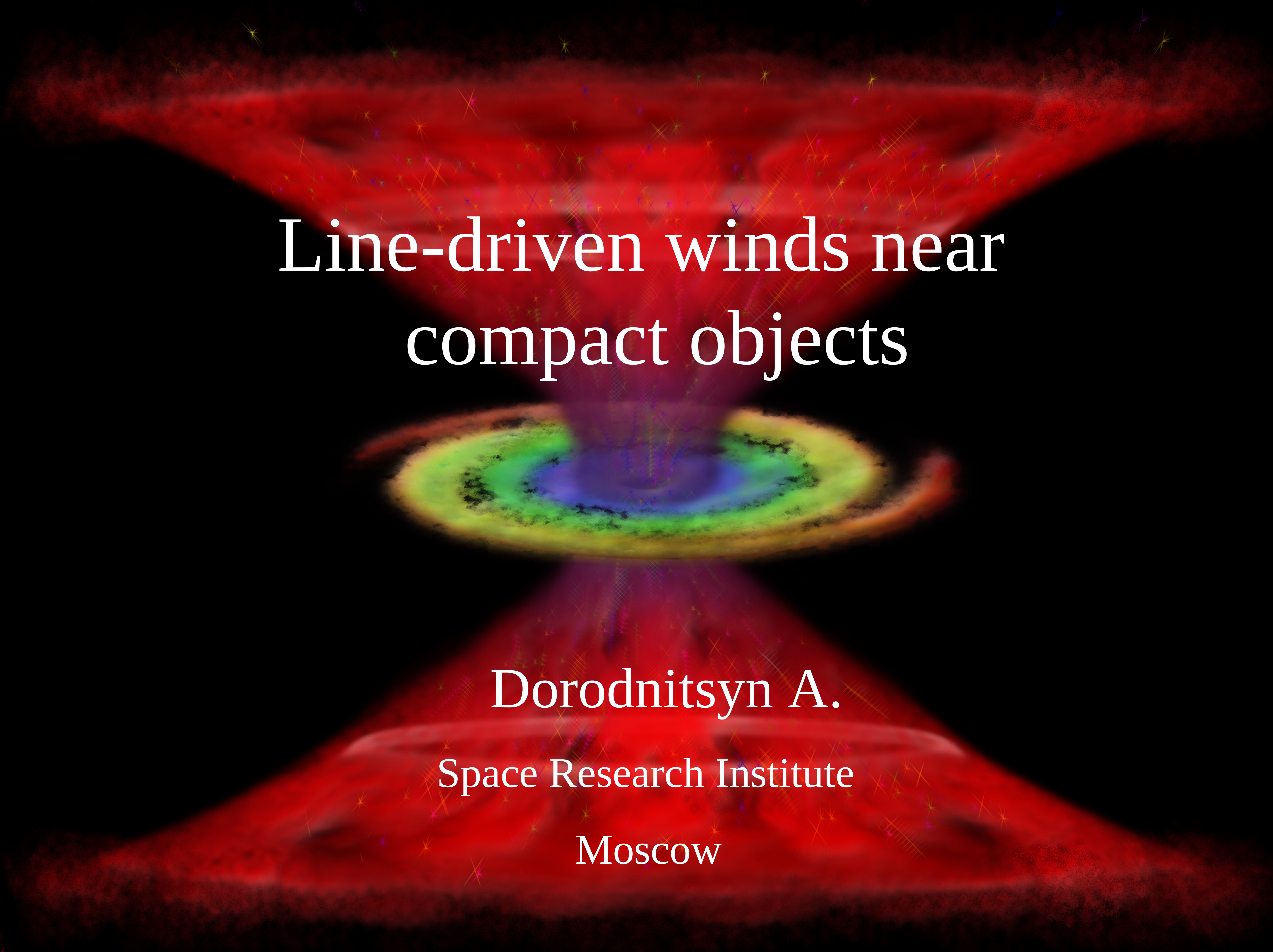


Line-driven winds near compact objects

Dorodnitsyn A.

Space Research Institute

Moscow

Sources of acceleration

- Magnetic driving

Jets (collimated) and bipolar(less collimated) outflows.
•nuclei of active galaxies
•galactic X-ray binaries
•Protostars

High Lorents factors
high degree of collimation

In fact very little is known about acctual B in accretion disks

- Radiation driving

"Natural" and almost inevitable mechanism for high luminosity disks

---

Overionization by the central source rises the problem of confinement

AGN

- NALs –
  - *Narrow absorption line region*
- BALs –
  - *Broad absorption line region*
- BELs –
  - *Broad emission region*

- *Narrow absorption line region seen in UV and X-ray spectra* $\sim 1000\ km/s$
- *The blue-shifted broad absorption lines the most convincing evidence of outflows with* $V^{\infty} = 0.2c$
- *Broad emission lines, UV –indicate outflows with velocities several thousand km/s*

Radiationally accelerated winds

- *O-type stars*

  theory of Castor, Abbott, Klein (1975)
  - pressure in lines
  - Sobolev effect

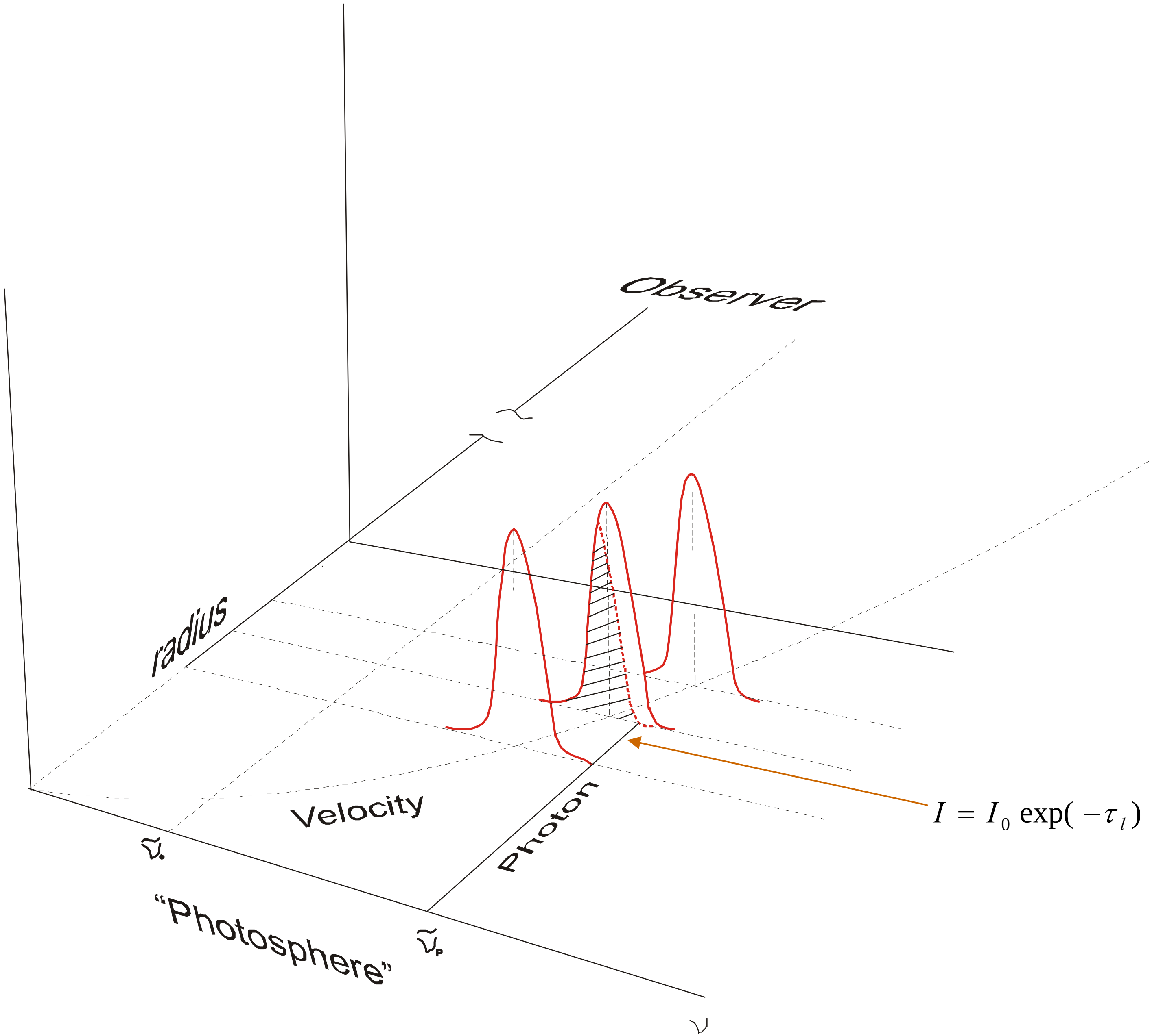
- *WR-stars - ?*
- *Evolved massive stars*

  - absorption of the radiation flux in continuum
  - all types of opacity
    - true absorption
    - lines
    - Dust

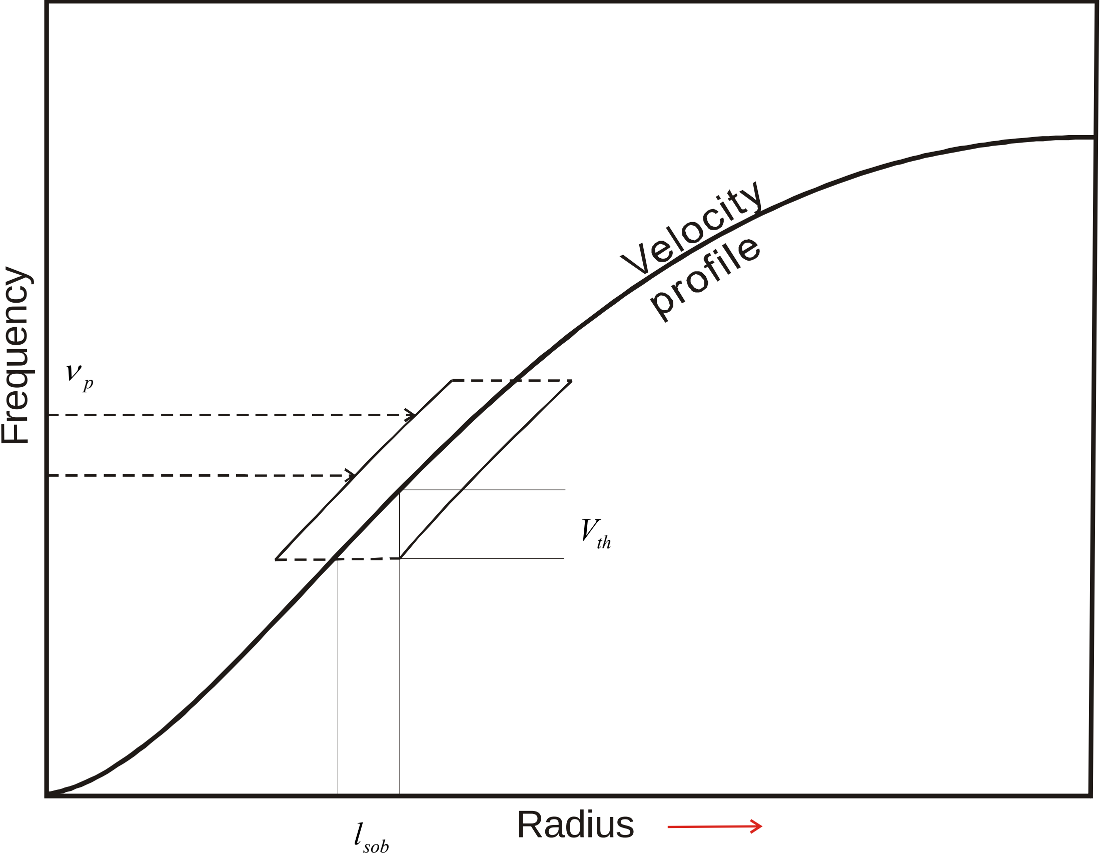
- *Line-driven winds from accretion disks*

  Arav et al, (1994, 2002)
  Murray at al. (1995) (a quasi-1D model)
  Proga et al. (1998,2000) (the 2D calculations of the accretion disk powered winds)
  Stevens & Kallman (1990) (winds from massive X-ray binaries , together with ionizing effects of the radiation from the central source)

  . . .


Observer
radius
Velocity
Photon
"Photosphere"
$I = I_0 \exp(-\tau_l)$

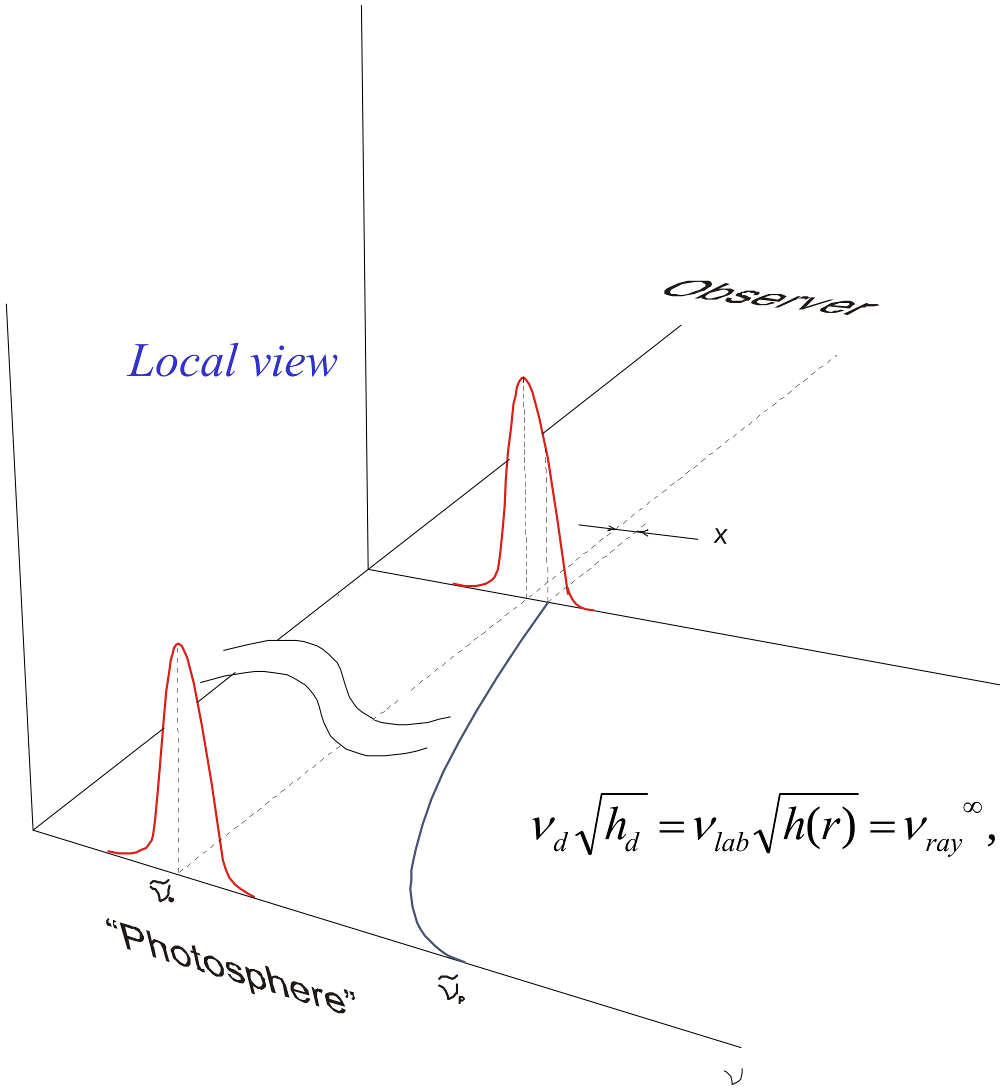
CAK-theory



$$\tau_l = \int_r^\infty \psi \, \rho \, \kappa_l \, dr \approx \frac{\rho \, \mathrm{v}_{th} \, \kappa_L}{\left| d\mathrm{v} / dr \right|}$$

$$f_l \sim \left(\frac{1}{\rho} \frac{d\mathrm{v}}{dr} \right)^\alpha$$

$$\mathrm{v} \frac{d\mathrm{v}}{dr} = \Phi(\mathrm{v}, r) + A(r) \left(\frac{d\mathrm{v}}{dr} \right)^\alpha$$



$$\nu_d \sqrt{h_d} = \nu_{lab} \sqrt{h(r)} = \nu_{ray}^{\infty},$$

- *A photon, emitted elsewhere in the "photosphere, may become resonant with the line transition downstream*
- *Since the line has a thermal width, the absorption takes place in a resonant layer of the typical size of about*

  Sobolev length

Gravitationally Exposed Flow

The key ingredient of the standard theory is that the optical depth (measured on the lab. frequency of the line transition) can be expressed as a function of the velocity gradient in the flow.

The same is true in the case when a photon, emitted somewhere deeply in the potential well, will become resonant with the line absorption both due to velocity diference and due to GR effect of redshifting.

Dorodnitsyn, A.V. 2003, *MNRAS*, 339, 569

Dorodnitsyn A. & Novikov I., ApJ, submitted
astro-ph/0409363

- To calculate the radiation pressure force taking into account gravitational redshifting

- What is the relative impact of gravitational redshifting in comparison with standard case

---

- only very simple input conditions are chosen
  - no ionization,
  - Spherical symmetry
  - CAK parameterization law

We may hope that approximately the same difference will hold between GEF and CAK cases in more realistic calculations

- Spherically-symmetric
- Background Schwarzschild metric
- Nonrelativistic, v/c terms retained only, Sobolev theory of the radiation transfer in lines

Radiation + Gravity

$$T^{\alpha\beta} = (P+\rho)u^{\alpha}u^{\beta} + P g^{\alpha\beta}$$

$$\rho = \rho_0(1+E_i),$$

$$\rho_0 = m_b n_b$$

matter

- Stress-energy tensor for the perfect gas

total mass-energy density

barionic rest-mass density

E_i *enternal energy of the perfect gas*

-

$$G^{\alpha\beta} = \int_0^{\infty} d\nu \oint d\Omega (\chi_{\nu} - \eta_{\nu}) n^{\alpha}$$

opacit y

emissivity

direction

- Four-force density

describes the process of the interaction of the matter with the radiation field

$$T^{\alpha\beta}{}_{;\beta} - G^{\alpha} = 0$$

Matter vs. radiation

- *Equation of motion*

  (Euler equation)

  Mihalas & Mihalas (1984)

  and references therein

$$(n_b\, u^{\alpha})_{;\alpha} = 0$$

Matter only

- *Continuity equation*

Such a simple split of radiation and matter is possible only if radiation and outflowing matter have no "weight". It is justified by our assumption of the background Schwarzschild *metric*

$$\frac{P+\rho}{h}\left(V\,h\frac{dV}{dr}+\frac{M}{r^2}\right)+\frac{dP}{dr}-\frac{1}{h}G^1=0$$

Continuity equation

$$\rho_0\,V\,r^2\sqrt{h}=\frac{\dot{M}}{4\pi}$$

Optical depth with gravitational + Doppler redshifting

$$\boxed{\tau_l = \chi_l \, l_{GEF},}$$

- Modified Sobolev scale

$$w = \frac{d}{dr}\sqrt{h}$$

~ acceleration of the particle that was initially at rest

$$l_{GEF} = \frac{V_{th}}{\sqrt{h}\dfrac{dV}{dr} + c\,w} \approx \frac{V_{th}}{\dfrac{dV}{dr} + \dfrac{1}{c}\dfrac{d\phi}{dr}}$$

A nonlinear character of the equation of motion

$$0 < \alpha < 1$$

$$F = v\frac{dv}{dr} + \frac{1}{\rho}\frac{dP}{dr} + \frac{d\phi}{dr} - \frac{L\sigma_e}{4\pi r^2 c} - \frac{L\sigma_e k}{4\pi r^2 c}\left(\frac{4\pi}{\left|\dot{M}\right|}\right)\left[vr^2\left(\frac{dv}{dr} + \frac{1}{c}\frac{d\phi}{dr}\right)\right]^{\alpha}$$

nonlinearity

nonlinear coupling

Towards a solution

$$F(p, \mathrm{v}', \mathrm{r}) = 0$$

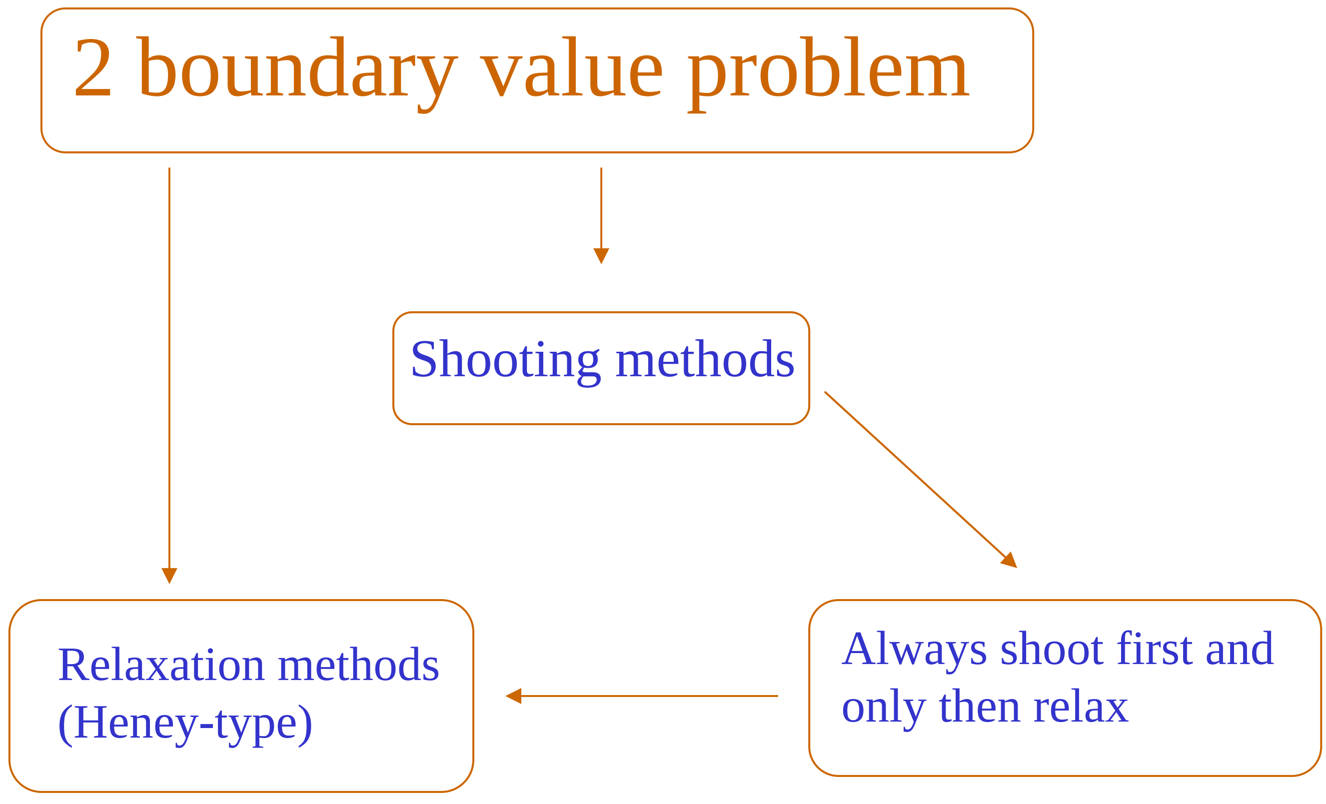
Equation of motion

$$\left(\frac{\partial F}{\partial r}\right)_{cr} = 0$$

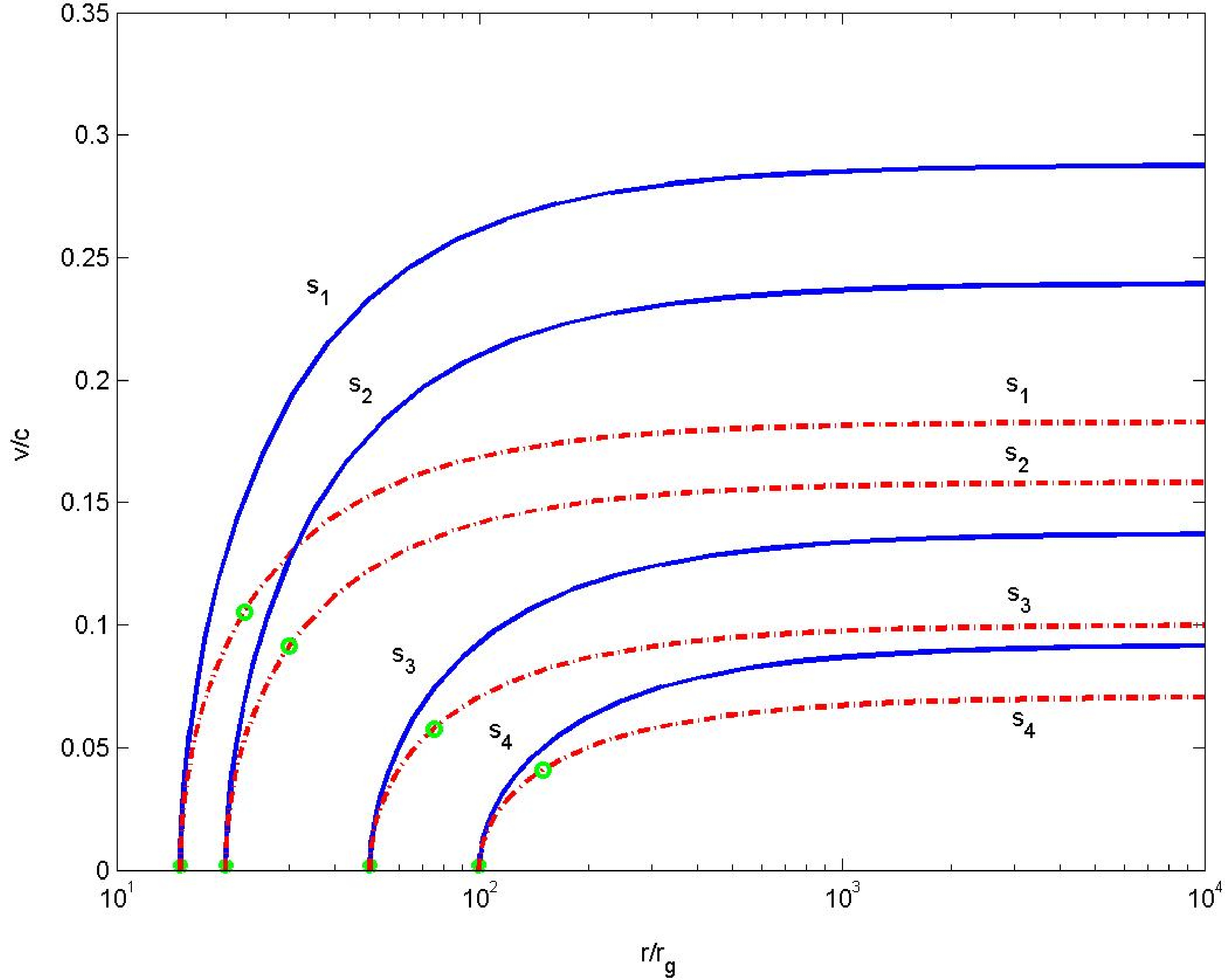
Singularity condition

$$\left(\frac{\partial F}{\partial r}\right)_{cr} + \mathrm{v}'_{cr}\left(\frac{\partial F}{\partial \mathrm{v}'}\right)_{cr} = 0$$

Regularity condition

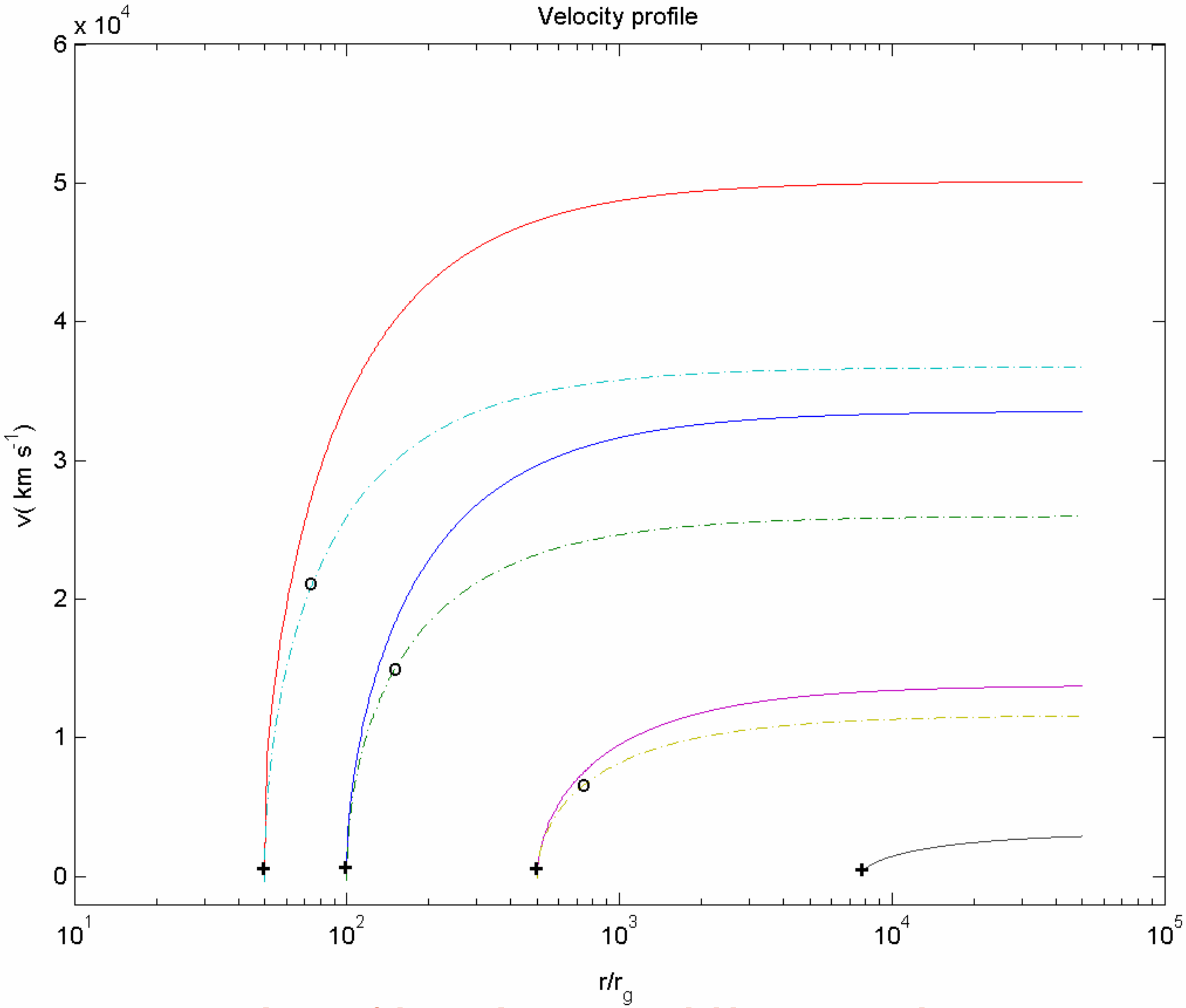

2 boundary value problem
Shooting methods
Relaxation methods (Heney-type)
Always shoot first and only then relax

Gravitationally Exposed Line-driven Flow

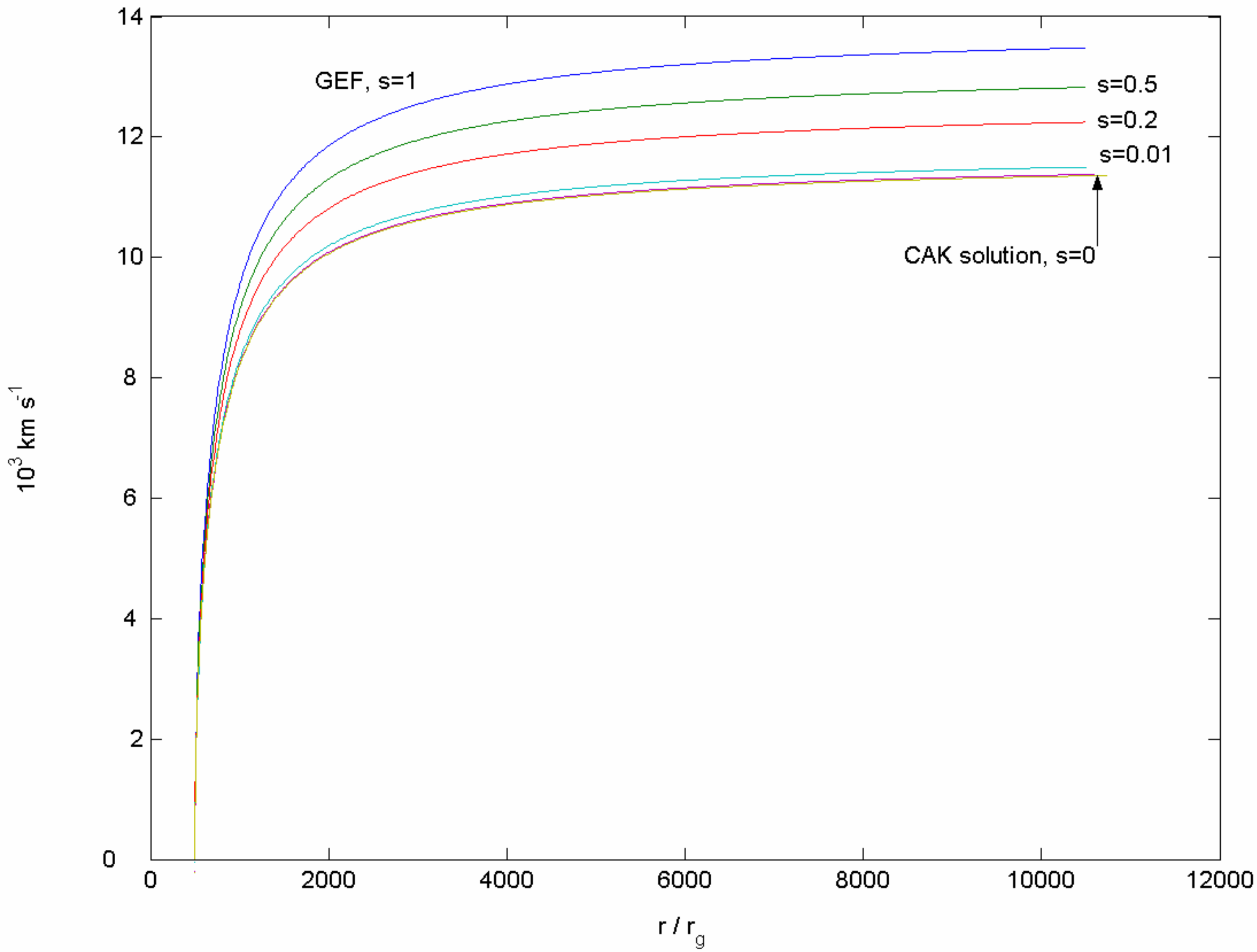


Model	$x_{c,GEF}$	$x_{c,CAK} - x_{c,GEF}$	$\frac{V^{\infty}{}_{GEF} - V^{\infty}{}_{CAK}}{V^{\infty}{}_{CAK}}$
S1	15	7.47	0.57
S2	20	9.95	0.51
S3	50	25	0.37
S4	100	50	0.2

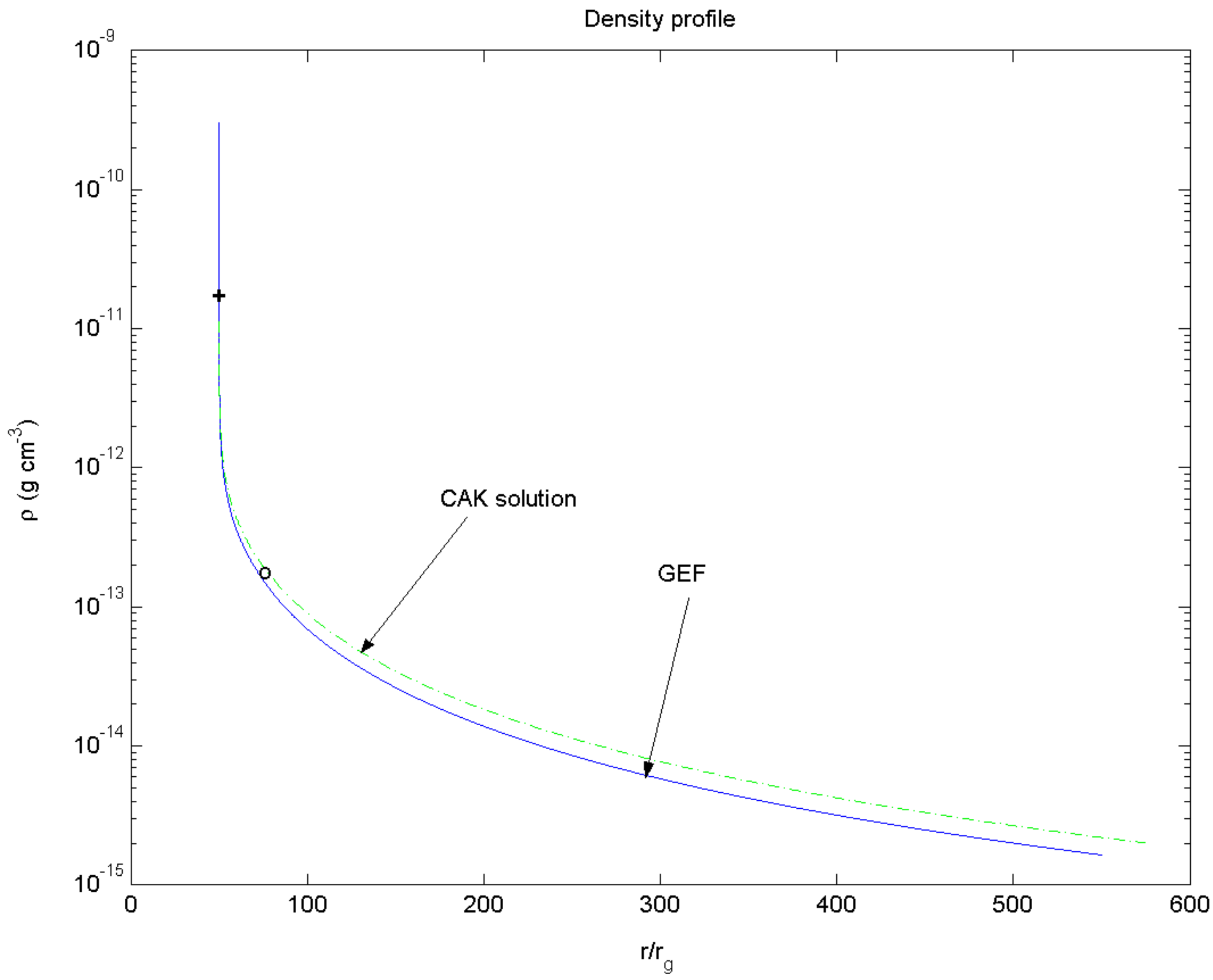
$x_c = r_c / r_g$ - position of the critical point



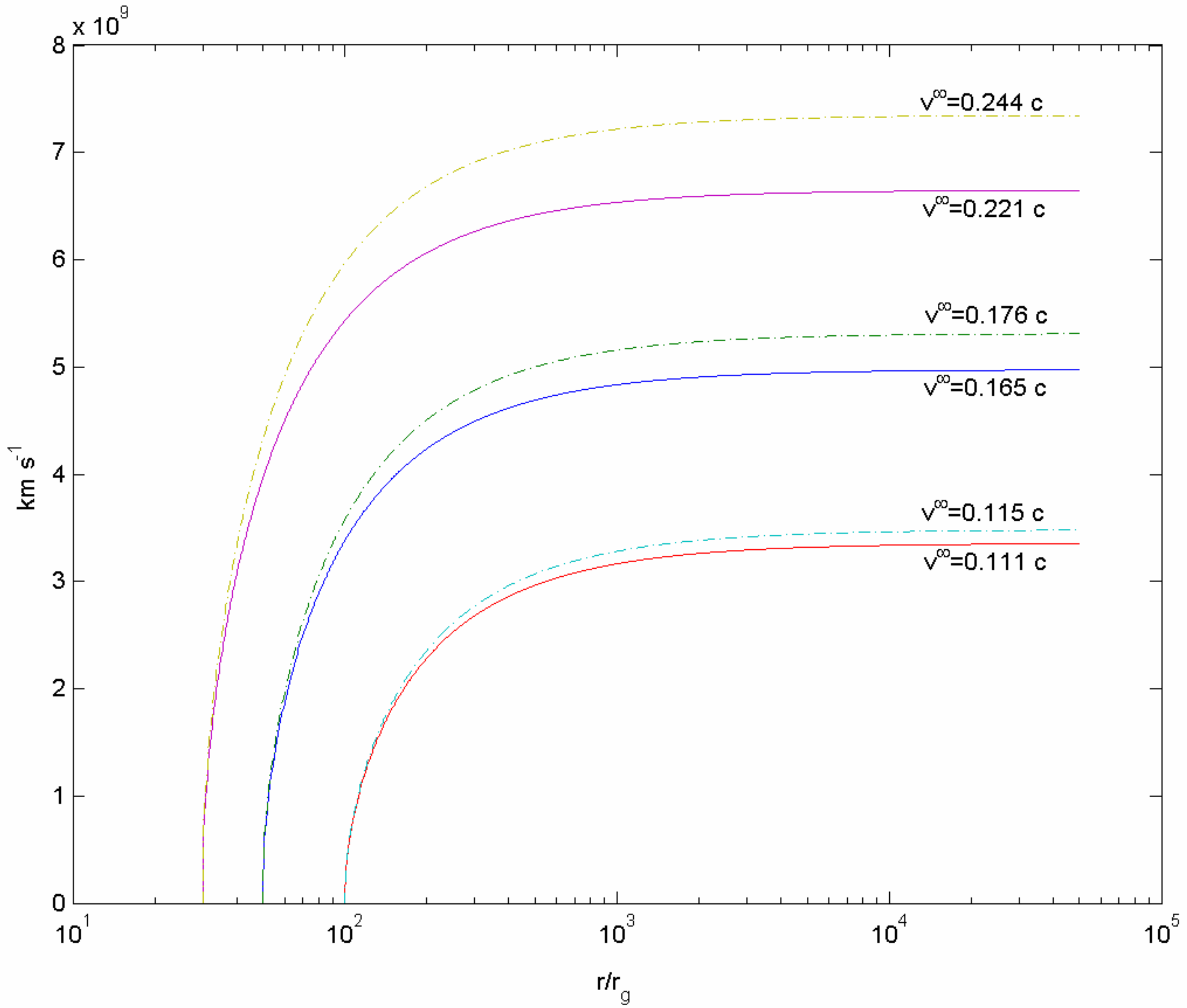
Solution of the wind equation. Solid line – GEF solution, dashed line - CAK solution. Crosses indicate GEF critical points, circles – CAK critical points.



Continuous transition of the solution from GEF case (s=1) to CAK case (s=0)



Density distribution in the wind.



Solid line indicates GEF solution for the Newtonian potential, dashed line – GEF solution for Paczynski-Wiita potential

Concluding Remarks

- A theory of winds that takes into account effects of strong gravitational fields has been developed
- It is demonstrated that a regime of the "GRAVITATIONALLY EXPOSED FLOW" rather than a standard line-driven wind (CAK-theory) is developed.
- The comparison of both regimes shows that it is of up to 40% increase of the efficiency of acceleration may be obtained.

Dorodnitsyn, A.V. 2003, *MNRAS*, 339, 569
Dorodnitsyn A.V. & Novikov I.D., ApJ, submitted