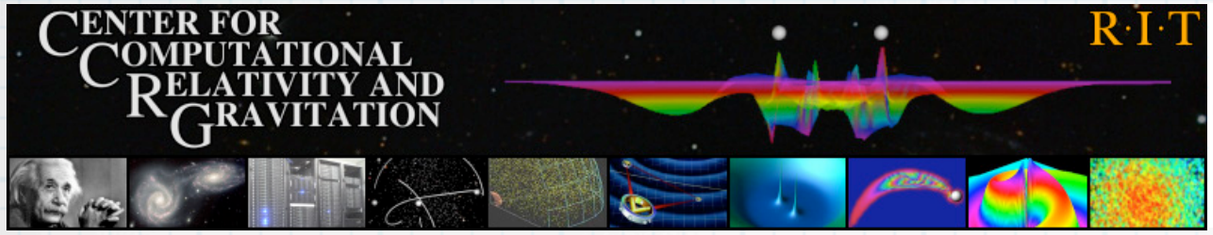

Disks around Kicked Black Holes

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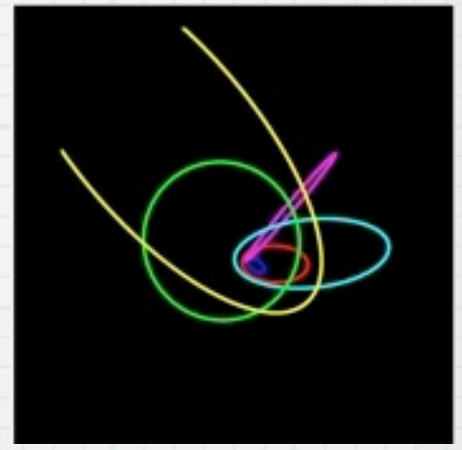
12th Eastern Gravity Meeting
June 16, 2009

Disks in Astrophysics

* Disks are a ubiquitous phenomena in astrophysics since angular momentum is conserved
* Food for AGNs when accreted onto SMBH
* Milky Way: 3-4 million $M_\odot$ SMBH
  * No AGN
  * Stars, Gas, Dust, etc. - Nature of the disk somewhat uncertain

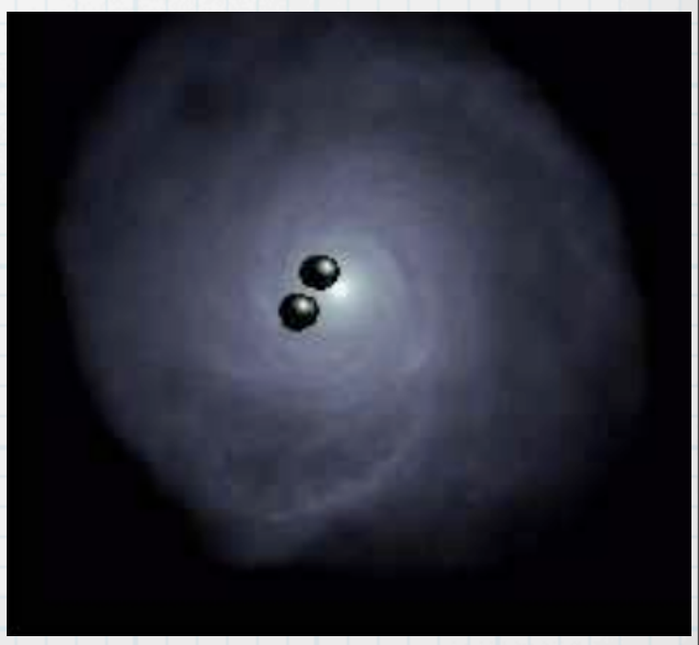


Top: Gualandris (RIT);
Bottom: NASA

Disks in relativity

* Near a BH, the ISCO acts as a sink for mass
* Shakura and Sunyaev - assume shear stress proportional to pressure, find complete solution in terms of alpha
* Close Binary BHs: Much more complicated...
  * Disk-Disk interactions
  * Spiral waves in circumbinary disks

Colpi et al. 2009



Timescales for merging BHs

* Once the radiation reaction timescale << disk inflow timescale, BHs decouple from the disk - $R \approx 10^3 M_{\rm BH}$ (Schnittman & Krolik 2008)
* This leaves the remaining circumbinary disk in a (post-)Newtonian regime
* After a merger/kick, the inner regions of the disk remain bound, and the outer parts unbound

A digression on Newtonian units

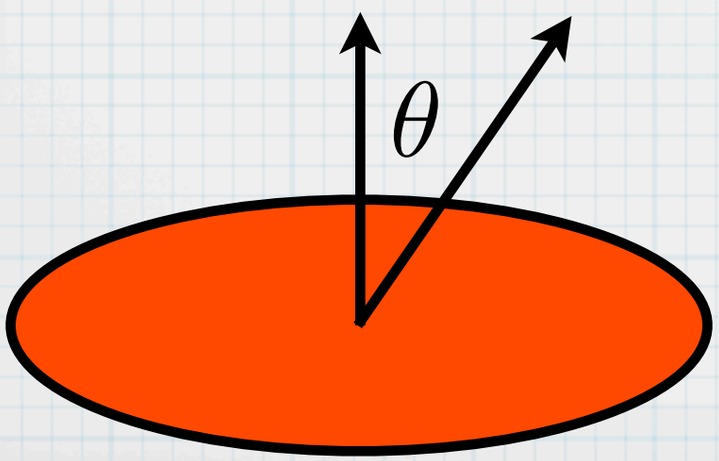
* G=1. G always equals 1.
* The natural velocity scale is the kick velocity, not c...

$$\hat{R} \equiv \frac{GM_{\rm BH}}{v_k^2} \approx 5.3 \times 10^{11} \left(\frac{M_{\rm BH}}{4 \times 10^6 M_\odot}\right) \left(\frac{v_k}{1000 {\rm km/s}}\right)^{-2} {\rm km} \approx 3500 {\rm AU} \approx 0.02 \ {\rm pc}$$

  * There is no inherent relation between the disk mass and the BH mass

A kicked BH disk model

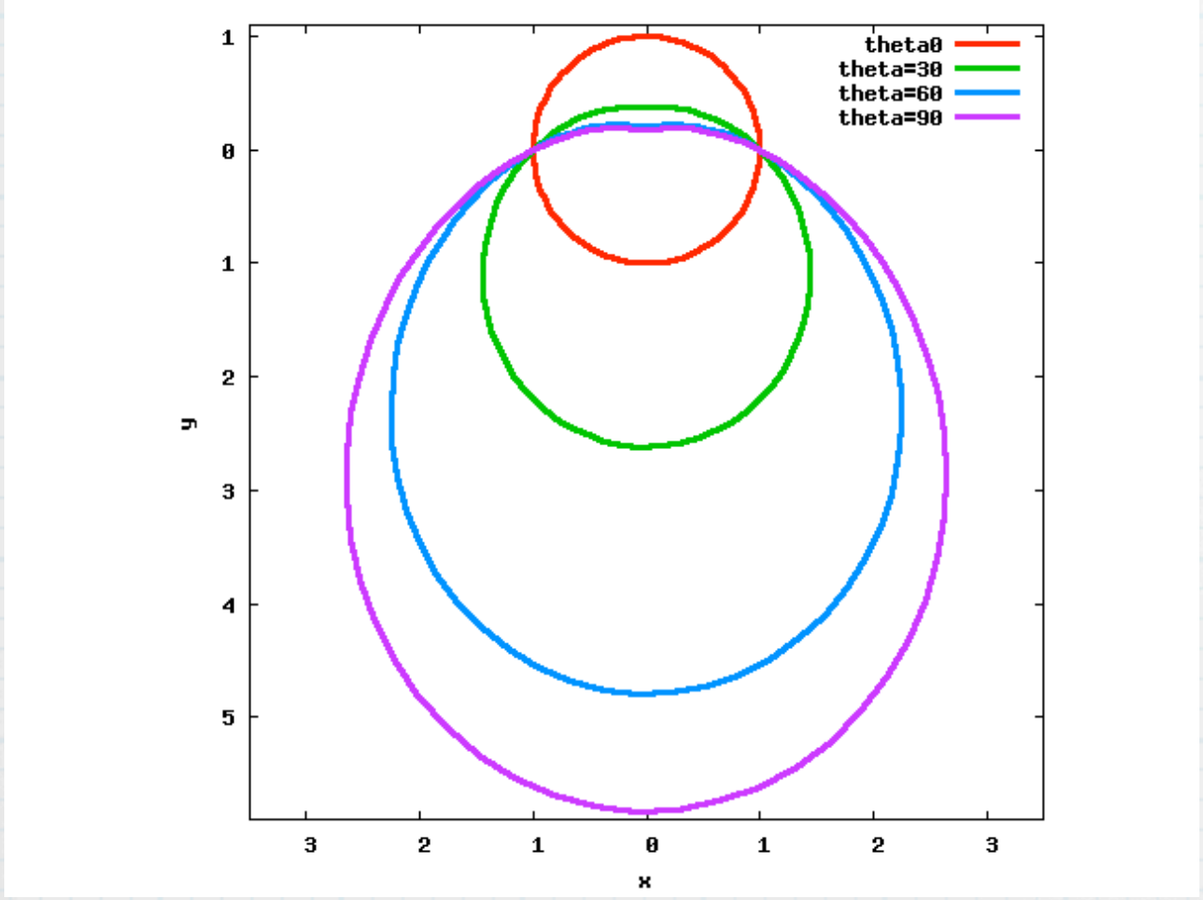
* Disk initially in the x-y plane, L in the +z direction
* Kick in the x-z plane, at an angle of θ from the vertical
* Assume Keplerian or quasi-Keplerian rotation

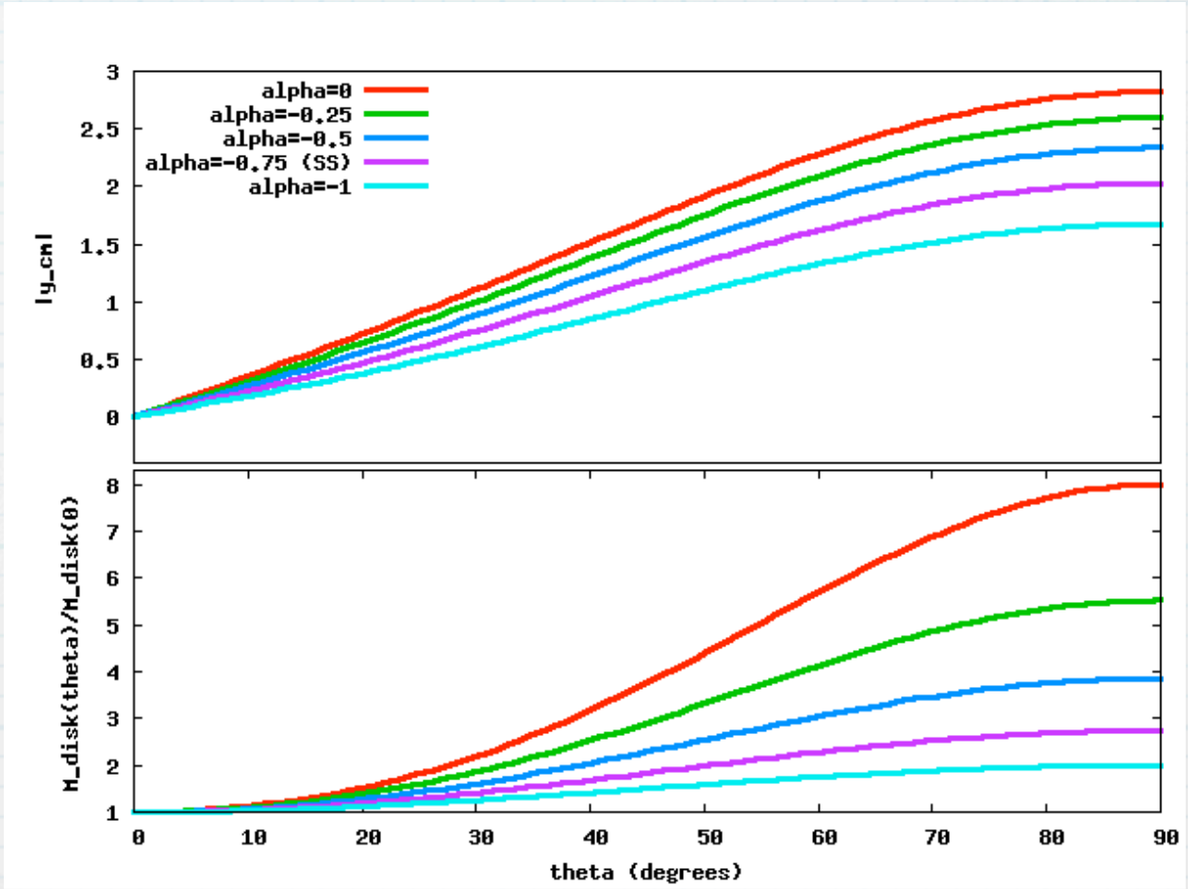


$$v_b(\phi) = \sin\theta\sin\phi + \sqrt{1.0 + \sin^2\theta\sin^2\phi}$$
$$r_b(\phi) = v_b(\phi)^{-2}$$

The kick angle

- The kick angle θ determines the bound portion of a Keplerian disk, in units of $\hat{R}$
- Disk masses can be determined if we assume $\sigma(r) \propto r^{\alpha}$

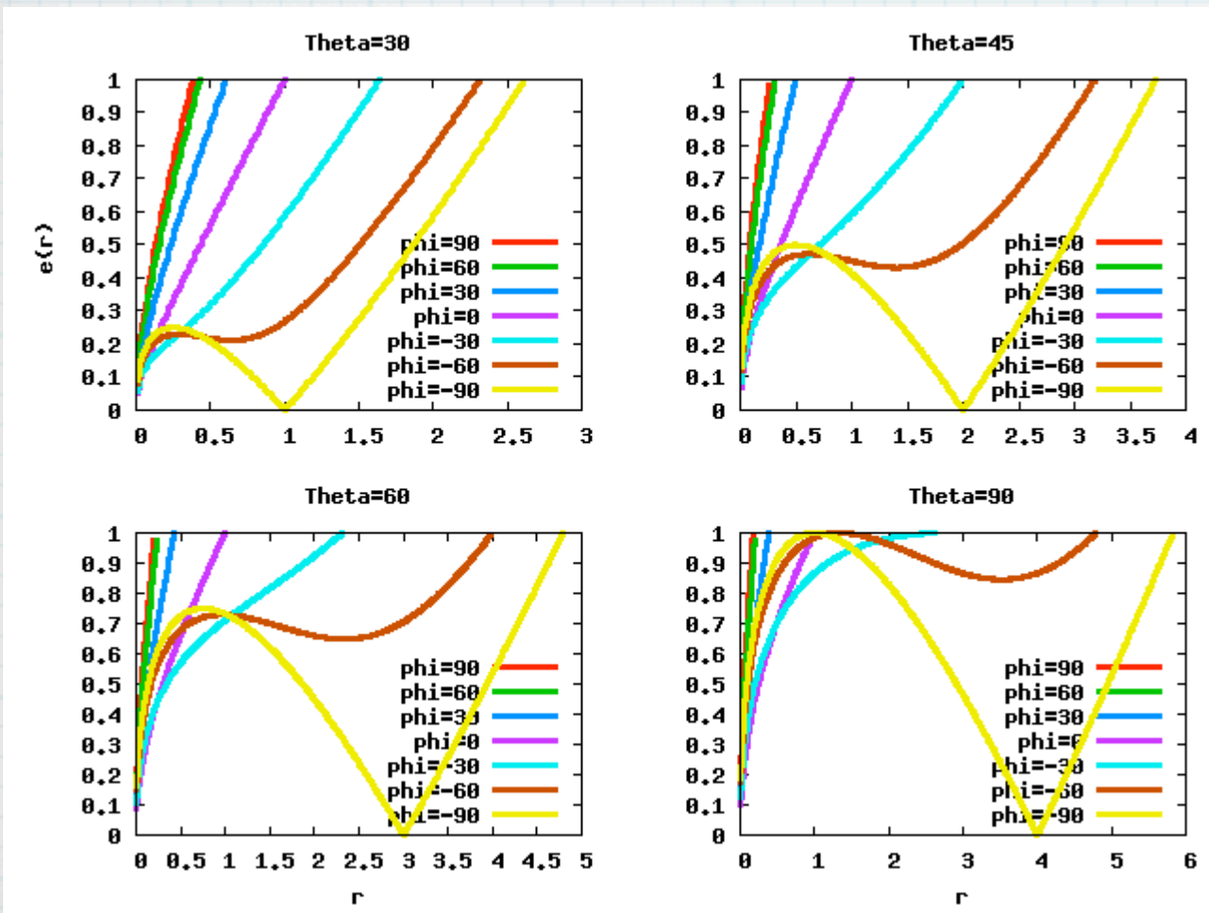




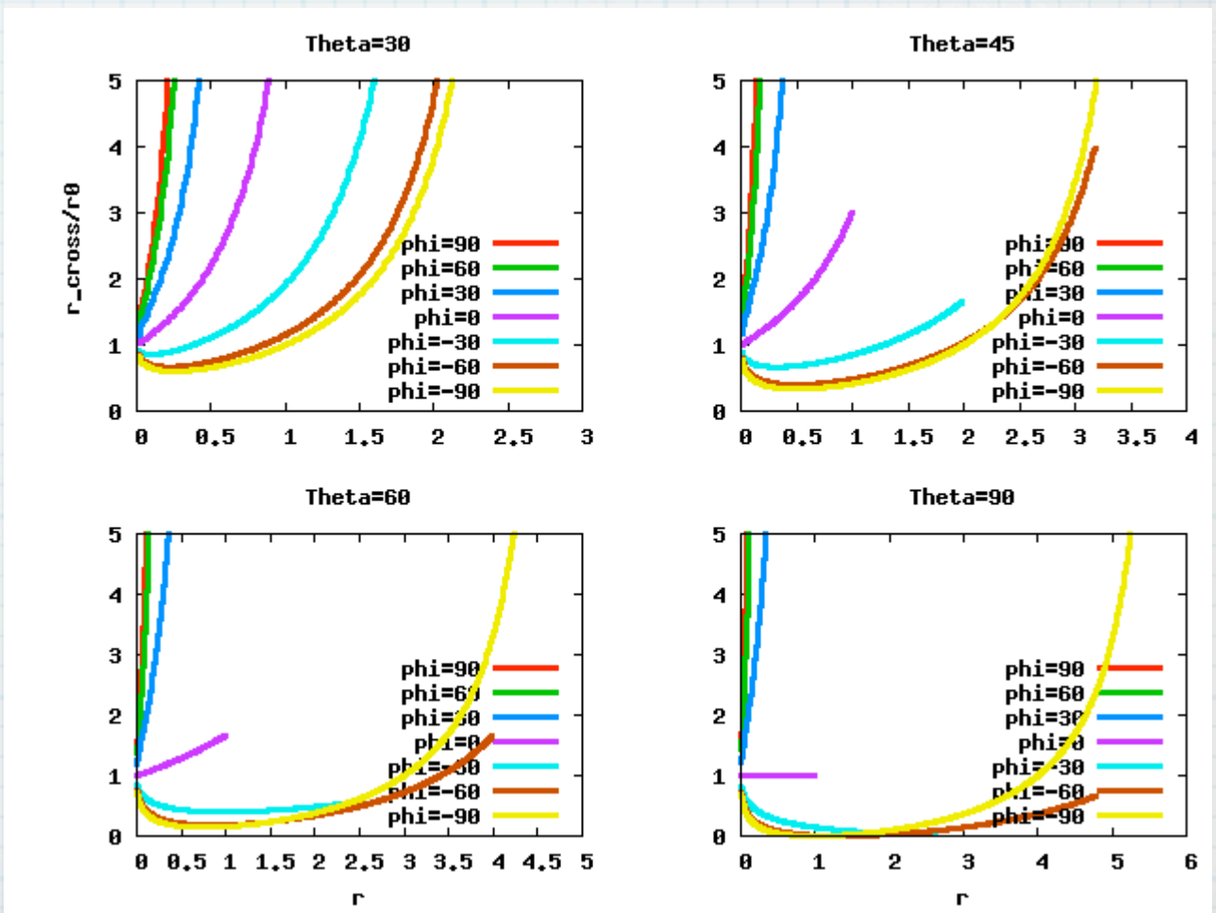
Collisionless disks

* Shields, Bonning et al. (2008) considered quasi-collisionless disks around kicked BHs
* All particle orbits are independent 2-body problems

Eccentricity vs radius

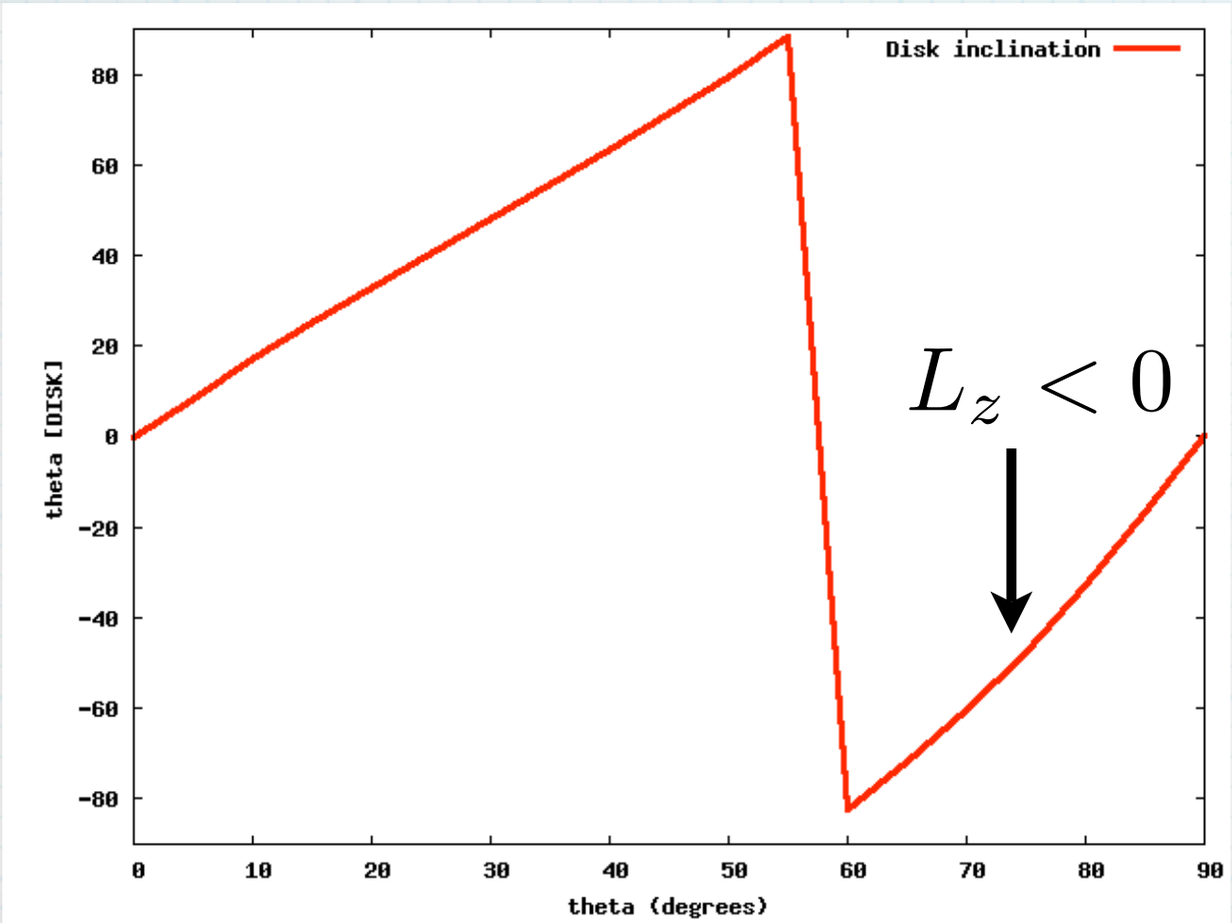


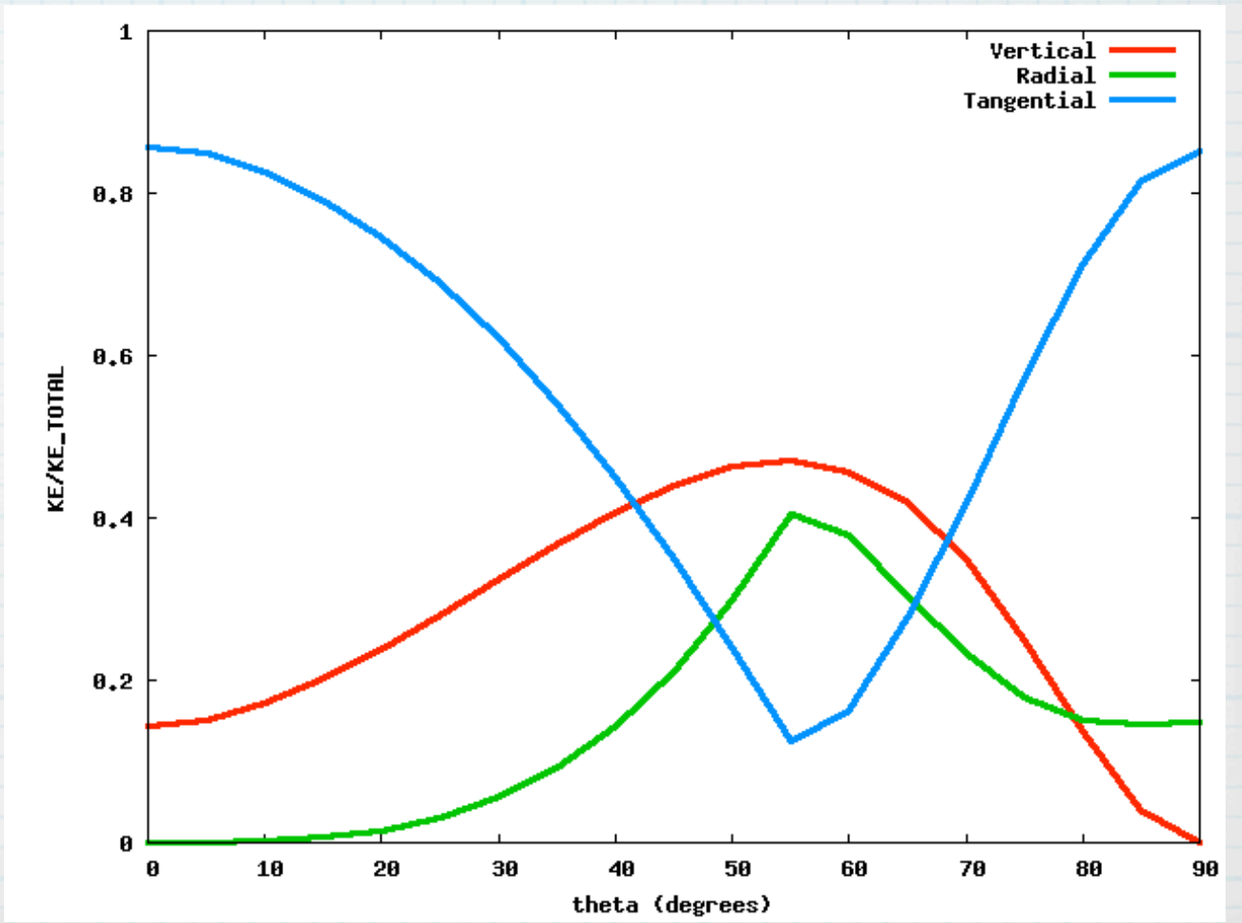
"Crossing radius" vs initial radius



Global features of the disk

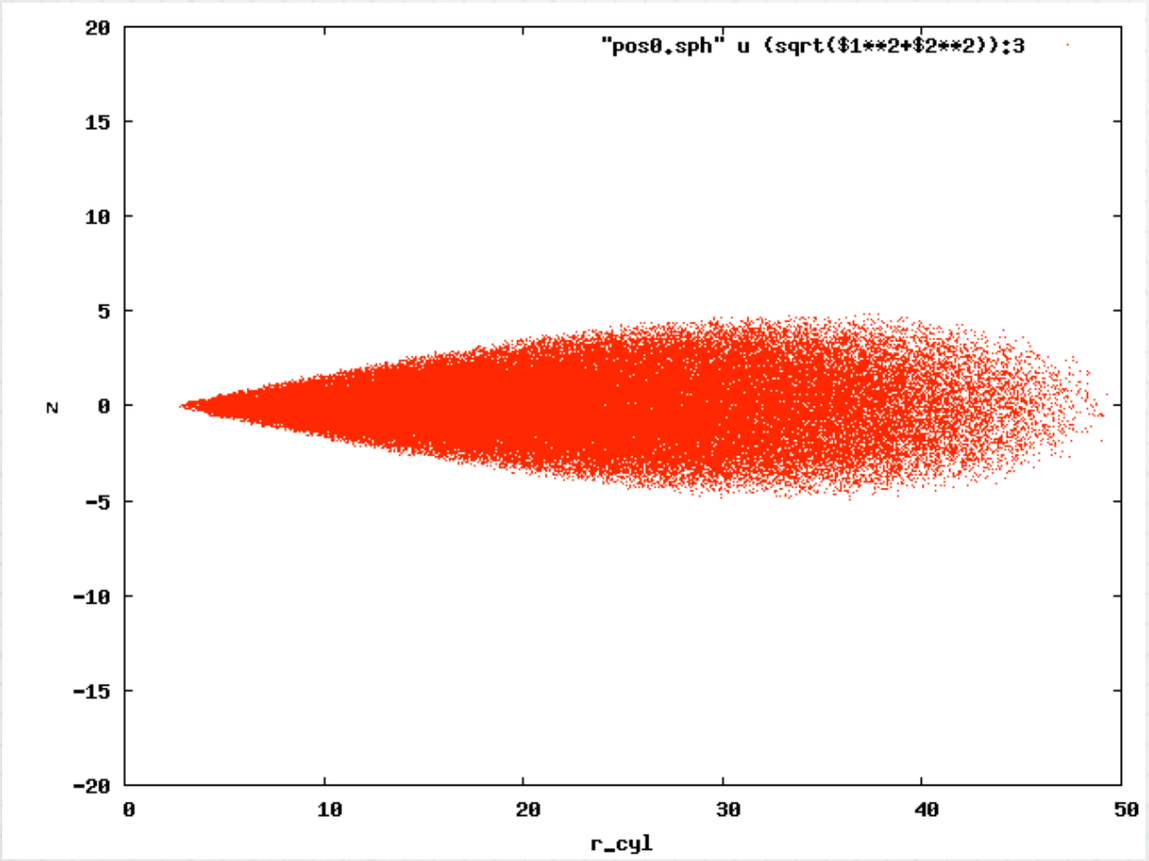
* Disk inclination angle differs from kick angle - reversal of direction for $\theta \gtrsim 60^\circ$
* Significant kinetic energy in vertical direction will be dissipated

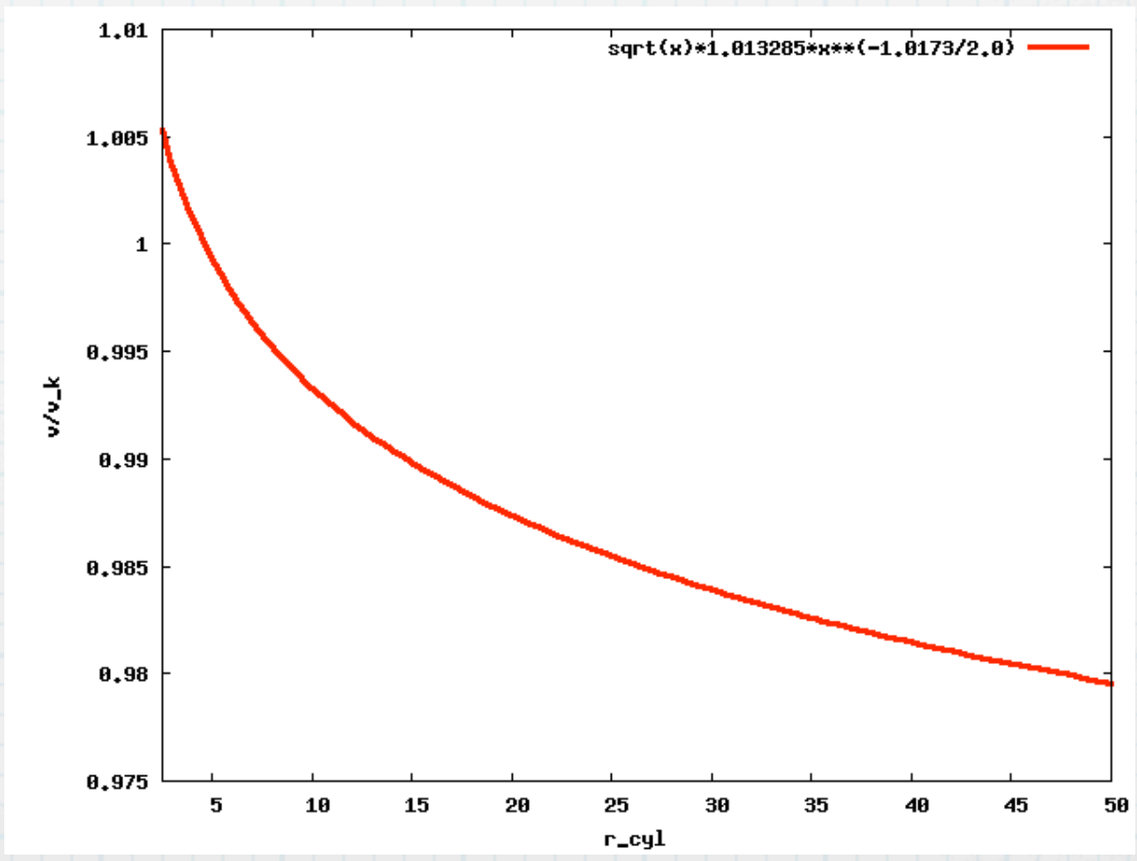




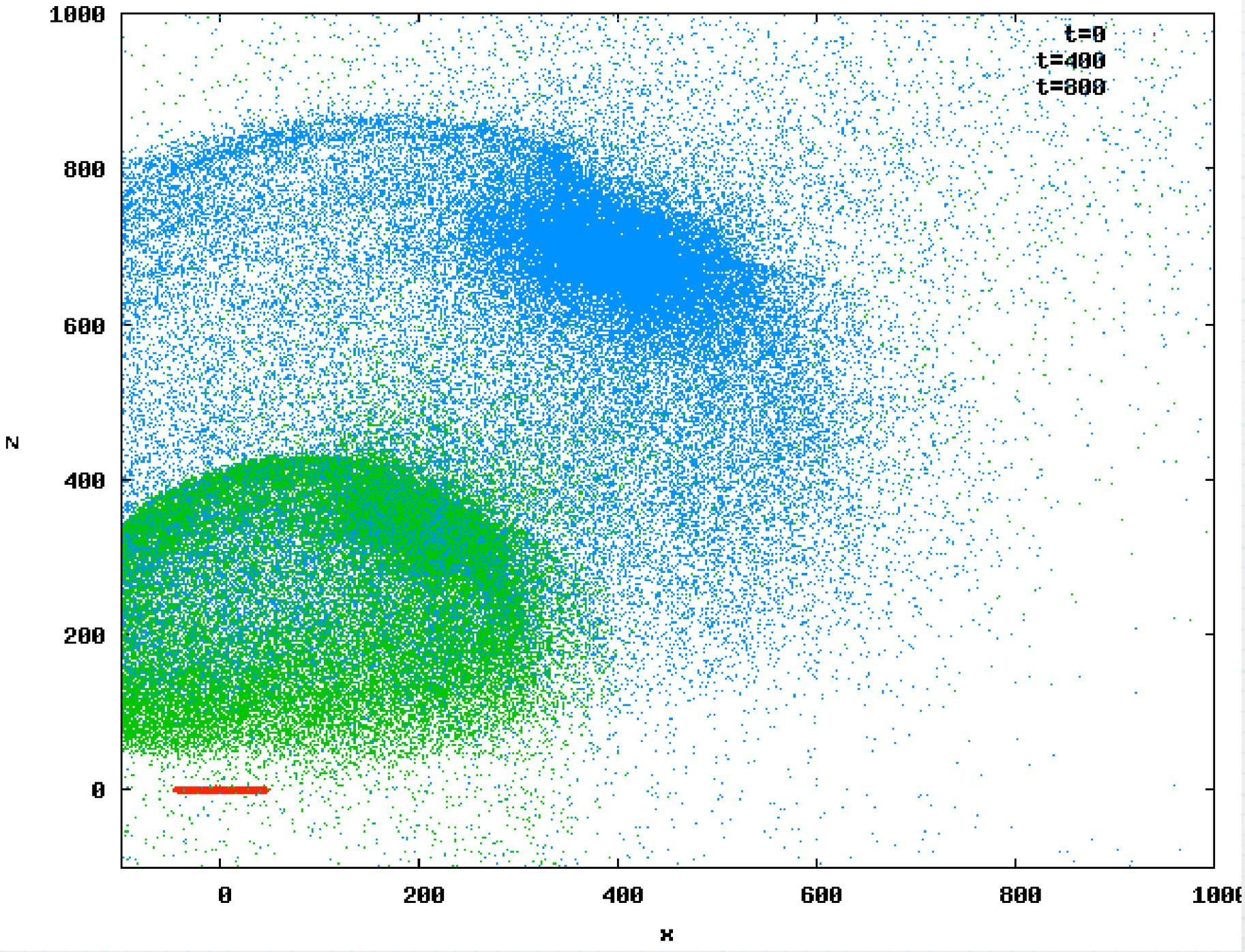
Collisional disks

* Newtonian SPH can track the disk evolution without recourse to moving grids
* Heating via artificial viscosity-induced shocking
* Self-gravity of the disk is ignored

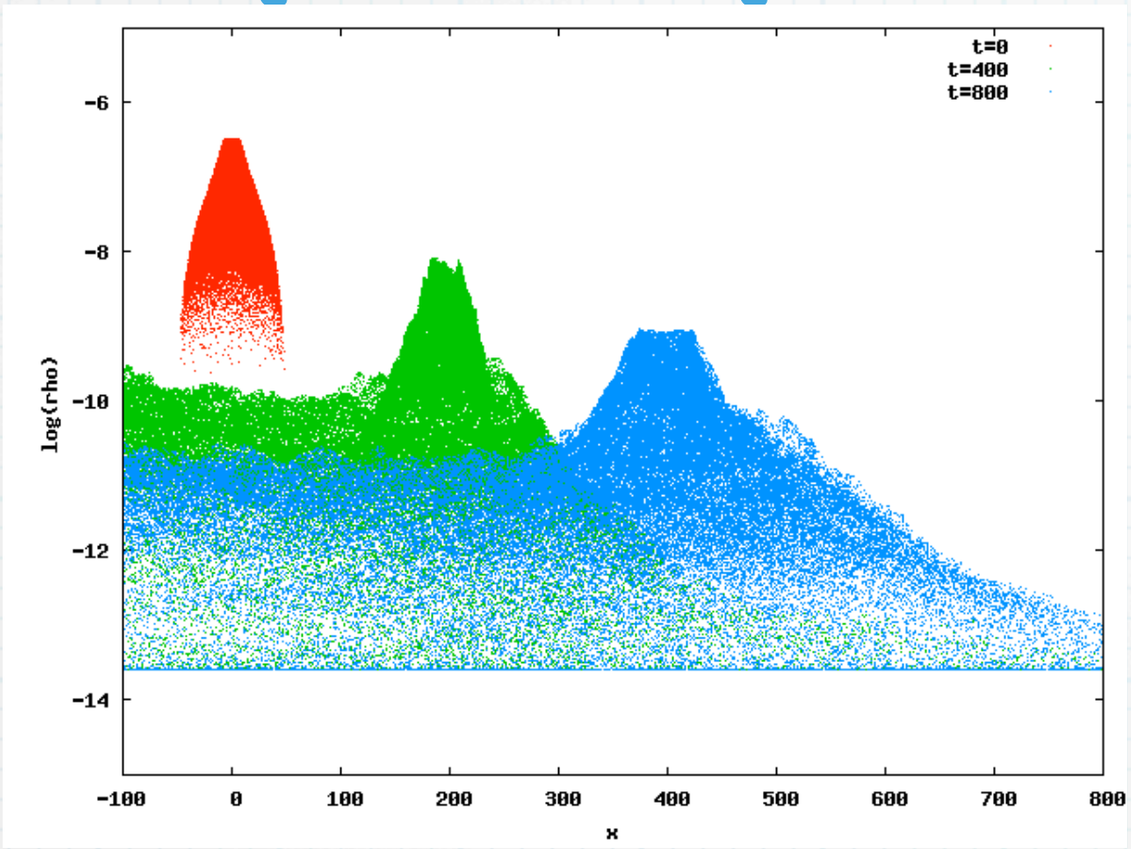


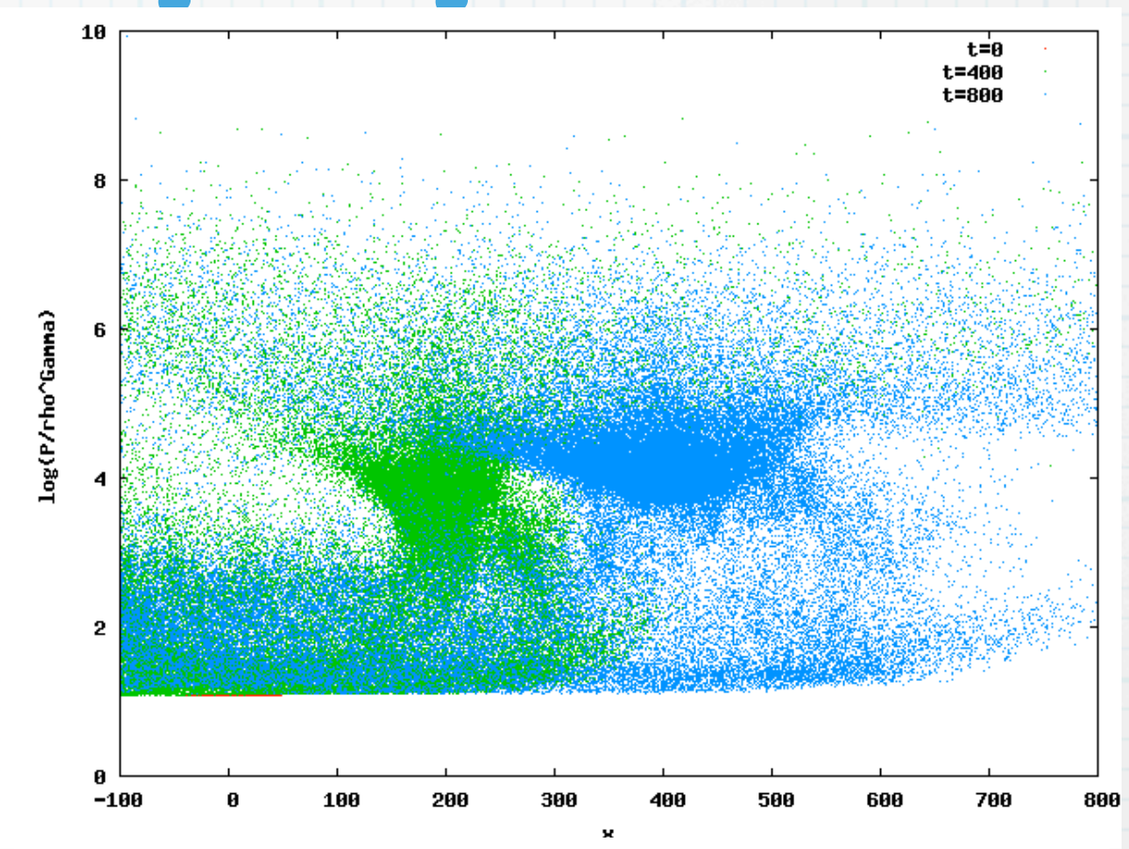


Evolution of a Kicked BH disk



Hydrodynamic properties

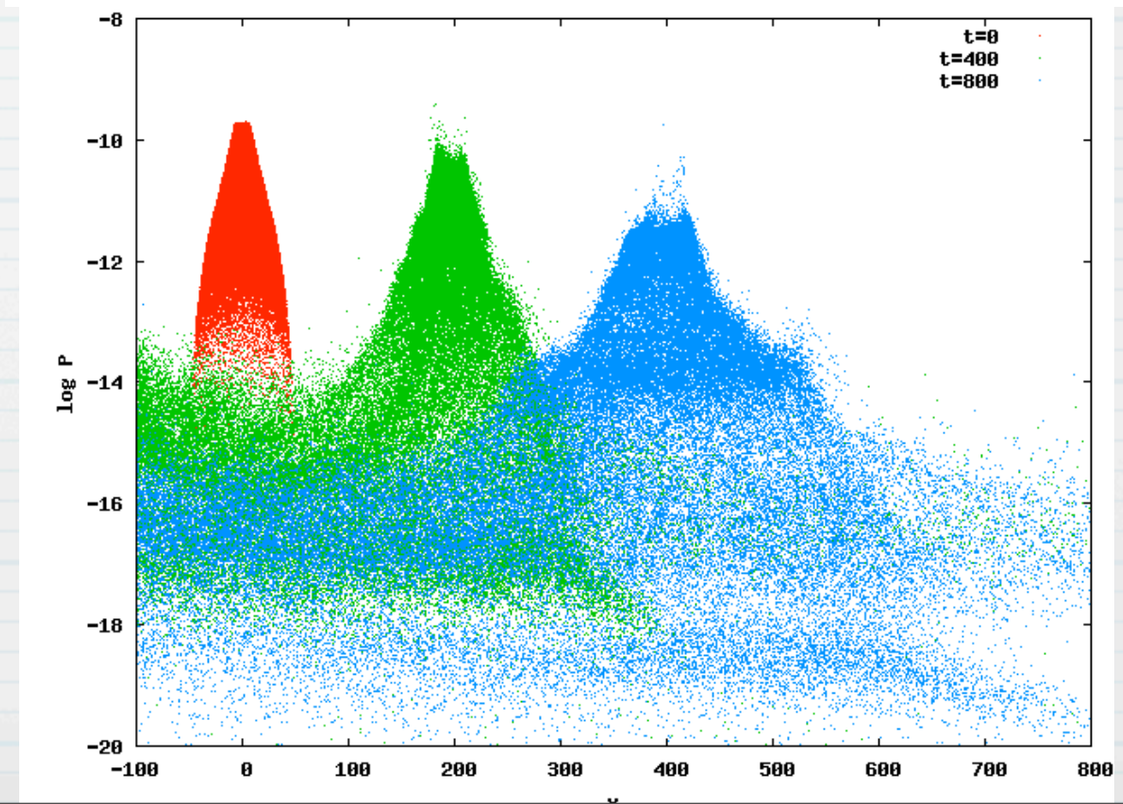




Top Left: $\log_{10} \rho$

Top Right: $\log_{10}(P/\rho^{\Gamma})$

Bottom: $\log_{10} P$



Future Work

* Nearly everything...