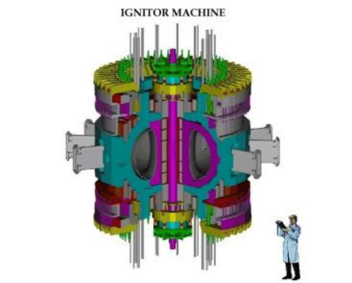
Features of the particle acceleration in compact astrophysical objects

V.S.Beskin

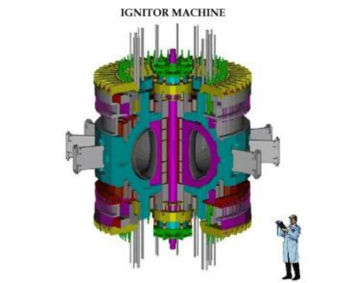
Lebedev Physical Institute, Moscow



Features of the b particle acceleration in compact astrophysical objects

V.S.Beskin

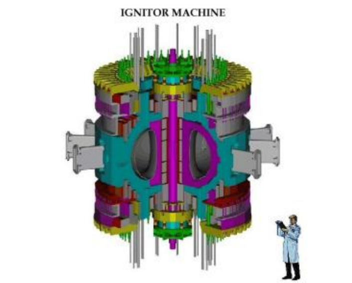
Lebedev Physical Institute, Moscow



Features of the bu particle acceleration in compact astrophysical objects

V.S.Beskin

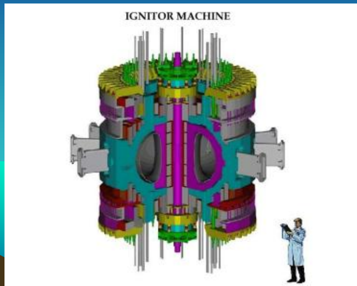
Lebedev Physical Institute, Moscow



Features of the bul particle acceleration in compact astrophysical objects

V.S.Beskin

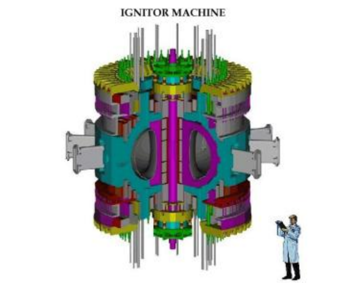
Lebedev Physical Institute, Moscow



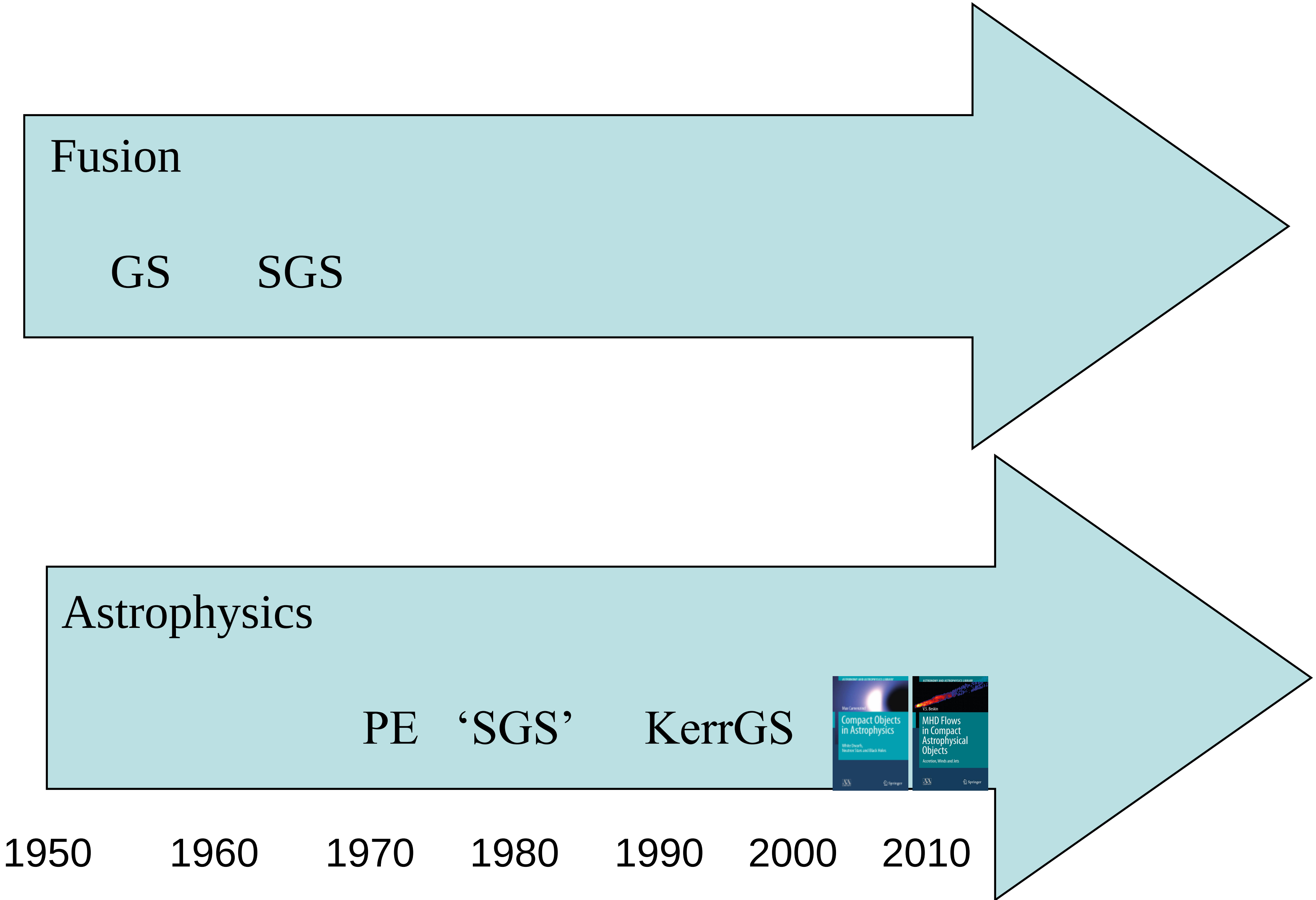
Features of the bulk particle acceleration in compact astrophysical objects

V.S.Beskin

Lebedev Physical Institute, Moscow



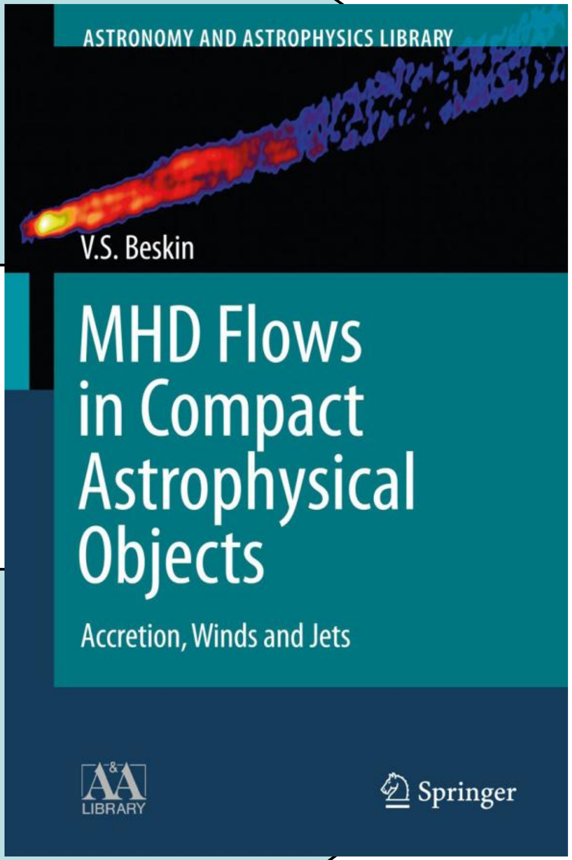
Fusion & Astrophysics



Fusion & Astrophysics

Fusion

GS SGS

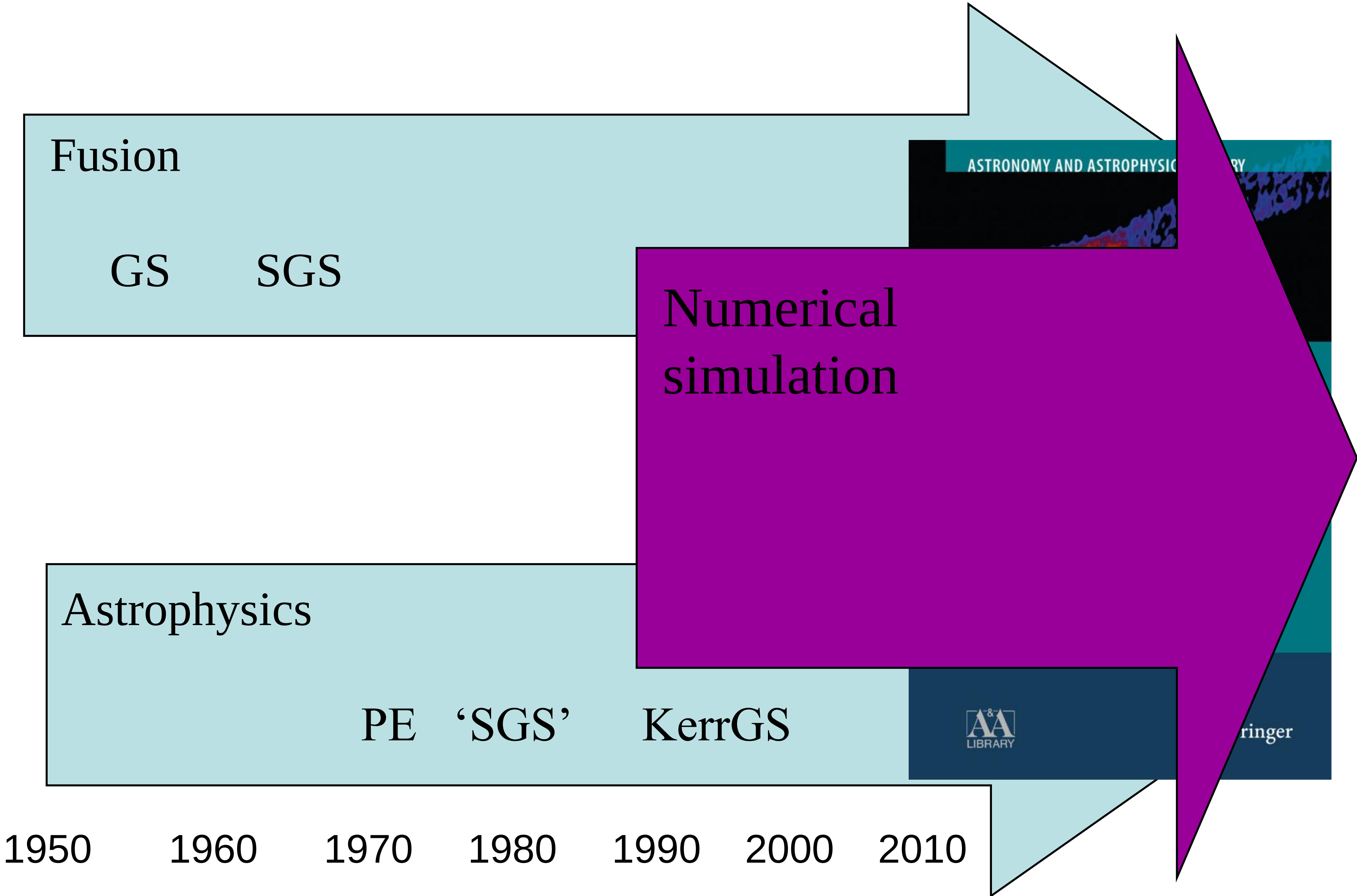


Astrophysics

PE ‘SGS’ KerrGS

1950 1960 1970 1980 1990 2000 2010

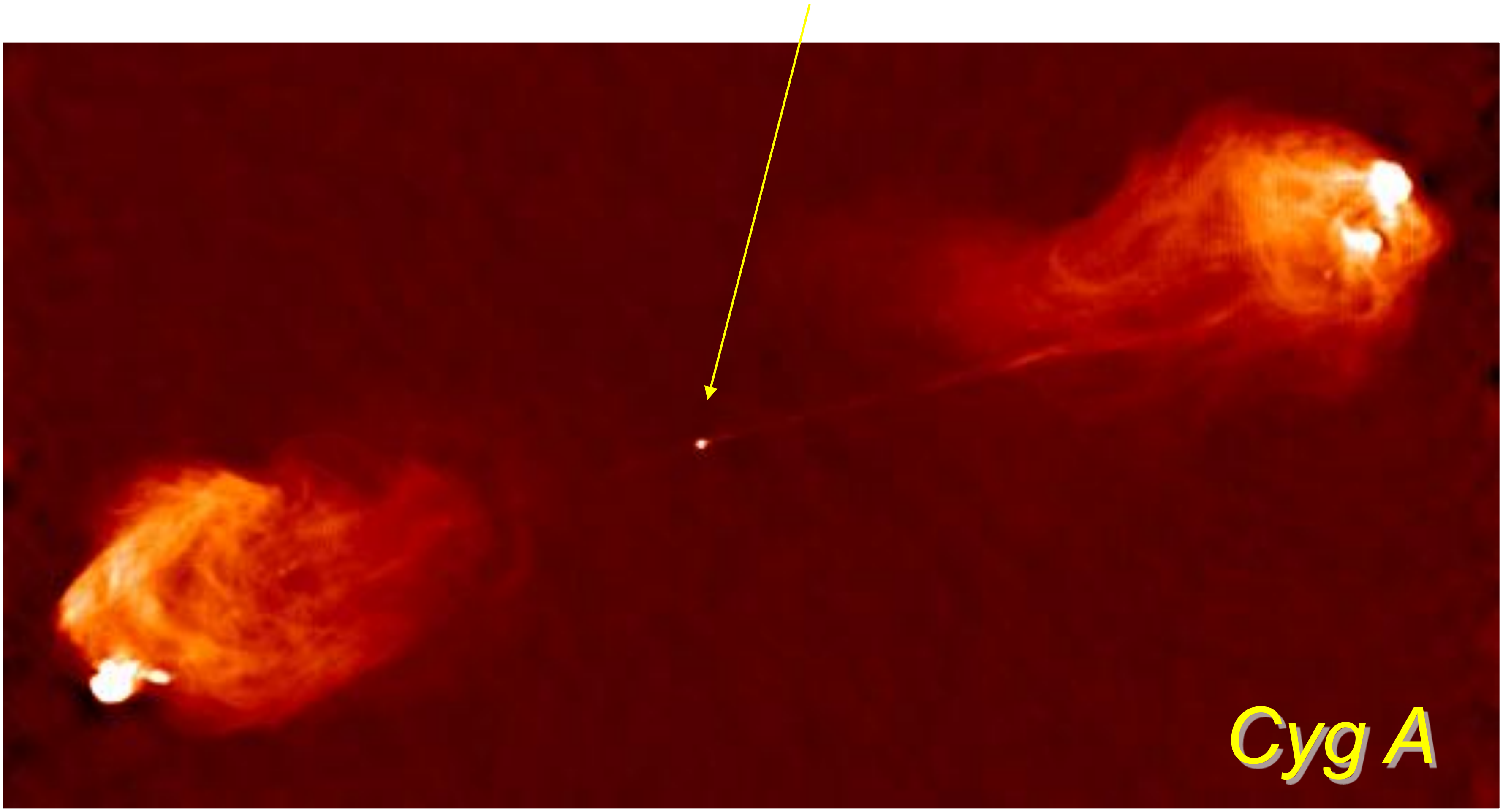
Fusion & Astrophysics



What do we see

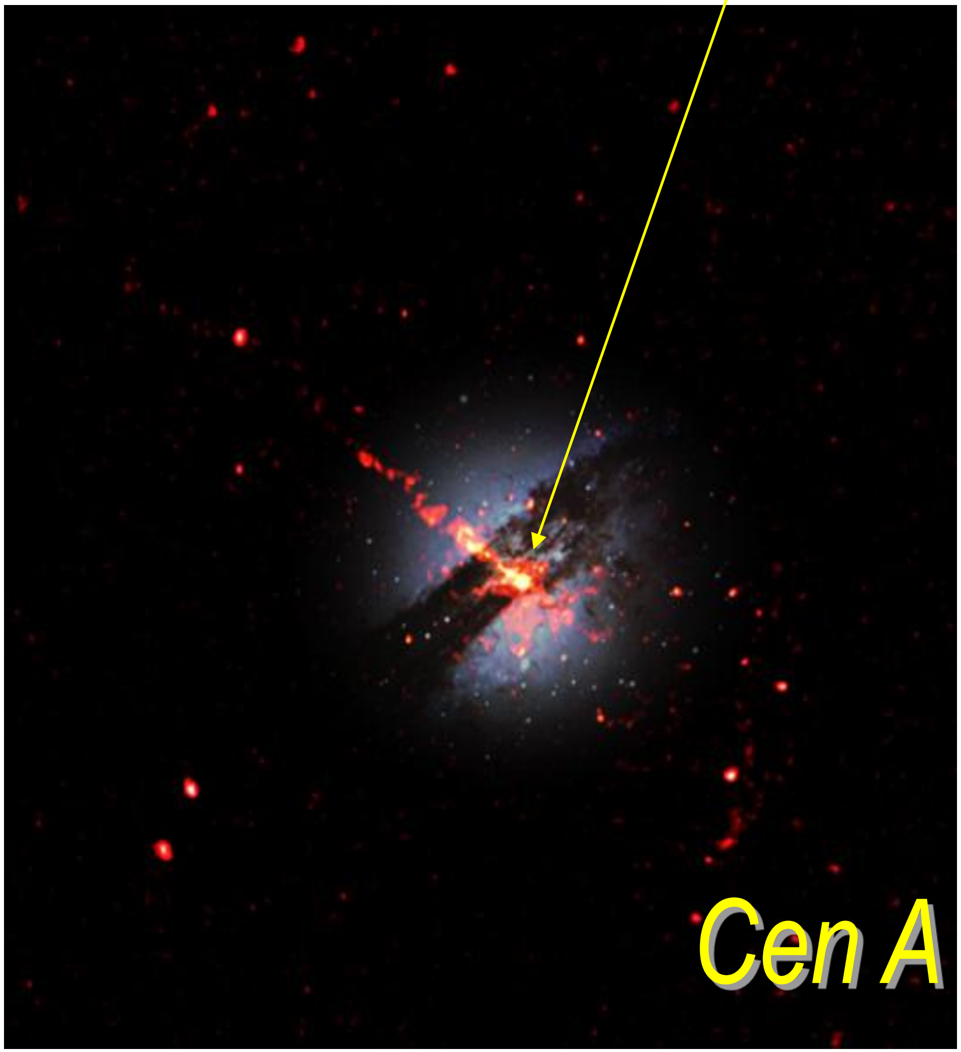
Active Galactic Nuclei (AGN)

$M \sim (10^6 – 10^9) M_\odot , \quad R \sim (10^{10} – 10^{13})$ cm

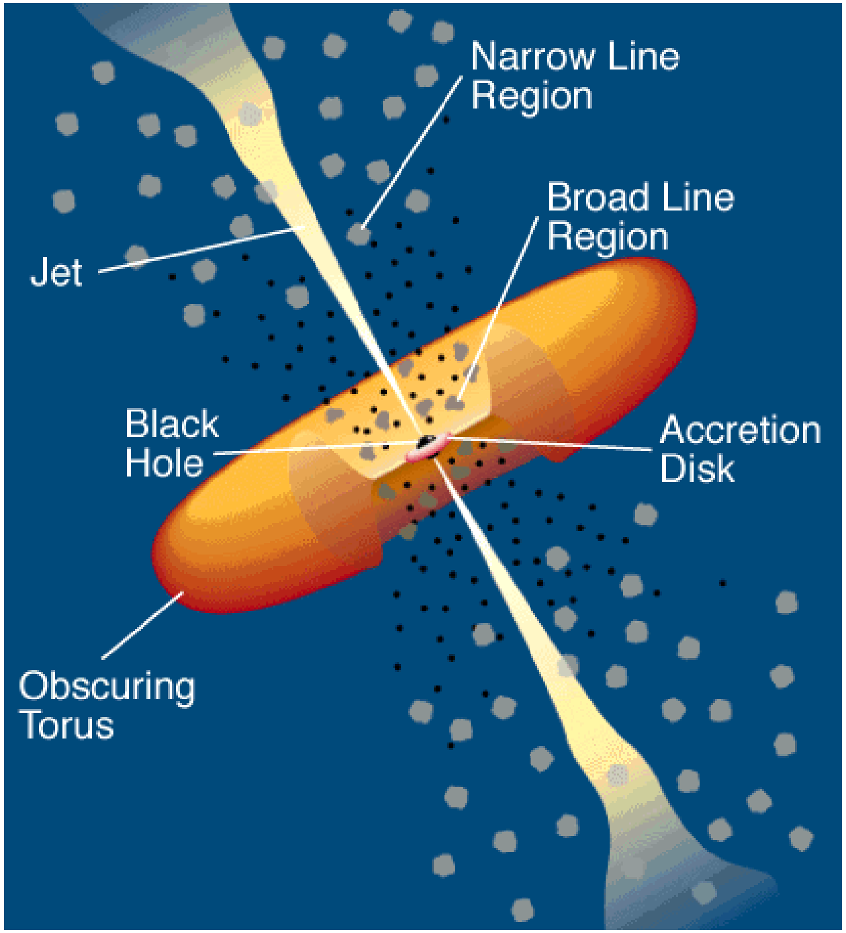


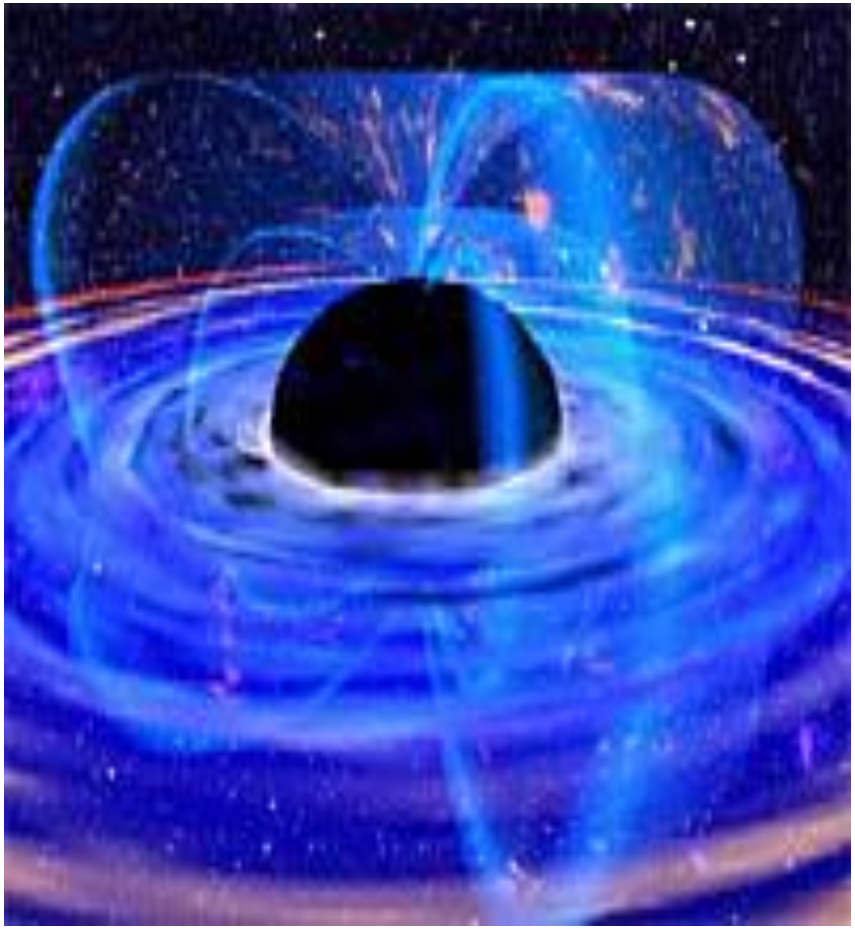
Active Galactic Nuclei (AGN)

$M \sim (10^6 - 10^9) M_\odot$, $R \sim (10^{10} - 10^{13})$cm

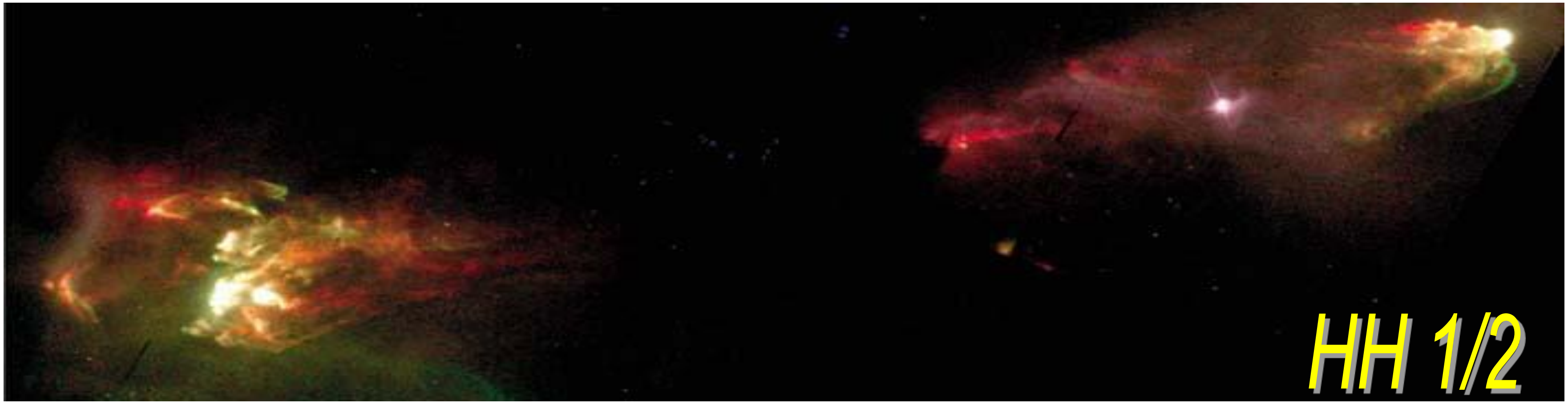


Active Galactic Nuclei (model)



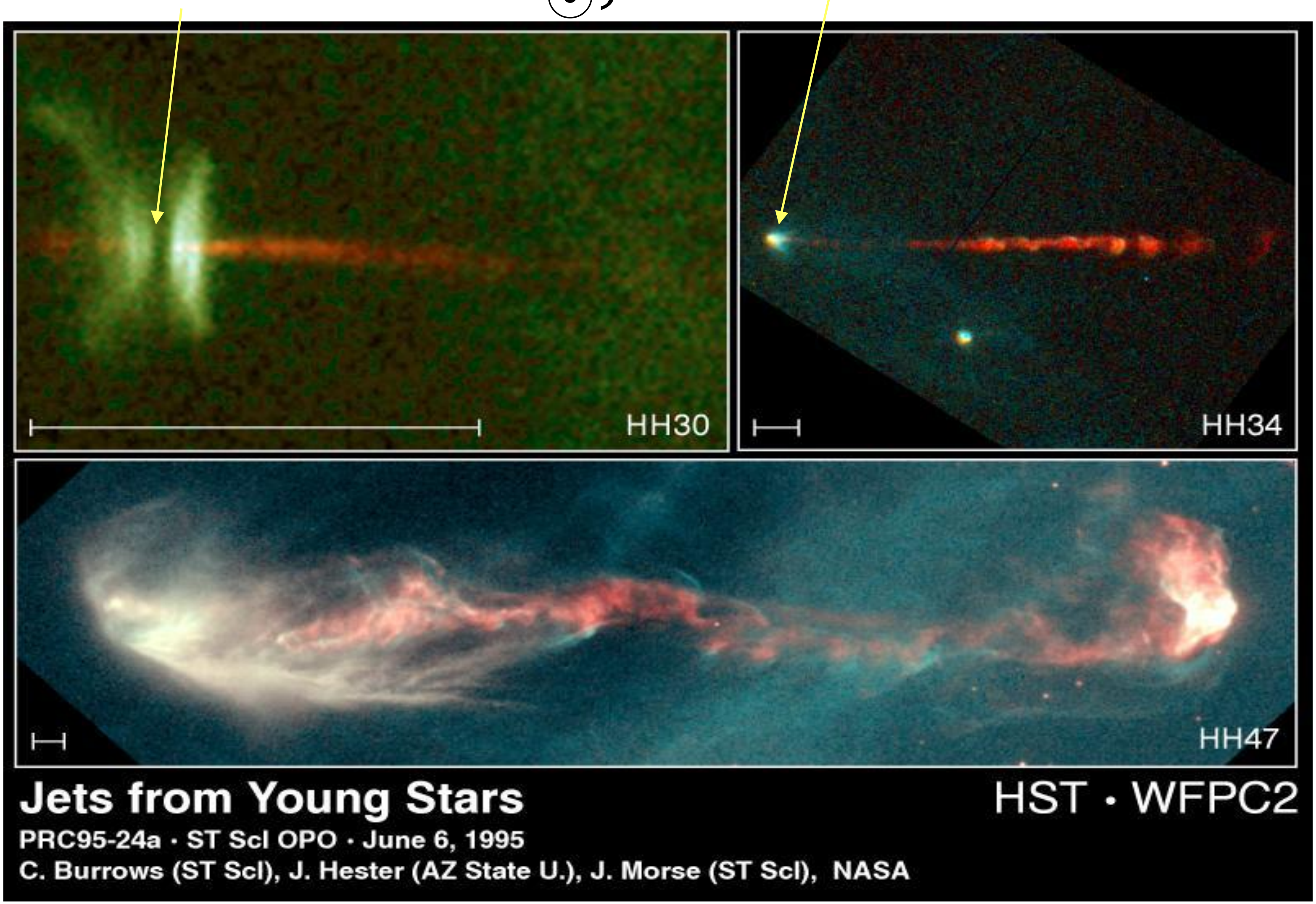


Young Stellar Objects (YSO)
$M \sim 10 M_{\odot}$, $R \sim 10^{10}$cm

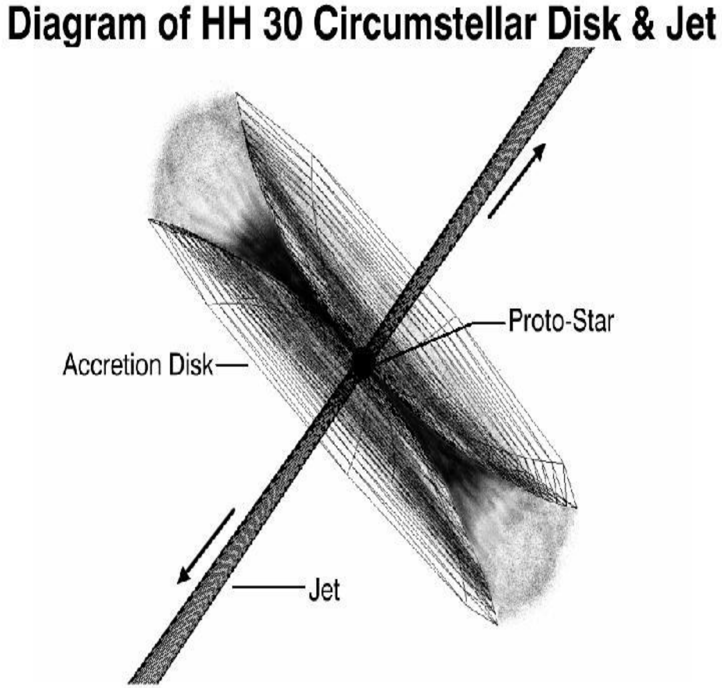


Young Stellar Objects (YSO)

$M \sim 10 M_\odot$, $R \sim 10^{10}$cm

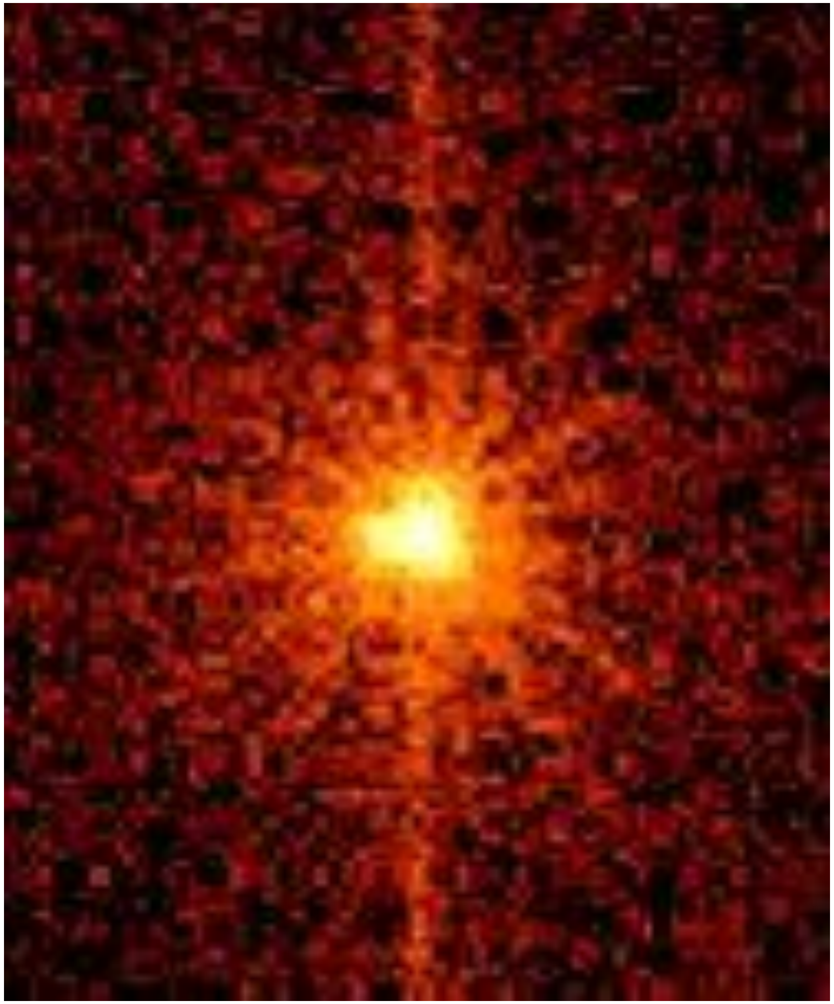


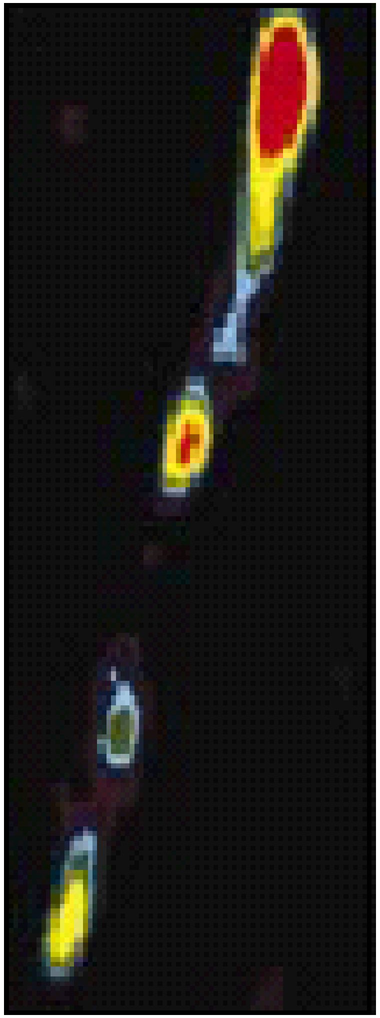
Young Stellar Objects (model)



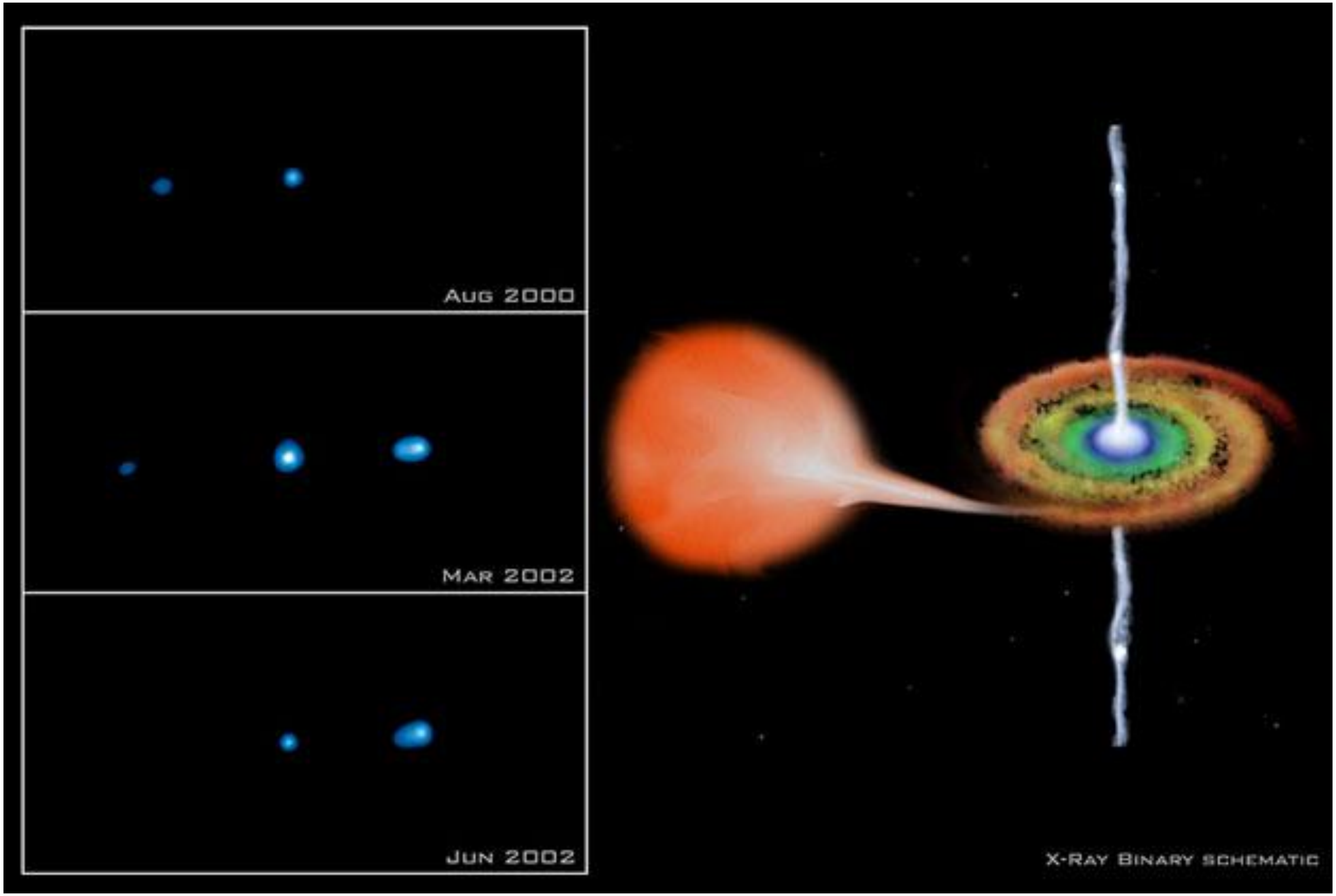
Microquasars (μQSO)

$M \sim (3\text{–}10)M_{\odot}\,,\ R \sim 10^6\text{cm}$



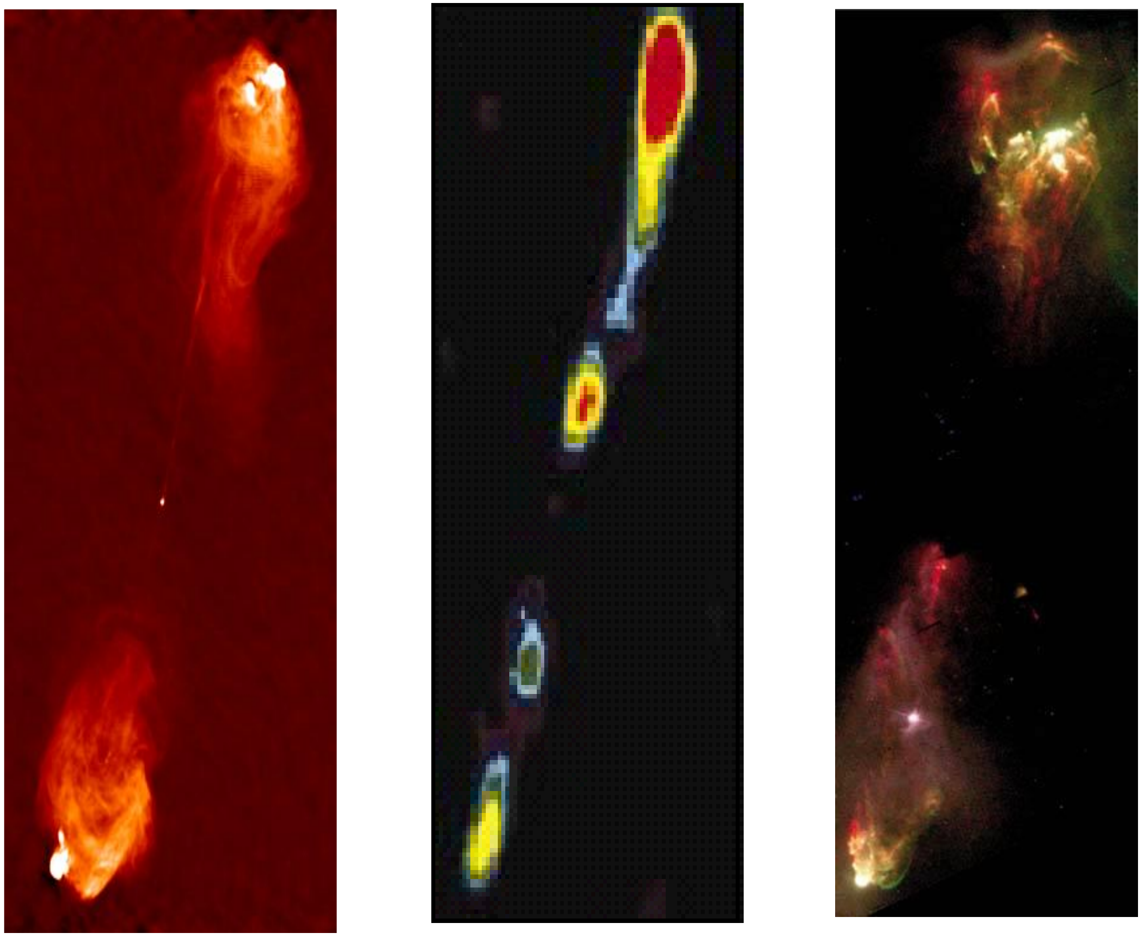


Microquasars (model)



What do we think

The same mechanism?



The same mechanism?

- Thermal (gas pressure)?
- Radiative (radiation pressure)?
- Electromagnetic (Ampere force)?

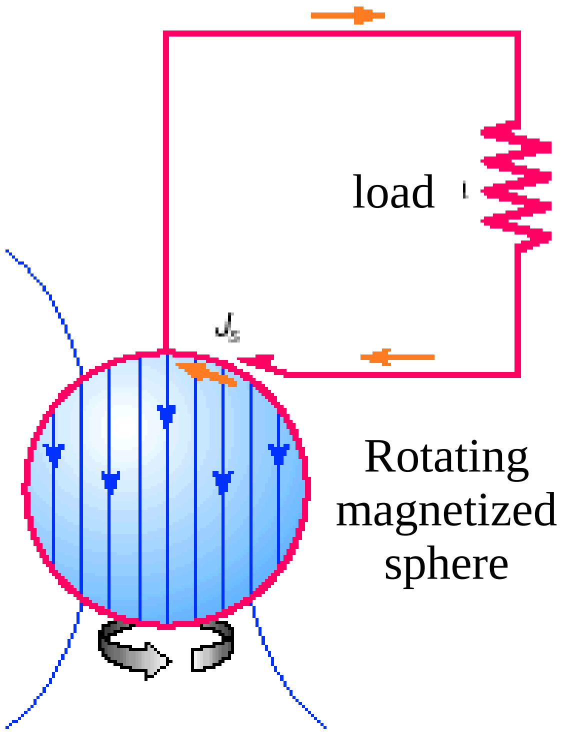
Main idea

Central engine is

an unipolar inductor

Unipolar Inductor

- Electric circuit is to be touched to the sphere at different latitudes.
- Electric circuit is to rotate with the angular velocity Ω which differs from the angular velocity of a sphere.
- The energy source is the kinetic energy of the rotation.
- EMF does not result from the Faraday effect.

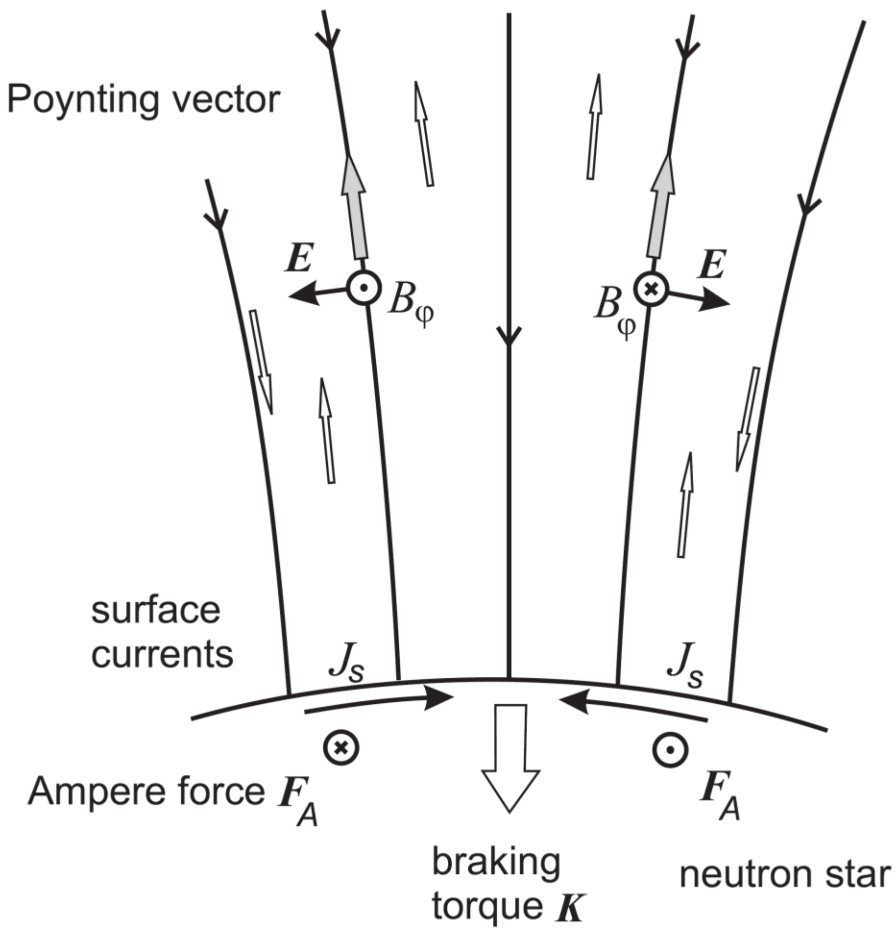


$$W_{tot} = IU$$

For the central engine to work

1. regular poloidal magnetic field,
2. rotation (inductive electric field $\boldsymbol{E}$, EMF U),
3. longitudinal current I (toroidal magnetic field B_φ).

An example – radio pulsars



V.Beskin – N.Vlahakis, Email 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.

Two first steps only

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

- **Reality**

Magnetization parameter σ

(maximum bulk Lorentz-factor)

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

$$r_F = R_L \sigma^{1/3}$$

Radio pulsars	10^3 – 10^5
AGNs	???
GRBs	10^2–10^4
YSOs	10^{-3}–10^{-7}

Multiplicity parameter λ

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

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

Radio pulsars	10^{3}–10^{5}
AGNs	???
GRBs	10^{13}–10^{14}

What a problem?

Specific features

Divergence of a flow

Relativistic motion

Rotation

Poynting dominated flow near the origin

Specific features

Divergence of a flow (4-5 order of magnitude)

Magnetized Wind

- Magnetization parameter

$$\sigma = e\Omega\,\Psi_{\rm tot}/\lambda m c^3 \gg 1$$

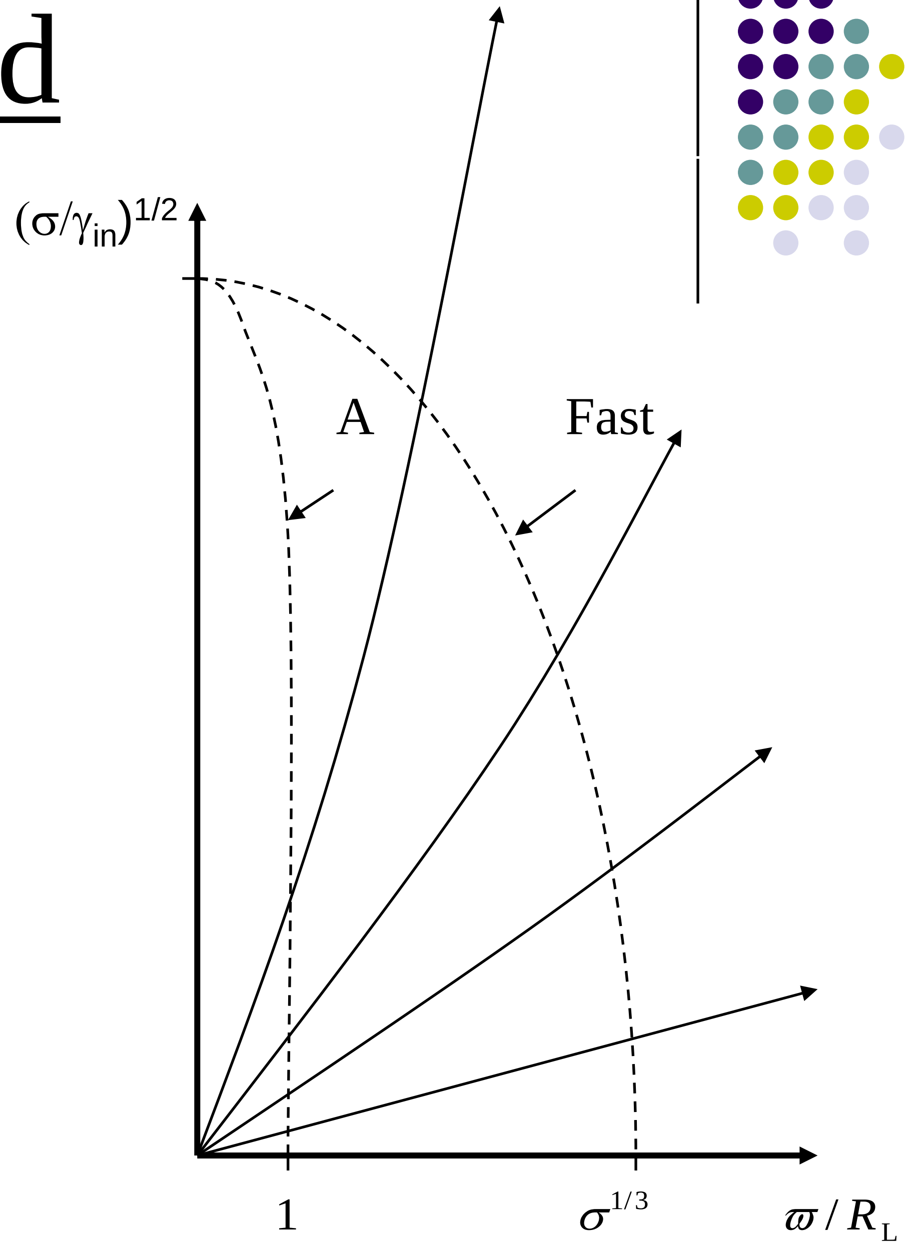
($\gamma = \sigma$ corresponds to full conversion)

- Position of the fast magnetosonic surface

$$r_{\rm F} = R_{\rm L}\,\sigma^{1/3}\sin^{-1/3}\theta$$

- Disturbance of the poloidal magnetic field at $r = r_{\rm F}$

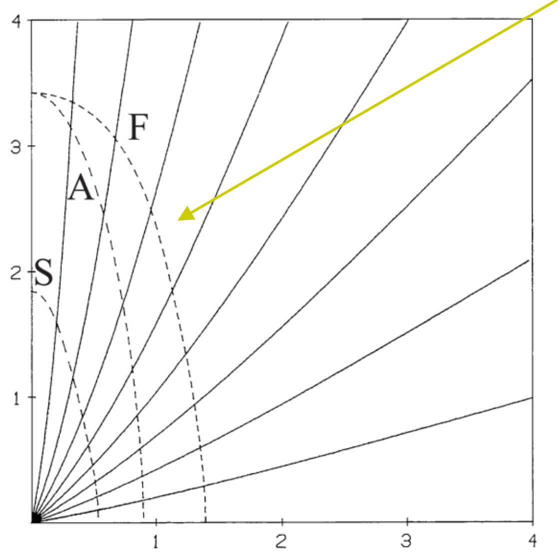
$$\delta\Psi/\Psi = \sigma^{-2/3}$$

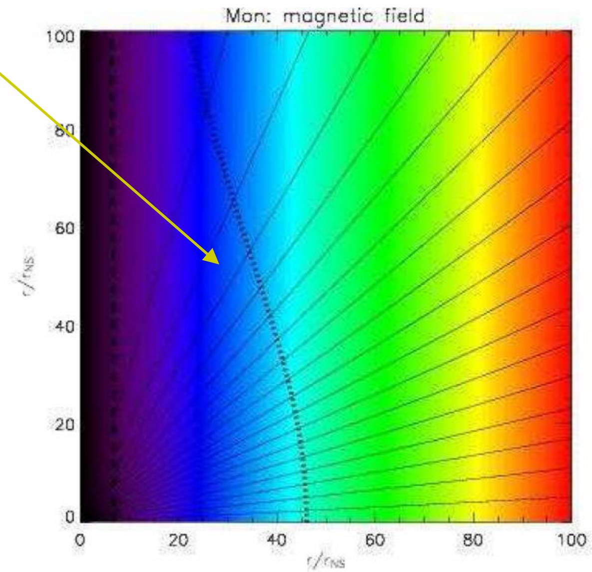


Nonrelativistic

Relativistic

$$r_{\mathrm{F}} = R_{\mathrm{L}}\ \sigma^{1/3} \sin^{-1/3}\theta$$





T.Sakurai.
A&A, **152**, 121
(1985)

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

Magnetized Wind (Acceleration)

- For $r < r_F$

$$\gamma \sim x = \Omega r \sin\theta / c$$

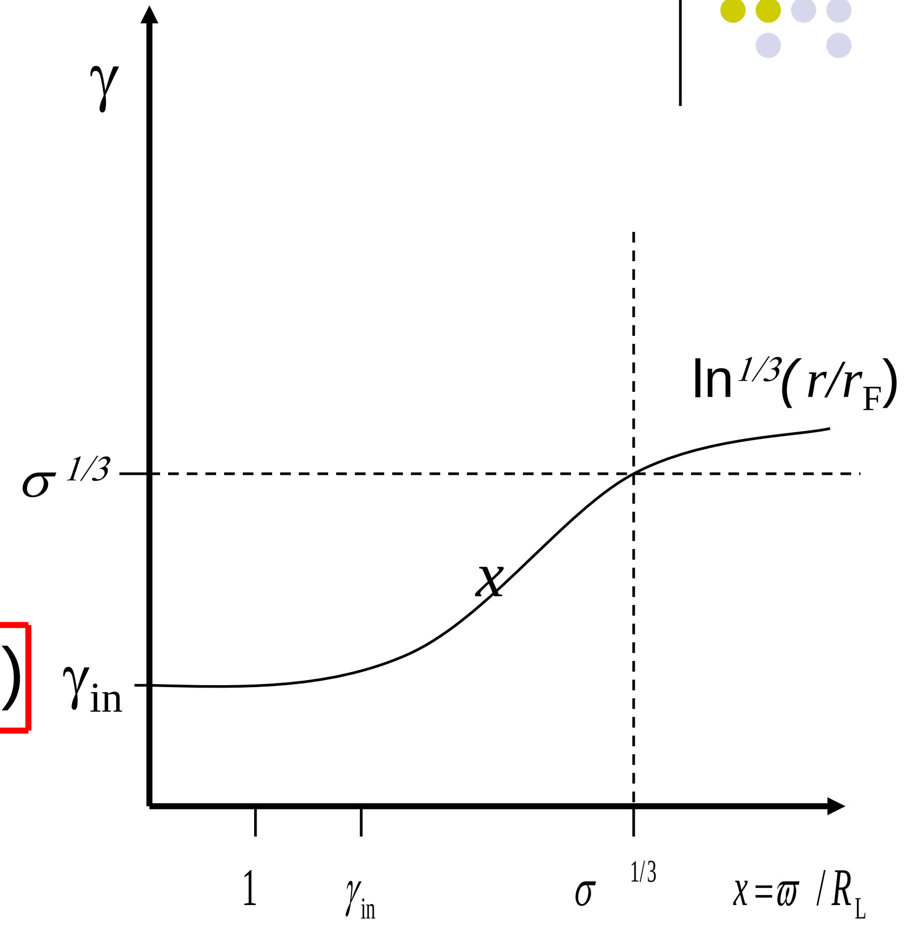
- Fast Magnetosonic Surface

$$\gamma(r_F) = \sigma^{1/3} \sin^{2/3}\theta \quad (\text{not } \sigma)$$

- For $r >> r_F$

$$\boxed{\Psi/\Psi_0 = 1 - \cos\theta + \sigma^{-2/3} \ln^{1/3}(r/r_F)}$$

$$\gamma \sim \sigma^{1/3} \ln^{1/3}(r/r_F)$$



Specific features

Divergence of a flow (4-5 order of magnitude)

Specific features

Divergence of a flow (4-5 order of magnitude)

The flow is to be transonic

Specific features

Divergence of a flow (4-5 order of magnitude)

The flow is to be transonic

- Current *I* is determined by the critical conditions, not by the outer load
- NOT the 'magnetic tower'

Energy Losses

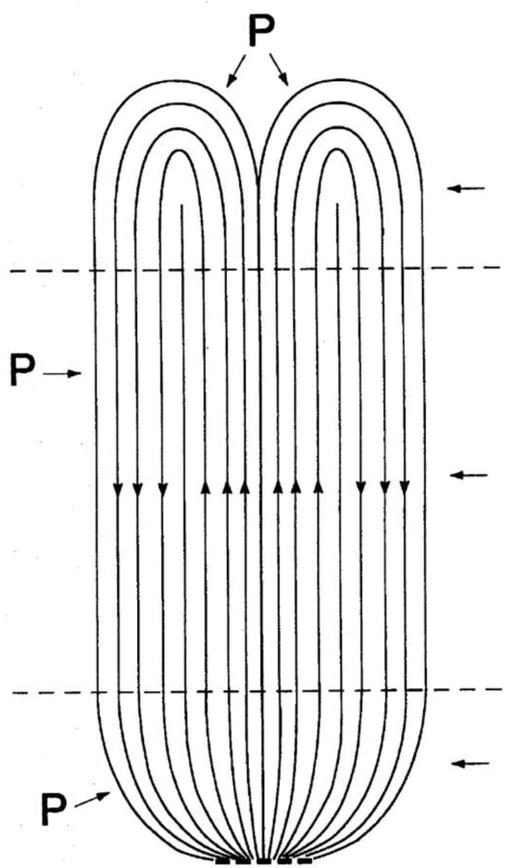
$$W_{\text{tot}} = IU$$

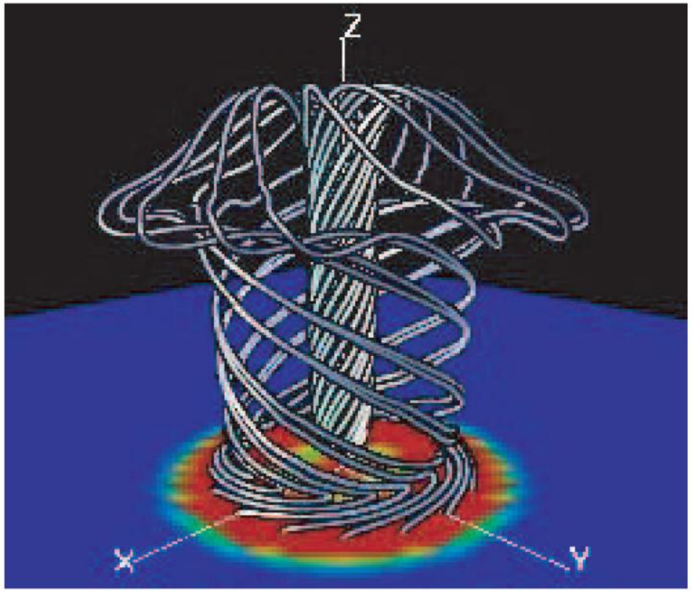
($I = I_{\text{GJ}}$ for relativistic flow)

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

Magnetic tower

Wind + diff. rotation





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

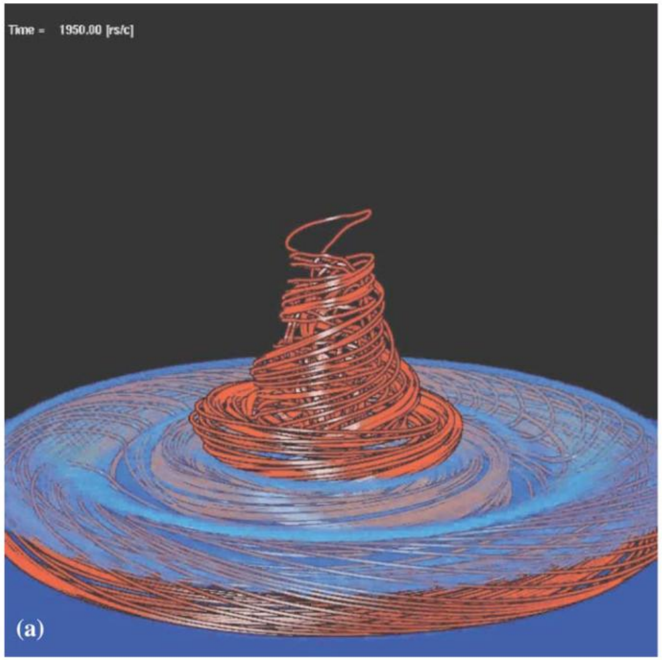
Y.Kato, M.R.Hayashi, R.Matsumoto. ApJ, **600**, 338 (2004)

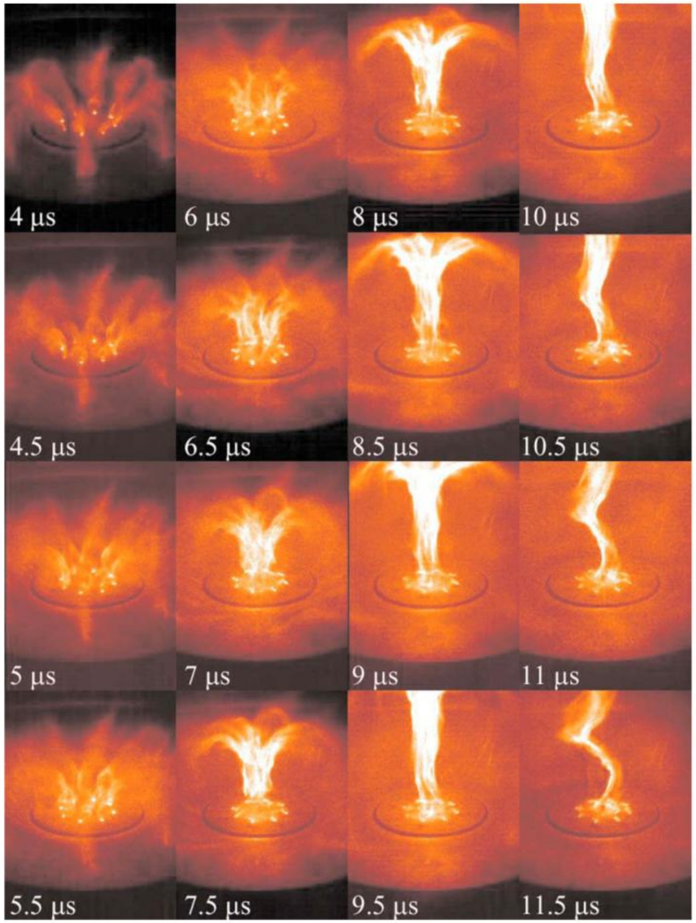
And in the laboratory

PHYSICS OF PLASMAS **16**, 041005 (2009)

Astrophysical jets: Observations, numerical simulations, and laboratory experiments

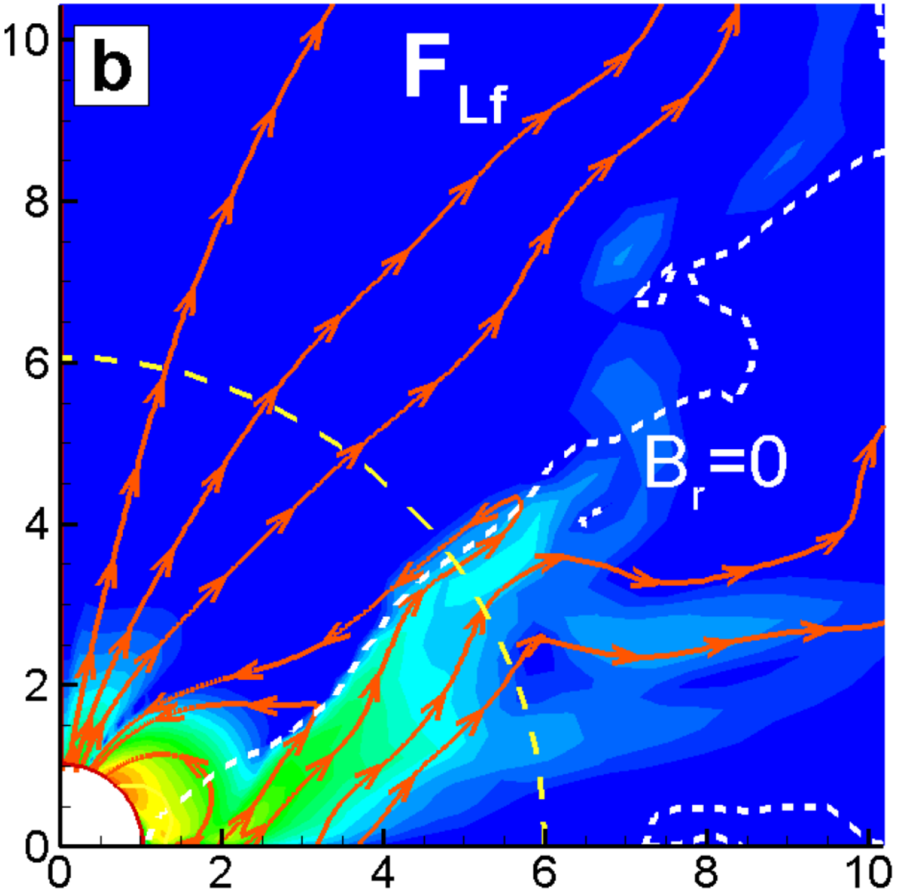
P. M. Bellan,[1] M. Livio,[2] Y. Kato,[3] S. V. Lebedev,[4] T. P. Ray,[5] A. Ferrari,[6] P. Hartigan,[7] A. Frank,[8] J. M. Foster,[9] and P. Nicolaï[10]





The role of the divergence

M. M.Romanova,
G. V.Ustyugova,
A. V. Koldoba,
R. V. E. Lovelace.
MNRAS, **399**, 1802
(2009)



Specific features

Relativistic motion

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

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

Specific features

Poynting dominated flow near the origin

Far from the origin $E \sim B$

Disturbance of the monopole magnetic field

V.S.Beskin & R.R.Rafikov.

MNRAS, **313**, 344, 2000

For electric current

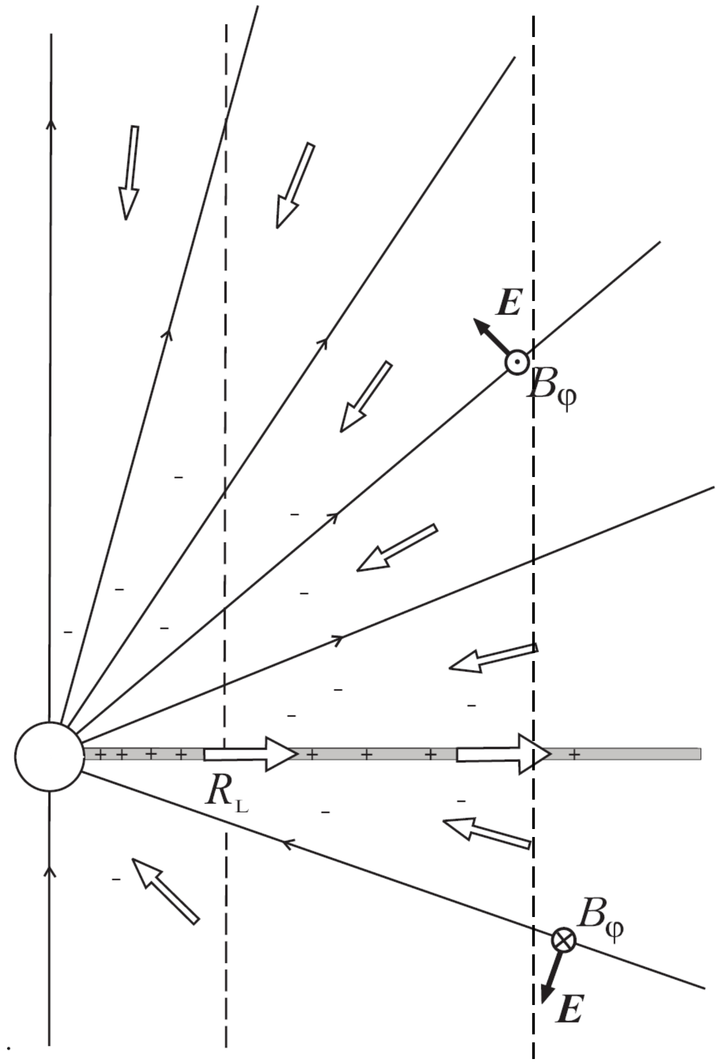
$I = I_{GJ}\,(1 - h)$

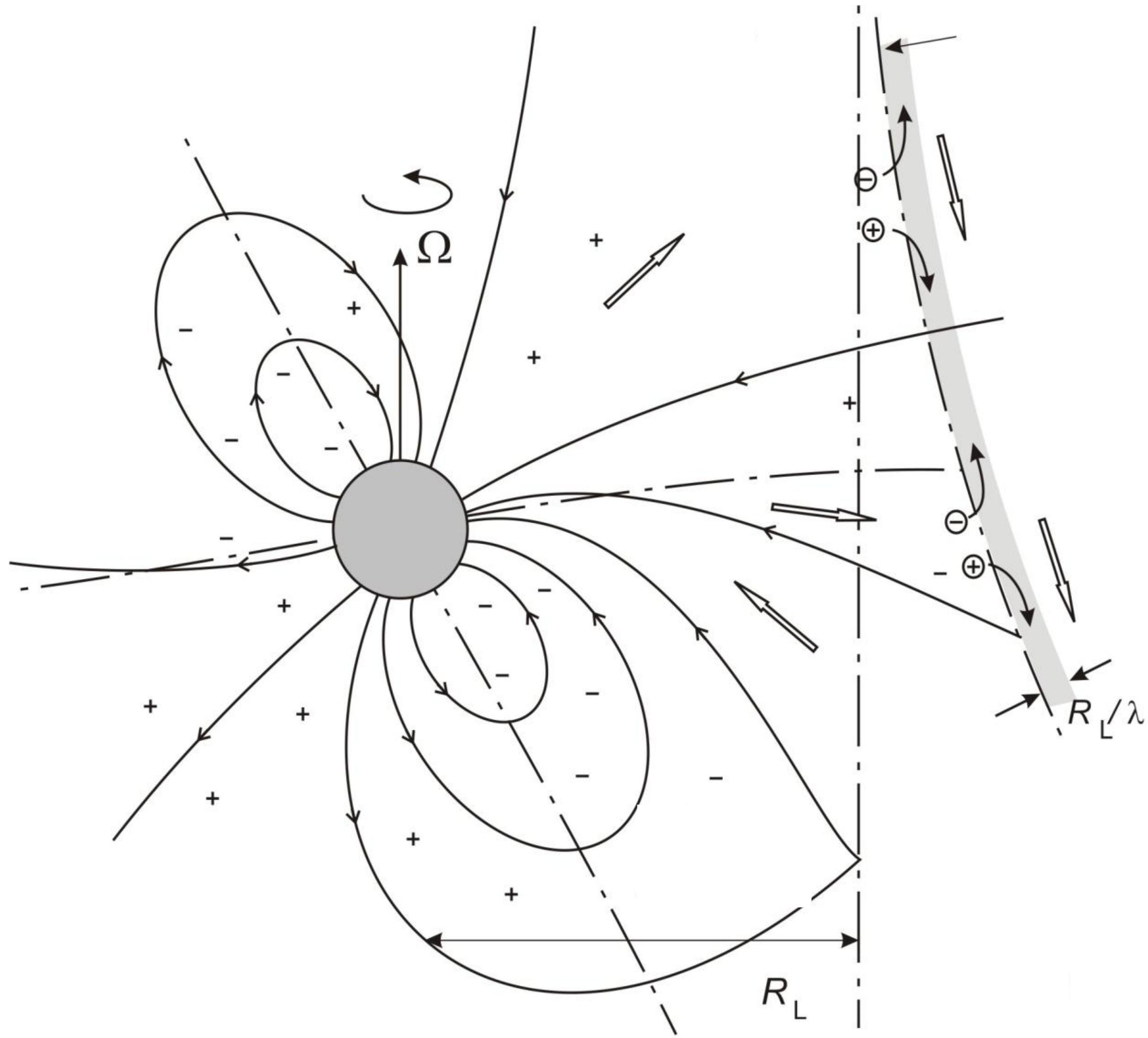
an exact solution is

$\Psi = \Psi_0[1 - \cos\theta + h(\Omega r/c)^2 \sin^2\theta \cos\theta]$

Light surface for $h < 0$ at

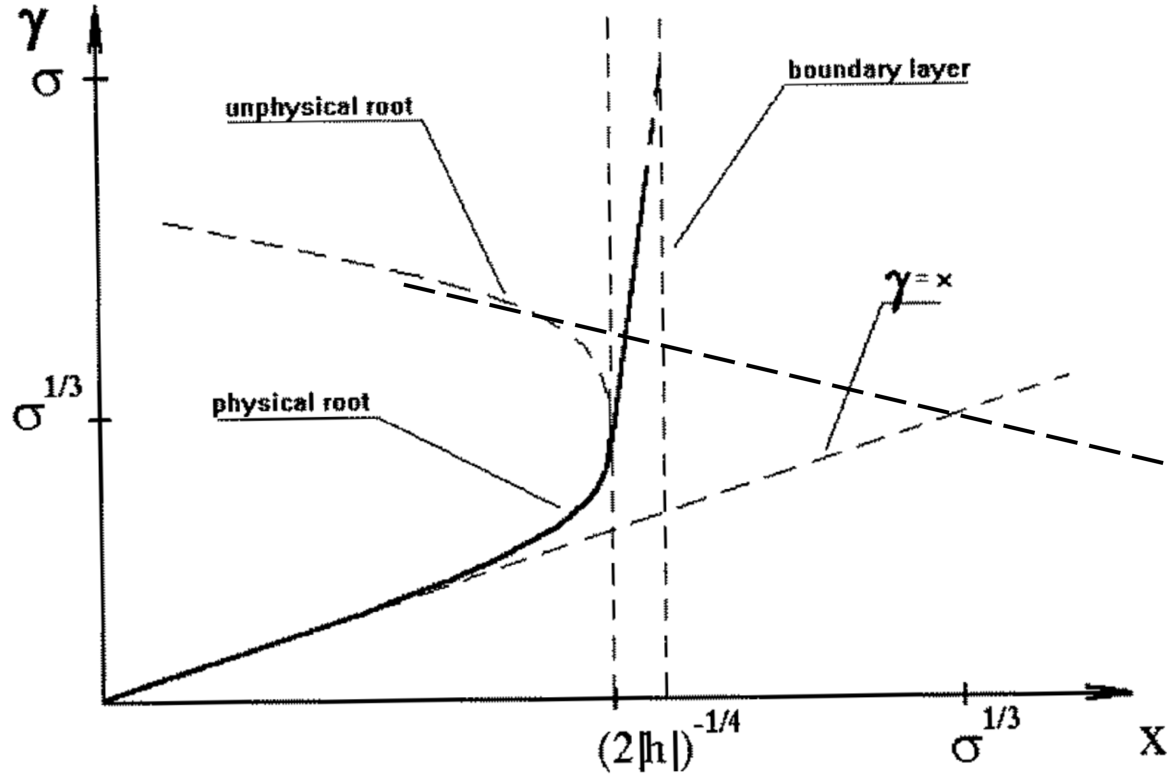
$r \sin\theta = (2h)^{-1/4} R_L$





Ω
R_L
R_L/λ

$$
\begin{aligned}
-\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(\zeta\sin\theta) = 2(\eta^{+}-\eta^{-}) - 2\left[\left(\lambda-\frac{1}{2}\cos\theta\right)\xi_r^{+} - \left(\lambda+\frac{1}{2}\cos\theta\right)\xi_r^{-}\right],\\
2(\eta^{+}-\eta^{-}) + \frac{\partial}{\partial r}\left(r^2\frac{\partial\delta}{\partial r}\right) + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\delta}{\partial\theta}\right) = 0,\\
\frac{\partial\zeta}{\partial r} = \frac{2}{r}\left[\left(\lambda-\frac{1}{2}\cos\theta\right)\xi_\theta^{+} - \left(\lambda+\frac{1}{2}\cos\theta\right)\xi_\theta^{-}\right],\\
\frac{\varepsilon}{\sin\theta}\frac{\partial^2 f}{\partial r^2} - \frac{\varepsilon}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial f}{\partial\theta}\right) = 2\frac{\Omega}{rc}\left[\left(\lambda-\frac{1}{2}\cos\theta\right)\xi_\varphi^{+} - \left(\lambda+\frac{1}{2}\cos\theta\right)\xi_\varphi^{-}\right],\\
\frac{\partial}{\partial r}\left(\xi_\theta^{+}\gamma^{+}\right) + \frac{\xi_\theta^{+}\gamma^{+}}{r} = 4\lambda\sigma\left(-\frac{1}{r}\frac{\partial\delta}{\partial\theta} + \frac{\zeta}{r} - \frac{\sin\theta}{r}\xi_r^{+} + \frac{c}{\Omega r^2}\xi_\varphi^{+}\right),\\
\frac{\partial}{\partial r}\left(\xi_\theta^{-}\gamma^{-}\right) + \frac{\xi_\theta^{-}\gamma^{-}}{r} = -4\lambda\sigma\left(-\frac{1}{r}\frac{\partial\delta}{\partial\theta} + \frac{\zeta}{r} - \frac{\sin\theta}{r}\xi_r^{-} + \frac{c}{\Omega r^2}\xi_\varphi^{-}\right),\\
\frac{\partial}{\partial r}\left(\gamma^{+}\right) = 4\lambda\sigma\left(-\frac{\partial\delta}{\partial r} - \frac{\sin\theta}{r}\xi_\theta^{+}\right),\\
\frac{\partial}{\partial r}\left(\gamma^{-}\right) = -4\lambda\sigma\left(-\frac{\partial\delta}{\partial r} - \frac{\sin\theta}{r}\xi_\theta^{-}\right),\\
\frac{\partial}{\partial r}\left(\xi_\varphi^{+}\gamma^{+}\right) + \frac{\xi_\varphi^{+}\gamma^{+}}{r} = 4\lambda\sigma\left(-\varepsilon\frac{c}{\Omega r\sin\theta}\frac{\partial f}{\partial r} - \frac{c}{\Omega r^2}\xi_\theta^{+}\right),\\
\frac{\partial}{\partial r}\left(\xi_\varphi^{-}\gamma^{-}\right) + \frac{\xi_\varphi^{-}\gamma^{-}}{r} = -4\lambda\sigma\left(-\varepsilon\frac{c}{\Omega r\sin\theta}\frac{\partial f}{\partial r} - \frac{c}{\Omega r^2}\xi_\theta^{-}\right).
\end{aligned}
$$



γ
σ
unphysical root
boundary layer
γ = x
σ^{1/3}
physical root
(2|h|)^{-1/4}
σ^{1/3}
x

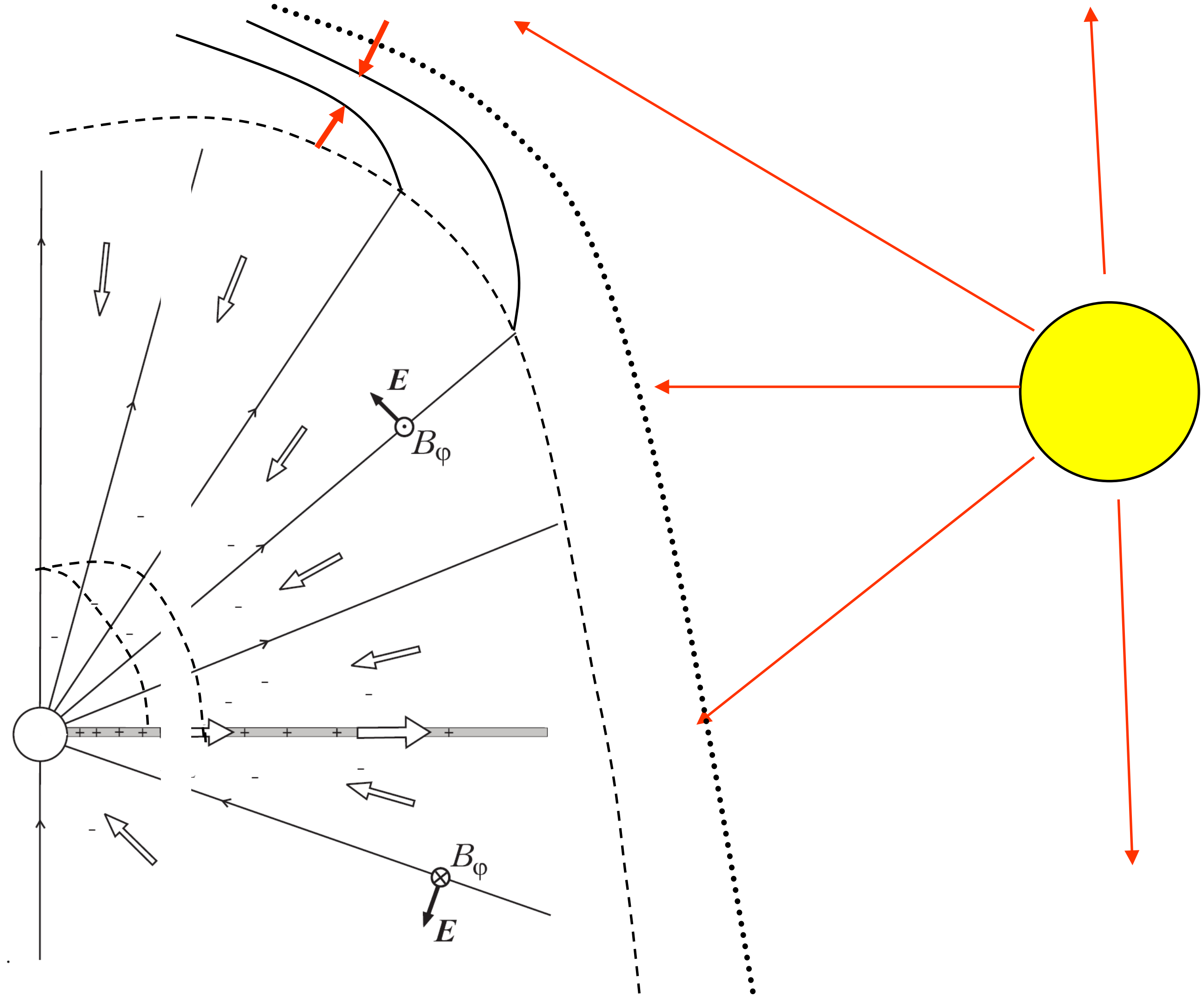
Properties

- Current sheet $\delta r \sim R_L/\lambda$

- Acceleration results from the motion perpendicular to magnetic field lines, $v_\theta \sim v_r$

- Particle energy $\gamma \sim \sigma$

Comment for TeV Binaries



What was done

Bulk particle acceleration

Grad – Shafranov Approach

In general case 2D axisymmetric stationary structure of the flow is determined by the second order partial differential equation containing invariants as free functions.

Full Version of the Grad – Shafranov Equation in the Kerr Metric

$$A\left[\frac{1}{\alpha}\nabla_k\left(\frac{1}{\alpha\varpi^2}\nabla^k\Psi\right)+\frac{1}{\alpha^2\varpi^2(\nabla\Psi)^2}\frac{\nabla^i\Psi\cdot\nabla^k\Psi\cdot\nabla_i\nabla_k\Psi}{D}\right]$$

$$+\frac{1}{\alpha^2\varpi^2}\nabla'_kA\cdot\nabla^k\Psi-\frac{A}{\alpha^2\varpi^2(\nabla\Psi)^2}\frac{1}{2D}\nabla'_kF\cdot\nabla^k\Psi$$

$$+\frac{\Omega_{\mathrm{F}}-\omega}{\alpha^2}(\nabla\Psi)^2\frac{\mathrm{d}\Omega_{\mathrm{F}}}{\mathrm{d}\Psi}+\frac{64\pi^4}{\alpha^2\varpi^2}\frac{1}{2\mathcal{M}^2}\frac{\partial}{\partial\Psi}\left(\frac{G}{A}\right)$$

$$-16\pi^3\mu n\frac{1}{\eta}\frac{\mathrm{d}\eta}{\mathrm{d}\Psi}-16\pi^3nT\frac{\mathrm{d}s}{\mathrm{d}\Psi}=0,$$

Algebraic Relations

$$\frac{I}{2\pi} = \frac{\alpha^2 L - (\Omega_{\rm F} - \omega)\varpi^2(E - \omega L)}{\alpha^2 - (\Omega_{\rm F} - \omega)^2\varpi^2 - \mathcal{M}^2},$$

$$\gamma = \frac{1}{\alpha\mu\eta}\frac{\alpha^2(E - \Omega_{\rm F} L) - \mathcal{M}^2(E - \omega L)}{\alpha^2 - (\Omega_{\rm F} - \omega)^2\varpi^2 - \mathcal{M}^2},$$

$$u_{\hat\varphi} = \frac{1}{\varpi\mu\eta}\frac{(E - \Omega_{\rm F} L)(\Omega_{\rm F} - \omega)\varpi^2 - L\mathcal{M}^2}{\alpha^2 - (\Omega_{\rm F} - \omega)^2\varpi^2 - \mathcal{M}^2}.$$

Algebraic Relations

$$\frac{I}{2\pi} = c\eta_{\rm n}\frac{L_{\rm n} - \Omega_{\rm F}\varpi^2}{1-\mathcal{M}^2},$$

$$v_\varphi = \frac{1}{\varpi}\frac{\Omega_{\rm F}\varpi^2 - L_{\rm n}\mathcal{M}^2}{1-\mathcal{M}^2},$$

- Subsonic flow $v_\varphi = \Omega_{\rm F}\, r \sin\theta$
- Supersonic flow $v_\varphi = L / r \sin\theta$, $v_{\rm p} \sim \Omega_{\rm F} r_{\rm F}$

The origin of an acceleration is a centrifugal force

Inside the critical surfaces the magnetic field plays a role of a sling, $\Omega = \Omega_F$, so that

$$v_\varphi(r_F) = \Omega_F r_F \sim (2E_n)^{1/2} = v_{inf}$$

$$v_p(r_F) \sim v_{inf}$$

Simple asymptotic solutions

The role of the curvature

Grad-Shafranov equation is the force-balance one.
For magnetically dominated case

$$\rho_e \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B}/c \sim 0.$$

After some algebra

$$\frac{S/c}{R_c} = \frac{1}{4\pi}\nabla\left(B_\varphi^2 - E^2\right) + \frac{1}{4\pi}\nabla\left(B_p^2\right)$$

If one can neglect the curvature R_c, then

$B^2_\varphi - E^2 \sim B^2_\varphi / \gamma^2$ and $B^2_\varphi = x^2 B^2_p$, so we return to

$$\boxed{\gamma = x}.$$

The role of the curvature

$$\frac{S/c}{R_{\rm c}} = \frac{1}{4\pi}\nabla\left(B_\varphi^2 - E^2\right) + \frac{1}{4\pi}\nabla\left(B_{\rm p}^2\right)$$

If one cannot neglect the curvature $R_{\rm c}$, then $S \sim (c/4\pi)B_\varphi^2$, and one can neglect the last term (Beskin, Zakamska, Sol, MNRAS, **347**, 587, 2004).

It gives $\gamma = (R_c/\varpi)^{1/2}$.

Magnetized Wind

- Magnetization parameter

$$\sigma = e\Omega\,\Psi_{\rm tot}/\lambda m c^3 \gg 1$$

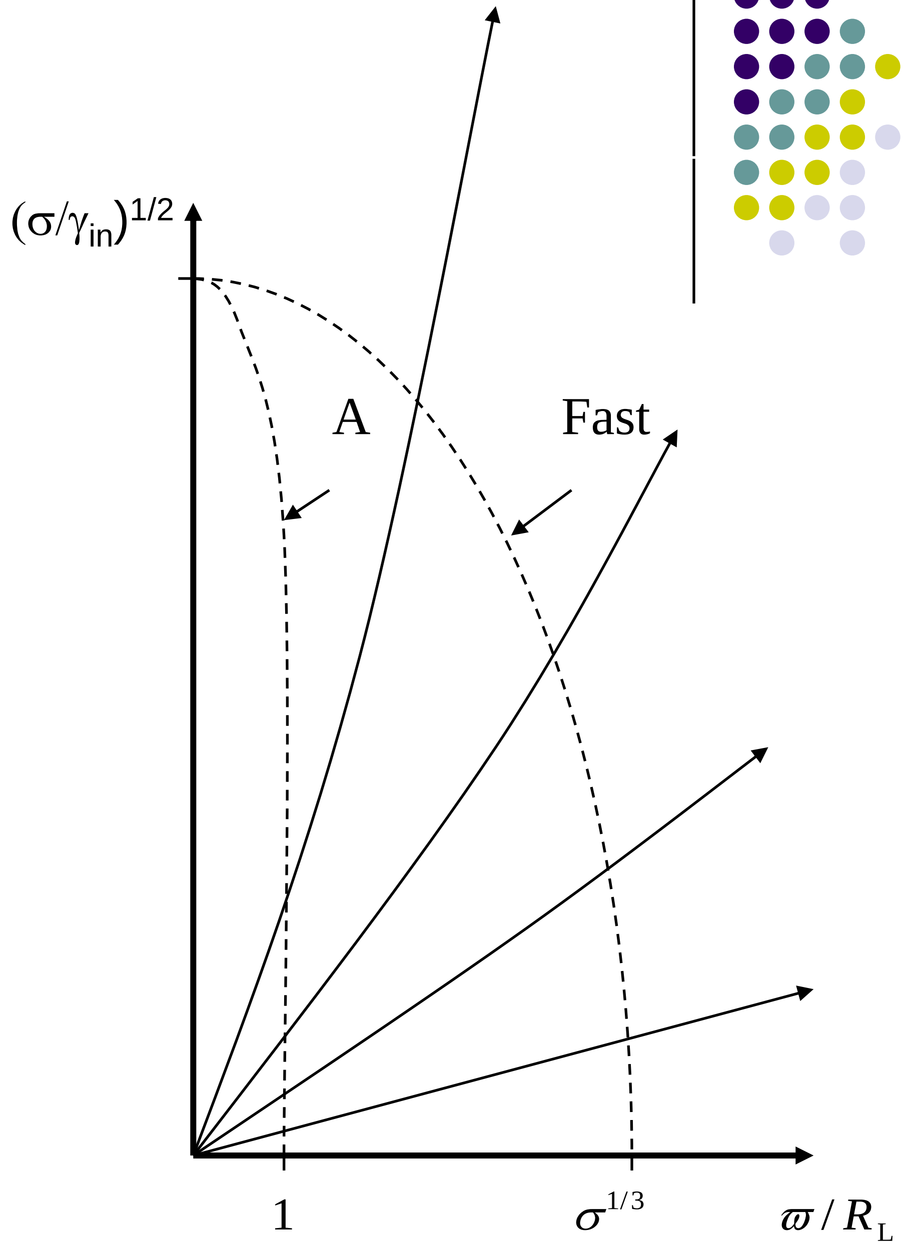
($\gamma = \sigma$ corresponds to full conversion)

- Position of the fast magnetosonic surface

$$r_{\rm F} = R_{\rm L}\,\sigma^{1/3}\sin^{-1/3}\theta$$

- Disturbance of the poloidal magnetic field at $r = r_{\rm F}$

$$\boxed{\delta\Psi/\Psi = \sigma^{-2/3}}$$



Magnetized Wind (Acceleration)

- For $r < r_F$

$$\gamma \sim x = \Omega r \sin\theta / c$$

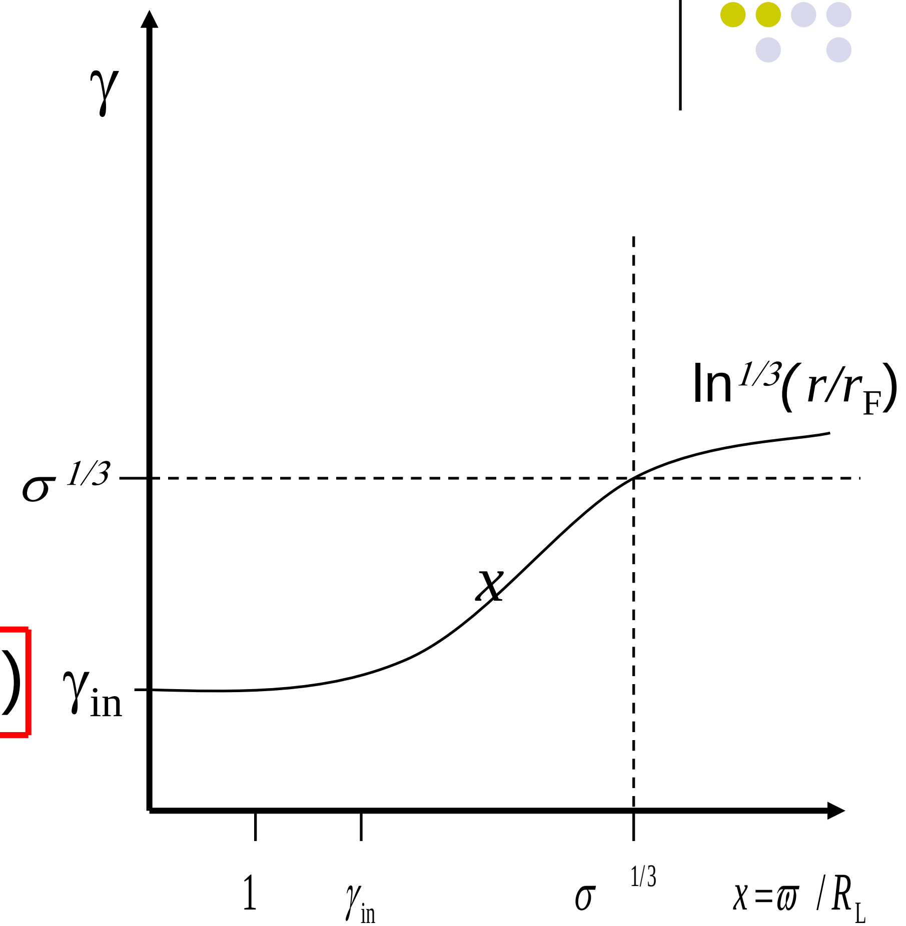
- Fast Magnetosonic Surface

$$\gamma(r_F) = \sigma^{1/3} \sin^{2/3}\theta \quad (\text{not } \sigma)$$

- For $r >> r_F$

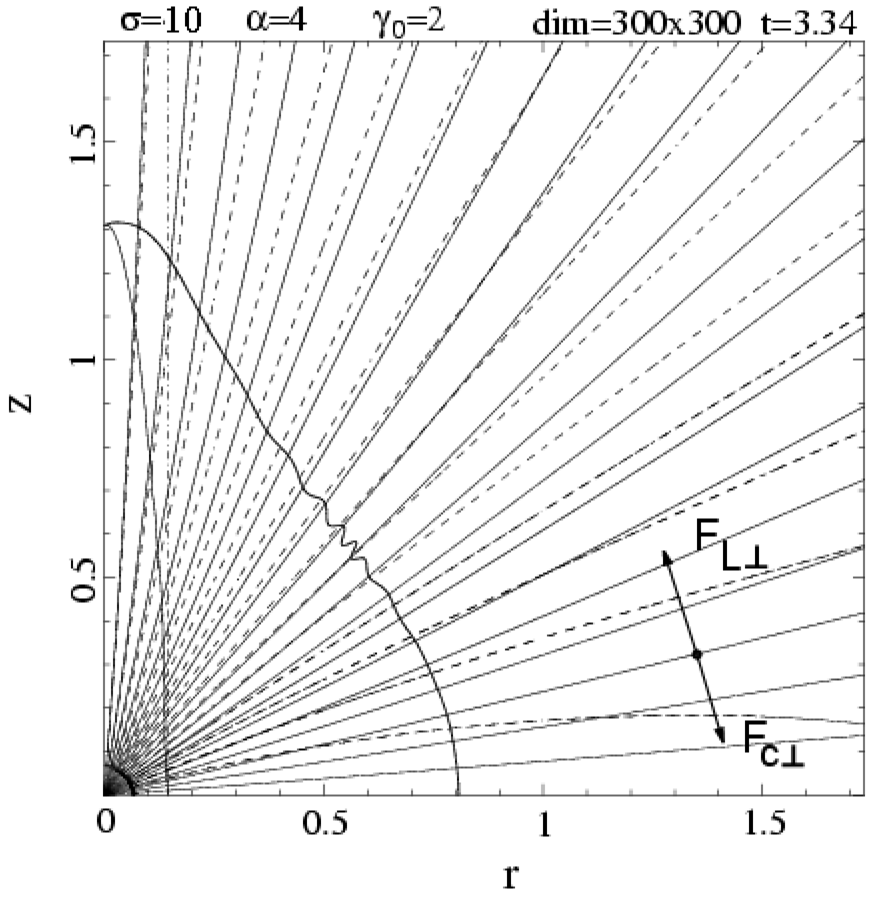
$$\Psi/\Psi_0 = 1 - \cos\theta + \sigma^{-2/3} \ln^{1/3}(r/r_F)$$

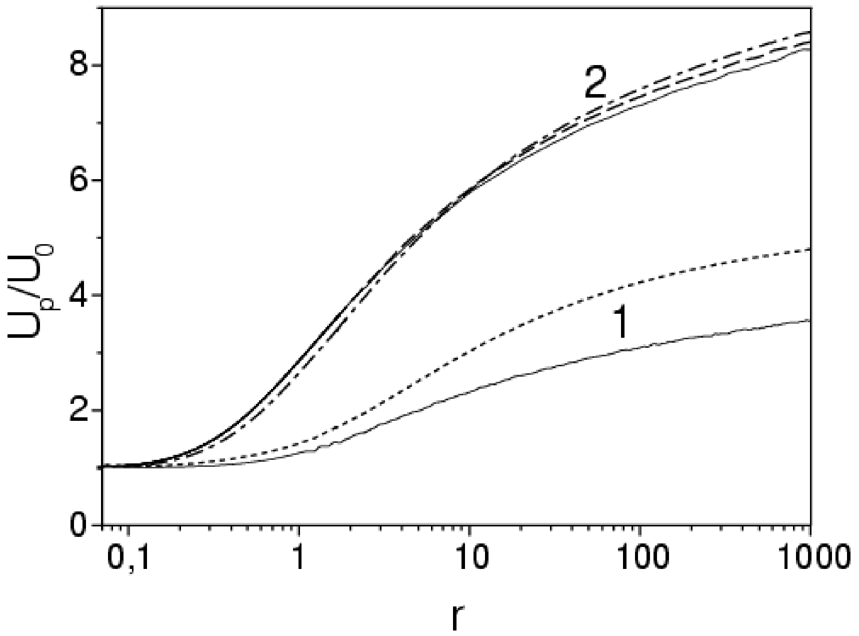
$$\gamma \sim \sigma^{1/3} \ln^{1/3}(r/r_F)$$



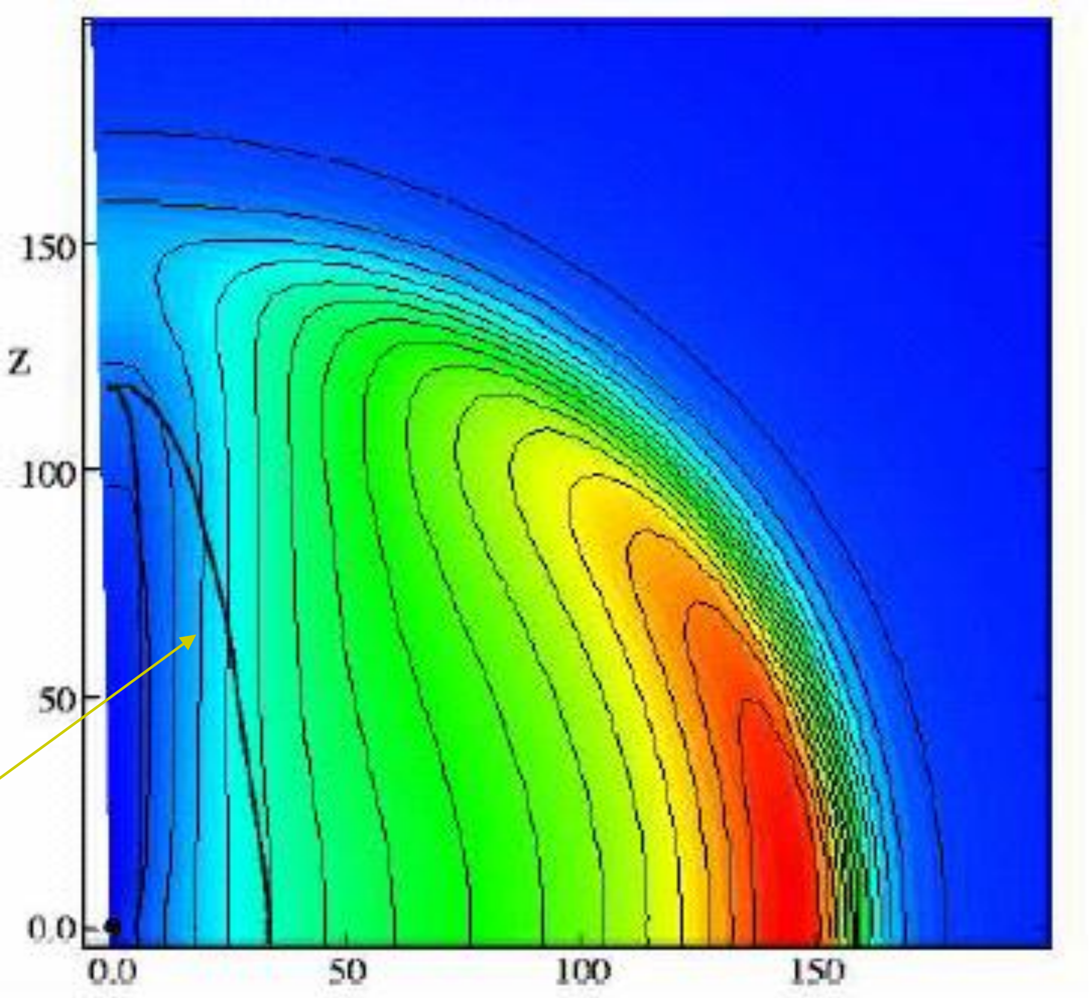
No collimation, no particle acceleration outside r_F

Numerical calculations (S.V.Bogovalov, A&A, **371**, 1155, 2001)





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



$$\gamma = x$$

Parabolic magnetic field

(V.S.Beskin & E.E.Nokhrina, MNRAS, **367**, 375, 2006)

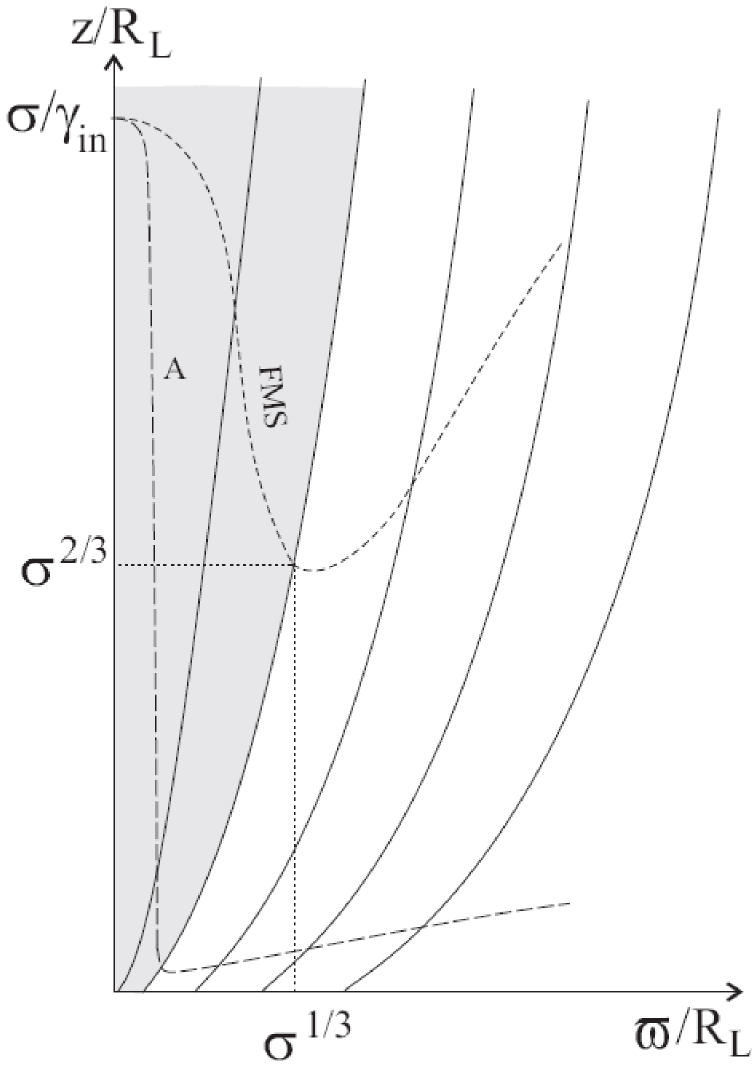
- FMS position

  $r_F = R_L(\sigma/\theta)^{1/2}$

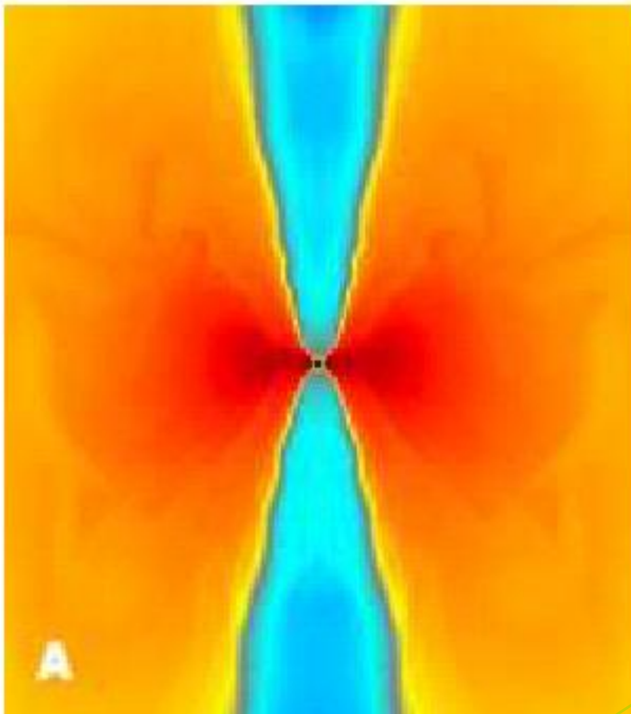
- Lorentz-factor varies from $\gamma_F = \gamma_{in}$ at radial distance $x = \gamma_{in}$ to

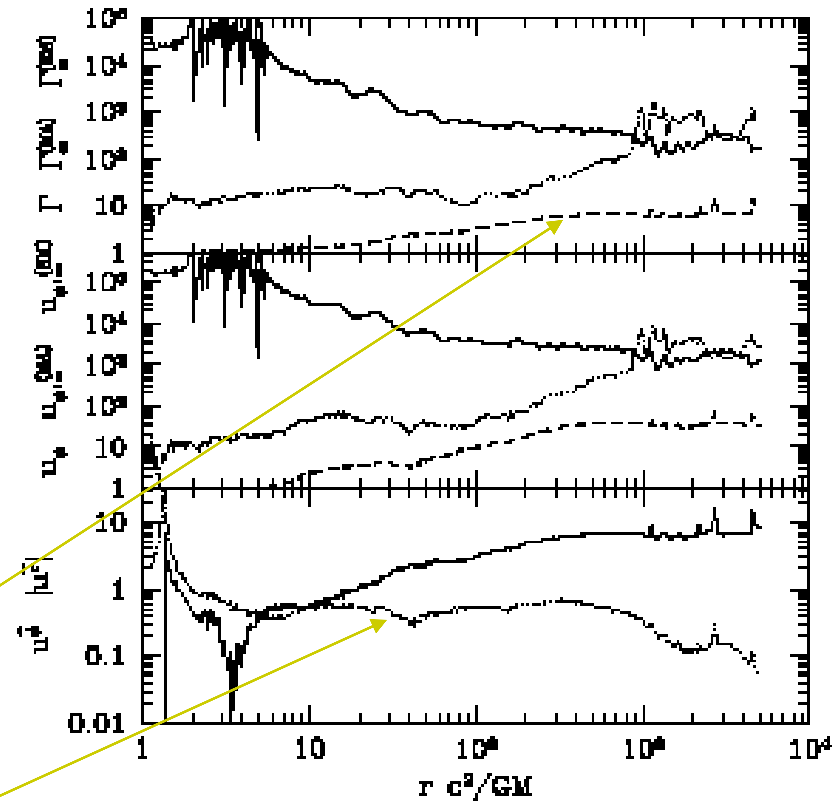
  $\gamma_F = \sigma^{1/3}$ at $x = \sigma^{1/3}$

- For $z > \sigma^{2/3} R_L$ the flow becomes 1D (cylindrical)



J.McKinney, MNRAS, **368**,1561 (2006)





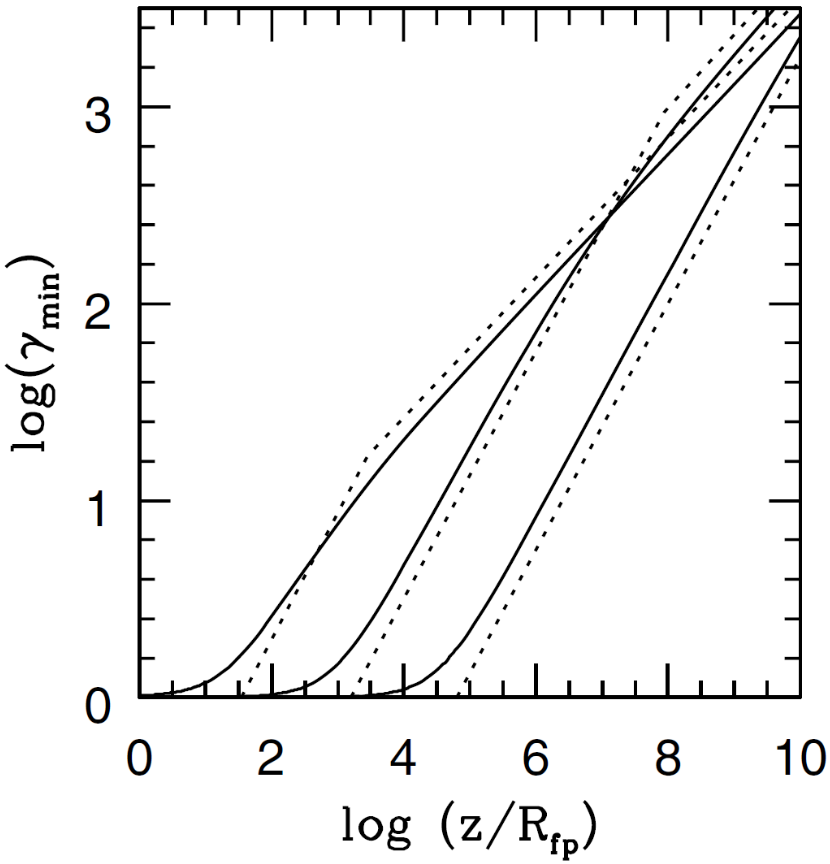
$\gamma\,(z) = (z/\,R_L)^{1/2}$, $u_\varphi = 1$

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

Self-similar solution $z \sim \varpi^{\alpha}$

For α > 2 $\gamma = x$

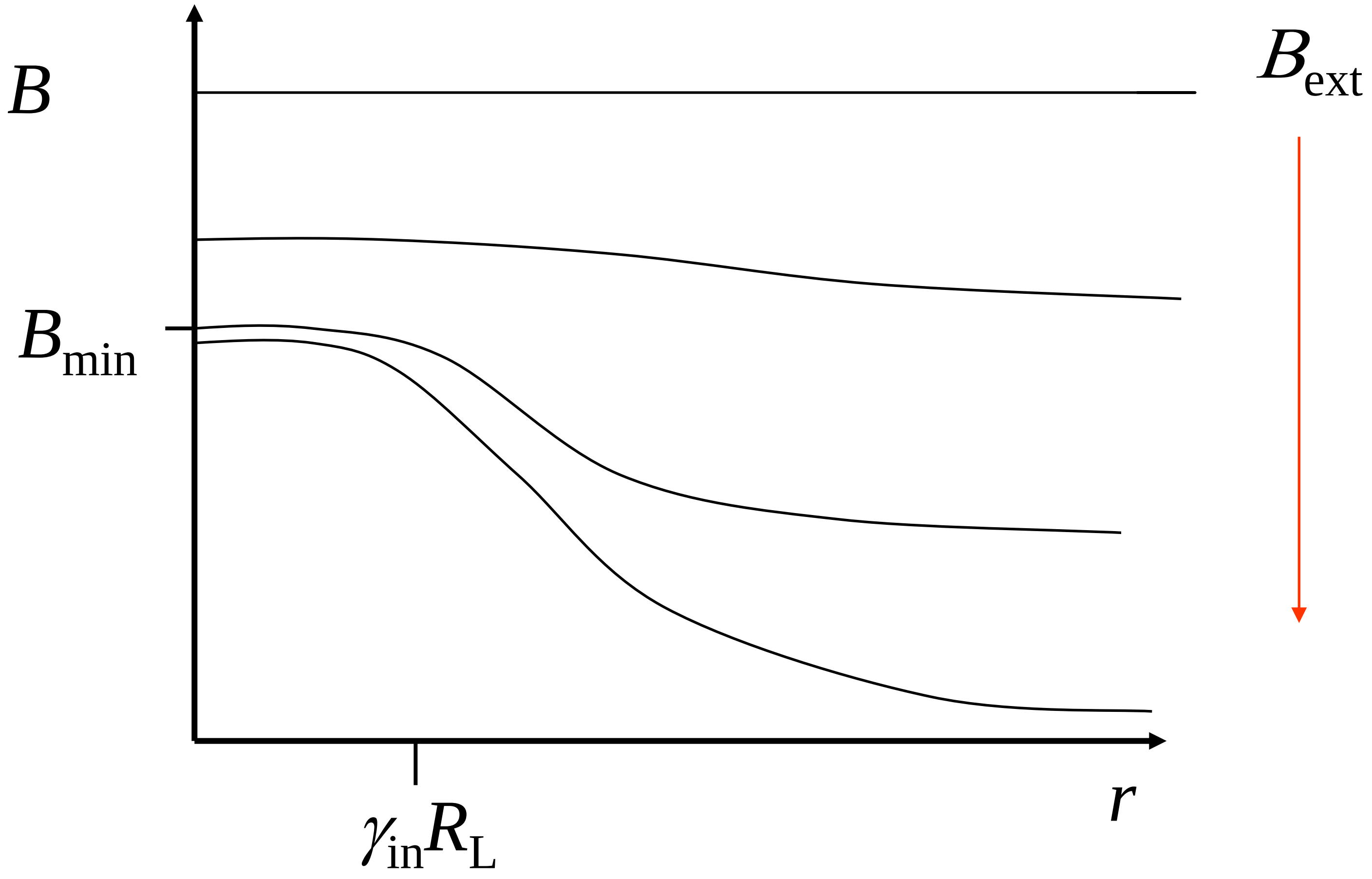
For α < 2 $\gamma = (R_c / \varpi)^{1/2}$

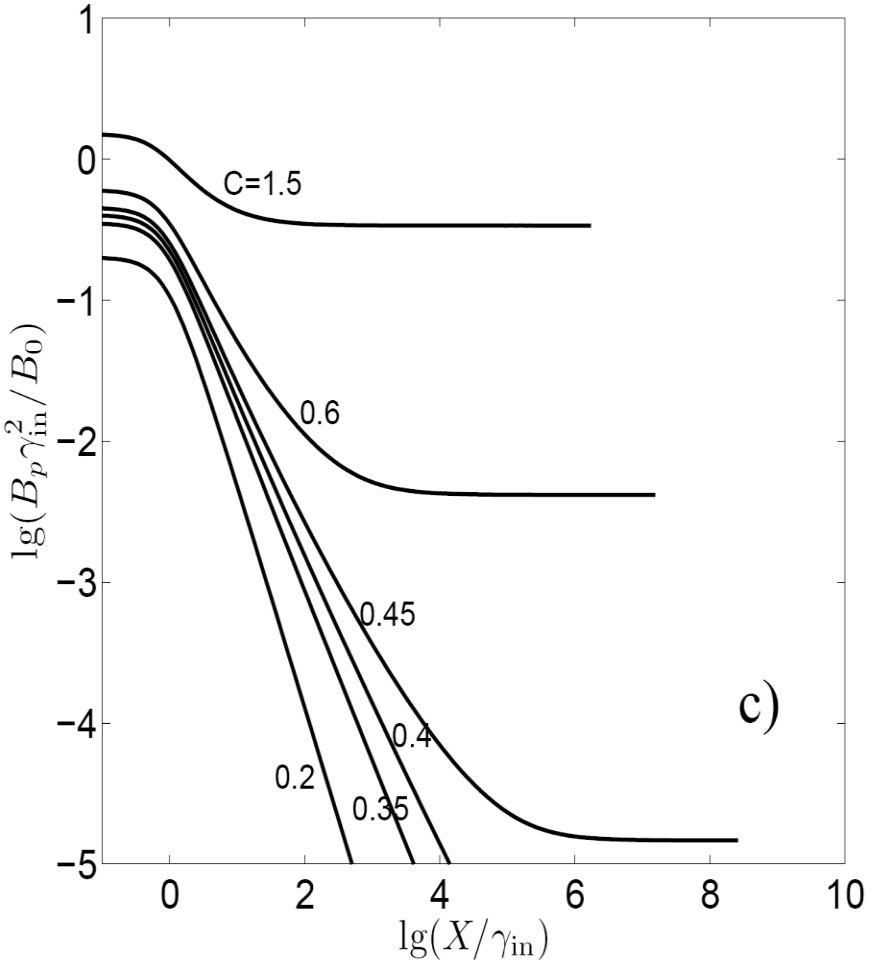


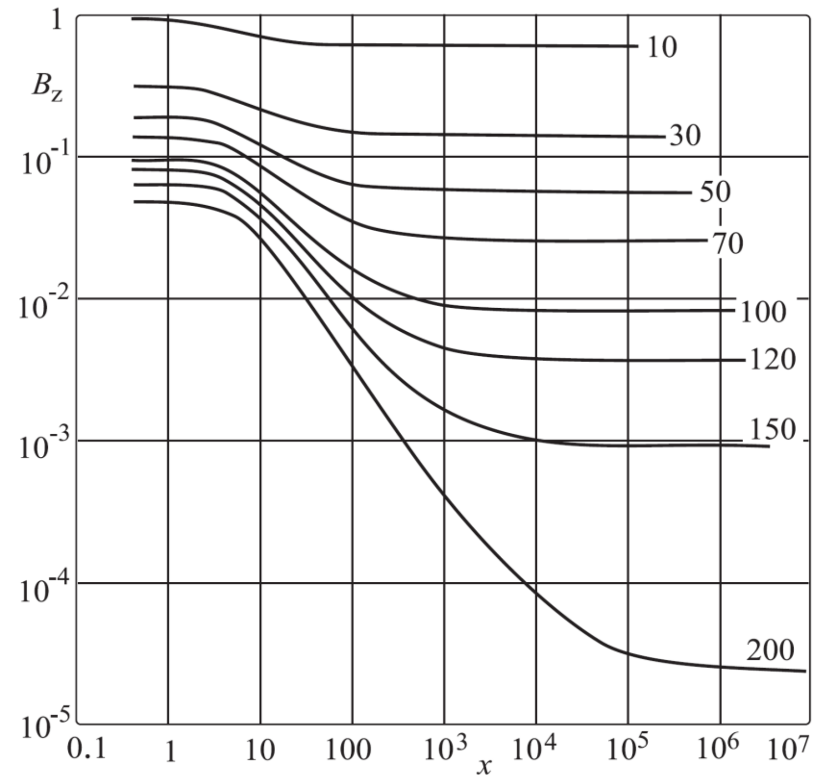
Central core

Central core $r_{core} = \gamma_{in} R_L$

$$B_{min} = B(R_L)/\sigma\gamma_{in}\,,\quad \Psi_{core} = (\gamma_{in}/\sigma)\ \Psi_0$$



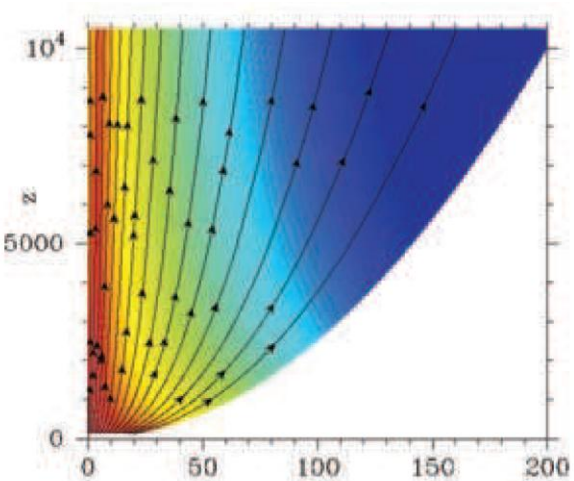


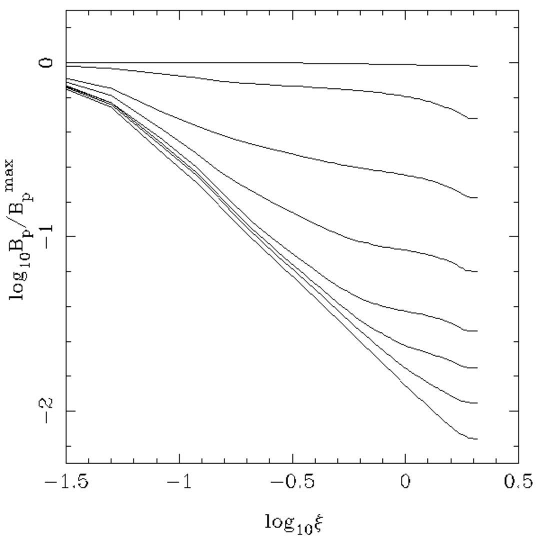


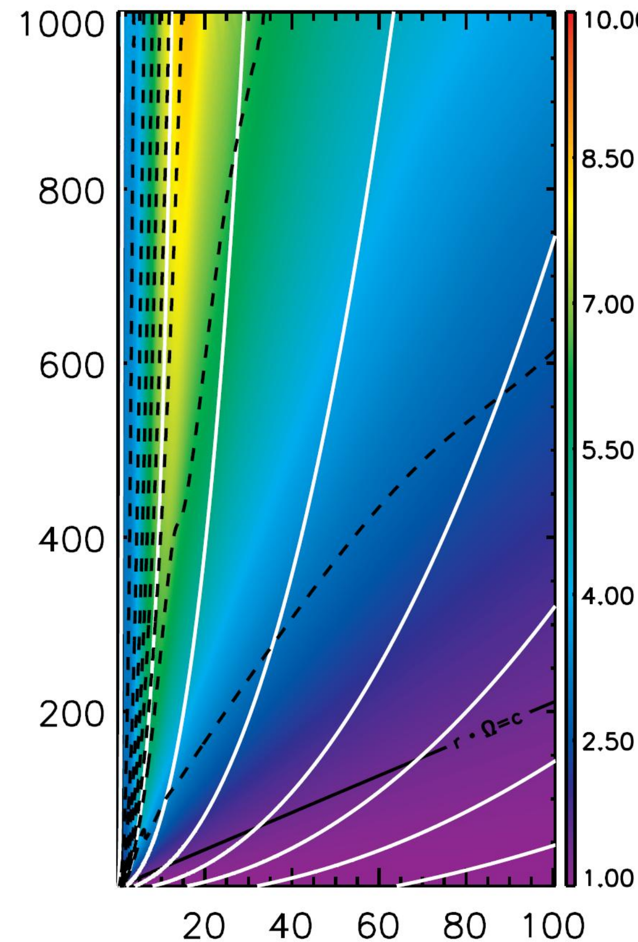
Yu.Lyubarsky,
ApJ. **698**, 1570, 2009

V.S.Beskin, E.E.Nokhrina,
MNRAS, **397**, 1486, 2009

Central core







S.Komissarov, M.Barkov, N.Vlahakis, A.Königl, MNRAS, **380**, 51, 2007

O.Porth, Ch.Fendt, Z.Meliani,B.Vaidya. ApJ (in press) (2011)

Conclusion

- Effective ($\gamma = x$) acceleration takes place for strong collimation only (parabolic or stronger)
- Ineffective acceleration for weak collimation (parabolic or weaker)
- Effective particle acceleration takes place only if

$$\varpi \sim \sigma R_L$$

- Effective particle acceleration is possible only if the curvature plays no role
- External media is necessary