From Megaparsecs to Milliparsecs:
Modeling the Environment of a Supermassive Black Hole Host Galaxy

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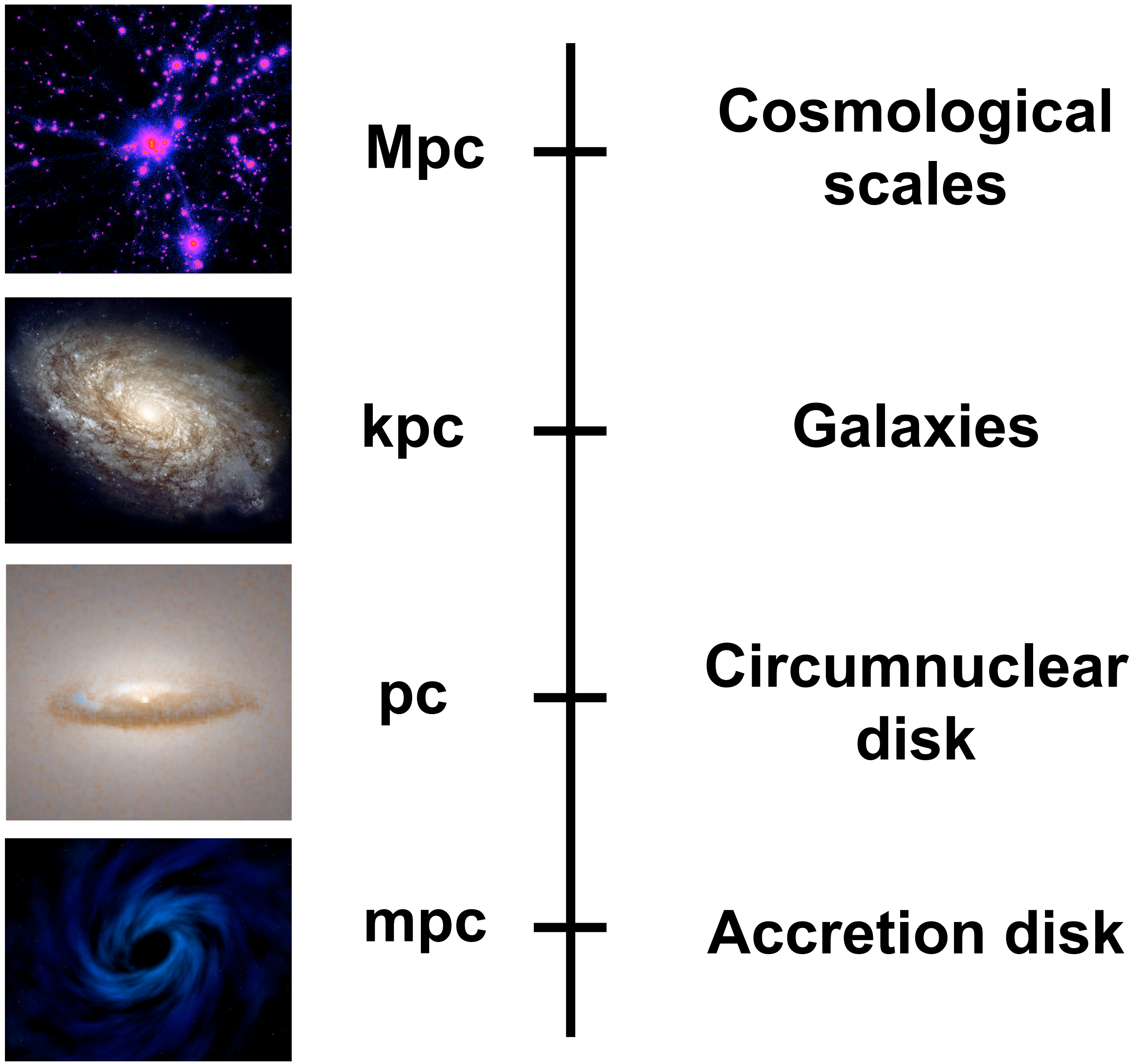
Outline

- Introduction and Motivation - Black Holes and Simulations
- Our Approach
- Properties of the Simulated Galaxy
- Conclusions


Mpc
Cosmological scales
kpc
Galaxies
pc
Circumnuclear disk
mpc
Accretion disk

The Classic Idea:

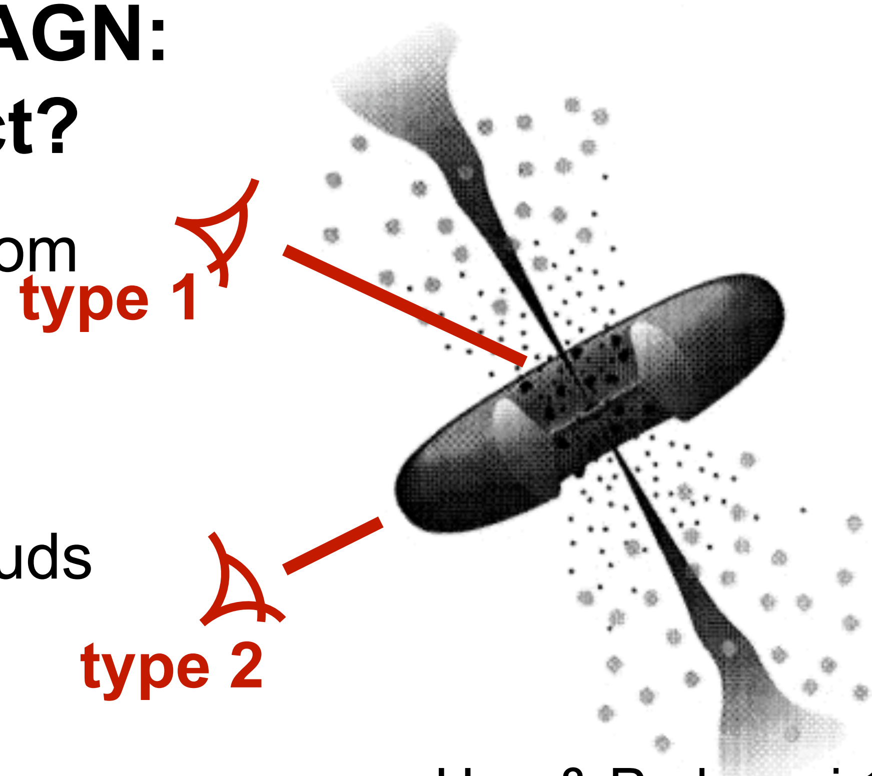
AGN are driven by accreting supermassive black holes.

Different Types of AGN: Orientation Effect?

•AGN - thermal emission from accretion disk

•dusty torus - IR emission

•Broad and Narrow line clouds emit high-excitation lines, close to nucleus



Urry & Padovani 1995

A Modern Interpretation: Unification?

Different types of galaxies, Type I & Type II AGN, ULIRGs, Radio Galaxies, etc. may be different stages of galaxy/supermassive black hole growth & evolution.

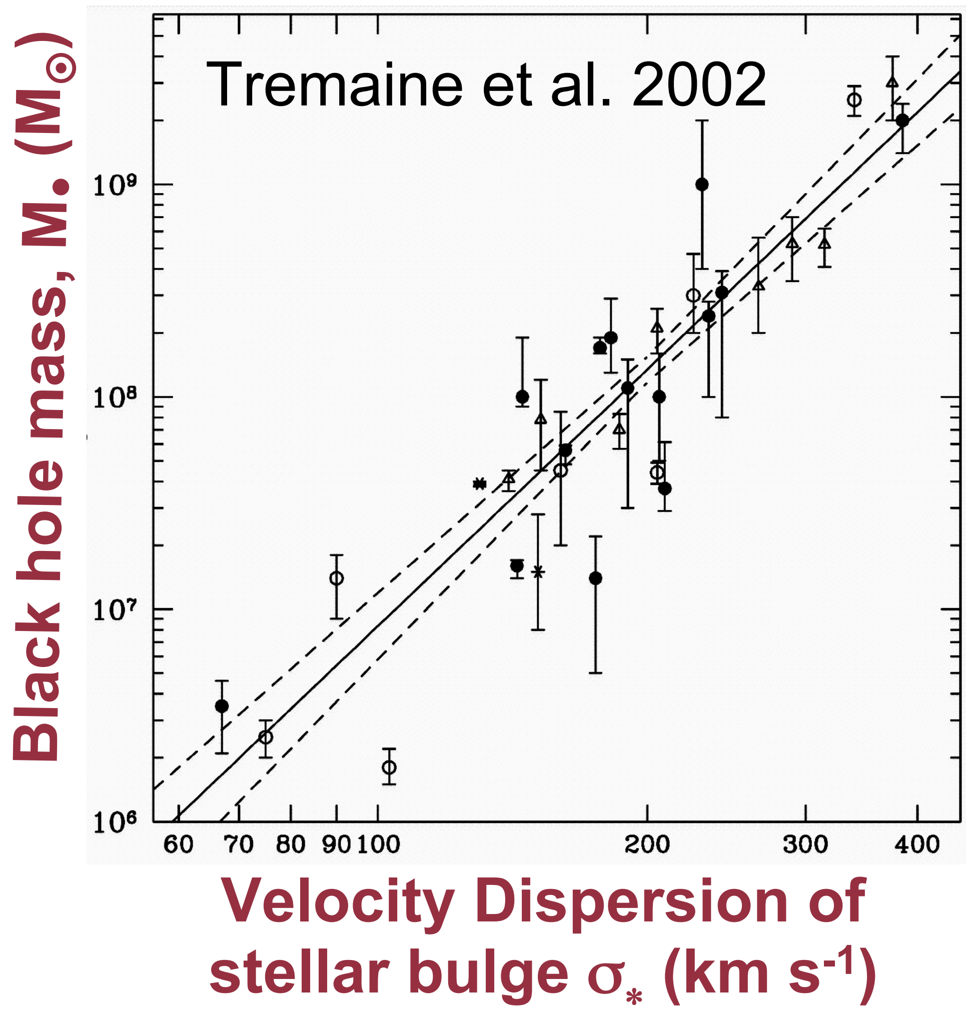
★ AGN feedback traces black hole growth and also plays a potentially important role in galaxy evolution

Supermassive Black Hole & Galaxy Co-Evolution

Properties of the bulge of a galaxy are related to the mass of the supermassive black hole:

e.g. $M_{\bullet}$-σ_{*}, $M_{\bullet}$-M_B relations

How is the black hole connected to the rest of the galaxy?



Understanding Feedback

- AGN play an important role in galaxy evolution
- Amount of energy potentially available in the form of AGN feedback is 10-30 times more than the energy of all SNe
- AGN feedback can influence the distribution of matter on cosmological scales

Therefore, important to understand *AGN fueling:*

How does gas get to sub-pc scales?
How long are fueling episodes?
Is fuel continuously provided?

Fueling Mechanisms

Major Mergers: Large scale gravitational torques drive angular momentum outward, allowing gas to funnel toward the central few hundred pc.

Bar Instabilities: Nested bars in galaxies (gaseous and stellar) can funnel gas inward to tens of pc (e.g. "Bars Within Bars" - Shlosman et al., 1989).

★ Large dynamic range from super-galactic scales to the scale of an AGN accretion disk! $> 10^8$ ★

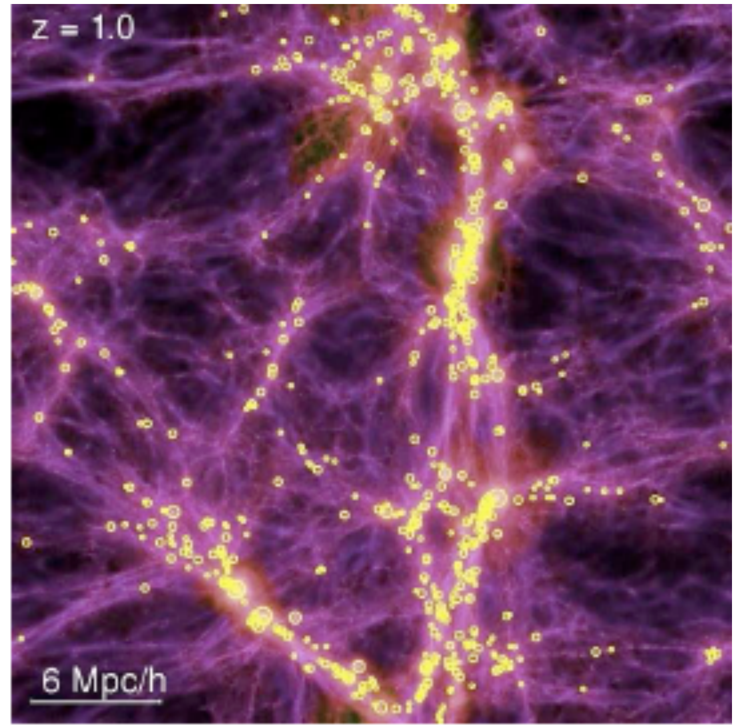
Secular Evolution

- Slow accretion of gas into galaxies (rather than accretion triggered by large dynamical disturbances)?
- Internal evolution, slowly driven by instabilities, waves, etc.
  - build “pseudo-bulges”
  - maintain star formation
  - feed supermassive black holes
- More important at low-*z*?

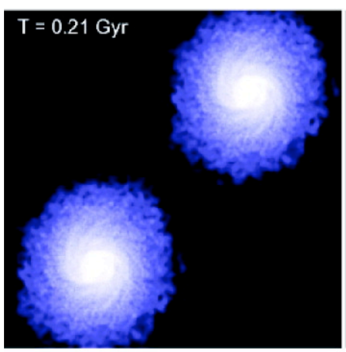
Large Scale Cosmological Simulations

Follow mergers and include prescriptions for feedback in order to reproduce

- black hole demographics
- global properties of galaxies (black hole-bulge relations, colors, etc…)

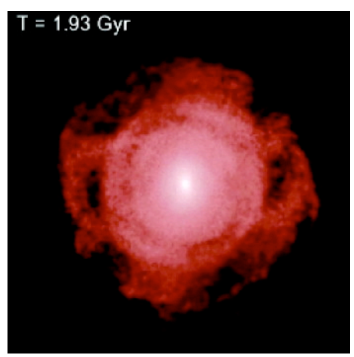


Black Hole population in cosmological simulation of Di Matteo et al. (2007) at z=1



simulated merger

Hopkins et al. 2007



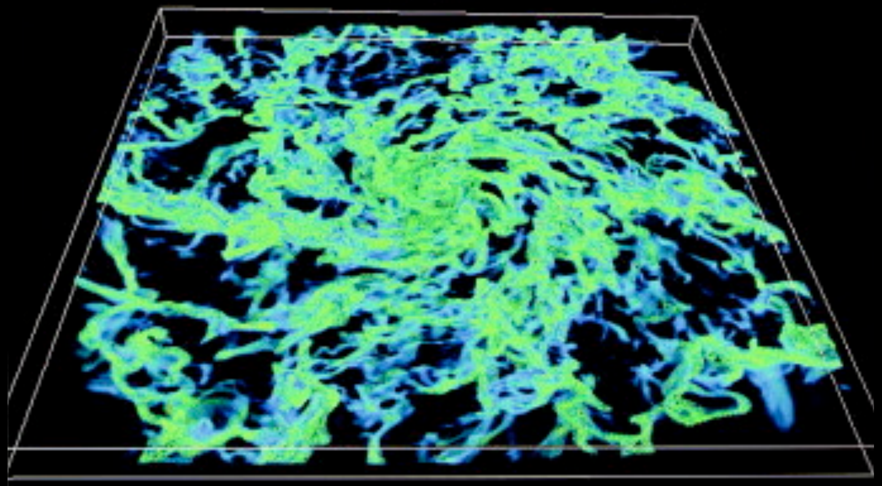
Galaxy scale simulations (central kpc and smaller)

e.g. Wada 2001, Escala 2007

•Multi-phase, super-sonic, turbulent ISM

•self-gravitating disks (responsible for filamentary structure) →

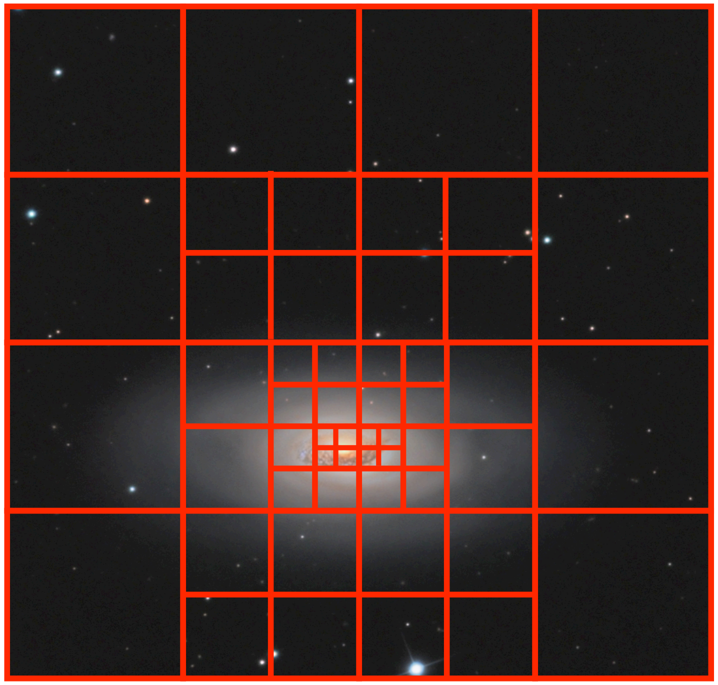
Density distribution in ISM of a simulated galaxy



↔ 256 pc

Adaptive Refinement Tree code

- Gas hydrodynamics on an **adaptive mesh**, allowing large dynamic range ($> 10^8$)
- Includes dark matter and stellar particles



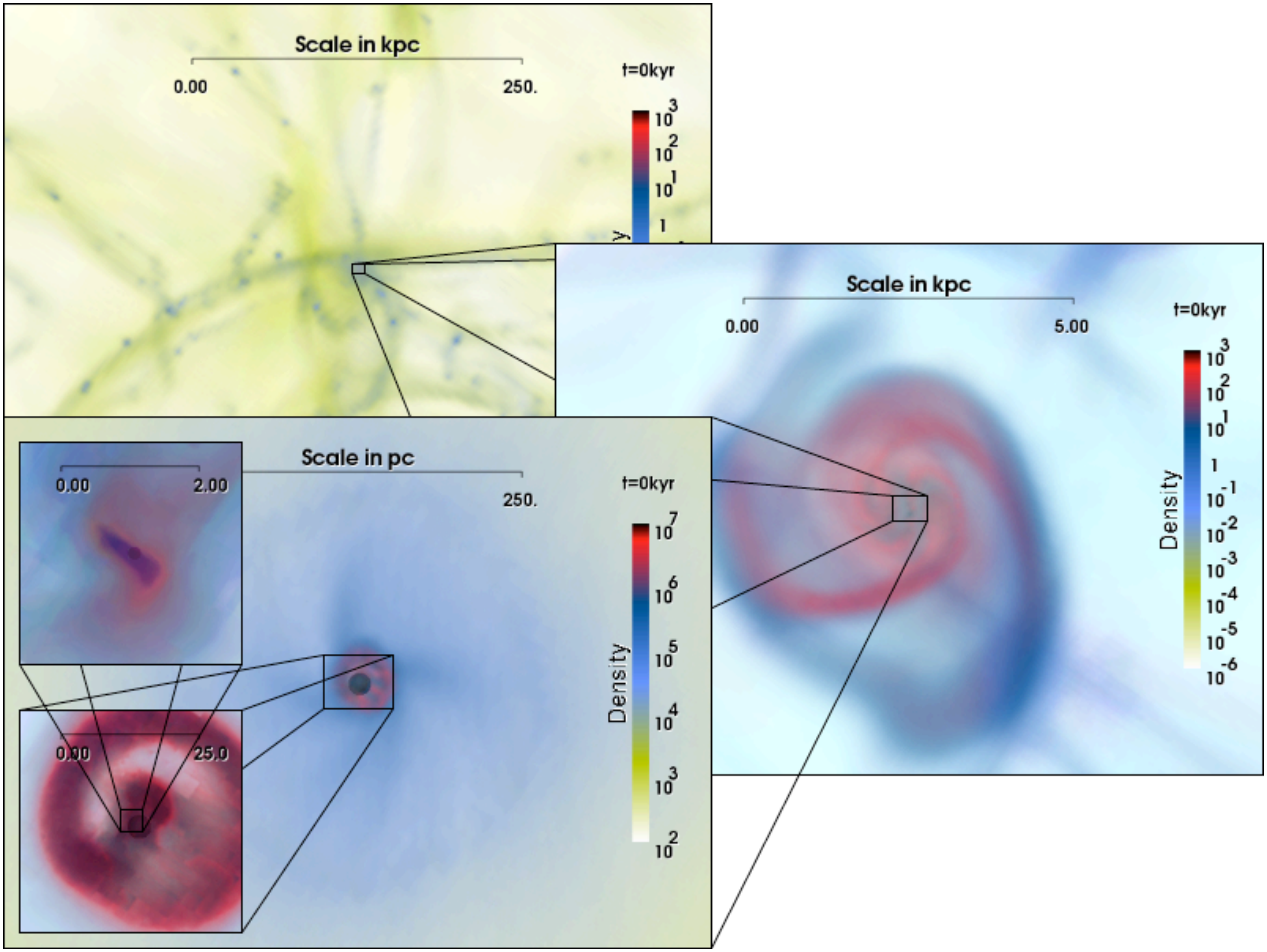
- Observationally motivated star formation rate
- Gas cooling by heavy elements and dust

Zooming-In

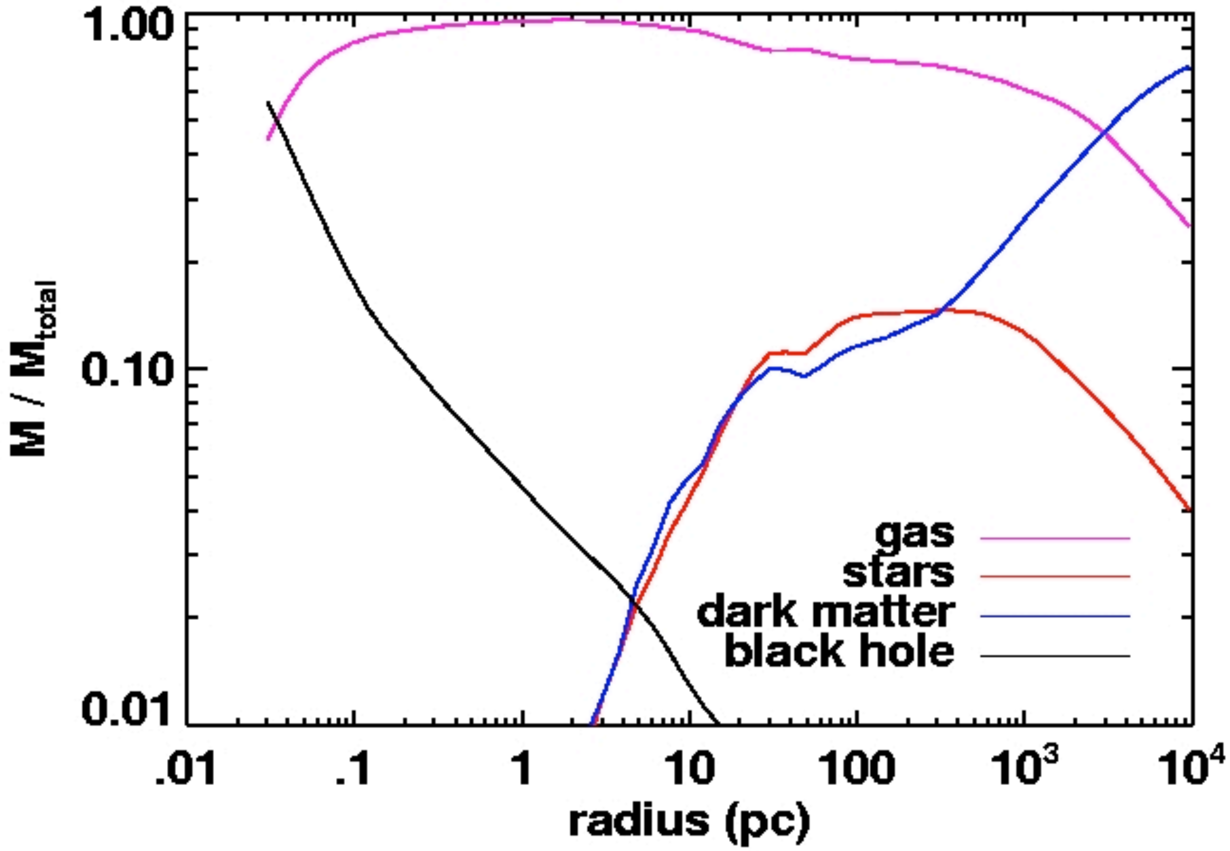
1. Begin with cosmological simulation containing a typical galaxy
2. Increase maximum resolution one level at a time, reaching quasi-steady state on each level before moving to the next
3. After reaching maximum resolution, replace fraction of gas in center with black hole particle
4. Continue evolution for several hundred thousand years

box size…………..**6 h^{-1} Mpc**
initial resolution…**50 pc** (9 levels refinement)
final resolution…. **0.03 pc** (20 levels refinement)
black hole mass...**3×10^7 $M_\odot$**

From Mega-pc to milli-pc

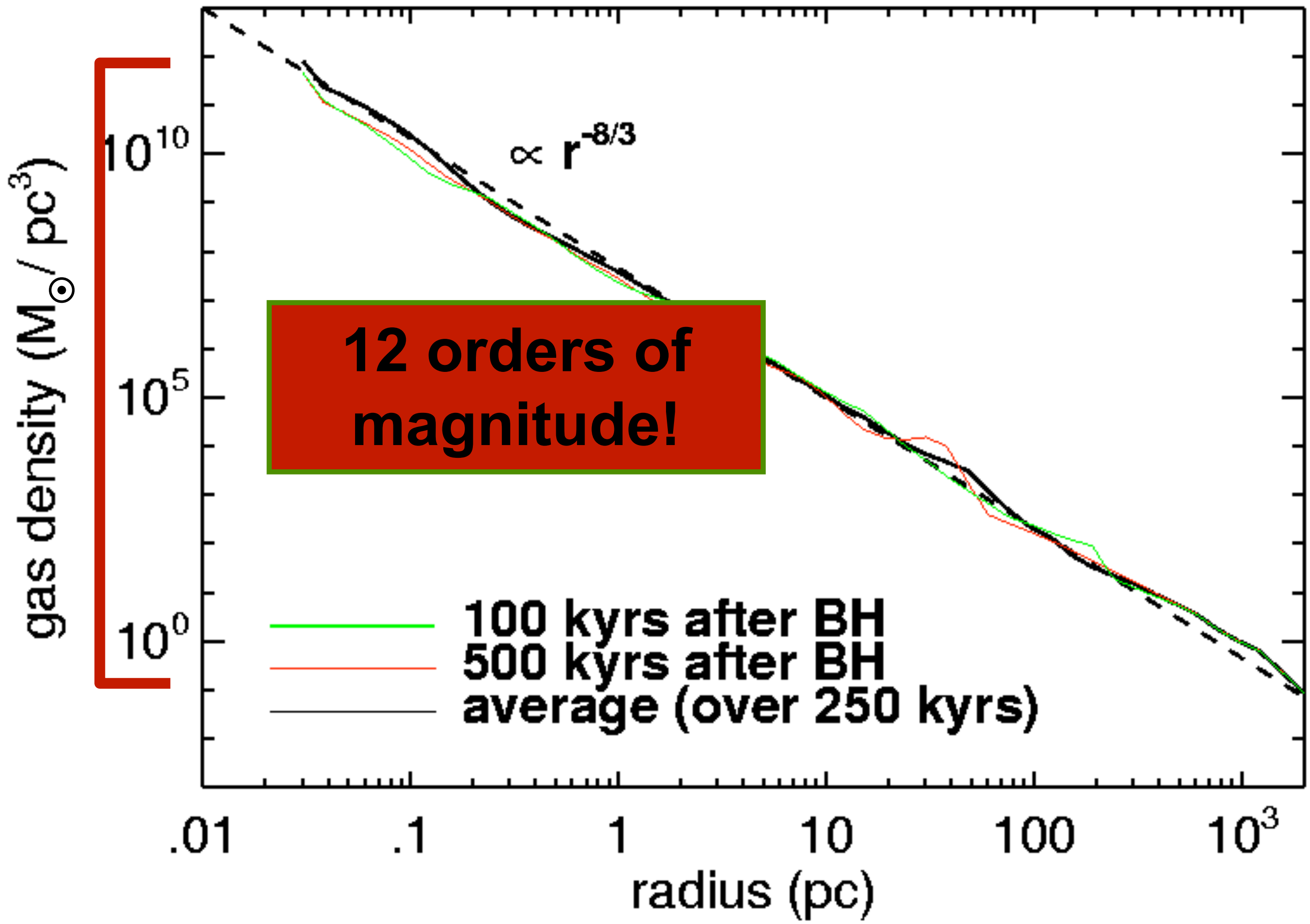


Galactic Structure



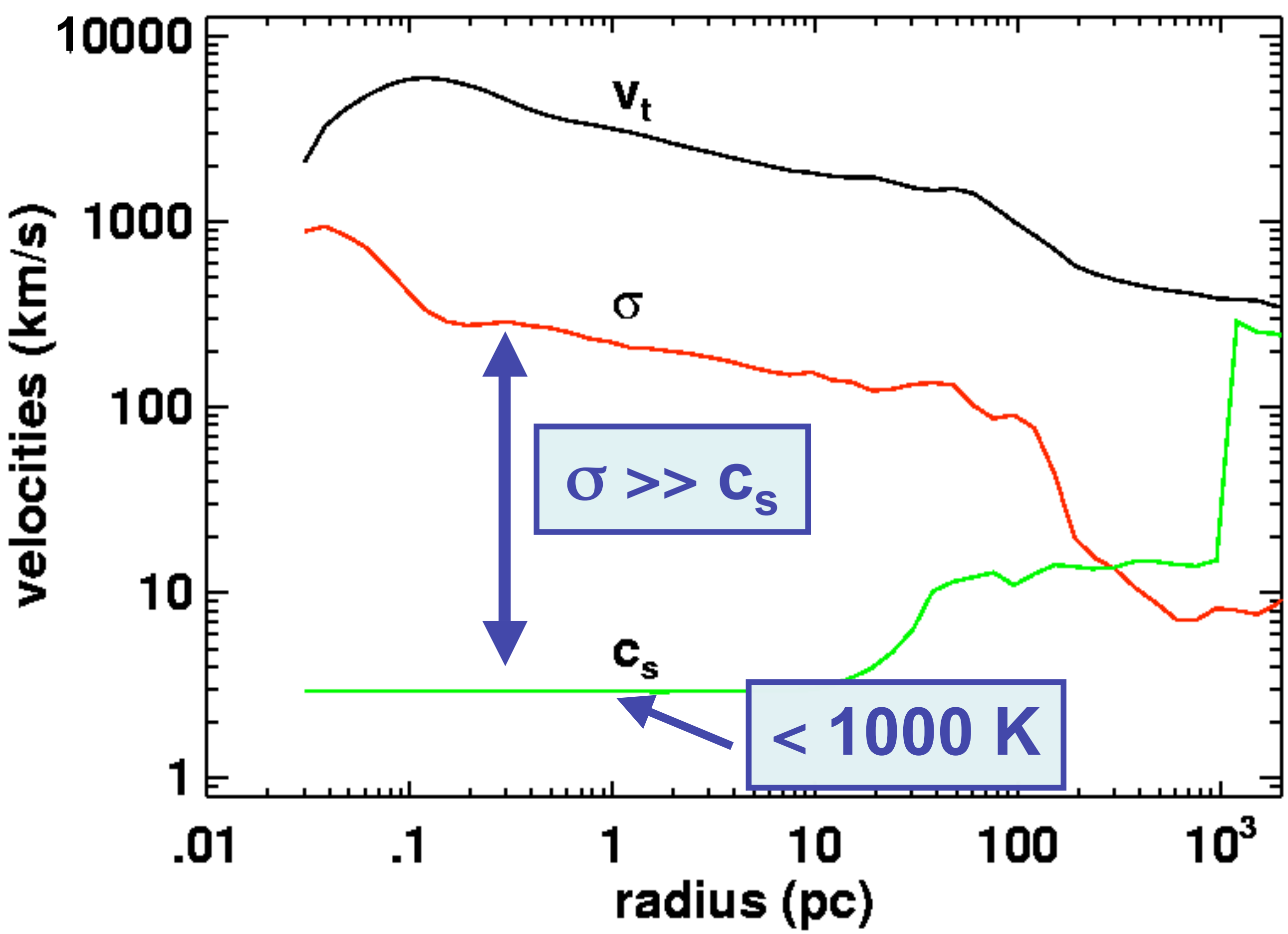
thin gas disk dominates gravity in the circumnuclear region

Galactic Structure



Galactic Structure

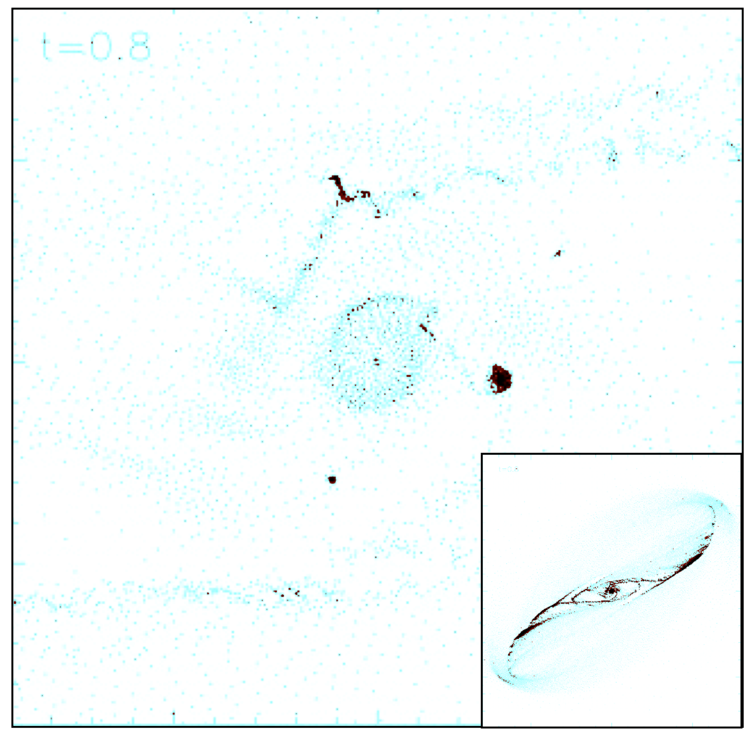
Super-sonic, cold, molecular gas disk



Instabilities

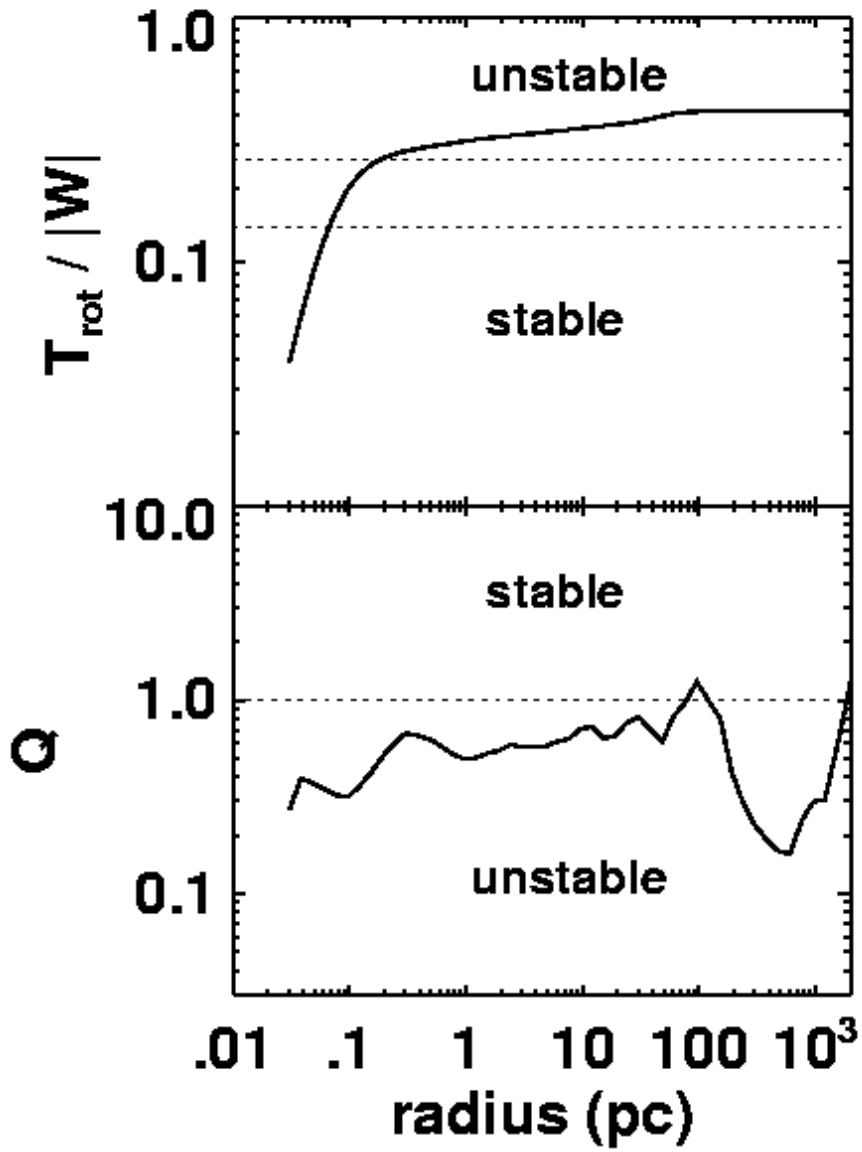
Self-gravitating, cold, rotationally dominated disks are susceptible to fragmentation.

- **bar, or other global non-axisymmetric instabilities**
- **spiral waves**
- **local instabilities and gravitational collapse**



Fukuda, Habe, & Wada 2000

Instabilities



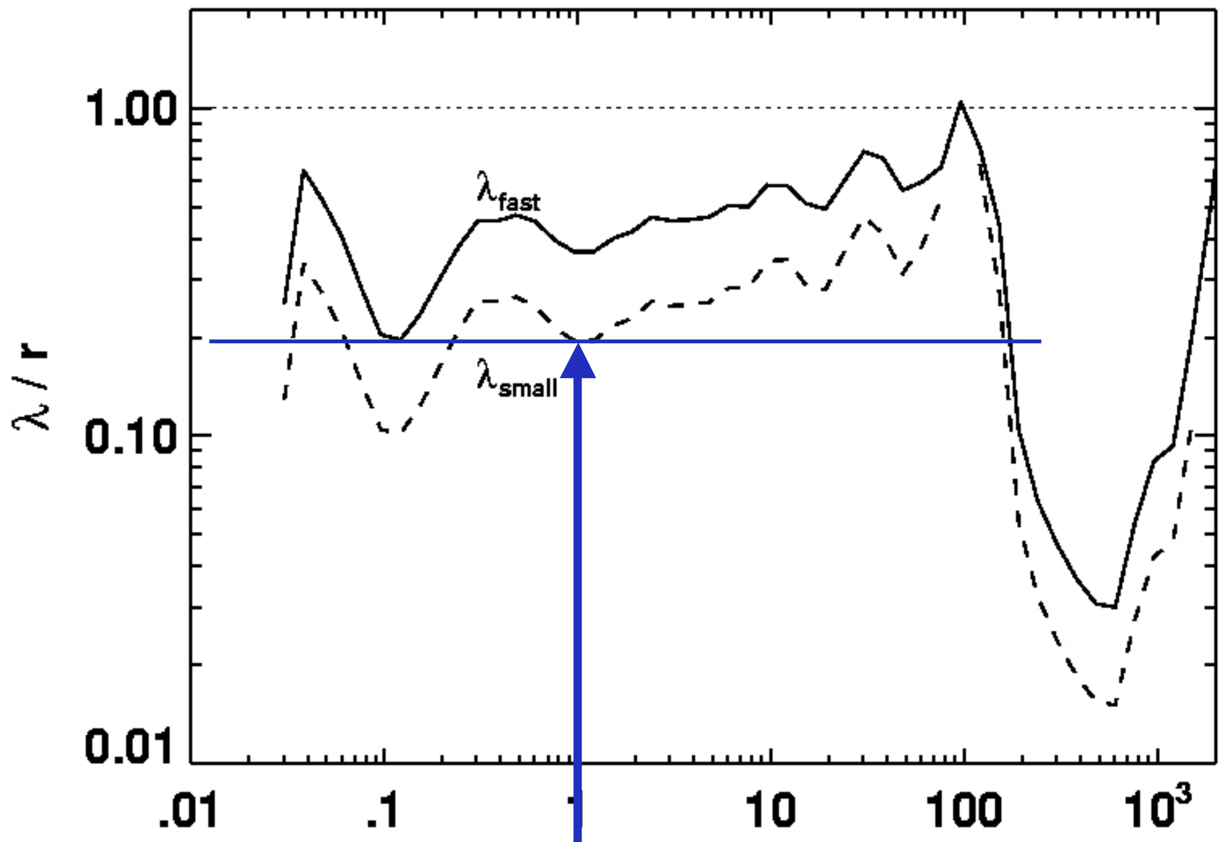
Global Instability - Rotational kinetic energy, T_{rot}, increases relative to potential energy of disk, **W**

Linear Instability - Toomre-**Q** parameter describes stability against axisymmetric perturbations in the disk

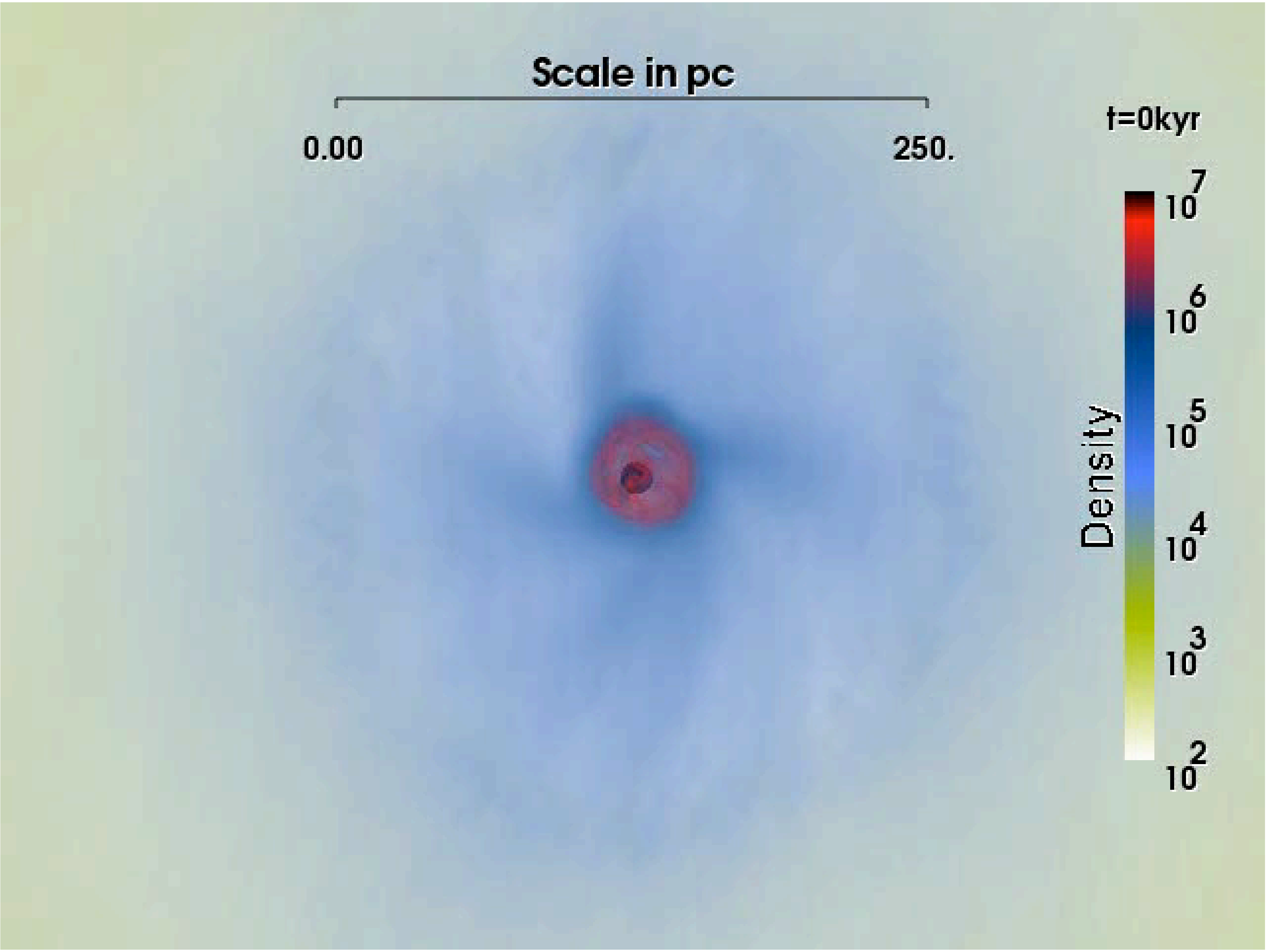
Scales

Where Q < 1, the scale of the instability can be estimated by

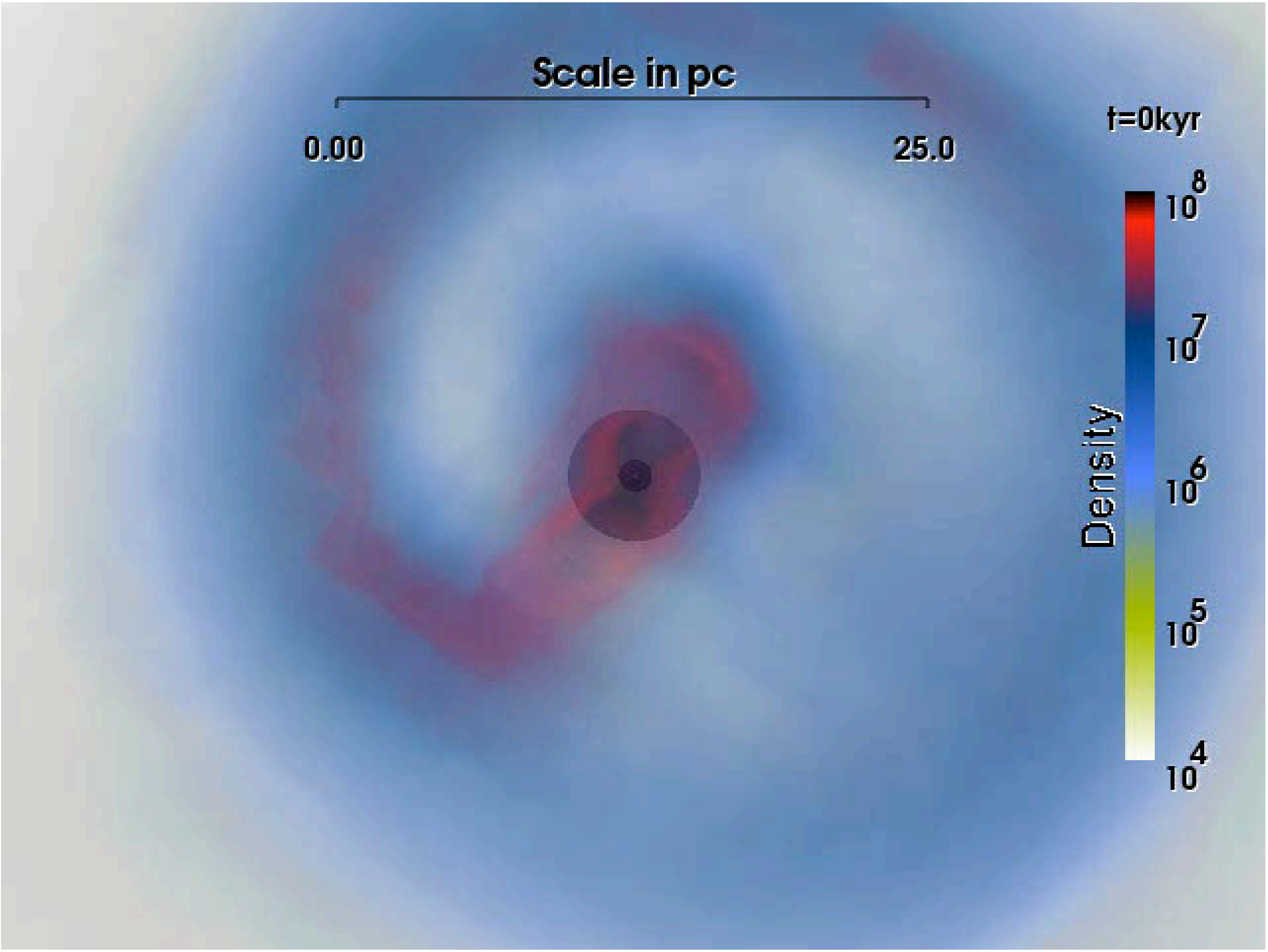
- the fastest growing, or most unstable mode, λ_{fast}
- the smallest scale on which the disk is unstable, λ_{small}



The disk is unstable on scales which are an appreciable fraction of the size of the system!

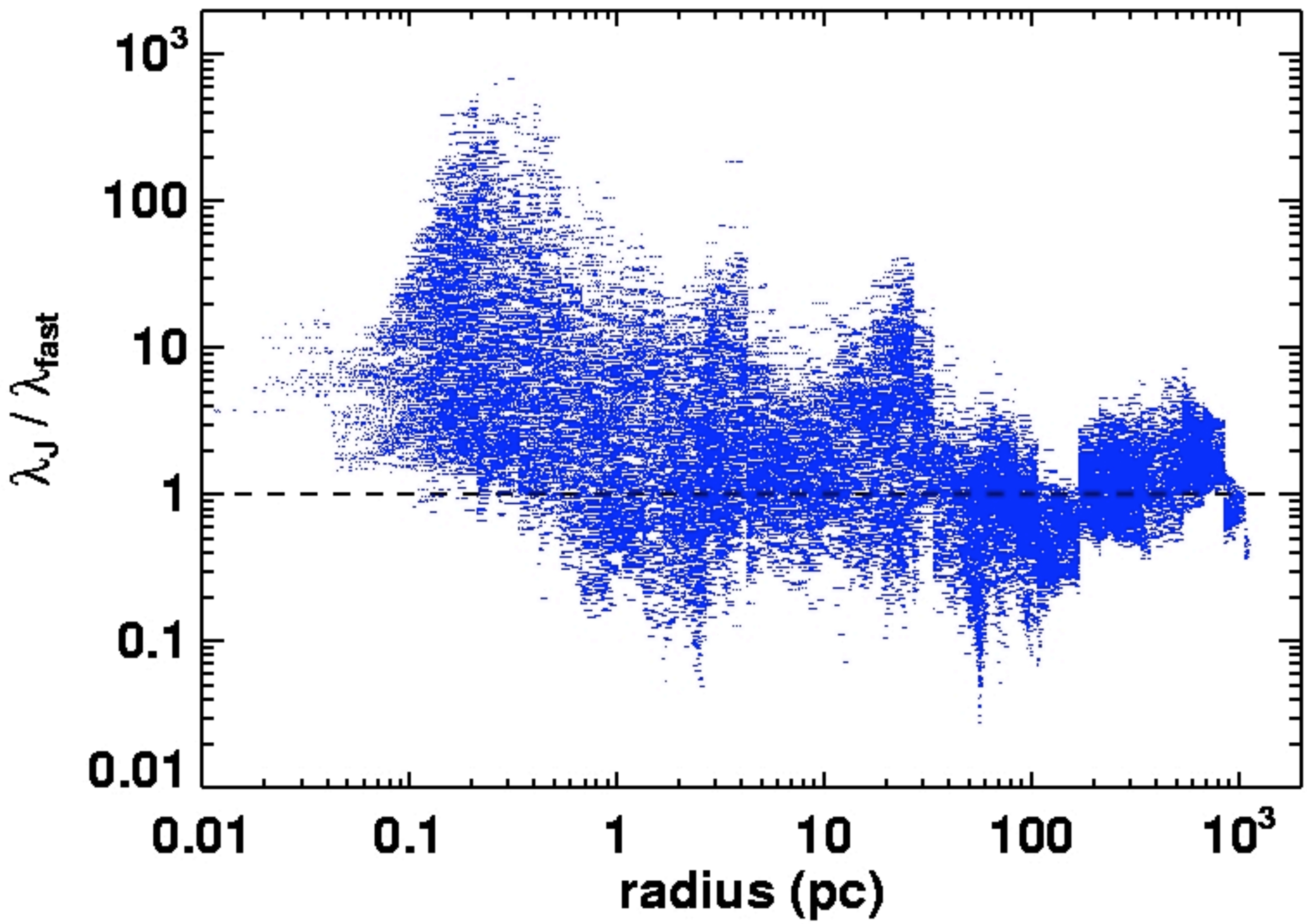


Scale in pc
0.00
250.
t=0kyr
Density
10^7
10^6
10^5
10^4
10^3
10^2



Scale in pc
0.00
25.0
t=0kyr
Density
10^8
10^7
10^6
10^5
10^4

Scales



Jeans scale comparable to λ_{fast} ➔
No widespread burst of star formation!

An Analytic Description

For an azimuthally symmetric, thin, viscous disk (Pringle 1981)

$$\frac{\partial}{\partial t}(J_{\rm z}) + \frac{1}{R}\frac{\partial}{\partial R}(R v_{\rm R} J_z) = \frac{1}{2\pi R}\frac{\partial G}{\partial R}$$

describes advection of an
momentum through the disk

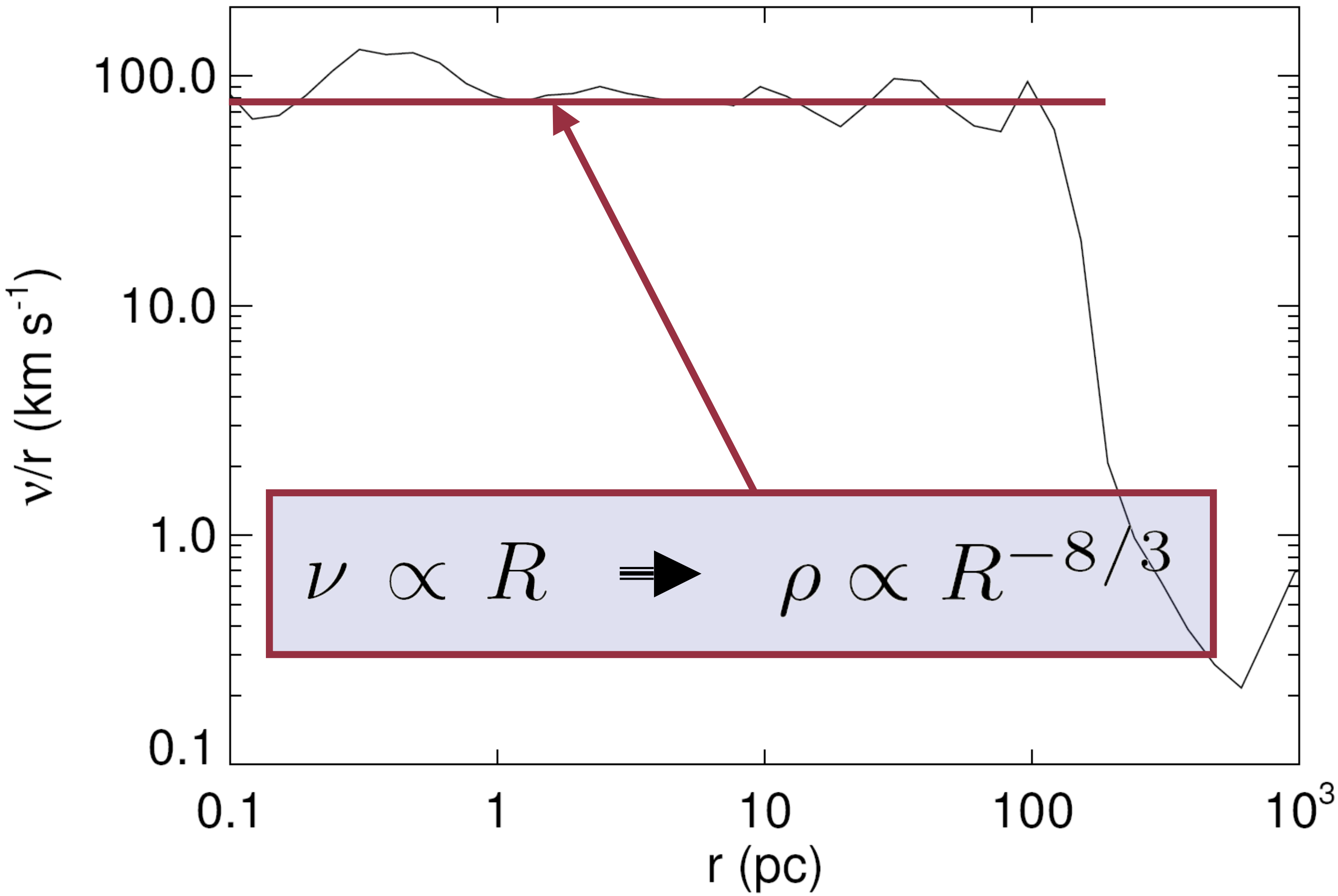
viscous torque term

$$G(R,t) = 2\pi\nu\Sigma R^3 \frac{\partial \Omega}{\partial R}$$

Torque, *G*, necessarily vanishes in case of solid body rotation

An Analytic Description

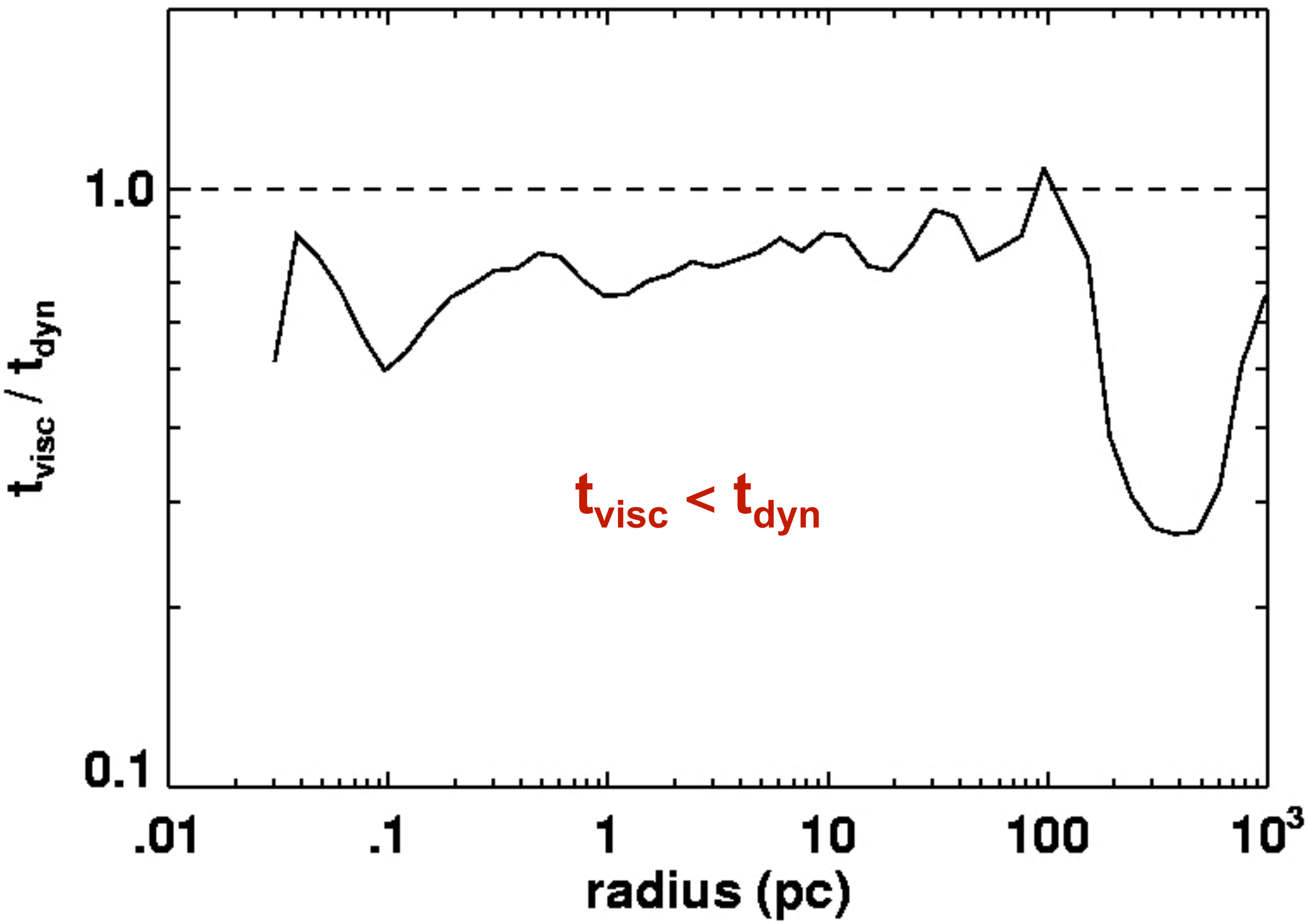
Turbulent Viscosity $\nu \sim \sigma_t \lambda_{fast}$



Summary

- The gas-dominated, self-gravitating disk reaches a ***quasi-stationary state***, following a ***power-law density profile*** $\propto r^{-8/3}$
- Disk is ***unstable on global scales***, but is locally stable and ***does not fragment into stars***
- Super-sonic, turbulent transport of angular momentum may help funnel gas toward the center (to feed the AGN)

Viscous Timescale



Angular Momentum Conservation