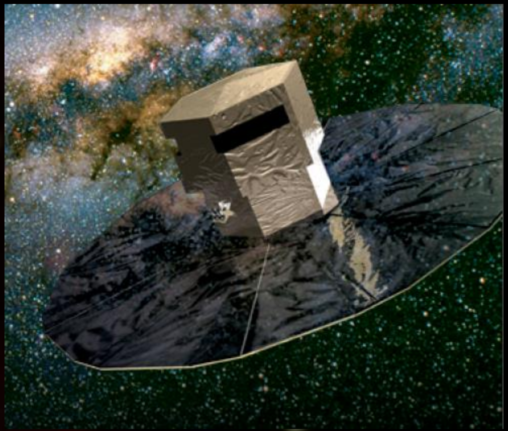
GAIA for AGN :



High energy radiations - Galactic Center and nearby AGNs

Helene Sol
CNRS, LUTH, Observatoire de Paris

GAIA for AGN and extragalactic science, Paris, July 8-9-10, 2015

Outline

Active Galactic Nuclei with GAIA : recent results

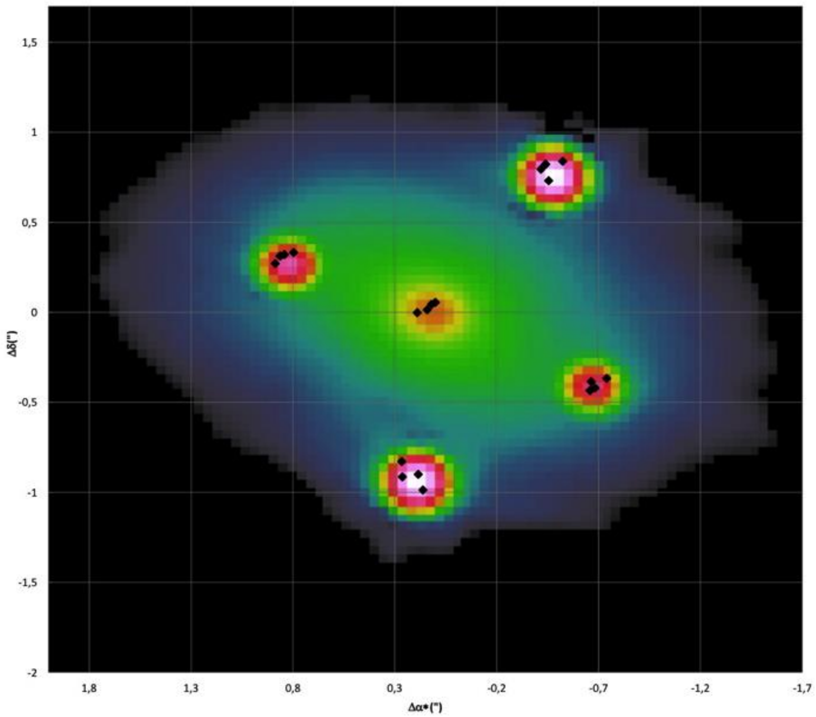
Synergies with High Energy issues

- **Galactic Center**

- **Nearby AGNs**

The AGN population at VHE and « preselected lists » of objects for GAIA ?

An AGN as « GAIA source of the week » : the Einstein cross



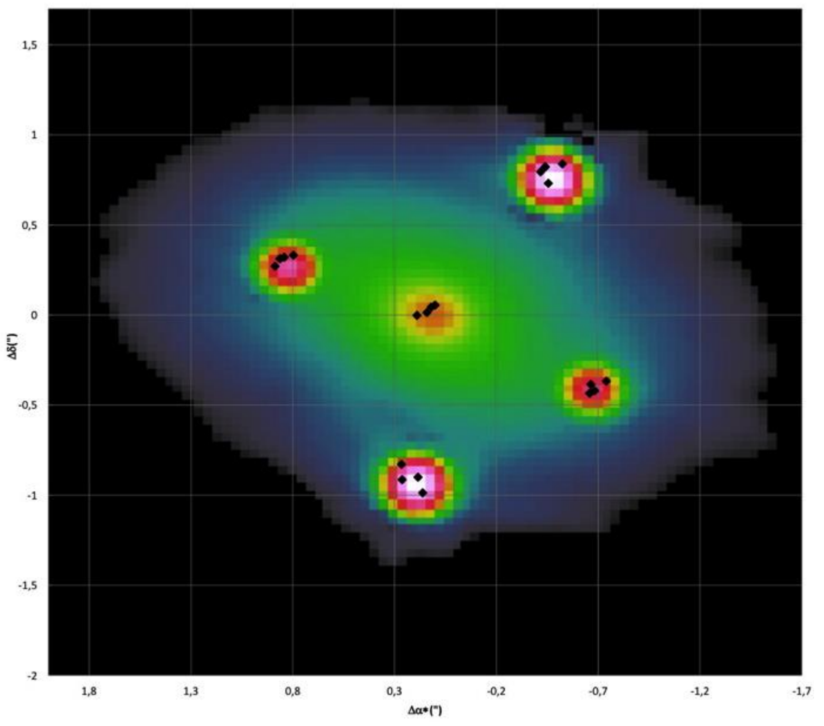
Testing general relativity and gravitational lensing with GAIA on the quasar Q 2237+030

Black points from GAIA superposed on HST images.
Image of ~ 2 sec x 2 sec.

GAIA Initial Data treatment, IDT
(credit ESA/GAIA et al)

GAIA succeeded to detect several times the 4 images of the quasar and the central galaxy acting as a lens, with its nucleus detected as a « pointlike star ».
Magnitudes ~ 17 to 19.
A current astrometric accuracy of about 100 mas (which will be much improved).

An AGN as « GAIA source of the week » : the Einstein cross



Remote quasar at z ~1.7
Nearby lens, at several 100 Mpc.

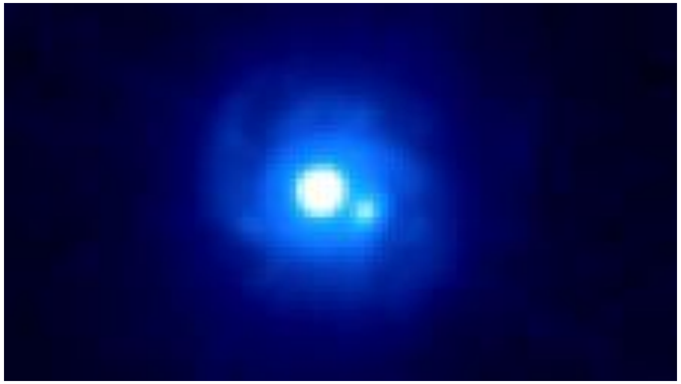
Almost perfect alignment between the quasar, the lens and the observer (< 50 mas).

All together these data provide an accuracy of 50 mas for the position of the Einstein cross.

Between April and December 2015, there will be 9 new observations of this source

→ Very high performance of detection
→ GAIA should detect 100 known gravitational lens and find new ones around quasars

Example of HE candidate : the gravitational lens on the flaring gamma-ray blazar B0218+357 detected by the FERMI satellite



Spiral arms of the lensing galaxy
+ 2 images of the background blazar, separated by 0.33''
HST image

FERMI found time delay of 11.46 days for gamma-ray flares between the two images → 1 day longer than the delay in radio → Tricky constraints !
Multi-lambda monitoring can constrain the:
- location of the various AGN emitting zones (HE zone much smaller) - lens mass distribution - microlensing effect - Hubble constant ...

A good synergy to optimize the scientific return of all involved experiments.

GAIA: alerts reported on AGN

Selected-gaia-science-alerts (current version of alert table on gaia.ac.uk) : a few alerts already identified with an AGN

- QSO, GALEX source, 2015-01-24
- QSO, z=1.05, 2015-01-18
- QSO, *r=19.1*, 2015-02-05
- AGN, QSO, slow rise over 5 months *(17.68 → 17.00),* 2014-12-07
- QSO, continuous rise on a blue source, broadline QSO in SDSS, 2014-11-03 *(18.08 → 17.56)*
- QSO at z=0.36, brightening of 1 magn, 2014-11-11 (Gaia14add); *18.71 → 17.70*
- Quasar, 2014-10-20, *19.45 → 18.94*
- Star forming galaxy, with transient which could be ~0.8 '' away from nucleus, 2014-11-11, *18.76 → 18.08*

→ Magnitudes down to 19.5, photometric alerts Δ ~ 0.5

The importance of various GAIA alerts for HE and VHE sciences

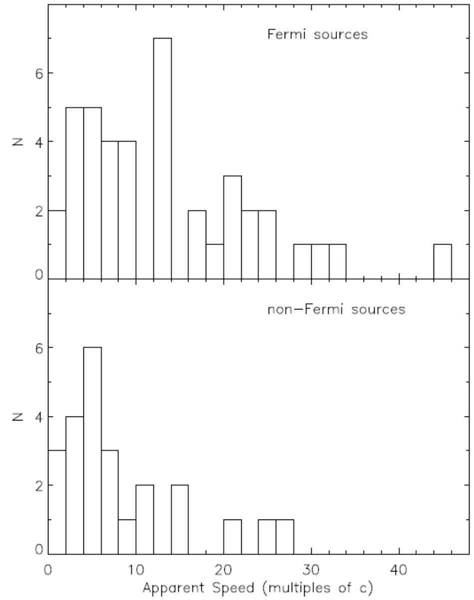
- AGN flares are still usually unpredictable except in rare cases of periodicity or quasi periodicity as for the blazar OJ 287 (binary BH candidate)

- But observing flaring AGN in gamma-rays is interesting for several issues: constrain the acceleration and emission process in AGN, study fast and microvariabity, detect faint or remote AGN, constrain the extragalactic background light, search for Lorentz invariance violation and signature of quantum gravity *(need to observe samples at various redshift) …*

- Observing blazars at weak or quiescent states in spectroscopy can be mandatory for some of them to measure their redshift (when the stellar light and spectral lines from the host galaxy are no more hidden by the very bright active nucleus)

- Astrometric alerts could be important as well, to point out new emerging knot from the central AGN core for instance *(detection by GAIA of photocenter motion)*

Connection between AGN gamma-ray emission and very high resolution data (in radio)



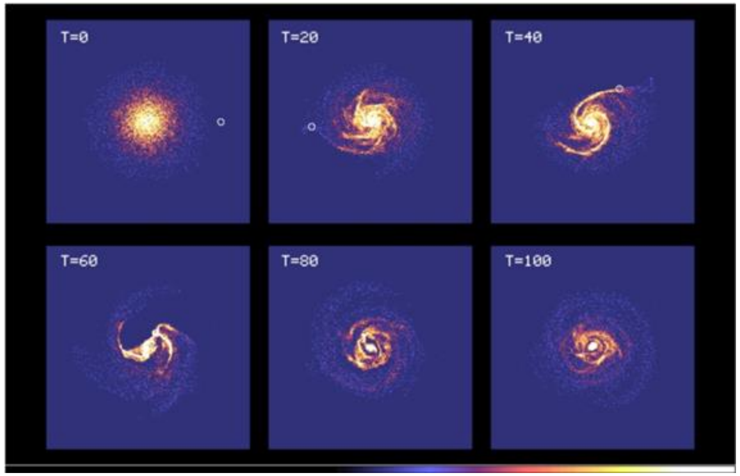
Sources in the 2FGL Fermi LAT catalog:
Show higher apparent VLBI speeds than non-Fermi sources *(Piner et al, 2012)*

→ ***GAIA extragalactic sources with high photocenter motion*** = *interesting candidates* for VHE gamma-ray observations

- Computing power of GAIA can handle highly crowded fields *(up to 200000 stars per square degree)*
- Measure of distance and motion of foreground star populations (mass, age, metal content) near the GC, with distances to within an accuracy of 20%
- Should provide some detailed 3D-map of central parts of the Galaxy + velocity fields → history of star formation, formation and evolution of the galaxy and its nucleus, merging event, « feeding » the monster and activity of the nucleus, influence of dark matter ??…
- Improve the distance estimate of the Galactic Center → fix the scale and improve the energy budget → more precise constraints on physical parameters on Sgr A*, etc

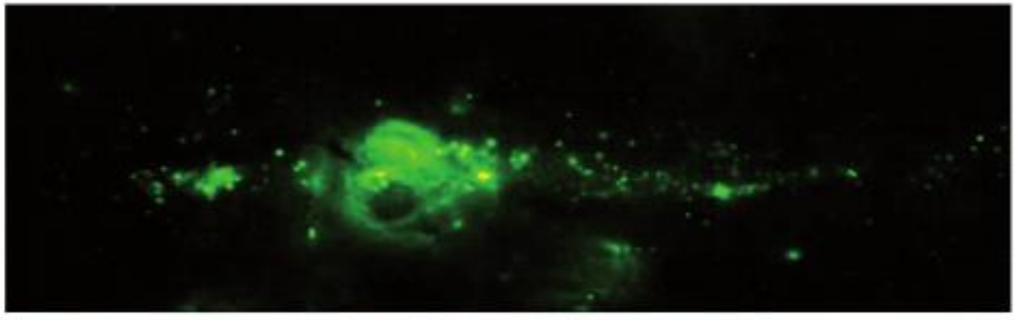
Some key questions on AGN/host galaxy connection to be studied with the G. C.

- Feeding the central engine versus the kinematics of the stars and the bulge/bar kinematics and inner disk structure
- How is angular momentum extracted, allowing to « feed» the monster ?
- Role of merger in the Galactic history
- Can accretion of a galactic satellite by the Milky Way result in an activation of the central black hole in the G.C. ?
- Relation between the Milky Way and its G.C.: are there some signatures of co-evolution ? (merger influence, AGN feedback …)
- Rotation curve and precise kinematics of our Galaxy, down to its central parts, to search for dark matter influence and constrain DM content and properties ?…



Simulation of a small galaxy merging with a massive disk galaxy *(GAIA)*

Galactic Center at HE and VHE: provide several constraints on the nucleus activity and the Dark Matter



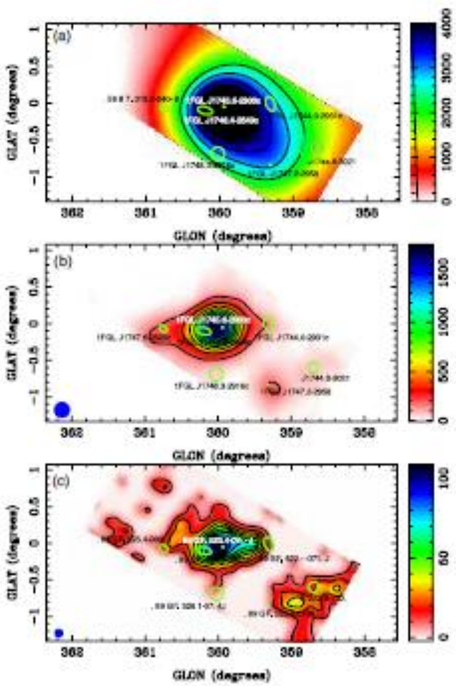
Far IR: trace warm dust and stellar activity
Spitzer satellite

X-rays: trace HE processes, particle acceleration, shocks, non-thermal emission, etc
Chandra satellite

The 2° x 0.8° region around the Galactic Center

A laboratory to study Galactic Nuclei: Dynamics of inner region (300 pc in radius) driven by the SMBH Sgr A* + a wealth of HE/VHE sources (star forming region with powerful winds, SNRs, PWNs, binaries, non-thermal filaments + a dense ISM (x10) and strong magnetic fields (> 50 µG compared to µG in the disk).
Moreover, the halo of Dark Matter of the Milky Way is believed to be peaked at the G.C.

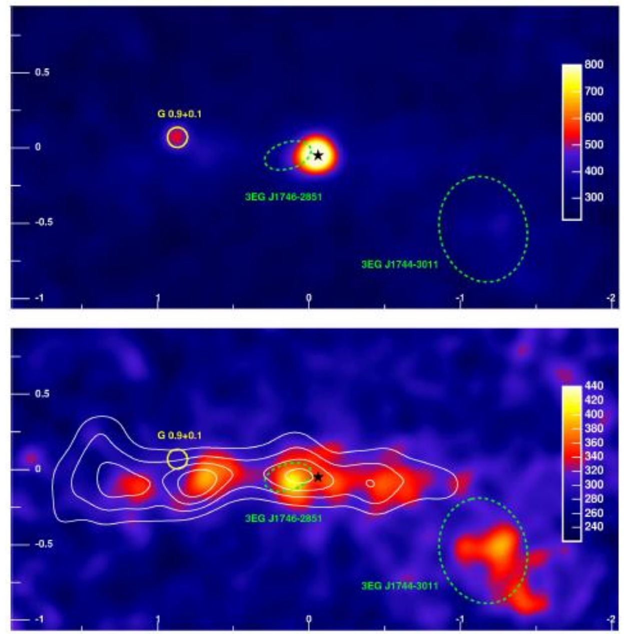
Galactic Center in HE and VHE gamma-rays



0.3-3 GeV

3-30 GeV

30-300 GeV



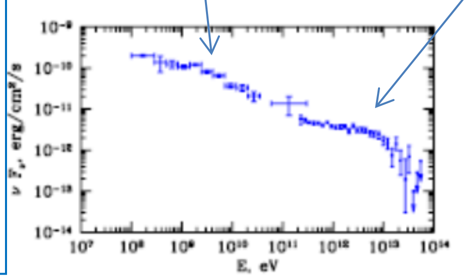
> 380 GeV
G.C. with
Sgr A* and
SNR

Same zone
after
substraction
of 2 sources

Maps of the G.C. region by FERMI
(Chernyakova et al, 2011)

Maps of the G.C. region by H.E.S.S.
(Aharonian et al, 2006)

Deduced
gamma-ray
spectrum
of GC source.
Nature ??



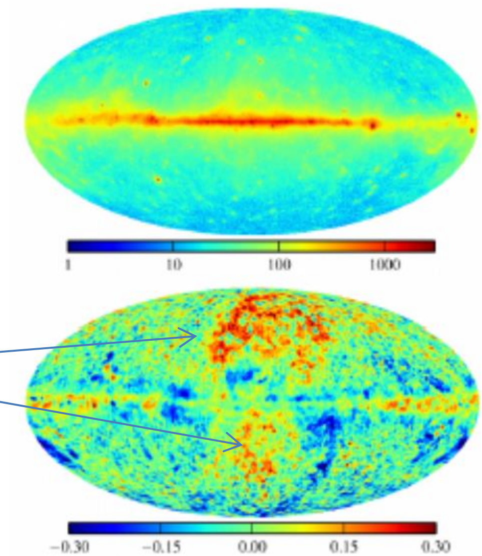
Distance ~ 8kpc
1° ~140 pc, 1'' ~ 40 mpc
Poor angular resolution
in gamma-rays → Sgr A* ??

Results on G. C. from gamma-rays data

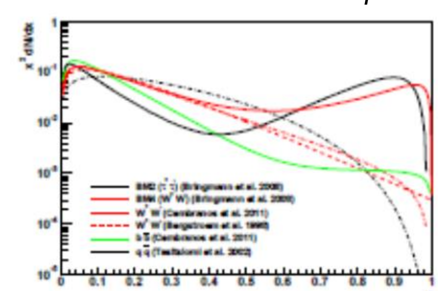
- A rich morphology of the inner region
- Many particle accelerators within the inner few 100 pc, with particles up to several tens of TeV
- Past and recent AGN activity of Sgr A* *(or alternatively star forming episodes ?)* are probably responsible for the diffuse VHE emission related to molecular clouds near the G.C., and the giant bubbles detected by FERMI
- Sgr A* is presently in a low state, but some evidence for a recent activity ~ 100 years ago, and earlier events
- The G.C probably hosts the largest concentration of dark matter in the Galaxy. DM annihilation could be detected by HE and VHE experiments (CTA project) since typical DM masses are expected in the range of 10 GeV to several 10 TeV.

(see review by van Eldik, 2015)

FERMI maps with bipolar outflows from the G.C.



Neutralino annihilation spectra



VERITAS (USA)

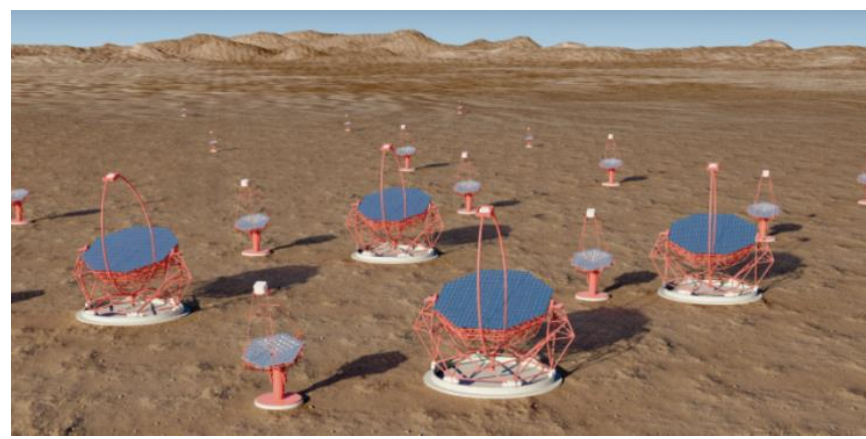
MAGIC (Canaries)

H.E.S.S. (Namibia)

VHE : Current ground-based Imaging Atmospheric Cherenkov Telescopes have detected ~ 150 sources & more than 50 Active Galactic Nuclei at Very High Energies, up to redshift ~ 0.6.

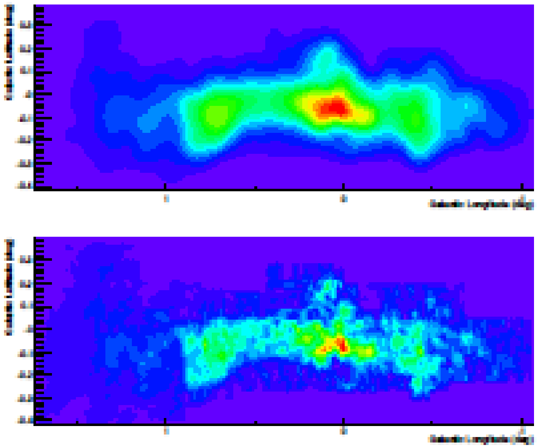
The next generation: CTA, an advanced ground based large γ-ray array

-10-fold increased sensitivity at TeV energies (mCrab) compare to current IACT
- 10-fold increased effective energy coverage, from 20 GeV to 300 TeV)
- Larger field of view (5° to 10°)
- Improved angular and spectral resolution
- Full sky coverage (North and South), various operating modes available.
- 30-years lifetime, partial operations starting from 2016-2017 → up to 2050 …



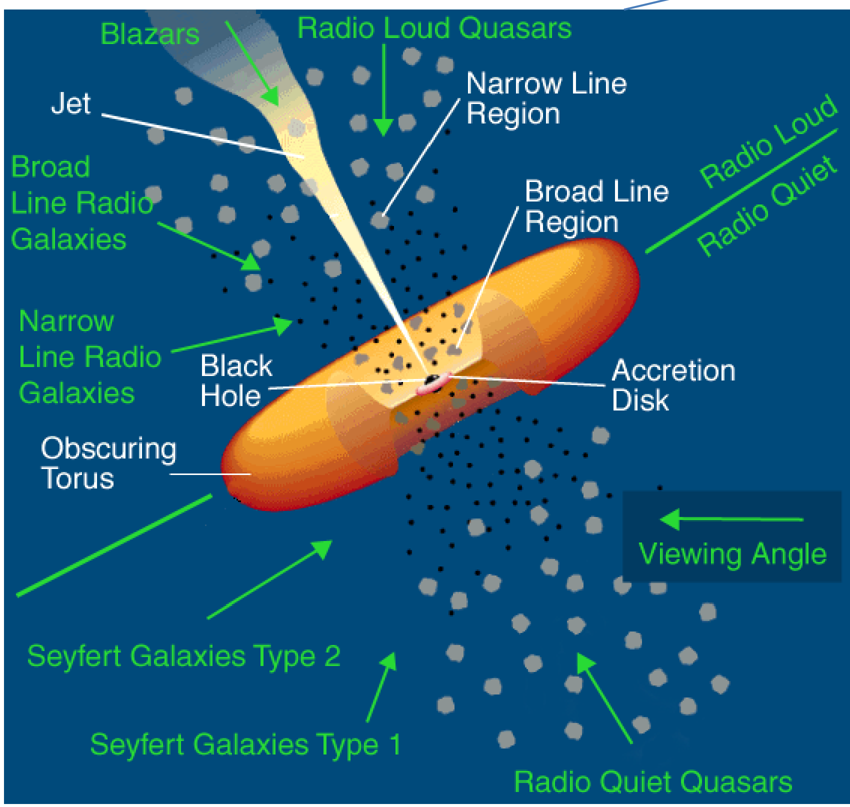
Some perspectives with CTA on the G.C. in coming years:

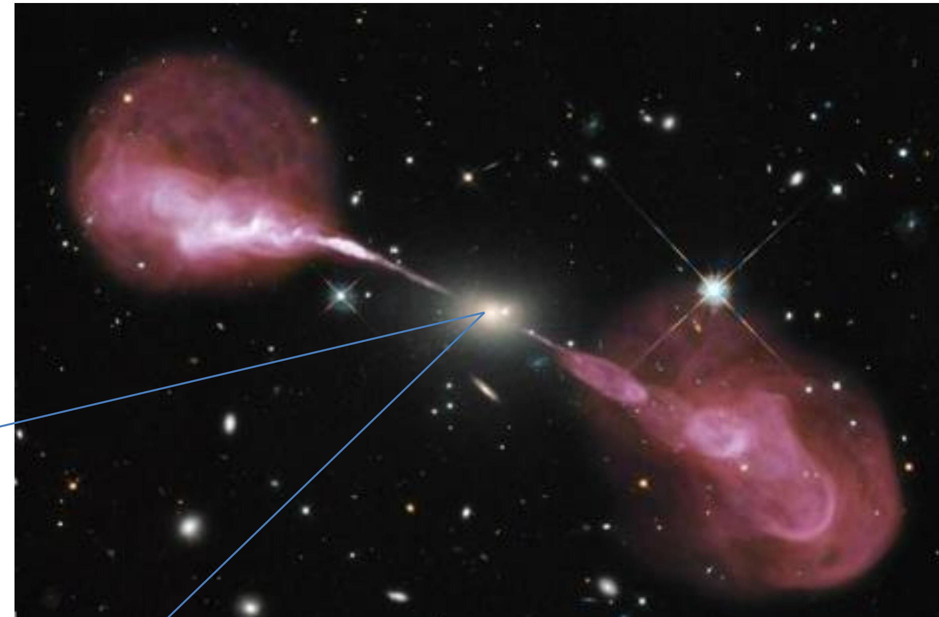
- Identify the nature of the central gamma-ray excess
- Search for annihilation of dark matter particles and constrain DM properties (DM particle mass, annihilation cross-sections, distribution …)
- Constrain scenarios for the diffuse VHE emission and high-states of the G.C. : Injection of cosmic rays – Connection with the kinematics of the Galaxy and activation of its nucleus



Simulated VHE maps of the diffuse emission as seen by H.E.S.S (top) and by CTA (bottom), produced by energetic proton-gas interaction in molecular clouds. Protons are injected from Sgr A* 10 000 years ago.

Nearby Active Galactic Nuclei



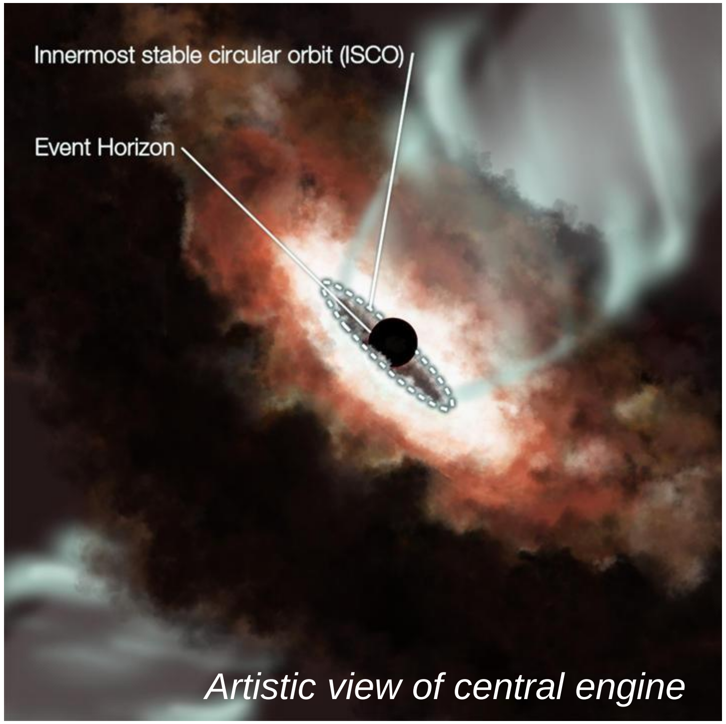


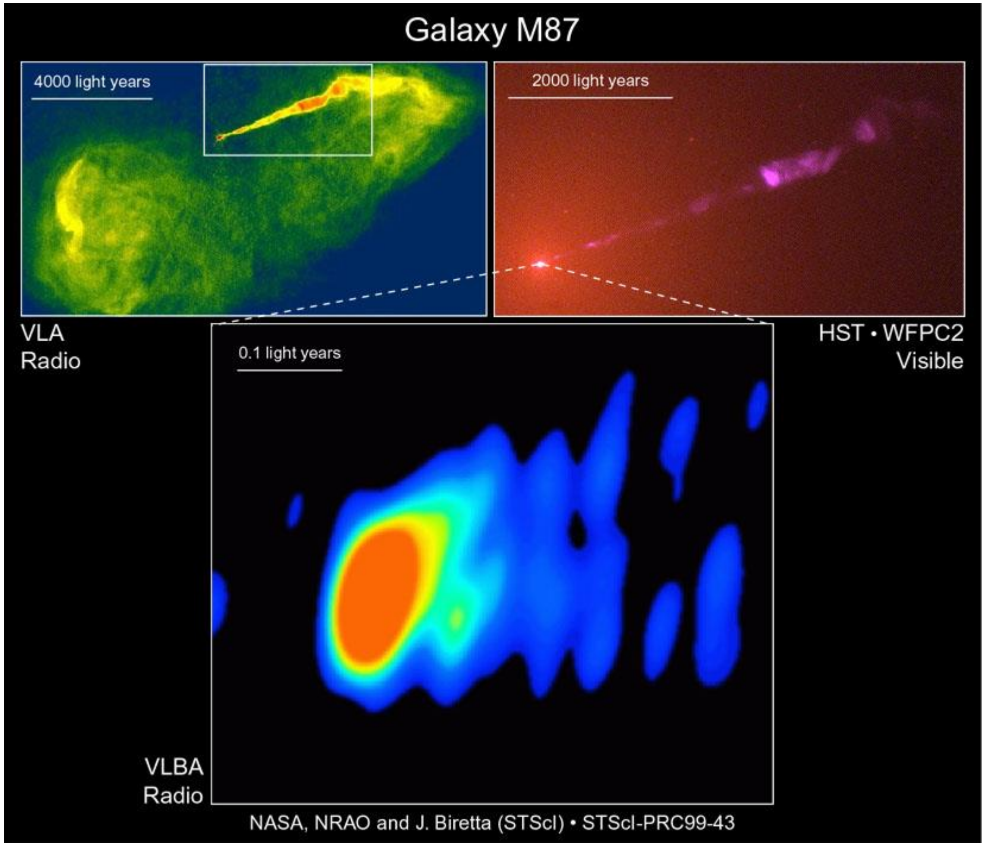
Large scale structure:
Radiogalaxy Hercules A
(VLA + HST)
$2.5 \times 10^9\ M_\odot$ Black Hole

Compact source:
Modelling AGN central core,
and AGN unification schemes

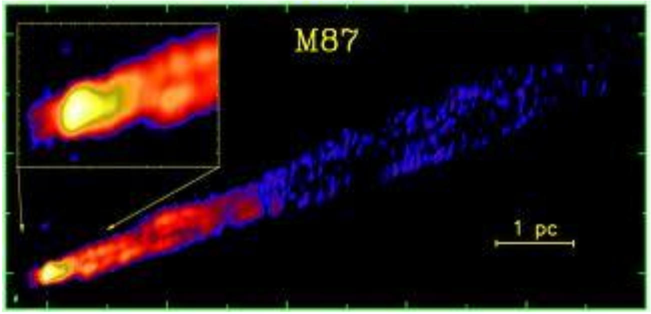
Nearby AGN with GAIA

- Compact core of AGN or nuclear knots in jets can be pointlike → proper apparent motion (~ photocenter motion) should be measurable (for z = 0.03, V_{app} = 1000 km/s corresponds to a proper motion of 3 microsecond per year).
- A few 1000 AGN should be measured with micro-arcsecond optical maps → can we expect superluminal motion maps from several hundred images over 5 years ?
- Various kinds of AGN: the nearest radio-loud ones (M87, Cen A) would be very interesting to follow with GAIA if they can be well detected. However their accretion regime (ADAF) results in low-magnitude disks with thermal emission possibly undetectable. Non-thermal emission of jet base could be possibly seen, depending on still unknown values of physical parameters in jets → detection would open a new avenue to better constrain jet physics (geometry, kinematics, particle acceleration and emission)



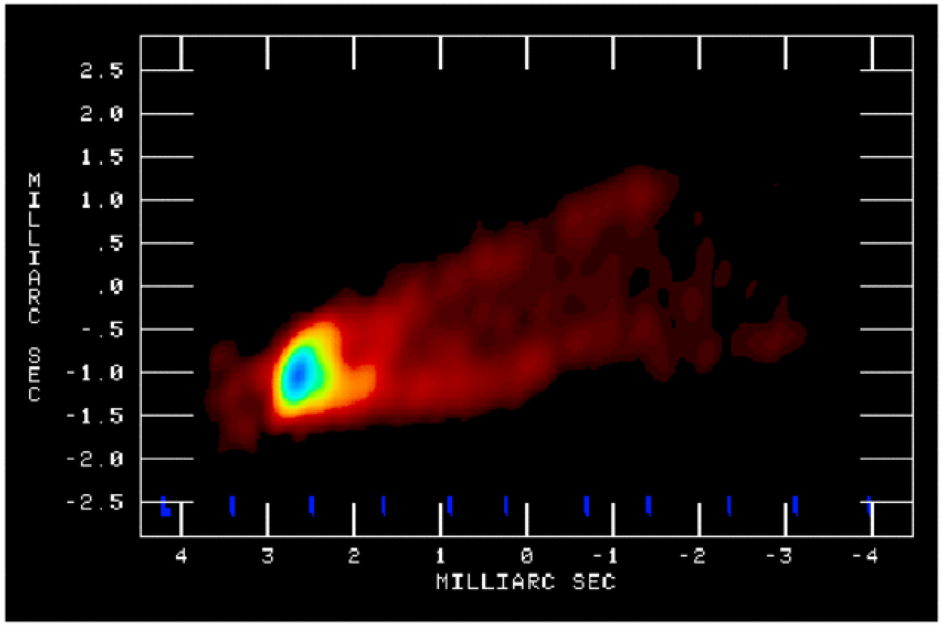


Radio VLBI data now probe the regions very close to the central black hole at a few Schwarzschild radius (sub-mas, sub-pc).
Here the **radio galaxy M87**

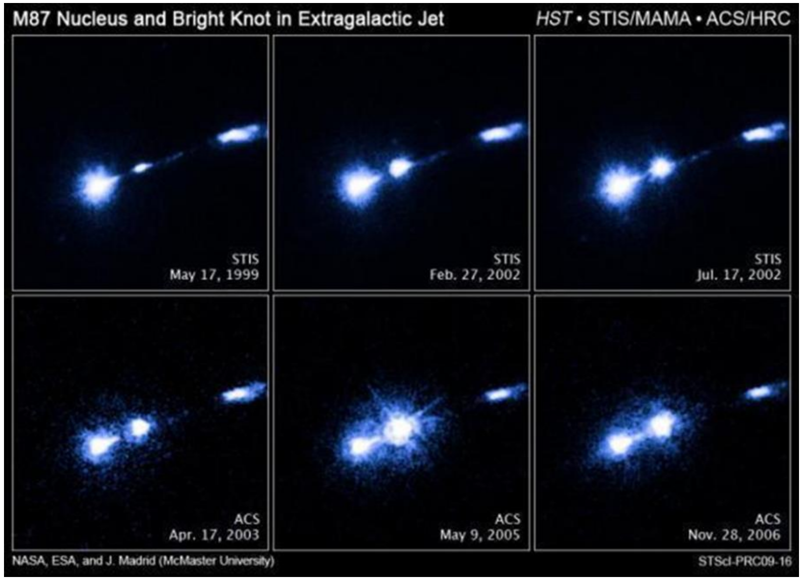


M87: Time evolution of radio VLBI jet on mas scale

Photometric, spectroscopic, and photocenter variation possibly detected by GAIA



Time evolution of optical jet on arcsec scale (HST-1 at 3'')



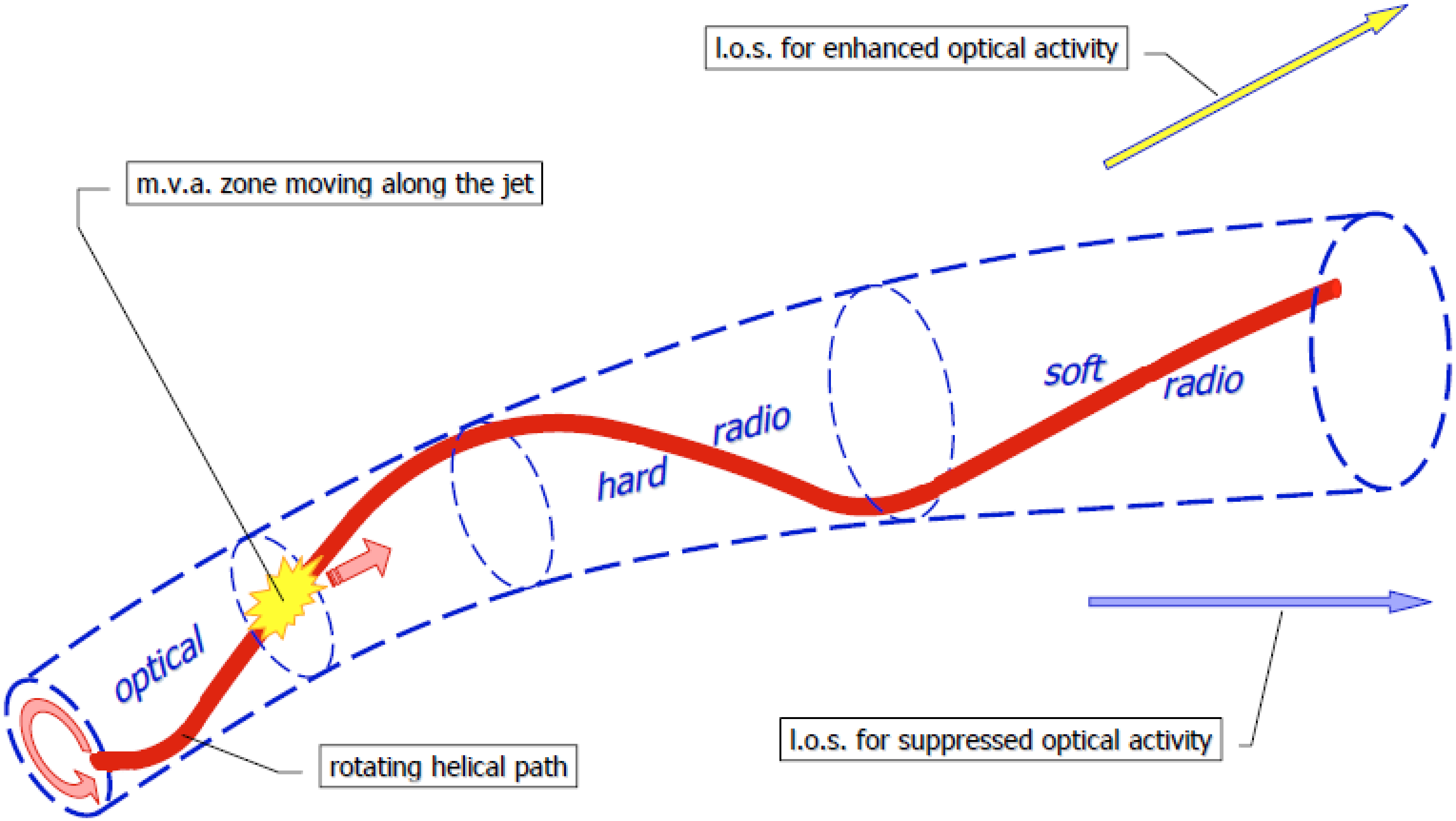
GAIA can detect photocenter motion on such spatial scale if the inner jet is bright enough in the optical range

→ ***Constraints on particle acceleration, radiation processes, jet formation***

Many sources of variability in jets are possible:
Instabilities, turbulence, change of particle injection rate at the base, acceleration of particles, change of beam direction (Doppler boosting) …

→ Clearly deserves further analysis

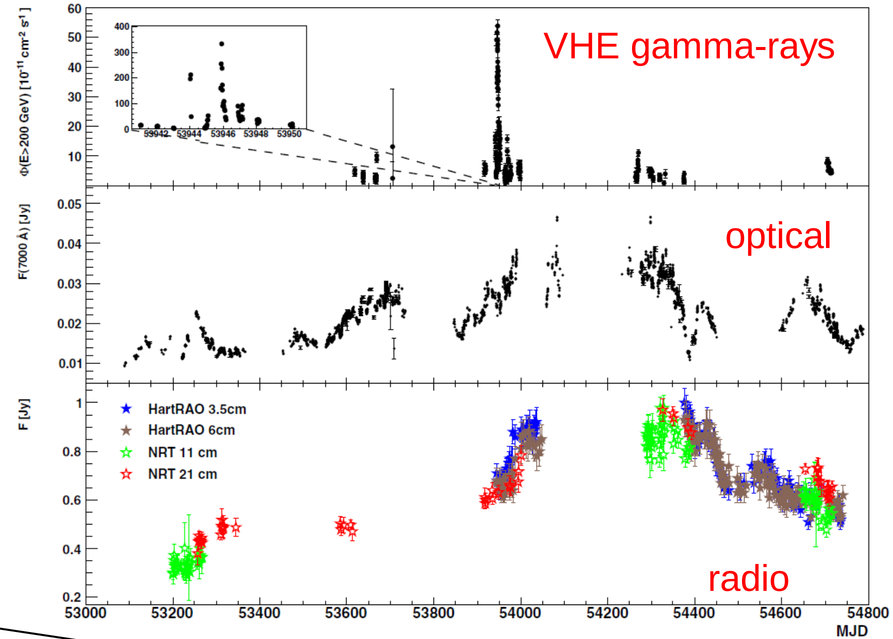
→ Optical data on sub-mas scale would significantly constrain almost all types of scenarios for jet base and formation

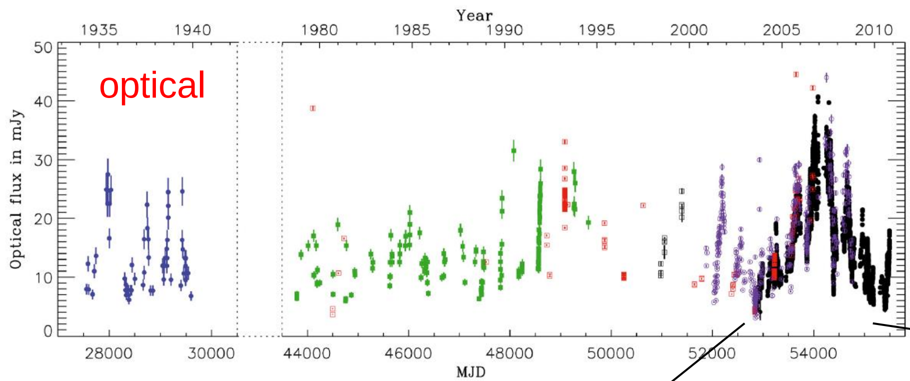


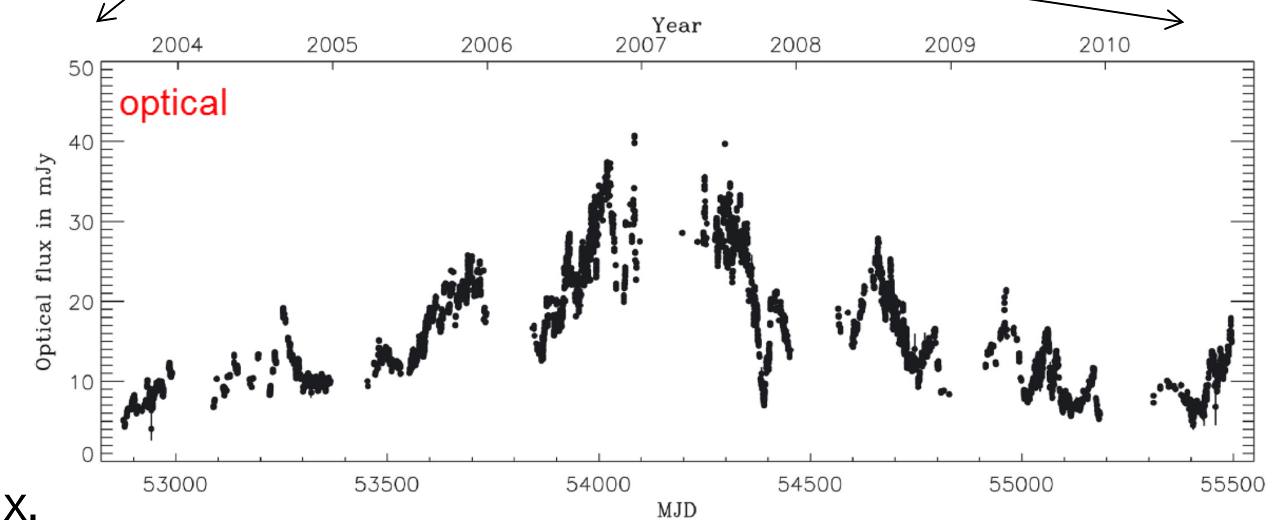
(from Villata et al, 2009)

Examples of MWL lightcurves from radio and optical ranges to VHE gamma-rays:
The blazar PKS 2155-304

From Abramowski et al, 2012 & Kastendieck et al, 2011





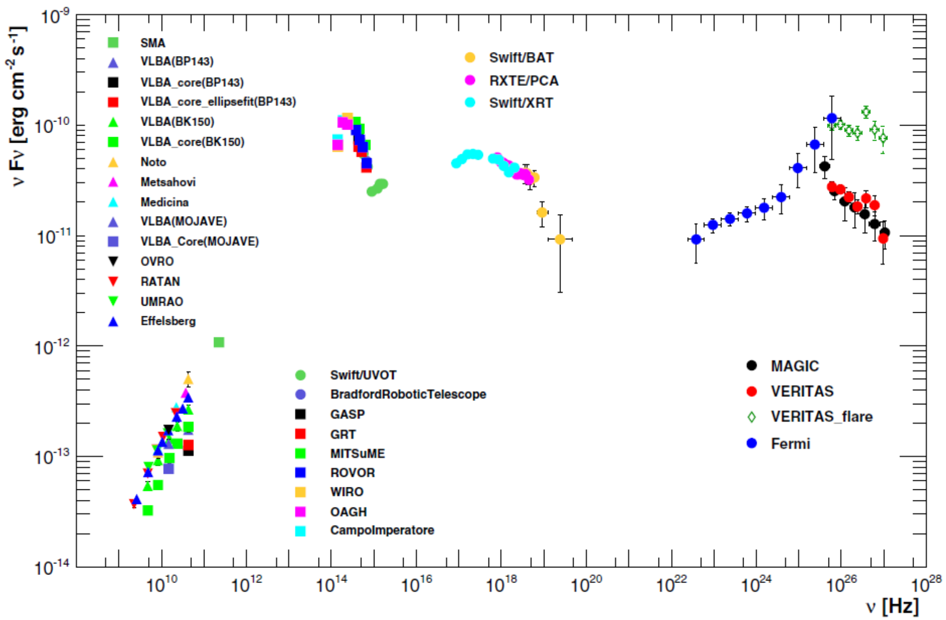


MWL variability, on all timescales.

Strong short VHE gamma flares occured during longer active state in optical (and radio) rang.

Factor up to 8 in optical flux.

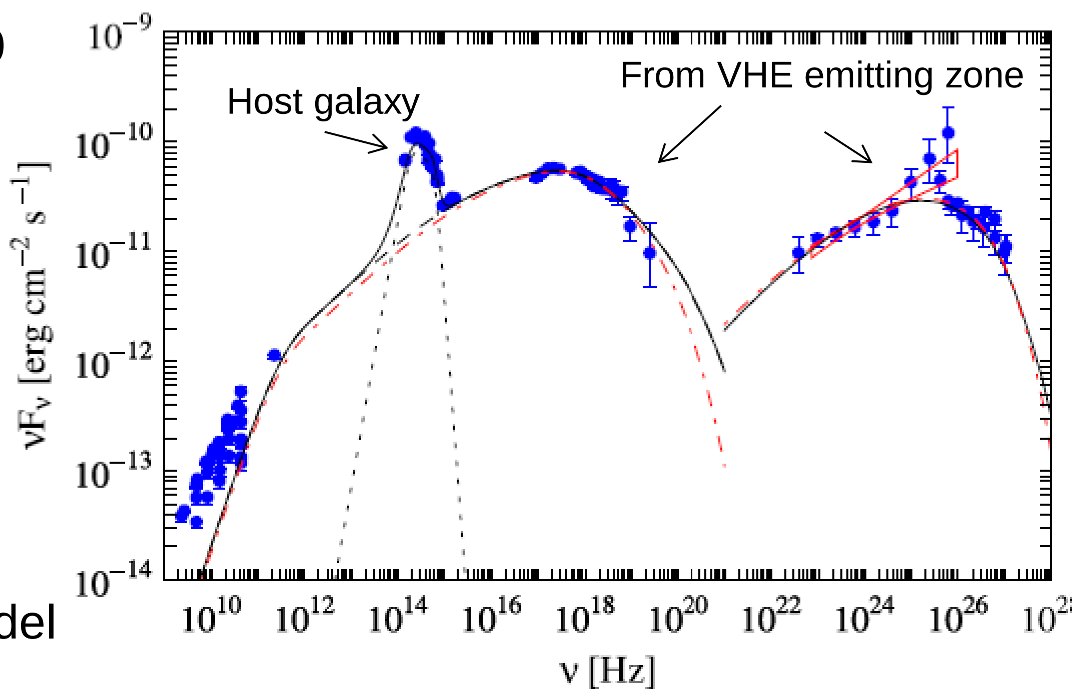
A typical nearby blazar: Mrk 501



Simultaneous MWL data provide the SED, Spectral Energy Distribution from radio to VHE

MWL campaign March-August 2009
From Abdo et al, 2011

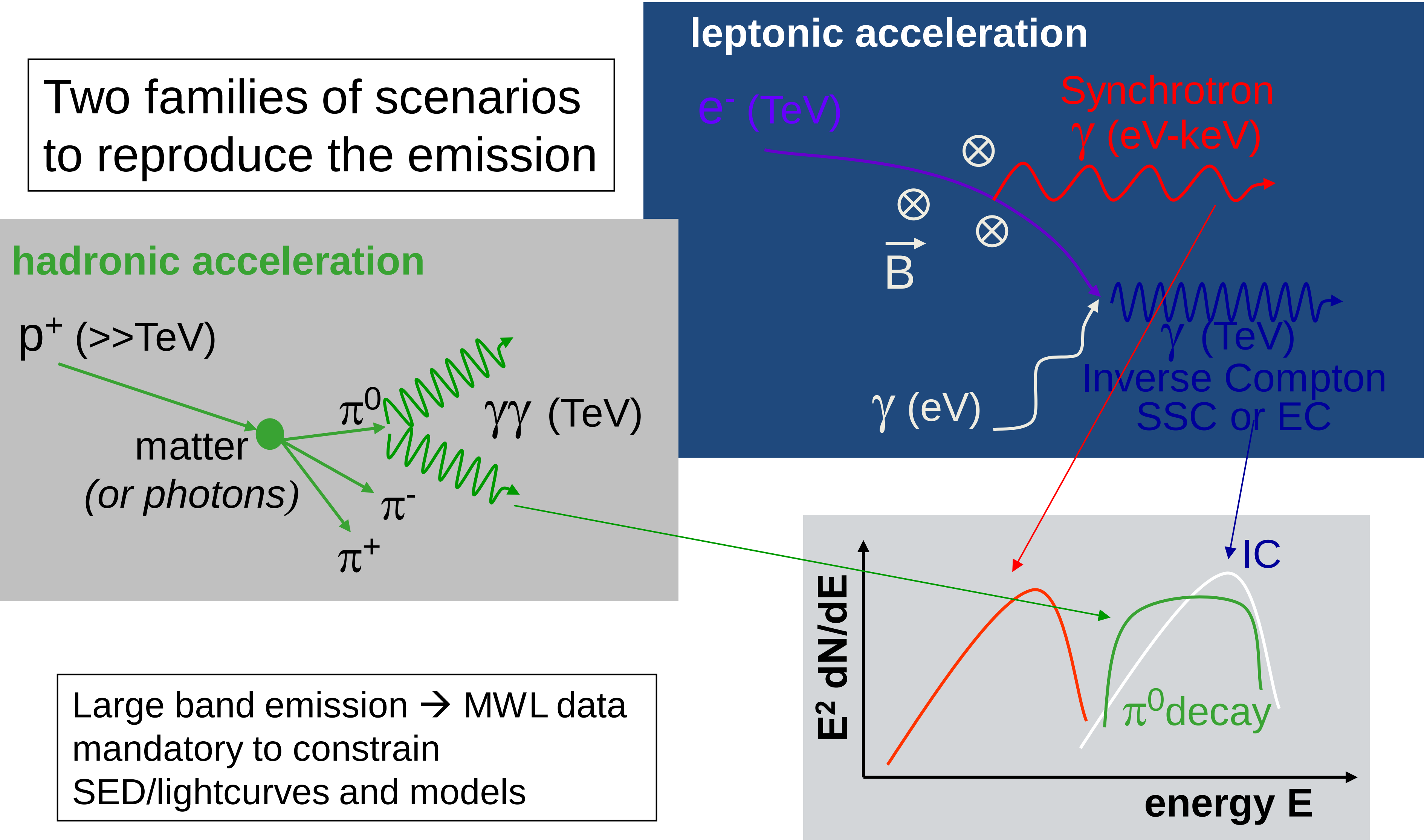
Some optical-VHE connection is expected in blazars.
Optical trigger was succesfully used by MAGIC for new detection at VHE.



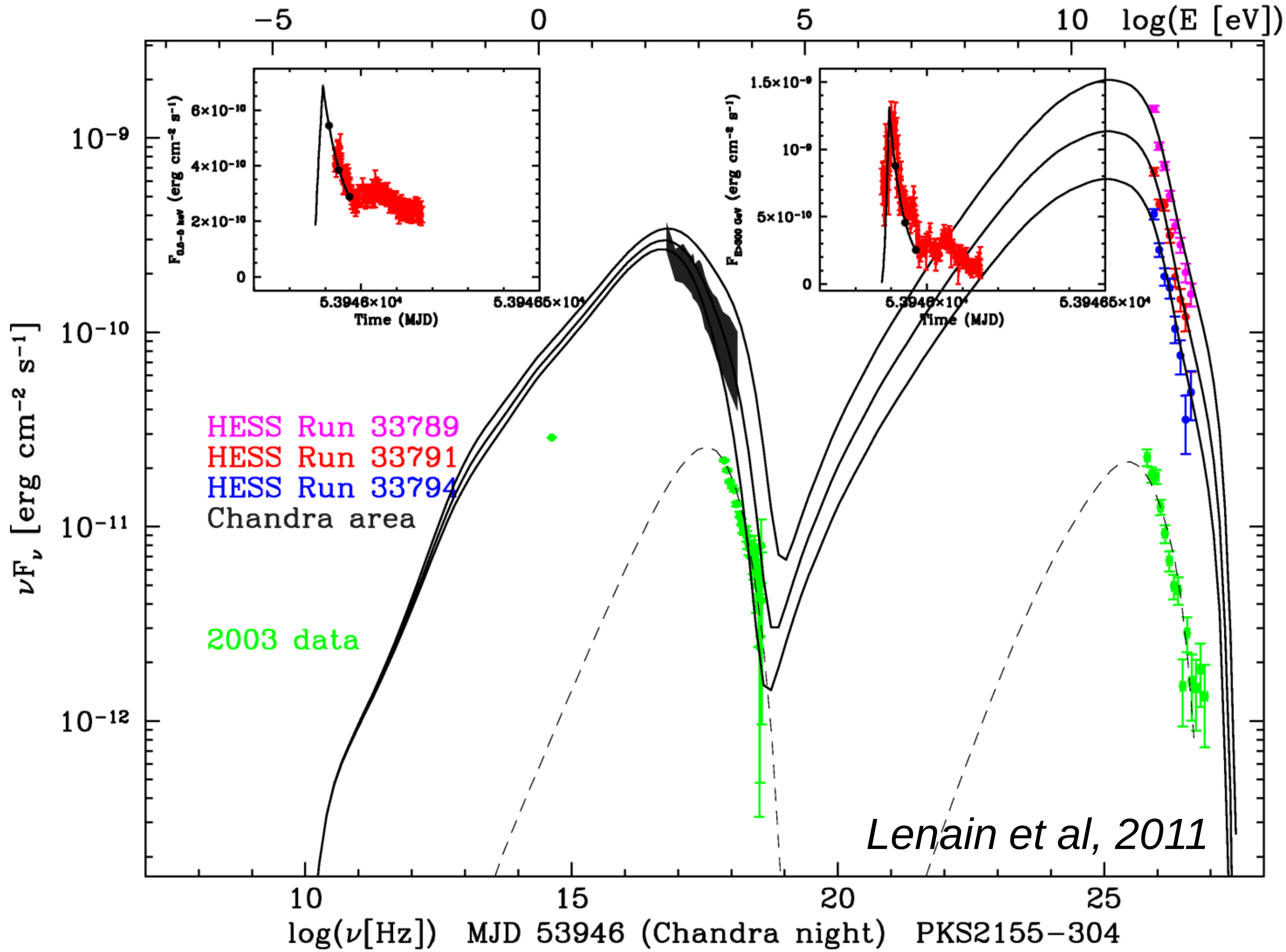
Fit by SSC model

AGN at VHE: non-thermal large band emission

Two families of scenarios to reproduce the emission



Large band emission → MWL data mandatory to constrain SED/lightcurves and models

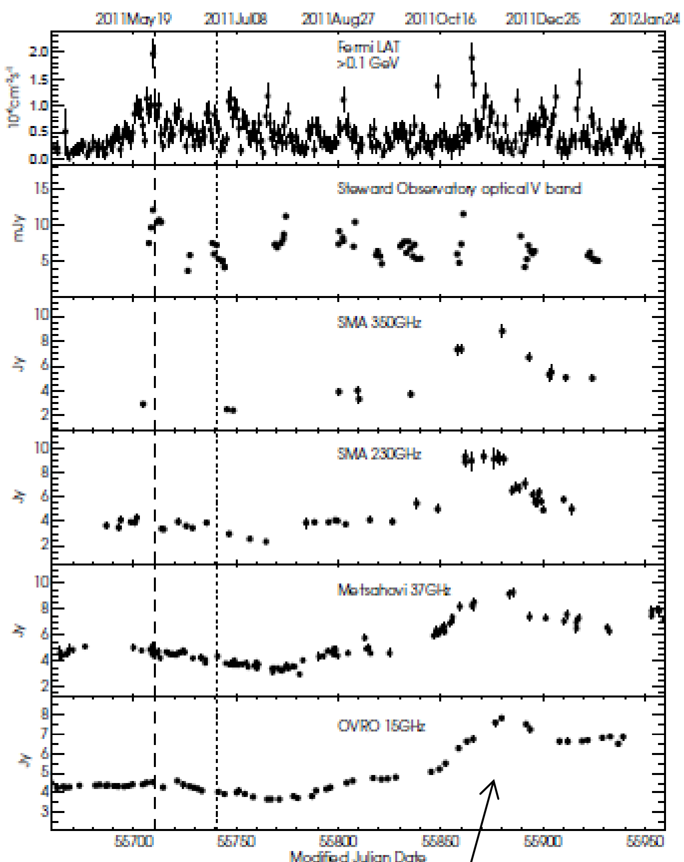


Fit of the 2nd big flare of **PKS2155** in 2006 by SSC time-dependent modeling :
Reproduce light curves and spectra of flare in X and gamma rays

→ X-rays and VHE highly correlated during flare

→ some direct correlation with optical is expected, although still difficult to put in evidence

Example of emergence of a new VLBI superluminal component from the core, at the time of a TeV flare in the source **BL Lac**
→ radio-VHE connection. Behavior in the optical range ?
→ strong ***interest of photocenter motion GAIA alerts***

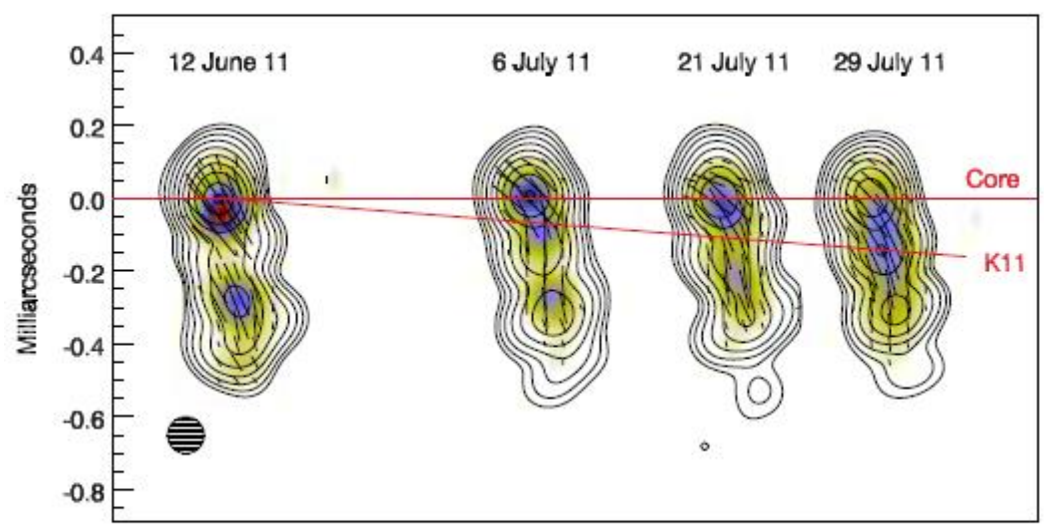


TeV and MWL flare

Radio flare ~ 4 months later

VHE flaring activity on June 28, 2011
from Arlen et al, 2012

K11 = new VLBI component



The case of Ap Librae

LBL, OVV, at z = 0.049

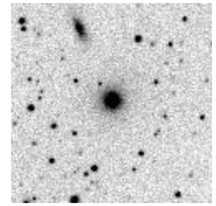
R, ESO 1m Schmidt

VLA 1.4 GHz

VLBA, MOJAVE 15 GHz

Max jet speed 1981+/- 60 µas /year, based on 3 moving knots

At 214 Mpc: 0.94 pc/mas



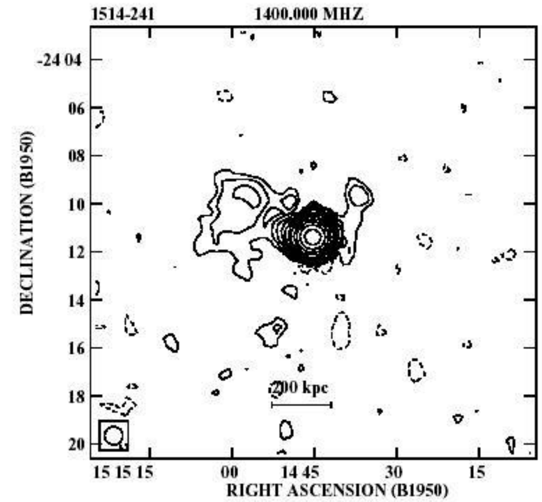
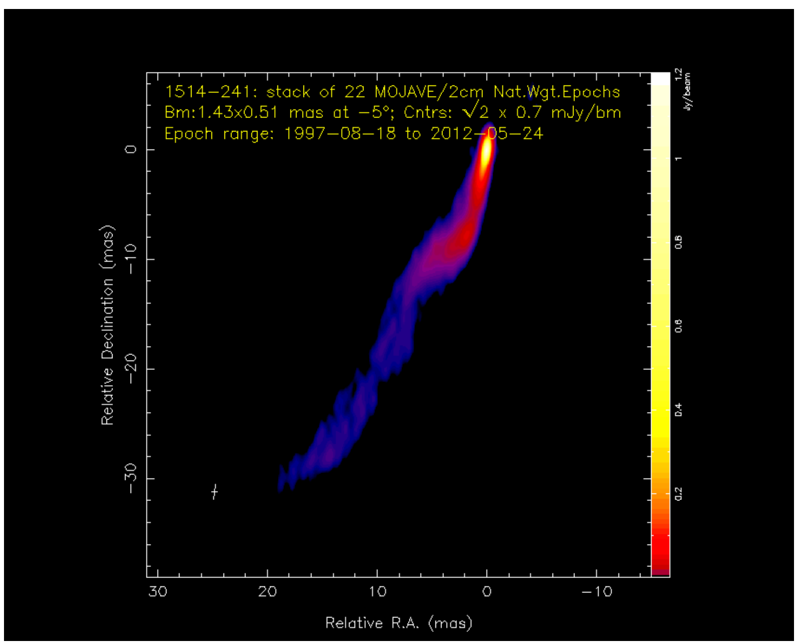
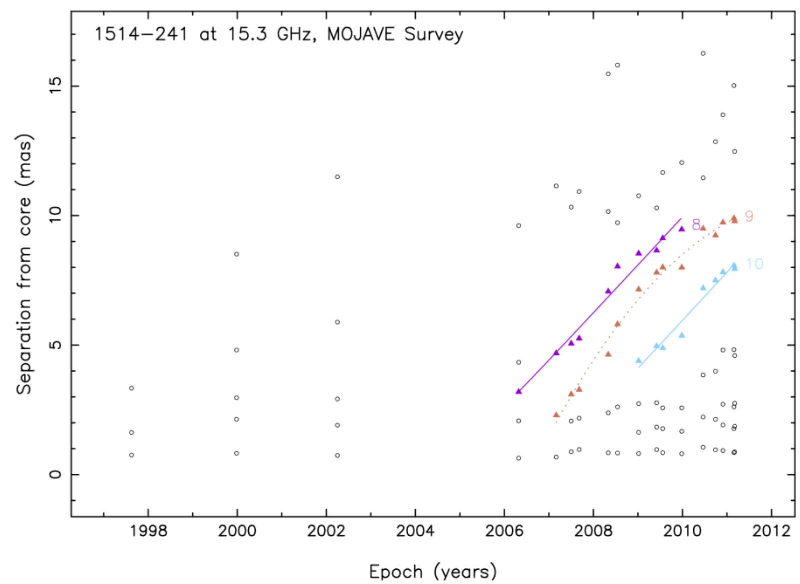
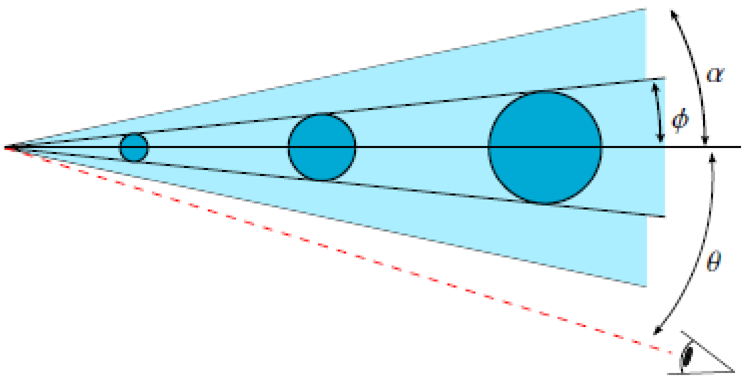
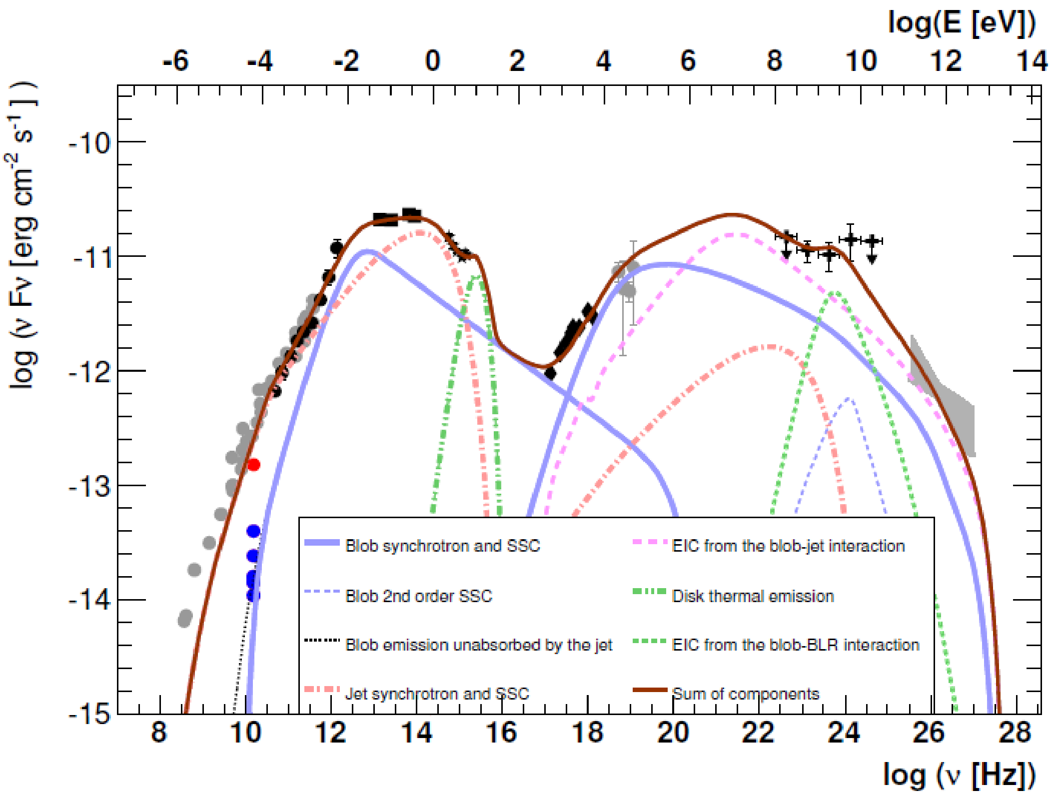


Fig. 23. 1514−241, VLA D configuration, 1.40 GHz (from NVSS, Condon et al. 1998). The restoring beam is 45.0 × 45.0 arcsec. The peak flux density is 1993 mJy/beam and the rms noise on the image is 0.40 mJy/beam









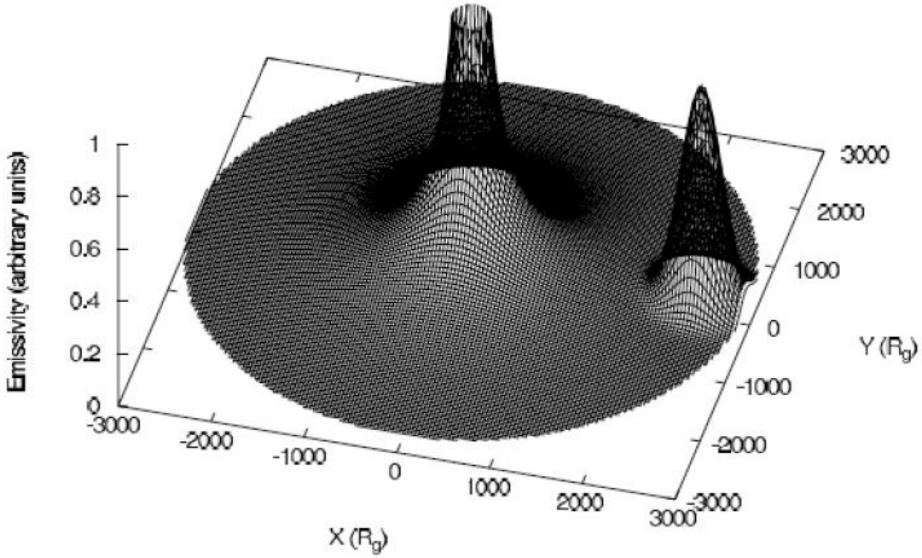
Blob-in-jet scenario for Ap Lib

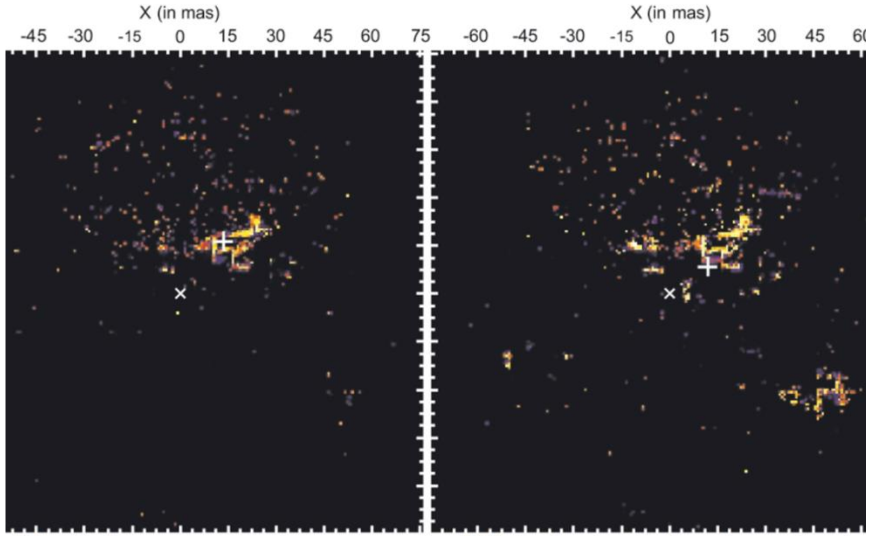
Radio VLBI + VHE data:
→ detailed description for the base of the jet provides a set of precise physical parameters (R, B, δ, N, γ, n, …)

→ sub-mas astrometry in optical and study of jet knots with GAIA could confirm (or dismiss) the model, and fix several assumptions and boundary conditions.

(Hervet et al, 2015)

Monitoring the thermal emission from bright standard disks





Model of a torus around a supermassive BH, the luminosity has changed and so has the inner radius, the photocenter moved by 8.4 mas

GAIA can detect photometric and photocentric variability of AGN due to the physics of the accretion in radio-quiet AGN (just a few seen at HE). Here two models of modified accretion disk and dust torus emissivity *(from Popovic et al 2012; Bonifacio, 2012)*

→ ***Constraints on the accretion regime, time evolution of disk and torus***

Possibly additional effects to disentangle: SN bursts, microlensing, BLR, non-thermal jets on mas and arcsec scale …

Multi-goal interest of GAIA data for AGN physics:

Monitoring: light curves, spectral changes, photocenter motions

Alerts: photometric, spectroscopic and astrometric ones

→ **Upward alerts**: detection of active states, which seems to favour VHE flares detection

→ **Downward alerts**: detection of a low activity level of the AGN, which can favour a better detection of host galaxy and host spectral lines, possibly allowing better redshift estimates (a real difficulty for many BL Lac objects seen at VHE)

Astrometric monitoring: possible detection of several optical components (knots in jets, disks, binary black holes ?...) + evolution of pc-scale jet at optical wavelength, a completely new information

Better estimates of the AGN contribution versus the host galaxy contamination in the optical fluxes

Possible discoveries of new AGN and new types of AGN (ex: transient activation of passive black hole by star capture)

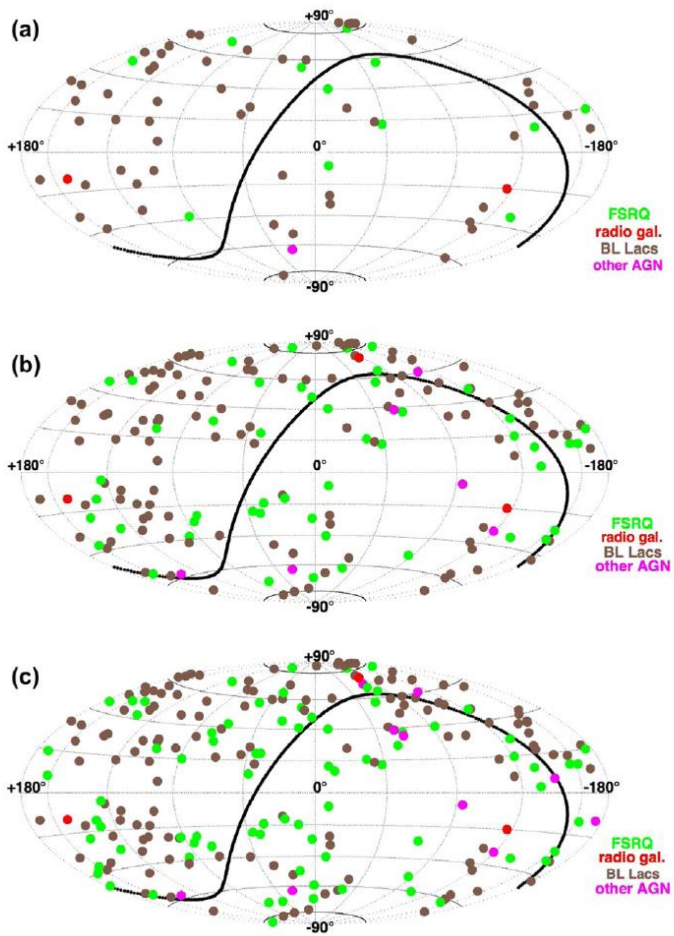
…

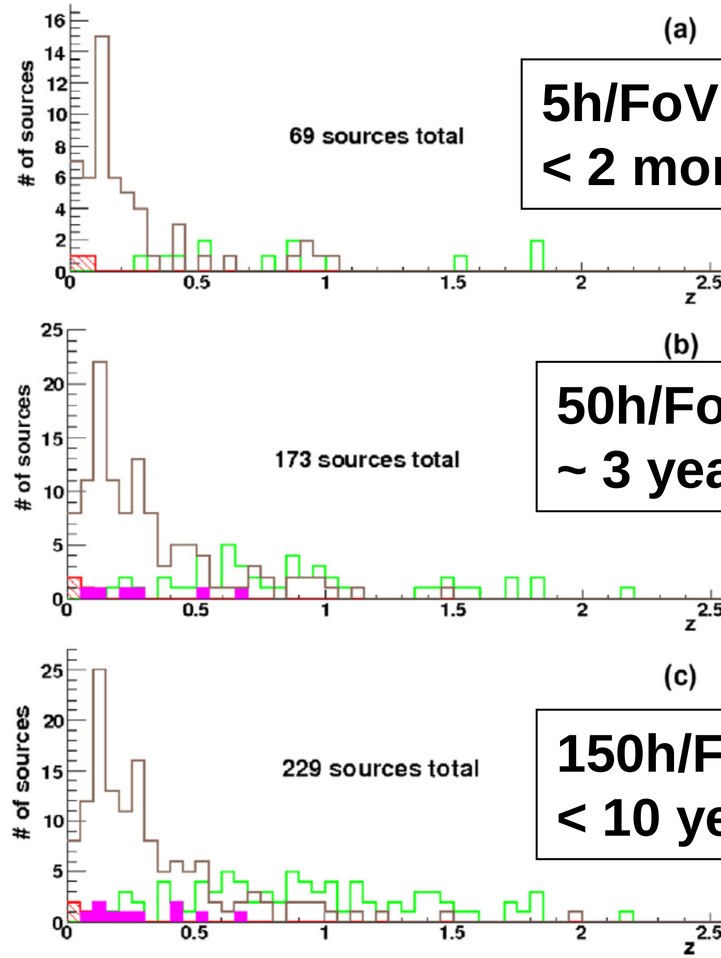
AGN population at VHE and

« preselected lists » of objects for GAIA ?

Active Galactic Nuclei with CTA

Extrapolation from Fermi





5h/FoV
< 2 months

50h/FoV
~ 3 years

150h/FoV
< 10 years

Assuming array B and 20° zenith angle over the whole sky *(Sol et al, 2014)*

Preselected list of HE/VHE targets for GAIA

- Include at least all AGN which are known TeV sources and « obvious » TeV candidates (i.e. a few hundreds)
- Extend to all AGN seen by Fermi at lower energy gamma-rays (> 1000 extragalactic sources in the new catalog) and to other possible TeV candidates
- Analysis of sources of the GAIA Celestial Reference Frame (GCRF) and of the thousands AGN of the ICRF, International Celestial Reference Frame
- GAIA could identify new interesting VHE candidates: all extragalatic GAIA sources with high photocenter motion, bright and enough nearby

2 Mauri J. Valtonen et al.

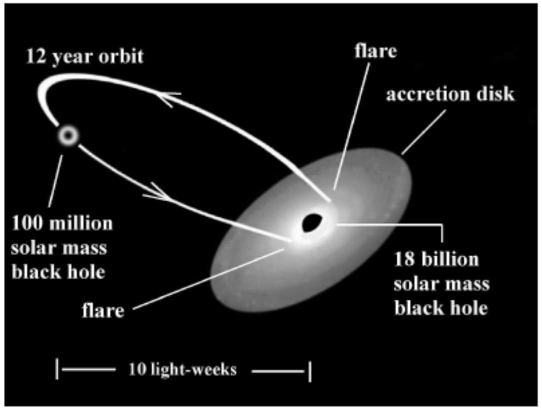


Figure 1. An illustration of the Sundelius et al. (1997) model. The jet is not shown, but it is taken to lie along the rotation axis of the accretion disc.

The peculiar LBL « OJ 287 »

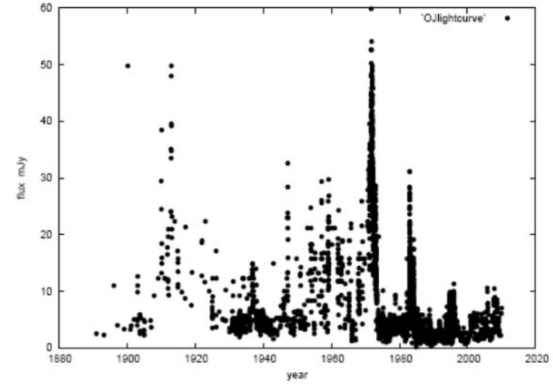


Fig. 1. The optical light curve of OJ 287 from 1891 to 2010. It includes unpublished data from R.Hudec and M.Basta

- z = 0.306
- Also known as « optically violent variable »
- Remarkable 12-year period discovered in long term optical light curve and confirmed in X-rays
- Many data available over decades from radio to X-rays
- Possible binary black hole
- Double-peaked outbursts often observed, and possible « pseudo-periodicity »
- Detected by Fermi, and predicted as detectable in VHE as well *(very good target for CTA)*
- Next « outburst » expected in ~ **2017**.

New physics: search for Lorentz Invariance Violation

- Quantum gravity models → possibility of energy dependence of the speed of light in vacuum (~ space-time distorsion) → velocity dispersion for massless particles at $E \sim E_{Planck}$:

$$c^2p^2 = E^2\,(1 \pm \xi_1(E/E_P) \pm \xi_2^{\,2}\,(E/E_P)^2 \pm \ldots)$$

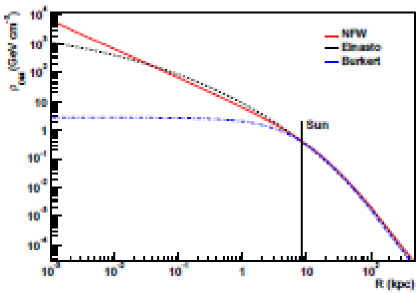
- Induced time delay between 2 photons with a difference in energy of ΔE

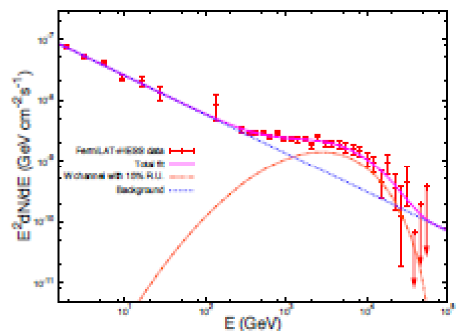
$$\Delta t \sim (\Delta E \,/\, \xi_\alpha\, E_P)^\alpha\,(L/c),$$ where L is the distance of propagation

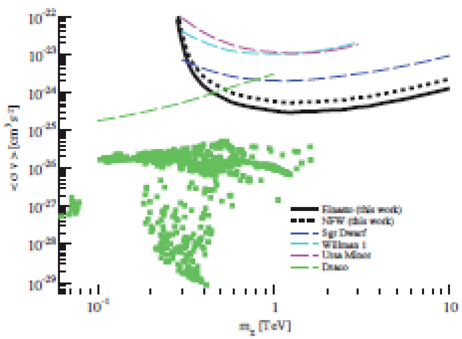
- Fermi with a GRB and HESS with a blazar: best constrain the linear and quadratic term with no time delay detection so far

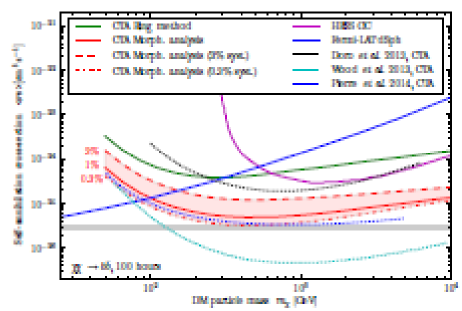
- Requires a large sample of variable sources, AGN and GRB, at various z to disentangle intrinsic and propagation effects, *and as bright as possible*

Dark matter studies

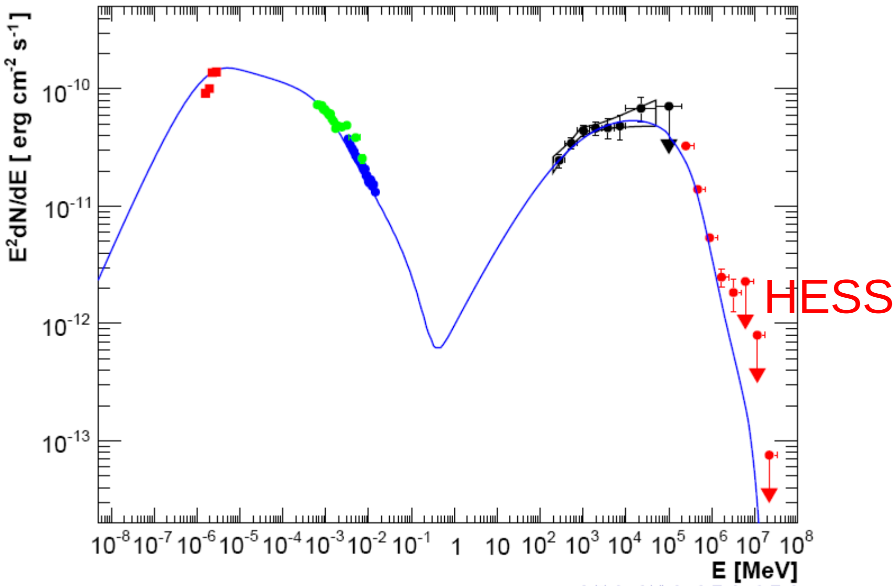








However, PKS 2155 in 2008 (lower state):



New multi-lambda campaign in 2008, including HESS, Fermi, RXTE, SWIFT, ATOM

Find complexity of correlation between various lambda :
Simple SSC model can not explain all correlation properties.
Correlations appear different between active and low states.

→ needs detailed radio-optical-X-γ monitoring for further analysis
→ ***interest of GAIA photometric and spectroscopic monitoring and alerts***