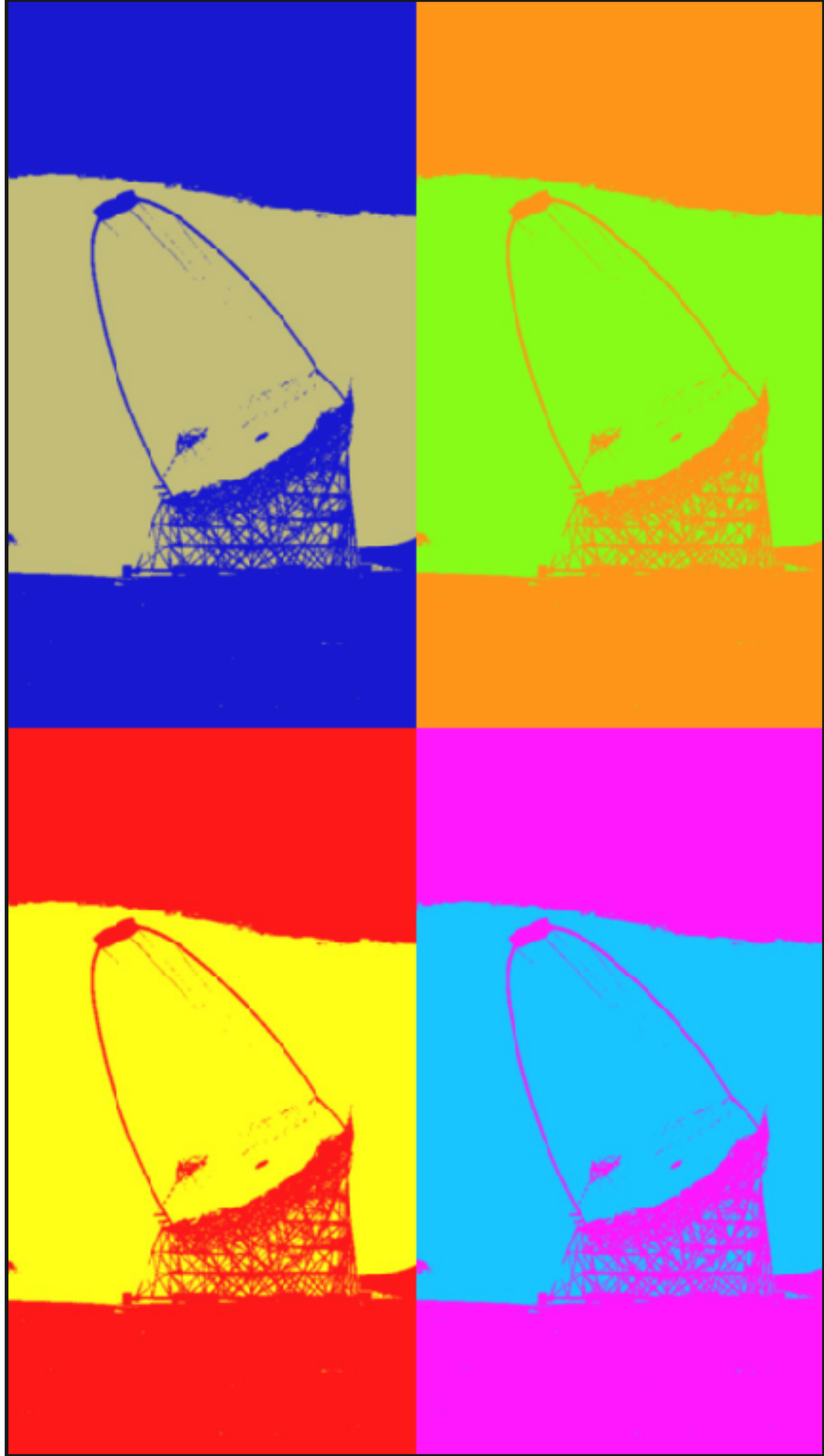
F2F Meeting on INFN Physics with CTA
Bari February 2018

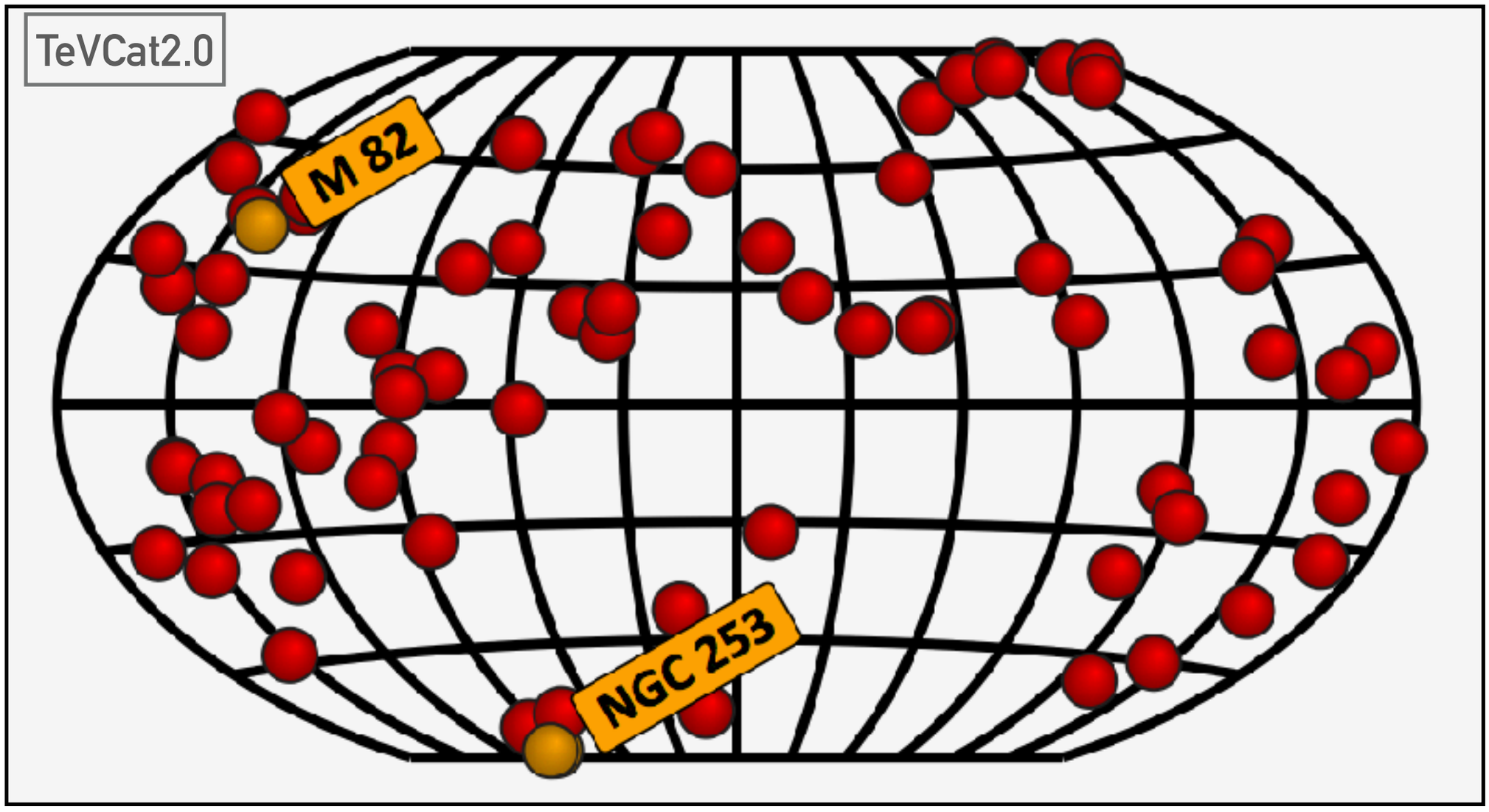
EXTRAGALACTIC PHYSICS: FROM MAGIC TO CTA

Elisa Prandini- prandini@pd.infn.it
University of Padua and INFN

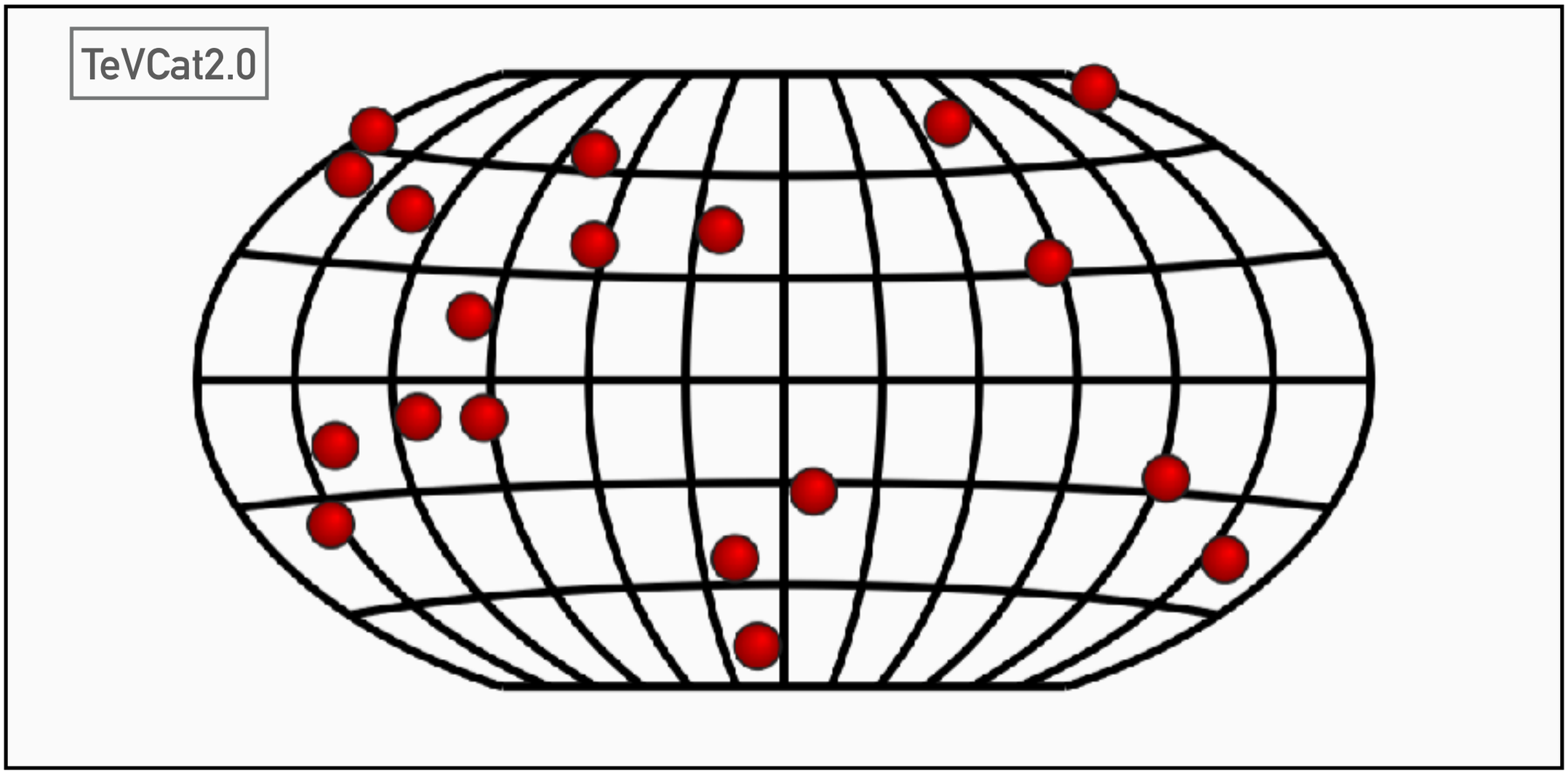


EXTRAGALACTIC TEV SOURCES (JANUARY 2018)

- 75 sources
- Only 2 non-AGN sources
  - 2 starburst galaxies (+ one source in Magellanic cloud classified as galactic)



. . . 10 YEARS AGO



Less than 20 sources known, the most distant at redshift ~0.2

MANY IMPROVEMENTS SINCE 2007

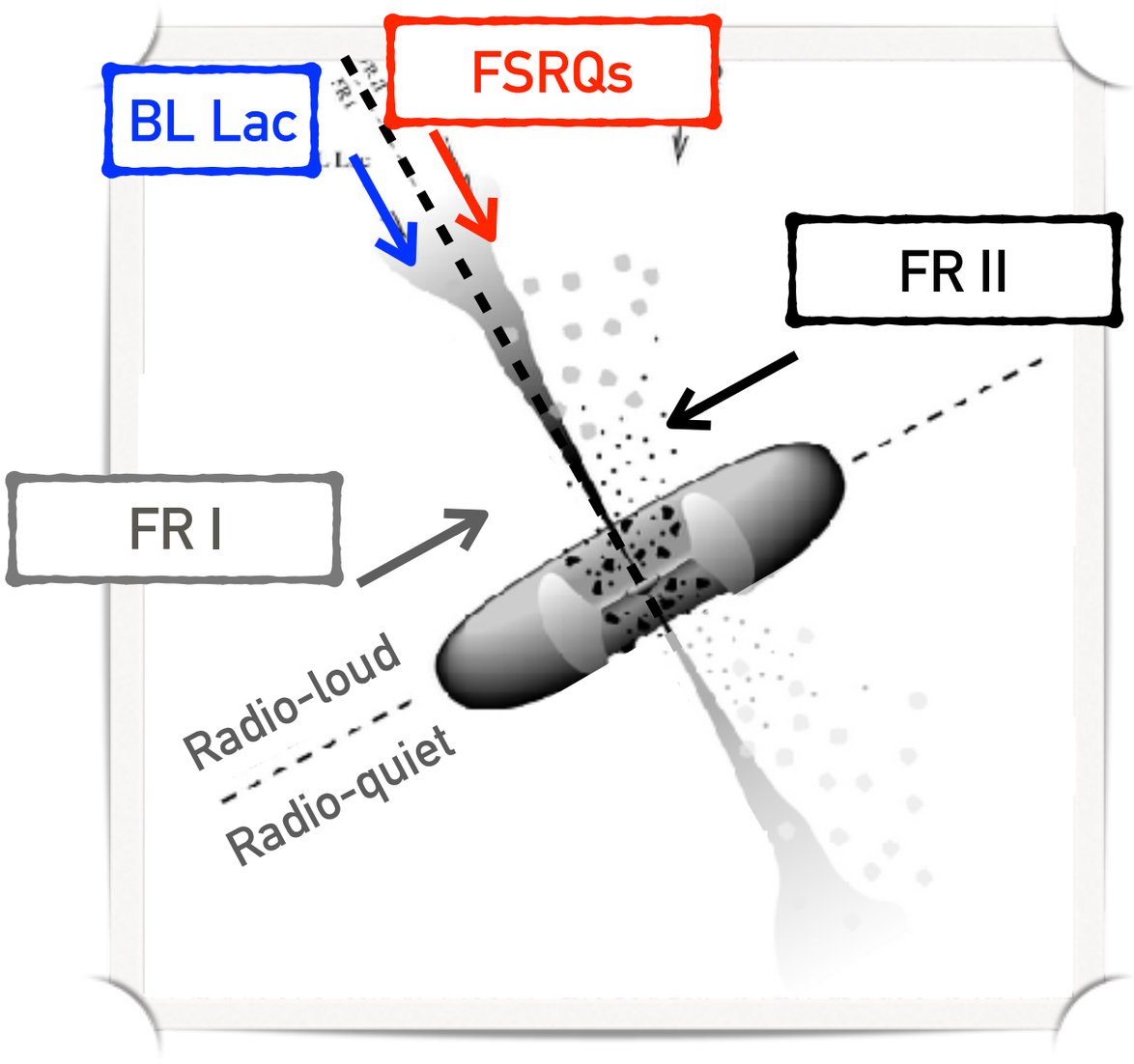
- Upgrades
  - **H.E.S.S.**: H.E.S.S. II and electronics upgrade
  - **MAGIC**: MAGIC II, MAGIC-I camera upgrade, electronics upgrade
  - **VERITAS**: camera upgrade, electronics and trigger upgrade, relocation of one telescope
- *Fermi*/LAT and AGILE in orbit
- Refined alert system between IACT and other facilities

THE FUTURE: CTA OBSERVATORY

E. Prandini - MAGIC and CTA

SELECTED RESULTS ON AGN PHYSICS

THE AGN MODEL



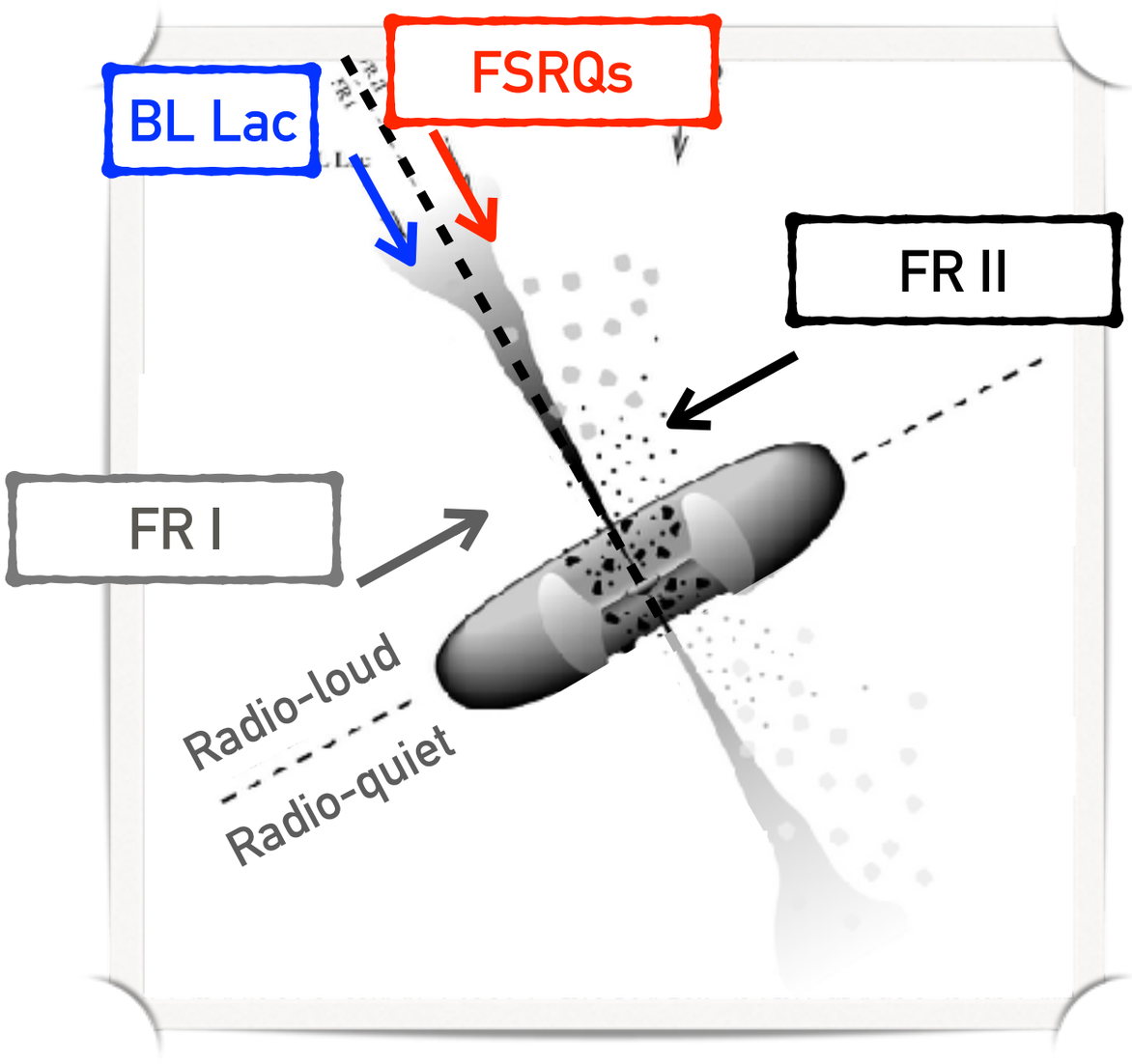
TeV emitters

- 5 radiogalaxies (misaligned blazars)
- 7 FSRQs
- ~60 BL Lac objects

Main unknowns

- Emitting region: size and location
- Emitting particles: role of hadrons
- Acceleration mechanism: shocks or other processes

THE AGN MODEL

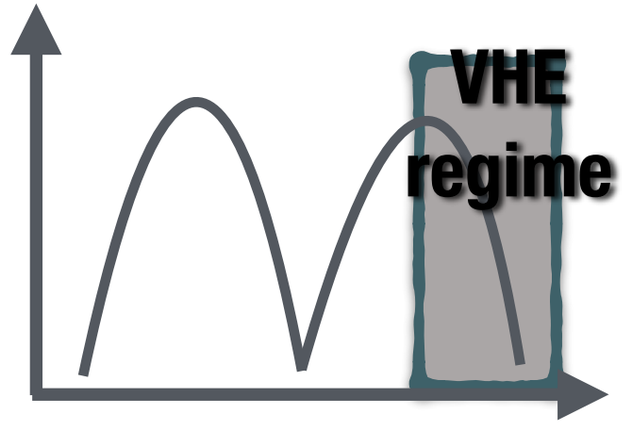


Shock in the jet model

- Acceleration of particles
- Emission:
  - Synchrotron
  - Inverse Compton
  - Photo-meson reactions (neutrinos)

Alternative models

- Magnetic reconnection
- Pulsar-like emission



THE GAMMA-RAY HORIZON

EBL photons

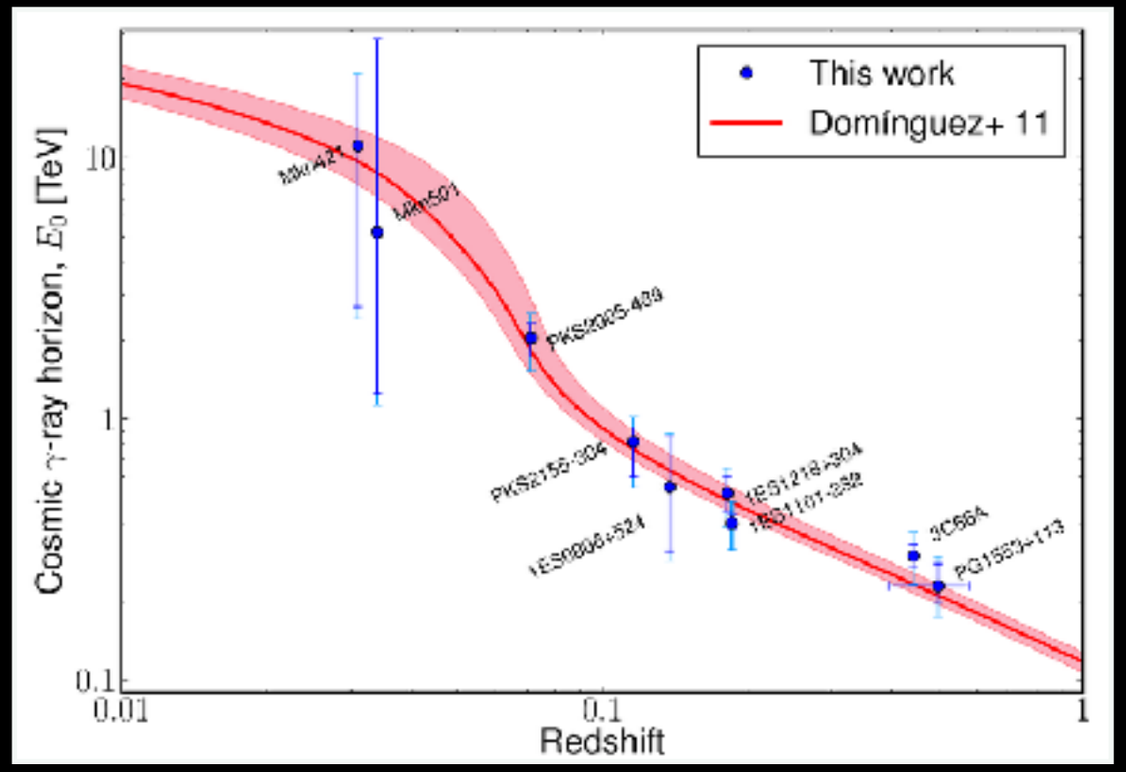
VHE photons

e^-

e^+

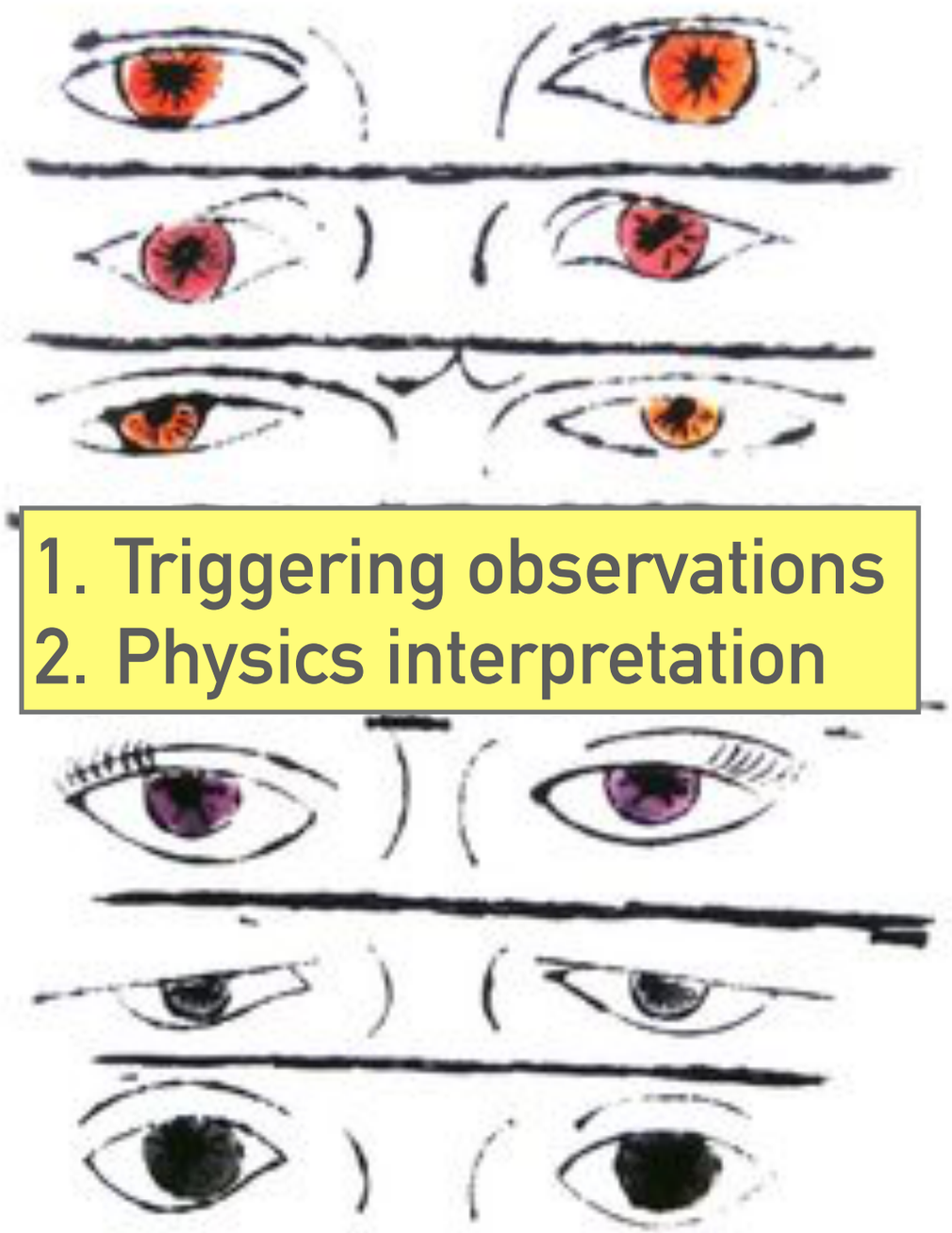
VHE photons and EBL photons: pair creation —>VHE flux reduction

Gamma-ray horizon: at a given redshift, the energy where the differential energy flux from the source is suppressed by a factor *e*



Domìnguez et al., ApJ, 770, 77 2013

THE IMPORTANCE OF MULTI-EYES



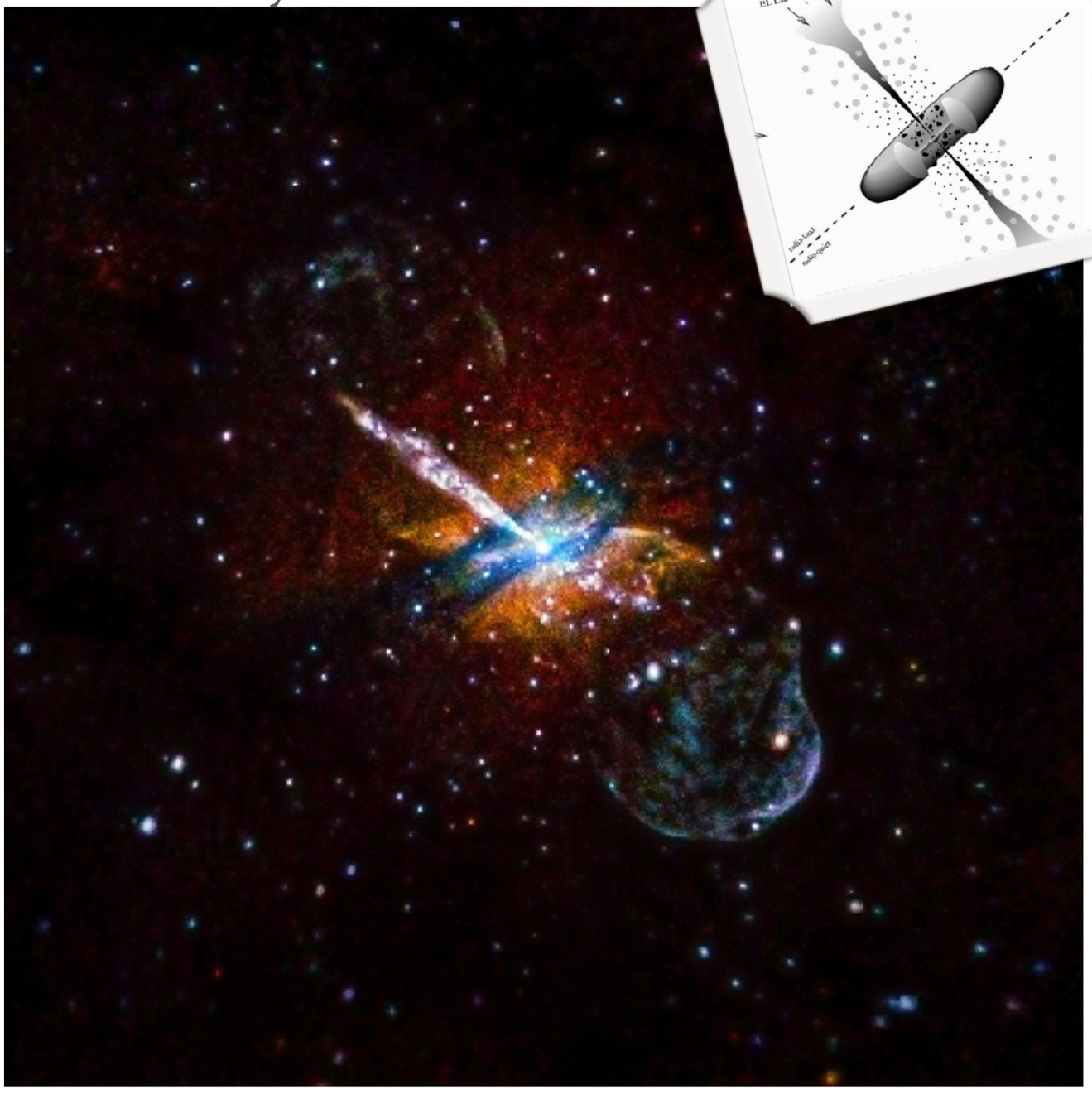
1. Triggering observations
2. Physics interpretation

- **Radio**: excellent PSF, long term monitoring, constrain the emitting region, especially in radio-galaxies
- **Optical**: long-term monitoring, frequent sampling, test variability, polarisation
- **X-ray**: frequent sampling (source-dependent) in blazars. In BL Lacs this is the frequency most connected to VHE gamma rays
- **HE gamma rays**: nearby range, almost continuous monitoring, essential for modelling
- **Neutrinos & UHECRs**: smoking gun for hadronic acceleration processes in acceleration region (UHECR origin)

MISALIGNED BLAZARS

MISALIGNED BLAZARS AT TEV

➤ Nearby sources

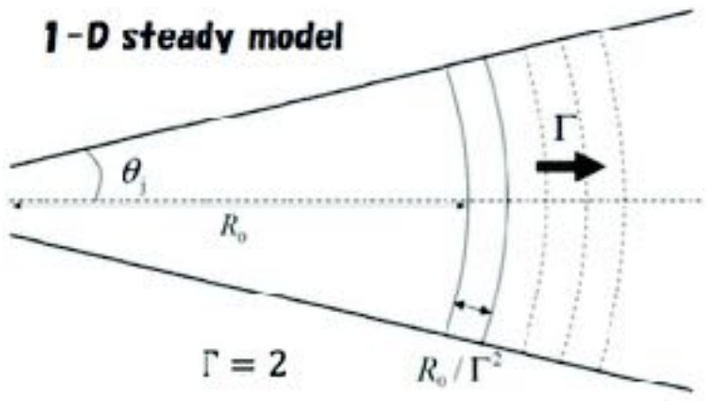


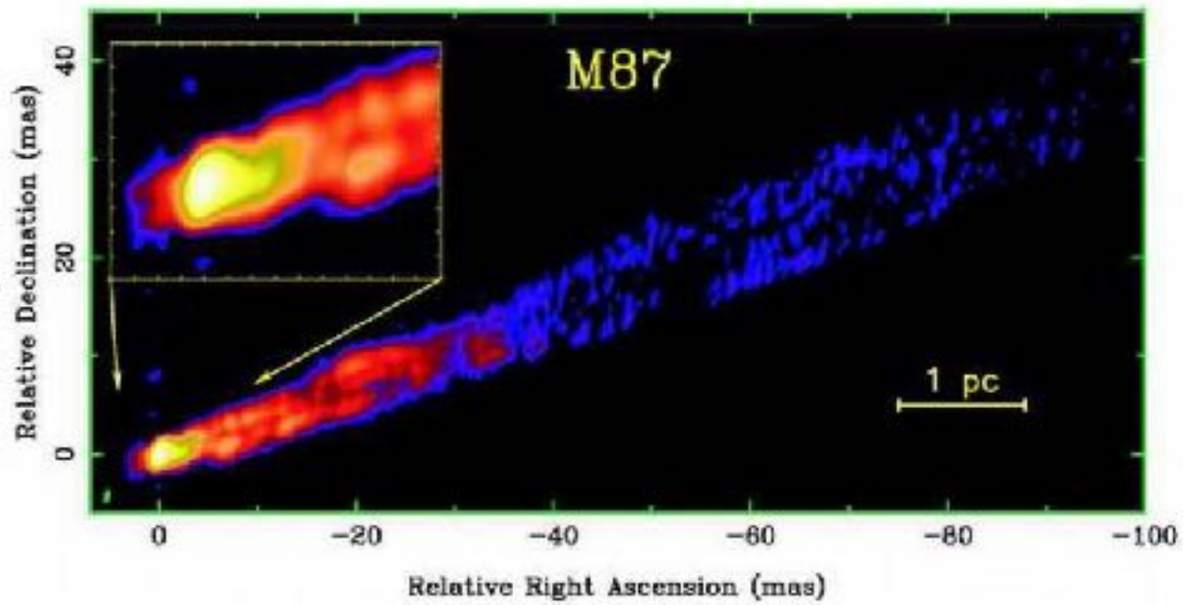
FR-I type (misaligned BL Lac)

Name	Distance
M 87	16 Mpc
Cen A	3.7 Mpc
NGC 1275	71 Mpc
IC 310 (?)	80 Mpc
PKS 0625-35 (?)	220 Mpc

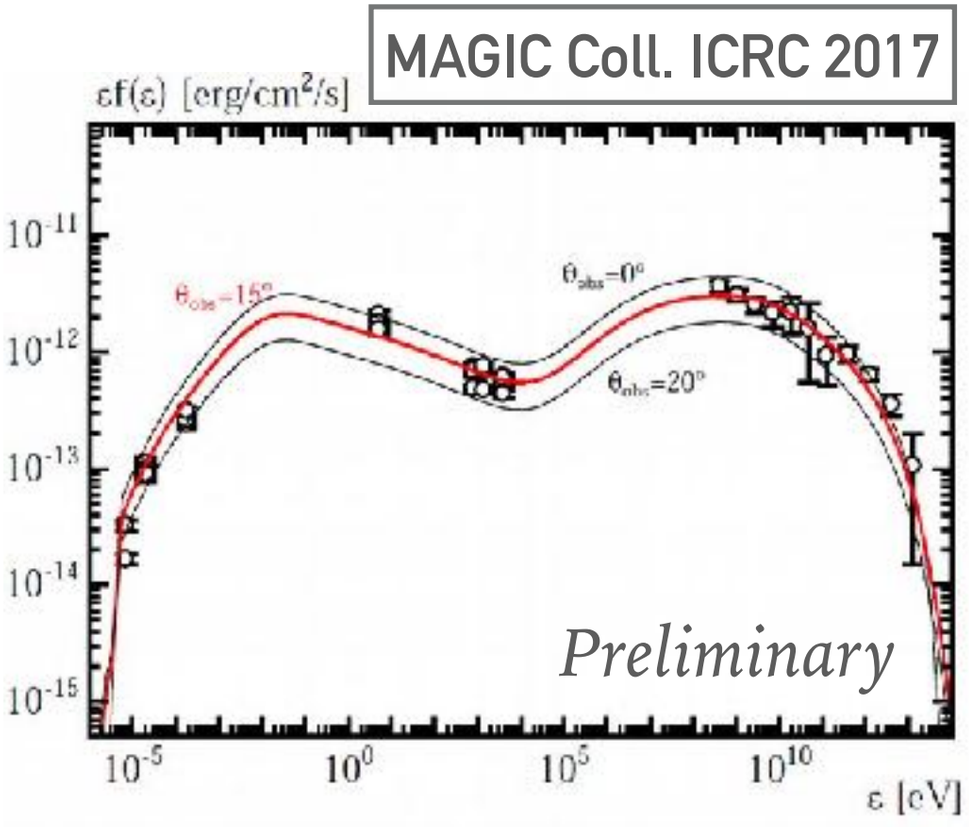
Unique opportunity to localise and characterise the emitting region of blazars (aligned counterpart)

M87 MWL OBSERVATIONS





- Best studied radio galaxy in VHE gamma rays

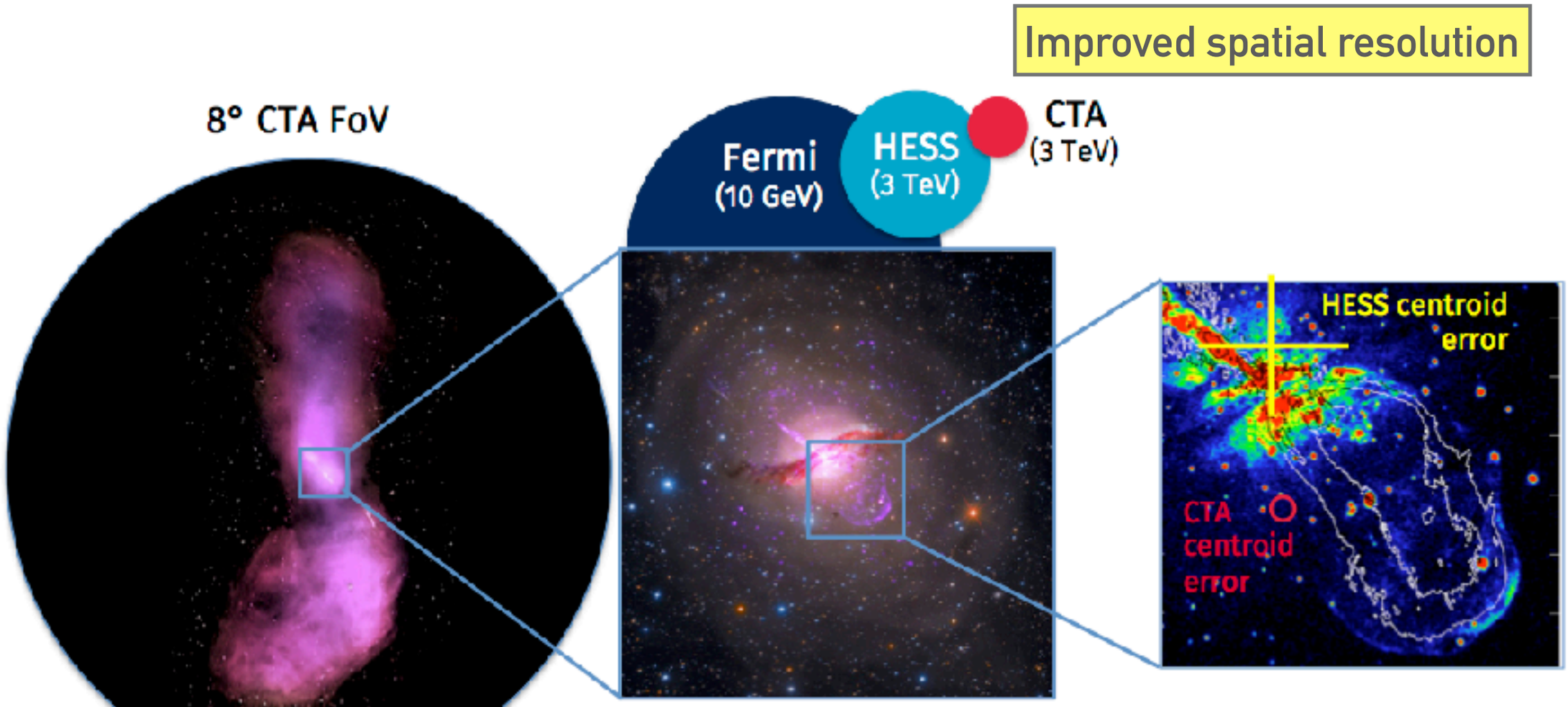


In collaboration with K. Asano

- **Monitored by MAGIC: over 150 h** gathered between 2012 and 2015
- No flares observed in that time
- VHE gamma- ray **spectrum extends up to 20 TeV** and connects smoothly to the GeV spectrum

The model requires energy density in the jet strongly dominated by particles

CTA PERSPECTIVES ON RADIO GALAXIES: CEN A

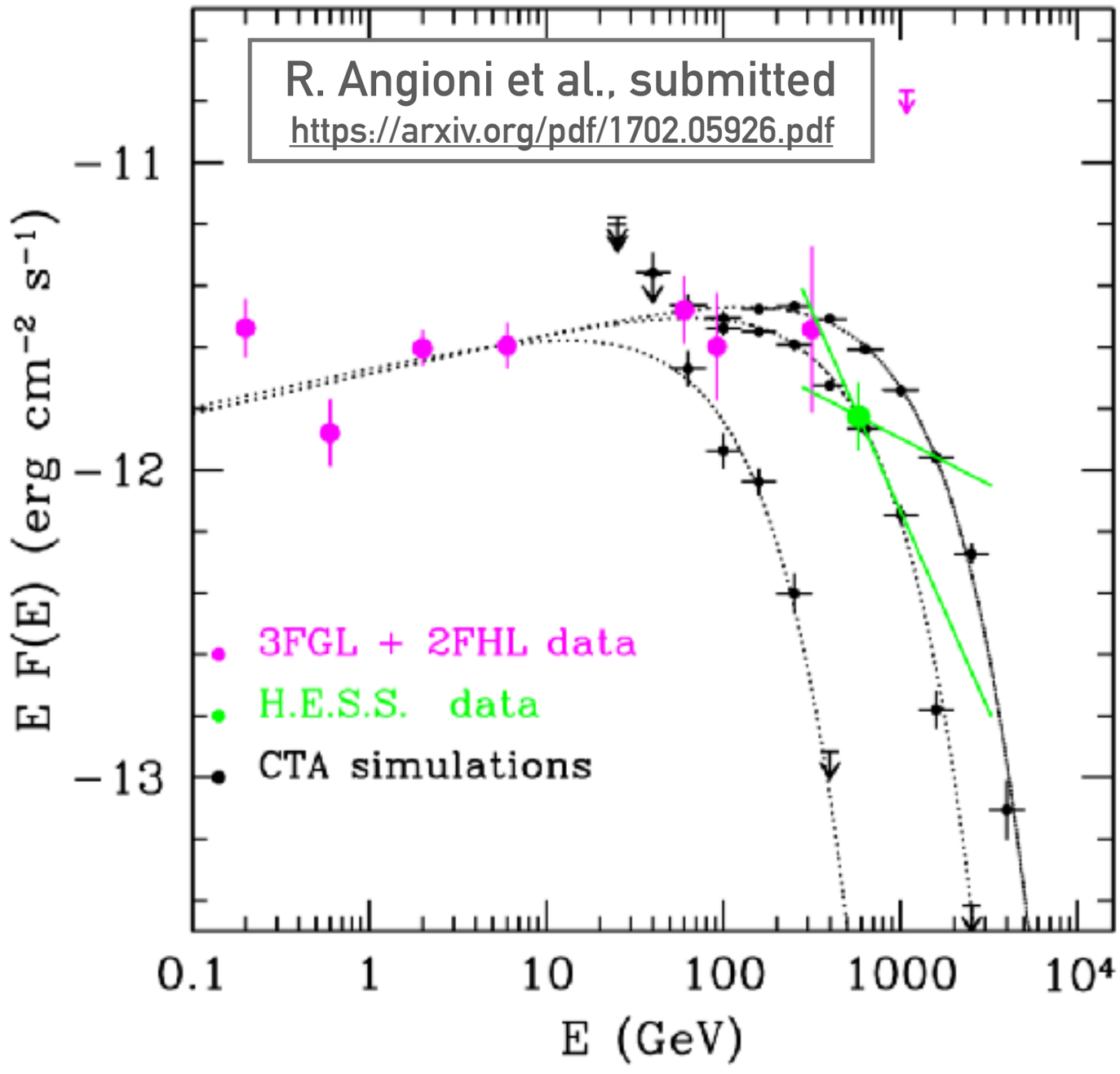


Centaurus A

With an 8 degree field of view (FoV), CTA will be able to cover the giant lobes of the nearby active galaxy Centaurus A in one exposure, despite an apparent size 20 times the diameter of the full moon (and a true size of around 2 million light years). Furthermore, CTA has the resolving power to see sub-structures in the inner regions of the active galaxy, something which is impossible with current gamma-ray telescopes.

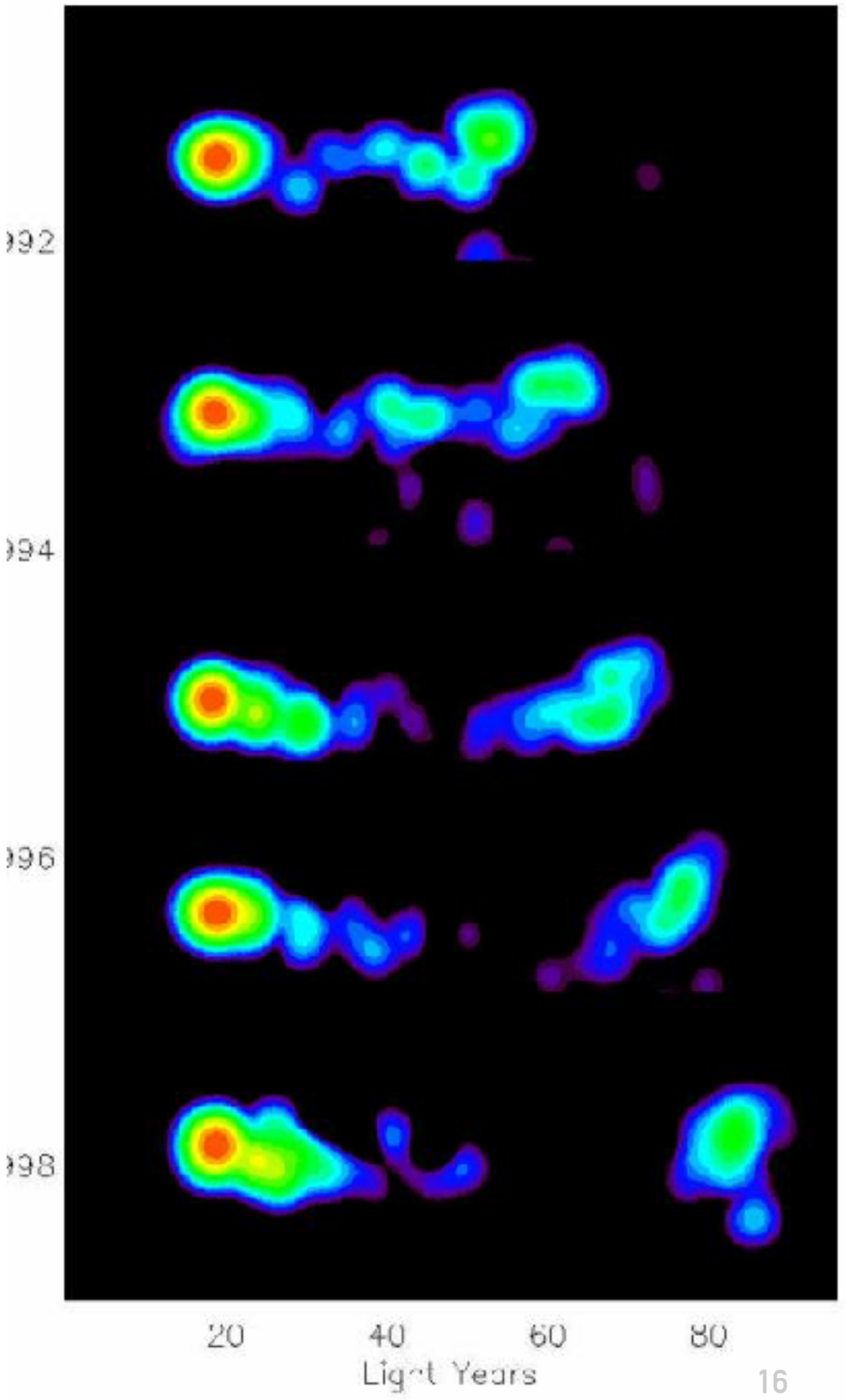
CTA PERSPECTIVES ON RADIO GALAXIES

Precise spectral measurements —> discrimination between models



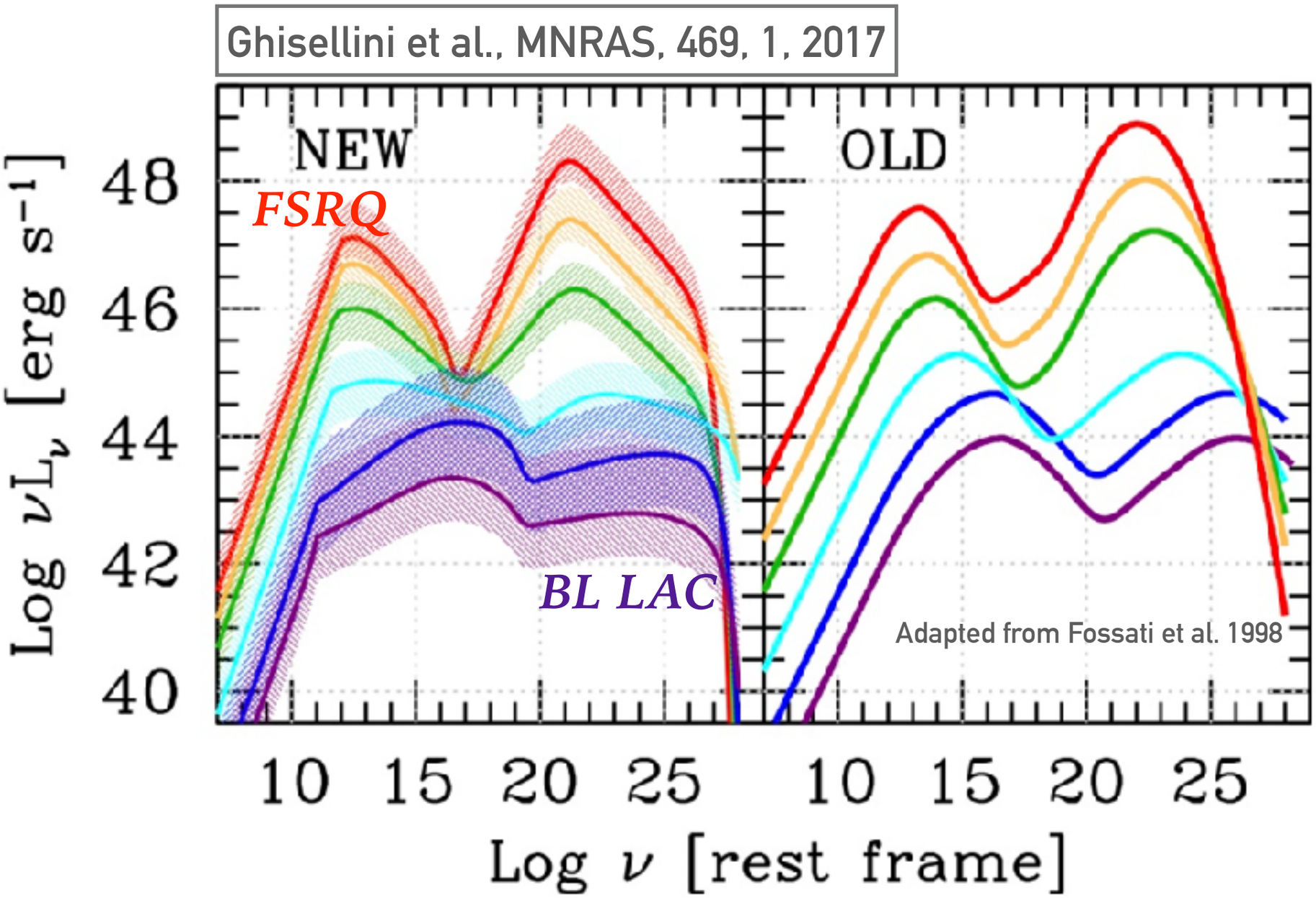
BLAZARS

FSRQs & BL Lacs



THE (FERMI) BLAZAR SEQUENCE

Ghisellini et al., MNRAS, 469, 1, 2017

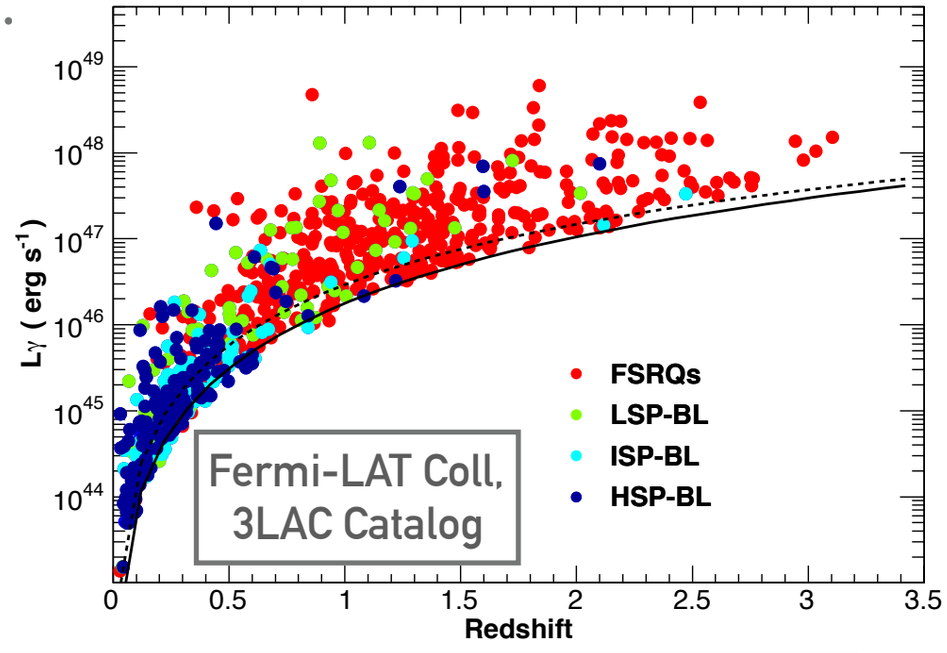


Anti-correlation between bolometric luminosity and energy of the peak(s)

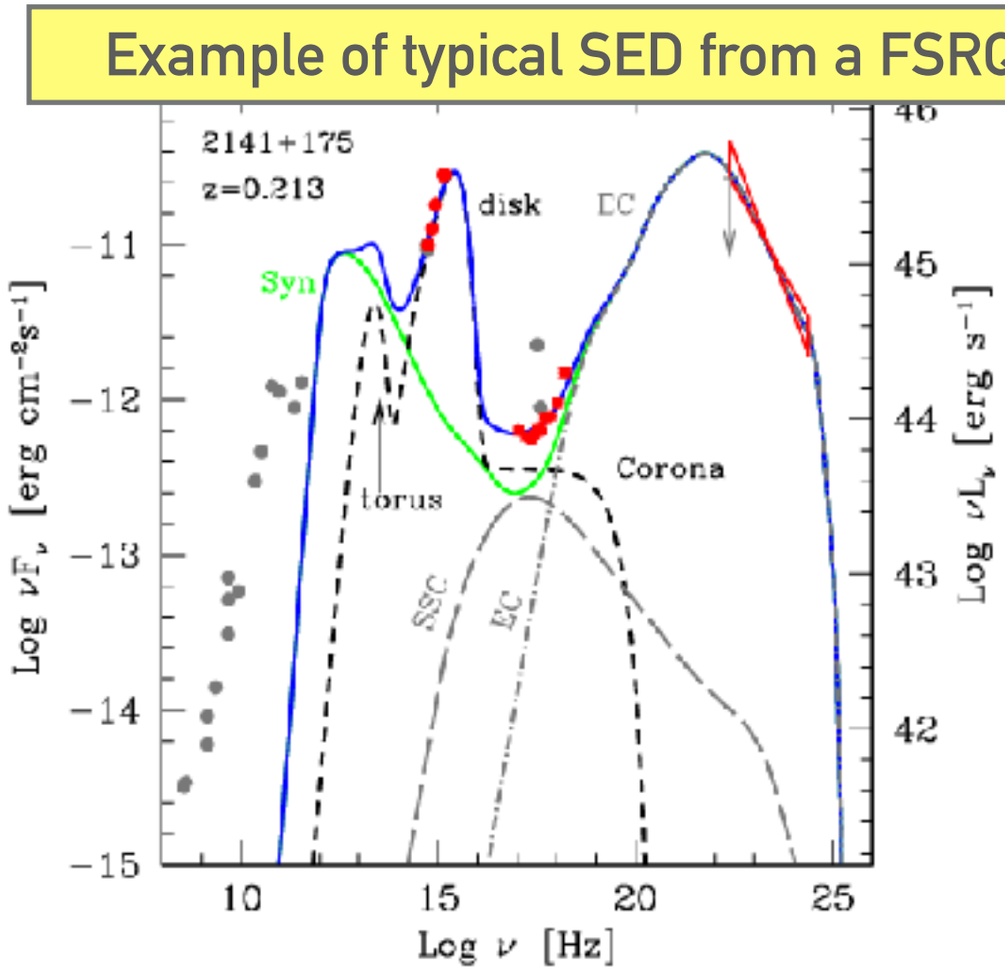
- FSRQs are very bright but their peaks are shifted to lower energies

GAMMA-RAY DETECTED FSRQS: GENERAL PROPERTIES

- *Fermi*-detected FSRQs have a larger redshift (up to z > 3);
- BL Lacs, instead, are located at relatively low redshift;
- But there are many BL Lacs with unknown redshift
- The SED is complex: different radiation fields superimposed
- Only 7 objects known at TeV energies

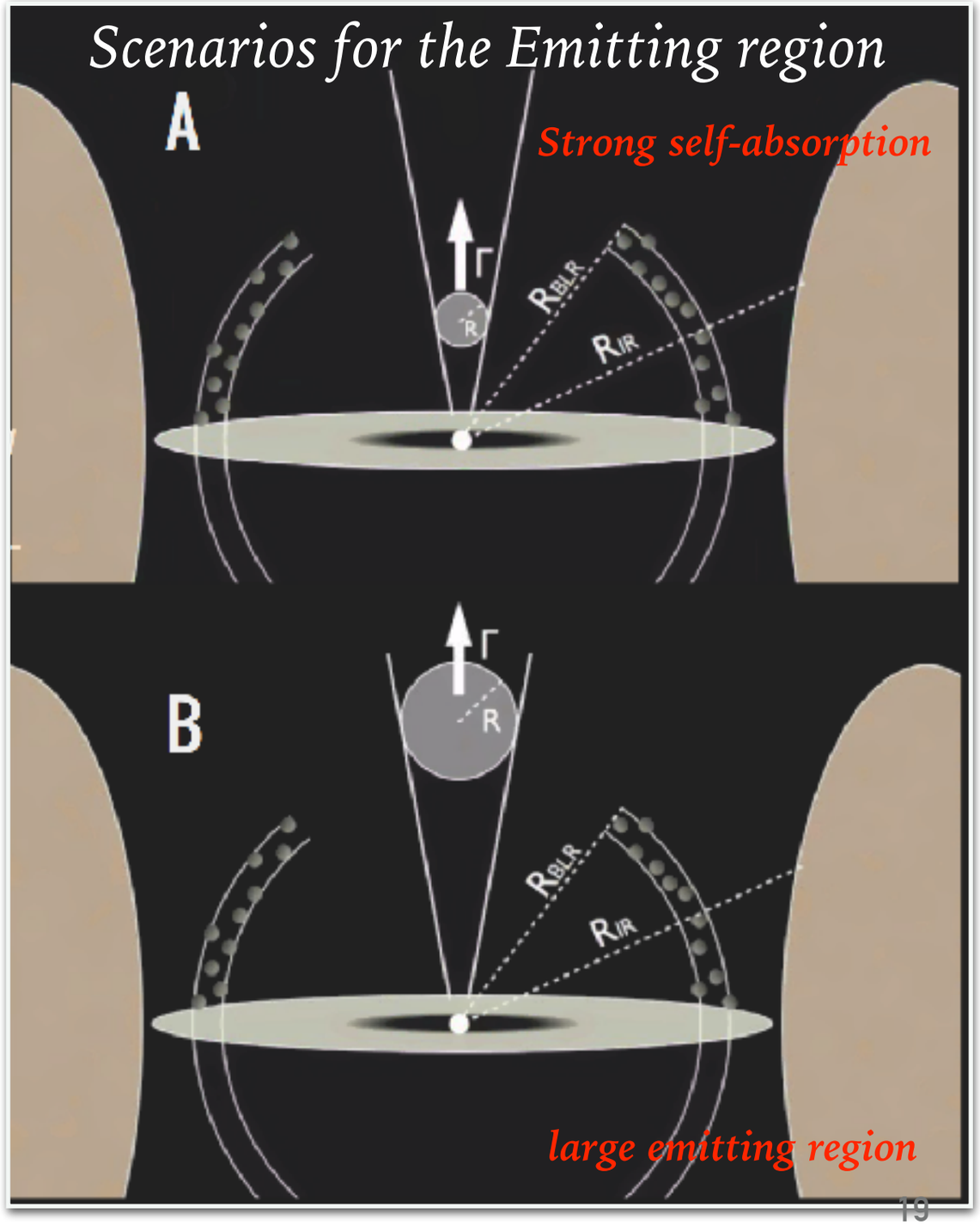


Example of typical SED from a FSRQ



TEV FSRQ

Source	z	Discoverer	Year
3C 279	0.5362	MAGIC	2006
PKS 1510-089	0.361	HESS	2009
PKS 1222+216	0.432	MAGIC	2010
B0218+367	0.944	MAGIC	2014
S4 0954+65	0.368	MAGIC	2015
PKS 1441+25	0.939	MAGIC	2015
PKS 0736+017	0.189	HESS	2016



TEV FSRQ: BREAKING THE DISTANCE RECORD!

- Sources detected up to redshift ~1

Source	z	Discoverer	Year
3C 279	0.5362	MAGIC	2006
PKS 1510-089	0.361	HESS	2009
PKS 1222+216	0.432	MAGIC	2010
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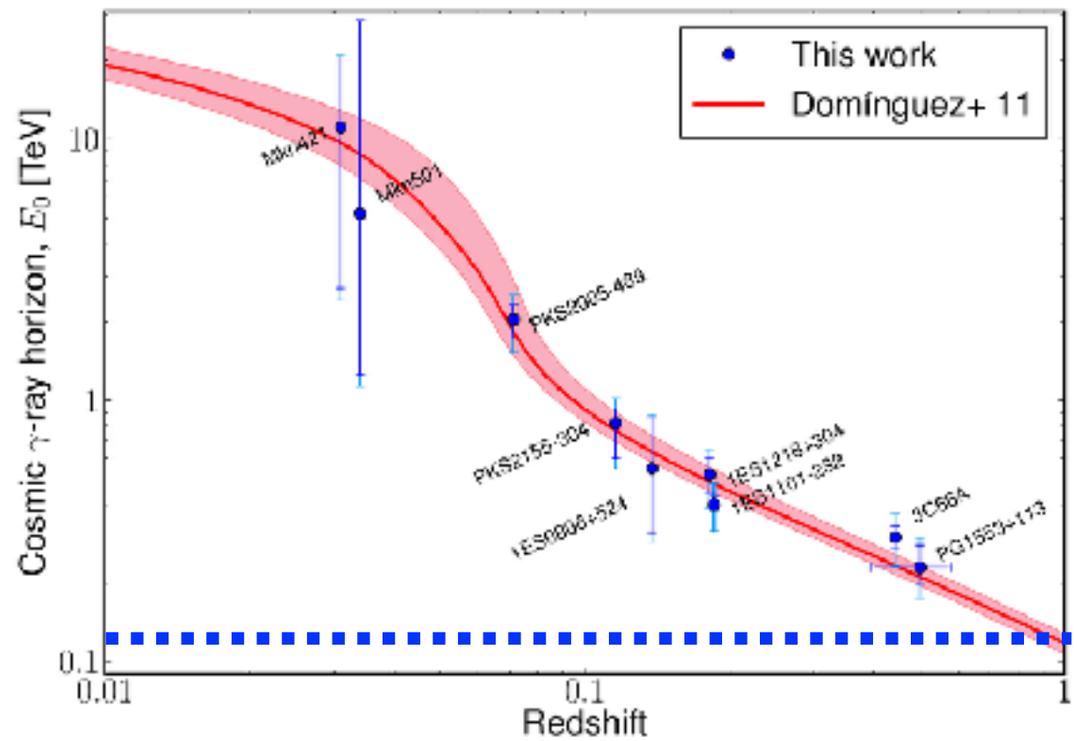
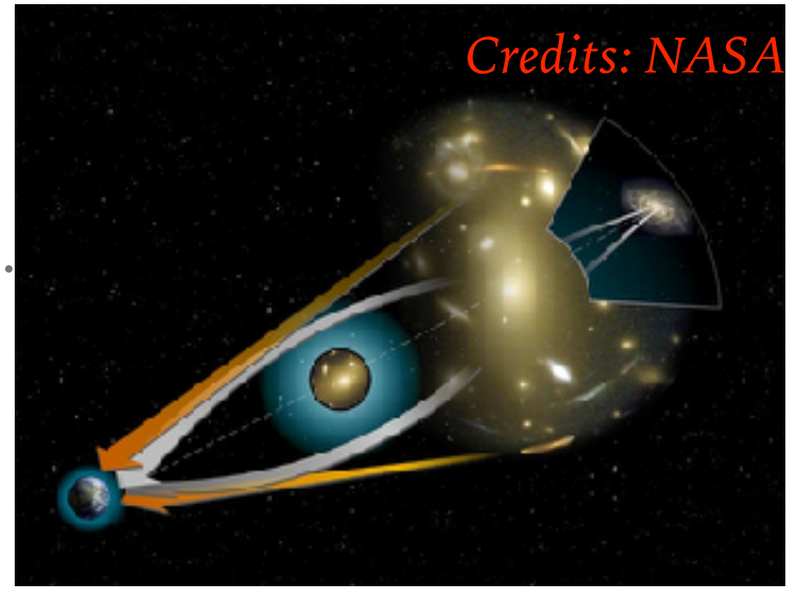
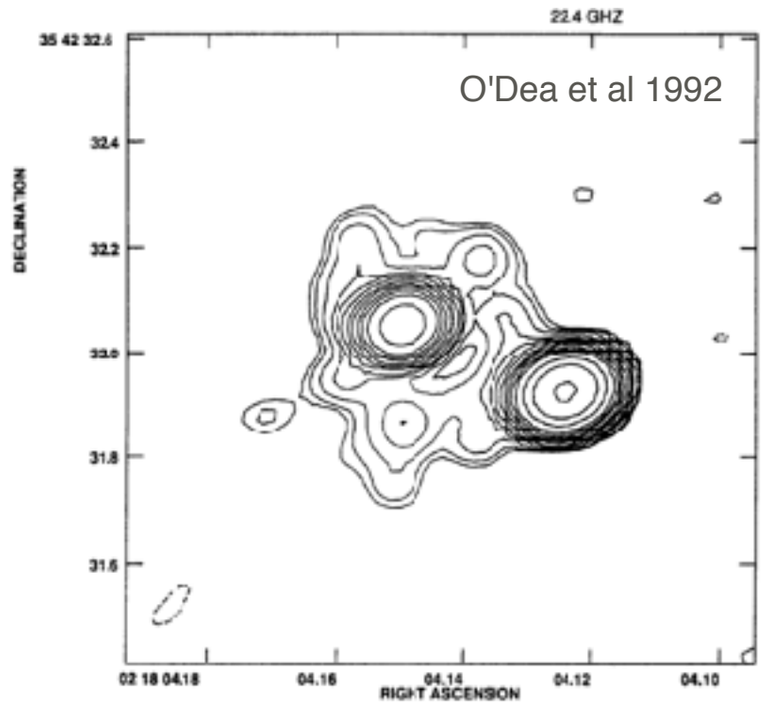
Domìnguez et al., ApJ, 770, 77 2013



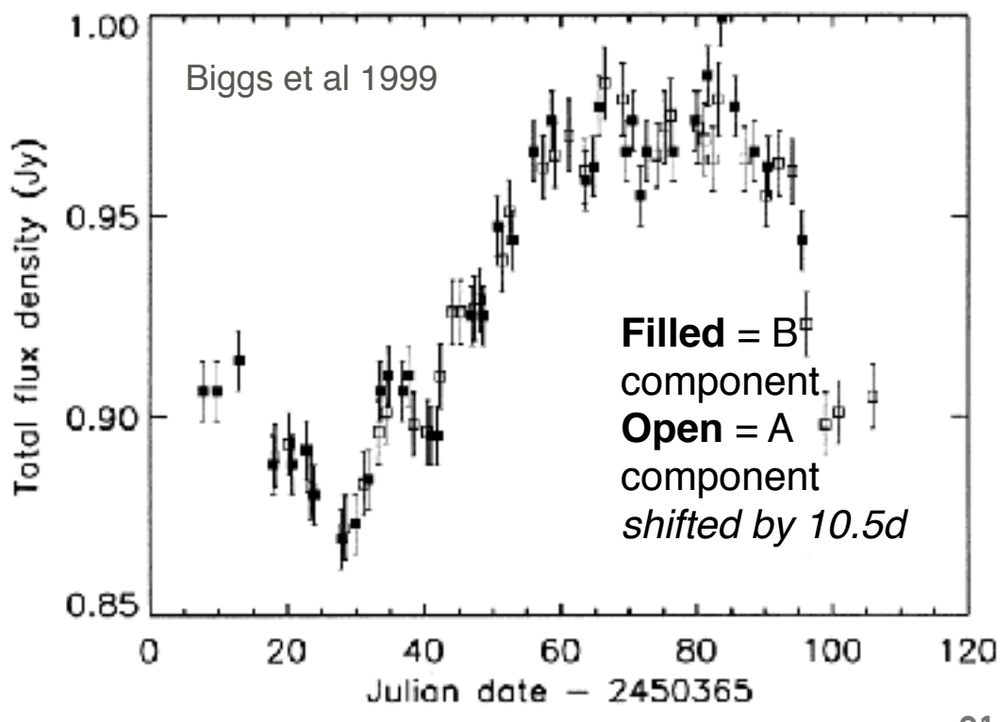
VHE flux only at ~ 100 GeV



B0218+357



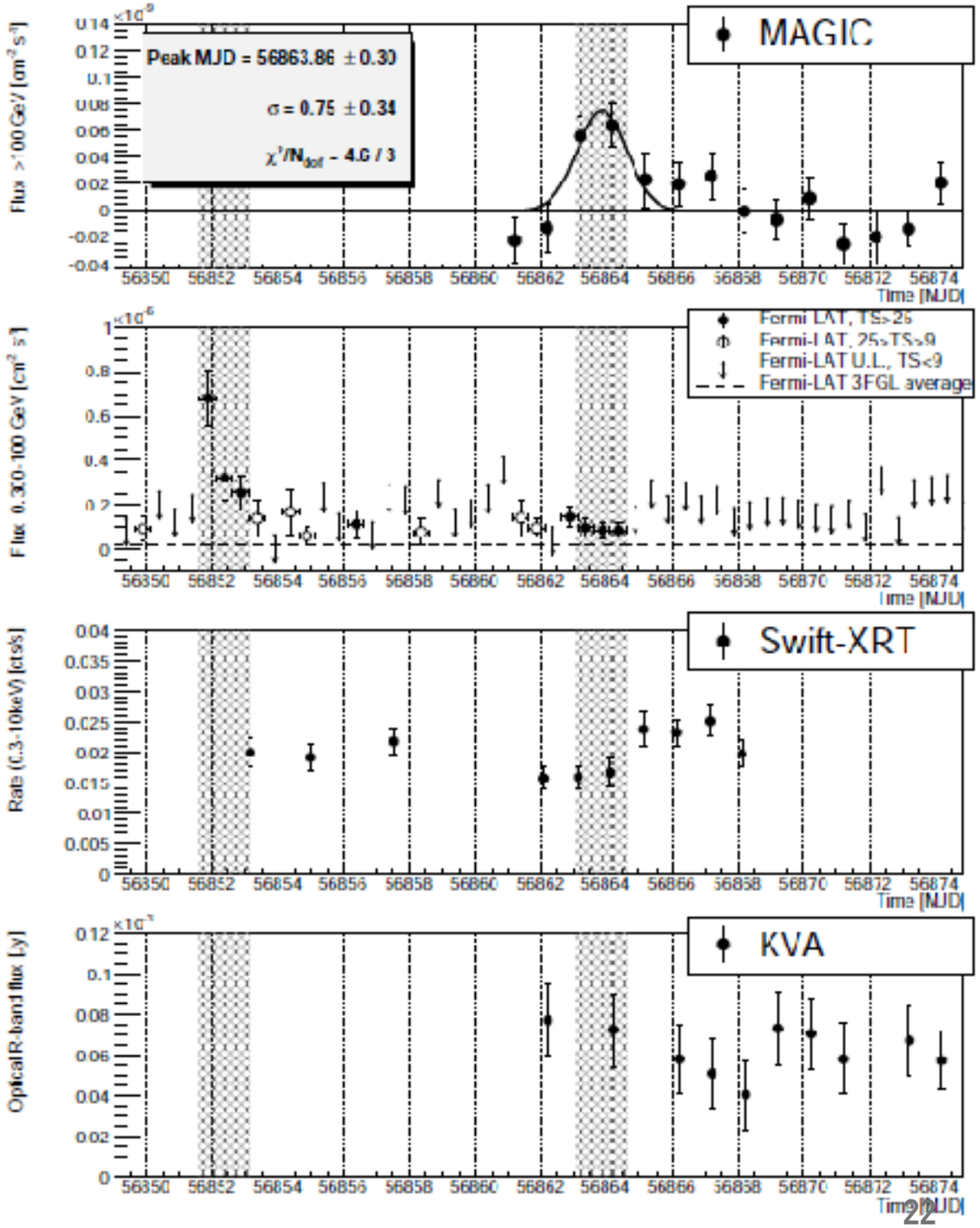
- **Gravitationally lensed blazar**
- Redshift: **0.944**+/-0.002
- Lens: galaxy B0218+357G (spiral seen face-on) at z=0.68
- In radio *double image* and *Einstein ring* is visible
- A **delay of ~10-12 days** between the emission from A and B images is seen in radio and GeV ranges



B0218+357– FIRST GRAVITATIONALLY LENSED SOURCE DETECTED IN VHE GAMMA RAYS

- **July 2014:** flare by ***Fermi*-LAT** (MAGIC in moon time *pause*)
- MAGIC detected the **delayed emission** exactly when expected
- The farthest VHE gamma-ray source (with known z)
- Photons seem to follow the same paths in the gravitational field up to at least 250 GeV

MAGIC Coll, A&A, 595, A98, 2016

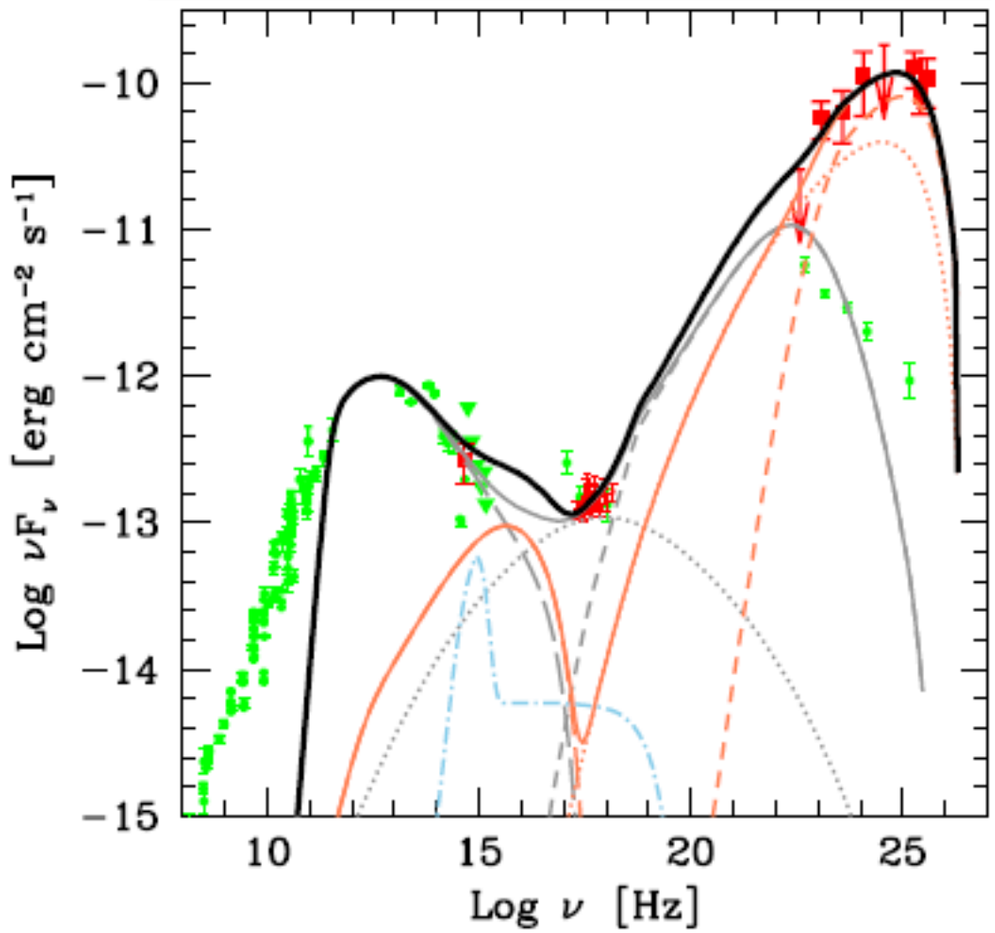


B0218+357– FIRST GRAVITATIONALLY LENSED SOURCE DETECTED IN VHE GAMMA RAYS

SED modelling is challenging:

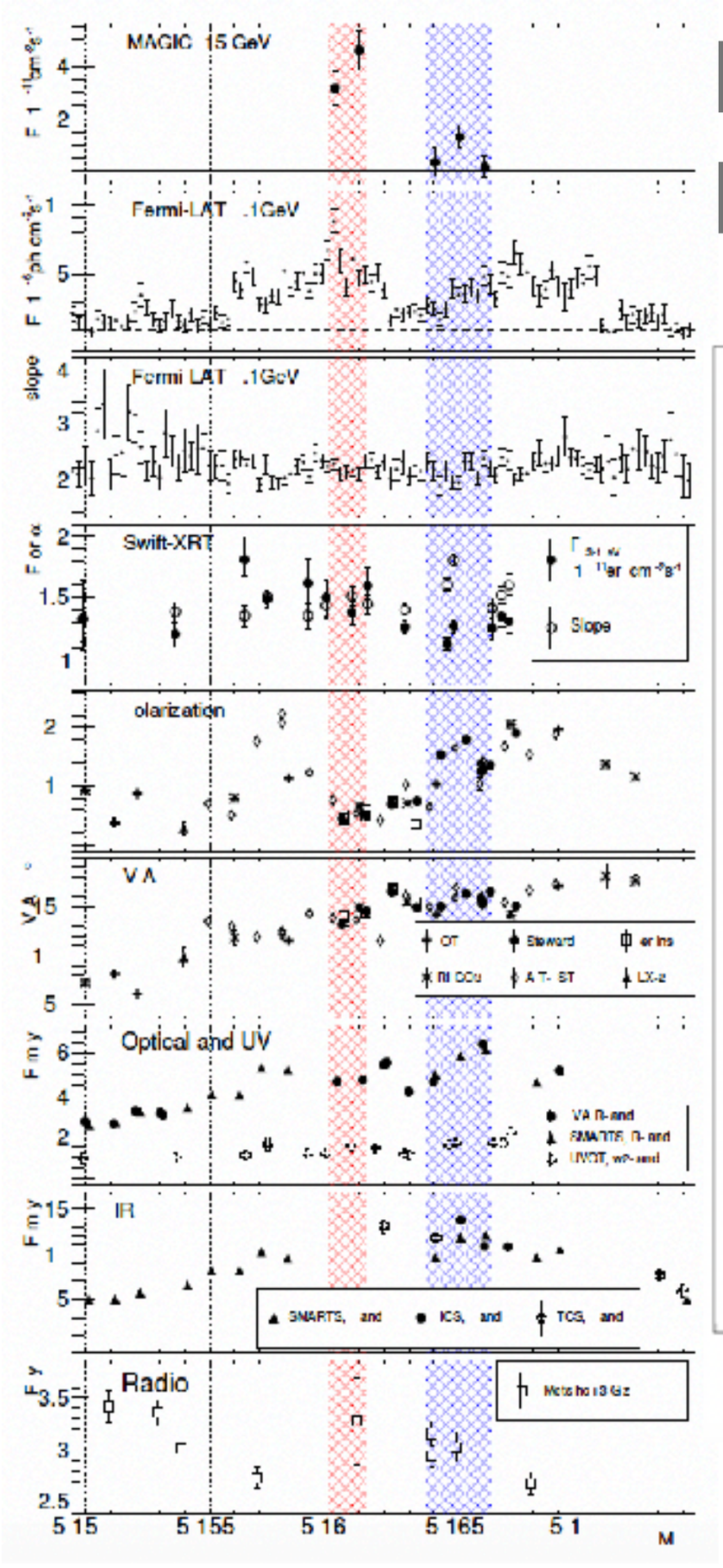
- one emission zone model: excluded by different variability optical-X and gamma rays and by extremely large doppler factor needed by the model
- two emission zones model: one inside and one just outside the BLR
  - External Compton emission outside BLR: VHE photons emission (1day variability allows this geometry)

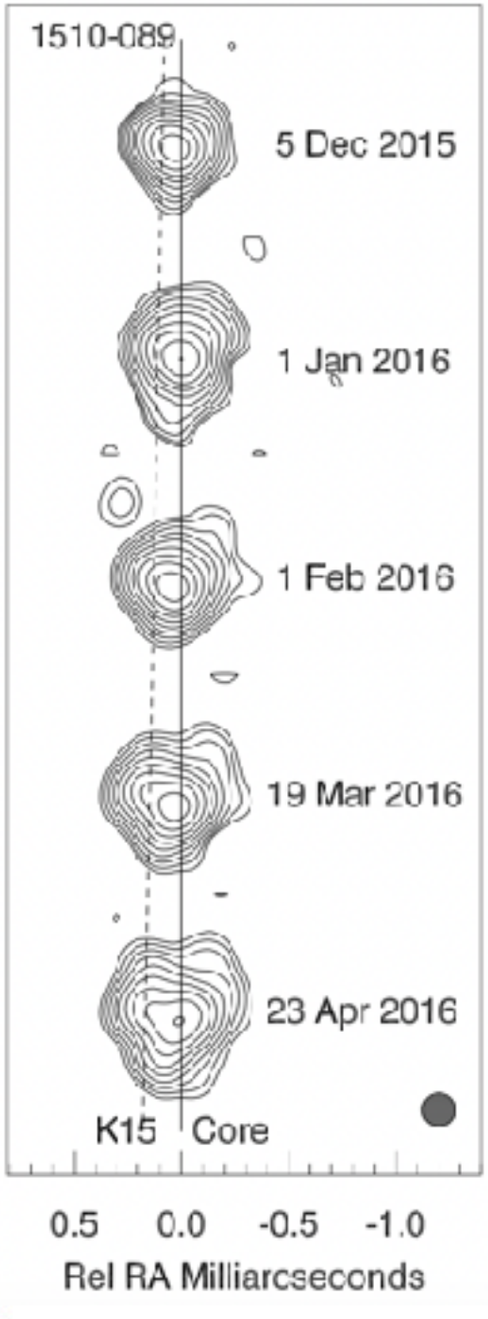
MAGIC Coll, A&A, 595, A98, 2016



PKS 1510-089 FLARING IN VHE FOR THE FIRST TIME (2015)

MAGIC Coll. A&A, 603, A29, 2017



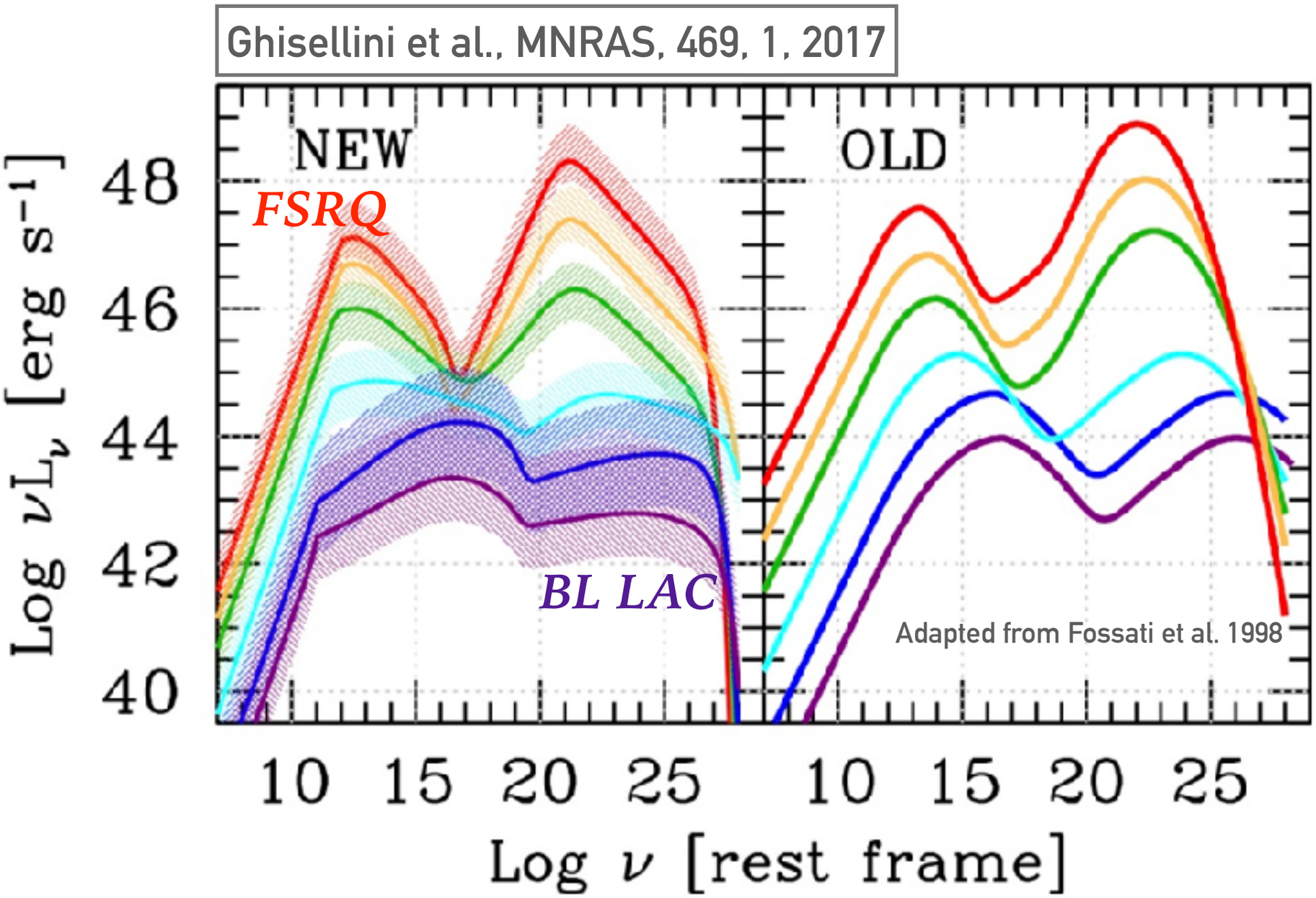


- High optical and gamma-ray state —> **trigger** MAGIC observations
- VHE gamma-ray flux ~4 times brighter than 2009 and 2012
- Similar VHE spectral shape (intrinsic slope=3.2 +/- 0.8)
- Smooth rotation of the Electric Vector Polarization Angle (EVPA) by ~100 degrees

Ejection of a new radio component

THE (FERMI) BLAZAR SEQUENCE

Ghisellini et al., MNRAS, 469, 1, 2017



Anti-correlation between bolometric luminosity and energy of the peak(s)

- LBL/IBL situation is similar to FSRQs case: peak at low energies / lower luminosity w.r.t. FSRQs

TEV BL LAC OBJECTS: IACTS OBSERVATION STRATEGIES

Early Science

New sources:

19 new sources discovered since 2013
(MAGIC, H.E.S.S., & VERITAS)
6 with unknown redshift

- Discovery of flaring sources: ToO observations from optical, X-ray, gamma, GW, neutrinos, other VHE gamma-ray instruments.
- Other new sources: catalogs

Monitored sources:

Classical blazars: Mkn 501, Mk 421, PKS 2155-304, 1ES 1959+650, …
Other sources: 1ES1218+304, 1ES 1011+496, 1ES 0229+200, PG 1553+113, …

AGN physics and fundamental physics studies
MWL strategy!

EXCITING NEWS!

- MAGIC follow-up of EHE **neutrino event** IceCube-170922A
- Fermi-LAT detected **enhanced gamma-ray emission from the blazar TXS 0506+056** located 6 arcmin from EHE 170922A
- MAGIC observations during 12 h from September 28th to October 3rd
- MAGIC detection at > 5 sigma C.L. above 100 GeV

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)

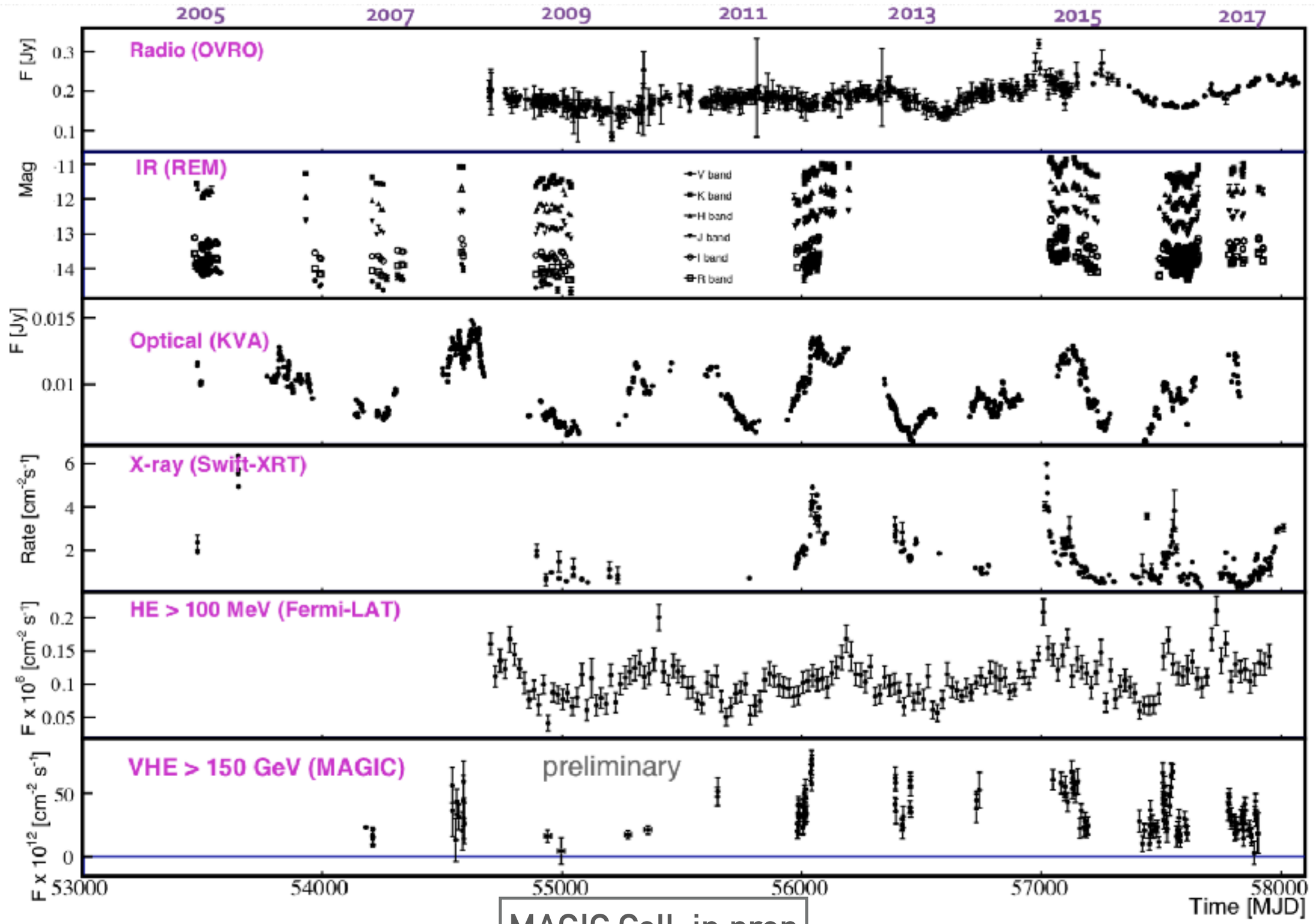
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

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

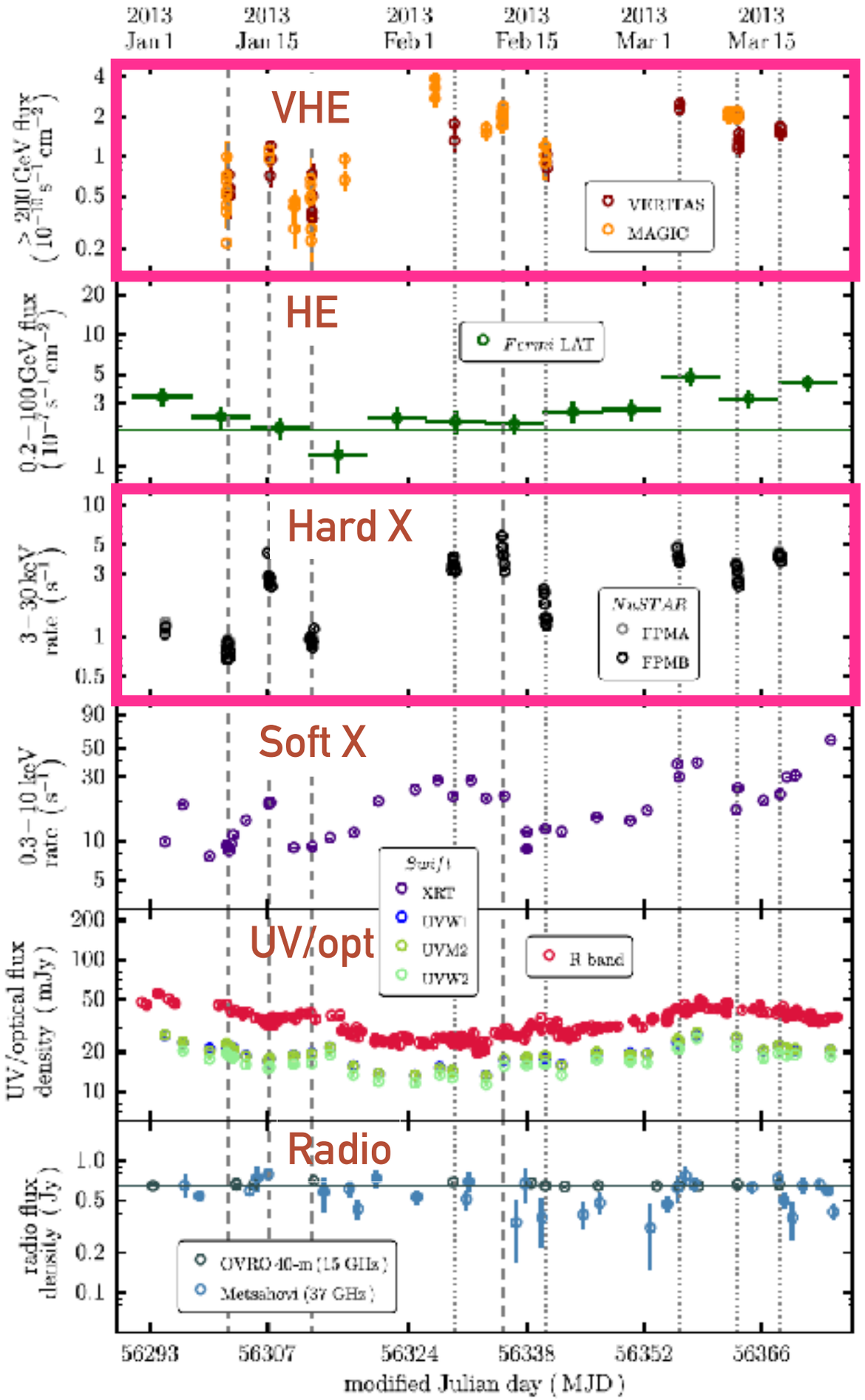
Tweet Recommend 448

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.

A CASE STUDY: PG 1553+113 QUASI PERIODIC OSCILLATIONS



MAGIC Coll. in prep



MKN 421 – MWL CAMPAIGN IN 2013

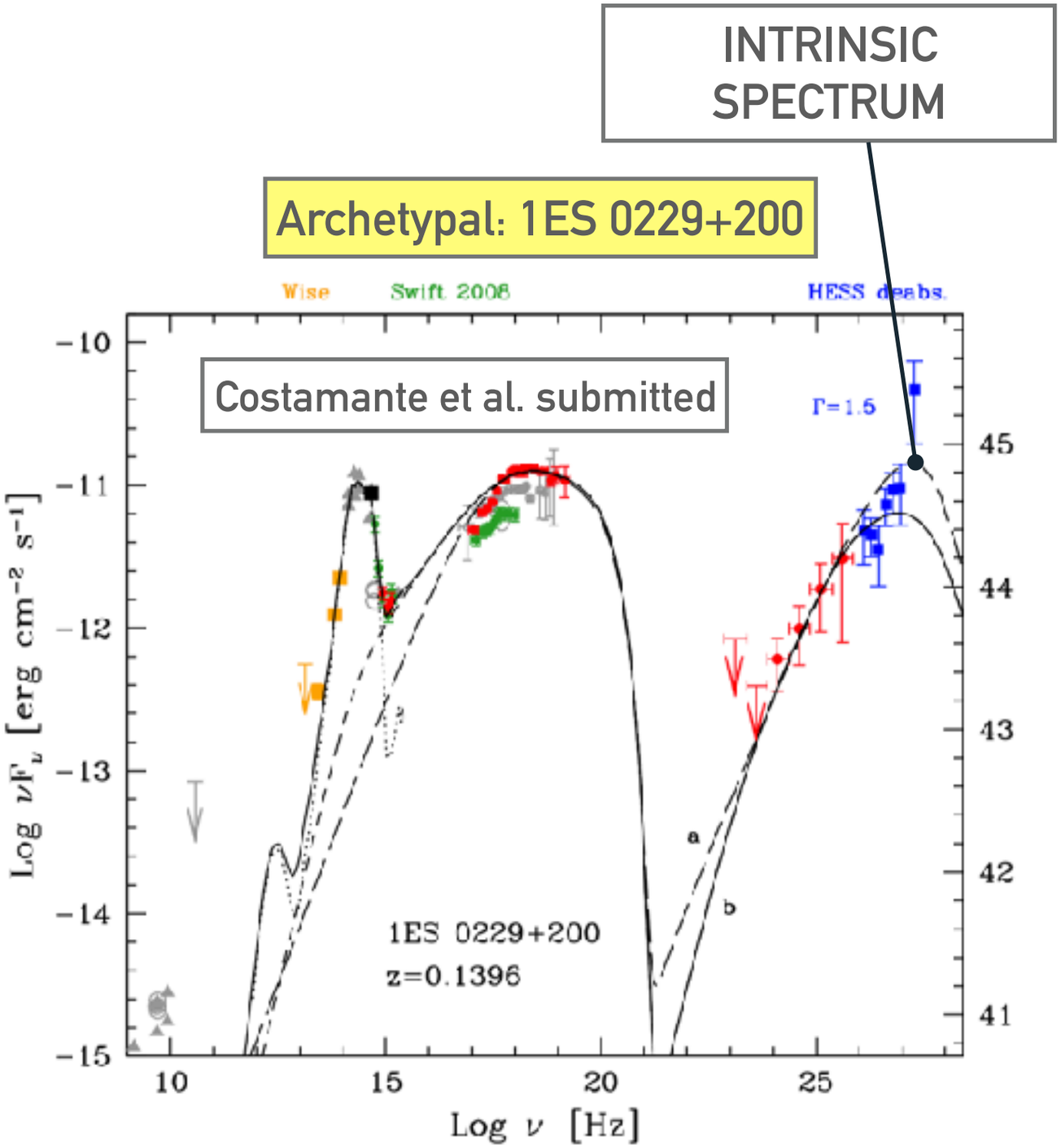
- Mkn 421 MAGIC+ VERITAS
- Hard X-rays: *NuSTAR*
- Monitoring during a low state: shift of the synchrotron peak
- LBL - HBL could be temporary characteristics

MWL data: suggest that there are multiple compact regions contributing to the broadband emission of Mrk 421 during low-activity states

MAGIC and VERITAS Coll., ApJ, 834, 1, 2, 2017

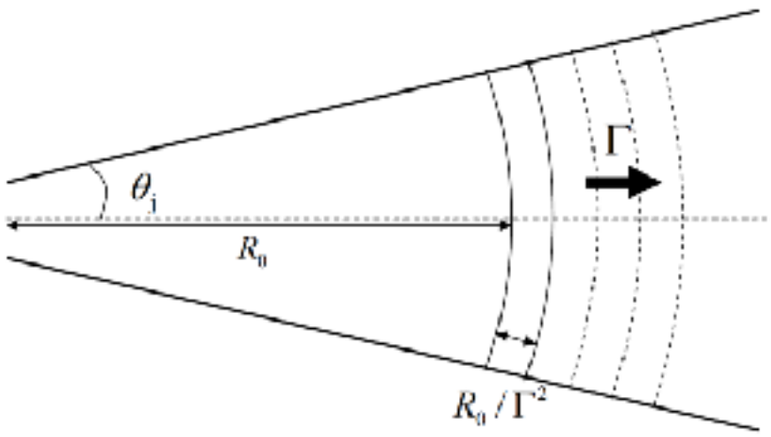
EXTREME BLAZARS

- A *new emerging population* of TeV emitting blazars (Bonnoli et al. 2015)
- The SED peaks are located at extremely high energies
  - Faint in *Fermi*/LAT
  - Hard X-rays are essential
- Hard spectrum: ideal probes for cosmological studies



EXTREME BLAZARS WITH MAGIC

- Simultaneous MAGIC and XRT observations of 9 objects
- Modelled with SSC model (1D steady model, Asano et al. 2014)



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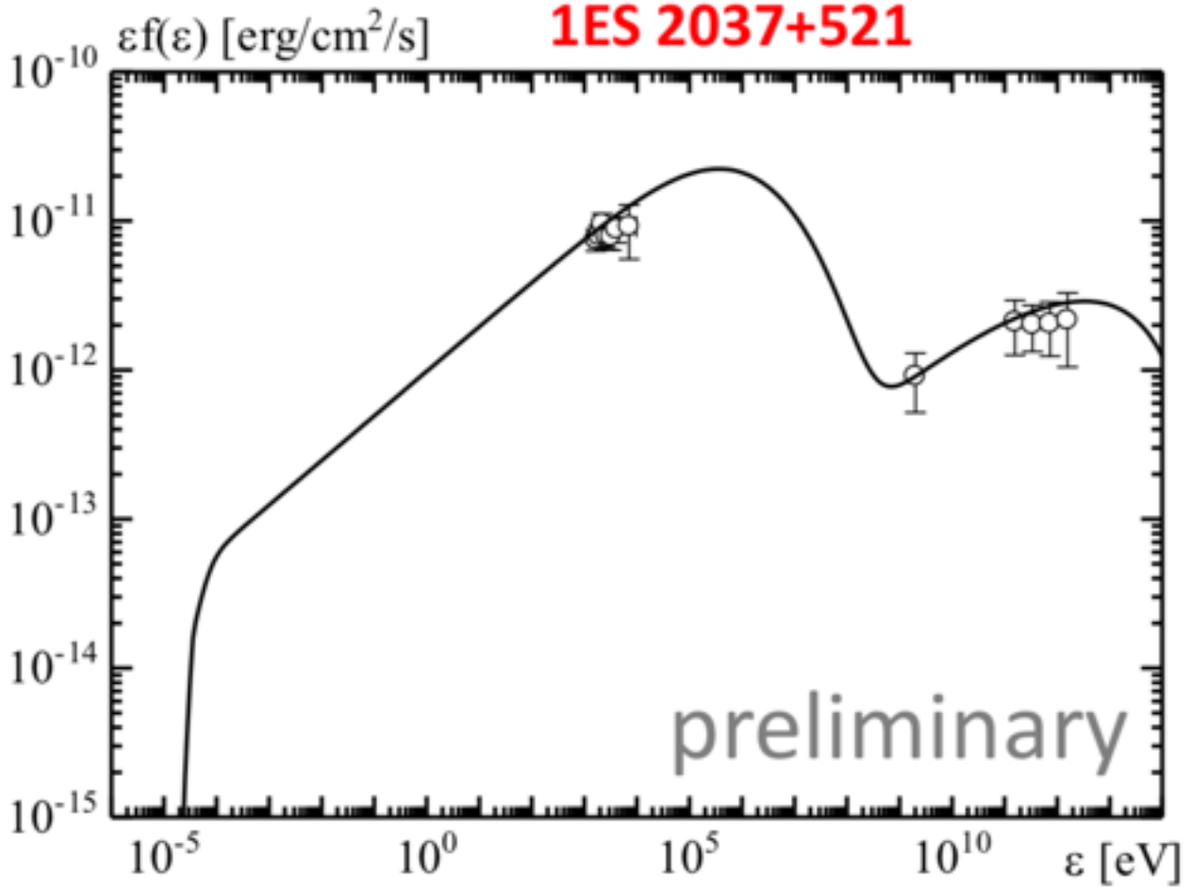


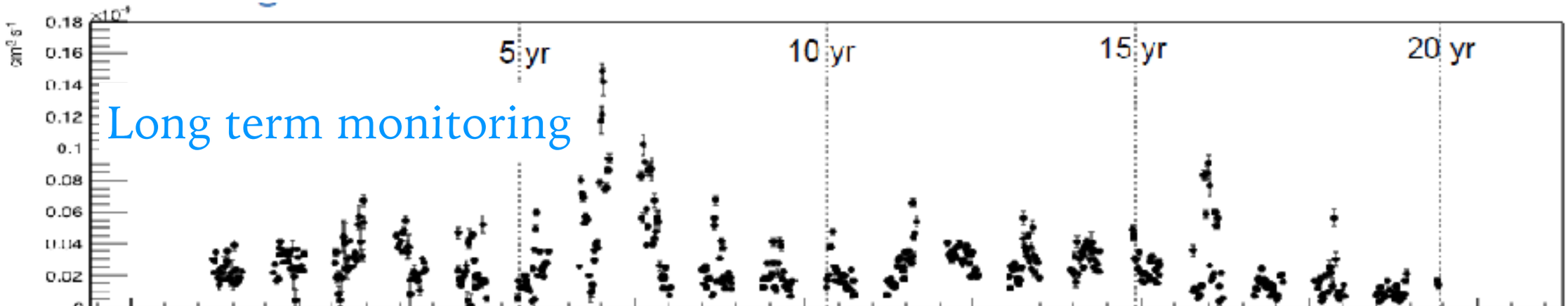
Extremely low magnetisation required

In collaboration with K. Asano

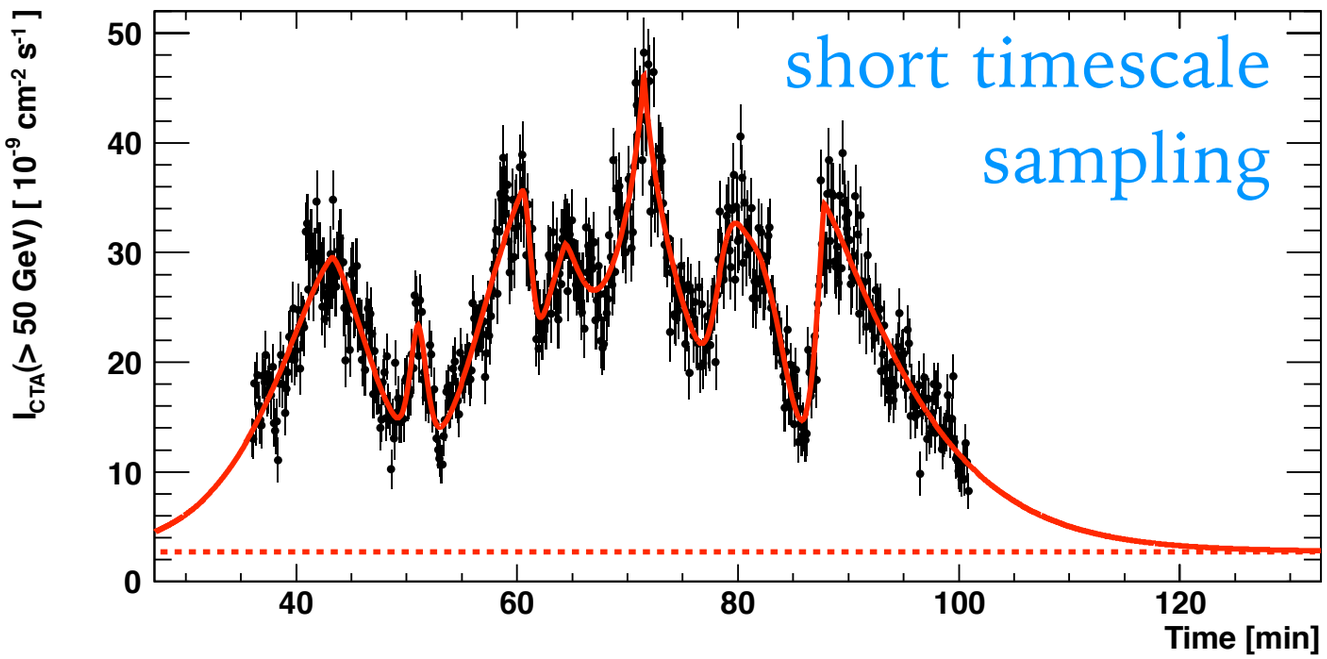
CTA PERSPECTIVES ON BLAZARS

E. Lindfors

- LC with unprecedented sensitivity:



from A. Zech



Variability from longest timescales:
- Duty Cycle
- (quasi) periodicities
- breaks in the power spectra

to shortest:
- size (location, nature) of the emission region
- acceleration and cooling mechanisms

H. Sol et al, for the CTA Consortium, Astroparticle Physics, 43 (2013), 215-240

MWL IN CTA ERA

E. Lindfors

- **Long term monitoring program:** Well sampled, simultaneous light curves at different wavelengths (X-ray, optical, radio) are necessary to allow us to search for correlations and time-lags between different bands. ***Optical photometry and polarimetry from dedicated telescope.***

- **AGN flares:** MWL coverage necessary, optical photometry and polarimetry from dedicated telescope. The dedicated optical telescopes will provide source of alerts triggered by high flux states and changes in polarization.

- **High quality spectra:** dedicated optical data will be very useful to e.g. compare the state of source vs. archival data.

SUMMARY: AGN PHYSICS

- The last few years were very exciting for the MAGIC Collaboration!
  - **Radio Galaxies**: long-term MWL monitoring of M87.
  - **FSRQs**: only few objects known, up to redshift ~1 (PKS 1441+25). Thanks to a strong cooperation with *Fermi*-LAT, the delayed emission from a gravitationally lensed blazar was discovered (B0218+357). MWL flare of PKS 1510-089, associated to the ejection of a new radio component in the jet.
  - **BL Lac**: new sources every year (mainly through ToO observations) and long-term monitoring of known sources (e.g. Mkn 421, PG 1553+113): test the emission model and reveals new features in blazars. Extreme blazars (1ES 2037+521) under study. In September 2017, discovery of a VHE gamma-ray emission from a flaring blazar (TXS 0506+056) in the region of a EHE neutrino detected by IceCube.

Multi-wavelength / multi messenger approach is essential

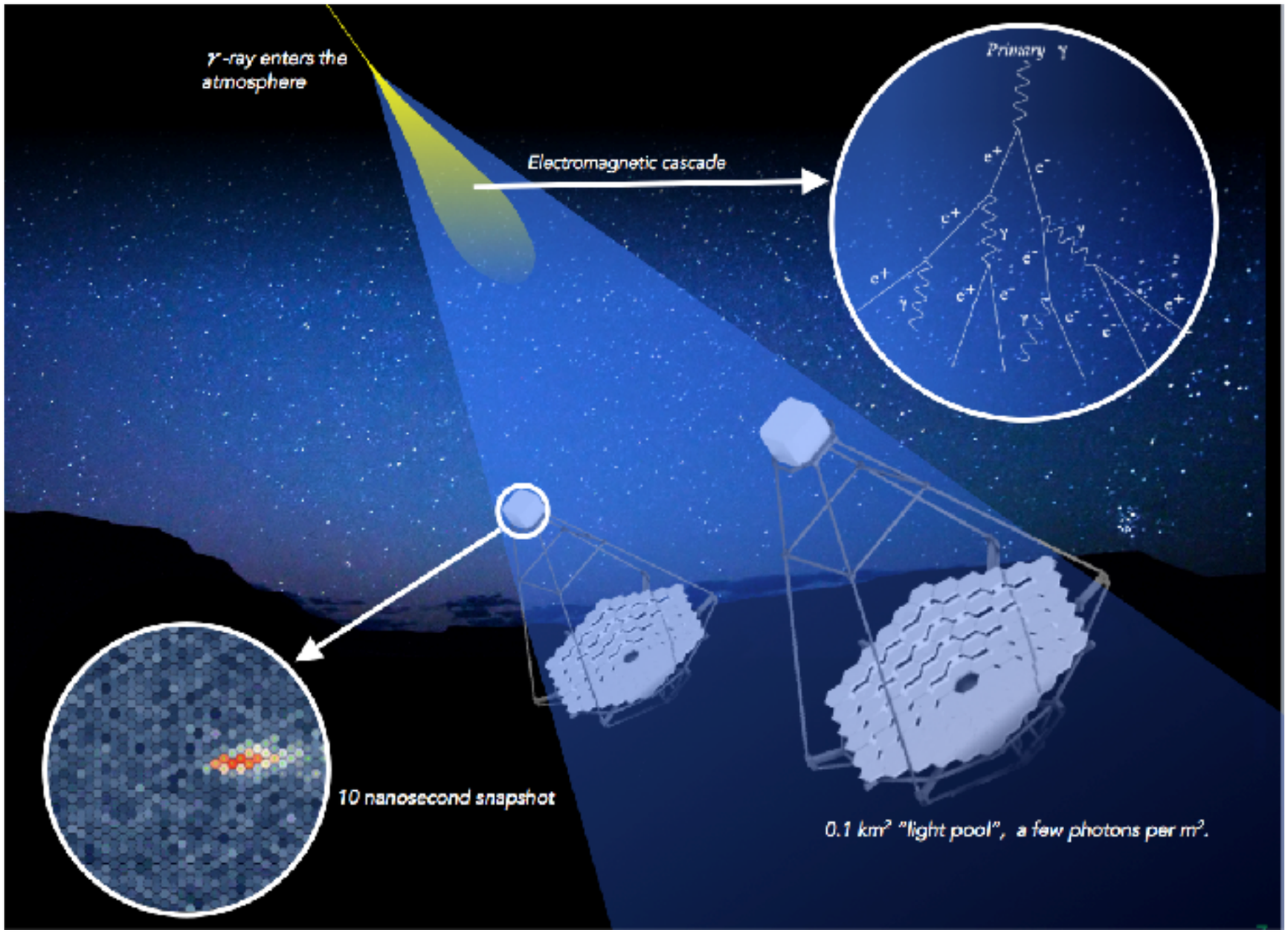
TOWARDS A VERY BRIGHT FUTURE

- MWL approach is essential
- Multi-messenger era has just started!
- CTA era is coming

TOWARDS A VERY BRIGHT FUTURE

BACKUP

IMAGING ATMOSPHERIC CHERENKOV TELESCOPE TECHNIQUE

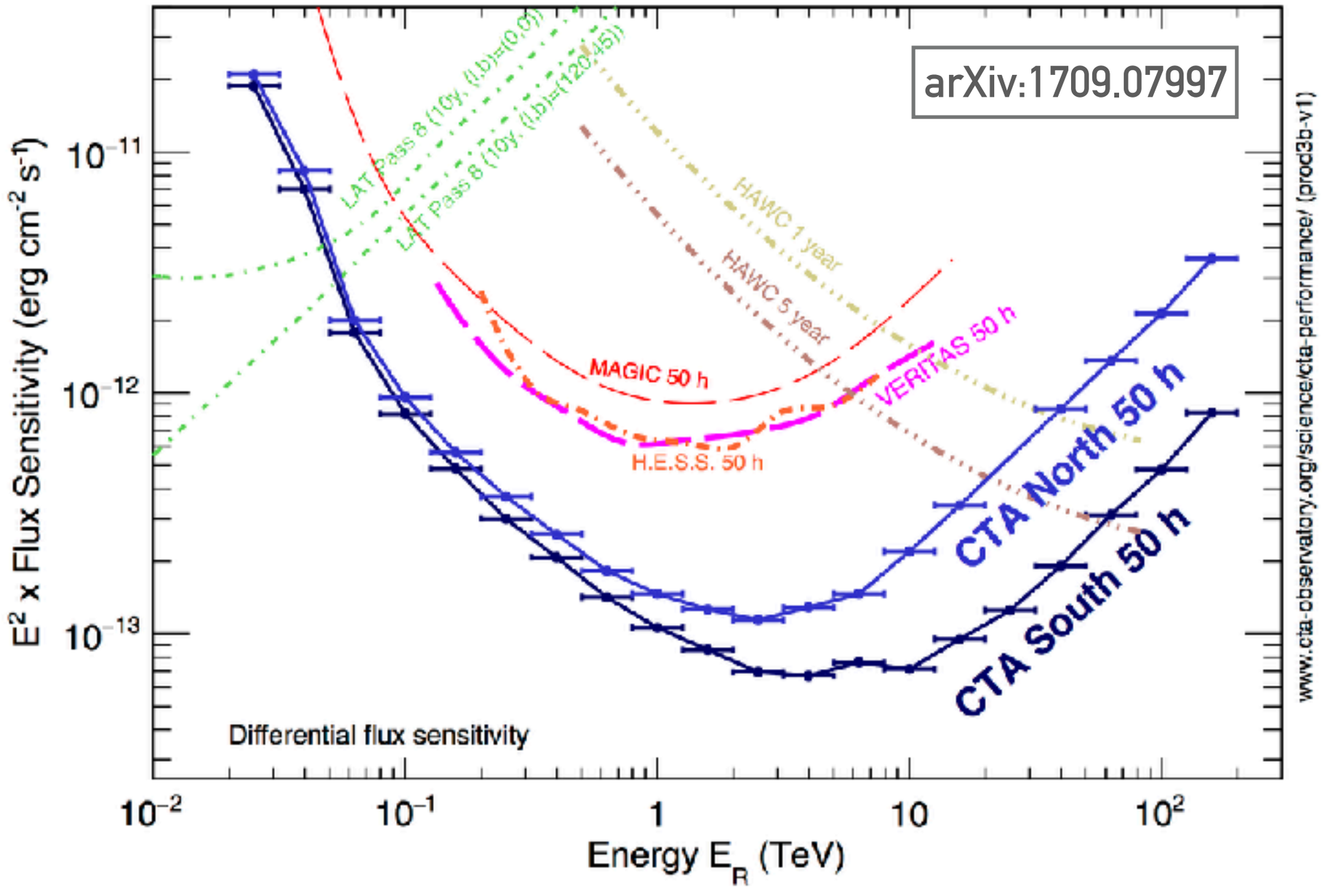


Main source of background: events created by hadronic showers (mainly cosmic ray protons)

Field of View: up to 10 degrees —> pointing to targets

VHE gamma rays from tens of GeV

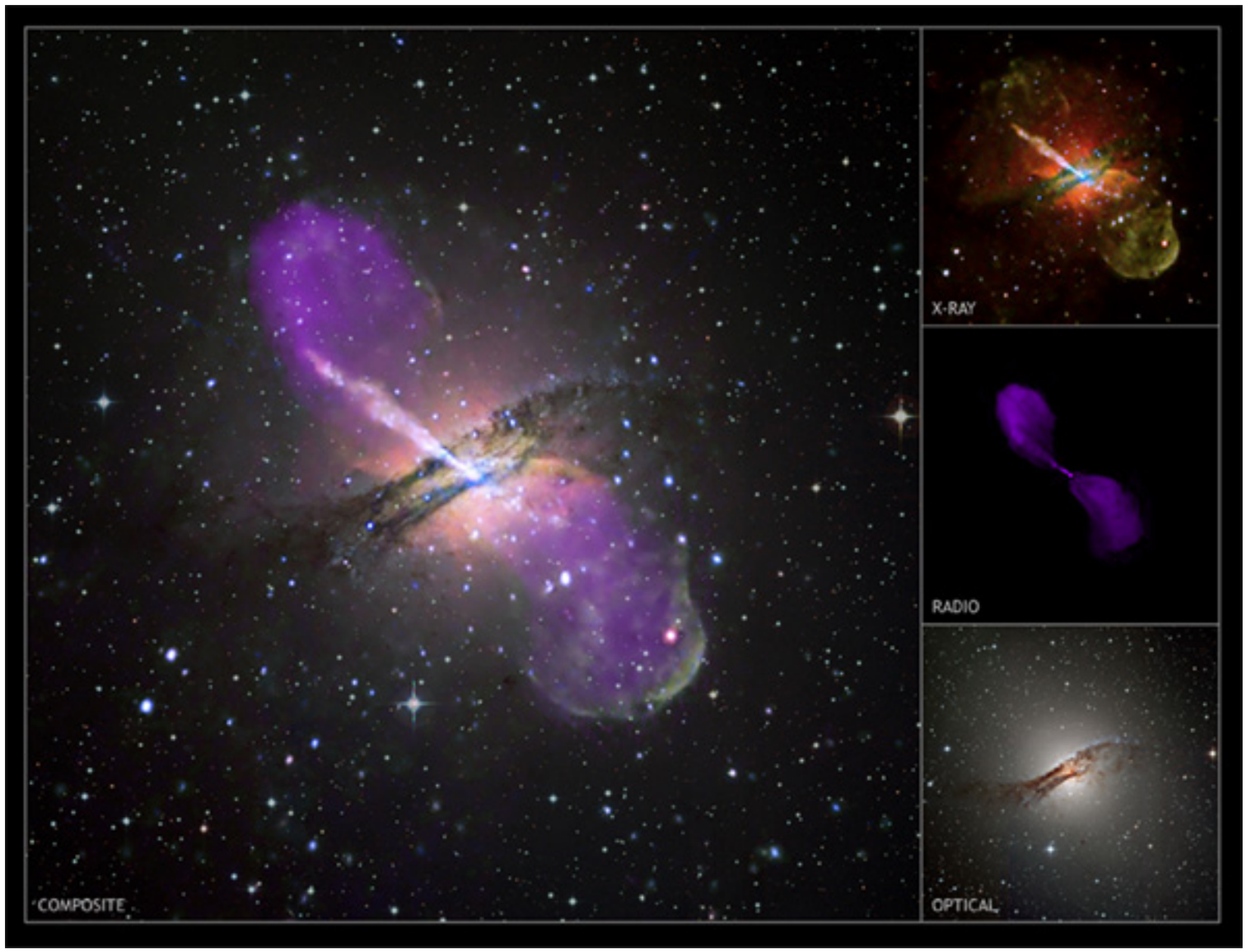
IACTs SENSITIVITY

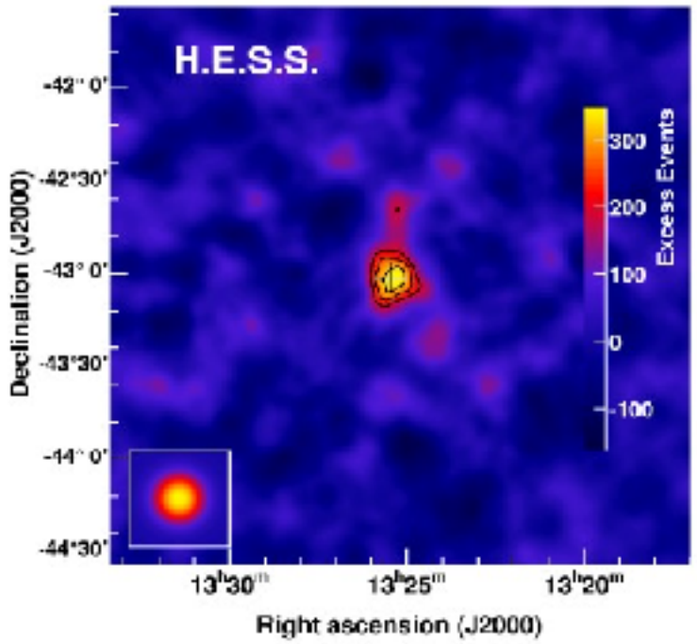


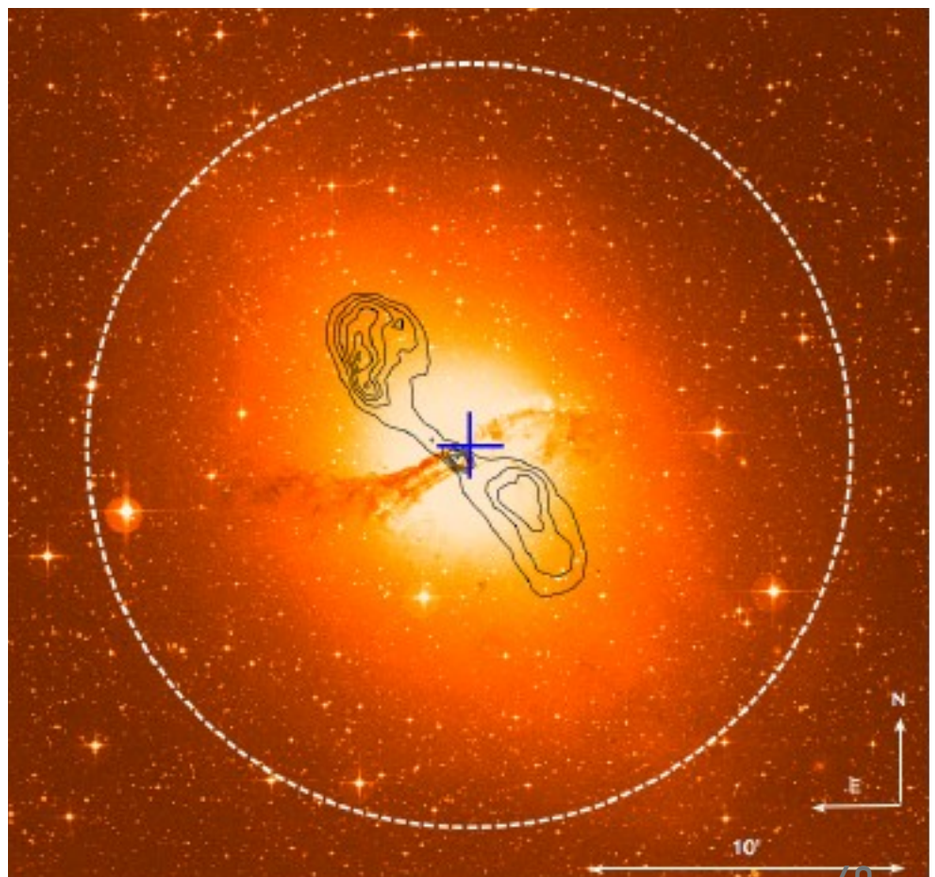
Current MAGIC sensitivity above 220 GeV: 0.66 % Crab Nebula flux in 50 hours

IACTs ANGULAR RESOLUTION

Centaurus A





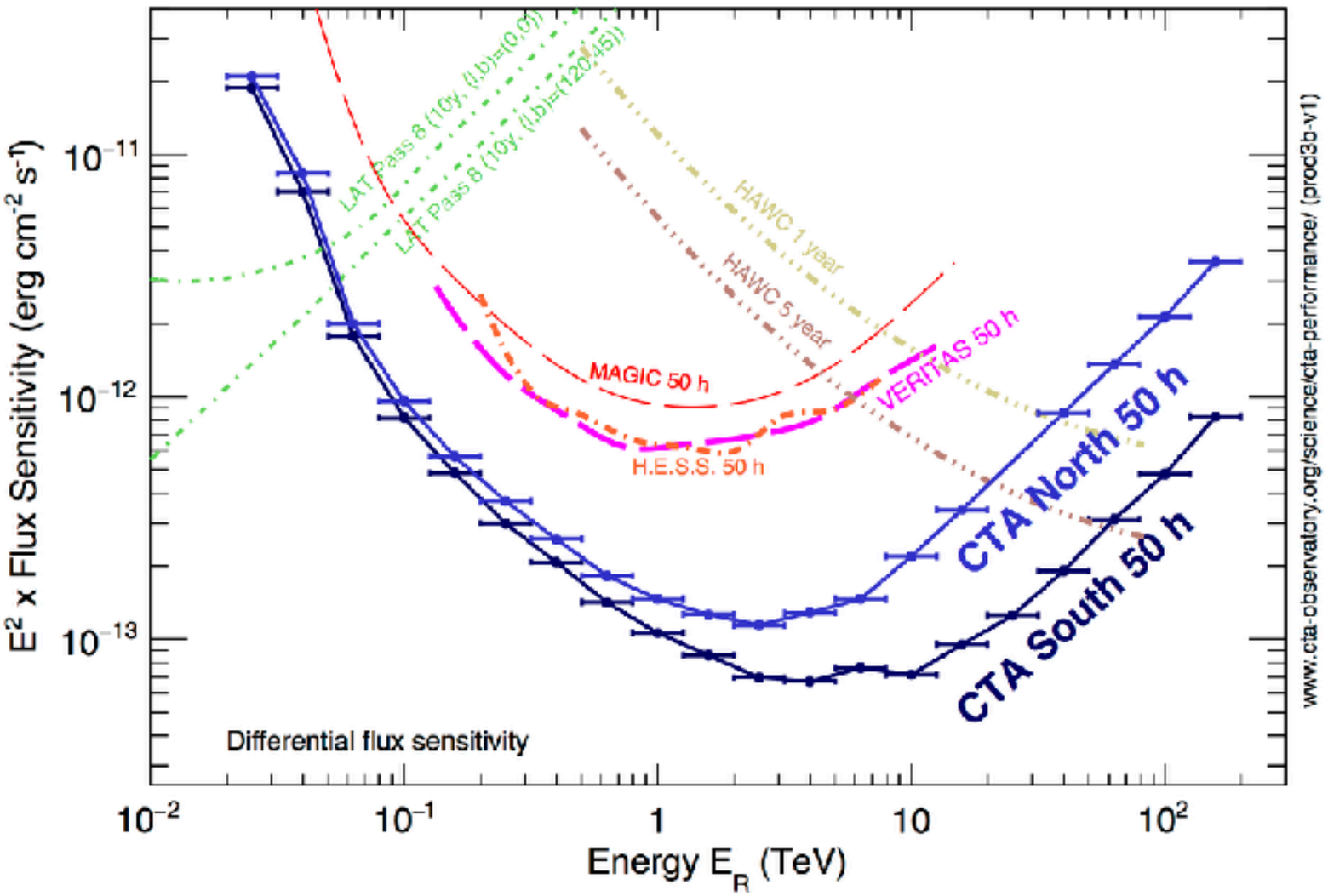


H.E.S.S. Coll. 2009

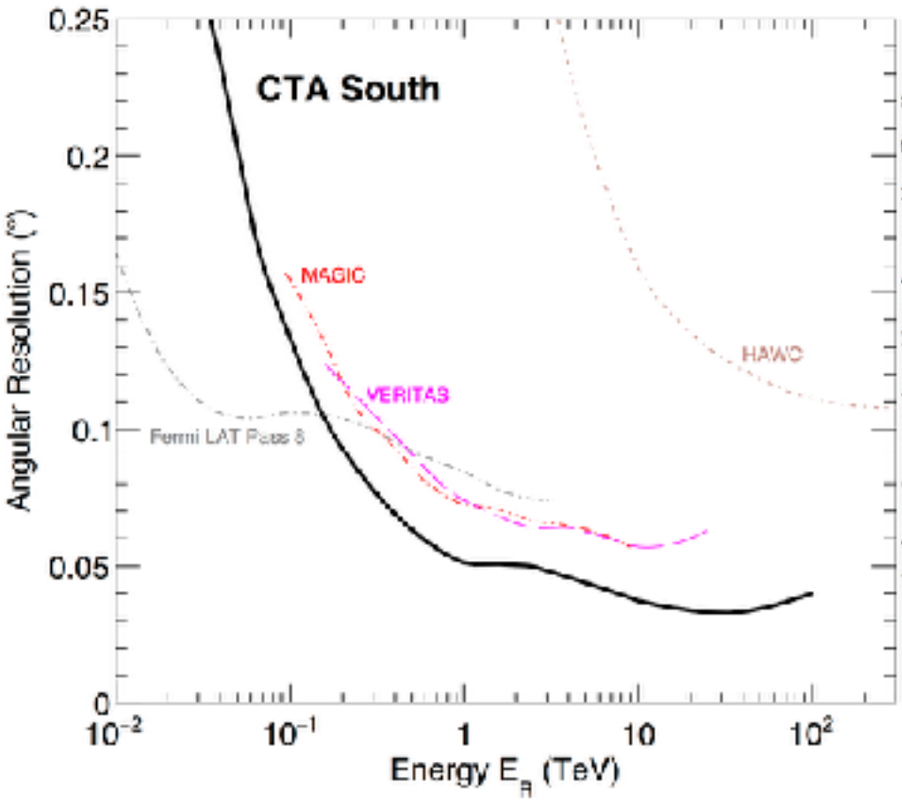
Resolution ~ 0.1 deg

CTA EXPECTED PERFORMANCES

A factor 5 to 20 improvement in sensitivity

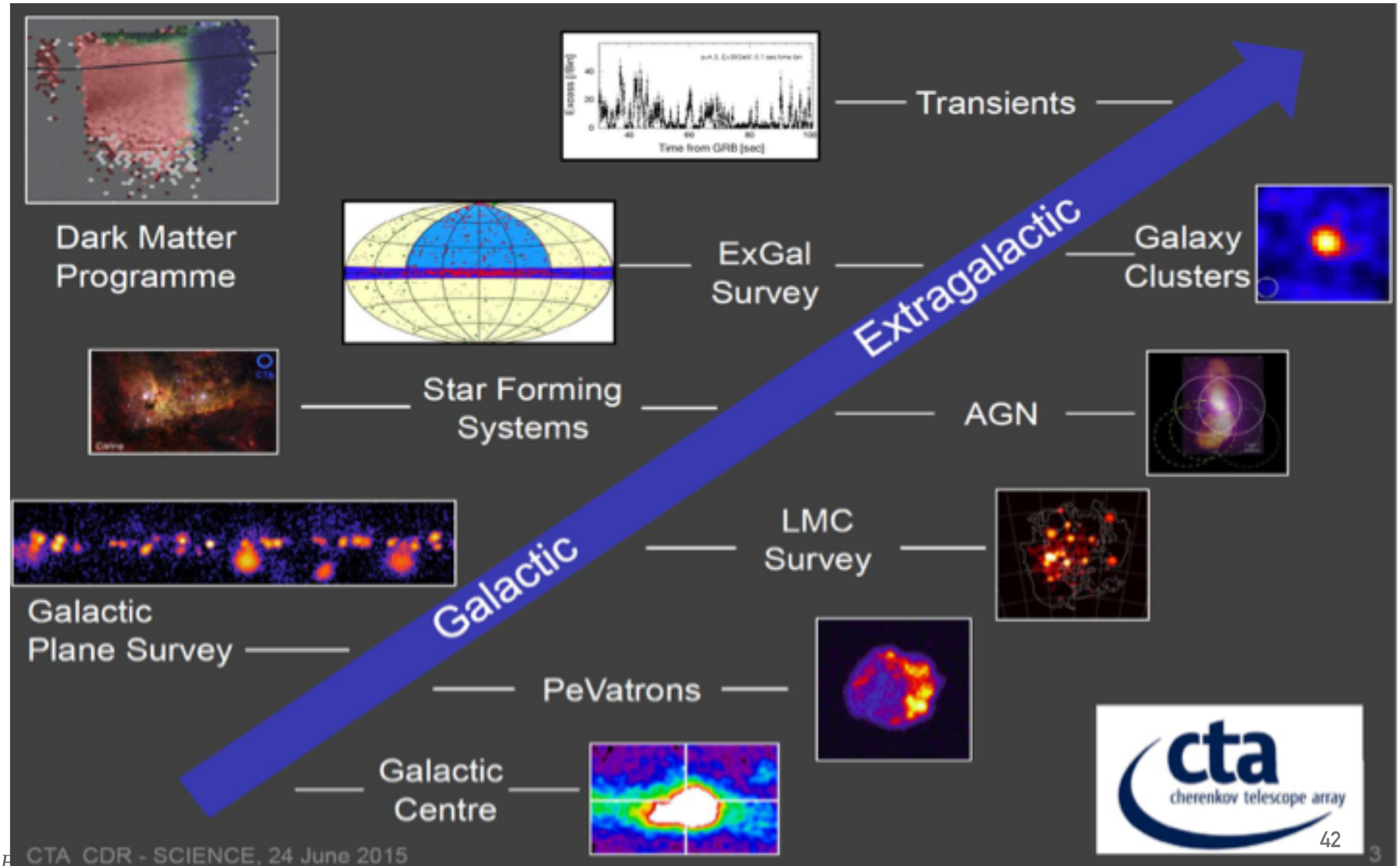


Angular resolution of 0.05 deg at 1 TeV



arXiv:1709.07997

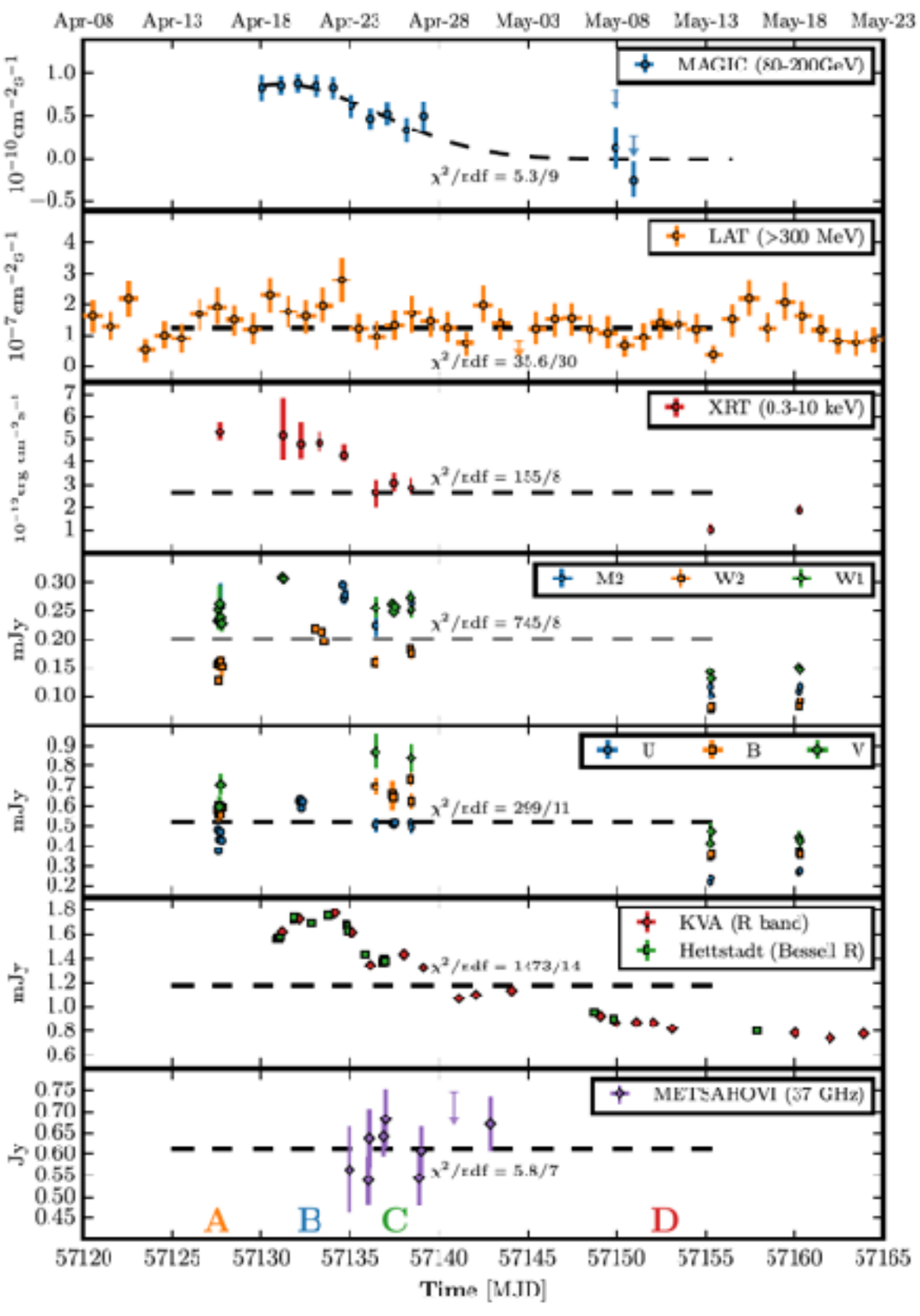
CTA KEY SCIENCE



PKS 1441+25

- April 2015: the FSRQ PKS 1441+25 (**z=0.939**) is active in **optical, X, and gamma rays**
- **MAGIC** observations **triggered** —> discovery of VHE signal!
- VERITAS observation triggered —> detection!

Multi-band light curve

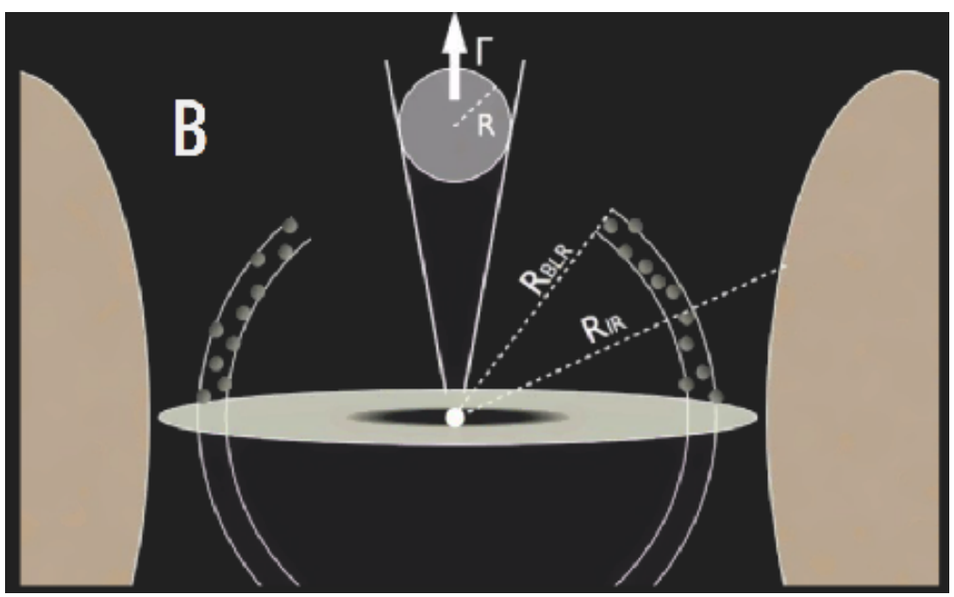


MAGIC Coll, ApJL, 815, 2, L23, 2015

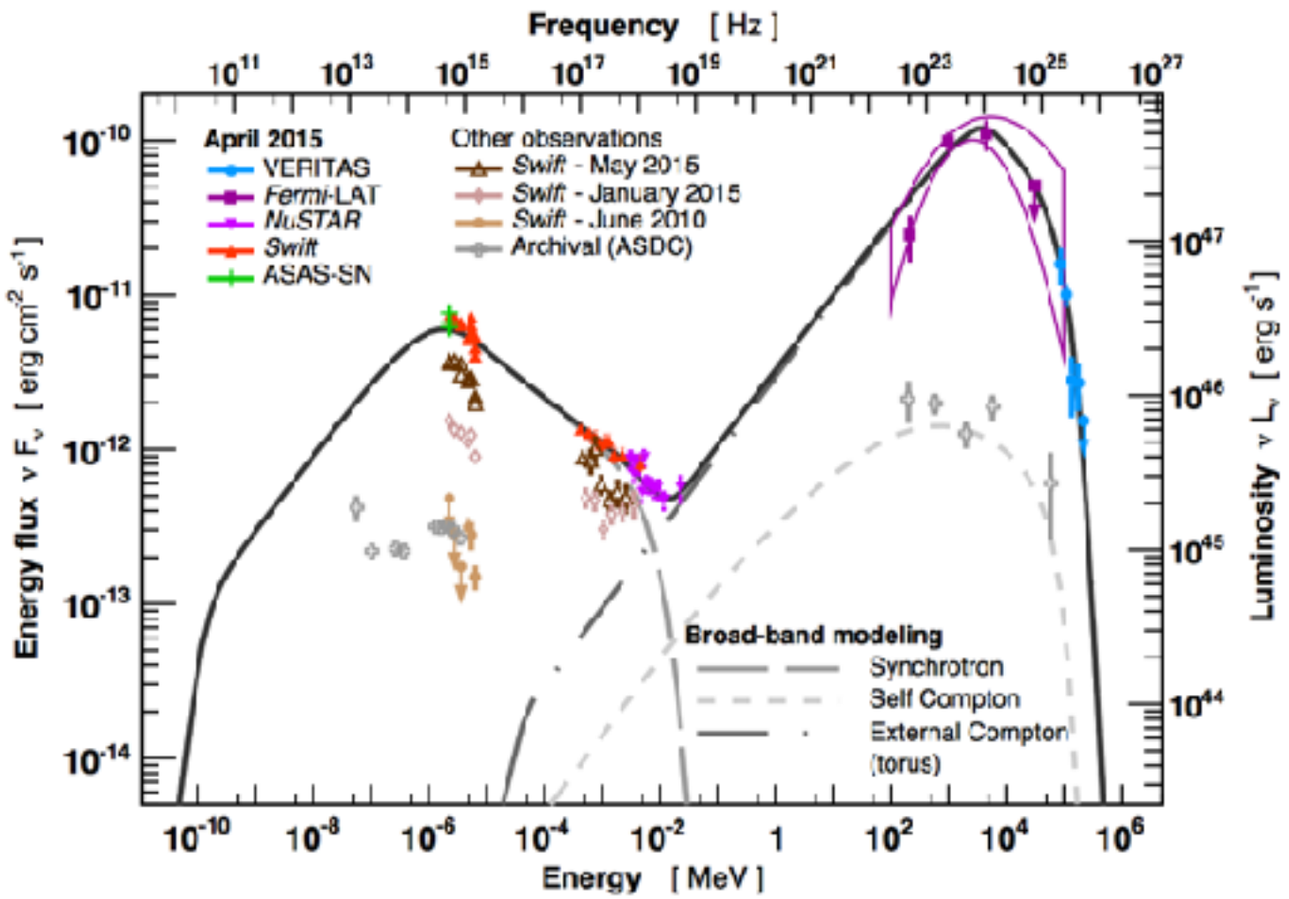
PKS 1441+25

- Variation timescale ~ days
- Variability in all bands
- High energy reached by the electrons

Emitting region constrained outside the BLR



VERITAS Coll, ApJL, 815, 2, L22, 2015



Model: synchrotron emission + external Compton of IR photons from the torus