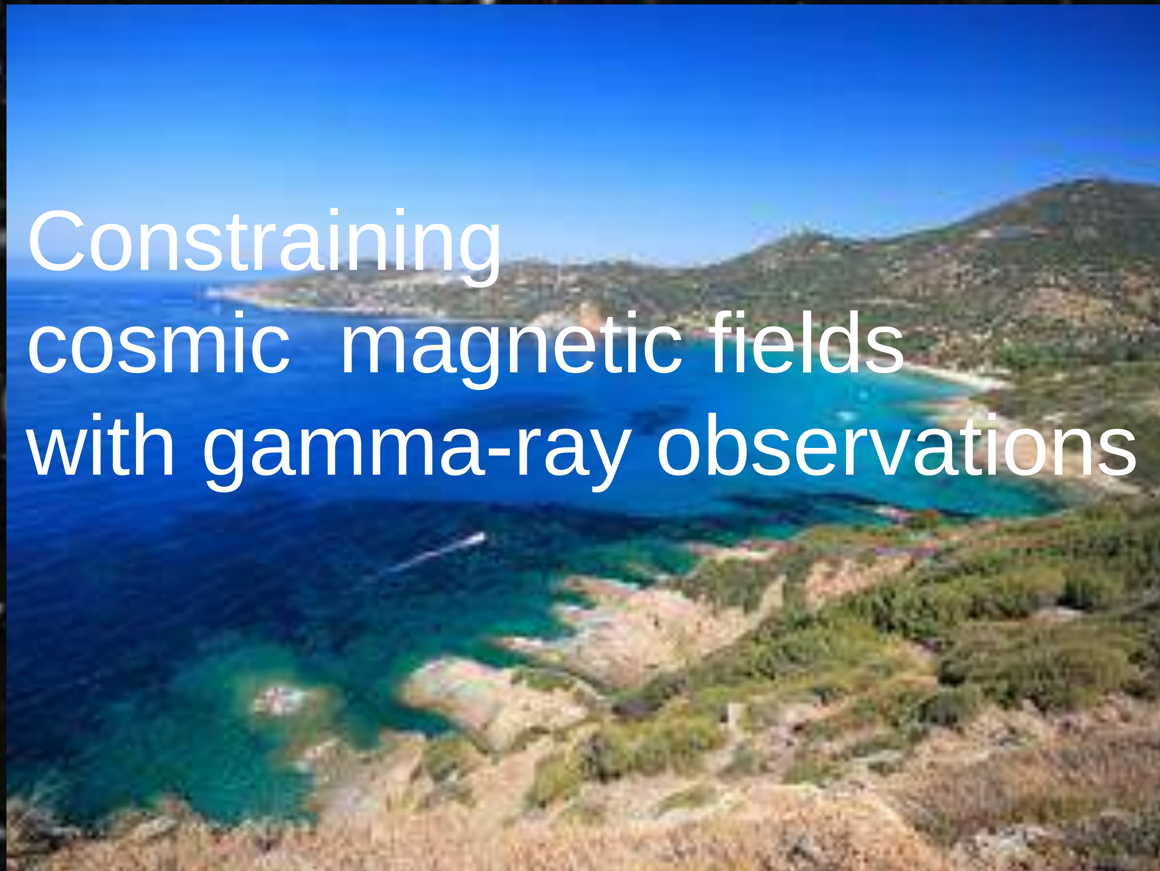
Constraining cosmic magnetic fields with gamma-ray observations



Hélène Sol
Paris Observatory, CNRS

Magnetic fields in the Universe: from Laboratory and Stars to primordial Structures
Cargèse International School 2015, October 5-9, 2015

Outline

I) Astronomy at Very High Energies (VHE)

II) Active Galactic Nuclei: Constraining magnetic field values in AGN jets

III) InterGalactic Magnetic Field: High-redshift AGN as beacons of TeV gamma-rays to probe the IGMF and the search for secondary GeV-TeV components

- extended emission and pair *haloes*
- pair *echoes*

IV) Search for haloes or echoes: current attempts and prospect with future gamma-ray instruments

I) ASTRONOMY AT VERY HIGH ENERGIES

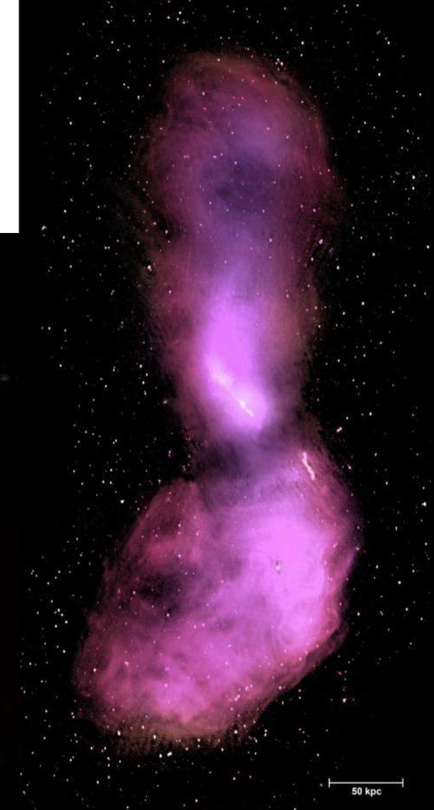
VERITAS (USA)

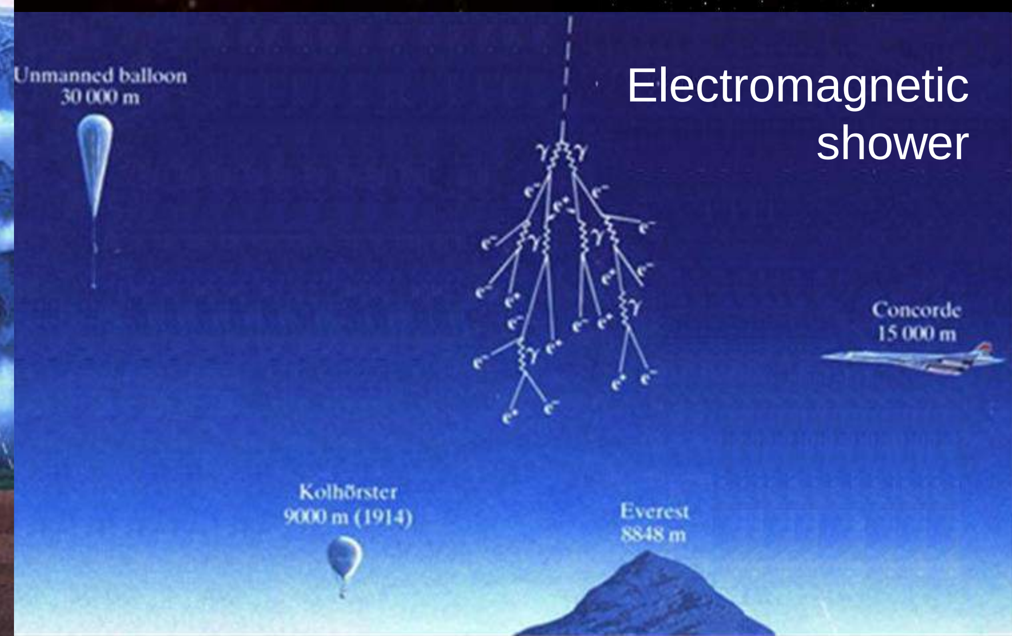
MAGIC (Canaries)

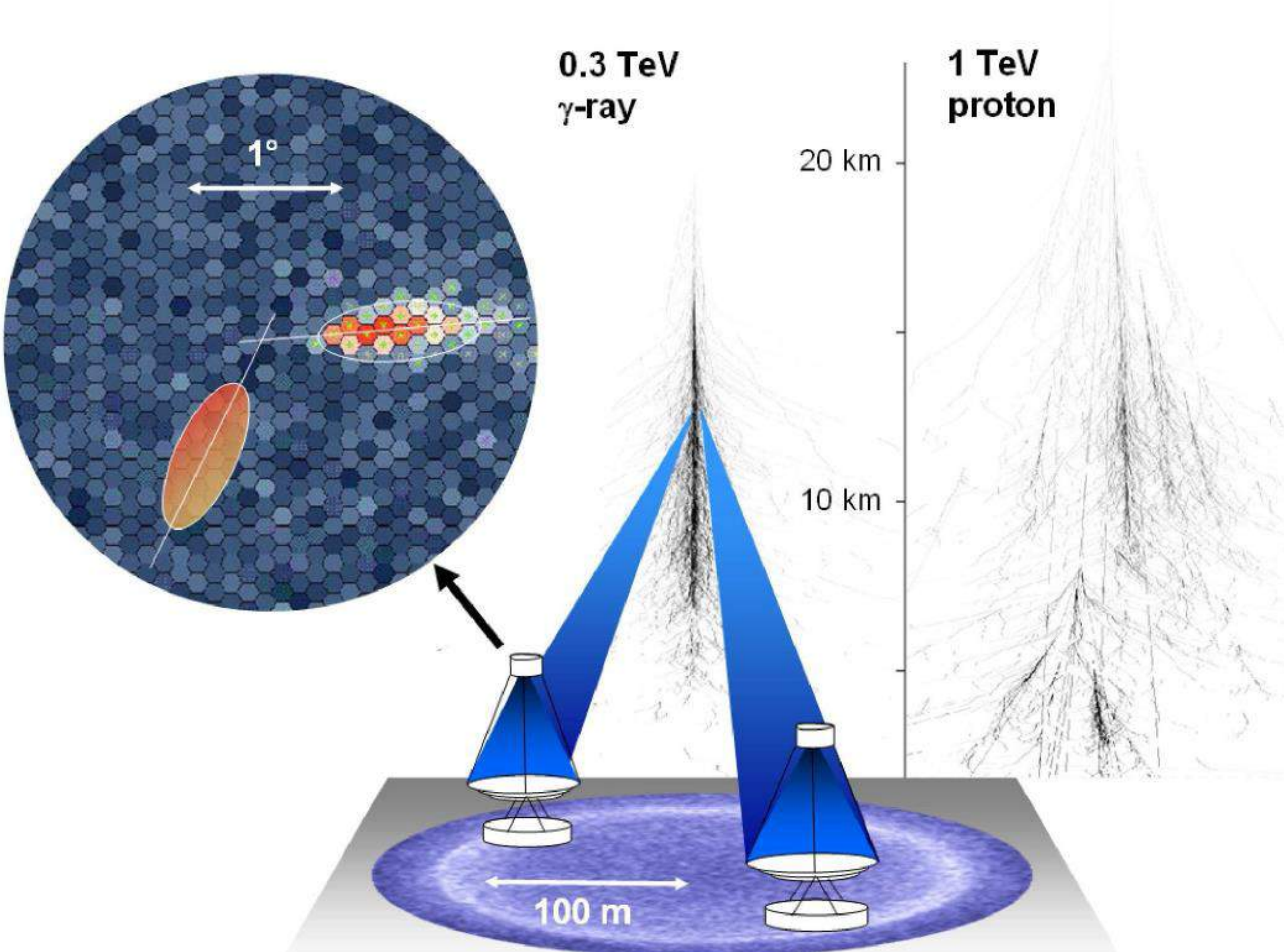
Present ground-based Imaging Atmospheric Cherenkov Telescopes have now detected up to ~ 167 cosmic sources at Very High Energies, galactic and extragalactic.

HESS in phase 2 (Namibia)
with its very large 28m-telescope

Detection of VHE gamma-rays : the atmosphere as 1st part of the detector





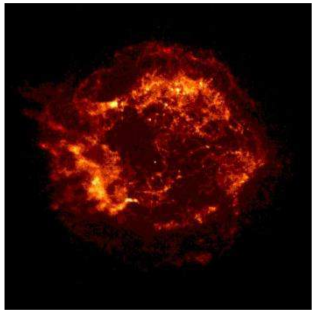


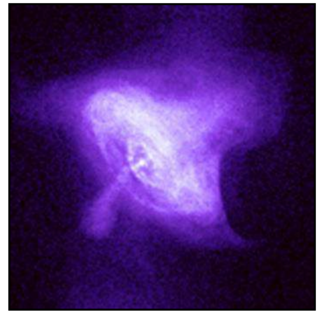
Arrays of telescopes allow a stereoscopic view of the showers

(from Hinton, Hoffman, 2010)

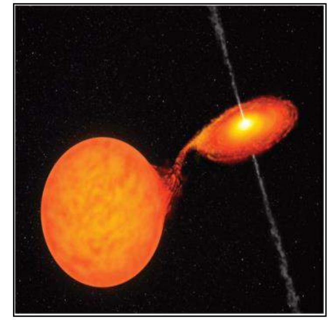
VHE science in a nutshell

SNRs
& ISM





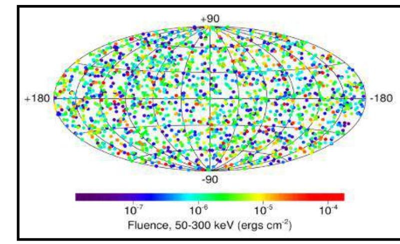
PWN & Pulsars



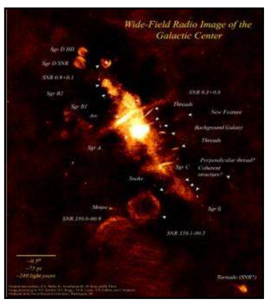
Binary systems

Physics of Cosmic Rays and particle accelerators

Galactic

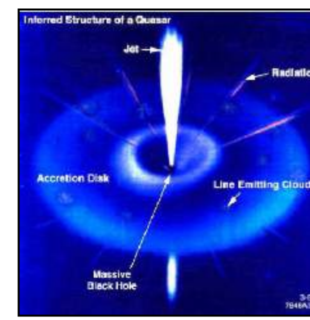


GRBs

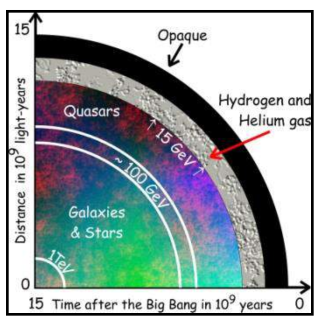


Galactic Center; Search for Dark Matter

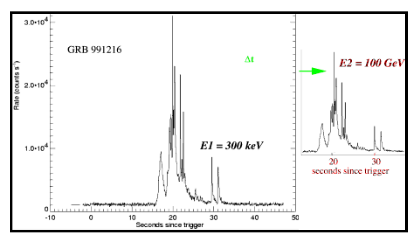
Extragalactic



AGNs & starburst galaxies

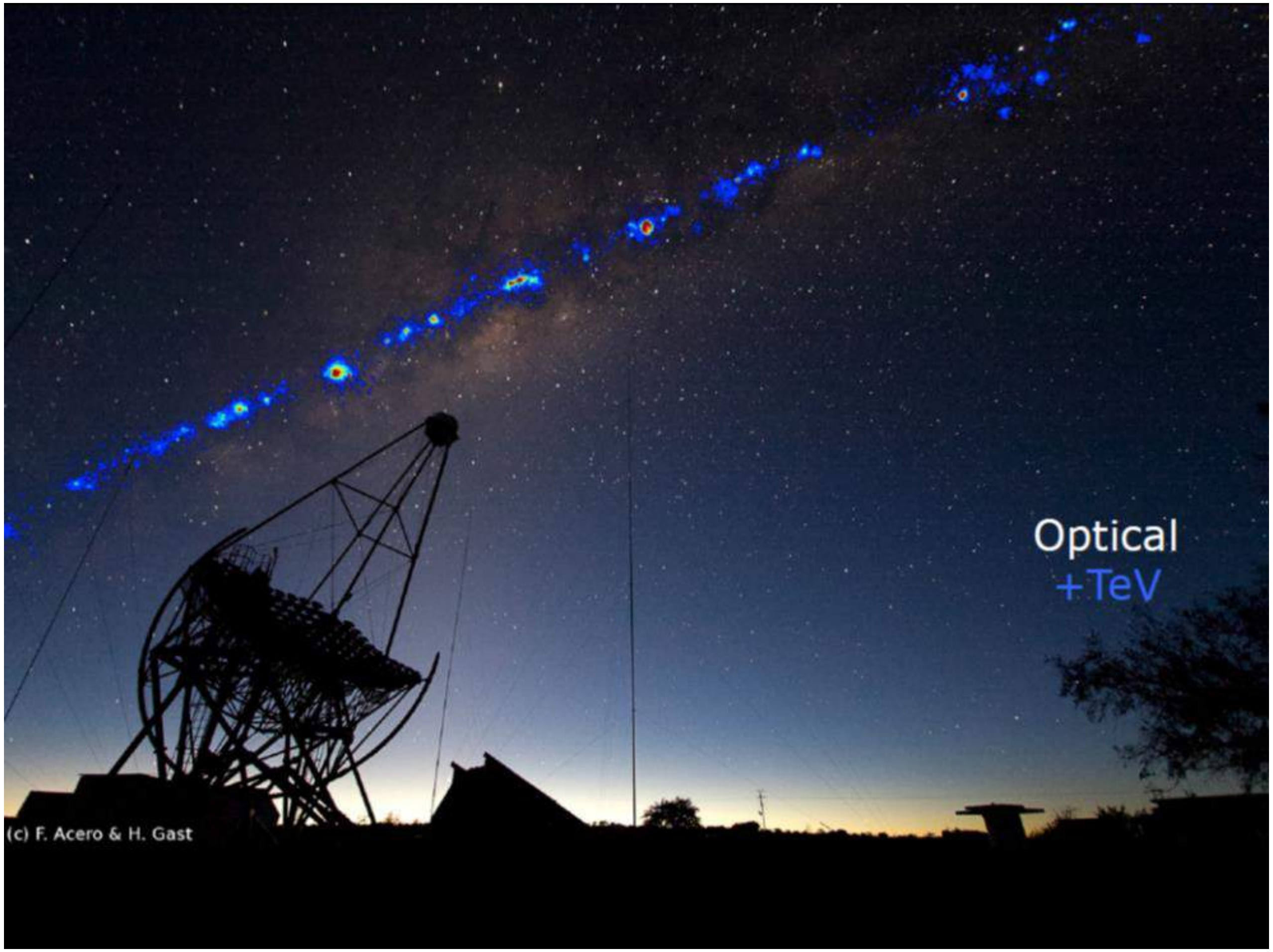


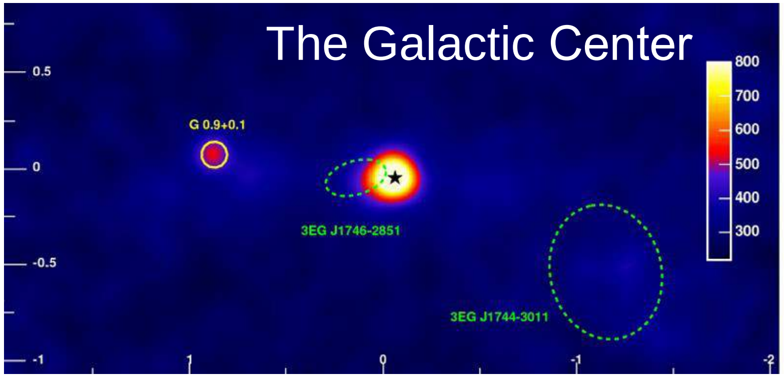
Gamma-ray horizon and diffuse backgrounds; Search for ALP

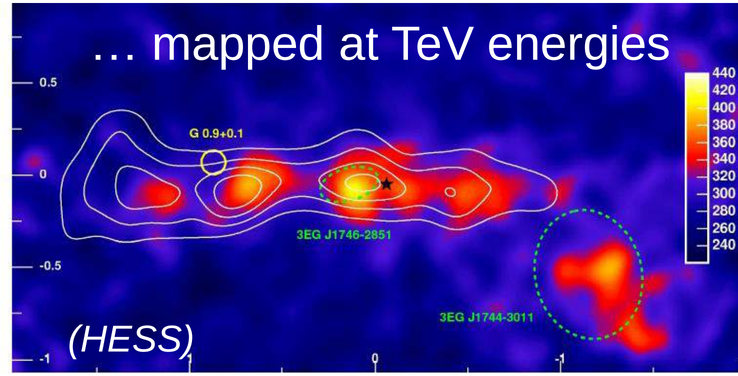


Test of the speed of light invariance (LIV) *the night sky in the optical range*

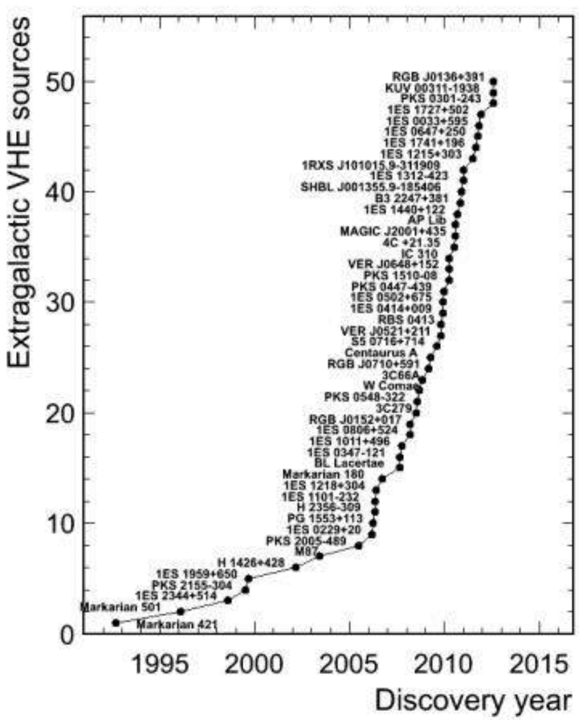
the night sky « seen » in VHE gamma-rays



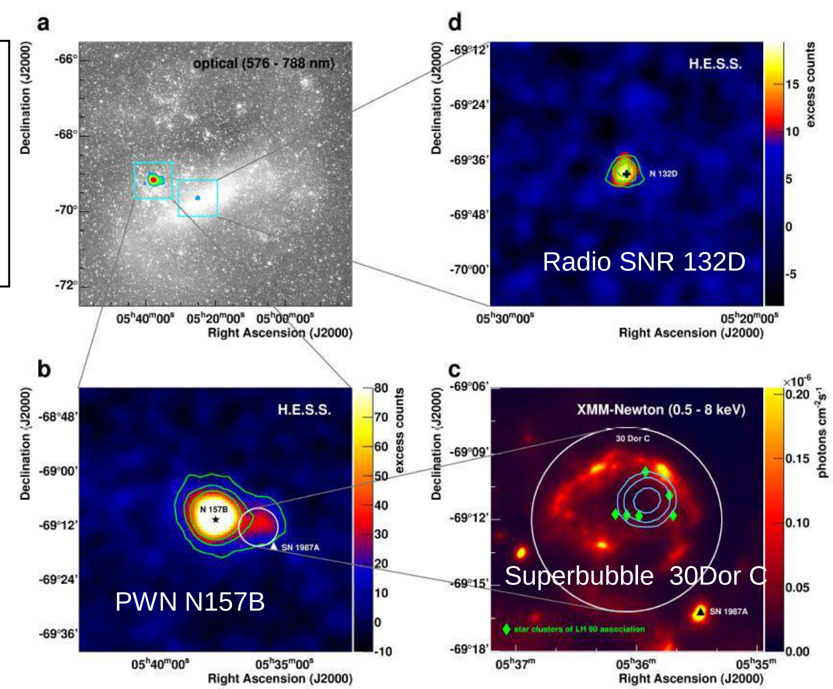




VHE science: A new branch of astronomy which emerged in 2005



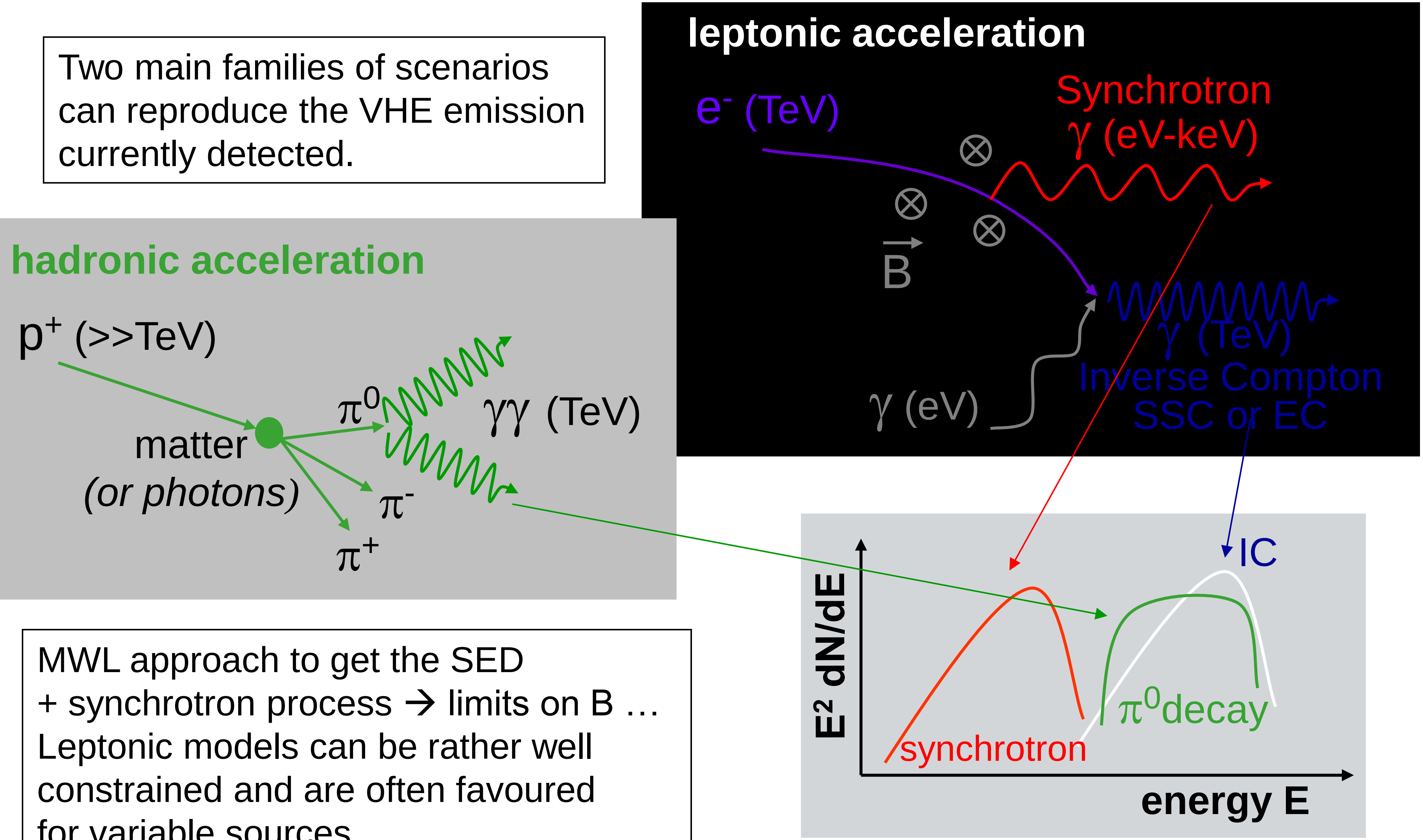
3 bright VHE sources in the LMC *(HESS, 2015)*



Now about 65 AGN, mostly blazars, with confirmed detection at TeV energies

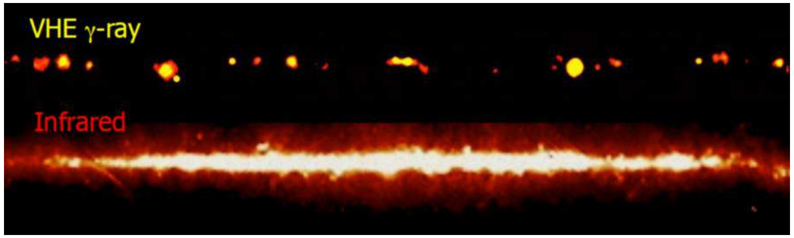
AGN at VHE: non-thermal large band emission

Two main families of scenarios can reproduce the VHE emission currently detected.



MWL approach to get the SED
+ synchrotron process → limits on B …
Leptonic models can be rather well constrained and are often favoured for variable sources.

VHE astronomy of near future ~ (a few) **thousands** of TeV sources **versus billions** of sources of radio, IR, optical, X-ray astronomy



Is VHE the 'poor' cousin of Astrophysics ? Not really

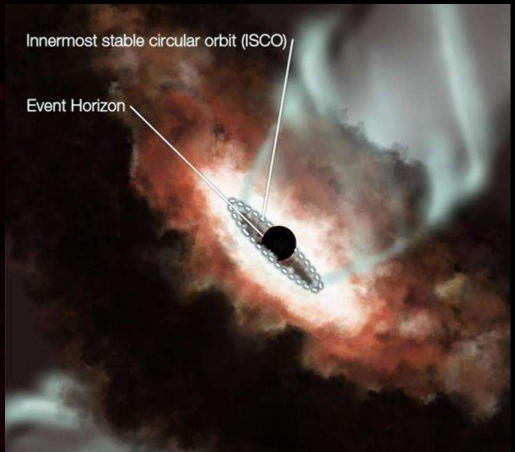
VHE astronomy = shapes the **energy skeleton of the universe**

Sparse but structuring vision of the cosmos

The **turbulent and transient** universe, **extreme and even cataclysmic** phenomena, **energy cycle** and transfer, **probe** of space-time

→ 2 examples here: AGN & IGMF

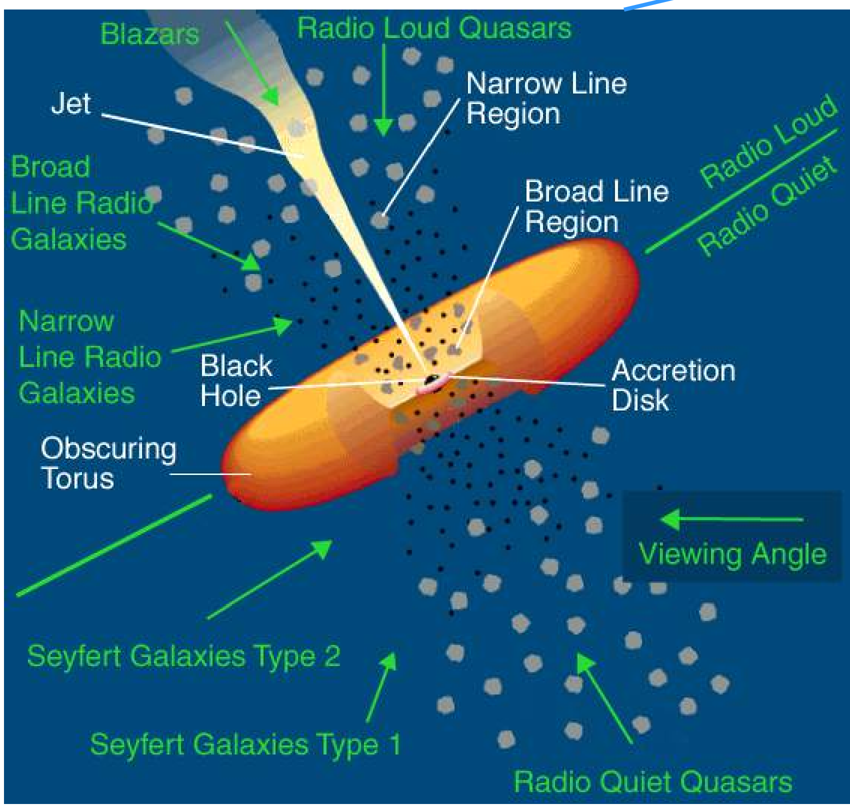
II) Magnetic field in AGN jets from VHE data

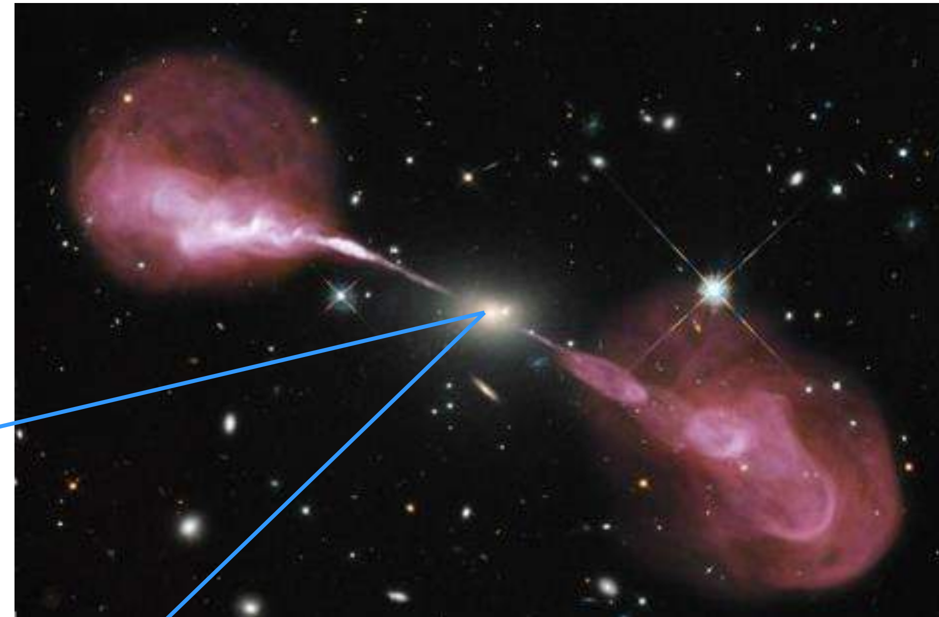


Artistic view of central engine

Multi-lambda view of Cen A

Active Galactic Nuclei in brief

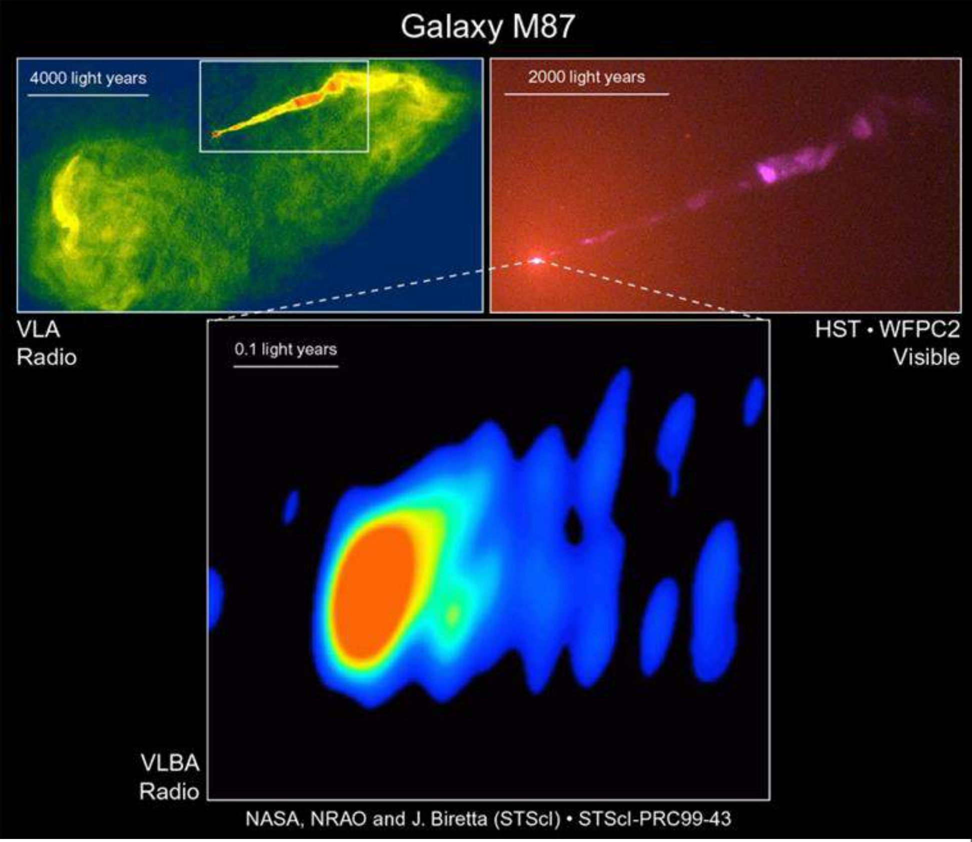




Large scale structure:
Radiogalaxy Hercules A
(VLA + HST)
2.5×10^9 $M_\odot$ Black Hole

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

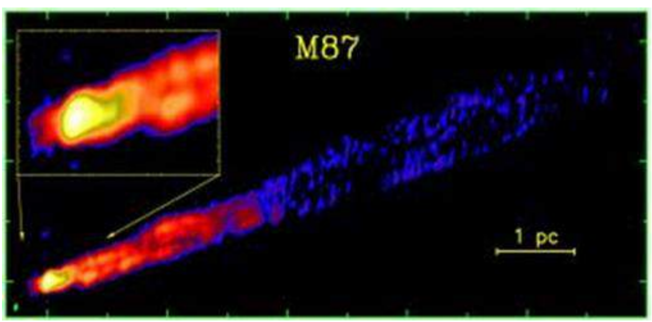
VHE AGN sample: dominated by blazars due to relativistic Doppler boosting

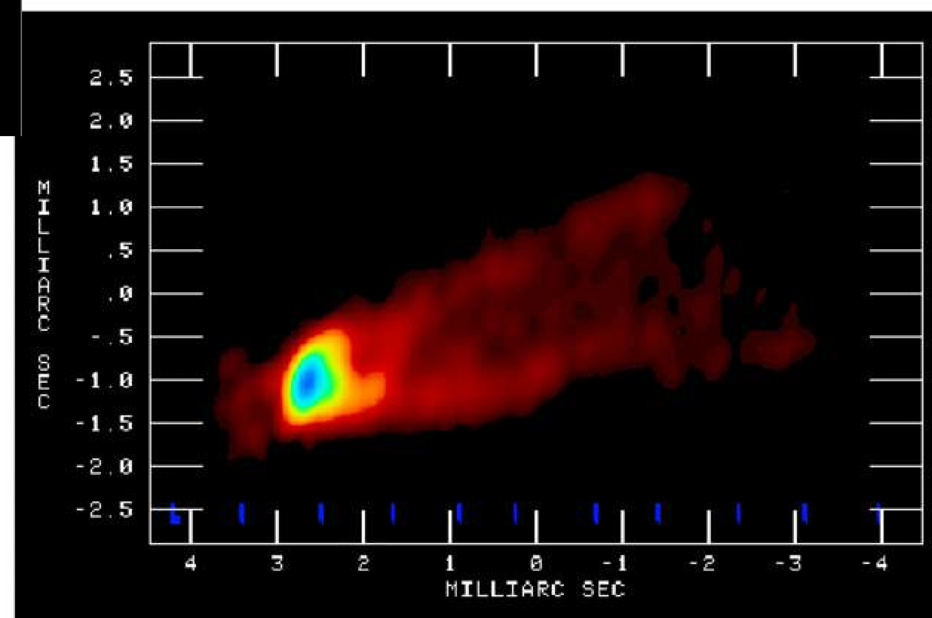


Here the radio galaxy **M87** from kpc to sub-pc scales.

Radio VLBI data can probe the regions very close to the central black hole down to a few Schwarzschild radius (sub-mas, sub-pc)

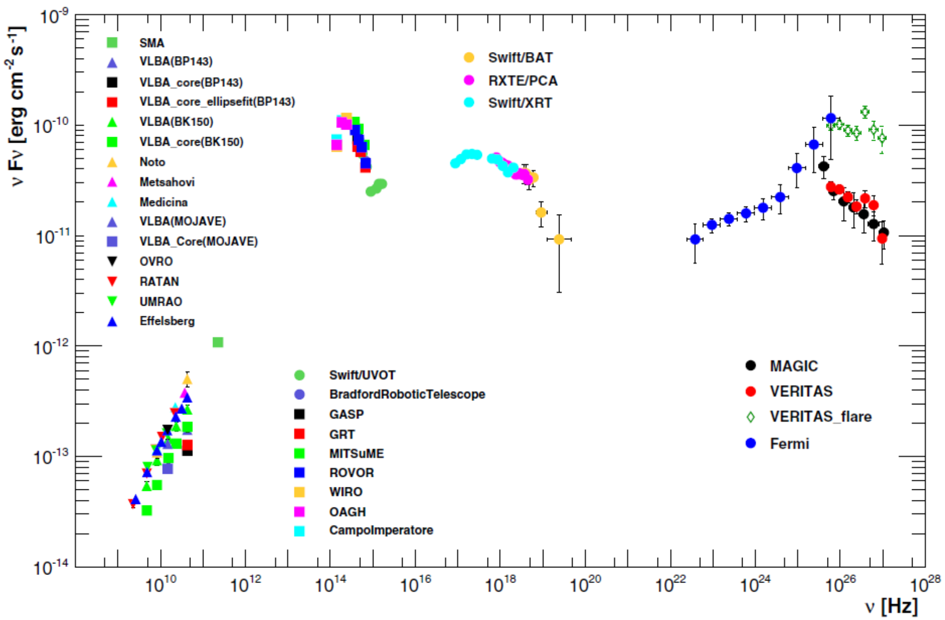
Time evolution of the radio VLBI jet on mas scale:



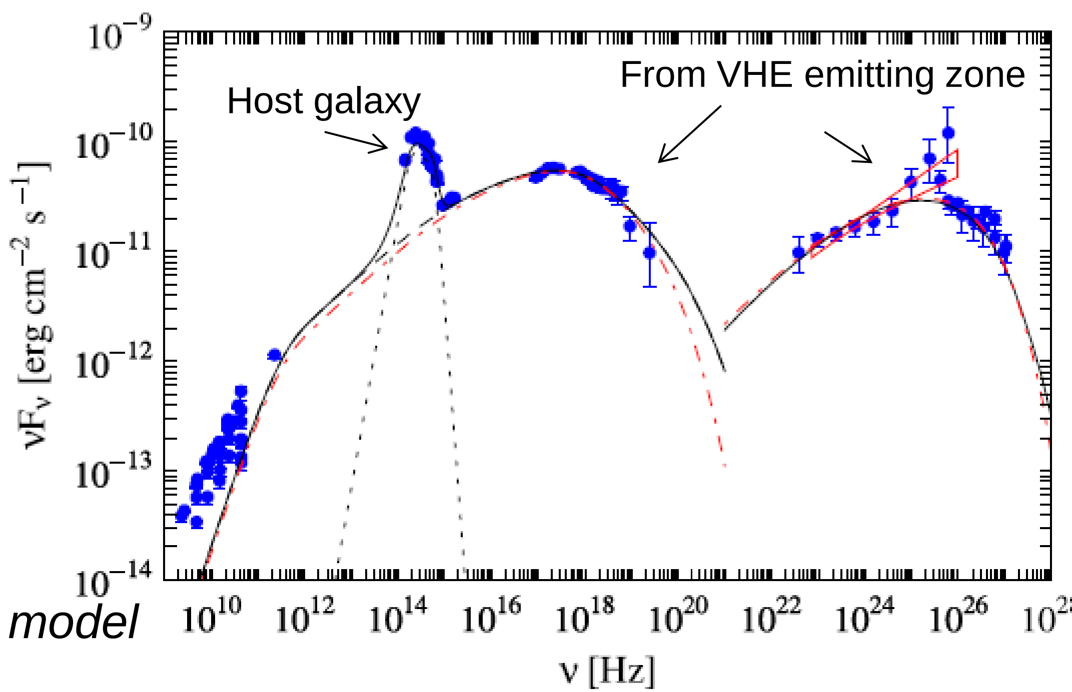


A typical northern HBL blazar:
Mrk 501

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



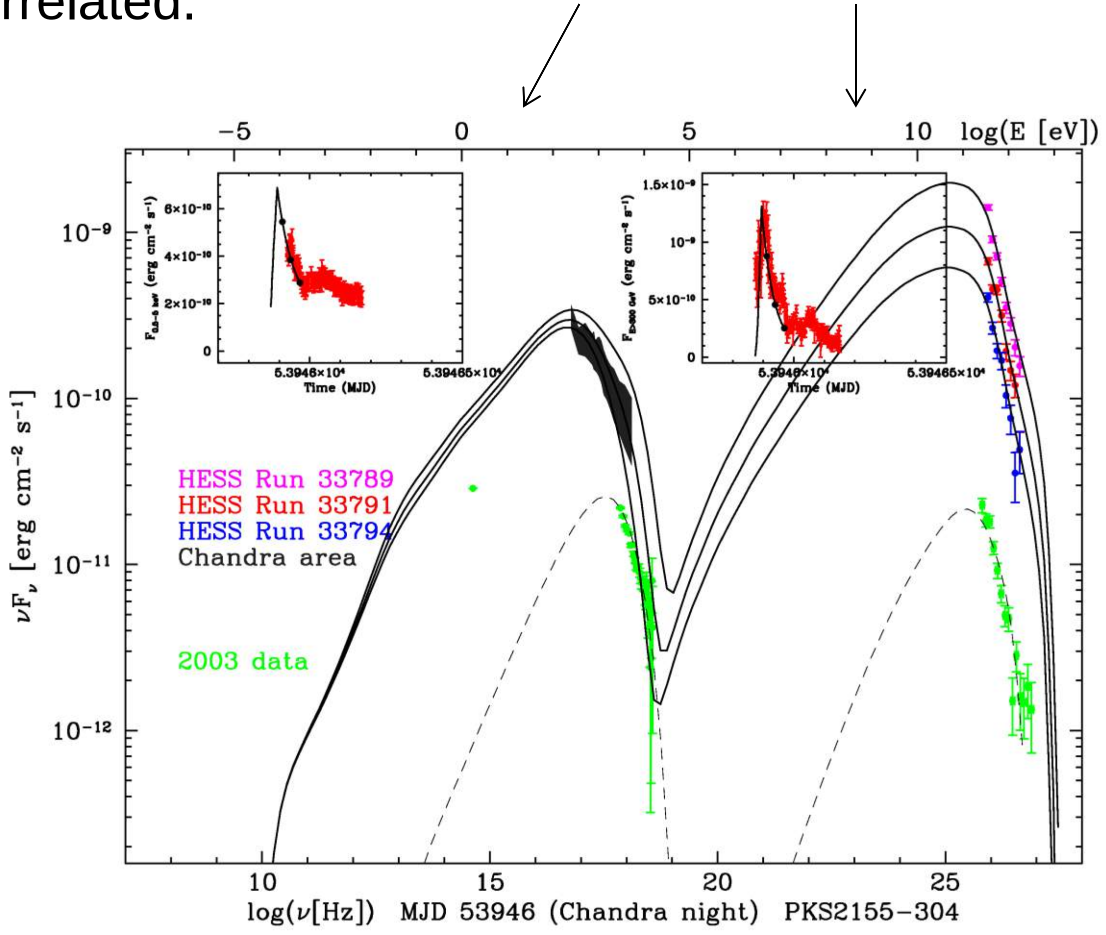
MWL campaign on Mrk 501
Example from Abdo et al, 2011



Here fit by stationary SSC model

A typical southern HBL blazar: **PKS 2155-304**

SSC time-dependent model can fit bright flaring events
Reproduce *light curves* and *spectra* of flare in X-rays and gamma rays which appear highly correlated.



(Lenain et al, 2011)

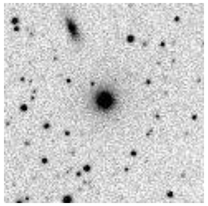
An intermediate blazar: **Ap Librae**

LBL type blazar, at z = 0.049

R, ESO 1m Schmidt

VLA 1.4 GHz

One of the rare intermediate blazars detected at VHE.



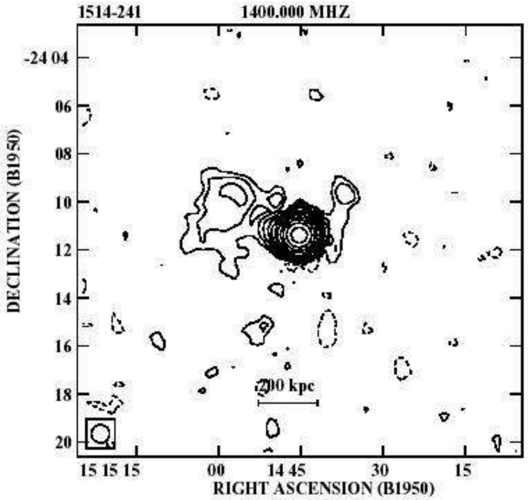
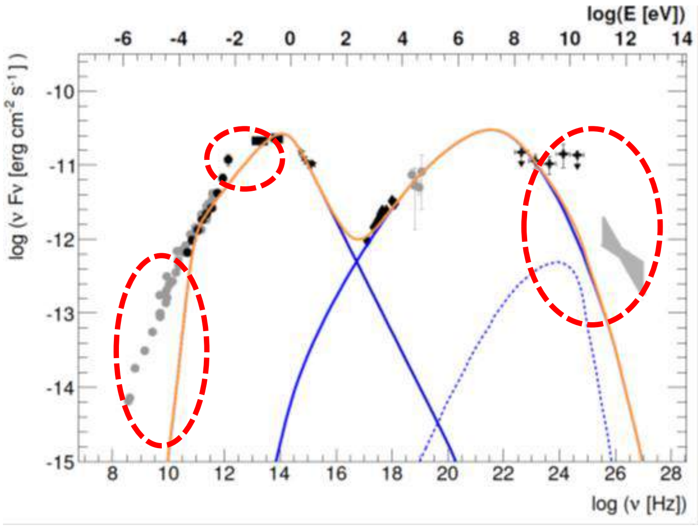
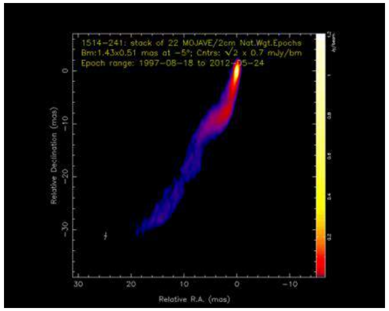


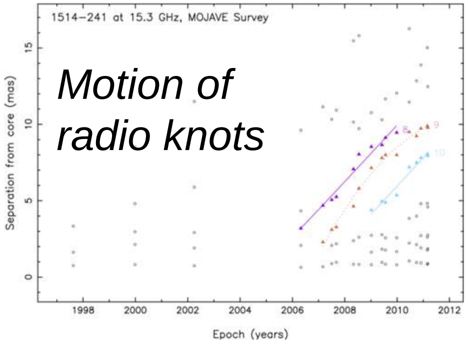
Fig. 23. 1514−241, VLA D configuration, 1.40 GHz (from NVSS, Condon et al. 1998). The restoring beam is 45.0 × 45.0 arcsec. The peak flux density is 1993 mJy/beam and the rms noise on the image is 0.40 mJy/beam



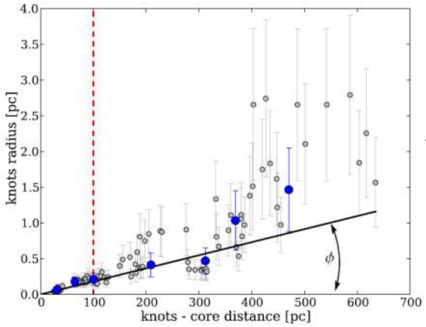
← Basic one-zone SSC models - with a single relativistic HE emitting blob - do not succeed to fit the SED of such intermediate source.

- Needs a more detailed scenario taking into account several effects negligible for extreme HBL type blazars mostly seen at VHE: influence of the jet in which the blob is embedded, jet-blob ‘interaction’, external Inverse-Compton on accretion disk radiation scattered by BLR clouds
- Problem: many additional free parameters!
- Constrain them from MWL data, especially VLBI ones which are detailed enough for an intermediate LBL type blazar to model its jet



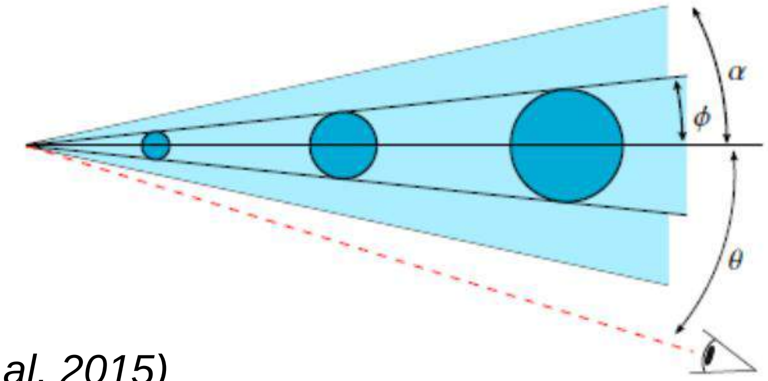


Motion of radio knots



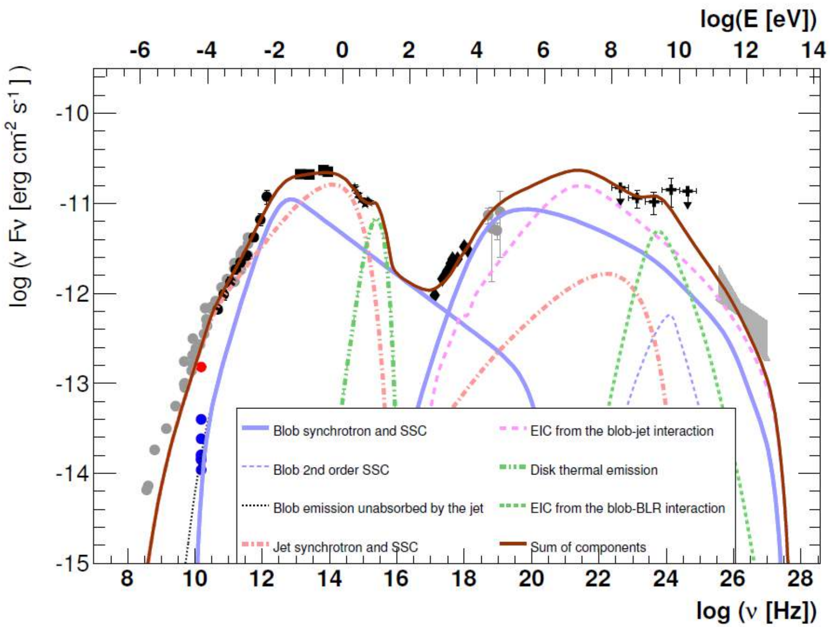
Expansion of radio knots

VLBA data from MOJAVE programme:
→ allow to fix speeds, viewing angles, opening angles, blob and jet expansion …
→ constrain the geometry and kinematics
→ scenario consistent with the assumption of continuity between VHE blobs evolving into radio knots with distance from the central engine.



(Hervet et al, 2015)

SED of AP Lib: well reproduced by a detailed blob-in-jet scenario



→ **B** ~ 0.06 to 0.08 G at 3pc

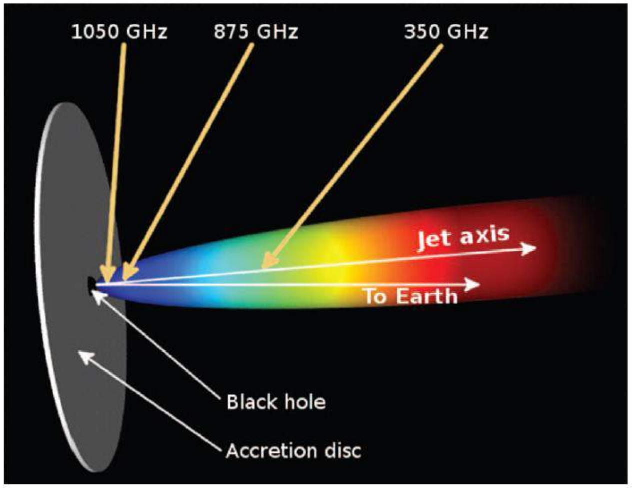
→ cold p^+e^- population dominates the non-thermal energetic one, with **density n_e** ~ 7 x 10^4 cm^{-3} in blob, and ~ 4 x 10^3 cm^{-3} in jet

(Hervet et al, 2015)

Blob parameters	Value	Unit
δ_b	22	–
θ_b	1.4	deg
K_b	2.0×10^5	cm^{-3}
n_1	2.0	–
n_2	3.6	–
$\gamma_{min/b}$	600	–
$\gamma_{max/b}$	4.0×10^6	–
$\gamma_{break/b}$	8.0×10^2	–
B_b	6.5×10^{-2}	G
R_b	6.2×10^{15}	cm
Jet parameters		
δ_{jet}	10.0	–
$K_{1,jet}$	50.0	cm^{-3}
n_{jet}	2.0	–
$\gamma_{max/jet}$	1.65×10^4	–
$B_{1,jet}$	8.0×10^{-2}	G
$R_{1,jet}$	2.5×10^{16}	cm
L	100	pc
α	0.4	deg
$D_{blob-BH}$	7.9×10^{18}	cm
nb_{slices}	50	–
Nucleus parameters		
T_{disk}	3.2×10^4	K
L_{disk}	5.0×10^{43}	erg s^{-1}
R_{BLR}	7.9×10^{18}	cm
τ_{BLR}	3.5×10^{-2}	–

Perspective: Faraday rotation measures could further validate (or not) the scenario proposed for AP Lib type sources, with RM = $8.1 \times 10^5 \int n_e B_{//} dl /(1+z)^2$

Such RM measures have been obtained by ALMA for PKS 1830-211, a gravitationnally lensed AGN at z = 2.7 *(Marti-Vidal et al, 2015)*



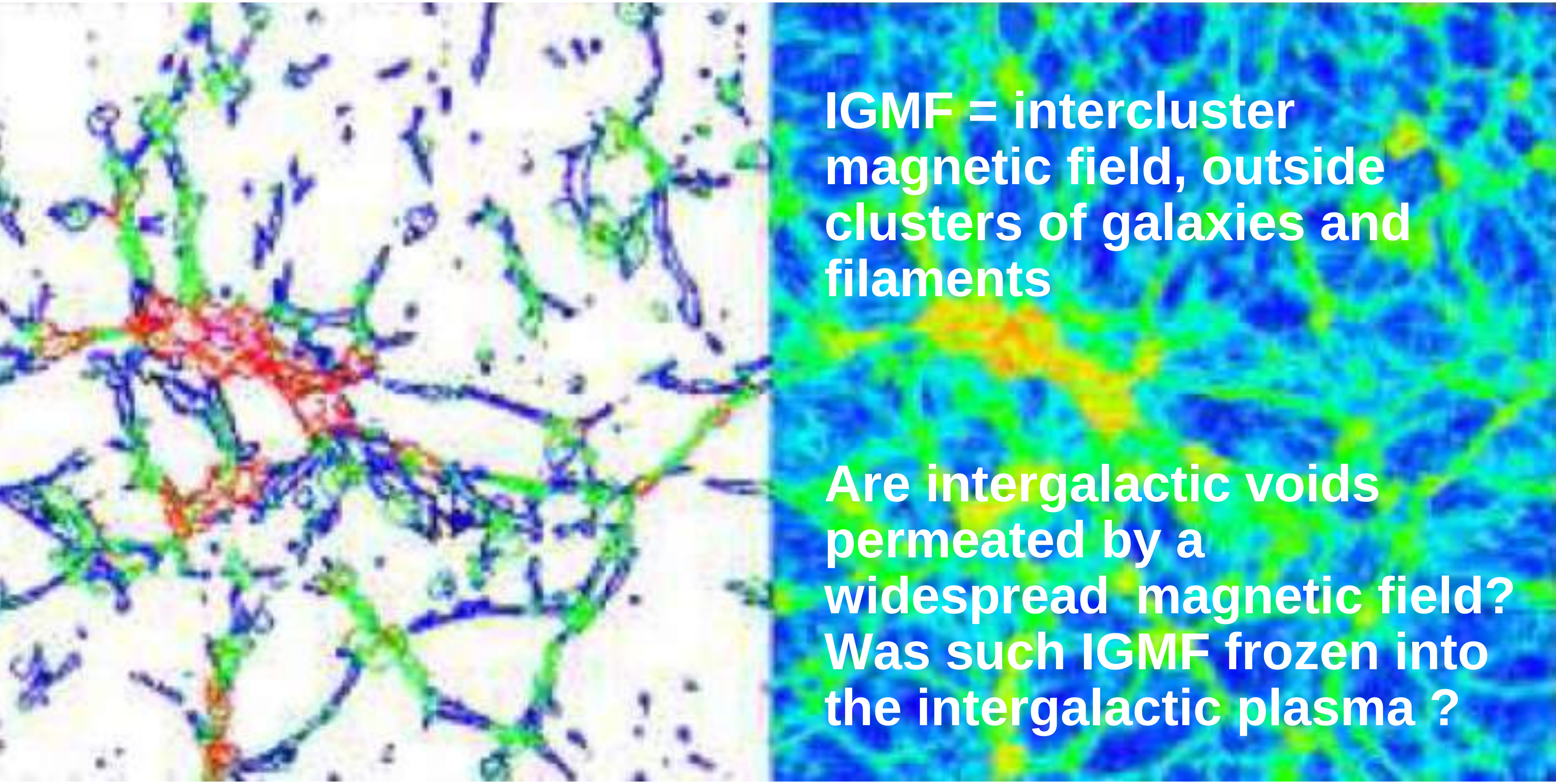
RM ~ 10^8 rad/m^2 suggest ***very high B*** at the jet base, B > tens of G at 0.01 pc.

Knowledge of densities in this jet would complete the description.

RM variations detected, possibly related to γ-ray flares observed at the same epochs.

*Interesting perspective of monitoring **B** and **n_e** close to central engines, further exploring the radio-gamma connection.*

III) Intergalactic Magnetic Field



Implications of detecting a non-zero IGMF:

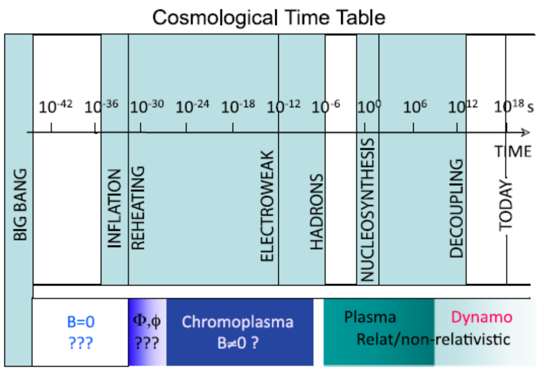
- Provides new information on the early universe
- Completes the dynamo description for the origin of cosmic magnetic fields.
- Provides magnetic seed fields for any dynamo amplification process
- Appears as an alternative to some dynamo scenarios,
  especially useful to explain young magnetized structures,
  with little time for dynamo growth.

Constraints on IGMF usually provide upper limits:

- Big-bang nucleosynthesis of light elements
  $B_{IG} < 10^{-6}$ G
- Cosmic microwave background anisotropies *(Daniela's talk)*
  $B_{IG} < 10^{-8} - 10^{-9}$ G …
- Faraday rotation measures of radio-loud AGN
  $B_{IG} < 6 \times 10^{-12}$ G $- 10^{-9}$ G *(model-dependent)* …

VHE emission from remote AGN can provide lower limits and could find evidence for a non-zero IGMF.

Generation of an IGMF? 1°) primordial universe



If B= 0 at the beginning, need to find a time/place where flux freezing is not valid to start the magnetic field …
(Widrow et al, 2012)

During inflation : Quantum fluctuations can produce large scale phenomena from microphysical processes. Low-conductivity permits increase of magnetic flux. Electromagnetic quantum fluctuations amplified during inflation could appear now as static IGMF, electric fields being screened later on during the highly conducting plasma epoch
(Grasso, Rubinstein, 2001;
Kandus et al, 2011)

Post inflation : Decoupling transitions of fundamental forces (changes in nature of particles and fields + release of free energy → electric currents → generation of magnetic fields).
Quark-hadron phase transition, electroweak phase transition
[1st order transition; bubbles and shock fronts …]

(Grasso, Rubinstein, 2001)

Generation of an IGMF?
2°) magnetized outflows and dynamo

- Difficulties of primordial B scenarios:

  - B from inflation are very weak,
  - B from phase transition tend to have very small scales

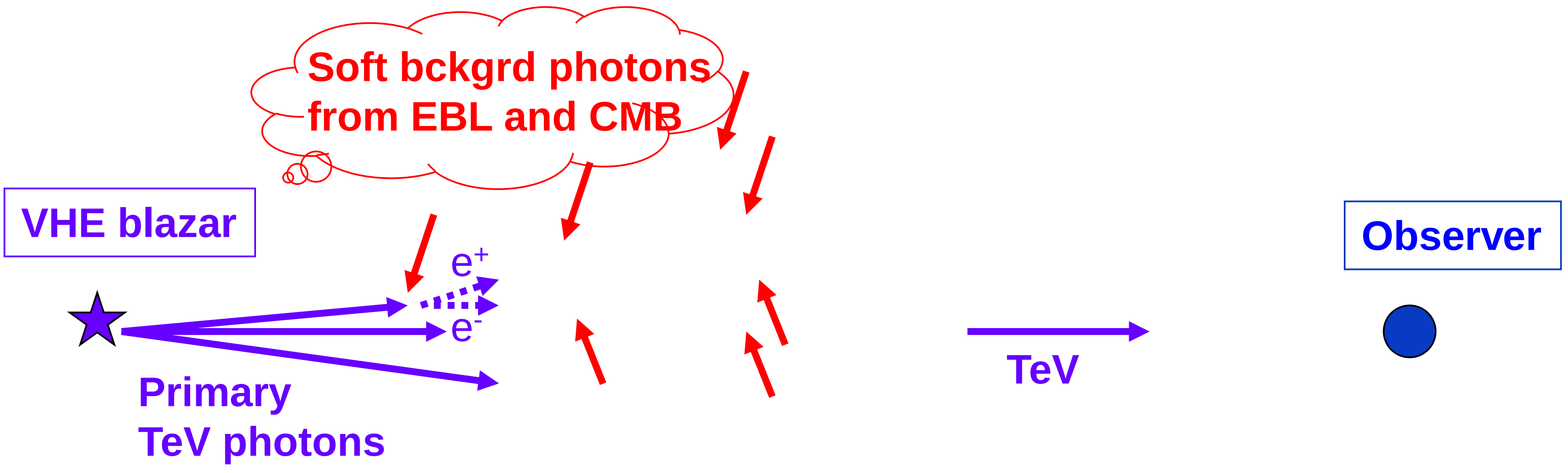
  → might be too weak or too small to serve as seed fields for galactic magnetic fields *(Kandus et al, 2011; Widrow et al, 2012)*

- Astrophysical origin of IGMF: later formation by ejection of magnetized plasmas into intergalactic space, from galaxies, AGN, starbursts, Pop III stars, large scale shocks *(Kronberg, 1994; Widrow et al, 2012; Ryu et al, 2012; Lilly, 2012 …).*

- Seed fields amplified by turbulent flows during the formation of large scale structure of the universe, magnetic helicity and inverse cascade process *(Ryu et al, 2011; Widrow et al, 2012 …)*

TeV gamma-ray signal from high-z blazars

TeV gamma-ray signal from high-z blazars

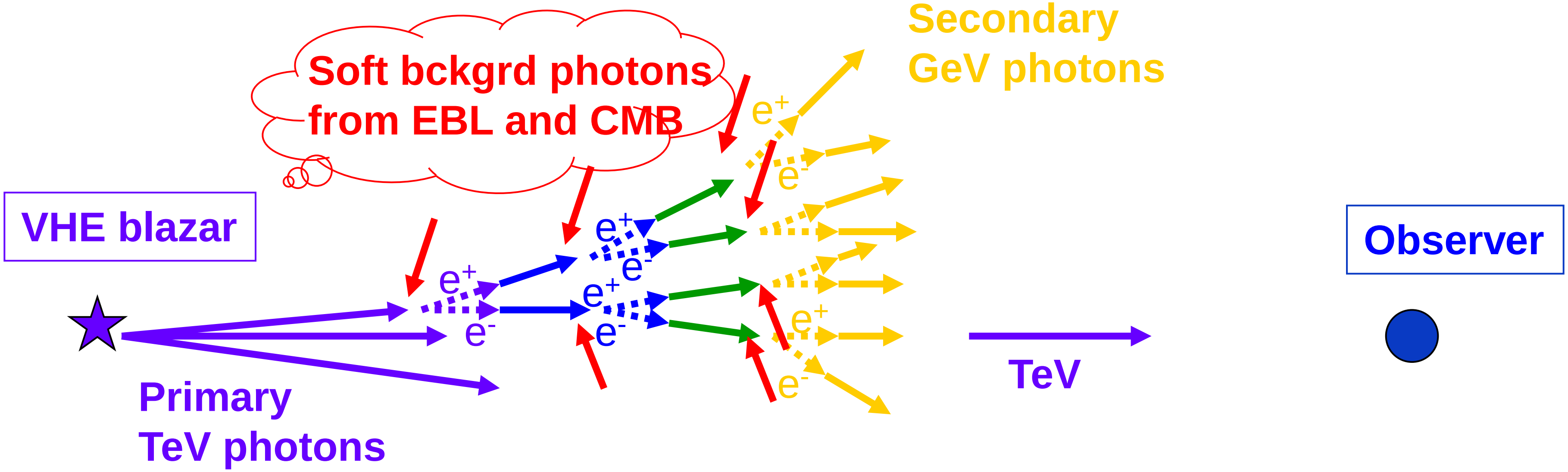


Cascades of e⁺ e⁻ pair creation
and Inverse-Compton emission

$\gamma_{\mathrm{VHE},1} + \gamma_{\mathrm{IR}\ (EBL)} \rightarrow e^{+} + e^{-}$

$e^{-}_{1} + \gamma_{\mathrm{IR}\ (CMB)} \rightarrow \gamma_{\mathrm{VHE},2} + e^{-}_{2}$

TeV gamma-ray signal from high-z blazars

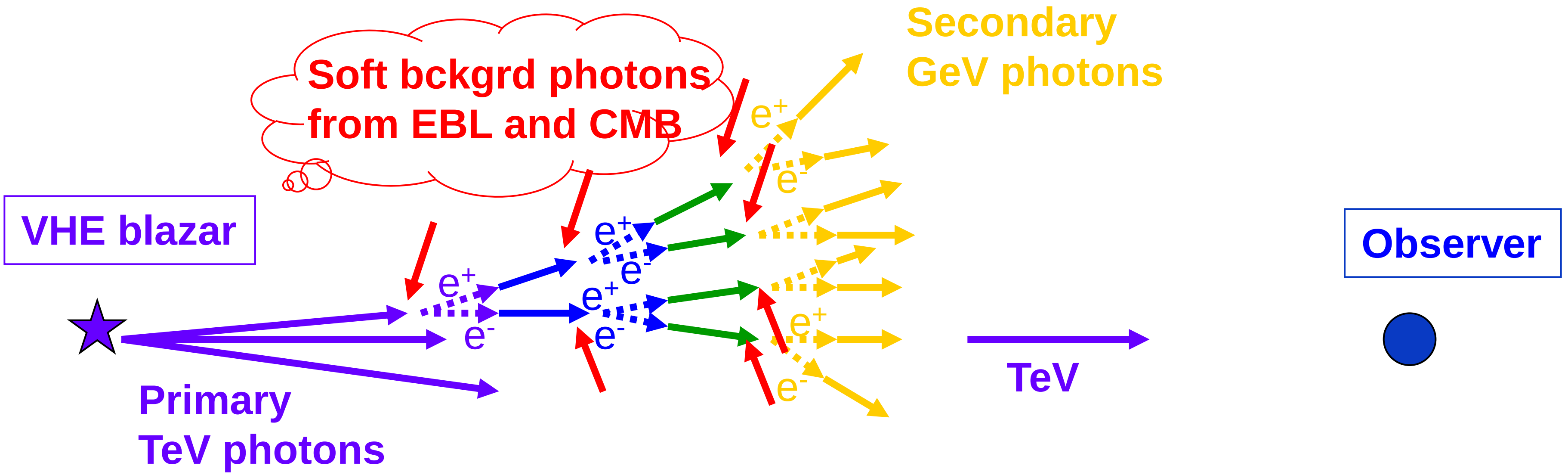


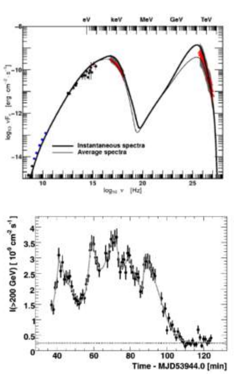
Cascades of $e^+ e^-$ pair creation
and Inverse-Compton emission

$$\gamma_{VHE,1} + \gamma_{IR\ (EBL)} \rightarrow e^+ + e^-$$

$$e^-_1 + \gamma_{IR\ (CMB)} \rightarrow \gamma_{VHE,2} + e^-_2$$

TeV gamma-ray signal from high-z blazars





Cascades → secondary GeV flux, ***dependent of the IGMF properties.***

1st approach description:

- Extended GeV emission around primary TeV signal
- Delay of secondary GeV emission after TeV flare

Detecting very low IGMF

Pair haloes

- Electromagnetic cascades from VHE gamma-rays of AGN absorbed by e^+e^- pair production on the intergalactic background radiation fields.

  Extended haloes (> 1 Mpc) are formed when velocities of pairs are isotropized by the ambient IGMF

(Aharonian et al, 1994)

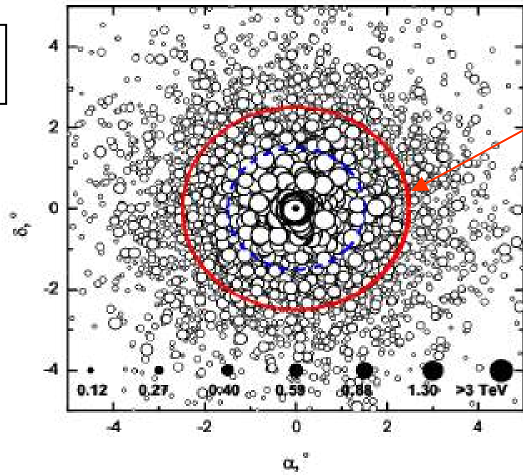
Pair echoes

- Delay in arrival times of gamma-rays from remote variable sources such as *gamma-ray bursts and flaring AGN*: VHE photons interact with CMB and extragalactic background light (EBL)
  - → production of e^+e^- pairs which Inverse-Compton scatter CMB photons and produce secondary VHE photons. IGMF deflects the pairs and delays the secondary gamma-ray pulse
  - → should be able to detect B_{IG} down to 10^{-24} G

(Plaga, 1994)

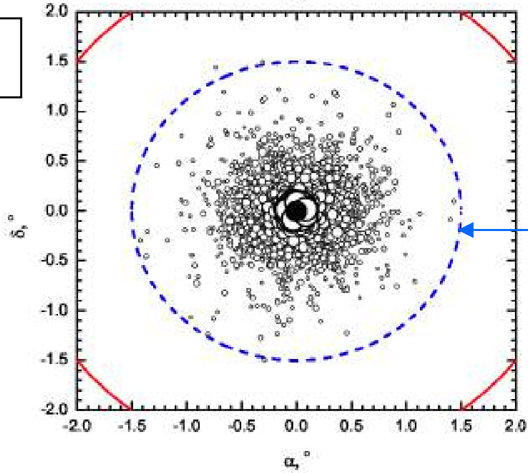
Virtual images of halos around AGN

for $B_{IG} = 10^{-14}$ G



2.5° radius

for $B_{IG} = 10^{-15}$ G

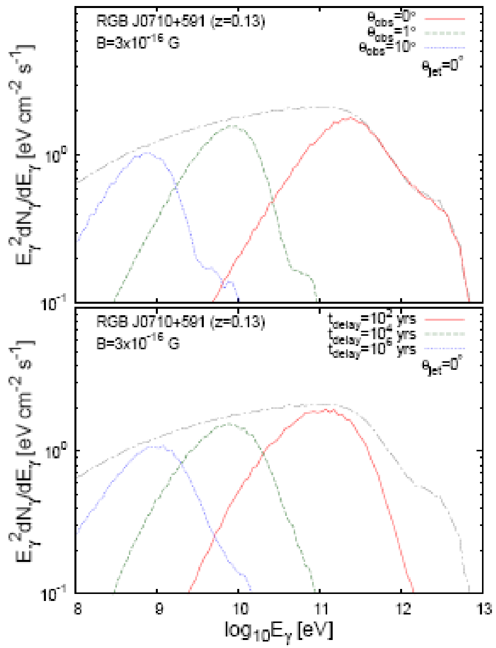


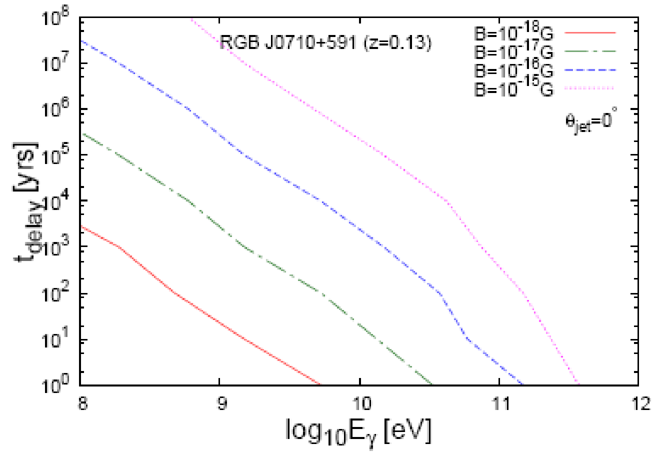
1.5° radius

Arrival directions of primary and secondary gamma-rays from a source at distance D = 120 Mpc (size of circles proportionnal to the photon energy).

(from Elyiv et al, 2009)

Simulations of pair echoes





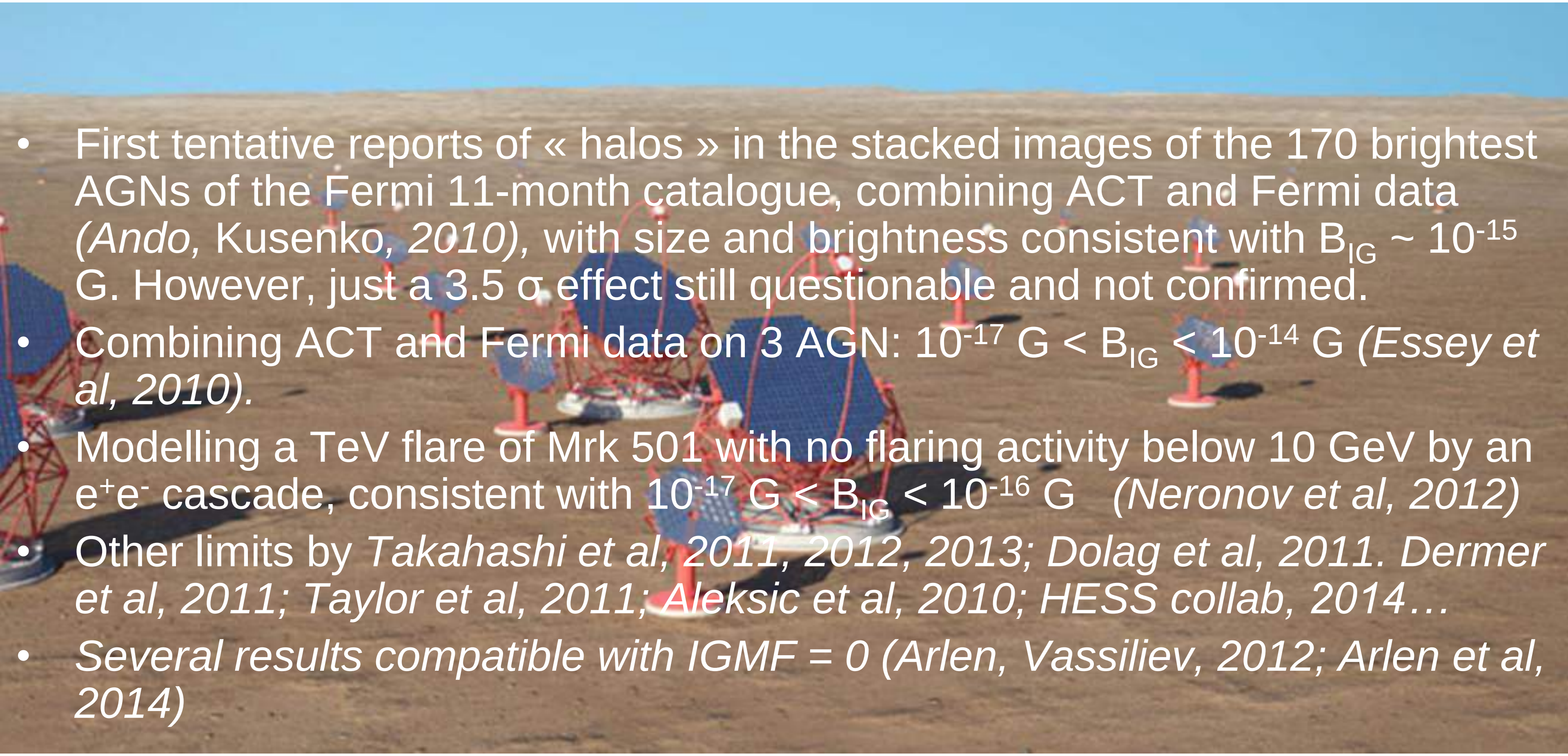
Arriving energy fluxes after injection of 100 TeV photons from z = 0.13
Top : for different viewing angles
Bottom : for different delay times

Corresponding mean time delay for different values of the IGMF

→ *Firm detection not so easy so far because of poor time coverage*

(from Taylor et al, 2011)

IV) Search for haloes and echoes

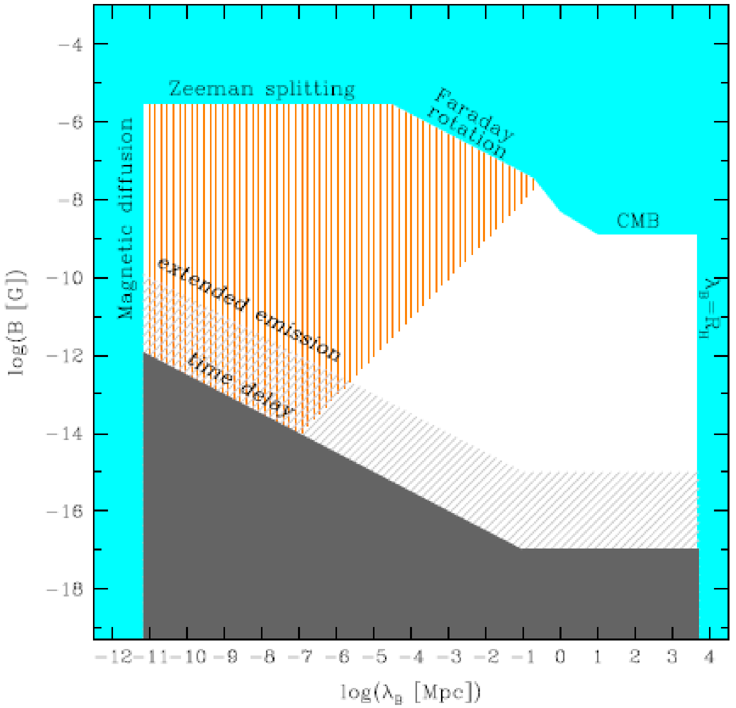


- First tentative reports of « halos » in the stacked images of the 170 brightest AGNs of the Fermi 11-month catalogue, combining ACT and Fermi data *(Ando,* Kusenko*, 2010),* with size and brightness consistent with $B_{IG} \sim 10^{-15}$ G. However, just a 3.5 σ effect still questionable and not confirmed.
- Combining ACT and Fermi data on 3 AGN: 10^{-17} G < B_{IG} < 10^{-14} G *(Essey et al, 2010).*
- Modelling a TeV flare of Mrk 501 with no flaring activity below 10 GeV by an e^+e^- cascade, consistent with 10^{-17} G < B_{IG} < 10^{-16} G *(Neronov et al, 2012)*
- Other limits by *Takahashi et al, 2011, 2012, 2013; Dolag et al, 2011. Dermer et al, 2011; Taylor et al, 2011; Aleksic et al, 2010; HESS collab, 2014…*
- *Several results compatible with IGMF = 0 (Arlen, Vassiliev, 2012; Arlen et al, 2014)*

→ *Only non-detection yet, or some clues for detection still to be confirmed*

→ *Provides **lower limits** on IGMF, assuming the pair cascade effect dominates the physics of propagation.*

Typical current constraints on the IGMF *including lower limits from γ-ray data:*



(Taylor et al, 2011)

Deep search for extended VHE halo by ACT for specific sources: only upper limits confirmed so far

Multi-lambda lightcurves: difficult to interpret in term of precise time delays. Long term variability poorly constrained.

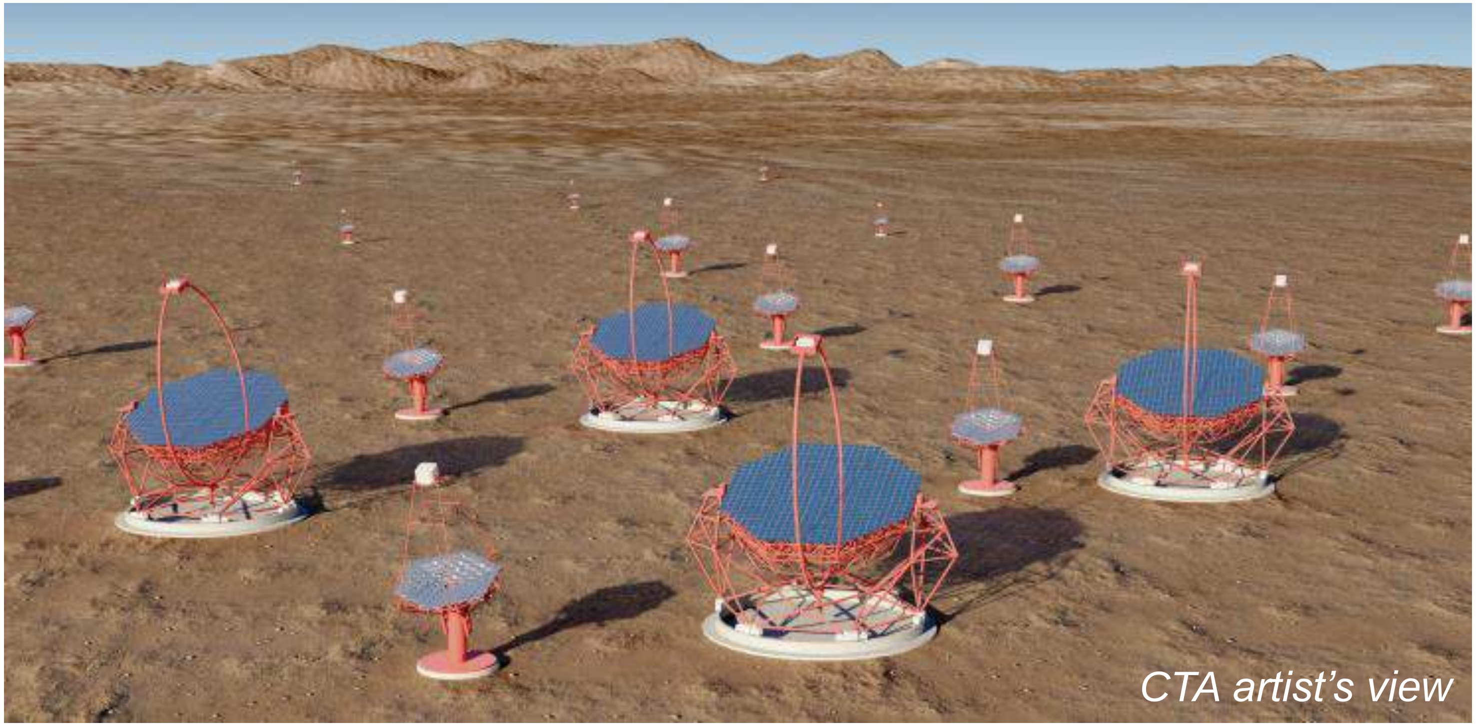
Interpretation still quite model-dependent:

Current debate on heating of the IGM due to plasma-beam instability, after the proposal by *Broderick, et al, 2012*

Positive detection of the cascade process would open new paths to characterize the IGMF and backgrounds

Next generation of ground-based astronomy : the CTA project, Cherenkov Telescope Array

- 10-fold increased sensitivity at TeV energies (mCrab)
- 10-fold increased effective energy coverage
- Larger field of view (5° to 10°)
- Improved angular and spectral resolution
- Full sky coverage (North and South) by IACT

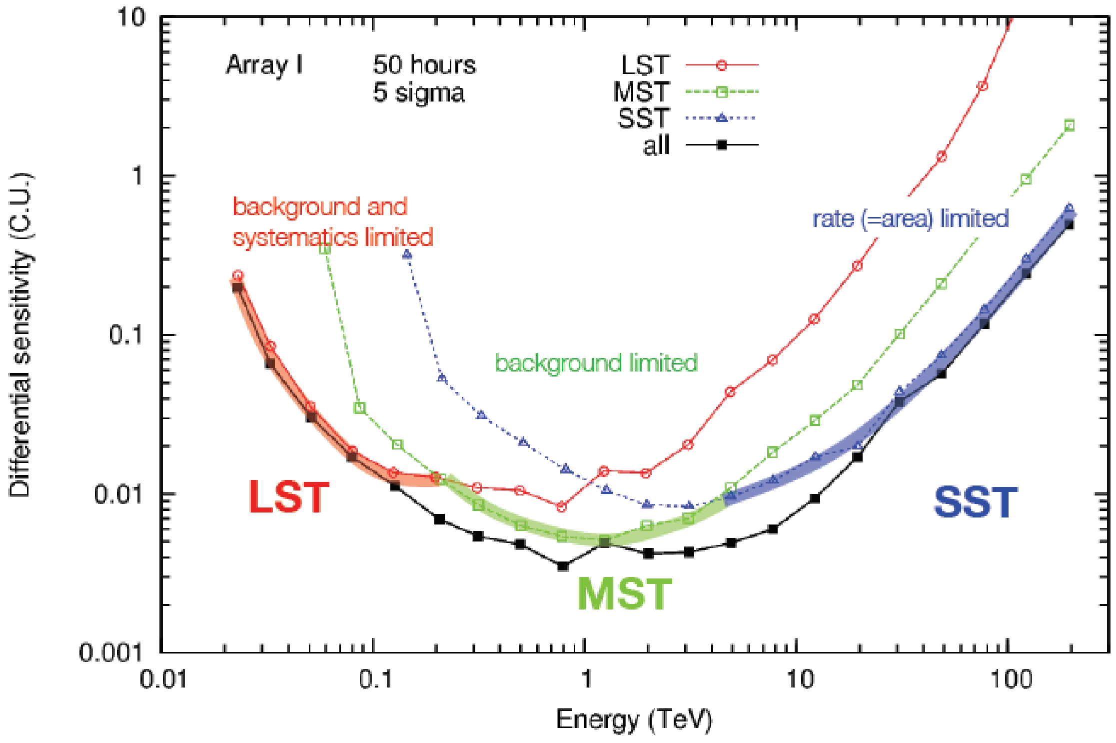


CTA artist's view

CTA: different sizes and types of telescopes to ensure a large spectral range, from ~ 20 GeV up to 300 TeV

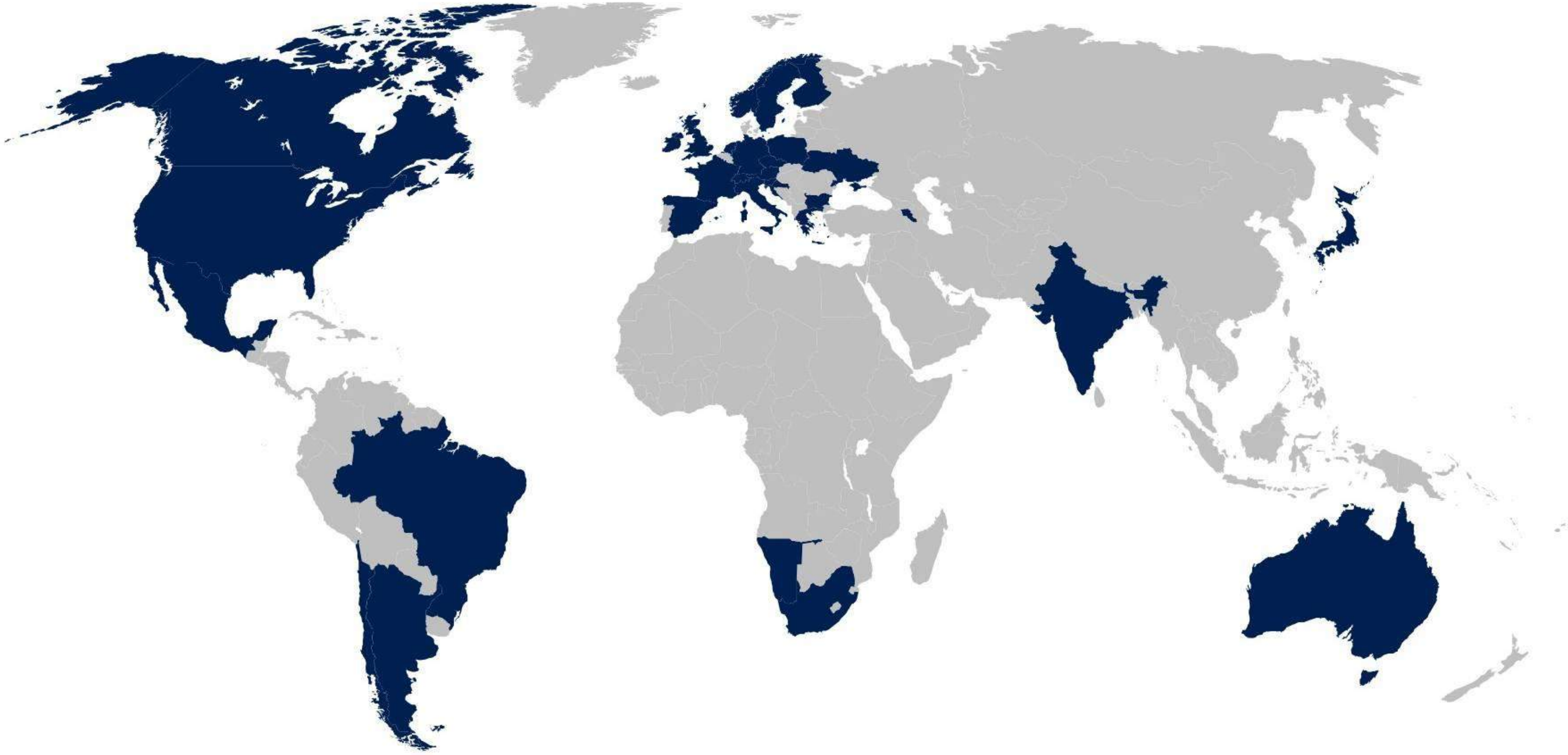
Deep observations in extended TeV domain,
with the opening of new window at extreme multi-TeV energies

LST ~ 23m   MST ~ 12m and SST ~ 4m



(ref: CTA)

CTA consortium: a global project

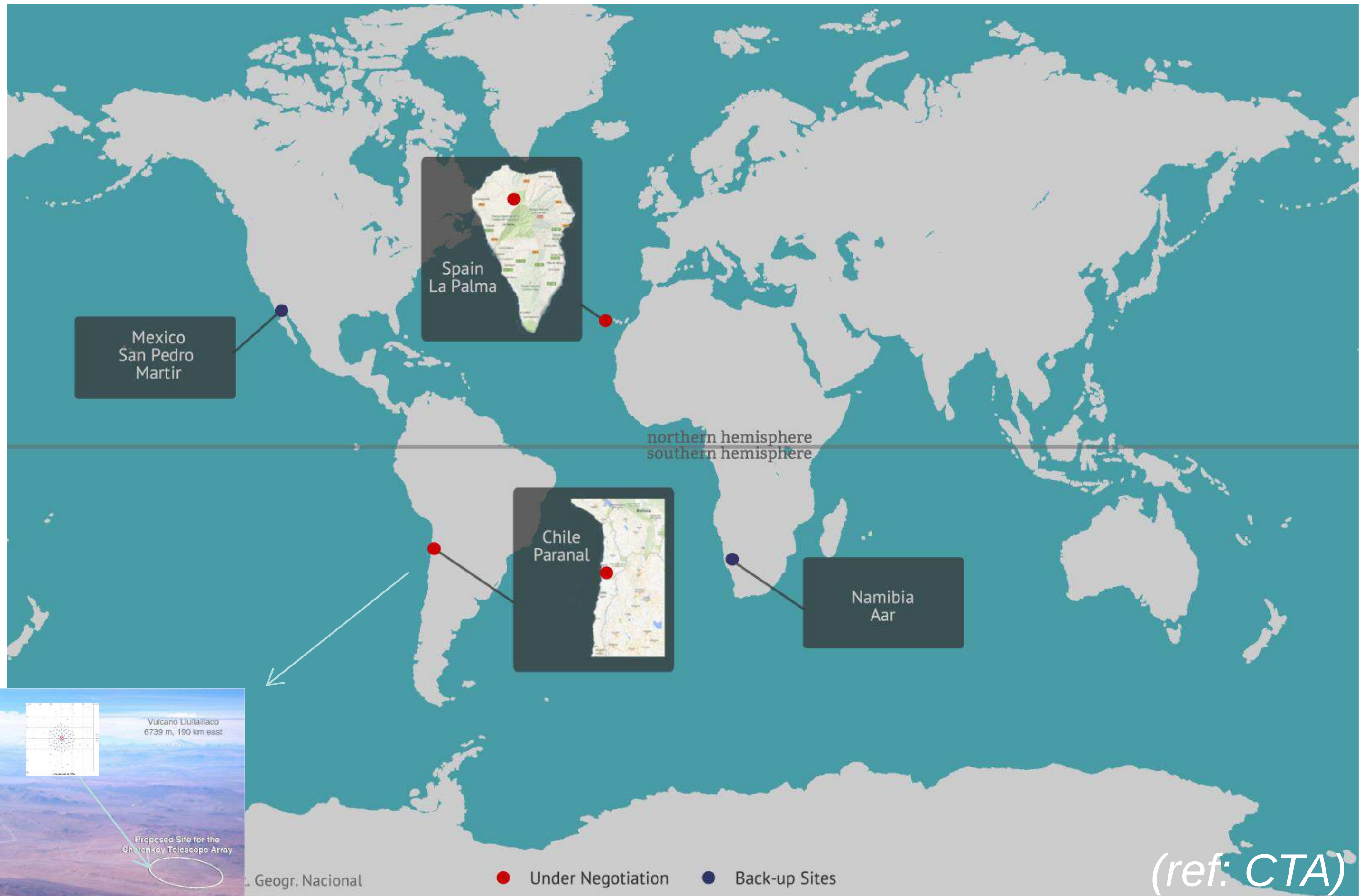


CTA Consortium status
31 countries
1270 members
424 FTE

New member : Thailand (Sept 2015)

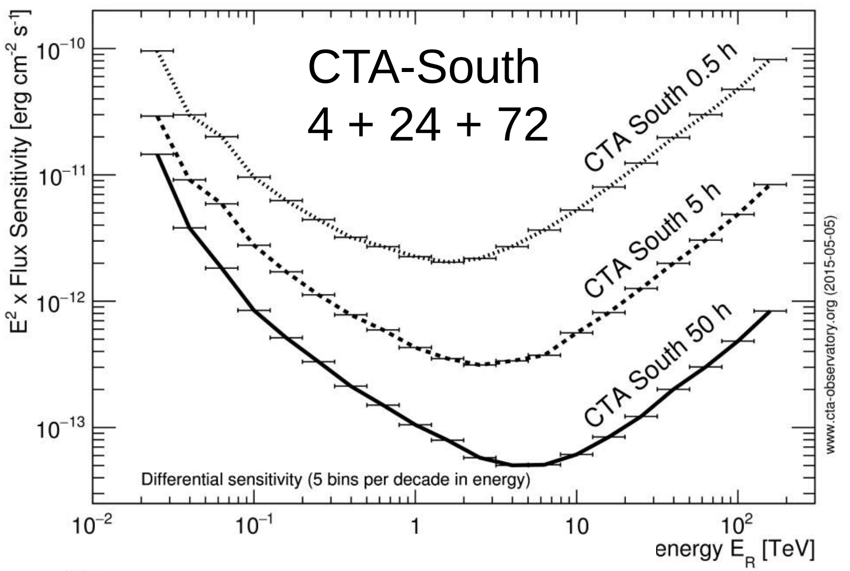
Ref: CTA, 2015

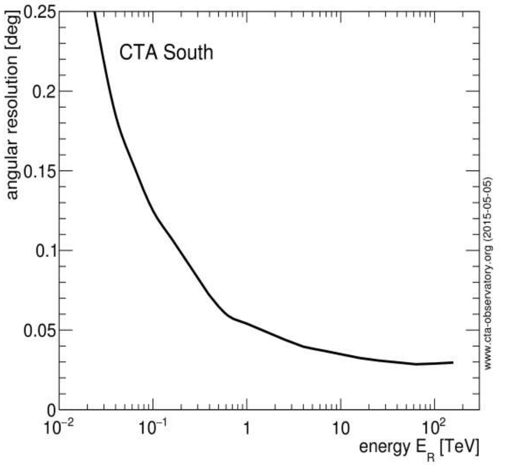
Two sites, South and North, chosen in July 2015: Armazones 2 (ESO) in Chile & La Palma (Canaries, Spain)

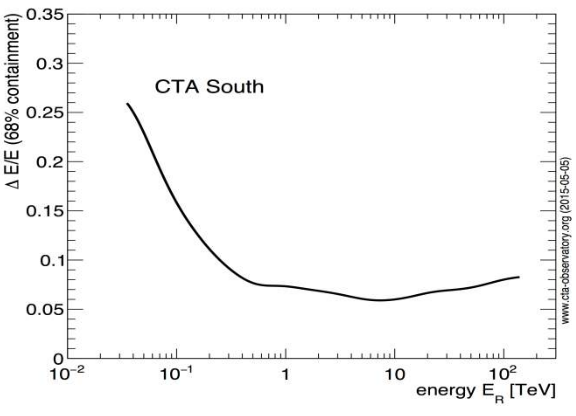


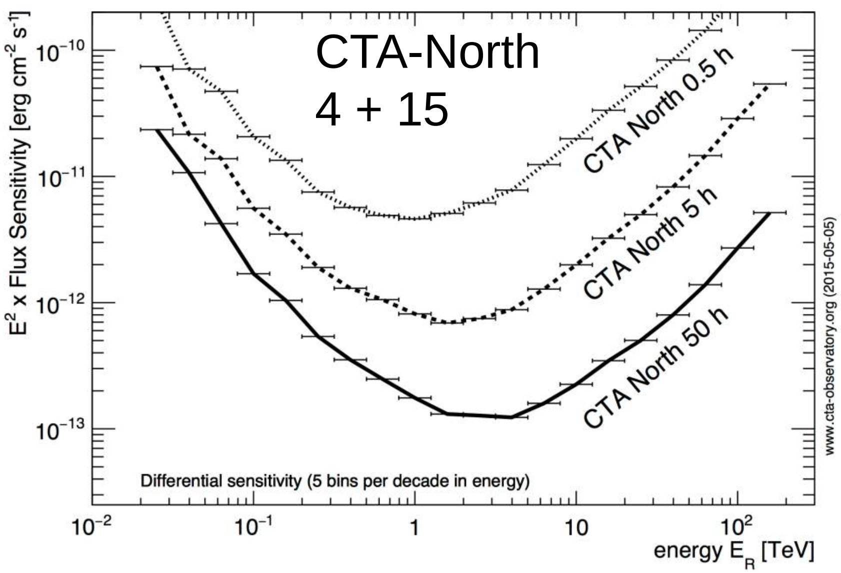
CTA Performance Page, a new public page with approved performance numbers:

https://portal.cta-observatory.org/CTA_Observatory/performance/SitePages/Home.aspx

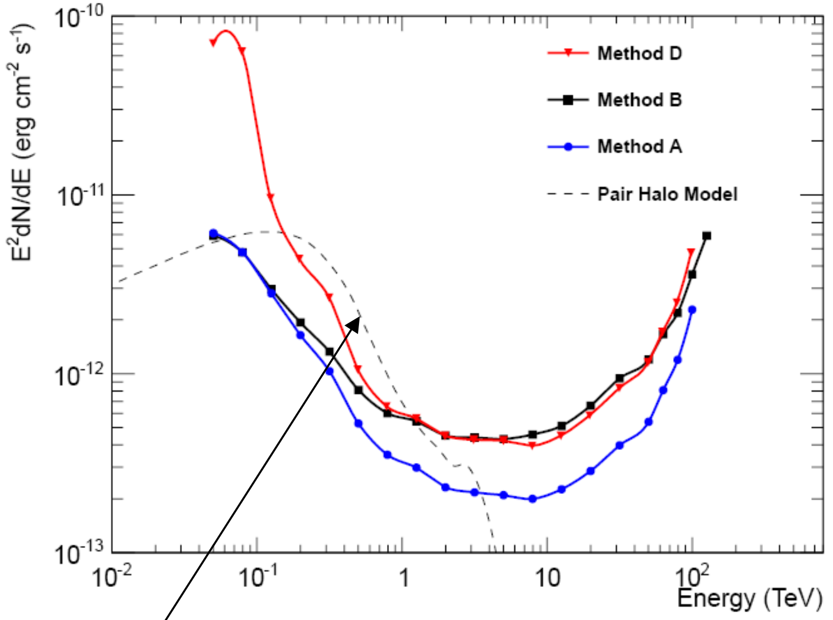






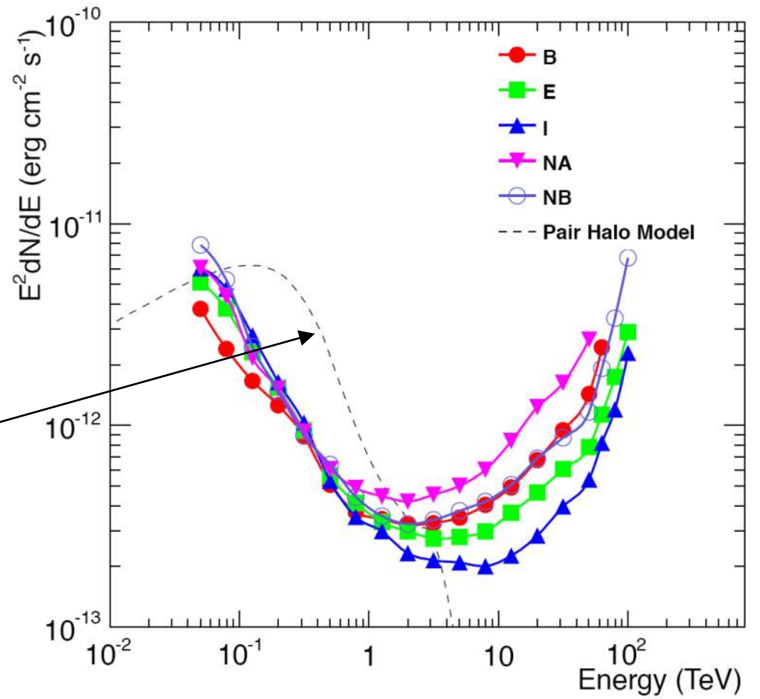


Flux sensitivity with CTA
for future pair halo detection



for 3 different analysis methods to search for the extension (configuration I for CTA array)

for 5 different CTA array configuration, 50 hours, 20° zenith angle (method A)



Differential angular distribution of a pair halo at z = 0.129 (1ES1426+482) and $E_\gamma > 100$ GeV [theoretical model from Eungwanichayapant, Aharonian, 2009; intermediate IGMF, mono-energetic primary at 100 TeV, 10^{45} erg/s]

(Sol et al, 2013; from Hinton & White)

Large FoV VHE detectors

HAWC, High Altitude Water Cherenkov Gamma-ray Observatory: TeV gamma-rays and cosmic rays *(100GeV-100TeV)*

Wide FoV (15% of sky) → very high duty cycle: covers half sky in one day

Array of particle counters, Water Cherenkov Detector, 300 water Cherenkov tanks ~22 000 m^2 detection area ~15x more sensitive than Milagro (Sierra Negra, Mexico, 4100m, 19° north)

LHAASO : Project of a Large High Altitude Air Shower Observatory in Tibet
Multiple detection method of CR and γ –rays.

→ Should significantly improve light curves for the search of echoes!!

Perspectives

for haloes → get detailed 2D imaging + VHE spectra

for echoes → get detailed light curves with good time coverage over a large spectral range

Any firm detection should constrain the scenarios and characterize IGMF and background properties *(see for instance Neronov et al, 2013)*

Also diffuse gamma-ray background studies provide new clues of non-zero IGM *(from Fermi data: Venters, Pavlidou, 2013; Chen et al, 2015, IGMF ~10^{-14} G on ~10 Mpc)*

Soon a new era for the IGMF ?...

Warning: Need to overcome theoretical issues on possible loss of energy of the cascades through beam-plasma instabilites, which could induce a specific heating of the intergalactic medium

Lower limits on IGMF are ***modified*** if such dissipative plasma effects influence the physics of pair cascades *(Broderick et al, 2012; Chang et al, 2014;Menzler, Schlickeiser, 2015; but see Venters, Pavlidou, 2013 for strong argument against)*

An additional ***« patchy » blazar heating*** of the intergalactic medium ?

(Lamberts et al, 2015)

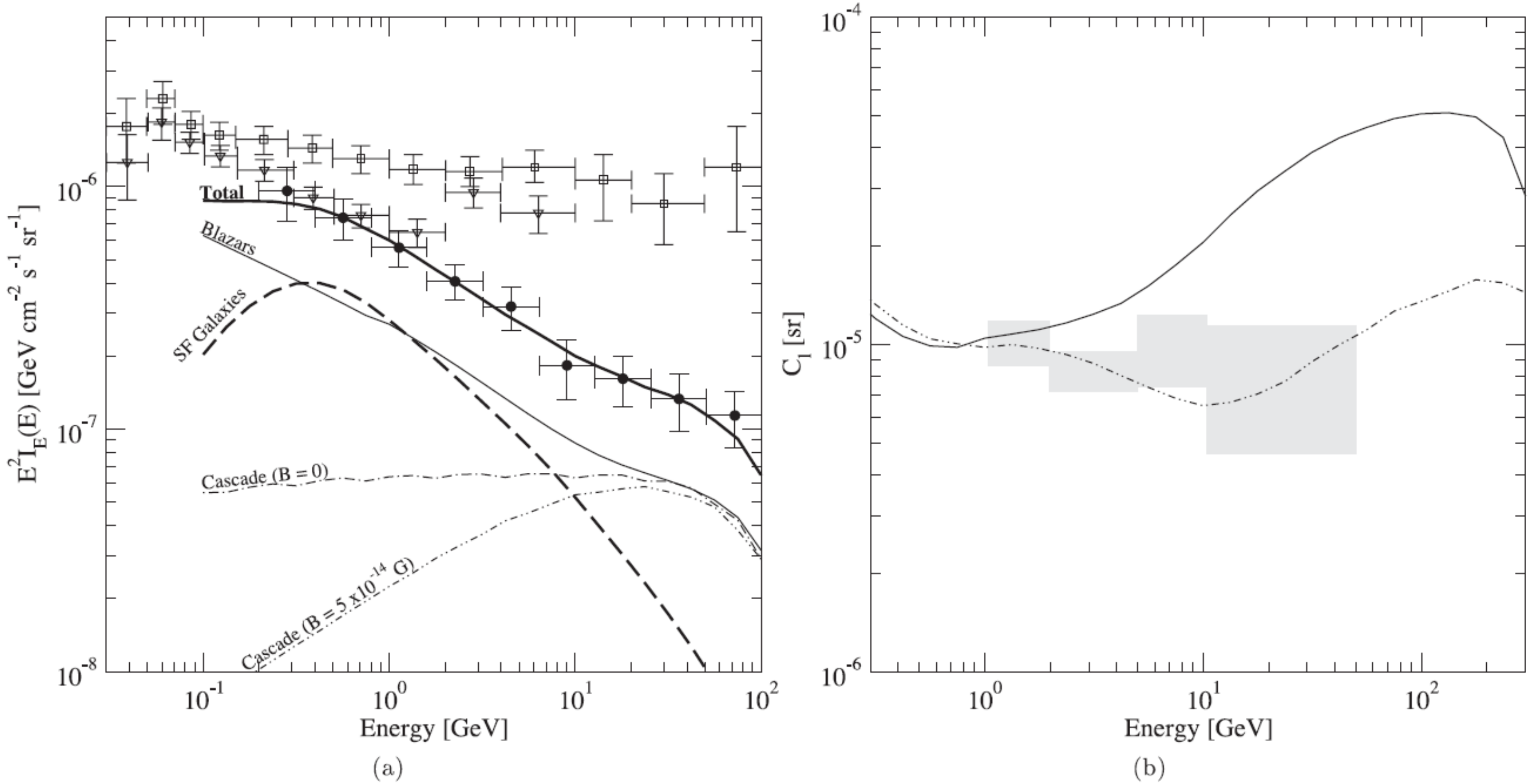
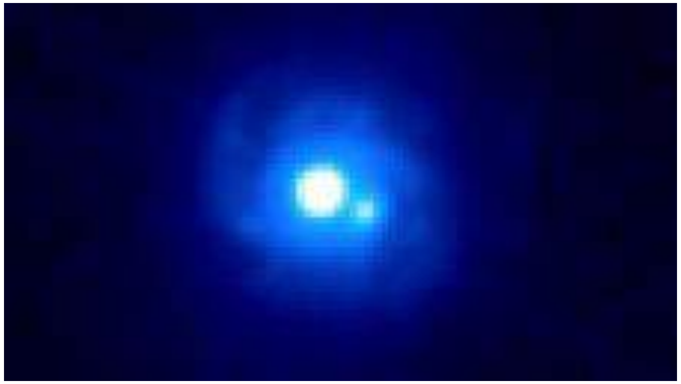


Figure 1. (a) The spectrum of the modelled EGB (thick solid line) together with individual components: intrinsic blazar emission, including both FSRQs and BL Lacs (thin solid line); SF galaxies (dashed line); EM cascades for zero IGMF (dot–dashed line) and non-zero IGMF (double dot–dashed). For reference, the spectra of the EGB based on both *Fermi* (filled circles; Abdo et al. 2010a) and EGRET data (open squares, Sreekumar et al. 1998; open triangles, Strong, Moskalenko & Reimer 2004) are also plotted. (b) The anisotropy energy spectra of the modelled contributions to the EGB. The solid line is the total model assuming zero IGMF. The double dot–dashed line is the total model assuming non-zero IGMF. Grey boxes represent the *Fermi*-LAT measurement of the anisotropy energy spectrum of the EGB (Ackermann et al. 2012a).

Studying the extragalactic gamma-ray background

(Venters, Pavlidou, 2013)

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

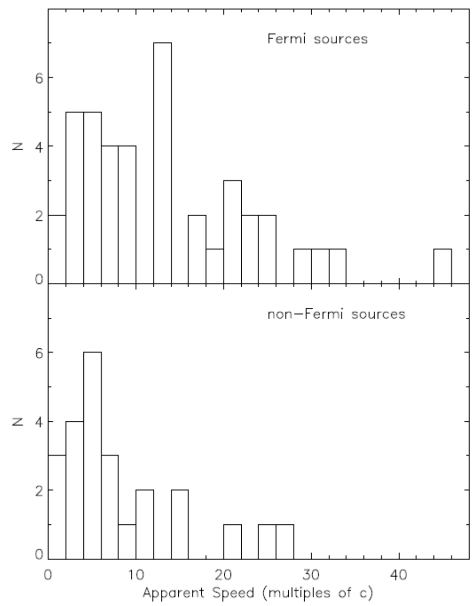


Spiral arms of the lensing galaxy
+ 2 images of the background blazar, separated by 0.33''
HST image

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.

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

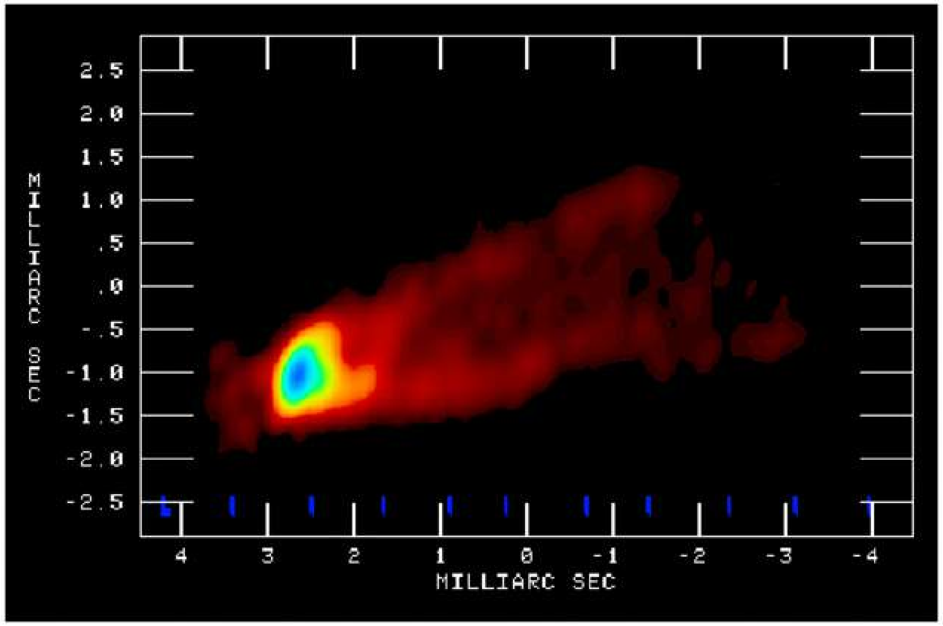


Sources in the 2FGL Fermi LAT catalog:
Show higher apparent VLBI speeds than non-Fermi sources *(Piner et al, 2012)*

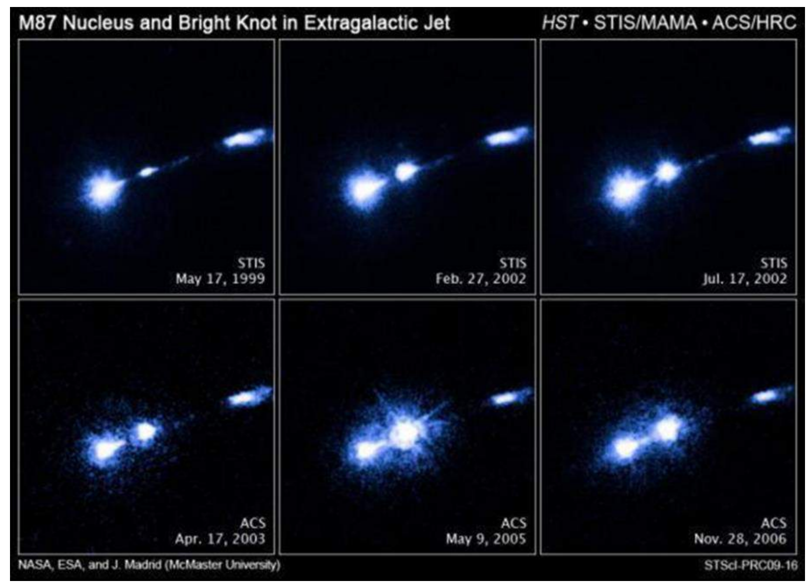
→ ***GAIA extragalactic sources with high photocenter motion*** = *interesting candidates* for VHE gamma-ray observations

M87: Time evolution of radio VLBI jet on mas scale

Photometric, spectroscopic, and photocenter variation possibly detected by GAIA



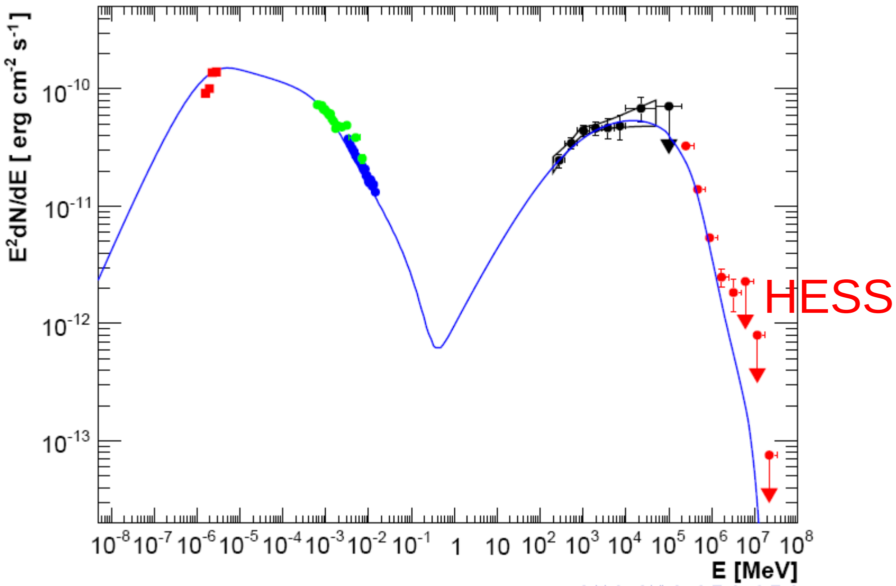
Time evolution of optical jet on arcsec scale (HST-1 at 3'')



Could 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***

However, PKS 2155 in 2008 (lower state):



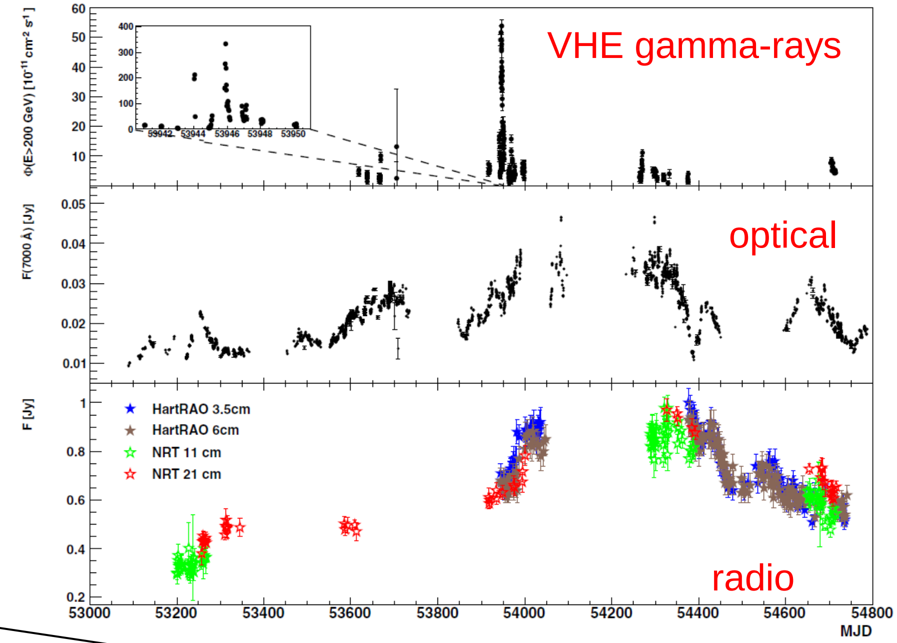
New multi-lambda campaign in 2008, including HESS, Fermi, RXTE, SWIFT, ATOM

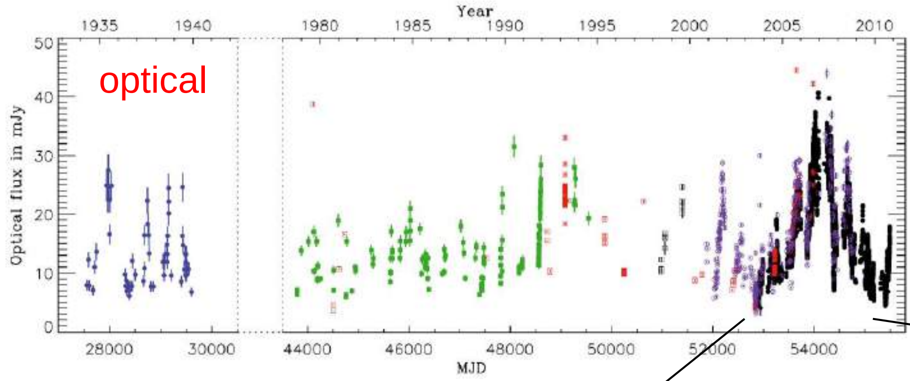
Find complexity of correlation between various lambda :
Simple SSC model can not explain all correlation properties.
Correlations appear different between active and low states.

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

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

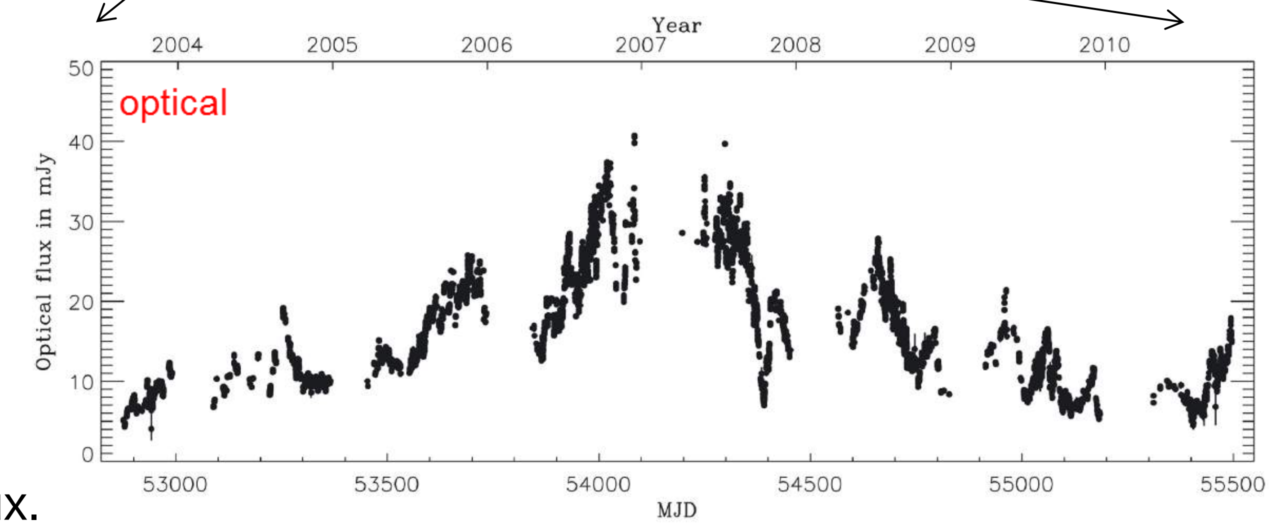




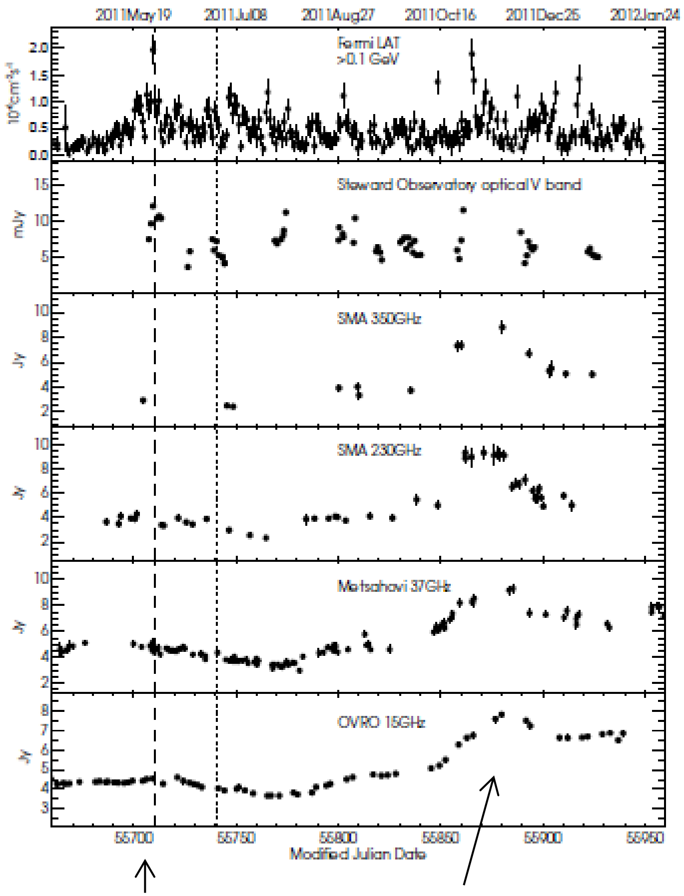
MWL variability, on all timescales.

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

Factor up to 8 in optical flux.



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 alerts***

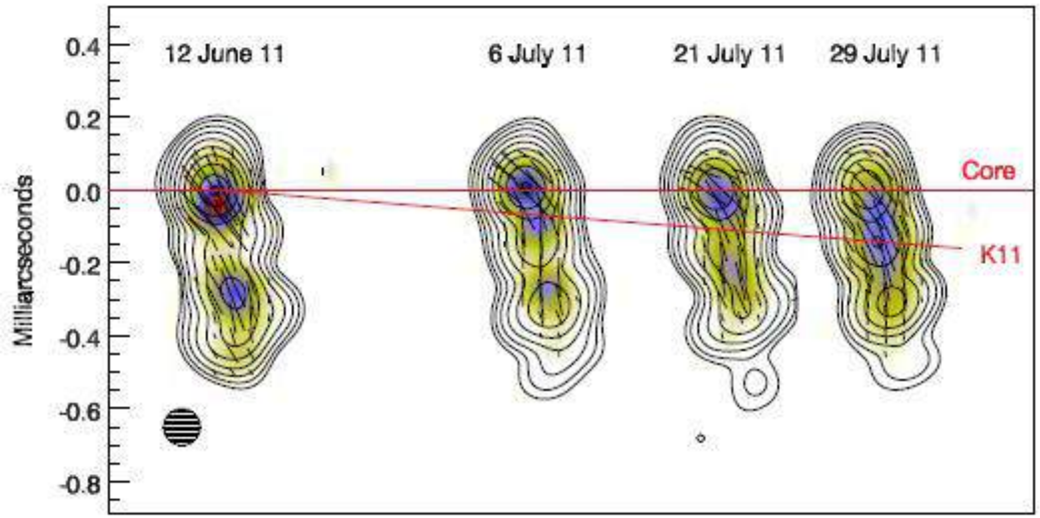


TeV and MWL flare

Radio flare ~ 4 months later

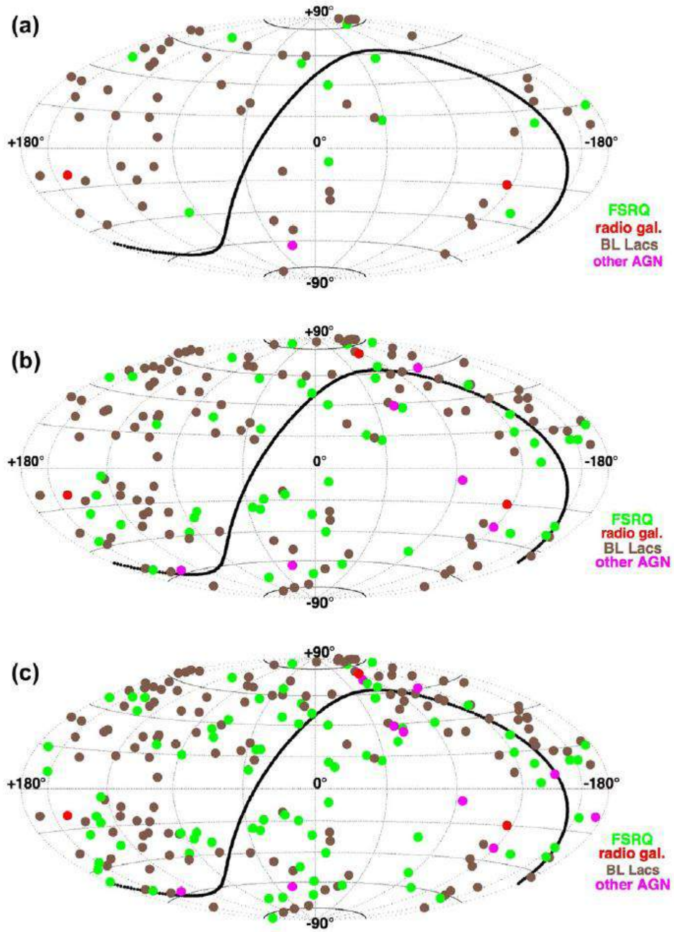
VHE flaring activity on June 28, 2011
from Arlen et al, 2012

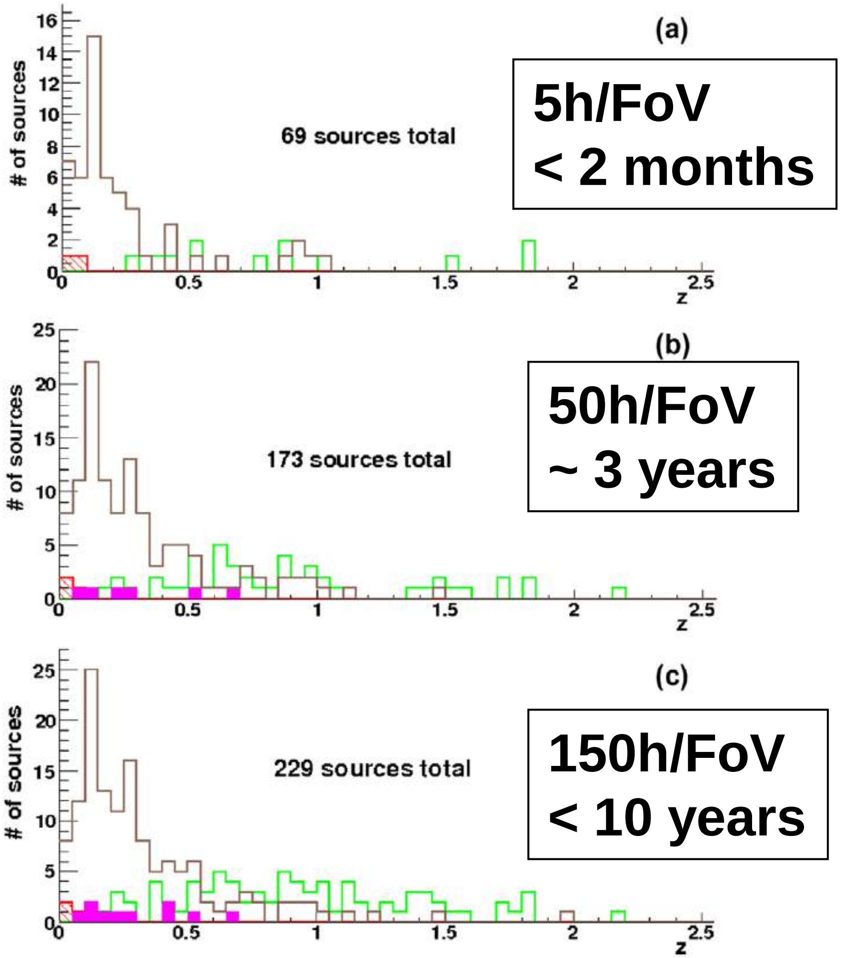
K11 = new VLBI component



Active Galactic Nuclei with CTA

Extrapolation from Fermi

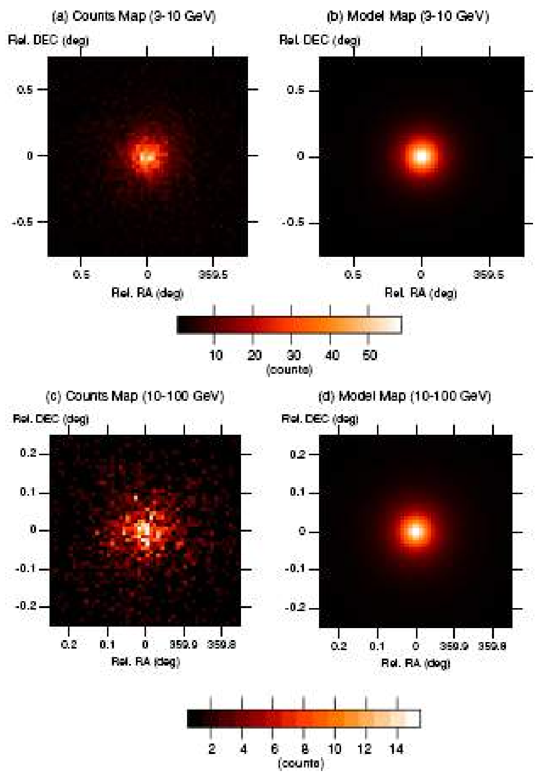


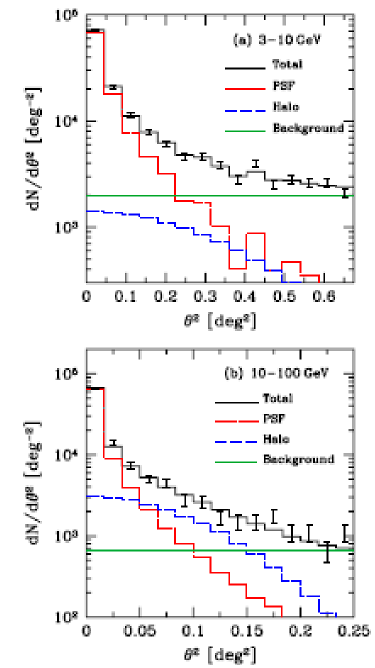


Assuming array B and 20° zenith angle over the whole sky *(Sol et al, 2014)*

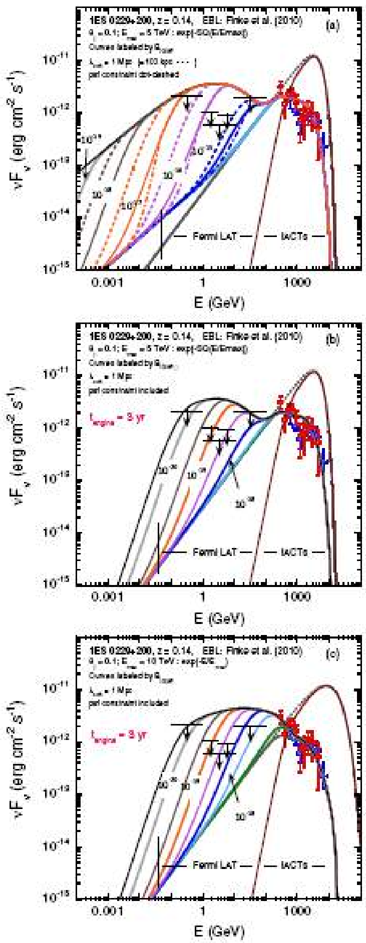
- Additional information could come from UHECR data. Magnetic fields in intergalactic voids act as a high-pass filter for energetic particles. Potential hot spots in the UHECR sky may reveal scattering centers rather than UHECR sources.
- However, requires chains of UHECR events (at different energies, deflection being inversely proportional to energy) and large data set at VHE (Auger North, JEM-EUSO).

- General warning: at the moment, conclusions are model-dependent. As an example, plasma beam instabilities can dissipate locally the energy of pairs → lower limits on IGMF deduced from non-detection of GeV secondary bump could be questionable *(Broderick et al, 2012).* But requires deeper analyses (non-linear evolution).
- Detailed data (2D imaging + VHE spectra) would constrain much better the situation.





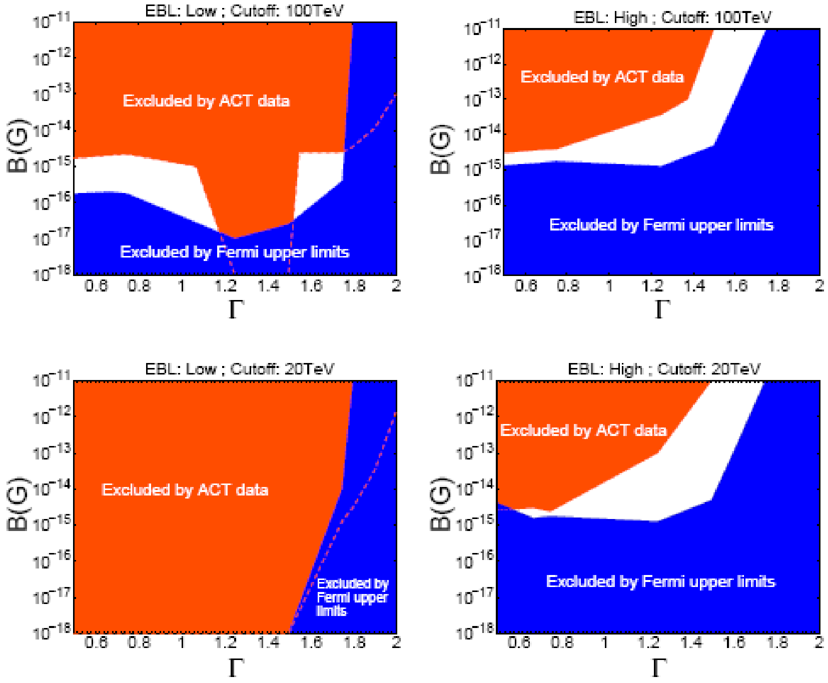
From Ando, Kusenko, 2010



Model of cascade radiation spectrum
(from Dermer et al, 2011)

Limits on the IGMF and intrinsic spectral index

Combined fit for the 3 sources 1ES0229+200, 1ES1101-232 and 1ES0347-121 at z = 0.14, 0.186, and 0.188.
For high and low EBL, and VHE cut-off at 20 and 100 TeV :



(From Essey et al, 2011)

Here 1 Mpc for IGMF correlation length
No cosmic ray contribution