Extragalactic Gamma-ray Astrophysics

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A very subjective review…

1. Blazars: relativistic jets
2. Other types of active galaxies
3. Starforming/starbursts galaxies
4. Clusters of galaxies
5. The Future

Blazars

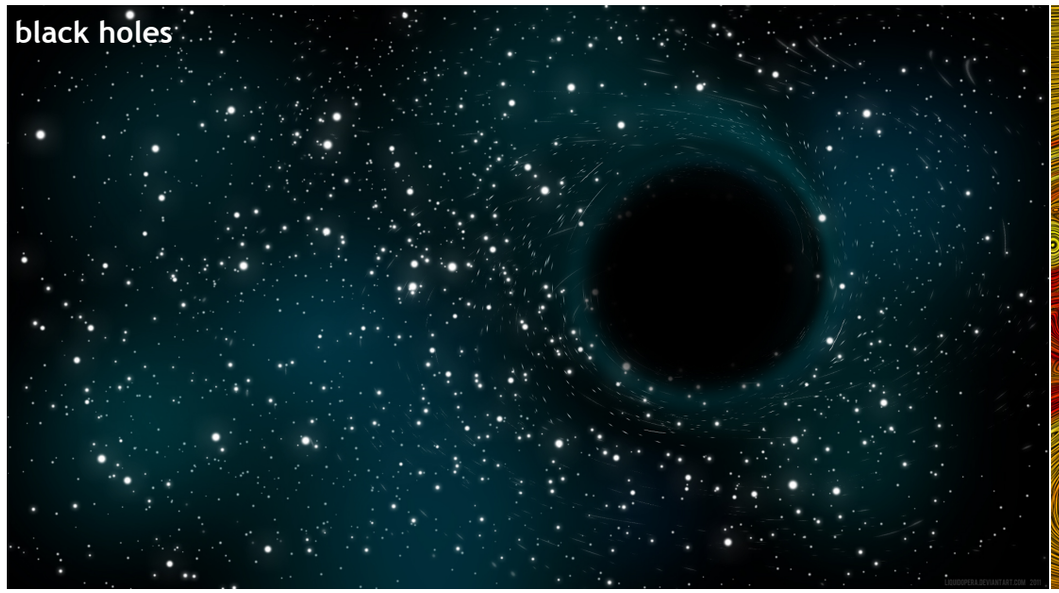
WHY SO VERY INTERESTING

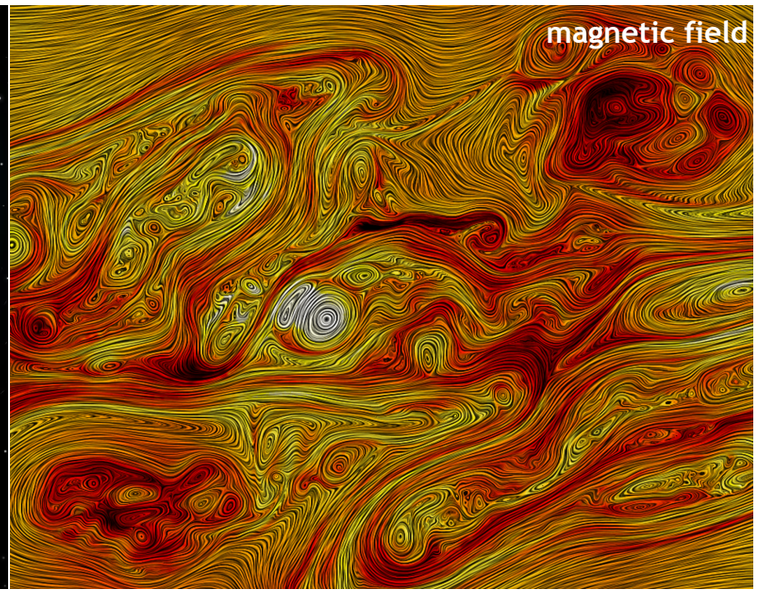
I) astrophysics: spinning supermassive black holes

II) plasma physics: relativistic, highly magnetised jets; very high energy particles

III) cosmology: galaxy formation and evolution; high redshift Universe

Spinning black hole + magnetic field





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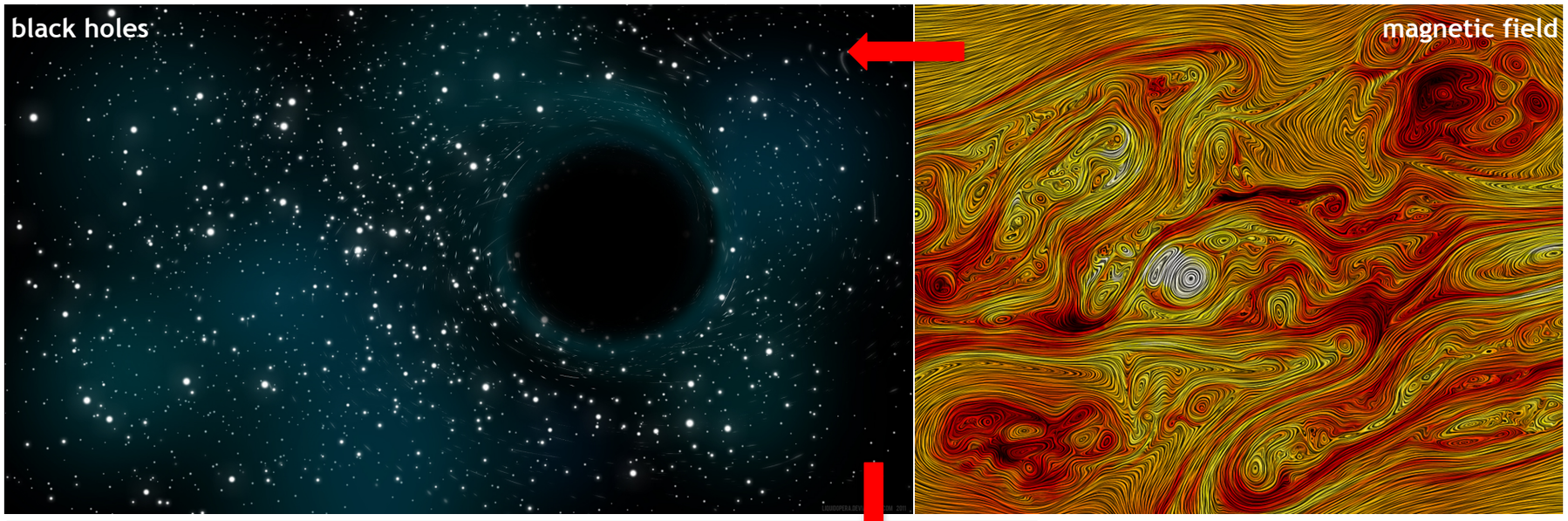
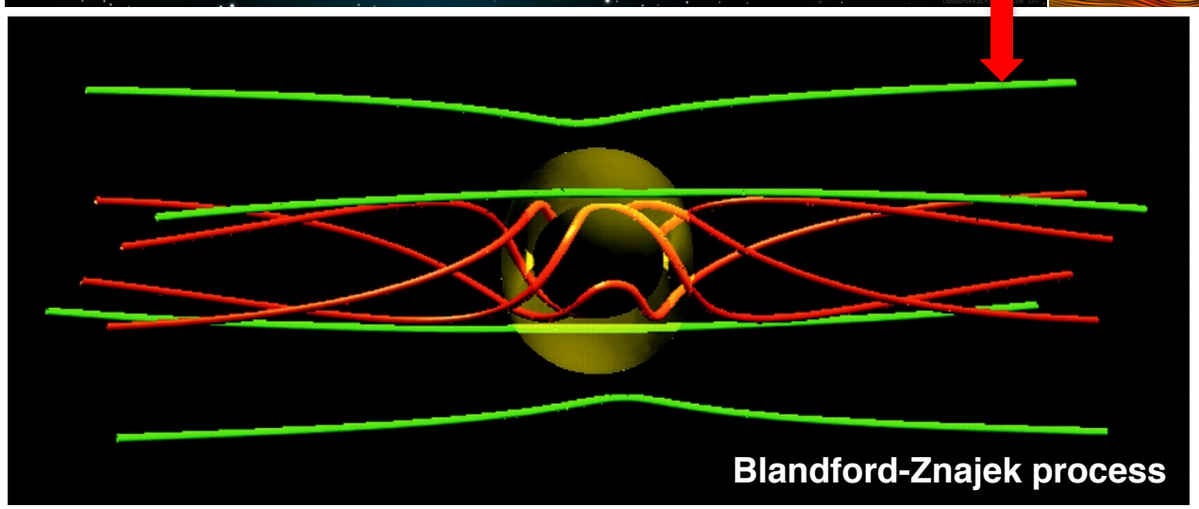
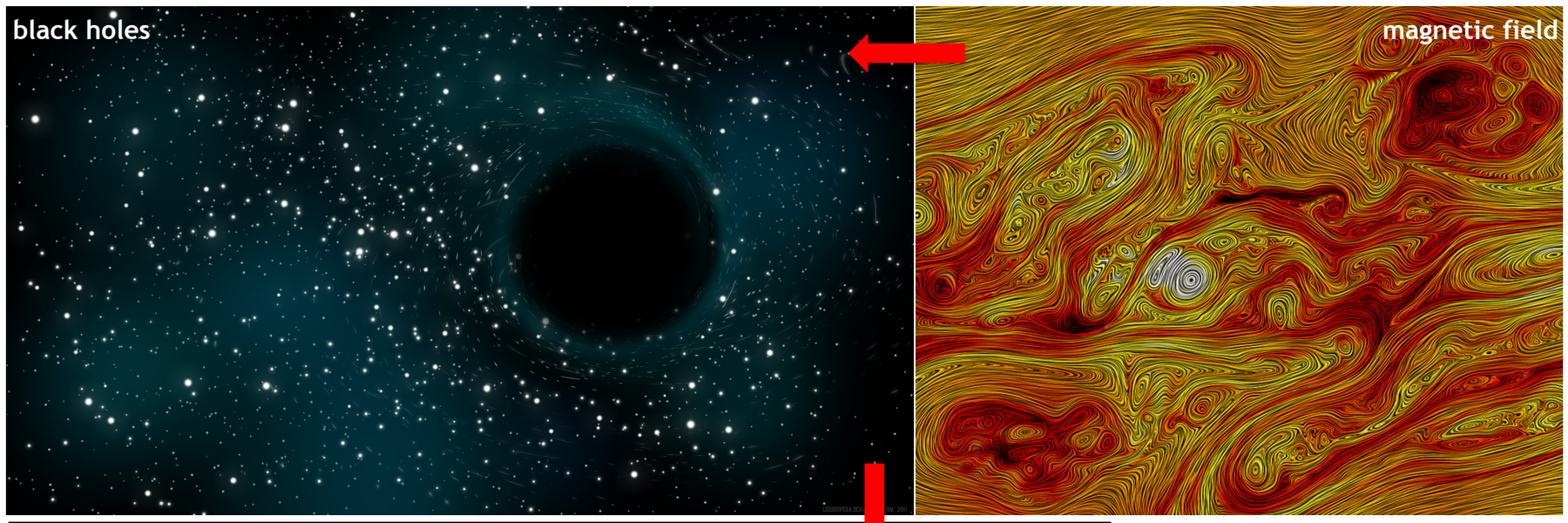
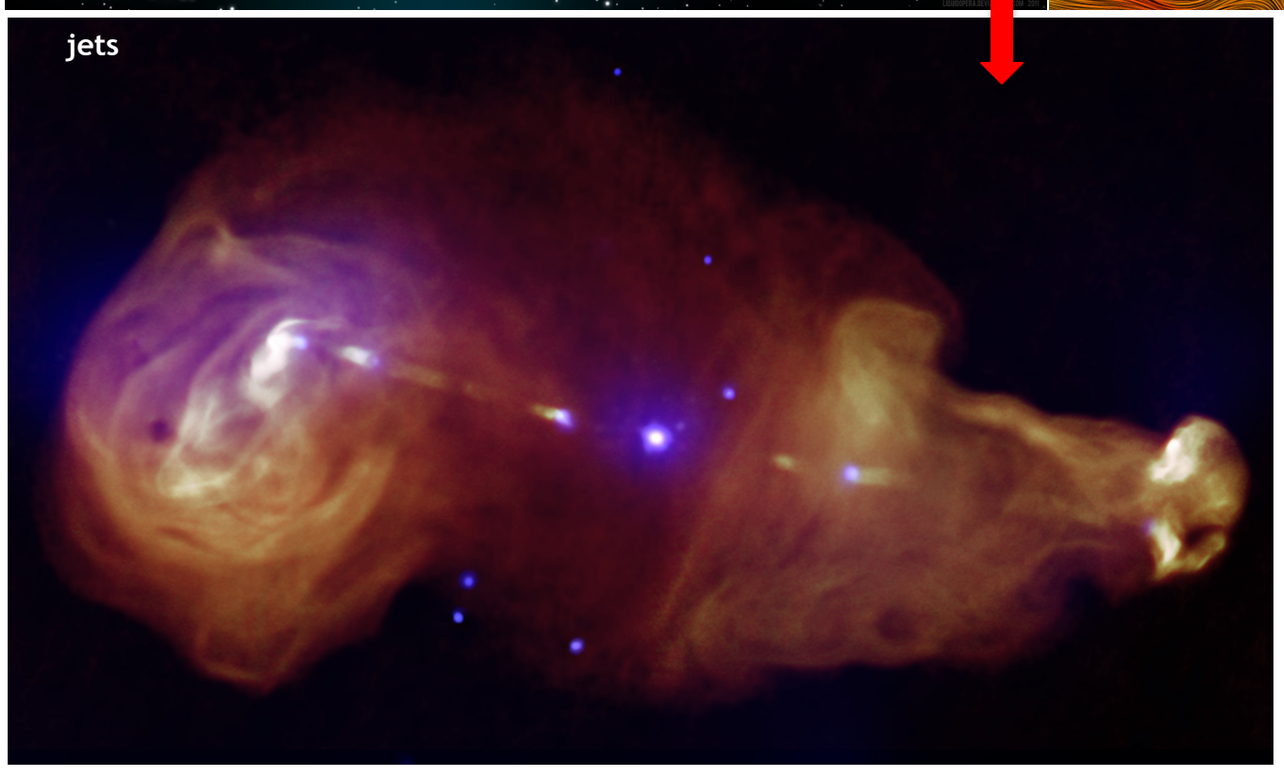


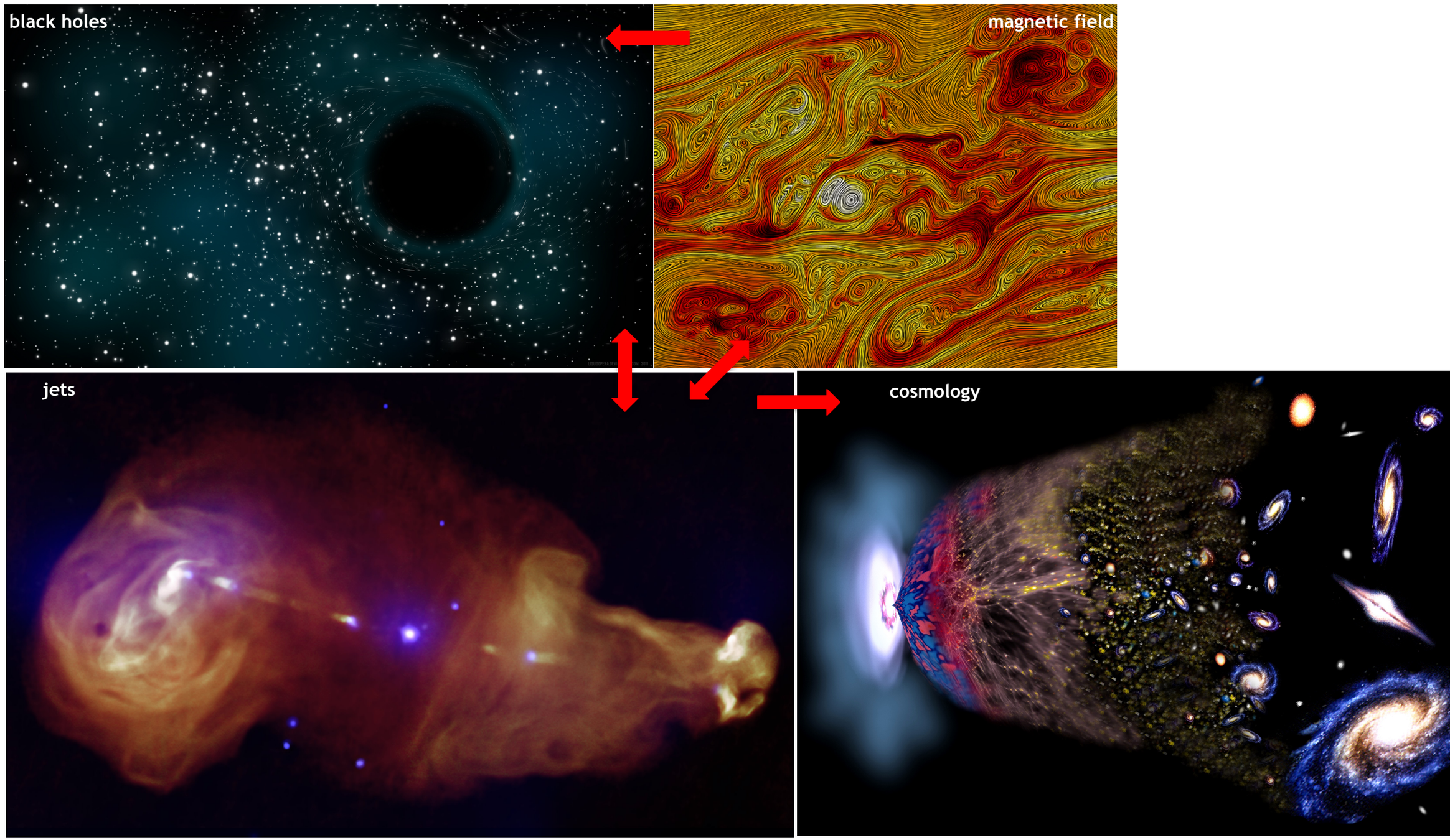


Spinning black hole + magnetic field = jets

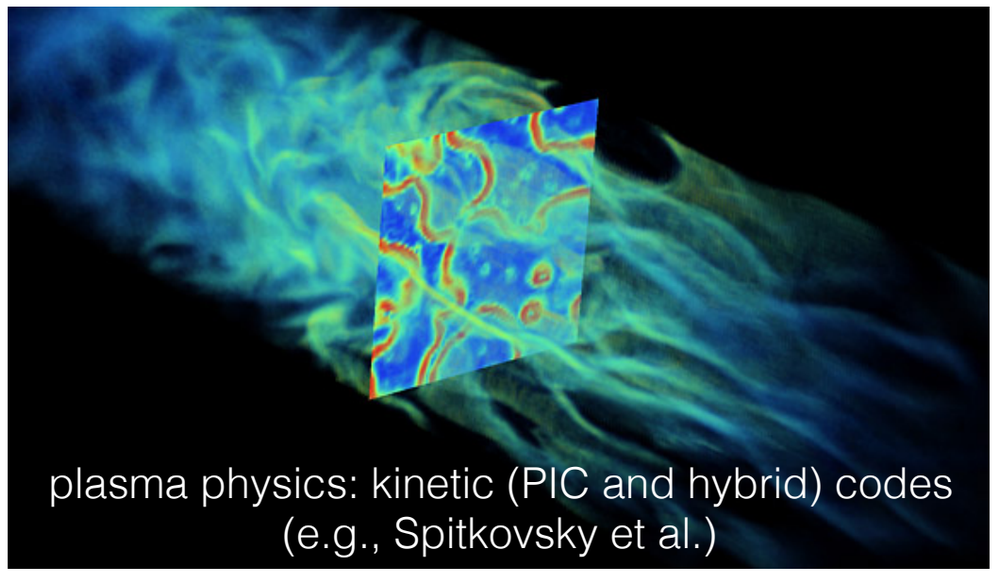




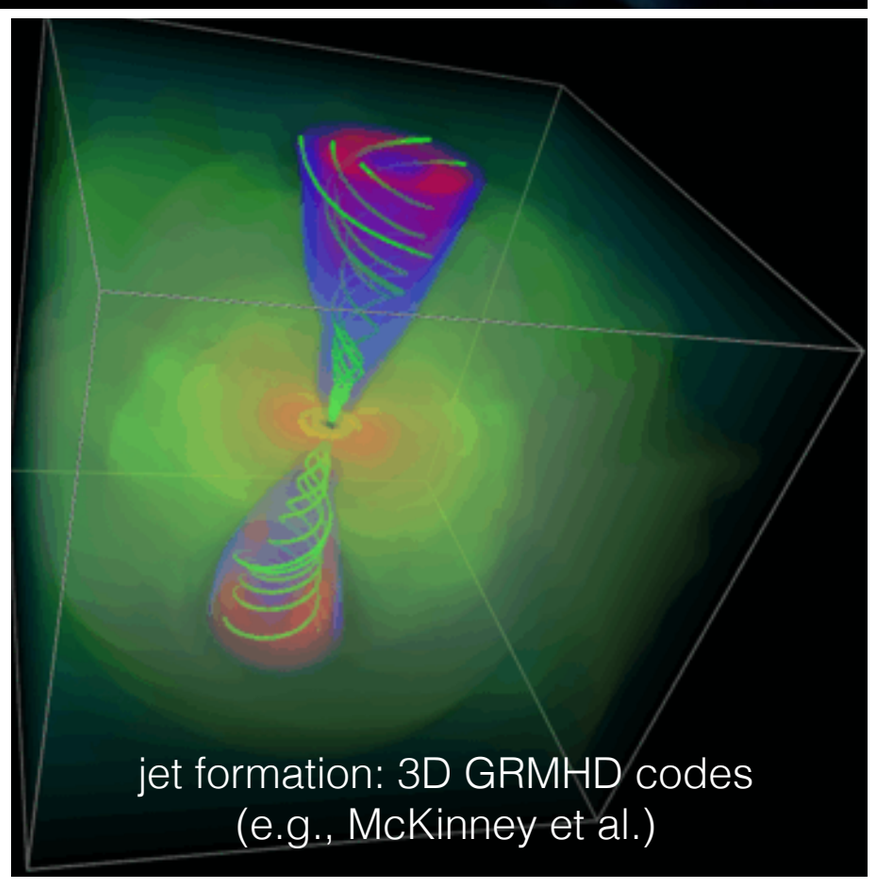
Co-evolution of supermassive black holes and their host galaxies



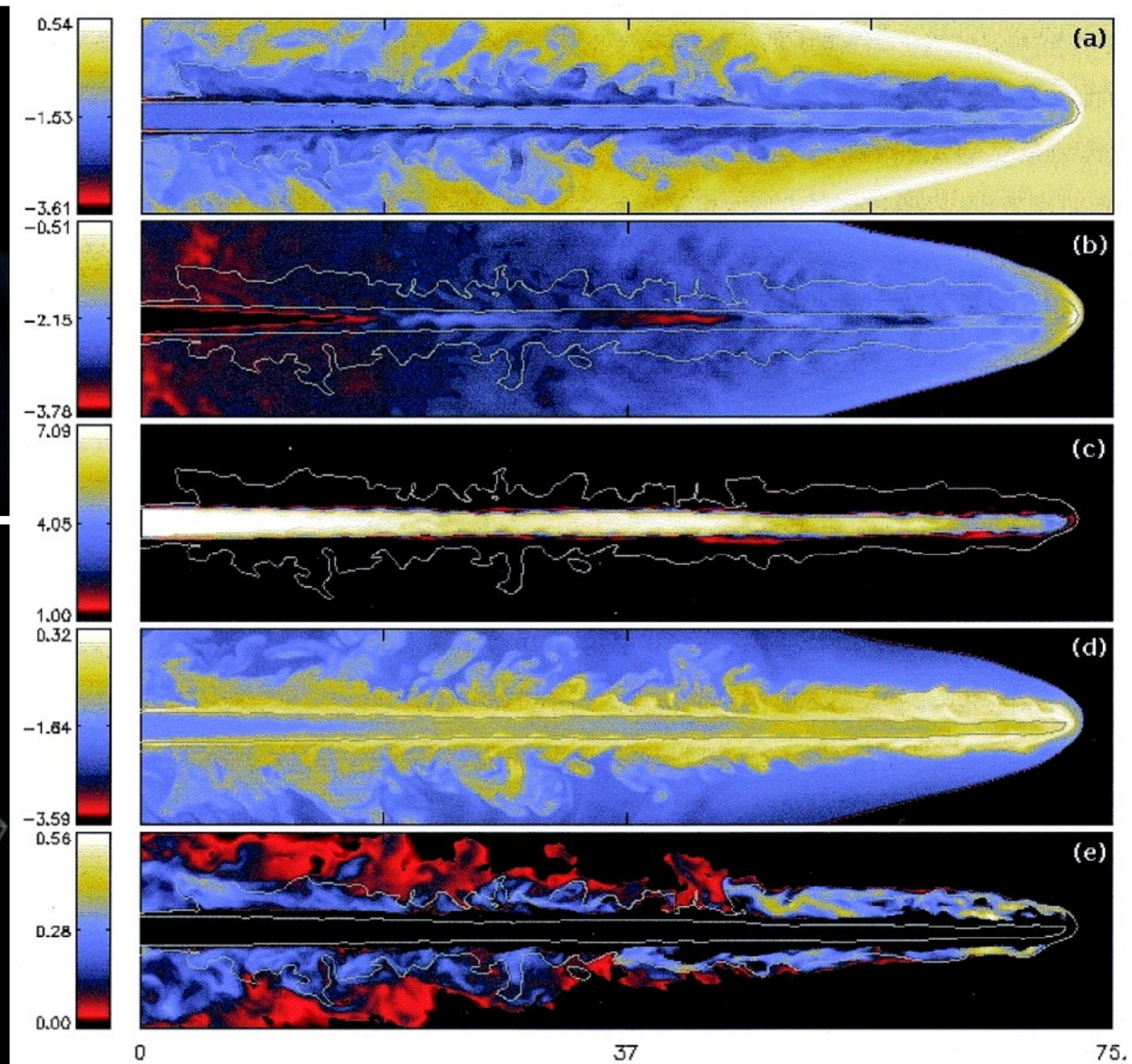
Relativistic jets in numerical simulations



plasma physics: kinetic (PIC and hybrid) codes
(e.g., Spitkovsky et al.)



jet formation: 3D GRMHD codes
(e.g., McKinney et al.)



long-term jet evolution: MHD codes
(e.g., Aloy et al.)

Blazars

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BLAZARS in GAMMA-RAYS

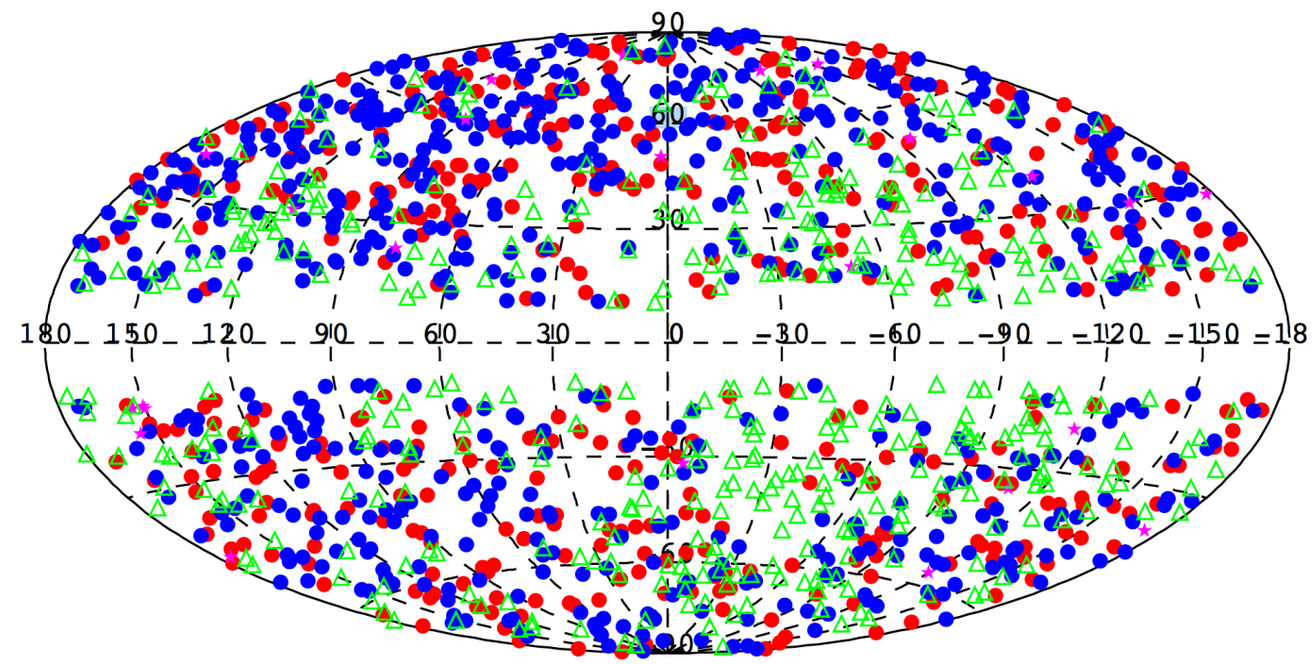
A) dominate the extragalactic gamma-ray sky; make up the bulk of the EGB (?)
B) beamed, non-thermal emission continua; very high energy particles accelerated in situ!
C) dramatic broad-band variability

Extragalactic gamma-ray sky

3FGL catalog includes **3033** sources detected with Fermi-LAT between 100 MeV and 300 GeV with TS>25 between 2008 August 4 and 2012 July 31.

3LAC catalog includes **1563** out of **2192** 3FGL sources located at |b| > 10deg, which are associated with high confidence with AGN: 467 FSRQs, 632 BL Lacs, 460 BCUs and 32 non-blazar AGN (radio galaxies, NLS1s, etc.).

The Bayesian Association Method applied to catalogs of sources that were already classified and/or characterized.



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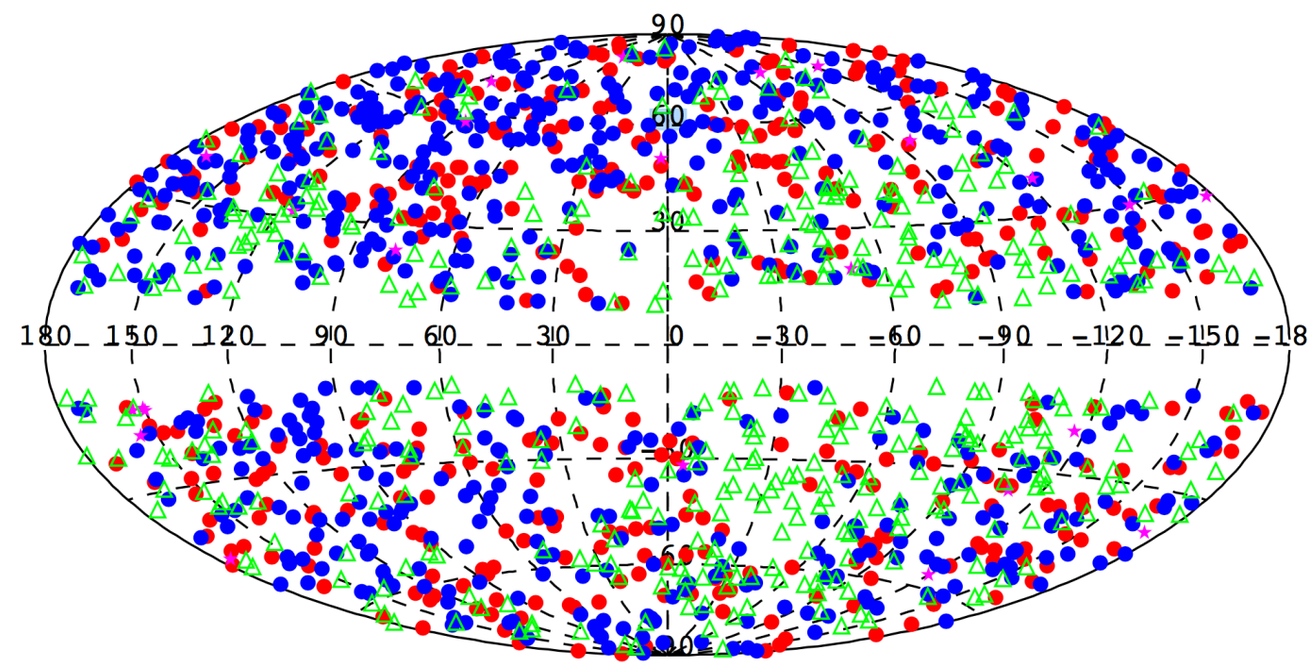
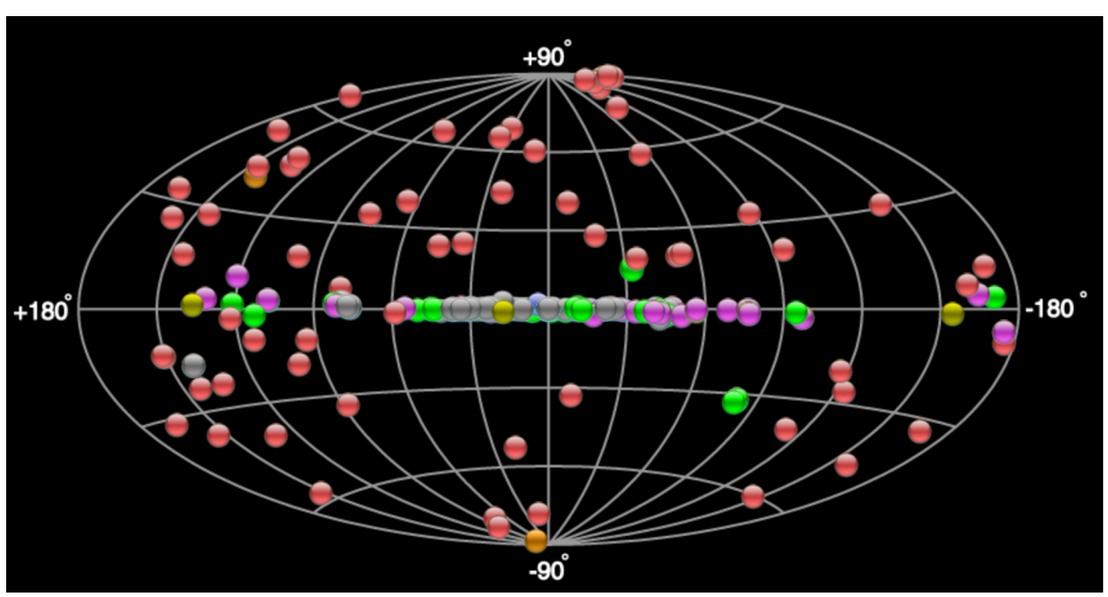
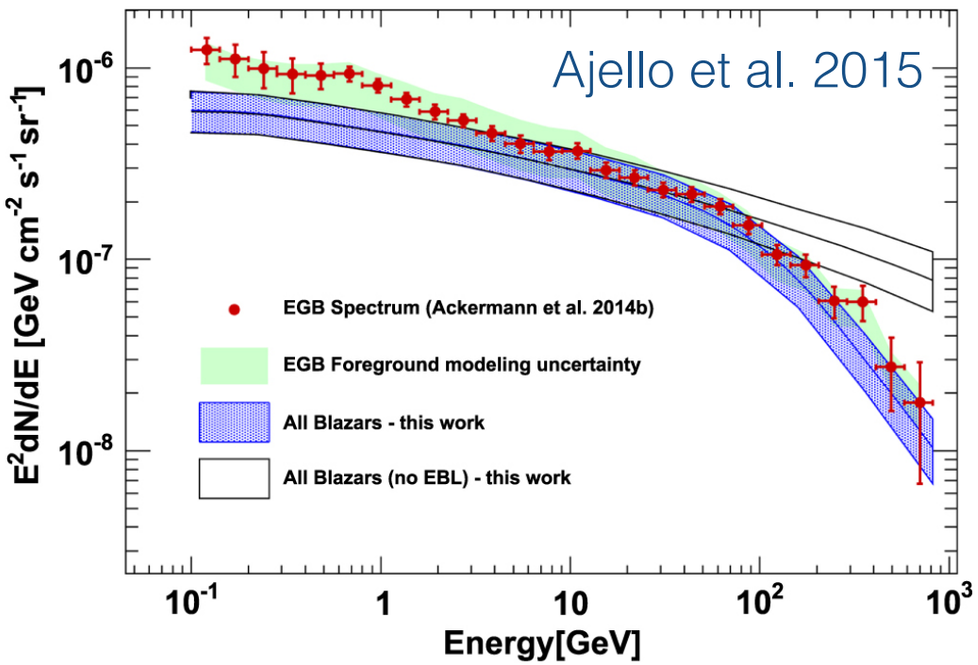


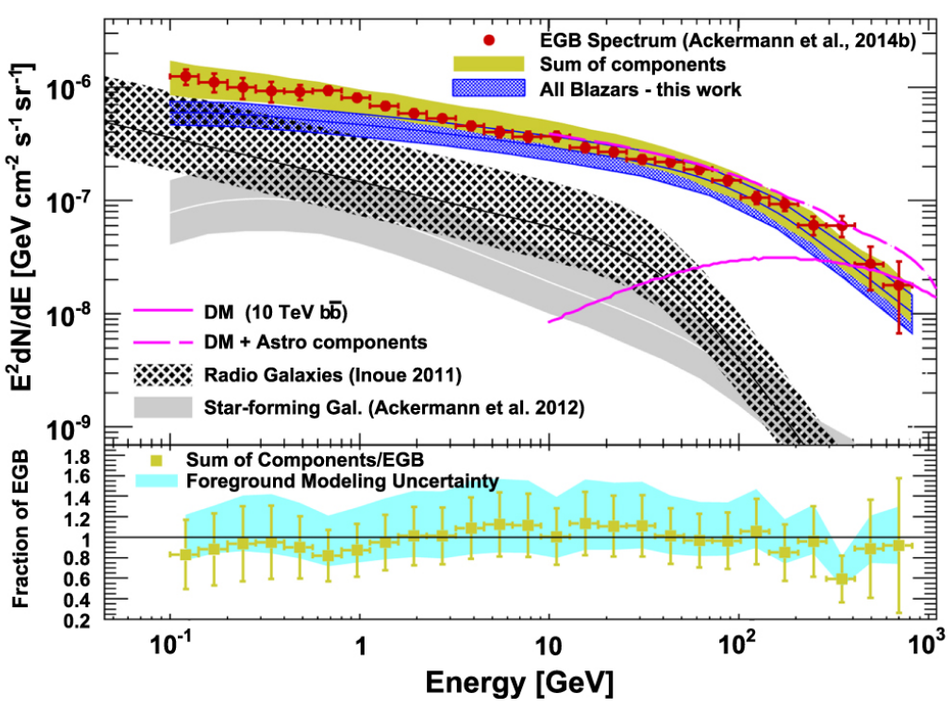


Extragalactic TeV sky is also dominated by blazars, mostly BL Lacs, plus some bright FSRQs and nearby radio galaxies.

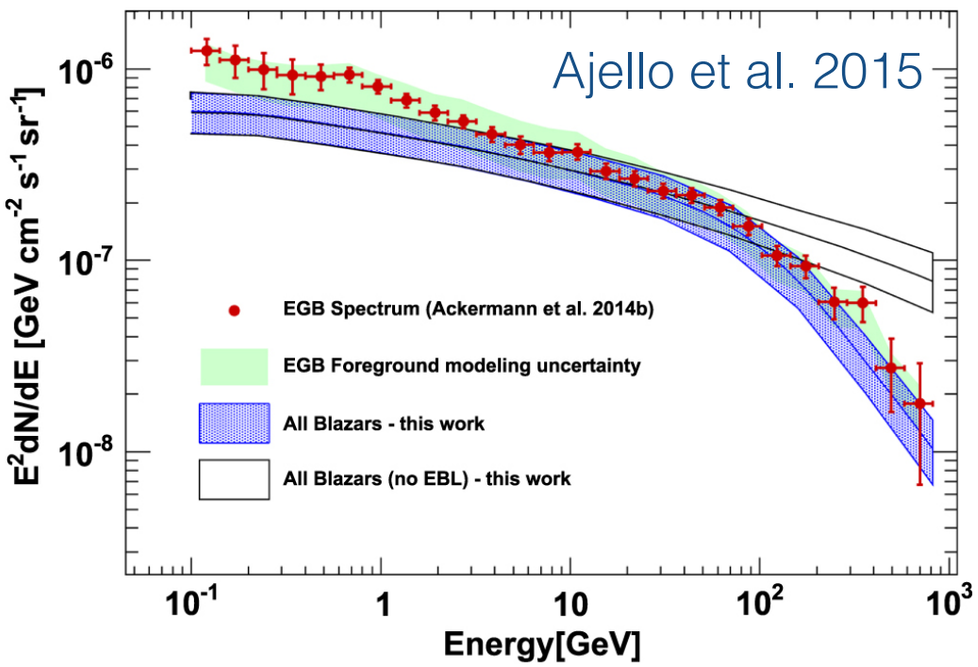
Pointing observations of "the most promising" targets selected among known prominent AGN.

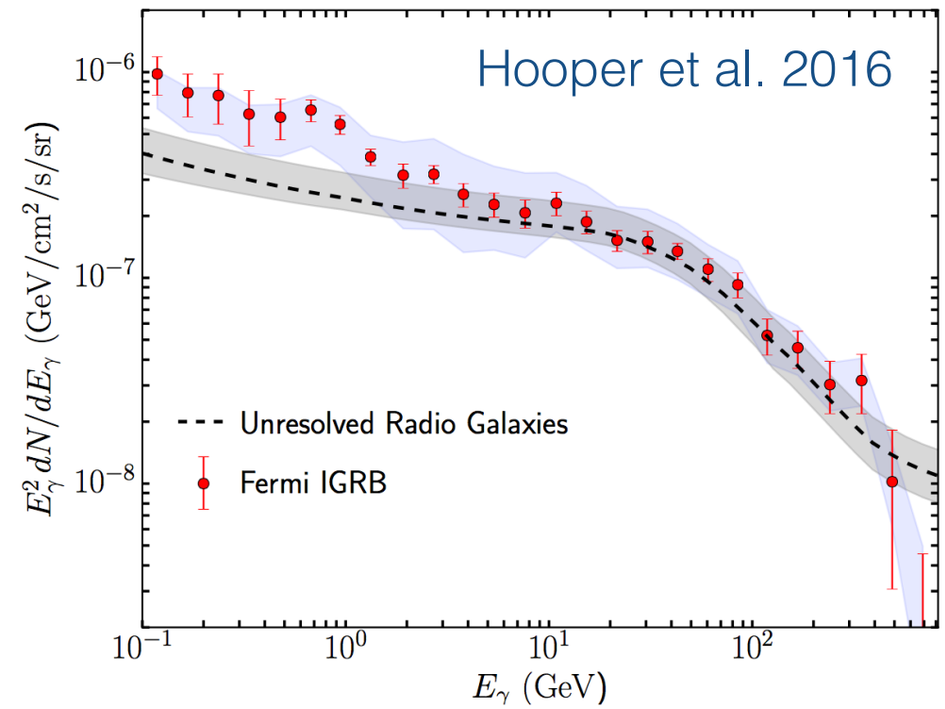
Extragalactic gamma-ray background: unresolved blazars

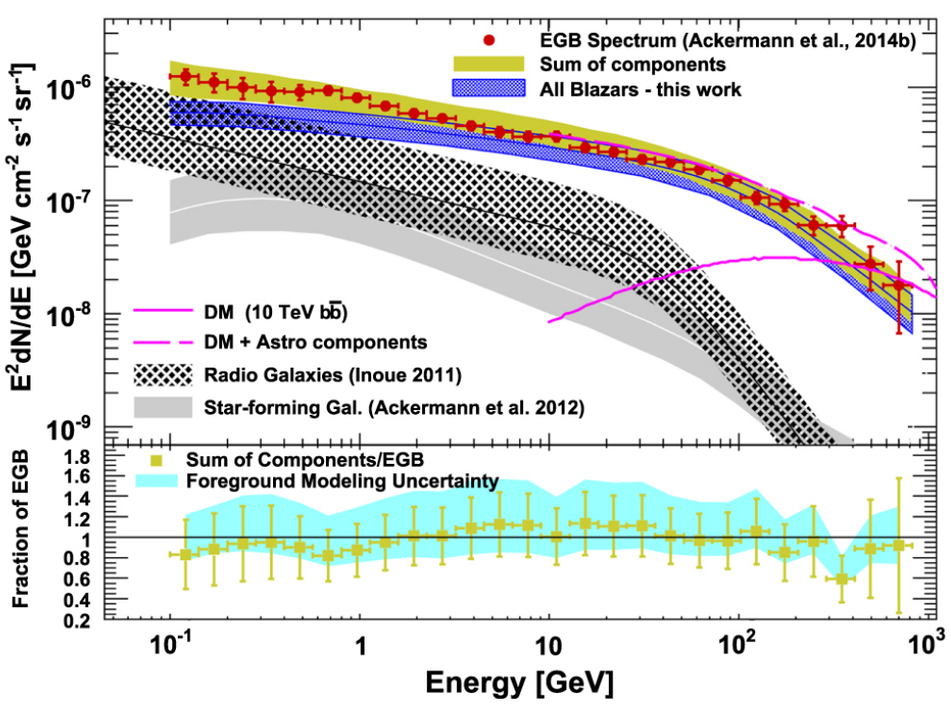


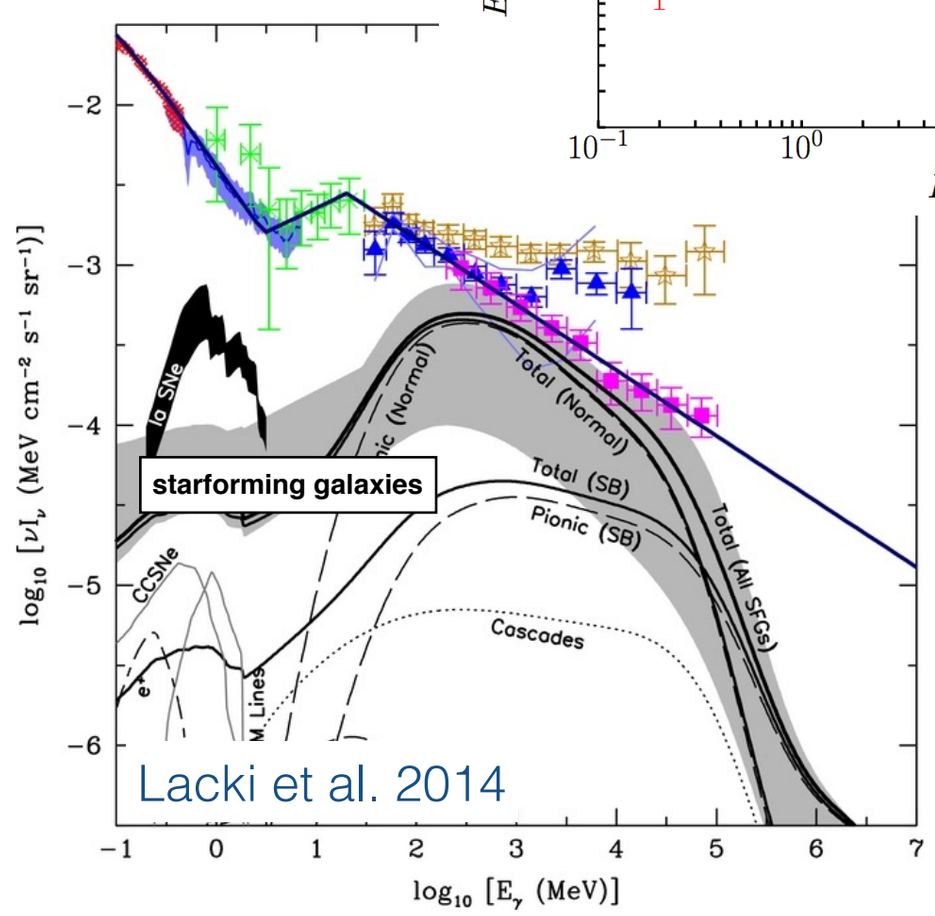


Extragalactic gamma-ray background: mostly blazars?

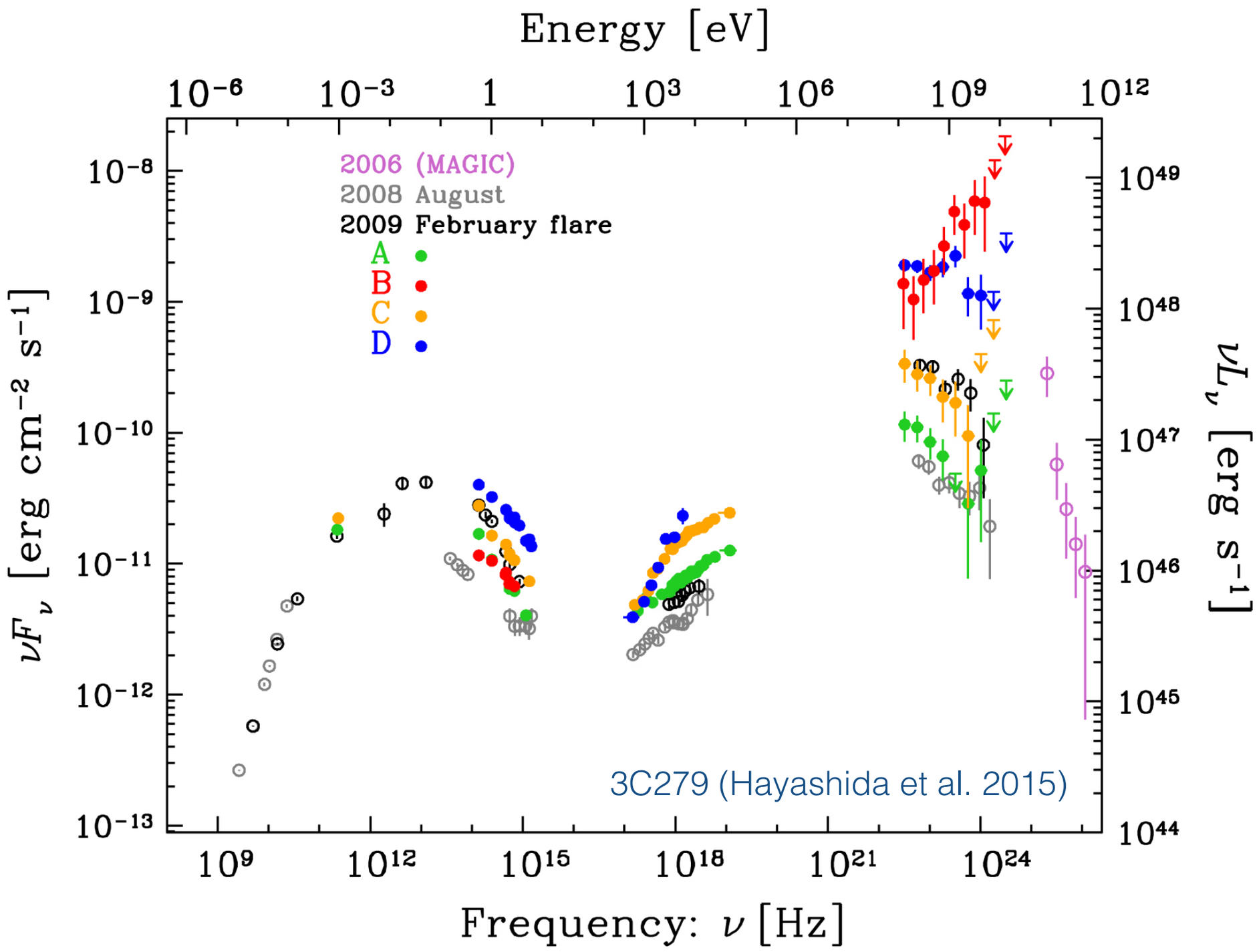








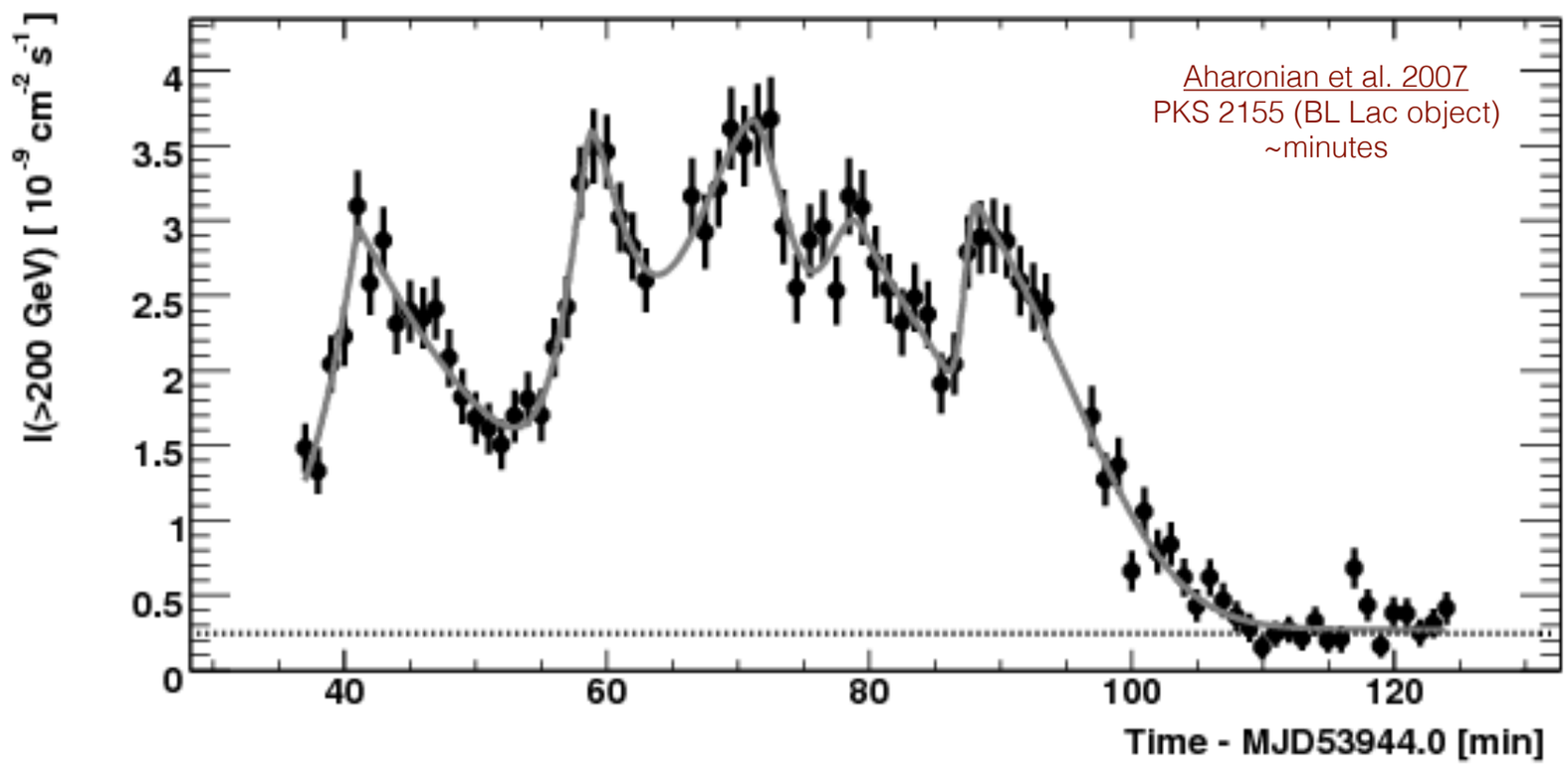
Non-thermal emission continua

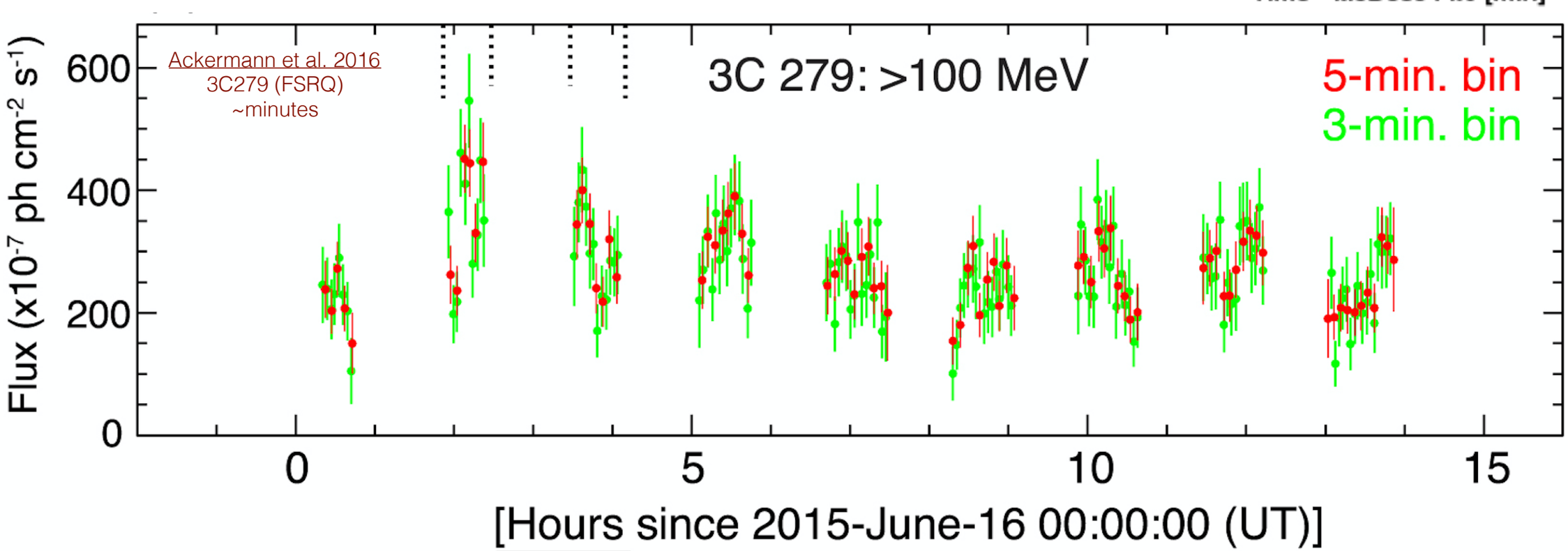


The bulk of the blazar radiative power released in gamma-rays!

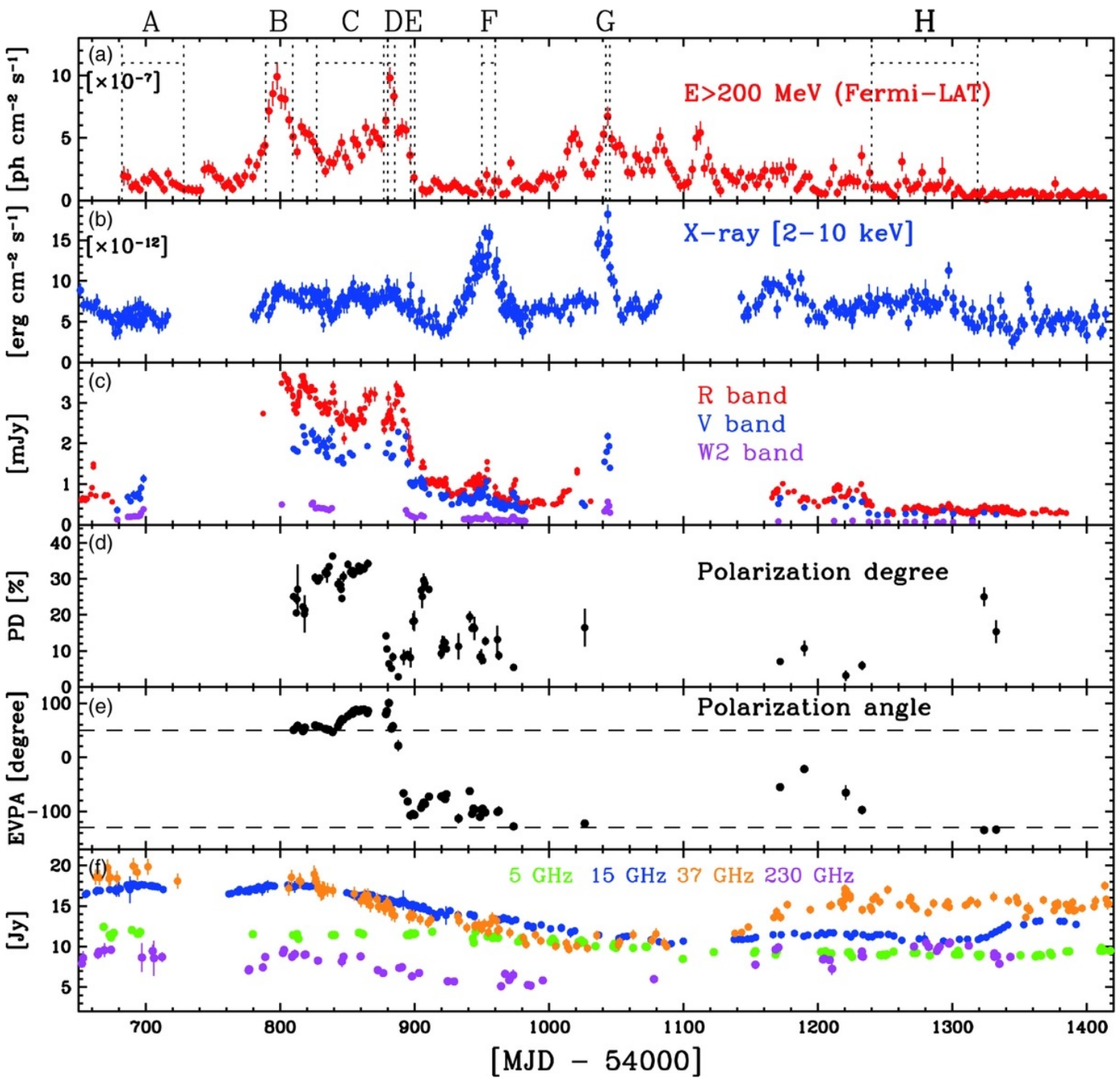
Dramatic gamma-ray variability

$$r_g \sim 10^{13}\,\mathcal{M}_8\,[\mathrm{cm}]$$
$$t_g \sim 10^{3}\,\mathcal{M}_8\,[\mathrm{s}]$$
$$\text{where } \mathcal{M}_8 \equiv \mathcal{M}/10^8 M_\odot$$





Complex MWL variability



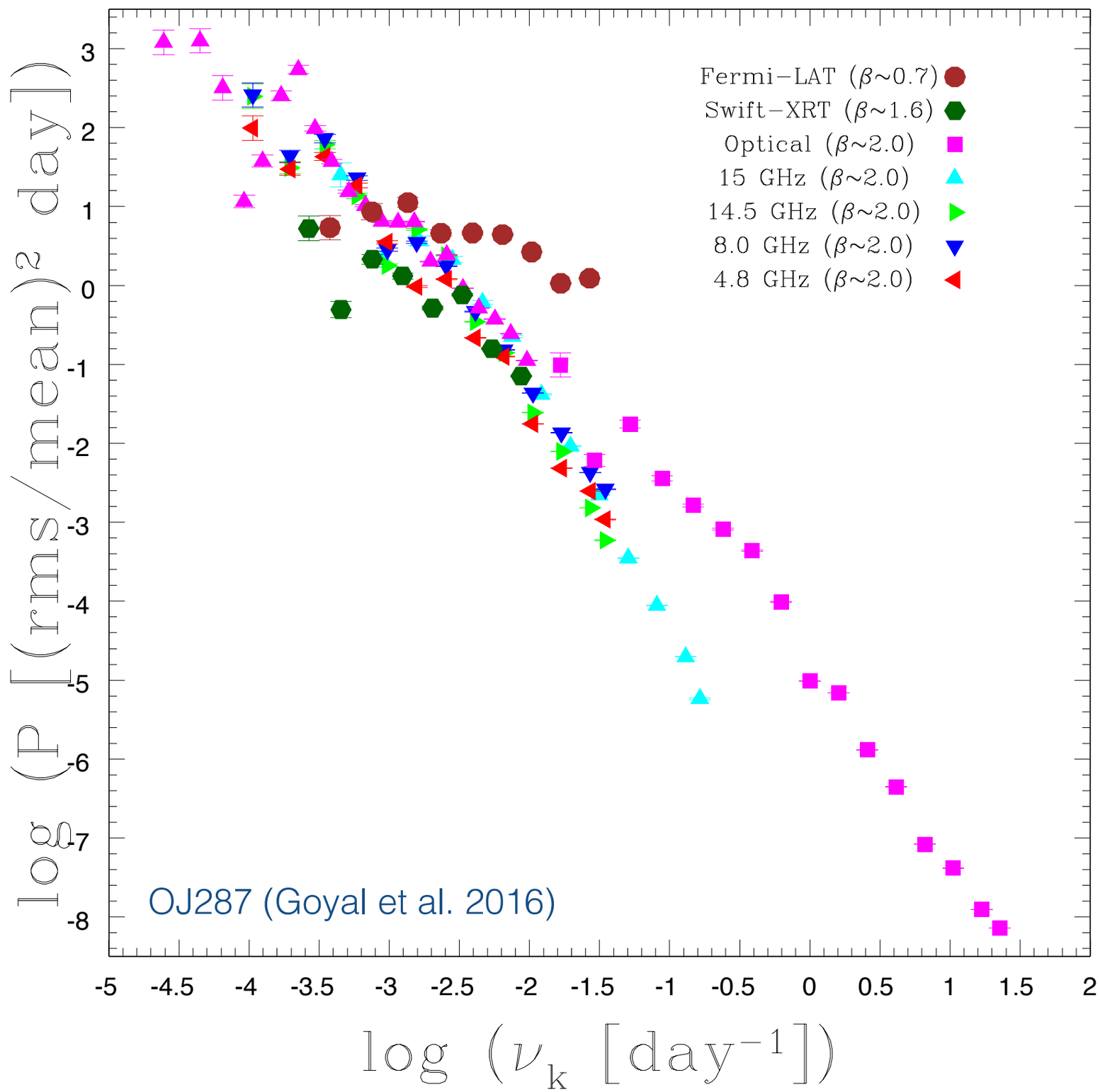
3C279 (Hayashida et al. 2012)

- Can we pinpoint the high-energy emission site from flux doubling timescales and MWL correlations?
- Can we infer robustly the jet parameters from modelling single isolated flaring events?

- inconclusive results regarding the observed MWL correlations;
- events claimed to be correlated, are often on different timescales, and have different variability amplitudes;

- is there any meaning behind “minimum variability timescales” inferred from single isolated flaring events as “flux doubling timescales”?
- can we say anything robust without continuous, long, and densely sampled MWL monitoring?

Pink/red noise!



A pure **red noise** ("damped process/random walk") type variability from hours to decades at radio and optical frequencies, with no "characteristic" timescales, indicating that ALL the variability is due to the underlying single stochastic process with very long relaxation timescale.

The PSD in gamma-rays is instead consistent with the **pink noise** ("flicker/long-memory process") type variability, at least on the timescales from years to days…

also Chatterjee et al. 2013/15, Isobe et al. 2015, Sobolewska et al. 2014

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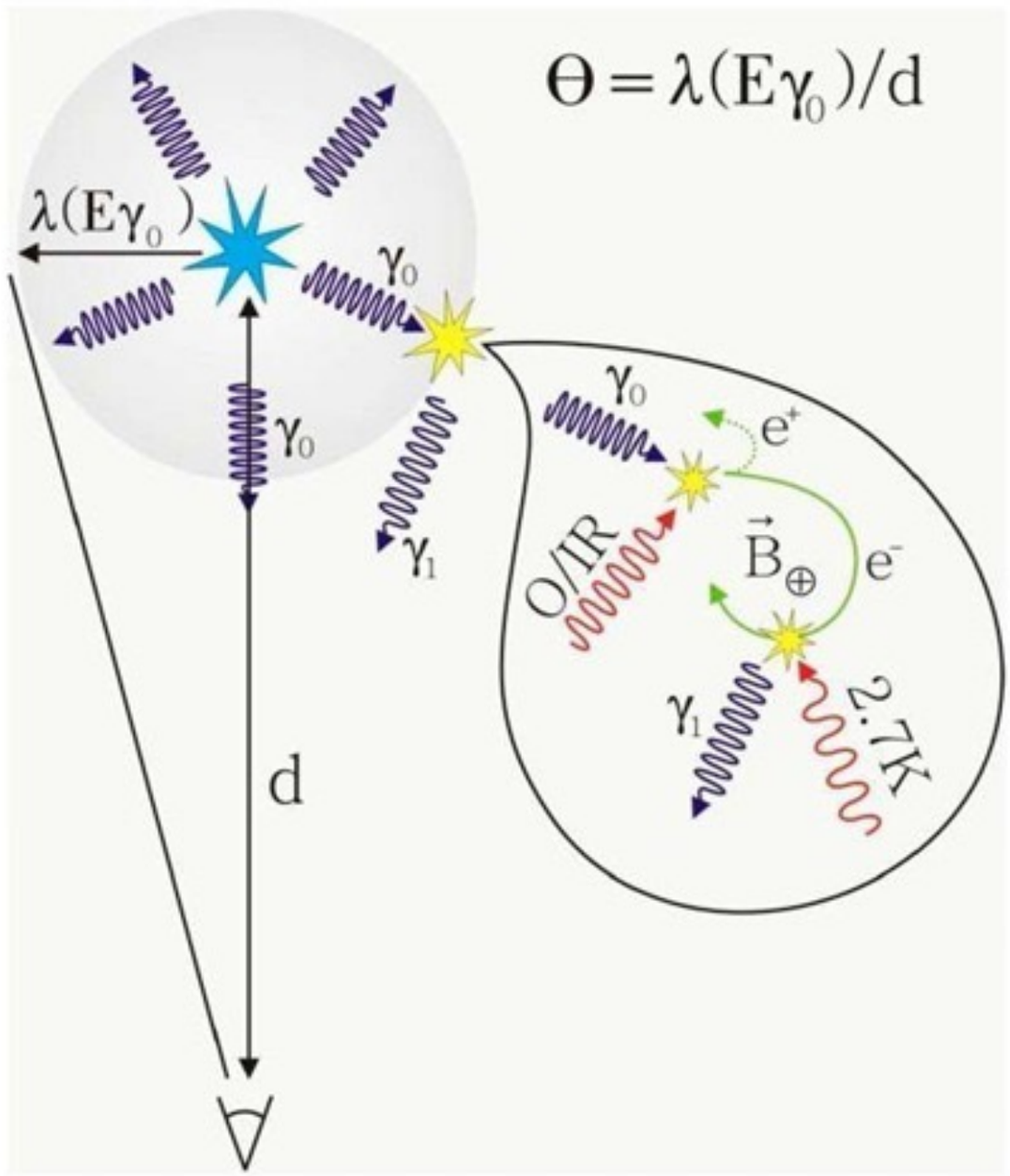
BLAZARS AS PROBES OF

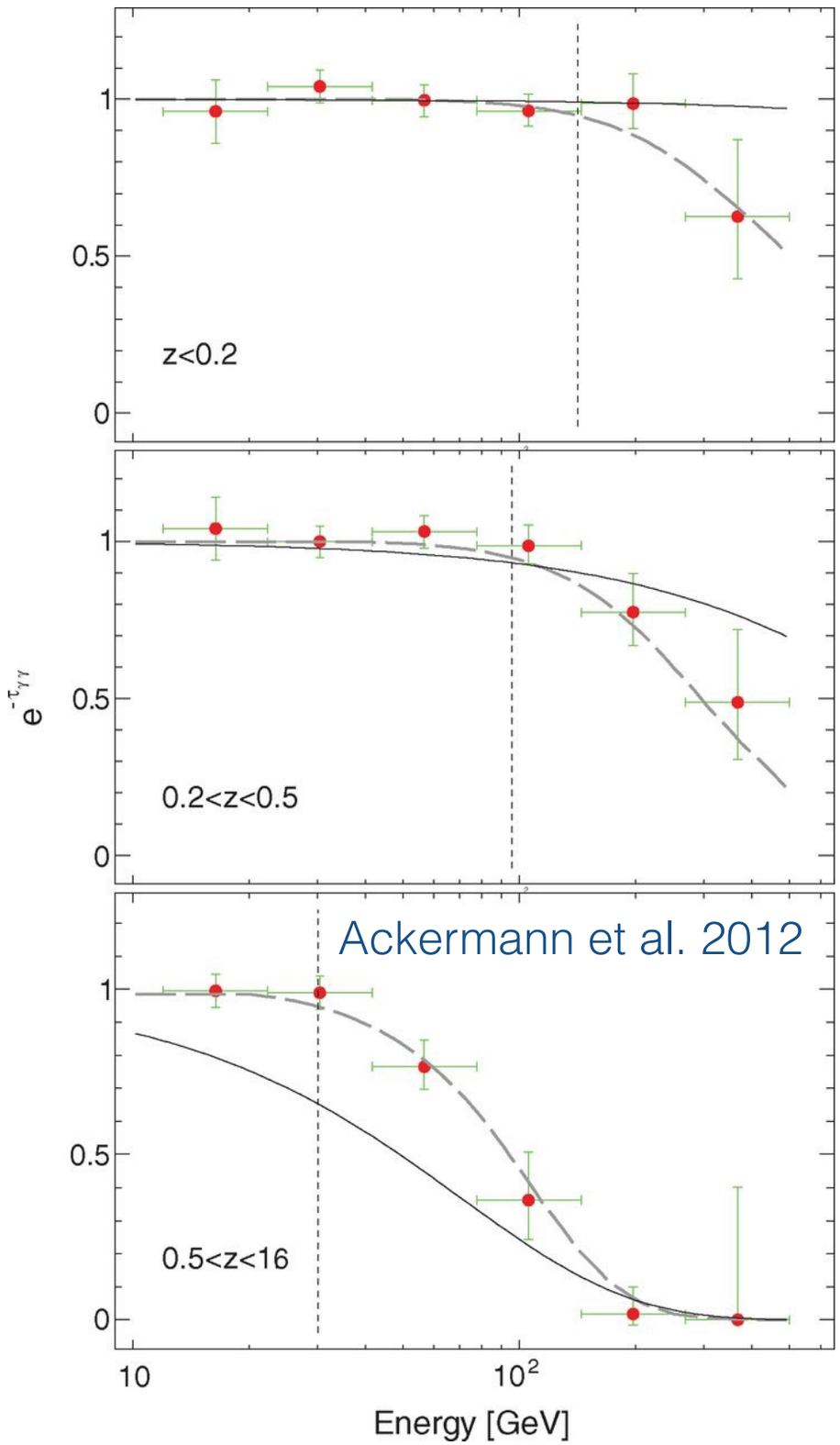
i) Extragalactic Background Light (EBL)
ii) Intergalactic Magnetic Field (IGMF)
iii) Lorentz Invariance Violation (LIV)

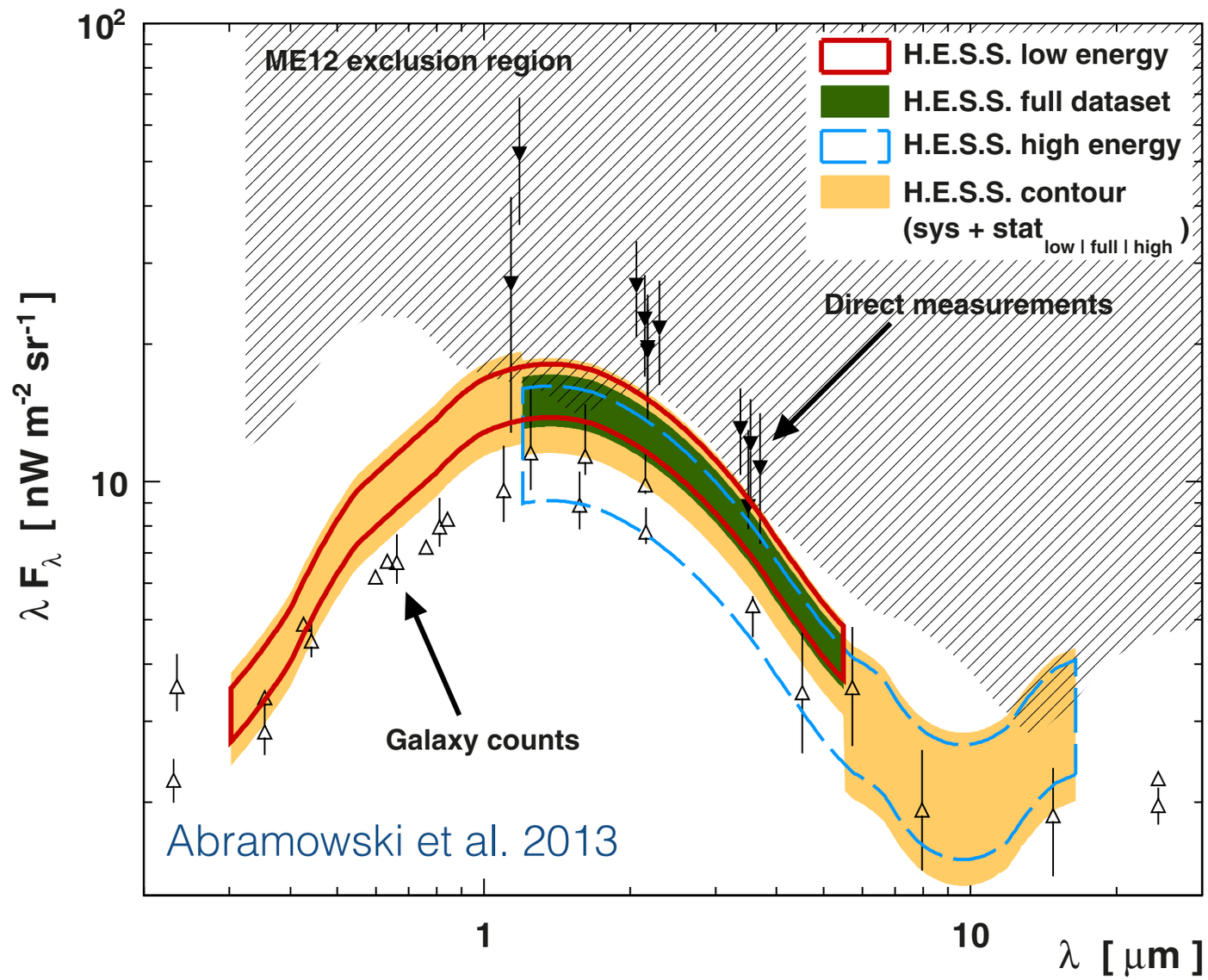
Extragalactic Background Light



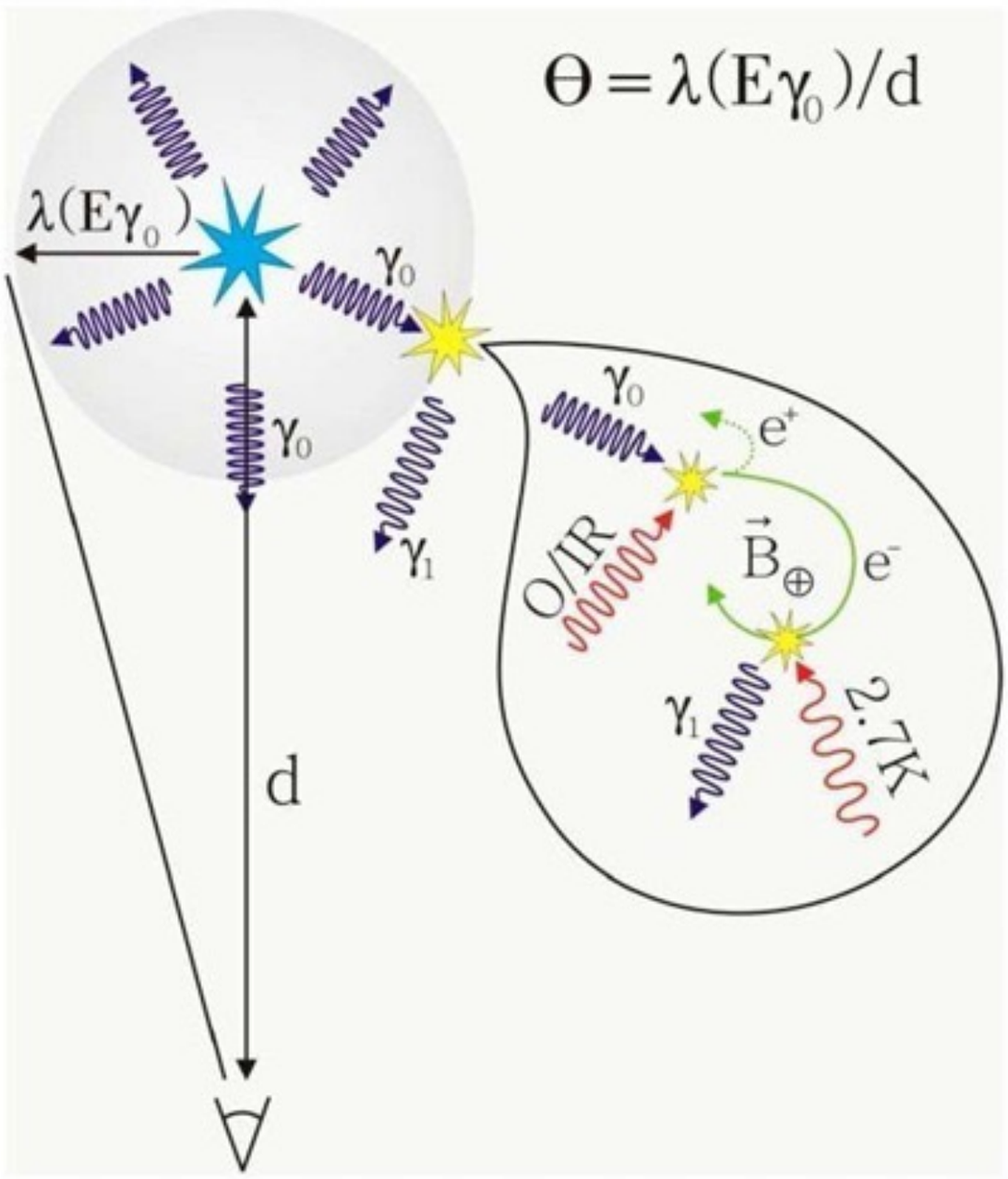
- The “Extragalactic Background Light” (EBL) is the background radiation originating as a superposition of the starlight emission from all the galaxies, re-processed by the interstellar medium over the entire history of the galaxy evolution -> crucial information about the structure formation in the Universe.
- Direct measurements of the EBL at various frequencies are hampered by a severe foreground contamination (Zodiacal light); secure lower limits for the EBL intensity provided by galaxy counts.
- Indirect EBL measurements via a detailed analysis of gamma-ray spectra of cosmologically distant sources: gamma-ray photons propagating on cosmological distances may be absorbed by the EBL via the photon-photon annihilation, and hence the observed gamma-ray emission is attenuated with respect to the intrinsic (source) emission.

EBL studies with blazars



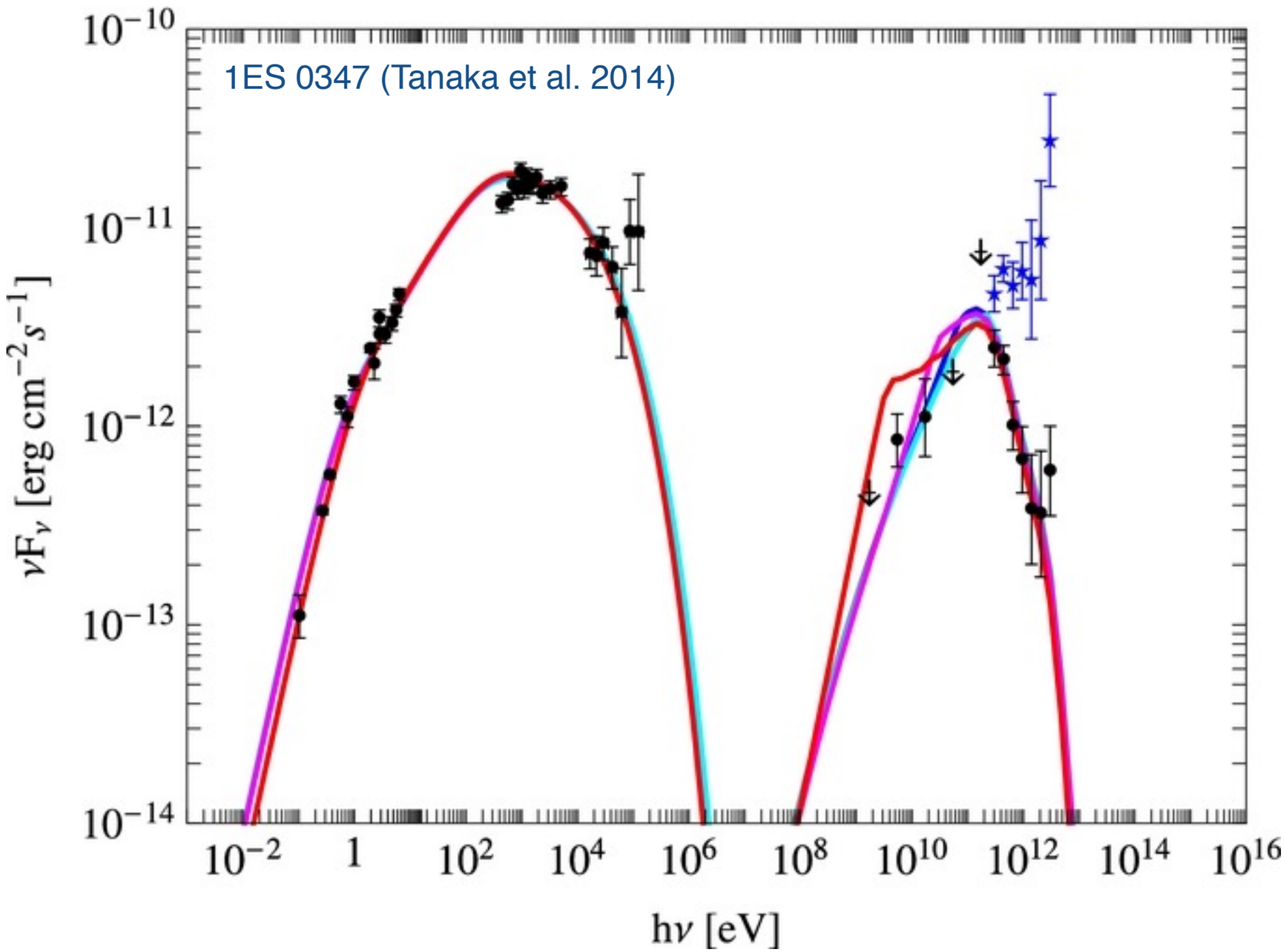


Intergalactic magnetic field



- The development (on cosmological scales) of the electromagnetic cascades initiated by the absorption of primary gamma-rays on the EBL photon field, depends on the magnetization of the intergalactic medium.
- During the photon-photon annihilation, high-energy electron-positron pairs are created, which then emit secondary gamma-rays via inverse-Comptonization of the EBL, which may next pair create again, and so on; pairs created in the intergalactic medium are however at the same time isotropized by the intergalactic magnetic field (IGMF), and subjected to synchrotron energy losses.
- Normalization and spectral shape of the reprocessed gamma-ray continua of blazar sources carry therefore important information on not only the EBL, but also the IGMF.

Constraining IGMF with blazars

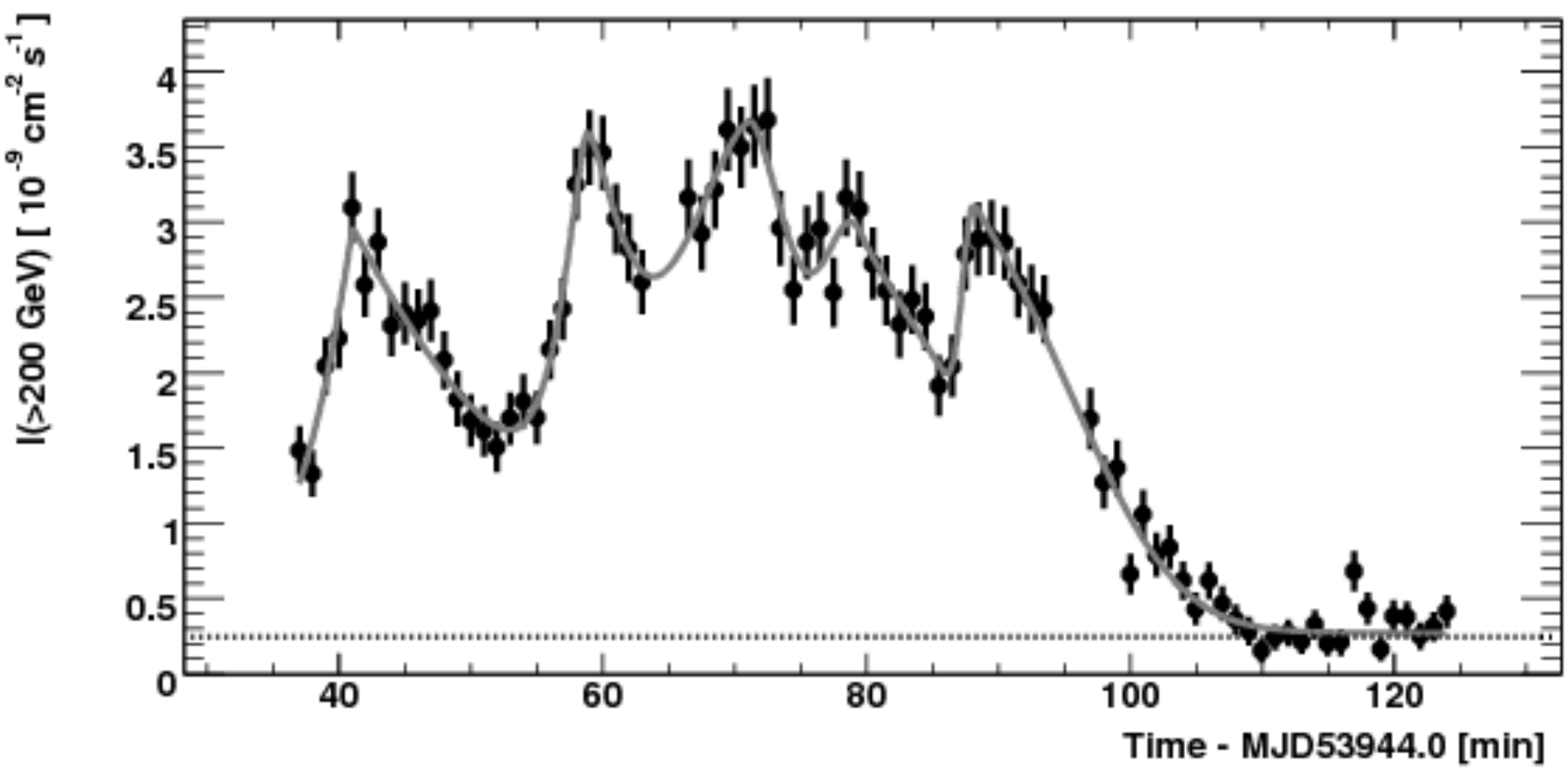


Black filled circles/arrows correspond to the observed fluxes/upper limits; blue stars denote the very high-energy gamma-ray fluxes corrected for the EBL absorption. The model curves included in the figure represent the sum of all the considered emission components (synchrotron, inverse-Compton, and cascade), for different values of the IGMF: 1e−17.5 G (blue), 1e−17 G (cyan), 1e−18 G (magenta), and 1e−19 G (red).

Lorentz Invariance Violation

One of the possibilities for a direct insight into the quantum properties of the spacetime continuum, is the detection of the Lorentz Invariance Violation, expected in some approaches to the quantum theory of gravity at energy scales of the order of the Planck mass 1.22e+28 eV.

The H.E.S.S. data for the exceptional flaring even in the TeV blazar PKS2155-304, allows one to put constraining upper limits on the quantum gravity mass scale >2.1e+27 eV for the linear term in the photon dispersion relation, and >6.4e+19 eV for the quadratic term (Abramowski et al. 2011).



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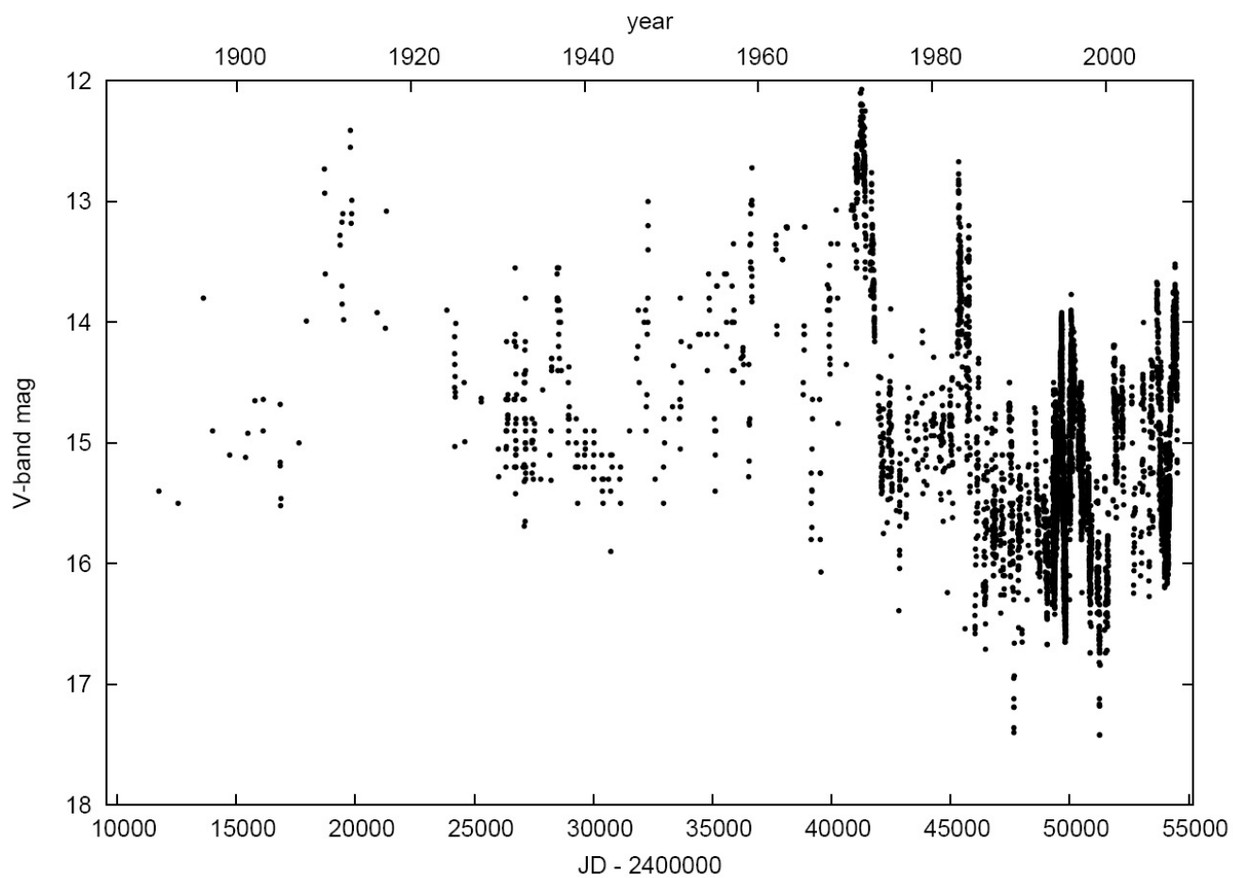
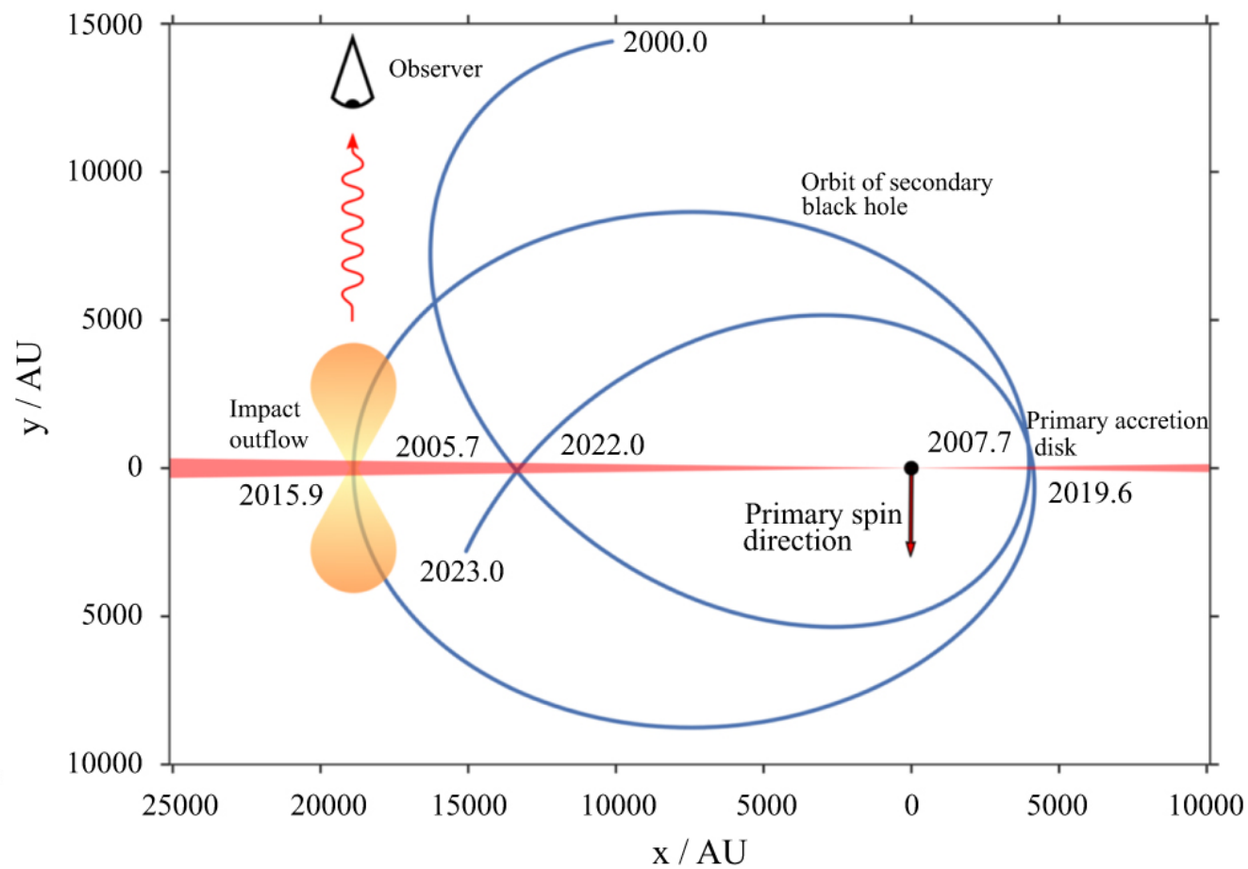
BLAZARS AS THE SOURCES OF

*) high-energy neutrinos ???
**) ultra high-energy cosmic rays (UHECRs) ???
***) gravitational waves (-> binary SMBHs) ???

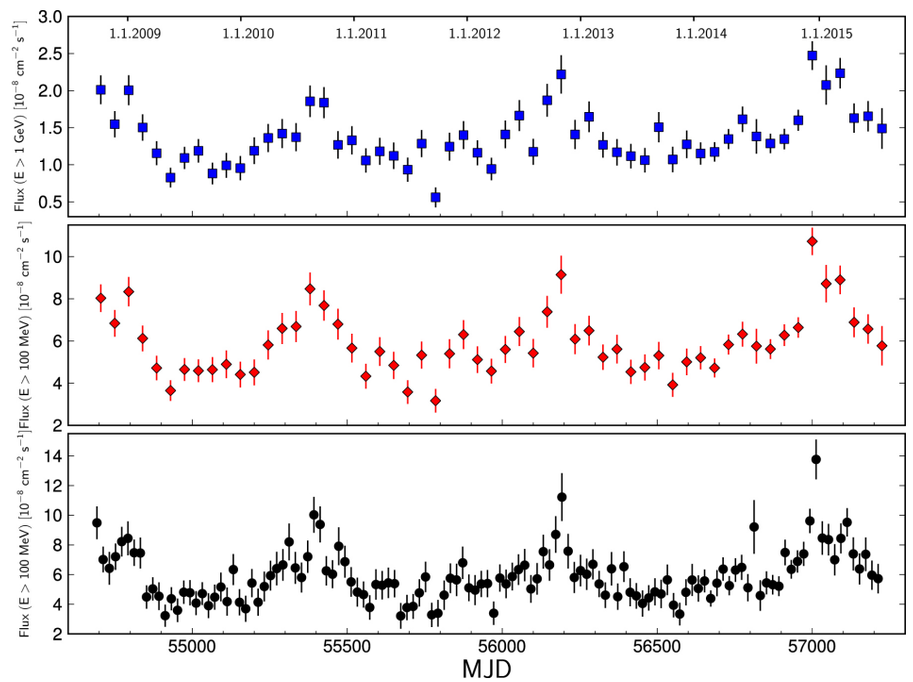
Binary SMBHs?

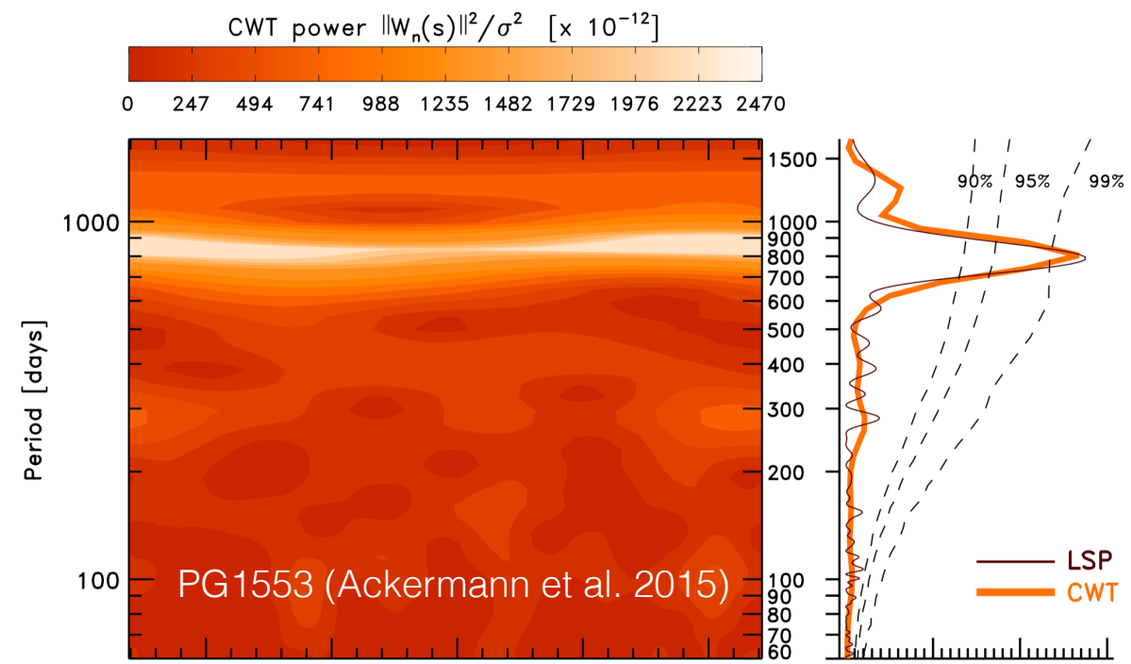




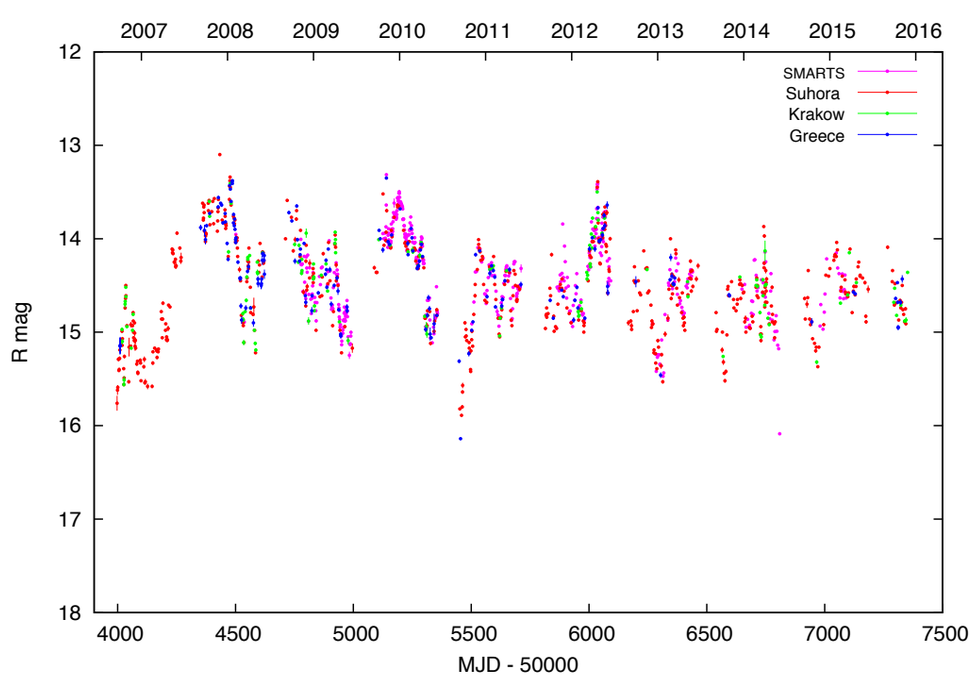
12 year periodicity in blazar OJ287 (optical) driven by the binary SMBHs?
Valtonen et al. 2016 and refs therein.

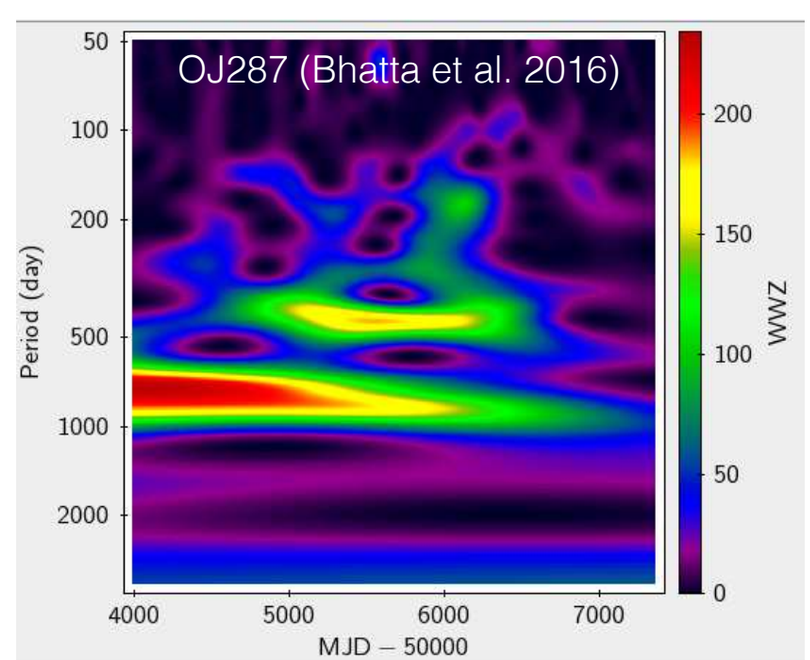
(Quasi-)periodic oscillations?

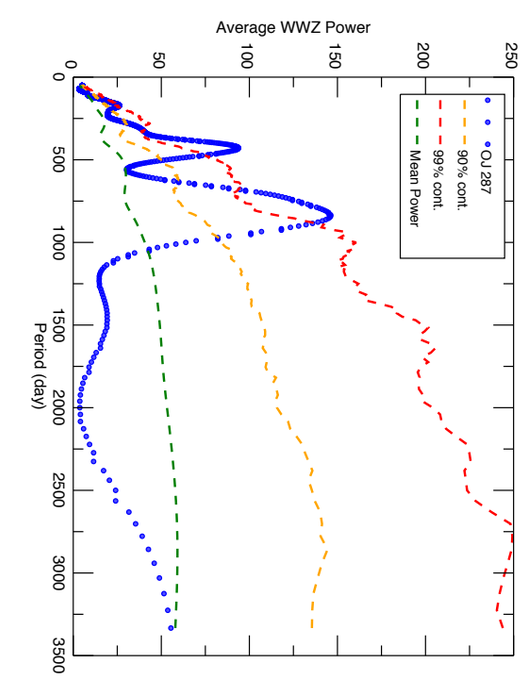




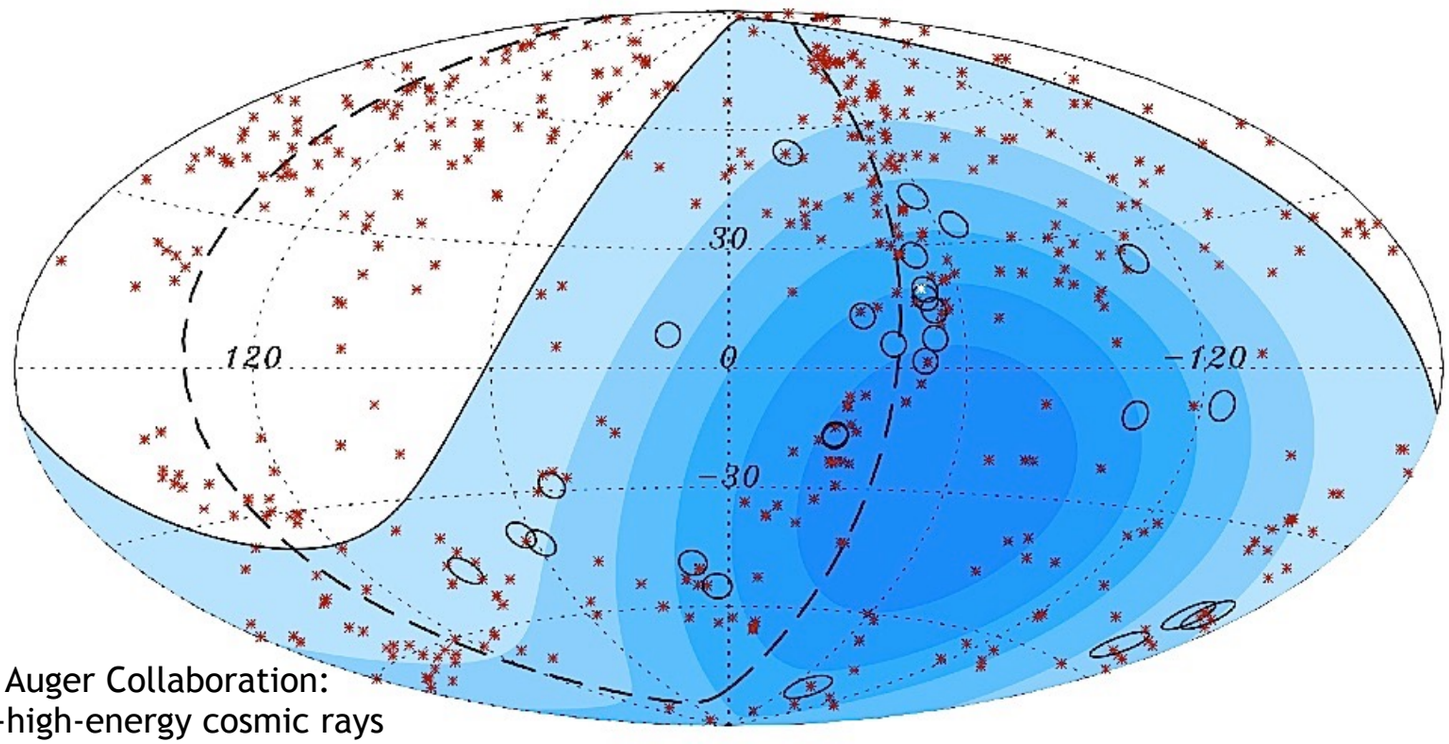
marginal significance, timescales of a few years, seem to be related to accretion disks rather than binary SMBHs



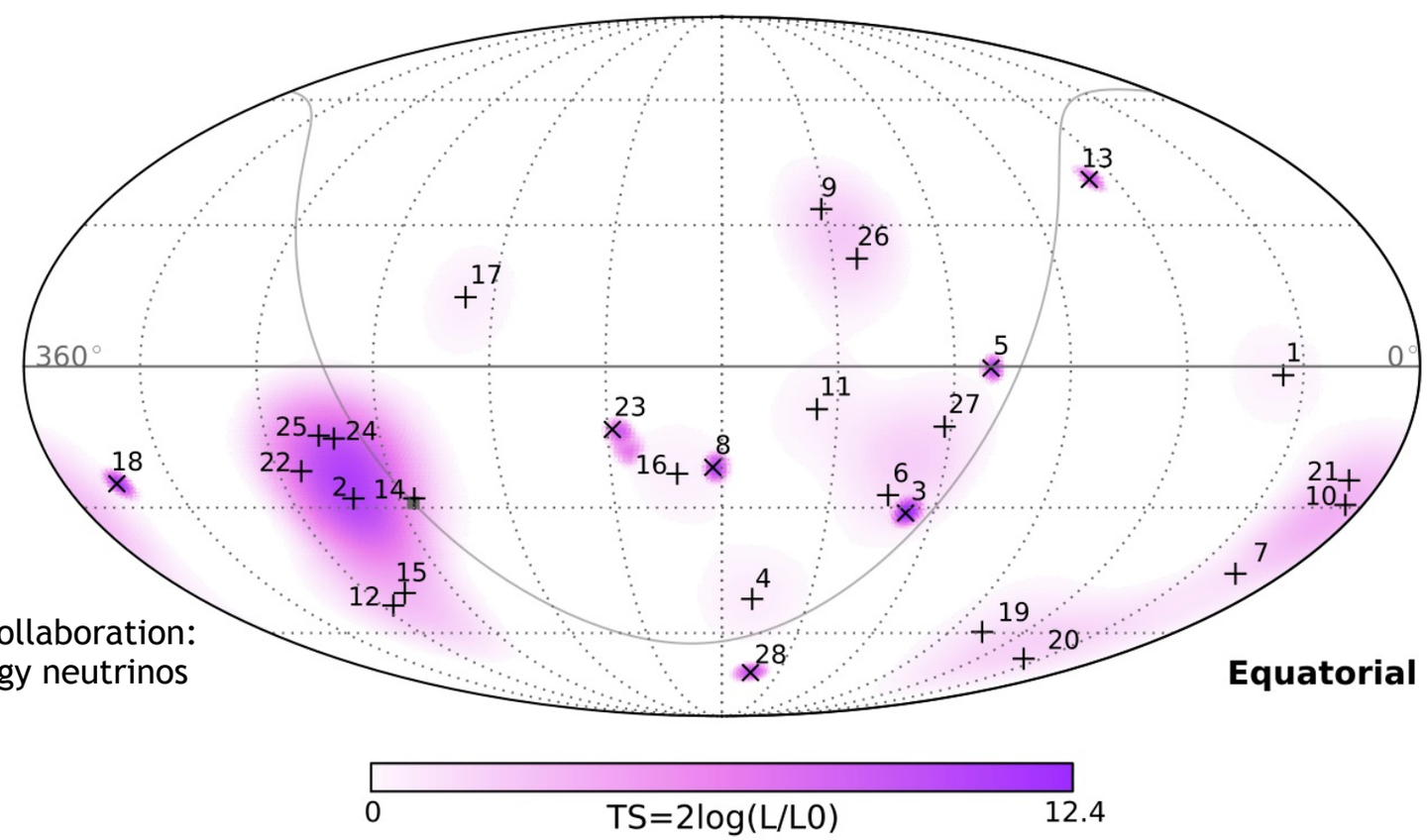




High-energy neutrinos and UHECRs



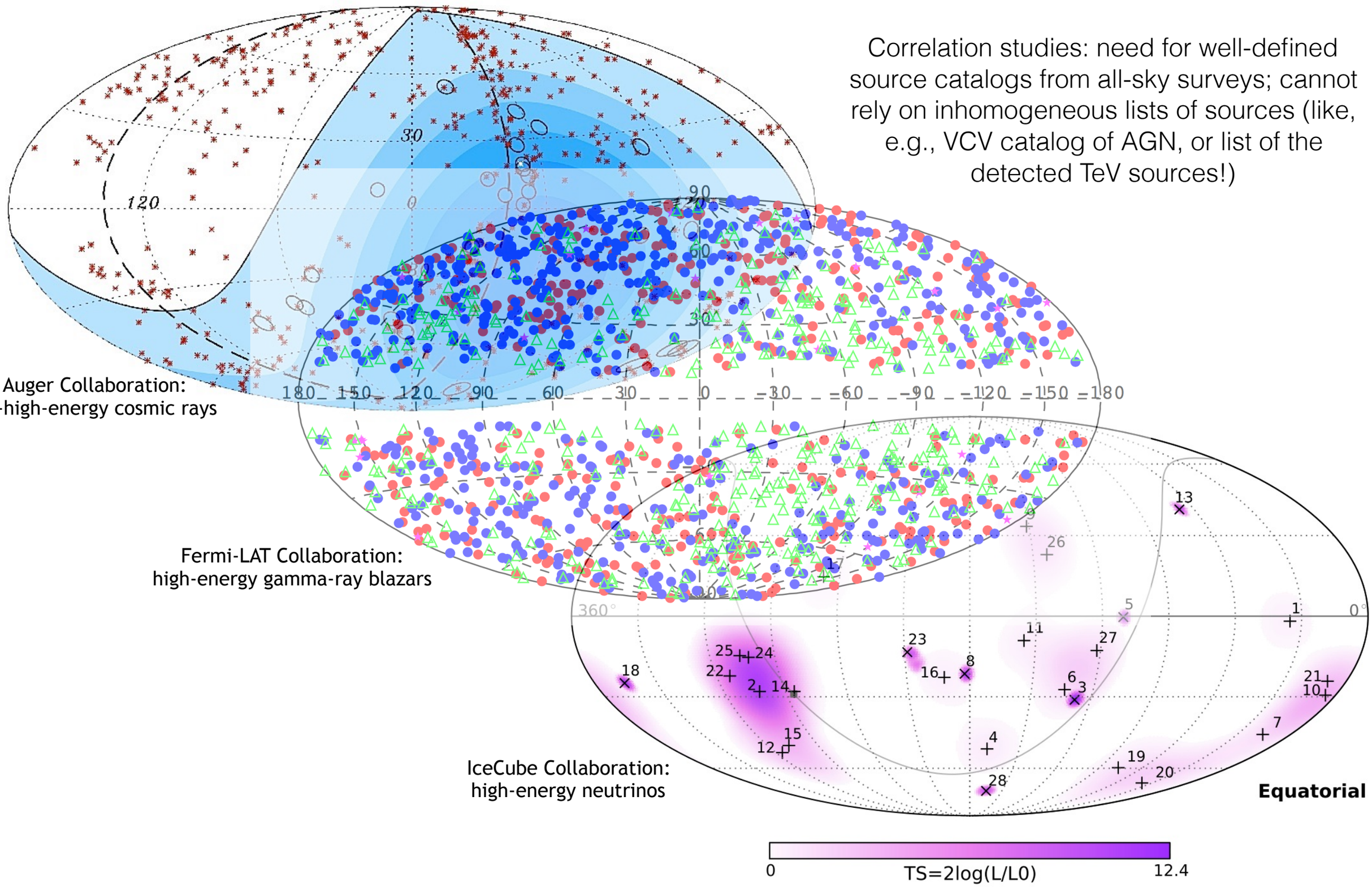
P. Auger Collaboration:
ultra-high-energy cosmic rays



IceCube Collaboration:
high-energy neutrinos

Blazars?

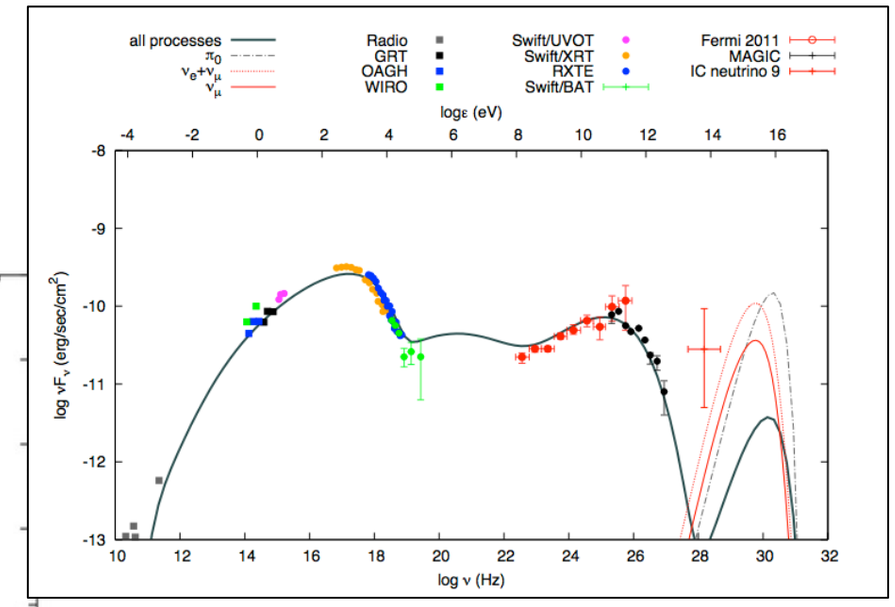
Correlation studies: need for well-defined source catalogs from all-sky surveys; cannot rely on inhomogeneous lists of sources (like, e.g., VCV catalog of AGN, or list of the detected TeV sources!)

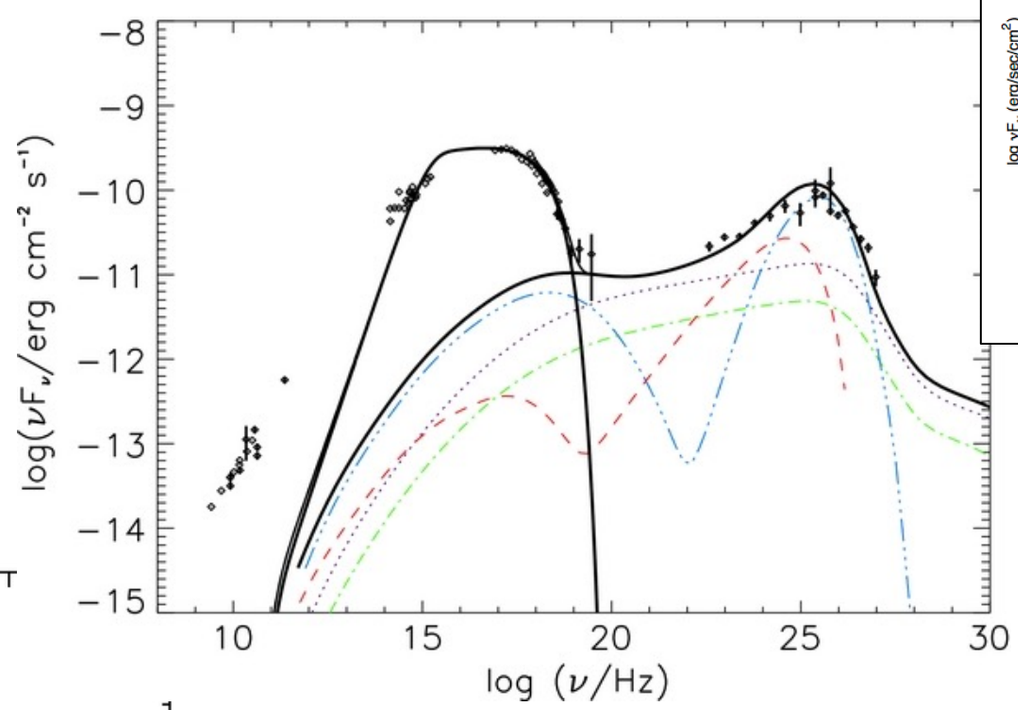


Hadronic or leptonic?

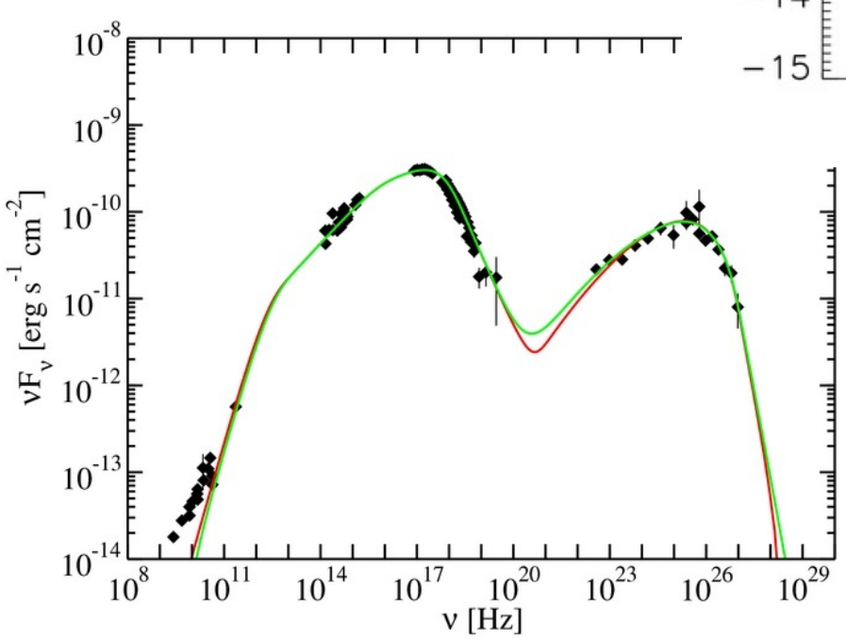
Leptons (very efficient emitters):
non-thermal bremsstrahlung, **synchrotron**, curvature, **inverse-Compton**

Hadrons (rather inefficient emitters):
synchrotron, inelastic proton-proton interactions, **photo-meson production**





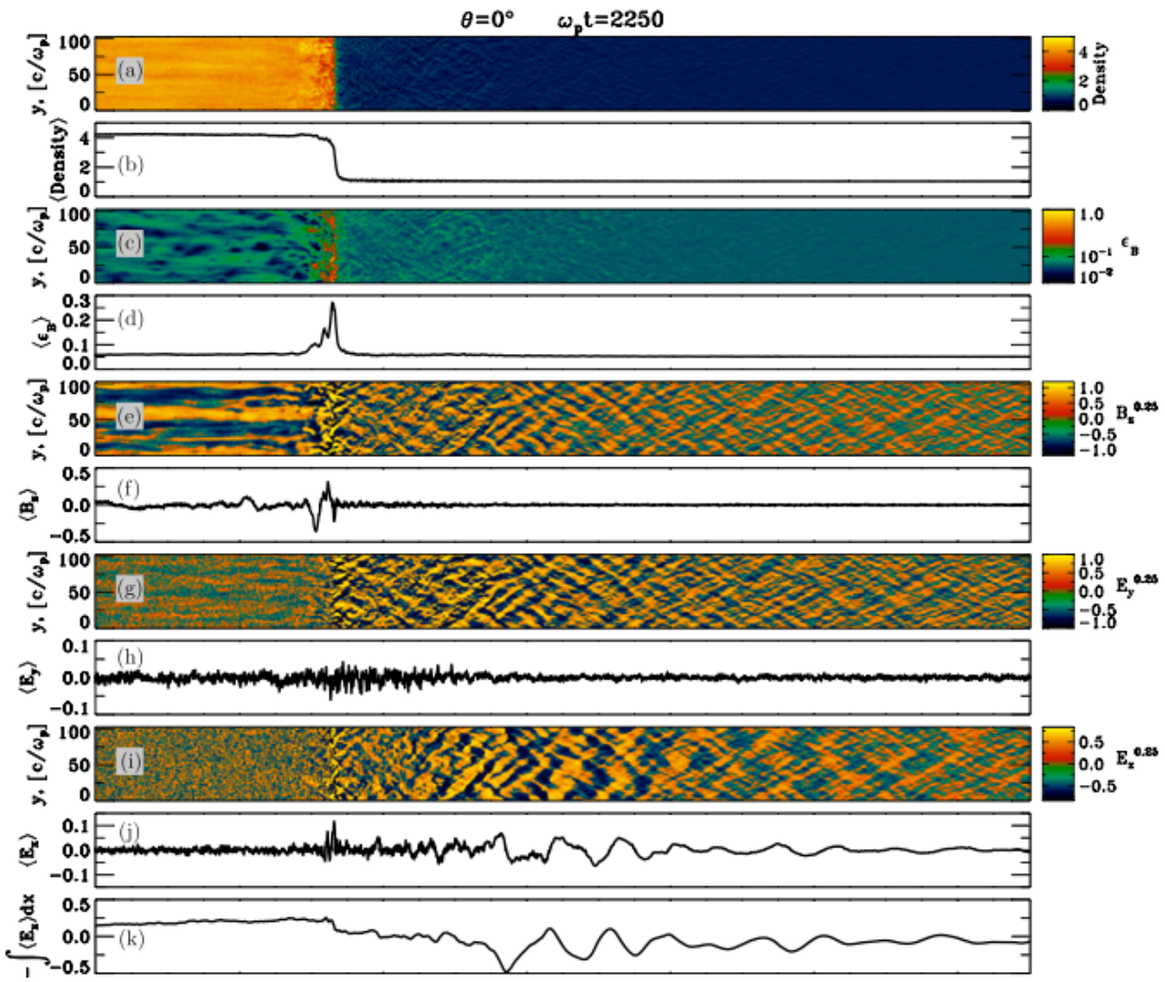
blazar Mrk 421
(Abdo et al. 2011, Petropolou et al. 2015)

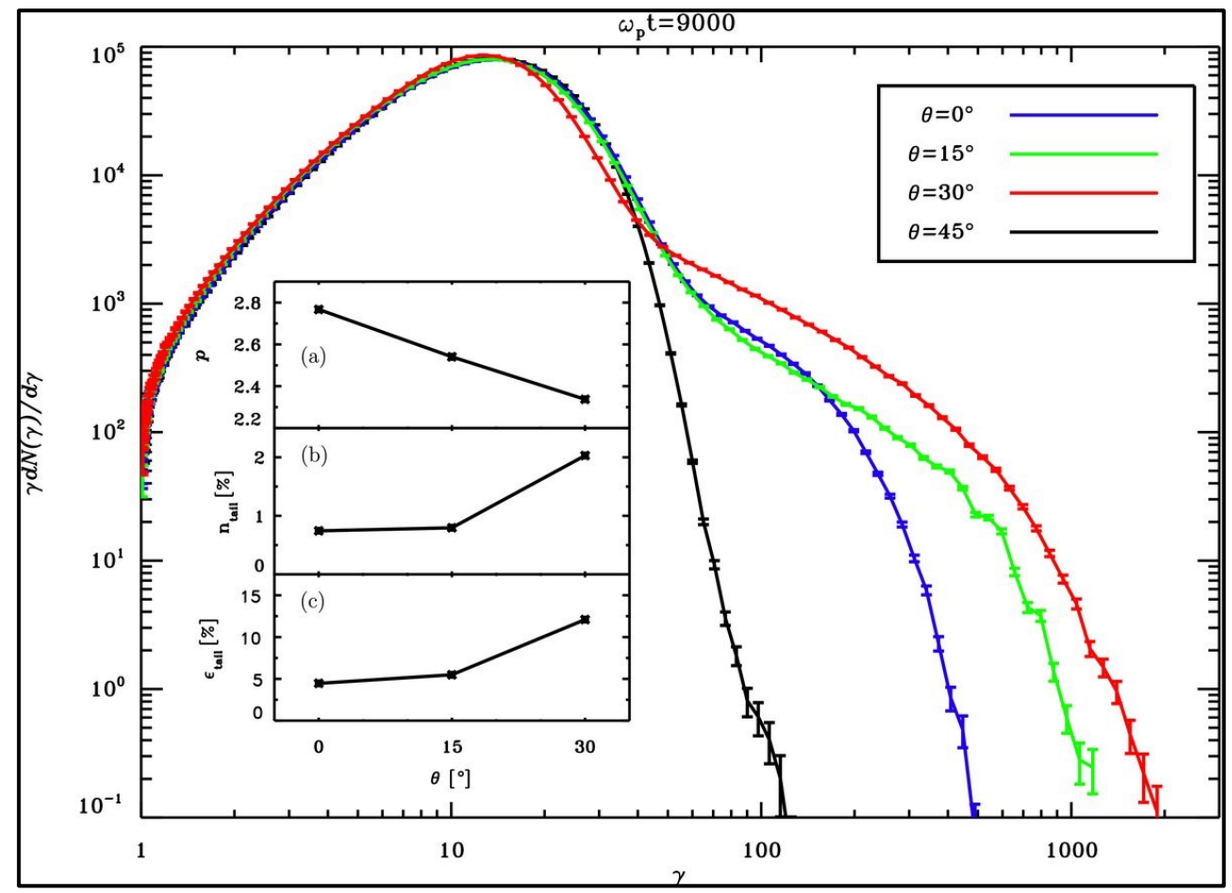


Modelling non-simultanoueus SEDs of blazar sources:
this is not the whole story… (e.g., extremely short gamma-ray variability observed seems to exclude hadronic emission models)

Should we really expect blazars to be UHECR or high-energy neutrino sources?

Relativistic shocks

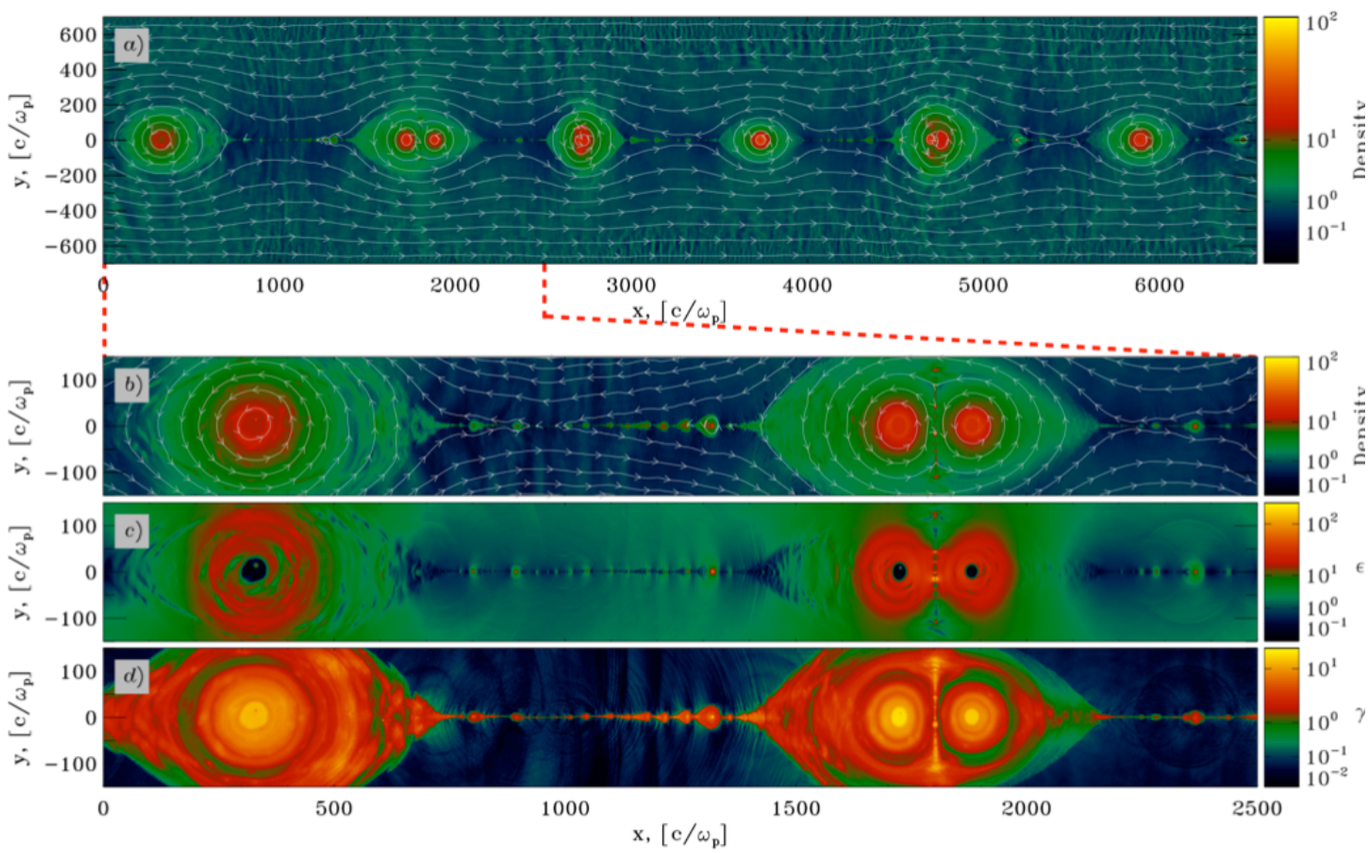


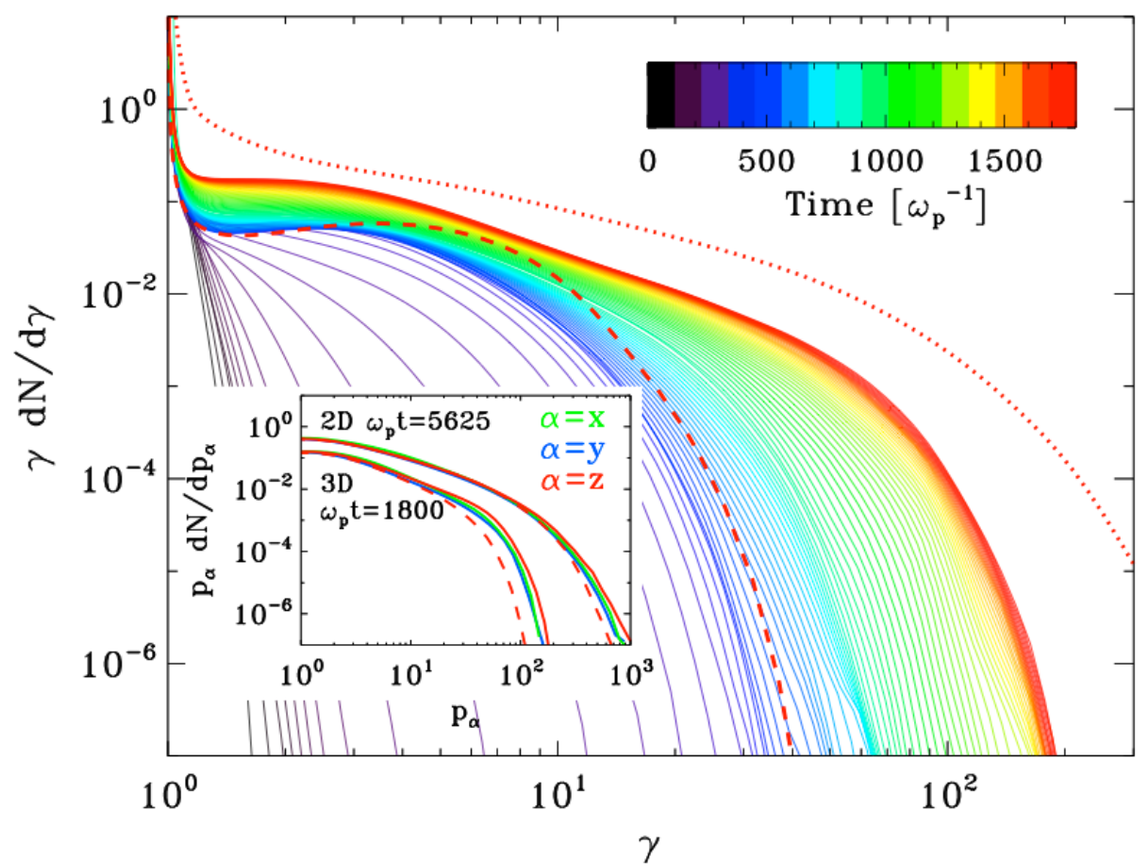


Steep particle spectra with very limited maximum energies and spectral indices depending on the magnetic field configuration and turbulence spectrum (Niemiec & Ostrowski, Spitkovsky et al.).

Not good news for hadronic emission models and the UHECR/neutrino production…

Relativistic reconnection





Efficient leptonic acceleration up to very high energies; power-law spectra with spectral indices depending on the plasma magnetisation — flat spectra for highly magnetised plasma, steep spectra for low magnetisation (Guo et al., Sironi & Spitkovsky).

Other types of AGN

1) Radio galaxies of various types

i) may dominate the extragalactic gamma-ray background

ii) “misaligned blazars" (parent population of blazar sources)

-> AGN unification scheme

iii) not only relativistic jets! also the diffuse lobes where the jets terminate (either compact lobes in young radio galaxies, or extended lobes in evolved radio galaxies)

-> the only gamma-ray images of extragalactic objects!

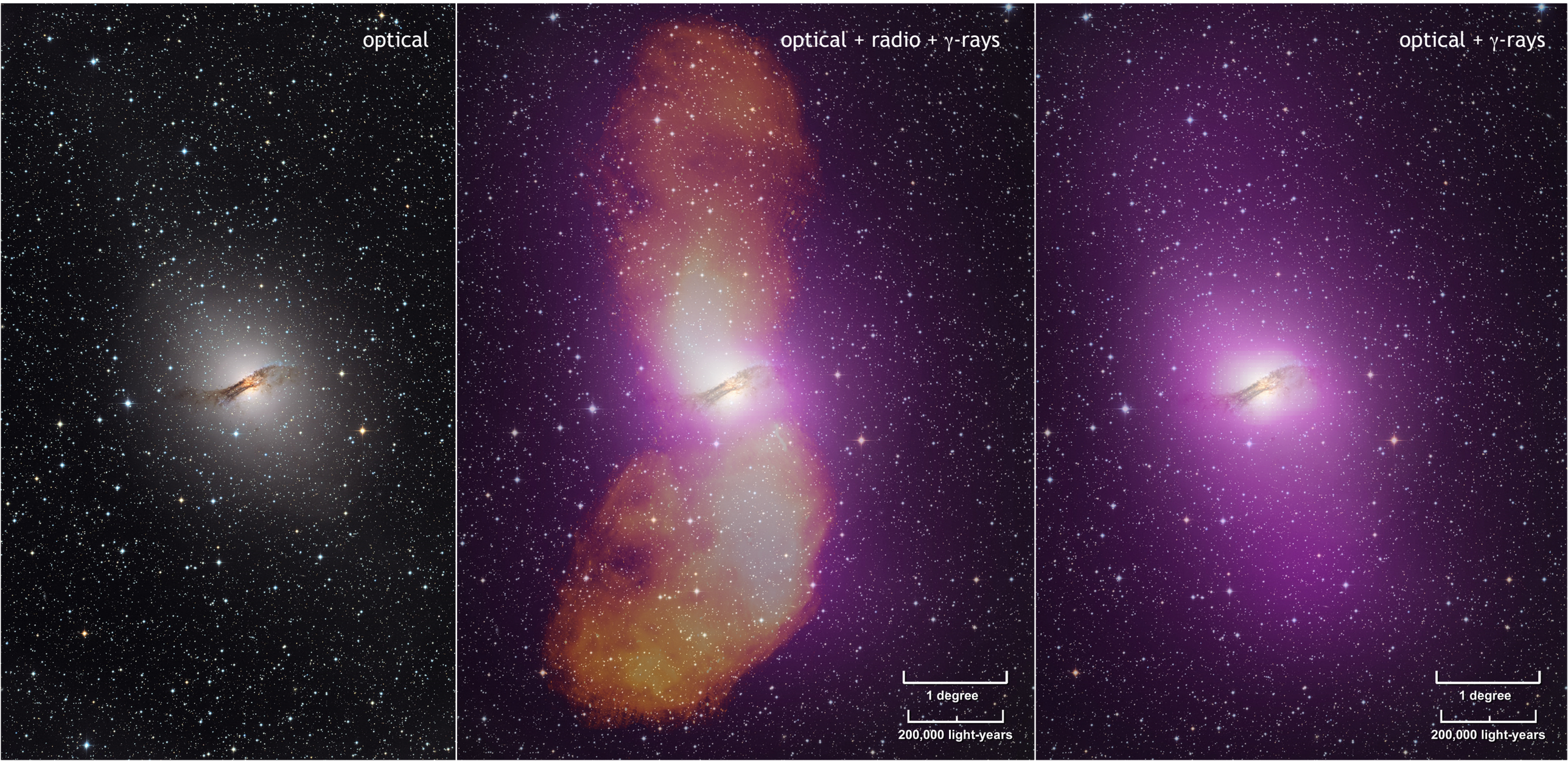
2) “Radio-quiet” AGN

i) a couple of nearby Seyferts, in which case the observed gamma-ray emission seems dominated by the starforming activity of host galaxies (rather than by the active nucleus; e.g., NGC1068)

ii) Circinus galaxy, in which case we may see some other emission component (disk outflow?)

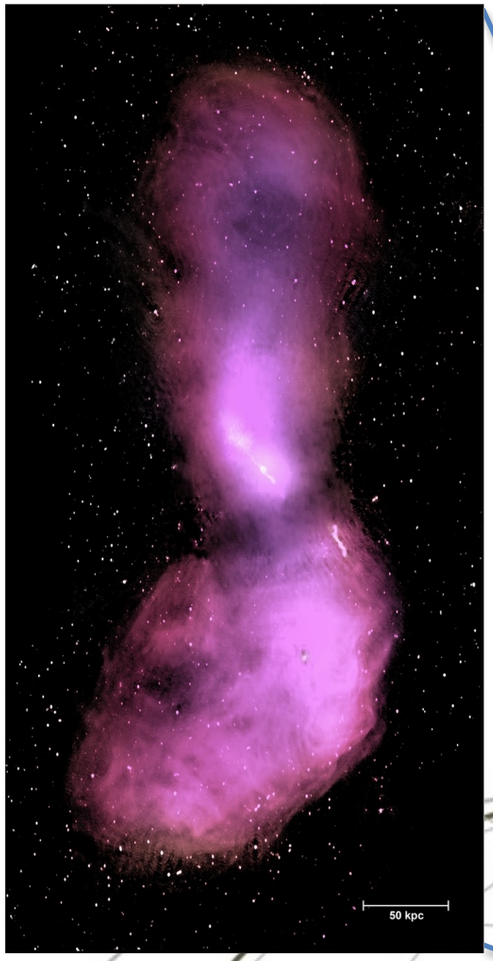
iii) a couple of tentative, potentially interesting identifications

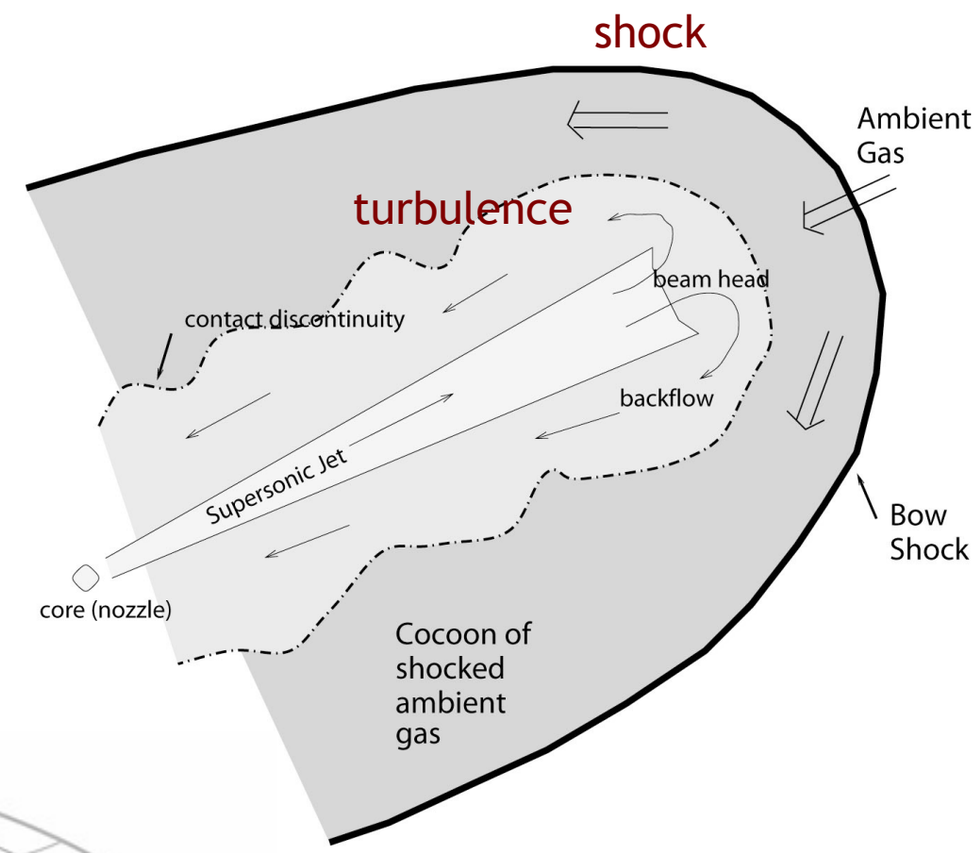
Giant lobes in Centaurus A

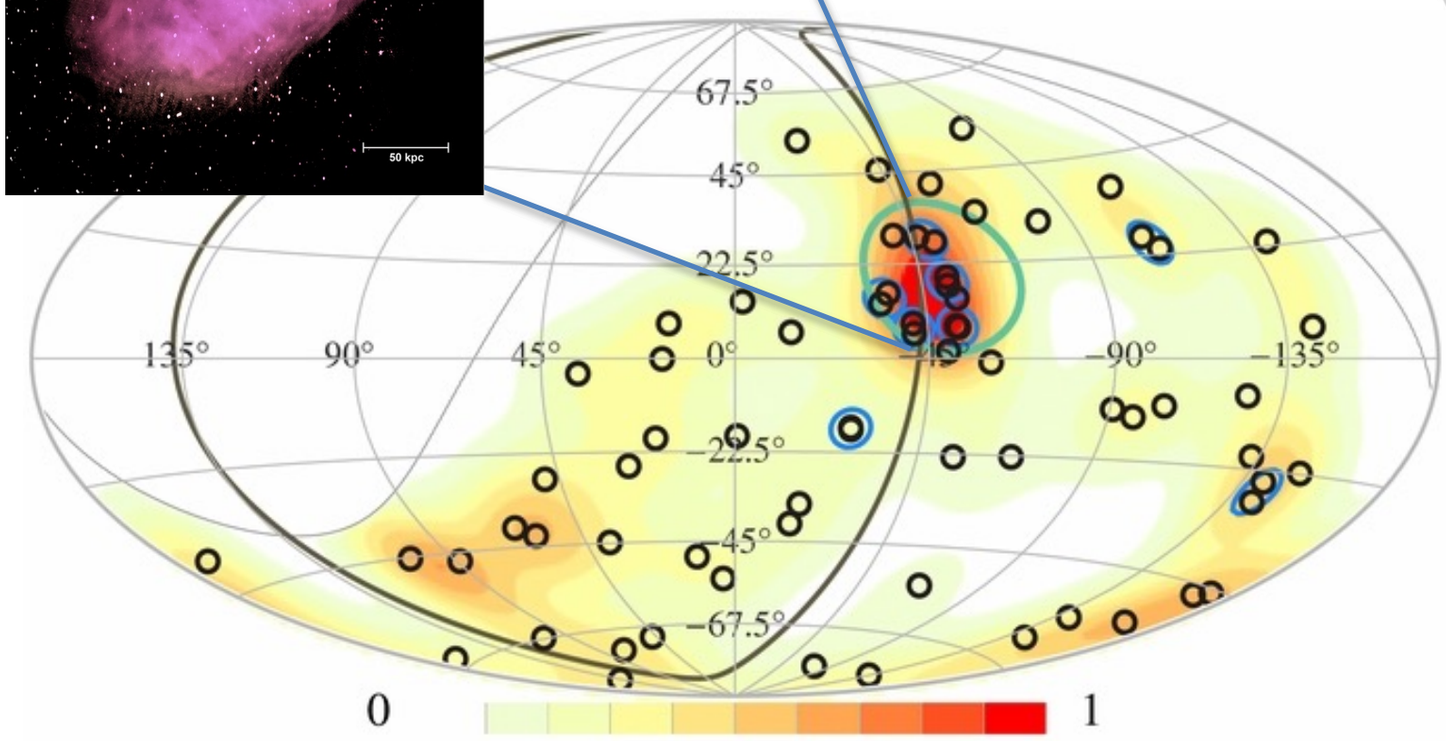


Abdo et al. 2010

UHECRs from giant lobes?





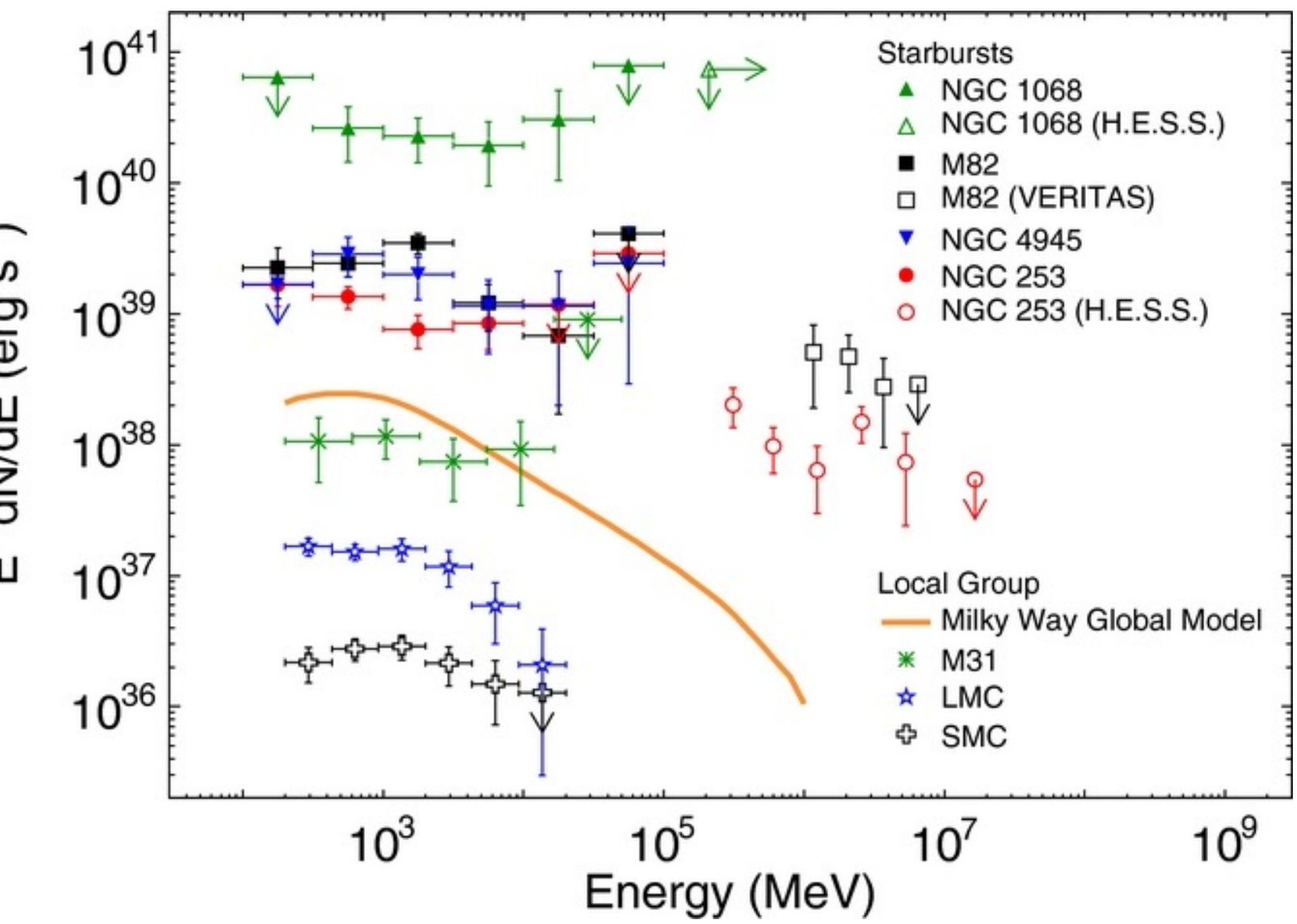


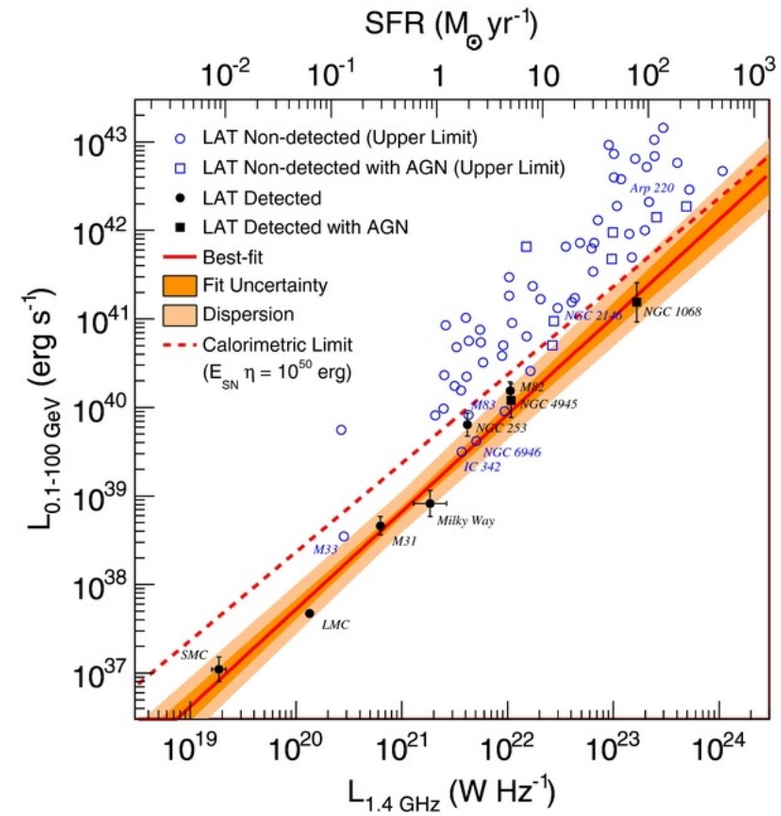
Fraschetti & Melia 2008
Hardcastle et al. 2009
Moskalenko et al. 2009

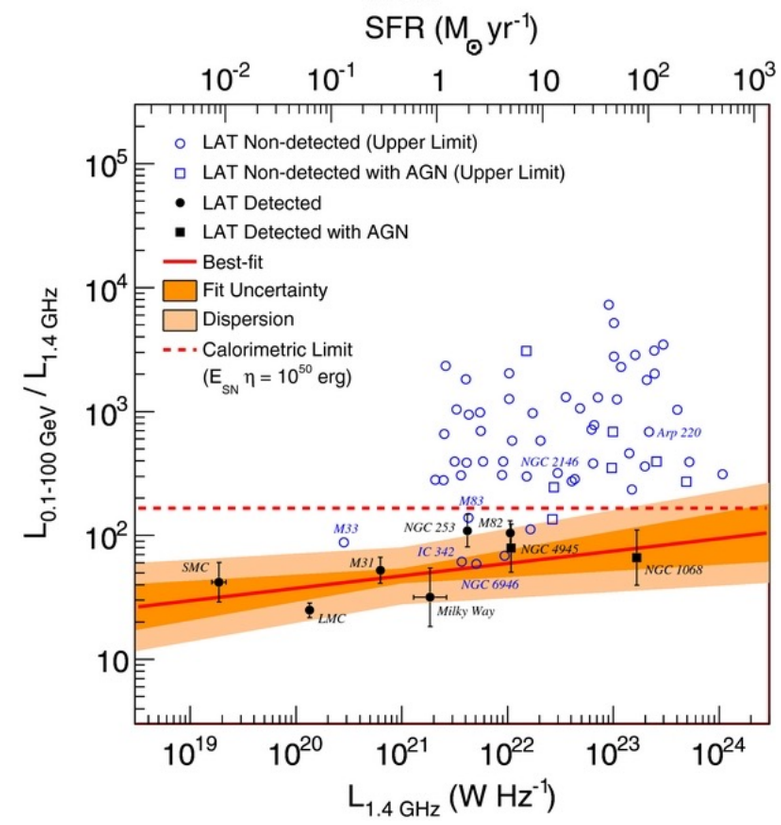
but see also
O'Sullivan et al. 2009
Stawarz et al. 2013

Starforming galaxies

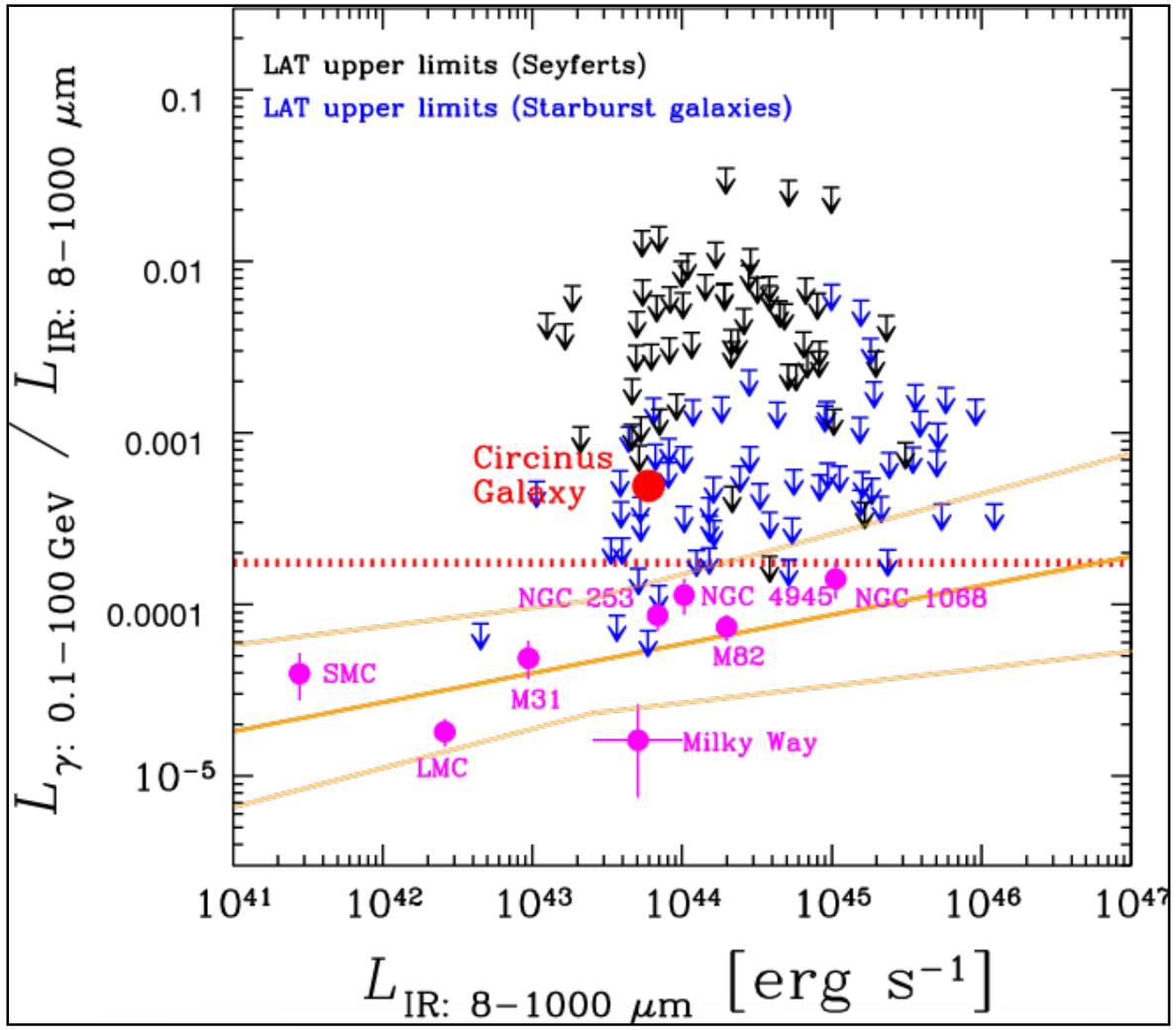
Ackermann et al. 2012





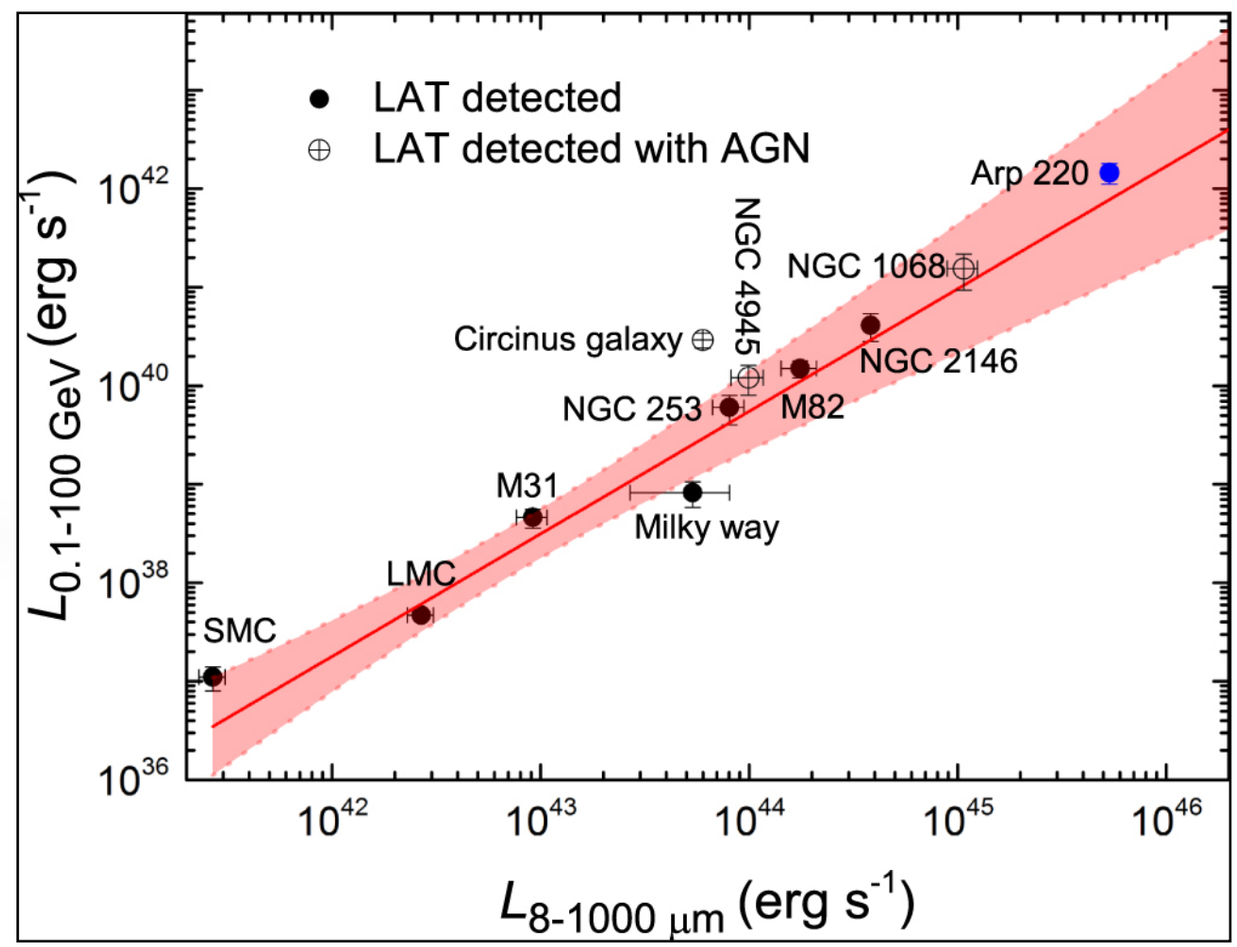


An update



Hayashida et al. 2013

Broadly consistent with the ISM dominating the observed gamma-ray emission (although what about flat TeV spectra of NGC253 and M82; also, what about Circinus galaxy?)

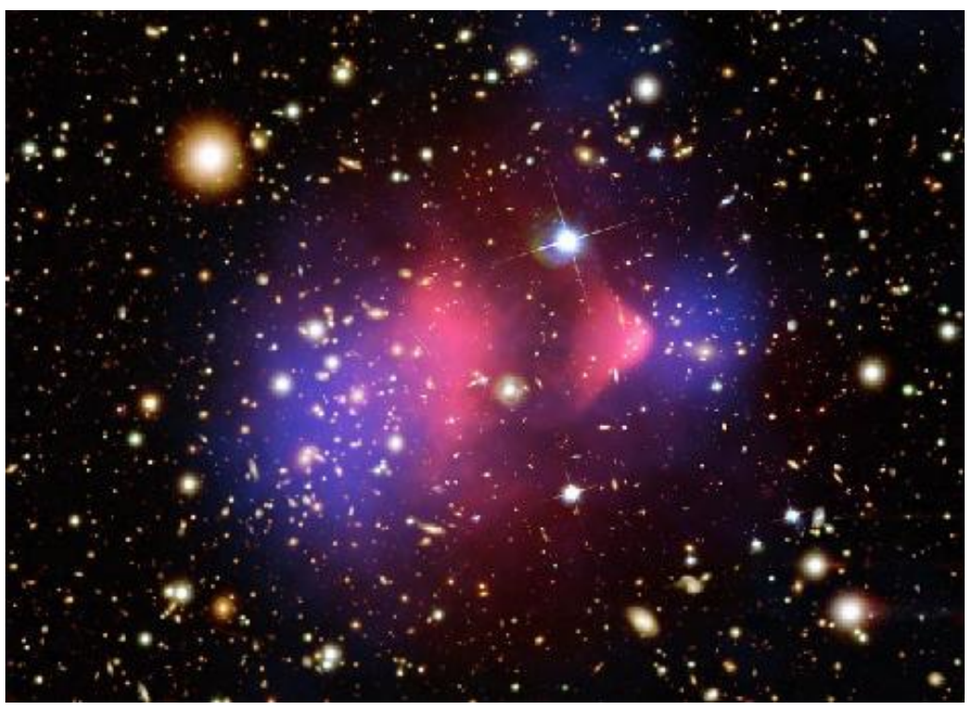


Peng et al. 2016

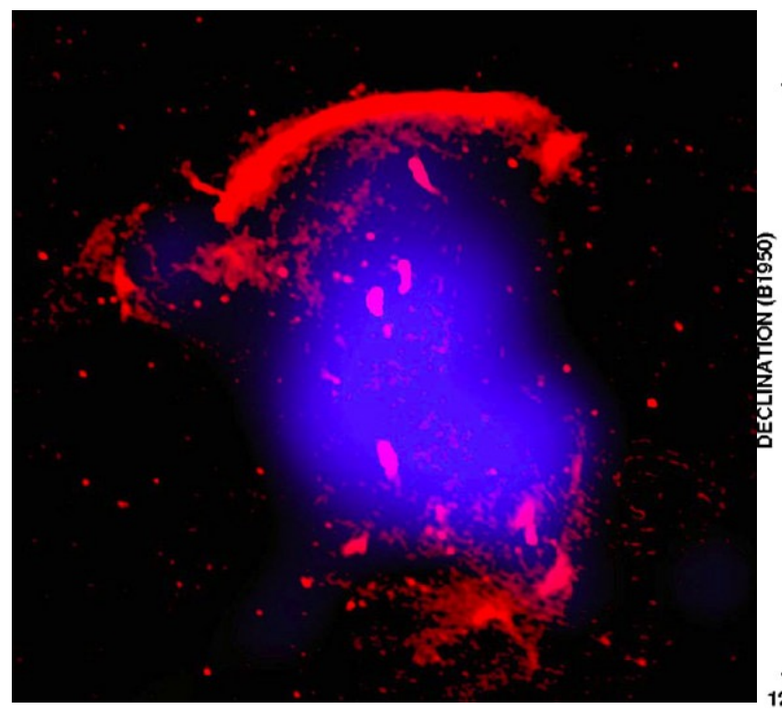
Clusters of galaxies

Merging processes leading to the formation of clusters of galaxies release huge amounts of gravitational energy ($\geq 10^{64}$ erg) on timescales of the order of ~Gyr.

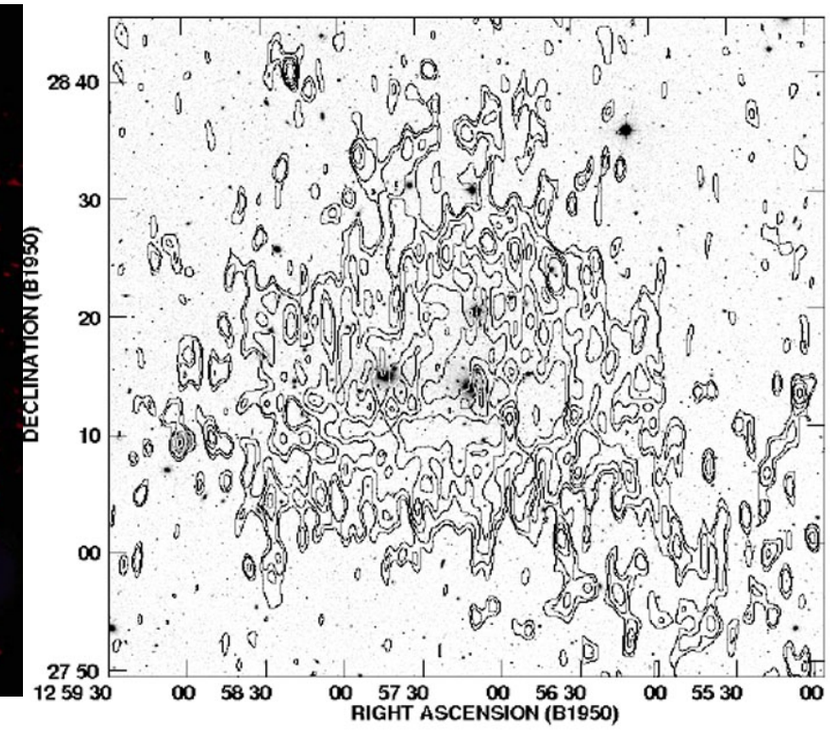
While much of this energy is contained in thermal plasma with temperatures 10 keV emitting X-ray photons via the bremsstrahlung process, part of it may be channeled to accelerate a small fraction of particles from the thermal pool to ultrarelativistic energies at large-scale merger shocks, and/or by turbulence in cluster radio halos.



Bullet cluster (Markevitch et al.)

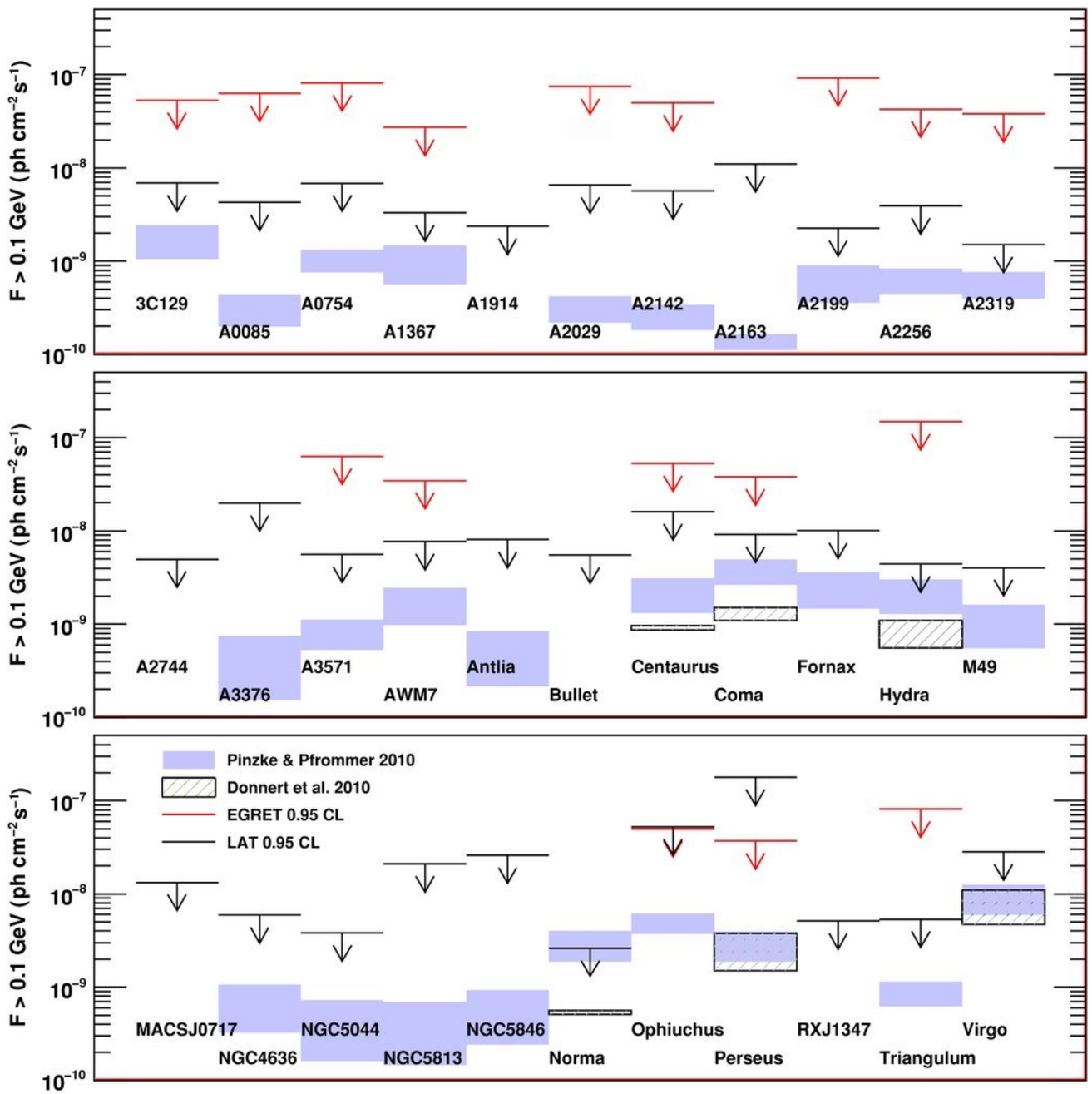


CIZAJ2242.8+5301 (van Weeren et al.)



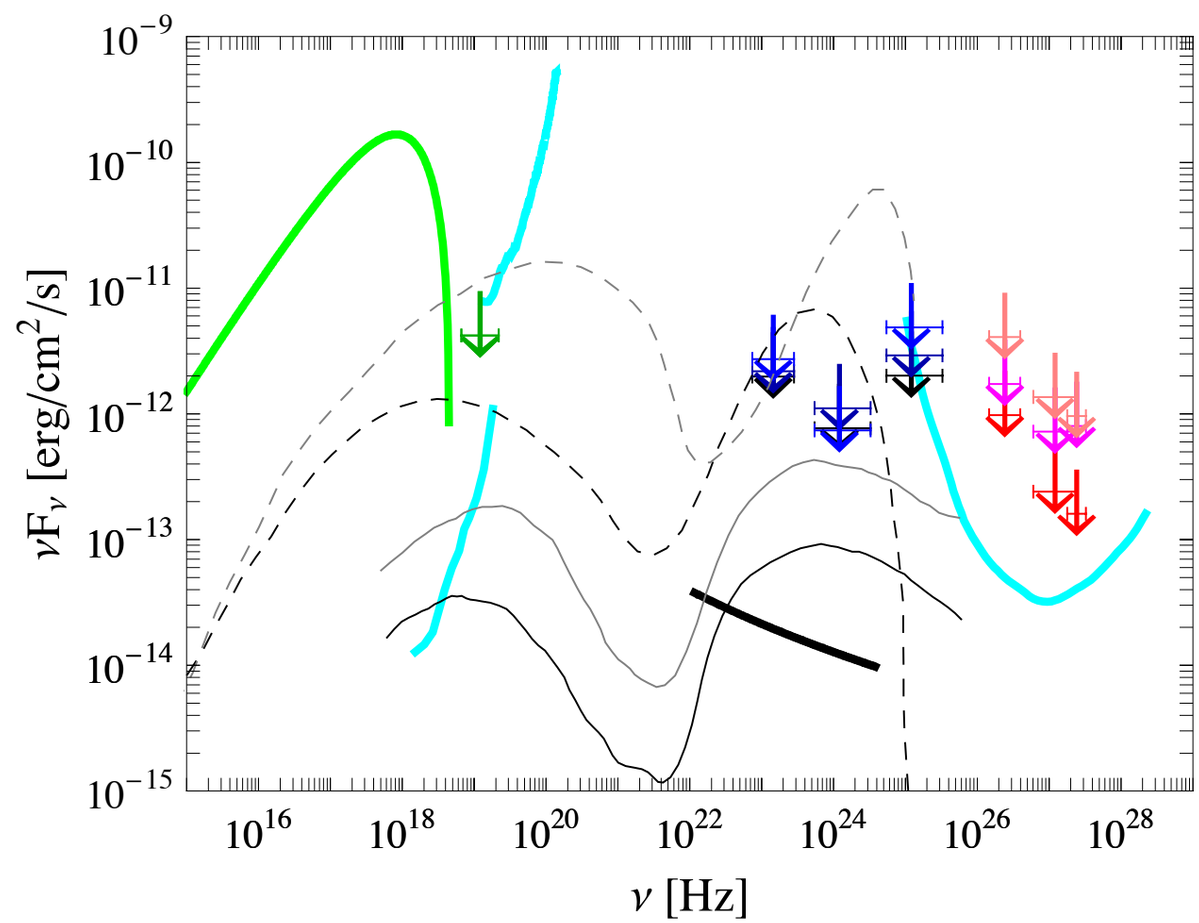
Coma cluster (Feretti et al.)

Gamma-ray quiet…

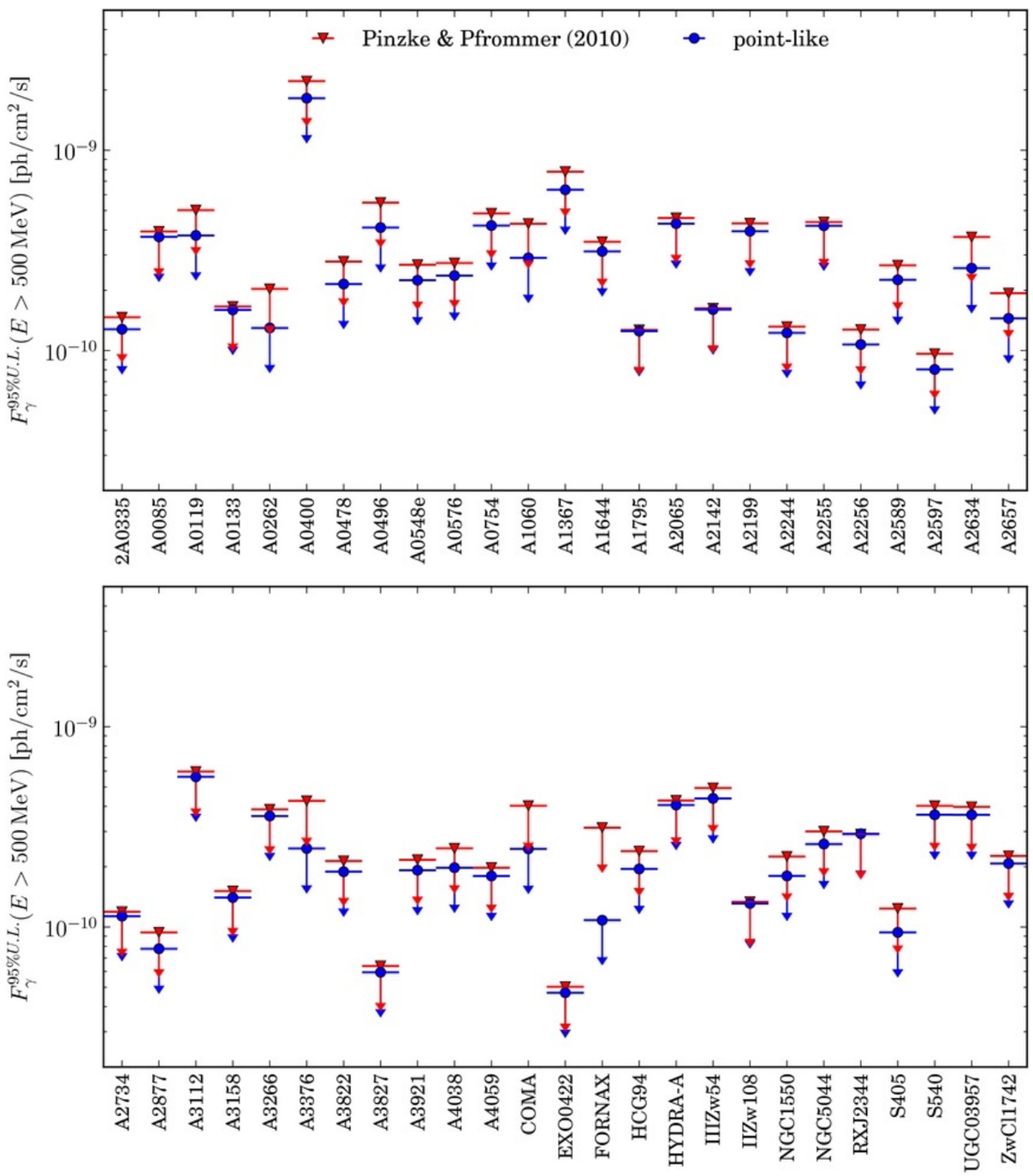


Ackermann et al. 2010

SED of the Coma clusters with various model predictions, and expected sensitivities of ASTRO-H (HXI and SGD) and CTA (Takahashi et al. 2013)



An update



Still upper limits, but already very constraining:

- the ICM magnetic field intensity > 1e-6 G
- the CR proton contribution to the ICM pressure <1%
- low efficiency of CR acceleration at low-M shocks
- hadronic origin of giant radio halos excluded

Ackerman et al. 2014: the 95% upper limits on hadronic CR-induced gamma-ray flux for each of our 50 galaxy clusters; the *individually* derived upper limits for both the extended emission (red downward triangle) and assuming the cluster emission to be point-like (blue circle); see also Ackermann et al. 2015, 2016.

The Future

1) Fermi-LAT

uninterrupted, long-term all-sky survey **IS** the legacy of the instrument; source identification: about one-third of the 3FGL sources is still unidentified!

2) CTA

extragalactic TeV survey may reveal very new classes of gamma-ray emitters

3) MeV satellites (e-ASTROGAM)

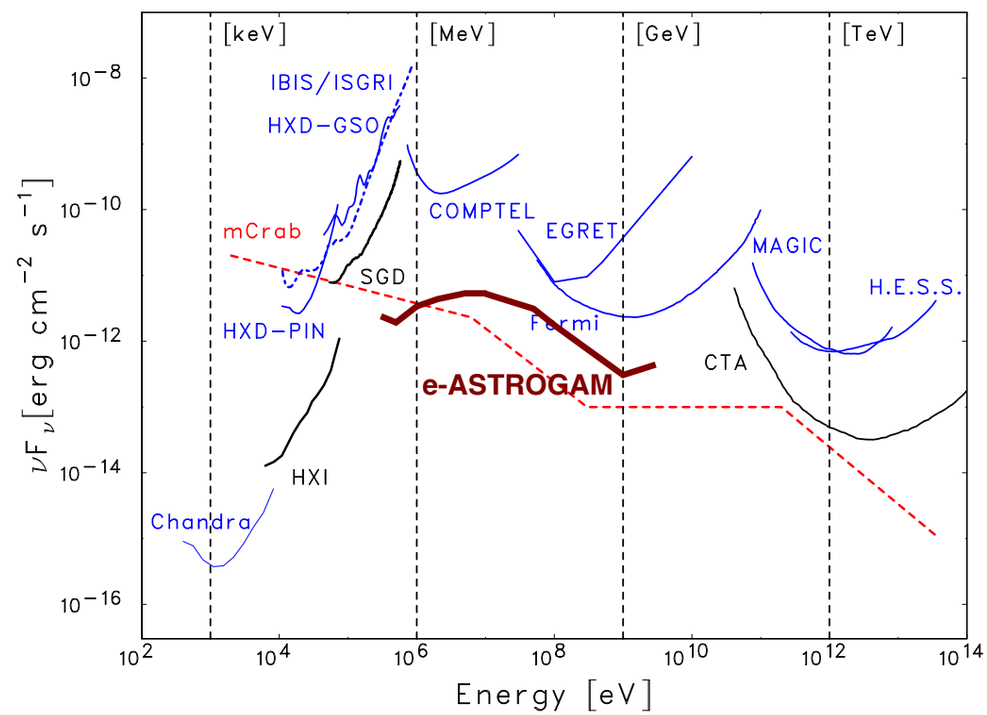
high-redshift blazars, tidal disruption events, etc….

4) Future X-ray polarimeters and spectrometers (XIPE, ATHENA)

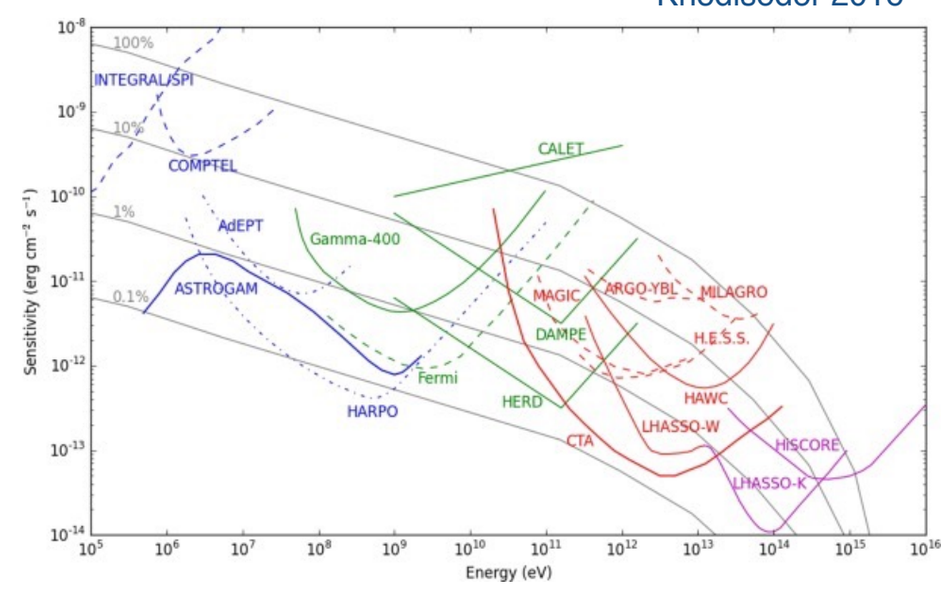
clusters of galaxies, AGN accretion disks/winds/ outflows, X-ray jets in blazar sources

5) Further synergy with neutrino and cosmic-ray experiments, as well as gravitational wave detectors

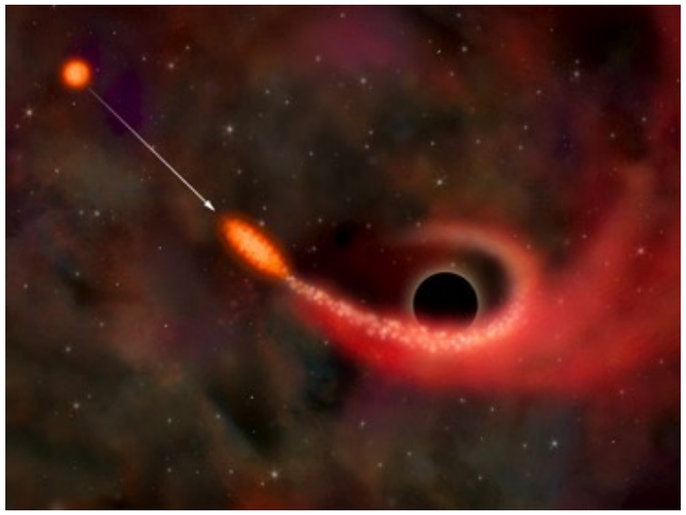
Takahashi et al. 2013
Tatischeff et al. 2016



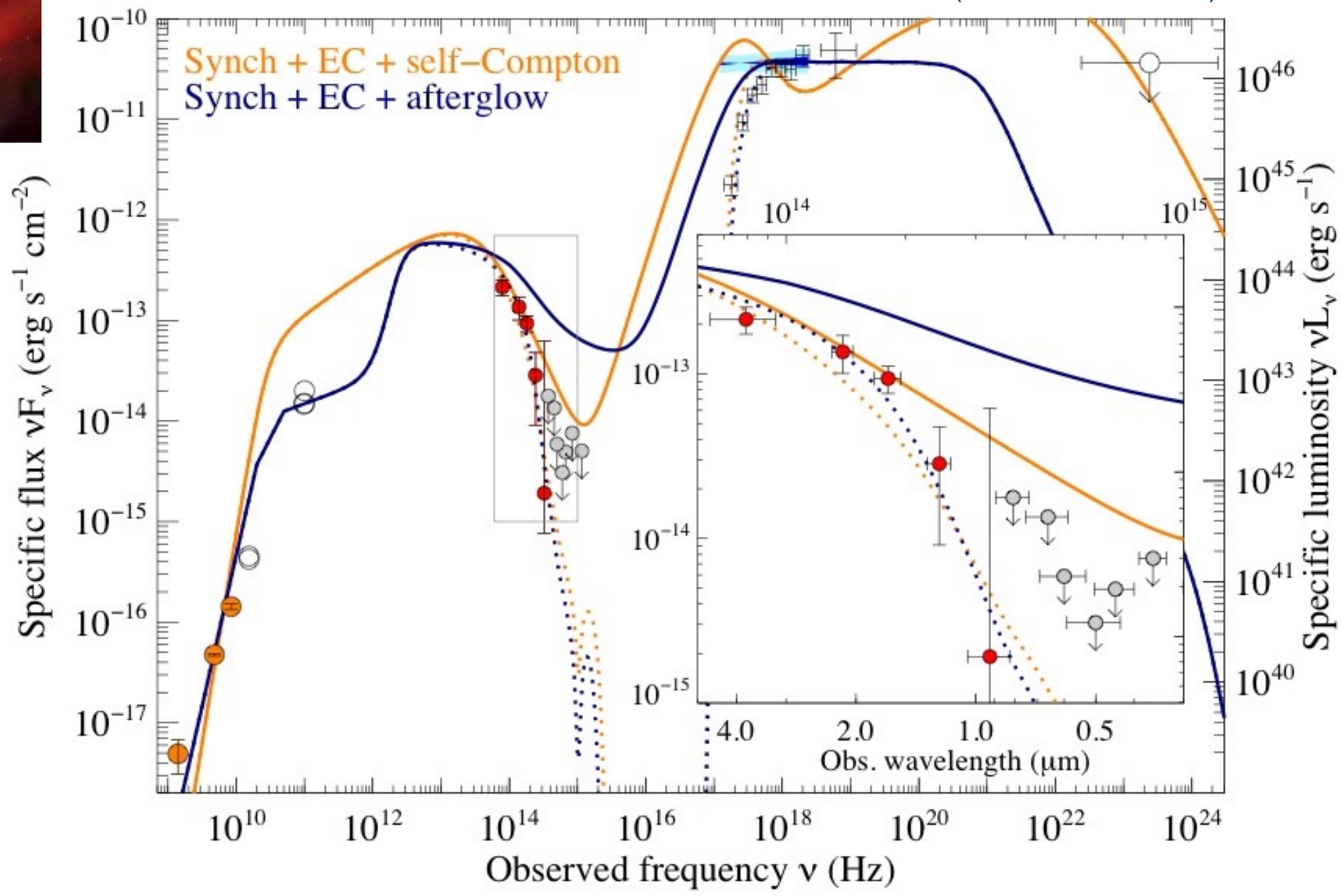
Knödlseder 2016



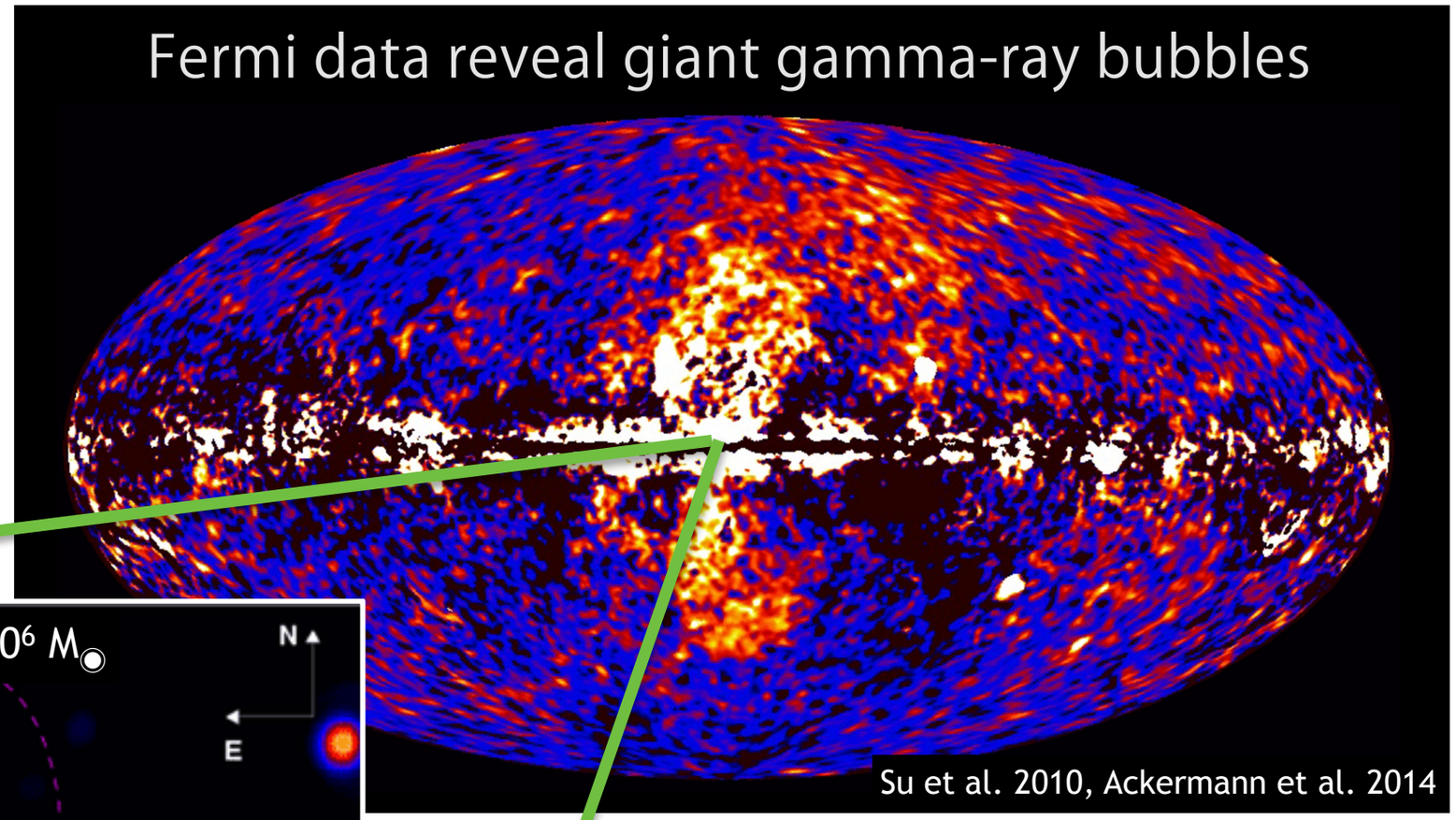
Tidal Disruption Events

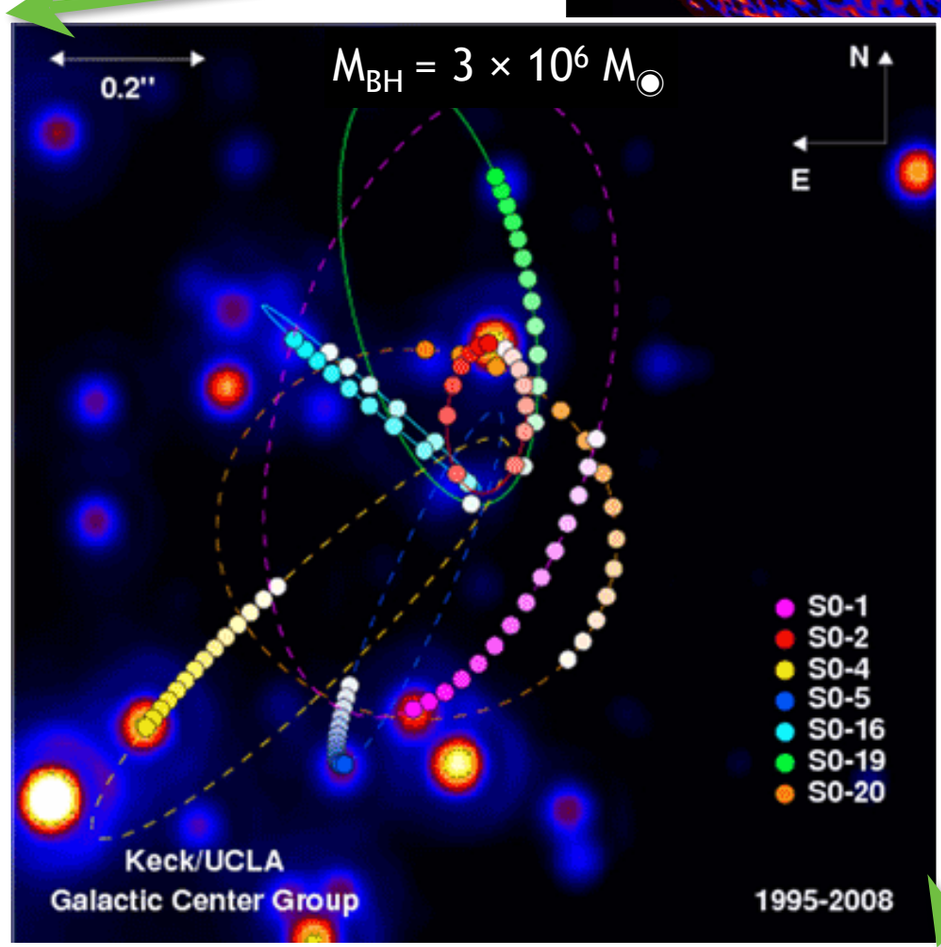


SWIFT 1644+57
(Bloom et al. 2011)

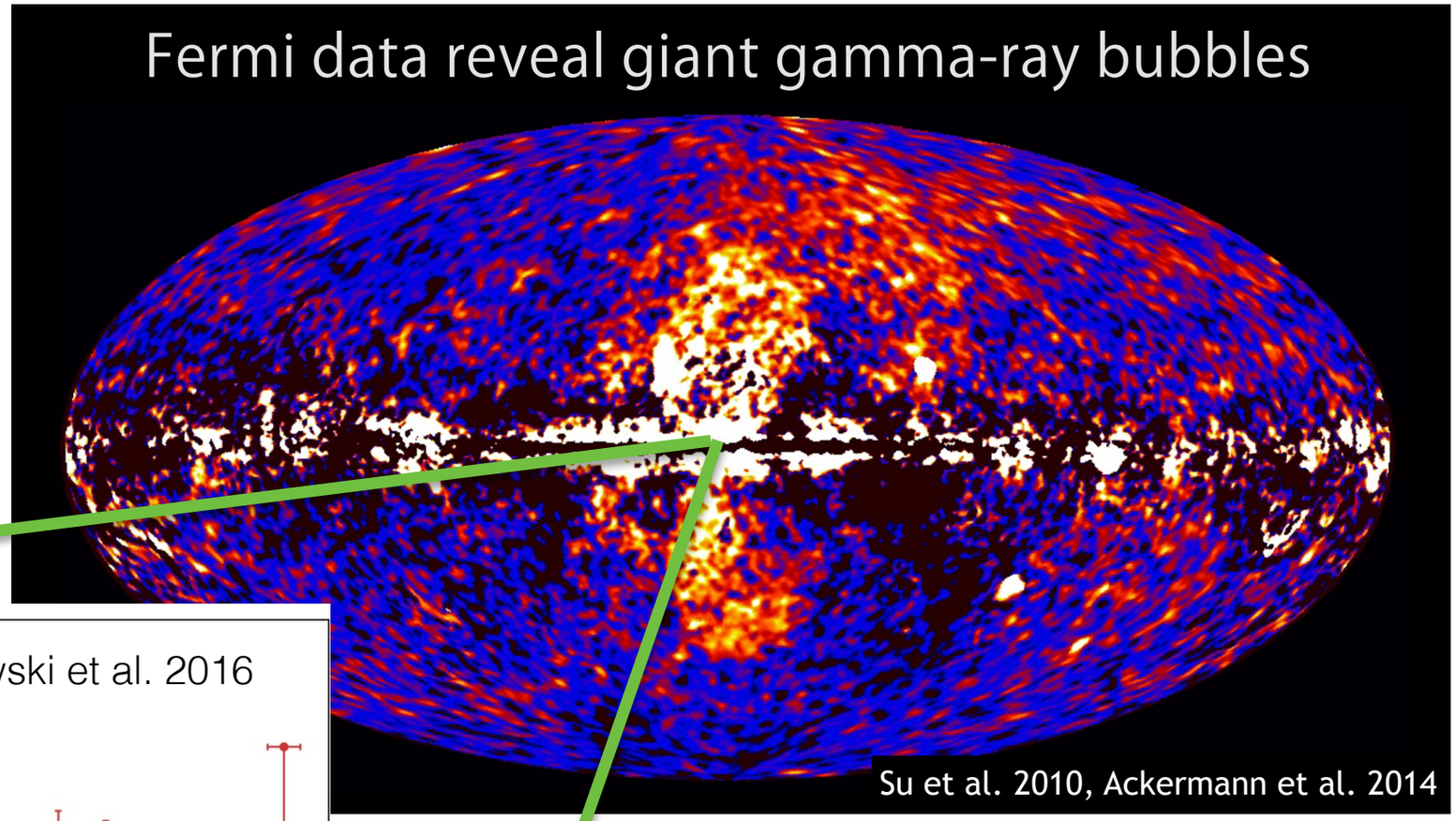


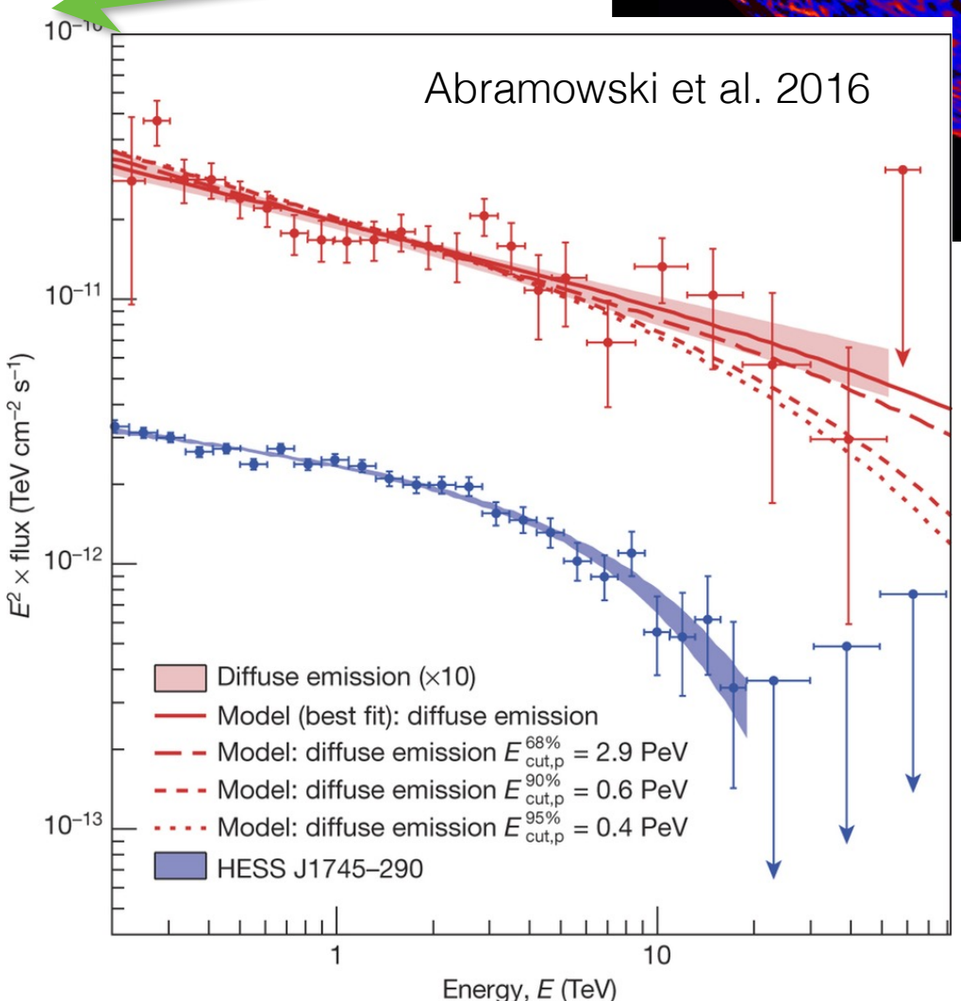
The nearest AGN



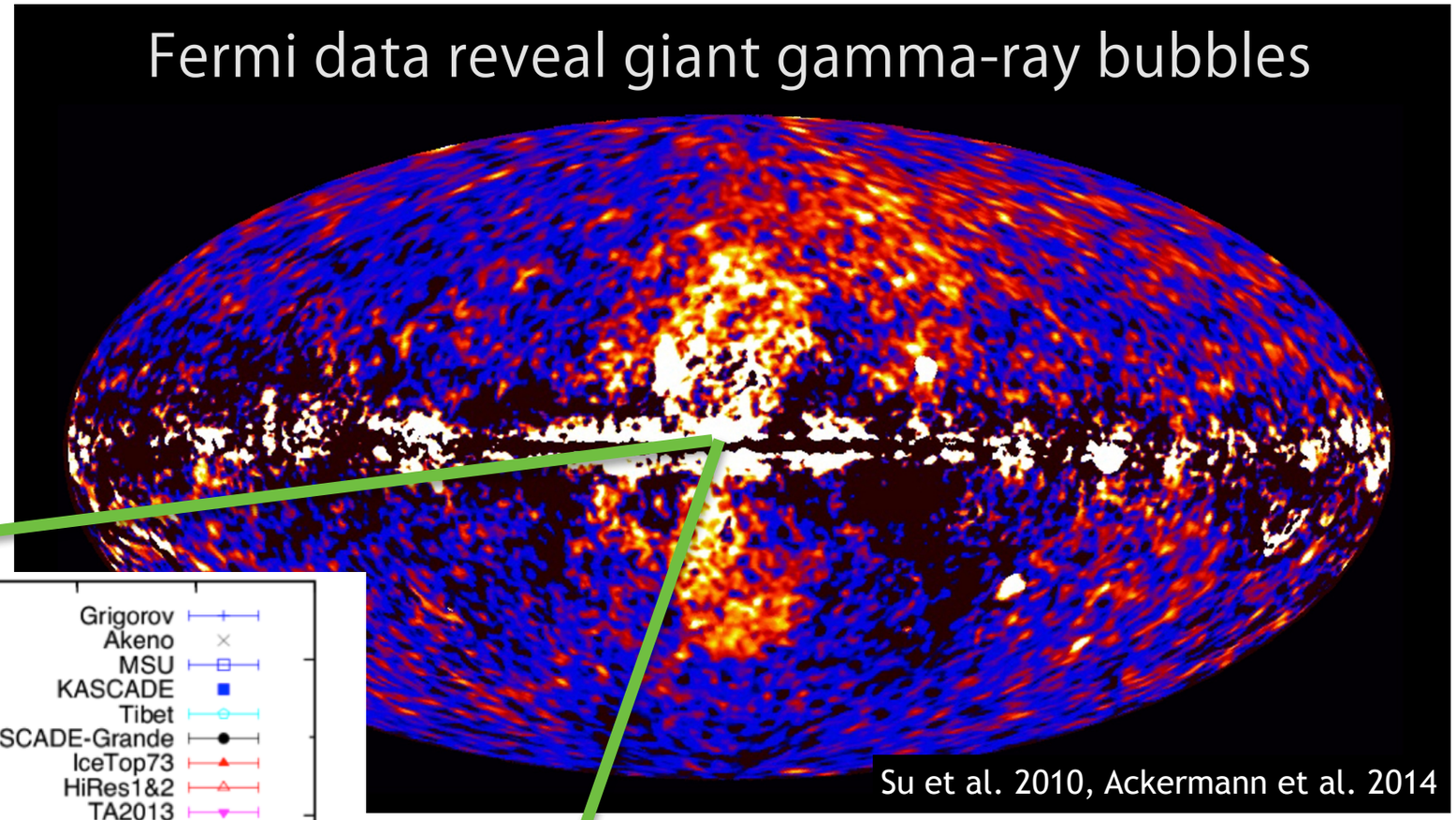


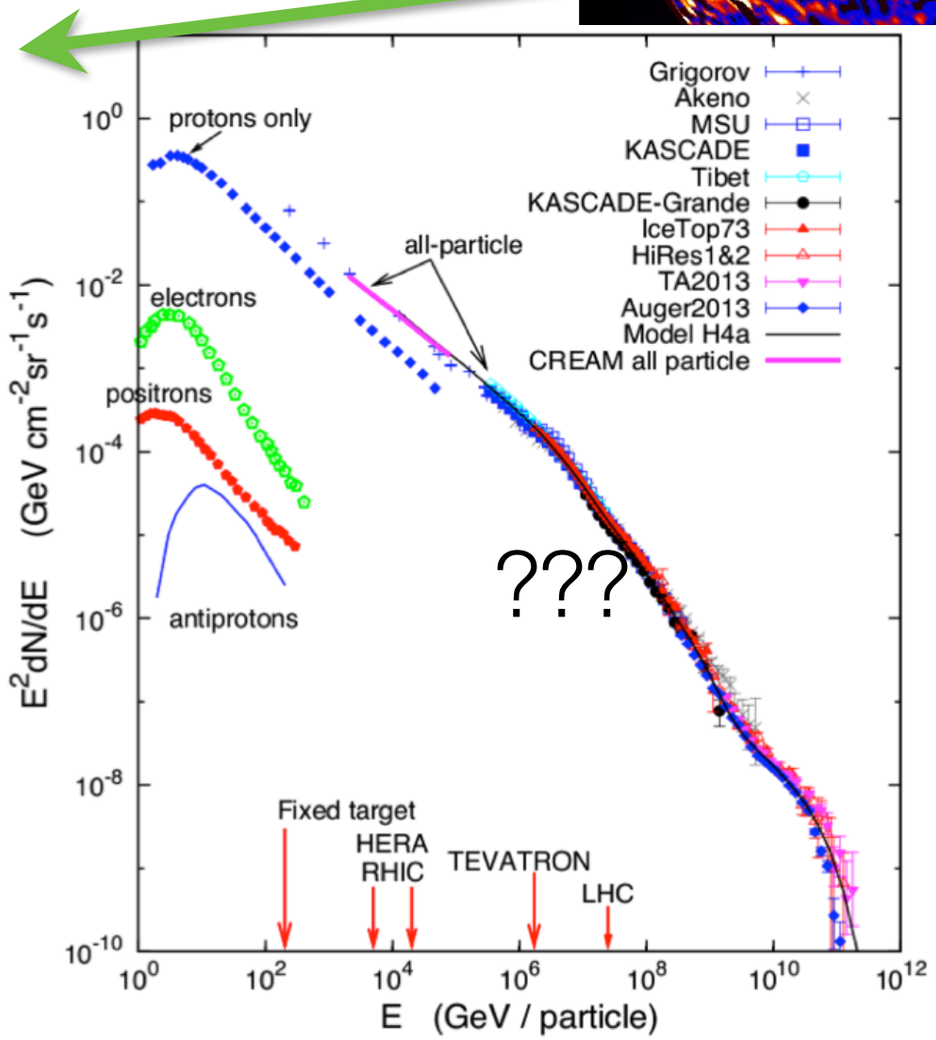
Sgr A* in gamma-rays





Source of >PeV cosmic rays?





Conclusions

1. **Blazars:** laboratories of relativity and plasma physics, probes of fundamental physics (LIV) and cosmology (EBL, IGMF)

2. **Other types of active galaxies:** a very diverse population (every galaxy is active at some level: SgrA*!), growing in number and relevance
3. **Starforming/starbursts Galaxies:** not simply scaled versions of the Milky Way (?)
4. **Clusters of Galaxies:** still gamma-ray quiet…

5. **The Future:** CTA, planned MeV and X-ray missions