New models of AGN disks

Khoperskov Sergey[1,2]

+ ARI-MAO-INASAN collaboration

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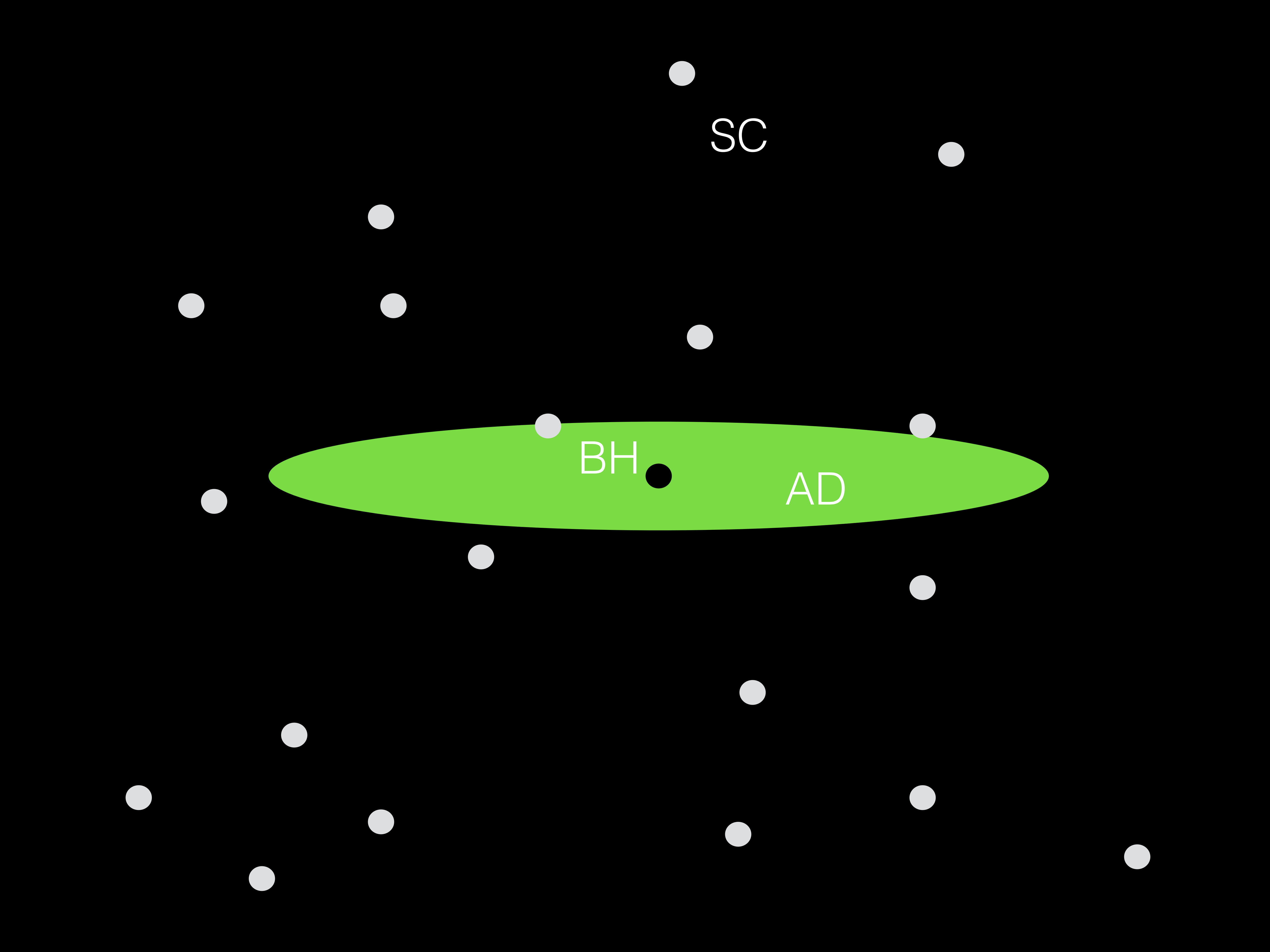
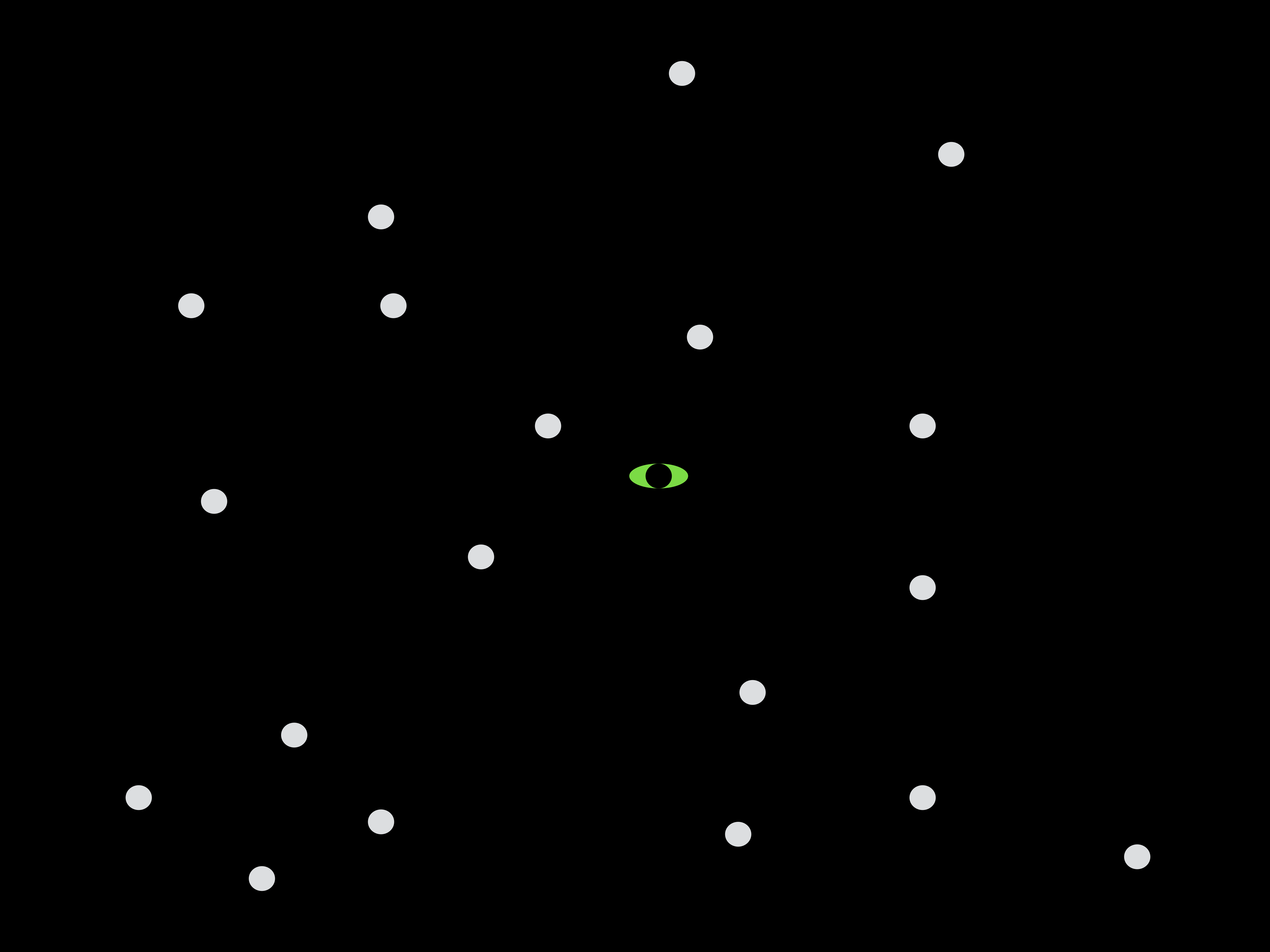
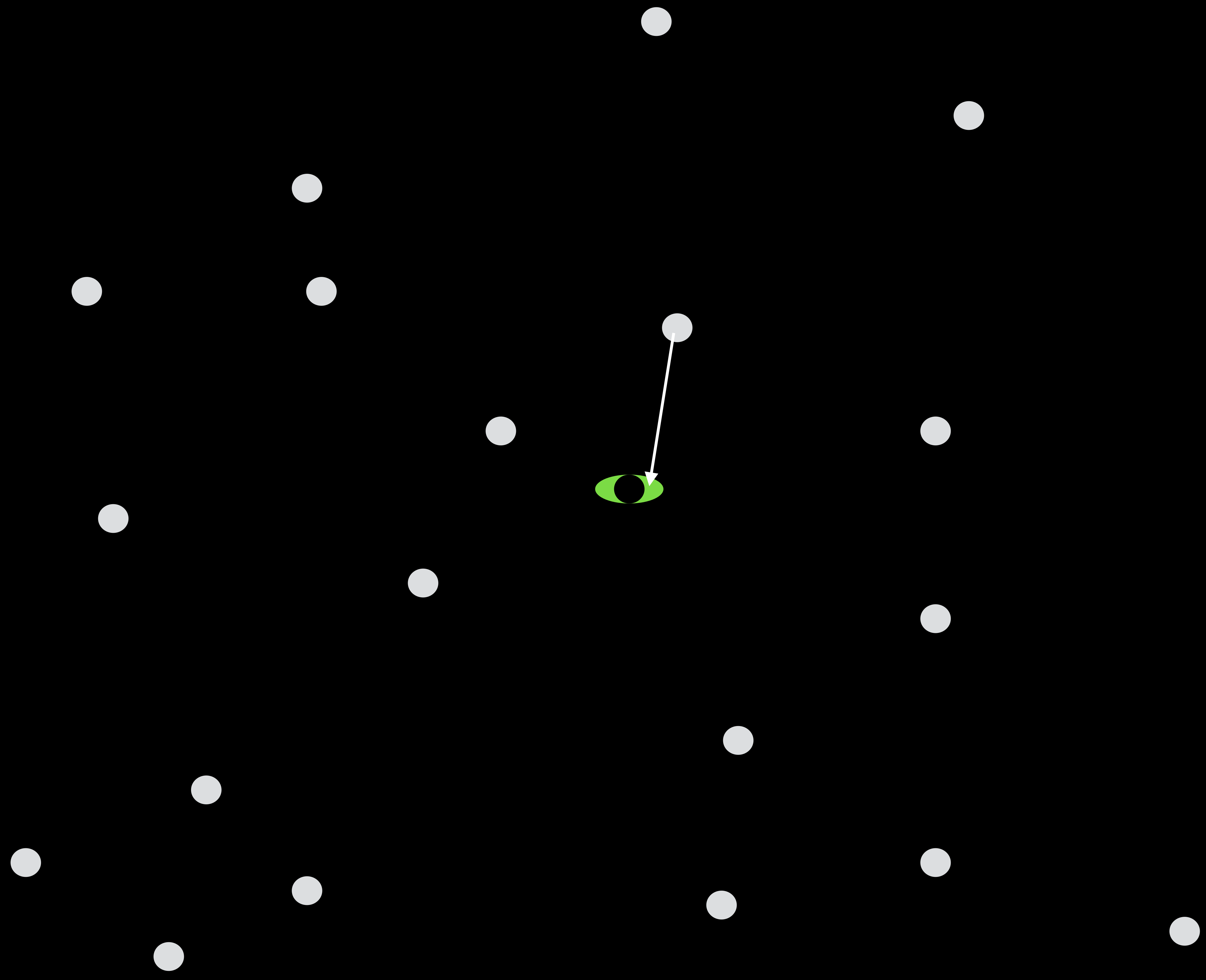
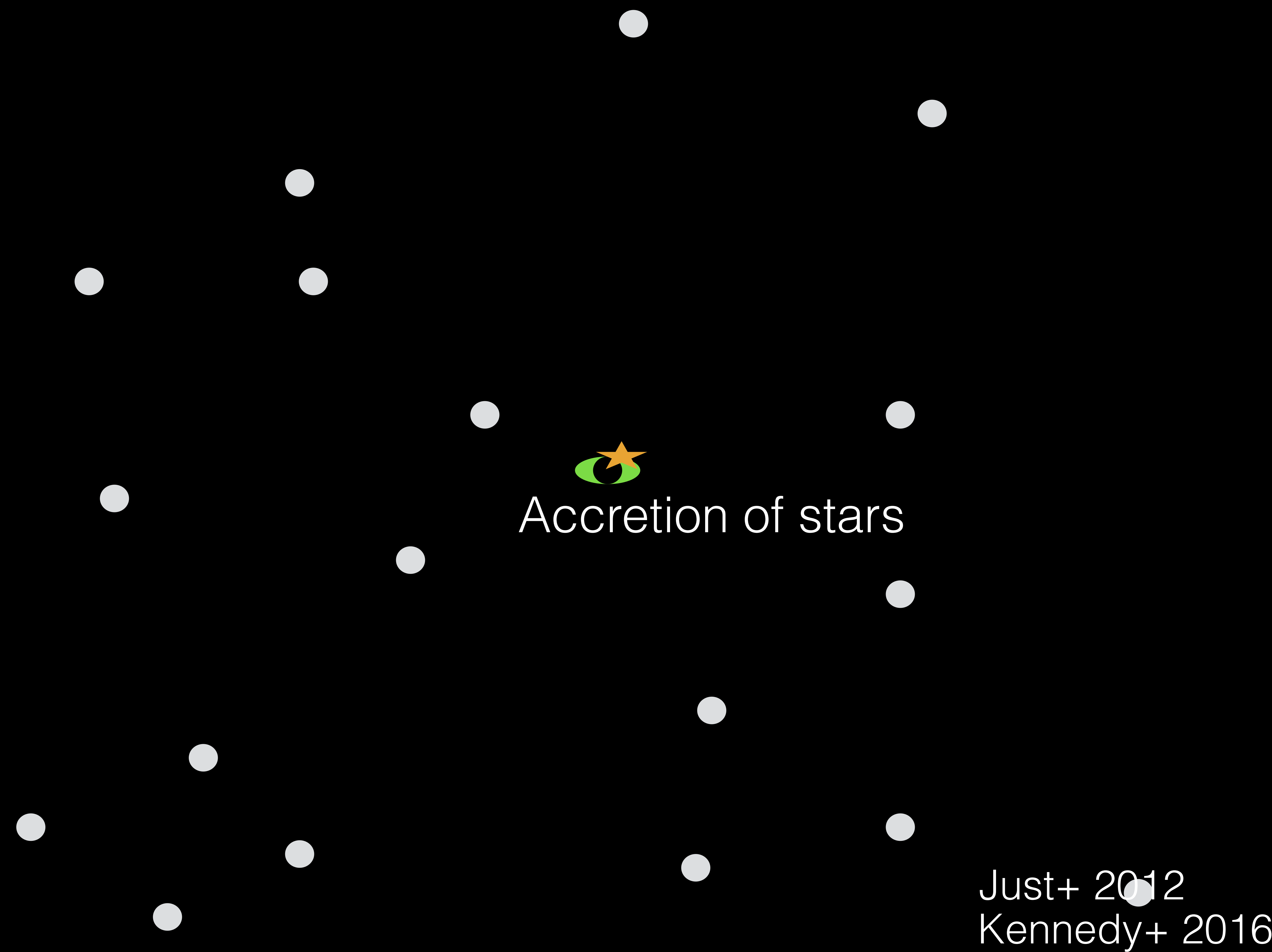
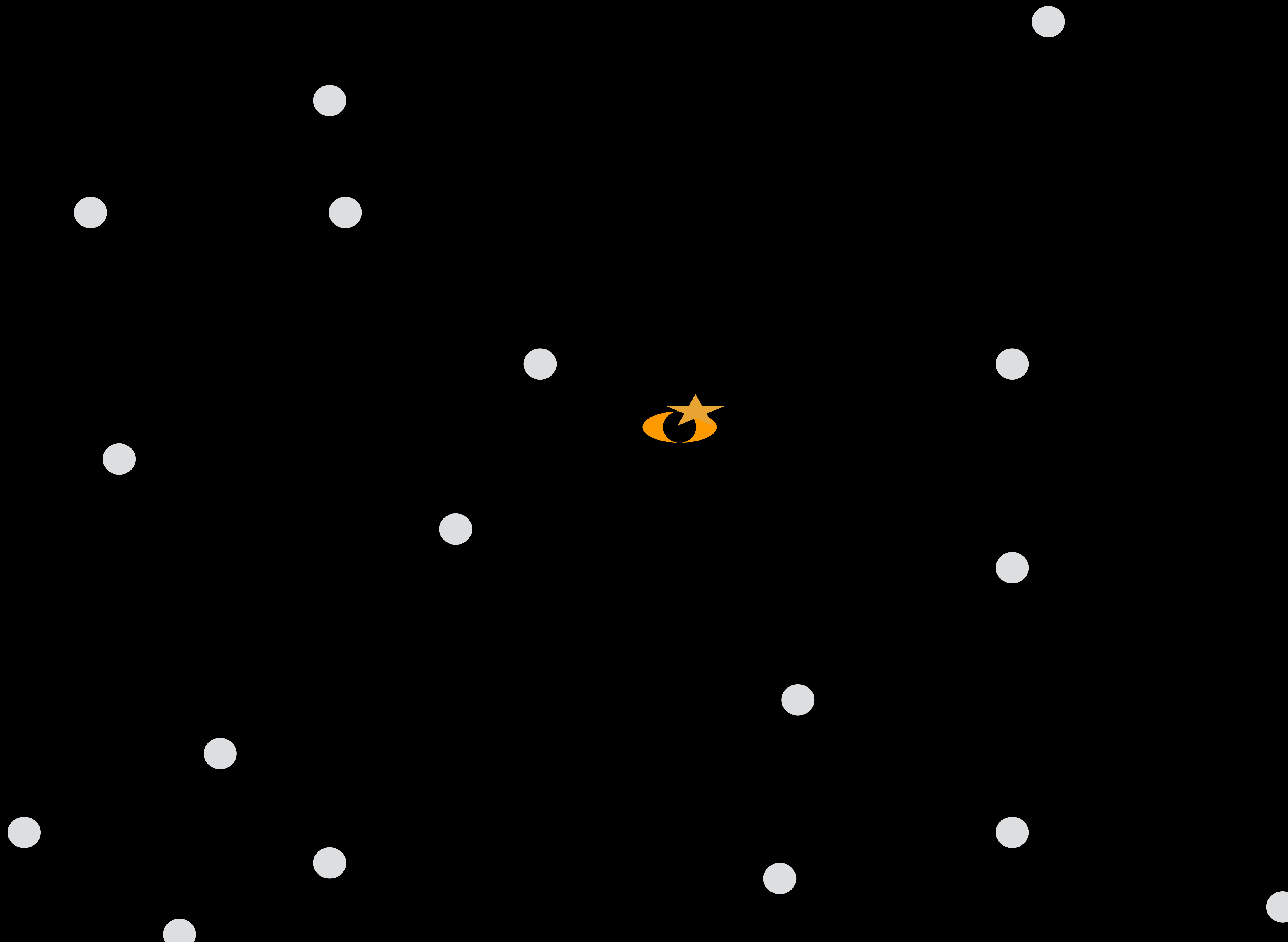

SC
BH
AD






Accretion of stars
Just+ 2012
Kennedy+ 2016

Issue: self consistent evolution
of accretion disk and stellar cluster around SMBH



Progress in code development

- **31 Aug - 10 Sept**

- **29 Sept - 07 Oct**

- **29 Jan - 12 Feb**

- **now (28-31 May)**

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  - Cartesian code
  - Initial equilibrium state
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  - Improved cylindrical hydro mesh
- **now (28-31 May)**

GAS DYNAMICS

- System of conservation laws

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} + \frac{\partial \boldsymbol{H}}{\partial z} = 0,$$

$$\boldsymbol{U} = \begin{bmatrix} \rho \\ M_x \\ M_y \\ M_z \\ E \\ B_x \\ B_y \\ B_z \end{bmatrix} \quad \boldsymbol{F} = \begin{bmatrix} \rho v_x \\ \rho v_x^2 + P + B^2/2 - B_x^2 \\ \rho v_x v_y - B_x B_y \\ \rho v_x v_z - B_x B_z \\ (E + P^*) v_x - (\boldsymbol{B} \cdot \boldsymbol{v}) B_x \\ 0 \\ B_y v_x - B_x v_y \\ B_z v_x - B_x v_z \end{bmatrix}$$

GAS DYNAMICS - TVD

$$TV = \sum_j |u_{j+1} - u_j| .$$

$$TV\left(u^{n+1}\right) \leq TV\left(u^n\right).$$

- System of conservation laws

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} + \frac{\partial \boldsymbol{H}}{\partial z} = 0,$$

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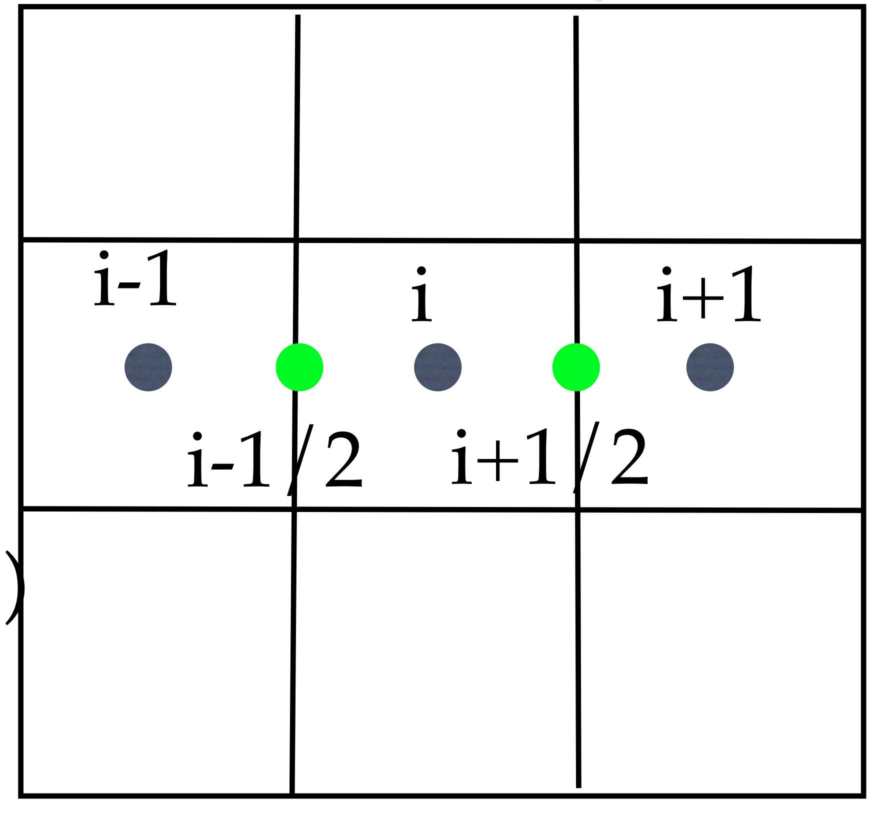
$$\begin{aligned} \boldsymbol{U}^{n+1}_{i,j,k} = \boldsymbol{U}^{n}_{i,j,k} &- \frac{\delta t}{\delta x}\left(\boldsymbol{F}^{n+1/2}_{i+1/2,j,k} - \boldsymbol{F}^{n+1/2}_{i-1/2,j,k}\right) \\ &- \frac{\delta t}{\delta y}\left(\boldsymbol{G}^{n+1/2}_{i,j+1/2,k} - \boldsymbol{G}^{n+1/2}_{i,j-1/2,k}\right) \\ &- \frac{\delta t}{\delta z}\left(\boldsymbol{H}^{n+1/2}_{i,j,k+1/2} - \boldsymbol{H}^{n+1/2}_{i,j,k-1/2}\right) \end{aligned}$$

All types of solutions
(shock, contact discontinuity, ...)
No artificial viscosity



Approximate solution of the Riemann problem

HLLC solver

Initial conditions

$$\rho(R,z) = \sigma_0 \frac{1}{h(R)} \left(\frac{R}{R_\mathrm{d}}\right)^{-p} \exp\left(-\frac{z^2}{h(R)^2}\right)$$

Novikov&Thorne (1973)

Temperature is a function of cylindrical radius

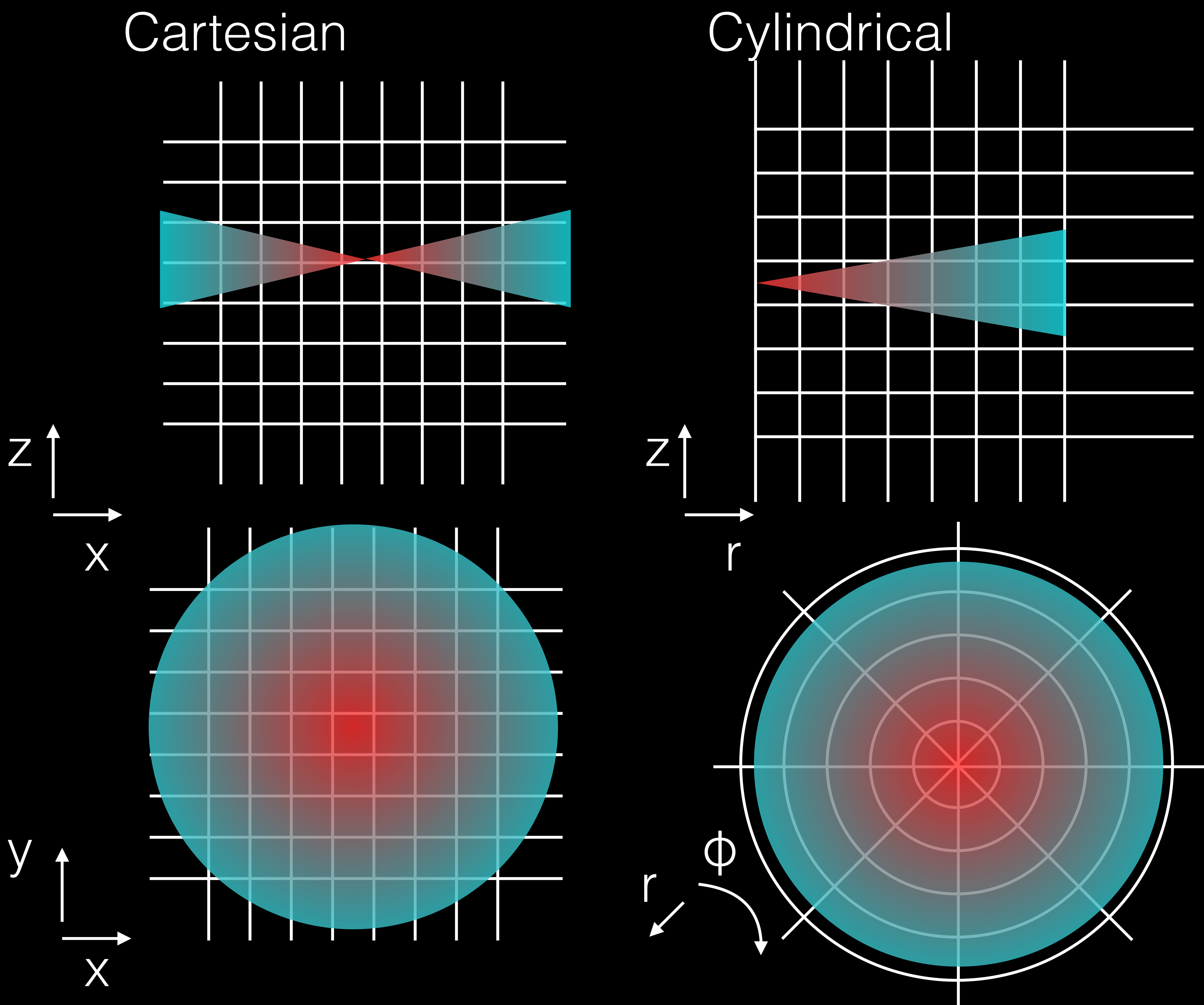
Disk thickness $h(R) = h_z R/R_{sg}$

Radial force balance -> keplerian rotation

$$\frac{\partial p}{\partial R} = \rho \mathbf{g}_R + \rho \frac{v_\varphi^2}{R}$$

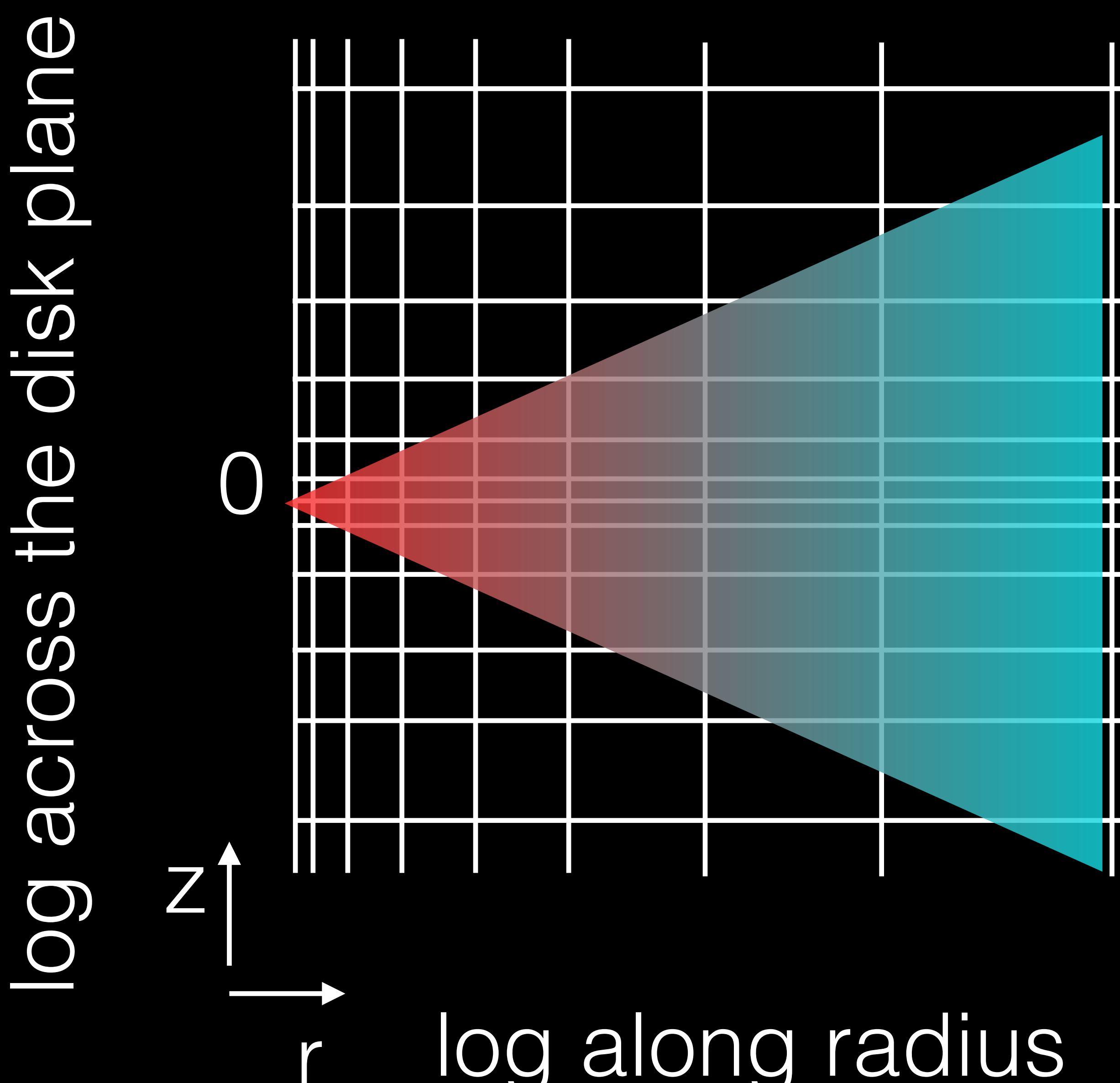
Just+ 2012
Kennedy+ 2016

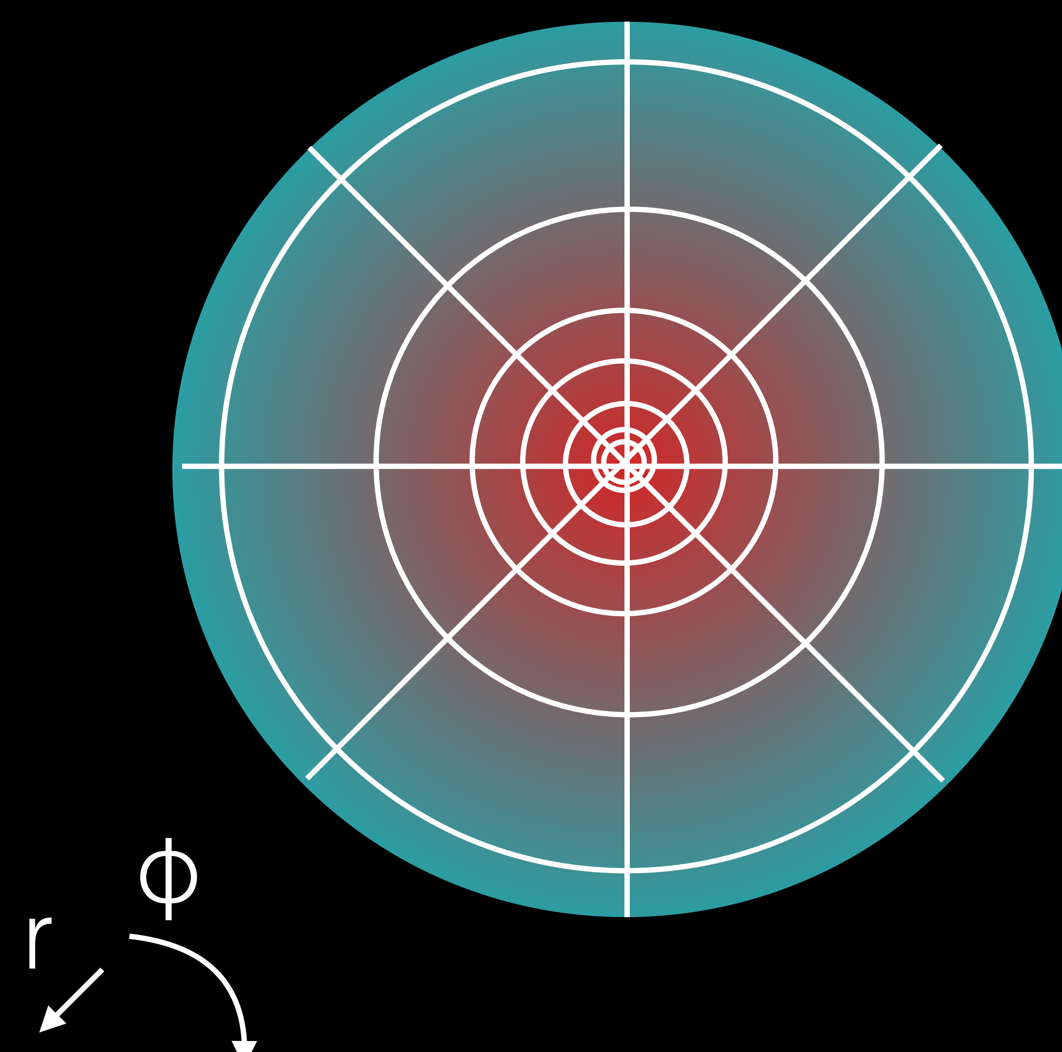
Hydro mesh geometry



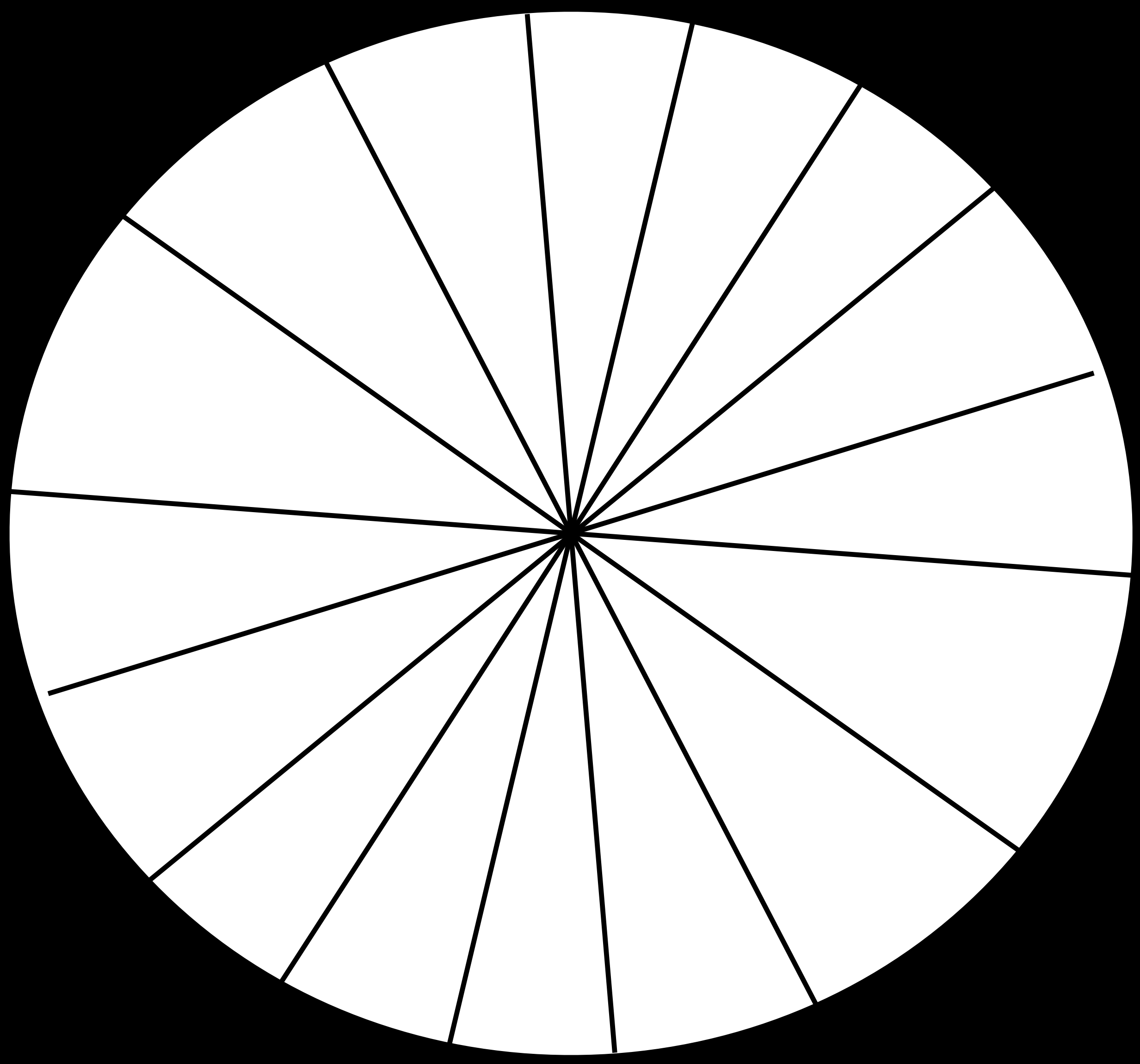
Hydro mesh geometry

Improved Cylindrical



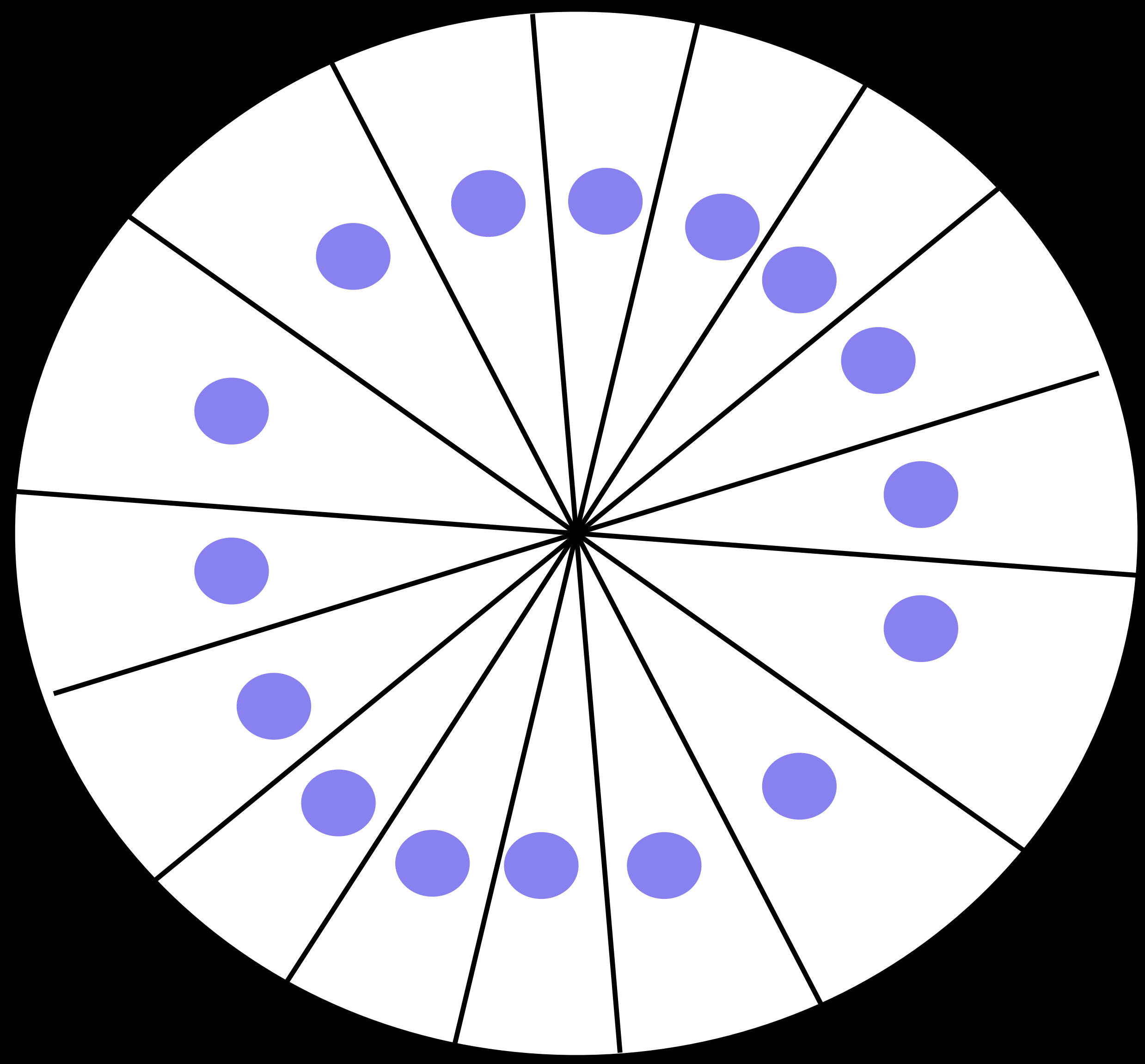


Disk center



Disk center

Hydro cell centers (i,j,k)



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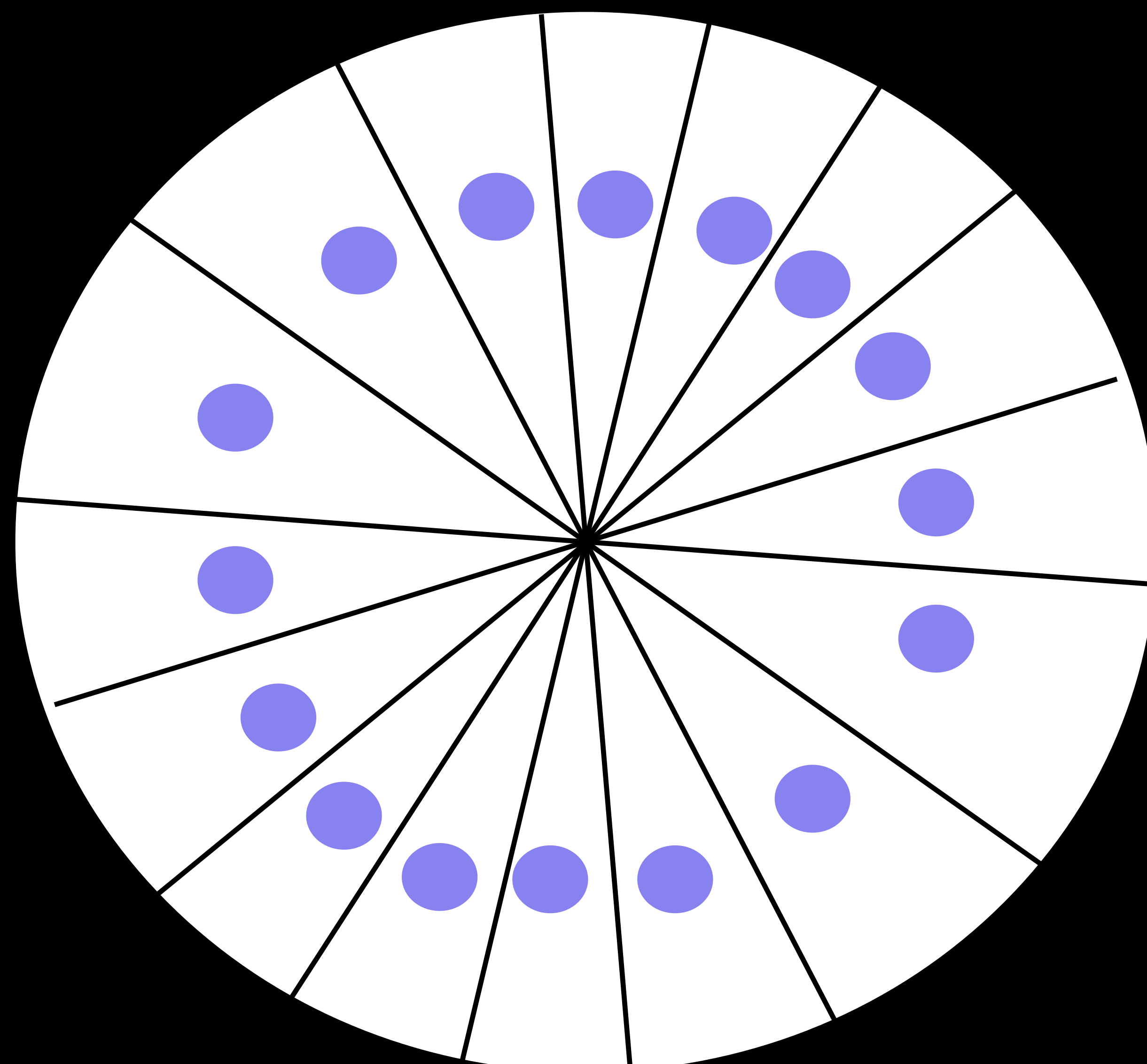
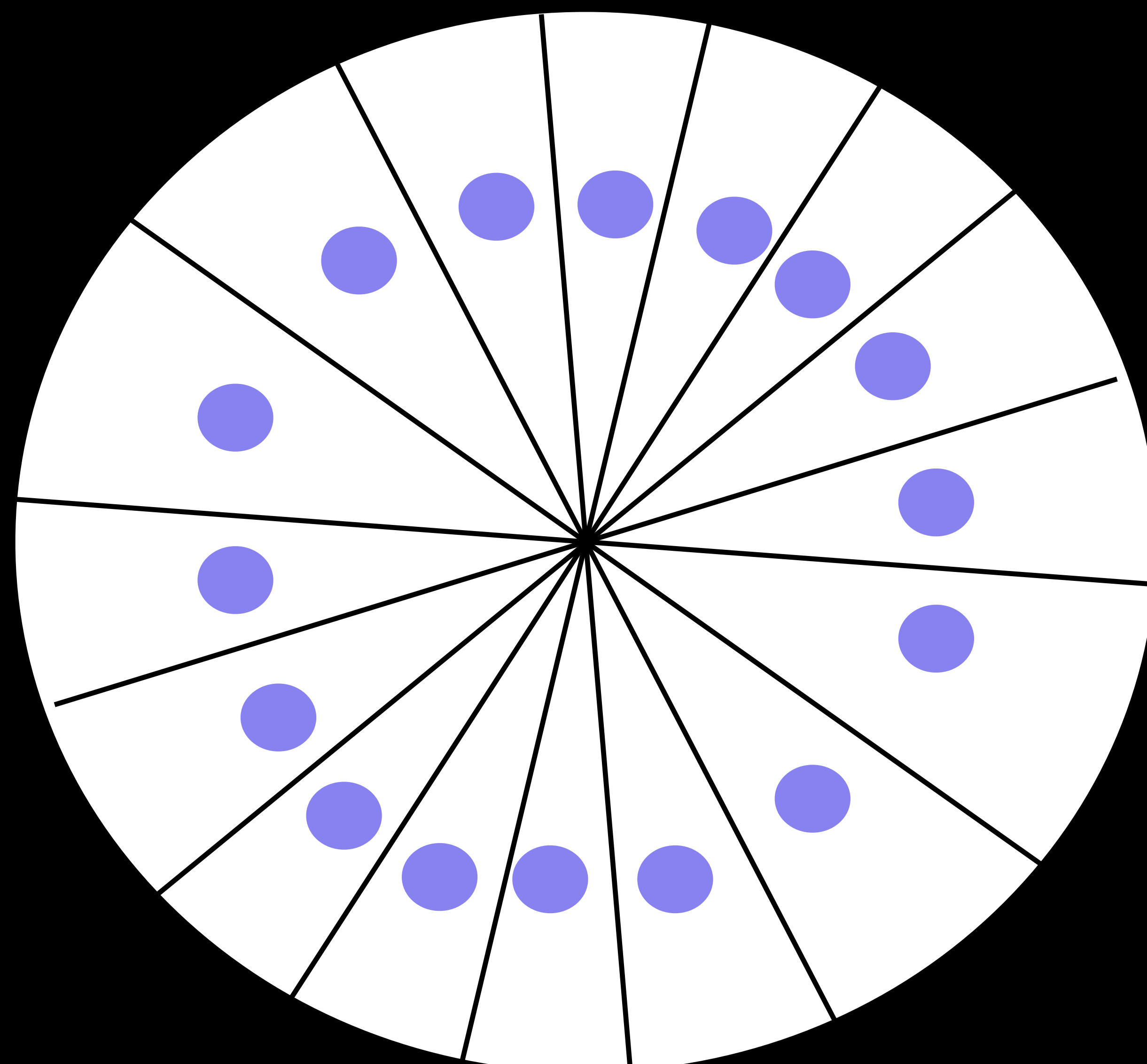


Hydro cell boundaries
(i+1/2, i-1/2 ,j+1/2, j-1/2,k)

Disk center

Hydro cell centers (i,j,k)



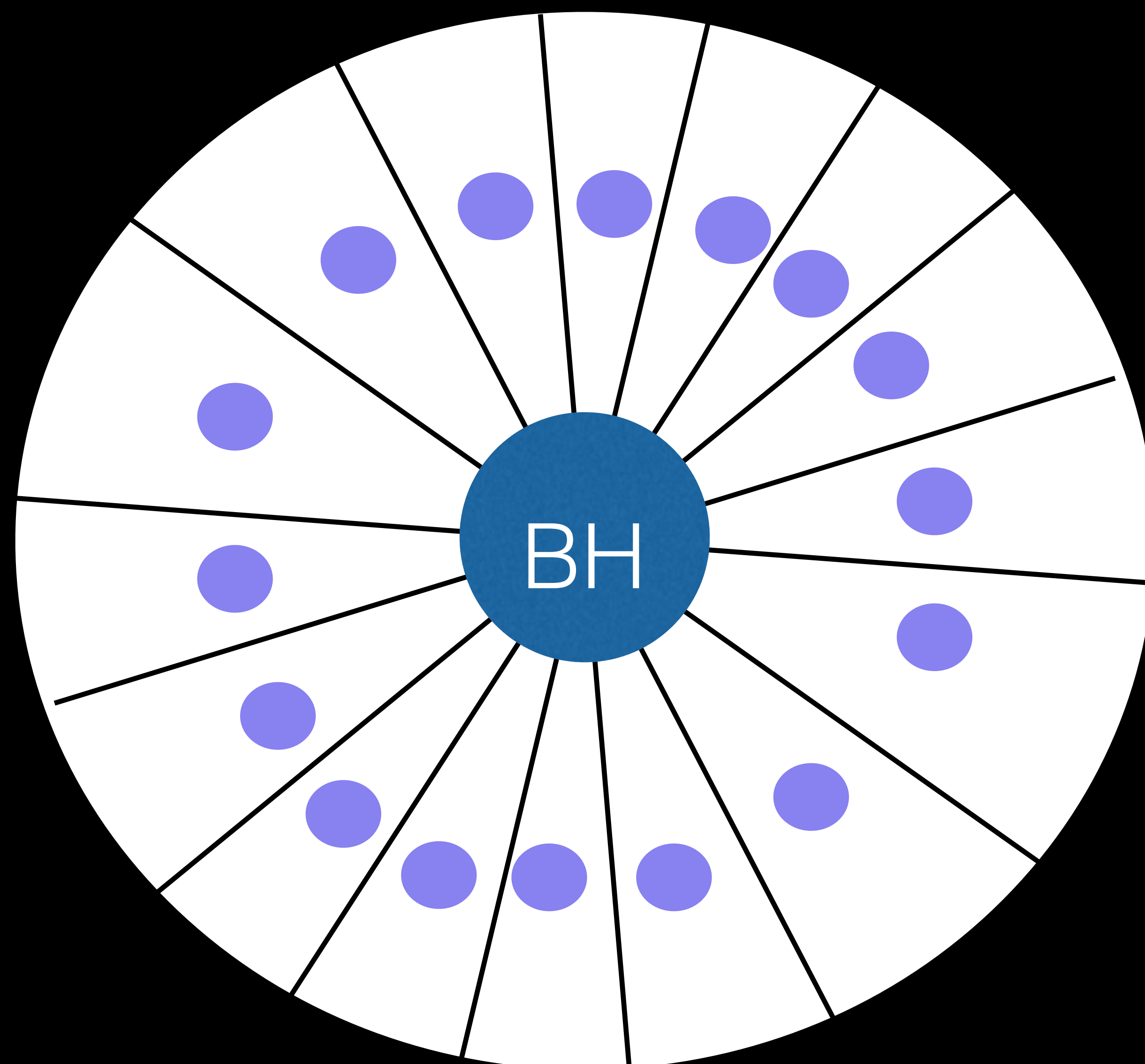
Hydro cell boundaries
(i+1/2, i-1/2 ,j+1/2, j-1/2,k)

Each cell within boundaries
contains homogeneous mass
& velocity distributions

Disk center

Hydro cell centers (i,j,k)

A part of mass within
the BH radius
is assumed to be
accreted



Hydro cell boundaries
(i+1/2, i-1/2 ,j+1/2, j-1/2,k)

Each cell within boundaries
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Viscosity in polar coordinates

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}+u_z\frac{\partial u_r}{\partial z}-\frac{u_\theta^2}{r}\right)=\rho g_r-\frac{\partial p}{\partial r}$$
$$+\frac{\partial}{\partial r}\left[\mu\left(-\frac{2}{3}\nabla\cdot\overline{V}+2\frac{\partial u_r}{\partial r}\right)\right]+\frac{1}{r}\frac{\partial}{\partial \theta}\left[\mu\left(\frac{1}{r}\frac{\partial u_r}{\partial \theta}+\frac{\partial u_\theta}{\partial r}\right)\right]$$
$$+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_r}{\partial z}+\frac{\partial u_z}{\partial r}\right)\right]+\frac{2\mu}{r}\left(\frac{\partial u_r}{\partial r}-\frac{1}{r}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r}{r}\right)$$

$$\rho\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+u_z\frac{\partial u_\theta}{\partial z}+\frac{u_r u_\theta}{r}\right)=\rho g_\theta-\frac{1}{r}\frac{\partial p}{\partial \theta}$$
$$+\frac{1}{r}\frac{\partial}{\partial \theta}\left[\mu\left(-\frac{2}{3}\nabla\cdot\overline{V}+\frac{2}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{2u_r}{r}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_\theta}{\partial z}+\frac{1}{r}\frac{\partial u_z}{\partial \theta}\right)\right]$$
$$+\frac{\partial}{\partial r}\left[\mu\left(\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}+\frac{1}{r}\frac{\partial u_r}{\partial \theta}\right)\right]+\frac{2\mu}{r}\left(\frac{1}{r}\frac{\partial u_r}{\partial \theta}+\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}\right)$$

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}\right)=\rho g_z-\frac{\partial p}{\partial z}$$
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$$+\frac{1}{r}\frac{\partial}{\partial \theta}\left[\mu\left(\frac{1}{r}\frac{\partial u_z}{\partial \theta}+\frac{\partial u_\theta}{\partial z}\right)\right]+\frac{\mu}{r}\left(\frac{\partial u_r}{\partial z}+\frac{\partial u_z}{\partial r}\right)$$

+ Eq. of energy

Simplified viscosity

$$\rho\left[\frac{\partial v_\phi}{\partial t}+v_r\frac{\partial v_\phi}{\partial r}+v_z\frac{\partial v_\phi}{\partial z}\right]$$
$$=-\frac{v_\phi v_r}{r}+\mu\left[\frac{\partial^2 v_\phi}{\partial r^2}+\frac{1}{r}\frac{\partial v_\phi}{\partial r}-\frac{v_\phi}{r^2}+\frac{\partial^2 v_\phi}{\partial z^2}\right].$$

$$\mu\left[\frac{\partial^2 v_\phi}{\partial r^2}+\frac{1}{r}\frac{\partial v_\phi}{\partial r}-\frac{v_\phi}{r^2}\right]=\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{r\phi}),$$

In the case of a thin accretion flow $\tau_{r\phi}$ component is the dominant contributor to the viscous stress (SS73): $\tau_{r\phi} = - \alpha p$

No self-gravity Model. Parameters

$M_{BH} = 1.5\ 10^9\ M_{sun}$

Evolution up to 0.5 Myr

Viscosity 0.005

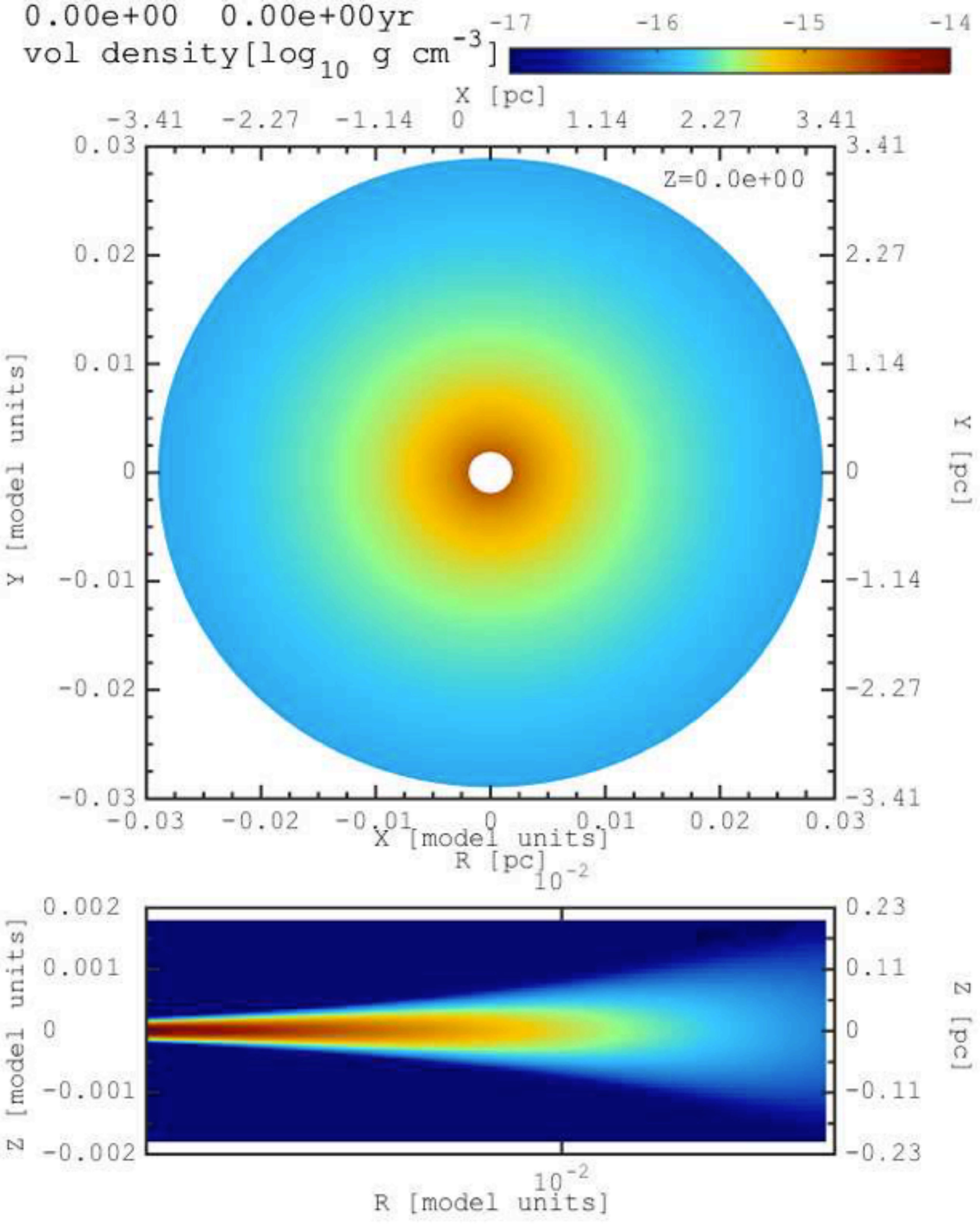
Hydro mesh 128x128x129

Hydro integration time step ~100 days

4 nodes on Kepler

Full integration time 12 hours

Density Movie



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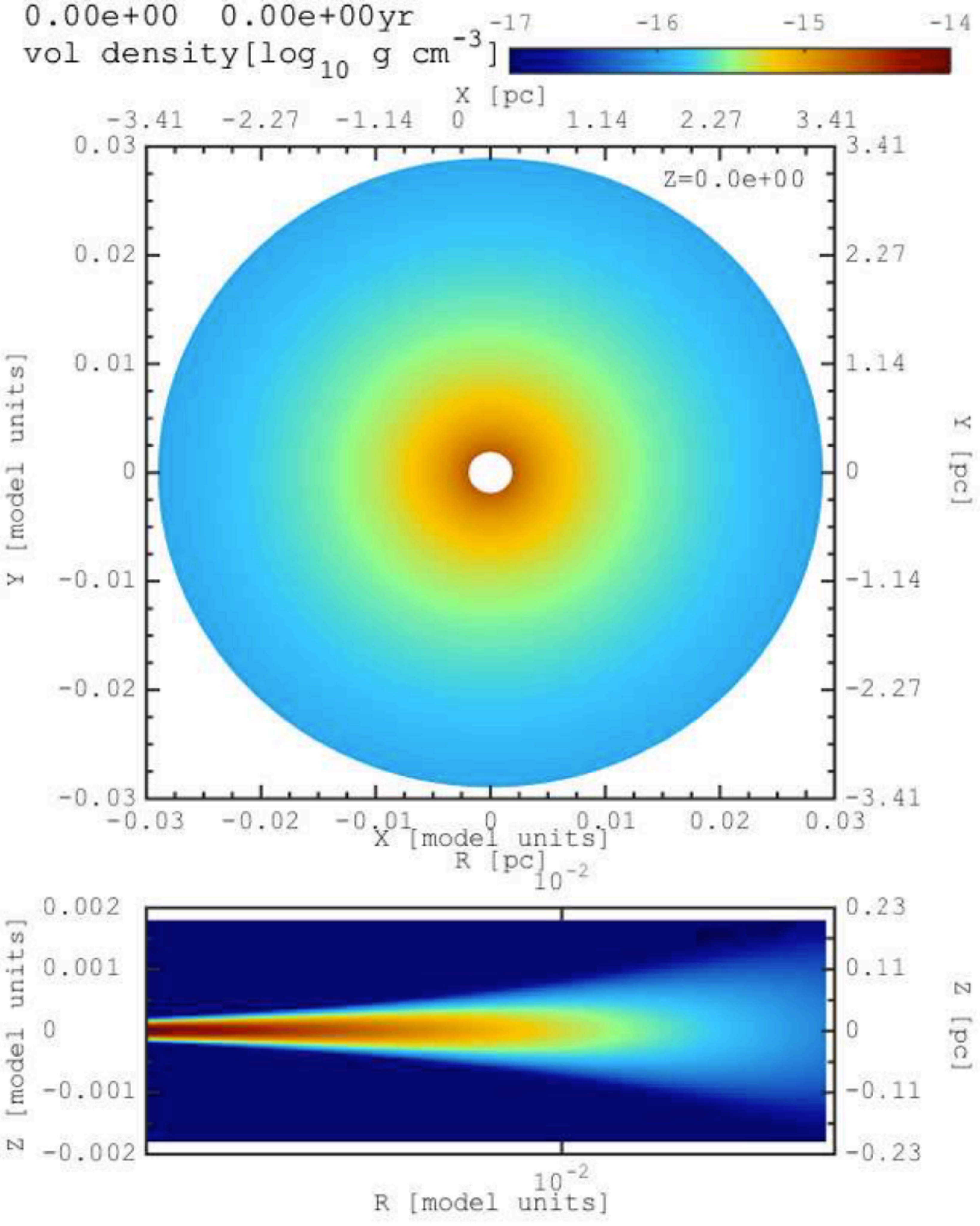
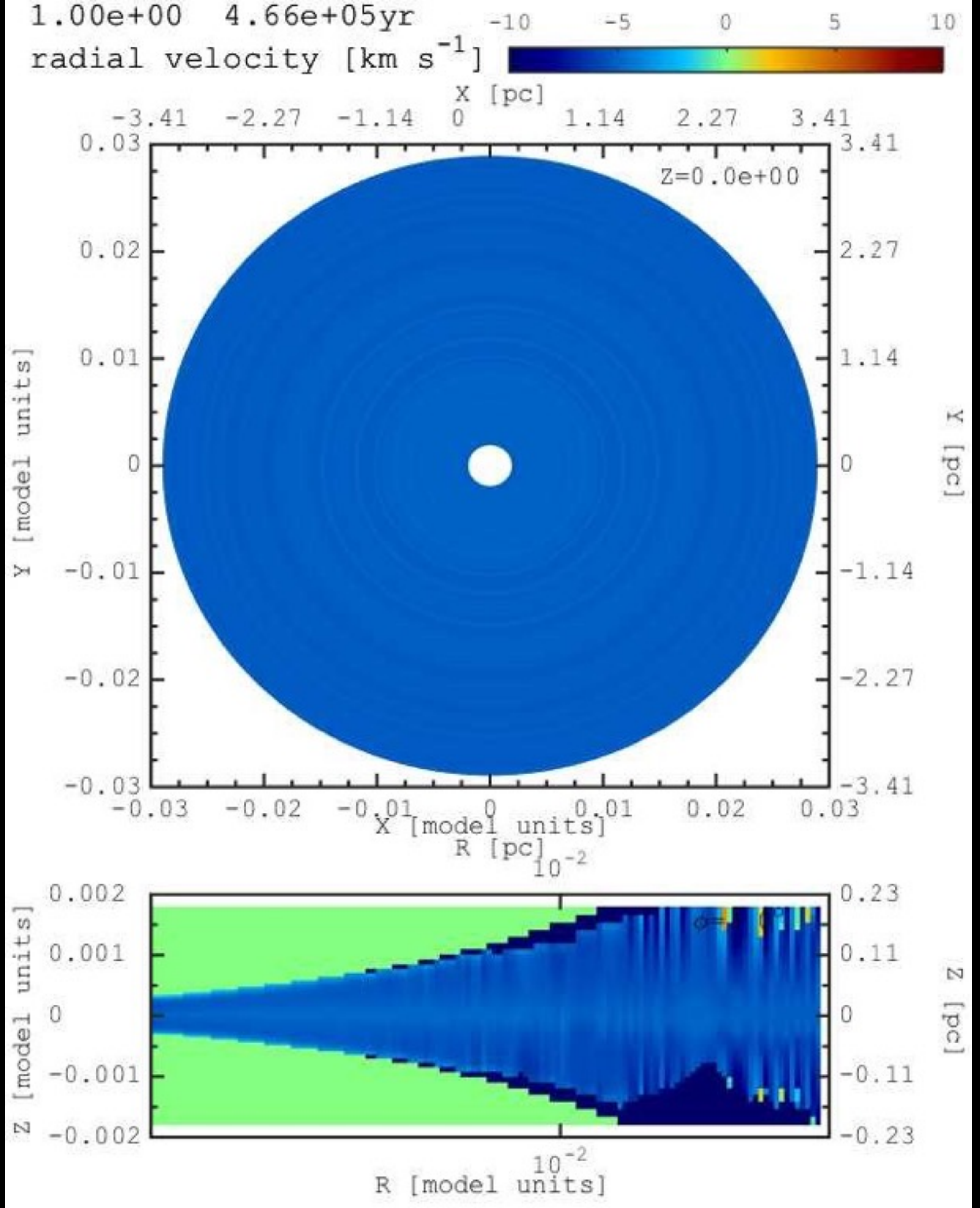
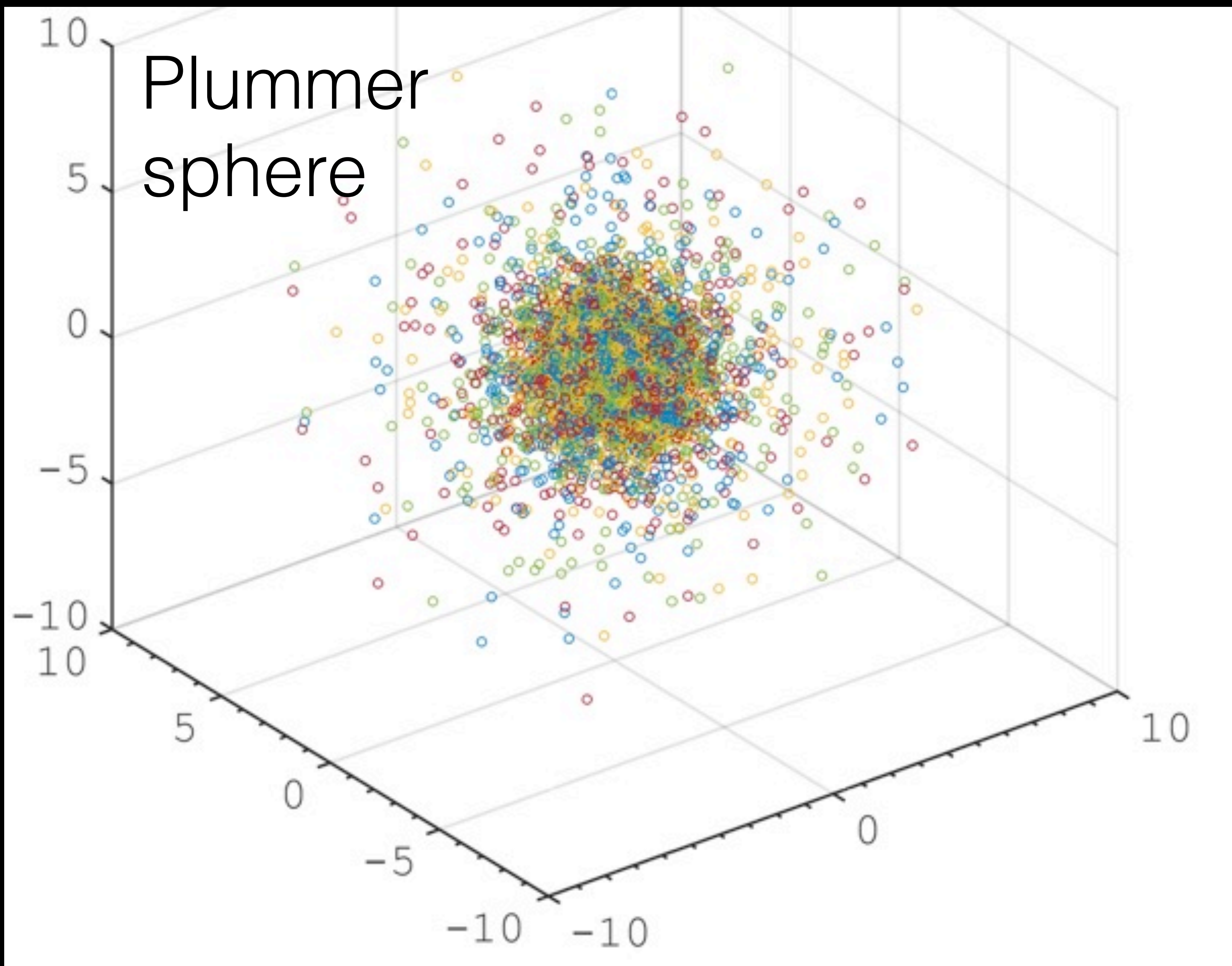


Radial velocity Maps



(Self) gravity



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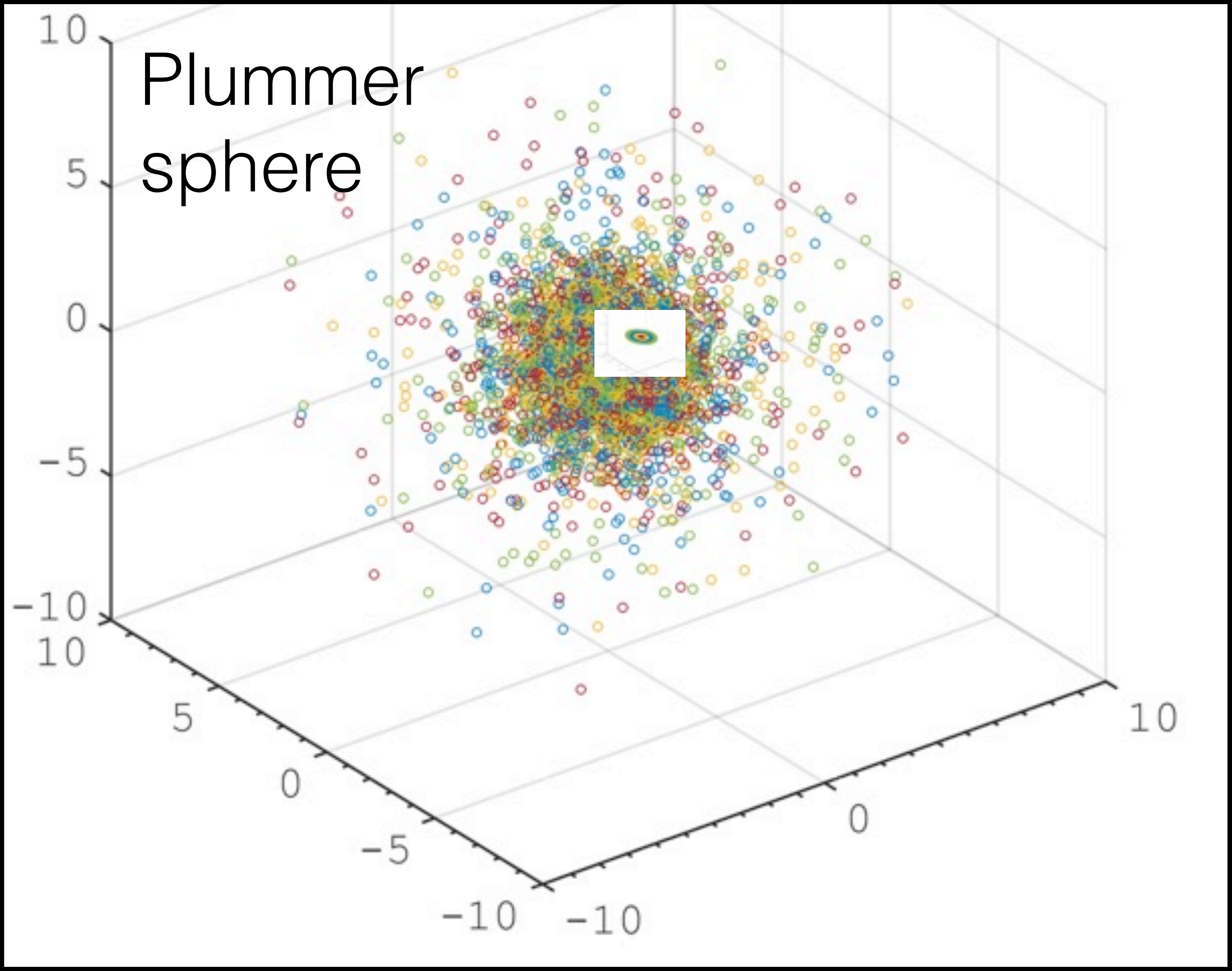

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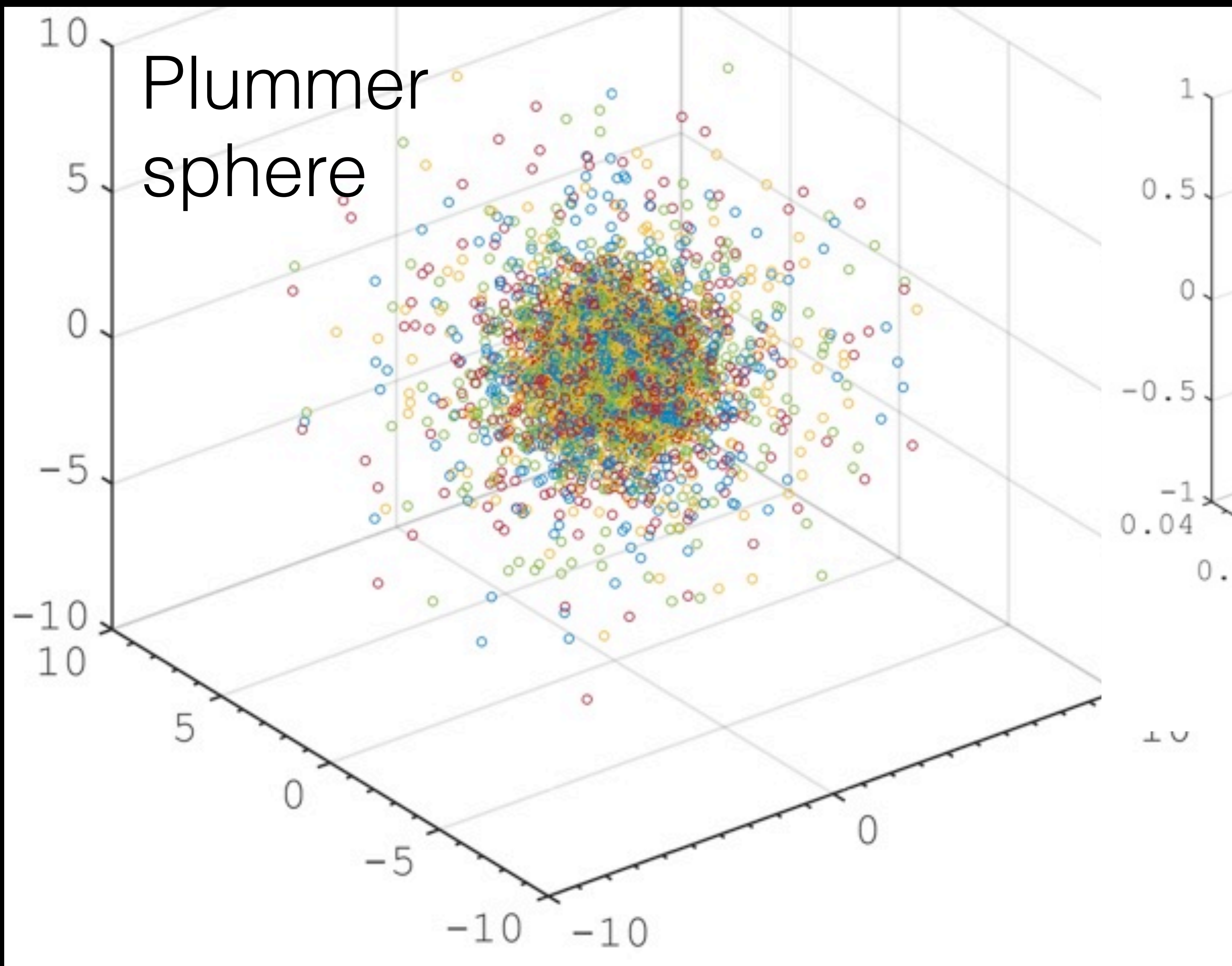
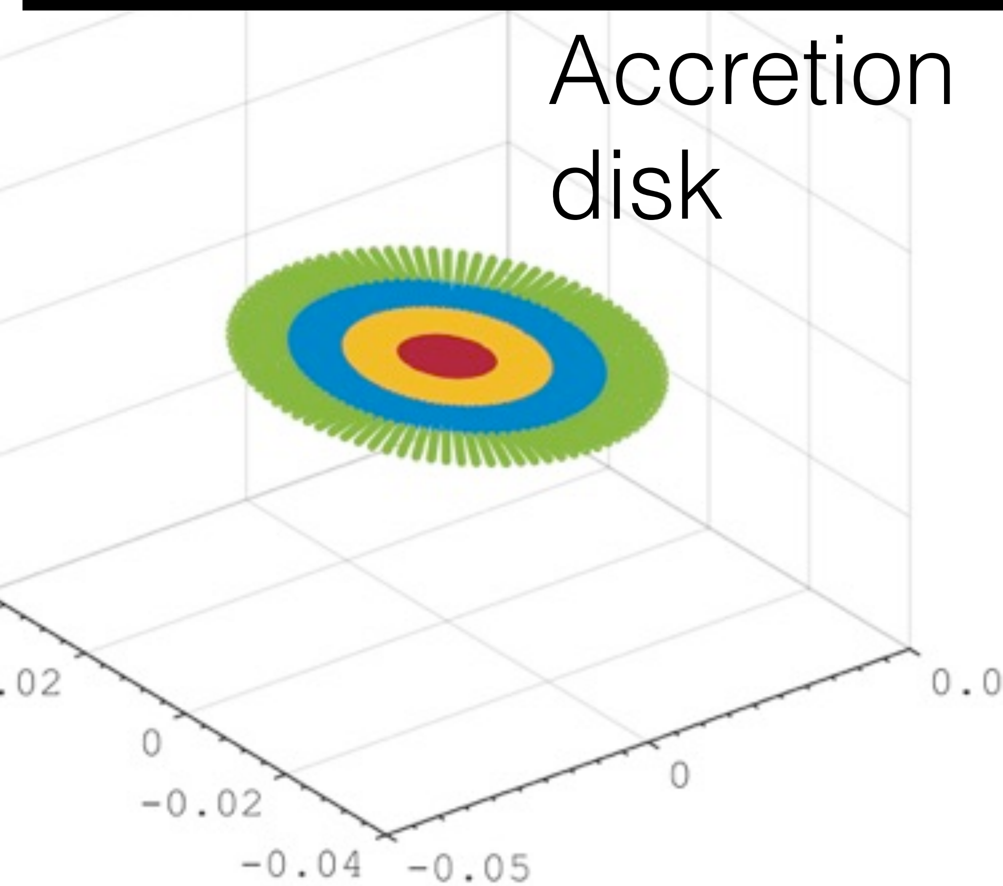
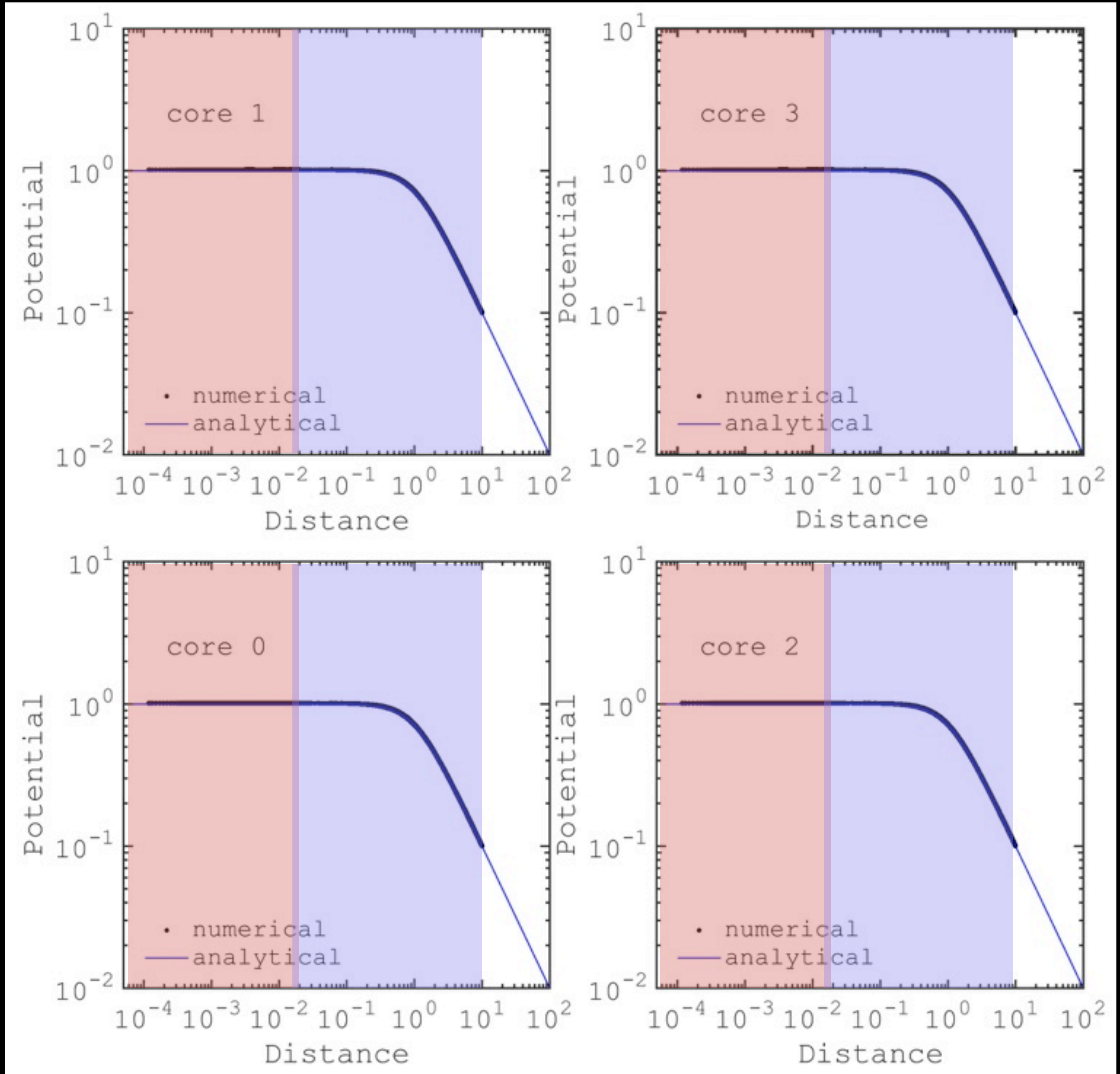


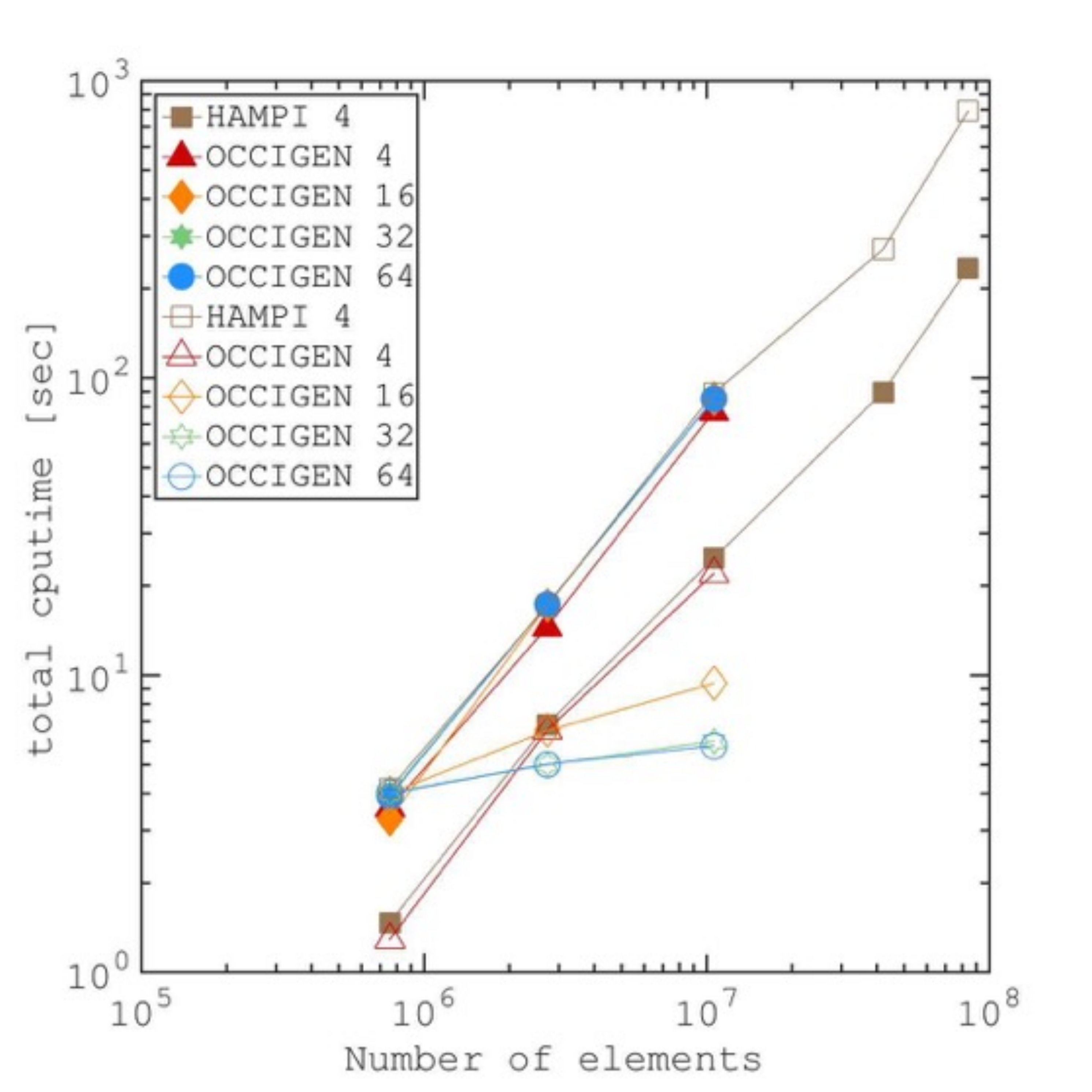


Plummer sphere

Acceleration for hydro cells and particles



MPI version. Performance test



example:

N-body
galaxy simulation

8 nodes - 64 cores

OCCIGEN

15 10^6 particles

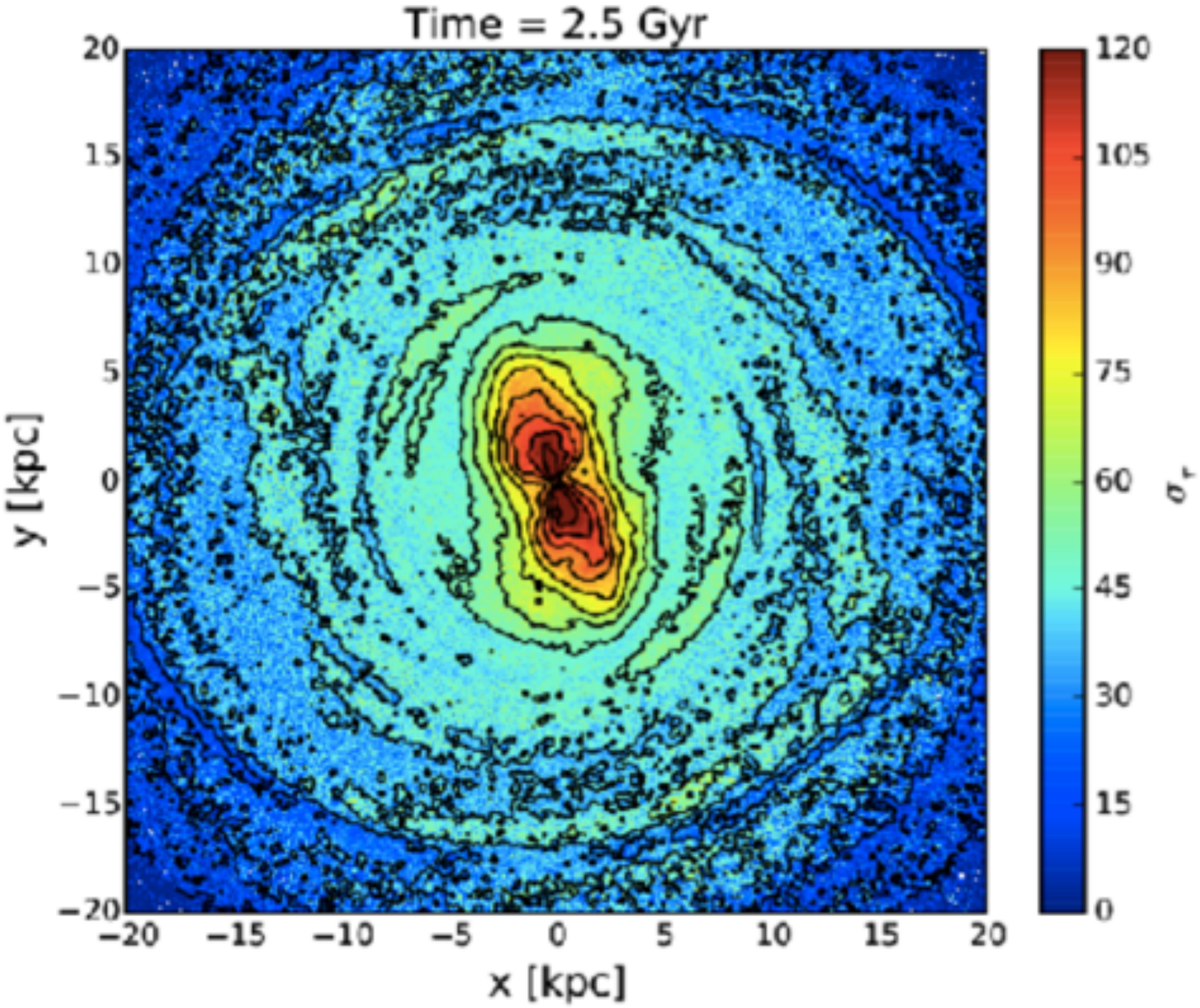
~7 days for 5 Gyr

Comparison "old" Treecode (Semelin & Combes 2002) with Sergey's Treecode

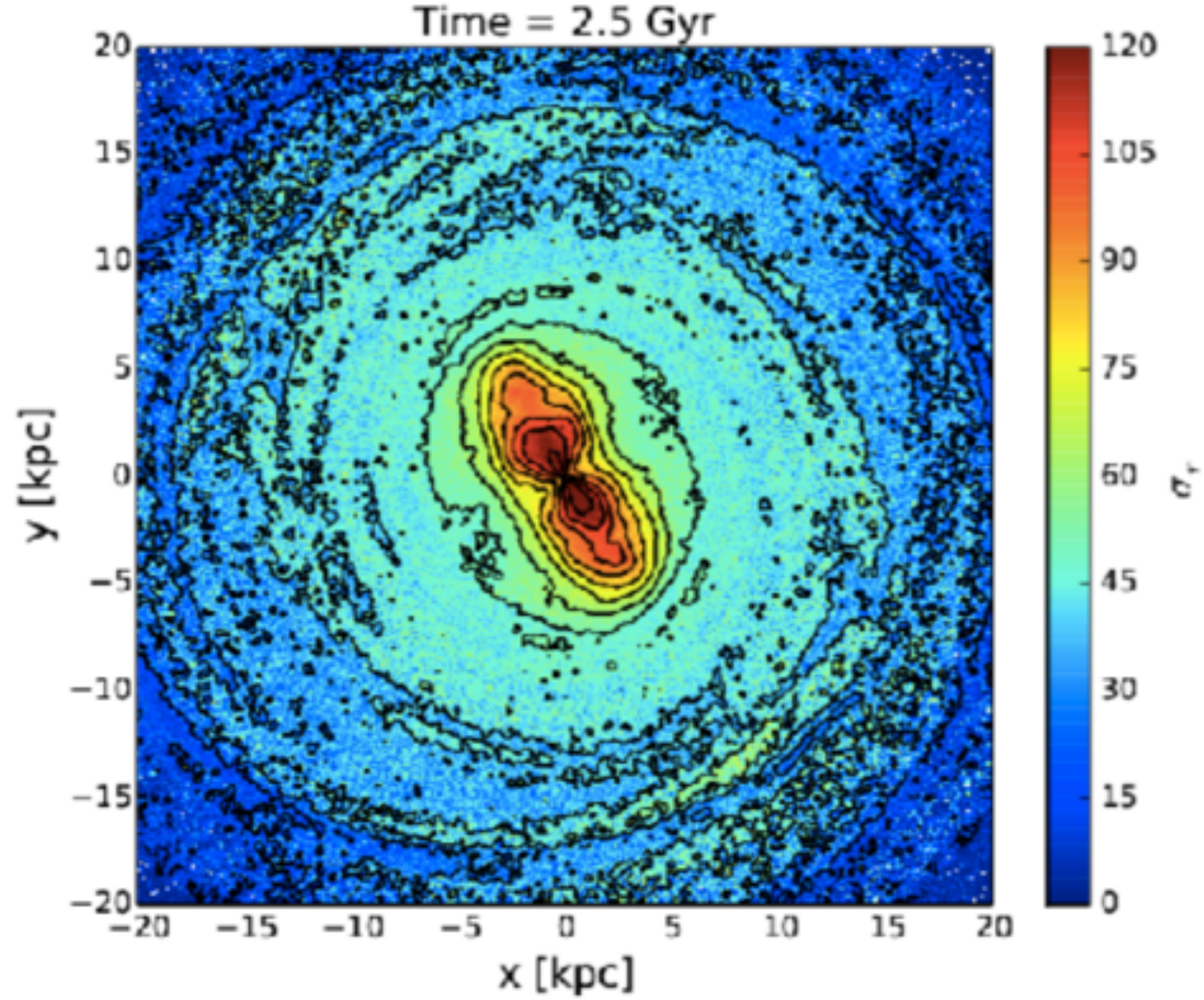
Simulation with 30M particles

Radial velocity dispersion map

Old



New



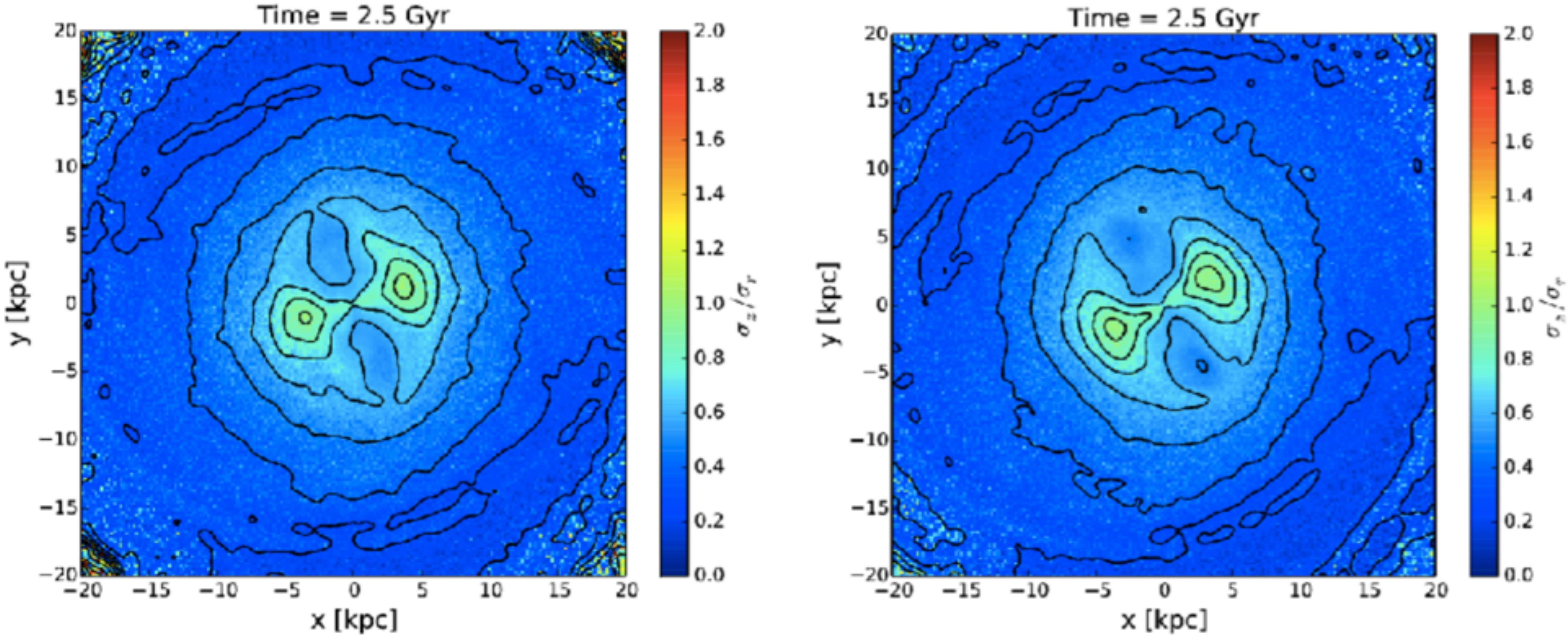
Comparison "old" Treecode (Semelin & Combes 2002) with Sergey's Treecode

Simulation with 30M particles

Ratio vertical to radial velocity dispersion map

Old

New



Self-gravity Model. Parameters

$M_{BH} = 1.5\ 10^8\ M_{sun}$

Evolution up to 0.5 Myr

Viscosity 0.005

Hydro mesh 128x128x129

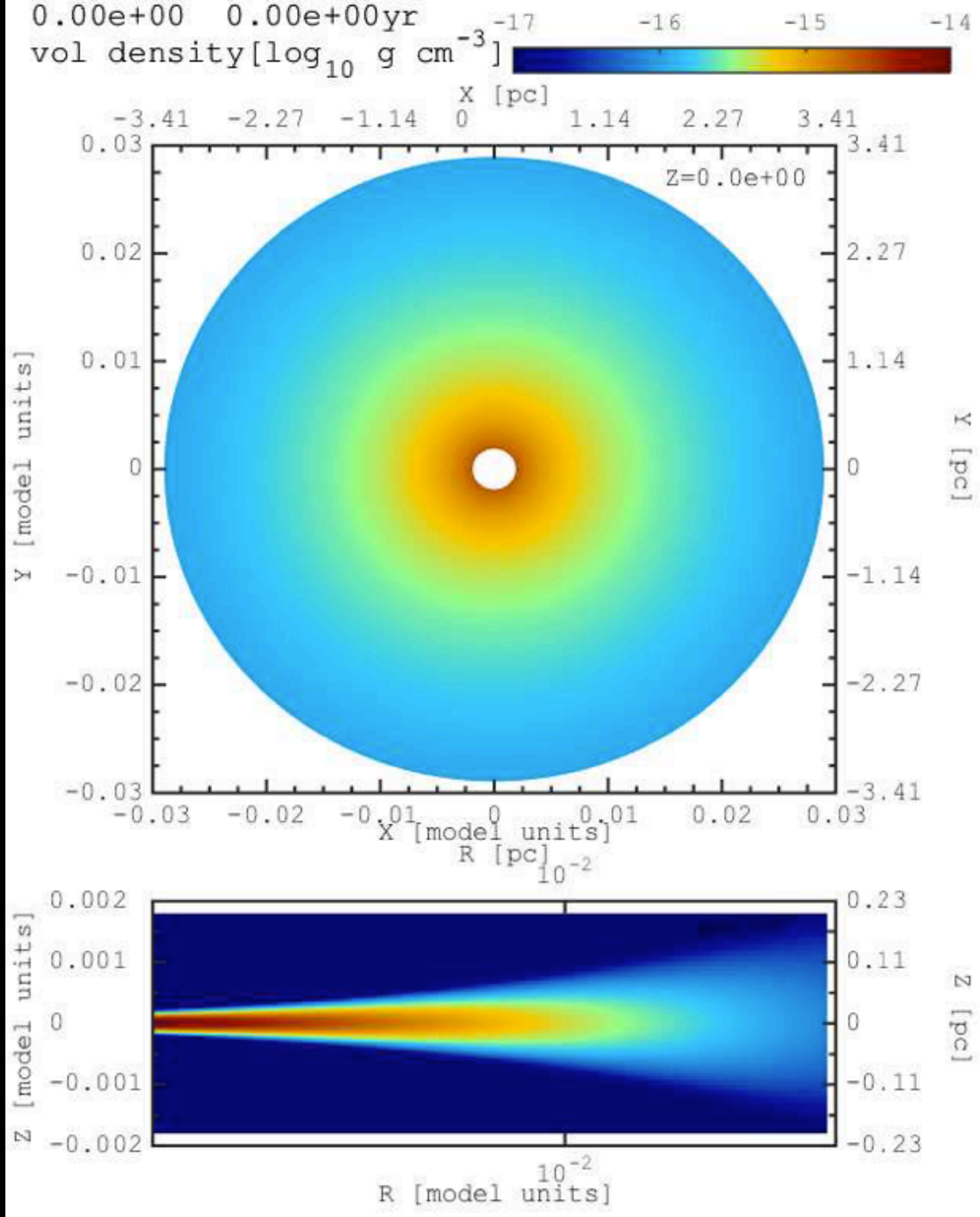
Plummer sphere, $N = 10^5$ particles

Hydro integration time step ~100 days

4 nodes on Kepler

Full integration time 28 hours

AD with self-gravity and stellar dynamics



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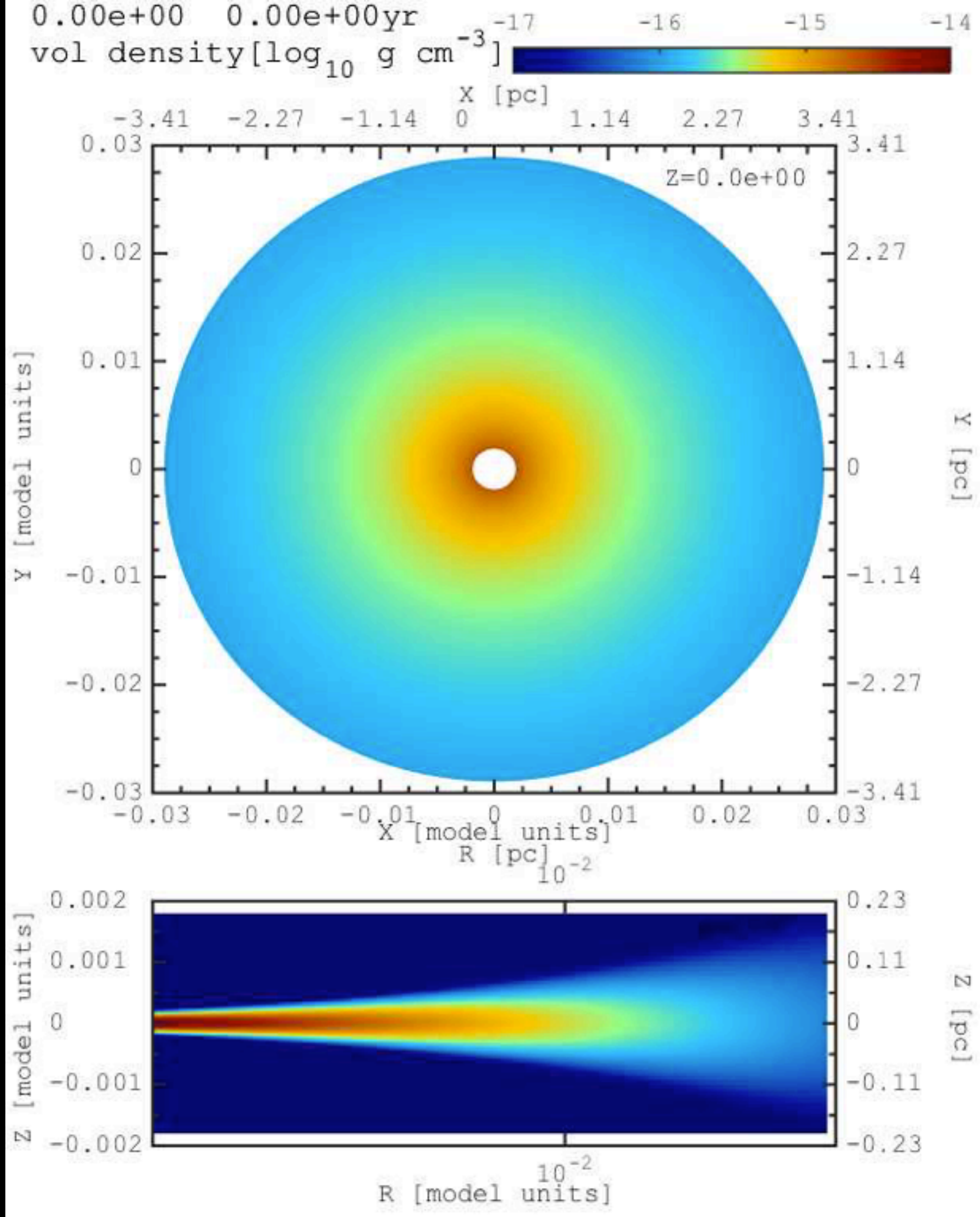
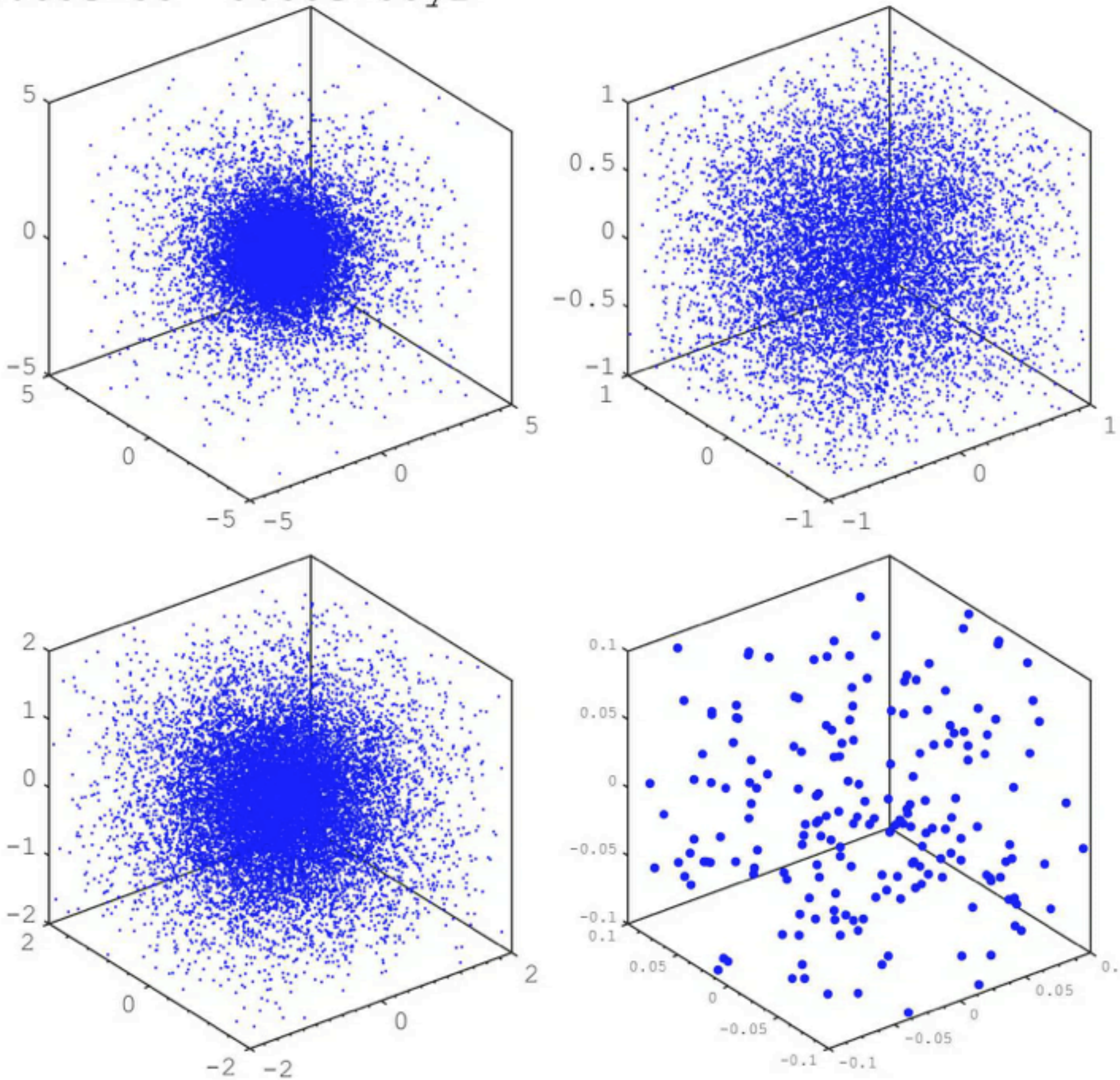
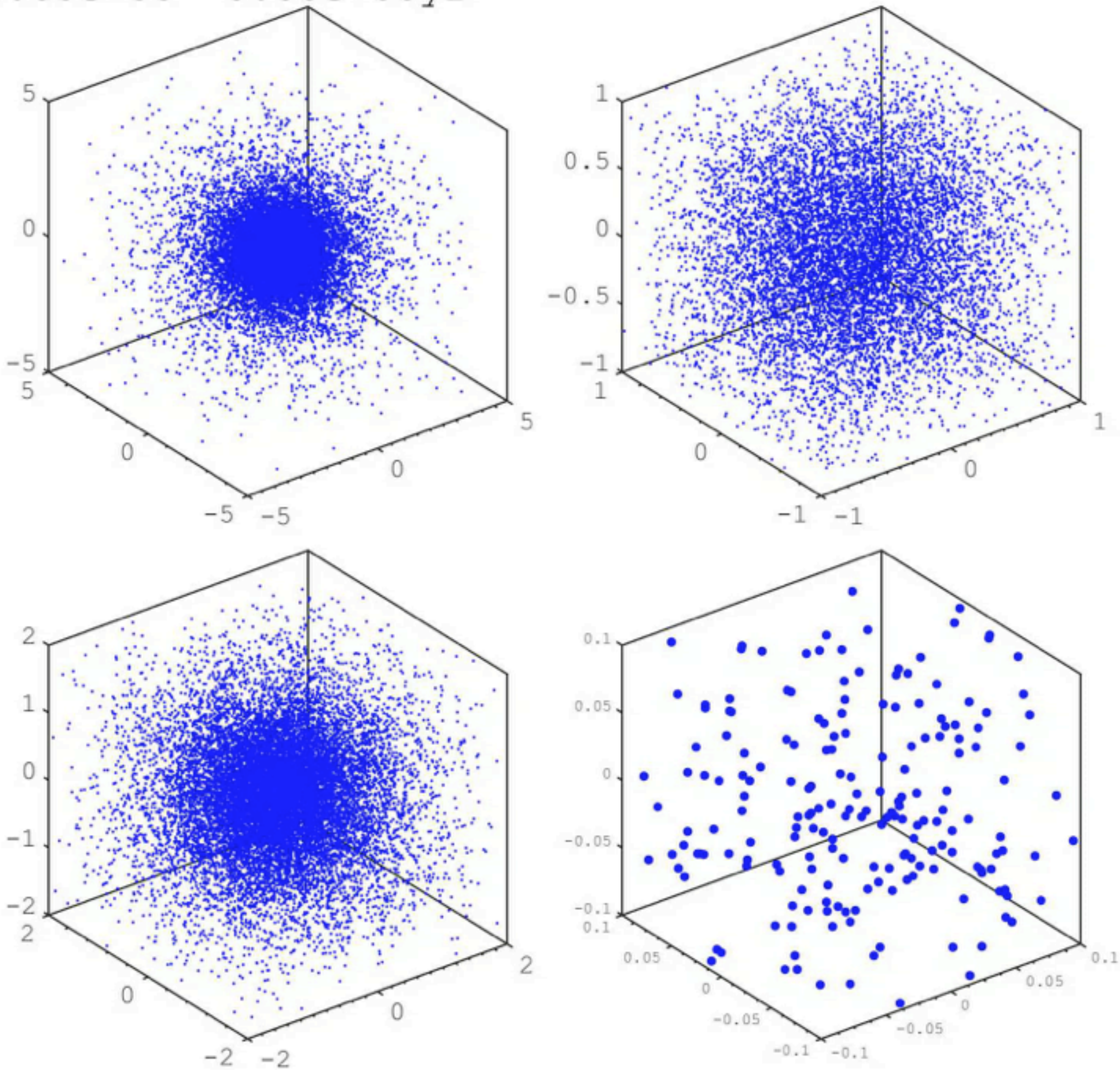


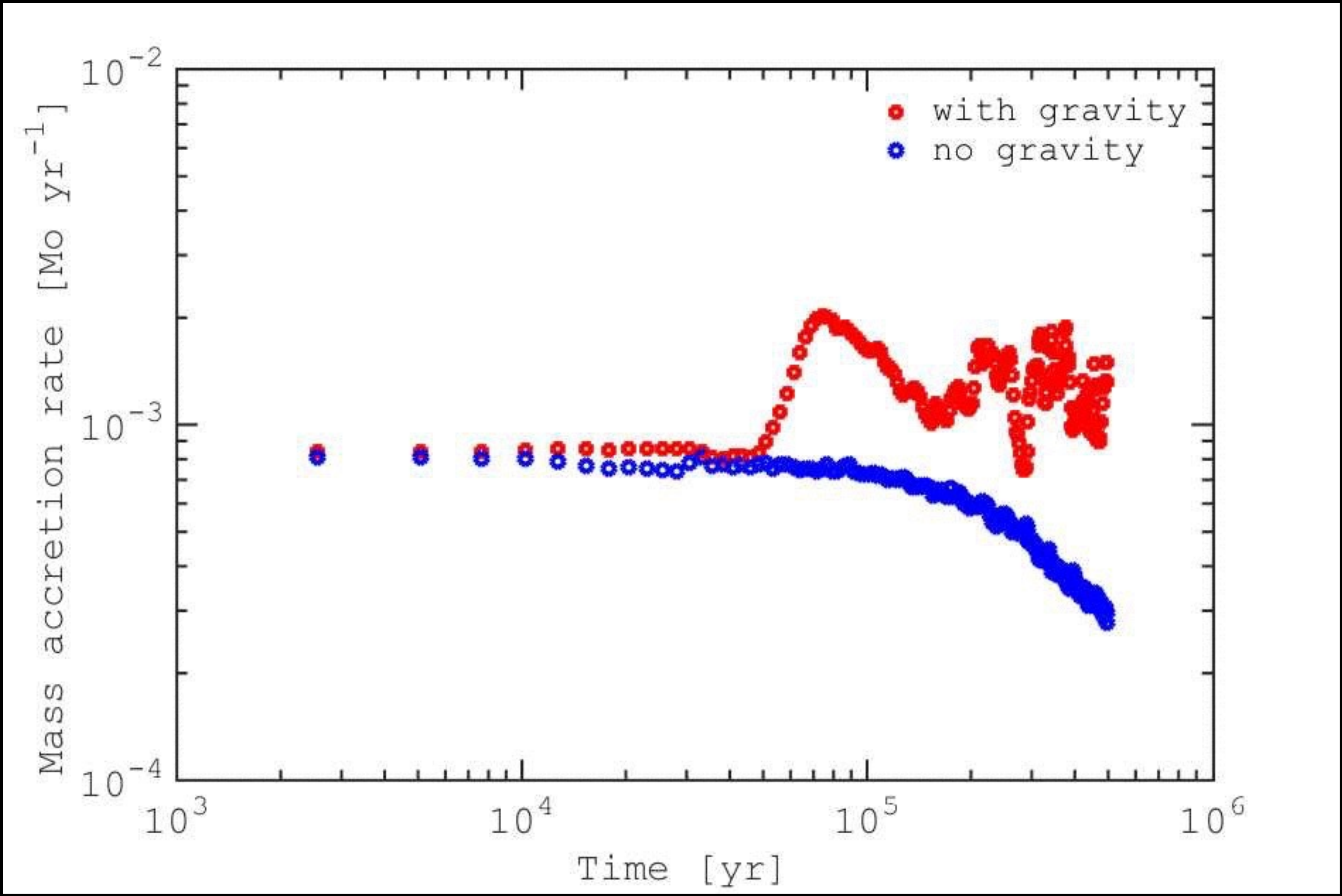
0.00e+00 0.00e+00yr



0.00e+00 0.00e+00yr



Mass accretion rate



Results. Current state

Results. Current state

- Stable AD (~10^6 yr) with α-viscosity and BH accretion

Results. Current state

- Stable AD ($\sim 10^6$ yr) with α-viscosity and BH accretion
- Tree Code based (self) gravity calculation and stellar particles dynamics

Results. Current state

- Stable AD ($\sim 10^6$ yr) with α-viscosity and BH accretion

- Tree Code based (self) gravity calculation and stellar particles dynamics

- MPI parallelization

Results. Current state

- Stable AD ($\sim 10^6$ yr) with α-viscosity and BH accretion

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Future steps

Results. Current state

- Stable AD (~10^6 yr) with α-viscosity and BH accretion
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Future steps

- Implementation of drag forces between AD and stars

Results. Current state

- Stable AD ($\sim 10^6$ yr) with α-viscosity and BH accretion
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Future steps

- Implementation of drag forces between AD and stars
- GPU parallelization