The Cosmic Battery in X-ray binaries

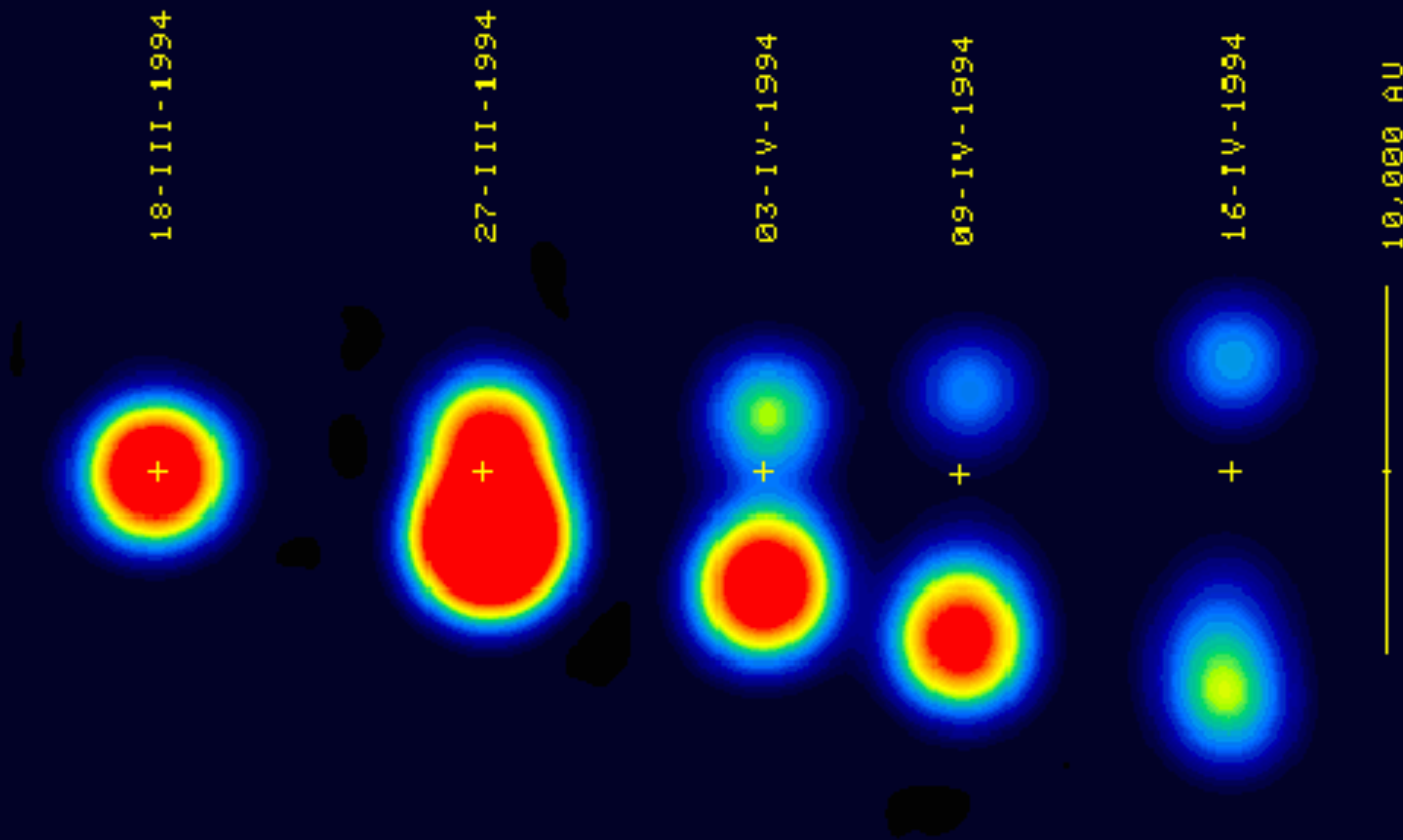
Ioannis Contopoulos
RCAAM, Academy of Athens

European Union
European Social Fund

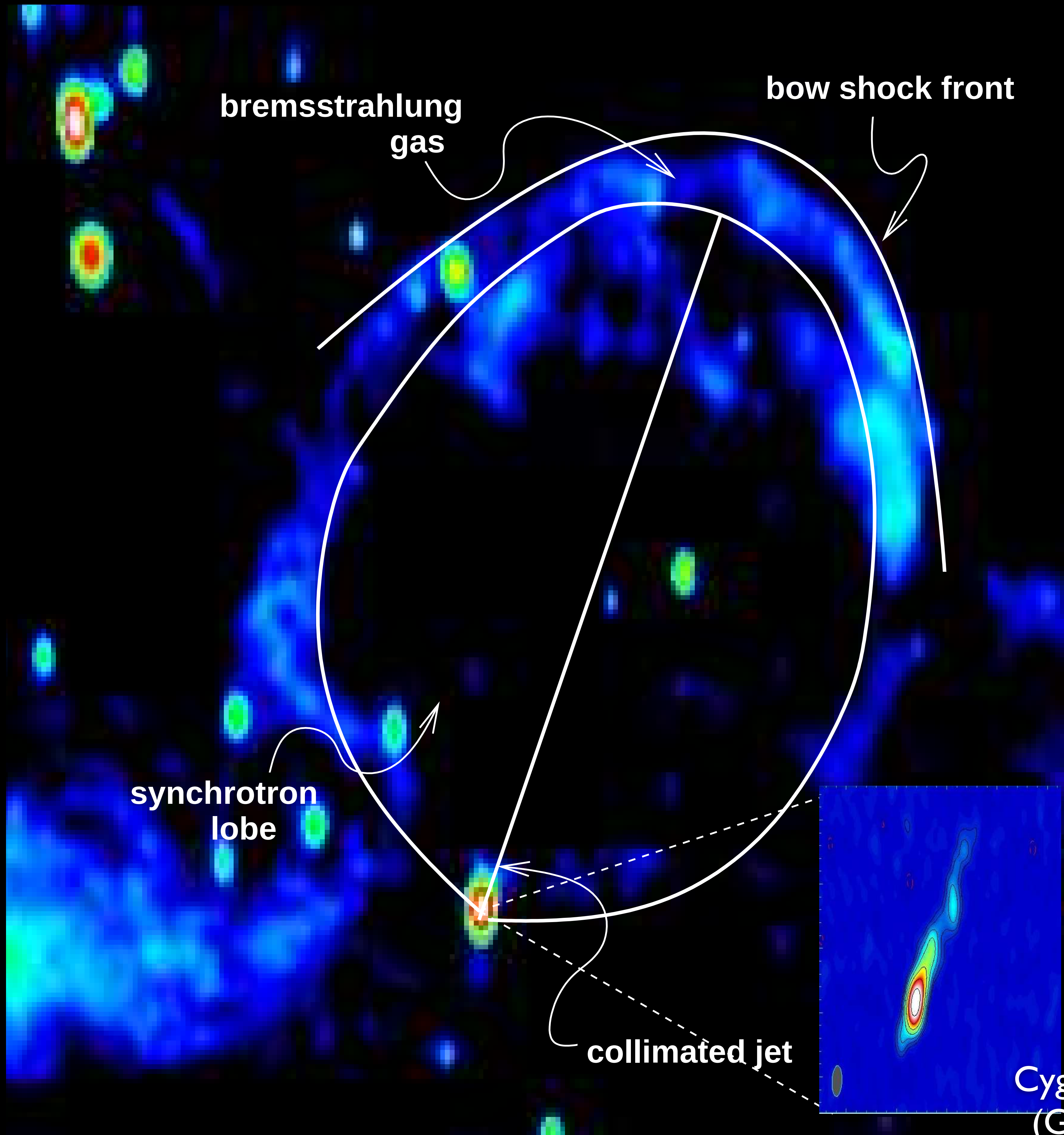
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY

NSRF
2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co- financed by Greece and the European Union



GRS 1915+105 (Mirabel 1994)



Cygnus X-1 jet lobe
(Gallo *et al.* 2005)

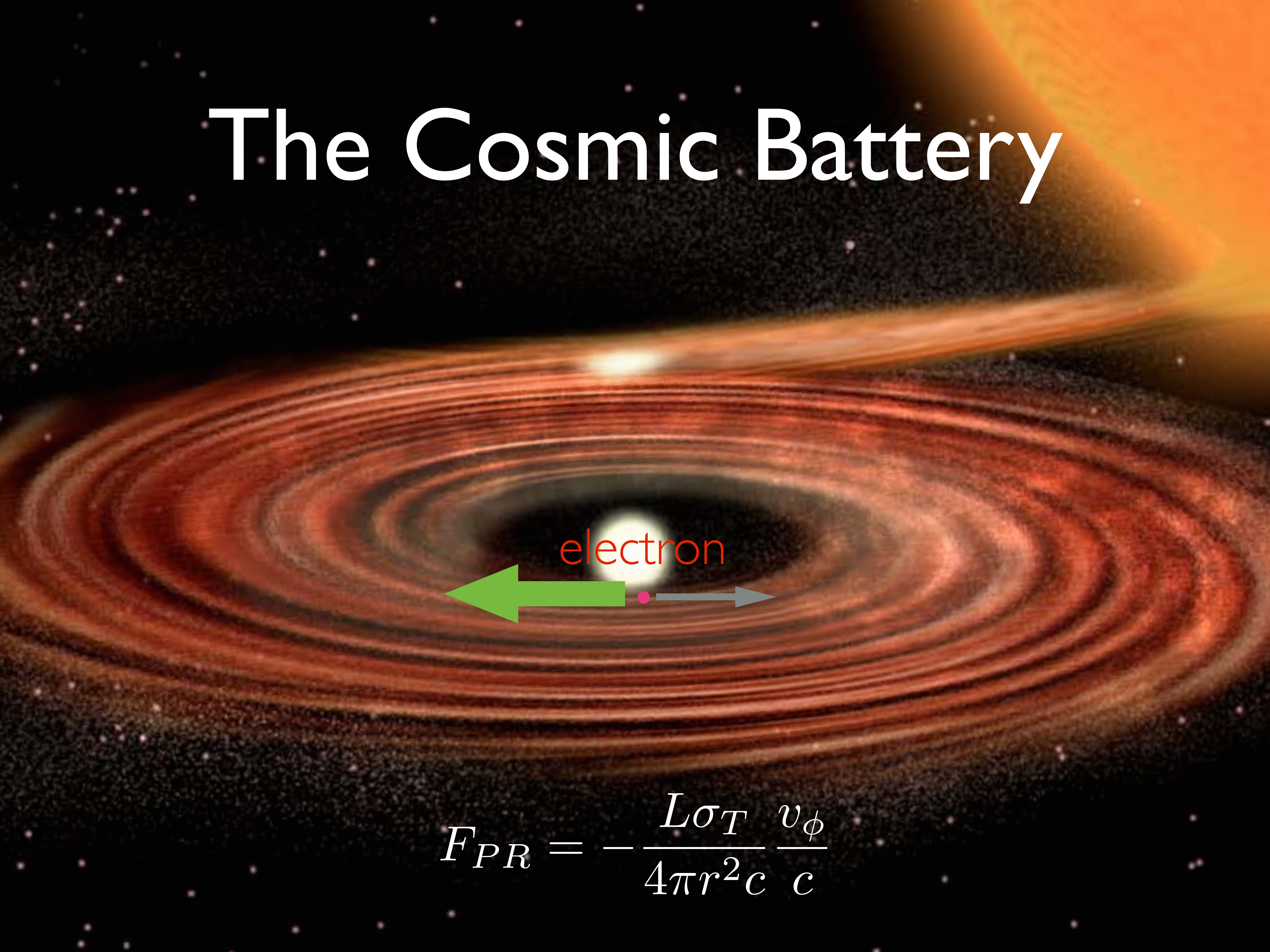

M87 (HST)

Artist’s impression

Where does the magnetic field come from?

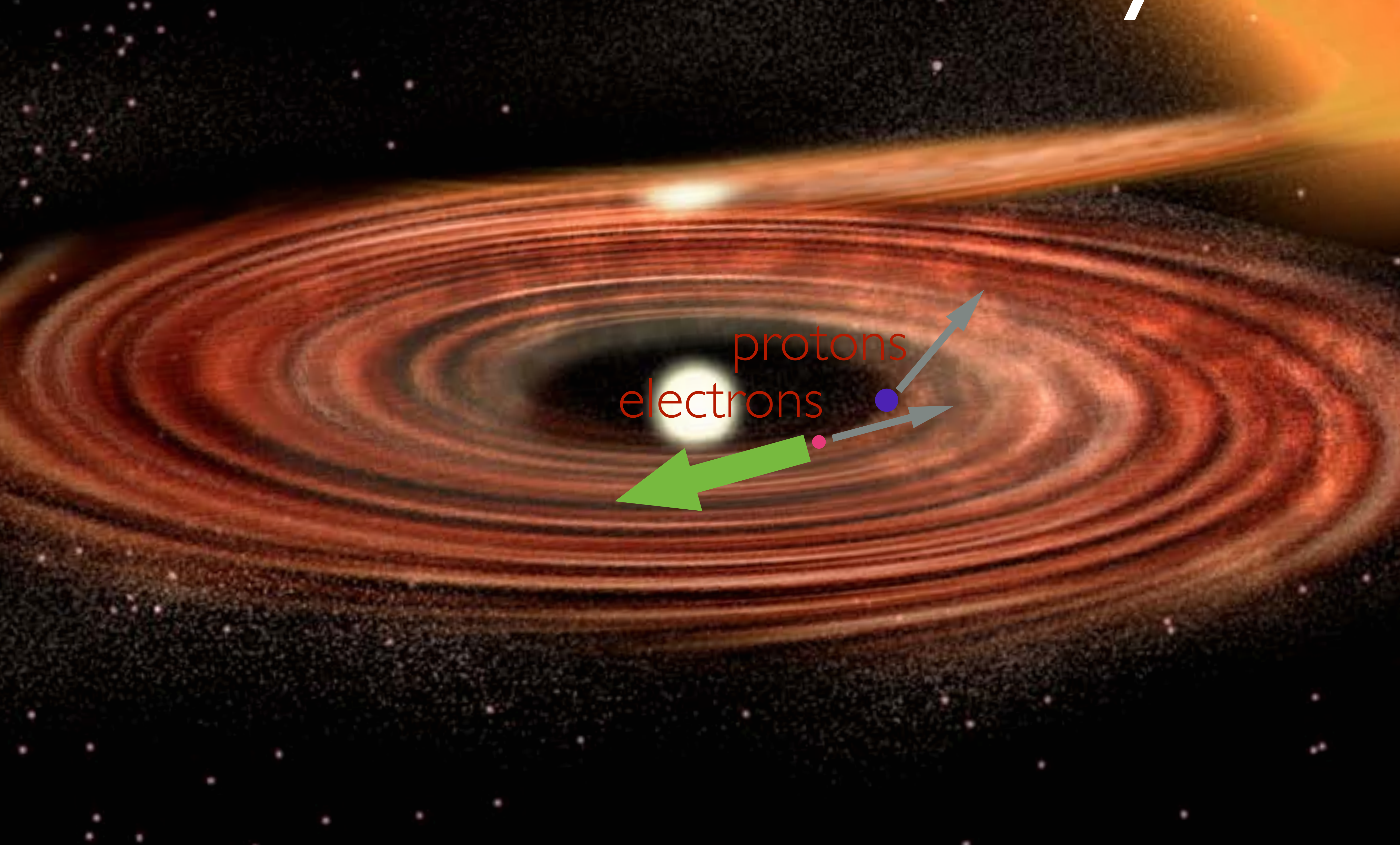
- The Cosmic Battery *(C, Kazanas 1998, ApJ)*
- The Cosmic Battery Revisited *(C, Kazanas, Christodoulou 2006, ApJ)*
- Simulations of the Poynting-Robertson Cosmic Battery in Resistive Accretion Disks *(Christodoulou, C, Kazanas 2008, ApJ)*

The Cosmic Battery



$$F_{PR} = -\frac{L\sigma_T}{4\pi r^2 c}\frac{v_\phi}{c}$$

The Cosmic Battery



- The Cosmic Battery *(Contopoulos, Kazanas 1998)*

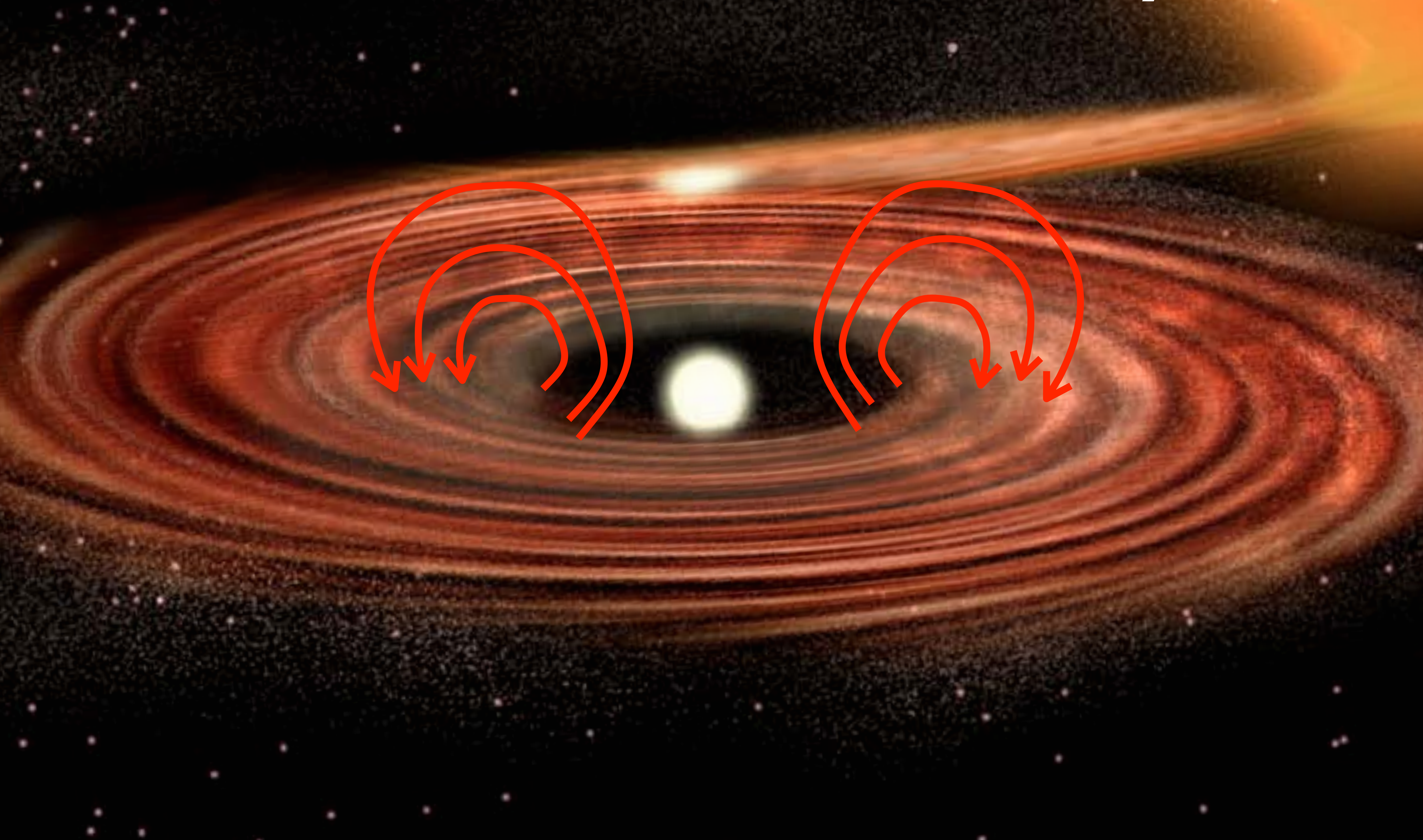
$$m_e\left(\frac{d\mathbf{v}_p}{dt}\right) = -e\left(\mathbf{E} + \frac{\mathbf{v}_e \times \mathbf{B}}{c}\right) + m_e\mathbf{g} + \mathbf{F}_{\rm rad}$$

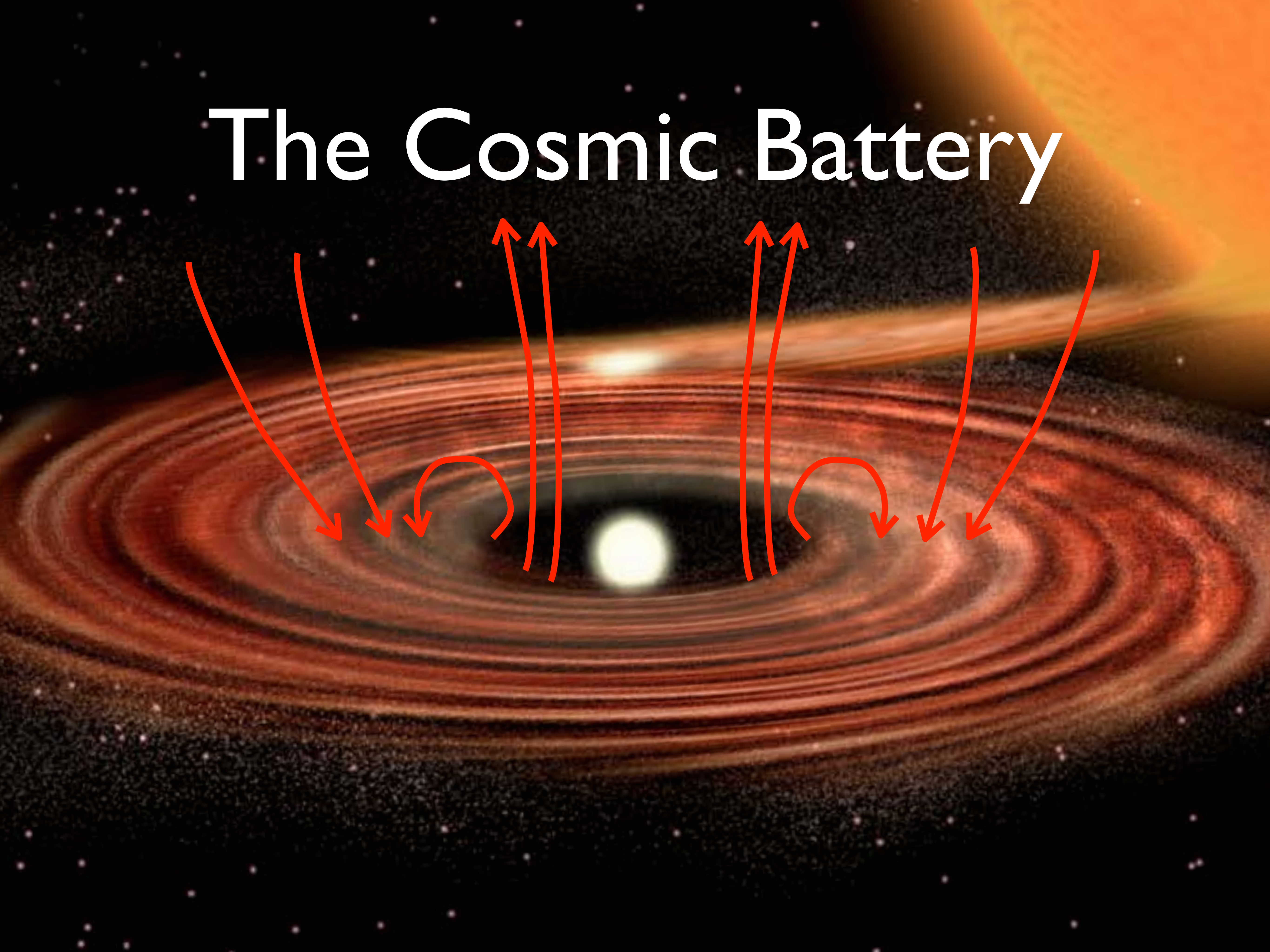
$$m_p\left(\frac{d\mathbf{v}_p}{dt}\right) = +e\left(\mathbf{E} + \frac{\mathbf{v}_p \times \mathbf{B}}{c}\right) + m_p\mathbf{g}$$

$$\mathbf{E} + \frac{\mathbf{v}_e \times \mathbf{B}}{c} = \frac{\mathbf{F}_{\rm rad}}{e}$$

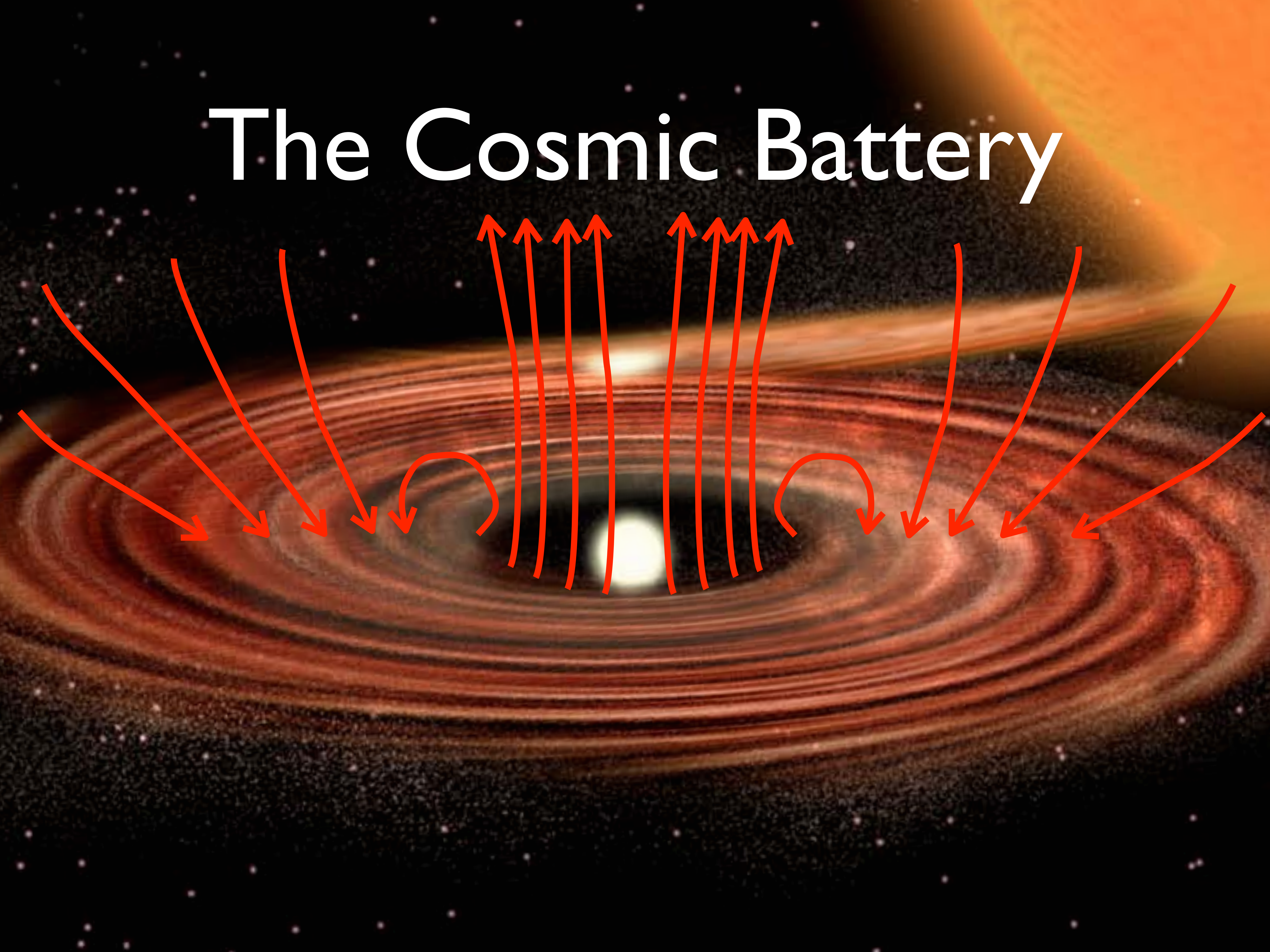
$$\begin{aligned}\frac{d\mathbf{B}}{dt} &= -c\nabla \times \mathbf{E} \\ &= \nabla \times (\mathbf{v}_e \times \mathbf{B}) - \nabla \times \left(\frac{c\mathbf{F}_{\rm rad}}{e}\right)\end{aligned}$$

The Cosmic Battery




The Cosmic Battery

The Cosmic Battery



- The Biermann Battery *(Biermann 1950)*

$$n_e m_e \left(\frac{d\mathbf{v}}{dt}\right) = -n_e e \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) - \nabla p_e + n_e m_e \mathbf{g}$$

$$+\mathbf{F}_{\text{`Ohm'}}$$

$$\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} = -\frac{\nabla p_e}{n_e e} + \frac{\mathbf{F}_{\text{`Ohm'}}}{n_e e}$$

$$\begin{aligned} \frac{d\mathbf{B}}{dt} &= -c\nabla \times \mathbf{E} \\ &= \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times \left(\frac{c\nabla p_e}{n_e e}\right) \\ &= \nabla \times (\mathbf{v} \times \mathbf{B}) - c\frac{\nabla n_e \times \nabla p_e}{n_e^2 e} \end{aligned}$$

$$-\nabla \times \left(\frac{c\mathbf{F}_{\text{`Ohm'}}}{n_e e}\right)$$

- Vorticity and magnetic fields

$$\frac{d\mathbf{v}}{dt} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p - \mathbf{g}$$

$$\frac{d\omega}{dt} = \nabla \times (\mathbf{v} \times \omega) + \frac{\nabla\rho \times \nabla p}{\rho^2} \quad , \quad \omega \equiv \nabla \times \mathbf{v}$$

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{\nabla n_e \times \nabla p_e}{n_e^2 e}$$

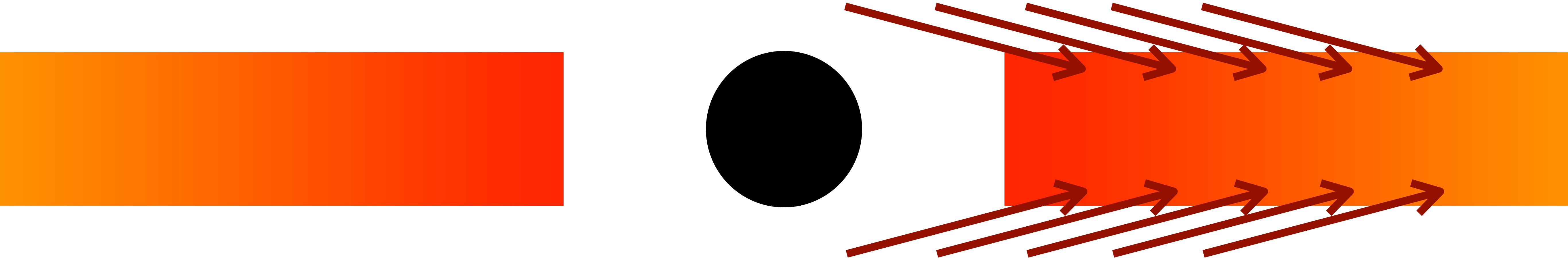
The Cosmic Battery

Object Parameters

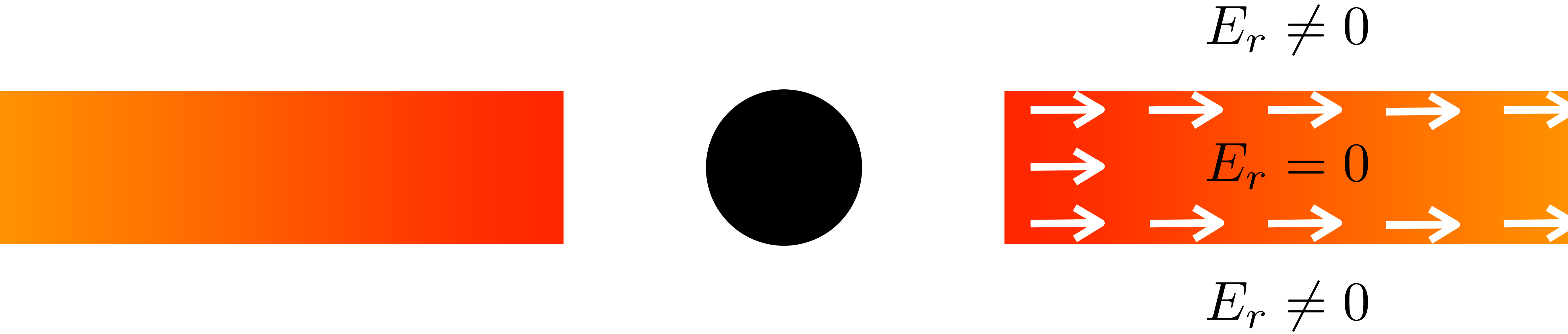
Object	$r_{\rm in}$ (cm)	L ($L_\odot$)	M ($M_\odot$)	$\tau_{\rm eq}$ (yr)	$B_{\rm eq} \equiv \Psi_{\rm eq}/r_{\rm in}^2$ (G)
Black Hole	3×10^6	10^4	10	7×10^{-4}	5×10^7
Neutron Star...	10^6	10^4	1	10^{-3}	2×10^7
White Dwarf...	10^8	10	1	2×10^4	2×10^4
Protosun	7×10^9	332	10^{-1}	2×10^9	8×10^3
AGN............	10^{13}	10^{12}	10^8	7×10^7	5×10^3
Galaxy	10^{22}	10^{10}	10^{10}	6×10^{30}	6×10^{-5}

Contopoulos & Kazanas 1998

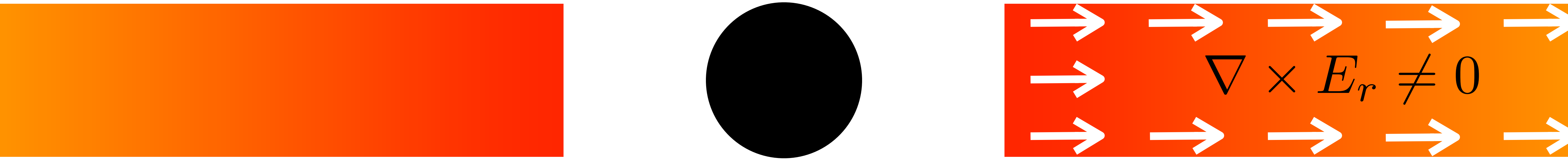
- The Biermann Battery *(Biermann 1950)*
- The Cosmic Battery *(Contopoulos, Kazanas 1998):*
  - Rotation of solar coronal layers *(Cattani, Sacchi 1966)*
  - Rotation of protogalaxies with respect to the cosmic microwave background radiation *(Harrison 1970; Mishustin, Ruzmaikin 1972)*
  - Ring currents and poloidal magnetic fields in nuclear regions of galaxies *(Lesch et al. 1989)*
  - A Cosmic Battery Reconsidered *(Bisnovatyi-Kogan, Lovelace, Belinski 2002)*
  - Disk accretion onto a black hole at subcritical luminosity *(Bisnovatyi-Kogan, Blinnikov 1977)*



Bisnovatyi-Kogan, Blinnikov 1977

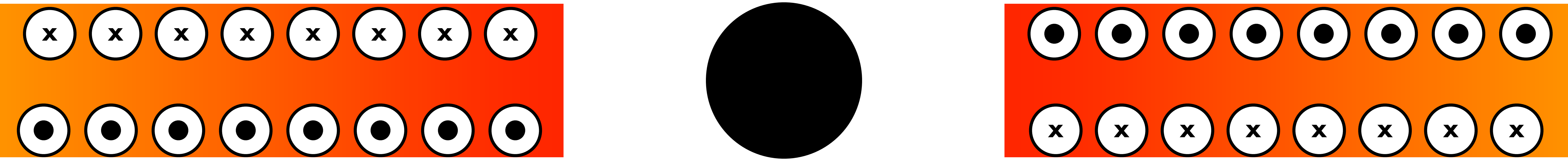


Bisnovatyi-Kogan, Blinnikov 1977



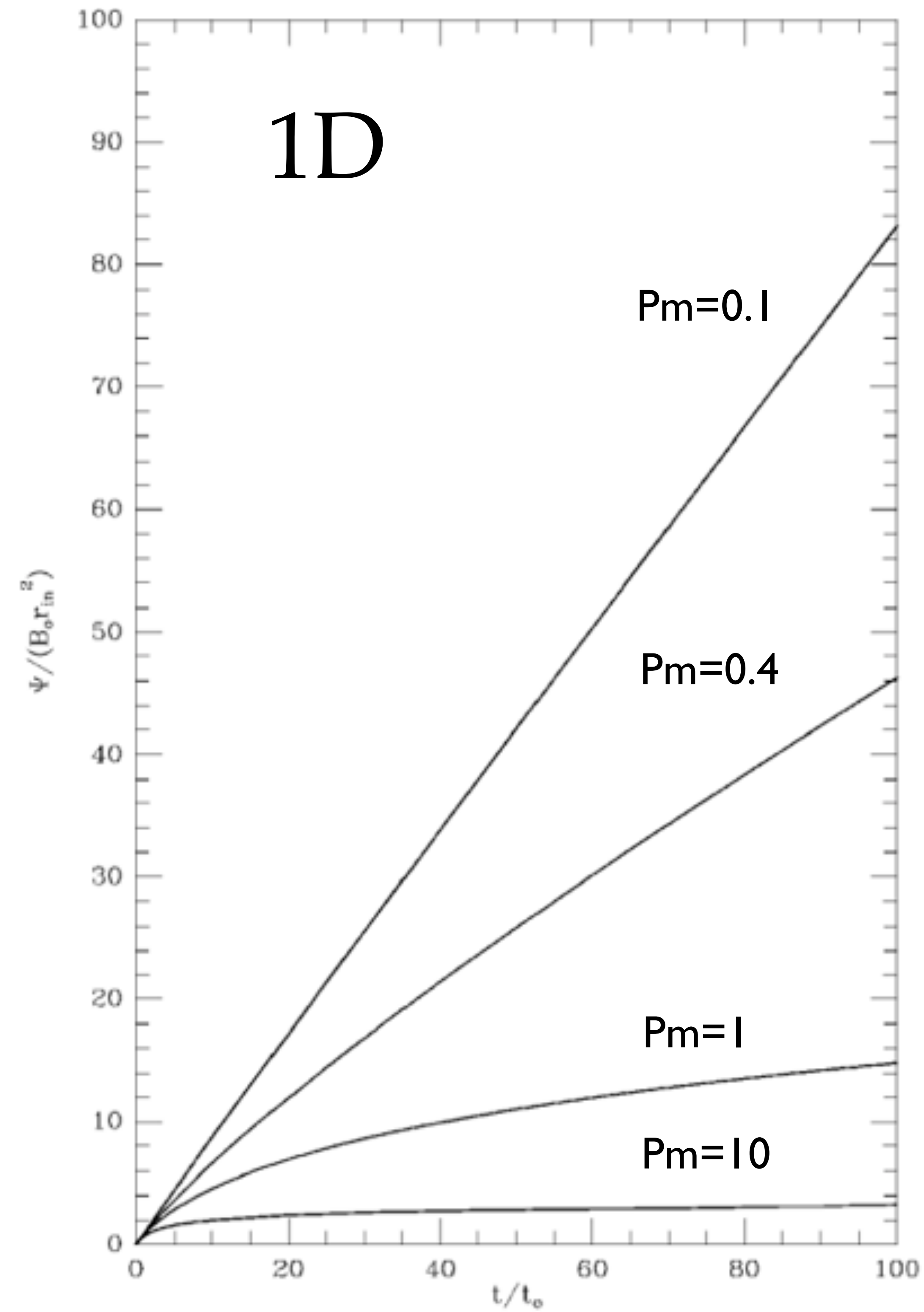
Bisnovatyi-Kogan, Blinnikov 1977

$$\frac{\partial B_\phi}{\partial t} \neq 0$$



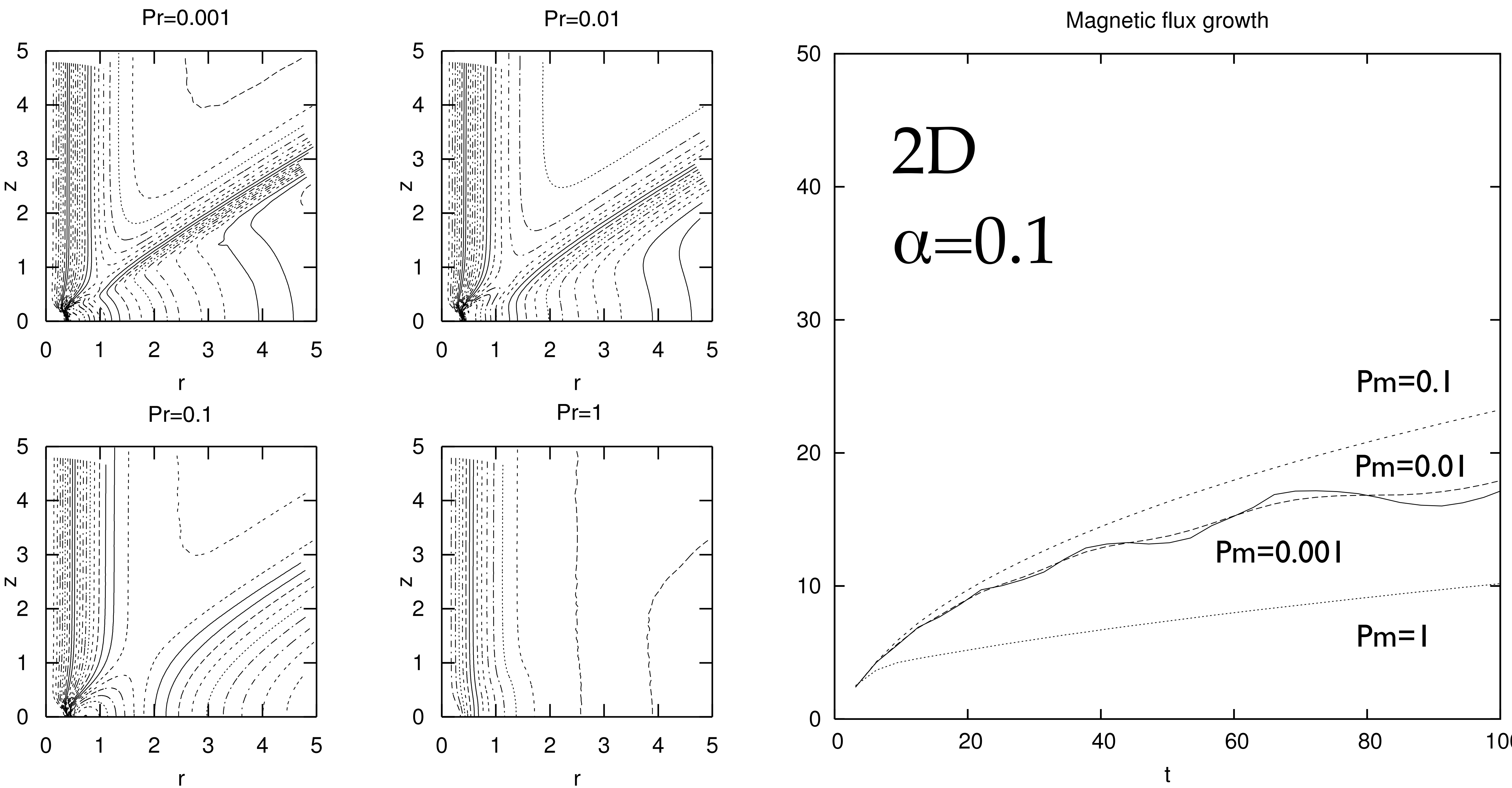
Bisnovatyi-Kogan, Blinnikov 1977

Numerical simulations



Contopoulos & Kazanas 1998

Numerical simulations



Contopoulos, Kazanas & Christodoulou 2006

Numerical simulations

- The Poynting-Robertson effect in GR: Monte Carlo ray-tracing *(Koutsantoniou, Contopoulos 2013)*
- Kinematic integration of the induction equation
- 2D/3D GR resistive MHD simulations with Cosmic Battery source term
- Where is the ISCO? *(Contopoulos, Papadopoulos 2012, 13)*

Jet formation

Evidence so far indicates that the production of Poynting-flux dominated relativistic jets requires a steady large-scale dipolar field near the black hole

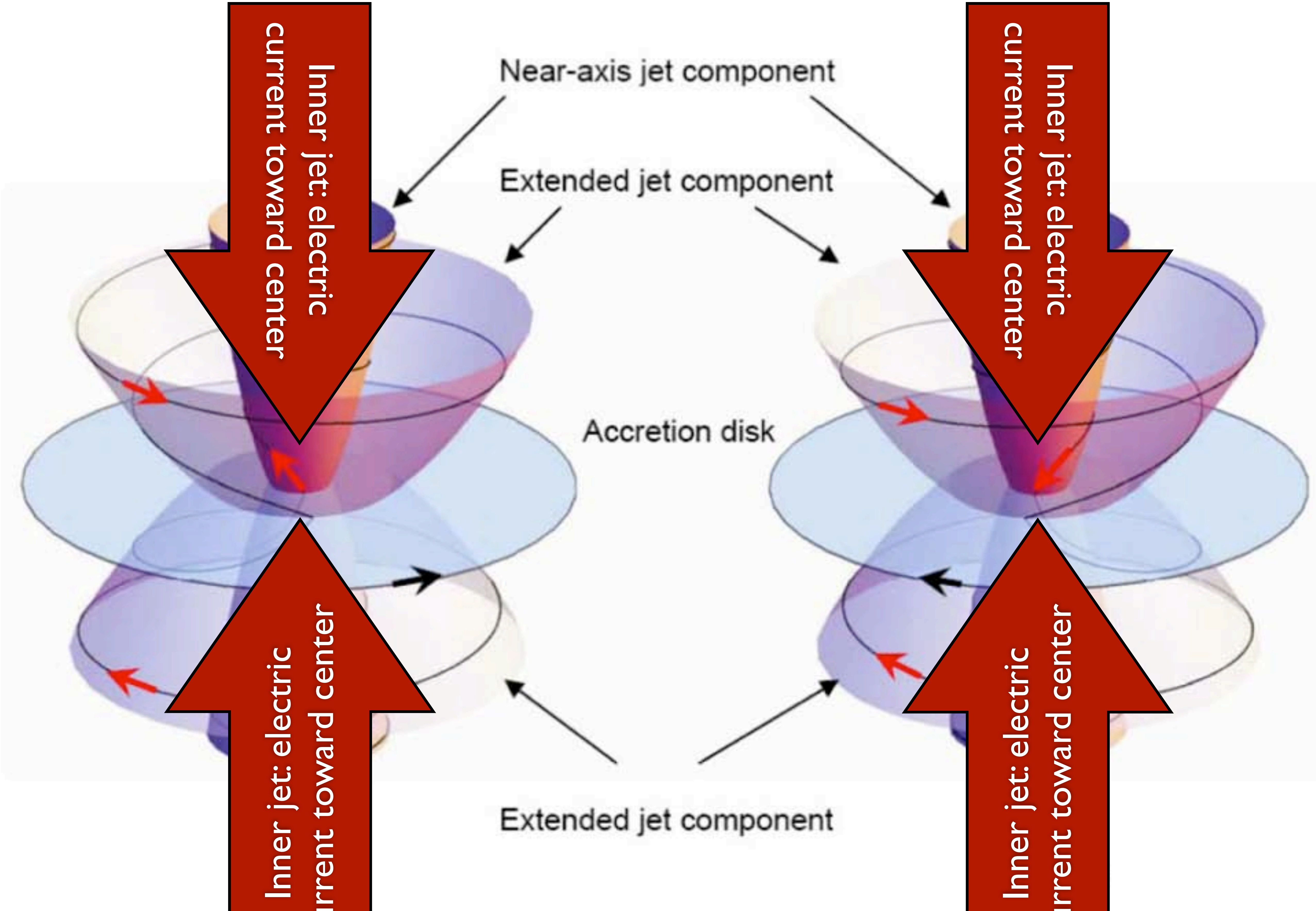
(McKinney, Tchekhovskoy, Blandford 2012)

The large-scale dipolar field required for jet formation is produced through the Poynting-Robertson drag on plasma electrons at the inner edge of the accretion disk around the central black hole

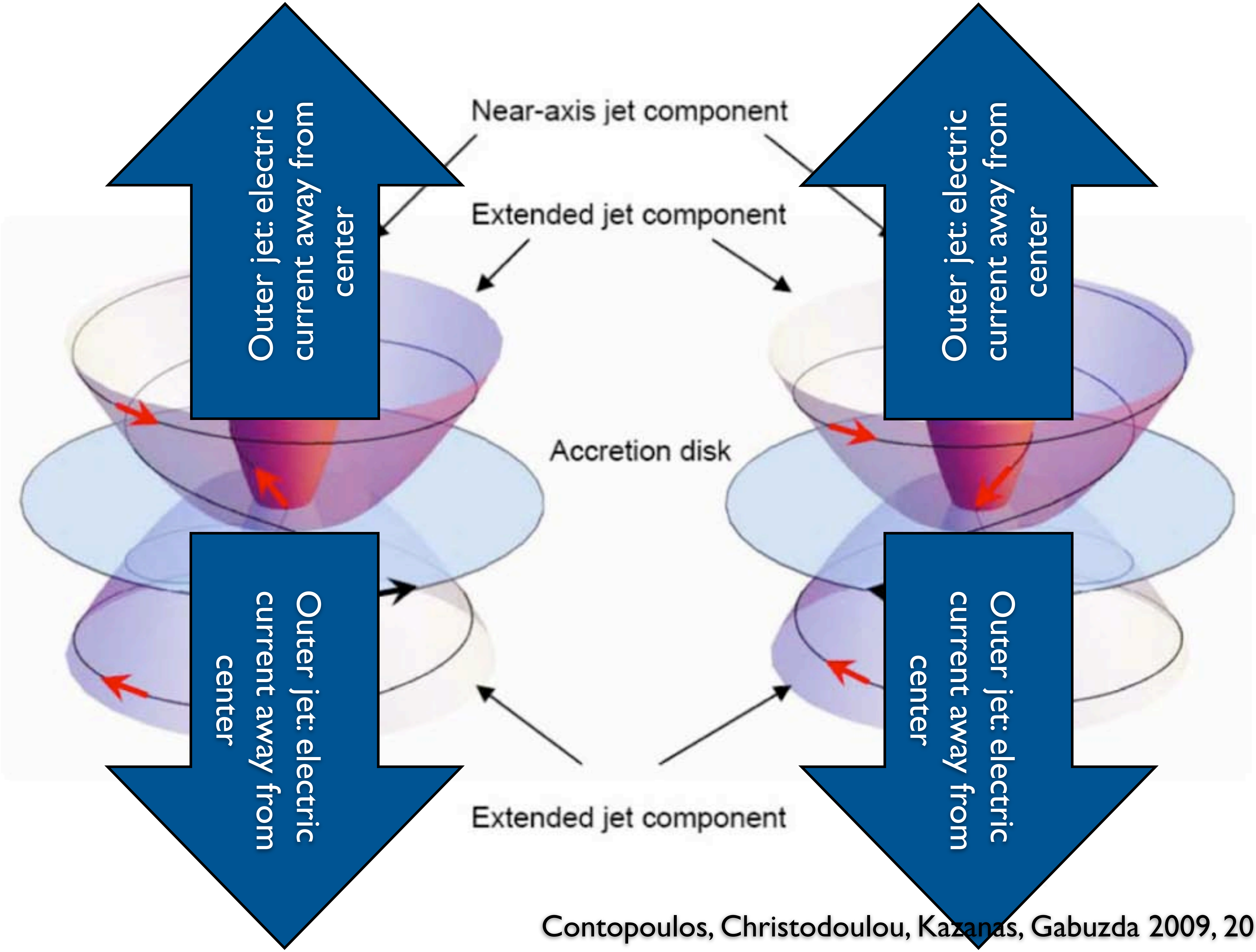
(Contopoulos, Kazanas 1998)

Observational evidence

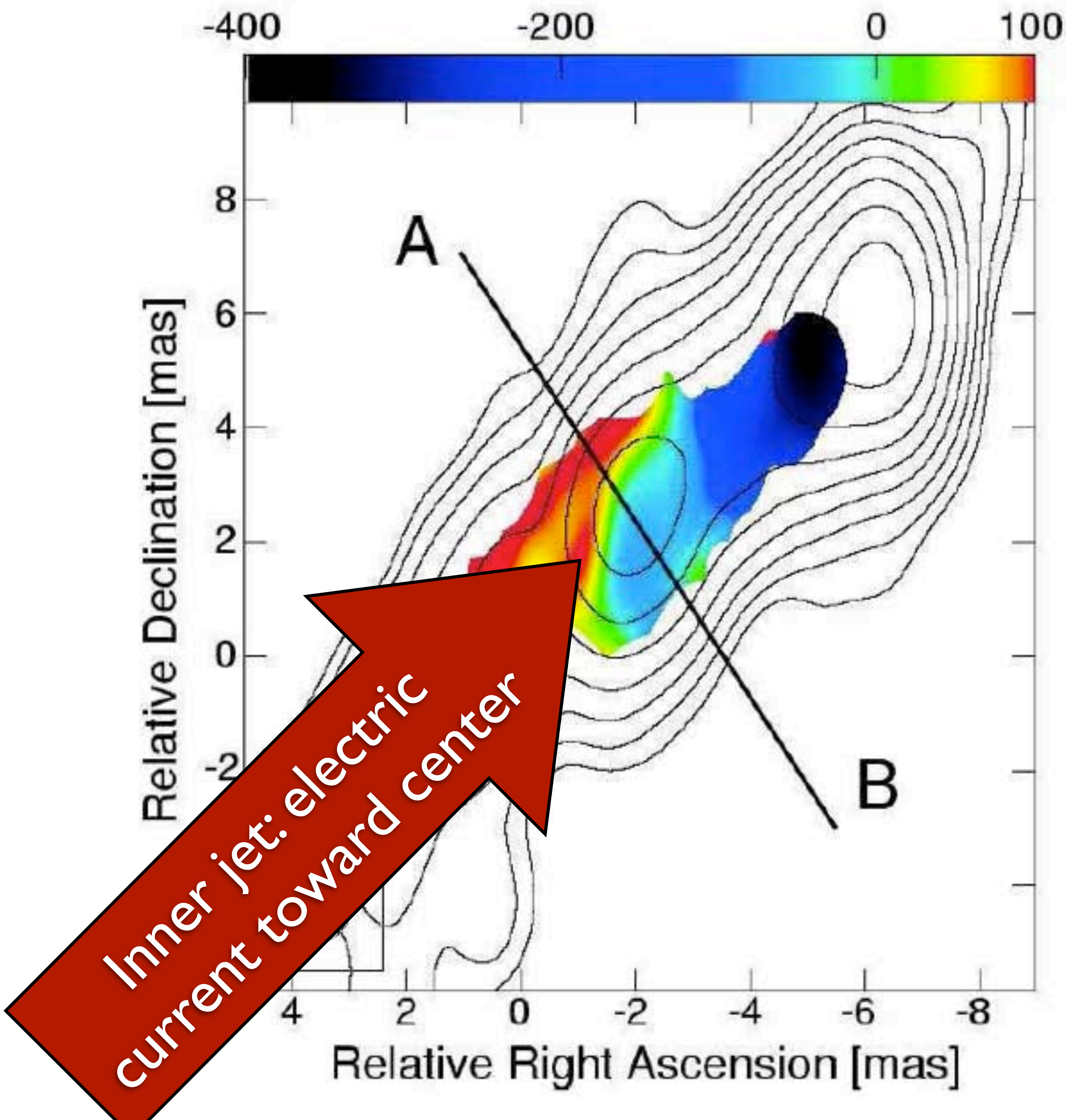
- Extragalactic jets:
  - The Invariant Twist of Magnetic Fields in the Relativistic Jets of Active Galactic Nuclei *(C, Kazanas, Christodoulou, Gabuzda 2009, ApJ)*
  - Evidence for Helical Magnetic fields in kpc-Scale AGN Jets and the Action of a Cosmic Battery *(Gabuzda, Christodoulou, C, Kazanas 2012, JPCS)*
- X-ray Binaries
  - Formation and destruction of jets in X-ray binaries *(Kylafis, C, Kazanas, Cristodoulou 2012, A&A)*
  - The HID in X-ray binaries *(Kazanas, Kylafis, C 2013)*



Contopoulos, Christodoulou, Kazanas, Gabuzda 2009, 2012



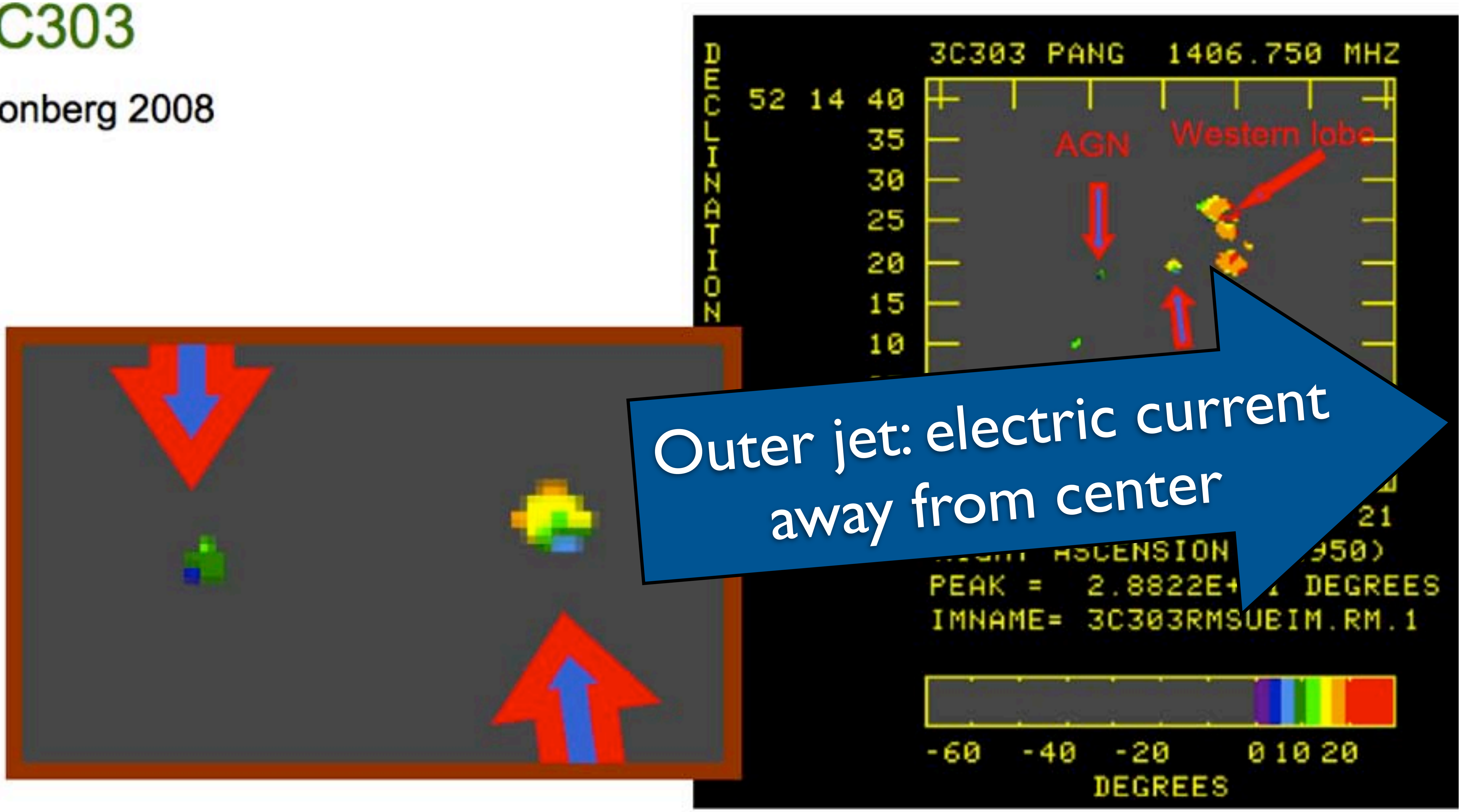
Contopoulos, Christodoulou, Kazanas, Gabuzda 2009, 2012



-400
-200
0
100
A
B
Relative Declination [mas]
Relative Right Ascension [mas]
Inner jet: electric current toward center

3C303

Kronberg 2008

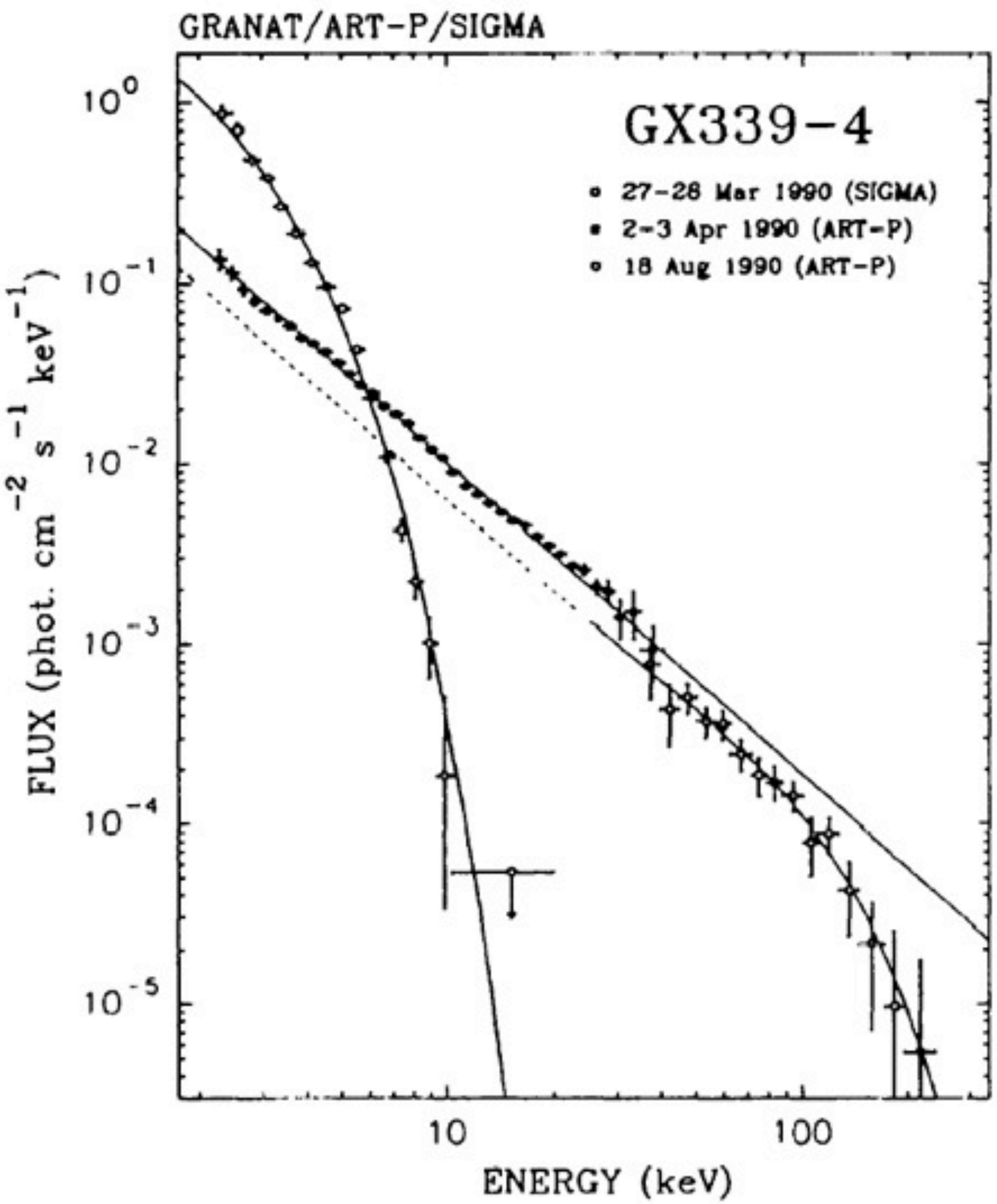


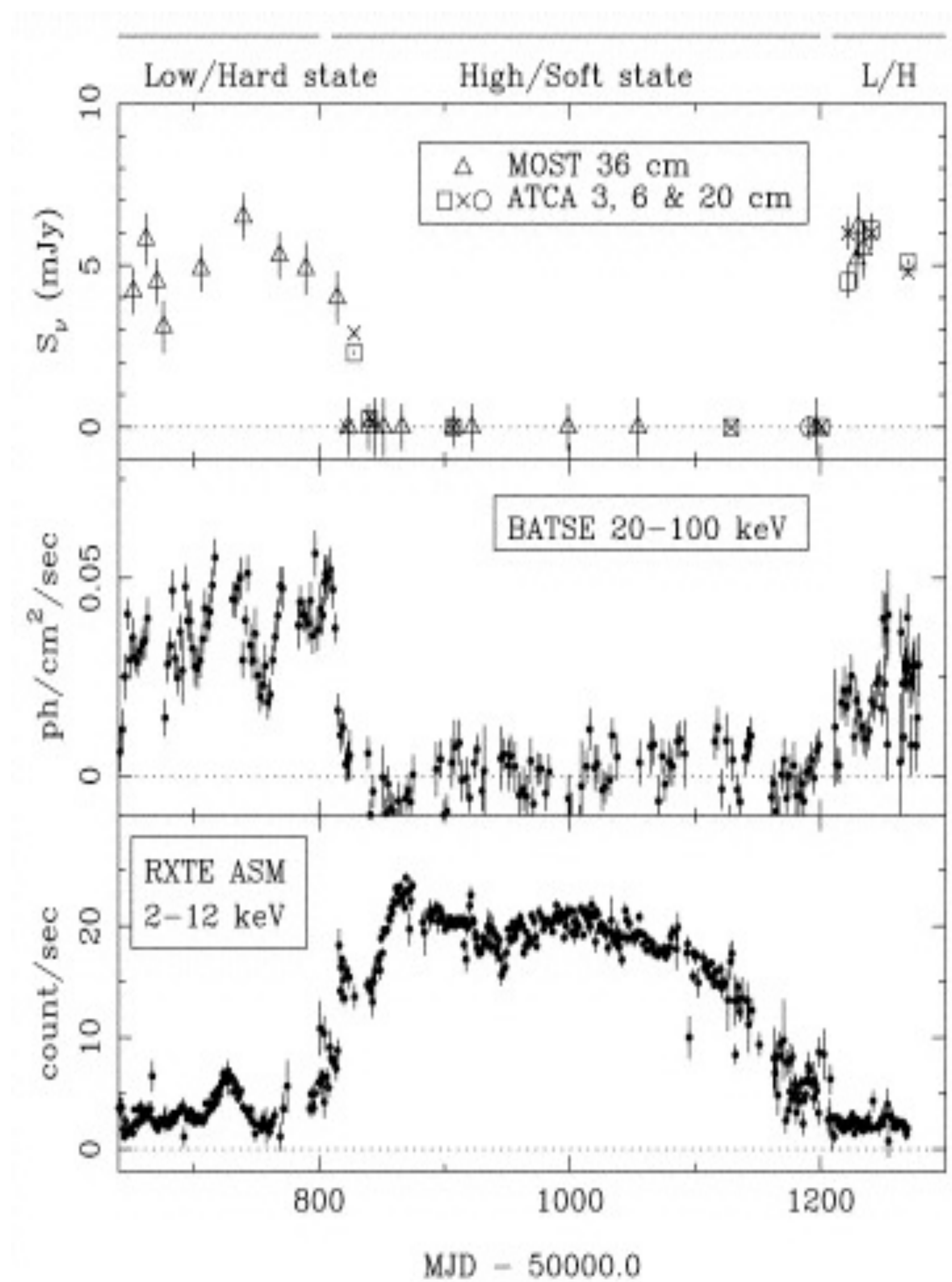
sources. Adding this information to the above indicates that the 3C303 jet has an average current within $\simeq 400$ pc of its axis, which is 7×10^{17} ampères, and directed away from the central BH (AGN) (Ji *et al.*, 2008). It is the largest electrical current ever measured. This result is of particular interest in the context of poynting flux energy flow models for extragalactic jets, as we shall discuss in the next section.

Kronberg *et al.* 2011

The Cosmic Battery in X-ray binaries: the Hardness-Intensity Diagram (HID)

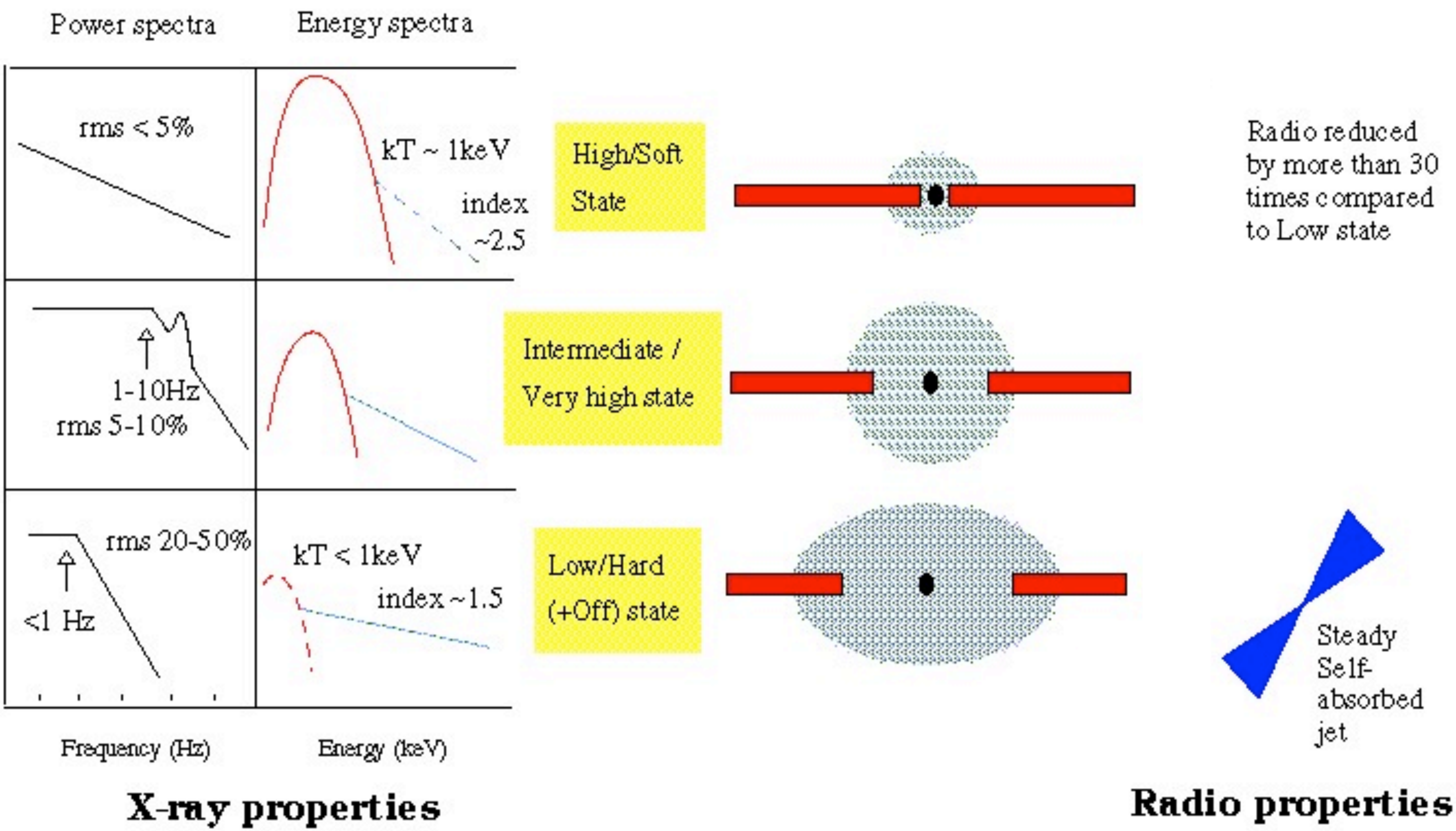
Spectral transitions





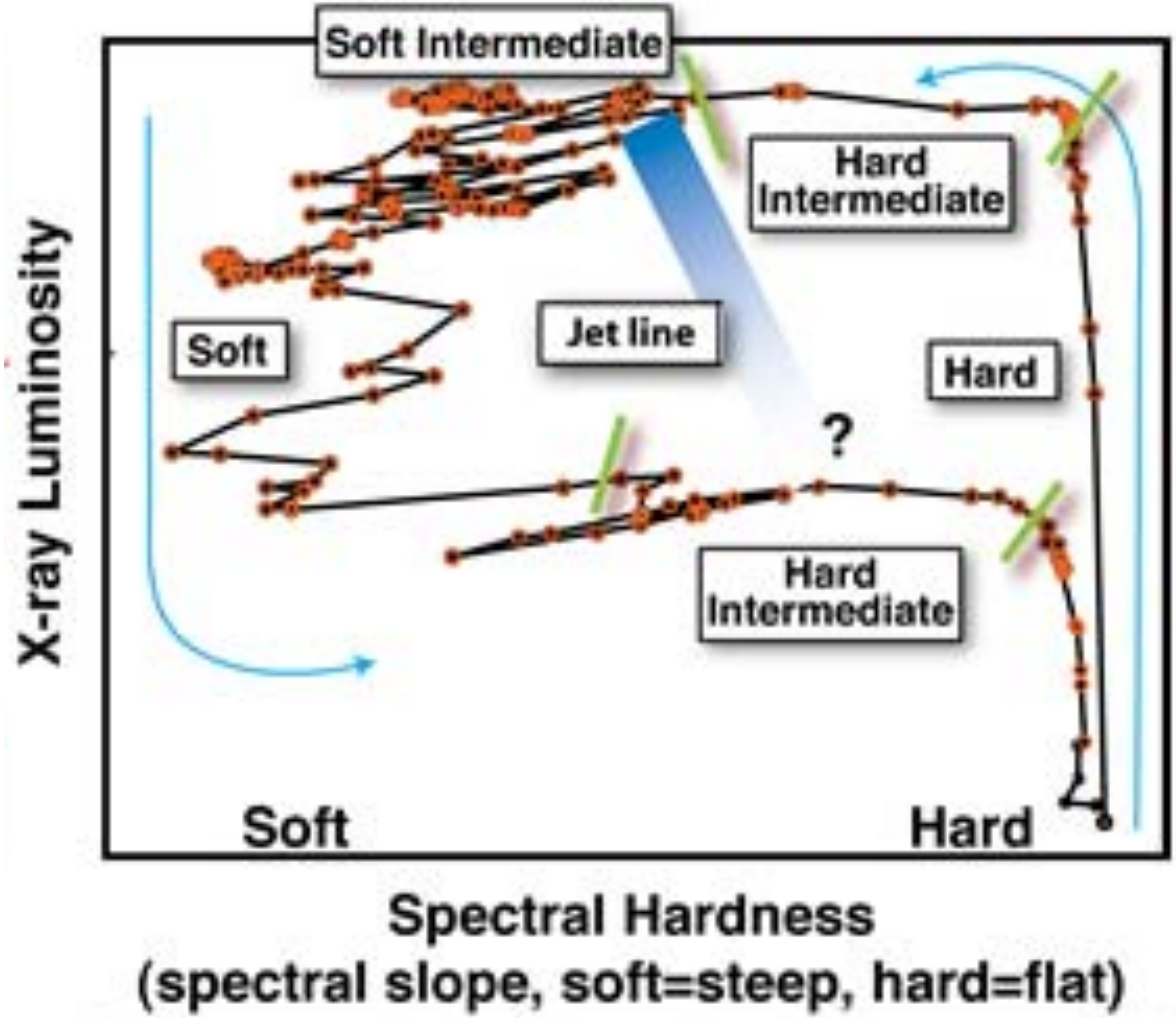
Grebenev *et al.* 1993

Spectral transitions



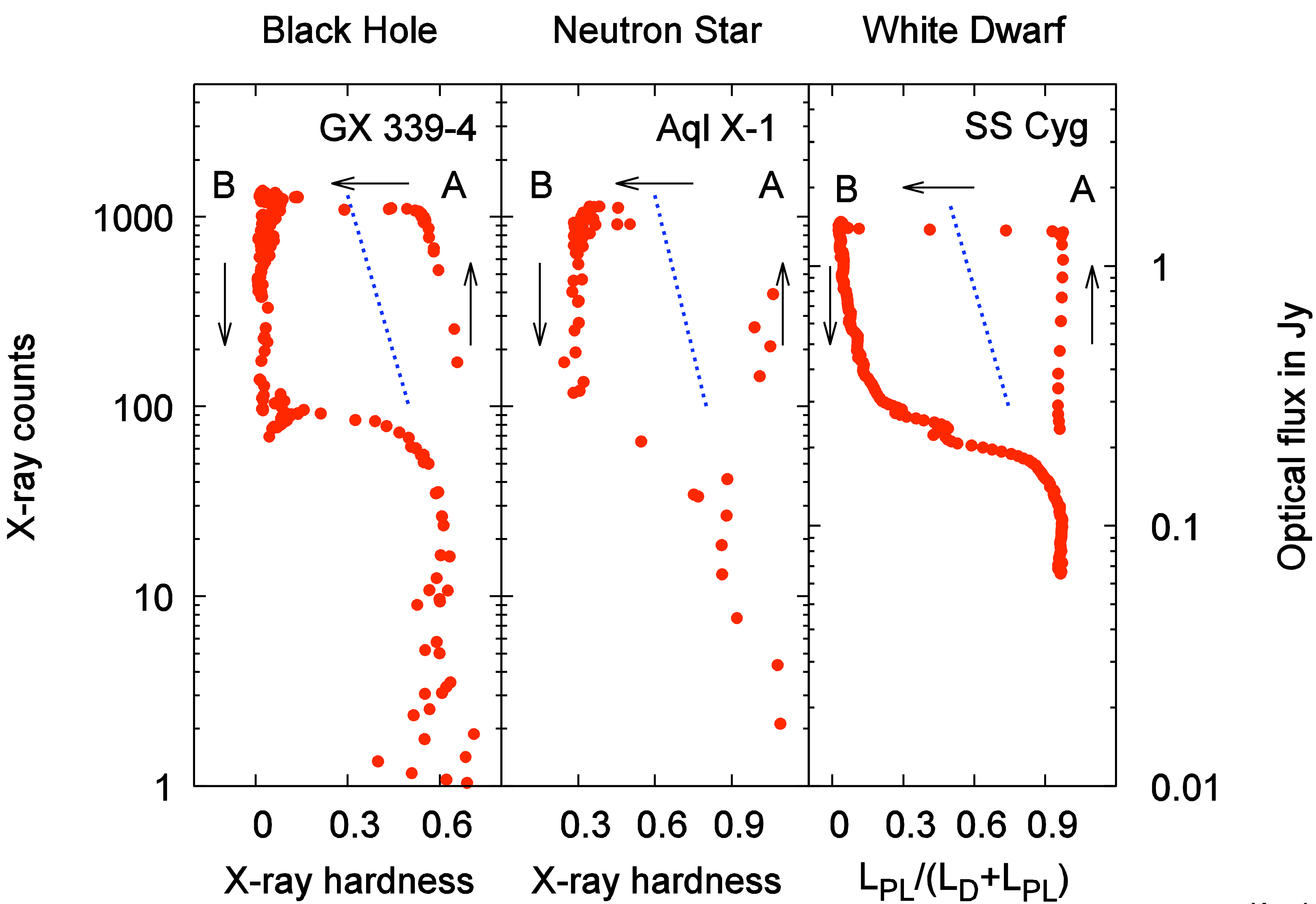
Fender 2001

The HID



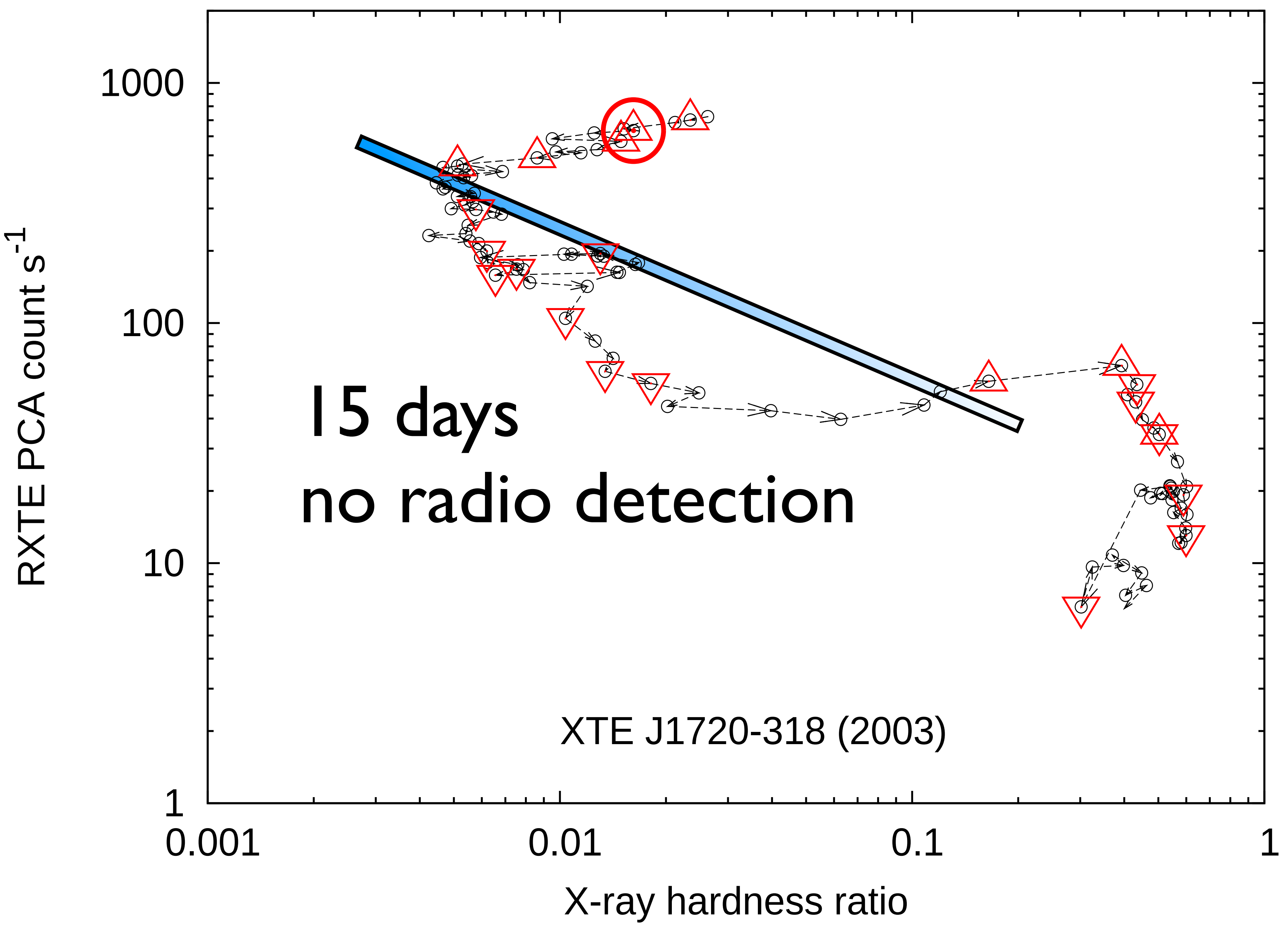
Belloni 2010

The HID

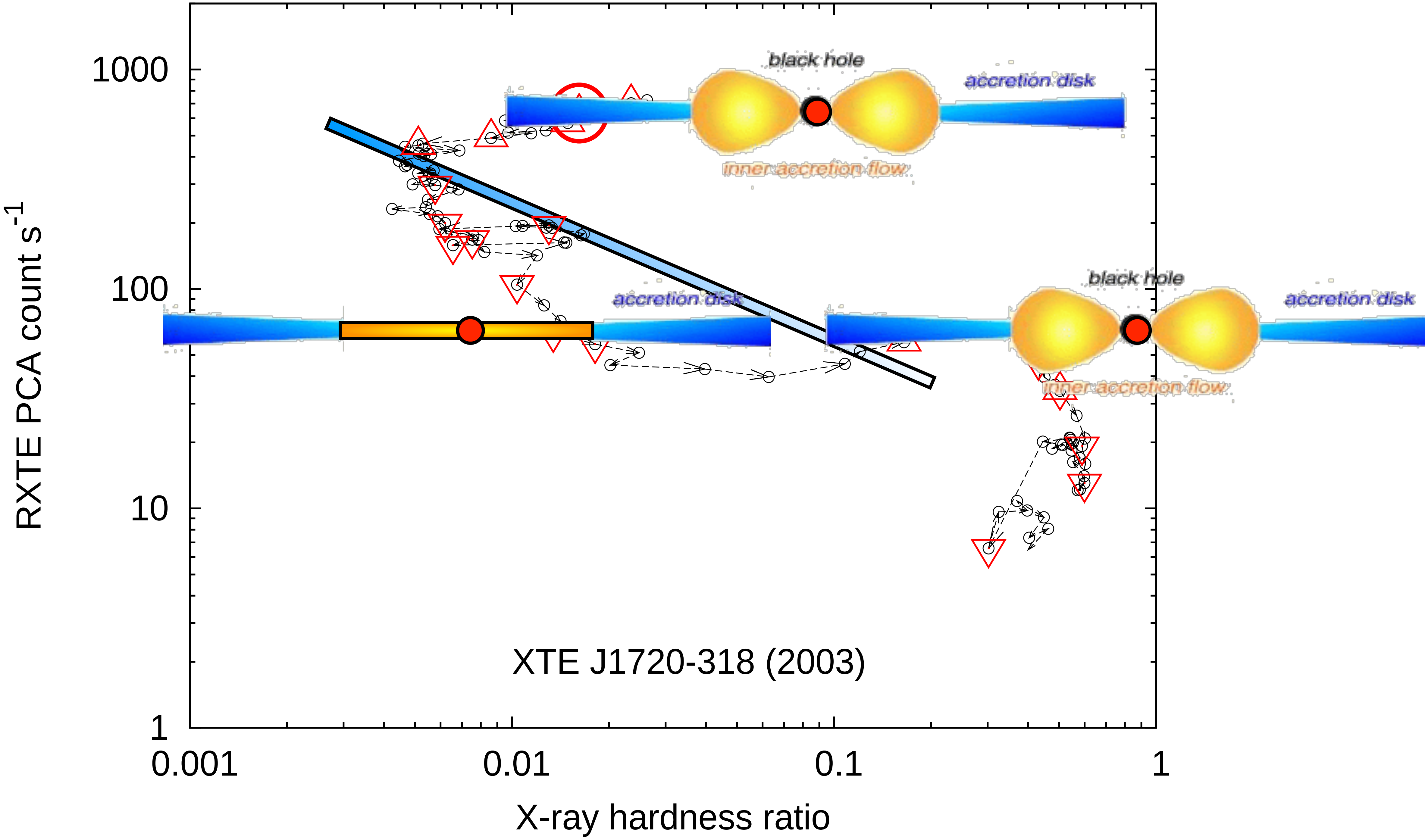


Kording *et al.* 2008

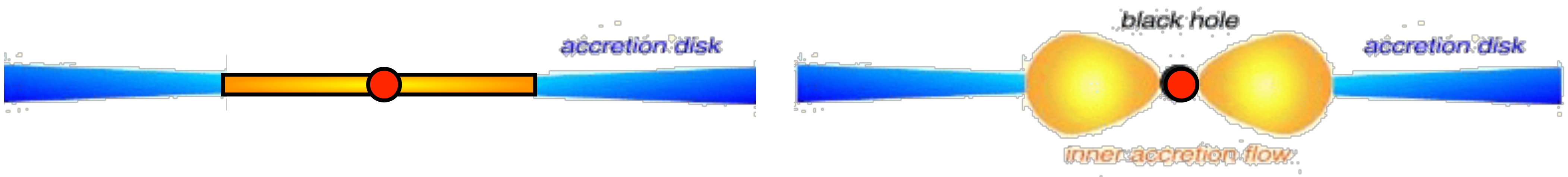
Jet formation and destruction



Jet formation and destruction



Jet formation and destruction



$$\begin{aligned} F_{PR} &= -\frac{L\sigma_T}{4\pi r^2 c}\frac{v_\phi}{c} \\ &\sim -\frac{[\sigma_B T^4 r h]\sigma_T}{4\pi r^2 c} \\ \tau &\sim \frac{rB}{cE} = \frac{rB}{cF_{PR}/e} \\ &\sim \text{hours if } h \sim r \\ &\sim \text{weeks -- months if } h \ll r \end{aligned}$$

$$B \sim 10^7 \ G \quad h \sim 0.1r \quad L \sim 0.1 L_{Edd} \quad M \sim 10 M_\odot$$

Kylafis, Contopoulos, Kazanas, Christodoulou 2012; Koutsantoniou, Contopoulos 2013

Other observations

- AGN MHD disk winds with $B \sim 1/r$, $n \sim 1/r$
  (Fukumura et al. 2012)
  - Not compatible with disk solutions *(Fereira, Li '90s)*
  - The magnetic field is not advected in, it diffuses out
    (Sikora, Begelman 2013; Lovelace et al.)

Thank you for your attention

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY

NSRF
2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co- financed by Greece and the European Union