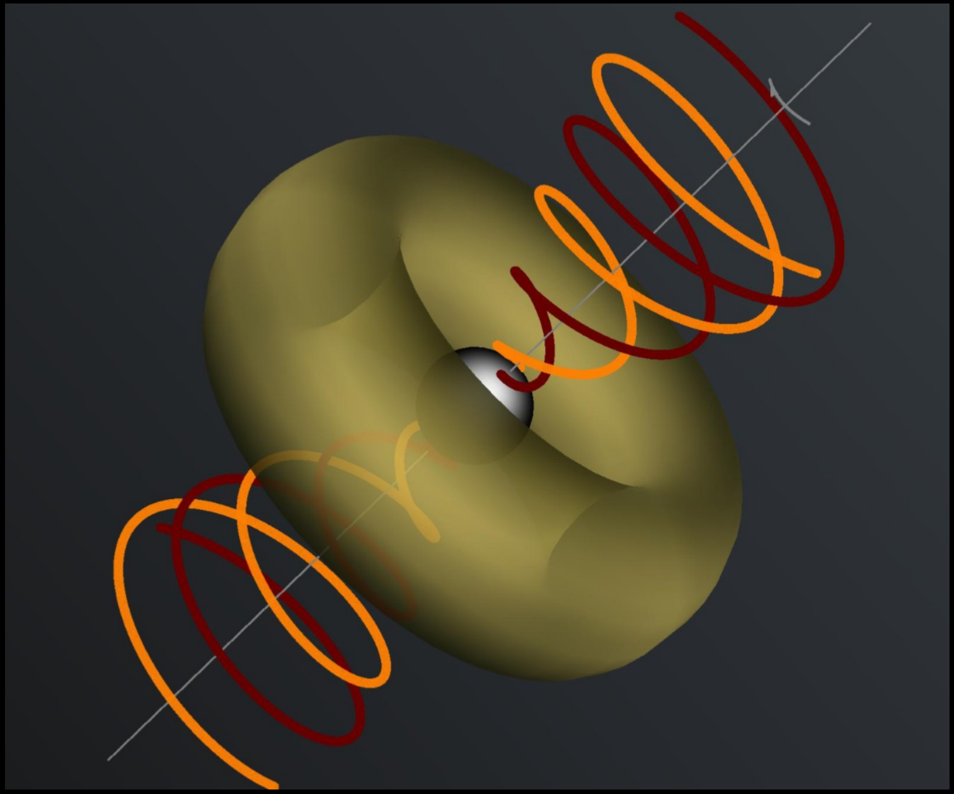
Black hole magnetospheres: how they work and application to GRBs



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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
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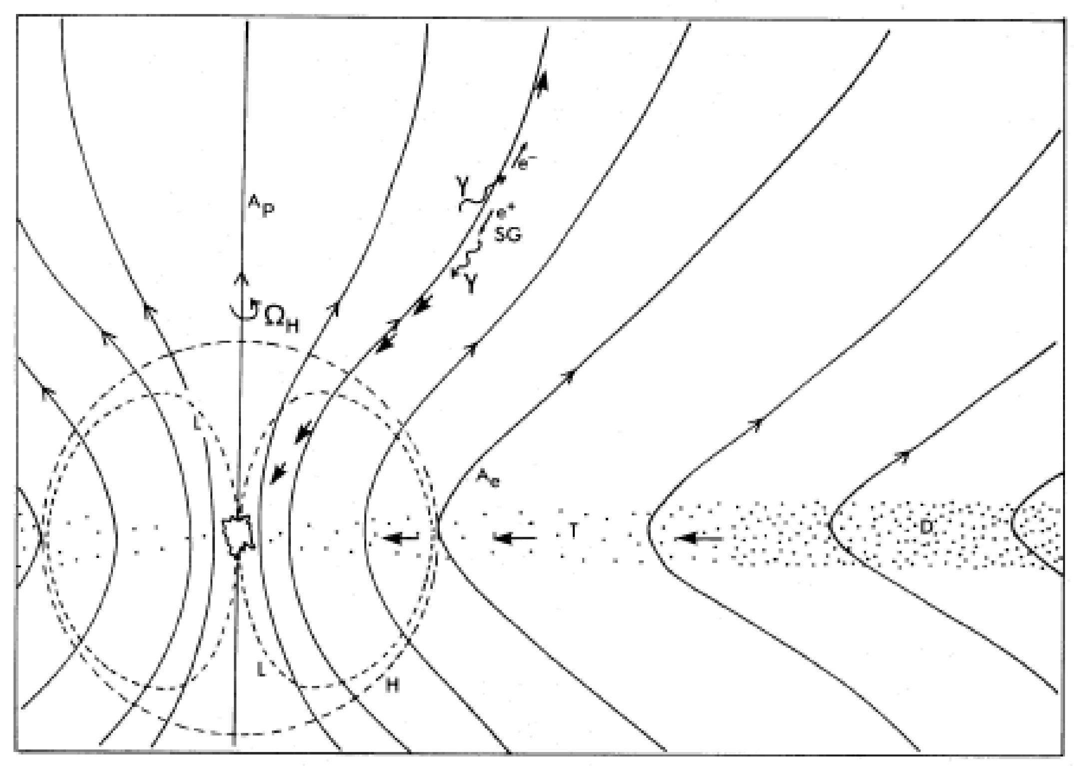
Co- financed by Greece and the European Union

Blandford & Znajek 1977

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

Magnetic field is supported by external currents in an accretion disc



Ingredients to describe the problem

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

Kerr metric

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

Macdonald & Thorne 1982

Ingredients to describe the problem

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

Ideal

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

force-free

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

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

Contopoulos, Kazanas, Papadopoulos 2013

Blandford & Znajek equation

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

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

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

$$-2\omega\Omega\varpi^2\frac{\Psi_{,\theta}}{\Delta}\frac{A_{,\theta}}{A} - 2Mr\Sigma_{,\theta}\frac{\Psi_{,\theta}}{\Delta\Sigma^2}$$

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

$$= -\frac{4\Sigma}{\Delta}II'$$

Contopoulos, Kazanas, Papadopoulos 2013

Blandford & Znajek equation

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

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

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

$$-2\omega\Omega\varpi^2\frac{\Psi_{,\theta}}{\Delta}\frac{A_{,\theta}}{A} - 2Mr\Sigma_{,\theta}\frac{\Psi_{,\theta}}{\Delta\Sigma^2}$$

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

$$= -\frac{4\Sigma}{\Delta}II'$$

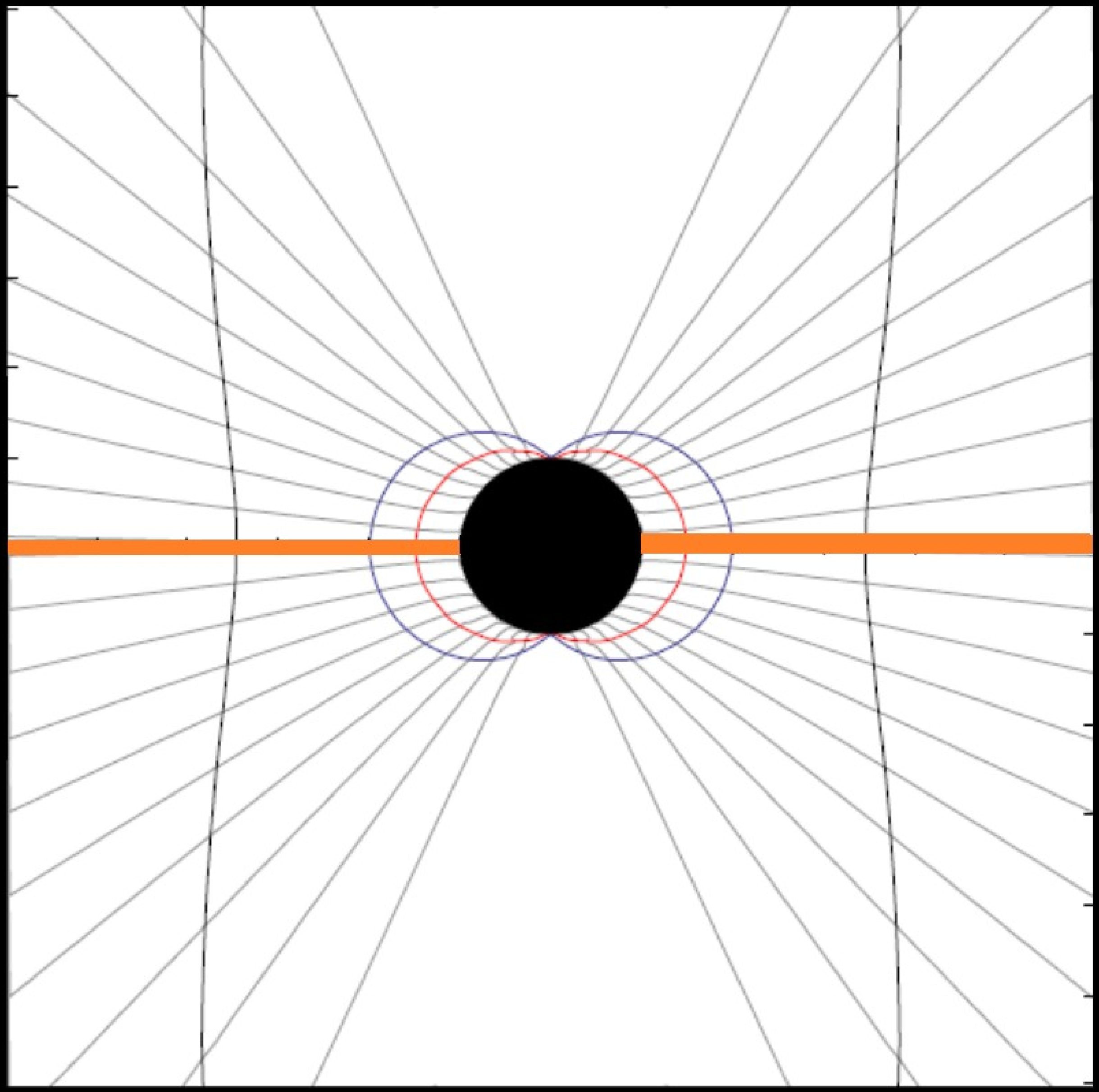
Nathanail & Contopoulos 2014

The Black Hole Problem has two light surfaces

$$\cdot\left[1 - \frac{2Mr}{\Sigma} + \frac{4Ma\omega r\sin^2\theta}{\Sigma} - \frac{\omega^2 A\sin^2\theta}{\Sigma}\right]$$

The electric current I(Ψ) and angular velocity of the field lines ω(Ψ) must be determined self-consistently

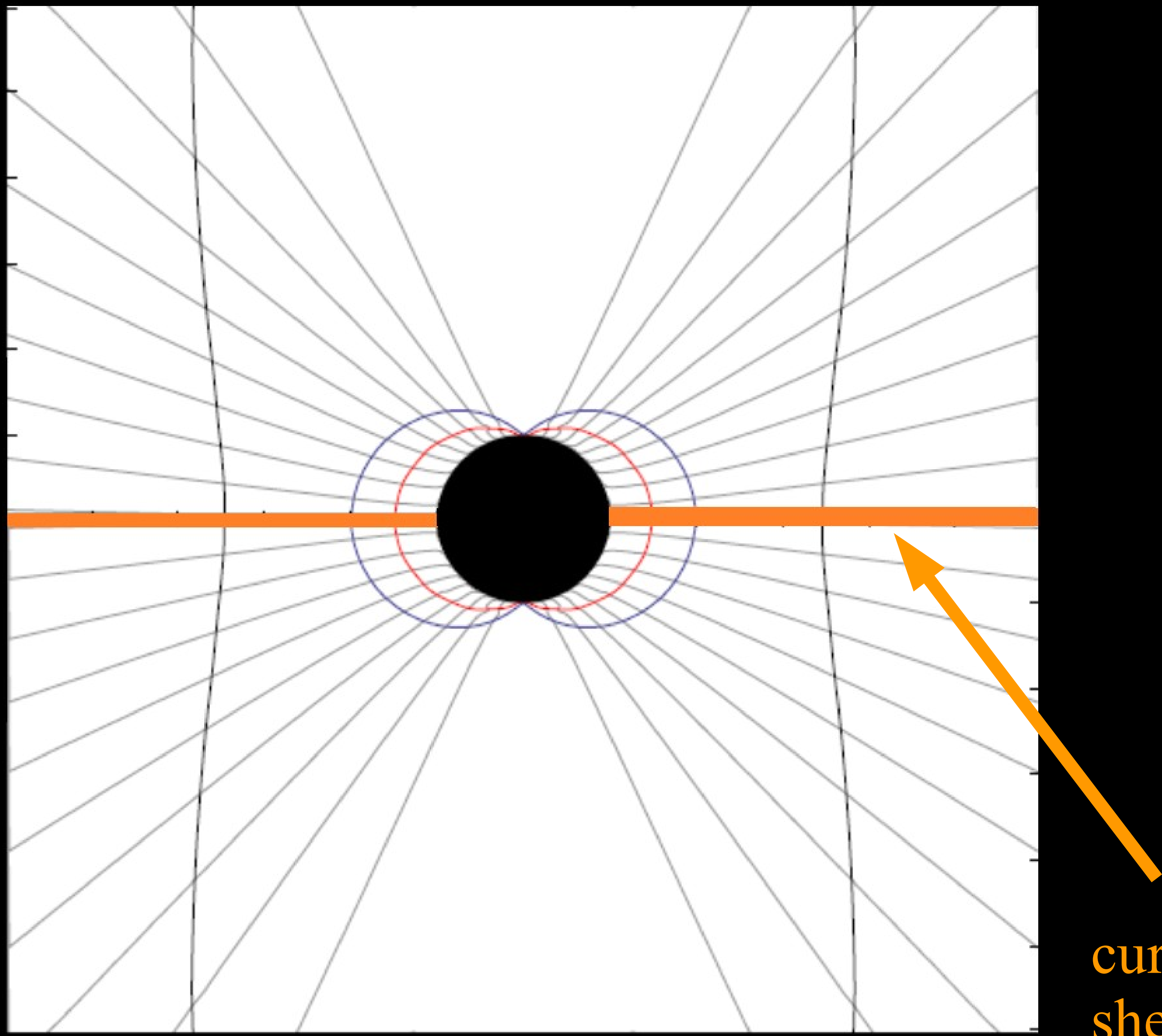
Nathanail & Contopoulos 2014



α = 0.999

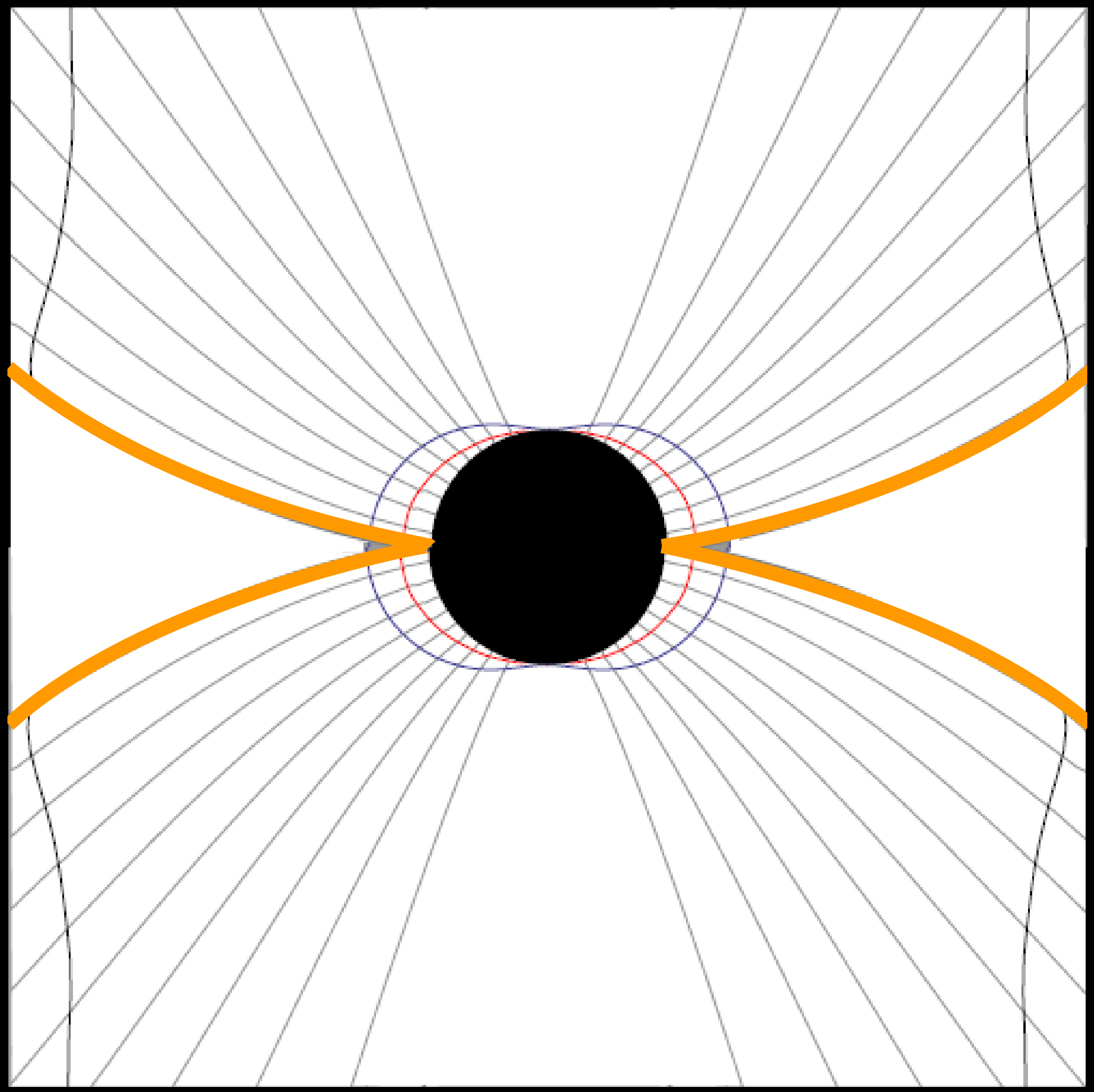
Nathanail & Contopoulos 2014

α = 0.999



Nathanail & Contopoulos 2014

$\alpha = 0.999$



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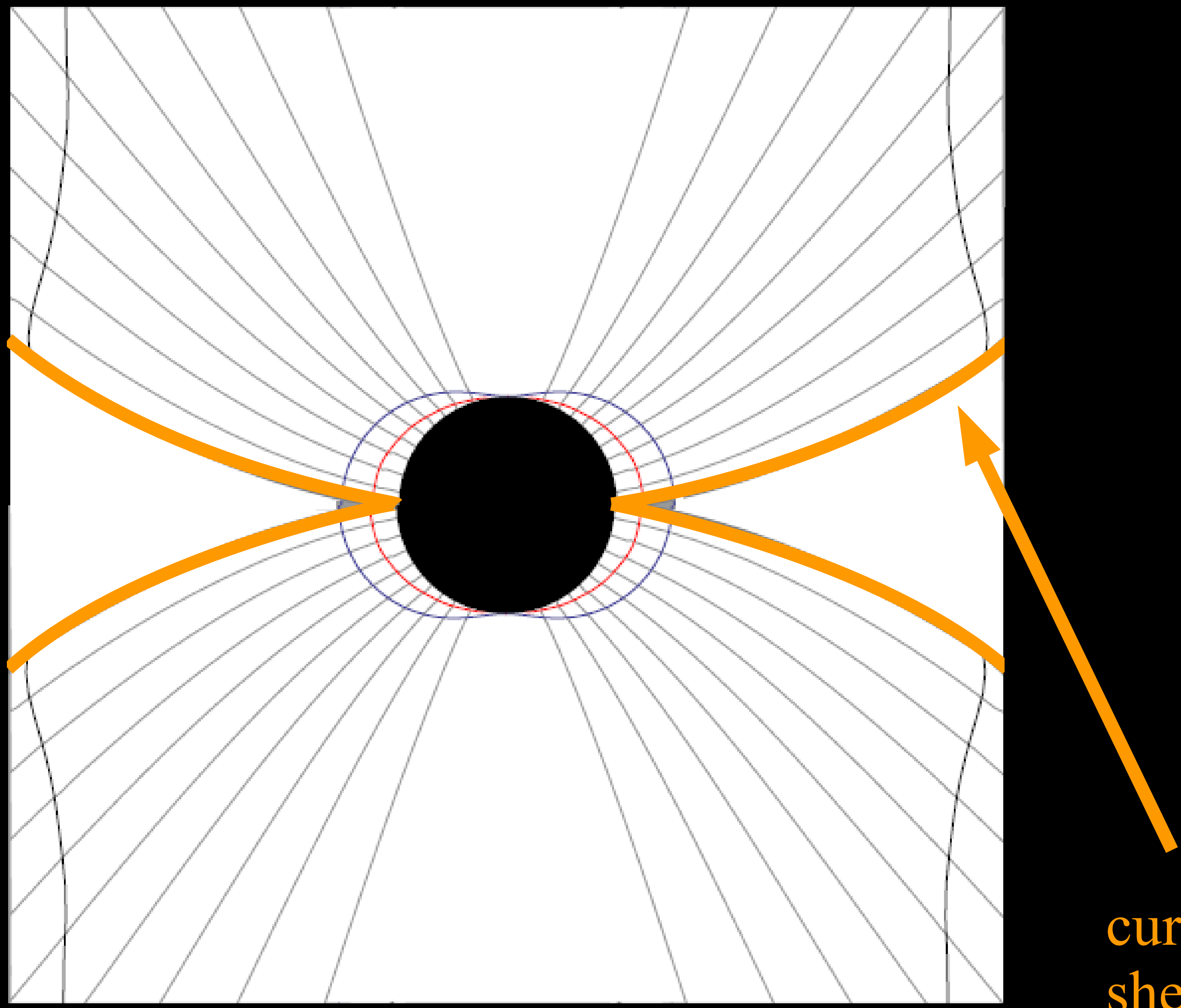
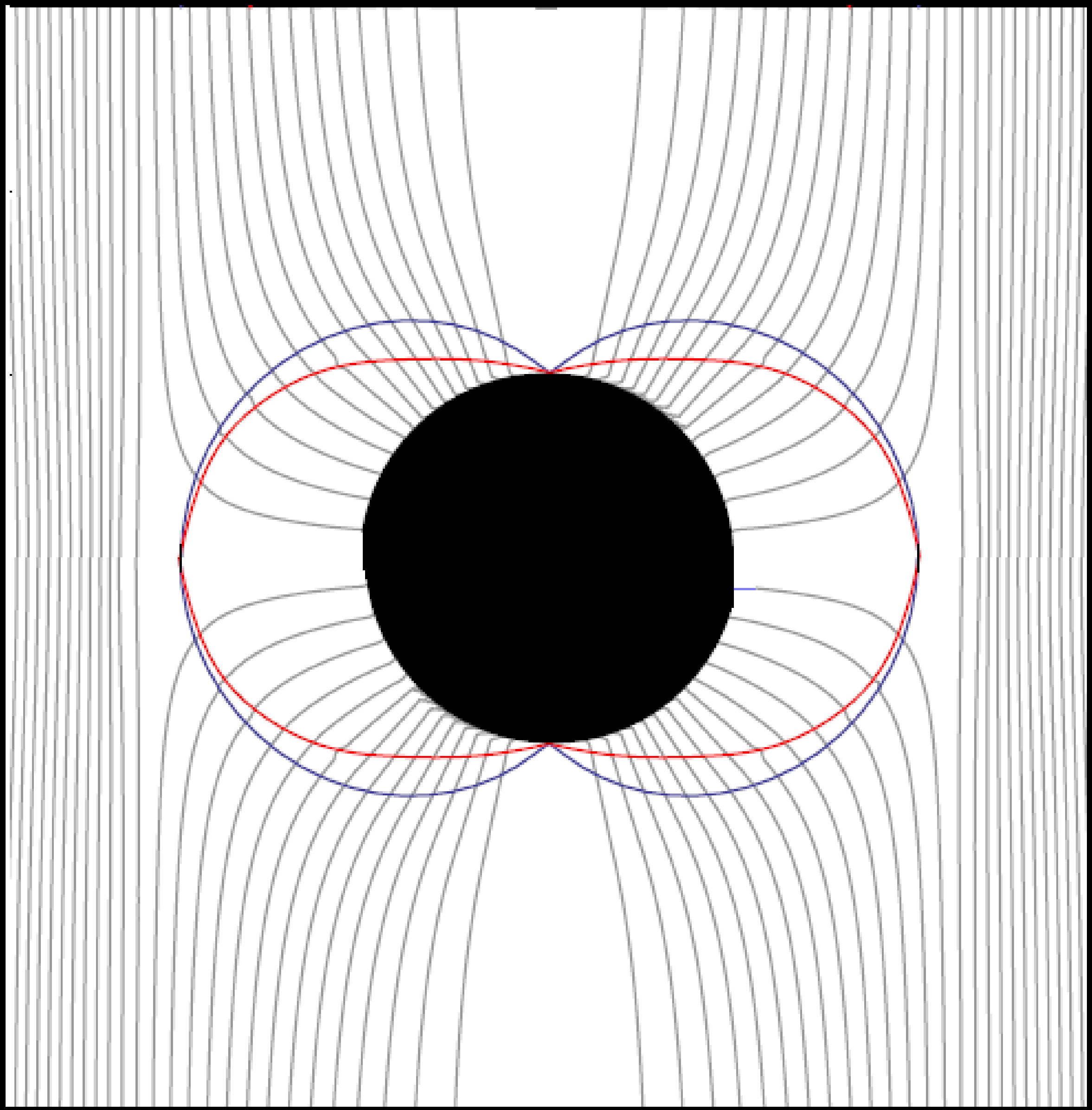
α = 0.999



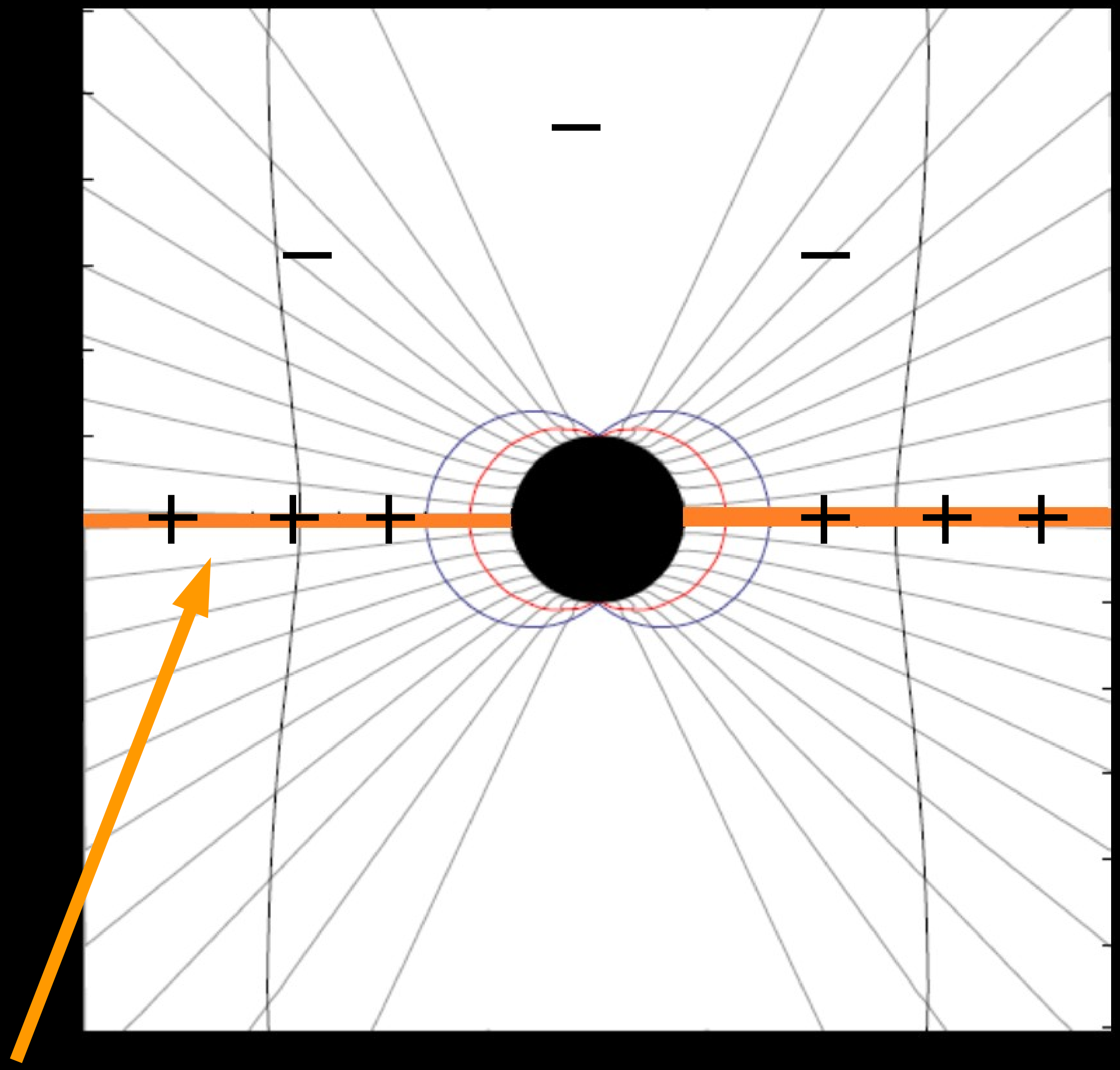
Nathanail & Contopoulos 2014

Only one Light Surface $\omega(\Psi)$ is given



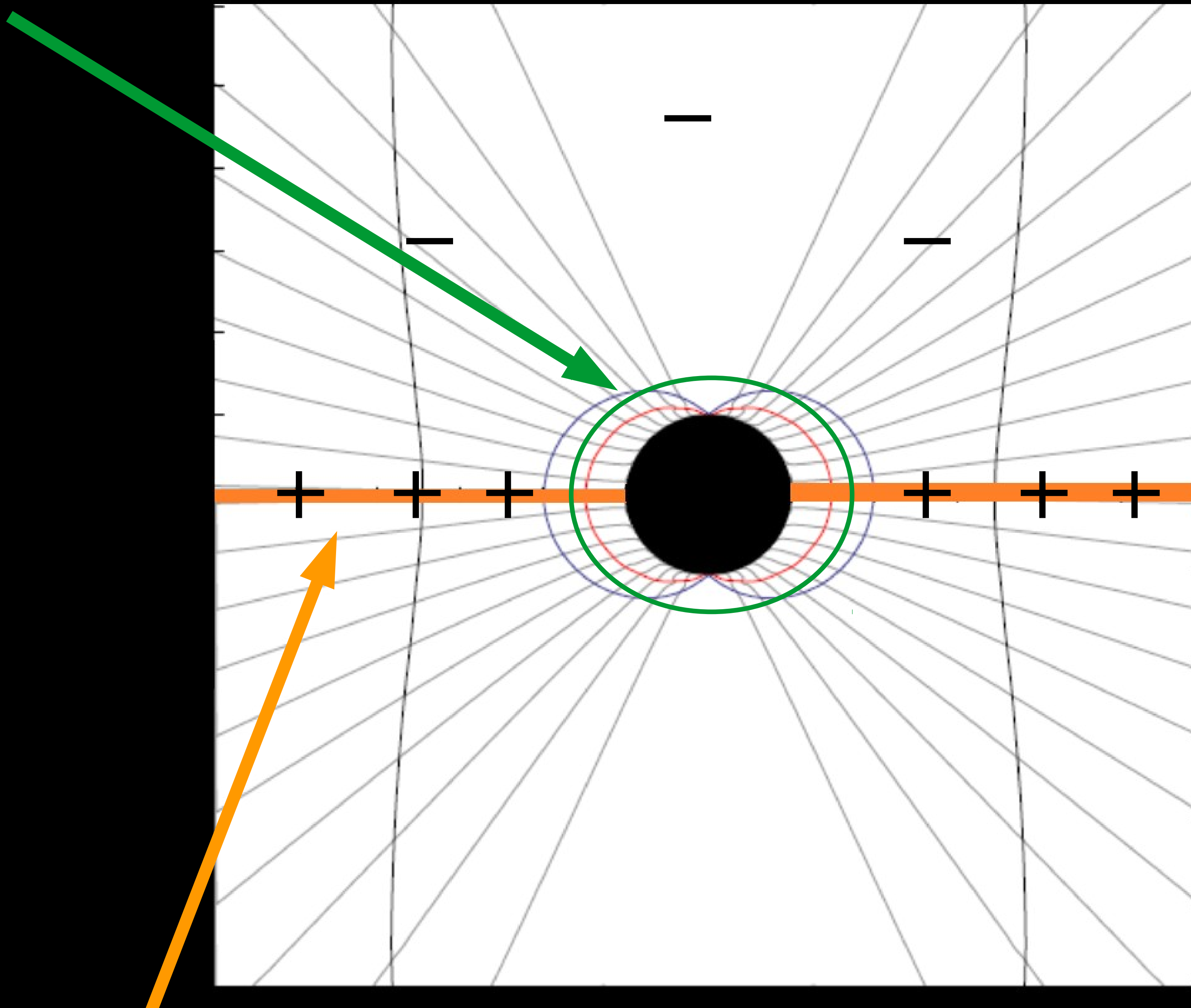
$\alpha = 0.999$

Nathanail & Contopoulos 2014



$E_{\parallel}$

The CS parallel electric field will accelerate particles zero charge surface



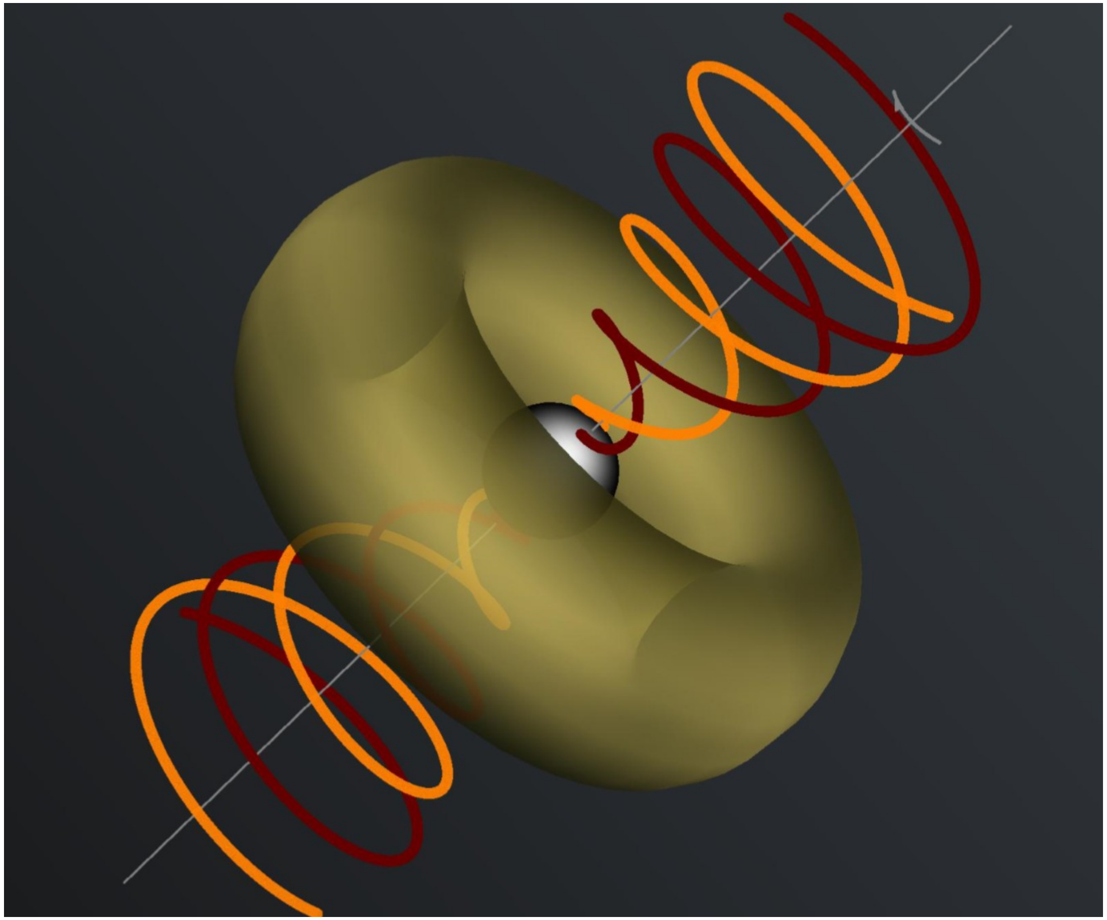
$E_{\parallel}$

The CS parallel electric field will accelerate particles

Prime movers in GRBs?

$$\dot{E} \approx -\frac{1}{6\pi^2 c}\Psi_m^2\Omega^2$$

BZ mechanism

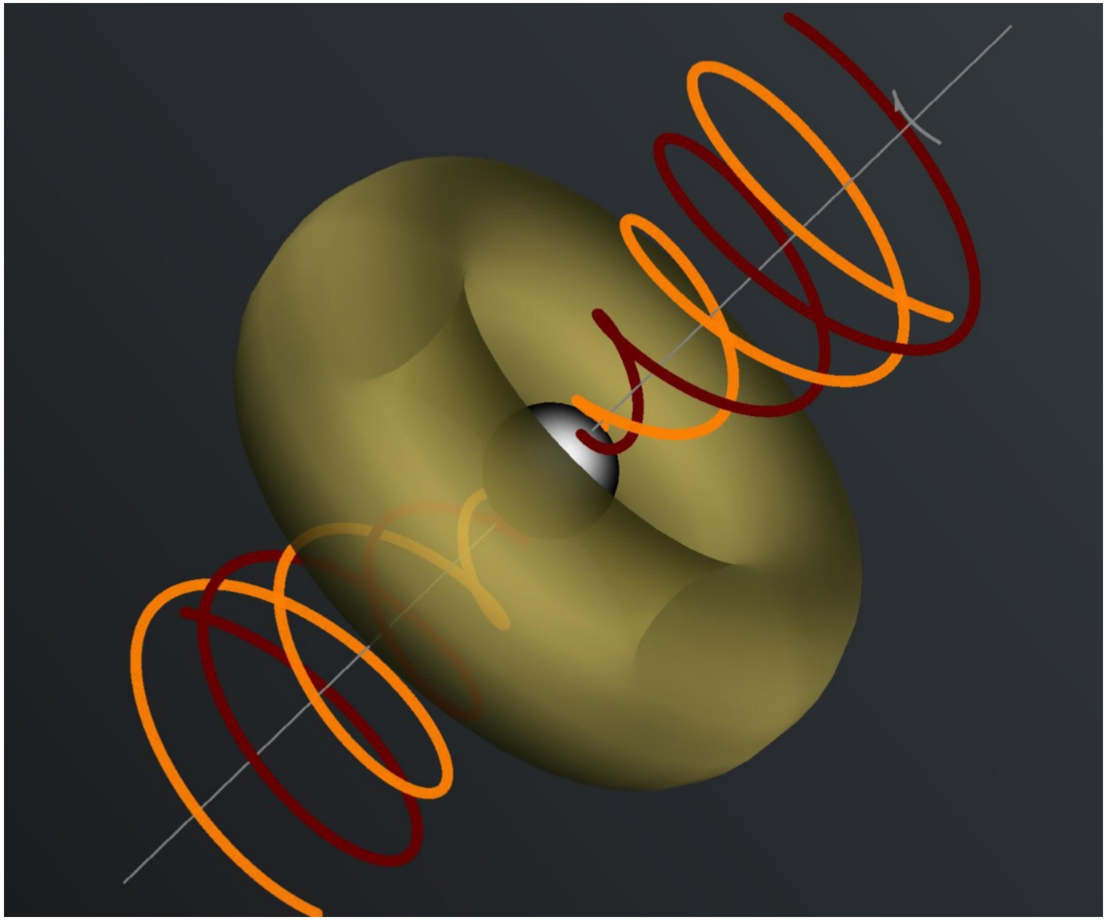


Rotational Energy of the Black Hole

$$\dot{E} \approx -\frac{1}{6\pi^2 c}\Psi_m^2\Omega^2$$

Equate with

$$\dot{E} = \frac{\mathcal{G}M^2}{c}\frac{\mathrm{d}(a\Omega/M)}{\mathrm{d}t}$$



Black Hole Spin Down

$$\dot{E} = \dot{E}_o \frac{W\left(-\frac{1}{2}e^{-\frac{1}{2}-\frac{t}{t_{BZ}}}\right)}{1+W\left(-\frac{1}{2}e^{-\frac{1}{2}-\frac{t}{t_{BZ}}}\right)}$$

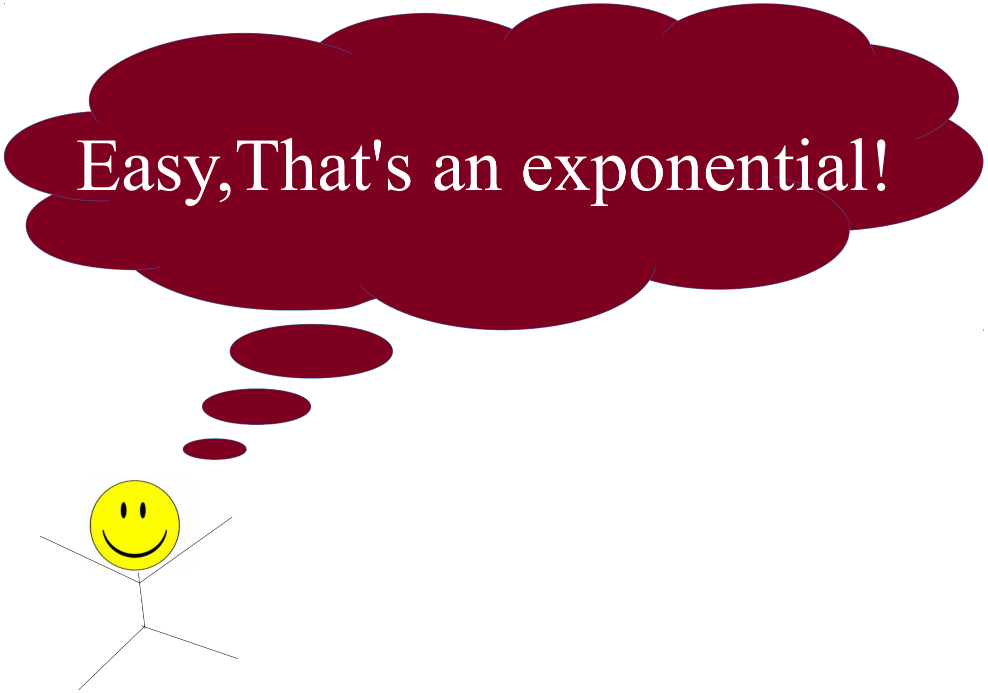
W(x)

Lambert *W* function

Contopoulos, Nathanail, Pugliese 2014

Black Hole Spin Down

$$\dot{E} \approx \dot{E}_o e^{-t/t_{BZ}}$$



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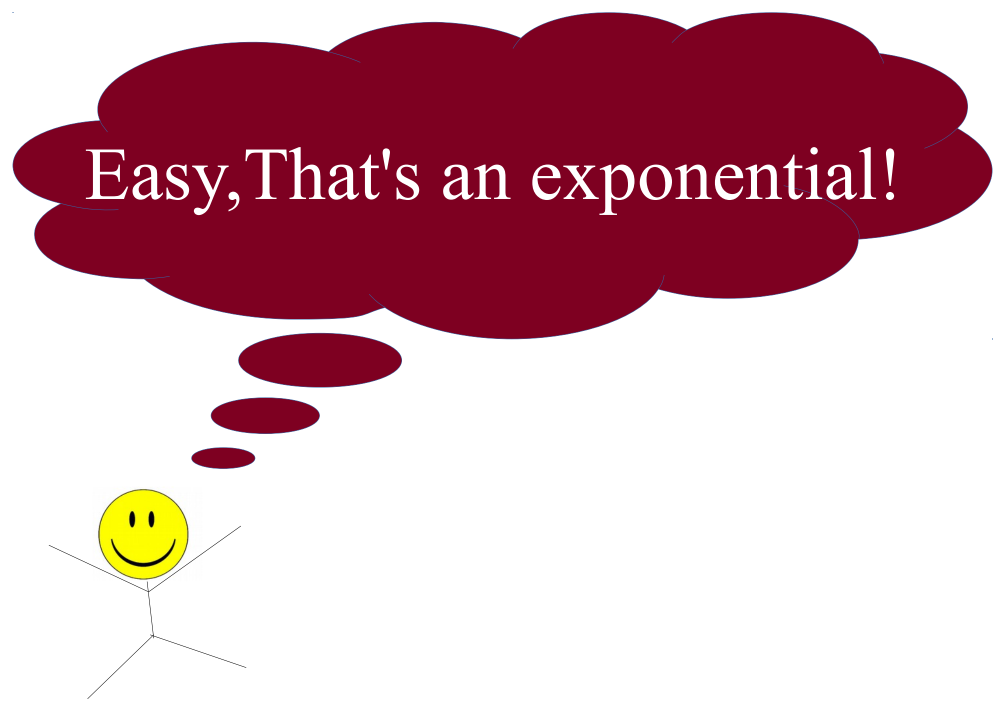
Can we observe this in GRBs?

See poster

$$\dot{E} \approx \dot{E}_o e^{-t/t_{BZ}}$$



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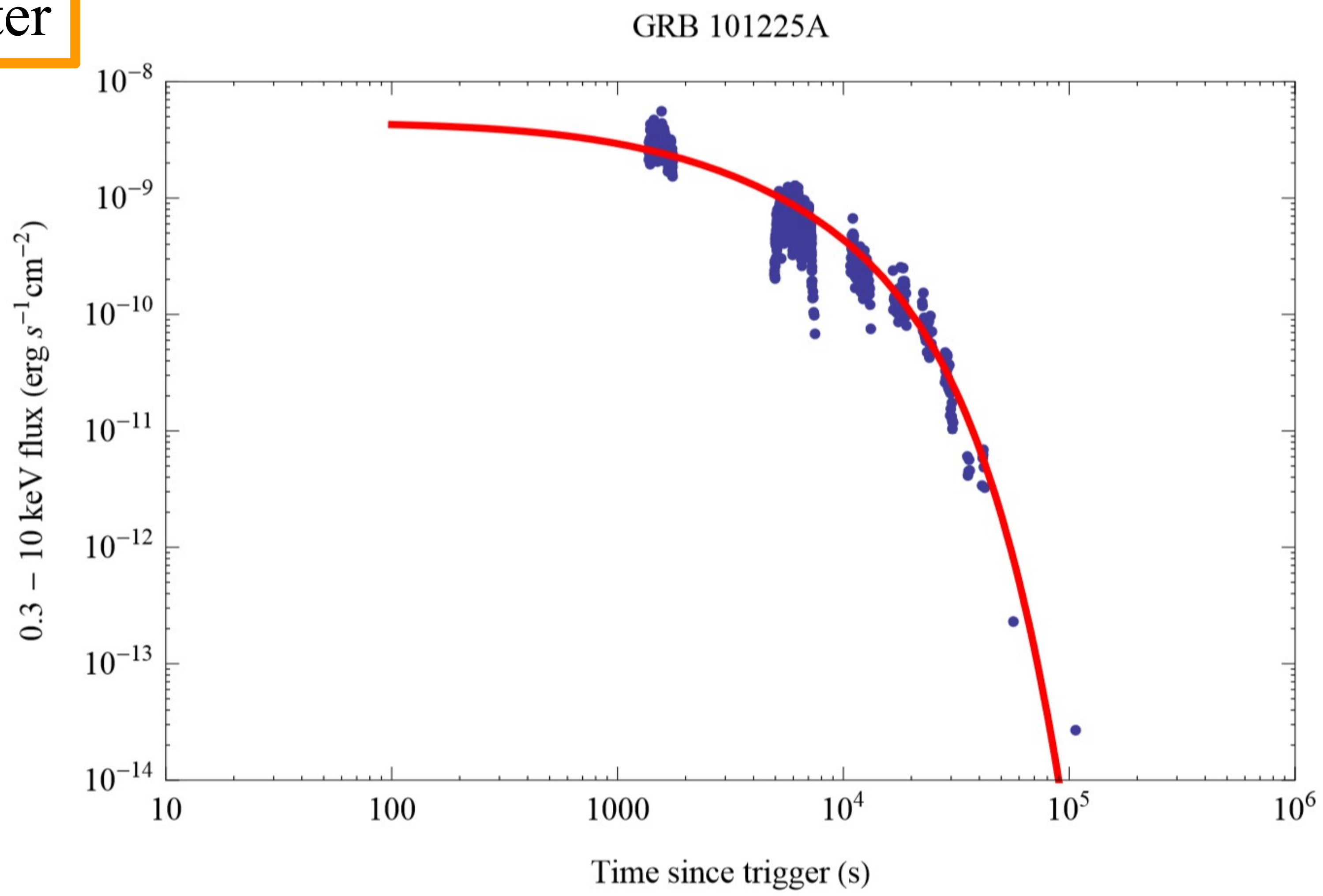
Following the central engine activity

See poster



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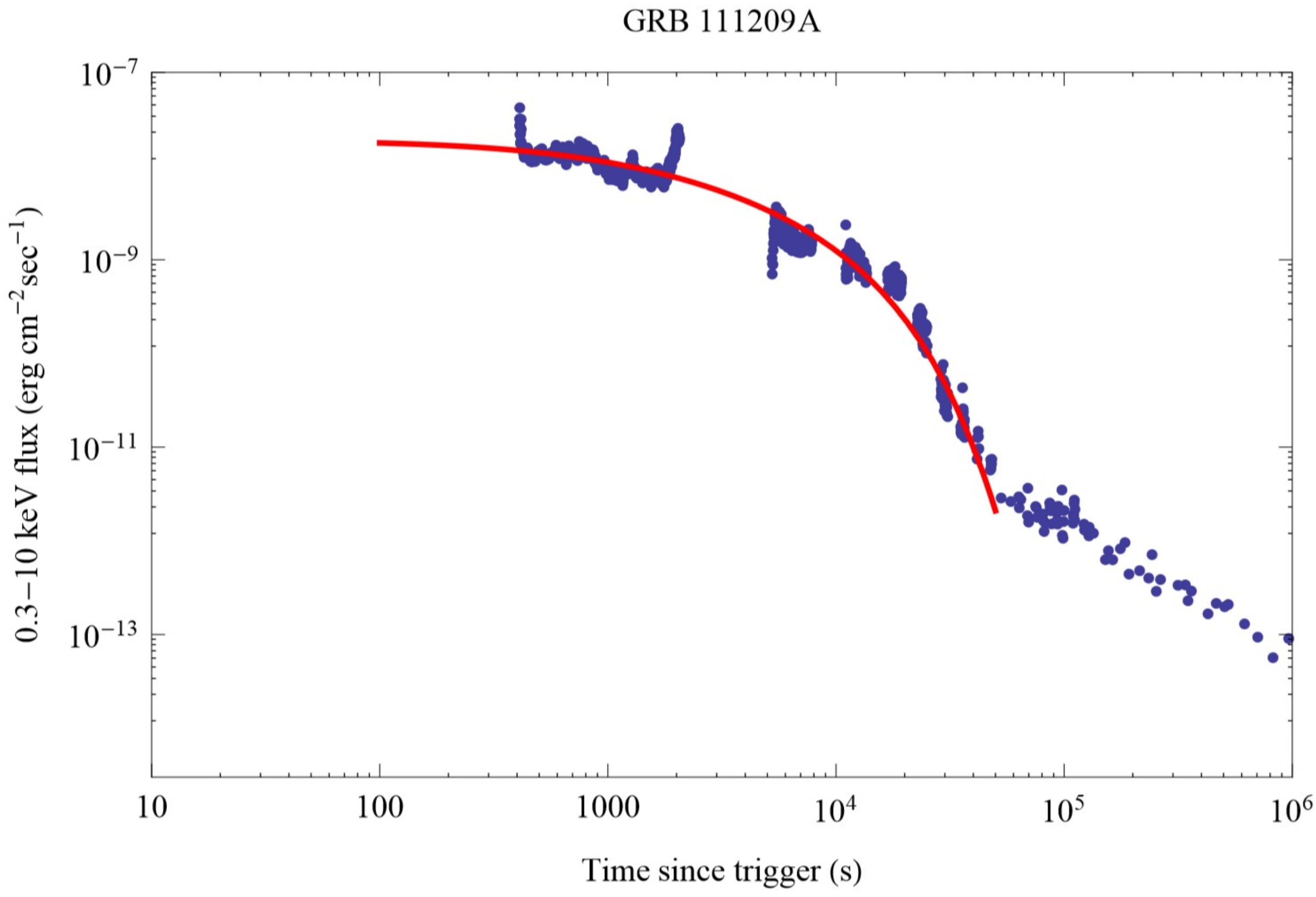
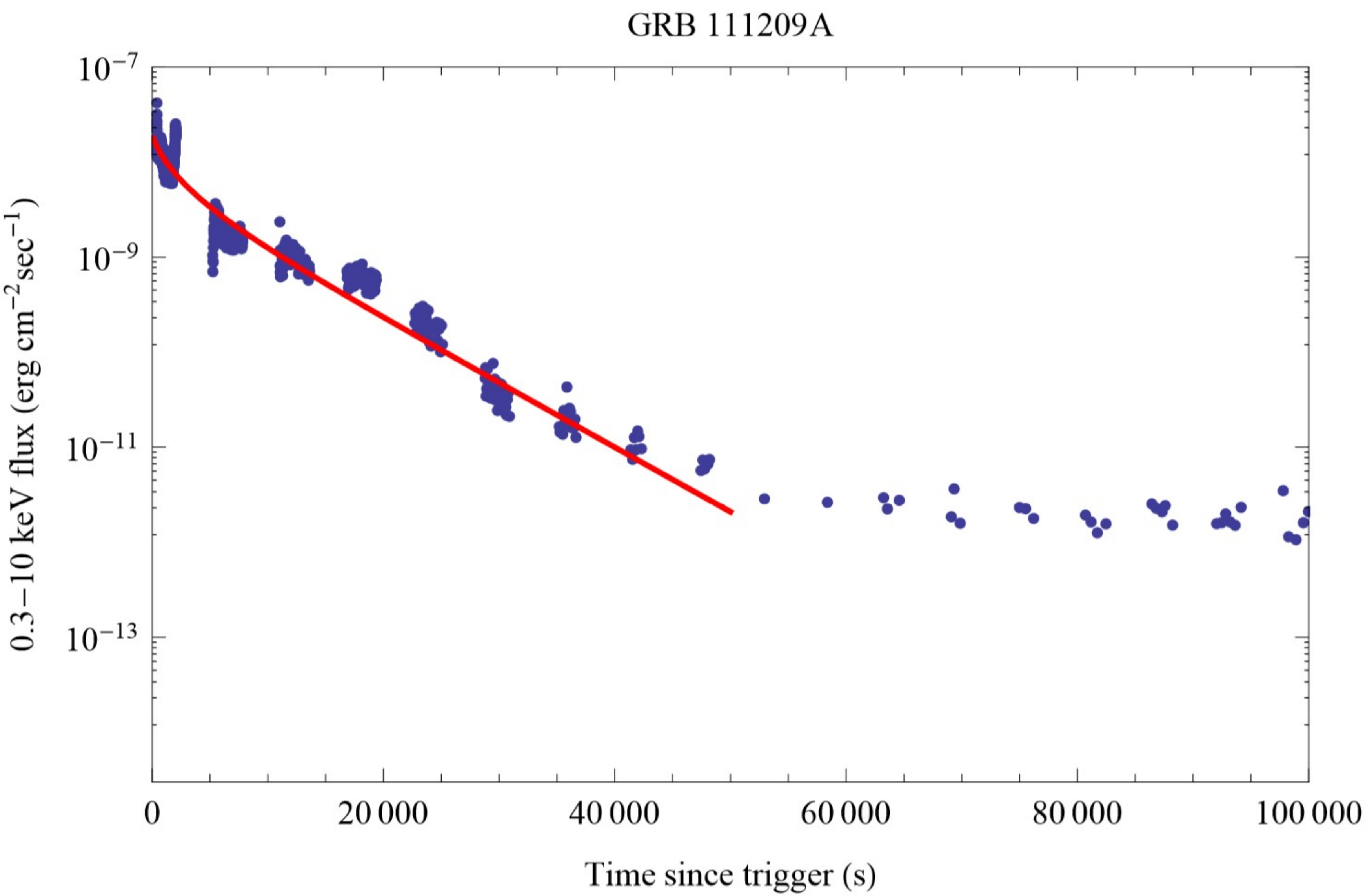
The end

Following the central engine activity

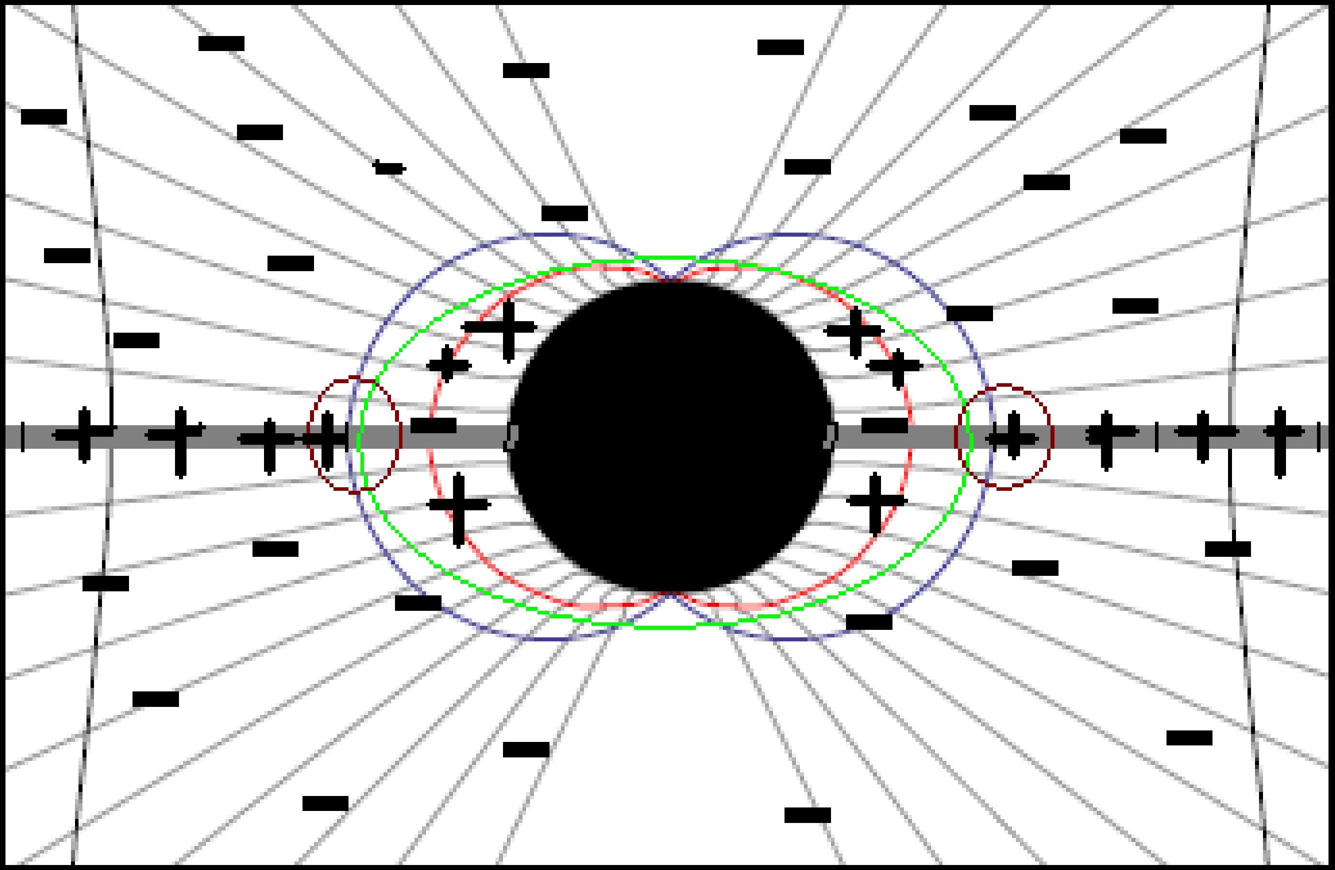


Following the central engine activity



Green line: zero charge surface

\+ - Charges

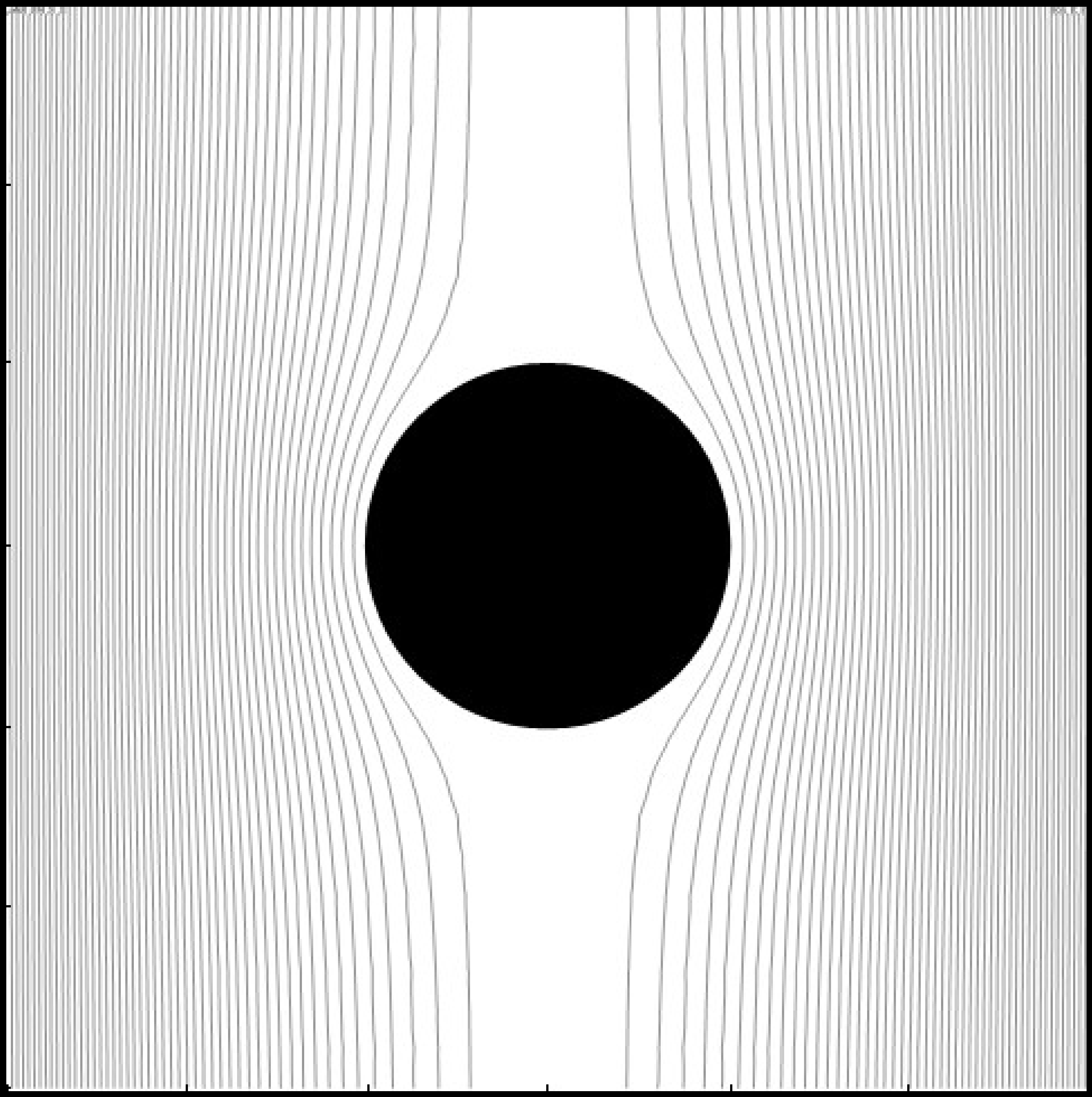


$E_{\parallel}$

a parallel electric field will accelerate particles

Electrovacuum

α = 0.999



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