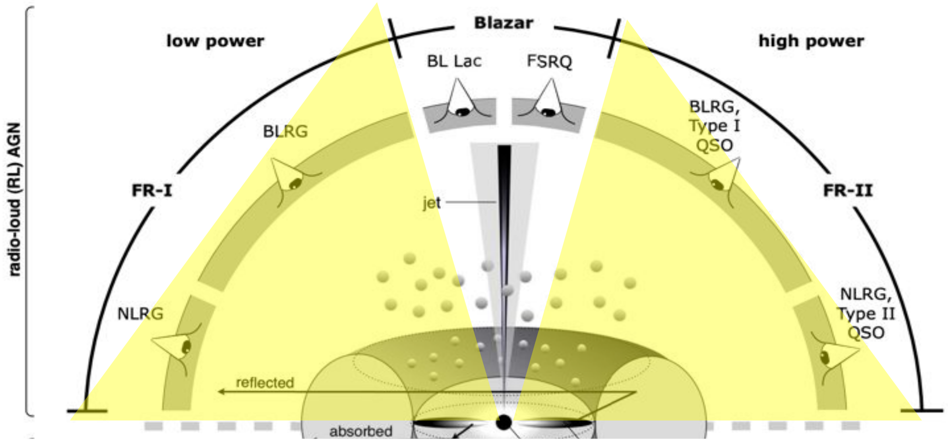
# The GeV to TeV View of Misaligned AGN

ELEONORA TORRESI, PAOLA GRANDI (INAF-OAS)

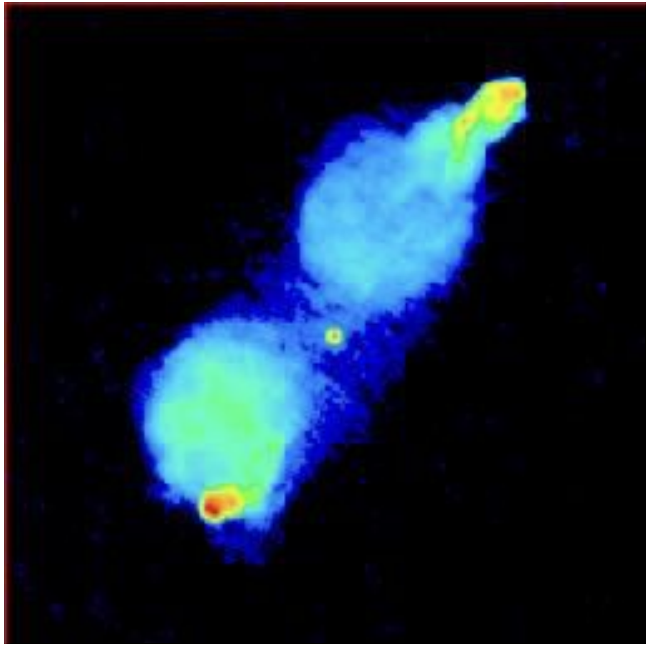
**OAS Very-High Energy Meeting, 9 June 2022**

# MISALIGNED AGN

- Radio galaxies and steep spectrum radio quasars;
- Resolved and possibly symmetrical structures in radio maps;
- Radio spectral indices $\alpha_r > 0.5$

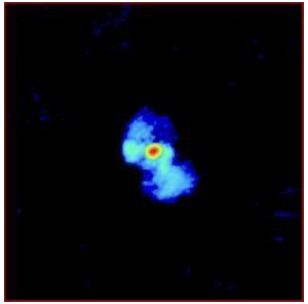



Beckmann & Shrader 2013

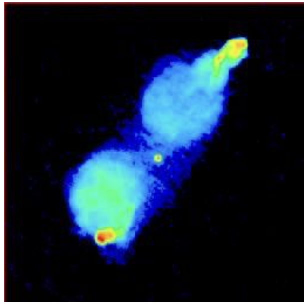


RADIO

# FRI



# FRII



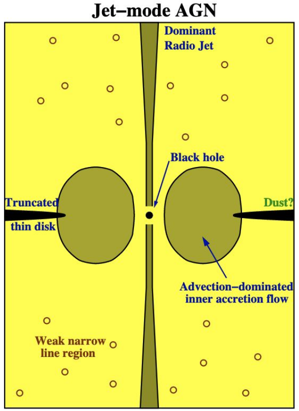
$P_{178MHz}=10^{25}$ W Hz$^{-1}$ sr$^{-1}$

Fanaroff & Riley (1974)

OPTICAL

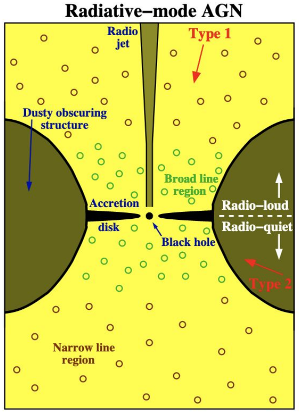
# LERG

low-excitation radio galaxies




# HERG

high-excitation radio galaxies

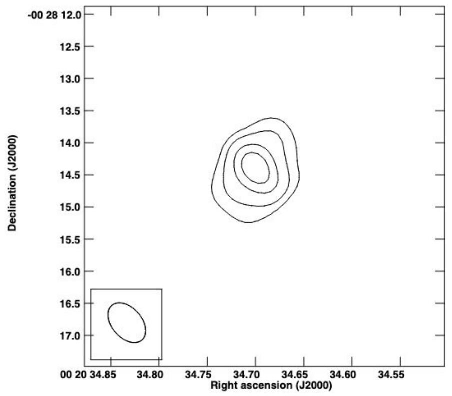


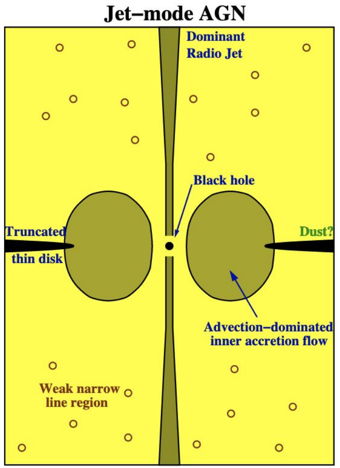

Laing+ 1994; Jackson&Rawlings 1997; Buttiglione+2009

Heckman & Best 2014

# FR0

- FR0 are **compact** radio sources: they lack the radio extension (but they are not young) Baldi & Capetti 2009, 2015; Ghisellini 2011
- FR0 represent the bulk of the RL AGN population in the local Universe (i.e. 80% of the sources appears unresolved at the 5" FIRST resolution) Baldi et al. 2018
- FR0 are similar to FRI in the optical and X-ray properties Baldi & Capetti 2009; Torresi et al. 2018
- The deficit of the extended radio emission has been not explained yet...
  - FR0 could be short-lived and/or recurrent episodes of AGN activity, not long enough for radio jets to develop at large scales (Sadler+14; Sadler16)
  - FR0 produce slow jets experiencing instabilities and entrainment in the dense interstellar medium of the host galaxy corona that causes their premature disruption (Bodo+2013; Baldi+15; Baldi+18)



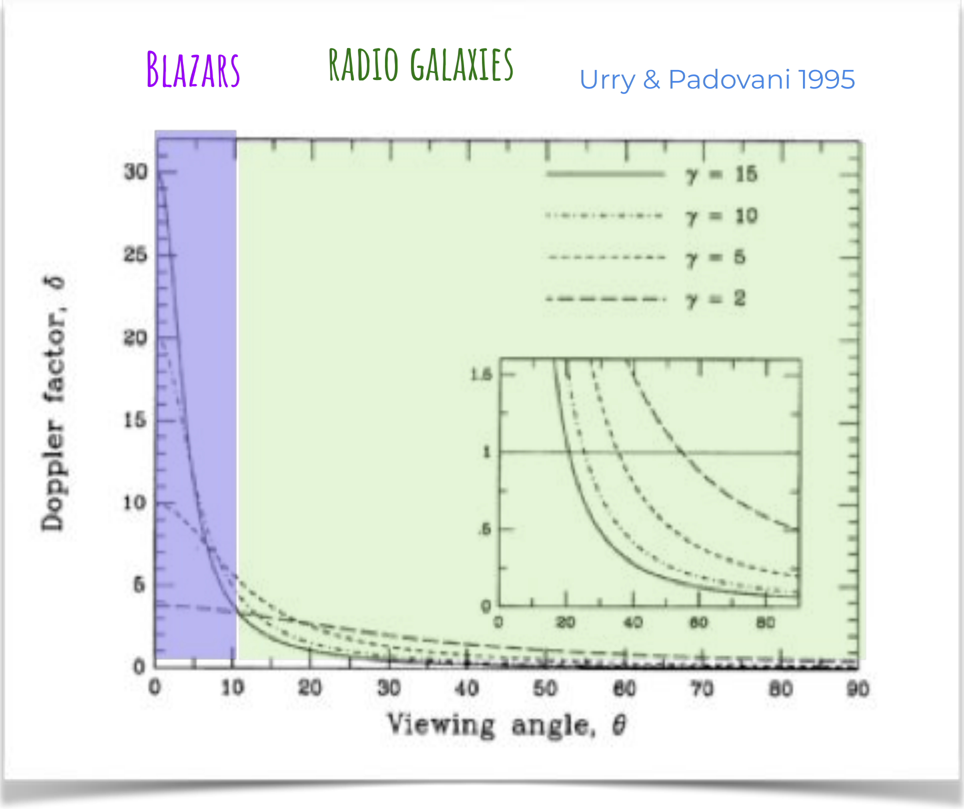

A FR0, Tol1326-379, detected in γ-rays Grandi et al. 2016

The large jet inclination angle disfavors the detection of MAGN at high energies (> 100 MeV)

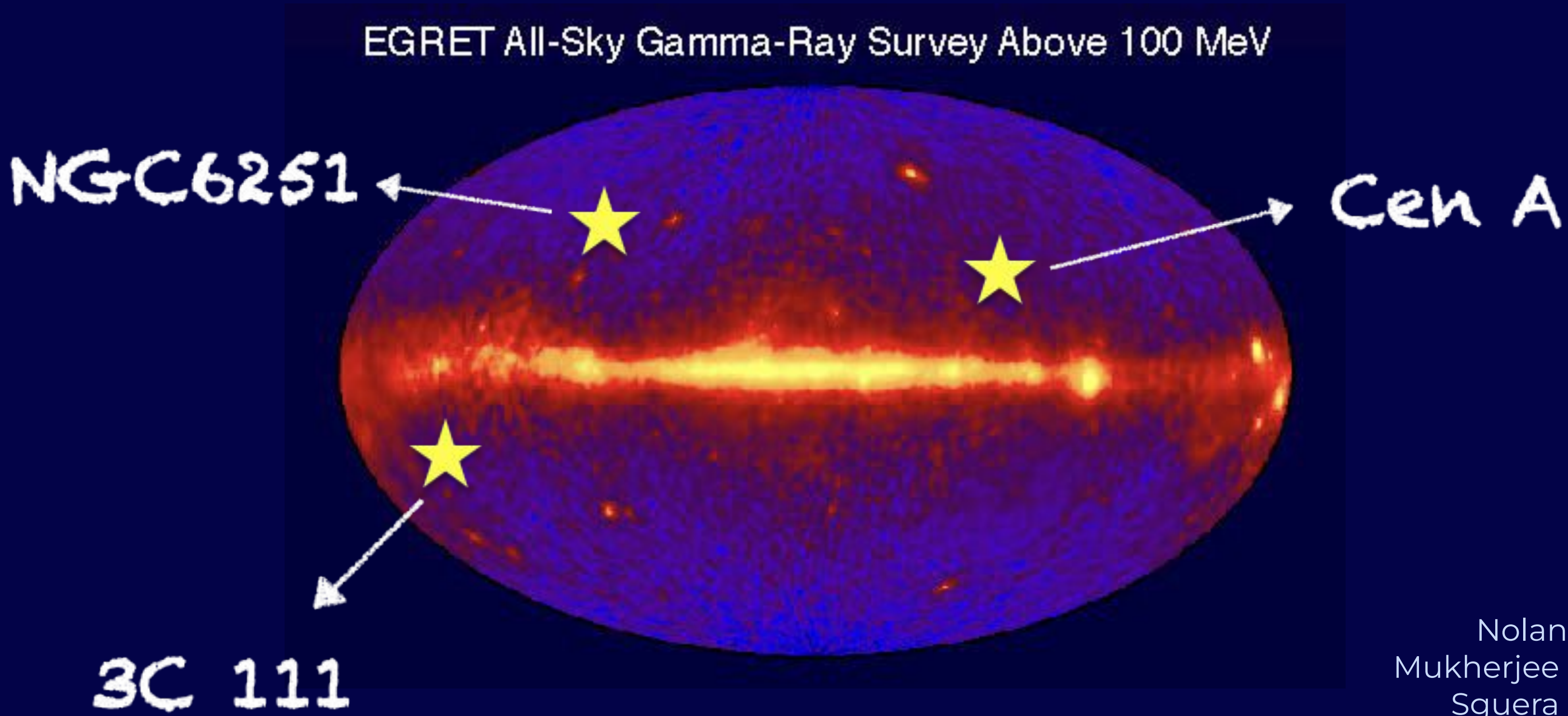
$$\delta = 1/\gamma(1-\beta \cos\theta)$$

$\gamma=(1-\beta^2)^{-1/2}$ = Lorentz factor

$\beta$ =v/c=bulk velocity



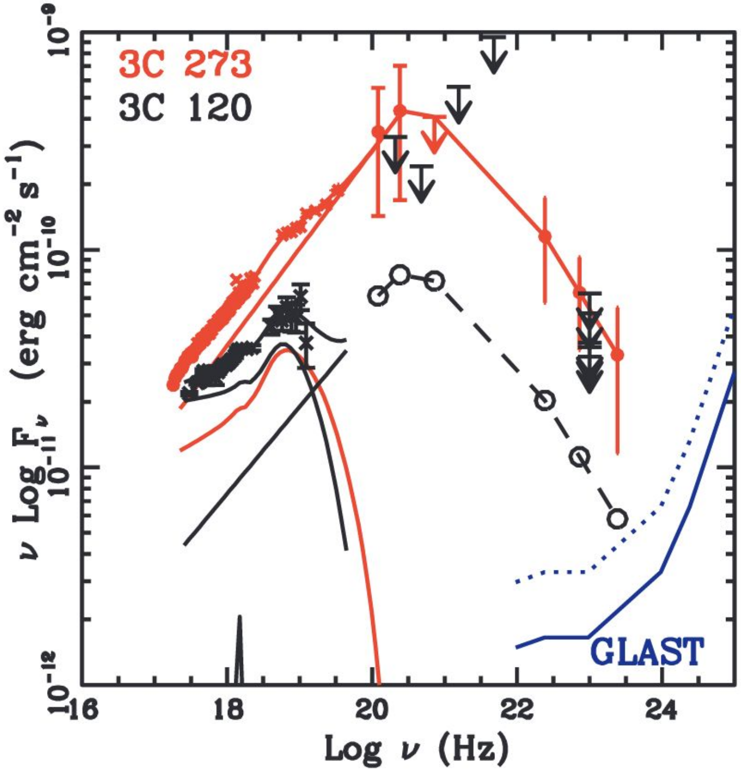
# ONLY 3 RADIO GALAXIES DETECTED BY EGRET




Nolan et al. 1996
Mukherjee et al. 2002
Sguera et al. 2005
Hartmann et al. 2008

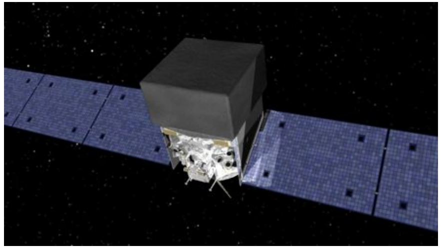
Before Fermi, some FRI and a few FRII were suggested to have fluxes above the LAT sensitivity threshold

(Stawarz+2003,2006; Ghisellini+2005; Grandi & Palumbo 2007)




Grandi & Palumbo 2007

# MAGN are gamma-ray emitters



After 15 months of survey Fermi/LAT observed 11 MAGN

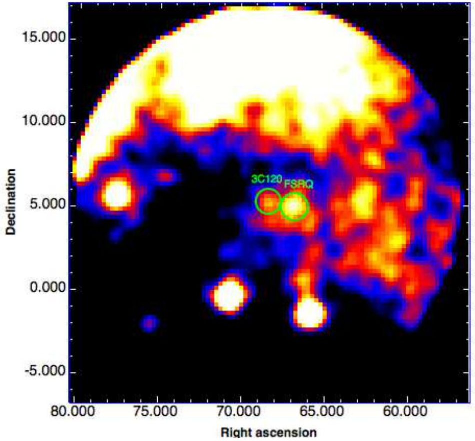
| Object | TS | Γ | Flux[a] (> 100 MeV) | *Log Lum*[b] (100 MeV-10 GeV) |
|---|---|---|---|---|
| 3C 78/NGC 1218 | 35 | 1.95±0.14 | 4.7 ±1.8 | 42.84 ±0.38 |
| 3C 84/NGC 1275 | 4802 | 2.13± 0.02 | 222 ±8 | 44.00 ±0.04 |
| 3C 111 | 34 | 2.6 ±0.2 | 40 ±8[c] | 44.00 ±0.27 |
| 3C 120 | 32 | 2.7±0.3 | 29 ±0.17 | 43.43 ±0.58 |
| PKS 0625-354[d] | 97 | 2.1±0.2 | 5 ±1 | 43.7±2.5 |
| 3C 207 | 79 | 2.5 ±0.1 | 23.7 ±3.9 | 46.44 ±0.16 |
| PKS 0943-76 | 65 | 2.83 ± 0.16 | 55 ±12 | 45.71±0.22 |
| M87/3C 274 | 194 | 2.21 ± 0.14 | 23.9 ± 6.2 | 41.67±0.26 |
| CENA | 1010 | 2.75± 0.04 | 214 ±12 | 41.13±0.06 |
| NGC 6251 | 143 | 2.52 ±0.12 | 36 ±8 | 43.30± 0.22 |
| 3C 380 | 95 | 2.5 ±0.3 | 31 ±18 | 46.57± 0.59 |

[a] - $\times 10^{-9}$ Phot $cm^{-2}$ $s^{-1}$

[b] - erg $s^{-1}$

[c] - Flux was estimated keeping the spectral slope fixed

[d] - Likelihood analysis limited to the 300 MeV-100 GeV. Flux (> 300 MeV); Lum extrapolated down to 100 MeV



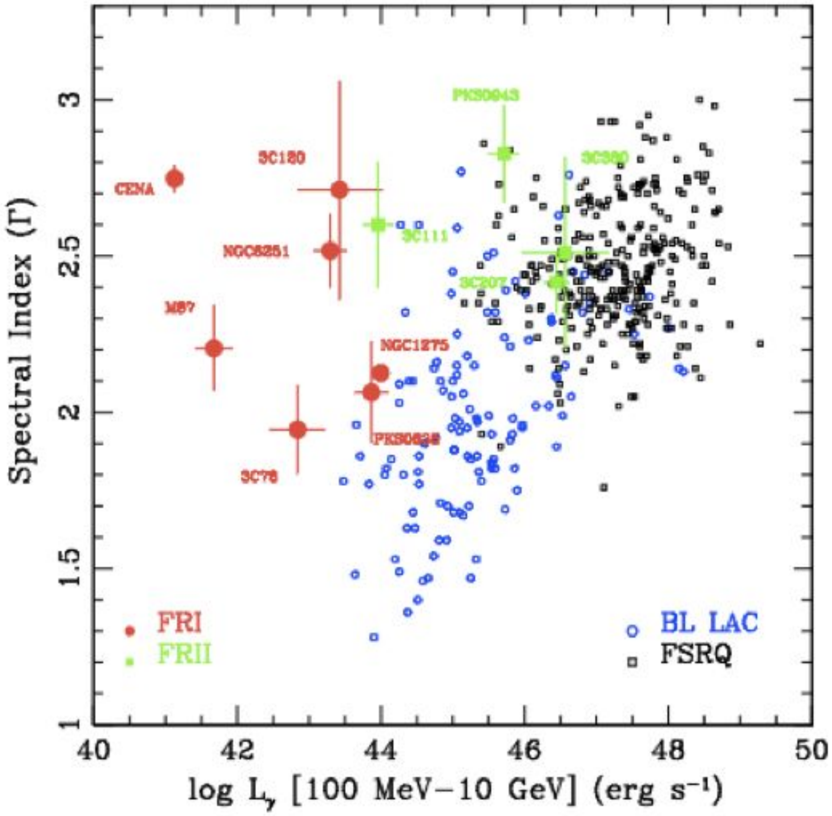

Abdo et al. 2010

Contact authors: P. Grandi, G. Malaguti, G. Tosti, C. Monte

MAGN are generally **faint** and **steep** in the GeV band

***-> de-boosted version of blazars***

15 MONTHS



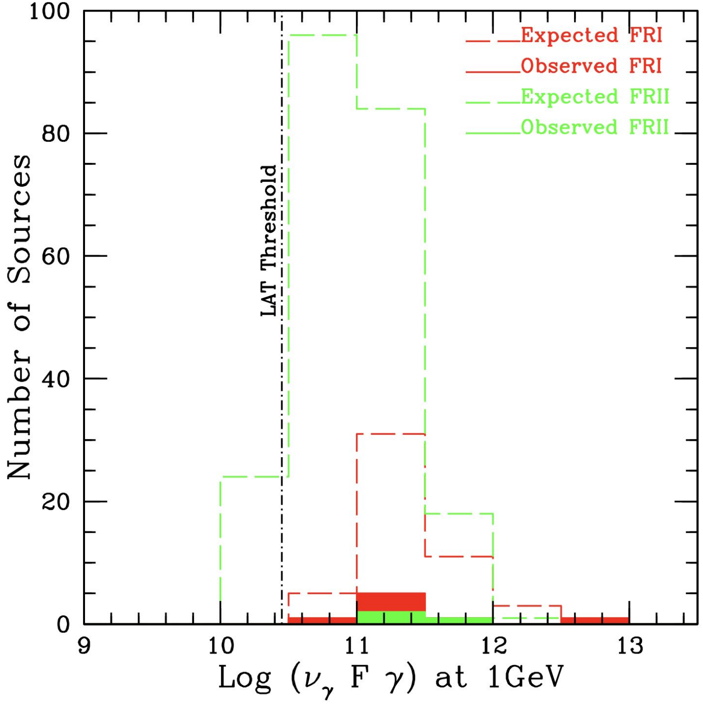

$F_{>0.1GeV} \sim 10^{-8}$ ph cm$^{-2}$s$^{-1}$

$\Gamma > 2.4$

Abdo et al. 2010

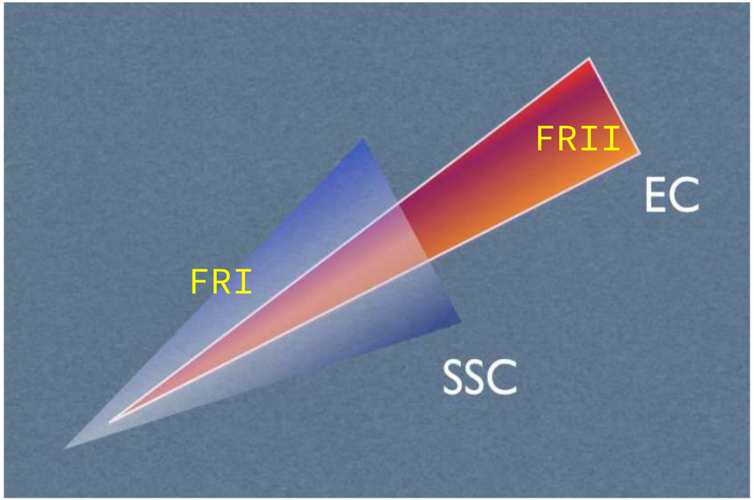
# FERMI/LAT PREFERENTIALLY DETECTS FRI

**Distance/faintness effects** cannot explain the scarcity of FRII radio galaxies in the GeV sky

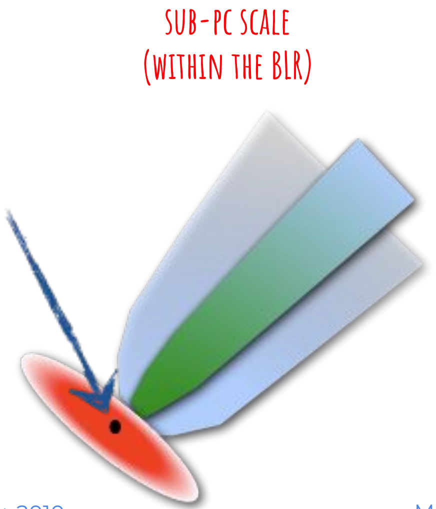



Grandi & Torresi 2012

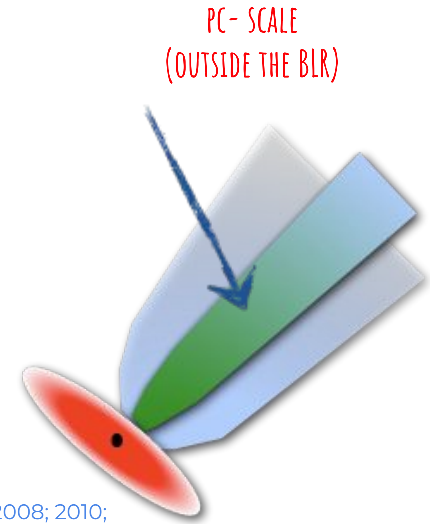
★ Different **jet activity**
★ Different **jet structure**



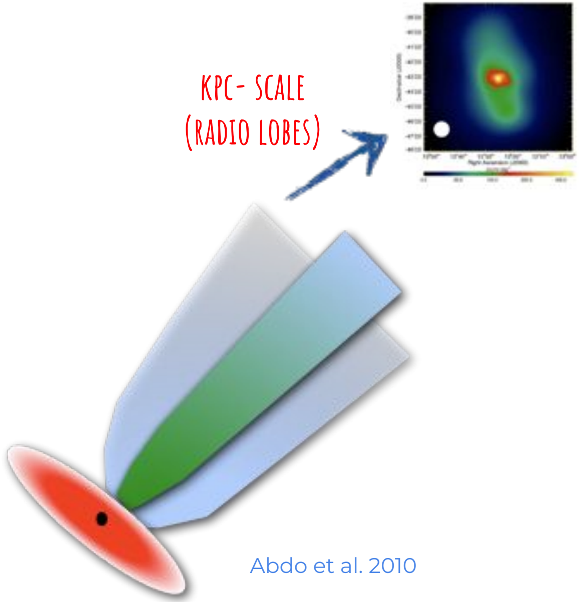
Although MAGN represent a few percent of the RL AGN population at GeV and TeV energies, they offer the **unique opportunity to study γ-ray emission processes at different sites from sub-pc up to kpc scales.**




Tavecchio + 2010;
Poutanen & Stern 2010;
Cerruti + 2013




Marscher + 2008; 2010;
Jorstad + 2001;2010;
Lähteenmäki & Valtaoja 2003;
Agudo + 2011ab



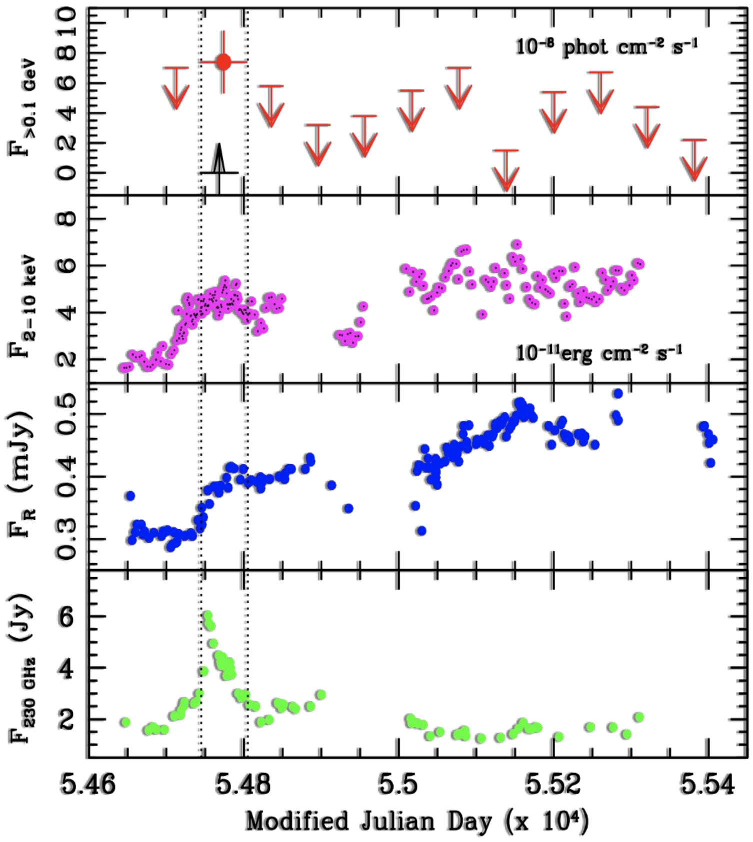

Abdo et al. 2010

Localizing where gamma-ray photons are dissipated with respect to the black hole has a strong impact on the physical models invoked to explain the HE emission.

see also Torresi 2020

# The multi-wavelenght flare of 3C 111

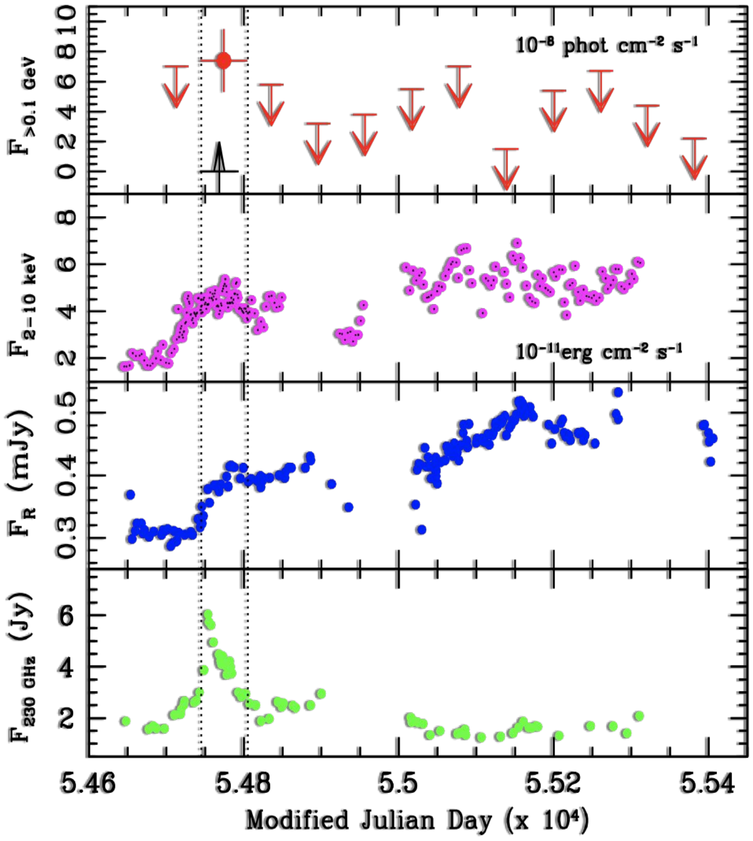
Grandi, Torresi & Stanghellini 2012

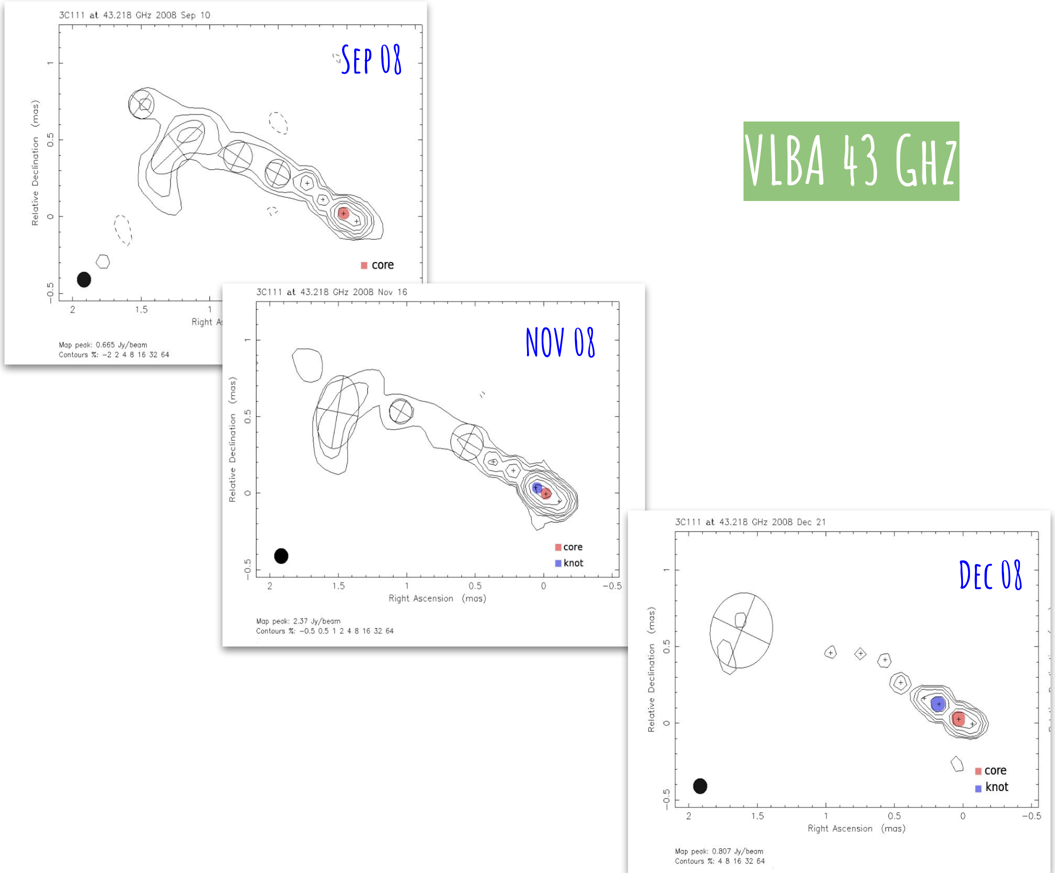



- 3C 111 was detected by Fermi/LAT exactly when mm-to-X-ray fluxes were increasing -> co-spatiality of the events;
- the γ-ray outburst occurred after a strong decrease (dip) of the X-ray flux and during the ejection of a new radio blob;

# The multi-wavelenght flare of 3C 111

Grandi, Torresi & Stanghellini 2012




VLBA 43 GHz

# The multi-wavelenght flare of 3C 111

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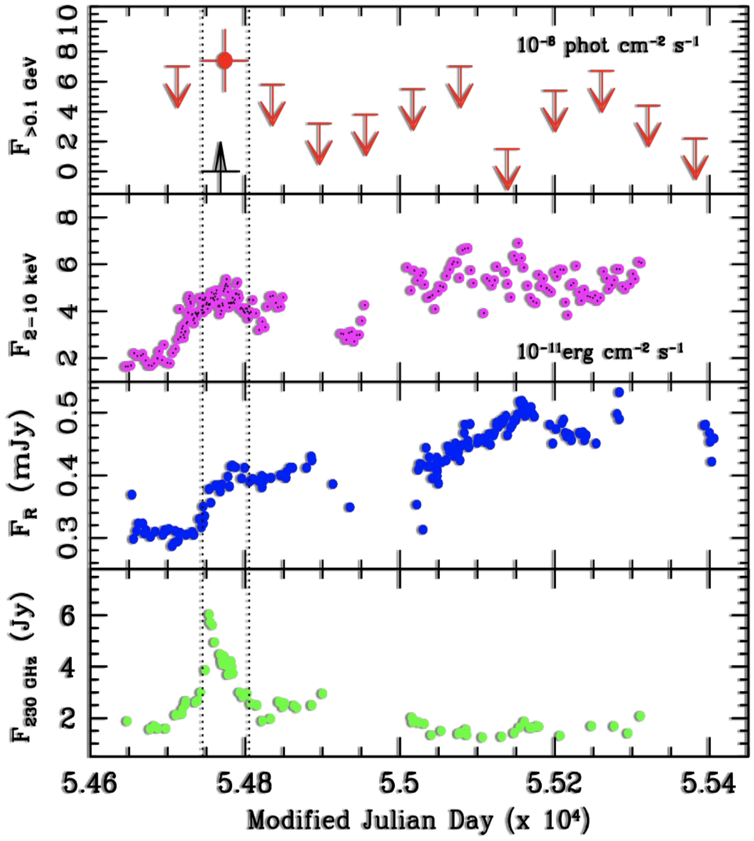


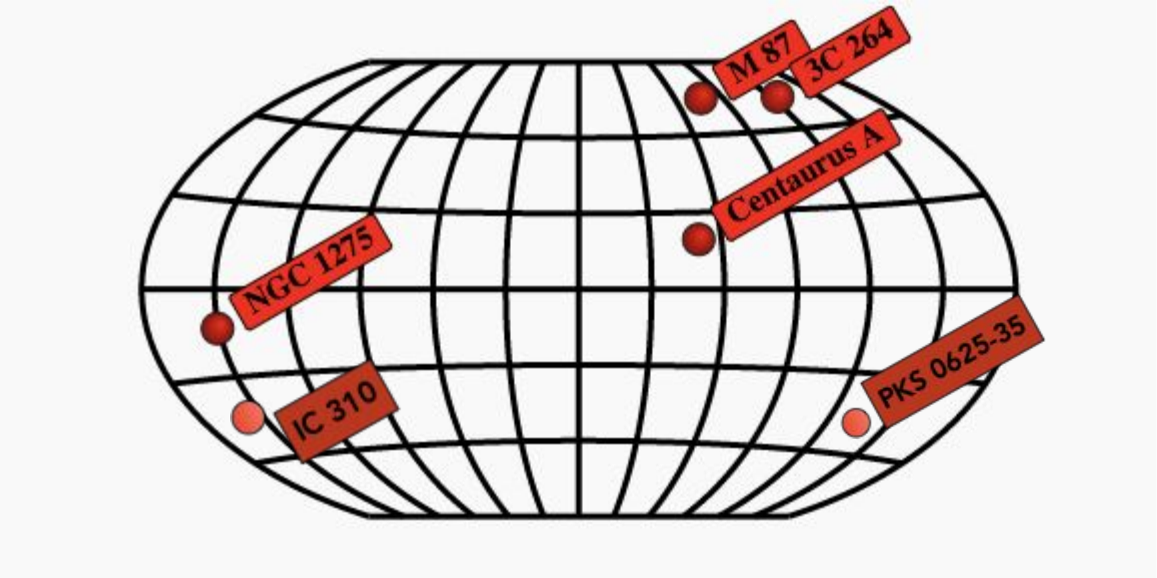

- 3C 111 was detected by Fermi/LAT exactly when mm-to-X-ray fluxes were increasing -> co-spatiality of the events;
- the γ-ray outburst occurred after a strong decrease (dip) of the X-ray flux (Chatterjee et al. 2011) and during the ejection of a new radio blob;
- the jet modification roughly follows the γ-ray flux evolution, revealing a direct connection between the outburst in the GeV band and the ejection of the radio knot.

➢ The emitting region is compact: **R < Δtδc < 0.1 pc** , δ ~ 3 (Jorstad et al. 2005);

➢ the distance of the emitting zone from the BH is **~0.3 pc.**

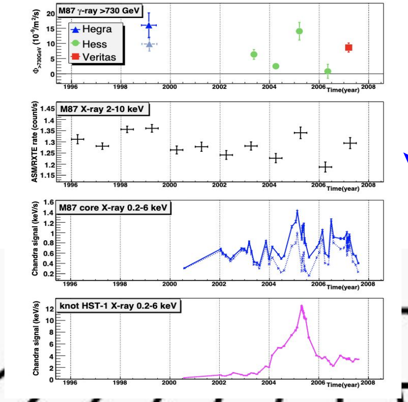
# MAGN at TeV energies

TeVCat

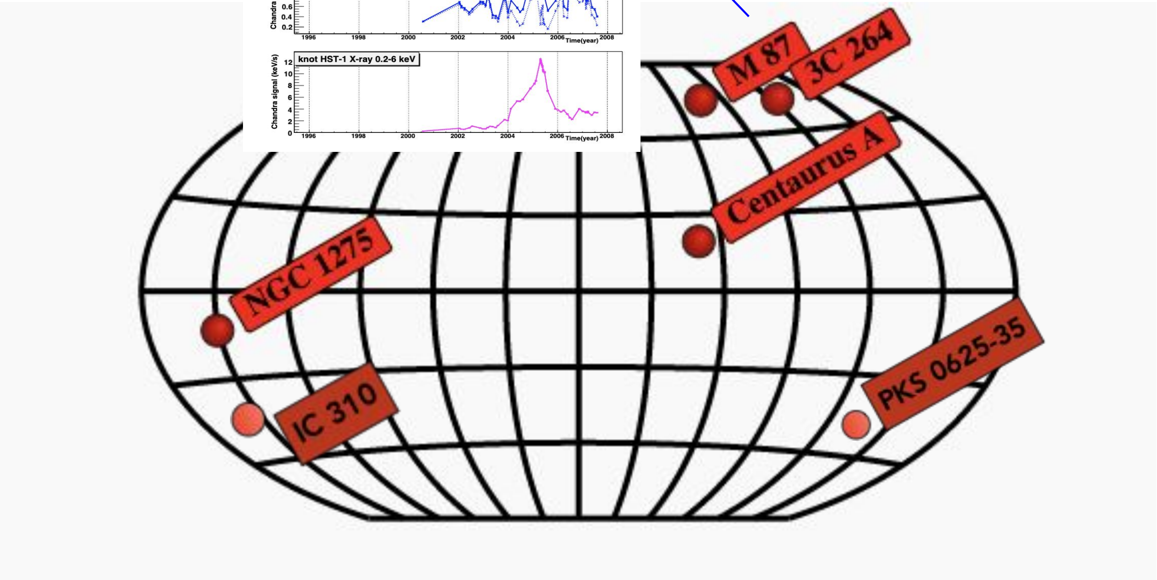



All FRI;  z<0.03

TeVCat




Localization of the VHE emitting region
(e.g. Acciari+2008)

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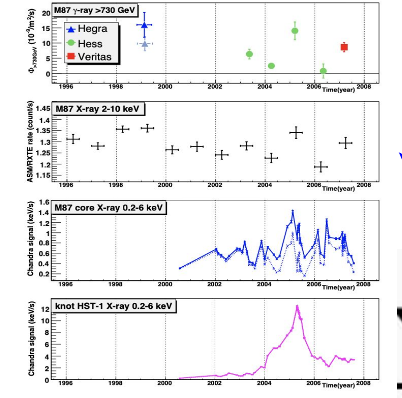


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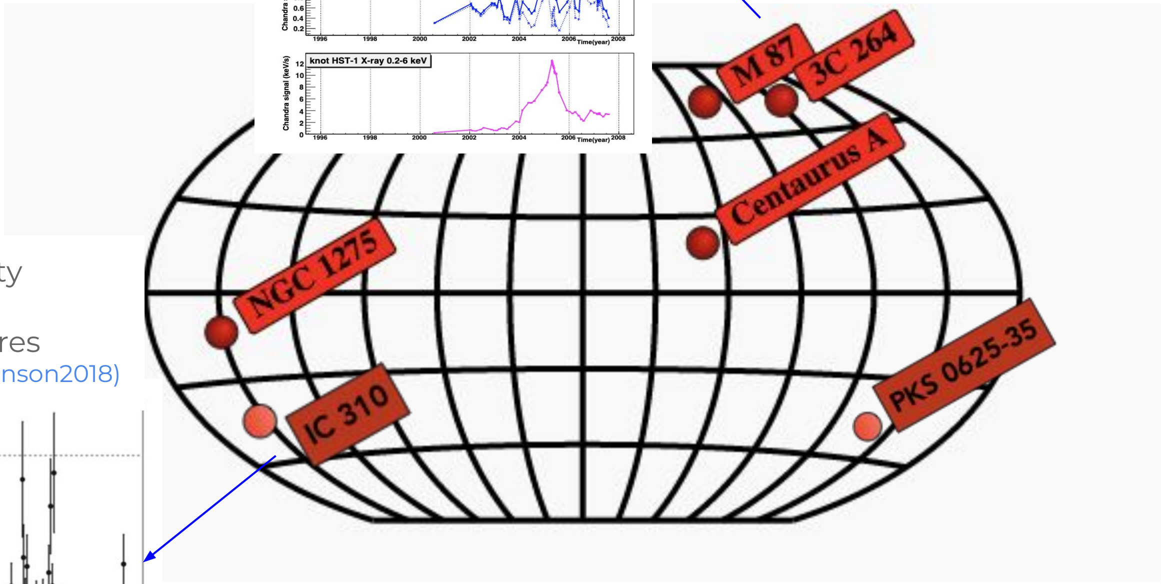
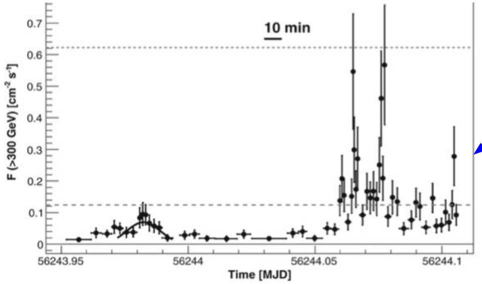



Very fast TeV variability probing small scale (sub-horizon) structures
(Aleksić+2014; Rieger&Levinson2018)

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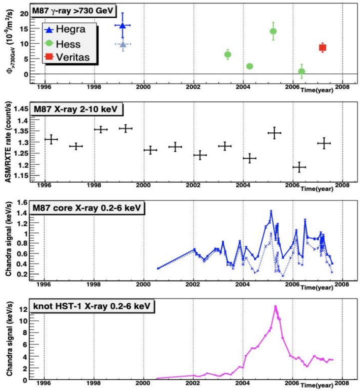


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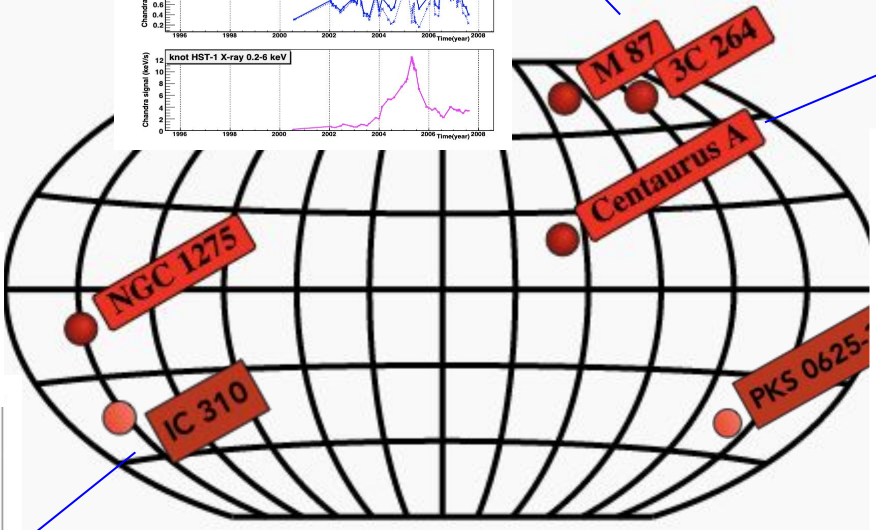
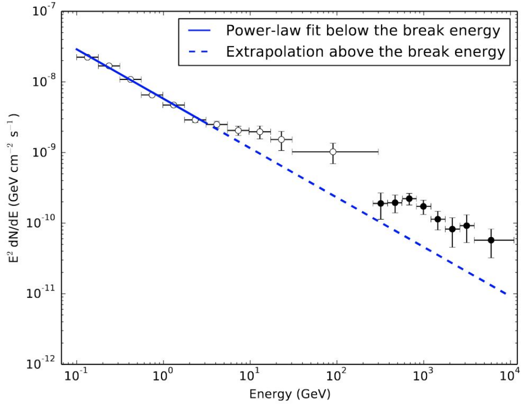



Second hard component
(Sahakyan+2013; Brown+2017; H.E.S.S. Coll. et al. 2018)

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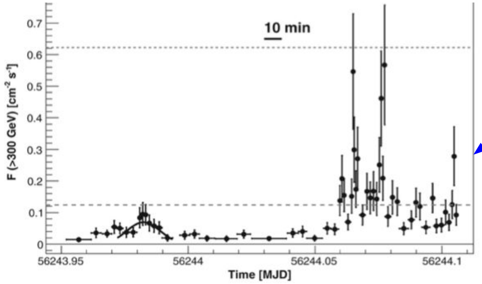


All FRI; z<0.03

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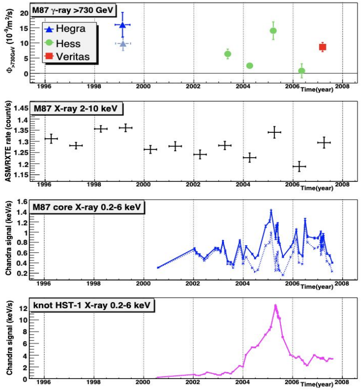


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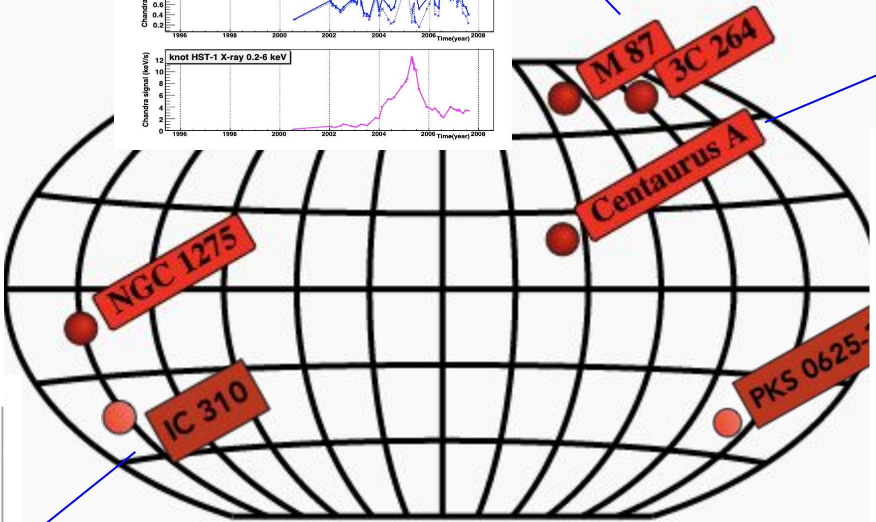
Talk by Giulia M.

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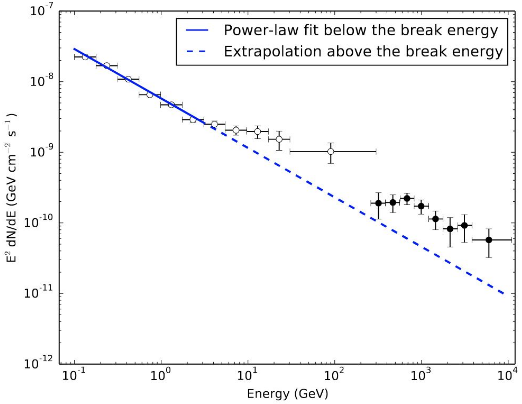


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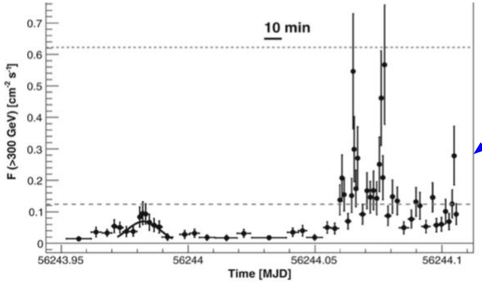
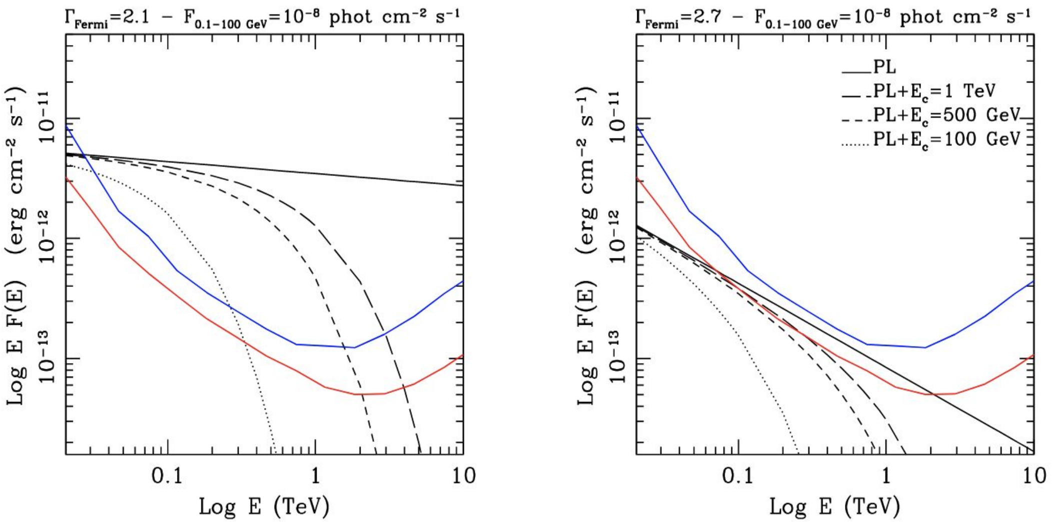



All FRI; z<0.03

# Radio galaxies with the Cherenkov Telescope Array

Angioni, Grandi, Torresi, Vignali, Knödlseder 2017

- Aim: evaluate the impact of the new generation CTA on the MAGN class, and propose possible observational strategies to optimize their detection
- Starting sample: 17 Fermi-LAT MAGN at z<0.15
- $F_{1\text{-}100\ GeV}$~$10^{-10}$-$10^{-8}$ ph $cm^{-2}$ $s^{-1}$
- Γ=1.8-2.8




*Flat* Fermi-LAT sources are more suitable CTA targets

# SIMULATION

- Energy range: 0.02-100 TeV
- CTA-North & CTA-South 50 hours
- *ctools*
- standard unbinned likelihood analysis

| Source | $k^b_{PL}$ | $TS_{PL}$ | $TS_{1\ TeV}$ | $TS_{0.5\ TeV}$ | $TS_{0.1\ TeV}$ |
|---|---|---|---|---|---|
| 3C 78 | 47 | 3113 | 256 | 96 | ... |
| Fornax A[c] | 20 | 1671 | 100 | 25 | ... |
| B2 0331+39 | 24 | 1049 | 65 | ... | ... |
| 3C 111 | 1.6 | ... | ... | ... | ... |
| 3C 120 | 1.9 | ... | ... | ... | ... |
| Pictor A | 3.3 | ... | ... | ... | ... |
| PKS 0625−35 | 300 | 154480 | 16987 | 7294 | 287 |
| 3C 189 | 13 | 321 | ... | ... | ... |
| 3C 264 | 33 | 2129 | 128 | 44 | ... |
| Tol 1326−379 | 0.7 | ... | ... | ... | ... |
| Cen B | 48 | 4066 | 520 | 212 | ... |
| 3C 303 | 32 | 3010 | 134 | 55 | ... |
| NGC 6251[d] | 55.3 | | | | 25 |

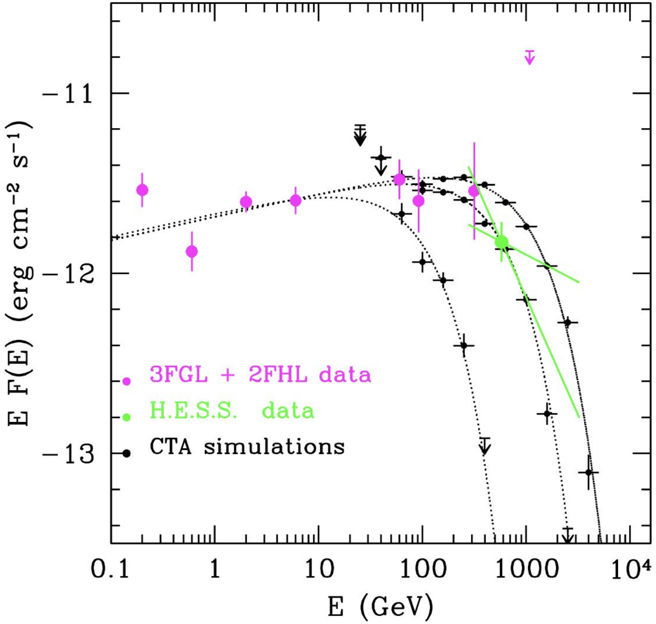
Dyrda+2015

Mukherjee 2018 (ATel #11436)

$TS=2Log(L/L_0)$

TS>100 (10σ)
TS>25 (5σ)

PKS 0625-35



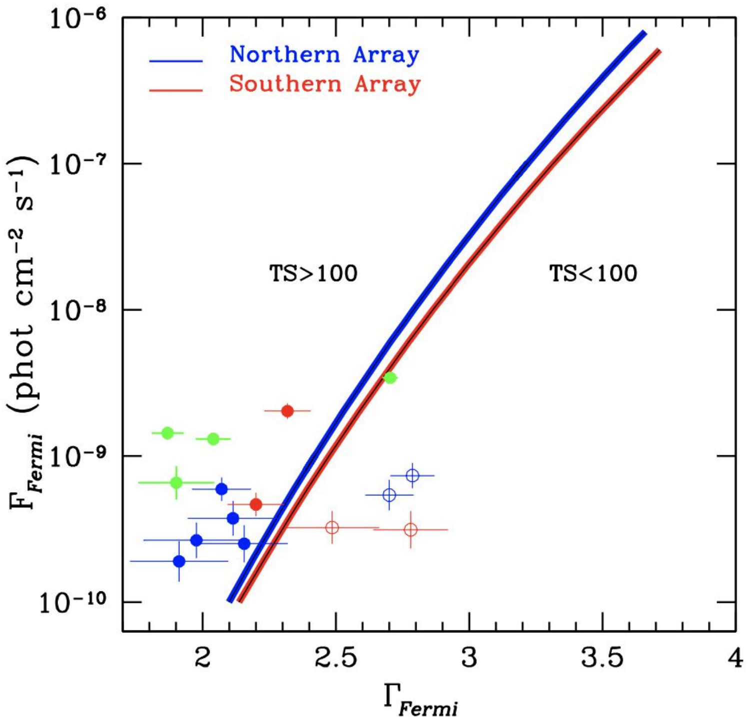

- ➢ CTA can provide high quality spectra for several MAGN
- ➢ Extension of their SED above 1 TeV
- ➢ Deeper investigation of the nature of the second emission peak

Diagnostic plot to verify the detectability of any AGN in the TeV band, with known photon index and flux in the 1-100 GeV band

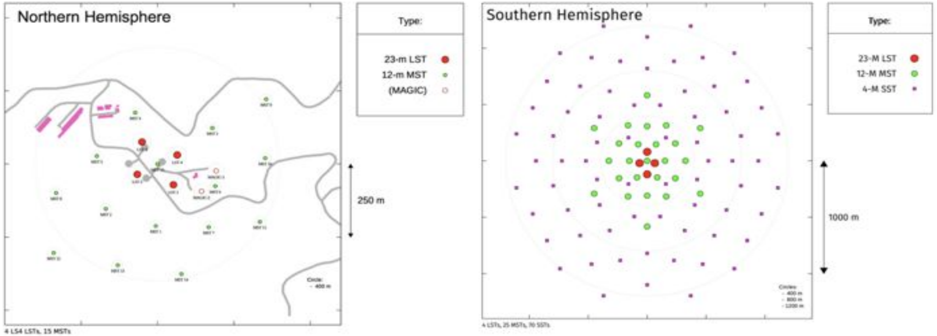
- ➢ Hard sources ($\Gamma_{Fermi} \leq 2.1$) can be easily revealed down to $F_{1\text{-}100\ GeV} \sim 10^{-10}$ ph cm$^{-2}$ s$^{-1}$
- ➢ MAGN with $\Gamma_{Fermi} \sim 2.4\text{-}2.8$ require $F_{1\text{-}100\ GeV} > 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ to be detected by CTA

- ❖ conservative approach, simple extrapolation of the Fermi-LAT power-law;
- ❖ a larger number of sources could be detected during flaring states

- ➢ These results are confirmed considering an expanded sample of MAGN (4FGL) Angioni 2020
- ➢ Finally, detection of FRII

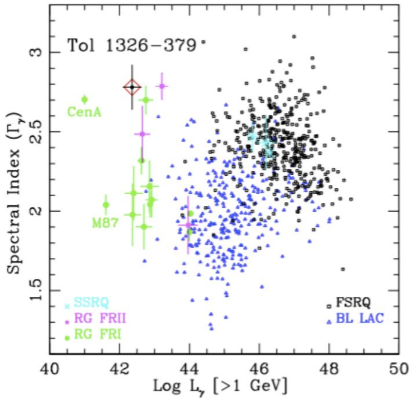


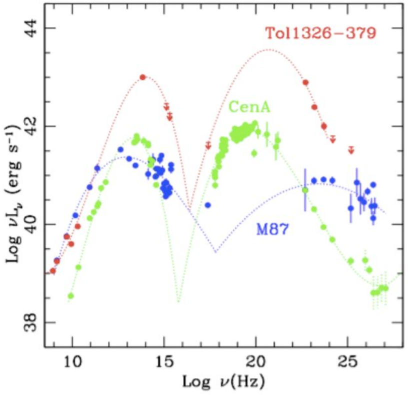
- **Long exposures** (~50 hours) for steep and faint sources
- Easily achieved through CTA **subarrays** (LST+MST)
- The number of predicted new TeV detections should be treated as a lower limit
- Improved simulations on 4FGL MAGN confirm these results; CTA would triple the number of TeV-detected radio galaxies (Angioni 2020)

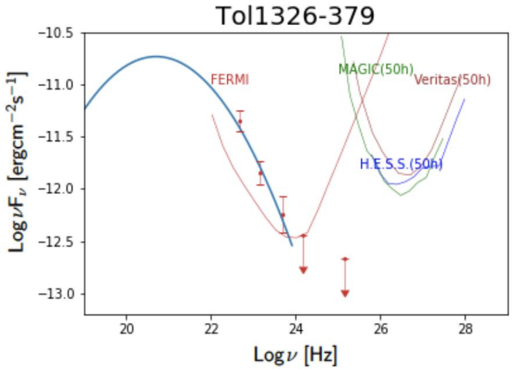


# THE HIGH-ENERGY VIEW OF FR0

Baldi, Torresi, Migliori, Balmaverde 2019




Only one FR0 associated with a Fermi-LAT γ-ray counterpart, up to now Grandi et al. 2016

The γ-ray luminosity is similar to FRI ($L\gamma$~$10^{42}$ erg $s^{-1}$) but with a steeper spectrum (Γ~2.8)

- Tol1326-379 could be oriented at a large inclination angle (as CenA, θ~50-80 deg)

or

- if the orientation angle is small (as M87, θ~15-25 deg) the SED of these two classes of sources are intrinsically different, i.e. different physical conditions of the high-energy dissipation regions.

A detection with current IACT seems unlikely. However, our knowledge of the FR0 class at high energies is still very limited, hence it will be important to investigate these sources with more sensitive observatories, such as CTA in the near future.

# SUMMARY

- MAGN are challenging targets for TeV observations; they represent a **unique γ-ray population** offering important physical insight w.r.t. blazars

- **CTA** is expected to improve our ability to reveal MAGN in the TeV sky thanks to its increased sensitivity
  -> population studies!

- HE/VHE studies of MAGN allow for deeply investigate the **accretion/ejection link**; results on other wavebands point out that accretion is the first driver of the FRI/FRII separation (see, e.g., Macconi et al. 2020; Grandi et al. 2021)

- The SED extension in the TeV regime will allow studying (i) acceleration processes in the jet; (ii) the jet structure and its link with the accretion type

- The **radio/γ-ray synergy** is fundamental; in these bands, the jet is not contaminated by thermal effects

- MAGN have been proposed as **neutrinos'** emitters: relativistic jets are likely powerful particles accelerators (e.g., Fraija et al. 2016; Hooper 2016; Murase 2018; Matthews et al. 2018; Tavecchio et a. 2018).

# Thank you!