Physics of AGN jets in the Fermi era

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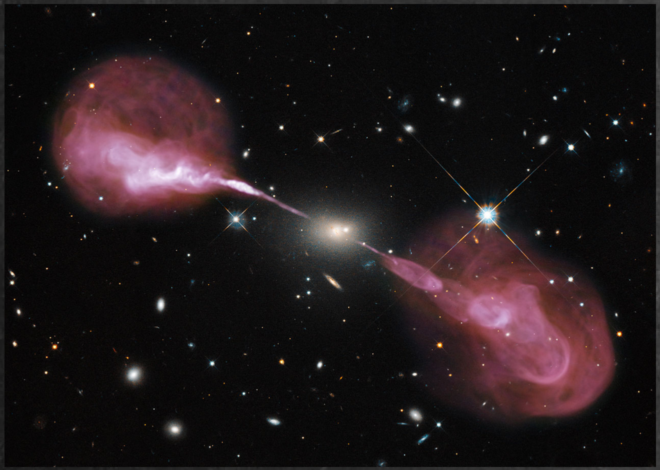
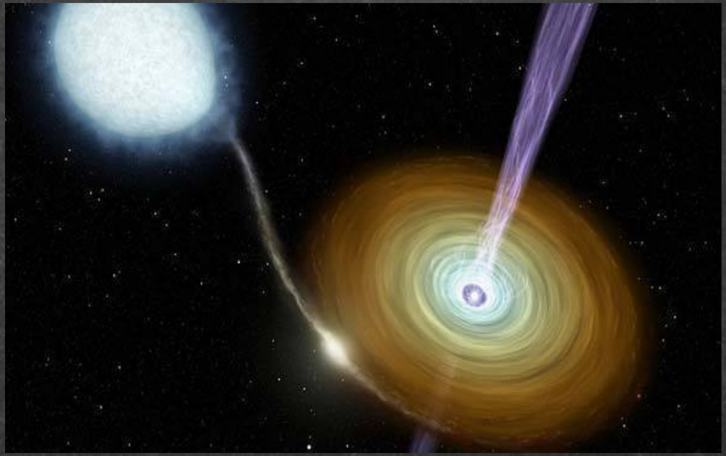
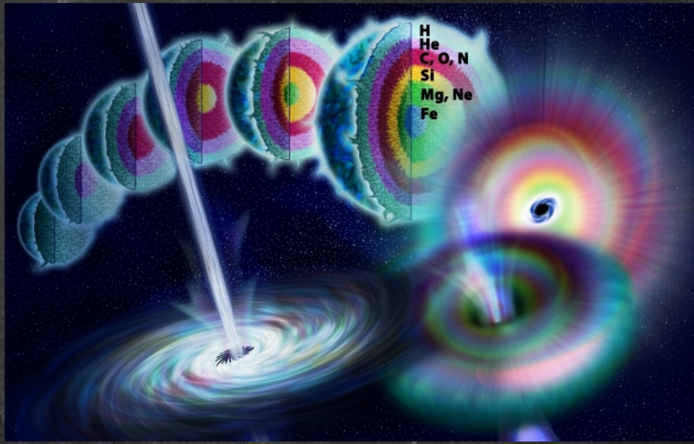
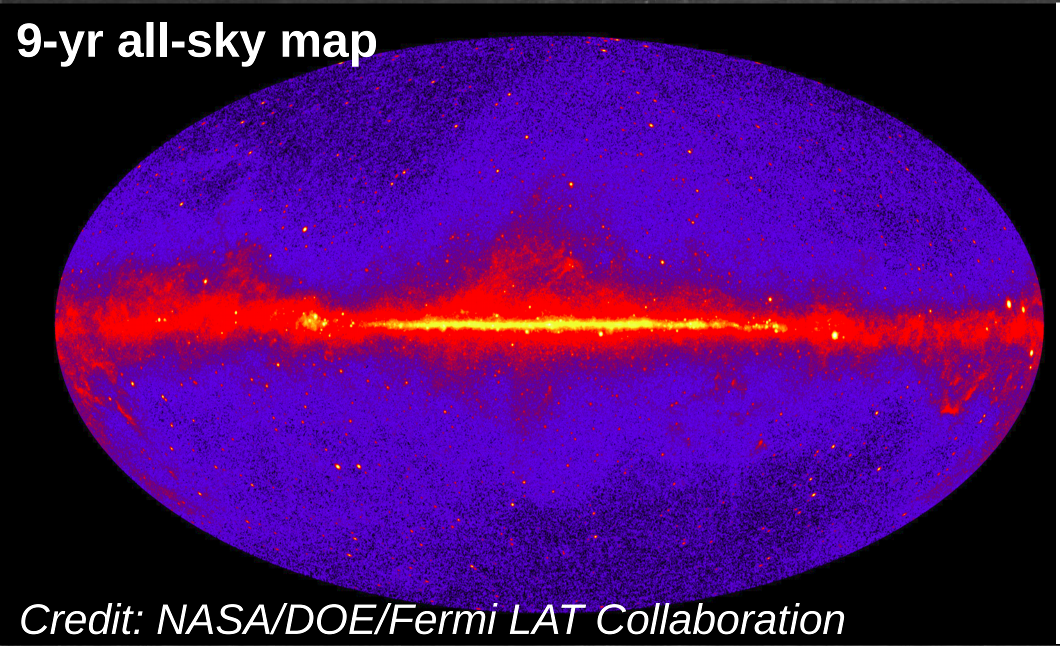
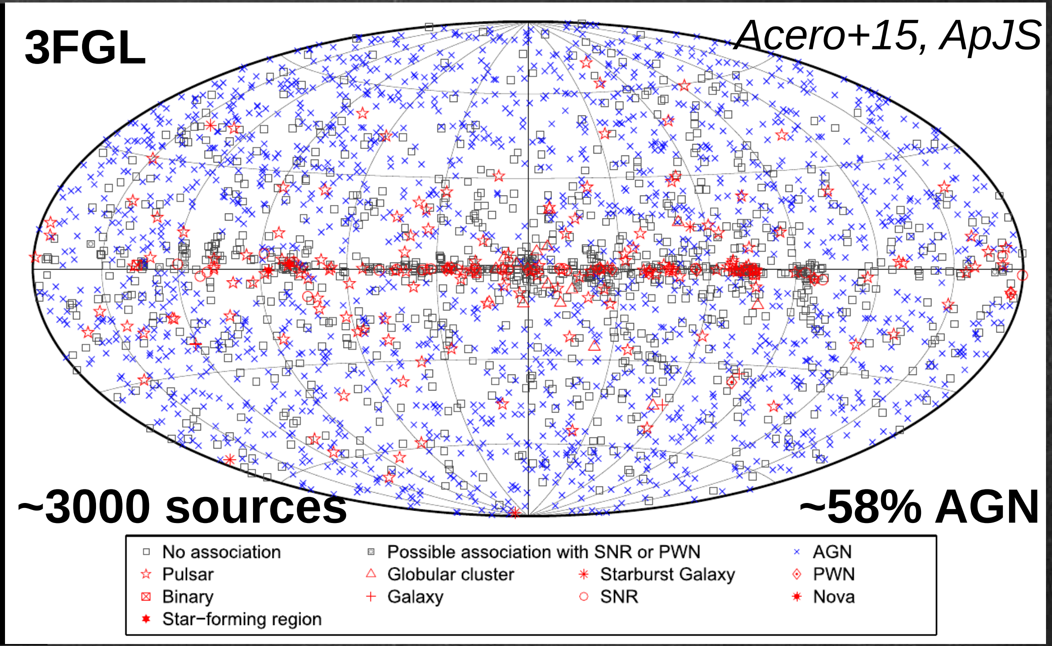
8th International Fermi Symposium, Baltimore, USA

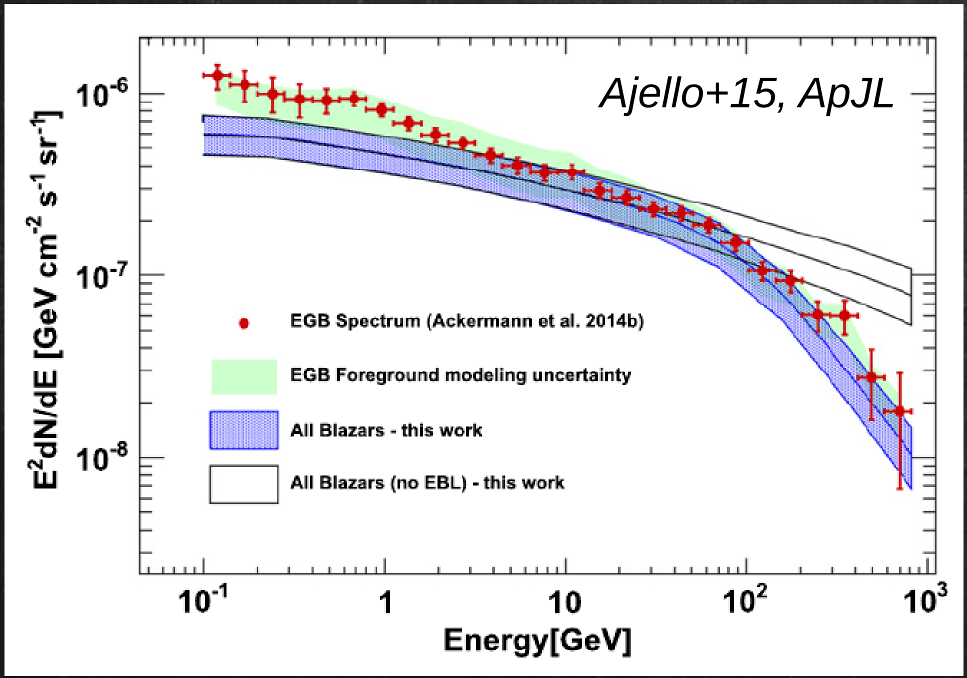
Relativistic jets are ubiquitous!

Active galactic nuclei (AGN)	X-ray binaries (XRBs)	Gamma ray bursts (GRBs)
		
This talk; see also talks by I. Christie, H. Zhang, E. Meyer & more in AGN sessions	See talks by Wilson-Hodge, H. Zhou & more in Galactic sessions	See talks by A. Beloborodov, B. Zhang, P. Beniamini & more in GRB sessions
Jet power ~ 10^{44} - 10^{48} erg s^{-1}	~ 10^{38} erg s^{-1}	~ 10^{52} erg s^{-1}
Lorentz factor ~ 3 - 30	~ 3	~ 300 - 1000

Extragalactic γ-ray sky dominated by AGN



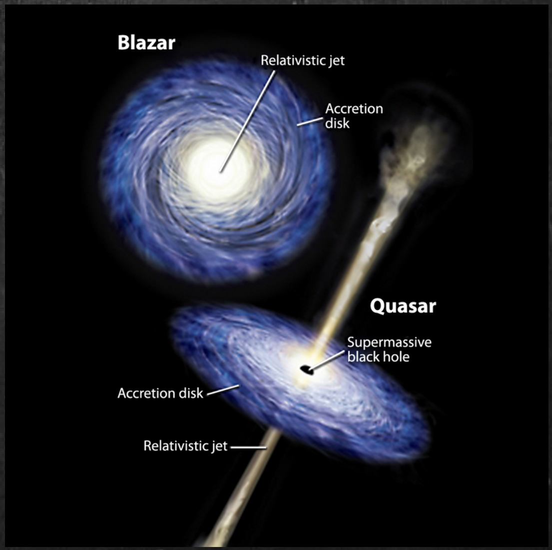




Blazar contribution to the extragalactic γ-ray background (EGB):

~ 100% at >100 GeV

~ 50 % at <100 GeV



Highlights from Fermi era

Large-scale jets

blazars

Inner jets

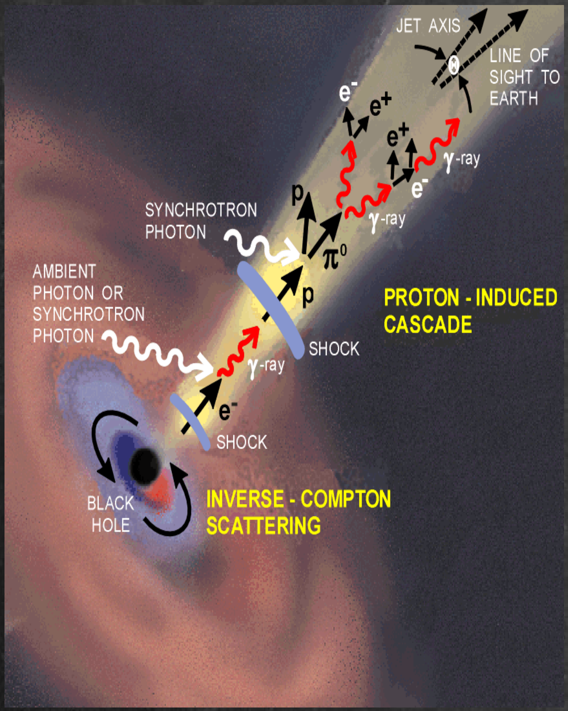
variability

Radio galaxies

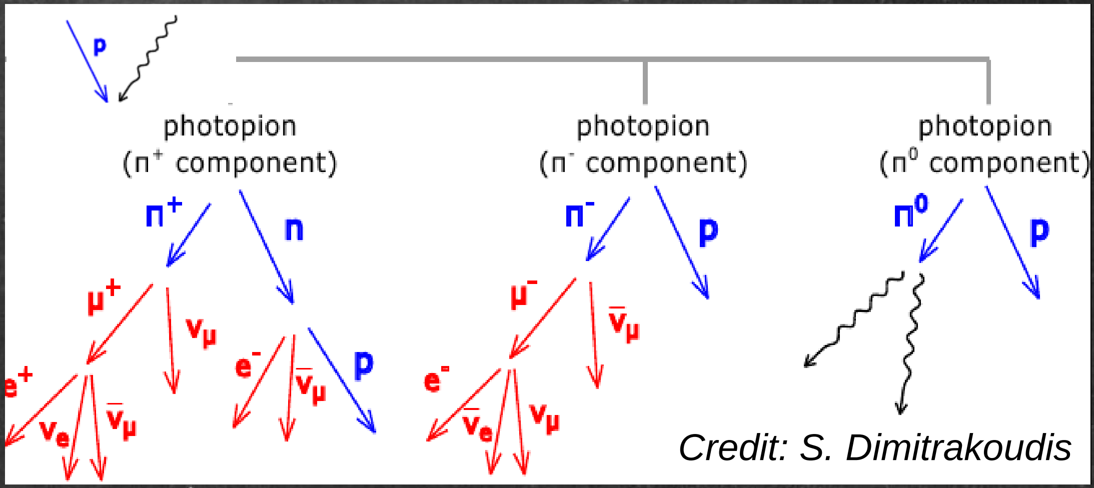
neutrinos

Neutrinos from blazar jets

(e.g. Mannheim '95, Halzen & Zas '97, Atoyan & Dermer '01, Murase+14, Petropoulou+15, Padovani, MP+15, Gao+15)



Production mechanism

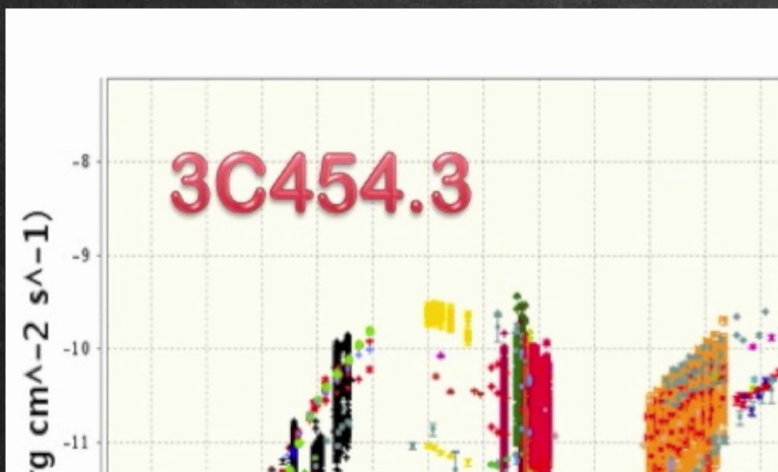


Ideal environment for ν production

- Powerful jets have the potential to accelerate and confine high-energy protons
- Many target photon fields are available (from e.g. jet , BLR, torus, disk)

The role of blazar flares

Blazars are variable sources across the electromagnetic spectrum!



Giommi ‘15, JHEA (https://tools.asdc.asi.it/SED/)

Neutrino flux can increase during flares

* If target photon luminosity increases, then:

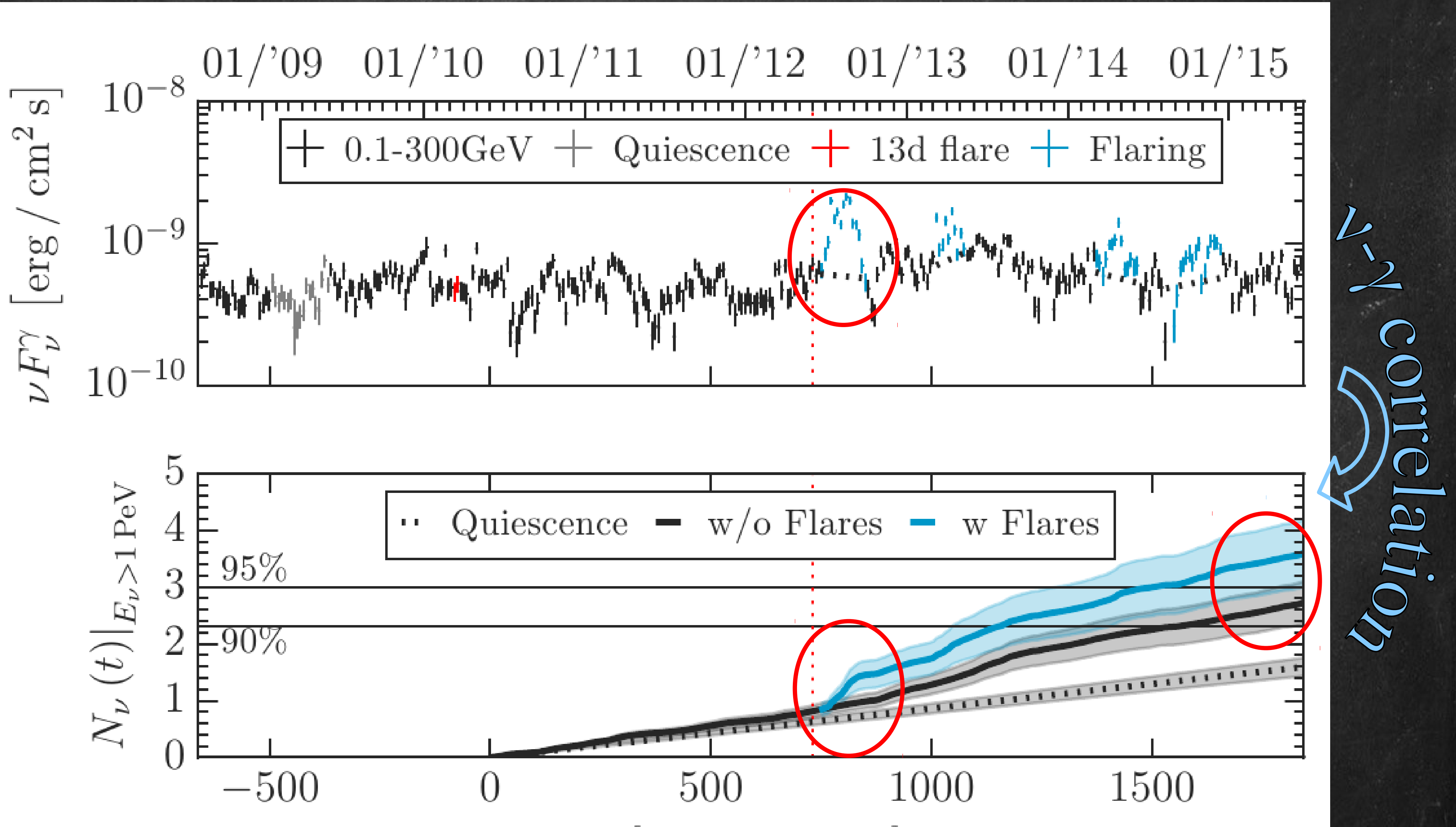
$$L_\nu \propto f_{p\gamma} L_p \propto \frac{L_{ph} L_p}{\varepsilon_{ph} t_\nu \delta^4}$$

* If γ-ray flare has a hadronic origin, then:

$$L_\nu \propto L_\gamma^a$$

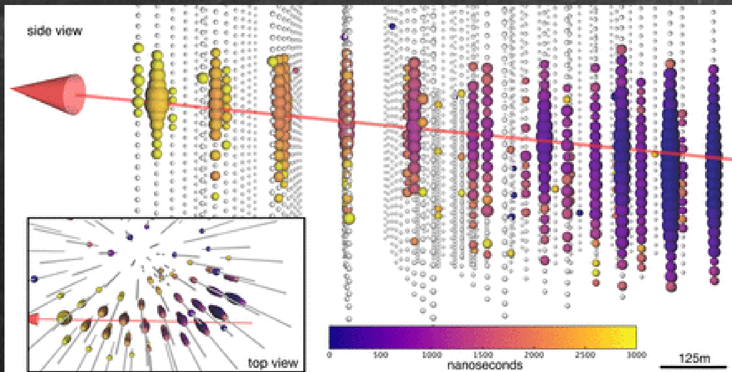
Fermi in understanding neutrino models

The 6.9 yr Fermi light curve (0.1-300 GeV) overlapping with the 5yr IceCube livetime



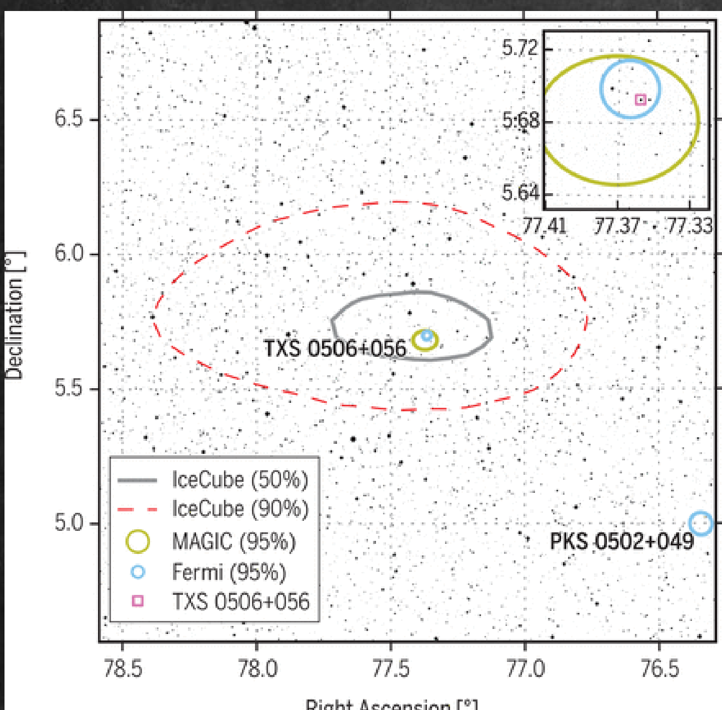
Petropoulou+16, APh

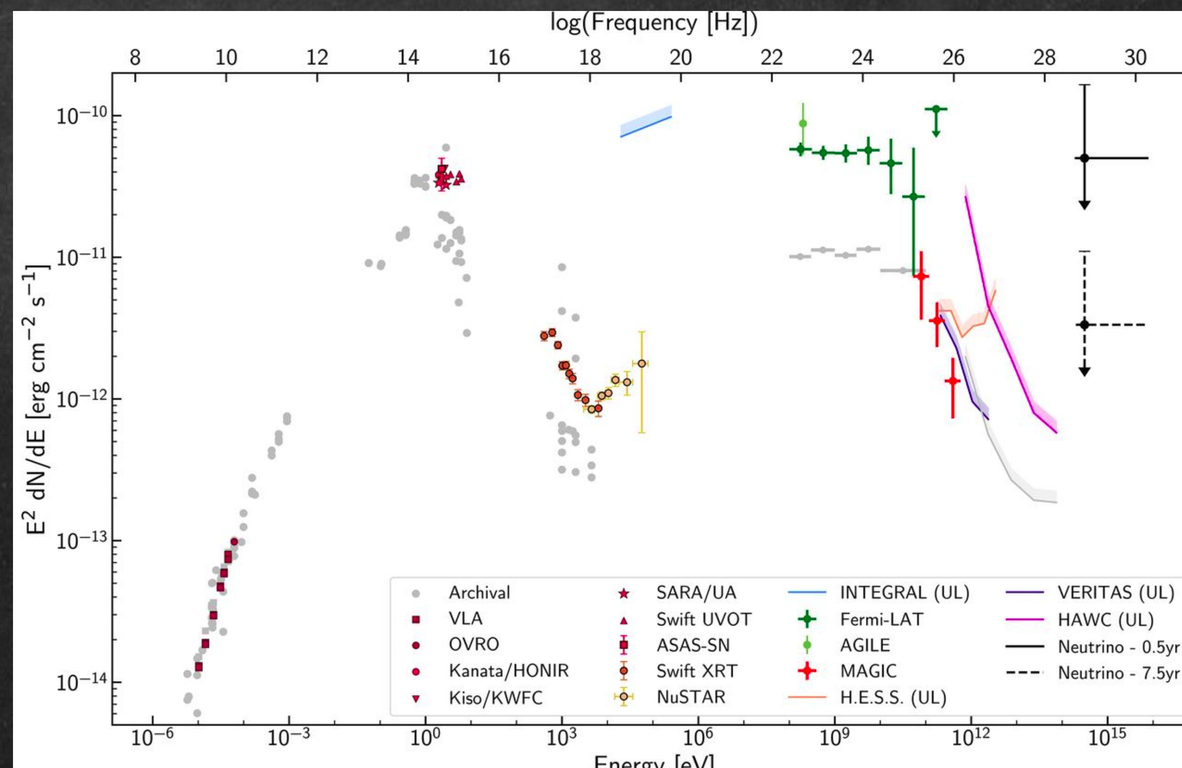
The multi-messenger flare of TXS 0506+056



IceCube Collaboration, '18, Science

- IC 170922A: track event with E_ν~300 TeV (ang. res. < 1 deg)
- Automatic public alert via AMON/GCN
- Fermi-LAT reported TXS 0506+056 was in a flaring state (Atel # 10791)
- Many MW observations followed





See talk by A. Franckowiak

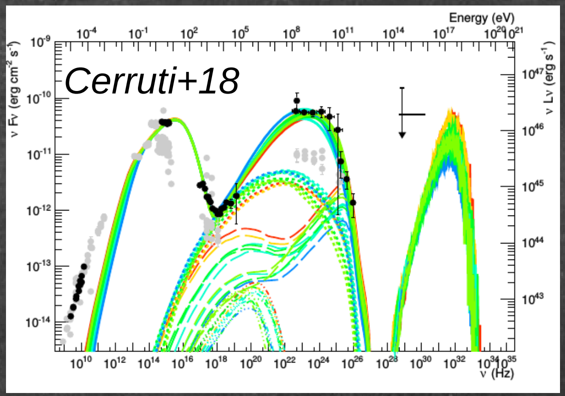
Interpretations

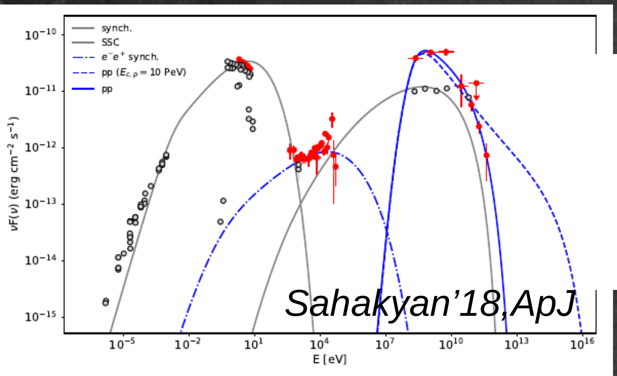
Photo-hadronic models

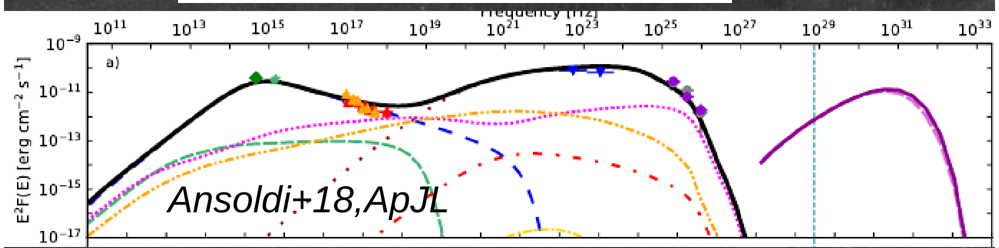
- *Ansoldi+18 for MAGIC, ApJL*
- *Cerruti+18 (1807.04335)*
- *Gao+18 (1807.04275)*
- *Keivani,Murase,MP+18, ApJ*
- *Murase, Oikonomou, MP '18, ApJ*

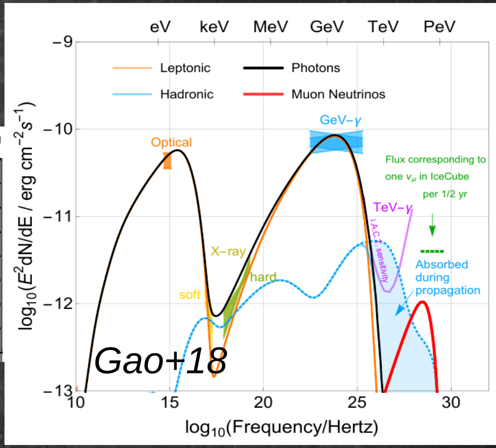
Hadro-nuclear models

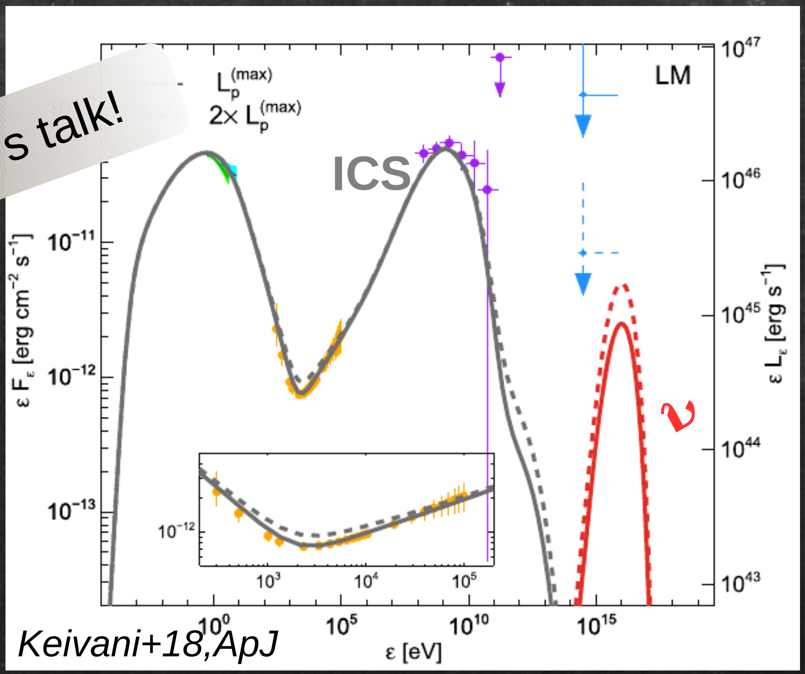
- *He+18 (1808.04330)*
- *Liu+18 (1807.05113)*
- *Murase, Oikonomou, MP '18, ApJ*
- *Sahakyan '18, ApJ*











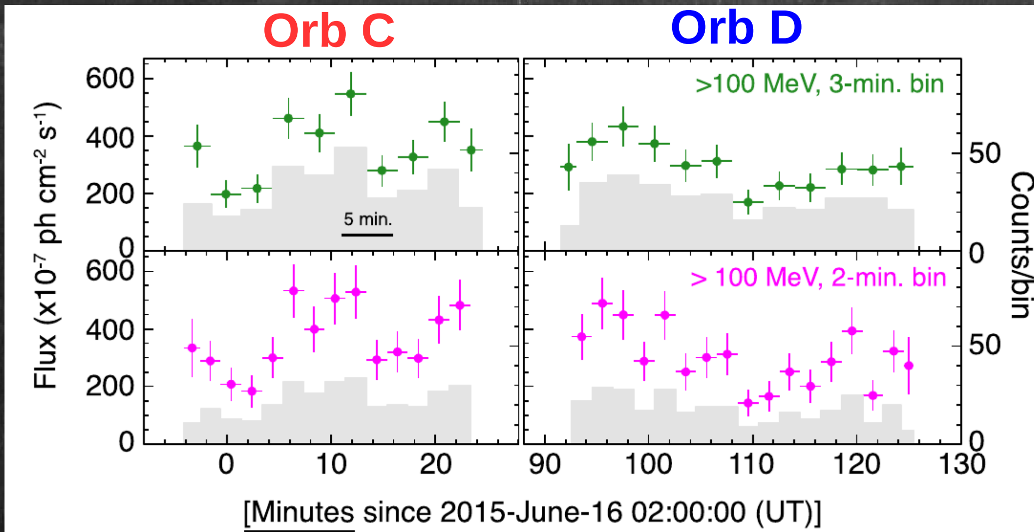
More in Keivani's talk!

$$F_{\nu} < 2\times10^{-12}\, erg/cm^2/s$$

$$U_p/U_e > 300$$

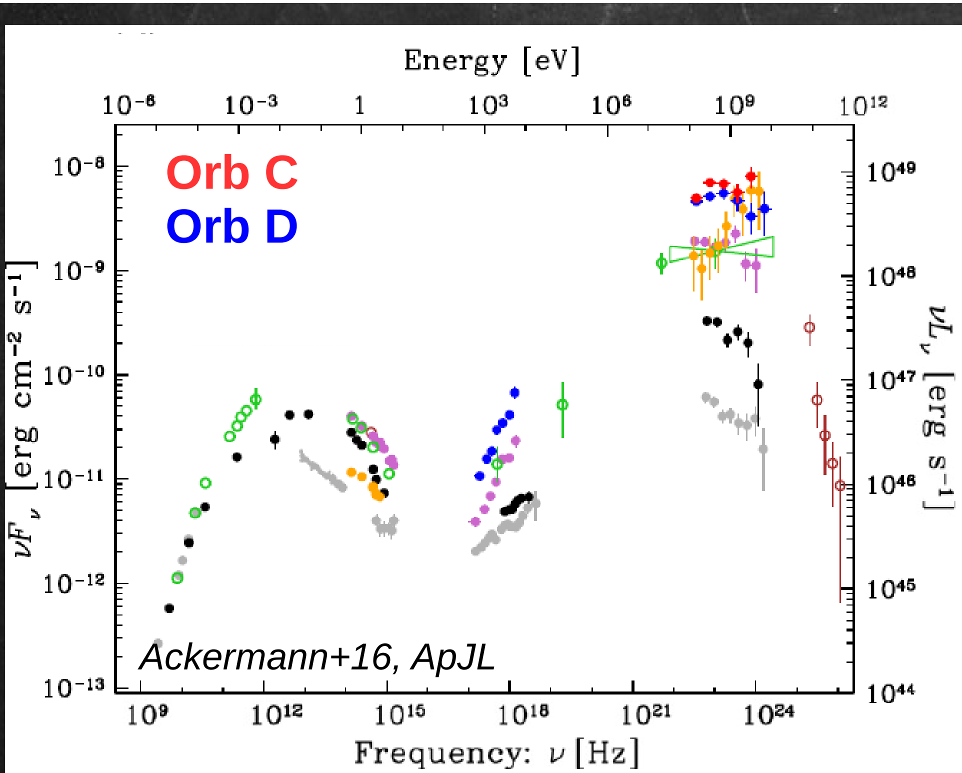
$$E_{p,max} < 0.3\, EeV$$

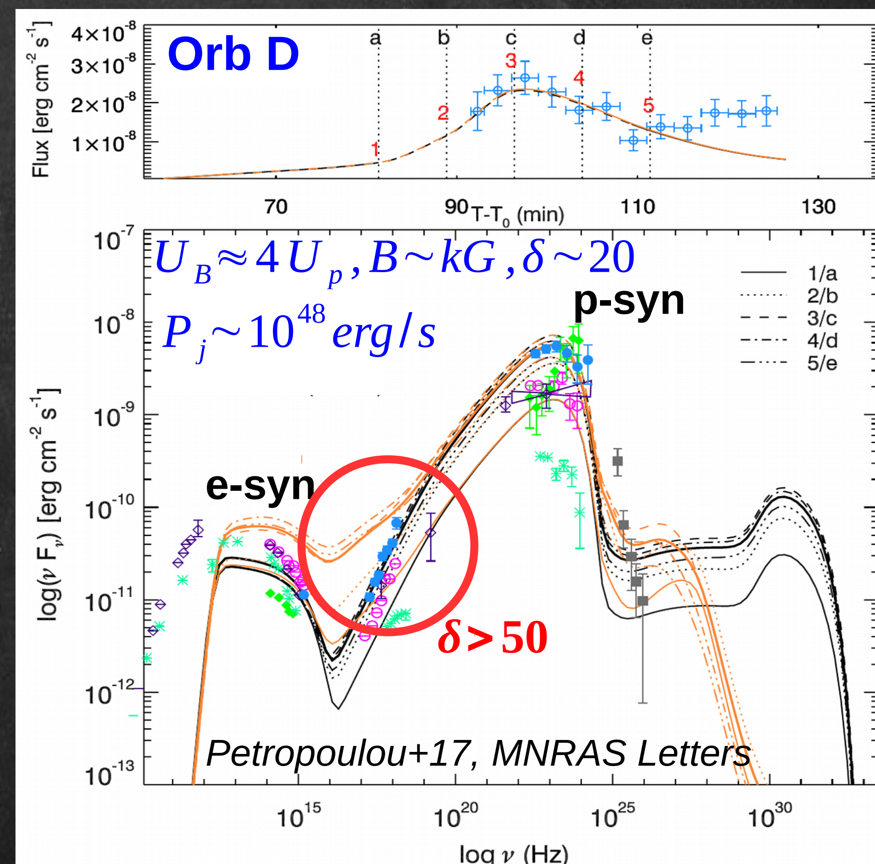
Fermi detects sub-orbital variability from 3C 279



Challenging for standard models because of:

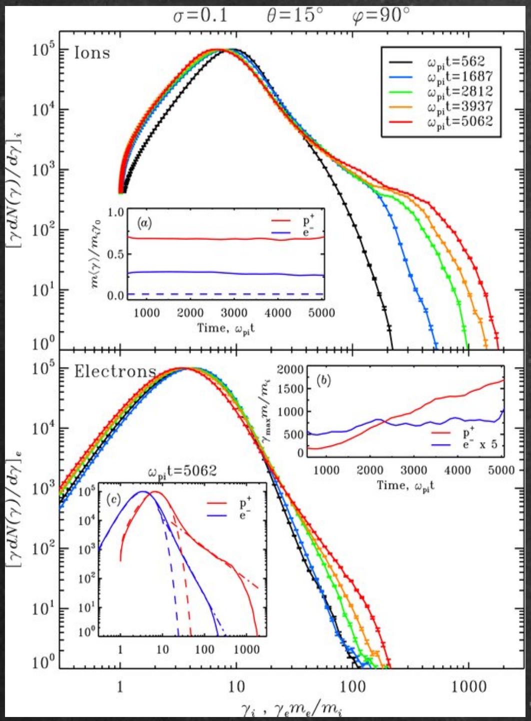
- Minute-scale duration
- High γ-ray luminosity (~ 10^{49} erg s^{-1})
- High Compton ratio (A_C~100)



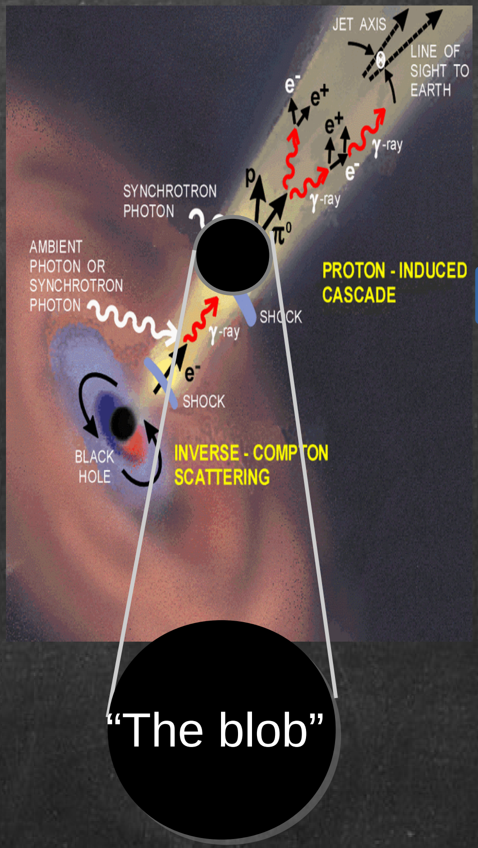


Status of blazar modeling

Particle acceleration

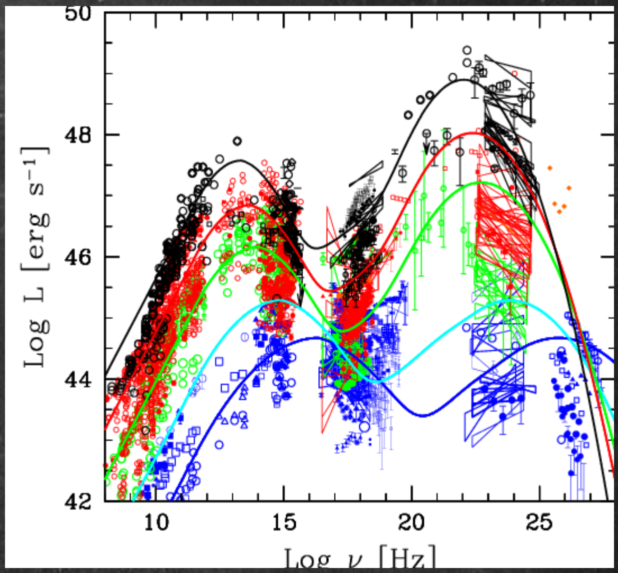


Injection of particles



Radiative processes

Photon spectrum



What's up next?

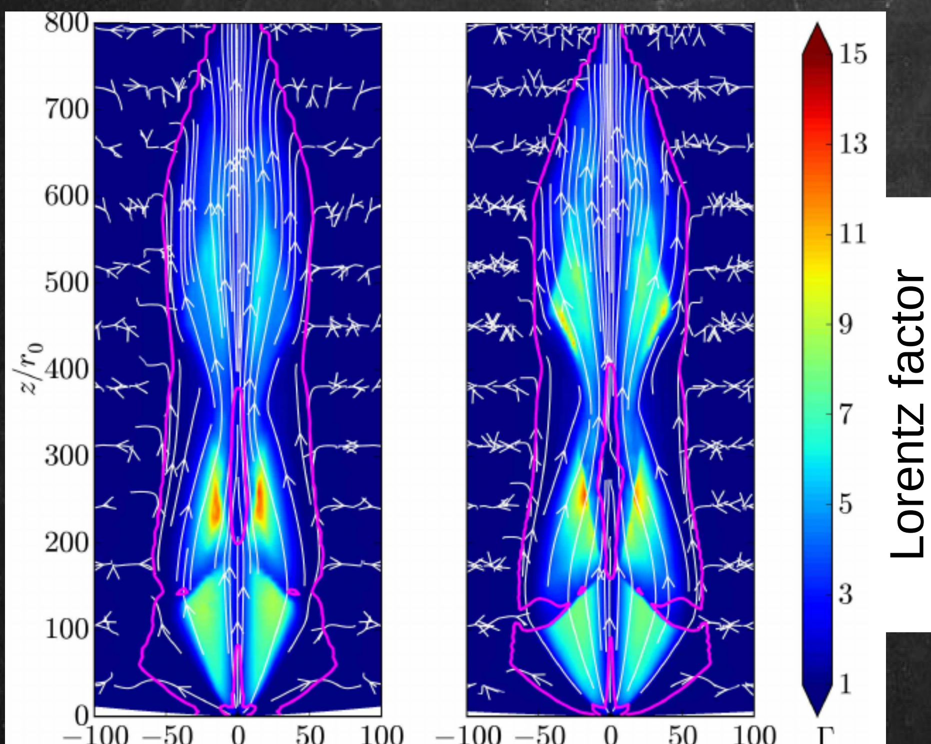
- Build a bottom-up theory for the origin of "blobs"
- Test theory predictions against spectro-temporal properties of blazar emission

Energy dissipation in jets

Shocks

* Internal shocks: time-dependent energy injection to the jet
* Recollimation shocks: abrupt changes in the density of external medium

(e.g. Kazanas & Ellison'86, ApJ; Blandford & Eichler'87; PhR, Kirk+98; A&A; Ostrowski'98, A&A; Boettcher & Dermer' 10, ApJ; Marscher+10, ApJ; Baring+17, MNRAS; for review, see Sironi+15, SSRv)

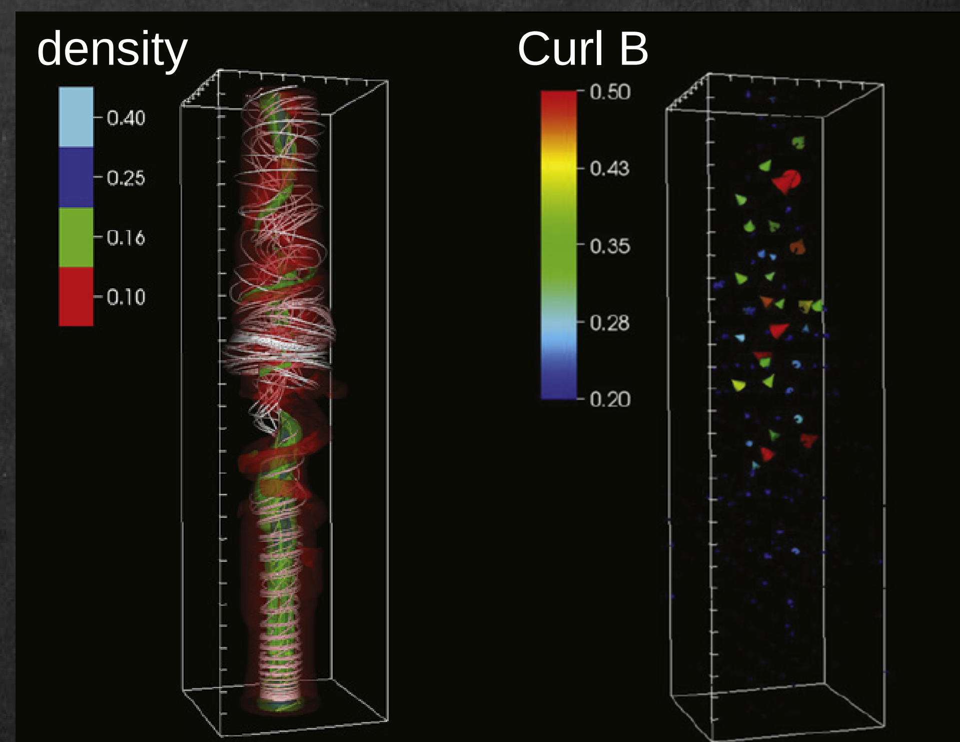


Barniol-Duran+17, MNRAS

Magnetic reconnection

* Magnetic kink instability at jet interior
* Striped wind structure of jet

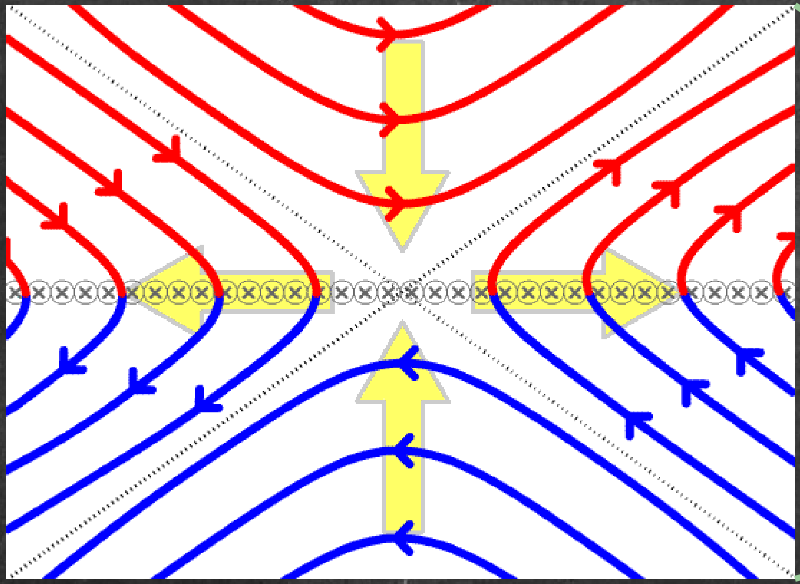
(e.g. Romanova & Lovelace '92, A&A; Eichler'93, ApJ; Begelman'98, ApJ; Giannios & Spruit'06, A&A; McKinney & Uzdensky '12, ApJ; Giannios & Uzdensky '18, MNRAS)



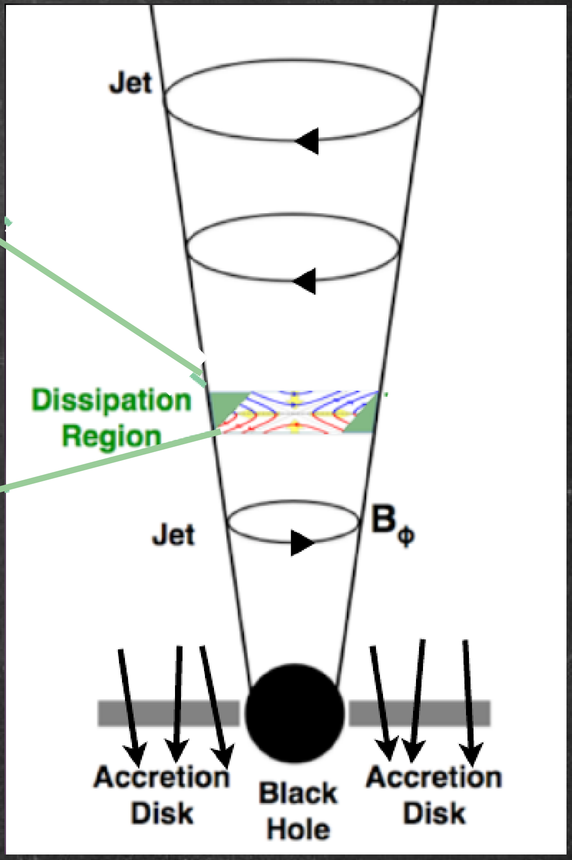
Singh+16, ApJ

Magnetic reconnection

Reconnecting field



Reconnecting field



* Magnetized plasma enters the reconnection region

* Plasma leaves the reconnection region at the Alfvén speed

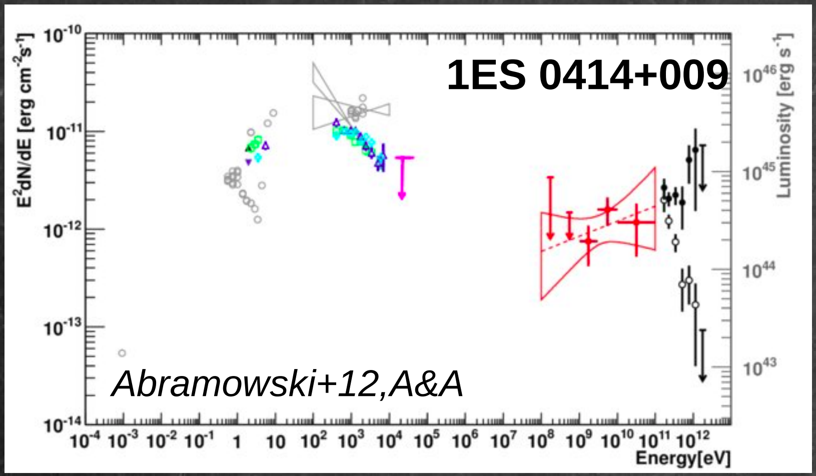
* Magnetic energy is transformed to heat, bulk plasma kinetic energy and non-thermal particle energy

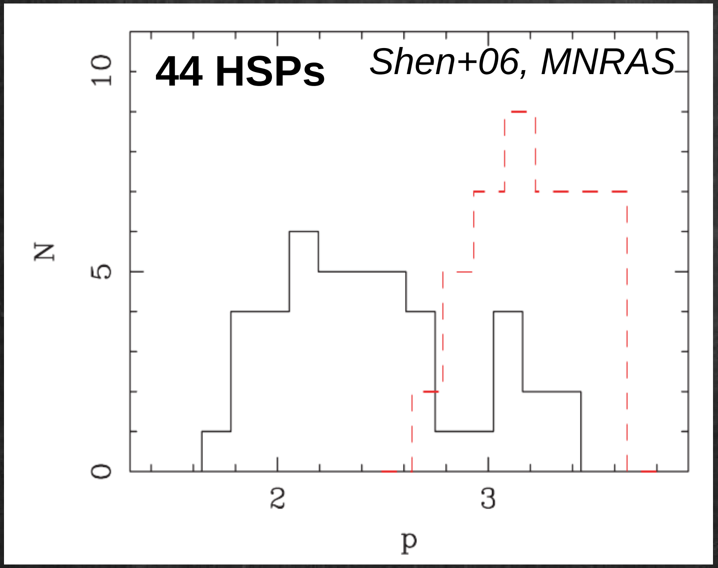
Relativistic regime

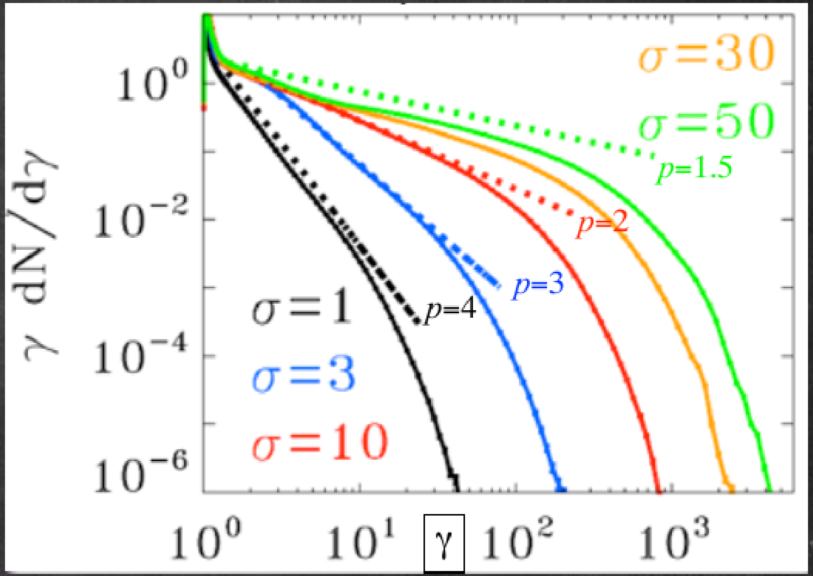
$$v_A \approx c$$

$$\sigma = \frac{B_0^2}{4\pi n_0 m c^2} > 1$$

Extended non-thermal distributions







Sironi & Spitkovsky '14, ApJ (Melzani+14, A&A; Guo+'15, ApJ; Werner+16, ApJ)

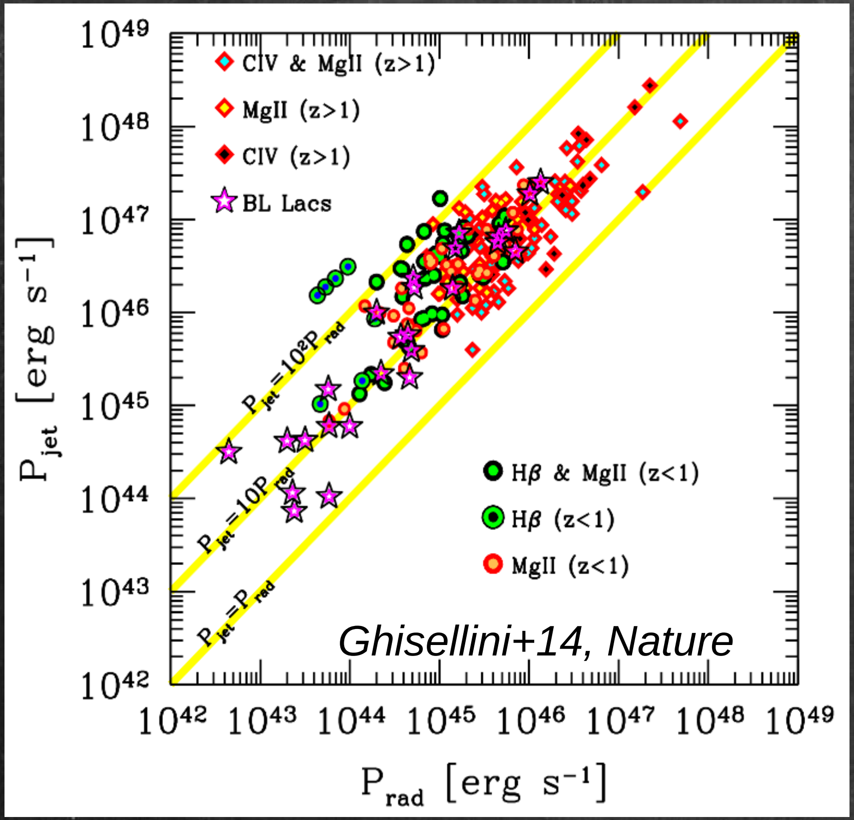
Broad non-thermal photon spectra →

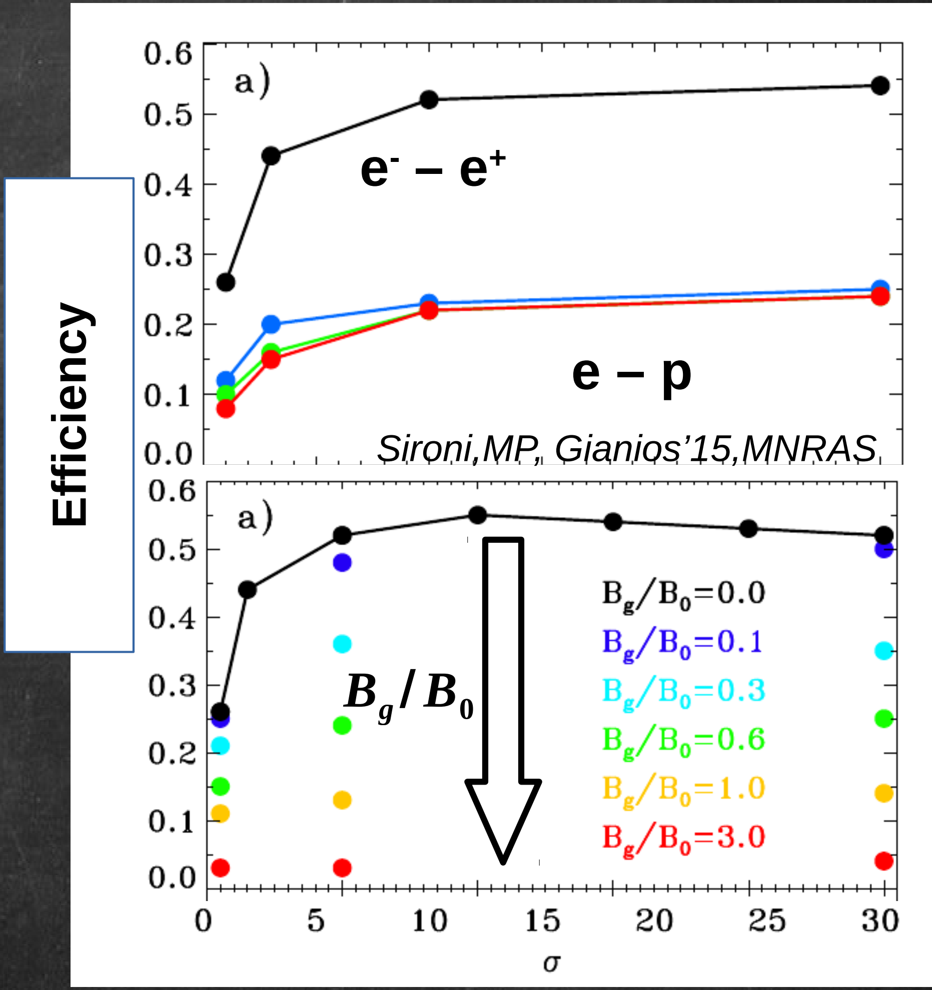
- Extended non-thermal distributions
- No unique power-law index

Relativistic reconnection →

- Extended non-thermal distributions
- Power-law index dependent on σ ($\sigma>10$, $p<2$)

Efficient energy dissipation

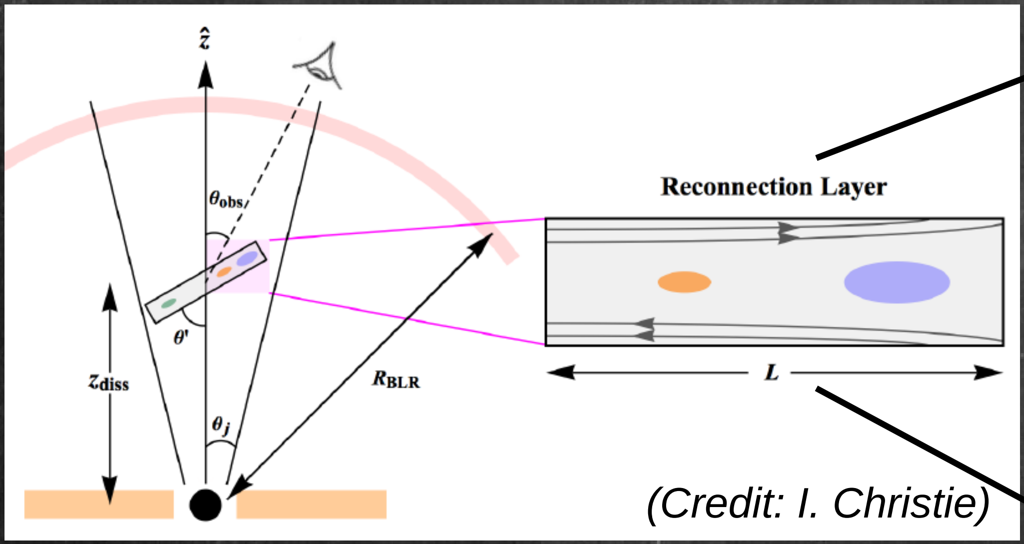


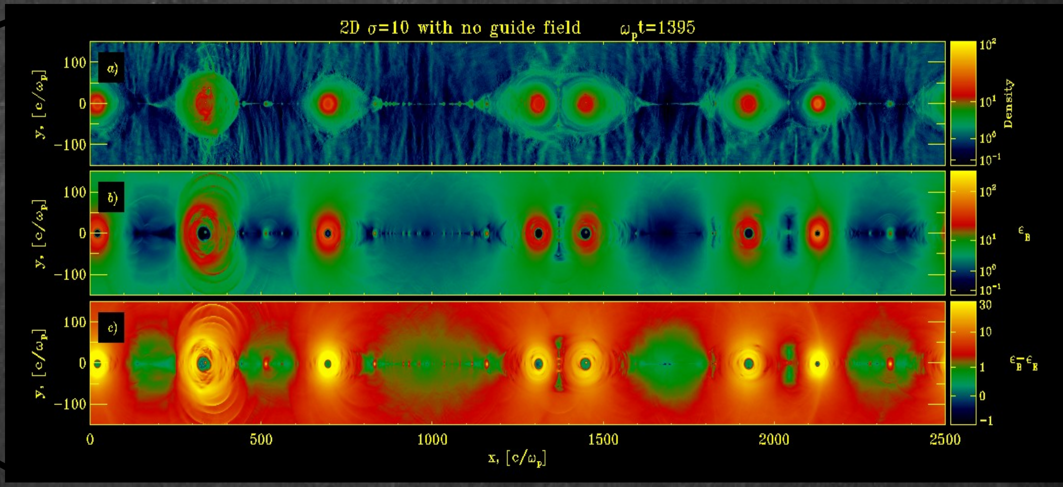


- Efficient energy dissipation
- Radiative power is ~1-10% of jet power

- it transfers ~ 50% of the flow energy (electron-positron plasmas) or ~ 25% (electron-proton) to the emitting particles
- Efficiency decreases with increasing guide field

Plasmoids in reconnection: the blobs of blazar emission

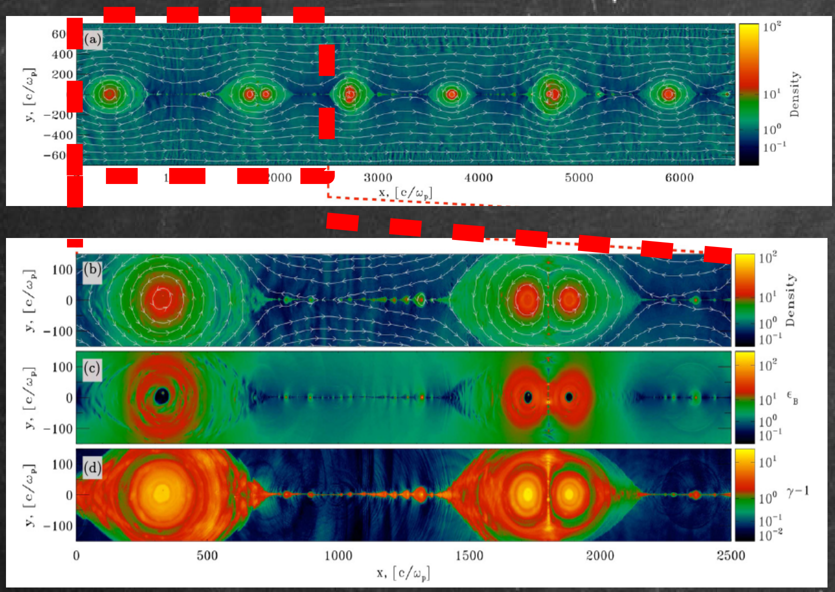




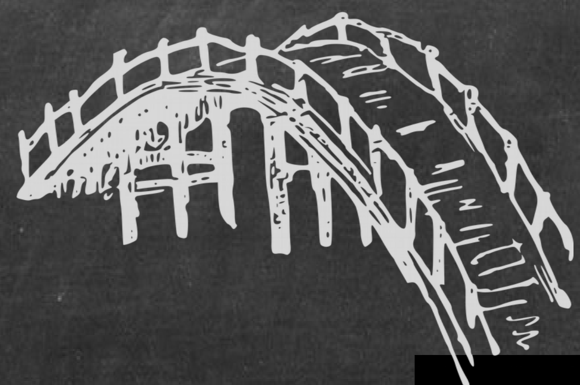
(Sironi, MP, Giannios' 15; Sironi, Giannios, MP '16)

* The layer fragments into plasmoids *(Loureiro+07,PhPl; Uzdensky+10, PhRvL)*
* Plasmoids move relativistically in the jet frame *(e.g. Giannios'09, MNRAS; Giannios '13, MNRAS)*
* Plasmoids have a power-law distribution of sizes *(e.g. Uzdensky+10,PhRvL; Loureiro+11, PhPl; Sironi, Giannios,MP'16, MNRAS; Petropoulou+18, MNRAS)*

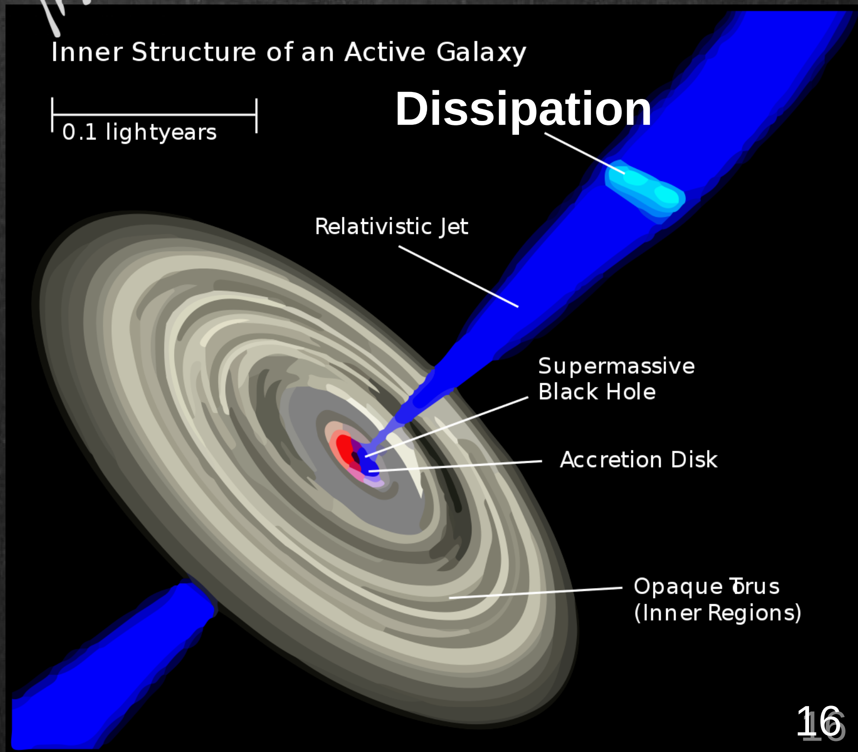
From microscoPIC to large scales



Self-similarity



Extrapolation to large scales



Variability at multiple scales

Each plasmoid produces a flare of characteristic duration and flux

(Giannios ‘09; Giannios’13; Petropoulou+16; Christie, MP+18)

Each reconnection layer produces a chain of plasmoids

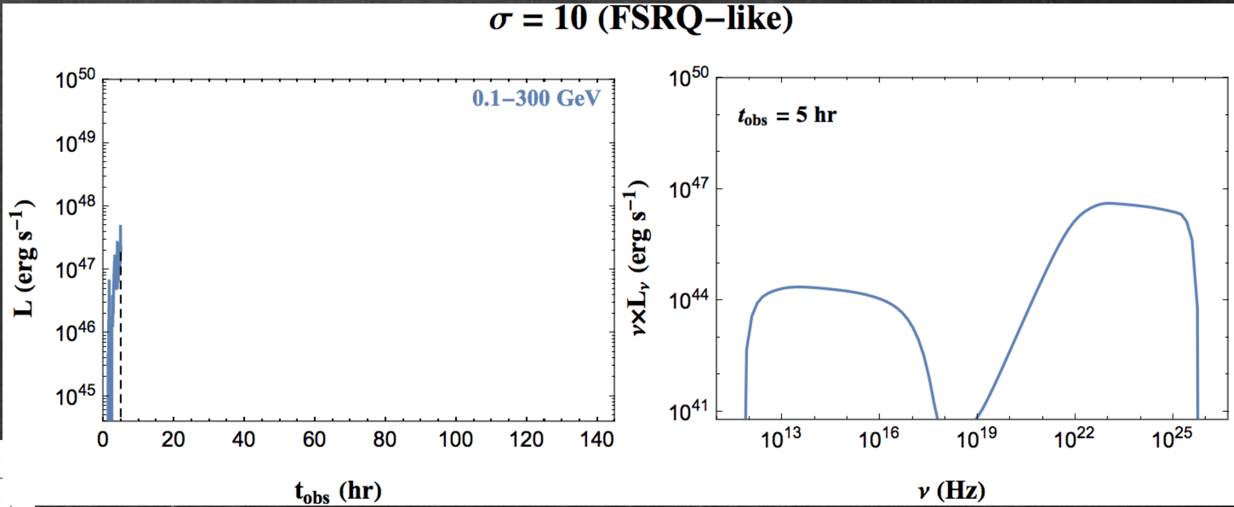
(Sironi,MP, Giannios ‘15; Sironi, Giannios, MP ‘16 Petropoulou+18; Christie,MP+18)

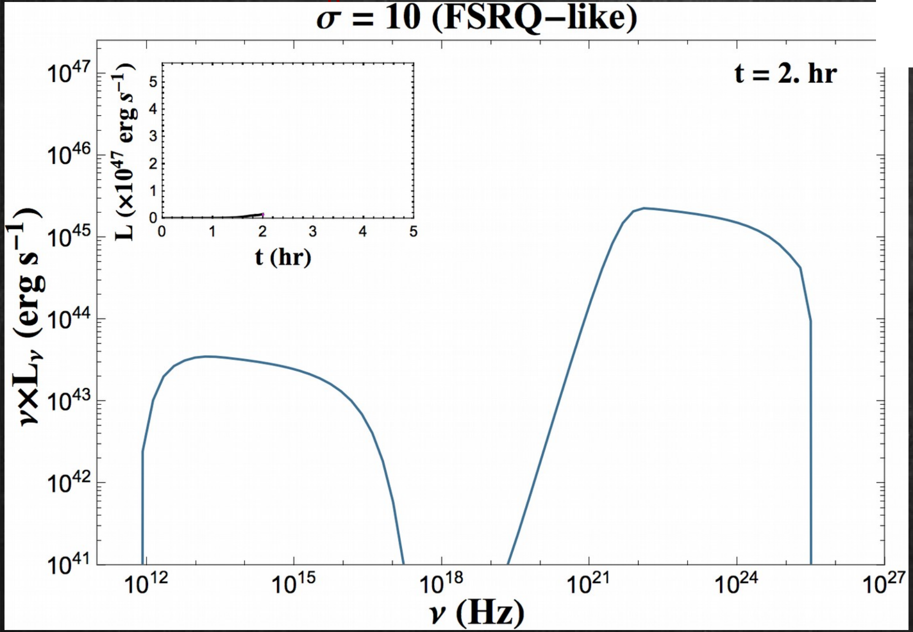
$$\Delta t_{1/2} \approx \frac{w_p}{\beta_g c \delta_p}$$

Plasmoid size (w_p)

Plasmoid Doppler factor (δ_p)

$$L_{pk} \approx \frac{f_{rec} L_j}{8 R^2 c \beta_j \Gamma_j^2} \beta_g c w_p^2 \delta_p^4$$

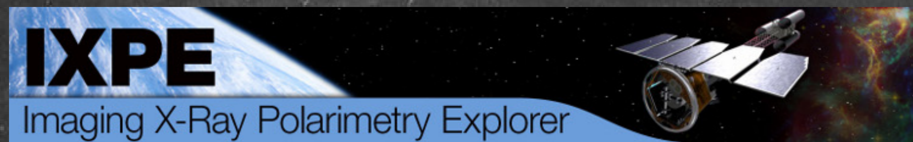


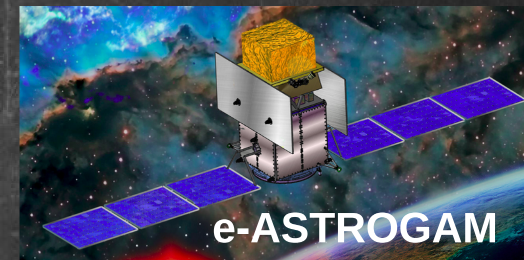


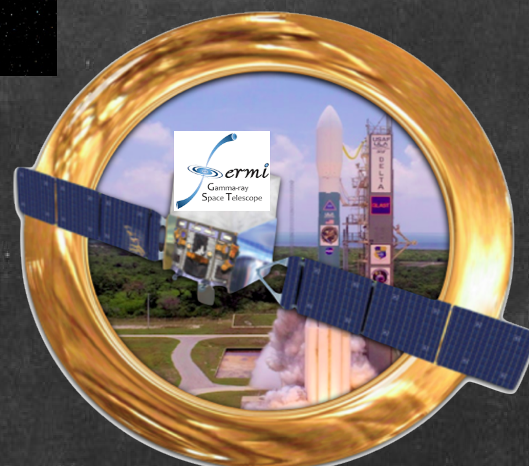
- Fast flares on top of slowly evolving envelope
- Physical model for multi-timescale variability in jets

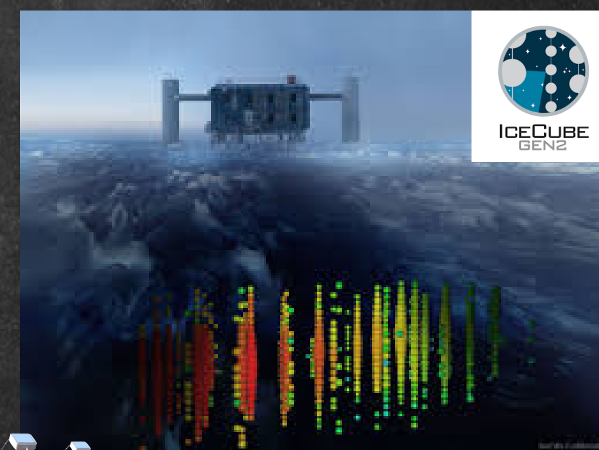
More in Christie’s talk!

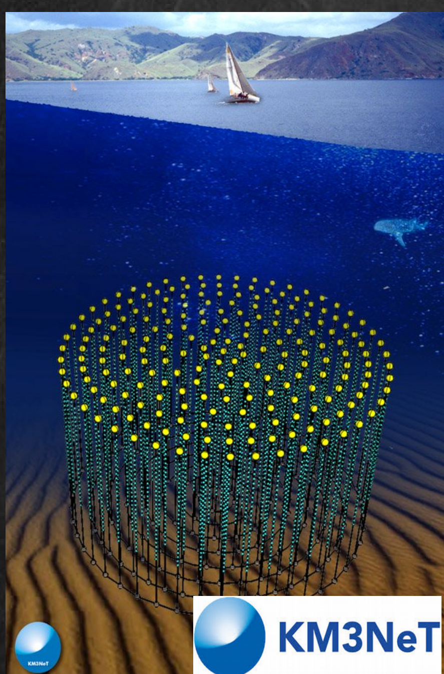
Future prospects

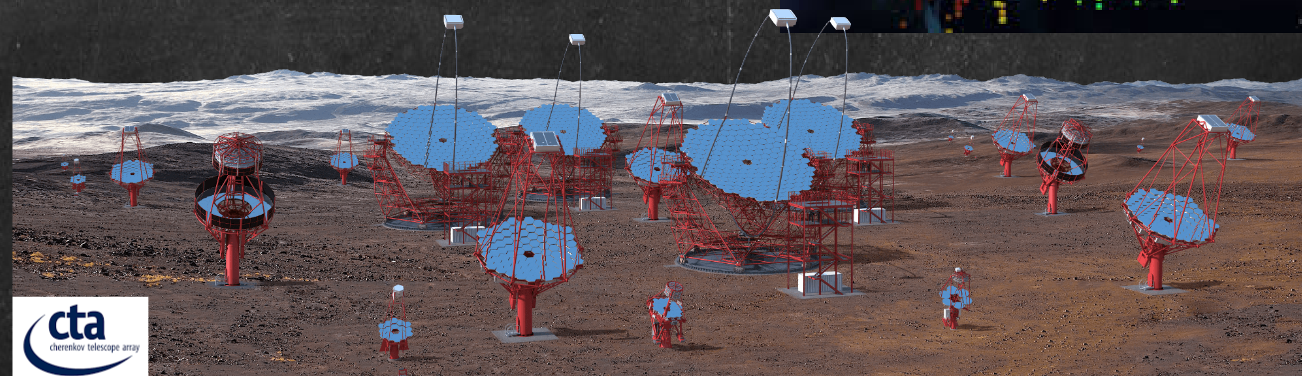












Summary

Fermi is the only mission that can perform long-term monitoring of blazar jets.

- Timing analysis of light curves
- Flare properties

Fermi's role in multi-messenger observations of blazar jets is central, as demonstrated by the flare of TXS 0506+056.

- Cosmic-ray content of jets
- Cosmic-ray acceleration in jets

Synergy of *Fermi* with Cherenkov telescopes delivers high-quality γ-ray spectra extending more than 4 decades in energy.

- Spectral breaks or attenuation features
- Multiple spectral components

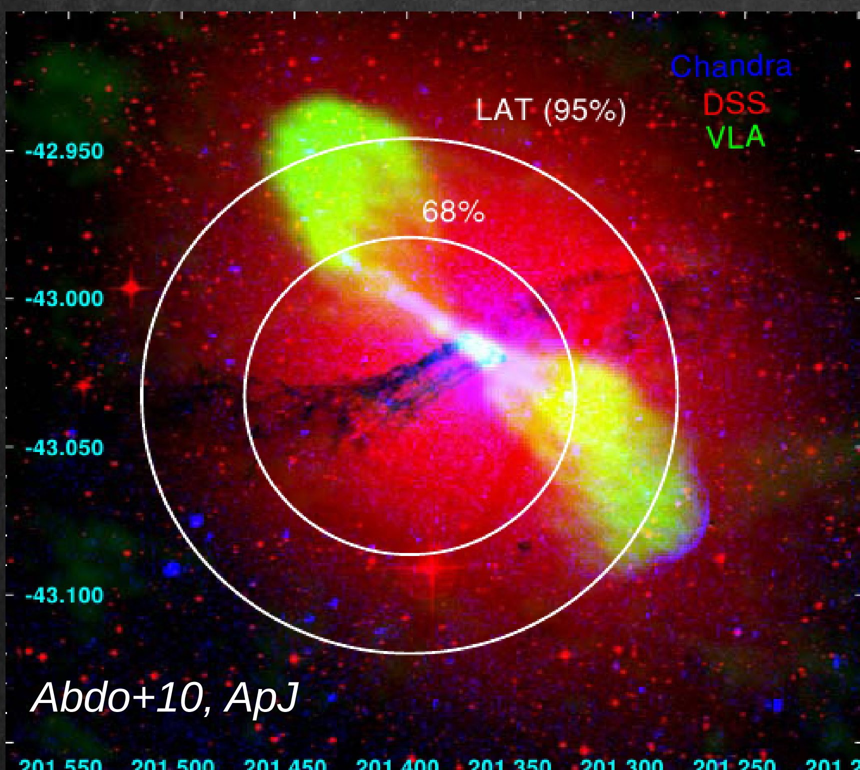
Fermi as an integral part in the map of future multi-messenger missions.

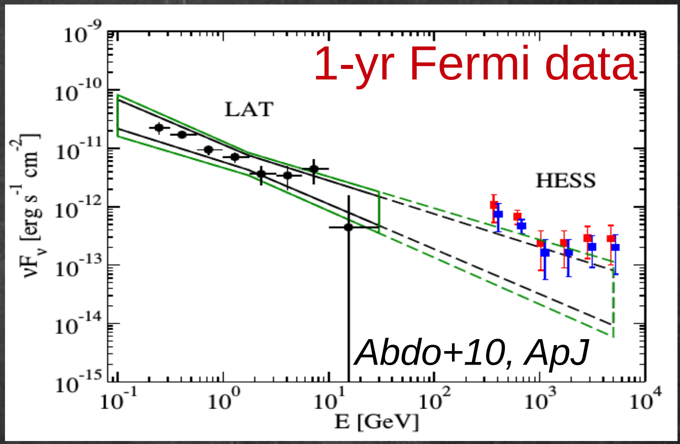
Thank you

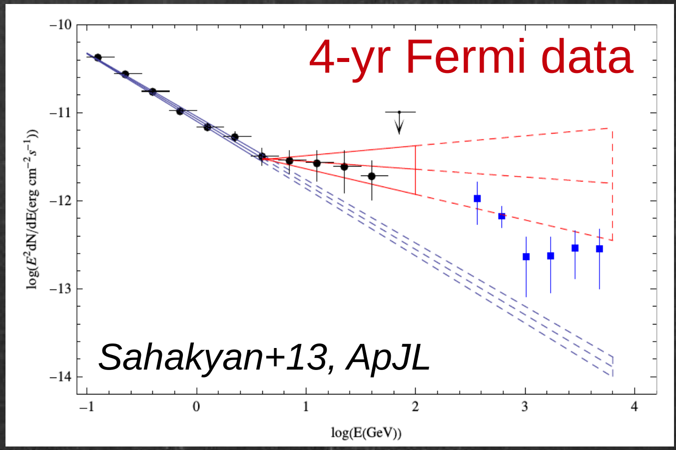
Back-up slides

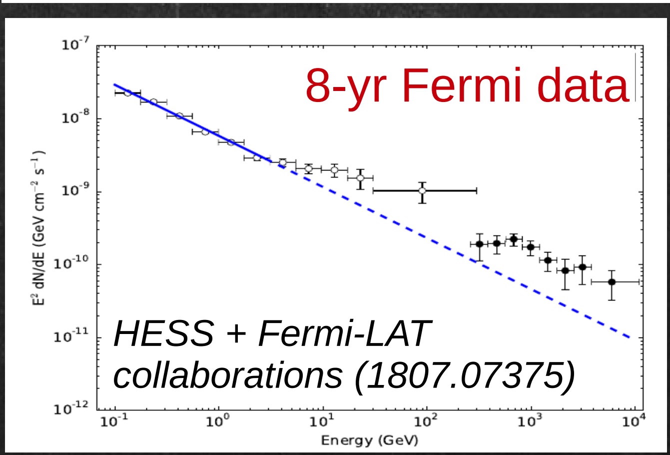
The γ-ray spectrum of Centaurus A

- Closest radio galaxy (FR I type)
- D=3.8 ± 0.1 Mpc *(Harris+10, PASA)*
- VHE γ-ray source *(Aharonian+09, ApJ)*
- *Fermi* after launch confirmed early EGRET detection *(Abdo+09, ApJ)*





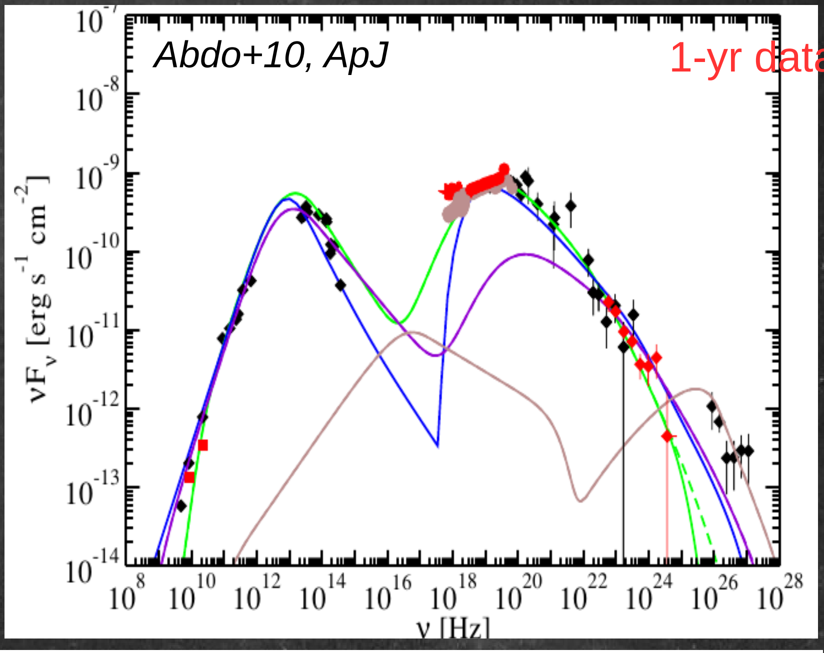


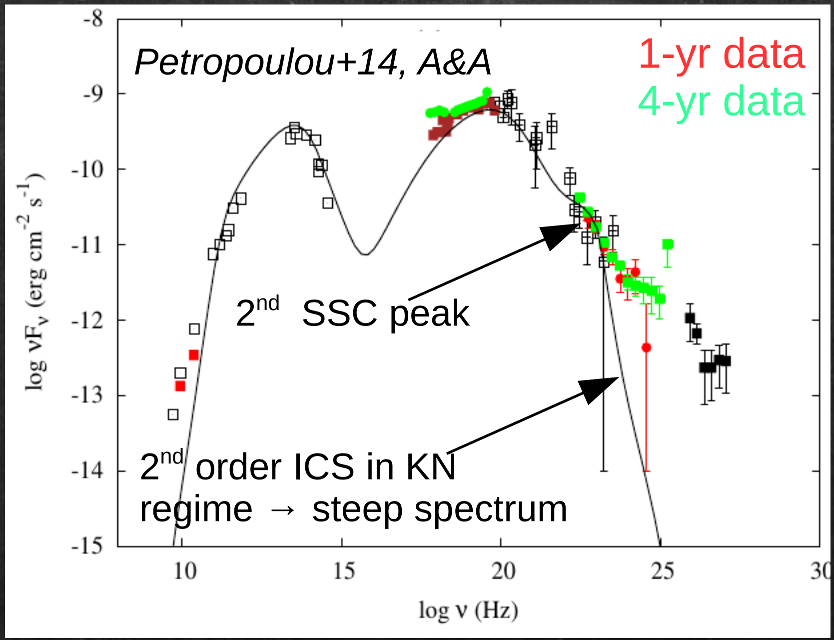


SSC modeling of Centaurus A

Cen A as misaligned blazar → SSC modeling of core emission

Parameter	Model SSC	Model SSC (Abdo et al. 2010a)
R (cm)	4×10^{15}	3×10^{15}
B (G)	6	6.2
δ	1	1
$\gamma_{e,min}$	1.3×10^{3}	300
γ_{br}	–	800
$\gamma_{e,max}$	10^{6}	10^{8}
$p_{e,1}$	–	1.8
$p_{e,2}$	4.3	4.3
ℓ_e^{inj}	6.3×10^{-3}	8×10^{-3}
ℓ_B	4.6×10^{-3}	3.7×10^{-3}





Large viewing angle → Weak Doppler boosting

$$L_{obs} \propto \delta^4 L_{e,co} \approx L_{e,co}$$

L_{obs} high → $L_{e,co}$ high → 2nd order SSC not negligible!

Alternative interpretations

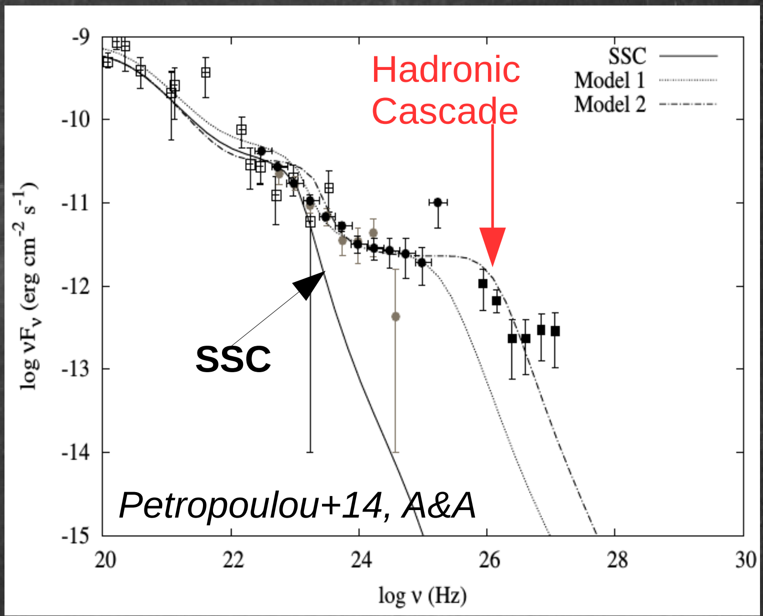
Inner jet models

- Leptonic processes in black-hole magnetosphere *(Rieger & Aharonian 09, ApJL)*
- SSC from 2 zones *(Joshi+18, MNRAS Letters; HESS & Fermi Collaborations '18)*
- Millisecond pulsar population *(Brown+17, A&A)*
- DM annihilation *(Brown+17, A&A)*
- ICS cascades on dusty tori *(Roustazadeh & Boettcher '11,ApJ)*
- *Photo-hadronic processes (Kachelriess+10, PASA; Reynoso+11,A&A; Petropoulou+14, A&A)*

Large-scale jet models

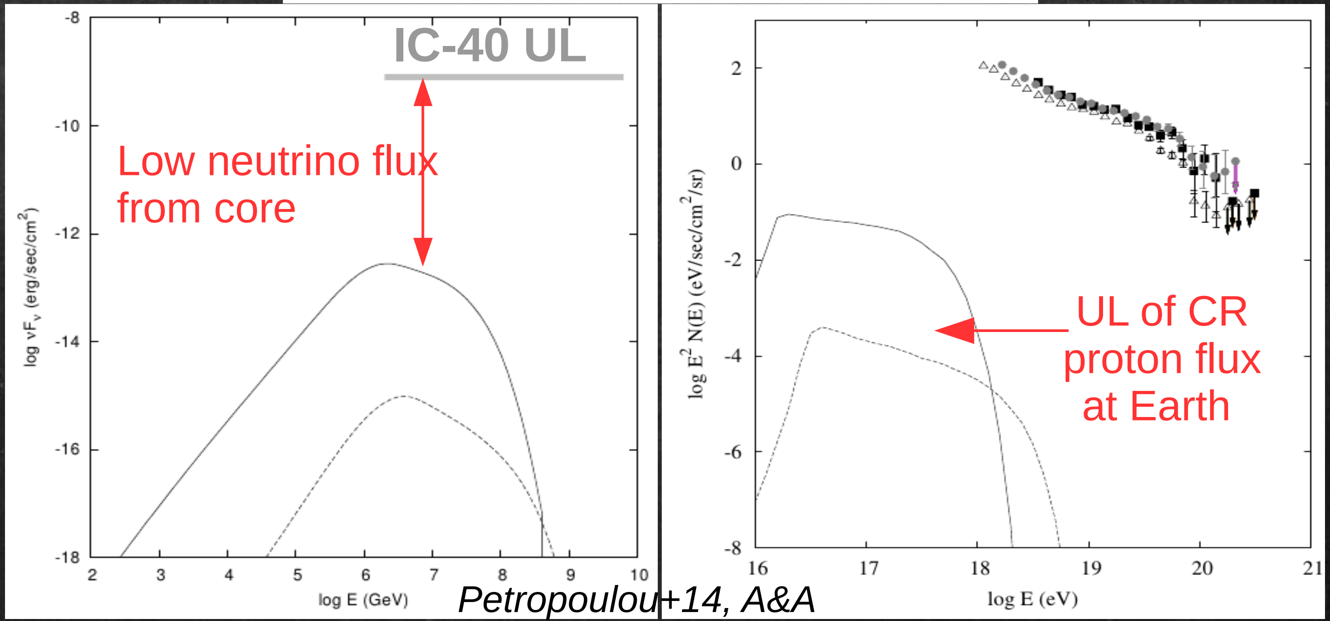
- ICS on background photons *(Hardcastle & Croston '11,MNRAS)*

γ

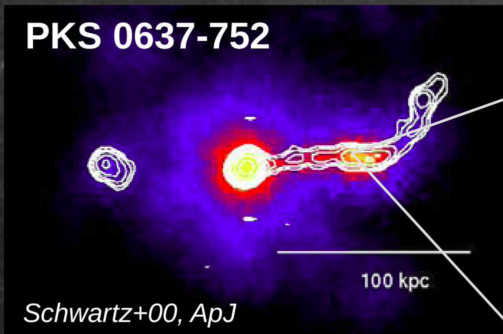


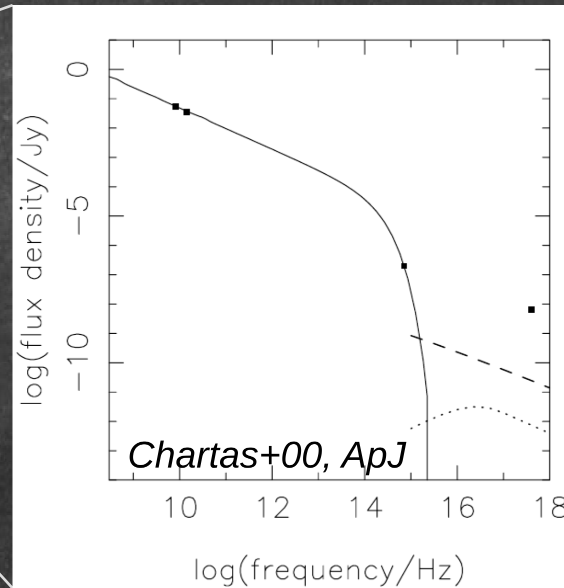
ν

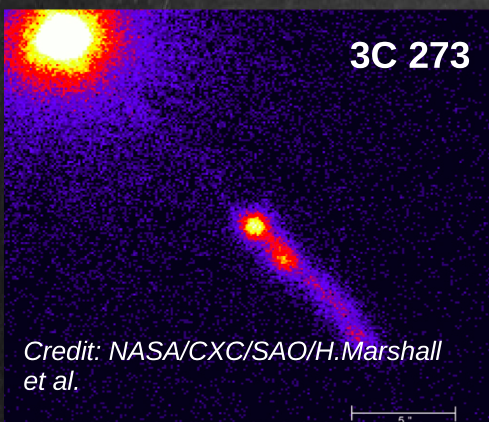
p

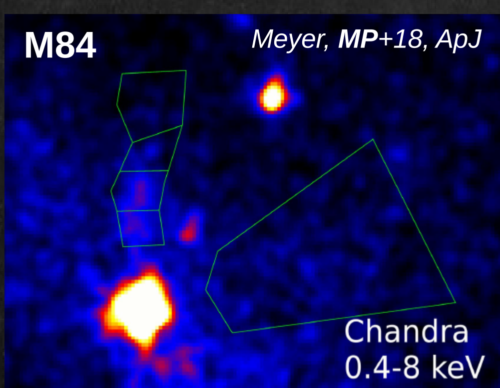


X-rays from large-scale AGN jets

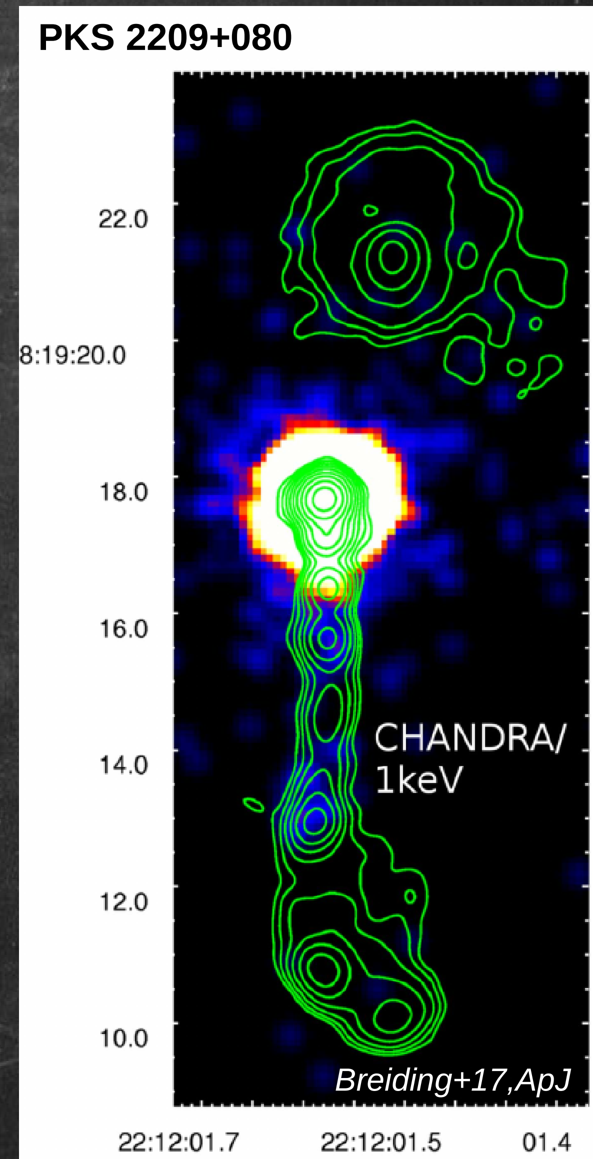








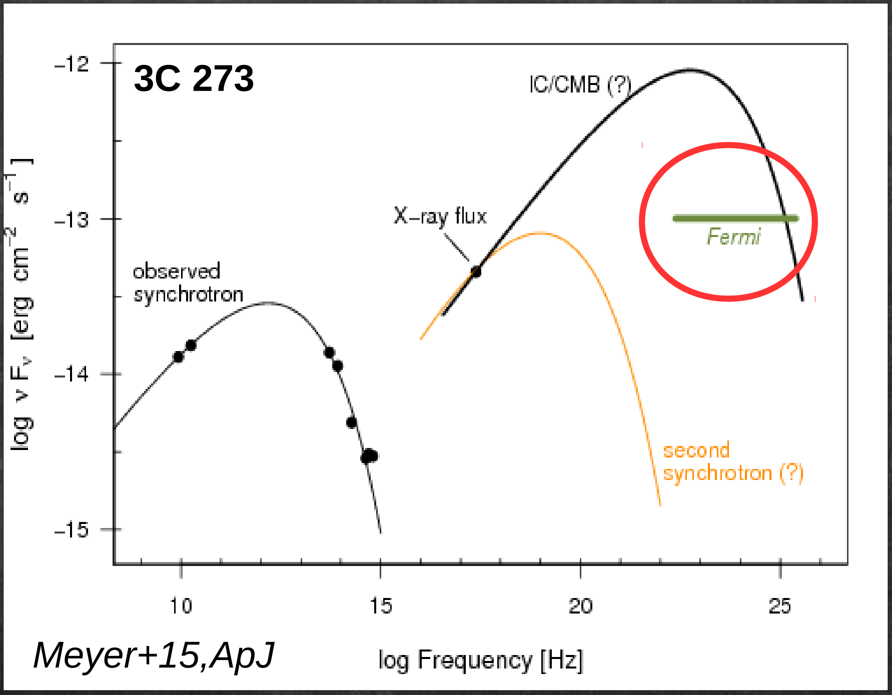
- X-ray emission not an extension of radio-optical spectrum
- SSC and IC/CMB (w/o beaming and in equipartition) under-predict X-ray flux



How are X-rays being produced?

IC/CMB model
(Tavecchio+00, ApJL; Celotti+01,MNRAS)

- Beaming (δ~10) from kpc-scale jet is necessary
- Electron distribution extends to low Lorentz factors (γ~20-200)
- Particles at low energies → increased jet power requirements
- No freedom in GeV flux predictions

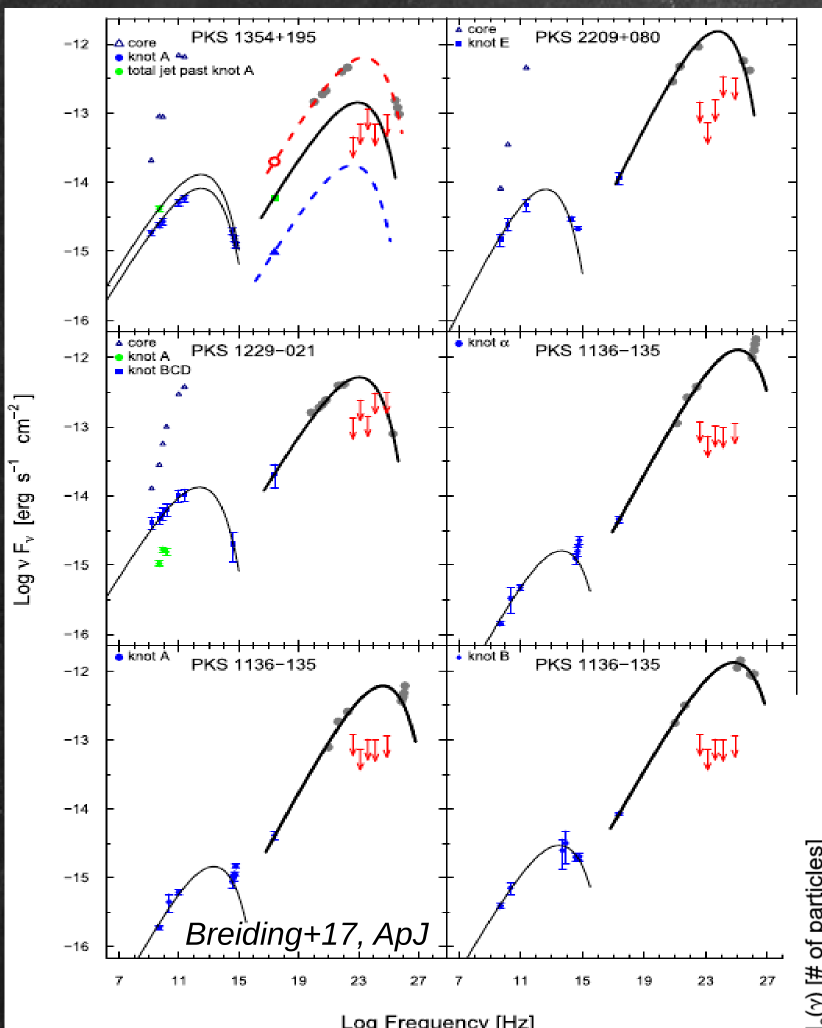


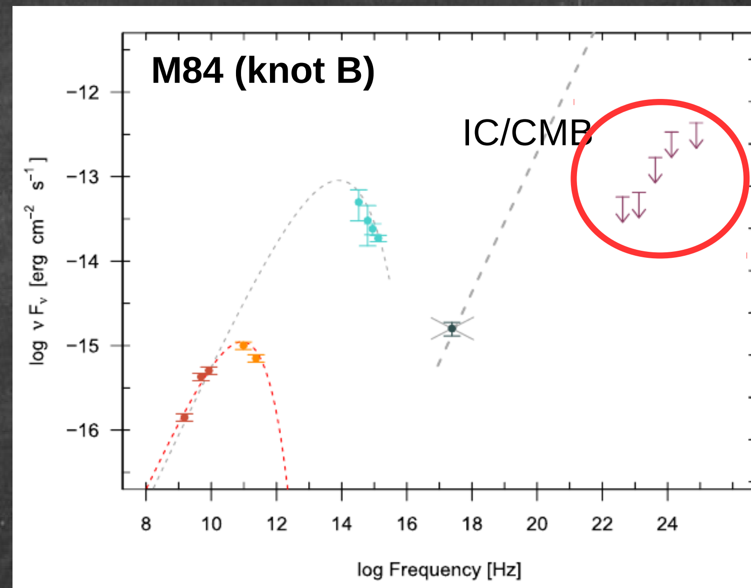
Electron synchrotron models
(e.g.Harris+04,ApJ; Hardcastle'06, MNRAS)

- Strong beaming is not required
- 2 electron distributions with different energy ranges
- 2nd electron distribution must begin from high Lorentz factors ($\gamma \sim 10^6$-10^7)
- Less energy-demanding
- Freedom in GeV flux predictions

Lepto-hadronic models
(Aharonian '02, MNRAS; Bhattacharyya & Gupta '16, ApJ; Kusunose & Takahara '17, ApJ; Meyer, MP+18, ApJ)

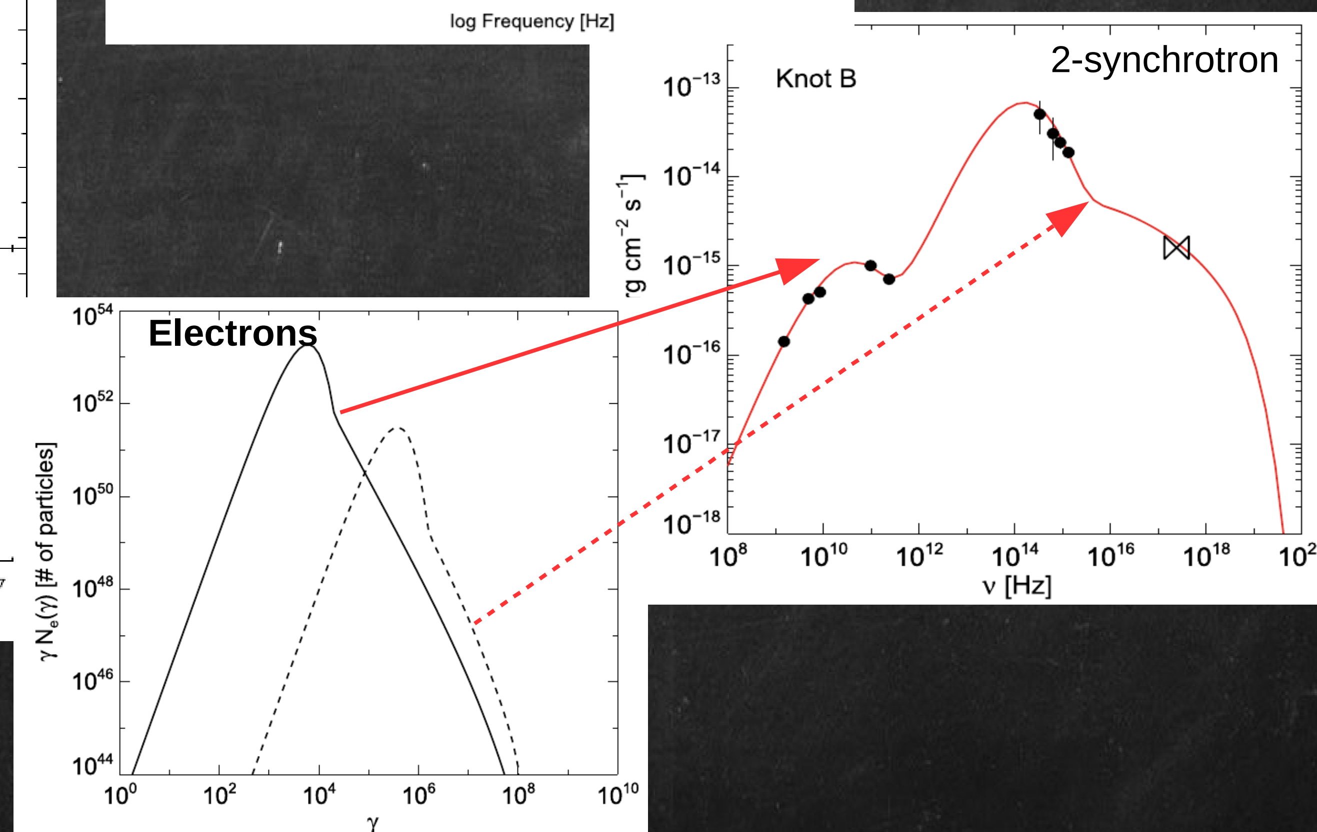
Fermi rules out the IC/CMB model





- Optical/UV not extension of radio spectrum
- > 2 spectral components ?

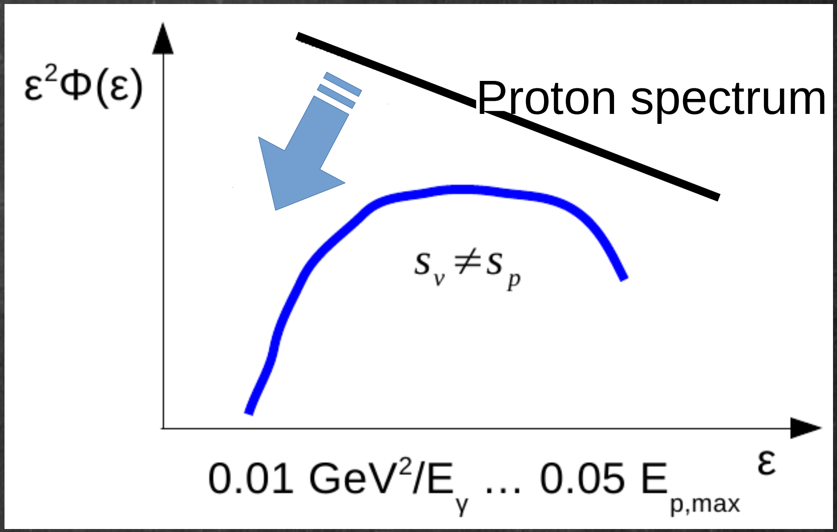
Meyer, MP+18, ApJ



Neutrino properties in a nutshell

Neutrino spectrum depends on:

- Density of target photons
- Energy spectrum of target photons
- Energy spectrum of protons



Typical neutrino energies

Production efficiency

Jet photons:

$$E_\nu \approx 0.05\, E_p \geqslant 90\, PeV\, \Gamma_1^2 \left(\varepsilon_s / 10\, eV \right)^{-1}$$

$$f_{p\gamma} \propto \frac{L_{ph}}{\varepsilon_{ph} R \delta^3} \propto \frac{L_{ph}}{\varepsilon_{ph} t_v \delta^4}$$

BLR photons:

$$E_\nu \approx 0.05\, E_p \geqslant 0.9\, PeV \left(\varepsilon_{BLR} / 10\, eV \right)^{-1}$$

$$f_{p\gamma} \propto \frac{L_{BLR}}{\varepsilon_{BLR} R_{BLR}}$$

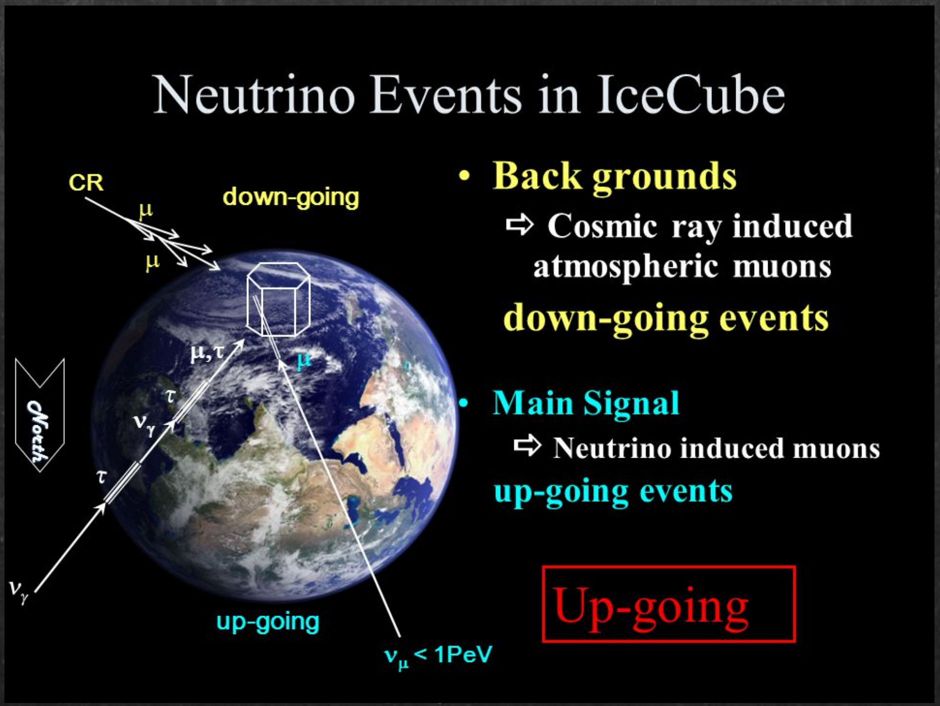
Effective areas of the analyses

Up-going events

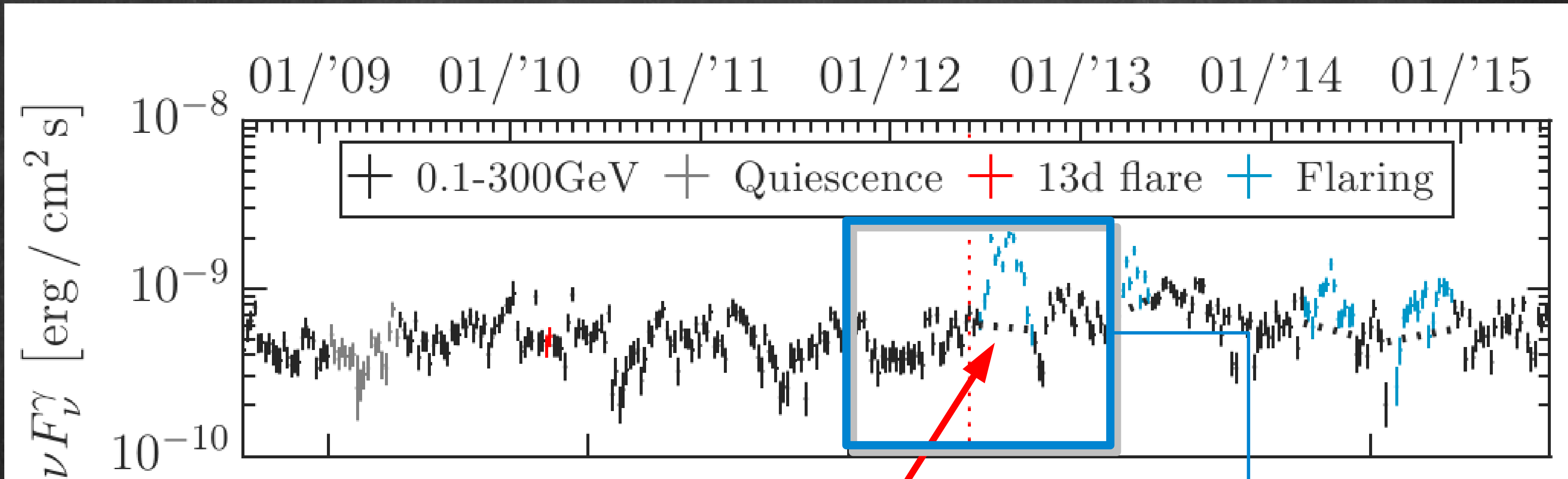
- Larger statistical sample
- Larger effective volume
- Atm. background not removed
- Poorer energy determination

High-energy starting events (HESE)

- Smaller statistical sample
- Smaller effective volume
- Atm. Background removed
- Accurate energy determination



Predicted #ν in 5yr IceCube livetime



Major GeV flares

No.	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)$
Flares 1a+1b	105	0.61 ± 0.16	46 ± 8
Flare 2	70	0.32 ± 0.07	27 ± 5
Flare 3	98	0.26 ± 0.05	23 ± 4
Flares 4a+4b	112	0.26 ± 0.05	23 ± 4
∑ Flares	385	1.46 ± 0.32	77 ± 7

Without GeV major flares

Season	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)^\dagger$
06/2010-05/2011	364	0.43 ± 0.06	34 ± 4
06/2011-05/2012	364	0.38 ± 0.05	32 ± 3
06/2012-05/2013	371	0.71 ± 0.11	51 ± 5
06/2013-05/2014	364	0.70 ± 0.11	50 ± 5
06/2014-05/2015	350	0.47 ± 0.06	38 ± 4
∑ w/o Flares	1834[a]	2.73 ± 0.38	94 ± 2
∑ w Flares	1834	3.59 ± 0.60	97 ± 2

* Similar probability for detecting at least 1 neutrino from the 2012 flare alone and the whole IC Season 3
* Still <50%

Constraining the model

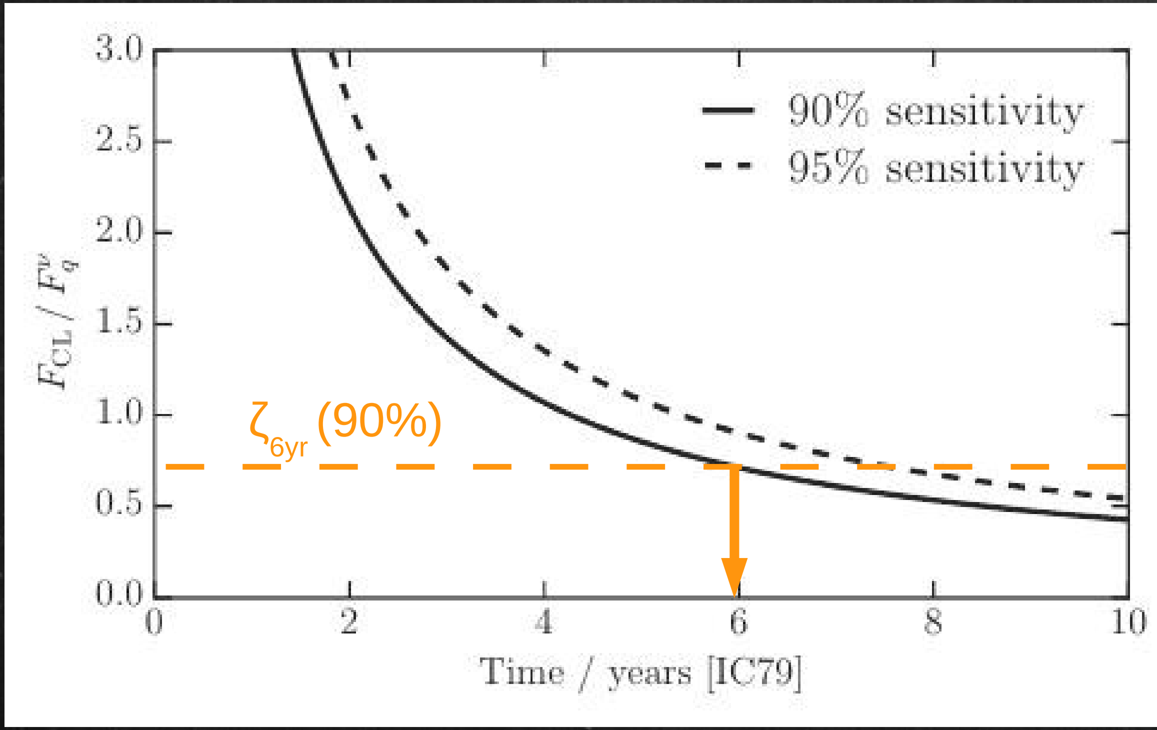
Q: What means a neutrino non-detection of Mrk 421?

A: Correlation between >1PeV ν and GeV γ-rays differs in major flares

OR

Much lower power is carried by CR in blazar jets

>100 TeV ν flux (normalized to 4e-10 erg/s/cm2) vs. T (yr) needed for IceCube ν detection at 90% (95%) CL

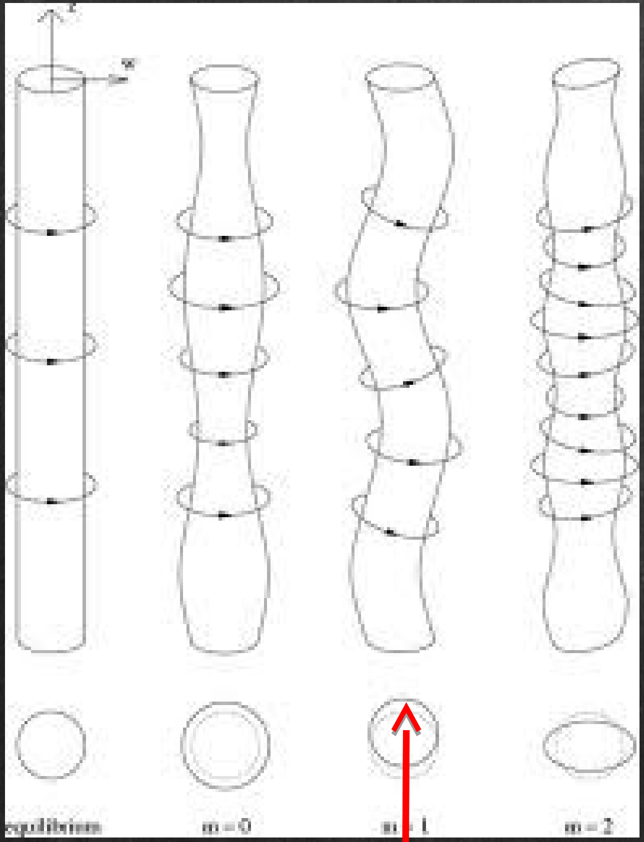


Upper limits on CR power given a non-detection (at 90%, 95% CL) of muon N (> 100 TeV) from Mrk 421 in X years.

X (yr)	ζ_X		$L_{p,X}$ (erg/s)	
	90%	95%	90%	95 %
6	0.71	0.9	6.2×10^{47}	7.8×10^{47}
8	0.53	0.68	4.6×10^{47}	5.9×10^{47}
10	0.43	0.54	3.7×10^{47}	4.7×10^{47}
20	0.21	0.27	1.8×10^{47}	2.3×10^{47}

Global instabilities

- Magnetized jets may be unstable
  (e.g. *Eichler 1993; Begelman 1998; Giannios & Spruit 2006; Porth & Komissarov 2015)*



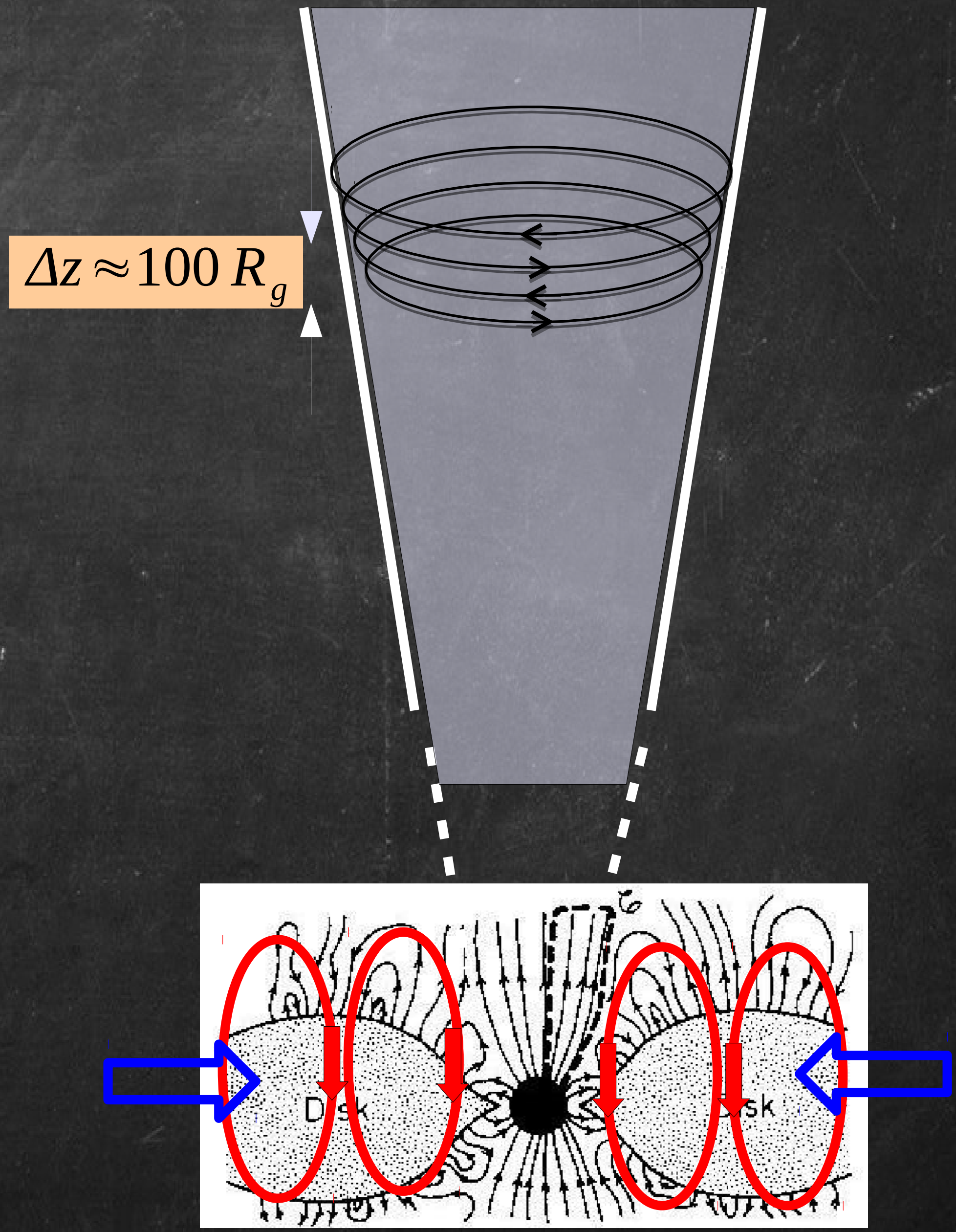
kink instability

Sites of jet's energy dissipation

(Barniol-Duran, Tchekhovskoy, Giannios, 2016)

Alternating magnetic fields

- The jet may contain field reversals with a scale ~100 R_g (e.g. *Parfrey, Giannios, Beloborodov 2015)*



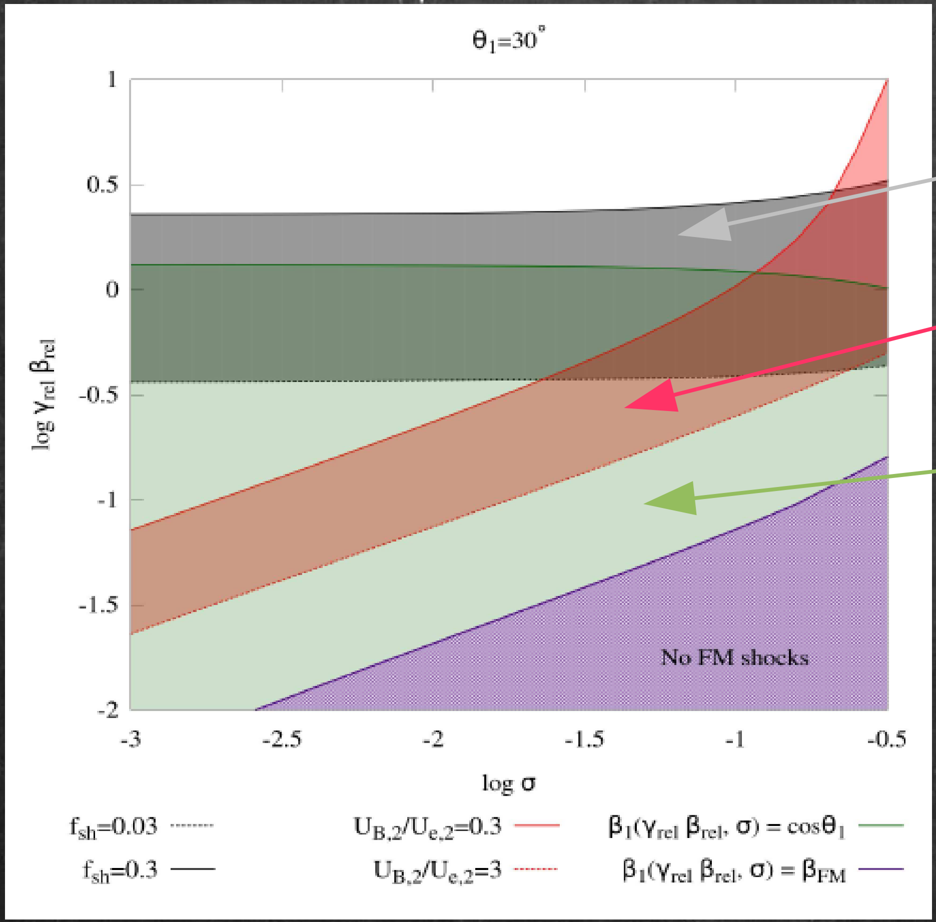
Magnetic field lines may reconnect if:

$$t_{\exp} \sim t_{rec}$$

$$\frac{z_{diss}}{\Gamma_j c} \sim \frac{100\, \Gamma_j R_g}{\varepsilon c}$$

$$z_{diss} \sim 100\, \Gamma_j^2 R_g / \varepsilon \approx 1\, pc\, M_8\, \Gamma_{j,1}^2\, \varepsilon_{-1}^{-1}$$

Relativistic magnetized shocks



4- velocity

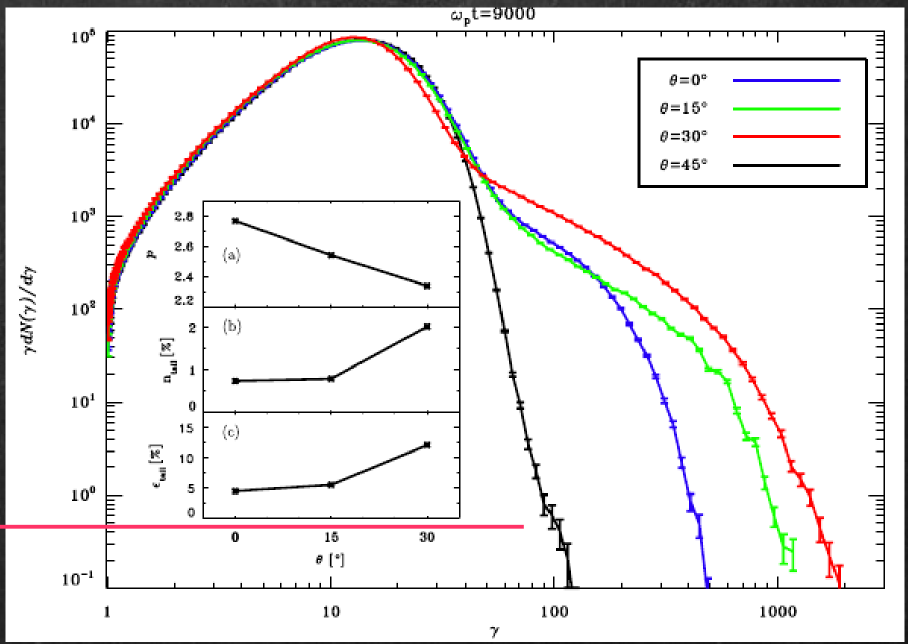
Magnetization

Dissipation efficiency

Equipartition between pairs & magnetic field

Subluminal shocks

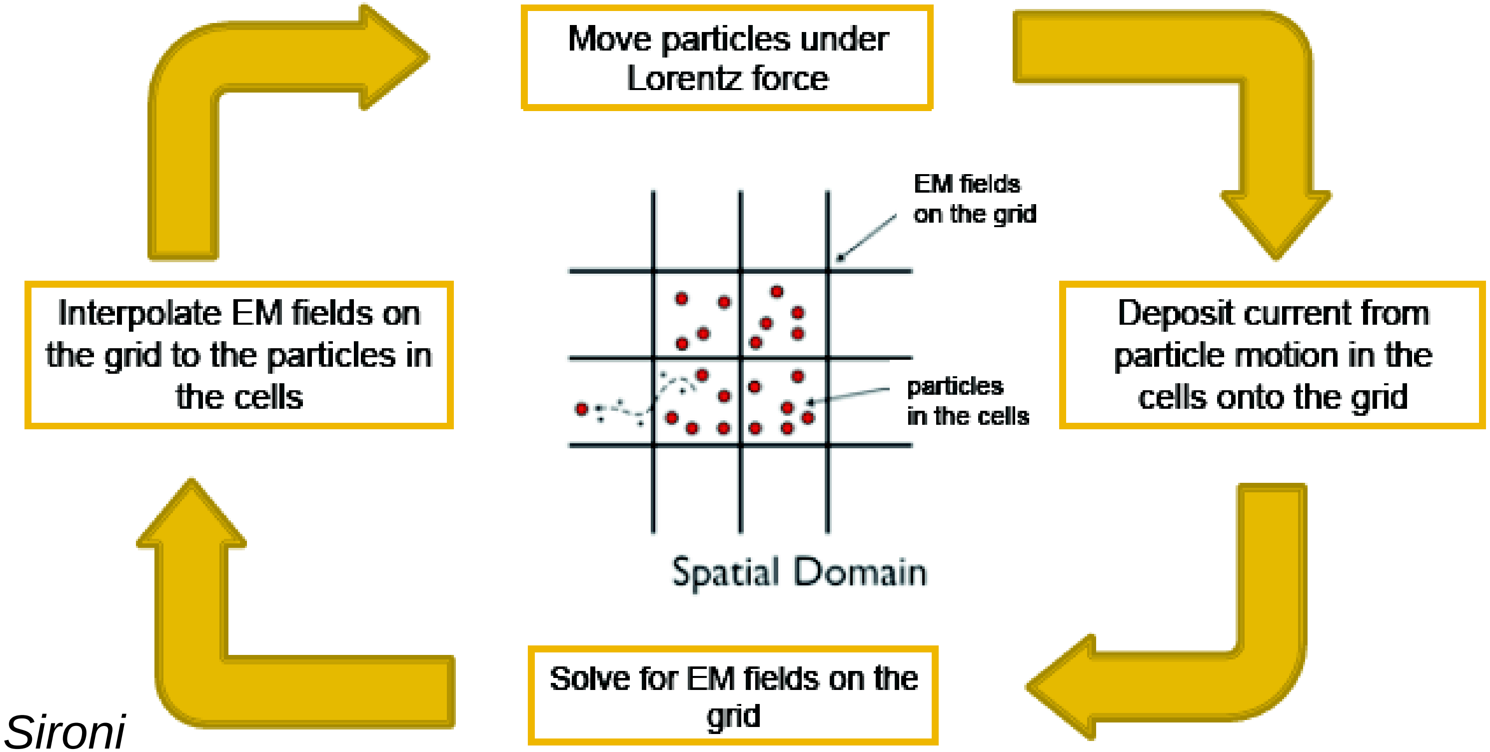
$$\cos\theta_1 < v_1/c$$



No particle acceleration for super-luminal shocks *(e.g. Kirk & Heaven 1987)*

(Sironi & Spitkovsky, 2009, MNRAS

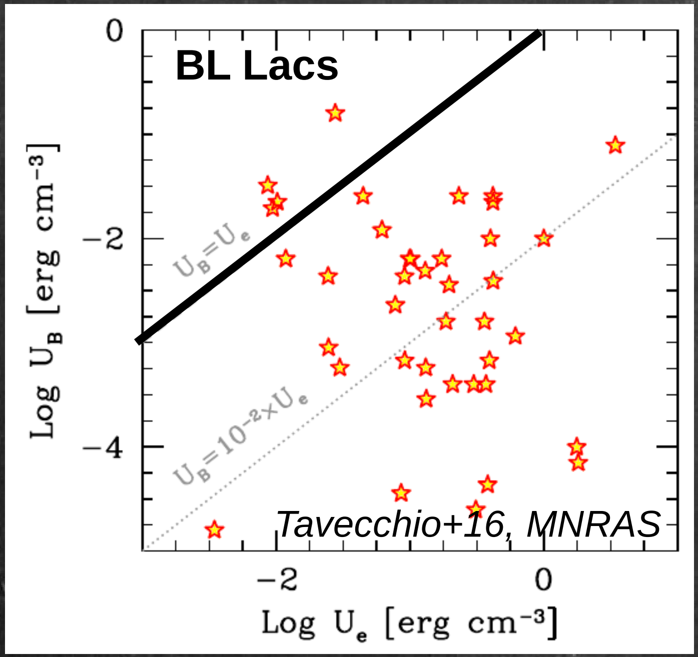
Particle-in-Cell simulations

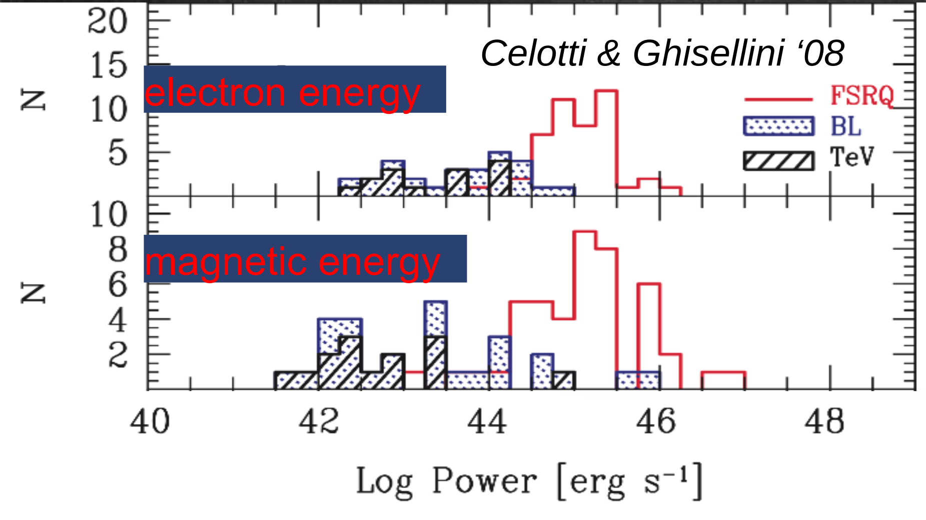


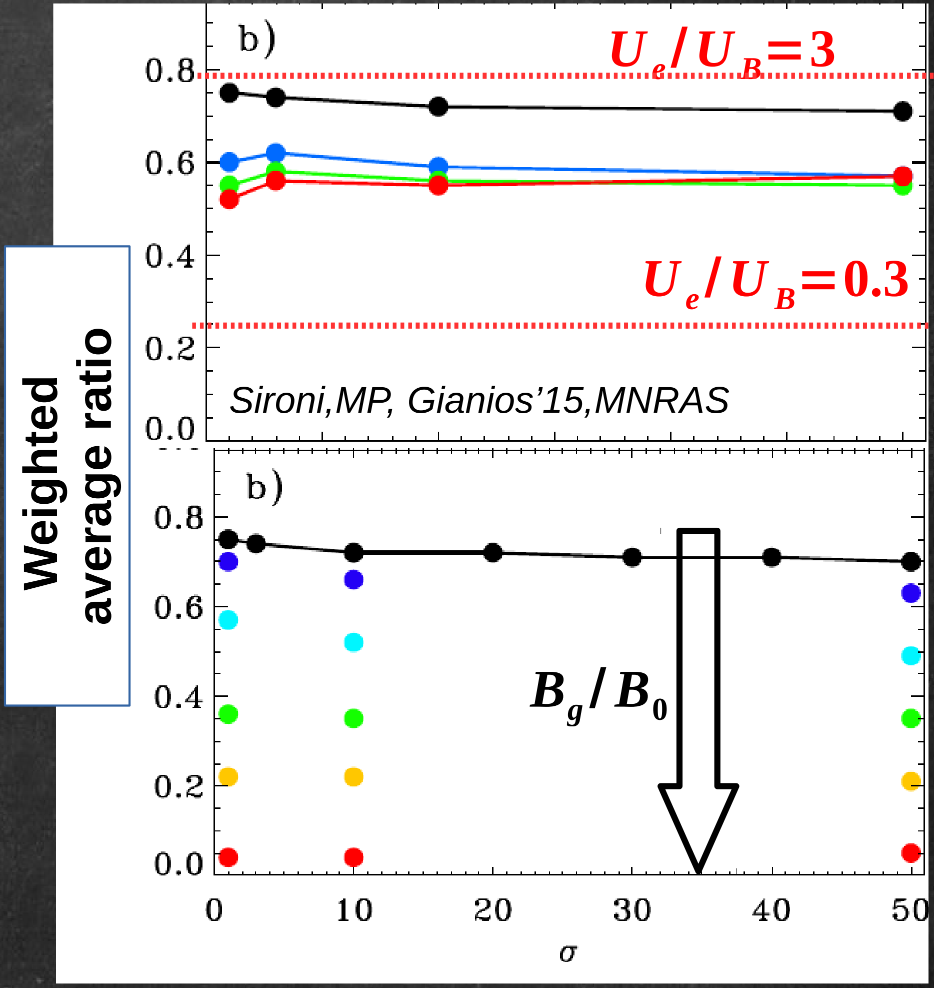
Credit: L. Sironi

- No approximations; full plasma physics of ions and electrons
- Tiny length scales need to be resolved → Large & expensive simulations
- Limited time coverage and spatial domains

Particles & fields in equipartition



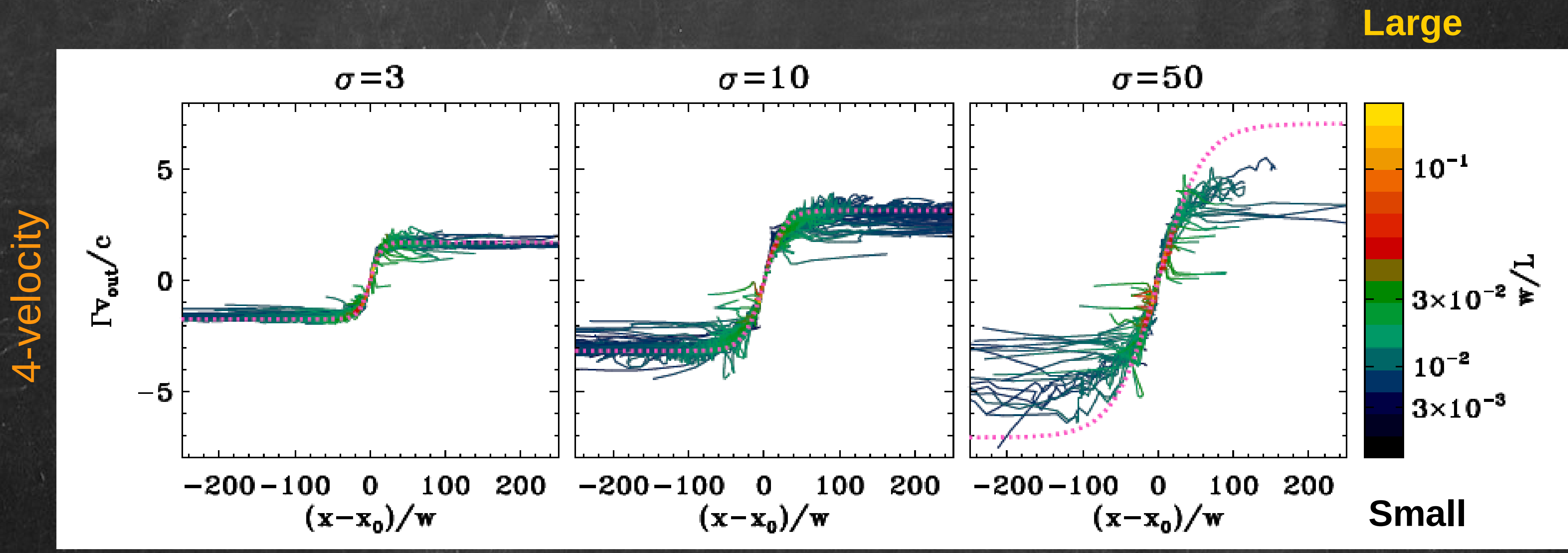




- Rough energy equipartition
- Results are model-dependent

- Rough energy equipartition
- $U_e >> U_B$ is not expected

Plasmoid acceleration



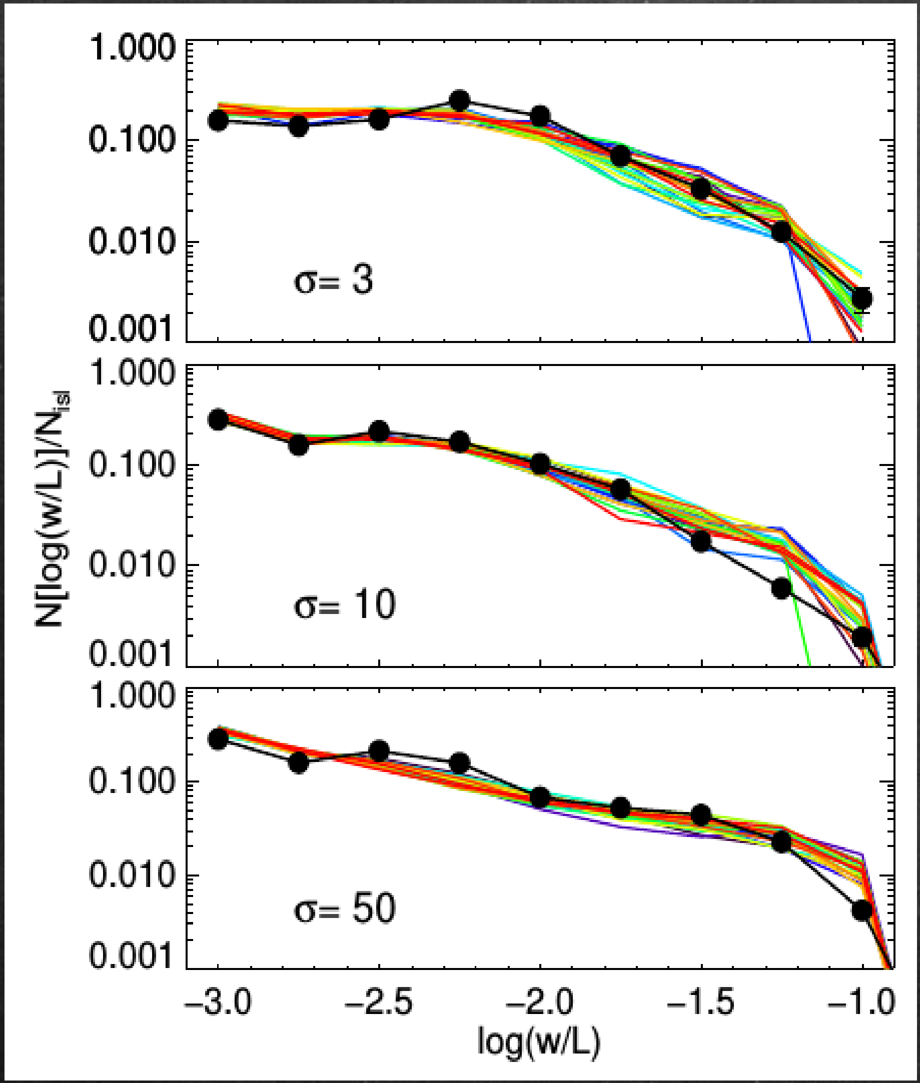
$$\beta_{co}\Gamma_{co} \approx f\left(\frac{X'}{w''}\right) \equiv \sqrt{\sigma}\tanh\left(\frac{\beta_{acc}}{\sqrt{\sigma}}\frac{X'-X'_0}{w''}\right)$$

- Acceleration due to tension force of reconnected B-field
- Universal acceleration profile
- Acceleration depends on: size & location

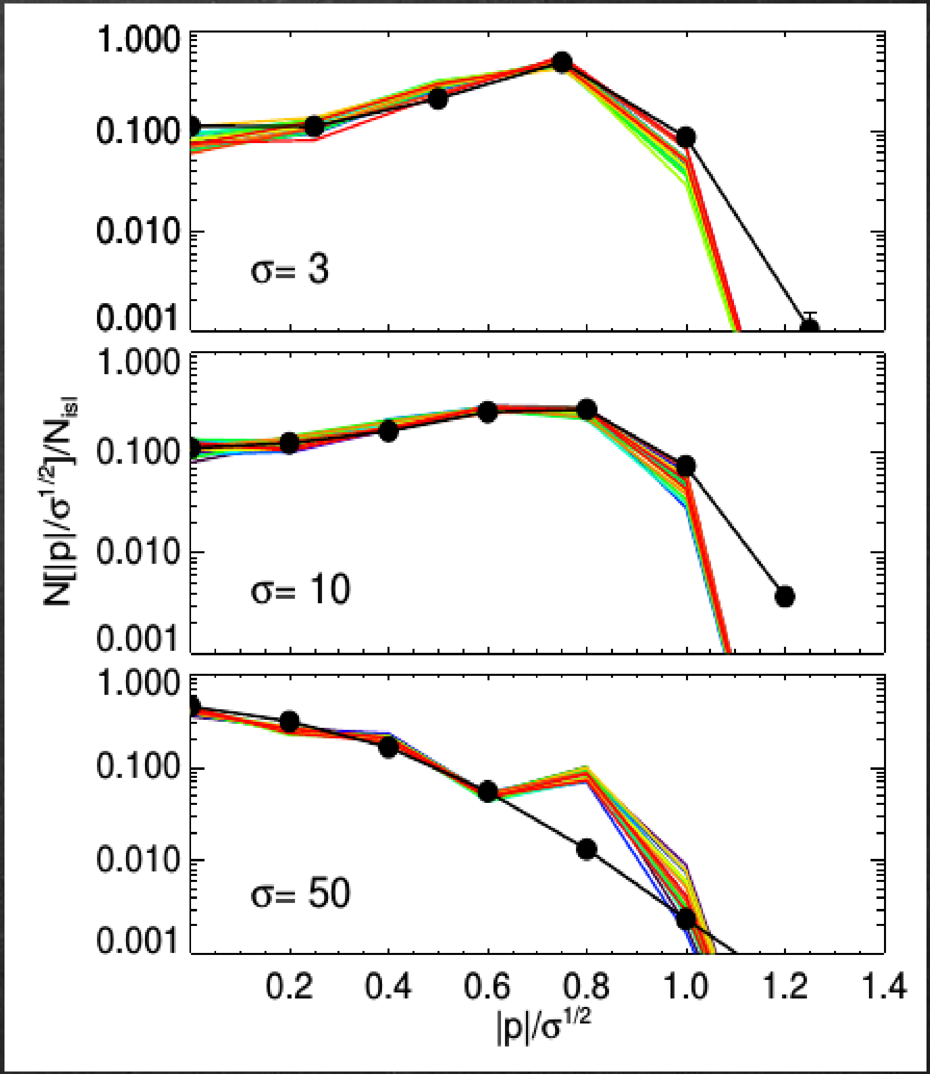
(Sironi, Giannios, Petropoulou 2016)

Plasmoid distributions

Distribution of sizes



Distribution of 4-velocities



*(**MP**, Christie + 2018, MNRAS)*