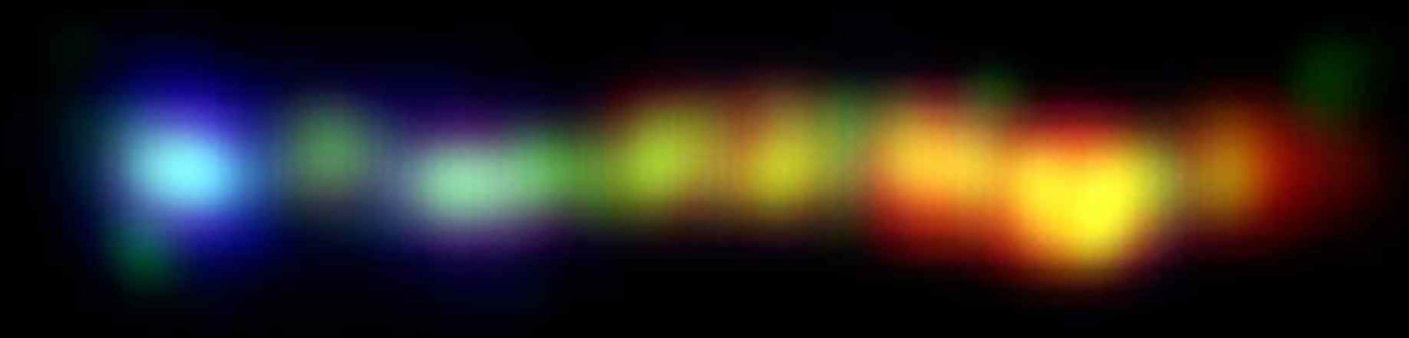
Extragalactic Sources at High Energies



the kpc jet from 3C273 seen with Chandra/HST/ Spitzer

CFRCos

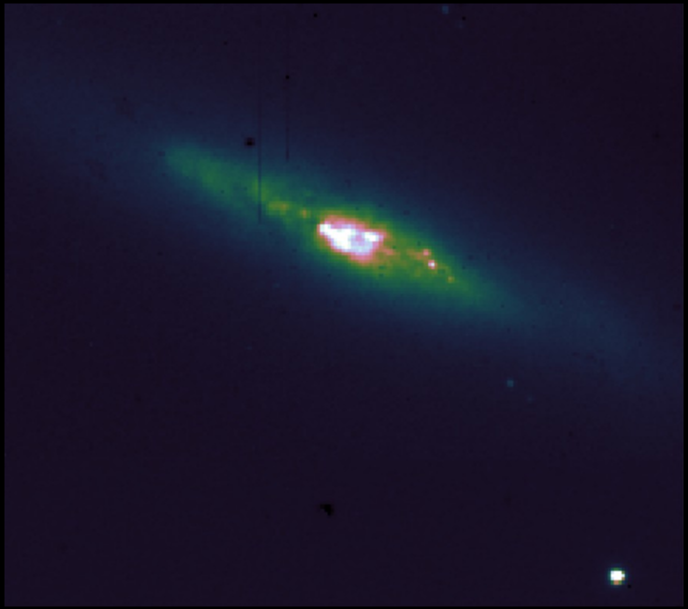
26 mars 2018

A. Zech (LUTH / Observatoire de Paris)

with feedback from
P. Martin, F. Acero, M. Lemoine-Goumard

A : What we have learnt and what we haven’t learnt yet.

Cosmic rays in galaxies and galaxy clusters.



M82 (J-band, OHP, M2 AAIS 2018)

Cosmic rays in galaxies and galaxy clusters

motivation :

- γ-rays should trace the cosmic-ray population in interactions with ISM, ICM.

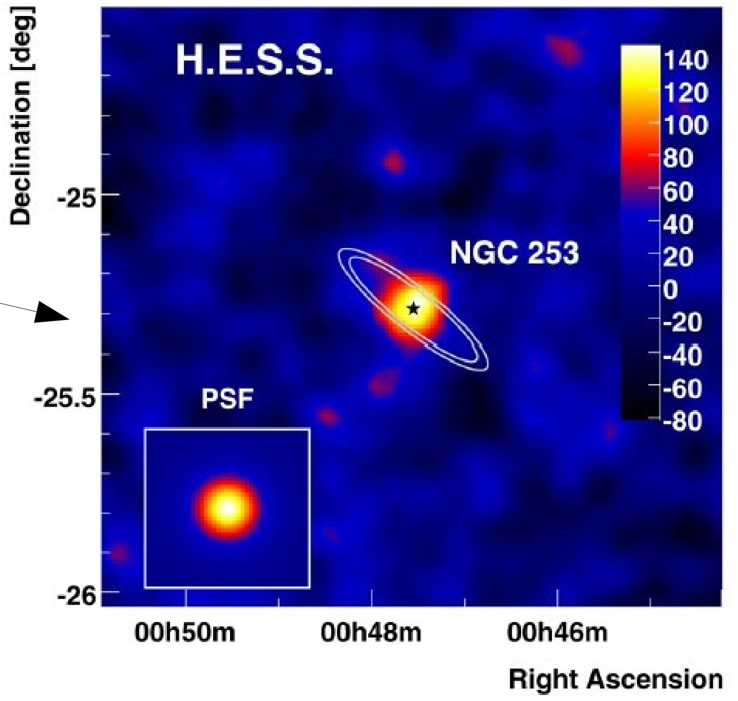
- Extragalactic sources provide outside view, complementary to studies of our Galaxy.

-> Insight into the connection of cosmic-ray acceleration and star formation on different scales.

problems :

- only the brightest and most nearby galaxies detectable today in γ-rays, and mostly as point sources

- how to distinguish diffuse emission from emission of unresolved individual sources ?



Abramowski et al. (2012)

Cosmic rays in **galaxies**

detections of star-forming & starburst galaxies :

- **detections at MeV / GeV** : M31, LMC, SMC, 4 starbursts

- M31, LMC, SMC are the only spatially resolved sources

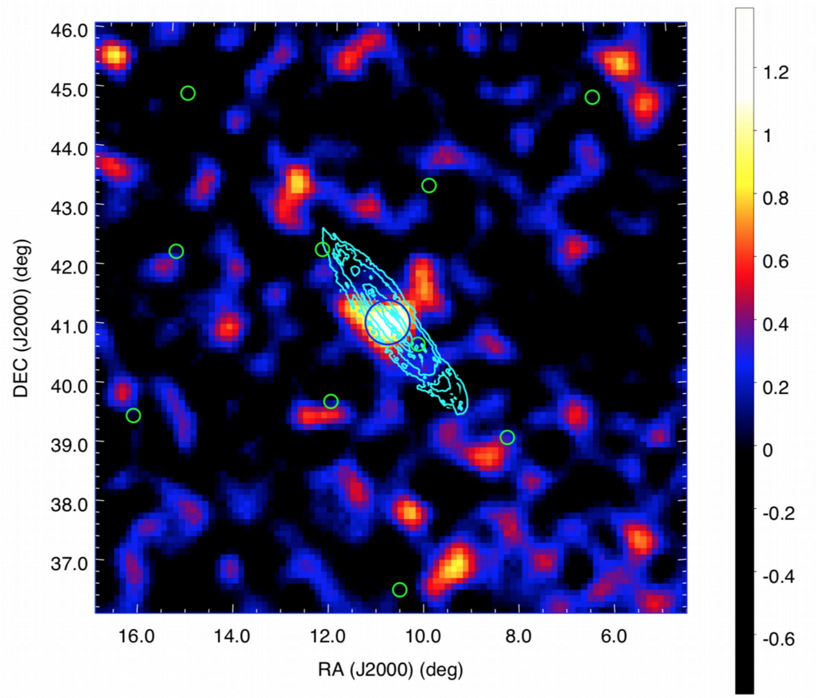
- M31 : emission from an unresolved population of millisecond pulsars (similar to GC excess) ?

- **detections at TeV** : M82, NGC253, LMC

- LMC : 3 individual sources resolved with HESS, but no detection of a diffuse component. (*Abramowski et al. 2015*)

- M82, NGC253 : dominance of diffuse hadronic γ-ray emission

- higher γ-ray emission matches the higher energy input by massive stars and supernovae, wrt. Milky Way.



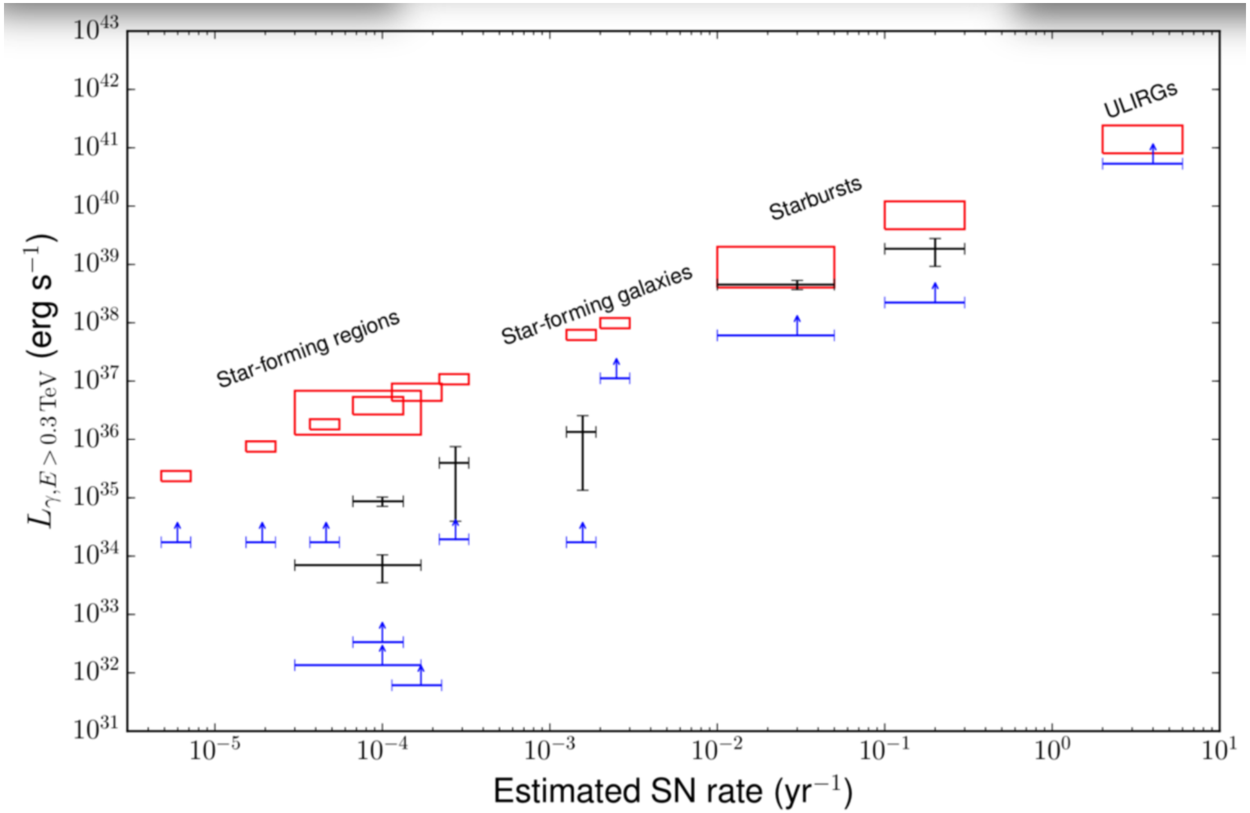
M31 seen with Fermi, Ackermann et al. (2017)

Cosmic rays in **galaxies**

open questions :

- Why does the γ-ray distribution in LMC, M31 not trace the gas distribution and SF regions ? Inhomogeneous CR distribution ? Unresolved sources ? Dark Matter ?

- How does CR acceleration/transport depend on global galactic properties ?



red : estimated calorimetric γ-ray luminosity

black : present high-energy data (VHE & Fermi extrapolations)

blue : expected CTA sensitivity

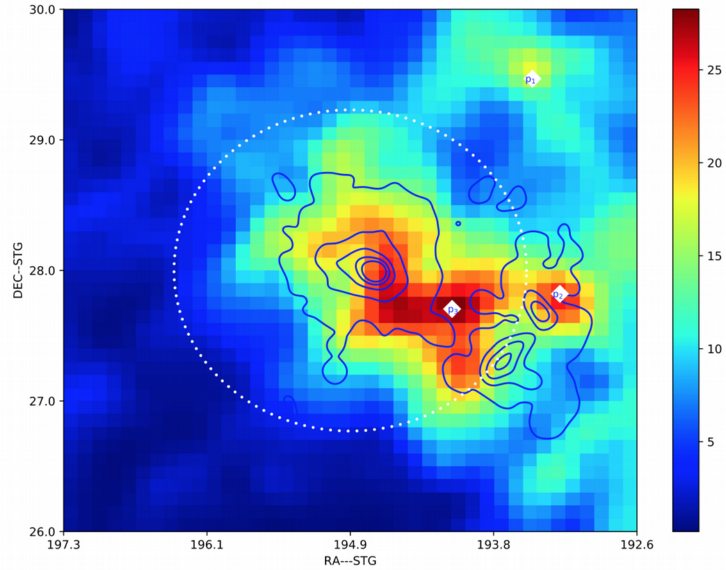
Science with the CTA (2018)

Cosmic rays in **galaxy clusters**

Cosmic-ray acceleration expected from individual sources (galaxies, AGN) and structure formation (merger, accretion shocks, turbulence).

- detections at MeV / GeV

- recent claim of a 6σ signal from the Coma cluster (*Xi et al. 2017, arXiv*).



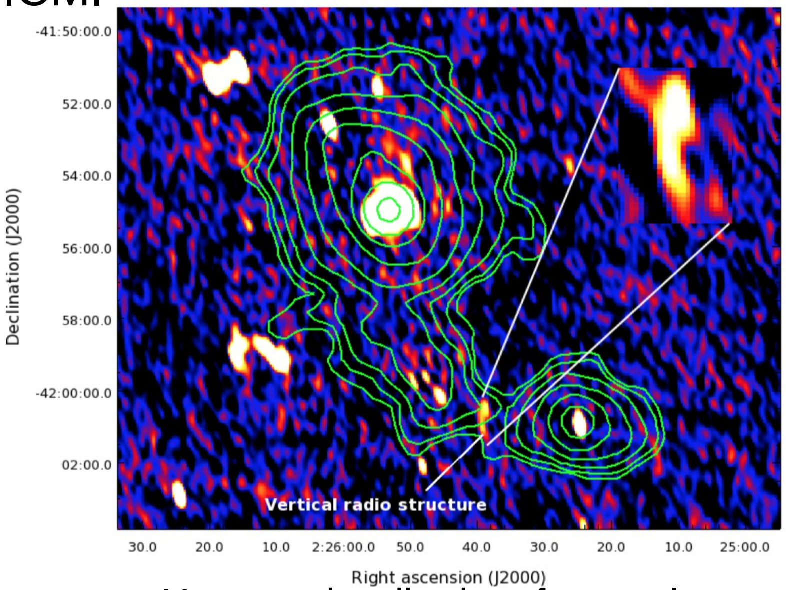
- detections in radio and X-rays

- detections of diffuse synchrotron radio emission confirms presence of relativistic electrons and magnetic fields in the ICM.

-> difficult to explain without hadron primaries due to short cooling time-scales for electrons.

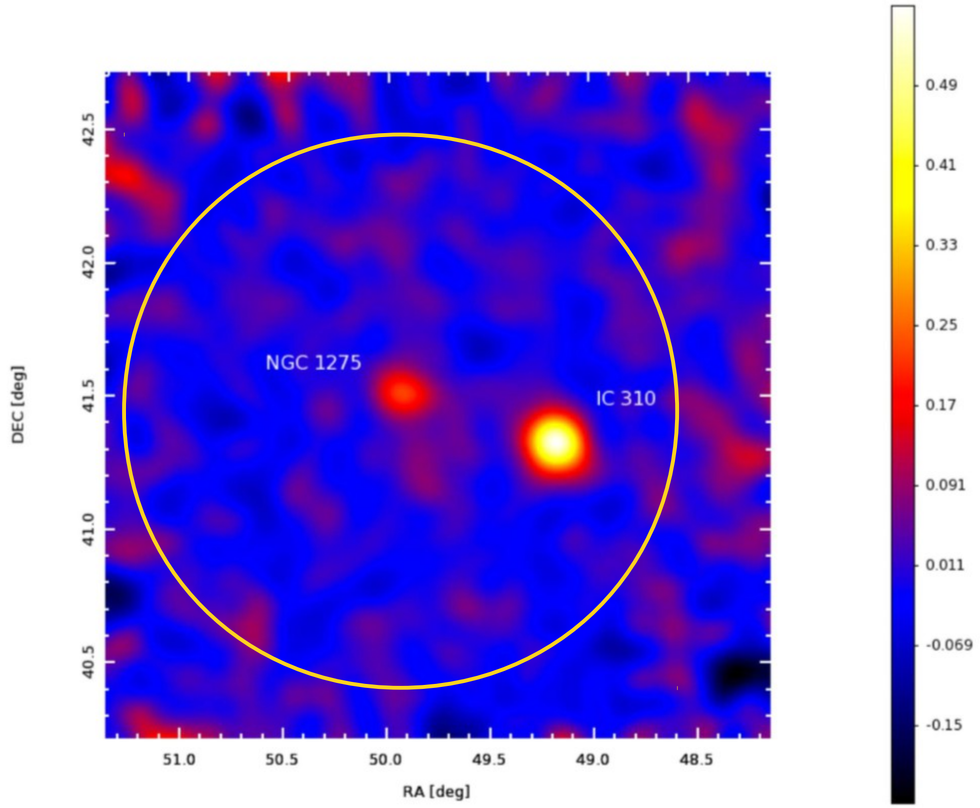
- radio and X-ray filaments are observed inside and between clusters

-> sites of particle acceleration through shocks, turbulence ?

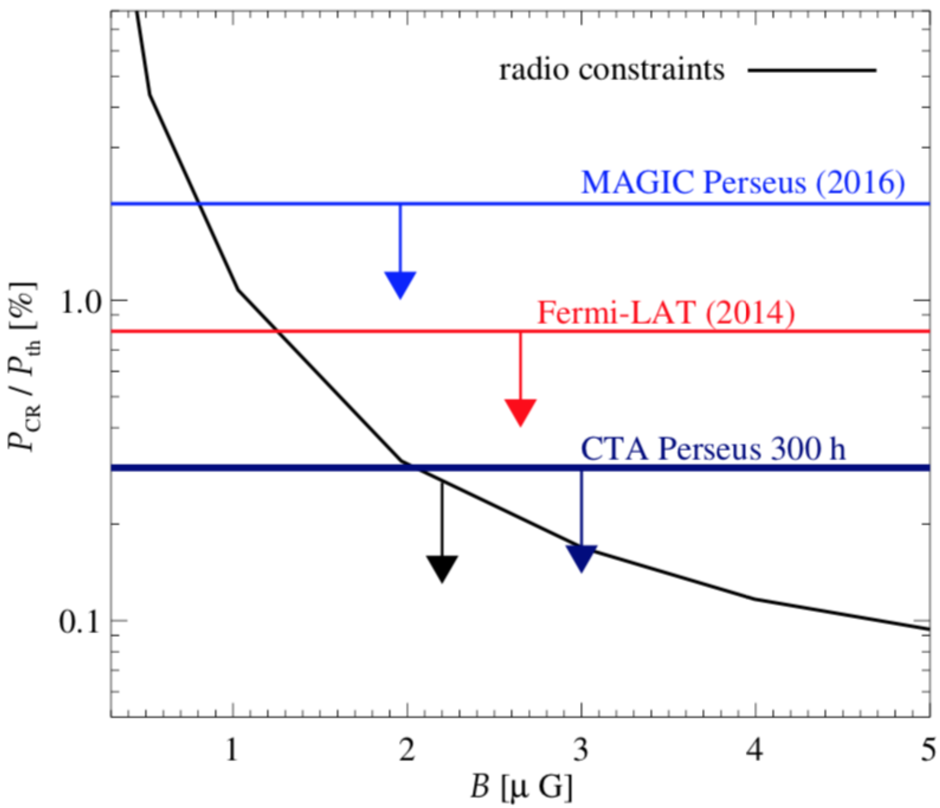


X-ray and radio data from galaxy cluster A3017, *Parekh et al. (2017)*

Cosmic rays in **galaxy clusters**



current VHE data from the
Perseus cluster, *MAGIC Collab. (2016)*
(yellow line - approximate size of cluster)



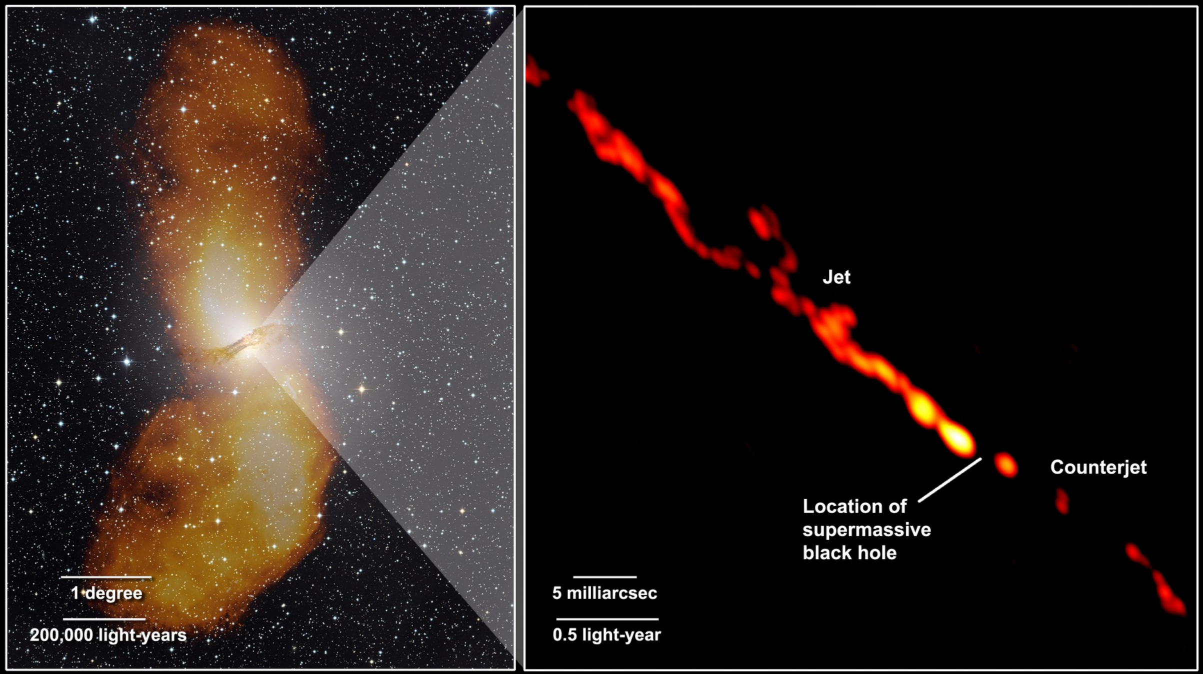
Science with the CTA (2018)

Characteristics of cosmic-ray acceleration and transport ?

-> Future observations at VHE should help to constrain the cosmic ray pressure, if one manages to separate diffuse emission from AGN emission.

A : What we have learnt and what we haven't learnt yet.

Cosmic rays in relativistic jets.



Centaurus A in the optical and radio (NASA / TANAMI)

Cosmic rays in relativistic jets

motivation :

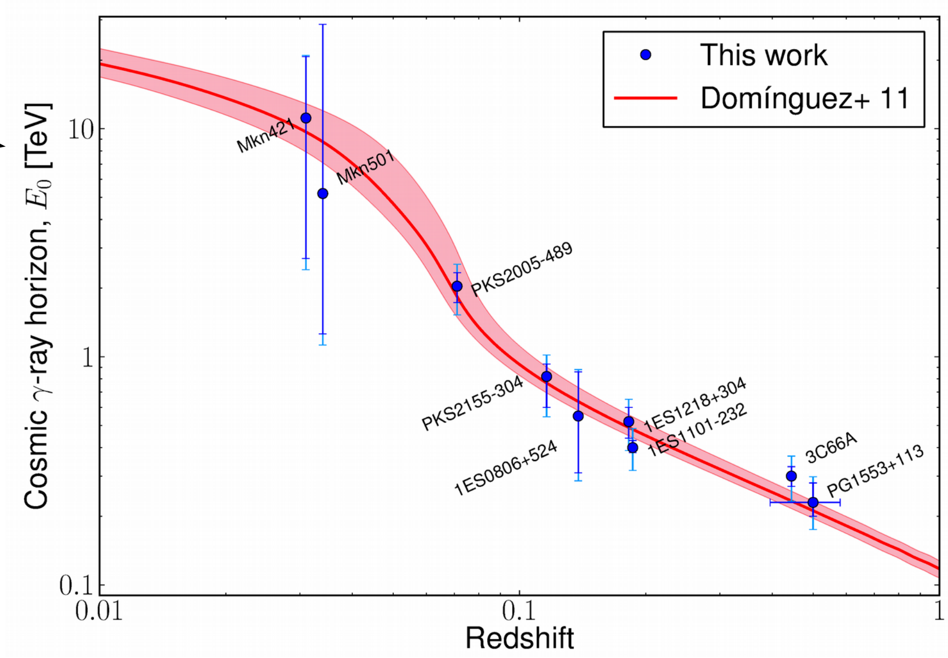
γ-rays probe acceleration of particles to very high energies in relativistic jets.
They provide information on physical conditions in the most energetic emission regions.

problems :

- Limited distance reach of Cherenkov telescopes due to EBL absorption (currently z <~ 1).

- Limited resolution at high energies (>> arc min) does generally not allow to resolve jets, lobes.

- Missing redshift information for many sources. (~ 50% of Fermi BL Lacs, ~70% of GRBs)



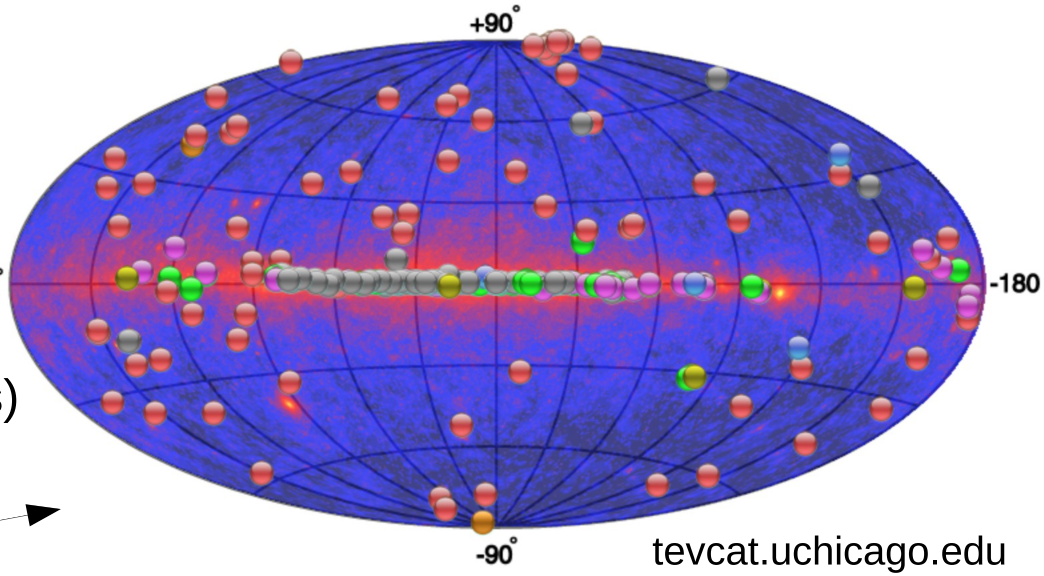
The “EBL horizon”,
Dominguez et al. (2013)
see also HESS Collab. (2017) for an update

Cosmic rays in relativistic jets : **AGN**

AGN detections :

- detections at MeV / GeV :

> 2900 blazars (>600 FSRQs, >1000 BL Lacs) seen with Fermi-LAT, plus a few other AGN types (21 radio galaxies - mostly FRI, 9 NLSy1s)



tevcat.uchicago.edu

extended : only Fornax A, Cen A lobes

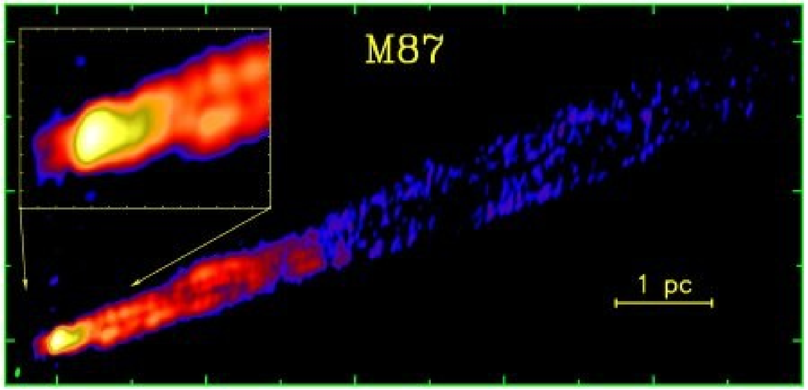
- detections at TeV :

~69 blazars (7 FSRQs, rest BL Lacs), 4 FRI radio-galaxies

- other wavelengths :

- Multi-wavelength coverage is essential for a full understanding of the sources.

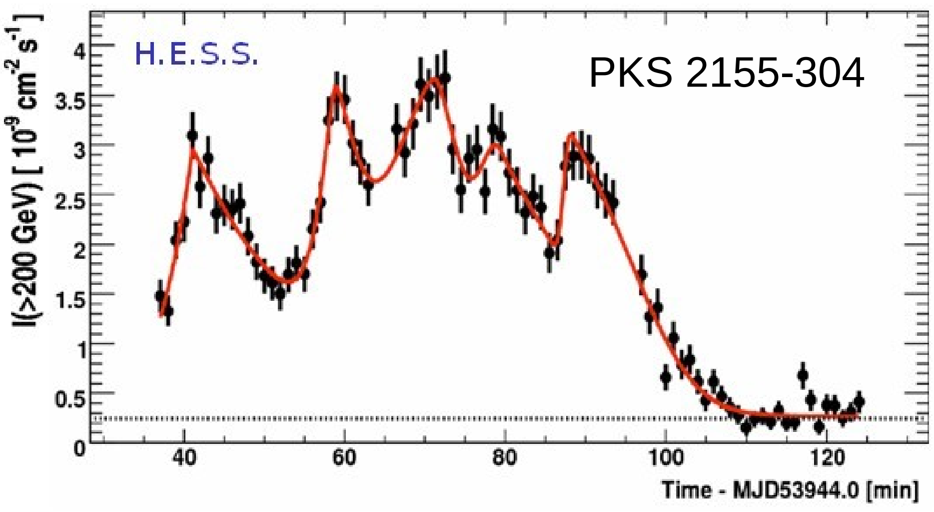
- VLBI : information on jet structure, existence of stationary and moving knots, from TANAMI, MOJAVE etc.

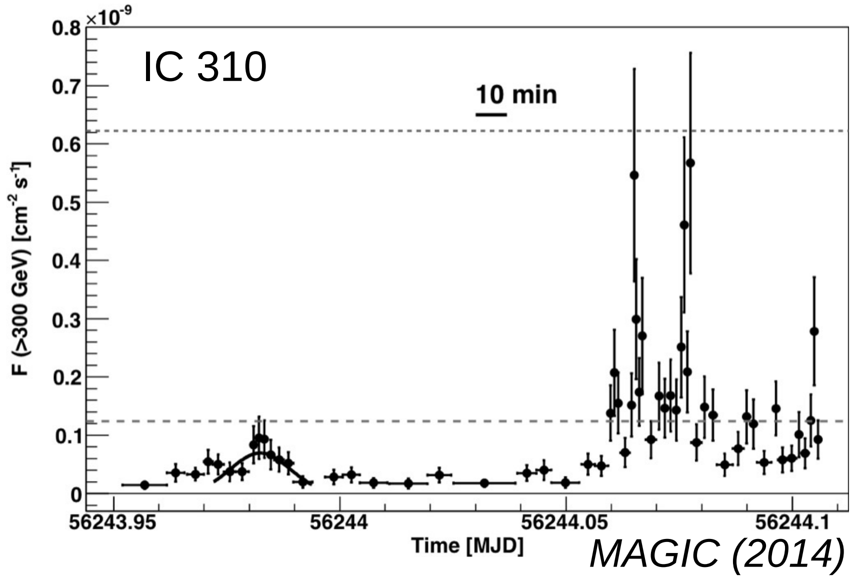


VLBA, Y.Y. Kovalev, MPIfR Bonn

Cosmic rays in relativistic jets : **AGN**

very rapid variability





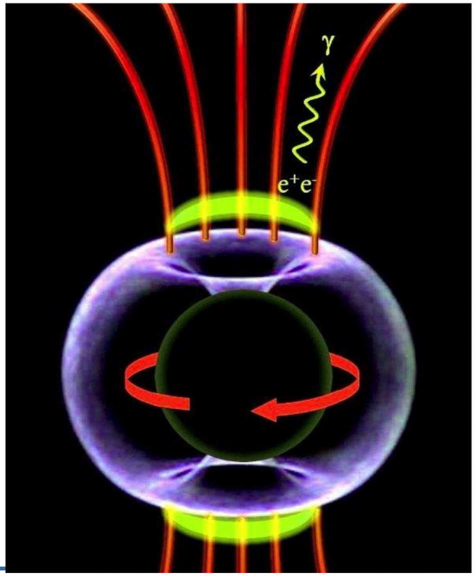
MAGIC (2014)

observed variability at the time scale of a few minutes requires very small emission region (< r_s) and/or extreme bulk Doppler factors (~100).

- **leptonic interpretation** : "needle/jet" model (*Ghisellini 2008*) or "jet-in-jet" model with magnetic reconnection (*Giannios 2009*)

- **hadronic interpretation** : collisions of jet with clouds or stellar envelopes (*Barkov 2011*).

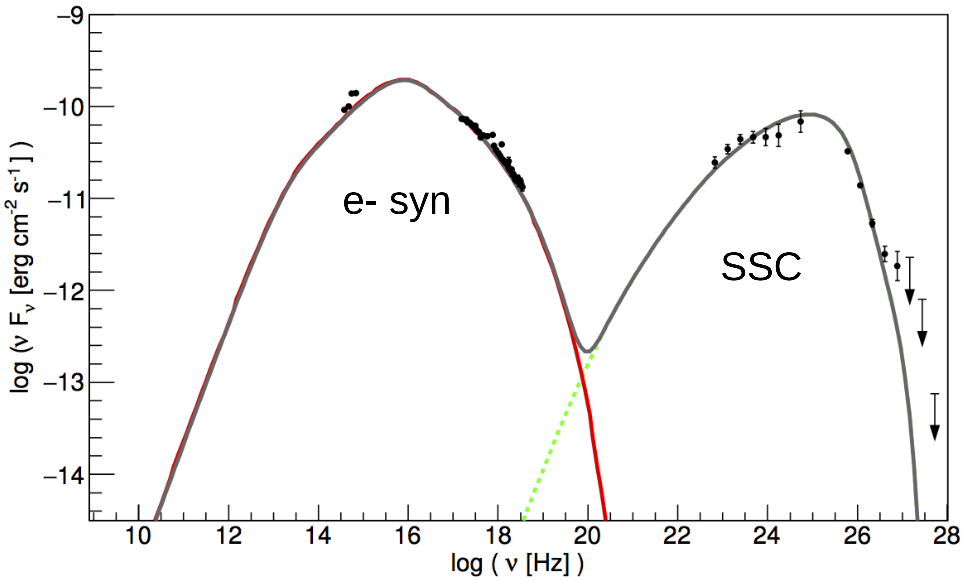
Pulsar-like particle acceleration or leptons or hadrons across a magnetospheric gap at the base of the radio jet ?

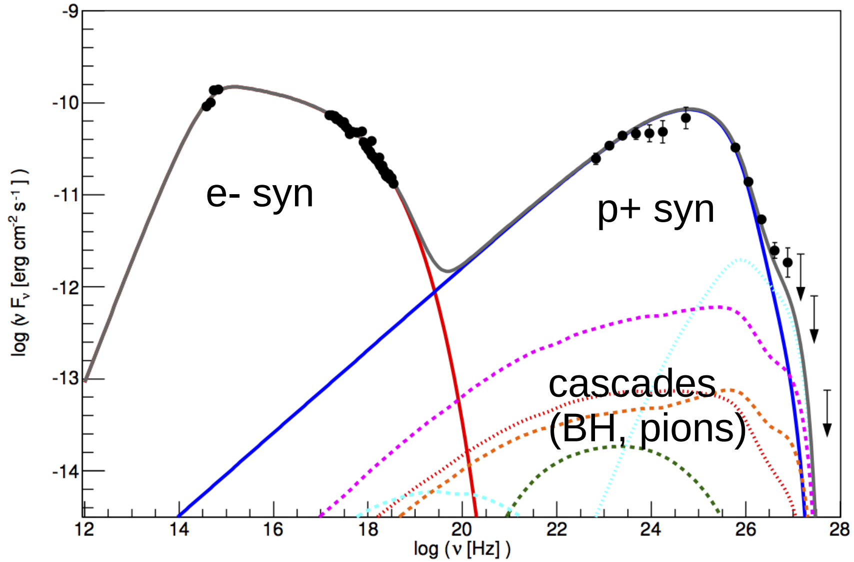


MAGIC (2014)

Cosmic rays in relativistic jets : **AGN**

degeneracy between leptonic and hadronic models for blazars





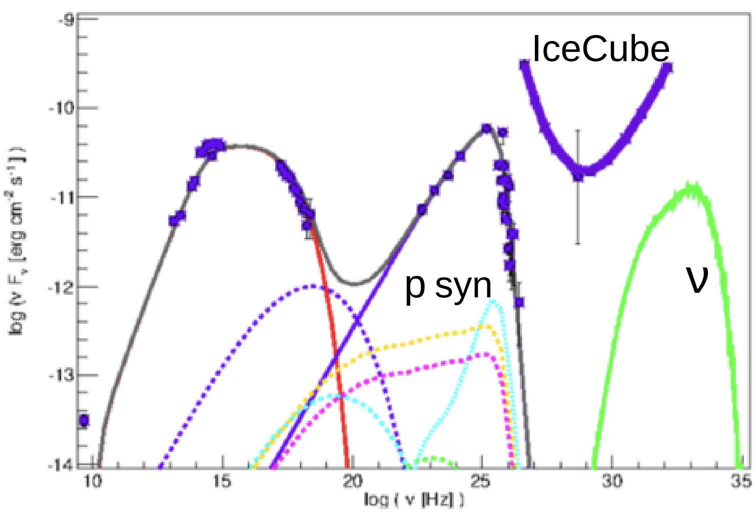
e.g. PKS 2155-304 in 2008 - leptonic model (left) vs. hadronic model (right) , *AZ, M. Cerruti et al. (2017*)

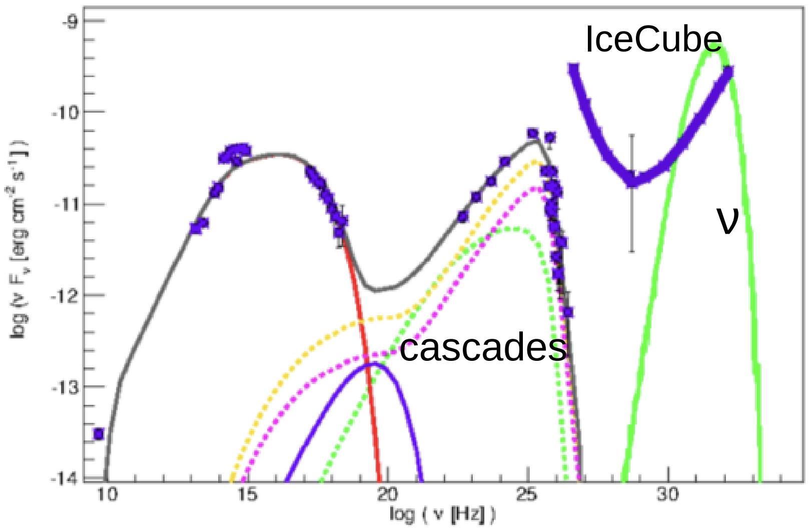
In general, leptonic models and hadronic models provide equally good representations of the multi-wavelength spectral distribution.

leptonic models	**hadronic models**
B-field : ~ 0.01 - 1 G	B-field : ~ 1 - 100 G
max. e- Lorentz factor ~ 10^4 - 10^6	max. p+ Lorentz factor ~ 10^9 - 10^{10}
	higher jet power (close to or above L_{Edd})
intrinsically shorter time scales	

Cosmic rays in relativistic jets : **AGN**

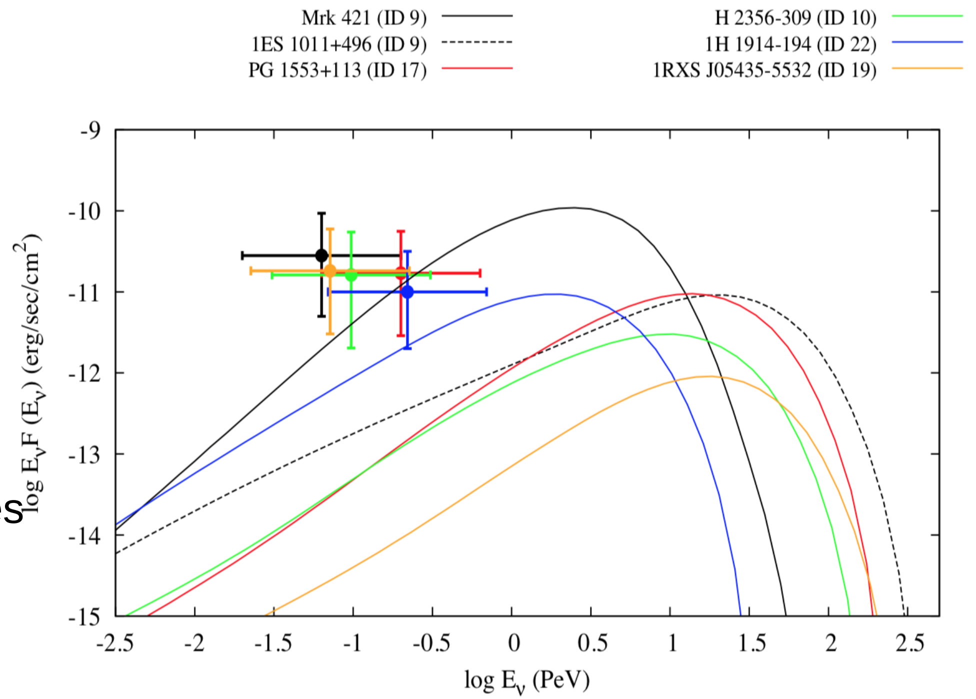
How to link gamma-ray emission to the expected neutrino flux ?





Two hadronic models for the blazar PG 1553+113 with estimated neutrino flux (green), compared to IceCube 4-year-flux limit (violet).
M. Cerruti, AZ et al. (2016)

Predicted neutrino flux varies a lot between different scenarios. In general, fluxes peak far above the Ice-Cube range.



Comparison of estimated neutrino fluxes with nearby IceCube neutrinos for six blazars.
M. *Petropoulou et al. (2015)*

Cosmic rays in relativistic jets : **GRBs**

GRB detections

MeV / GeV :

~ 2 GRBs / 3 days detected with Fermi-GBM (keV / MeV)

more than 140 GRBs detected with Fermi-LAT (> 20 MeV)

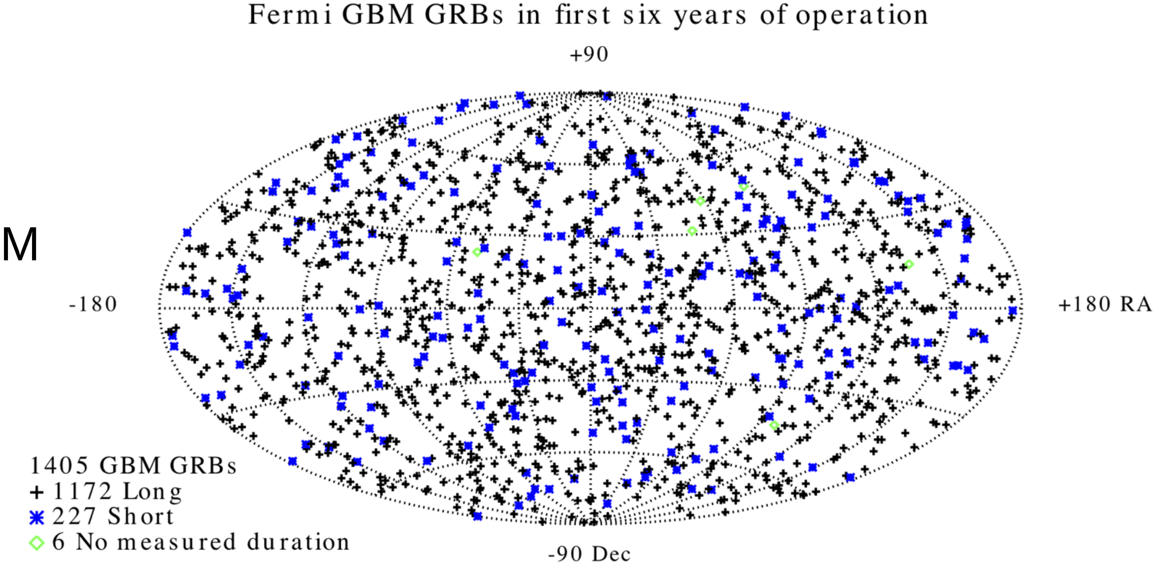
-> several GRB spectra show a high-energy power-law extension or cut-off

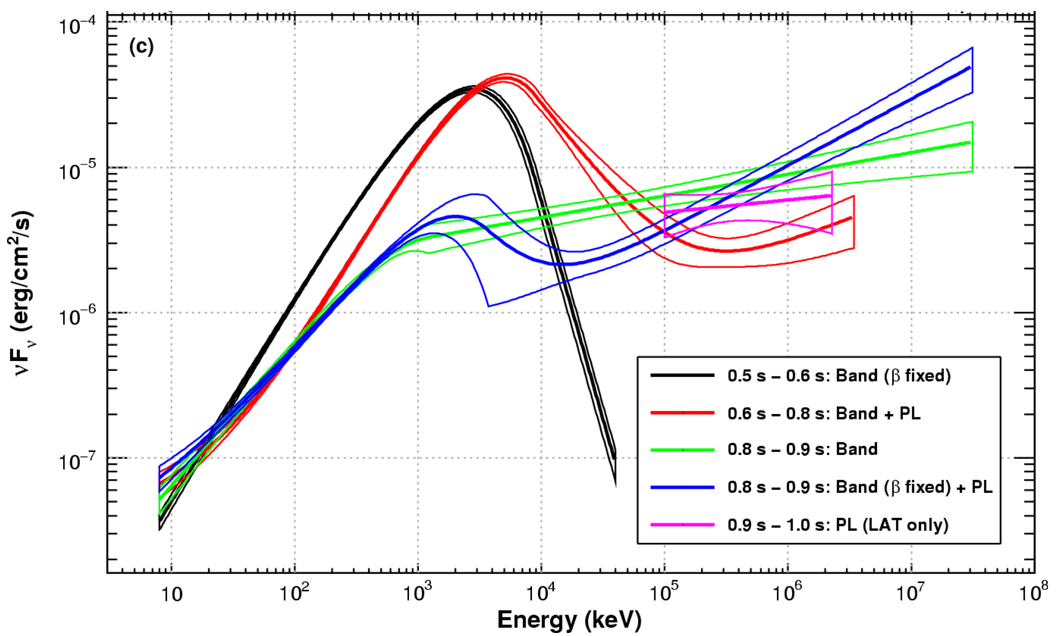
-> detection of γ-rays at a few 10 GeV implies efficient particle acceleration and large bulk Lorentz factors (opacity constraints)

-> high-energy emission has delayed onset

other wavelengths :

- MWL observations of afterglows;
important also for source identification, redshift...





GRB 090510. Fermi time-resolved spectrum *(Pelassa & Ohno 2010)*

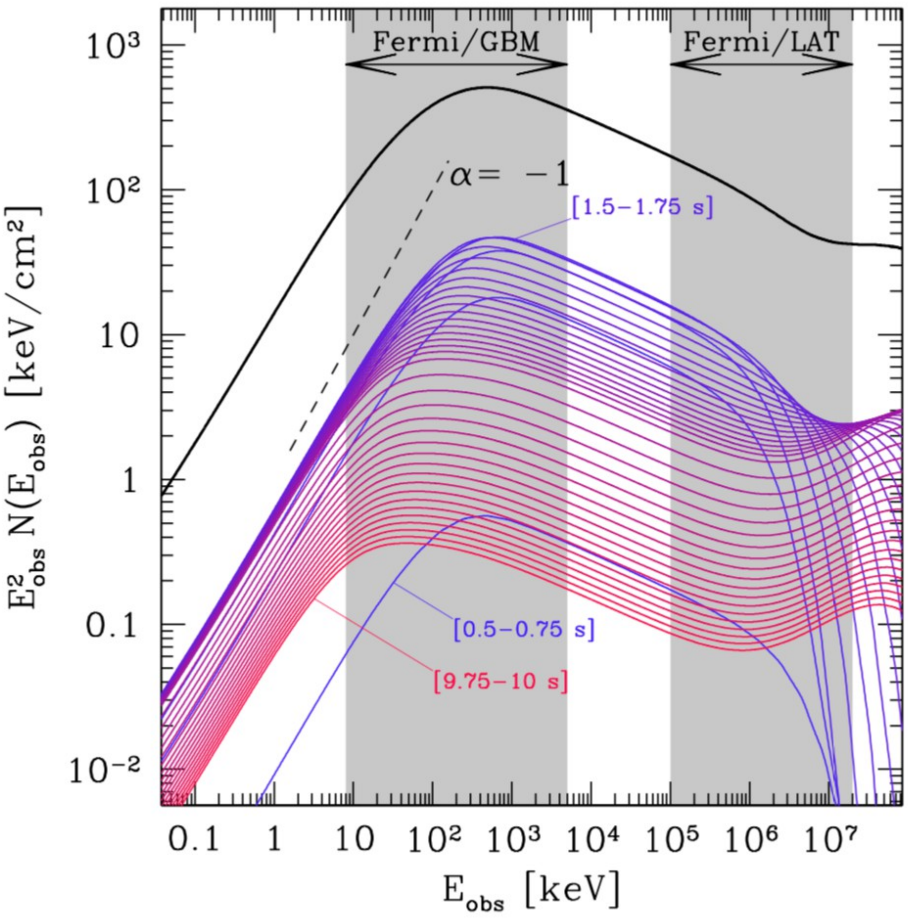
Cosmic rays in relativistic jets : **GRBs**

leptonic emission models for GRBs

In the internal shock model, the high energy component arises as a combination of electron synchrotron, Inverse Compton and γγ-absorption.

Internal shocks could have significant contribution to the prompt Fermi-LAT emission.

The high-energy component might be also (partially?) due to an early afterglow emission. (e.g. *Ioka et al. (2010))*

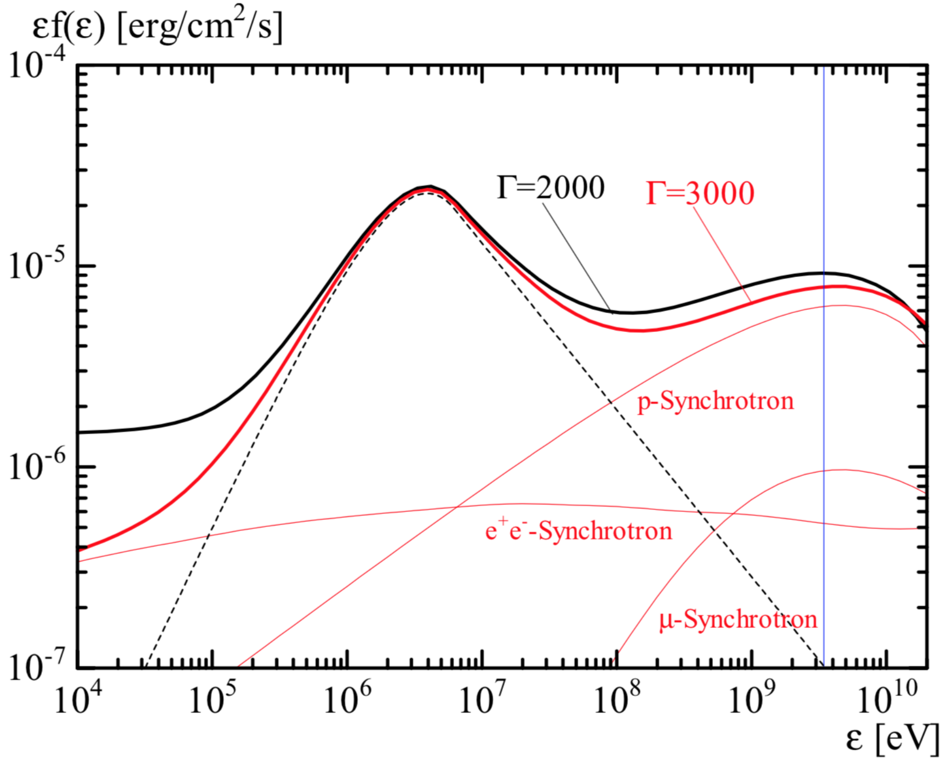


spectral evolution for the internal shock model with varying fraction of accelerated electrons
Bosnjak & Daigne (2014)

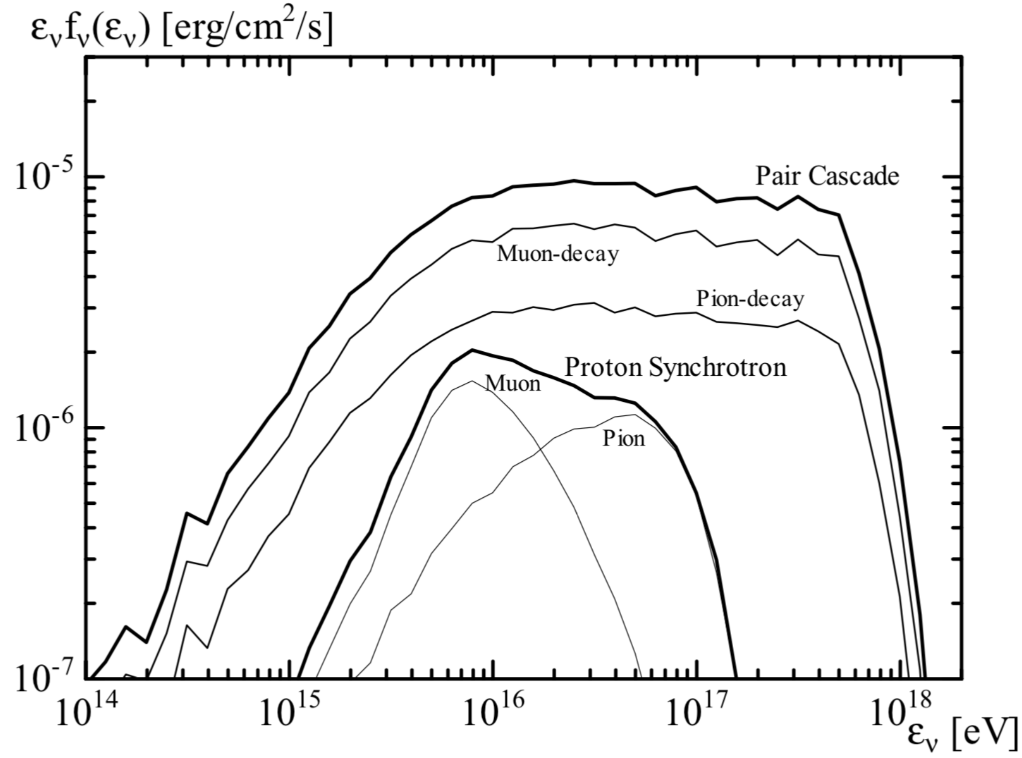
Uncertainties on the underlying physics :
- shock acceleration in mildly relativistic regime
- relativistic ejection by compact sources

Cosmic rays in relativistic jets : **GRBs**

hadronic emission models for GRBs



Asano et al. (2009)
proton-synchrotron models



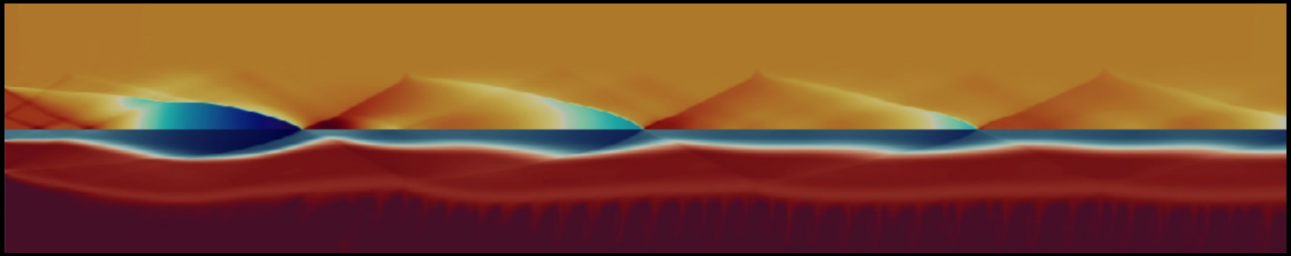
Asano et al. (2009)
expected neutrino spectra

In hadronic models, the hard spectral component above the Band function can be ascribed to pion production and resulting cascades or proton synchrotron emission (during prompt phase).

Similar problems to hadronic blazar models :
- large jet power requirement
- large range of neutrino flux predictions

B : What is needed to improve our understanding ?

Models & Theory



MHD jet model , Hervet, Meliani et al. (2017)

Models & Theory

What model developments are needed to advance ?

AGN (similar for GRBs ?):

- more complete hadronic models (include nuclei, external photon fields, time dependency, ...)

- combination of a realistic (MHD) description of jet launching and propagation with the radiative processes in the emission region ?

- full description of particle acceleration ?

galaxies & galaxy clusters :

- models for CR acceleration/transport in ISM conditions strongly different from Milky Way (e.g. starbursts)

- AGN feedback in galaxy clusters ?

Would it help to make (more) codes publicly available to incite developments ?

Models & Theory

Which inputs from theory are needed to advance ?

AGN & GRB :

- acceptable parameter limits for different acceleration processes.
  (particle spectra, maximum and minimum Lorentz factors, acceleration time scales...)

- limits on acceptable jet power for a given accretion process ? Bulk Lorentz factor ?

- constraints on ratio of hadron / lepton density for a given acceleration process.

galaxies & galaxy clusters :

- Dependance of particle acceleration/re-acceleration/escape on ISM conditions.

B : What is needed to improve our understanding ?

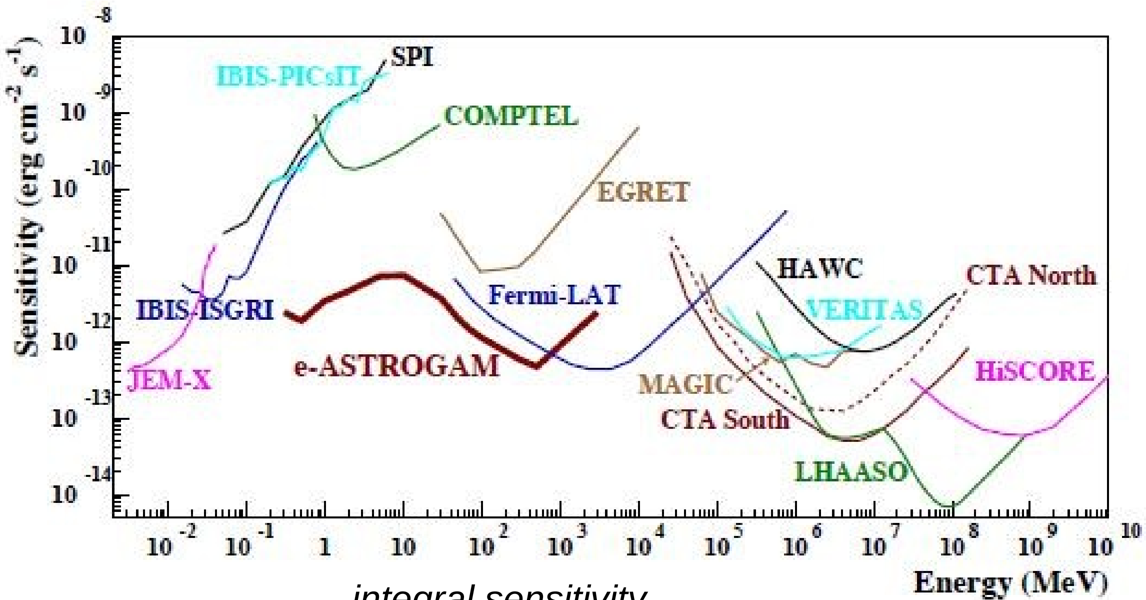
Future Instruments

the GCT prototype for CTA in Meudon (2015)

Future Instruments : VHE

GRBs :

- exploring the complete high-energy
  component of GRBs. (*CTA*)
  (But only small source statistics.)



integral sensitivity
(IACTs 50 h, LHAASO, HAWC 1 yr)
LHAASO website

AGN :

- better reach of high-redshift
  and low-luminosity blazars; detection of
  other gamma-loud AGN classes ?;
  probing variability time scales below a minute;
  morphology of nearby radio-galaxies?;
  emission of AGN flare alerts as VOEvent (*CTA)*.

- *LHAASO* , *HiSCORE* : probably very little signal from extragalactic sources above 10 TeV
  (soft spectra, EBL absorption)

galaxies & galaxy clusters :

- detection of γ-rays from Perseus cluster ? morphological study ? (*CTA*)

- diffuse emission from LMC or others ? (*CTA*)

Future Instruments : gamma & X-rays

AGN & GRBs :

- All-sky coverage crucial for **GRB alerts** and **AGN flares** (*SVOM*)

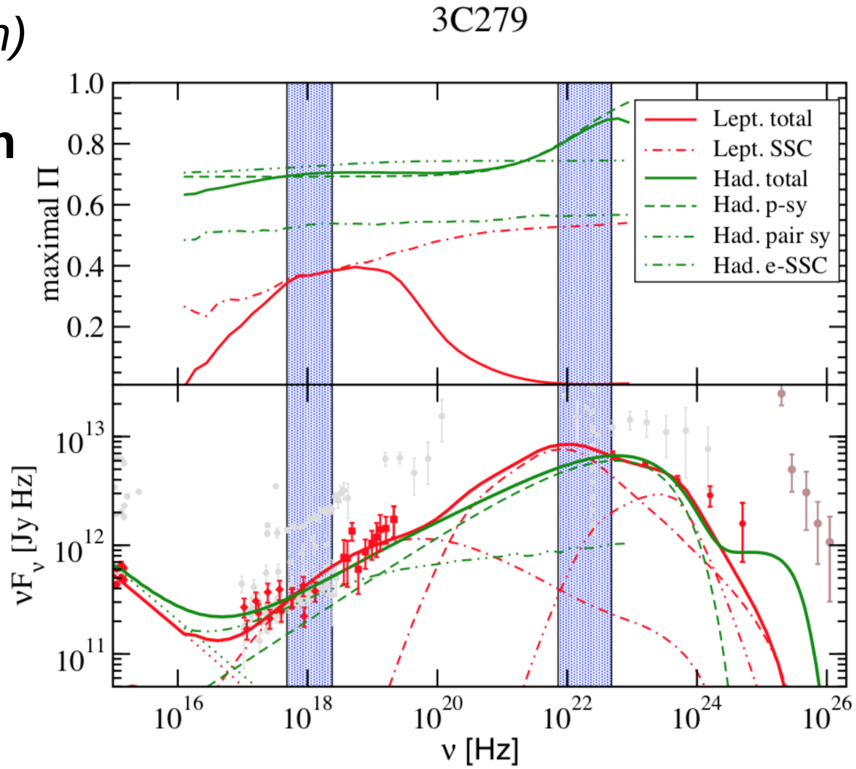
- *NuStar*'s hard X-ray coverage is very constraining for blazar spectra. (in the future: *Athena, SVOM, eAstrogam)*

- first high resolution measurements of **X-ray polarisation** will add a new observable to our data sets (*IXPE*) !

  -> Information on magnetic fields, distinction between different radiation mechanisms.

galaxies & galaxy clusters :

- more detailed data on filaments in galaxy clusters ? (*Athena*)



maximum polarization for leptonic and hadronic blazar models
Zhang & Böttcher (2013)

Future Instruments : UV to IR

AGN & GRBs :

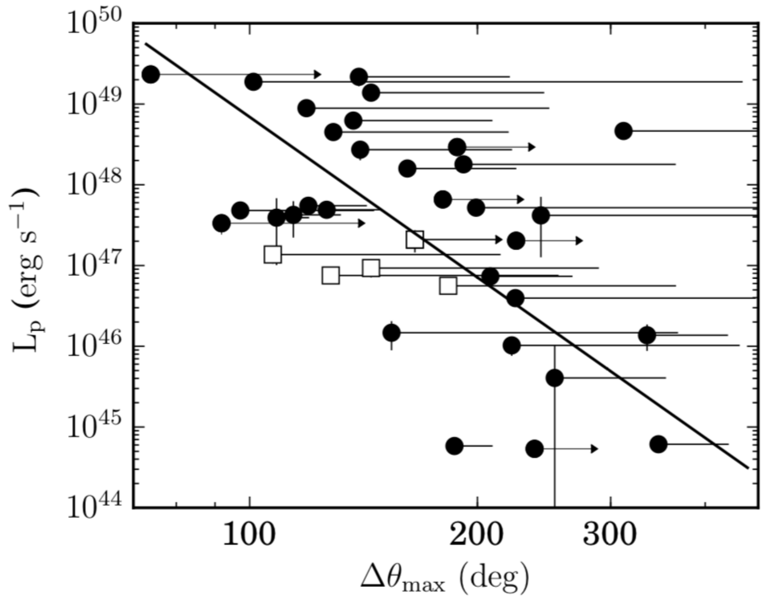
- UV to IR spectral data are very important for a full view of the spectral distribution of AGN (dust torus and accretion disk) and GRB afterglow

- high-resolution spectra needed for **redshift** determination

- **optical flare alerts** for AGN from *LSST, ...* ?

- changes in the **optical polarisation** (rotation of electric vector position angle) are correlated with high-energy AGN flares

-> helps localize emission region, probe conditions



changes in optical polarisation (RoboPol) are correlated with γ-ray (Fermi) amplitudes of blazar flares
Blinov et al. (2017)

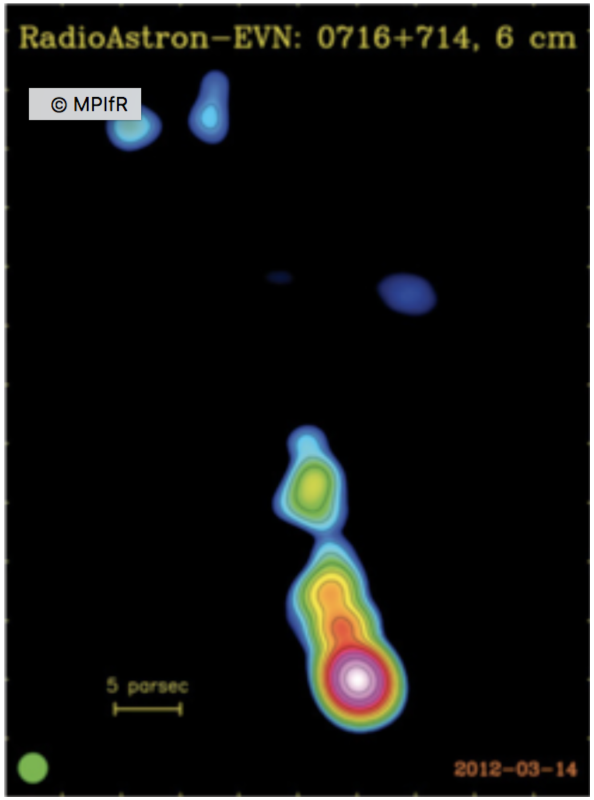
Future Instruments : sub-mm to radio

AGN :

- VLBI observations crucial to determine structure of radio jets (moving and stationary knots, radio core, lobes...) *SKA as part of VLBI network*

- **Magnetic field measurements** in radio jets through Faraday rotation measures with VLBI.

- **µ-arcsecond** resolution with mm-VLBI (*EHT*) and space VLBI (*RadioAstron*, ...)



galaxies & galaxy clusters :

- Mapping of **molecular gas** that is target for cosmic rays (*ALMA*)

- Radio synchrotron emission constrains magnetic field and particle content of galaxy clusters. (*SKA)*

- Radio observations of galactic winds/outflows in nearby objects. (*SKA*)

Conclusions

A :
- **galaxies** : γ-ray distribution reveals a complex morphology - hard to distinguish diffuse emission and emission from unresolved sources

- **galaxy clusters** : high-energy information from future instruments on CR acceleration and propagation on large scales.

- **AGN and GRBs** : Degeneracy between leptonic and hadronic scenarios due to lack of observational and theoretical constraints.

Not mentioned : information on UHECR interactions from **diffuse extragalactic γ-ray background**. (e.g. *Globus et al. 2017*)

B:
- A challenge for future models : combine more closely a physical description of the environment (jet, ISM...) with acceleration mechanisms and radiative transfer.

- Organisation of multi-wavelength and multi-messenger monitoring (including polarisation) of the sky and follow-up of AGN flares and GRBs is essential.

Extragalactic Sources at High Energies

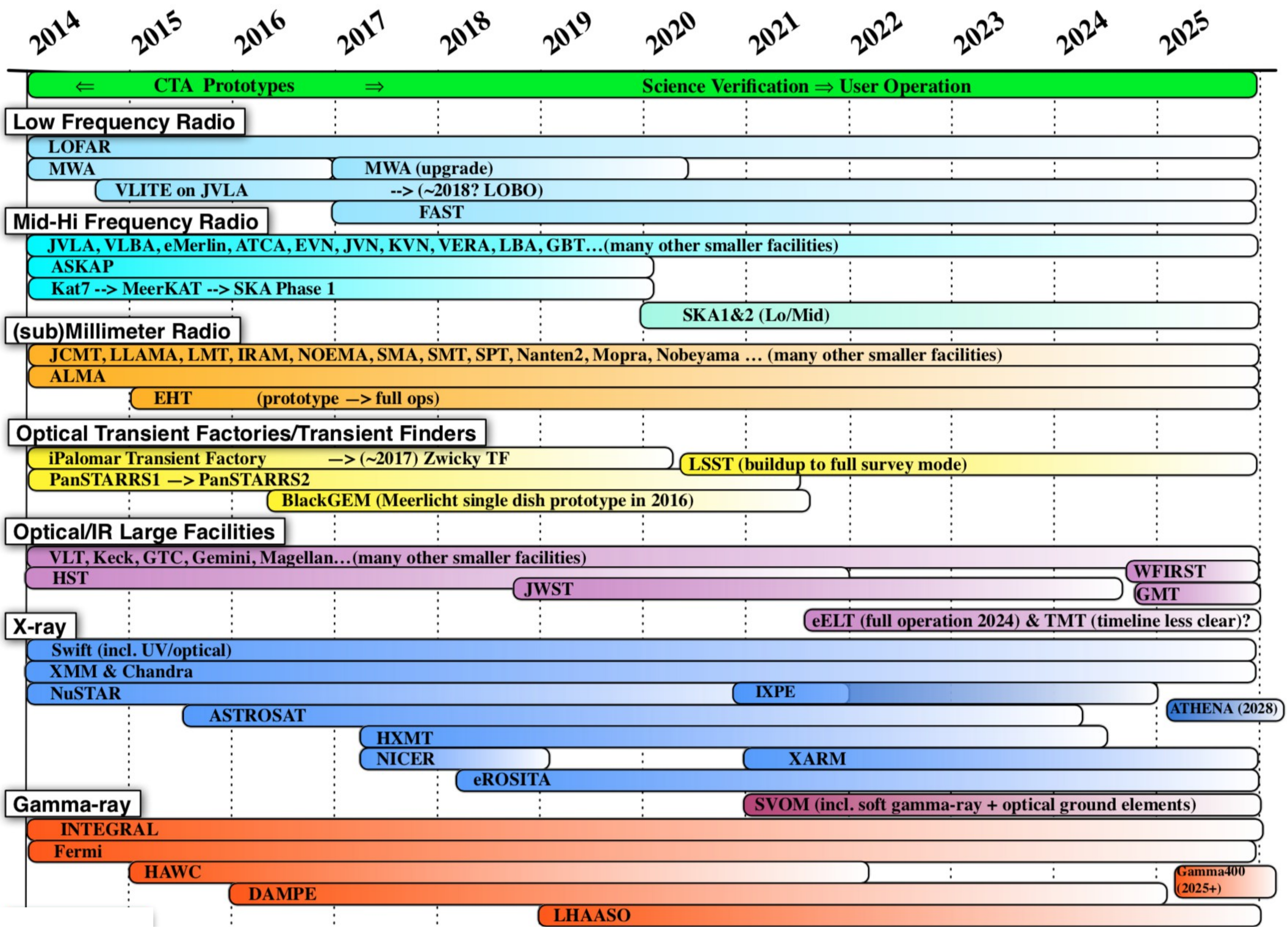
A : What we have learnt and what we haven't learnt yet.

- **Cosmic rays in galaxies and galaxy clusters**
- **Cosmic rays in relativistic jets**

B : What is needed to improve our understanding ?

- **Models & Theory**
- **Future instruments**

Future Instruments



Science with CTA (2018)

Cosmic rays in relativistic jets : **AGN**

open questions :

- MWL variability is complex - difficulty of correlations between high energies and optical-radio. “Orphan” flares as evidence for hadronic processes ?

- Very rapid variability on the minute time scale challenges our understanding of the emission mechanism.

- No consensus on location of emission region and particle acceleration process in AGN.

- Detection of “extreme blazars” with intrinsic peaks in the TeV range are difficult to explain.

- Are γ-loud radio-galaxies “mis-aligned” blazars ? Why are there so few γ-loud FR II radio galaxies ?

- Evidence for hadronic interactions in Fornax A ?

- Do we see emission from leptonic / hadronic / mixed particle populations ?

- How to correlate γ-rays to neutrino emission and UHECR production ?

- ...

Cosmic rays in relativistic jets : **GRBs**

open questions :

- Origin of the hard spectral component observed in some GRBs at high energies ?
  Emission during prompt phase or in early afterglow ?

- Origin of delay of LAT emission wrt. GBM ?

- Origin of the temporally extended LAT-detected emission often lasting ~ $10^2 – 10^3$ s,
  in certain cases without associated detectable keV–MeV emission.

- Leptonic or hadronic origin of the observed emission ?

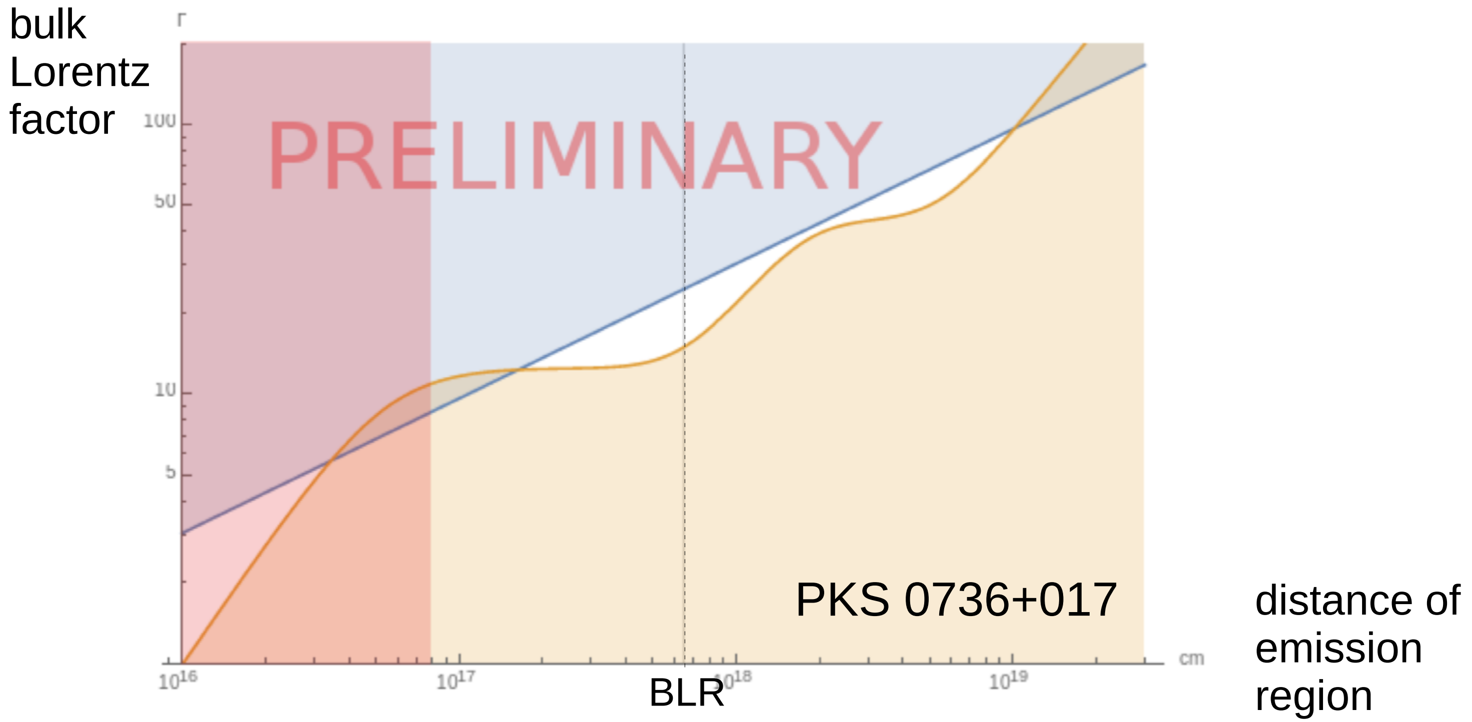
- How many different GRB classes ?

- Are all short GRBs due to BH / binary
  mergers ?

- ...

Cosmic rays in relativistic jets : **AGN**

emission region : constraints from high-luminosity blazars



Constraining the distance of the emission region :
Constraints from opacity (red), variability time scale (blue), Inverse Compton cooling time scale (orange).

Best estimate (assuming a single-zone, leptonic emission scenario) is within the Broad Line Region, with minimum bulk Lorentz factor of ~10.

Cerruti et al. (2017), following Nalwajko et al. (2014)

A : Conclusions

- **galaxies** : γ-ray distribution reveals a complex morphology - hard to disentangle interstellar emission from populations of sources.

- **galaxy clusters** : high-energy information from future instruments on CR acceleration and propagation on large scales

- **AGN and GRBs** : Degeneracy between leptonic and hadronic models due to lack of obs. constraints on source parameters.
  -> Hadronic models require in general much larger jet power, but cannot be ruled out. MWL temporal information is very useful to constrain models.

Not mentioned : Indirect information on UHECR interactions from **diffuse extragalactic γ-ray background**. (e.g. Globus et al. 2017)