The force-free magnetosphere of a rotating black hole

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- ...Goldreich & Julian laid the foundations for the theory of 'pulsar electrodynamics' in 1969...
- ...A compelling mechanism by which black holes can energize quasars was not found until 13 years after the quasar discovery... The long delay is surprising, since the mechanism is essentially the same as in the pulsar case: magnetic fields, embedded in a rotating black hole and a surrounding accretion disk, transmit rotational and orbital energy to distant radiating particles...
- Many astrophysicists feel uncomfortable in curved spacetime...

Macdonald & Thorne 1982

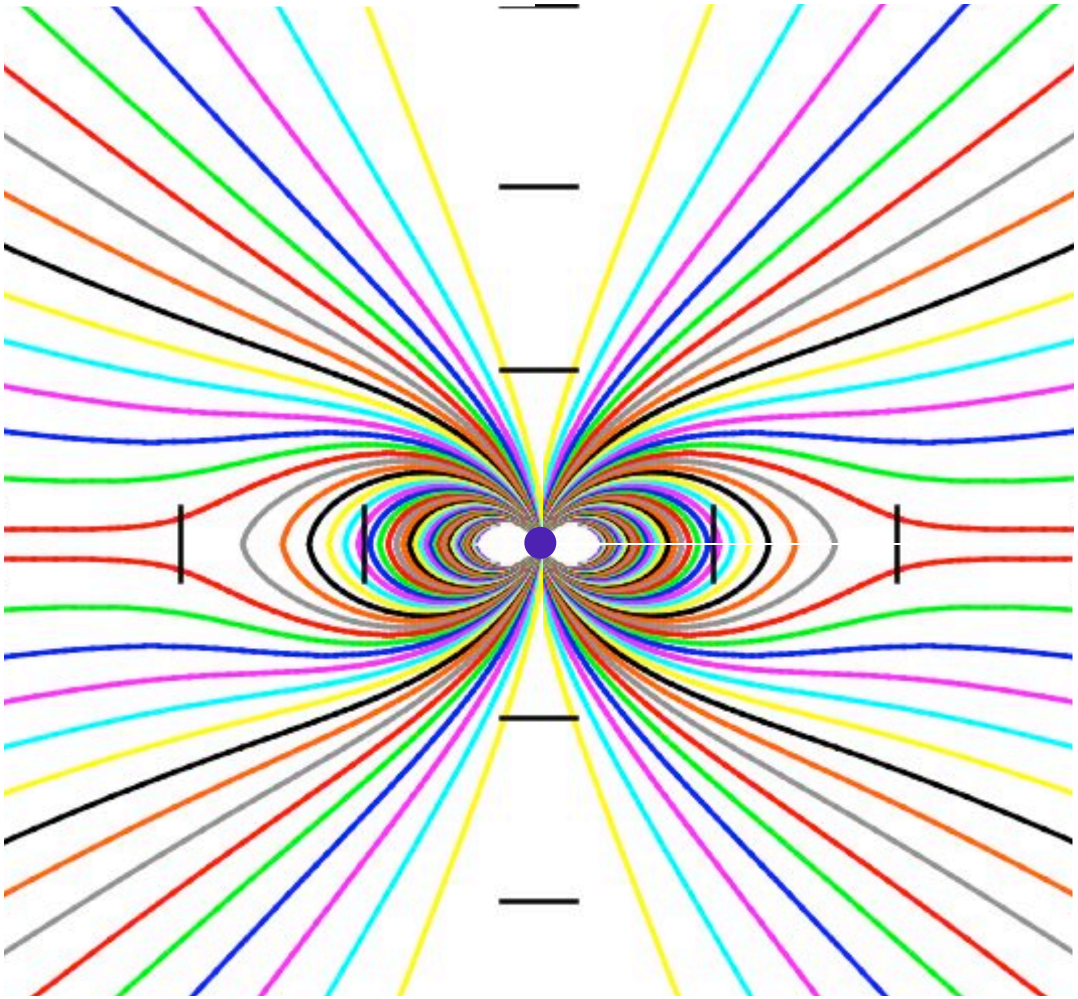
- Macdonald & Thorne reformulated electrodynamics with the hope that it may catalyze pulsar-experienced astrophysicists to begin research on black-hole electrodynamics and to bring to bear on this topic their lore about the 'axisymmetric pulsar problem'...

Macdonald & Thorne 1982

Topics

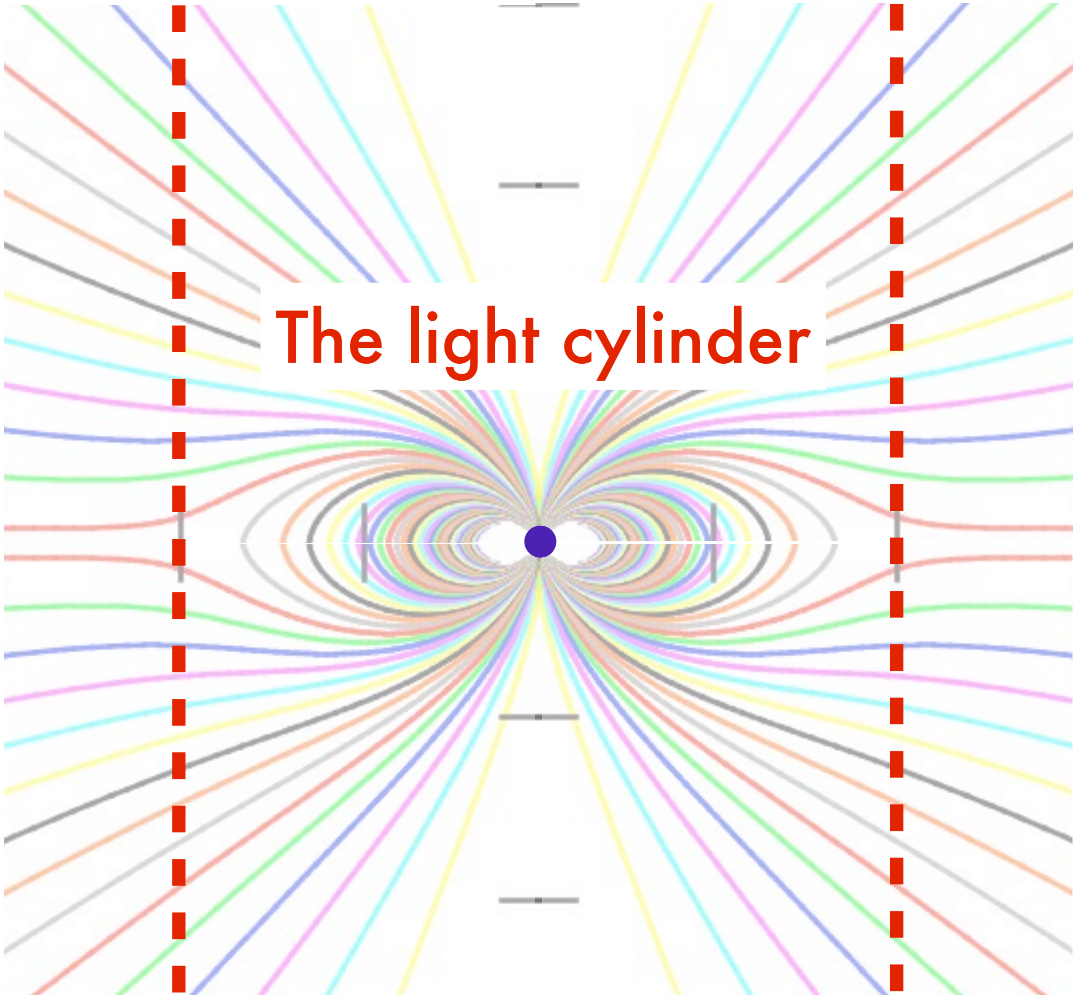
- The analogy with pulsars
- The GR pulsar equation
  - The generalized light cylinders
  - Solution
- Black hole jets
- The Cosmic Battery

The analogy with pulsars



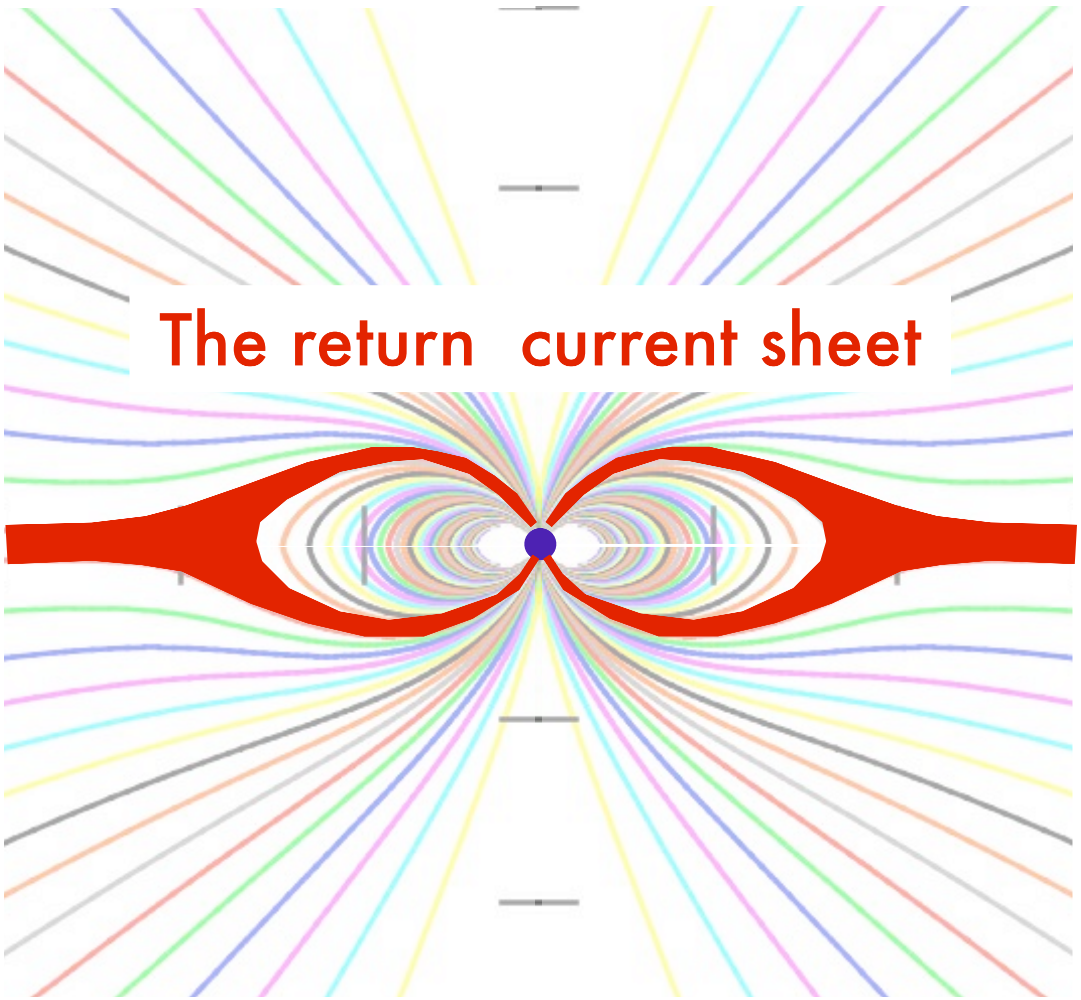
Contopoulos, Kazanas & Fendt 1999

The analogy with pulsars



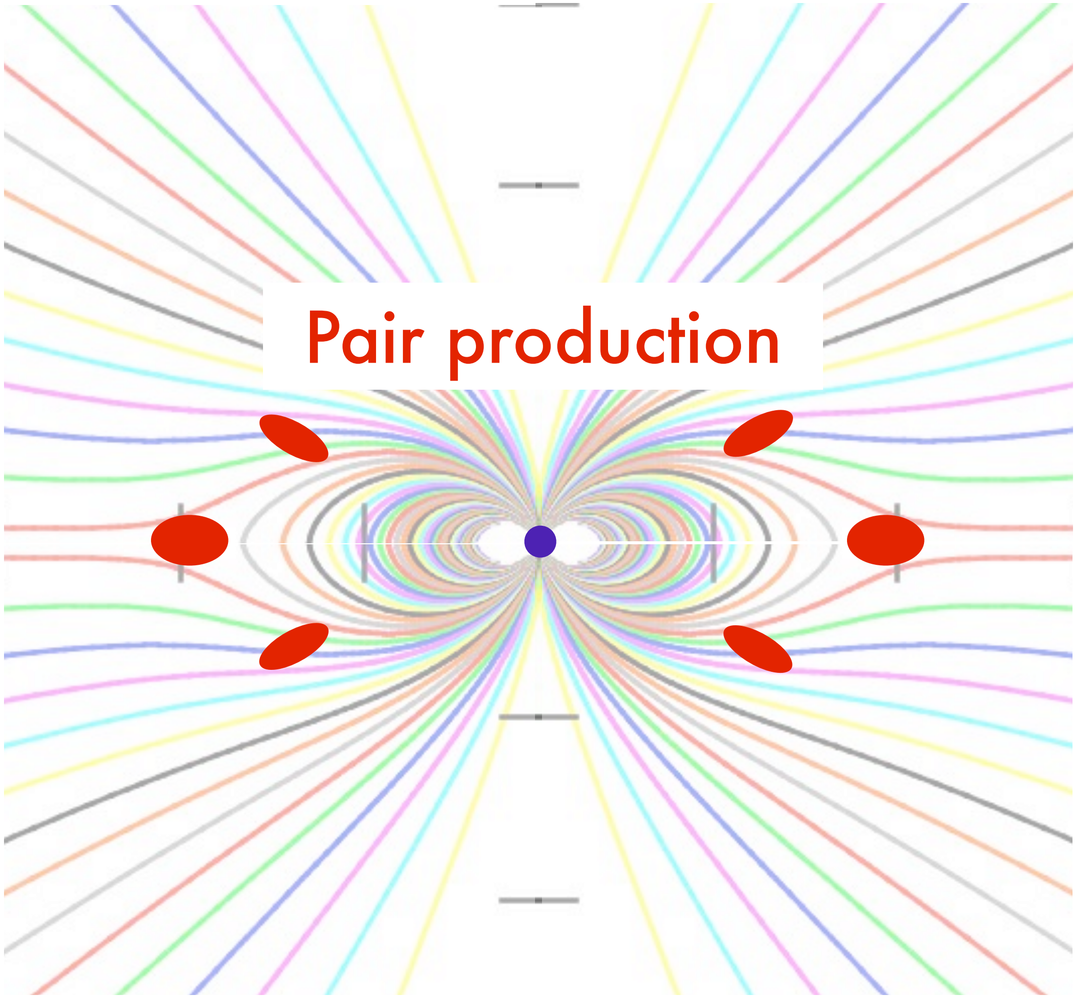
Contopoulos, Kazanas & Fendt 1999

The analogy with pulsars



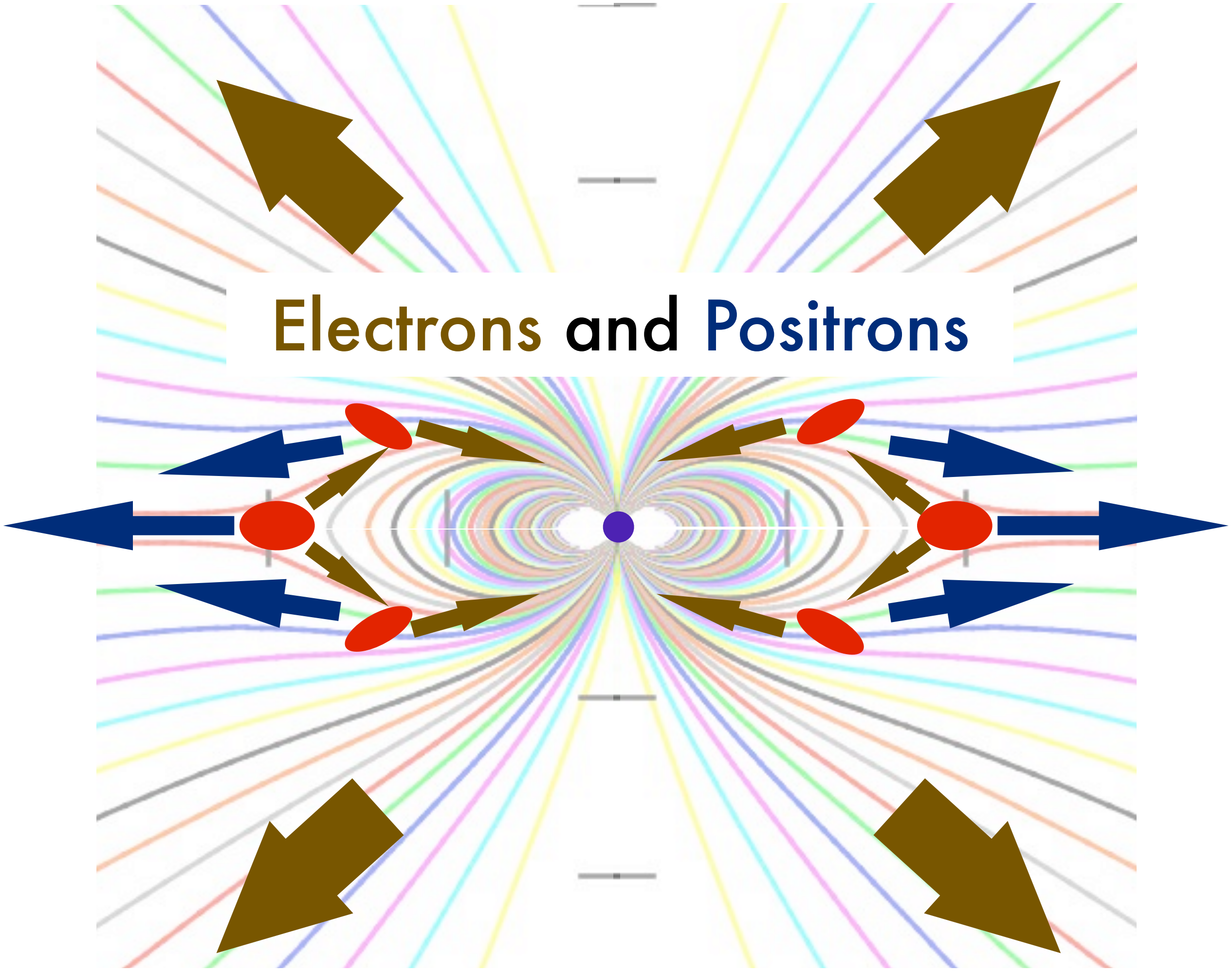
Contopoulos, Kazanas & Fendt 1999

The analogy with pulsars



Contopoulos, Kazanas, Harding, Kalapotharakos

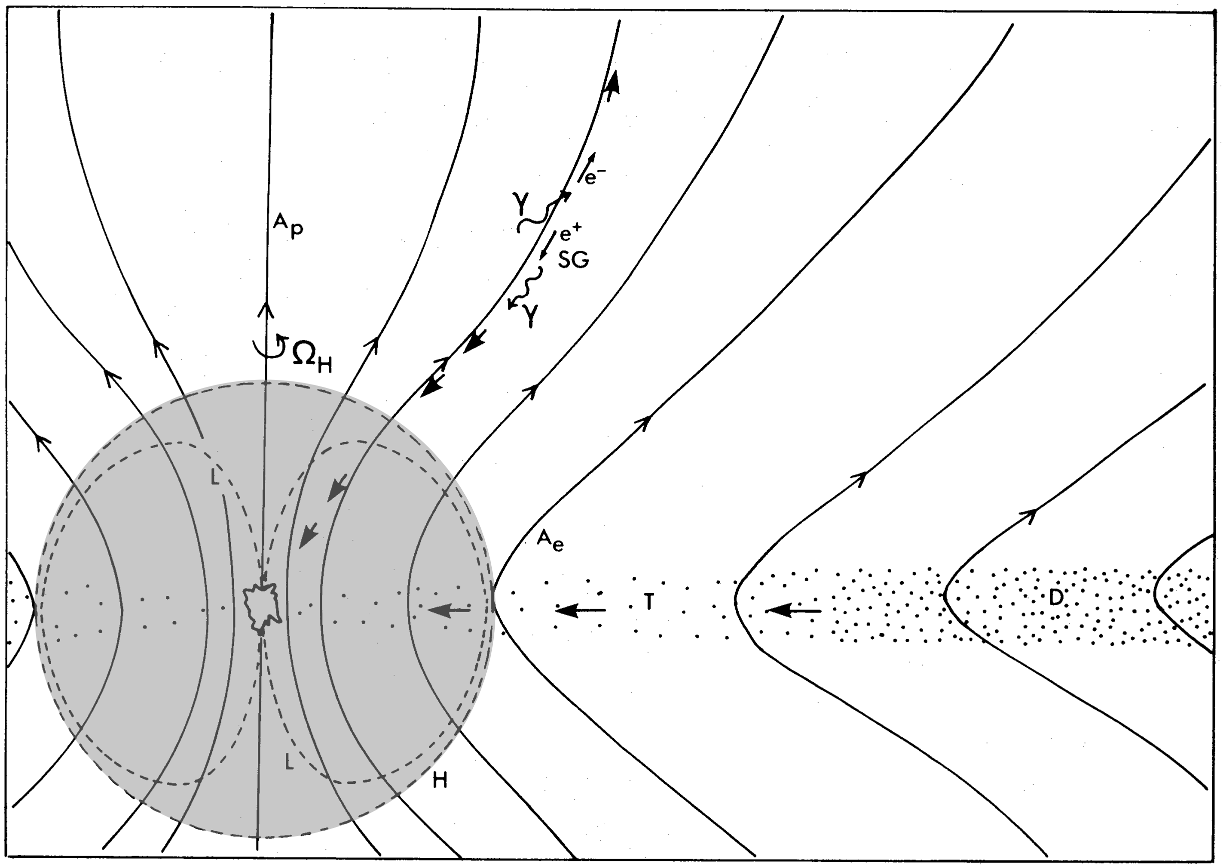
The analogy with pulsars



Contopoulos, Kazanas, Harding, Kalapotharakos

Blandford-Znajek revisited

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



Blandford, Znajek 1977

Blandford-Znajek revisited

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

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

The GR pulsar equation

$$\begin{aligned} ds^2 &= g_{\mu\nu} dx^\mu dx^\nu \\ &= -\alpha^2 dt^2 + \frac{A \sin^2\theta}{\Sigma}(d\phi - \Omega dt)^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 \end{aligned}$$

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

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

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

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

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

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

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

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

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

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

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

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

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

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

Contopoulos, Kazanas & Papadopoulos 2013

The GR pulsar equation

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

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

- 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

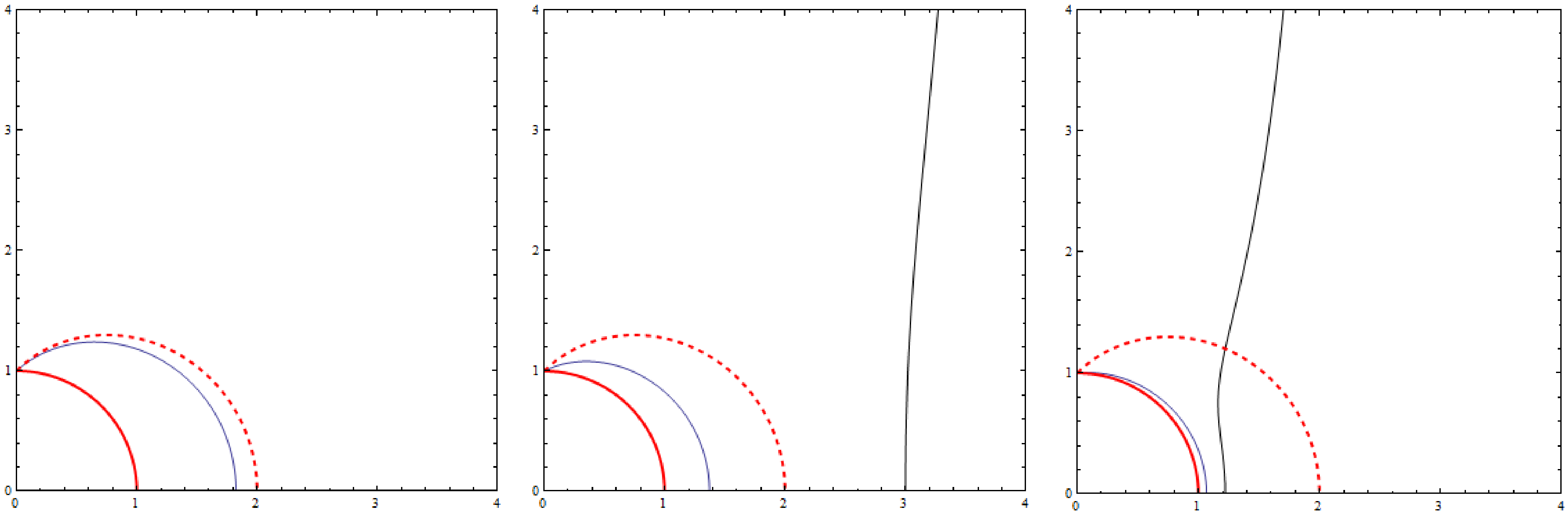
$$1 - \frac{\omega^2 A \sin^2\theta}{\Sigma} + \frac{4M\alpha\omega r \sin^2\theta}{\Sigma} - \frac{2Mr}{\Sigma} = 0$$

- 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

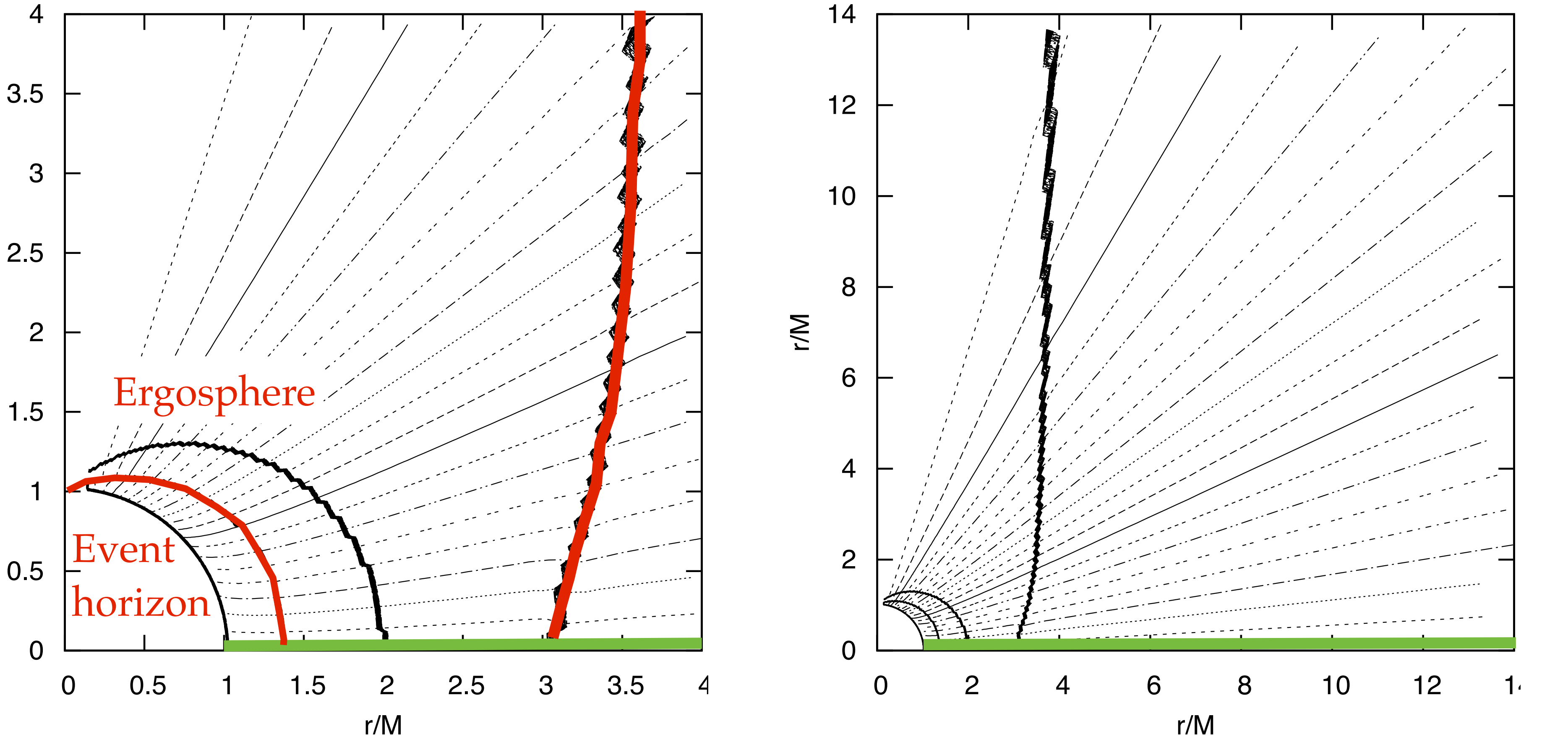
$\alpha = M,\ \omega = 0.1\ \Omega_{BH}$ | $\alpha = M,\ \omega = 0.5\ \Omega_{BH}$ | $\alpha = M,\ \omega = 0.9\ \Omega_{BH}$



Contopoulos, Kazanas, Papadopoulos 2013

The GR pulsar equation

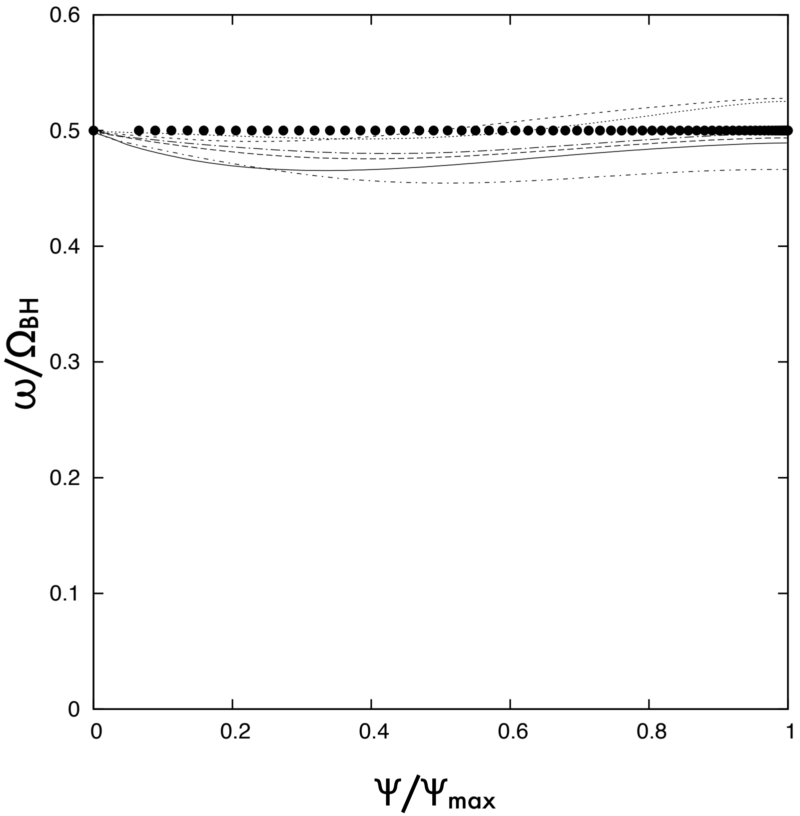
$\alpha = 0.9999M,\ \omega \sim 0.5\ \Omega_{BH}$

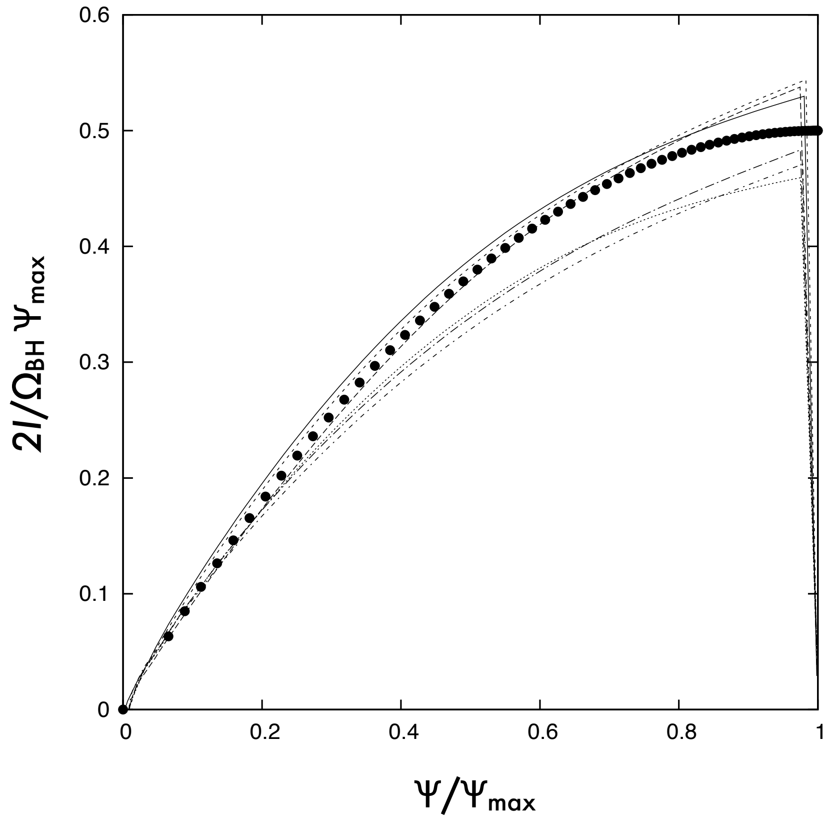


Contopoulos, Kazanas & Papadopoulos 2013

Blandford-Znajek revisited

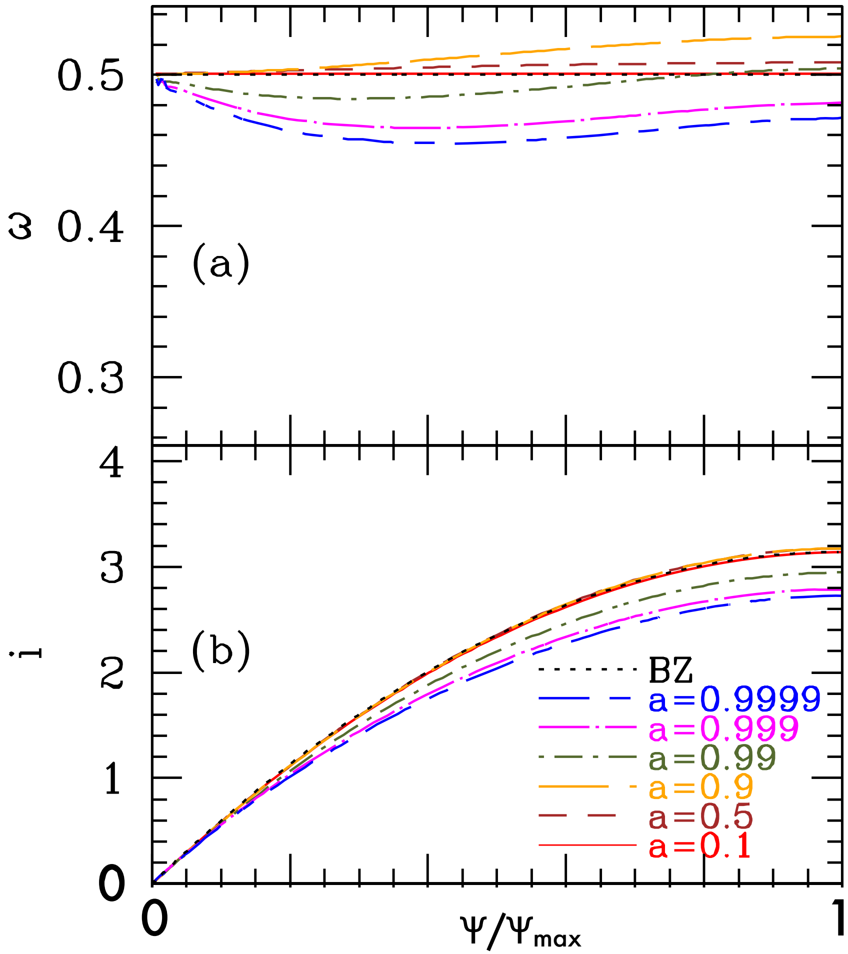
α=0.7-0.9999M, $\omega \sim 0.5\ \Omega_{BH}$



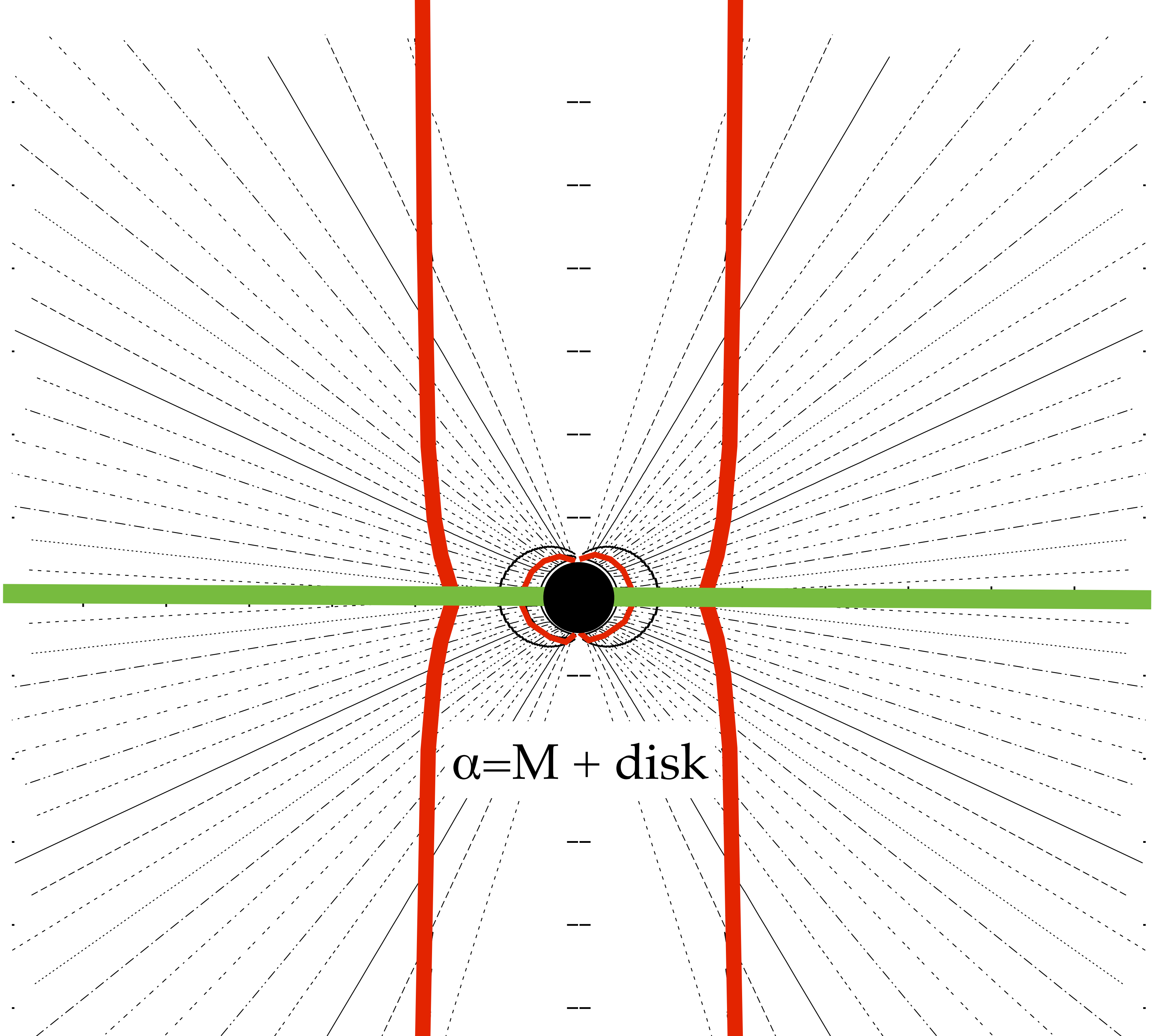


Contopoulos, Kazanas & Papadopoulos 2013

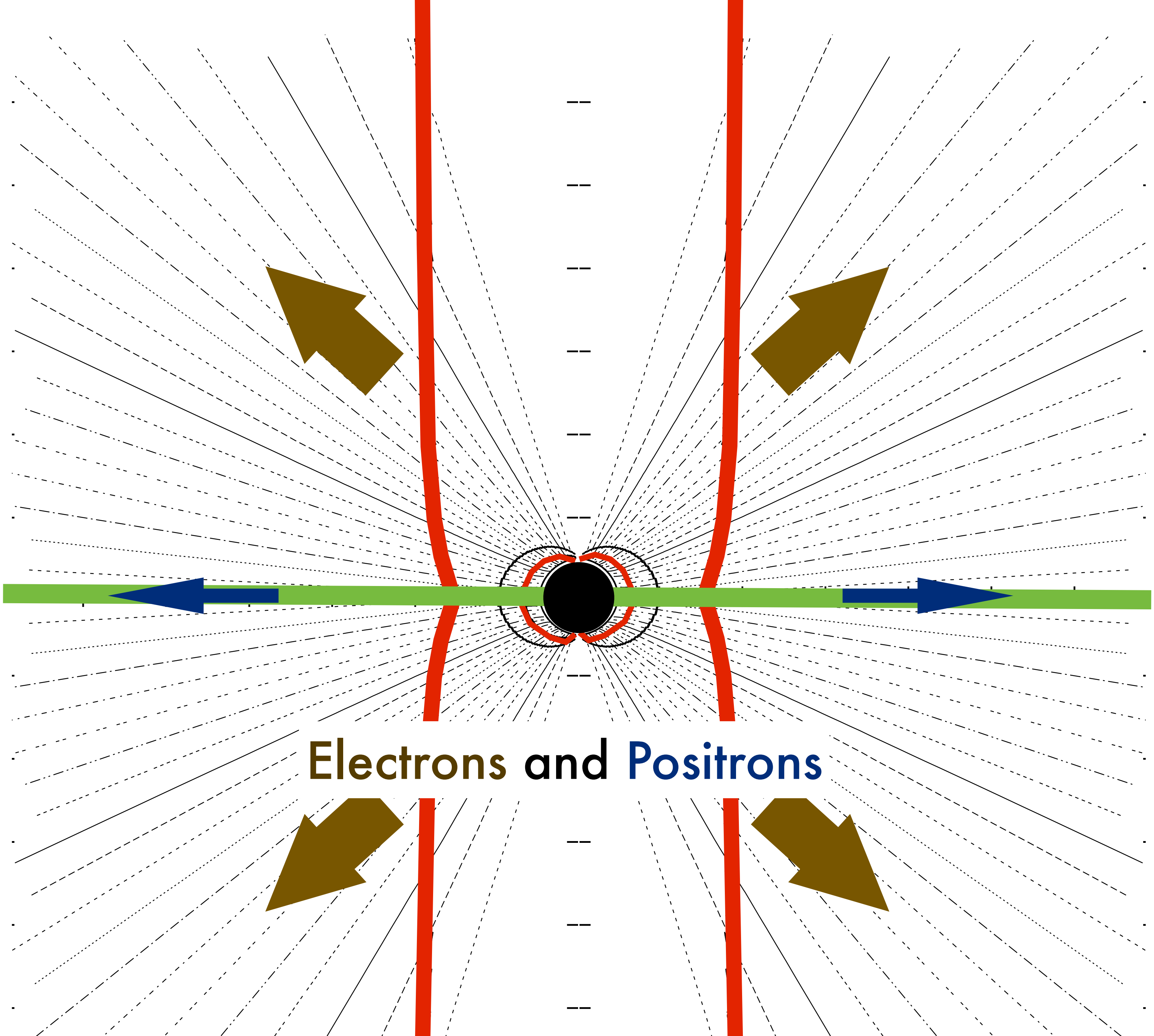
Blandford-Znajek revisited

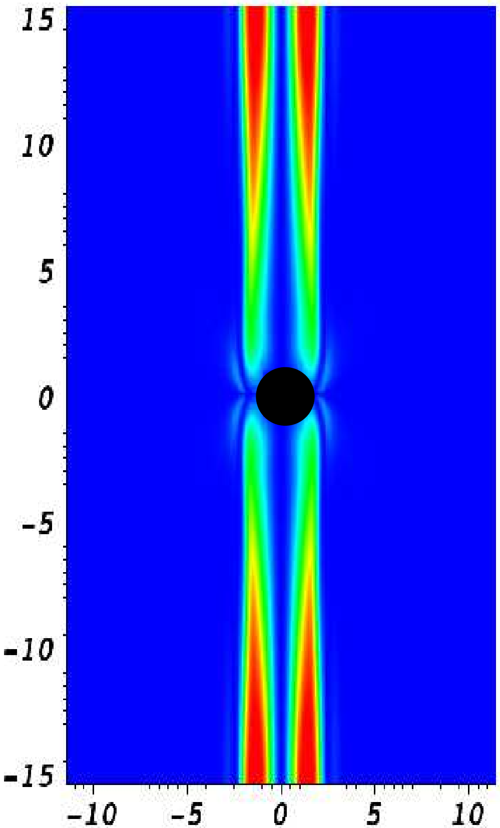


Tchekhovskoy, Narayan & McKinney 2010

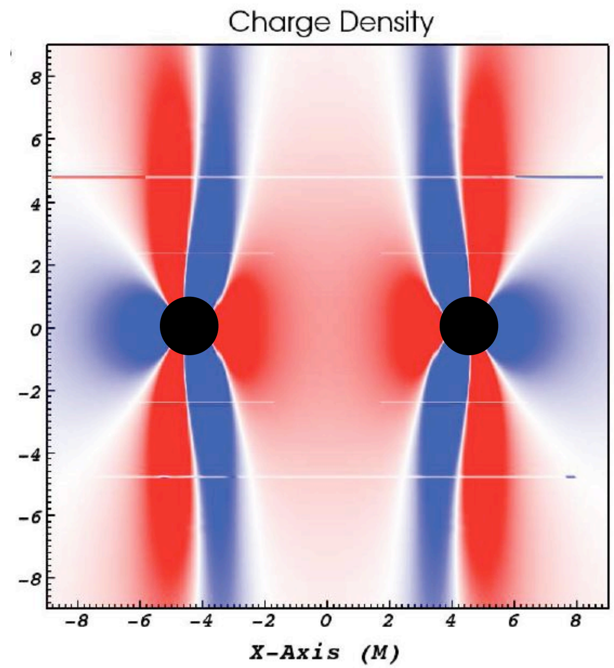


α=M + disk

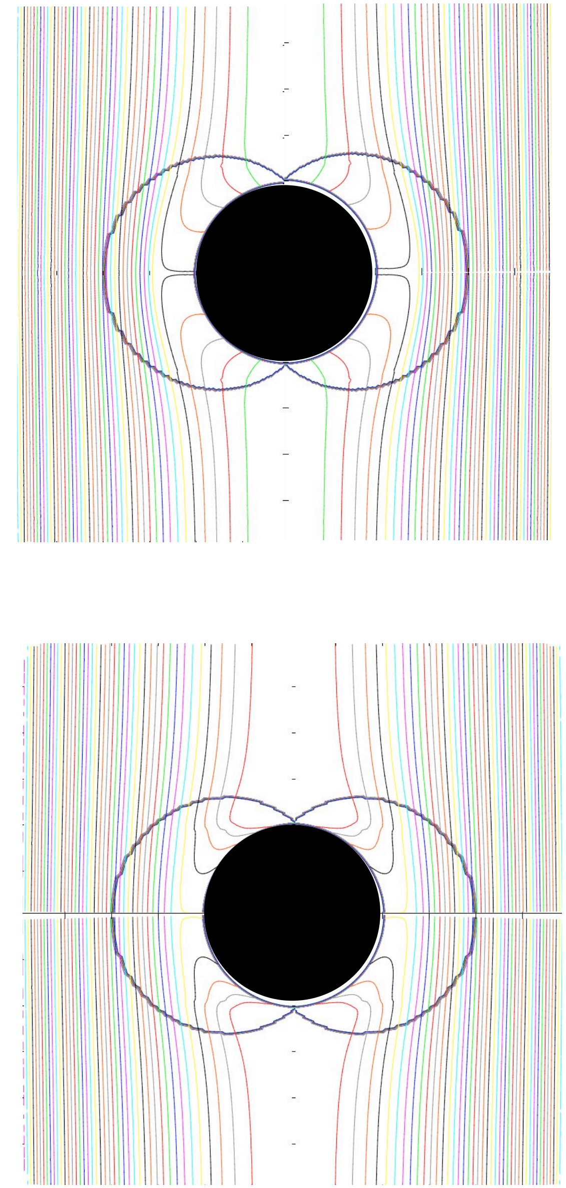

Electrons and Positrons



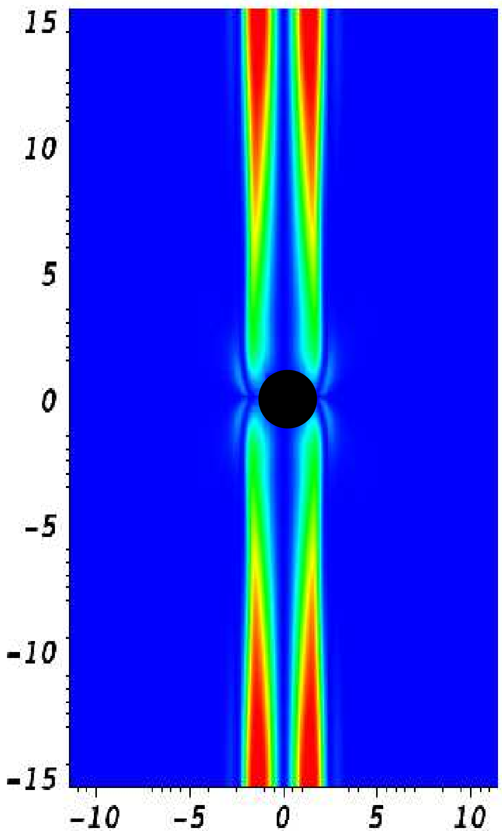
Palenzuela, Bona, Lehner, Reula 2011



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



Contopoulos et al. 2013 (in preparation)



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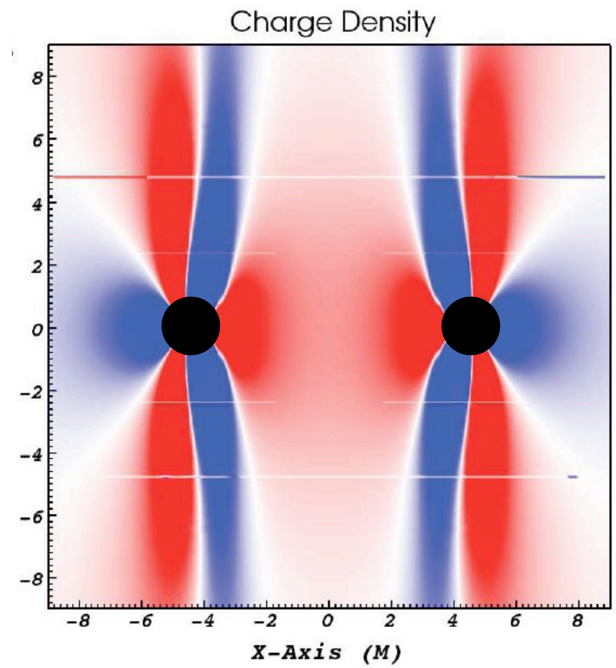
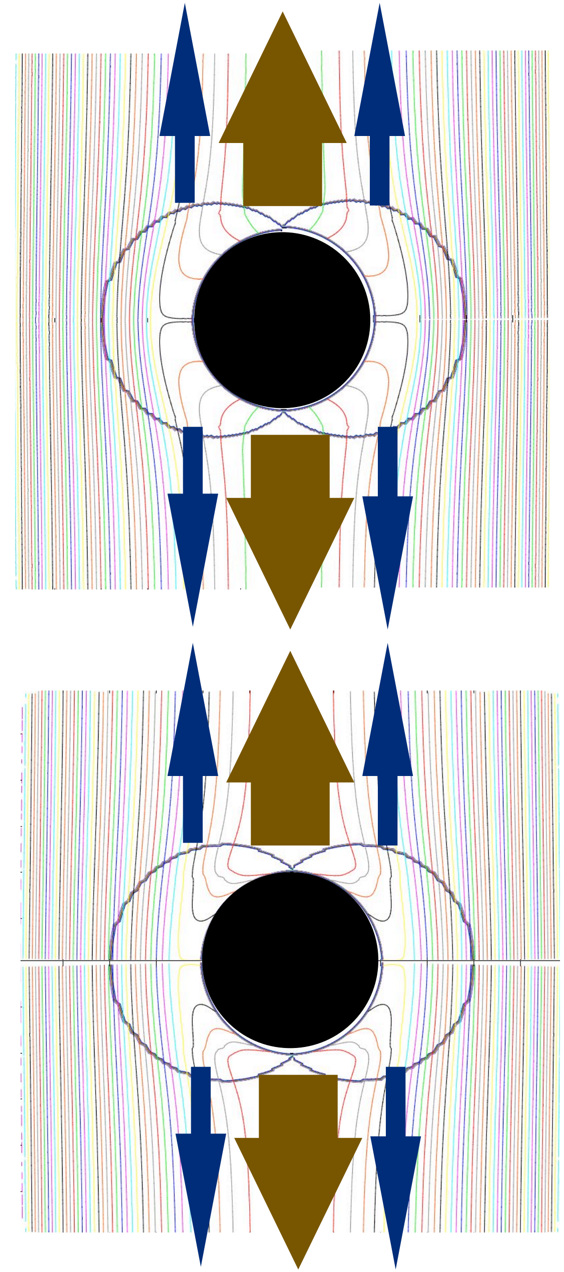


Alic, Moesta, Rezzolla, Jaramillo, Palenzuela, Zanotti 2013



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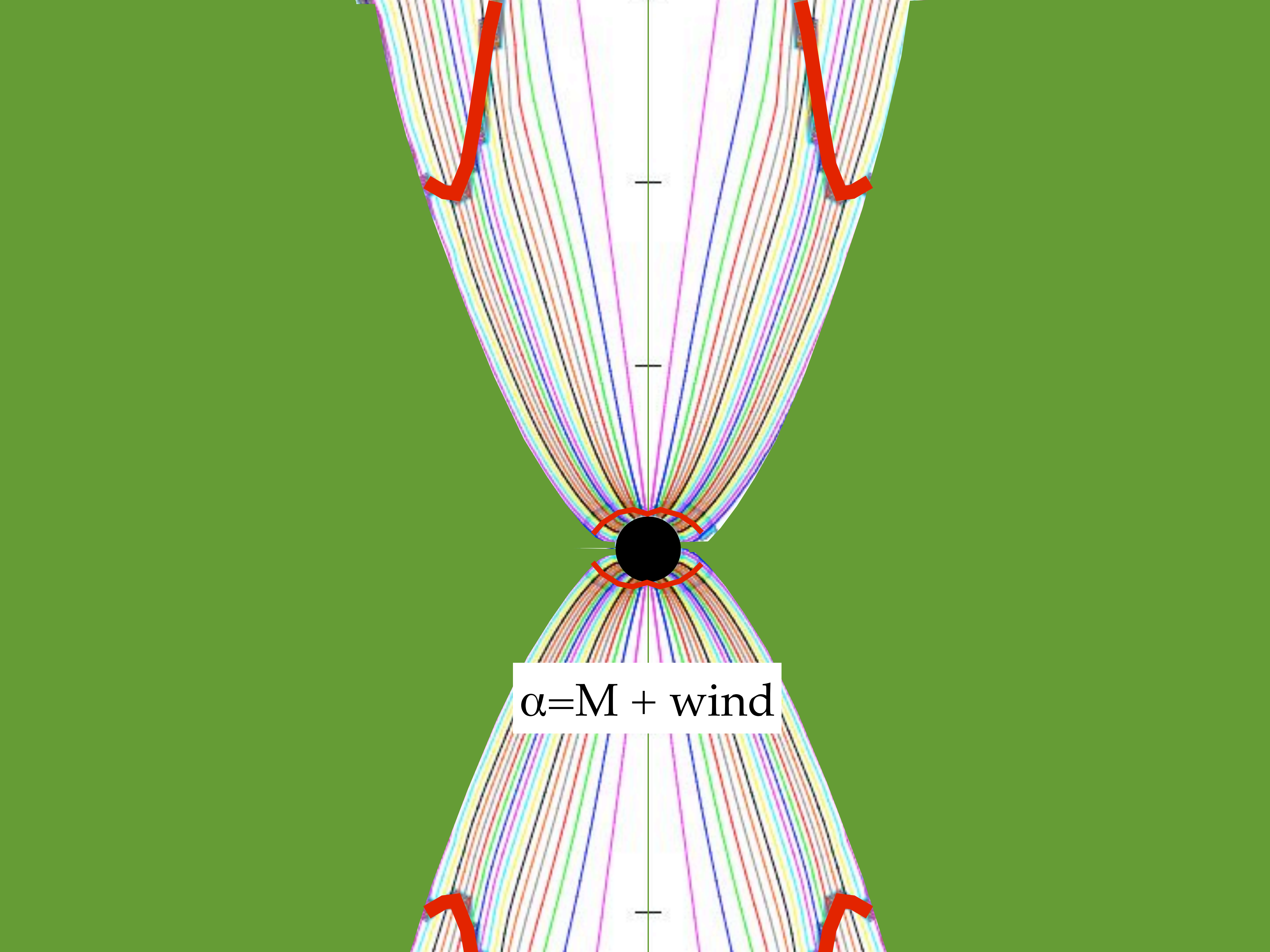
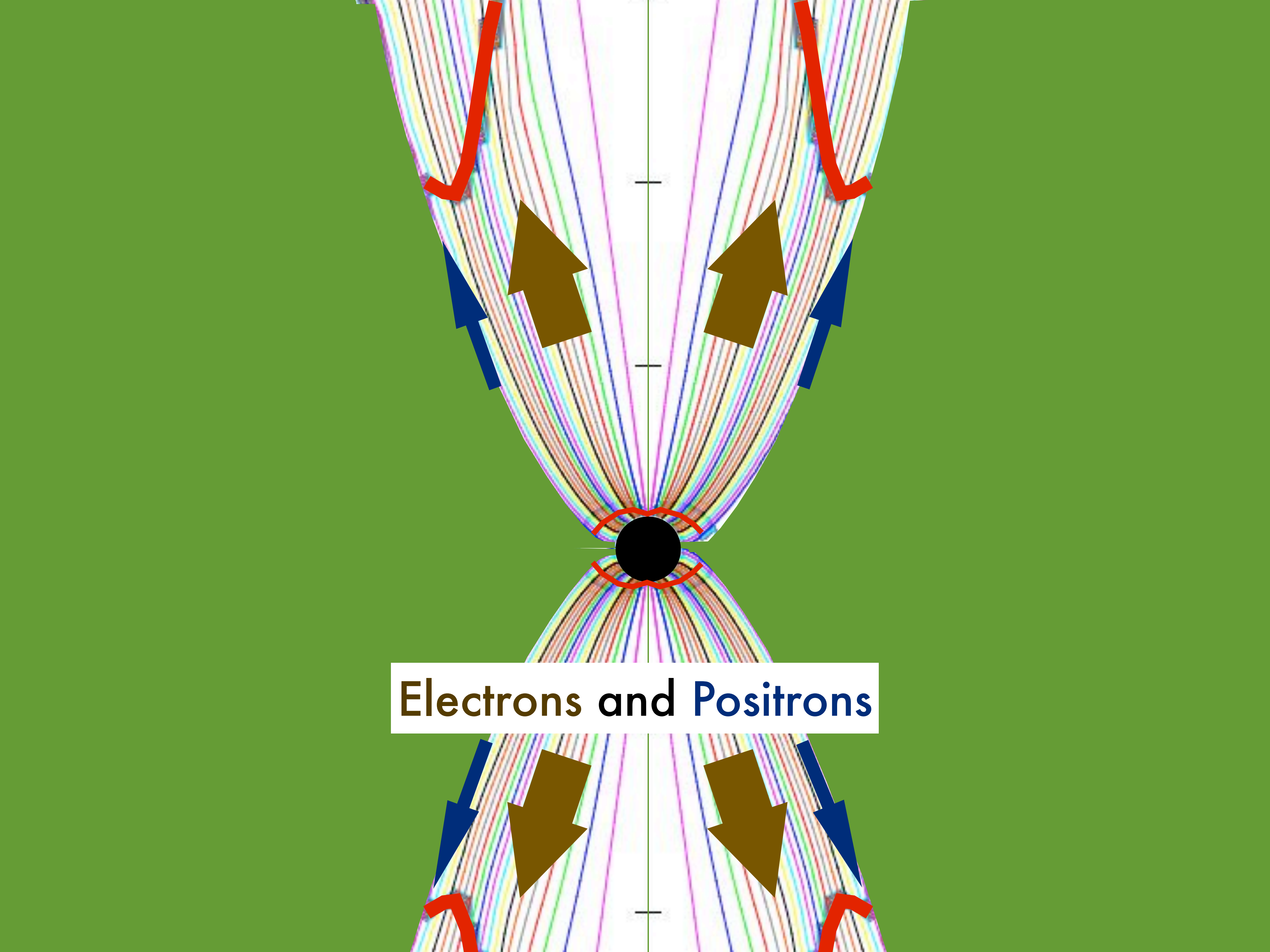
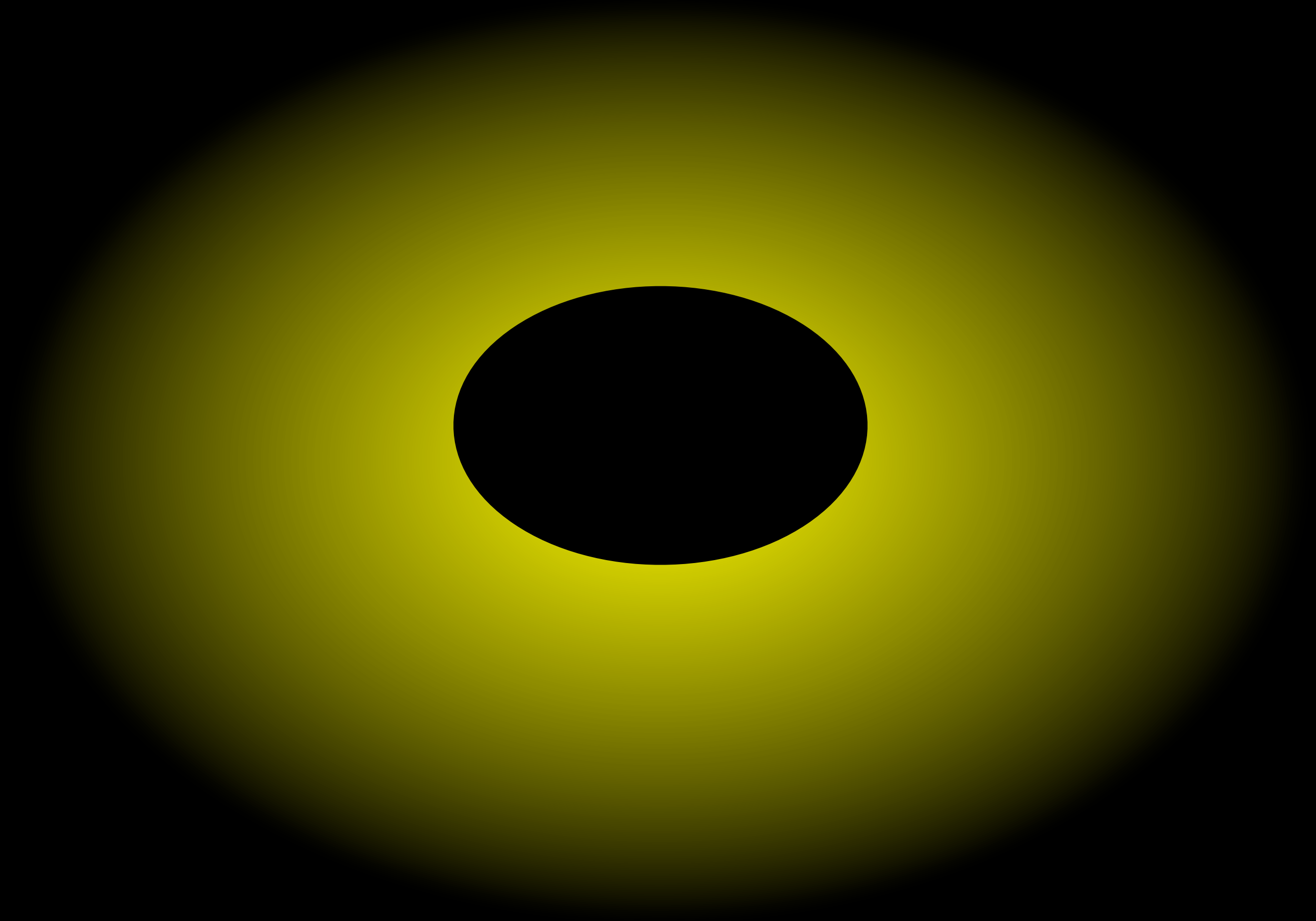
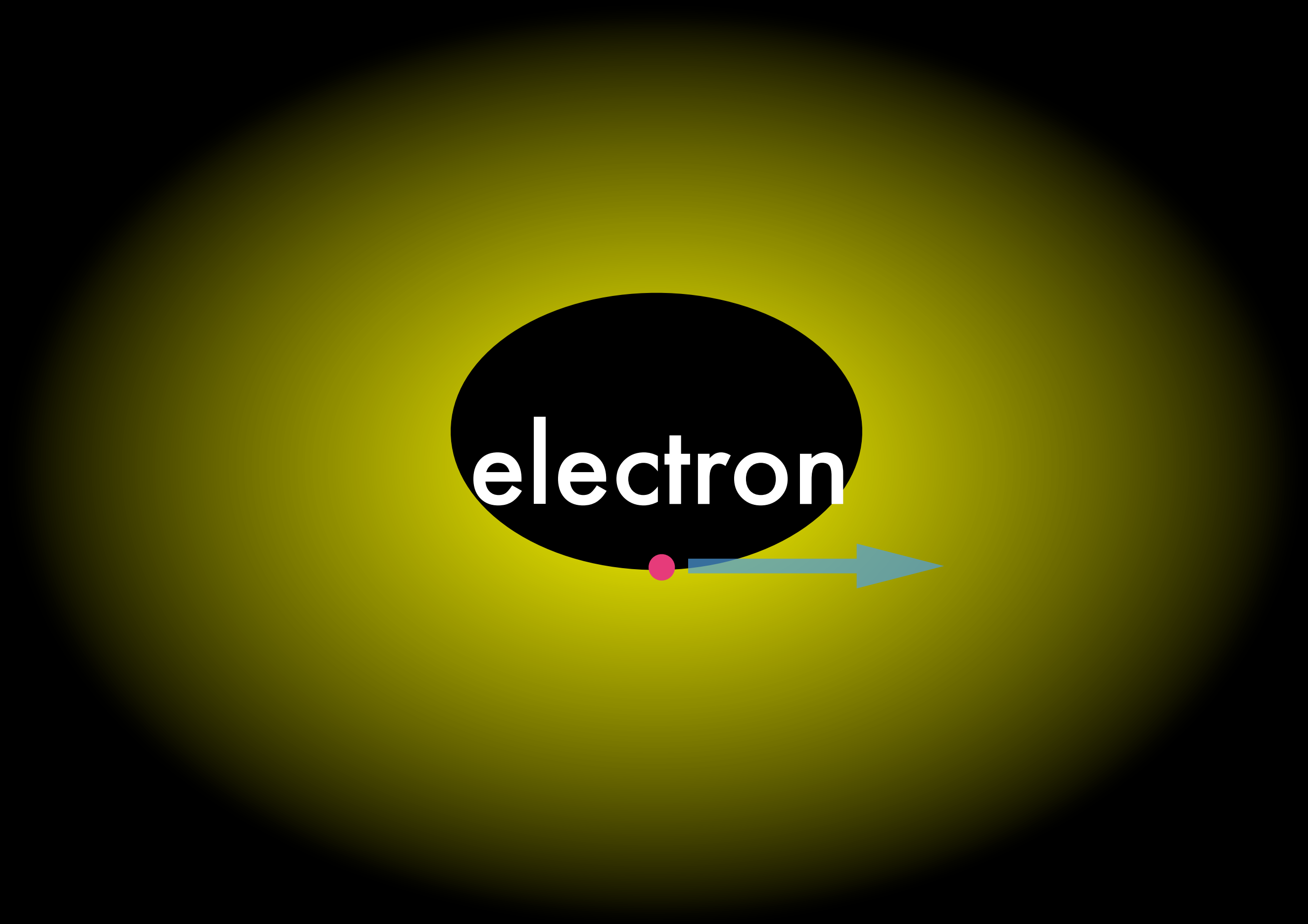

α=M + wind


Electrons and Positrons

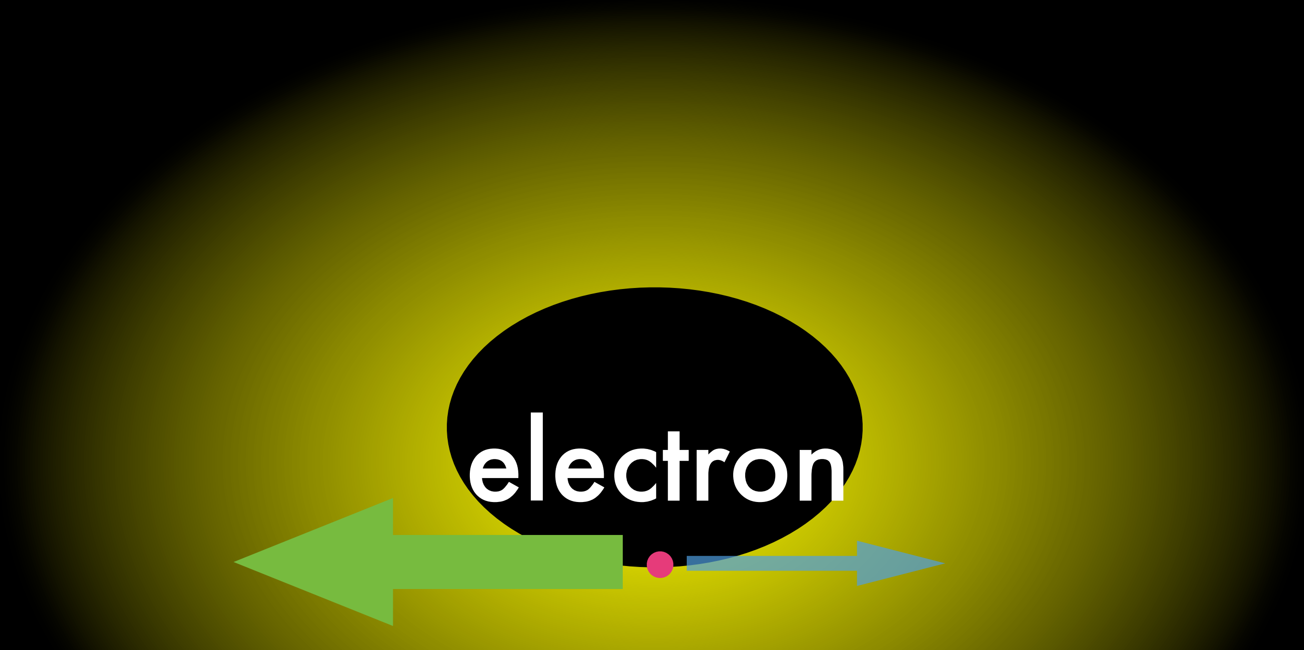
The Cosmic Battery



The Cosmic Battery



The Cosmic Battery

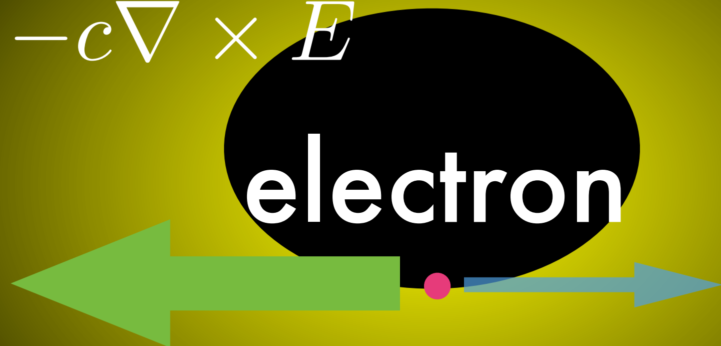


$$F_{PR} = -\frac{L\sigma_T}{4\pi r^2 c}\frac{v_\phi}{c}$$

The Cosmic Battery

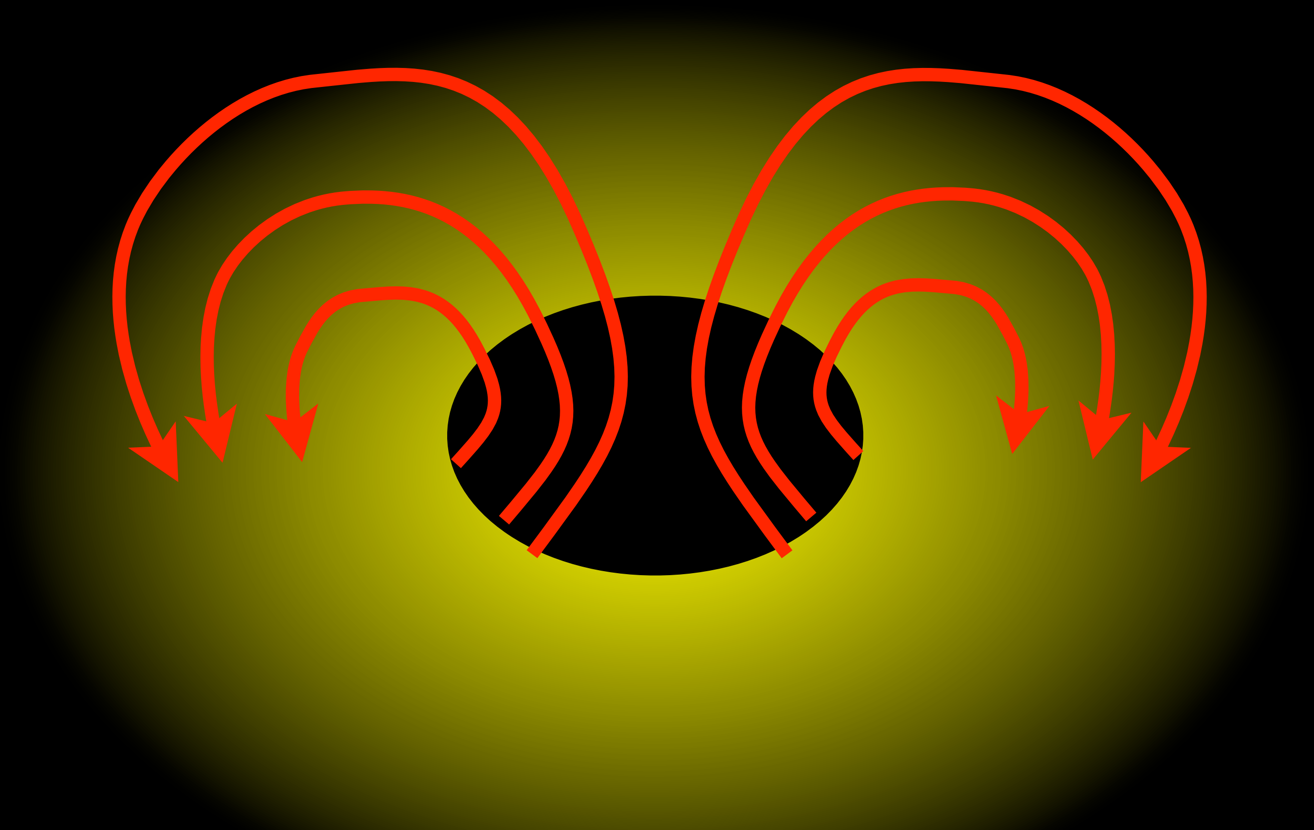
$$\nabla \times B = \frac{4\pi}{c} J \qquad -eE + F_{PR} = m_e \frac{\mathrm{d}v_e}{\mathrm{d}t}$$

$$\frac{\partial B}{\partial t} = -c\nabla \times E \qquad eE = m_p \frac{\mathrm{d}v_p}{\mathrm{d}t}$$



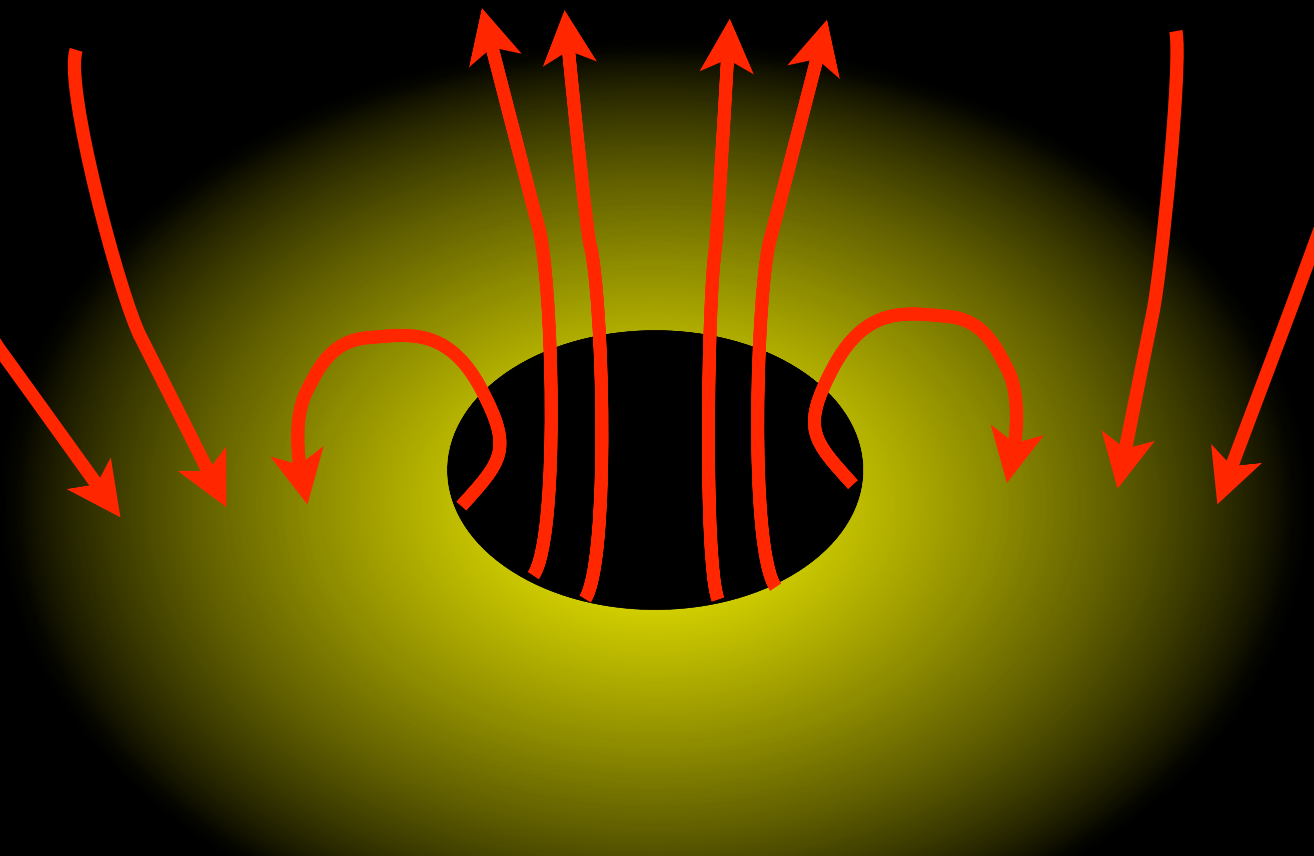
$$F_{PR} = -\frac{L\sigma_T}{4\pi r^2 c} \frac{v_\phi}{c}$$

The Cosmic Battery



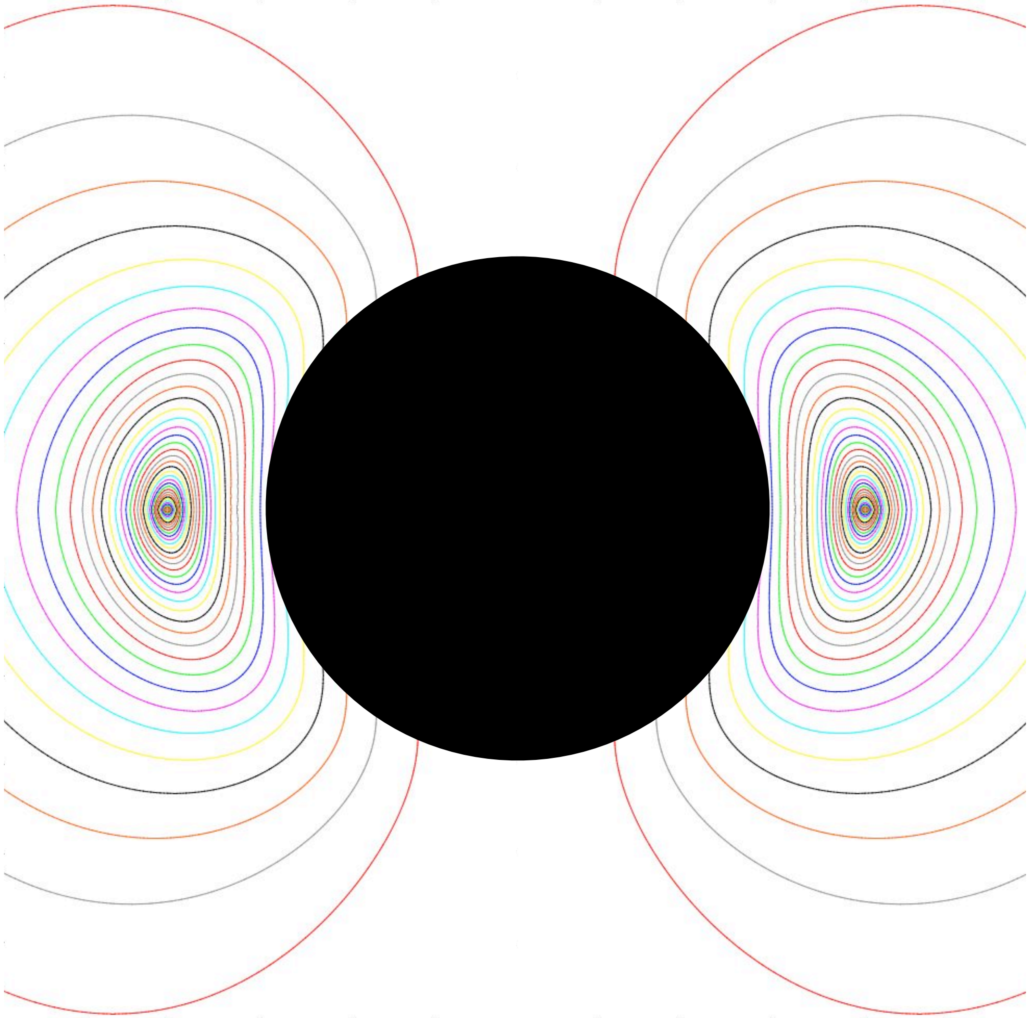
$$\frac{\partial B}{\partial t} = -c\nabla \times (\ldots + F_{PR}/e)$$

The Cosmic Battery



$$\frac{\partial B}{\partial t} = -c\nabla \times (\ldots + F_{PR}/e)$$

The Cosmic Battery



Conclusions

- In analogy with pulsars…
  - The light cylinder determines a unique solution
  - Isolated black holes do not produce jets
  - “Operational” black holes need very efficient pair formation above the horizon
- The background magnetic field may be generated in situ by the Cosmic Battery