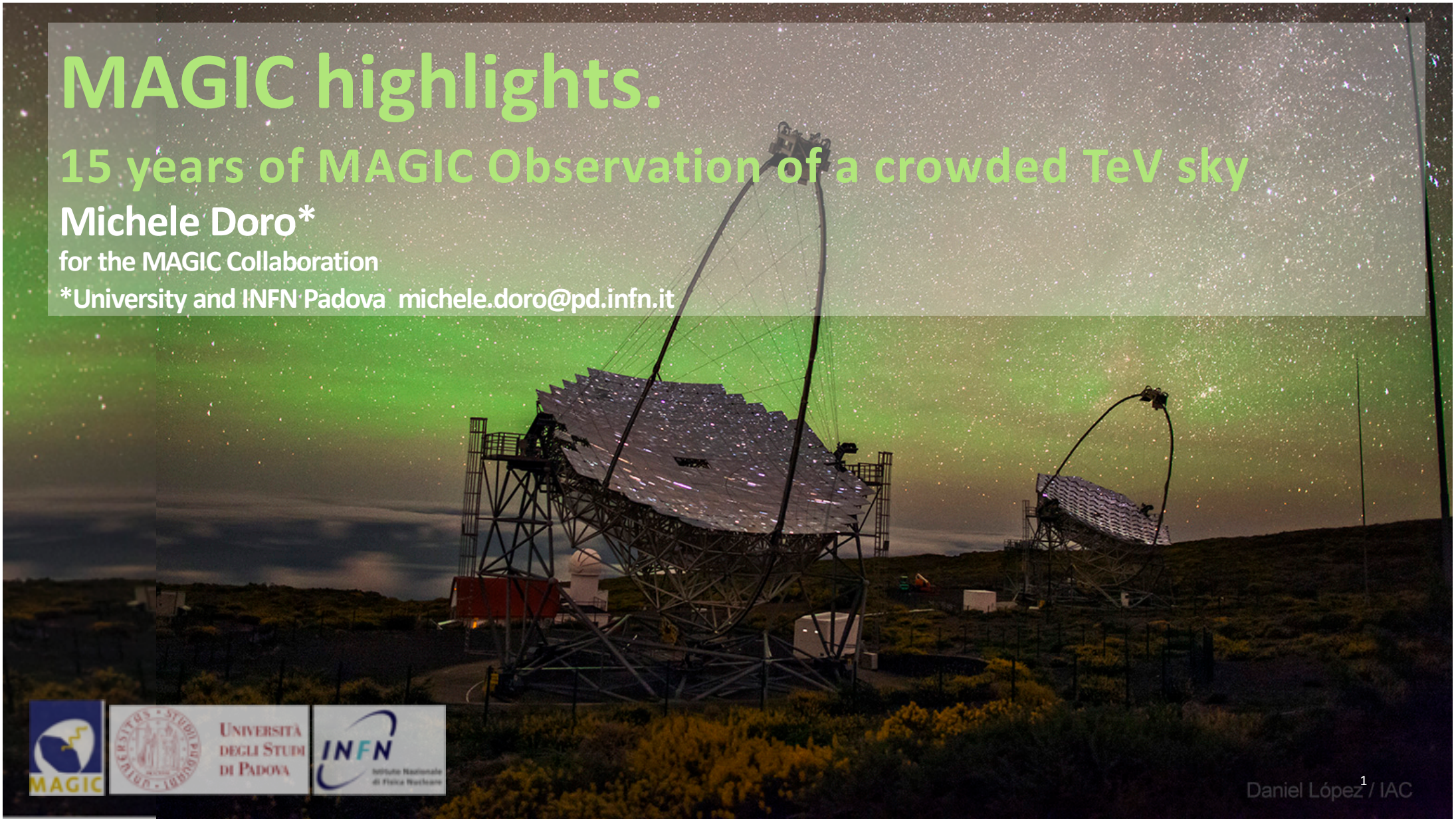
MAGIC highlights.

15 years of MAGIC Observation of a crowded TeV sky

Michele Doro*

for the MAGIC Collaboration

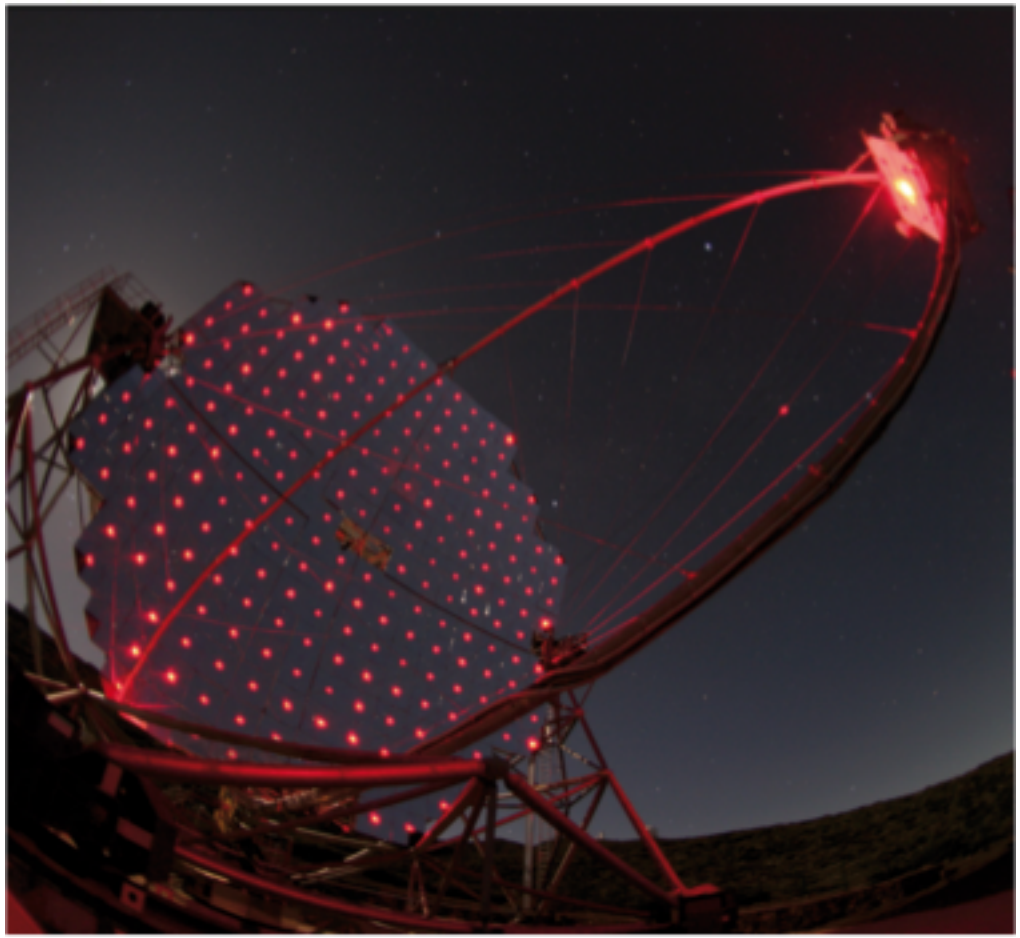
*University and INFN Padova michele.doro@pd.infn.it

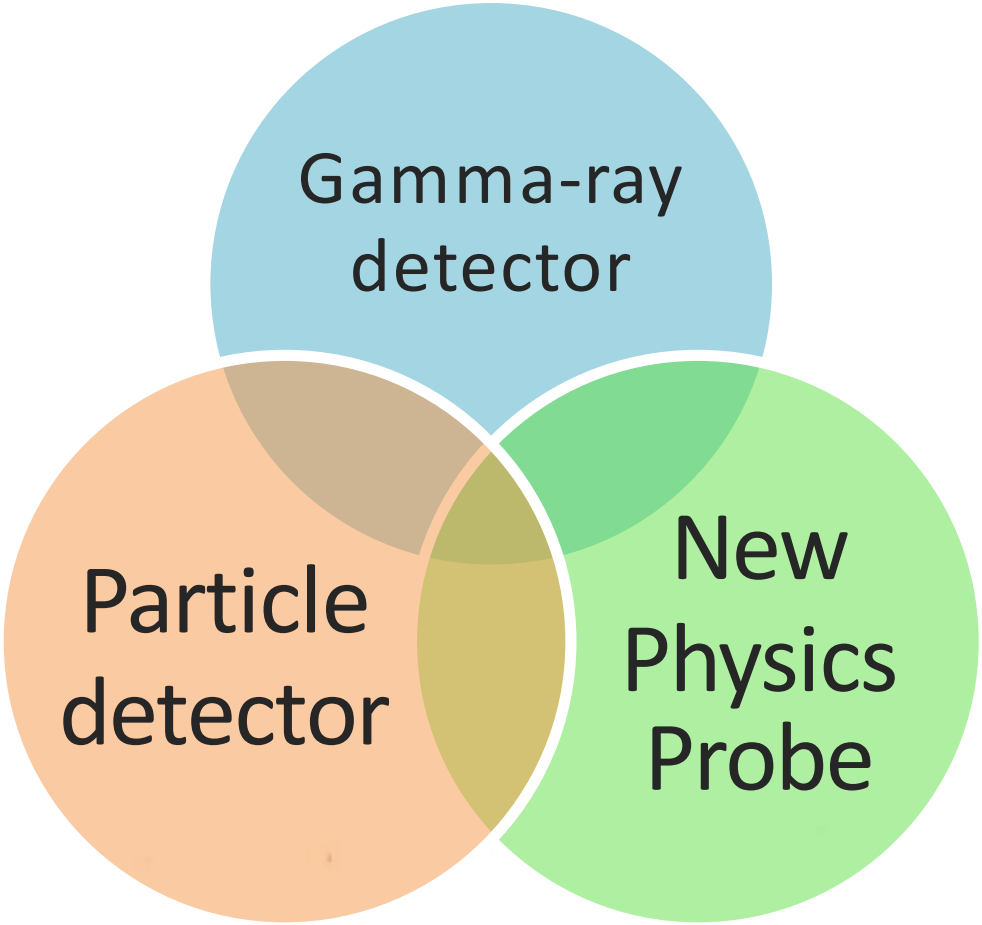


Happy 15° birthday MAGIC Florian Goebel telescopes!

First light in October 2003

Outline





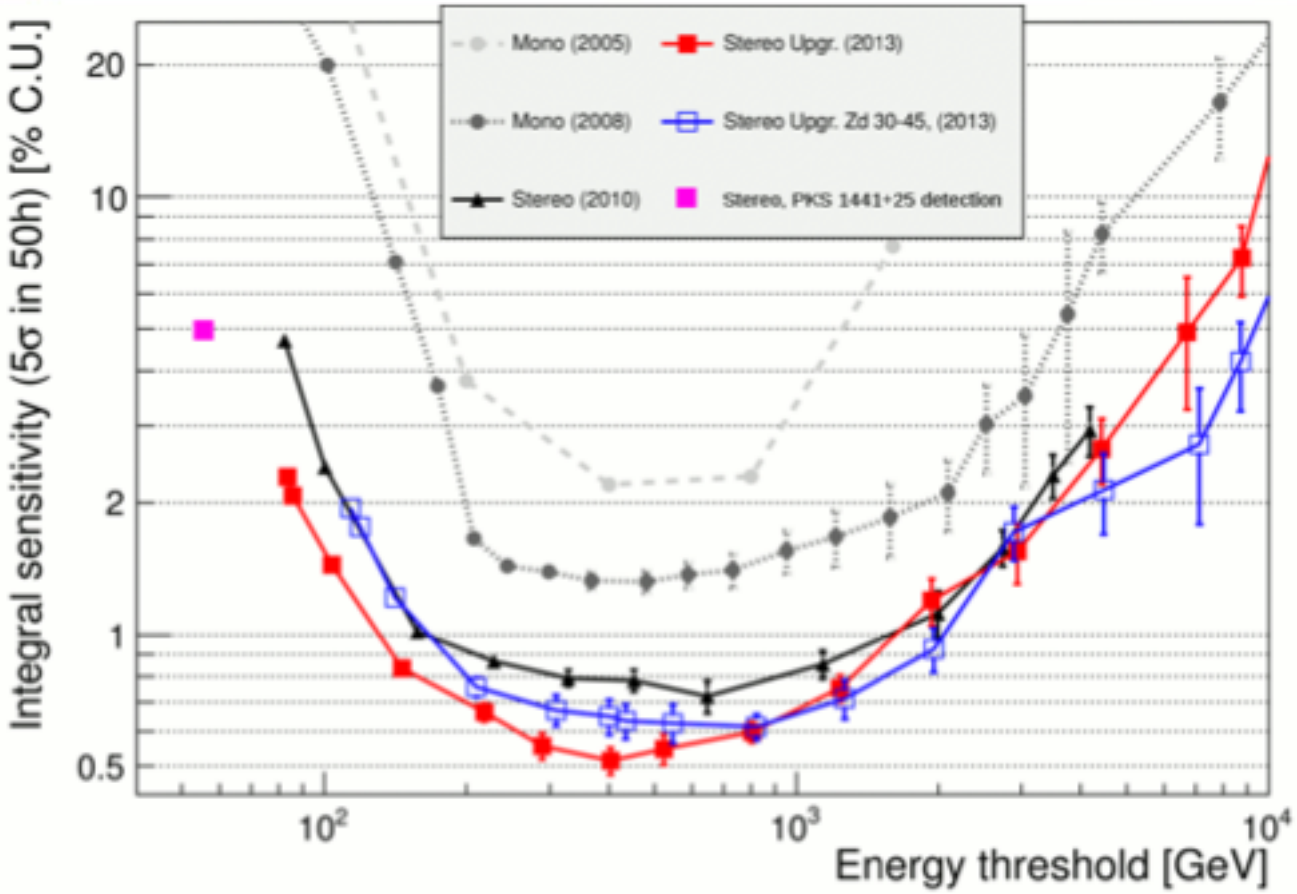
MAGIC Facts

- Started as **a single telescope** in 2003
- Operating in **stereo-mode** since 2009
- Designed optimized for: **low-energy, fast repositioning**

- ❖ Collaboration of **~160 scientists** from Germany, Spain, Italy, Switzerland, Finland, Croatia, Bulgaria, Poland, India and Japan
- ❖ 17m diameter dish
- ❖ Energy range: 70 GeV-30 TeV (with standard trigger) and down to 30 GeV (with *sumtrigger*)
- ❖ **Angular resolution**: <0.08°; **Energy resolution**: ~15-25%
- ❖ **Pointed mode** observations (Field of View: ~3.5°)

Astronomic Observatory of Roque de Los Muchachos (~2200 m a.s.l.), La Palma (Spain)

A continuous effort



4-fold improvement in sensitivity over the last decade

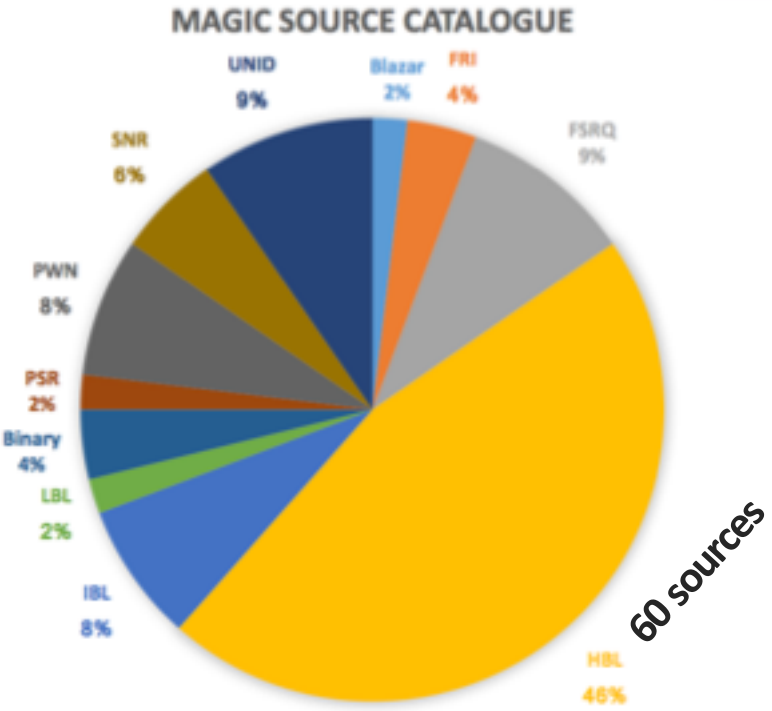
→ ~10-fold improvement at the lowest energies !!

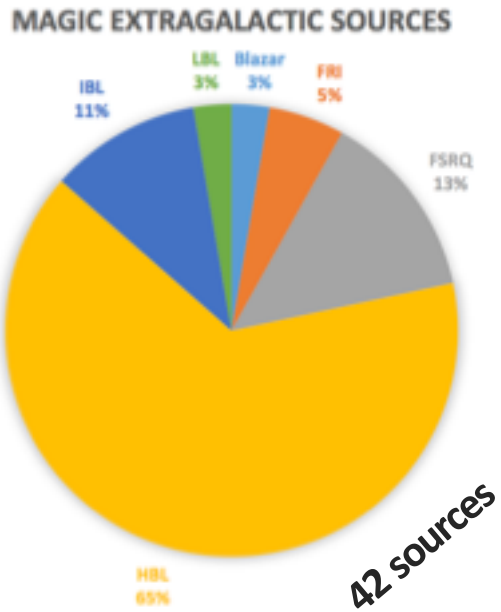
- **Mono**:
  - Light Gray circles: first installation (2005)
  - Dark gray: different readout system (2008)
- **Stereo**-phase:
  - **Black** triangles: stereo phase 1 (2010)
  - Squares: stereo after camera upgrade:
    - **zenith angle below 30◦ (red, filled),**
    - **30 – 45◦ (blue, empty)**
- **Sum-trigger** allowed <50 GeV

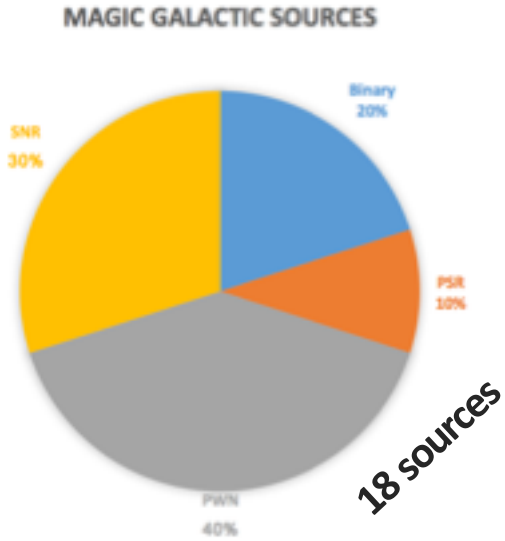
← 16 times less needed observation time!

The MAGIC "catalogues"

From TeVCat 2.0 http://tevcat2.uchicago.edu/

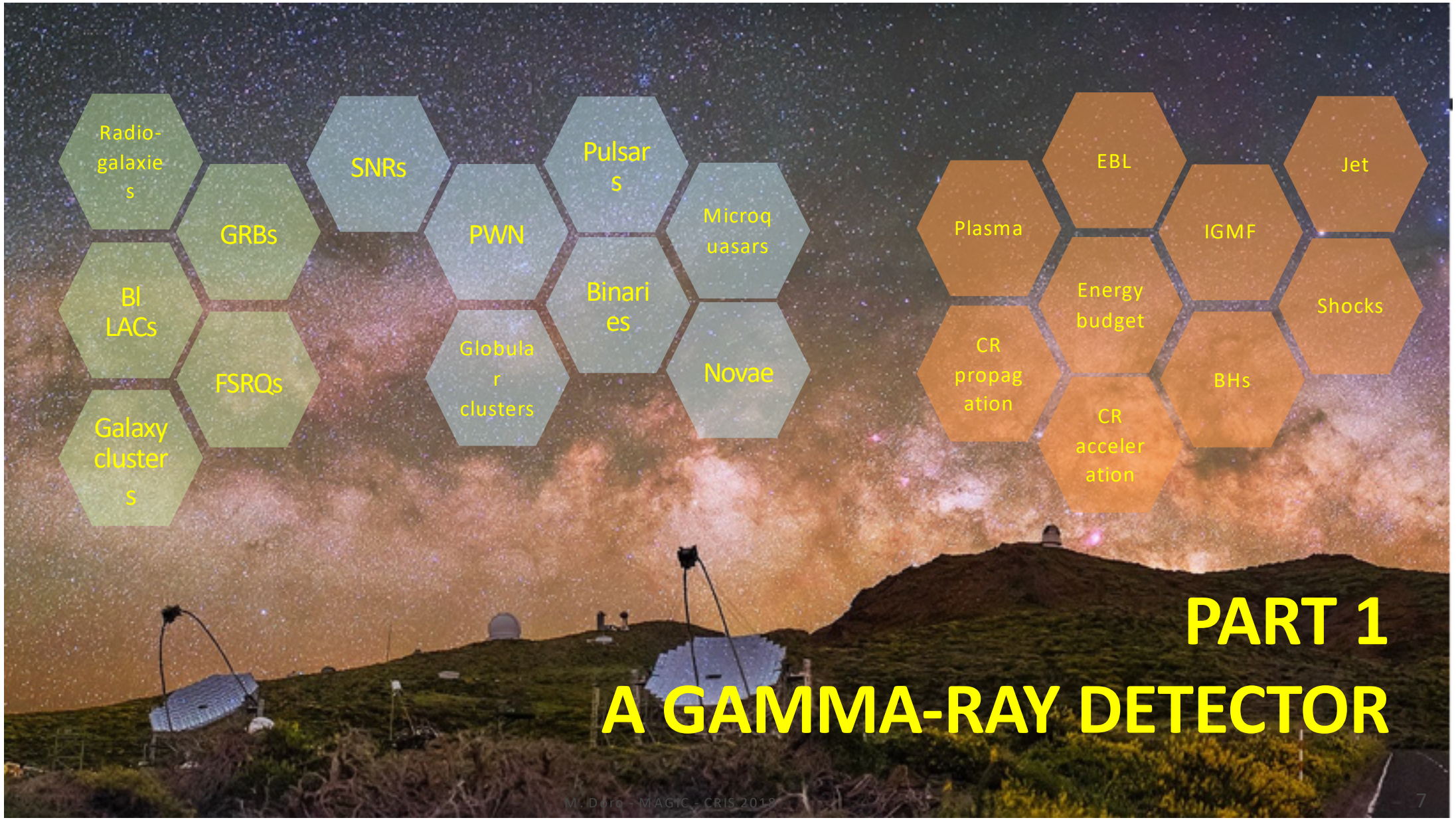




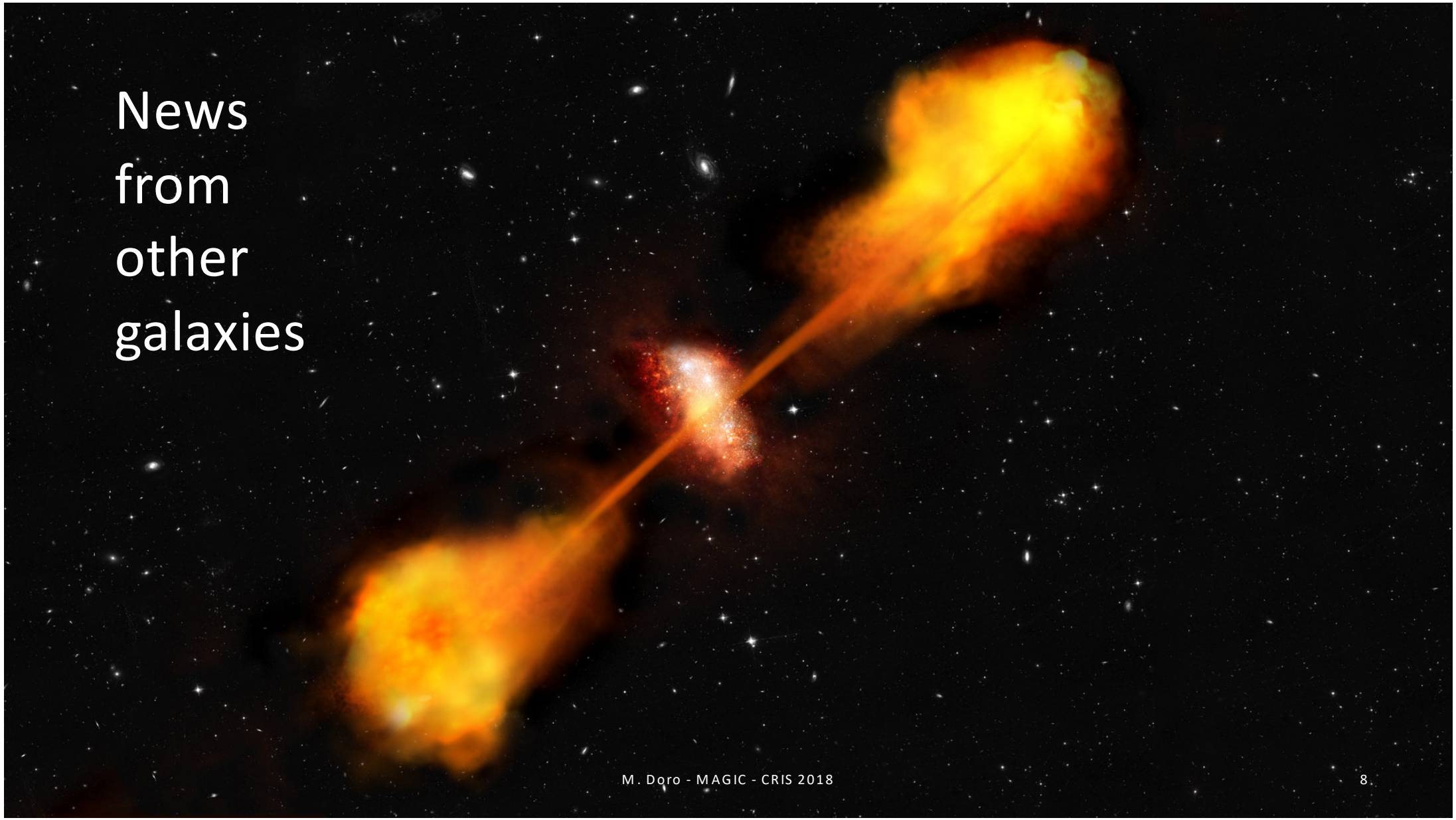


- MAGIC is in the N-hemisphere: optimized for extra-gal. physics

Dark Catalogue (many sources pointed and not detected)

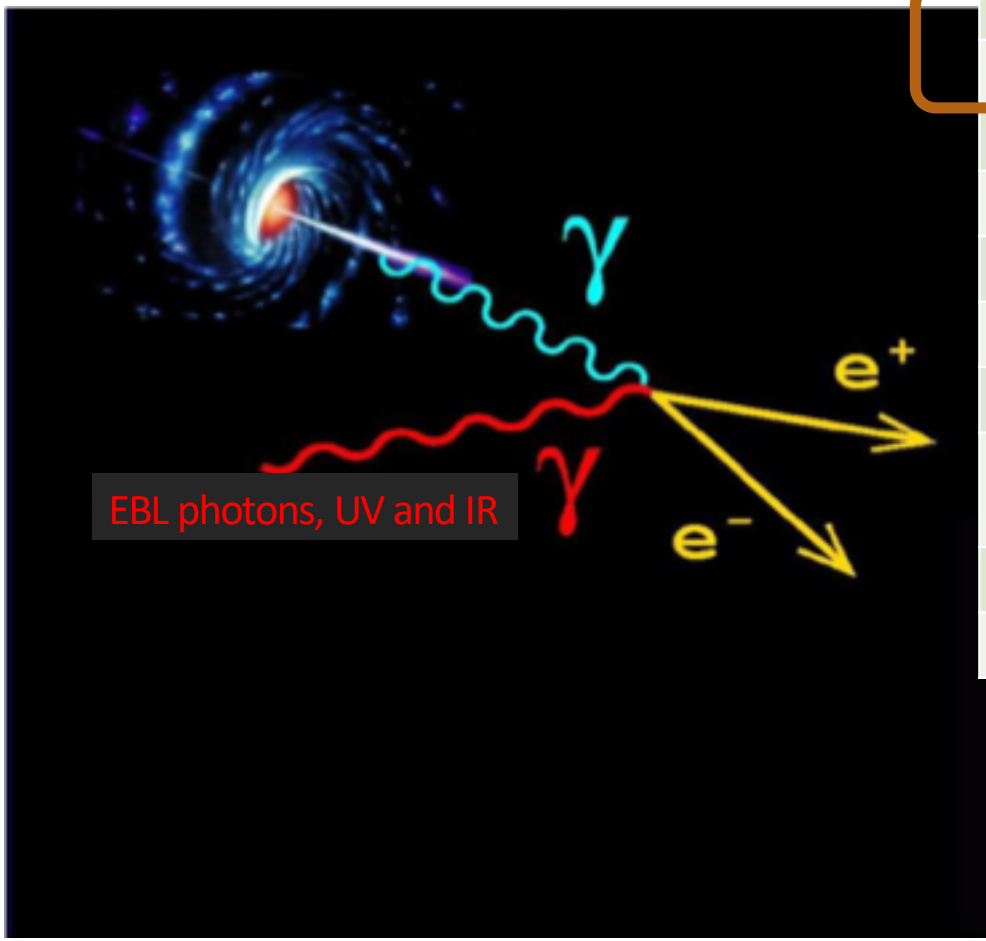

Radio-galaxies
GRBs
SNRs
PWN
Pulsars
Microquasars
BL LACs
FSRQs
Binaries
Globular clusters
Novae
Galaxy clusters
Plasma
EBL
IGMF
Jet
Energy budget
Shocks
CR propagation
CR acceleration
BHs
PART 1
A GAMMA-RAY DETECTOR

News from other galaxies



1/ MAGIC designed to expand the TeV universe

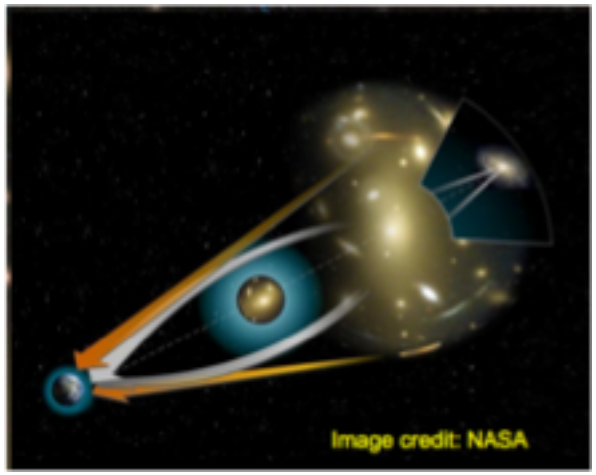
TeV photons with EBL photons



Blazar	Redshift	Discover	Year
B0218+35	**0.944**	**MAGIC**	2014
PKS 1441+25	**0.939**	**MAGIC**	2015
TON 599	0.725	**MAGIC**	2017
PKS 1424+240	0.604	VERITAS	2009
3C 279	0.536	**MAGIC**	2006
1ES 0033+113	0.467	**MAGIC**	2016
PKS 1222+216 (4C +21.35)	0.432	**MAGIC**	2010
PG 1553+113	>0.4	**MAGIC/ HESS**	2005
S4 0954+65*	0.368	**MAGIC**	2015
PKS 1510-089	0.361	HESS	2009

Farthest objects ever observed in TeV sky!

Gravitational lensed gamma-rays

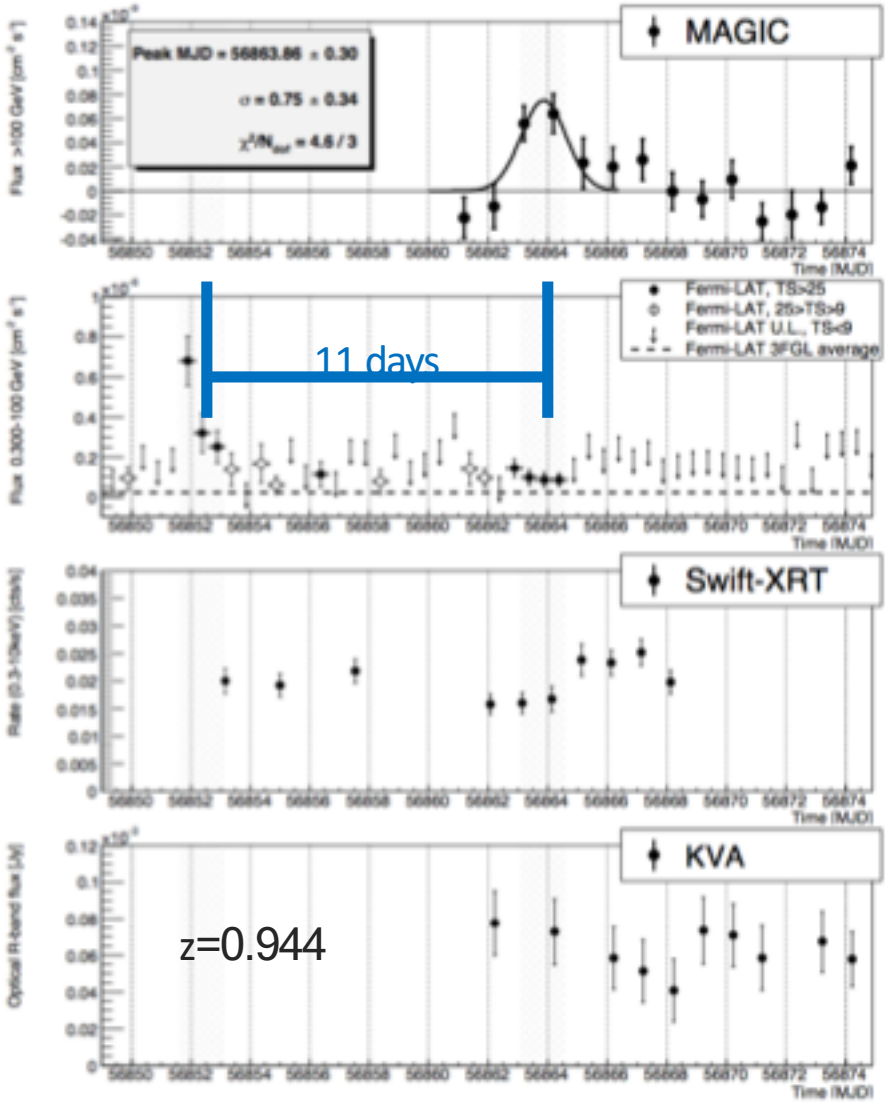


QSO B0218+357 is a gravitationally lensed blazar at redshift: 0.944 where the lens is probably a spiral galaxy B0218+357G at z=0.68

11-days is the time-delay

In 2014, Fermi got the first flare, and 11 days after, MAGIC detected the afterlight

- MAGIC could not observe the leading image due to the Full Moon.
- First gravitationally-lensed VHE gamma rays ever observed
- 2hours, 6 sigma significance



Detection of very high energy gamma-ray emission from the gravitationally-lensed blazar QSO B0218+357 with the MAGIC telescopes
MAGIC Collaboration (M.L. Ahnen *et al.*). Sep 5, 2016. 11 pp.
e-Print: arXiv:1609.01095 [astro-ph.HE] | PDF

TON 599 (z=0.725)

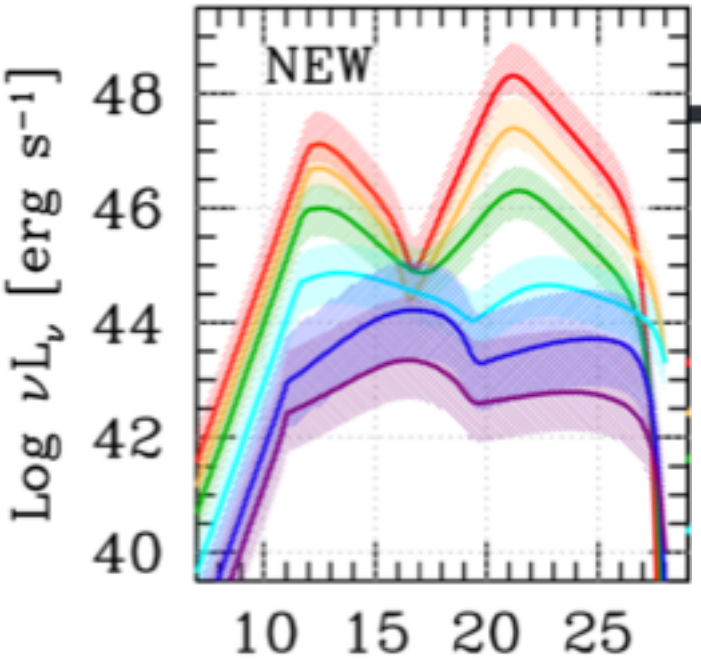
Detection of very-high-energy gamma-ray emission from the FSRQ Ton 0599 with the MAGIC telescopes

ATel #11061; *Razmik Mirzoyan (Max-Planck-Institute for Physics, Munich), on behalf of the MAGIC collaboration*
on 15 Dec 2017; 16:21 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, TeV, VHE, Blazar

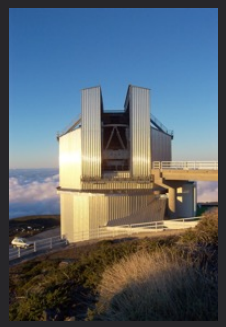
Referred to by ATel #: 11073, 11075, 11624

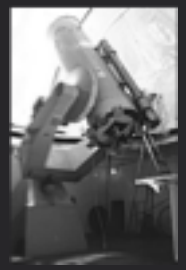
The MAGIC collaboration reports on the first time detection of very-high-energy (VHE; E>100 GeV) gamma-ray emission from Ton 0599 (RA:+11:59:31.83 DEC:+29:14:43.83, J2000). The object was observed with the MAGIC telescopes for ~1 hour on 2017/12/15 (MJD 58102.2). The preliminary analysis of these data resulted in the detection of Ton 0599 with a statistical significance of about 10 standard deviations. The VHE flux of this detection was estimated to be around 0.15x10^-9 [ph/cm2/s] (corresponding to about 0.3 CU) above 100 GeV, with a soft spectrum. TON599 is a gamma-ray FSRQ at z=0.72 which is in a remarkably high state from optical to gamma-ray since October 2017 (ATel #10931, #10932, #10937, #10938, #10948, #10949). MAGIC observations on TON 0599 will continue during the next days and multi-wavelength observations are strongly encouraged. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and A. Stamerra (antonio.stamerra@inaf.it)



2/ Multi-wavelength network (trigger and monitoring)

TNG





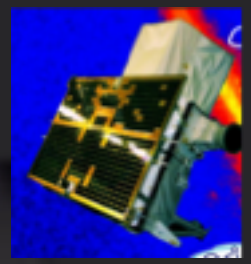
KVA

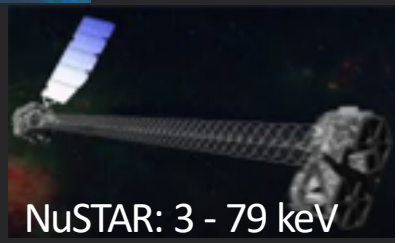
Swift: 15 - 150 keV

XMM: 0.1 - 12 keV

ASTROSAT

OVRO





NuSTAR: 3 - 79 keV

Fermi-LAT

KaVA

KaVa

X-ray

Optical/IR

AGILE

FACT

Veritas

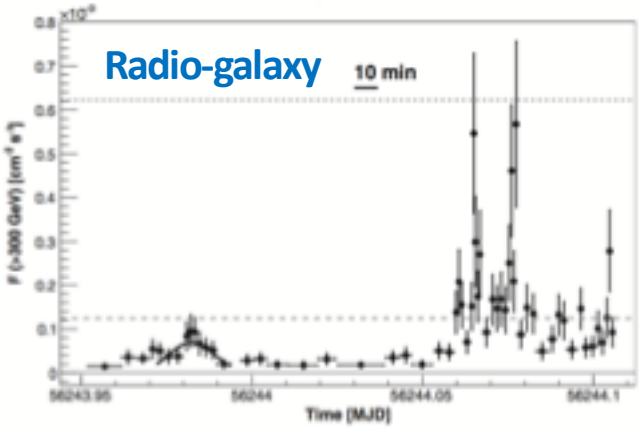
Radio

Gamma

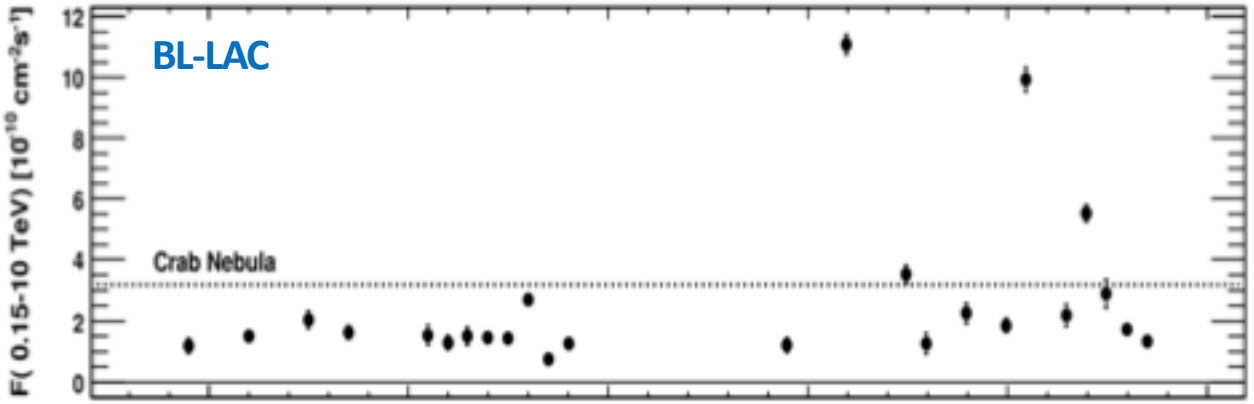
HESS

EHT

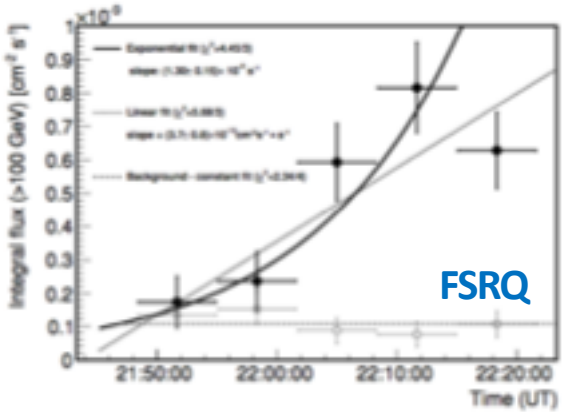
→ Flares provides insight on BH or jets mechanisms



IC310. Doubling time 4.8 min



Mrk501 2005. Flux doubling time ~2min

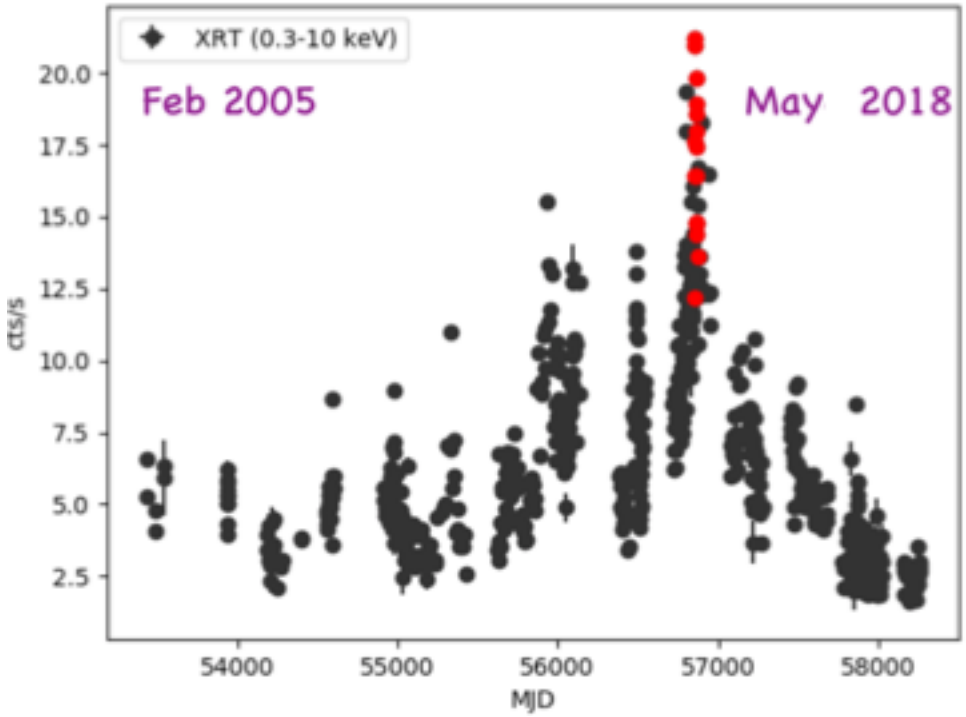


PKS1222. Doubling time 10 min

- Extremely fast variability in all classes Radio-galaxy, Bl-LAC and FSRQ.
- One can infer size of emission region with indirect better “angular resolution” than any other instrument

Extreme X-ray activity in Mrk501 in 2014

Largest X-ray flux by Swift in 13 years



Radio

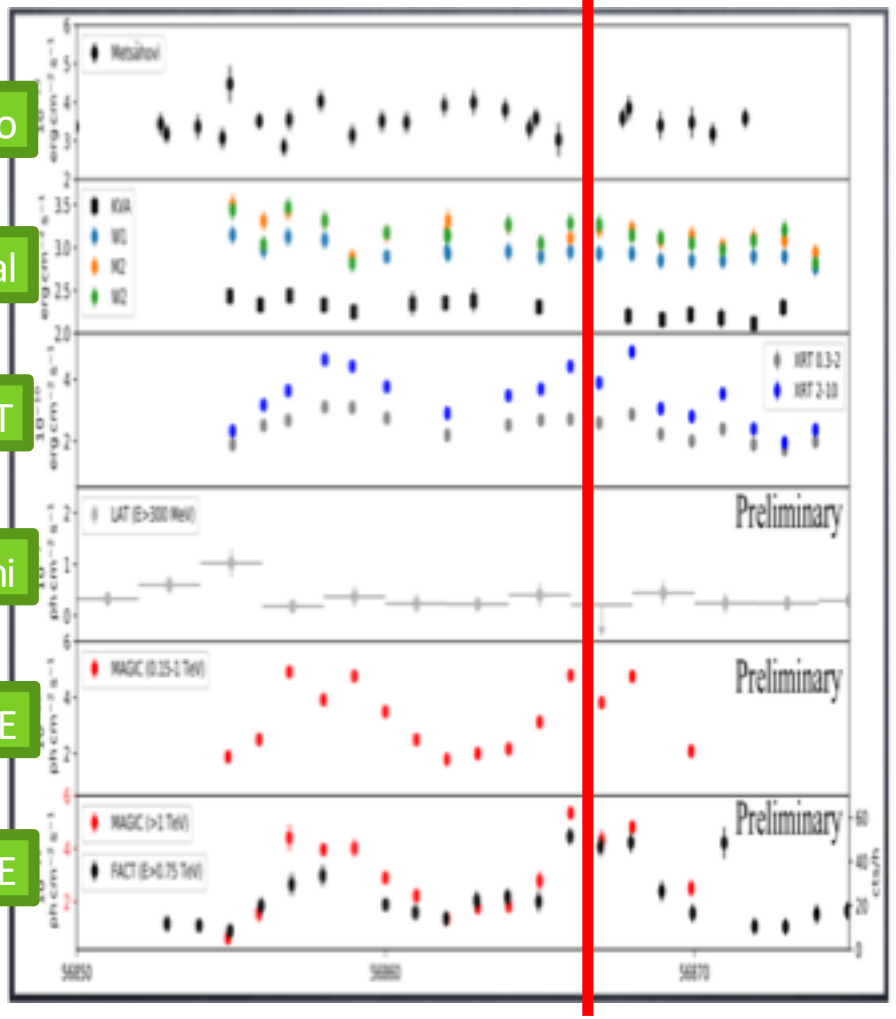
Optical

XRT

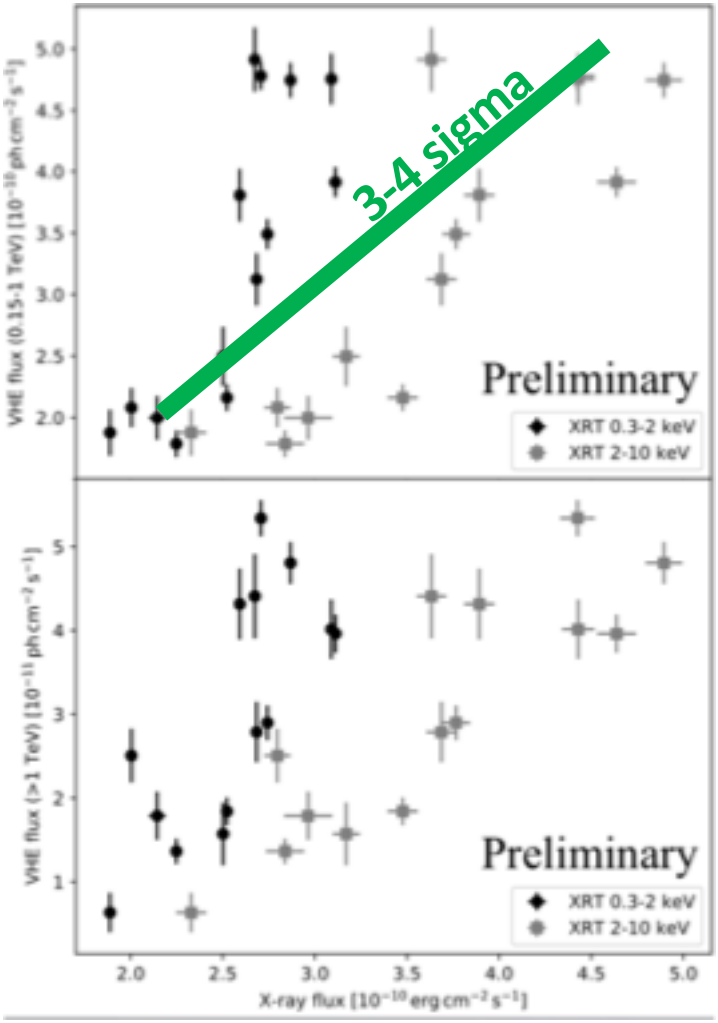
Fermi

MAGIC=LE

MAGIC-HE



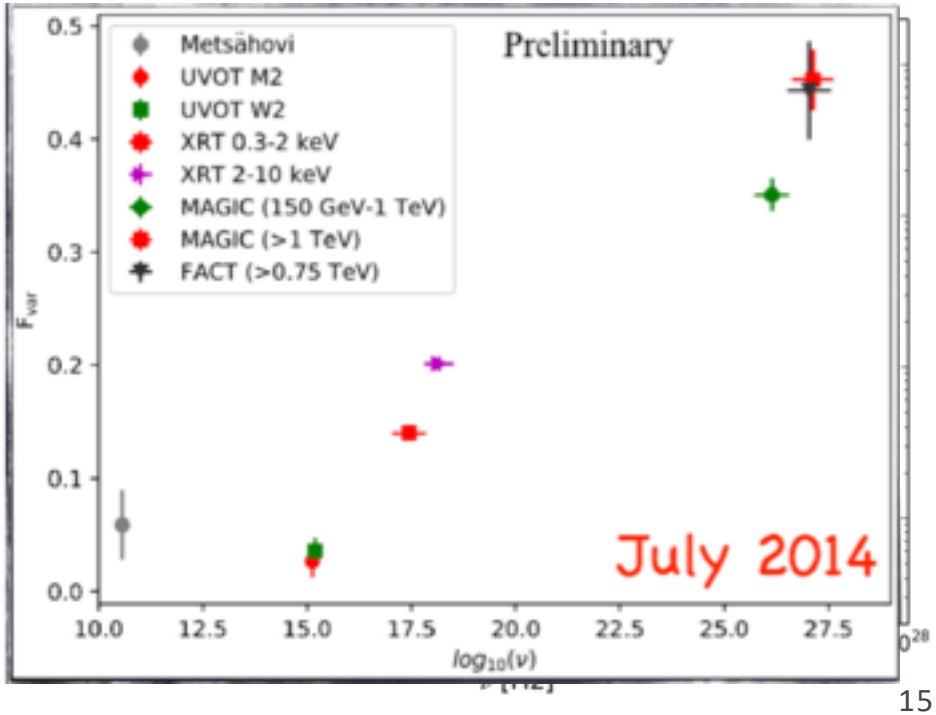
Flux variability and correlations



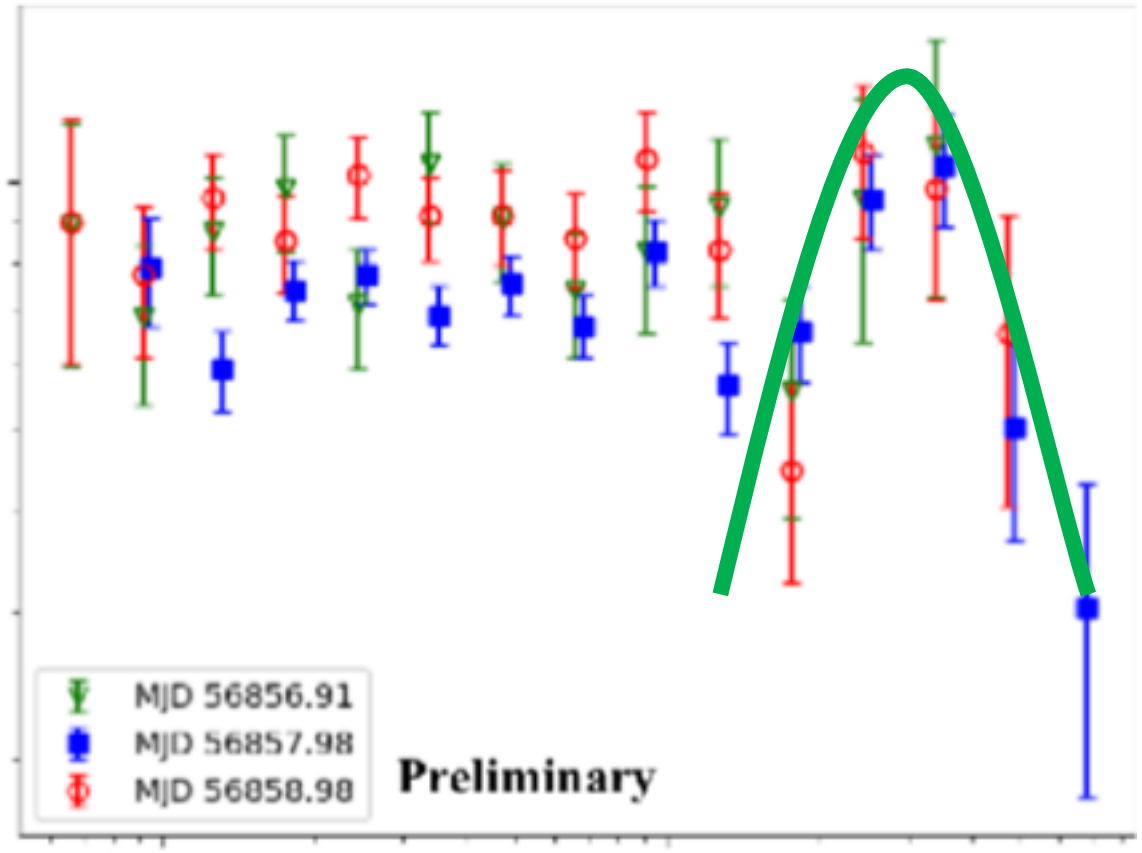
← X and gamma seem correlated: same acceleration mechanism

Fractional variability→

$$F_{\mathrm{var}} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$



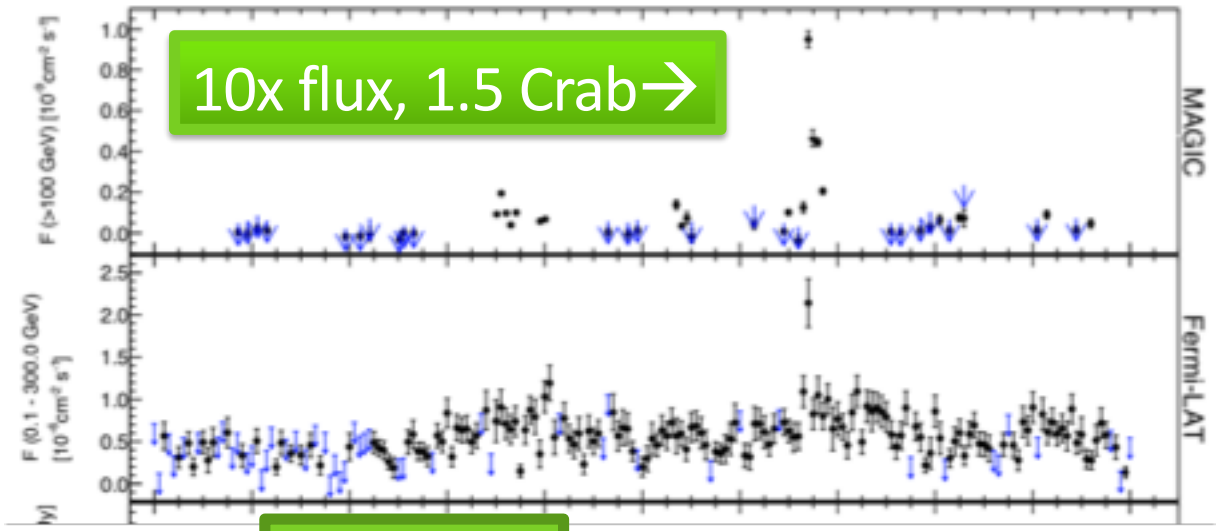
Wait, what happened in July 19-21?

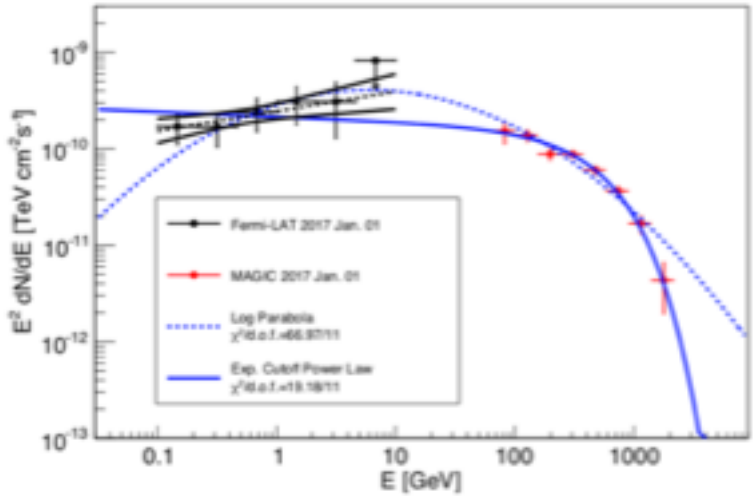


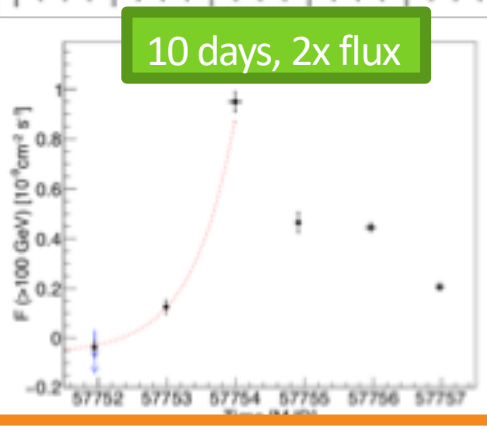
- Hint of spectral feature at 3-400 GeV over three consecutive nights!!
- **Emission from a second component?**

See talk by J. Becerra past week in:

New Year's eve's Fireworks: NGC1275





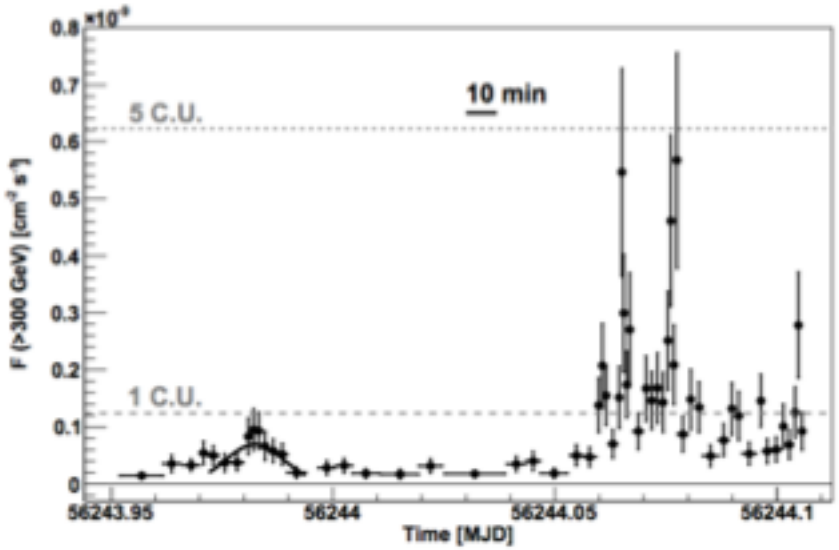


- Models tested: magnetospheric gaps, relativistic blobs propagating in the jet (mini-jets) or external cloud (or star) entering the jet.
- Non worked to model 10 day 2x flux flare

«Flaring activity of NGC 1275 in 2016-2017 measured by MAGIC» AA accepted 2018

A thunderstorm in the BH of IC310

Aleksic et al., SCIENCE (2014)



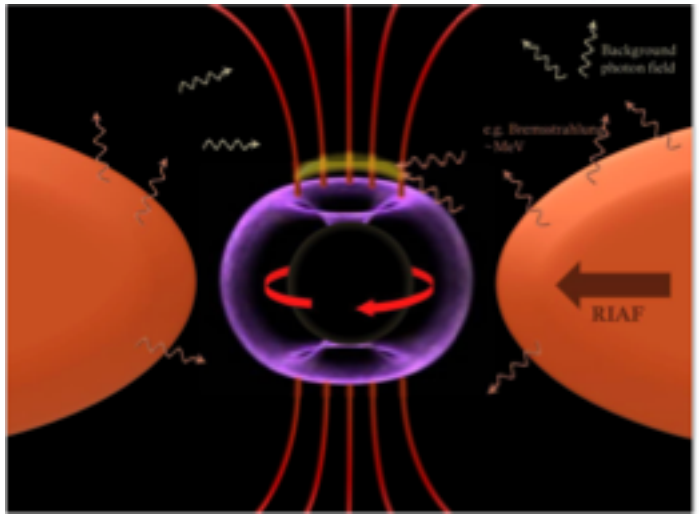
Aleksić et al. 2014, *Science*

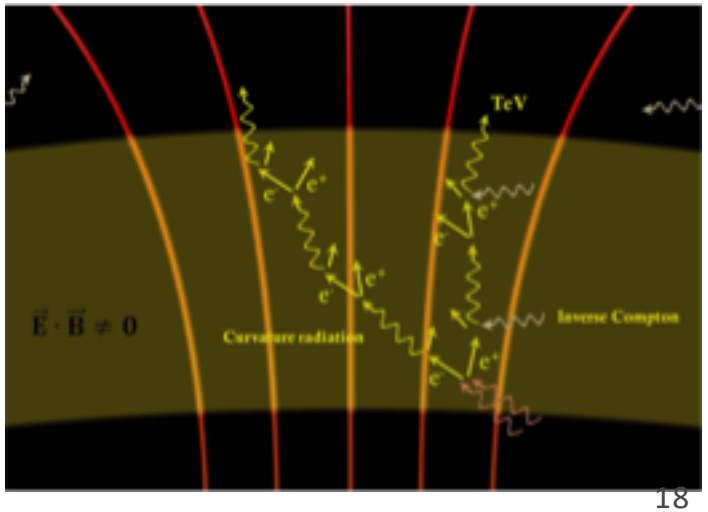
Explanation (pulsar-like):
particle acceleration by the electric field across a **magnetospheric gap** at the base of the radio jet. Electric fields can exist in vacuum gaps when the density of charge carriers is too low to warrant their shortcut.

In 2014, MAGIC saw an impressive flare of the radio-galaxy **IC310**

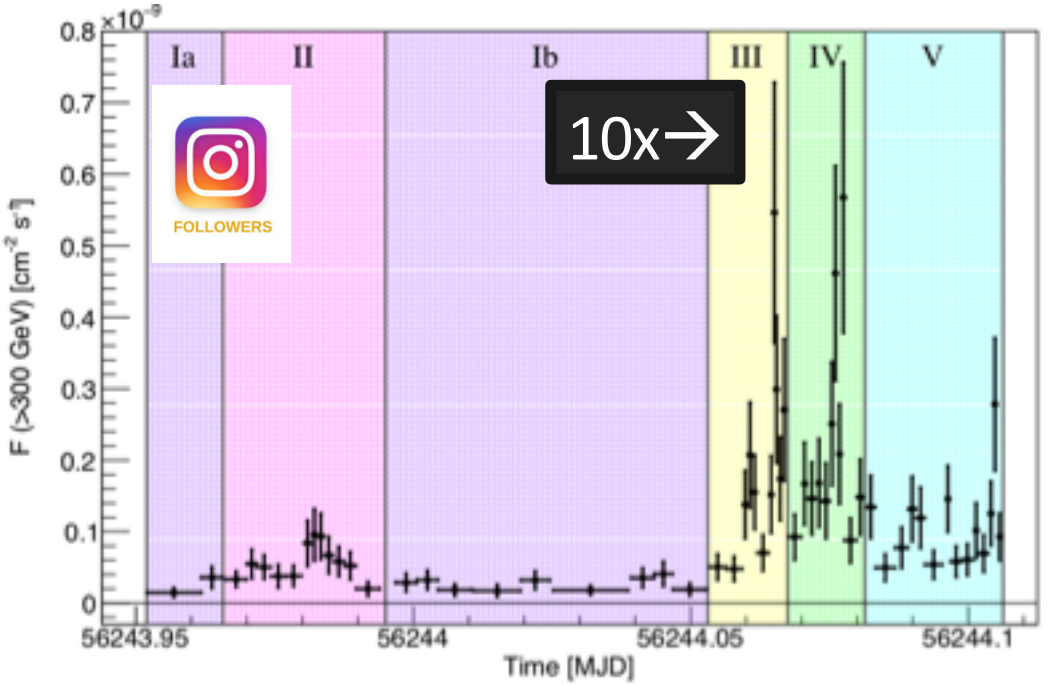
Flux-flare was 2x in 4.8 minutes!

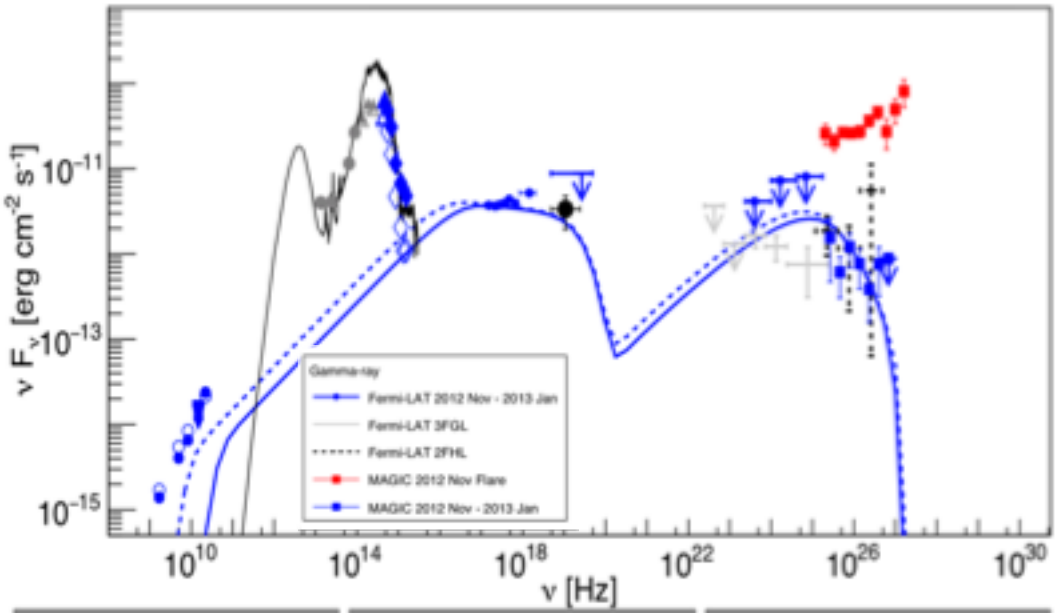
What mechanisms could provide such boost?
Emission region must have size smaller than the 20% of BH





IC310 multi-w campaign after flare

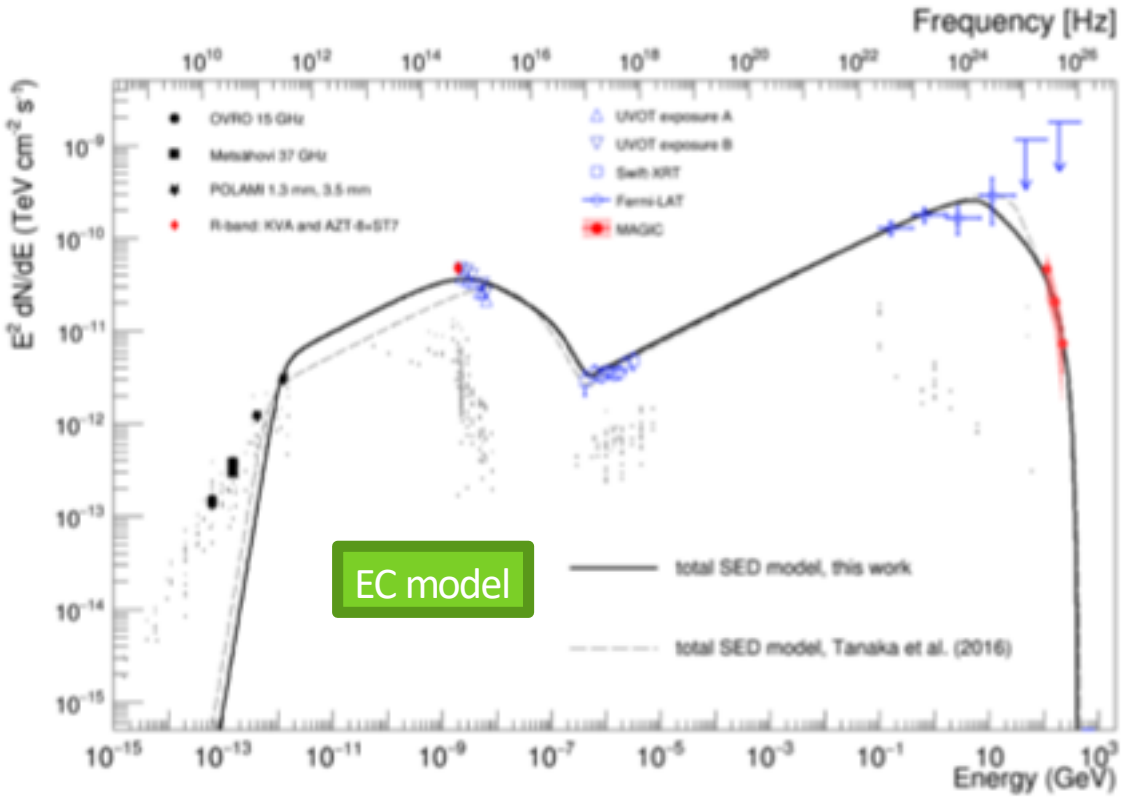




First multi-wavelength campaign: *one-zone synchrotron self-Compton* model using parameters comparable to those found for other gamma-ray-emitting misaligned blazars.

First Multi-wavelength Campaign on the Gamma-ray-loud Active Galaxy IC 310
M.L. Ahnen *et al.*. Mar 22, 2017. 15 pp.
Published in **Astron.Astrophys. 603 (2017) A25**
DOI: 10.1051/0004-6361/201630347

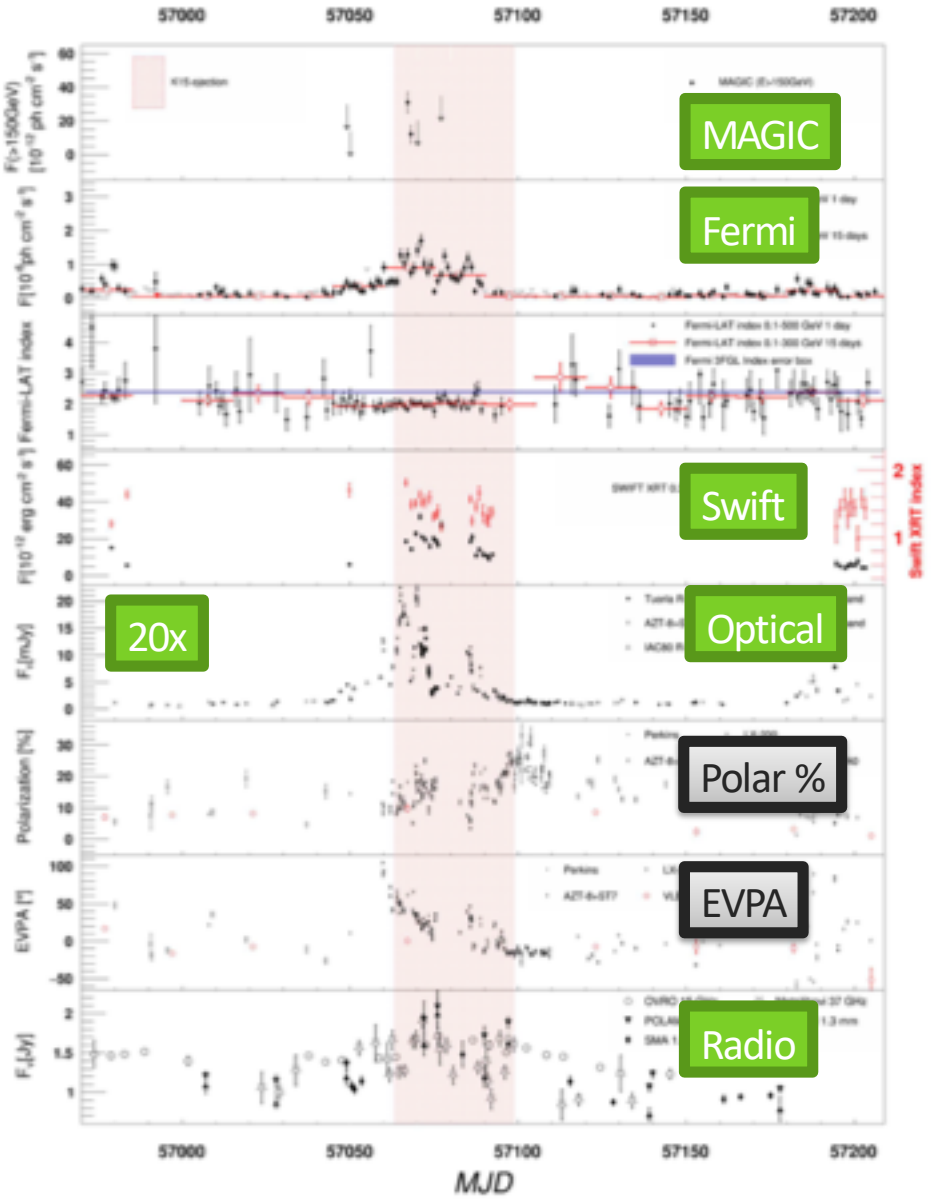
Discovery of FSRQ S4 0954+65



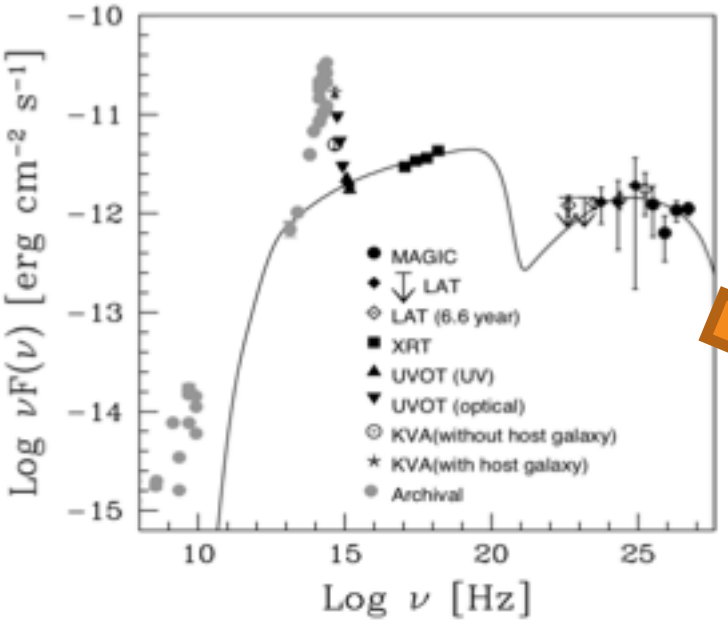
The detection of the blazar S4 0954+65 at very-high-energy with the MAGIC telescopes during an exceptionally high optical state

MAGIC Collaboration (M.L. Ahnen *et al.*). Jan 12, 2018. 15 pp.

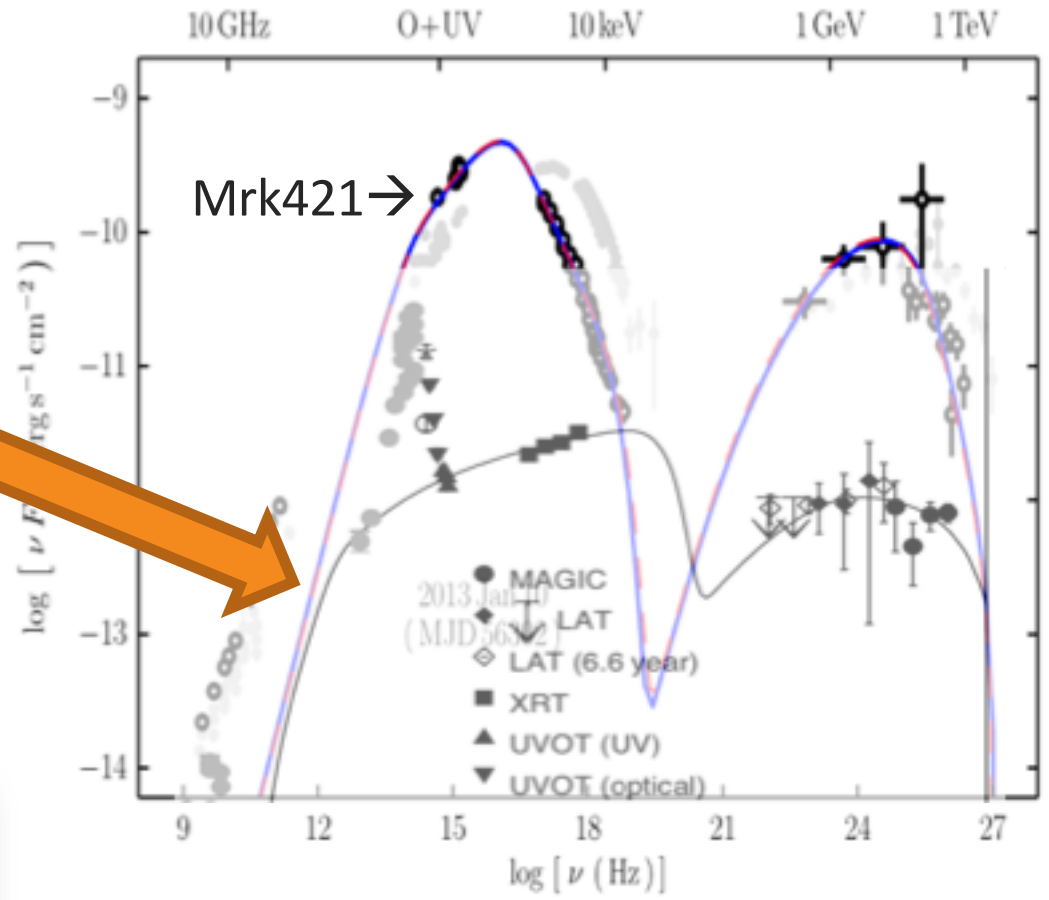
e-Print: arXiv:1801.04138 [astro-ph.HE] | PDF



Digging the low-luminosity 1ES 1741+196

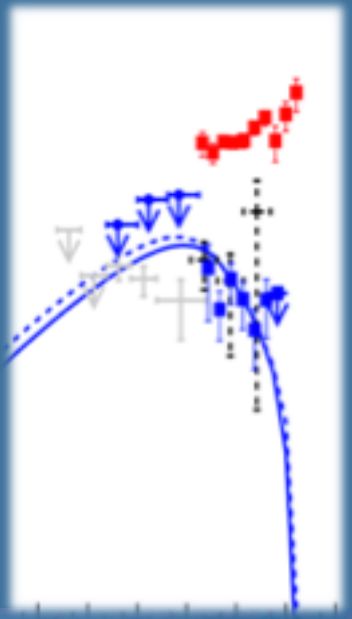


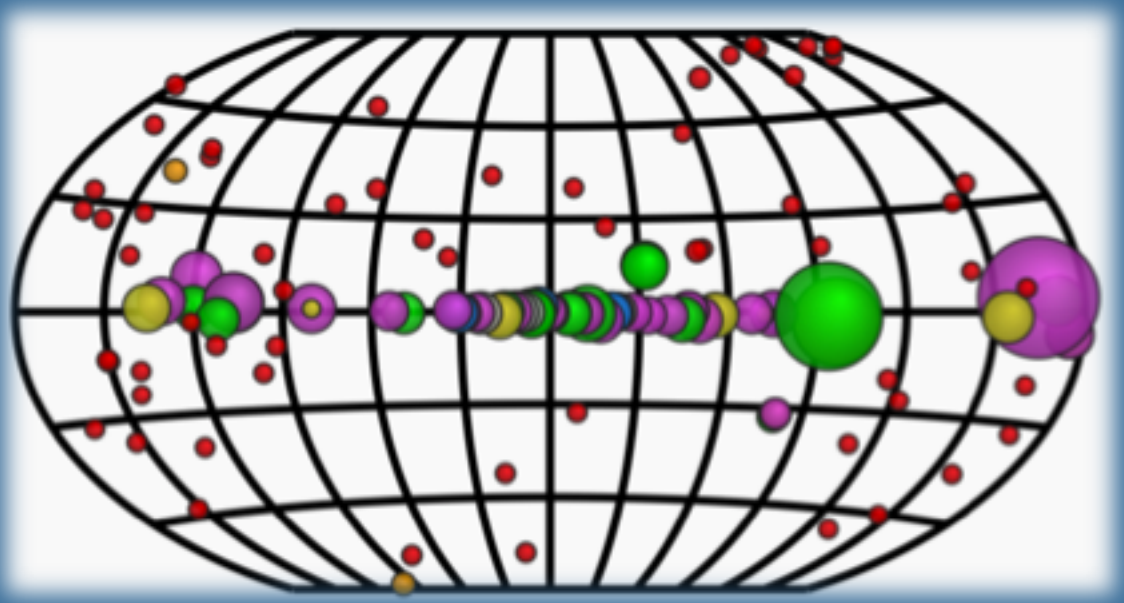
Need more sensitive instruments



MAGIC detection of very high energy γ-ray emission from the low-luminosity blazar 1ES 1741+196
MAGIC and Fermi-LAT Collaborations (M.L. Ahnen (ETH, Zurich (main)) *et al.*). Feb 22, 2017. 8 pp.
Published in **Mon.Not.Roy.Astron.Soc. 468 (2017) no.2, 1534-1541**

Intermediate conclusions on AGN





IceCube-170922A

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)

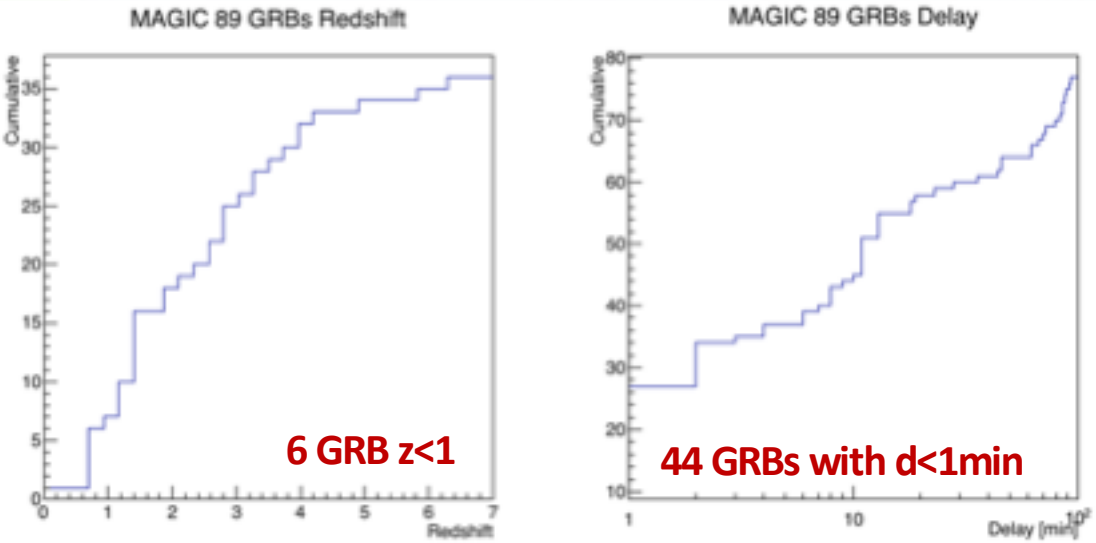
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

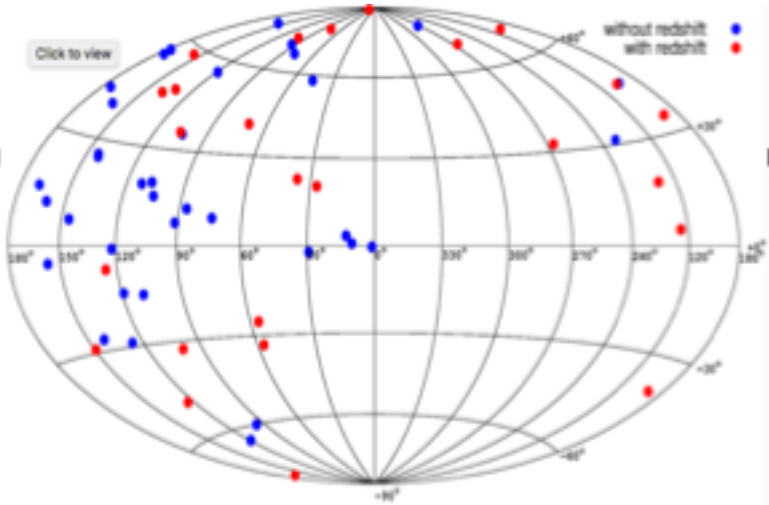
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

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 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.

GRB program

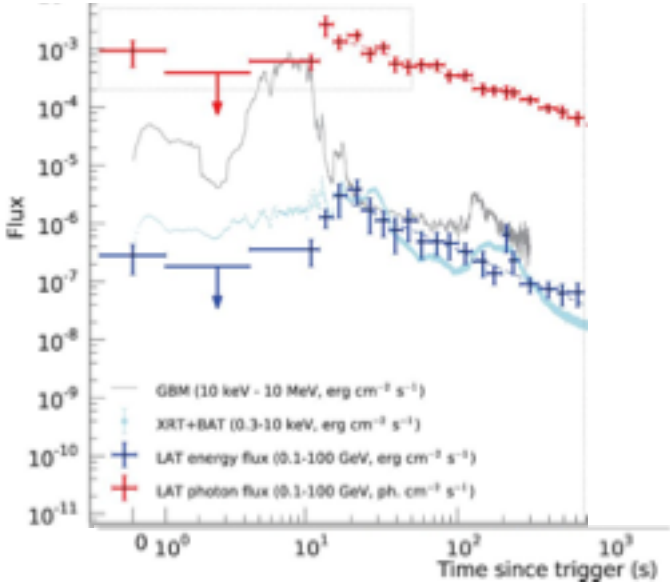
http://www.asdc.asi.it/tegrbcat/





- MAGIC was built to fast-reposition to GRB alert (20sec between any pos) and to get the lowest energy threshold
  - Although late VHE signal may be expected→
- **90+ GRBs** observed by MAGIC
- No significant hints at any target ☹, however, our eye is keen now

Ackermann, M. et al., 2014, Science, 343, 42

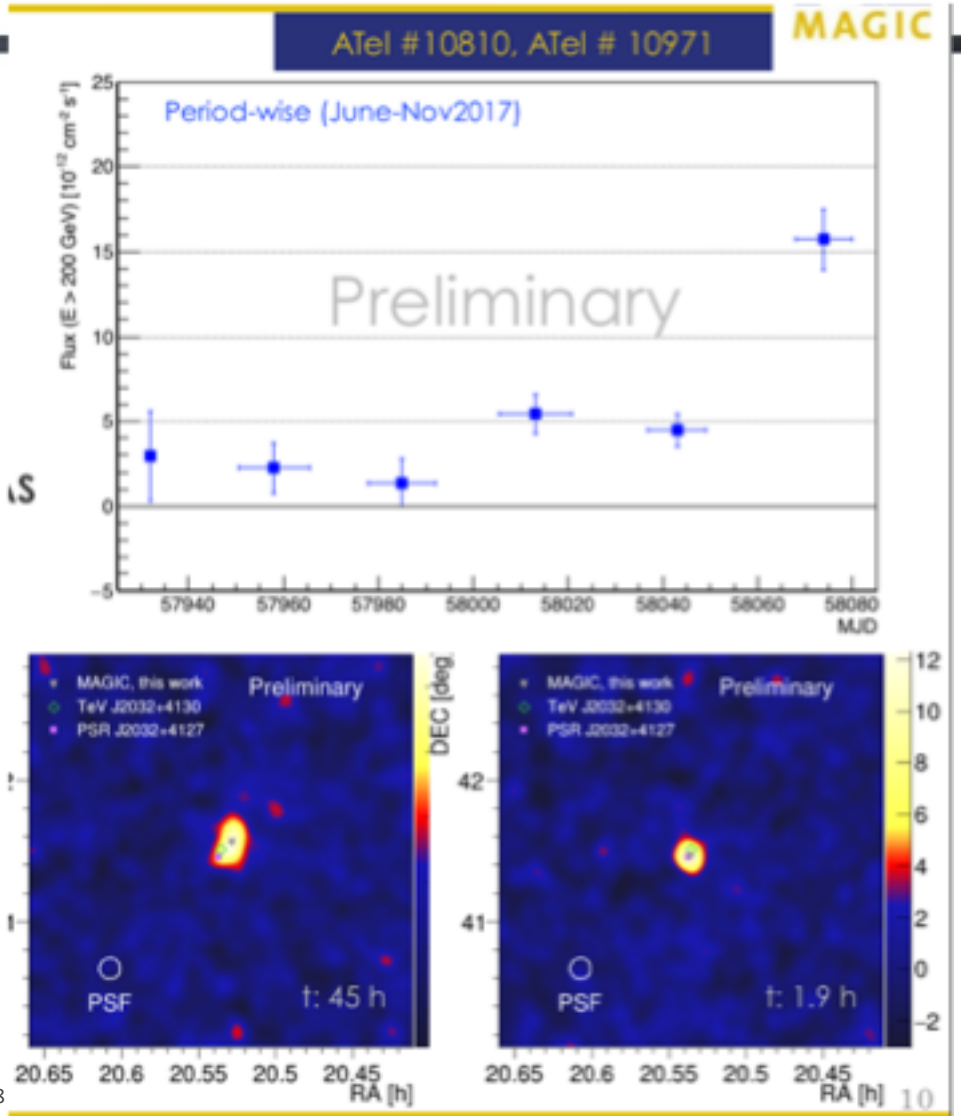



News from our galaxy
58 degrees

VHE emission from PSR J2032+4107

A binary system pulsar+star with ~**50y period**!

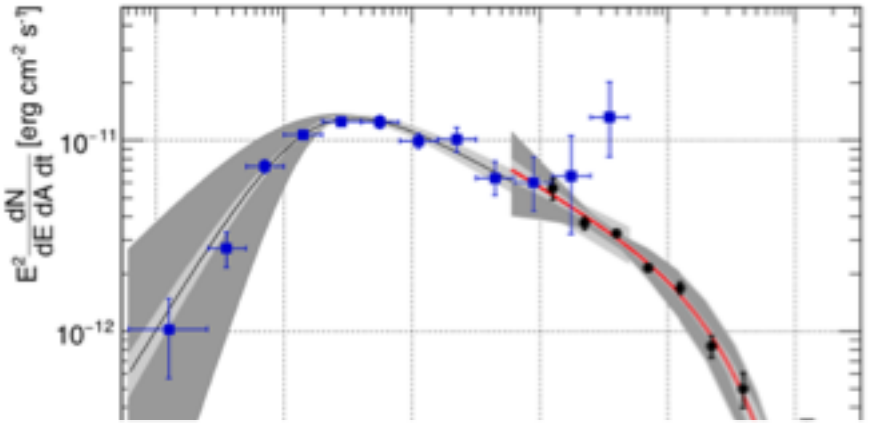
- Monitored by MAGIC and VERITAS
- Periastron Nov 2017: from 10x in 120 days
- Results to be published soon!

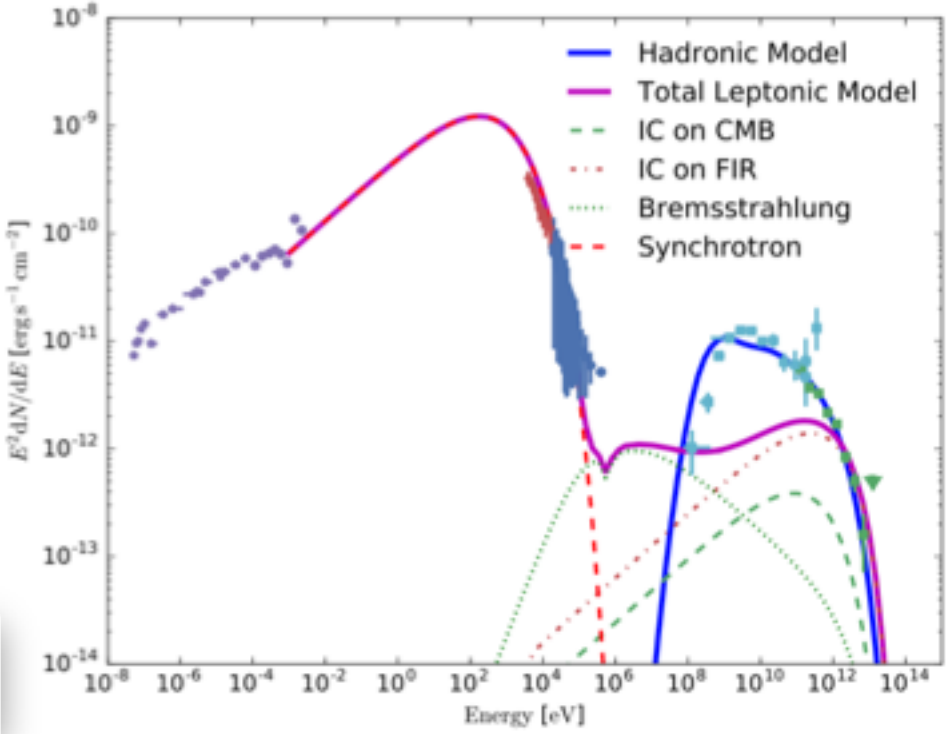


A. Lopez TEXAS17

CasA SNR is not PeV emitting

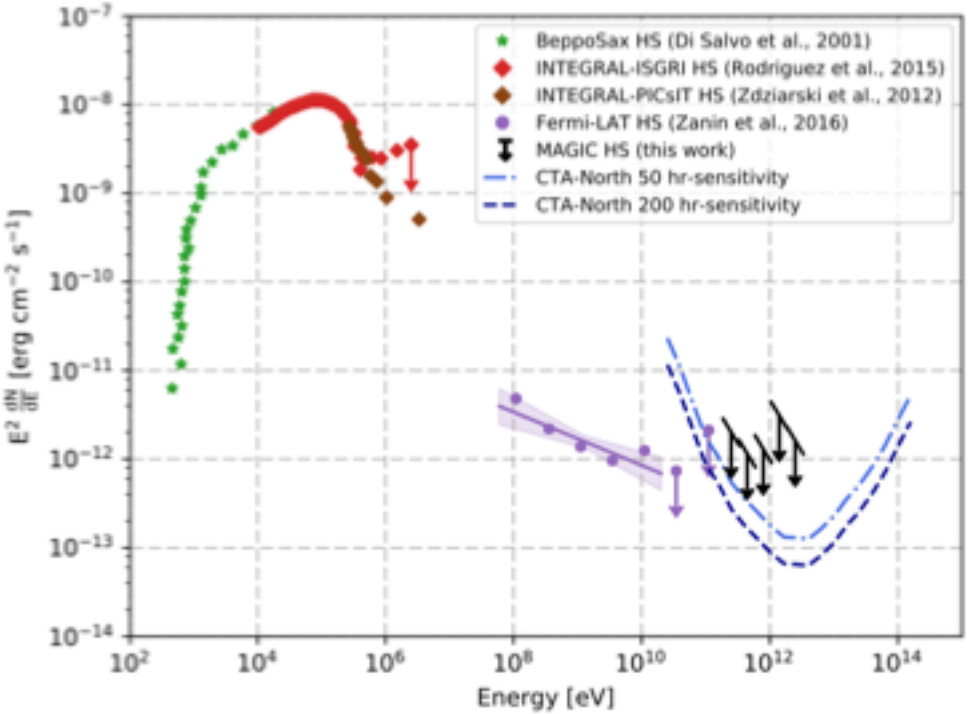
- Supernova Remnants are expected to be able to acccelerate particles to PeV
- Cas A observed for 158 h of good data: **cutoff at 3.5 TeV**
- Hadronic-majority model preferred by data

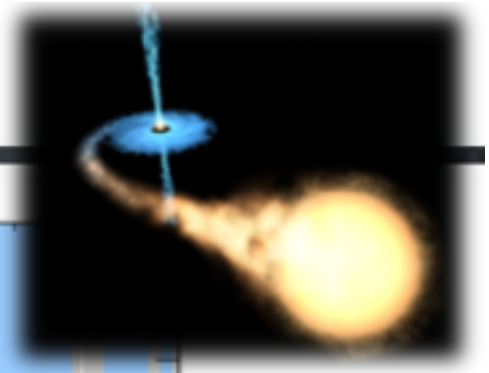


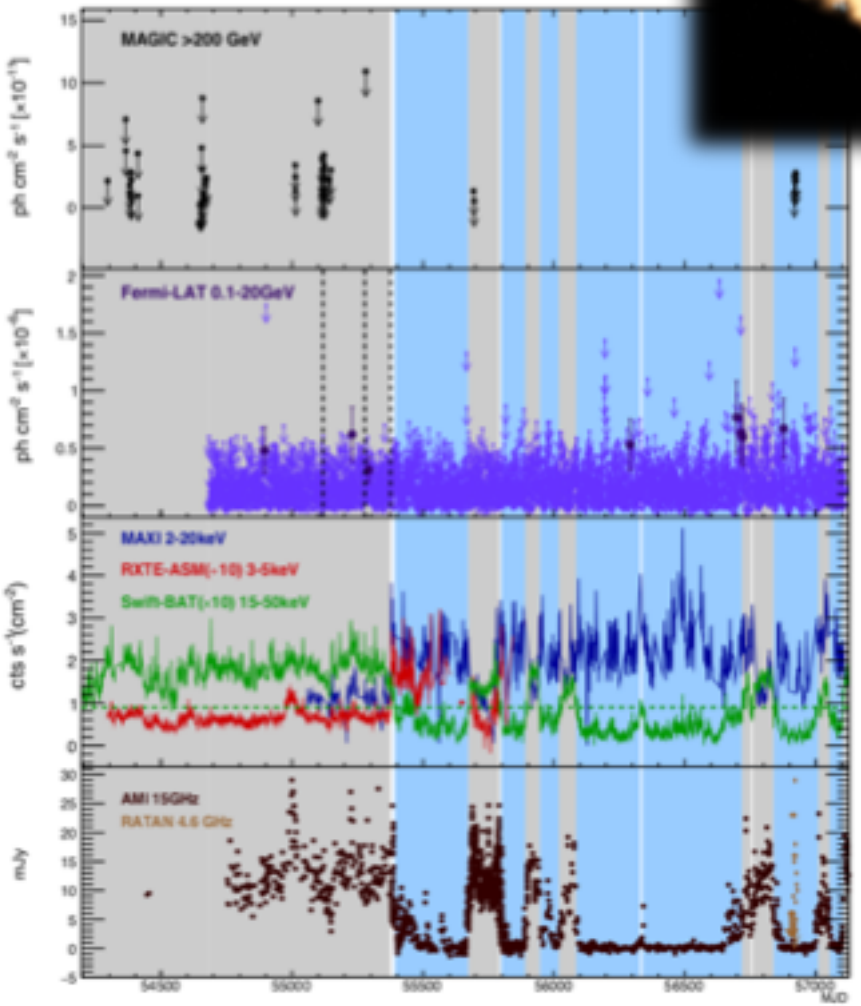


A cut-off in the TeV gamma-ray spectrum of the SNR Cassiopeia A
MAGIC Collaboration (M.L. Ahnen (Zurich, ETH) *et al.*). Jul 5, 2017. 7 pp.
Published in **Mon.Not.Roy.Astron.Soc. 472 (2017) no.3, 2956-2962**

Cygnus X-1 never shown TeV anytime in 100h over 5y and all states

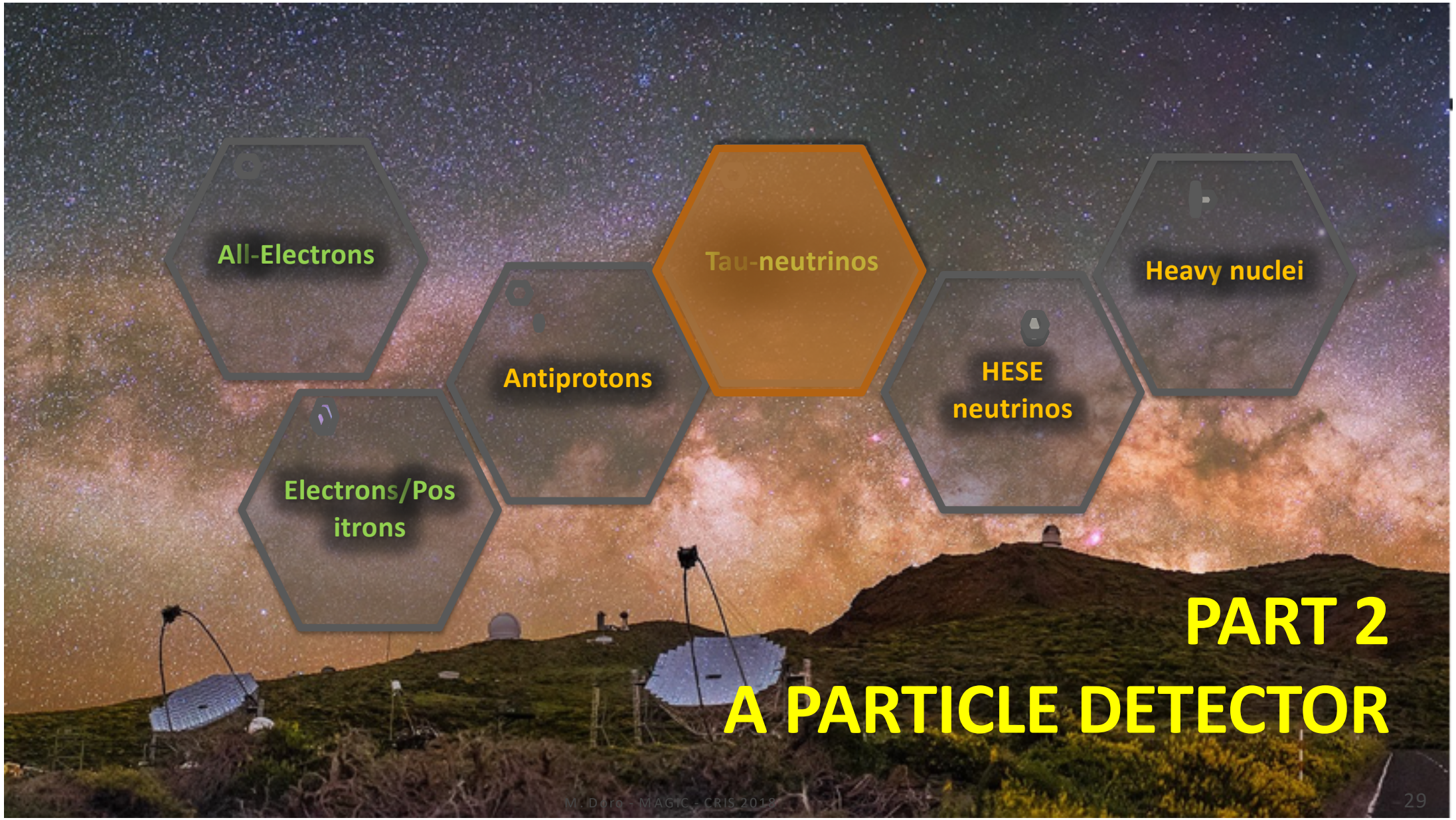






Search for very high-energy gamma-ray emission from the microquasar Cygnus X-1 with the MAGIC telescopes

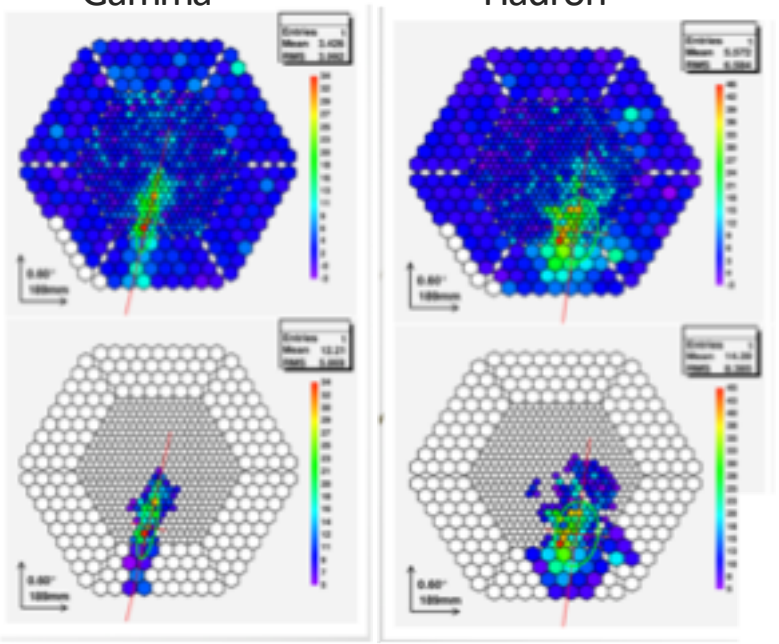
MAGIC Collaboration (M.L. Ahnen (ETH, Zurich (main)) *et al.*). Aug 11, 2017. 12 pp.
Published in **Mon.Not.Roy.Astron.Soc. 472 (2017) no.3, 3474-3485**


All-Electrons
Tau-neutrinos
Heavy nuclei
Antiprotons
HESE neutrinos
Electrons/Positrons
PART 2
A PARTICLE DETECTOR

Events classification

Gamma

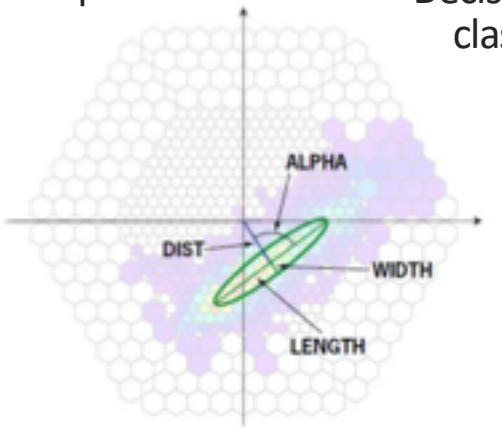
Hadron

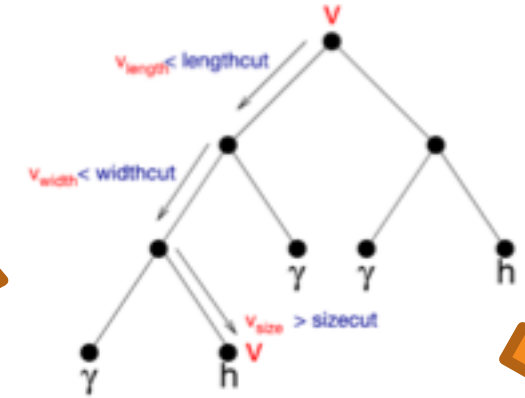


Shape and time evolution can change between event classes

1

Image parameters



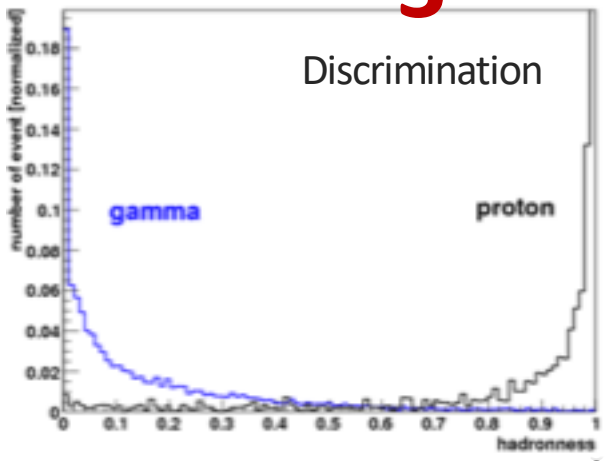


2

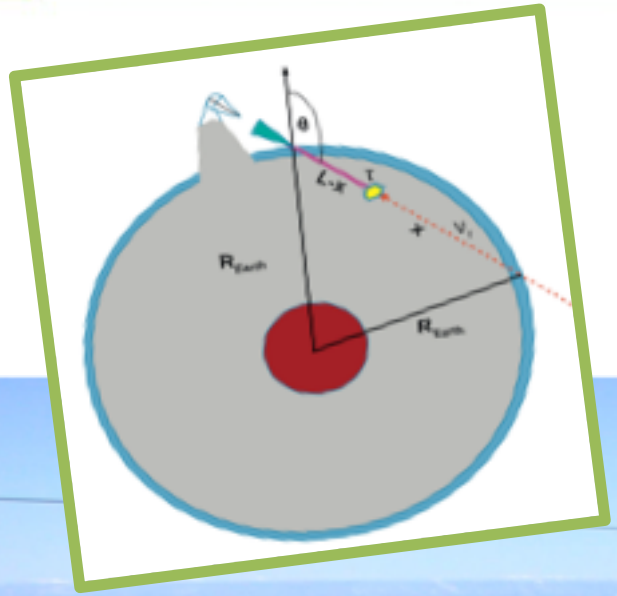
Decision trees for classification

3

Discrimination



Earth-skimming Neutrinos



- **Tau neutrinos may** reach Earth thanks to mixing

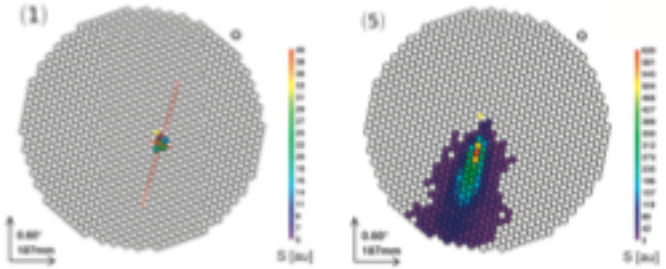
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

- **Earth-skimming emerging Tau-lepton** can **generate atmospheric showers**

- Window to the ocean:
- 80x5 deg
- 91.5 deg ZA

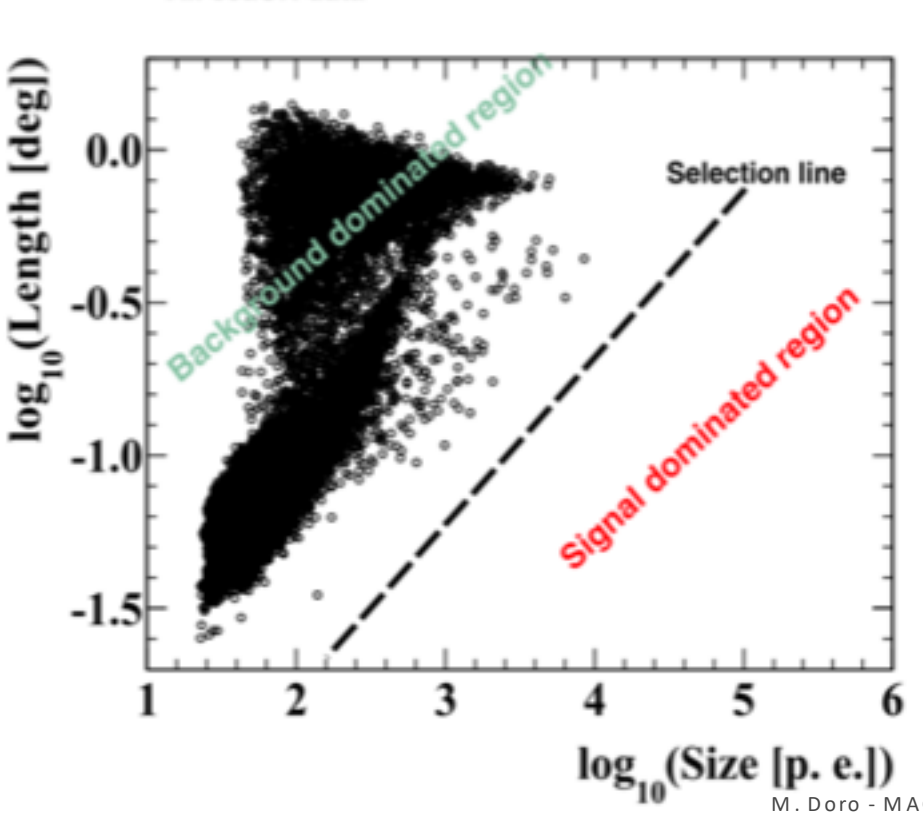
D. Fargion, Astrophys.J. 570, 909 (2002).
X. Bertou et al., Astropart.Phys. 17, 183 (2002).
E. Zas, New J.Phys. 7, 130

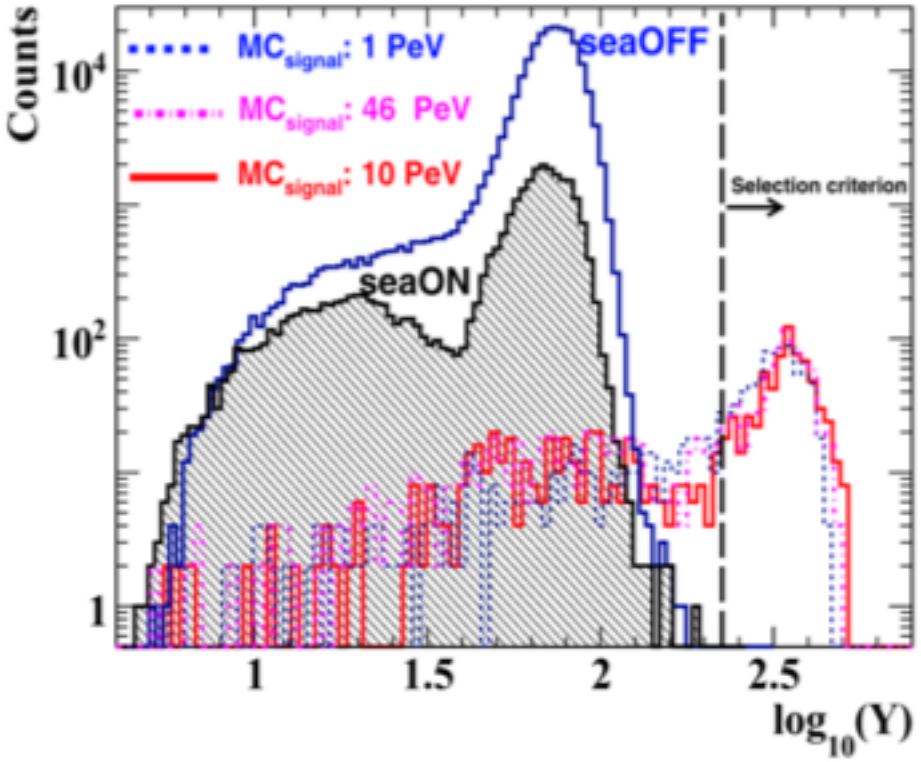
Discrimination



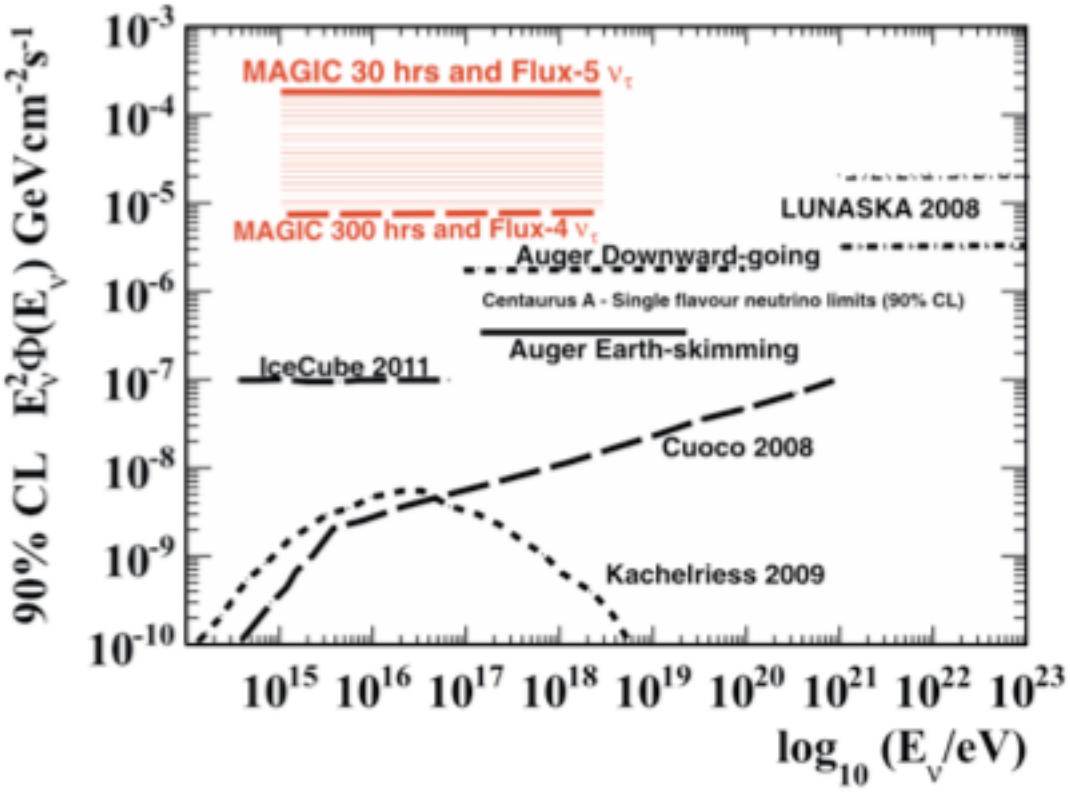
- Discriminated by (larger) Size and Length of the images

$$\log_{10}(Y) = \log_{10}(Size[\text{p.e.}]) * \cos(\alpha) - \log_{10}(Length[\text{deg}]) * \sin(\alpha), \text{ where } \alpha = 63.435^{\circ}.$$



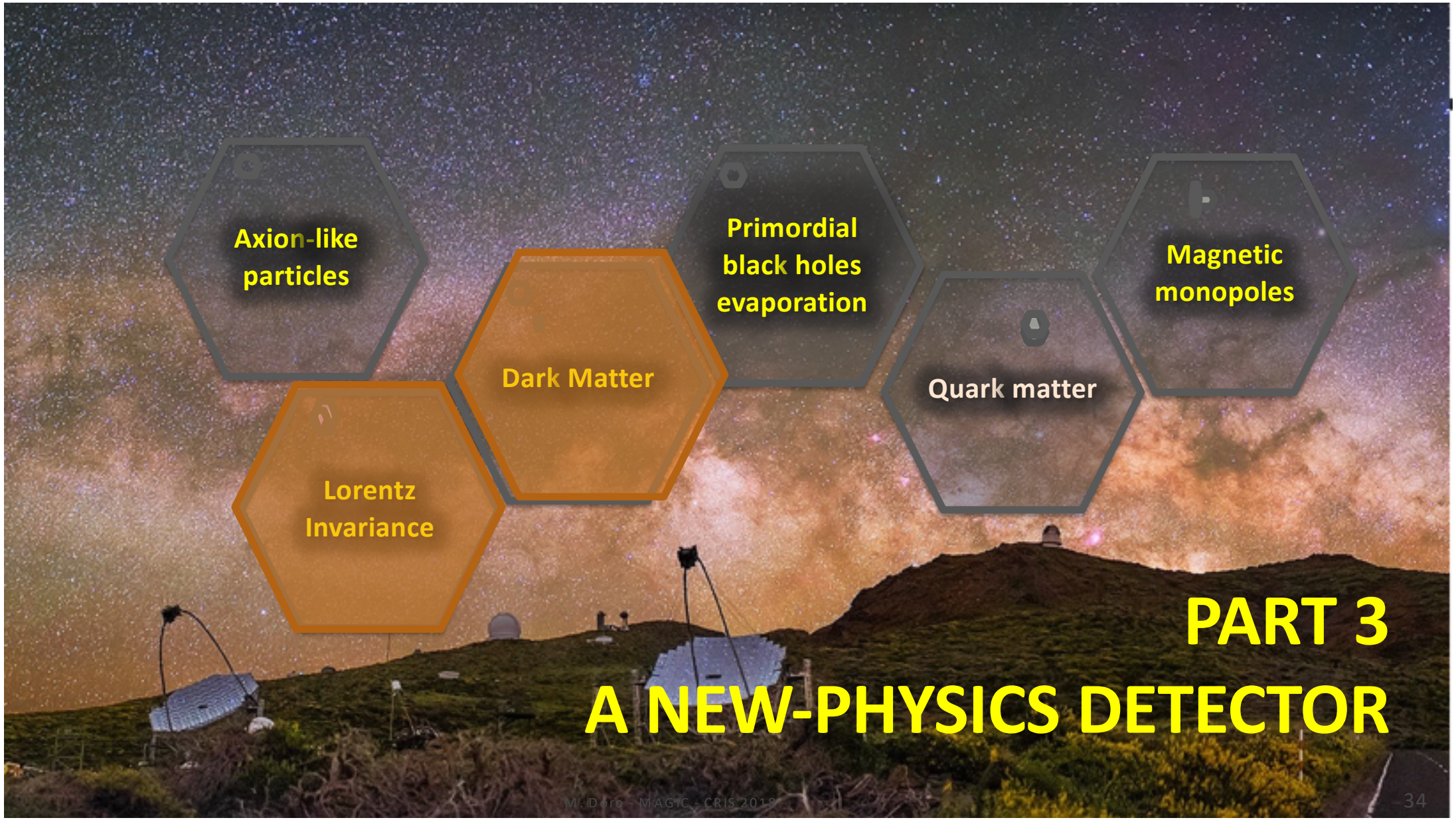


Performance and Expectations



Limits on the flux of tau neutrinos from 1 PeV to 3 EeV with the MAGIC telescopes
MAGIC Collaboration (M.L. Ahnen (ETH, Zurich (main)) *et al.*). May 7, 2018. 14 pp.
e-Print: arXiv:1805.02750 [astro-ph.IM] | PDF

- Sensitivity cannot be improved, need large obs.time
- **Diffuse neutrino** flux is low
- **Bright flares (GRB, AGN) that** pass through the "ocean window"


Axion-like particles
Dark Matter
Primordial black holes evaporation
Quark matter
Magnetic monopoles
Lorentz Invariance
PART 3
A NEW-PHYSICS DETECTOR

Dark matter searches: 1000h+ in a decade

MAGIC	Class	Target	Year	Obs. Time	Ann.	Decay
Mono	MW	Galactic Center	2006/07	25	-	-
	DSG	Draco	2007	7.8	X	-
		Willman 1	2008	15.5	X	-
		Segue 1	2008/09	29.4	X	-
	Unid	3EG1835	2007	25	X	-
	GC	Perseus	2008	24.4	-	-
	CR	All-electrons	2009/10	14	-	-
Stereo	Unid	Many	2009/12	71.3	F	-
	DSG	Segue 1	2010/13	158	X	X
	GC	Perseus	2009/14	253	F	F
	CR	All-electrons	2012/14	40	-	-
		Positrons			F	-
	MW	Galactic Center	2012/16	67	F	F

MD XXV ECRS 2016 Proceedings

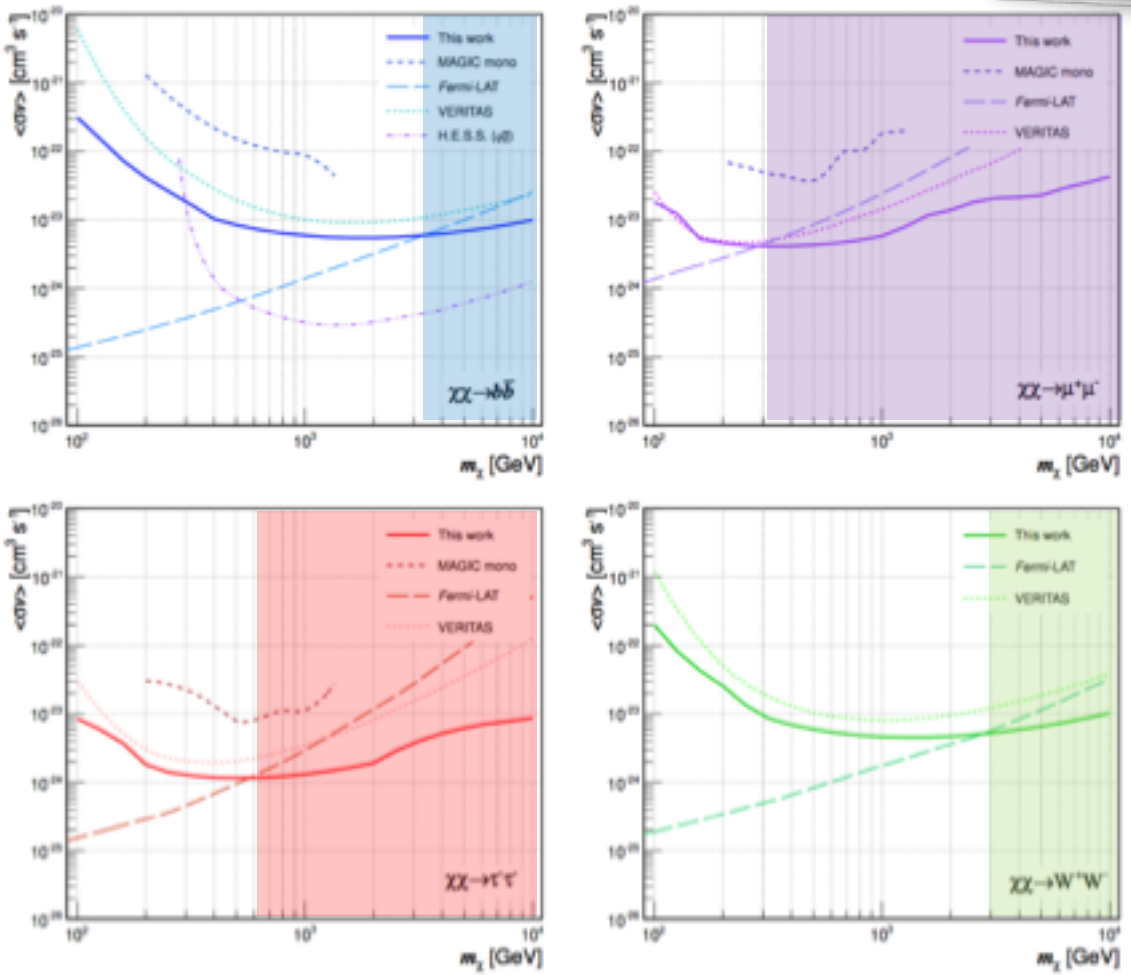
About 1000 h in a decade ←

Segue 1 Deep Scan with MAGIC stereo

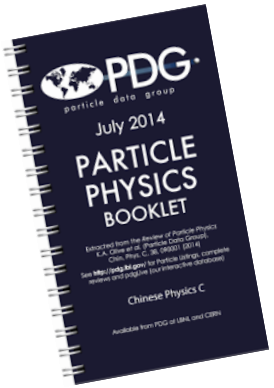
Best limits from dwarfs in high-mass range

- **Longest exposure on a single dSph**: Segue 1: **160 hours**.
- Optimized statistical treatment allowed performance boost

See Aleksic+ **JCAP 1210 (2012) 032**



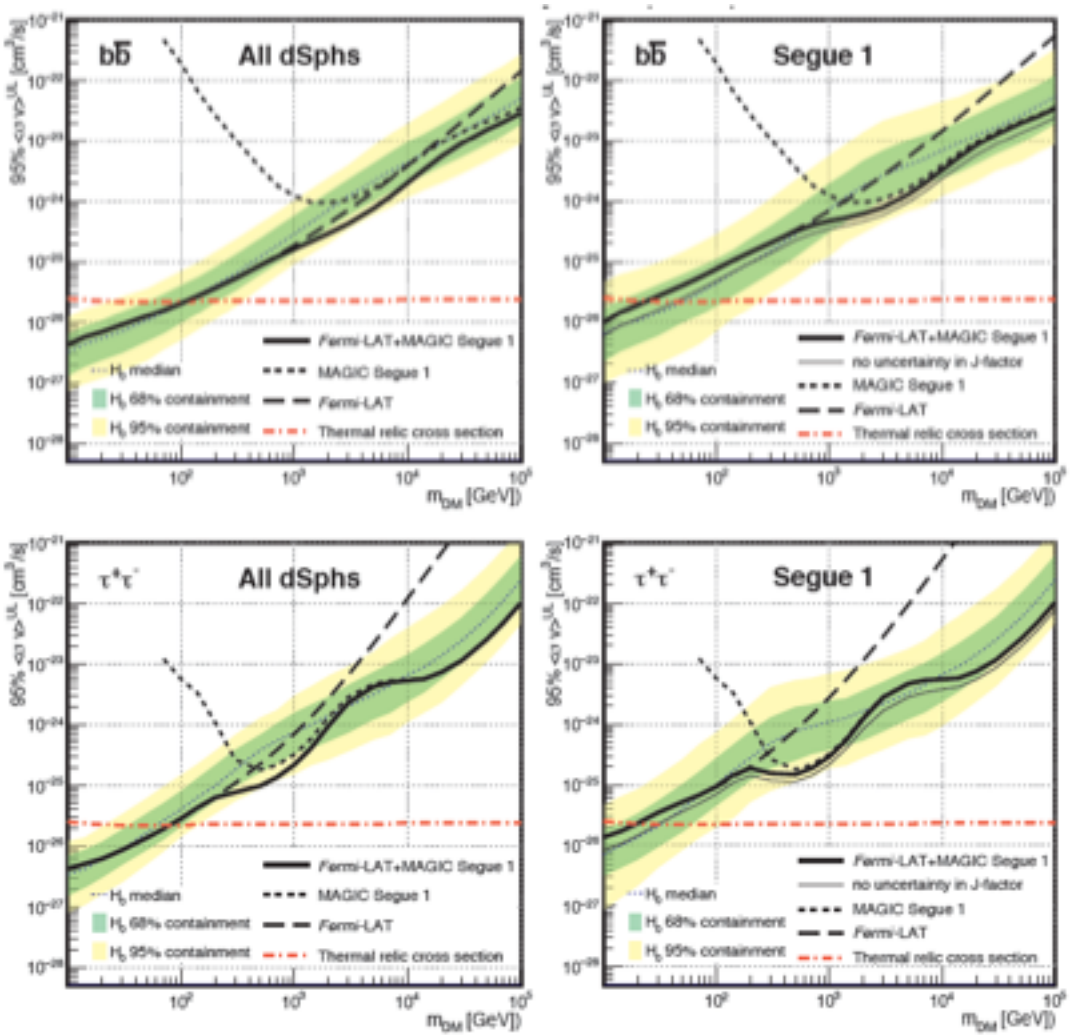
- Strongest constraints above few hundreds GeV according to channel
- Results made into the PDG



MAGIC + Fermi combined

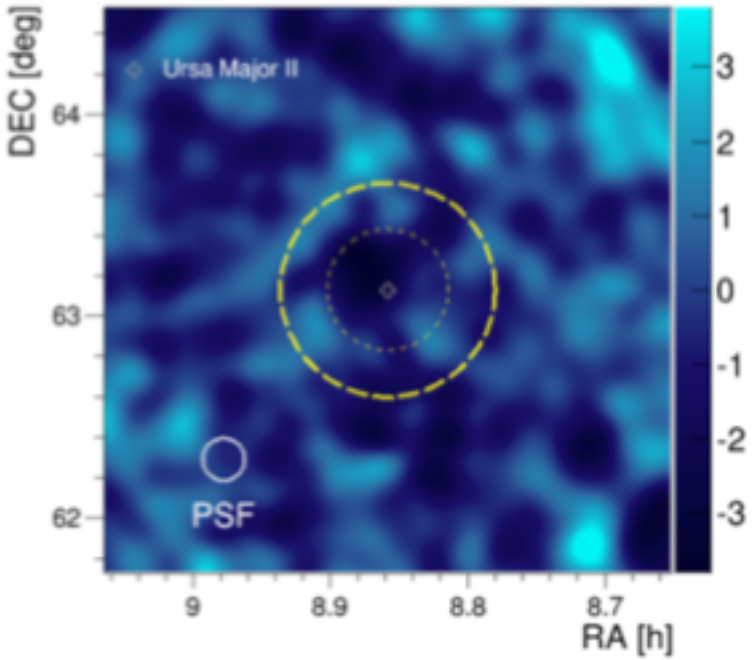
- MAGIC: Segue 1 (158 h) and Fermi-LAT: 15 dwarfs (6 years, Pass8)
- **Effective combination (2x stronger constraints) in the range 300-500 GeV**
- **A project between MAGIC, VERITAS, HESS and Fermi started *to combine them all***

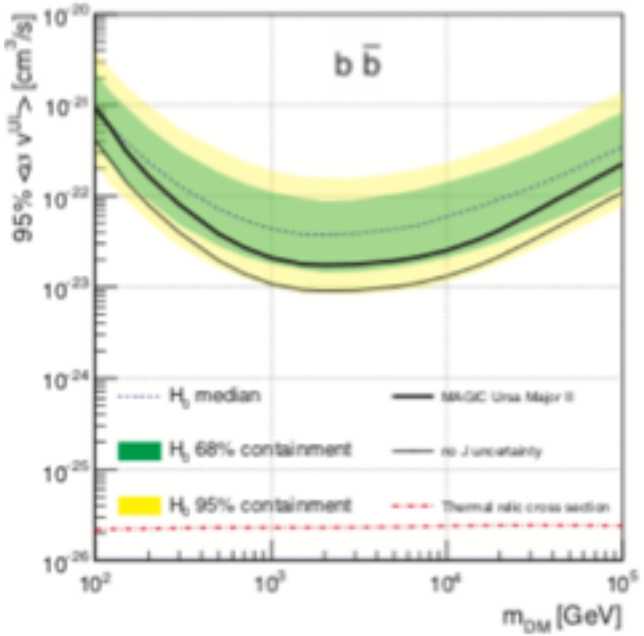
JCAP 02 (2016) 039

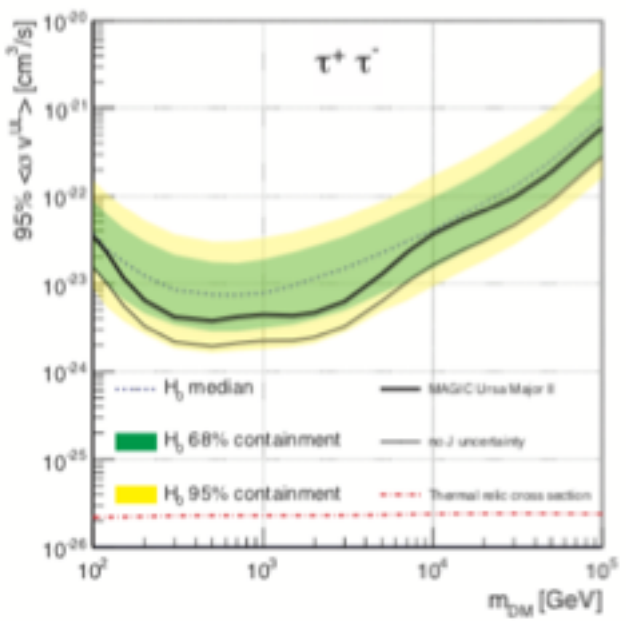


JCAP02(2016)039

Another dSph in the portfolio: Ursa Maior 2







$$\log_{10}(J(\theta_{\max})\ [\mathrm{GeV^2\ cm^{-5}}]) = 19.42^{+0.44}_{-0.42}$$

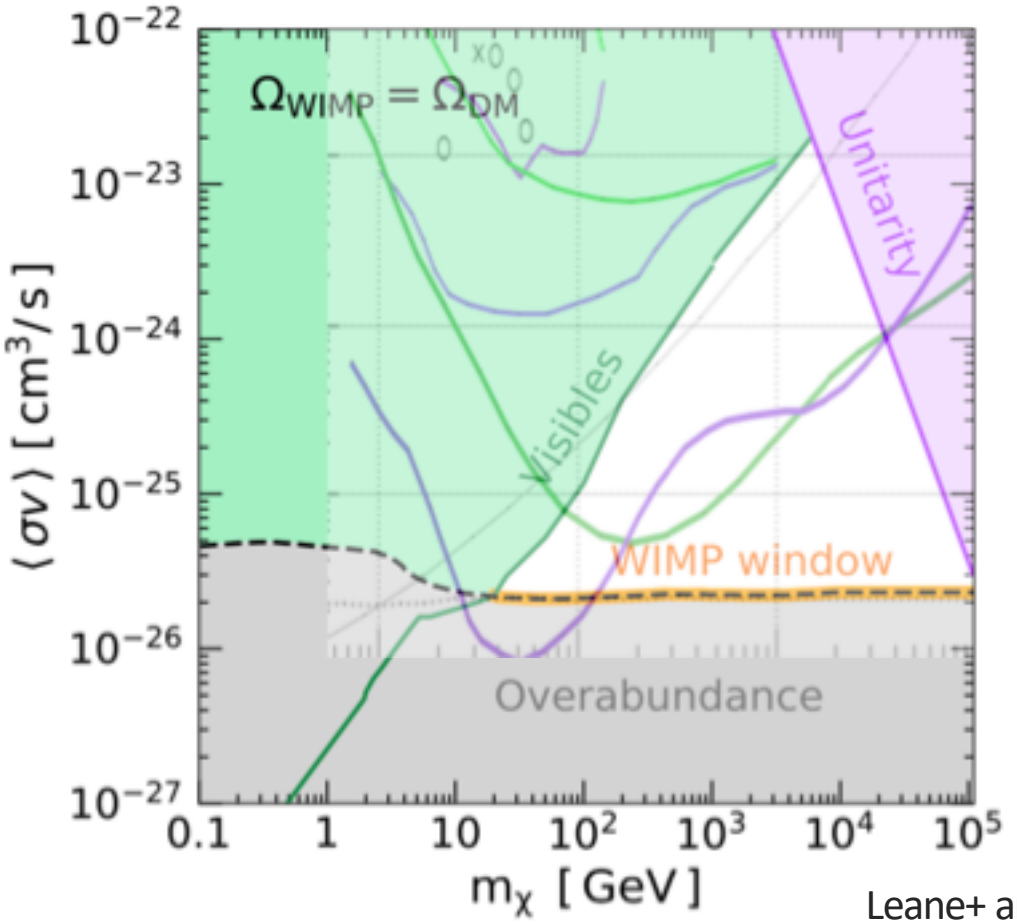
$$\mathrm{M/L} \sim 4000^{+3700}_{-2000}\ M_\odot/L_\odot$$

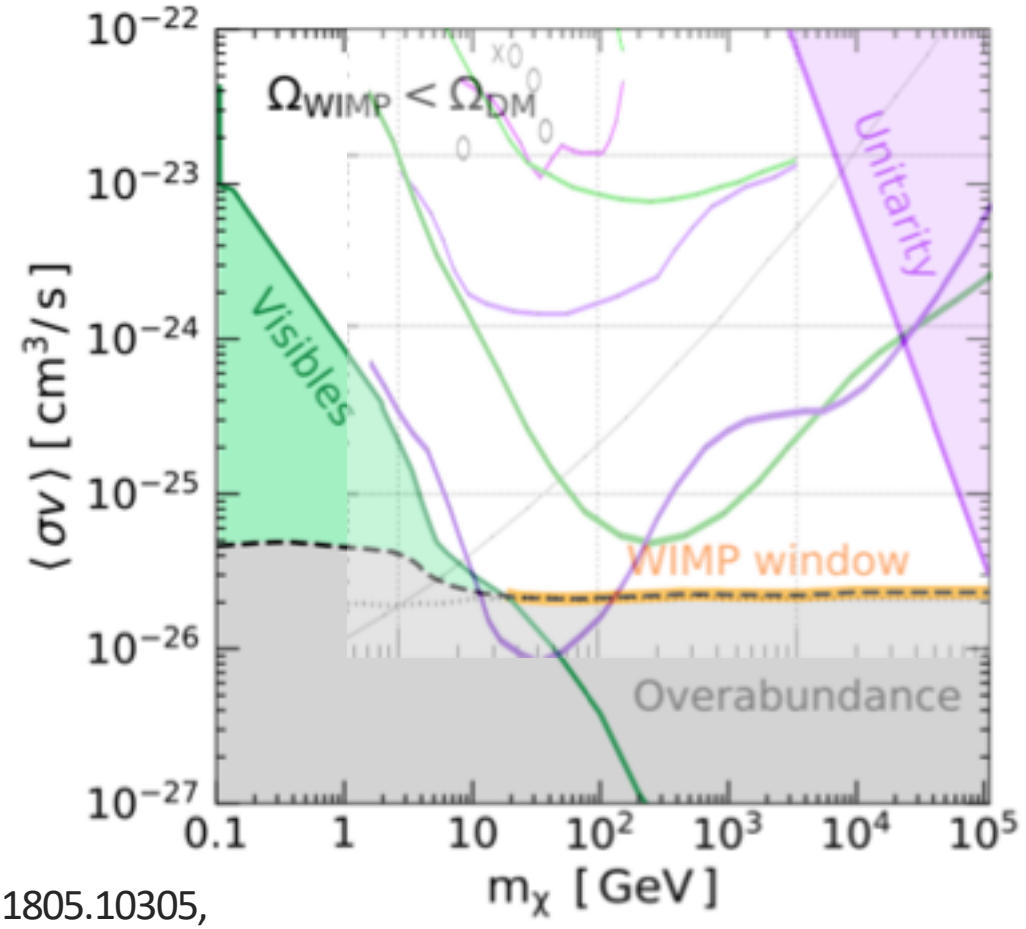
distance of $\sim$ 30 kpc

Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II with the MAGIC Telescopes
MAGIC Collaboration (M.L. Ahnen (ETH, Zurich (main)) *et al.*). Dec 7, 2017. 21 pp.
Published in **JCAP 1803 (2018) no.03, 009**

Are we close or far?

dSph with J=10x J_Segue, in 500h



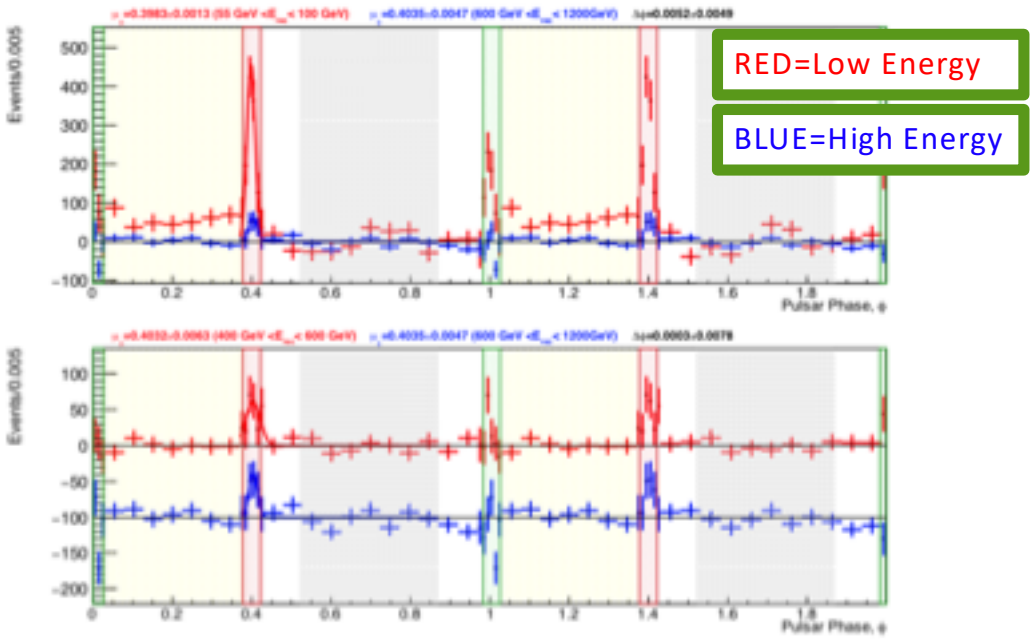


Leane+ arXiv:1805.10305,

Is the speed of light constant after all?

First results with pulsed light

$$u_\gamma(E) = \frac{\partial E}{\partial p} \approx c \cdot \left[1 - \sum_n \xi_n \frac{n+1}{2} \left(\frac{E}{E_{\mathrm{QG}_n}}\right)^n\right]$$



LORENTZ-INV[illegible]ITH CRAB PULSAR

Case	Crab Puls[illegible] (W/o Systematics	GRB090510 (Best of 3 Methods)
$\xi_1 = +1$	7.8×10^{17}	9.3×10^{19}
$\xi_1 = -1$	6.4×10^{17}	1.3×10^{20}
$\xi_2 = +1$	8.0×10^{10}	1.3×10^{11}
$\xi_2 = -1$	7.2×10^{10}	9.4×10^{10}

Constraining Lorentz invariance violation using the Crab Pulsar emission observed up to TeV energies by MAGIC
MAGIC Collaboration (M.L. Ahnen (ETH, Zurich (main)) *et al.*). Sep 1, 2017. 17 pp.
Published in **Astrophys.J.Suppl. 232 (2017) no.1, 9**

CONCLUSIONS

Conclusions

- The pace of results produced by IACTs in this mature stage is very large
- Analyses more complex: multi-w campaigns, tau-neutrinos, Lorentz Invariance from pulsars
- A new community is emerging whose expertise is unique for CTA
- Perfect moment to get people involved in learning and developing science with IACTs

Announcements

- **2018:** MAGIC introduced the **ASSOCIATED SCIENTIST** and **EXTERNAL SCIENTIST PROPOSALS**
- **2017:** MAGIC introduced the **light PHD program** (MAGIC data accessible to PhD joint programs)

(ASK ME IF INTERESTED)


KEEP
CALM
&
ENJOY
PORTOPALO
Thanks!