P.N.Lebedev
Physical Institute

Paradigms shift in the theory of radio pulsars

V.S.Beskin

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Delusions shift in the theory of radio pulsars

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Delusions shift in the theory of radio pulsars

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No GRB, FRB, Magnetars, but PSR, AGN jets

Plan

Historical overview

Paradigm #1 »»»»»» Paradigm #2 »»»»»» Paradigm #3

$\delta U_\perp$ problem & dissipation – two (three!) fluid effects

Central core

Plan

Historical overview

Paradigm #1 »»»»»» Paradigm #2 »»»»»» Paradigm #3

$\delta U_\perp$ problem & dissipation – two (three!) fluid effects

Central core

NB – orthogonal pulsars as a test of pulsar physics

We still do not now

The mechanism of coherent radio emission

D.Melrose, V.Usov, Yu.Lyubarsky, G.Machabeli & G.Melikidze, R.Blandford & M.Lyutikov, BGI, etc. (1970-1980)

Plasma physics »»»»»» PIC

Sign of $\mathbf{\Omega B}$ – only sharp, only obtuse, or arbitrary

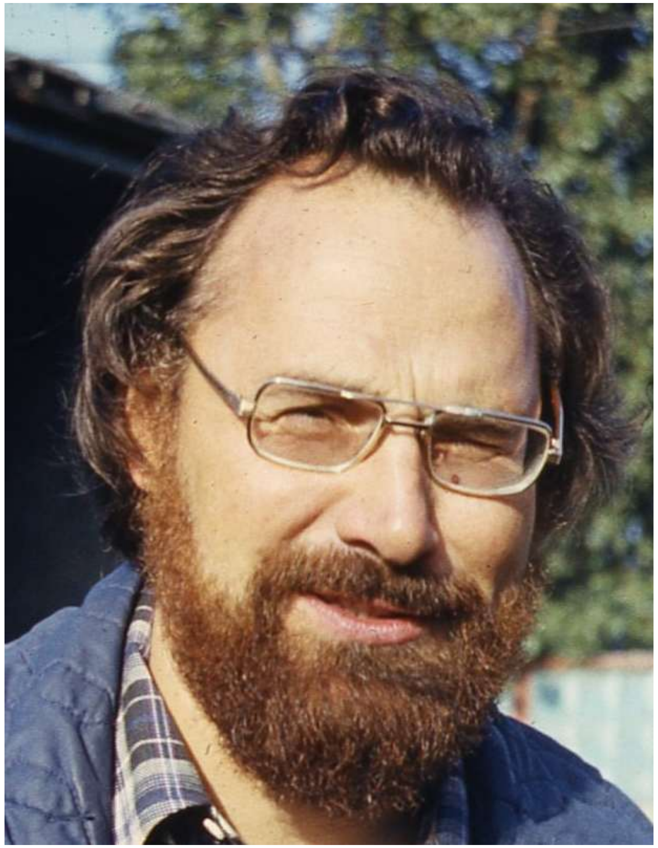
$$\rho_{GJ} = -\frac{\mathbf{\Omega B}}{2\pi c} \propto \cos\chi$$

Alignment/counter-alignment – evolution of inclination angle χ

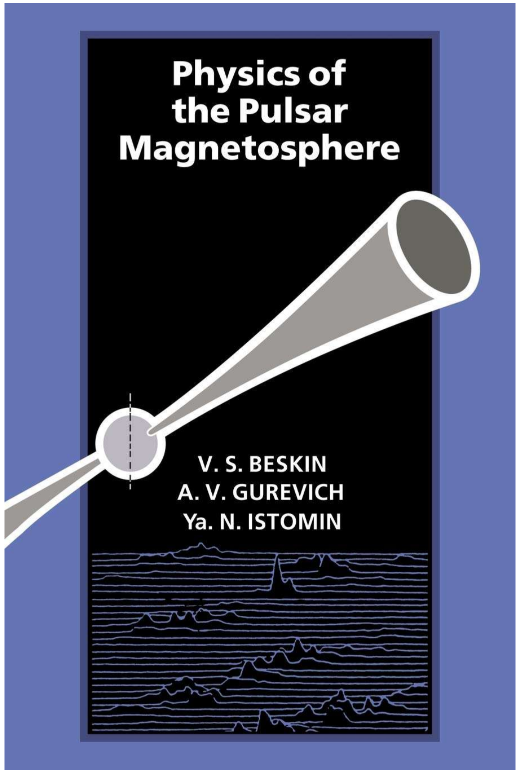
BGI

(1983, 1984, 1988, 1993)

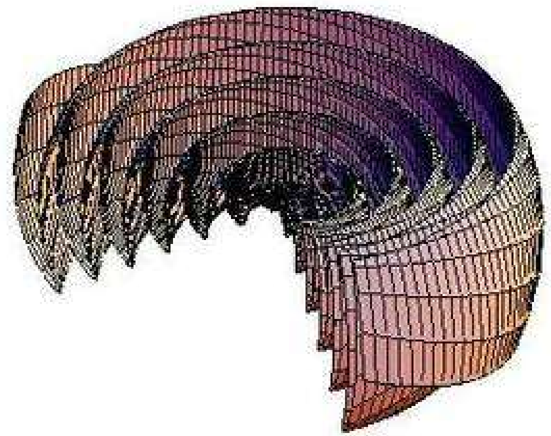
Alexander Gurevich
(1930-2023)



Yakov Istomin
(1946-2022)



Paradigm shift #1



Energy losses

Magnetodipole »»»»»» pulsar wind

F.Pacini. Ap Lett., **3**, 225 (1968)

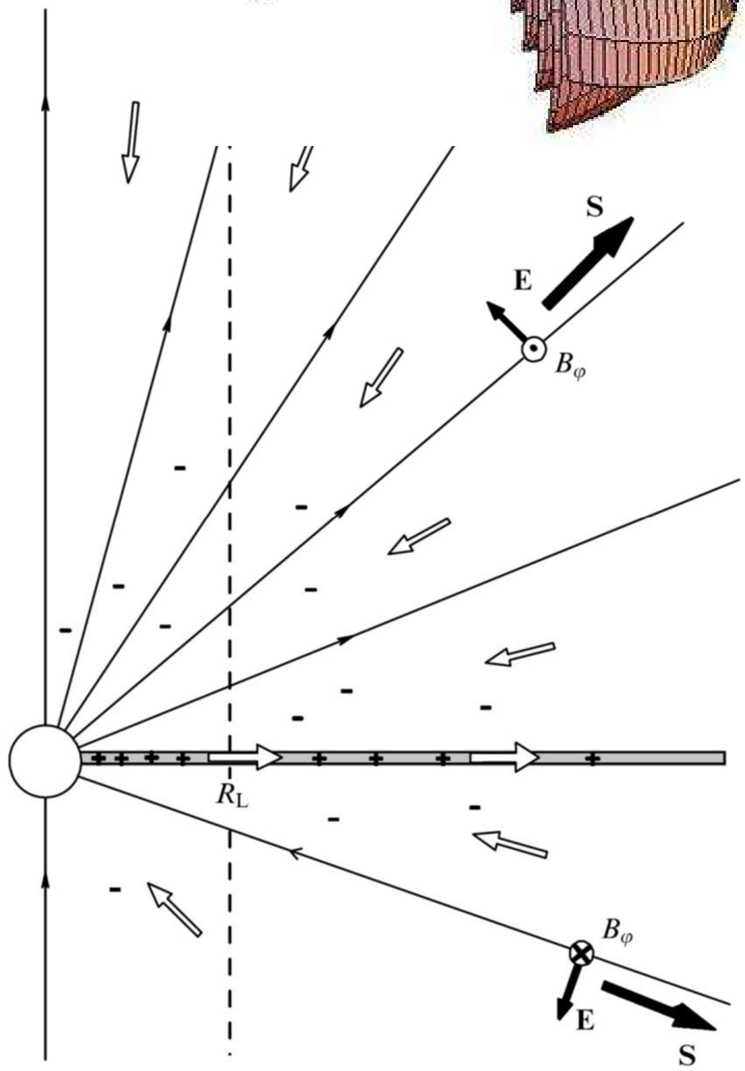
$$W_{\rm tot}^{\rm (V)} = -I_{\rm r}\Omega\dot{\Omega} = \frac{1}{6}\,\frac{B_0^2\Omega^4R^6}{c^3}\sin^2\chi$$

F.C.Michel, ApJ, **180**, L133 (1973)

S.V.Bogovalov, A&A, **349**, 1017 (1999)

$$W_{\rm tot} = -I_{\rm r}\Omega\dot{\Omega} = \frac{1}{6}\,\frac{B_0^2\Omega^4R^6}{c^3}$$

$$W_{\rm tot} = IU$$



Paradigm shift #1

Energy losses

Magnetodipole »»»»»»» pulsar wind

F.Pacini. Ap Lett., **3**, 225 (1968)

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F.C.Michel, ApJ, **180**, L133 (1973)

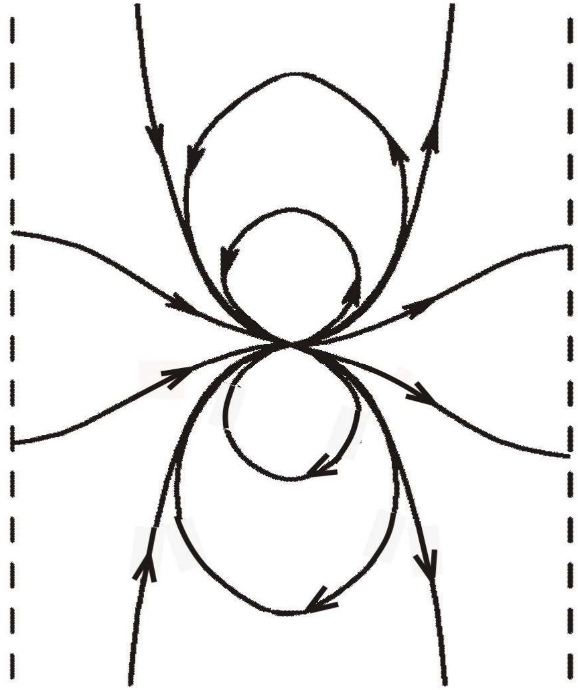
S.V.Bogovalov, A&A, **349**, 1017 (1999)

$$W_{\rm tot} = -I_{\rm r}\Omega\dot{\Omega} = \frac{1}{6}\frac{B_0^2\Omega^4R^6}{c^3}$$

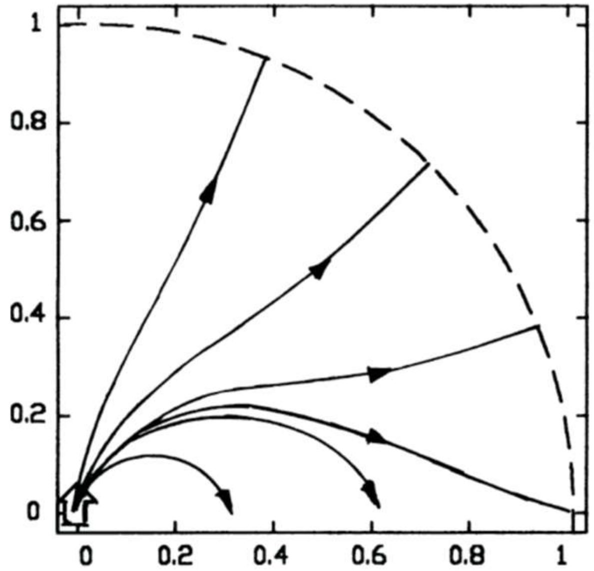
VSB, A.V.Gurevich, Ya.N.Istomin, JETP, **58,** 235 (1983)

L.Mestel, P.Panagi, S.Shibata, MNRAS, **309**, 388 (1999)

For $j_{\parallel} = 0$ $\quad B_{\varphi} \propto (1 - x_r^2)^2$



$\chi = 90^\circ$



Paradigm shift #1

Energy losses

Magnetodipole **»»»»»»** pulsar wind

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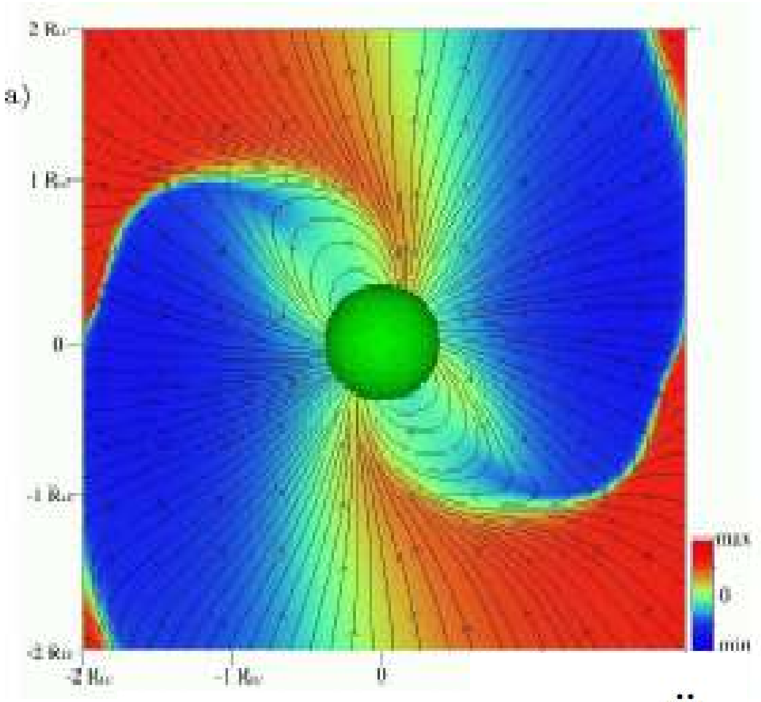
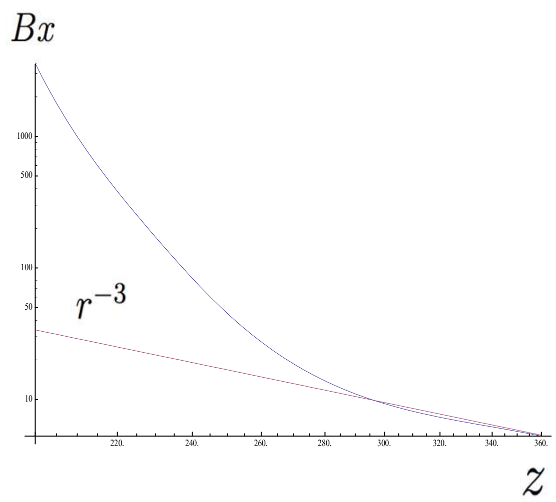


In vacuum $B_x = \frac{\ddot{m}}{cr}$

VSB, A.V.Gurevich, Ya.N.Istomin, JETP, **58,** 235 (1983)

L.Mestel, P.Panagi, S.Shibata, MNRAS, **309**, 388 (1999)

For $j_{\|} = 0$ $\qquad B_\varphi \propto (1 - x_r^2)^2$



A.Spitkovsky, ApJ, **648**, L51 (2006)

$$W_{\rm tot}^{\rm (MHD)} \approx \frac{1}{4}\,\frac{B_0^2\Omega^4R^6}{c^3}(1+\sin^2\chi)$$

Pulsar wind – not a split-monopole

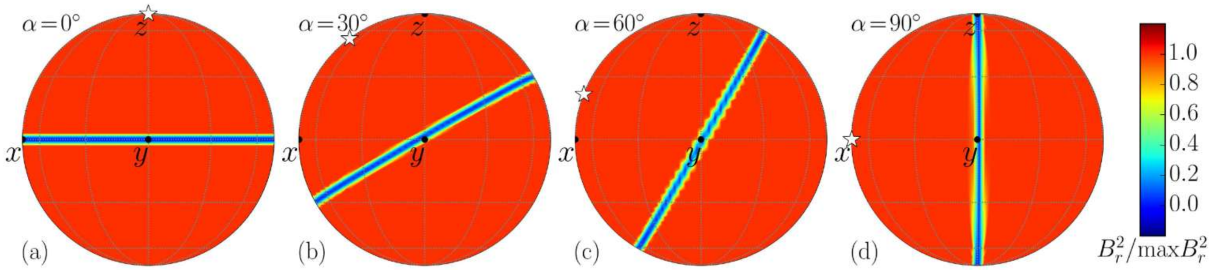
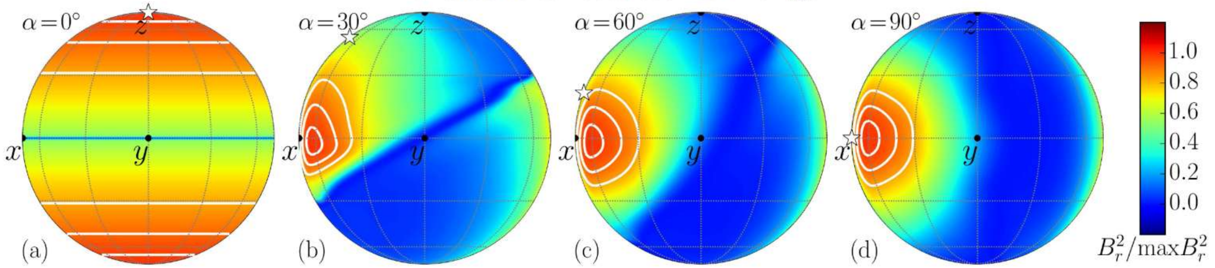


Figure 12. Colour-coded surface distribution of B_r^2 in the split-monopole solution (Bogovalov 1999). The current sheet, in which the radial magnetic field vanishes, describes the orientation of the current sheet in the numerical force-free solutions shown in Fig. 6.

Numerical force-free solution at $r = 6R_{\rm LC}$:

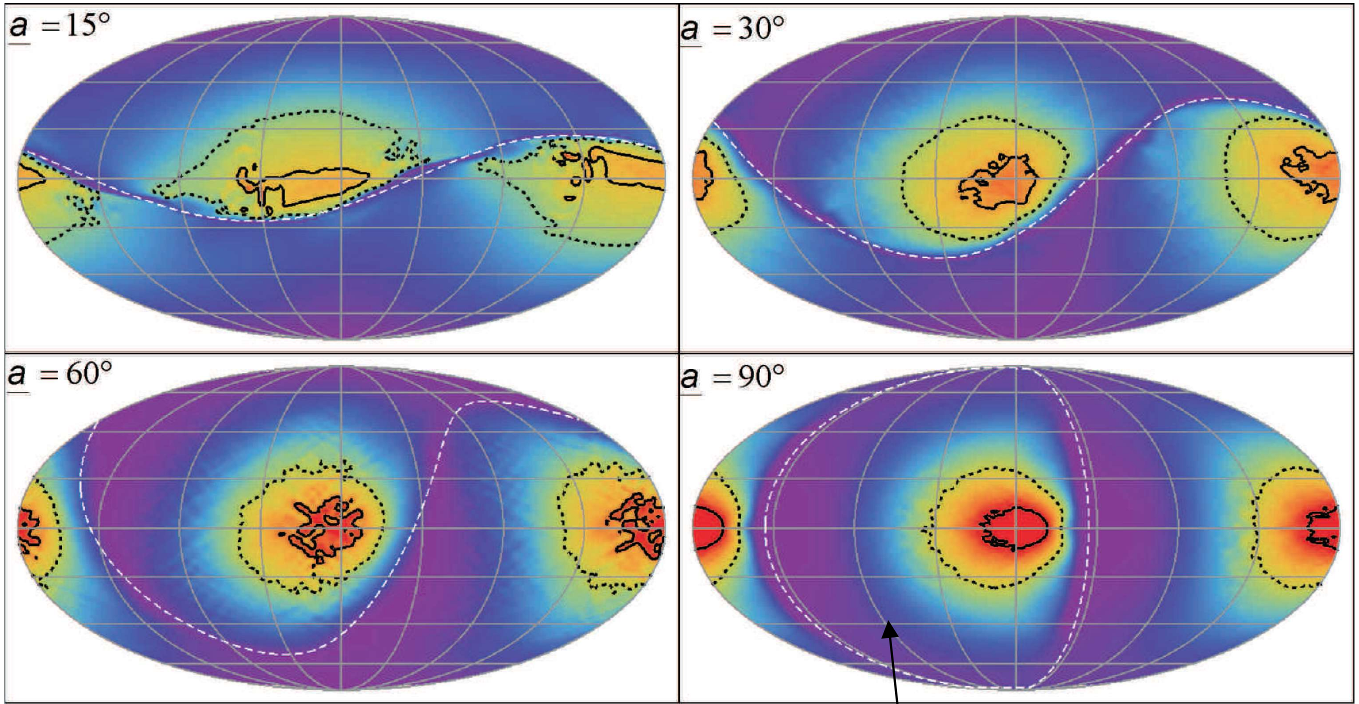


A.Tchekhovskoy, A.Philippov, A.Spitkovsky, MNRAS, **457**, 3384 (2015)

Orthogonal rotator contains no current sheet

$$W_{\rm tot}(\theta) = \sin^2\theta B_r^2(\theta)$$

Pulsar wind – not a split-monopole



C.Kalapotharakos, I.Contopoulos, D.Kazanas, MNRAS, **420**, 2793 (2012)

Orthogonal rotator contains no current sheet

$$B_r \approx B_0 \frac{R^2}{r^2} \sin\theta \cos(\varphi - \Omega t + \Omega r/c),$$

$$B_\varphi = E_\theta \approx -B_0 \frac{\Omega R^2}{cr} \sin^2\theta \cos(\varphi - \Omega t + \Omega r/c).$$

Paradigm shift #2

'Vacuum gap'

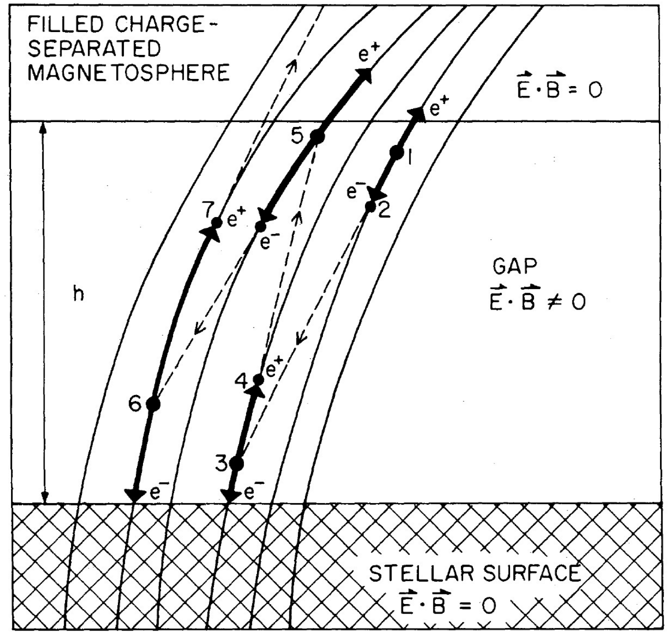
RS »»»»»» Arons

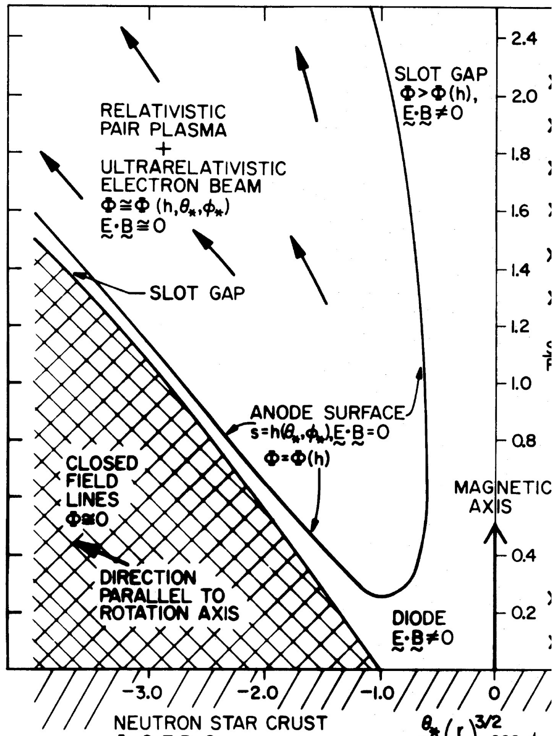
M.Ruderman, P.Sutherland, ApJ, **196**, 51 (1975)

J.Arons (1978 -1982)

RS – stationarity, almost vacuum gap, no particle ejection from the surface, arbitrary angle χ

Arons – stationarity, not a vacuum gap, free particle ejection from the surface, $\chi < 90°$



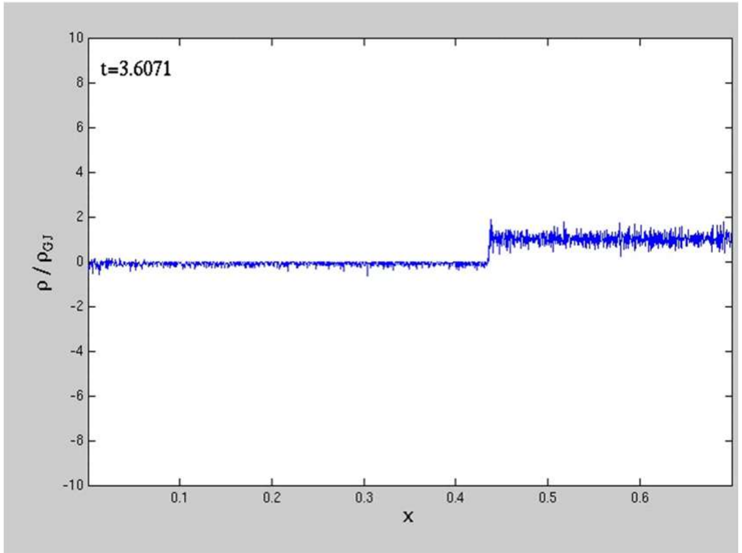


Paradigm shift #2

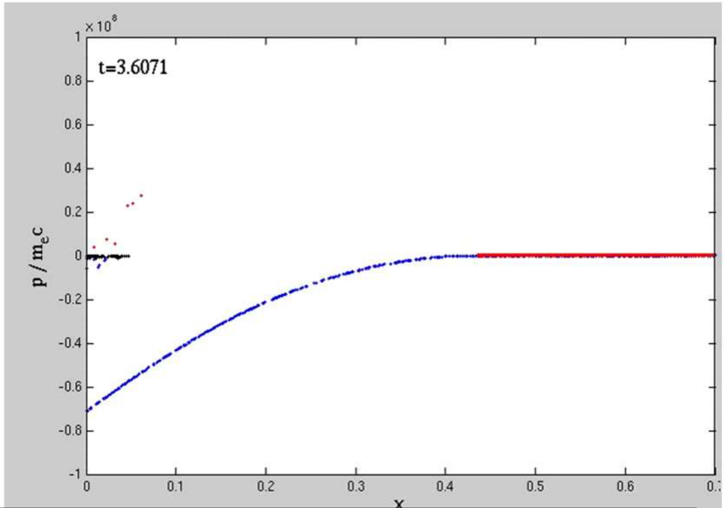
'Vacuum gap'

RS »»»»»» Arons »»»»»» PIC (~RS)

M.Ruderman, P.Sutherland, ApJ, **196**, 51 (1975)
J.Arons (1978 -1982)



RS – stationarity, almost vacuum gap, no particle ejection from the surface, arbitrary angle χ



Arons – stationarity, not a vacuum gap, free particle ejection from the surface, $\chi < 90°$

$$H_{\rm RS} = 1.1 \times 10^4 |\cos\theta_b|^{-3/7} R_{c,7}^{2/7} P^{3/7} B_{12}^{-4/7} \, {\rm cm}$$

PIC – nonstationary ~ vacuum gap, arbitrary χ

A.Timokhin, MNRAS, **368,** 1055 (2006) , A.Timokhin, J.Arons, MNRAS, **429**, 20 (2013)

Paradigm shift #3

Longitudinal current

$j_{\mathrm{m}} = j_{\mathrm{GJ}}$ »»»»»» $j_{\mathrm{m}} > j_{\mathrm{GJ}}$

$$\rho_{\mathrm{GJ}} = -\frac{\Omega B}{2\pi c} \propto \cos\chi$$

Electric current is determined by inner magnetosphere

$j_{\mathrm{m}} \leq j_{\mathrm{GJ}}$ – strong inclination angle dependence (BGI)

Arons, BGI +, before 1999

Electric current is determined by outer magnetosphere

$j_{\mathrm{m}} > j_{\mathrm{GJ}}$ – weak inclination angle dependence (MHD)

I.Contopoulos, D.Kazanas, Ch.Fendt, ApJ, **511**, 351 (1999)
A.Spitkovsky. ApJ, **648**, L51 (2006) +

Paradigm shift #3

Longitudinal current

$j_m = j_{GJ}$ »»»»»»» $j_m > j_{GJ}$

$$\rho_{GJ} = -\frac{\Omega B}{2\pi c} \propto \cos\chi$$

Electric current is determined by inner magnetosphere

$j_m \leq j_{GJ}$ – strong inclination angle dependence (BGI)

L.Mestel, Astrophys. Space Sci. **24,** 289 (1973)

$$\mathbf{j} = \rho_e[\mathbf{\Omega} \times \mathbf{r}] + i_{\|}\mathbf{B} \qquad \mathbf{B}\nabla i_{\|} = 0.$$

Electric current is determined by outer magnetosphere

$j_m > j_{GJ}$ – weak inclination angle dependence (MHD)

A.Gruzinov, Phys. Rev. Lett. **94,** 021101 (2005)

$$\mathbf{j}_G(\mathbf{E},\mathbf{B}) = \frac{\left(\mathbf{B}\,[\nabla \times \mathbf{B}] - \mathbf{E}\,[\nabla \times \mathbf{E}]\right)\mathbf{B} + (\nabla\mathbf{E})[\mathbf{E} \times \mathbf{B}]}{B^2}$$

Paradigm shift #3

Longitudinal current – energy losses

$j_{\rm m} = j_{\rm GJ}$ »»»»»»» $j_{\rm m} > j_{\rm GJ}$ $W_{\rm tot} = IU$

Electric current is determined by inner magnetosphere

$j_{\rm m} \leq j_{\rm GJ}$ – strong inclination angle dependence (BGI)

BGI

$$W_{\rm tot}^{\rm (BGI)} = i_{\rm s}^{\rm A}(\Omega, B)\, \frac{f_*^2(\chi)}{4}\, \frac{B_0^2\Omega^4 R^6}{c^3} (\cos^2\chi + C)$$

Electric current is determined by outer magnetosphere $C \sim \left(\frac{\Omega R}{c}\right)^{1/2}$

$j_{\rm m} > j_{\rm GJ}$ – weak inclination angle dependence (MHD)

A.Spitkovsky. ApJ, **648**, L51 (2006) +

$$W_{\rm tot}^{\rm (MHD)} \approx \frac{1}{4}\, \frac{B_0^2\Omega^4 R^6}{c^3} (1 + \sin^2\chi)$$

Paradigm shift #3

Longitudinal current – angle χ evolution

$j_{\rm m} = j_{\rm GJ}$ »»»»»» $j_{\rm m} > j_{\rm GJ}$

$$I_{\rm r}\dot{\Omega} = K_{\parallel}^{A} + [K_{\perp}^{A} - K_{\parallel}^{A}]\sin^2\chi,$$
$$I_{\rm r}\Omega\dot{\chi} = [K_{\perp}^{A} - K_{\parallel}^{A}]\sin\chi\cos\chi.$$

Electric current is determined by inner magnetosphere

$j_{\rm m} \le j_{\rm GJ}$ – strong inclination angle dependence (BGI)

BGI

Counter-alignment

Electric current is determined by outer magnetosphere

$j_{\rm m} > j_{\rm GJ}$ – weak inclination angle dependence (MHD)

A.Tchekhovskoy, A.Philippov, A.Spitkovsky, MNRAS, **457**, 3384 (2016)

Alignment

Paradigm shift #3

Longitudinal current – potential drop

$$\rho_{GJ} = -\frac{\Omega B}{2\pi c} \propto \cos\chi$$

$j_m = j_{GJ}$ »»»»»» $j_m > j_{GJ}$

Electric current is determined by inner magnetosphere

ψ_{max} – strong inclination angle dependence (BGI)

RS, BGI

$$\psi_{max} \approx 2\pi \rho_{GJ} R_0^2$$

Electric current is determined by outer magnetosphere

ψ_{max} – weak inclination angle dependence (MHD)

A.Timokhin. MNRAS, **408,** 2092 (2010) +

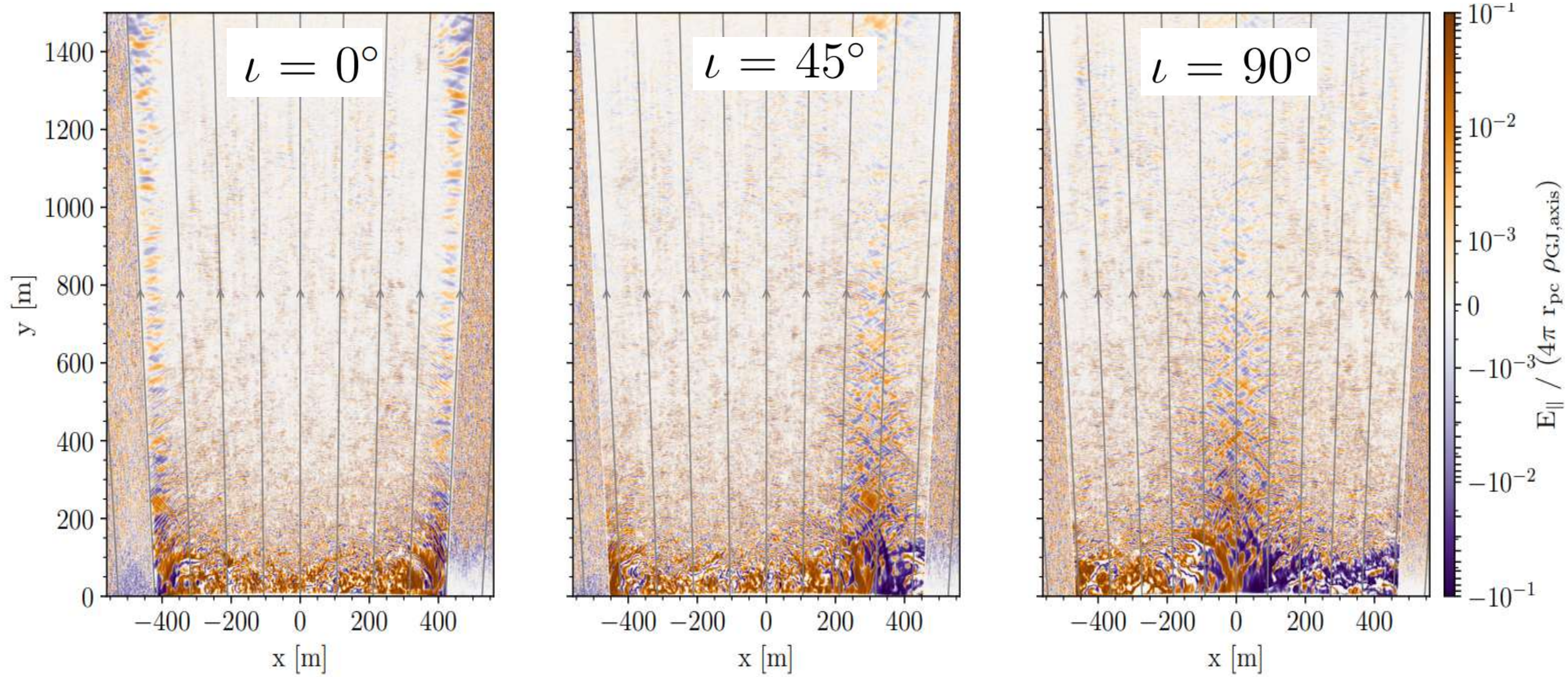
$$\frac{\partial E}{\partial t} = -4\pi(j - j_m)$$

Paradigm shift #3

Longitudinal current – potential drop

$$j_{\rm m} = j_{\rm GJ} \quad \text{»»»»»»»} \quad j_{\rm m} > j_{\rm GJ}$$

$$\rho_{\rm GJ} = -\frac{\Omega B}{2\pi c} \propto \cos\chi$$



J.Benáček, A.Timokhin, P.A.Muñoz, A.Jessner,T.Rievajová, M.Pohl, J.Büchner, A&A, **691**, 137 (2024)

$$\frac{\partial E}{\partial t} = -4\pi(j - j_{\rm m})$$

Alternative

MHD + PIC

Electric current ≥ GJ
Potential drop ≥ vacuum
death line
alignment

Orthogonal interpulse pulsars:
potential drop >> vacuum gap death line

BGI

Electric current ≤ GJ
Potential drop ≤ vacuum
death line
counter-alignment

Orthogonal interpulse pulsars:
potential drop ~ vacuum gap death line

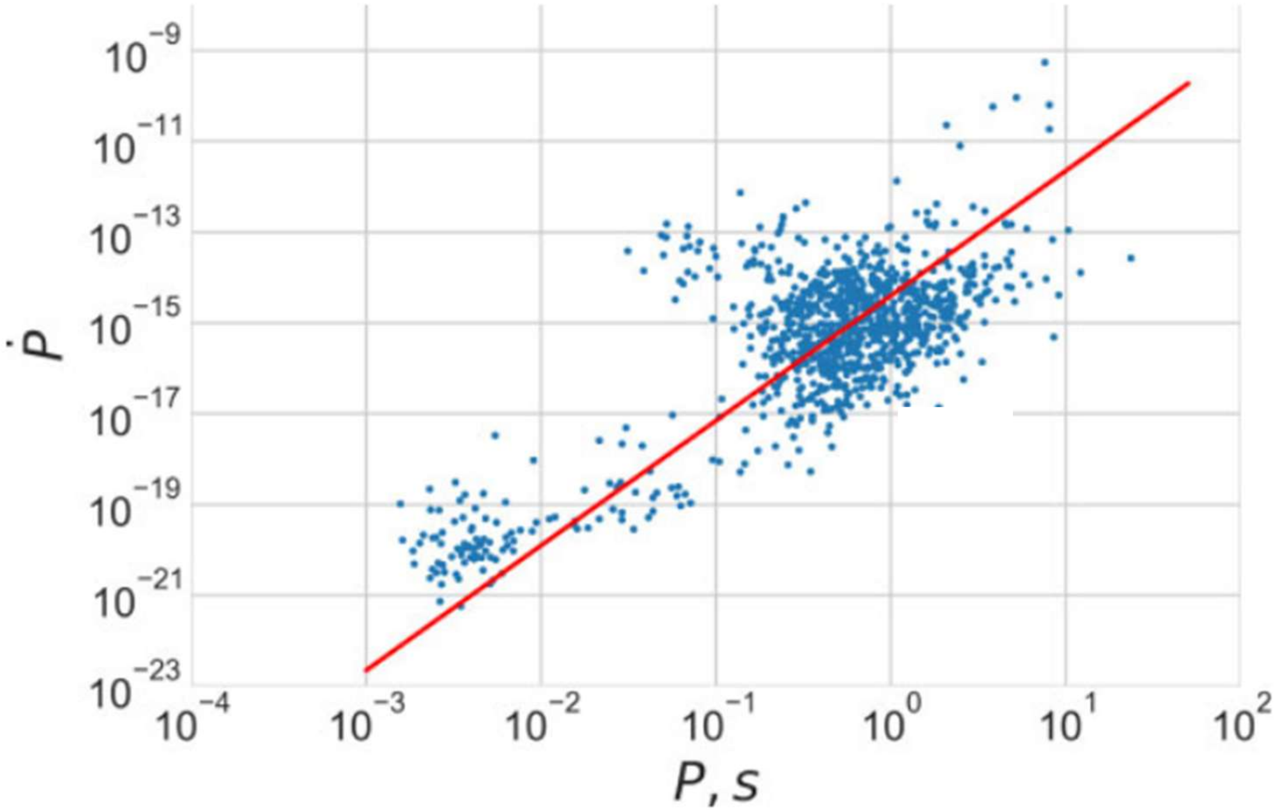
Death line

M.Ruderman, P.Sutherland, ApJ**, 196**, 51 (1975)

$$\psi_{\rm RS} > \psi_{\rm max}$$

$$\psi_{\rm max} \approx 2\pi \rho_{\rm GJ} R_0^2$$

RS – original version

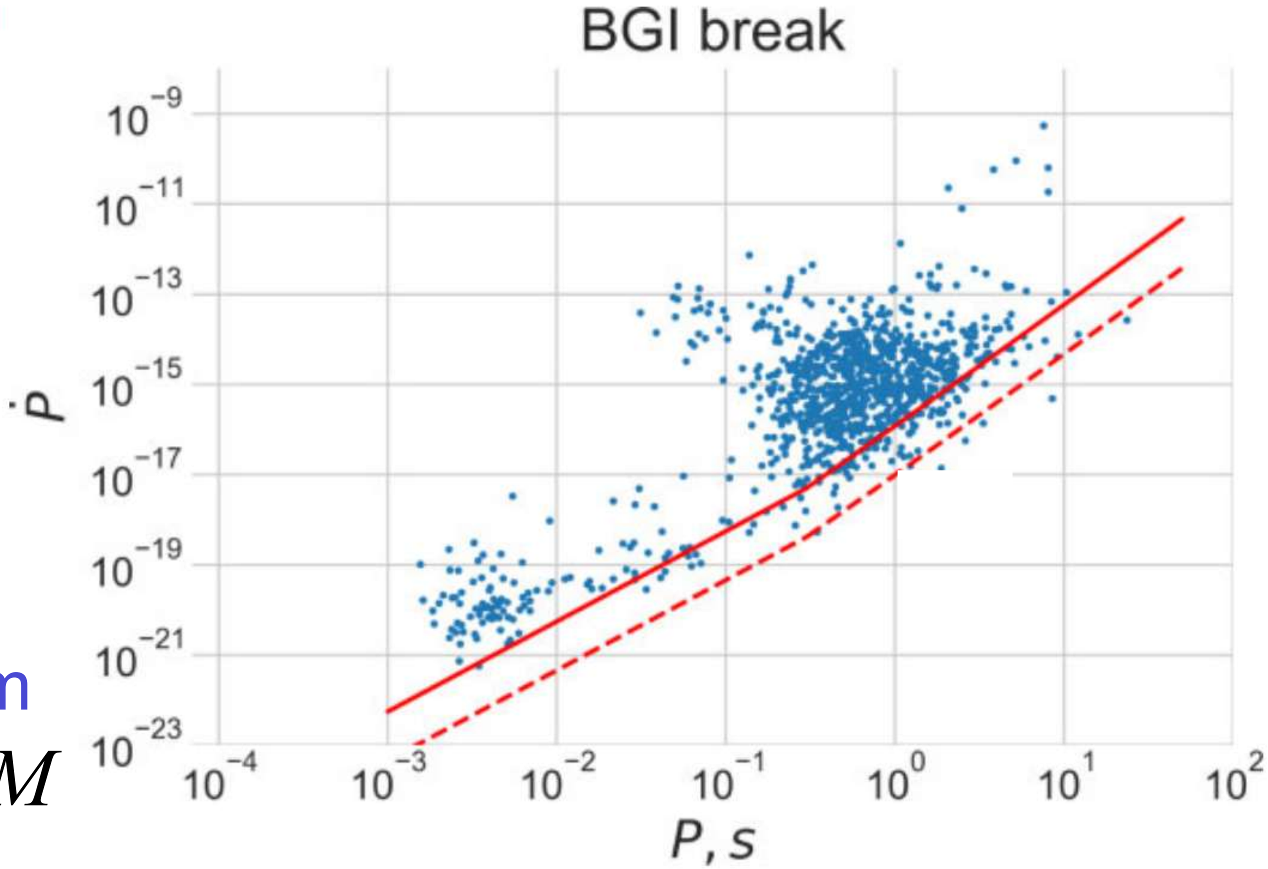


Death line

VSB, A.Yu.Istomin, MNRAS, **516**, 5084 (2022)

$$\psi_{\rm RS} > \psi_{\rm max}$$

$$\psi_{\rm max} \approx 2\pi \rho_{\rm GJ} R_0^2$$



RS – after correction

GR

curvature spectrum

spread in R and M

Death line

MHD + PIC

Potential drop – not vacuum

$$\psi_{\max} \gtrsim 2\pi \rho_{\rm GJ} R_0^2$$

weak dependence on χ

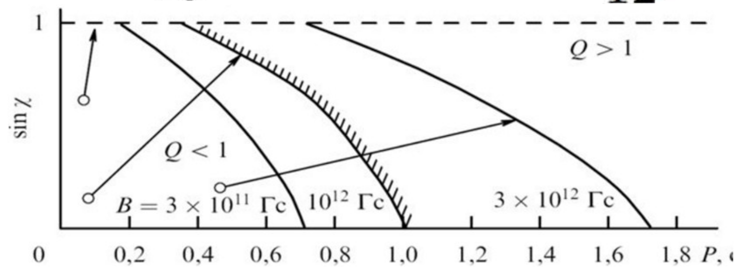
BGI (RS)

Potential drop – vacuum

$$\psi_{\max} \approx 2\pi \rho_{\rm GJ} R_0^2$$

strong dependence on χ

$$\cos\chi > k\, P^{15/7}\, B_{12}^{-8/7}$$



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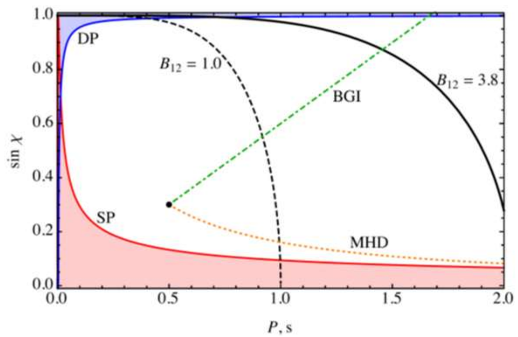

E.M.Novoselov, VSB, A.K.Galishnikova, M.M.Rashkovetskyi, A.V.Biryukov. MNRAS, **494**, 3899 (2020)

Death line

MHD + PIC

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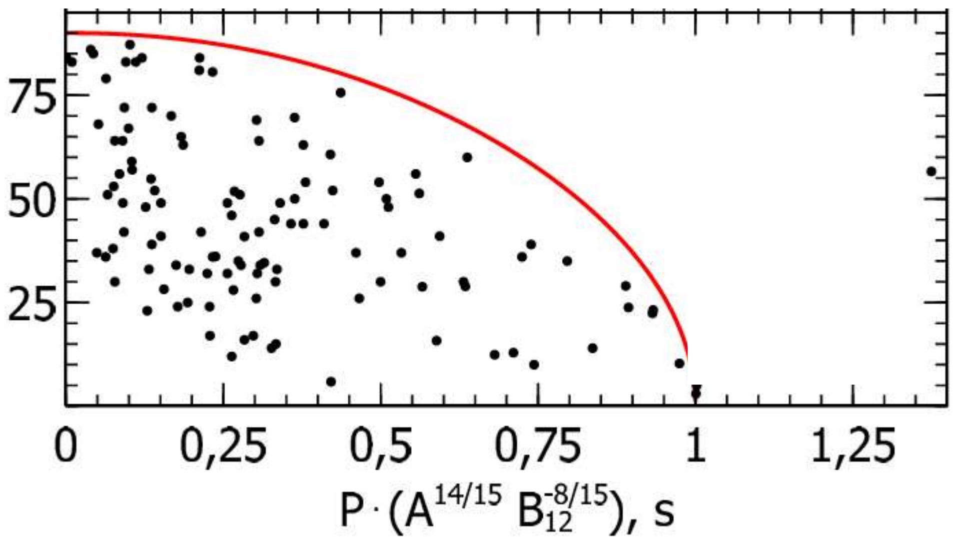


E.M.Novoselov, VSB, A.K.Galishnikova, M.M.Rashkovetskyi, A.V.Biryukov. MNRAS, **494**, 3899 (2020)

Inclination angle

MHD + PIC

BGI

Alignment

T.M.Tauris, R.N.Manchester, MNRAS, **298**, 625 (1998)

M.D.T. Young, L.S. Chan, R.R. Burman, D.G. Blair, MNRAS, **402**, 1317 (2010)

K.Maciesiak, J.Gil, V.A.R.M.Ribeiro, MNRAS, **414**, 1314 (2011)

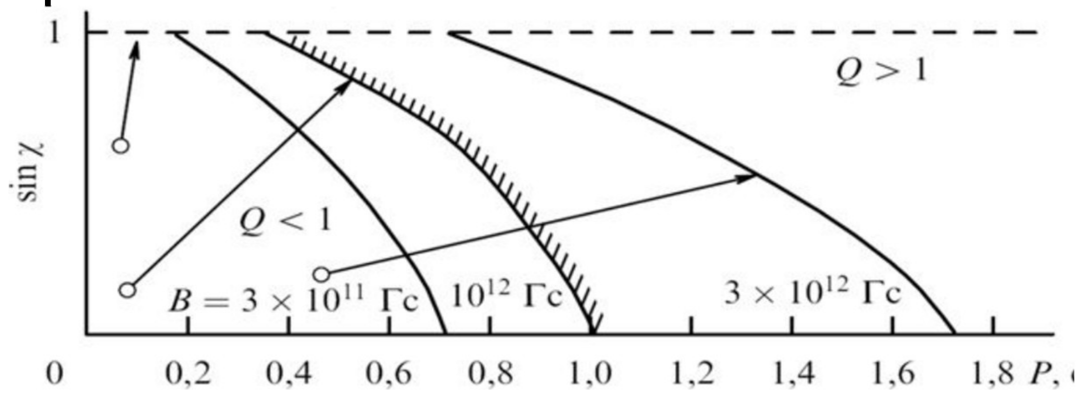
(S.Johnston, M.Kramer, A. Karastergiou, J. Keith, L.S. Oswald, A. Parthasarathy, P. Weltevrede, MNRAS, **520**, 4801 (2023)

A.Tchekhovskoy, A.Philippov, A.Spitkovsky, MNRAS, **457**, 3384 (2016)

Counter-alignment

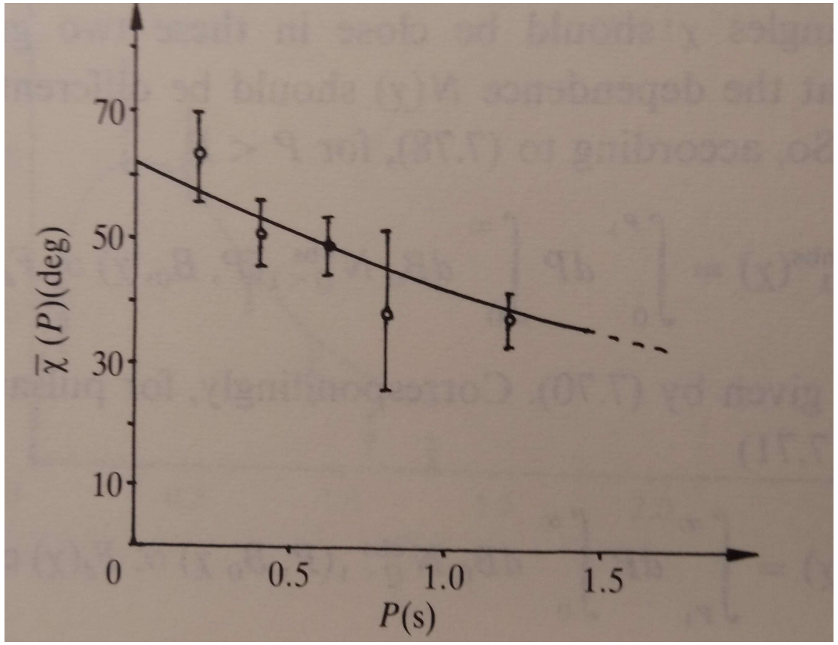
BGI

A.G.Lyne, C.A.Jordan, F. Graham-Smith,C.M.Espinoza,B.W.Stapper, P.Weltevrede, MNRAS, **446,** 857 (2015)

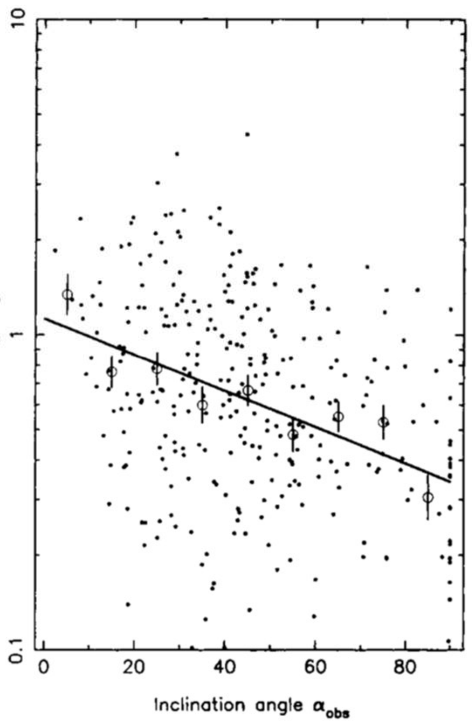


Inclination angle

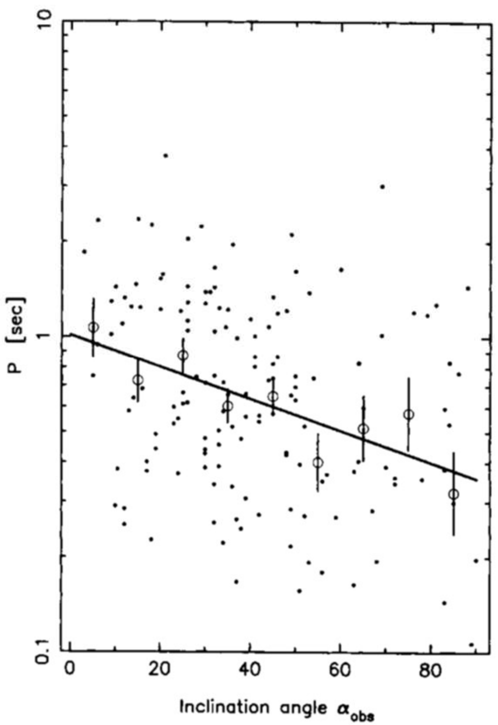
Key test – inclination angle evolution



Gould



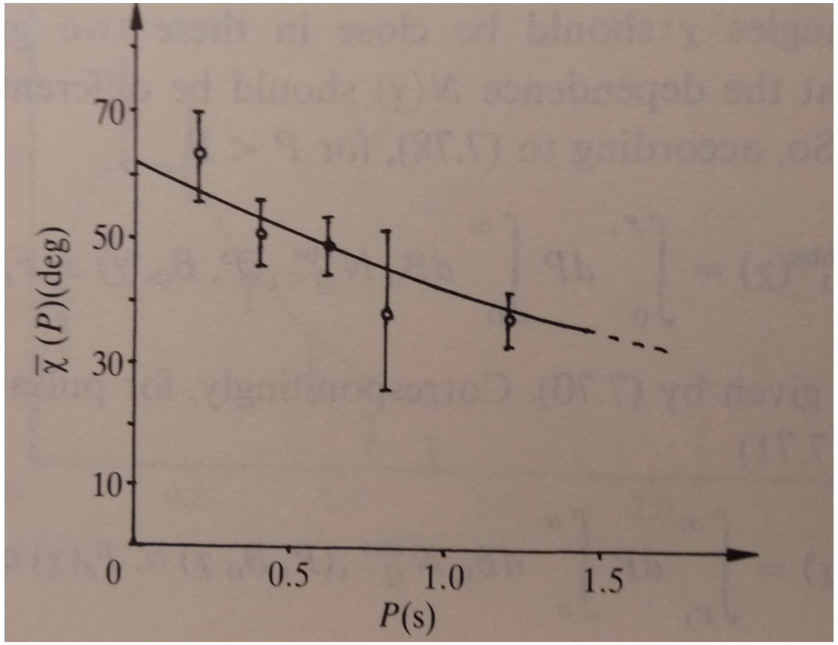
Rankin



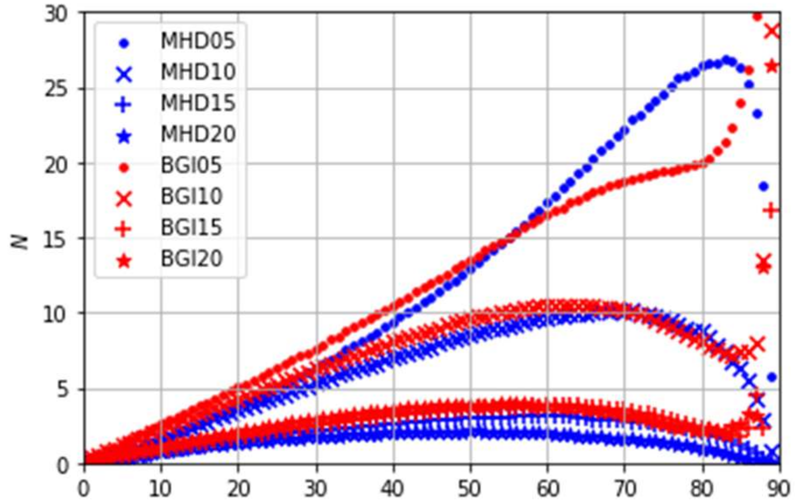
VSB, A.V.Gurevich, Ya.N.Istomin
Physics of the pulsar magnetosphere
Cambridge Univ. Press, 1993

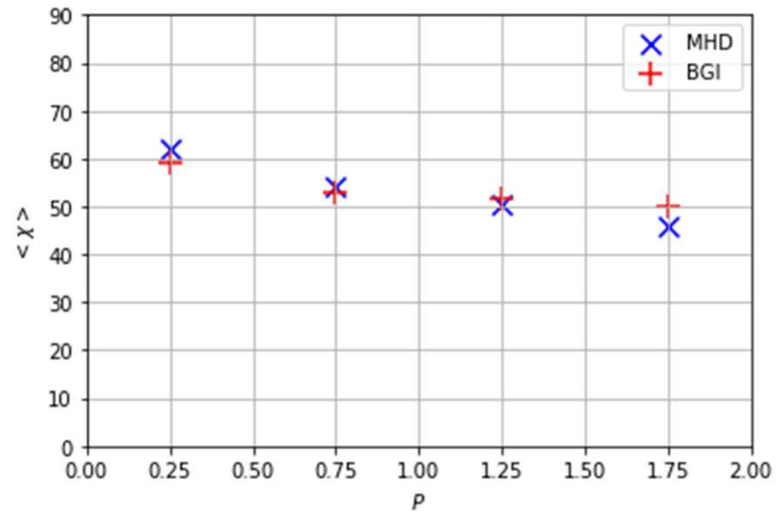
T.M.Tauris, R.N.Manchester
MNRAS, **298**, 625 (1998)

Inclination angle



VSB. A.B.Gurevich. Ya.N.Istomin.
Physics of the pulsar magnetosphere,
Cambridge Univ. Press, 1993

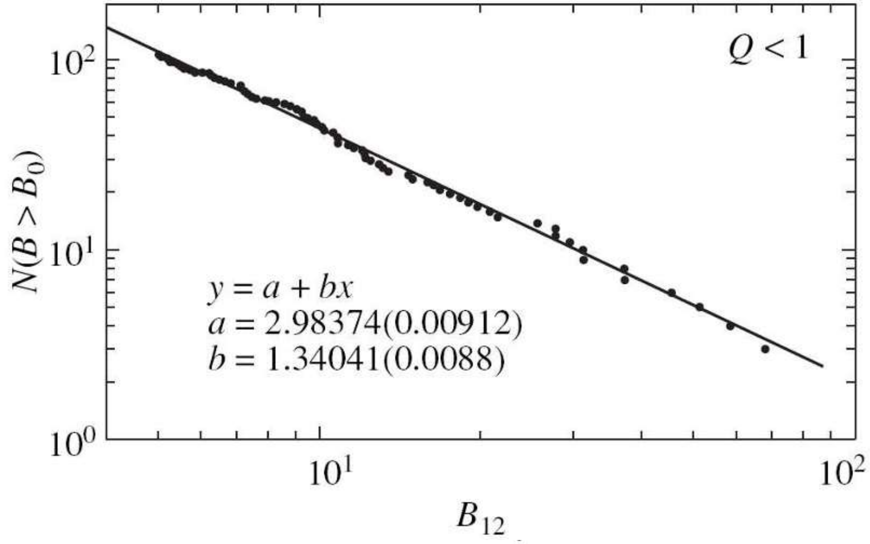


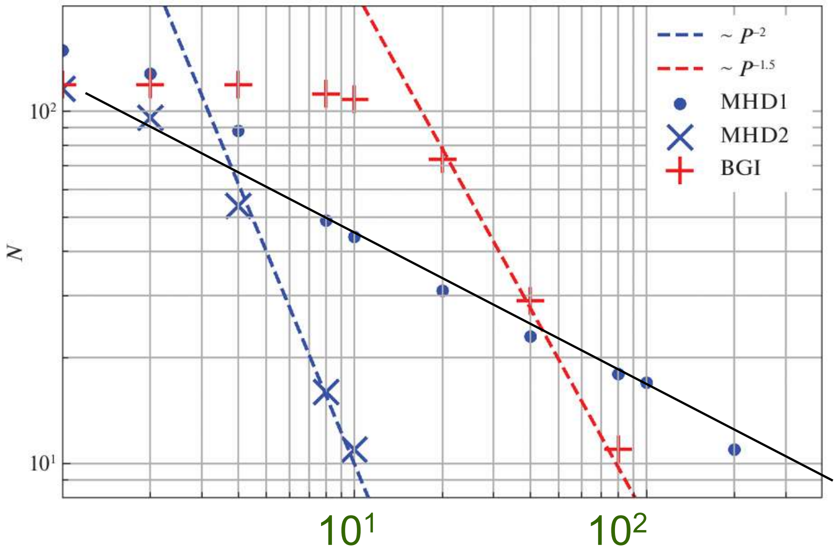


VSB, D.S.Zagorulya, A.Yu.Istomin
Astron. Lett, **47**, 709 (2021)

Magnetic field – power-law tail

$$p(\log B_0) = \frac{1}{\sqrt{2\pi}\sigma_{B_0}} \exp\left(-\frac{(\log B_0 - \mu_{B_0})^2}{2\sigma^2_{B_0}}\right)$$





M.Gullón, J.A.Miralles, D.Viganò, J.Pons,
MNRAS, **443**, 1891 (2014)

VSB, S.A.Eliseeva,
Astron. Lett, **31**, 263 (2005)
VSB, D.S.Zagorulya, A.Yu.Istomin,
Astron. Lett, **47**, 709 (2021)

Alternative

MHD + PIC

Orthogonal interpulse pulsars:

potential drop >> vacuum gap

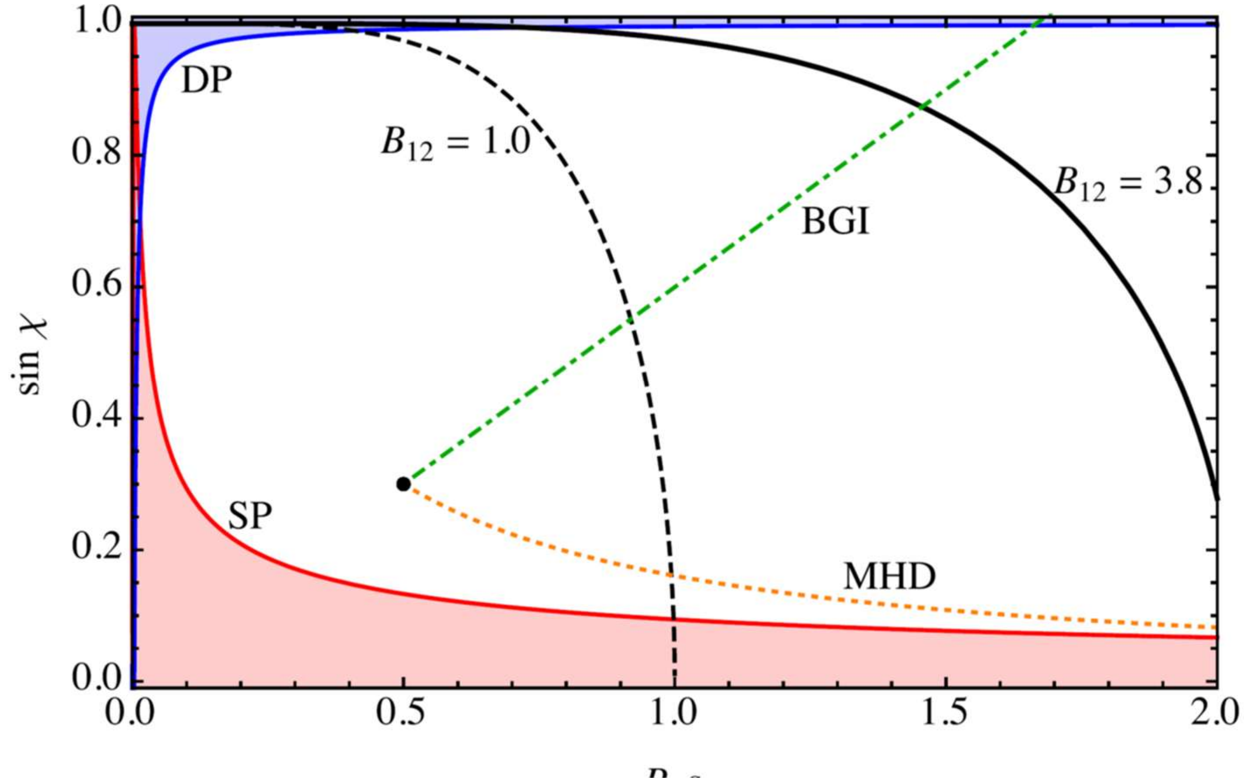
$$\frac{\partial E}{\partial t} = -4\pi(j - j_{\mathrm{m}})$$

BGI

Orthogonal interpulse pulsars:

potential drop ~ vacuum gap

$$\psi_{\max} \approx 2\pi\rho_{\mathrm{GJ}} R_0^2$$



Death line – RS, no PIC

F.A.Kniazev, A.Yu.Istomin, VSB, Astron. Lett., **50**, 821 (2024)

Orthogonal pulsars $P < 0.2\, B_{12}^{16/37}\, s$ $\cos\chi > k\, P^{15/7}\, B_{12}^{-8/7}$

FAST + MeerKAT

	$P < 0.033\ s$	$0.033\ s < P < 0.5\ s$	$0.5 s < P < 1 s$	$P > 1 s$
Novoselov et al	– –	$(18 \div 26)/968$ $(1.8 \div 2.6)\%$	$(3 \div 5)/725$ $(0.4 \div 0.7)\%$	$(0 \div 1)/694$ $(0.0 \div 0.1)\%$
FAST	8/73 11.0%	14 /233 6.0%	3/177 1.7%	1/198 0.5%
MeerKAT	0/1 0%	25/590 4.2%	4/414 1.0%	0/265 0%

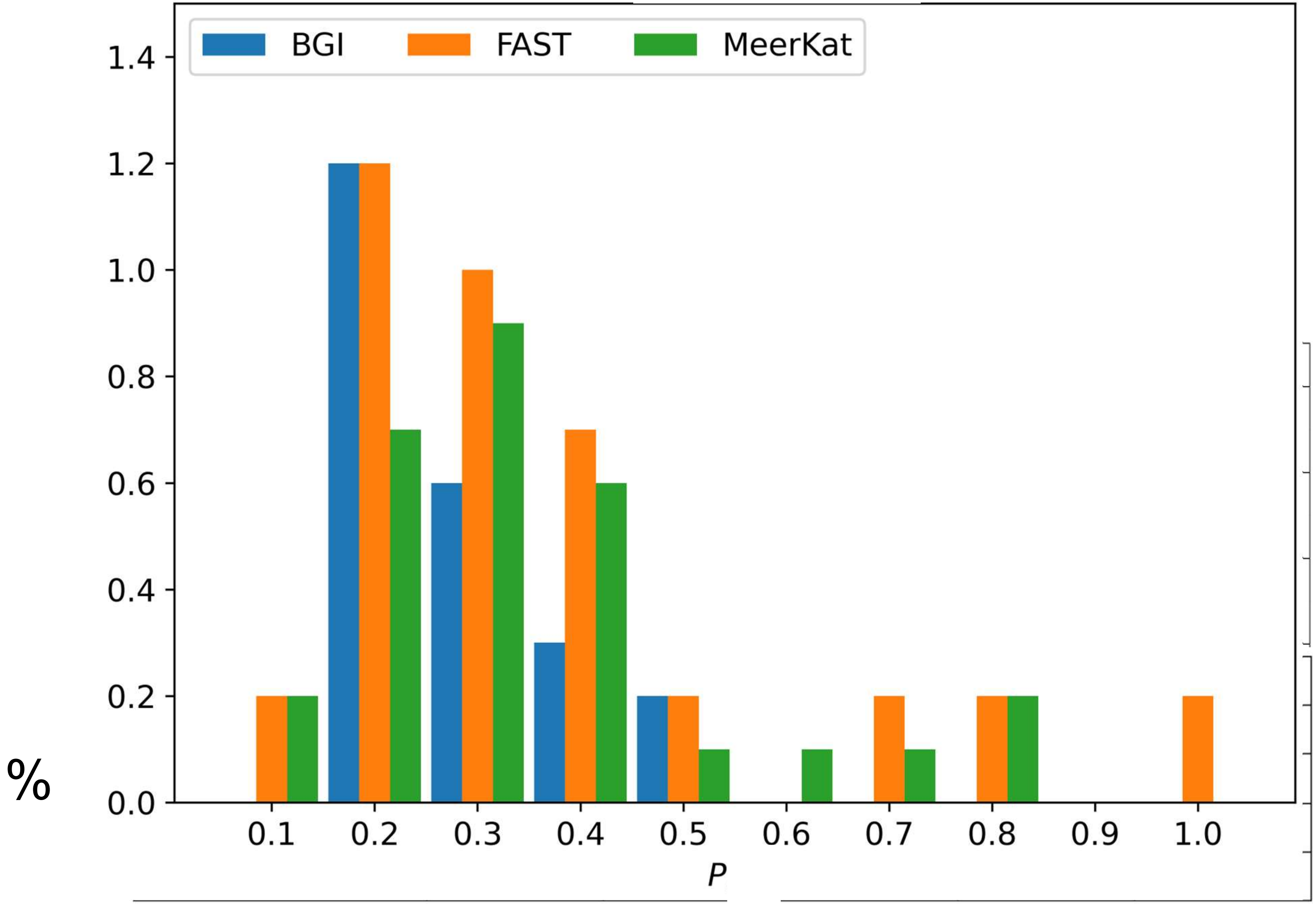
%

P (s)	0.03–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5
BGI	0.0	1.2	0.6	0.3	0.2
Novoselov et al.	$0.4 \div 0.6$	$1.0 \div 1.9$	$1.4 \div 1.6$	$0.6 \div 0.8$	$0.2 \div 0.4$
FAST	0.4	2.1	1.7	1.3	0.4
MeerKAT	0.3	1.2	1.5	1.0	0.3

Death line – RS, no PIC

F.A.Kniazev, A.Yu.Istomin, VSB, Astron. Lett., **50**, 821 (2024)

Orthogonal pulsars $P < 0.2\, B_{12}^{16/37}$ s $\cos\chi > k\, P^{15/7}\, B_{12}^{-8/7}$



Death line – RS, no PIC

F.A.Kniazev, A.Yu.Istomin, VSB, Astron. Lett., **50**, 821 (2024)

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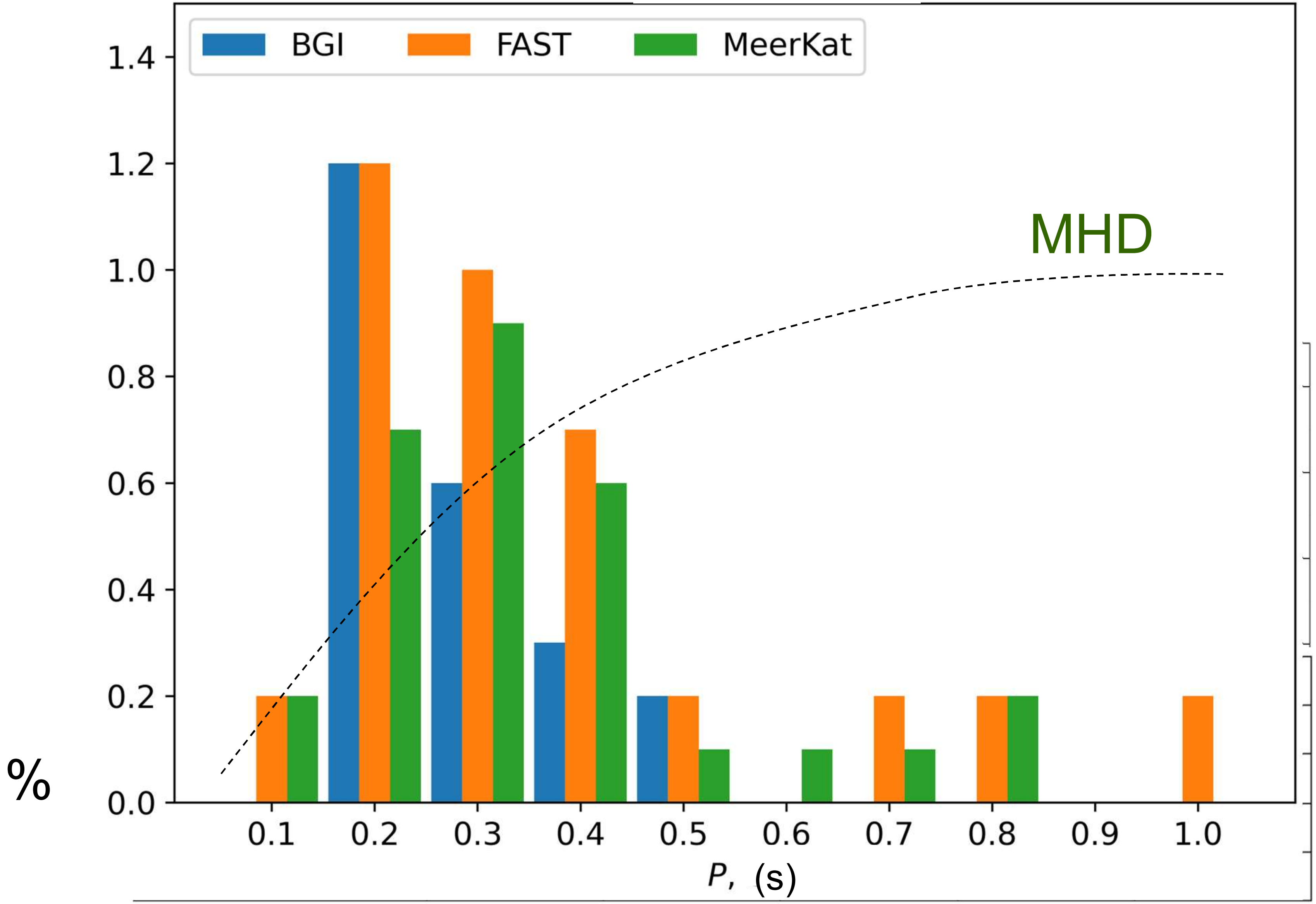


Death line – RS, no PIC

VSB, A.Yu.Istomin, A.G.Mikhaylenko, MNRAS, **526**, 1633 (2023)
A.Yu.Istomin, F.A.Kniazev, VSB, Astronomy Reports, **68**, 1271 (2024)

Why?

Possible answer – hollow cone

1). <u>Hole itself (no particles)</u>

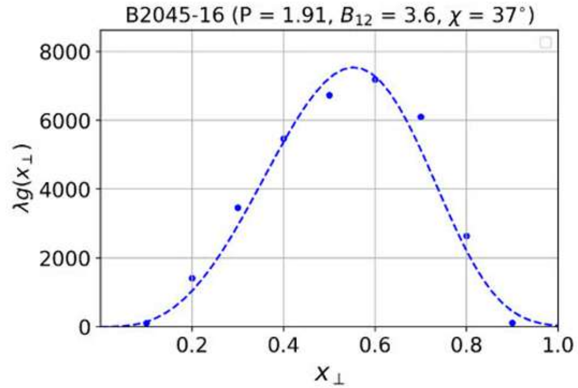
2). Potential drop

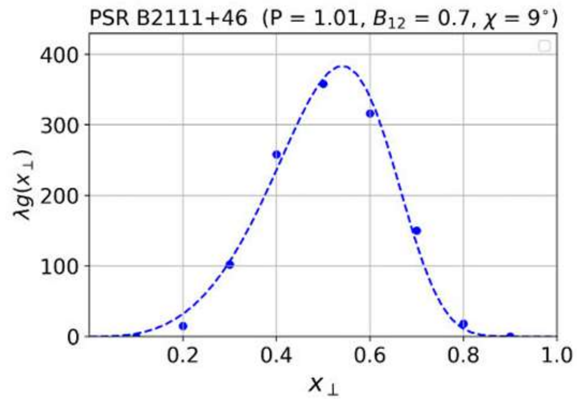
$$R_c \sim R^2/r_\perp$$

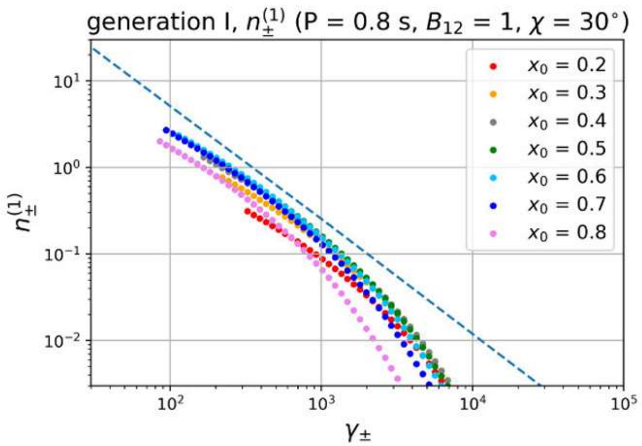
$$\lambda\, g(r_\perp) \propto r_\perp^3.$$

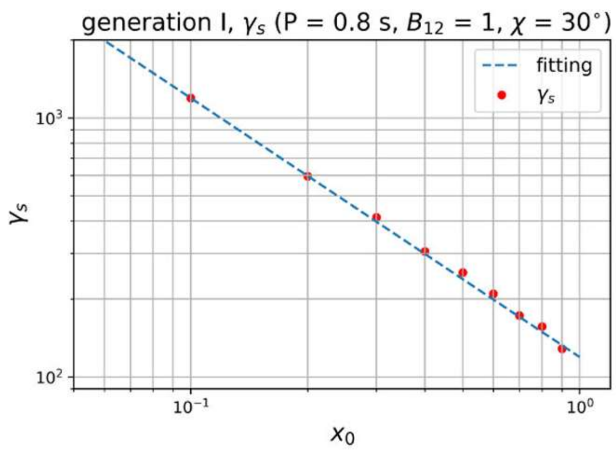
$$\gamma_\pm = k \times 100\, P^{1/2} \left(\frac{R_0}{r_\perp}\right)$$

$$\gamma_s = <1/\gamma^3>^{-1/3}$$









Death line – RS, no PIC

VSB. A.B.Gurevich. Ya.N.Istomin.Physics of the pulsar magnetosphere, Cambridge Univ. Press, 1993

Why?

Possible answer – hollow cone

1). Hole itself (no particles)

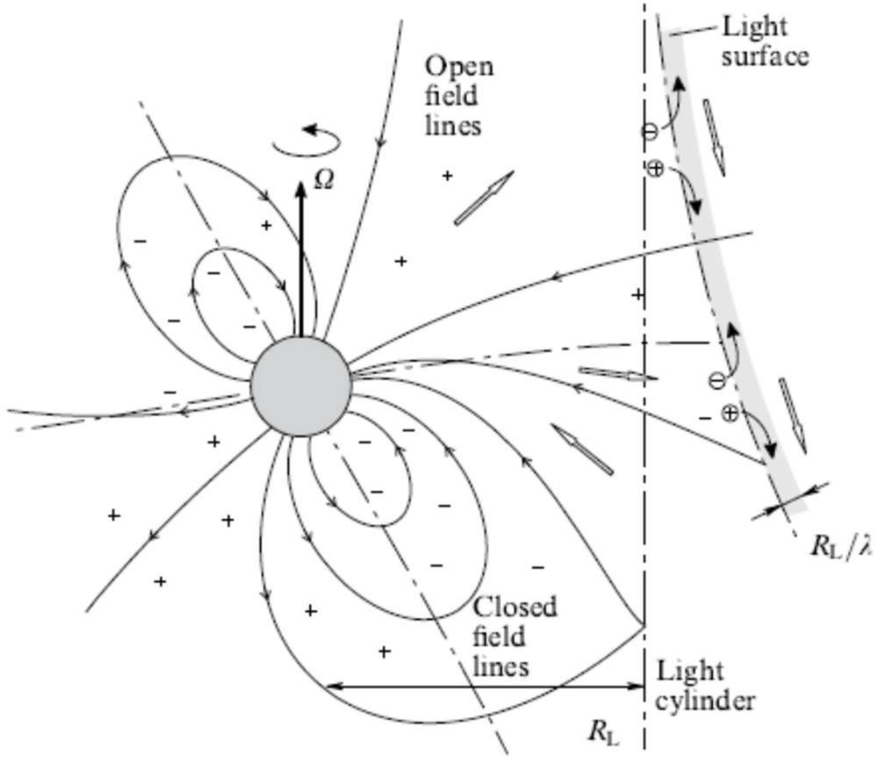
2). Potential drop

$$\mathbf{E} + \boldsymbol{\beta}_{\mathrm{R}} \times \mathbf{B} = -\nabla \psi$$

$$\boldsymbol{\beta}_{\mathrm{R}} = \frac{\boldsymbol{\Omega} \times \mathbf{r}}{c}$$

$$\mathbf{B} \cdot \nabla i_{\parallel} = 0$$

$$\mathbf{B} \cdot \nabla \psi = 0$$



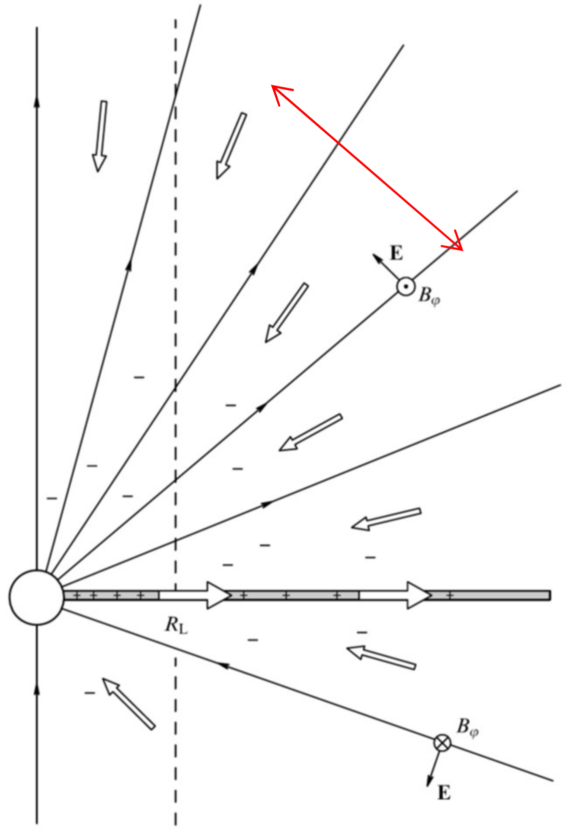
$$\nabla \times \{(1 - \boldsymbol{\beta}_{\mathrm{R}}^2)\mathbf{B} + \boldsymbol{\beta}_{\mathrm{R}}(\boldsymbol{\beta}_{\mathrm{R}} \cdot \mathbf{B}) + [\boldsymbol{\beta}_{\mathrm{R}} \times \nabla \psi]\} = \frac{4\pi}{1 - \boldsymbol{\beta}_{\mathrm{R}}^2 + \boldsymbol{\beta}_{\mathrm{R}}[\nabla \psi \times \mathbf{B}]/B^2} \left[\frac{i_{\parallel}}{c} \left((1 - \boldsymbol{\beta}_{\mathrm{R}}^2)\mathbf{B} + [\boldsymbol{\beta}_{\mathrm{R}} \times \nabla \psi]\right) + \frac{[\nabla \psi \times \mathbf{B}]}{B^2} \left(\frac{\boldsymbol{\Omega} \cdot \mathbf{B}}{2\pi c} + \frac{1}{4\pi}(\nabla^2 \psi - (\boldsymbol{\beta}_{\mathrm{R}} \nabla)(\boldsymbol{\beta}_{\mathrm{R}} \nabla \psi)) \right) \right].$$

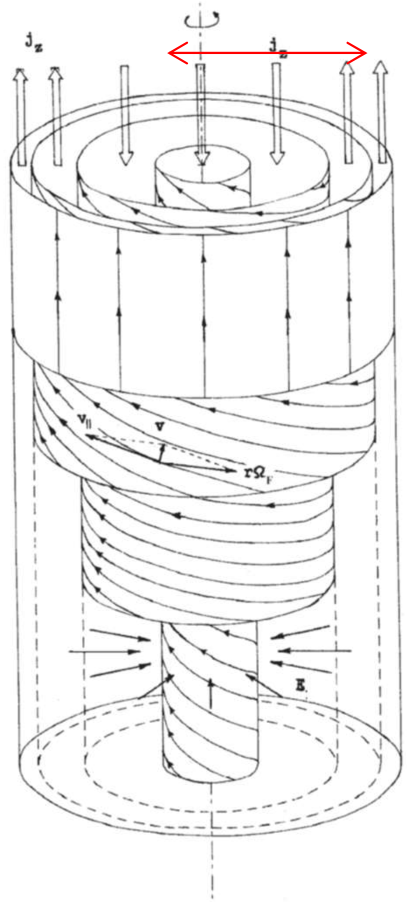
Theoretical challenge – δU problem

F.C.Michel (1973)

What to do with (enormous) potential difference?

Ferraro isorotation law implies constant electric potential ($\Omega_{\rm F}$) along magnetic field lines.





Theoretical challenge – δU problem

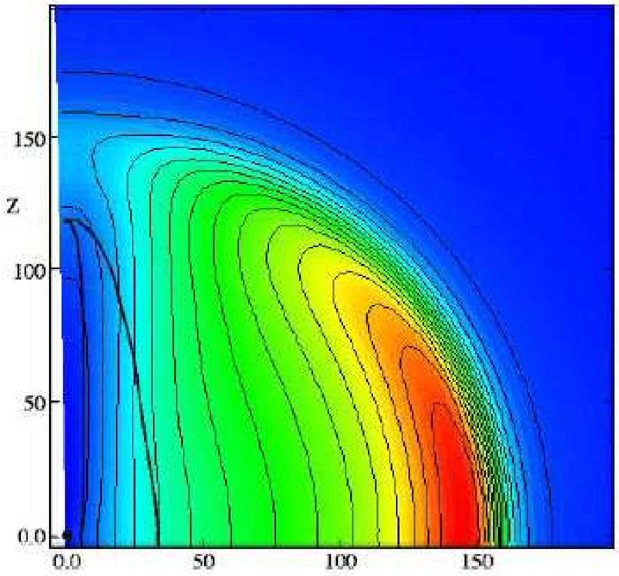
Longitudinal electric field?

Magnetically dominated wind → Any disturbance → Longitudinal electric field

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

Theoretical challenge – δU problem

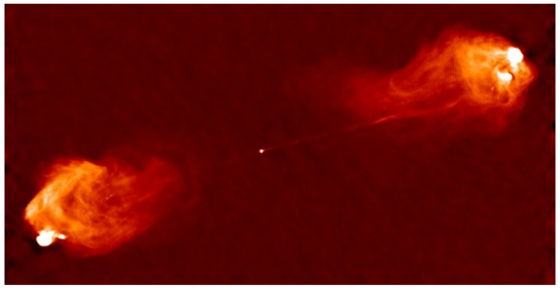
Switch-on wave, if there is no ambient medium



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

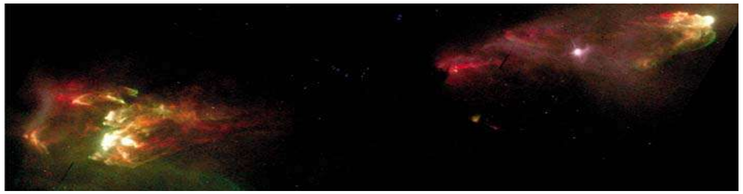
But what to do if we have it?

Lobes in AGN



Stellar wind in close binaries

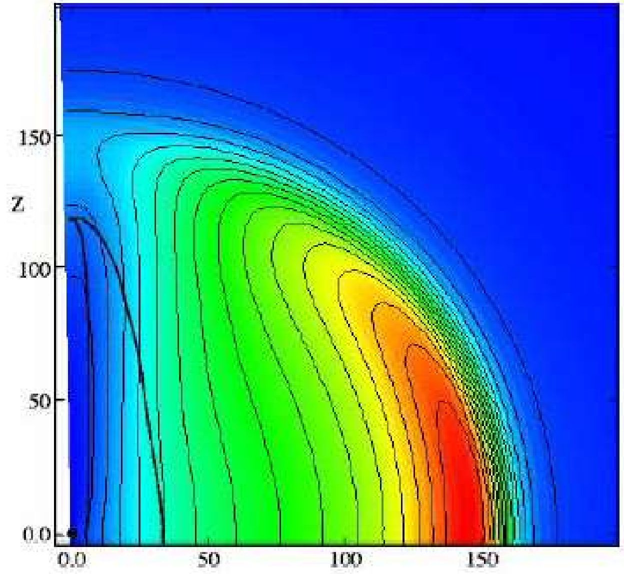
HH objects in YSO



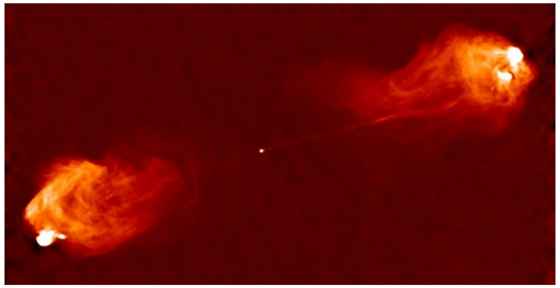
Black widows

Theoretical challenge – δU problem

If there is no external environment, the solution can be extended up to infinity



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



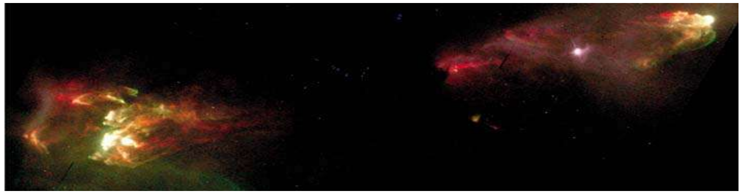
But what to do if we have it?

Lobes in AGN

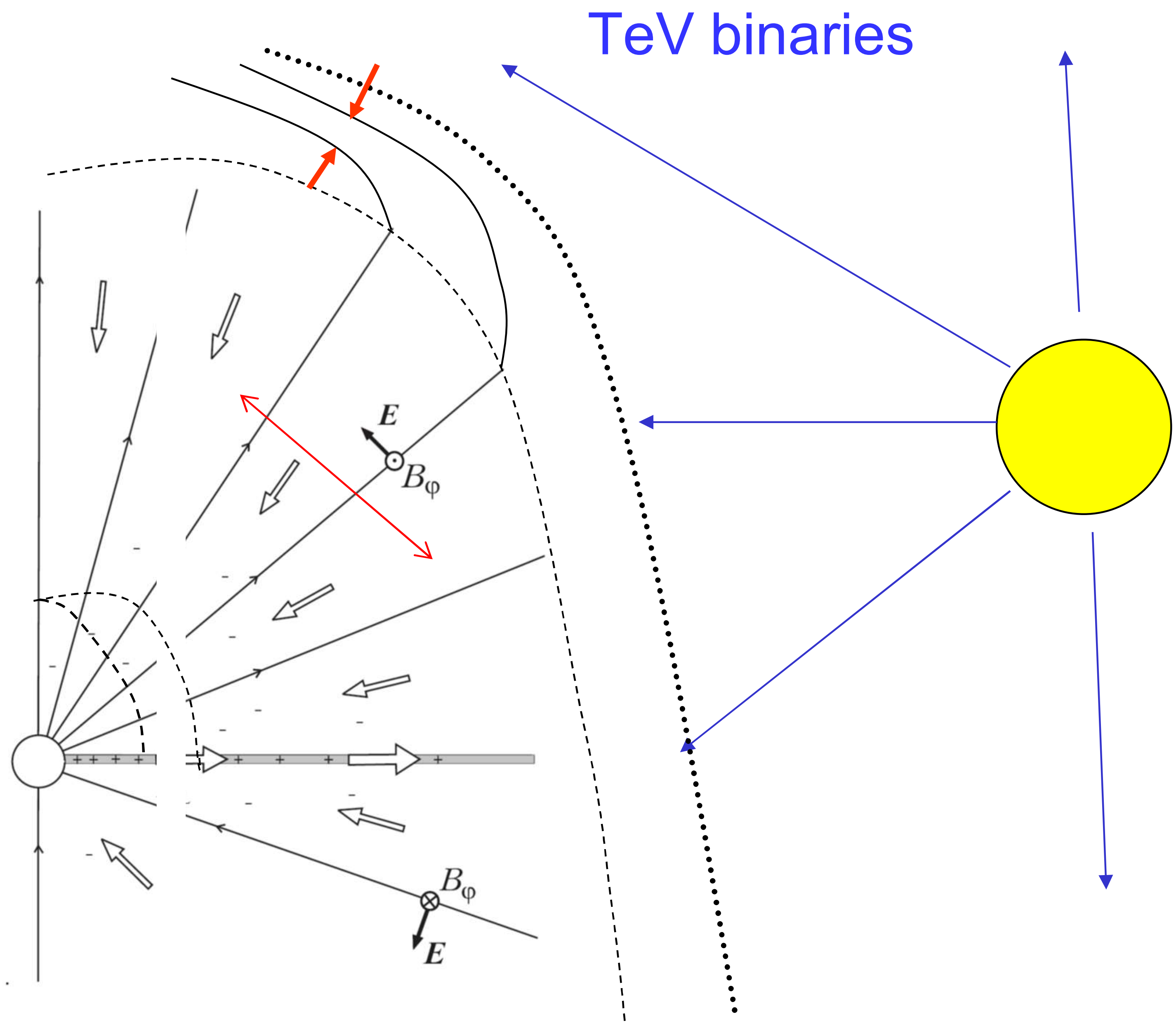
Stellar wind in close binaries

HH objects in YSO

Black widows



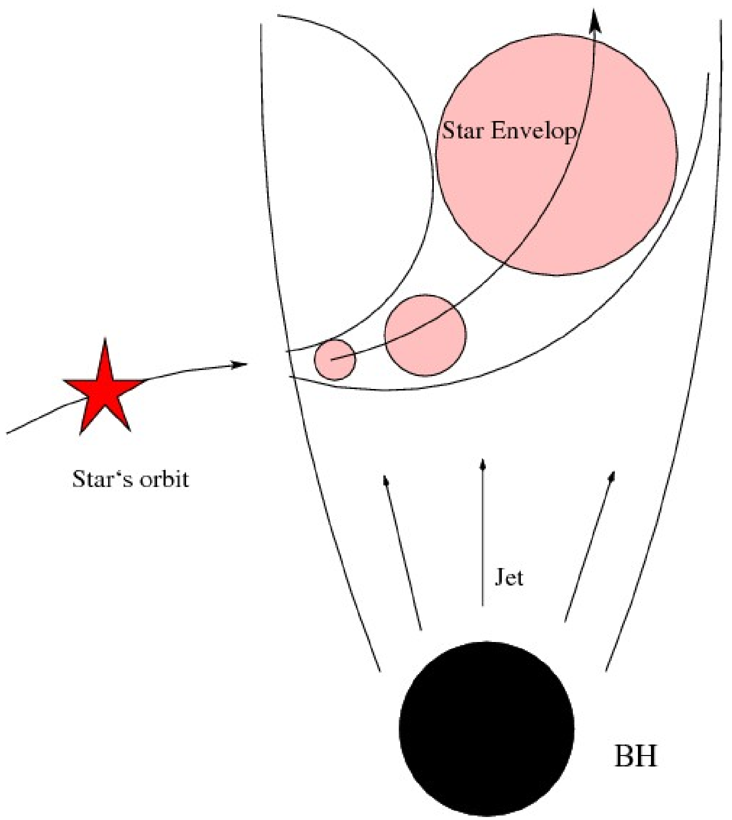
Theoretical challenge – δU problem

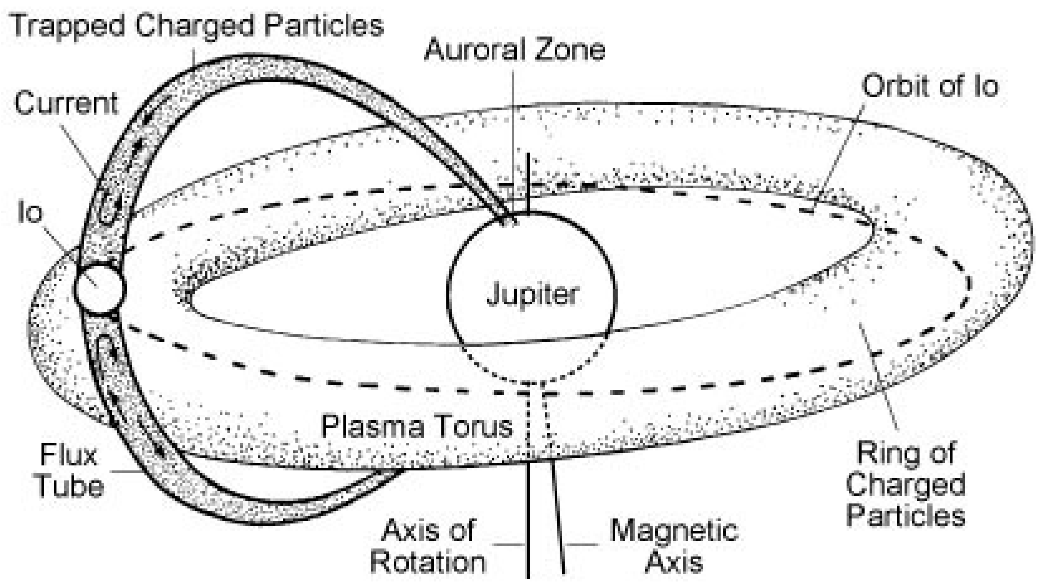


Theoretical challenge – δU problem

MHD simulations
do not include
δU into consideration

Io-Jovian
electromagnetic
interaction

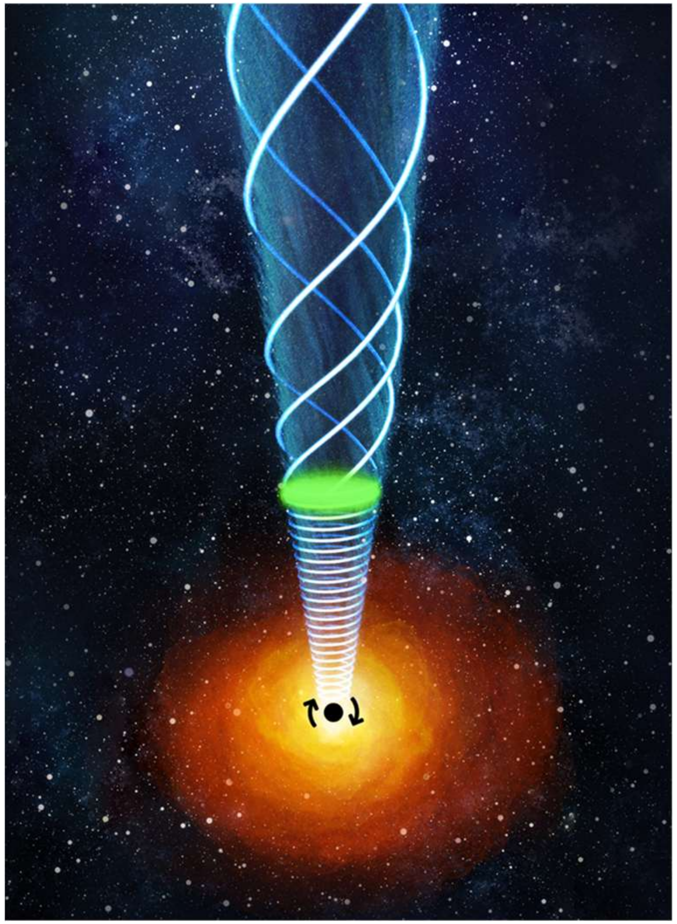




D.V.Khangulyan et al, ApJ, **774**, 113 (2013)

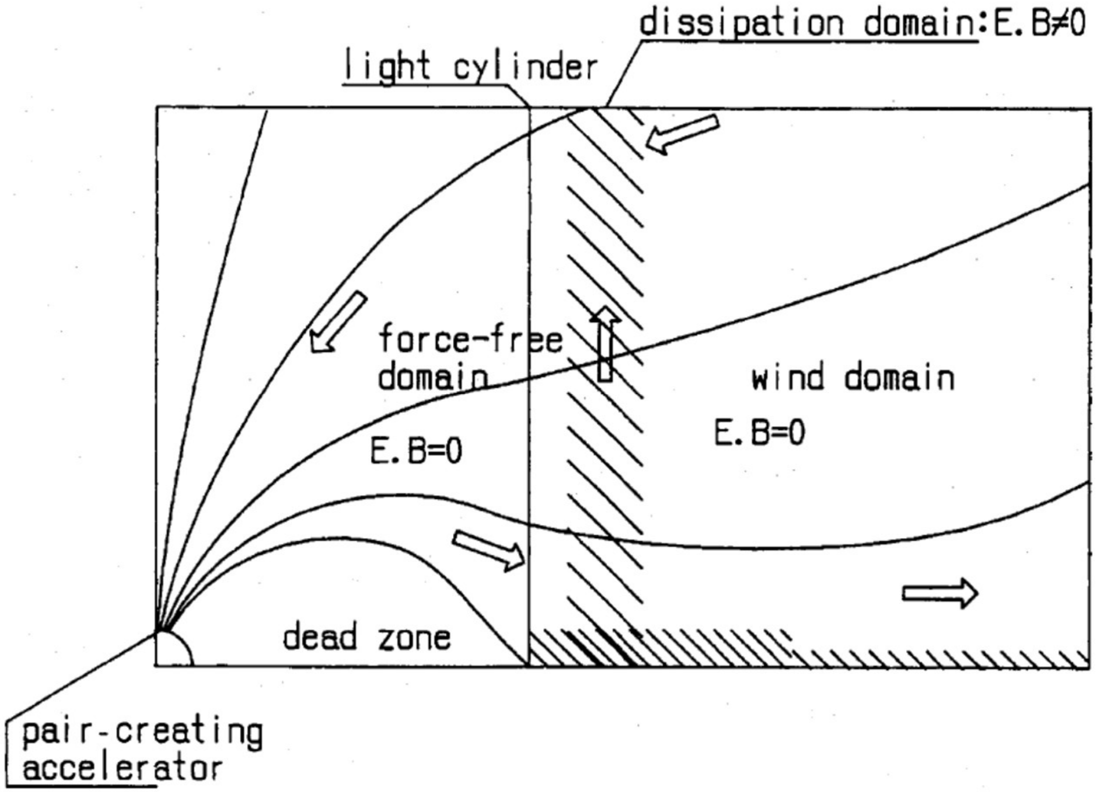
Theoretical challenge – δU problem

Dissipation layer
in relativistic jets



J.Park, K.Takahashi, K.Toma et al
arXiv (2025)

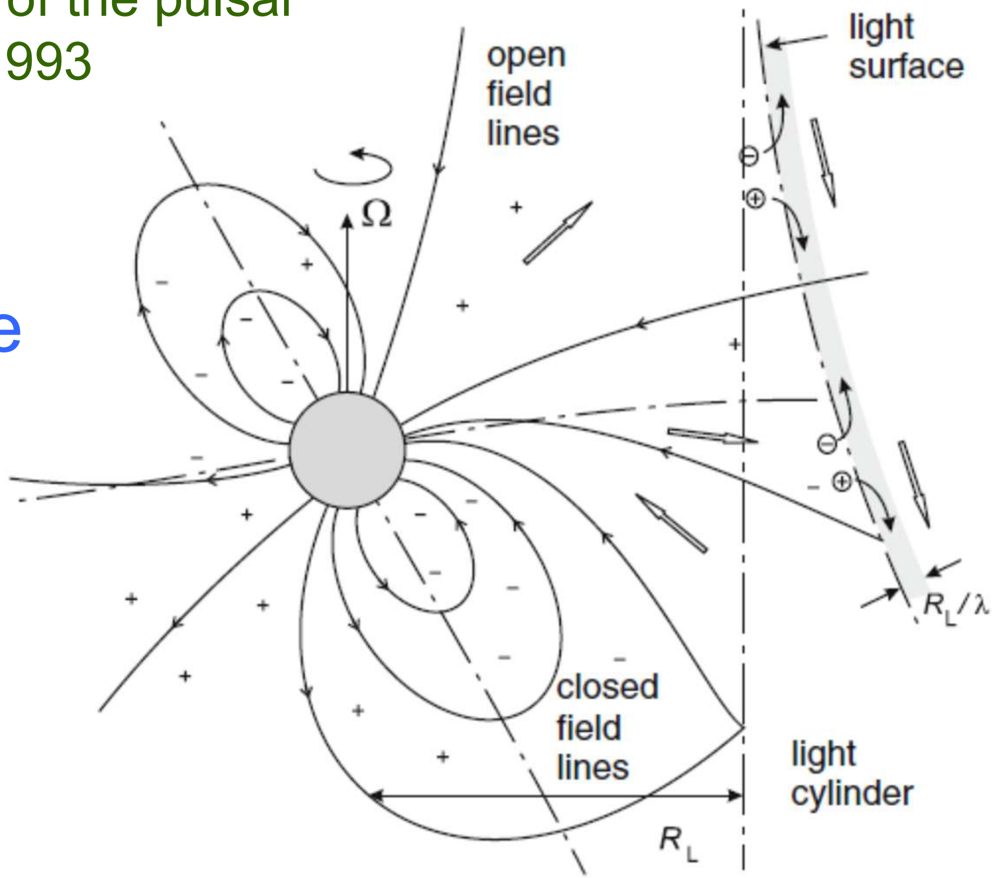
Dissipation layer
in radio pulsars



L.Mestel, S.Shibata,
MNRAS, **271**, 621 (1994)

BGI

VSB. A.B.Gurevich. Ya.N.Istomin. Physics of the pulsar magnetosphere, Cambridge Univ. Press, 1993



- Goldreich-Julian current
- Light surface at finite distance
- Effective acceleration up to

  $\Gamma \sim \sigma_M$

- Energy losses

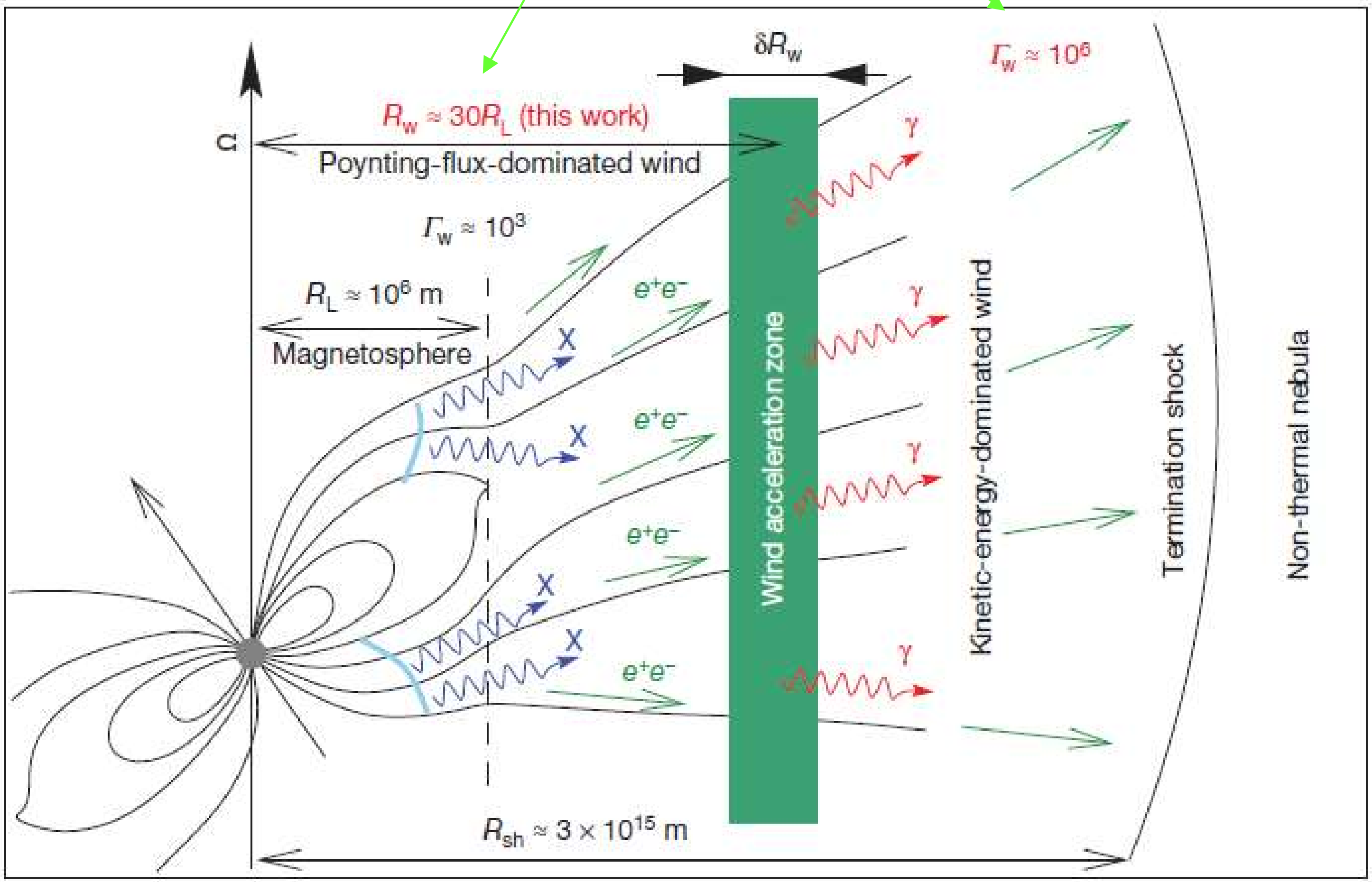
- $$W_{\rm tot}^{\rm (BGI)} = i_{\rm s}^{\rm A}(\Omega, B)\,\frac{f_*^2(\chi)}{4}\,\frac{B_0^2\Omega^4R^6}{c^3}\,\cos^2\chi$$

LETTER

doi:10.1038/nature10793

Abrupt acceleration of a 'cold' ultrarelativistic wind from the Crab pulsar

F. A. Aharonian[1,2], S. V. Bogovalov[3] & D. Khangulyan[4]



LETTER

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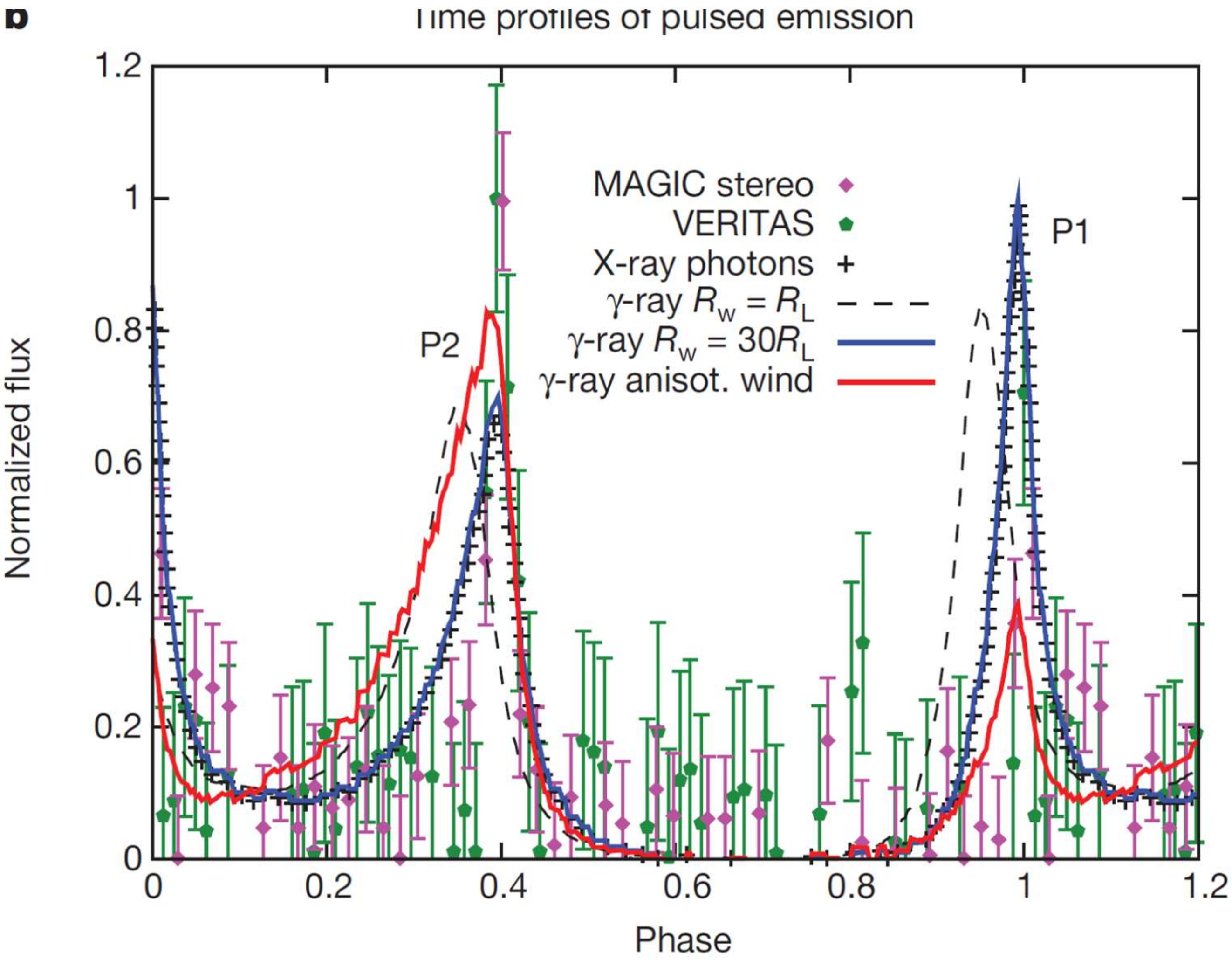


VB – N.Vlahakis, private communication (2007)

>It's so nice your results are in agreement with our
> analytical calculations.

Yes, it is nice that the situation is pretty clear now.

Only two first steps…

- Force-free
- MHD σ
- Two-fluid λ
- Radiation drag l_a
-
-
-

- **Reality**

$$\sigma = \frac{\Omega^2 \Psi_{\rm tot}}{8\pi^2 c^2 \mu\eta}$$

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

Only two first steps…

- Force-free
- MHD — σ
- Two-fluid — λ
- Radiation drag — l_a
- PIC
-
-

- **<u>Reality</u>**

$$\sigma = \frac{\Omega^2 \Psi_{\rm tot}}{8\pi^2 c^2 \mu \eta}$$

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

Two-fluid effects

VSB, R.R.Rafikov, MNRAS, **313**, 433 (2000)
VSB, N.L.Zakamska, H.Sol, MNRAS, **347**, 587 (2004)

Force-free (or MHD) correction

$$n^{+} = \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda - K(r_\perp) + \eta^{+}(r_\perp, z)\right],$$

$$n^{-} = \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda + K(r_\perp) + \eta^{-}(r_\perp, z)\right],$$

$$v_z^{\pm} = c\left[1 - \xi_z^{\pm}(r_\perp, z)\right],$$

$$v_r^{\pm} = c\xi_r^{\pm}(r_\perp, z),$$

$$v_\varphi^{\pm} = c\xi_\varphi^{\pm}(r_\perp, z).$$

$$\Phi(r_\perp, z) = \frac{B_0}{c}\left[\int_0^{r_\perp}\Omega_{\rm F}(r')r'\,{\rm d}r' + \Omega_0 r_\perp^2\delta(r_\perp, z)\right],$$

$$\Psi(r_\perp, z) = \pi B_0 r_\perp^2\left[1 + f(r_\perp, z)\right].$$

$$-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = 2(\eta^{+} - \eta^{-}) - 2\left[(\lambda - K)\xi_z^{+} - (\lambda + K)\xi_z^{-}\right],$$

$$2(\eta^{+} - \eta^{-}) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right] + r_\perp^2\frac{\partial^2\delta}{\partial z^2} = 0,$$

$$r_\perp\frac{\partial\zeta}{\partial z} = 2\left[(\lambda - K)\xi_r^{+} - (\lambda + K)\xi_r^{-}\right], \qquad (43)$$

$$-r_\perp^2\frac{\partial^2 f}{\partial z^2} - r_\perp\frac{\partial}{\partial r_\perp}\left[\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left(r_\perp^2 f\right)\right] = 4\frac{\Omega_0 r_\perp}{c}\left[(\lambda - K)\xi_\varphi^{+} - (\lambda + K)\xi_\varphi^{-}\right], \qquad (44)$$

$$\frac{\partial}{\partial z}\left(\xi_r^{+}\gamma^{+}\right) = -\xi_r^{+}F_{\rm d}(\gamma^{+})^2 + 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left[-\frac{\partial}{\partial r_\perp}(r_\perp^2\delta) + r_\perp\zeta - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_z^{+} + \frac{c}{\Omega_0}\xi_\varphi^{+}\right], \qquad (45)$$

$$\frac{\partial}{\partial z}\left(\xi_r^{-}\gamma^{-}\right) = -\xi_r^{-}F_{\rm d}(\gamma^{-})^2 - 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left[-\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right) + r_\perp\zeta - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_z^{-} + \frac{c}{\Omega_0}\xi_\varphi^{-}\right], \qquad (46)$$

$$\frac{\partial}{\partial z}\left(\gamma^{+}\right) = -F_{\rm d}(\gamma^{+})^2 + 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_r^{+}\right), \qquad (47)$$

$$\frac{\partial}{\partial z}\left(\gamma^{-}\right) = -F_{\rm d}(\gamma^{-})^2 - 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_r^{-}\right), \qquad (48)$$

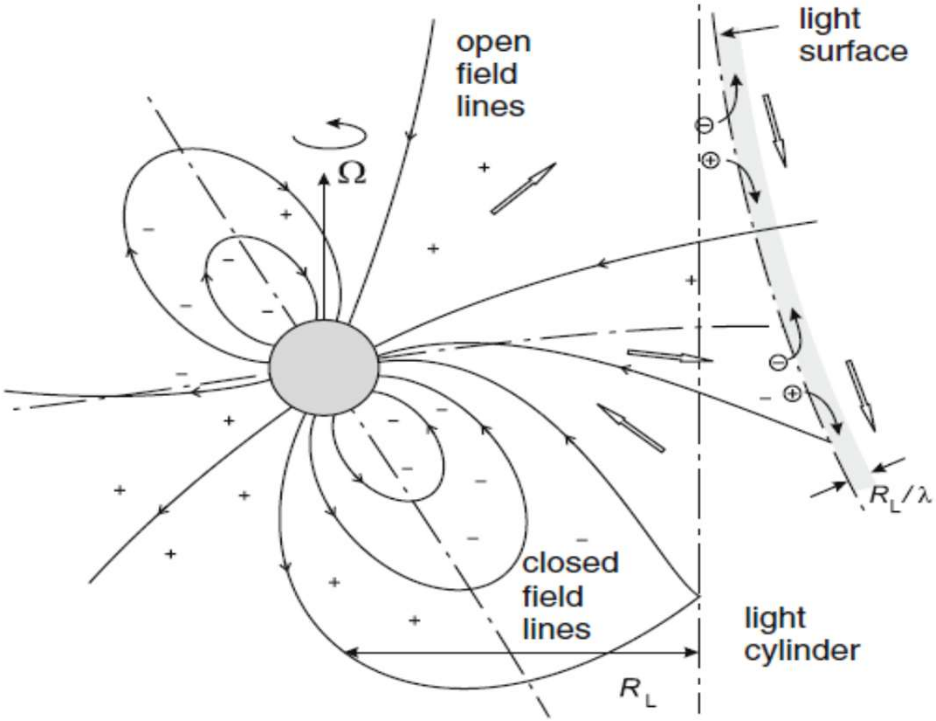
$$\frac{\partial}{\partial z}\left(\xi_\varphi^{+}\gamma^{+}\right) = -\xi_\varphi^{+}F_{\rm d}(\gamma^{+})^2 + 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-\frac{1}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^{+}\right), \qquad (49)$$

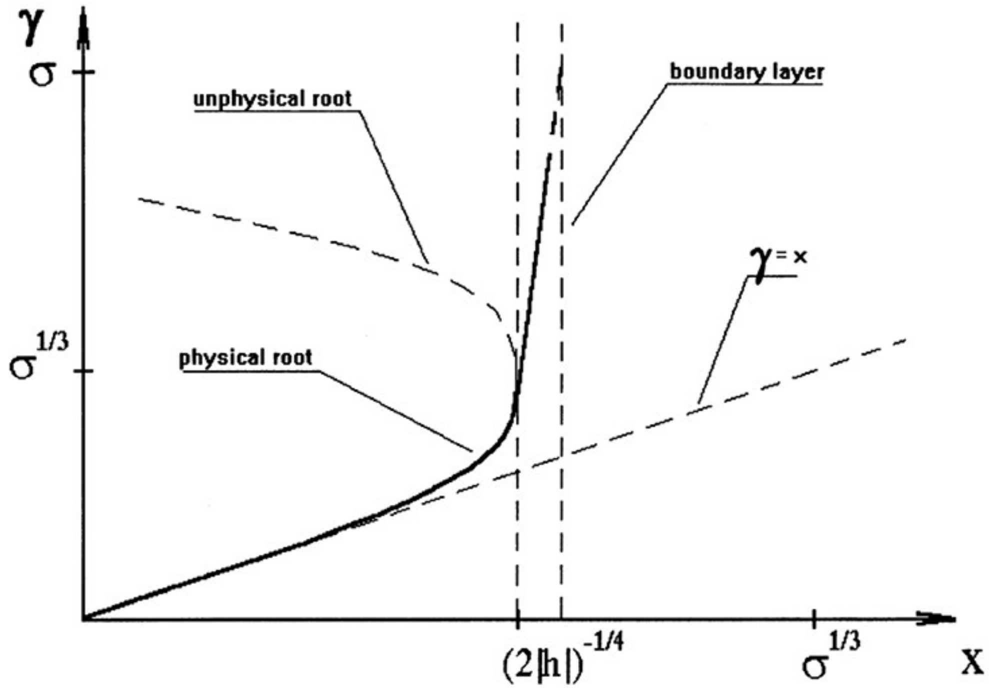
$$\frac{\partial}{\partial z}\left(\xi_\varphi^{-}\gamma^{-}\right) = -\xi_\varphi^{-}F_{\rm d}(\gamma^{-})^2 - 4\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-\frac{1}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^{-}\right). \qquad (50)$$

Two-fluid effects

VSB, R.R.Rafikov, MNRAS, **313**, 433 (2000)

Adrupt acceleration





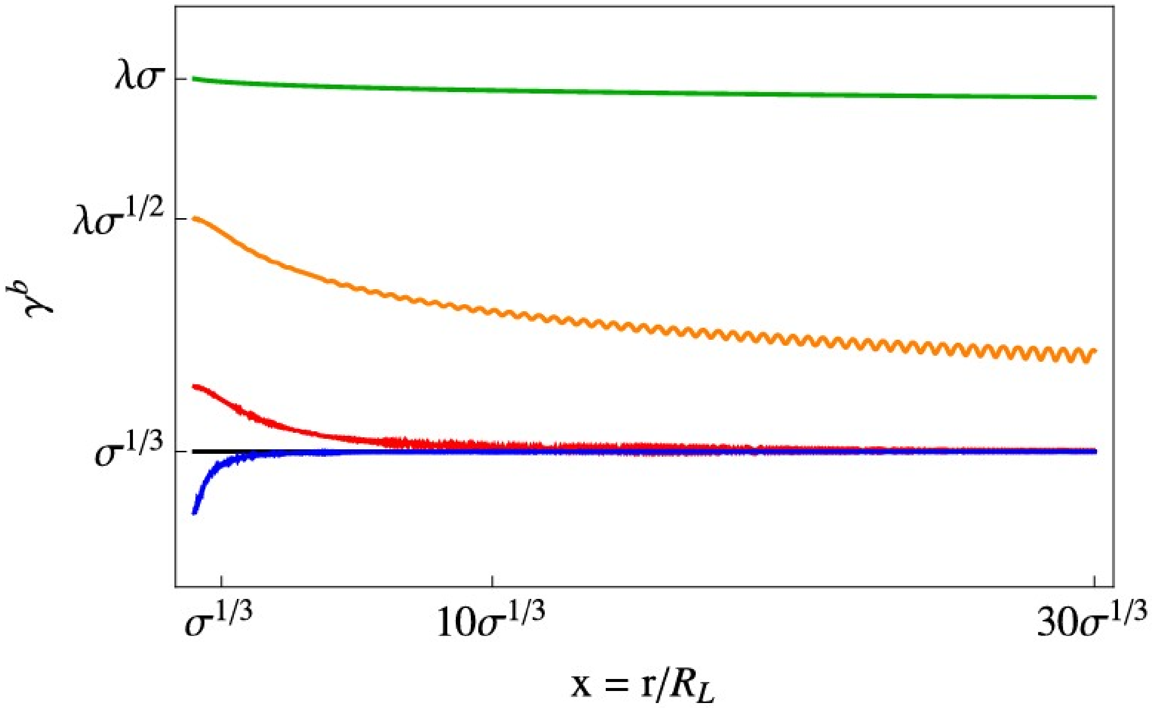
Two-fluid effects

V.V.Prokofev, L.I.Arzamasskiy, VSB, MNRAS, **454**, 2146 (2015)

Primary beam

vs

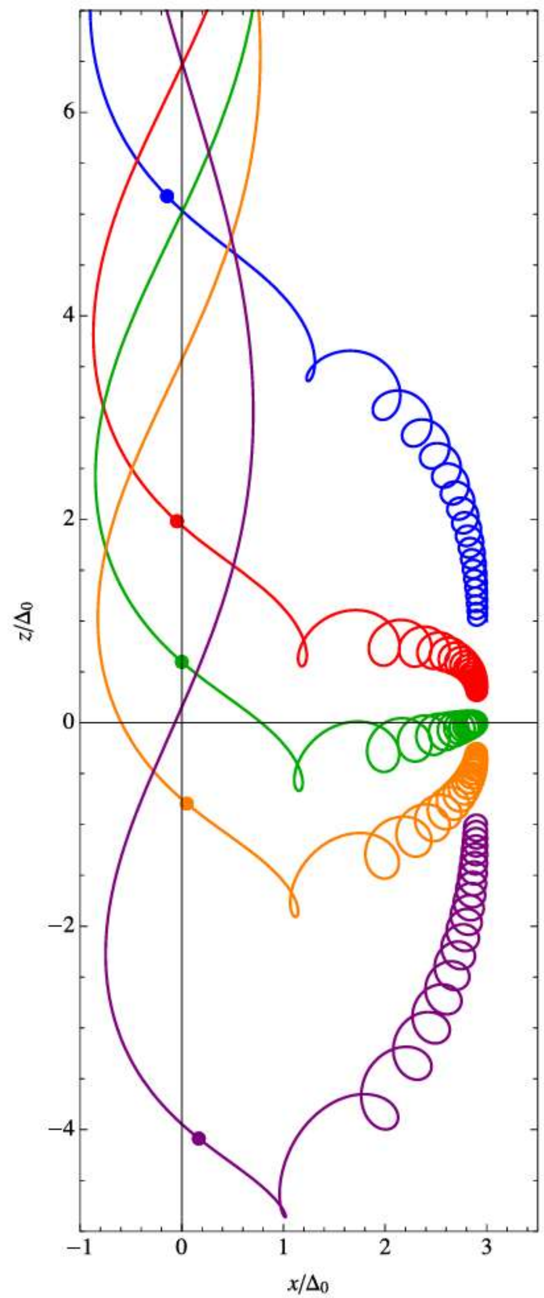
Fundamental theorem – outside R_{L} hydrodynamical Lorentz-factor Γ corresponds exactly to the drift velocity (N.Vlahakis 2004, VB 2005, Tchekhovskoy et al 2008, VB 2010).



Two-fluid effects

V.V.Prokofev, L.I.Arzamasskiy, VSB, MNRAS, **474**, 1526 (2018)

Time-dependent
current sheet



Two-fluid effects

VSB, A.V.Chernoglazov, MNRAS, **463**, 3398 (2016)

Photon drag

0. Drag force → radial current

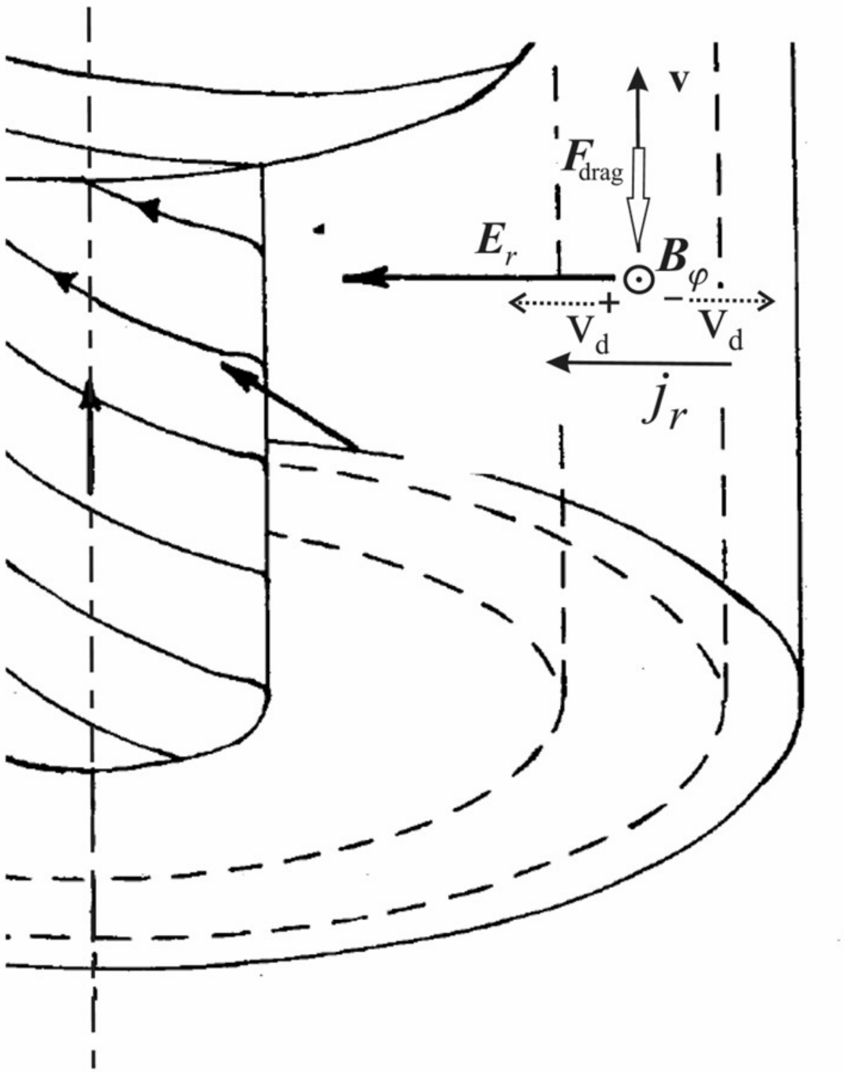
$$V_{\rm d} \sim c\frac{F_{\rm drag}}{eB_{\varphi}}$$

$$j_r \sim \lambda \rho_{\rm GJ} V_{\rm d},$$

1. Radial current → dissipation

$$\mathrm{div}(\mathbf{S}_{\rm em} + \mathbf{S}_{\rm part}) = -n_{\rm e} m c^2 F_{\rm d}$$

$$\frac{\delta S_{\rm part}}{\delta S_{\rm em}} = \frac{1}{1+x^2}$$



Two-fluid effects

VSB, A.V.Chernoglazov, MNRAS, **463**, 3398 (2016)

Photon drag

0. Drag force → radial current

$$V_{\rm d} \sim c\frac{F_{\rm drag}}{eB_\varphi}$$

$$j_r \sim \lambda\rho_{\rm GJ}V_{\rm d},$$

2. Force-free → MHD

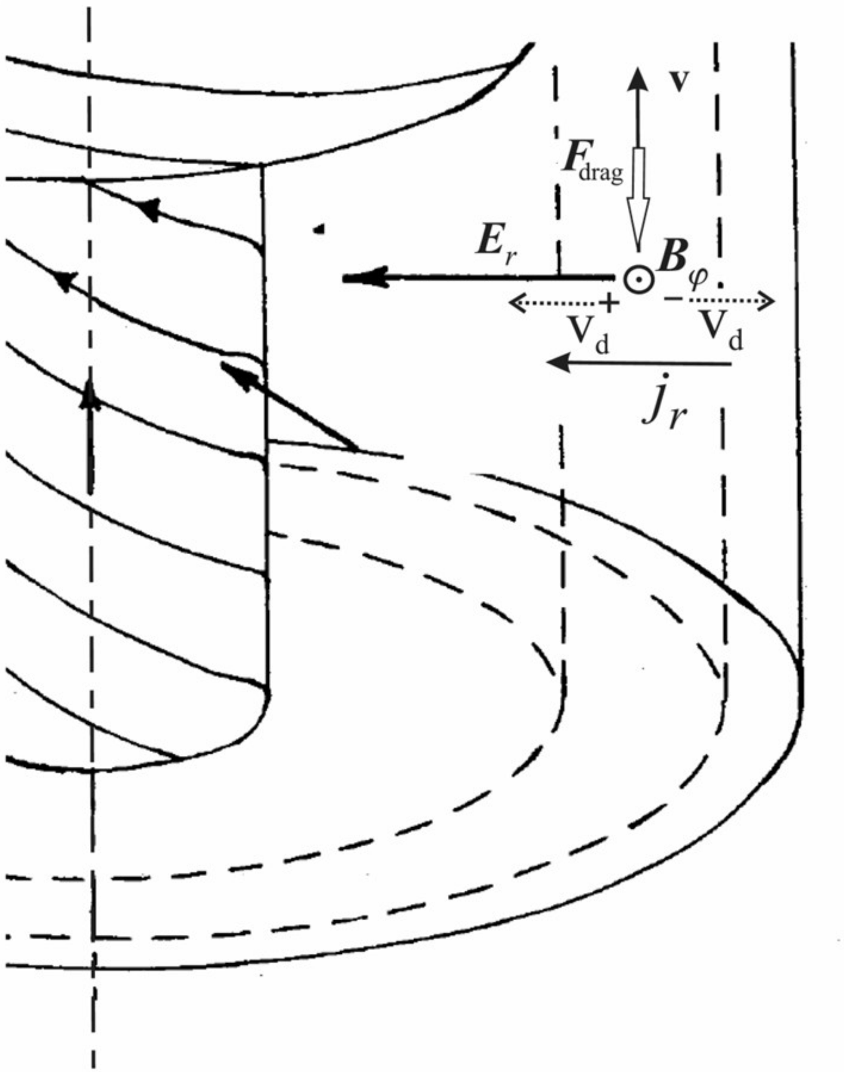
$$v_z^{\pm} = c\left[1 - \xi_z^{\pm}(r_\perp, z)\right],$$

$$v_r^{\pm} = c\xi_r^{\pm}(r_\perp, z),$$

$$v_\varphi^{\pm} = c\xi_\varphi^{\pm}(r_\perp, z).$$

The same ***E*** and ***B*** if

$$\xi_\varphi^{\pm} = x\xi_z^{\pm}$$



Two-fluid effects

VSB, A.V.Chernoglazov, MNRAS, **463**, 3398 (2016)

Photon drag

0. Drag force → radial current

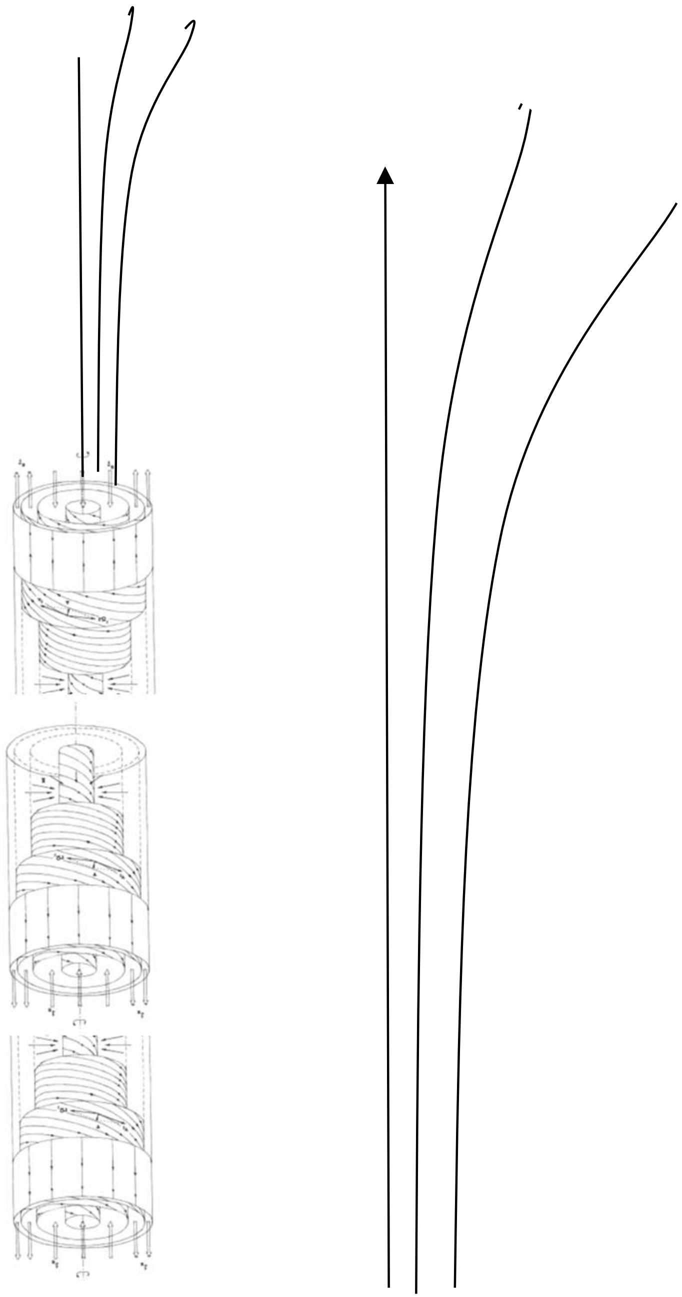
$$V_{\rm d} \sim c\frac{F_{\rm drag}}{eB_\varphi}$$

$$j_r \sim \lambda\rho_{\rm GJ}V_{\rm d},$$

3. Equipotentiality

$$\Phi(r_\perp, z) = \frac{B_0}{c}\left[\int_0^{r_\perp}\Omega_{\rm F}(r')r'\,{\rm d}r' + \Omega_0 r_\perp^2\delta(r_\perp, z)\right],$$

$$\Psi(r_\perp, z) = \pi B_0 r_\perp^2\left[1 + f(r_\perp, z)\right]$$

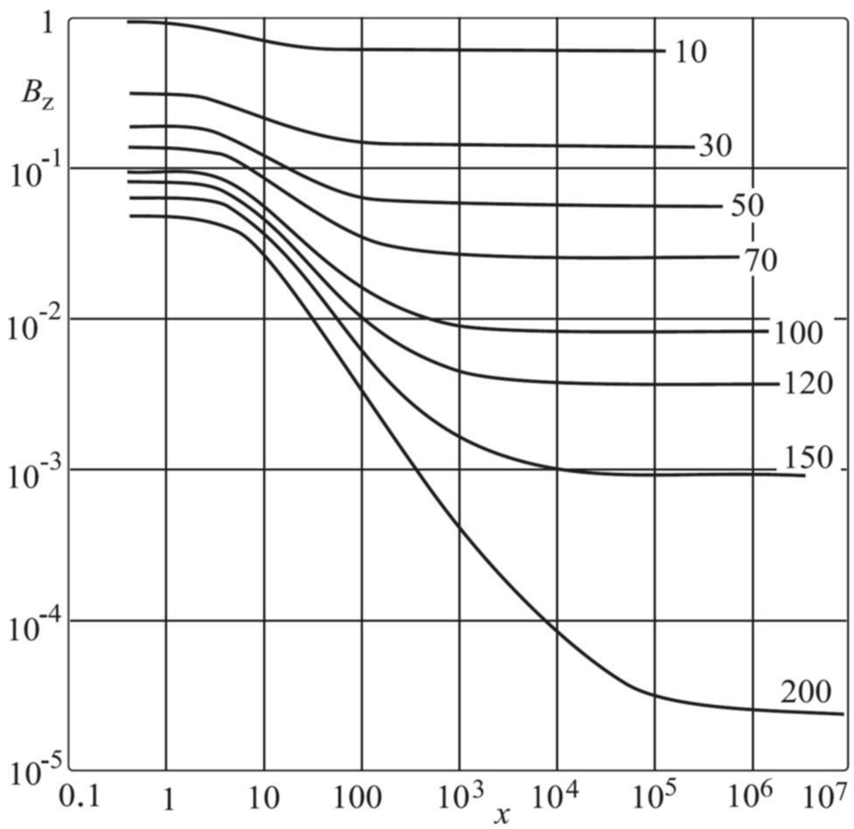


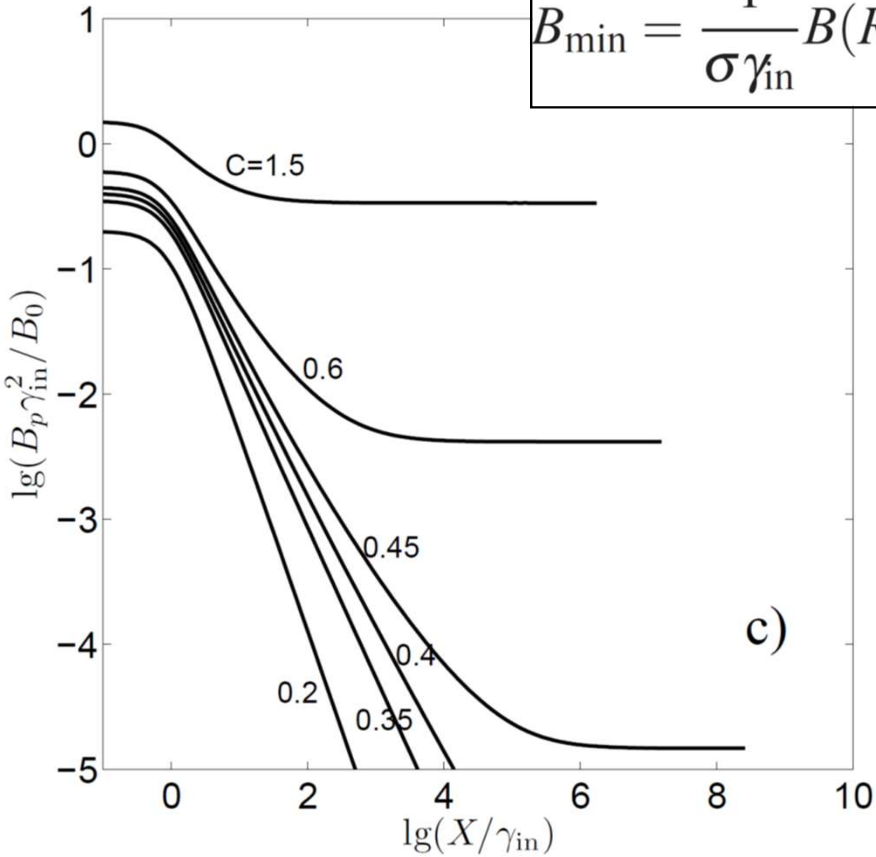
Central core

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

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

$$B_{\min} = \frac{1}{\sigma \gamma_{\text{in}}} B(R_{\text{L}})$$

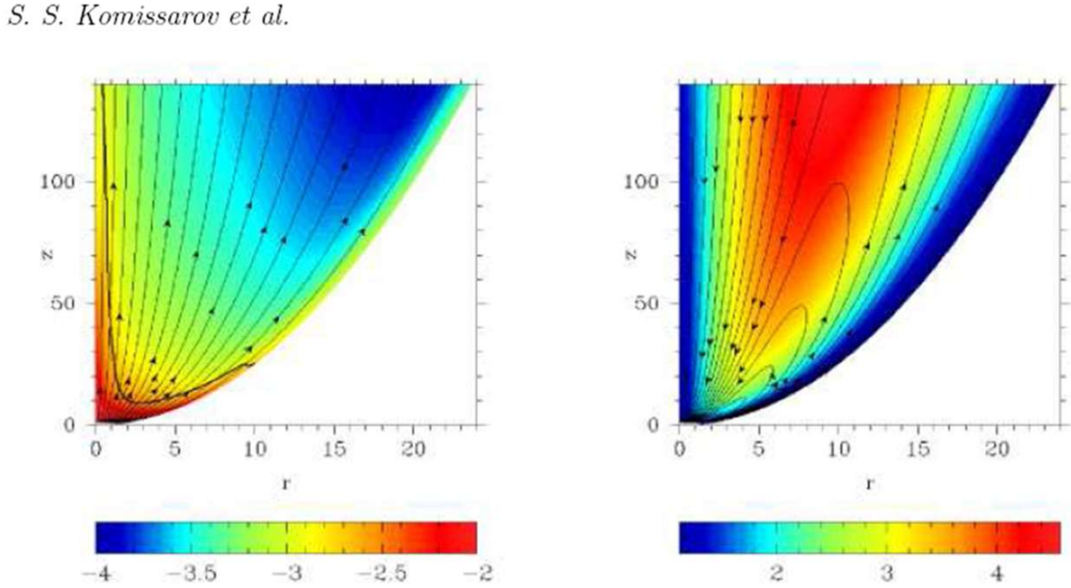




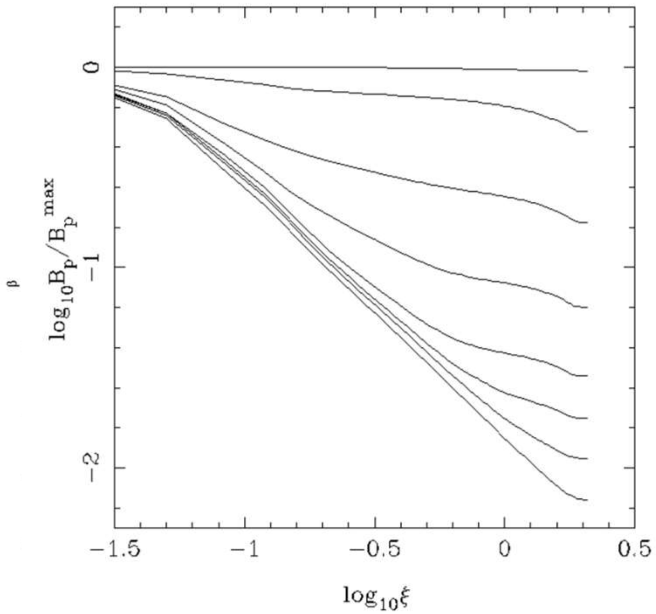
VB, E.E.Nokhrina,
MNRAS, **389**, 335 (2007)
MNRAS, **397,** 1486 (2009)

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

Central core



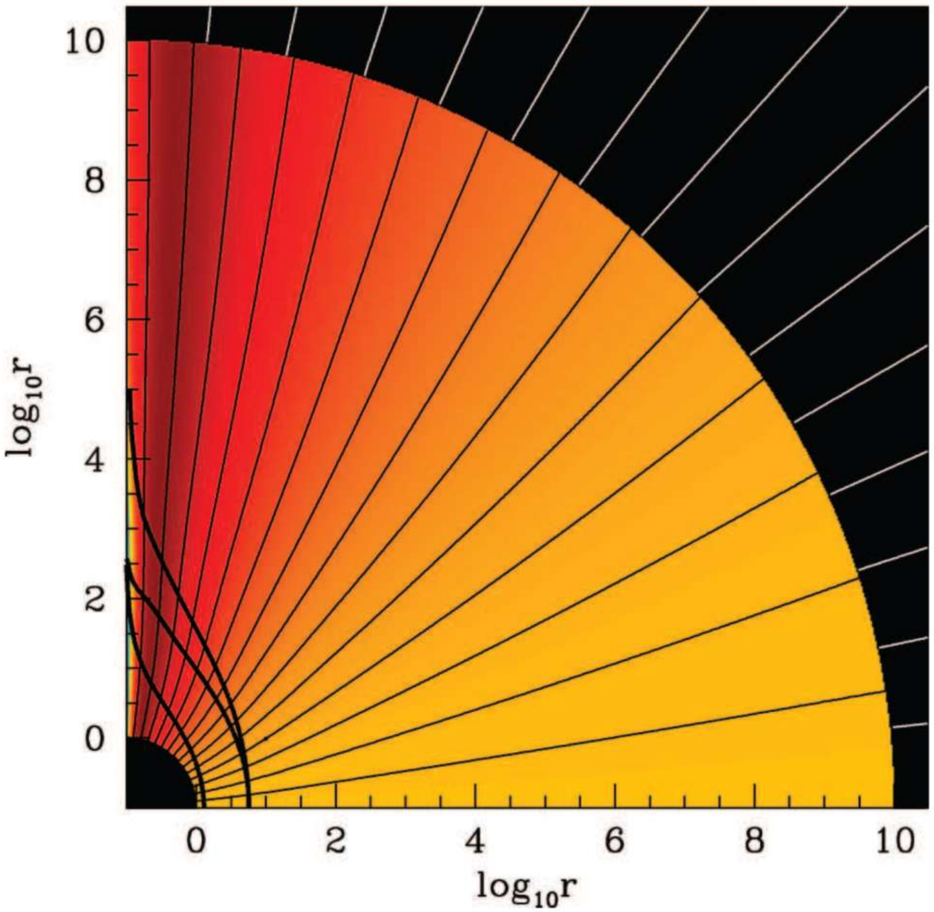
$$B_{\min} = \frac{1}{\sigma_M \gamma_{\rm in}} B(R_{\rm L})$$

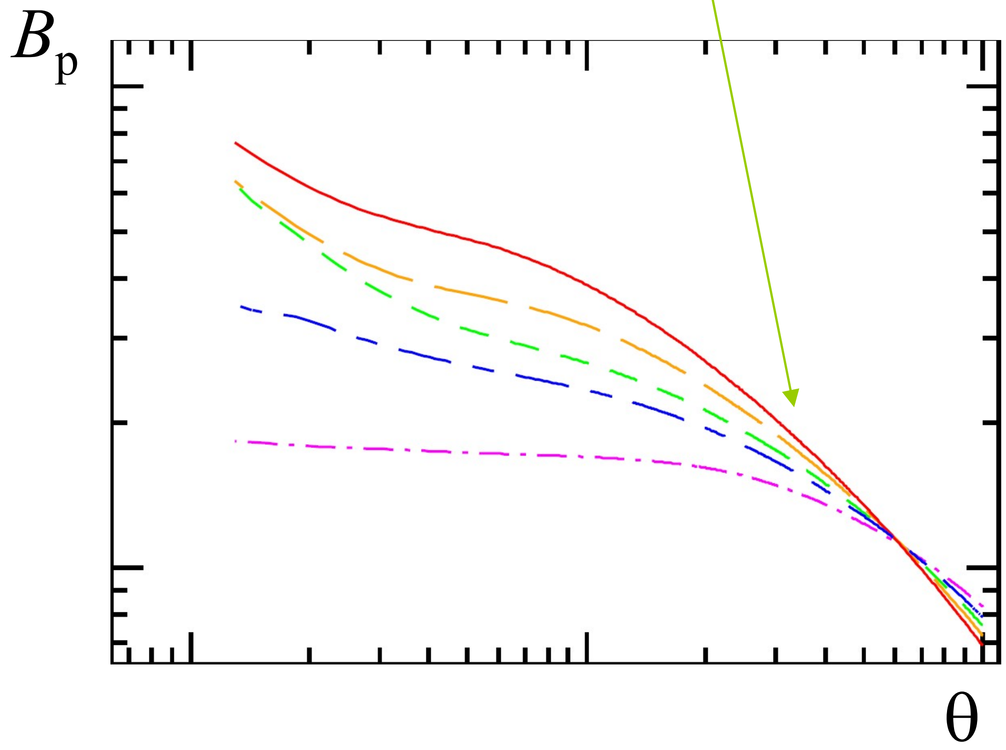


S.Komissarov, M.Barkov, N.Vlahakis, A.Königl, MNRAS, **380**, 51 (2006)

Central core

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





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

Central core

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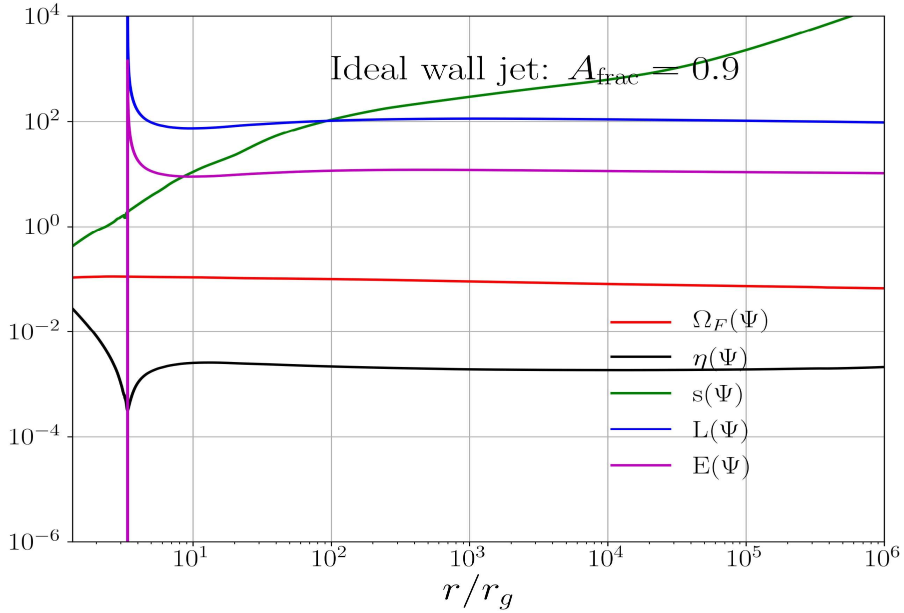
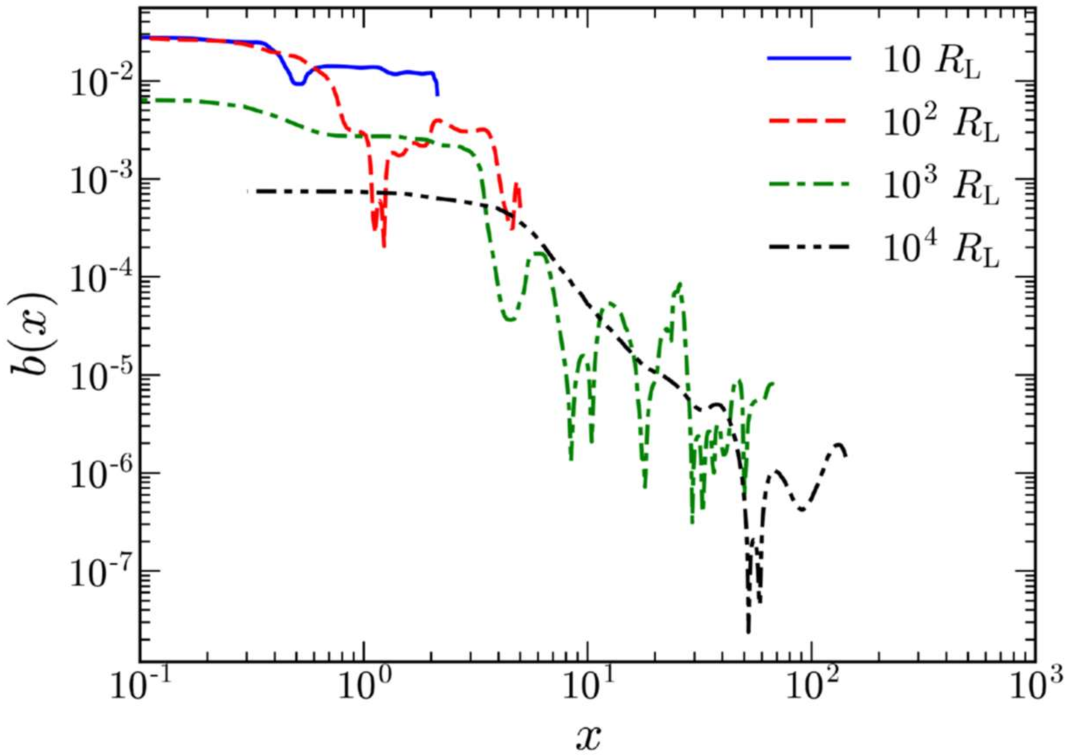
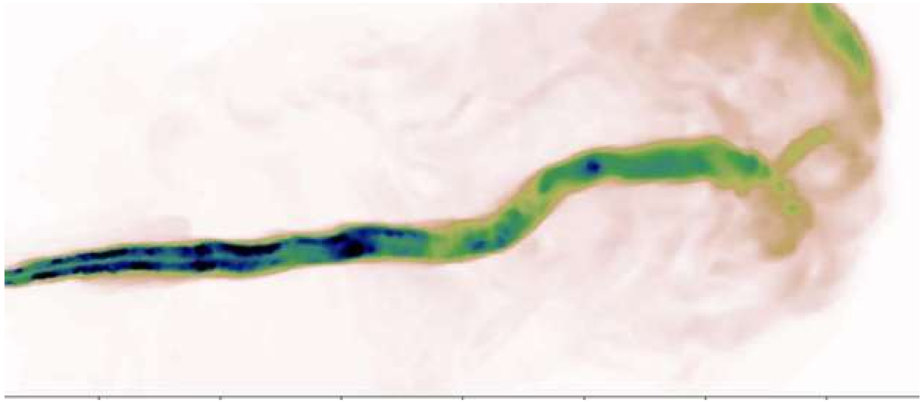
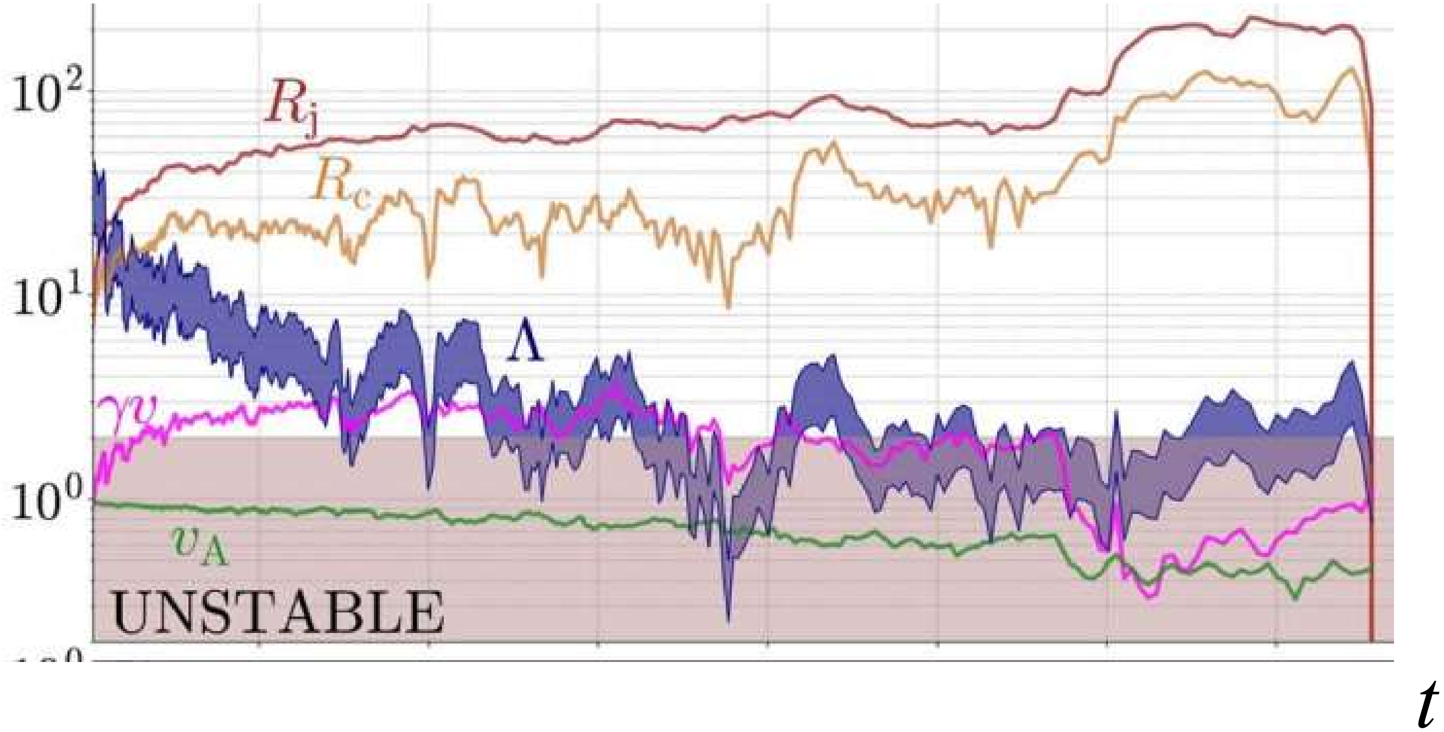




Central core

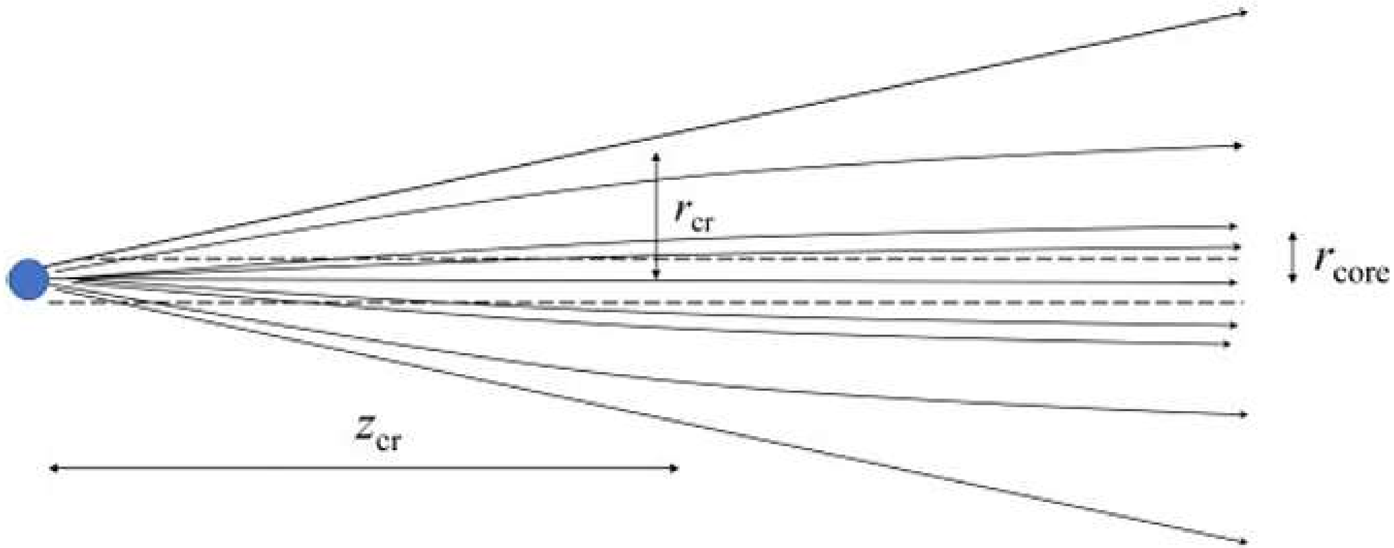
A.Lalakos, A.Tchekhovskoy, O.Bromberg, O.Gottlieb, J.Jacquemin-Ide, M.Liska, H.Zhang
ApJ, **964, 79** (2024)

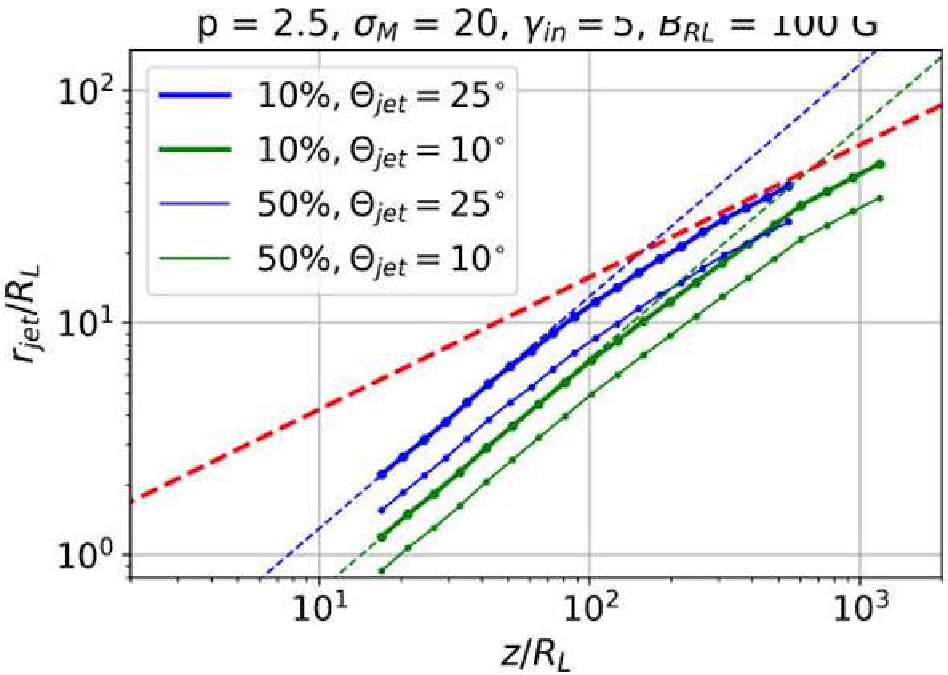


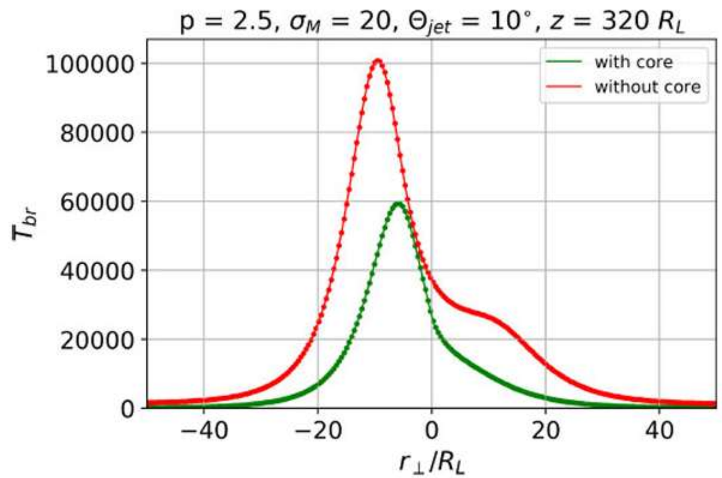


Central core

VSB, T.I.Khalilov, E.E.Nokhrina, I.N.Pashchenko,E.V.Kravchenko, MNRAS, **528**, 6046 (2024)







Central core

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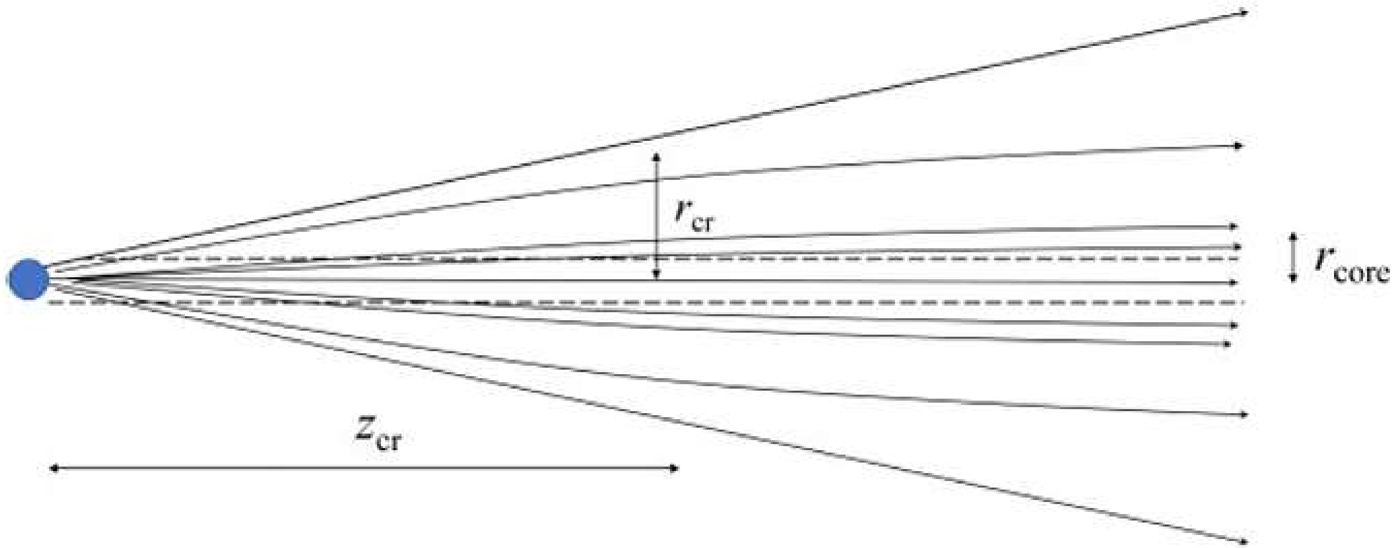
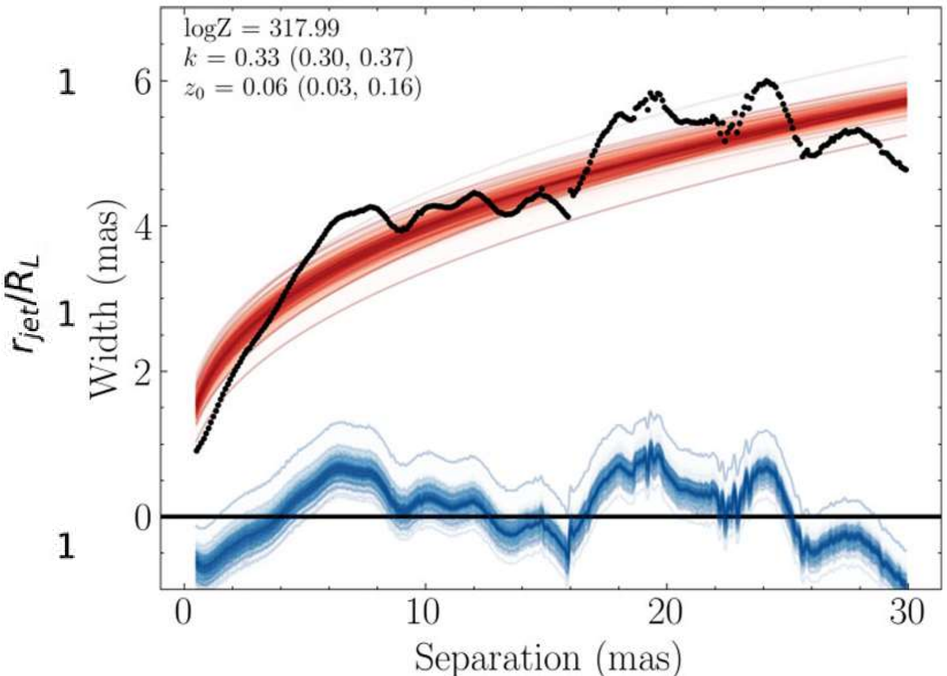
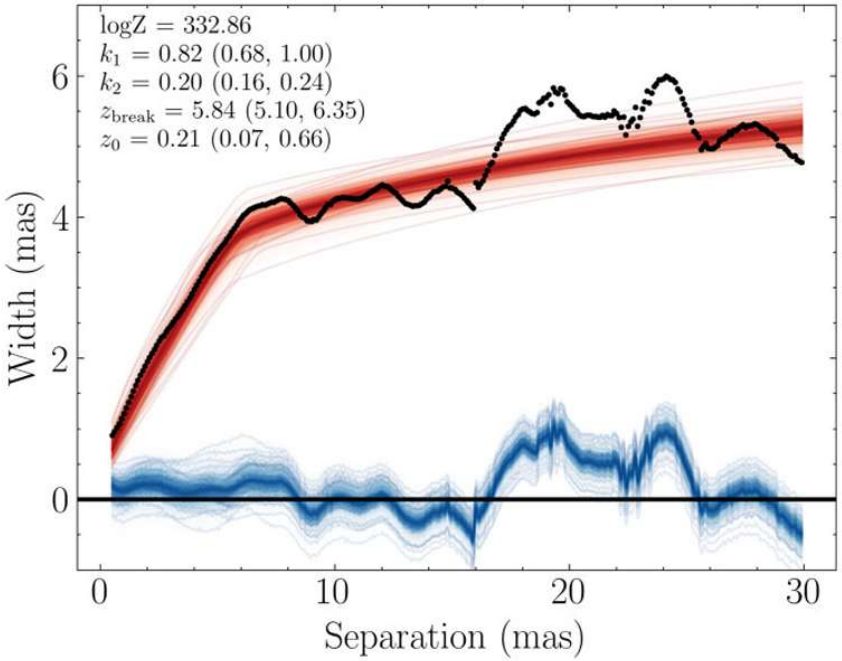
MNRAS, **528**, 6046 (2024)







Conclusion

In radio pulsars there are three gaps

- inner gap
- outer gap
- the gap between the theorist and observers

In relativistic jets there are no serious gaps

- inner structure of jets both theoretically and observationally


ありがとう、日本!