Black Hole Magnetospheres

Ioannis Contopoulos, RCAAM, Academy of Athens

European Union
European Social Fund

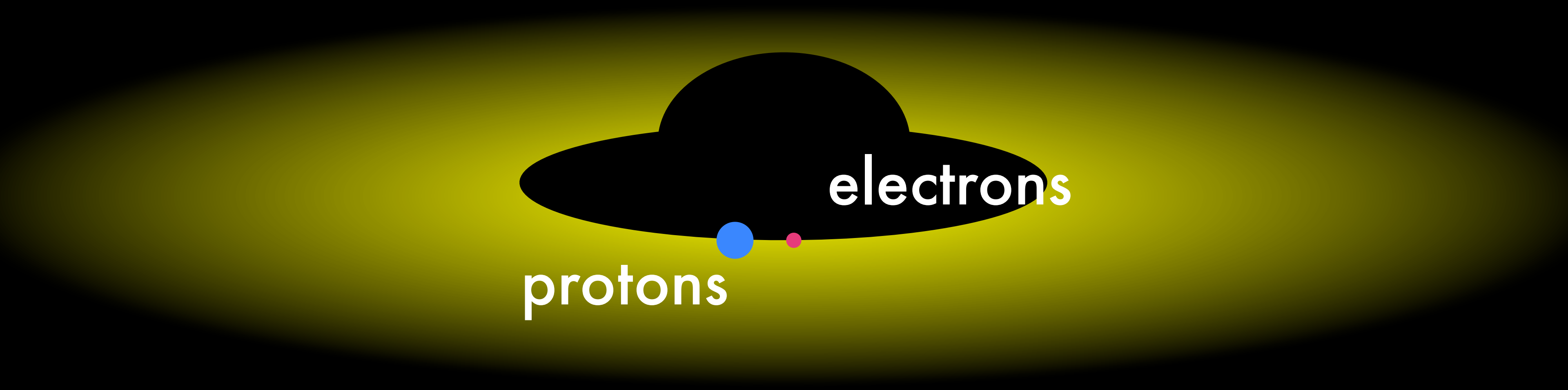
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY

NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co- financed by Greece and the European Union

The Cosmic Battery

Contopoulos & Kazanas 1998



The Cosmic Battery

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Koutsantoniou & Contopoulos 2014 (in prep.)

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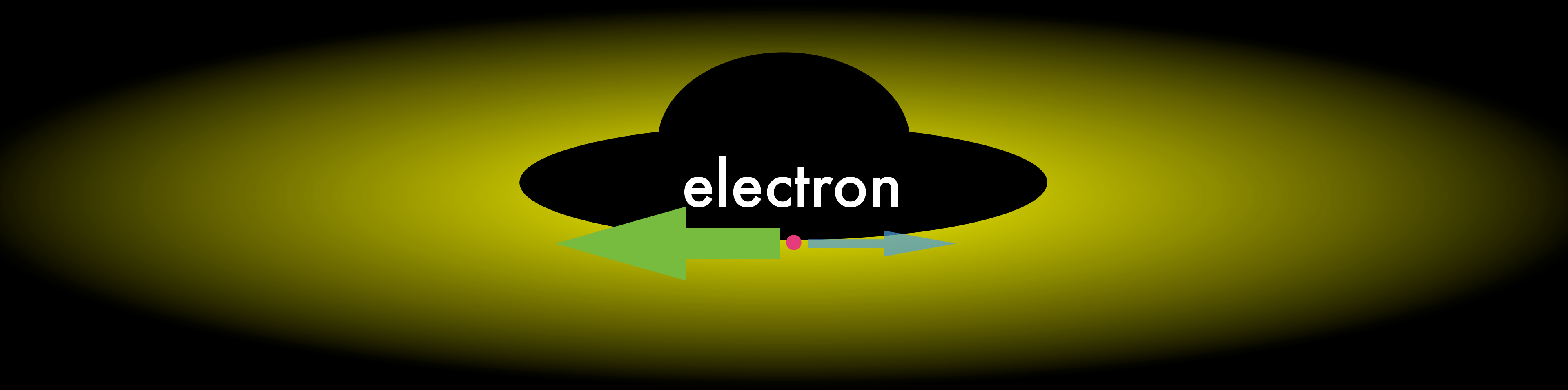

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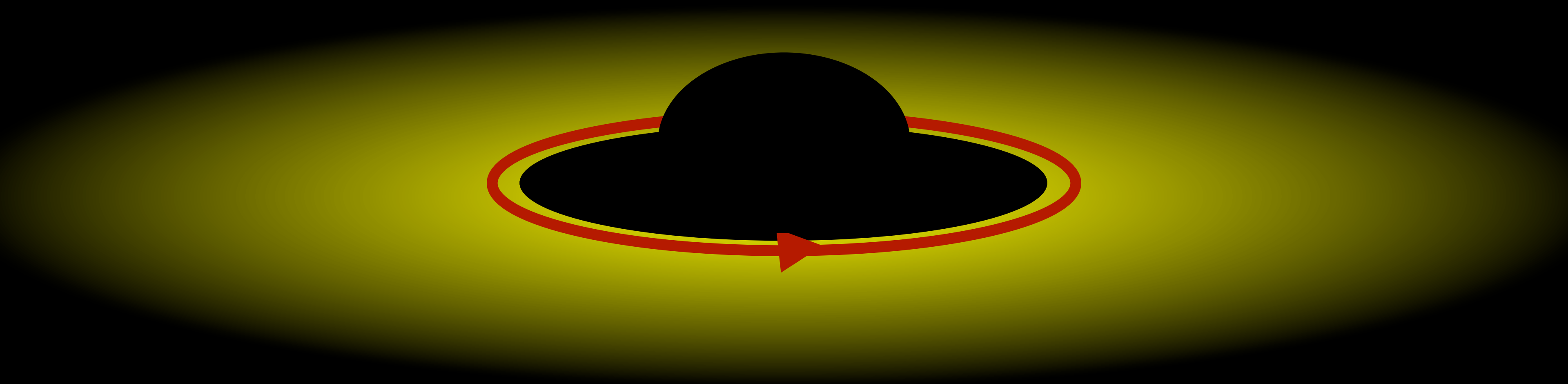

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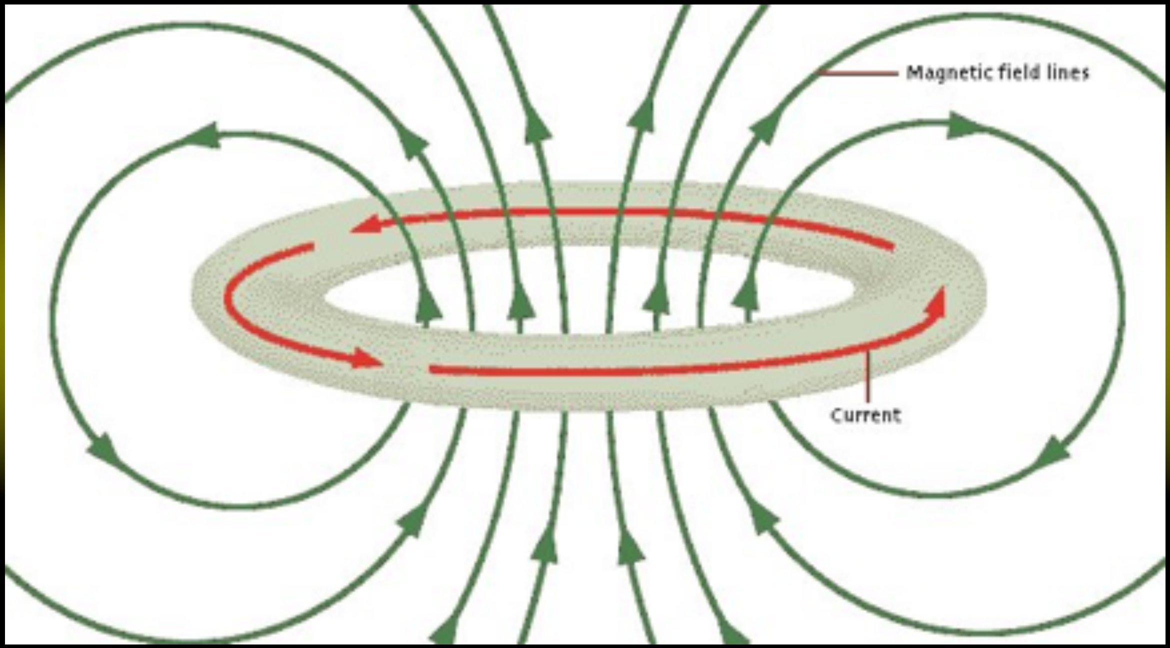
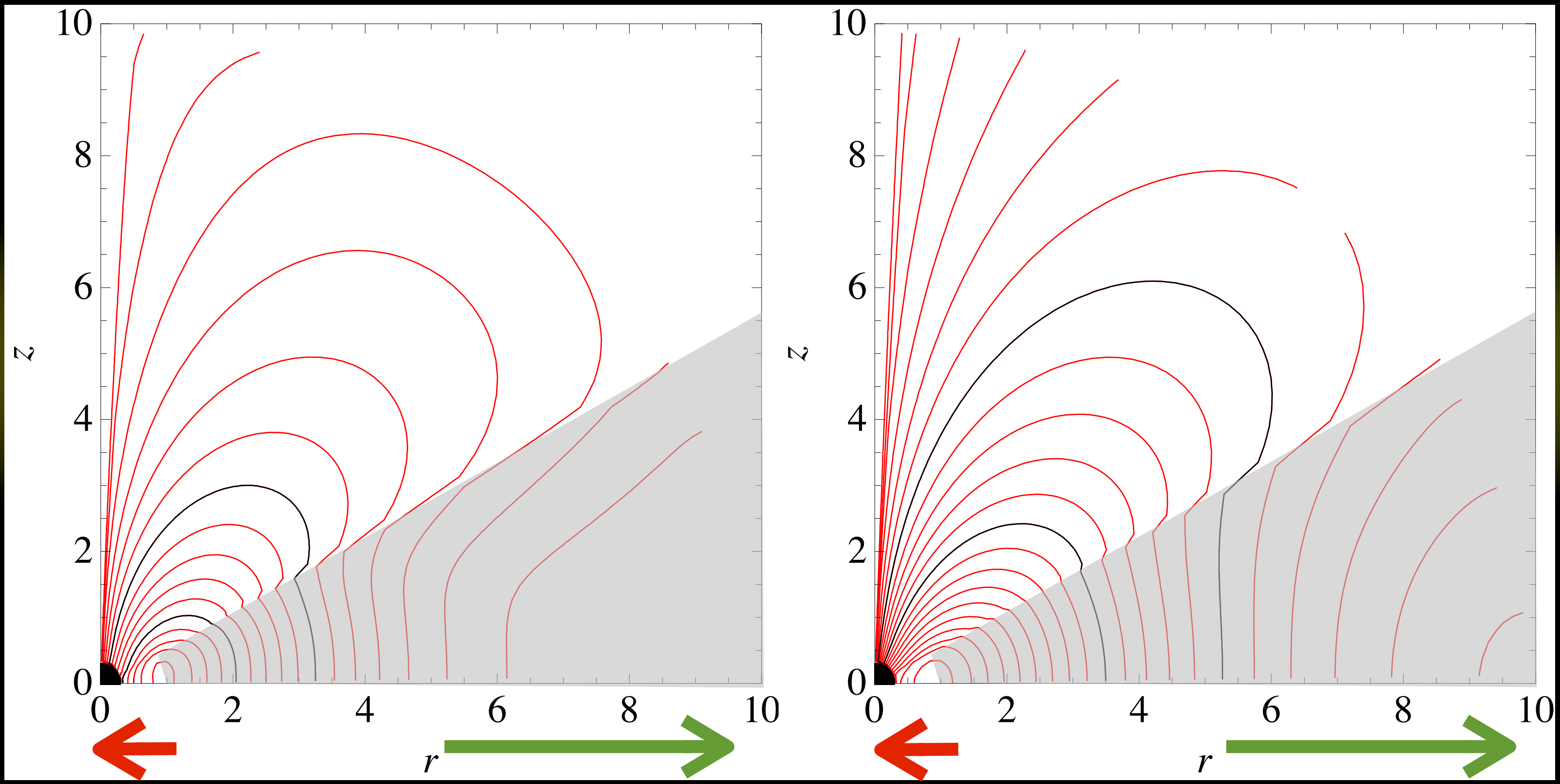


The Cosmic Battery

Koutsantoniou & Contopoulos 2014 (in prep.)

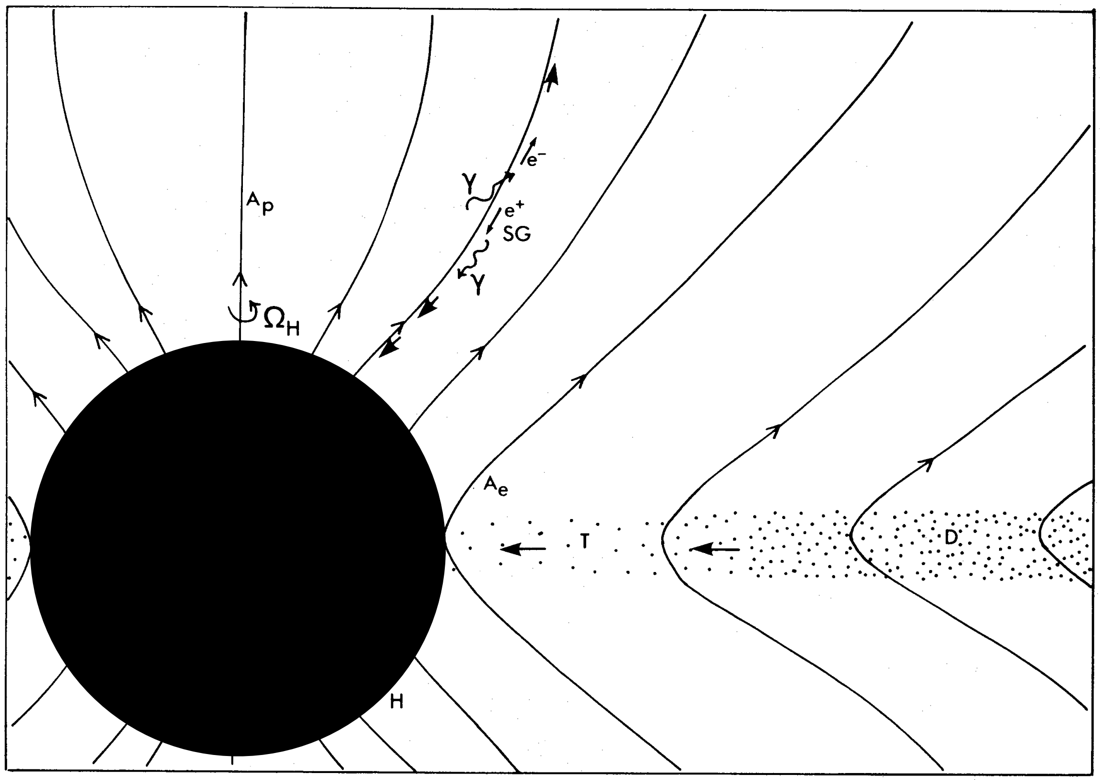
$$\frac{\partial \Psi_m}{\partial t} = 2\pi \alpha r \left(v \times B - \frac{f_{\rm rad}^{\phi}}{e} + \eta \nabla \times B \right)$$



The Cosmic Battery

Katsanikas & Contopoulos 2014 (in prep.)

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



Blandford
Znajek 1977

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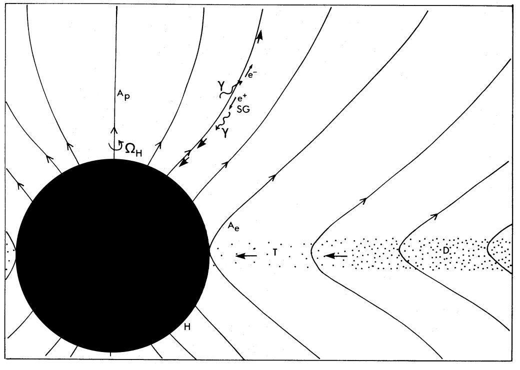

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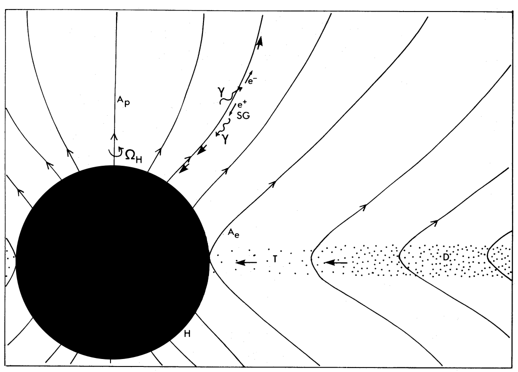
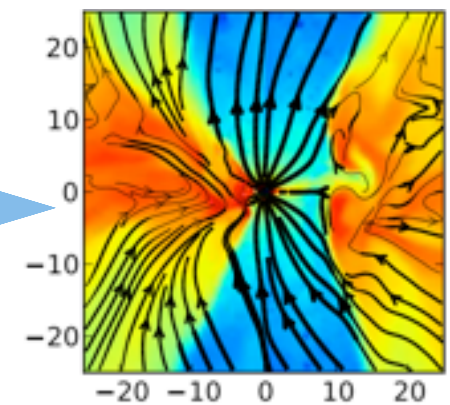


Blandford
Znajek 1977

+ 33 years



Narayan
Tchekhovskoy
McKinney 2010...

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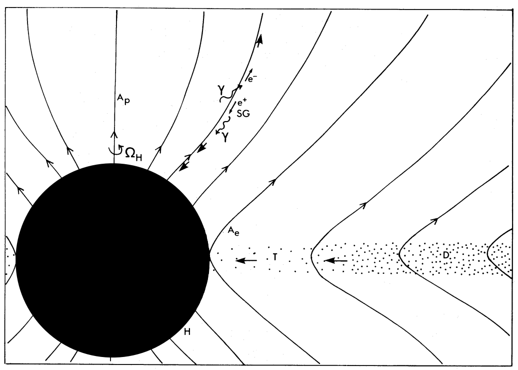

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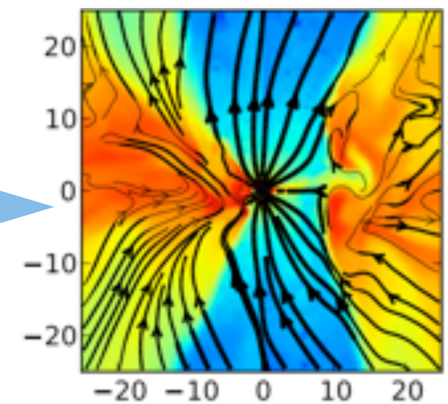

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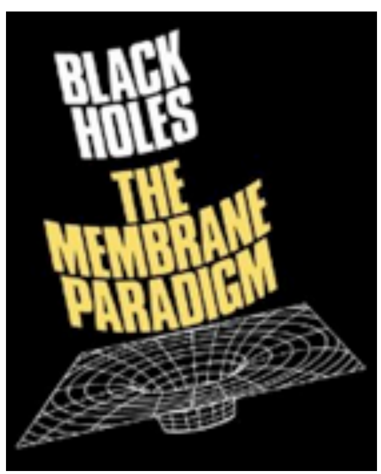
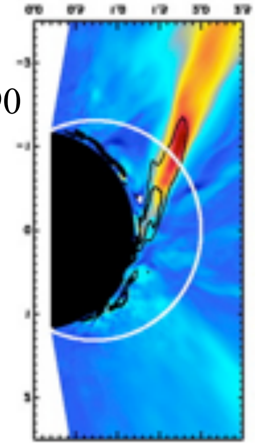
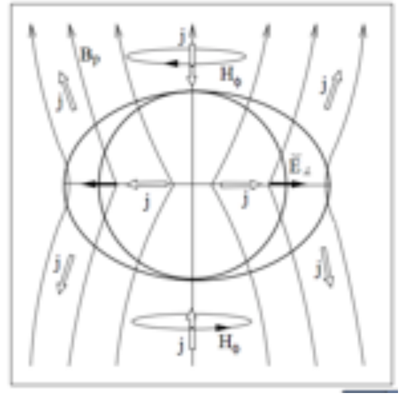


Price
Thorne 1988

Punsly
Coroniti 1990





Komissarov 2004

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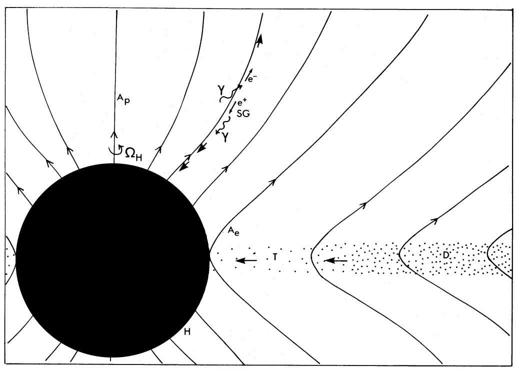

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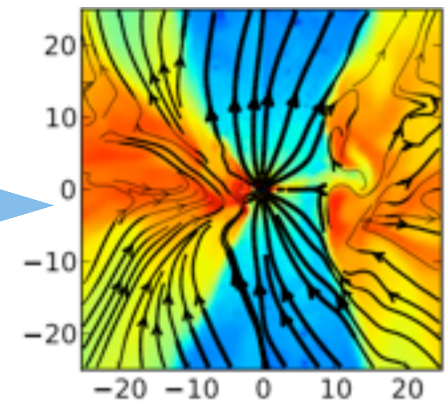

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McKinney 2010...

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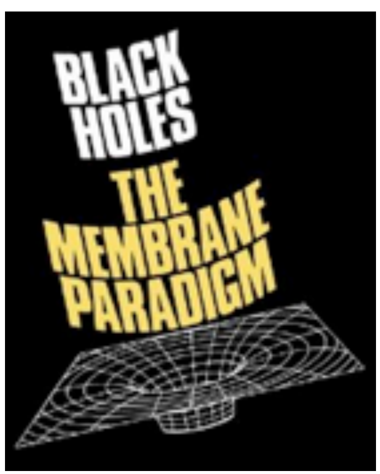

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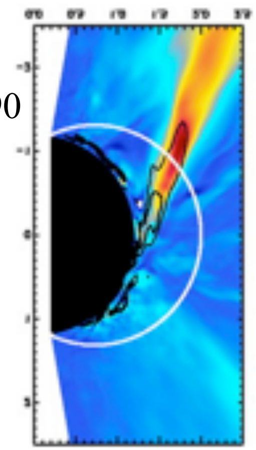

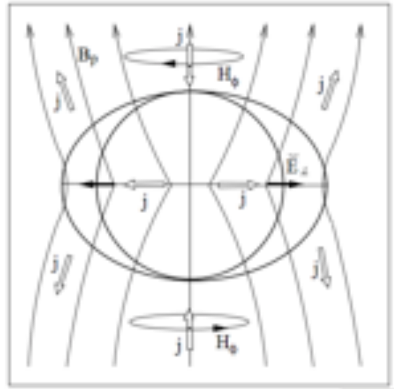

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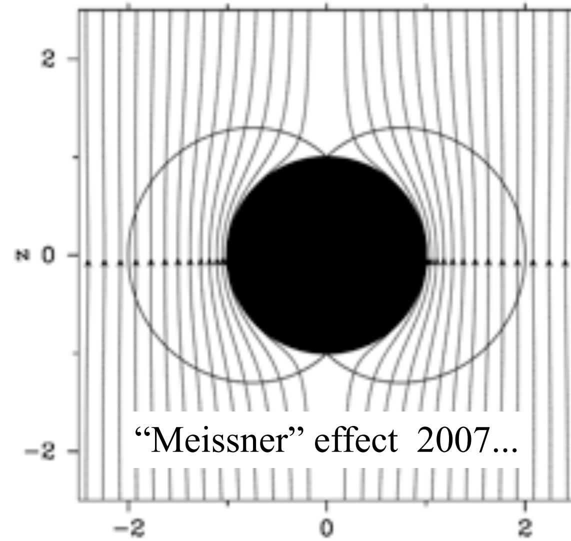
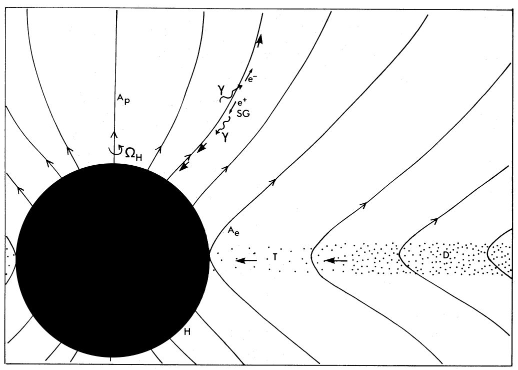


“Meissner” effect 2007...

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



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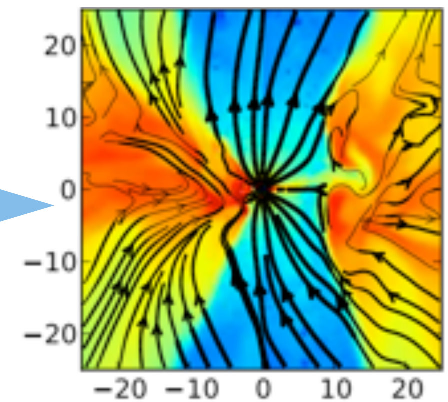

Narayan
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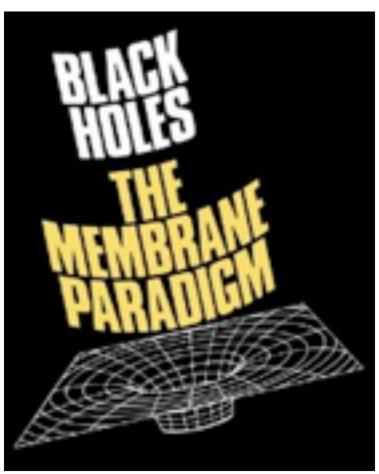

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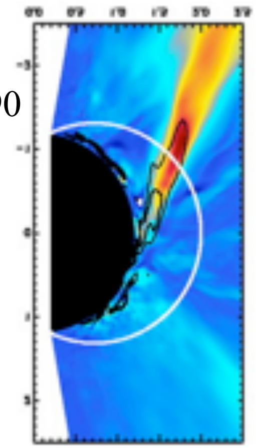
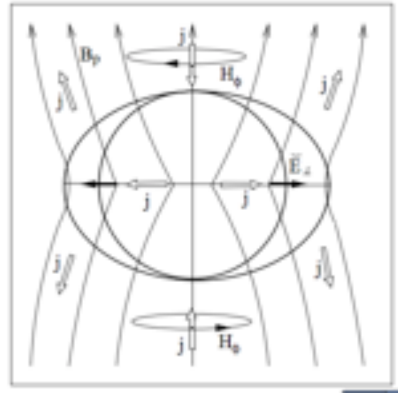
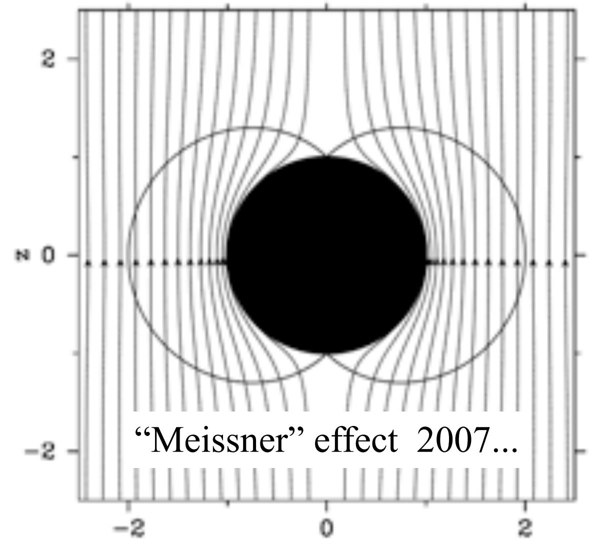




Komissarov 2004



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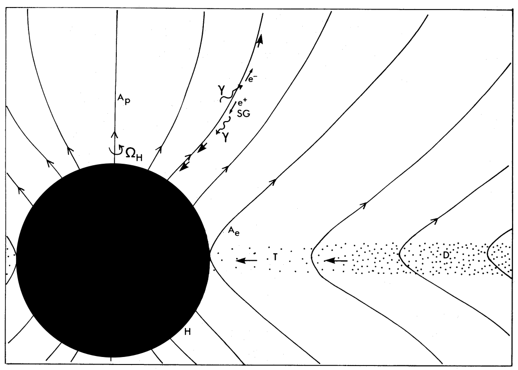

Blandford
Znajek 1977

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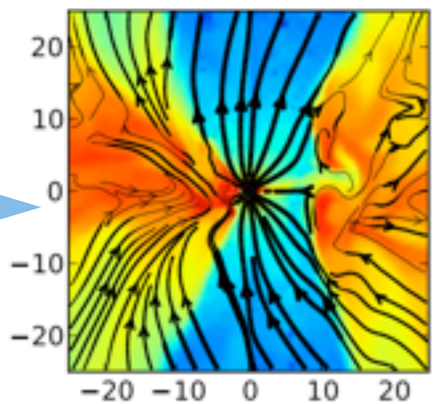
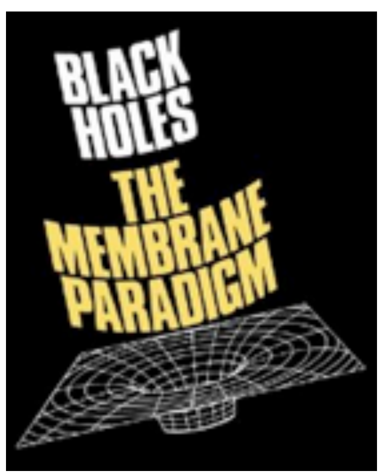


Narayan
Tchekhovskoy
McKinney 2010...



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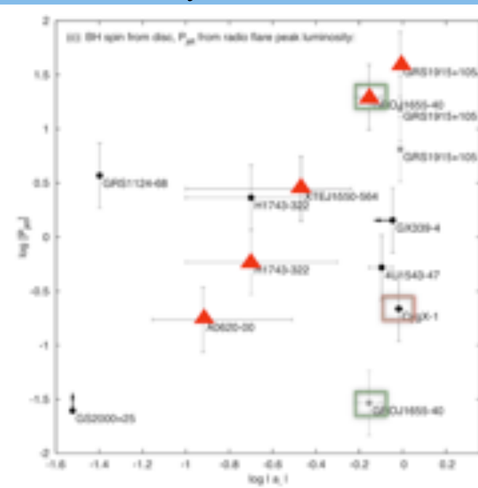
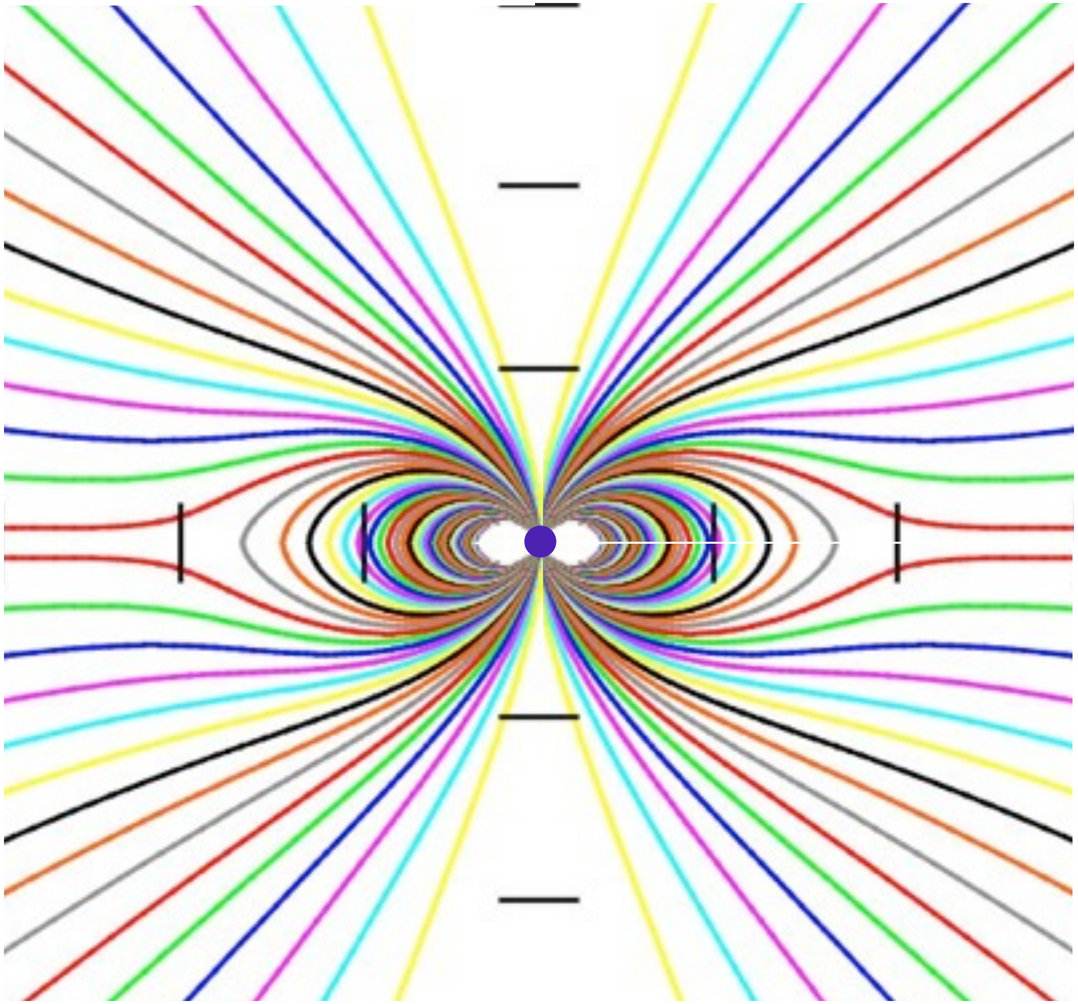


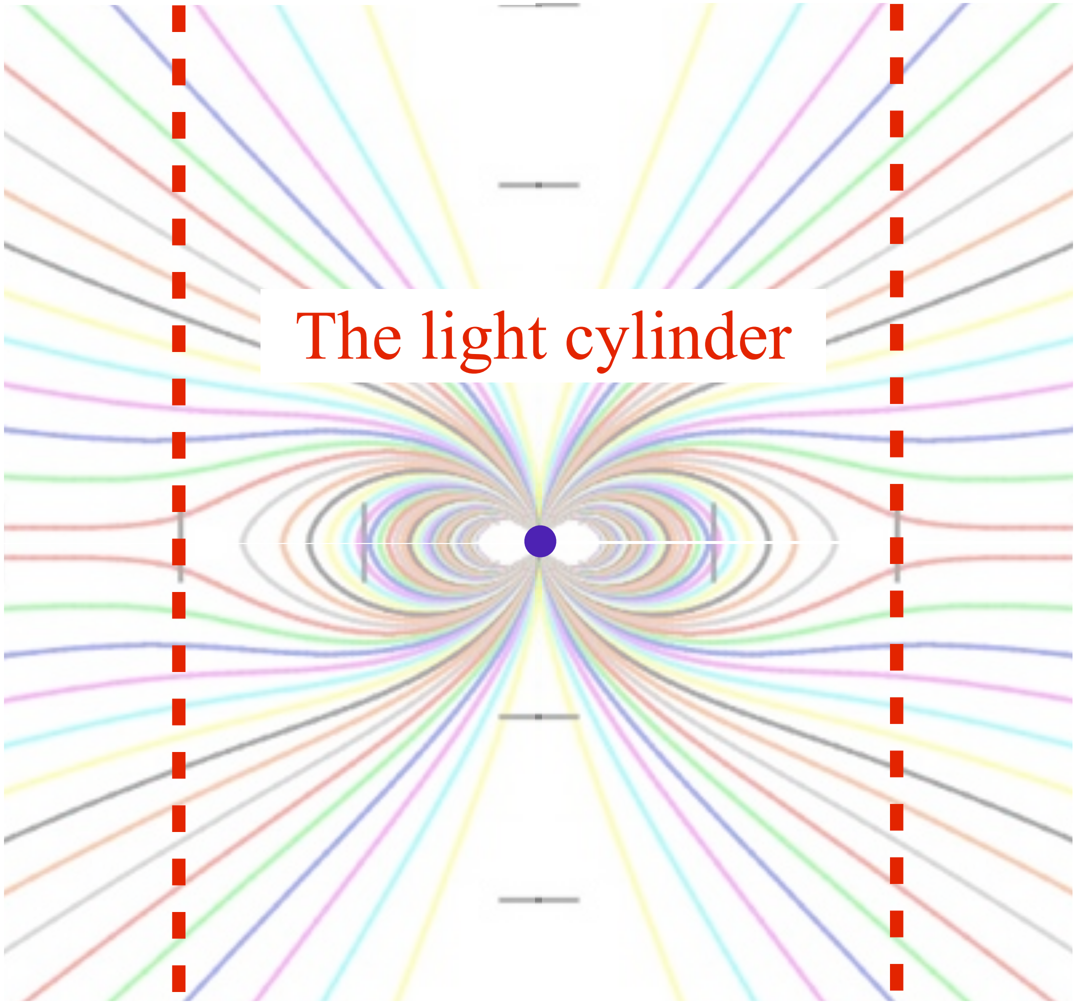
Narayan & McClintock 2012
Russell, Gallo & Fender 2013

The analogy with pulsars



Contopoulos, Kazanas & Fendt 1999

The analogy with pulsars



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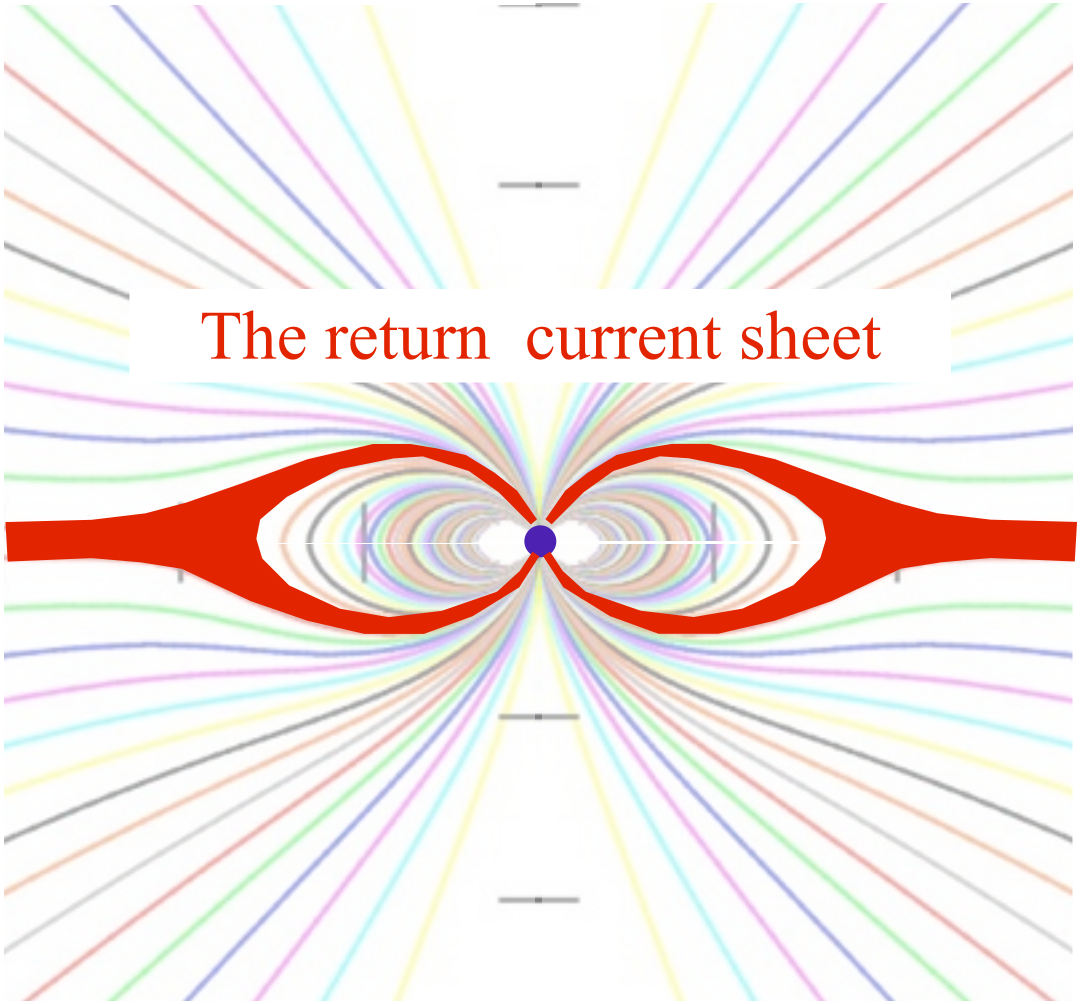

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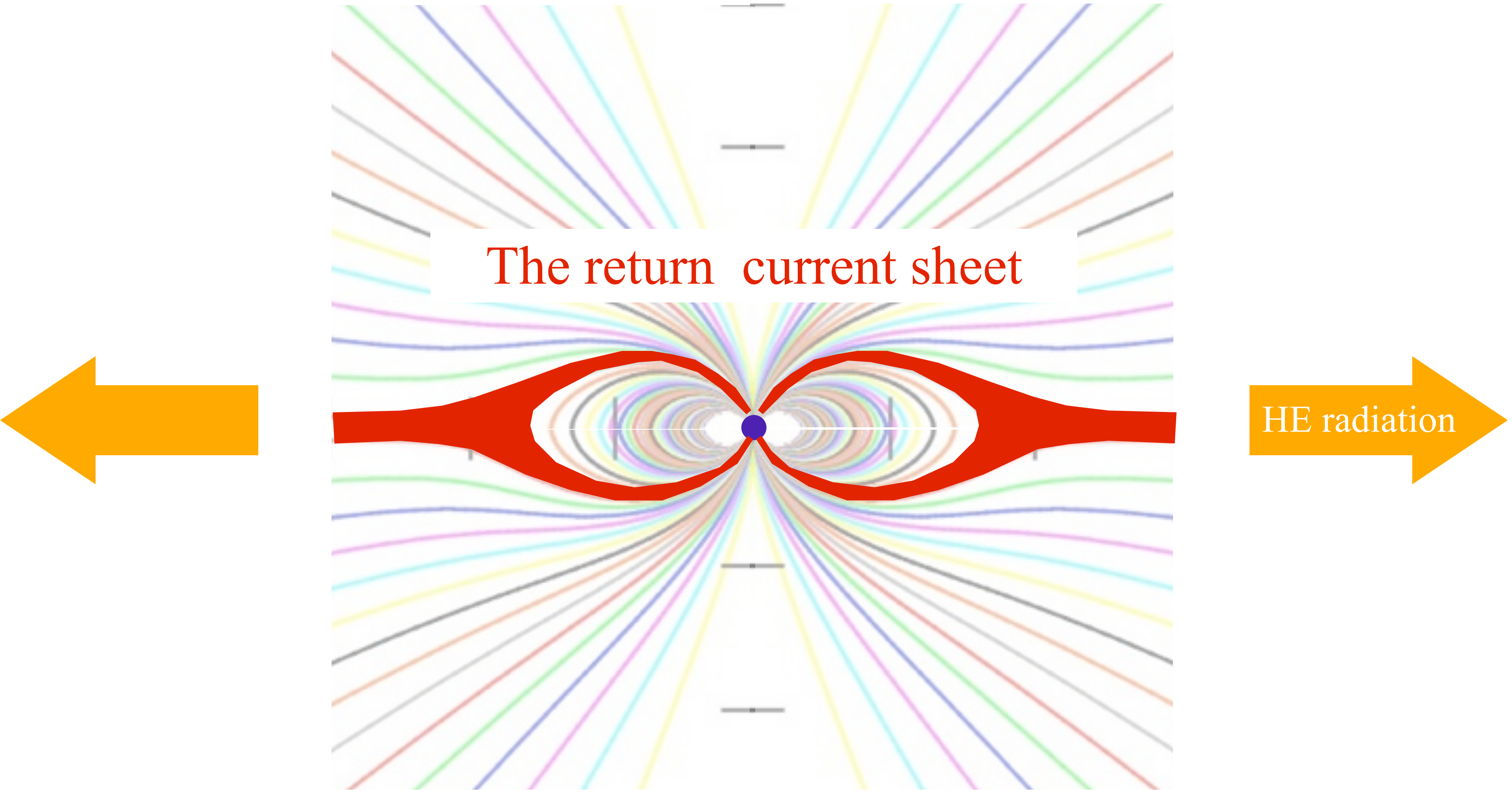
The analogy with pulsars



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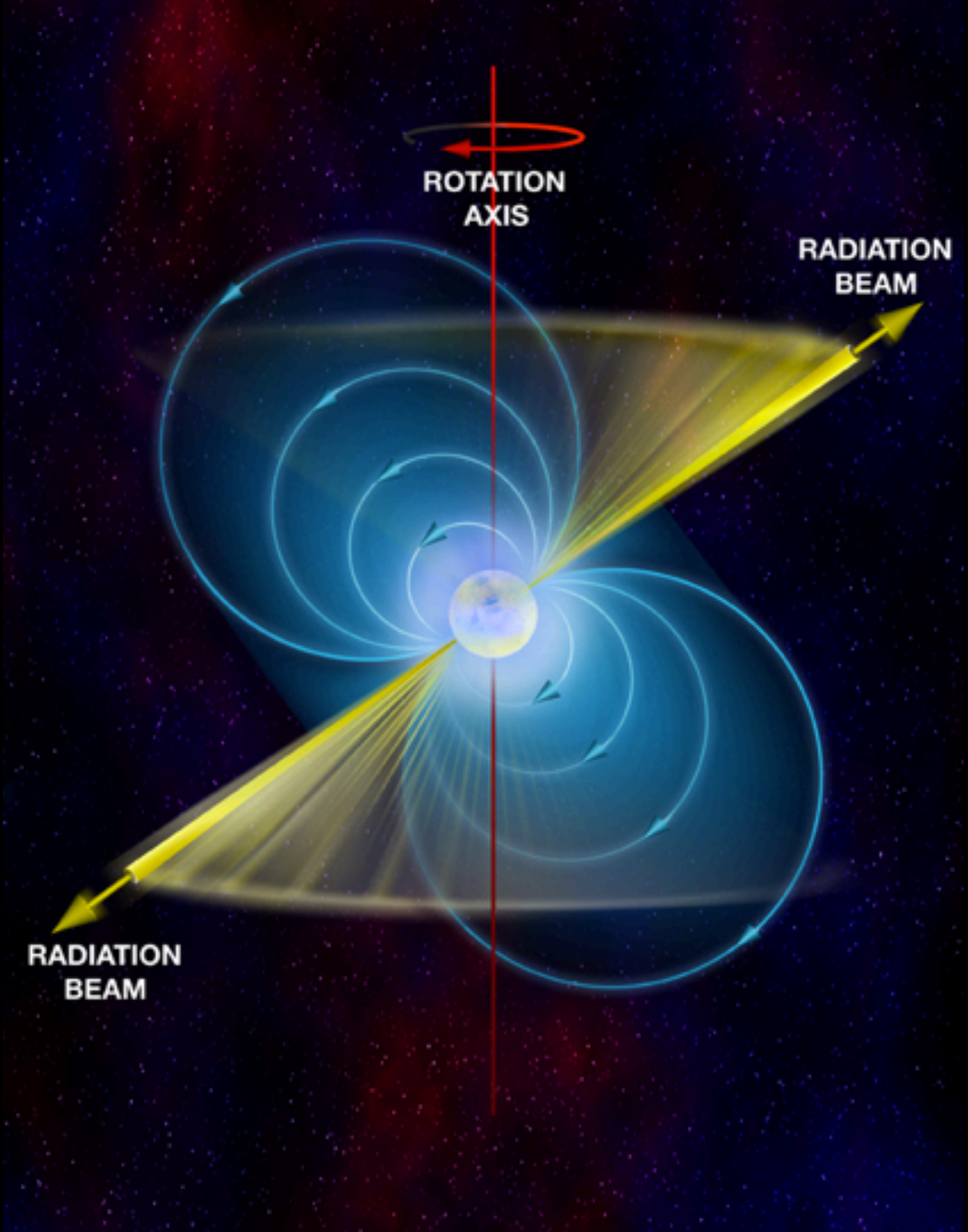
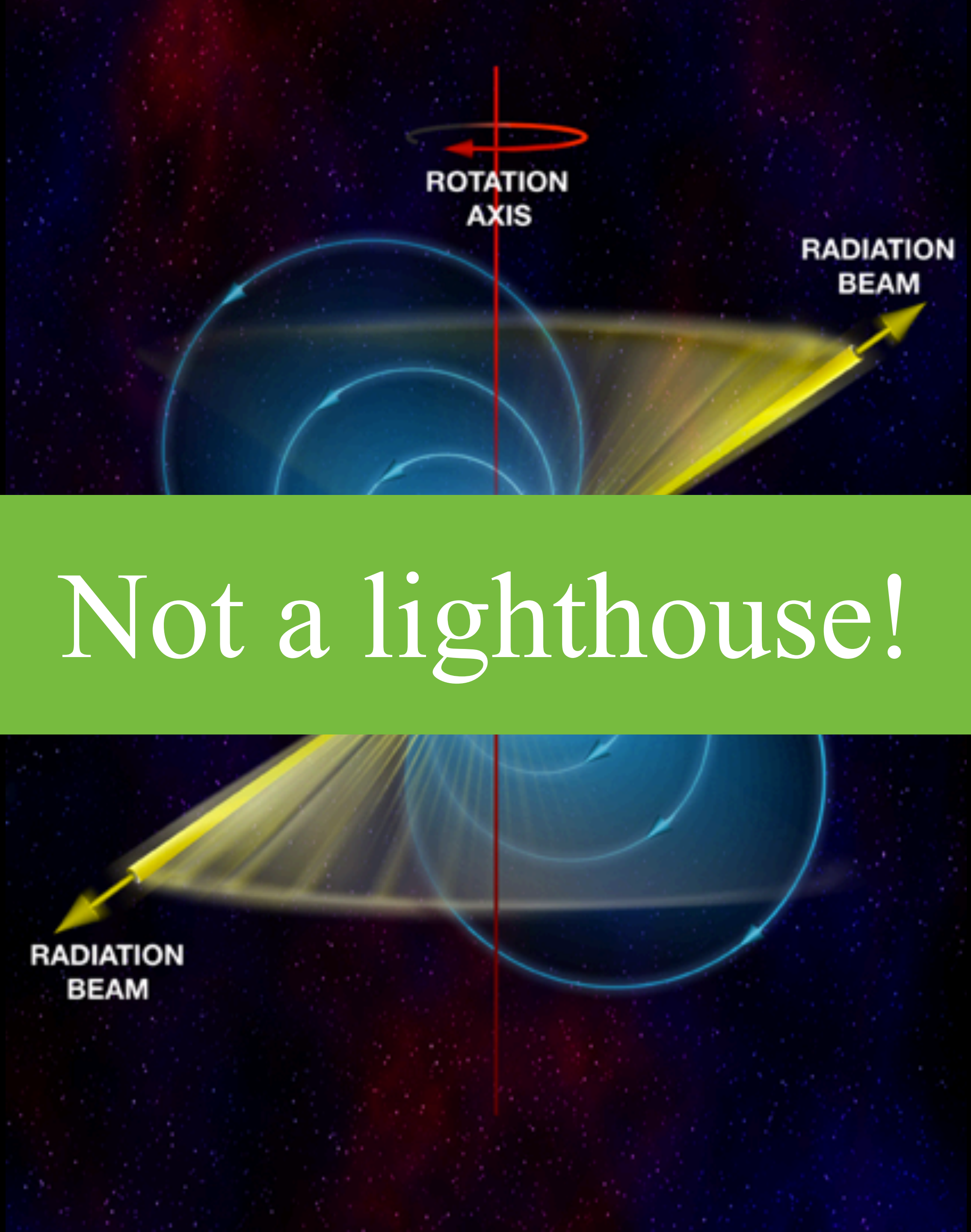

ROTATION AXIS
RADIATION BEAM
RADIATION BEAM



Not a lighthouse!

An “orthogonal” emitter

The GR pulsar equation

$$ds^2 = -\alpha^2 dt^2 + \varpi^2 (d\phi - \Omega dt)^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2$$

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

$$\mathbf{B}(r,\theta) = \frac{1}{\sqrt{A}\sin\theta} \left\{ \Psi_{,\theta} \mathbf{e}_{\hat{r}} - \sqrt{\Delta}\Psi_{,r} \mathbf{e}_{\hat{\theta}} + \frac{2I\sqrt{\Sigma}}{\alpha} \mathbf{e}_{\hat{\phi}} \right\}$$

$$\mathbf{E}(r,\theta) = \frac{\Omega - \omega}{\alpha\sqrt{\Sigma}} \left\{ \sqrt{\Delta}\Psi_{,r} \mathbf{e}_{\hat{r}} + \Psi_{,\theta} \mathbf{e}_{\hat{\theta}} + 0 \mathbf{e}_{\hat{\phi}} \right\}$$

$$\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$$

Nathanail & Contopoulos 2014

The GR pulsar equation

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

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

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

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

Contopoulos, Kazanas & Papadopoulos 2013

The 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 GR pulsar equation

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

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

- The pulsar light cylinder: r sinθ = c/ω
- The electric current *I(Ψ)* must be determined self-consistently

Contopoulos, Kazanas & Fendt 1999

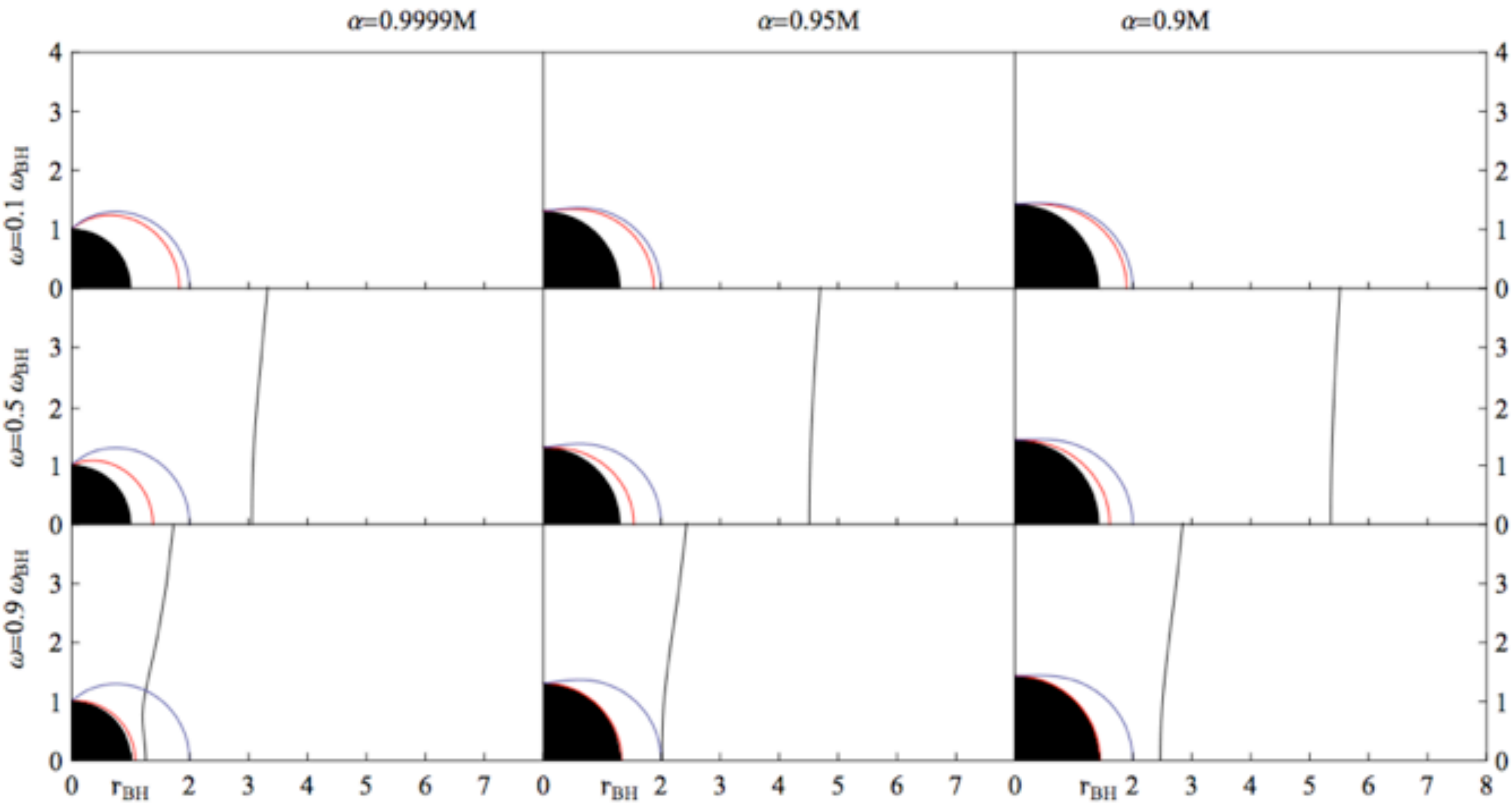
The GR pulsar equation

$$\alpha^{-1}(\omega - \Omega)\varpi = \pm 1$$

- The black hole possesses two light surfaces
- The electric current $I(\Psi)$ must be determined self-consistently together with the angular velocity of the magnetic field $\omega(\Psi)$

Contopoulos, Kazanas & Papadopoulos 2013

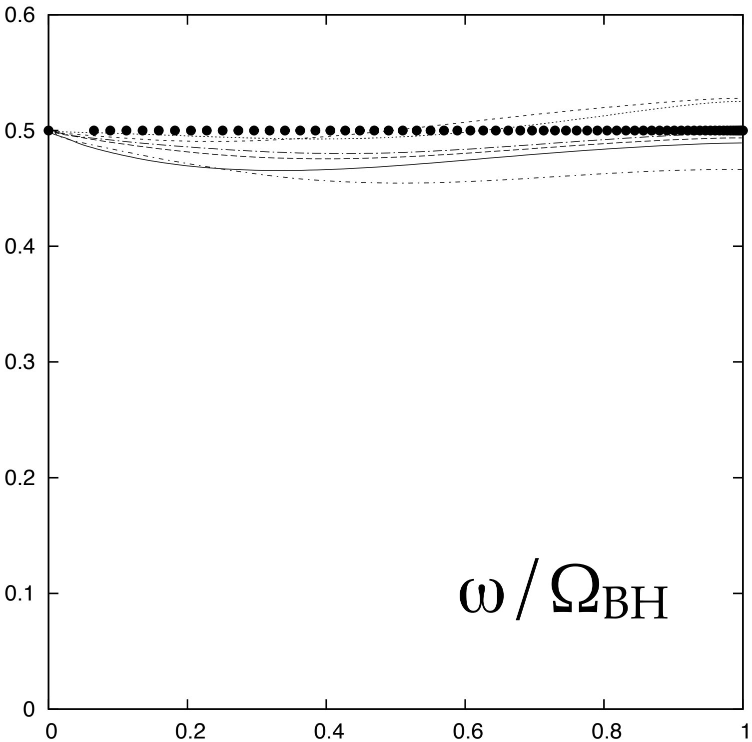
The GR pulsar equation

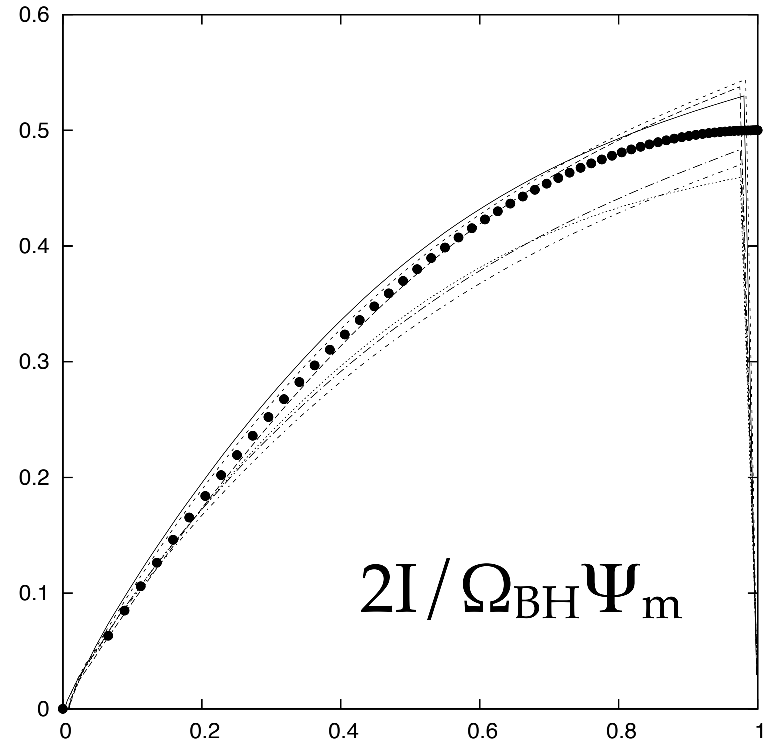


Nathanail & Contopoulos 2014

The GR pulsar equation

α=0.7-1 M, ω~0.5 Ω_{BH}





Contopoulos , Papadopoulos & Kazanas 2013

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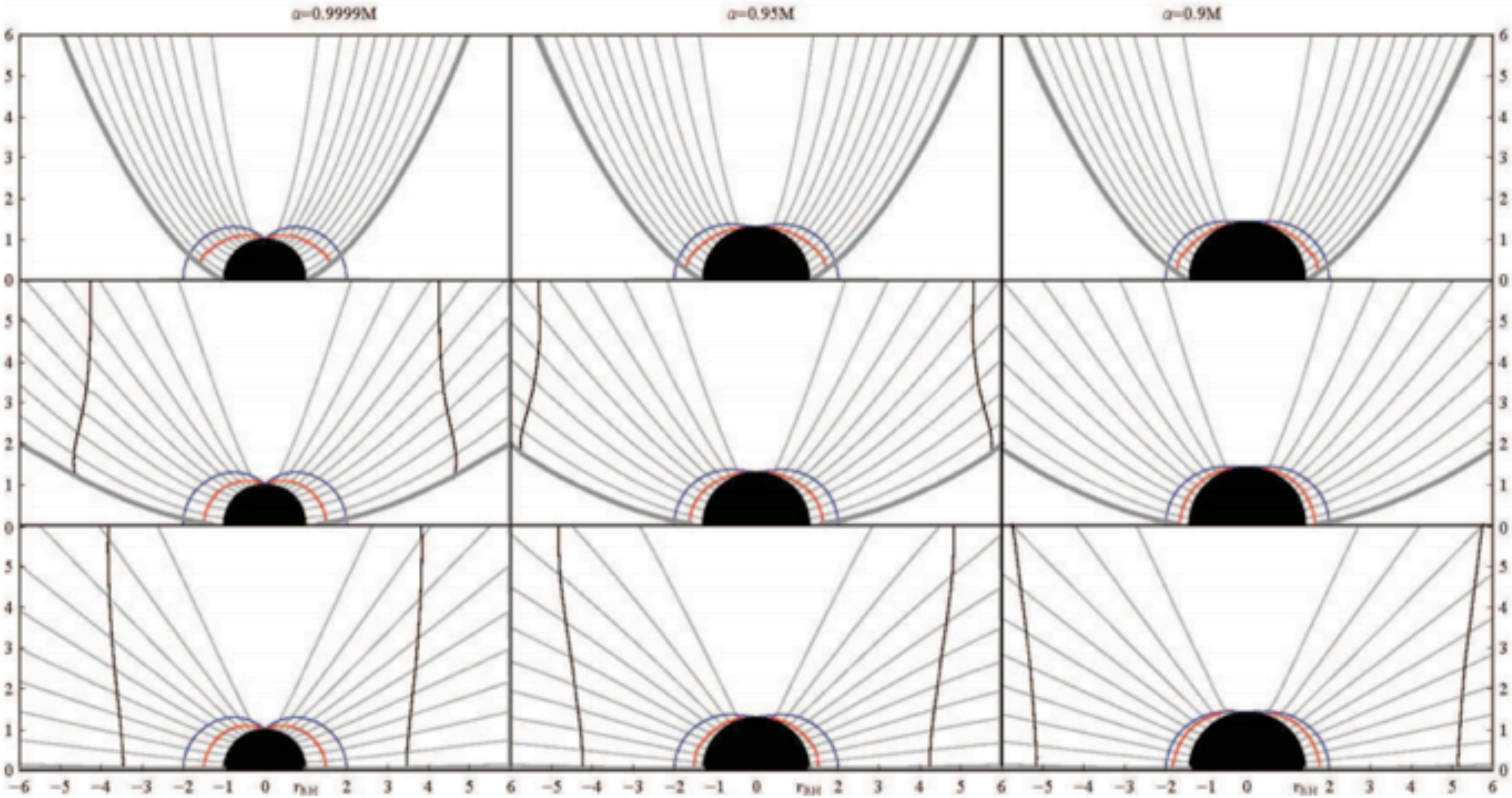

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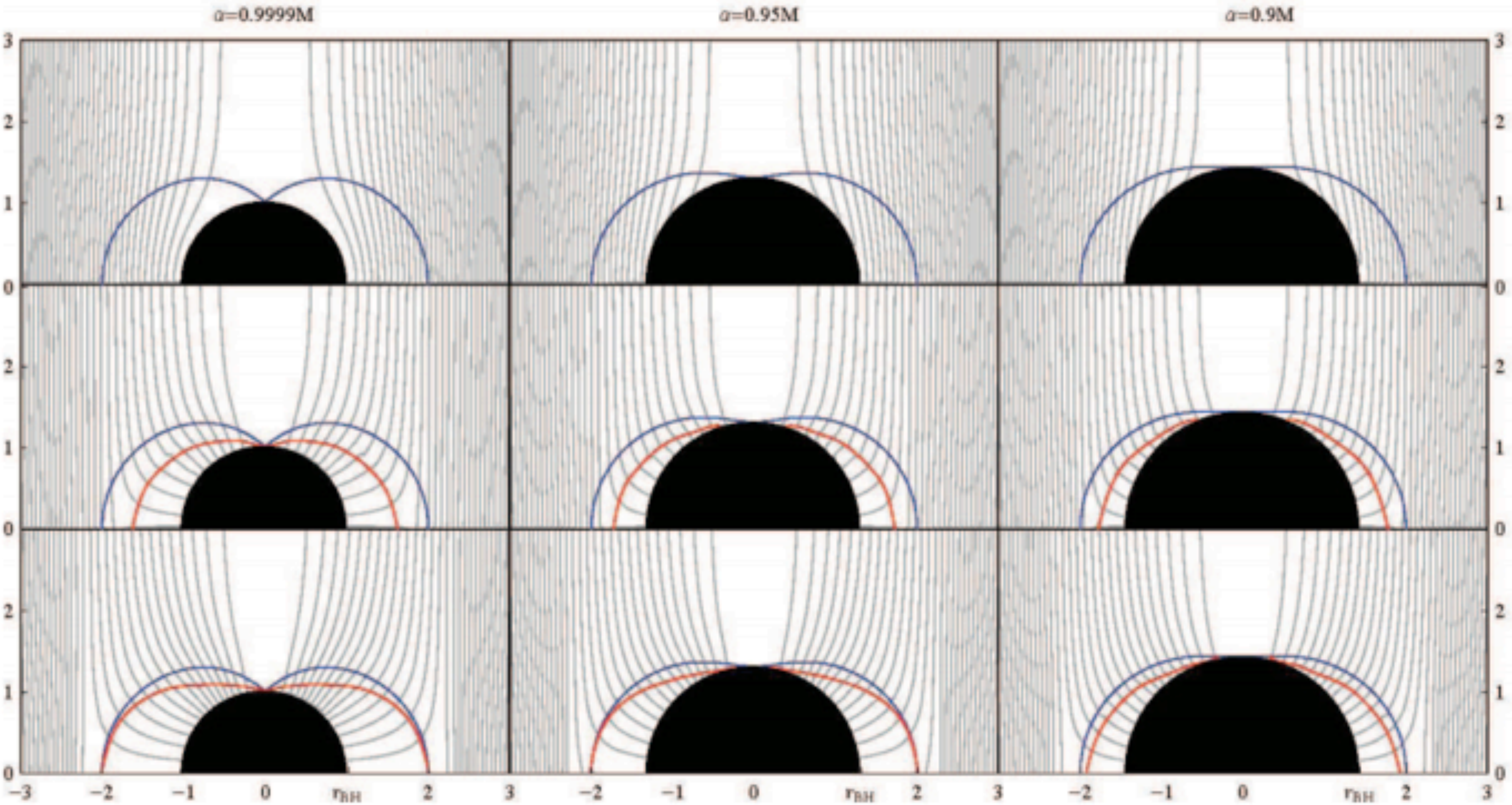

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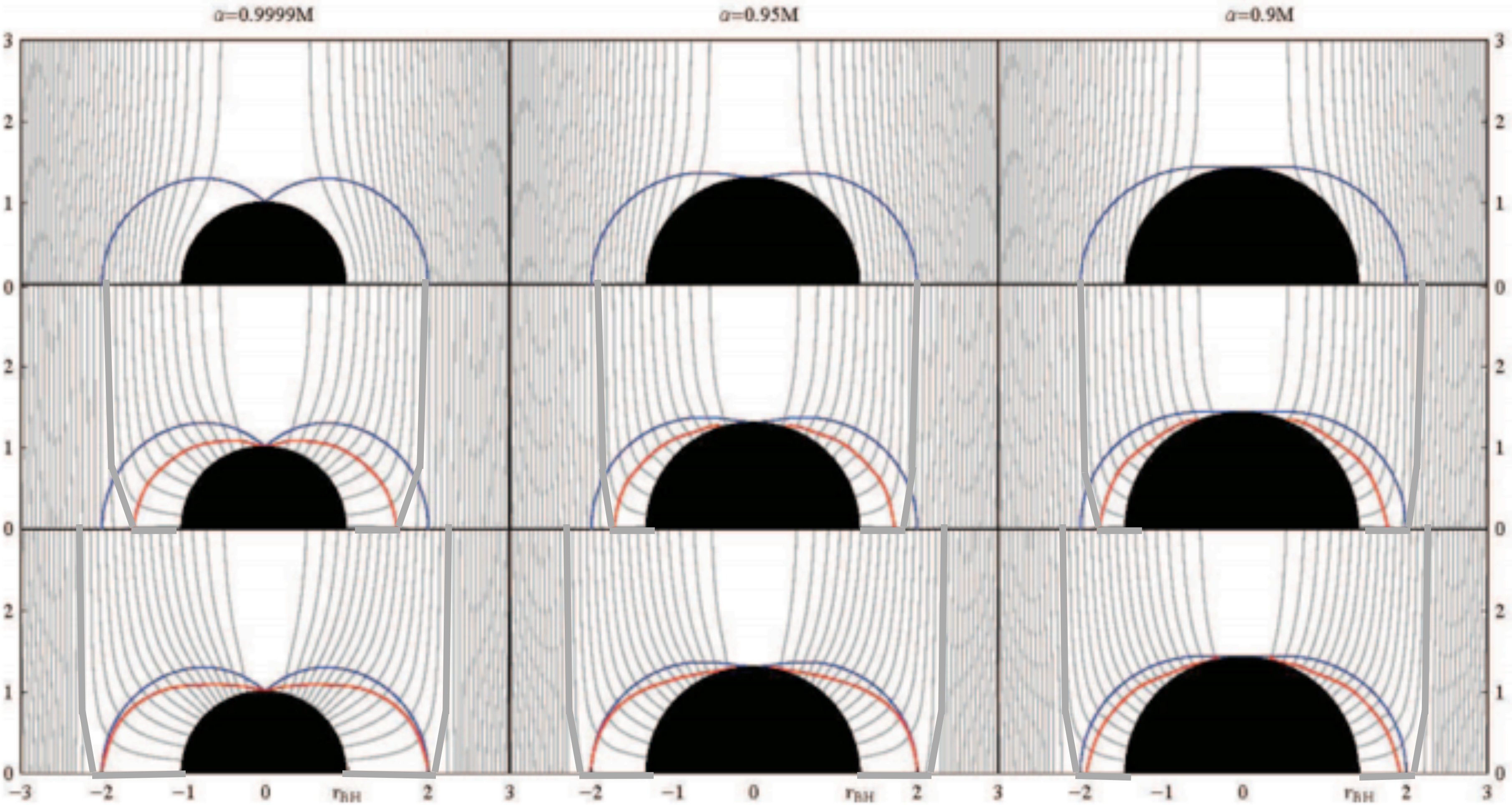

Nathanail & Contopoulos 2014

The GR pulsar equation

$$E^\theta = \pm B^\phi \text{ at `infinity'}$$

$$I(\Psi) = -0.5\omega(\Psi)\Psi_{,\theta}\sin\theta$$

Infinity

$$I(\Psi) = -0.5(\Omega_{\rm BH} - \omega(\Psi))\frac{\sqrt{A}}{\Sigma}\Psi_{,\theta}\sin\theta$$

Horizon

Nathanail & Contopoulos 2014

The GR pulsar equation

$$E^\theta = \pm B^\phi \text{ at 'infinity'}$$

$$I(\Psi) = -0.5\omega(\Psi)\Psi_{,\theta}\sin\theta$$

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

Infinity

$$I(\Psi) = -0.5(\Omega_{\rm BH} - \omega(\Psi))\frac{\sqrt{A}}{\Sigma}\Psi_{,\theta}\sin\theta$$

$$4II' = \left((\omega - \Omega_{\rm BH})^2\Psi_{,\theta\theta} + (\omega - \Omega_{\rm BH})^2\frac{\cos\theta}{\sin\theta}\Psi_{,\theta} - \frac{\Sigma_{,\theta}}{\Sigma}\Psi_{,\theta} + \omega'(\omega - \Omega_{\rm BH})\Psi_{,\theta}^2\right)\frac{A}{\Sigma^2}\sin^2\theta$$

Horizon

Nathanail & Contopoulos 2014

Black hole spindown

Reducible rotational BH energy

$$E \sim M r_{\rm BH}^2 \Omega^2 \sim 10^{53} M/M_\odot \ {\rm erg}$$

Black hole spindown

Reducible rotational BH energy

$$E \sim M r_{\rm BH}^2 \Omega^2 \sim 10^{53} M/M_{\odot} \text{ erg}$$

+ magnetic field

Black hole spindown

$$\dot{E}_{\mathrm{BZ}} \sim -\Psi_m^2 \Omega^2 \sim -\Omega^2$$

Black hole spindown

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$$\dot{E} \sim M r_{\mathrm{BH}}^2 \Omega \dot{\Omega}$$

Black hole spindown

$$\dot{E}_{\mathrm{BZ}} \sim -\Psi_m^2 \Omega^2 \sim -\Omega^2$$

$$\dot{E} \sim M r_{\mathrm{BH}}^2 \Omega \dot{\Omega}$$

$$\sim e^{-t/\tau_{\mathrm{BZ}}}$$

Black hole spindown

$$\dot{E}_{\rm BZ} \sim -\Psi_m^2 \Omega^2 \sim -\Omega^2$$

$$\dot{E} \sim M r_{\rm BH}^2 \Omega \dot{\Omega}$$

$$\sim e^{-t/\tau_{\rm BZ}}$$

$$B_o \sim 10^7 \ {\rm G} \qquad \tau_{\rm BZ} \sim 1000 \ {\rm Gyr}$$

BZ simulations in stationary spacetime (fixed BH spin)

How about Gamma-ray bursts?

How about Gamma-ray bursts?

Black hole spindown

$$\dot{E}_{\rm BZ} \sim -\Psi_m^2 \Omega^2 \sim -\Omega^2$$

$$\dot{E} \sim M r_{\rm BH}^2 \Omega \dot{\Omega}$$

$$\sim e^{-t/\tau_{\rm BZ}}$$

$$B_o \sim 10^{15} \text{ G} \qquad \tau_{\rm BZ} \sim 10^3 - 10^4 \text{ sec}$$

Collapsar simulations in stationary spacetime (fixed BH spin)

Black hole spindown

$$\dot{E}_{\rm BZ} \sim -\Psi_m^2 \Omega^2 \sim -\Omega^2$$

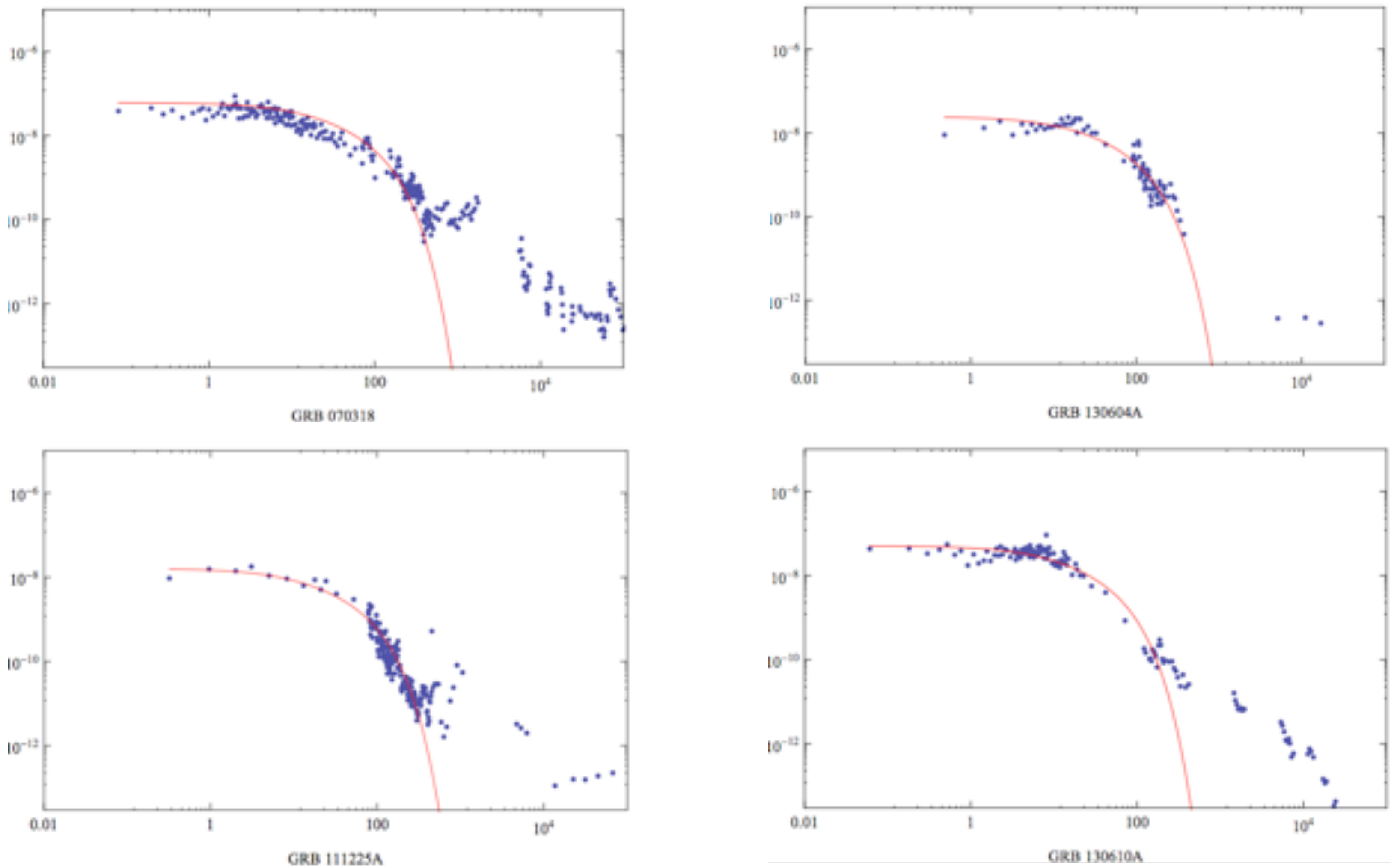
$$\dot{E} \sim M r_{\rm BH}^2 \Omega \dot{\Omega}$$

$$\sim e^{-t/\tau_{\rm BZ}}$$

$$B_o \sim 10^{16}\ {\rm G} \qquad \tau_{\rm BZ} \sim 10 - 100\ {\rm sec}$$

The "orthogonal" GRB: Contopoulos, Nathanail & Pugliese 2014

Probe of BH magnetosphere



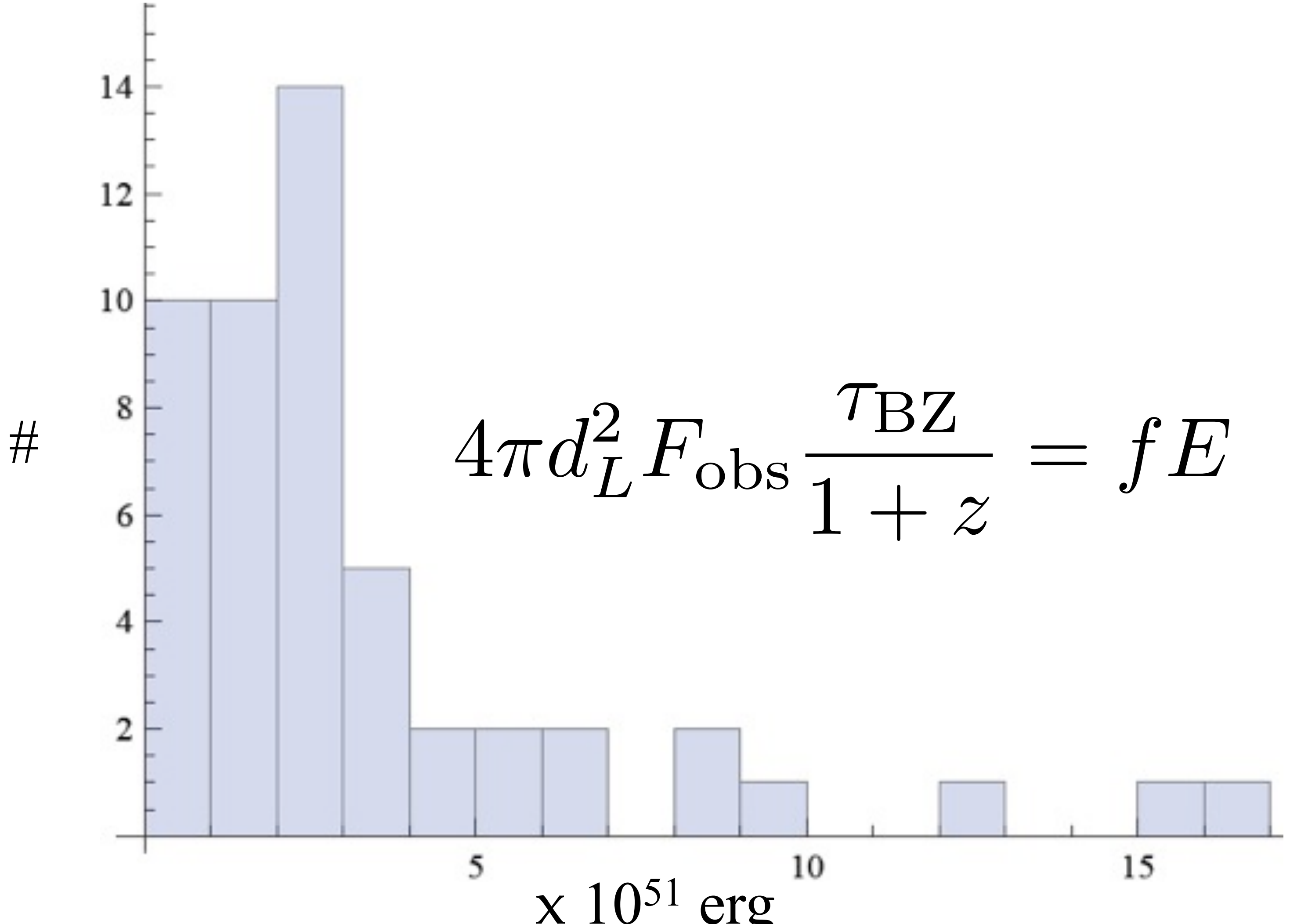
Contopoulos, Nathanail & Pugliese 2014

Probe of BH magnetosphere

$$4\pi d_L^2 F_{\rm obs} \frac{\tau_{\rm BZ}}{1+z} = fE$$

Nathanail, Contopoulos & Basilakos 2014 (in prep.)

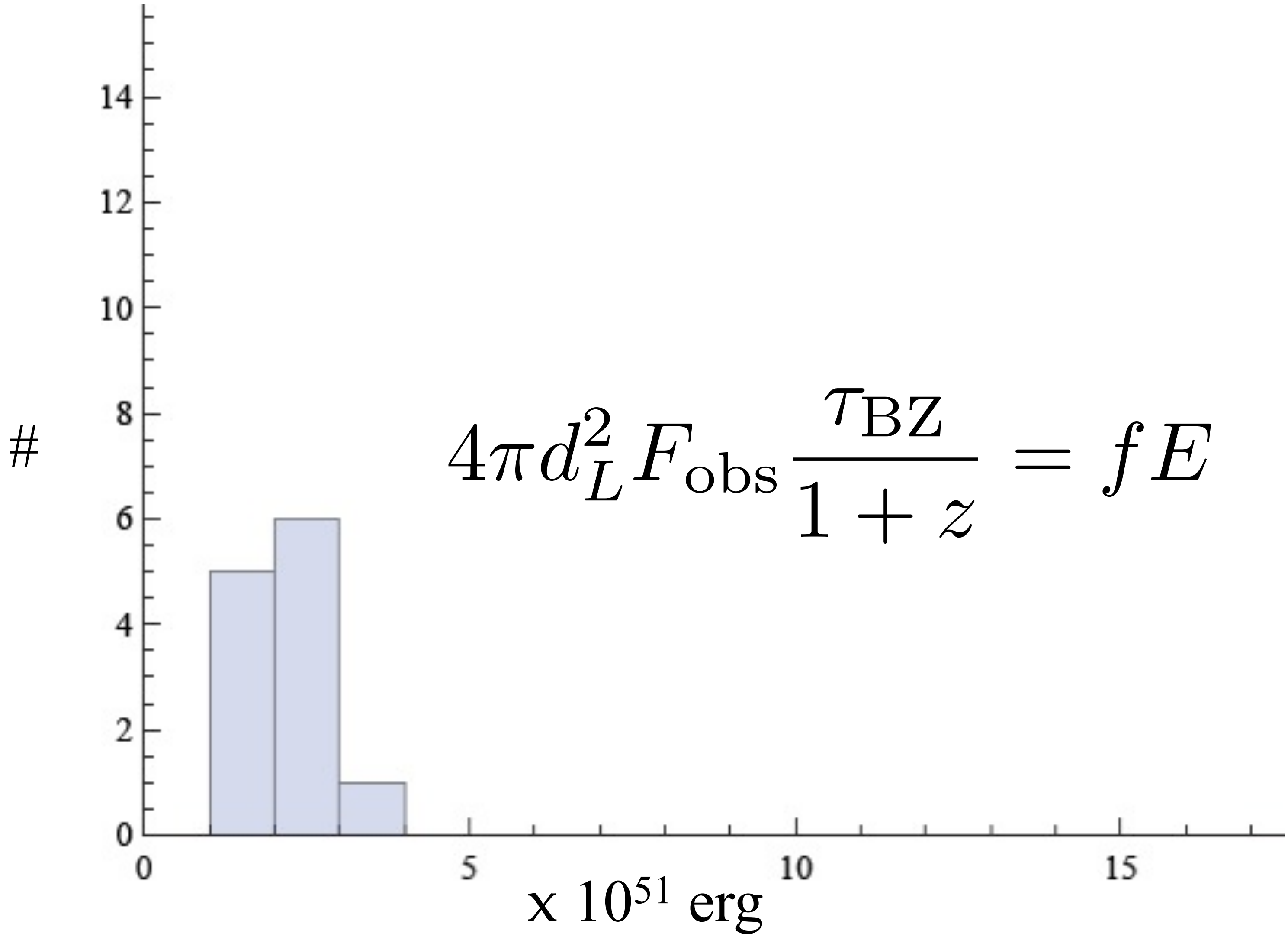
Probe of BH magnetosphere



$$4\pi d_L^2 F_{\rm obs}\frac{\tau_{\rm BZ}}{1+z} = fE$$

Nathanail, Contopoulos & Basilakos 2014 (in prep.)

Are GRBs standard candles?



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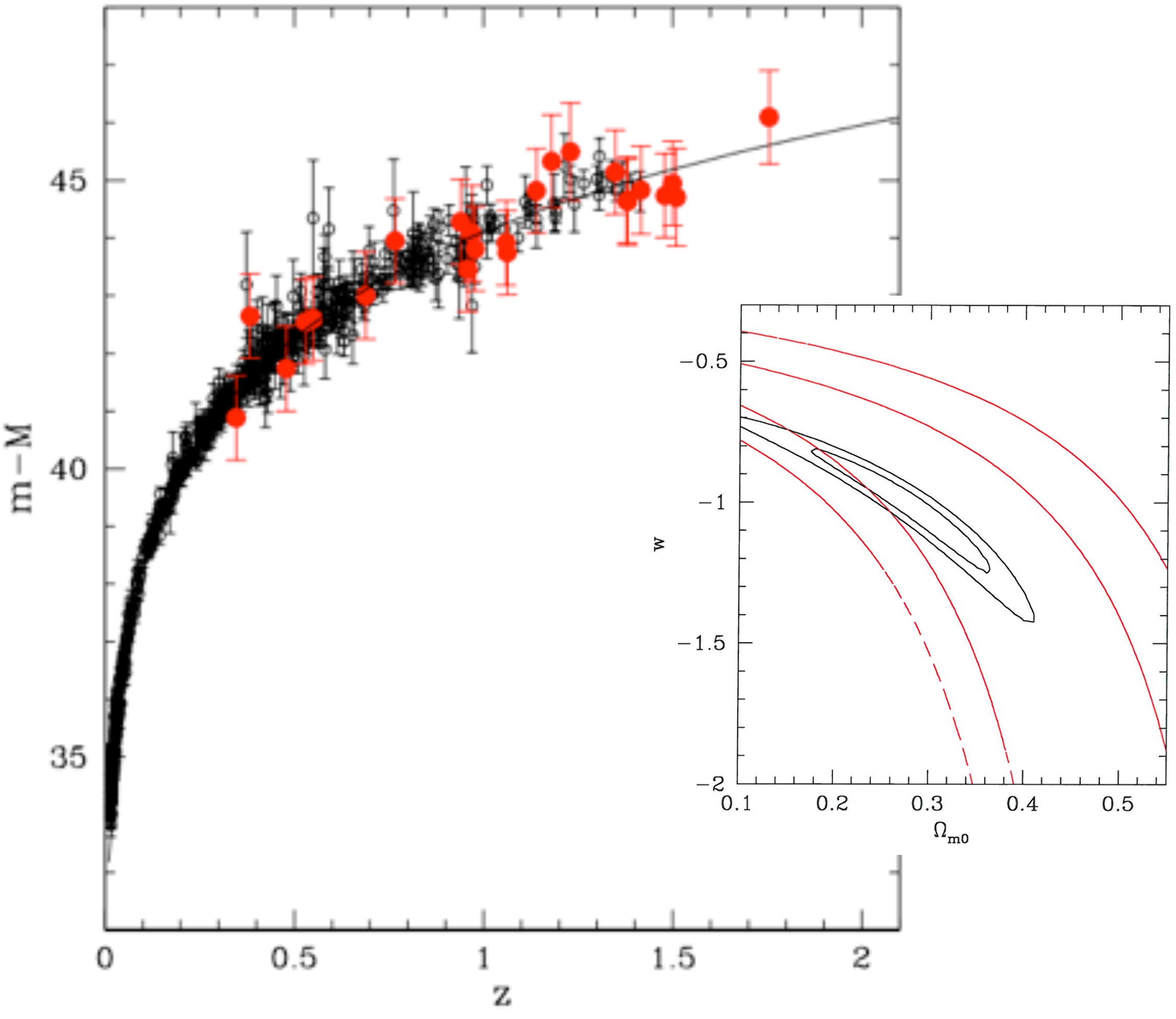

Nathanail, Contopoulos & Basilakos 2014 (in prep.)

Summary

- The Cosmic Battery: astrophysical magnetic fields generated at the inner edge of the accretion disk. The field is held by the inner disk. The return field diffuses outward through the outer disk.

Summary

- Black hole and pulsar magnetospheres:
    - The “membrane” does not teach us much
    - Inner Light Surface
    - Electric current sheet
    - Orthogonal emitters

Summary

- GRBs as standard candles in Cosmology?

Thank you

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