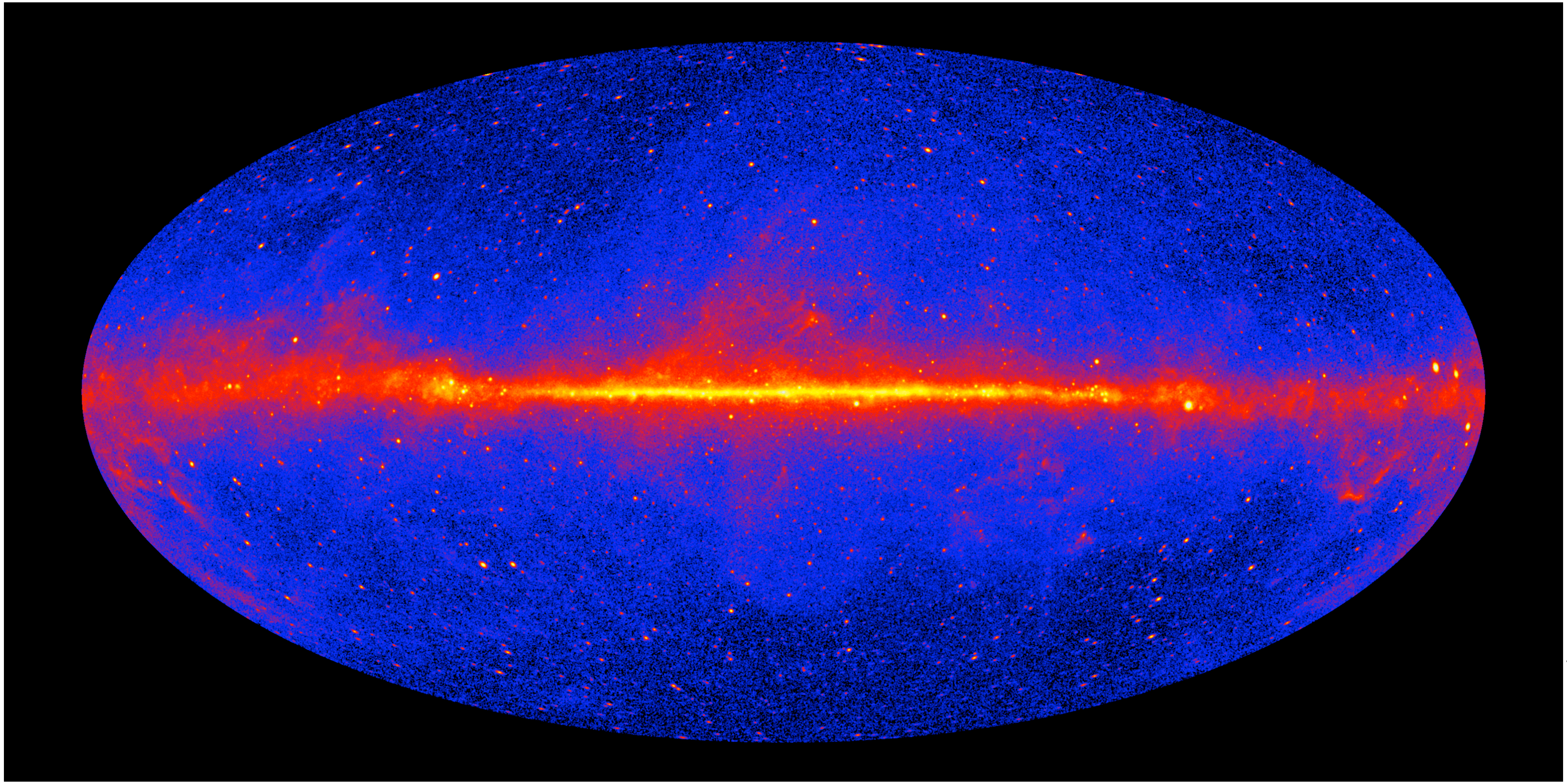
Science
with IACTs
(& friends…)

Giacomo Bonnoli
INAF- OA Brera

Credits to:
lots of people for
lots of slides!

The Fermi all-sky survey



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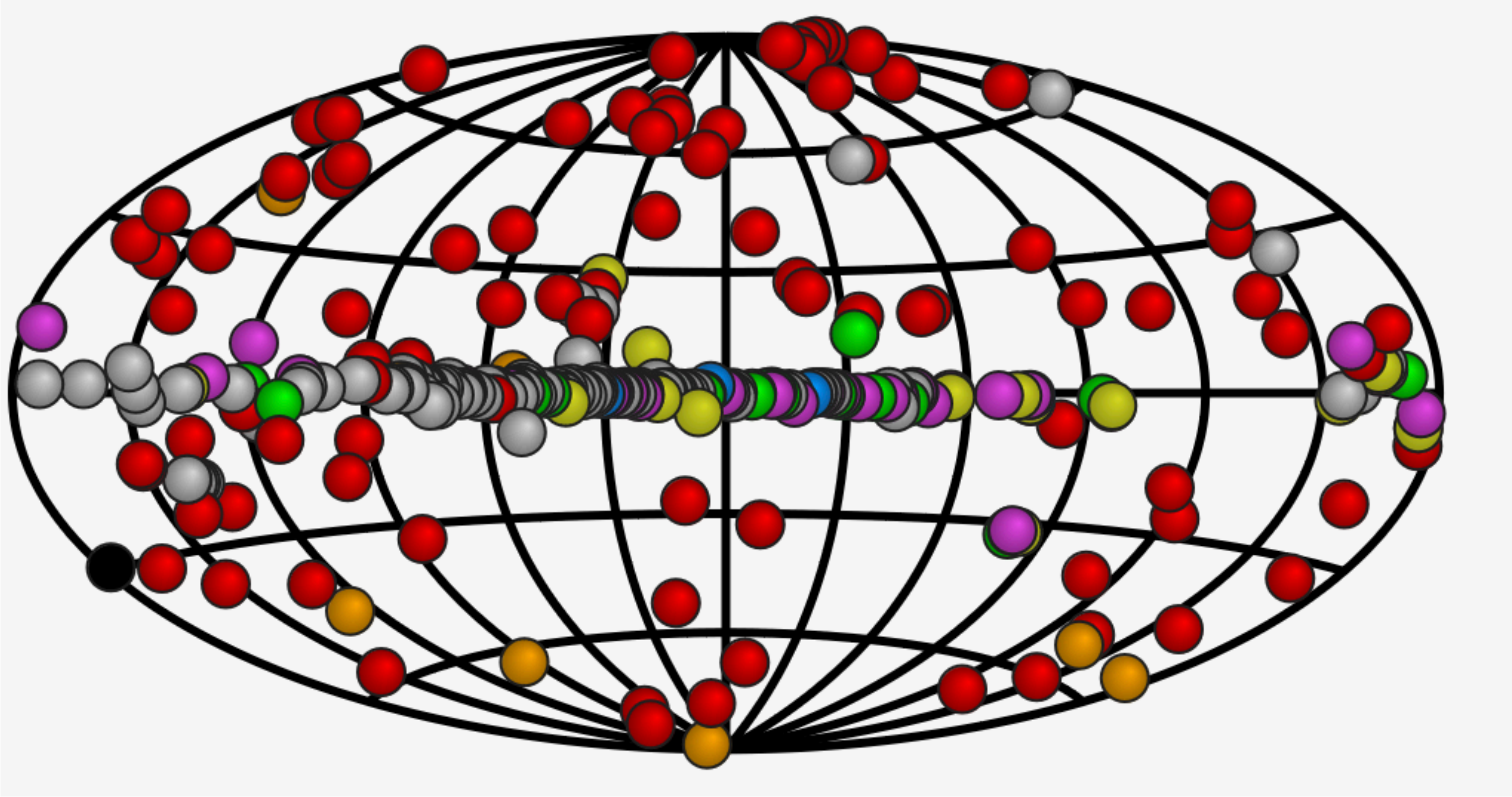
The VHE sky so far

http://tevcat2.uchicago.edu/

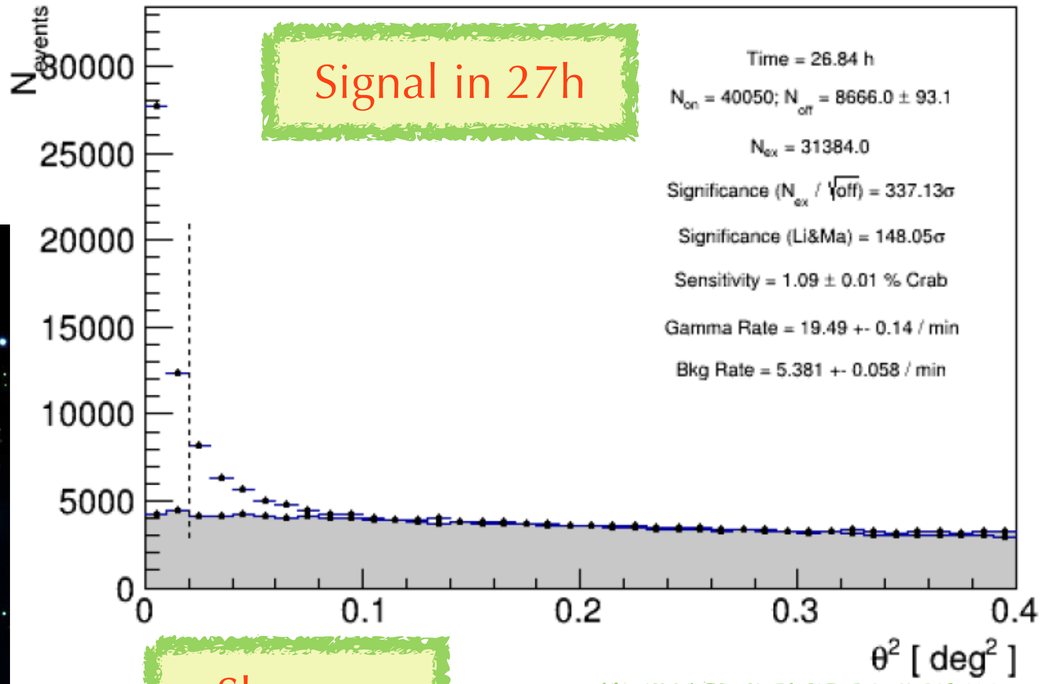


- GRB, Starburst, Superbubble
- PWN, TeV halo, PWN/TeV Halo, Composite SNR, BIN
- UNID, TeV halo, DARK
- HBL, IBL, FSRQ, AGN (unknown type), FRI, Blazar, BL Lac (class unclear), EHBL, LLAGN, LBL
- Shell, SNR/Molec. Cloud, Giant Molecular Cloud, Composite SNR
- Binary, PSR, Gamma BIN, Nova, Microquasar
- TeV halo
- Massive Star Cluster, Globular Cluster

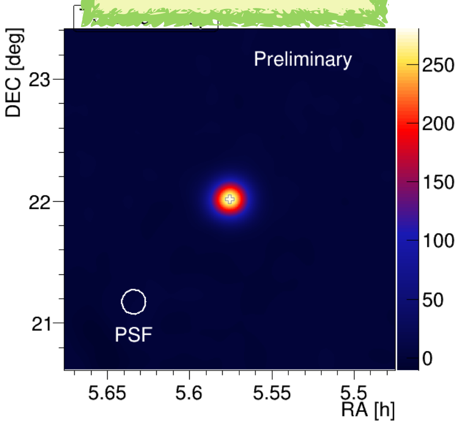
Crab Nebula: the TeV standard candle

Remnant of the 1054 a.C. SuperNova

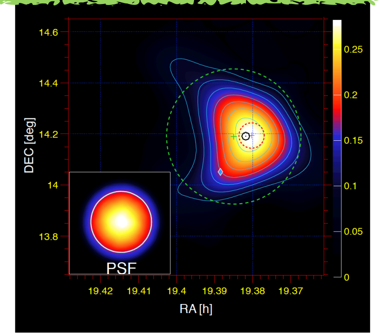
Signal in 27h



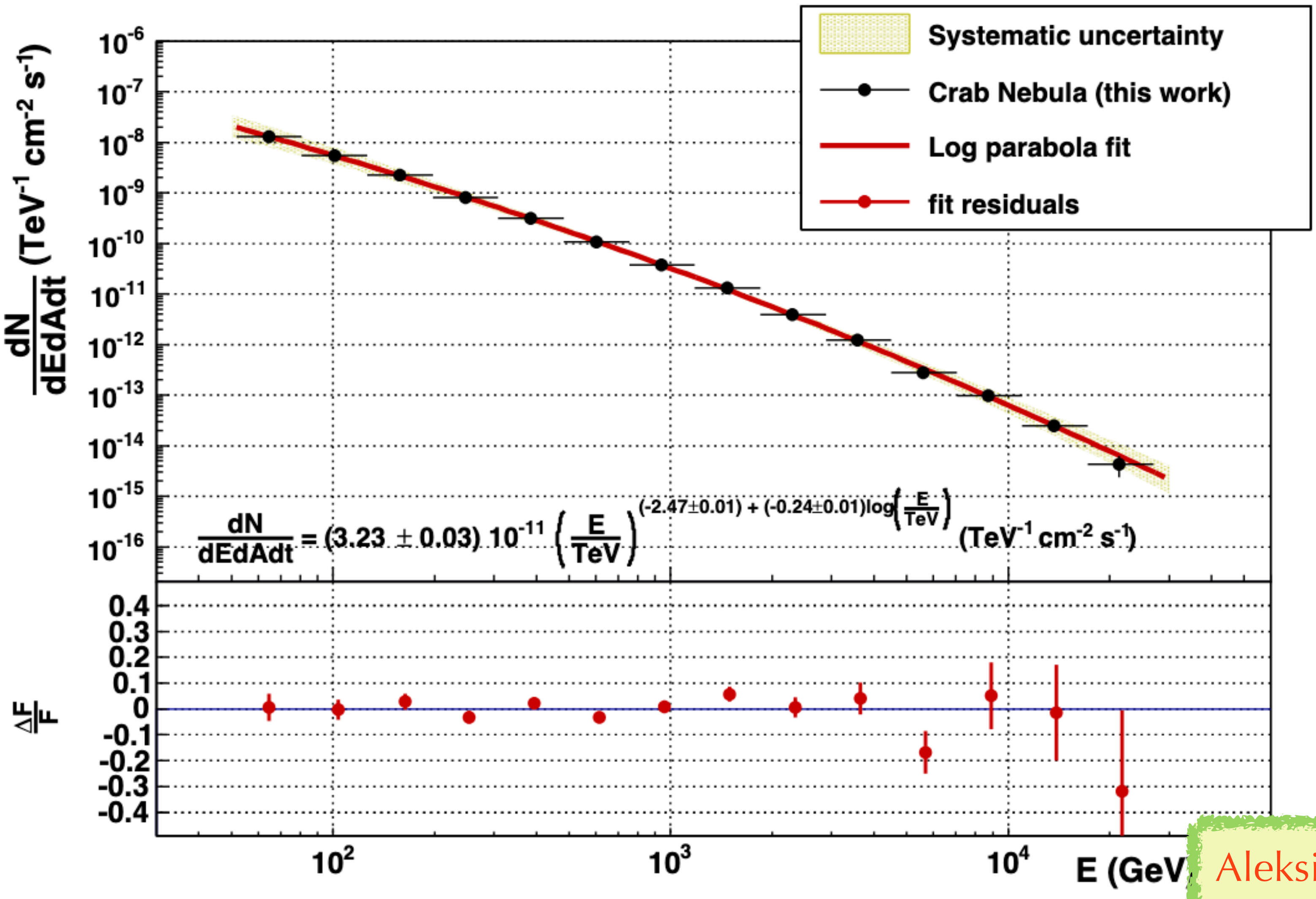
Skymap



W51 (extended)



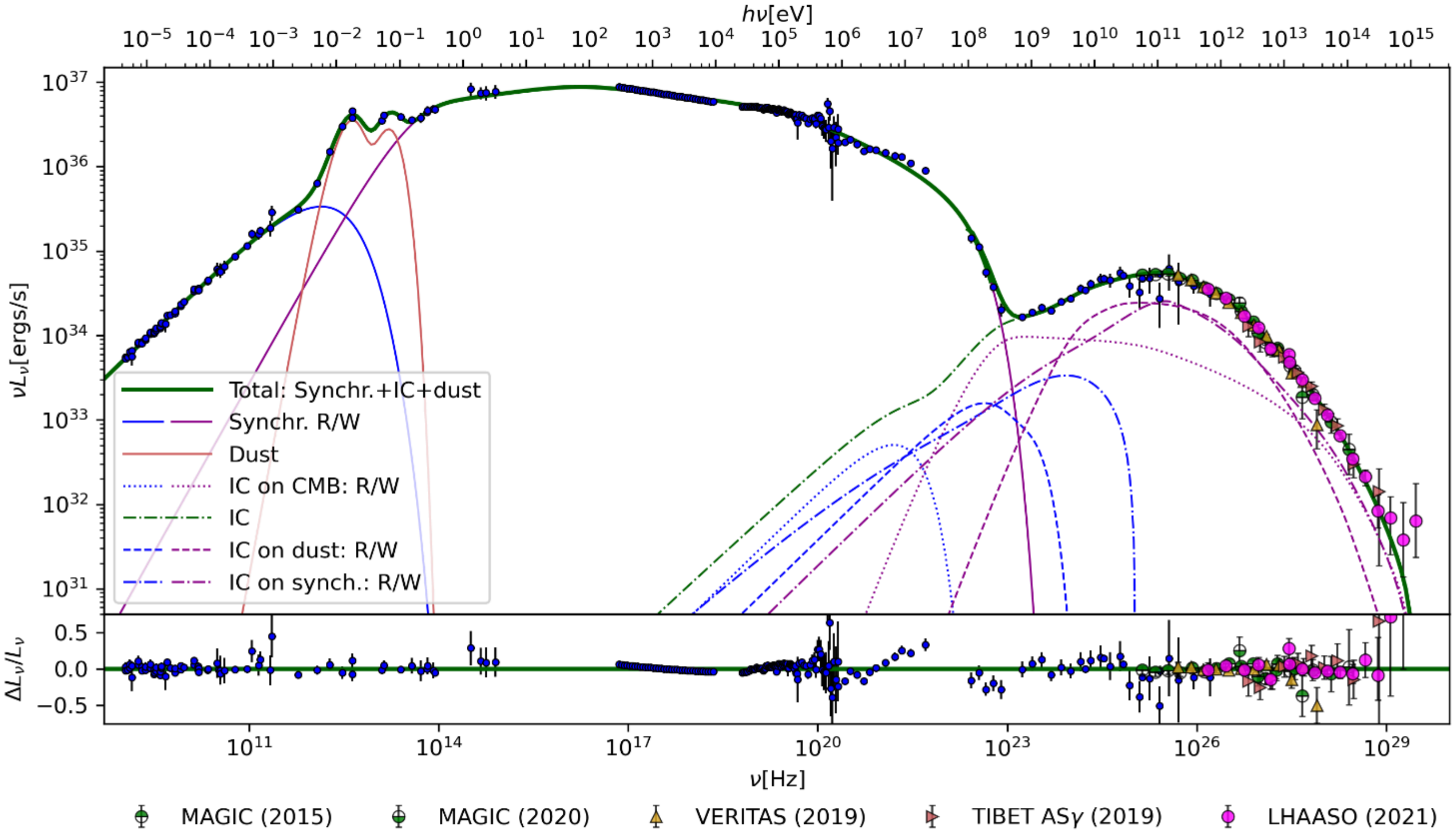
VHE gamma-ray spectrum of Crab Nebula



Aleksić+ JHEAP, 2015

Broadband SED of the Crab Nebula

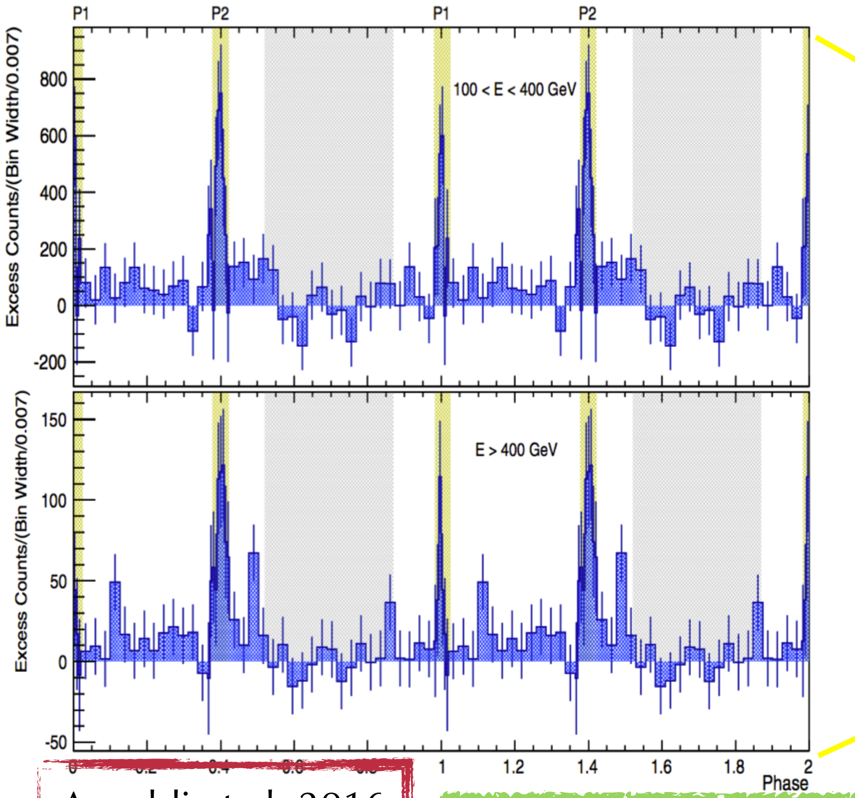
Energy	Instrument	References
Radio	WMAP	(1)
	Planck for the HFI instrument	(2)
Sub-mm/IR	*Herschel*	(3)
	WISE	(3)
X-ray to γ−ray	Crab	(4)
	NuSTAR	(5)
	Fermi-LAT	(6)
VHE	H.E.S.S.	(7)
	VERITAS	(8)
	MAGIC	(9)
	Tibet ASγ	(10)
	HAWC	(11)
	LHAASO WCDA, KM2A	(12)



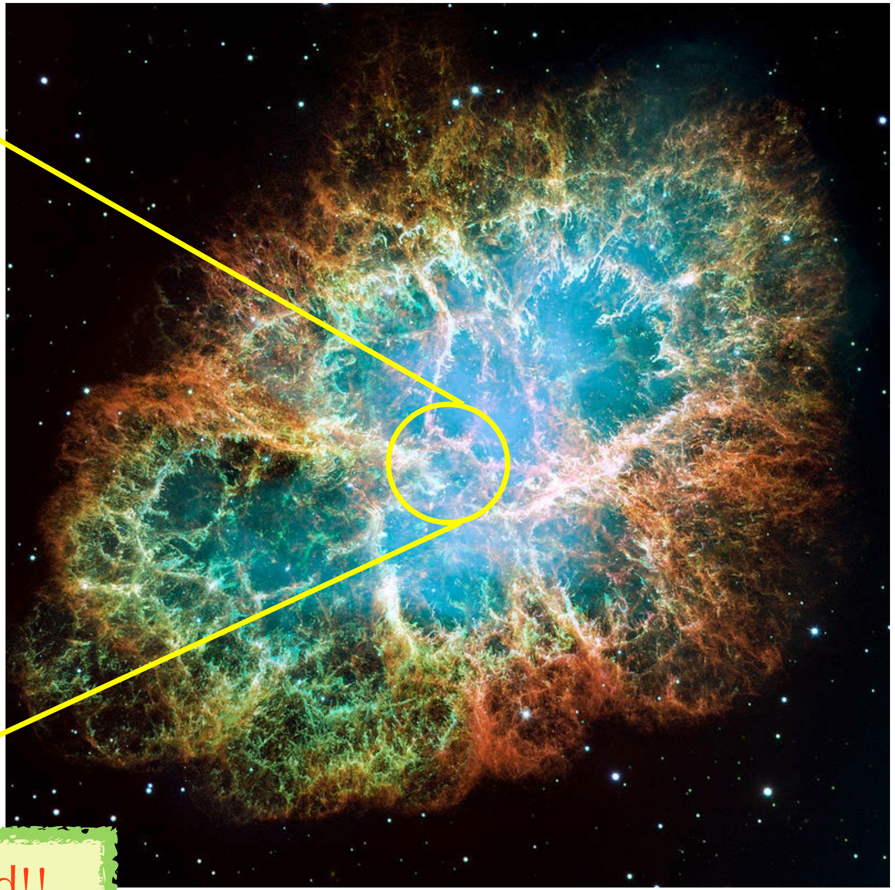
Dirson & Horns, A&A, 2023

The Crab Pulsar:
TeV pulsed emission from a rotating neutron star

- Inverse Compton emission due to relativistic particles from a pulsar with T=33 ms



Ansoldi et al. 2016



All models challenged!!

Science motivation for CTAO

E.g. Cosmic Ray Origin:

Quantitative understanding of cosmic ray spectra & yield

Presumably only very young SNR accelerate to 10^{15} eV;

only a handful of these currently active in our Galaxy

Energy and shape of cutoffs ?

Probing escape of CRs from SNR using ambient gas

k A. Garlick / space-art.co.uk

Science motivation for CTAO

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Energy and shape of cutoffs ?

Probing escape of CRs from SNR using ambient gas

current instruments probe SNR only up to few kpc

k A. Garlick / space-art.co.uk

Science motivation for CTAO

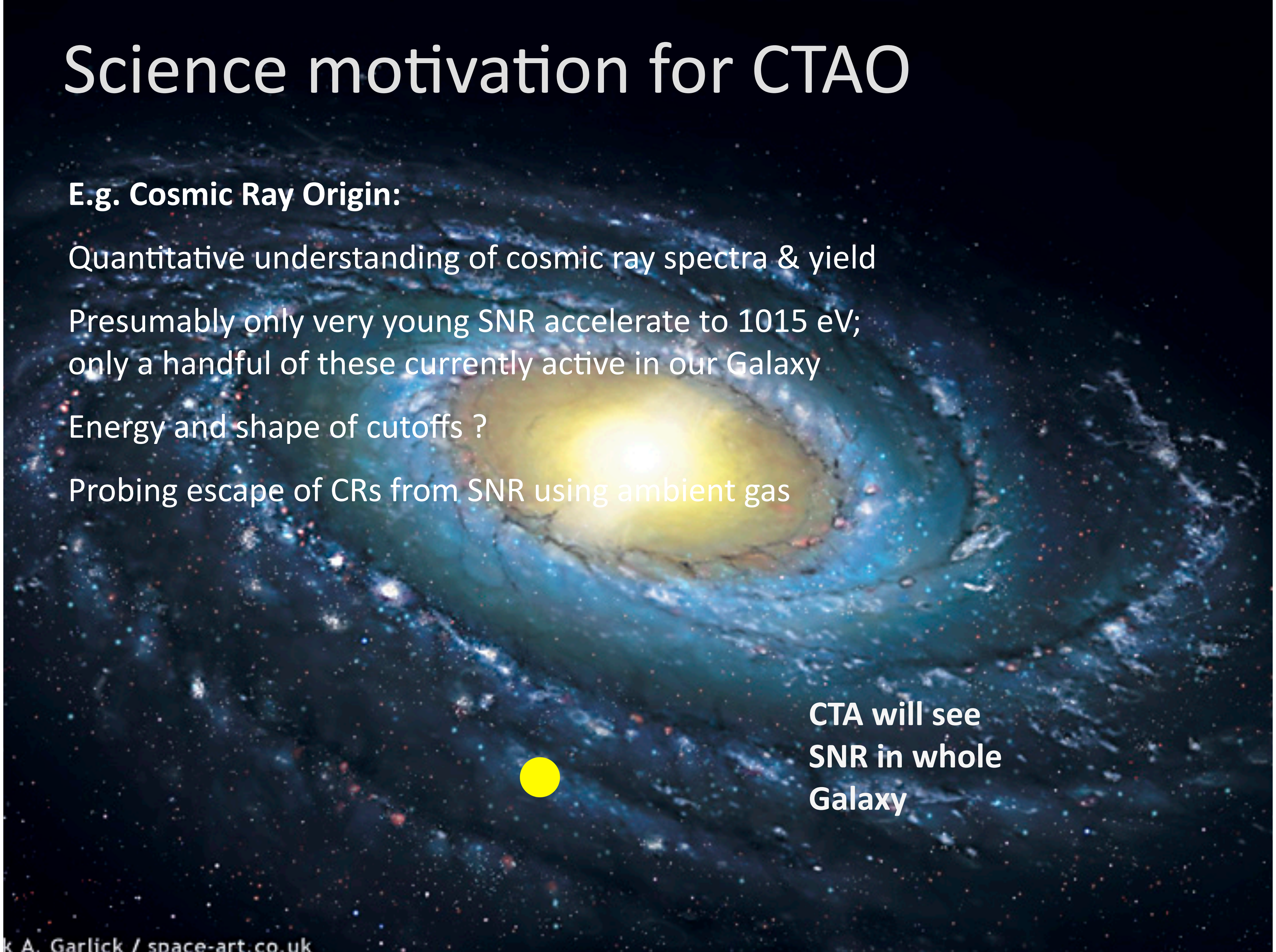
E.g. Cosmic Ray Origin:

Quantitative understanding of cosmic ray spectra & yield

Presumably only very young SNR accelerate to 1015 eV;
only a handful of these currently active in our Galaxy

Energy and shape of cutoffs ?

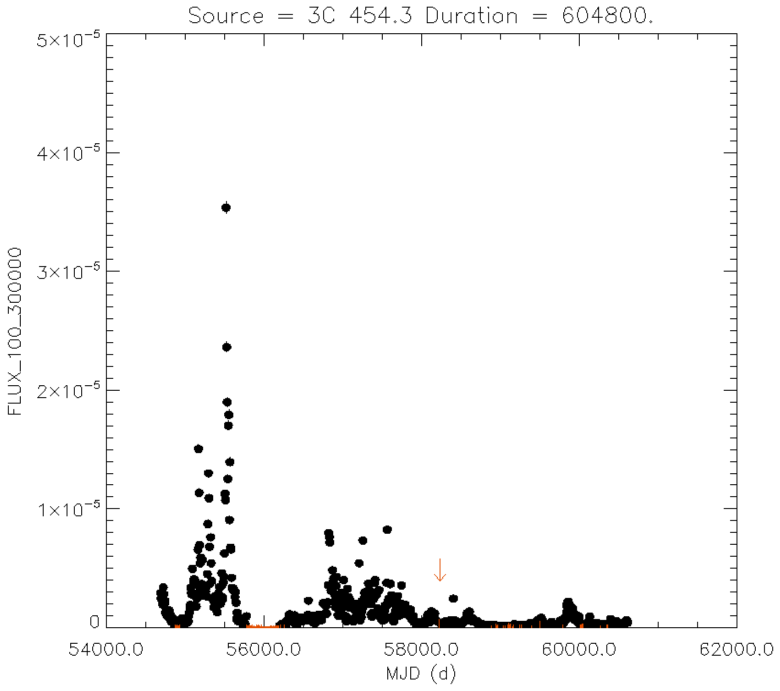
Probing escape of CRs from SNR using ambient gas



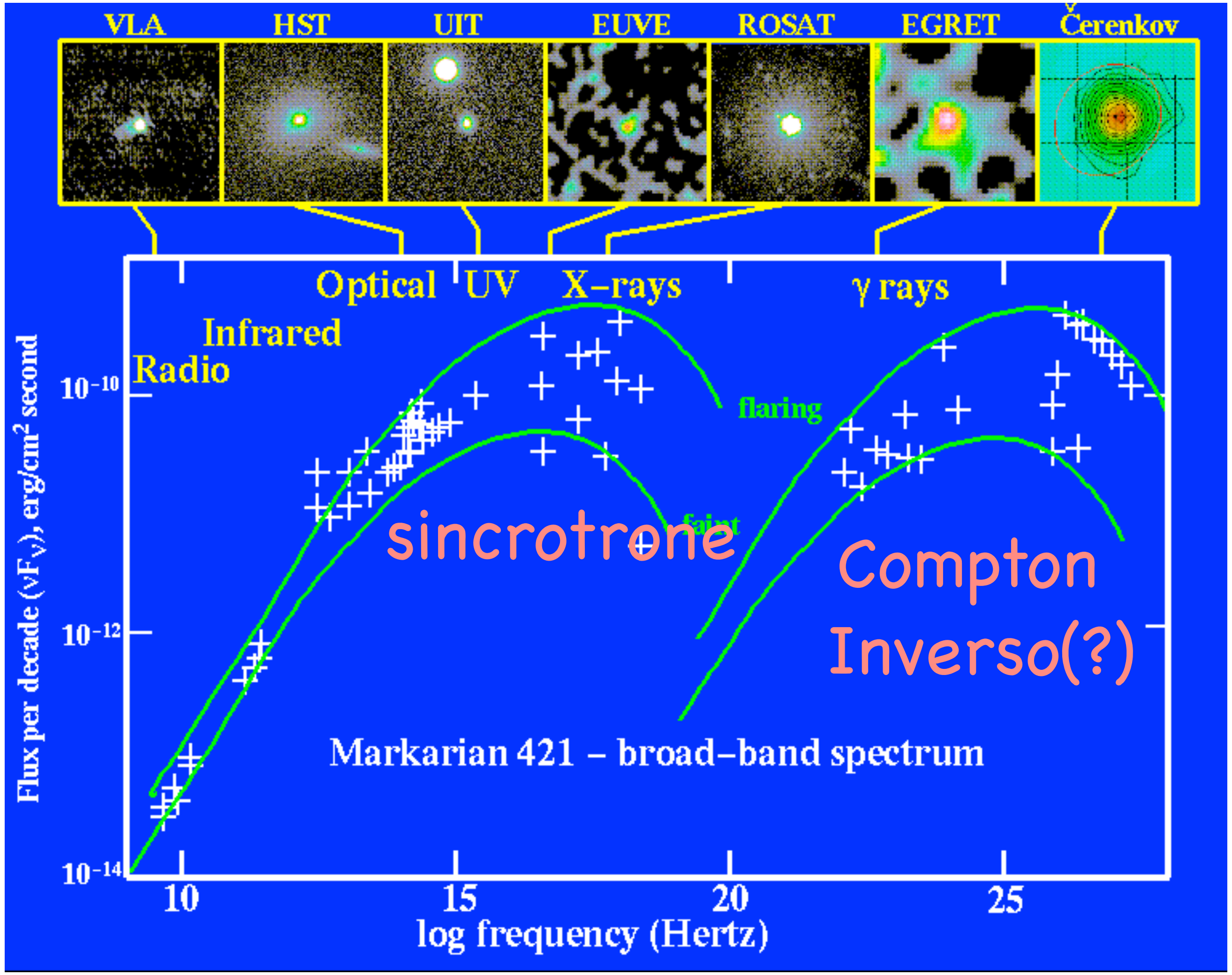
Broad band SED for the blazar Mrk 421

Extended over the whole EM spectrum

Extremely variable



Important observational effort



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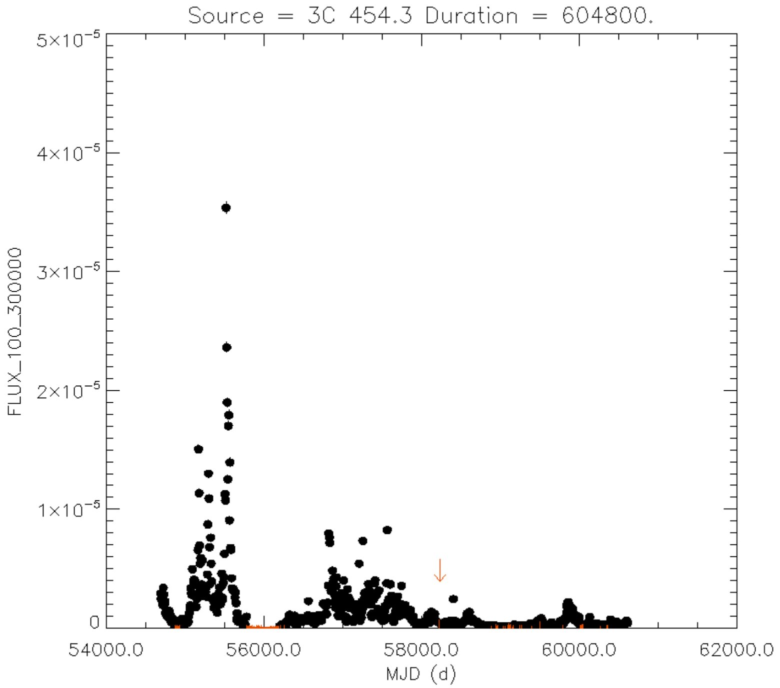

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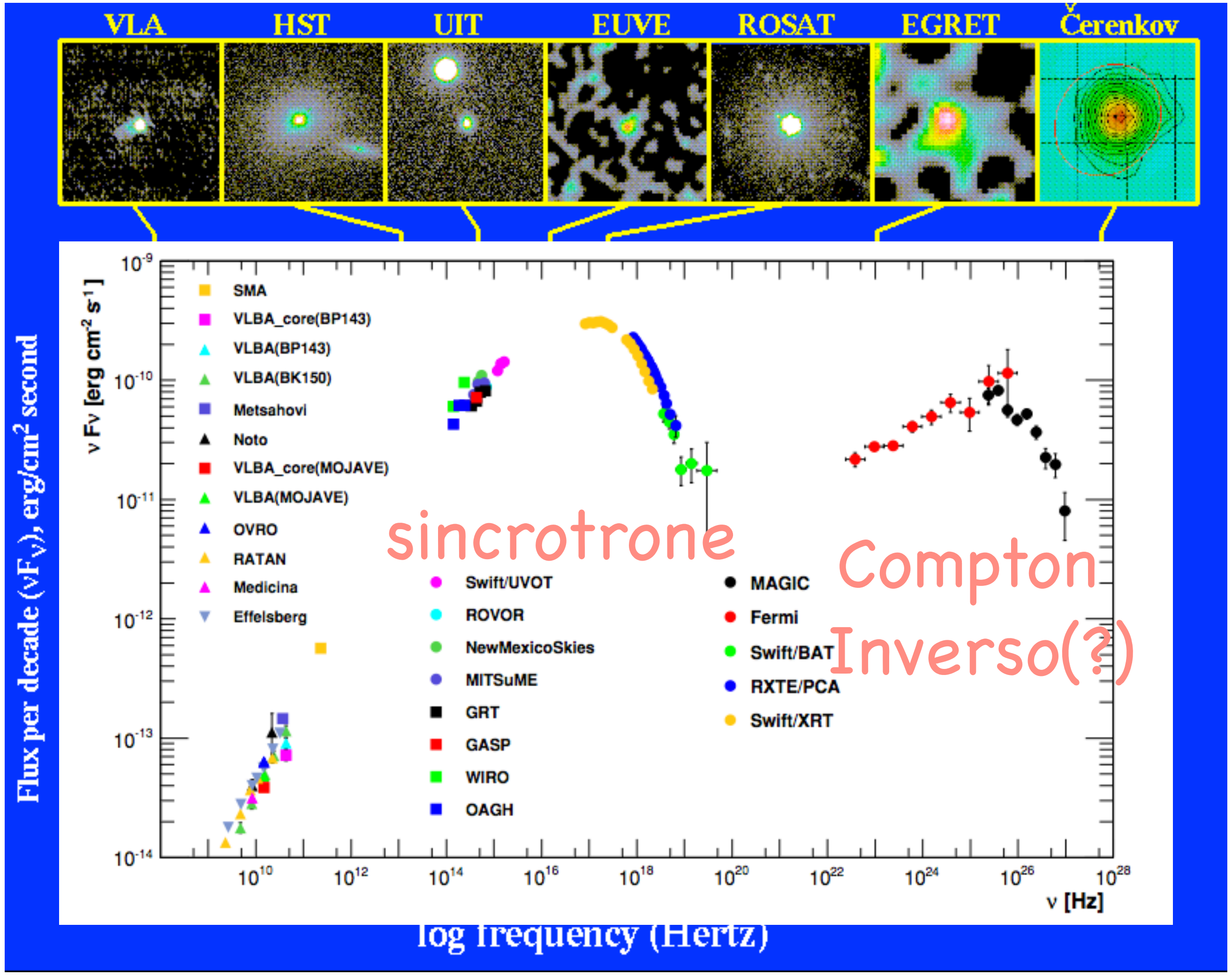
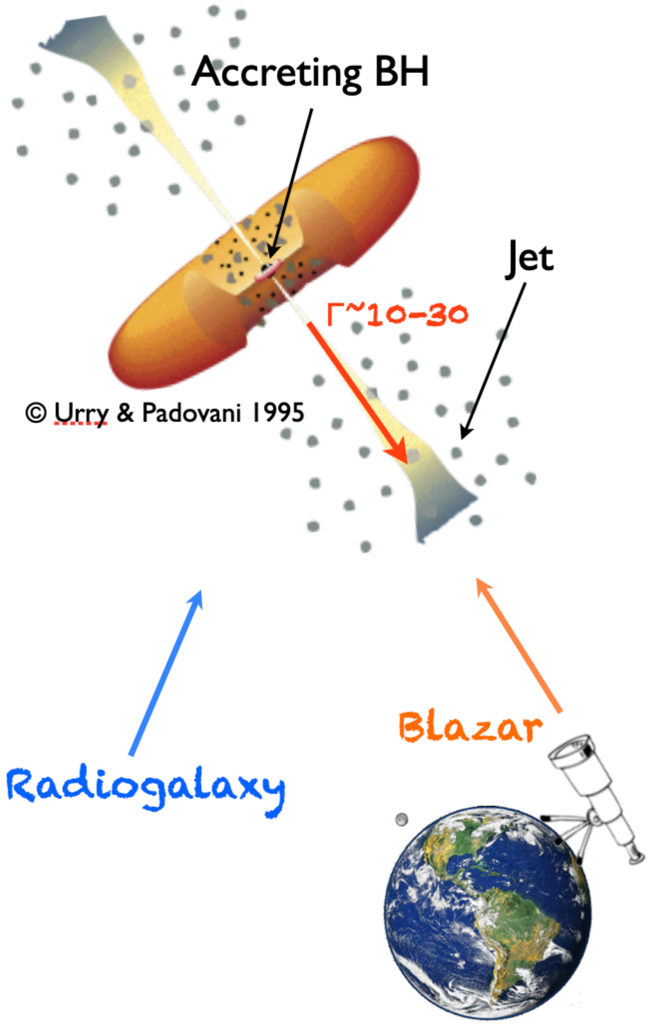
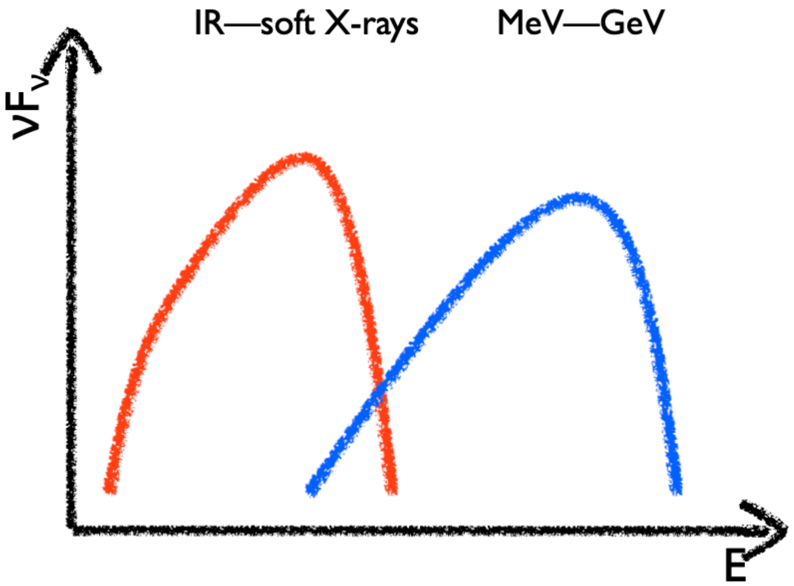


Blazars

Courtesy of F. Tavecchio

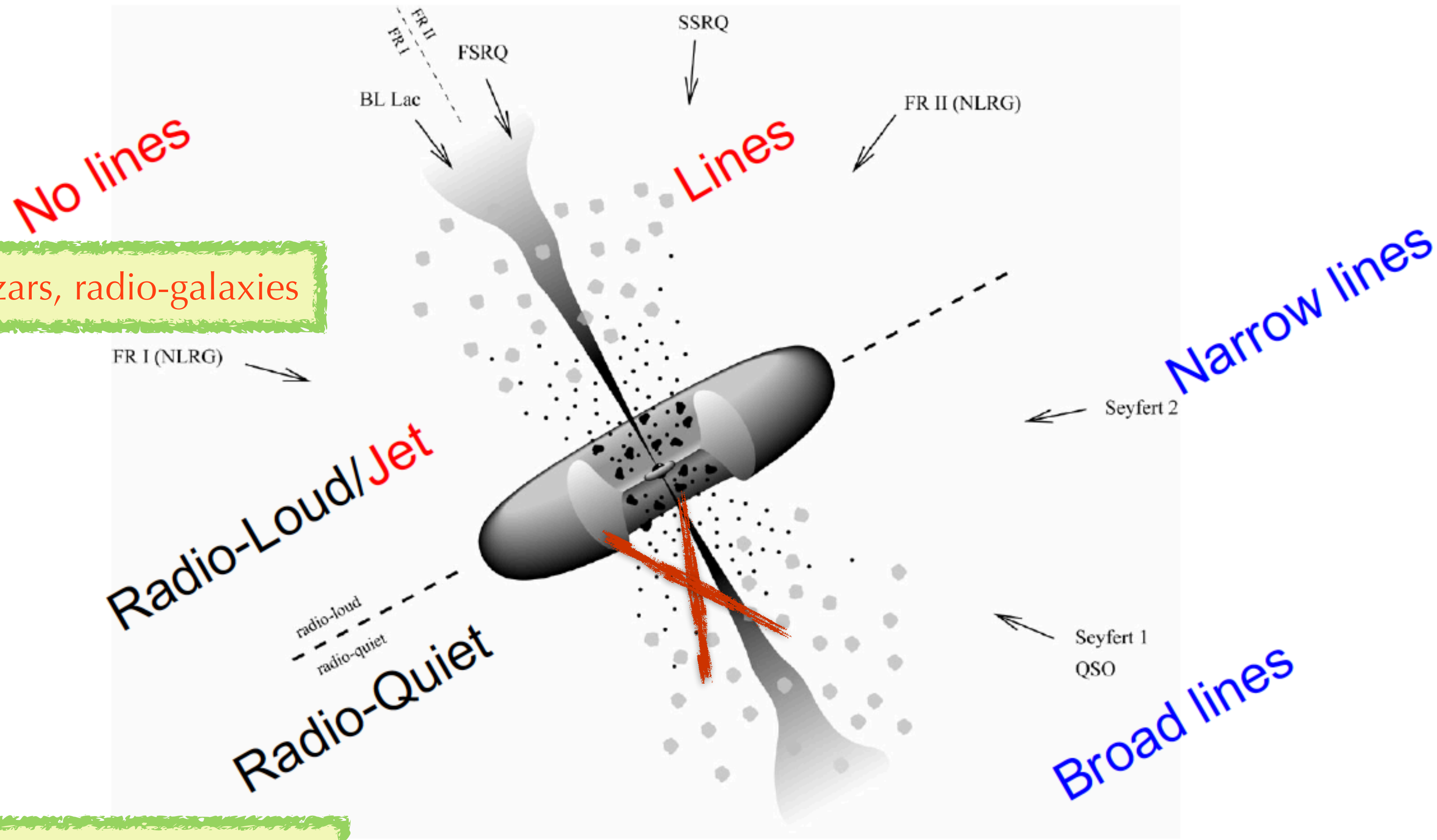




SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

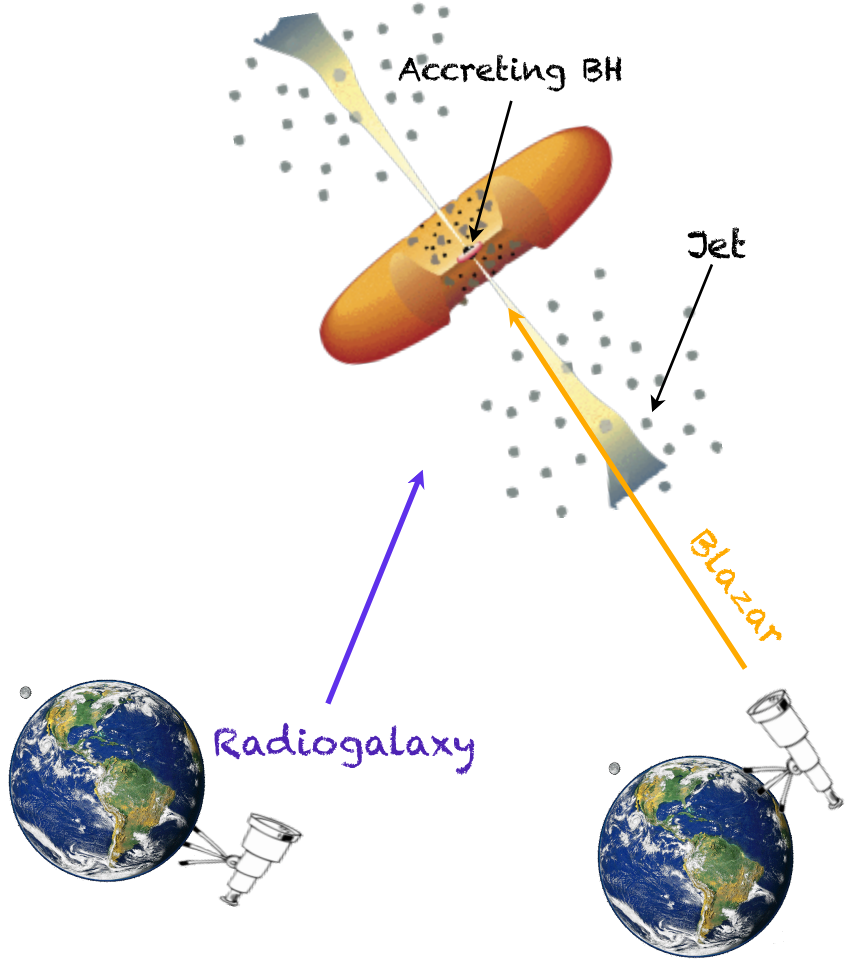
AGN unified model

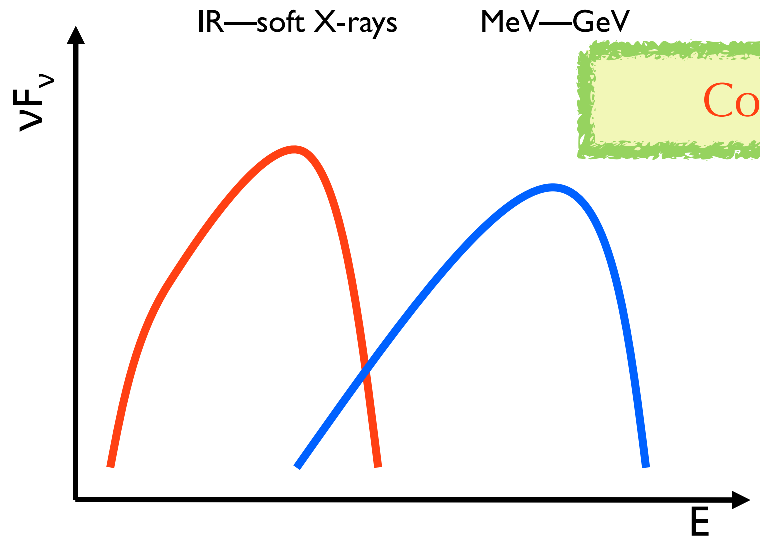
Radio-Loud: blazars, radio-galaxies



Radio-Quiet: quasars, Seyfert

Jets pointing at us: BLAZARS





Courtesy of F. Tavecchio

SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

$$L_{\rm obs} = L'\delta^4 \qquad \delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

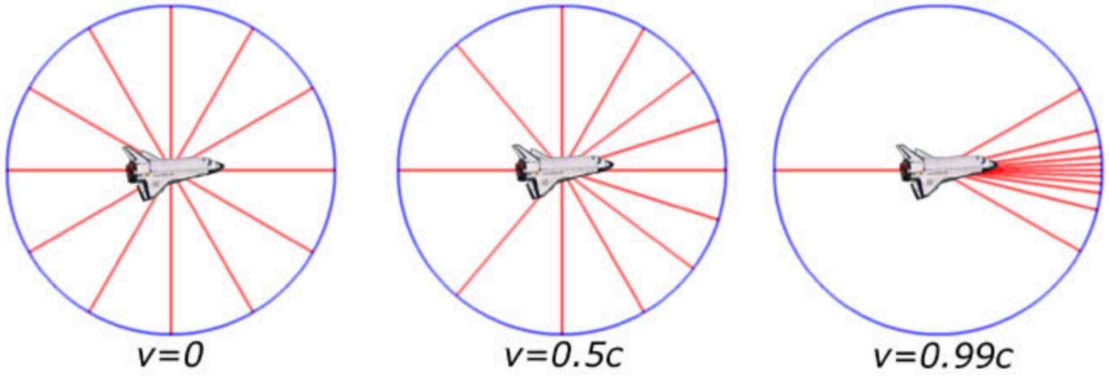
Synchrotron and IC in leptonic models.

Also hadronic scenarios
(synchrotron or photo-meson emission)

Special relativity at work

Courtesy of F. Tavecchio

Doppler beaming



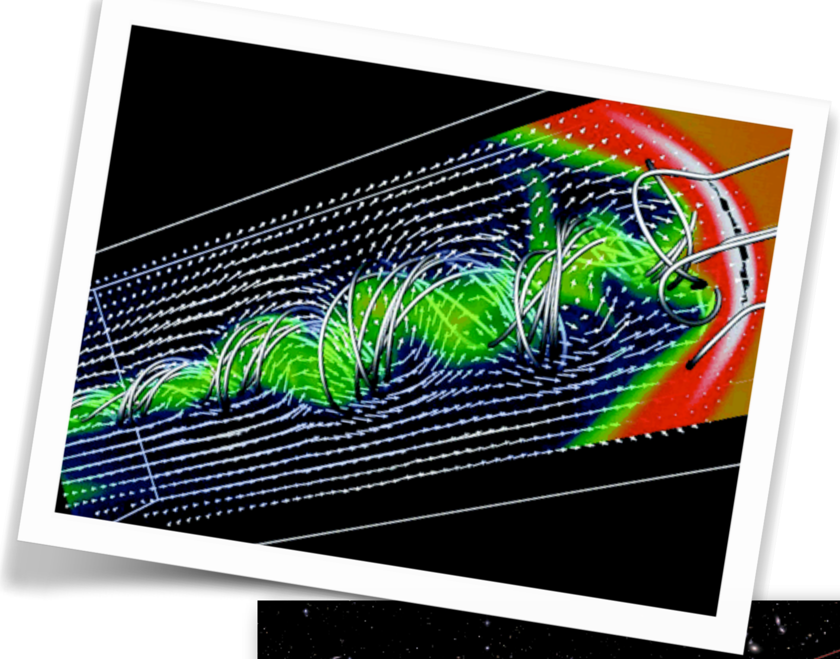
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta_v)}$$

Amplification	$L_{obs} = L'\delta^4$
Blueshift	$\nu_{obs} = \nu'\delta$
Shortening of timescales	$t_{obs} = t'/\delta$

$$\delta \approx 10 - 20$$

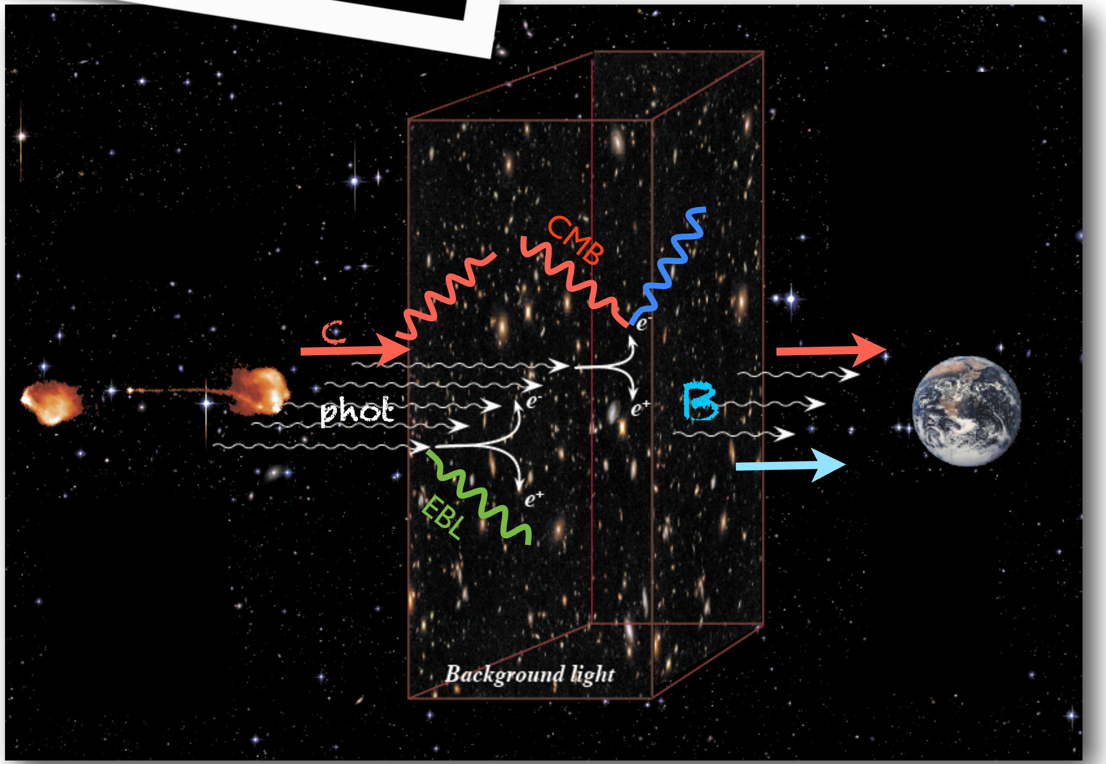
Jet physics

Particle acceleration
Plasma and B-field physics
Reconnection vs shock
Hadronic vs leptonic emission
Location of emission region
...



Propagation effects

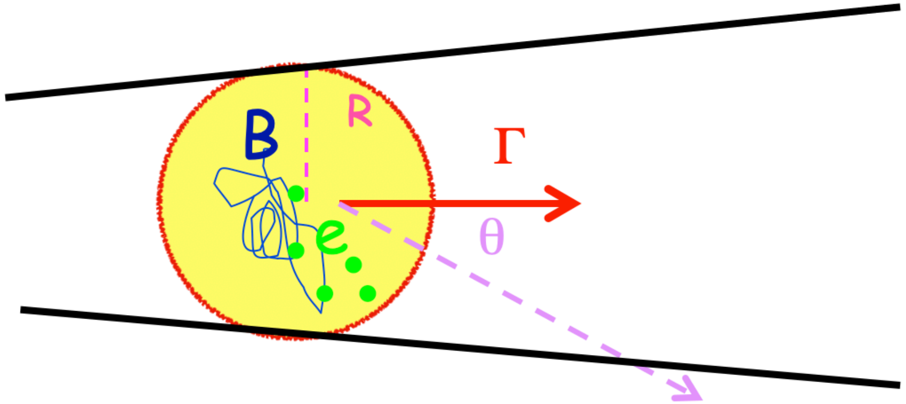
Extragalactic background light
Intergalactic magnetic field
Hadronic beams
LIV and ALPs-induced effects and other anomalies

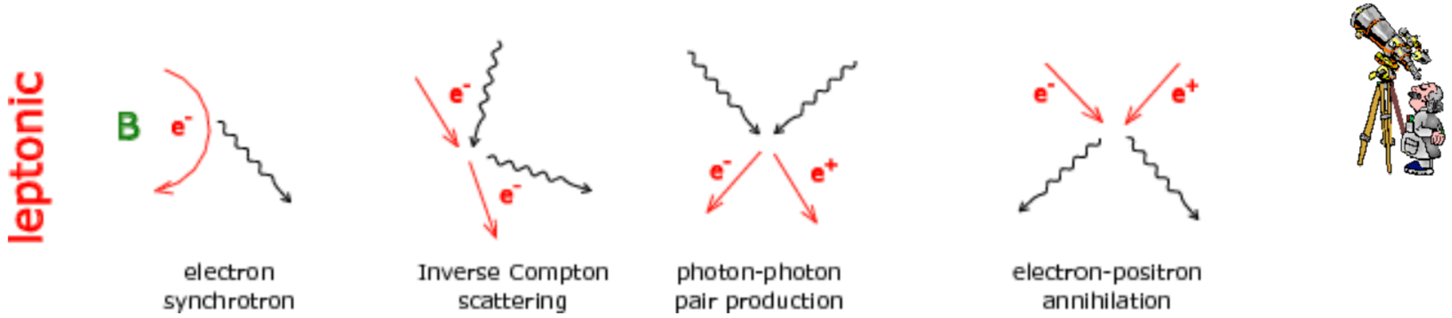


Courtesy of F. Tavecchio

A simple leptonic model

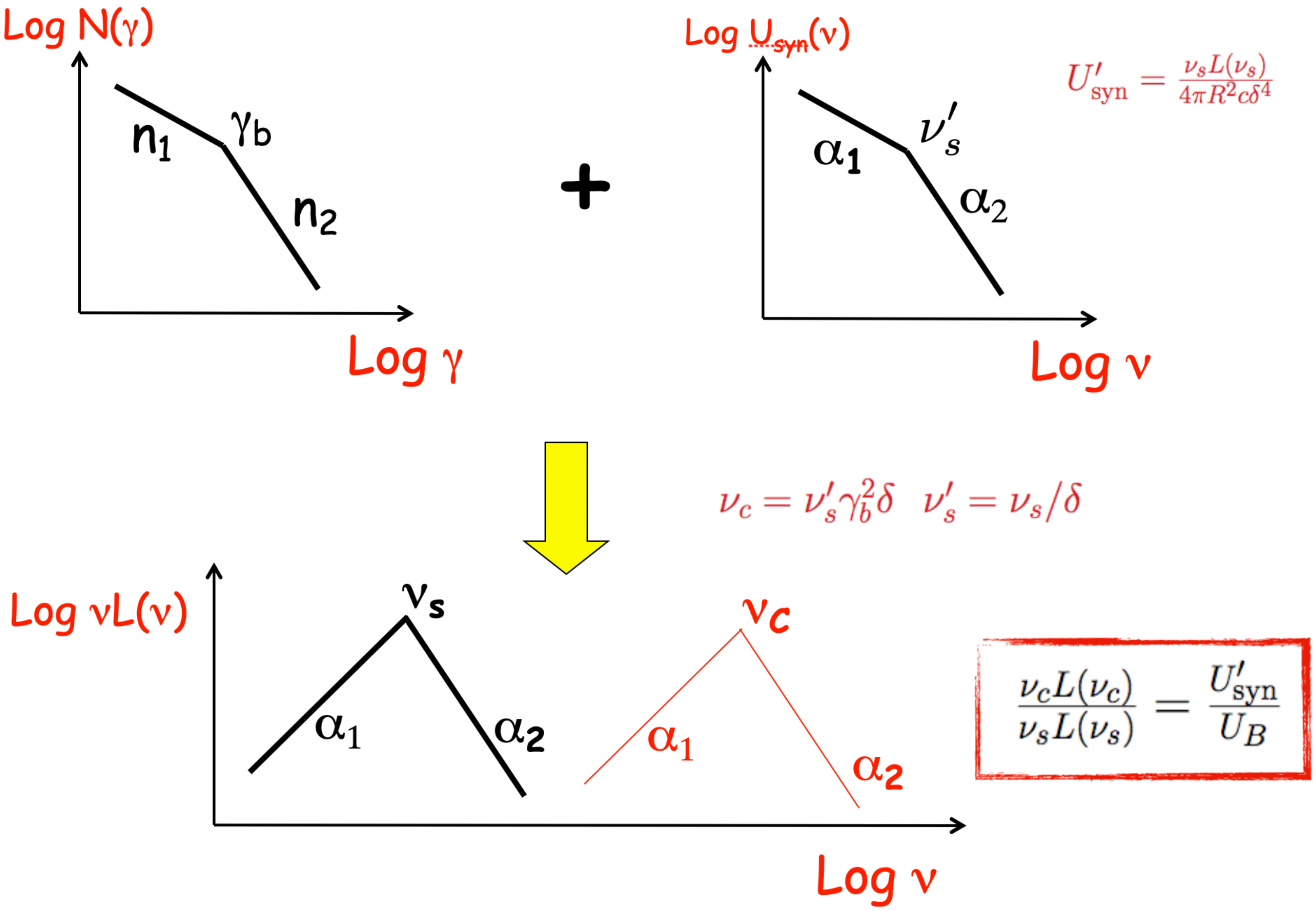
Courtesy of F. Tavecchio



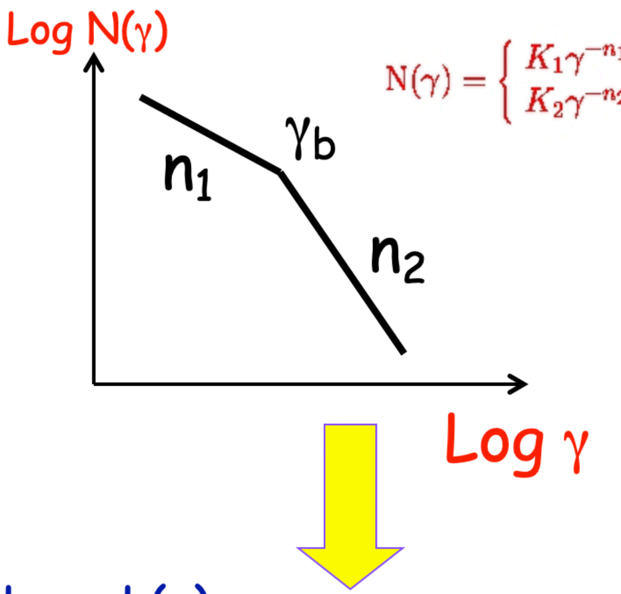


Hadron not important for the emission (but not for energetics!)

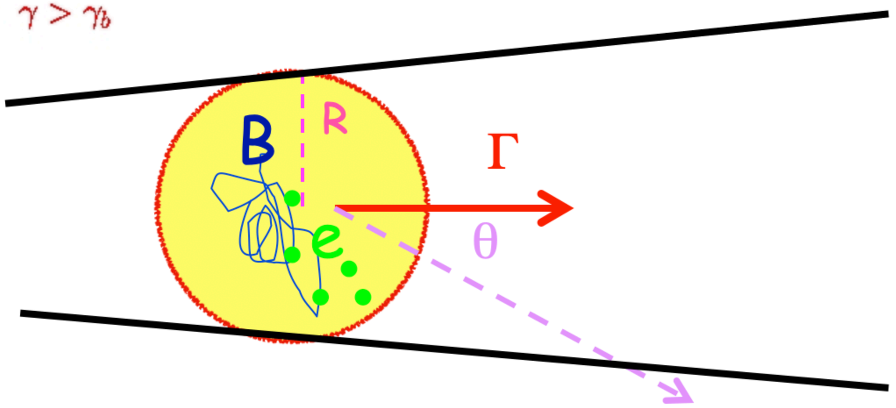
Courtesy of F. Tavecchio

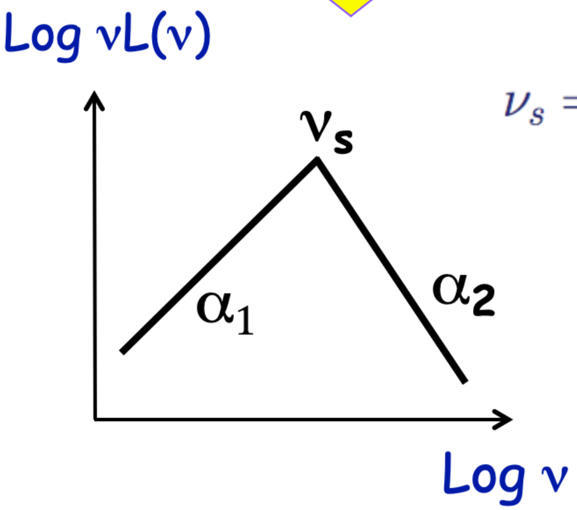


Synchrotron Self-Compton model



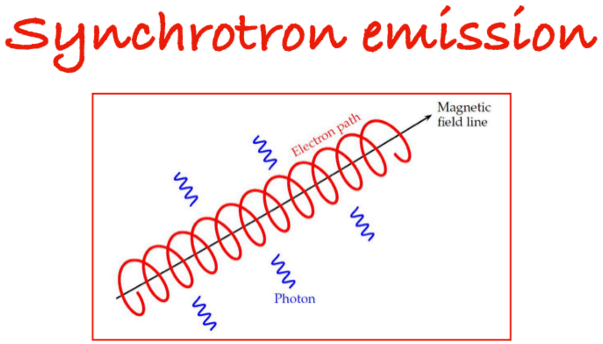
$$N(\gamma) = \begin{cases} K_1\gamma^{-n_1} & \gamma < \gamma_b \\ K_2\gamma^{-n_2} & \gamma > \gamma_b \end{cases}$$





$$\nu_s = 3 \times 10^6 B \gamma_b^2 \delta$$

$$\alpha_i = \frac{n_i - 1}{2}$$



In principle, in this simple version of the Synchrotron-Self Compton (SSC) model, all parameters can be constrained by quantities available from observations:

Courtesy of F. Tavecchio

7 free parameters

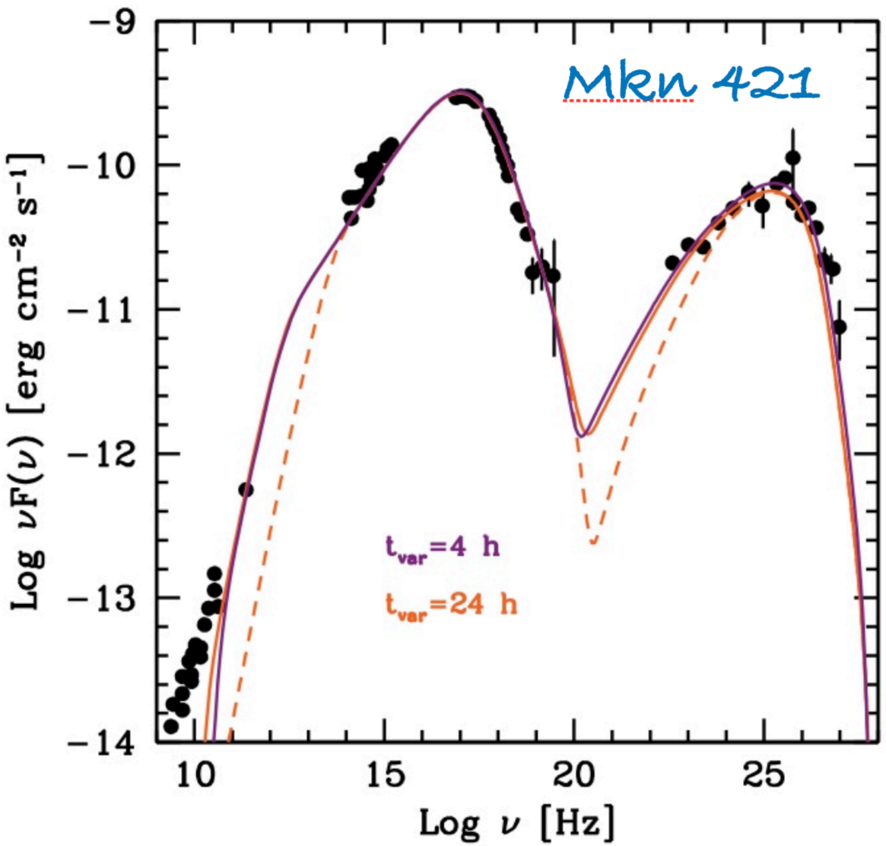
R B N_0 γ_b n_1 n_2 δ

7 observational quantities

ν_s L_s ν_C L_C t_{var} α_1 α_2

Tavecchio, Maraschi & Ghisellini 1998

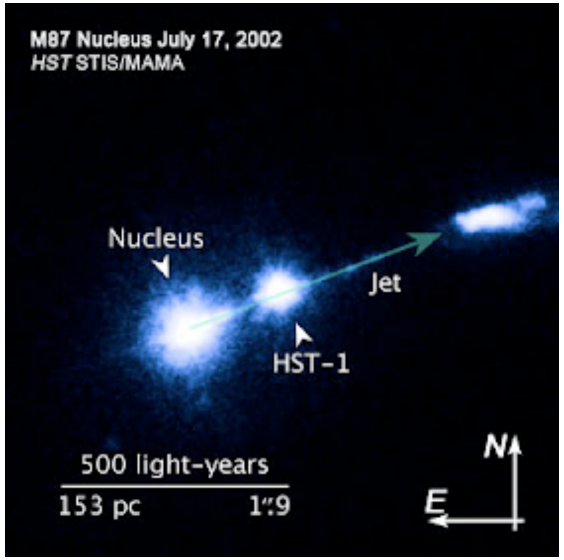
An application

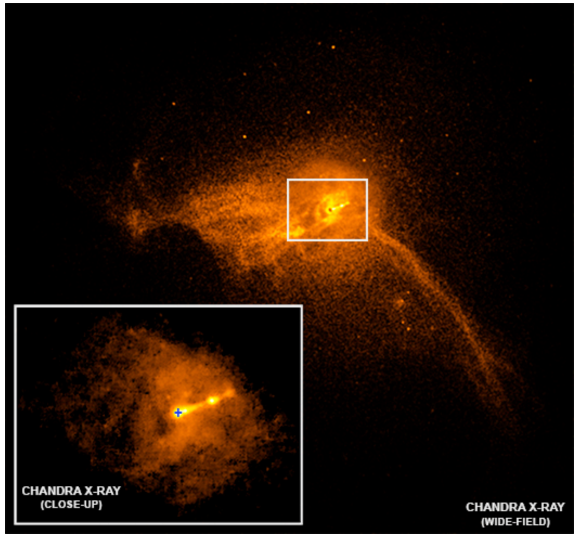


Tavecchio and Ghisellini 2016

Model (1)	γ_{min} (2)	γ_b (3)	γ_{max} (4)	n_1 (5)	n_2 (6)	B (7)	K (8)	R (9)	δ (10)
1	500	1.7×10^5	2×10^6	2.2	4.8	0.075	1.3×10^4	1	25
2	700	2.5×10^5	4×10^6	2.2	4.8	0.06	3.2×10^3	3.6	14

VHE flares in M87: where?



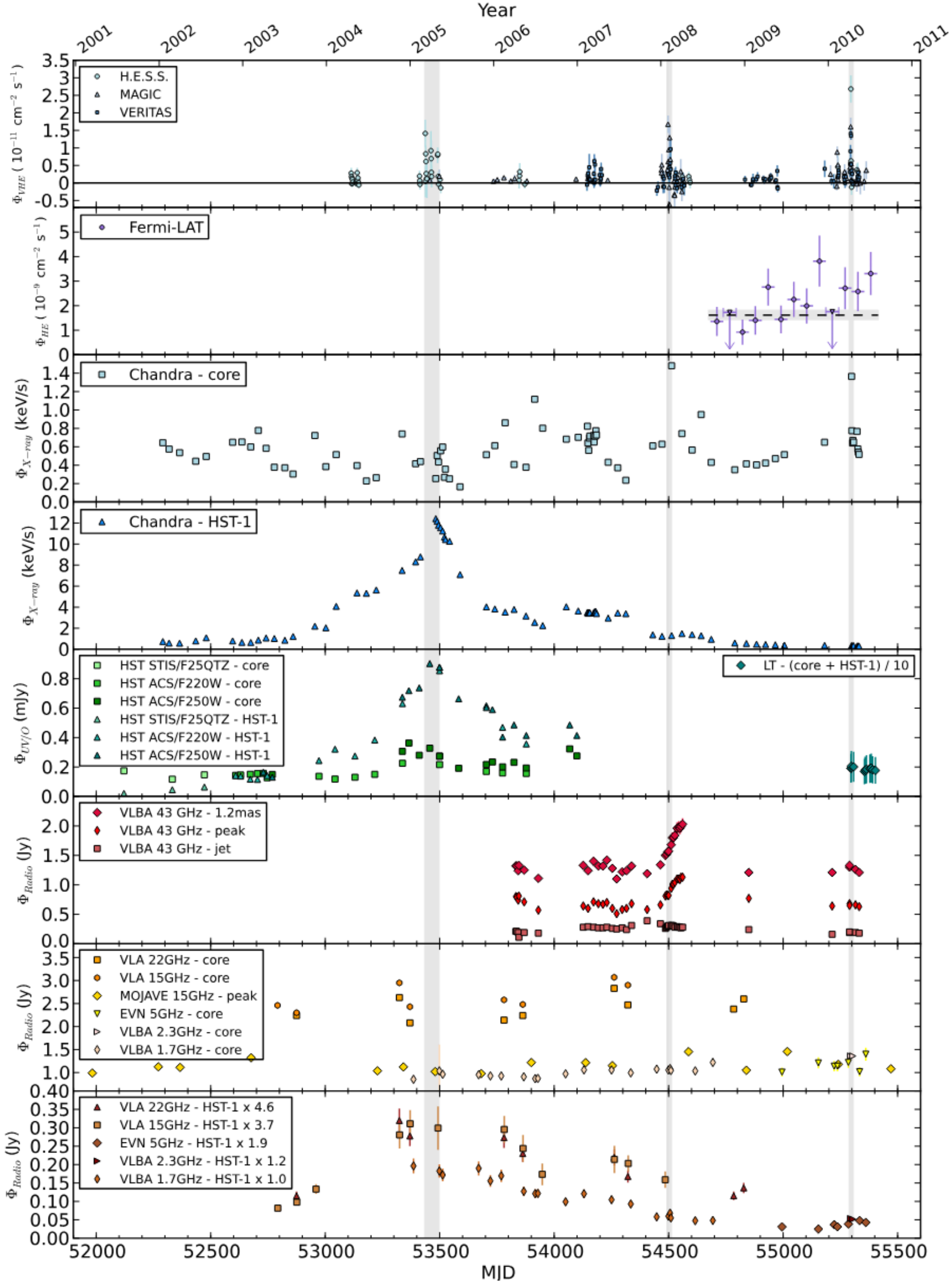


Abramowski+, A&A, 2012

In the core or in HST-1?

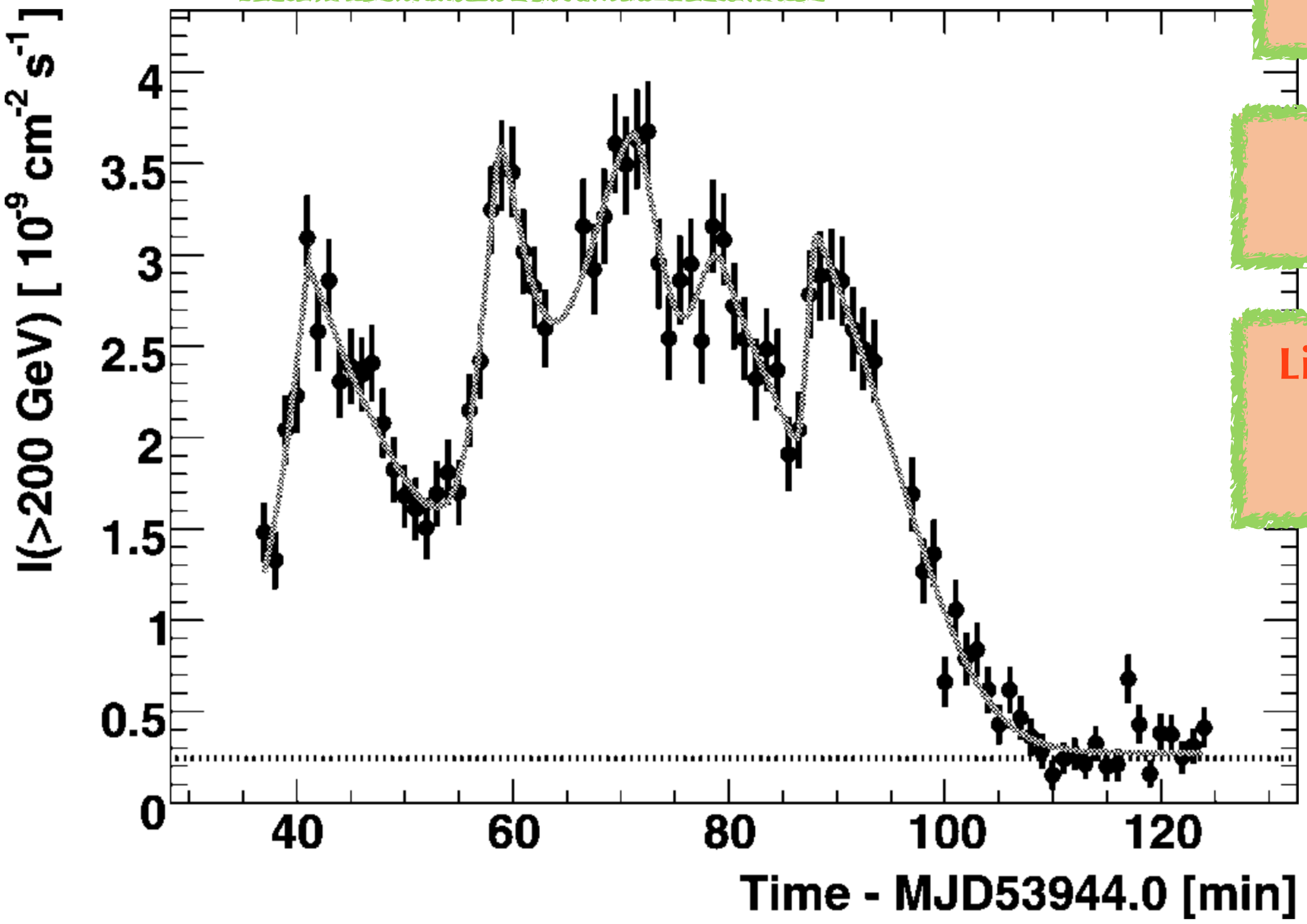
IACT resolution cannot discriminate the two (separation is ~0.9 arcs)

Combining information from different instruments is crucial!



The giant flare of the blazar PKS2155-304

Aharonian+, ApJ, 2007

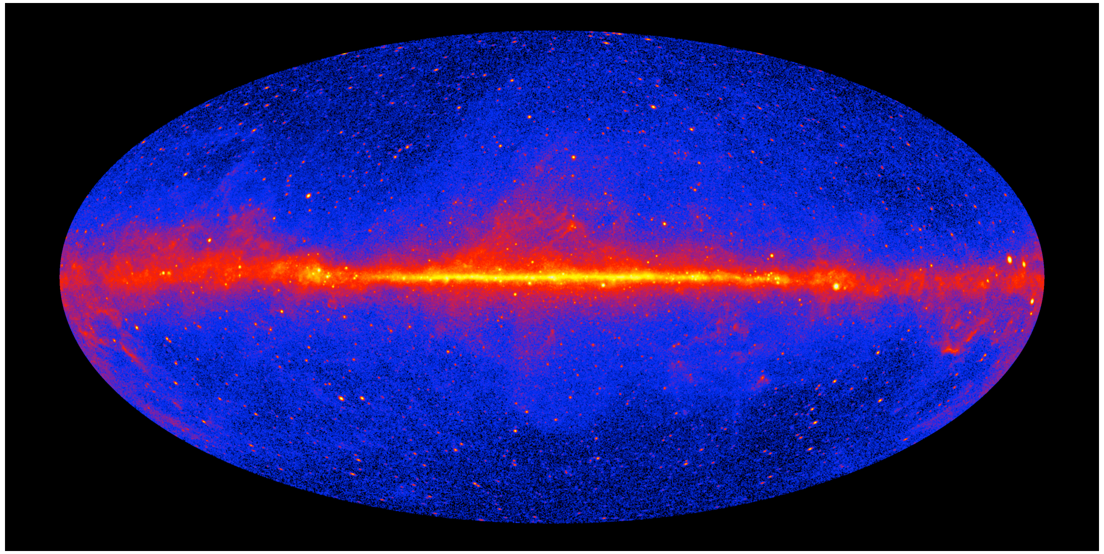


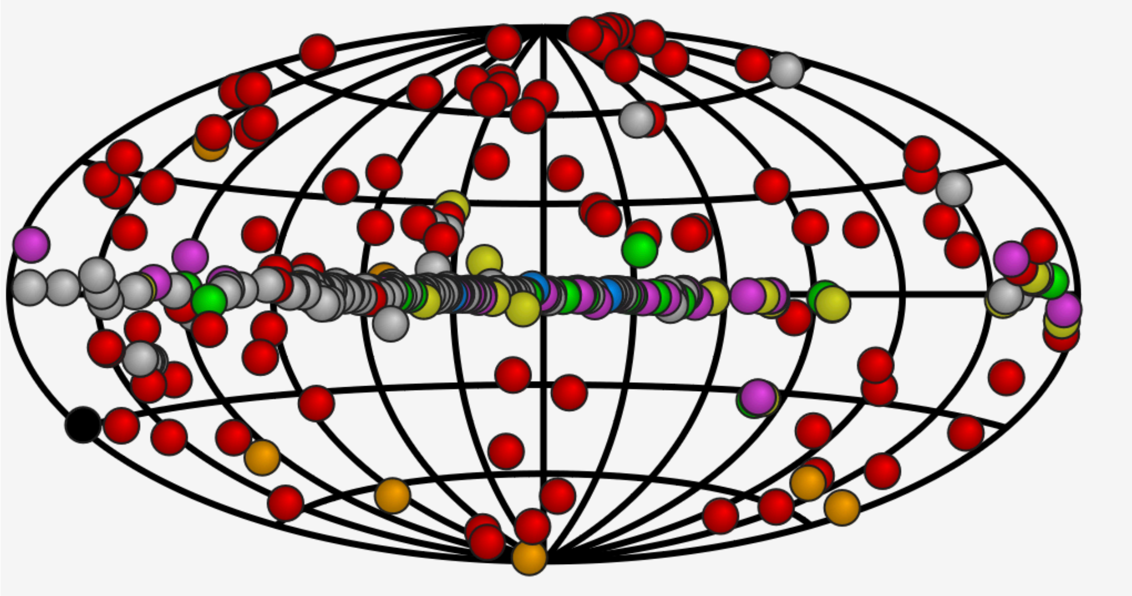
Up to 17 C.U

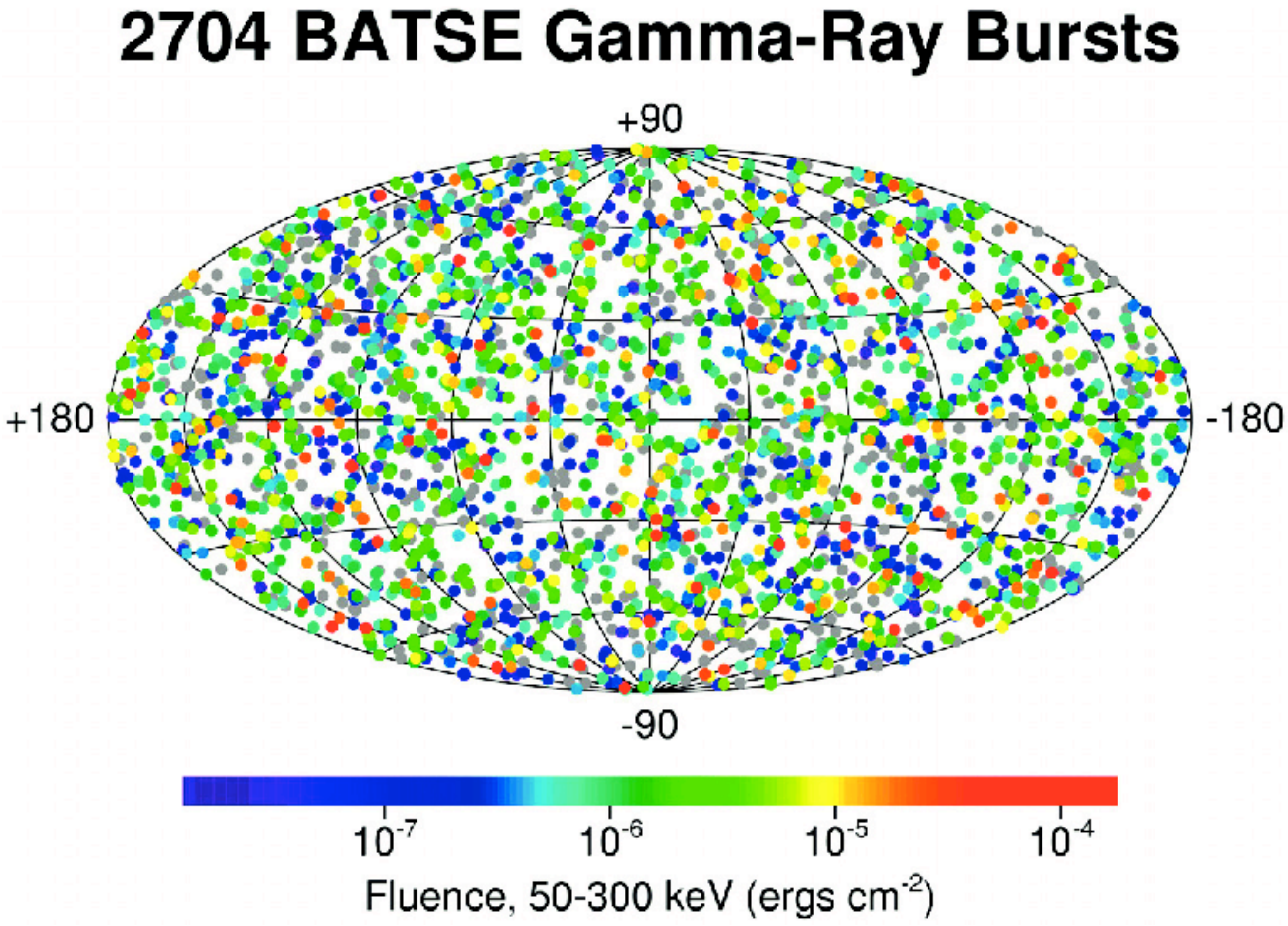
Fast variability, at few minutes scales

Limit to dimension of the emission region by causality condition

Gamma-ray bursts with IACTs



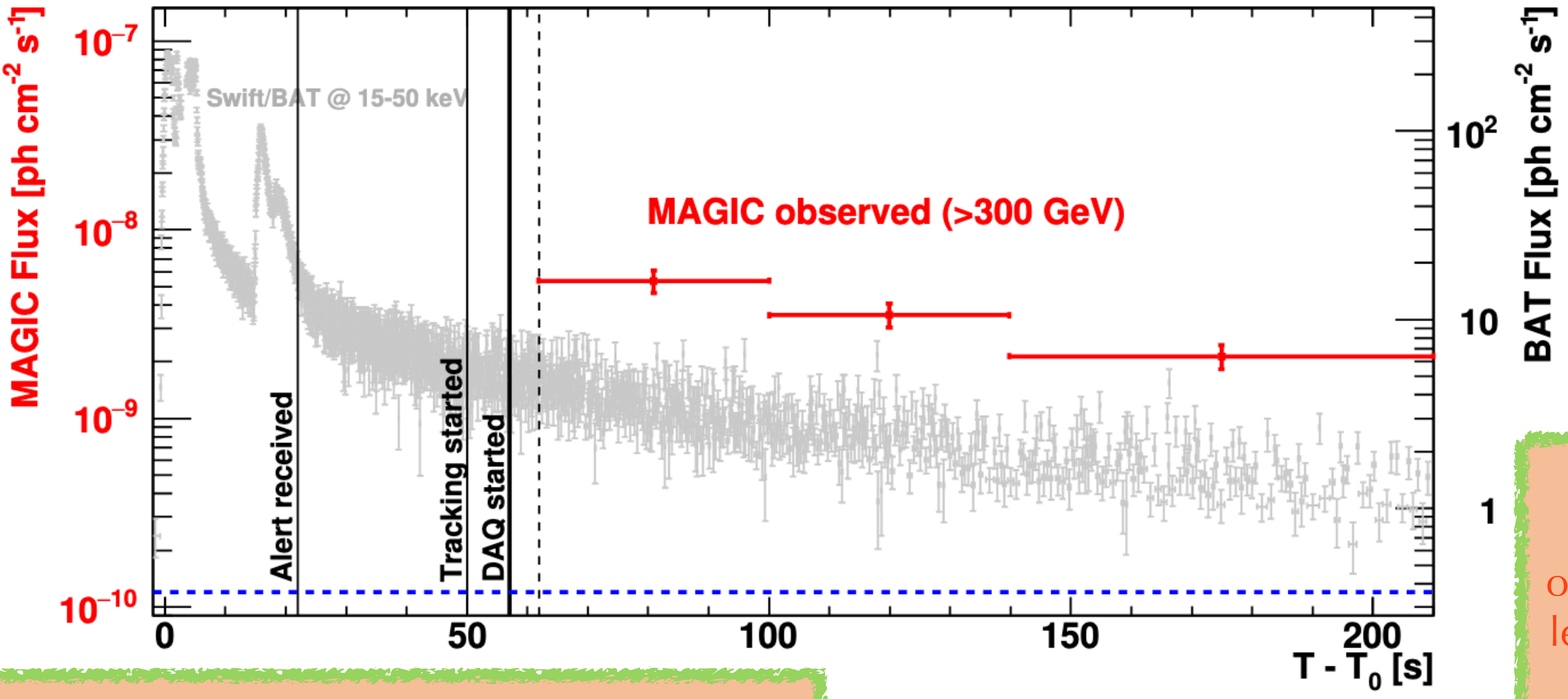




After 15 years of unsuccessful attempts…

Acciari+, Nature, 2019

GRB190114C



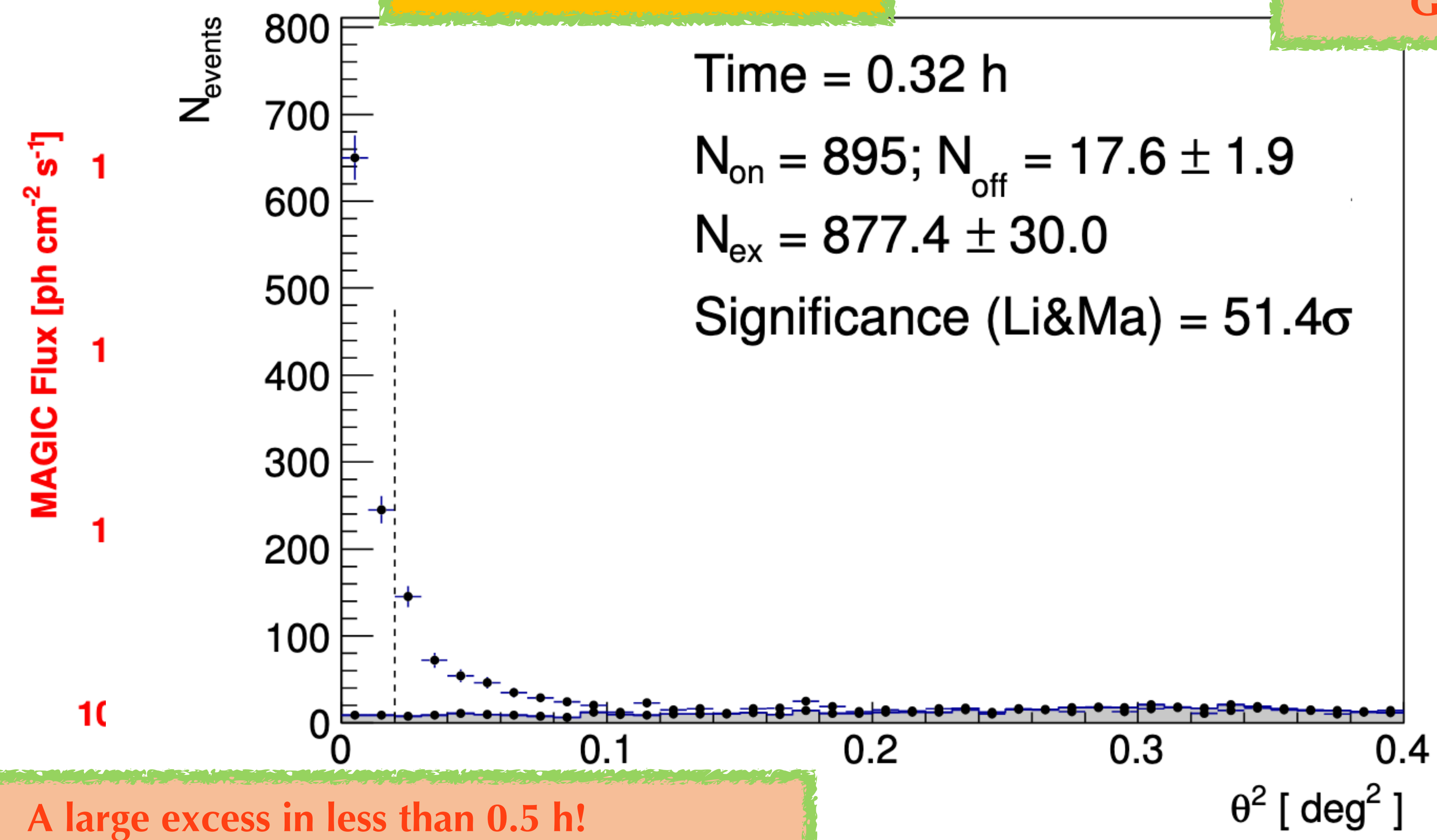
MAGIC repoints and start observation within less than 1 minute since t_0

A large excess in less than 0.5 h!

After 15 years of unsuccessful attempts…

Acciari+, Nature, 2019

GRB190114C

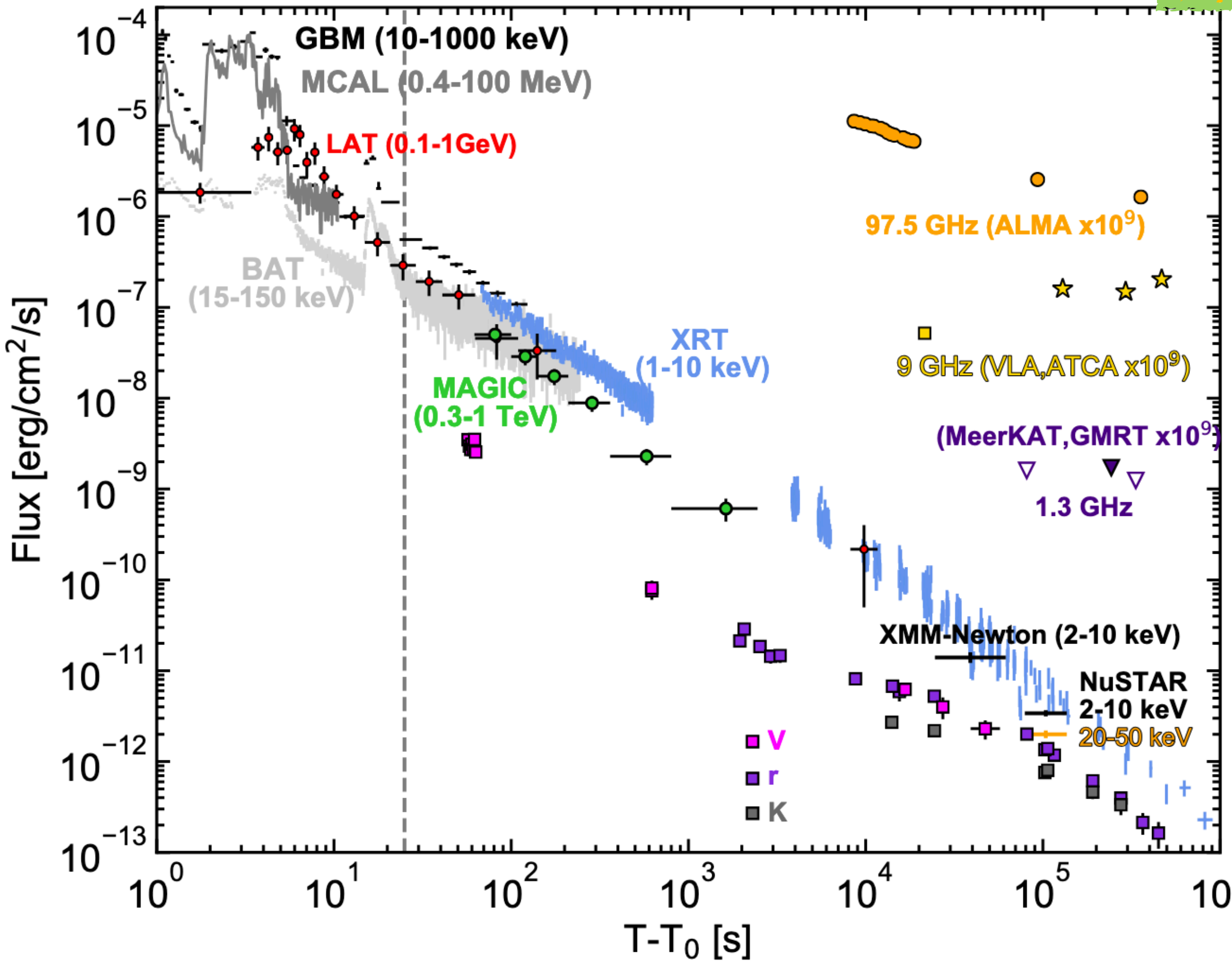


MAGIC repoints and start observation within less than 1 minute since t_0

A large excess in less than 0.5 h!

Multiwavelength light-curve

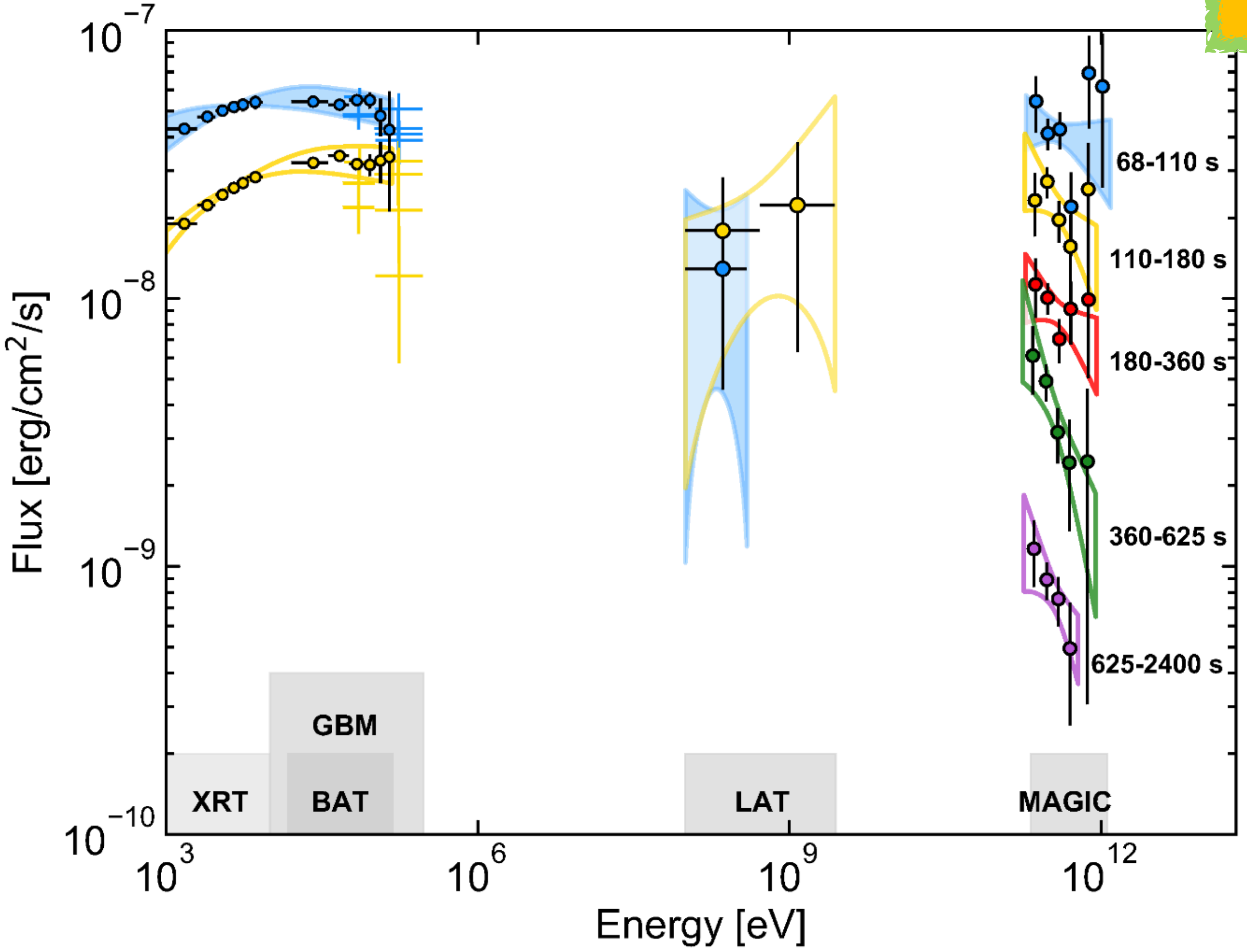
Acciari+, Nature, 2019



Afterglow fluxes decay as a power of time

Time-resolved SEDs

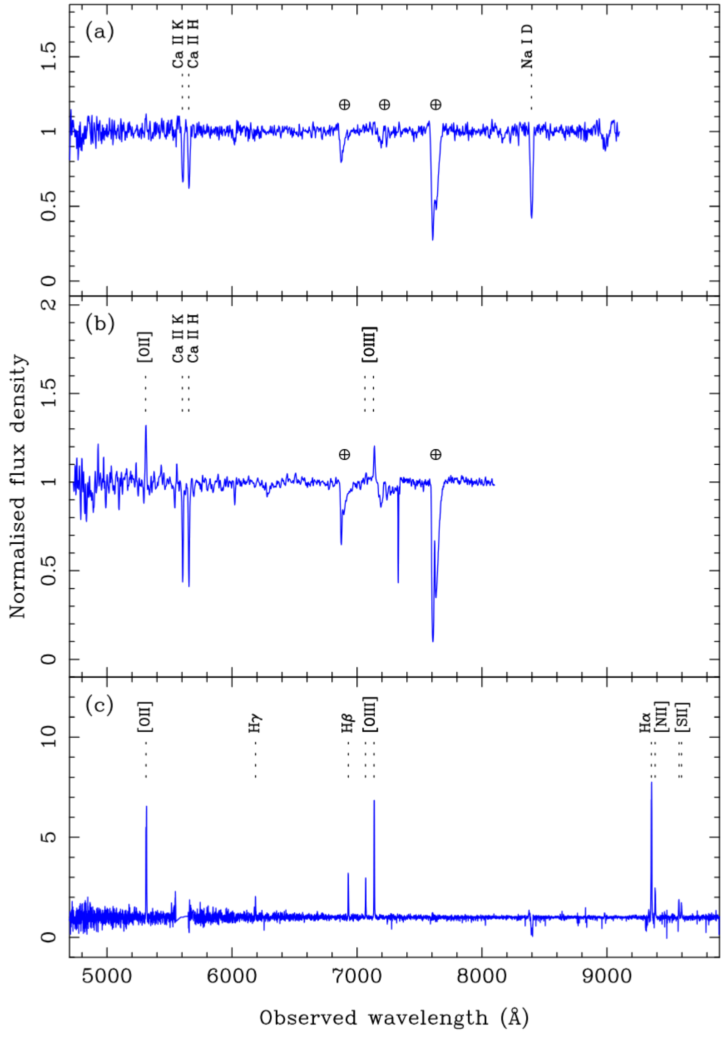
Acciari+, Nature, 2019



Distance of the host galaxy

Acciari+, Nature, 2019

Optical spectrum with redshifted absorption and emission lines



Science motivation for CTAO

Many key phenomena within reach of a 10x more sensitive instrument

VHE gamma rays from galaxy clusters

VHE spectra of GRBs

Redshift evolution of EBL

Dark matter WIMP annihilation

…

An application: IACTs and muon tomography of volcanoes

An application: IACTs
tomography of volcanoes

Catalano+, NIMPA, 2016

Nuclear Instruments and Methods in Physics Research A 807 (2016) 5–12

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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ELSEVIER

Volcanoes muon imaging using Cherenkov telescopes

CrossMark

O. Catalano [a], M. Del Santo [a,*], T. Mineo [a], G. Cusumano [a], M.C. Maccarone [a], G. Pareschi [b]

[a] *INAF, Istituto di Astrofisica Spaziale e Fisica cosmica di Palermo, via U. La Malfa 153, I-90146 Palermo, Italy*
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Silicon photomultiplier

A B S T R A C T

A detailed understanding of a volcano inner structure is one of the key-points for the volcanic hazards evaluation. To this aim, in the last decade, geophysical radiography techniques using cosmic muon particles have been proposed. By measuring the differential attenuation of the muon flux as a function of the amount of rock crossed along different directions, it is possible to determine the density distribution of the interior of a volcano. Up to now, a number of experiments have been based on the detection of the muon tracks crossing hodoscopes, made up of scintillators or nuclear emulsion planes.

Using telescopes based on the atmospheric Cherenkov imaging technique, we propose a new approach to study the interior of volcanoes detecting of the Cherenkov light produced by relativistic cosmic-ray muons that survive after crossing the volcano. The Cherenkov light produced along the muon path is imaged as a typical annular pattern containing all the essential information to reconstruct particle direction and energy. Our new approach offers the advantage of a negligible background and an improved spatial resolution.

To test the feasibility of our new method, we have carried out simulations with a toy-model based on the geometrical parameters of ASTRI SST-2M, i.e. the imaging atmospheric Cherenkov telescope currently under installation onto the Etna volcano. Comparing the results of our simulations with previous experiments based on particle detectors, we gain at least a factor of 10 in sensitivity. The result of this study shows that we resolve an empty cylinder with a radius of about 100 m located inside a volcano in less than 4 days, which implies a limit on the magma velocity of 5 m/h.

An application: IACTs
tomography of volcanoes

Catalano+, NIMPA, 2016

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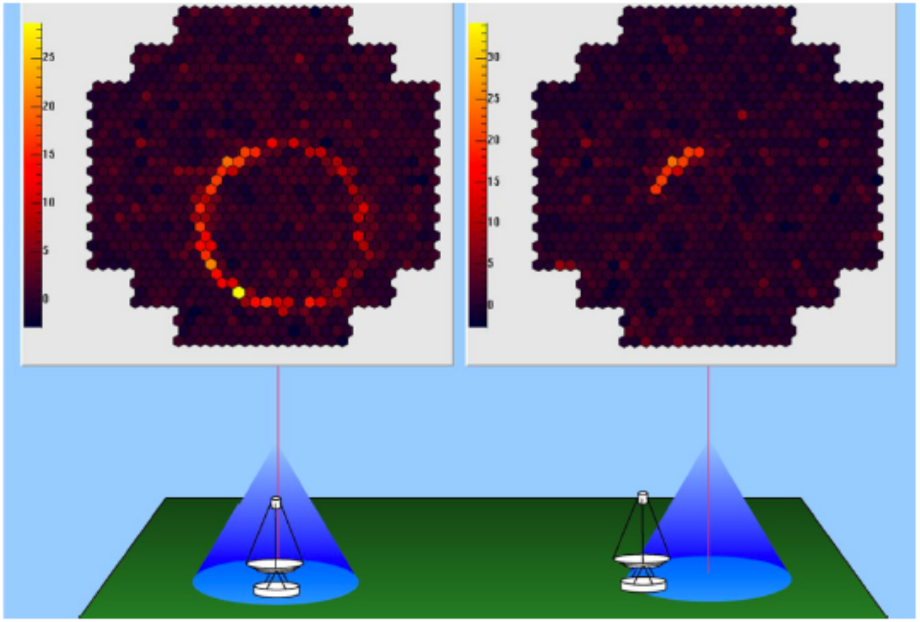

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An application: IACTs tomography of volcanoes

Catalano+, NIMPA, 2016

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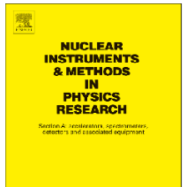

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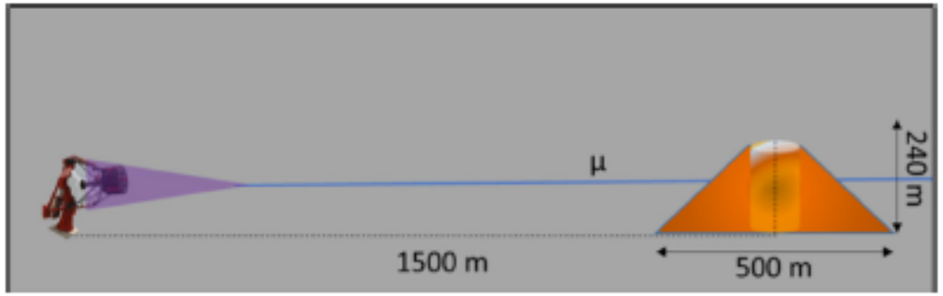
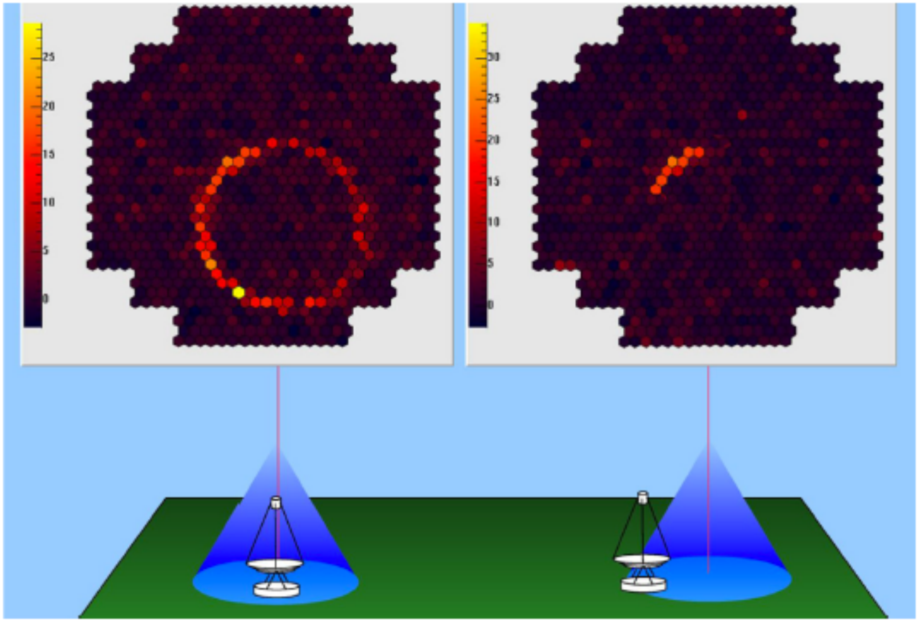
O. Catalano [a], M. Del Santo [a,*], T. Mineo [a], G. Cusumano [a], M.C. M

[a] INAF–Istituto di Astrofisica Spaziale e Fisica cosmica di Palermo, via U. La Malfa 153, I-90146 Palermo, Italy





of a volcano inner structure is one of the key-points for the volcanic hazards
the last decade, geophysical radiography techniques using cosmic muon
ed. By measuring the differential attenuation of the muon flux as a function of
along different directions, it is possible to determine the density distribution
Up to now, a number of experiments have been based on the detection of the
scopes, made up of scintillators or nuclear emulsion planes.
d on the atmospheric Cherenkov imaging technique, we propose a new
erior of volcanoes detecting of the Cherenkov light produced by relativistic
vive after crossing the volcano. The Cherenkov light produced along the muon
annular pattern containing all the essential information to reconstruct particle
new approach offers the advantage of a negligible background and an
n.
our new method, we have carried out simulations with a toy-model based on
of ASTRI SST-2M, i.e. the imaging atmospheric Cherenkov telescope currently
e Etna volcano. Comparing the results of our simulations with previous
icle detectors, we gain at least a factor of 10 in sensitivity. The result of this
study shows that we resolve an empty cylinder with a radius of about 100 m located inside a volcano in
less than 4 days, which implies a limit on the magma velocity of 5 m/h.

An application: IACTs and tomography of volcanoes

Catalano+, NIMPA, 2016

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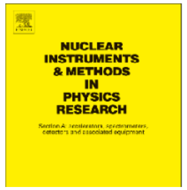

Volcanoes muon imaging using Cherenkov telesco

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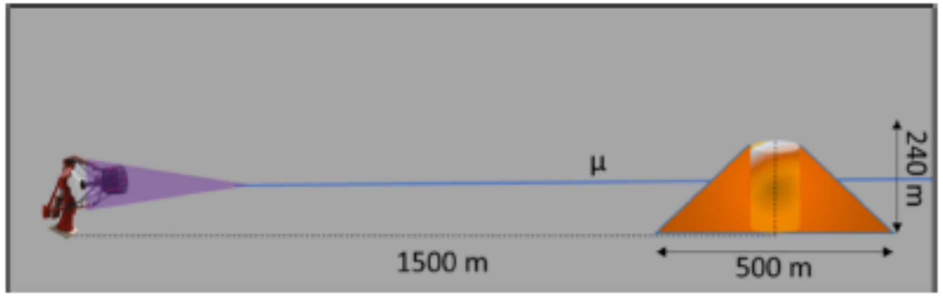

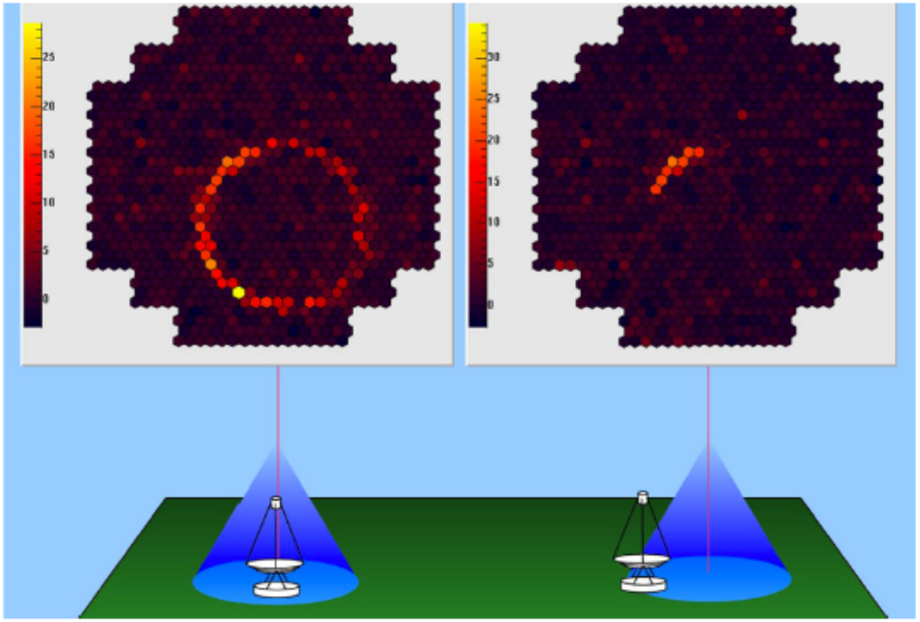

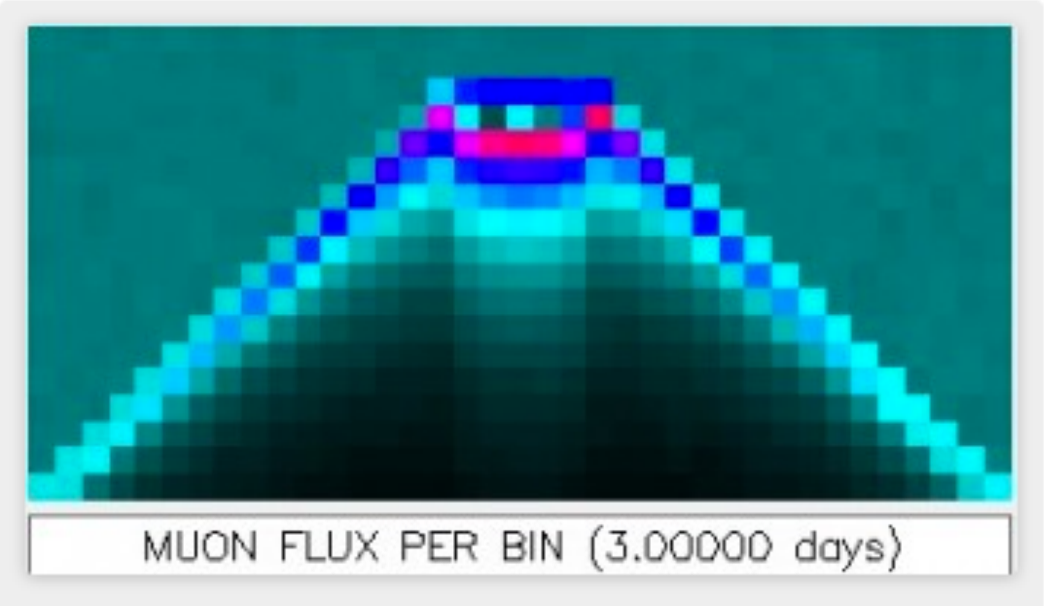

study shows that we resolve an empty cylinder with a radius of about 100 m located inside a volcano in less than 4 days, which implies a limit on the magma velocity of 5 m/h.

Thanks!!

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