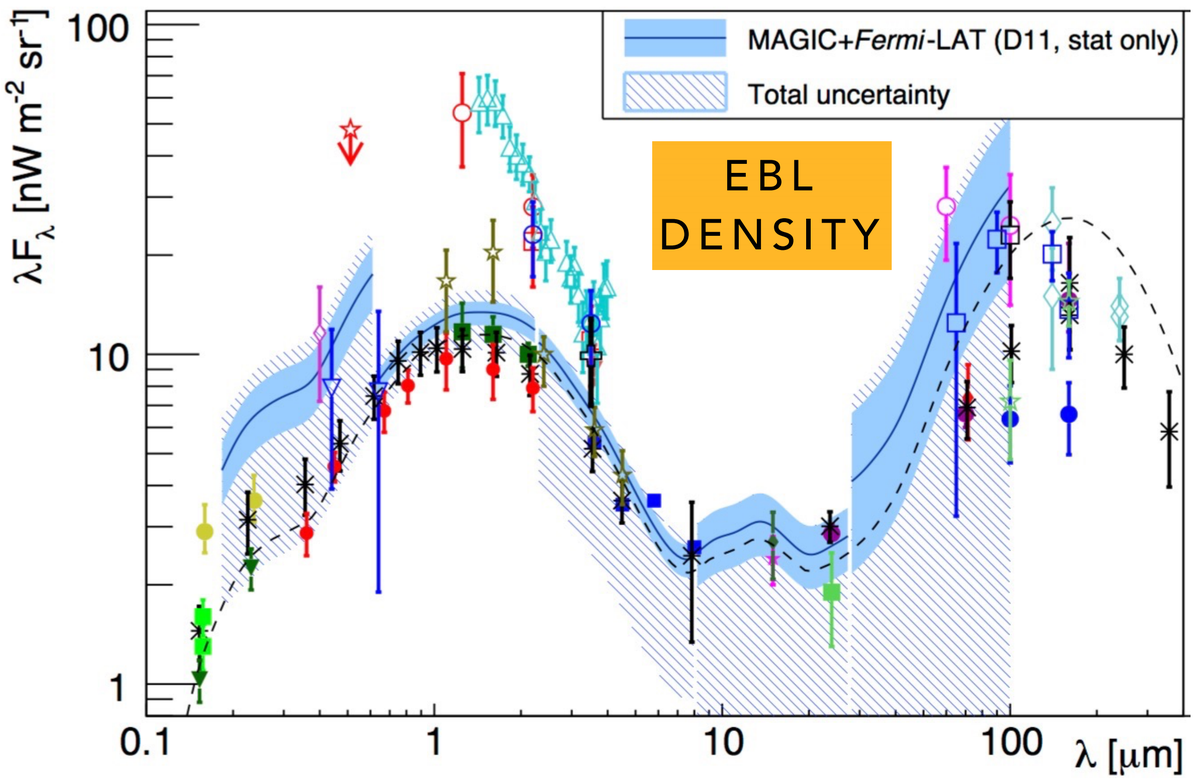
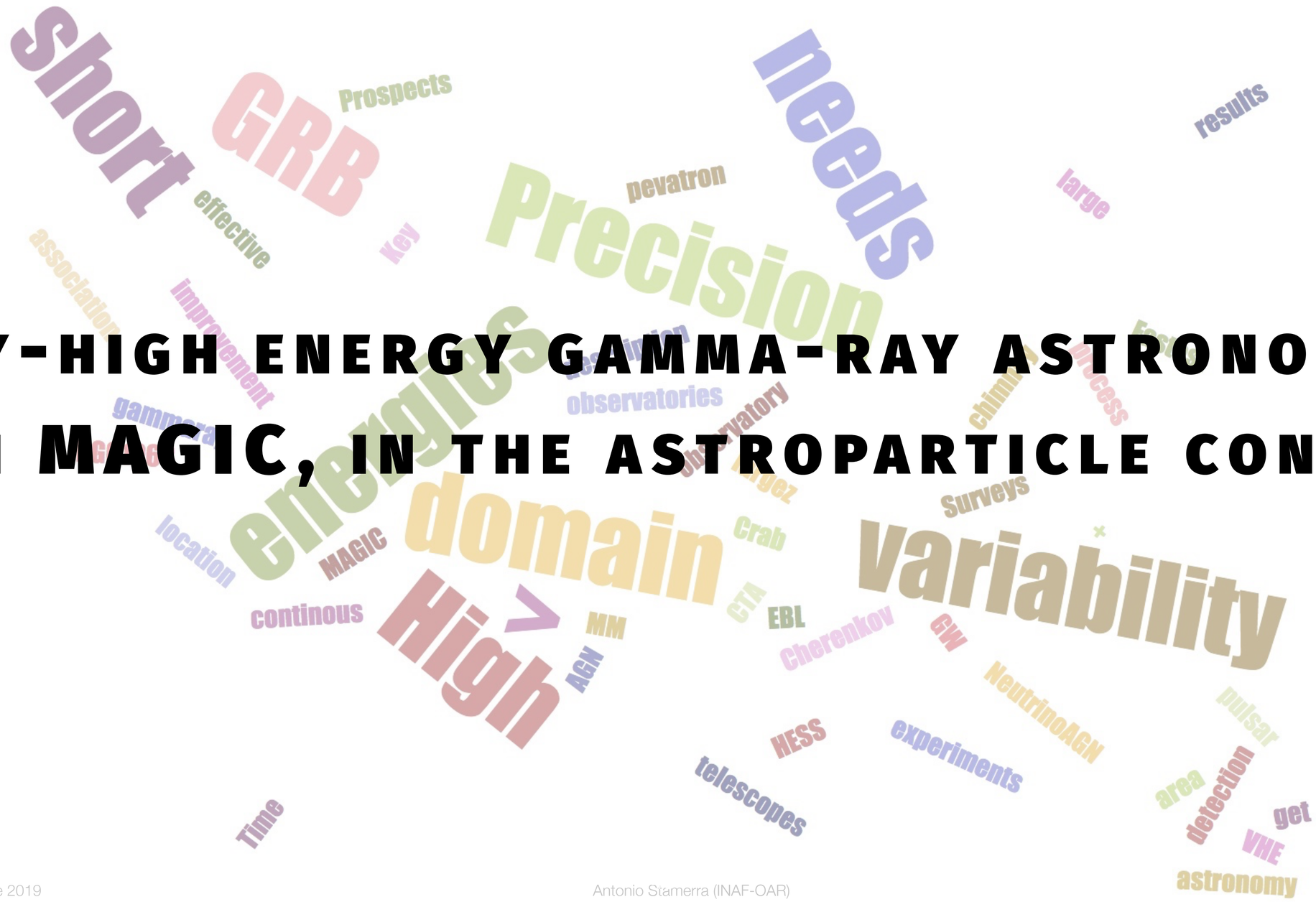
- Combined spectrum of Fermi/LAT and MAGIC
- Different intrinsic spectral models
- **Studies on systematics**
  - intrinsic models
  - instrument response



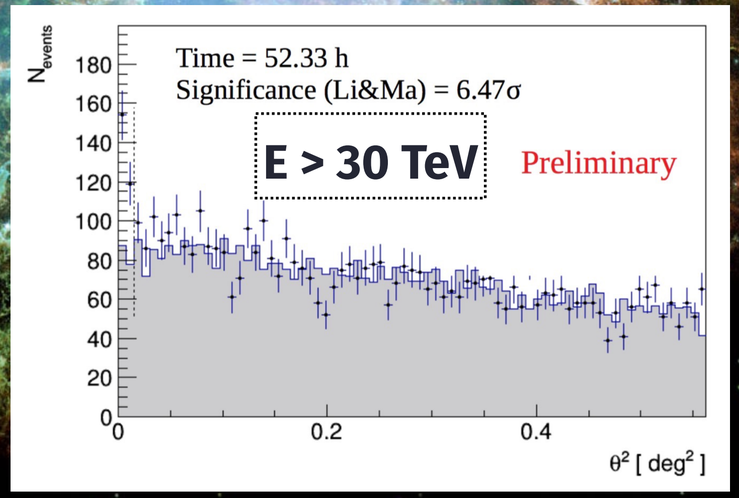
MAGIC coll., MNRAS acc., Measurement of the Extragalactic Background Light using MAGIC and Fermi-LAT gamma-ray observations of blazars up to z = 1 https://arxiv.org/abs/1904.00134

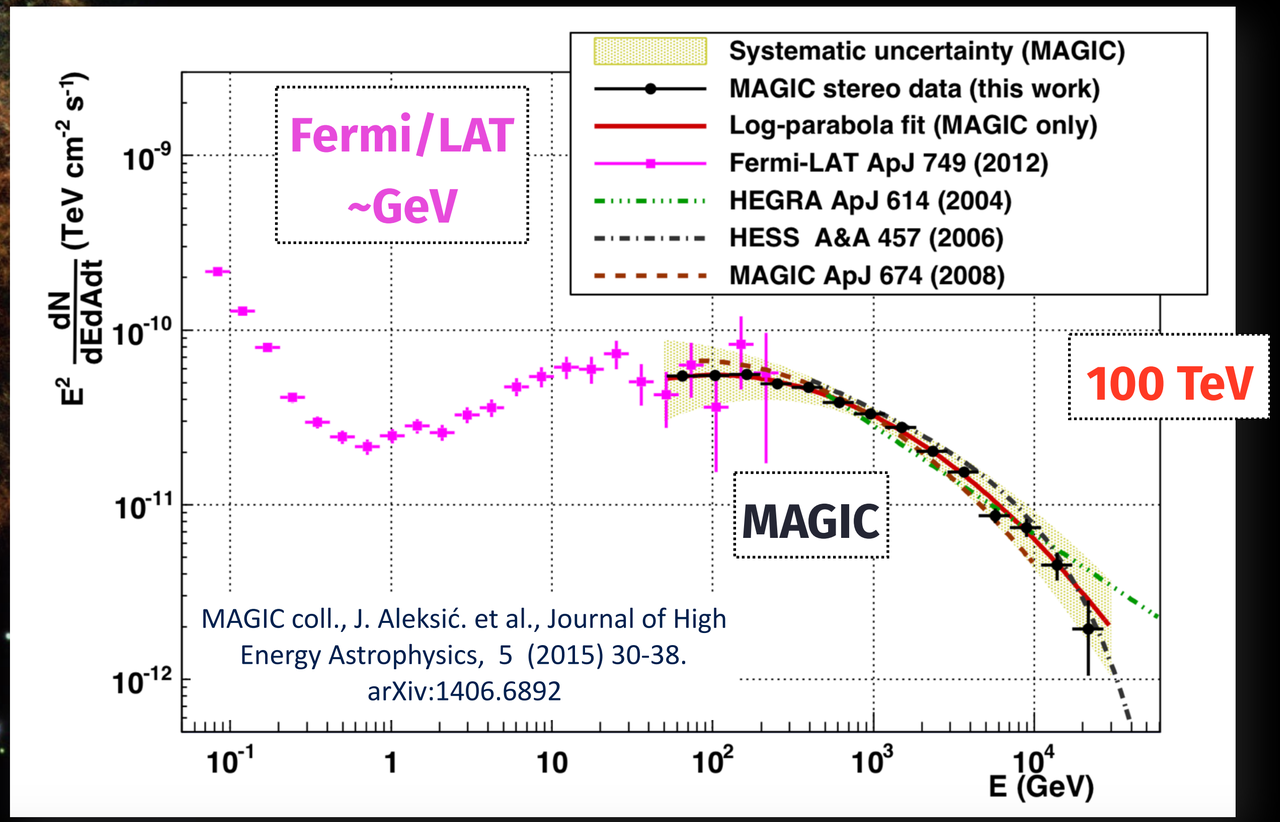
Very-high energy gamma-ray astronomy with MAGIC, in the astroparticle context



EXTREME ENERGIES

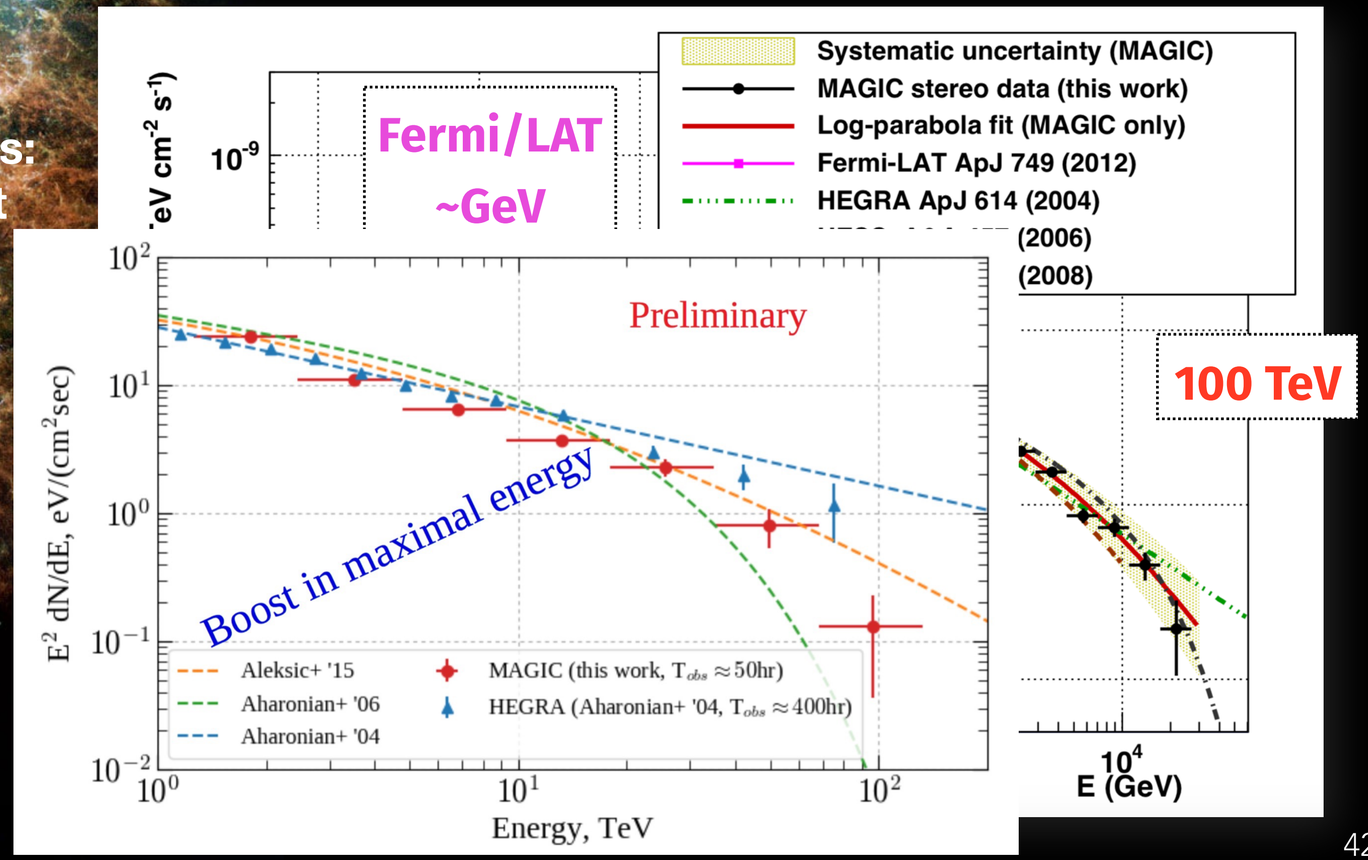
- **Crab Nebula in the 100 TeV domain**
- **Extend the spectrum up to > 100 TeV**
- **Recent measurement by HAWC (2.5 years integration time)**





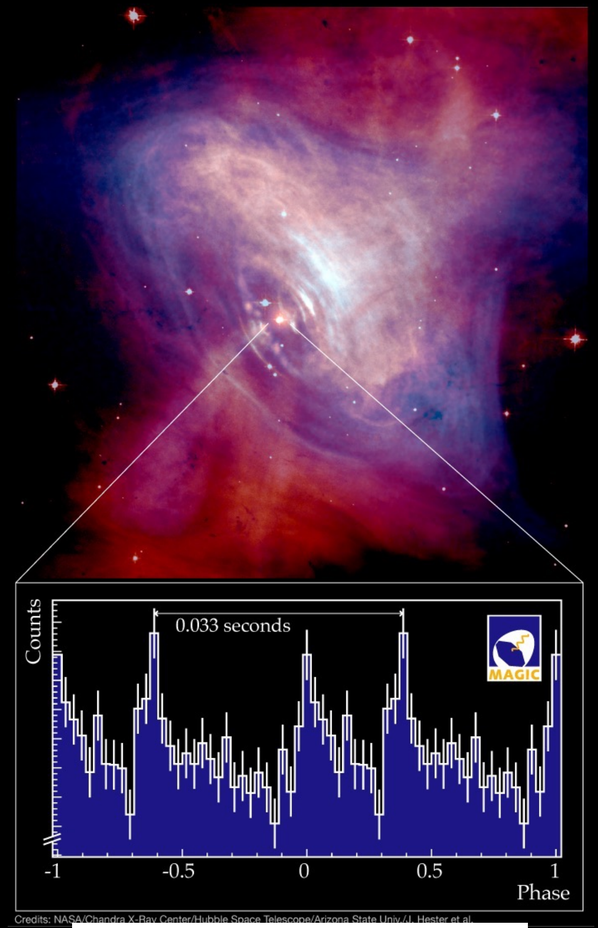
EXTREME ENERGIES

- Crab Nebula in the 100 TeV domain
- Extend the spectrum up to > 100 TeV
- Recent measurement by HAWC (3 years integration time)
- MAGIC observations at very large zenith angles: greater collection area -> enhance statistics at highest energy.



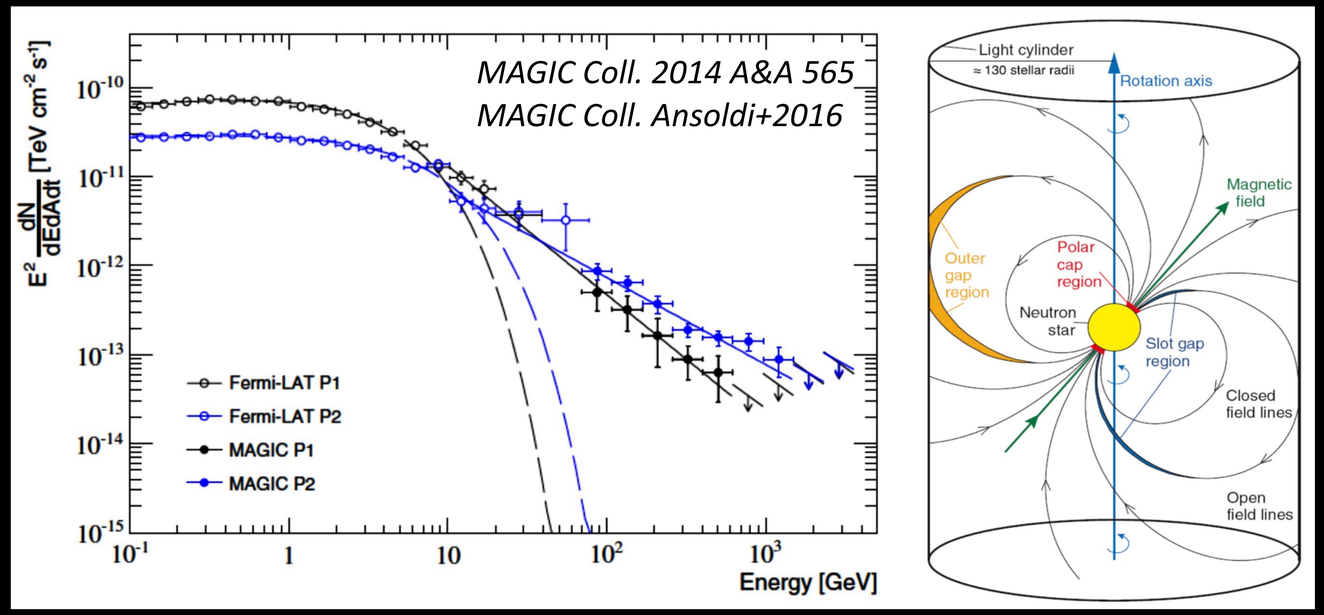
EXTREME ENERGIES

- Crab pulsar



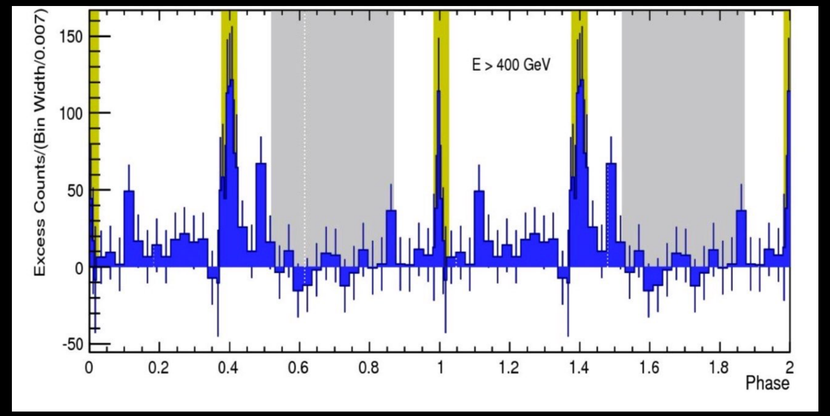
MAGIC Coll. 2008, Science 322

pulsar
Spectrum



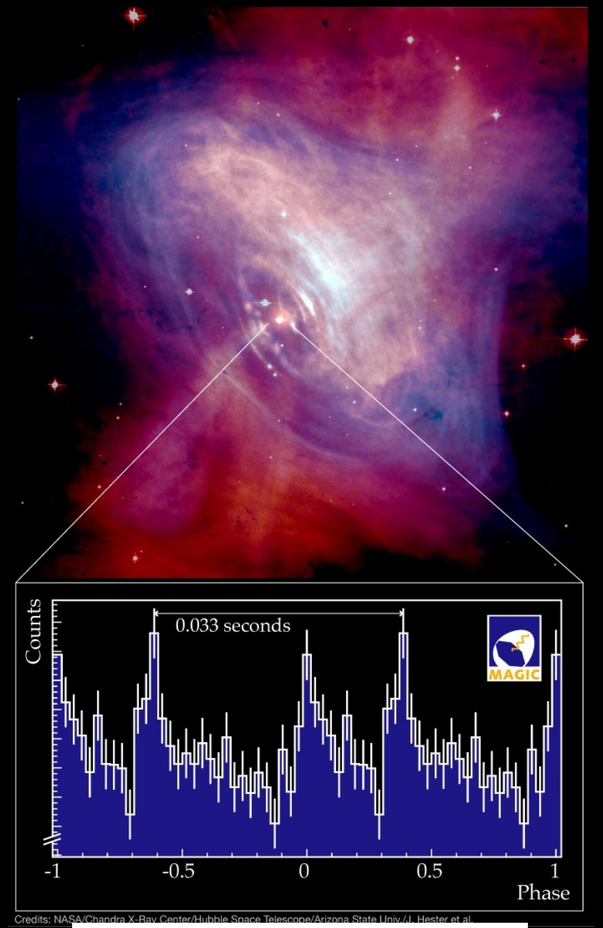
Phaseogram

E>400 GeV



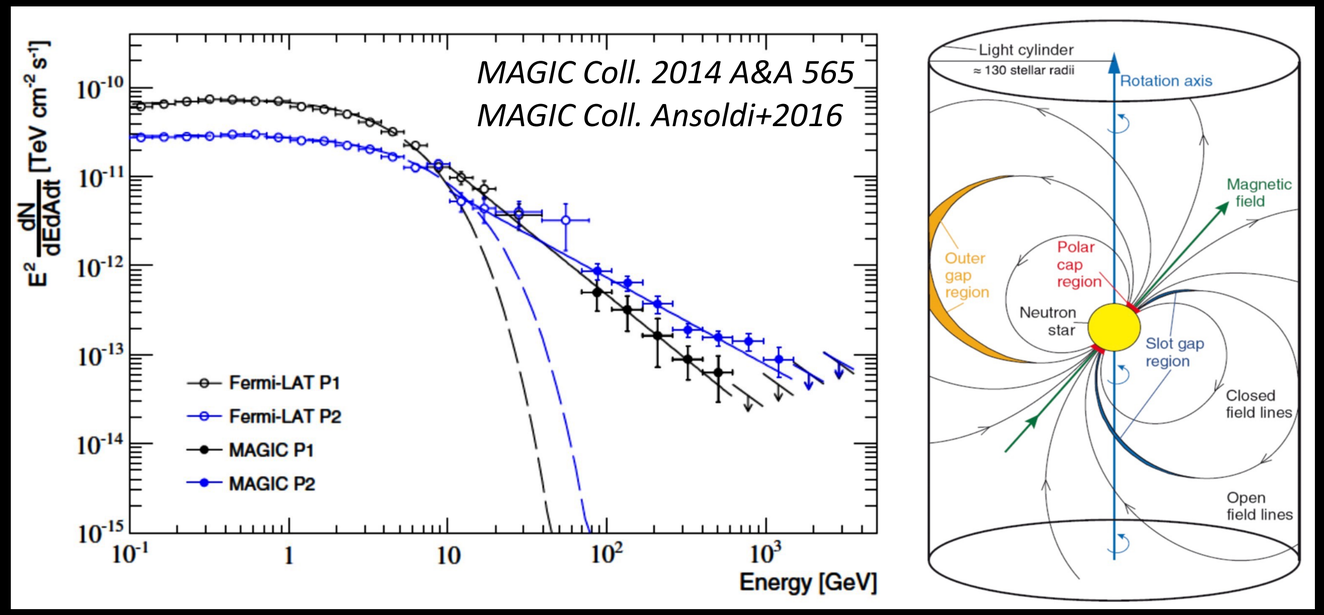
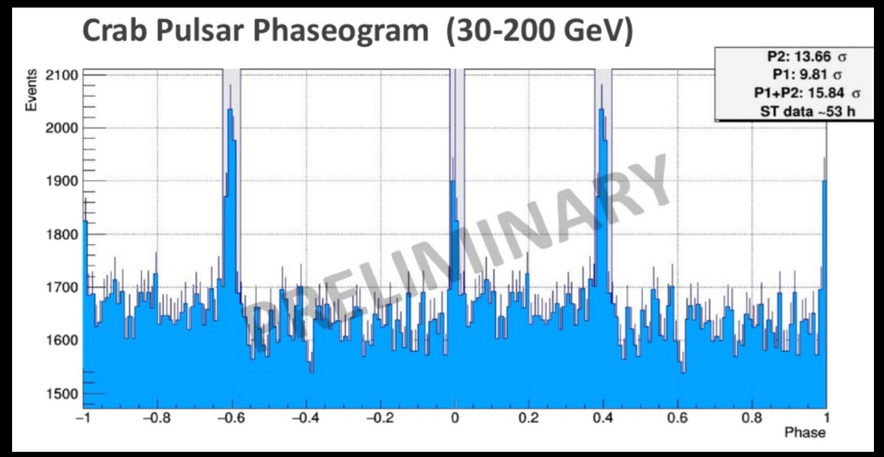
EXTREME ENERGIES

- Crab pulsar



MAGIC Coll. 2008, Science 322

pulsar
Spectrum



- Lower the energy threshold down to 30 GeV
- Sum-Trigger system