Plasma Astrophysics

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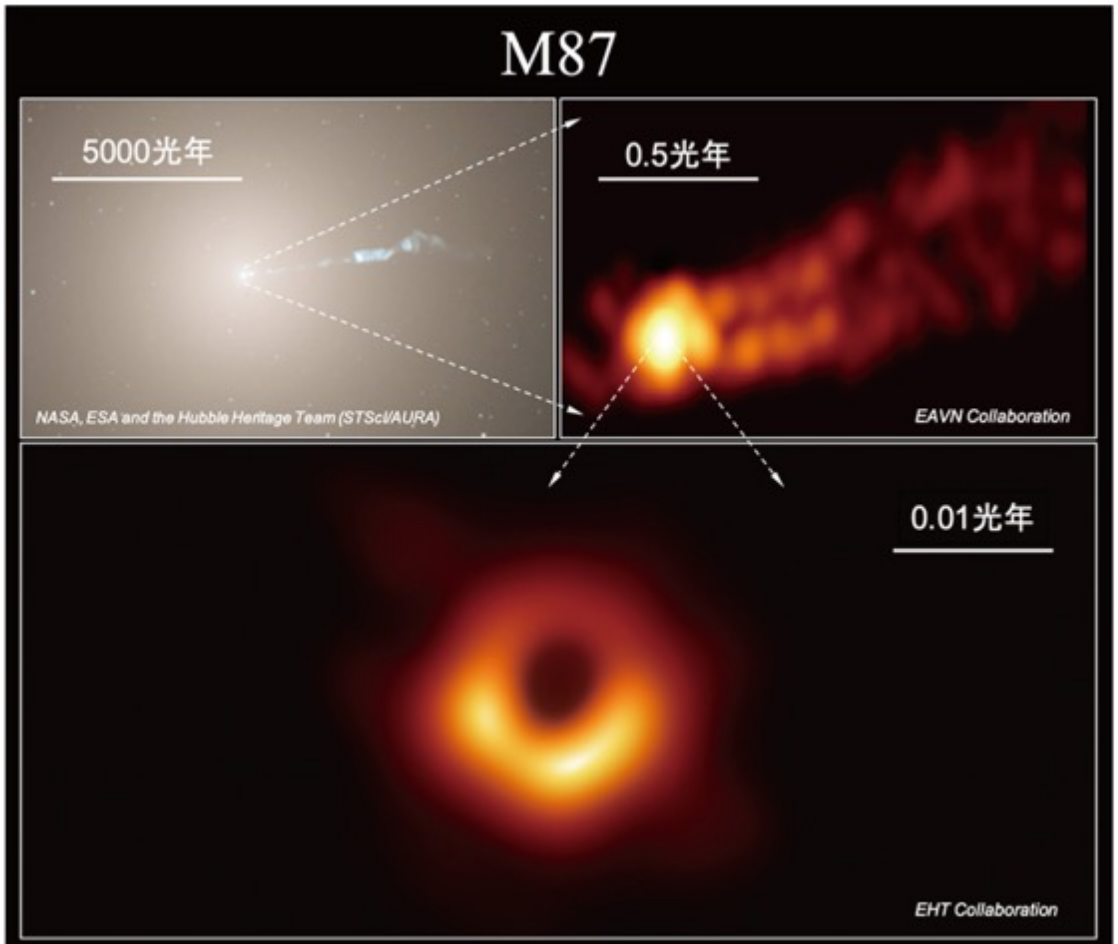
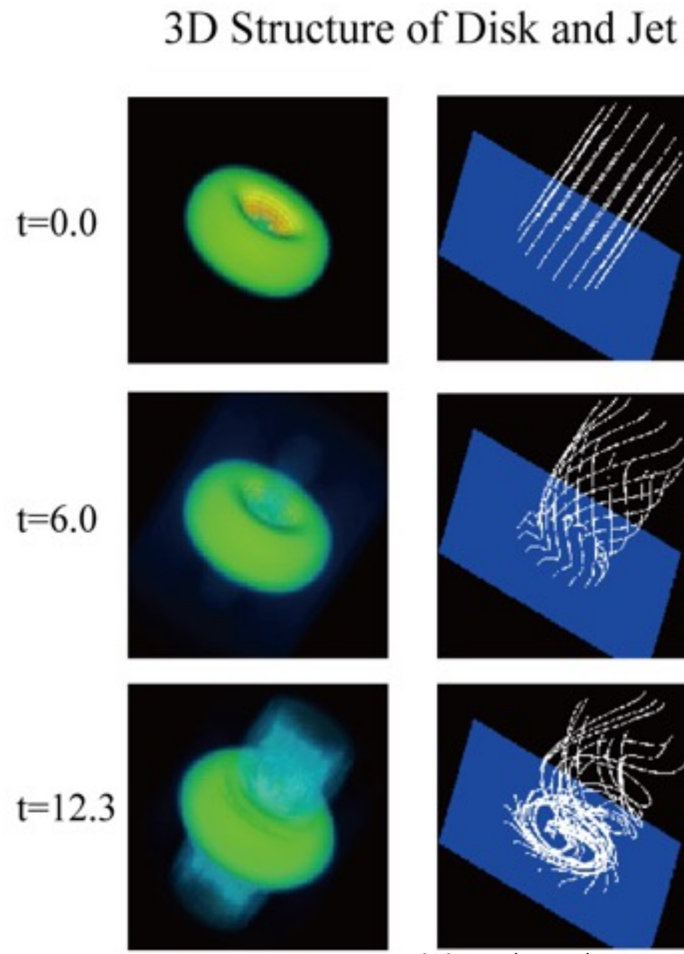
Class 5:PHY249 (2020Spring)



Event Horizon Telescope (2020)



Tajima Shibata (1997) p. 387

Plasma Astrophysics (Tajima, 2020)

----- ------ ------ ------ ------ ------- general overview

- Class 1: Introduction to "plasma astrophysics"

  instabilities vs. structure formation of plasma

  exemplary processes in plasma astrophysics, plasma β

- Class 2: Gravity + Plasma + B

  magnetic Buoyancy, magneto-rotational instability (MRI)

  explosive evolution of flux tubes, filamentary Universe

- Class 3: Accretion disk and jets

  MRI on accretion disk, anomalous viscosity, jet formation

  Stimulus to evolution of the Universe

-------- ------- -------- ------- -------- now specific realizations

- Class 4: Neutron star-neutron star collision

  gravitational wave and γ-bursts

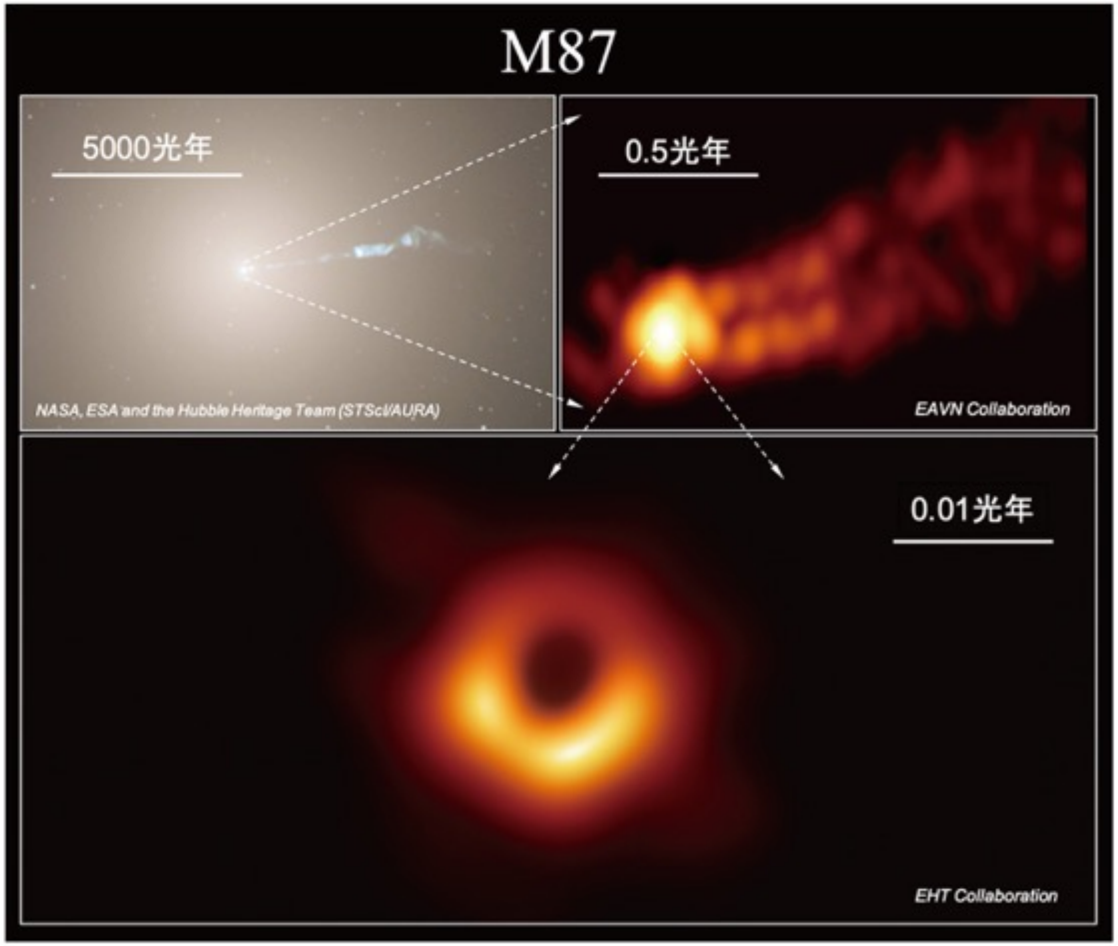
- Class 5: **"Physiology" of accretion disks**

  (Episodic eruptions and extreme high energy cosmic rays)

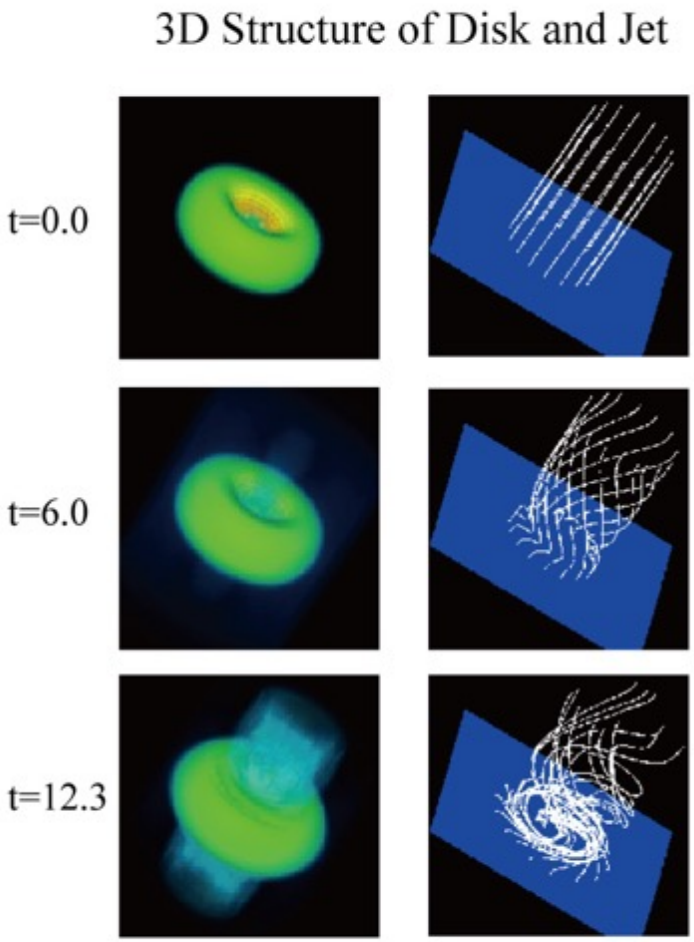
  Mother Nature's accelerator (from Fermi → new paradigm)

“Physiology” of Discovered and Predicted BH

M87 blackhole: by Event Horizon Telescope (2019)



Prediction: Tajima and Shibata
“Plasma Astrophysics” (1997)



“Physiology” of various AGNs

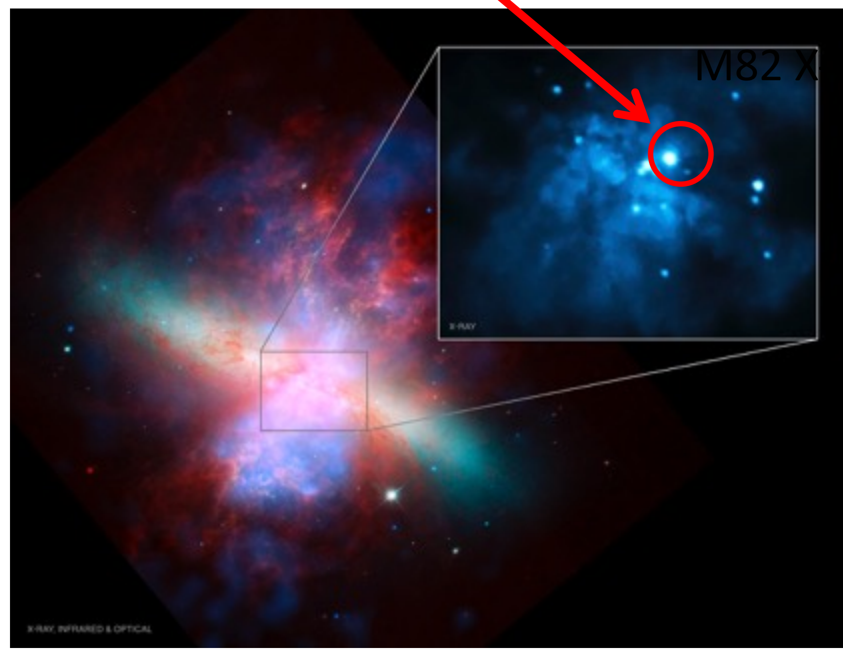
Cen A

- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets

M82: Nearest Starburst Galaxy

M82 X-1: 1000-10000 Ms BH

Just after the collision with M81

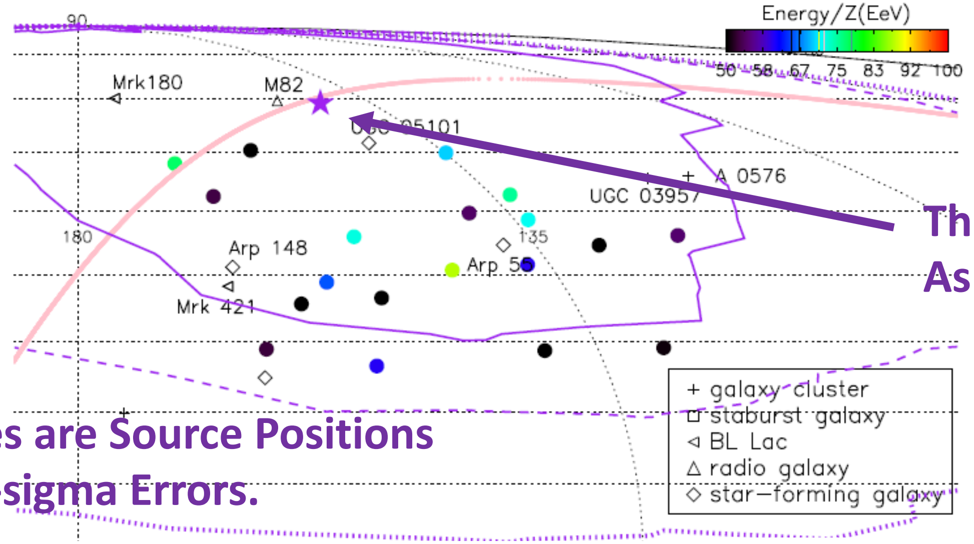


Composite of X-ray, IR, and optical emissions

NASA / CXC / JHU / D. Strickland; optical: NASA / ESA / STScI / AURA/ Hubble Heritage Team; IR: NASA / JPL-Caltech /Univ. of AZ / C. Engelbracht; inset – NASA / CXC / Tsinghua University / H. Feng et al.

TA Hot Spot: UHECRs from M82?

He, Kusenko, Nagataki + PRD 2016.



The most likely Source Position As a Result of Our Analysis.

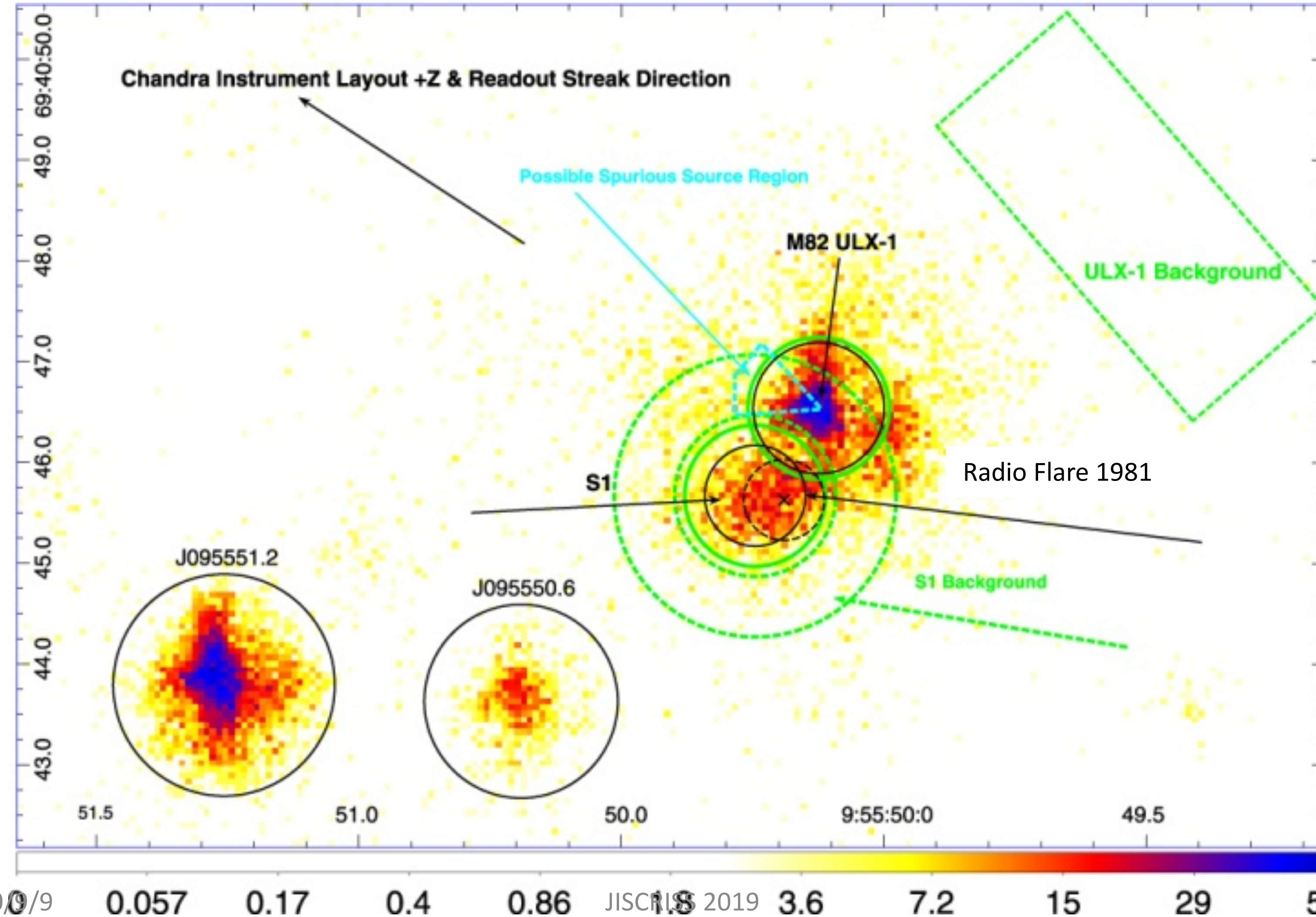
Purple Lines are Source Positions With 1,2,3-sigma Errors.

M82 is very Close from the most likely Source Position!

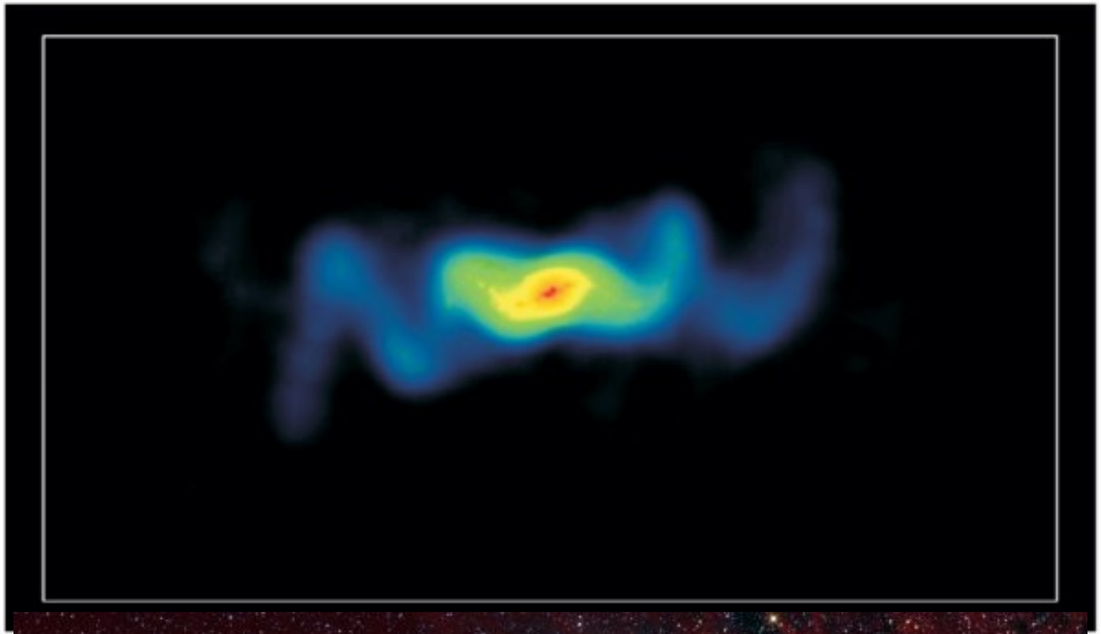
Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
best-fit	-	-	$17.4^{+17.0}_{-11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	10.5	10.0	41.8
Mrk 421	blazar	134	11.2	9.9	35.6

An AGN-like Jet in M82?
X-ray/Radio (flare in 1981)

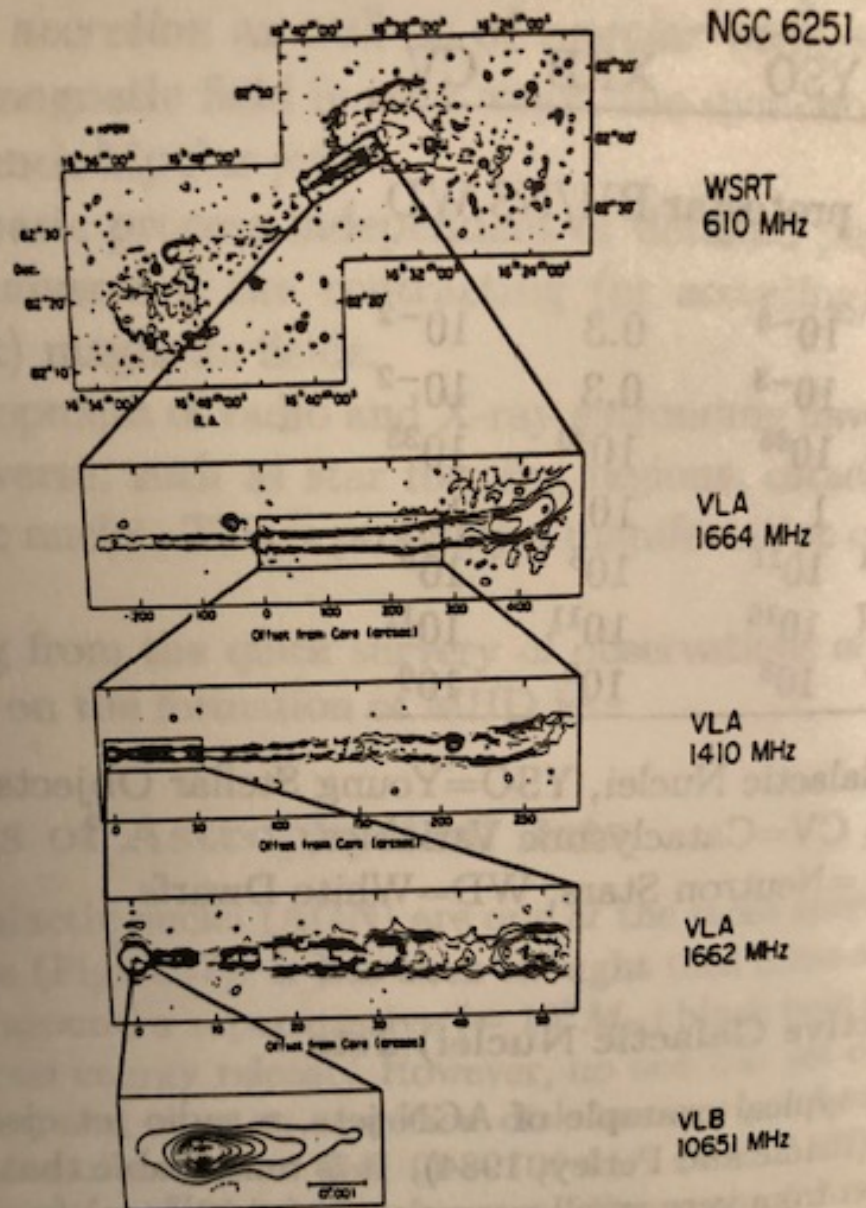
Xu et al. 2015 ApJ Letters 799, L28



SS433 precession jets



Extended structure of jets



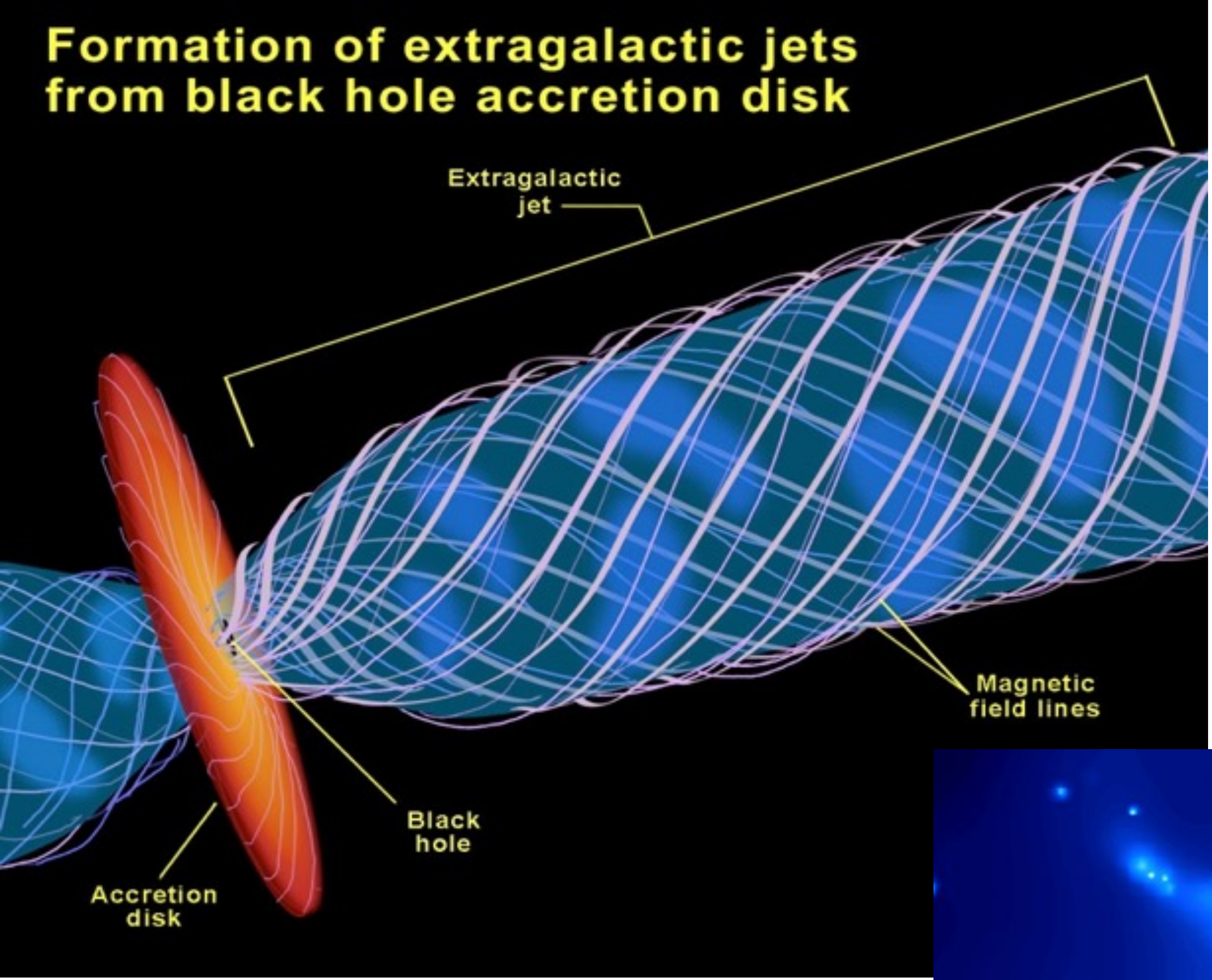
Radio images of jets ejected from nucleus of radio galaxy, NGC6251 (from Brid

Jets deliver the momentum, energy, and mass to the furthest

Jets and accretion disks: also introduce dissipative parts in collective modes

→ accelerates evolution of Universe

Text p. 356



Fermi's '**Stochastic Acceleration'**
(large synchrotron radiation loss)

↓

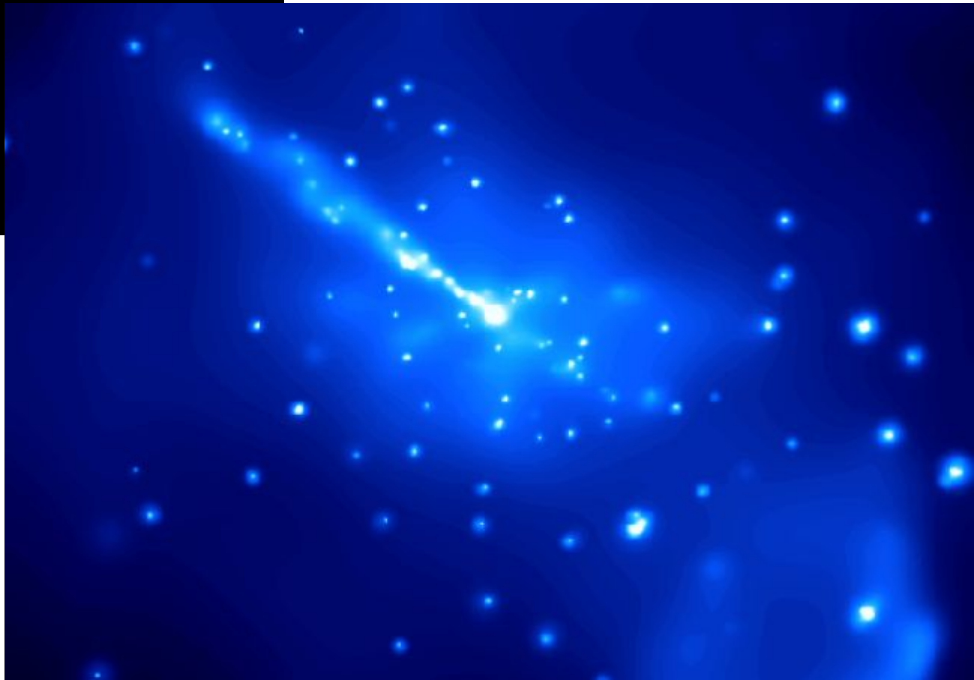
Coherent wakefield acceleration
(no limitation of the energy)

Nature's LWFA : Blazar jets

extreme high energy cosmic rays (~10^{21} eV)

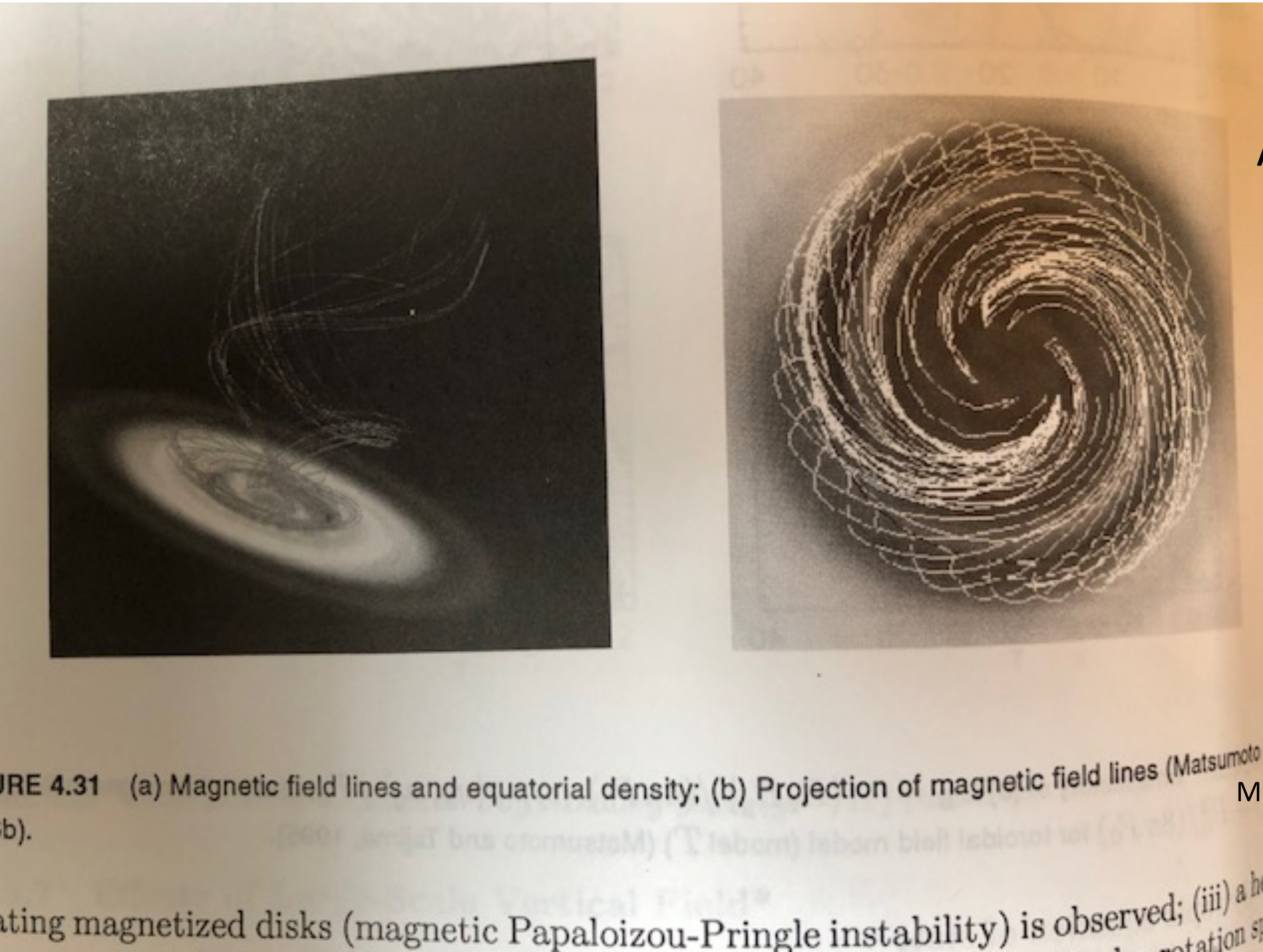
episodic γ-ray bursts observed

consistent with LWFA theory



Ebisuzaki-Tajima (2014)

Magneto-Rotational Instability (MRI)



Accretion disk

rotating plasma

B-fields

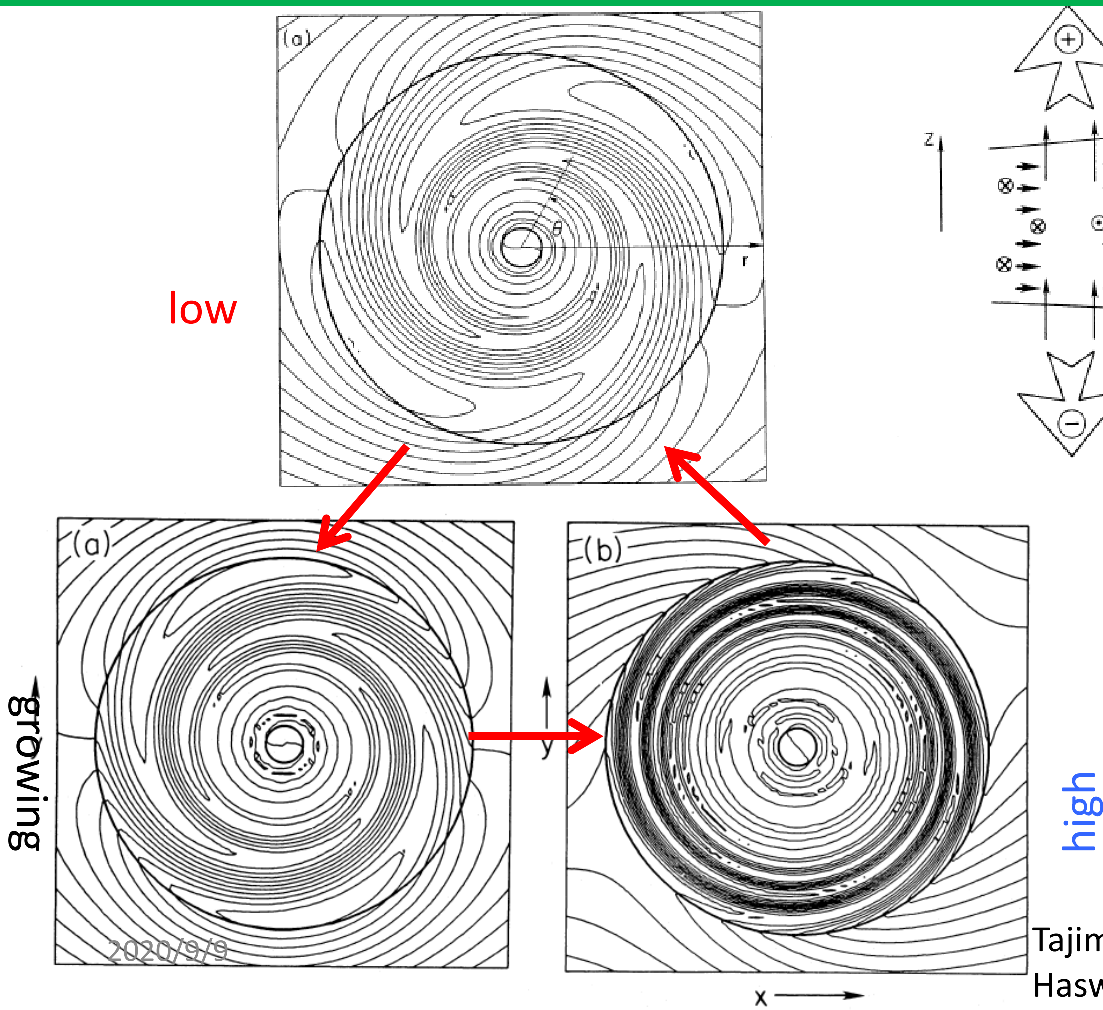
Balbus-Hawley (1991)

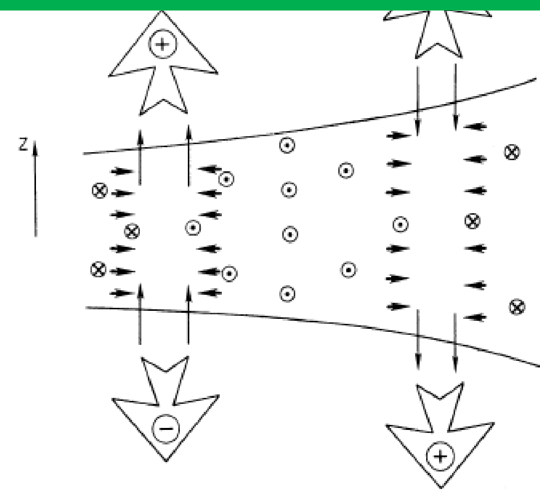
Matsumoto Tajima (1995)

Tajima, Shibata (1997)

Eruption of magnetic field in an accretion disk

A Burst of Electromagnetic Disturbance

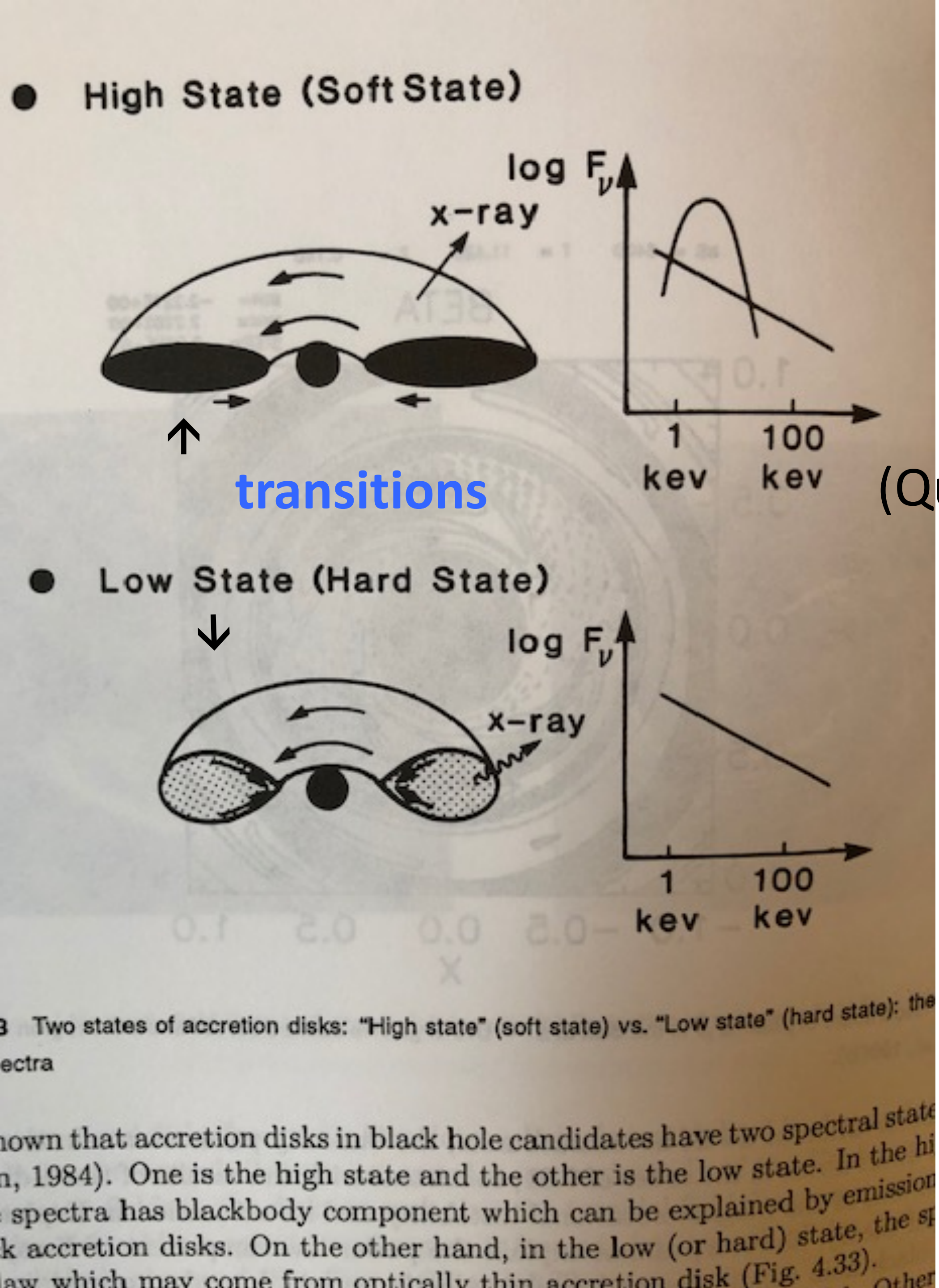




Transition between
high (eruption) and
low (recovery) states

Tajima and Gilden 1987, ApJ 320, 741-745
Haswell, Tajima, and Sakai, 1992, ApJ, 401, 495-507

Episodic transitions of accretion disks with B



(Quasi-)<u>steady state</u> accretion disks

cf.

<u>Episodic</u> accretion disks

"breathing" disks

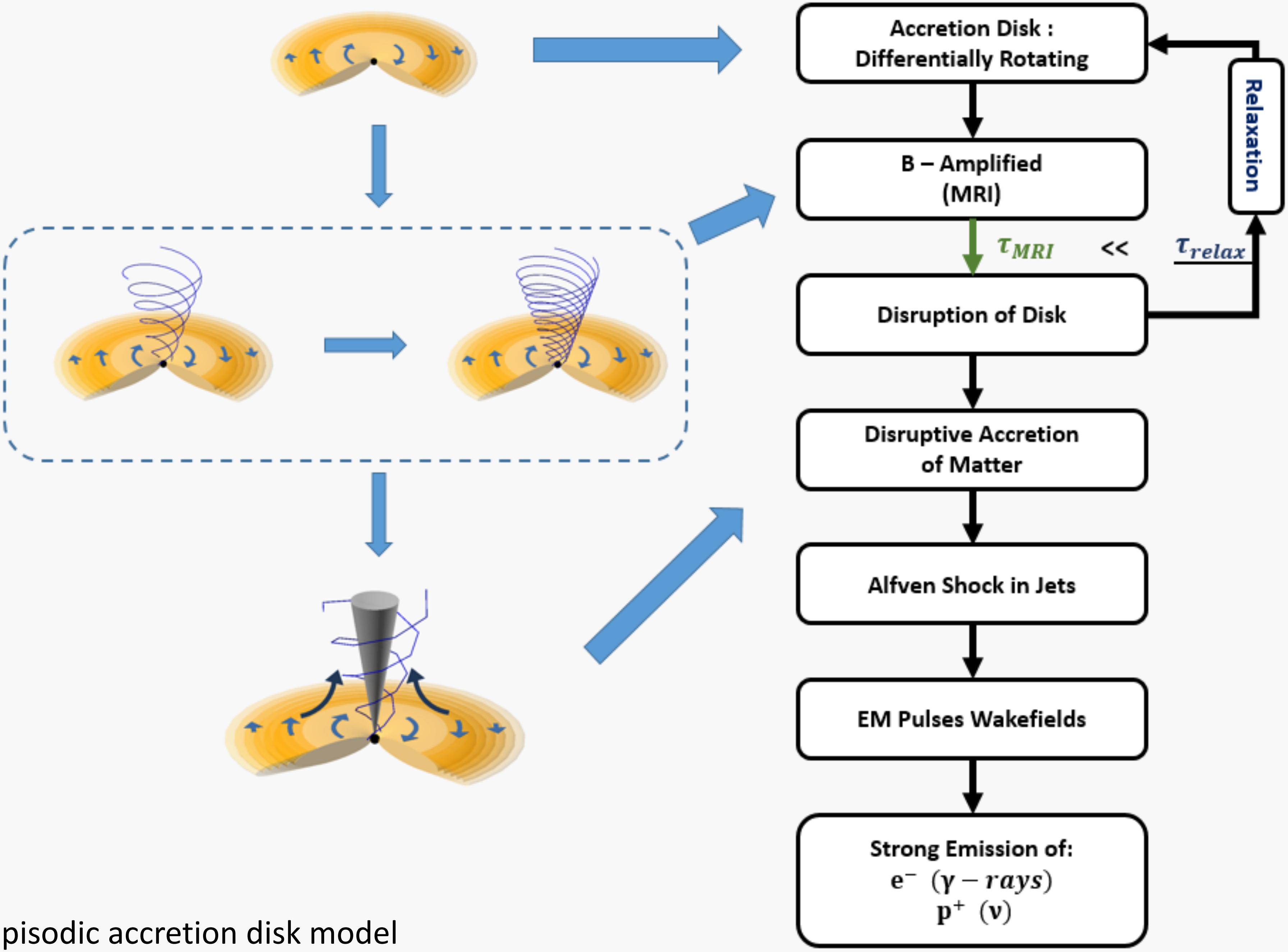
transitions between the **states**

<u>**soft** state</u> (β >>1)

↑↓

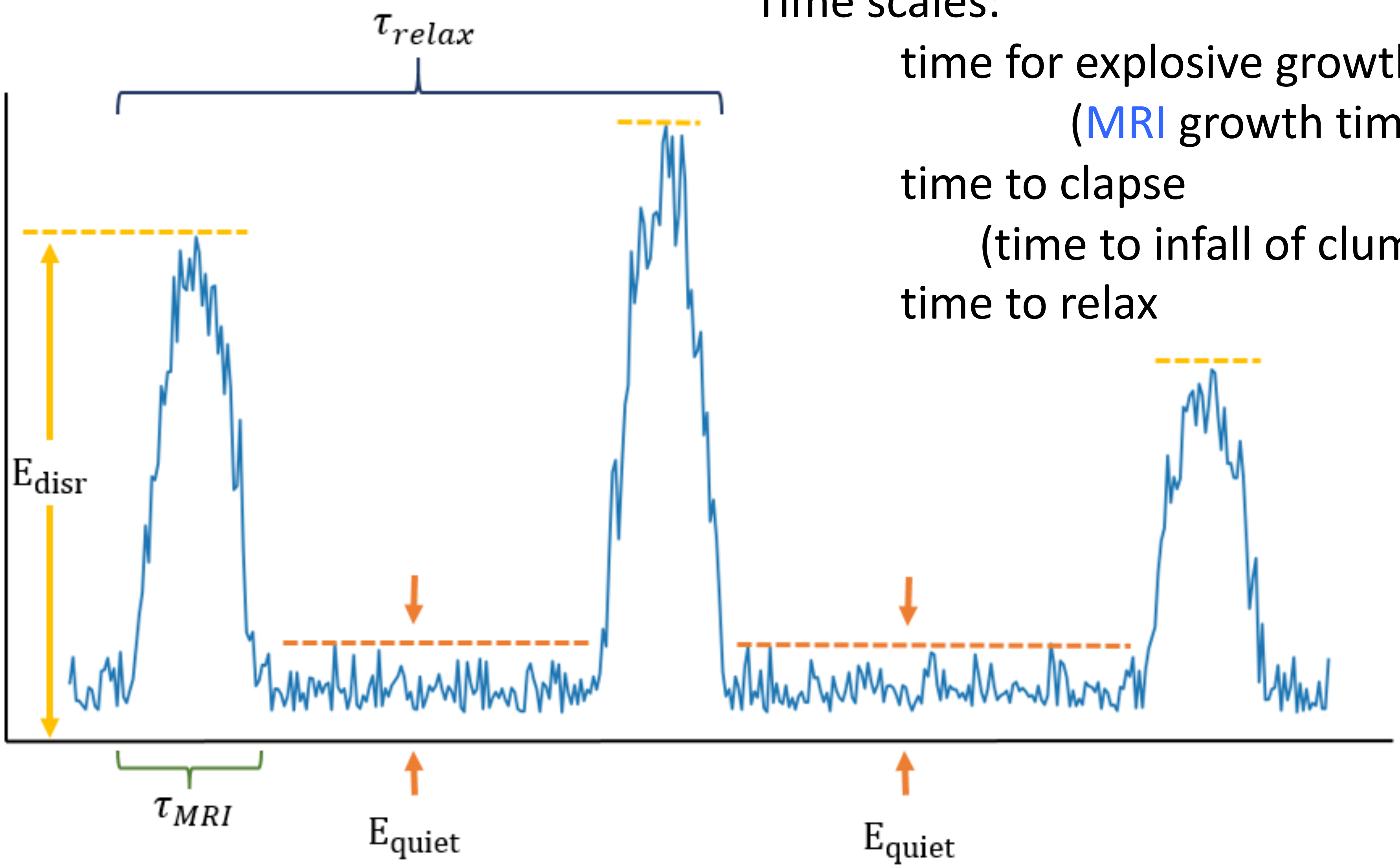
<u>**hard** state</u> (β ~ 1)

Tajima, Shibata (1997) pp. 348-353.



Episodic accretion disk model
Abazajian, Tajima, Ebisuzaki

Episodic eruption of accretion disk



Time scales:

time for explosive growth
(MRI growth time)

time to clapse
(time to infall of clump)

time to relax

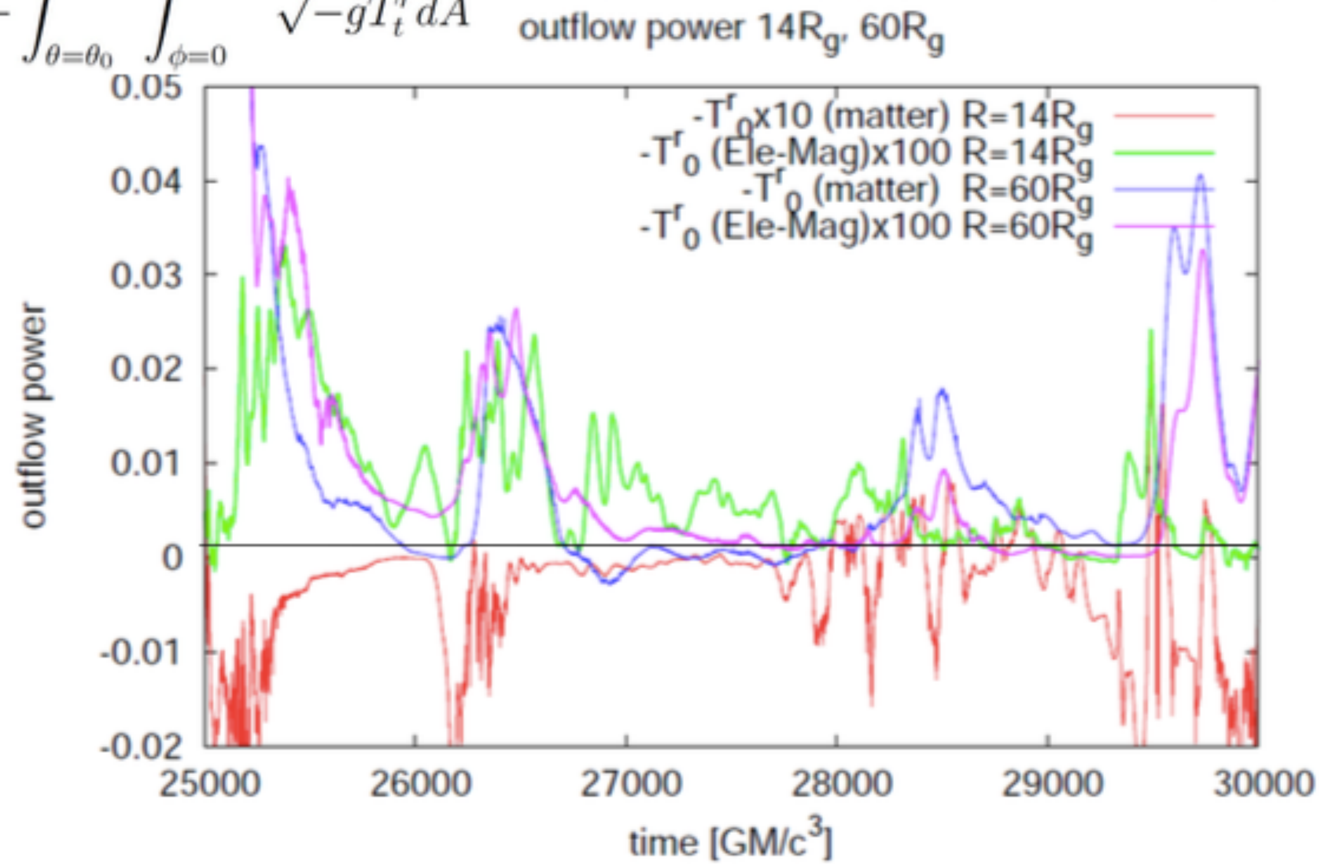
General Relativistic MHD simulation of accretion disk + jets: episodic feature

Outflow luminosity (0<θ<10°)

$$E_{\text{dot}} = -\int_{\theta=\theta_0}^{\theta=\theta_1}\int_{\phi=0}^{\phi=2\pi}\sqrt{-g}\,T^r_t\,dA$$

$\theta_0=0$

$\theta_1=10$



Short time variavilitry (Δt~a few tensGM/c³) in electromagnetic components (green and pink) : Good agreement with Ebisuzaki & Tajima(2014) $t_{var} \sim M$

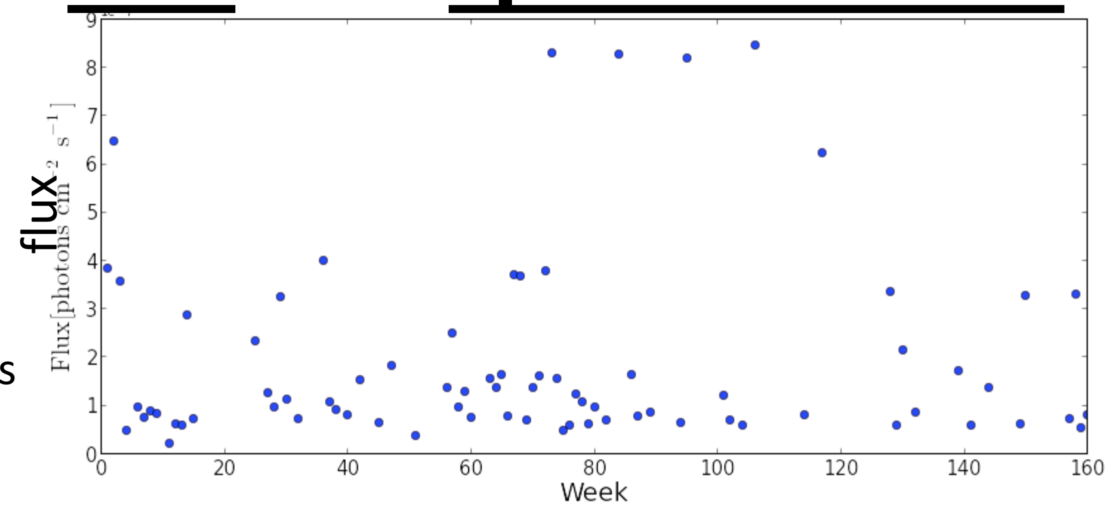
=> possible origine for flares in blazars,

strong Alfven wave mode => Application t wake field acc. for UHECRs

A. Mizuta, T. Ebisuzaki (2018)

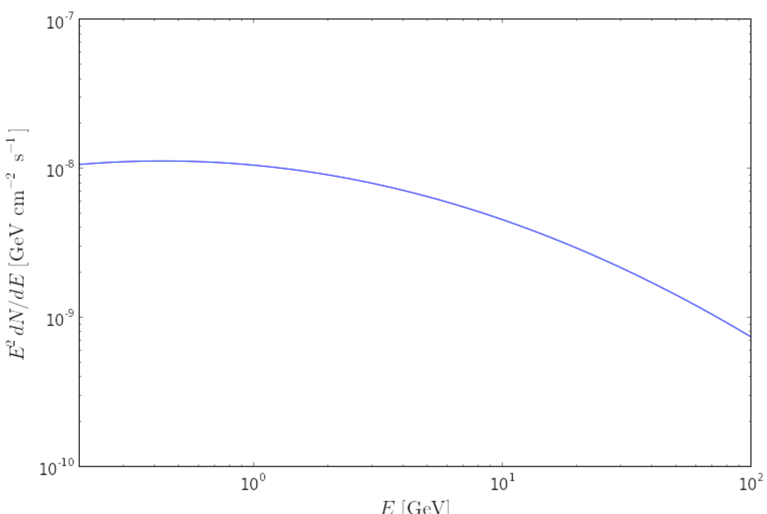
Blazar shows anti-correlation between γ burst flux and spectral index

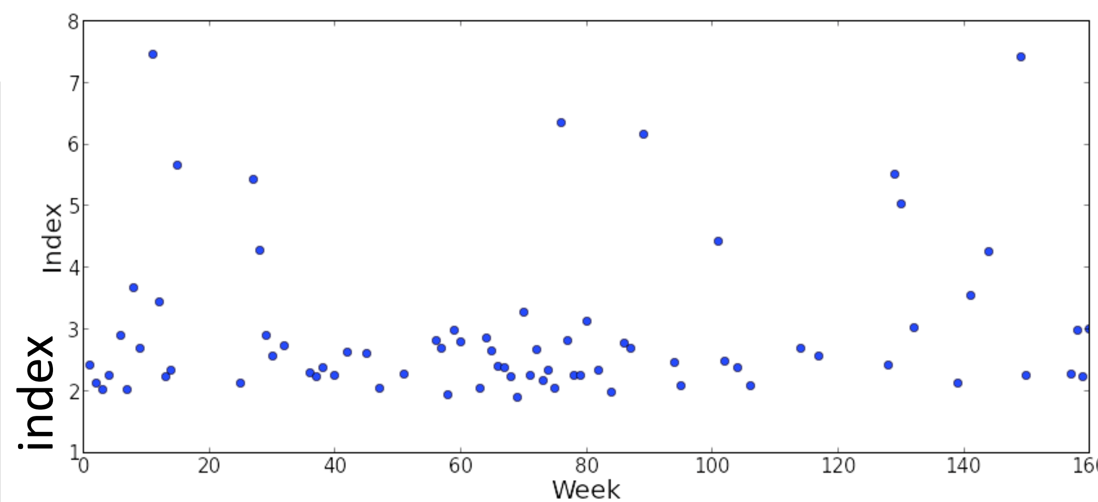
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



Rise time < week (less than a unit),
Period between bursts ~> 10 weeks
Spectral index => 2
(~ Ebisuzaki/Tajima theory)

→ all quantitatively consistent with Wakefield theory





time

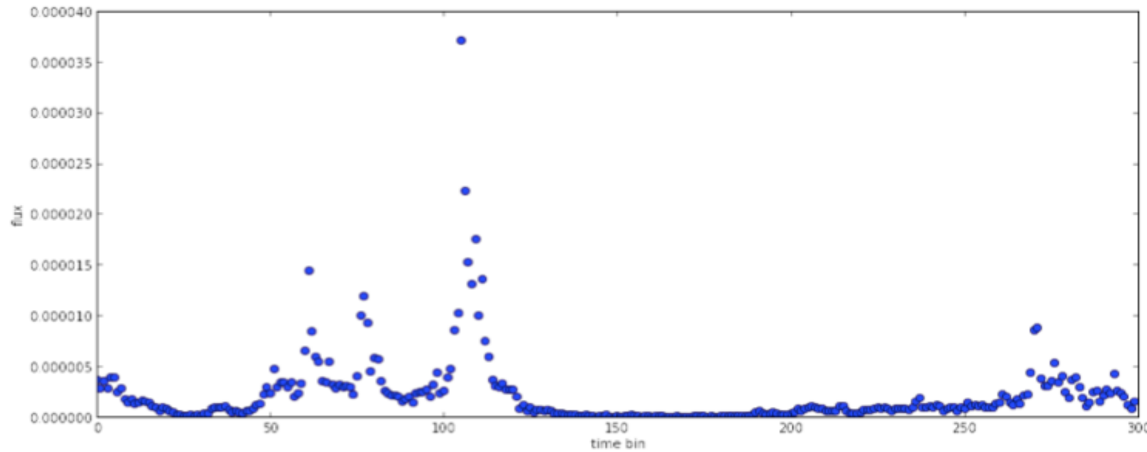
N. Canac, K. Abazajian (2020)

Again, Anti-correlation even in a bigger blazar

Blazar: 3C454.3

$M \sim 10^9 M_{Sun}$

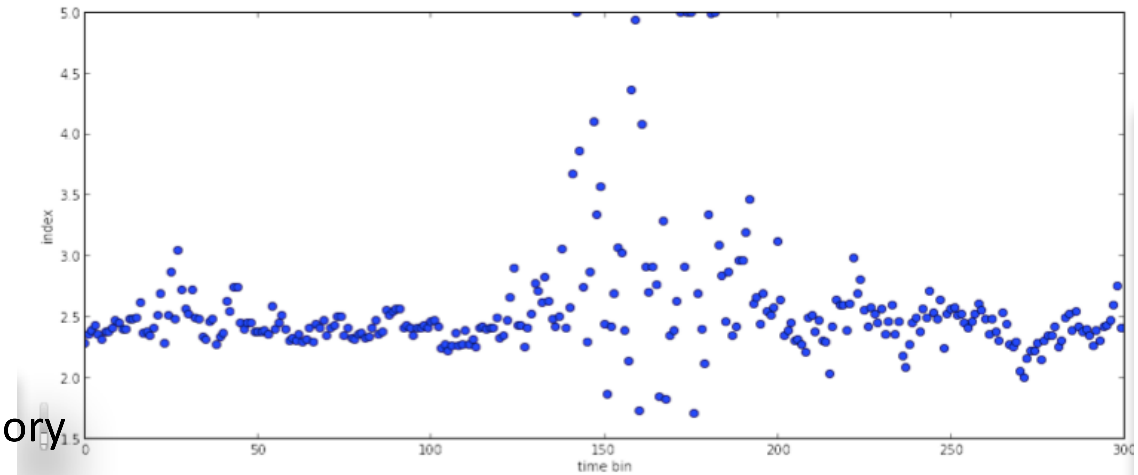
flux



Same anti-correlation as AO0235+164

The rise time and burst periods a lot longer (by an order of magnitude)

index



Quantitative agreement and **<u>correct scaling</u>** with Blazar mass with (broader sense of) Wakefield theory (Ebisuzaki/Tajima)

period ~ *M* ; luminosity ~*M*

time

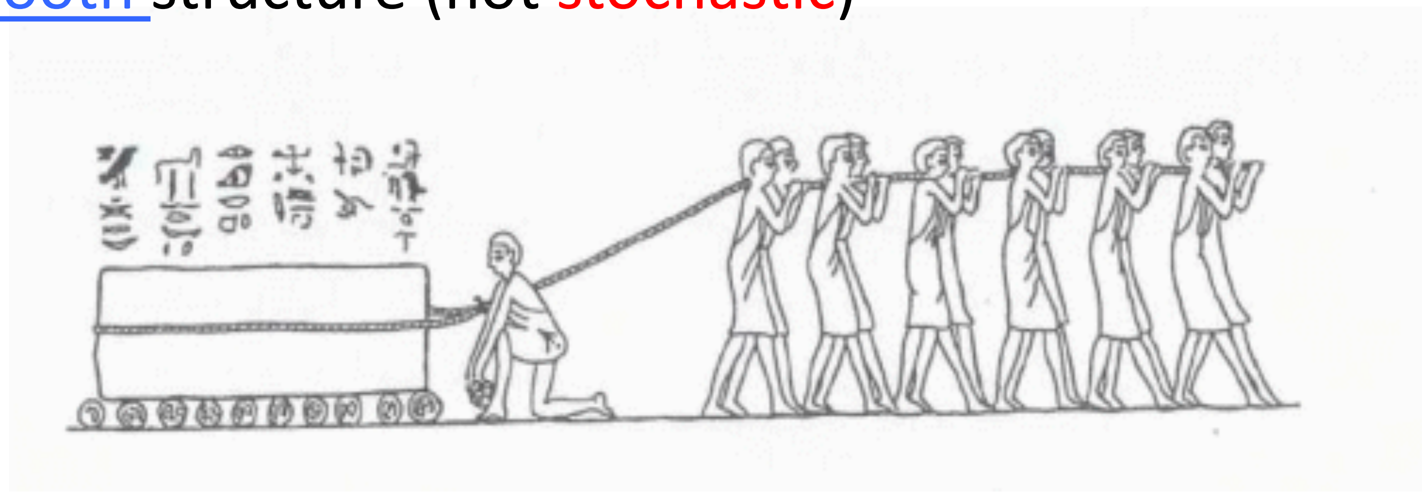
N. Canac, K. Abazajian (2020)

Plasma's Collective Force / Modes

(vs. single-particle force)

Collective force ~$\boldsymbol{N^2}$ (nonlinear 🡐 linear force ~N)

Coherent and smooth structure (not stochastic)



enhancement by $10^3 – 10^4$ (even by $\mathbf{10^{6-12}}$) >> interaction of one particle x one particle

Collective mode delivery (EM x plasma x B)←→ long-ranged force (gravity, EM)

what difference?

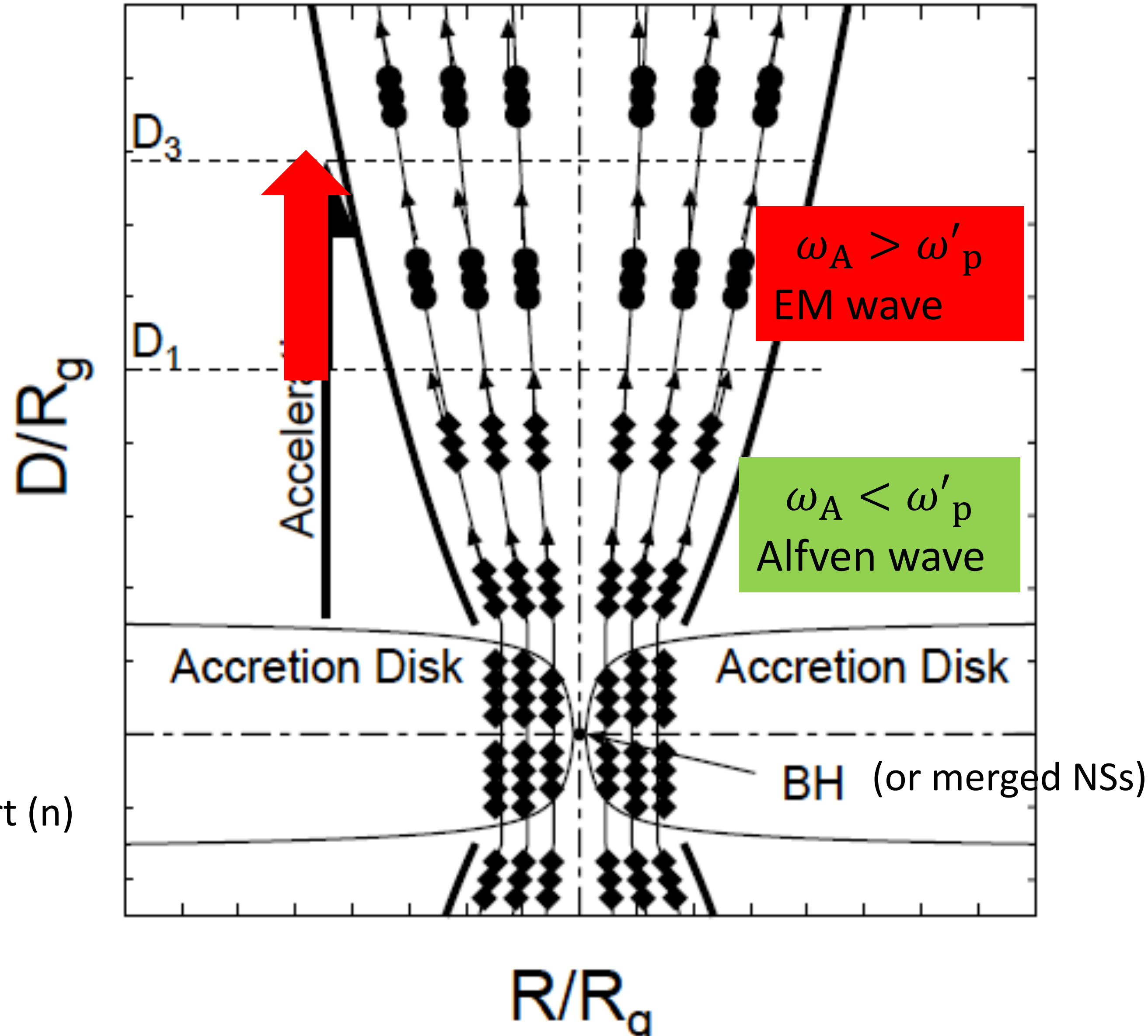
e.g. jet

e.g. galaxy-galaxy interaction

Wakefield generation in Jet

← n_e decreases

V_A ~ B / sqrt (n)



T. Ebisuzaki and T. Tajima, Astropart. Phys. (2014)