Thin accretion disc in strong gravity influenced by interaction with radiation field

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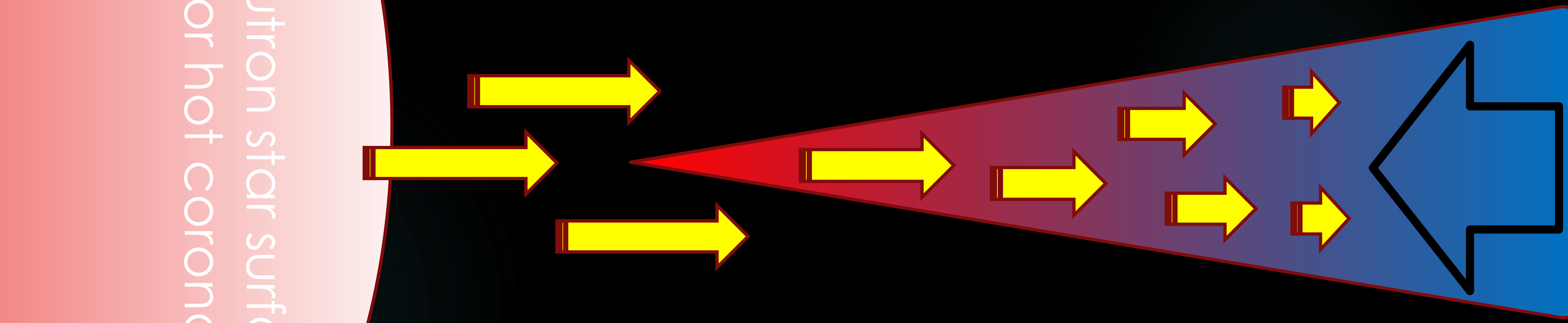
Introduction and motivation

- Accretion structures in the vicinity of **neutron stars radiate a sizable fraction of their Eddington luminosity** are significantly influenced by the radiation emitted from the surface of stars and from the boundary layer. Apart from the radiation pressure, the accreted matter is also affected by the **Poynting-Robertson effect**, which causes angular momentum loss and therefore acts as an **additional source of viscosity in the disk**. Using numerical simulations, we studied the influence of the Poynting-Robertson drag on the **thin accretion disks** in close vicinity of a neutron star. We adopted fully relativistic descriptipn of interaction of disc matter with the radiation field. In the parallelized simulation code, we implement the complete general relativistic description of the Poynting-Robertson effect including the **influence of density redistribution on the optical depth of the disk**. The modelled motion of matter in the disk thus results from a **complex interplay of strong gravitational field, the Poynting – Robertson effect, radiation pressure and disk viscosity**.

The Model: Key Assumptions

- Kerr background geometry
- Radiation field with constatnt angular momentum
- Thin equatorial disc with constant accretion inflow



- Initial structure of the disc : Shakura-Sunyaev model with α - prescription
- Matter interacts with radiation by the Thomson scattering
- Thomson scattering generates time dependent radial optical depth of the disc

The model: gravitational and radiation fields

- Kerr geometry background

$$ds^2 = -\left(1 - \frac{2r}{\Sigma}\right) dt^2 - \frac{4ra}{\Sigma}\sin^2\theta\, dt\, d\varphi + \frac{\Sigma}{\Delta} dr^2 + \Sigma\, d\theta^2 + \left(r^2 + a^2 + \frac{2ra^2\sin^2\theta}{\Sigma}\right)\sin^2\theta\, d\varphi^2$$

- Test radiation field propagated in the equatorial plane

- Field parameters:
  - Angular momentum, $\lambda = -\frac{k_\phi}{k_t}$ We set it to zero (case of radially emitted photons)
  - Direction of photon motion in ZAMO frame $\cos\beta = \frac{\lambda\sqrt{\Delta}}{g_{\phi\phi}(1 - \lambda\Omega_{ZAMO})}$
  - Relative luminosity $\mathcal{L} = \frac{L_\infty}{L_{\rm Edd}}$

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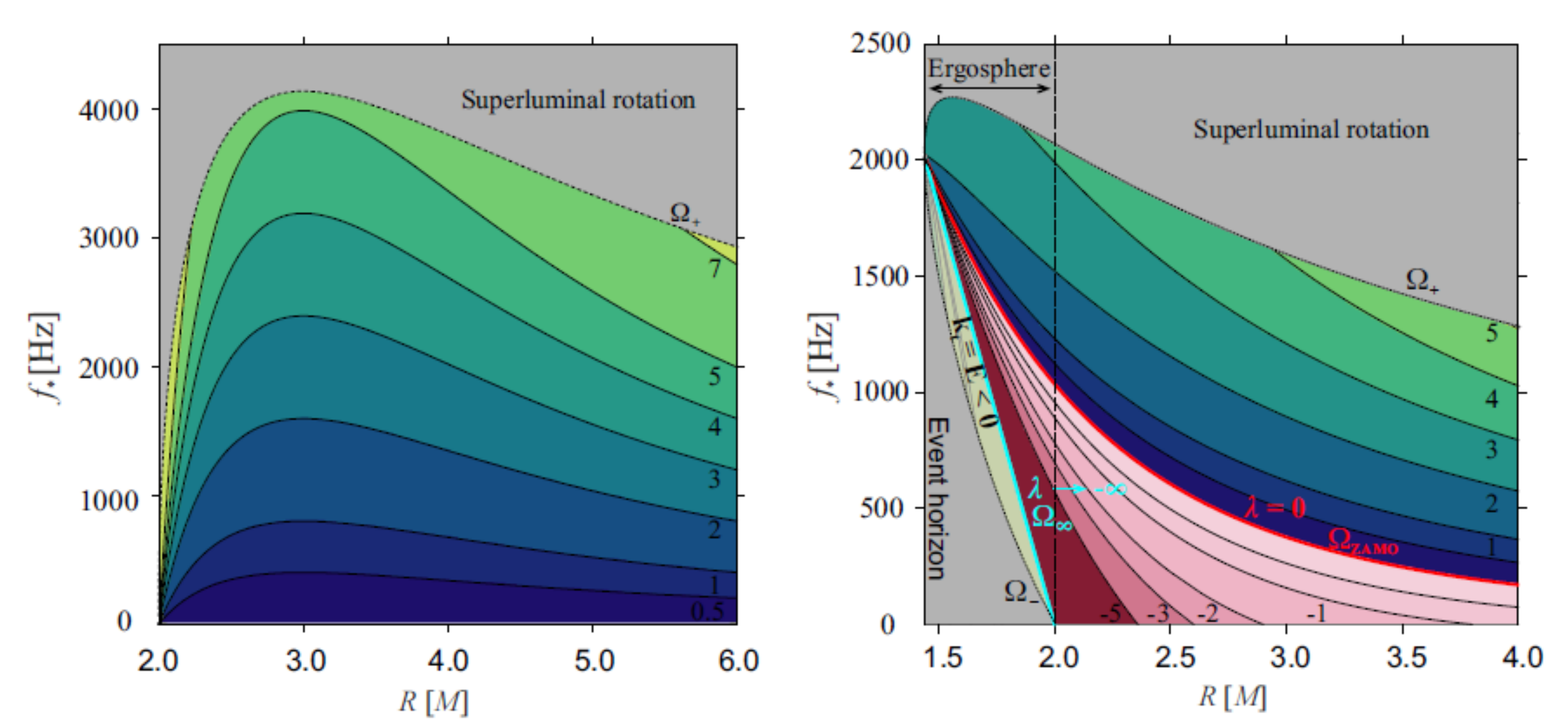
Angular momentum of the radiation field
Radially Emitted Photons



The model: Disc

- Hybrid dics model based on colective behaviour of test particles driven by gravity and radion field
- Constat inflow (injection) of the test particles into the out radius of area of interest (ISCO - 100M)
- Initial state (without radiation): the Shakura-Sunyaev quasi-Keplerian disc model with α - viscosity prescription
- Angular momentum advection is neglected
- Mass to radiation conversion efficiency $\eta = 0.1$
- Semi-analytical quantities
  - Initial radial velocity profile $v_{visc}(r) = 1.1 \times 10^6 \, cm \, s^{-1} \alpha^{4/5} \dot{m}^{2/5} m^{-1/5} \eta^{-2/5} x^{-2/5}$
  - Initial density profile $\rho(r) = 10.3 \, g \, cm^{-3} \alpha^{-7/10} \dot{m}^{2/5} m^{-7/10} \eta^{-2/5} x^{-33/20}$
  - Half-thickness of the disc $H(r) = 3.5 \times 10^3 \, cm \, \alpha^{-1/10} \dot{m}^{1/5} m^{11/10} \eta^{-1/5} x$

The Model: Equations of Motion

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} = -\sqrt{\frac{\Delta}{g_{\phi\phi}}}\gamma^{-2}\sin\alpha\left(a^{\hat{r}} + 2\nu\cos\alpha\theta^{\hat{r}}{}_{\hat{\phi}}\right) + \Psi\left[\cos(\alpha-\beta)-\nu\right]\left[1-\nu\cos(\alpha-\beta)\right],$$

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = -\sqrt{\frac{\Delta}{g_{\phi\phi}}}\nu^{-1}\cos\alpha\left(a^{\hat{r}} + 2\nu\cos\alpha\theta^{\hat{r}}{}_{\hat{\phi}} + \nu^2 k^{\hat{r}}_{(lie)}\right) + \Psi\left[\nu^{-1}-\cos(\alpha-\beta)\right]\sin(\alpha-\beta),$$

$$\frac{\mathrm{d}r}{\mathrm{d}t} = v^r = \sqrt{\frac{\Sigma}{g_{\phi\phi}}}\nu\sin\alpha,$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \omega = \frac{\sqrt{\Delta}}{g_{\phi\phi}}\nu\cos\alpha + \Omega_{ZAMO}$$

$$\Psi = \frac{\lambda\mathcal{L}}{\gamma\sqrt{g_{\theta\theta}\,g_{\phi\phi}}\cos\beta|\sin\beta|}.$$

- Two pair of equations
  - 1. Magnitude and direction of velocity in ZAMO frame
  - 2. Radial and angular velocity in coordinate frame

In the equations we use following quantities expressed with respect to the ZAMO frame (see [5] for details), the Lorentz factor $\gamma = 1/\sqrt{1-\nu^2}$, the radial component of the particle 4-acceleration $a^{\hat{r}} = ((r^2+a^2)^2 - 4a^2r)/(r^3\Delta^{1/2}g_{\phi\phi})$, the radial component of shear vector§ $\theta_{\hat{\phi}} = -a(3r^2+a^2)/(r^3 g_{\phi\phi})$ and the radial component of associated Lie relative curvature … $^{1/2}(r^3-a^2)/(r^3 g_{\phi\phi})$.

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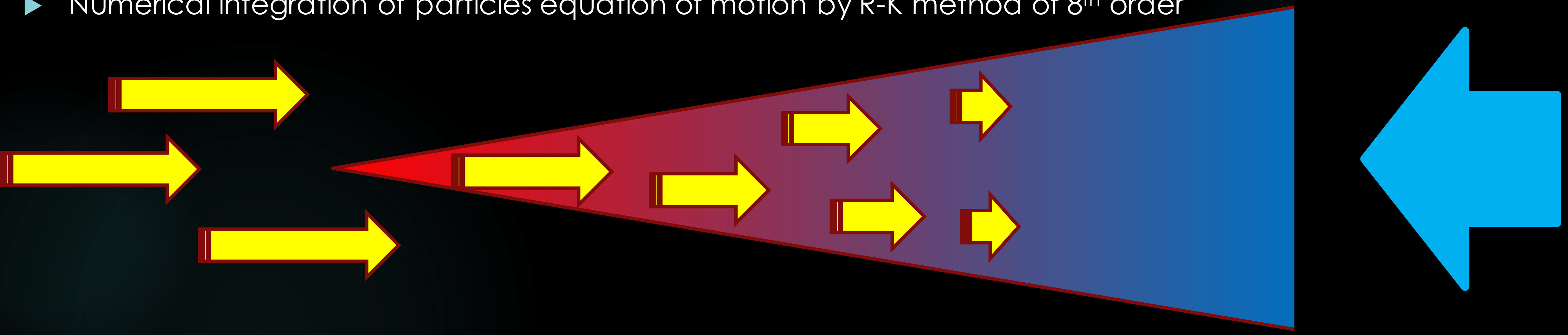
The Model: Radiation-Disk Interaction

- Thomson scattering
- Optical depth $$\tau_r(r) = \sigma_T \int_{r_{inner}}^{r} n(r)\,\mathrm{d}r$$
- Effective luminosity $$L_{eff}(r) = L_0(r)\,e^{-\tau_r(r)}$$
- Poynting Robertson radius $\mathbf{r_{PR}}$ – boundery between inner disc area driven by radiation influence and quasi-Keplearian outer disc area

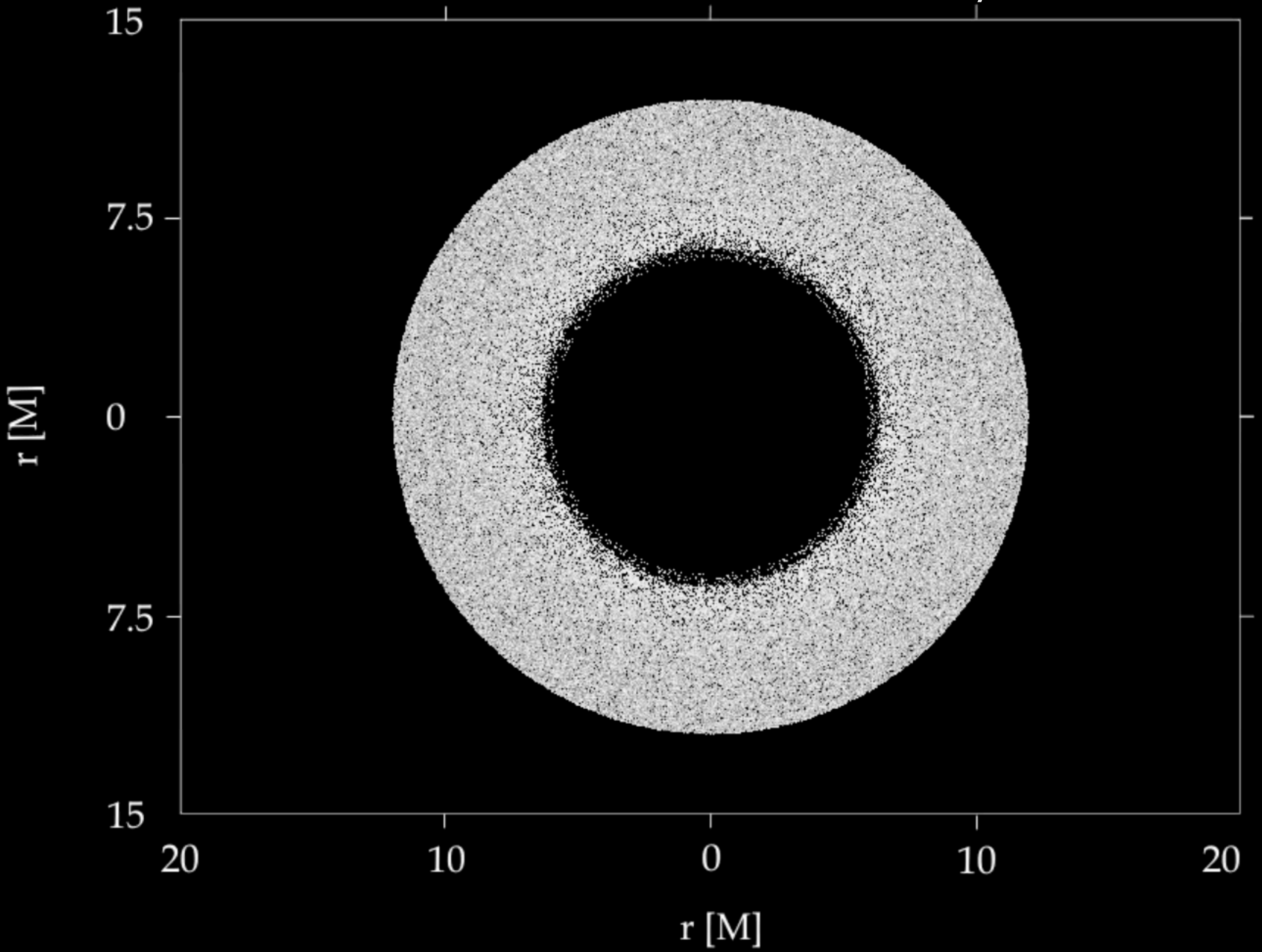
Numerical Approach

- New code **PRTrajectories** (developed in C++, massive parallelization using OpenMP)
- Injection of the particles on the outer edge of interest area (100M) with quasi-Keplerian boundary condition
- Up to 20 millions particles in the simulations
- Numerical integration of particles equation of motion by R-K method of 8th order

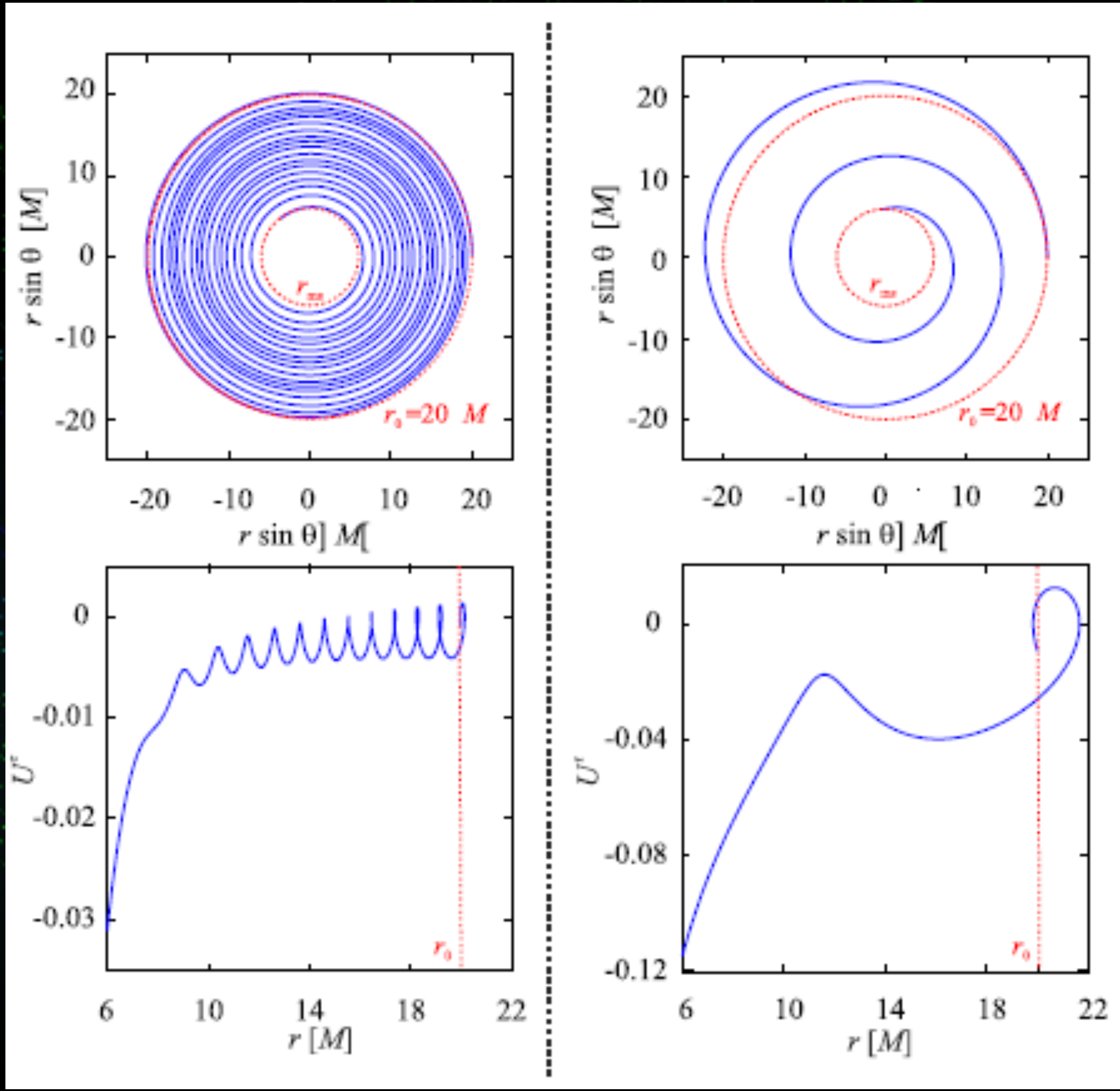


- Time resolution 20 – 70 μs
- Two phases of simulation run
  - 1:Creating quasi-Keplerian quasi stationary disc (Shakura-Sunyaev model with α - prescription)
  - 2: Evolution of the disc under influence of radiation field until reaching new quasi stationary state

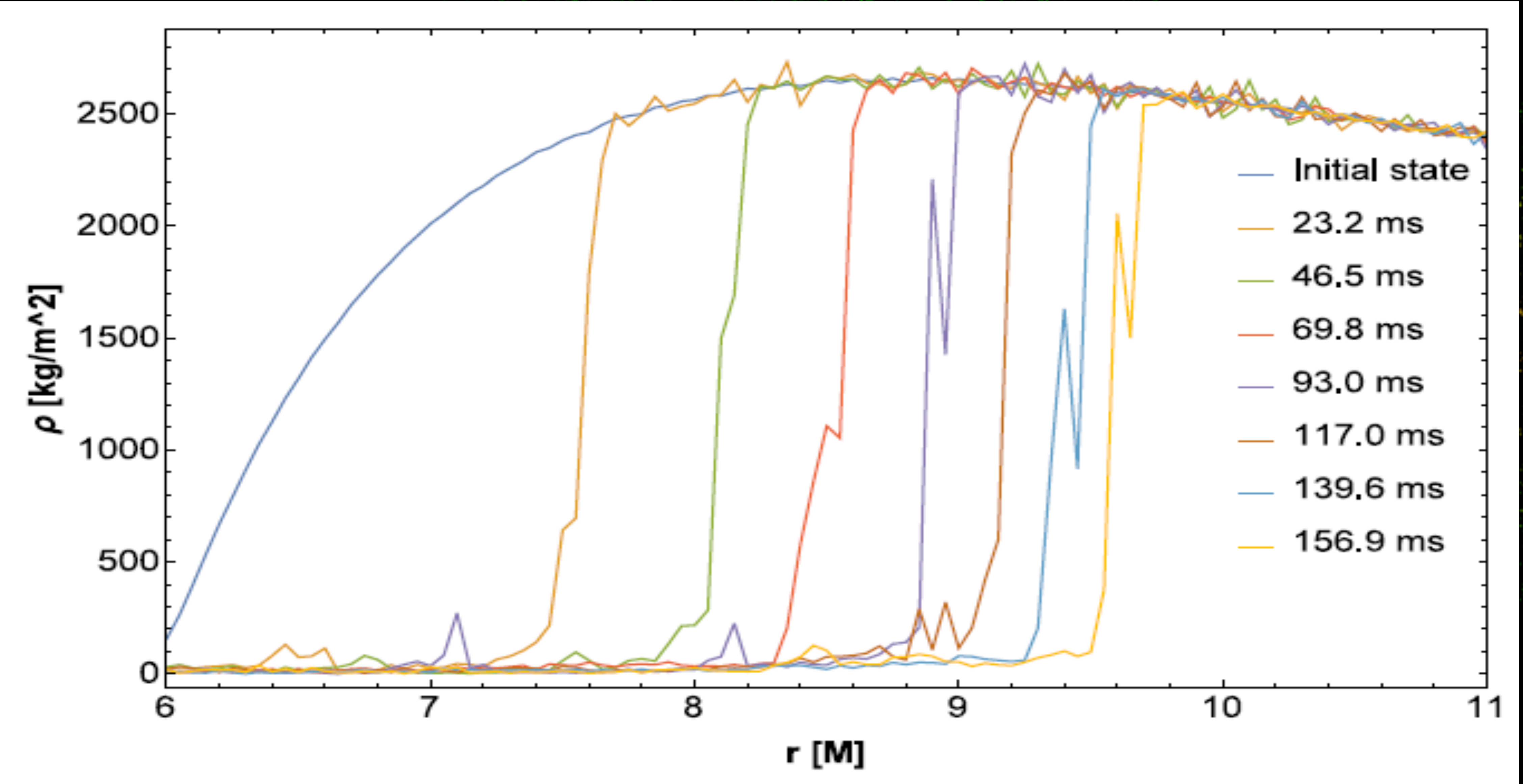
$\mathcal{L} = 0.01$: Time Evolution of Particles Density Distribution



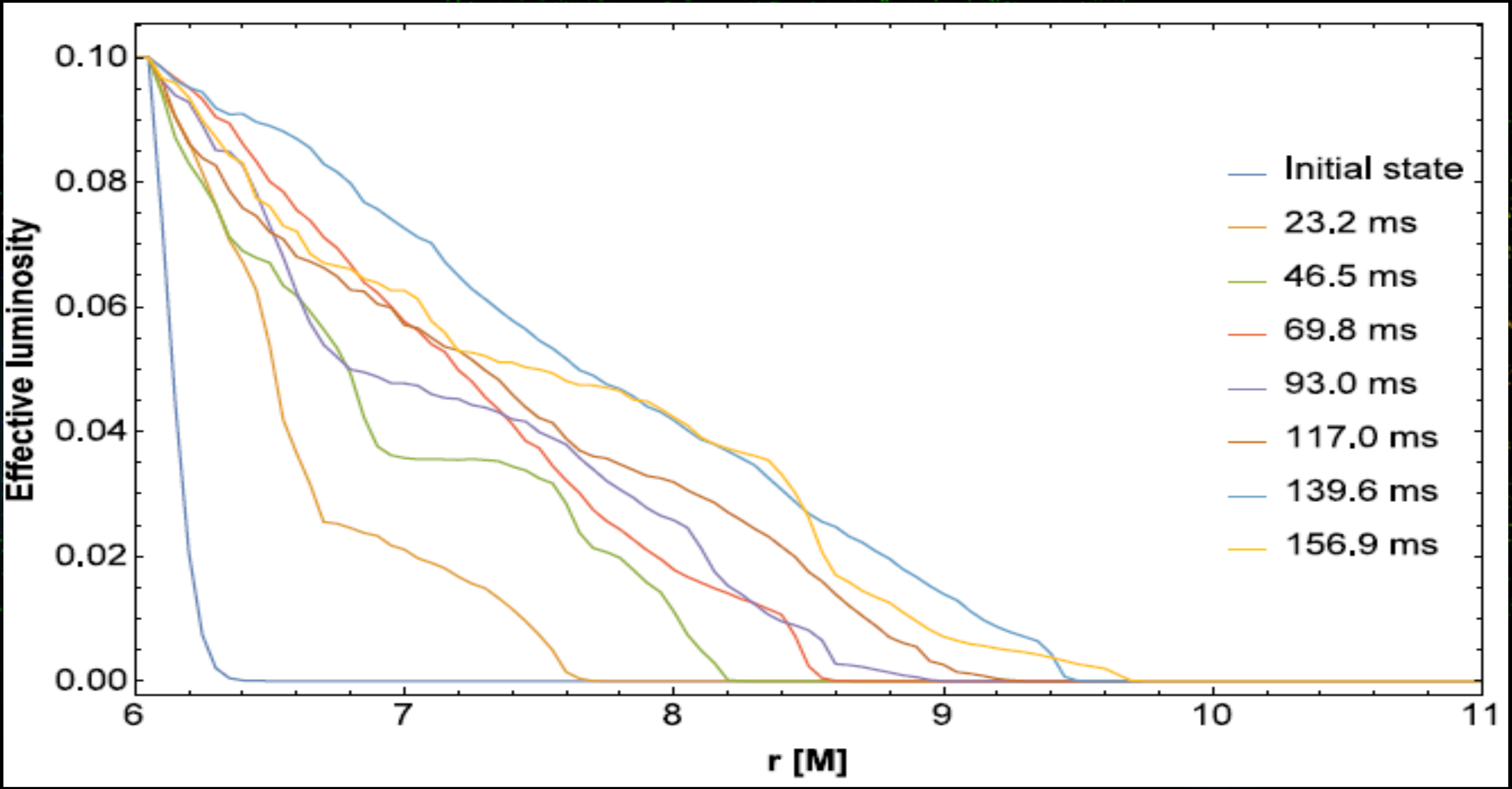
Simulation results: Particle Trajectories



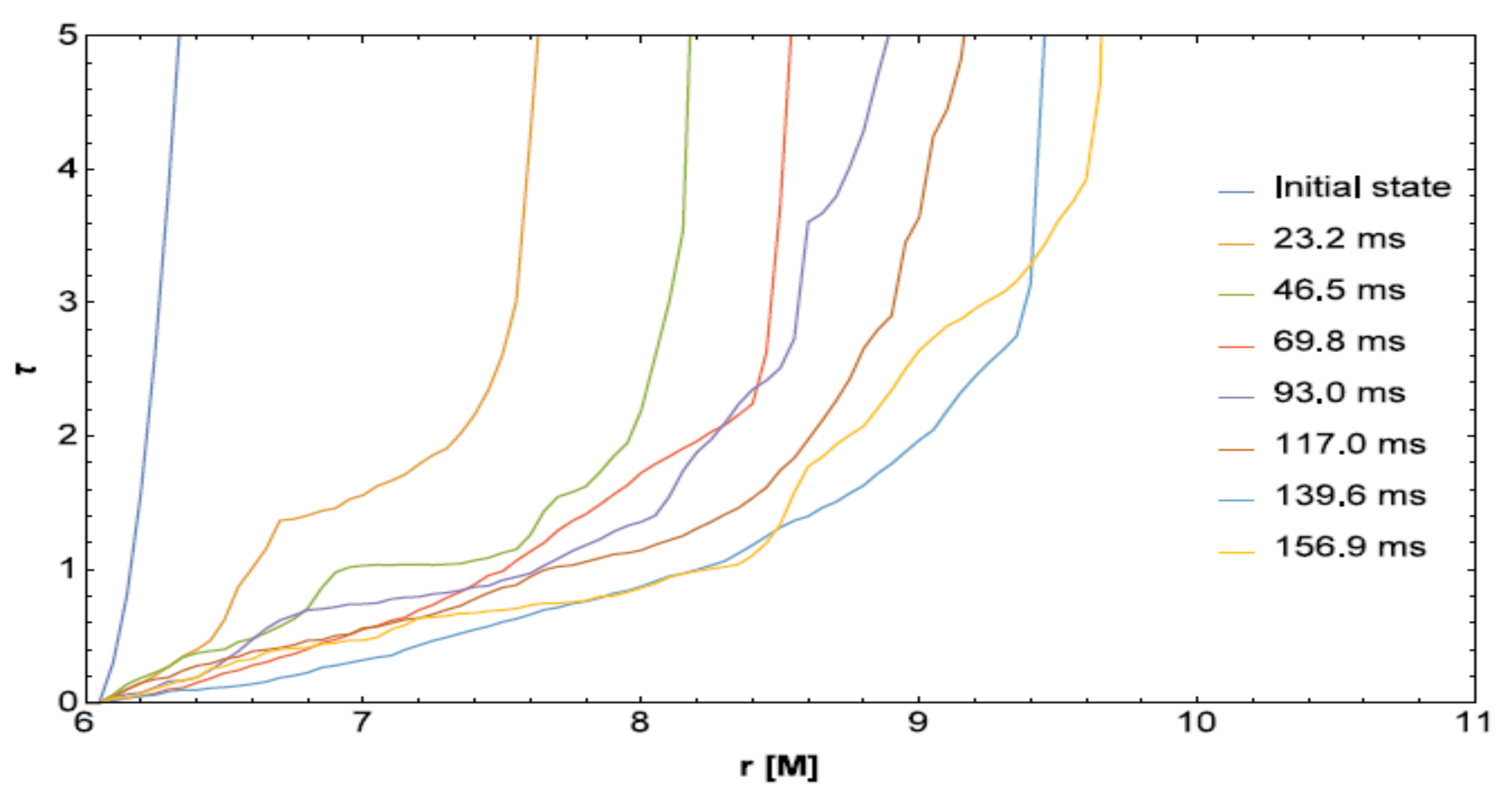
$\mathcal{L} = 0.01$: Time Evolution of Density Profile



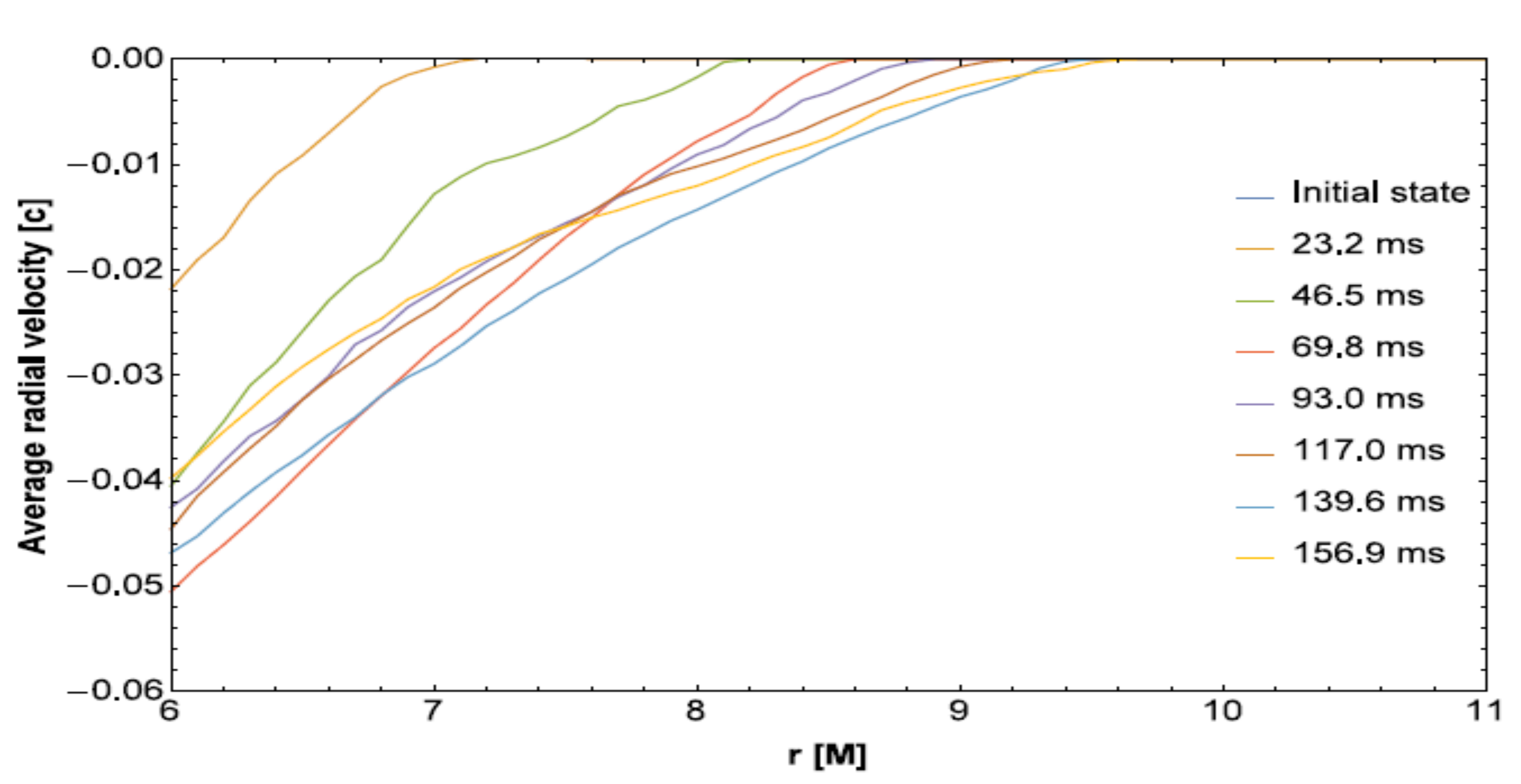
$\mathcal{L} = 0.01$: Time Evolution of Effective Luminosity



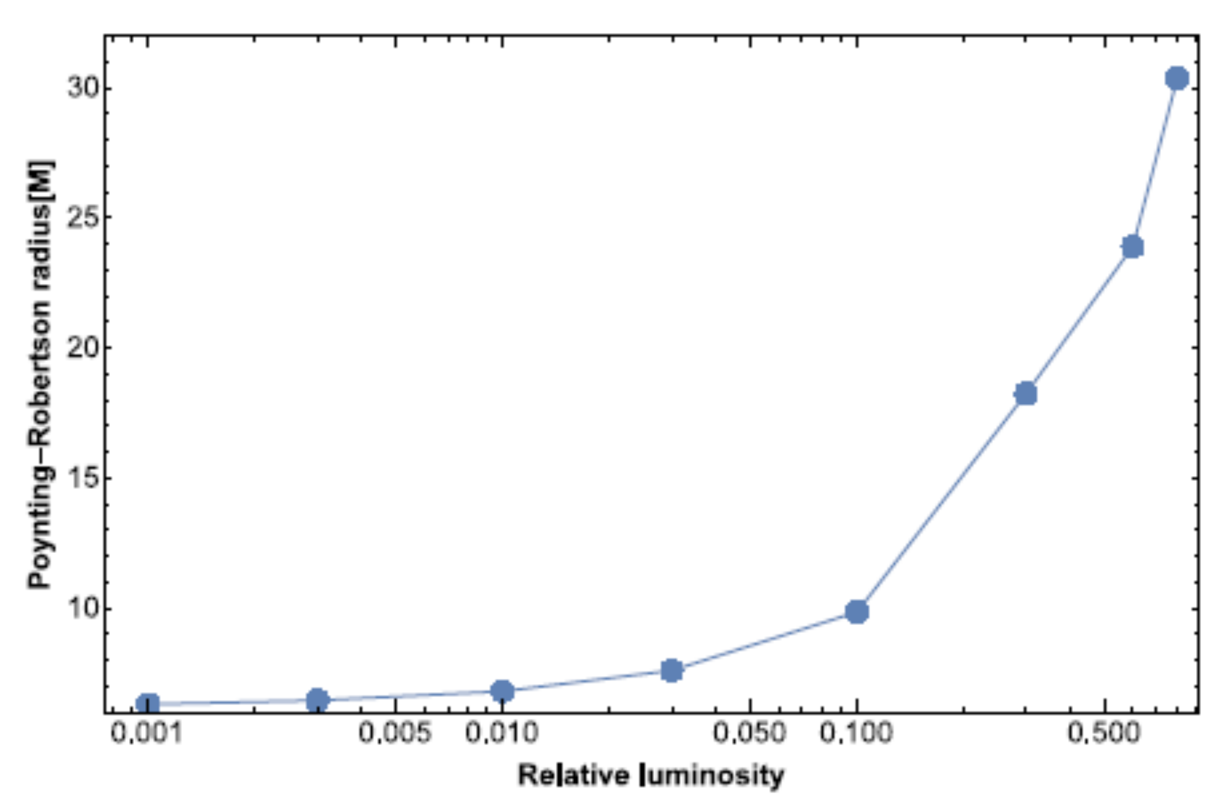
$\mathcal{L} = 0.01$: Time Evolution of Optical Depth

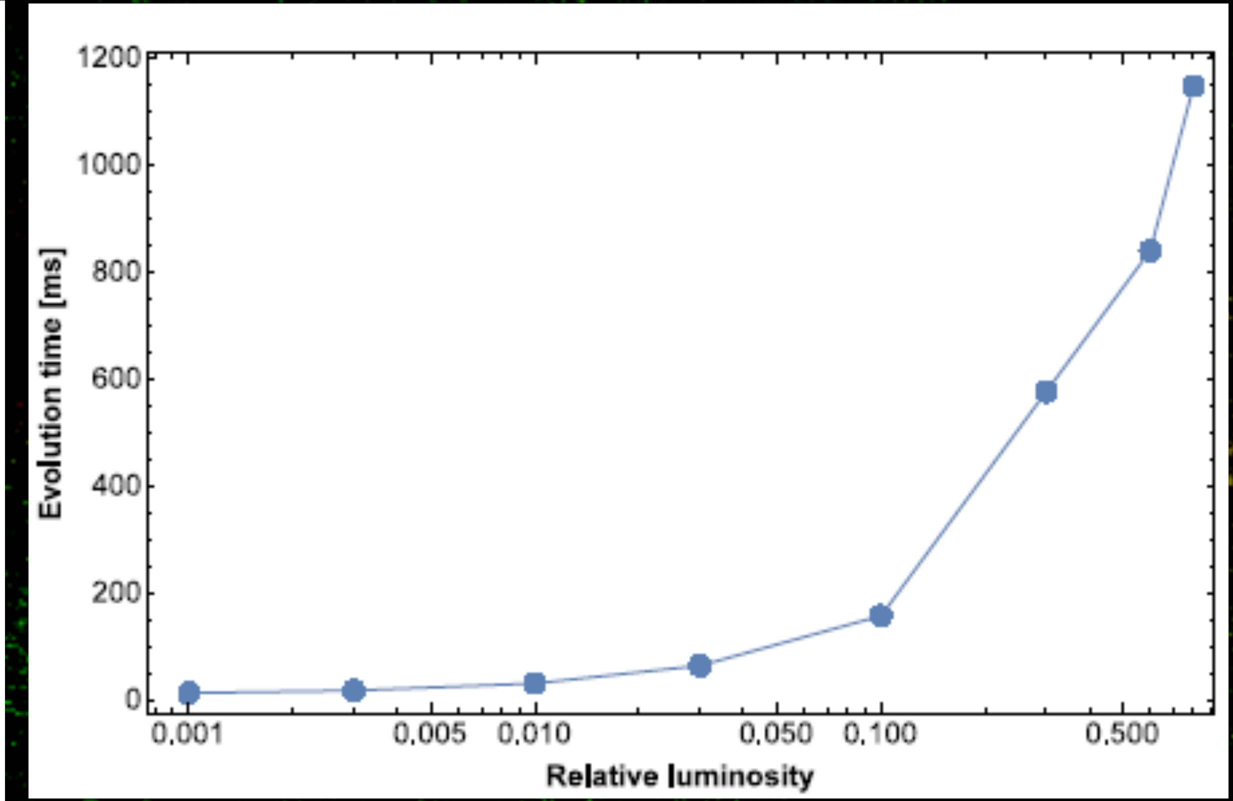


$\mathcal{L} = 0.01$: Time Evolution of Average Radial Velocity

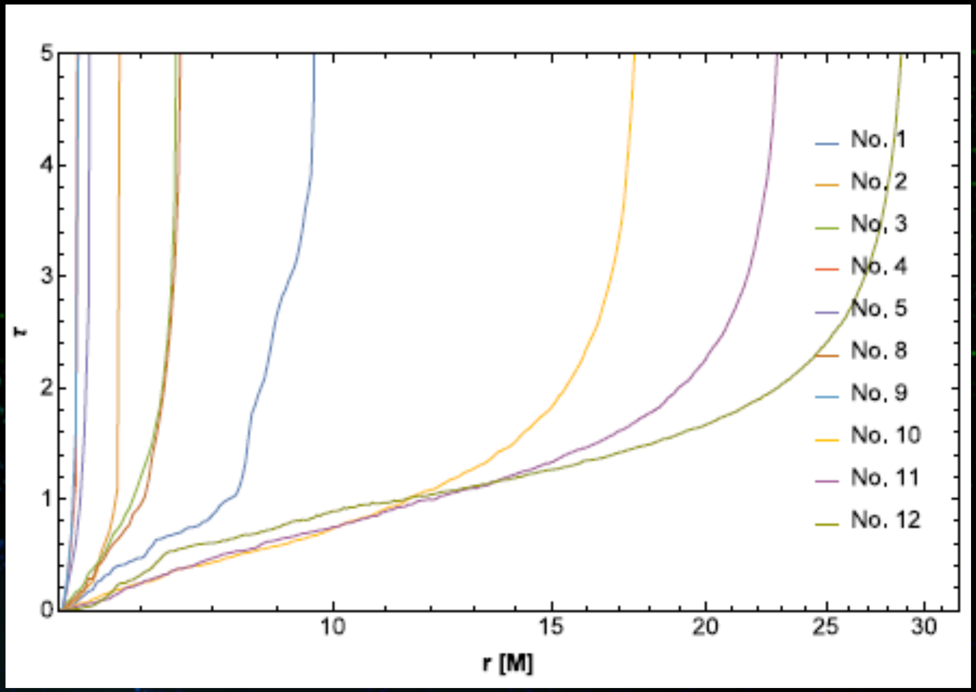


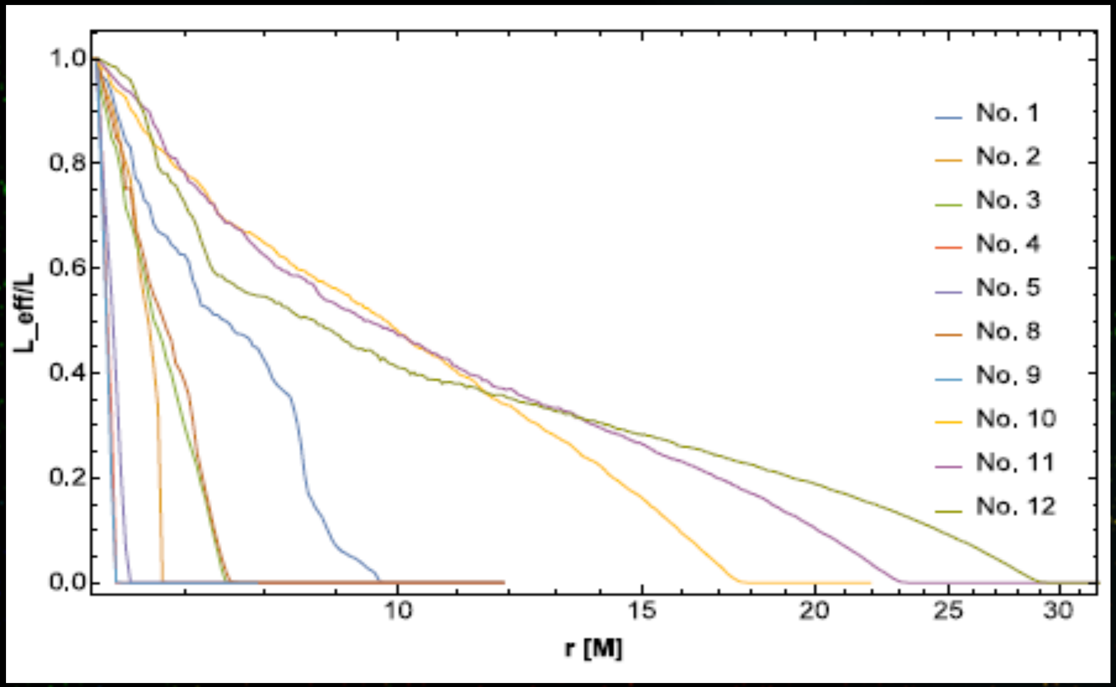
Final PR radius and evolution time as functions of relative luminosity

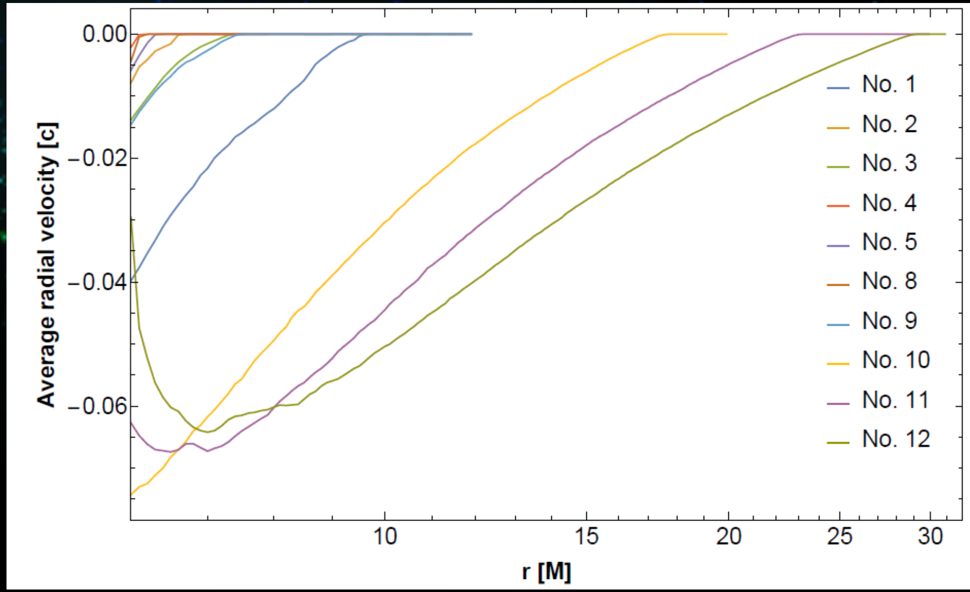




Summary of simulation results

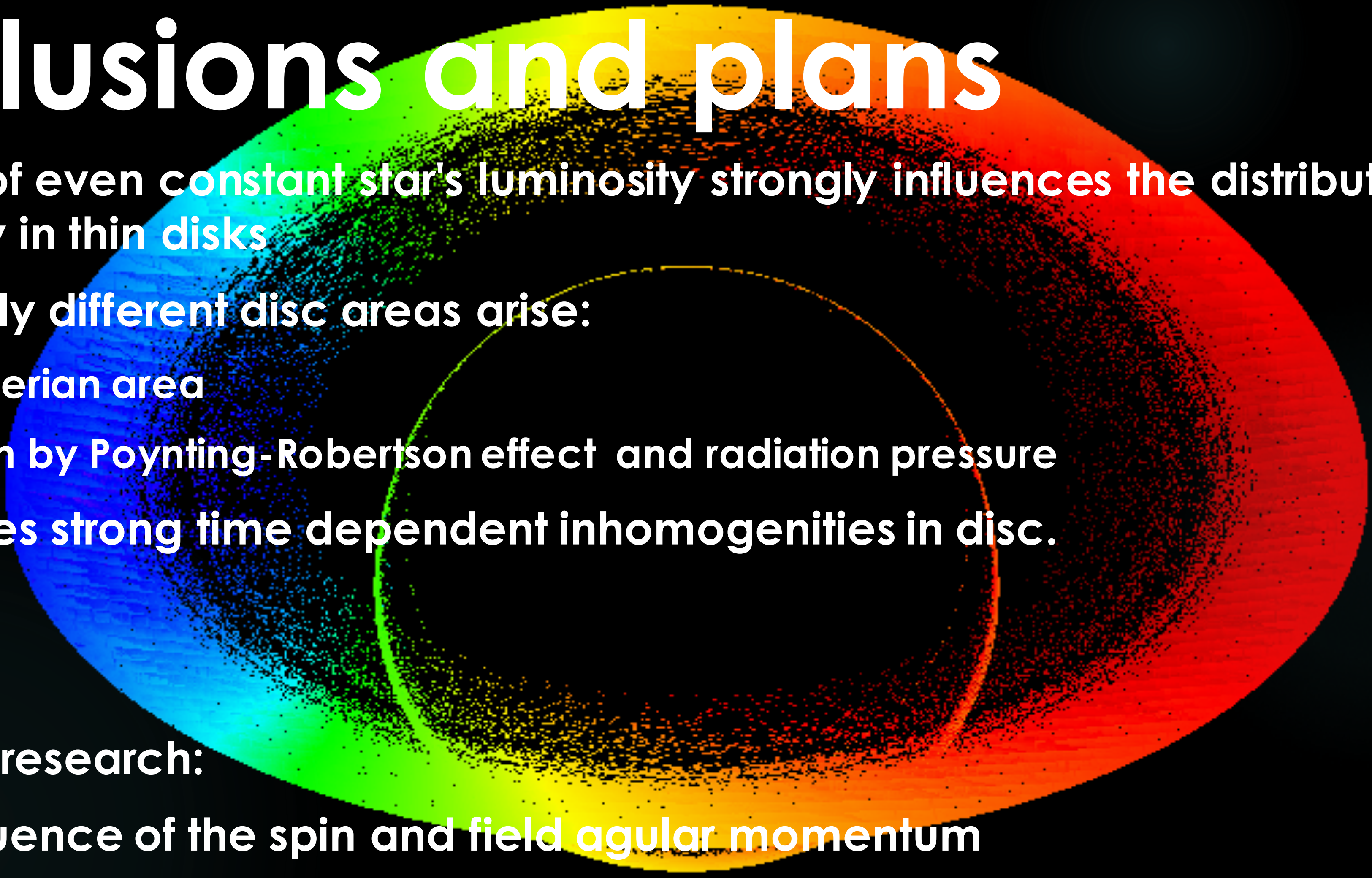






Simulations parameters/Output values									
No.	$\mathcal{L}$	a	α	$\frac{M}{M_\odot}$	$\frac{\Delta_t}{\mu s}$	$\frac{R_{inner}}{M}$	$\frac{R_{outer}}{M}$	$\frac{r_{pre}}{M}$	$\frac{t_{stat}}{ms}$
1	0.1	0	0.01	1.5	22.1	6.0	12.0	9.85	156.9
2	0.01	0	0.01	1.5	22.1	6.0	12.0	6.80	30.6
3	0.03	0	0.01	1.5	22.1	6.0	12.0	7.60	63.8
4	0.001	0	0.01	1.5	22.1	6.0	8.0	6.30	12.6
5	0.003	0	0.01	1.5	22.1	6.0	8.0	6.45	17.3
6	0.01	0.5	0.01	5	73.9	4.233	8.0	4.683	15.3
7	0.01	0.9	0.01	5	73.9	2.321	8.0	2.478	6.0
8	0.01	0	0.1	1.5	22.1	6.0	12.0	7.75	48.5
9	0.01	0	0.001	1.5	22.1	6.0	8.0	6.3	10.6
10	0.3	0	0.01	1.5	22.1	6.0	22.0	18.25	575.8
11	0.6	0	0.01	1.5	22.1	6.0	35.0	23.90	839.0
12	0.8	0	0.01	1.5	22.1	6.0	50.0	30.35	1147.6

Conclusions and plans



- The presence of even constant star's luminosity strongly influences the distribution of mass density in thin disks
- Two qualitatively different disc areas arise:
  - 1. quasi-Keplerian area
  - 2. area driven by Poynting-Robertson effect and radiation pressure
- PR effect creates strong time dependent inhomogenities in disc.

- Plans for future research:
  - Explore Influence of the spin and field agular momentum
  - The spectral properties (line profiles) of disc driven by radiation field
  - Explore relation of time dependent inhomogenities to the QPOs
  - Relation to an observational data
  - Modelling the disk behaviour during a thermonuclear burst, when the luminosity of a neutron star is close to the Eddington limit