

# How do Black Holes Get Their Gas?

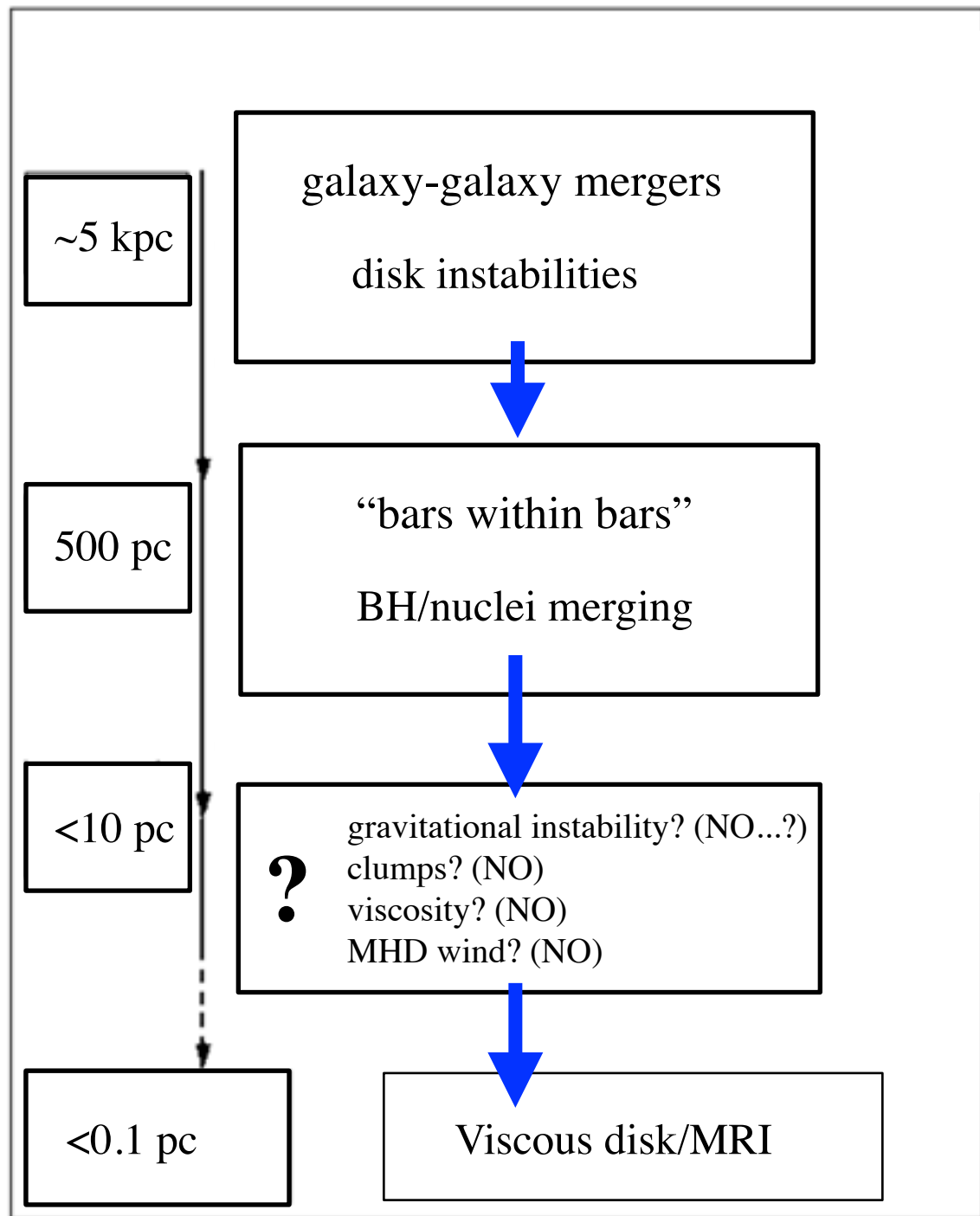


Philip Hopkins

Eliot Quataert, Lars Hernquist, T. J. Cox, Kevin Bundy, Jackson DeBuhr,  
Volker Springel, Dusan Keres, Gordon Richards, Josh Younger,  
Desika Narayanan, Paul Martini, Adam Lidz, Tiziana Di Matteo, Yuexing Li,  
Alison Coil, Adam Myers, Patrik Jonsson, Chris Hayward

- Focus: Most luminous QSOs  
( $\sim 1\text{-}10 M_{\text{sun}}/\text{yr}$ )

- ‘Bottleneck’ at  
<10-50pc: BH begins  
to dominate the potential  
(e.g. Goodman et al.,  
Jogee et al., Martini et al.)



- Galaxy merger: good way to get lots of gas to small scales!
- *If* BHs trace spheroids, then  
\*most\* mass added in violent events that also build bulges

Komossa

- Problem:  
Scale of merger:  $\sim 100$  kpc  
Viscous disk:  $\sim 0.1$  pc
- Solution 1: simple prescription
- Solution 2: re-simulate  
 (“zoom in”) and see what happens!

Komossa

# Simulations:

FOLLOWING THE GAS IN...

- Here: Focus on *robust* conclusions

# Simulations:

## FOLLOWING THE GAS IN...

- Need to include:
- Here: Focus on *robust* conclusions

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- Need to include:
  - Gas+Stars
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# Simulations:

## FOLLOWING THE GAS IN...

- Need to include:
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  - Self-gravity!
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# Simulations:

## FOLLOWING THE GAS IN...

- Need to include:
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  - Self-gravity!
  - Cooling
- Here: Focus on *robust* conclusions

# Simulations:

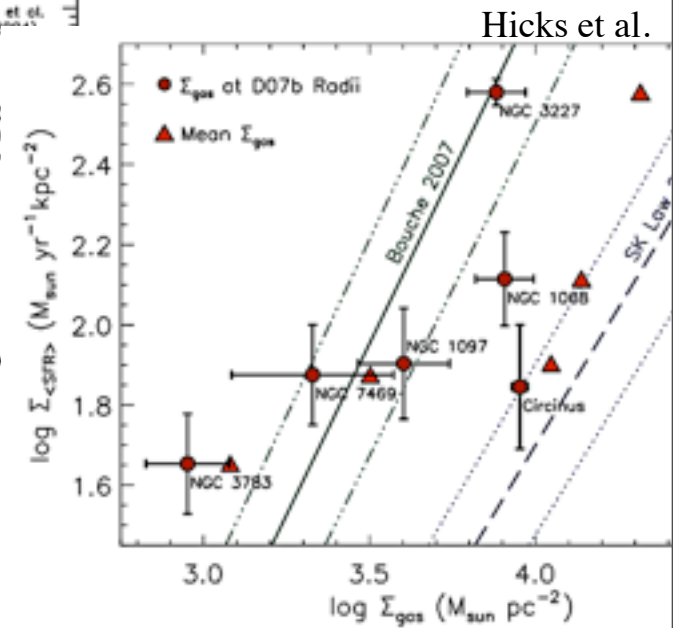
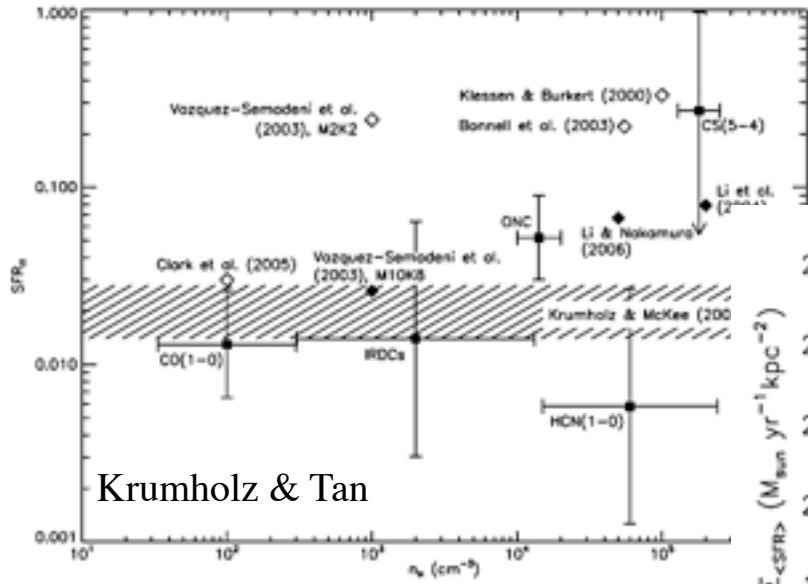
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- Need to include:
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  - Star formation
  
- Here: Focus on *robust* conclusions

Simulations:

FOLLOWING THE GAS IN...

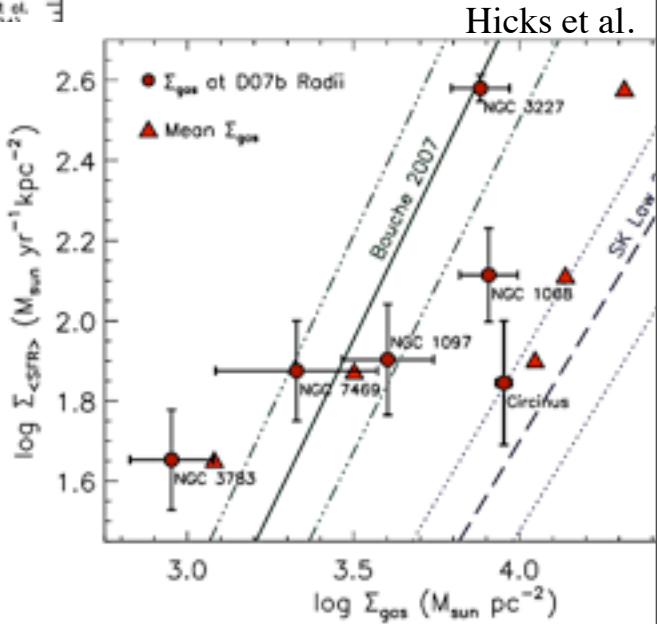
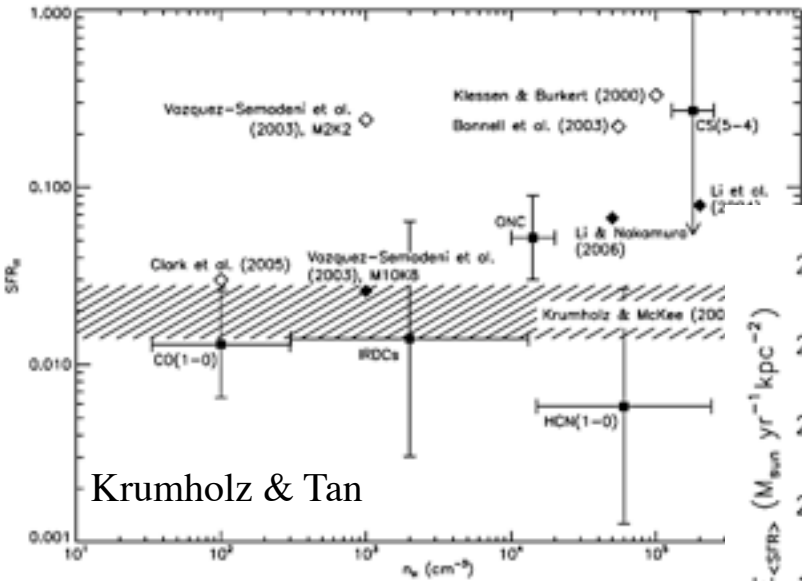
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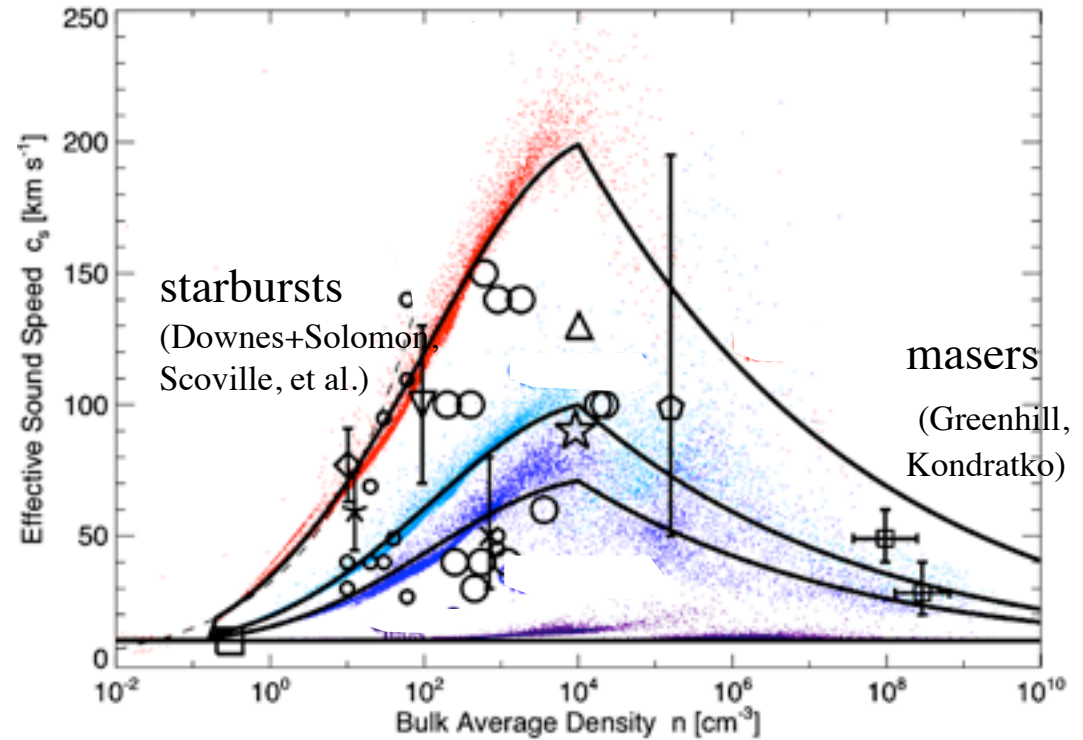
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- ‘Feedback’
  - Admit we don’t understand it!
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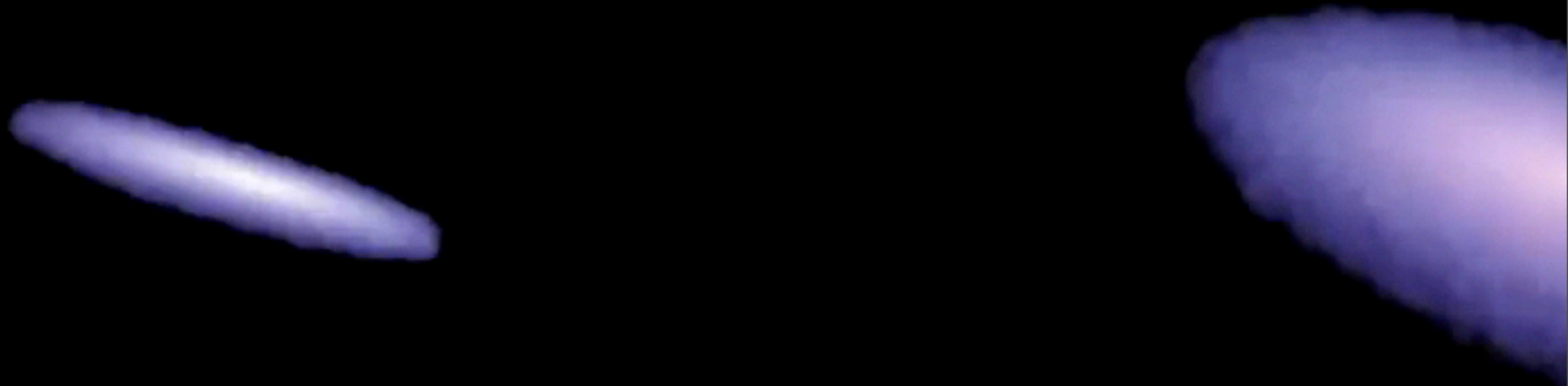
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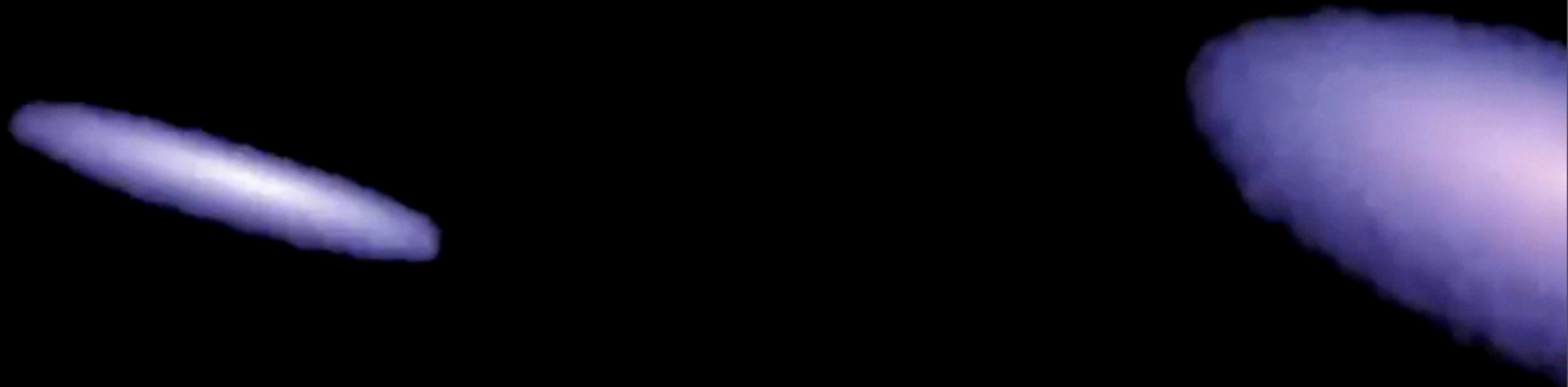
T = 0 Myr

Gas



T = 0 Myr

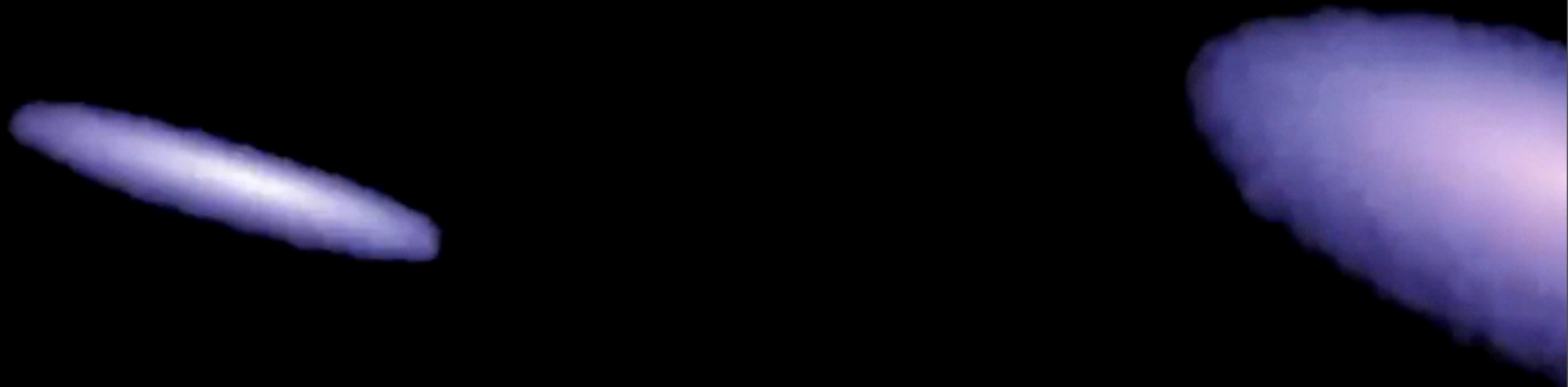
Gas



Tidal torques  $\Rightarrow$  large, rapid gas inflows (e.g. Barnes & Hernquist 1991)

T = 0 Myr

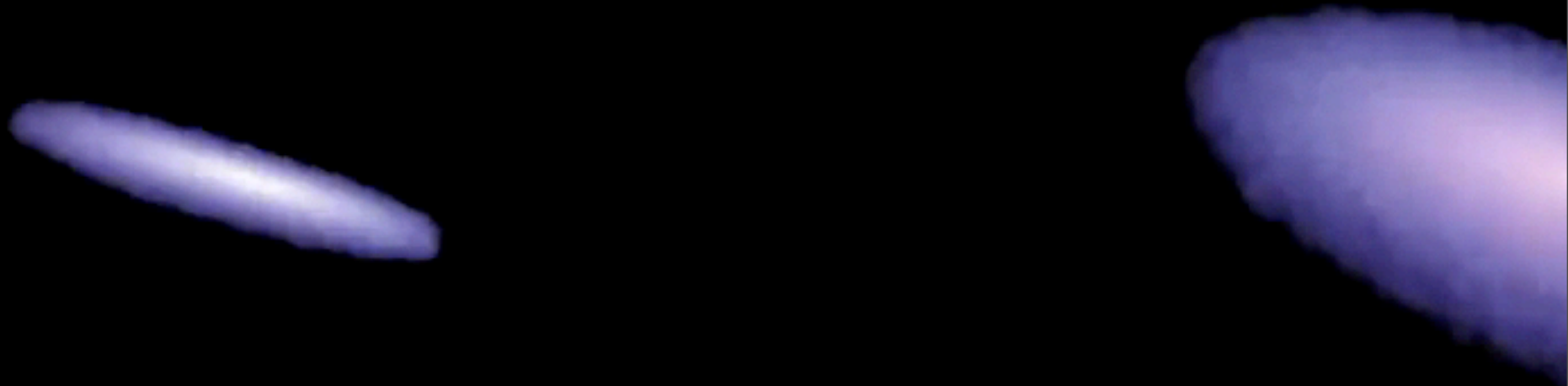
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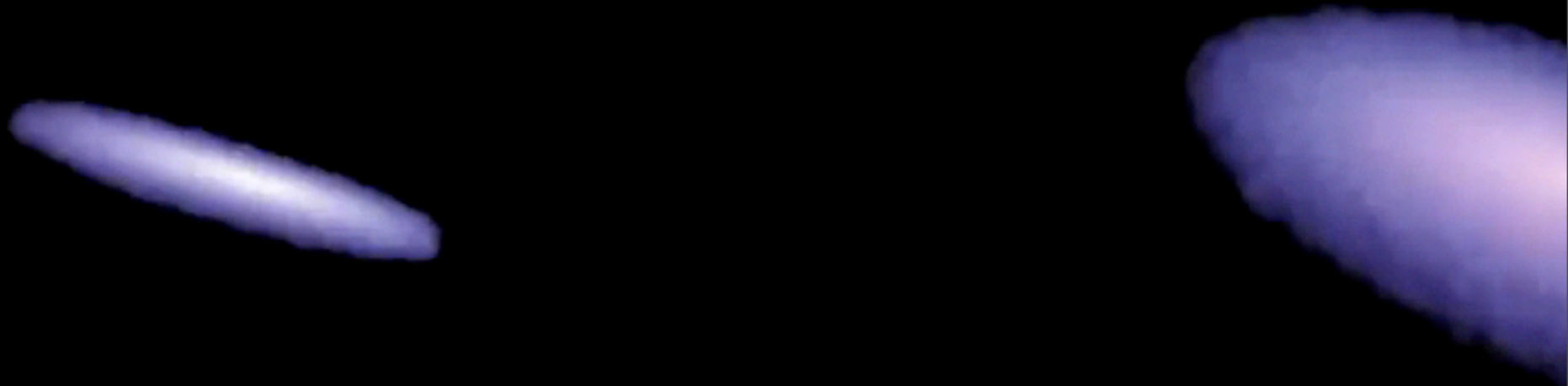
Gas



Triggers Starbursts (e.g. Mihos & Hernquist 1996)

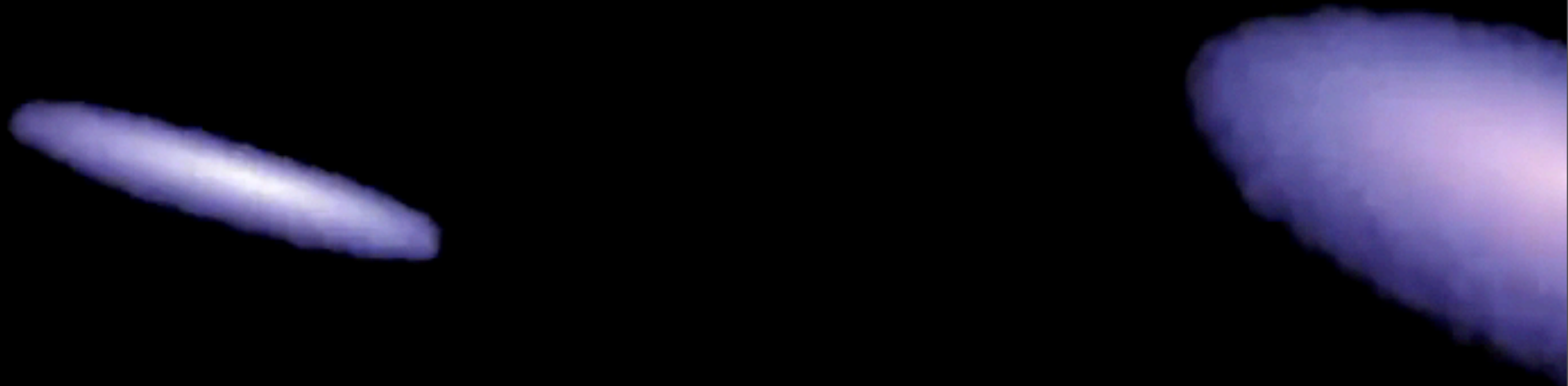
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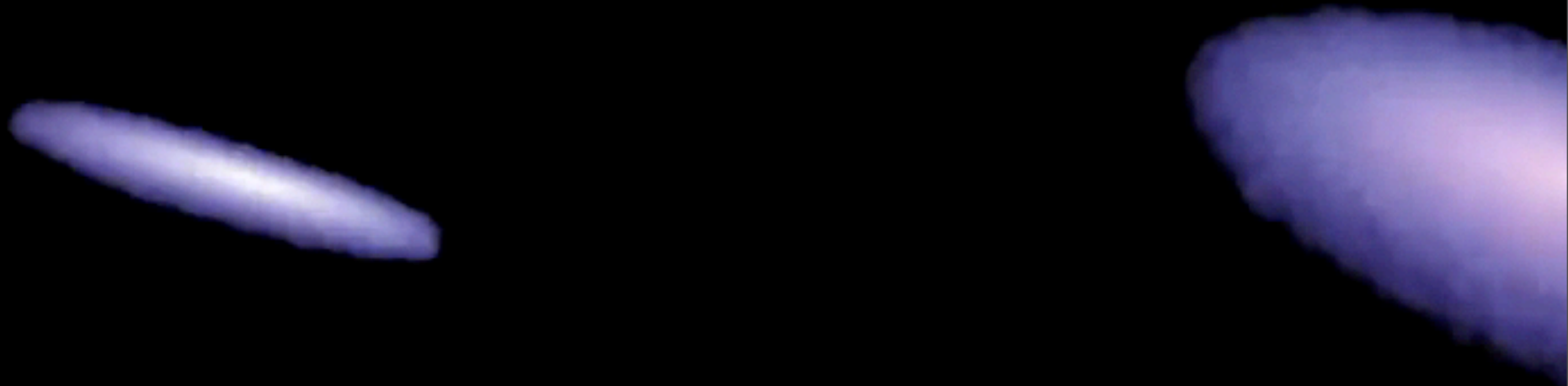
Gas



Fuels Rapid BH Growth?  
(e.g. Di Matteo et al., PFH et al. 2005)

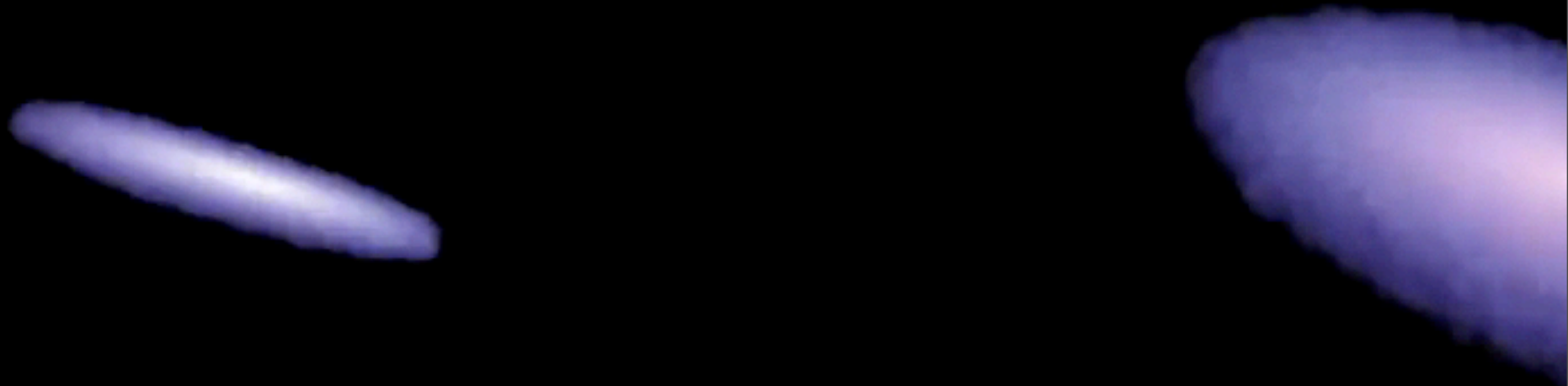
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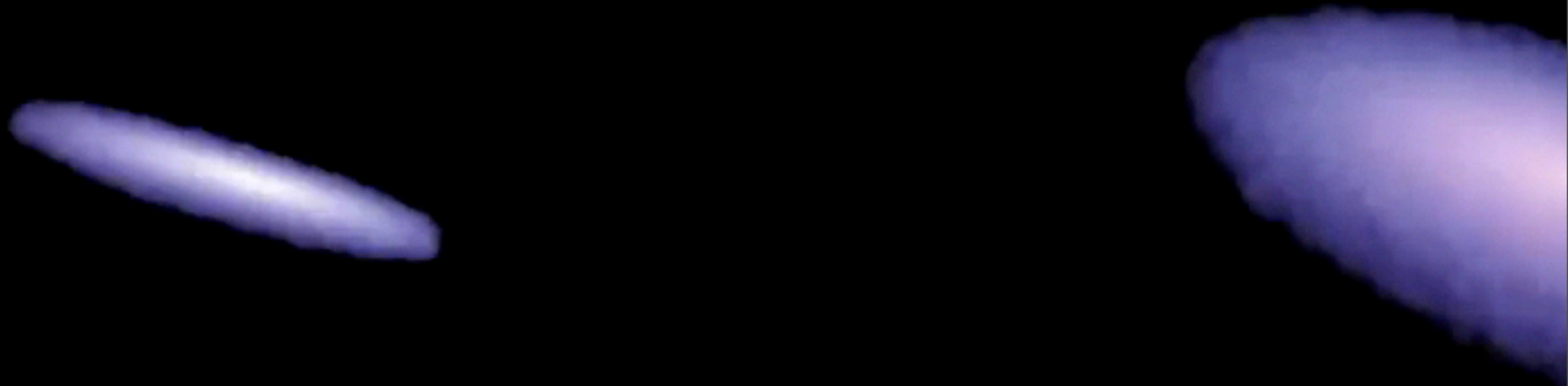
Gas



Large-scale simulation:  
follow gas to sub-kpc scales

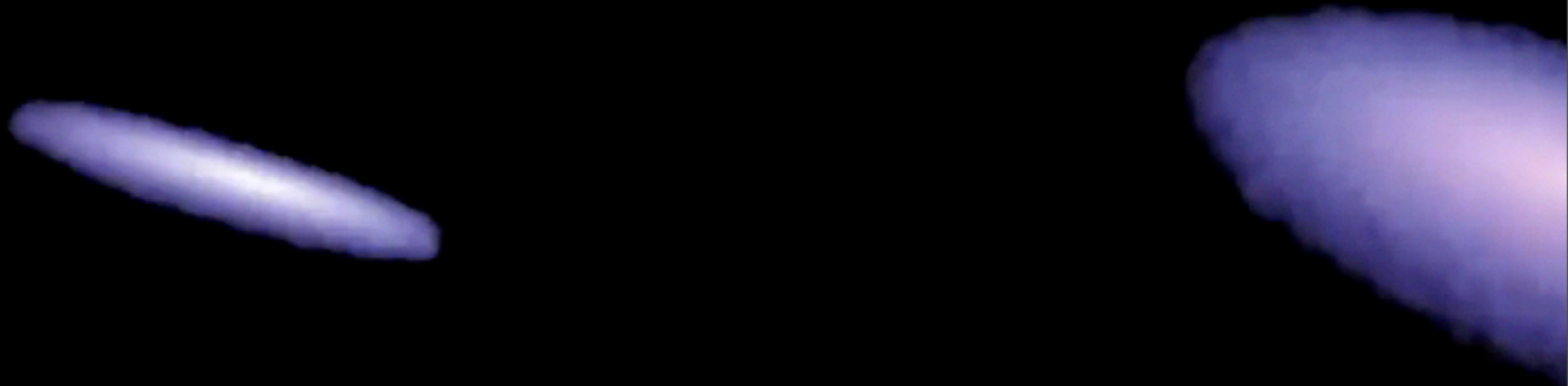
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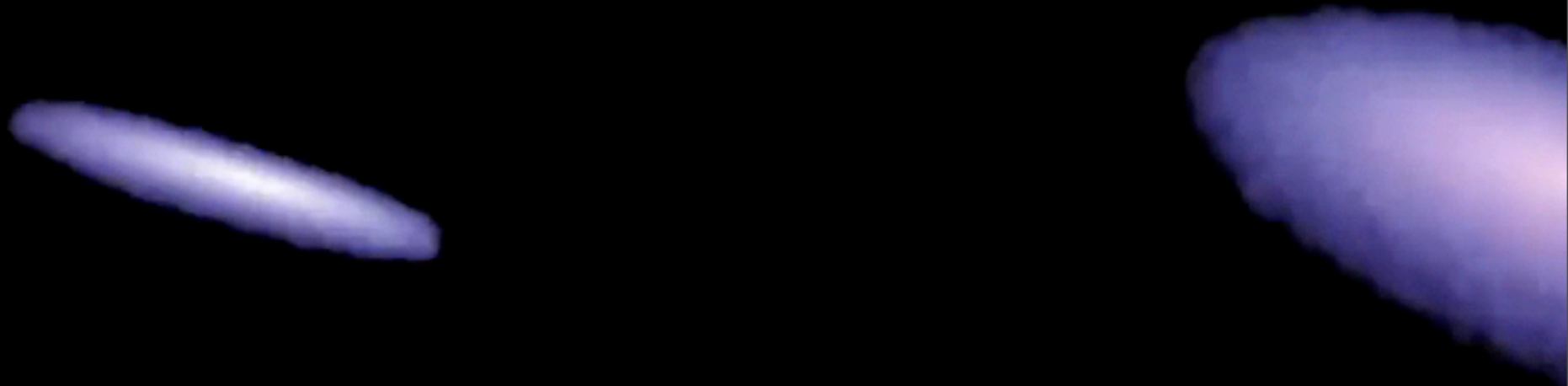
T = 0 Myr

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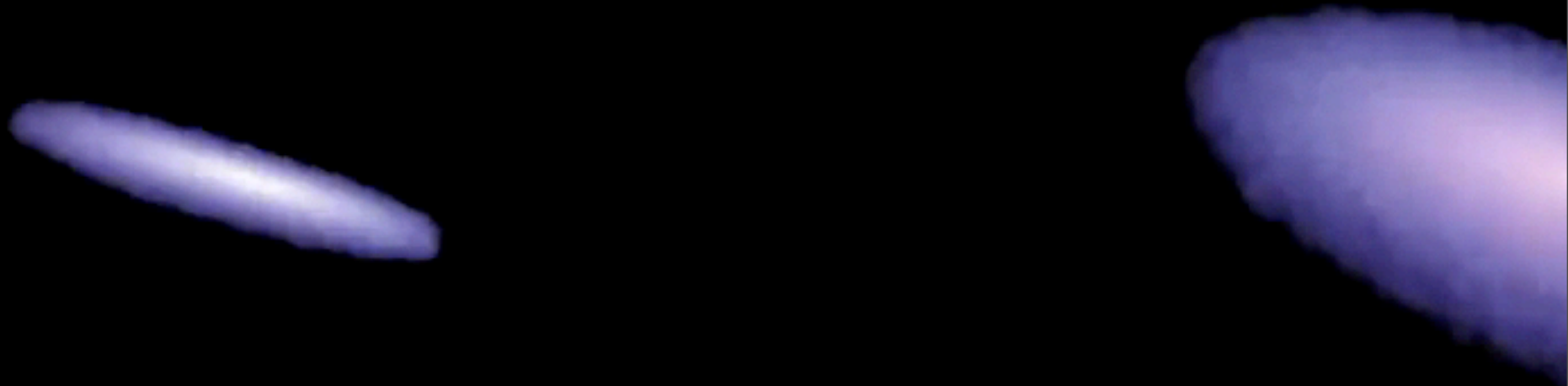
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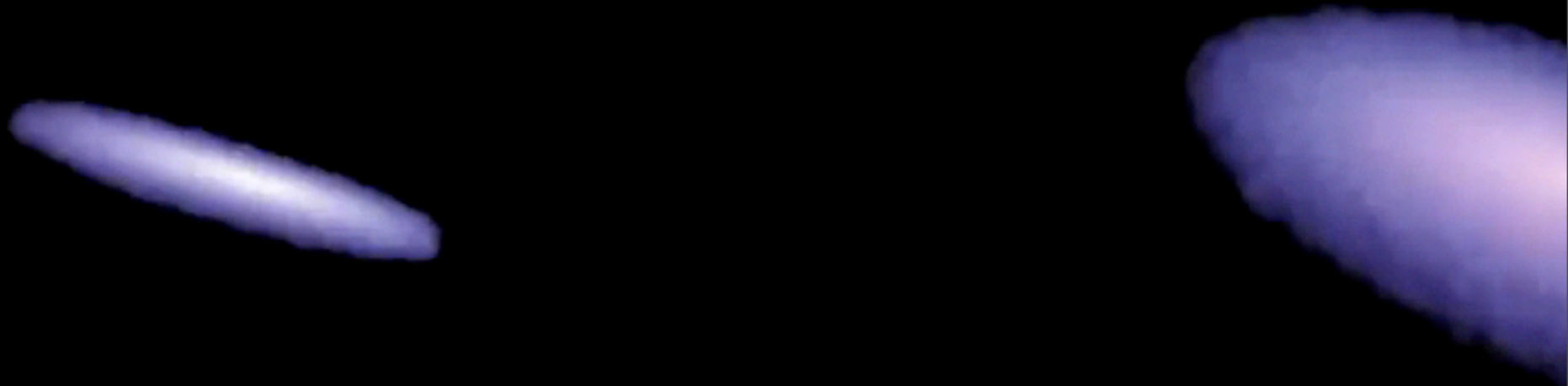
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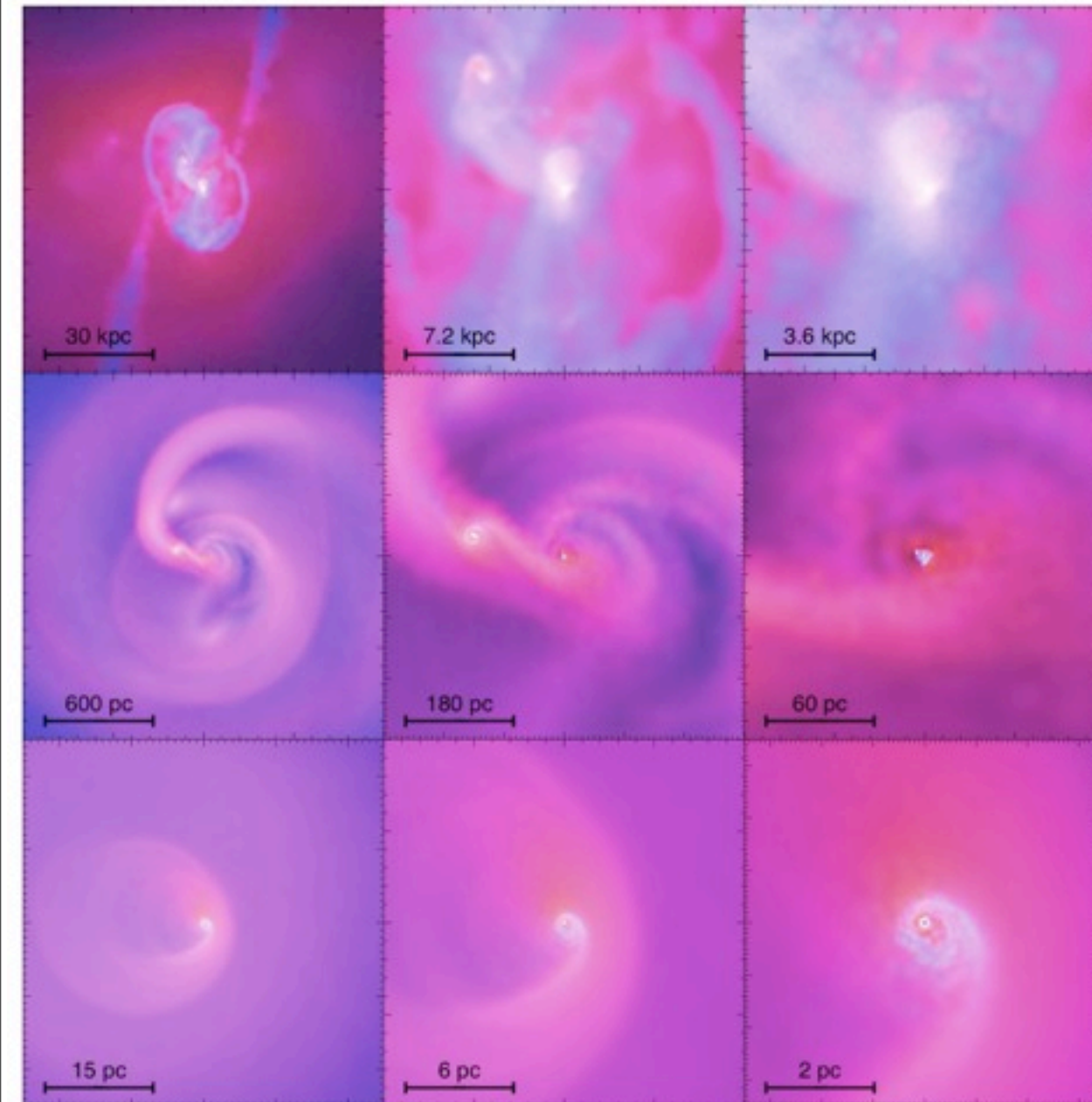
T = 0 Myr

Gas



# How do massive BHs get their gas?

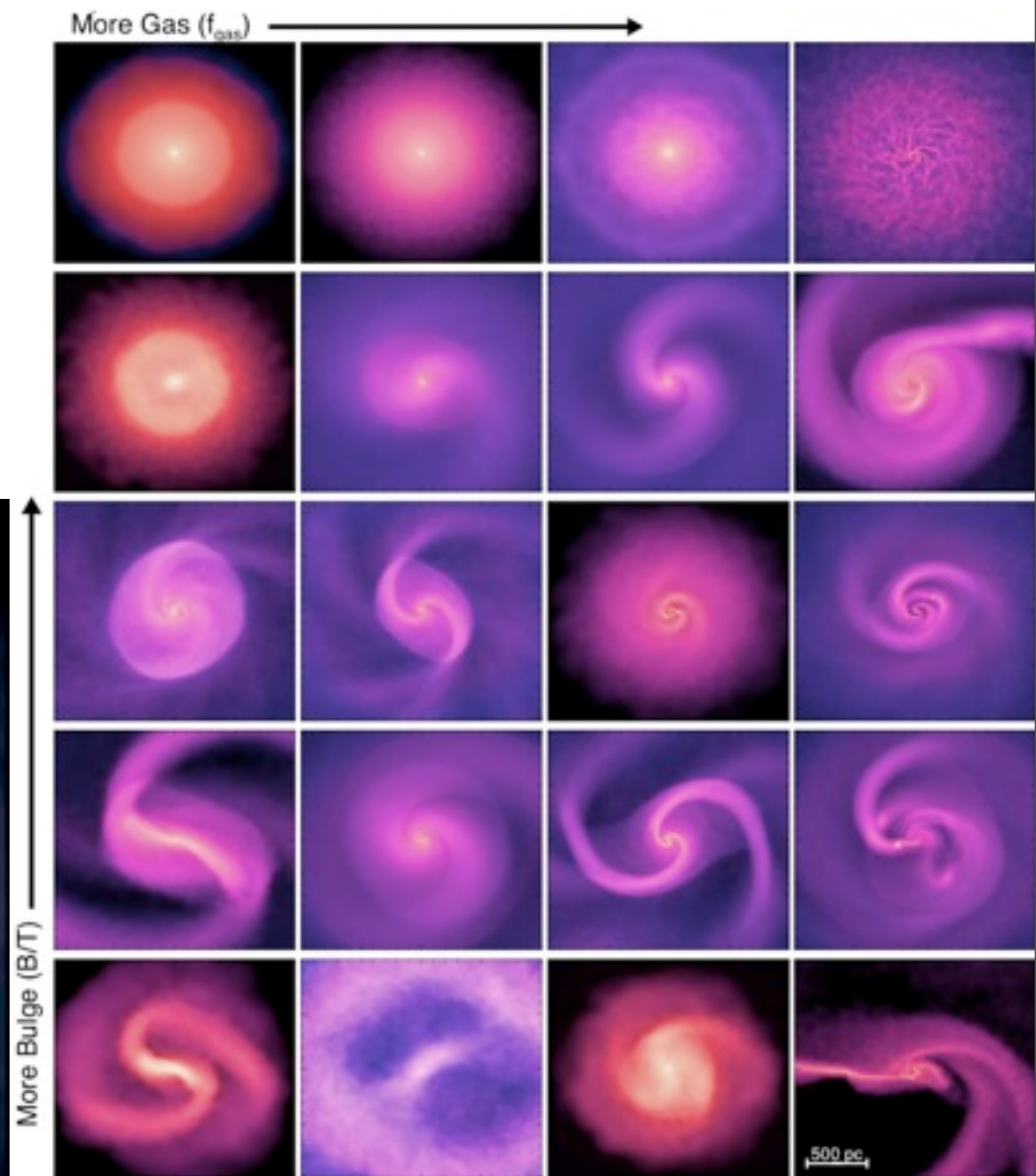
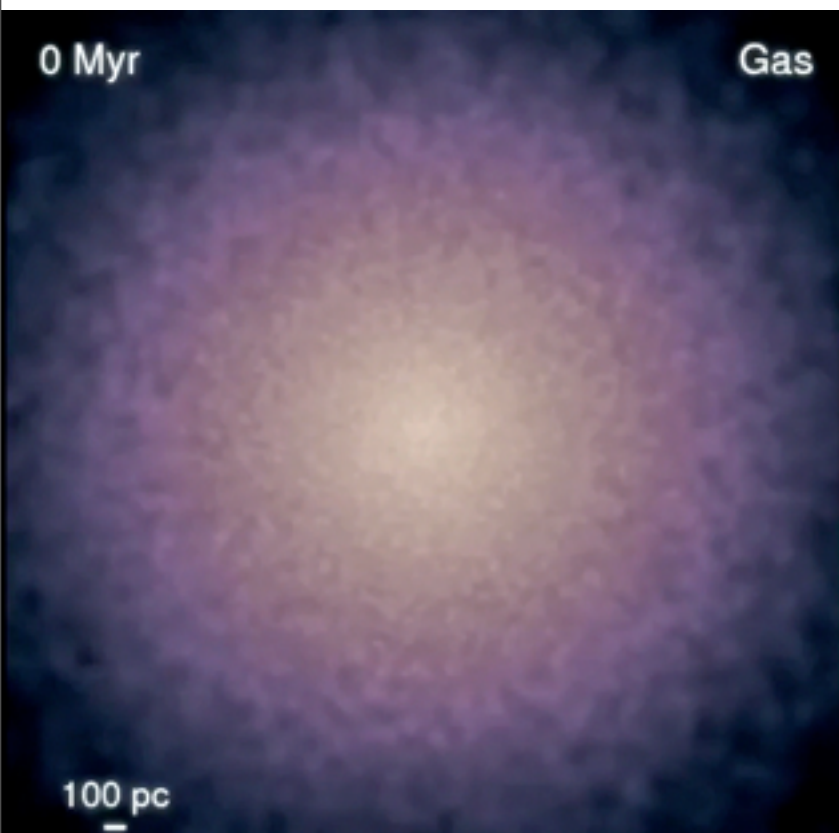
## CAN WE FUEL THE MONSTER?



- Cascade of instabilities: merger not efficient inside  $\sim$ kpc
- Any mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

# Sub-kpc scales: “Stuff within Stuff”

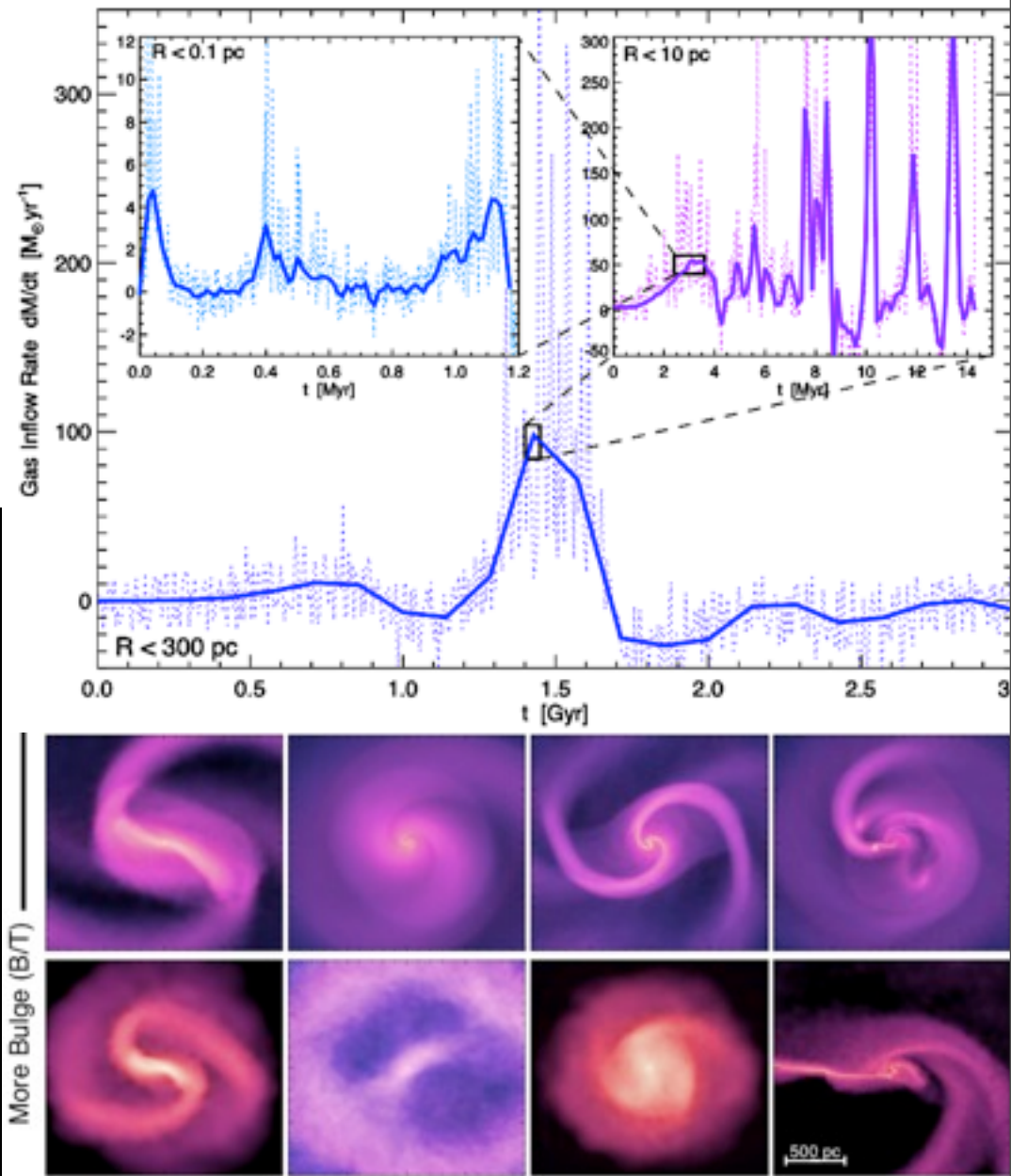
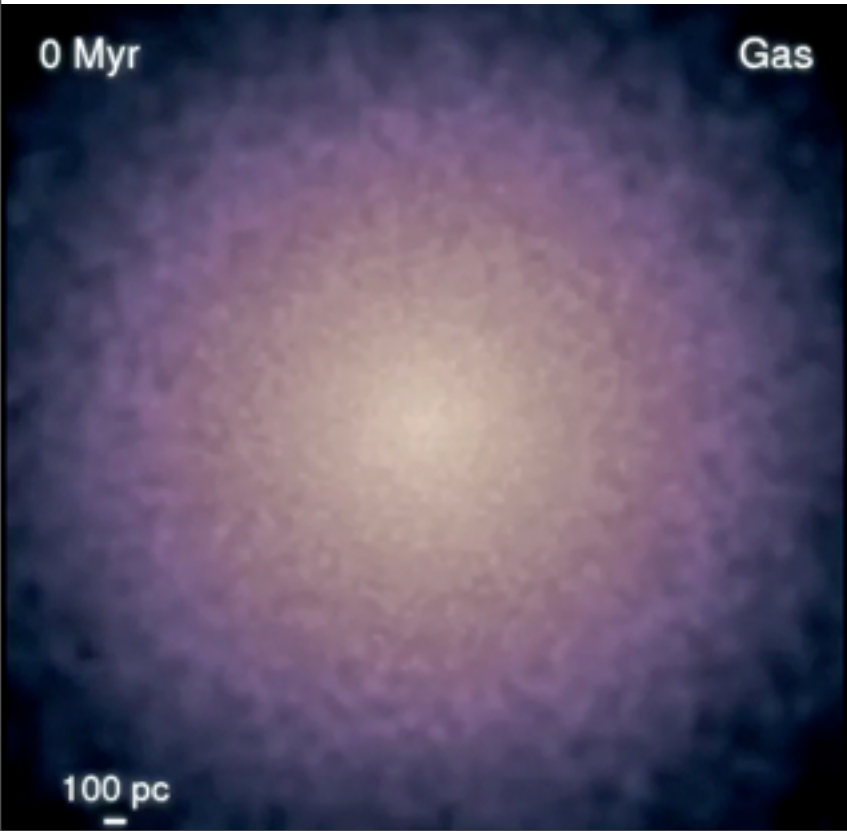
- Diverse morphologies on sub-kpc scales: not just bars!
- Inflow is *not* smooth/continuous

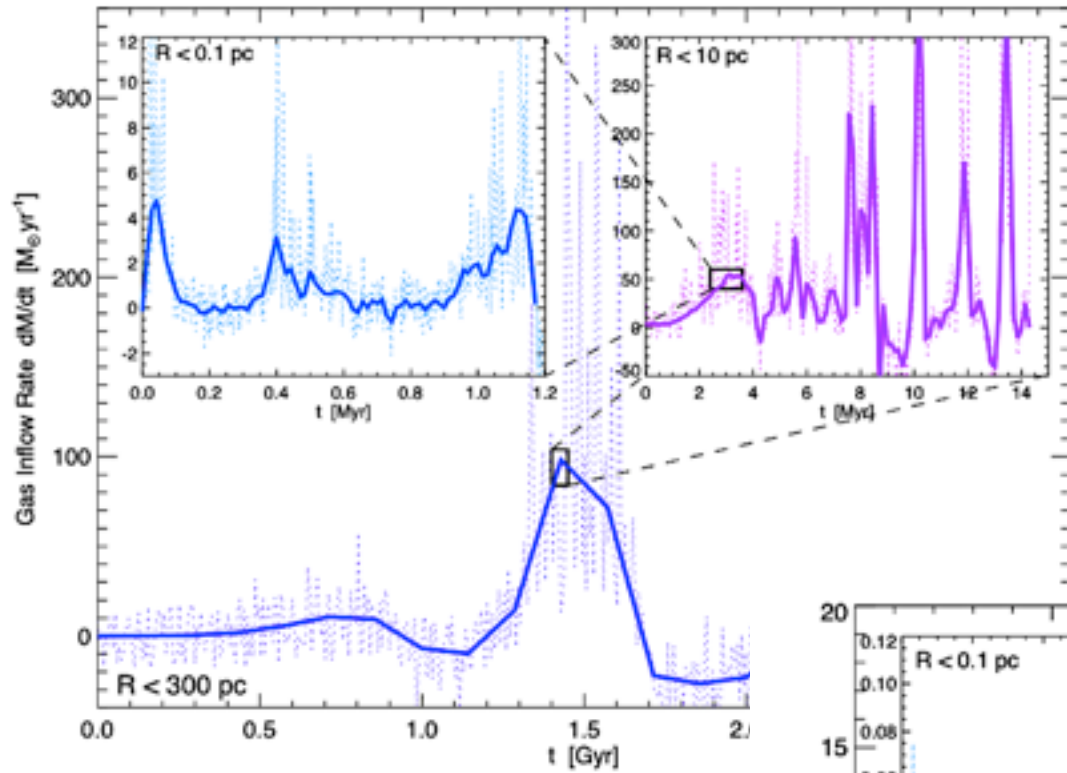




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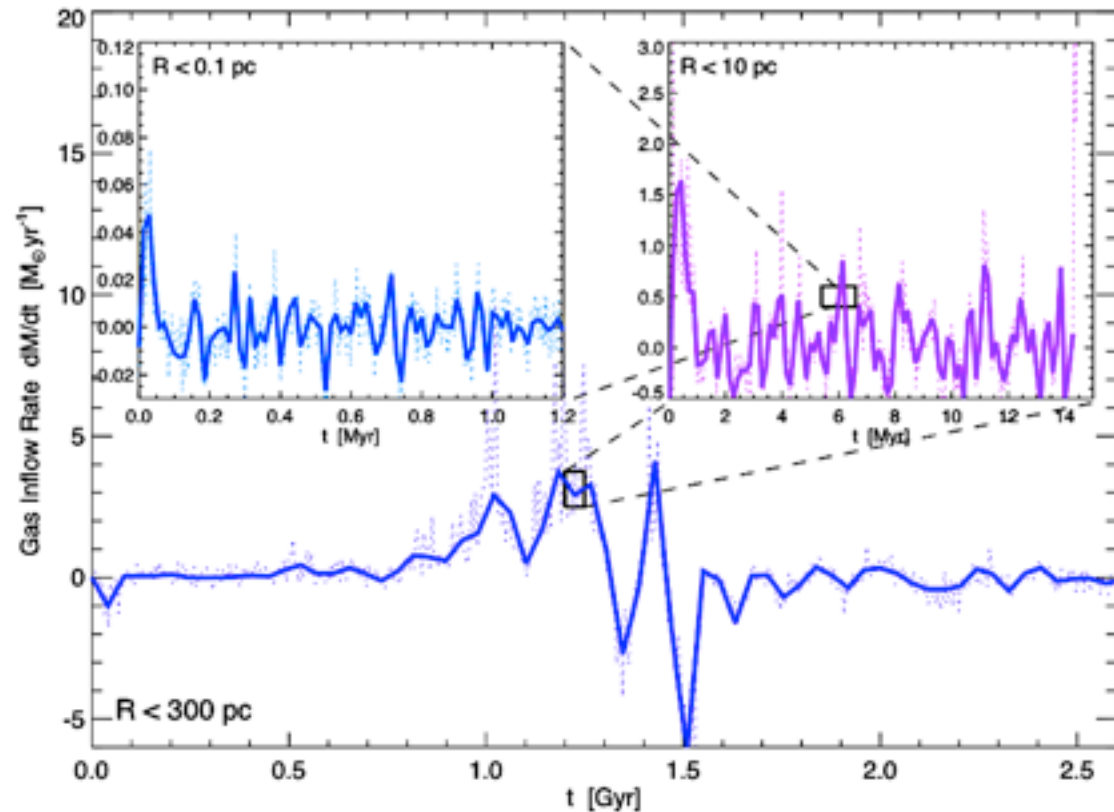
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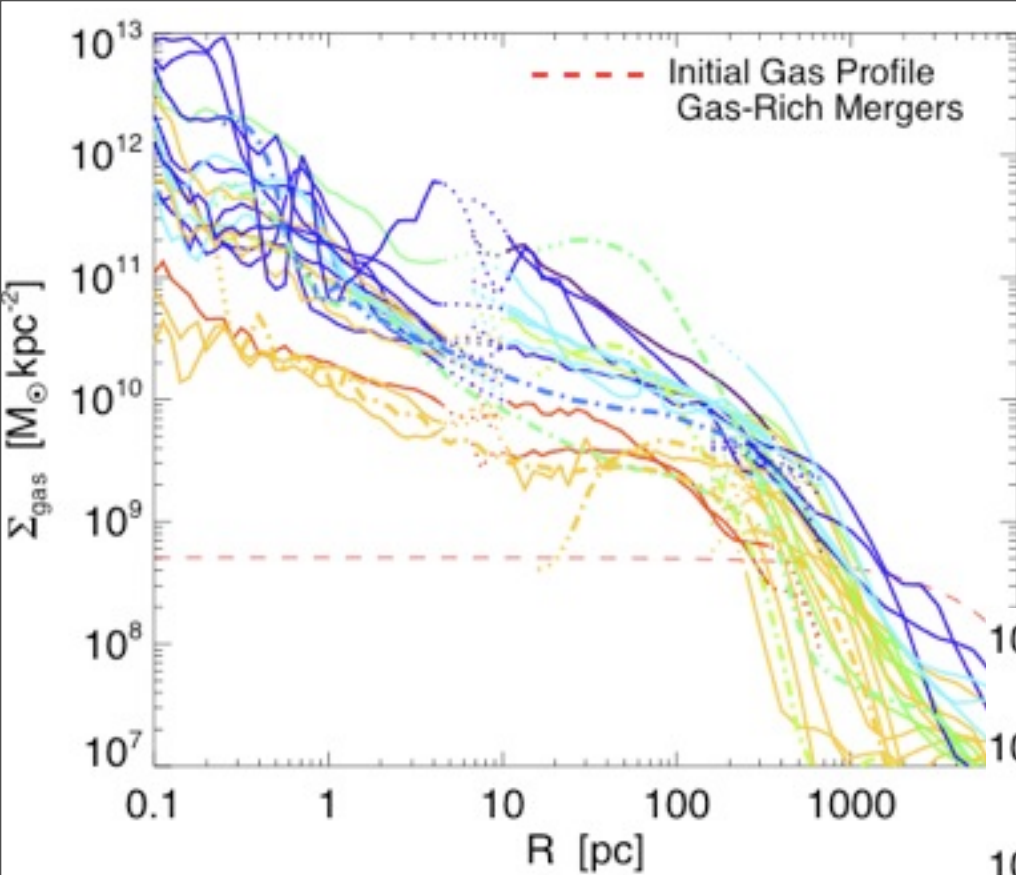


Gas-rich merger  
(lots of inflow)

Weakly bar-unstable disk  
(less inflow)

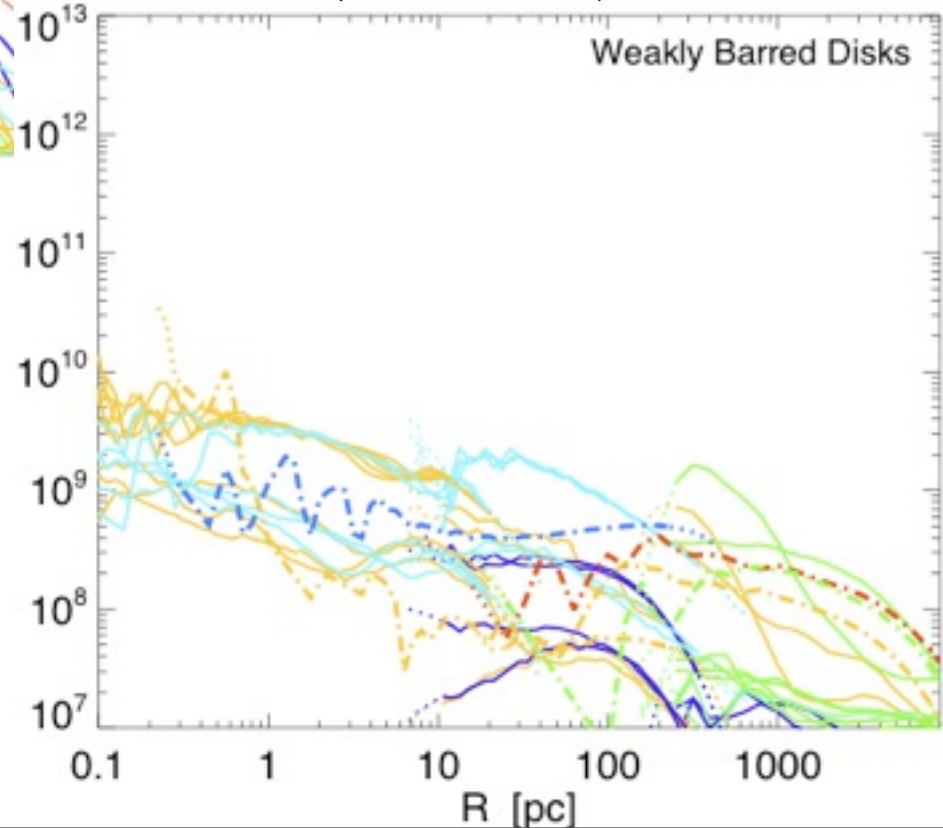


- Key parameter:  
Gas driven in, vs.  
pre-existing bulge/BH mass



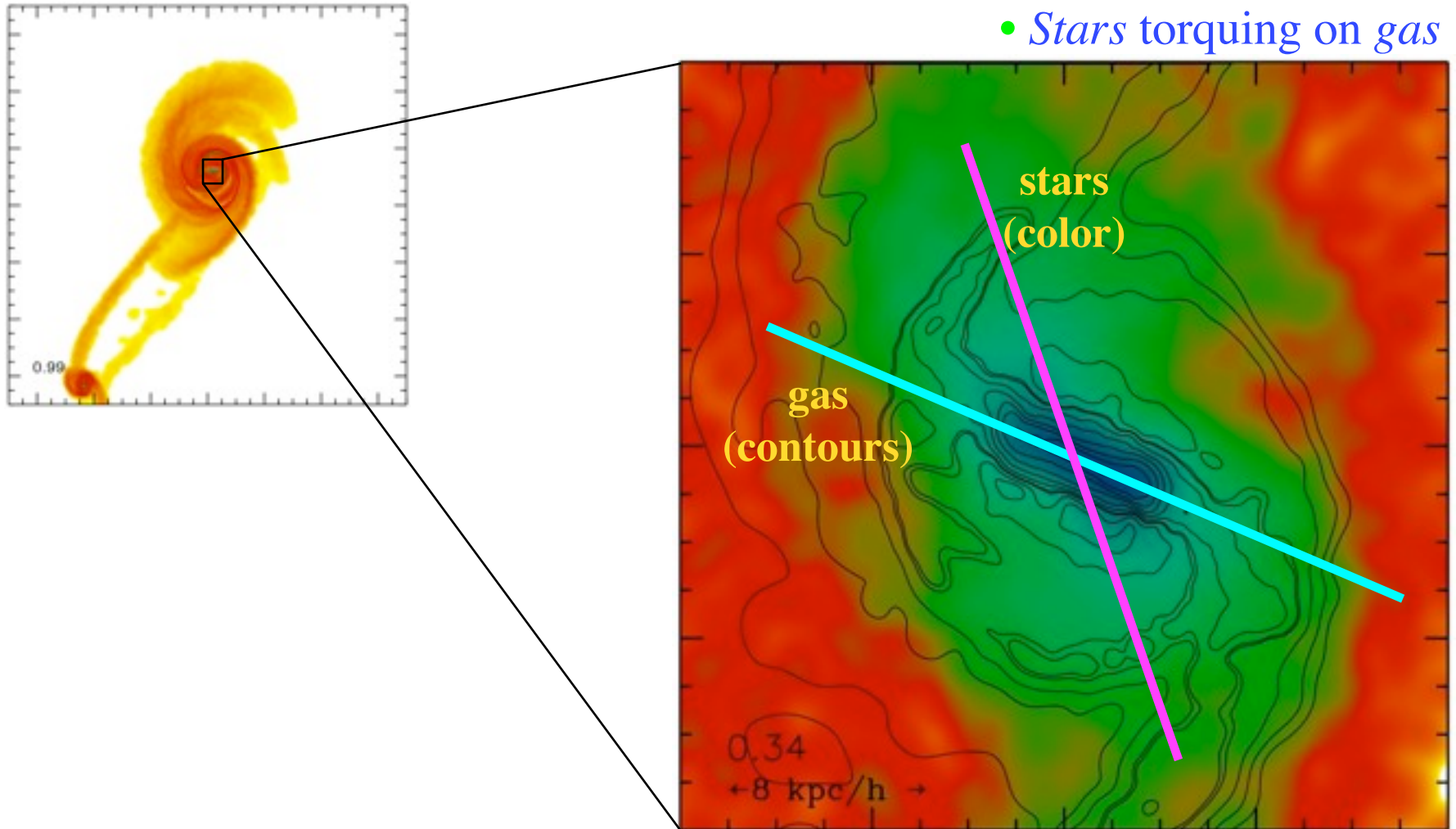
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- Gravity dominates torques from 0.1 - 10,000 pc:

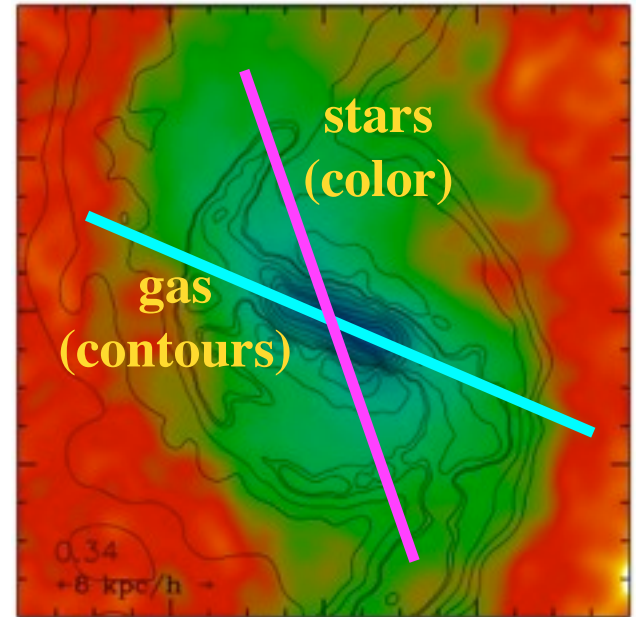




## How does this work?

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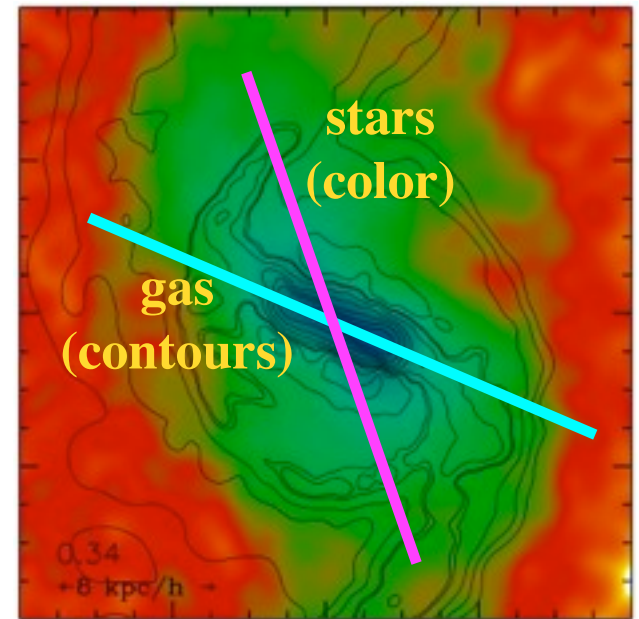
- Build analytic models:
  - Structure
  - Growth rates
  - Stability
  - Inflow rates



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standard (dissipationless) formulation: spiral waves

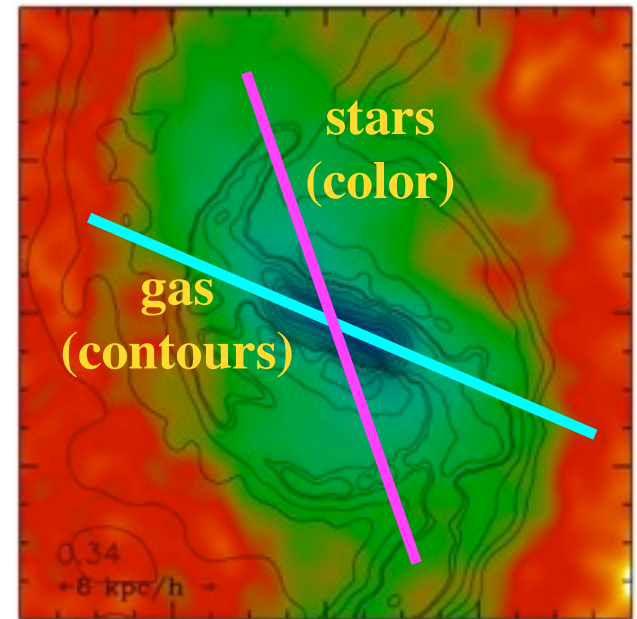
carry the angular momentum: (Lynden-Bell & Kalnajs '72)

$$\dot{M}_{\text{inflow}} = \Gamma[k, |a|]/\Omega R^2 \sim \frac{|a|^2}{|kR|^2} \frac{M_{\text{disk}}}{M_{\text{tot}}} \frac{M_{\text{gas}}}{t_{\text{dyn}}} \quad (|kR| \gg 1)$$

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- Build analytic models:

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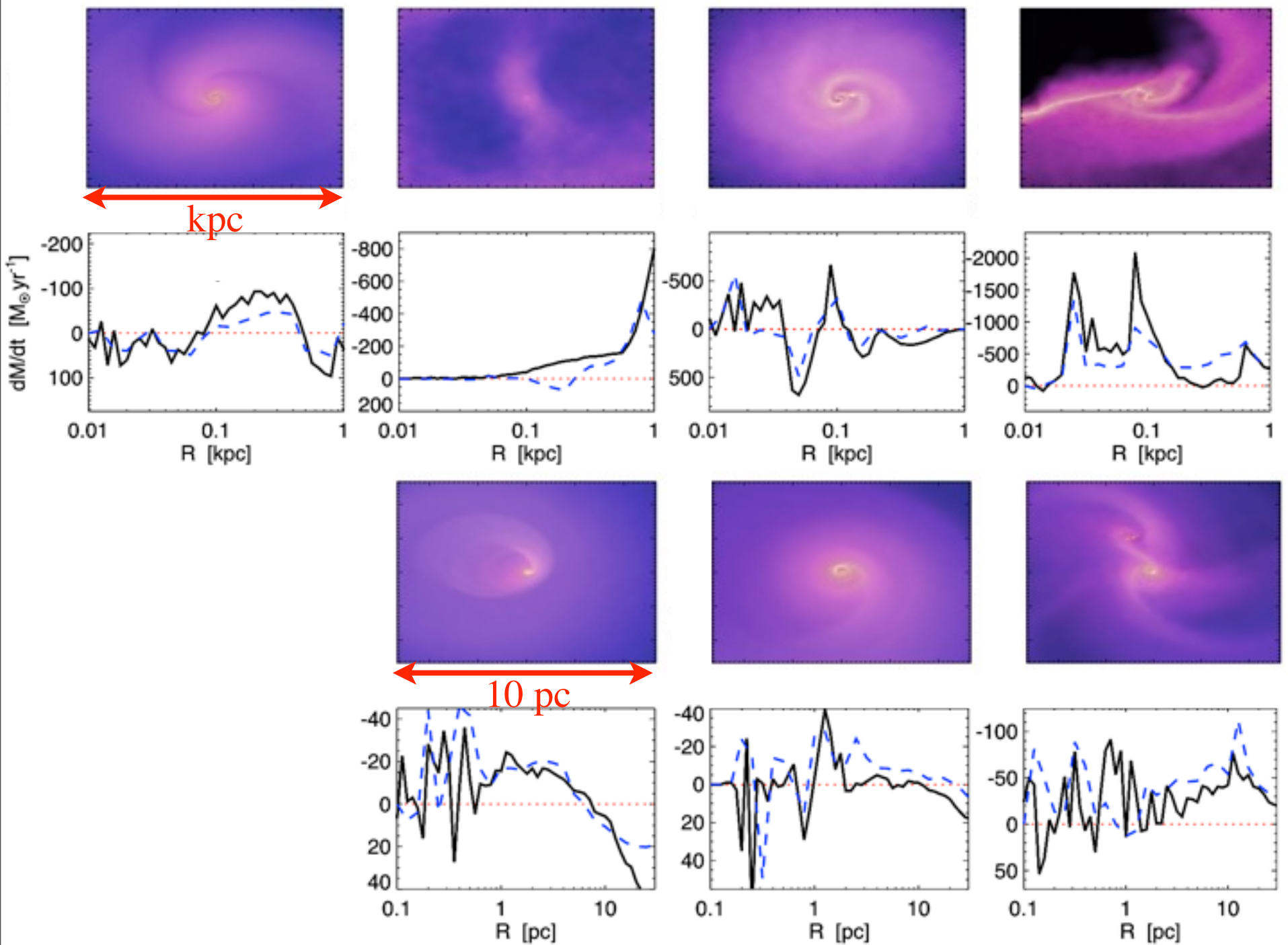
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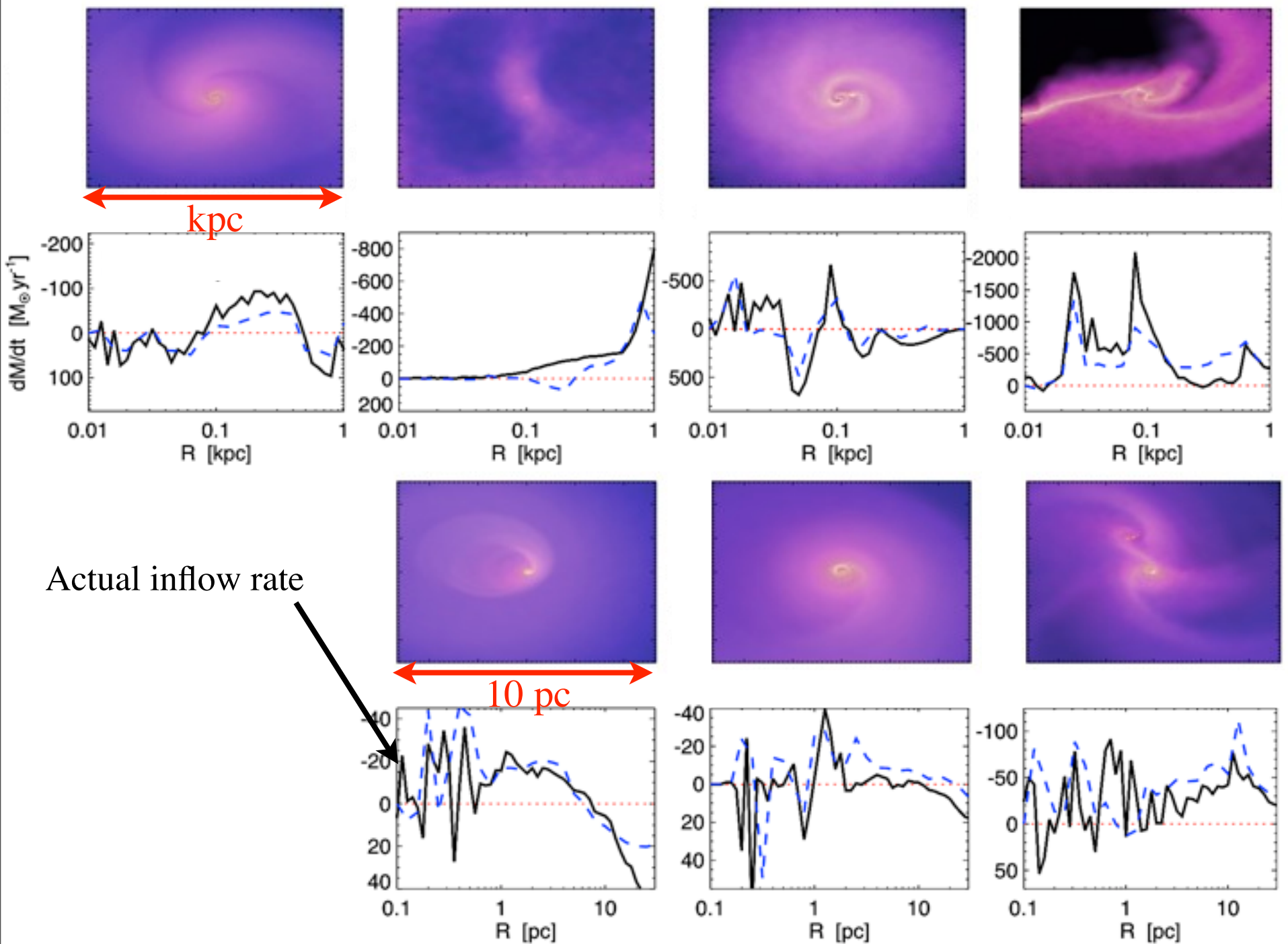
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with shocks & dissipation:

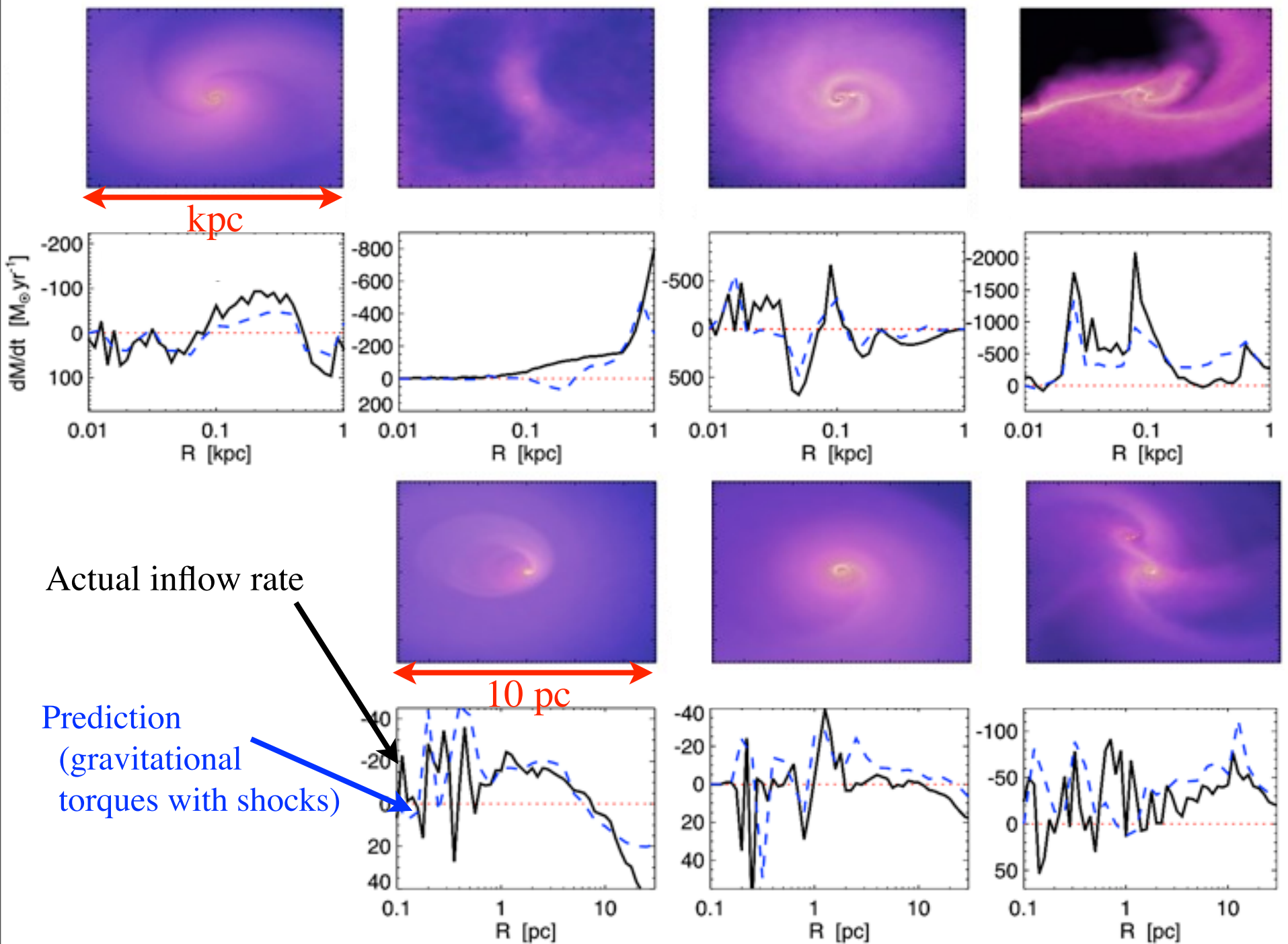
$$\dot{M}_{\text{inflow}} = \Sigma_{\text{gas}} R^2 \Omega \left| \frac{\Phi_1}{V_c^2} \right| \frac{m \text{sign}(\Omega - \Omega_p)}{1 + \partial \ln V_c / \partial \ln R} F(\zeta) \sim |a| \frac{M_{\text{gas}}}{t_{\text{dyn}}}$$

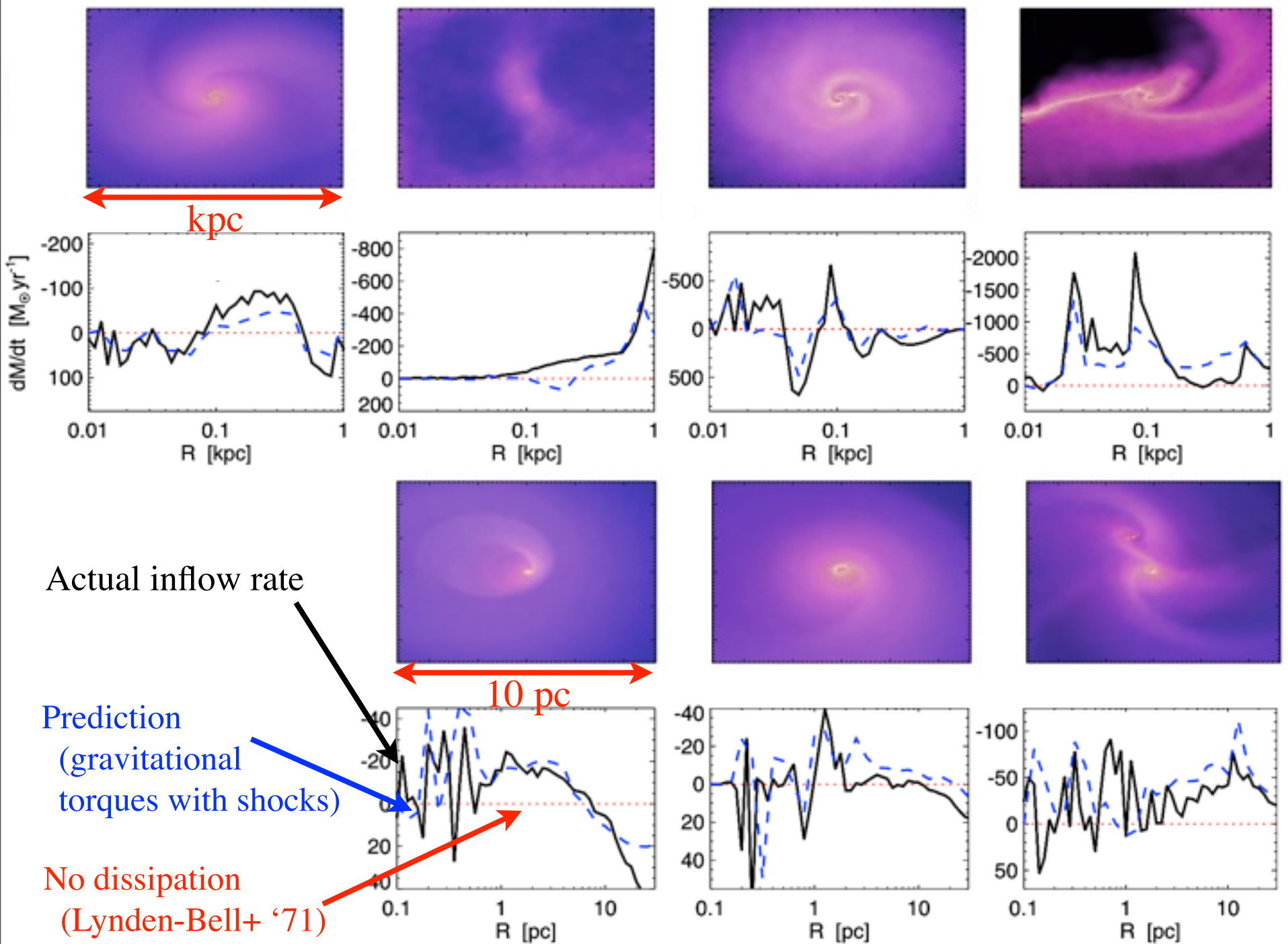
>100x larger!!!











Can we build a better accretion rate estimator?



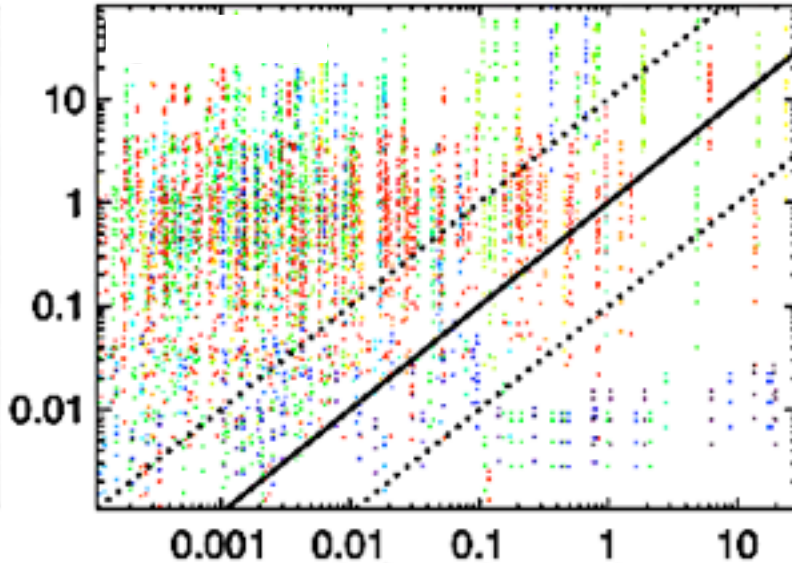
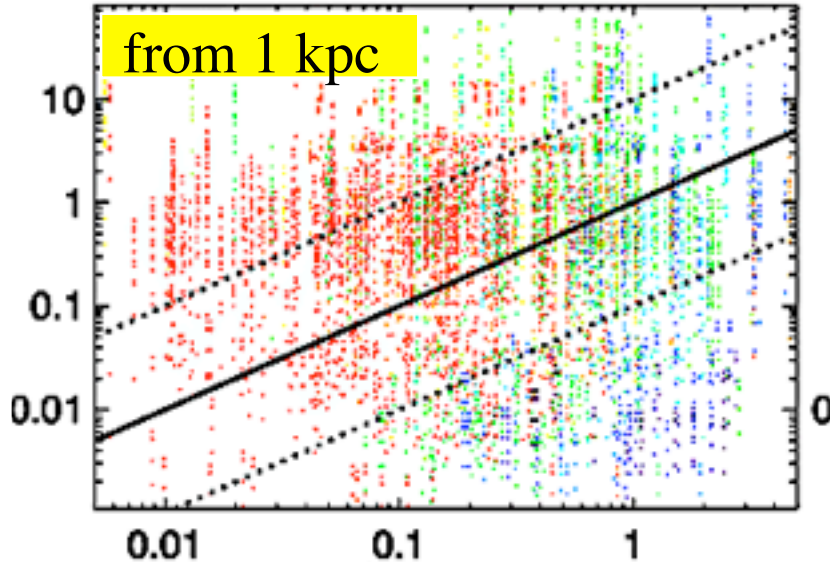
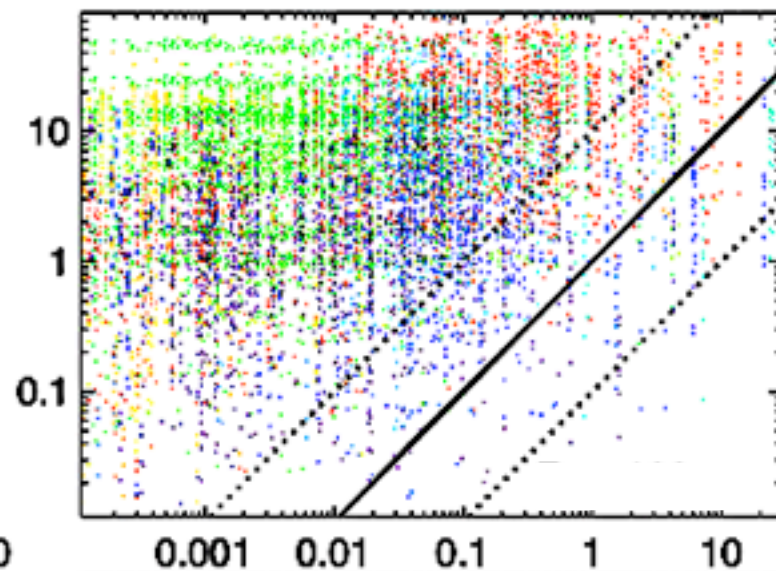
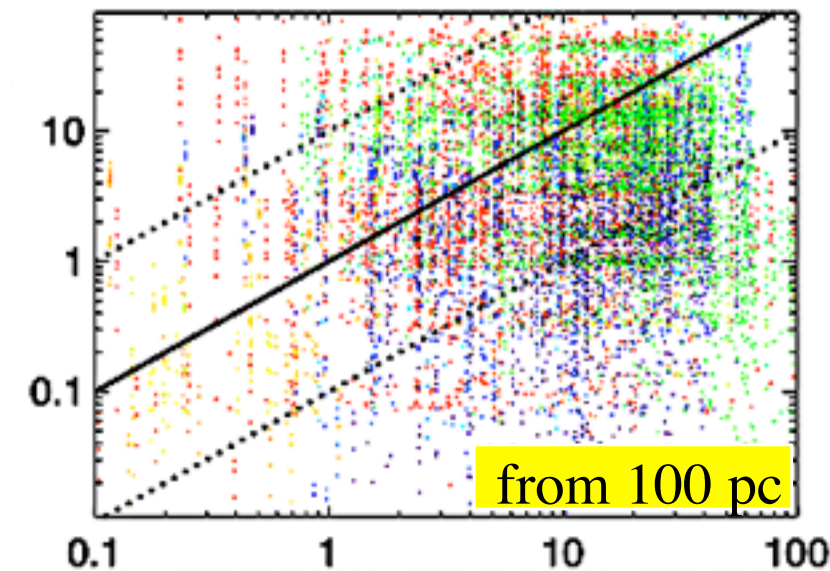
## Can we build a better accretion rate estimator?

Derive ‘Gravitational Torque’ Rate:

$$\dot{M} \approx 10 M_{\odot} \text{ yr}^{-1} \left( \frac{\text{Disk}}{\text{Total}} \right)^{5/2} M_{\text{BH}, 8}^{-1/6} M_{\text{gas}, 9} R_{0,100}^{-3/2}$$

Inflow from  $\sim \text{kpc}$  to  $\sim 0.1 \text{ pc}$  is NOT viscous or Bondi-Hoyle:

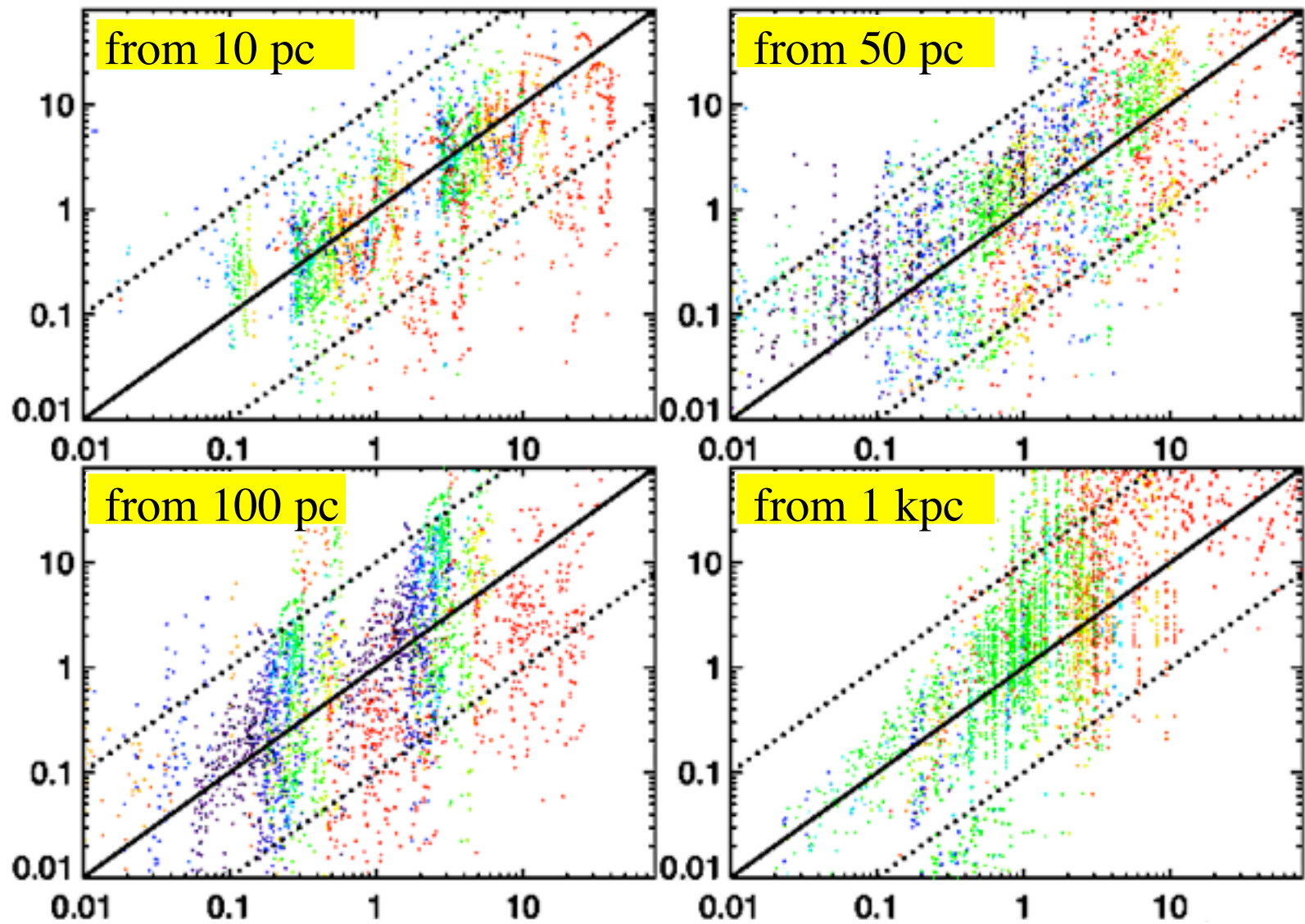
Actual inflow rate onto BH [ $M_{\text{sun}}/\text{yr}$ ]



Viscous:  $\sim c_s^2 \Sigma_{\text{gas}} \Omega^{-1}$

Bondi:  $\sim G^2 M_{\text{BH}}^2 \rho c_s^{-3}$

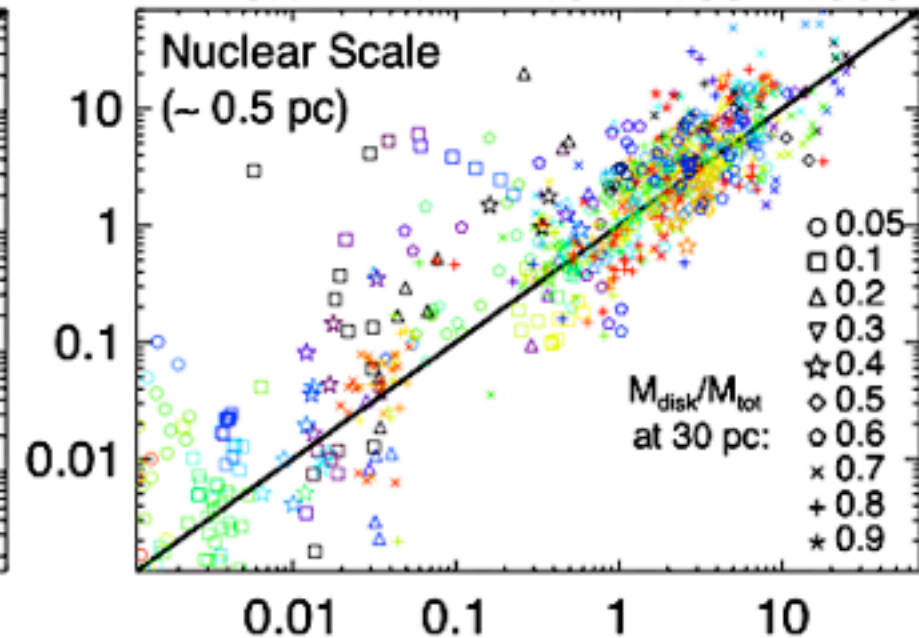
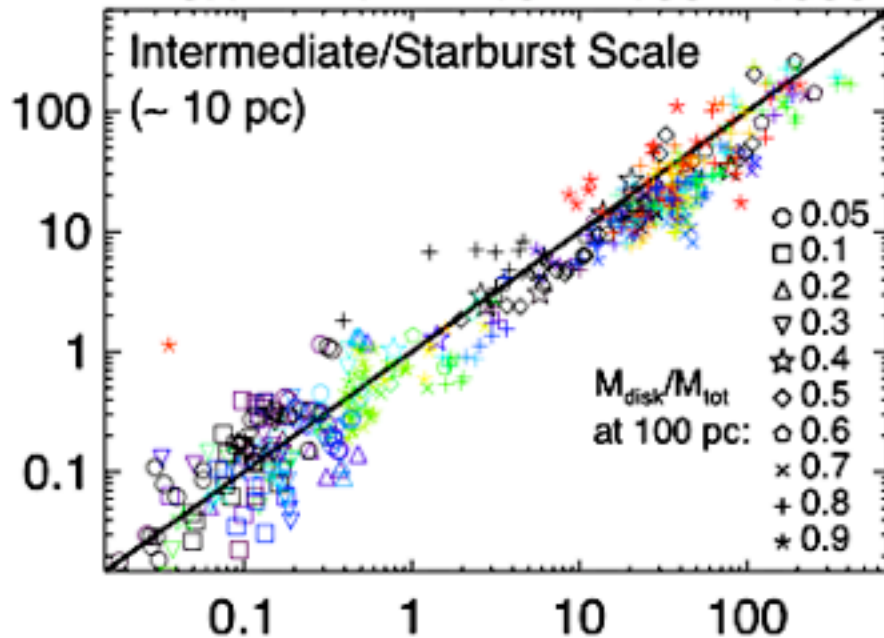
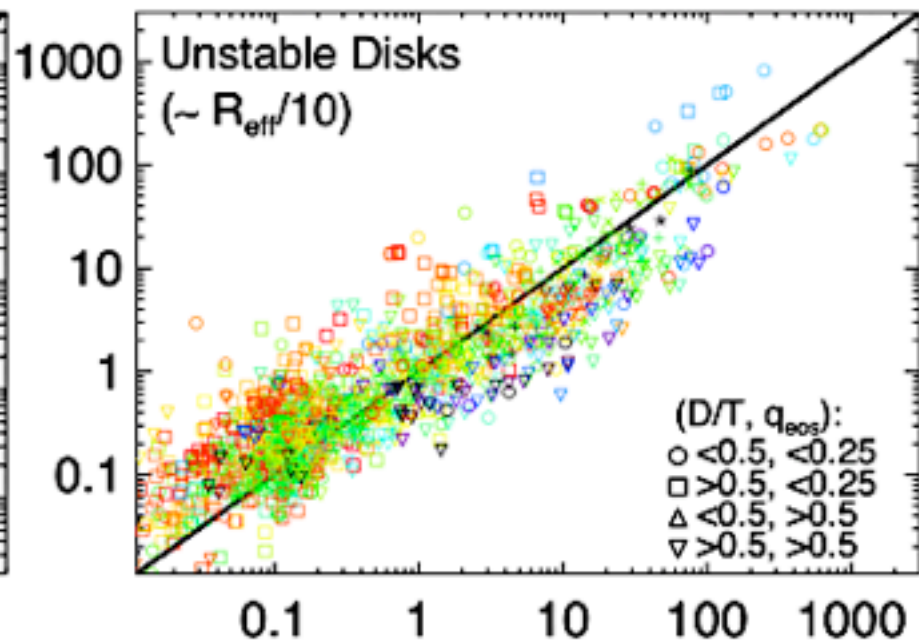
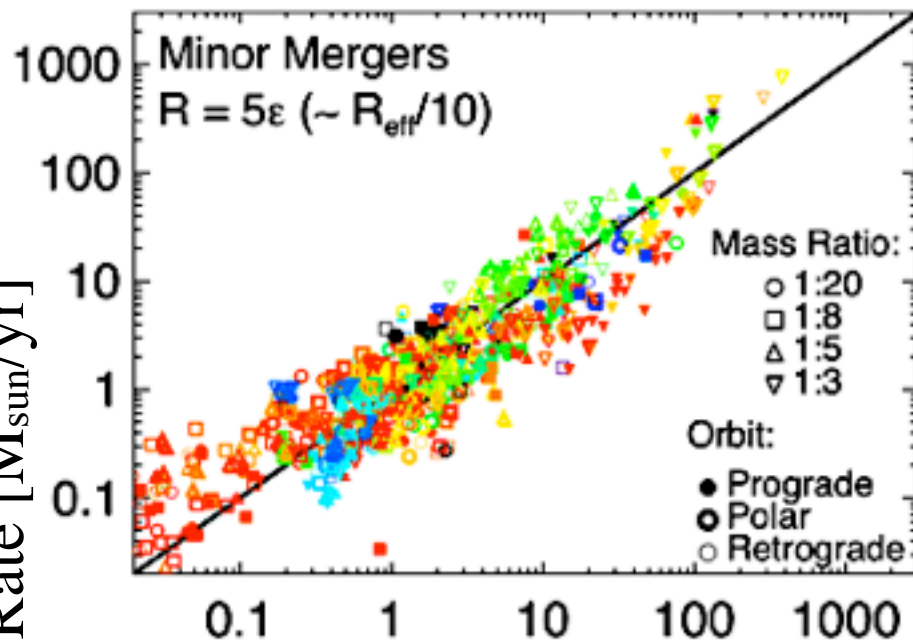
Actual inflow rate onto BH [ $M_{\text{sun}}/\text{yr}$ ]



Gravitational Prediction



True Inflow Rate [ $M_{\text{sun}}/\text{yr}$ ]

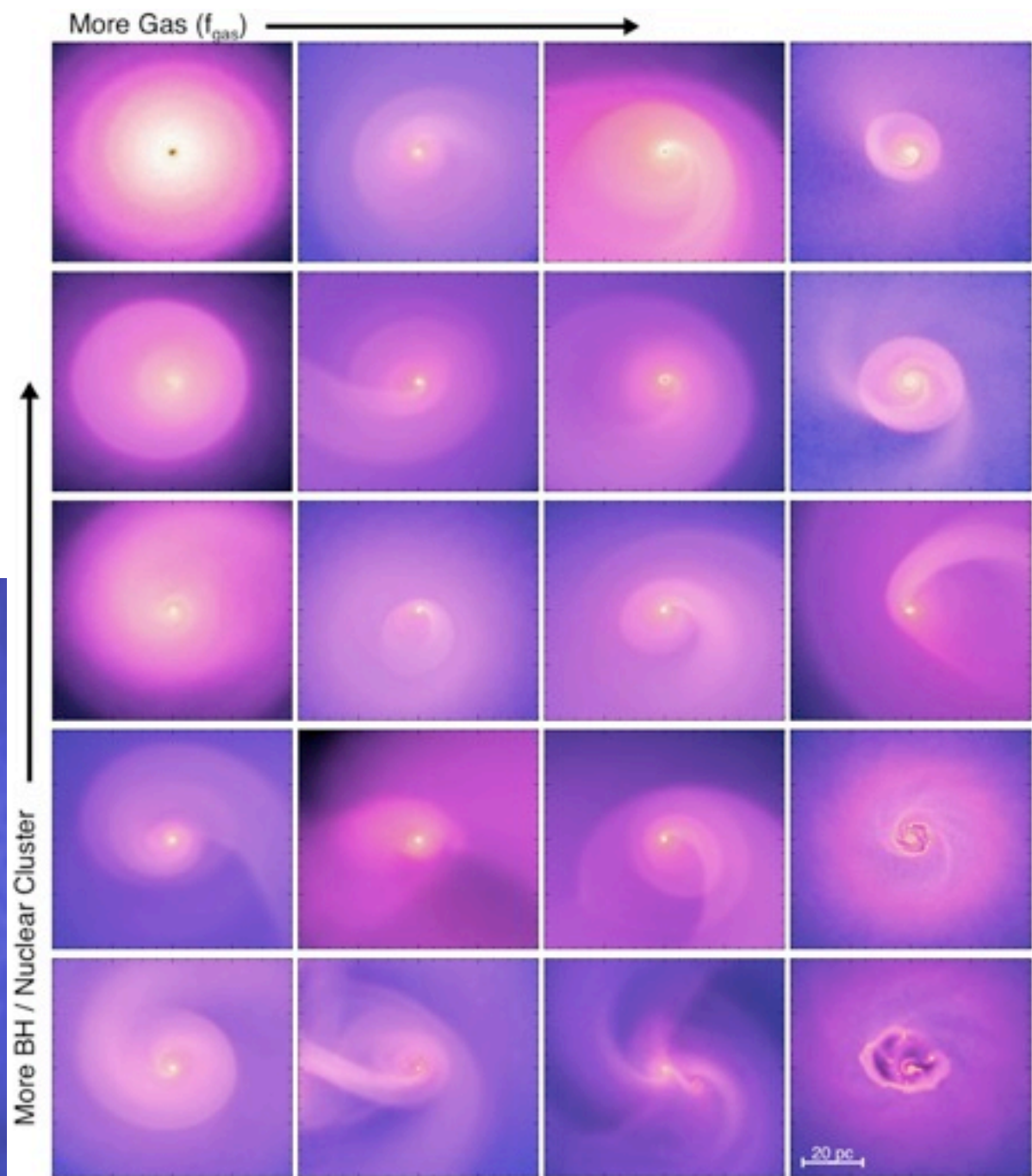
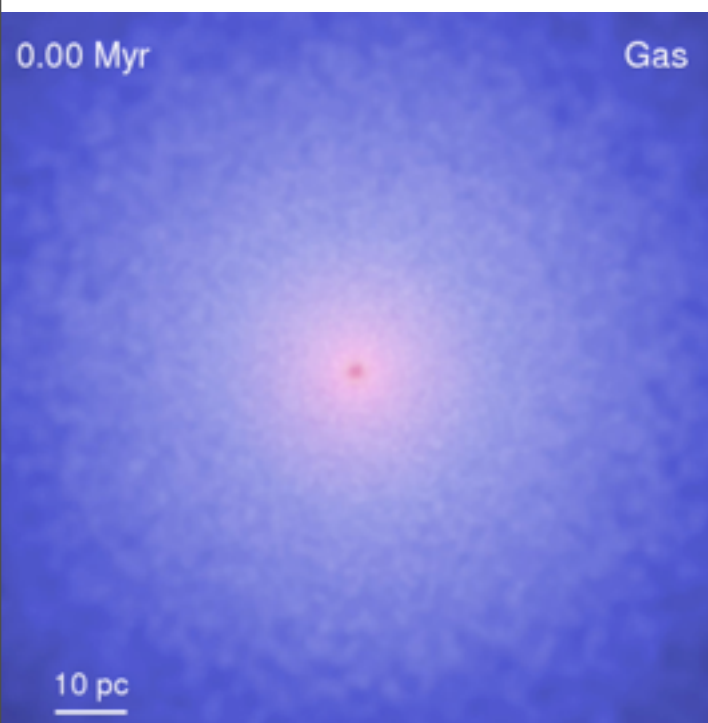


Predicted (New Gravitational Scaling)

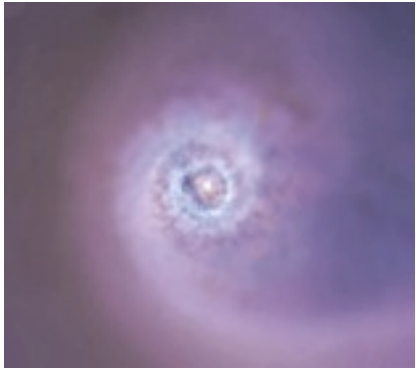
So, what about the “small” scales  
near the BH?

# $\sim 10$ pc scales: Nuclear eccentric disks

- Inside BH radius of influence: develop thick, precessing disks
- Need *both* star formation and self-gravity



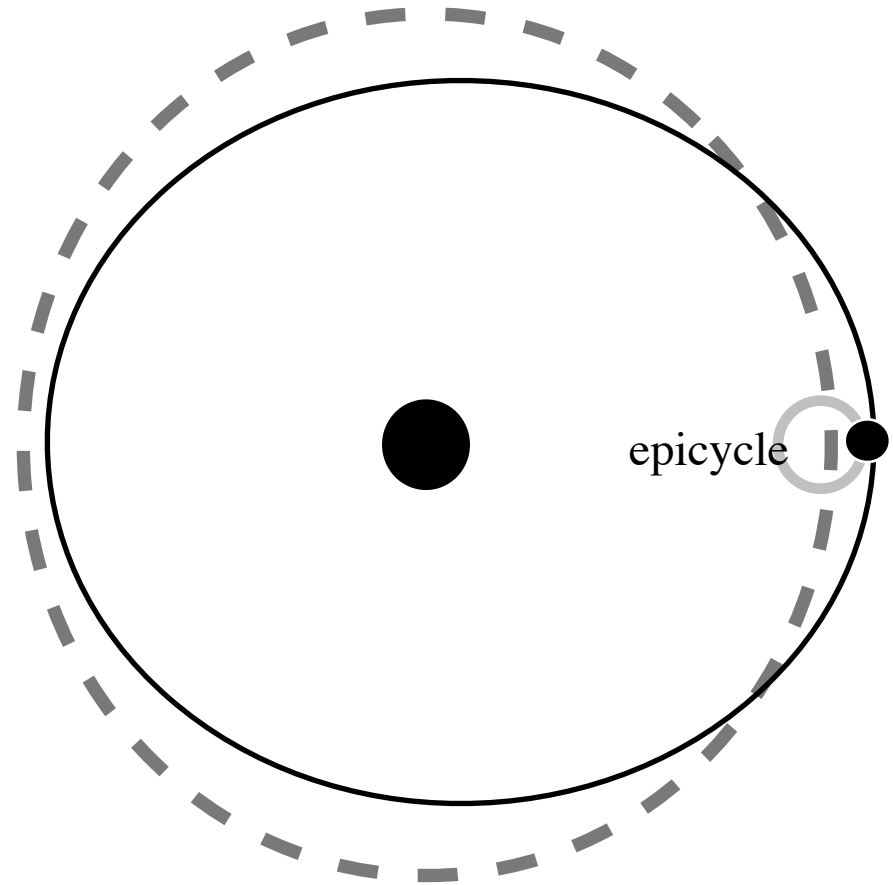
Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential



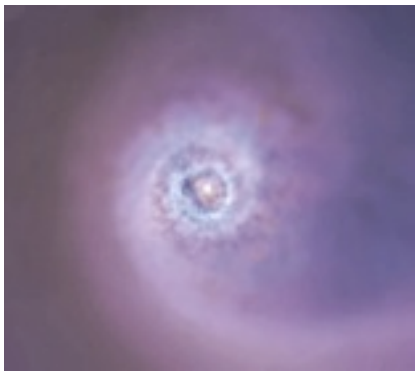
Keplerian potentials  
are special:

$$\kappa = \Omega$$

Hence, closed  
elliptical orbits!

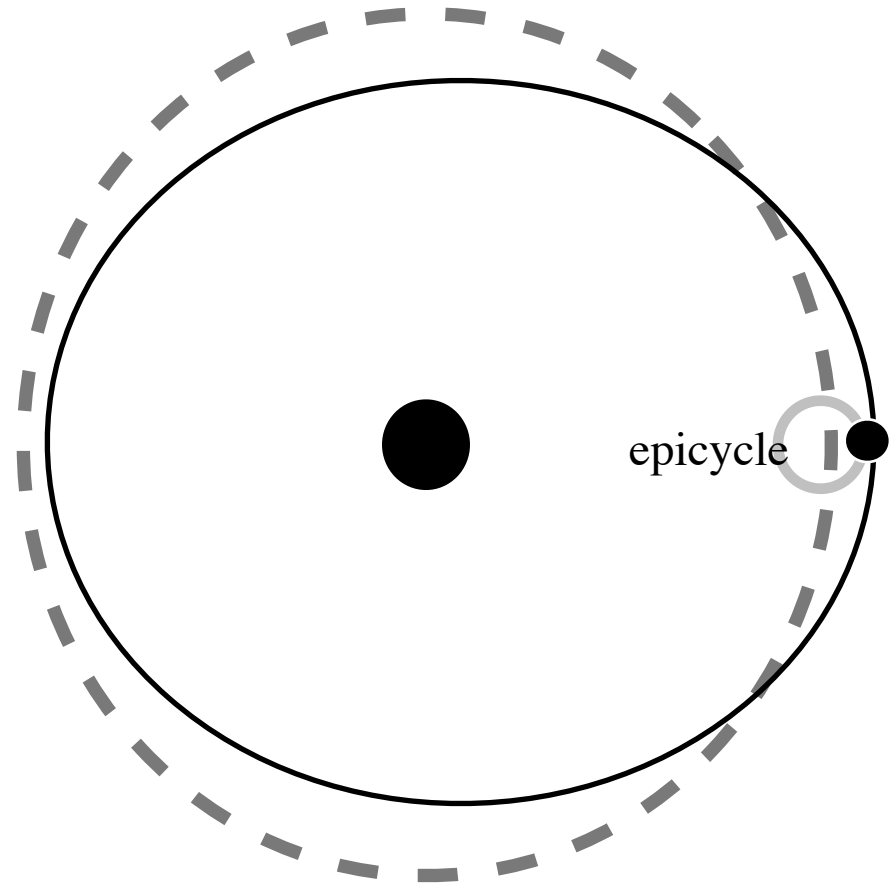


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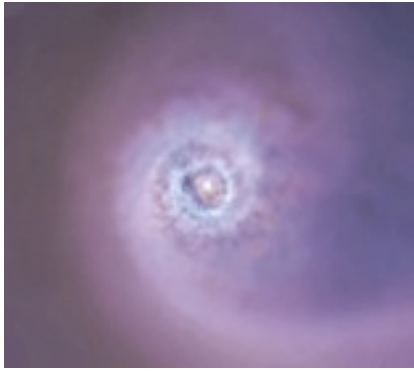
Disturb the stars with some perturbation in the disk:

$$\delta\Sigma \propto \cos m\phi$$





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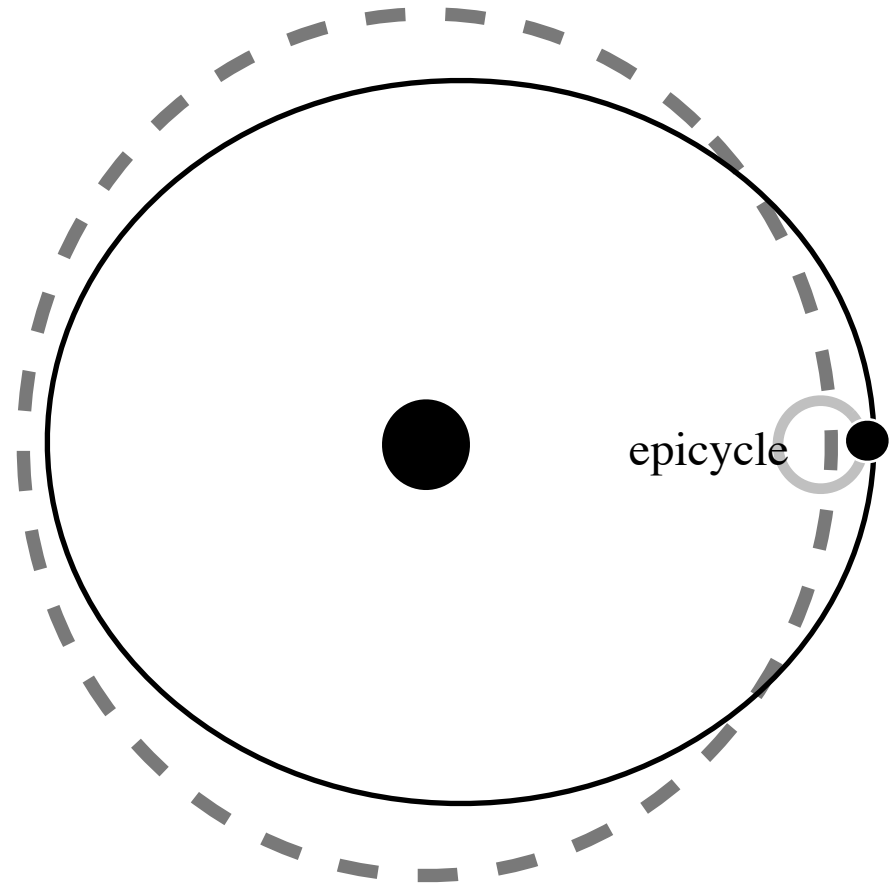


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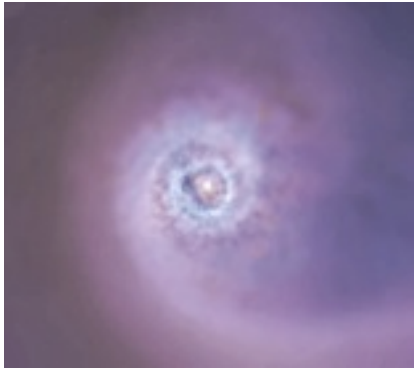
$$\delta\Sigma \propto \cos m\phi$$

*Generically*, force some deviations/torques/etc:

$$\left| \frac{\delta v}{V_c} \right| \sim \left( \frac{\delta\Sigma}{\Sigma} \right) \frac{M_{\text{disk}}(< r)}{M_{\text{BH}}}$$



Eccentric/lopsided disks ( $m=1$  modes) are special in a near-Keplerian potential



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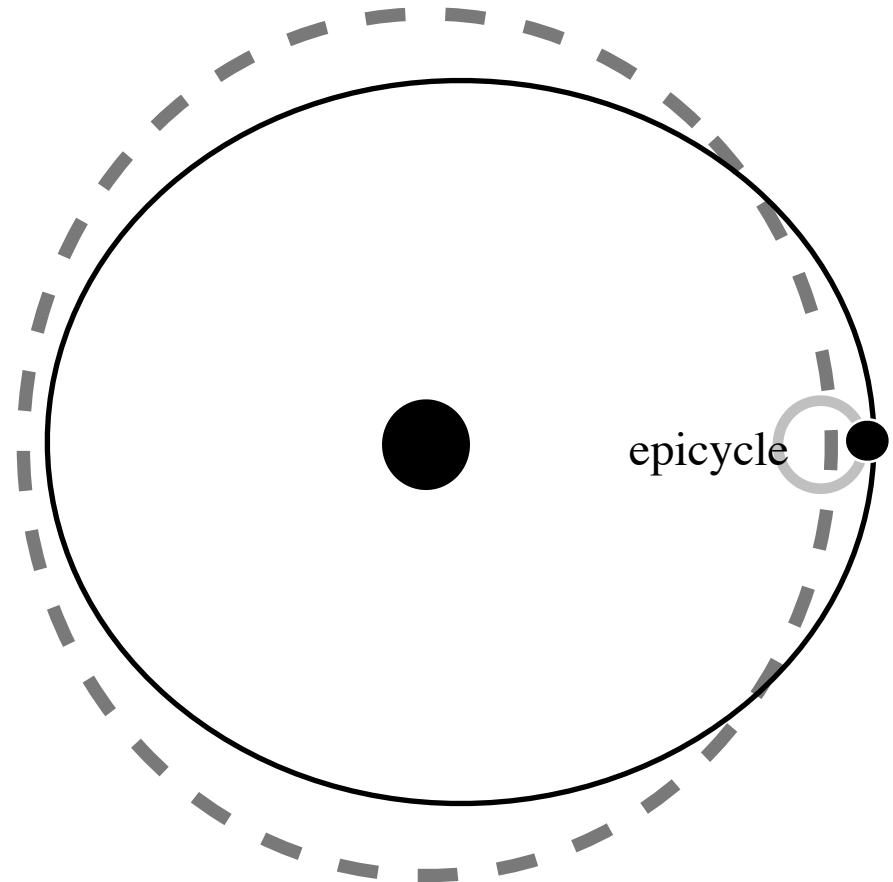
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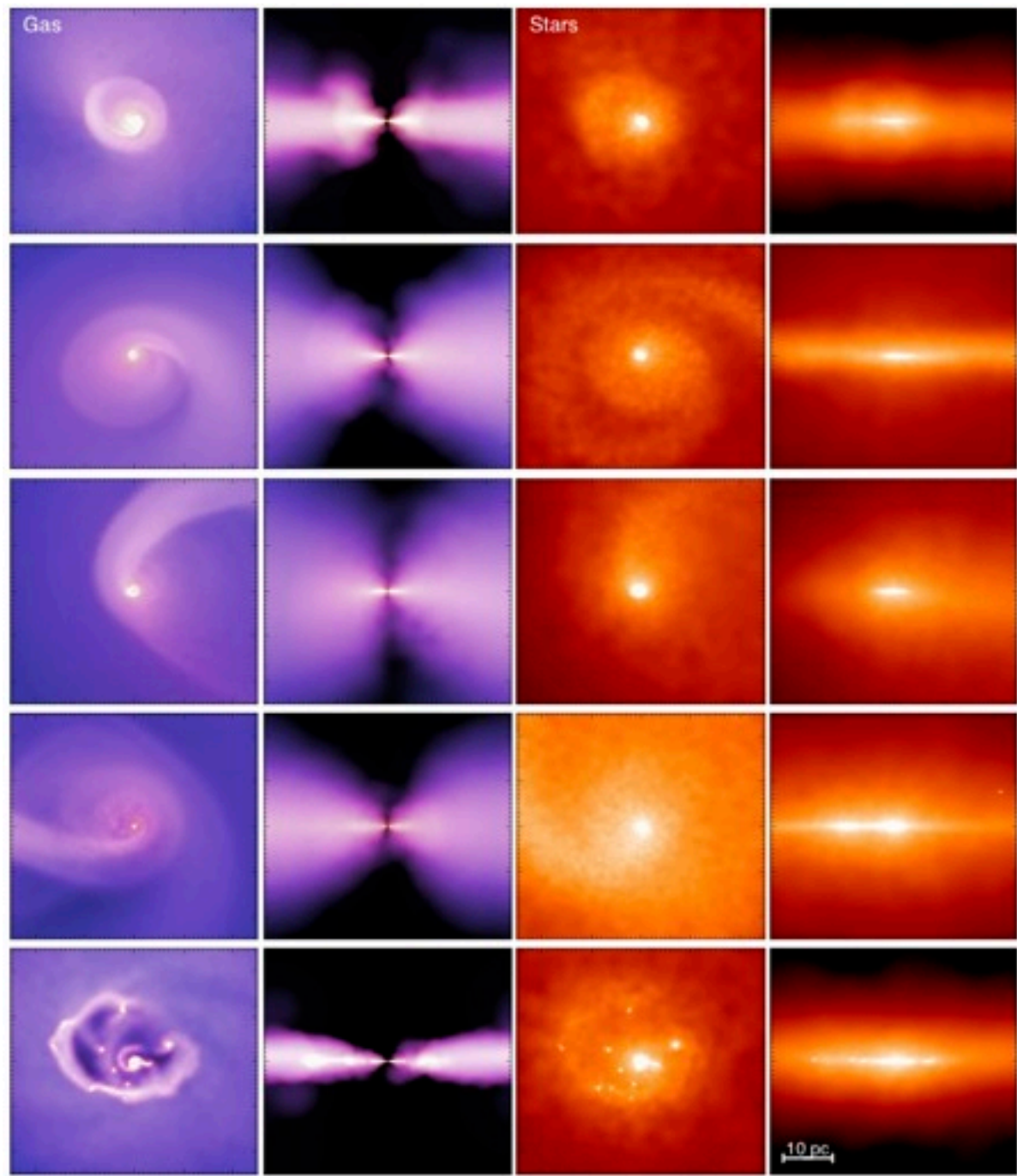
$$\left| \frac{\delta v}{V_c} \right| \sim \left( \frac{\delta\Sigma}{\Sigma} \right) \frac{M_{\text{disk}}(< r)}{M_{\text{BH}}}$$

But, if (and *only* if)  $m=1$ :

$$\left| \frac{\delta v}{V_c} \right| \sim \left( \frac{\delta\Sigma}{\Sigma} \right)$$



Relic,  $\sim$ pc-scale nuclear  
stellar disk....



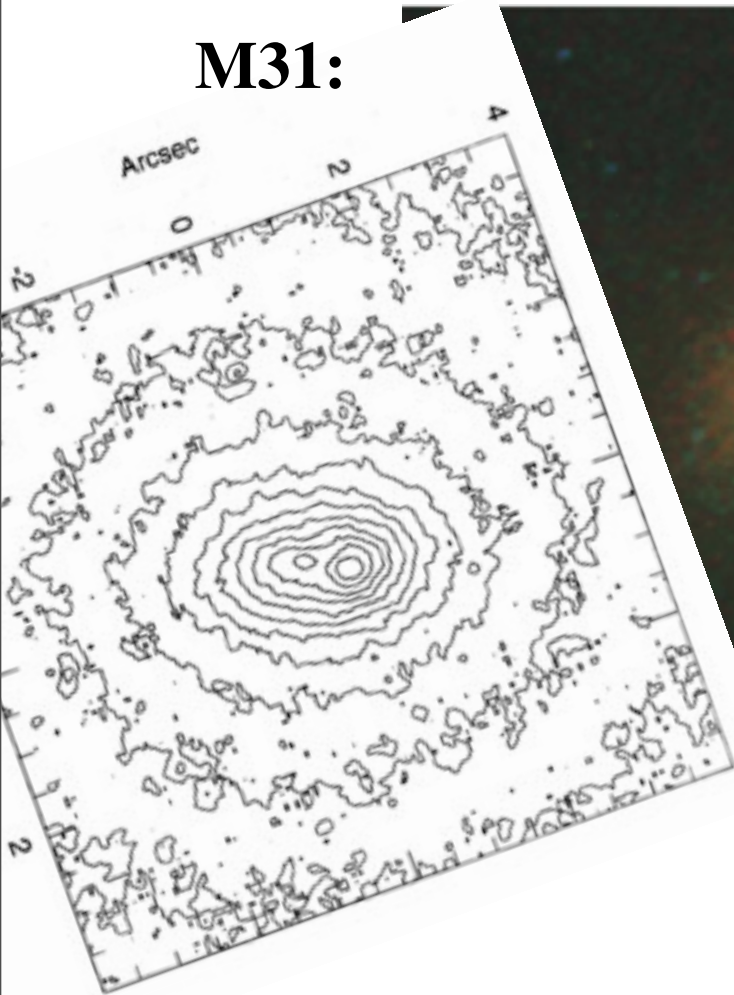
- Gas-stellar exchange dramatically enhances torques
- Drives  $\sim 10 M_{\text{sun}}/\text{yr}$  inflow
- Leave relic stellar disks?

- These are observed!

M31, NGC4486B, many candidates

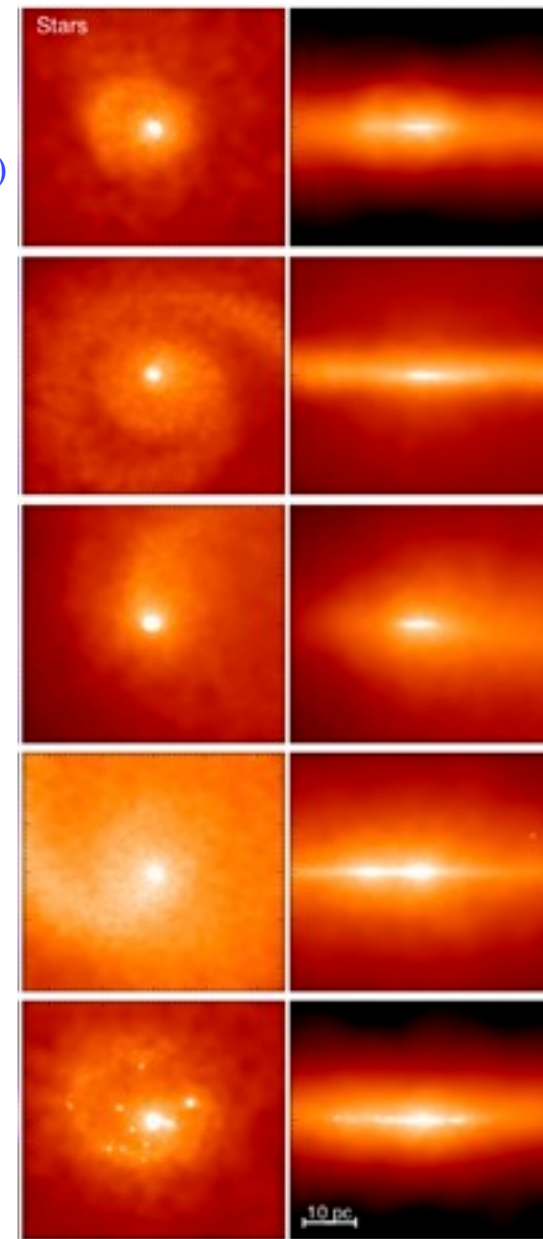
(NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)

**M31:**



Lauer et al. 1993

Kormendy & Bender 1999



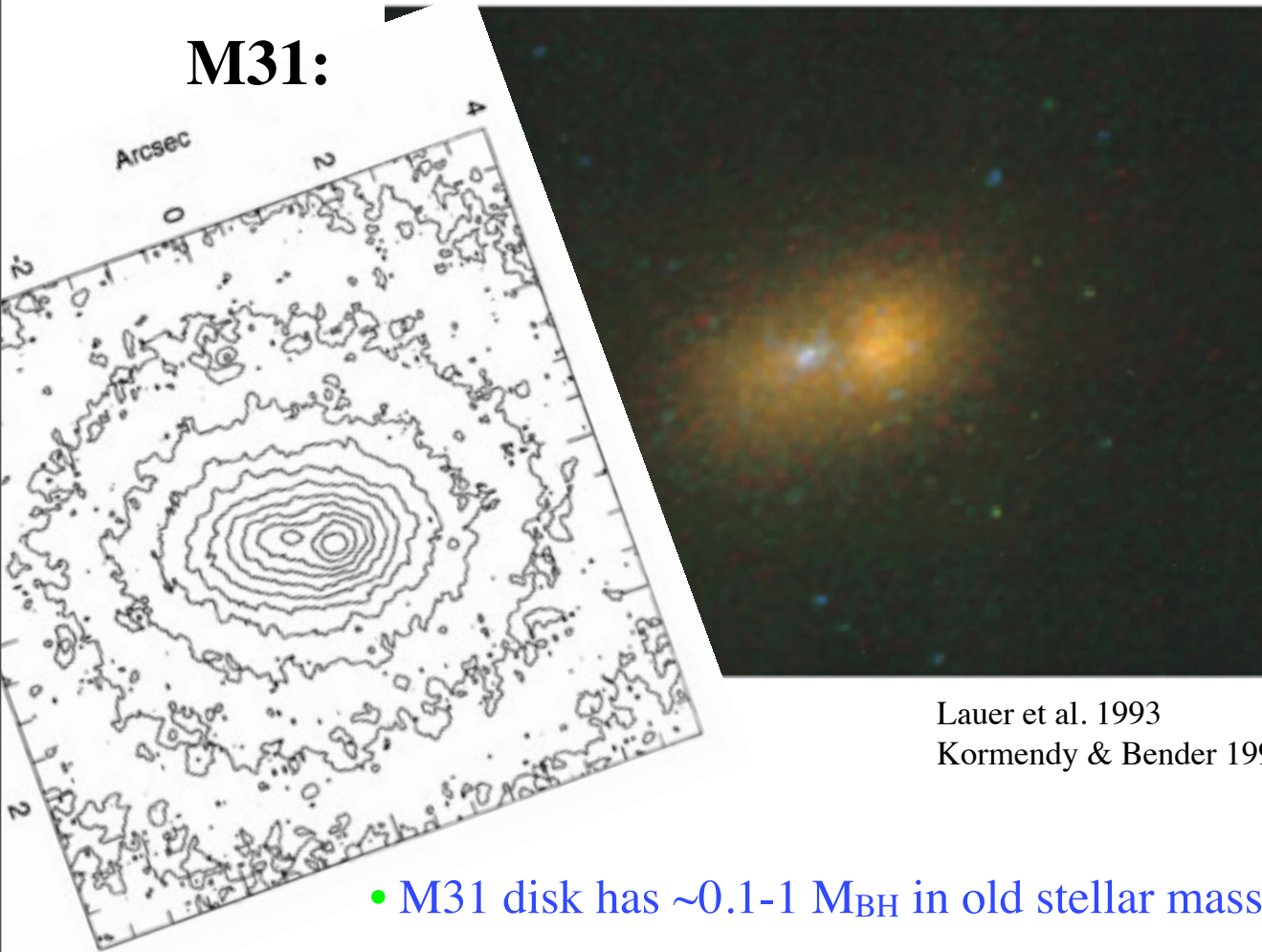


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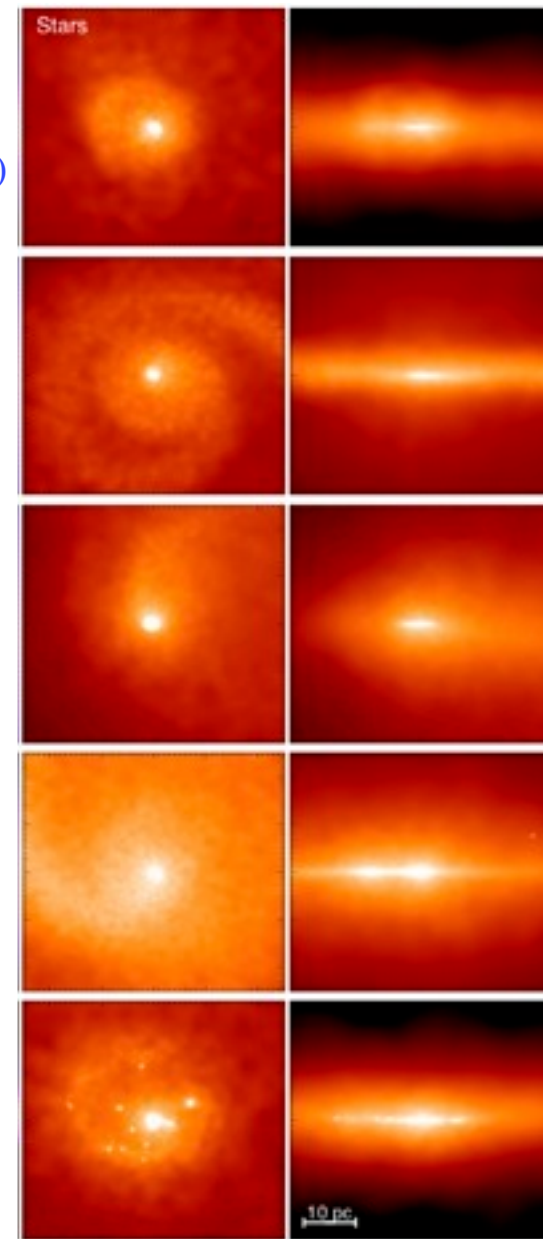
## M31:



Lauer et al. 1993

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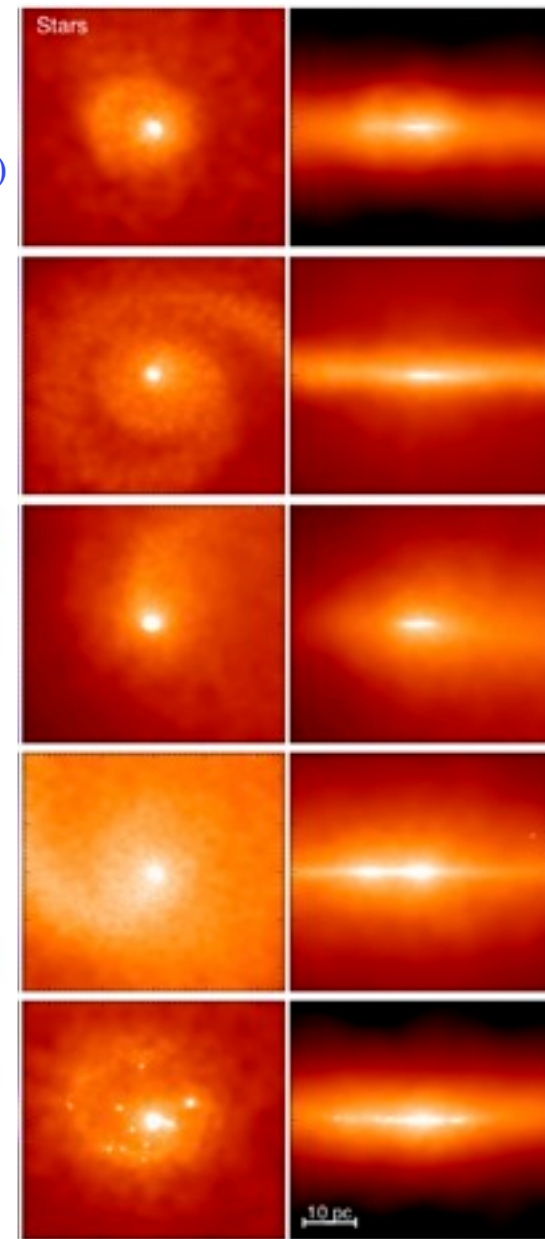
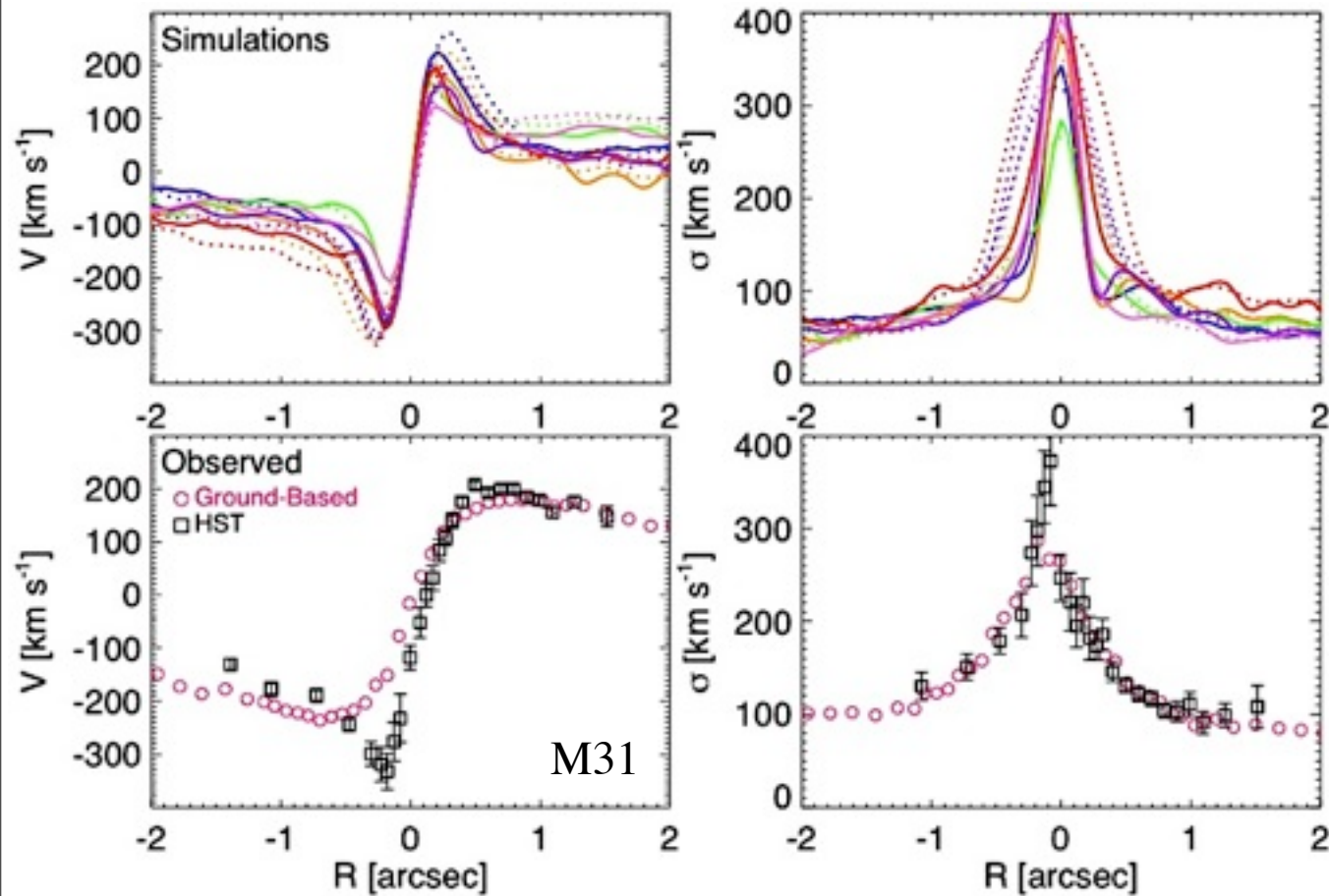
- M31 disk has  $\sim 0.1-1 M_{\text{BH}}$  in old stellar mass
- Outer radius  $R \sim 1-10 \text{ pc}$
- Moderate thickness, high eccentricity



- These are observed!

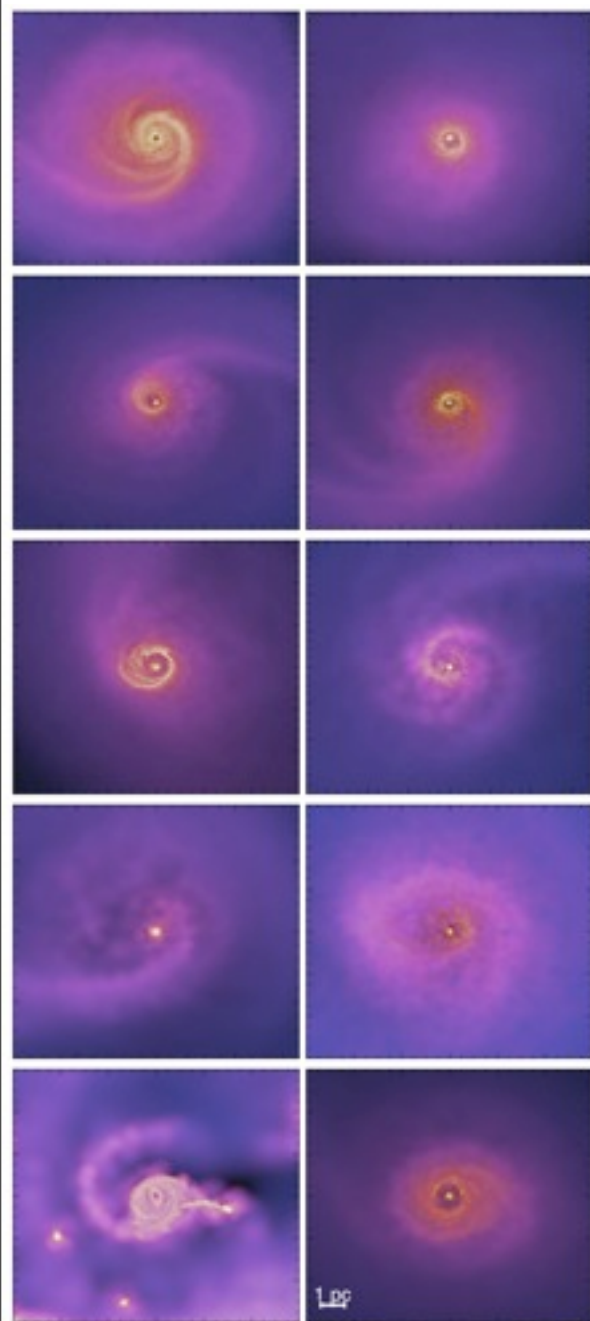
M31, NGC4486B, many candidates

(NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)



- “run backwards”: the M31 disk implies accretion at  $\sim 0.5\text{--}3 M_{\text{sun}}/\text{yr}$  ( $\sim L_{\text{Edd}}$ ) for  $\sim 100 \text{ Myr}$  ( $\sim M_{\text{BH}}$ ) !

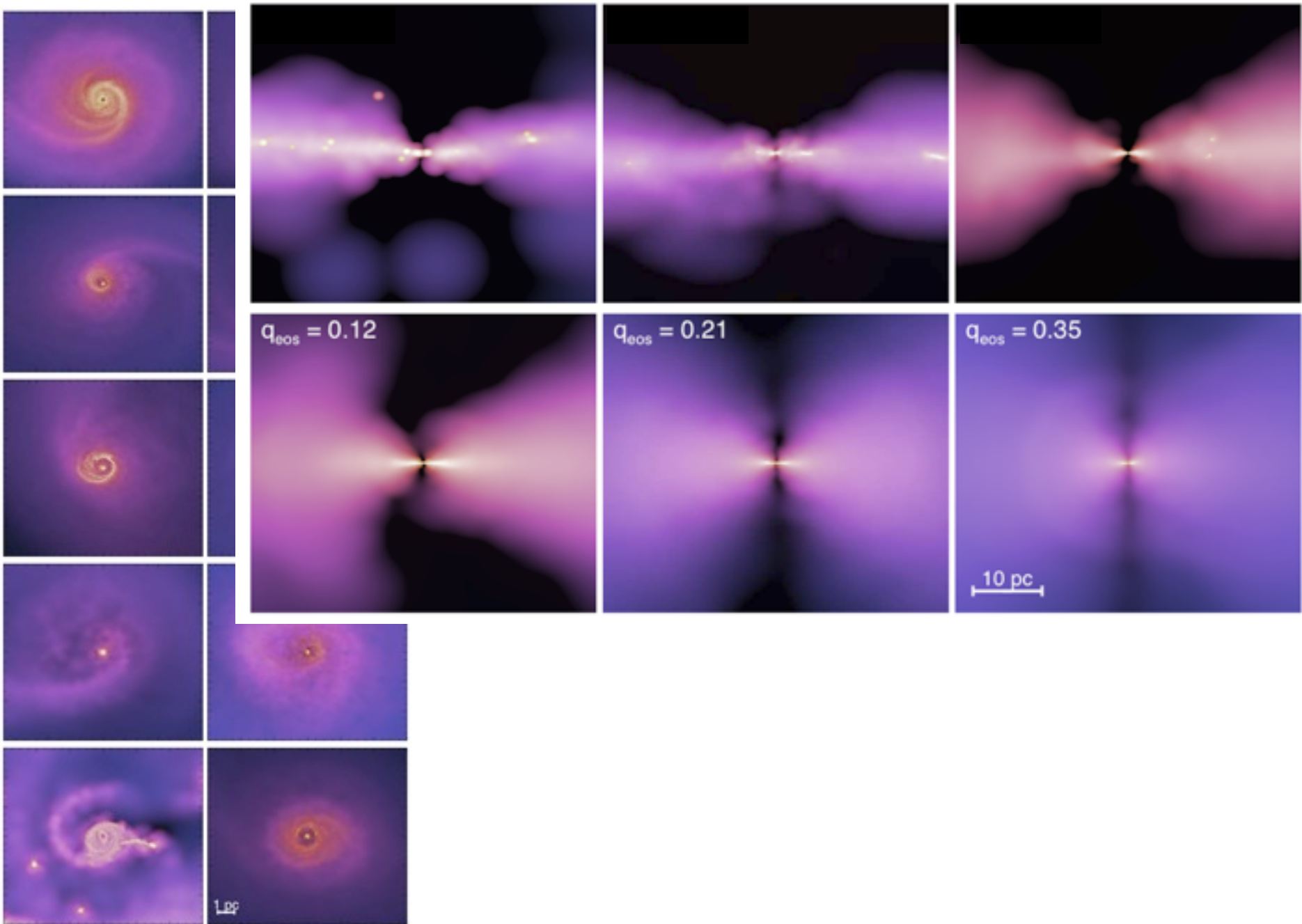
What about the obscuration from these disks?



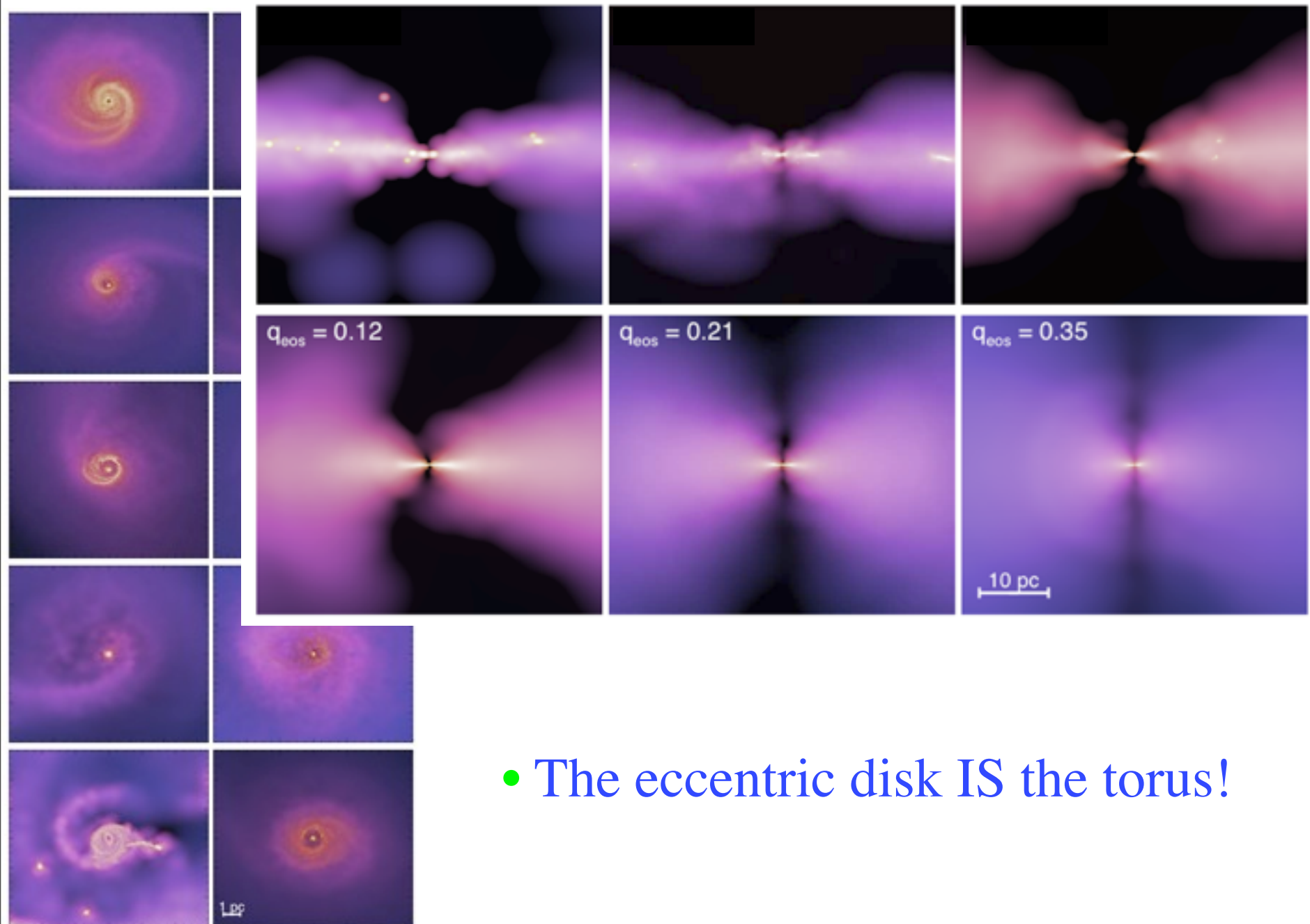
- Lots of gas in this disk during the inflow stages...



What about the obscuration from these disks?

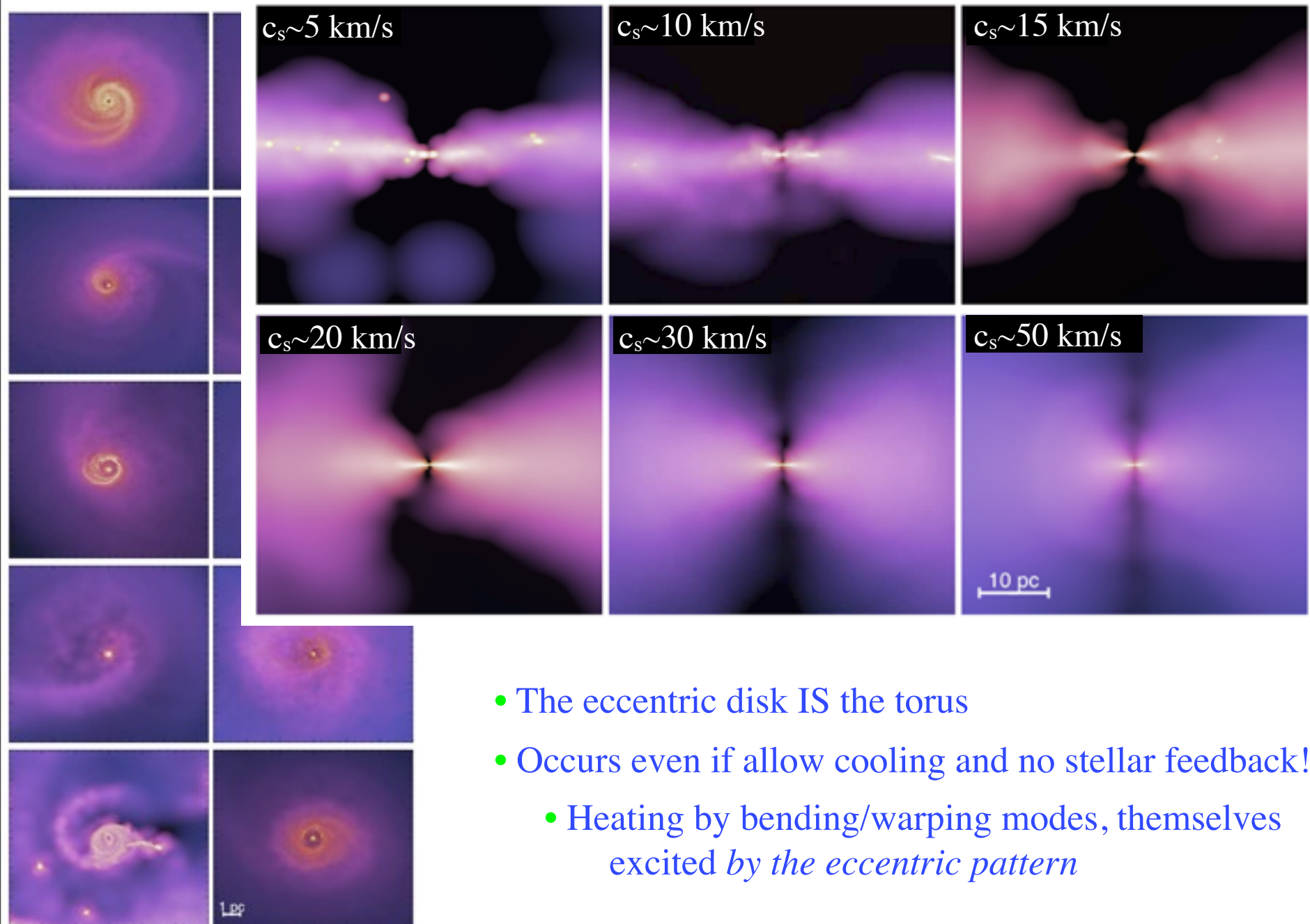


What about the obscuration from these disks?



- The eccentric disk IS the torus!

## What about the obscuration from these disks?



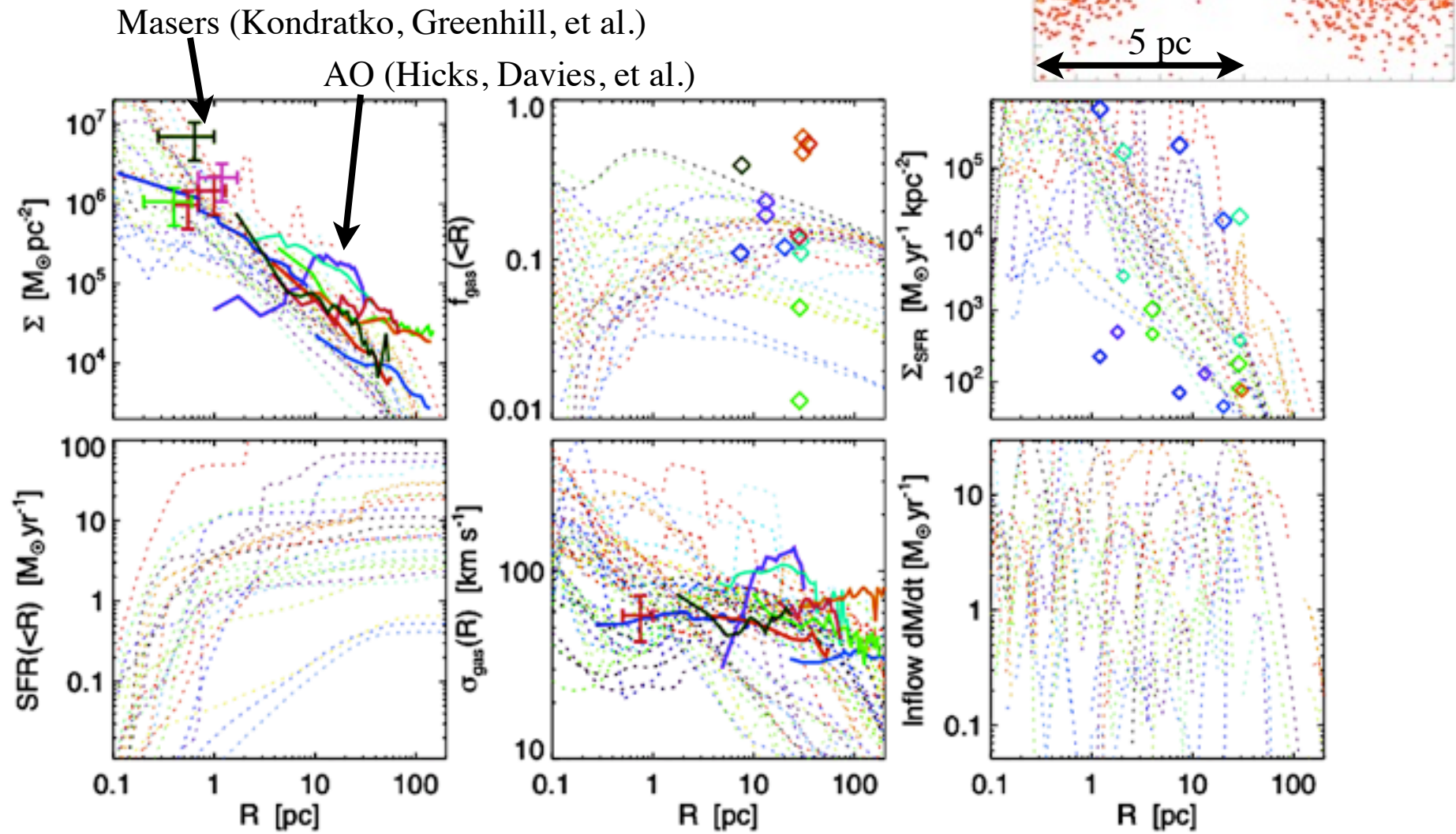
# Summary

- Fueling Most Luminous BHs:  
Global gravitational instabilities CAN power  $\sim 10 M_{\text{sun}}/\text{yr}$ ! Really!
  - New  $\dot{M}$  estimator: neither viscous nor Bondi
- “Stuff within Stuff”: Cascade of instabilities with diverse morphology
  - Doesn't matter how *first* ‘get down’ from large scales
- Accretion rates & orientations are stochastic
  - Vary on *all* timescales
  - Angular momentum changes rapidly - no correlation with host disk
- The torus is the disk: a dynamical accretion driver
  - Bending/warping instabilities: thick even without stellar feedback
- Stellar nuclear disk ‘relics’: M31 & 4486b:  
Can we directly observe the ‘fossil’ of the accretion driver & torus ?

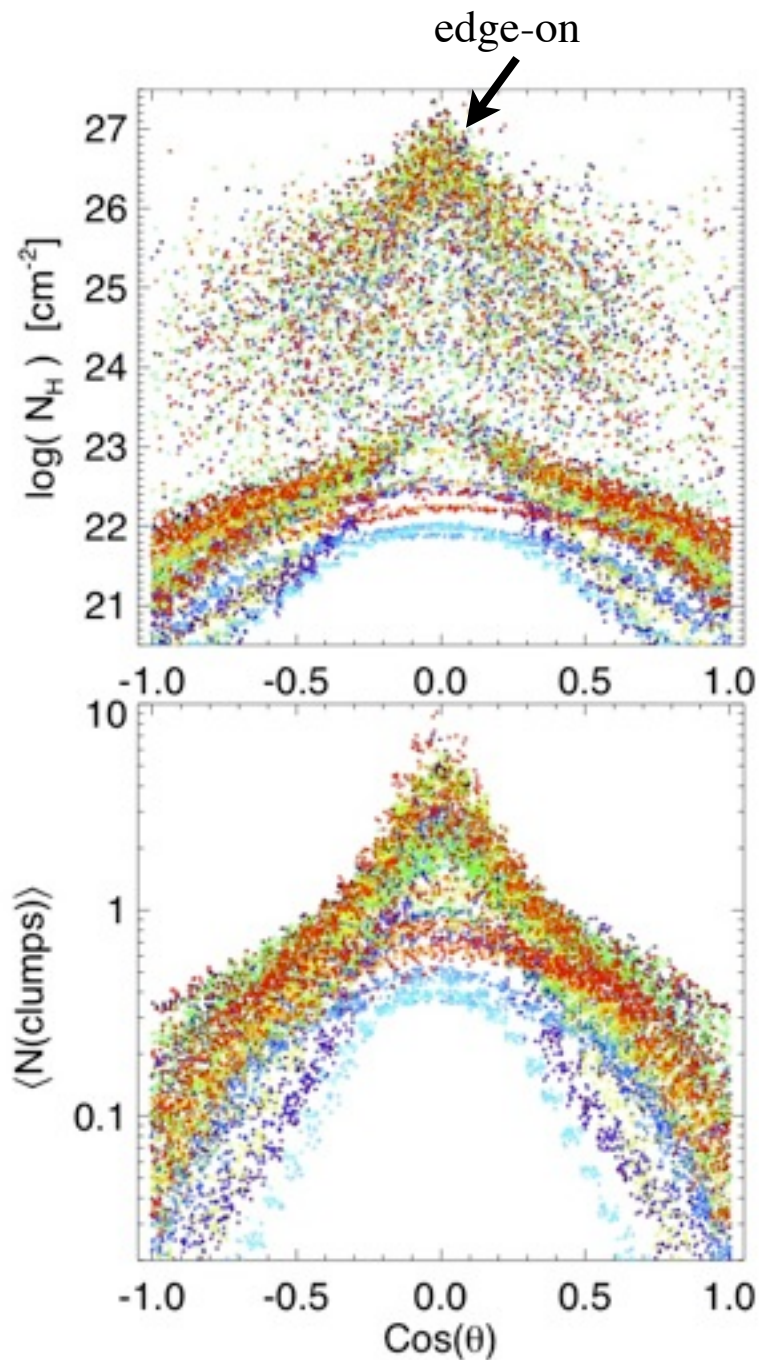
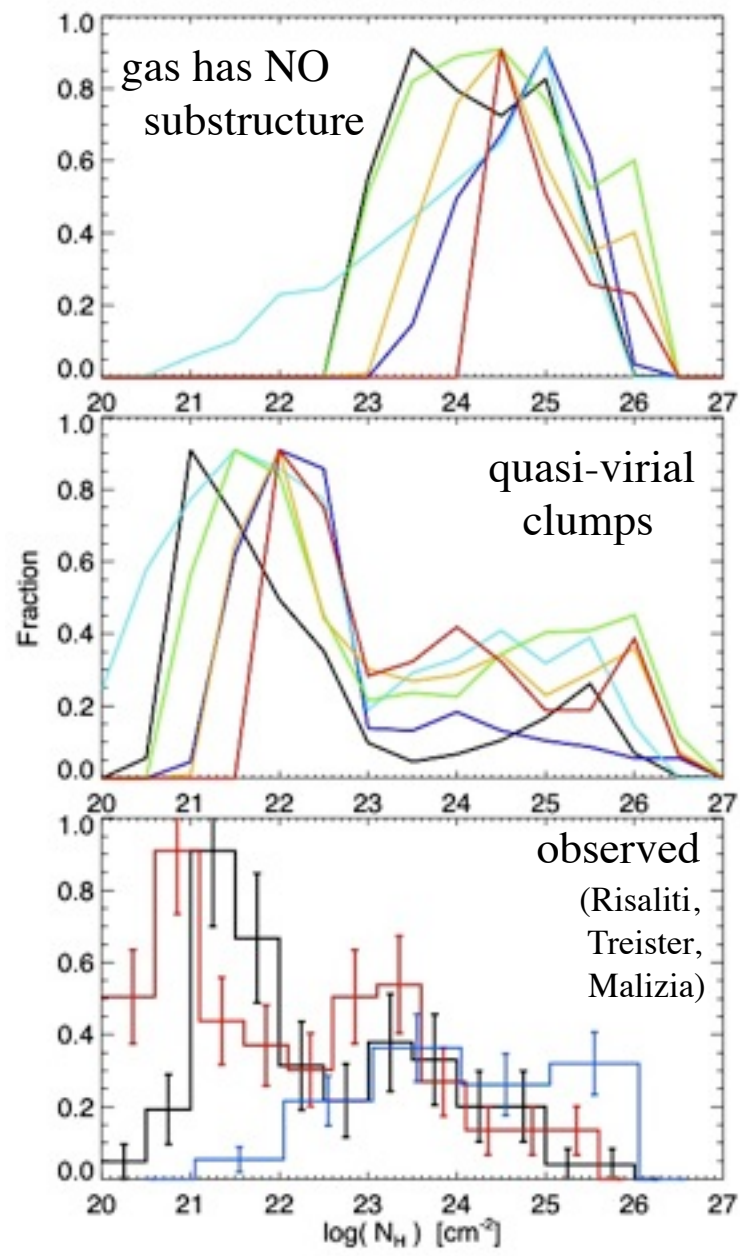


Obscuration and the ‘torus’

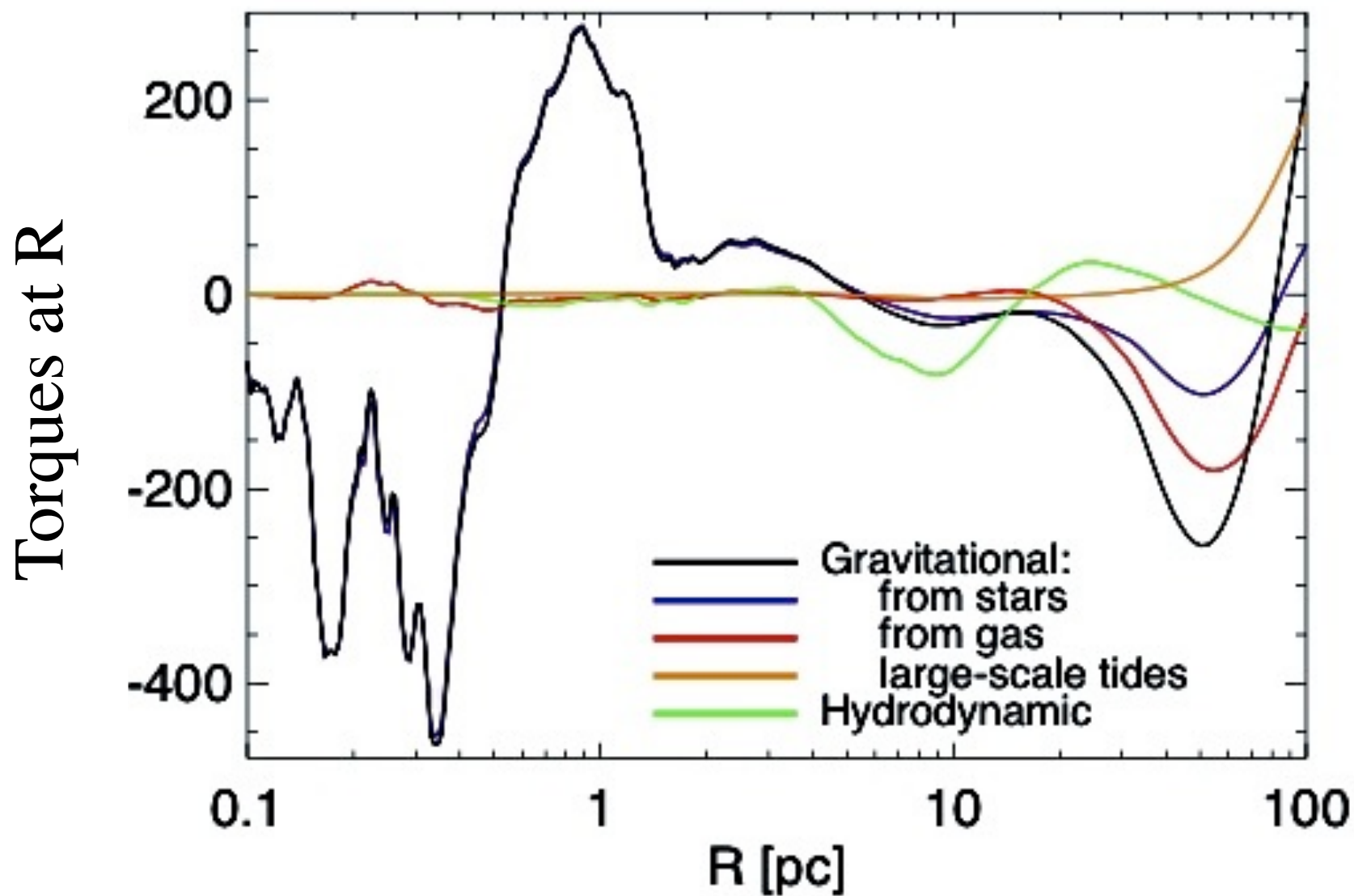
- Observed surface densities and kinematics arise naturally



• Compare column density distributions:



- Gravity dominates torques from 0.1 - 10,000 pc



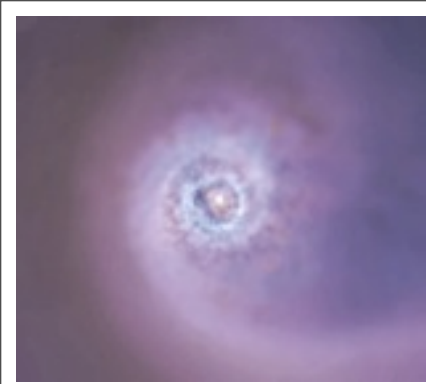


- $m=1$  ‘slow’ modes are special in a near-Keplerian potential

Disturb the stars with some  
perturbation in the disk:

$$\delta\Sigma \propto \cos m\phi$$

number of ‘arms’  $\nearrow$



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$$m \neq 1 :$$

Near a BH:  $\frac{1}{\Delta} \rightarrow \frac{1}{(1-m)\Omega^2}$

$$\Omega^2 \propto r^{-3} : \frac{1}{\Delta} \rightarrow 0$$

$$|\mathbf{e}| \sim \left( \frac{\delta\Sigma}{\Sigma} \right) \frac{M_{\text{disk}}(< r)}{M_{\text{BH}}}$$

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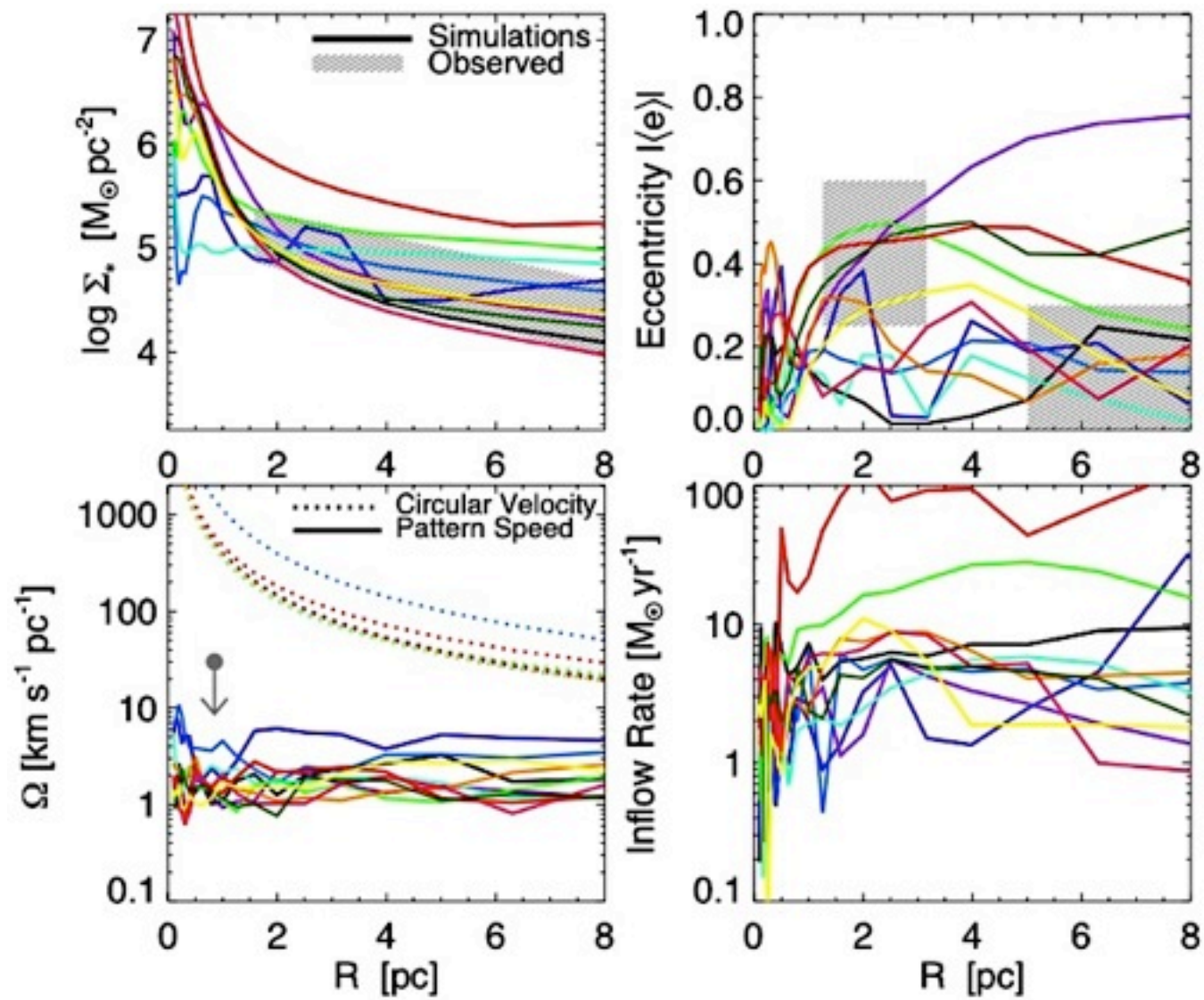
$$m = 1 :$$

$$\Delta \rightarrow 0 \text{ (resonance)}$$

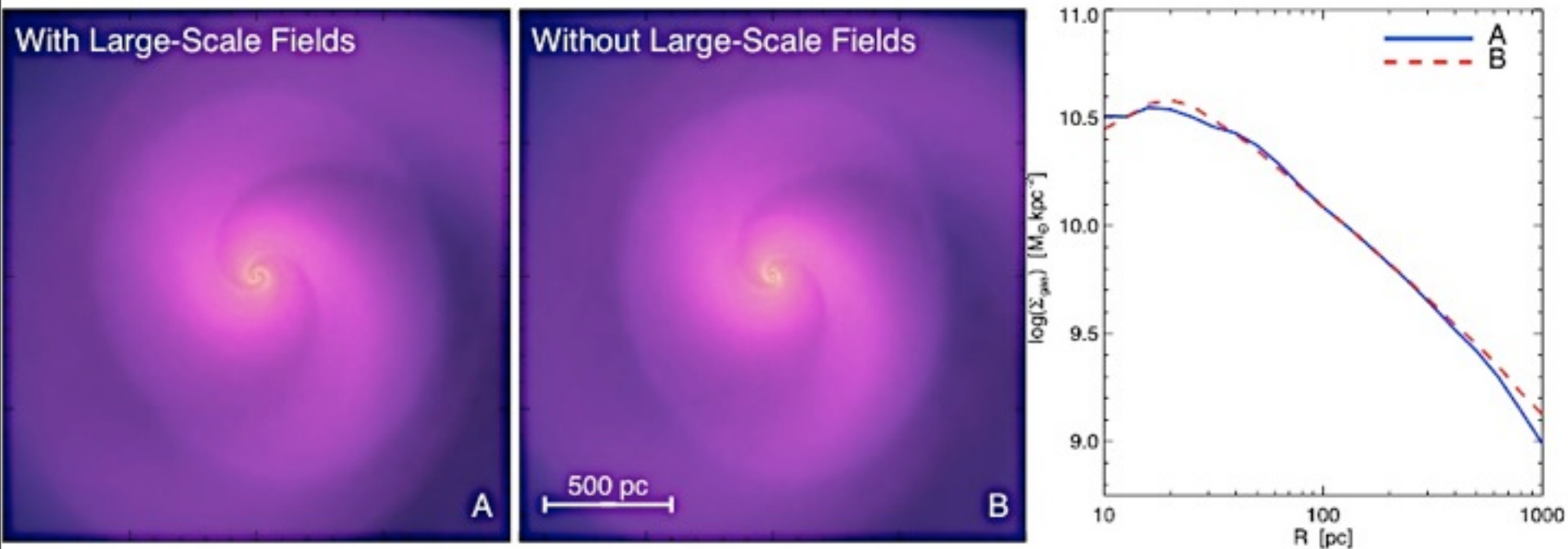
$$|\mathbf{e}| \sim \frac{\delta\Sigma}{\Sigma}$$

- Strong torques can propagate to all  $r$  (even  $\ll 0.1\text{pc}$ )  
INDEPENDENT of  $M_{\text{disk}}(<r)/M_{\text{BH}}$

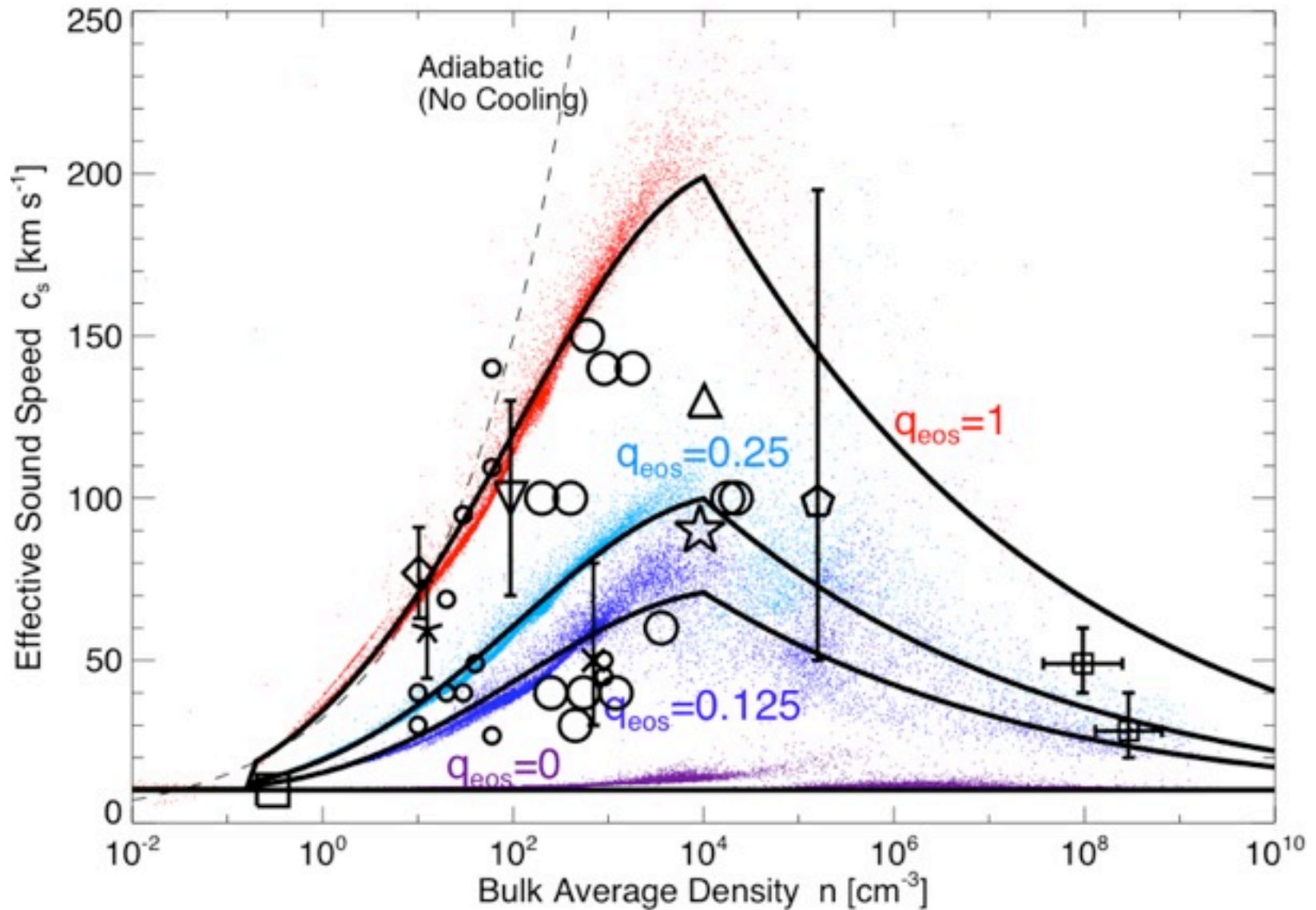




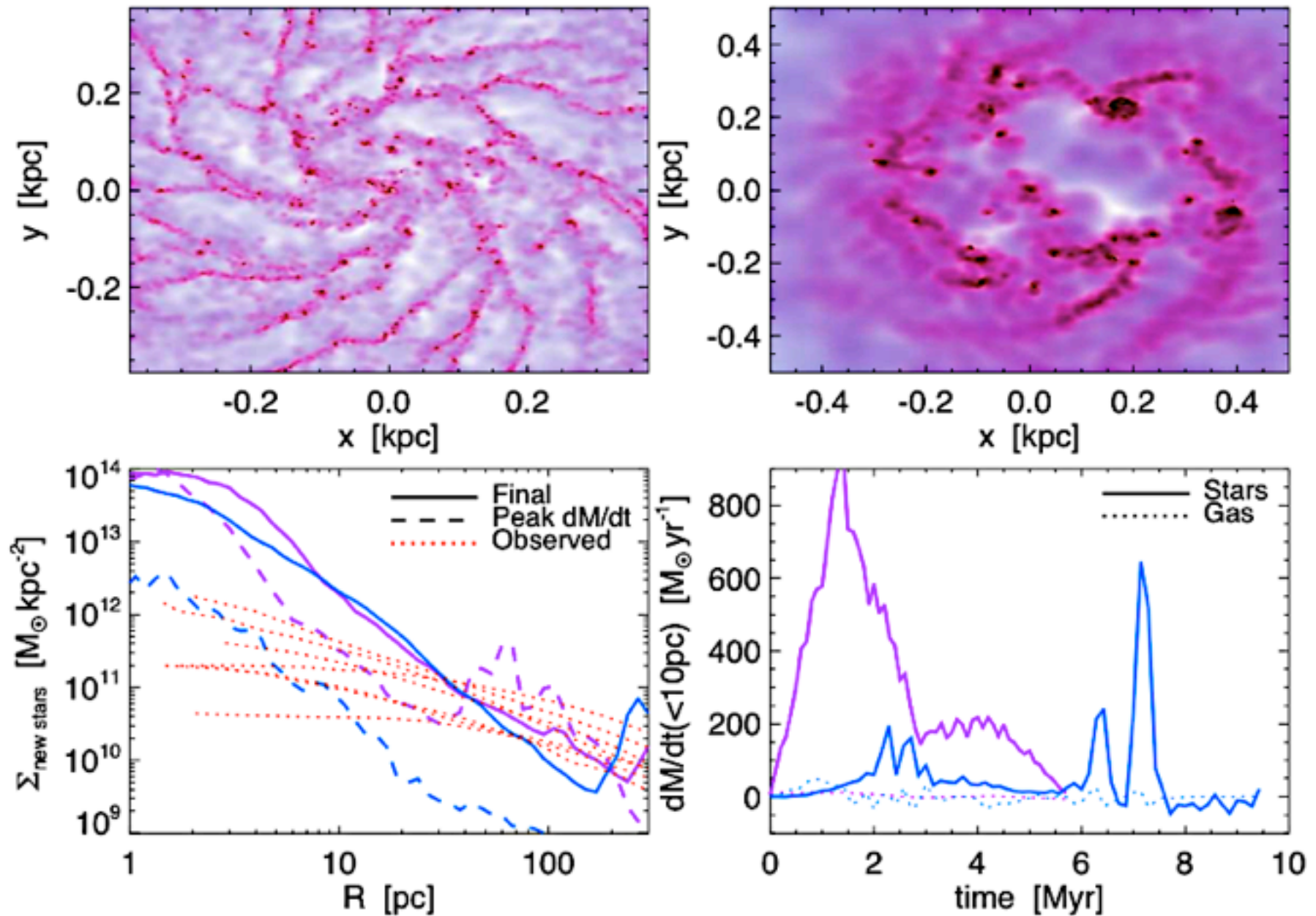
# Large-Scale Tides are Not Important for AGN:



# The Effective Stellar Feedback on Small Scales: (REQUIRE SOME SUB-RESOLUTION MODEL)

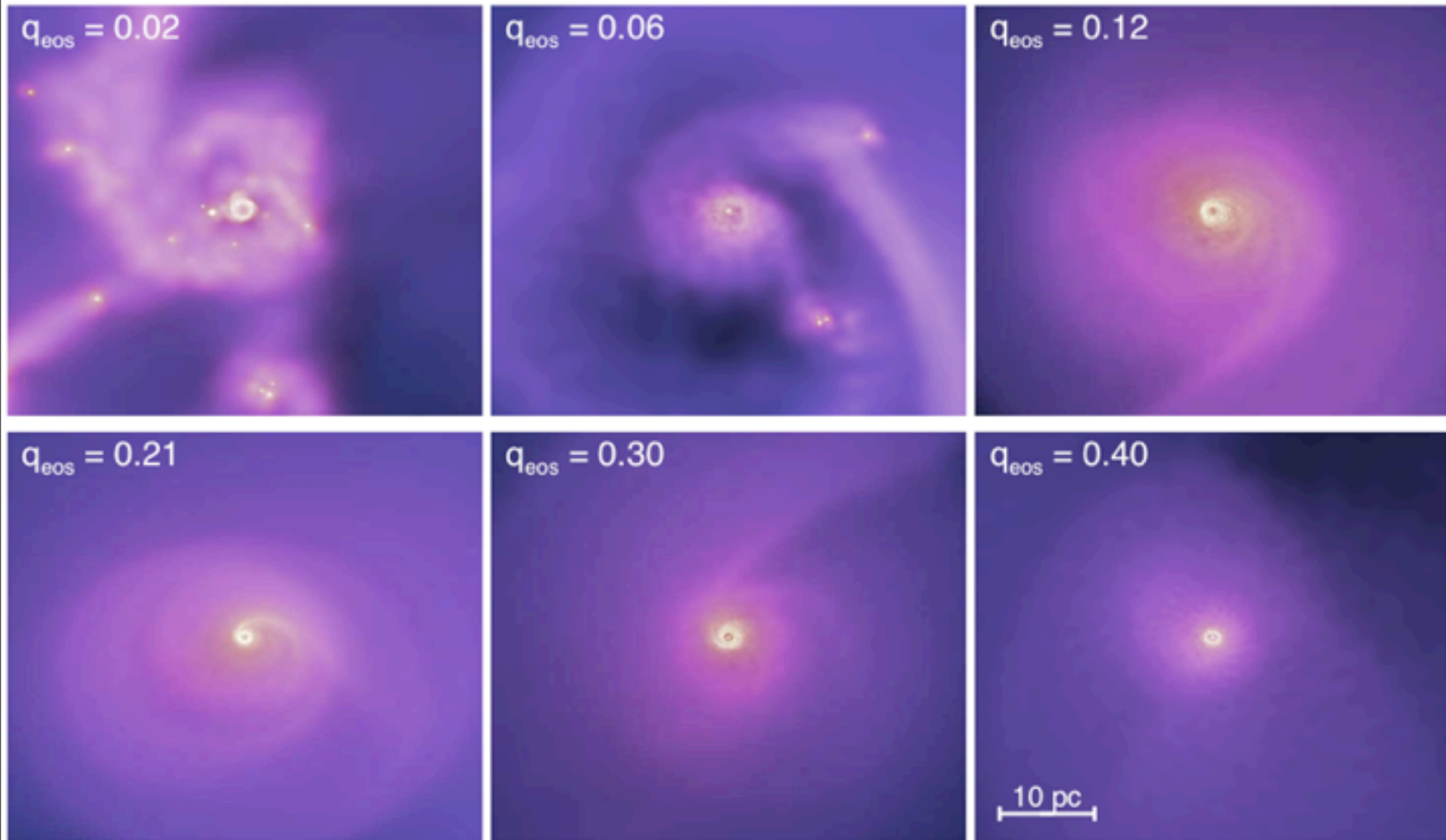


## A “No Feedback” ISM is Ruled Out on Small Scales:

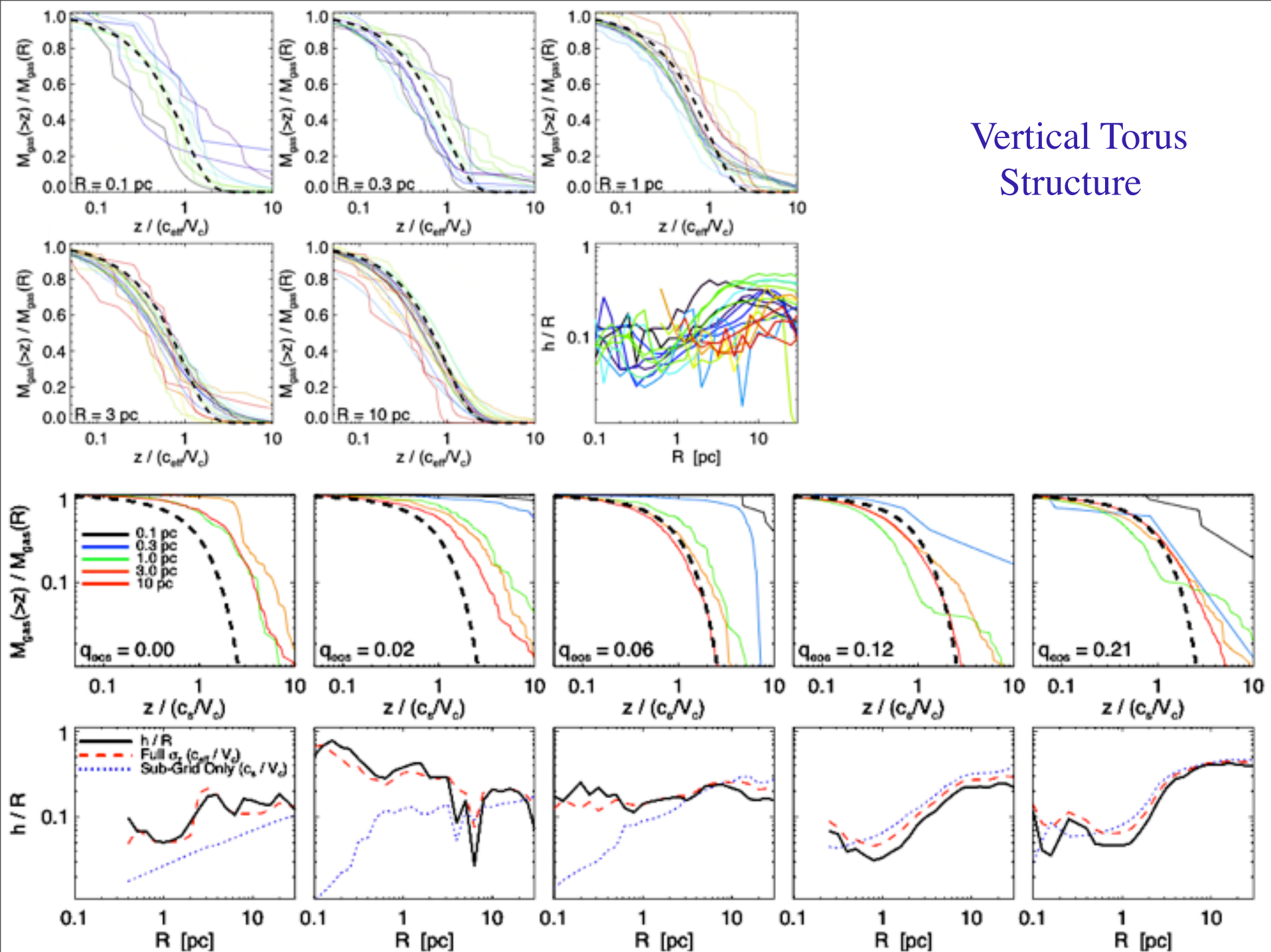


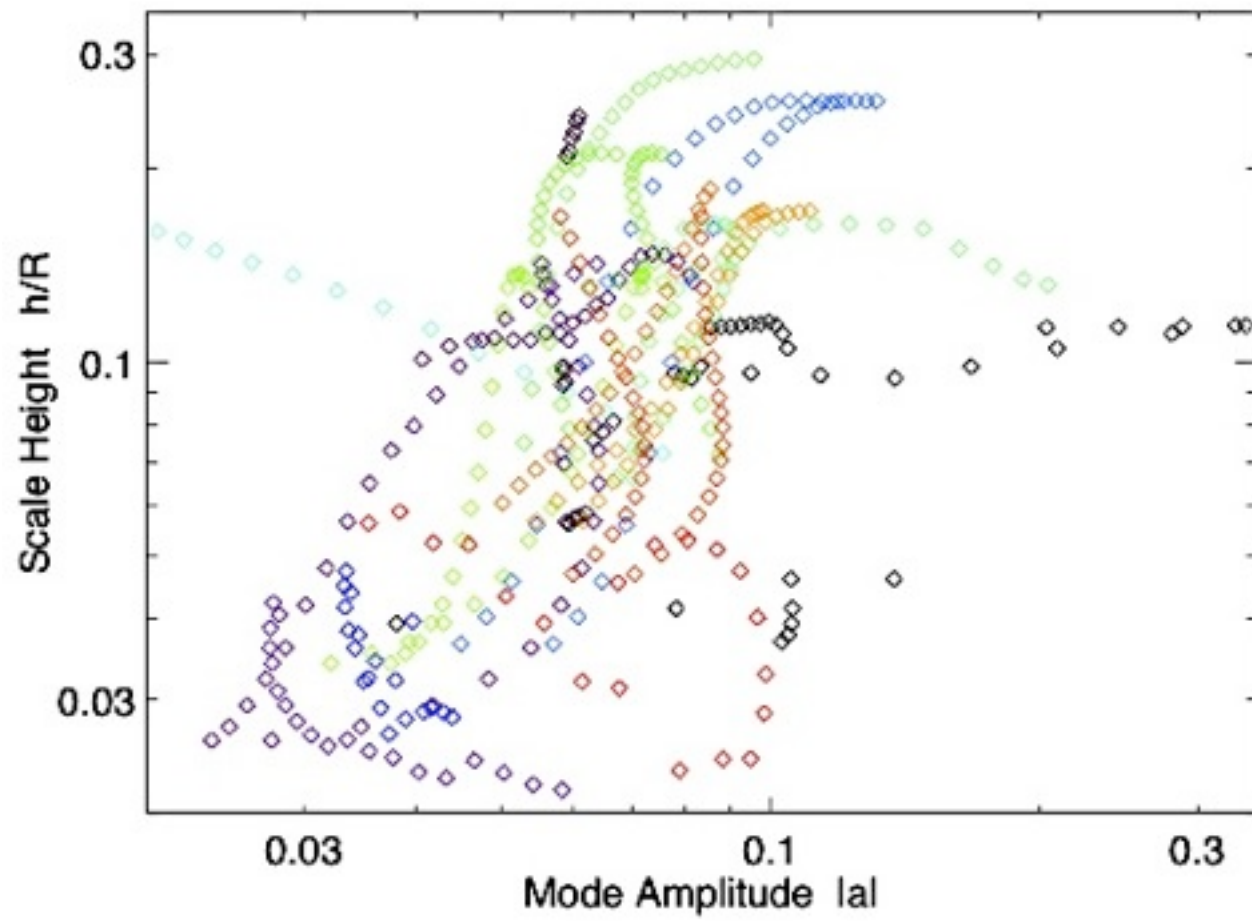


But qualitative conclusions are insensitive to the gas microphysics

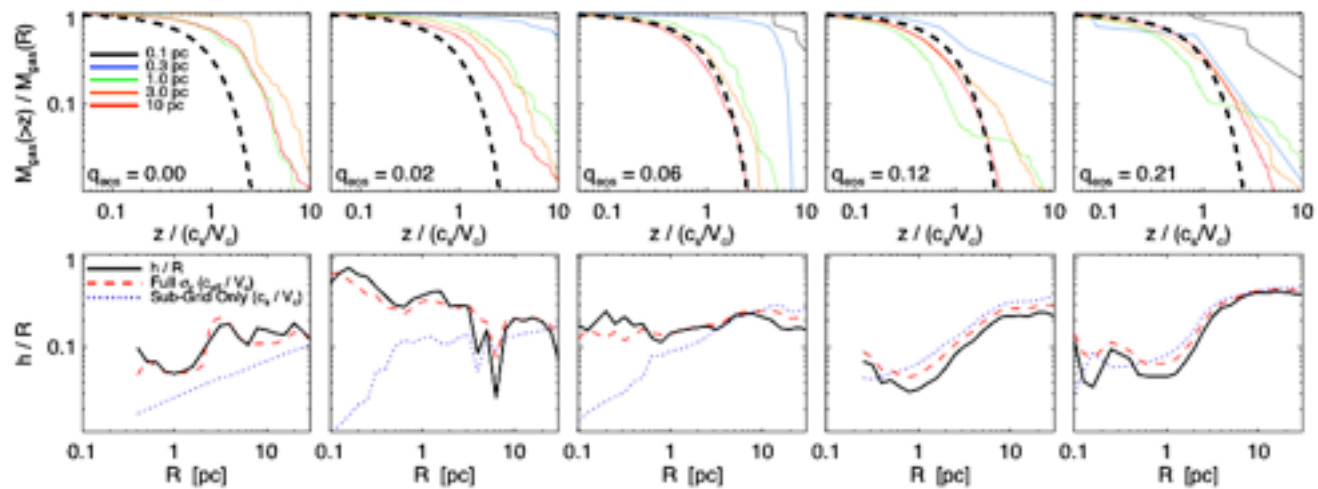


# Vertical Torus Structure



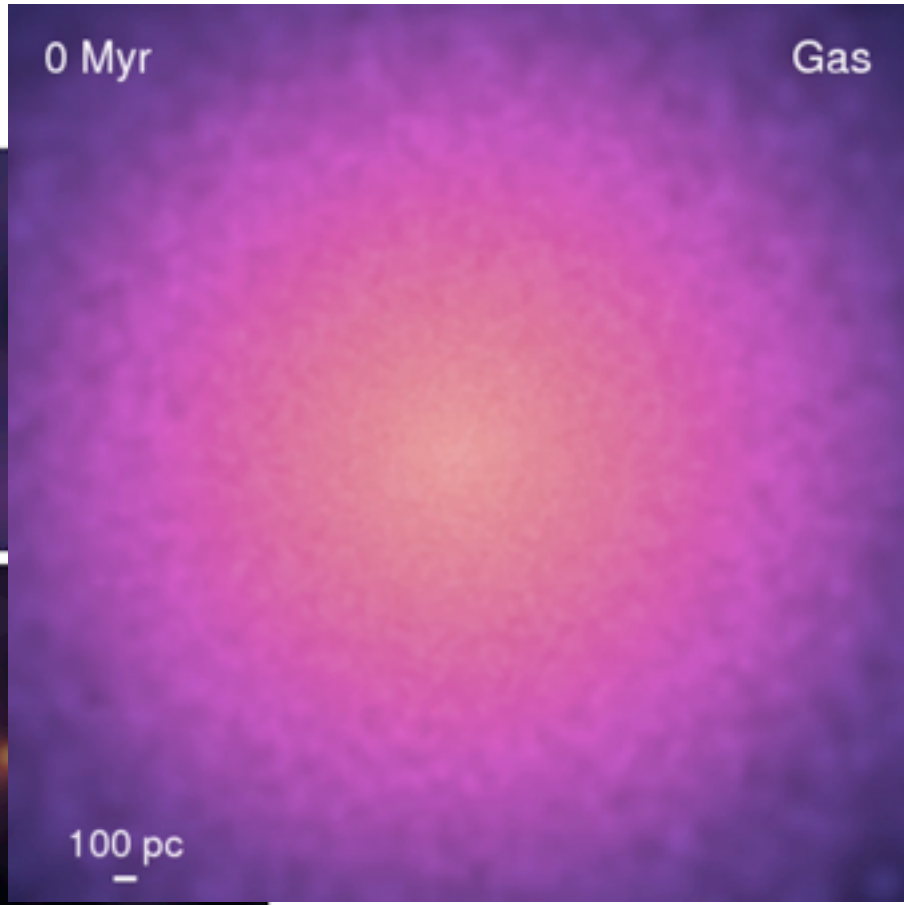
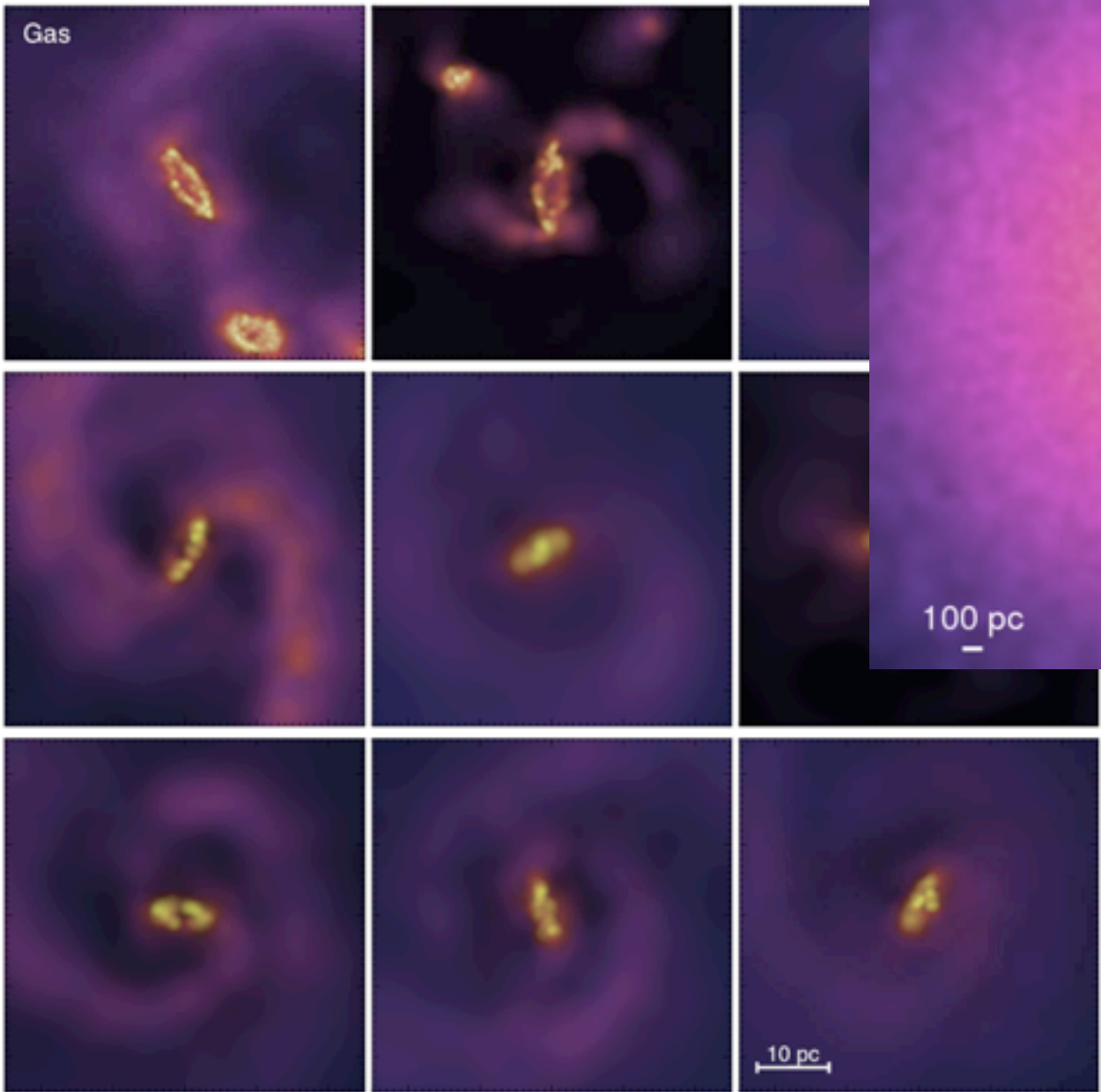


## Vertical Torus Structure





Mis-alignments with the parent disk are common



- Implications for:
  - BH spin
  - BH-BH mergers
  - Recoils
  - Variability

## Torus-Host disk misalignments:

