Black hole Magnetospheres
and
The Orthogonal GRB model

Antonios Nathanail, 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
EUROPEAN SOCIAL FUND
Co- financed by Greece and the European Union

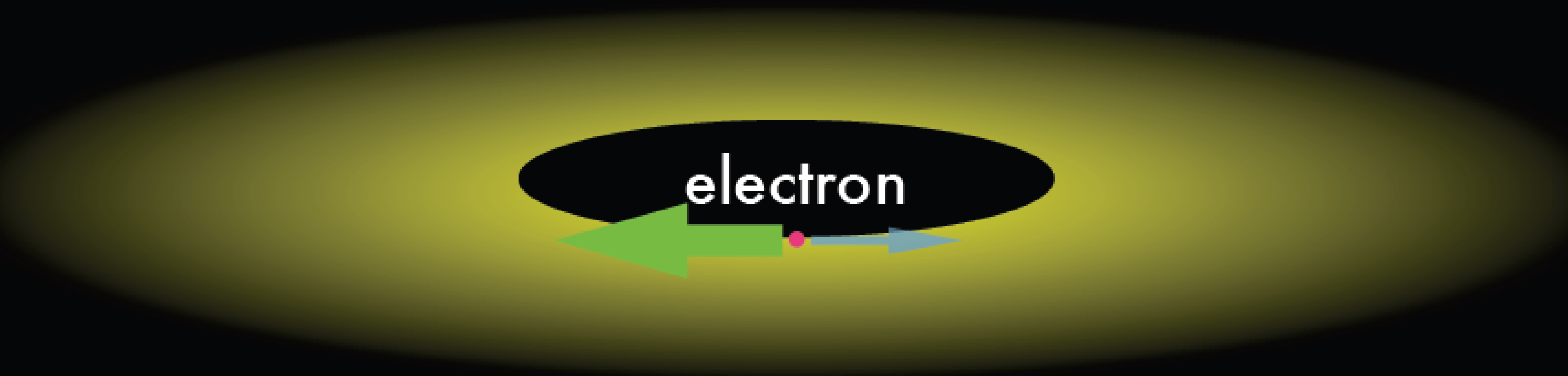
Our team at the Academy

- Ioannis Contopoulos
- Daniela Pugliese
- Elpida Koutsantoniou
- Antonios Nathanail
- Theocharis Apostolatos (U of Athens)

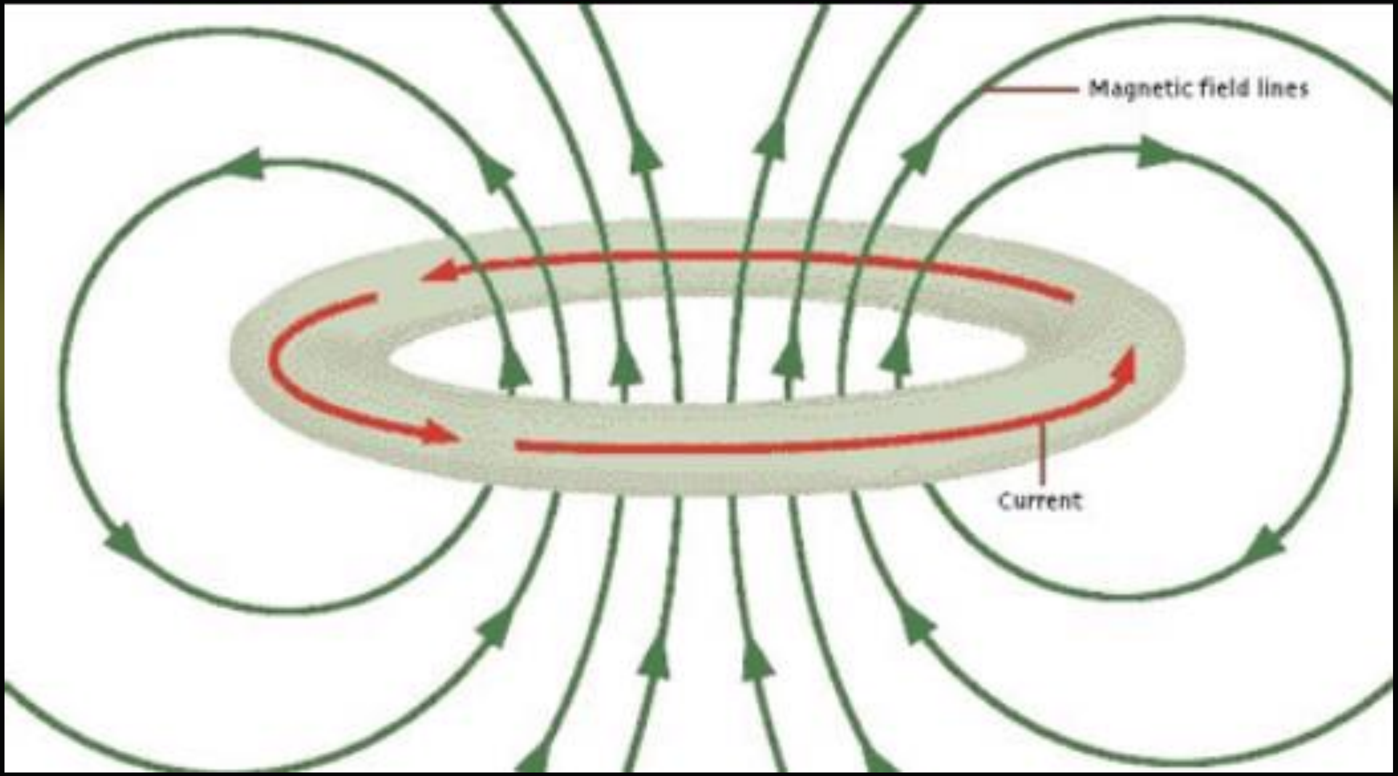
Co- financed by Greece and the European Union

Our aim is to understand:

- The origin of cosmic magnetic fields
- Cosmic Battery
- The Blandford & Znajek mechanism
- What is the structure of the black hole magnetosphere
- The analogy with pulsars



The Cosmic Battery



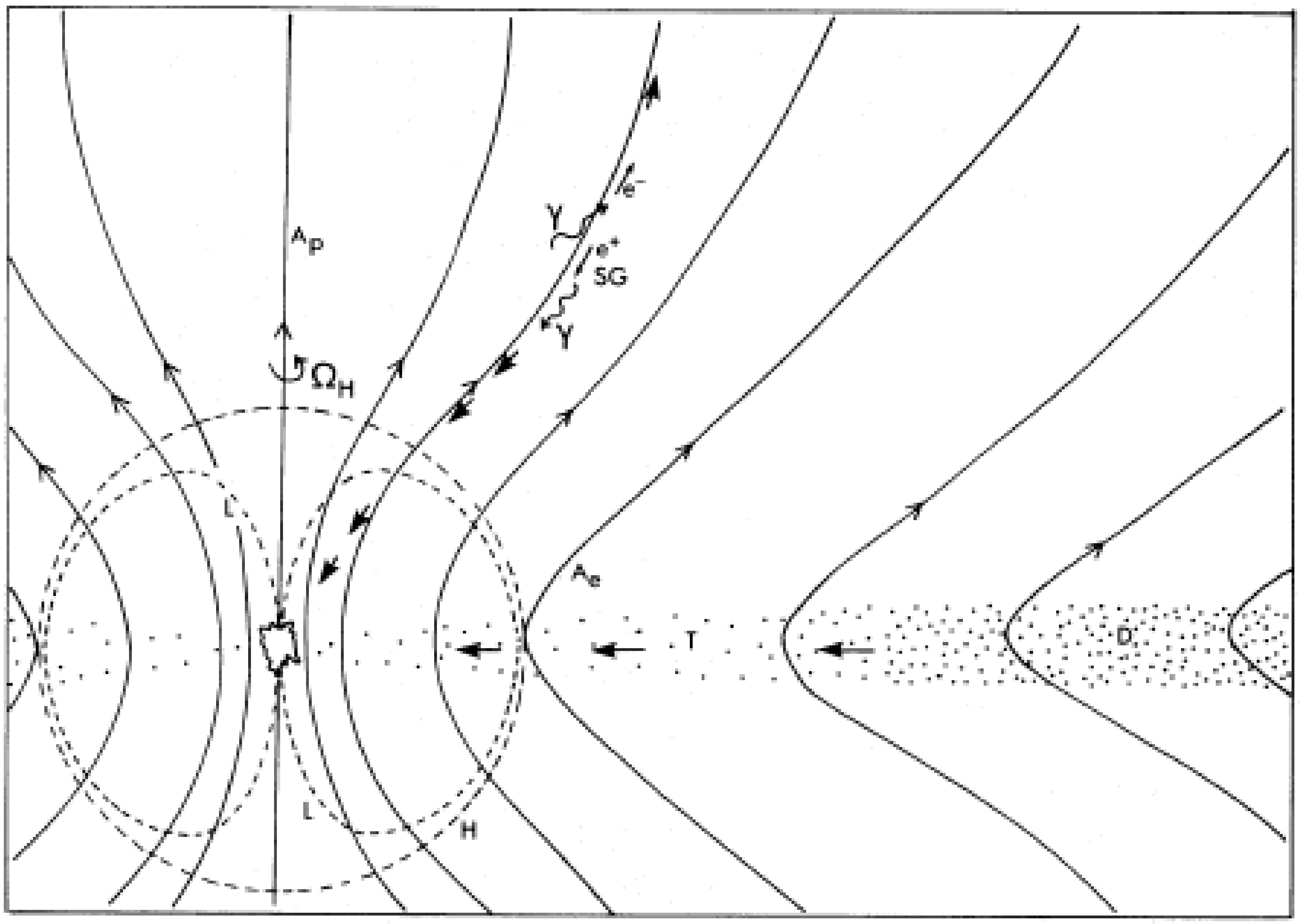
The Cosmic Battery

Blandford & Znajek mechanism (1977)

$$\mathcal{E}_{EM} \propto \omega(\Omega_{\rm BH} - \omega)\Psi_m^2 \sim \Omega_{\rm BH}^2 \Psi_m^2$$

- Rotating black hole
- Magnetic field supported by external currents
- Pair production & force free magnetosphere
- Intense flux of electromagnetic energy

Blandford & Znajek mechanism (1977)



MacDonald & Thorne (1982)

Things look familiar

All the insight from pulsar electrodynamics and other astrophysical problems

GR Pulsar equation

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu$$
$$= -\alpha^2\mathrm{d}t^2 + \frac{A\sin^2\theta}{\Sigma}(\mathrm{d}\phi - \Omega\mathrm{d}t)^2 + \frac{\Sigma}{\Delta}\mathrm{d}r^2 + \Sigma\mathrm{d}\theta^2$$

Kerr metric

$$\tilde{\nabla}\cdot\tilde{B} = 0$$
$$\tilde{\nabla}\cdot\tilde{E} = 4\pi\rho_e$$
$$\tilde{\nabla}\times(\alpha\tilde{B}) = 4\pi\alpha\tilde{J}$$
$$\nabla\times(\alpha\tilde{E}) = 0\ .$$

Contopoulos, Kazanas & Papadopoulos 2013

GR Pulsar equation

$$\tilde{E} \cdot \tilde{B} = 0$$

$$\tilde{B}(r,\theta) = \frac{1}{\sqrt{A}\sin\theta}\left\{\Psi_{,\theta}, -\sqrt{\Delta}\Psi_{,r}, \frac{2I\sqrt{\Sigma}}{\alpha}\right\}$$

$$\tilde{E}(r,\theta) = \frac{\Omega-\omega}{\alpha\sqrt{\Sigma}}\left\{\sqrt{\Delta}\Psi_{,r}, \Psi_{,\theta}, 0\right\} \ .$$

Force free $\rho_e \tilde{E} + \tilde{J} \times \tilde{B} = 0$

Contopoulos, Kazanas & Papadopoulos 2013

The "Huge" GR Pulsar equation

$$\left\{\Psi_{,rr} + \frac{1}{\Delta}\Psi_{,\theta\theta} + \Psi_{,r}\left(\frac{A_{,r}}{A} - \frac{\Sigma_{,r}}{\Sigma}\right) - \frac{\Psi_{,\theta}}{\Delta}\frac{\cos\theta}{\sin\theta}\right\}\cdot\left[1 - \frac{\omega^2 A\sin^2\theta}{\Sigma} + \frac{4M\alpha\omega r\sin^2\theta}{\Sigma} - \frac{2Mr}{\Sigma}\right]$$

$$-\left(\frac{A_{,r}}{A} - \frac{\Sigma_{,r}}{\Sigma}\right)\Psi_{,r} - \left(2\frac{\cos\theta}{\sin\theta} - \frac{A_{,\theta}}{A} + \frac{\Sigma_{,\theta}}{\Sigma}\right)(\omega^2 A\sin^2\theta - 4M\alpha\omega r\sin^2\theta + 2Mr)\frac{\Psi_{,\theta}}{\Delta\Sigma}$$

$$+\frac{2Mr}{\Sigma}\left(\frac{A_{,r}}{A} - \frac{1}{r}\right)\Psi_{,r} + \frac{4\omega M\alpha r\sin^2\theta}{\Sigma}\left\{\Psi_{,r}\left(\frac{1}{r} - \frac{A_{,r}}{A}\right) - \frac{\Psi_{,\theta}}{\Delta}\frac{A_{,\theta}}{A}\right\}$$

$$-\frac{\omega'\sin^2\theta}{\Sigma}(\omega A - 2\alpha Mr)\left(\Psi_{,r}^2 + \frac{1}{\Delta}\Psi_{,\theta}^2\right) = -\frac{4\Sigma}{\Delta}II'$$

Contopoulos, Kazanas & Papadopoulos 2013

The “small” Pulsar equation

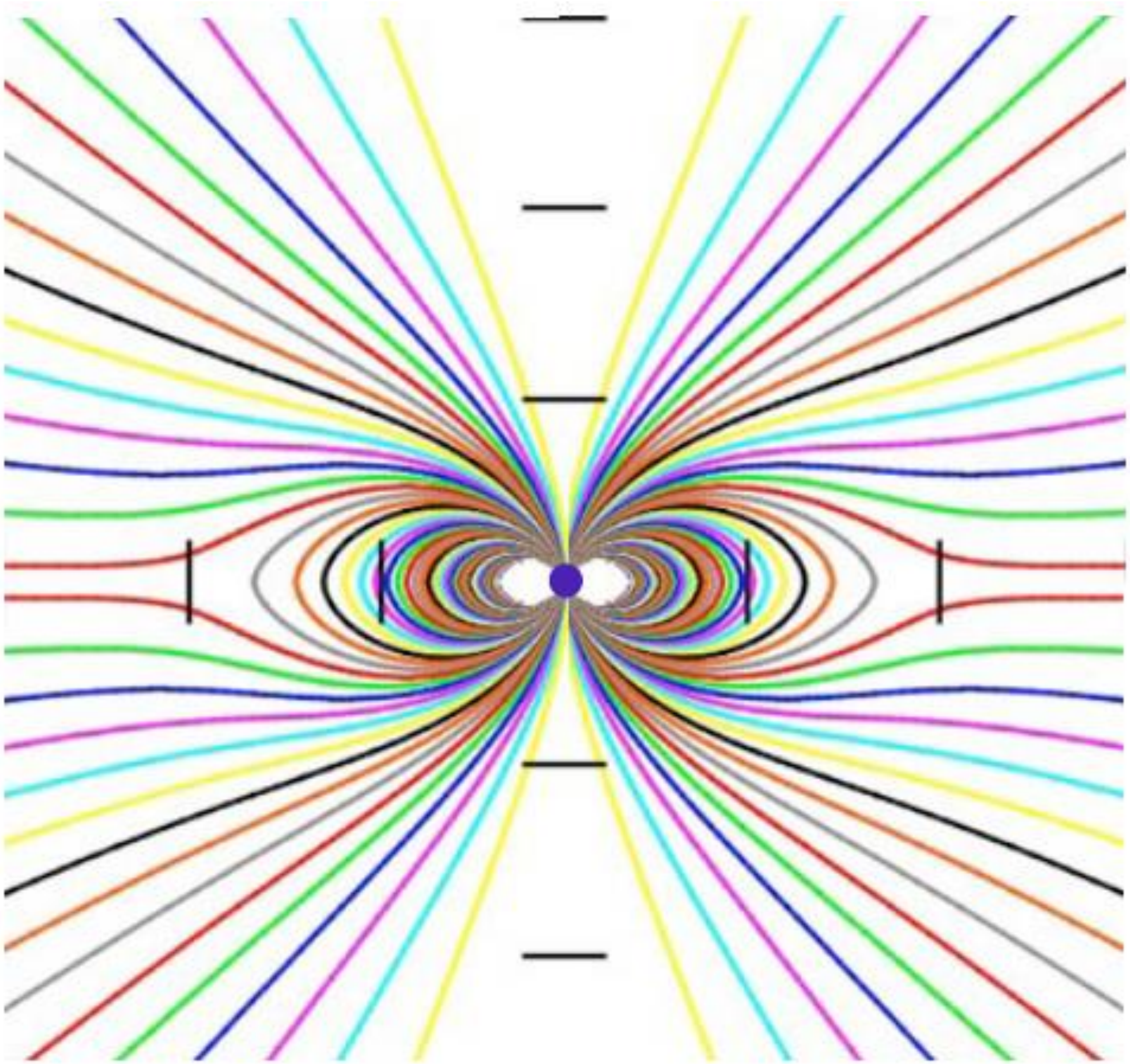
$$\left(\Psi_{,rr} + \frac{1}{r^2}\Psi_{,\theta\theta} + \frac{2\Psi_{,r}}{r} - \frac{1}{r^2}\frac{\cos\theta}{\sin\theta}\Psi_{,\theta}\right) \cdot [1 - \omega^2 r^2 \sin^2\theta]$$

$$-\frac{2\Psi_{,r}}{r} - 2\omega^2 \cos\theta \sin\theta \Psi_{,\theta} - \omega\omega' r^2 \sin^2\theta \left(\Psi_{,r}^2 + \frac{1}{r^2}\Psi_{,\theta}^2\right) = -4II'$$

Pulsar Light cylinder: r sin θ= c / ω

The electric current $I(\Psi)$ must be determined self-consistently

The Pulsar Problem



Contopoulos, Kazanas, Fendt (1999)

GR Pulsar equation

$$1 - \frac{\omega^2 A \sin^2\theta}{\Sigma} + \frac{4M\alpha\omega r \sin^2\theta}{\Sigma} - \frac{2Mr}{\Sigma} = 0$$

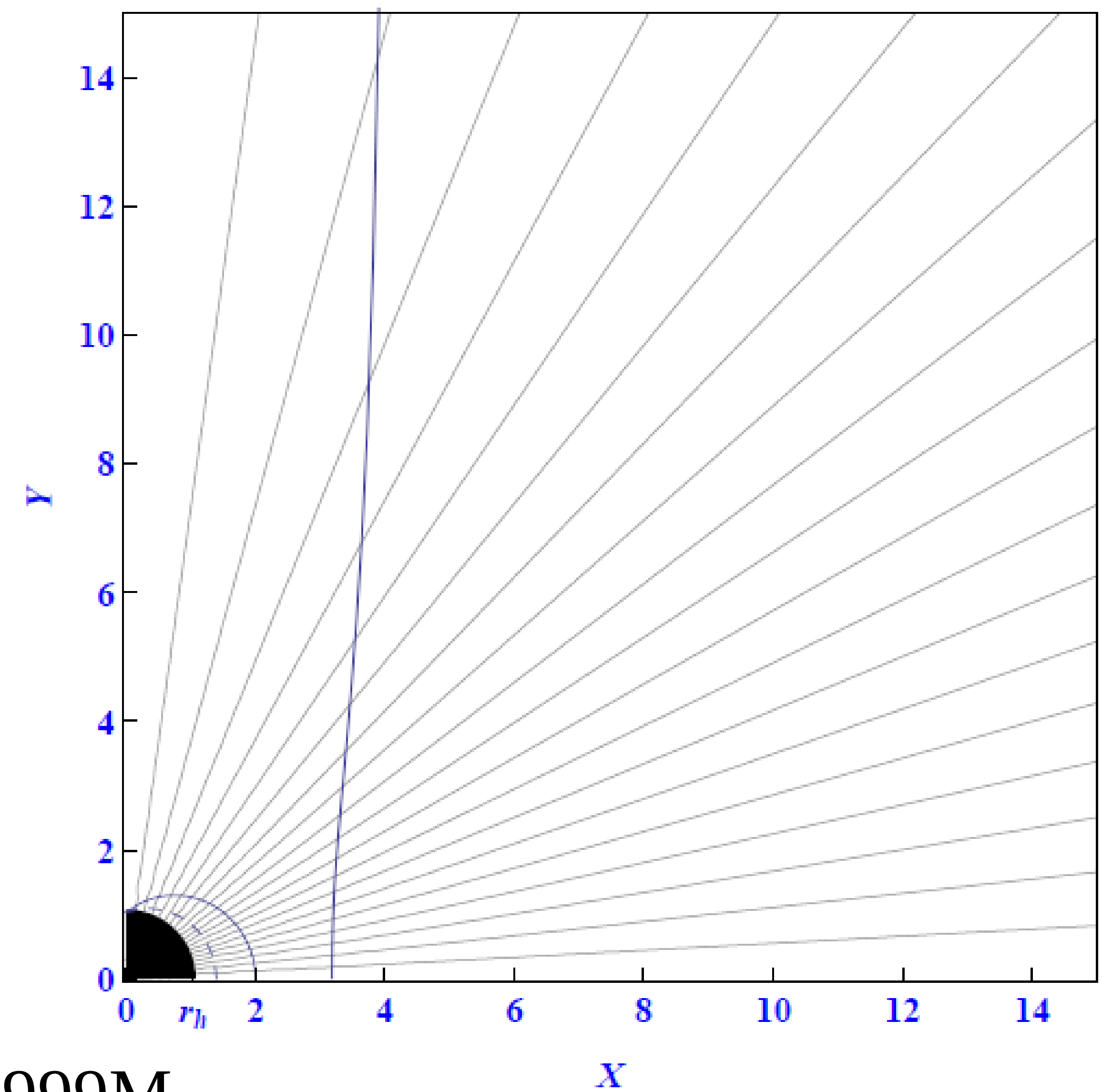
Two light surfaces one inside the ergosphere and one similar to the light cylinder

Two free functions to find self consistently :

$I(\Psi)$ and $\omega(\Psi)$

The current and the angular velocity of the magnetic field

Black hole monopole solution

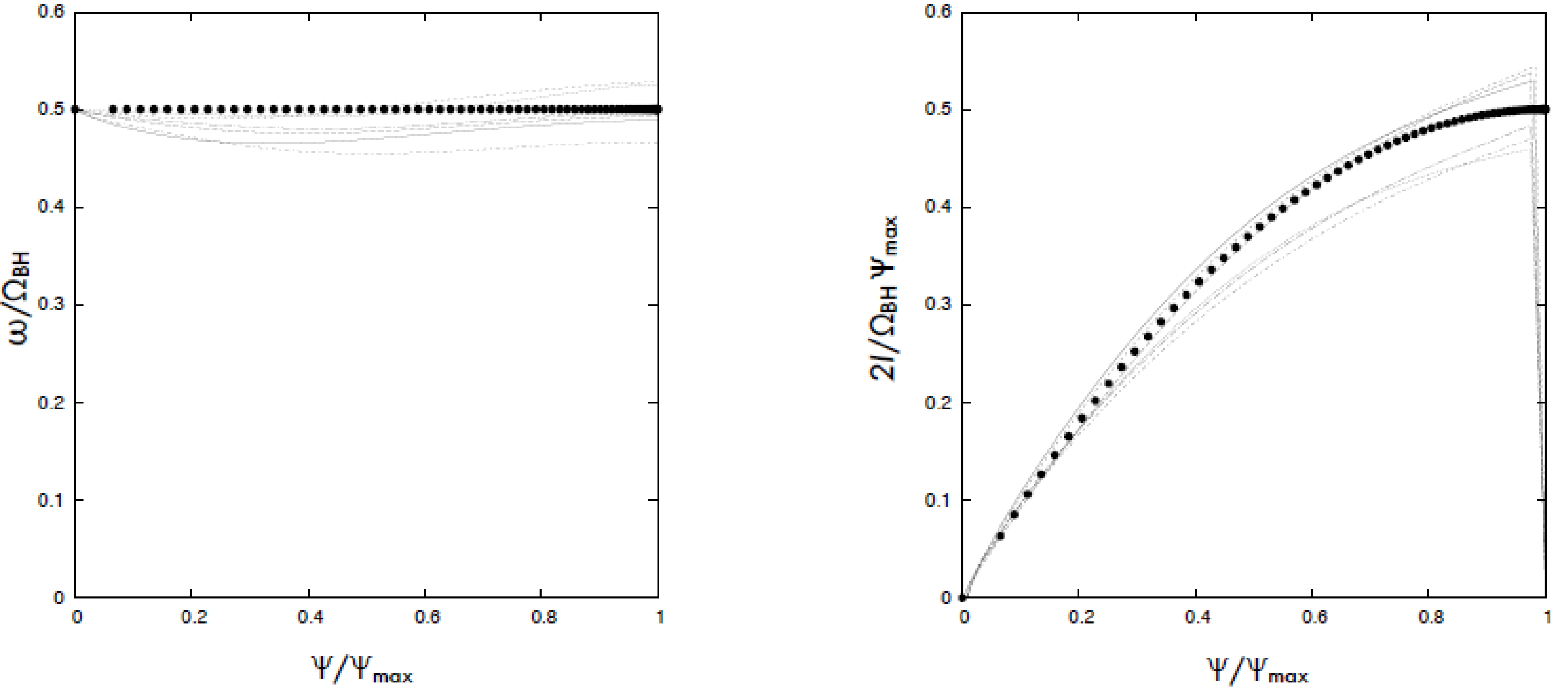


a=0.999M

Contopoulos, Kazanas & Papadopoulos 2013

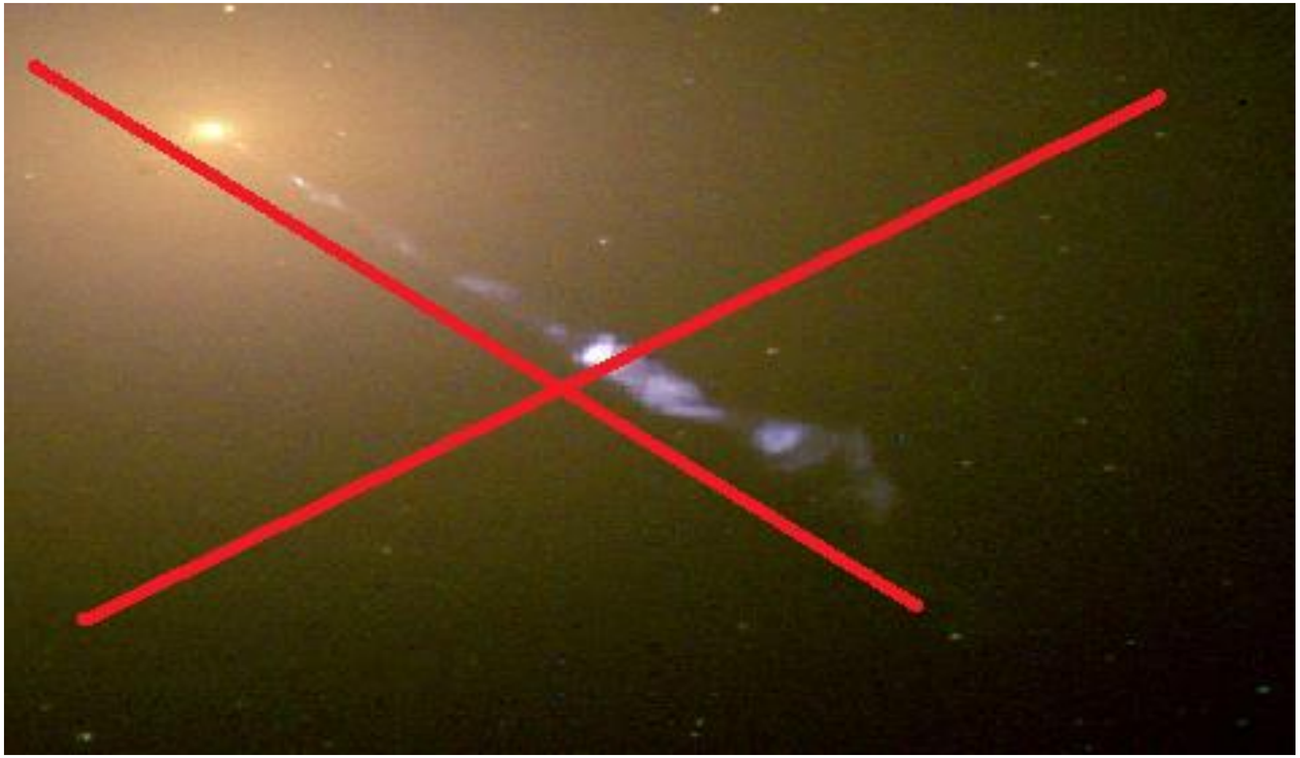
GR Pulsar equation

α=0.7-1 M, ω~0.5 Ω_{BH}

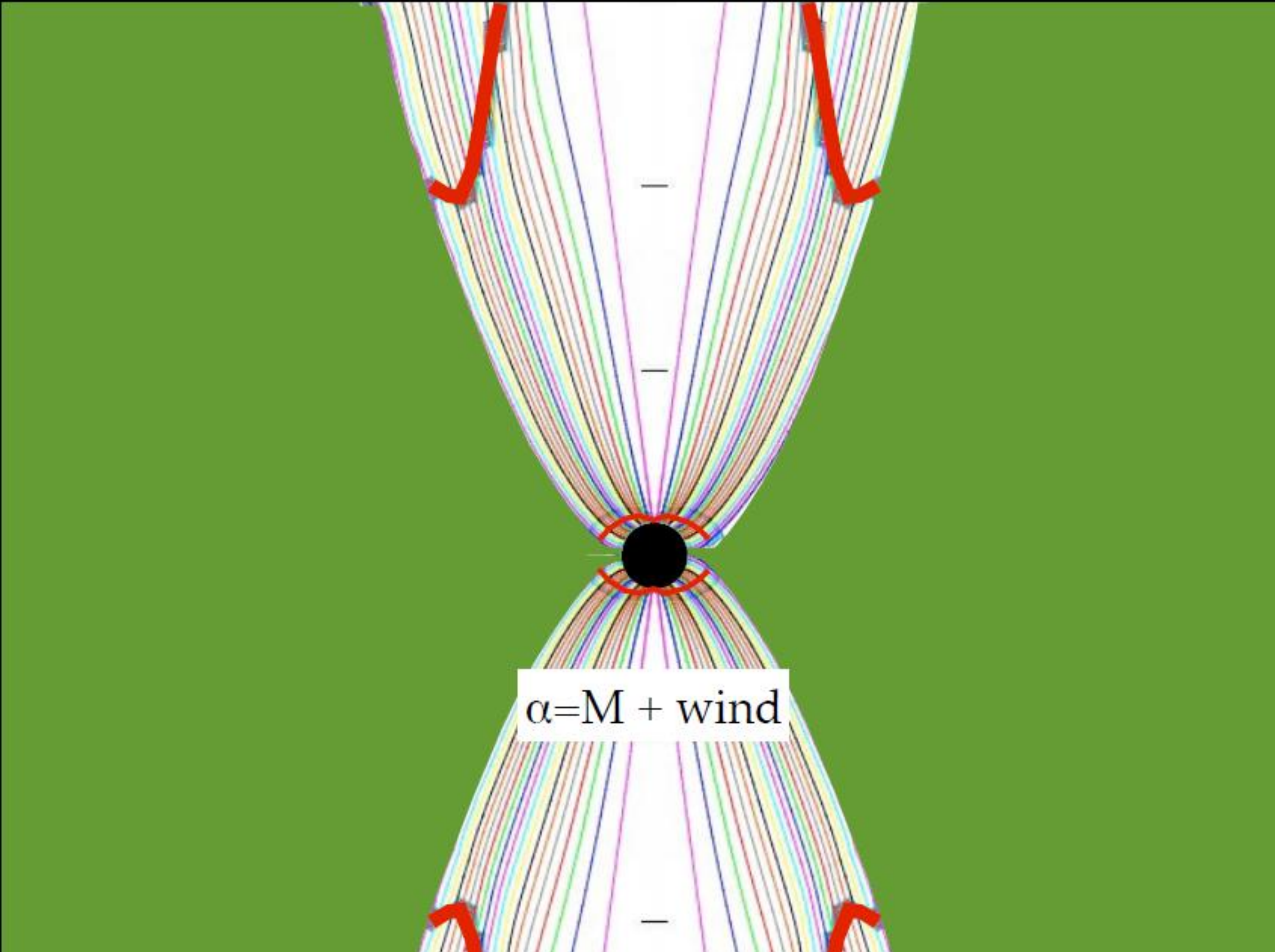


Contopoulos, Kazanas & Papadopoulos 2013

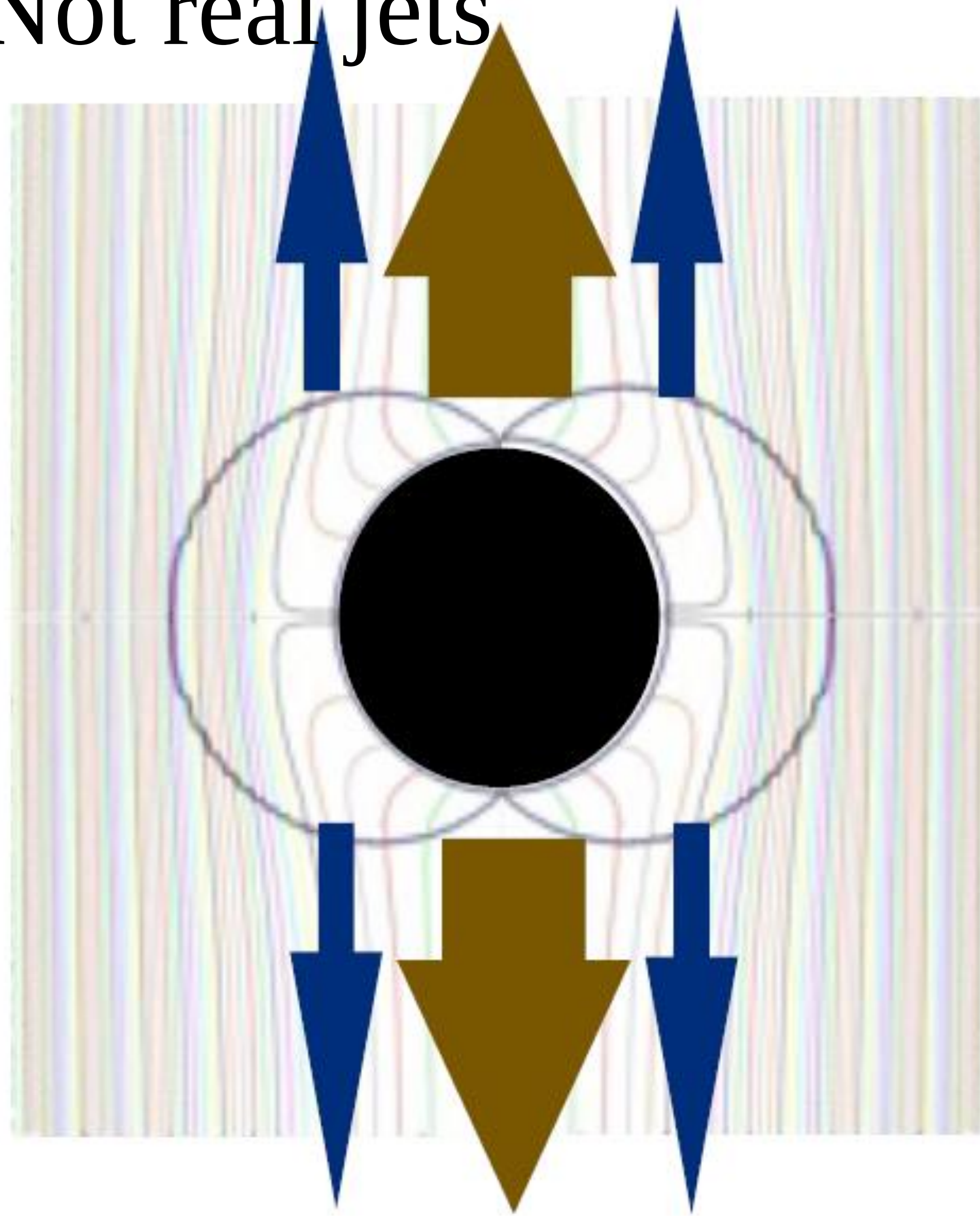
No jet found in these solutions



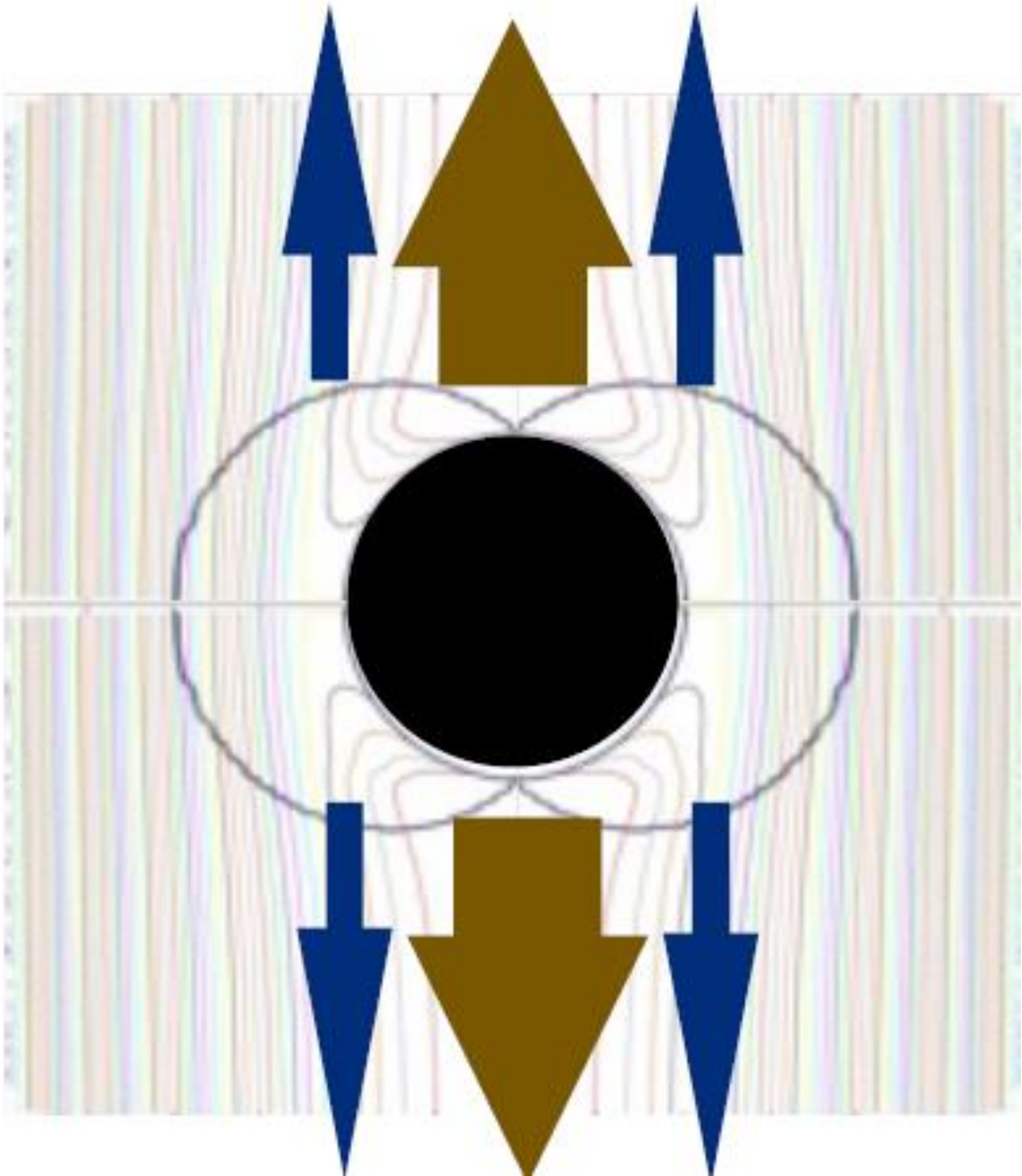
Something is needed to collimate the jet


α=M + wind

Not real jets



Not real jets

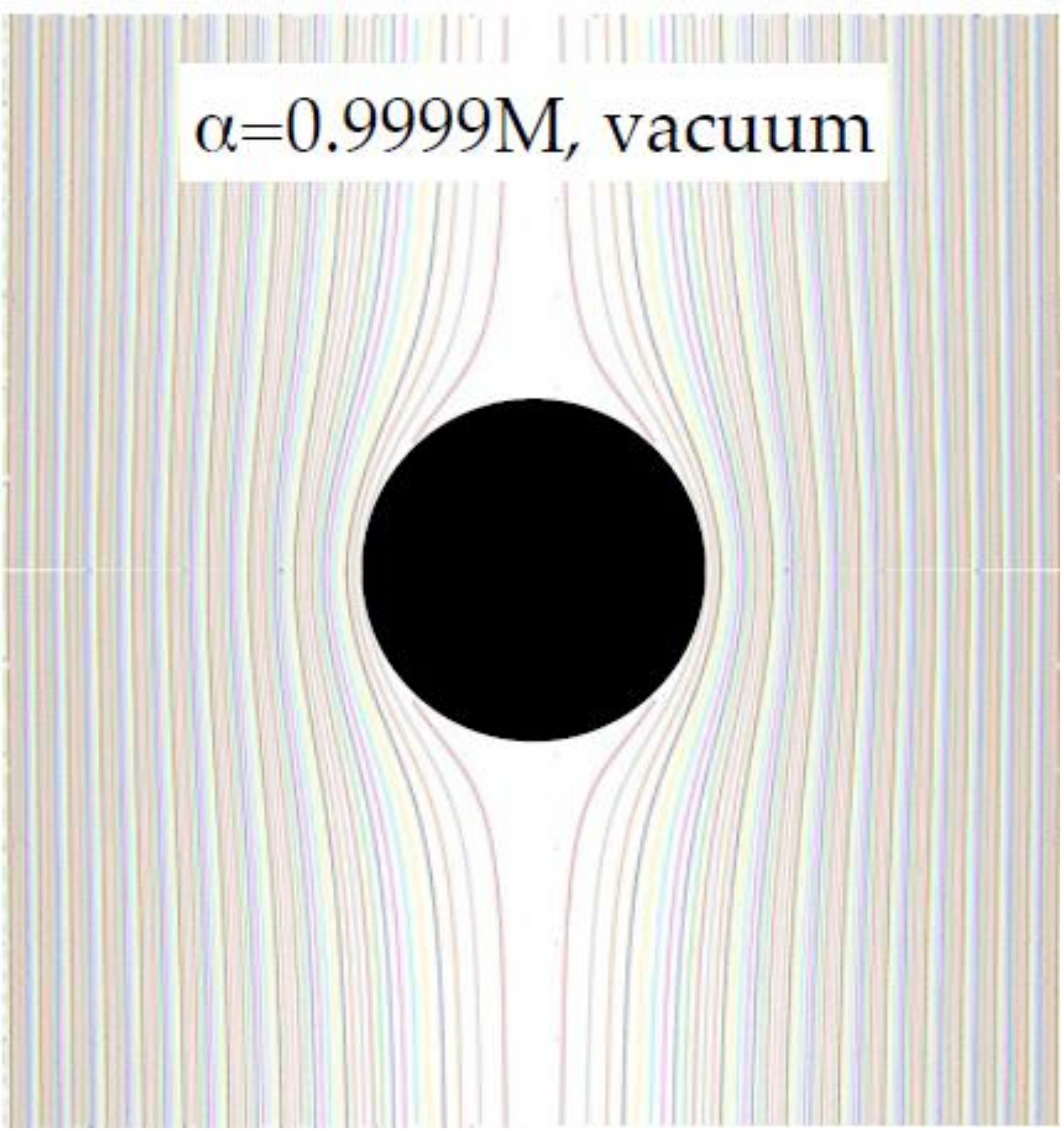


Vacuum Solutions

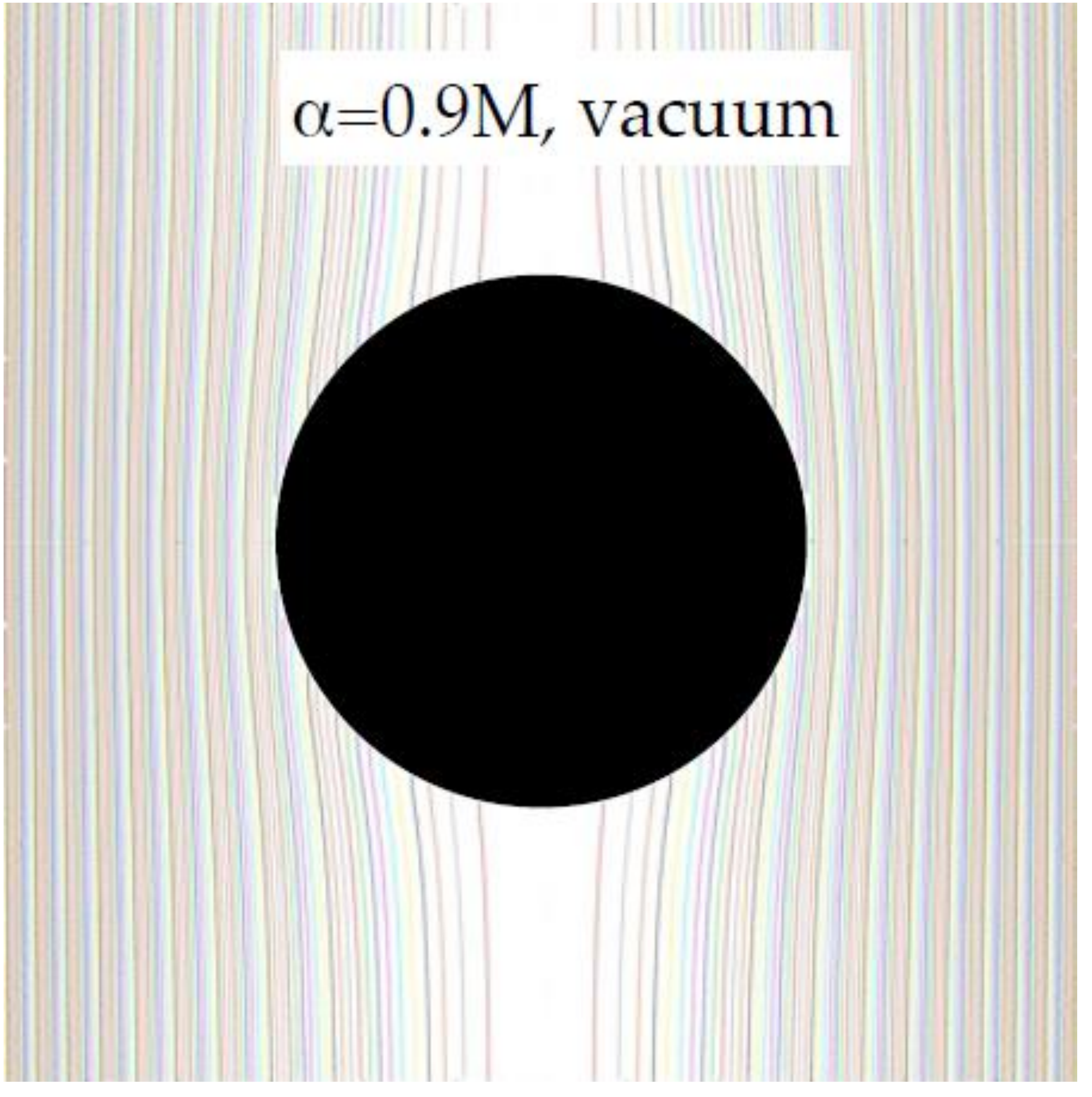
$$\tilde{\nabla} \times (\alpha \tilde{B}) \,|^{\phi} = 0$$

It is the same if you put in the equation I=0, ω=Ω everywhere

Vacuum Solutions



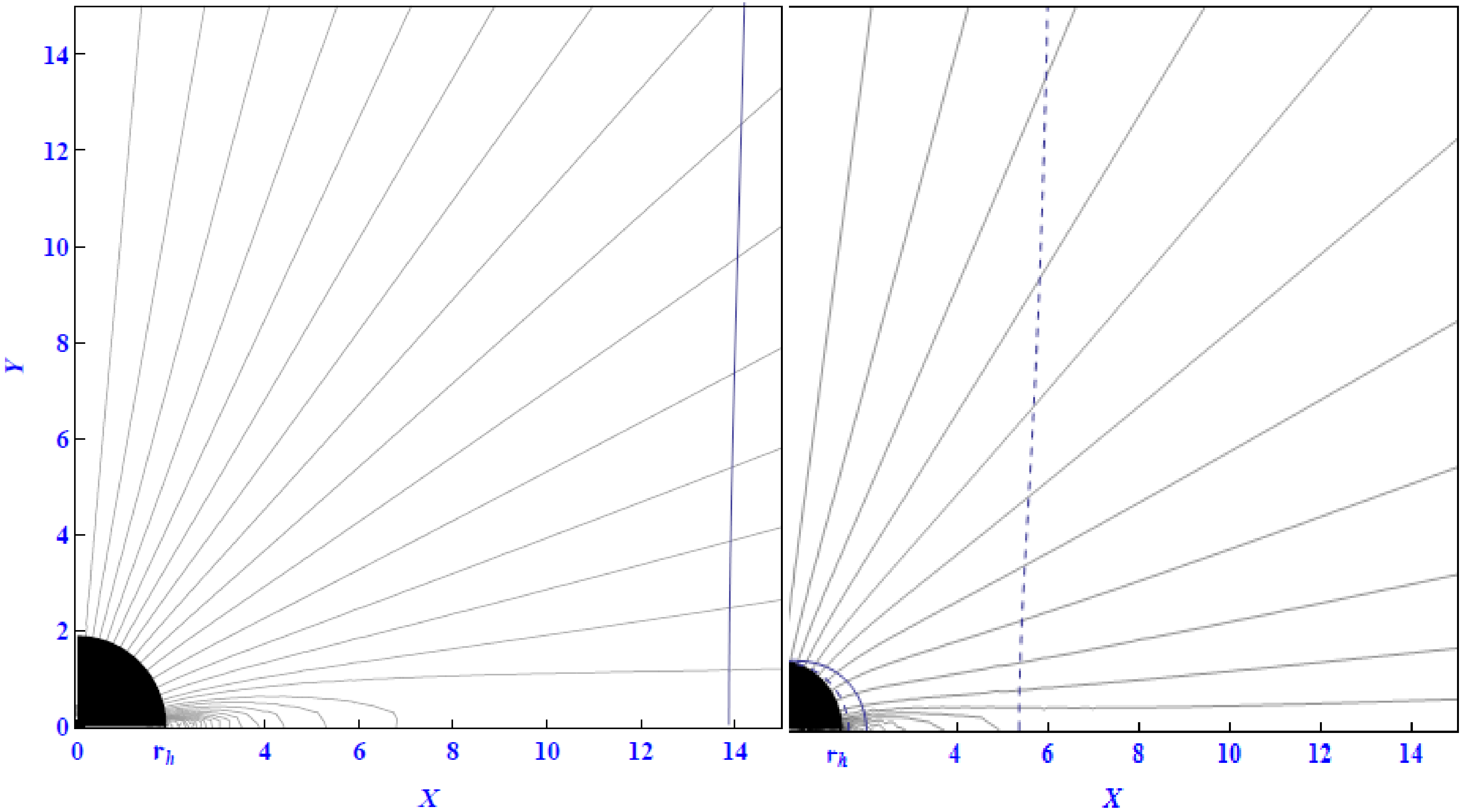
Vacuum Solutions



The analogy with the pulsar

- When the accretion disc is starting to disperse a magnetospheric charge is there rotating
- This charge can support a dipole magnetic field distorted by the rapid rotation
- We have a magnetosphere with closed and open field lines
- Neither system forms relativistic jets on its own

The magnetic black hole



a=0.5

Nathanail et.al in preparation

a=0.9

The orthogonal GRB model

$$\dot{E} \sim M r_{bh}^2 \omega \dot{\omega}$$

$$\dot{E}_{BZ} \sim \Psi^2 \omega^2 \sim \omega^2 \sim e^{-t/\tau}$$

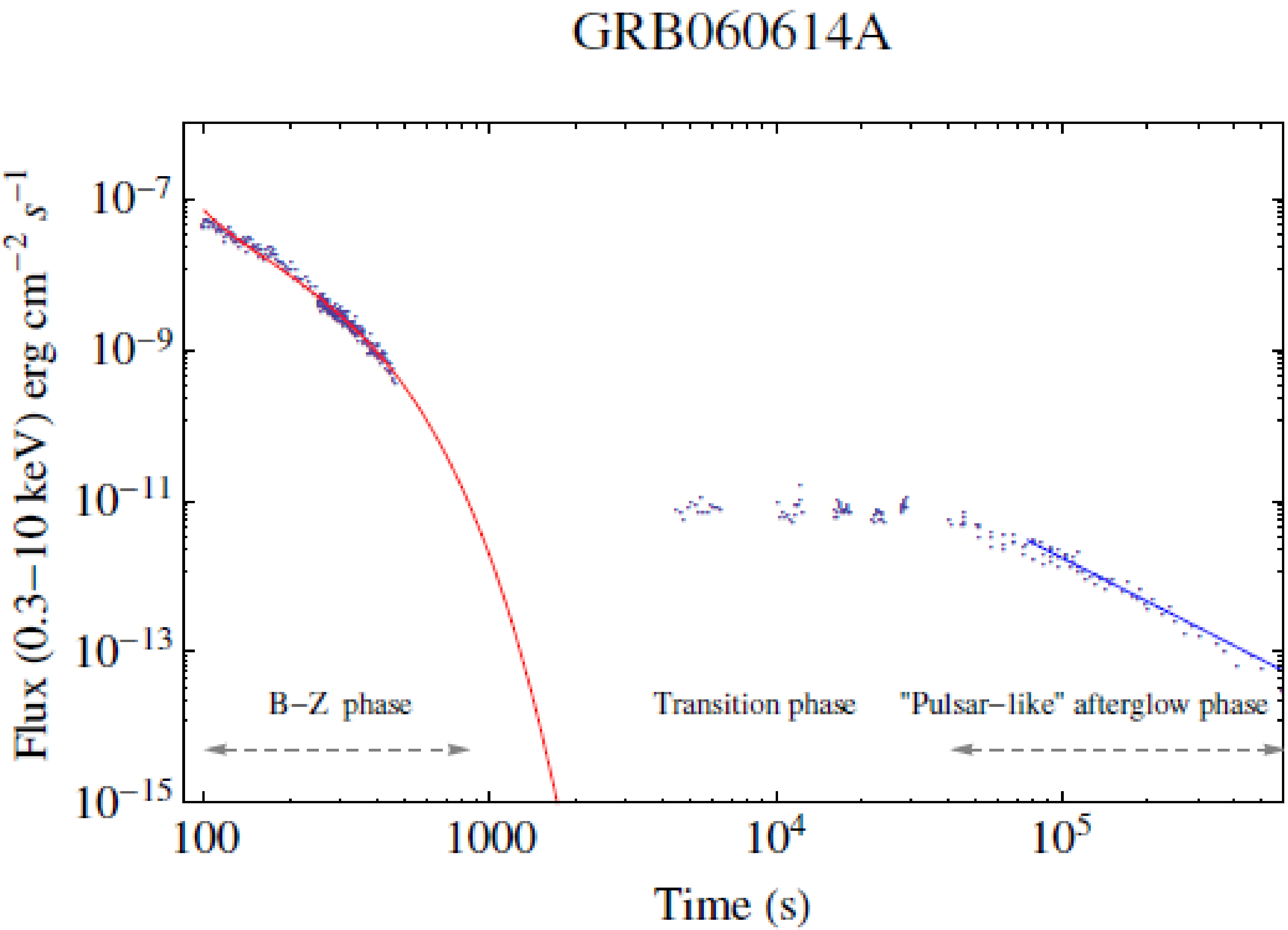
$$\dot{E}_{\rm puls} \sim \Psi_{\rm open}^2 \omega^2 \sim \omega^8 \sim t^{-4/3}$$

Contopoulos, Nathanail & Pugliese 2013

The orthogonal GRB model

- As in pulsars, high energy radiation is generated in the equatorial current sheet
- Our model is 'orthogonal' to the standard GRB model where all the action takes place along a relativistic jet emitted along the rotation and magnetic axis

The orthogonal GRB model



Contopoulos, Nathanail, Pugliese 2013

$$\dot{E}_o \tau_{\rm BZ} = 10^{55} M_{10} \text{ erg}$$

$$\tau_{\rm BZ} \sim 10 - 100 \text{ sec}$$

$$\dot{E}_o \sim 10^{53} \text{ erg/sec}$$

$$B_o \sim 10^{16} \text{ G}$$

The end

Thank you

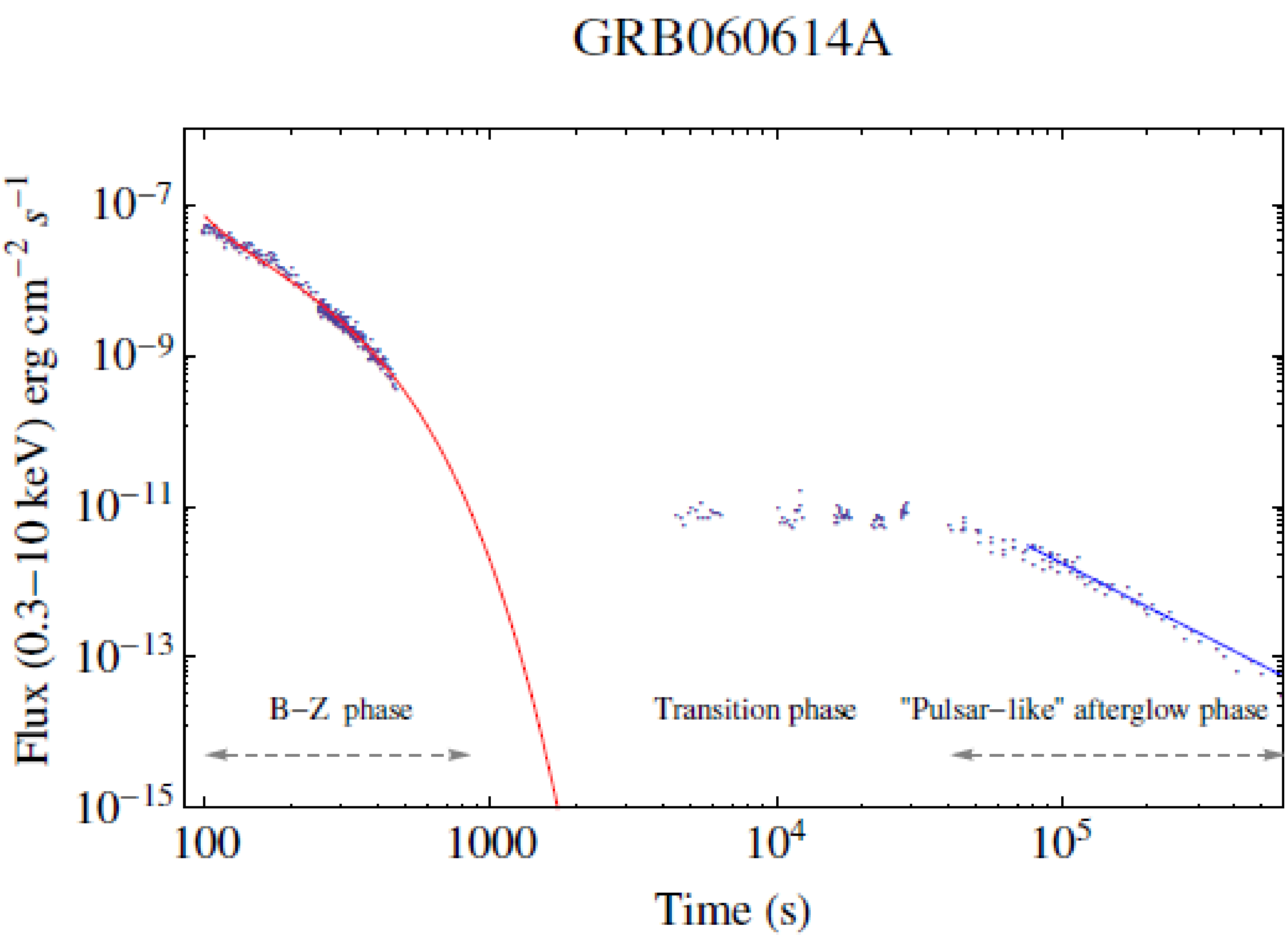
European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY
NSRF 2007-2013
EUROPEAN SOCIAL FUND
Co- financed by Greece and the European Union

$$\left\{\Psi_{,rr}+\frac{1}{\Delta}\Psi_{,\theta\theta}+\Psi_{,r}\left(\frac{A_{,r}}{A}-\frac{\Sigma_{,r}}{\Sigma}\right)-\frac{\Psi_{,\theta}}{\Delta}\frac{\cos\theta}{\sin\theta}\right\}\cdot\left[1-\frac{\omega^2 A\sin^2\theta}{\Sigma}+\frac{4M\alpha\omega r\sin^2\theta}{\Sigma}-\frac{2Mr}{\Sigma}\right]$$

$$-\left(\frac{A_{,r}}{A}-\frac{\Sigma_{,r}}{\Sigma}\right)\Psi_{,r}-\left(2\frac{\cos\theta}{\sin\theta}-\frac{A_{,\theta}}{A}+\frac{\Sigma_{,\theta}}{\Sigma}\right)(\omega^2 A\sin^2\theta-4M\alpha\omega r\sin^2\theta+2Mr)\frac{\Psi_{,\theta}}{\Delta\Sigma}$$

$$+\frac{2Mr}{\Sigma}\left(\frac{A_{,r}}{A}-\frac{1}{r}\right)\Psi_{,r}+\frac{4\omega M\alpha r\sin^2\theta}{\Sigma}\left\{\Psi_{,r}\left(\frac{1}{r}-\frac{A_{,r}}{A}\right)-\frac{\Psi_{,\theta}}{\Delta}\frac{A_{,\theta}}{A}\right\}$$

$$-\frac{\omega'\sin^2\theta}{\Sigma}(\omega A-2\alpha Mr)\left(\Psi_{,r}^2+\frac{1}{\Delta}\Psi_{,\theta}^2\right)=-\frac{4\Sigma}{\Delta}II'$$



GRB060614A
Flux (0.3–10 keV) erg cm^{-2} s^{-1}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
100
1000
10^4
10^5
Time (s)
B−Z phase
Transition phase
"Pulsar−like" afterglow phase