# Black holes
# for education and intuition

*V.S.Beskin*

*Lebedev Institute*
*Moscow Institute of Physics fnd Technology*

# 2005-2009

k


В.С. Бескин
ОСЕСИММЕТРИЧНЫЕ
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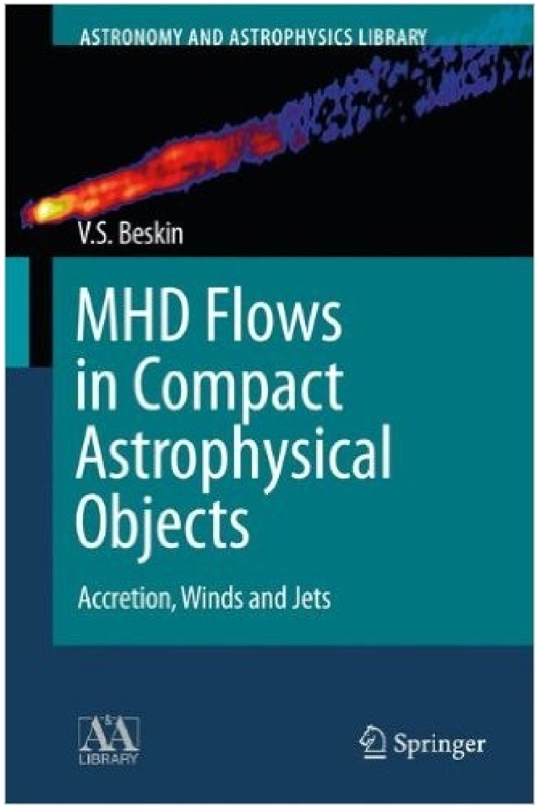
В АСТРОФИЗИКЕ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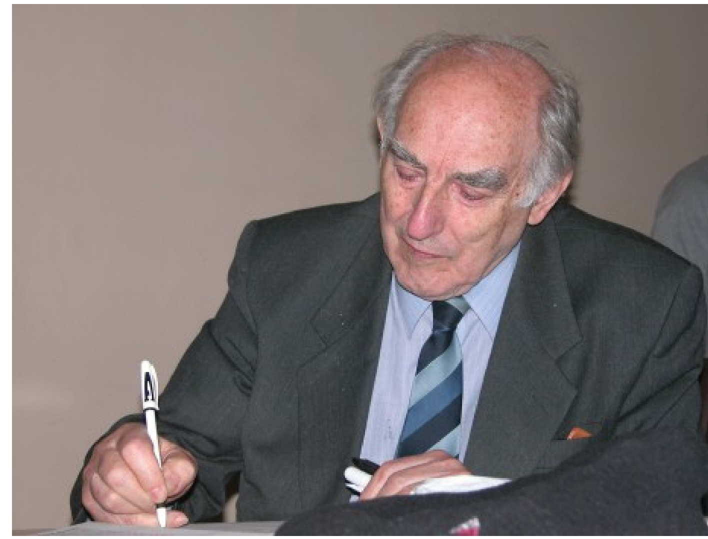
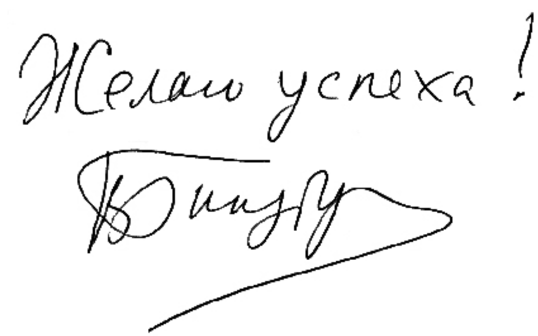
# USA – 2007

**CITA,**
(R.Rafikov
A.Shirokov)
**McMaster**
()
**Rochester**
(V.Pariev)
**Cornell -2**
()
**Chicago**
(L.Malyshkin)
**Harvard**
(A.Tchekhovskoy,
R.Shcherbakov,
S.Eliseeva)
**Princeton**
(N.Zakamska)

# Problems of physics and astrophysics (MIPT)

- Since 1968



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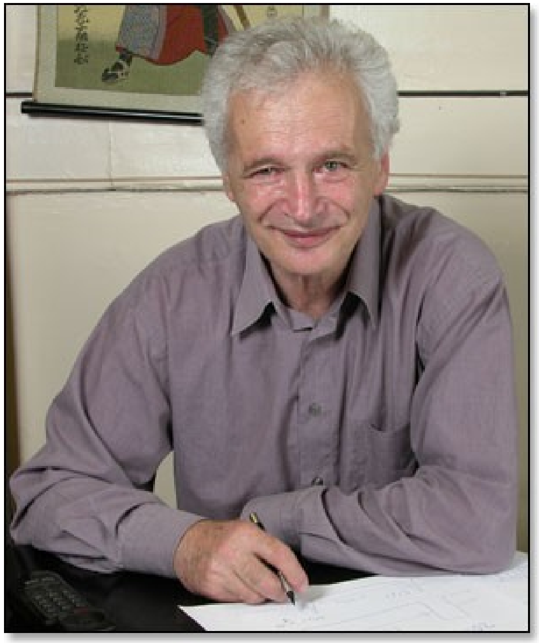
# Problems of physics and astrophysics (MIPT)

- Since 2009



A.V.Gurevich

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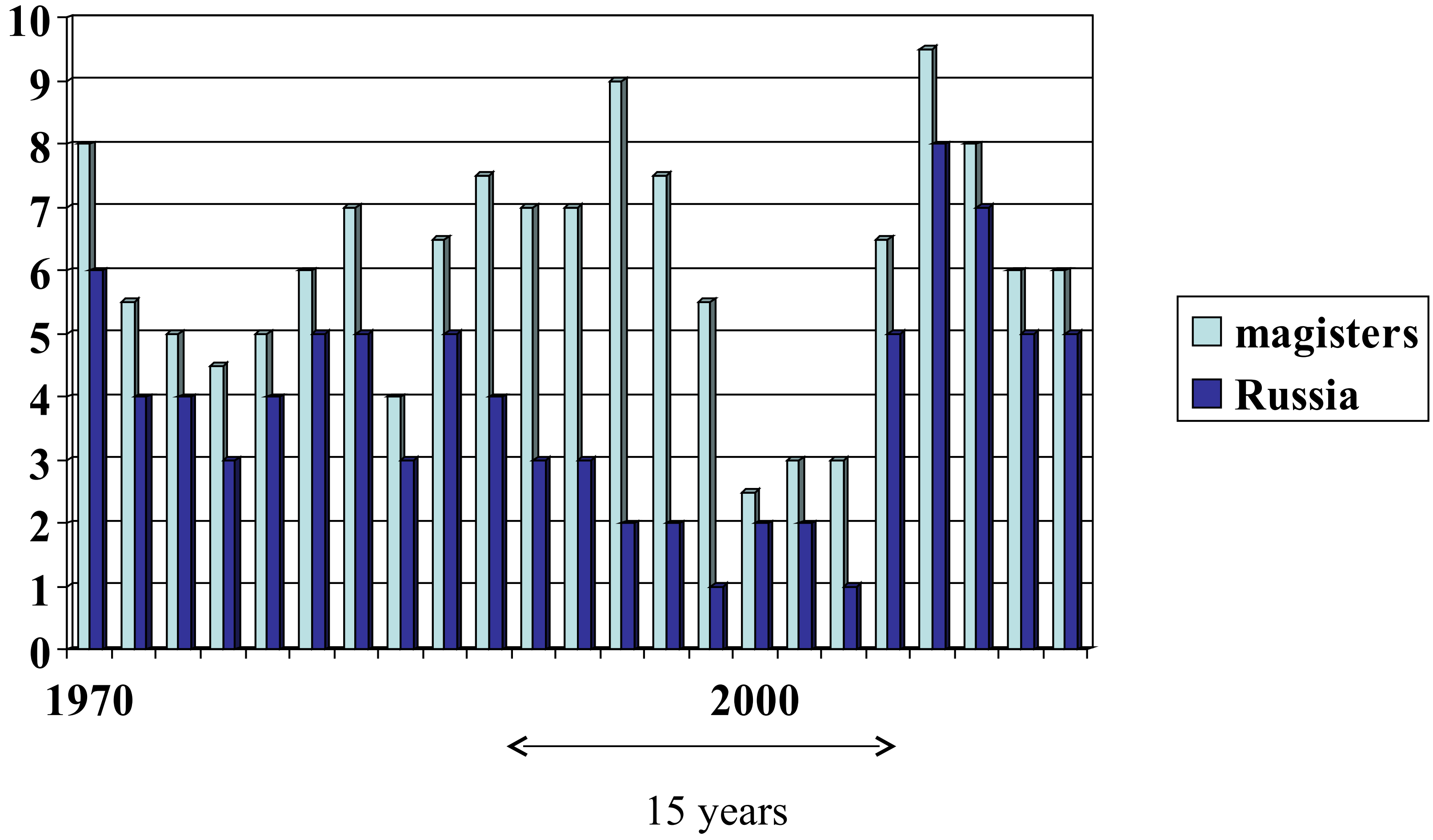
# Magisters



# USA

**Princeton – 2**
(Rafikov, Zakamska)
**Harvard – 2**
(Tchekhovskoy, Shcherbakov)
**Madison – 2**
(Pariev, Lazarian)
**MIT – 1**
(Shirokov)
**Chicago – 1**
(Malyshkin)
**Ohio – 1**
(Pidoprygora)
**Kansas – 1**
(Shandarin)
**Arizona – 1**
(Kuznetsova)
**Garching – 1**
(Kompaneetz,
**Quinn Mary – 1**
Polnarev
**Weizmann – 1**
Usov
**Moscow – 1**
Nokhrina

# Europe

**Princeton – 2**
(Rafikov, Zakamska)
**Harvard – 2**
(Tchekhovskoy, Shcherbakov)
**Madison – 2**
(Pariev, Lazarian)
**MIT – 1**
(Shirokov)
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(Kompaneetz,
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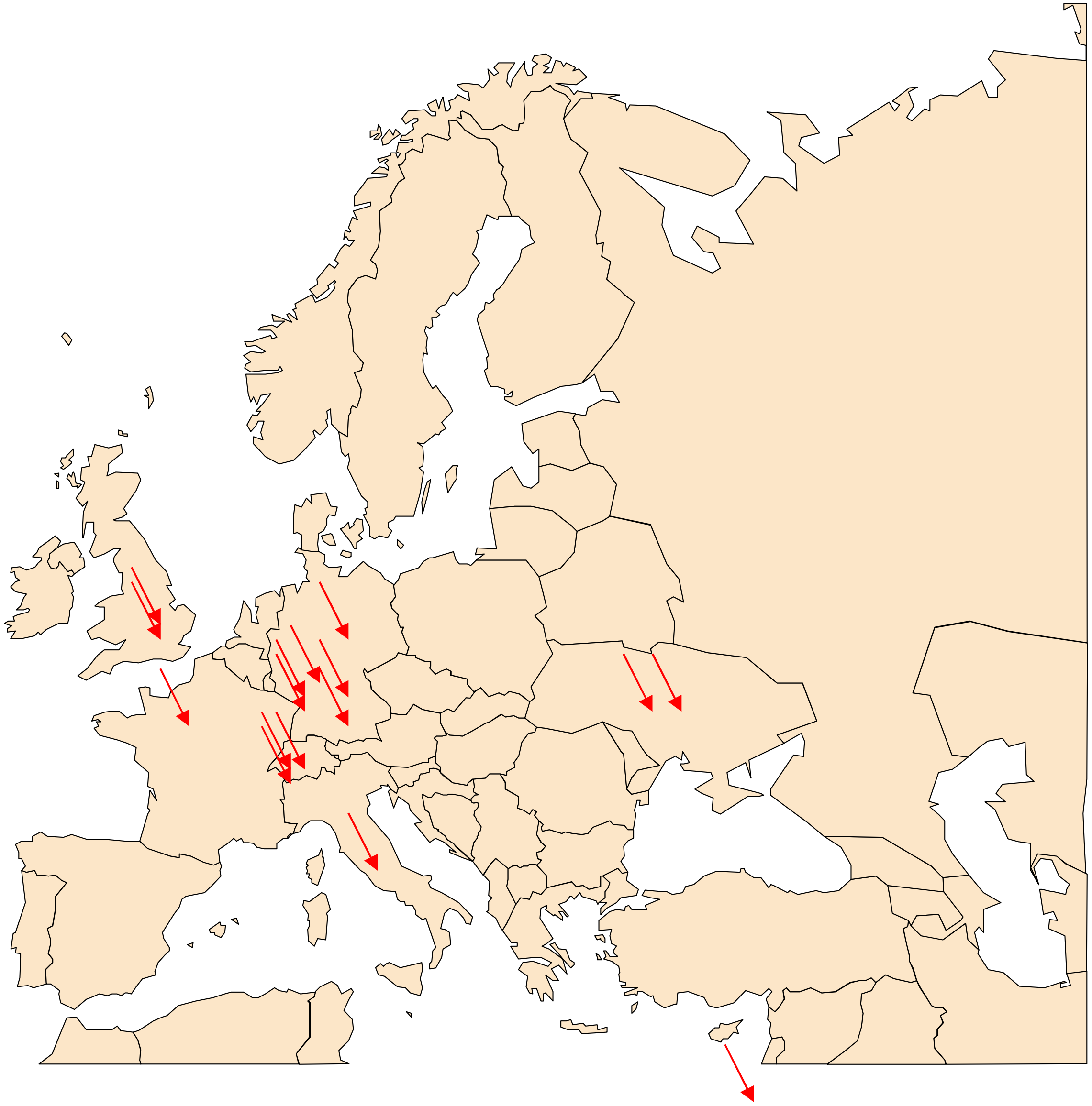
Polnarev
**Weizmann – 1**
Usov
**Moscow – 1**
Nokhrina



# Other

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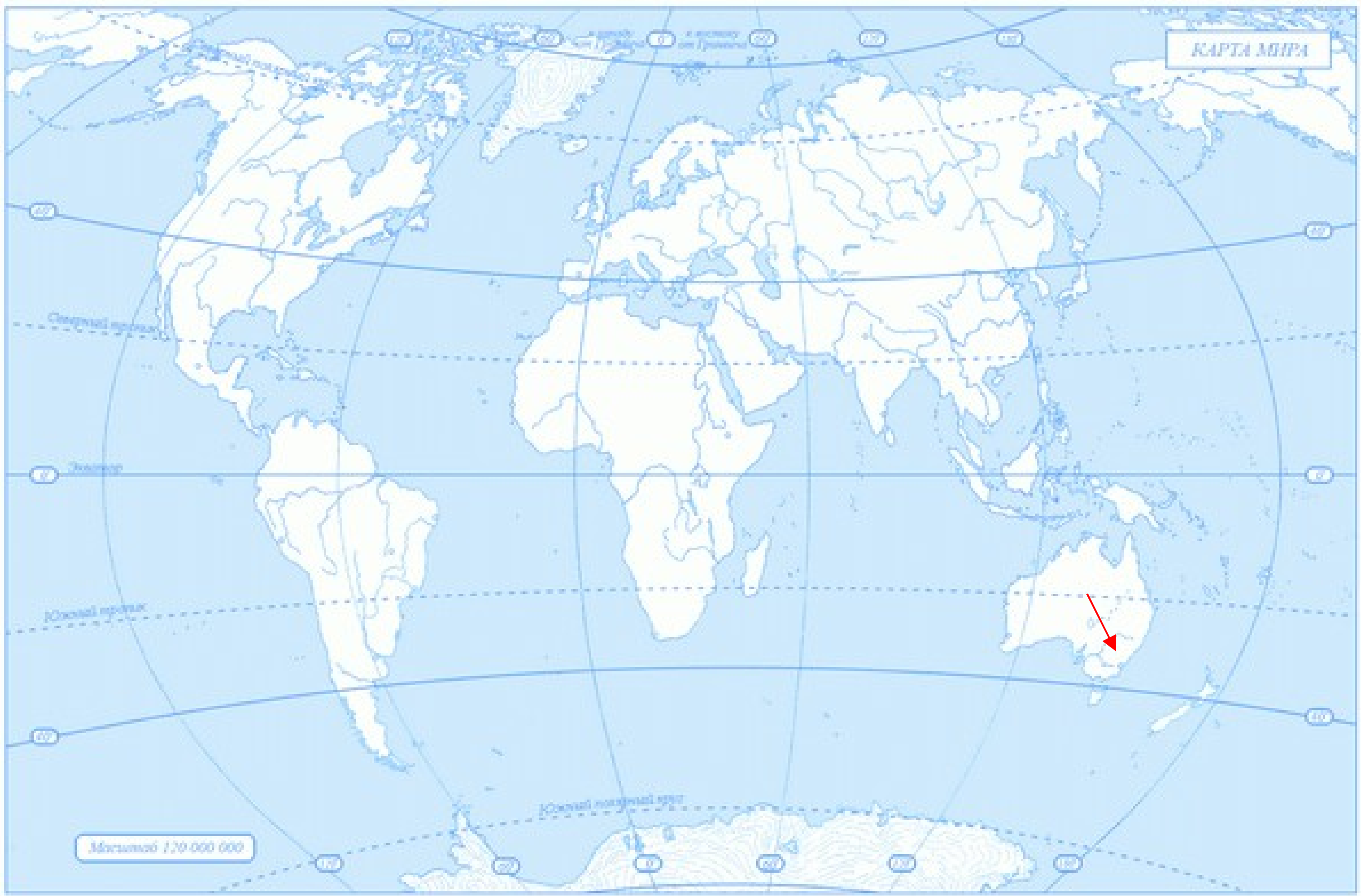
**Moscow – 1**
Nokhrina



# Astrophysics 70-ties

- (3) General Relativity – V.Frolov

- (4) Introduction to Astrophysics – L.Ozernoy
- (4) Plasma, MHD – V.Tsytovich, S.Syrovatskii
- (4) Radiation processes – V.Sazonov

# Astrophysics

- (3) General Relativity – A&M Zelnikov
- (3) Introduction to Cosmology – V.Sirota
- (4) Introduction to Astrophysics – VB
- (4) Plasma, MHD – V.Tsytovich, VB
- (4) Radiation processes – V.Dogiel
- (5) Physical Cosmology – V.Lukash

# Astrophysics

- (1) Introduction

- (3) General Relativity – A&M Zelnikov
- (3) Introduction to Cosmology – V.Sirota
- (4) Introduction to Astrophysics – VB
- (4) Plasma, MHD – V.Tsytovich, VB
- (4) Radiation processes – V.Dogiel
- (5) Physical Cosmology – V.Lukash

# Two examples

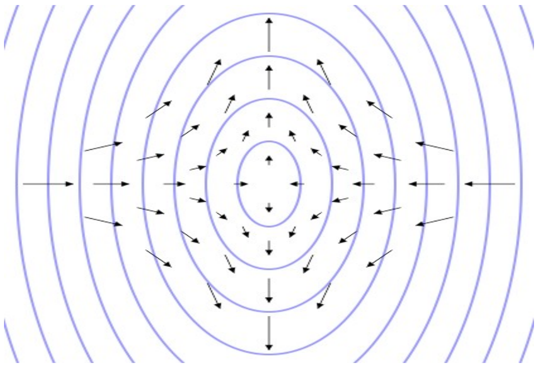
- Einstein gravitational radiation energy losses
- M.P.Bronstein's breakthrough


Gravitation and Astrophysics

Quantum Mechanics and Astrophysics

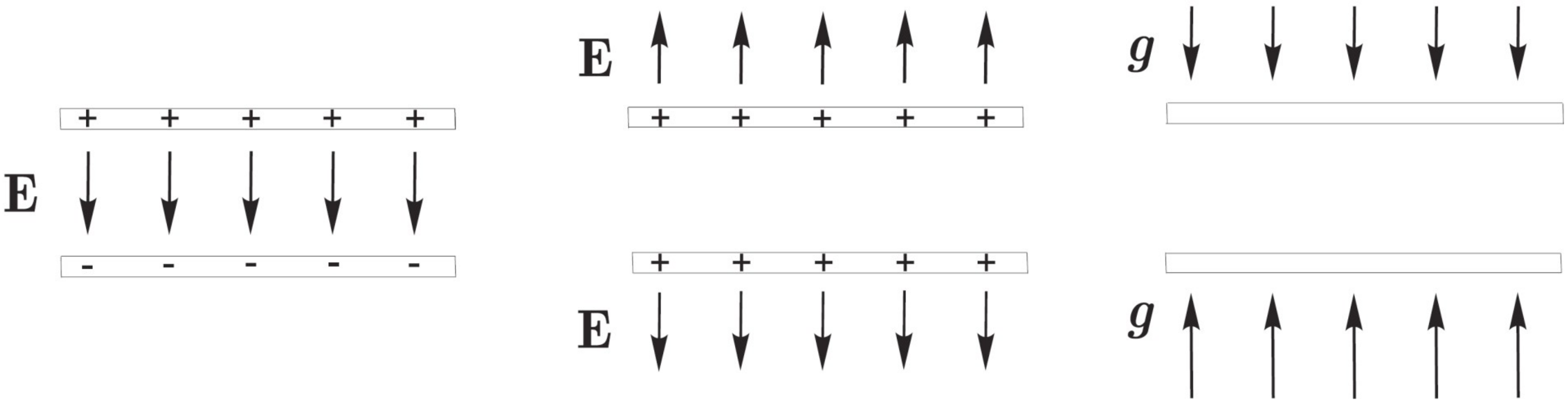
# Einstein gravitational losses

Is it possible to obtain Einstein formula in such a condition?



# Einstein gravitational losses

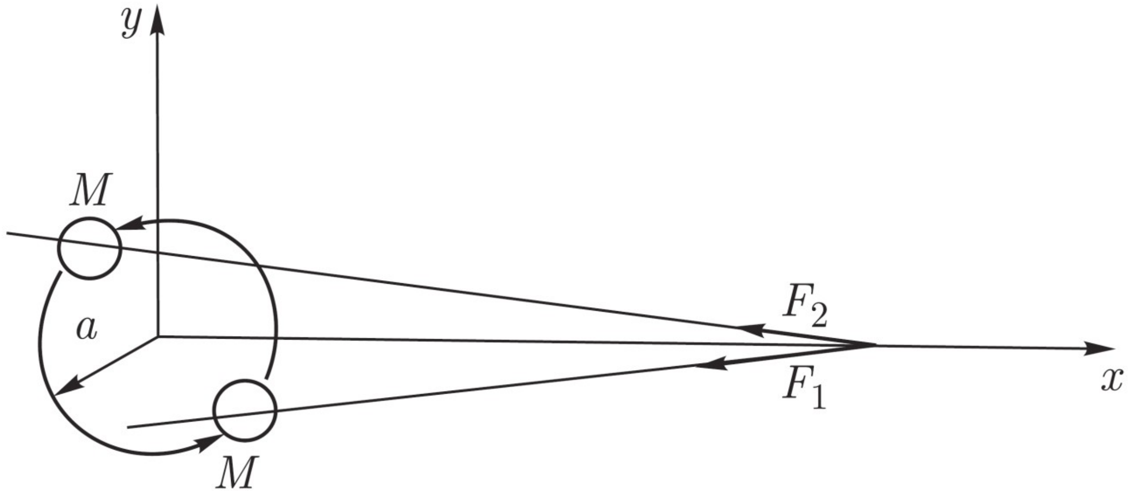
## Energy density




$$\varepsilon_{\rm em} = \frac{E^2}{8\pi} \qquad\qquad \varepsilon_{\rm g} = \frac{g^2}{8\pi G}$$

# Einstein gravitational losses

Near zone




$$g_y = -\frac{GMa\sin\Omega t}{(r^2 + a^2 - 2ar\cos\Omega t)^{3/2}} + \frac{GMa\sin\Omega t}{(r^2 + a^2 + 2ar\cos\Omega t)^{3/2}}$$

$$g_y = -3\frac{GMa^2\sin(2\Omega t)}{r^4}$$

# Einstein gravitational losses

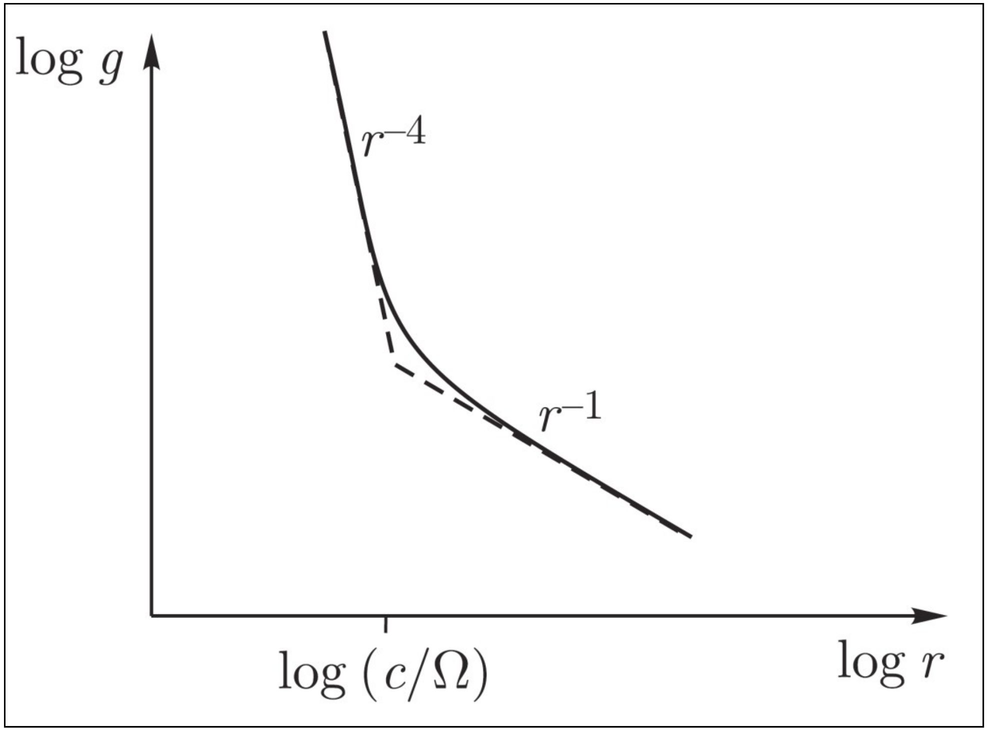
Energy flux

$$W_{\rm md} \approx 4\pi r^2 \varepsilon_{\rm g} \; c$$

$$\varepsilon_{\rm g} = \frac{g^2}{8\pi G}$$

$$g(r) \sim \frac{A_g}{r}$$

$$A_g \sim \frac{GMa^2\Omega^3}{c^3}$$




$$W_{\rm g} \sim \frac{G^4 M^5}{c^5 a^5}$$

# Einstein gravitational losses

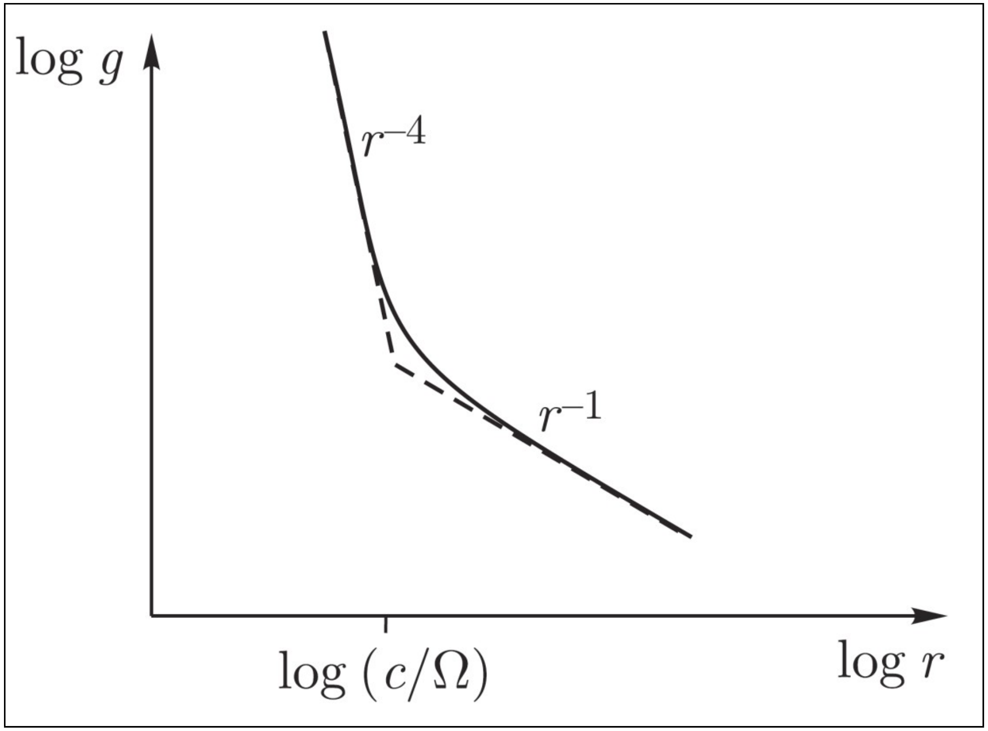
Energy flux

$$W_{\mathrm{md}} \approx 4\pi r^2 \varepsilon_{\mathrm{g}} \;\; c$$

$$\varepsilon_{\mathrm{g}} = \frac{g^2}{8\pi G}$$

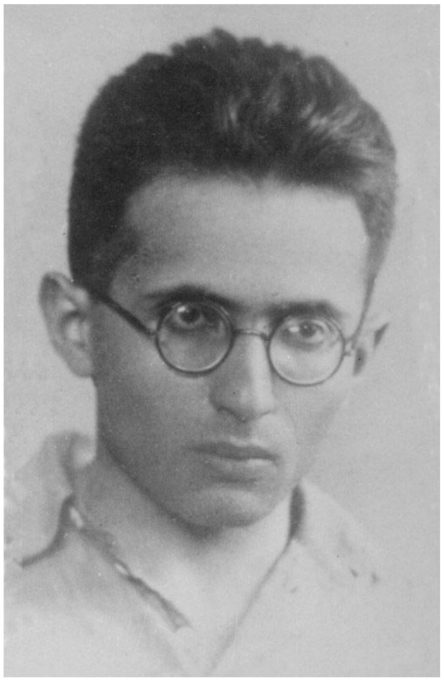
$$g(r) \sim \frac{A_g}{r}$$

$$A_g \sim \frac{GMa^2\Omega^3}{c^3}$$




$$W_{\mathrm{g}} \sim \frac{G^4 M_1^2 M_2^2 (M_1 + M_2)}{c^5 a^5}$$

# M.P.Bronstein's breakthrough



M.P.Bronstein
(1906-1938)

V.Berestetsky

A.Migdal

# Quantum resolution limit

1935

On scales smaller than Planck length, space-time ceases to be continuous.

An attempt to measure with a probe of mass $M$ a small scale $\Delta x$, according to the uncertainty relation, leads to probe motion, and, according to GR, to the curvature of space.

Matvei Bronstein and quantum gravity: 70th anniversary of the unsolved problem
Phys. Uspekhi, **48** 1039–1053 (2005)

# Quantum resolution limit

1935

CONCLUSION:

On a small scale, quantum mechanics and general relativity are incompatible.

$$\Delta[00, 1] > h^{2/3} G^{2/3} / c T V^{4/9}$$

$$\Delta[00,\ 1] > \frac{h^{2/3} G^{1/3}}{c^{1/3} \rho^{1/3} V^{2/3} T}$$

Matvei Bronstein and quantum gravity: 70th anniversary of the unsolved problem
Phys. Uspekhi, **48** 1039–1053 (2005)

# Quantum resolution limit

GR – gravitational radius

$$r_{\mathrm{g}} = \frac{2GM}{c^2}$$

$$g \sim GM/r^2$$

$$g_{\mathrm{cr}} \sim \frac{c^4}{GM}$$

$$F_{\mathrm{cr}} \sim \frac{c^4}{G}$$

# Quantum resolution limit

GR – motion results in additional forces

Maxwell equations

$$\operatorname{div}\mathbf{E} = 4\pi\rho_{\mathrm{e}},$$
$$\operatorname{rot}\mathbf{E} + \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} = 0,$$
$$\operatorname{div}\mathbf{B} = 0,$$
$$\operatorname{rot}\mathbf{B} - \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} = \frac{4\pi}{c}\mathbf{j}.$$

$$\mathbf{F} = e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)$$

Weak field limit of Einstein equations

$$\operatorname{div}\mathbf{g} = -4\pi G\rho_{\mathrm{m}},$$
$$\operatorname{rot}\mathbf{g} = 0,$$
$$\operatorname{div}\mathbf{H} = 0,$$
$$\operatorname{rot}\mathbf{H} - \frac{4}{c}\frac{\partial\mathbf{g}}{\partial t} = -\frac{16\pi}{c}G\rho_{\mathrm{m}}\mathbf{v}.$$

$$\mathbf{F} = M\left(\mathbf{g} + \frac{\mathbf{v}}{c}\times\mathbf{H}\right)$$

# Quantum resolution limit

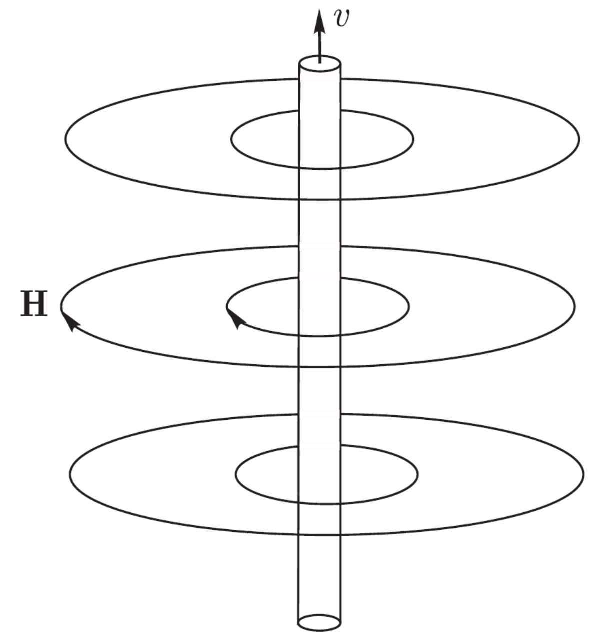
GR – motion results in additional forces

$$B = 2I/(cr)$$

$$H \sim G I_{\mathrm{M}} / c \Delta x$$

$$I_{\mathrm{M}} \sim \pi \Delta x^2 \rho_{\mathrm{m}} v$$

$$\rho_{\mathrm{m}} \mathbf{v} \sim \frac{M}{(\Delta x)^3} \Delta \mathbf{v}$$




$$\mathbf{F} = M\left(\mathbf{g} + \frac{\mathbf{v}}{c} \times \mathbf{H}\right)$$

# Quantum resolution limit

QM – the sourse of motion

$$H \sim \frac{GM\Delta v}{c(\Delta x)^2} \sim \frac{G\hbar}{c(\Delta x)^3}$$

$$\Delta F \sim MH\Delta v/c$$

$$\boxed{\Delta F \sim \frac{G\hbar^2}{c^2(\Delta x)^4}}$$

$$F_{\rm cr} \sim \frac{c^4}{G}$$

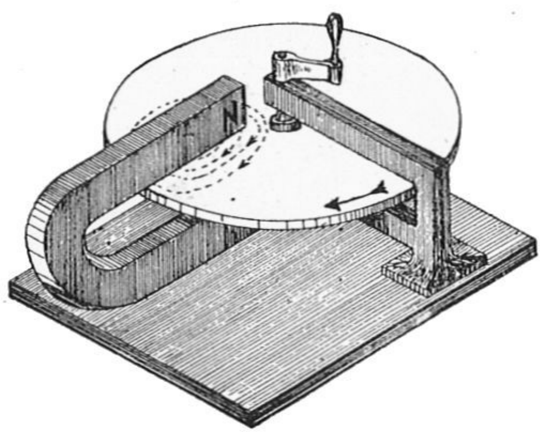
# Two 'bad' interpretations

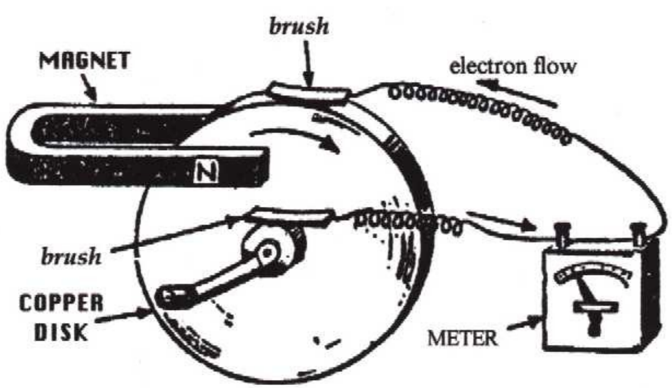
- Black hole as unipolar inductor
- Gravity as media with $n < 0$

# Black hole as unipolar inductor

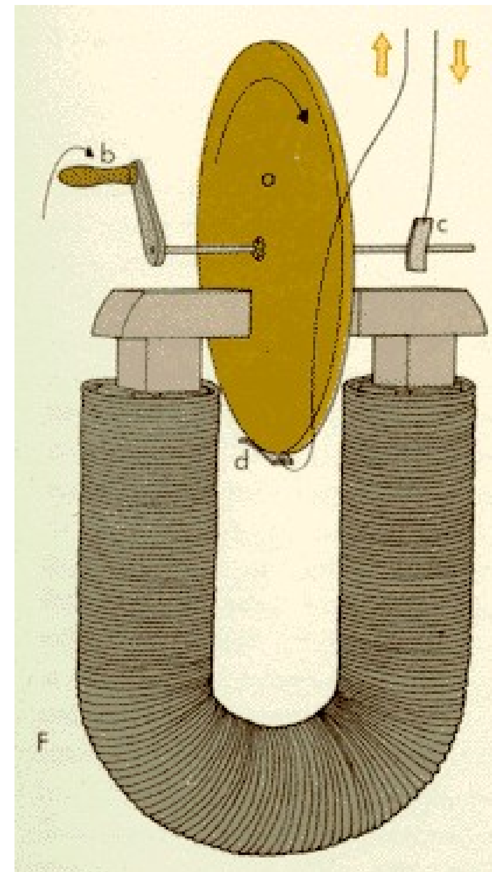
- Unipolar inductor works as Faraday disk, but not due to Faraday law
- Black hole works due to Faraday law

# Faraday’s disk



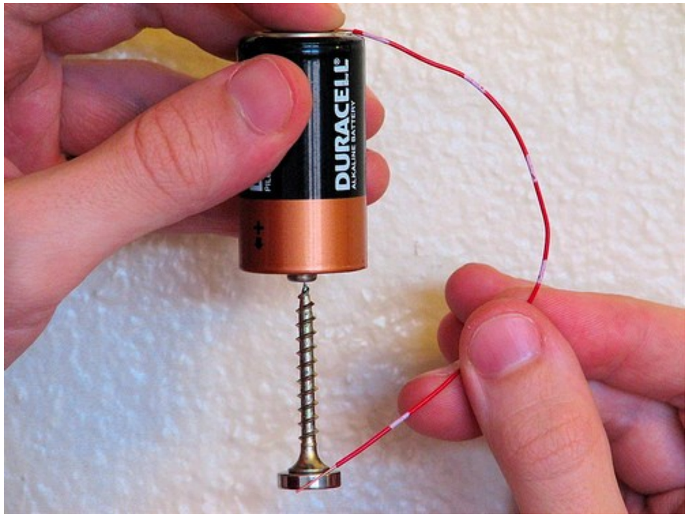


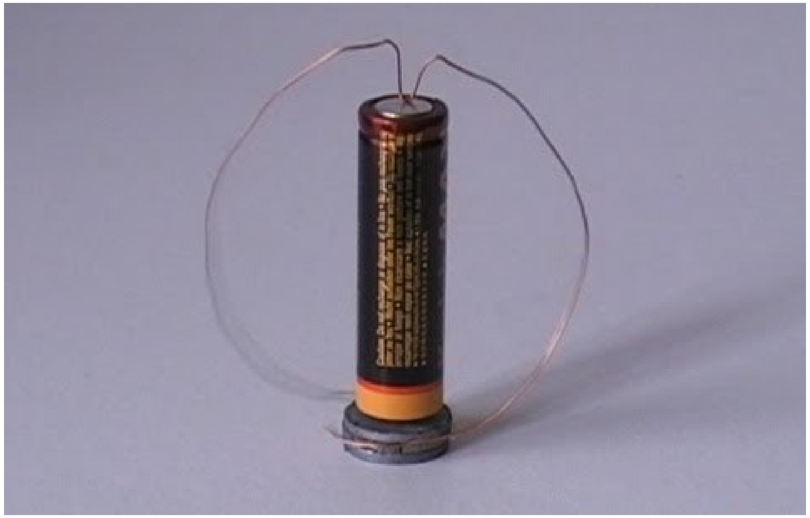

***Faraday's disk dynamo*** - for producing continuous (pure) dc voltage. This was the world's first electrical generator.



# Inverse problem

- The simplest EM engine



# Black hole as Faraday disk

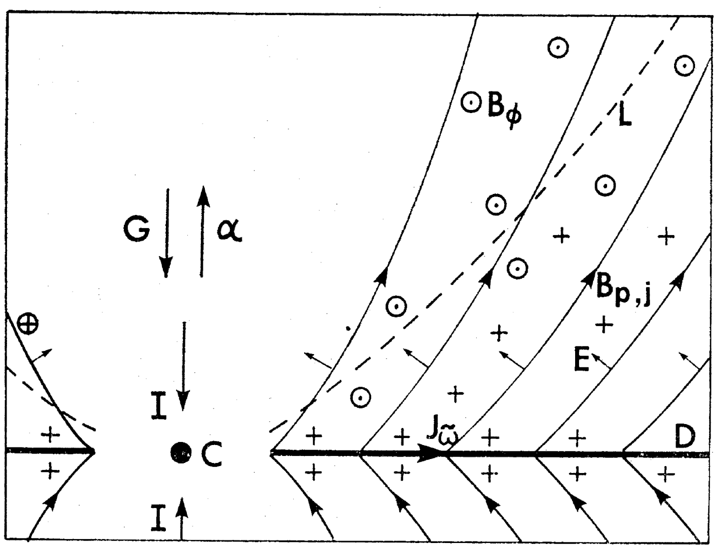
R.Blandford (1976)

R.Lovelace (1976)

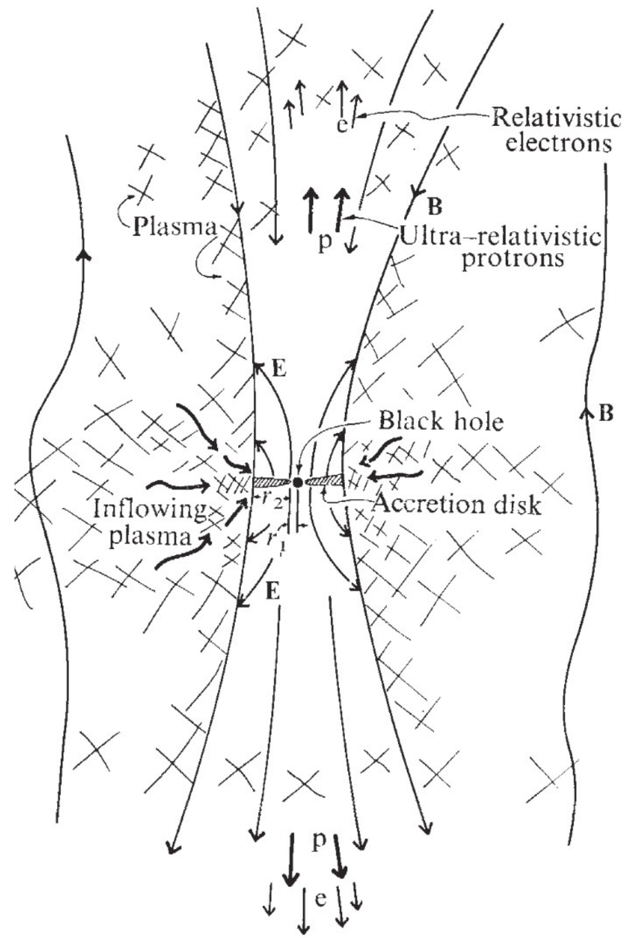
# Black hole as Faraday disk

R.Blandford (1976)

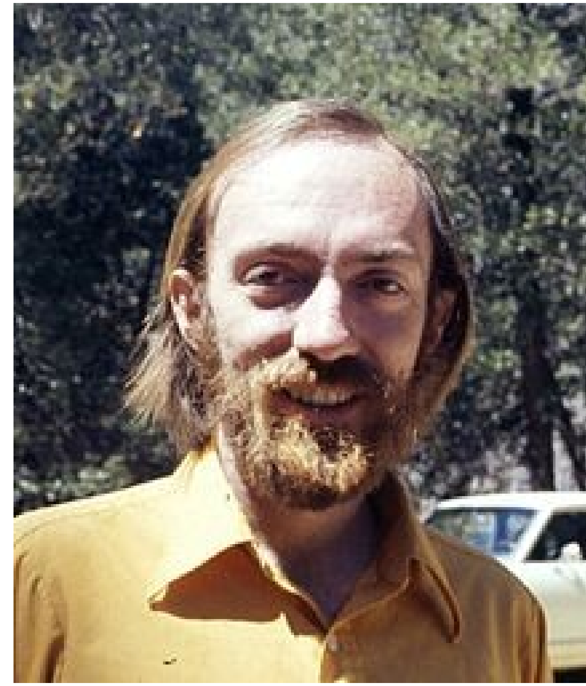
$$W_{\rm BZ} \sim (\Omega r_{\rm g}/c)^2 B^2 r_{\rm g}^2 c$$




R.Lovelace (1976)



# K.Thorne



BH fields

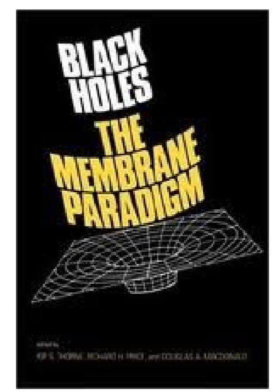
$$E_{\mathrm{H}} = \alpha E_{\hat{\theta}}$$
$$B_{\mathrm{H}} = \alpha B_{\hat{\varphi}}$$

Ohm's law

$$E_{\hat{\theta}} = -B_{\hat{\varphi}}$$

$$\mathbf{J}_{\mathrm{H}} = \frac{c}{4\pi}\mathbf{E}_{\mathrm{H}}$$

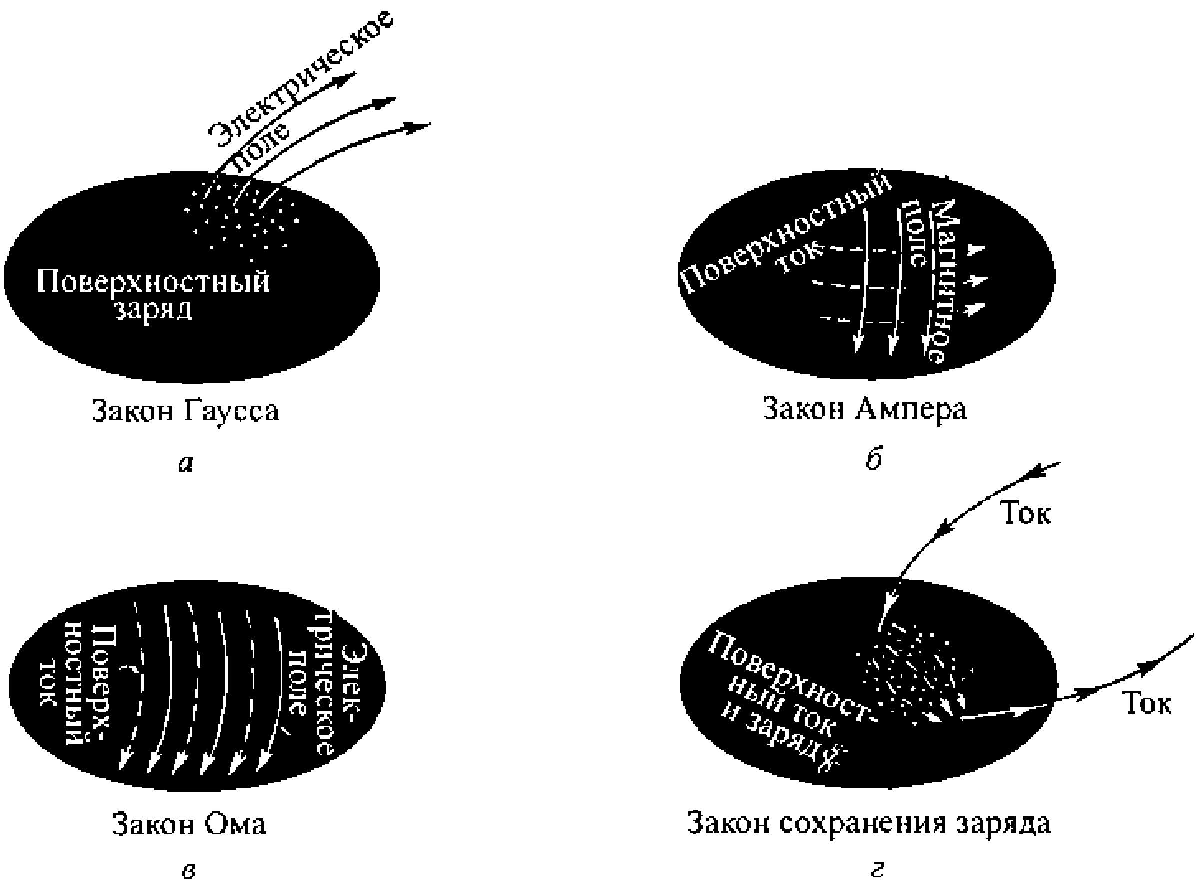
$$\boxed{\mathcal{R} = 4\pi/c = 377 \text{ O}}$$

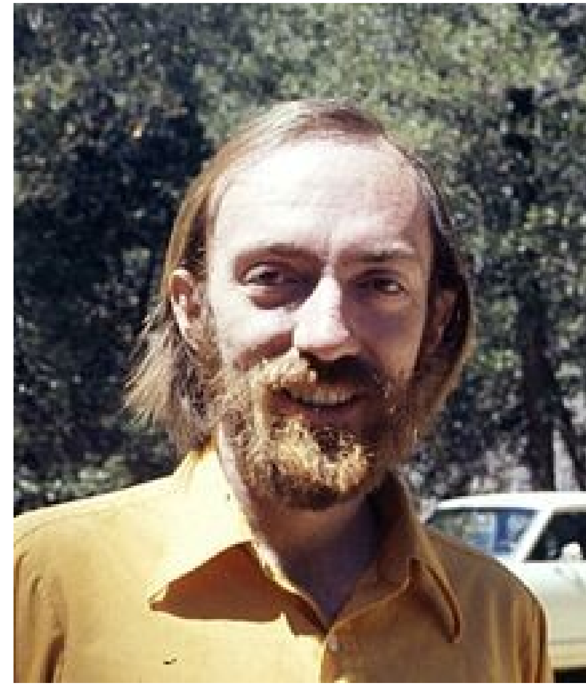


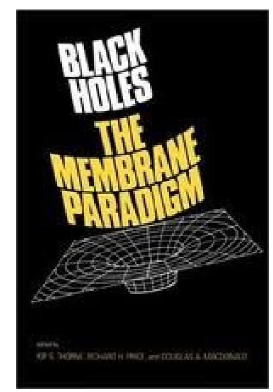

'Ampere' force

$$W_{\mathrm{tot}} = \int \left[\mathbf{E}_{\mathrm{H}}\mathbf{J}_{\mathrm{H}} - \beta_{\mathrm{g}}\left(\sigma_{\mathrm{H}}\mathbf{E}_{\mathrm{H}} + \mathbf{J}_{\mathrm{H}} \times \mathbf{B}_{\mathrm{n}}\right)\right] \mathrm{d}S.$$

# K.Thorne



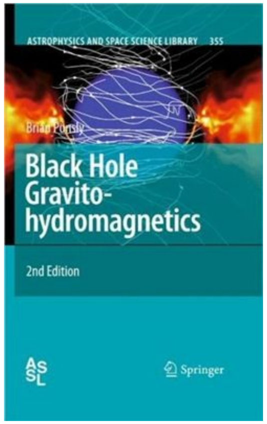



## ‘Ampere’ force

$$W_{\rm tot} = \int \left[\mathbf{E}_{\rm H}\mathbf{J}_{\rm H} - \beta_{\rm g}\left(\sigma_{\rm H}\mathbf{E}_{\rm H} + \mathbf{J}_{\rm H}\times\mathbf{B}_{\rm n}\right)\right]{\rm d}S.$$

# B.Punsly

- The horizon isn't in casual connection with the outer space*.
- The horizon isn't a material boundary of a black hole*.
- Black hole cannot be a battery (the source of the exterior forces)*.

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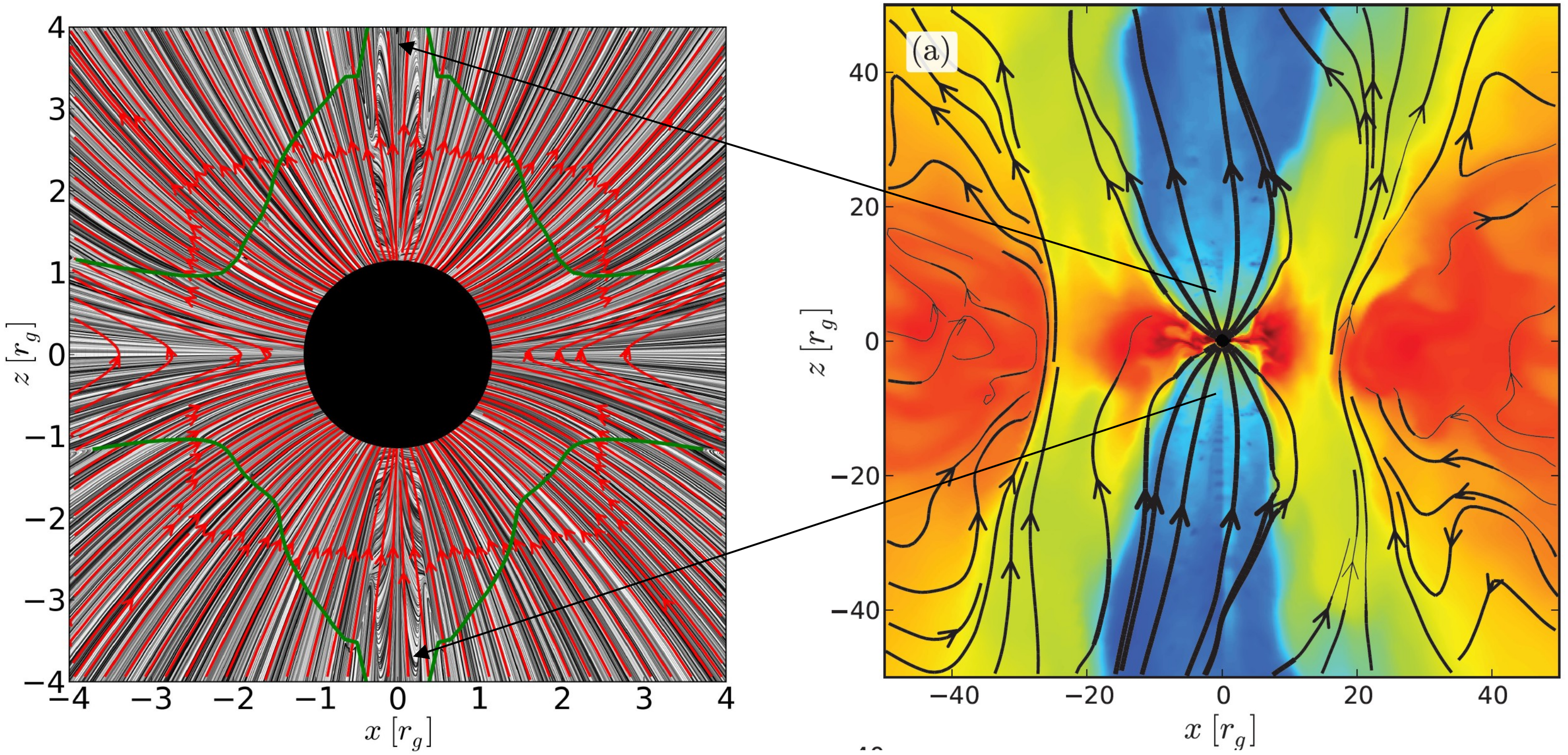
* Very serious objections

# McKinney J.C., Tchekhovskoy A., Blandford R.D.
# MNRAS, **423**, 3083 (2012)

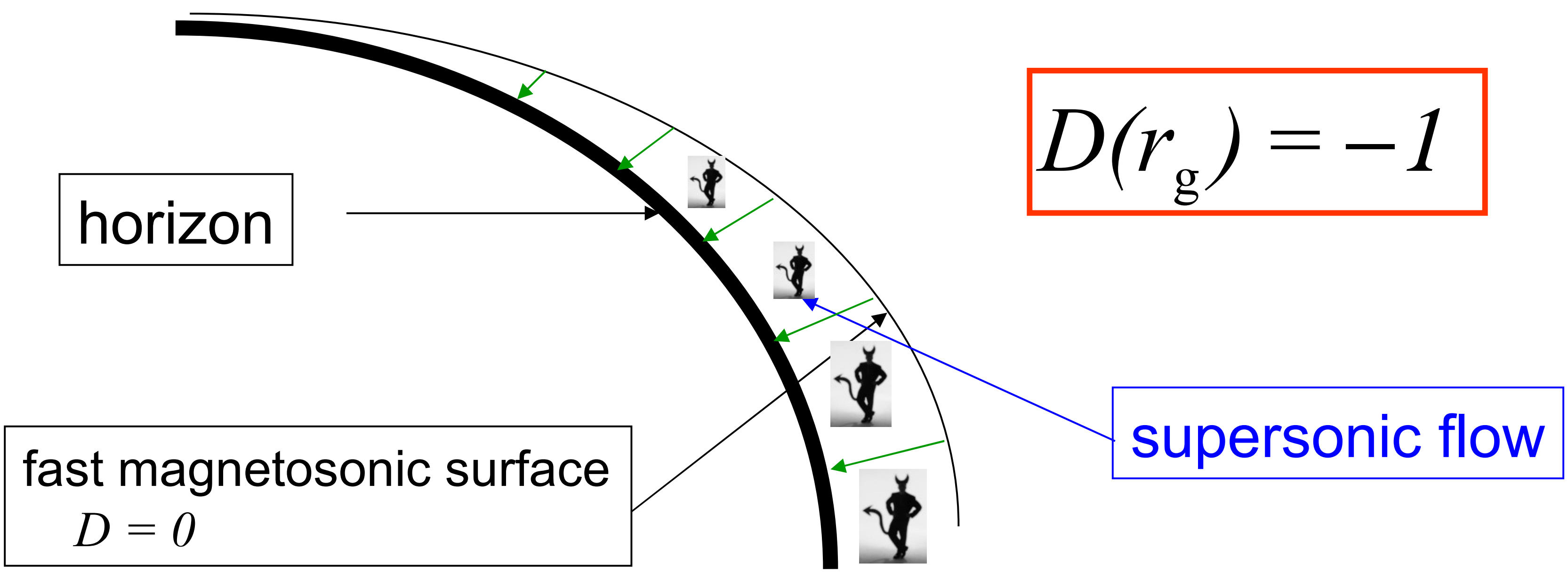



Monopole + Cylinder

# Force-free limit

Force-free limit of the critical condition on the fast magnetosonic surface is “the boundary condition on the horizon”

$$D(r_g) = -1$$



# Gravity as a media with $n < 0$

# L.D.Landau & E.V.Lifshits, Field Theory

$$\mathbf{D} = \frac{\mathbf{E}}{\sqrt{h}} + \mathbf{H} \times \mathbf{g}, \qquad \mathbf{B} = \frac{\mathbf{H}}{\sqrt{h}} + \mathbf{g} \times \mathbf{E}. \tag{4}$$

$$\operatorname{div} \mathbf{D} = 4\pi\varrho$$

$$\operatorname{curl} \mathbf{E} = -\frac{1}{c\sqrt{\gamma}} \frac{\partial}{\partial t} (\sqrt{\gamma}\, \mathbf{B}) \tag{5}$$

$$\operatorname{div} \mathbf{B} = 0$$

$$\operatorname{curl} \mathbf{H} = \frac{1}{c\sqrt{\gamma}} \frac{\partial}{\partial t} (\sqrt{\gamma}\, \mathbf{D}) + \frac{4\pi}{c} \mathbf{s} \tag{6}$$

The reader should note the analogy (purely formal, of course) of equations (5) and (6) to the Maxwell equations for the electromagnetic field in material media. In particular, in a static gravitational field the quantity $\sqrt{\gamma}$ drops out of the terms containing time derivatives, and relation (4) reduces to $\mathbf{D} = \mathbf{E}/\sqrt{h}$, $\mathbf{B} = \mathbf{H}/\sqrt{h}$. We may say that with respect to its effect on the electromagnetic field a static gravitational field plays the role of a medium with electric and magnetic permeabilities $\varepsilon = \mu = 1/\sqrt{h}$.

# Two presentations

## Thorne-Macdonald

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= 4\pi\rho_{\mathrm{e}}, \\
\nabla \cdot \mathbf{B} &= 0, \\
\nabla \times (\alpha \mathbf{E}) &= \mathcal{L}_{\beta}\mathbf{B} - \frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \times (\alpha \mathbf{B}) &= \frac{\partial \mathbf{E}}{\partial t} - \mathcal{L}_{\beta}\mathbf{E} + 4\pi\alpha\mathbf{j}.
\end{aligned}
$$

## Landau-Lifshits

$$
\begin{aligned}
\nabla \cdot \mathbf{D} &= 4\pi\rho_{\mathrm{e}}, \\
\nabla \cdot \mathbf{B} &= 0, \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \times \mathbf{H} &= \frac{\partial \mathbf{D}}{\partial t} + 4\pi\left(\alpha\mathbf{j} - \rho_{\mathrm{e}}\beta\right).
\end{aligned}
$$

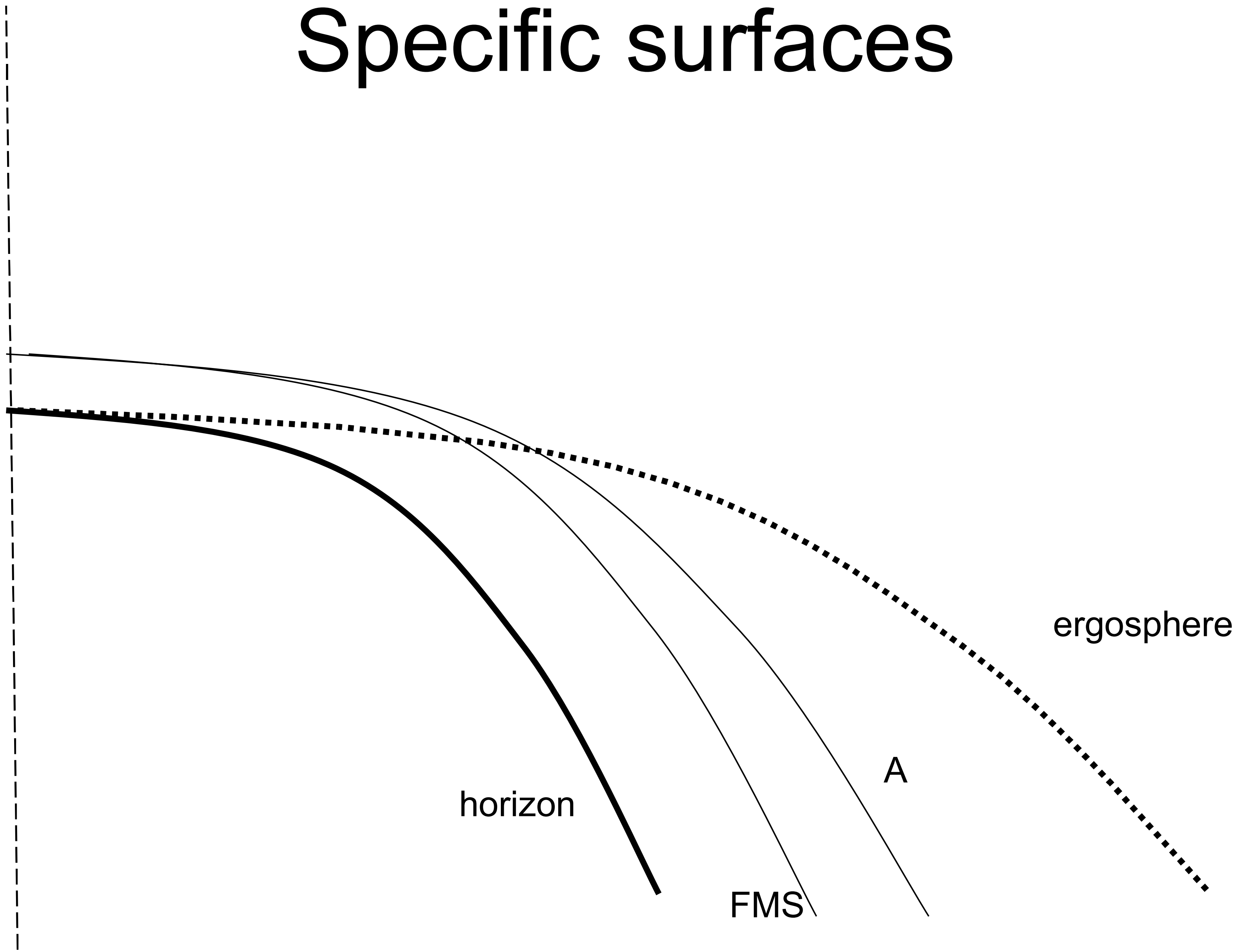
$$
\begin{aligned}
\mathbf{E} &= \alpha\mathbf{D} + \beta \times \mathbf{B}, \\
\mathbf{H} &= \alpha\mathbf{B} - \beta \times \mathbf{D}
\end{aligned}
$$

# Energy equation

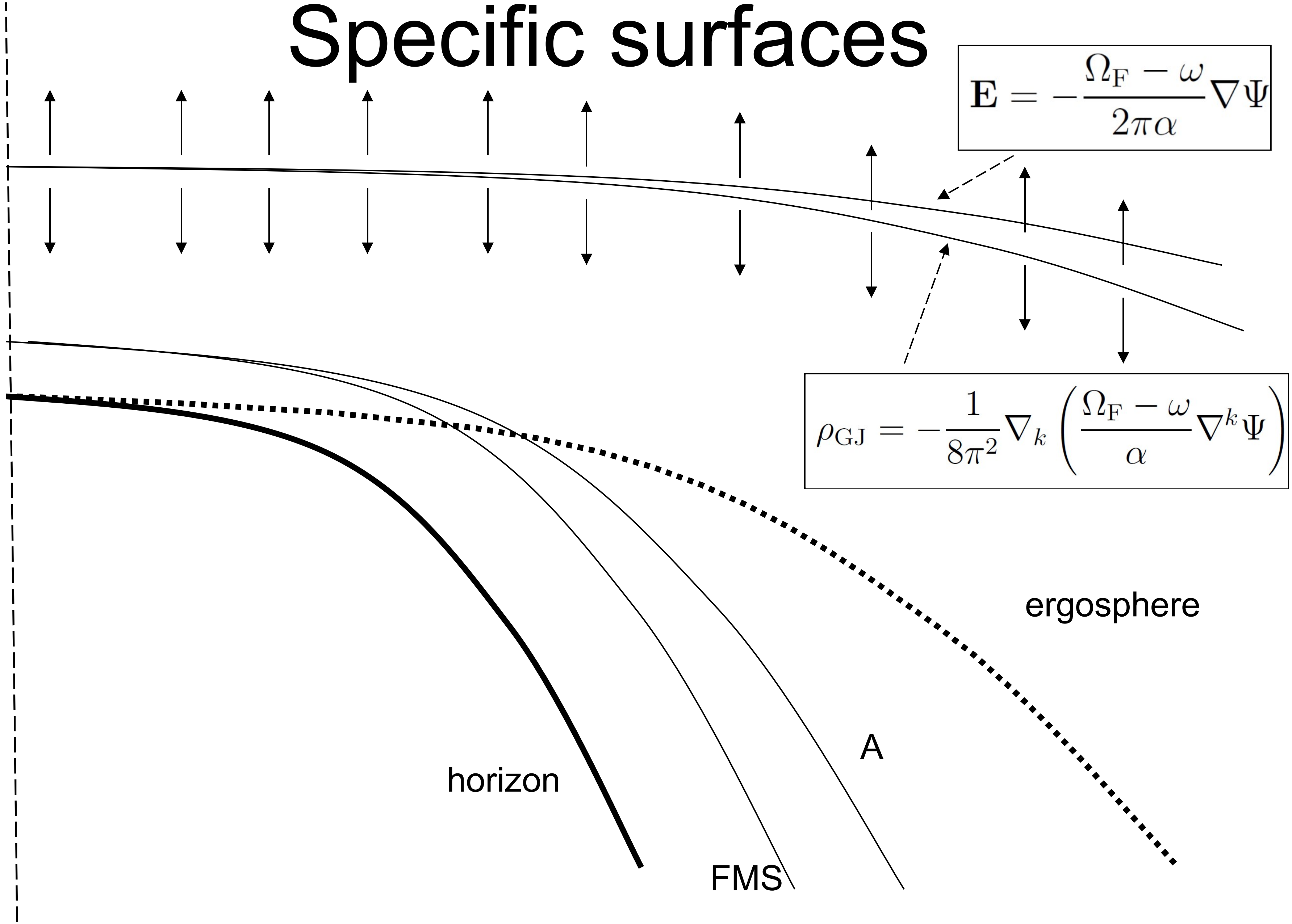
$$\frac{\partial}{\partial t}\left(\frac{\mathbf{ED}+\mathbf{BH}}{8\pi}\right)+\nabla\left(\frac{1}{4\pi}[\mathbf{E}\times\mathbf{H}]\right)=-(\mathbf{EJ}).$$

Does this energy equation have sense?

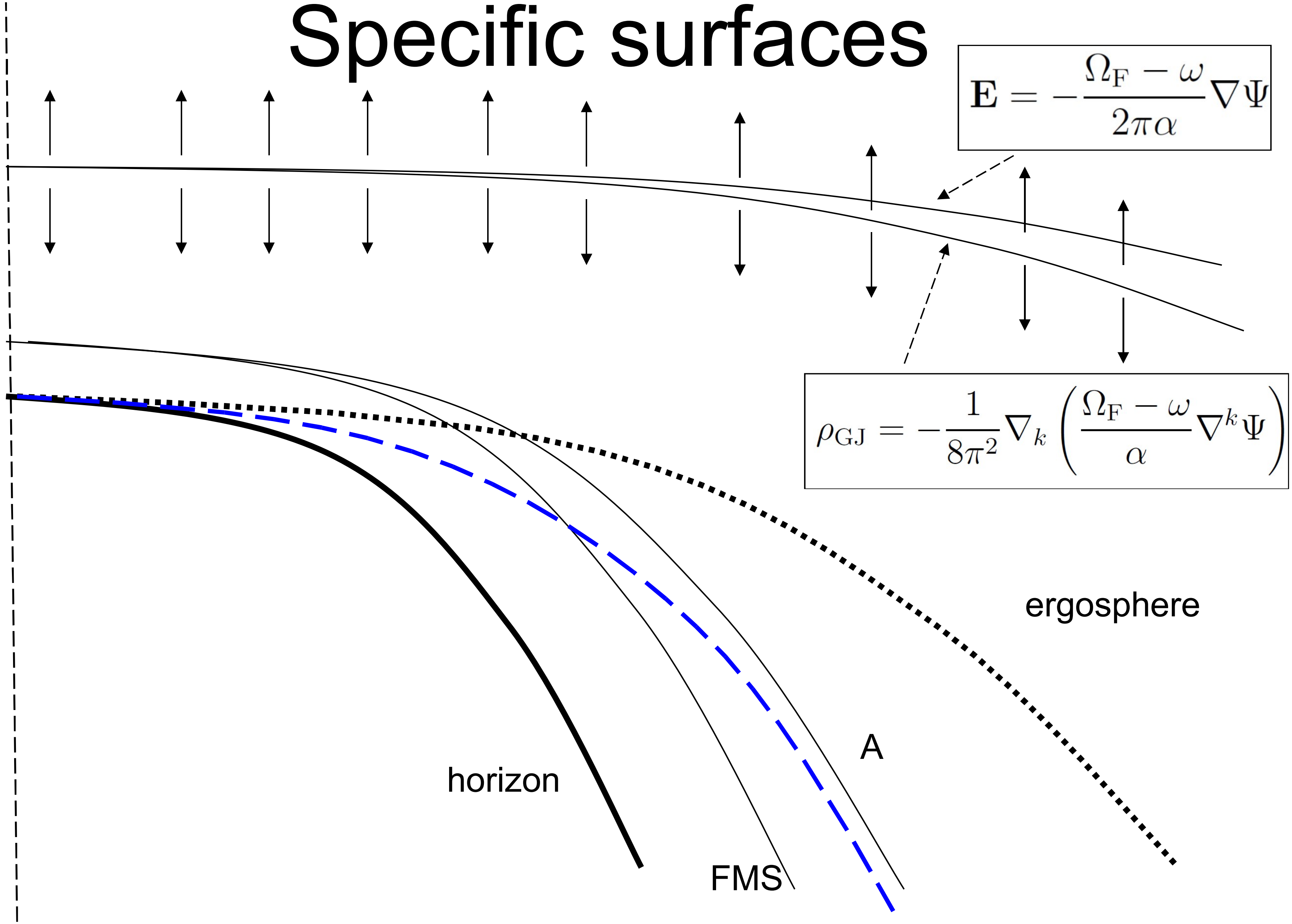
# Specific surfaces



# Specific surfaces



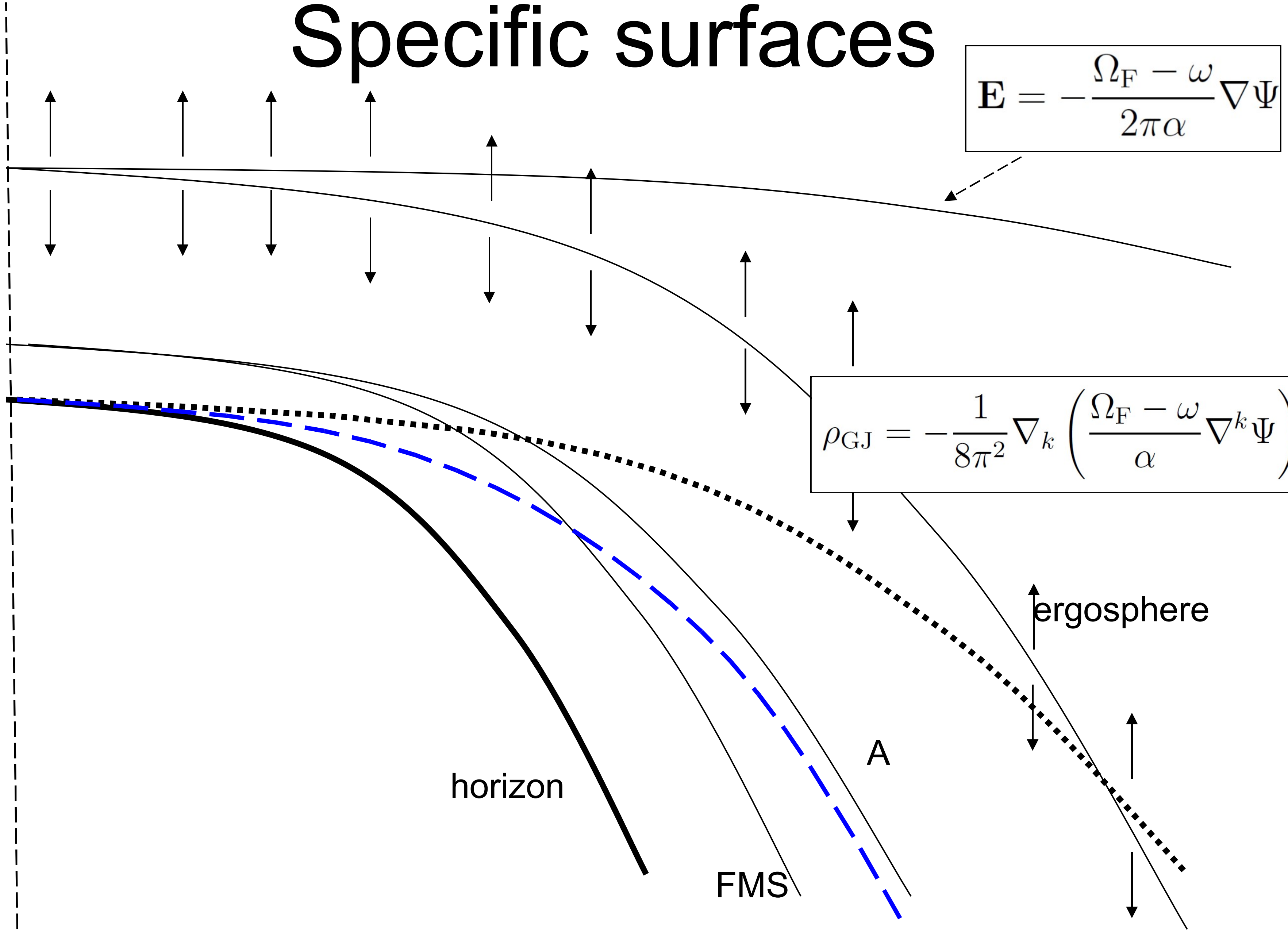
# Specific surfaces



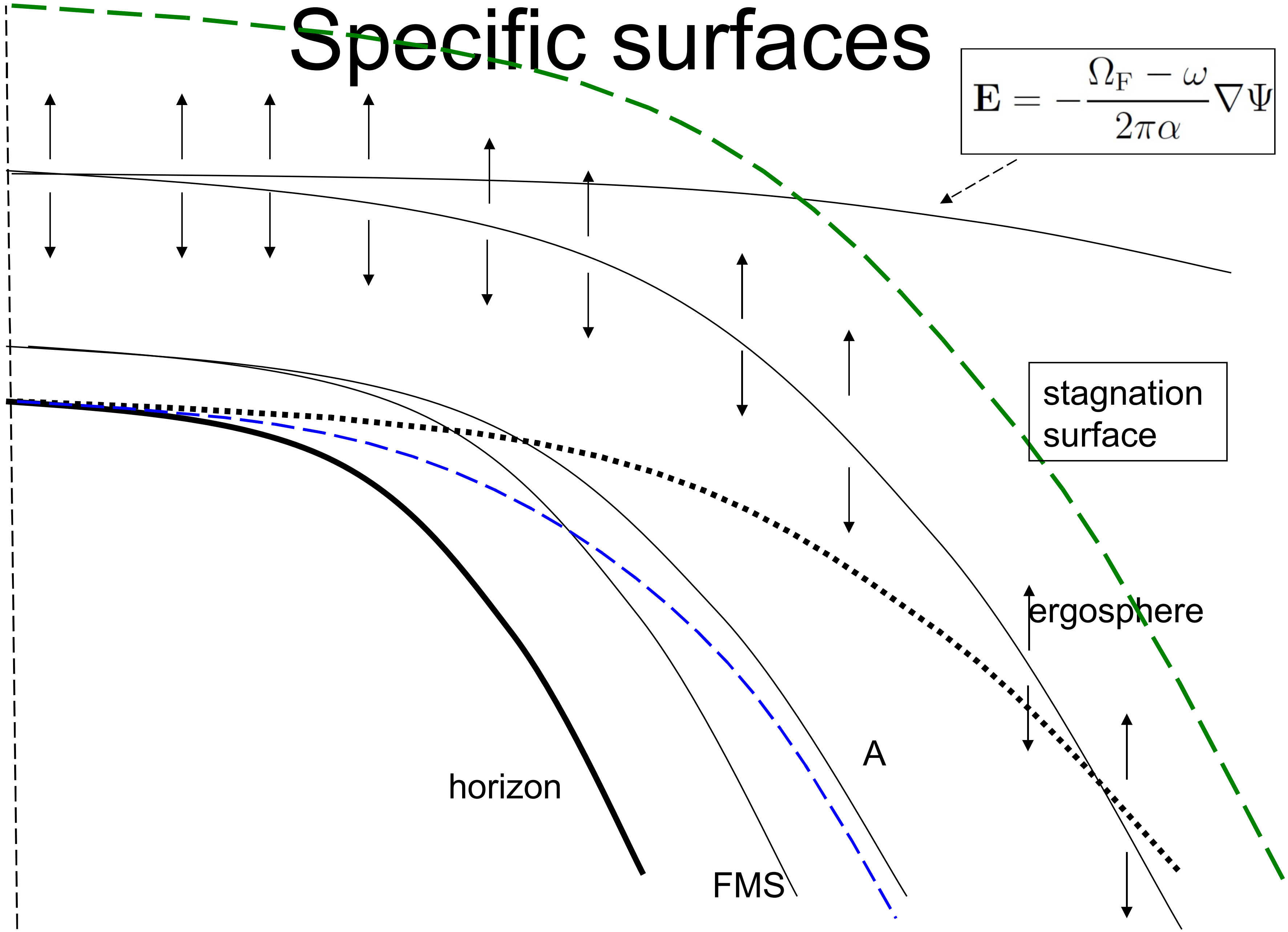
# Specific surfaces

$$\mathbf{E} = -\frac{\Omega_{\rm F} - \omega}{2\pi\alpha}\nabla\Psi$$

$$\rho_{\rm GJ} = -\frac{1}{8\pi^2}\nabla_k\left(\frac{\Omega_{\rm F} - \omega}{\alpha}\nabla^k\Psi\right)$$



# Specific surfaces

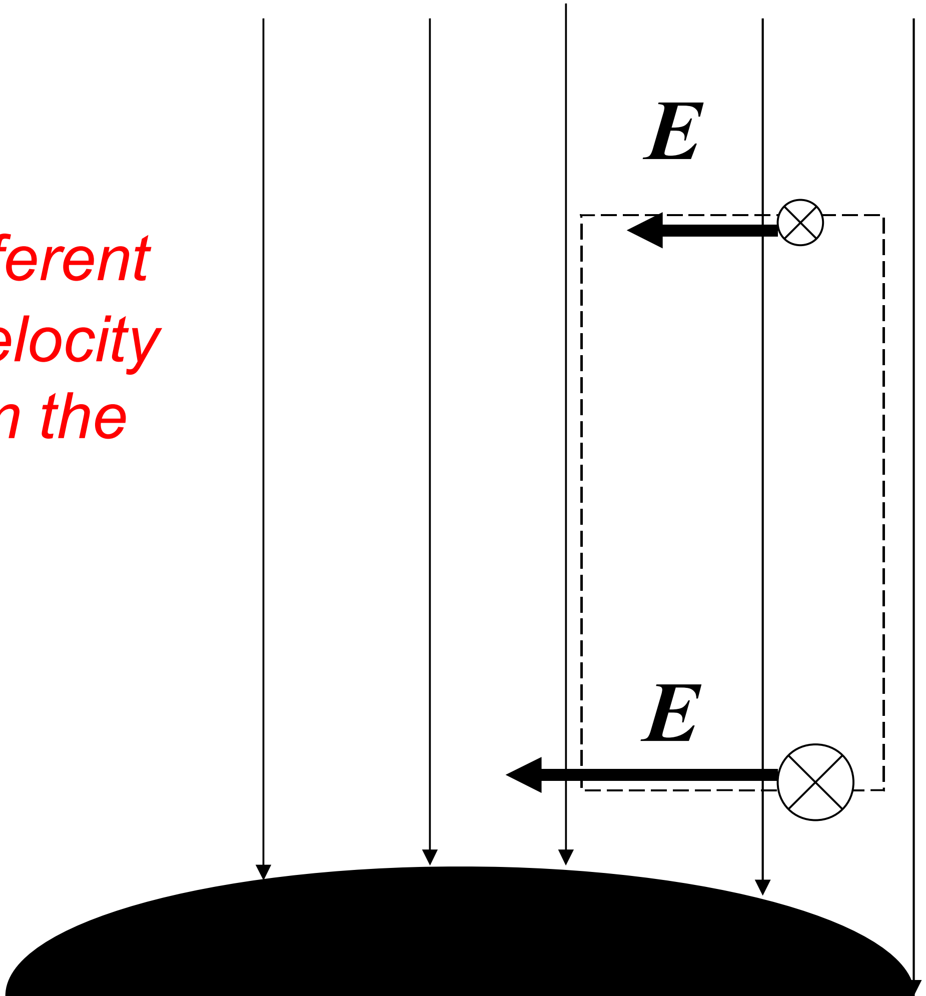


# The answer

The motion relatively ZAMOs results in the generation of the electric field.

$$\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}/c$$

*EMF results from the different Lense-Thirring angular velocity at different distances from the black hole.*




Laboratory frame

# Gravity as a media with $n < 0$

Extra objections

- Main effect is hidden
- Has a sense for linear response only (nonlocal!)
- Media with $n < 0$ are open systems

Thanks a lot!