Where does the magnetic field come from?

Ioannis Contopoulos
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European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
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MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY
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The induction equation

$$\frac{\partial B}{\partial t} = -c \, \nabla \times E$$

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Battery

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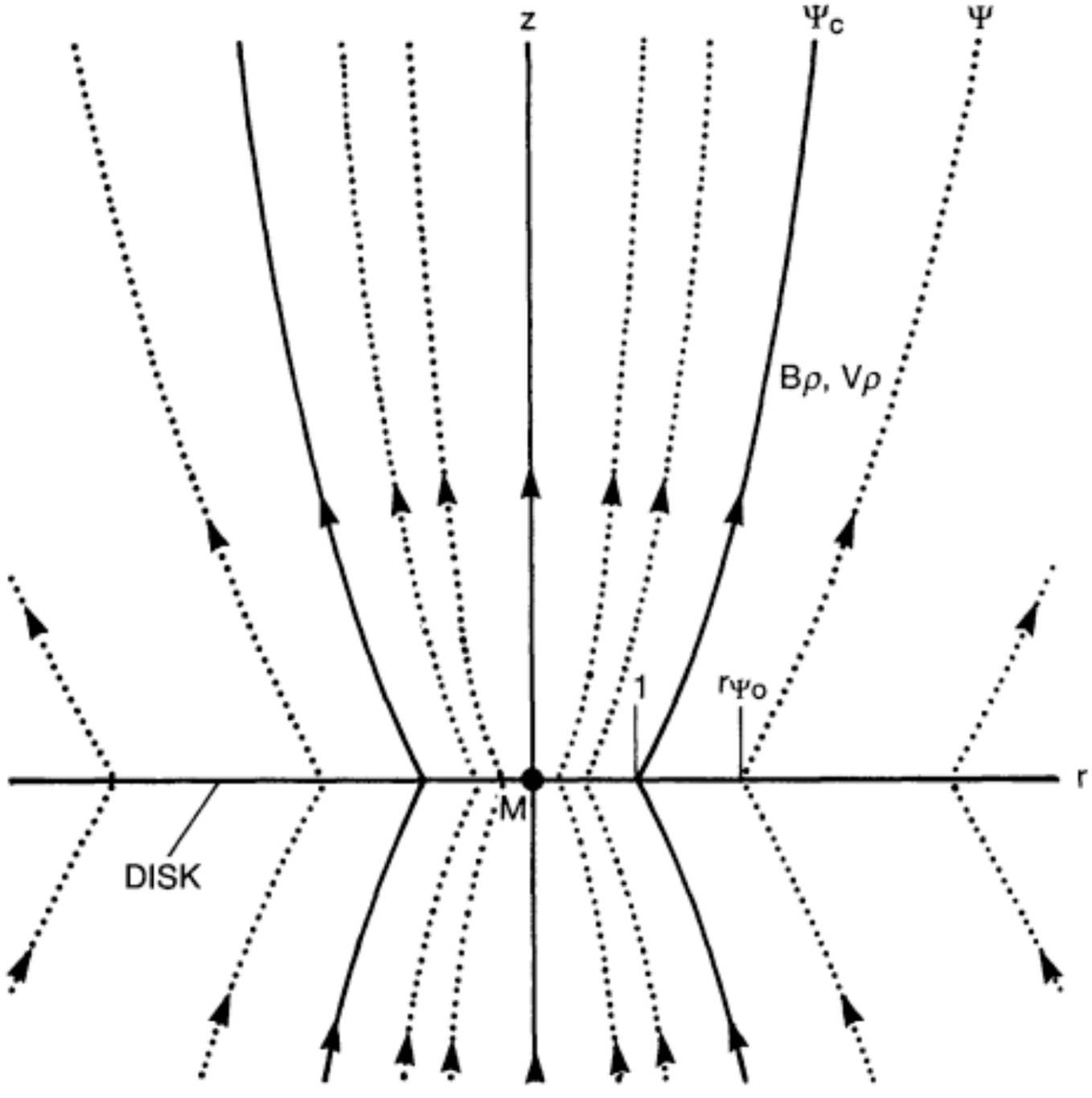
$$\frac{\partial \Psi}{\partial t} = 0 \ , \quad E_\phi = 0 \ , \quad v \parallel B \ , \quad \eta = 0$$

80s



Blandford & Payne, Lovelace, Contopoulos, Begelman, Li...

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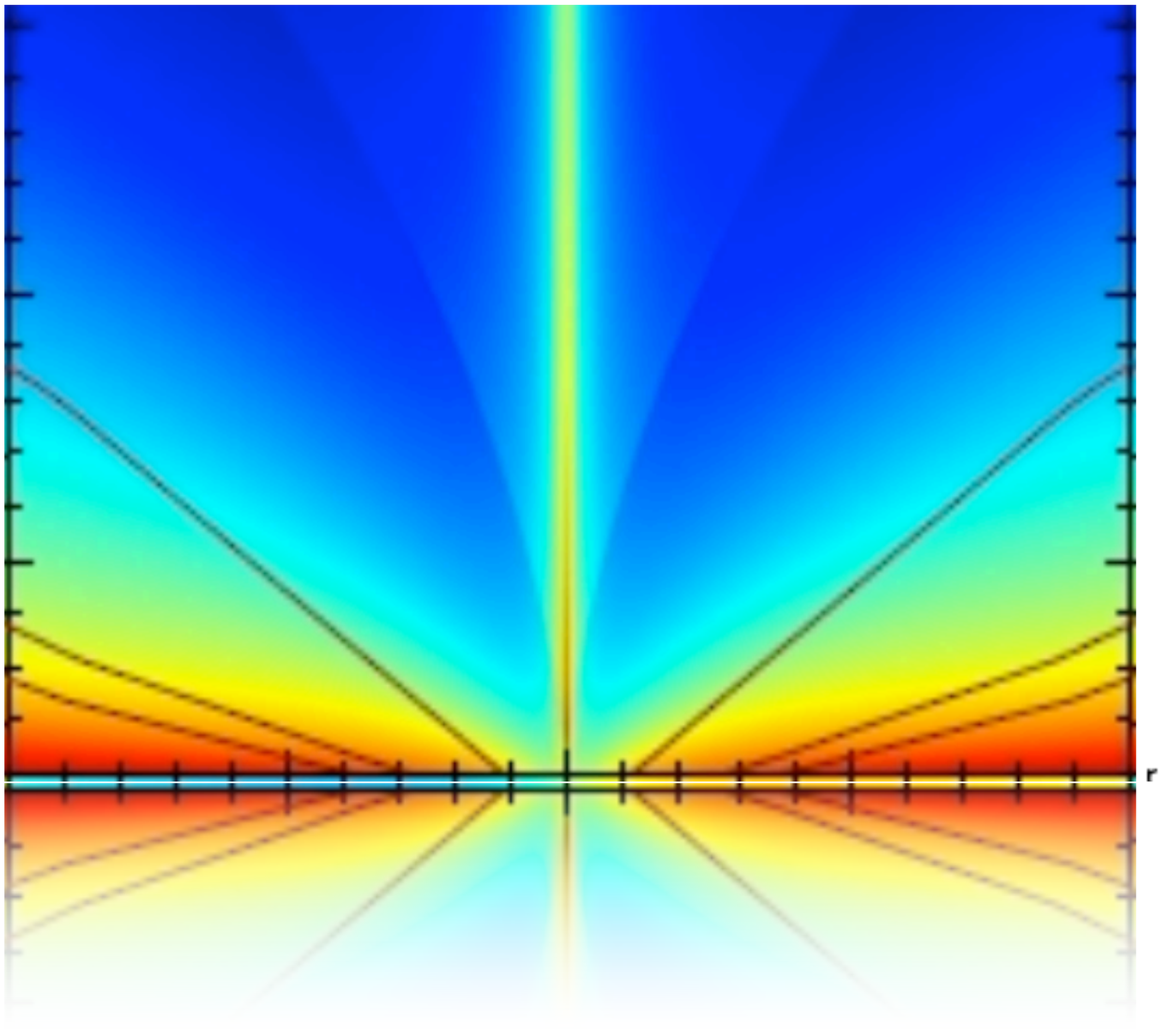
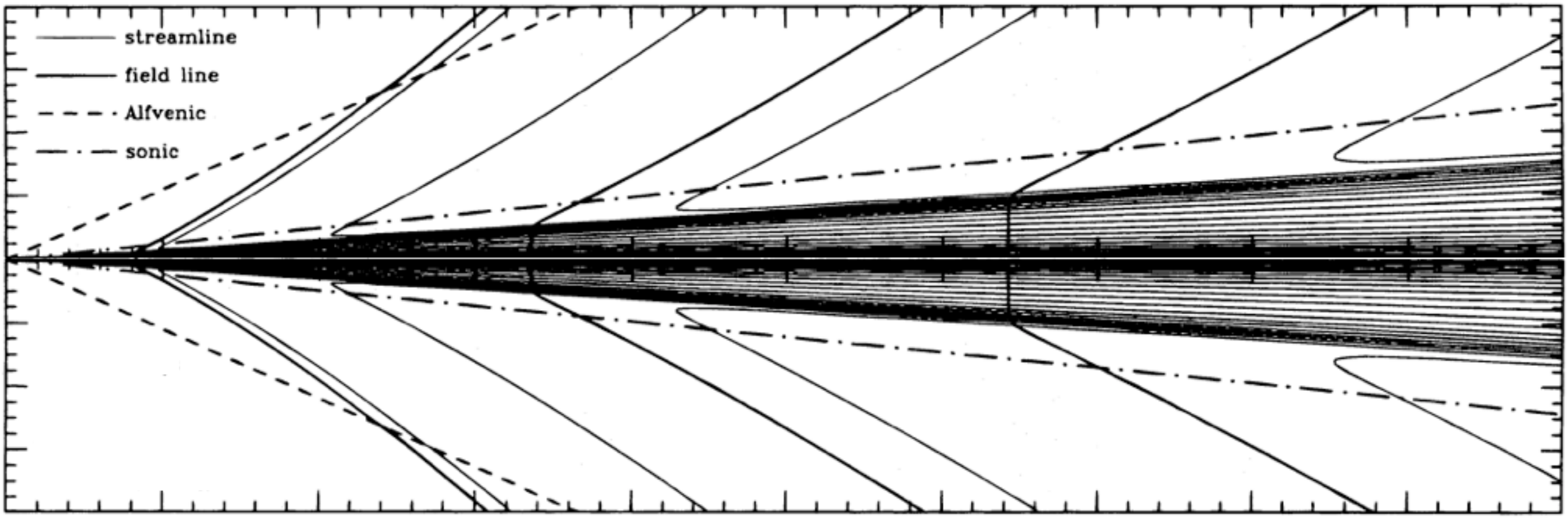
2000s



Mignone, Massaglia, Vlahakis, Tsinganos

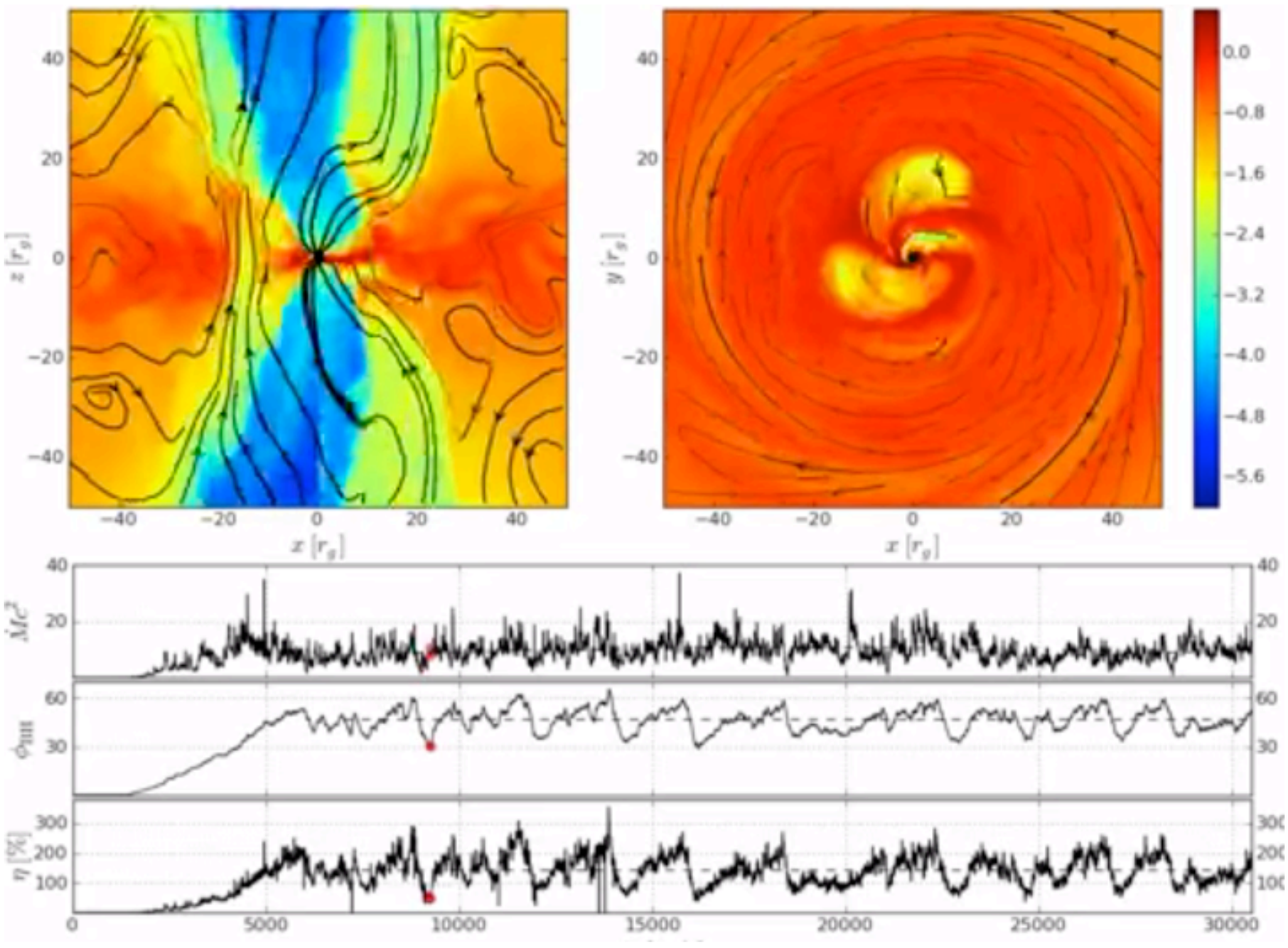
$$\frac{\partial \Psi}{\partial t} = 0 \ , \quad E_\phi = 0 \ , \quad v \nparallel B \ , \quad \eta \neq 0$$

90s



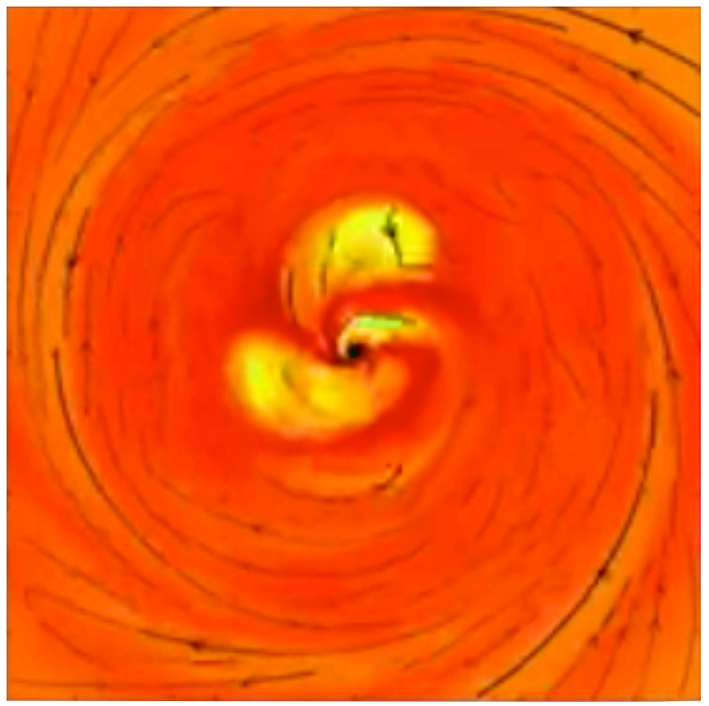
Li, Ferreira, Pelletier...

2000s



Narayan, McKinney, Tchekhovskoy

2000s



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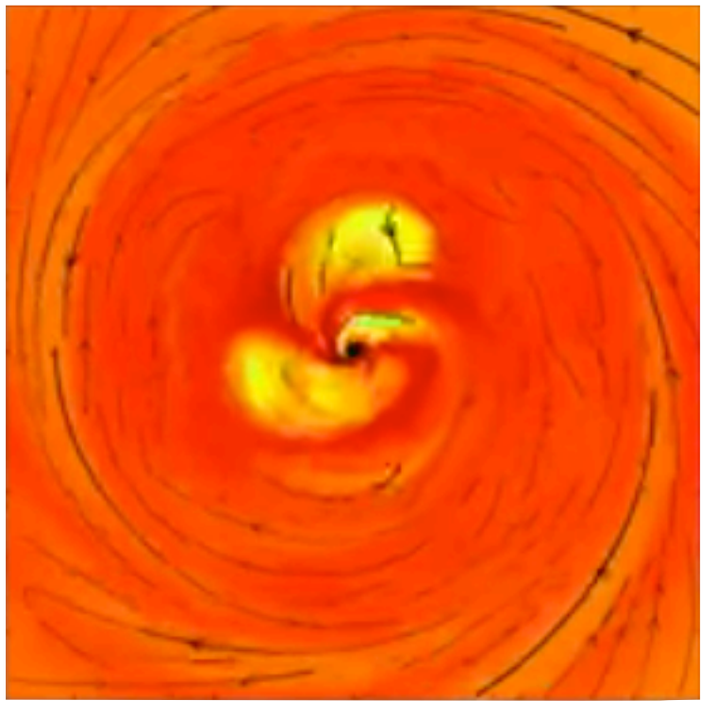

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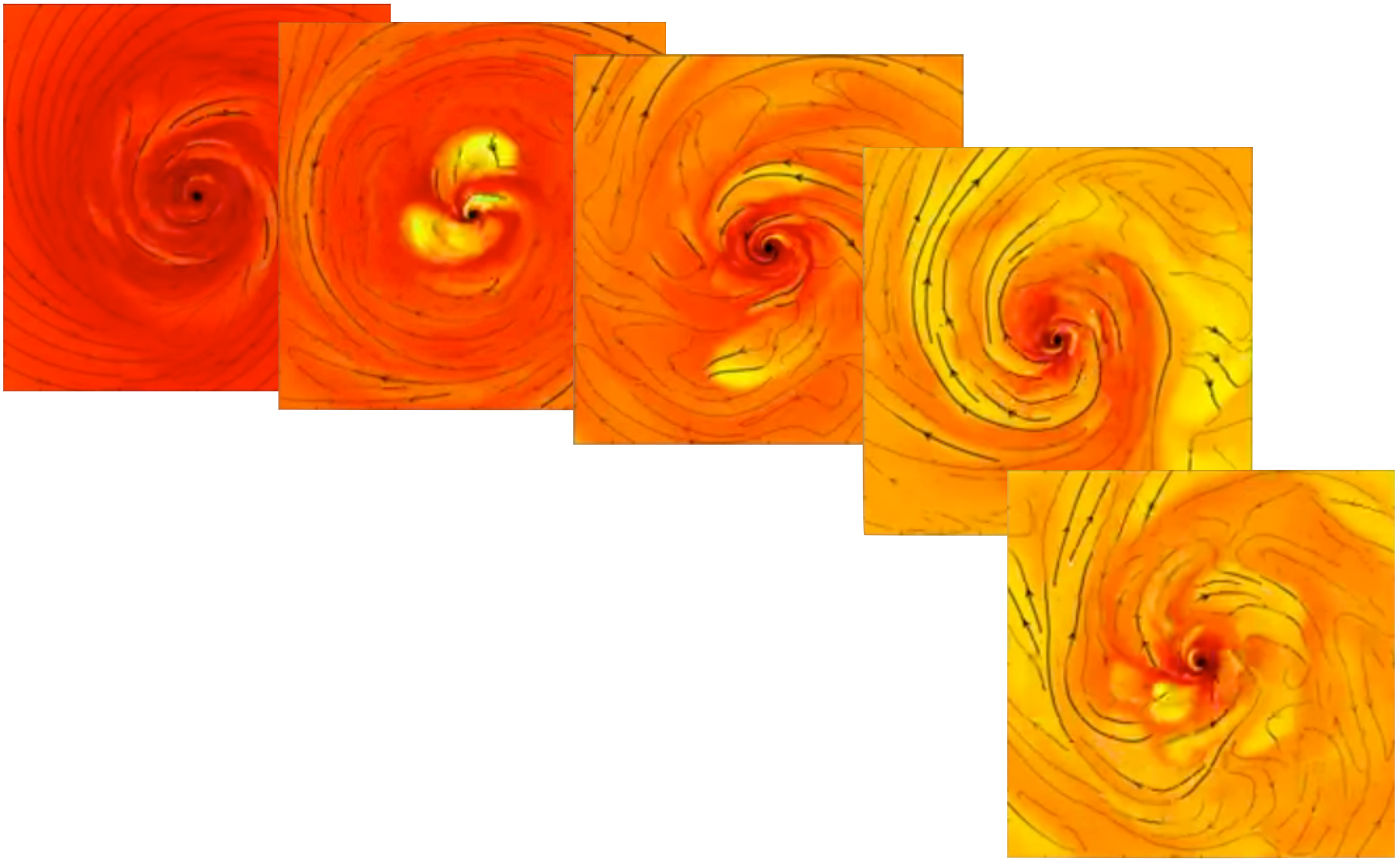

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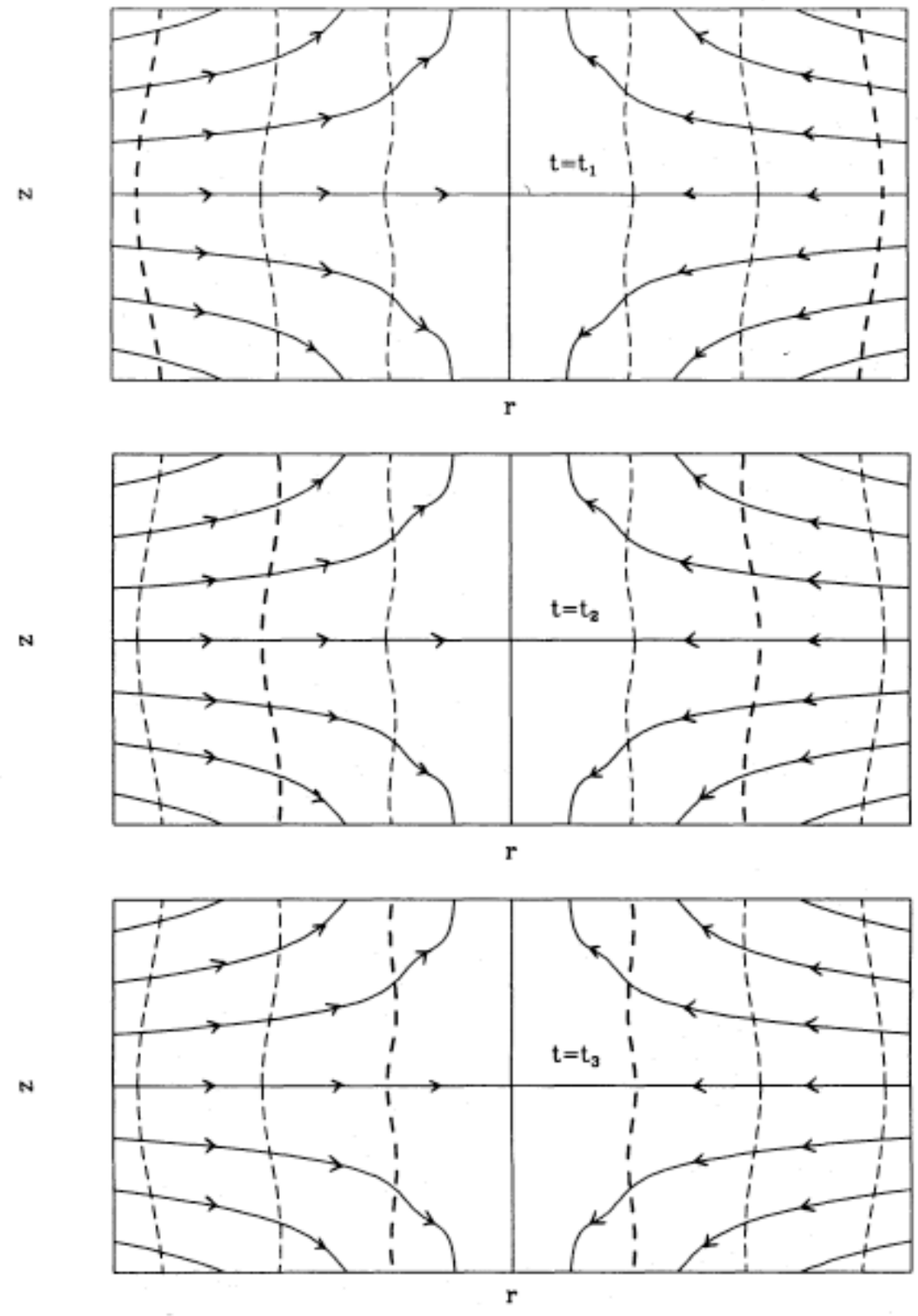

Contopoulos 1996

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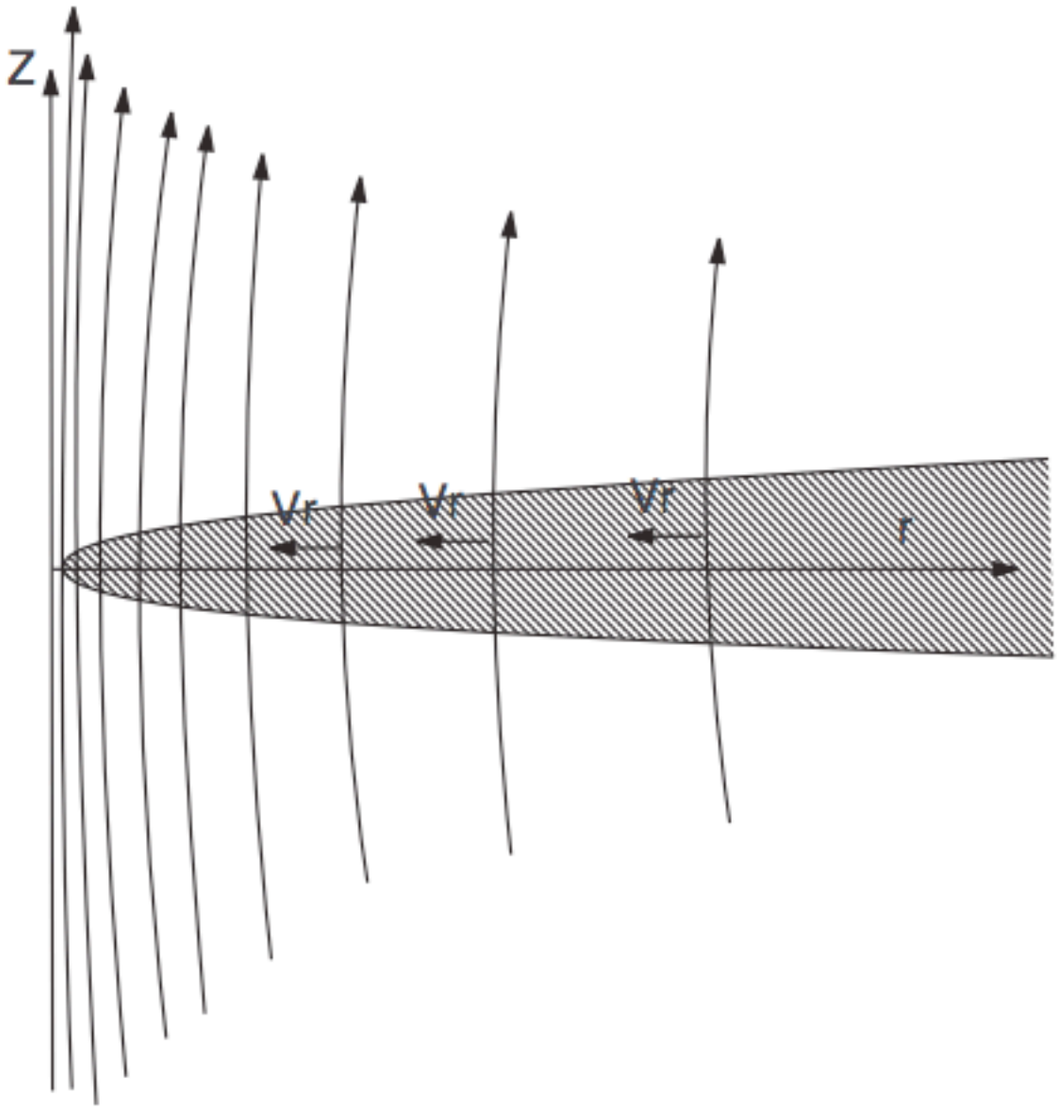
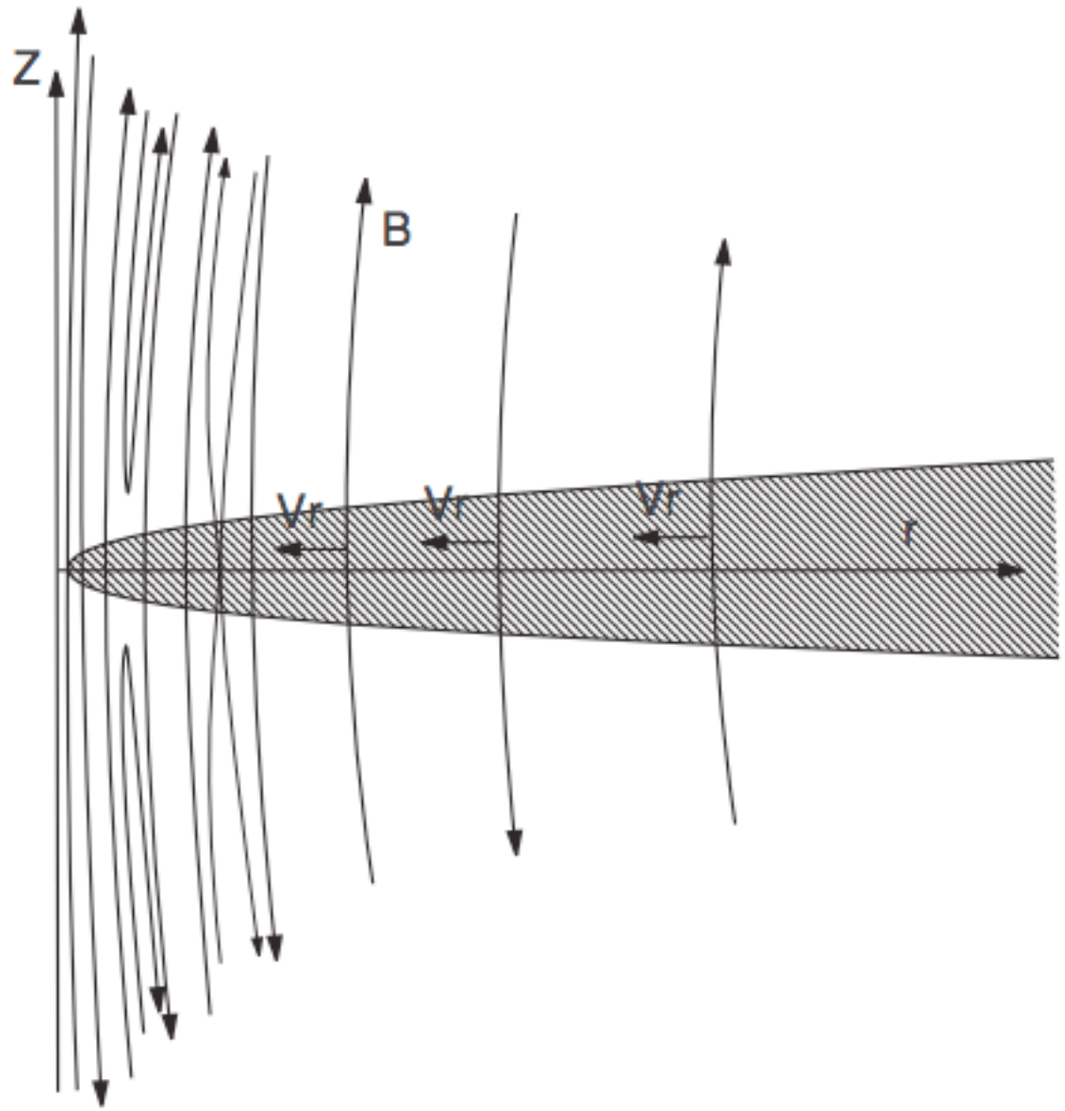
2000s

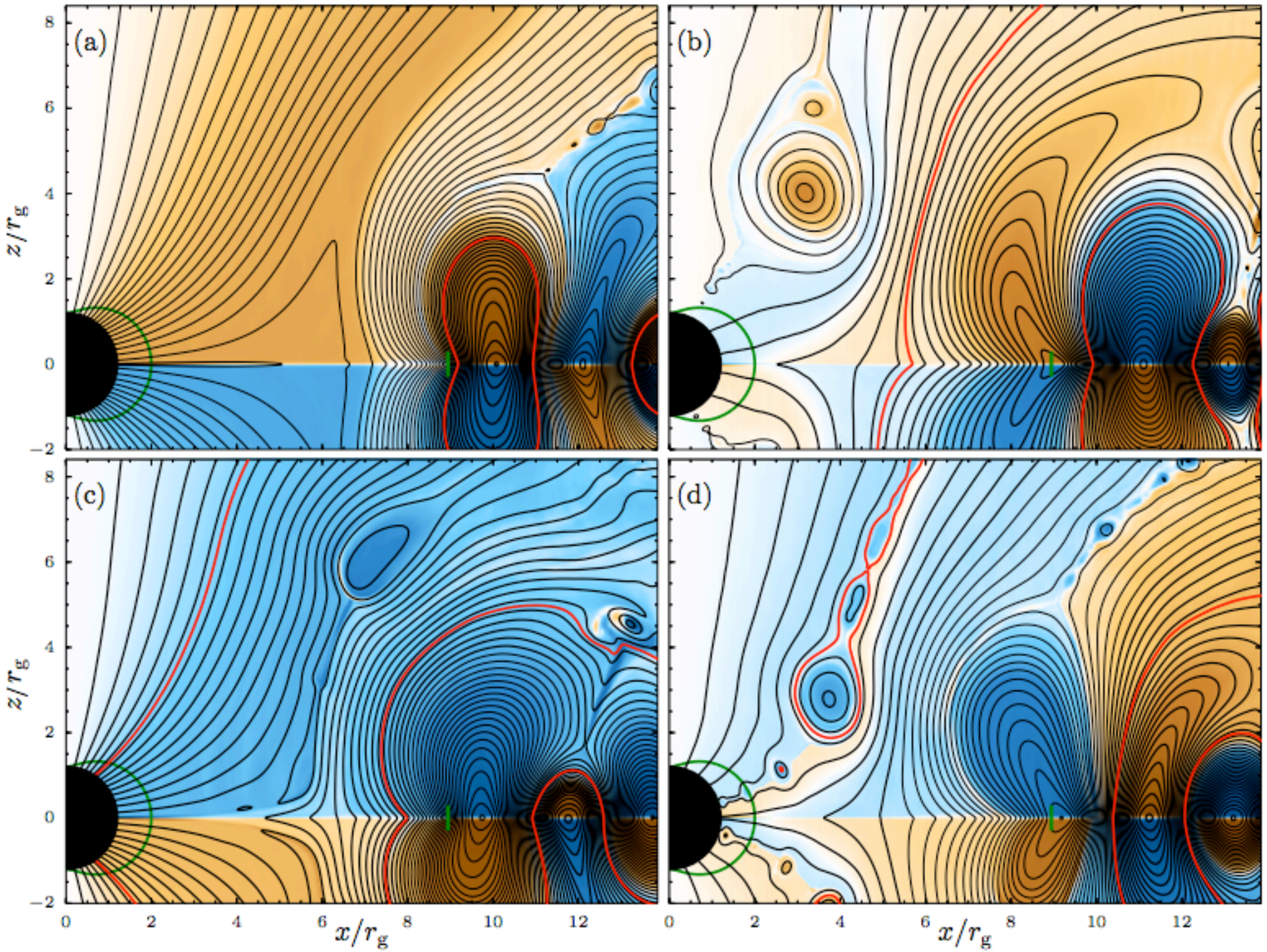




Bogovalov

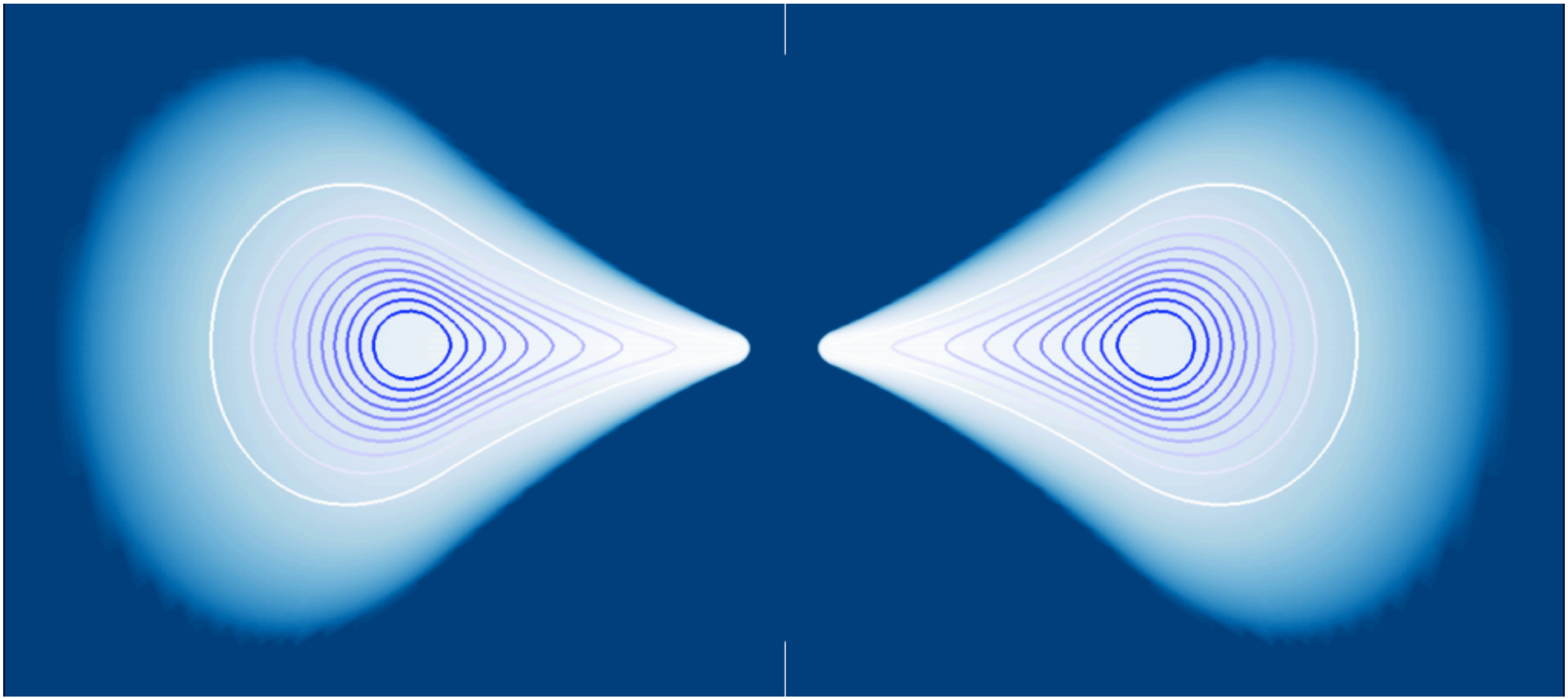
$$\frac{\partial \Psi}{\partial t} \neq 0 \ , \quad E_\phi \neq 0 \ , \quad v \nparallel B \ , \quad \eta = 0$$

2000s



Parfrey, Giannios

Magnetic field ‘reservoir’?



Narayan and collaborators

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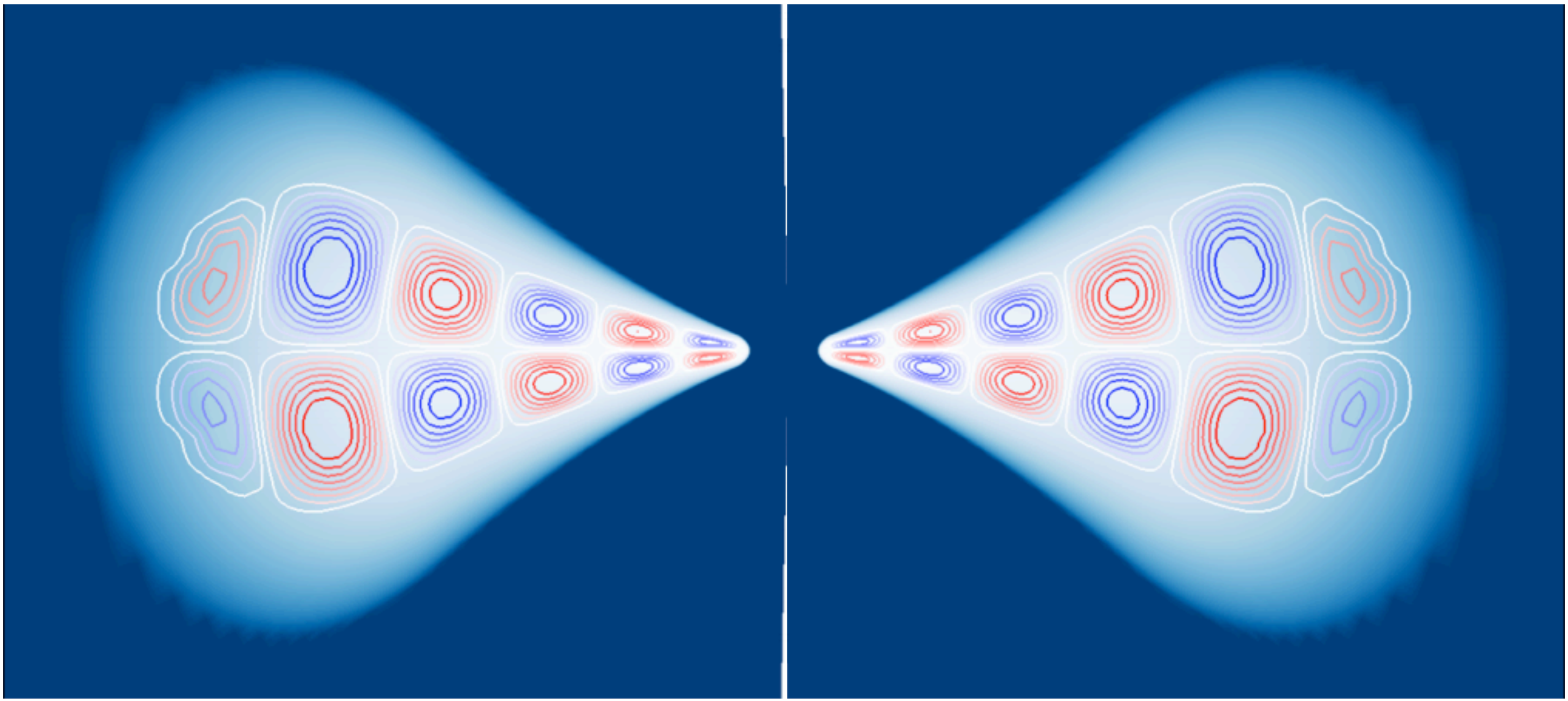

Narayan and collaborators

ADVECTION/DIFFUSION OF LARGE-SCALE B FIELD IN ACCRETION DISKS

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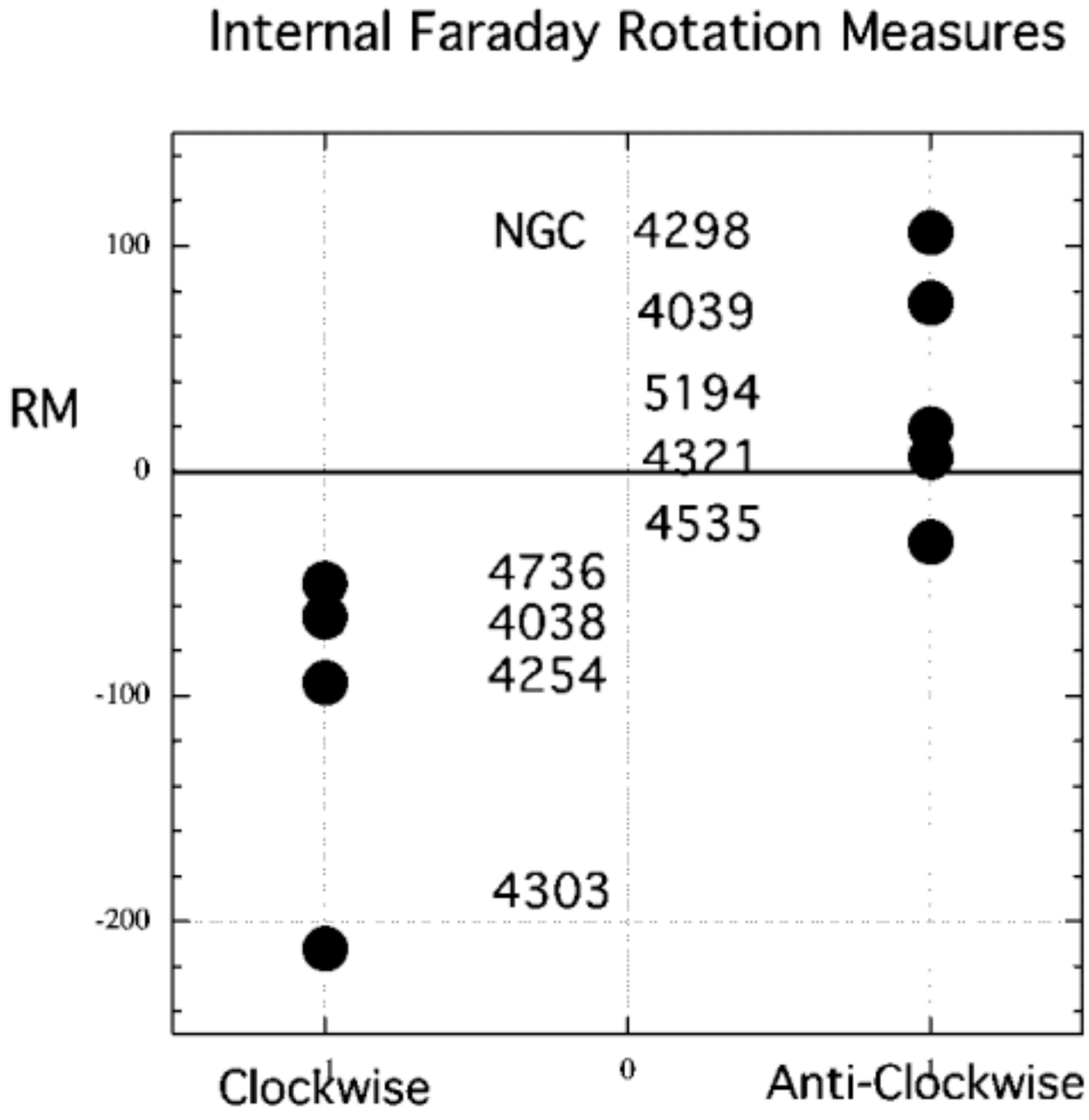
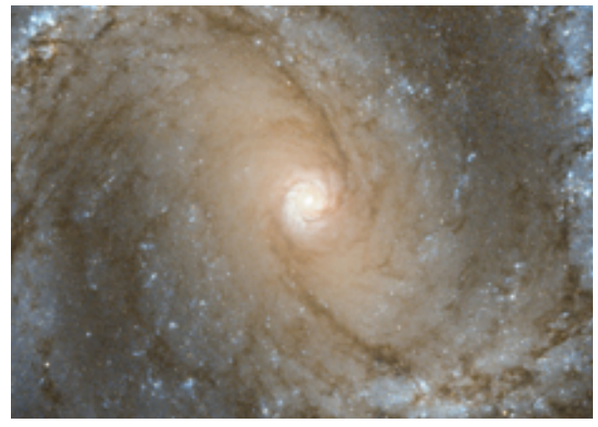
ABSTRACT

Activity of the nuclei of galaxies and stellar mass systems involving disk accretion to black holes is thought to be due to (1) a small-scale turbulent magnetic field in the disk (due to the magnetorotational instability, MRI), which gives a large viscosity enhancing accretion, and (2) a large-scale magnetic field, which gives rise to matter outflows and/or electromagnetic jets from the disk which also enhances accretion. An important problem with this picture is that the enhanced viscosity is accompanied by an enhanced magnetic diffusivity, which acts to prevent the buildup of a significant large-scale field. Recent work has pointed out that the disk's surface layers are nonturbulent, and thus highly conducting (or nondiffusive) because the MRI is suppressed high in the disk where the magnetic and radiation pressures are larger than the thermal pressure.

'Enhanced viscosity is accompanied by an enhanced magnetic diffusivity, which acts to prevent the buildup of a significant large-scale field'

$$\mu_B \cdot \Omega > 0$$





Lynden-Bell 2013

‘Battery’?

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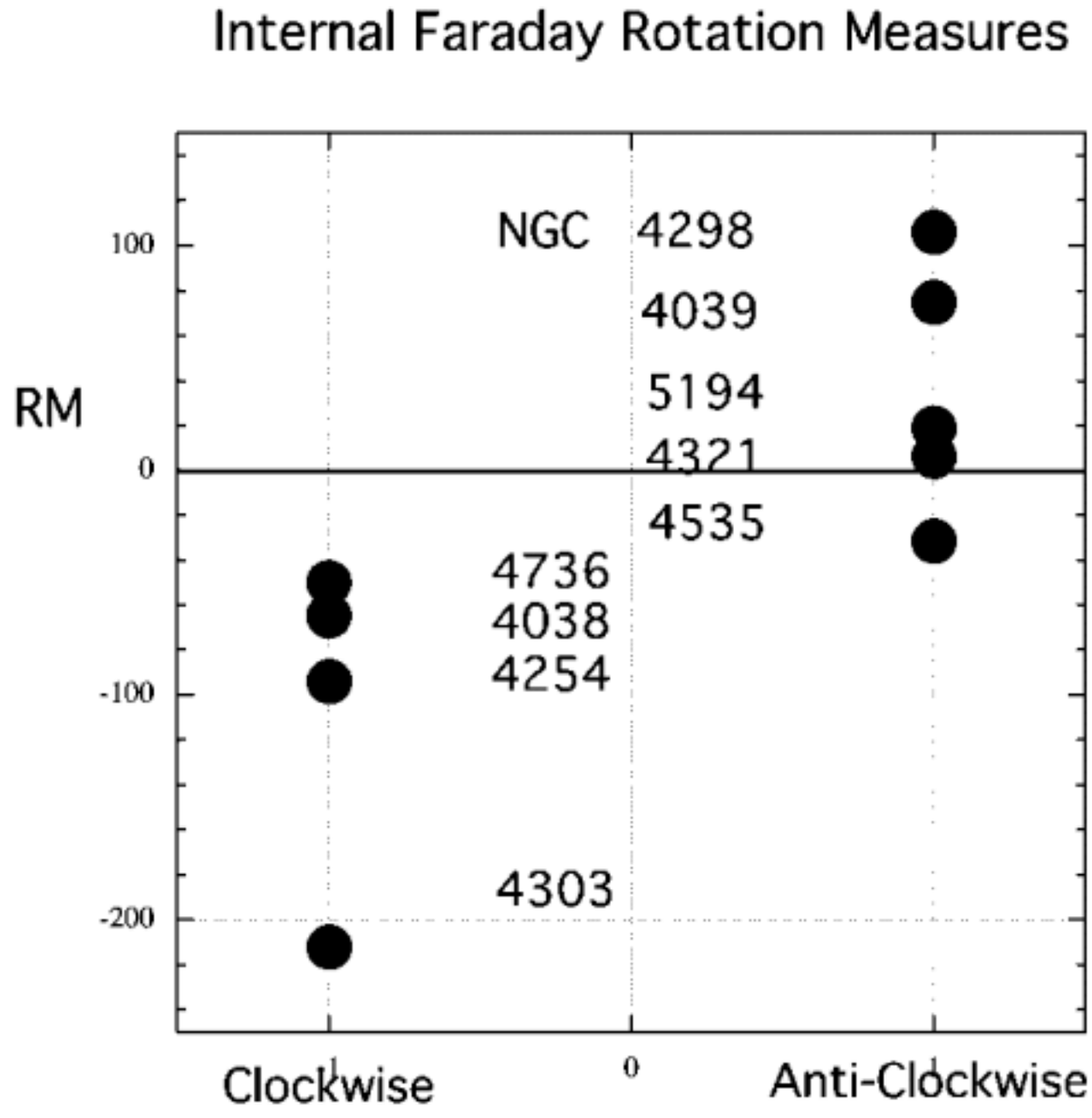

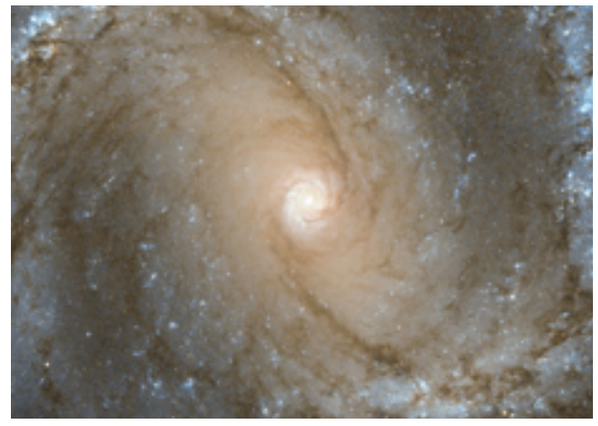

Lynden-Bell 2013

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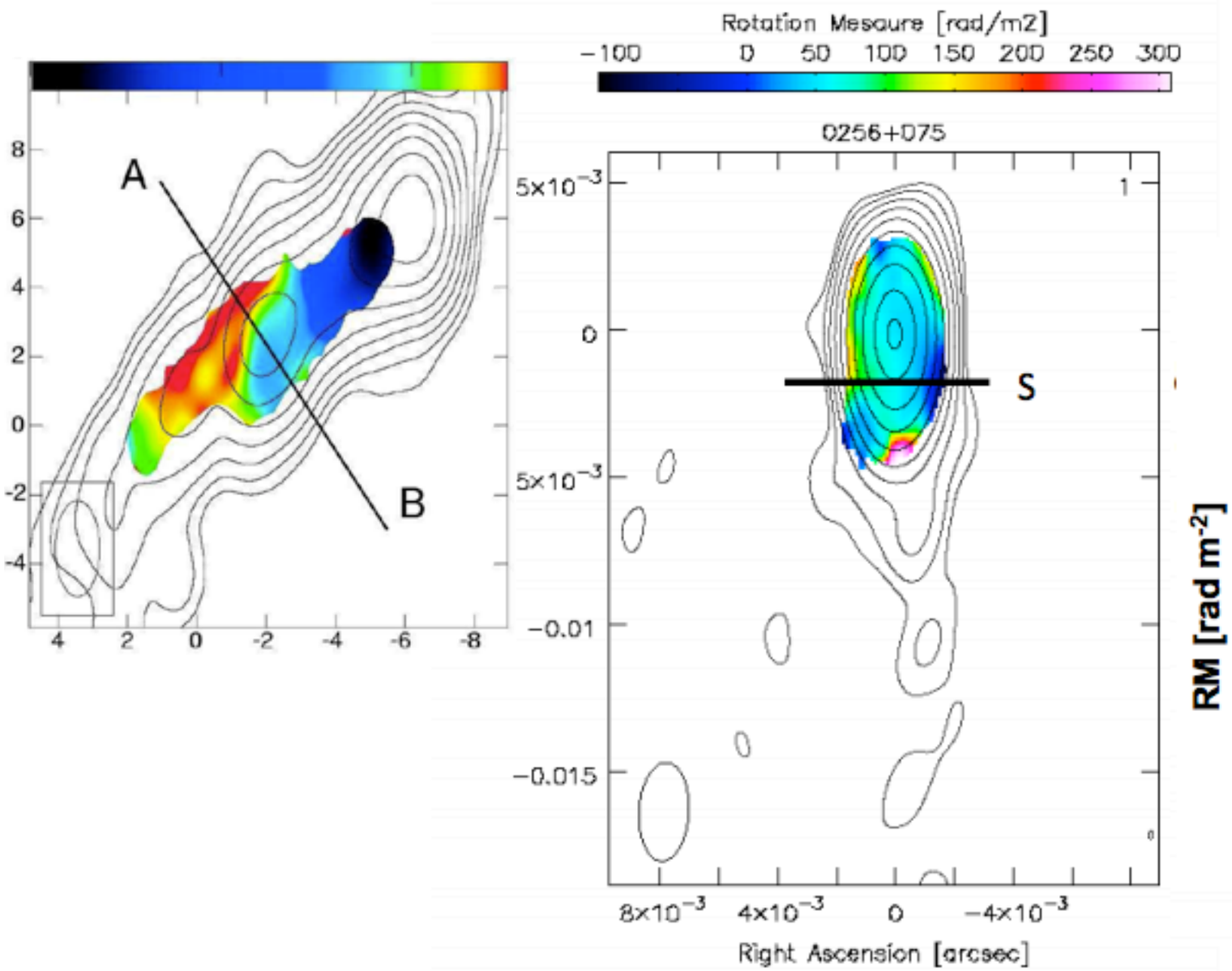
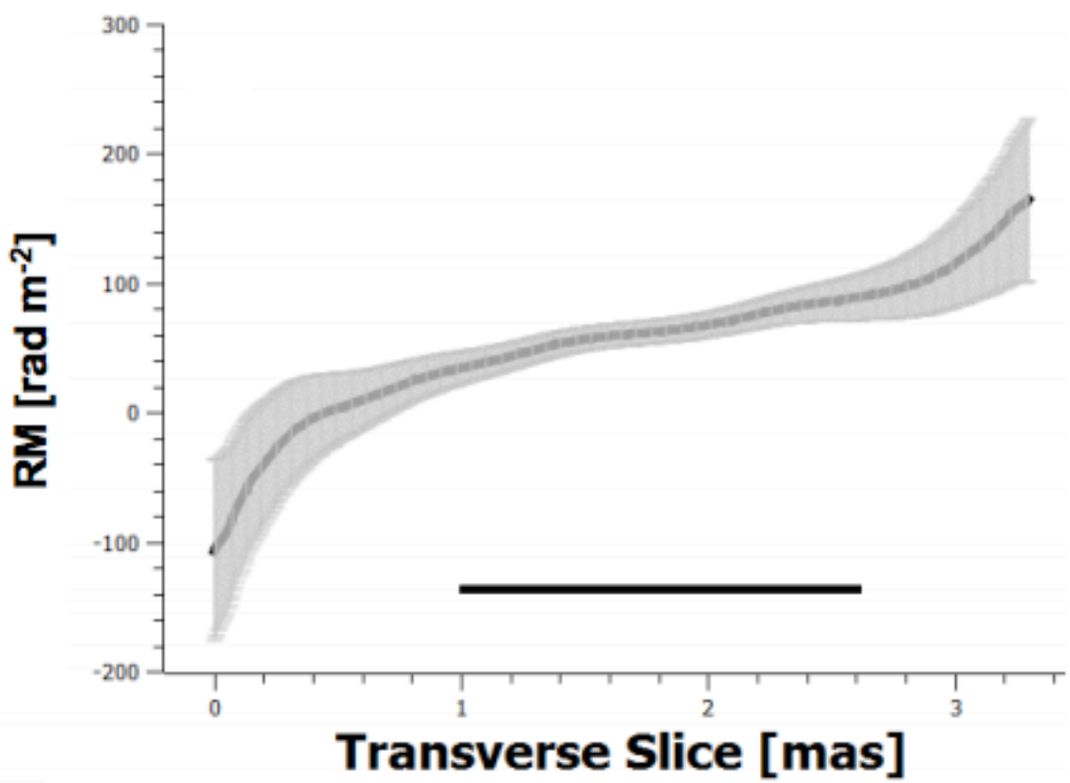


“There are currently 27 reports of monotonic RM gradients with significances >3σ in the literature, of which 20 are CW (1% probability that this came about by chance!)”

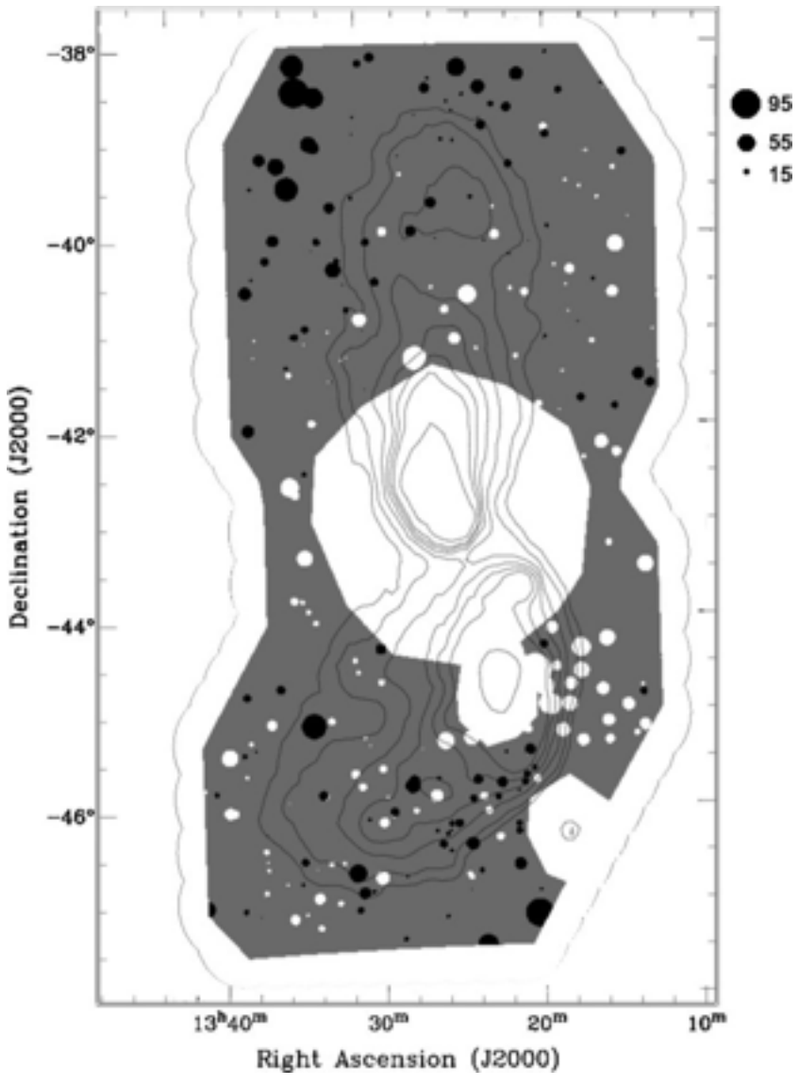
The electric current flows mostly toward the origin of the jet



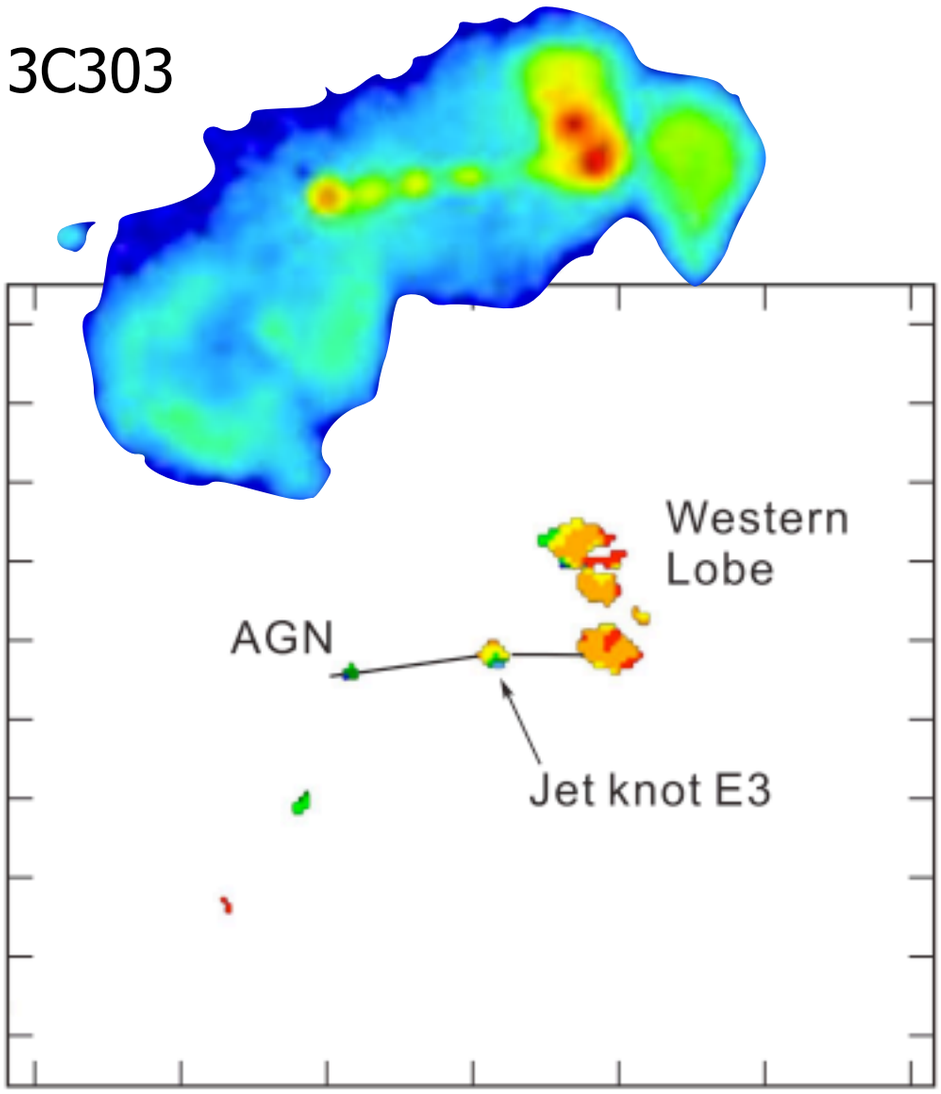
Gabuzda and collaborators

‘Battery’?

Centaurus A



3C303



“The largest electric current in the Universe” flows away from the origin of the jet (Kronberg et al. 13)

Gabuzda, Contopoulos, Kazanas, Christodoulou

A Cosmic Battery

90s

A Cosmic Battery

90s

Gargantua is a massive, ‘gently spinning’ black hole (Interstellar)

A Cosmic Battery

90s

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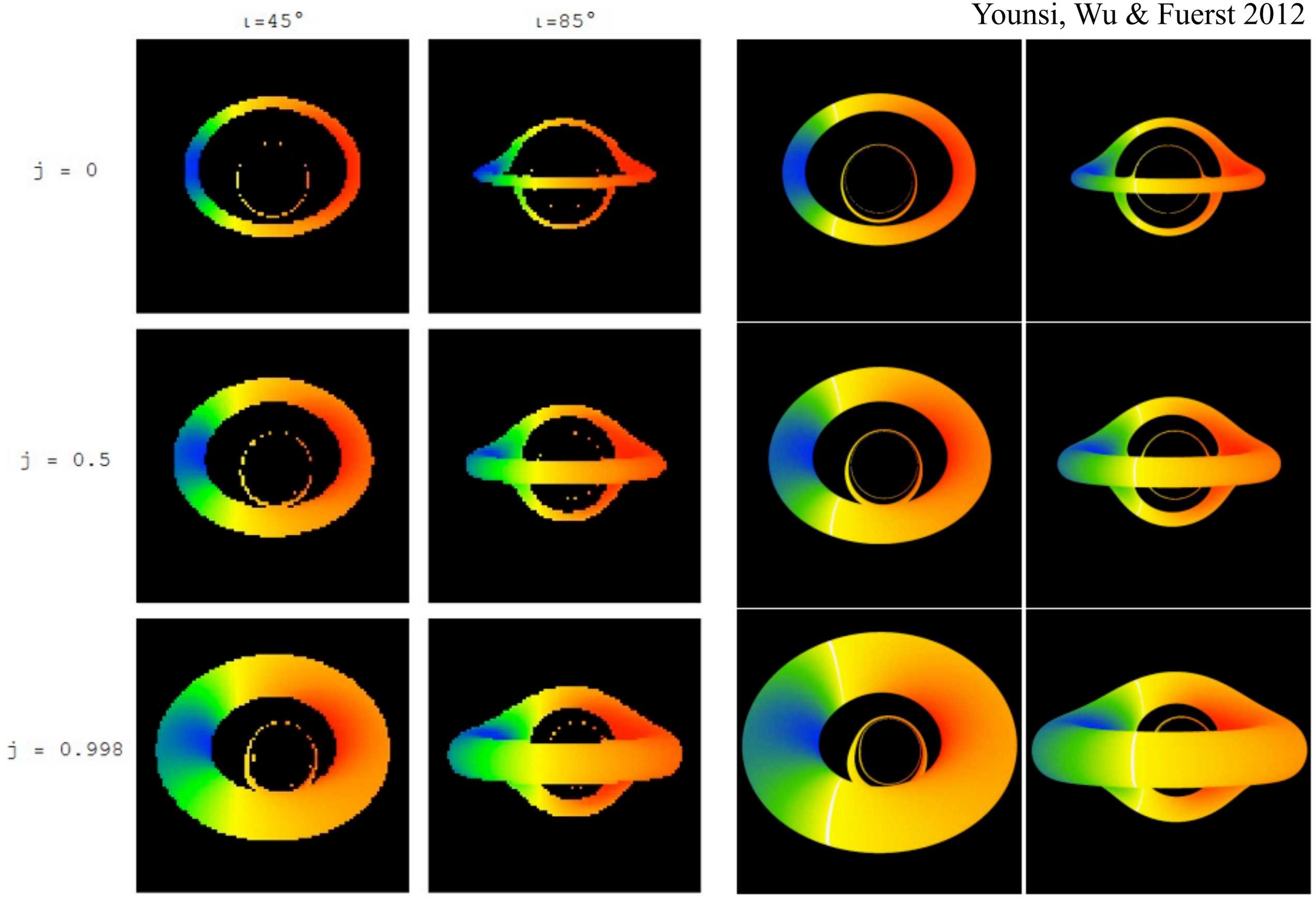
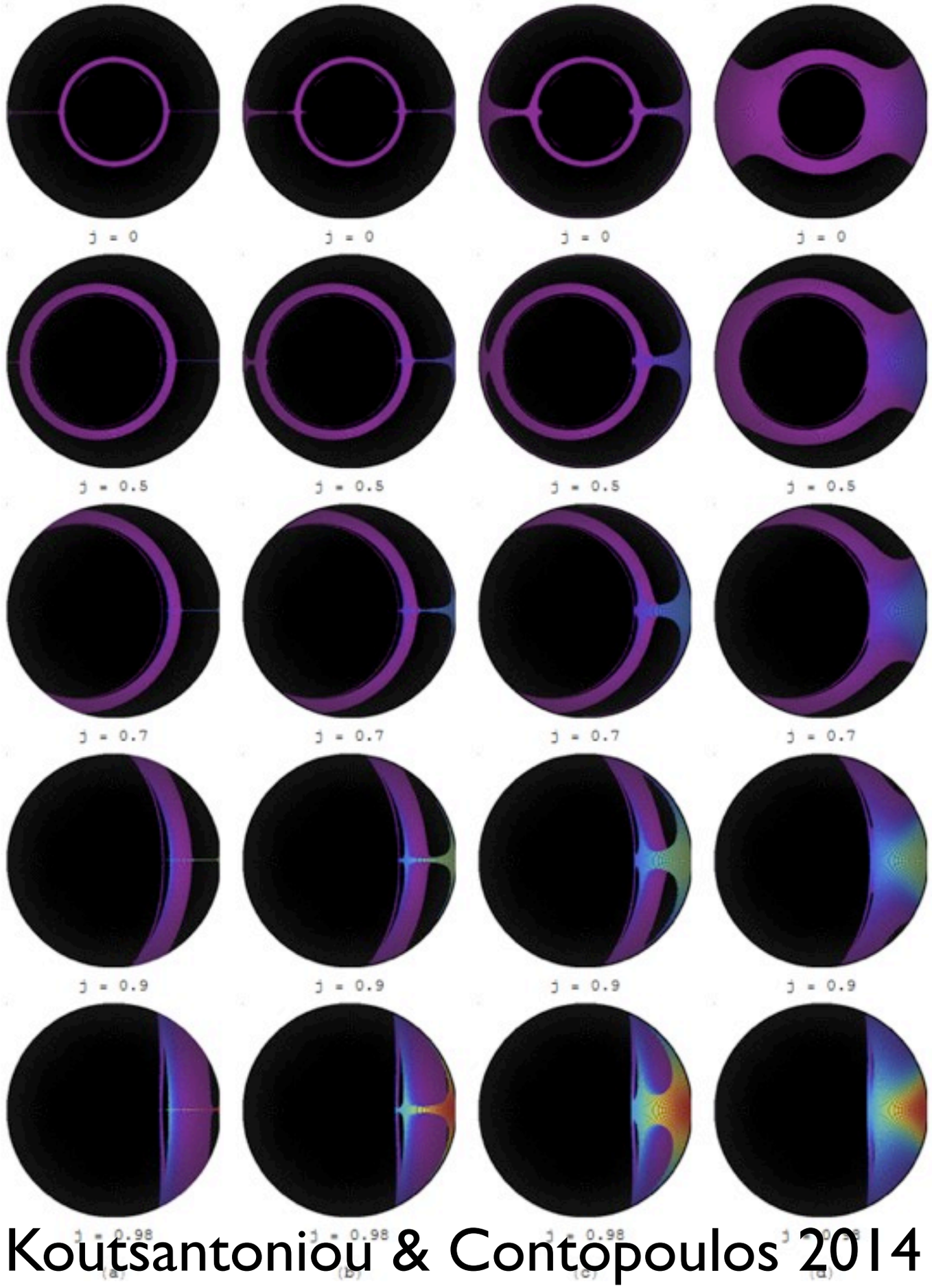
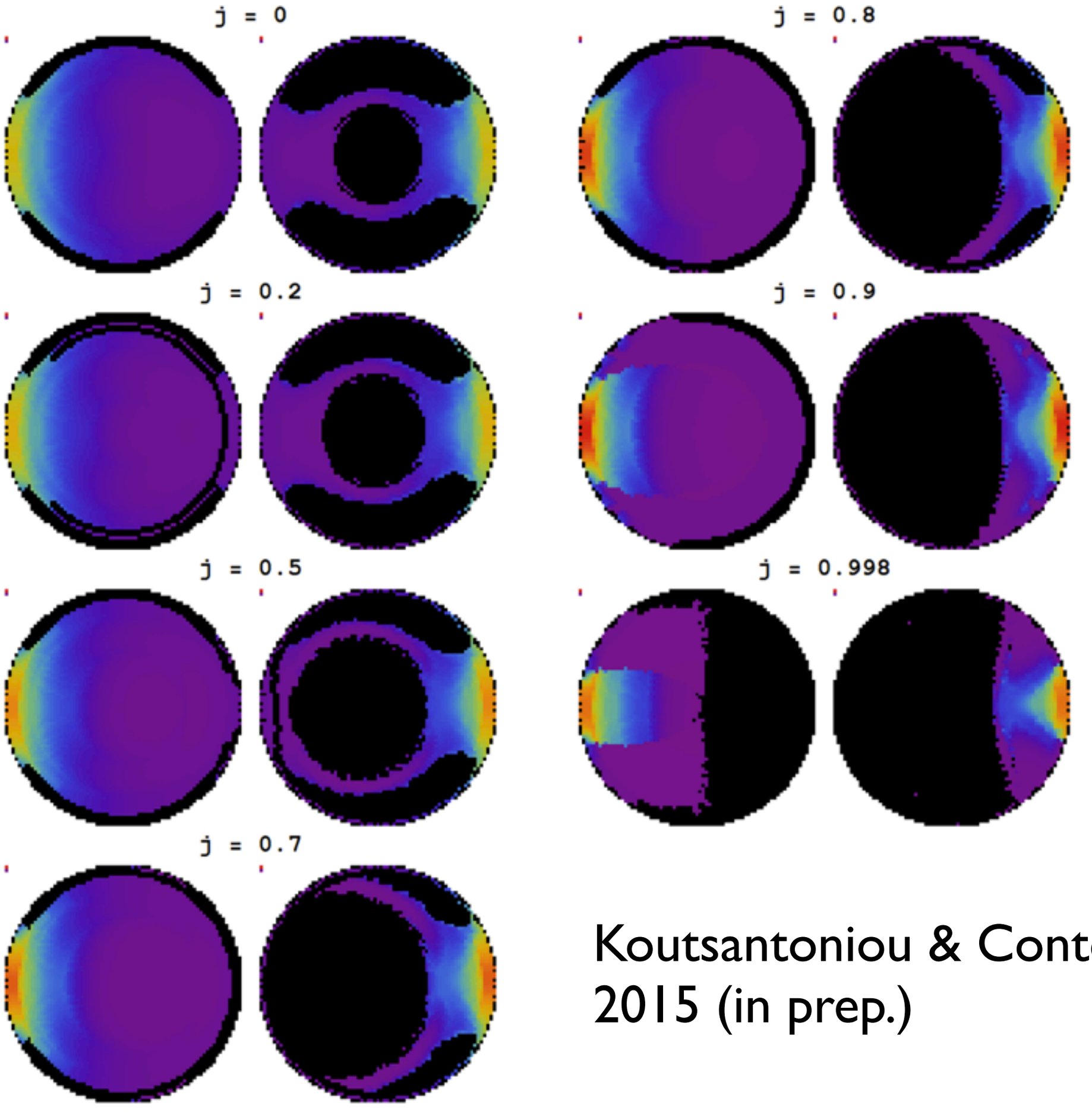
Younsi, Wu & Fuerst 2012



Koutsantoniou & Contopoulos 2015 (in prep.)



Koutsantoniou & Contopoulos 2014



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Radiation dynamics

$$T^{\hat{\mu}\hat{\nu}} = \int\!\!\int\ I_\nu(r,\theta,\hat{a},\hat{b};\nu)\ \mathrm{d}\nu\ n^{\hat{\mu}} n^{\hat{\nu}}\ \mathrm{d}\Omega$$

$$= \int I(r,\theta,\hat{a},\hat{b})\ n^{\hat{\mu}} n^{\hat{\nu}}\ \mathrm{d}\Omega$$

$$I(r,\theta,\hat{a},\hat{b}) = \int_0^{\tau_{\max}} \left(\frac{\nu}{\nu_\mathrm{s}}\right)^4 I_\mathrm{s}\ \mathrm{e}^{-\tau}\ \mathrm{d}\tau$$

$$\frac{\nu}{\nu_\mathrm{s}} = \frac{\alpha_\mathrm{s}}{\alpha} \cdot \frac{1+\omega\frac{p_\phi}{p_t}}{1+\omega_\mathrm{s}\frac{p_\phi}{p_t}} \cdot \frac{1}{1-\mathrm{v}^{\hat{\phi}}\cos\psi}$$

Koutsantoniou & Contopoulos 2014, 15

Radiation dynamics

$$m_{\rm e}\frac{{\rm d}^2 x^i_{\rm e}}{{\rm d}\tau^2} + m_{\rm e}\Gamma^i_{\nu\kappa}u^\nu_{\rm e}u^\kappa_{\rm e} = f^i_{\rm rad} - {\rm e}E^i$$

$$m_{\rm p}\frac{{\rm d}^2 x^i_{\rm p}}{{\rm d}\tau^2} + m_{\rm p}\Gamma^i_{\nu\kappa}u^\nu_{\rm p}u^\kappa_{\rm p} = {\rm e}E^i$$

$$E^i \approx \frac{f^i_{\rm rad}}{\rm e}$$

Contopoulos & Kazanas 1998

A Cosmic Battery

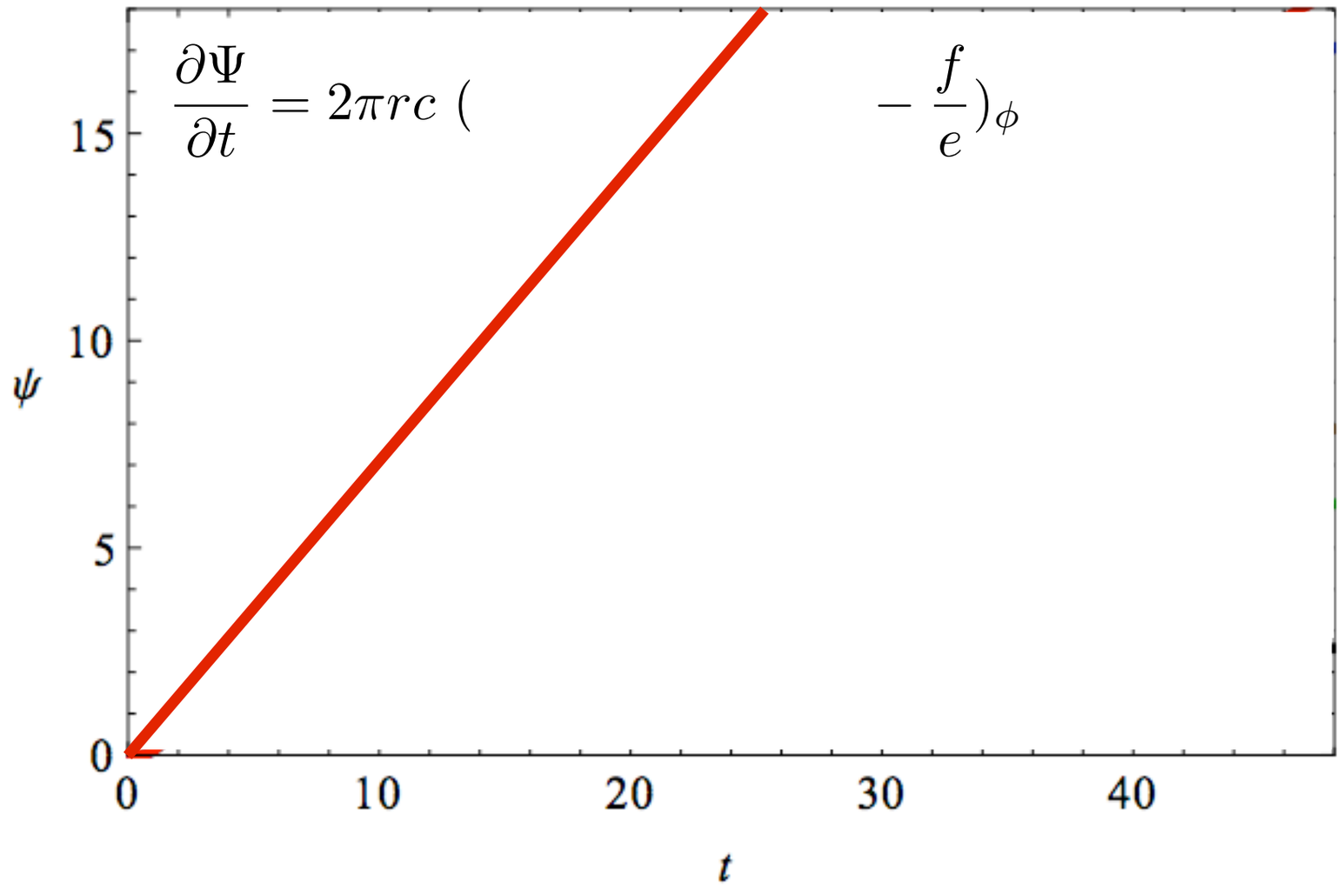
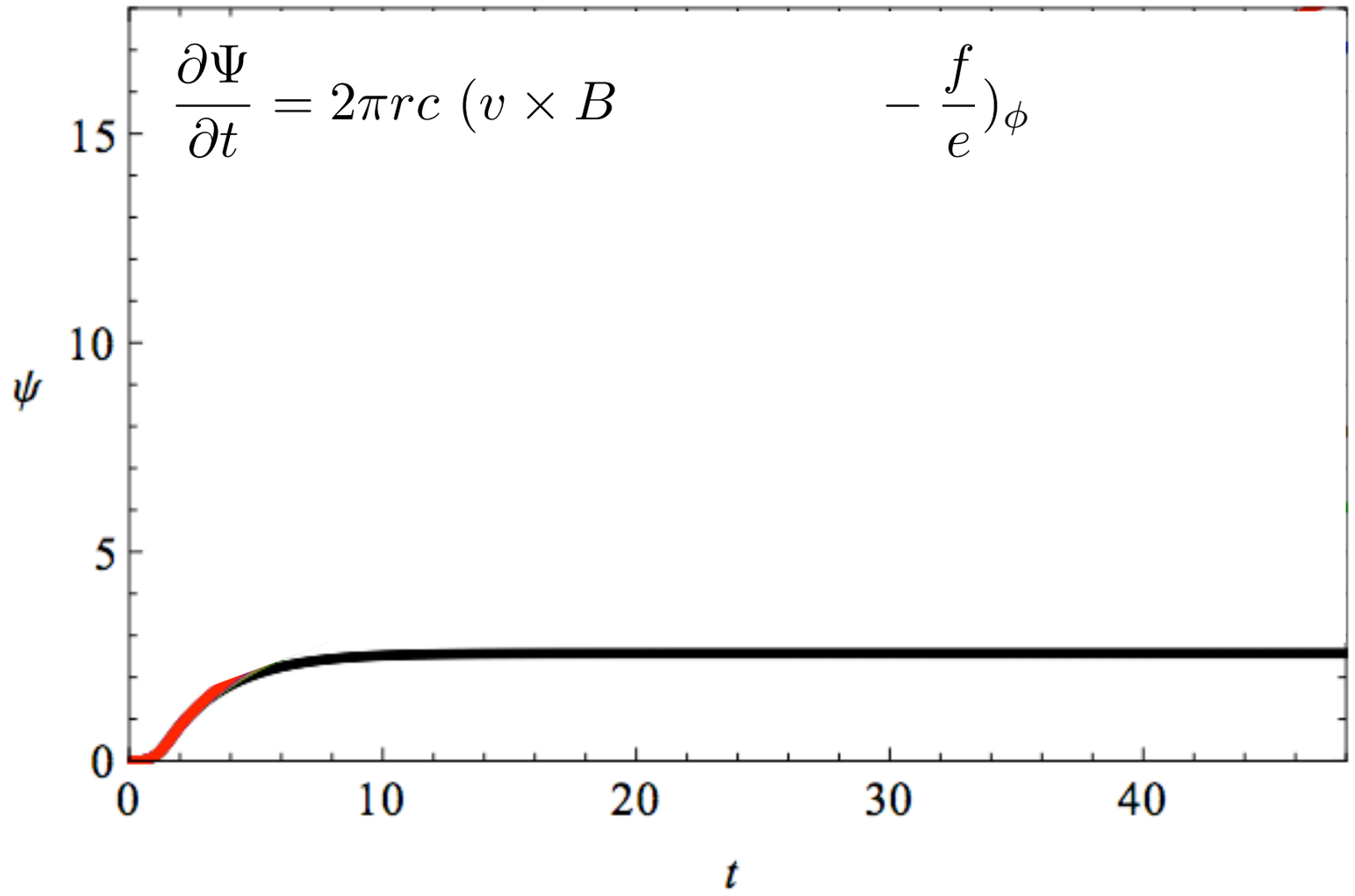


Figure 3. Evolution of the magnetic flux Ψ accumulated on the central object (in units of $\Psi_{\rm acc}$) for various values of the magnetic Prandtl number (from top to bottom: $\mathcal{P}_m = 0.2, 0.4, 1, 10, 100$, and 100 with finite optical depth in the disk). Time in units of $t_{\rm acc}$

Contopoulos, Nathanail & Katsanikas 2015

A Cosmic Battery



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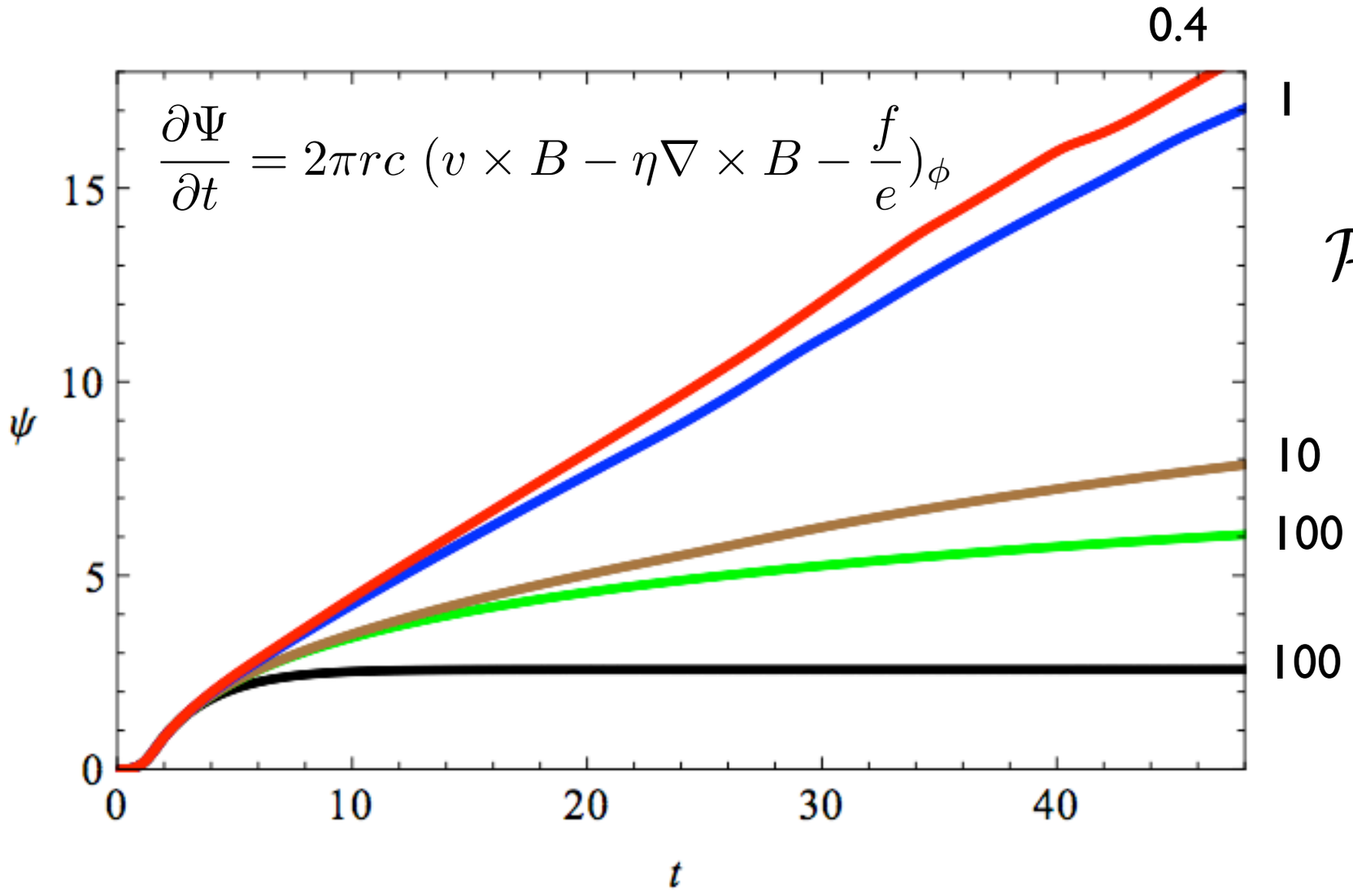

$$\mathcal{P}_m \equiv \frac{\nu}{\eta}$$

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Contopoulos, Nathanail & Katsanikas 2015

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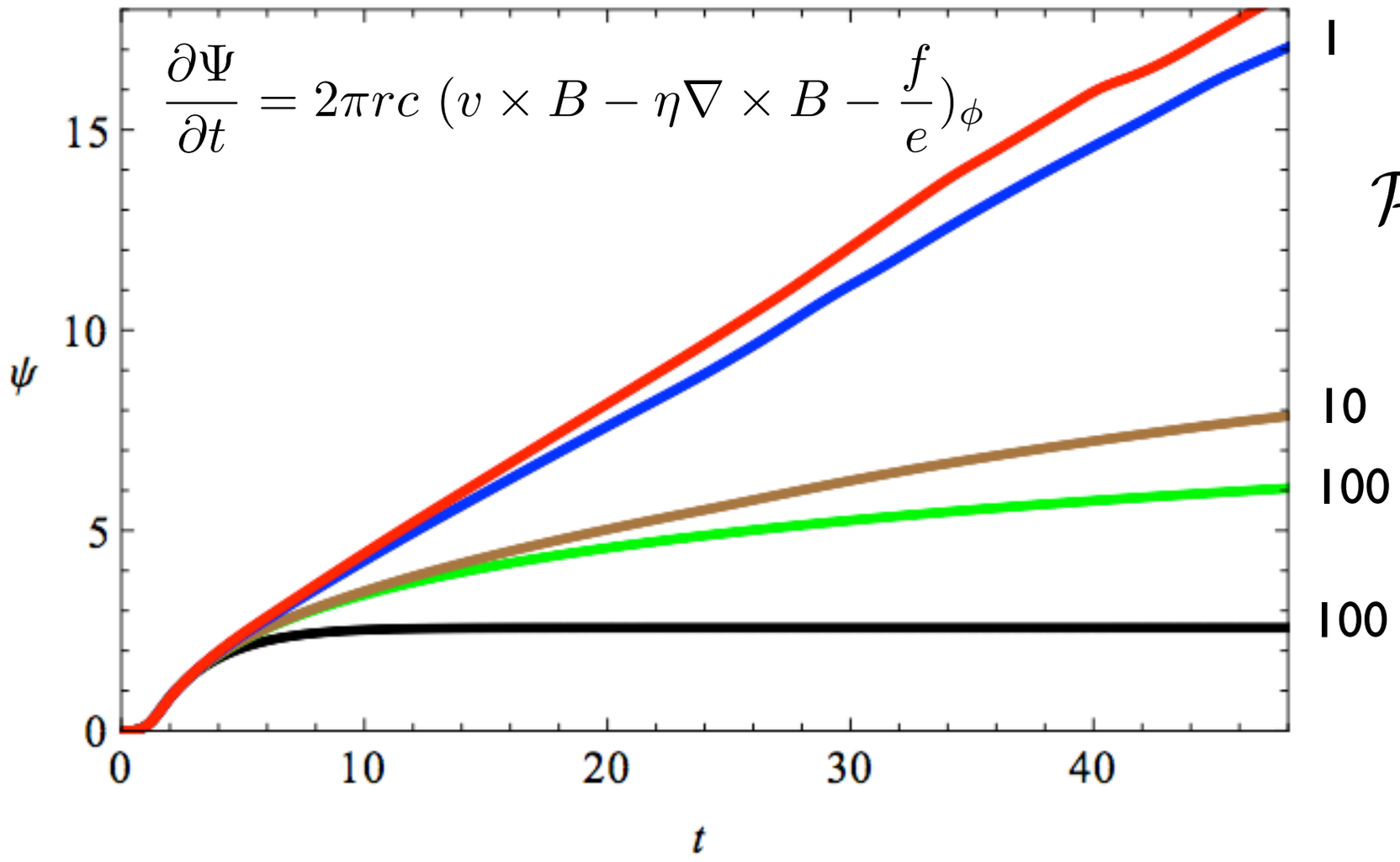

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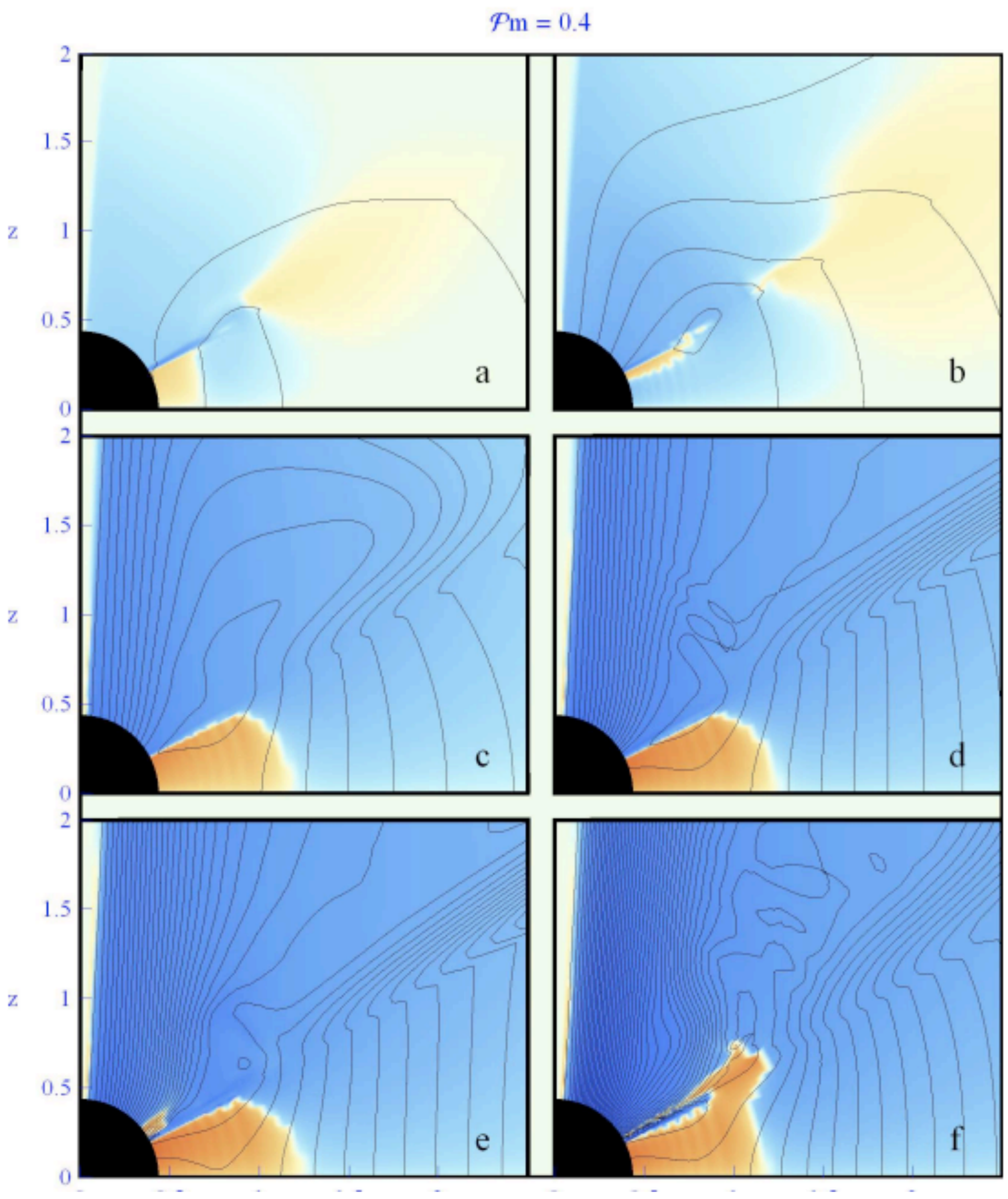
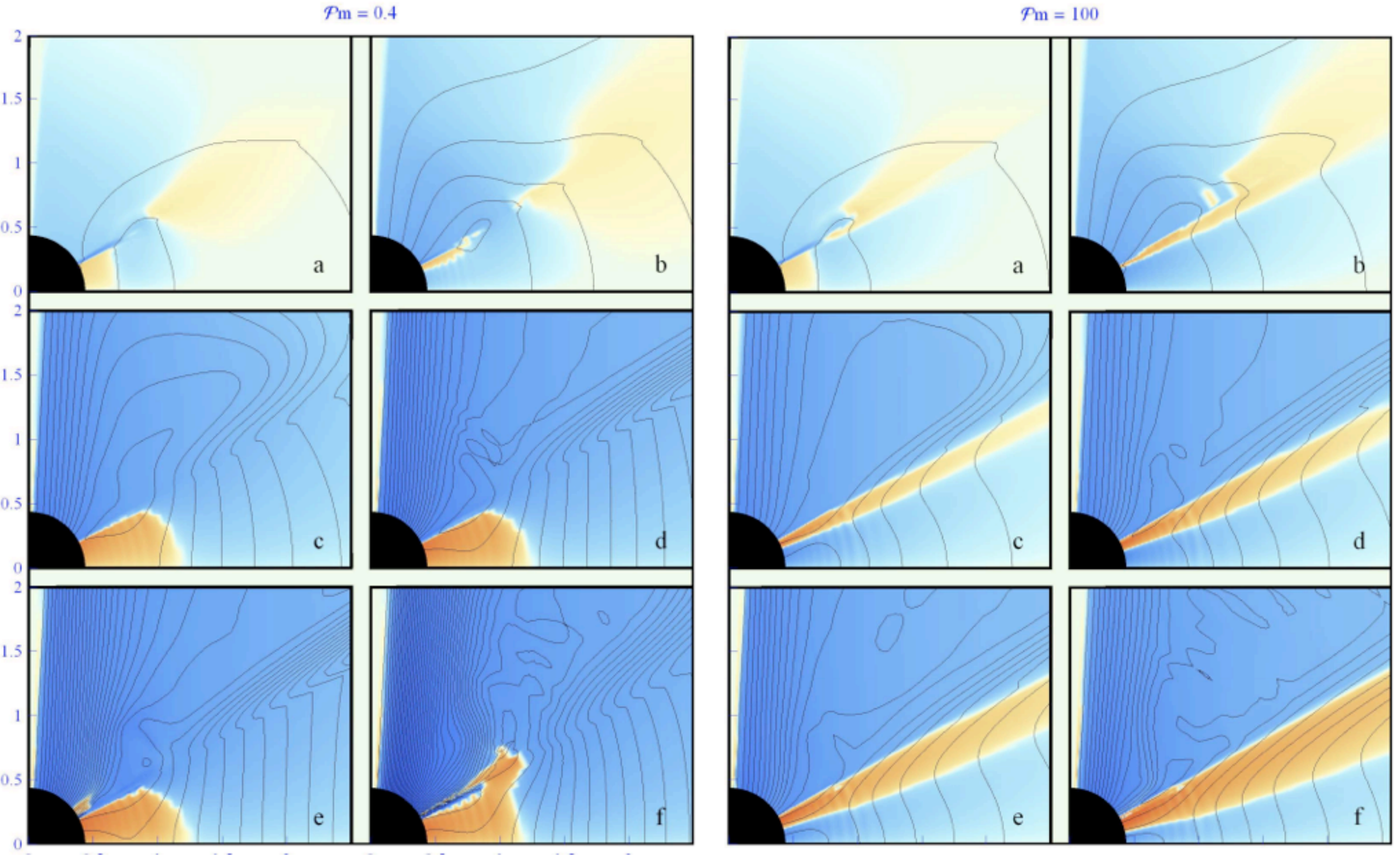


Contopoulos, Nathanail & Katsanikas 2015



Contopoulos, Nathanail & Katsanikas 2015

A Cosmic Battery

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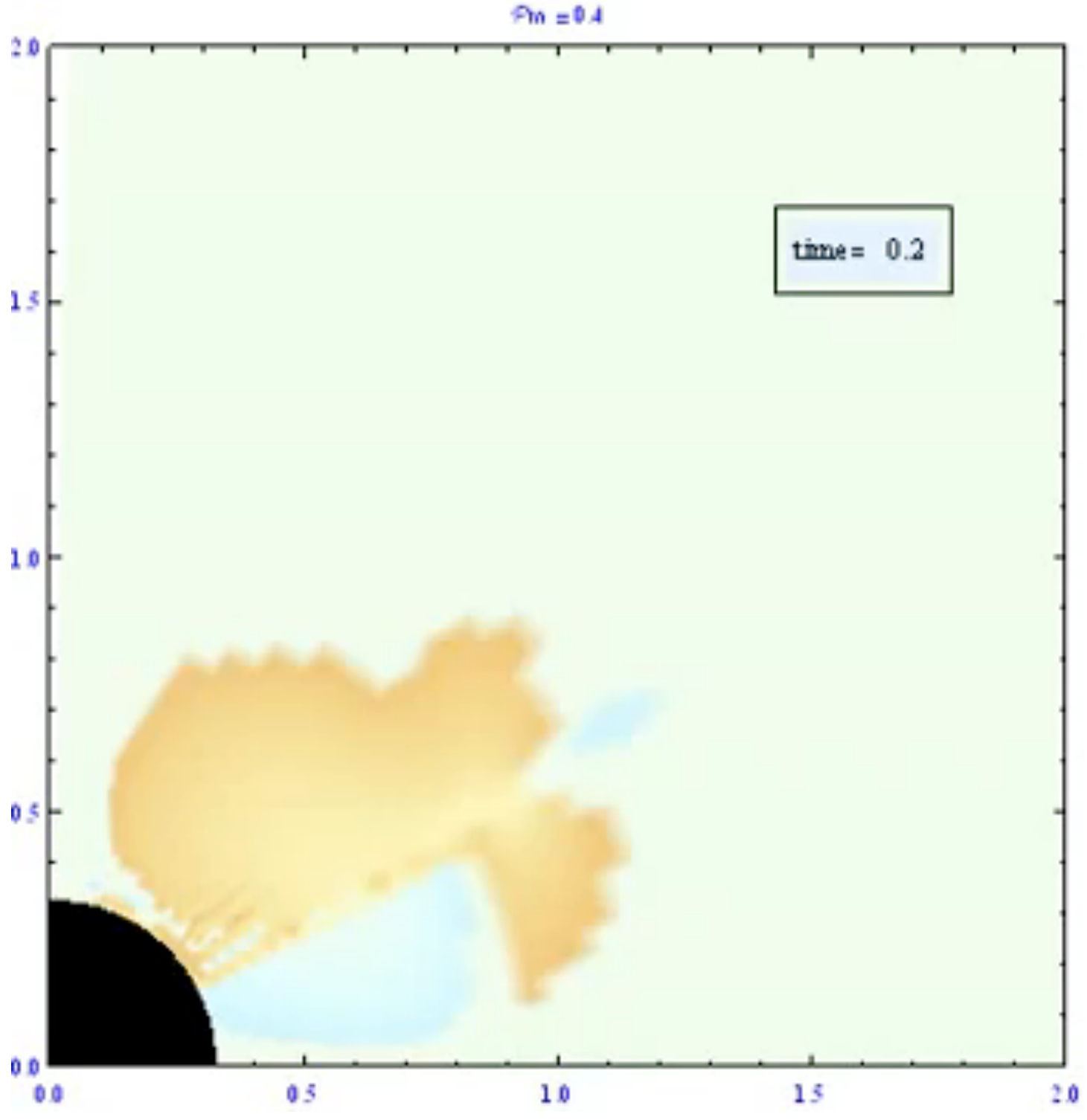


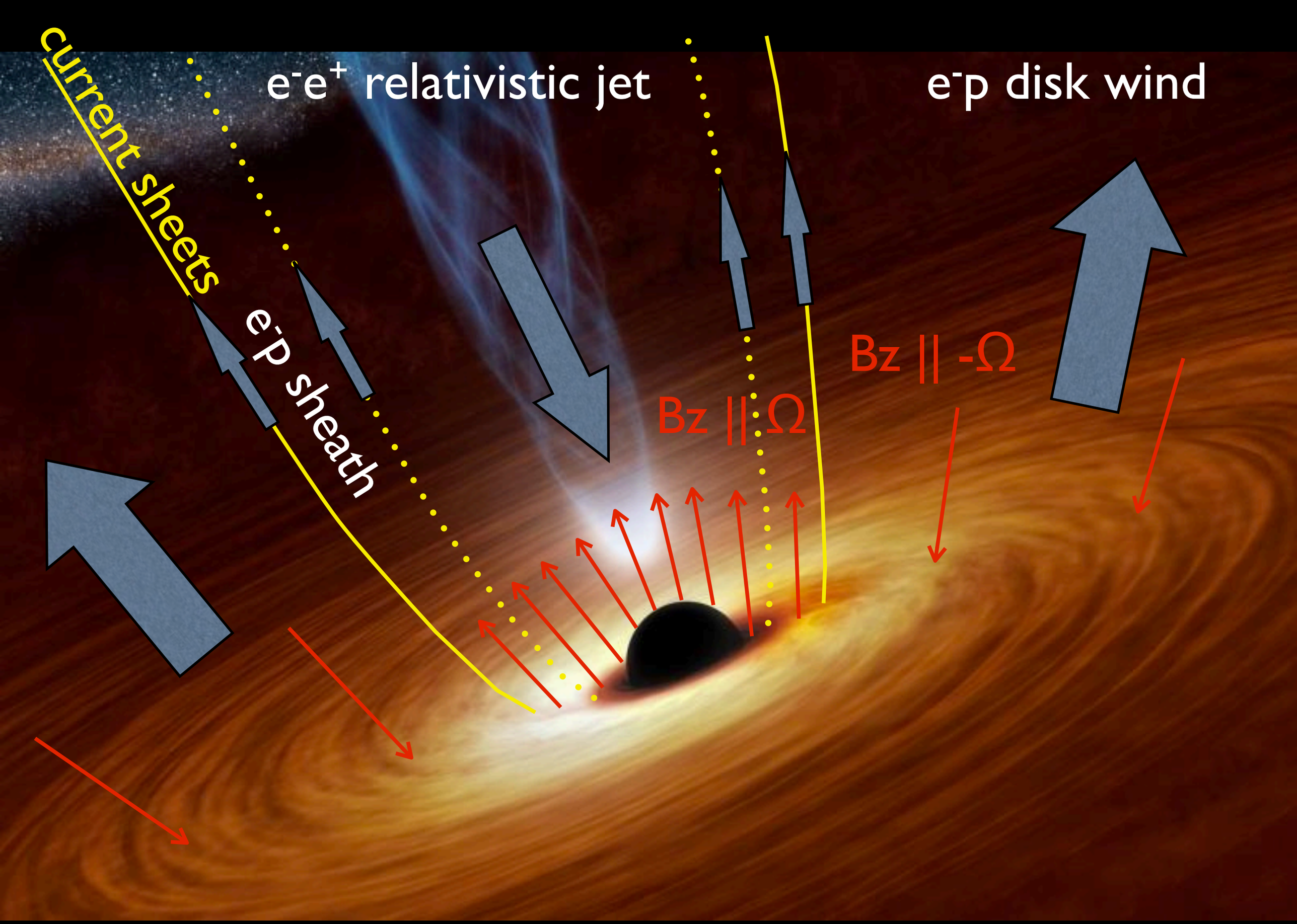
Contopoulos, Nathanail & Katsanikas 2015

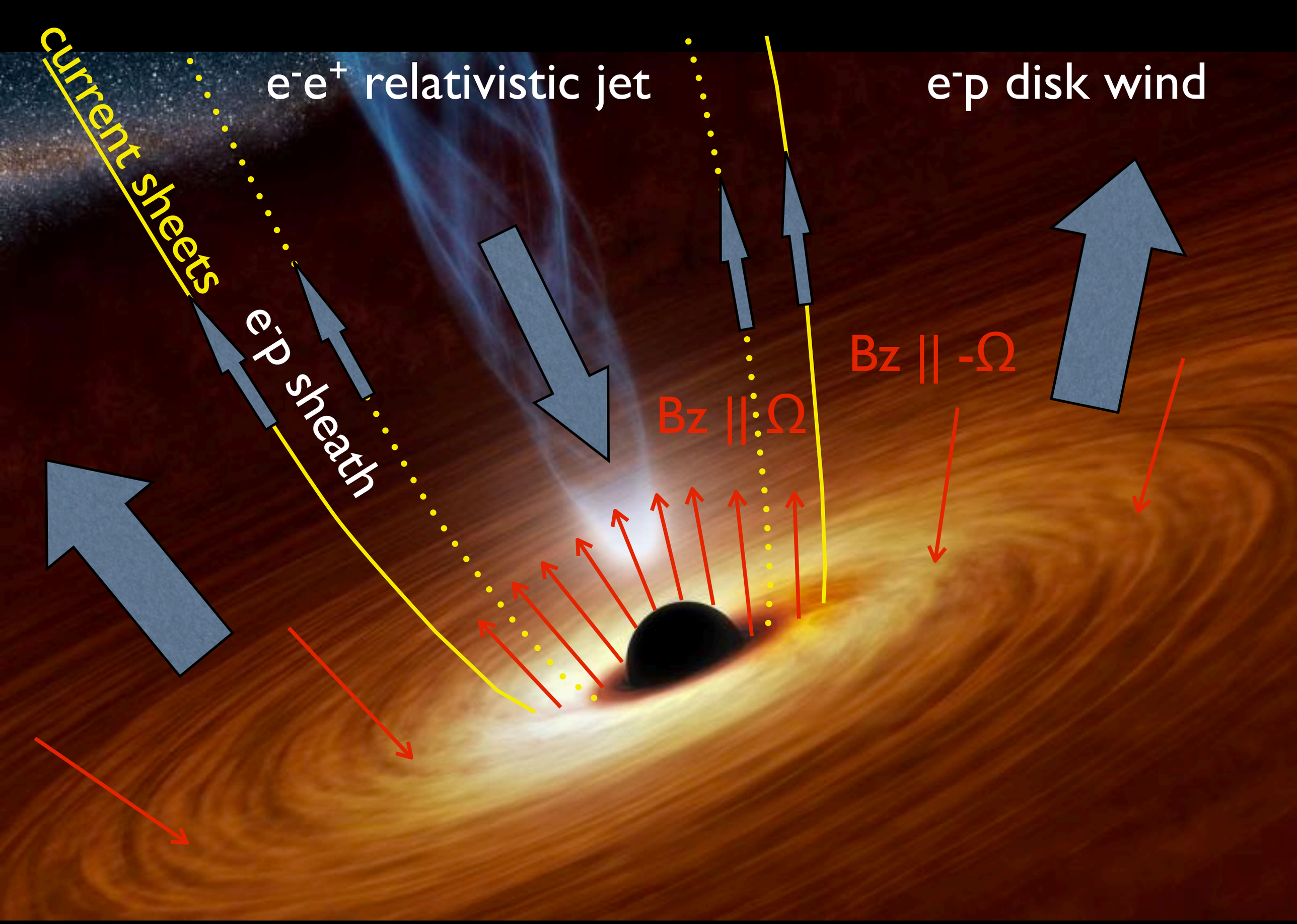
A Cosmic Battery

Contopoulos, Nathanail & Katsanikas 2015

The magnetic field in the jet:

- Significant? Probably yes
- Organized? Probably yes (but hard to see)
- Origin? Battery at the inner edge of the accretion disk (one polarity is held around the central black hole, the other diffuses outward). Generates naturally a core-jet/sheath/disk-wind structure
- Axial field? || Ω in the jet. Closes outside
- Axial electric current (toroidal field)? Towards the origin of the jet. Closes along the surface of the jet


current sheets
e⁻e⁺ relativistic jet
e⁻p disk wind
e⁻p sheath
Bz || Ω
Bz || -Ω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