Center for Astrophysics, Harvard University

Magnetized accretion.

Quasi-spherical case.

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under advisement of

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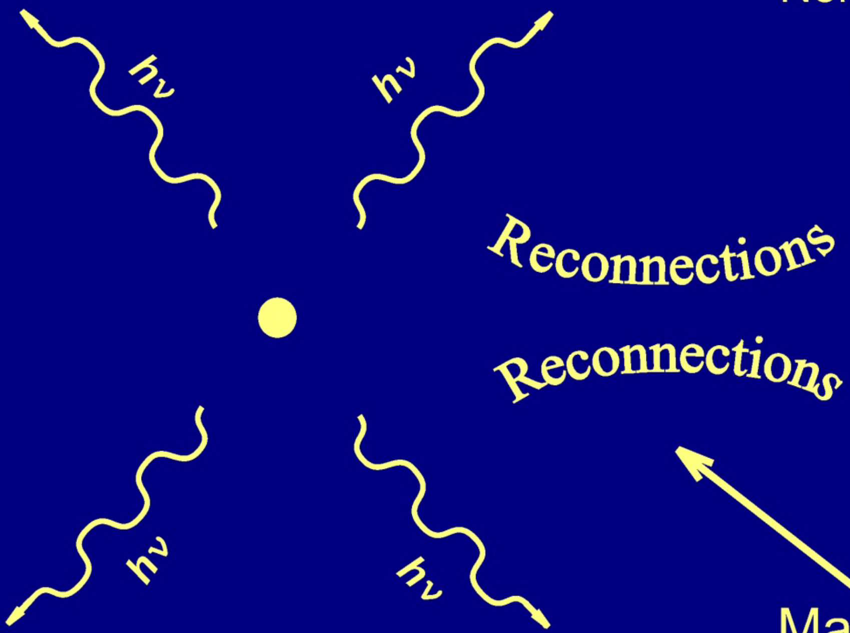
8 December, 2006

What is it about?



Non-linear regime

$$\frac{B^2}{8\pi} \sim nkT$$

External medium

$$\frac{B^2}{8\pi} << nkT$$

$$B \cdot r^2 = const$$

$$\frac{B_r^{\,2}}{8\pi \cdot n \cdot m_e c^2 r_g / r} \sim r^{-\frac{3}{2}}$$

Magnetic helicity
conservation

Outline

Perturbations near spherical solution

Flux tube approximation

Magnetic helicity conservation

Model with Reconnections

Free parameters

Matching External Medium

Dynamics of the Flow

Non-thermal electrons

Synchrotron + Compton radiation

Spectrum, comparison to observations

Decomposition of the flow

$$\boxed{\vec{V}(r,\theta,\varphi,t) = \vec{u}(r,\theta,\varphi,t) - v(r)\vec{e}_r}$$

Random velocity field

Regular radial inflow

$$\boxed{\vec{v}_A(r,\theta,\varphi,t) = \frac{\vec{B}(r,\theta,\varphi,t)}{\sqrt{4\pi < \rho >}}}$$

Random magnetic field

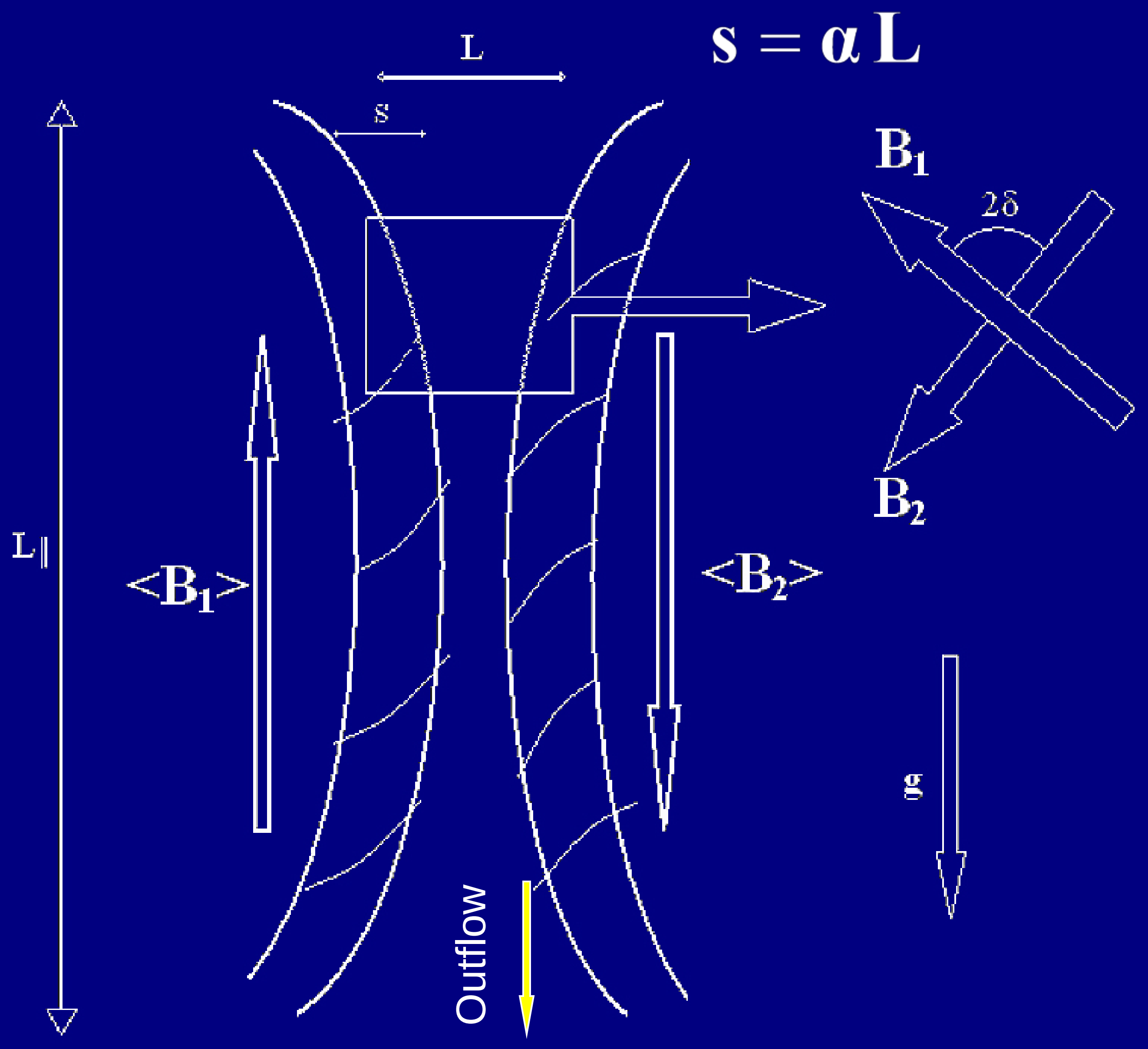
$$< v(r) \cdot \vec{u}(r,\theta,\varphi,t) >_t = 0$$ – all cross-terms vanish

$$< v_{Ai}(r,\theta,\varphi,t) \cdot u_k(r,\theta,\varphi,t) >_t = 0$$ – no dynamo action

$$< \vec{u}(r,\theta,\varphi,t)^2 >_t = \frac{u^2(r)}{2}$$ – turbulent kinetic energy density

$$< \vec{v}_A(r,\theta,\varphi,t)^2 >_t = \frac{{v_A}^2(r)}{2}$$ – turbulent magnetic energy density

Flux tube approximation



Back-reaction of the magnetic field

$$B = \left\langle \alpha^2 B_{tube}{}^2 \right\rangle^{1/2}$$

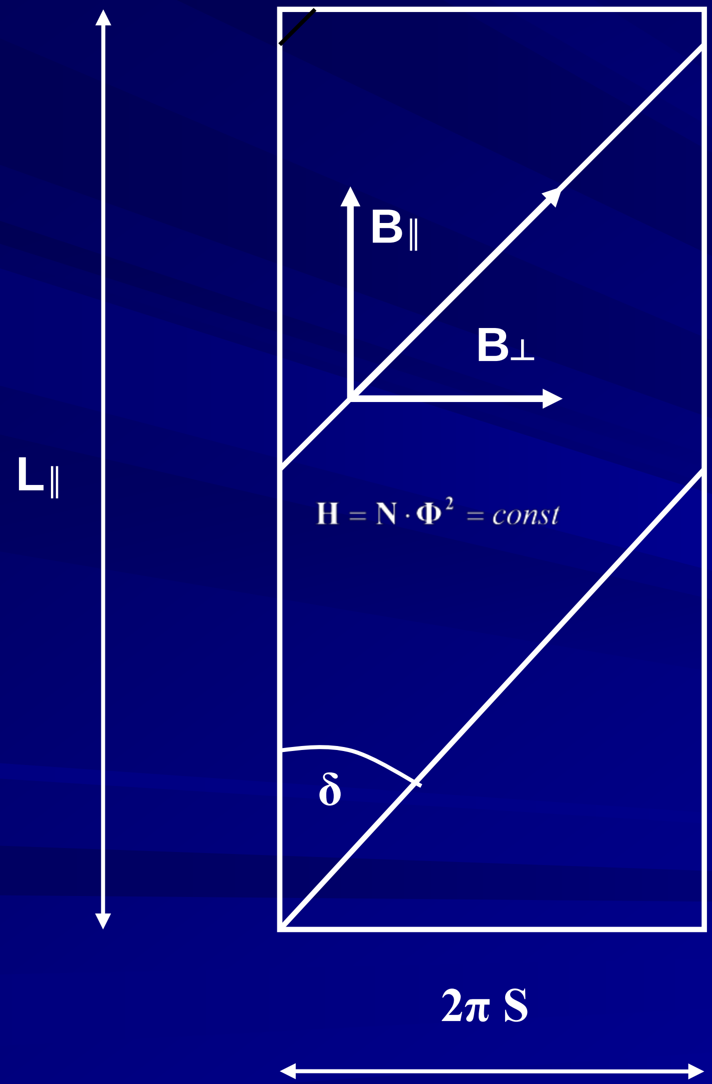
$$B_r >> B_\theta , B_\varphi$$ but $$\frac{\partial B_r}{\partial r} \sim \frac{\partial B_\theta}{r \partial \theta} \sim \frac{\partial B_\varphi}{r \cdot \sin(\theta) \partial \varphi}$$

$$F_r = \left\langle J_\theta B_\varphi - J_\varphi B_\theta + B_r \frac{\mathrm{div}(\vec{B})}{4\pi} \right\rangle_{\theta,\varphi} = \frac{1}{8\pi \cdot r^4} \frac{\partial}{\partial r} (r^4 B_r{}^2)$$

Scharlemann, 1983

Magnetic energy advection = $$\frac{v}{c} \frac{\partial (\text{energy density} - \text{strain})}{\partial r} = O(B_\theta{}^2, B_\varphi{}^2)$$

Magnetic helicity



$$H = N \cdot \Phi^2 = const$$

N – number of twists

Φ **– magnetic flux**

$$r \cdot v_A{}^2 \tan(\delta) = const$$

System of equations

6 independent quantities: $\rho(r), v(r), T(r), v_A(r), v_{turb}(r), L(r)$

$$\rho(r)v(r)r^2 = \dot{M} \qquad (1)$$

$$\boxed{\exp\left(-\frac{r}{r_{max}}\right)}$$

Euler equation (2)

Energy equation (3)

$$\frac{\partial\left(B^2\right)}{\partial r} = -4\frac{B^2}{r} + \left(\frac{B^2 v_{in}}{v L} - \frac{4\pi Q_m \rho}{v}\right)\exp\left(-\tan(\delta)\right) \qquad (4)$$

$$\frac{\partial\left(v_{turb}{}^2\right)}{\partial r} = -2\frac{v_{turb}{}^2}{r} - \frac{v_A{}^2 v_{in}}{v L}\exp\left(-\tan(\delta)\right) + \frac{v_{turb}{}^3}{v L} \qquad (5)$$

$$L = \beta r \qquad (6)$$

Find the maximum possible accretion rate

Free parameters?

$$\beta = \frac{L}{r} \sim 0.001 \div 0.1$$ – size of the turbulent cell

$$\alpha = \frac{s}{L} \sim 0.3 \div 1$$ – geometric factor for the magnetic field distribution

$$Q_m = (0.05 \div 0.3) * \text{Energy release by stellar wind}$$

$$v_{in} = \min(0.05 v_A, v_{turb})$$ – reconnection inflow speed

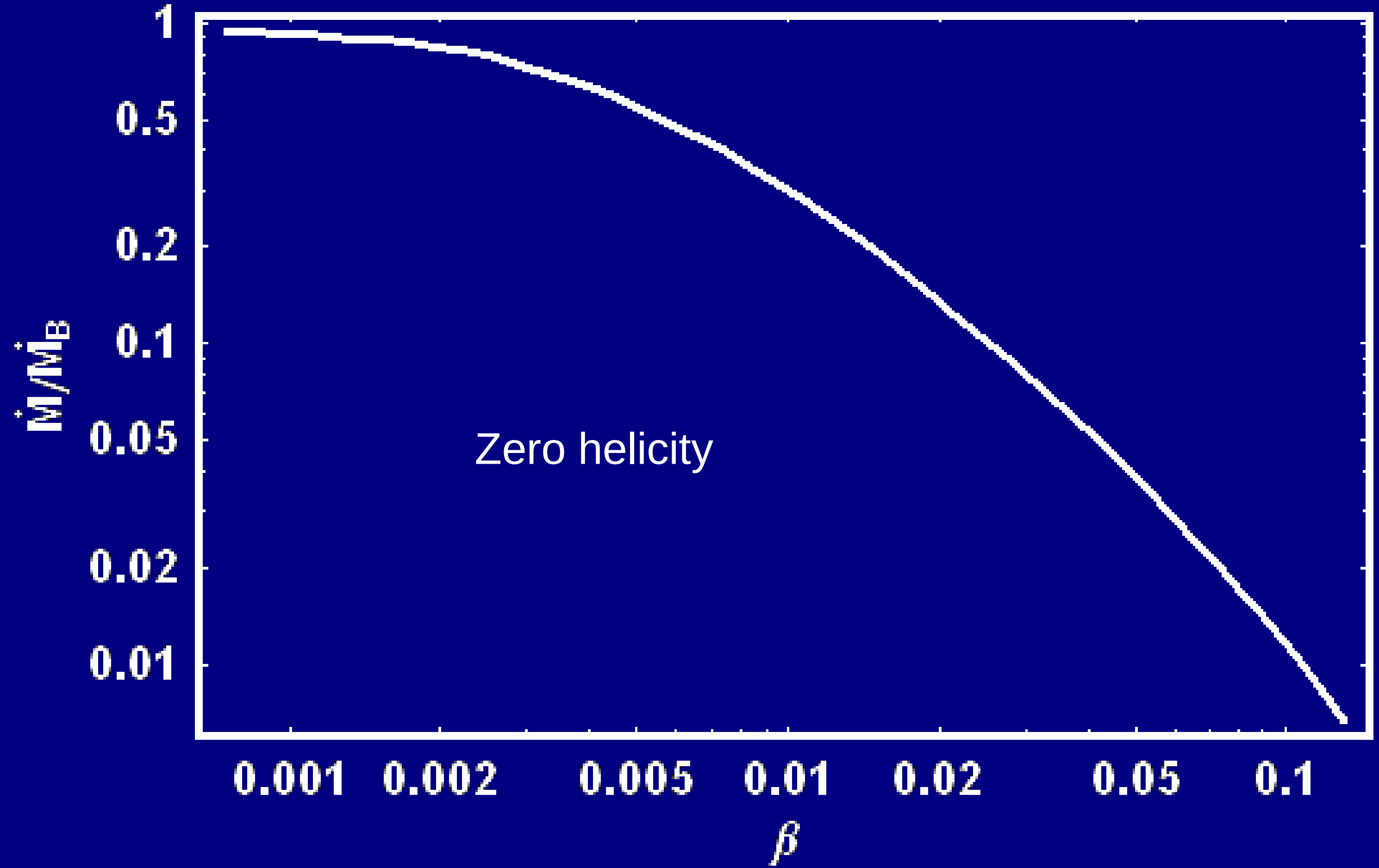
$$\tan(\delta(r_{max})) = 0.01 \div 0.3$$ – magnetic helicity normalized to maximum value

$$r_{max} = 0.5 \div 2\, r_B$$ – radius of transition to the external medium

Results. Dependence on reconnection rate

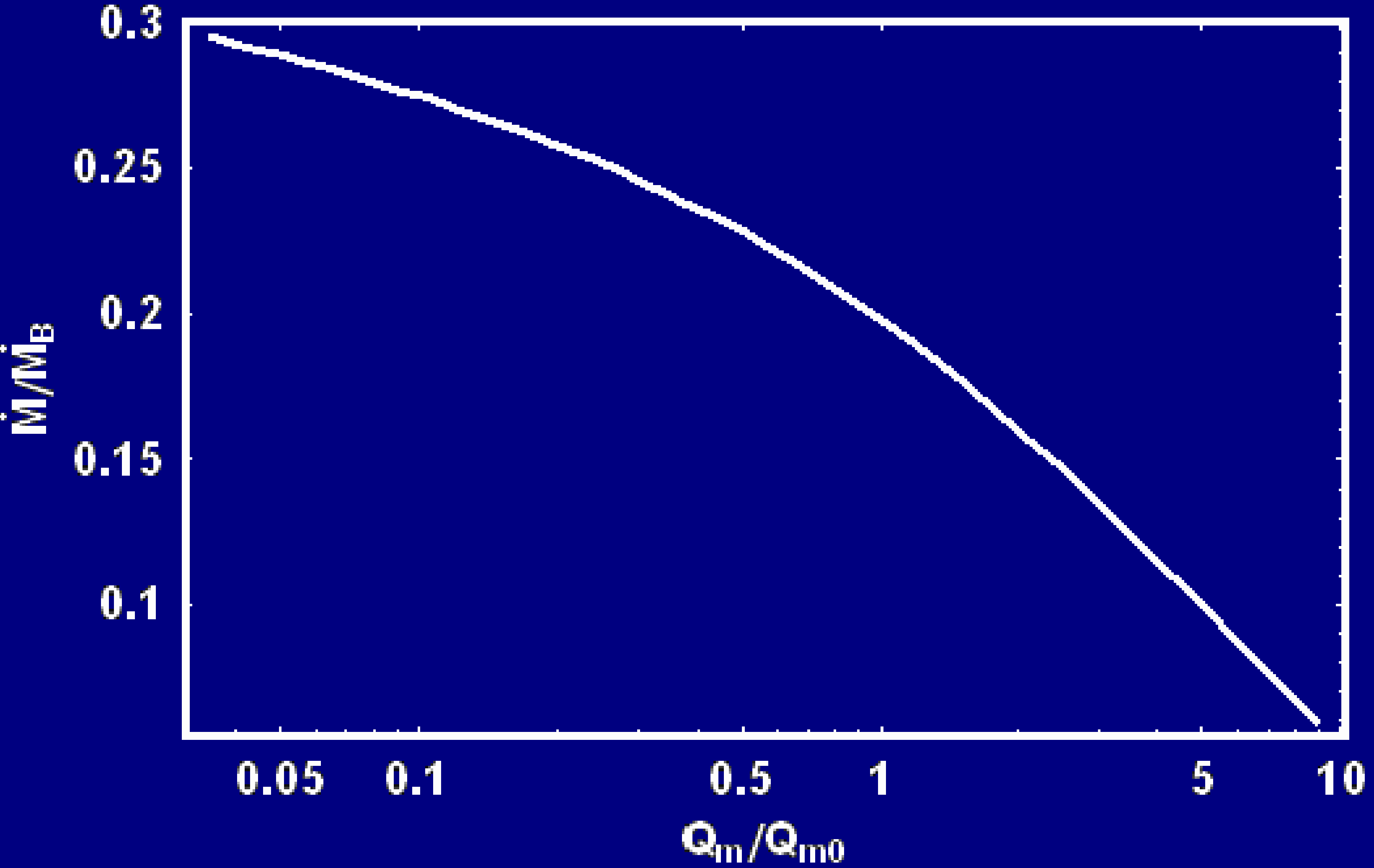
$$M_{BH} = 3.6 \cdot 10^6 M_\otimes \quad T_\infty = 1.5 \cdot 10^7 K \quad n_\infty = 130/cm^3$$

$$Q_{m0} = 10^5 erg/s/g \quad \dot{M}_B = 1.0 \cdot 10^{-6} M_\otimes/year$$

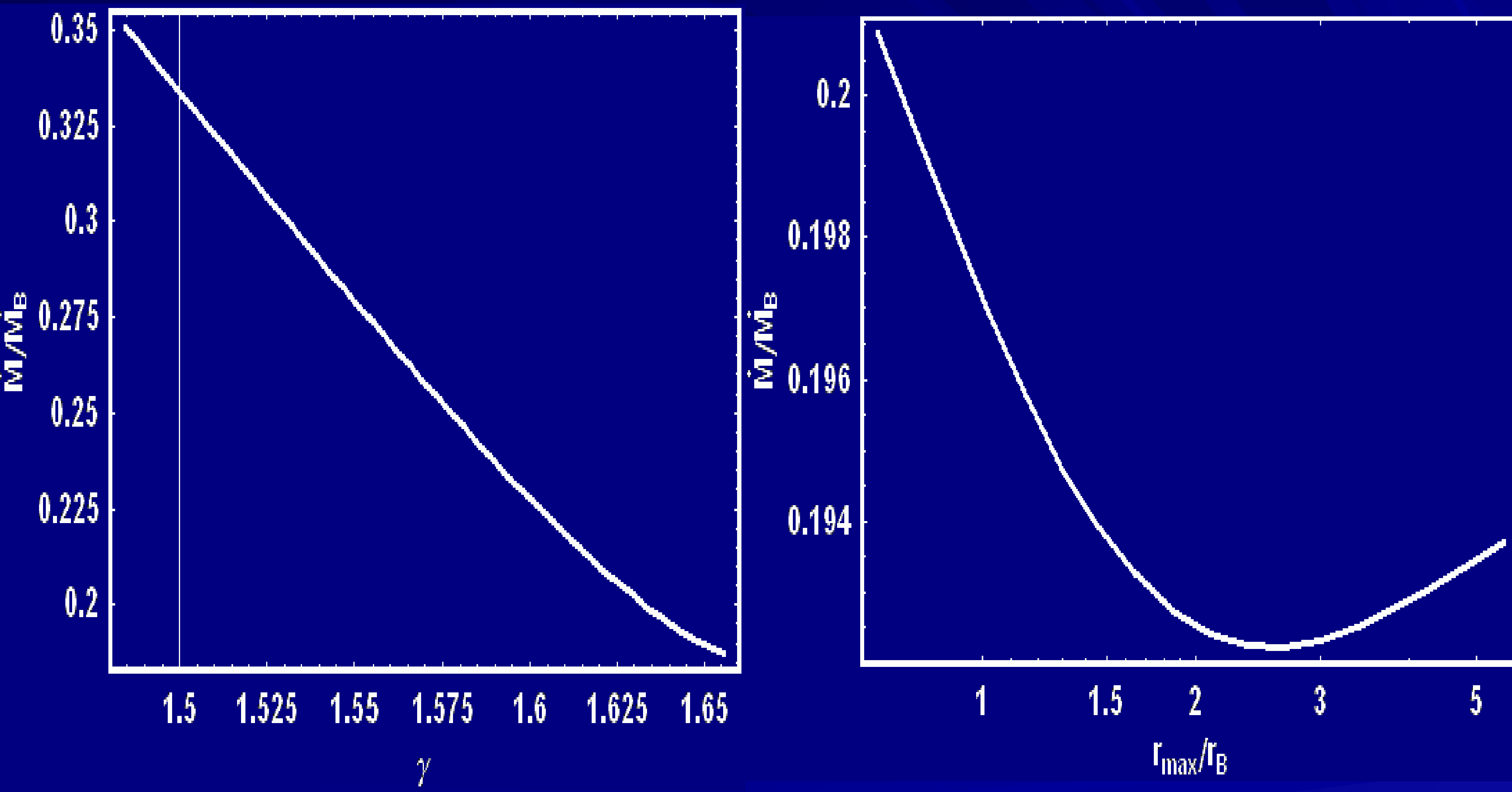


Results. Dependence on the energy input

$$\beta = 0.015$$

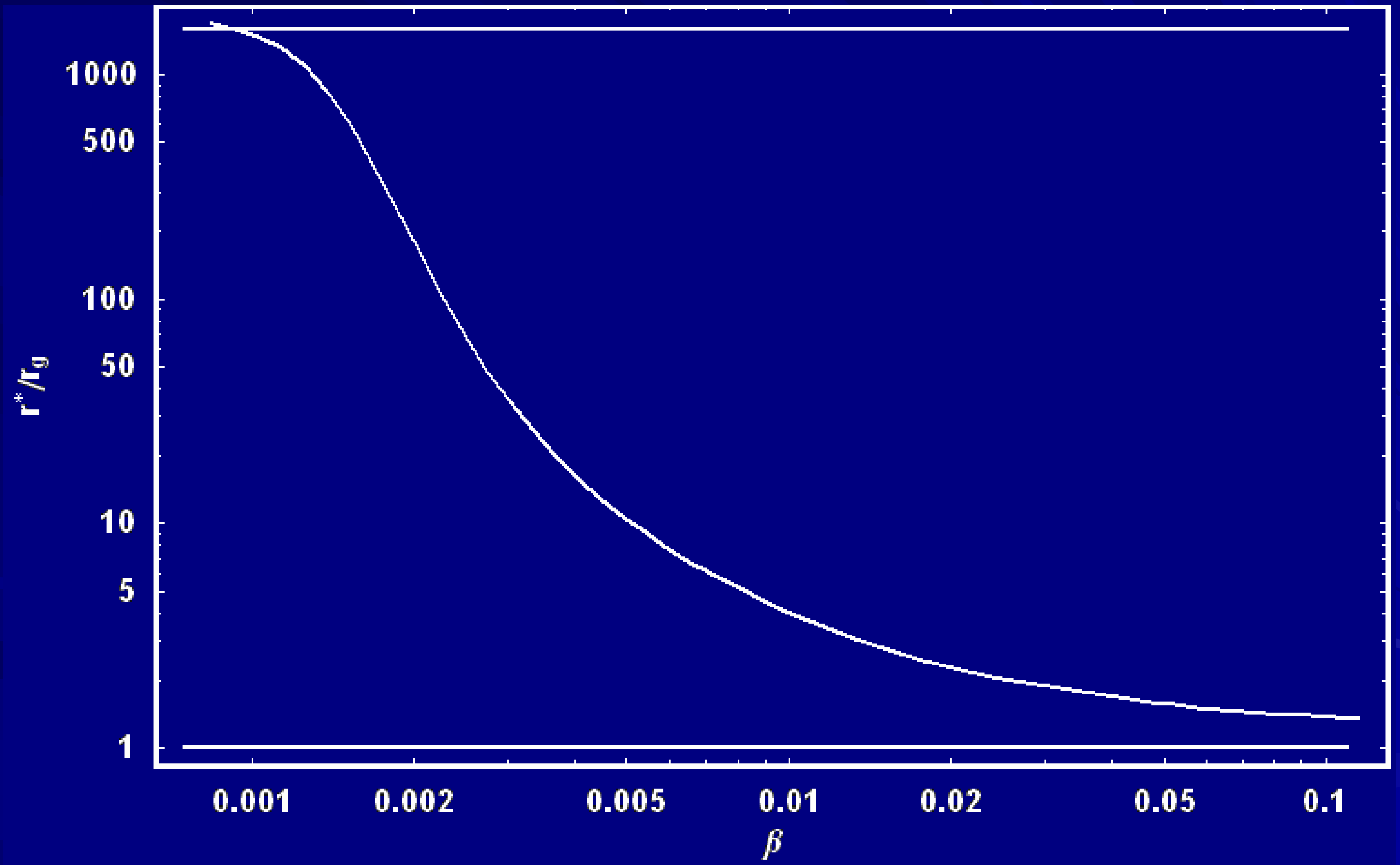


Results. Dependence on γ_{gas} and r_{max}



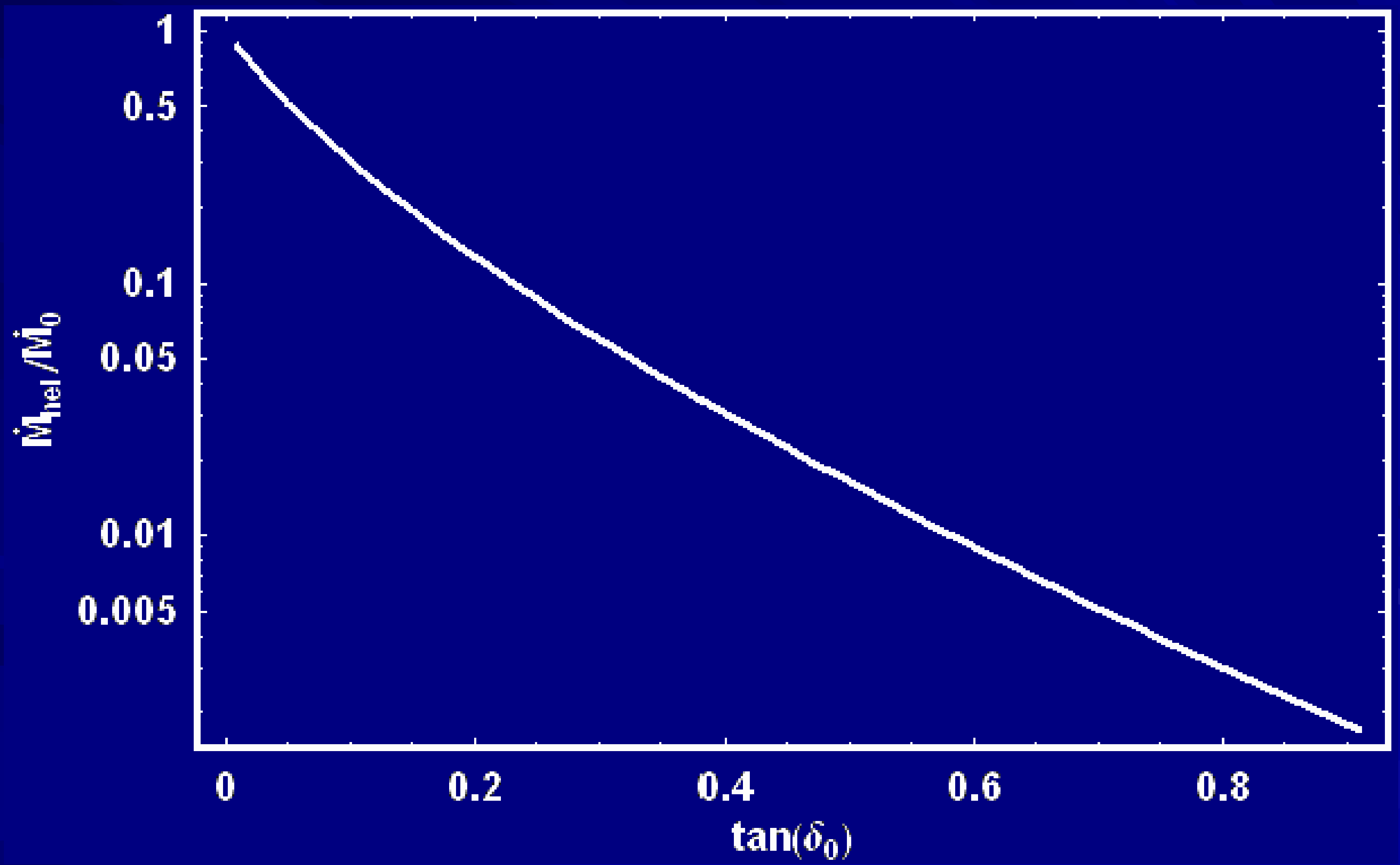
Results. Sonic radius

$$\gamma_{gas} = 1.645$$

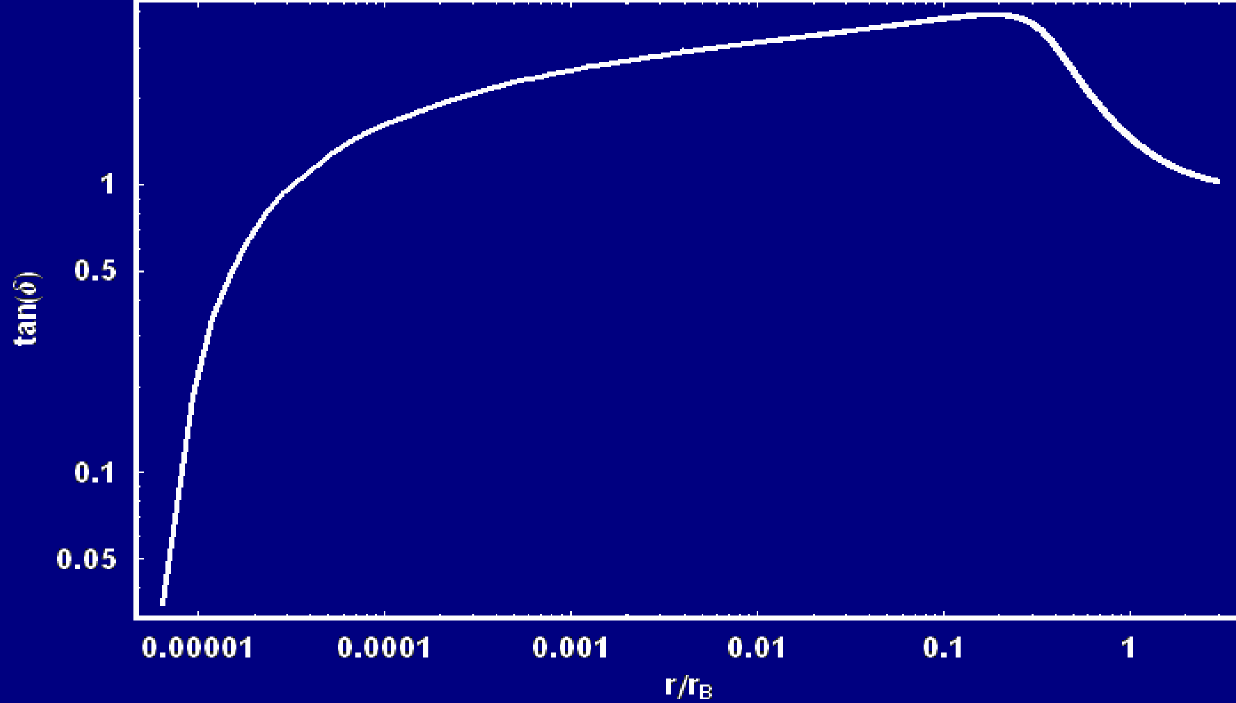


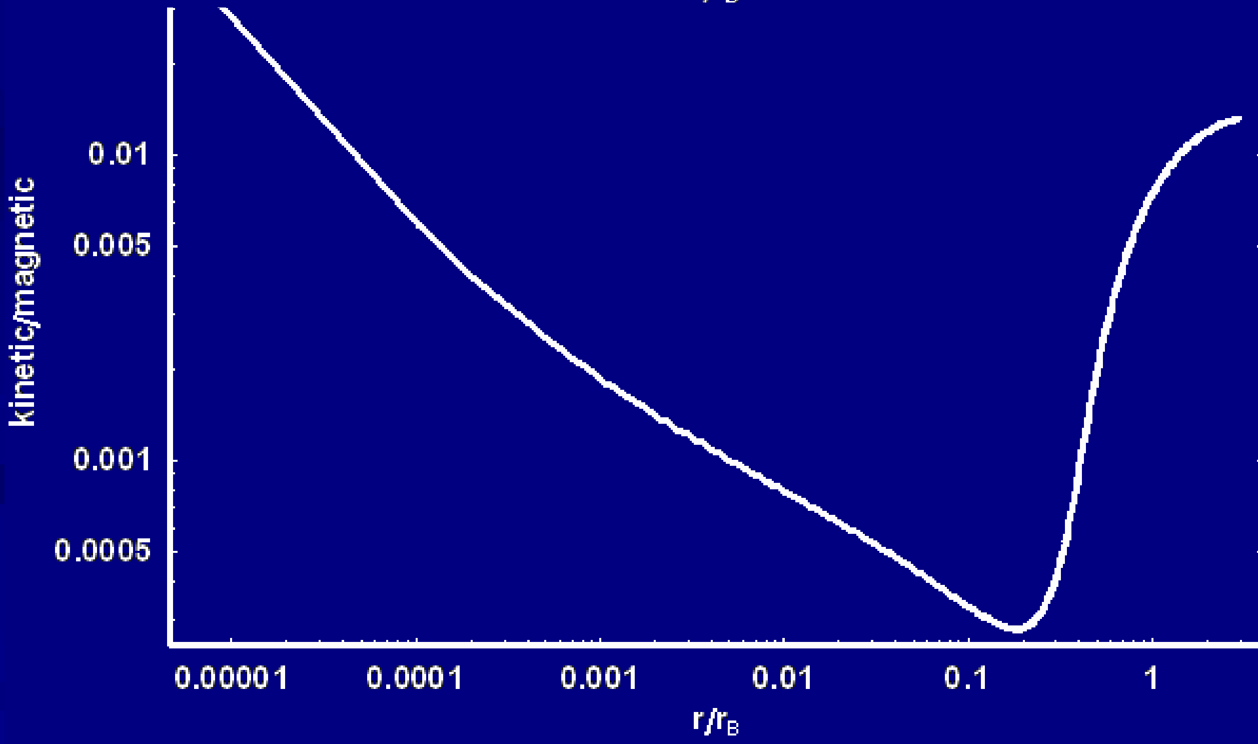
Accretion rate for non-zero Helicity

$$\beta = 0.13, \ \ M_0 = 7 \cdot 10^{-3} M_B$$

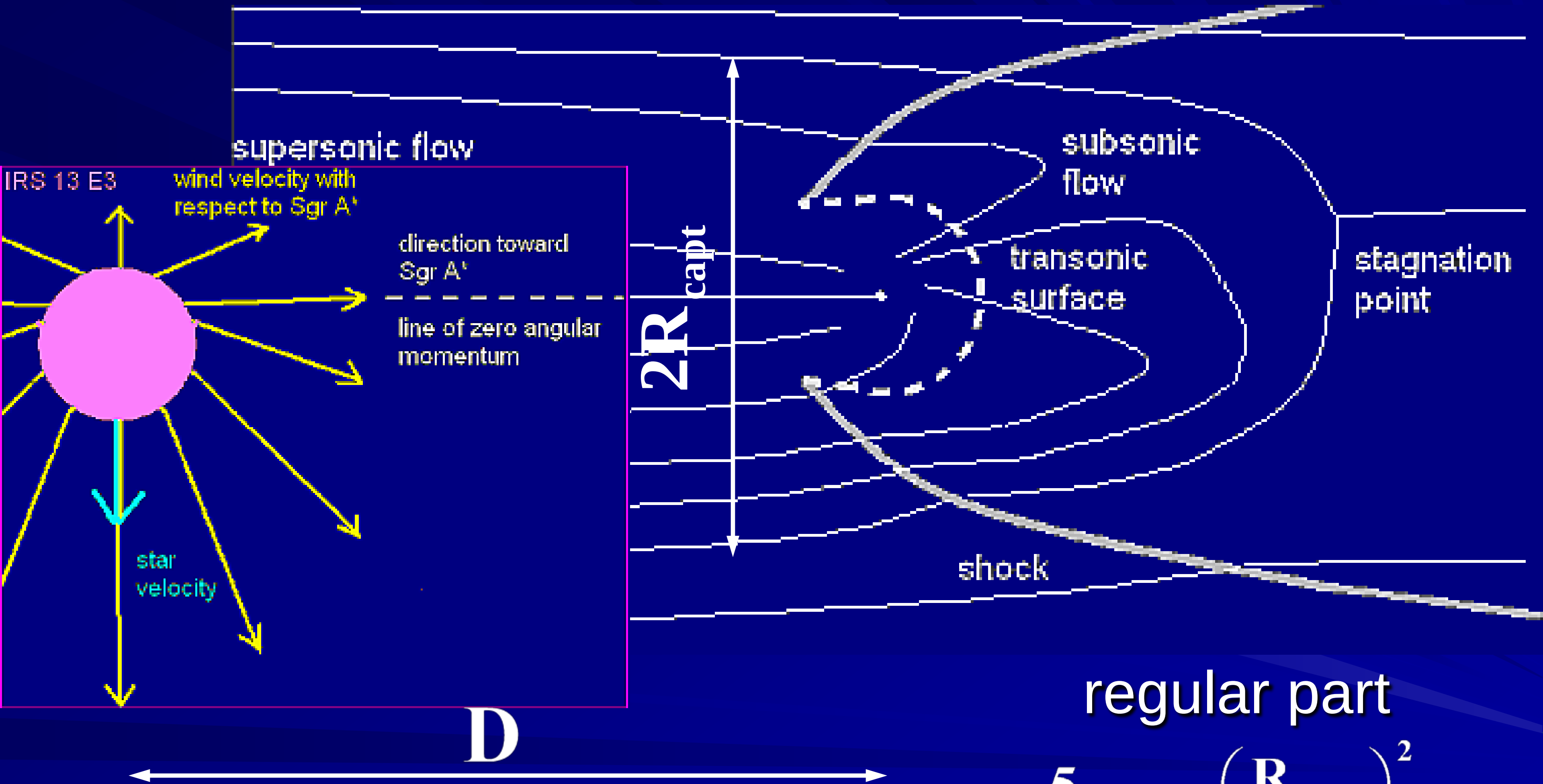


On the way to force-free





Angular momentum



regular part

$$L_m = \frac{5}{4} v_{star} D \left(\frac{R_{capt}}{D} \right)^2 \sim \dot{M}$$

Moscibrodzka, 2006

Conclusions about dynamics

I constructed and solved the model that:

- **accounts for non-ideal behavior of plasma**
- **distinguishes magnetic and kinetic turbulent energies**
- **gives a match to the external medium**

Is it realistic?

- **1-T approximation – ✓**
- **sufficiently low angular momentum – ✓**
- **No convection – ☹**

The only test – comparison to observations

Non-thermal electrons

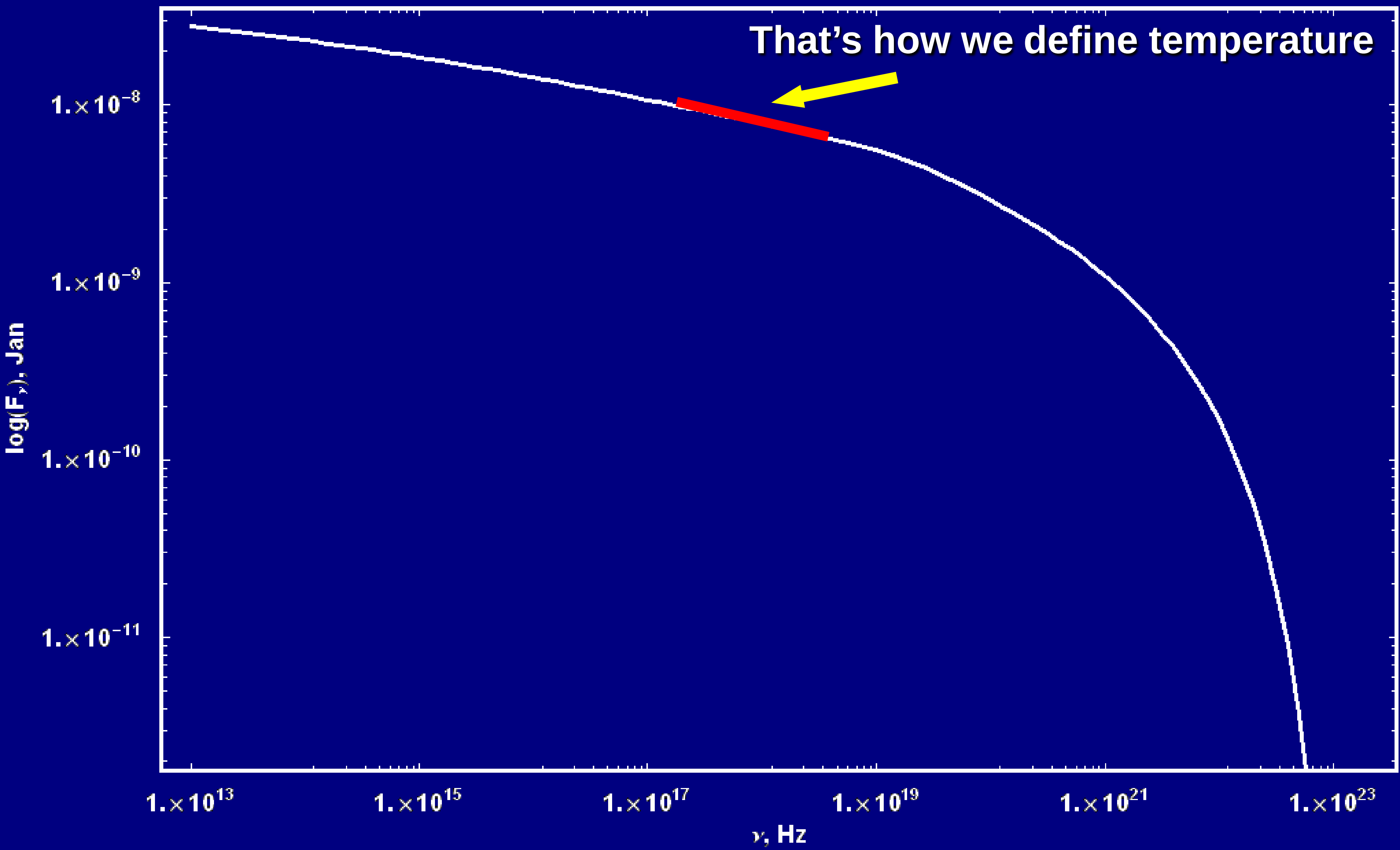
$$\gamma_{min} = 1 + \frac{k_B T}{m_e c^2} \qquad \gamma_{max} = \frac{e L B}{m_e c^2} \frac{v_{turb}}{c}$$

Acceleration profile: $$f(\gamma) = \frac{1}{(\gamma - 1)^2} \exp\left(- \frac{\gamma}{\gamma_{max}} \right) \sim \gamma^{-2}$$

Distribution function $$p(\gamma, r)$$

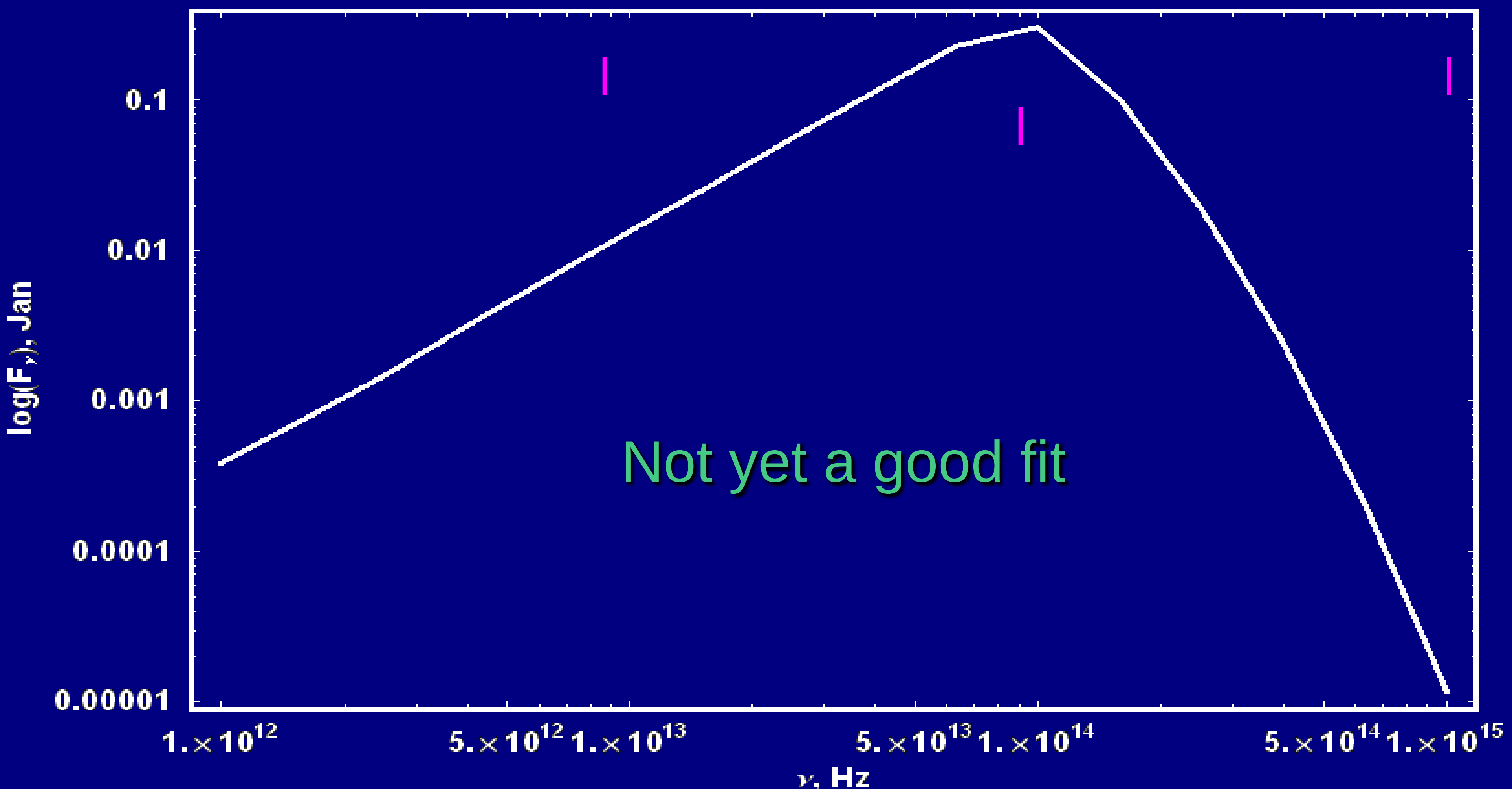
$$\boxed{\frac{d\,p(\gamma, r(t))}{dt} = 0.1 \cdot f(\gamma) \cdot \frac{Q_{rec.vol}}{n(r) m_e c^2 \log(\gamma_{max} / (\gamma_{min} - 1))}}$$

Bremsstrahlung

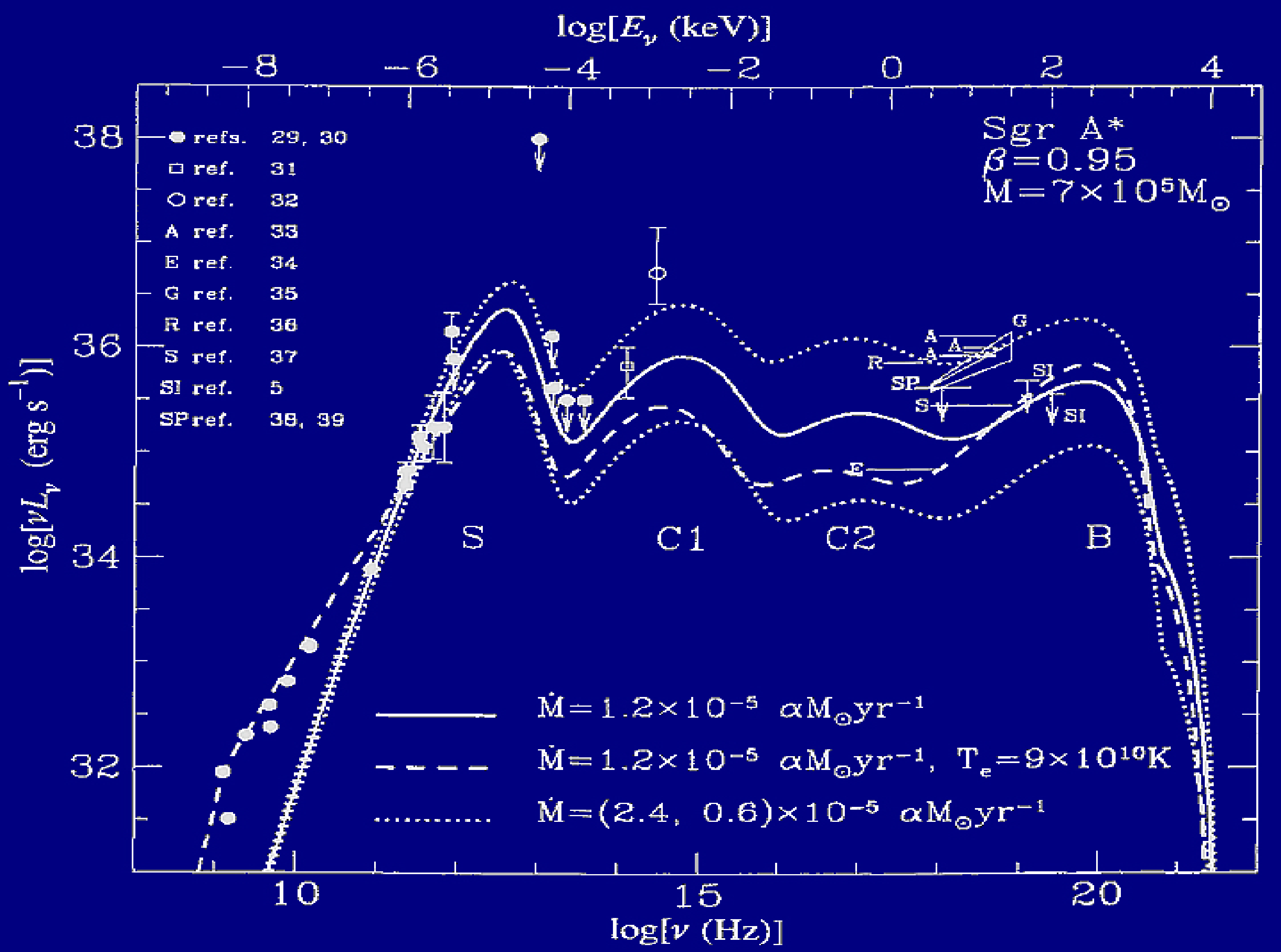


Synchrotron radiation

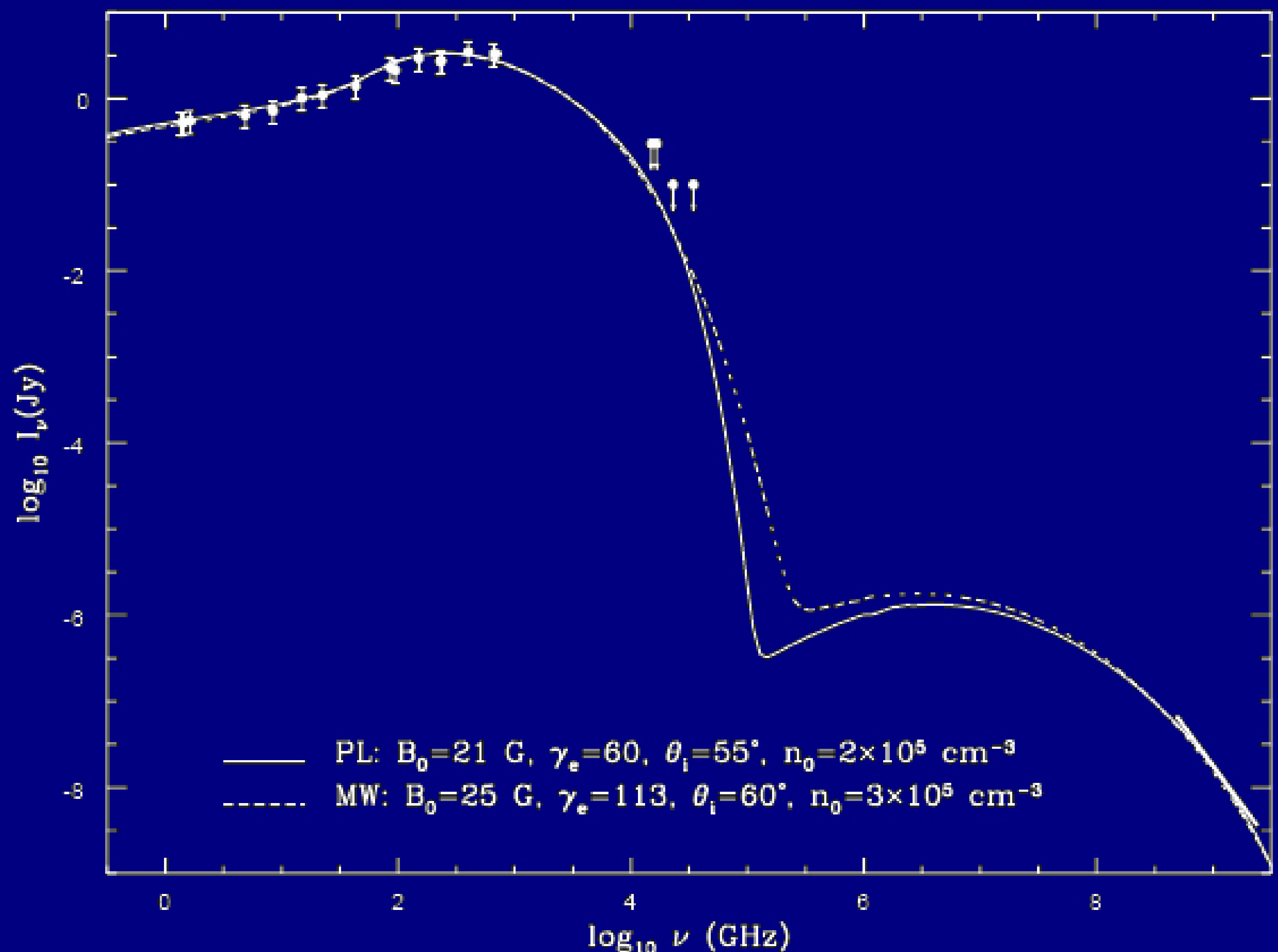
$$\beta = 0.004,\ \dot{M} = 0.62\dot{M}_B$$



Fit by Ramesh, 2002



Fit by Falcke, 2001



To Do about the spectrum

- Compton scattering
- relativistic and gravitational Doppler shifts
- Razin effect in plasma
- conversion of Langmuir waves into photons
- radiation from non-thermal electrons?

Best fit model