# MAGNETIC RECONNECTION IN RELATIVISTIC JETS

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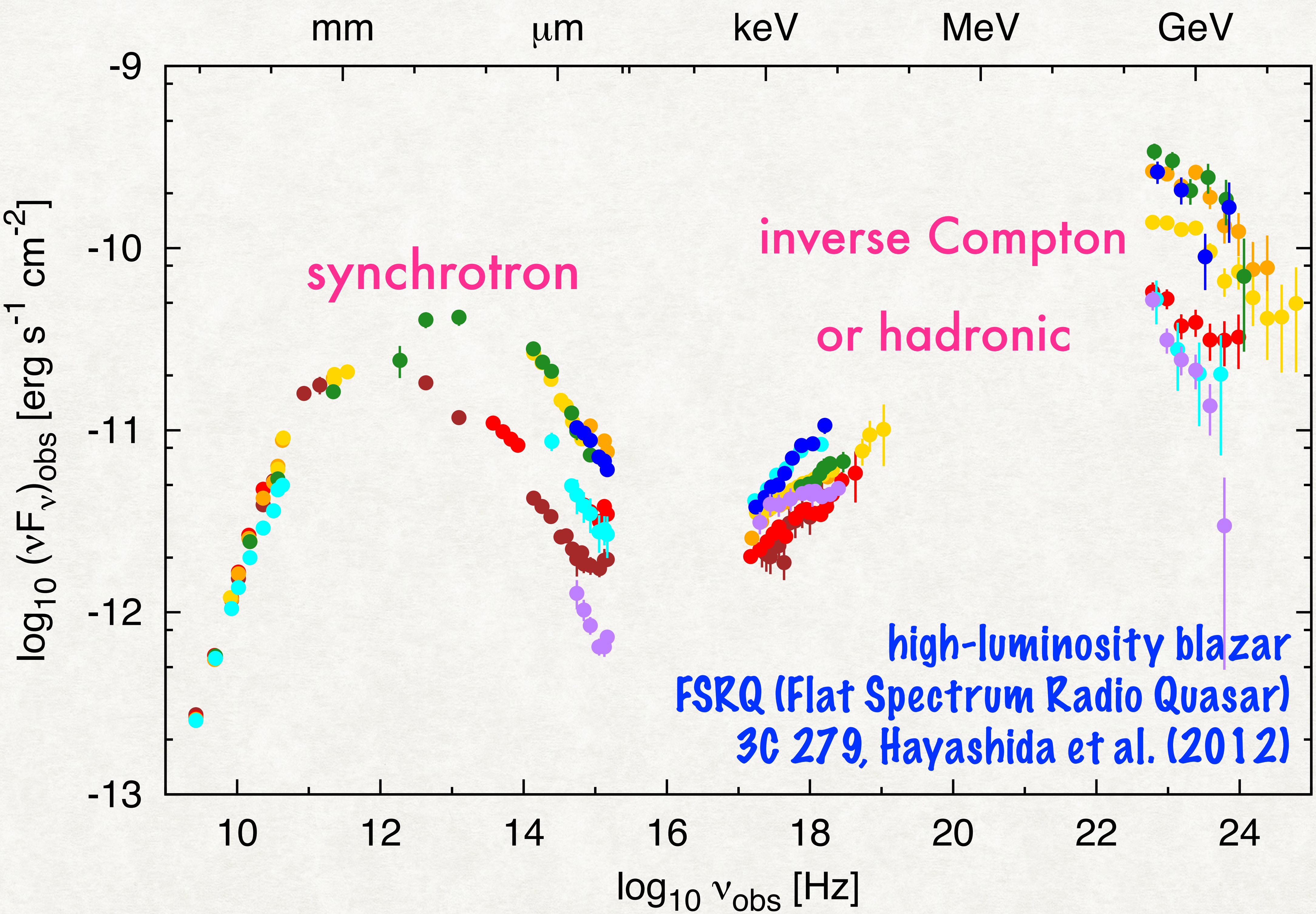
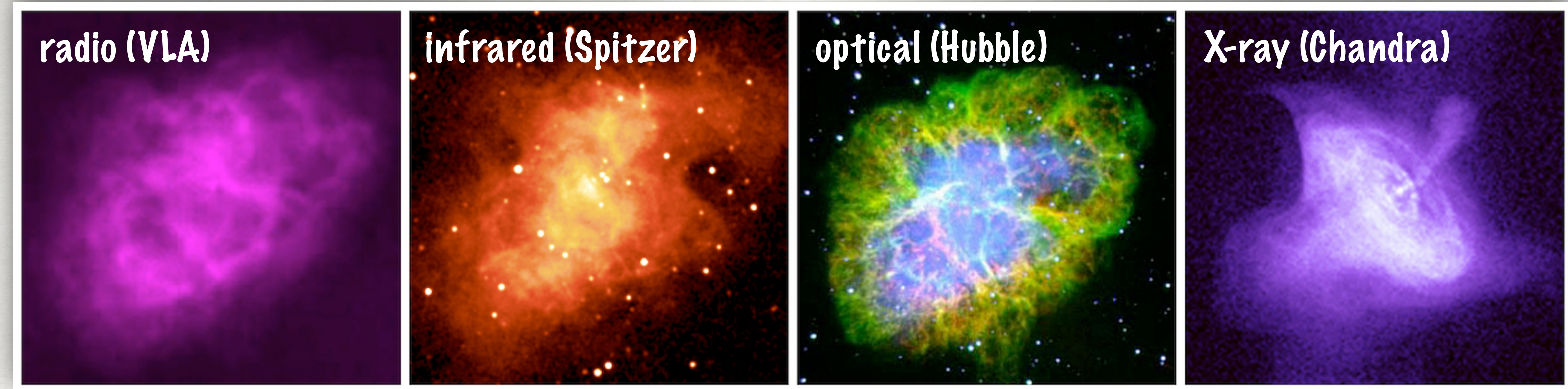
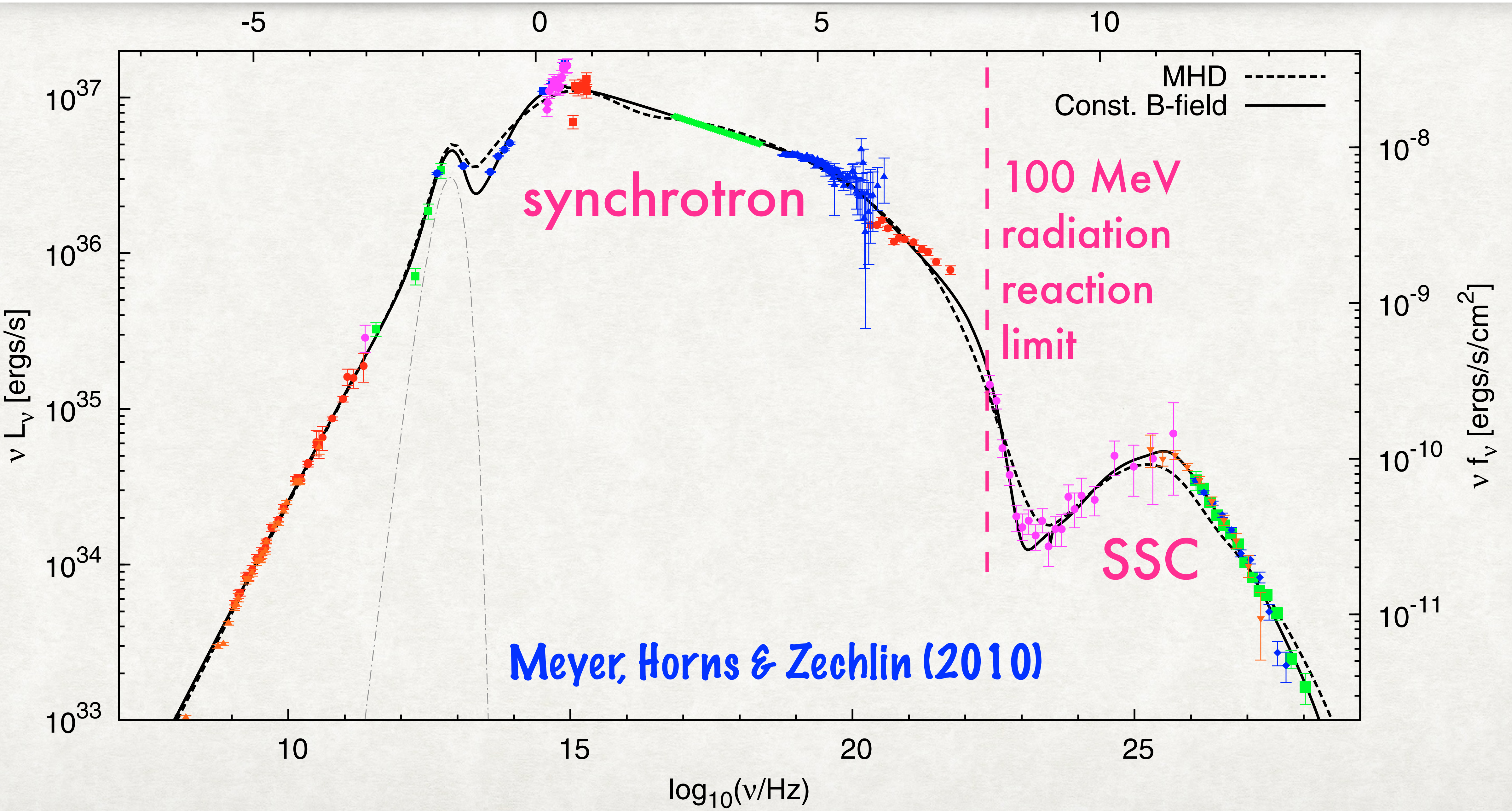
POLAND

# Spectral Energy Distributions of Blazars

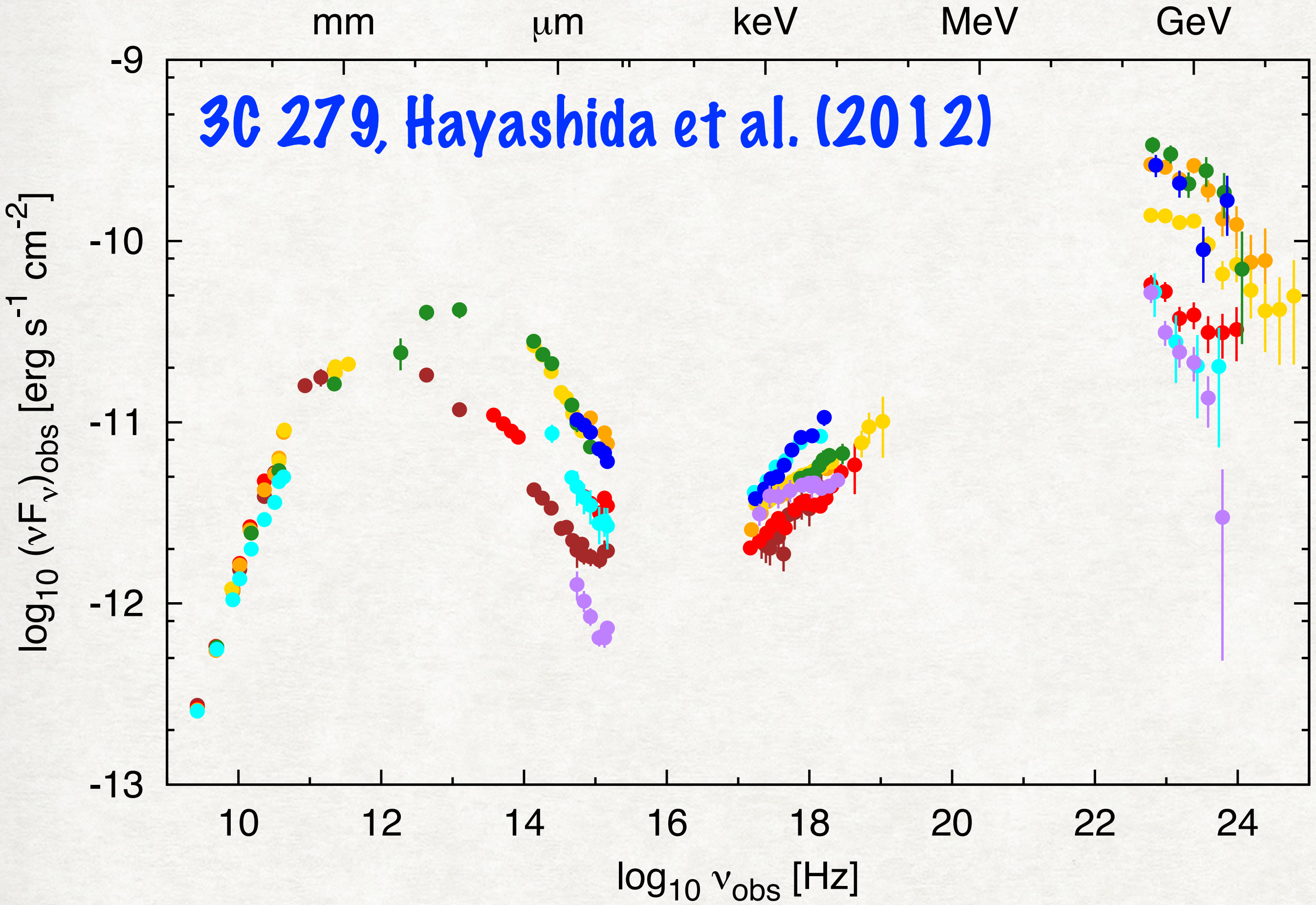


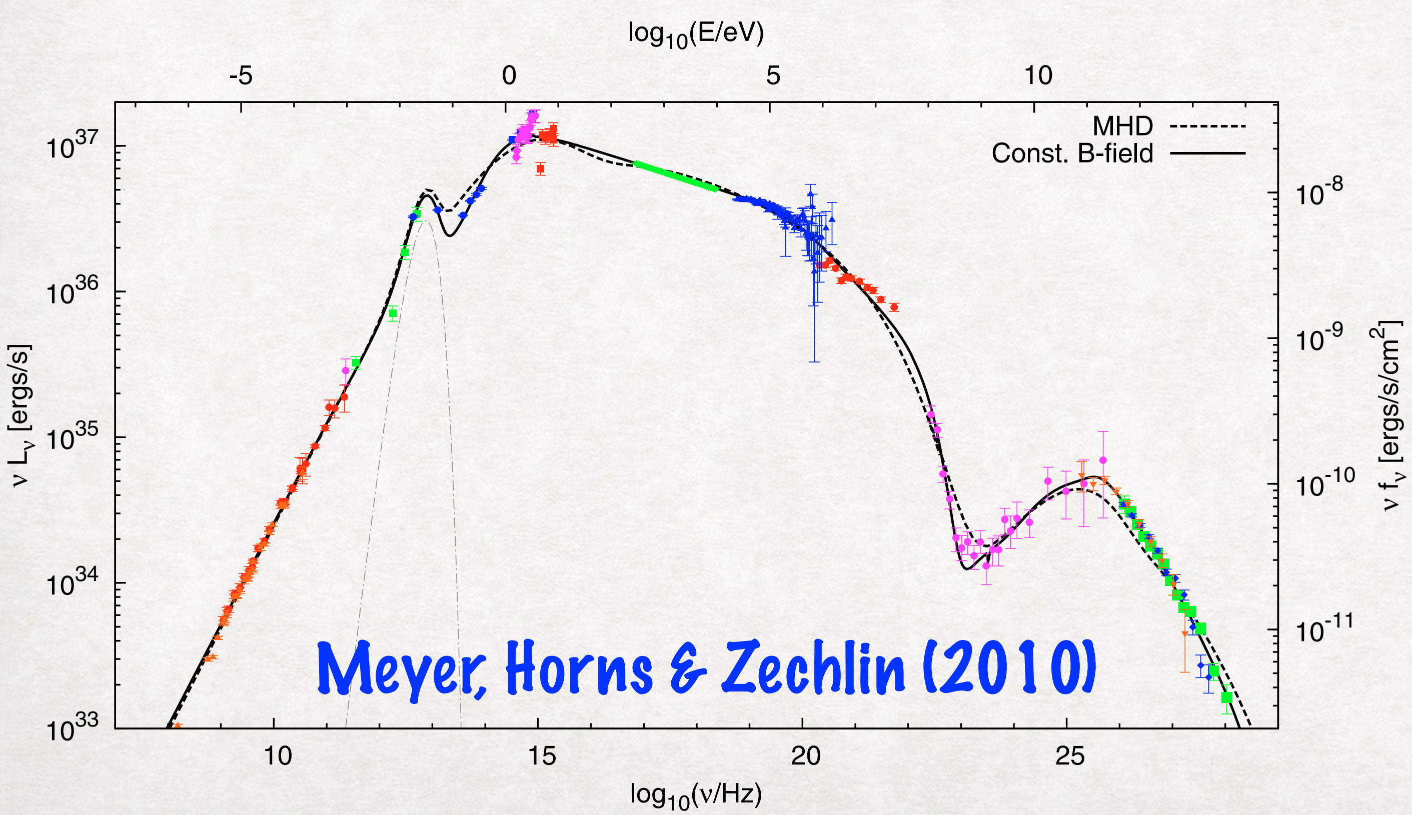

- despite strong variability, the SED is stable, electron distribution is robust


radio (VLA)
infrared (Spitzer)
optical (Hubble)
X-ray (Chandra)


-5
0
5
10
MHD
Const. B-field
synchrotron
100 MeV
radiation
reaction
limit
SSC
Meyer, Horns & Zechlin (2010)
$10^{37}$
$10^{36}$
$10^{35}$
$10^{34}$
$10^{33}$
$\nu L_\nu$ [ergs/s]
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$\nu f_\nu$ [ergs/s/cm$^2$]
10
15
20
25
$\log_{10}(\nu/\mathrm{Hz})$

# WHY ARE BLAZAR SEDS NOT CRAB-LIKE?




- synchrotron SED of the Crab extends to 100 MeV
- synchrotron SED of FSRQs extends to 10 eV / Doppler
- what determines $\gamma_{\rm max} \sim 10^3$ in FSRQs?
- a radiative cooling limit implies $\xi = \lambda_{mfp}/R_{\rm L} \sim 10^7$ for shocks **(Inoue & Takahara 1996)** or $\beta_{\rm rec} = E/B \sim 10^{-9}$ for reconnection **(KN 2016)**

# Hard Particle Spectra in Relativistic Reconnection

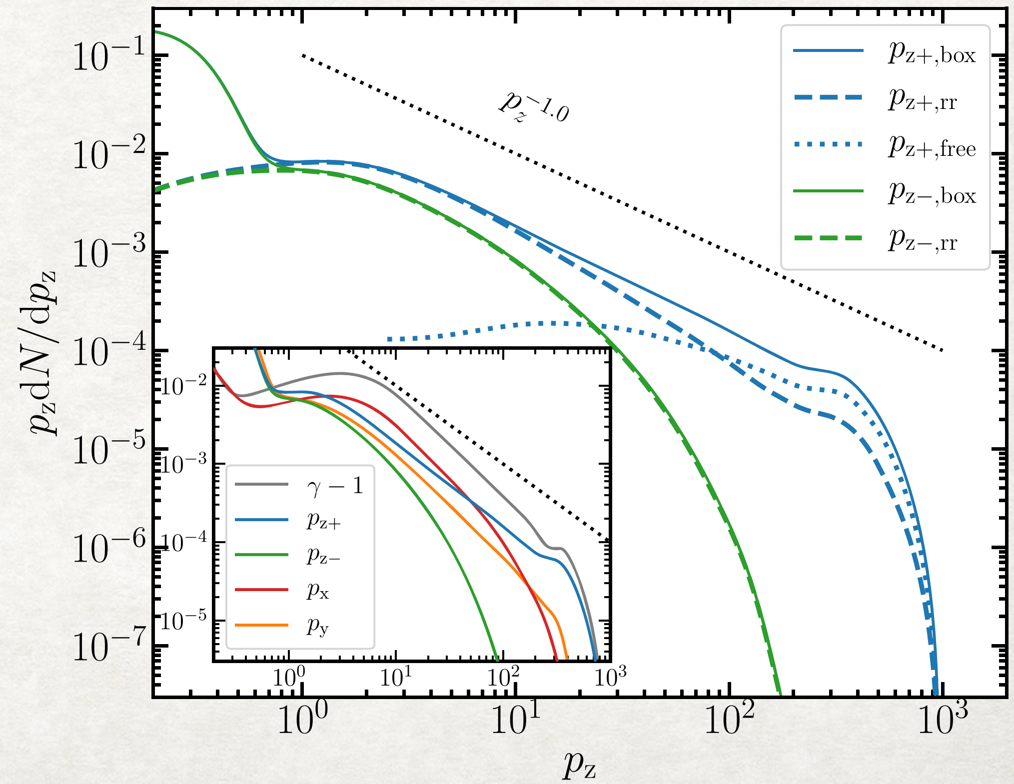
- reconnection produces power-law distributions that are hardening with increasing sigma
  $dN/d\gamma \propto \gamma^{-p}$ with $p \to 1$ for $\sigma \gg 1$
  (Sironi & Spitkovsky 2014, Guo et al. 2014, Werner et al. 2016)

- high-energy cut-off is exponential with $\gamma_{\max} \sim \mathcal{O}(\sigma)$

- $p \to 2$ in very large plasmoids in 2D
  (Petropoulou & Sironi 2018)

- 3D relativistic reconnection produces hard particle spectra
  $f(\gamma) \propto \gamma^{-p}$ with $p \sim 1.5$
  (Zhang, Sironi & Giannios 2021)

Zhang, Sironi & Giannios (2021)



# EXTREME LOCAL MAGNETIZATIONS IN JETS?

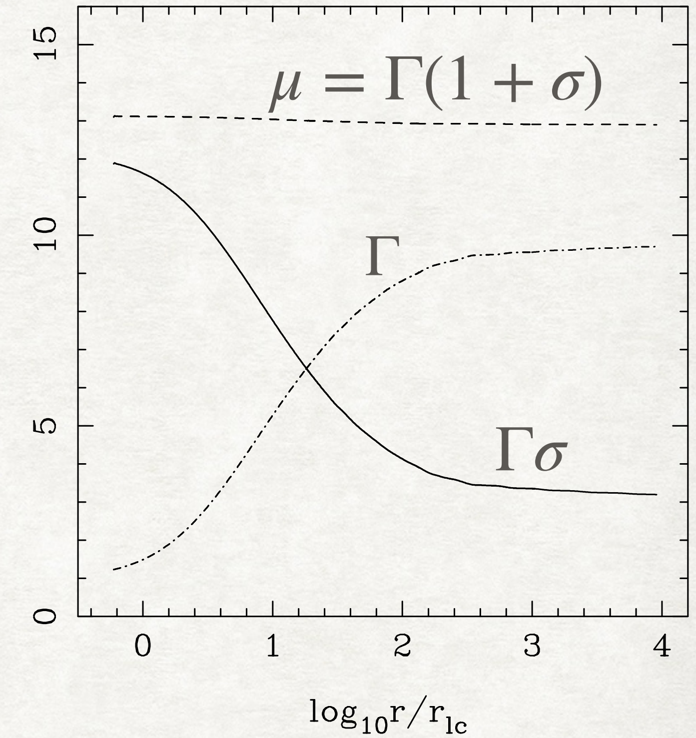
- maximum electron energy limited by maximum local electron magnetization $\gamma_{\rm e,max} \sim \sigma_{\rm e,max} \sim 10^6$ for BL Lacs ($10^3$ for FSRQs) **(KN 2016, Sobacchi & Lyubarsky 2020)**

- mean initial total magnetization for bulk jet acceleration $\langle \sigma_{\rm tot,ini} \rangle \sim \Gamma_{\rm jet} \sim 20$

- caveat 1: whether shocks or reconnection, emitting regions close to equipartition, can be very different from the background **(Sironi, Petropoulou & Giannios 2015)**

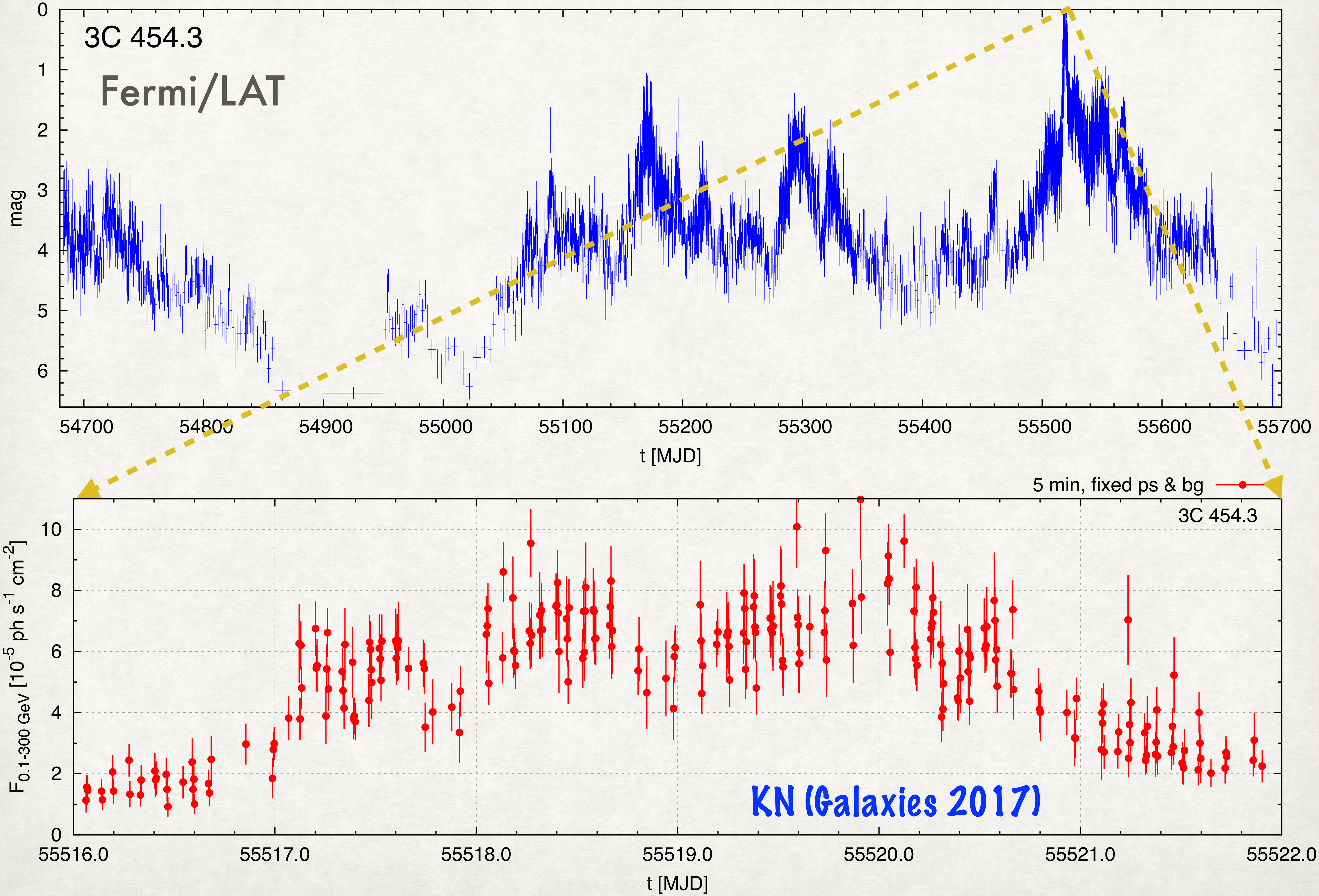
- caveat 2: distinguish electron and proton magnetizations
  $\sigma_{\rm e}/\sigma_{\rm p} \sim (m_{\rm p}/m_{\rm e})\,(\,<\gamma_{\rm e}>/<\gamma_{\rm p}>\,)^{-1}\,(n_{\rm e}/n_{\rm p})^{-1} \gg 1$

- the magnetization of jets may be highly inhomogeneous, e.g., due to filamentary proton loading **(KN 2016)**

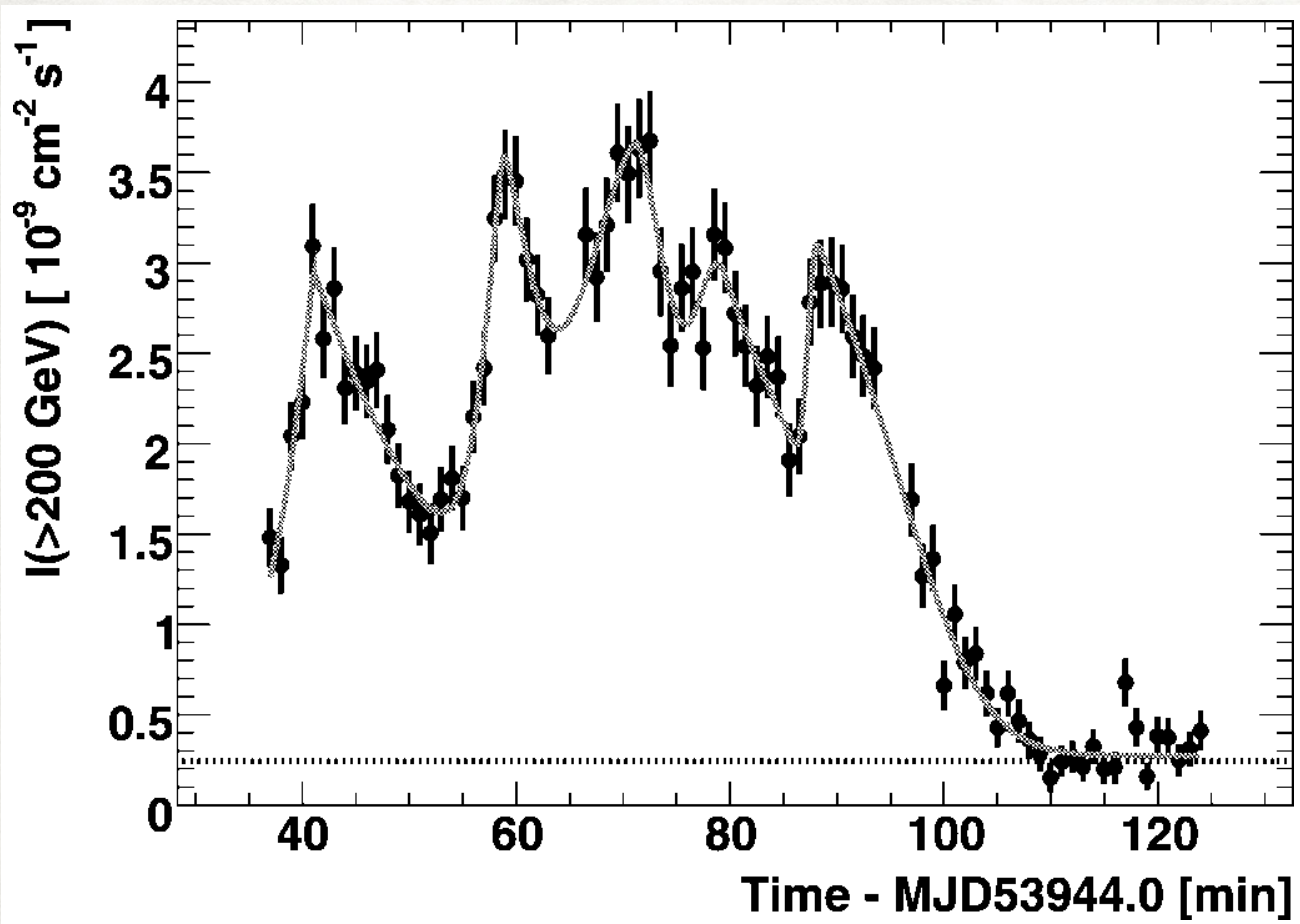



**Komissarov et al. (2007)**

# Gamma-ray variability of blazars



# Rapid TeV Variability



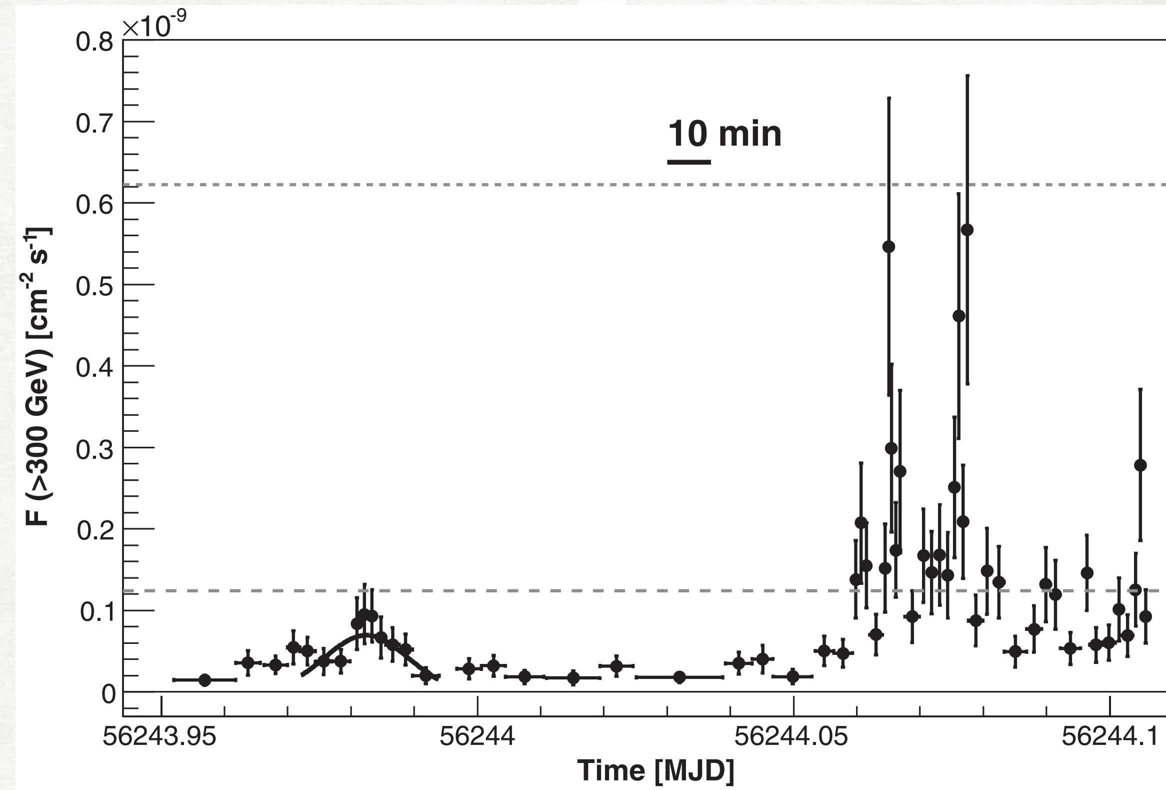



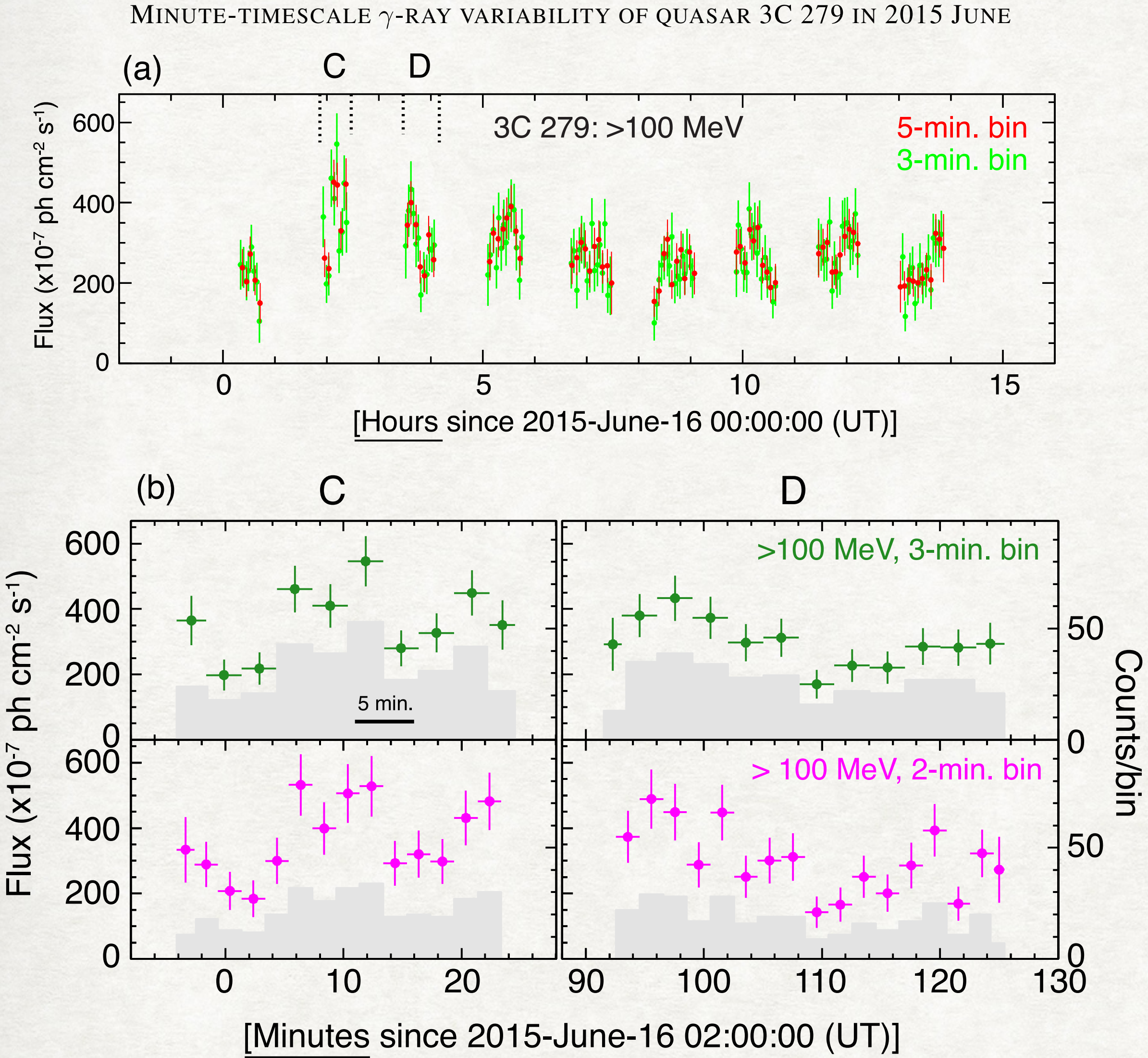

**Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes on the night of 12/13 November 2012, above 300 GeV.** As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972-56243.994) has been fitted with a Gaussian distribution. Vertical error bars show 1 SD statistical uncertainity. Horizontal error bars show the bin widths.

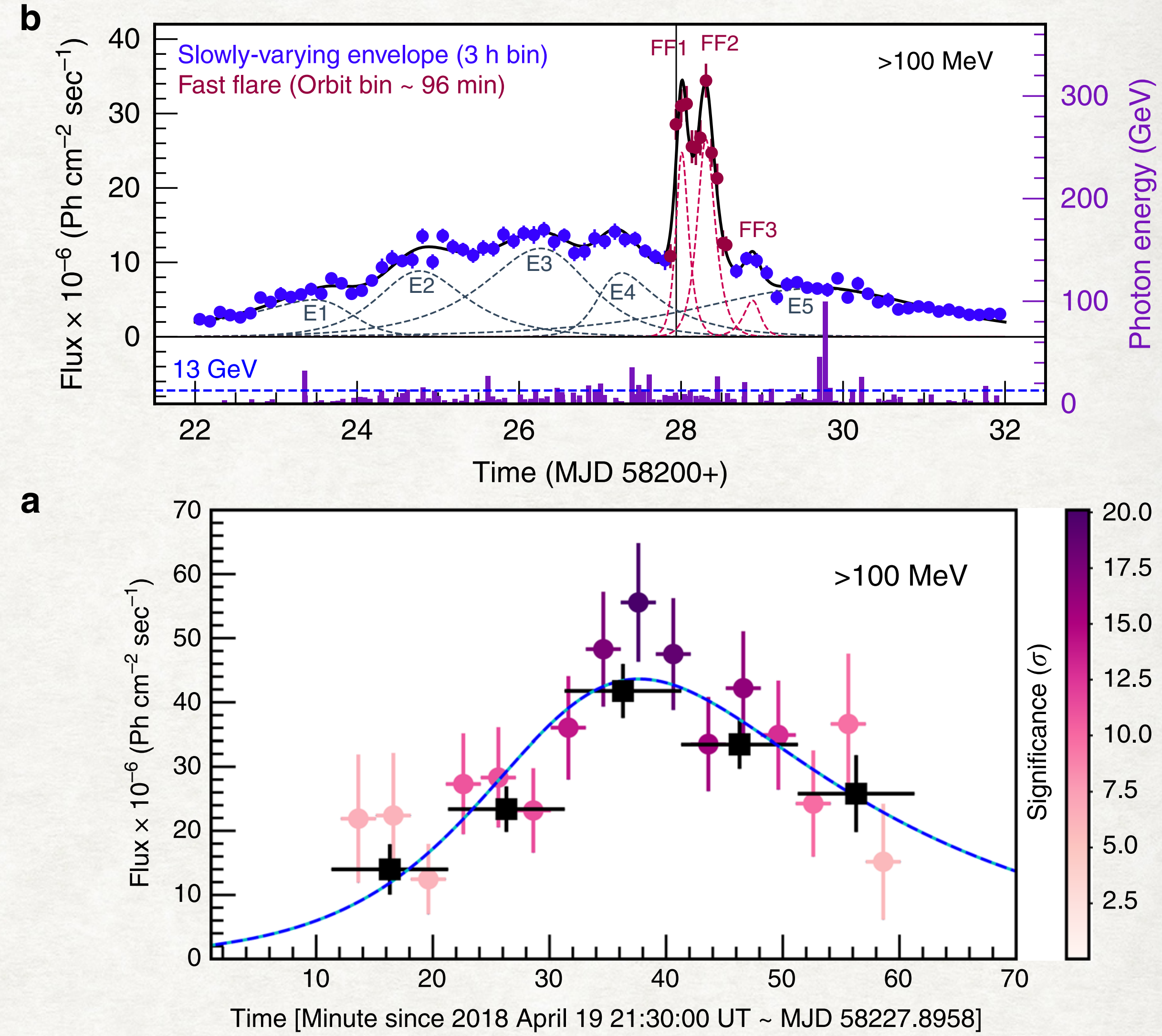
PKS 2155-304
H.E.S.S. Collaboration (2007)

IC 310
MAGIC Collaboration (2014)

- low-power BL Lacs / FR Is: gamma-ray emission could be produced very close ( $\sim 10^{1-2}\,R_{\rm g}$) to the SMBH

# RAPID GEV VARIABILITY




**Fermi-LAT Collaboration (Ackermann et al. 2016)**

see also Meyer, Scargle & Blandford (2019)

**Shukla & Mannheim (Nature Comm. 2020)**

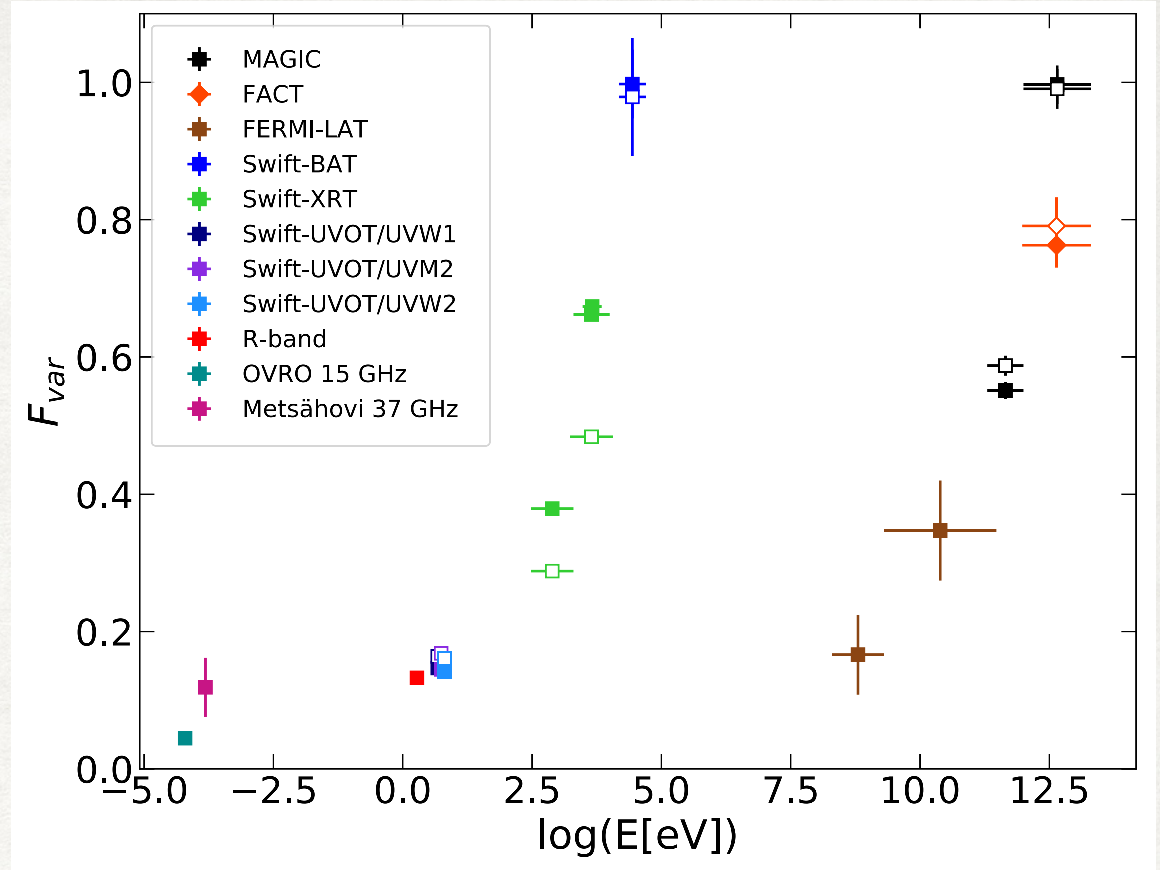
- high-power FSRQs: gamma-rays would be absorbed if produced too close ($\lesssim 10^{4-5}\,R_{\rm g}$) to the SMBH
- energy density challenge: how to put a large fraction of jet power through a tiny cross section? **(KN et al. 2012)**

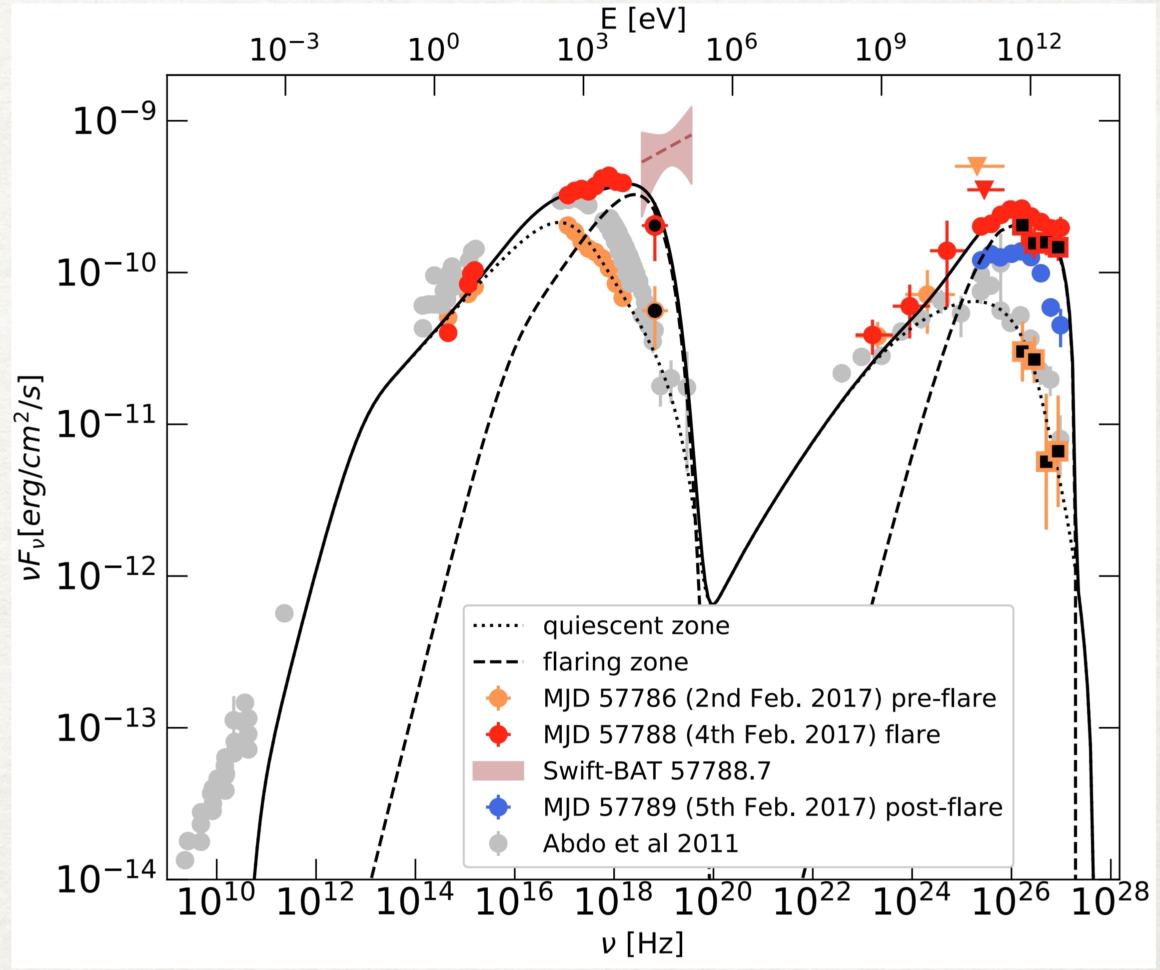
# Multiwavelength variability

- fractional variability

$$F_{\text{var}} = \sqrt{\frac{S^2 - \langle \sigma_{\text{err}}^2 \rangle}{\langle x \rangle^2}}$$

- variability is the strongest for synchrotron and IC signals produced by electrons with $\gamma \sim \gamma_{\max}$

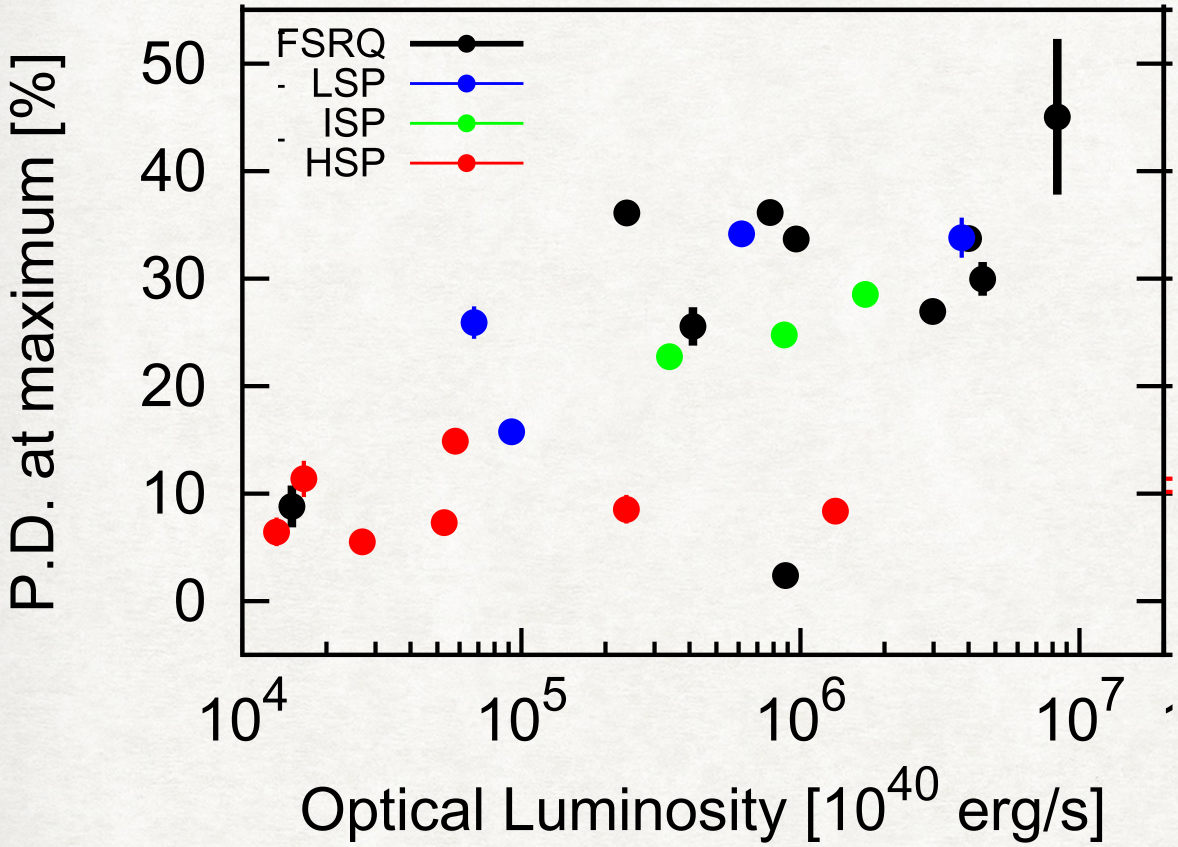


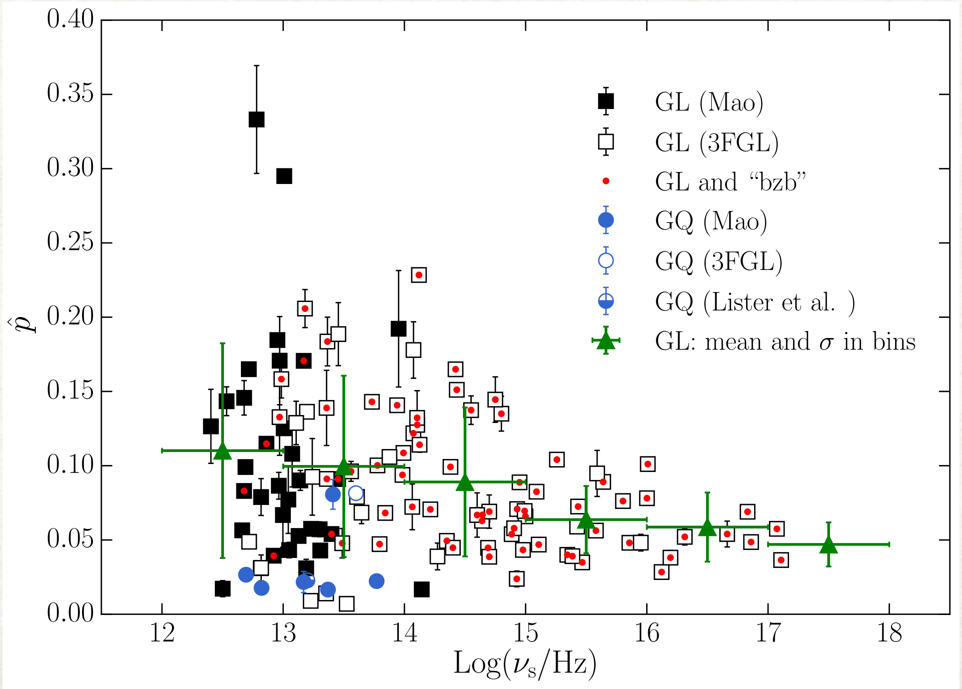

Mrk 421 (Acciari et al. 2021)

# Optical polarization of blazars

Itoh et al. (2016)

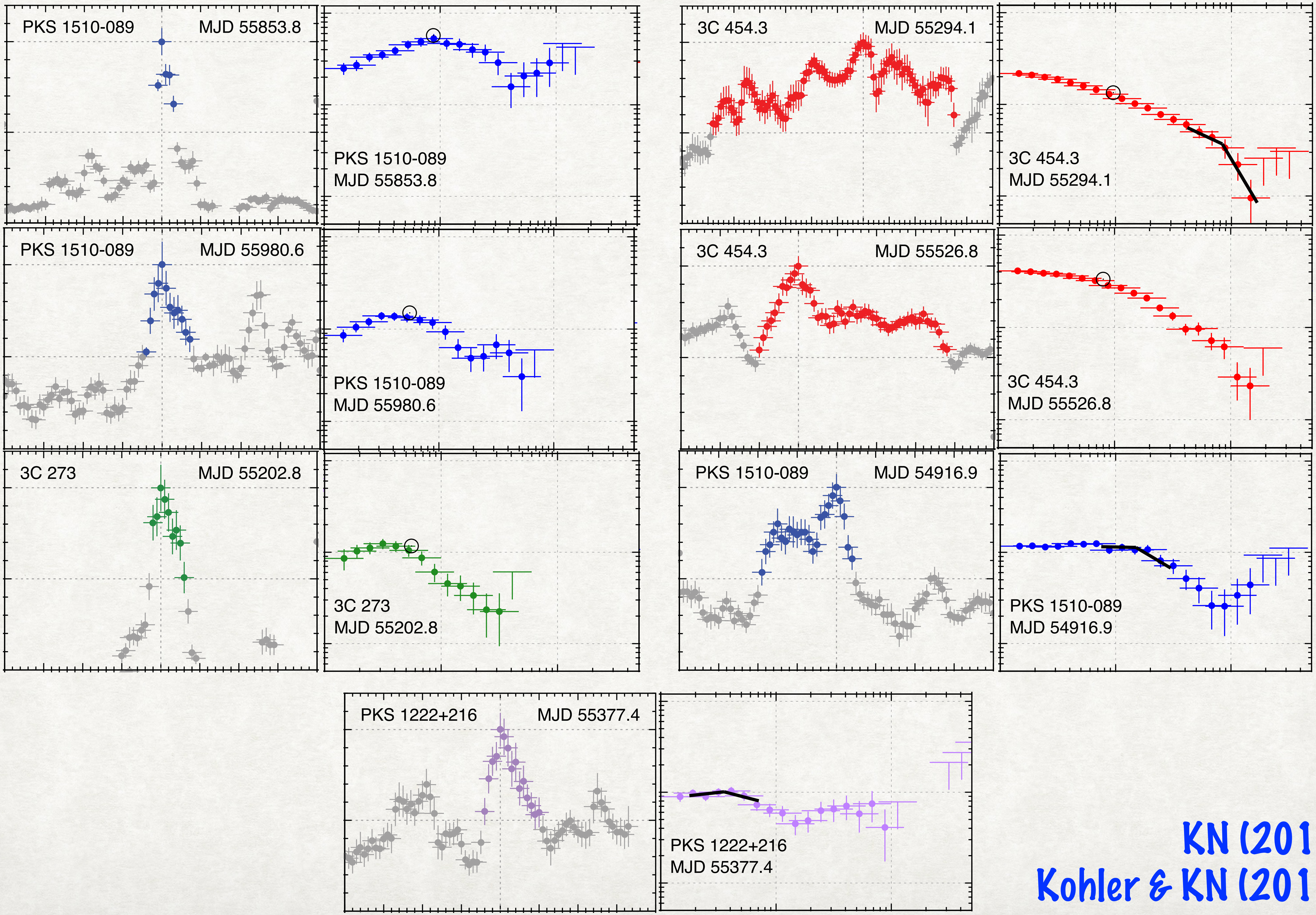



Angelakis et al. (2016)



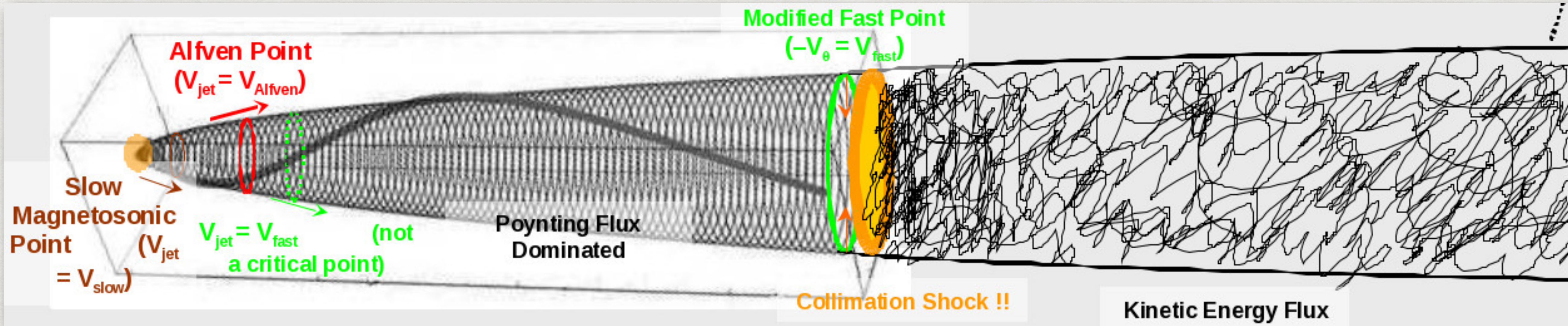

- FSRQs show systematically higher optical polarization and variability than BL Lacs
- synchrotron SED of FSRQs extend to optical, of BL Lacs to X-rays
- optical emission of FSRQs produced by $\gamma \sim \gamma_{\rm max}$ electrons, of BL Lacs by $\gamma \ll \gamma_{\rm max}$ electrons
- BL Lacs depolarized due to larger number of emitting regions (turbulent eddies?)
- prediction for IXPE: HBLs should be highly polarized $\Pi \sim 40\,\%$ !

# SIMPLE VS COMPLEX BLAZAR FLARES

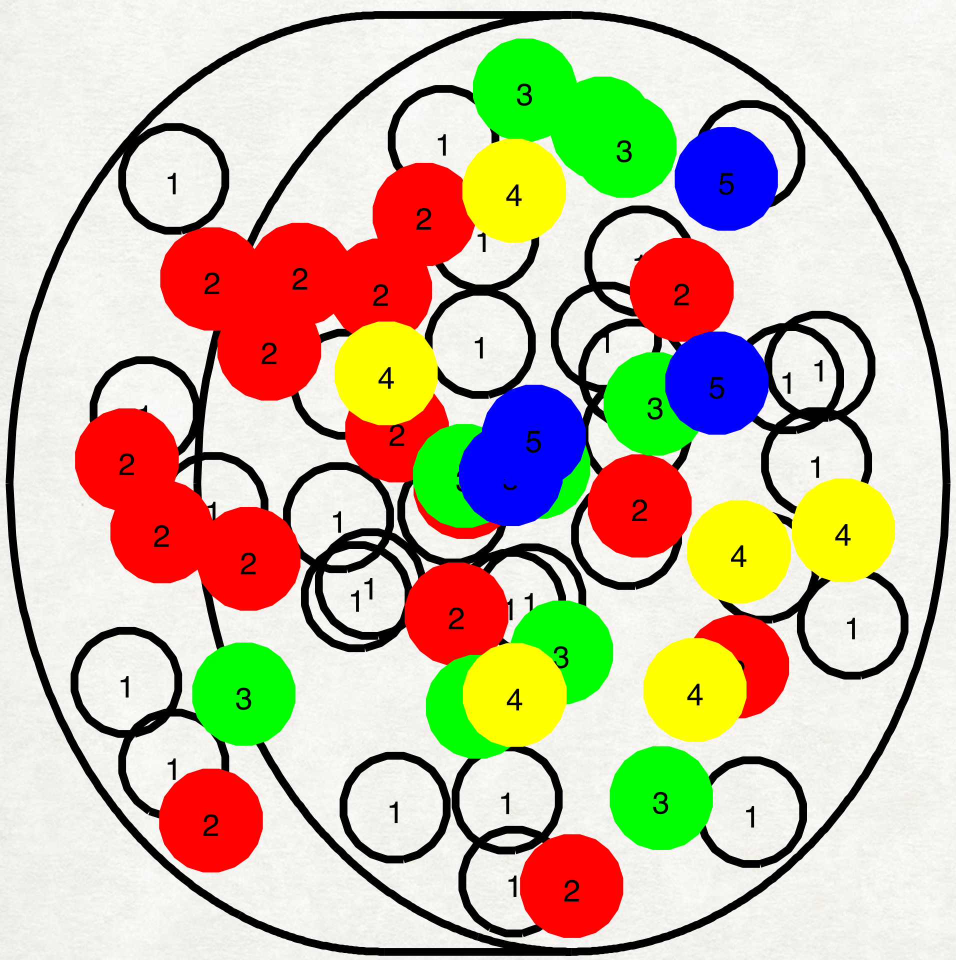



KN (2013)
Kohler & KN (2015)

# Are relativistic jets turbulent?



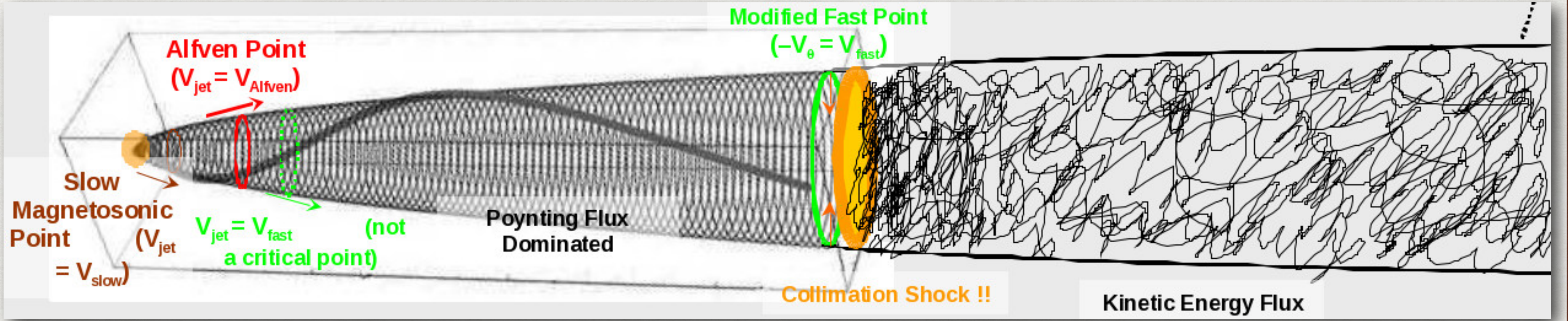

D. Meier

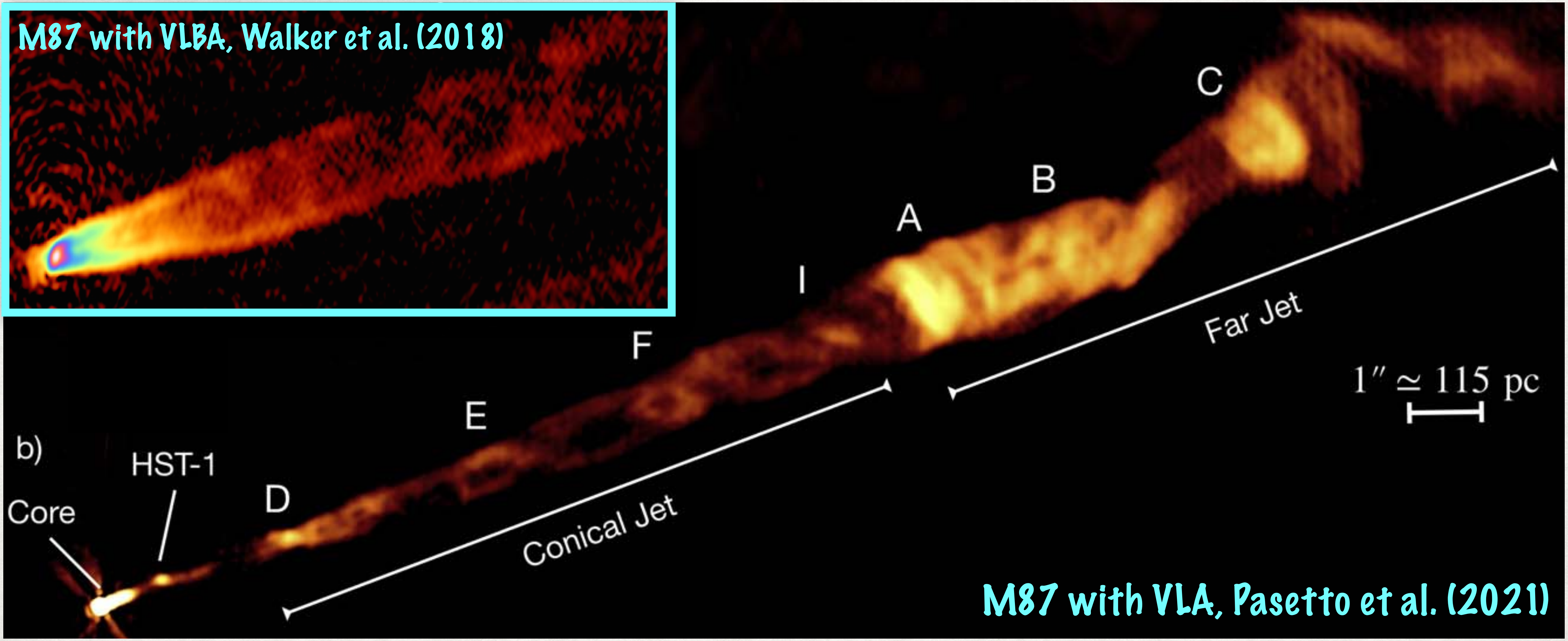


Marscher & Jorstad (2010)

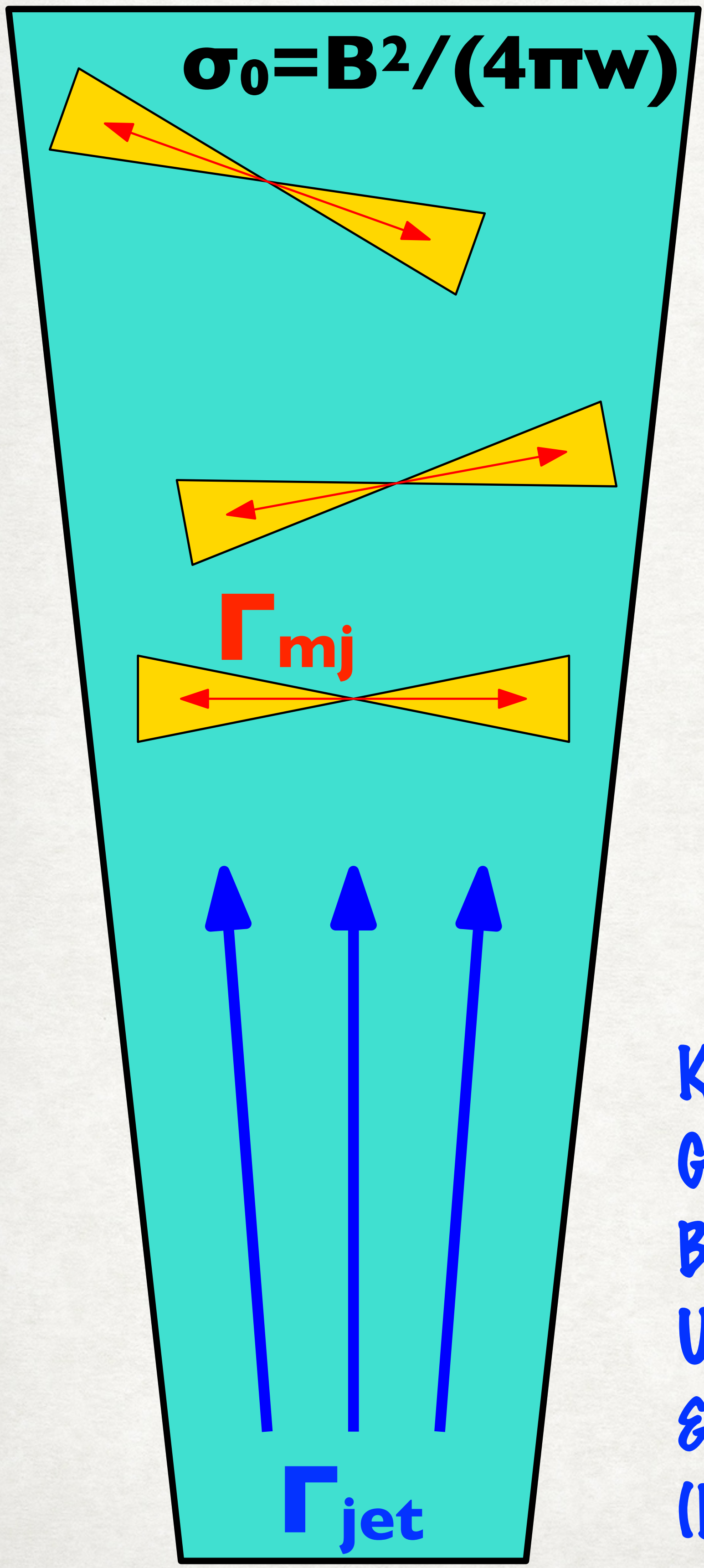
- individual turbulent eddies may produce electron distributions with different $\gamma_{\max}$ and random polarization angles
- distribution of $\gamma_{\max}$ values would explain fractional variabilities $F_{\mathrm{var}}(\nu_{\mathrm{obs}})$ and polarization degrees $\Pi(\nu_{\mathrm{obs}})$

# IS THERE A TRANSITION FROM ORDER TO TURBULENCE?



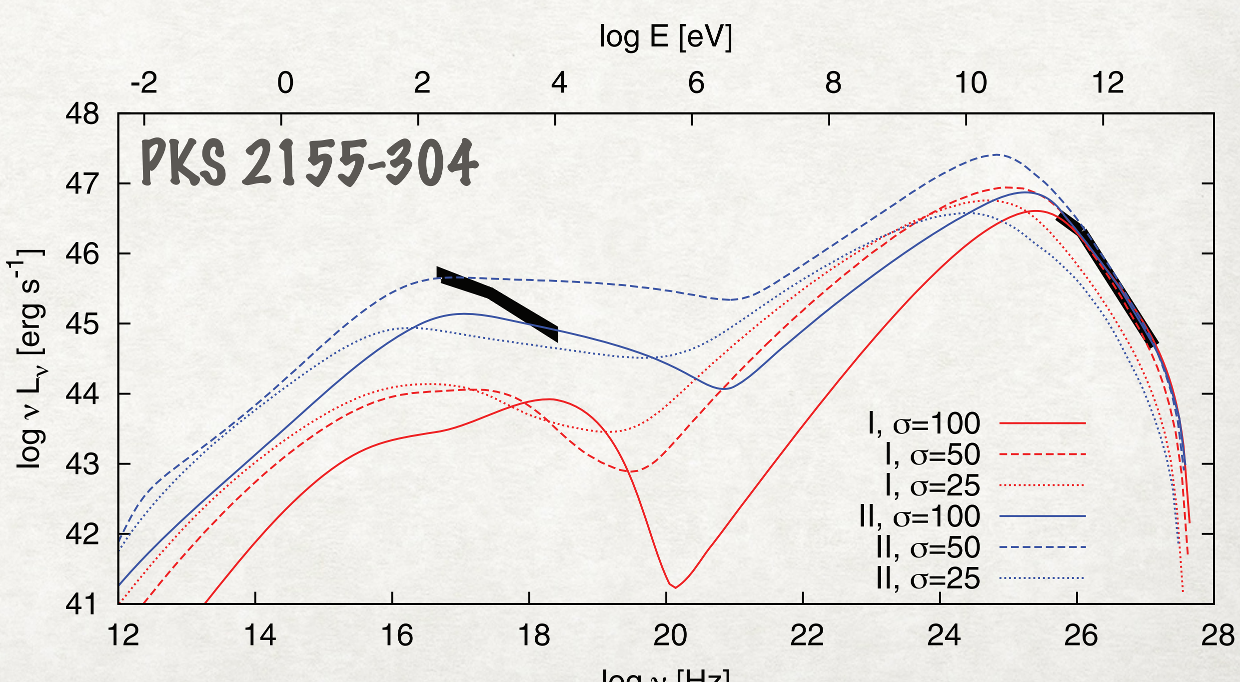



# MINIJETS MODEL

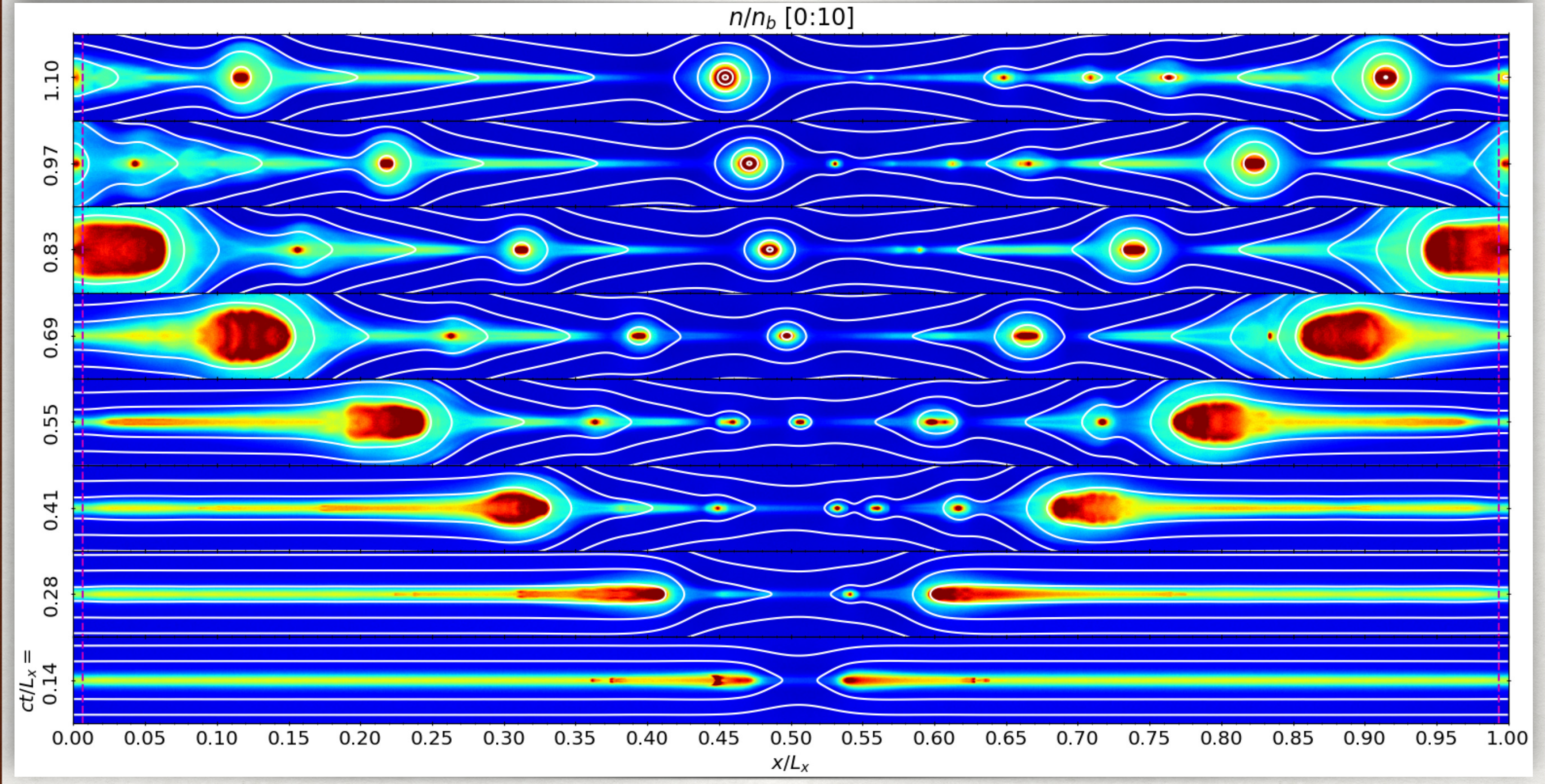



- reconnection produces localized relativistic outflows (minijets) with $\Gamma_{mj}$ within a larger relativistic jet
- explains additional relativistic Lorentz boost ($\Gamma_{fl}\sim\Gamma_{jet}\Gamma_{mj}$) and local dissipation
- based on relativistic Petschek reconnection model (Lyubarsky 2005)
- depends on the scaling of minijet Lorentz factor with jet magnetization $\Gamma_{mj} \propto \sigma_0^{1/2}$ in relativistic regime (Giannios, Uzdensky & Begelman 2009)

KN, Giannios, Begelman, Uzdensky & Sikora (MNRAS 2011)



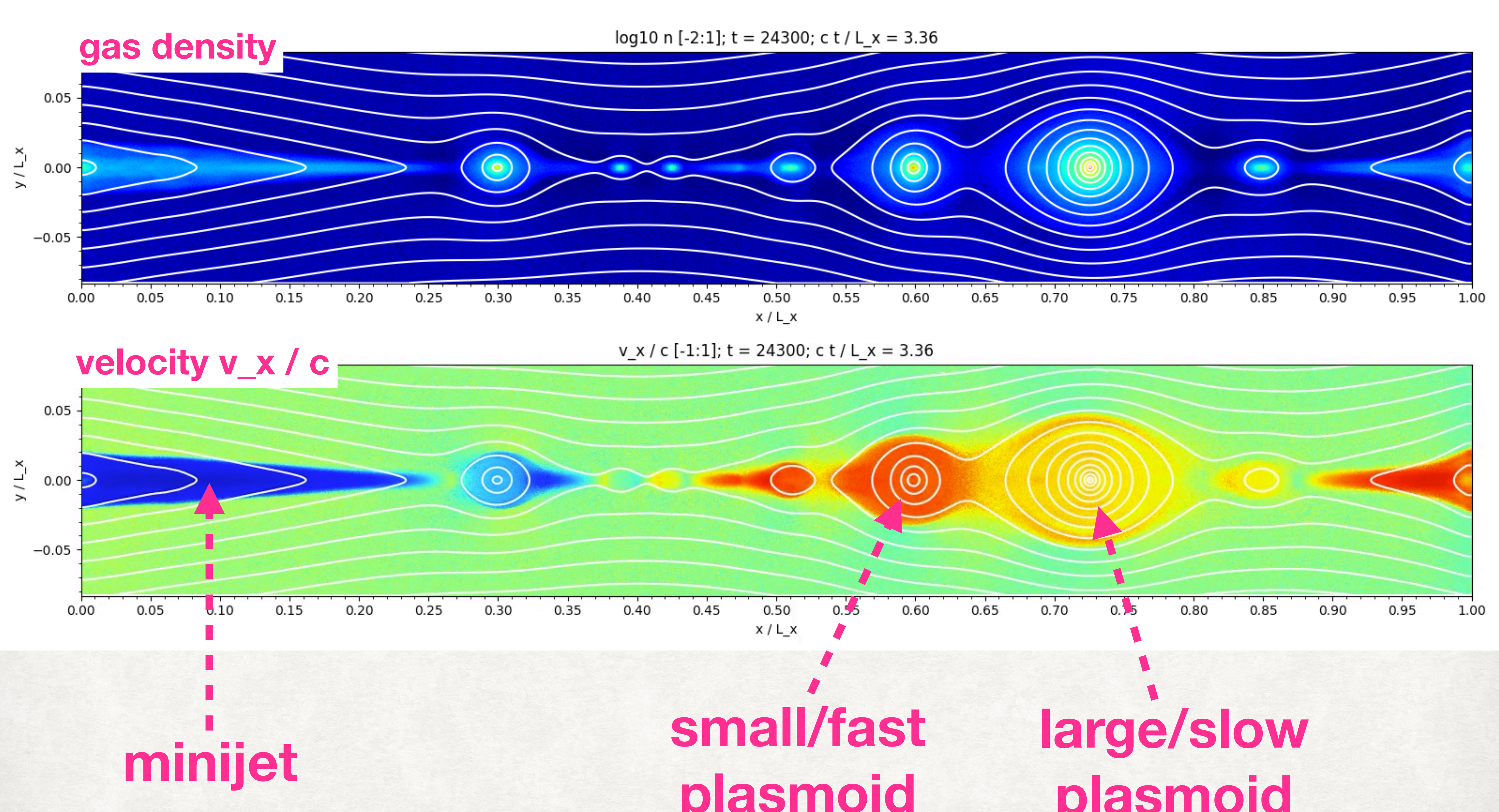
# PLASMOID RECONNECTION WITH OPEN BOUNDARIES




J. Ortuño-Macías & KN (2020)

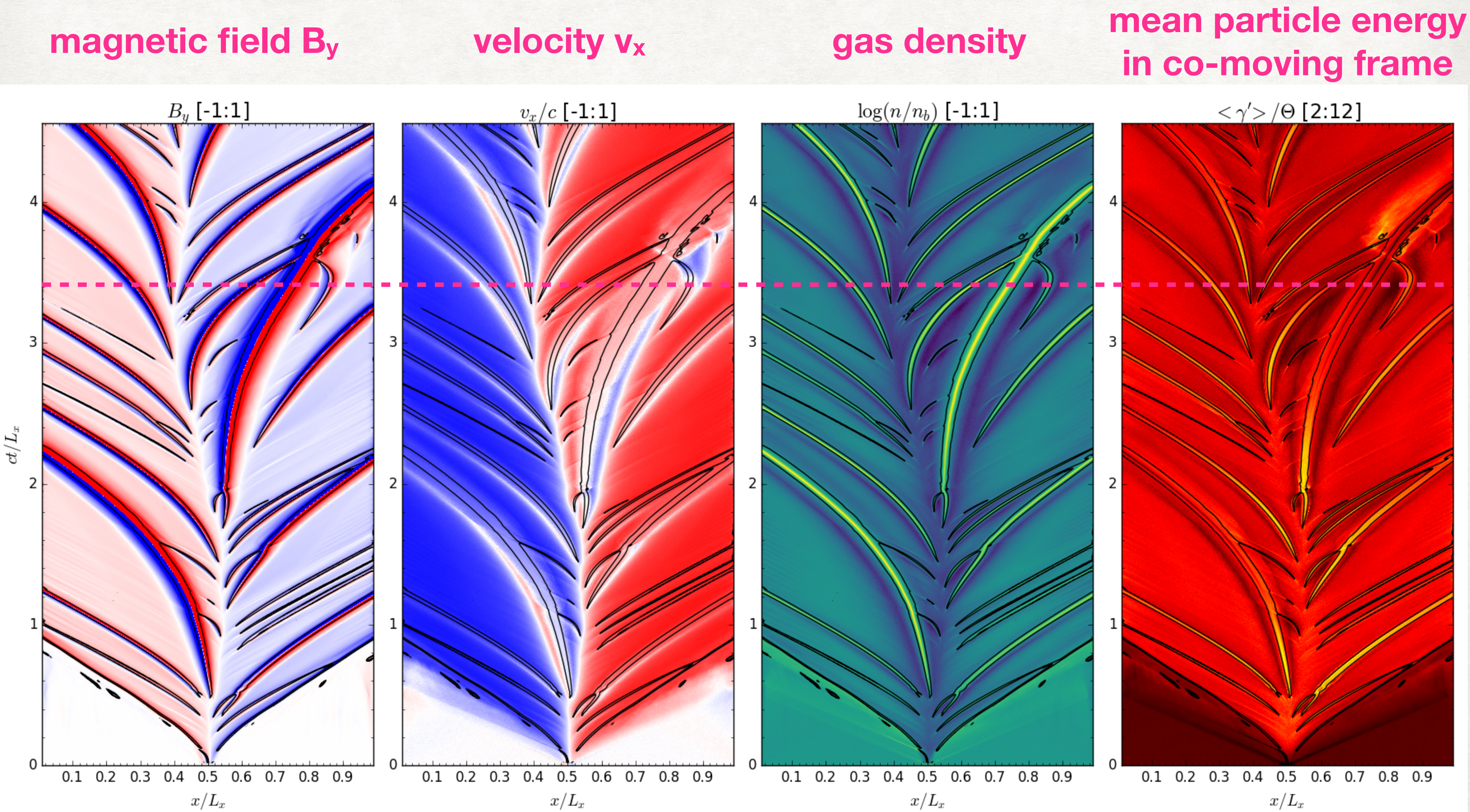
see also
Daughton et al. (2006)
Sironi et al. (2016)

# PARTICLE-IN-CELL SIMULATION OF RELATIVISTIC RECONNECTION WITH OPEN BOUNDARIES

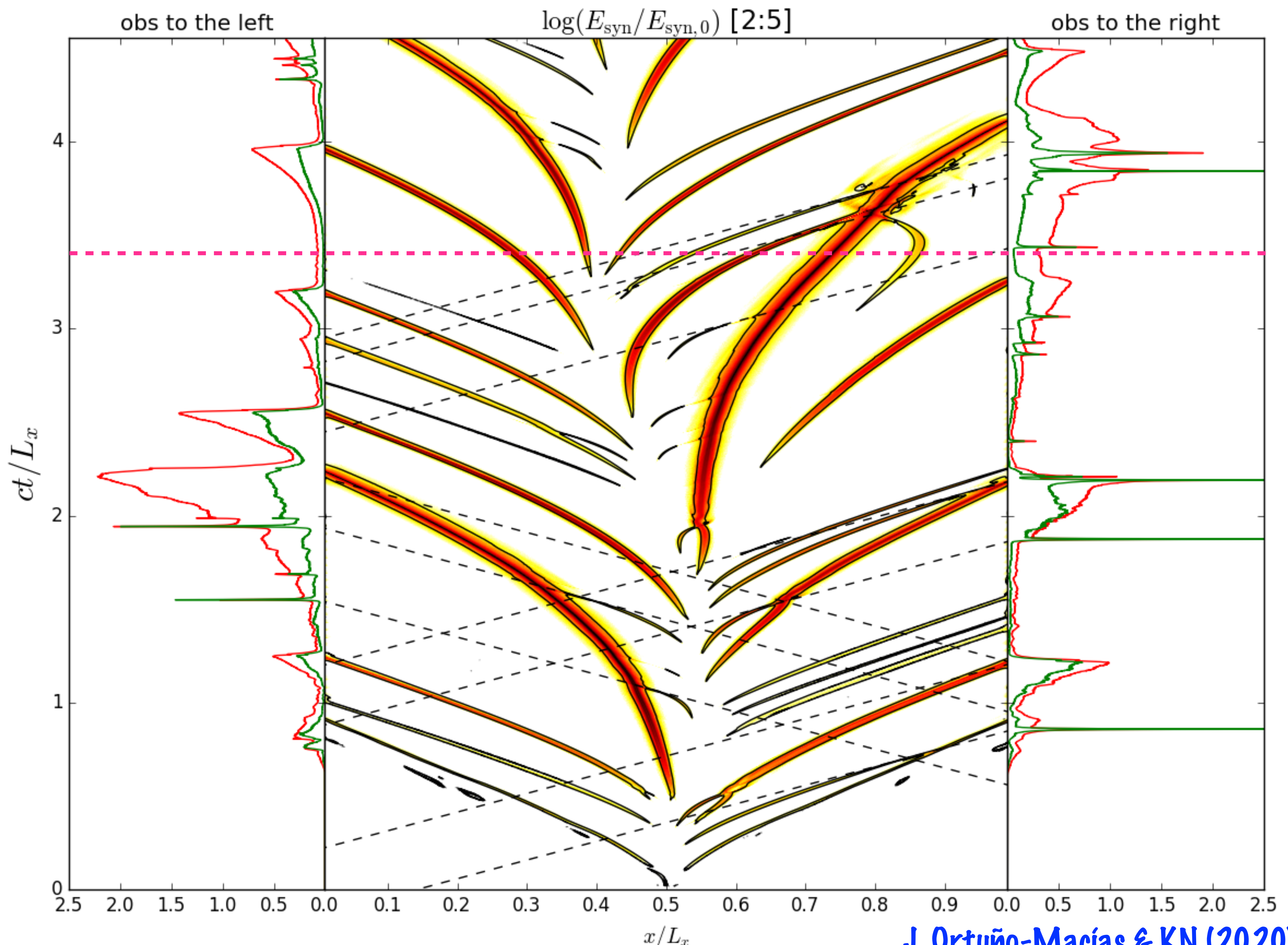



J. Ortuño-Macías & KN (2020)

# Reconnection with open boundaries: spacetime diagrams

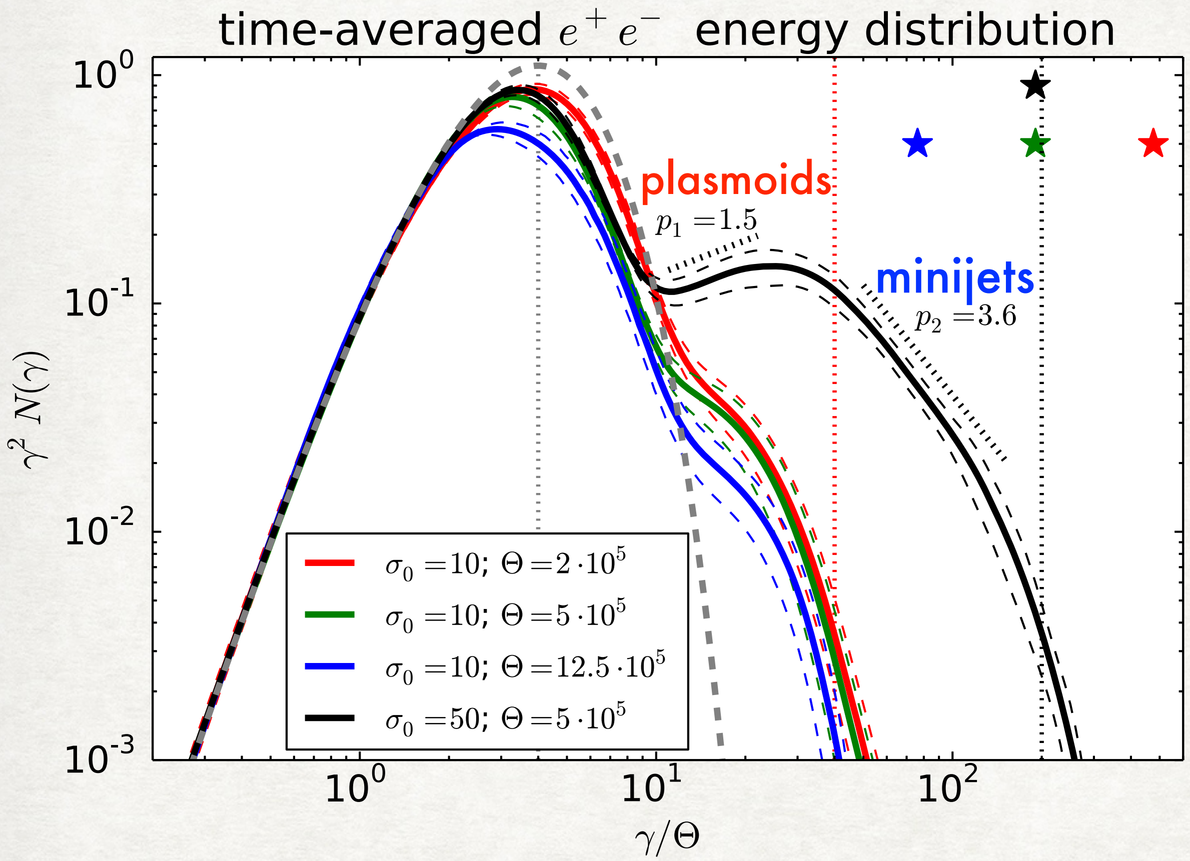


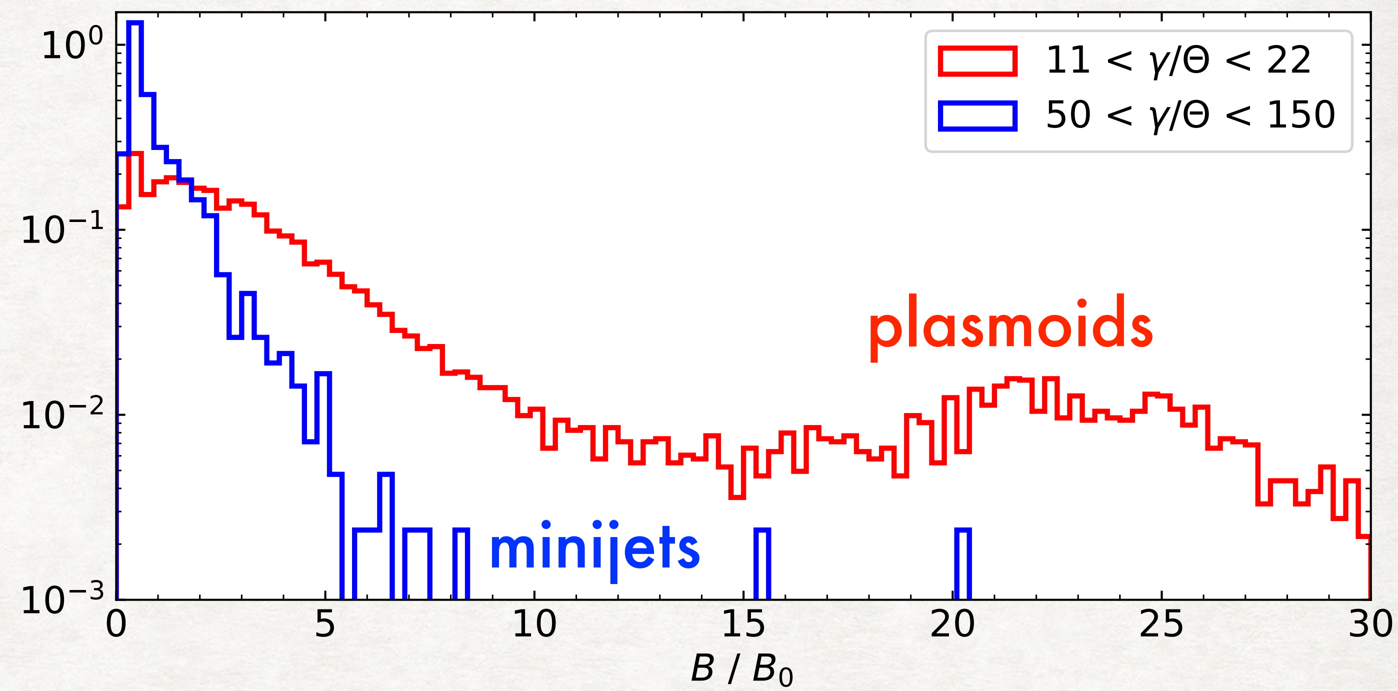

J. Ortuño-Macías & KN (2020)

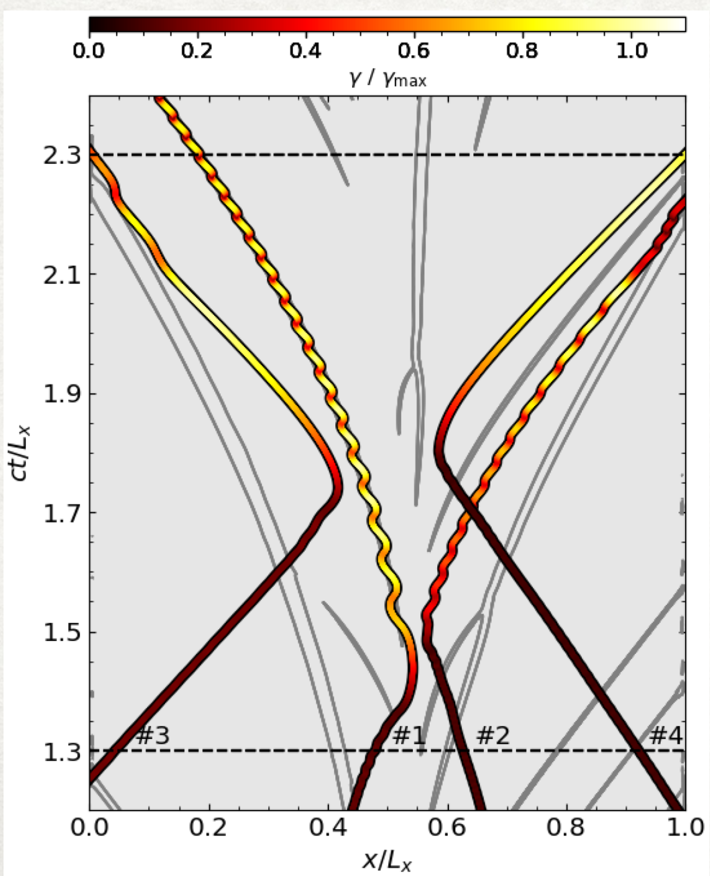


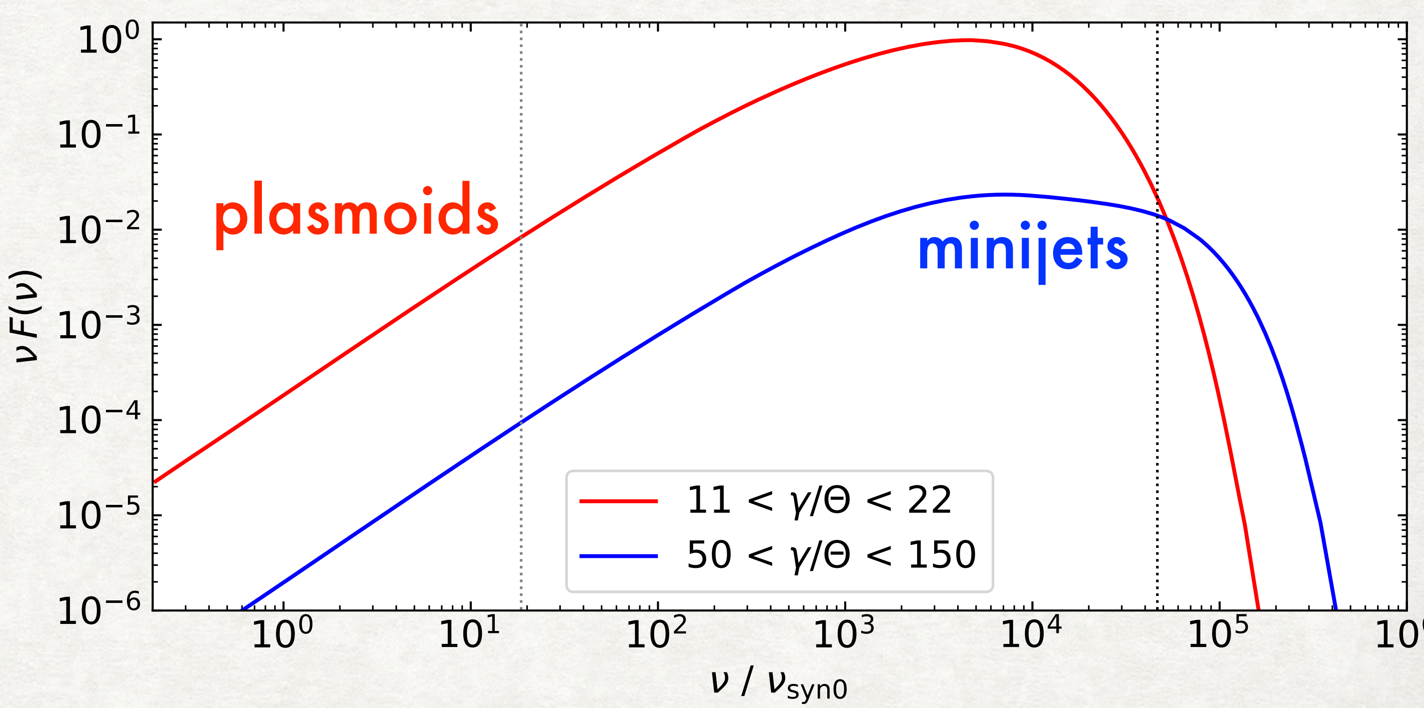

J. Ortuño-Macías & KN (2020)

# Particle Acceleration: Plasmoids vs Minijets



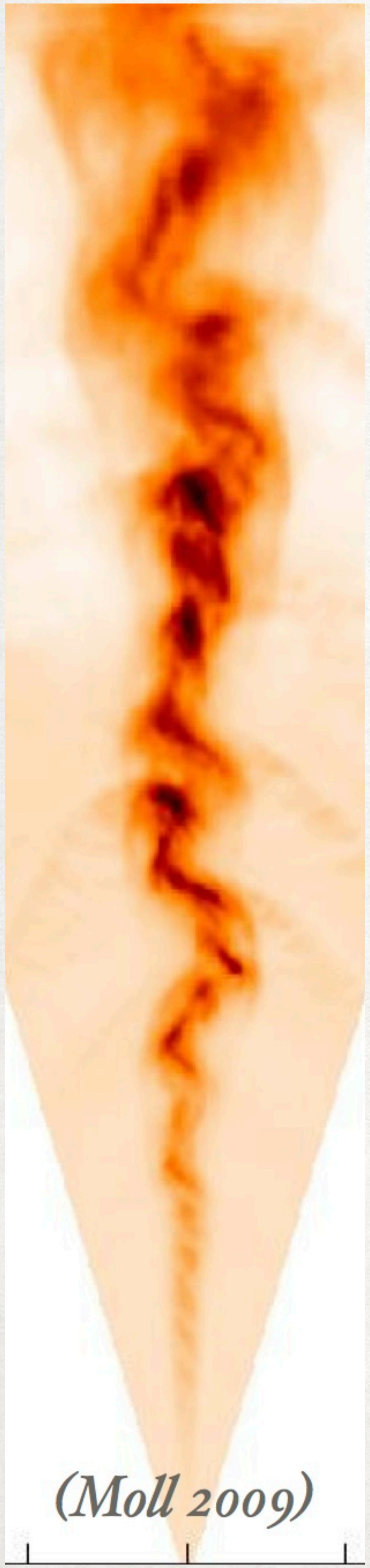




J. Ortuño-Macías & KN (2020)

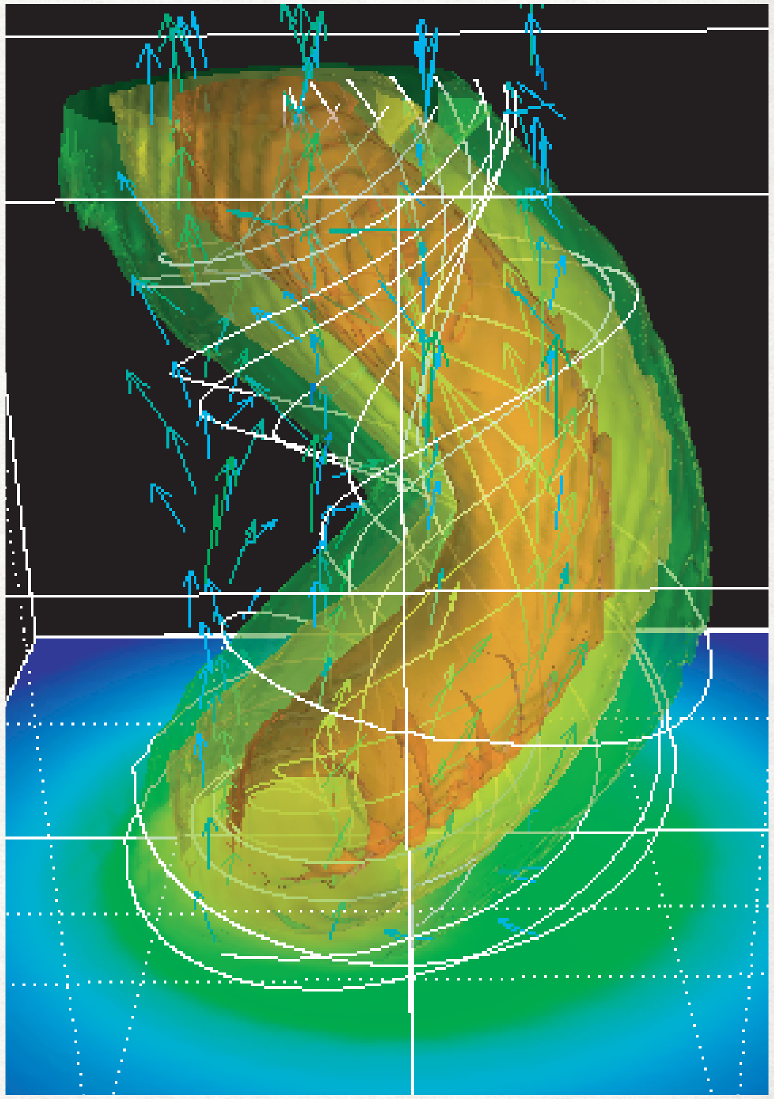
# Instabilities of jets with toroidal magnetic fields




- toroidal magnetic field supported by gas pressure is unstable
  (Kruskal & Schwarzschild 1954)

- magnetic fields in expanding jets become increasingly toroidal
  $B_\phi \propto R^{-1}$, $B_\mathrm{p} \propto R^{-2}$

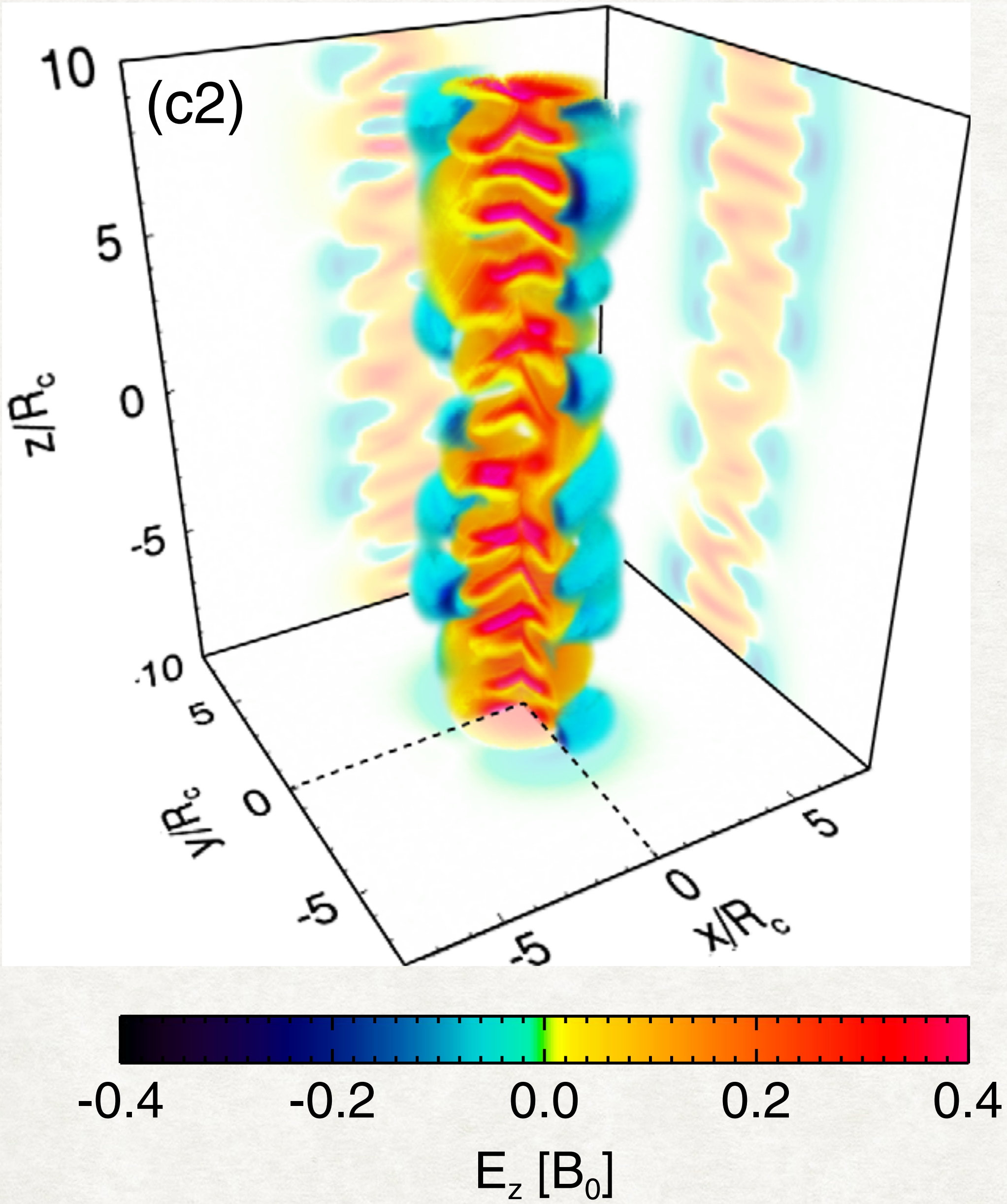
- jets may need to dissipate their magnetic fields via magnetic reconnection
  (Giannios & Spruit 2006)



Mizuno et al. (2011)

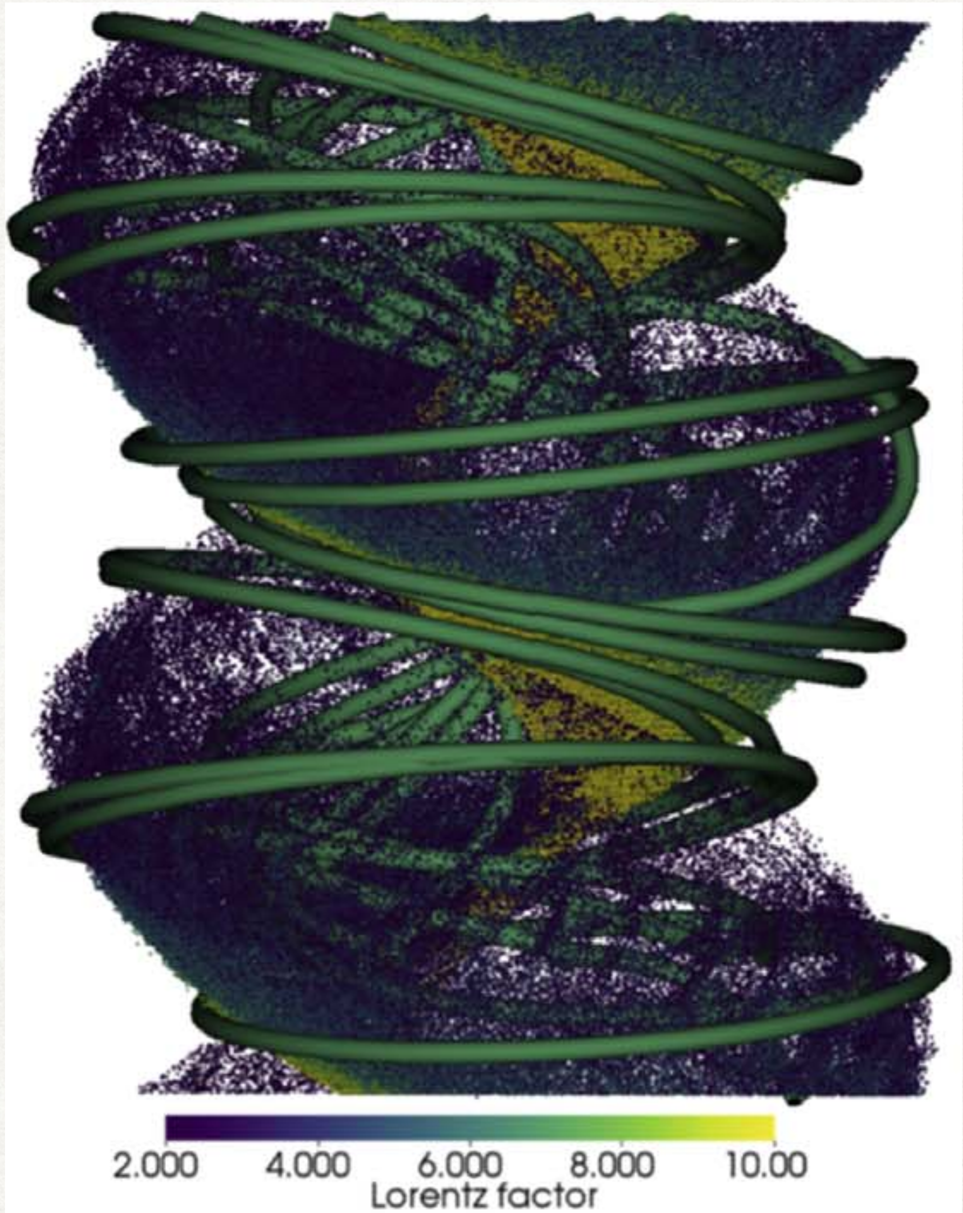
# KINETIC SIMULATIONS OF INSTABILITIES IN CYLINDRICAL JETS WITH TOROIDAL MAGNETIC FIELDS

gas pressure balanced
(Z-pinch)




Alves, Zrake & Fiuza (2018)

axial magnetic field balanced
(force-free screw-pinch)

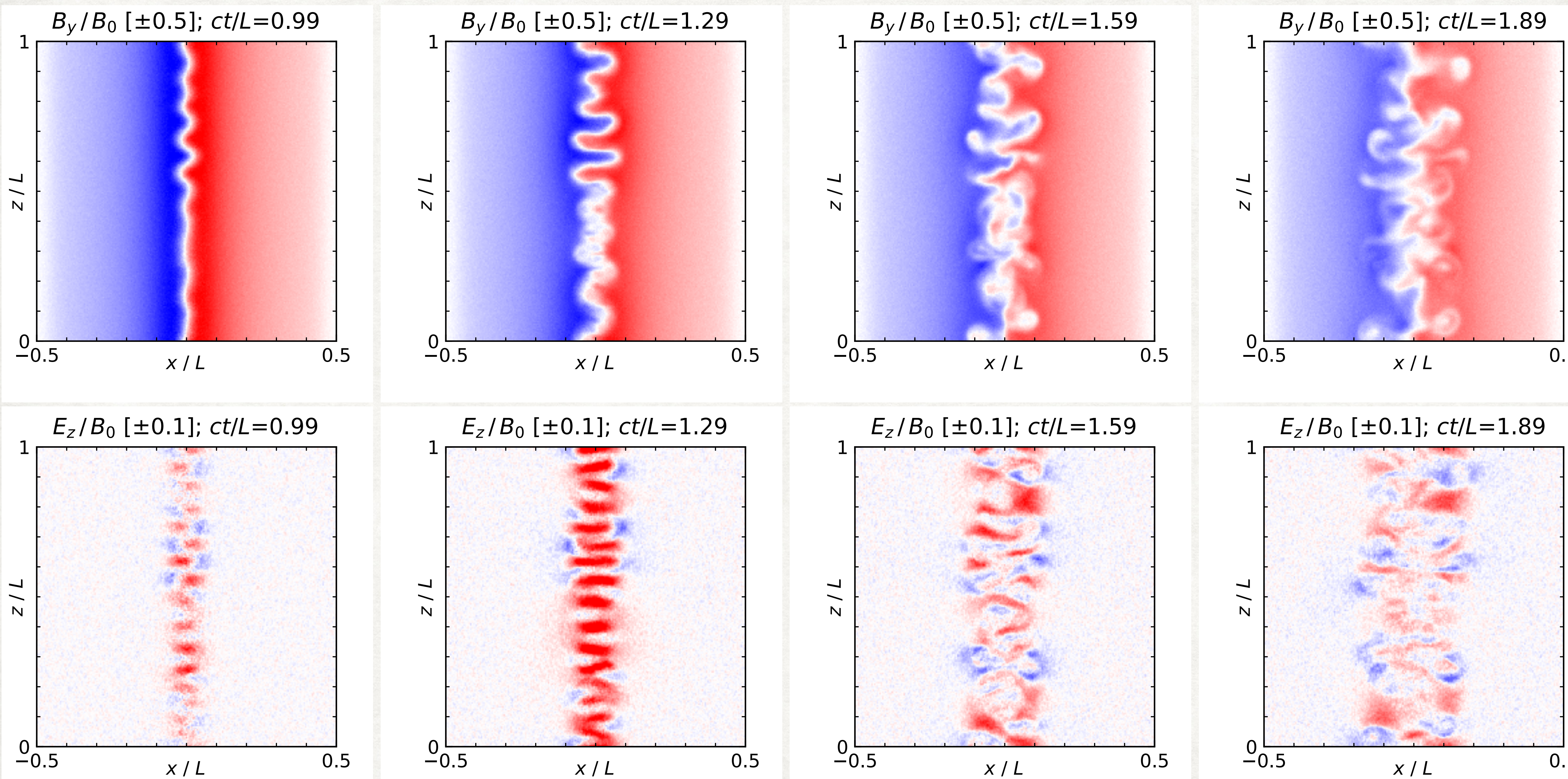



Davelaar, Philippov, Bromberg & Singh (2020)

efficient particle acceleration found in both cases

# KINETIC SIMULATIONS OF INSTABILITIES IN CYLINDRICAL JETS WITH TOROIDAL MAGNETIC FIELDS

3D, periodic boundaries, static equilibrium, pair plasma
moderately relativistic magnetization, highly relativistic temperature




José Ortuño-Macías, KN, D. Uzdensky, M. Begelman, G. Werner, A. Chen, B. Mishra (in prep.)

# Mixed Pressure Balance

- radial force balance:

$$\frac{B_\phi}{4\pi r}\frac{\mathrm{d}(rB_\phi)}{\mathrm{d}r} + \frac{1}{8\pi}\frac{\mathrm{d}B_z^2}{\mathrm{d}r} + \frac{\mathrm{d}P_{rr}}{\mathrm{d}r} = 0$$

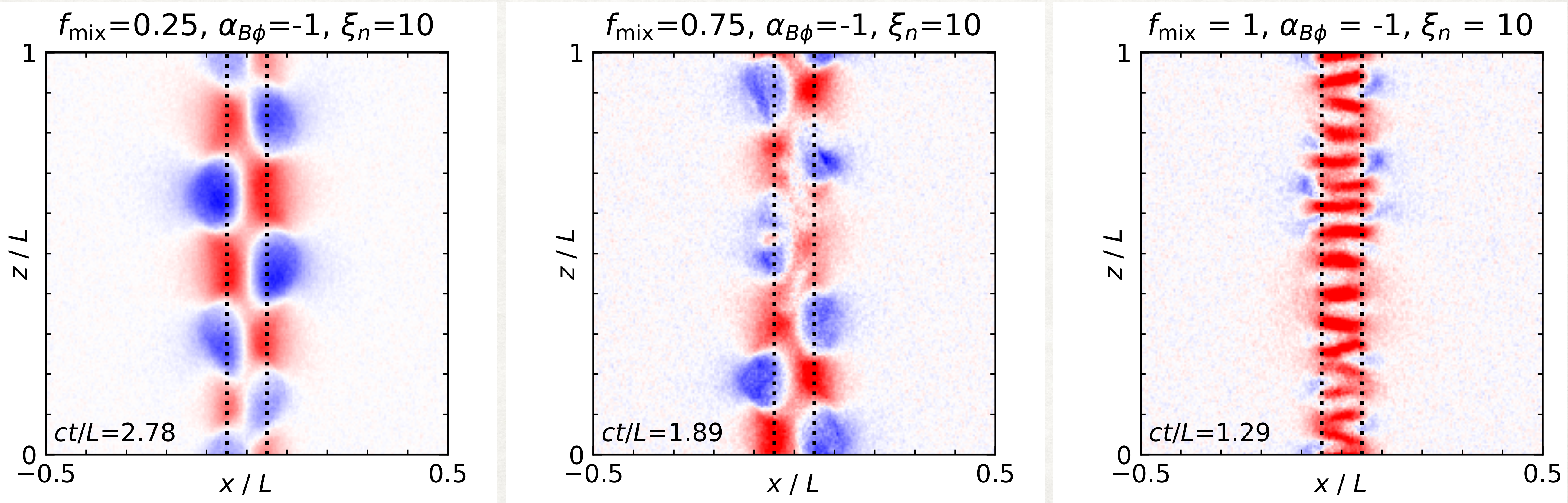
- introducing the pressure mixing parameter $f_{\mathrm{mix}}$:

$$\frac{\mathrm{d}P_{rr}}{\mathrm{d}r} = -f_{\mathrm{mix}}\frac{B_\phi}{4\pi r}\frac{\mathrm{d}(rB_\phi)}{\mathrm{d}r}$$

$$\frac{\mathrm{d}B_z^2}{\mathrm{d}r} = -(1-f_{\mathrm{mix}})\frac{2B_\phi}{r}\frac{\mathrm{d}(rB_\phi)}{\mathrm{d}r}$$

- $f_{\mathrm{mix}} = 0$ means $\mathrm{d}P_{rr}/\mathrm{d}r = 0$
  $B_\phi$ balanced by $B_z$
  force-free limit

- $f_{\mathrm{mix}} = 1$ means $B_z = 0$
  $B_\phi$ balanced by $P_{rr}$
  Z-pinch limit

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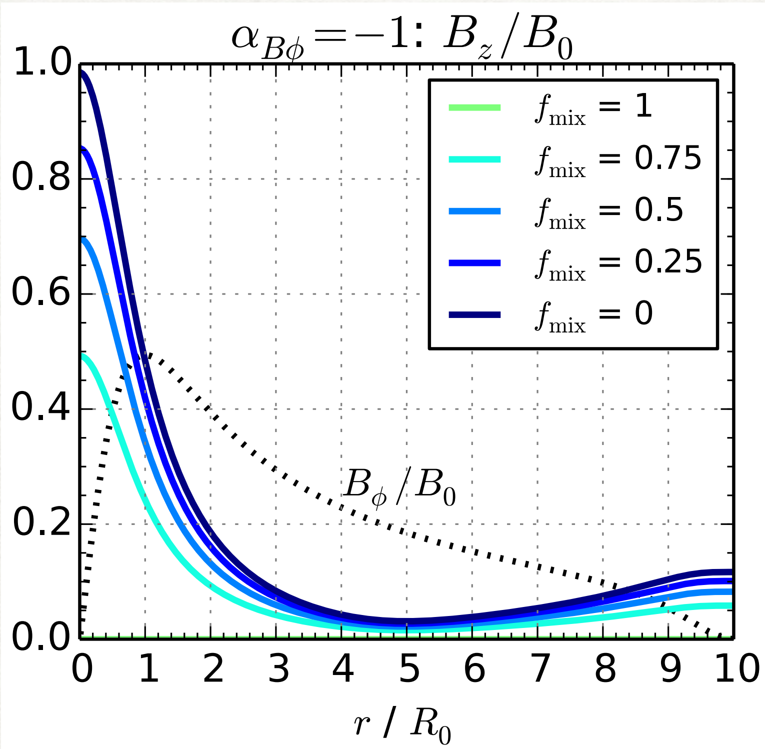
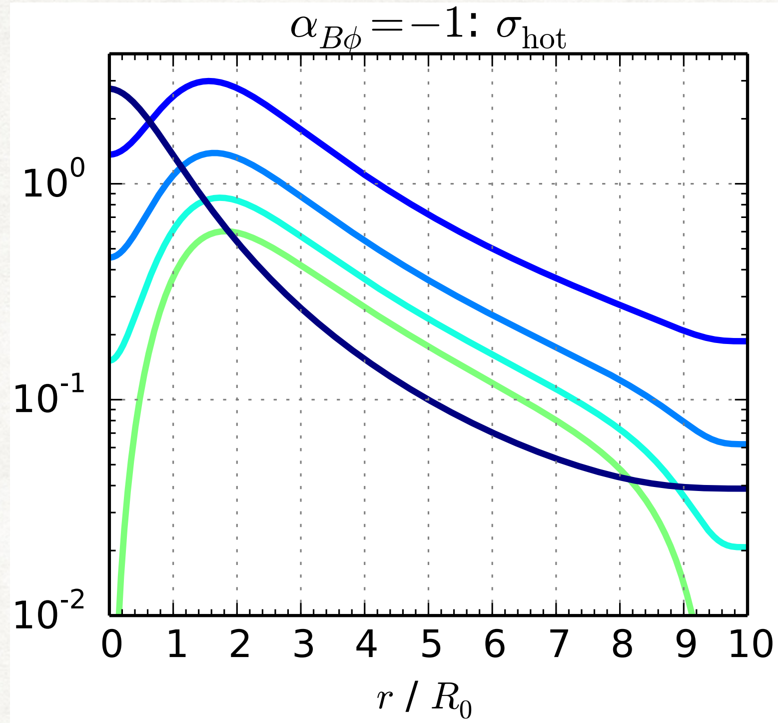
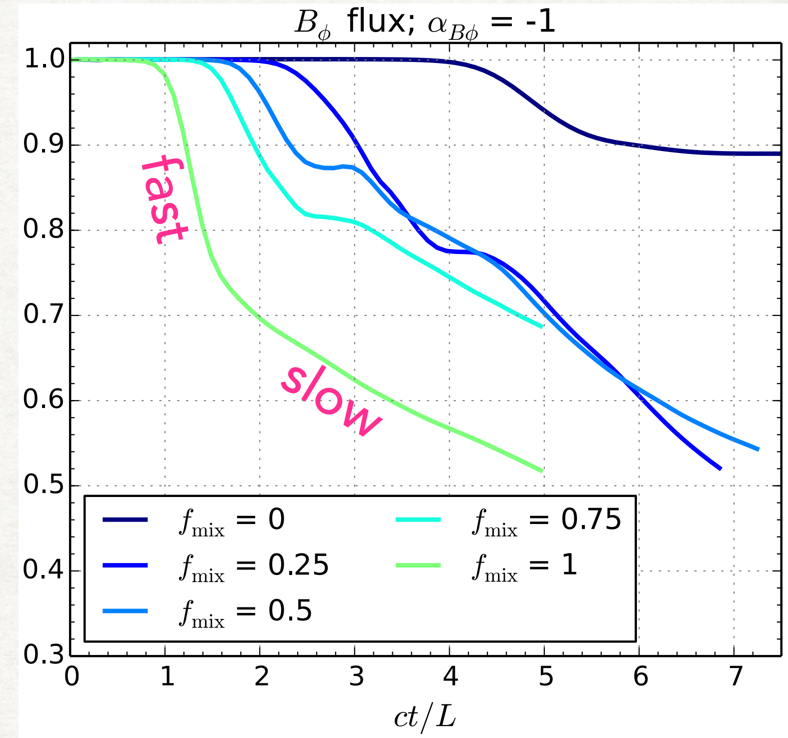
## initial B-field profiles



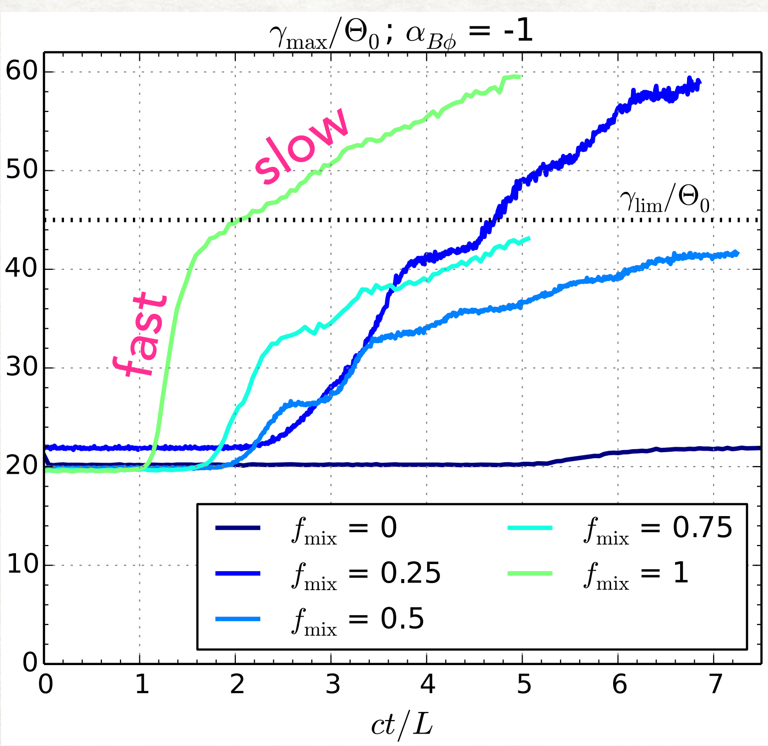

## initial magnetization



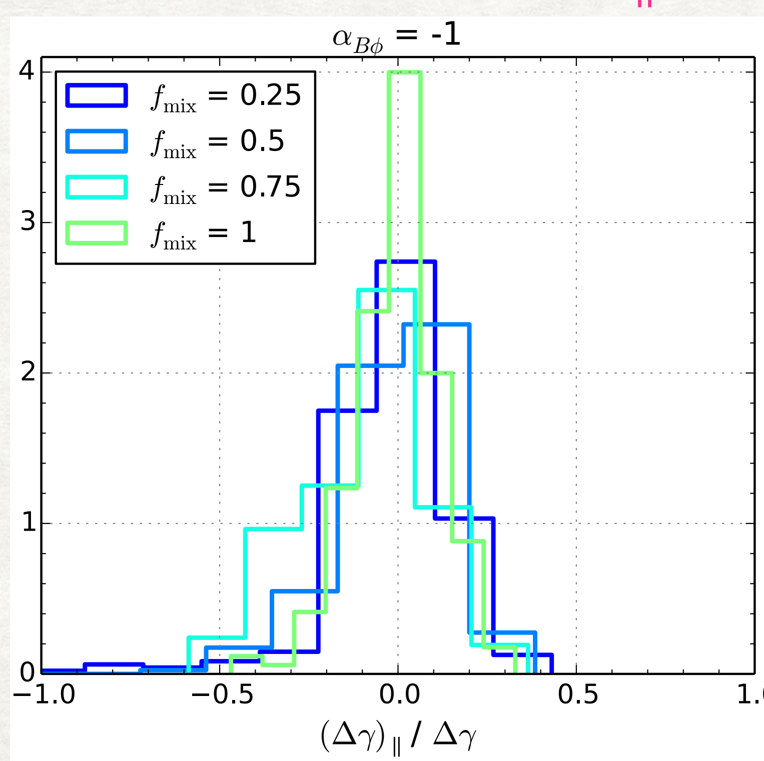

## $B_\phi$ flux dissipation




## particle acceleration




## acceleration by $E_\parallel$



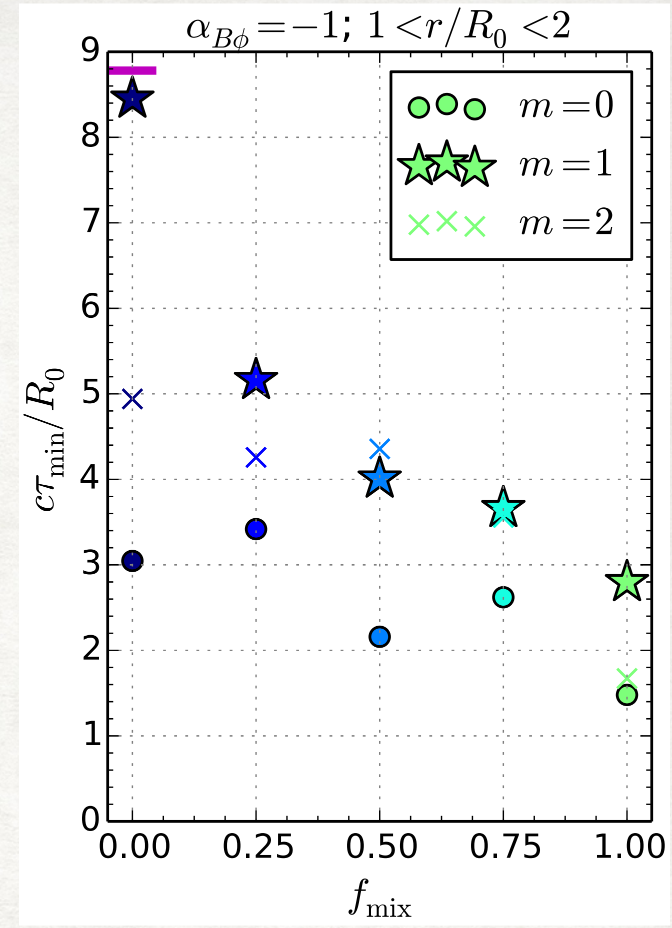

- fast magnetic dissipation and particle acceleration by $\vec{E} \perp \vec{B}$ until the **(Alves et al. 2018)** confinement limit $\gamma_{\rm lim} = eB_0R_0/mc^2$

**José Ortuño-Macías, KN, D. Uzdensky, M. Begelman, G. Werner, A. Chen, B. Mishra (in prep.)**

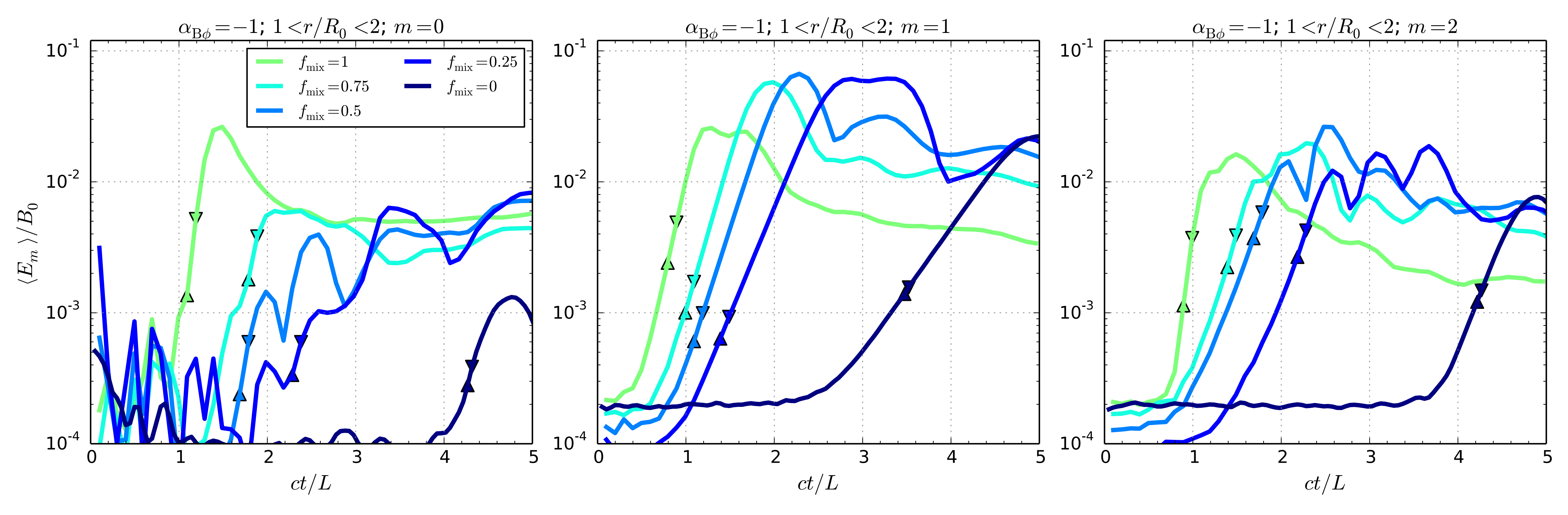
# Pinch vs. Kink Modes

- pressure-driven modes ( $f_{\rm mix} \to 1$ ) grow faster
- $m = 1$ kink modes dominate for $f_{\rm mix} < 1$, comparable to $m = 0$ pinch modes for $f_{\rm mix} = 1$

minimum growth time scales




$E_z$ amplitudes in time




José Ortuño-Macías, KN, D. Uzdensky, M. Begelman, G. Werner, A. Chen, B. Mishra (in prep.)

# Summary

- Relativistic AGN jets manifest robust particle acceleration through luminous highly variable non-thermal emission observed in blazars.
- The maximum electron energy $\gamma_{\max}$ attains characteristic values for main blazar types (FSRQs and BL Lacs), but what determines them?
- The scenario involving relativistic magnetic reconnection requires an extreme contrast of magnetization values (KN 2016).
- Relativistic jets are likely turbulent with a large number of emitting regions with stochastic parameter values.
- Magnetic reconnection can be triggered in relativistic jets by global magnetic field reversals or instabilities of toroidal magnetic field.
- The minijets scenario has been revisited, they co-exist with plasmoids, accelerating particles to higher energies, but less luminous due to low particle density (J. Ortuño-Macías & KN 2020).
- Instabilities of cylindrical jets investigated by kinetic simulations: gas pressure balanced Z-pinches grow faster with comparable kink and pinch modes (J. Ortuño-Macías et al., in prep.).

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