Black hole jets

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MANAGING AUTHORITY
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- Do black holes have charge? **NO**

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- Do black holes have magnetic fields? **NO**

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- Do black holes have magnetic fields? **NO**
- Do black holes have jets? **YES**

The analogy with pulsars

- Do black holes have charge?
- Do black holes have magnetic fields?
- Do black holes have jets?

The analogy with pulsars

- Do black holes have charge? **YES**
- Do black holes have magnetic fields? **YES**
- Do black holes have jets? **NO**

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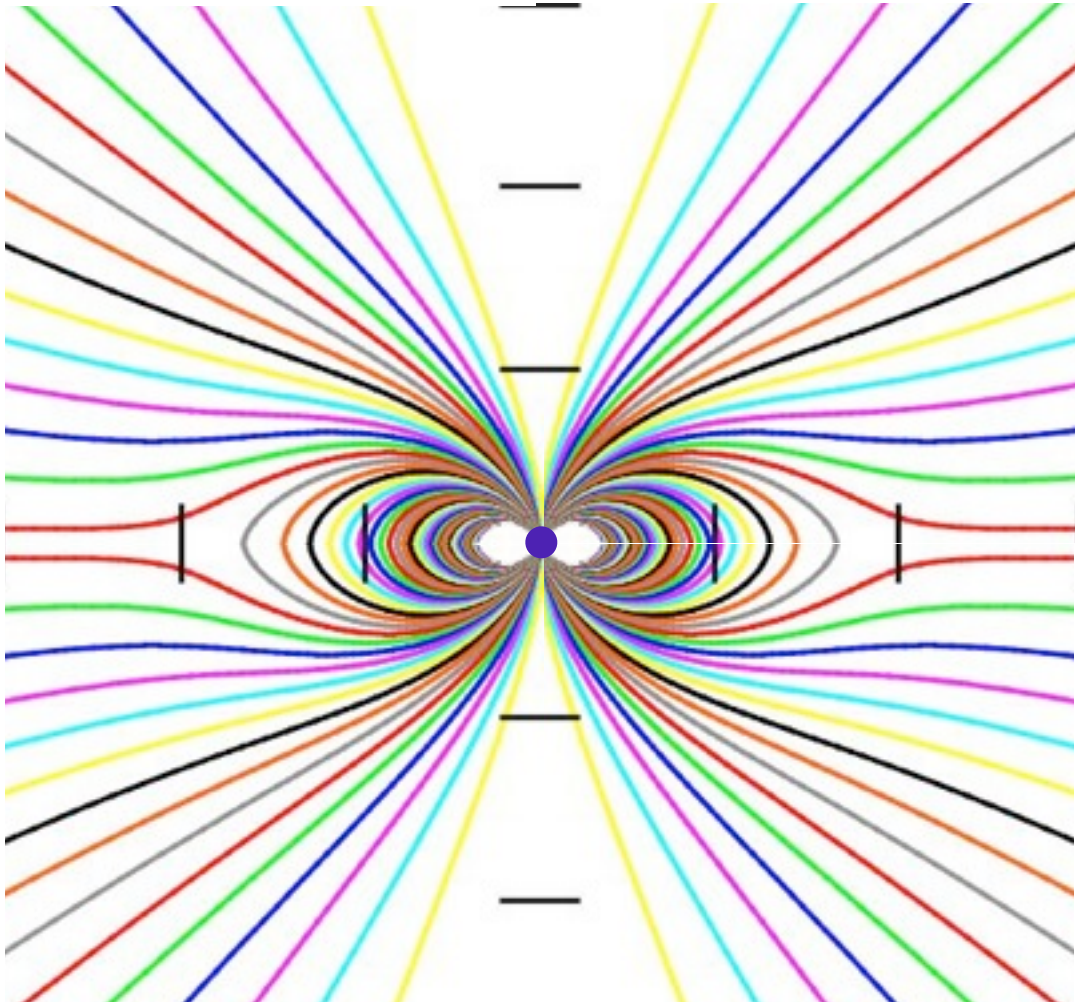
The analogy with pulsars

- Many astrophysicists feel uncomfortable in curved spacetime...
- Macdonald & Thorne reformulated electrodynamics with the hope that it may catalyze pulsar-experienced astrophysicists to begin research on black-hole electrodynamics and to bring to bear on this topic their lore about the 'axisymmetric pulsar problem'...

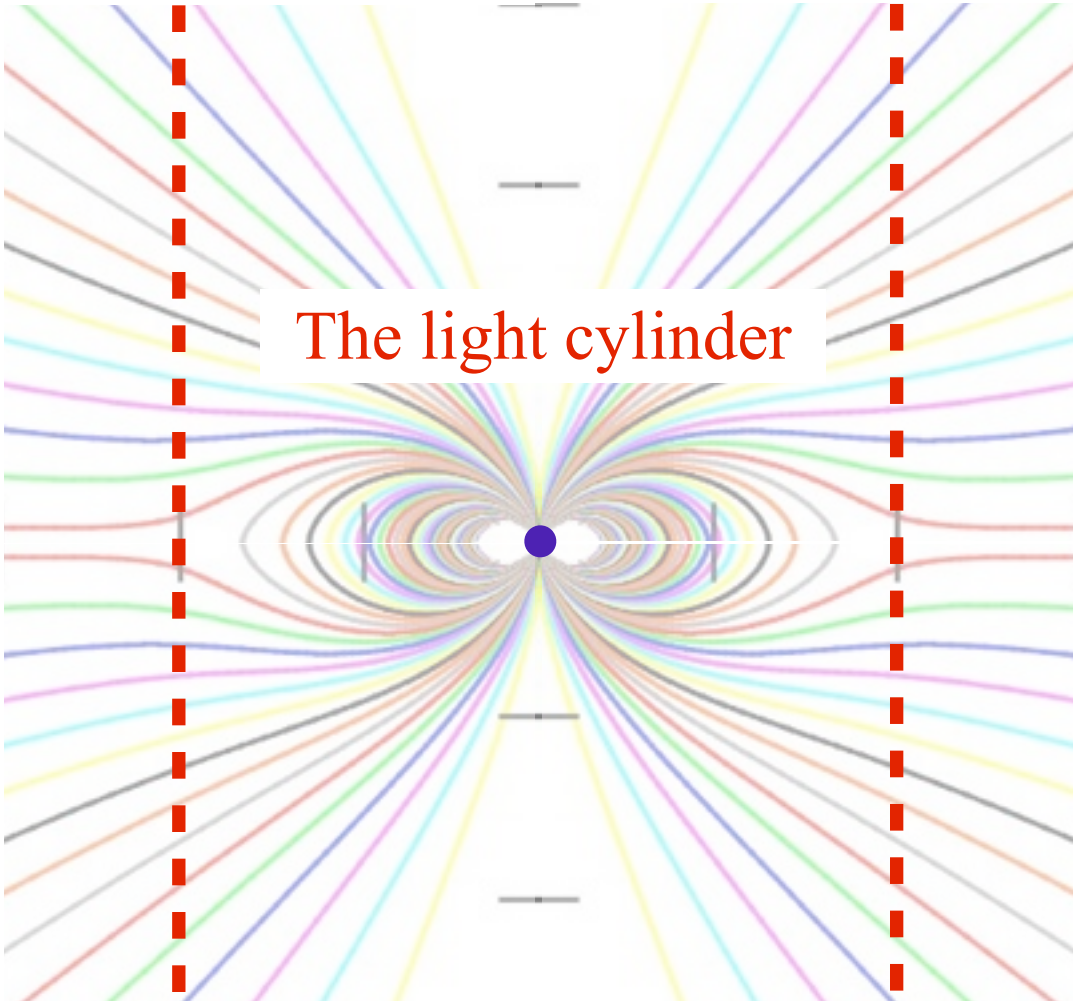
Macdonald & Thorne 1982

The analogy with pulsars



Contopoulos, Kazanas & Fendt 1999

The analogy with pulsars



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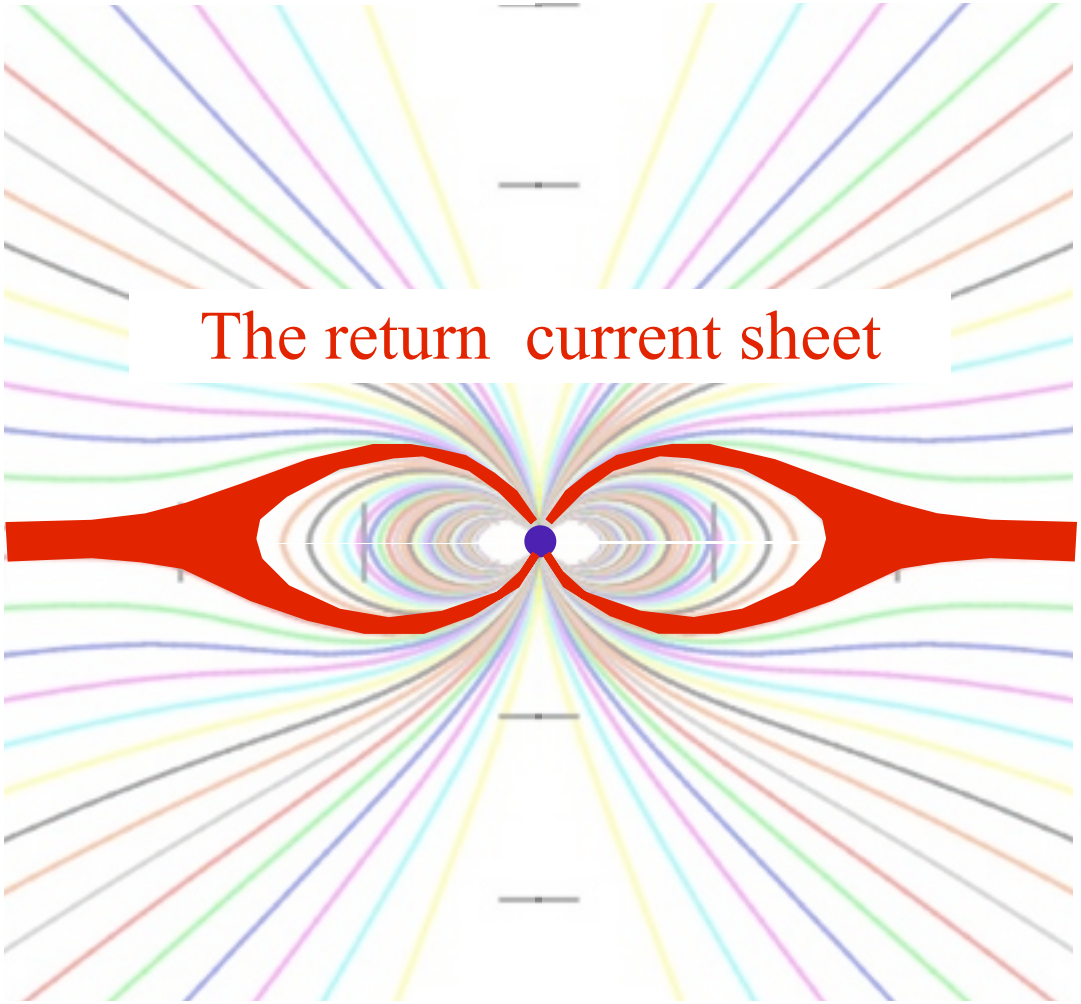
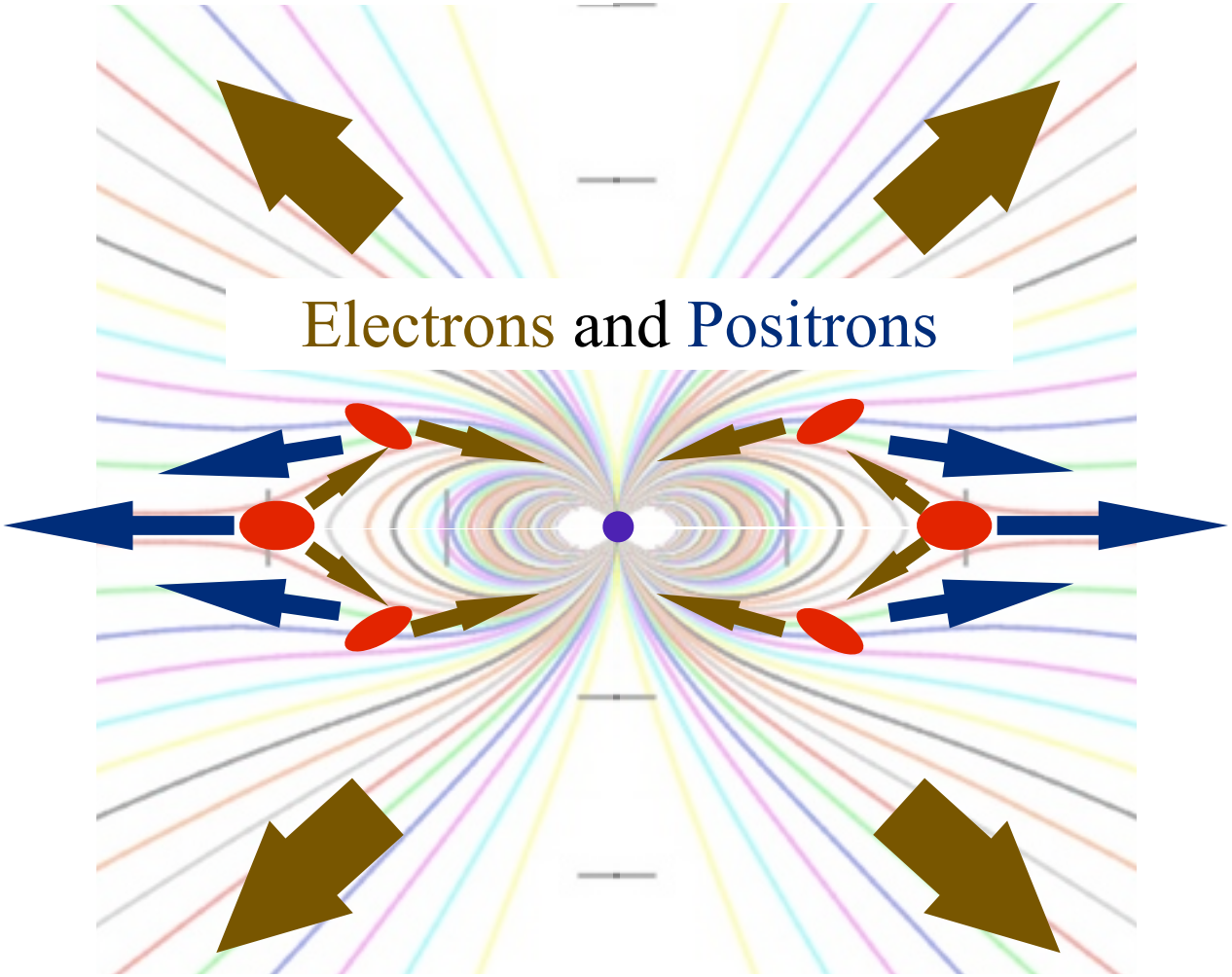
The analogy with pulsars



Contopoulos, Kazanas & Fendt 1999

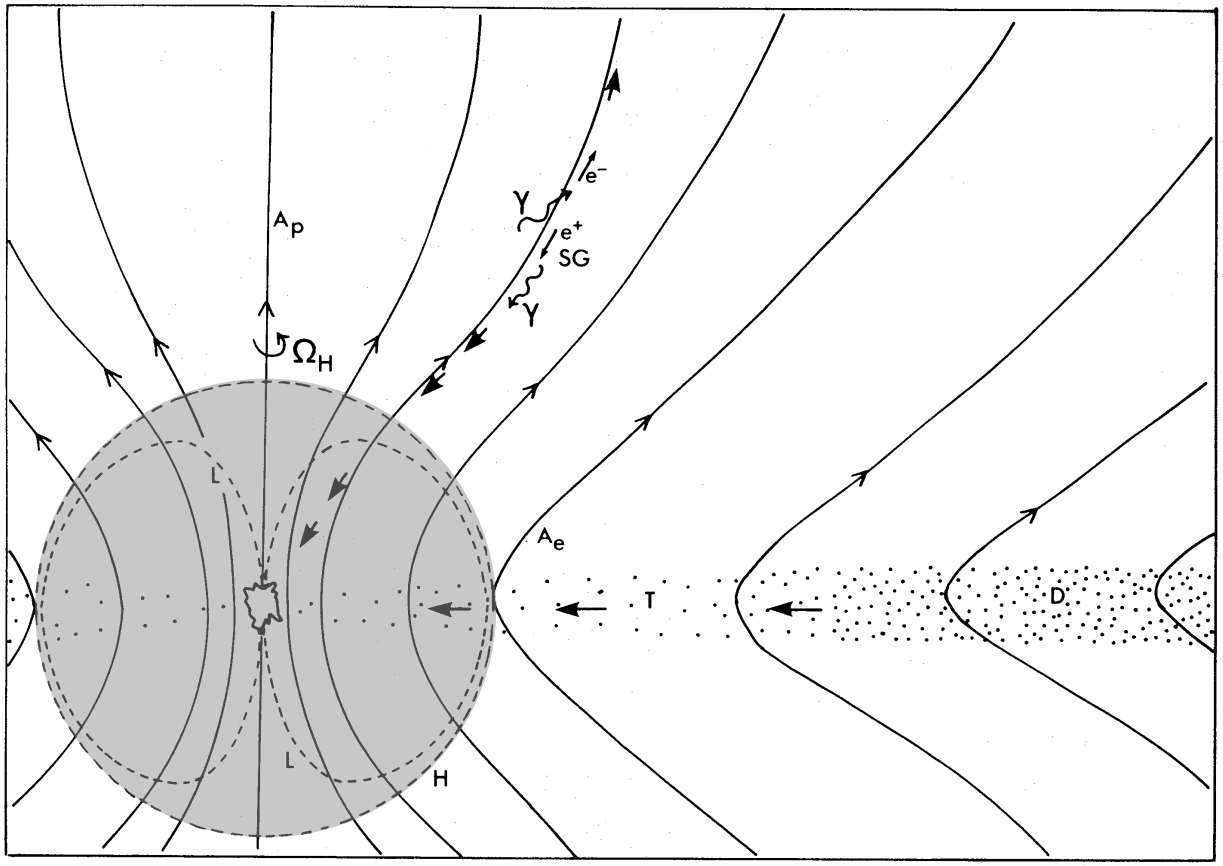
The analogy with pulsars



Contopoulos, Kazanas, Harding, Kalapotharakos

Blandford-Znajek

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

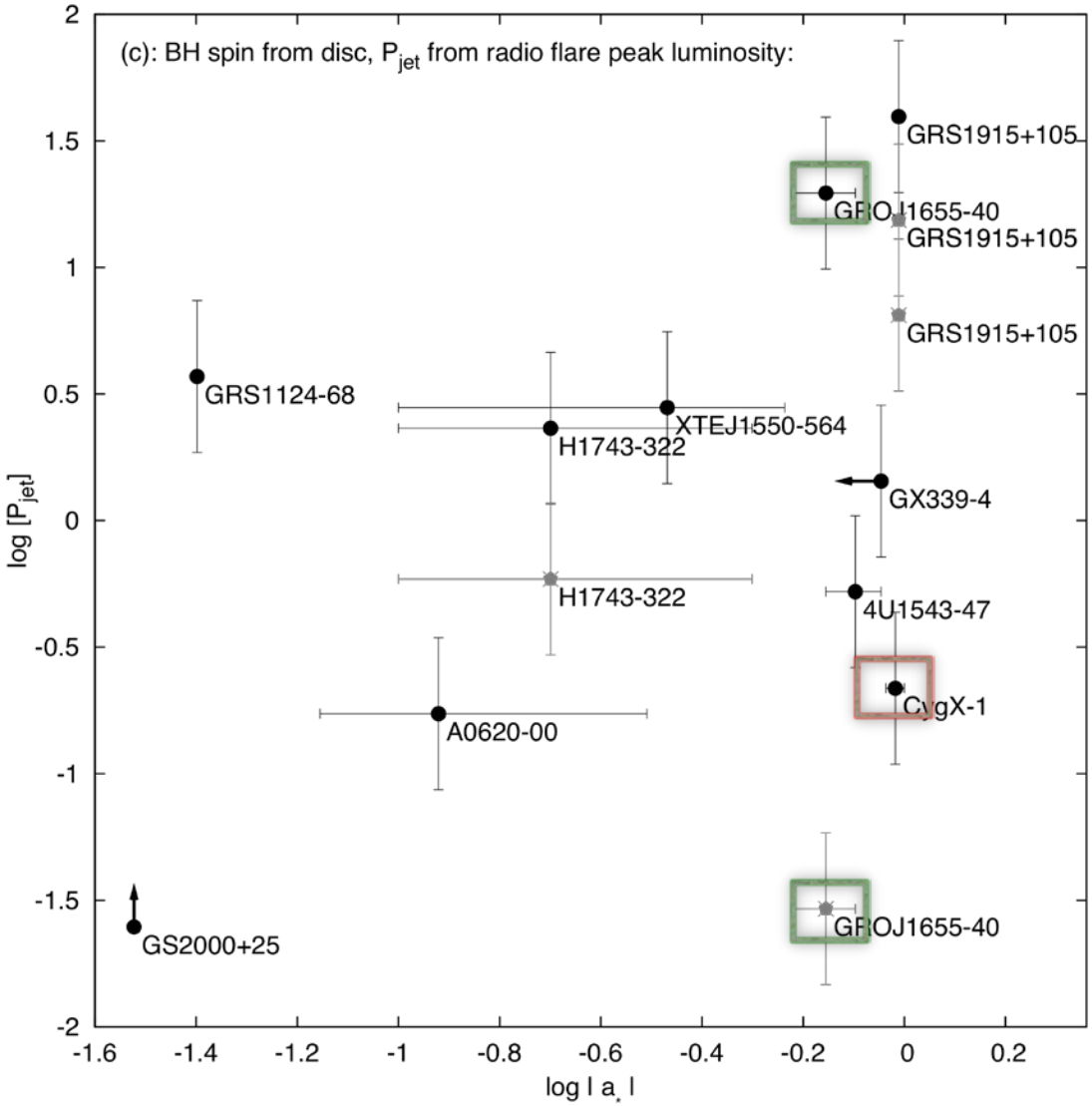


Blandford & Znajek 1977

Blandford-Znajek

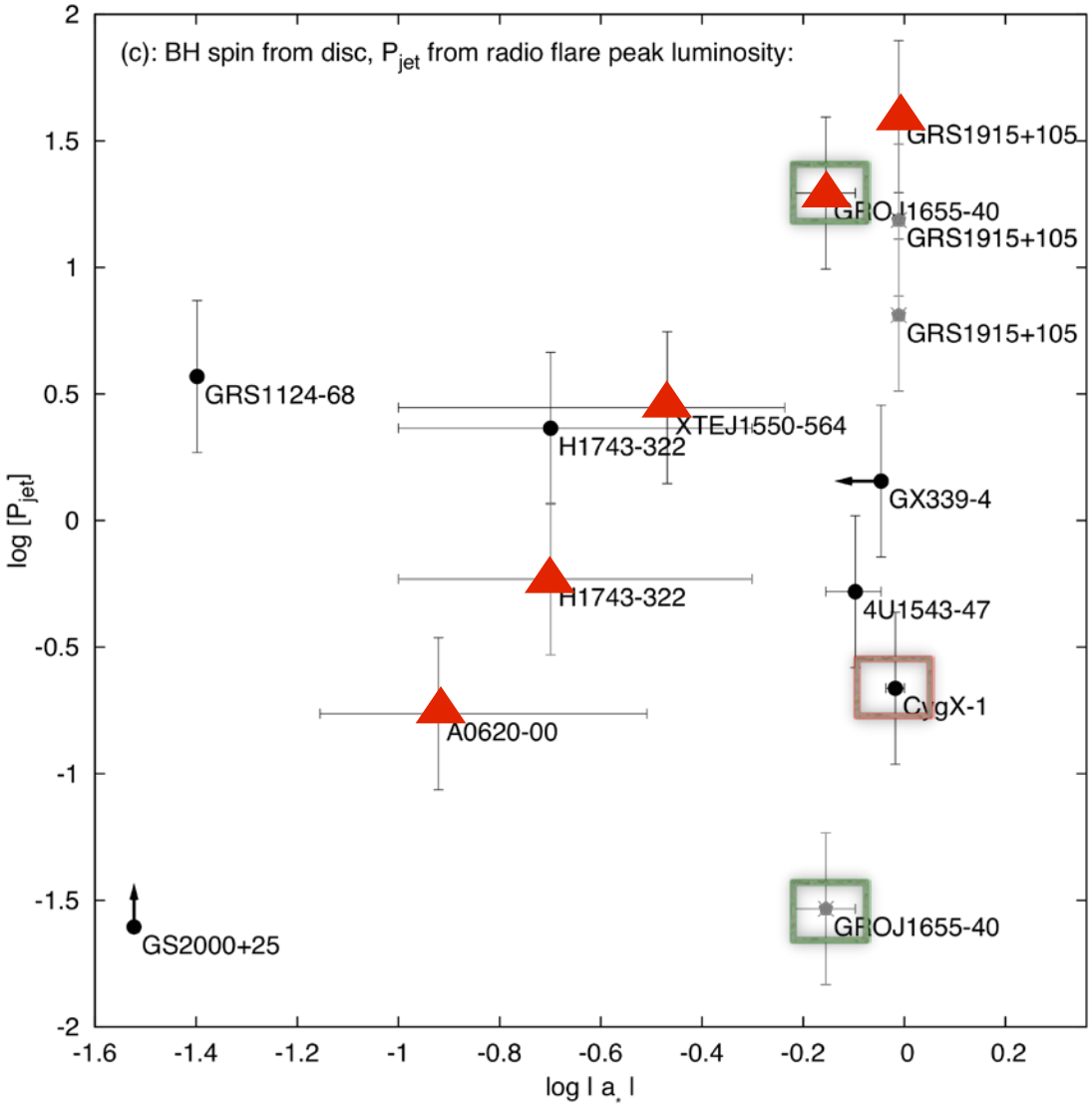
- Radio loud/radio quiet AGN
- Jet formation and disruption in X-ray binaries
- No relation between BH spin and jet power?!!

Blandford-Znajek



Russell, Gallo & Fender 2013

Blandford-Znajek



Steiner et al. 2013
Narayan & McClintock 2012
Russell, Gallo & Fender 2013

The GR pulsar equation

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

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

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\end{aligned}
$$

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

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

Contopoulos, Kazanas & Papadopoulos 2013

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

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

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

Contopoulos, Kazanas & Papadopoulos 2013

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

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

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

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

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

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

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

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

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

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

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

- The pulsar light cylinder: $r\sin\theta = c/\omega$
- The electric current $I(\Psi)$ must be determined self-consistently

Contopoulos, Kazanas & Fendt 1999

The GR pulsar equation

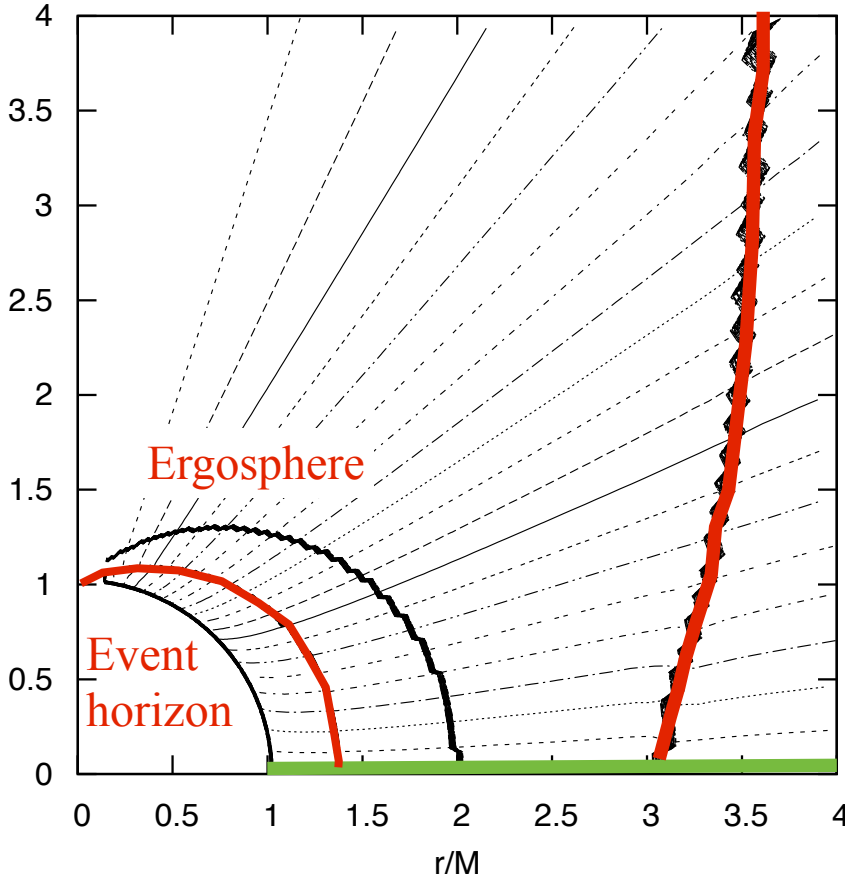
$$1-\frac{\omega^2 A\sin^2\theta}{\Sigma}+\frac{4M\alpha\omega r\sin^2\theta}{\Sigma}-\frac{2Mr}{\Sigma}=0$$

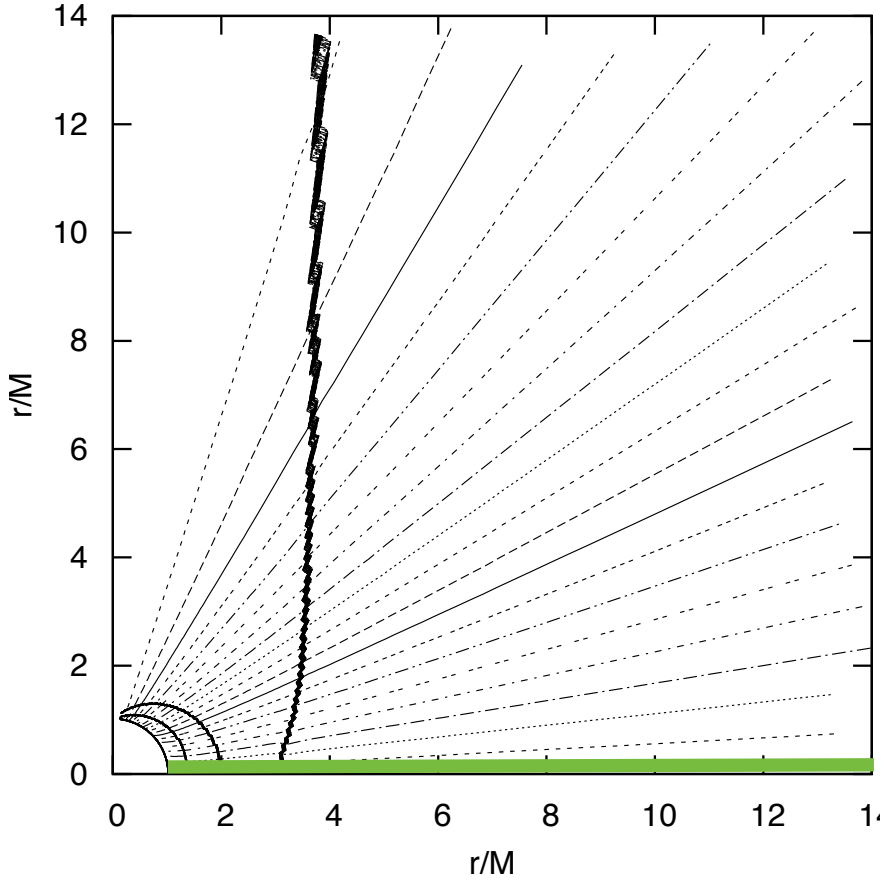
- The black hole possesses two light surfaces
- The electric current *I(Ψ)* must be determined self-consistently together with the angular velocity of the magnetic field ω(Ψ)

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

α=0.9999M, ω~0.5 Ω_{BH}

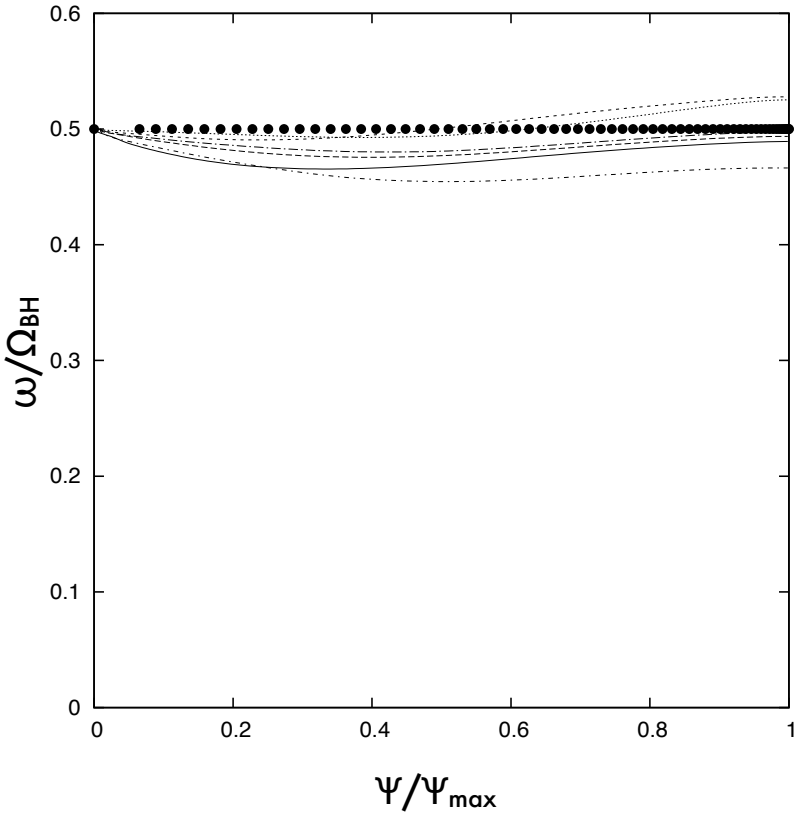


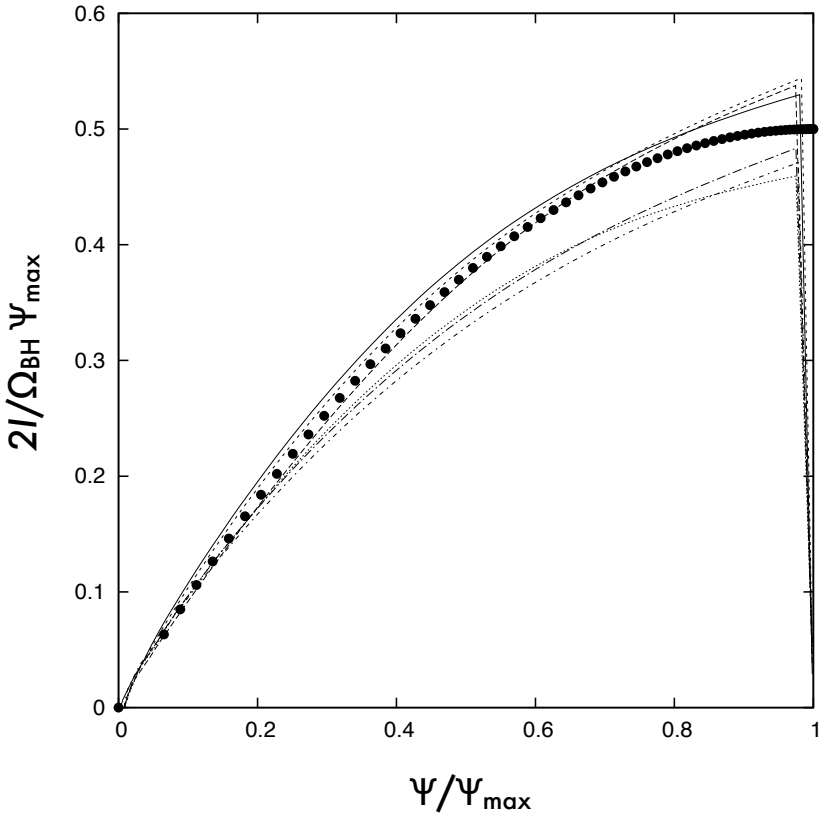


Contopoulos, Kazanas & Papadopoulos 2013

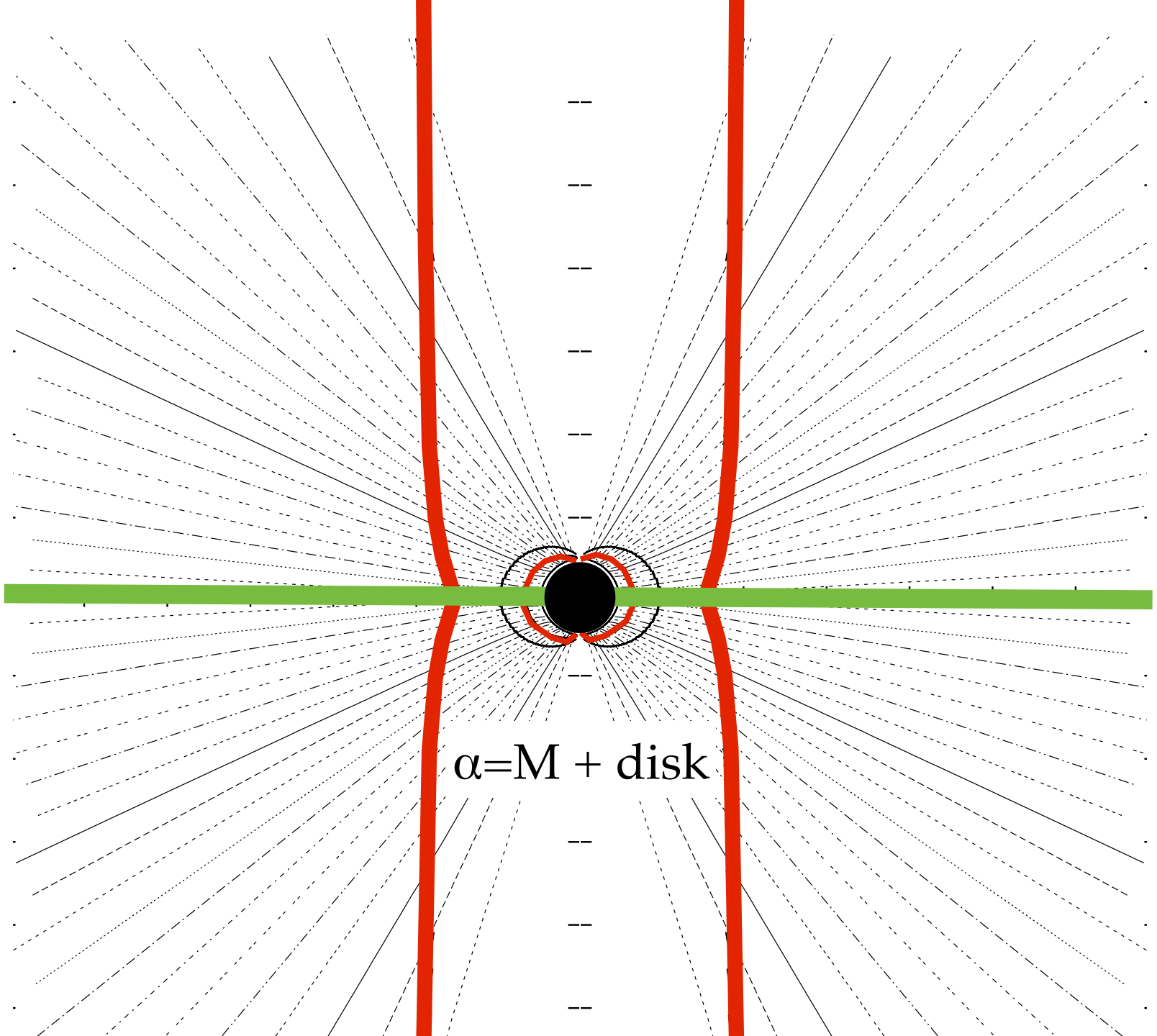
Blandford-Znajek revisited

α=0.7-0.9999M, $\omega \sim 0.5\ \Omega_{BH}$

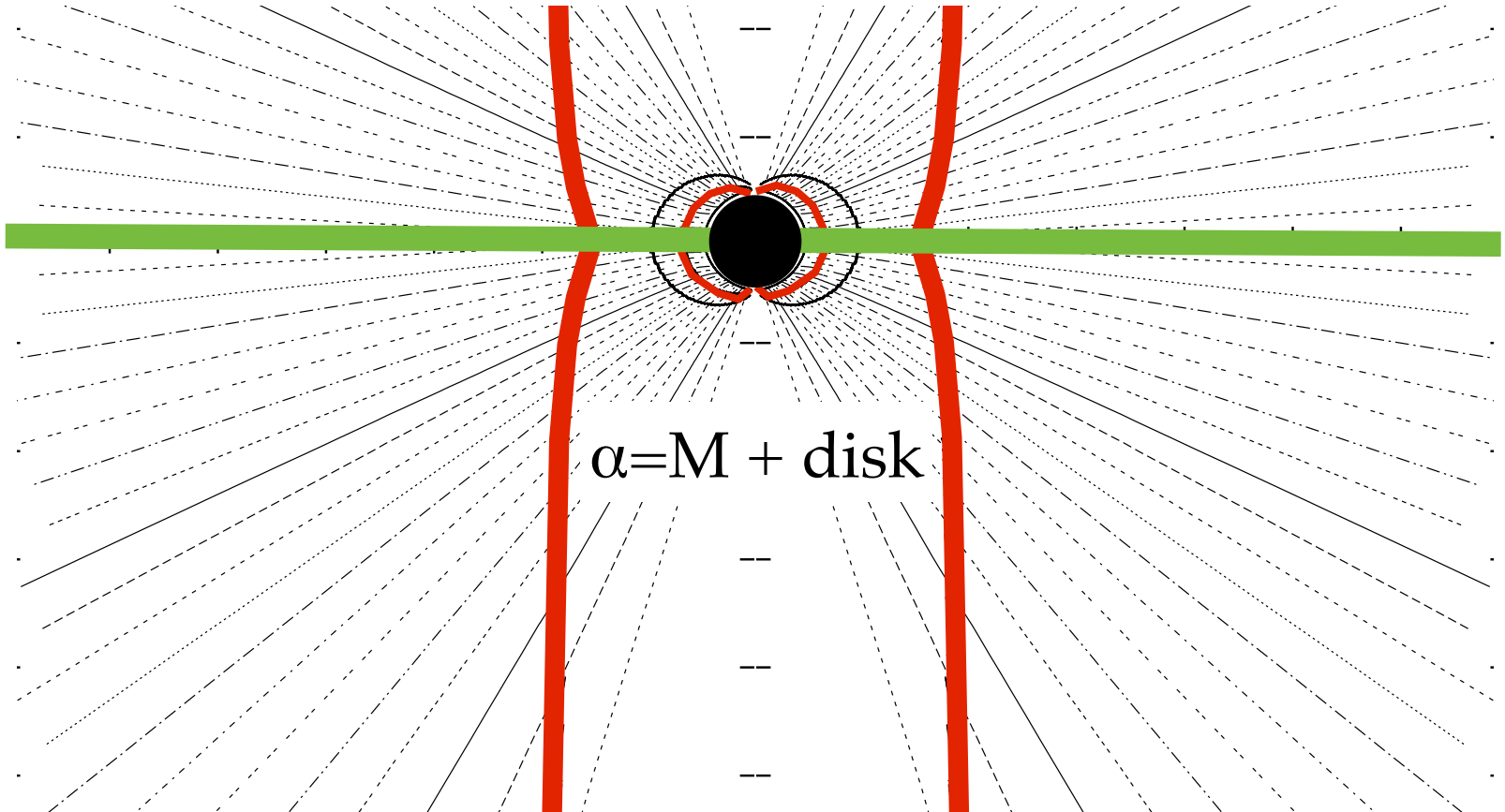


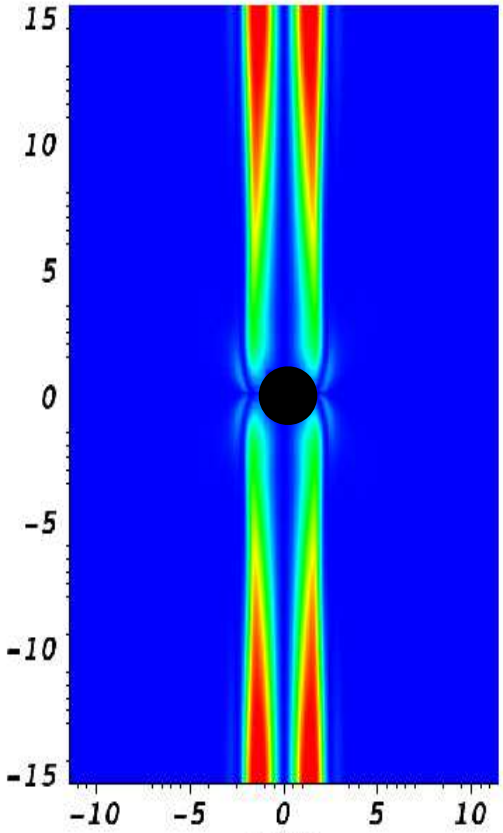


Contopoulos, Kazanas & Papadopoulos 2013

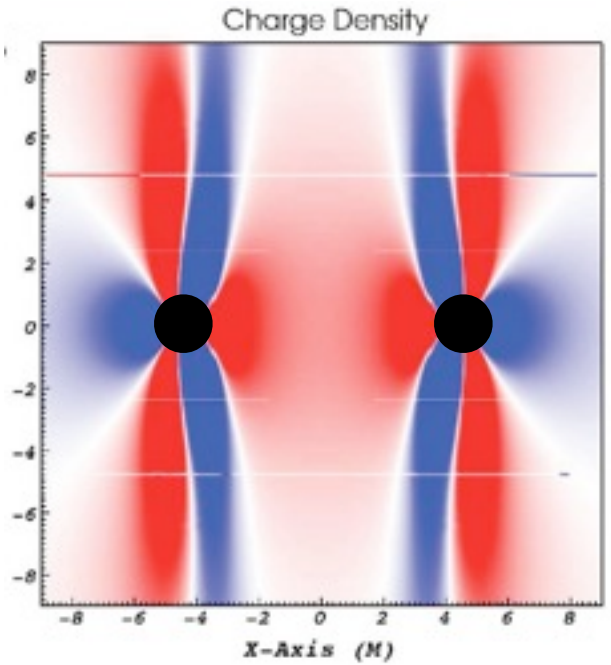

α=M + disk

No jets!

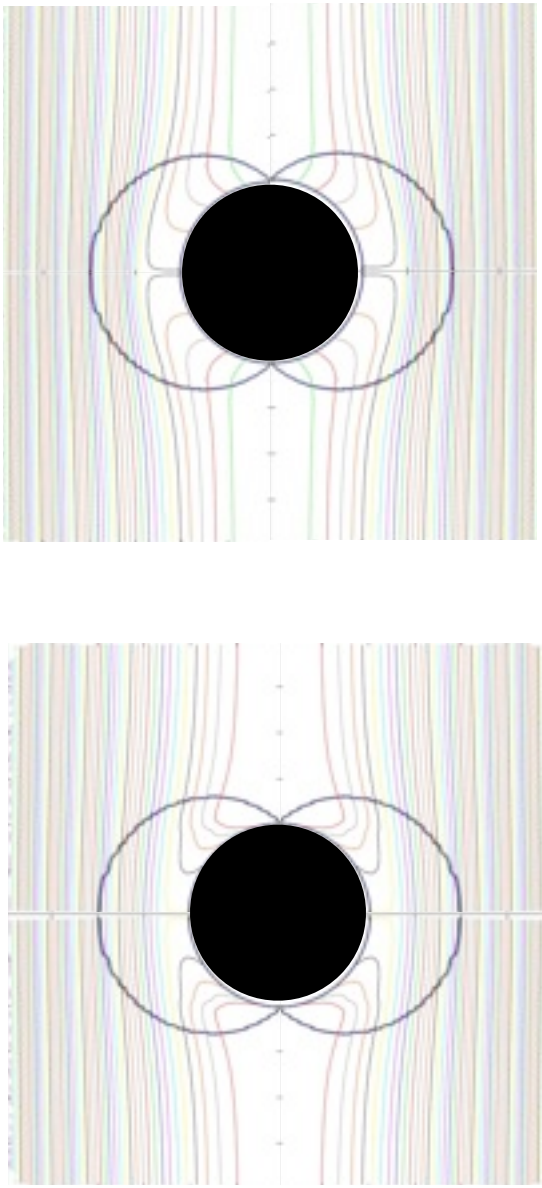




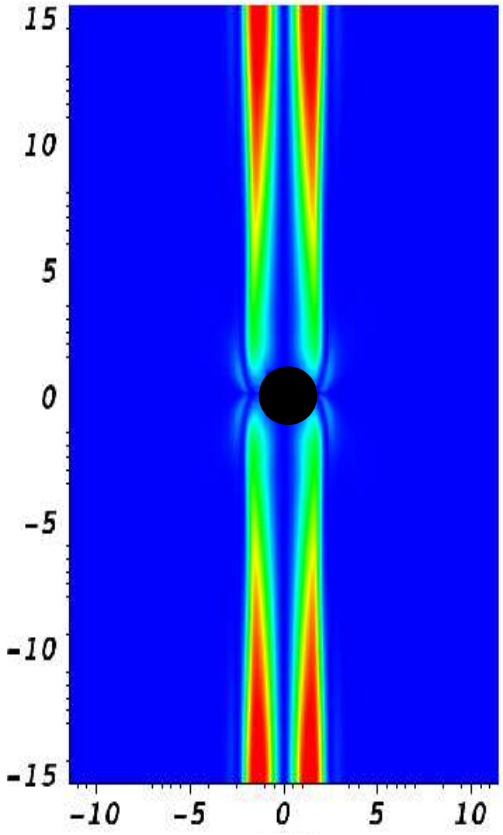
Palenzuela, Bona, Lehner, Reula 2011



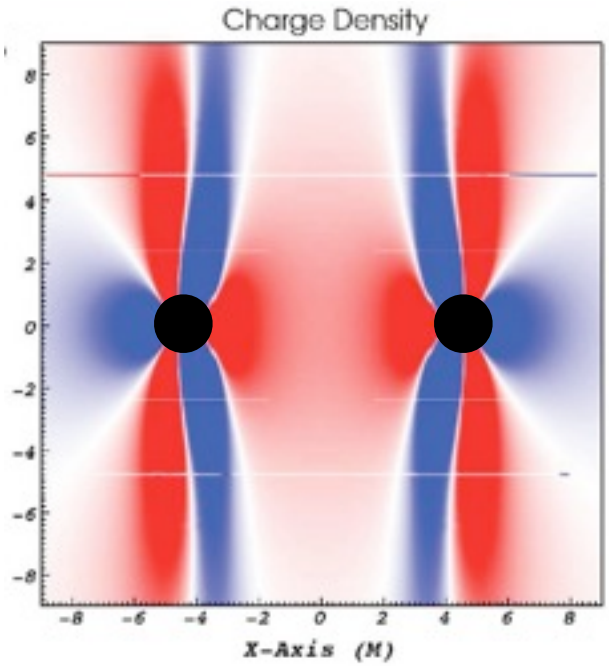
Alic, Moesta, Rezzolla, Jaramillo, Palenzuela, Zanotti 2013



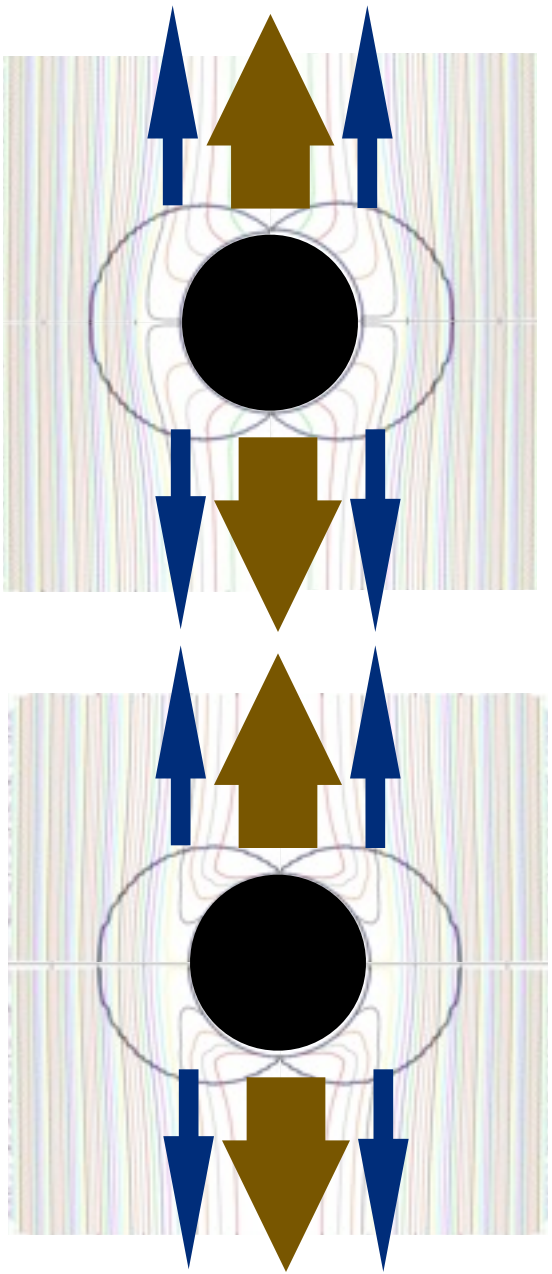
Contopoulos et al. 2013 (in preparation)



Palenzuela, Bona, Lehner, Reula 2011



Alic, Moesta, Rezzolla, Jaramillo, Palenzuela, Zanotti 2013



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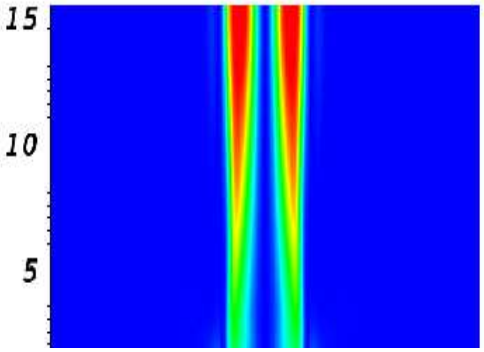
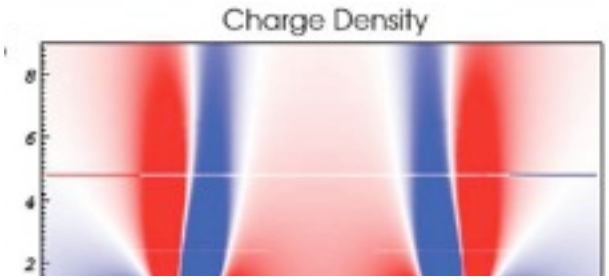
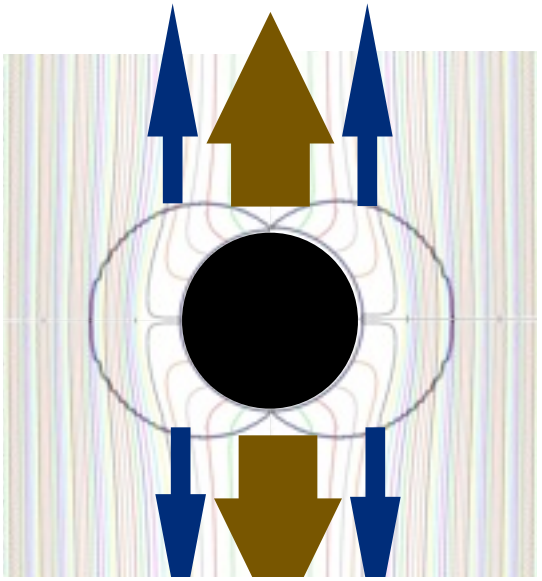
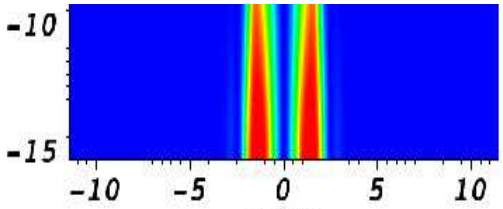
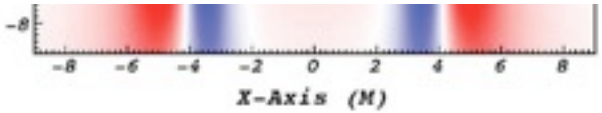


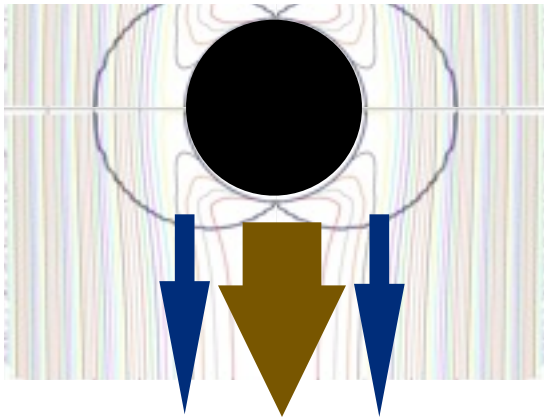




Not real jets!







Palenzuela, Bona, Lehner, Reula 2011

Alic, Moesta, Rezzolla, Jaramillo, Palenzuela, Zanotti 2013

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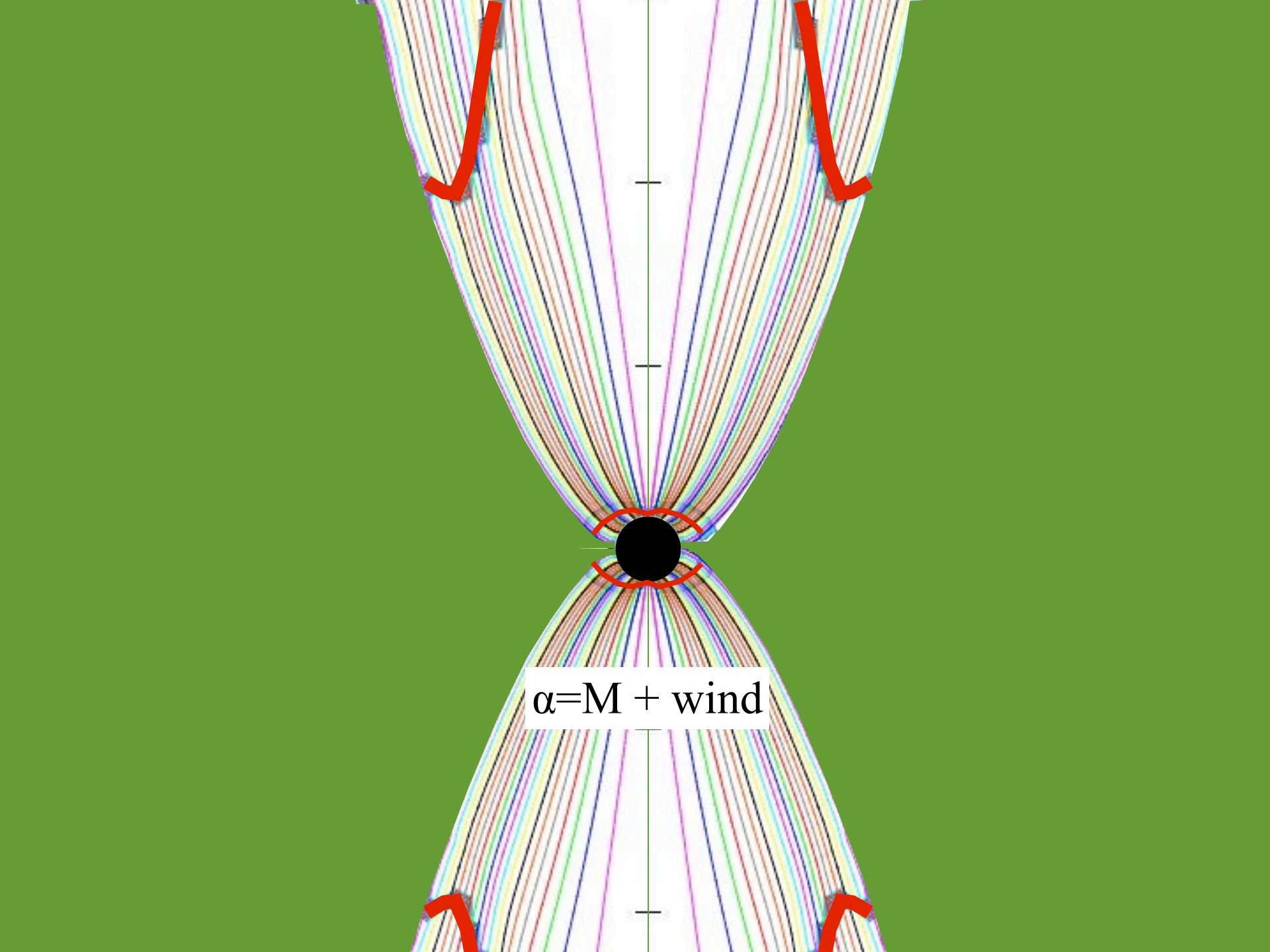
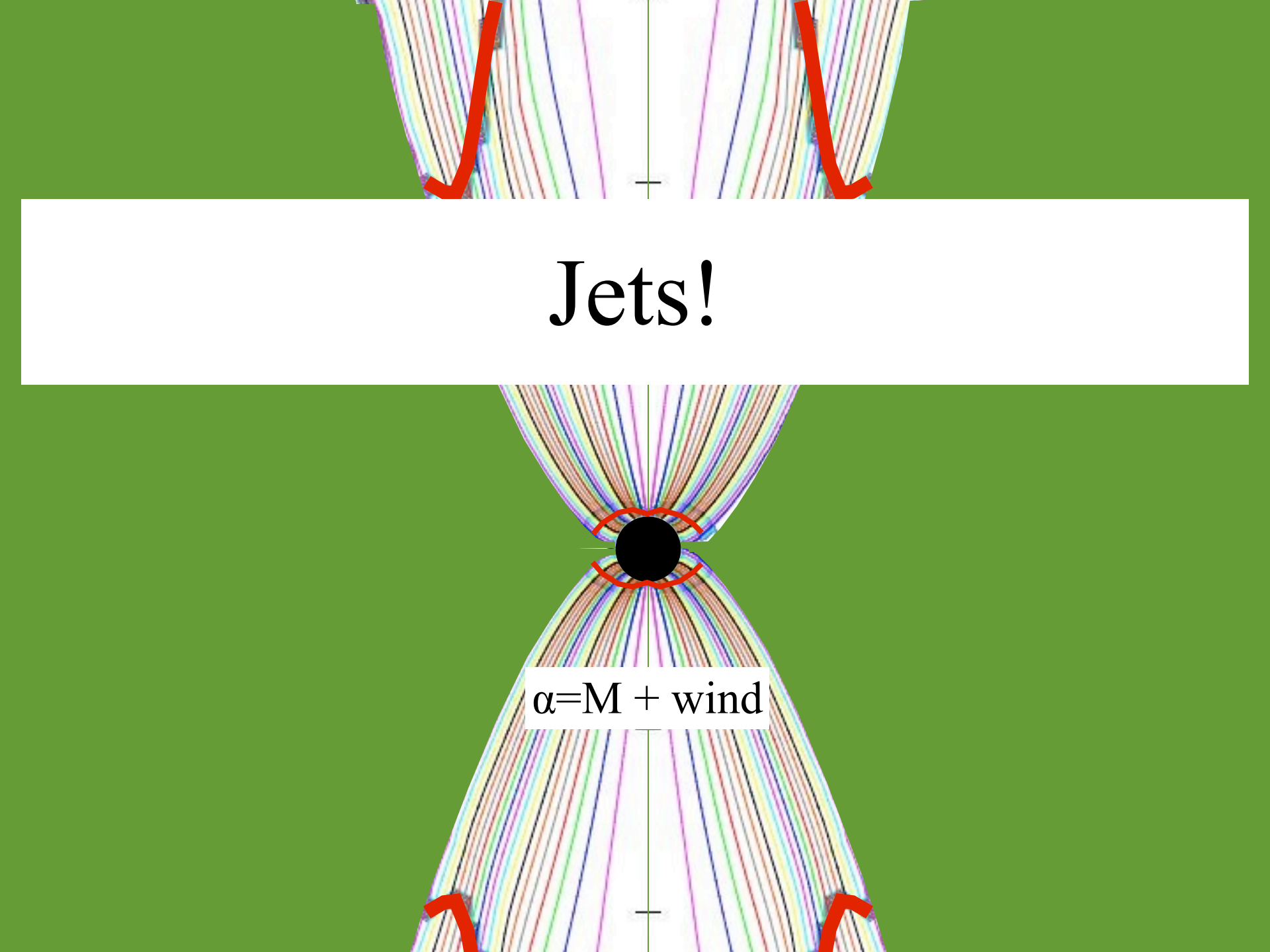
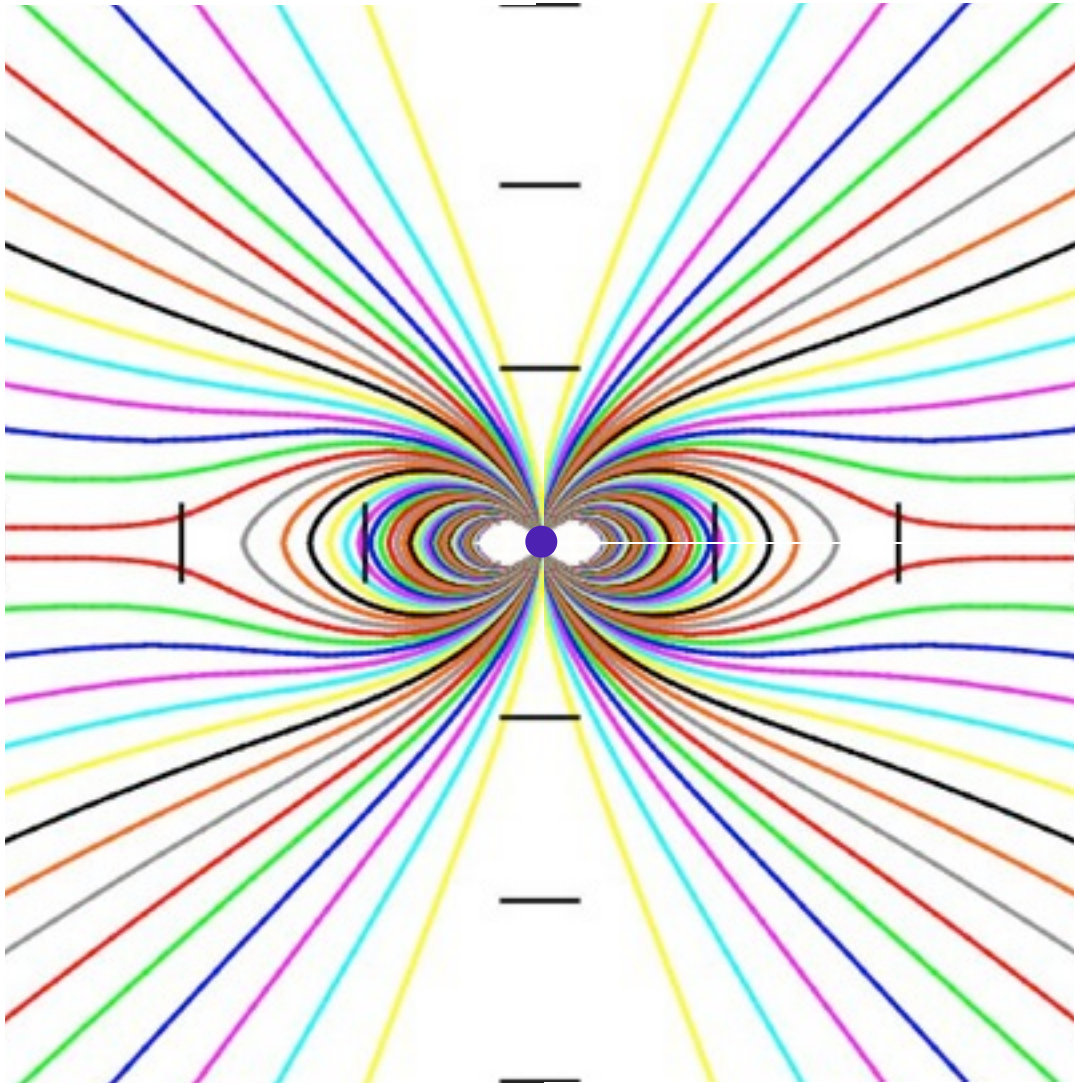
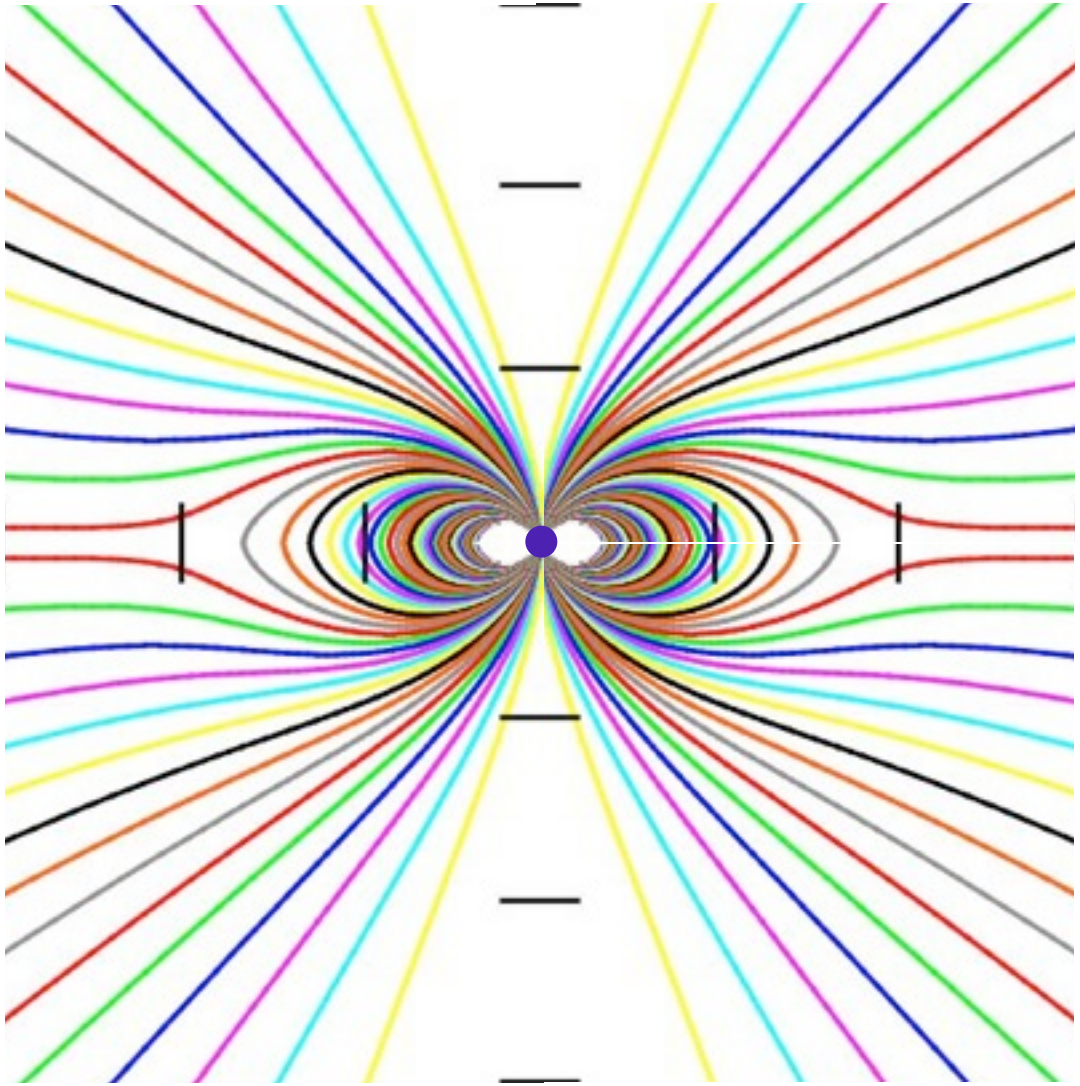

α=M + wind


Jets!
α=M + wind

The magnetic black hole

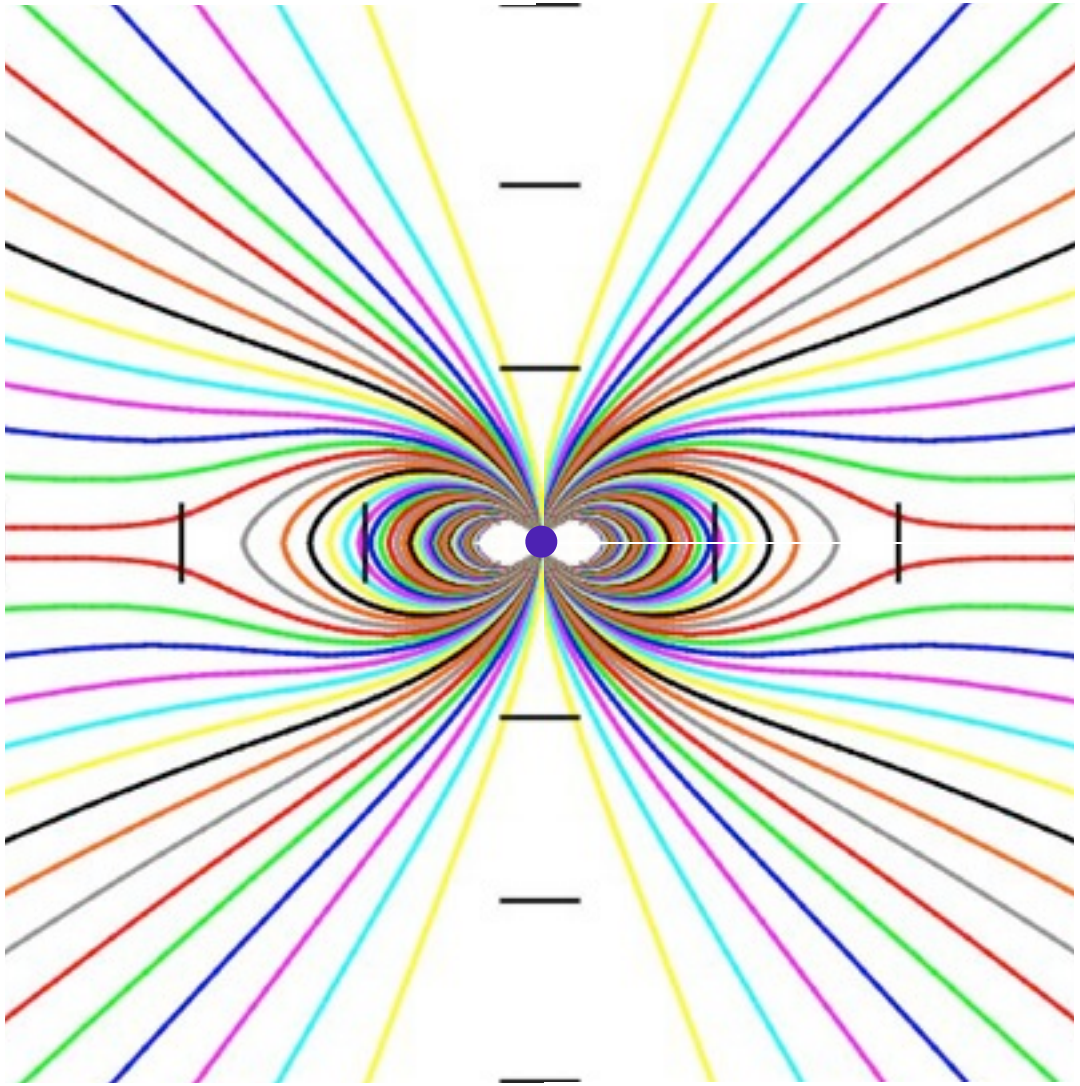


The magnetic black hole



B_o

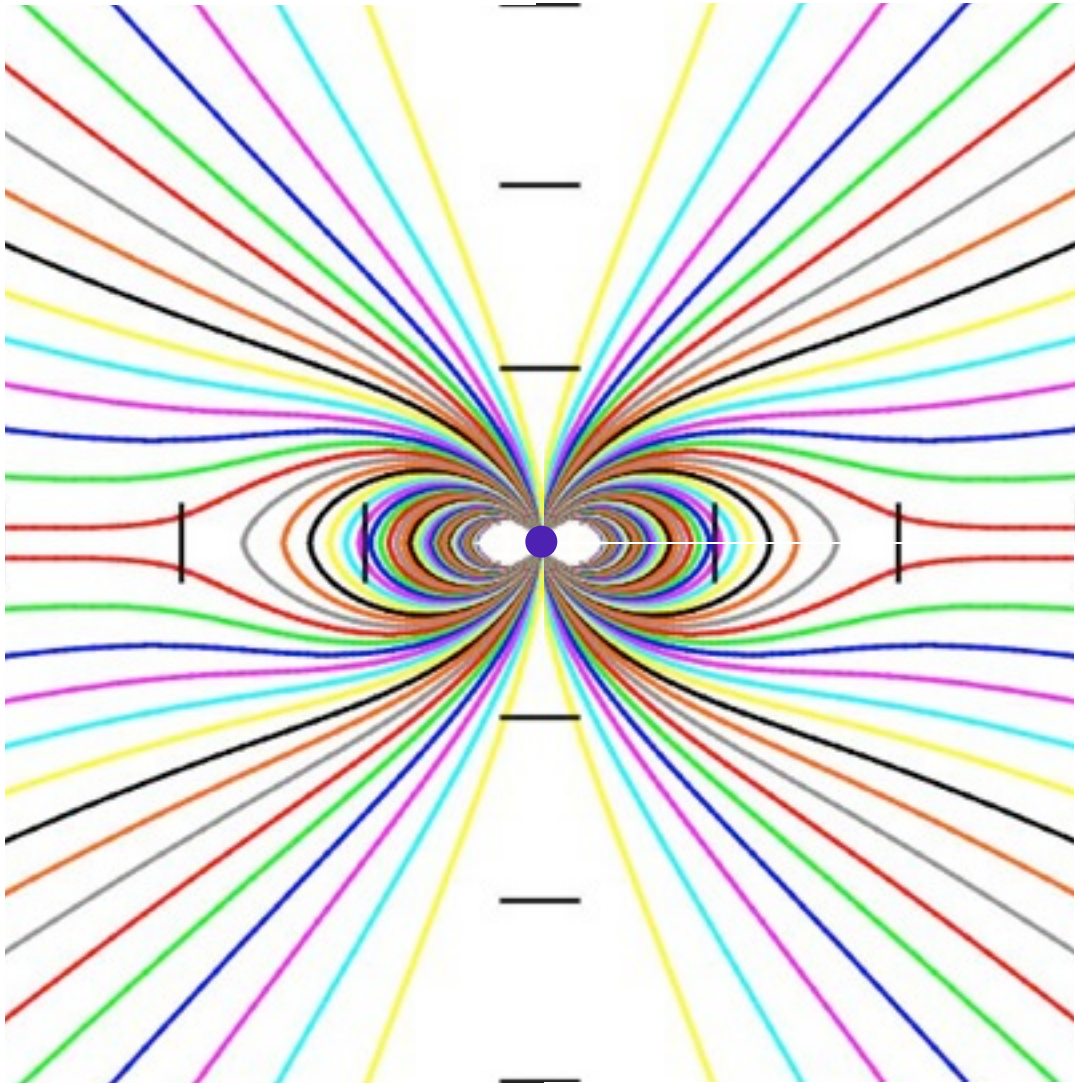
The magnetic black hole



$$B_o$$

$$Q \sim B_o r_*^2 \left(\frac{\omega r_*}{c}\right)$$

The magnetic black hole

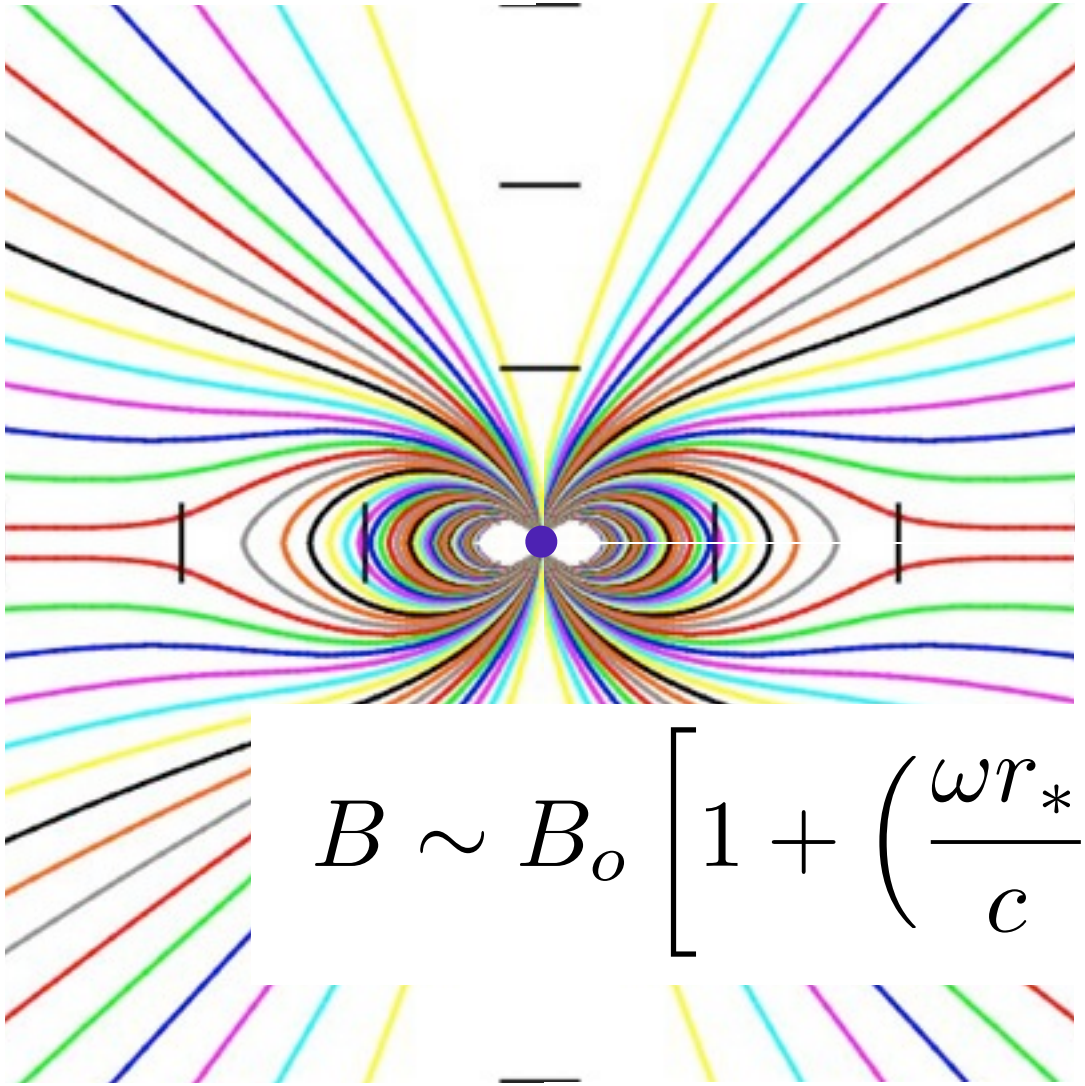


$$B_o$$

$$Q \sim B_o r_*^2 \left(\frac{\omega r_*}{c}\right)$$

$$\delta B \sim \frac{Q\omega}{r_* c}$$

The magnetic black hole



$$B_o$$

$$Q \sim B_o r_*^2 \left(\frac{\omega r_*}{c}\right)$$

$$\delta B \sim \frac{Q\omega}{r_* c}$$

$$B \sim B_o \left[1 + \left(\frac{\omega r_*}{c}\right)^2\right] \sim B_o \gamma$$

The magnetic black hole

$$B \sim \frac{Q\omega}{r_{bh}c} \sim B_o \left(\frac{\omega r_{bh}}{c}\right)^2$$

The magnetic black hole

$$B \sim \frac{Q\omega}{r_{bh}c} \sim B_o \left(\frac{\omega r_{bh}}{c}\right)^2$$

The Kerr-Newman black hole

The magnetic black hole

$$B \sim \frac{Q\omega}{r_{bh}c} \sim B_o \left(\frac{\omega r_{bh}}{c}\right)^2$$

The Kerr-Newman black hole

$$B_{KN} \sim 10^{19}\ G$$

The magnetic black hole

$$B \sim \frac{Q\omega}{r_{bh}c} \sim B_o \left(\frac{\omega r_{bh}}{c}\right)^2$$

The Kerr-Newman black hole

$$B_{KN} \sim 10^{19}\ G$$

$$B_{MBH} \sim 10^{15}\ G$$

The magnetic black hole

$$B \sim \frac{Q\omega}{r_{bh}c} \sim B_o \left(\frac{\omega r_{bh}}{c}\right)^2$$

The Kerr-Newman black hole

$$B_{KN} \sim 10^{19}\ G$$

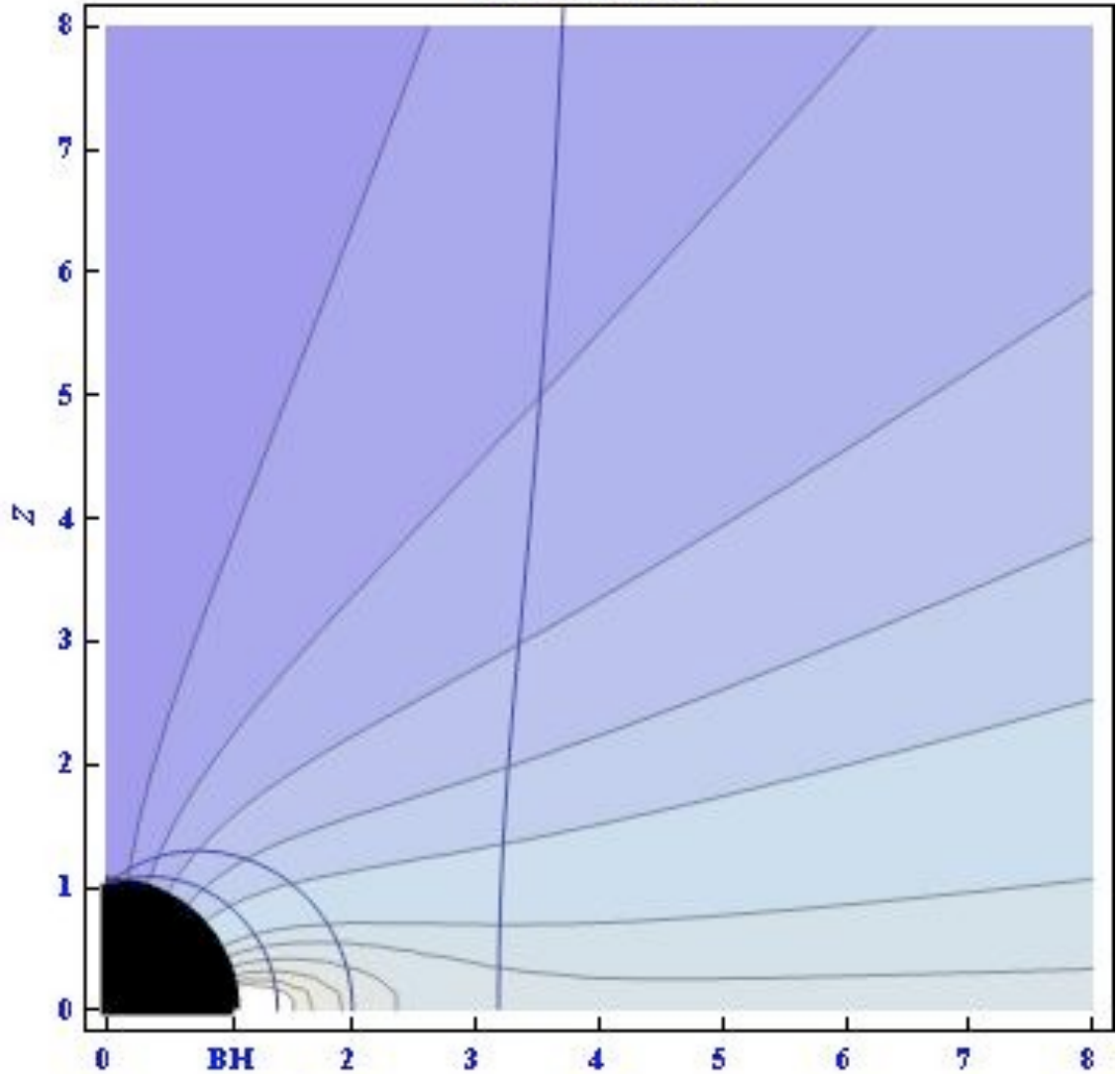
$$B_{MBH} \sim 10^{15}\ G$$

$$B_{eq} \sim 10^{7-8}\ G$$

The magnetic black hole

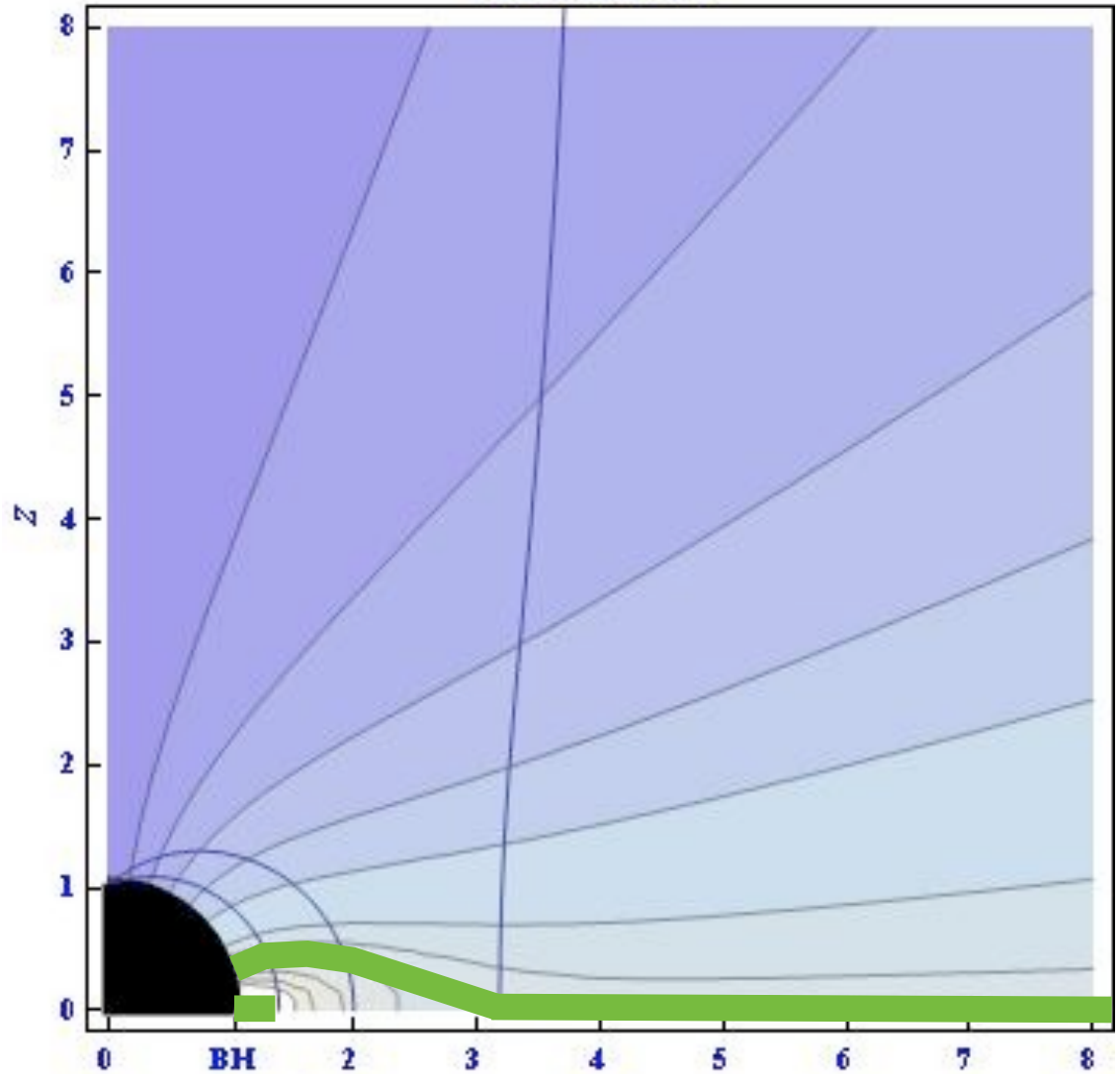
- A Kerr black hole with its own magnetic field
- Pulsar-like boundary conditions on the horizon

The magnetic black hole



Contopoulos, Nathanail, Pugliese 2013

The magnetic black hole



Contopoulos, Nathanail, Pugliese 2013

The magnetic black hole

$$\dot{E}_{t=0} \sim 10^{51} \text{ erg/sec}$$

The magnetic black hole

$$\dot{E}_{t=0} \sim 10^{51} \text{ erg/sec}$$

Is it relevant for GRB?

Contopoulos, Nathanail, Pugliese 2013

The magnetic black hole

$$\dot{E}_{t=0} \sim 10^{51} \text{ erg/sec}$$

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Contopoulos, Nathanail, Pugliese 2013

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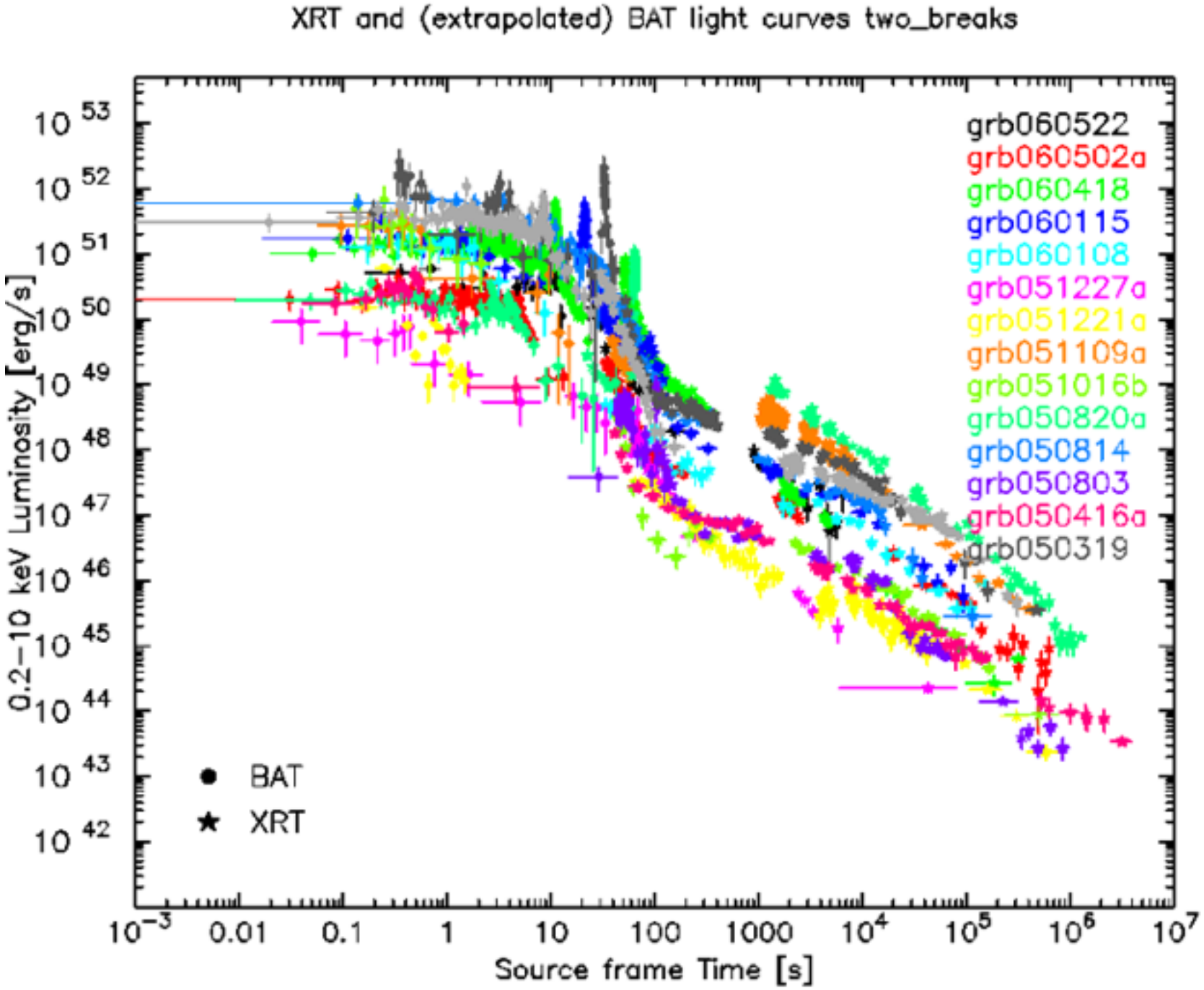
$$\dot{E}_{MBH} \sim \omega^8 \sim (t/\tau)^{-4/3}$$

Contopoulos, Nathanail, Pugliese 2013


XRT and (extrapolated) BAT light curves two_breaks
0.2−10 keV Luminosity [erg/s]
Source frame Time [s]
grb060522
grb060502a
grb060418
grb060115
grb060108
grb051227a
grb051221a
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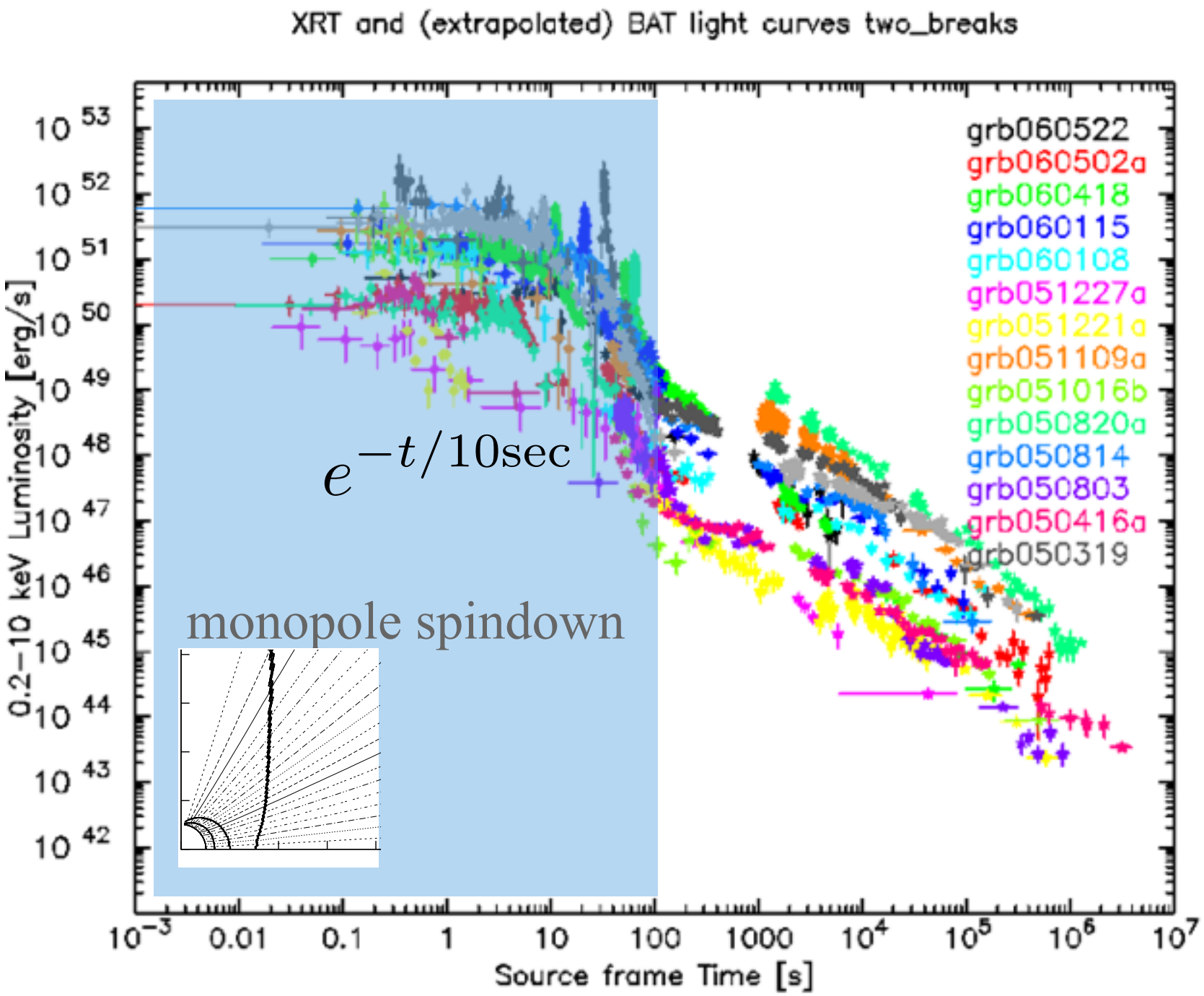
BAT
XRT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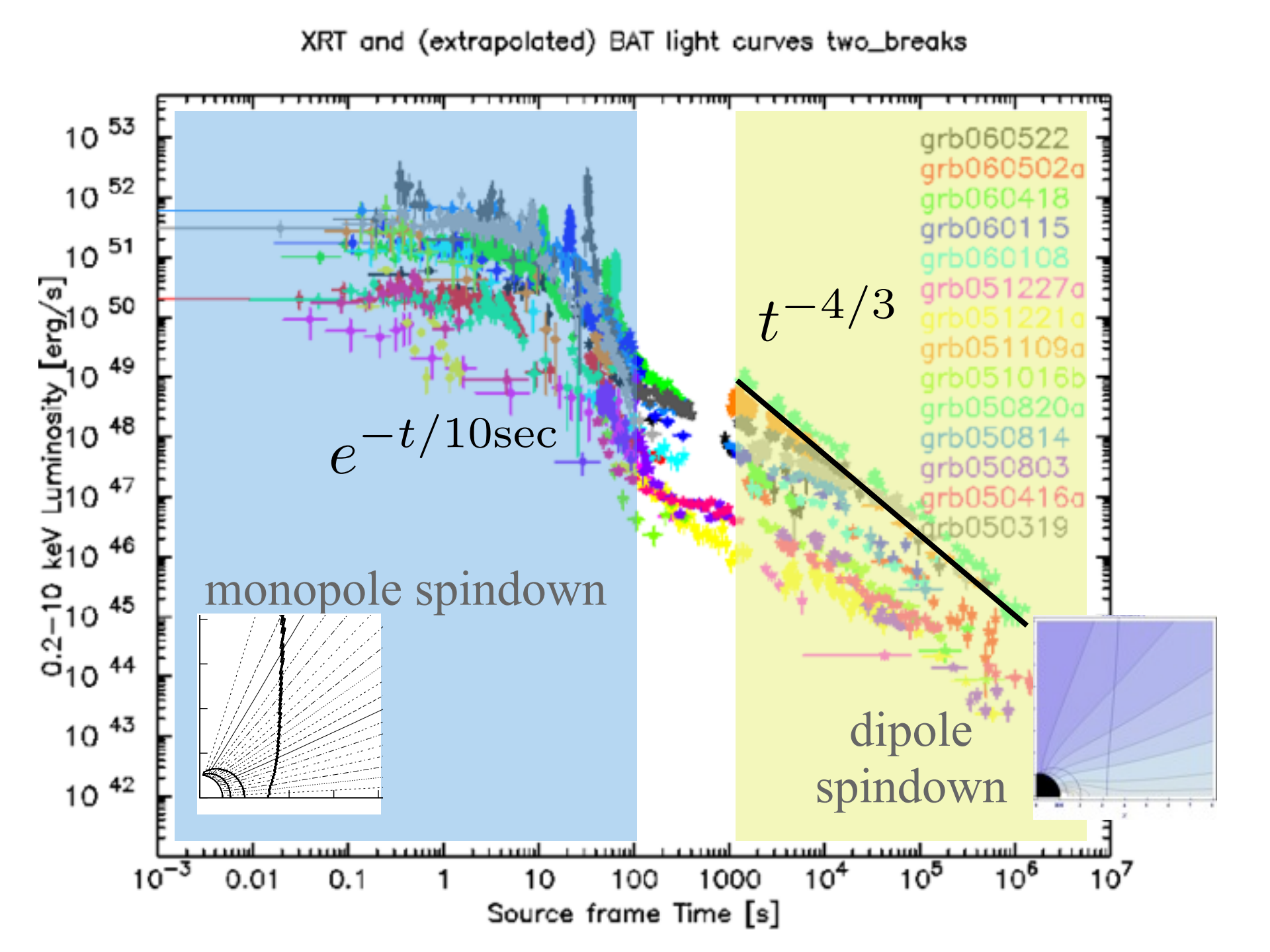
grb050803
grb050416a
grb050319
$e^{-t/10\mathrm{sec}}$
monopole spindown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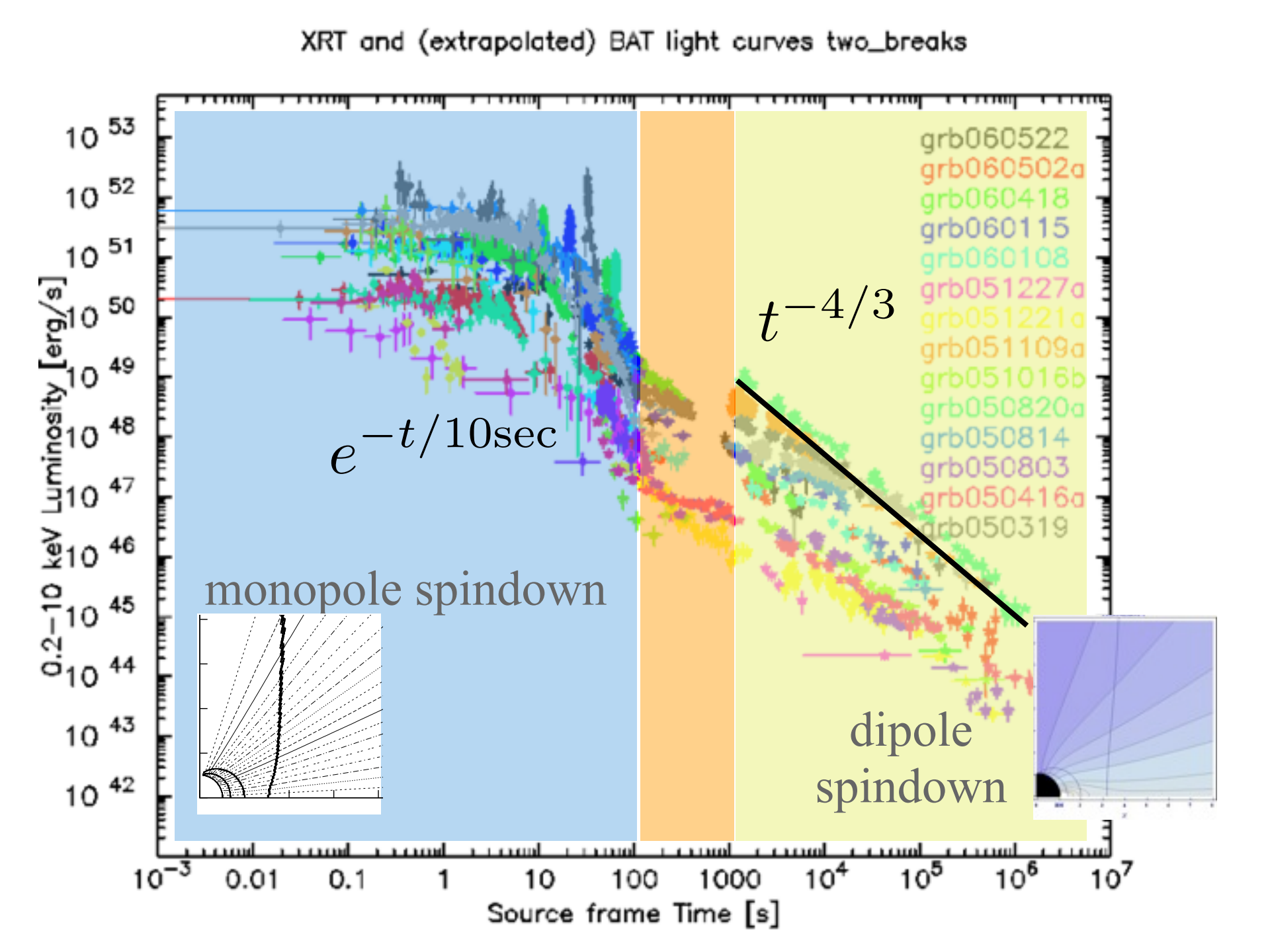
grb050814
grb050803
grb050416a
grb050319
$e^{-t/10\mathrm{sec}}$
$t^{-4/3}$
monopole spindown
dipole spindown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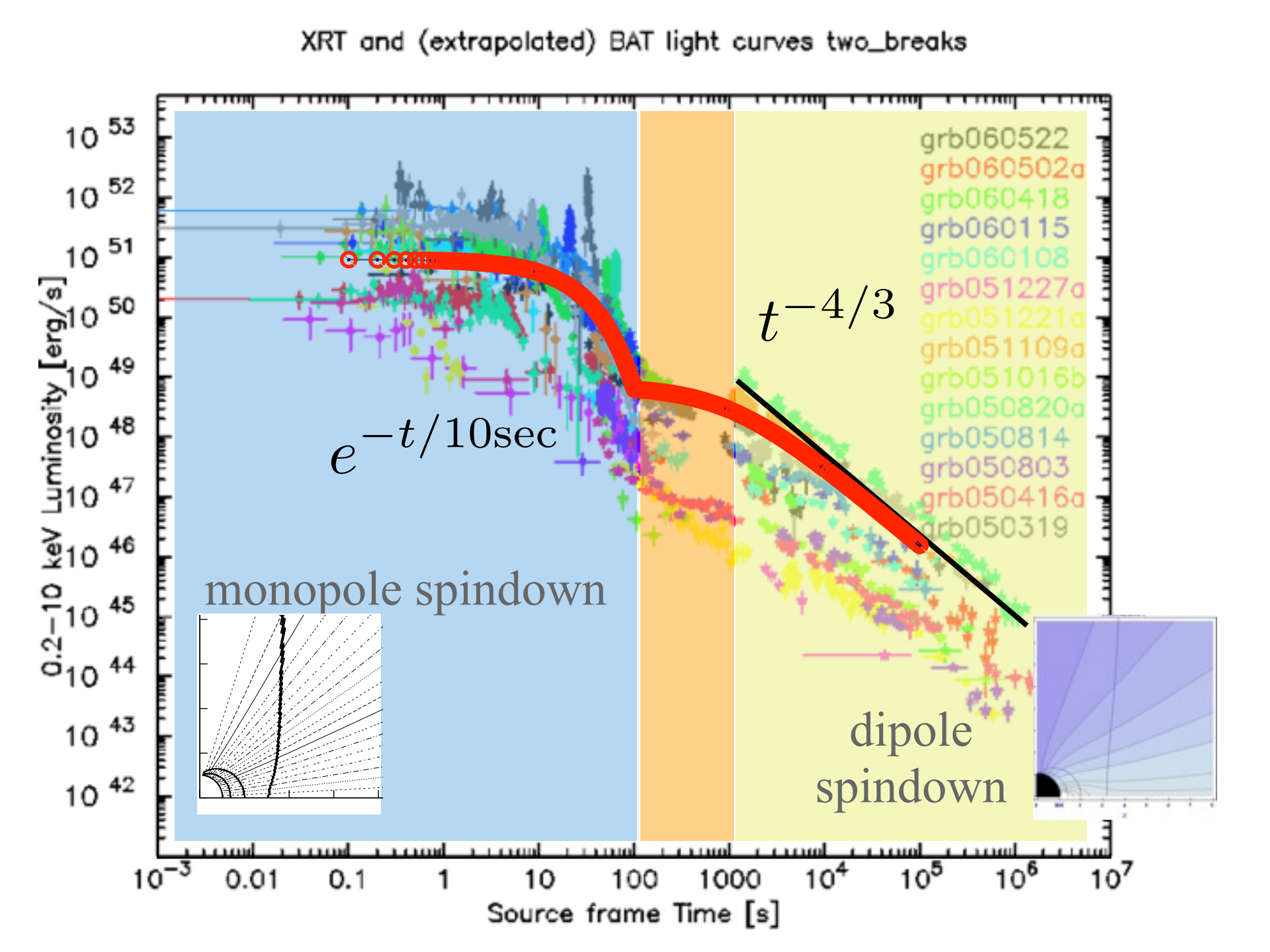
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Conclusions

- The black hole magnetic field may be generated in the accretion disk (Cosmic Battery)
- Stellar mass black holes gain charge and magnetic field during their formation (MBH)
- MBH: an “orthogonal” GRB model?
- Isolated black holes do not produce jets