Internal structure of relativistic jets

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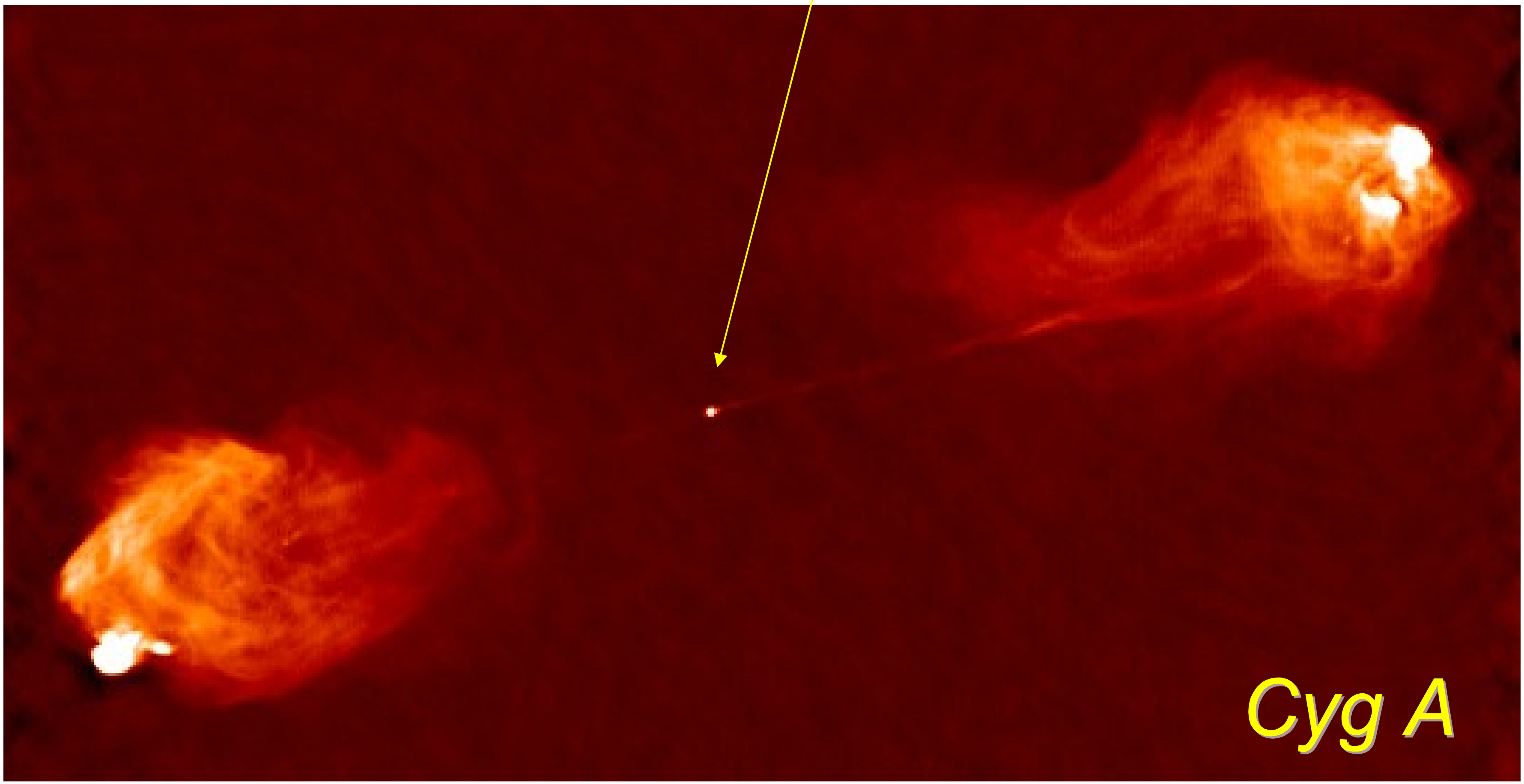
Plan

- 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

Active Galactic Nuclei (AGN)

$$M \sim (10^8 - 10^9) M_\odot, \quad R \sim 10^{13} \mathrm{cm}$$



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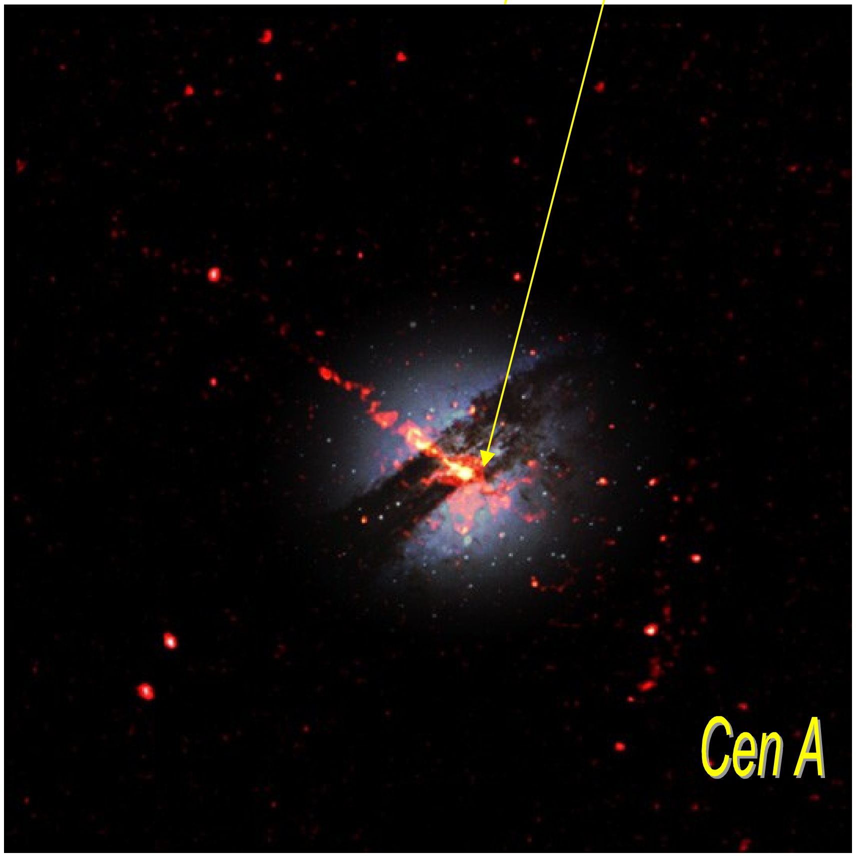
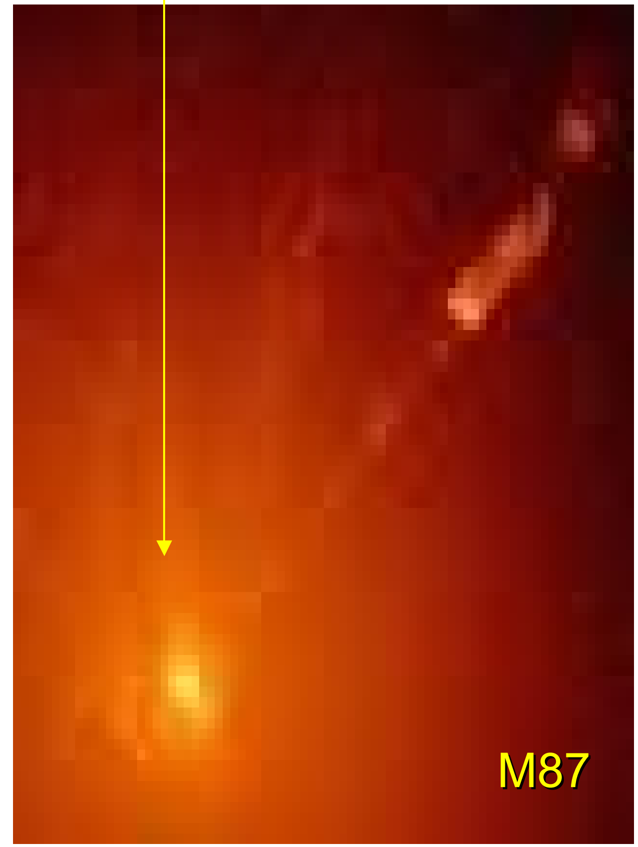
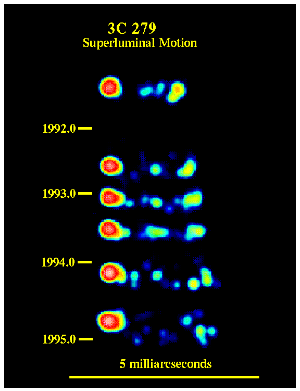


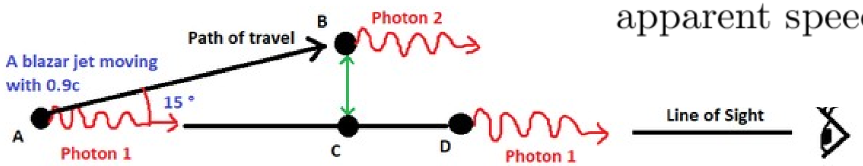


Internal structure – observations

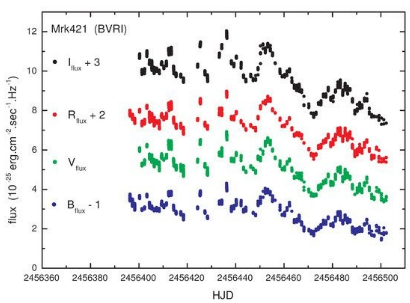
[More than 50 years](#)



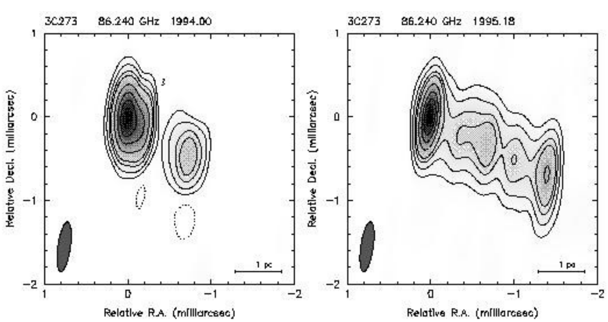
Superluminal motion



$$\text{apparent speed} = \frac{v \sin(\theta)}{[1 - (v/c)\cos(\theta)]}$$



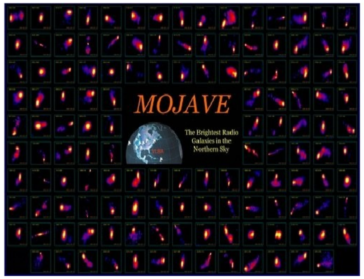
Intraday variability



Unresolved core/jet

Internal structure – observations

Last 10 years – new possibilities



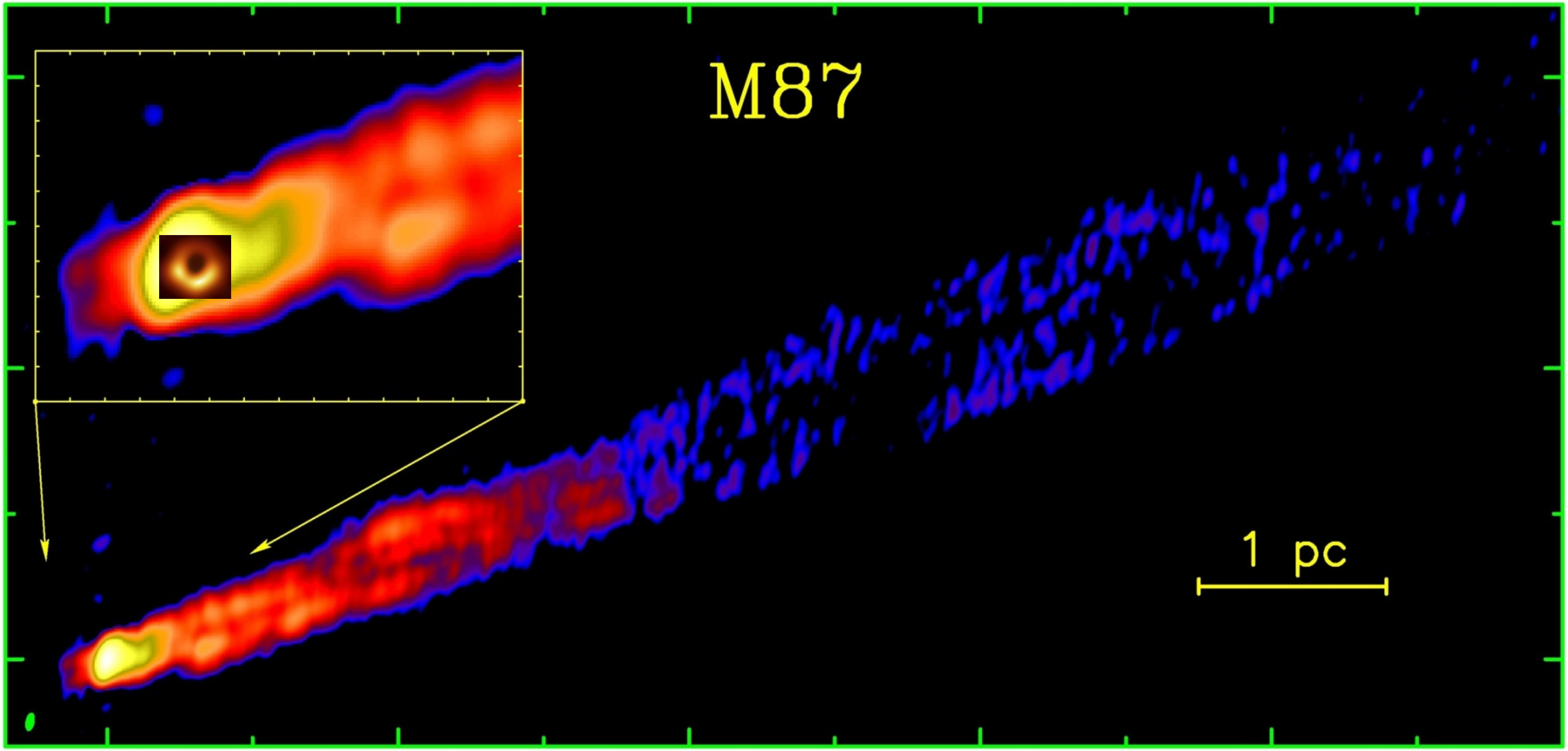
Time (MOJAVE)

Base (RadioAstron)

Frequency (EHT)

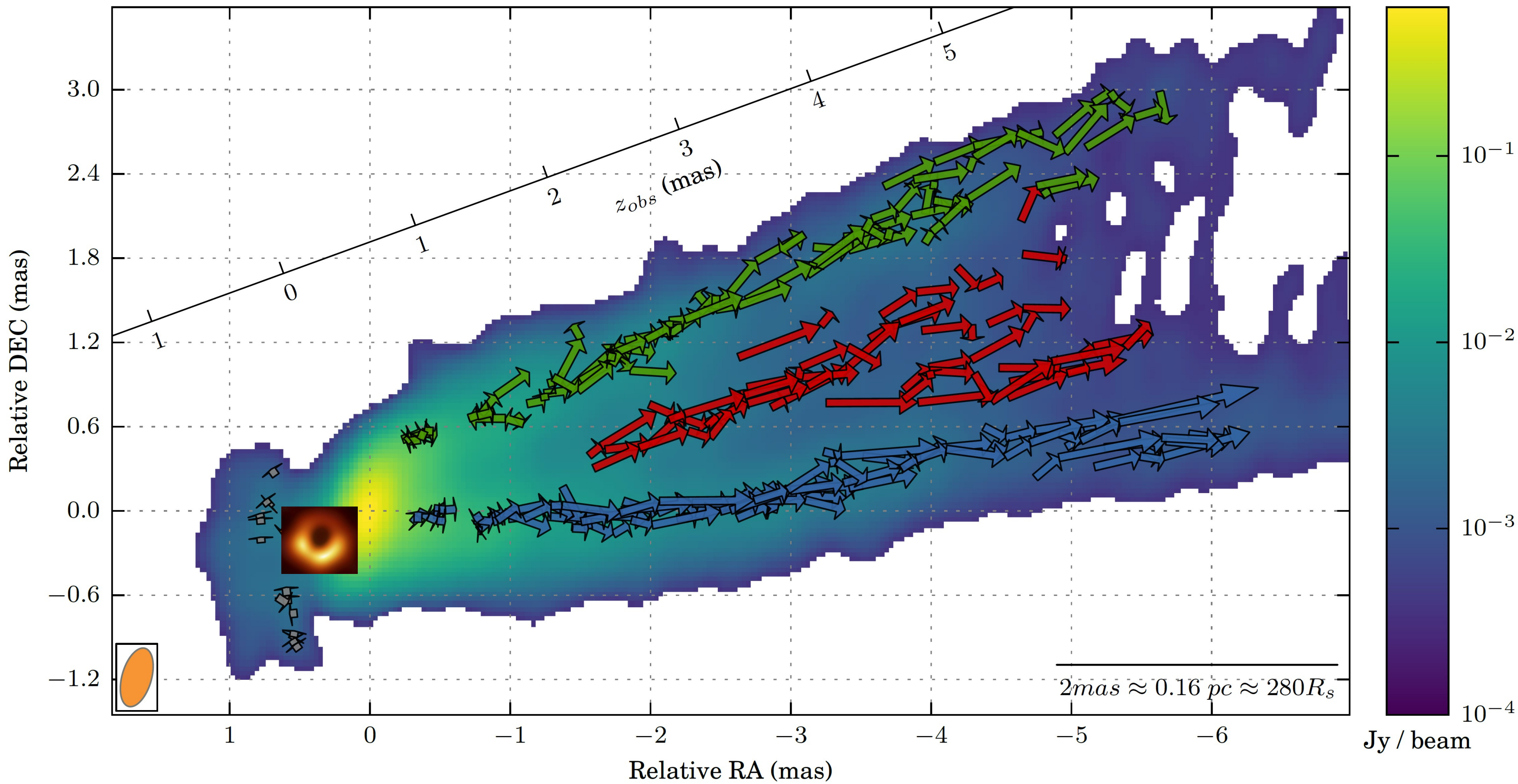
Internal structure – observations

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



Internal structure – observations

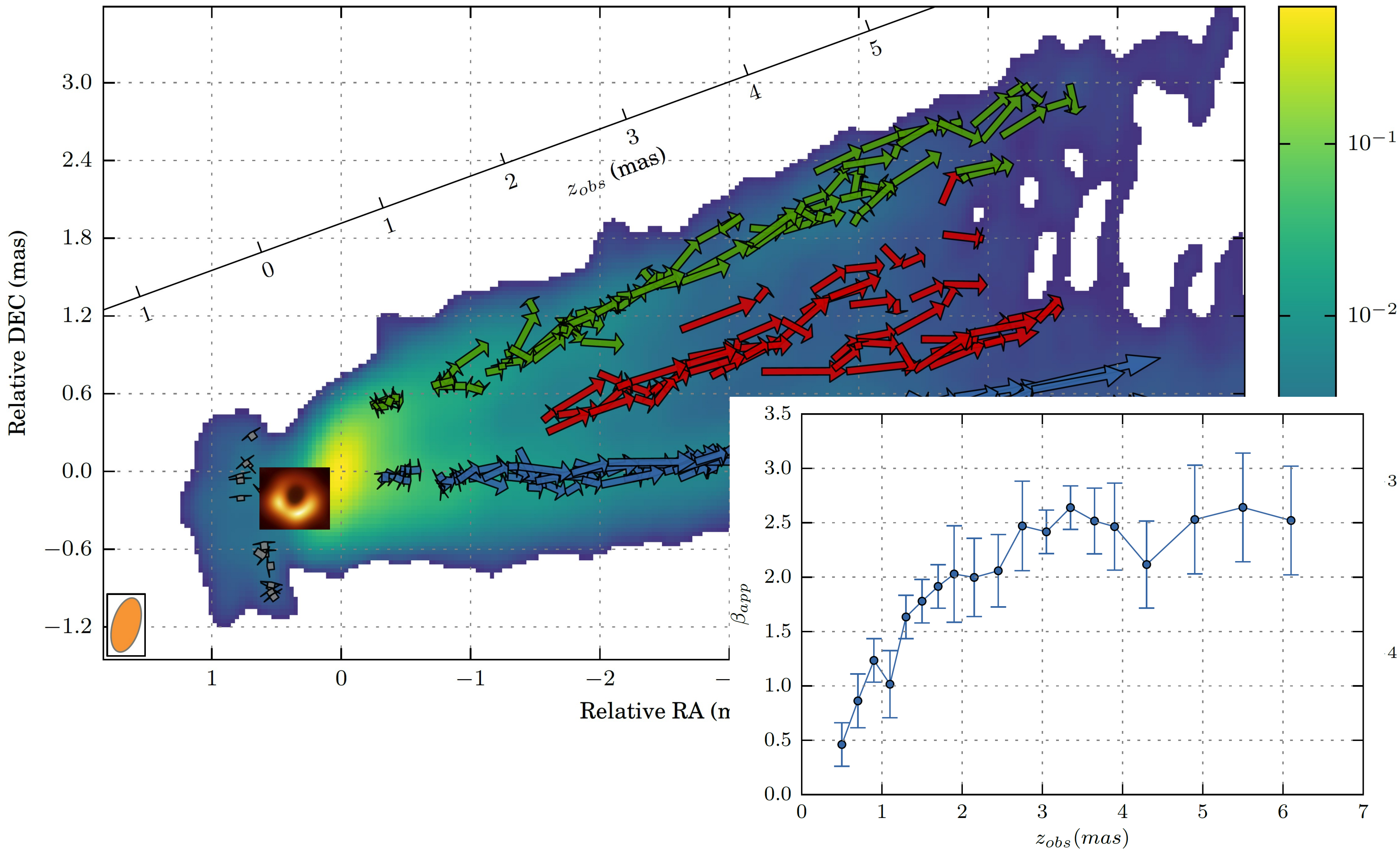
F. Mertens, A.P.Lobanov, R.C.Walker, P.E.Hardee, A&A, **595**, A54 (2016)



Internal structure – observations

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

Acceleratrion



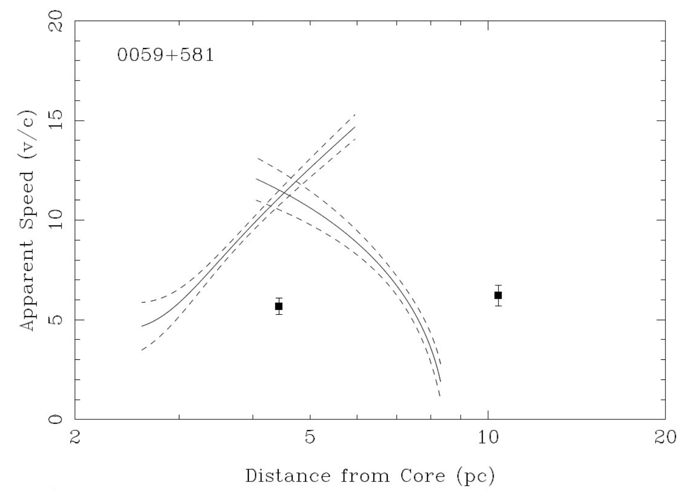
Internal structure – observations

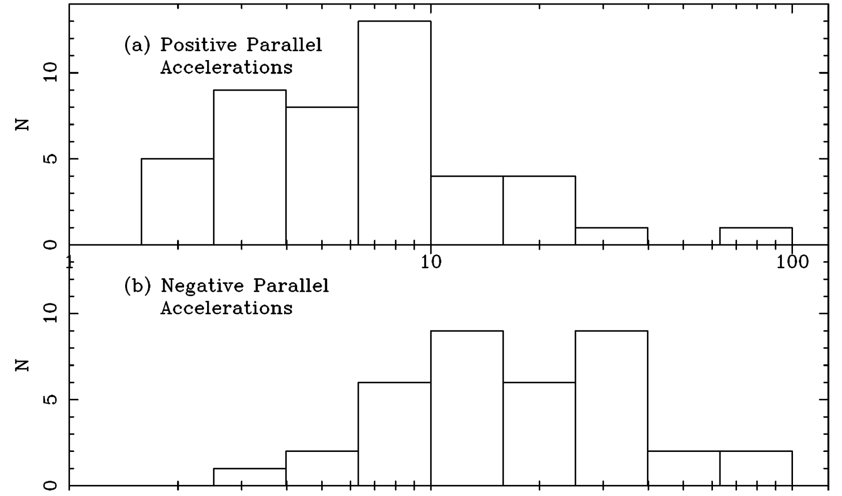
D.C. Homan, M.L.Lister, Y.Y.Kovalev et al, ApJ, **798**, 134 (2015)

Acceleratrion

MOJAVE XII

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

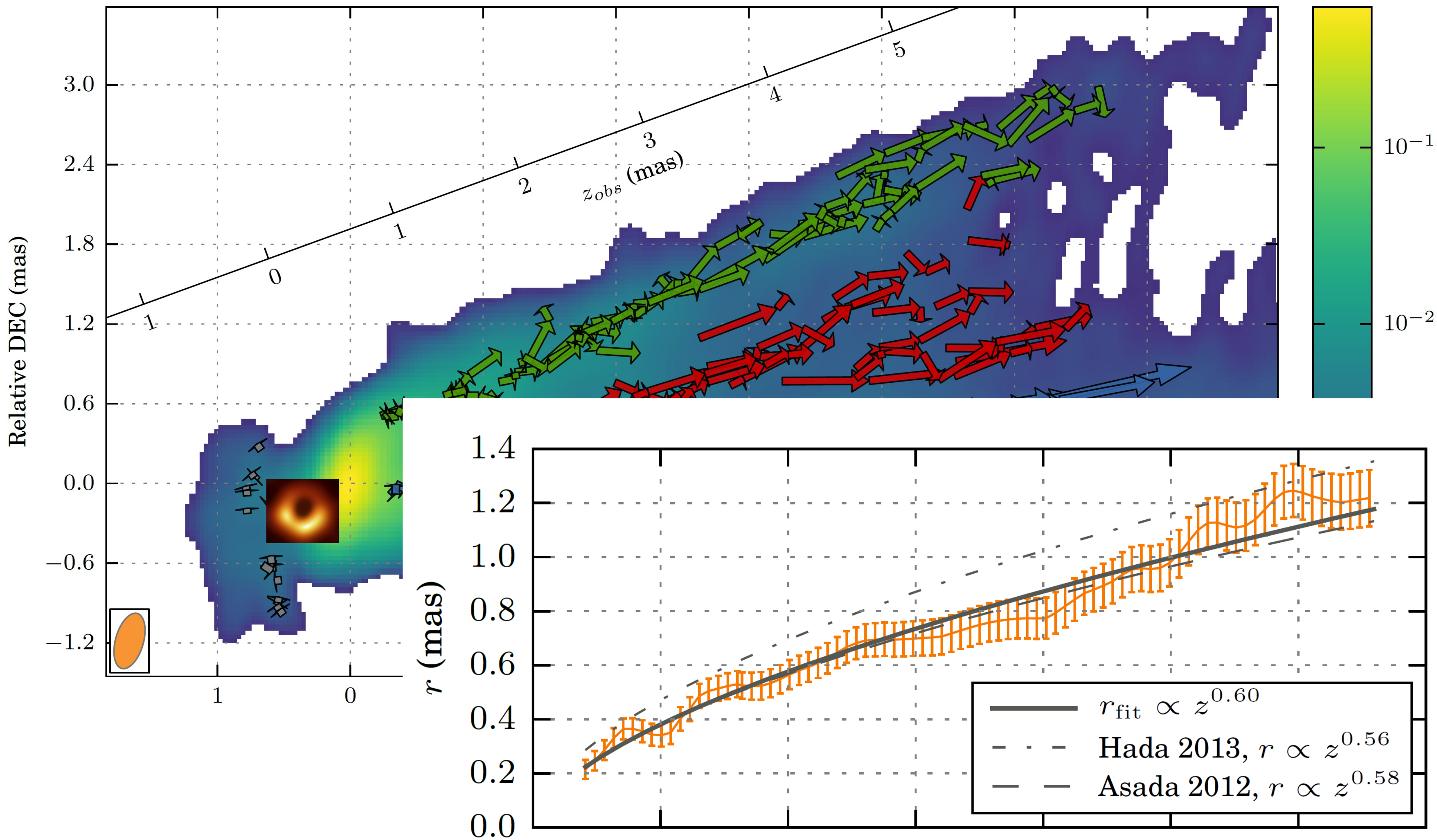




Internal structure – observations

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

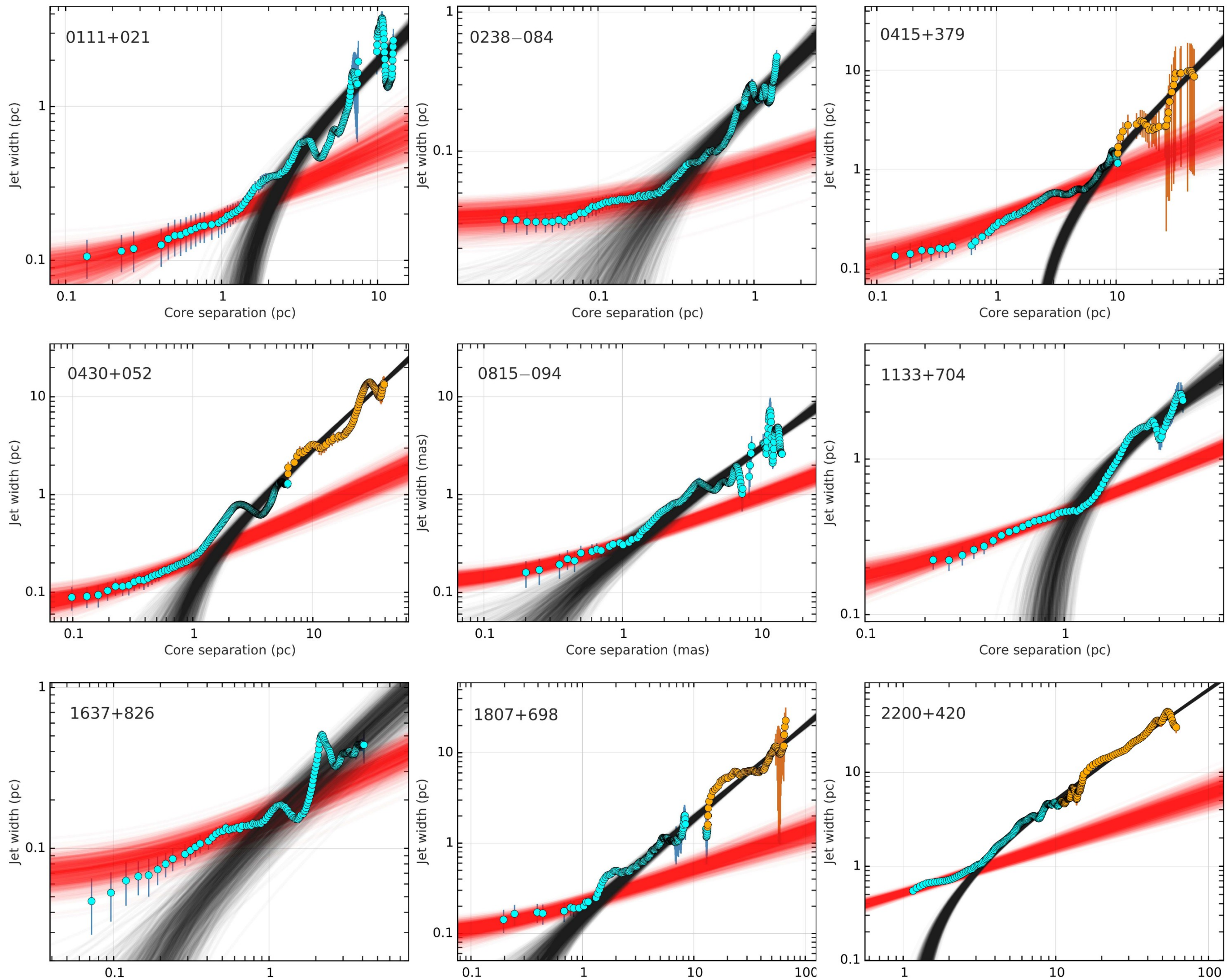
Collimation



Internal structure – observations

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

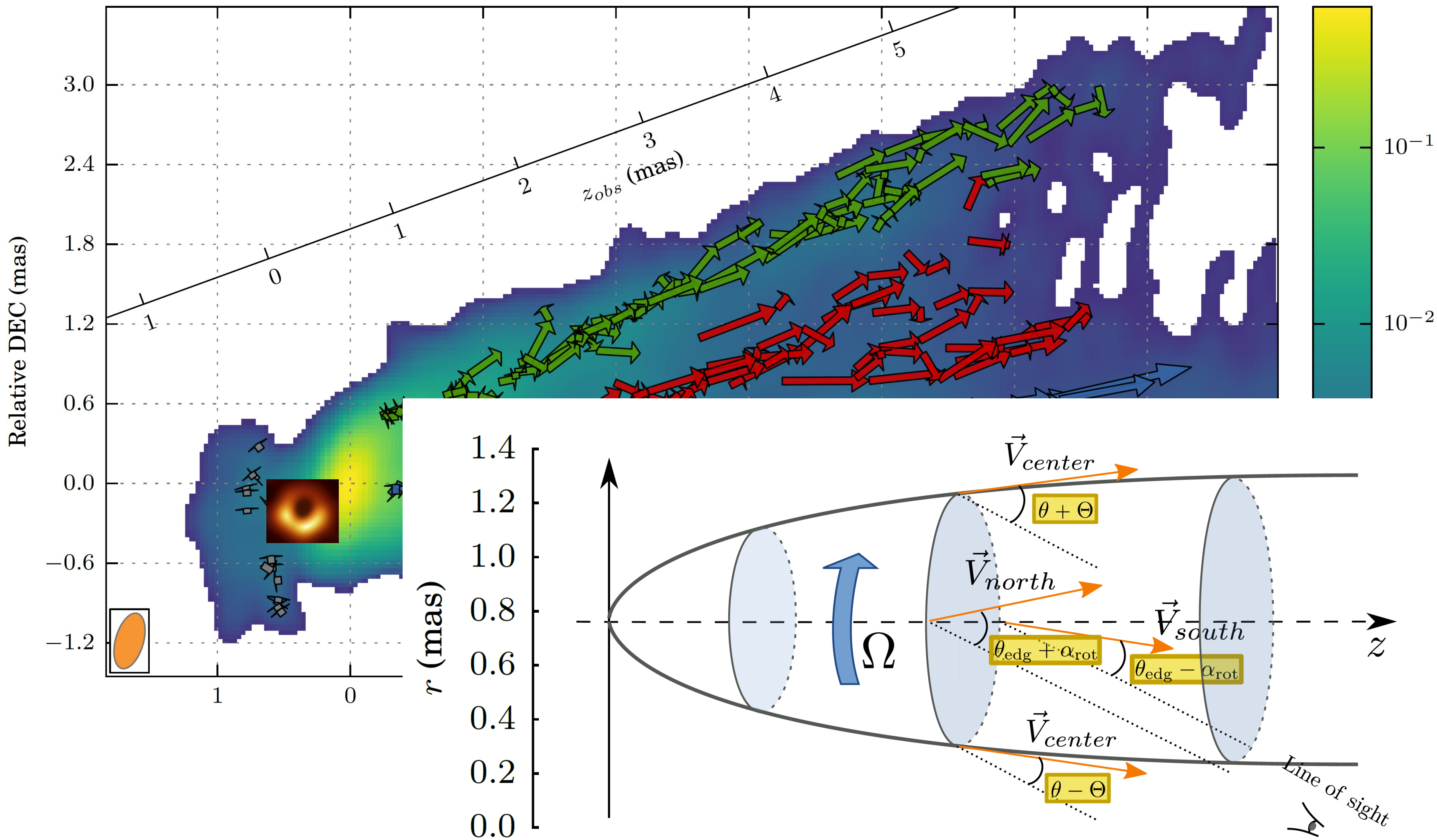
Collimation



Internal structure – observations

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

Rotation



Internal structure – observations

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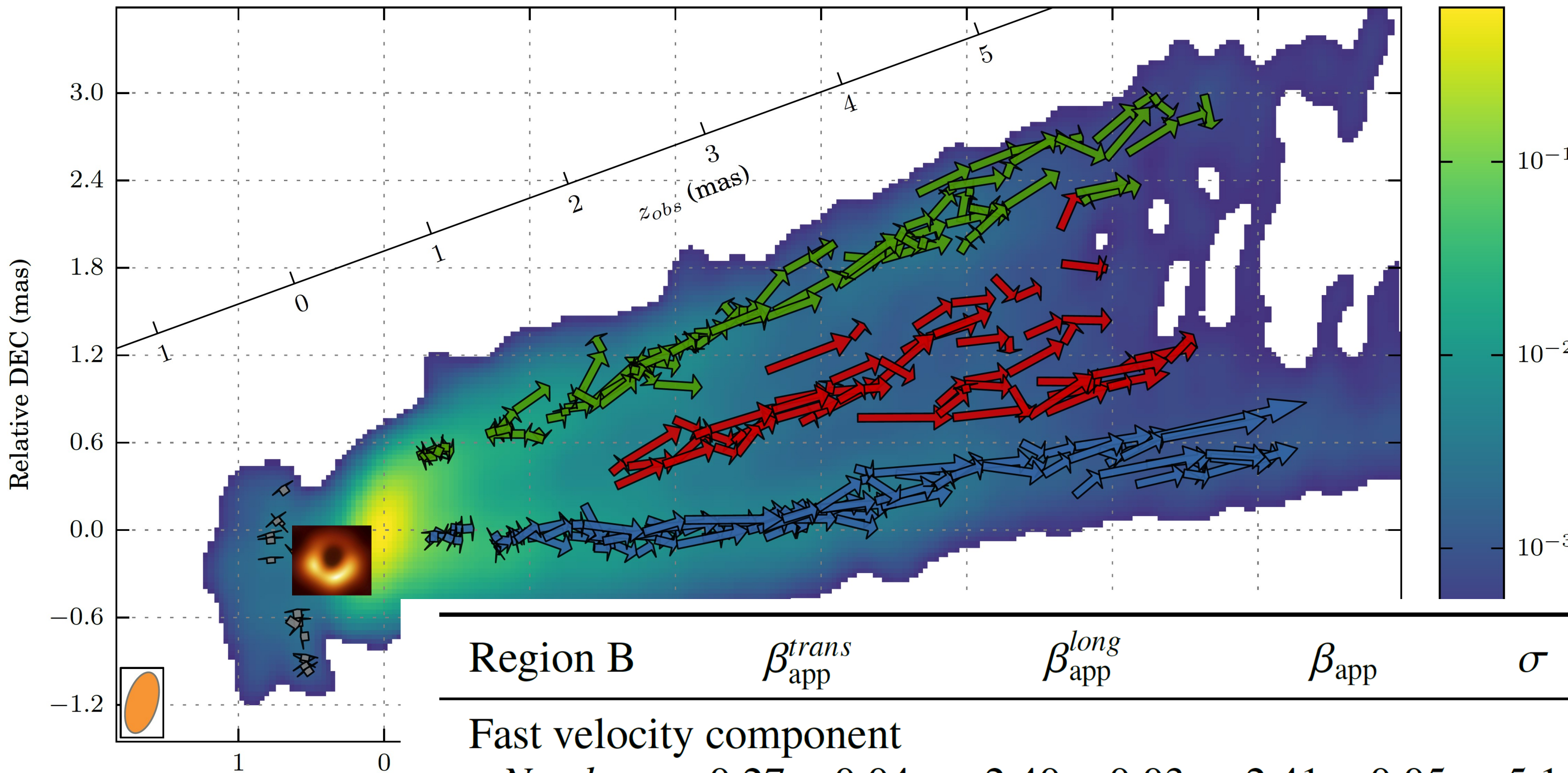
Rotation



Region B	$\beta_{\rm app}^{trans}$	$\beta_{\rm app}^{long}$	$\beta_{\rm app}$	σ
Fast velocity component				
North	0.27 ± 0.04	2.40 ± 0.03	2.41 ± 0.05	5.1
Center	−0.1 ± 0.1	2.32 ± 0.17	2.32 ± 0.20	4.0
South	−0.41 ± 0.07	2.16 ± 0.14	2.20 ± 0.15	2.5

Internal structure – observations

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

Rotation

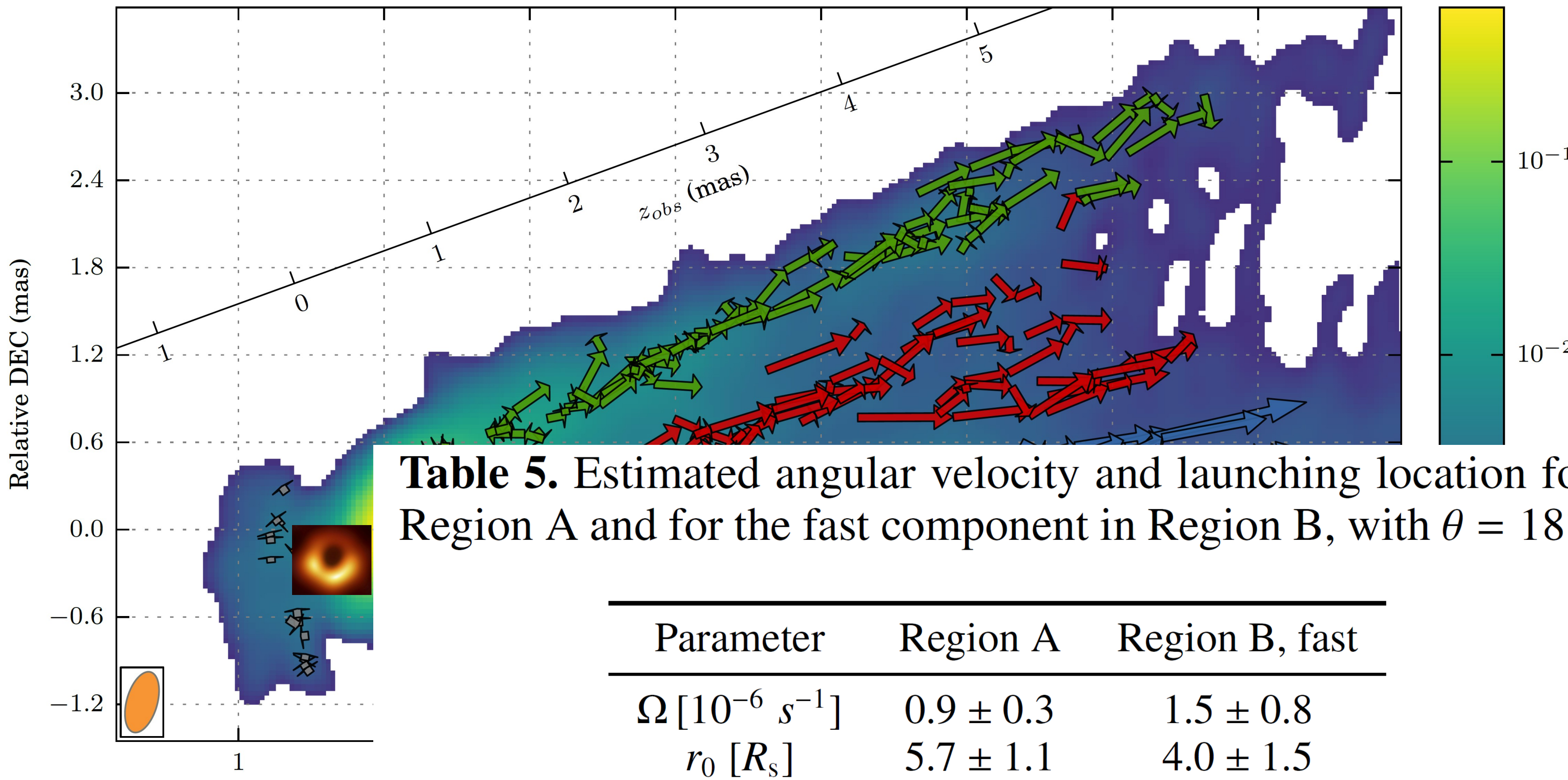
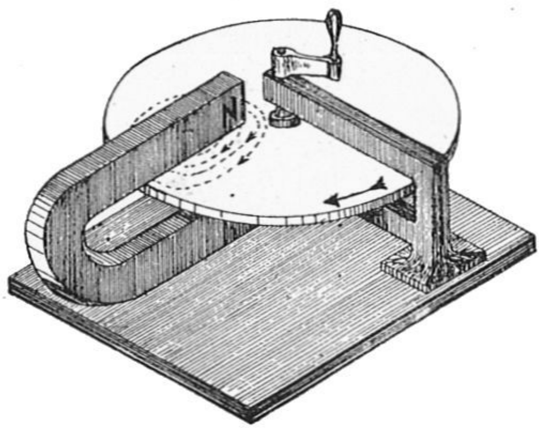


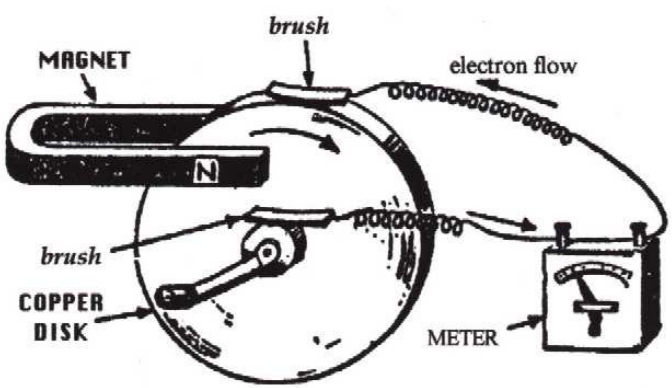
Table 5. Estimated angular velocity and launching location for Region A and for the fast component in Region B, with $\theta = 18°$.

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

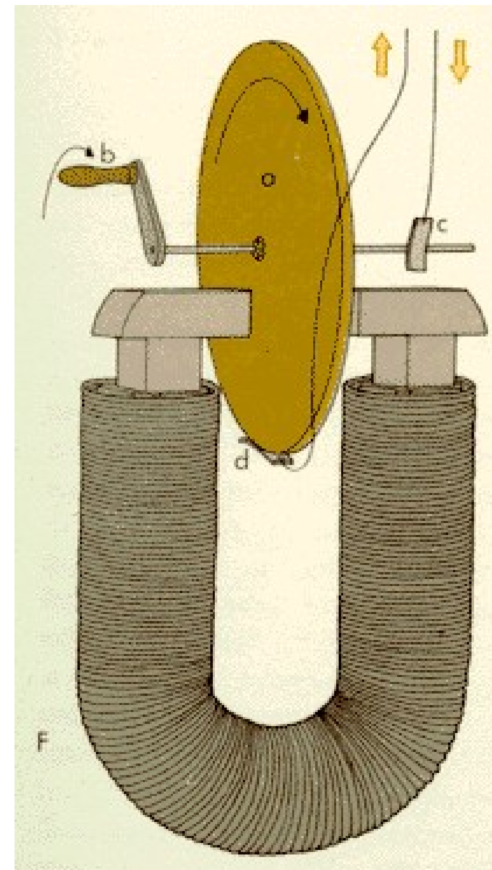
Confirmation of MHD model (goto end)

“Central engine” is a Faraday disk

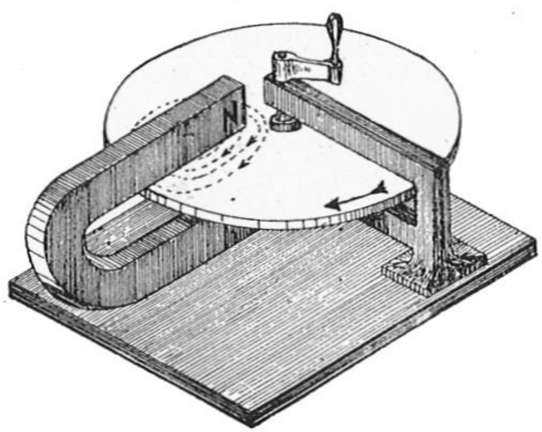


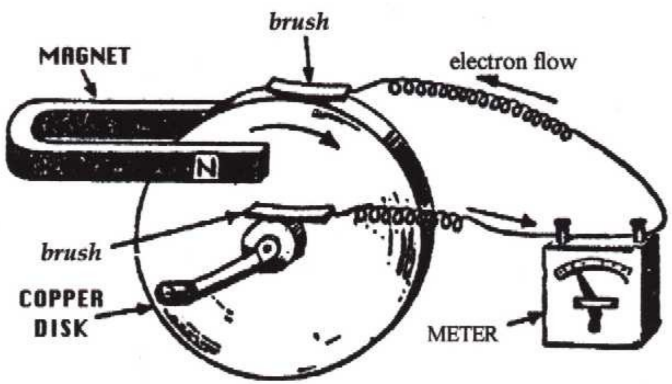


Faraday's disk dynamo - for producing continuous (pure) dc voltage. This was the world's first electrical generator.



"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

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

Dynamo-machine

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

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

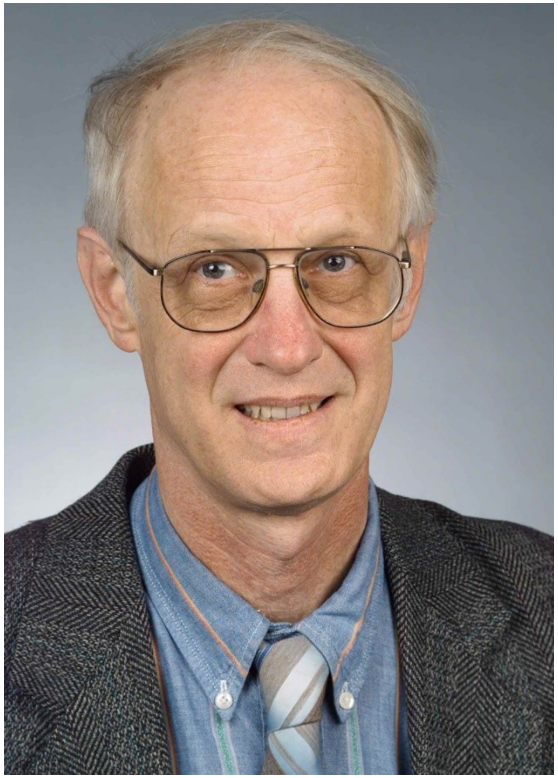
$$I \sim I_{\text{GJ}} = \pi R_0^2 c \rho_{\text{GJ}}$$

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

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

Is black hole a Faraday disk?

R.Blandford (1976)



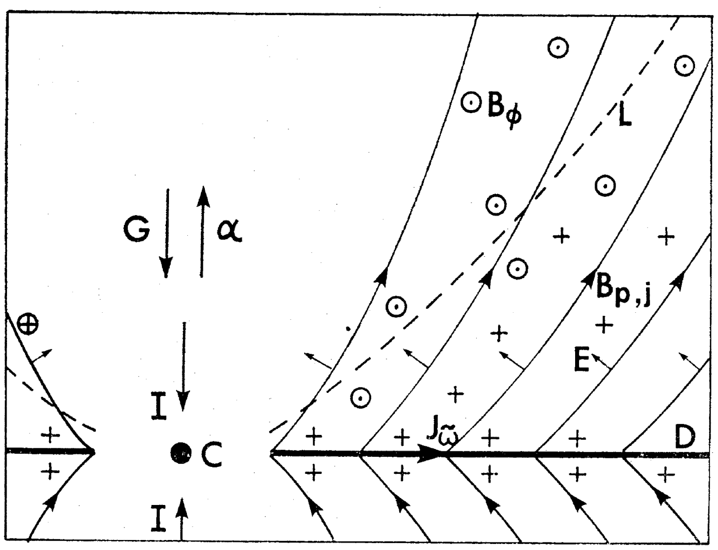
R.Lovelace (1976)

Is black hole a Faraday disk?

BZ = Faraday disk?

R.Blandford (1976), BZ (1977)

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



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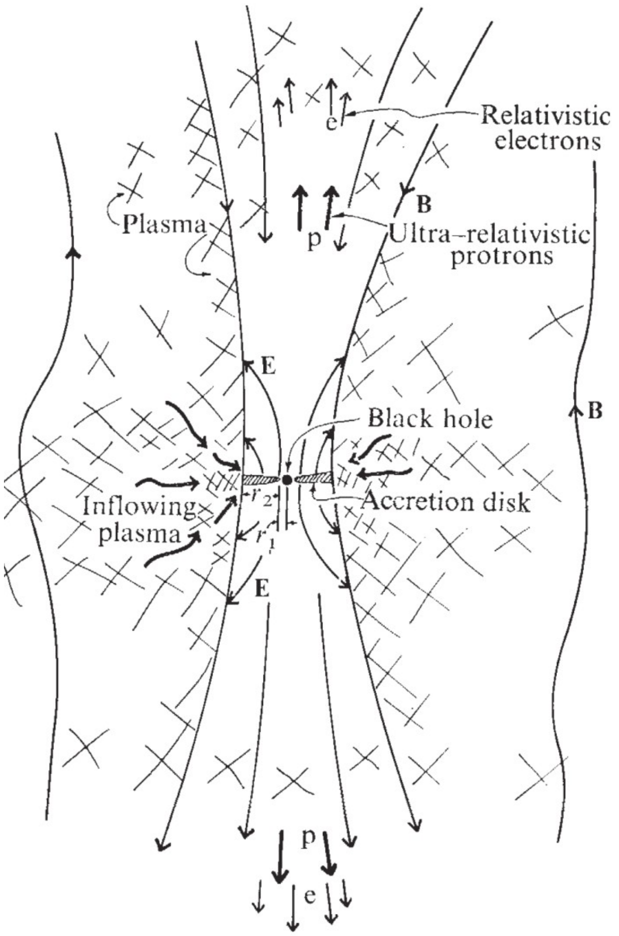


Is black hole a Faraday disk?

Membrane paradigm

BH fields

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

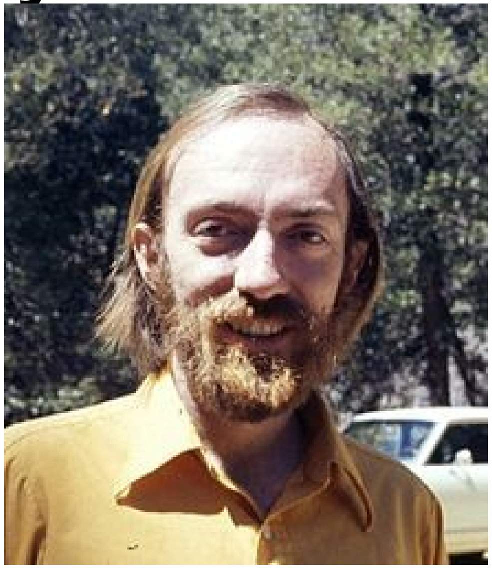
$$B_{\rm H} = \alpha B_{\hat\varphi}$$

"Ohm's law"

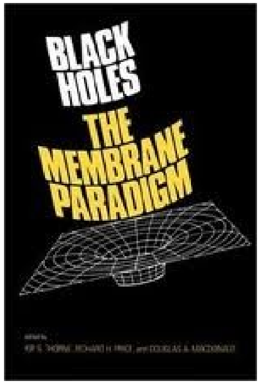
$$\boxed{E_{\hat\theta} = -B_{\hat\varphi}}$$

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

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



K.Thorne



= BZ "boundary condition" at the horizon

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

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

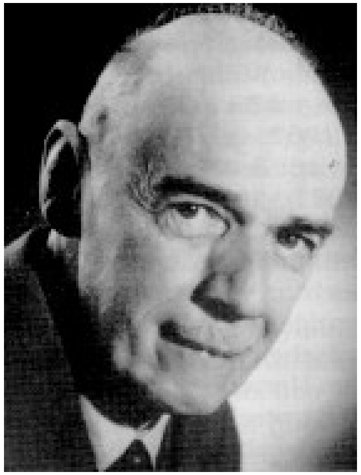
$$I \sim \delta U/\mathcal{R} \sim I_{\rm GJ}$$

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)

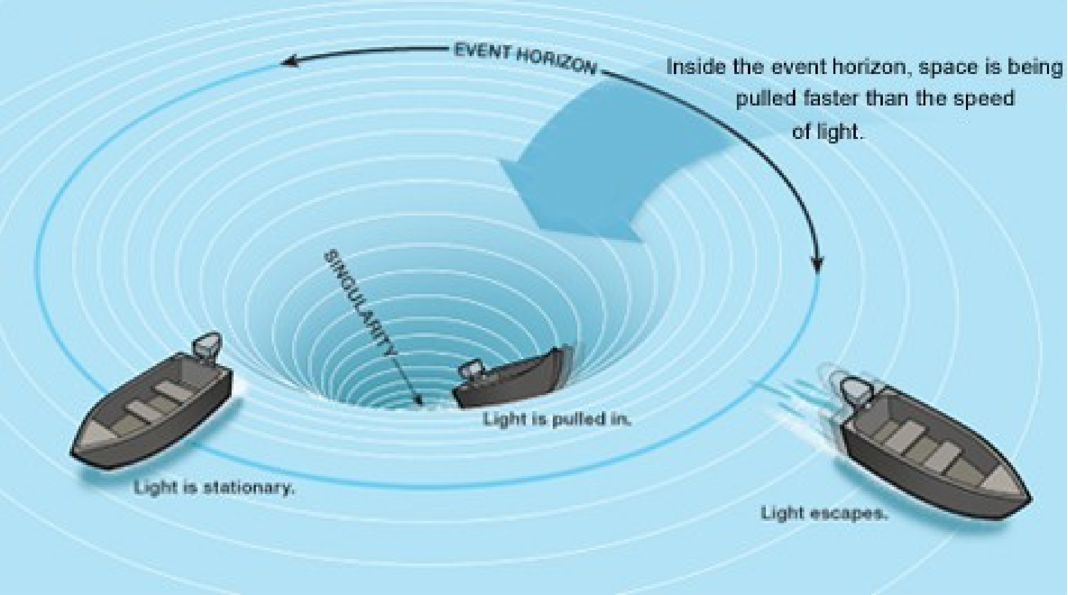
Inhomogeneously moving space can be detected.

Not a Faraday disk, but it doesn't matter

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

Schwarzschild black hole

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

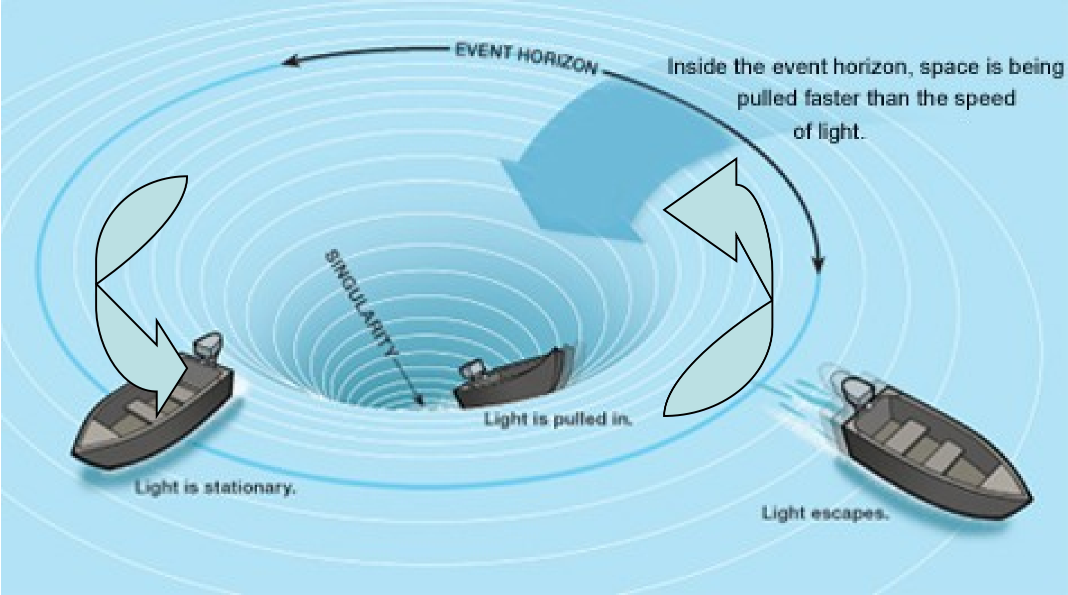


for laboratory at rest – tidal forces

Not a Faraday disk, but it doesn't matter

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

Kerr black hole

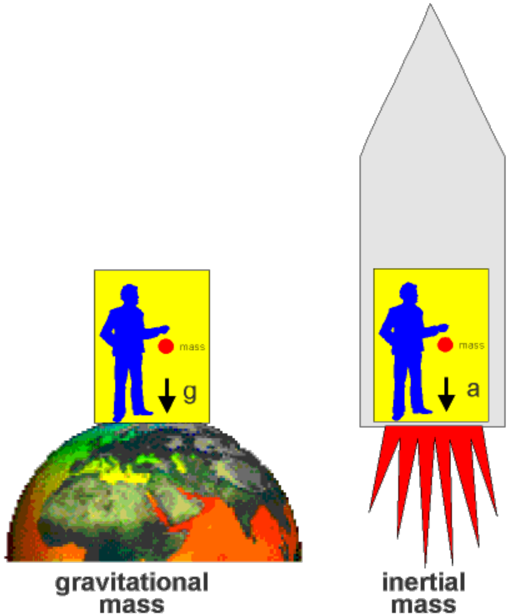


for laboratory at rest – gyroscope precession

Not a Faraday disk, but it doesn't matter

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

accelerating reference frame

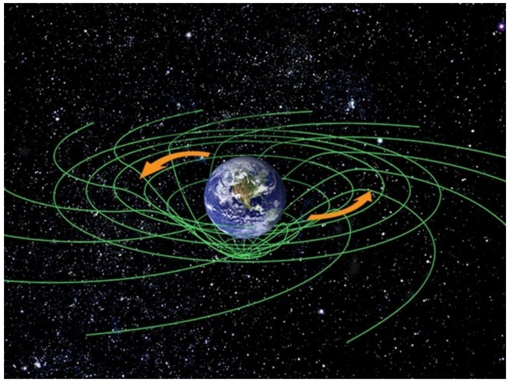


$$\mathbf{g} \sim \mathbf{E}$$

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

rotating reference frame

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



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

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

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

$$\operatorname{div} \mathbf{g} = -4\pi G\rho_{\mathrm{m}},$$

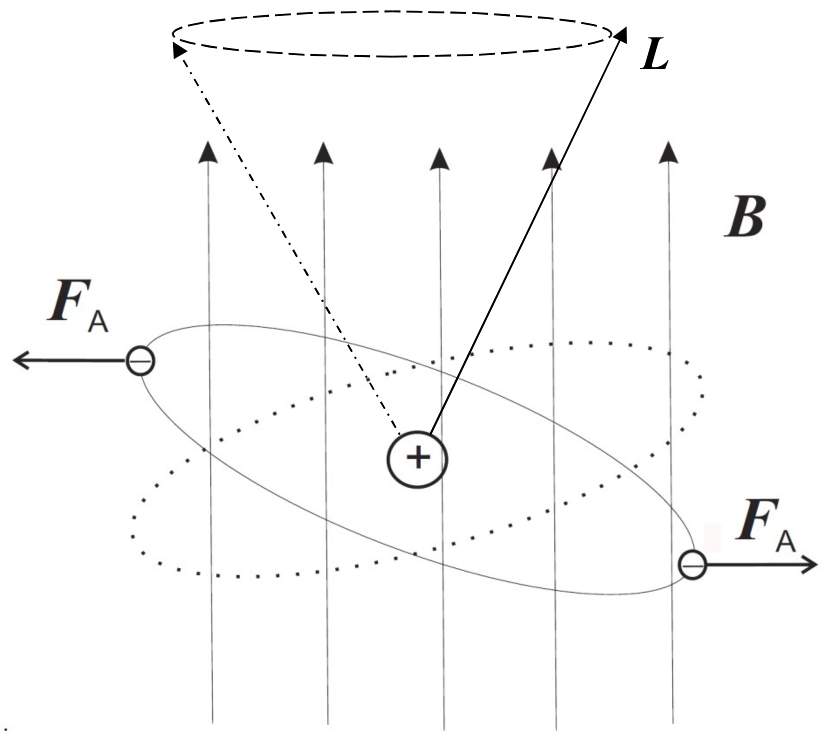
$$\operatorname{rot} \mathbf{g} = 0,$$

$$\operatorname{div} \mathbf{H} = 0,$$

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

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

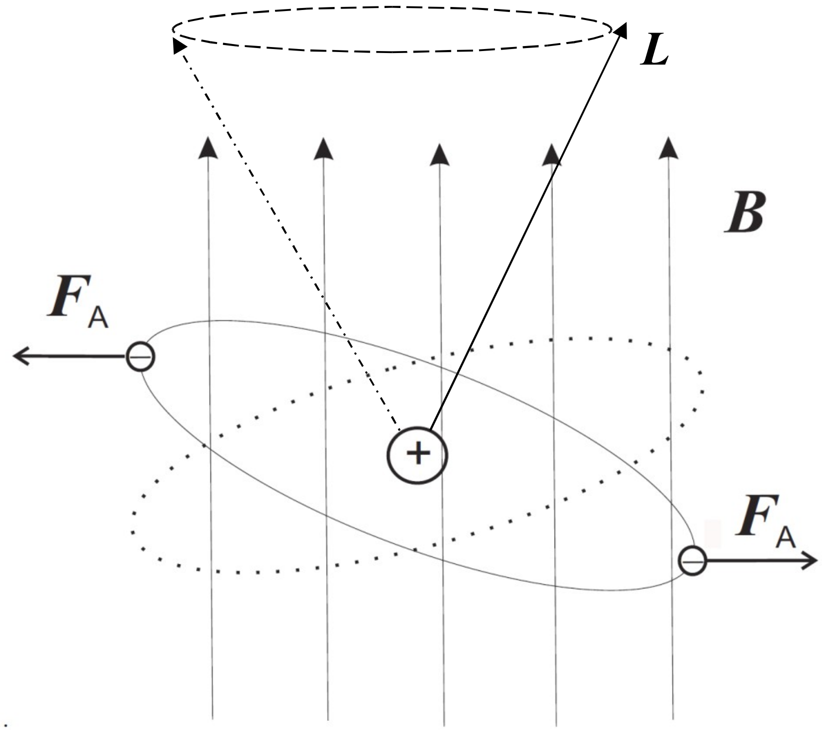
Not a Faraday disk, but it doesn't matter

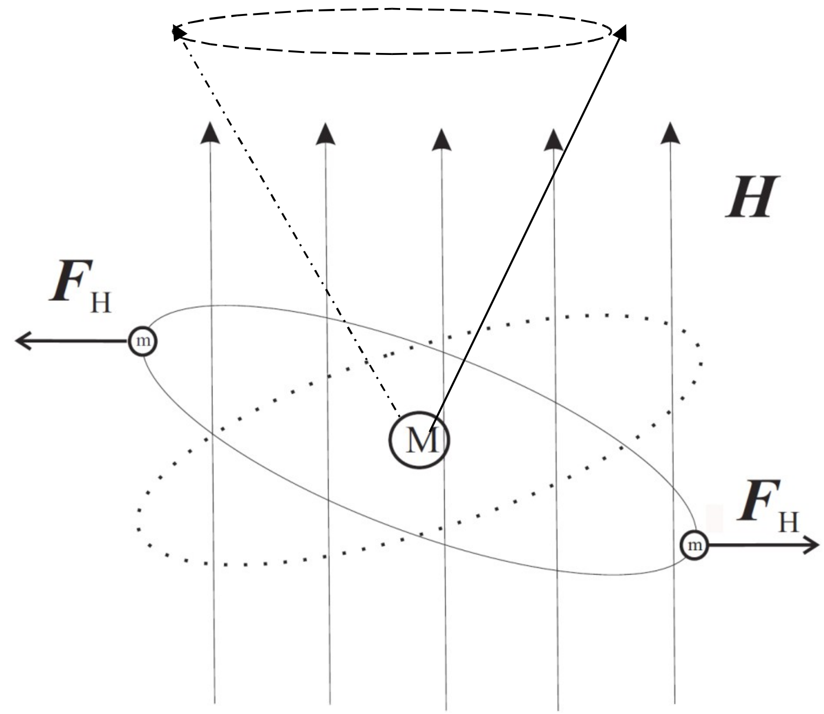


Larmor precession
due to Lorentz force

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

Not a Faraday disk, but it doesn't matter





Larmor precession
due to Lorentz force

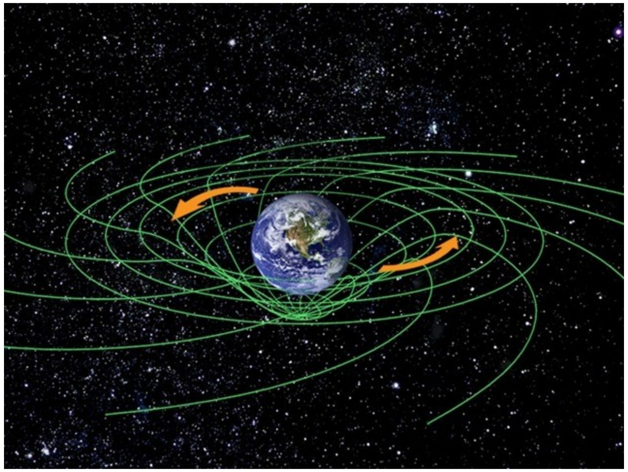
frame-dragging precession
due to 'Lorentz' force

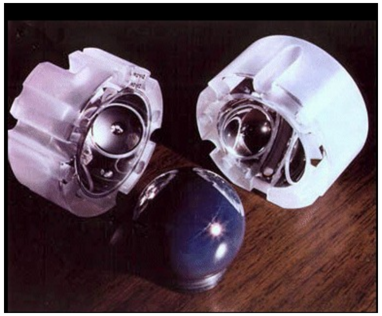
$$\Omega_{\rm L} = \frac{eB}{2m_{\rm e}c}$$

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

Not a Faraday disk, but it doesn't matter

Gravity Probe B





$$\mathbf{g} = -\frac{GM}{r^2}\mathbf{n},$$

$$\mathbf{H} = \frac{2G}{c}\frac{\mathbf{J}_r - 3\mathbf{n}(\mathbf{J}_r\mathbf{n})}{r^3}$$

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

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

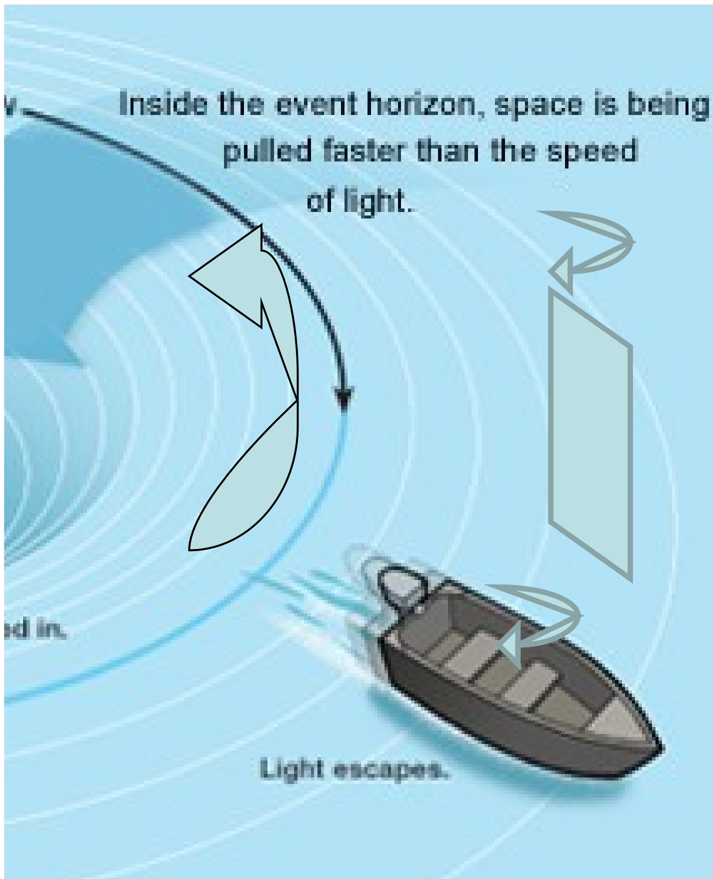
$$\Omega_{\rm g} = \frac{1+\gamma}{2}\frac{GJ_r}{r^3c^2}$$

(−0,0372±0,0072) “/год

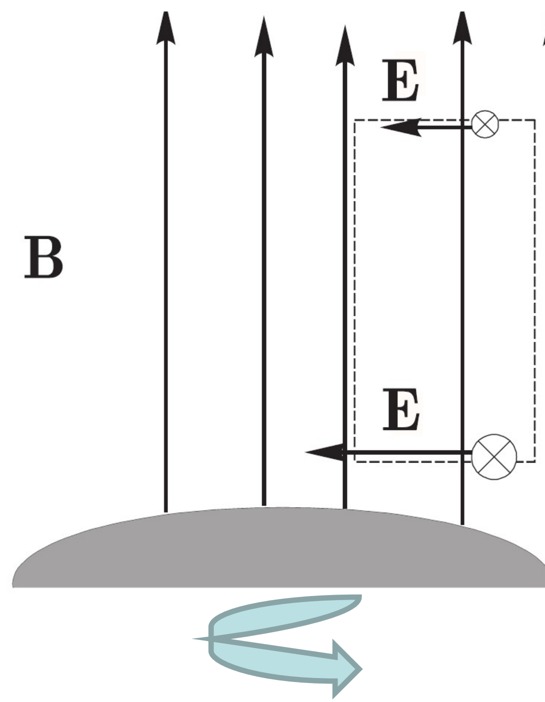
−0,0392 “/год

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

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

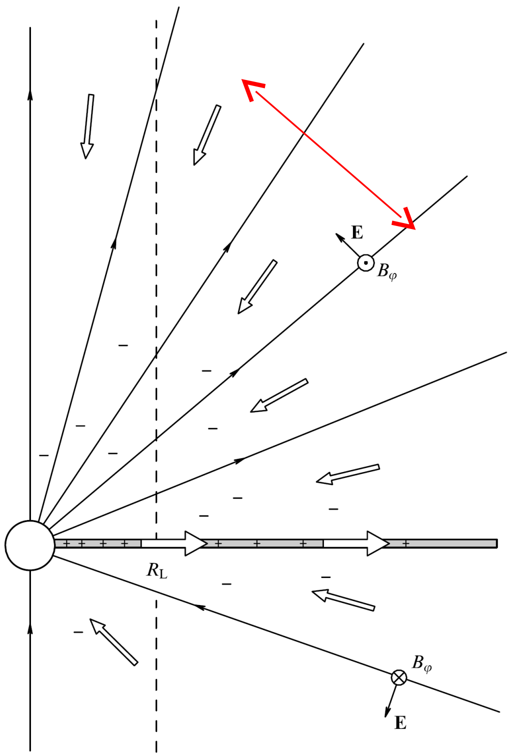
EMF results from frame-dragging (Lense-Thirring) effect which mimics the time-dependence due to inhomogeneous flow of space through the circuit.

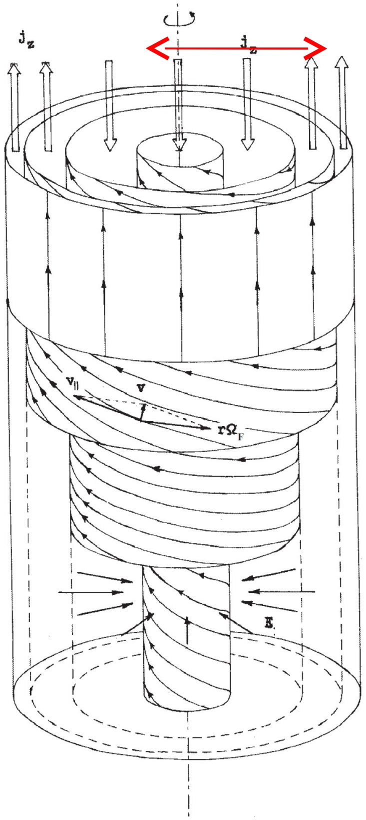
$$\nabla \times (\alpha \mathbf{E}) = \mathscr{L}_{\hat{\beta}} \mathbf{B}$$

Magnetically dominated outflow

F.C.Michel, ApJ, **180**, 133 (1973)

- Regular magnetic field
- Longitudinal electric current
- Rotation





Main parameters

- Michel magnetization parameter F.C.Michel, ApJ, **158**, 727 (1969)
  (maximal bulk Lorentz-factor)

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

μ now

- Multiplicity parameter

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

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

- Total potential drop

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

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

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

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

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 $n_{\rm syn} = \xi n_{\rm e}$.

$$\xi \approx 0.01$$

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

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

Core shift and jet parameters

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

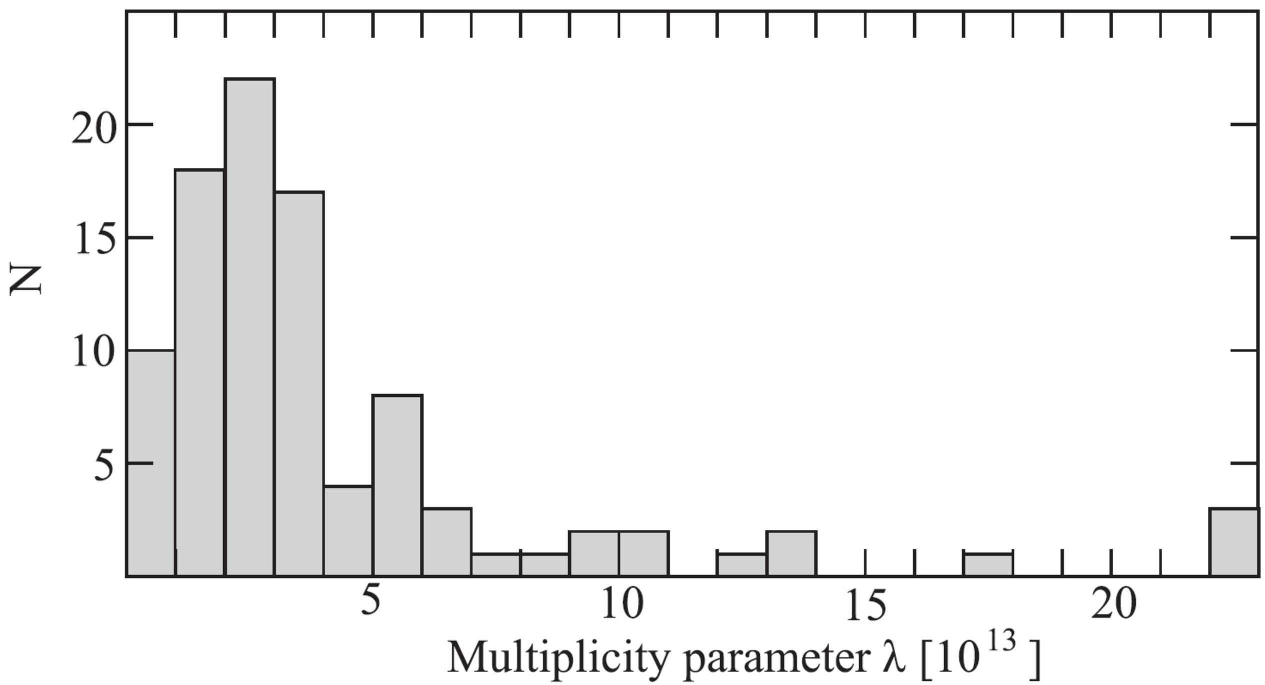


Figure 1. Distributions of the multiplicity parameter λ for the sample of 97 sources. Two objects with $\lambda = 2.8 \times 10^{14}$ and 3.6×10^{14} lie out of the shown range of values.

Core shift and jet parameters

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

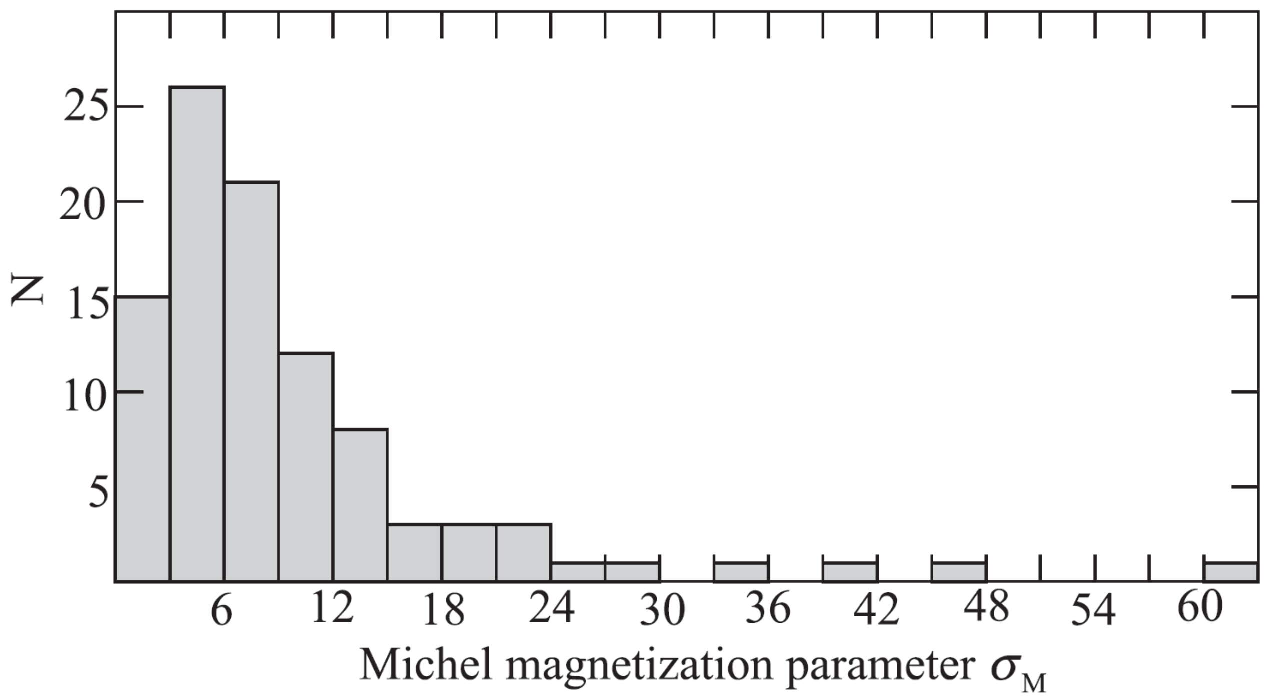
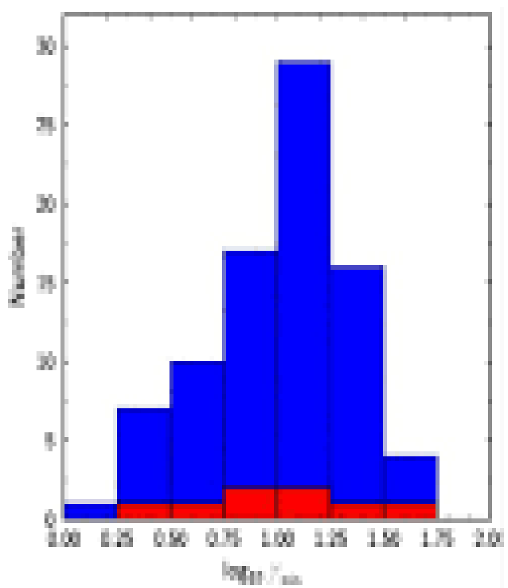


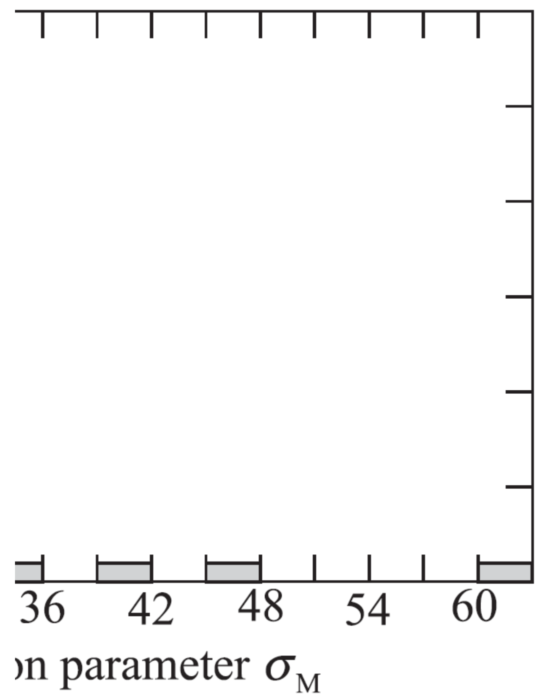
Figure 2. Distributions of the Michel magnetization parameter σ_M for the sample of 97 sources.

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

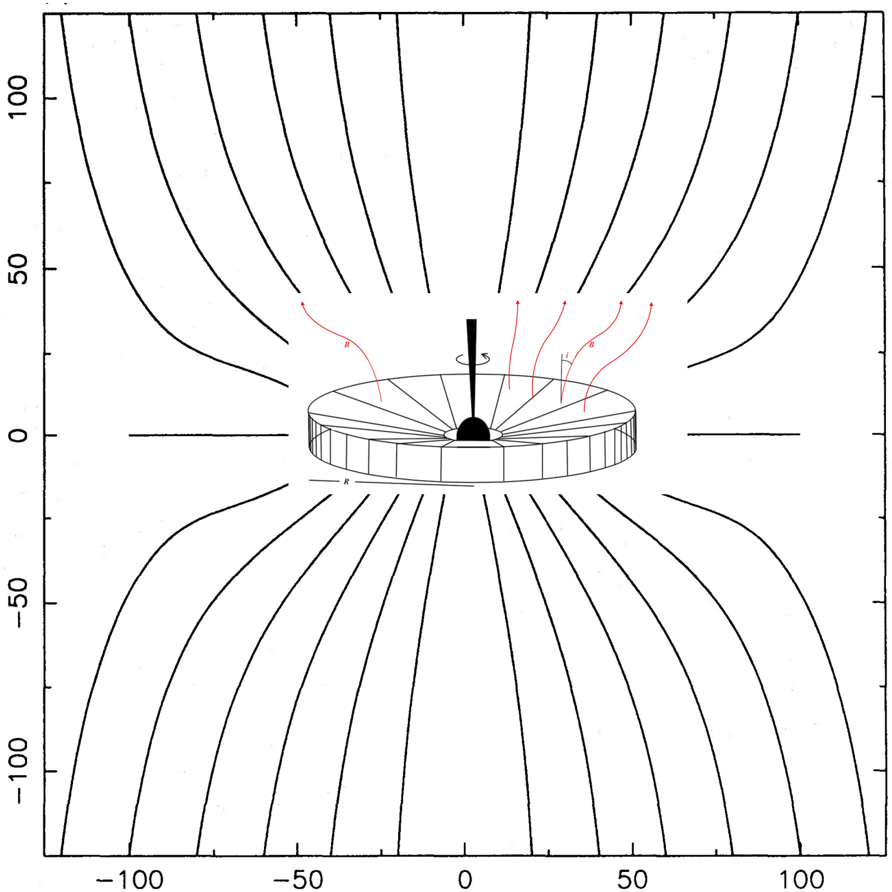
Magnetic field magnitude: Eddington value is necessary

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

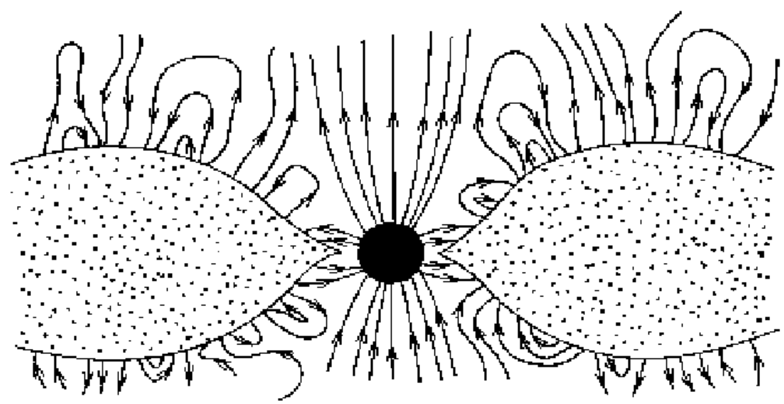
Theoretical challenge – B_0 problem

Magnetic field generation: external vs internal

external (advection)



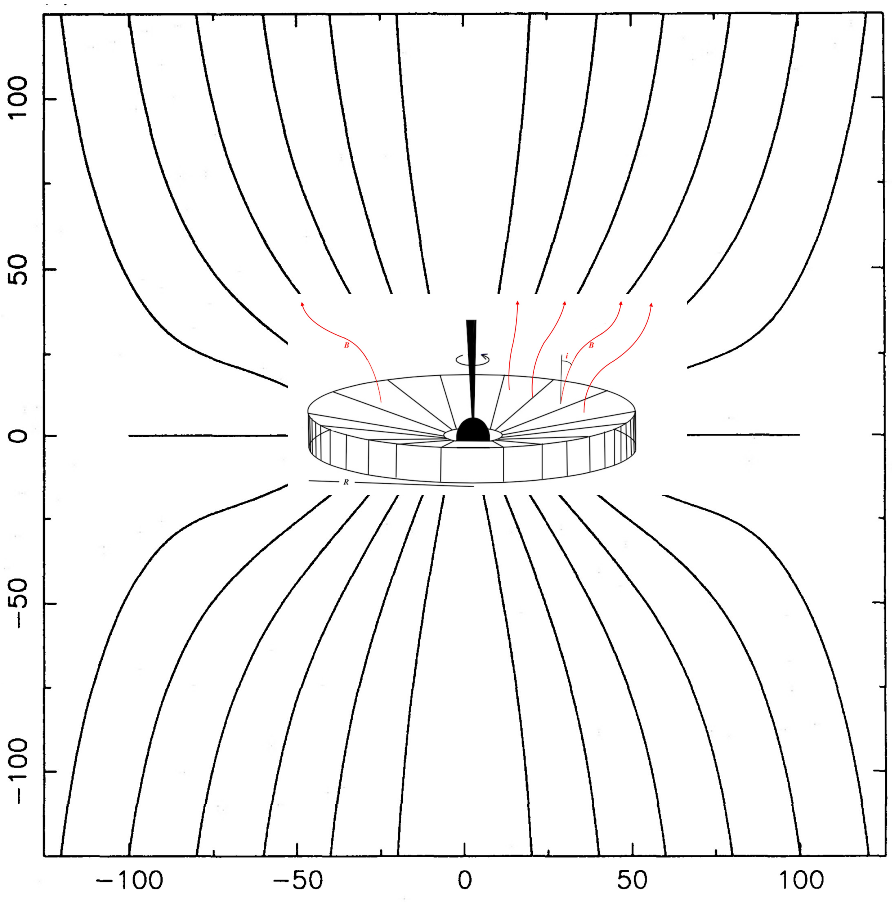
internal (dynamo)



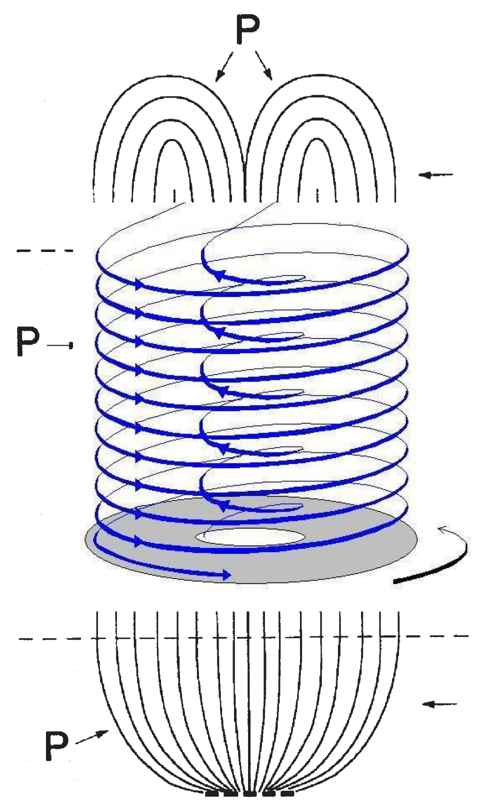
Theoretical challenge – B_0 problem

Magnetic field topology: external vs internal

homogeneous

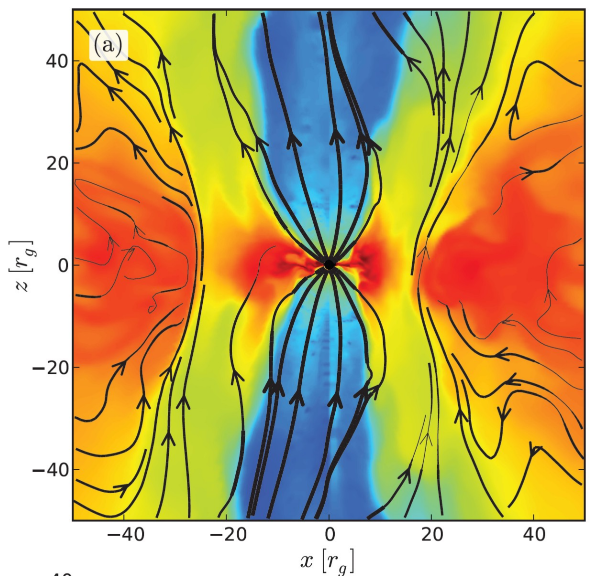


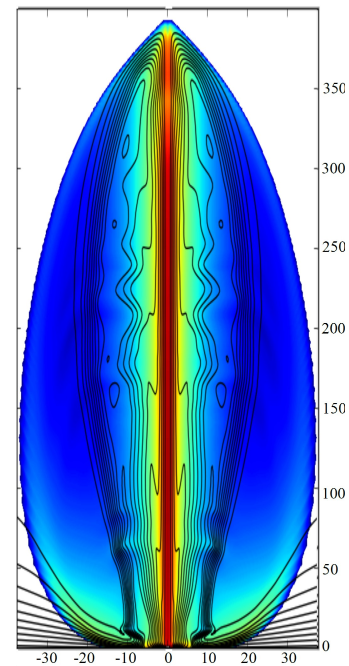
magnetic tower (RFP)



Theoretical challenge – B_0 problem

Magnetic field topology: homogeneous vs RFP





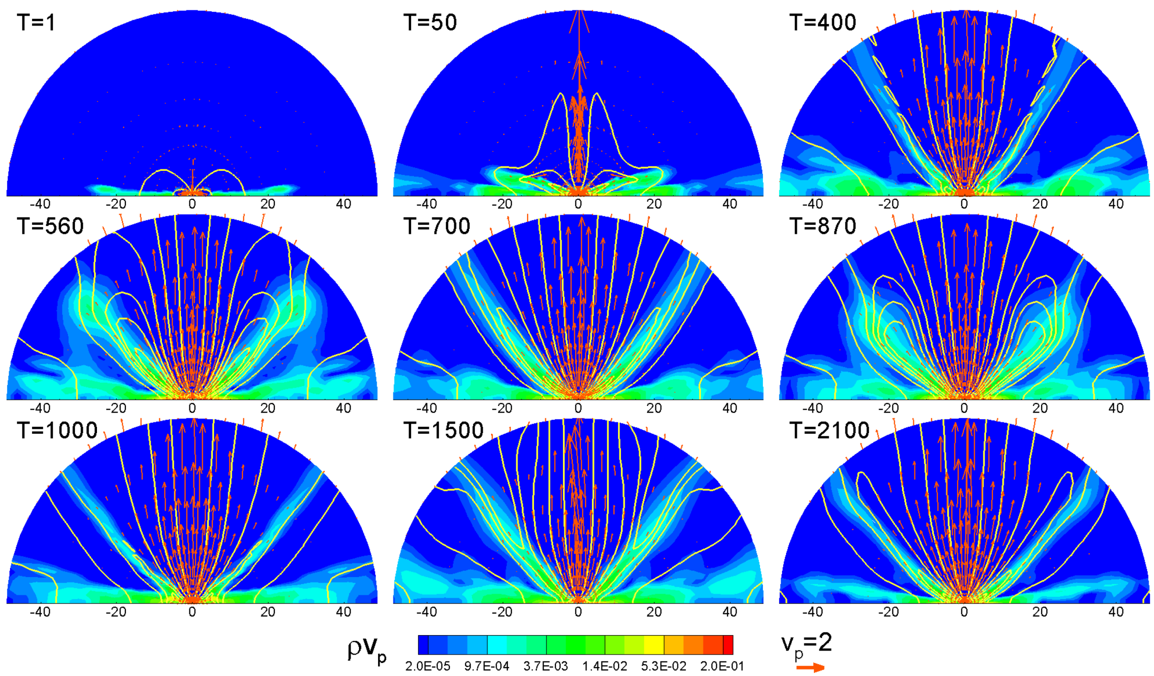
J.McKinney, A.Tchekhovskoy, R.Blandford

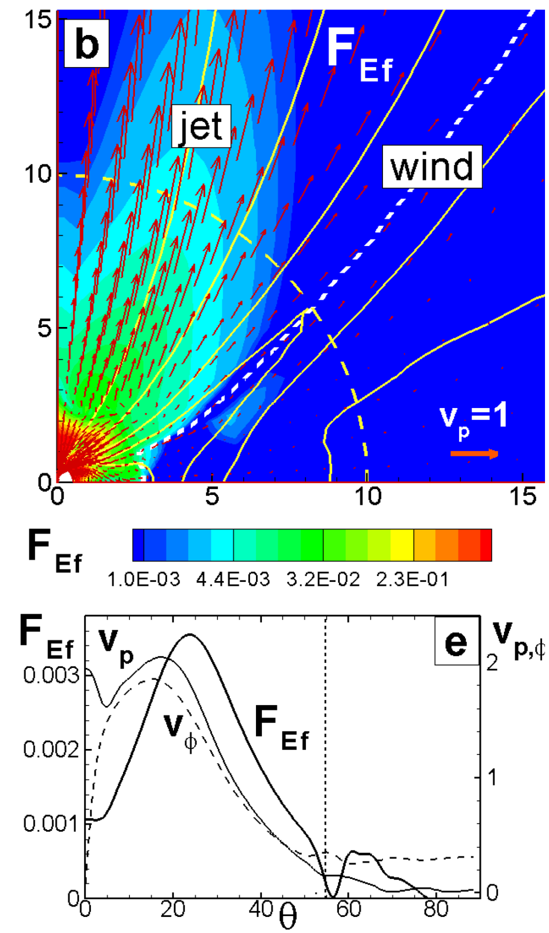
O. Bromberg, A. Tchekhovskoy

Theoretical challenge – B_0 problem

Magnetic field topology: homogeneous vs RFP

(evolution of dipole field)

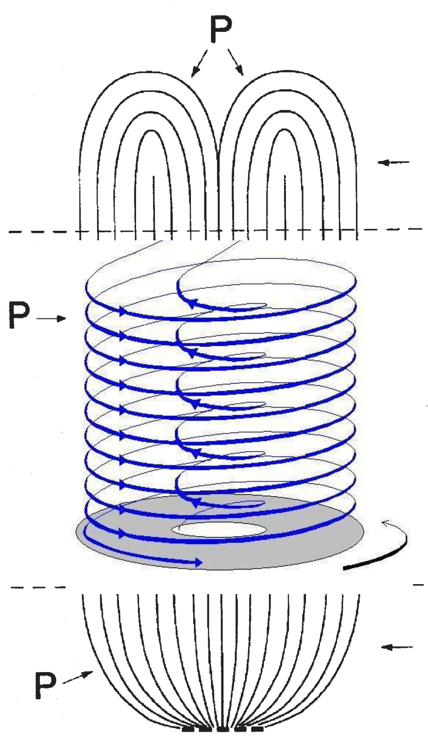




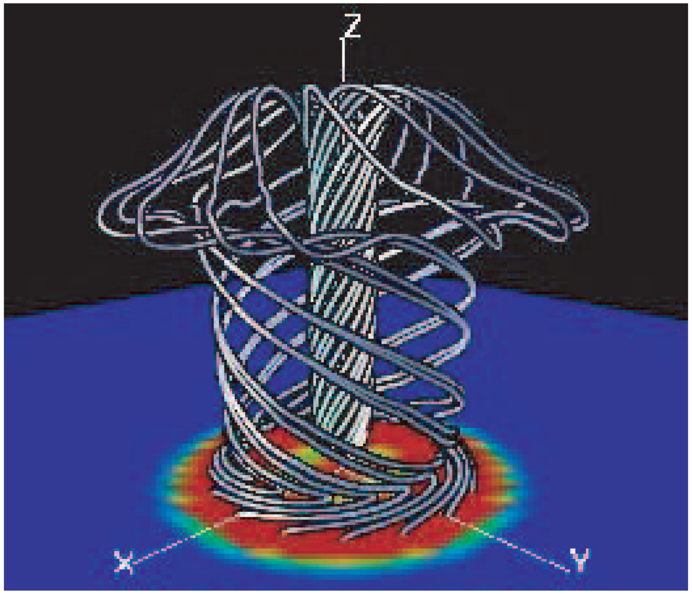
M.M.Romanova et al, MNRAS, **399**, 1802 (2009)

Theoretical challenge – B_0 problem

Magnetic tower (wind + diff. rotation)



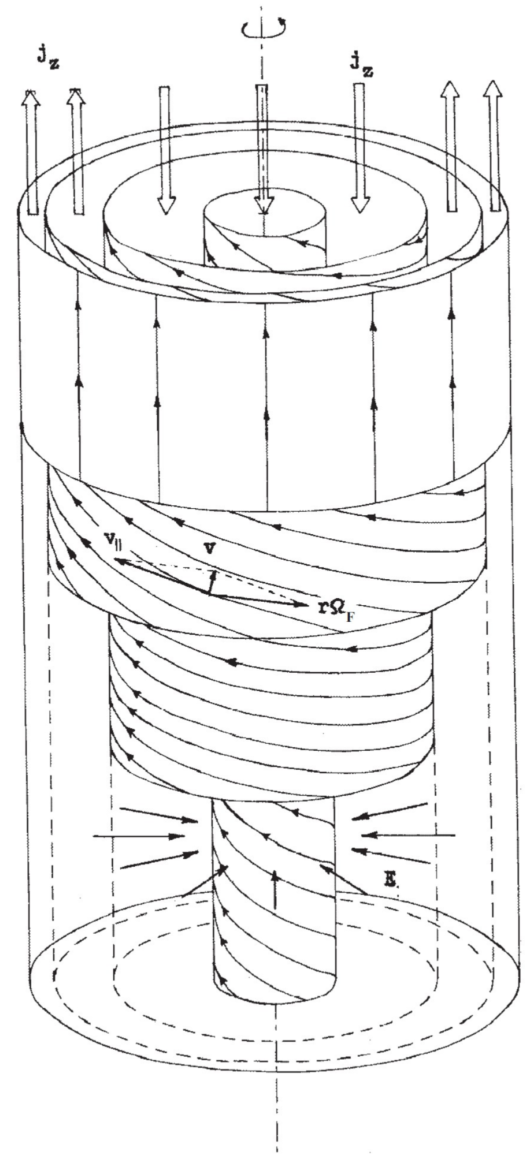
D.Lynden-Bell, MNRAS, **279**, 389 (1996)



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

Statement #3

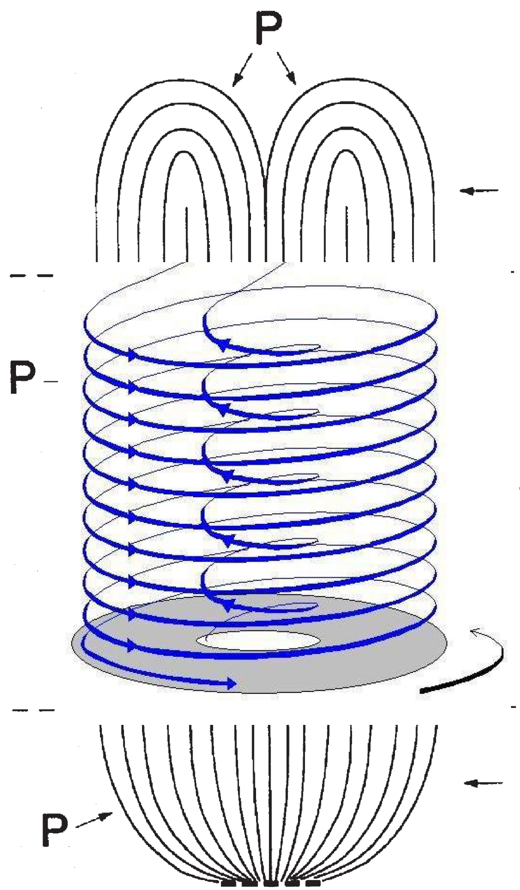
- Approximation of the homogeneous poloidal magnetic field is a reasonable model of relativistic jets.
- Total electric current can be zero.

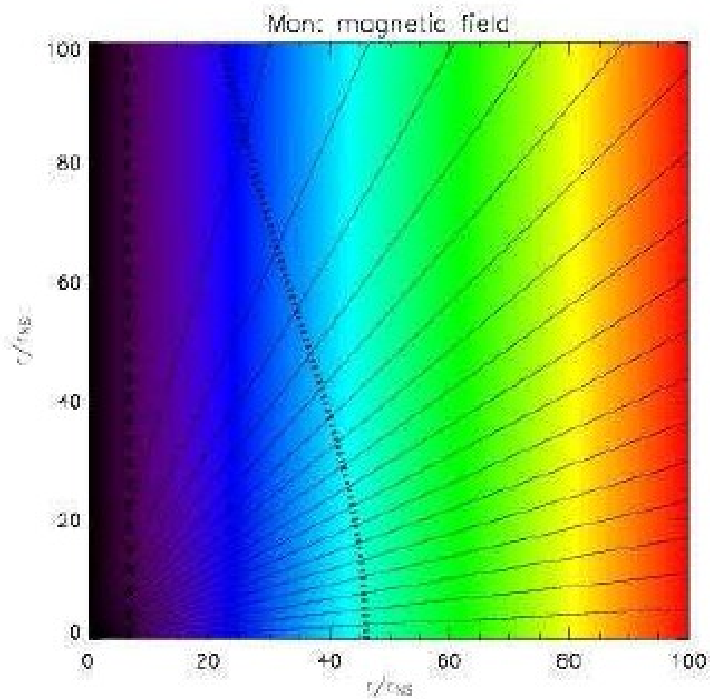


Theoretical challenge – I problem

Magnetic tower (cylindrical) vs diverging outflow (spherical)

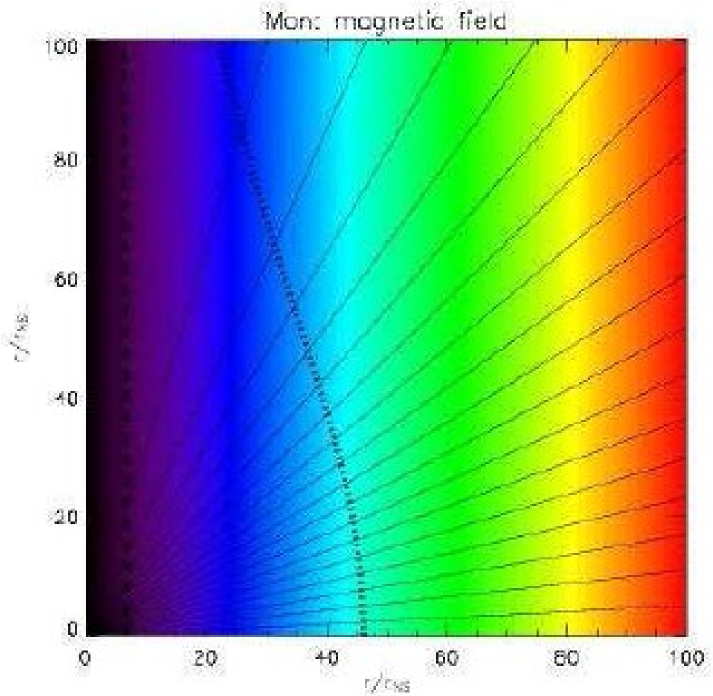
subsonic vs transonic





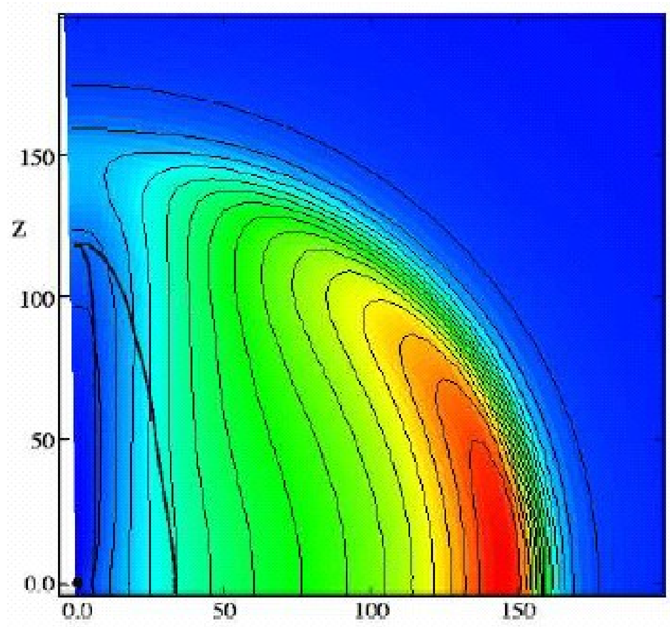
D.Lynden-Bell, MNRAS, **279**, 389 (1996)

Theoretical challenge – I problem



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

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

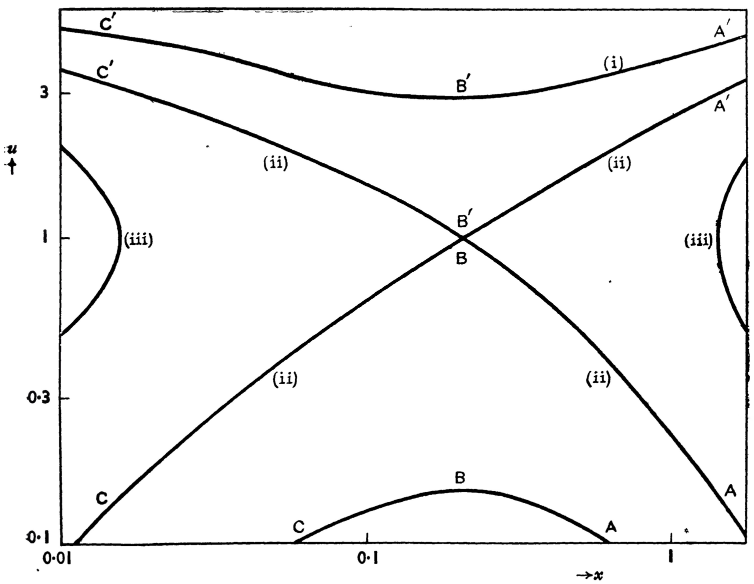


$$\gamma \approx \frac{\Omega r_\perp}{c}$$

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

Theoretical challenge – I problem

Critical condition on the sonic surface determines accretion rate



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

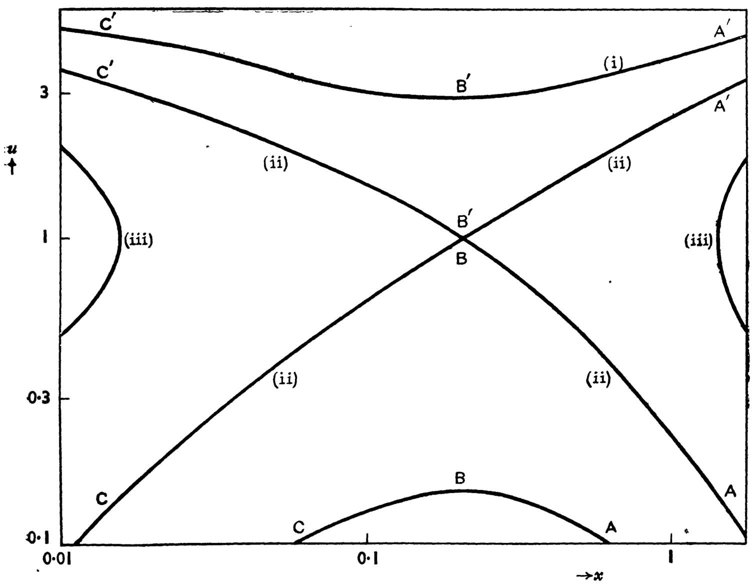
H.Bondi, MNRAS, **112**, 195 (1952)

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

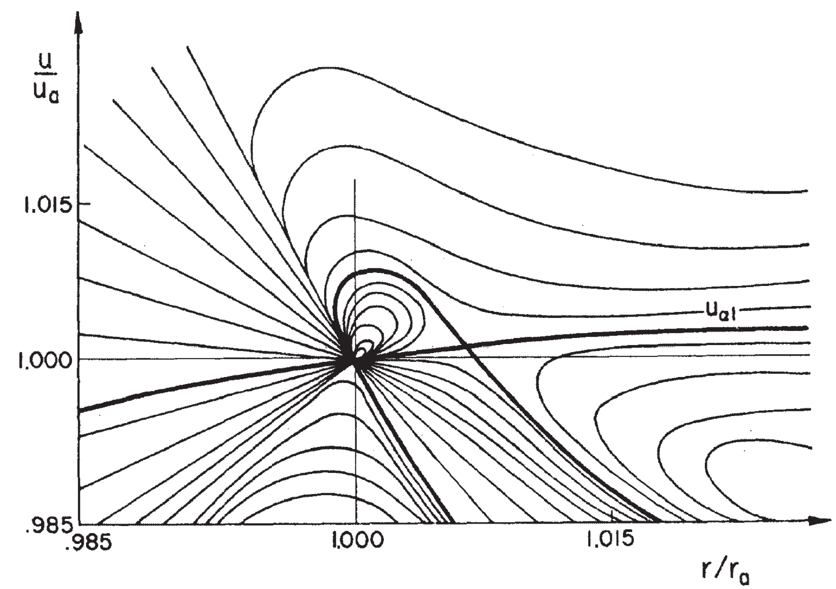
Theoretical challenge – I problem

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)

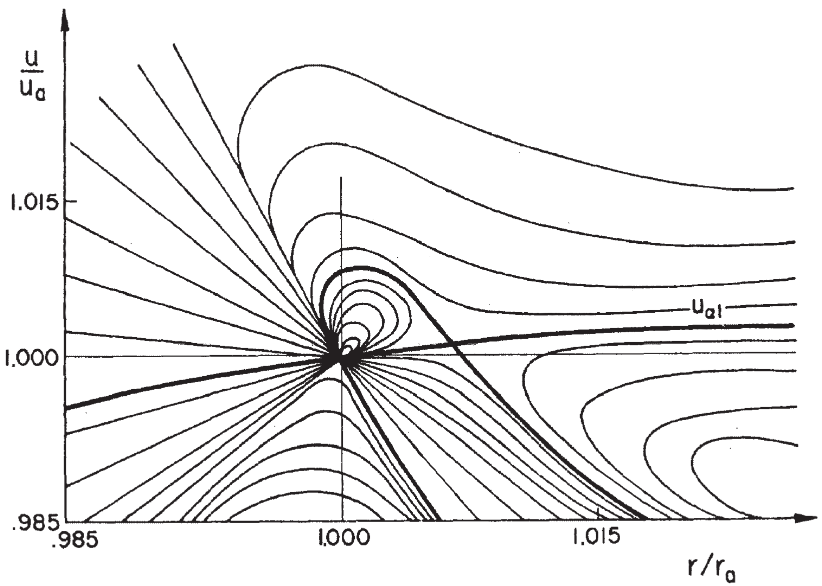
$$\Phi_{\rm cr} = 4\pi r_*^2 c_* n_* = \pi \left(\frac{2}{5-3\Gamma}\right)^{(5-3\Gamma)/2(\Gamma-1)} \frac{(GM)^2}{c_\infty^3} n_\infty$$

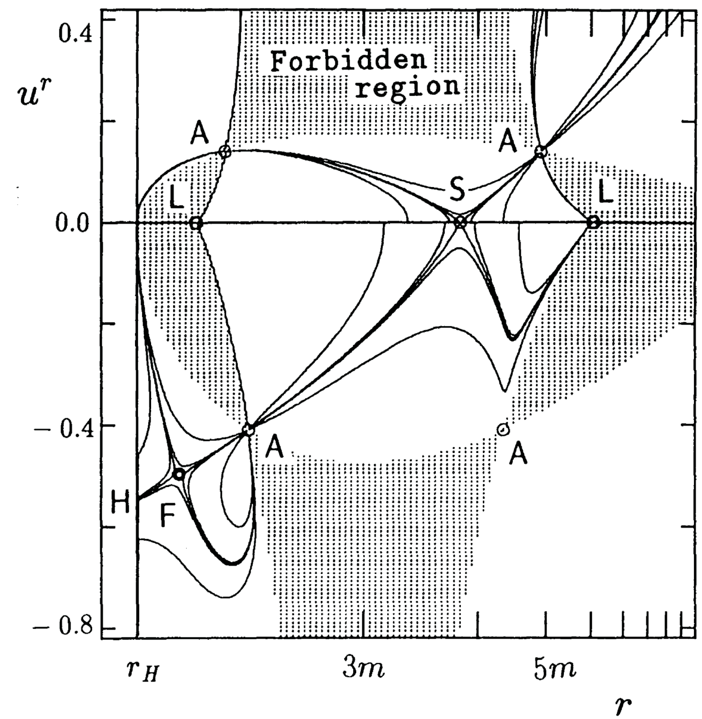
$$I \sim I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

Theoretical challenge – I problem

Critical condition on the (fast magneto)sonic surfaces determine

electric current I + angular velocity Ω_F





E.J.Weber, L.Davis, ApJ, **148**, 217 (1967) M.Takahashi et al, ApJ, **363,** 206 (1990)

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

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

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

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

is the critical condition on the inner fast magnetosonic surface.

As

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

we return to

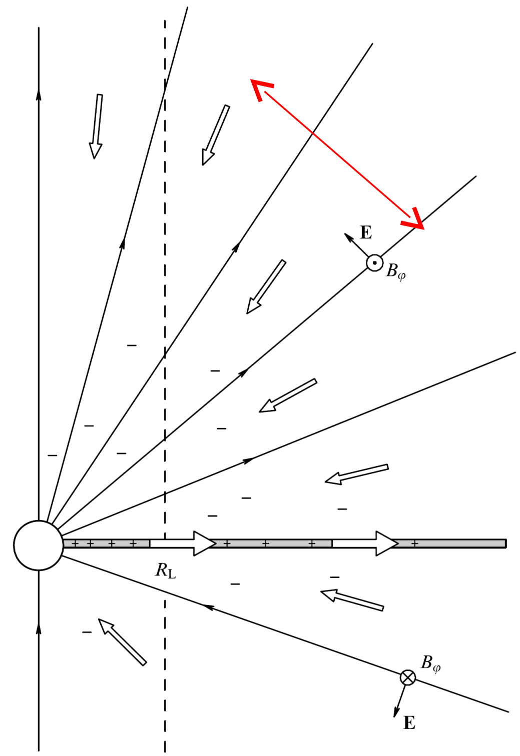
$$\boxed{W_{\rm BZ} \sim (\Omega r_{\rm g}/c)^2 B^2 r_{\rm g}^2 c}$$

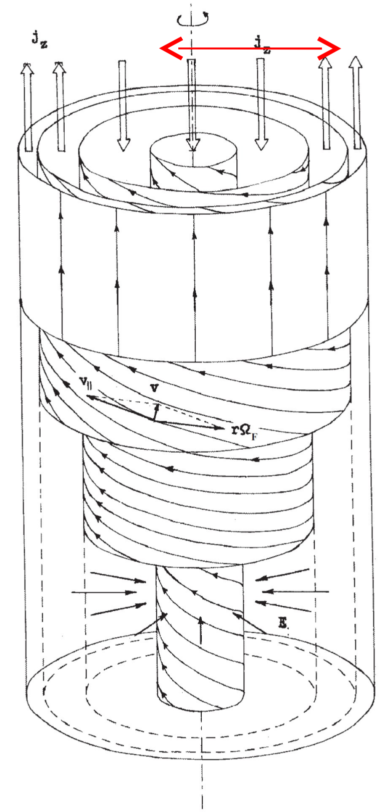
Theoretical challenge – δU problem

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

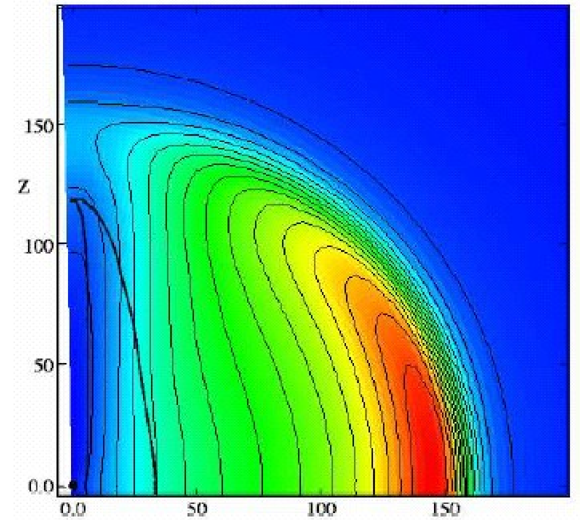
Longitudinal electric field?

Magnetically dominated wind → Any disturbance → Longitudinal electric field

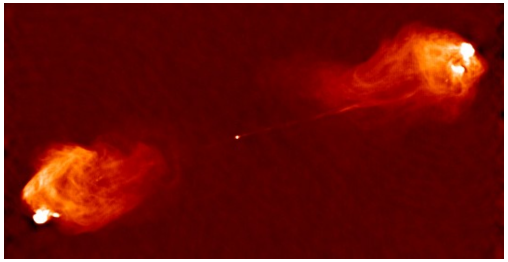
$$E_\perp \longrightarrow E_{||}$$

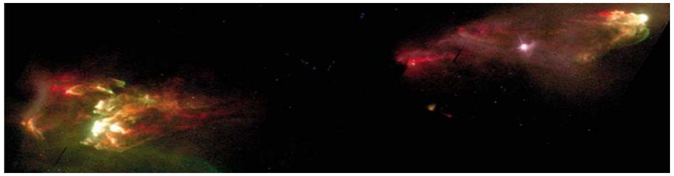
Theoretical challenge – δU problem

Switch-on wave, if there is no ambient pressure



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





But what to do if we have it?

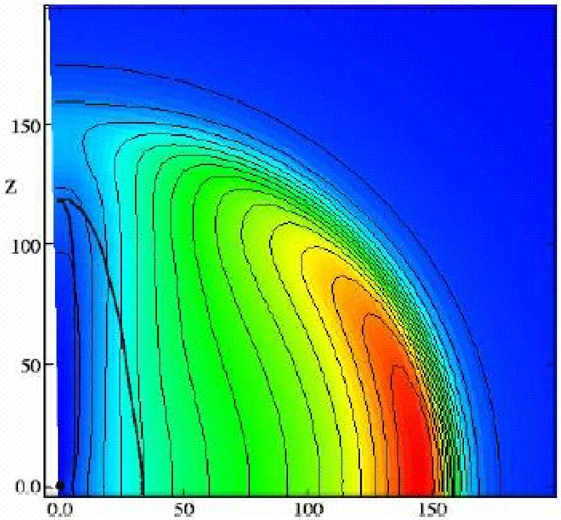
Lobes in AGN

HH objects in YSO

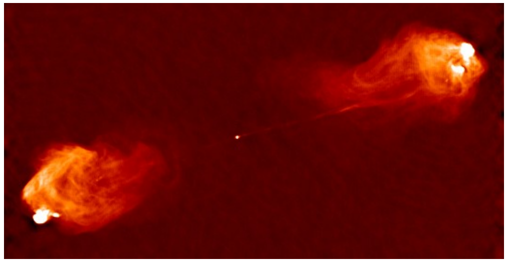
Stellar wind in close binaries

Theoretical challenge – δU problem

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



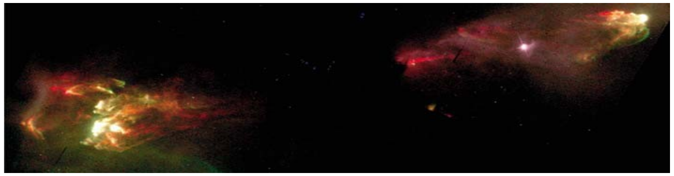
S.Komissarov, MNRAS, **350**, 1431 (2004)



But what to do if the wind meets the ambient?

Lobes in AGN

HH objects in YSOs

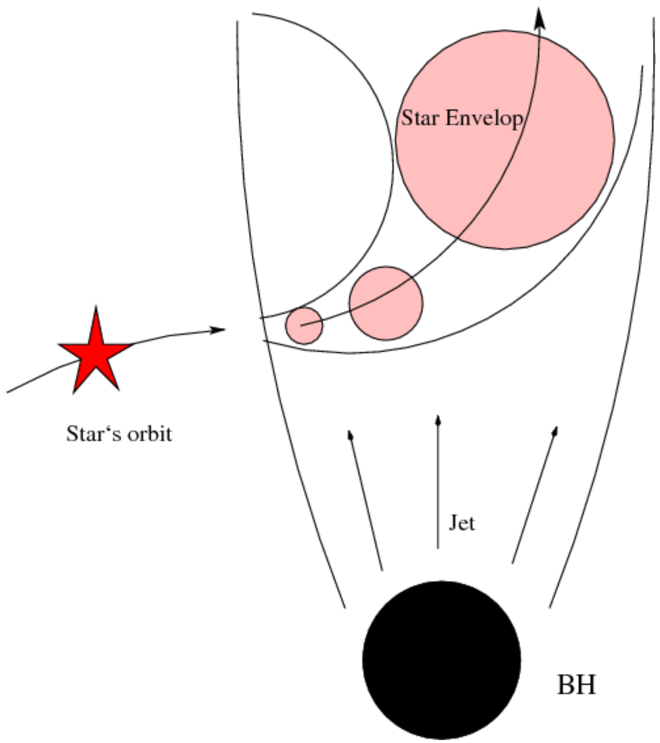


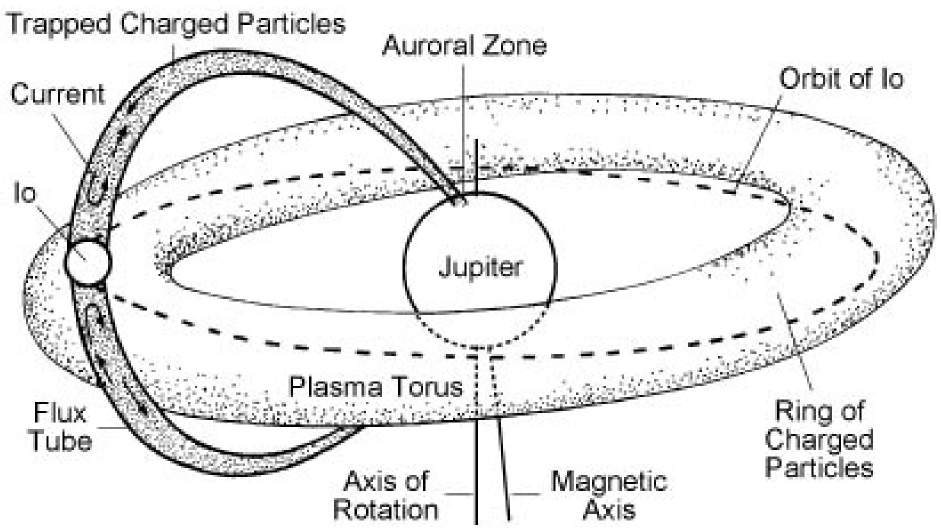
Stellar wind in binaries

Theoretical challenge – δU problem

MHD simulations
do not include
δU into consideration

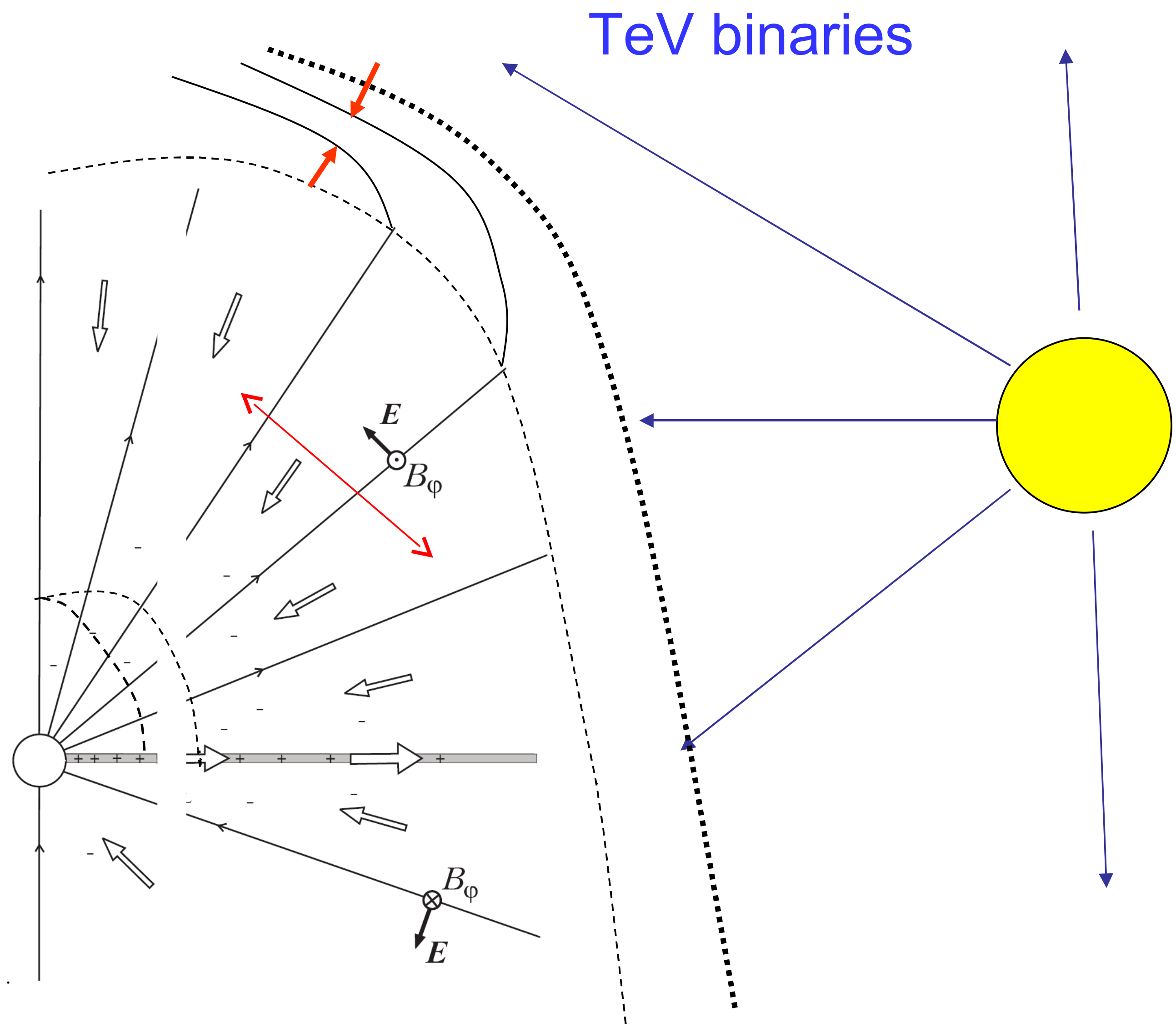
Io-Jovian
electromagnetic
interaction



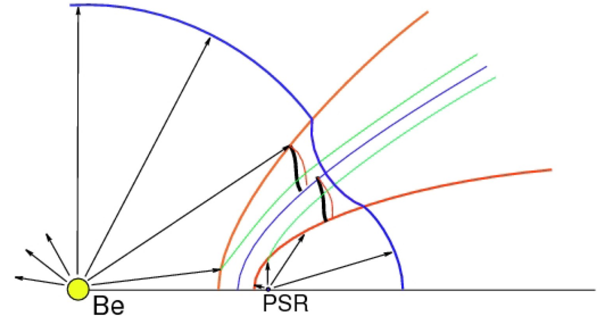


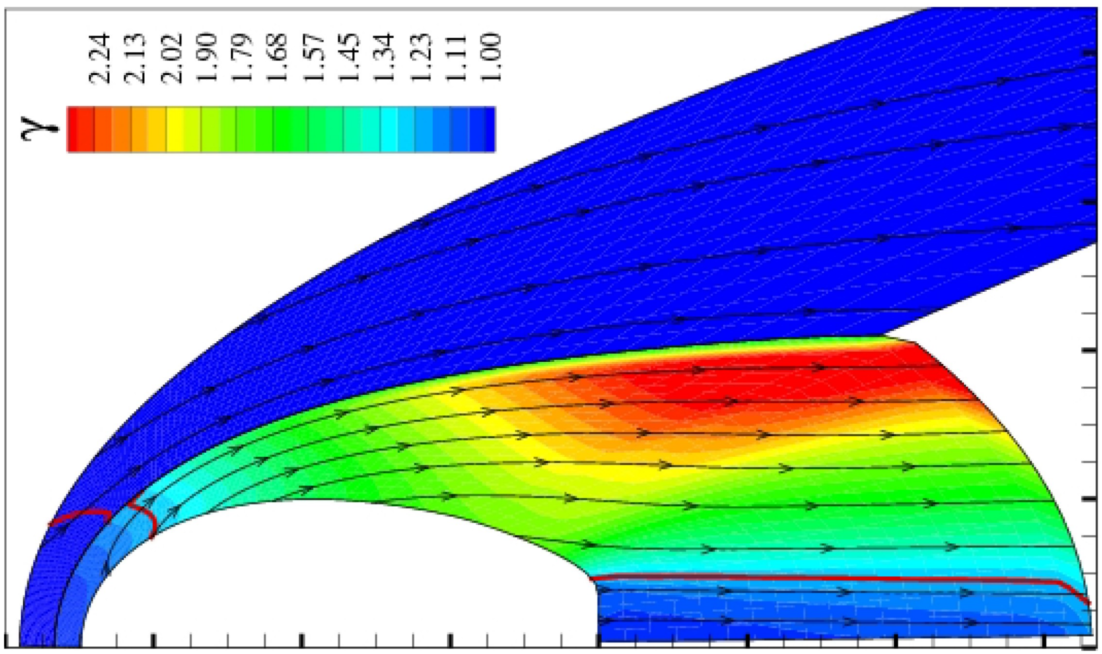
D.V.Khangulyan et al, ApJ, **774**, 113 (2013)

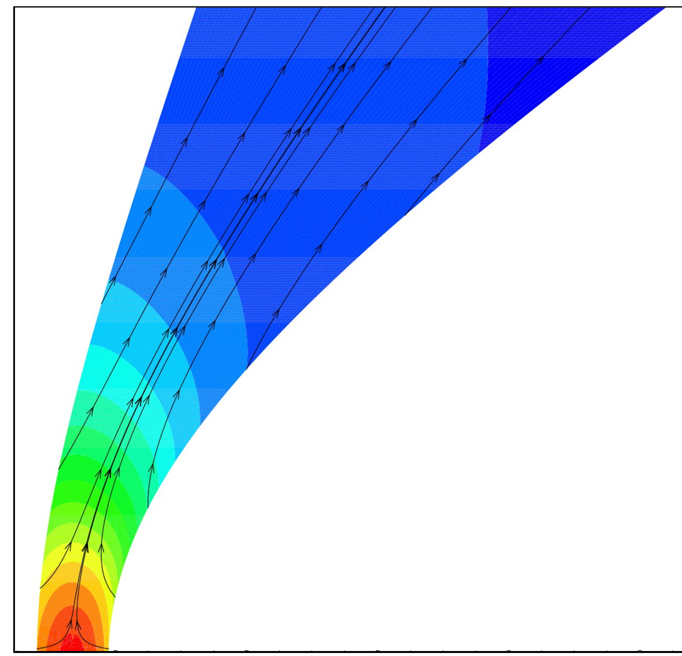
Theoretical challenge – δU problem



Theoretical challenge – δU problem







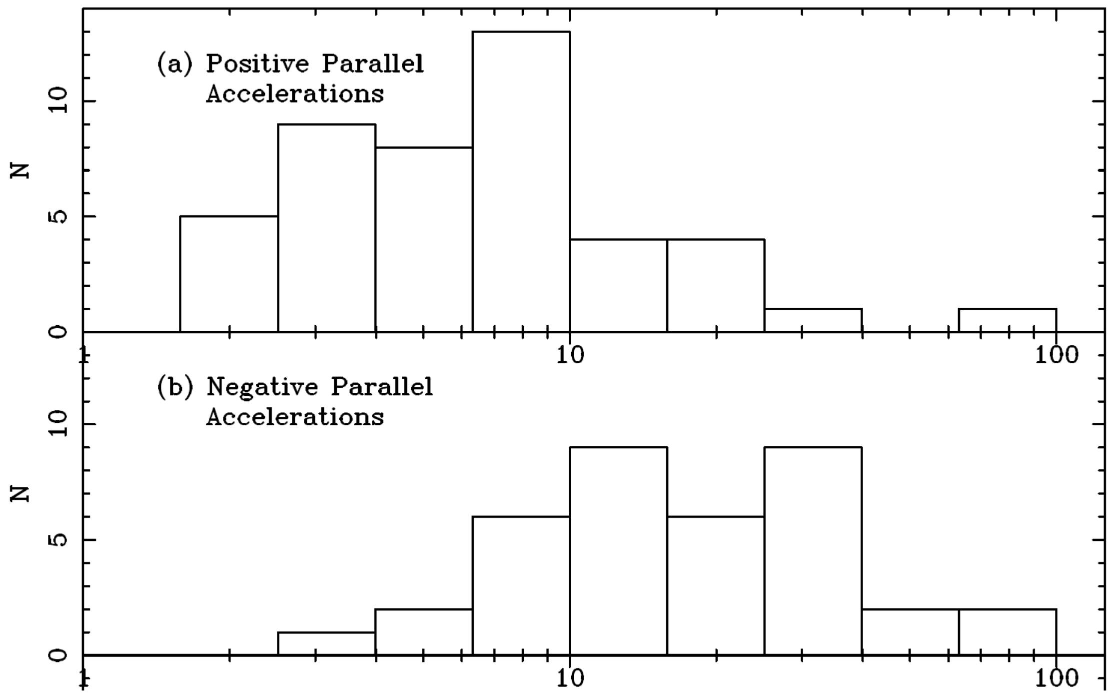
S.V.Bogovalov, D.Khangulyan, A.V.Koldoba, G.V.Ustyugova, F.Aharonian,
MNRAS, **387**, 63 (2008) MNRAS **419**, 3426 (2012)

Internal structure – AGN

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

Acceleration at small distances, decceleration at large distances.

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



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)

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

μ now

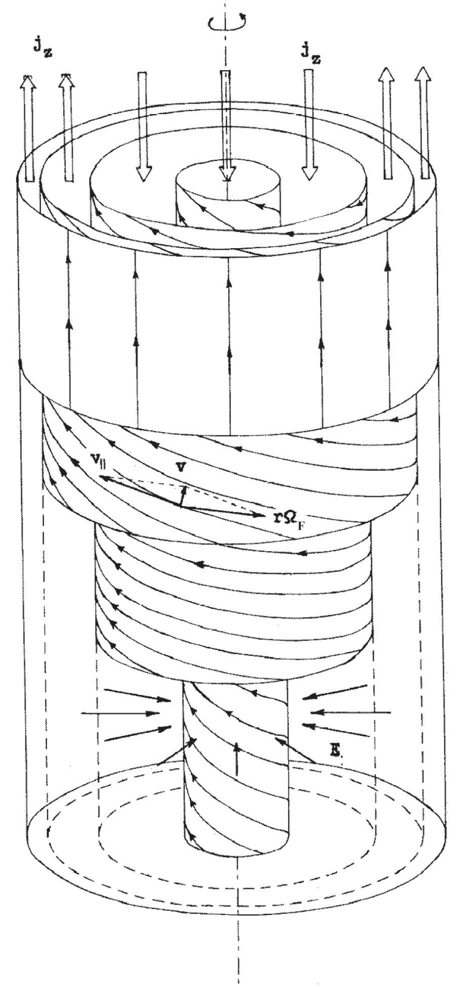
- Multiplicity parameter

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

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

- Total potential drop

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

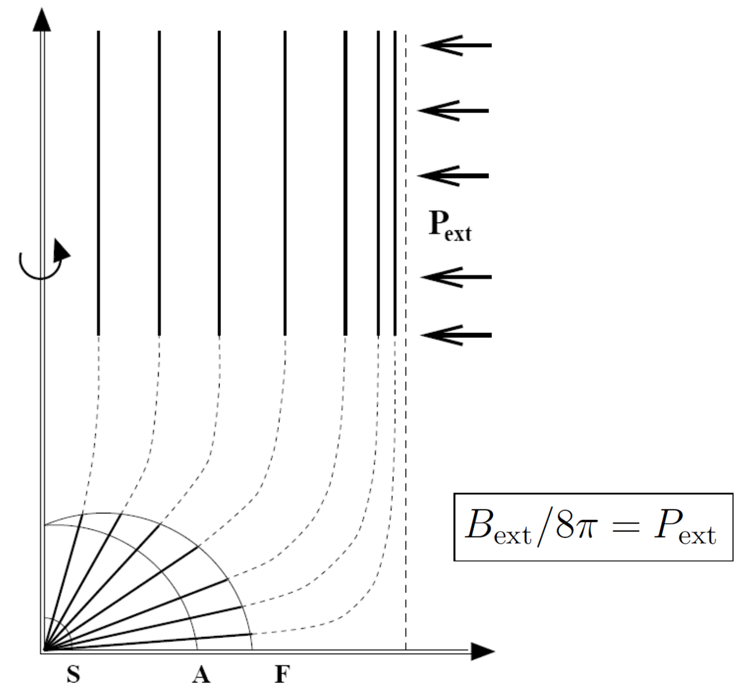


Jets – theory

- 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

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



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

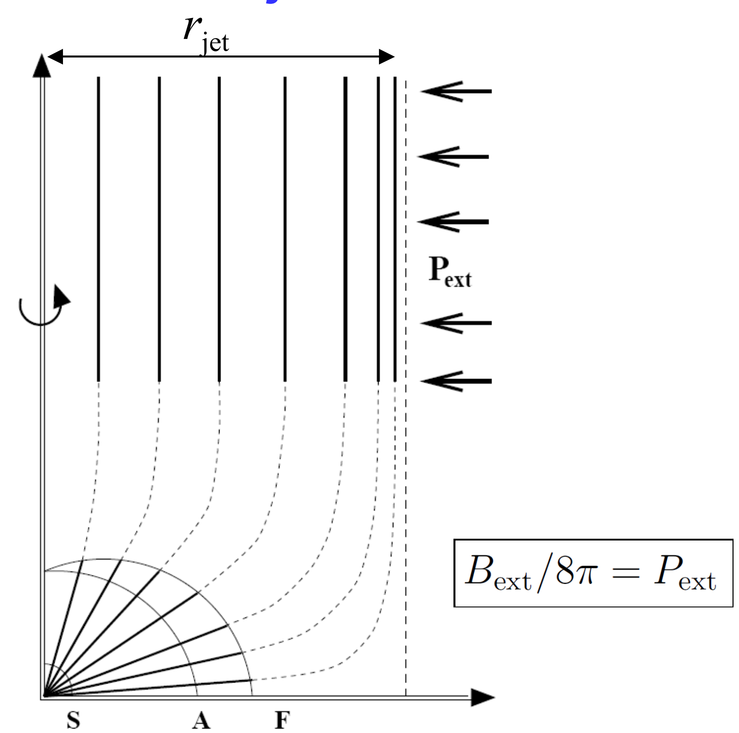
T.Lery, J.Heyvaerts, S.Appl, C.A.Norman, A&A, **347**, 1055 (1999)

Jets – theory

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

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

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

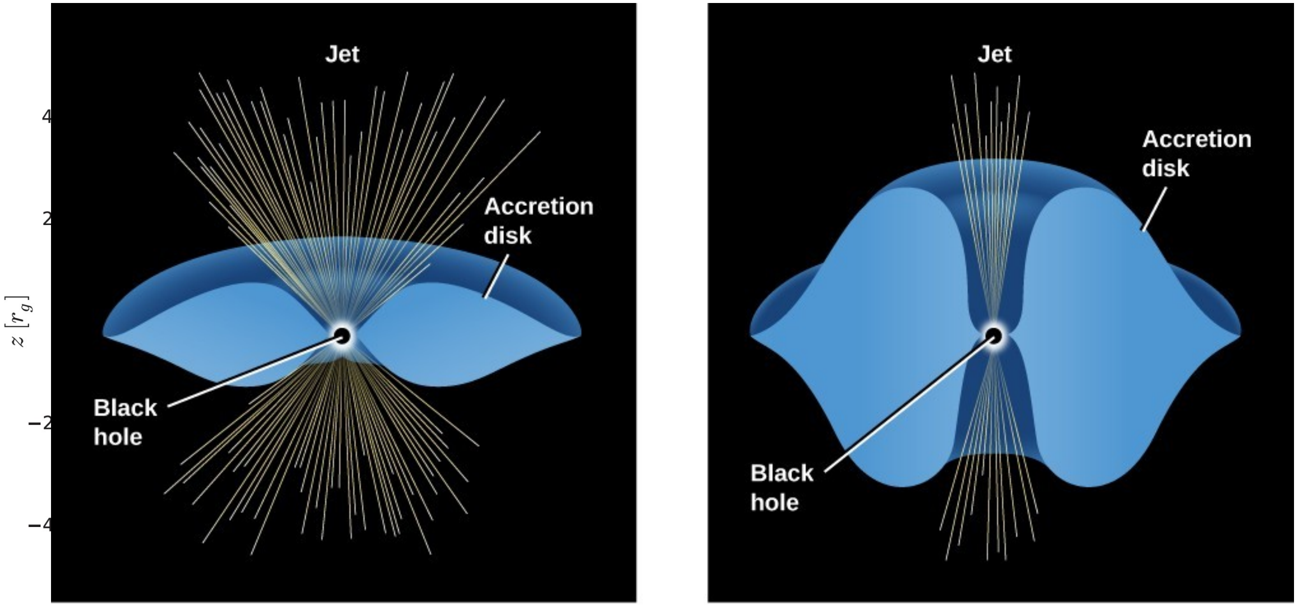


VB, L.M.Malyshkin. Astron. Lett., **26**, 208 (2000)
VB. Phys. Uspekhi, **40**, 659 (1997)

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

Jets – theory

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

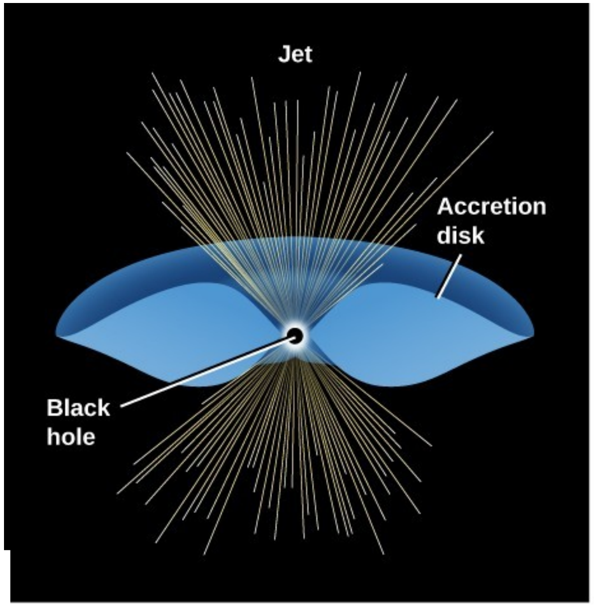


(a) (b)

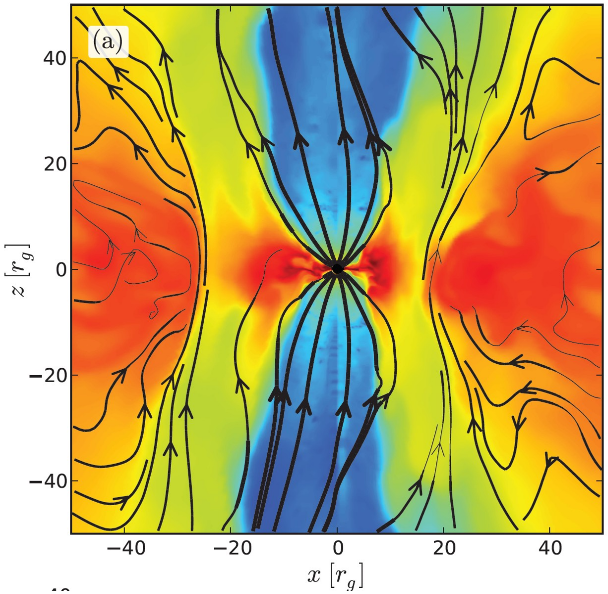
J

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.



(a)



(b)

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

Jets – theory

Simple asymptotic solutions for Lorentz-factor

Quasi-cylindrical flows ($\Gamma < \sigma_M$)

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

Quasi-radial flows

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

Jets – theory

Simple asymptotic solutions for Lorentz-factor

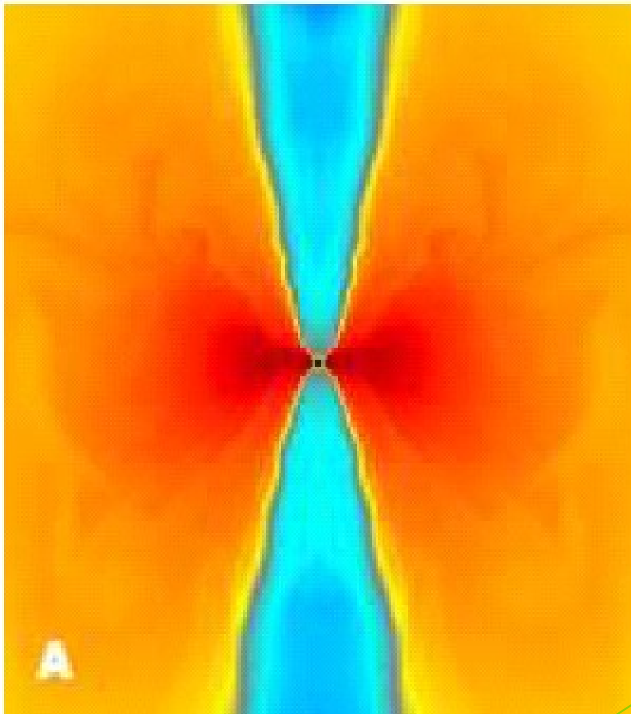
Quasi-cylindrical flows ($\Gamma < \sigma_M$)

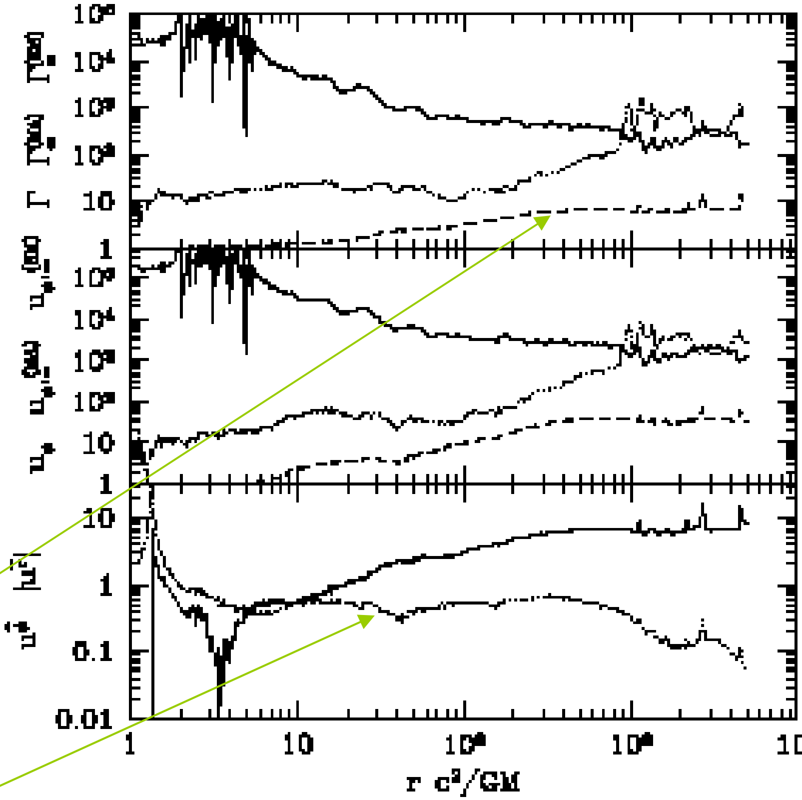
$$\boxed{\Gamma = x_r} \qquad x_r = \Omega_F r_\perp / c$$

This is an asymptotic behavior!

Jets – theory

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



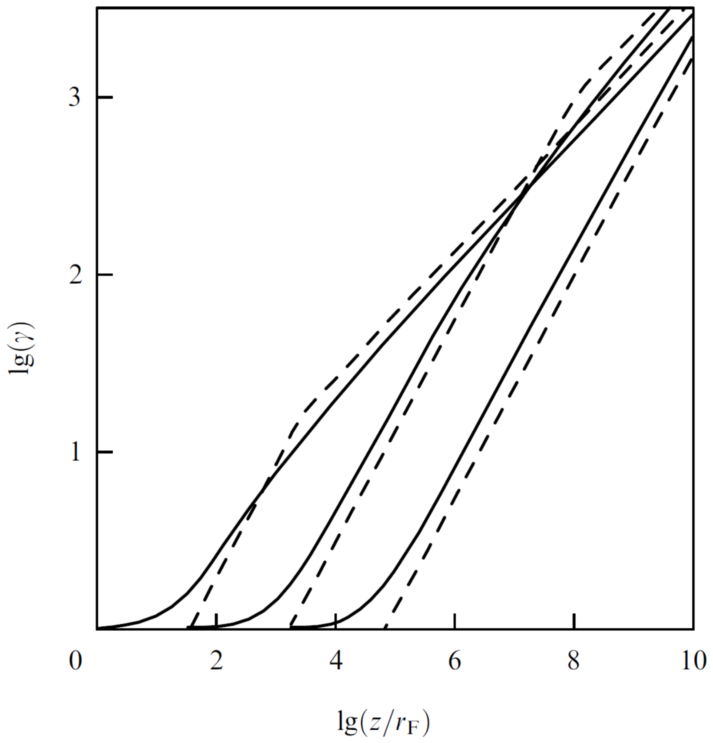


$$\Gamma(z) = (z/R_L)^{1/2}, \; u_\varphi = 1$$

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)

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

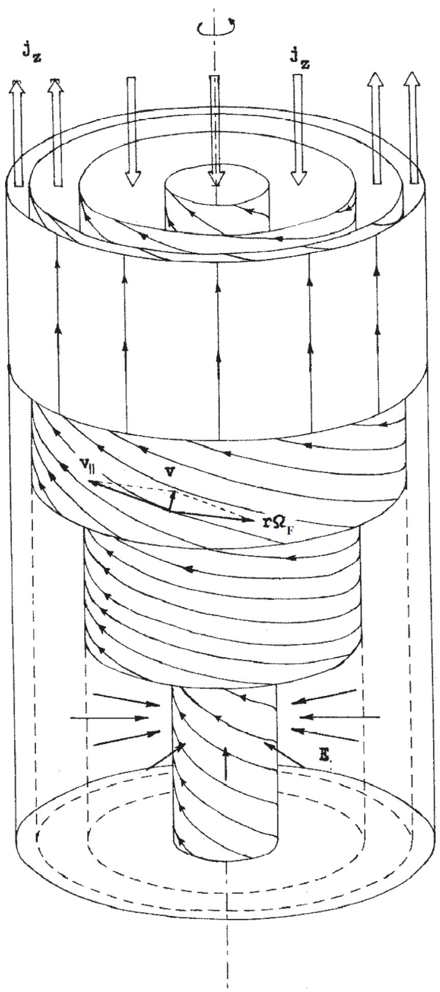
$$r_{\rm core} = \gamma_{\rm in} R_{\rm L}$$

Jets – theory

Transverse profile of the poloidal magnetic field

And this was odd, because…

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



Jets – theory

Transverse profile of the poloidal magnetic field

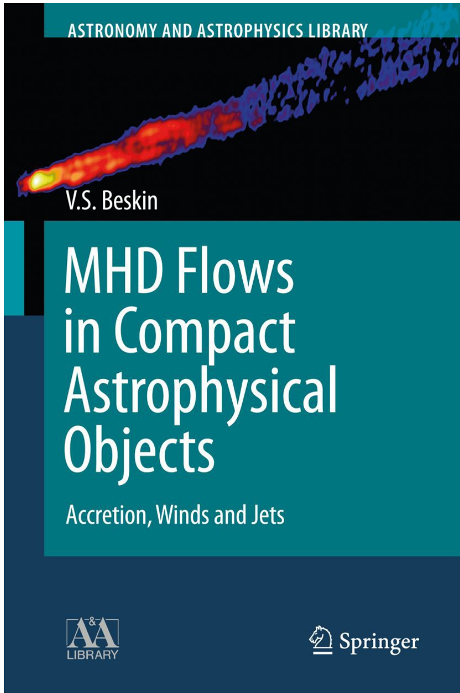
Theorem 5.2. *In the relativistic case, in the presence of the environment with rather high pressure ($B_{\rm ext} > B_{\rm min}$) the poloidal magnetic field inside the jet remains practically constant: $B_{\rm p} \approx B_{\rm ext}$. For small external pressure ($B_{\rm ext} < B_{\rm min}$) in the 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

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

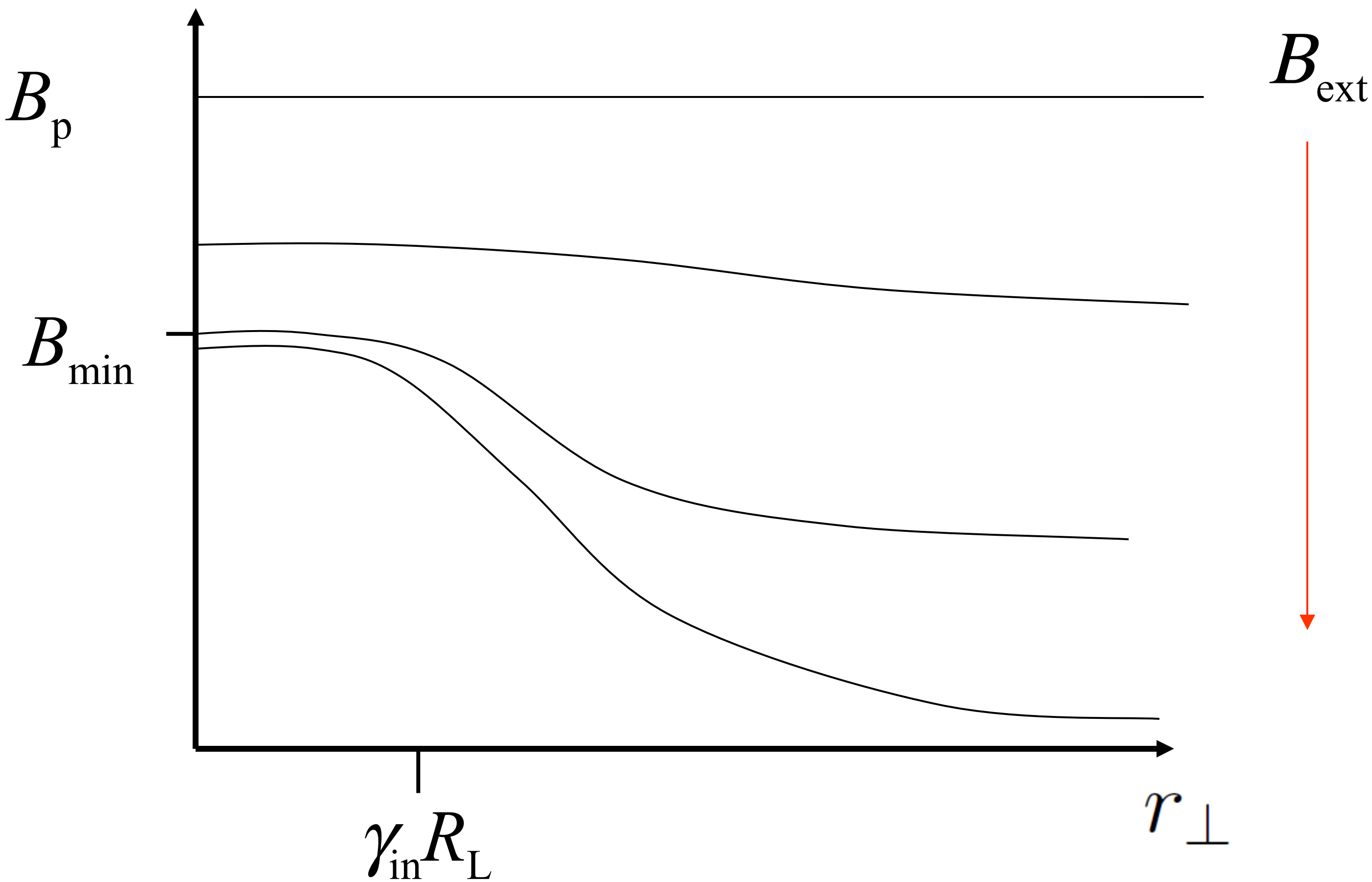
where $\alpha < 2$.



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

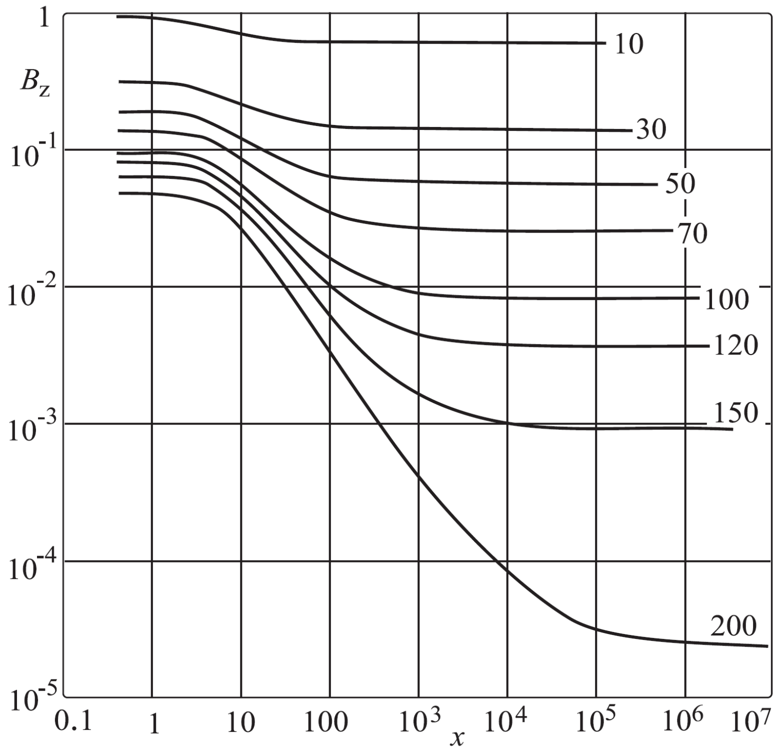
Central core

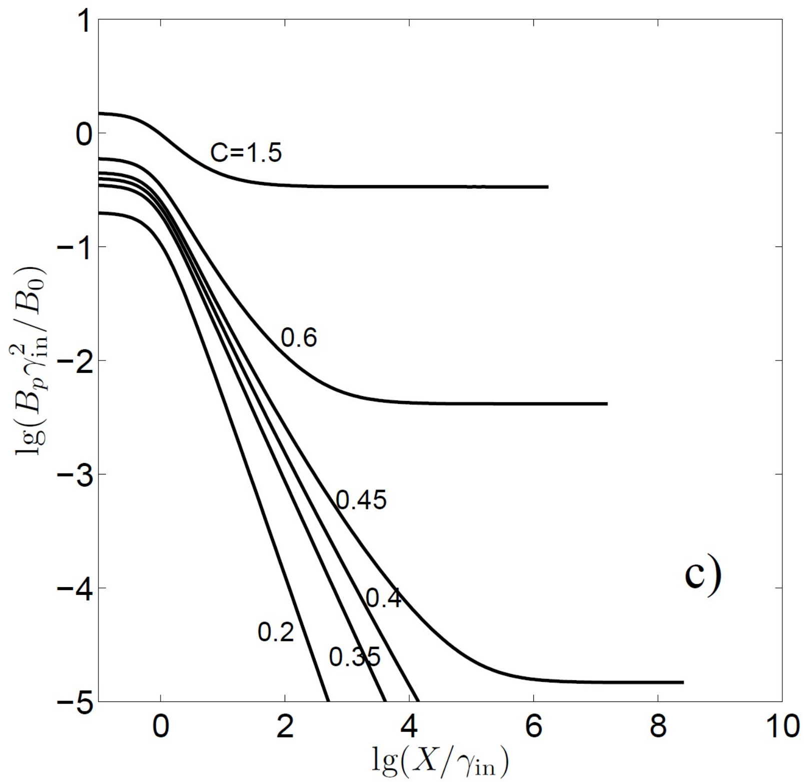
$$B_{\rm min} = \frac{1}{\sigma_{\rm M}\gamma_{\rm in}} B(R_{\rm L}) \qquad r_{\rm core} = \gamma_{\rm in} R_{\rm L}$$



Central core

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



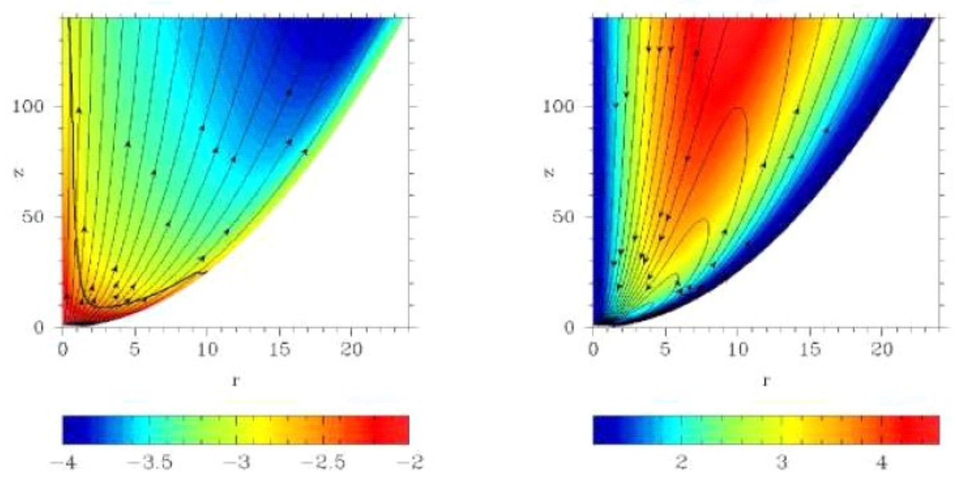


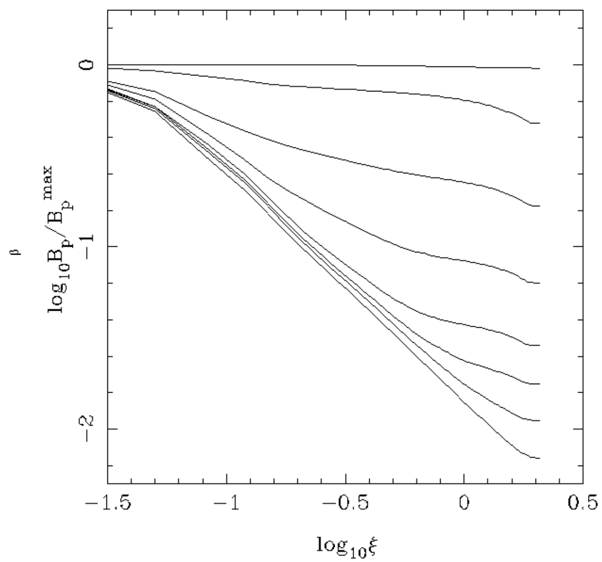
VB, E.E.Nokhrina,
MNRAS, **389**, 335 (2007)
MNRAS, **397,** 1486 (2009)

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

Central core

S. S. Komissarov et al.

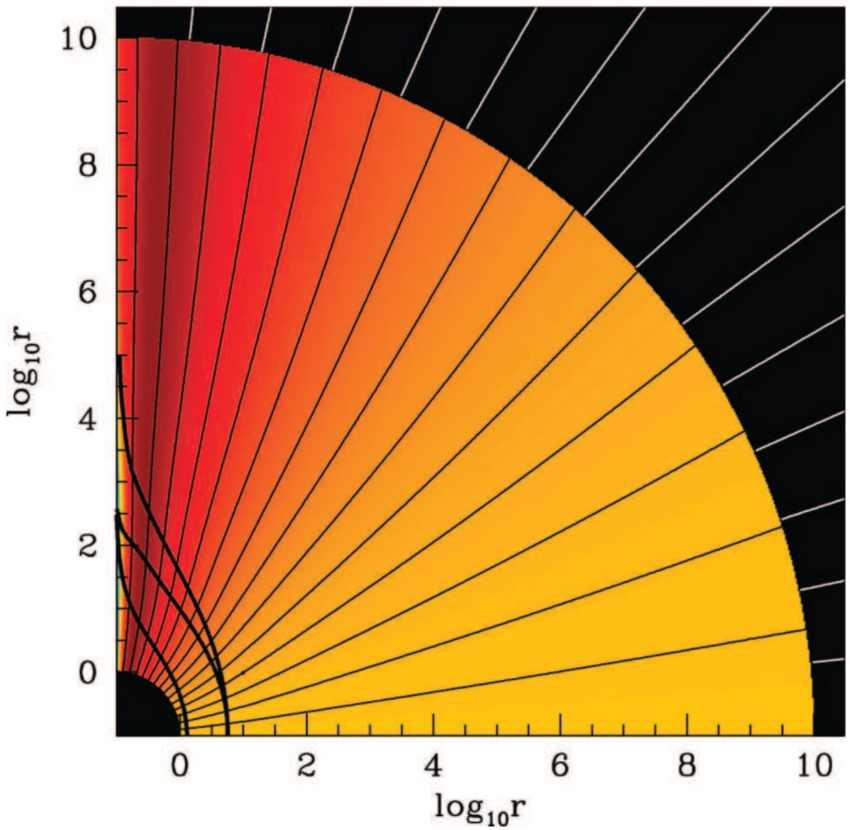


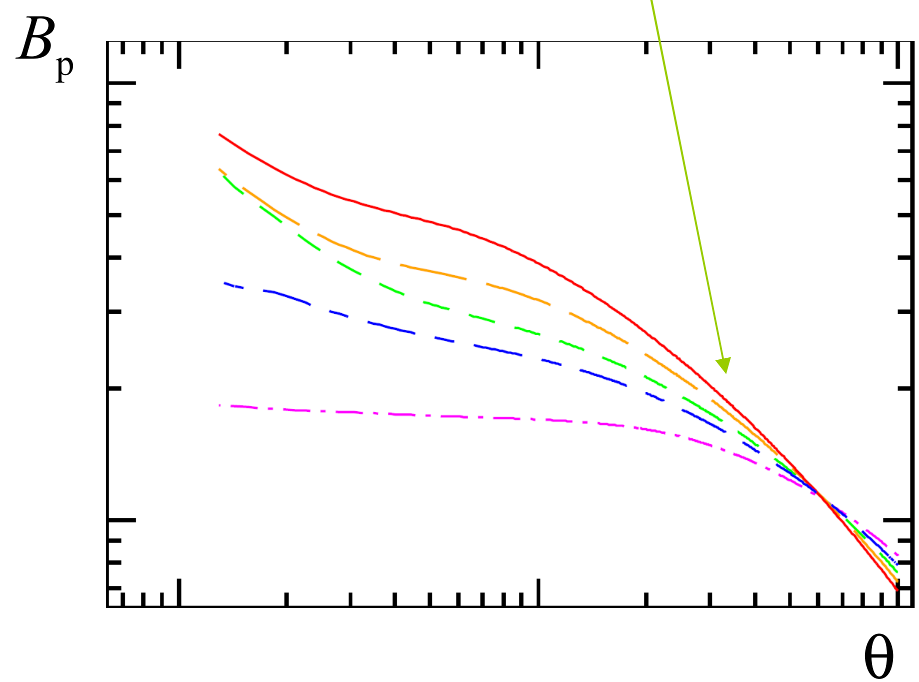


S.Komissarov, M.Barkov, N.Vlahakis, A.Königl, MNRAS, **380**, 51 (2006)

Central core

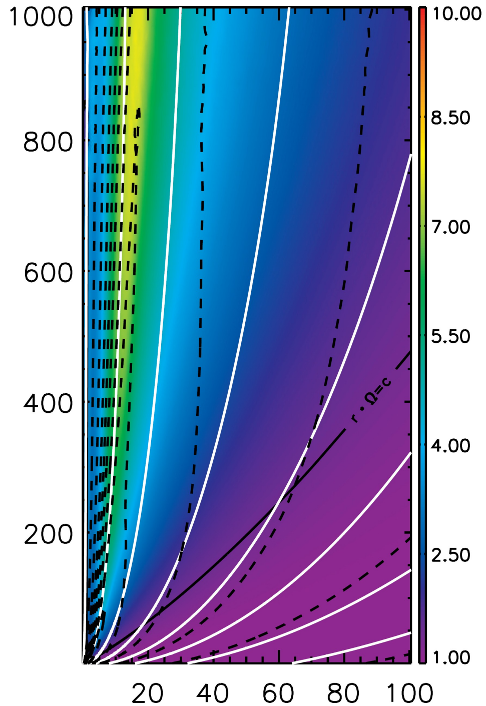
$$B_{\min} = \frac{1}{\sigma_M \gamma_{\text{in}}} B(R_L)$$

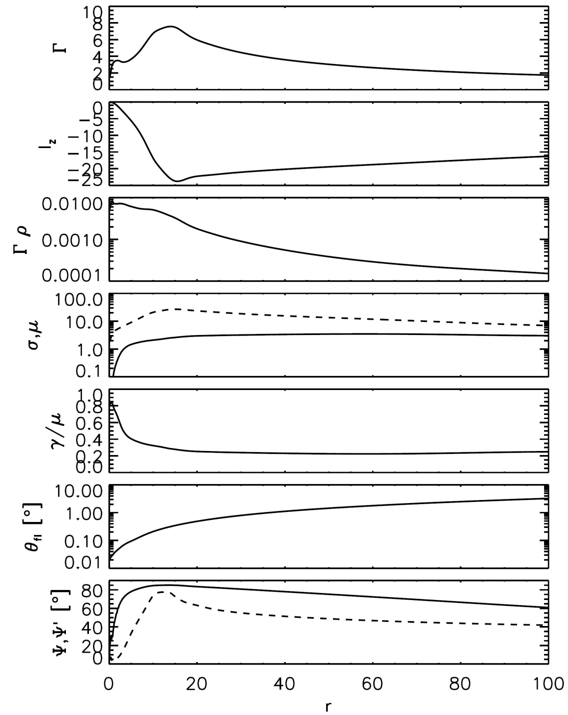


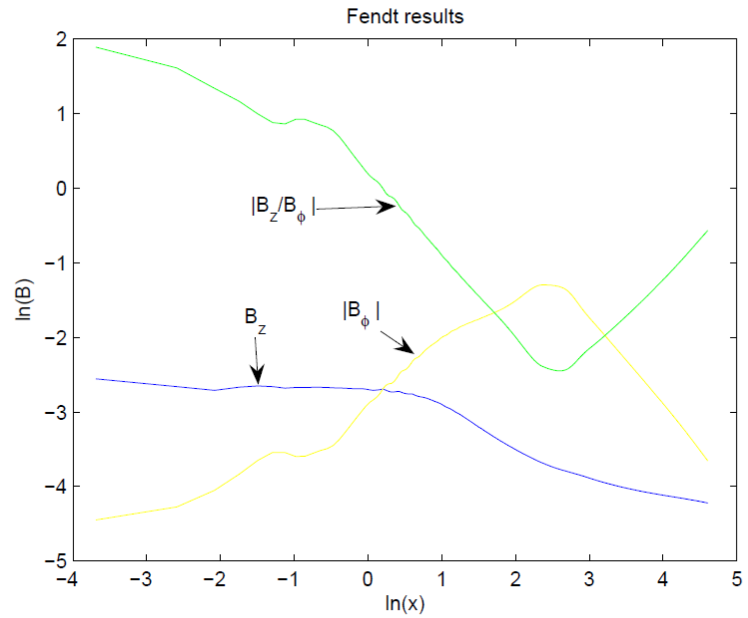


A.Tchekhovskoy, J.McKinney, R.Narayan, ApJ, **699**, 1789 (2009)

Central core



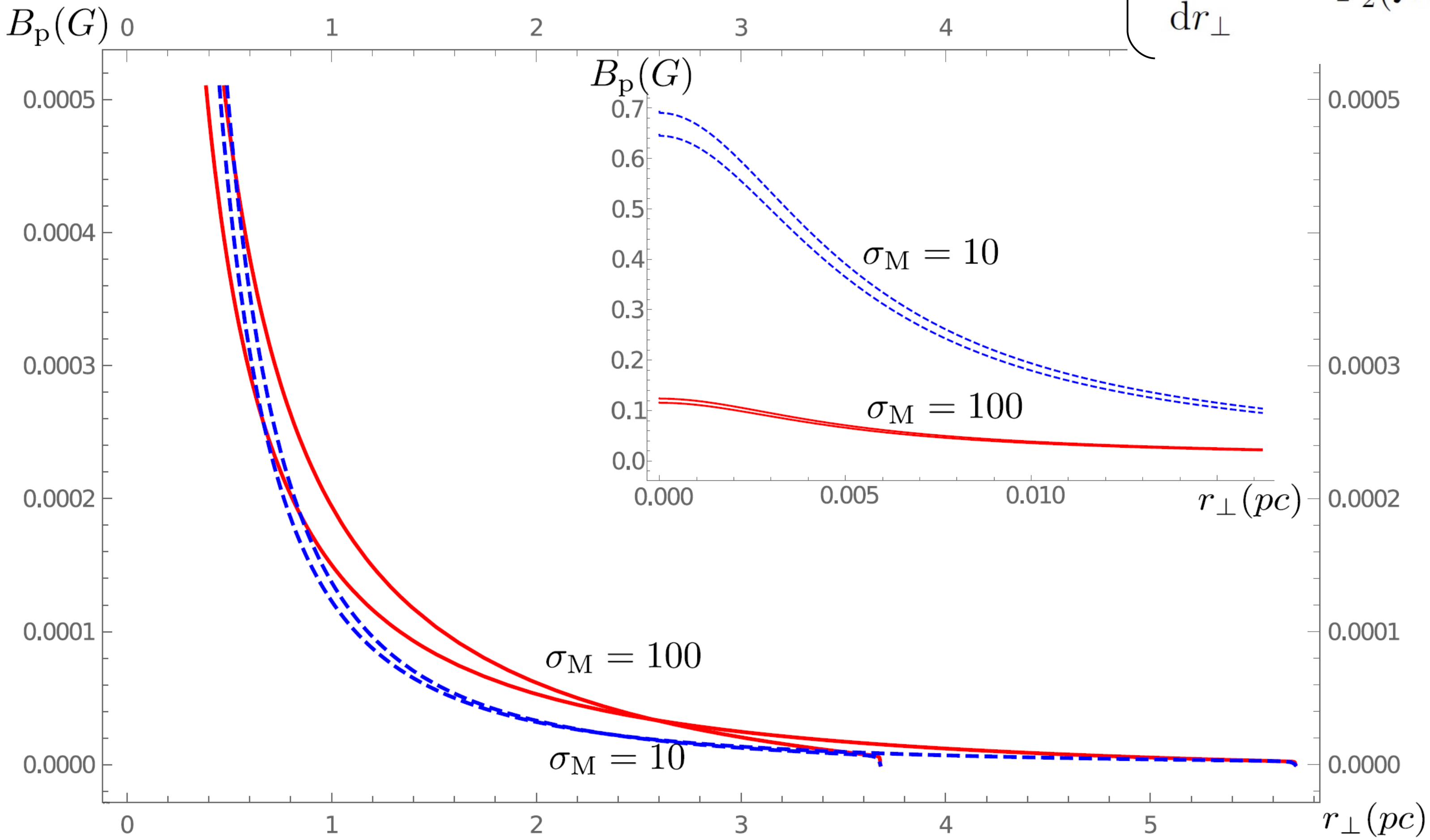




O.Porth, Ch.Fendt, Z.Meliani, B.Vaidya, ApJ, **737**, 42 (2011)

Internal structure

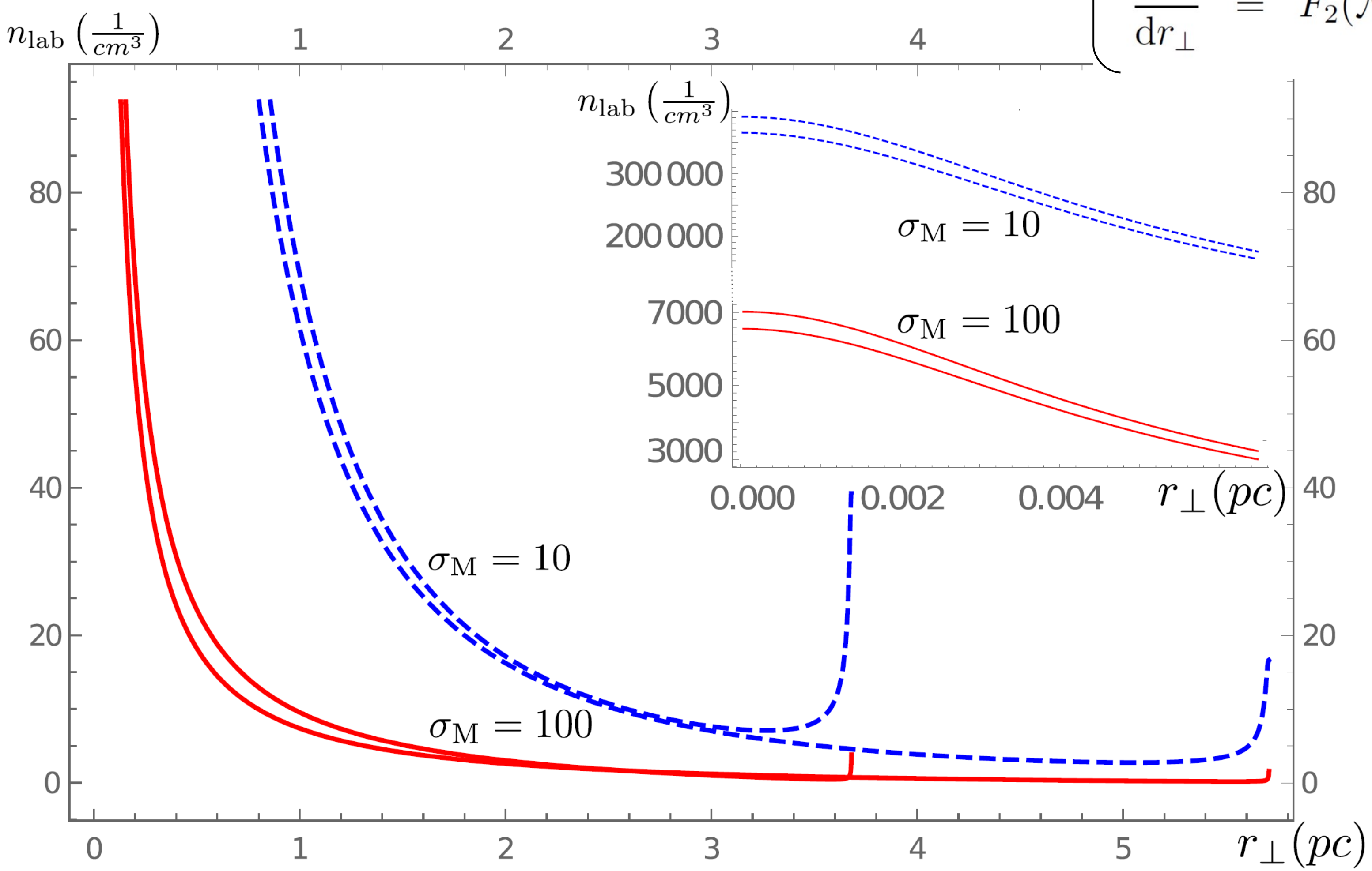
$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



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

Internal structure

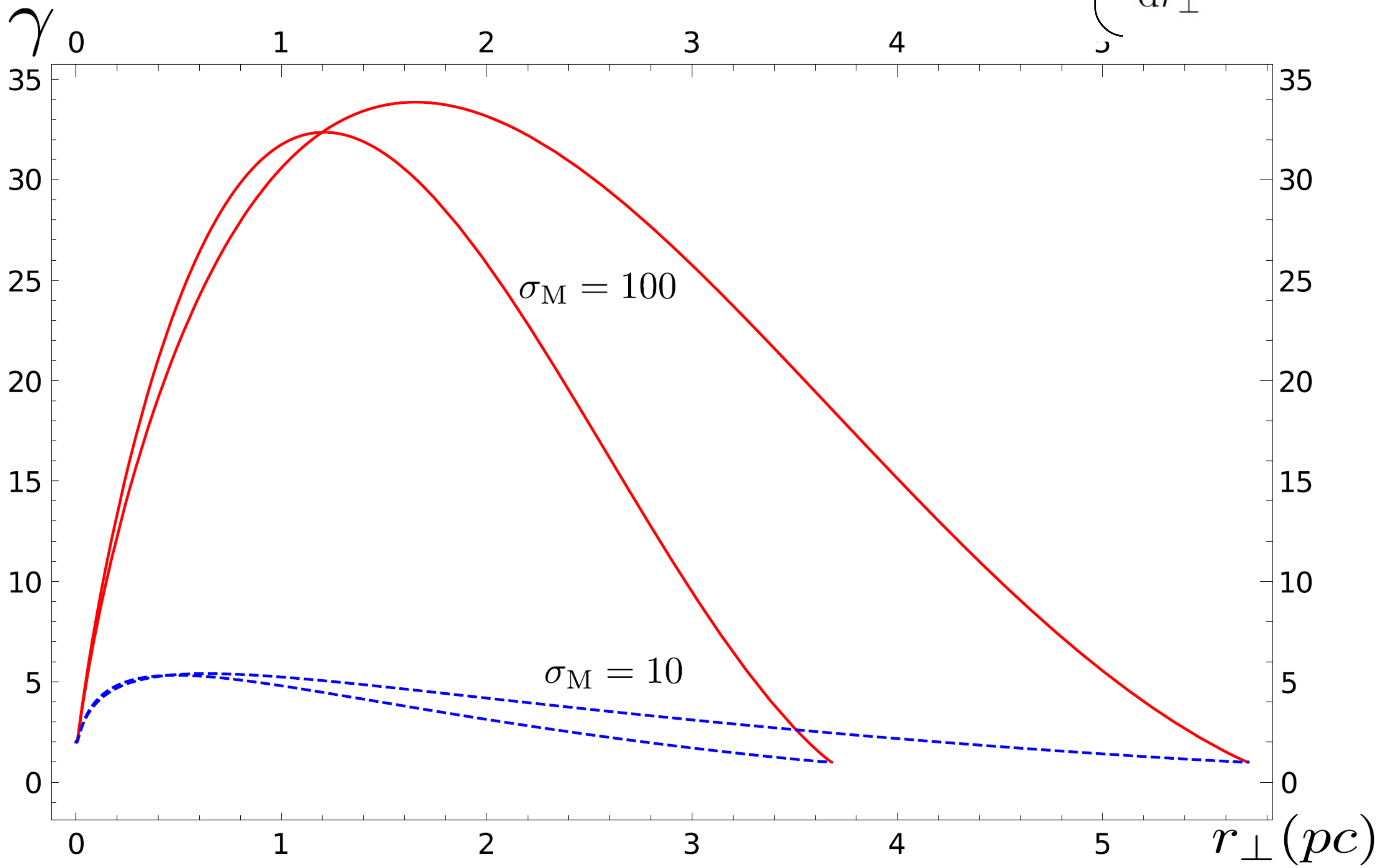
$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



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

Internal structure

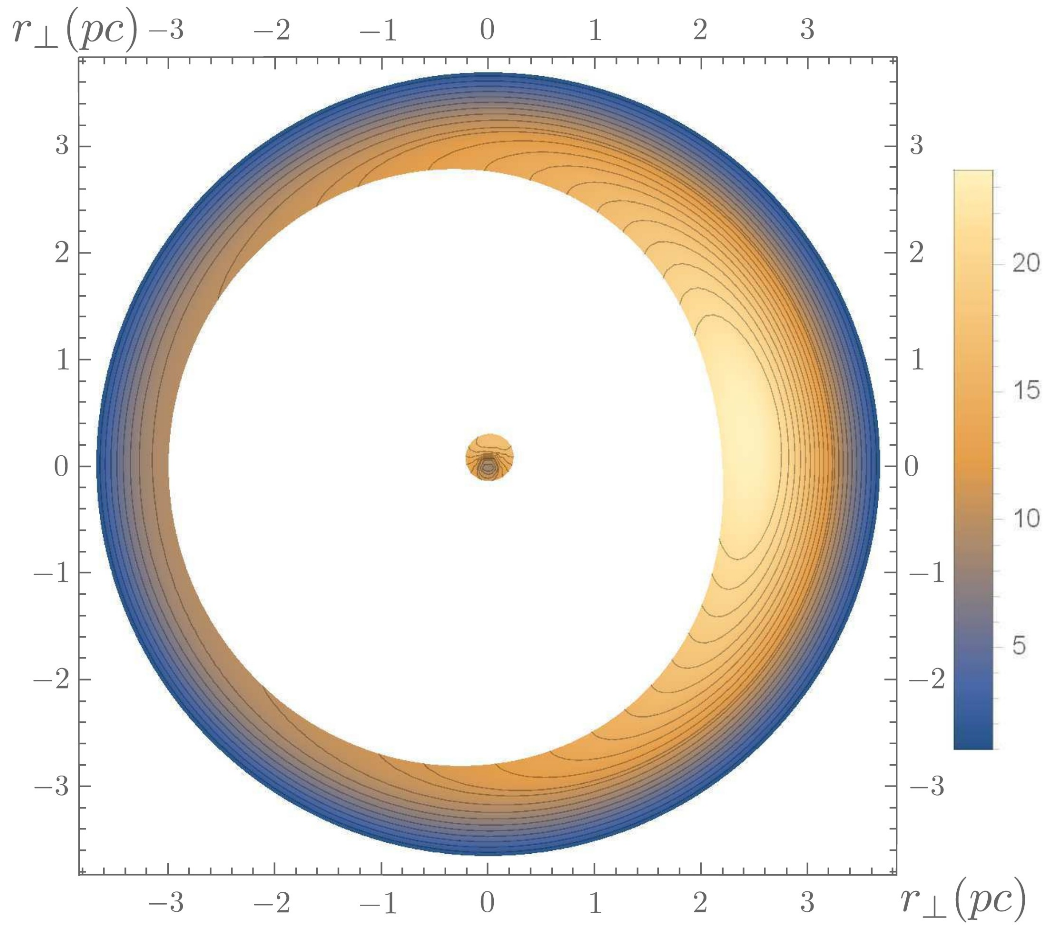
$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



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)

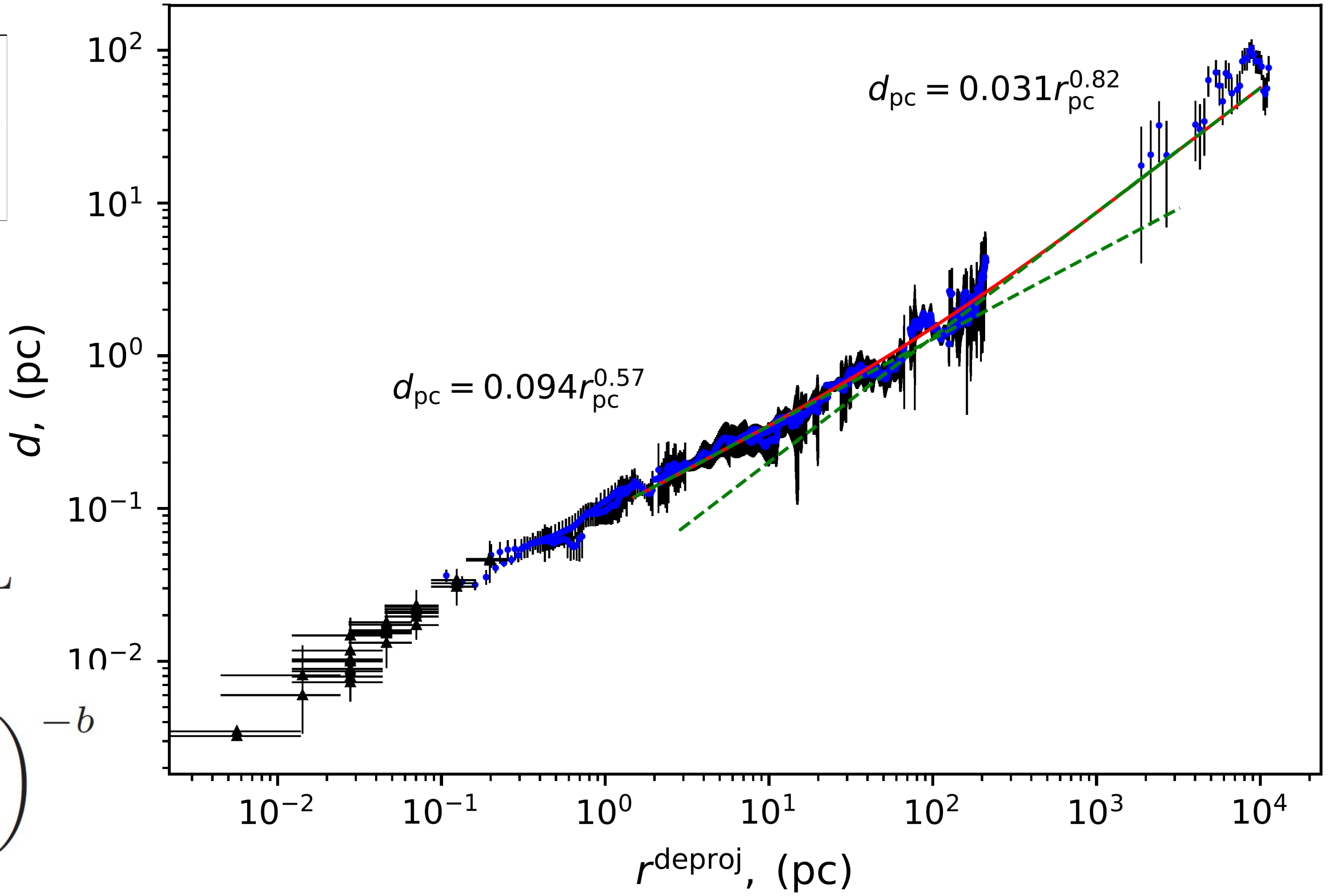
Jet boundary shape break

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

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

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

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



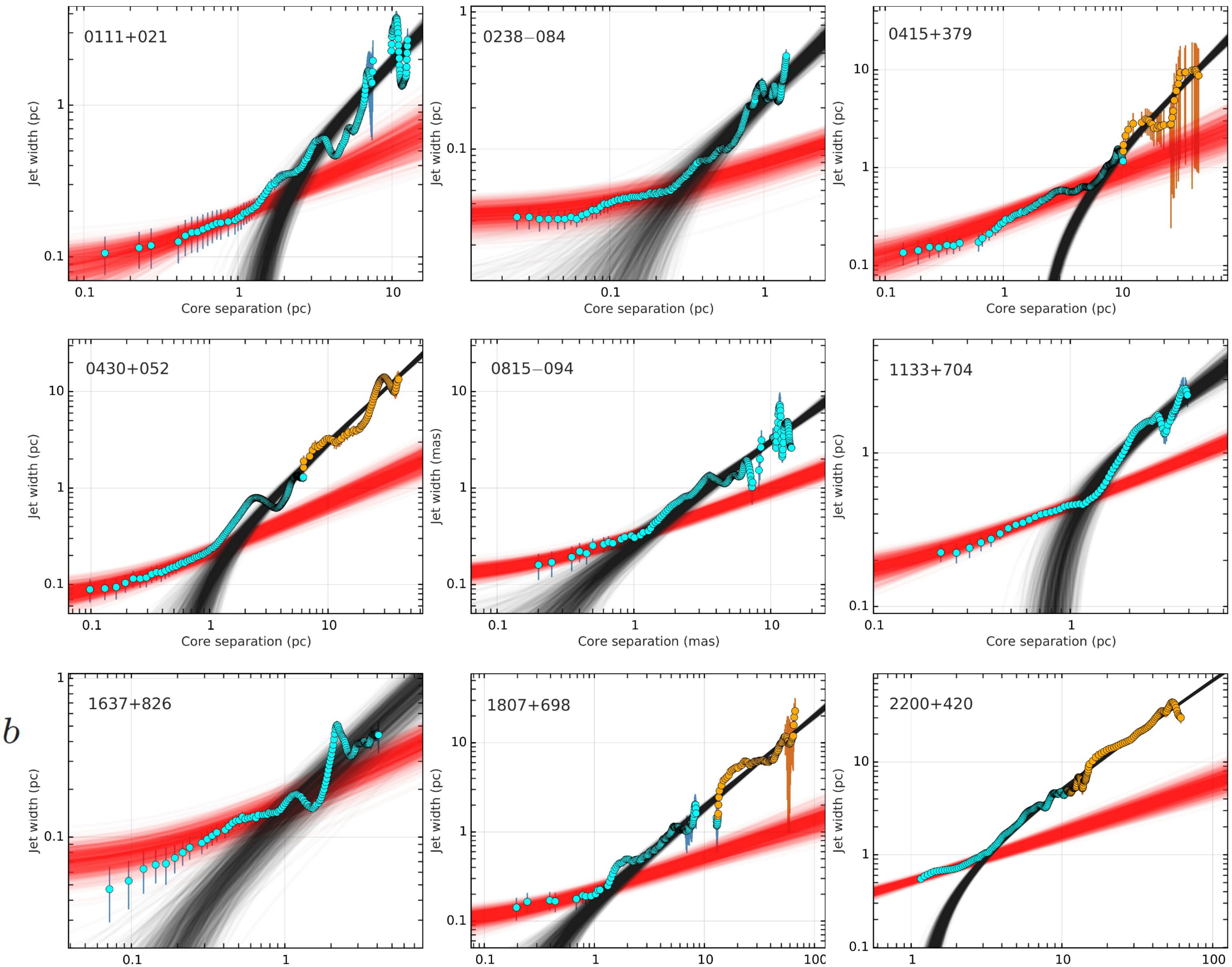
Jet boundary shape break

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

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

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

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



Jet boundary shape break

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

Slow acceleration along the jet

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

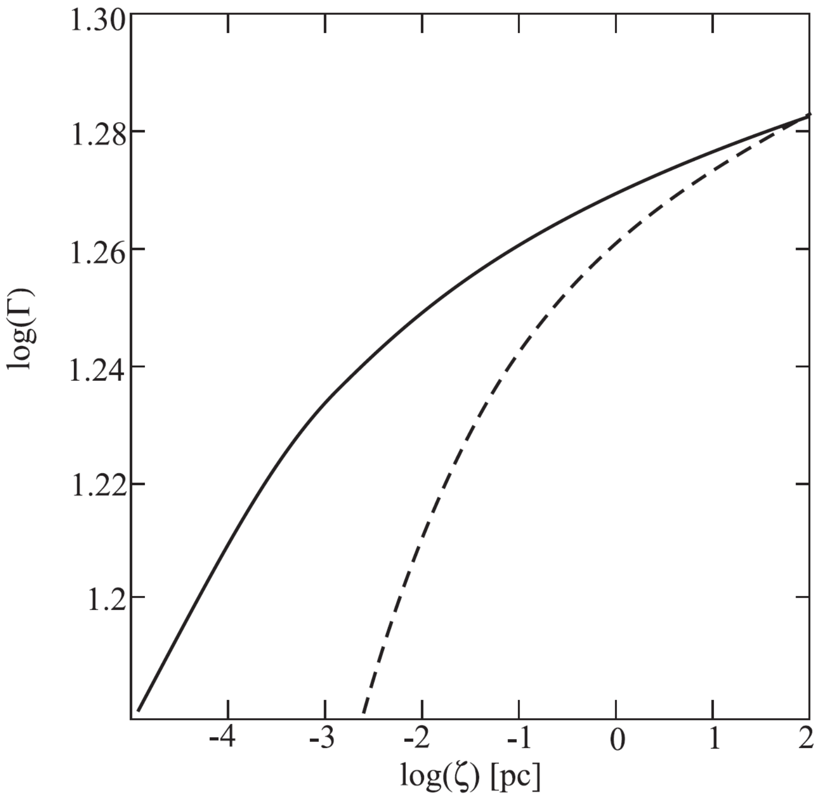


Figure 5. Dependence of Lorentz factor on coordinate along the jet in assumption of $\zeta \propto r_{\perp}^{3}$ (solid line) and $\zeta \propto r_{\perp}^{2}$ (dashed line) form of the jet.

Statement #6

- Saturation
- Central core
- Inhomogeneous Lorentz factor

Conclusion

Go ahead!