On the internal structure of relativistic jets

V.S. Beskin

P.N.Lebedev Physical Institute

Moscow Institute of Physics and Technology (National Research University)

This presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]

Plan

- Thanks
- AGN Jets – internal structure (observations)
- AGN Jets – internal structure (interpretation and problems)

  Is “central engine” a Faraday disk?

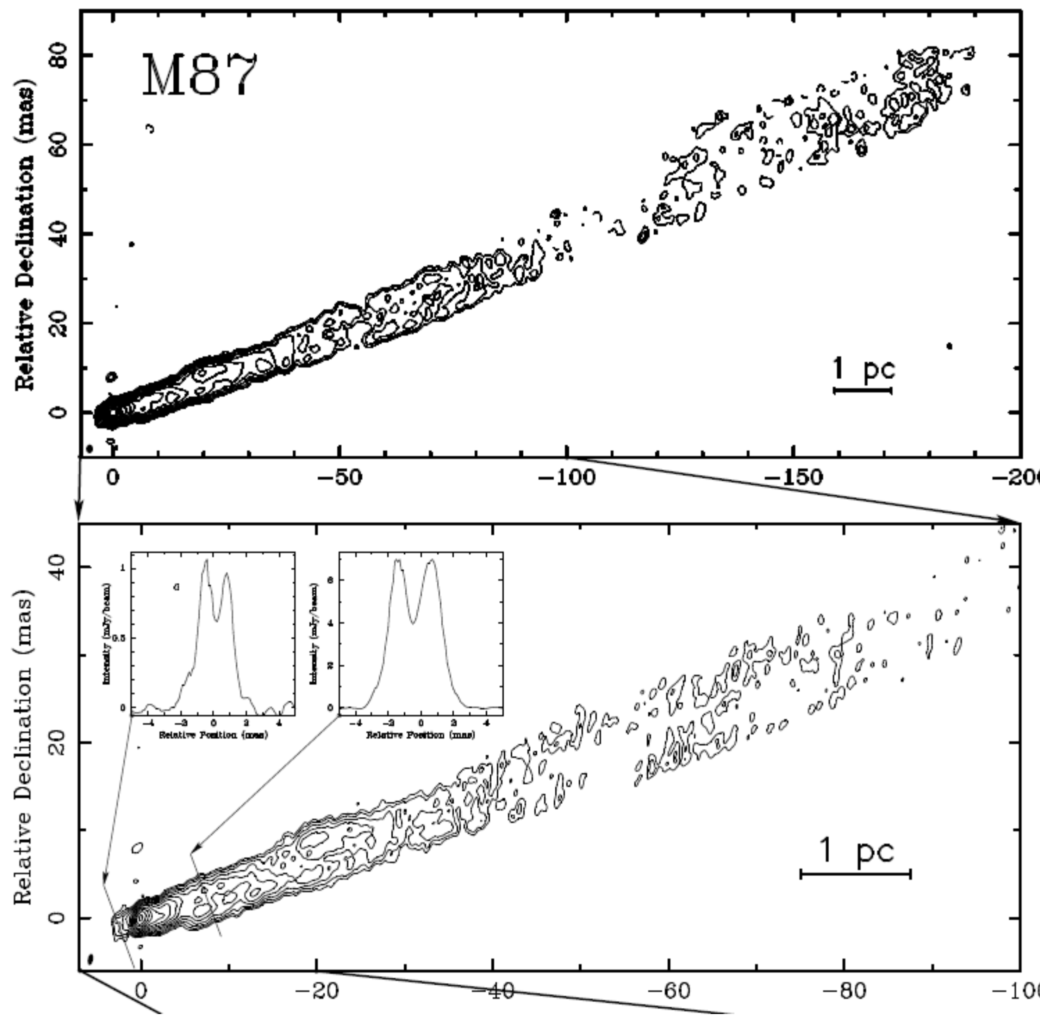
  Theoretical challenge – magnetic field

  Theoretical challenge – electric current

  Theoretical challenge – potential drop
- AGN Jets – internal structure (theory)
- Thanks again

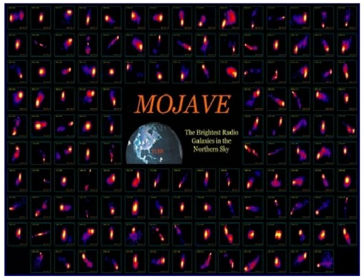
Internal structure – observations

Y.Y.Kovalev et al, ApJ, **668**, L27 (2007)



Internal structure – observations

Last 10 years – new possibilities



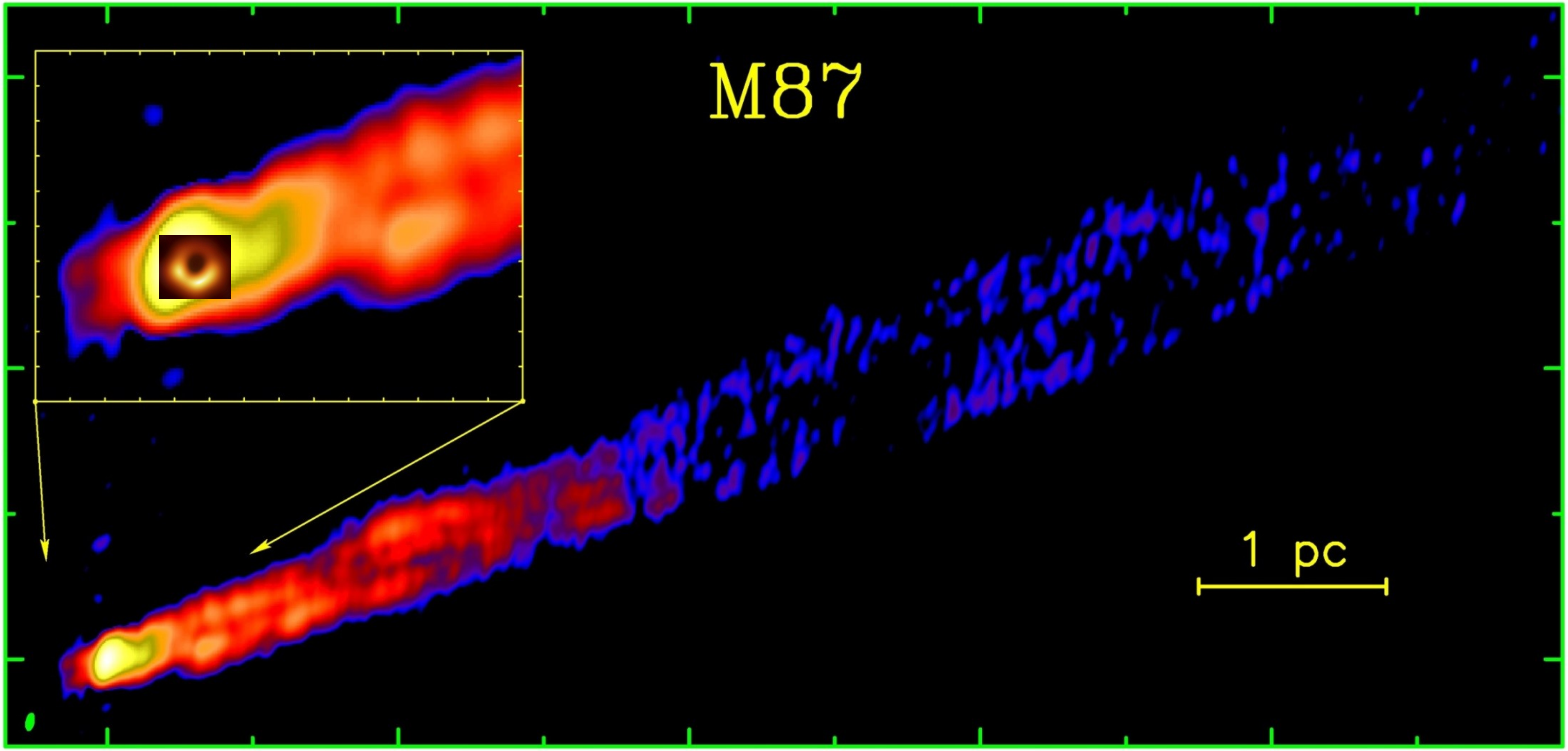
Time (MOJAVE)

Base (RadioAstron)

Frequency (EHT)

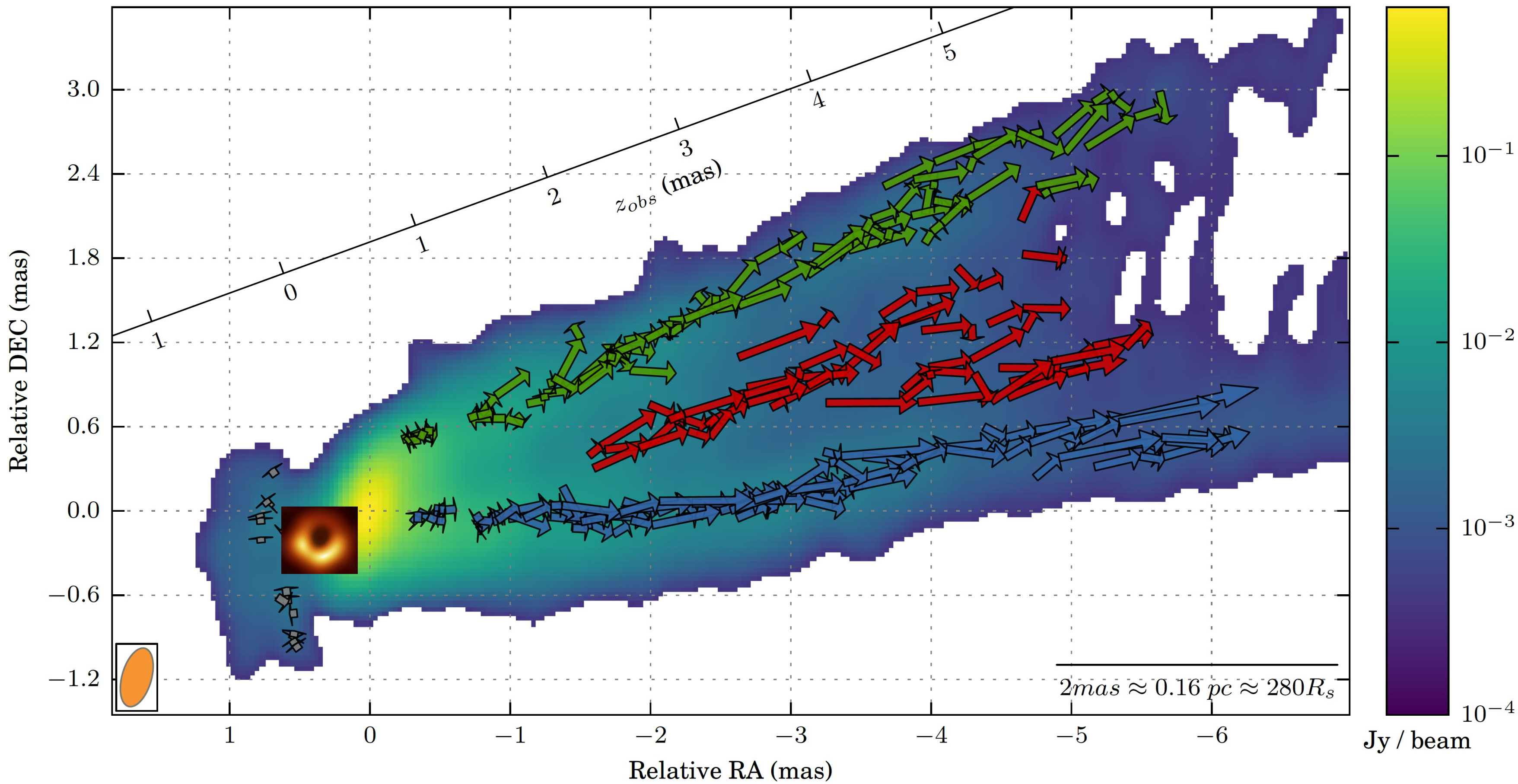
Internal structure – observations

Y.Y.Kovalev et al, ApJ, **668**, L27 (2007)



Internal structure – observations

F. Mertens, A.P.Lobanov, R.C.Walker, P.E.Hardee, A&A, **595**, A54 (2016)



Internal structure – observations

F. Mertens, A.P.Lobanov, R.C.Walker, P.E.Hardee, A&A, **595**, A54 (2016)

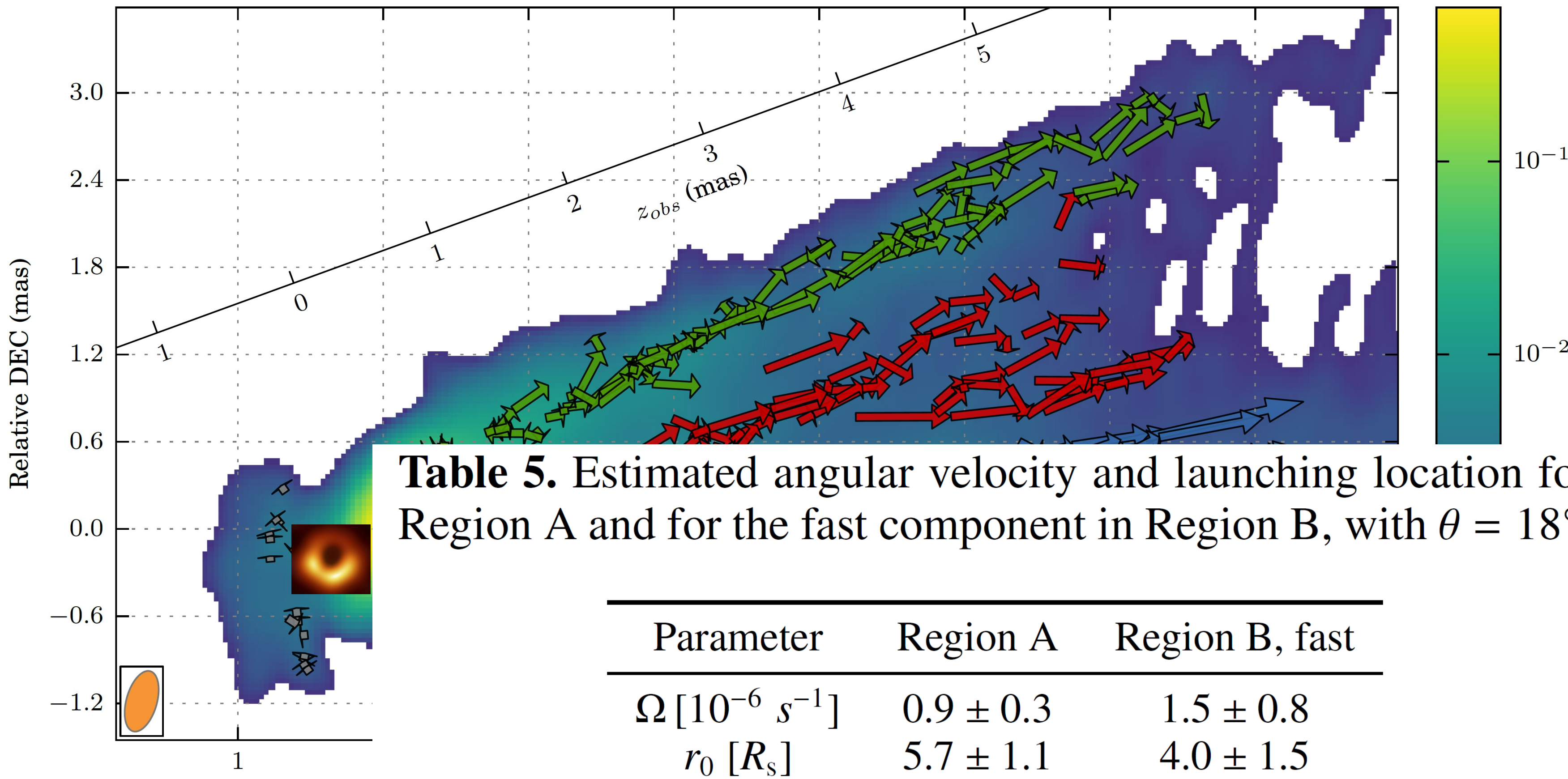
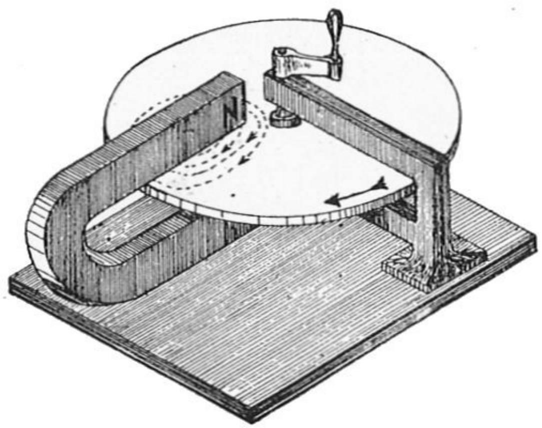


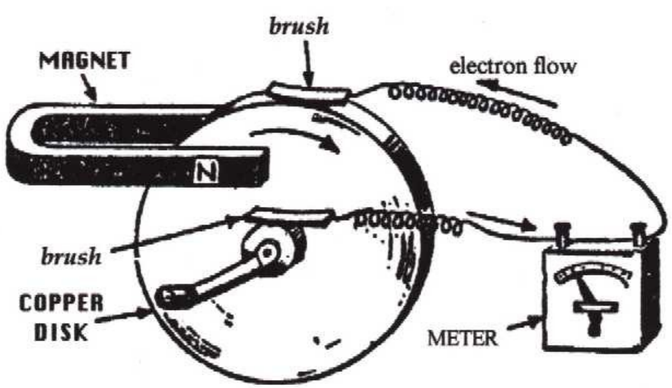
Table 5. Estimated angular velocity and launching location for Region A and for the fast component in Region B, with $\theta = 18°$.

Parameter	Region A	Region B, fast
$\Omega\ [10^{-6}\ s^{-1}]$	0.9 ± 0.3	1.5 ± 0.8
$r_0\ [R_s]$	5.7 ± 1.1	4.0 ± 1.5
$r_{lc}\ [R_s]$	19 ± 5	11 ± 6

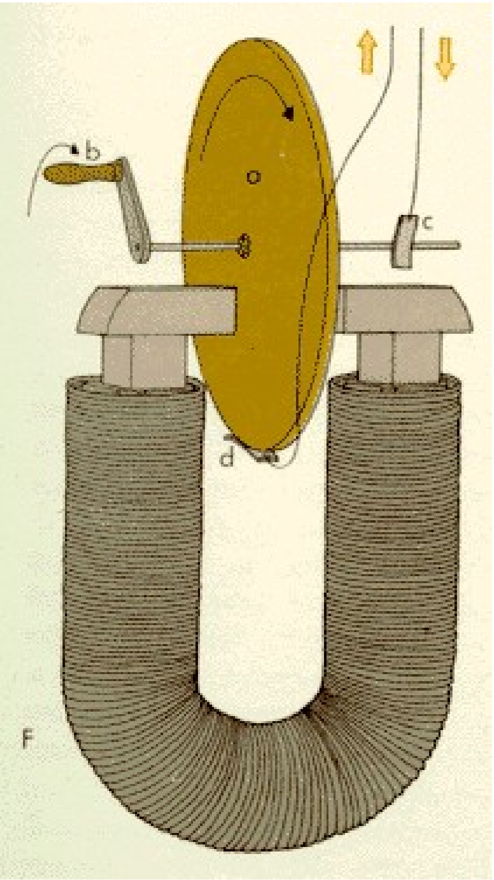
Confirmation of MHD model

“Central engine” is a Faraday disk

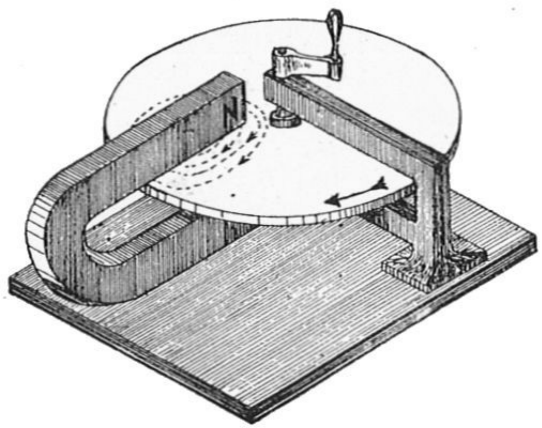


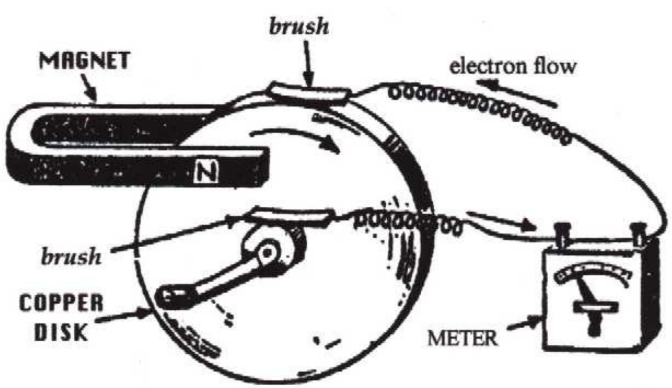


Faraday's disk dynamo - for producing continuous (pure) dc voltage. This was the world's first electrical generator.



“Central engine” is a Faraday disk





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

Dynamo-machine

- a magnet
- a rotation
- a wire
- a handle

Time-independent

“Central engine” is a Faraday disk

$$W_{\rm tot} = I\delta U$$

Dynamo-machine

- a magnet
- a rotation
- a wire
- a handle

$$\delta U \sim E\,R_0 \sim \left(\frac{\Omega R_0}{c}\right) B_0 R_0$$

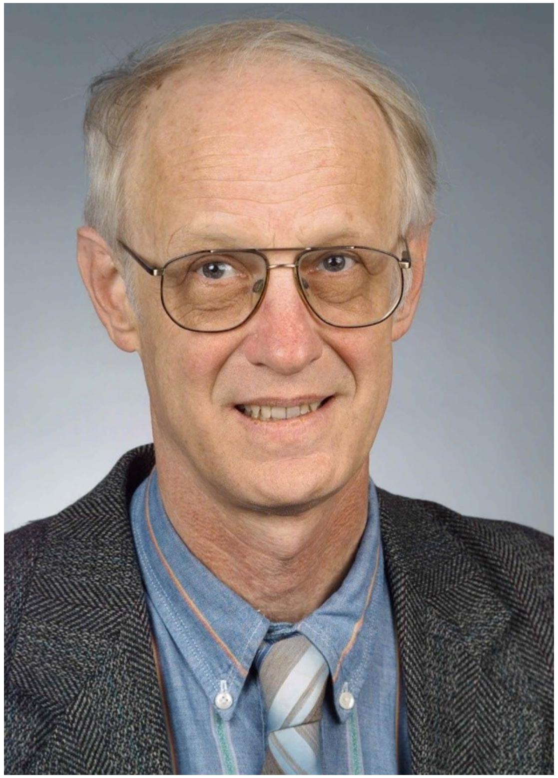
$$I \sim I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

$$\rho_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

$$\boxed{W_{\rm tot} \approx \left(\frac{\Omega R_0}{c}\right)^2 B_0^2 R_0^2 c}$$

Is black hole a Faraday disk?

R.Blandford (1976)



R.Lovelace (1976)

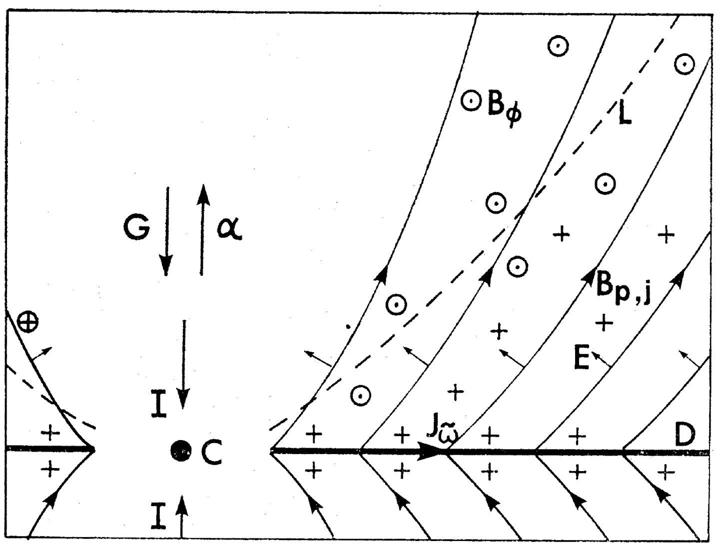
Is black hole a Faraday disk?

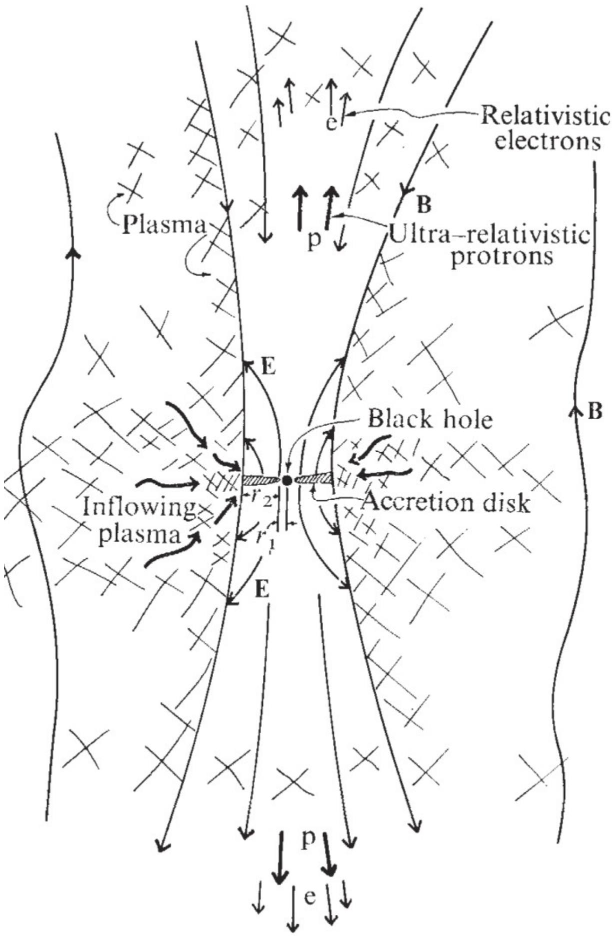
BZ = Faraday disk?

R.Blandford (1976), BZ (1977)

R.Lovelace (1976)

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





Is black hole a Faraday disk?

Membrane paradigm

BH fields

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

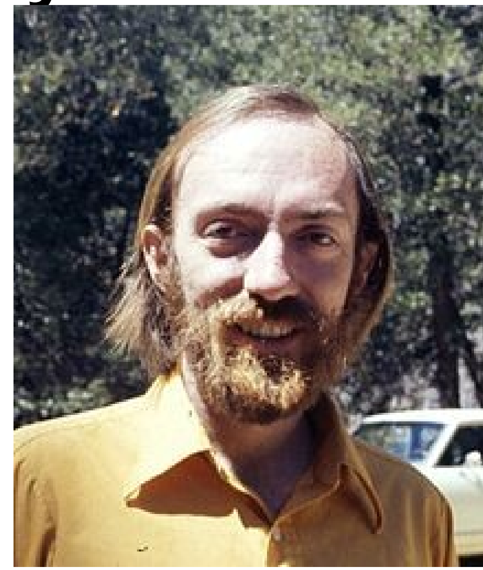
$$B_{\mathrm{H}} = \alpha B_{\hat{\varphi}}$$

"Ohm's law"

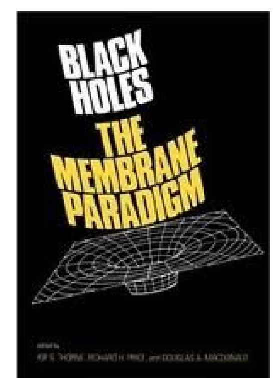
$$\boxed{E_{\hat{\theta}} = -B_{\hat{\varphi}}}$$

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

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



K.Thorne



= BZ "boundary condition" at the horizon

$$\boxed{4\pi I(\Psi) = [\Omega_{\mathrm{H}} - \Omega_{\mathrm{F}}(\Psi)] \sin\theta \frac{r_{\mathrm{g}}^2 + a^2}{r_{\mathrm{g}}^2 + a^2\cos^2\theta} \left(\frac{\mathrm{d}\Psi}{\mathrm{d}\theta}\right)}$$

Statement #1

Evaluation

$$W_{\rm tot} = I\delta U$$

is universal and can be used for rotating black holes at the base of relativistic jets.

According to membrane paradigm

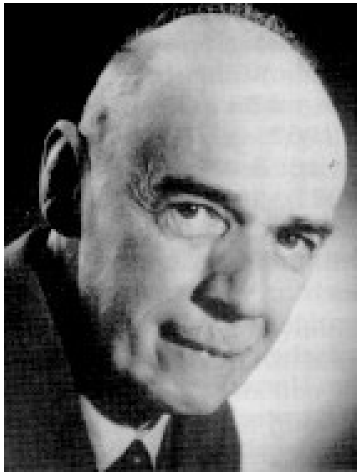
$$I \sim \delta U/\mathcal{R} \sim I_{\rm GJ}$$

and, hence, we return to

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

Not a Faraday disk, but it doesn't matter

BZ due to Frame-dragging (Lense-Thirring) effect



Homogeneously moving space cannot be detected.

(First Newton Law)

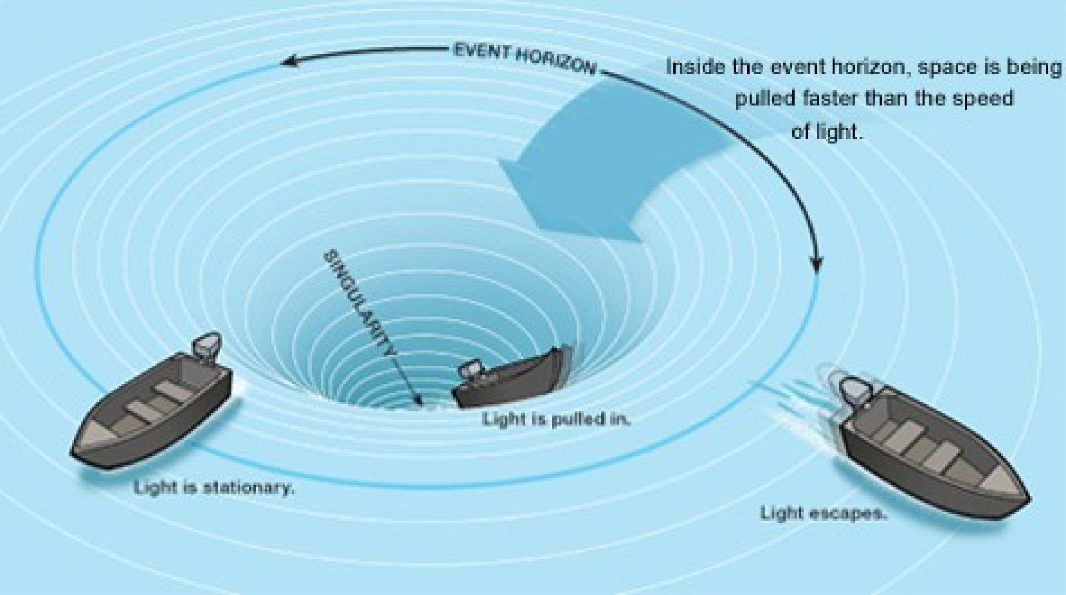
Inhomogeneously moving space can be detected.

Not a Faraday disk, but it doesn't matter

BZ due to Frame-dragging (Lense-Thirring) effect

Schwarzschild black hole

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

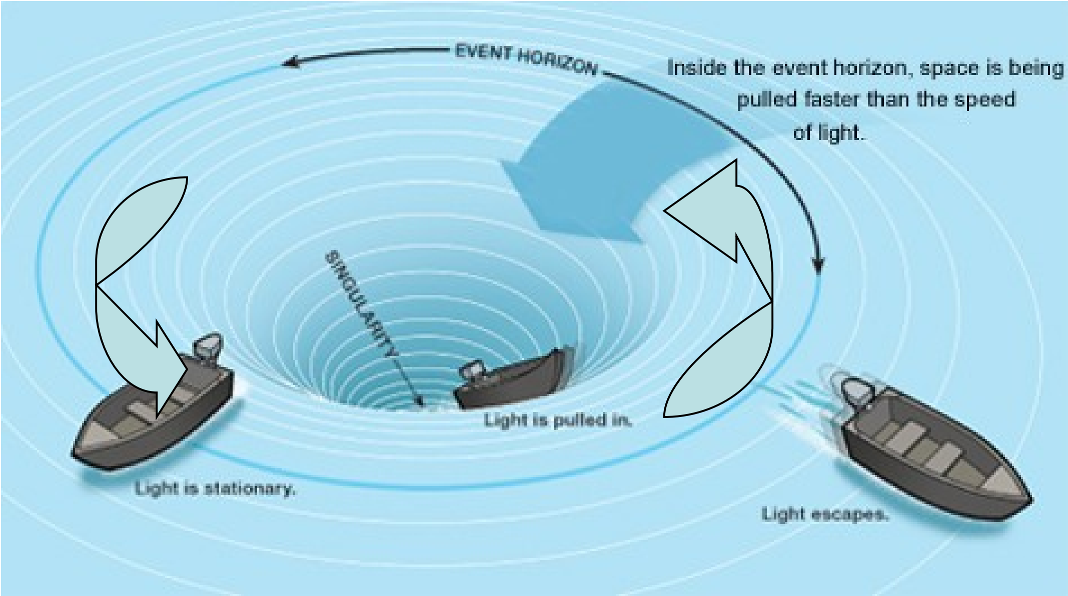


for laboratory at rest – tidal forces

Not a Faraday disk, but it doesn't matter

[BZ due to Frame-dragging (Lense-Thirring) effect]

Kerr black hole



for laboratory at rest – gyroscope precession

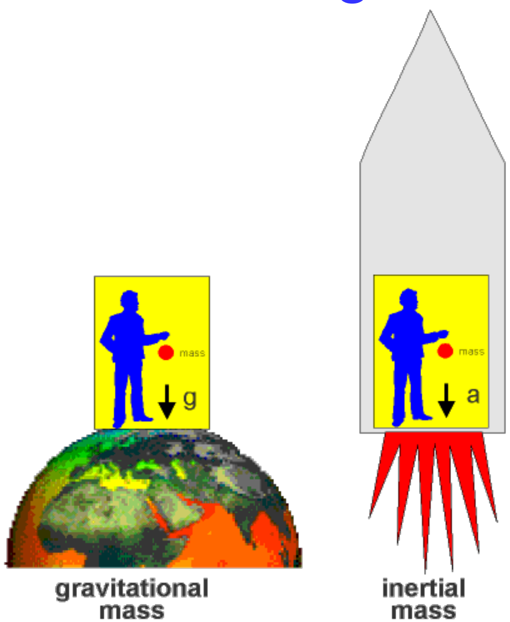
Not a Faraday disk, but it doesn't matter

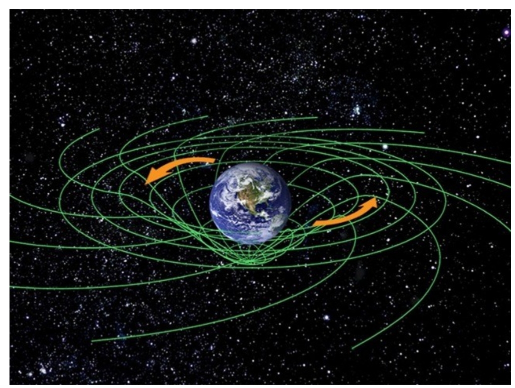
[BZ due to Frame-dragging (Lense-Thirring) effect]

accelerating reference frame

rotating reference frame

$$\mathbf{F}_{\mathrm{C}} = 2M\,[\mathbf{v} \times \mathbf{\Omega}]$$





$$\mathbf{g} \sim \mathbf{E}$$

$$\mathbf{F} = M\,\mathbf{g}$$

$$\mathbf{g} \sim \mathbf{E}, \quad \mathbf{H} \sim \mathbf{B}$$

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

Not a Faraday disk, but it doesn't matter

Gravito-magnetic field

GR: masses produce $\mathbf{g}$

mass motion produces $\mathbf{H}$

Maxwell equations

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

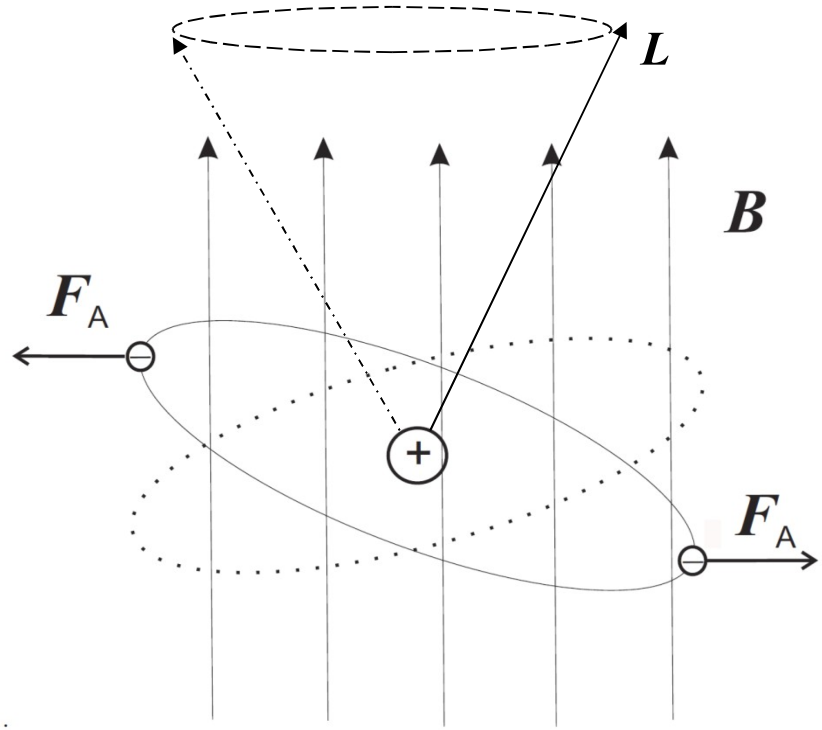
$$\mathbf{F} = e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)$$

Einstein equations for weak fields

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

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

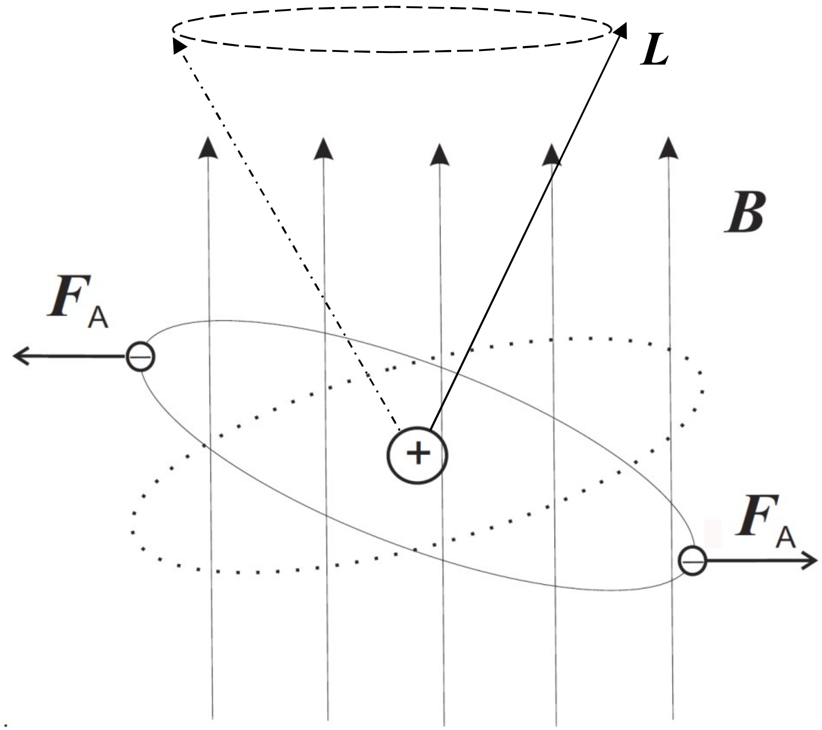
Not a Faraday disk, but it doesn't matter

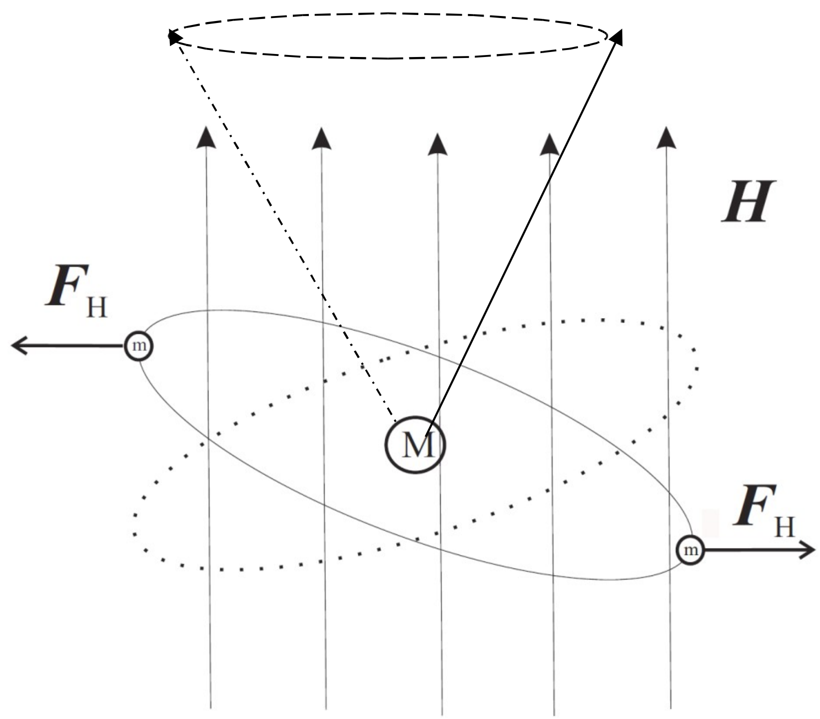


Larmor precession
due to Lorentz force

$$\Omega_{\mathrm{L}} = \frac{eB}{2m_{\mathrm{e}}c}$$

Not a Faraday disk, but it doesn't matter





Larmor precession
due to Lorentz force

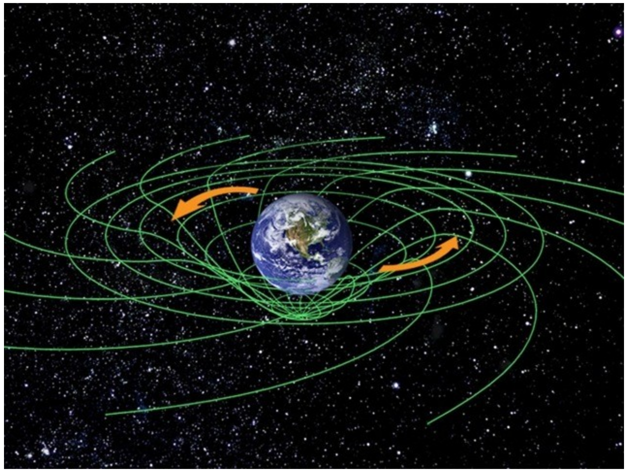
frame-dragging precession
due to 'Lorentz' force

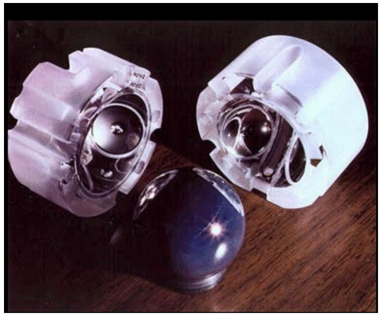
$$\Omega_{\mathrm{L}} = \frac{eB}{2m_{\mathrm{e}}c}$$

$$\Omega_{\mathrm{g}} = \frac{H}{2c}$$

Not a Faraday disk, but it doesn't matter

Gravity Probe B





$$
\begin{aligned}
\mathbf{g} &= -\frac{GM}{r^2}\mathbf{n}, \\
\mathbf{H} &= \frac{2G}{c}\frac{\mathbf{J}_r - 3\mathbf{n}(\mathbf{J}_r\mathbf{n})}{r^3}
\end{aligned}
$$

$$\Omega_{\mathrm{g}} = \frac{H}{2c}$$

Not a Faraday disk, but it doesn't matter

Gravity Probe B

Geodesic precession

$$\Omega_{\rm geo} = \frac{1+2\gamma}{2}\,\frac{GMv}{r^2c^2}$$

(−6,6018±0,0183) "/год

−6,6061 "/год

Frame-dragging precession

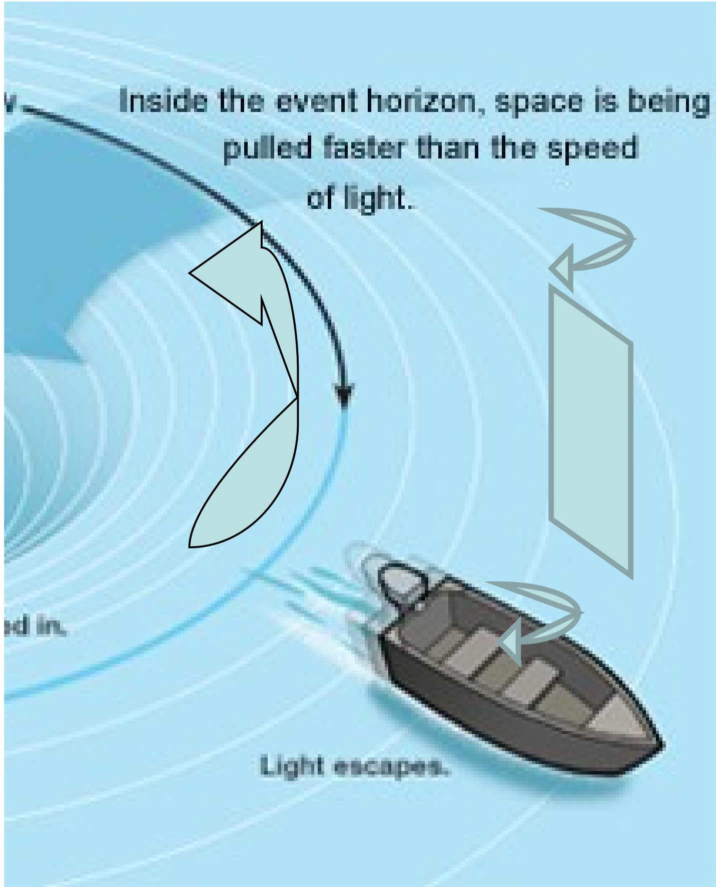
$$\Omega_{\rm g} = \frac{1+\gamma}{2}\,\frac{GJ_r}{r^3c^2}$$

(−0,0372±0,0072) "/год

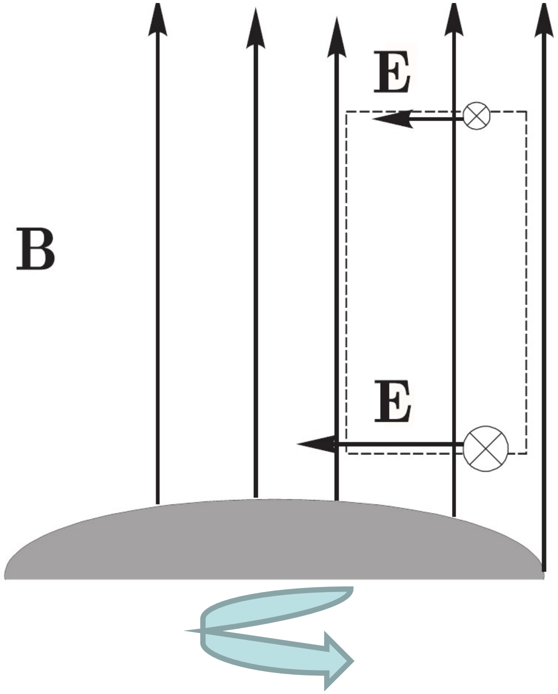
−0,0392 "/год

Not a Faraday disk, but it doesn't matter

BZ due to Frame-dragging (Lense-Thirring) effect



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



for laboratory at rest – "rotation", i.e. EMF

Statement #2

BZ = Faraday induction law + Penrose process

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

EMF results from frame-dragging (Lense-Thirring) effect which mimics the time-dependence due to inhomogeneous flow of space through the circuit.

$$\nabla \times (\alpha \mathbf{E}) = \mathscr{L}_{\hat{\beta}} \mathbf{B}$$

Main parameters

- Michel magnetization parameter (maximal bulk Lorentz-factor)

$$\boxed{\sigma_{\mathrm{M}} = \frac{\Omega_0 e B_0 r_{\mathrm{jet}}^2}{4\lambda m_{\mathrm{e}} c^3}}$$

μ now

- Multiplicity parameter

$$\boxed{\lambda = \frac{n^{(\mathrm{lab})}}{n_{\mathrm{GJ}}}}$$

$$\rho_{\mathrm{GJ}} = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}$$

- Total potential drop $\lambda\sigma_{\mathrm{M}} \sim \dfrac{eE_r r_{\mathrm{jet}}}{m_{\mathrm{e}} c^2}$

Main parameters

Magnetization – multiplication connection

$$\sigma_{\rm M} = \frac{\Omega_0 e B_0 r_{\rm jet}^2}{4\lambda m_{\rm e} c^3}$$

MHD 'central engine' energy losses

$$\lambda = \frac{n^{\rm (lab)}}{n_{\rm GJ}}$$

$$W_{\rm tot} \approx \left(\frac{\Omega R_0}{c}\right)^2 B_0^2 R_0^2 c$$

After some algebra

$$\boxed{\sigma_{\rm M} \sim \frac{1}{\lambda}\left(\frac{W_{\rm tot}}{W_{\rm A}}\right)^{1/2}}$$

$$W_{\rm A} = m_{\rm e}^2 c^5/e^2 \approx 10^{17}\,{\rm erg\,s^{-1}}$$

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

- No assumption about equipartition (in both cases we know the bulk particle energy Γmc^2).

$$\Gamma \sim \sigma_{\rm M}$$

- The only free parameter is the fraction of synchrotron radiating particles $n_{\rm syn} = \xi n_{\rm e}$.

$$\xi \approx 0.01$$

$$\lambda = 7.3 \times 10^{13} \left(\frac{\eta}{\mathrm{mas\,GHz}}\right)^{3/4} \left(\frac{D_{\rm L}}{\mathrm{Gpc}}\right)^{3/4} \times \left(\frac{\chi}{1+z}\right)^{3/4} \frac{1}{(\delta \sin\varphi)^{1/2}} \frac{1}{(\xi\gamma_{\min})^{1/4}}$$

$$\sigma_{\rm M} = 1.4 \left[\left(\frac{\eta}{\mathrm{mas\,GHz}}\right)\left(\frac{D_{\rm L}}{\mathrm{Gpc}}\right)\frac{\chi}{1+z}\right]^{-3/4} \times \sqrt{\delta \sin\varphi}\,(\xi\gamma_{\min})^{1/4} \sqrt{\frac{P_{\rm jet}}{10^{45}\,\mathrm{erg\,s^{-1}}}}$$

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov, MNRAS, **447,** 2726 (2015)

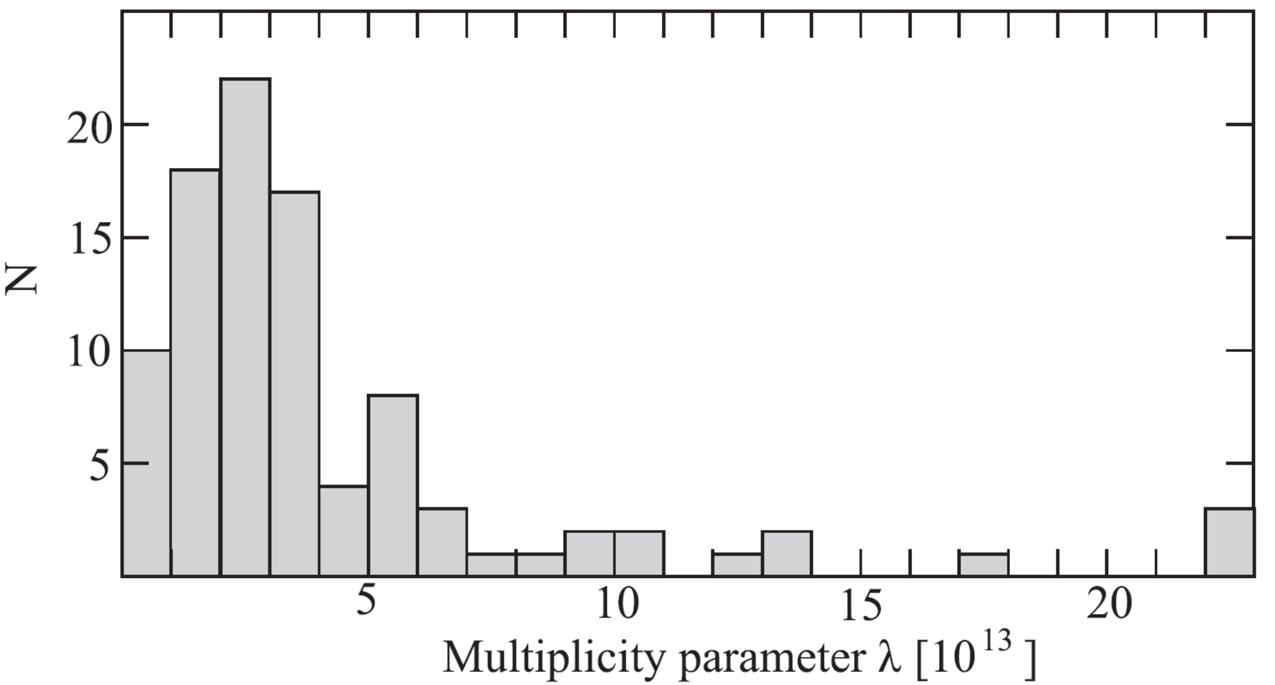


Figure 1. Distributions of the multiplicity parameter λ for the sample of 97 sources. Two objects with $\lambda = 2.8 \times 10^{14}$ and 3.6×10^{14} lie out of the shown range of values.

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov, MNRAS, **447,** 2726 (2015)

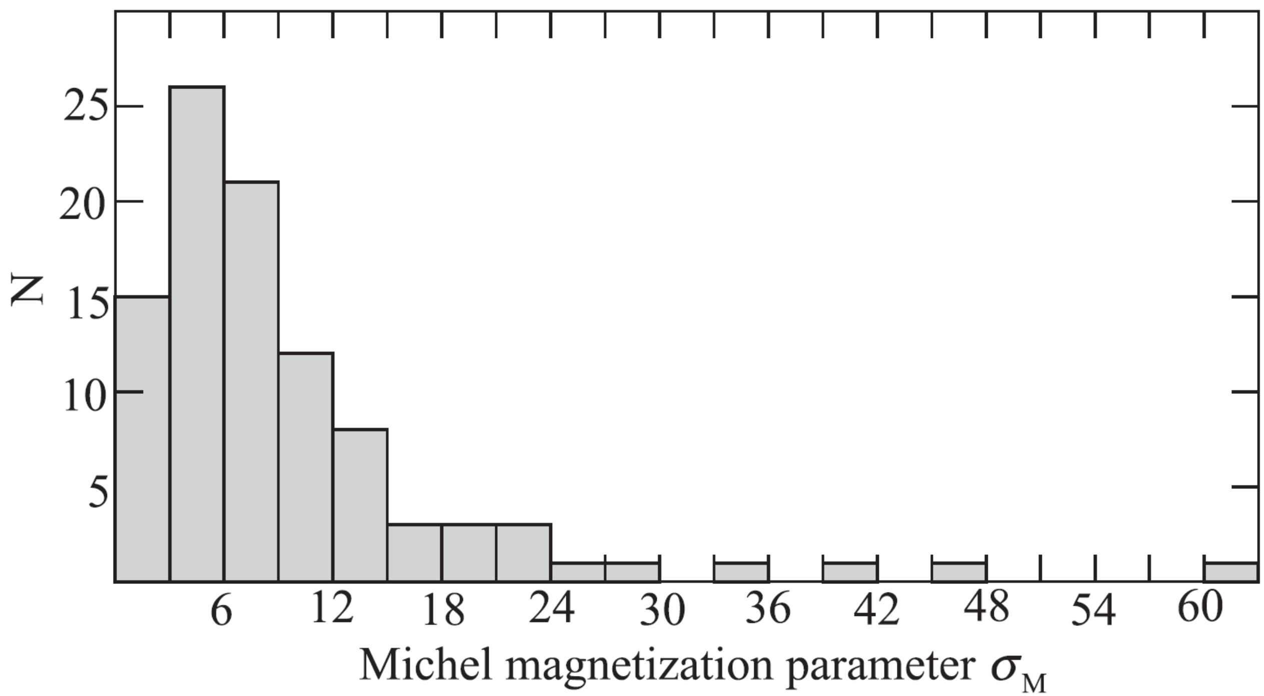
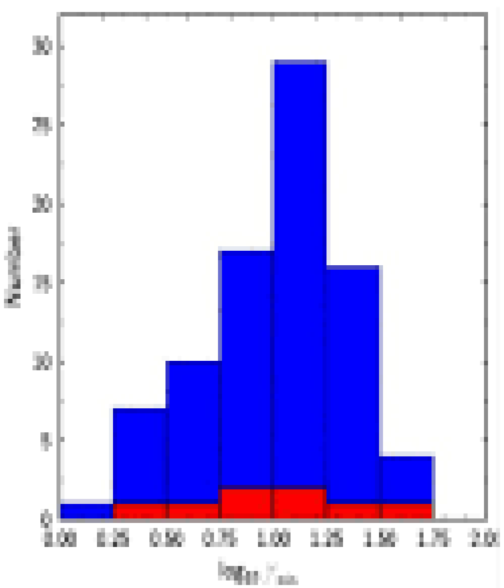


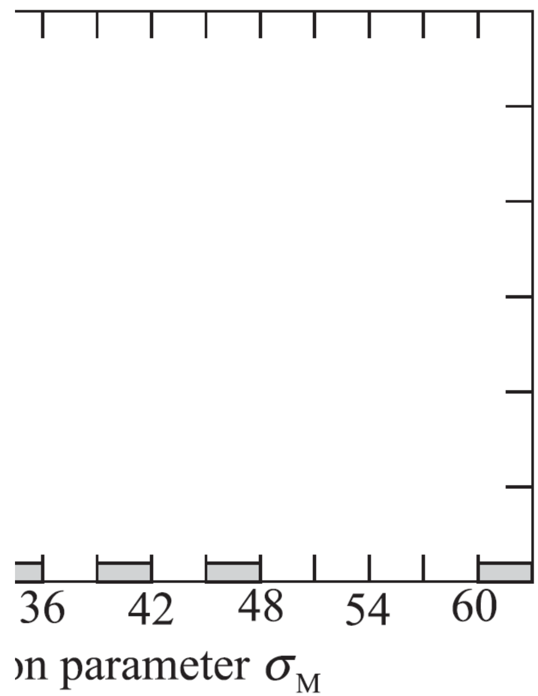
Figure 2. Distributions of the Michel magnetization parameter σ_M for the sample of 97 sources.

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov, MNRAS, **447,** 2726 (2015)



Distribution of Lorentz factors inferred from superluminal motion Blue = AGNs; red = microquasars (Fender 05)



ıetization parameter σ_M for the

A remark

Electron-positron vs electron-proton

$$\sigma_{\mathrm{M}} \sim \frac{1}{\lambda}\left(\frac{W_{\mathrm{tot}}}{W_{\mathrm{A}}}\right)^{1/2}$$

$$W_{\mathrm{A}} = m_{\mathrm{e}}^2 c^5 / e^2 \approx 10^{17}\,\mathrm{erg\,s^{-1}}$$

Theoretical challenge – B_0 problem

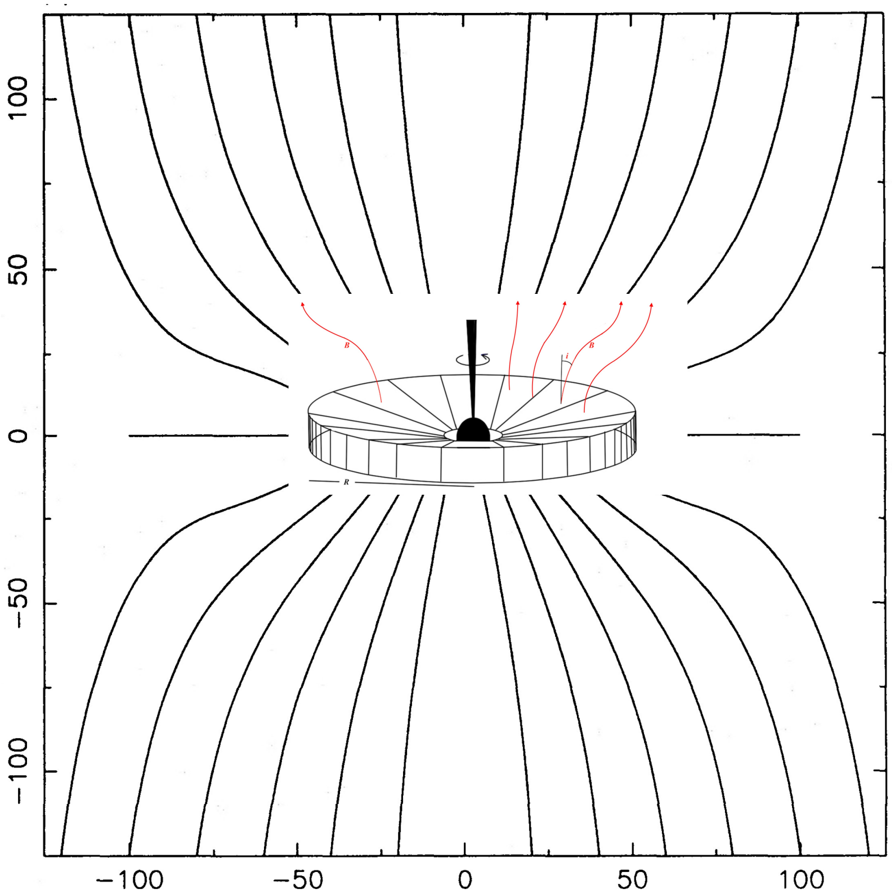
Magnetic field magnitude: Eddington value is necessary

$$B_{\mathrm{Edd}} \approx 10^4\,\mathrm{G}\left(\frac{M}{10^9 M_\odot}\right)^{-1/2}$$

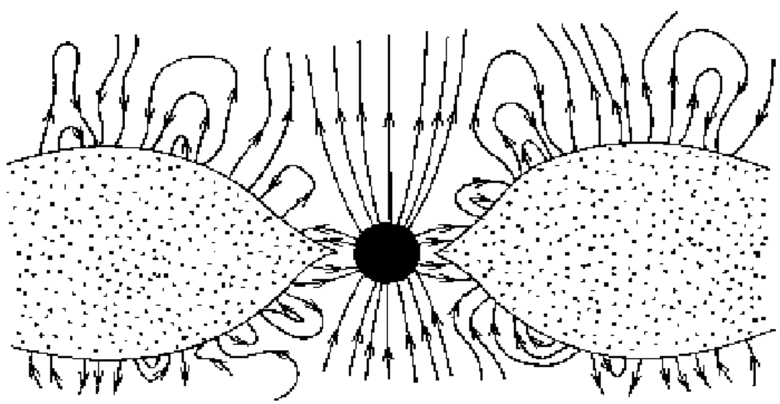
Theoretical challenge – B_0 problem

Magnetic field generation: external vs internal

external (advection)



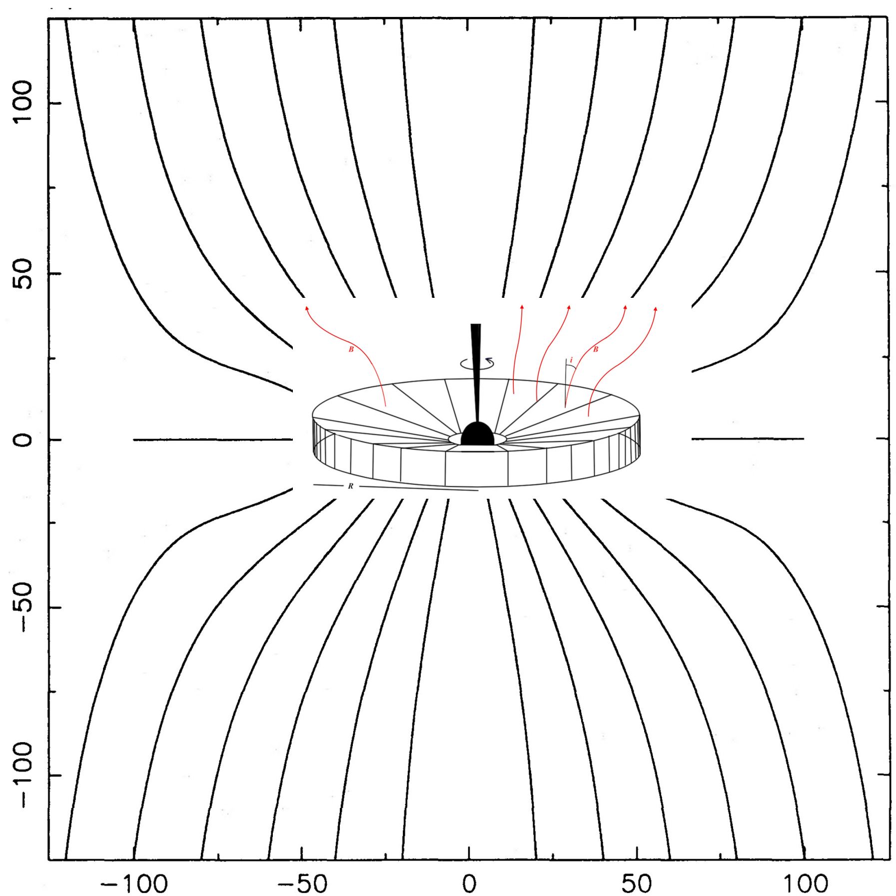
internal (dynamo)



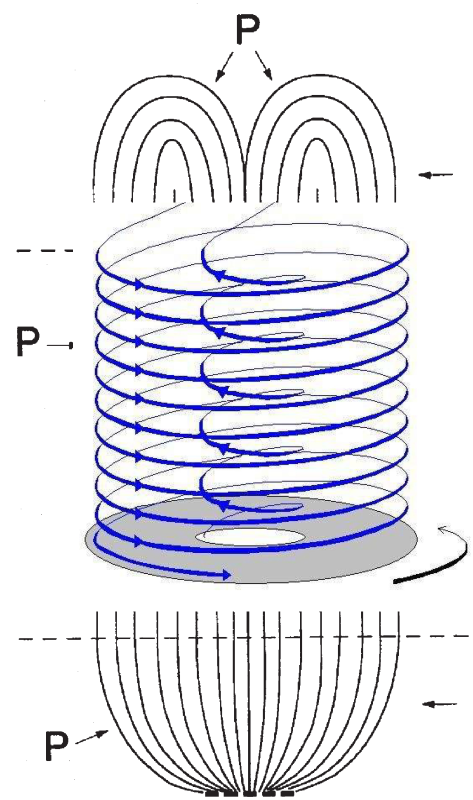
Theoretical challenge – B_0 problem

Magnetic field topology: external vs internal

homogeneous

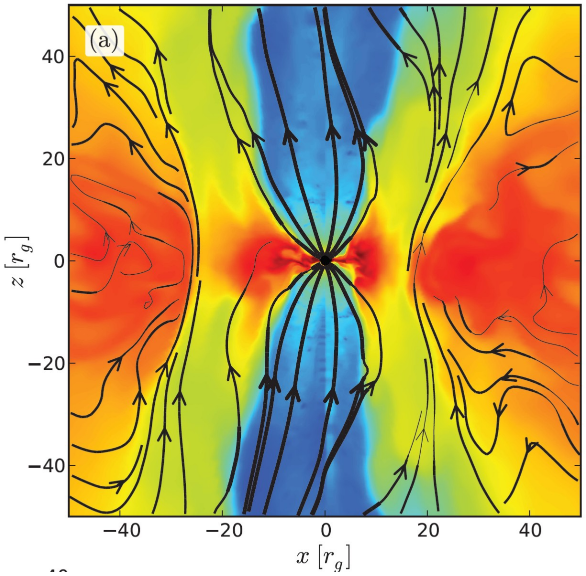


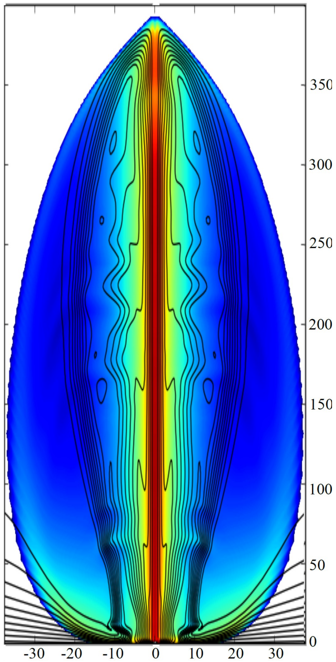
magnetic tower (RFP)



Theoretical challenge – B_0 problem

Magnetic field topology: homogeneous vs RFP





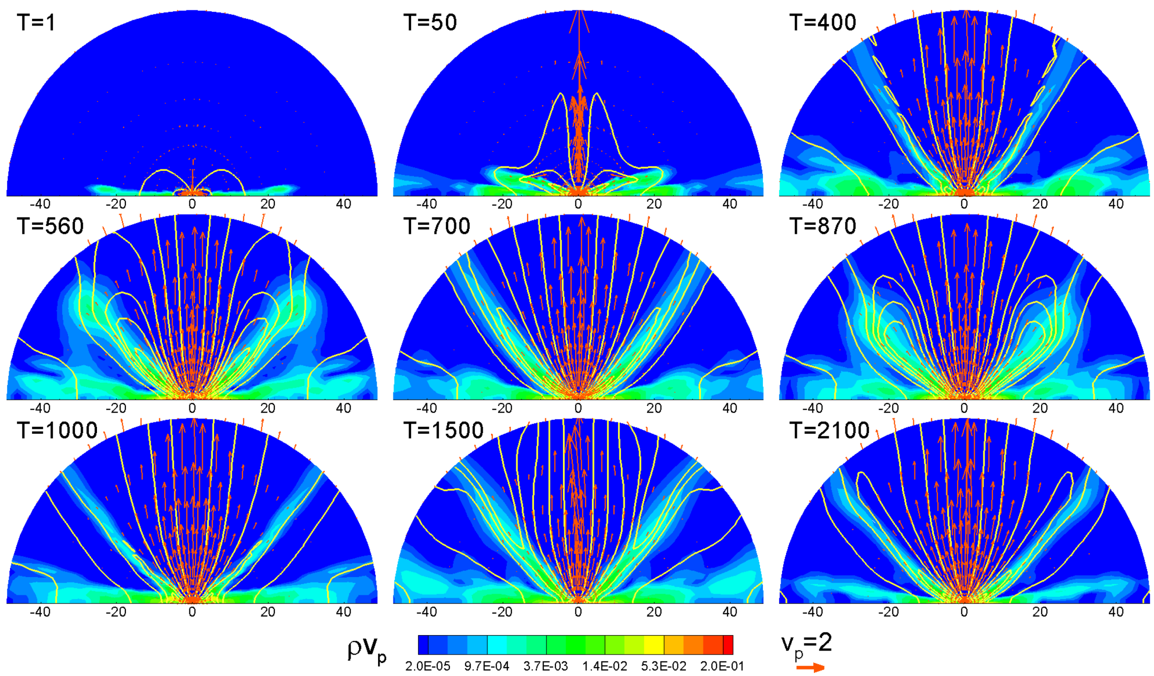
J.McKinney, A.Tchekhovskoy, R.Blandford

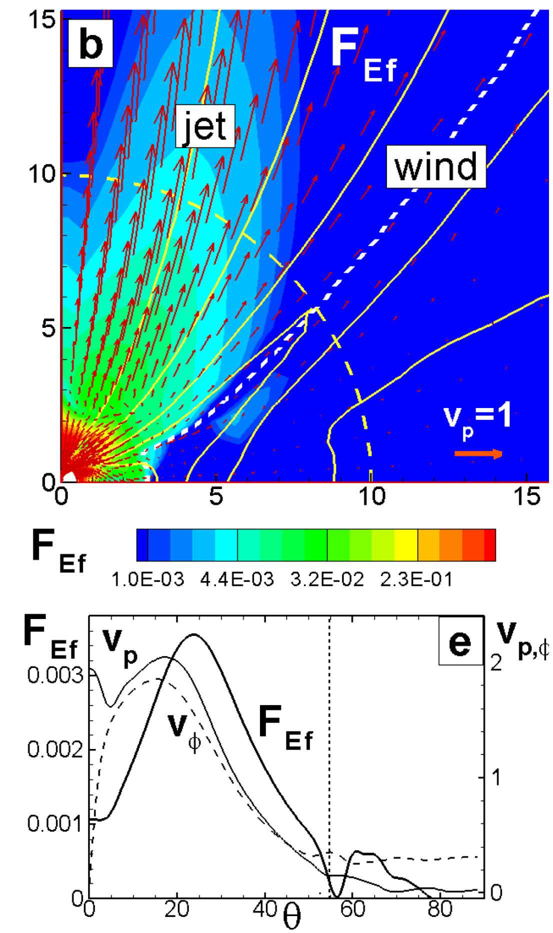
O. Bromberg, A. Tchekhovskoy

Theoretical challenge – B_0 problem

Magnetic field topology: homogeneous vs RFP

(evolution of dipole field)

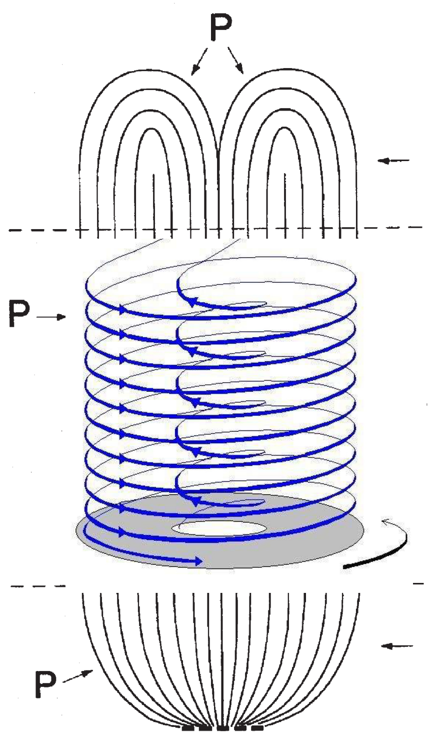




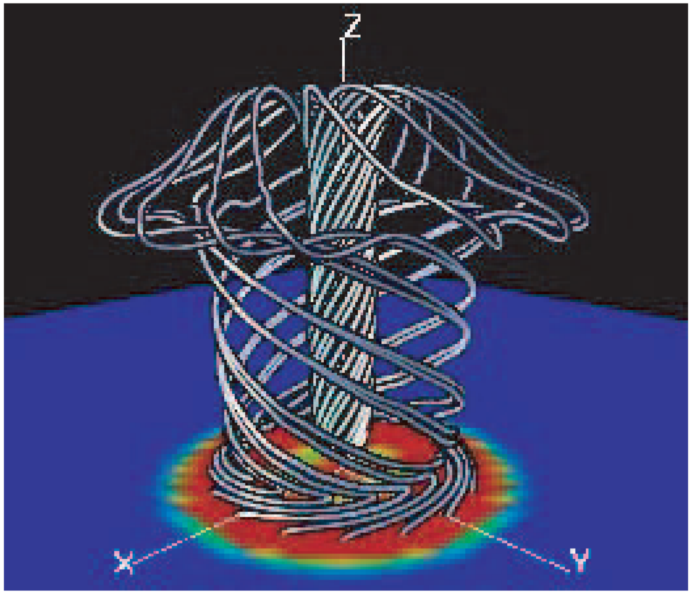
M.M.Romanova et al, MNRAS, **399**, 1802 (2009)

Theoretical challenge – B_0 problem

Magnetic tower (wind + diff. rotation)



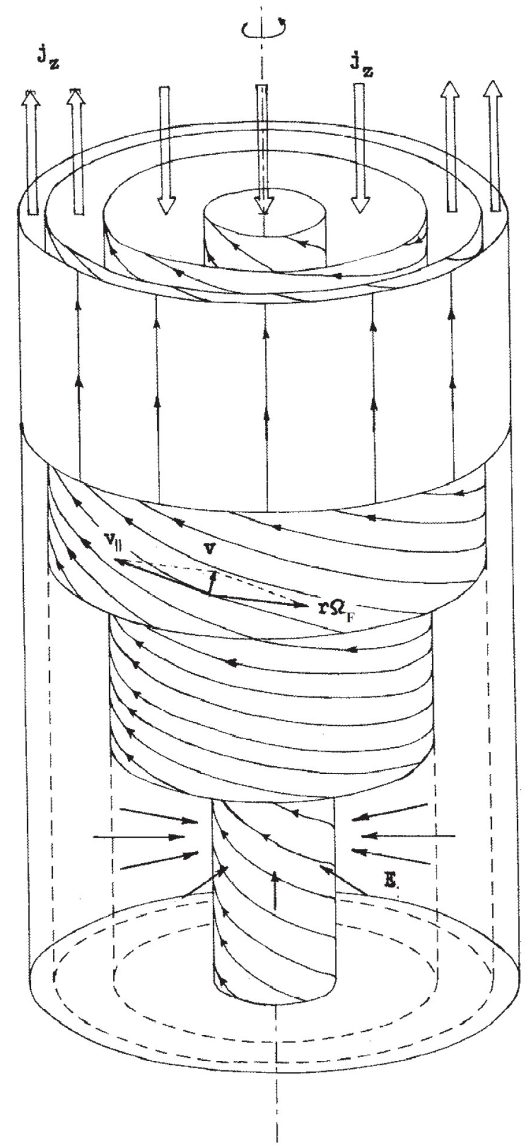
D.Lynden-Bell, MNRAS, **279**, 389 (1996)



Y.Kato, M.R.Hayashi, R.Matsumoto, ApJ, **600**, 338 (2004)

Statement #3

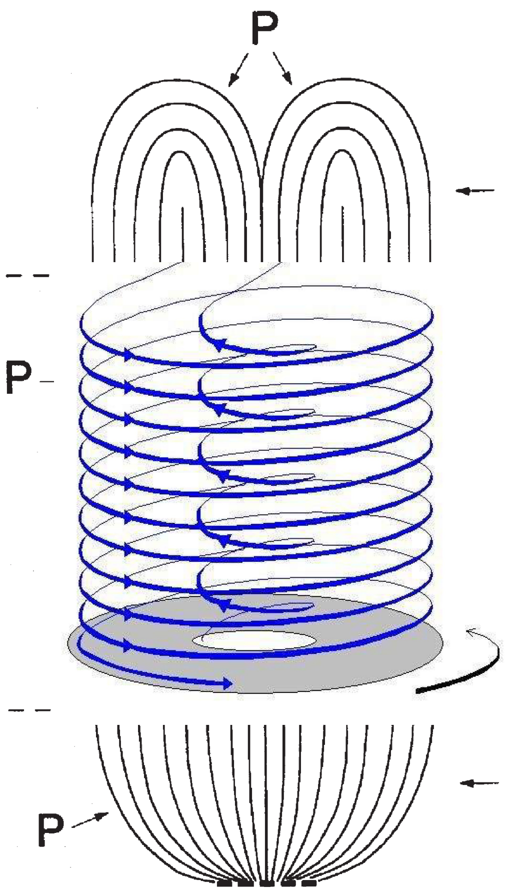
- Approximation of the homogeneous poloidal magnetic field is a reasonable model of relativistic jets.
- Total electric current can be zero.

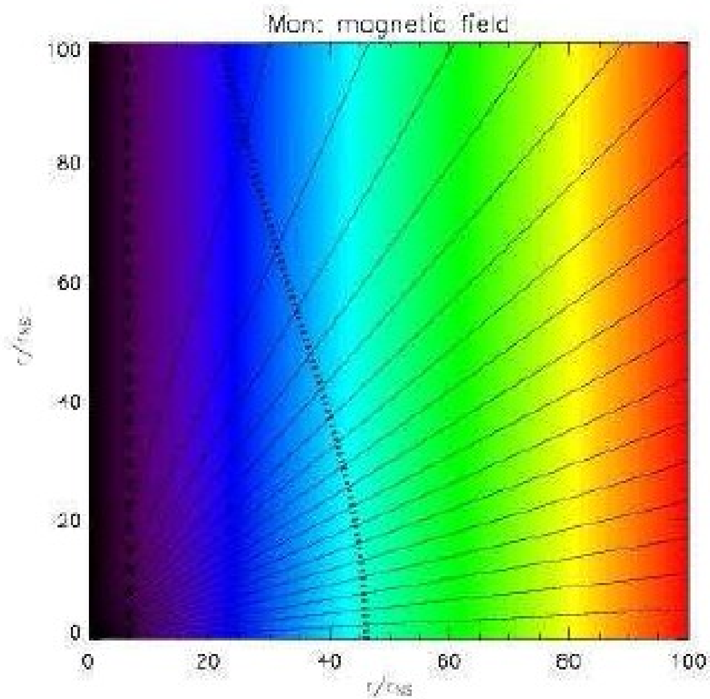


Theoretical challenge – I problem

Magnetic tower (cylindrical) vs diverging outflow (spherical)

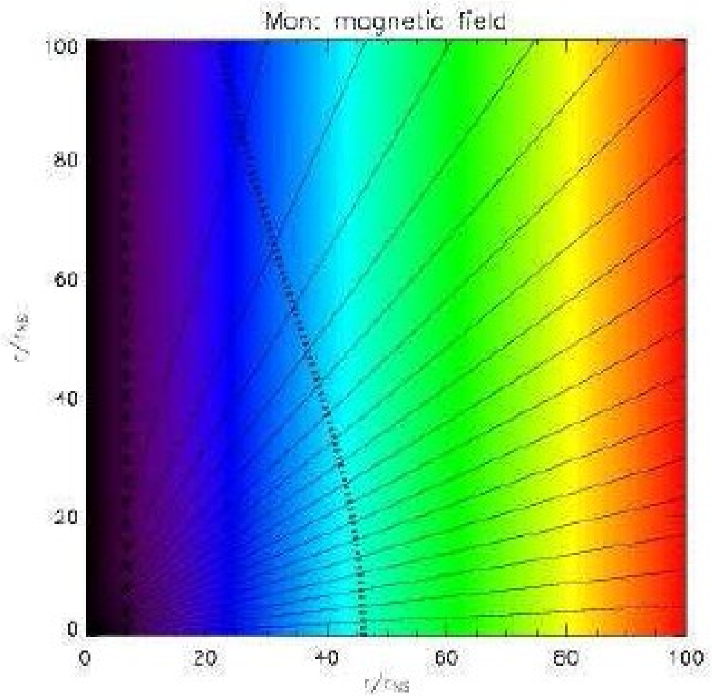
subsonic vs transonic

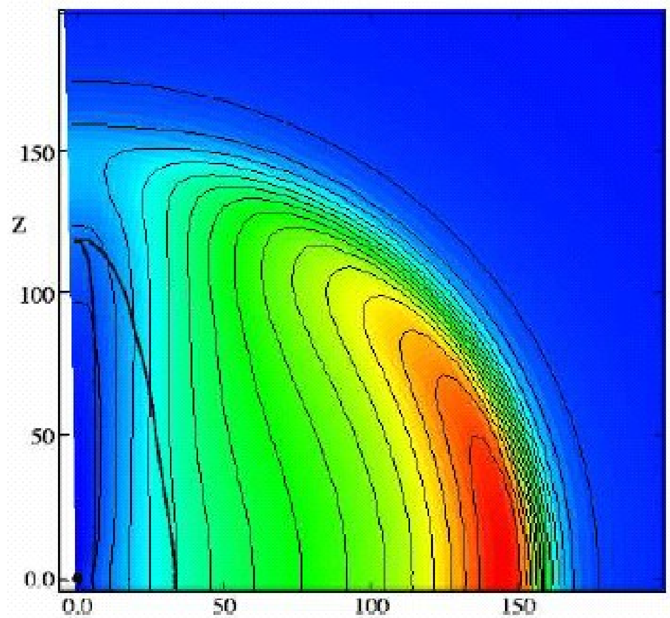




D.Lynden-Bell, MNRAS, **279**, 389 (1996)

Theoretical challenge – I problem





$$r_{\rm F} \approx \sigma_{\rm M}^{1/3} R_{\rm L} \sin^{1/3}\theta$$

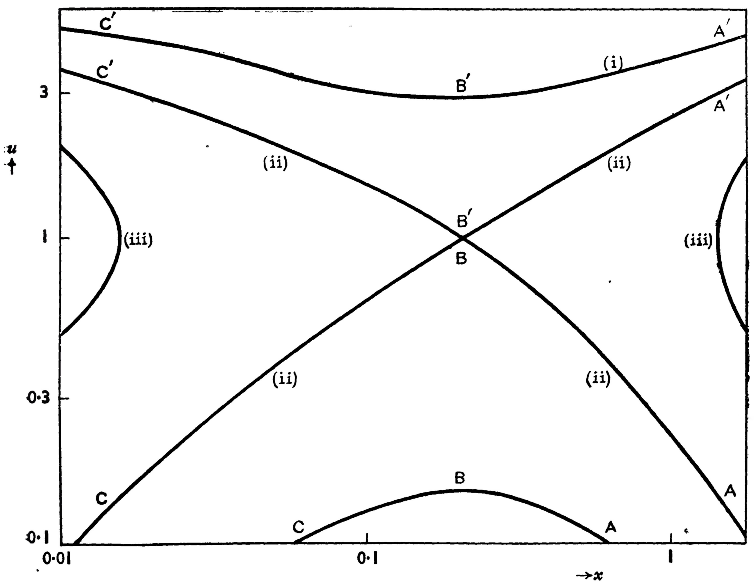
$$\gamma \approx \frac{\Omega r_\perp}{c}$$

N.Bucciantini, T.Thompson, J.Arons, E.Quataert, L.Del Zanna, MNRAS, **368**, 1717 (2006)

S.Komissarov, MNRAS, **350**, 1431 (2004)

Theoretical challenge – I problem

Critical condition on the sonic surface determines accretion rate



$$\frac{r}{n}\frac{\mathrm{d}n}{\mathrm{d}r} = \frac{2v^2 - \dfrac{GM}{r}}{c_s^2 - v^2}$$

H.Bondi, MNRAS, **112**, 195 (1952)

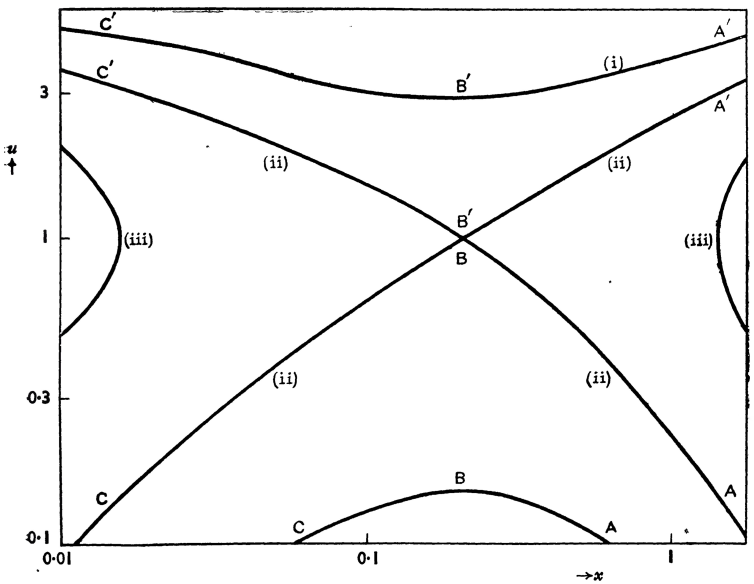
$$\Phi_{\mathrm{cr}} = 4\pi r_*^2 c_* n_* = \pi \left(\frac{2}{5-3\Gamma}\right)^{(5-3\Gamma)/2(\Gamma-1)} \frac{(GM)^2}{c_\infty^3} n_\infty$$

Theoretical challenge – I problem

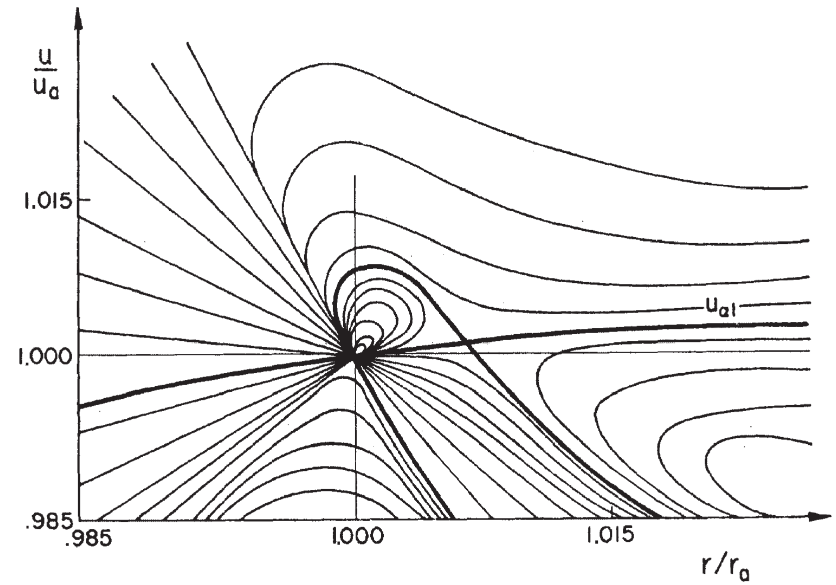
Critical condition on the (fast magneto)sonic surface determines

accretion rate

electric current I



H.Bondi, MNRAS, **112**, 195 (1952)



E.J.Weber, L.Davis, ApJ, **148**, 217 (1967)

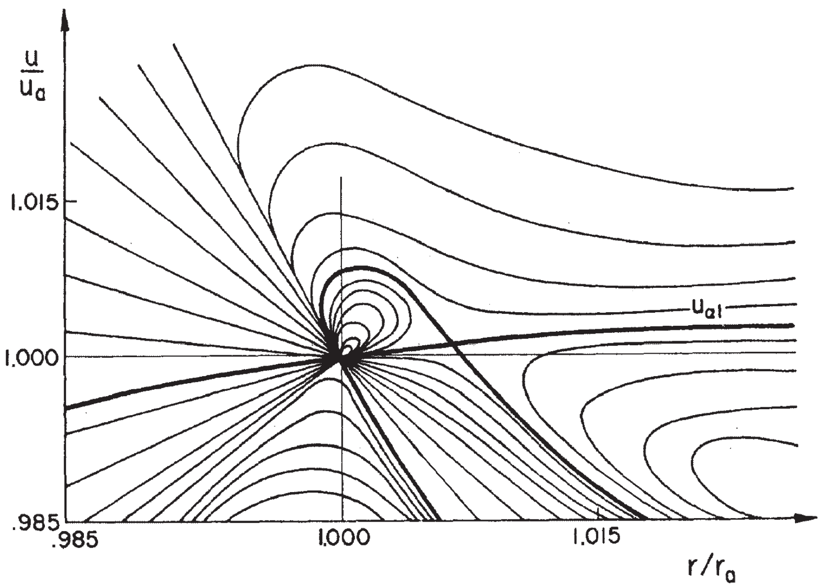
$$\Phi_{\rm cr} = 4\pi r_*^2 c_* n_* = \pi \left(\frac{2}{5-3\Gamma}\right)^{(5-3\Gamma)/2(\Gamma-1)} \frac{(GM)^2}{c_\infty^3} n_\infty$$

$$I \sim I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

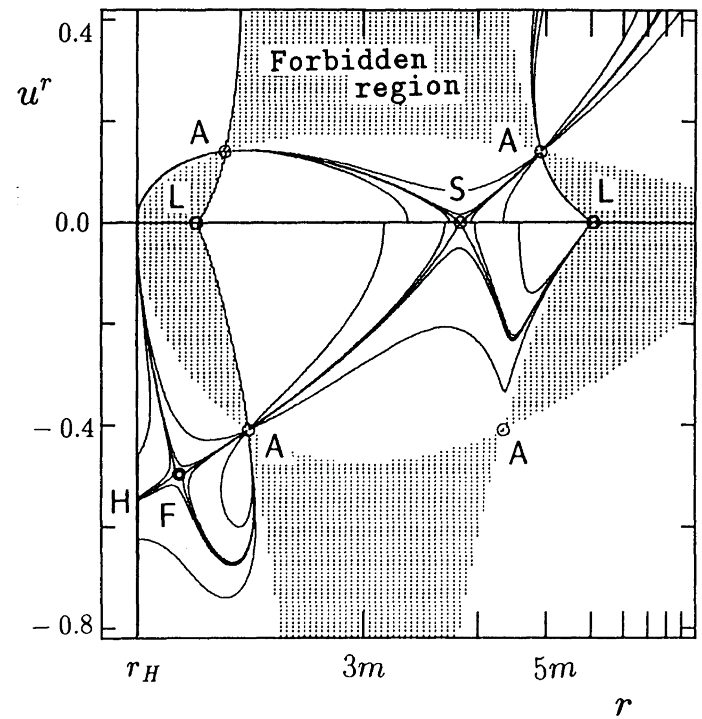
Theoretical challenge – I problem

Critical condition on the (fast magneto)sonic surfaces determine

electric current I + angular velocity $\Omega_{\rm F}$



E.J.Weber, L.Davis, ApJ, **148**, 217 (1967)



M.Takahashi et al, ApJ, **363,** 206 (1990)

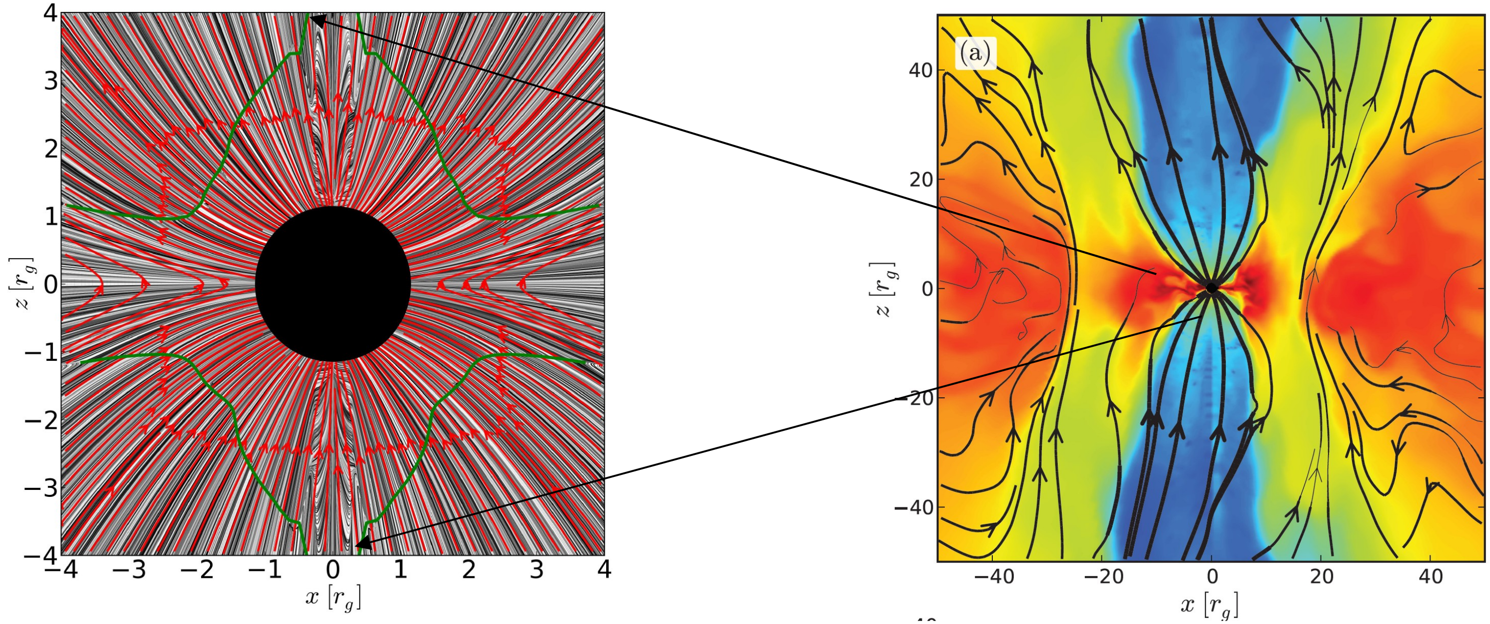
$$I \sim I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

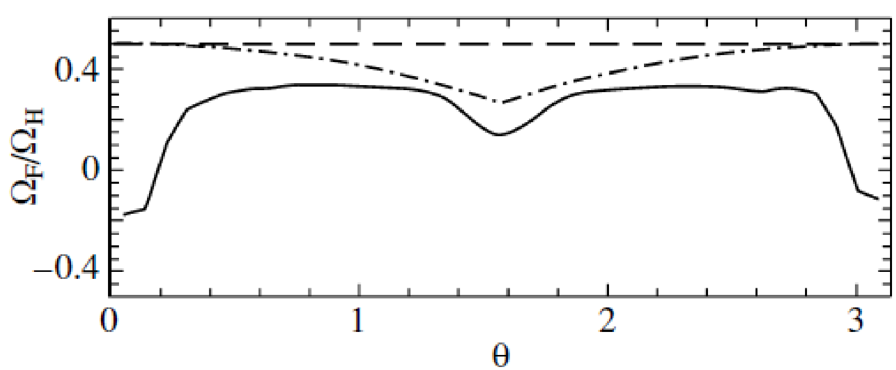
$$\Omega_{\rm F} \sim \Omega_{\rm H}/2$$

Let's check

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

Parabolic?



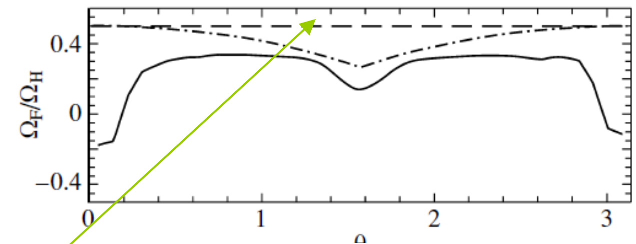


Let's check

R.Blandford, R.Znajek, MNRAS, **179**, 433 (1977)

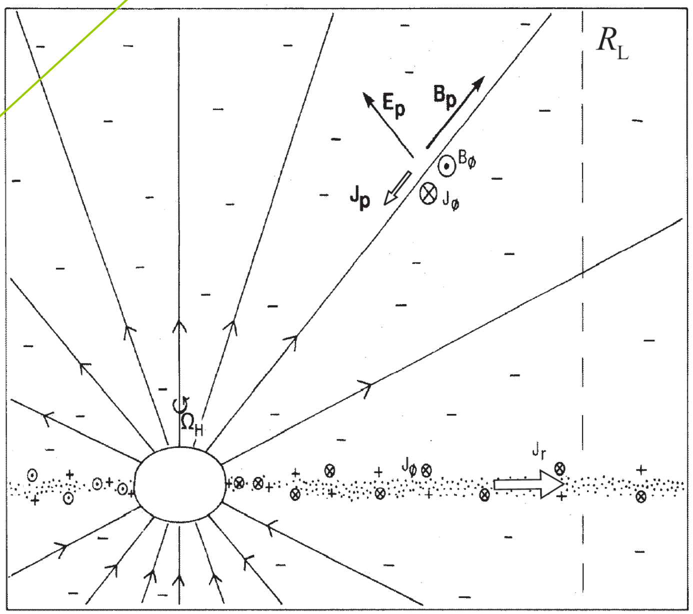
Monopole + Monopole

$$\Psi_0^{(2)} = \Psi_0(1-\cos\theta).$$



Horizon 'boundary condition'

$$4\pi I(\Psi) = [\Omega_H - \Omega_F(\Psi)]\sin\theta\frac{d\Psi}{d\theta}$$



At large distances

$$4\pi I(\theta) = \Omega_F(\theta)\Psi_0\sin^2\theta.$$

Then

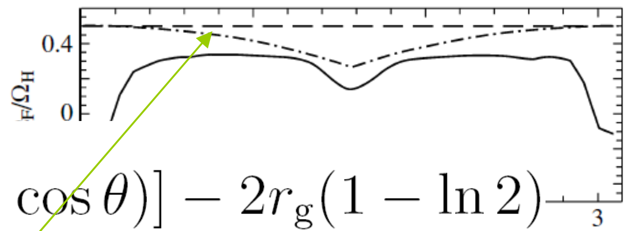
$$\Omega_F = \frac{\Omega_H}{2}, \qquad I(\Psi) = I_M = \frac{\Omega_F}{4\pi}\left(2\Psi - \frac{\Psi^2}{\Psi_0}\right).$$

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

Let’s check

R.Blandford, R.Znajek, MNRAS, **179**, 433 (1977)

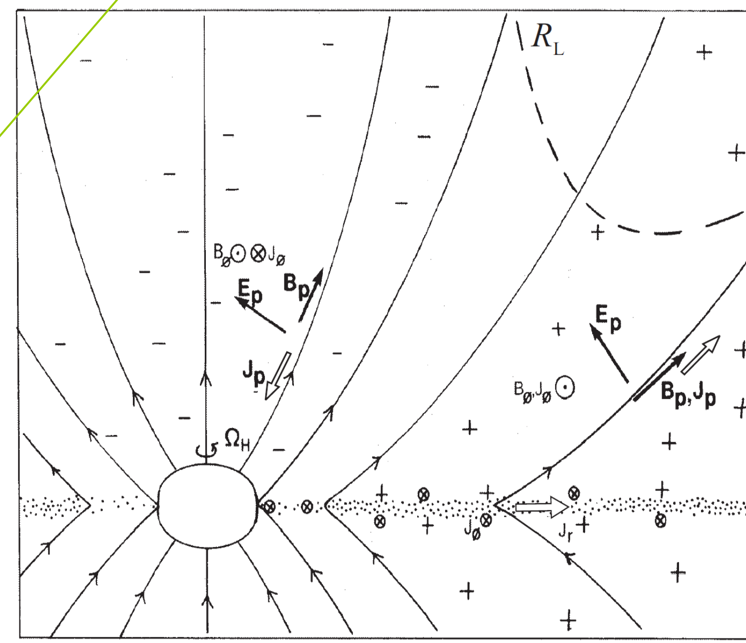
Parabolic + Parabolic



$$\Psi_0^{(1)}(r,\theta) = r(1-\cos\theta) + r_{\rm g}(1+\cos\theta)[1-\ln(1+\cos\theta)] - 2r_{\rm g}(1-\ln 2)$$

Horizon ‘boundary condition’

$$4\pi I(\Psi) = [\Omega_{\rm H} - \Omega_{\rm F}(\Psi)]\sin\theta \frac{r_{\rm g}^2 + a^2}{r_{\rm g}^2 + a^2\cos^2\theta}\left(\frac{{\rm d}\Psi}{{\rm d}\theta}\right)$$



At large distances

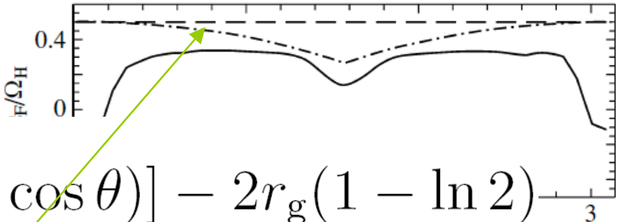
Then

$$\Omega_{\rm F}(r_{\rm g},\theta) = \frac{\Omega_{\rm H}\sin^2\theta[1+\ln(1+\cos\theta)]}{4\ln 2 + \sin^2\theta + [\sin^2\theta - 2(1+\cos\theta)]\ln(1+\cos\theta)}$$

Let's check

R.Blandford, R.Znajek, MNRAS, **179**, 433 (1977)

Parabolic + Parabolic

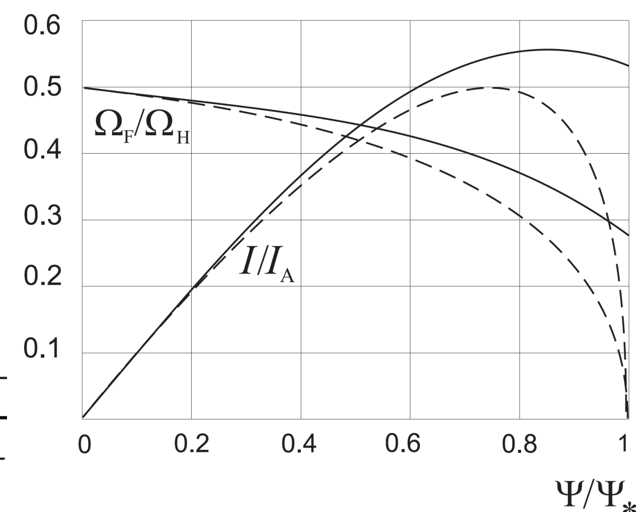


$$\Psi_0^{(1)}(r,\theta) = r(1-\cos\theta) + r_{\rm g}(1+\cos\theta)[1-\ln(1+\cos\theta)] - 2r_{\rm g}(1-\ln 2)$$

Horizon 'boundary condition'

$$4\pi I(\Psi) = [\Omega_{\rm H} - \Omega_{\rm F}(\Psi)]\sin\theta \frac{r_{\rm g}^2 + a^2}{r_{\rm g}^2 + a^2\cos^2\theta}\left(\frac{{\rm d}\Psi}{{\rm d}\theta}\right)$$

At large distances



Then

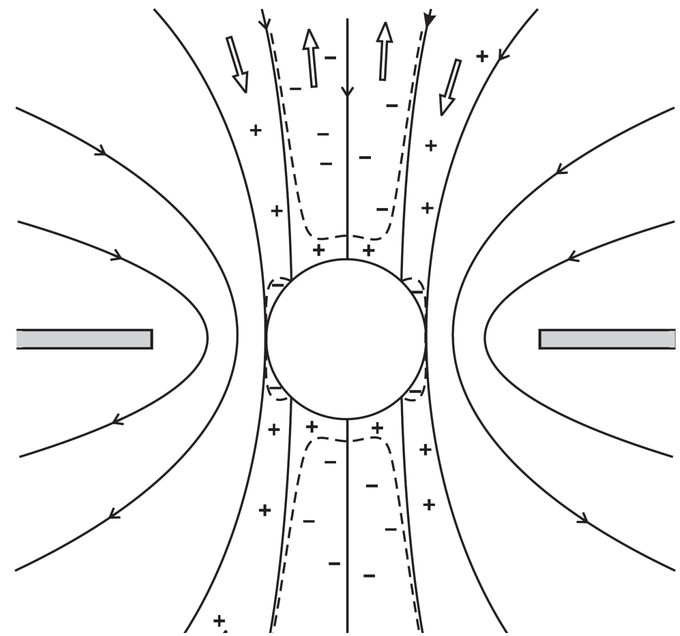
$$\Omega_{\rm F}(r_{\rm g},\theta) = \frac{\Omega_{\rm H}\sin^2\theta[1+\ln(1 -}{4\ln 2 + \sin^2\theta + [\sin^2\theta - 2(1 +}$$

Let's check

VB, Ya.N.Istomin, V.I.Pariev, in 'From Beams to Jets', Cambridge Univ. Press (1992)

Homogeneous + Monopole

$$\Psi(r,\theta) = \Psi_0 \left[1 - \sqrt{\frac{1}{2}\left(1-\frac{r^2}{b^2}\right) + \sqrt{\frac{1}{4}\left(1-\frac{r^2}{b^2}\right)^2 + \frac{r^2\cos^2\theta}{b^2}}}\right]$$

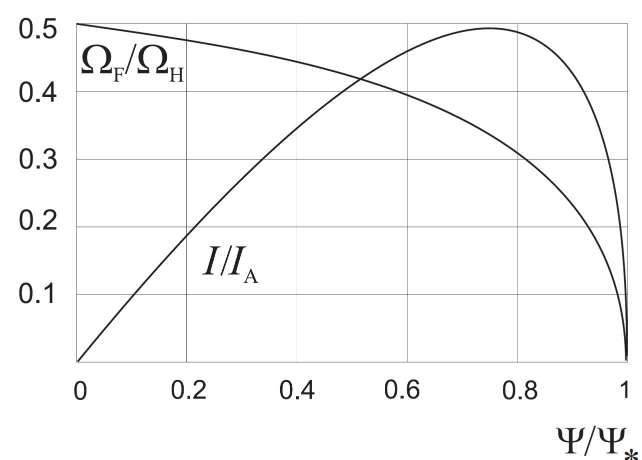


Horizon 'boundary condition'

$$4\pi I(\Psi) = 2\Psi\sqrt{1-\Psi/\Psi_*}\,[\Omega_{\rm H} - \Omega_{\rm F}(\Psi)]$$

At large distances

$$4\pi I(\theta) = \Omega_{\rm F}(\theta)\Psi_0 \sin^2\theta.$$

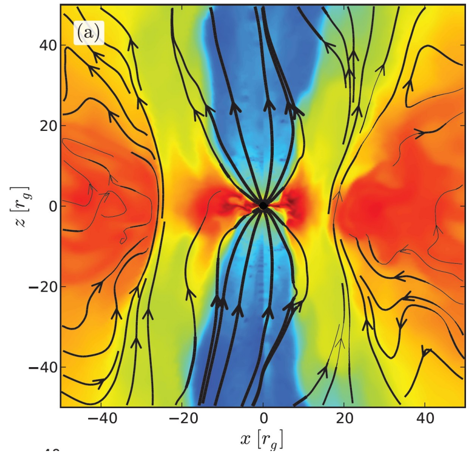


Then

$$\Omega_{\rm F}(\Psi) = \frac{\sqrt{1-\Psi/\Psi_*}}{1+\sqrt{1-\Psi/\Psi_*}}\,\Omega_{\rm H}$$

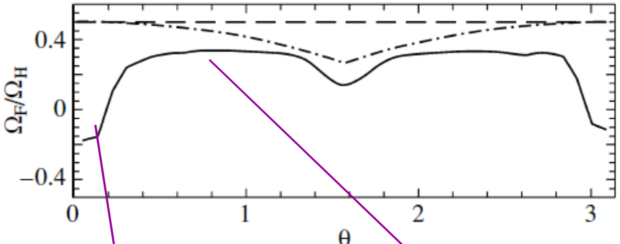
Let's check

VB, A.A.Zheltoukhov. Astron. Lett., **39**, 215 (2013)



Monopole + Cylinder

From numerical simulation



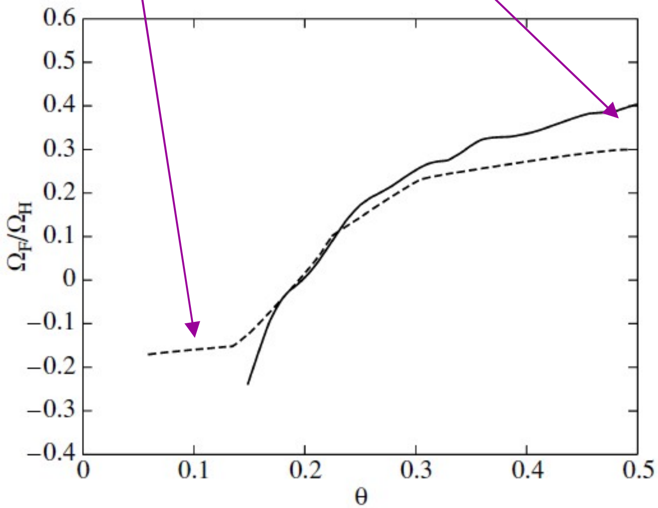
Horizon 'boundary condition'

$$A_3 = \frac{1}{2\pi}\sin\theta \frac{r_g^2 + a^2}{r_g^2 + a^2\cos^2\theta}\left(\frac{d\Psi}{d\theta}\right)$$

At large distances

$$A_1(\Psi) = \varpi^2 B_z$$

$$A_2(\Psi) = c^2 \int_0^{\varpi} x^2 \frac{d}{dx}(B_z)^2\, dx$$



Then

$$\Omega_F = \Omega_H\left[\frac{A_3}{A_3 + A_1} + \frac{A_2}{\Omega_H^2 A_1 A_3\left(1 + \sqrt{1 - \frac{A_2(A_3^2 - A_1^2)}{\Omega_H^2 A_1^2 A_3^2}}\right)}\right]$$

Statement #4

Outflow is transonic, so the electric current is determined by critical condition at the fast magnetosonic surface.
For double transonic relativistic flow

$$I \sim I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

and

$$\Omega_{\rm F} \sim \Omega_{\rm H}/2$$

Statement #5

Membrane paradigm resistivity $\mathcal{R} = 4\pi/c = 377\ \mathrm{O}$

corresponding to "boundary condition" on the horizon

$$4\pi I(\Psi) = [\Omega_{\mathrm{H}} - \Omega_{\mathrm{F}}(\Psi)] \sin\theta \frac{r_{\mathrm{g}}^2 + a^2}{r_{\mathrm{g}}^2 + a^2 \cos^2\theta} \left(\frac{\mathrm{d}\Psi}{\mathrm{d}\theta}\right)$$

is the critical condition on the inner fast magnetosonic surface.

As

$$\Omega_{\mathrm{F}} \sim \Omega_{\mathrm{H}}/2$$

we return to

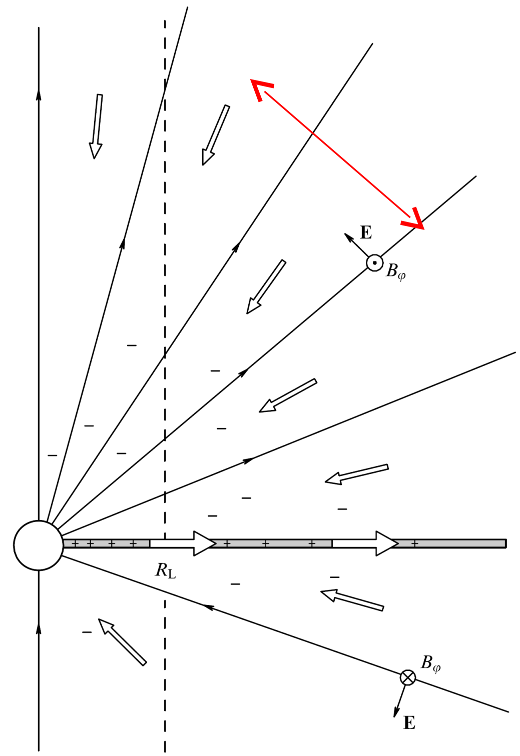
$$\boxed{W_{\mathrm{BZ}} \sim (\Omega r_{\mathrm{g}}/c)^2 B^2 r_{\mathrm{g}}^2 c}$$

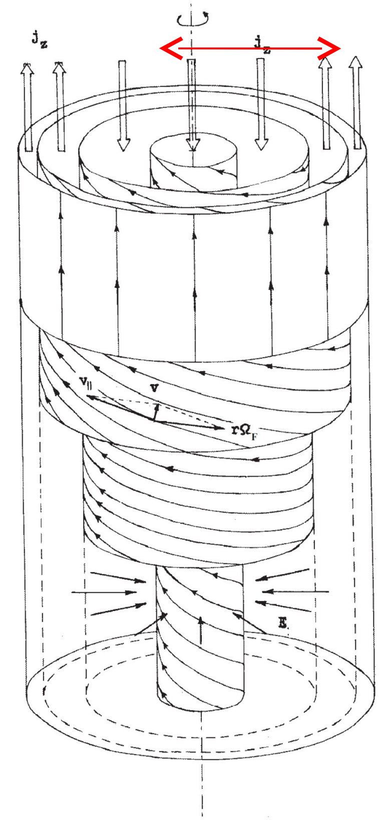
Theoretical challenge – δU problem

F.C.Michel (1973)

What to do with (enormous) potential difference?

Ferraro isorotation law implies constant electric potential (Ω_{F}) along magnetic field lines.





Theoretical challenge – δU problem

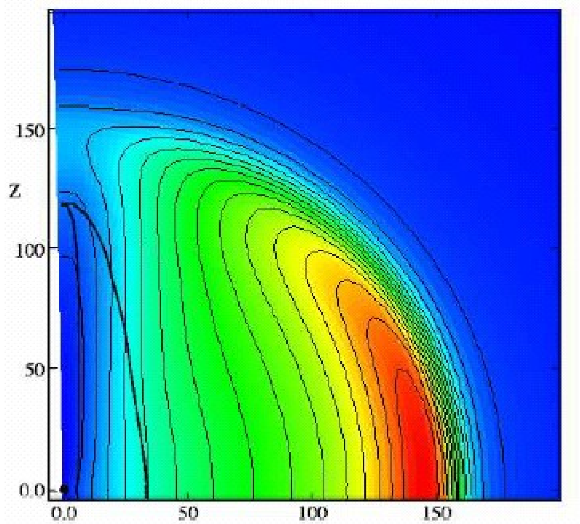
Longitudinal electric field?

Magnetically dominated wind → Any disturbance → Longitudinal electric field

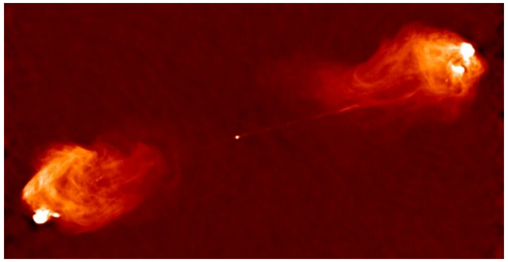
$$\mathrm{E}_\perp \longrightarrow E_{||}$$

Theoretical challenge – δU problem

Switch-on wave, if there is no ambient pressure



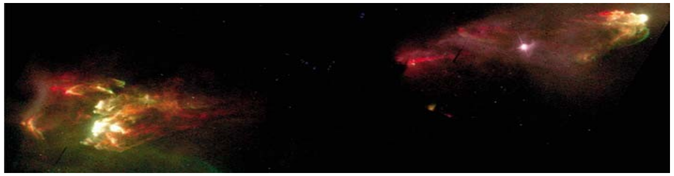
S.Komissarov, MNRAS, **350**, 1431 (2004)



But what to do if we have it?

Lobes in AGN

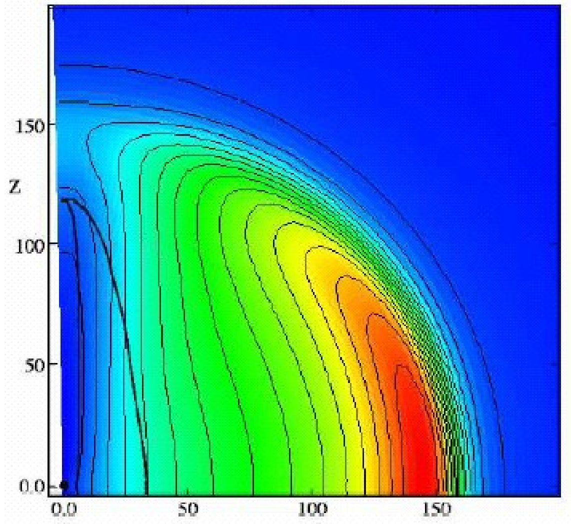
HH objects in YSO



Stellar wind in close binaries

Theoretical challenge – δU problem

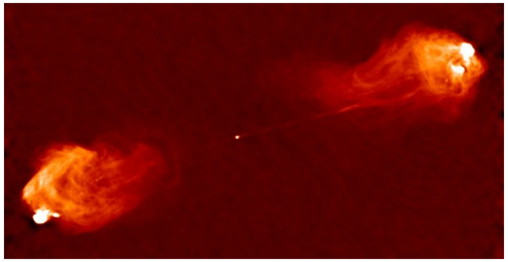
If there is no external environment, one can prolong the solution up to infinity.



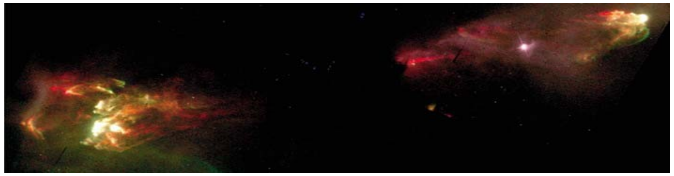
S.Komissarov, MNRAS, **350**, 1431 (2004)

But what to do if the wind meets the ambient?

Lobes in AGN



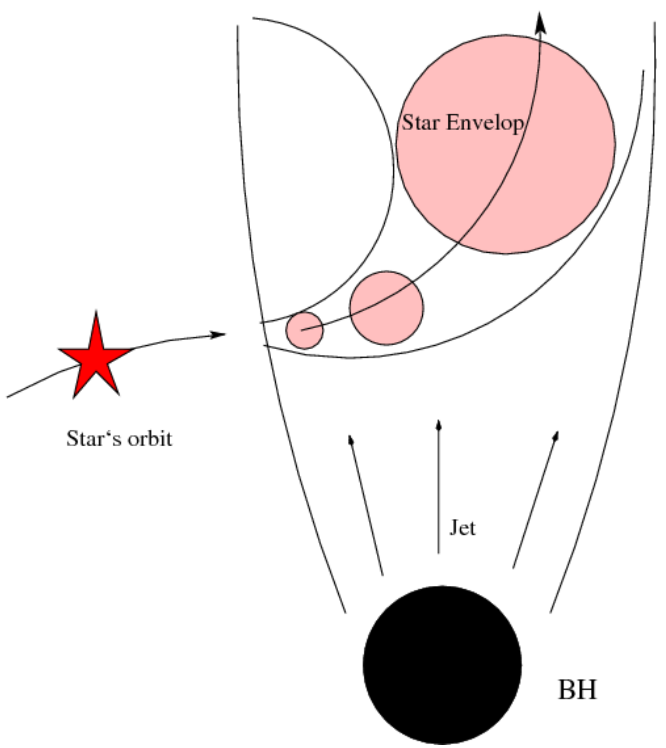
HH objects in YSOs



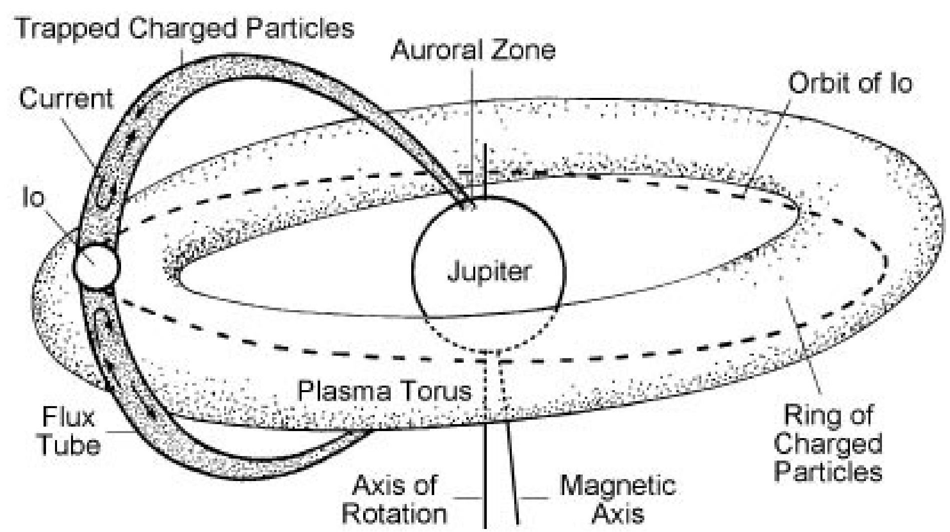
Stellar wind in binaries

Theoretical challenge – δU problem

MHD simulations
do not include
δU into consideration

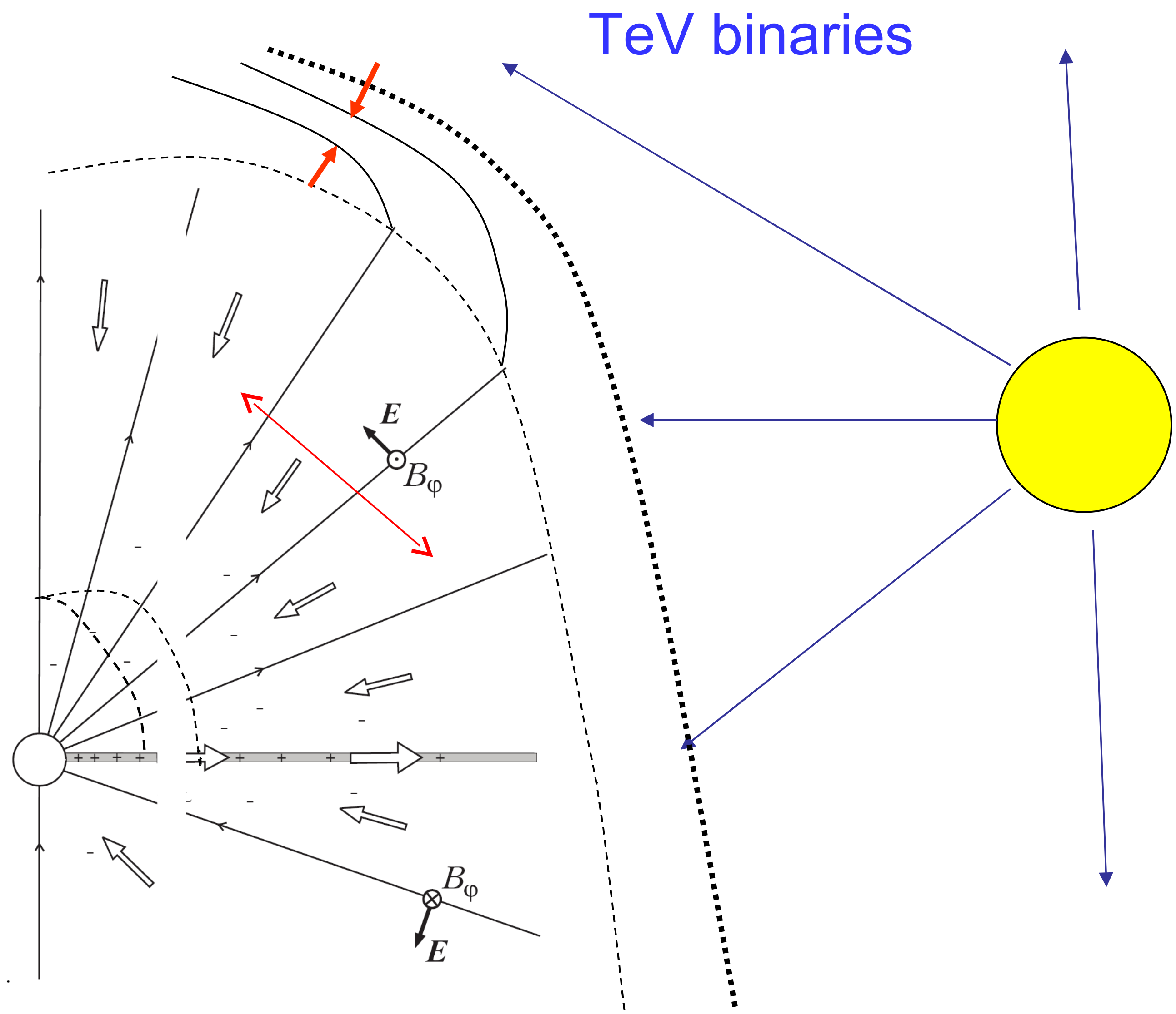


Io-Jovian
electromagnetic
interaction

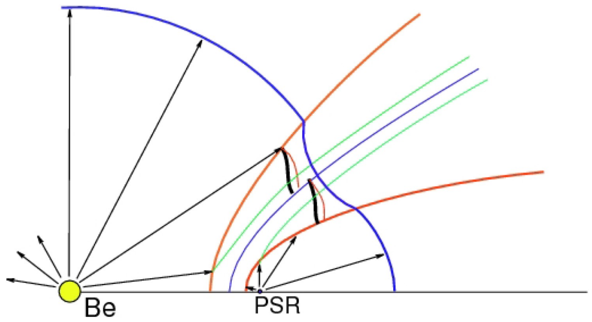


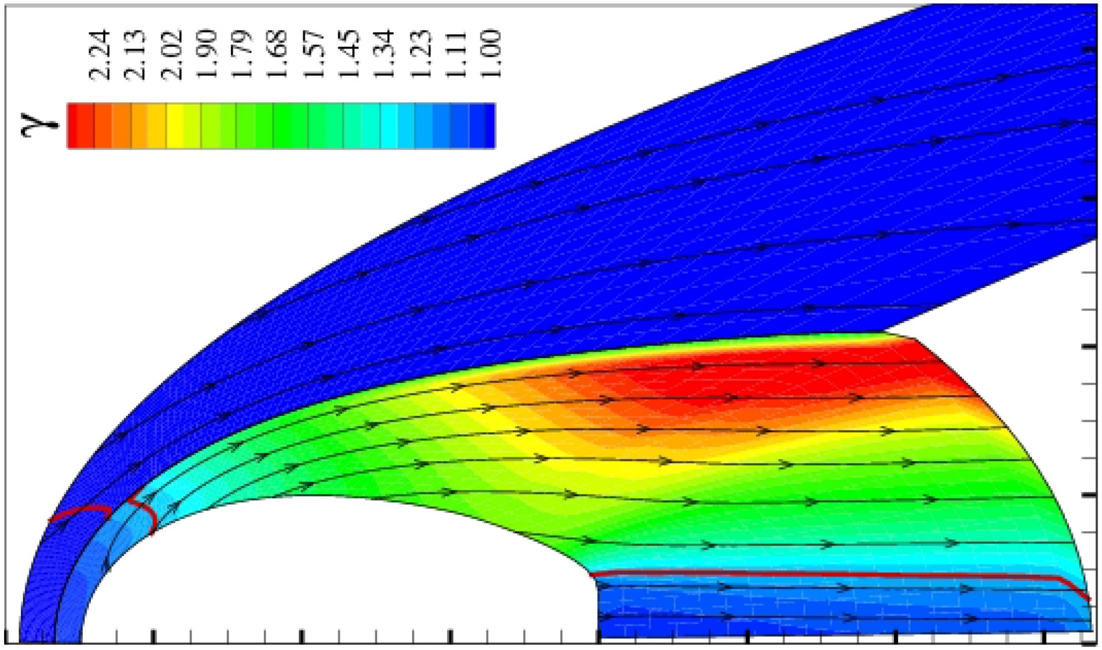
D.V.Khangulyan et al, ApJ, **774**, 113 (2013)

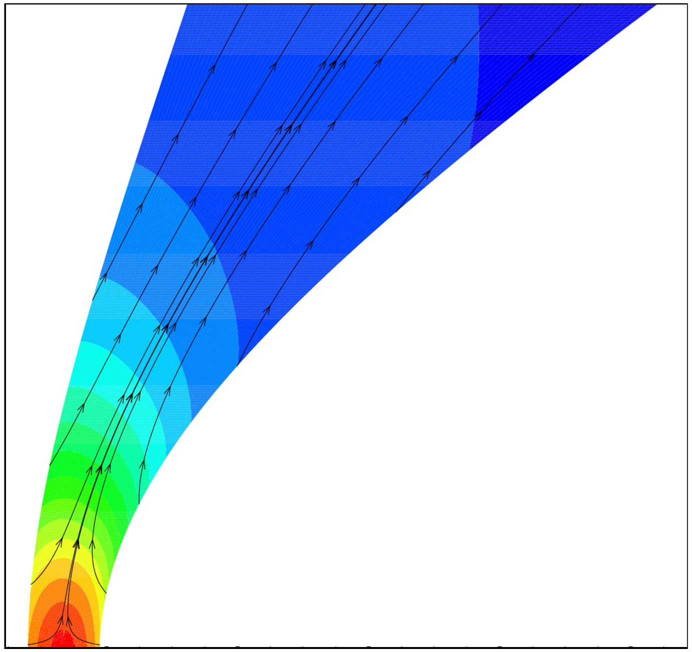
Theoretical challenge – δU problem



Theoretical challenge – δU problem







S.V.Bogovalov, D.Khangulyan, A.V.Koldoba, G.V.Ustyugova, F.Aharonian,
MNRAS, **387**, 63 (2008)

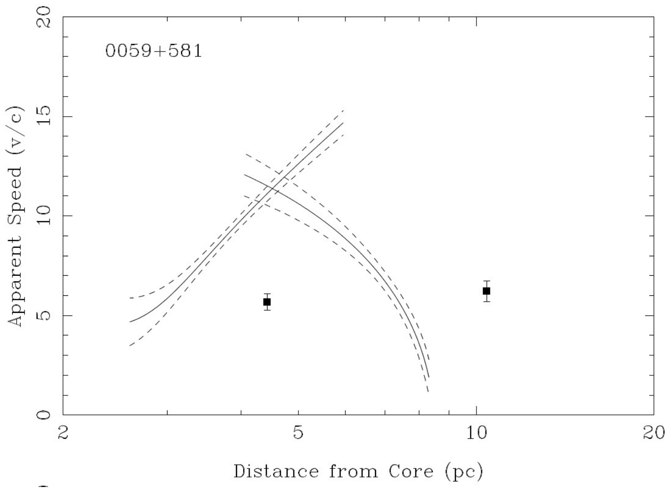
MNRAS **419**, 3426 (2012)

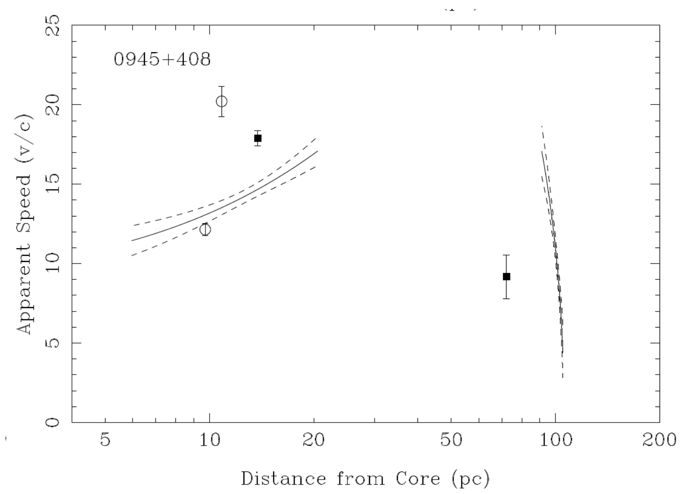
Internal structure – AGN

Homan D. C. et al, ApJ, **789**, 134 (2015)

Acceleration at small distances,
decceleration at large distances.

$$\dot{\Gamma}/\Gamma = 10^{-3}\ \mathrm{yr}^{-1}$$





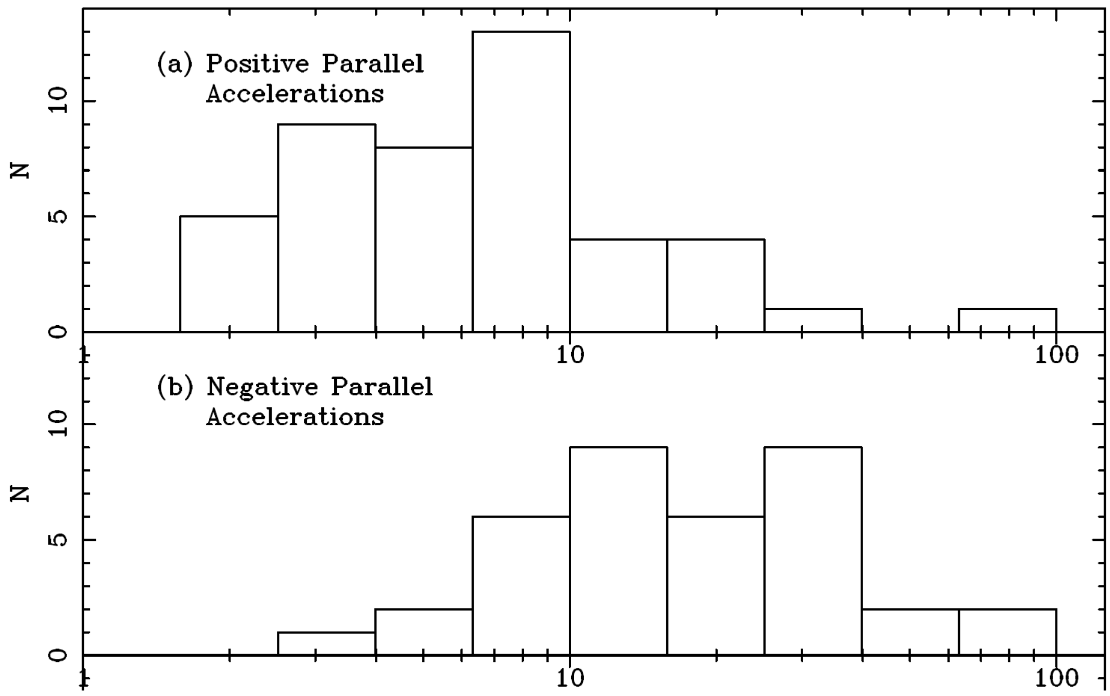
Internal structure – AGN

Homan D. C. et al, ApJ, **789**, 134 (2015)

Acceleration at small distances,

decceleration at large distances.

$$\dot{\Gamma}/\Gamma = 10^{-3}\ \mathrm{yr}^{-1}$$



pc (projection)

Jets – theory

- It is necessary to include external media into consideration. It is the ambient pressure that determines jet transverse scale and particle energy.

- Simple asymptotic solutions for the bulk Lorentz-factor.

- Transverse profile of the poloidal magnetic field.

- Magnetization – multiplication connection.

Jets – theory

Main parameters

- Michel magnetization parameter (maximal bulk Lorentz-factor)

$$\boxed{\sigma_{\mathrm{M}} = \frac{\Omega_0 e B_0 r_{\mathrm{jet}}^2}{4\lambda m_{\mathrm{e}} c^3}}$$

μ now

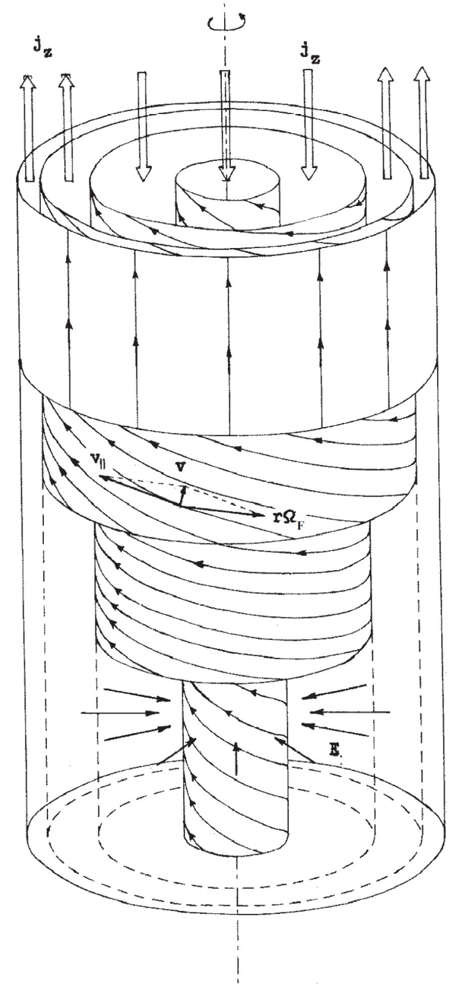
- Multiplicity parameter

$$\boxed{\lambda = \frac{n^{(\mathrm{lab})}}{n_{\mathrm{GJ}}}}$$

$$\rho_{\mathrm{GJ}} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

- Total potential drop

$$\lambda\sigma_{\mathrm{M}} \sim \frac{eE_r r_{\mathrm{jet}}}{m_{\mathrm{e}}c^2}$$

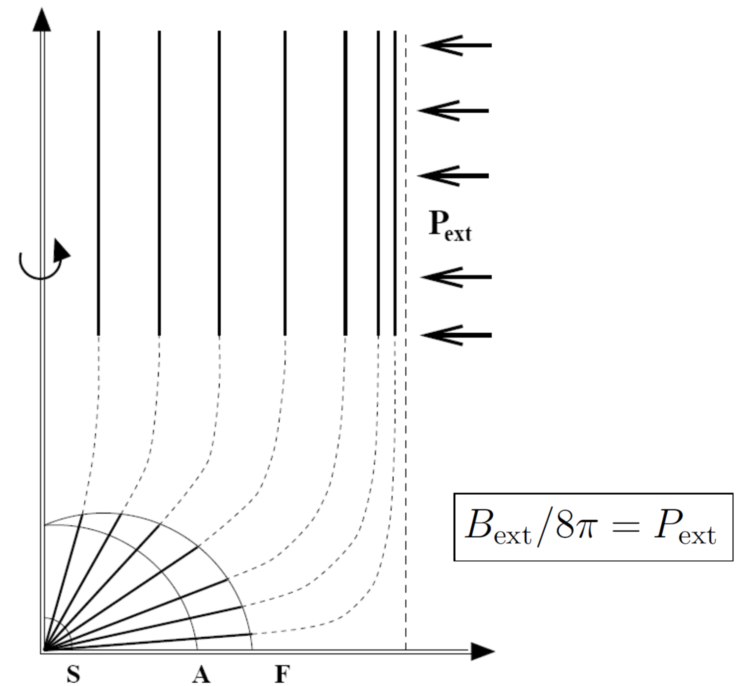


Jets – theory

- It is necessary to include the external media into consideration. It is the ambient pressure that determines the jet transverse scale and particle energy.

1D approach for cylindrical jets

$$\left\{ \begin{array}{rcl} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} & = & F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} & = & F_2(\mathcal{M}^2, \Psi, r_\perp) \end{array} \right.$$



VB, L.M.Malyshkin. Astron. Lett., **26**, 208 (2000)
VB, Phys. Uspekhi, **40**, 659 (1997)

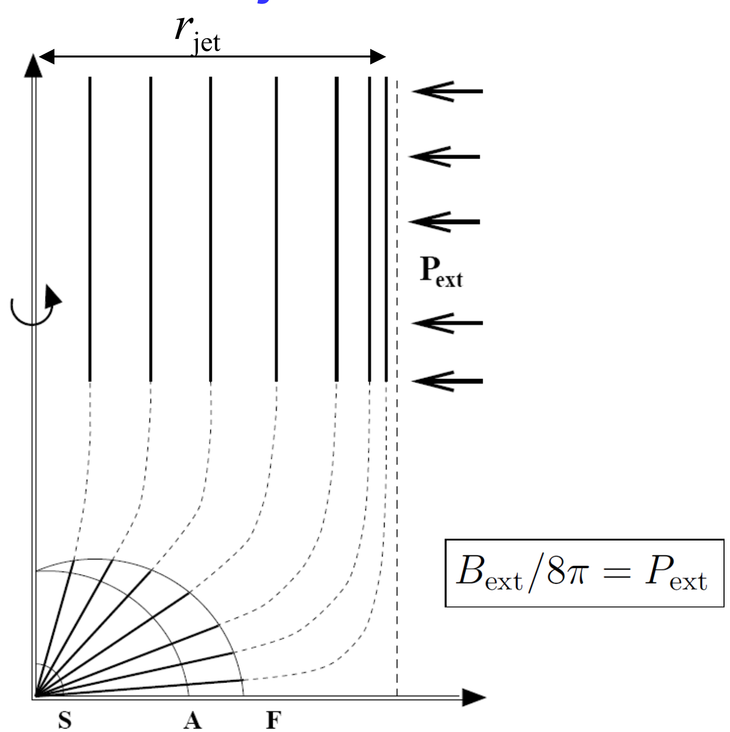
T.Lery, J.Heyvaerts, S.Appl, C.A.Norman, A&A, **347**, 1055 (1999)

Jets – theory

- It is necessary to include the external media into consideration. It is the ambient pressure that determines the jet transverse scale and particle energy.

$$r_{\rm jet} \sim R \left(\frac{B_{\rm in}^2}{8\pi P_{\rm ext}} \right)^{1/4}$$

$$\boxed{\frac{W_{\rm part}}{W_{\rm tot}} \sim \frac{1}{\sigma_{\rm M}} \left[\frac{B^2(R_{\rm L})}{8\pi P_{\rm ext}} \right]^{1/4}}$$



VB, L.M.Malyshkin. Astron. Lett., **26**, 208 (2000)
VB. Phys. Uspekhi, **40**, 659 (1997)

T.Lery, J.Heyvaerts, S.Appl, C.A.Norman. A&A, **347**, 1055 (1999)

Jets – theory

Simple asymptotic solutions for Lorentz-factor

Quasi-cylindrical flows ($\Gamma < \sigma_{\mathrm{M}}$)

$$\boxed{\Gamma = x_r} \qquad x_r = \Omega_{\mathrm{F}} r_{\perp}/c$$

Quasi-radial flows

$$\boxed{\Gamma = C\sqrt{\frac{R_{\mathrm{c}}}{r_{\perp}}}}$$

Jets – theory

Simple asymptotic solutions for Lorentz-factor

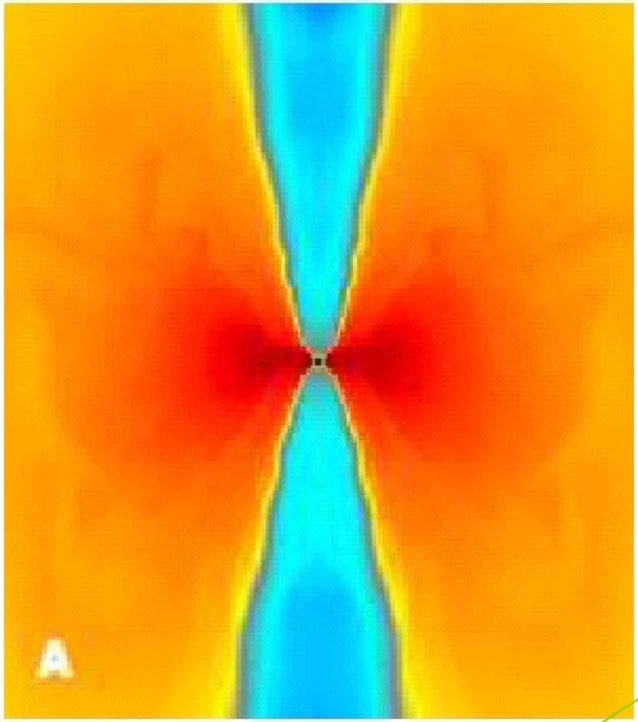
Quasi-cylindrical flows ($\Gamma < \sigma_{\mathrm{M}}$)

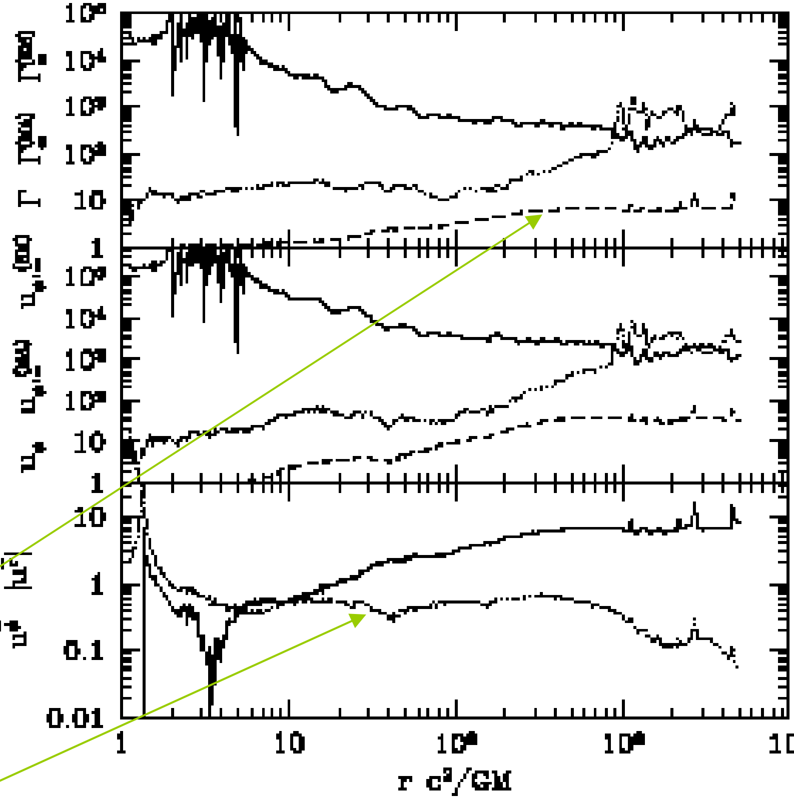
$$\boxed{\Gamma = x_r} \qquad x_r = \Omega_{\mathrm{F}} r_{\perp}/c$$

This is an asymptotic behavior!

Jets – theory

J.McKinney, MNRAS, **367**, 1797 (2006)



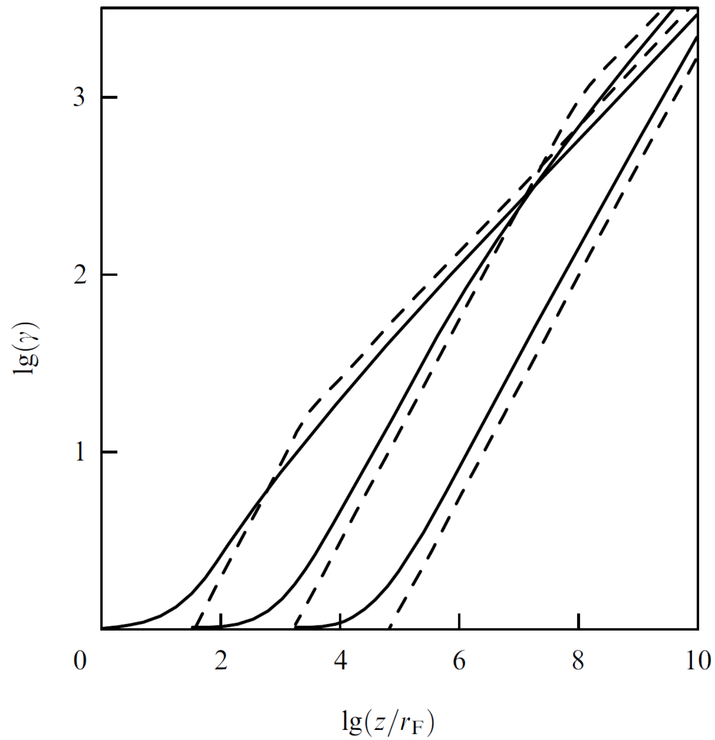


$$\Gamma(z) = (z/R_L)^{1/2},\ u_\varphi = 1$$

Jets – theory

Parabolic structure terminates the efficiency of acceleration

- Self-similar solution $z \sim r_\perp{}^k$
- For $k > 2$
  $\Gamma = x_r \sim z^{1/k}$
- For $k < 2$
  $\Gamma = (R_c r_\perp)^{1/2}$
  $\sim z^{(k-1)/k}$
- *Parabolic* $k = 2$



R. Narayan, J.McKinney, A.F.Farmer, MNRAS, **375**, 548, 2006

In all cases $\Gamma\theta \sim 1$

Jets – theory

Transverse profile of the poloidal magnetic field

T.Chiueh, Zh.-Yu.Li, M.C.Begelman. ApJ, **377**, 462 (1991)

D.Eichler. ApJ, **419**, 111 (1993)

S.V.Bogovalov. Astron. Lett., **21**, 565 (1995)

M.Camenzind. In Herbig-Haro Flows and the Birth of Low Mass Stars. Eds. Reipurth B., Bertout C. (1997)

$$\boxed{B_{\rm p} = \frac{B_0}{1 + (r_{\perp}/r_{\rm core})^2}}$$

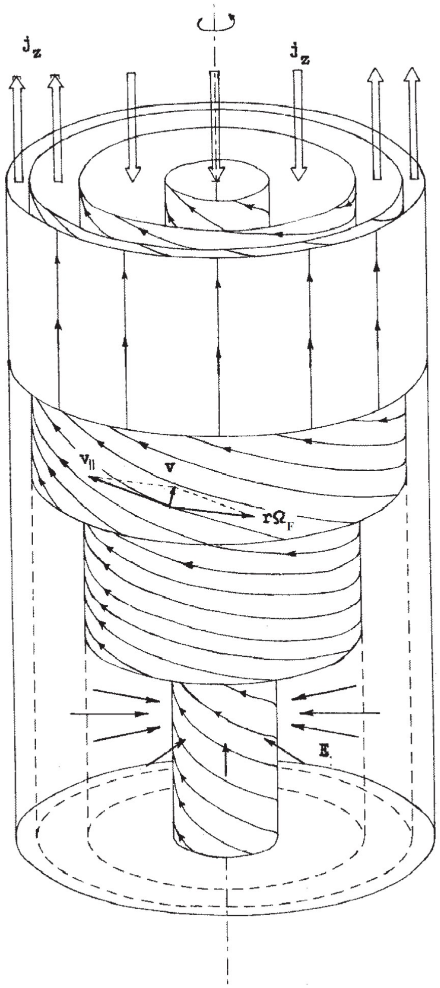
$$r_{\rm core} = \gamma_{\rm in} R_{\rm L}$$

Jets – theory

Transverse profile of the poloidal magnetic field

And this was odd, because…

homogeneous poloidal magnetic field is the solution for magnetically dominated flow.



Jets – theory

Transverse profile of the poloidal magnetic field

Theorem 5.2. *In the relativistic case, in the presence of the environment with rather high pressure ($B_{\rm ext} > B_{\rm min}$) the poloidal magnetic field inside the jet remains practically constant: $B_{\rm p} \approx B_{\rm ext}$. For small external pressure ($B_{\rm ext} < B_{\rm min}$) in the vicinity of the rotation axis there must form a core region $r_\perp < \varpi_{\rm c} = \gamma_{\rm in} R_{\rm L}$ with the magnetic field $B_{\rm p} \approx B_{\rm min}$ (5.69) containing only a small part of the total magnetic flux Ψ_0:*

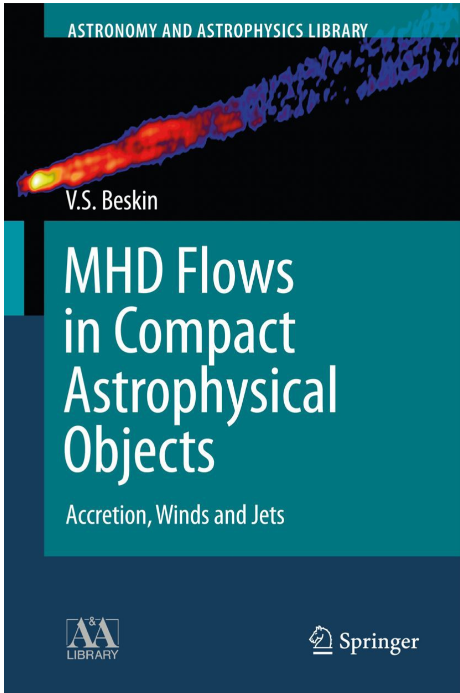
$$\frac{\Psi_{\rm core}}{\Psi_0} \approx \frac{\gamma_{\rm in}}{\sigma}.$$

For $r_\perp < \varpi_{\rm c}$, the poloidal magnetic field $B_{\rm p}$ decreases as

$$B_{\rm p} \propto r_\perp^{2-\alpha},$$

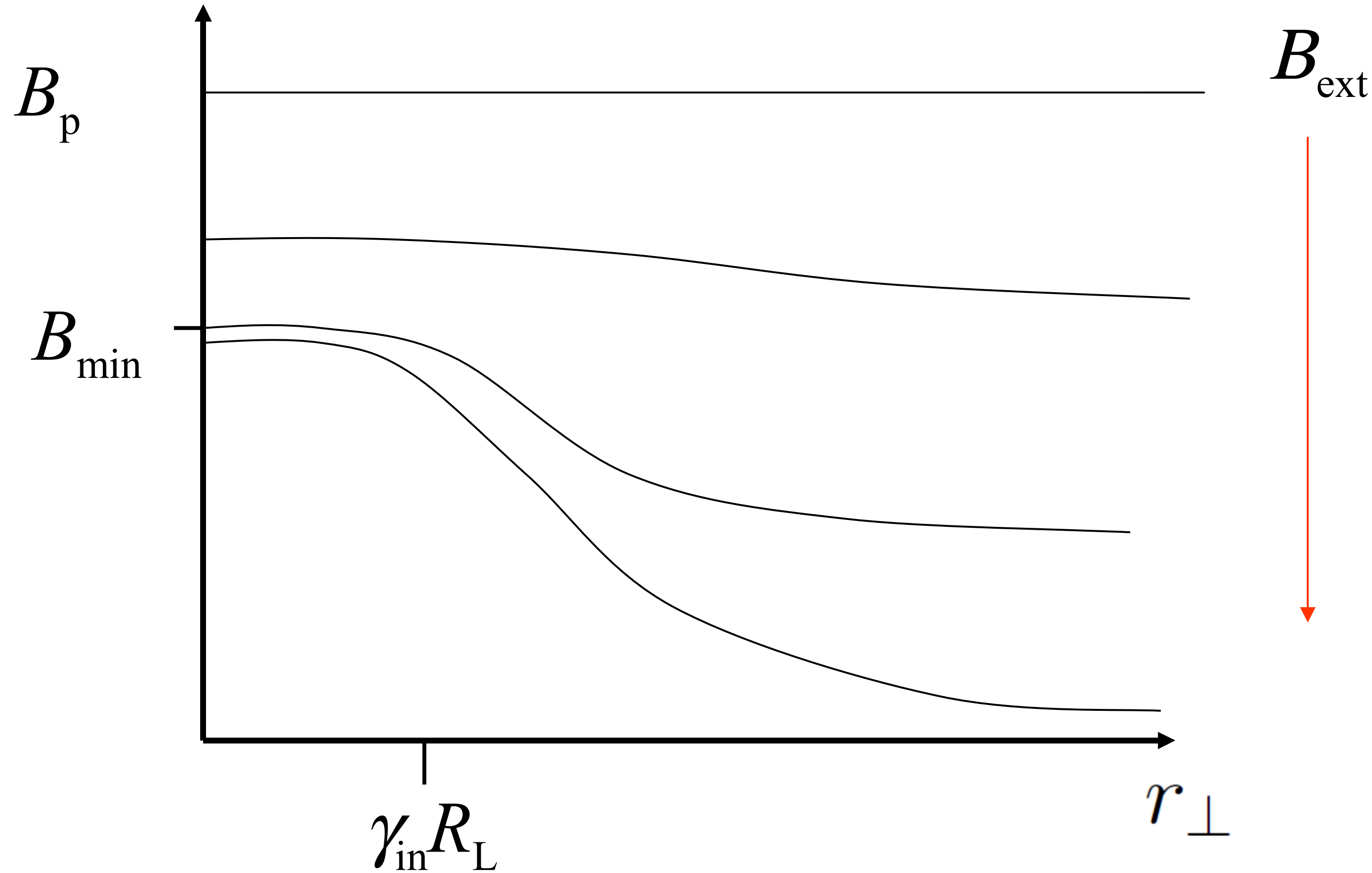
where $\alpha < 2$.

$$B_{\rm min} = \frac{1}{\sigma \gamma_{\rm in}} B(R_{\rm L}) \qquad B(R_{\rm L}) = \Omega^2 \Psi_{\rm tot}/\pi c^2 \qquad B_{\rm p}^2/8\pi \approx P_{\rm ext}$$



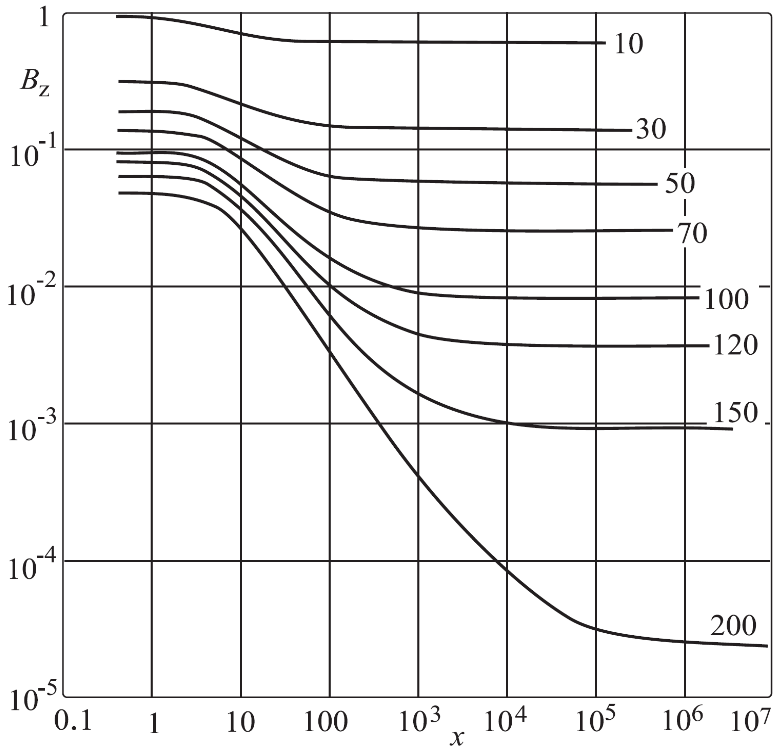
Central core

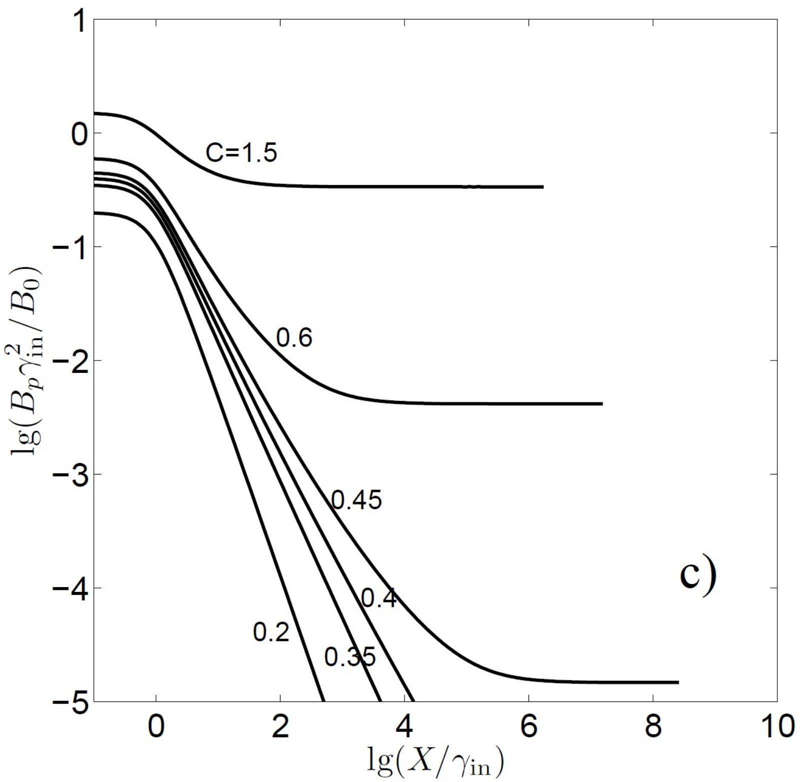
$$B_{\min} = \frac{1}{\sigma_{\mathrm{M}}\gamma_{\mathrm{in}}} B(R_{\mathrm{L}}) \qquad r_{\mathrm{core}} = \gamma_{\mathrm{in}} R_{\mathrm{L}}$$



Central core

$$\begin{cases} \dfrac{d\mathcal{M}^2}{dr_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{d\Psi}{dr_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



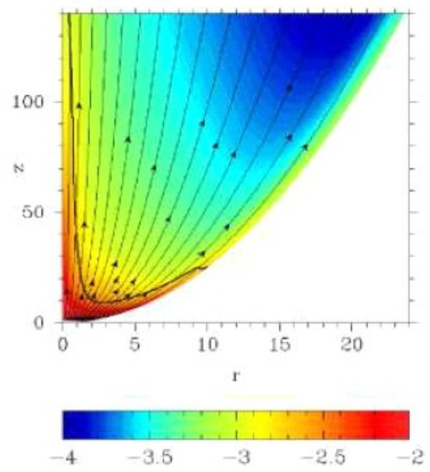


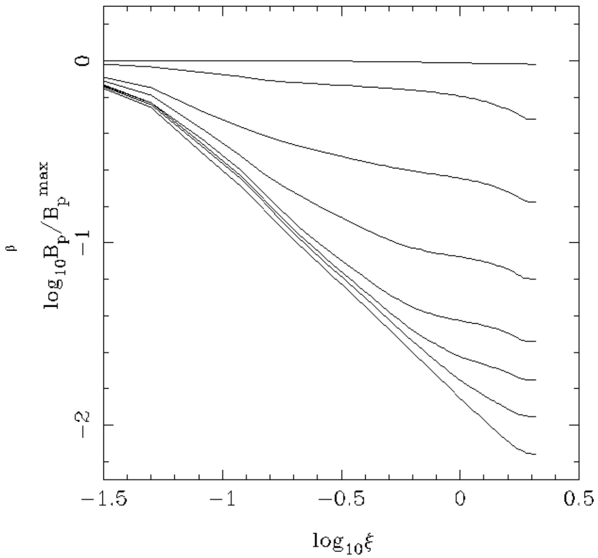
VB, E.E.Nokhrina,
MNRAS, **389**, 335 (2007)
MNRAS, **397,** 1486 (2009)

Yu.Lyubarsky, ApJ,
698, 1570 (2009)

Central core

S. S. Komissarov et al.

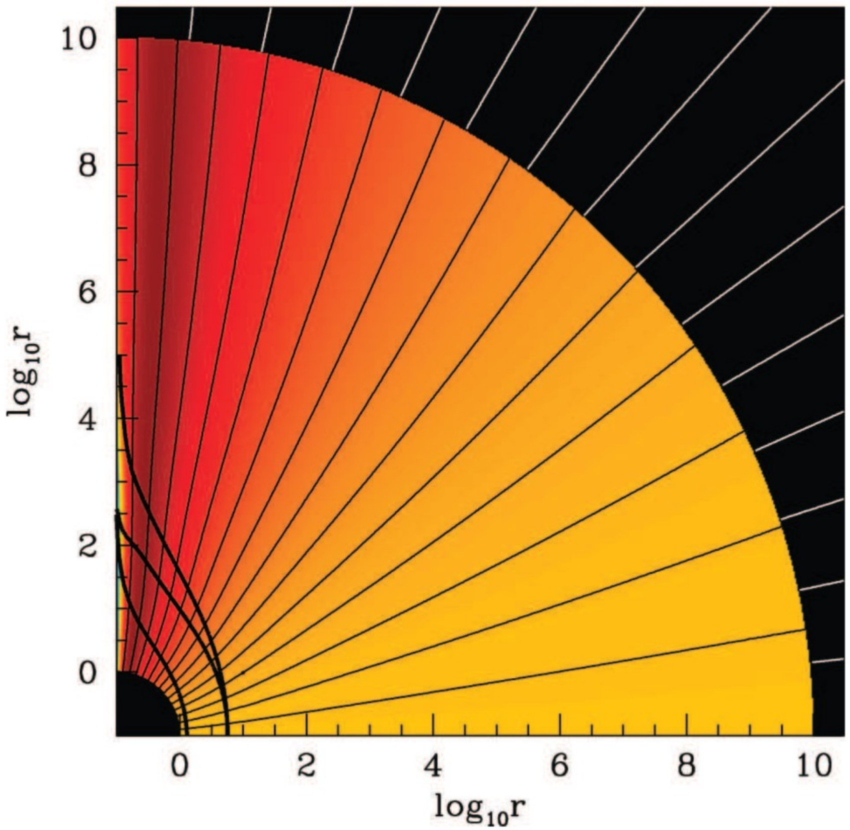


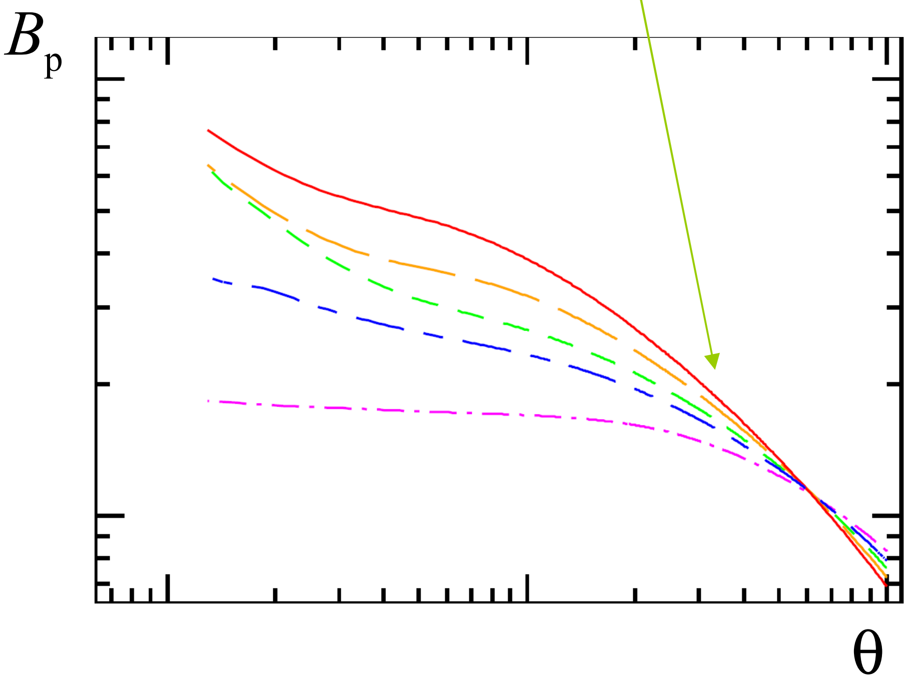


S.Komissarov, M.Barkov, N.Vlahakis, A.Königl, MNRAS, **380**, 51 (2006)

Central core

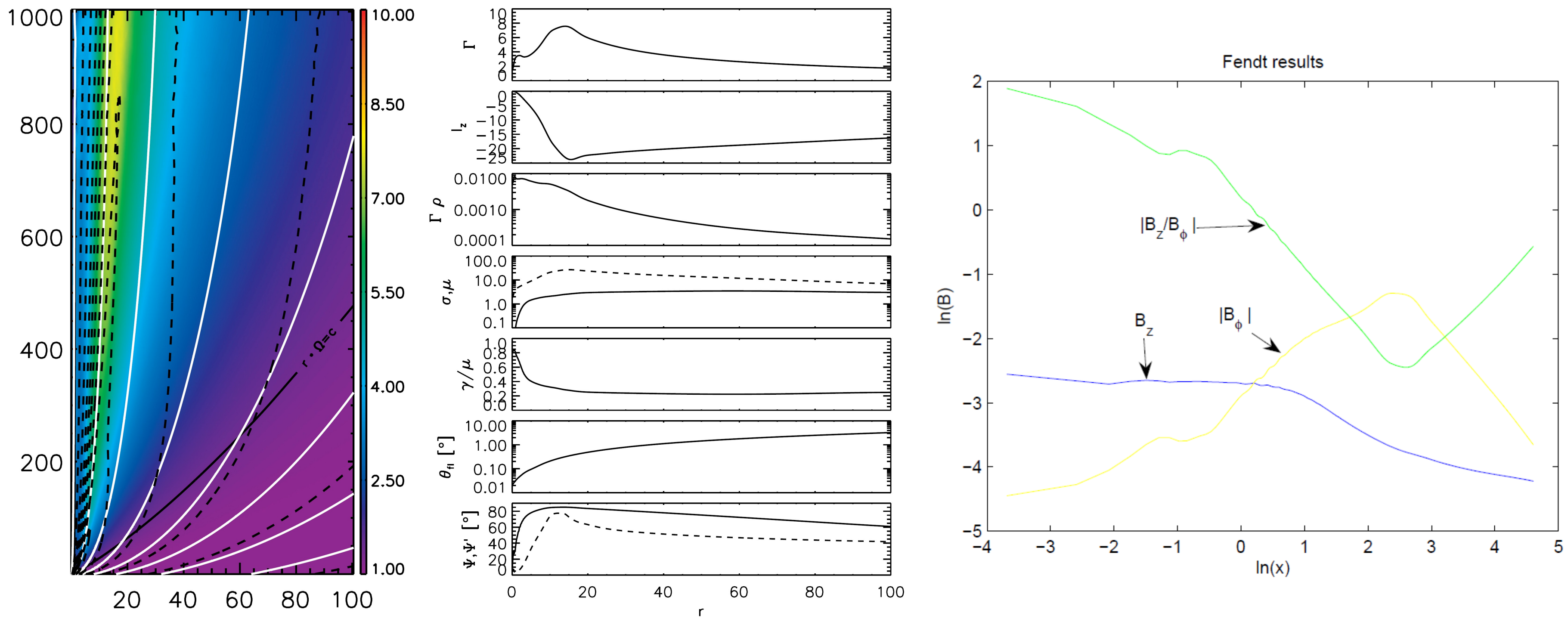
$$B_{\rm min} = \frac{1}{\sigma_{\rm M}\gamma_{\rm in}} B(R_{\rm L})$$





A.Tchekhovskoy, J.McKinney, R.Narayan, ApJ, **699**, 1789 (2009)

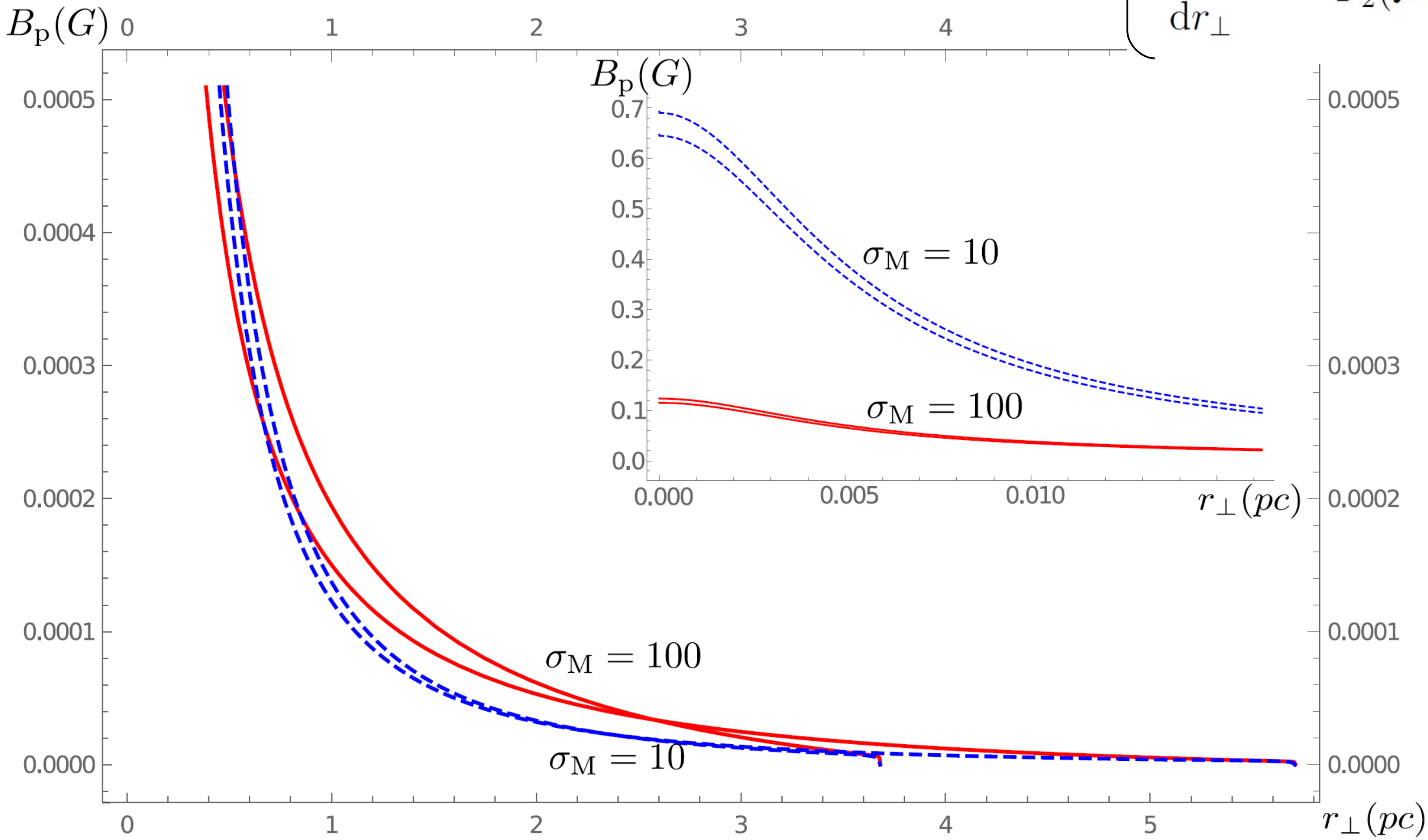
Central core



O.Porth, Ch.Fendt, Z.Meliani, B.Vaidya, ApJ, **737**, 42 (2011)

Internal structure

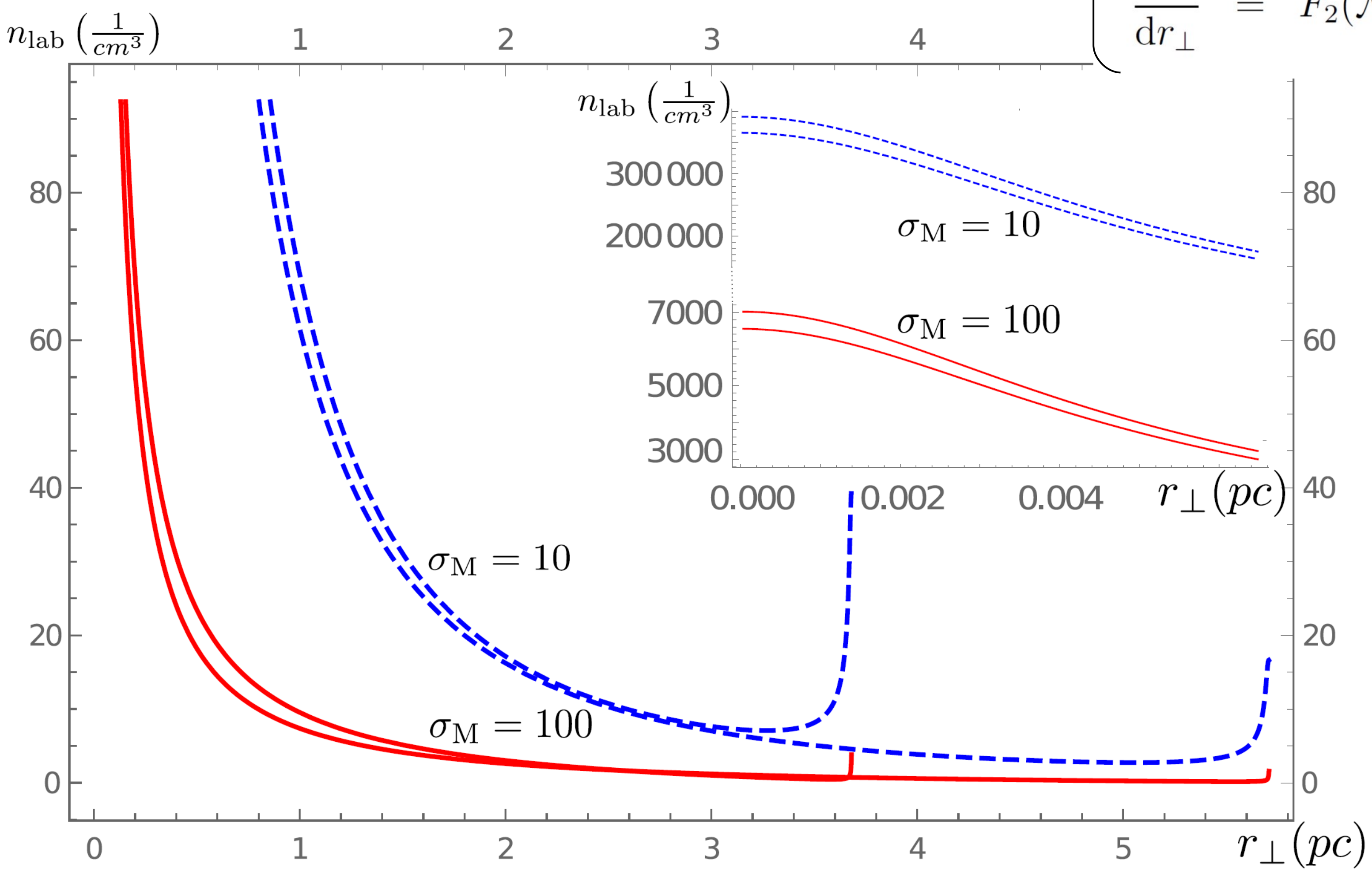
$$
\begin{cases}
\dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\
\dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp)
\end{cases}
$$



A.V.Chernoglazov,VB, V.I.Pariev, MNRAS (2019)

Internal structure

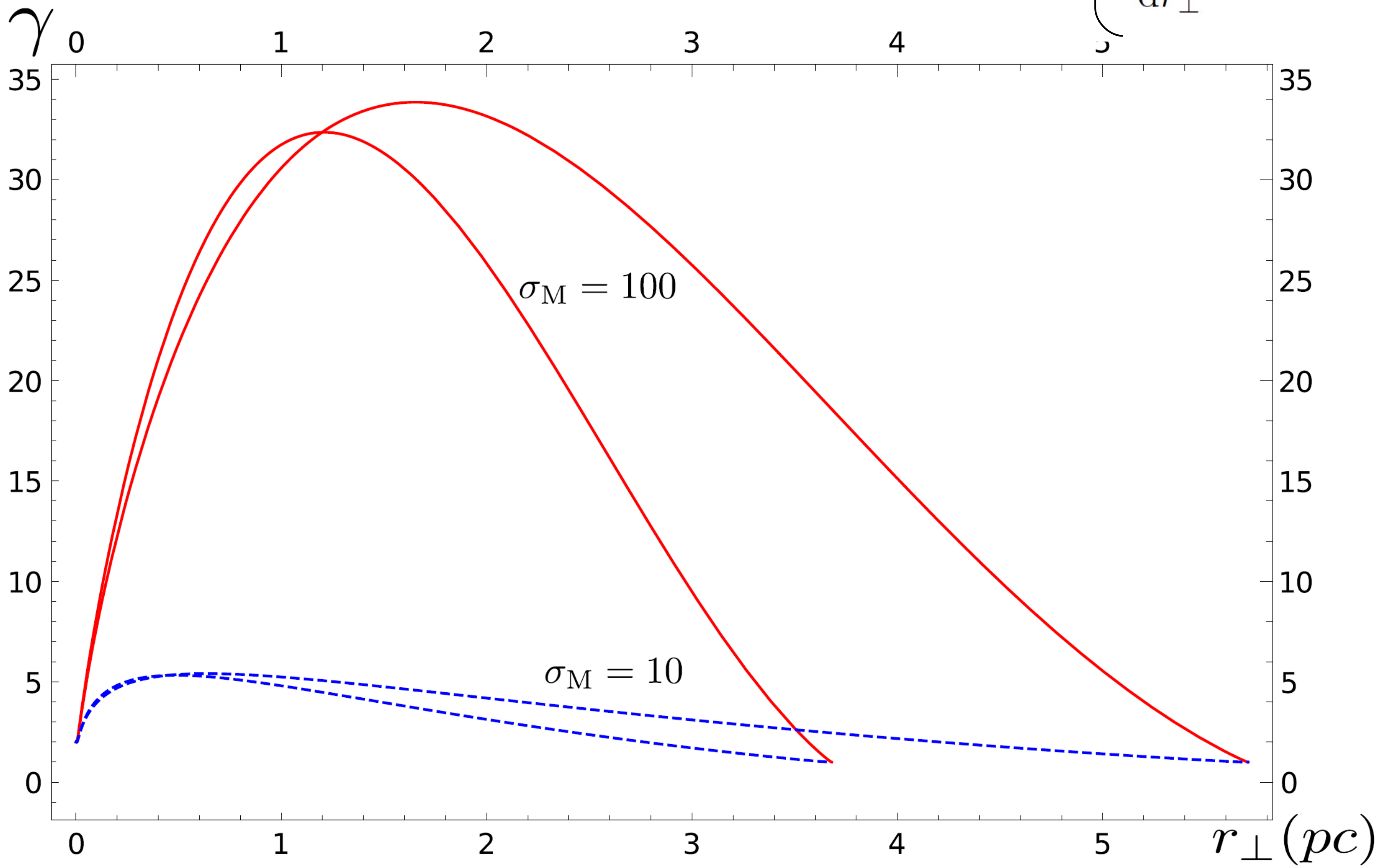
$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



A.V.Chernoglazov,VB, V.I.Pariev, MNRAS (2019)

Internal structure

$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$

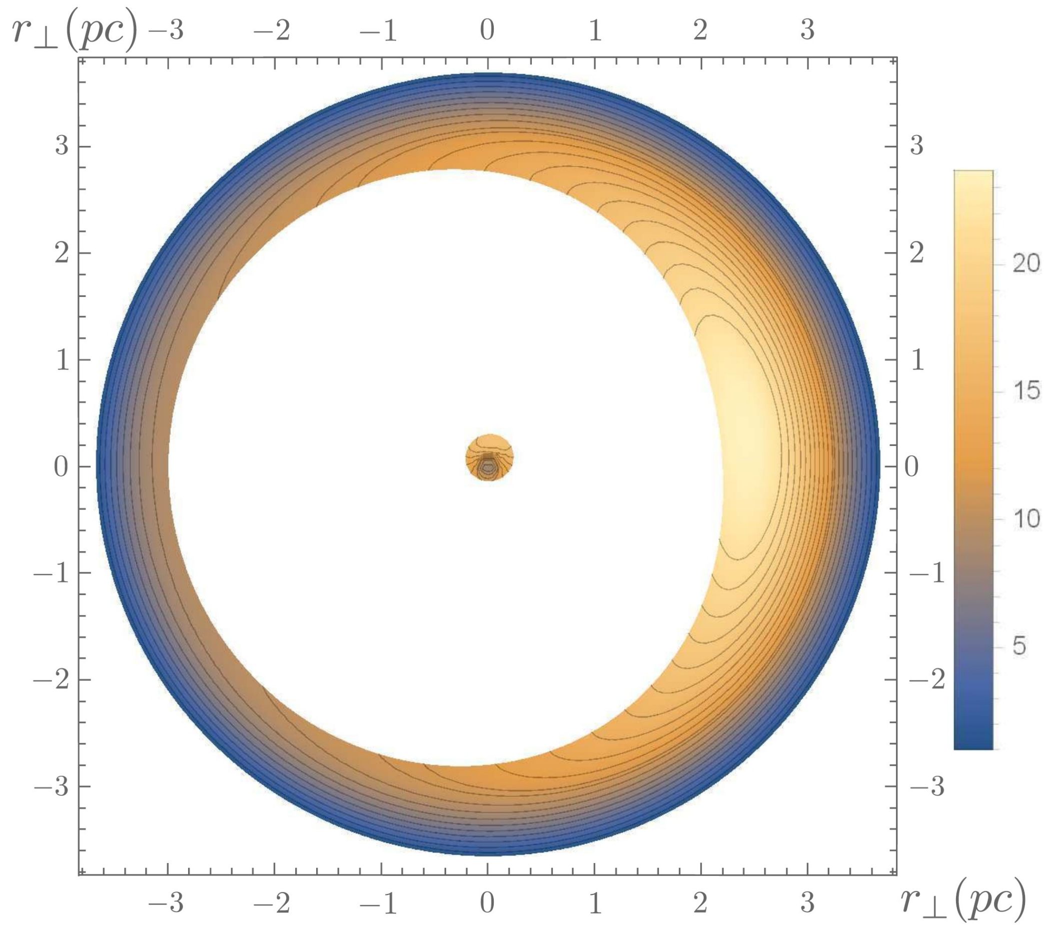


A.V.Chernoglazov,VB, V.I.Pariev, MNRAS (2019)

Internal structure

Map of Doppler-factor

+ $1/\gamma$ diagram



A.V.Chernoglazov,VB, V.I.Pariev, MNRAS (2019)

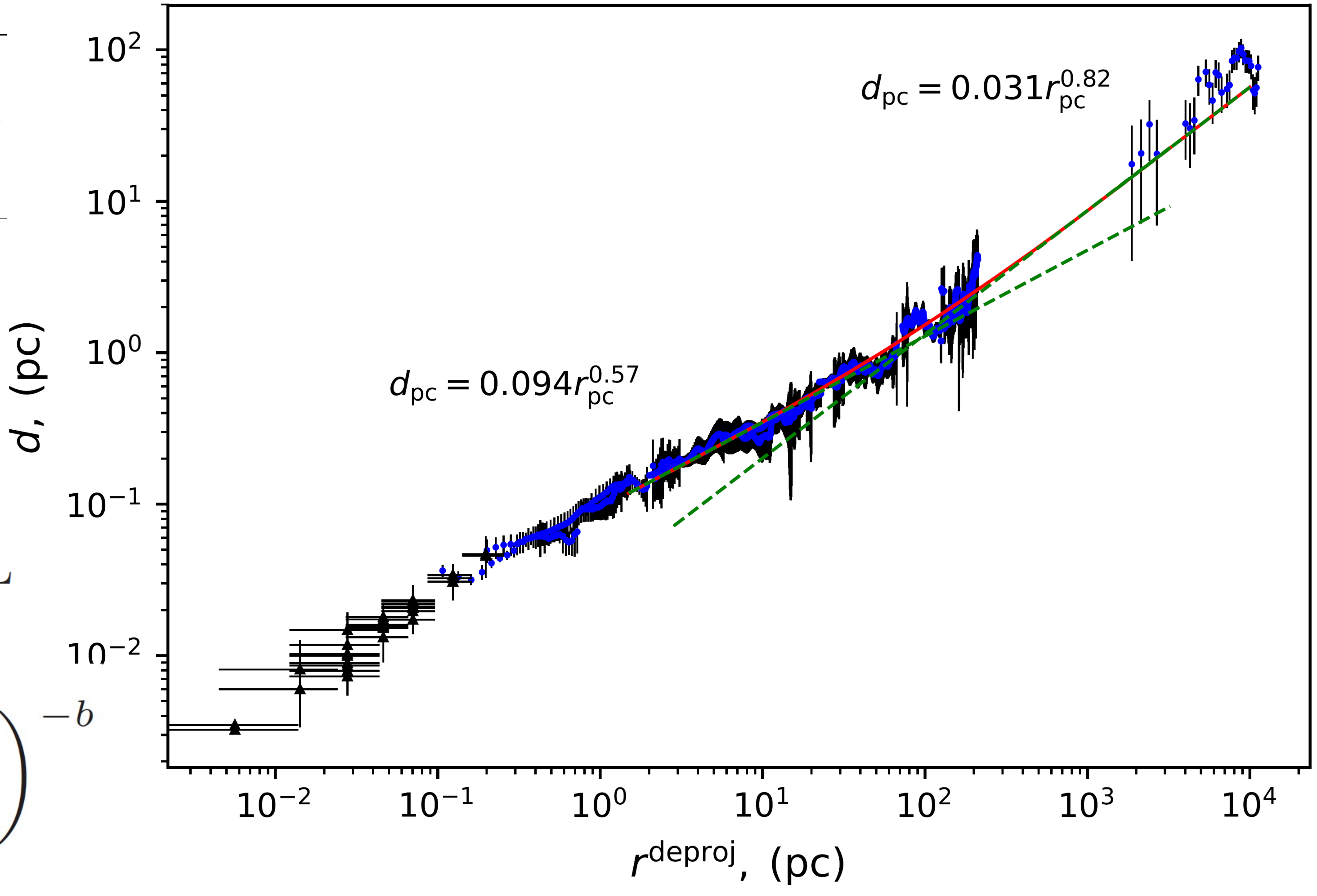
Jet boundary shape break

E.E.Nokhrina, L.I.Gurvits, VB, M.Nakamura, K.Asada, K.Hada, MNRAS (in press)

$$\gamma(r_\perp) = \frac{r_\perp}{R_\mathrm{L}}$$

$$d_\mathrm{sat} \approx \sigma_\mathrm{M} R_\mathrm{L}$$

$$P_\mathrm{ext} = P_0 \left(\frac{r}{r_0}\right)^{-b}$$



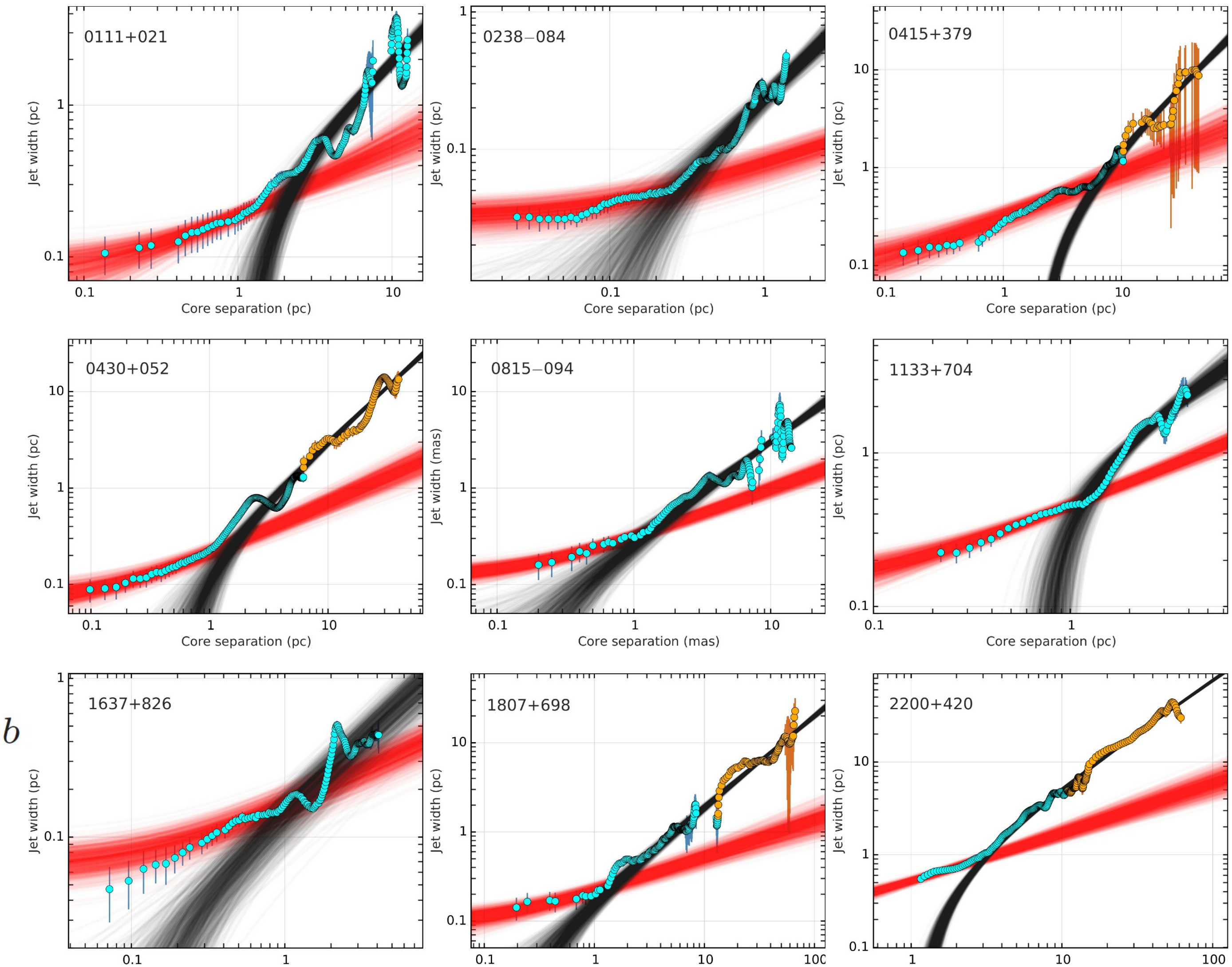
Jet boundary shape break

Y.Y.Kovalev, A.B.Pushkarev, E.E.Nokhrina, VB, A.V.Chernoglazov, M. L. Lister, T.Savolainen, MNRAS, (in press)

$$\boxed{\gamma(r_\perp) = \frac{r_\perp}{R_\mathrm{L}}}$$

$$d_\mathrm{sat} \approx \sigma_\mathrm{M} R_\mathrm{L}$$

$$P_\mathrm{ext} = P_0 \left(\frac{r}{r_0}\right)^{-b}$$



Jet boundary shape break

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

Slow acceleration along the jet

$$\dot{\Gamma}/\Gamma = 10^{-3}\ \mathrm{yr}^{-1}$$

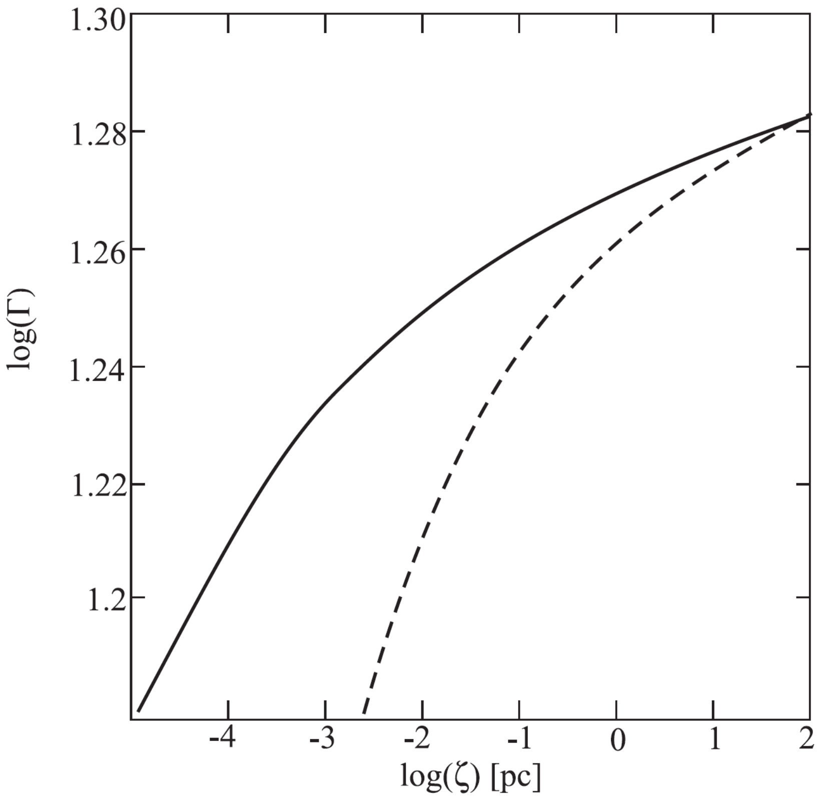


Figure 5. Dependence of Lorentz factor on coordinate along the jet in assumption of $\zeta \propto r_{\perp}^{3}$ (solid line) and $\zeta \propto r_{\perp}^{2}$ (dashed line) form of the jet.

Statement #6

- Saturation
- Central core
- Inhomogeneous Lorentz factor

Conclusion

Go ahead!