How do Black Holes Get Their Gas?

Philip Hopkins

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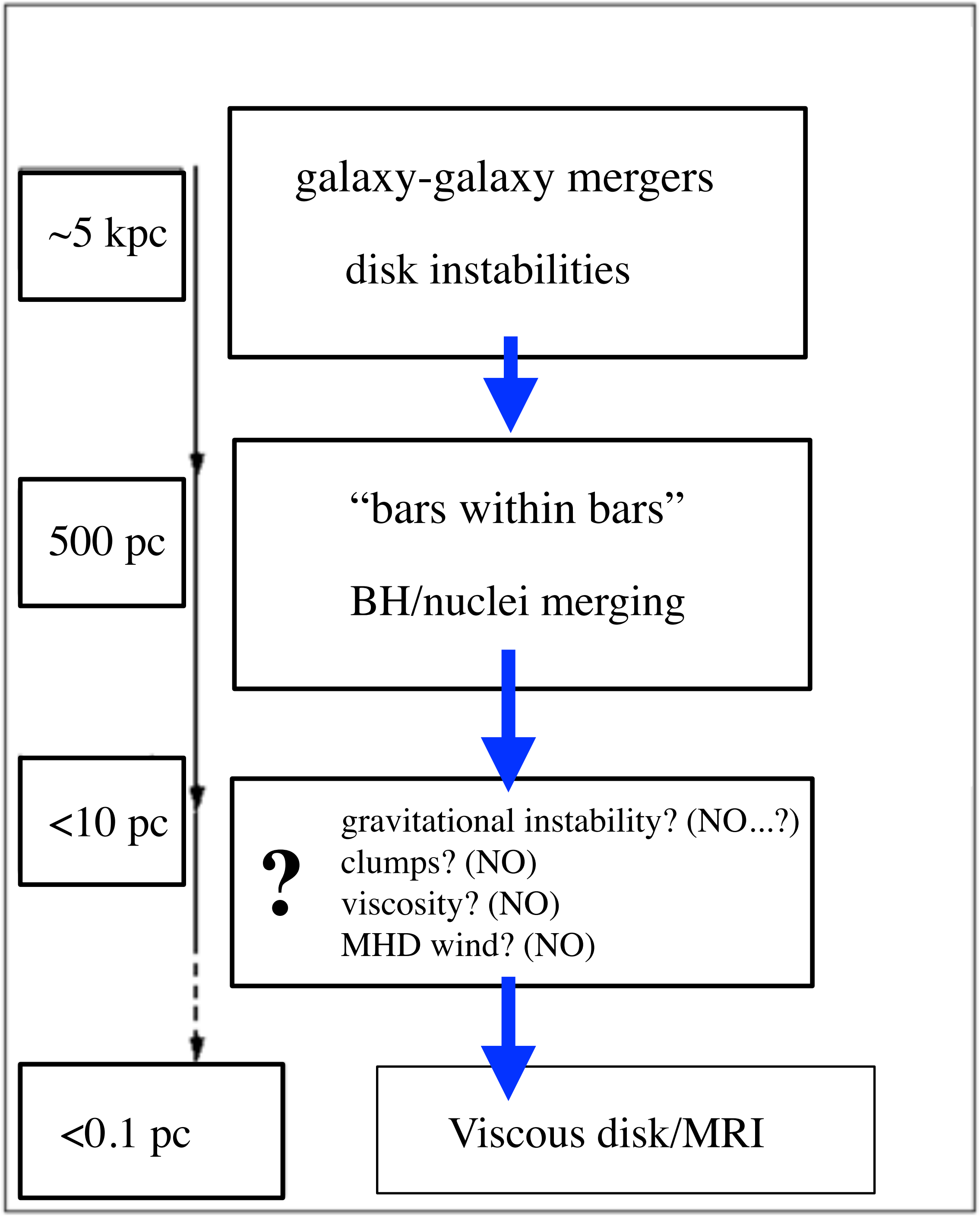
Alison Coil, Adam Myers, Patrik Jonsson, Chris Hayward

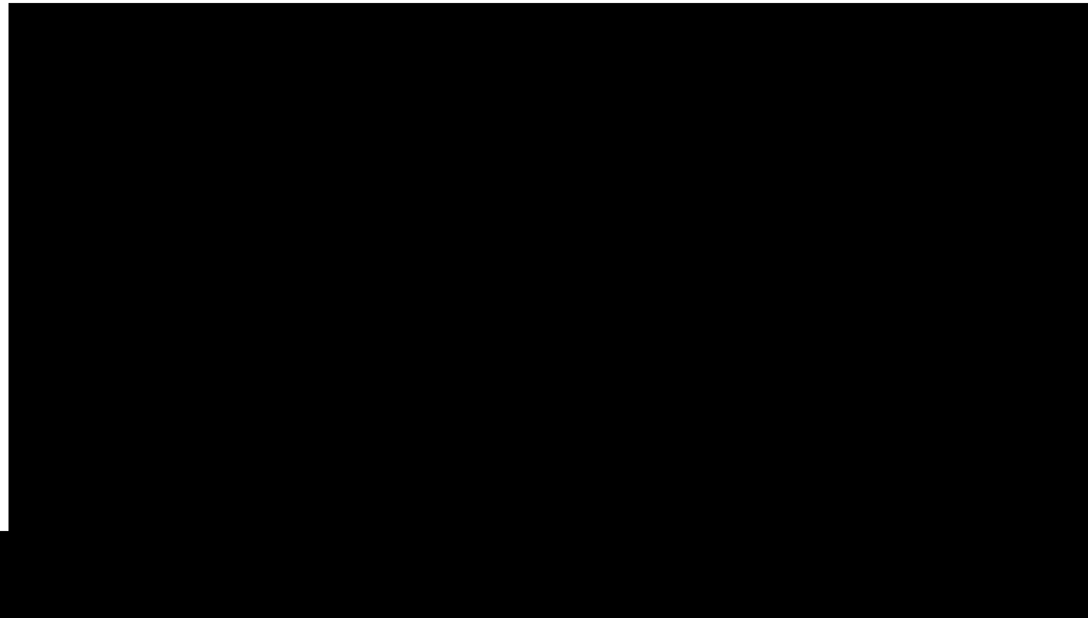
- Focus: Most luminous QSOs (~1-10 M_{sun}/yr)
- 'Bottleneck' at <10-50pc: BH begins to dominate the potential

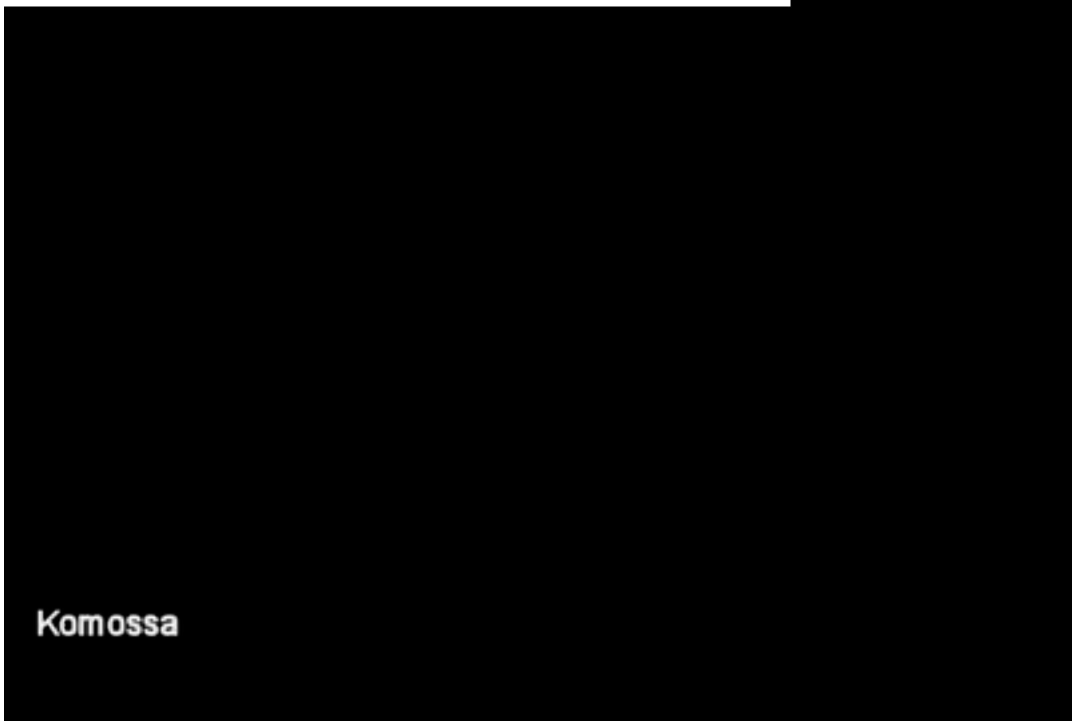
  (e.g. Goodman et al., Jogee et al., Martini et al.)



- 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

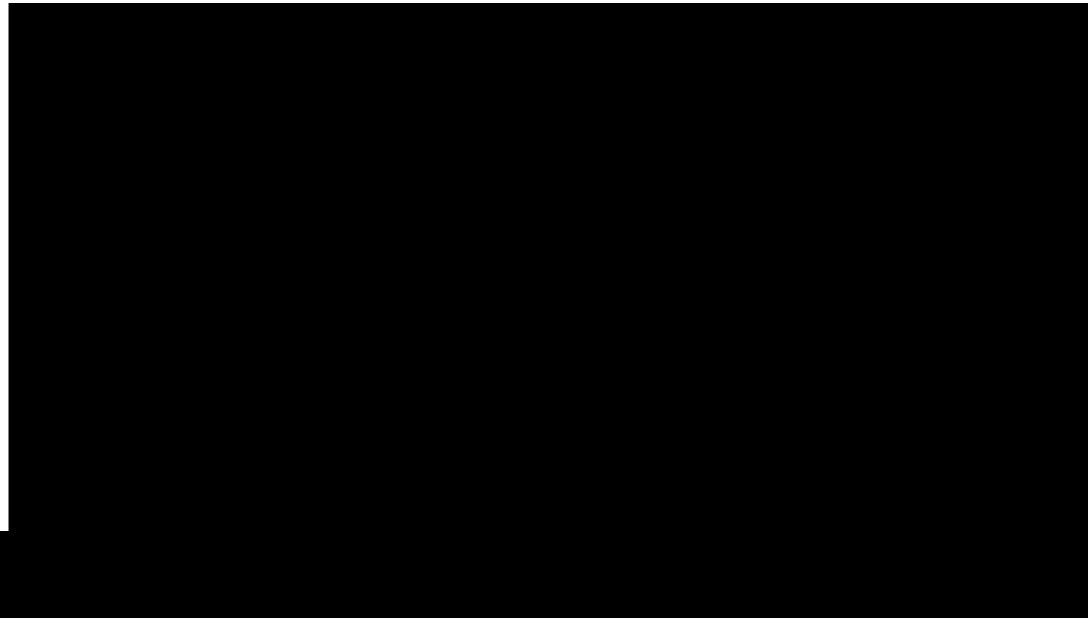


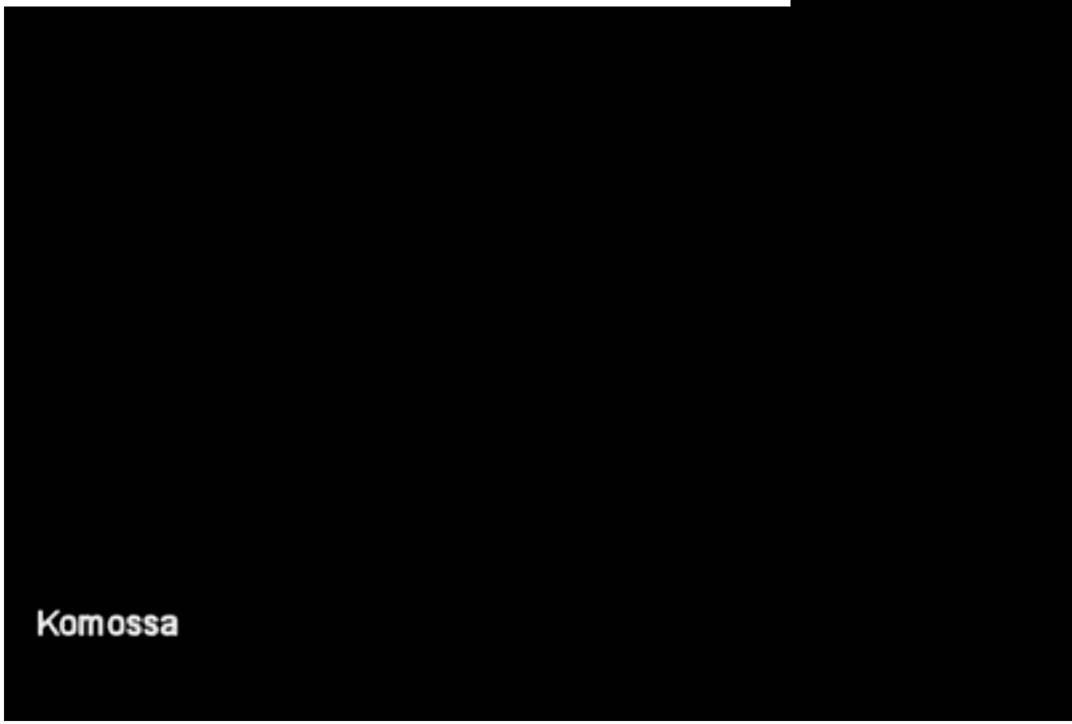


- Problem:
  Scale of merger: ~100 kpc
  Viscous disk: ~0.1 pc

- Solution 1: simple prescription

- Solution 2: re-simulate ("zoom in") and see what happens!





Simulations:

FOLLOWING THE GAS IN...

- Here: Focus on *robust* conclusions

Simulations:

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- Need to include:

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Simulations:

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- Need to include:
  - Gas+Stars

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Simulations:

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- Need to include:
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    - Self-gravity!

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Simulations:

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  - Star formation
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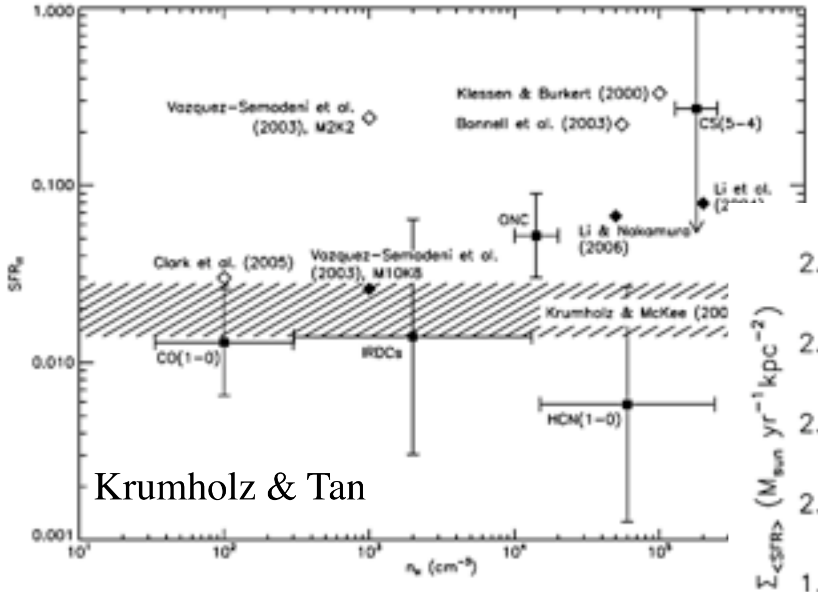
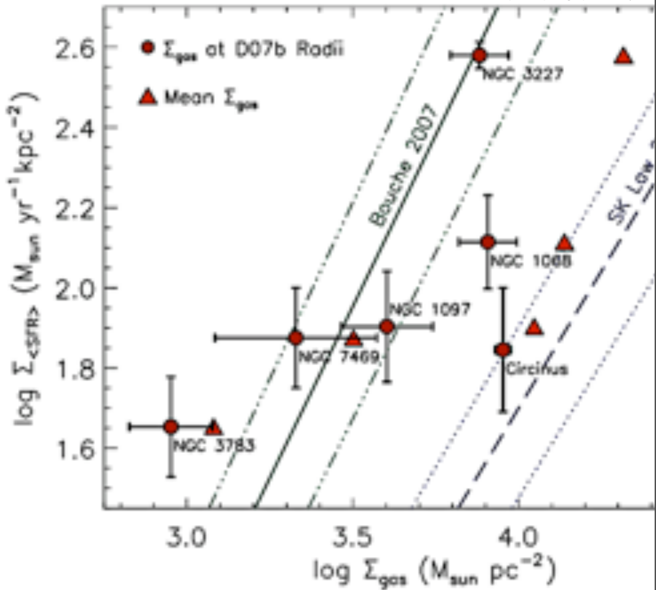


Hicks et al.



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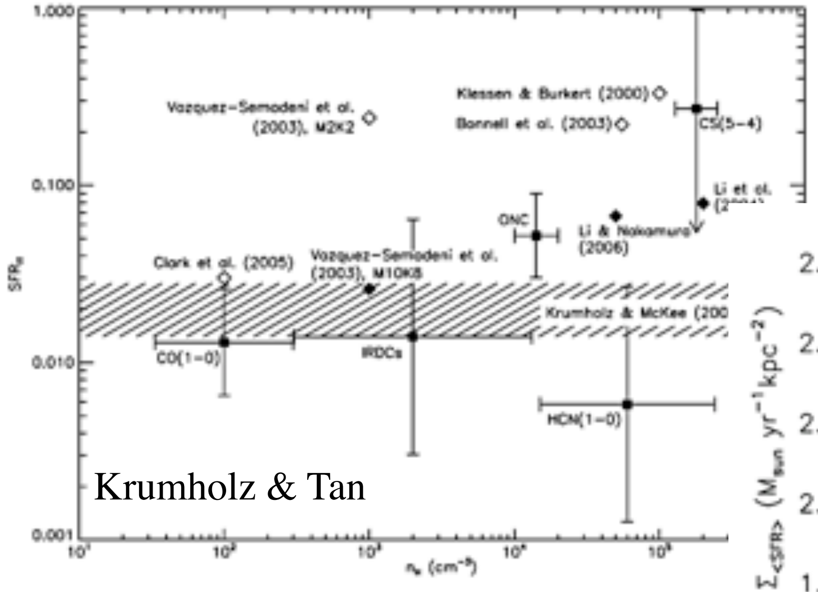
      - Admit we don't understand it!



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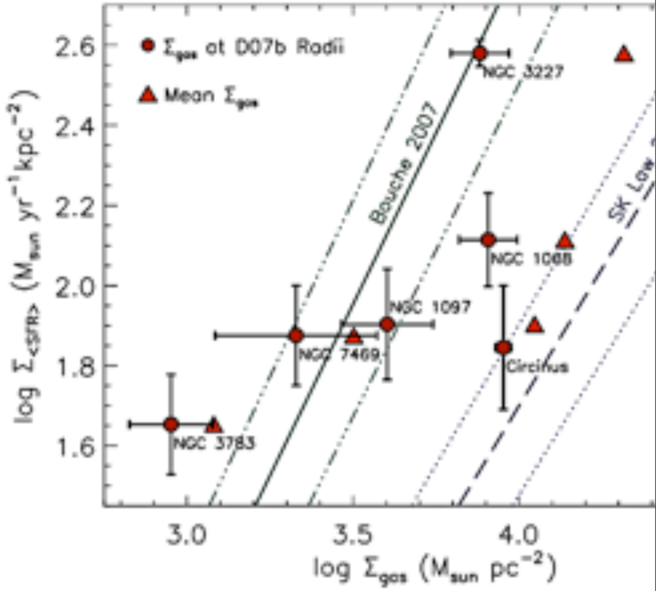

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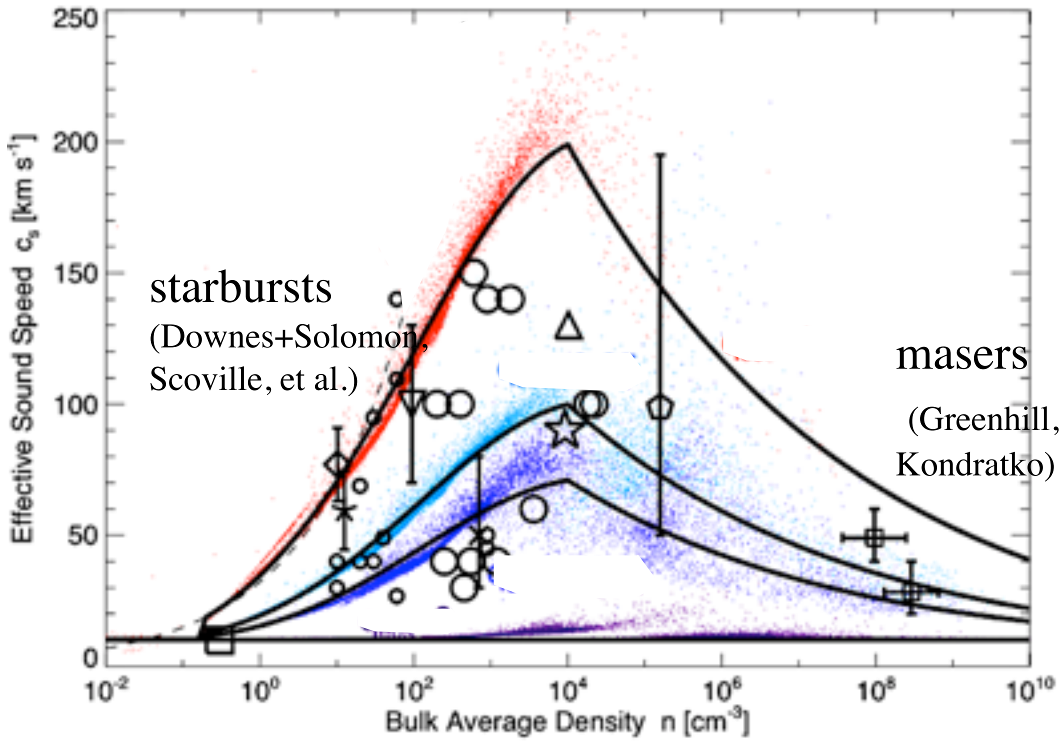

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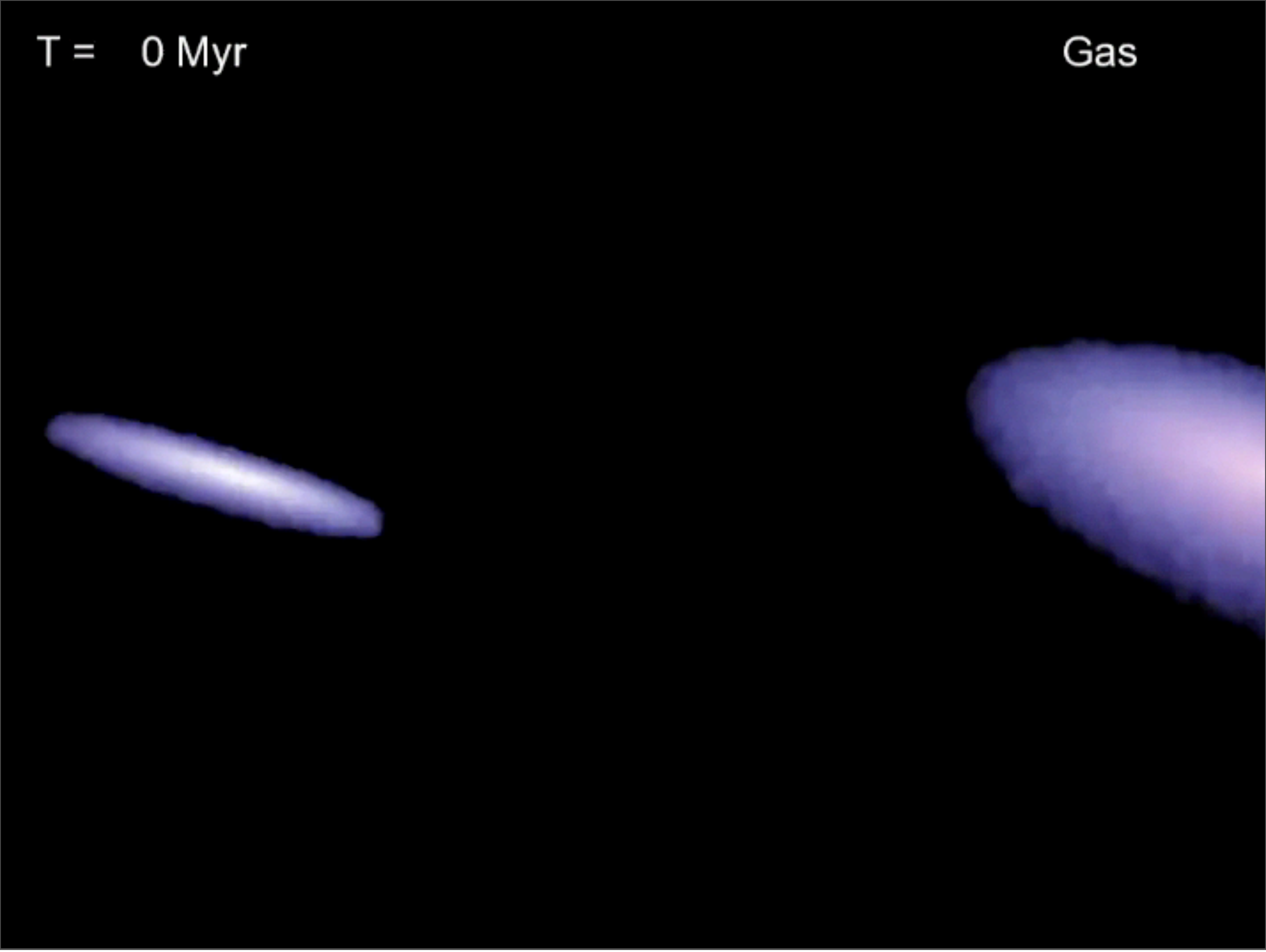
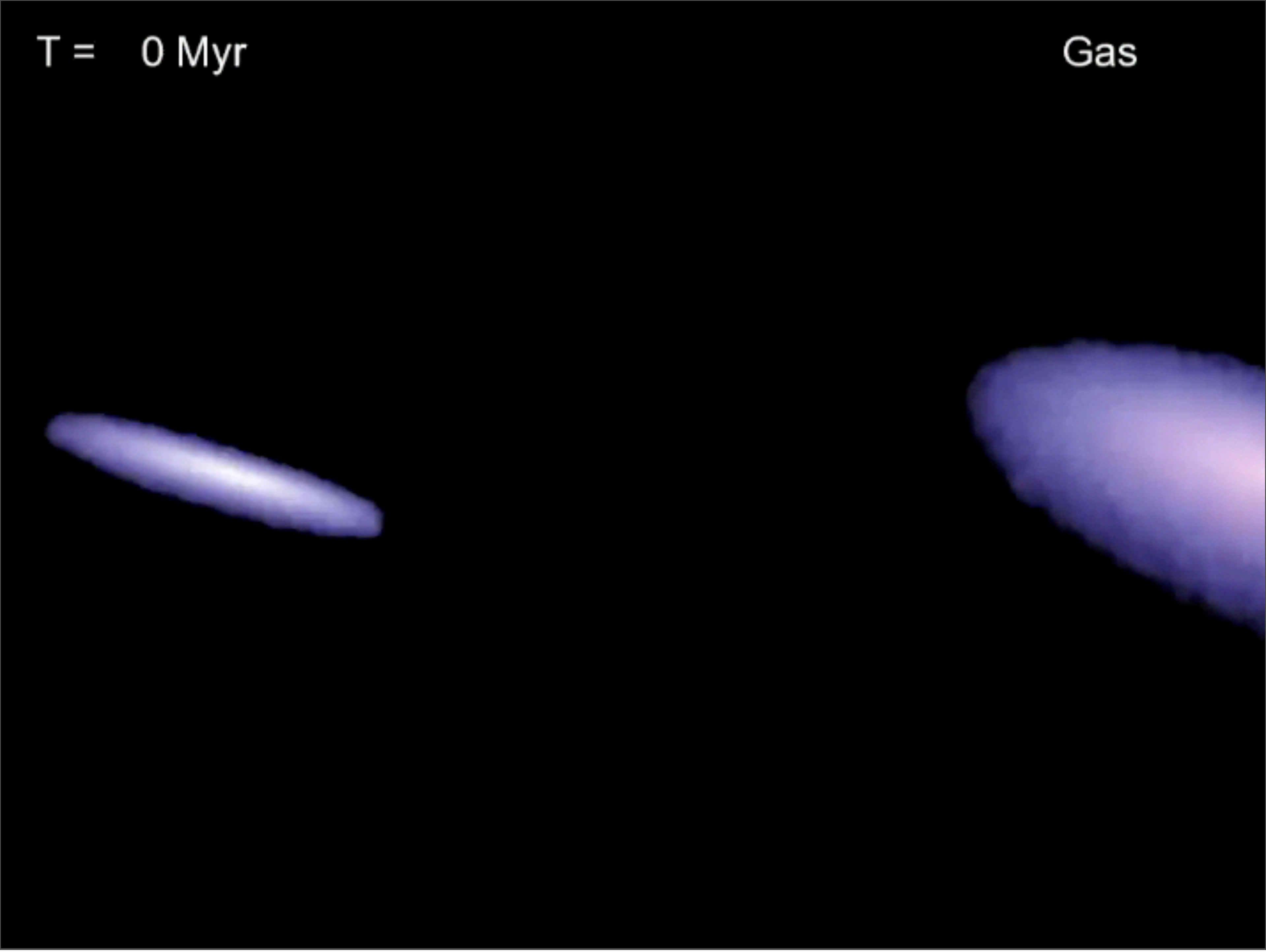

T = 0 Myr
Gas

Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)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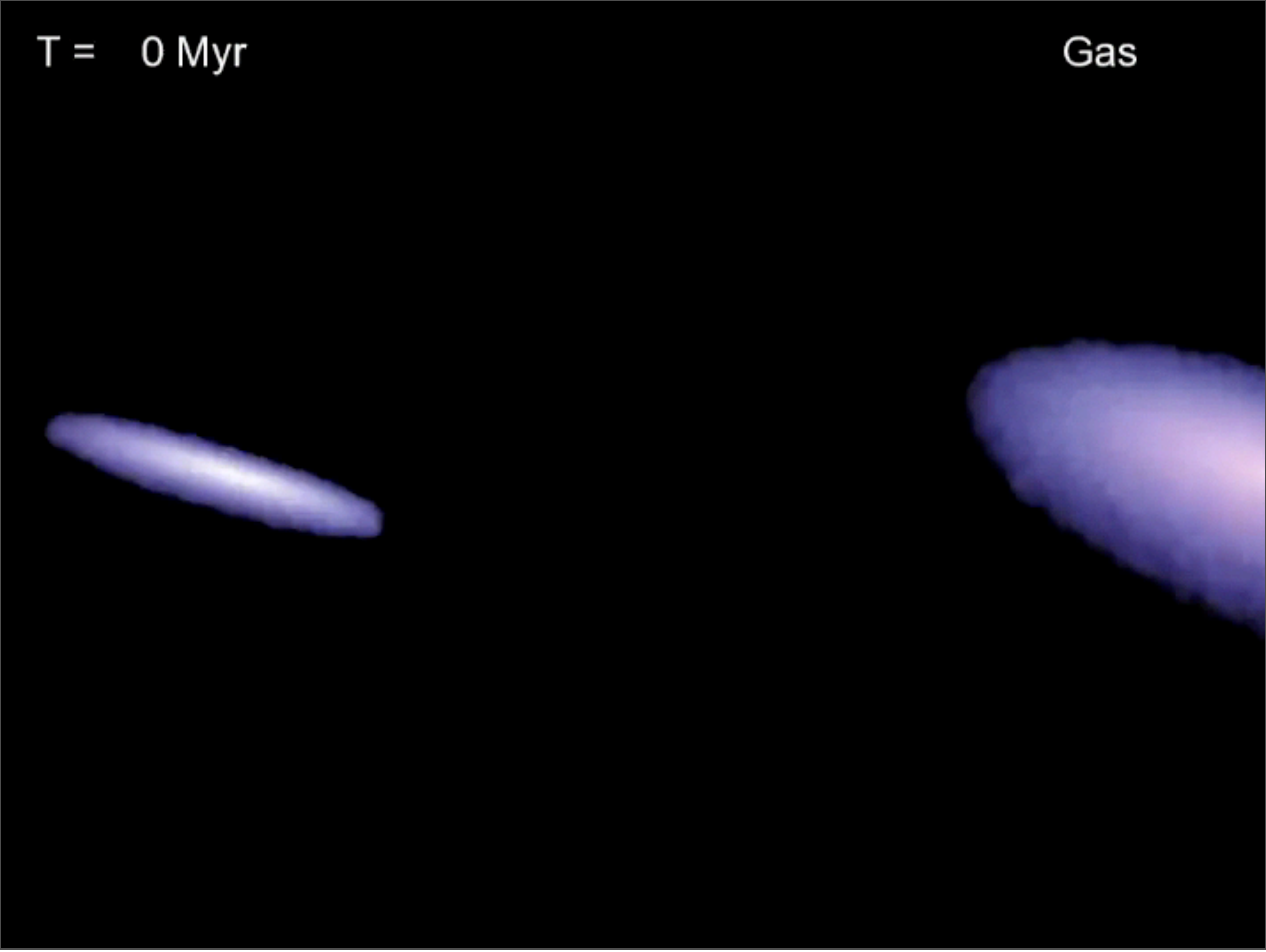
Triggers Starbursts (e.g. Mihos & Hernquist 1996)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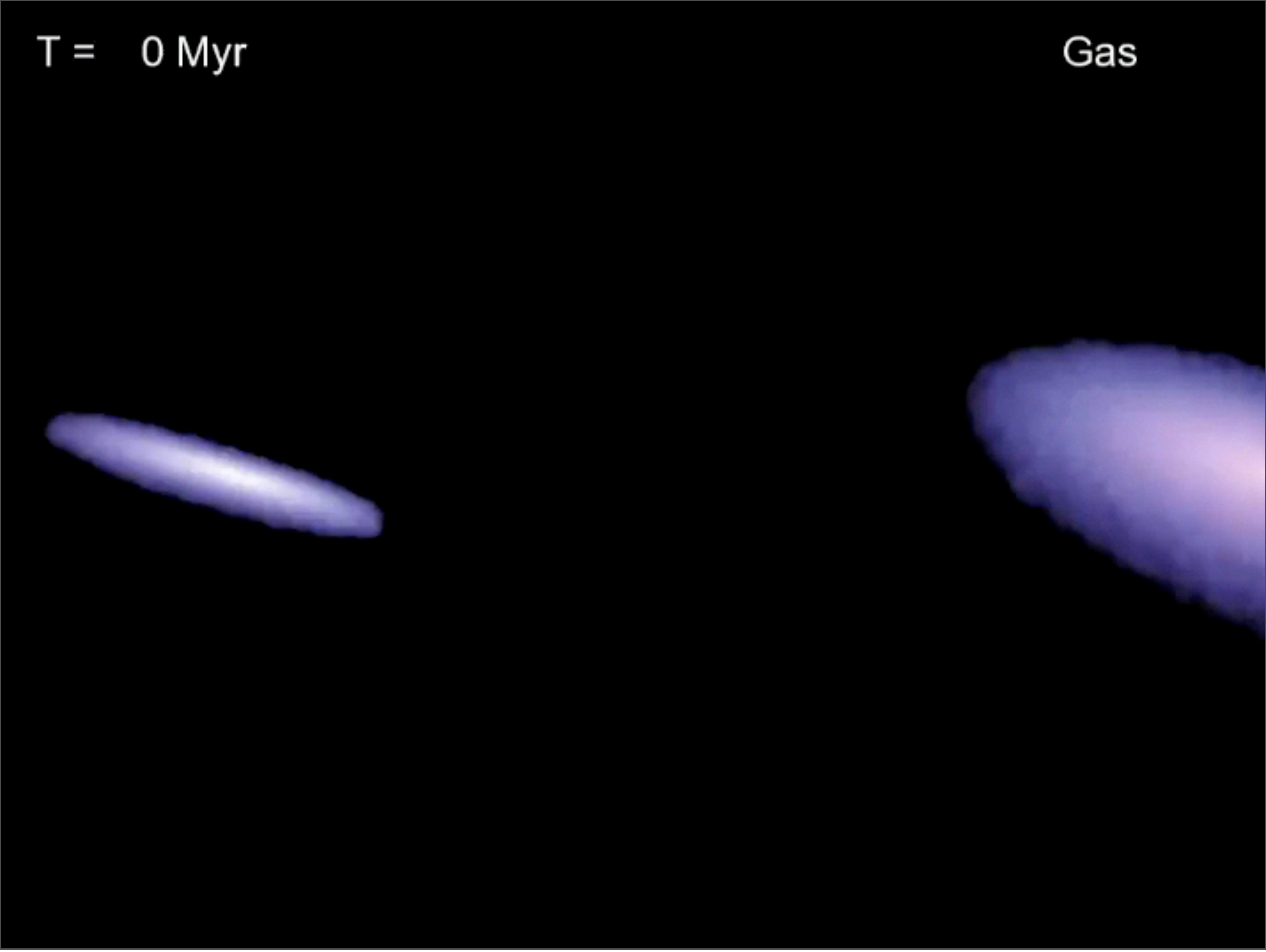
Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)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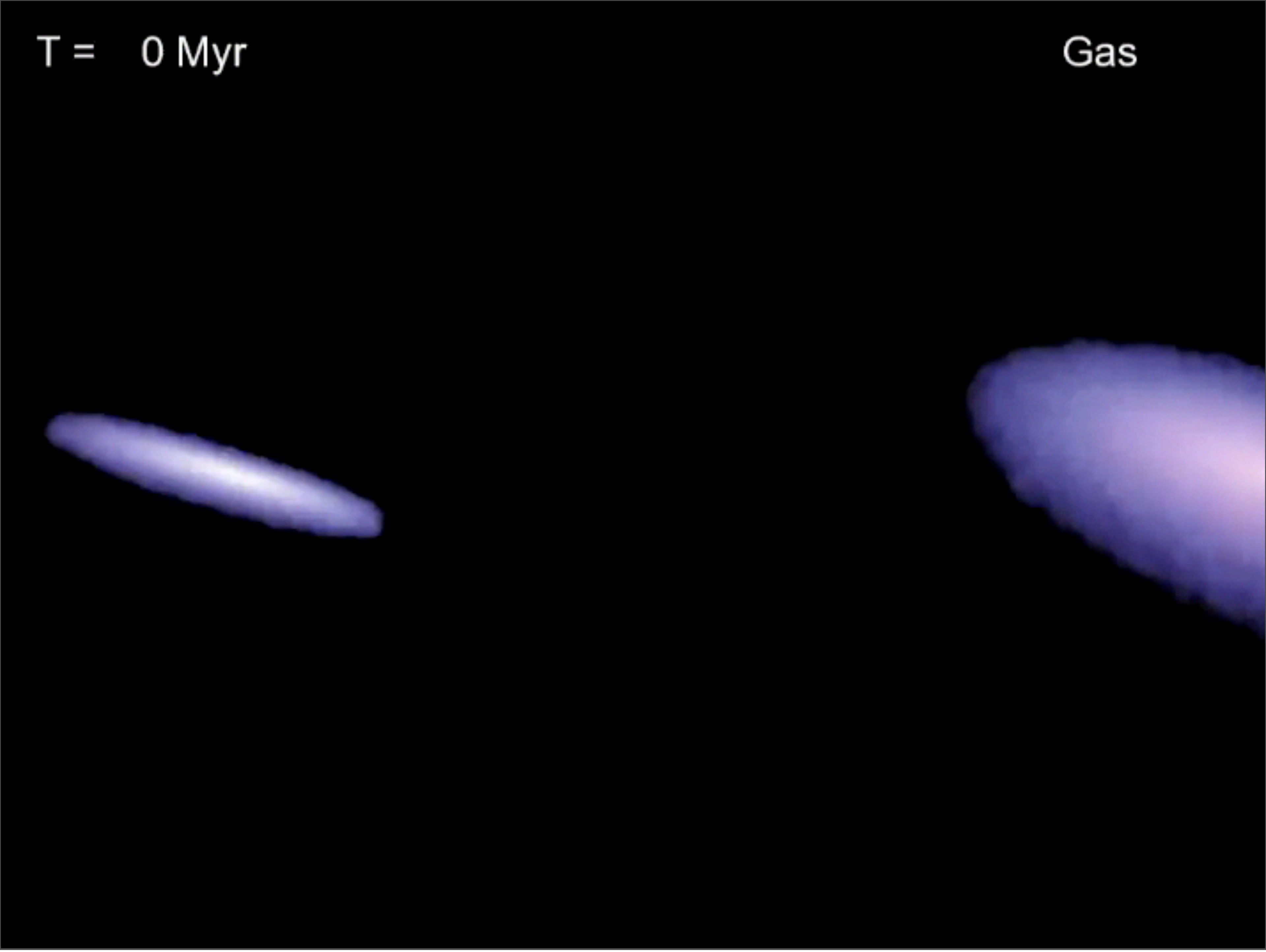
Gas

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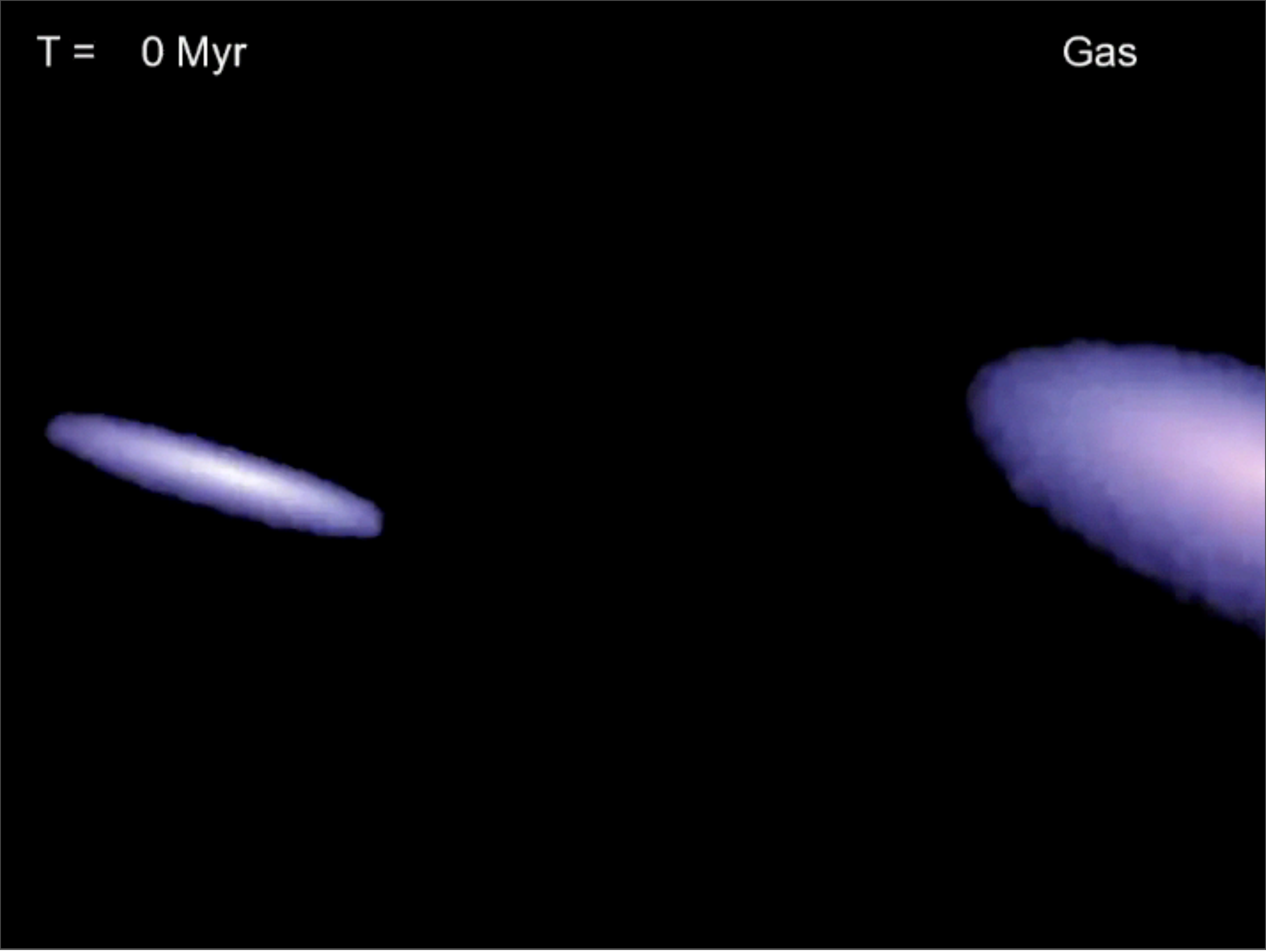
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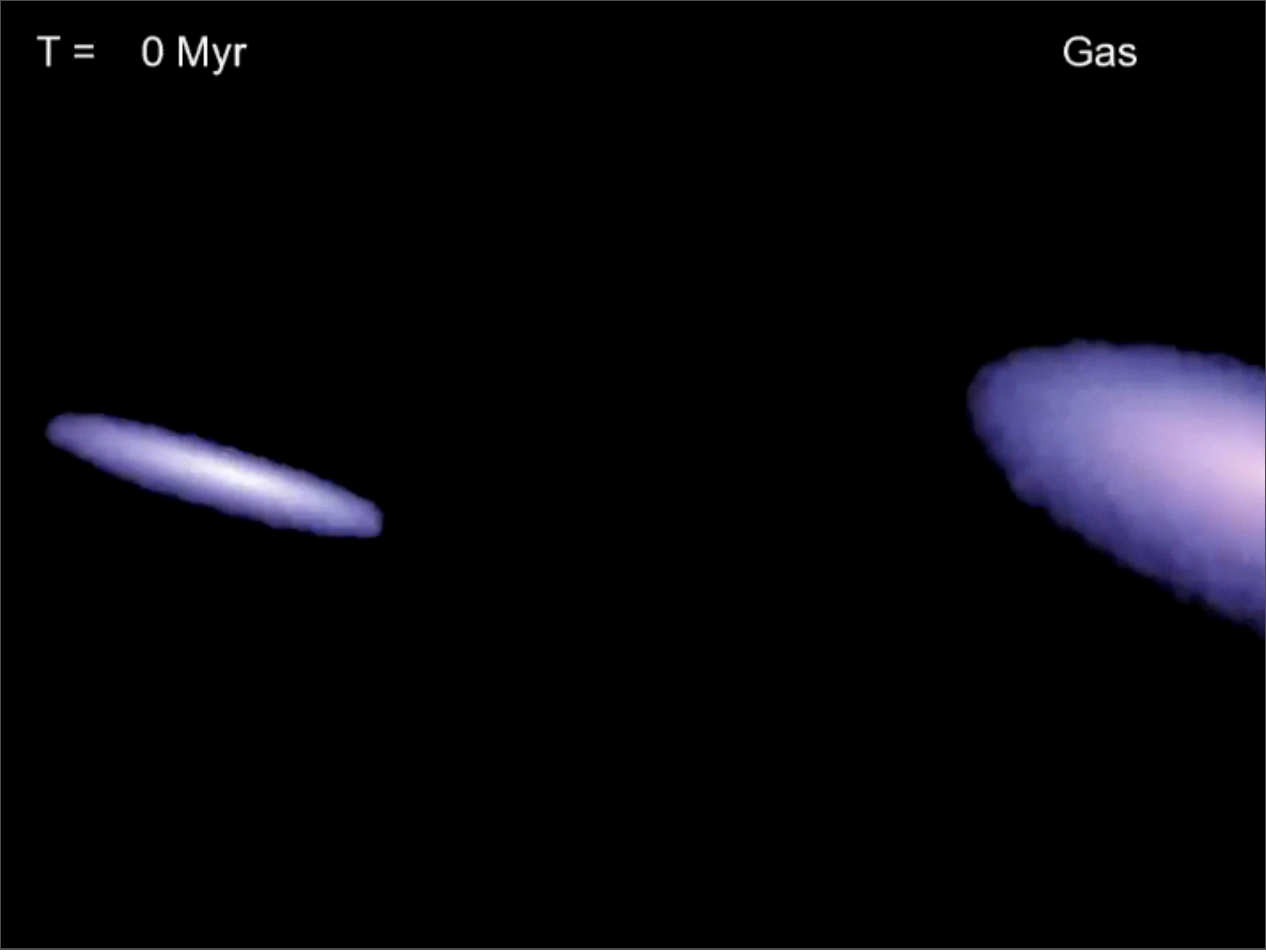
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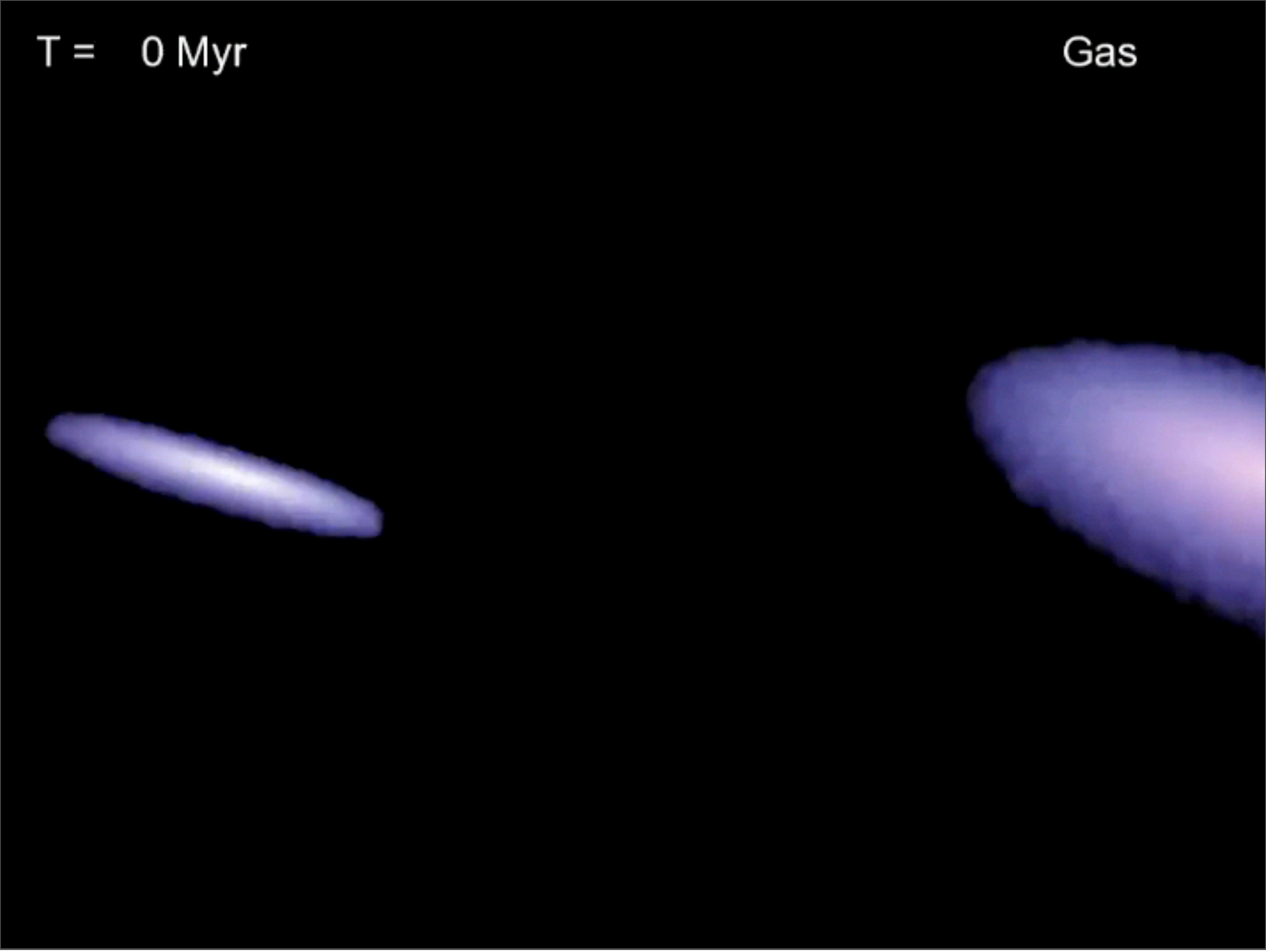
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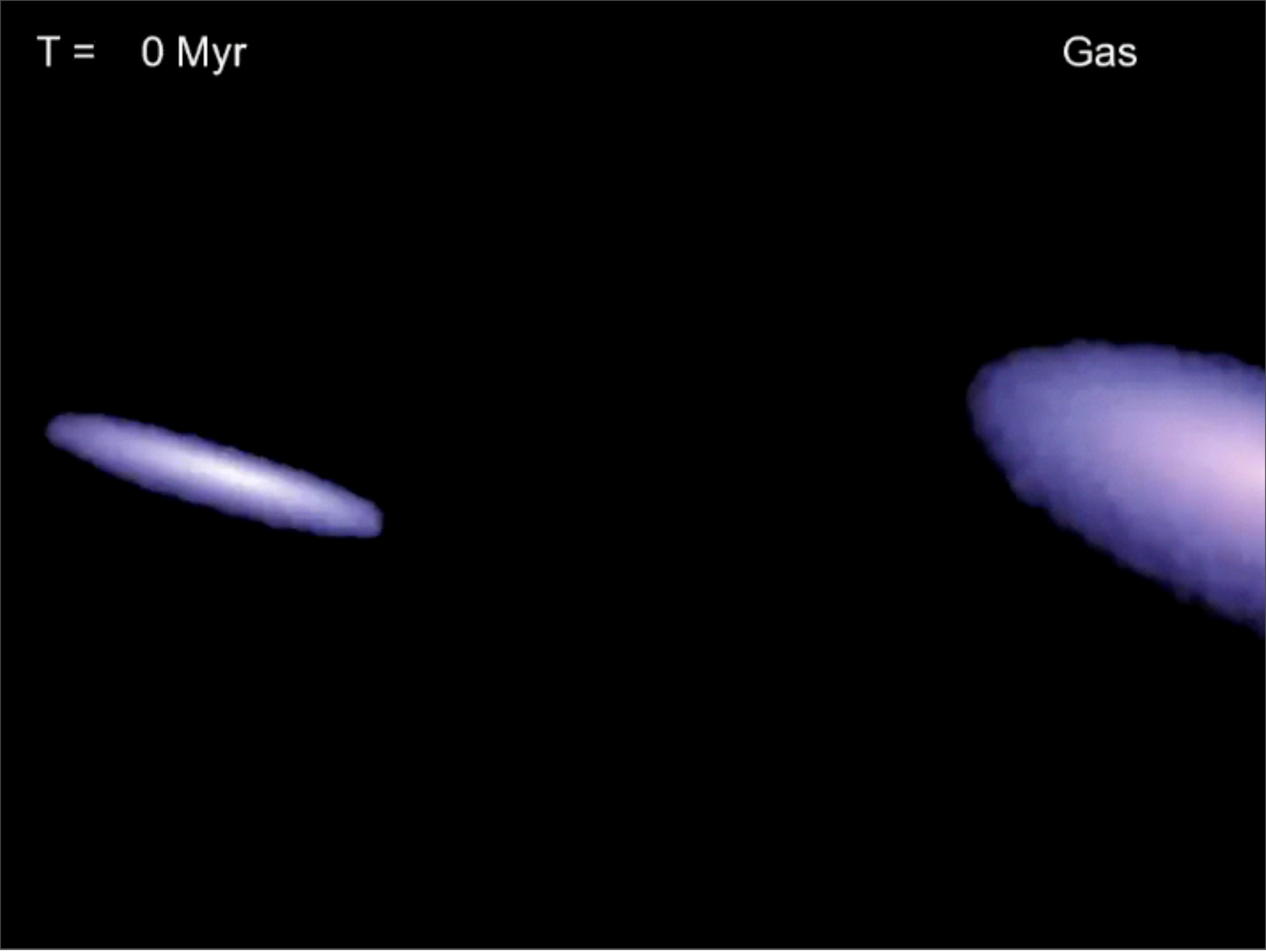
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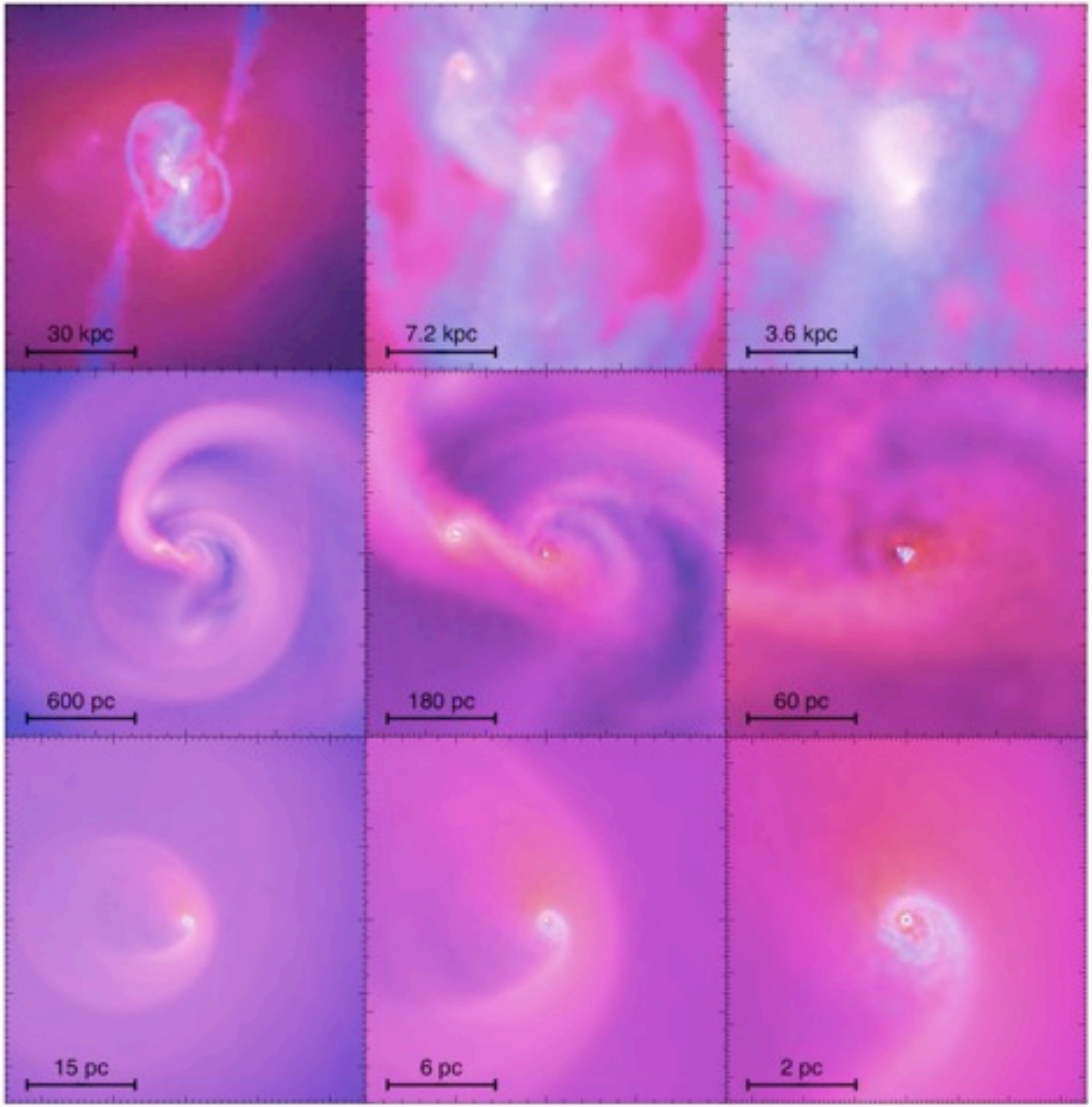
Gas

How do massive BHs get their gas?

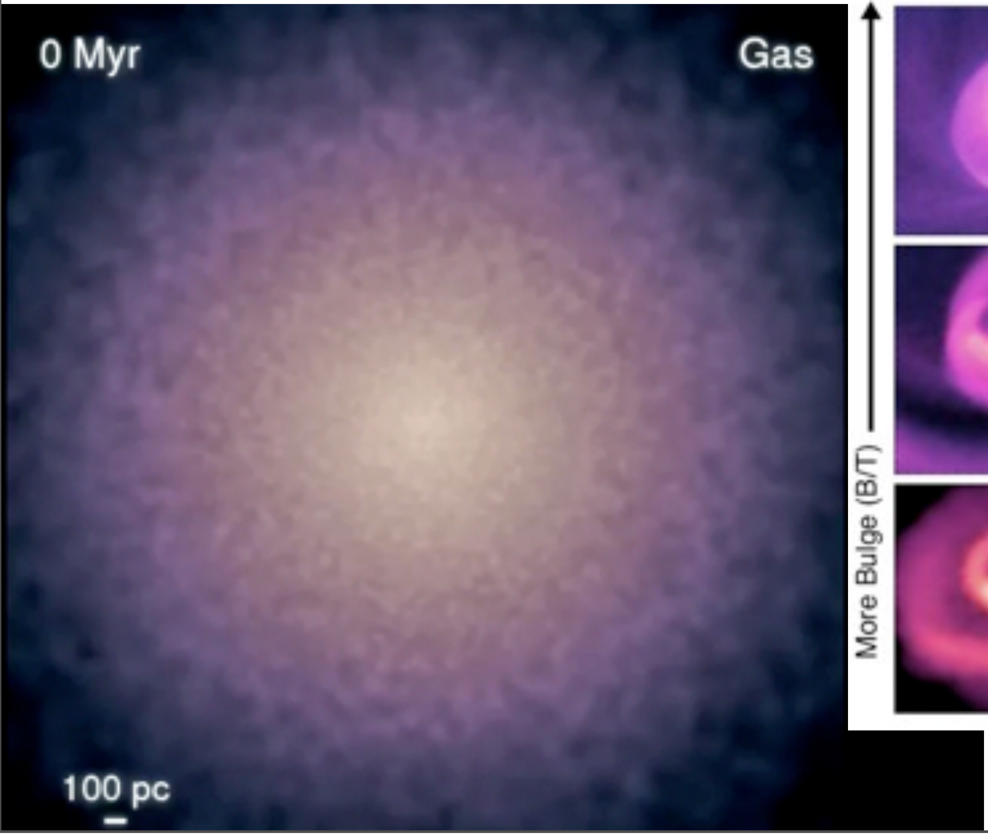
CAN WE FUEL THE MONSTER?

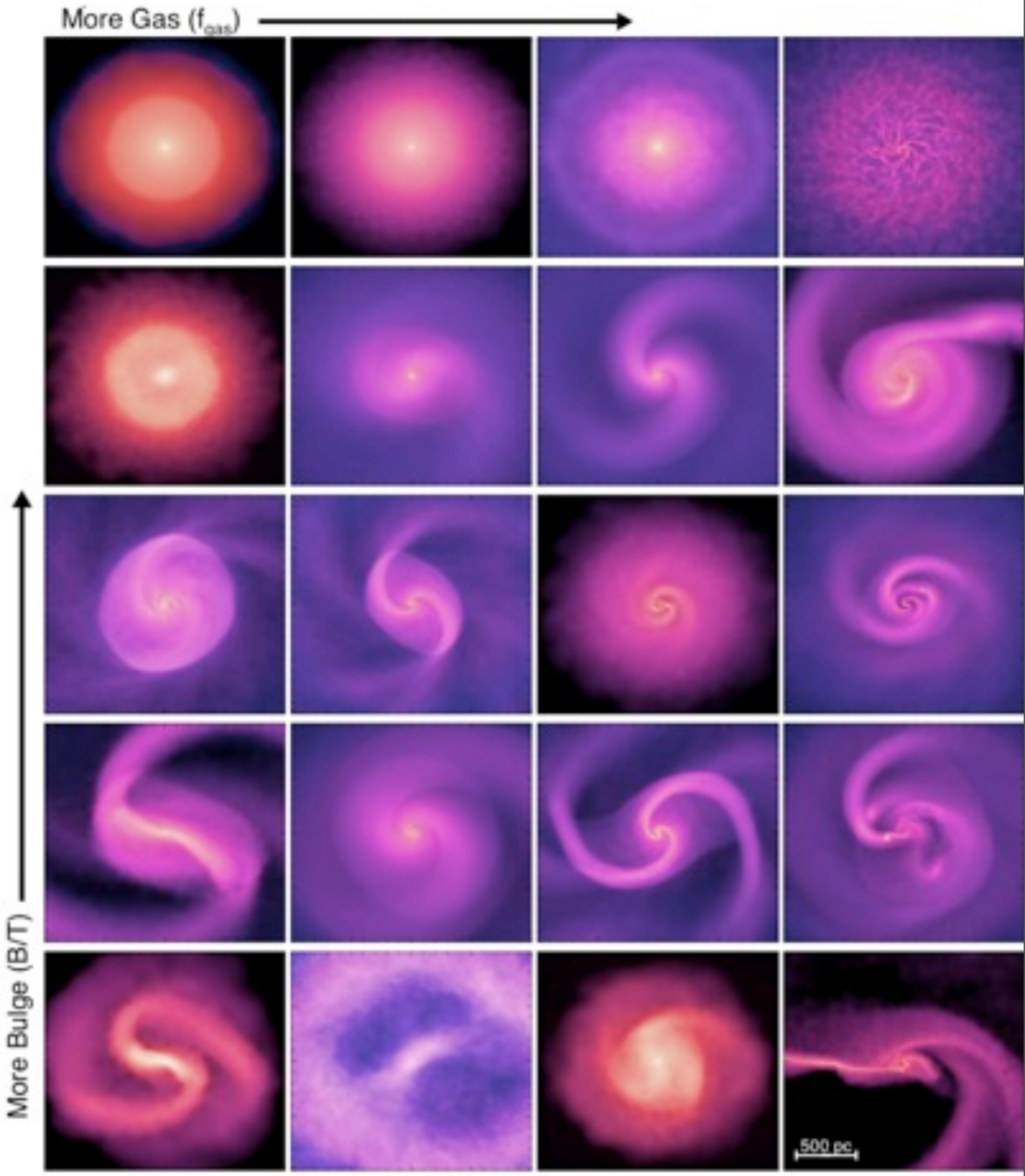


- Cascade of instabilities: merger not efficient inside ~kpc
- *Any* mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

Sub-kpc scales: "Stuff within Stuff"

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





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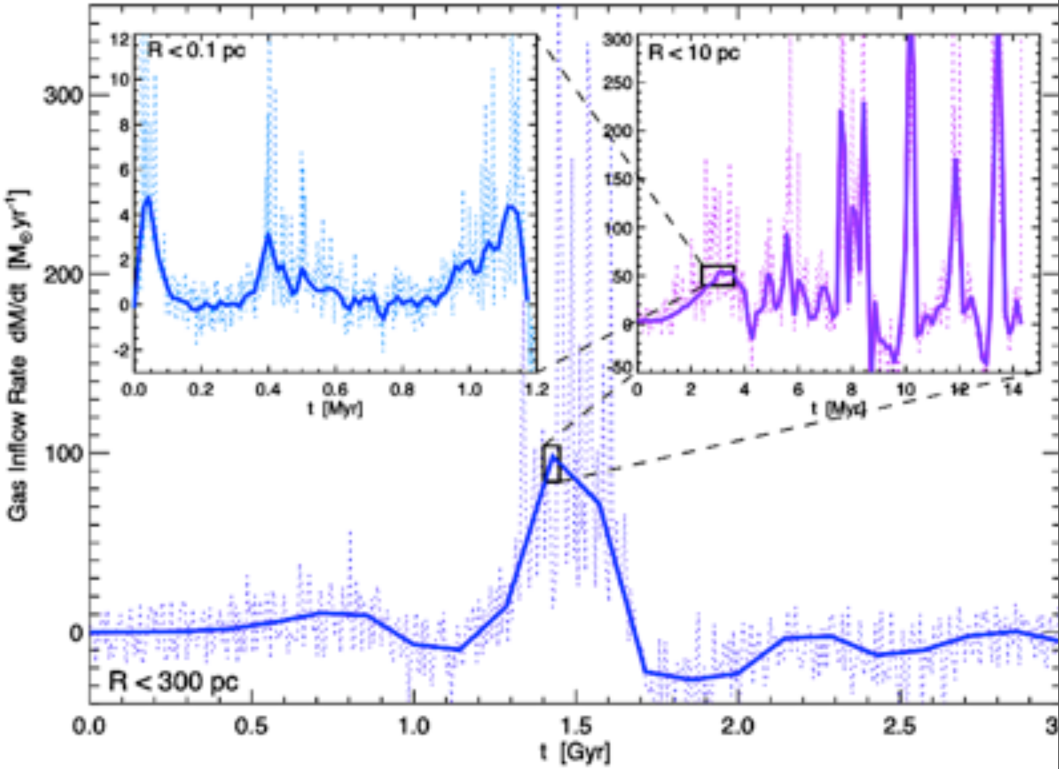
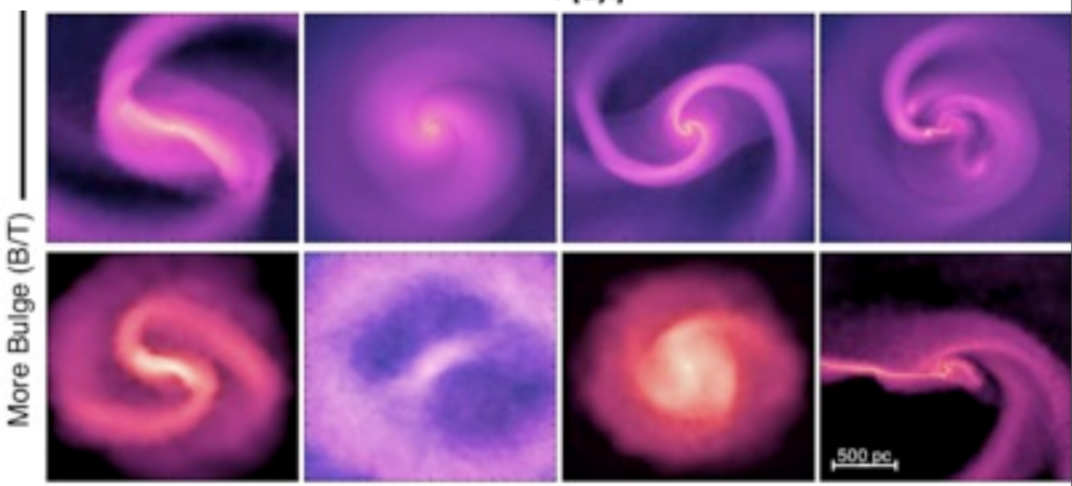
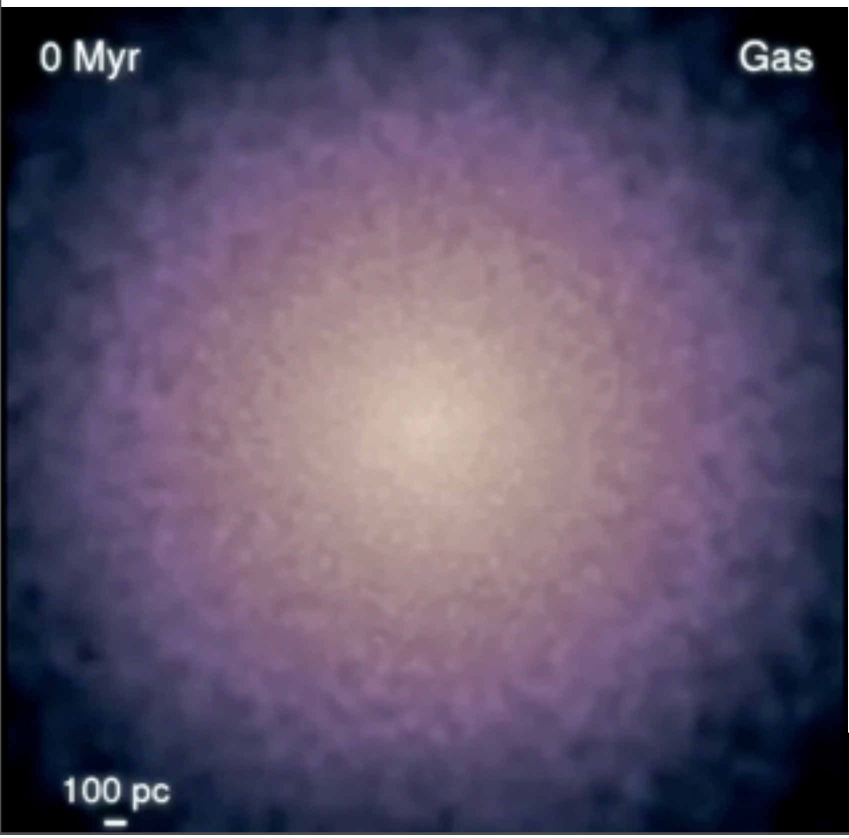
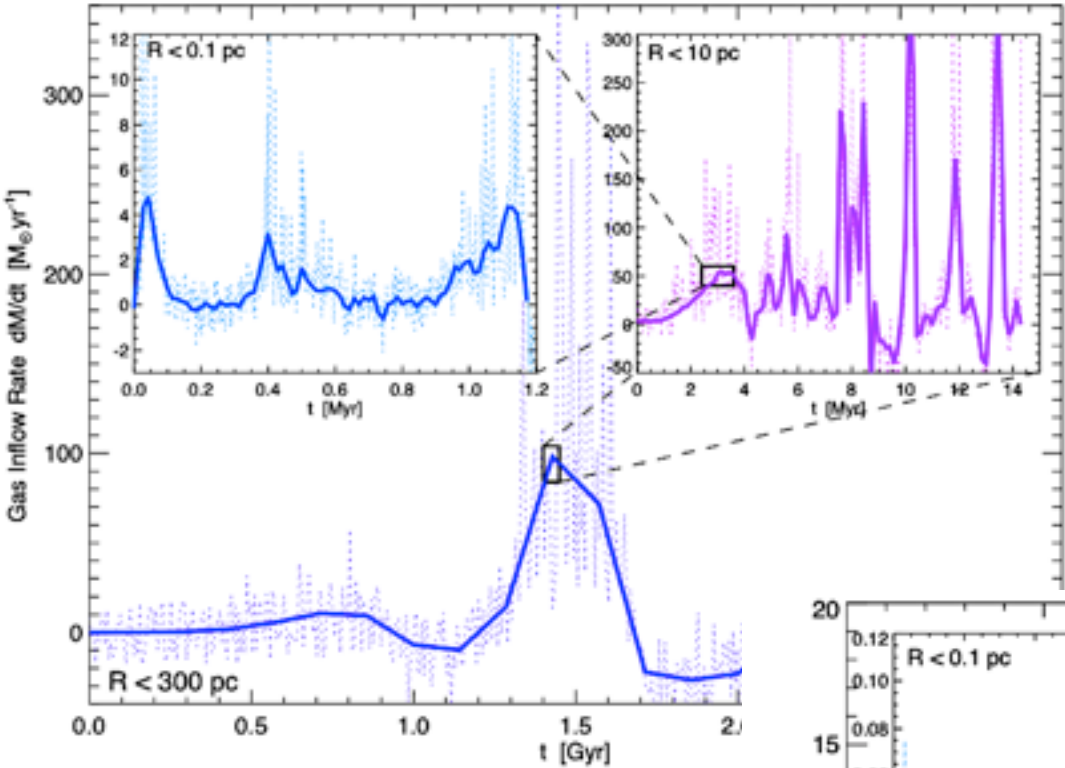


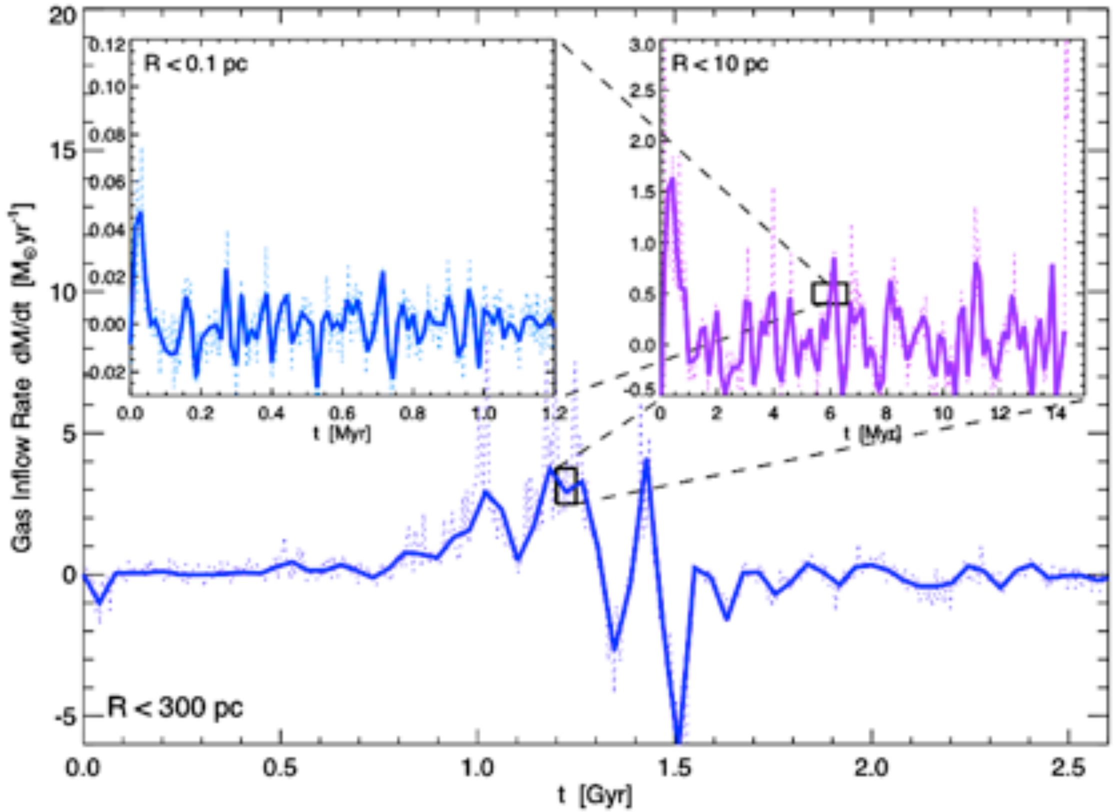




Gas-rich merger
(lots of inflow)



Weakly bar-unstable disk
(less inflow)



- Key parameter:
  Gas driven in, vs.
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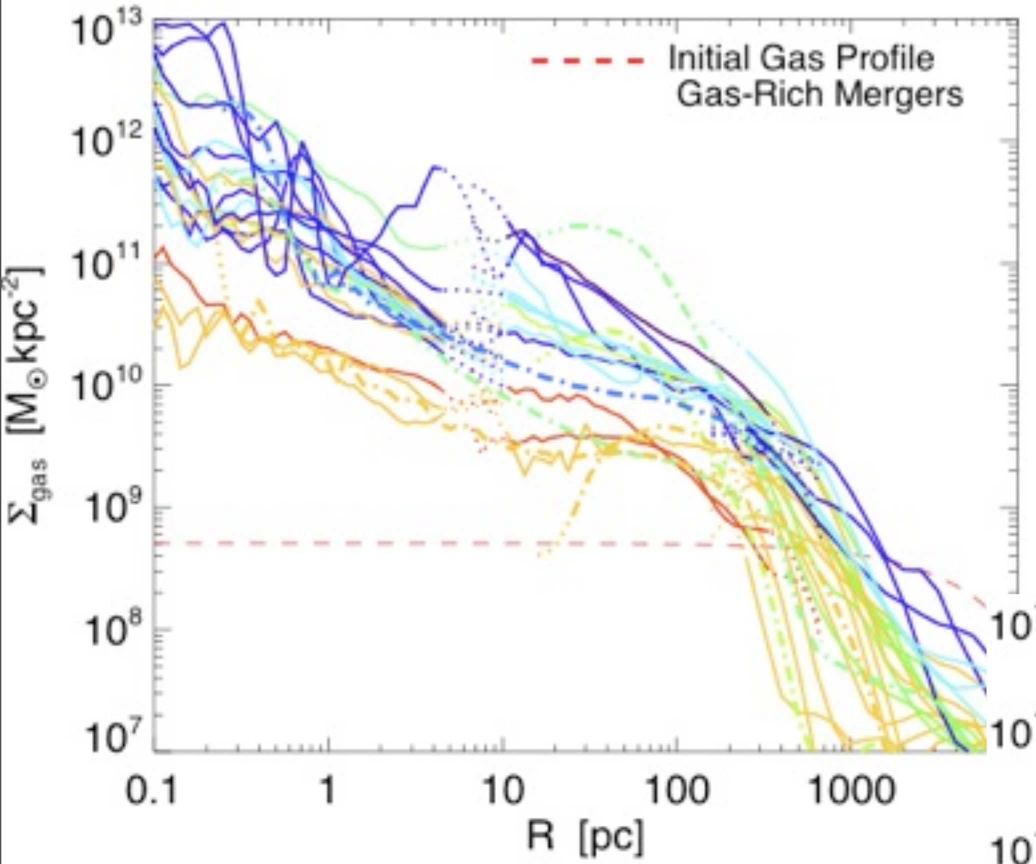

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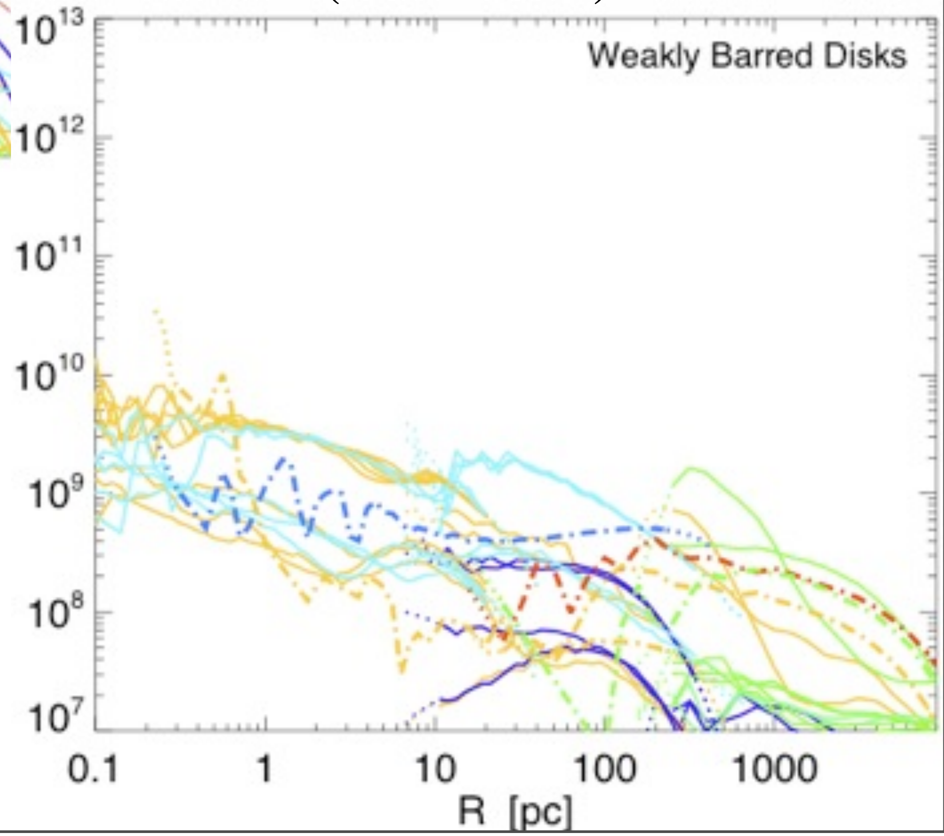
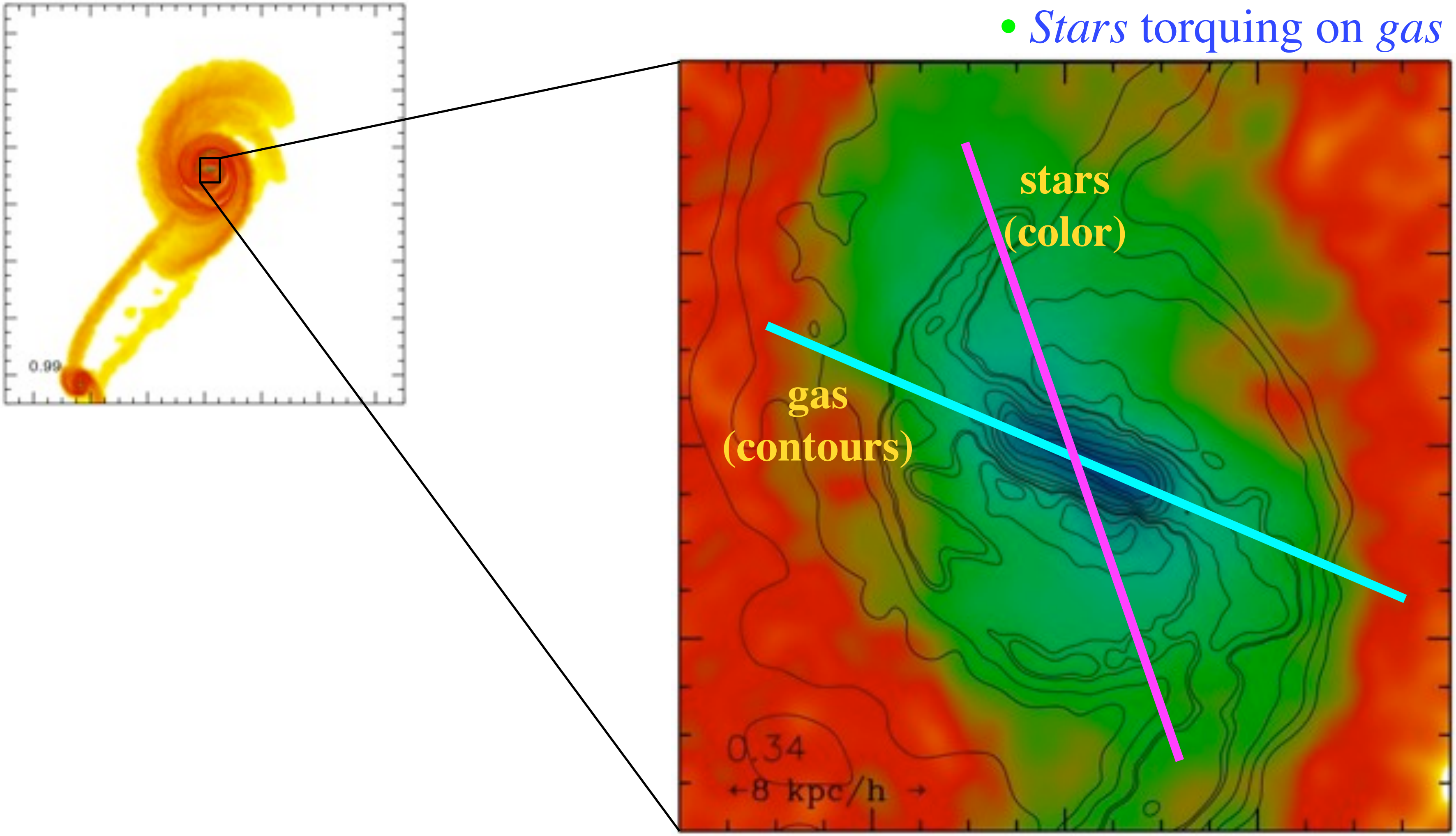


- Key parameter:
  Gas driven in, vs.
  pre-existing bulge/BH mass

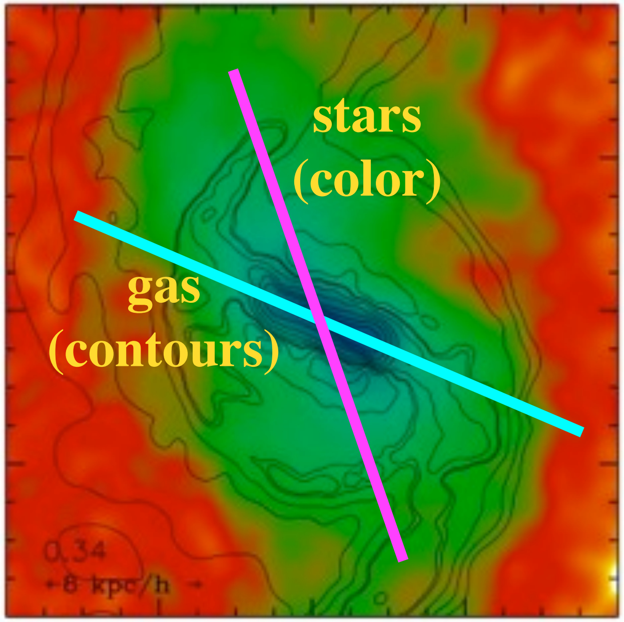
- Gravity dominates torques from 0.1 - 10,000 pc:

- *Stars* torquing on *gas*



How does this work?

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



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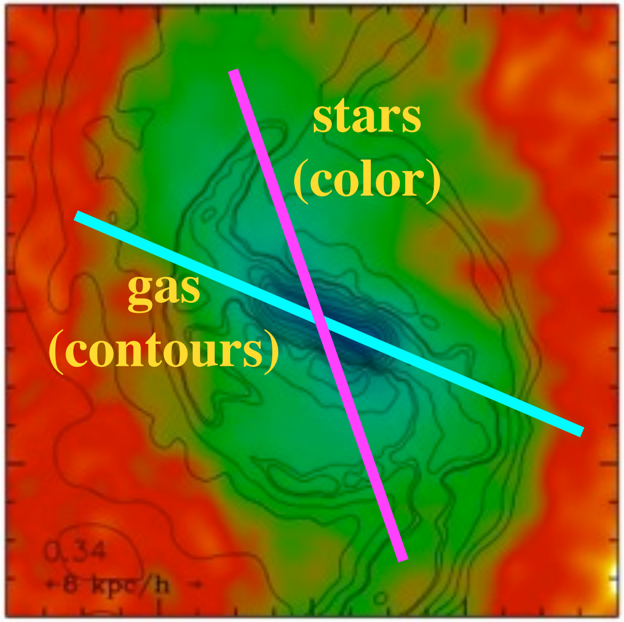

standard (dissipationless) formulation: spiral waves carry the angular momentum: (Lynden-Bell & Kalnajs '72)

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

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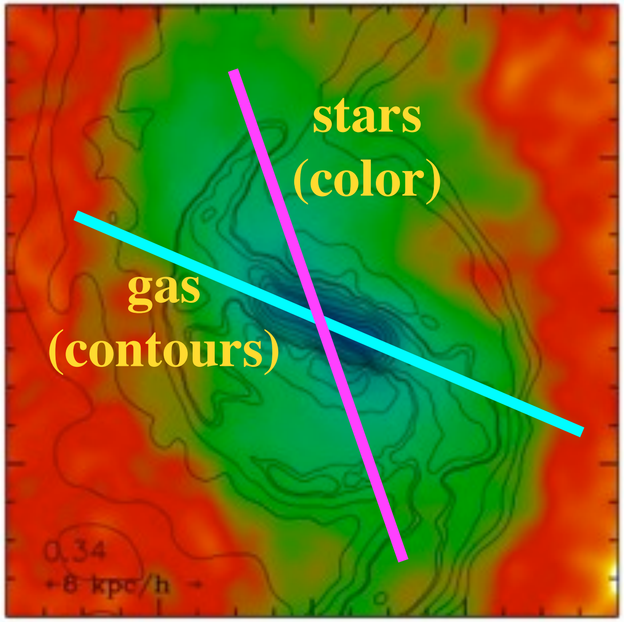

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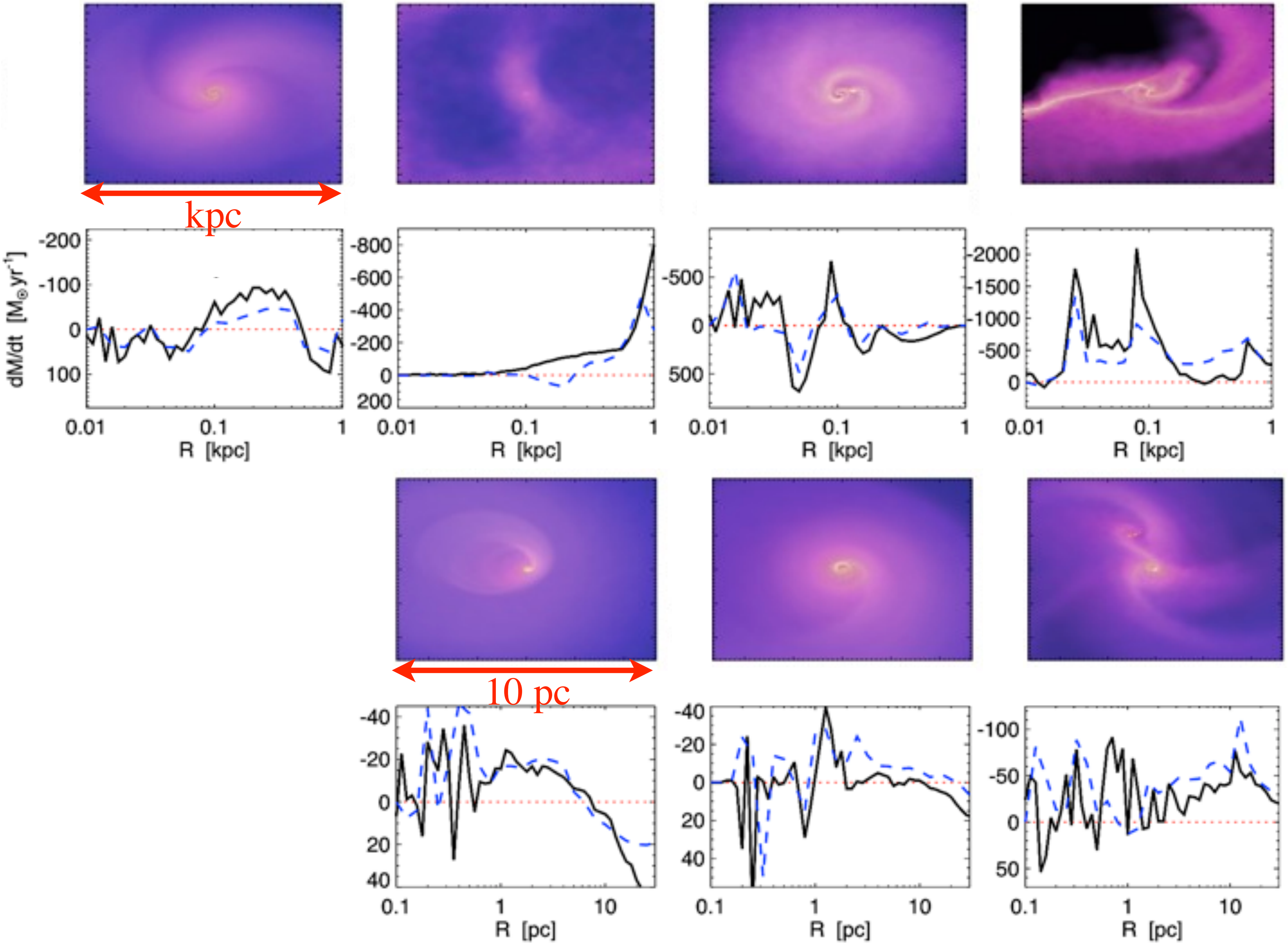
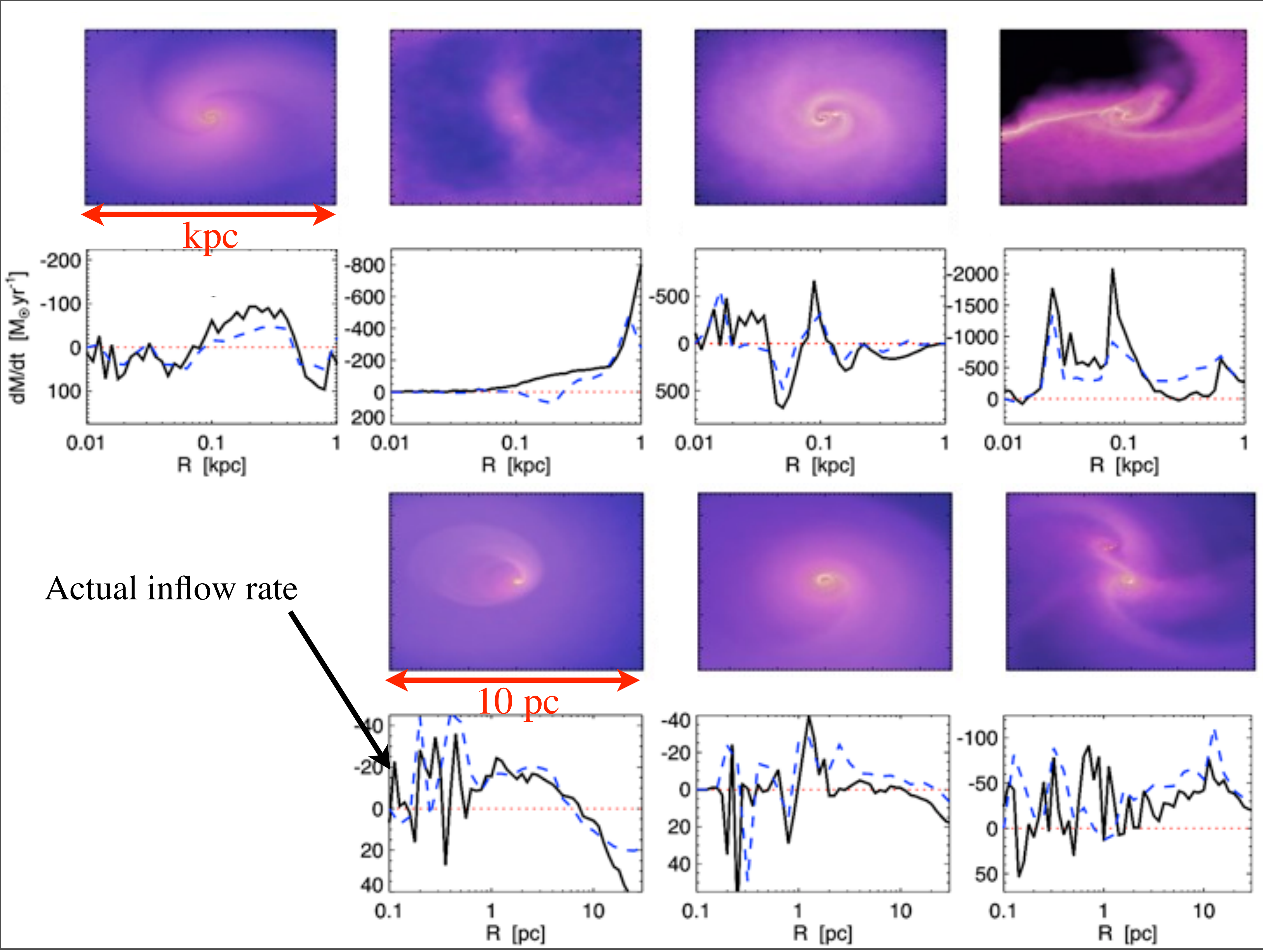
with shocks & dissipation:

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

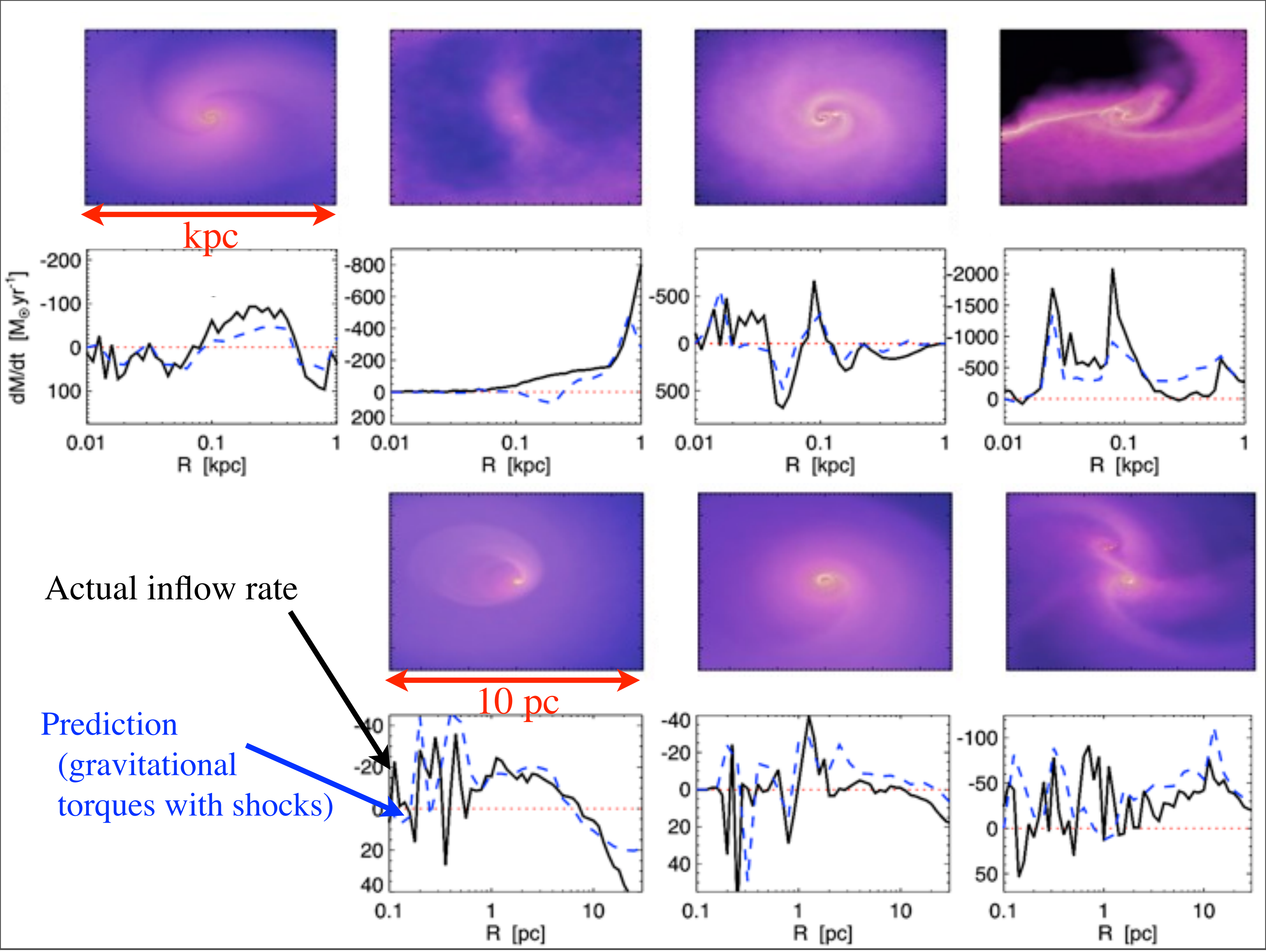
>100x larger!!!



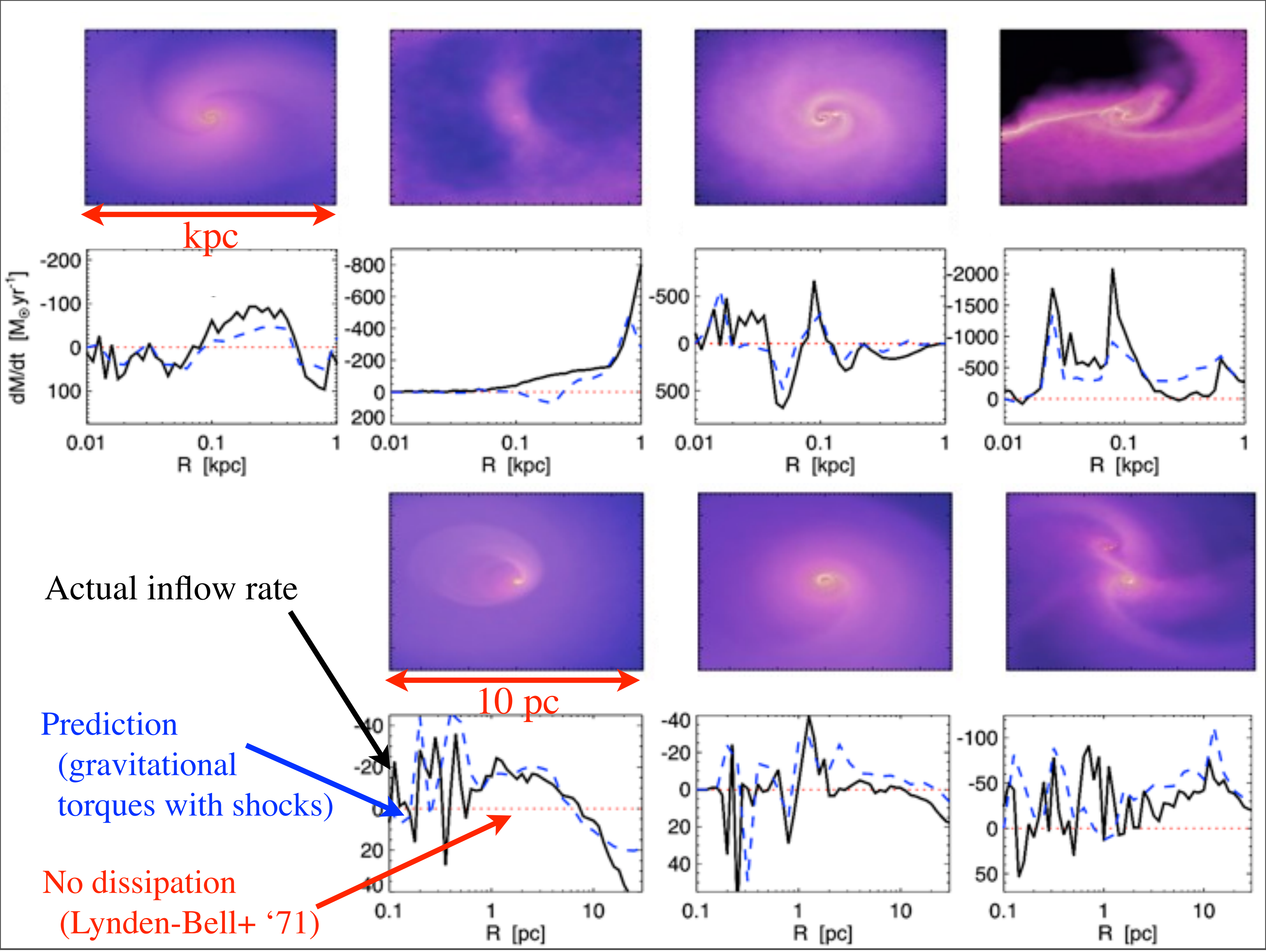
kpc
10 pc
dM/dt [M⊙ yr⁻¹]
R [kpc]
R [kpc]
R [kpc]
R [kpc]
R [pc]
R [pc]
R [pc]



kpc
dM/dt [M⊙yr⁻¹]
R [kpc]
R [kpc]
R [kpc]
R [kpc]
Actual inflow rate
10 pc
R [pc]
R [pc]
R [pc]



kpc
dM/dt [M⊙yr⁻¹]
R [kpc]
Actual inflow rate
Prediction
(gravitational
torques with shocks)
10 pc
R [pc]


kpc
dM/dt [M$_\odot$ yr^{-1}]
-200
-100
0
100
0.01
0.1
1
R [kpc]
-800
-600
-400
-200
0
200
-500
0
500
-2000
-1500
-1000
-500
0
Actual inflow rate
10 pc
Prediction
(gravitational
torques with shocks)
No dissipation
(Lynden-Bell+ '71)
-40
-20
0
20
40
-100
-50
50
0.1
1
10
R [pc]

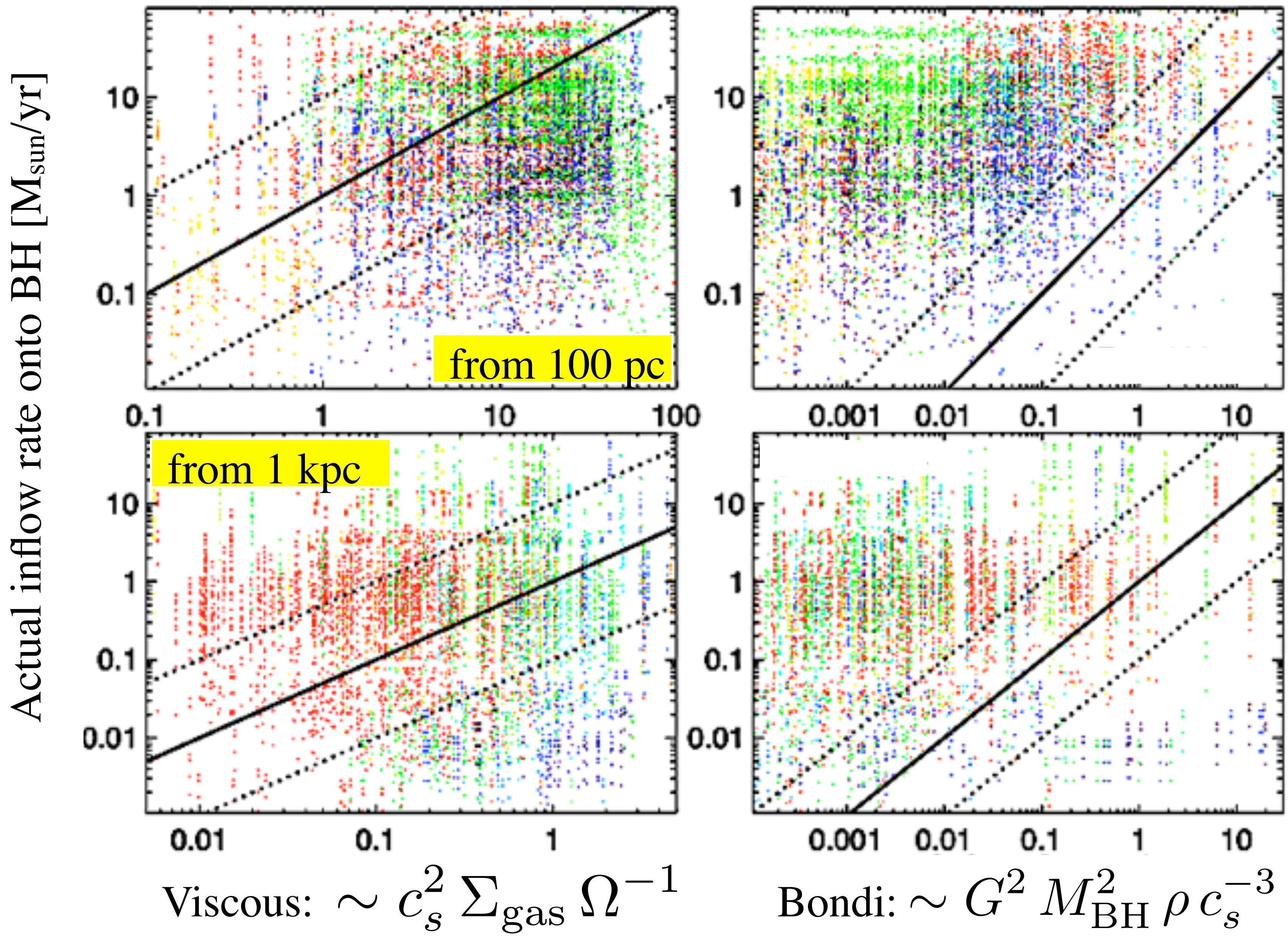
Can we build a better accretion rate estimator?

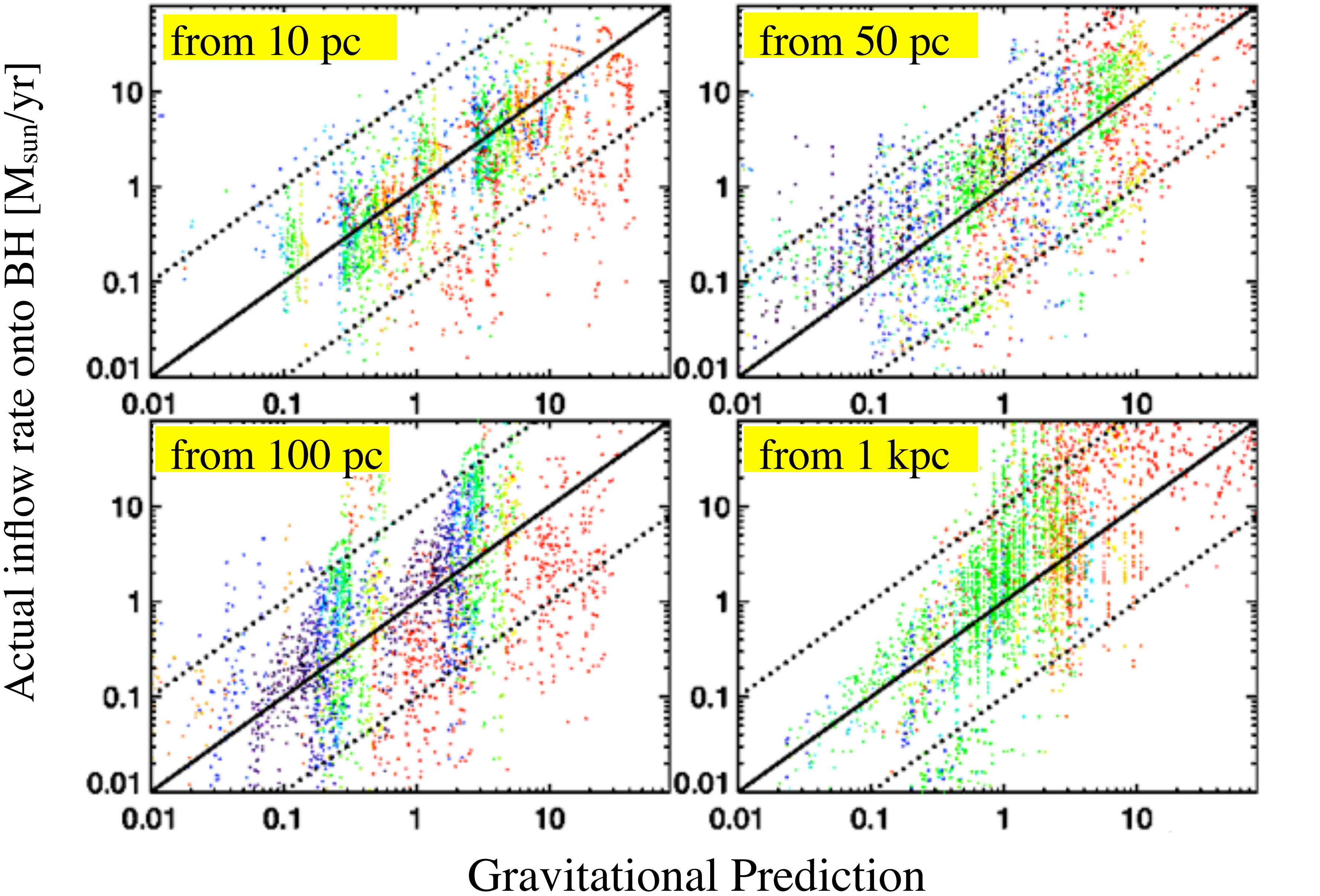
Can we build a better accretion rate estimator?

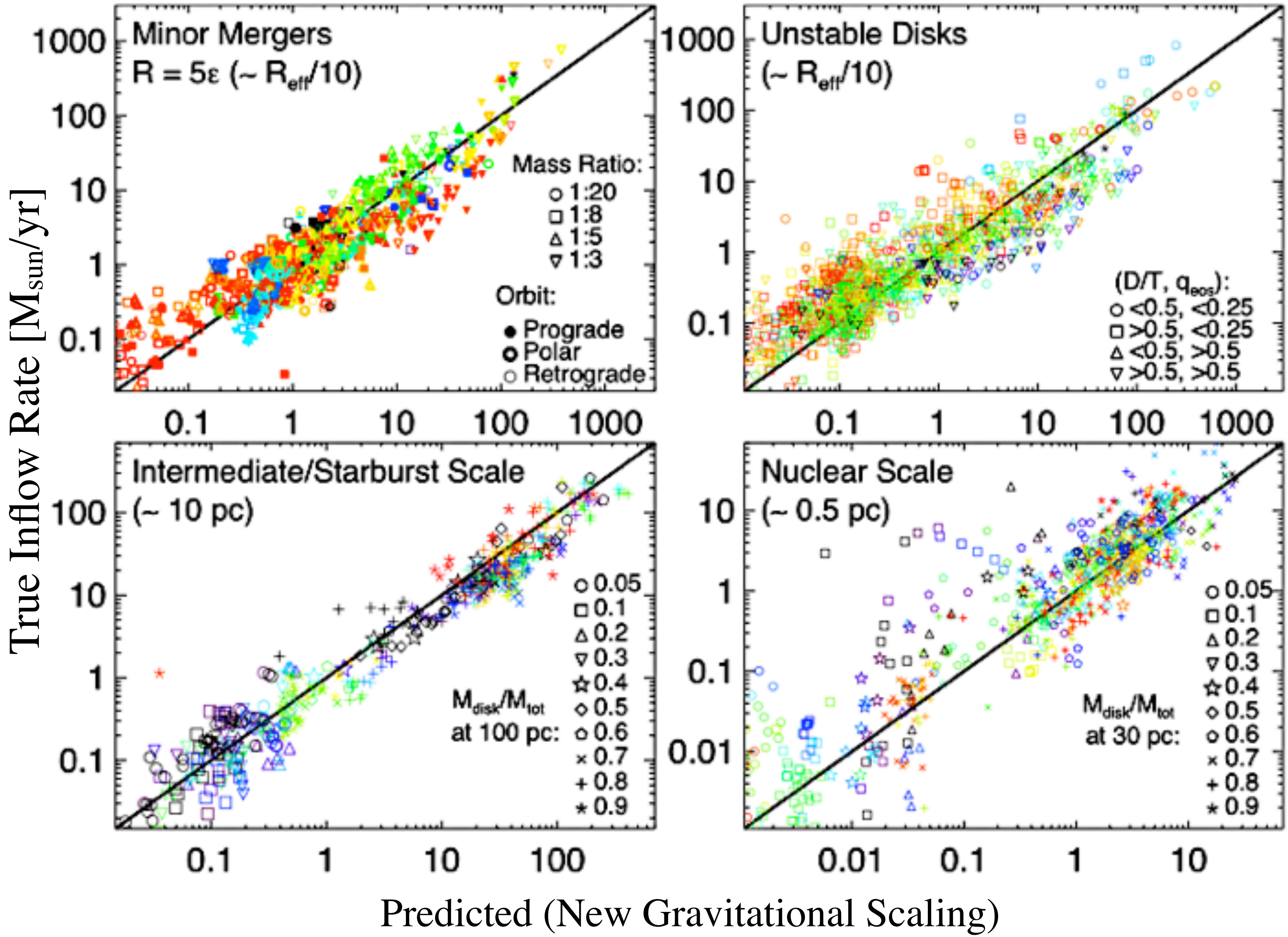
Derive 'Gravitational Torque' Rate:

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

Inflow from ~kpc to ~0.1 pc is NOT viscous or Bondi-Hoyle:




from 10 pc
from 50 pc
from 100 pc
from 1 kpc
Actual inflow rate onto BH [M_sun/yr]
Gravitational Prediction
0.01
0.1
1
10



Minor Mergers
R = 5ε (~ R_eff/10)
Mass Ratio:
1:20
1:8
1:5
1:3
Orbit:
Prograde
Polar
Retrograde
Unstable Disks
(~ R_eff/10)
(D/T, q_eos):
<0.5, <0.25
>0.5, <0.25
<0.5, >0.5
>0.5, >0.5
Intermediate/Starburst Scale
(~ 10 pc)
M_disk/M_tot
at 100 pc:
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Nuclear Scale
(~ 0.5 pc)
M_disk/M_tot
at 30 pc:
True Inflow Rate [M_sun/yr]
Predicted (New Gravitational Scaling)

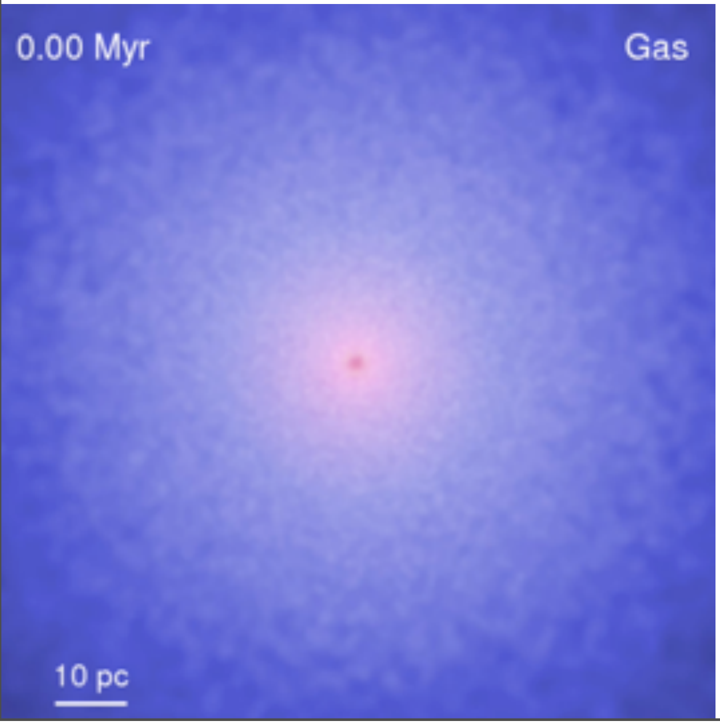
So, what about the “small” scales

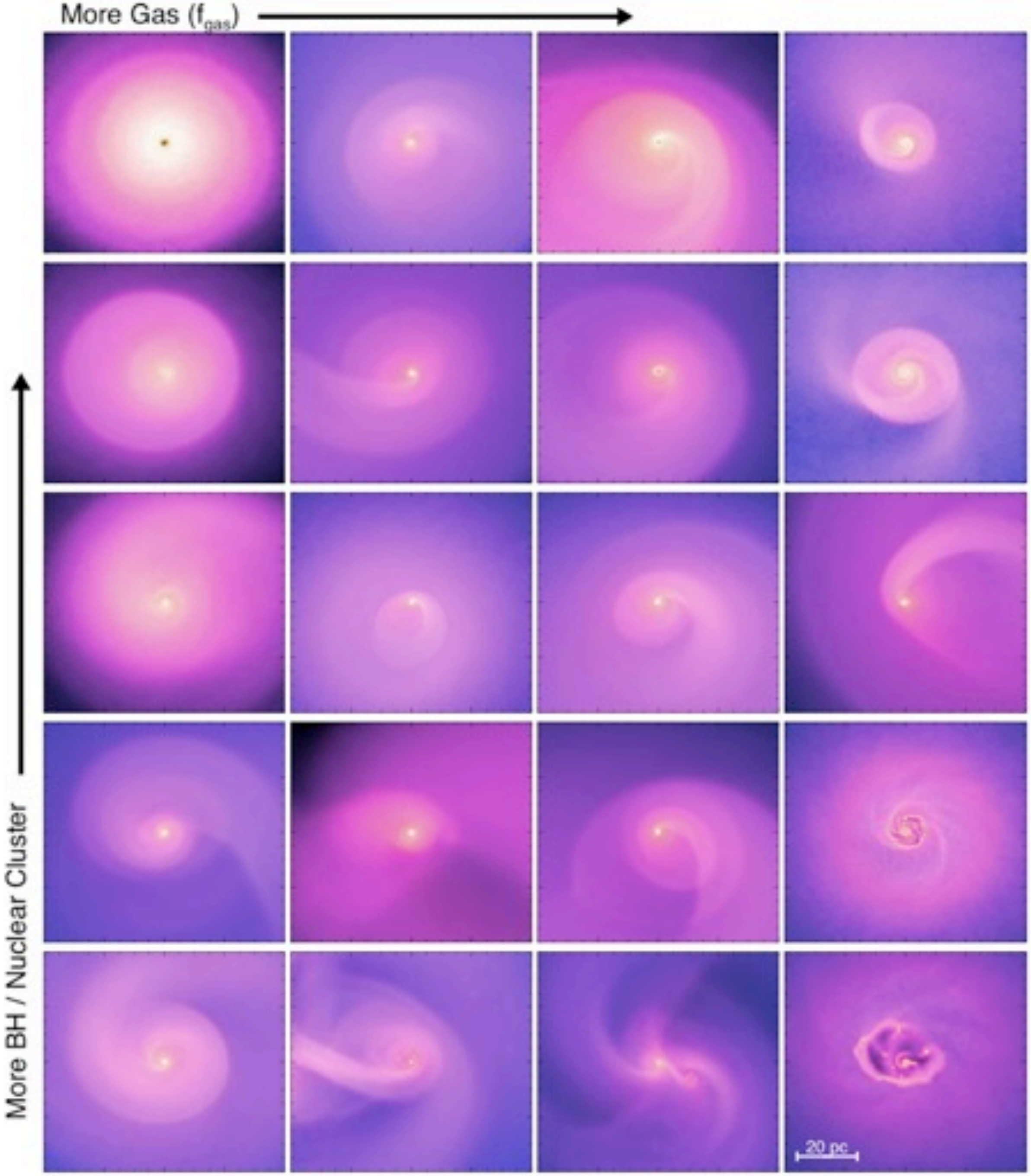
near the BH?

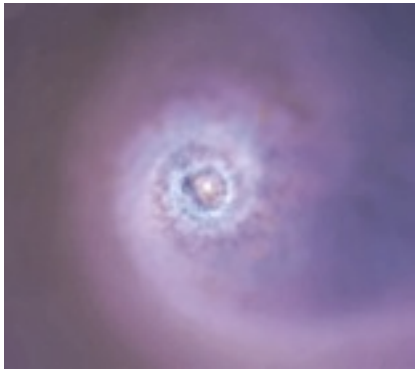
~10 pc scales: Nuclear eccentric disks

- Inside BH radius of influence: develop thick, precessing disks

- Need *both* star formation and self-gravity





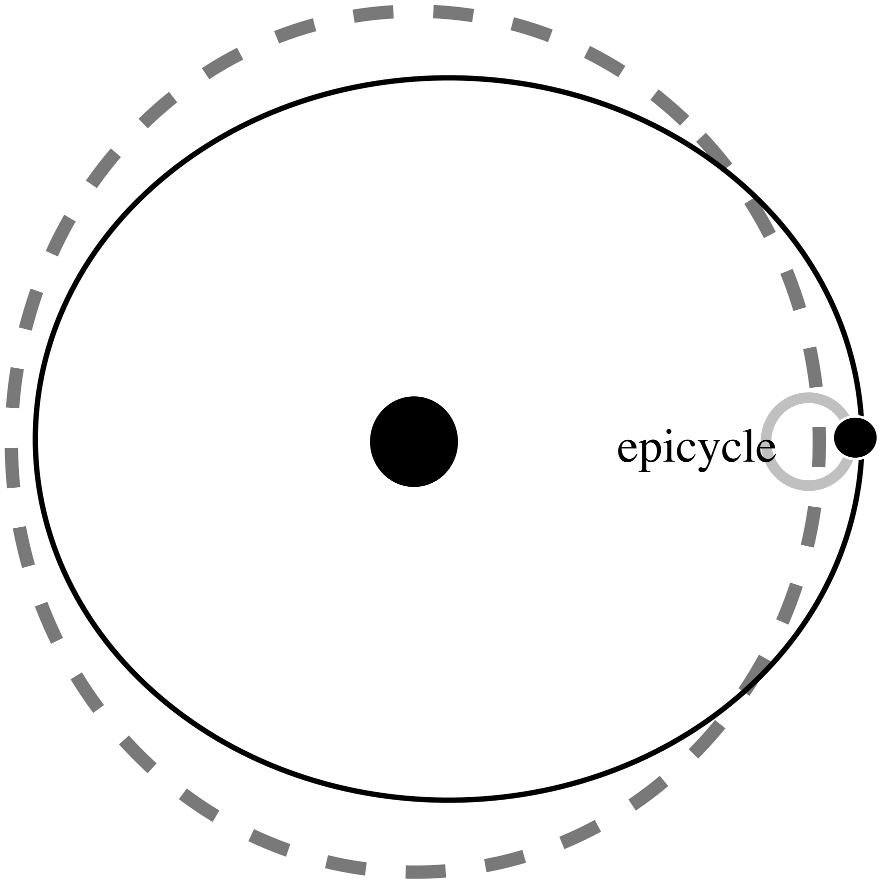


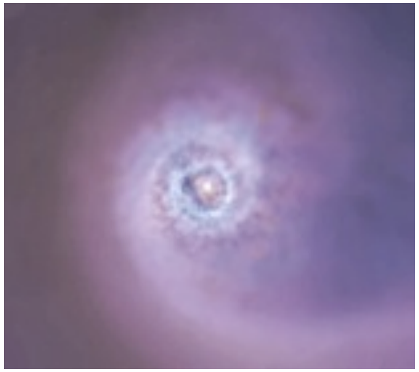
Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential

Keplerian potentials are special:

$$\kappa = \Omega$$

Hence, closed elliptical orbits!

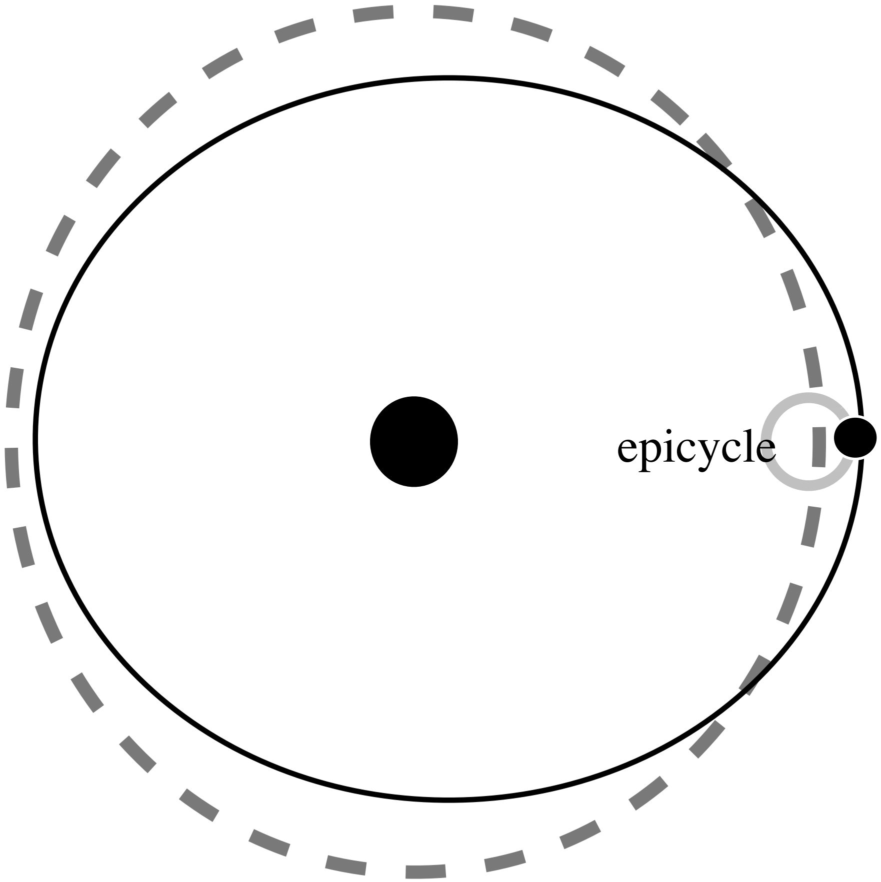


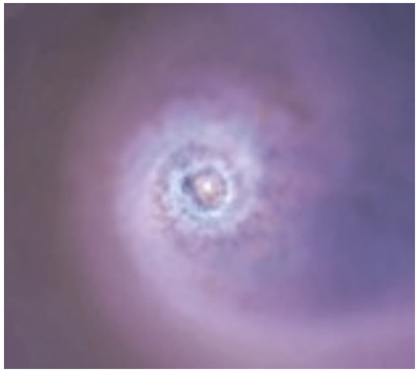


Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential

Disturb the stars with some perturbation in the disk:

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





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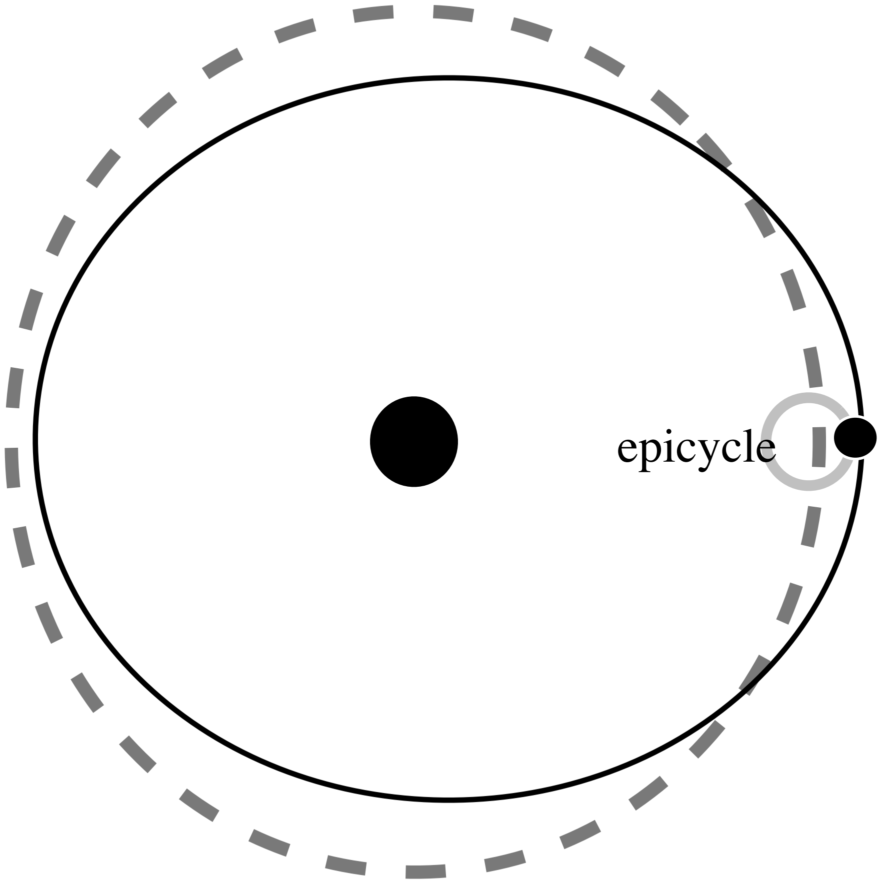
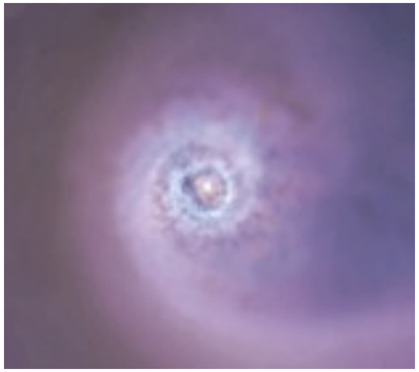
$$\left|\frac{\delta v}{V_c}\right| \sim \left(\frac{\delta\Sigma}{\Sigma}\right) \frac{M_{\rm disk}(<r)}{M_{\rm BH}}$$





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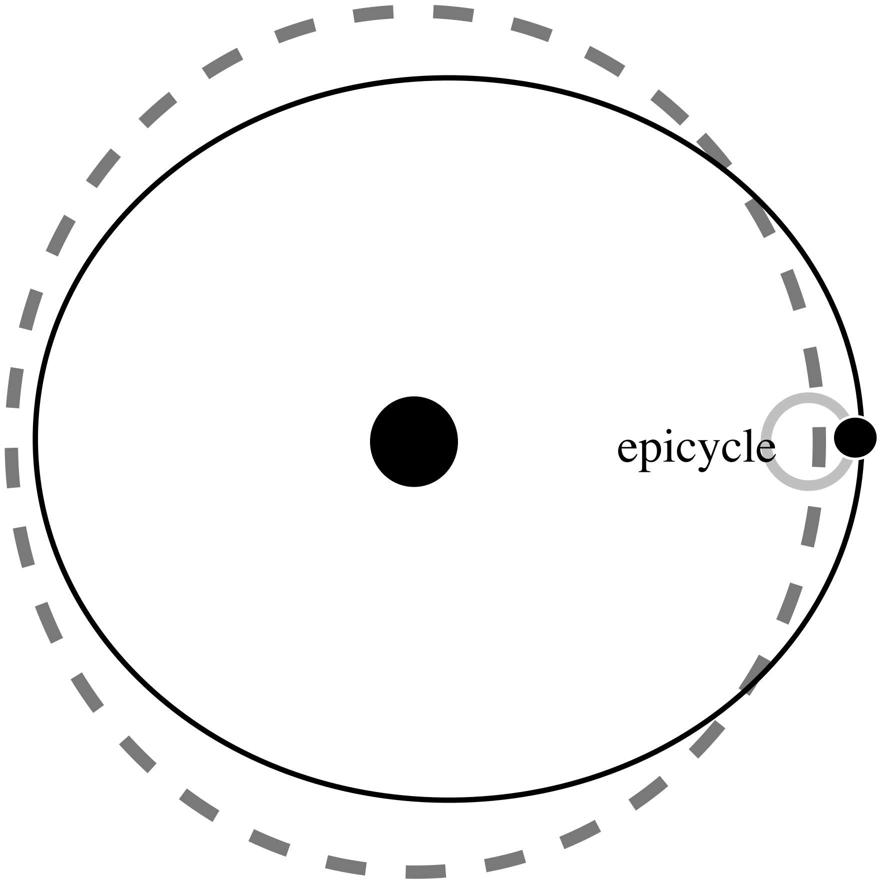
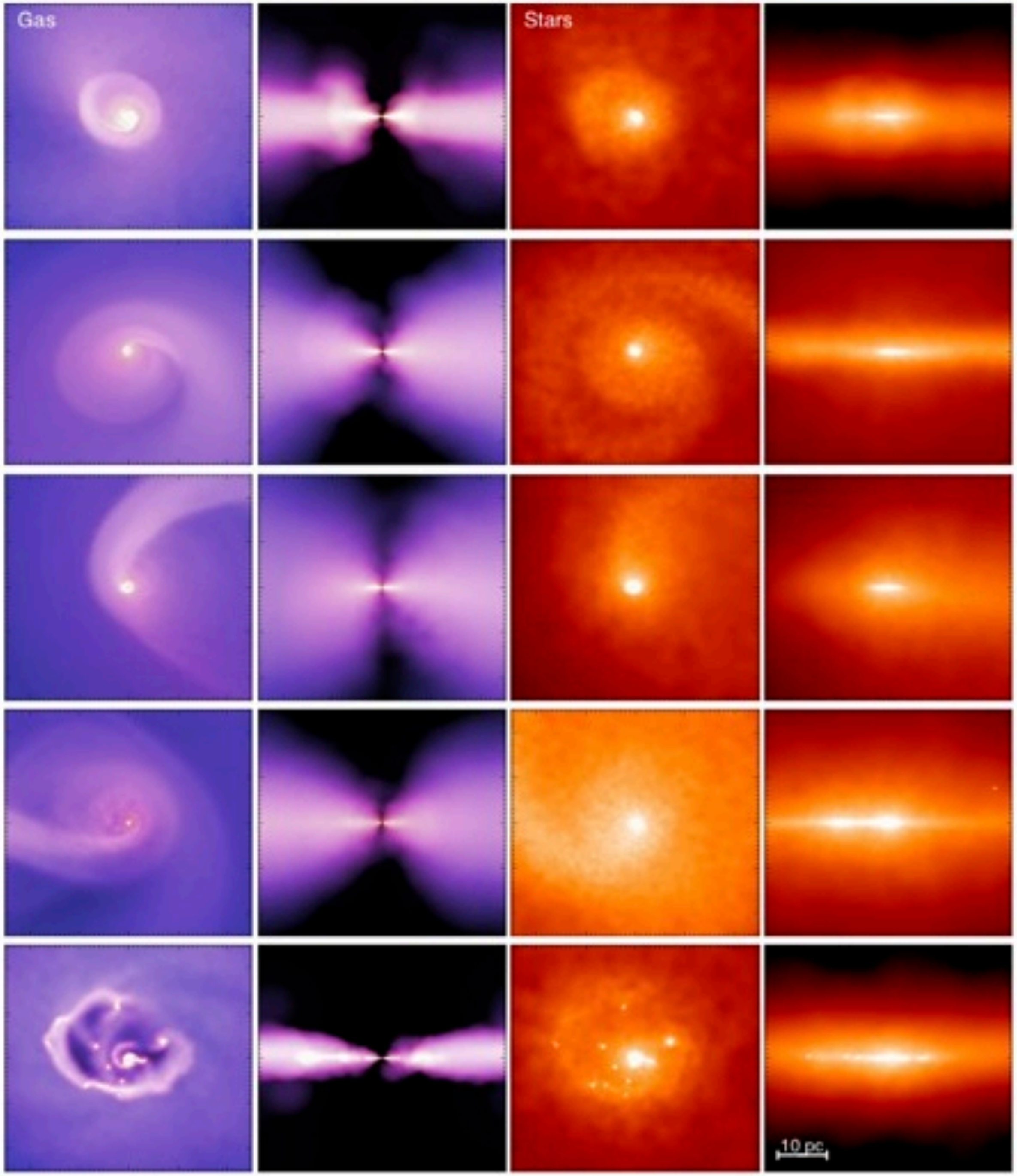
But, if (and *only* if) m=1:

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

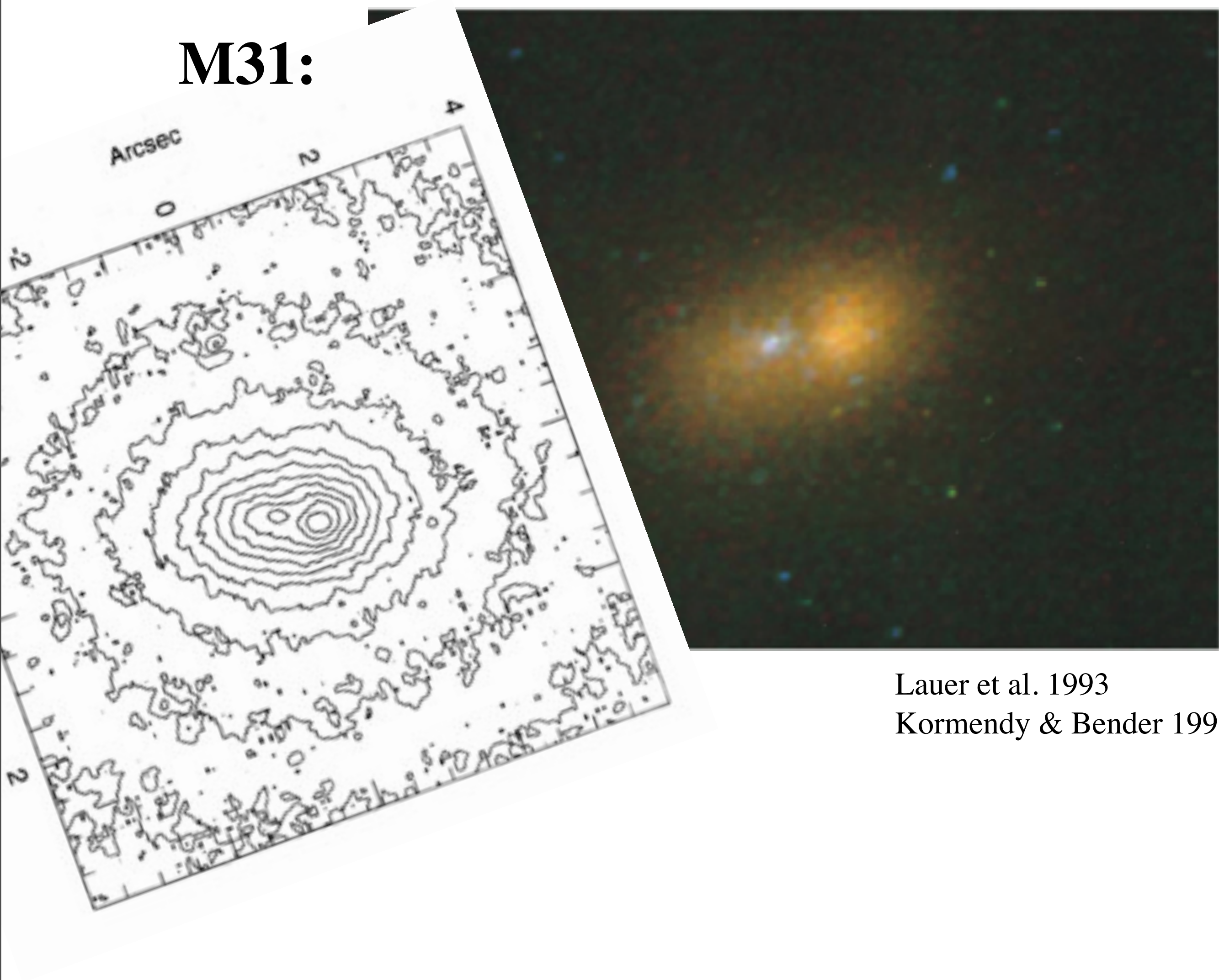


- Gas-stellar exchange dramatically enhances torques
- Drives ~10 M_{sun}/yr inflow
- Leave relic stellar disks?

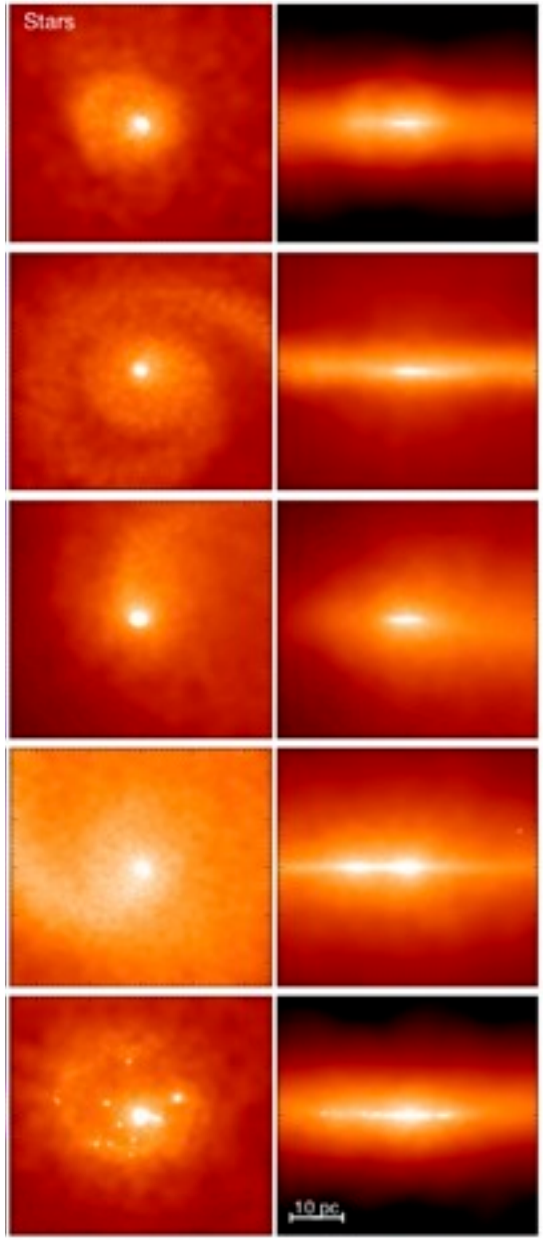


- These are observed!
  M31, NGC4486B, many candidates
  (NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)

M31:



Lauer et al. 1993
Kormendy & Bender 1999



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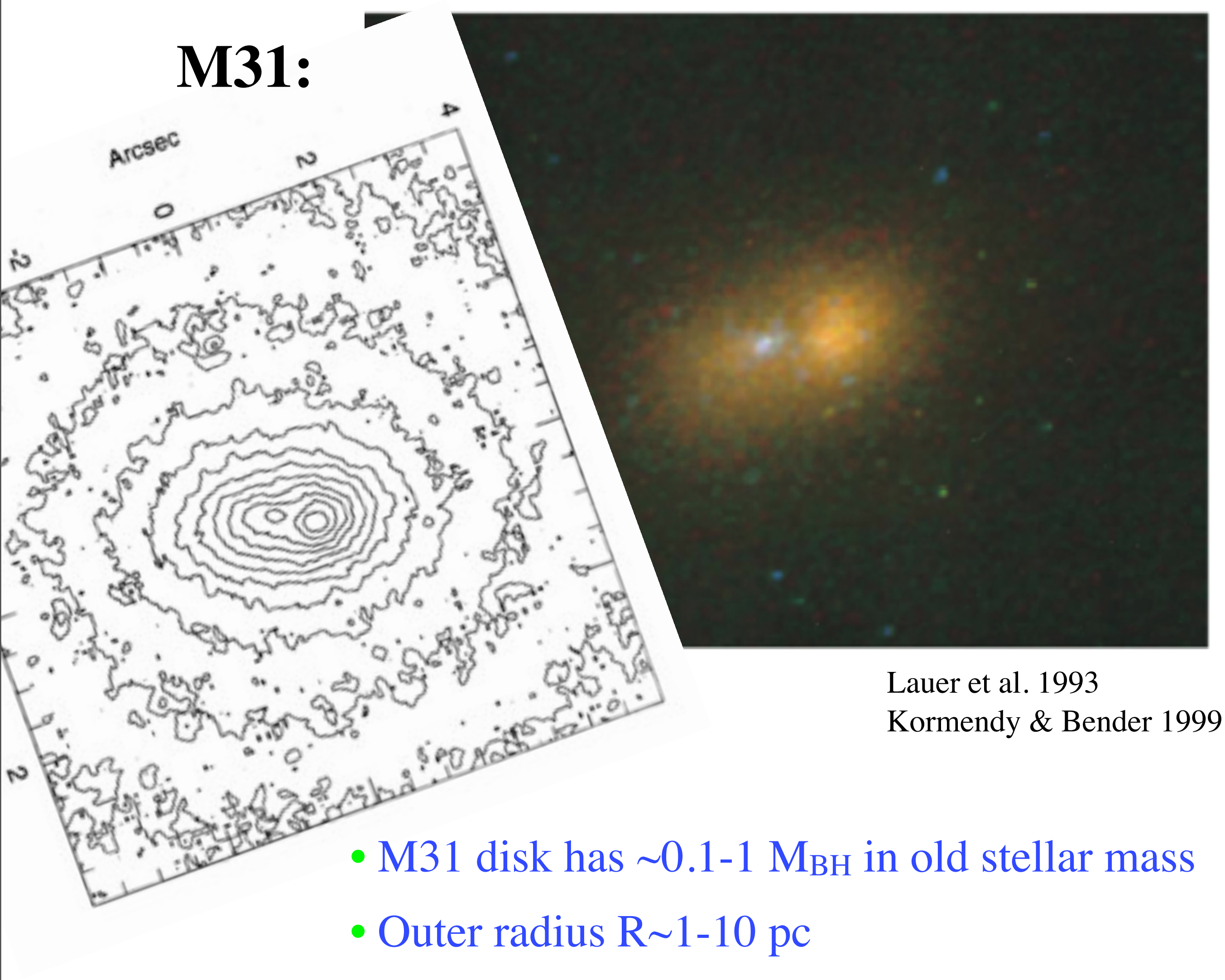

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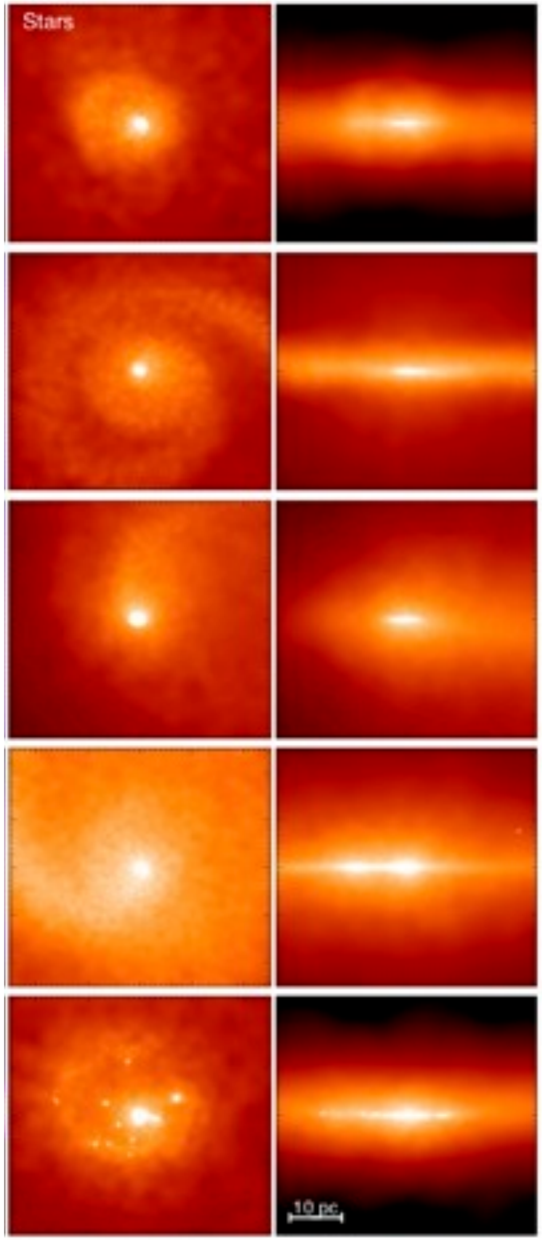
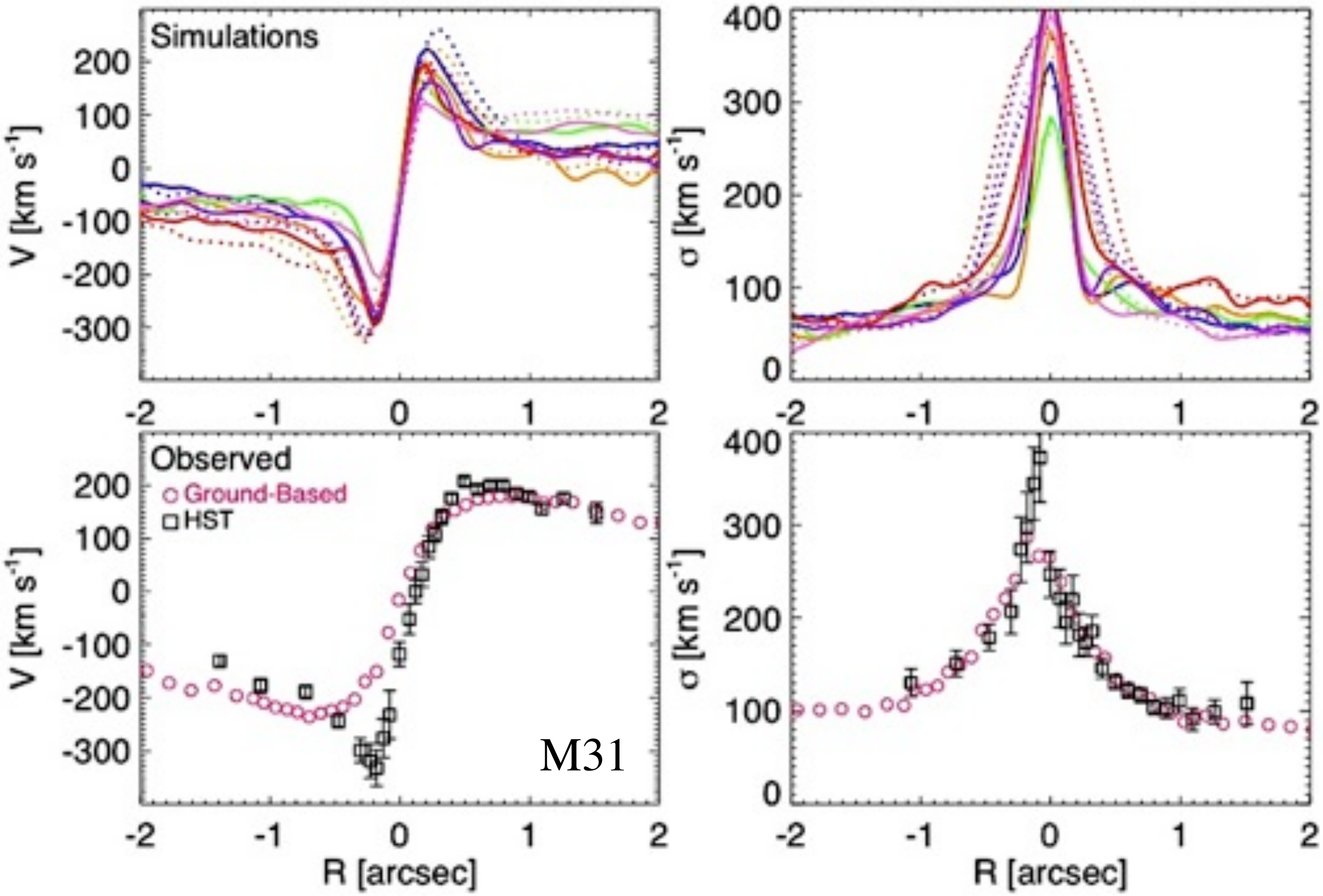
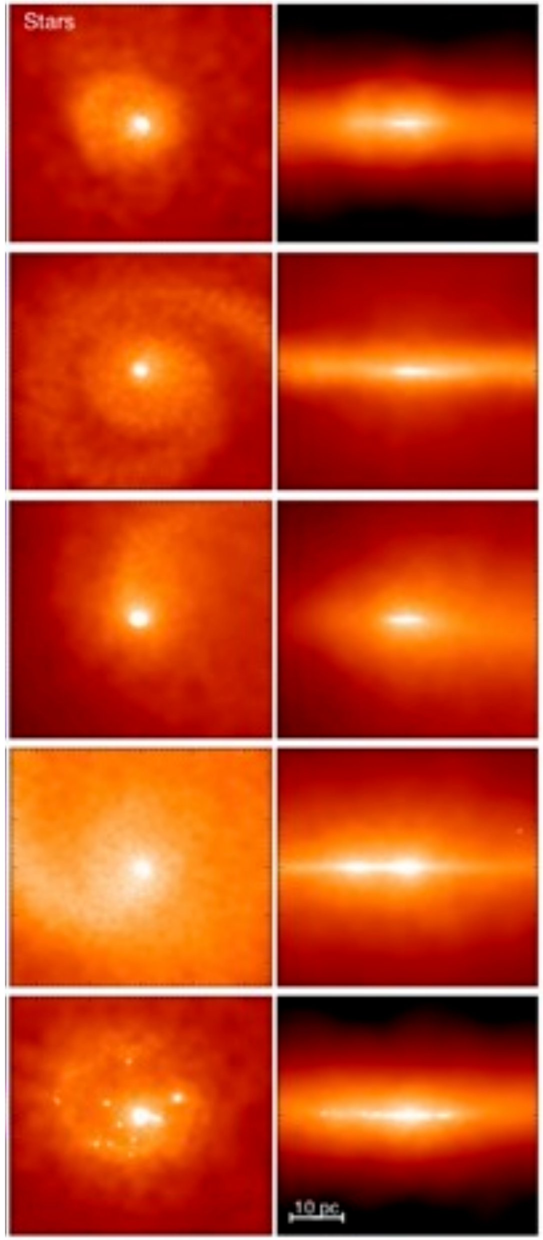


- M31 disk has ~0.1-1 M_{BH} in old stellar mass
- Outer radius R~1-10 pc
- Moderate thickness, high eccentricity

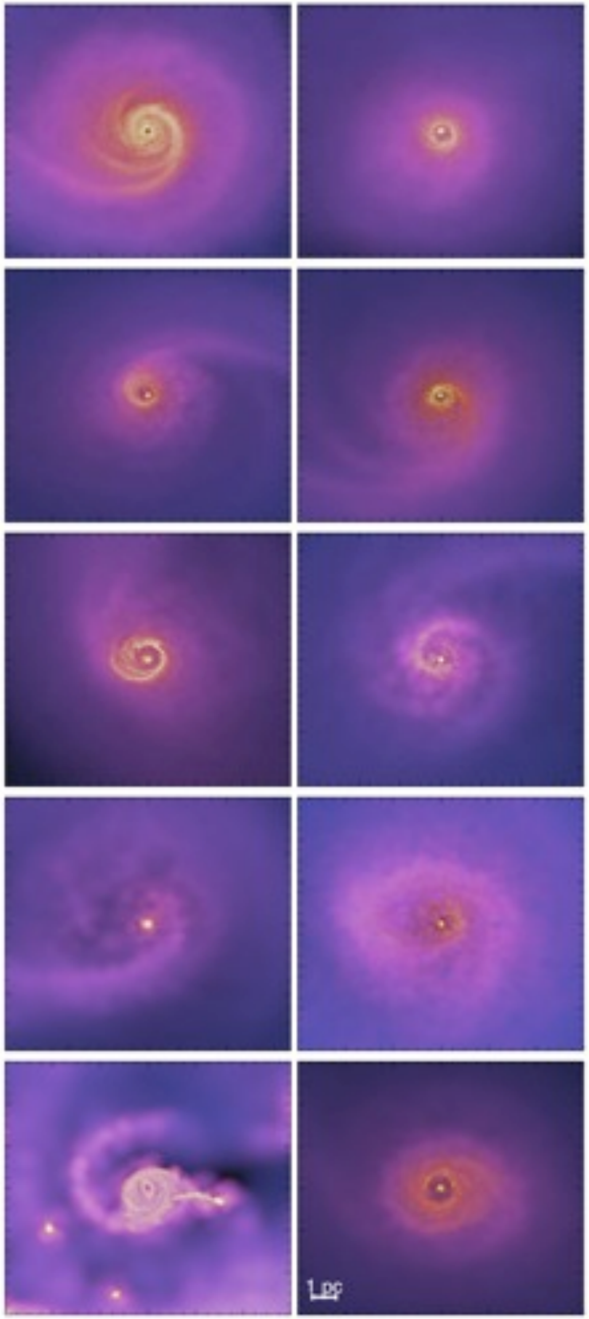
- These are observed!
  M31, NGC4486B, many candidates
  (NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)





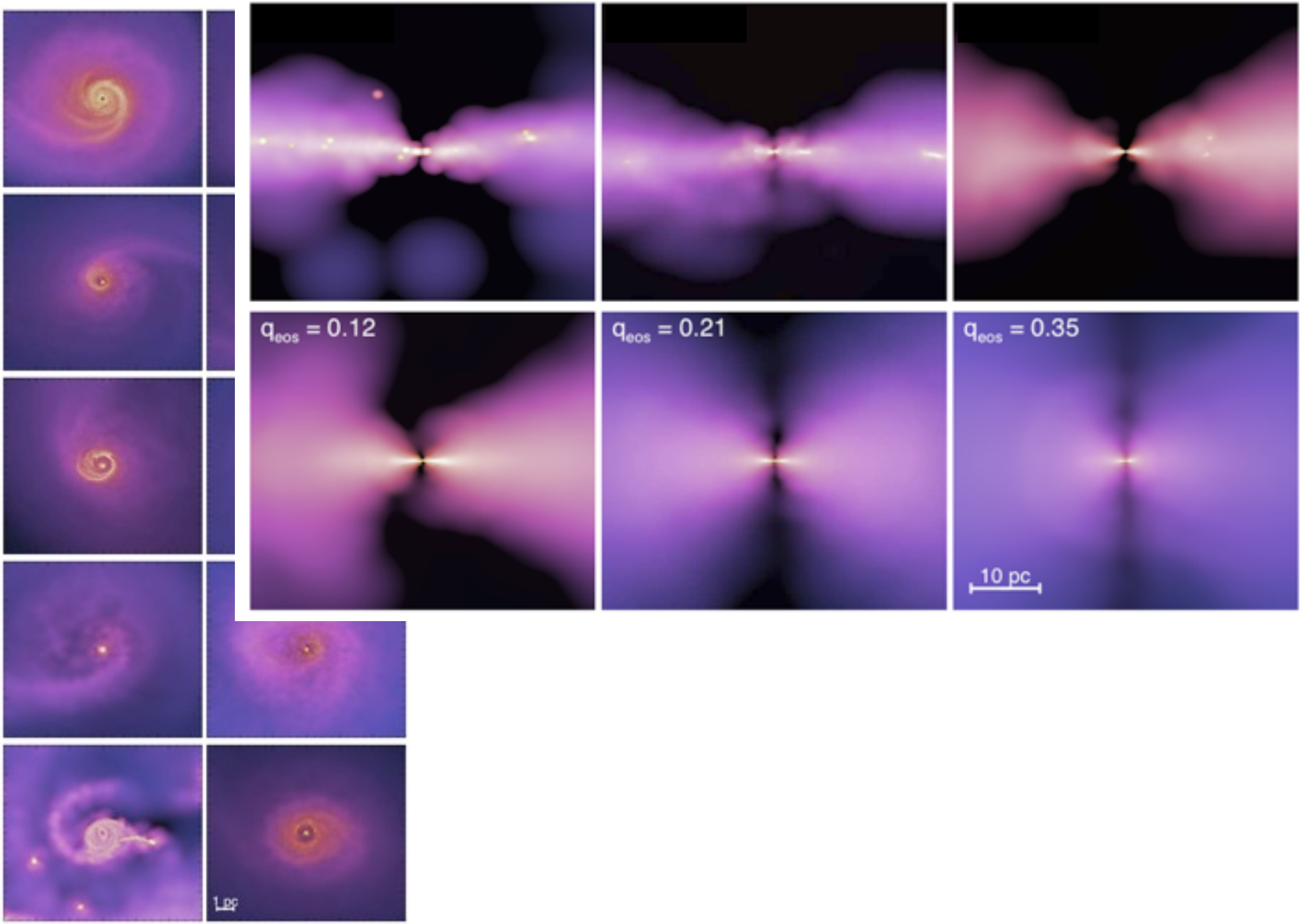
- "run backwards": the M31 disk implies accretion at
  ~0.5-3 M_{sun}/yr (~L_{Edd}) for ~100 Myr (~ M_{BH}) !

What about the obscuration from these disks?



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

What about the obscuration from these disks?



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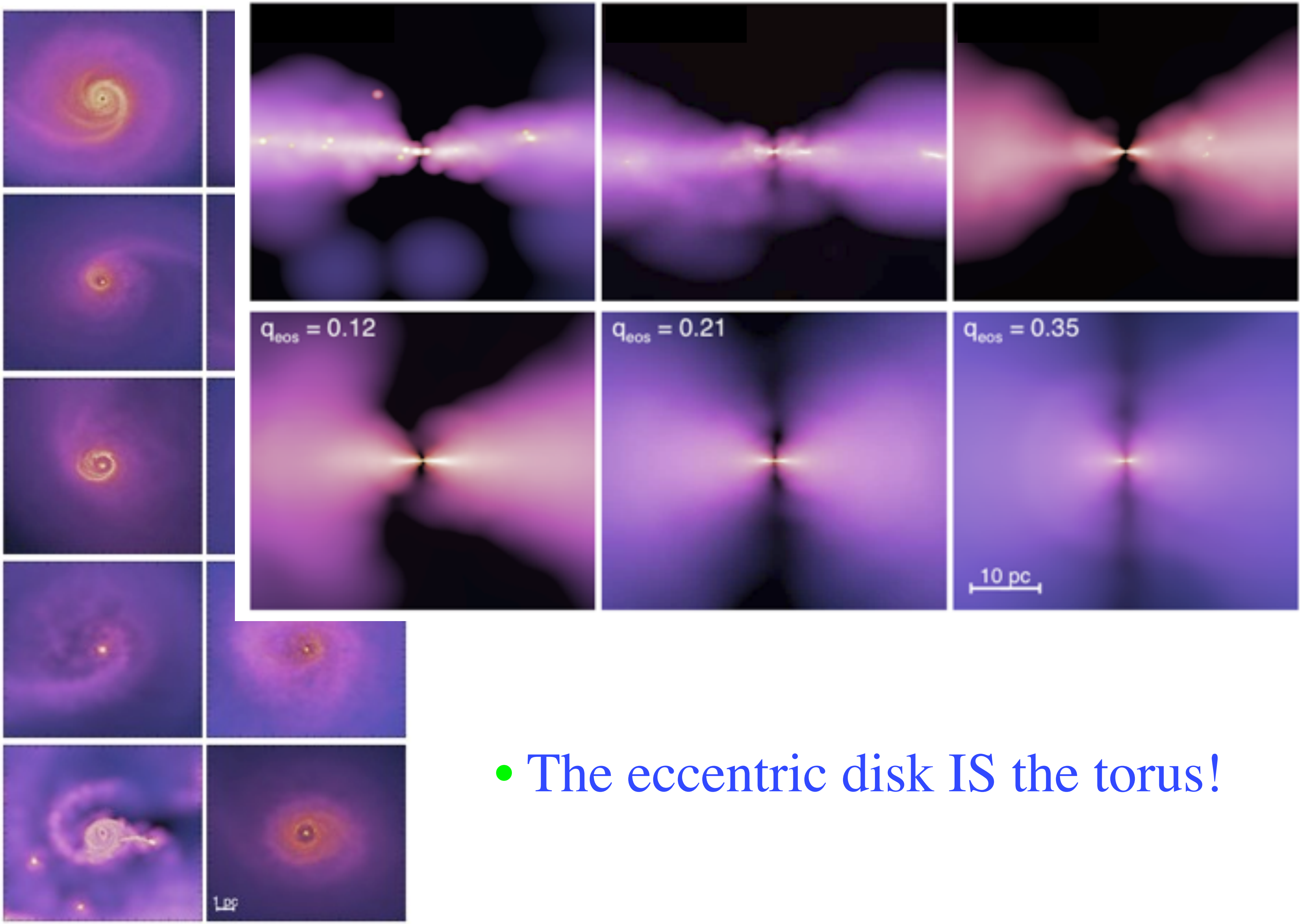

- The eccentric disk IS the torus!

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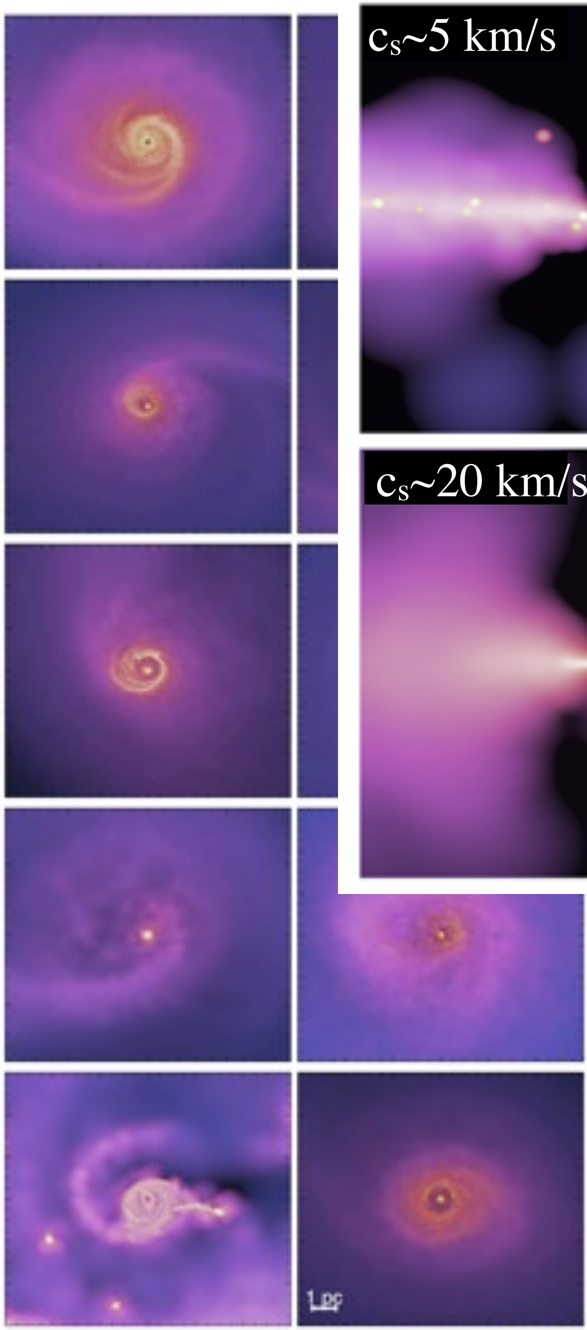
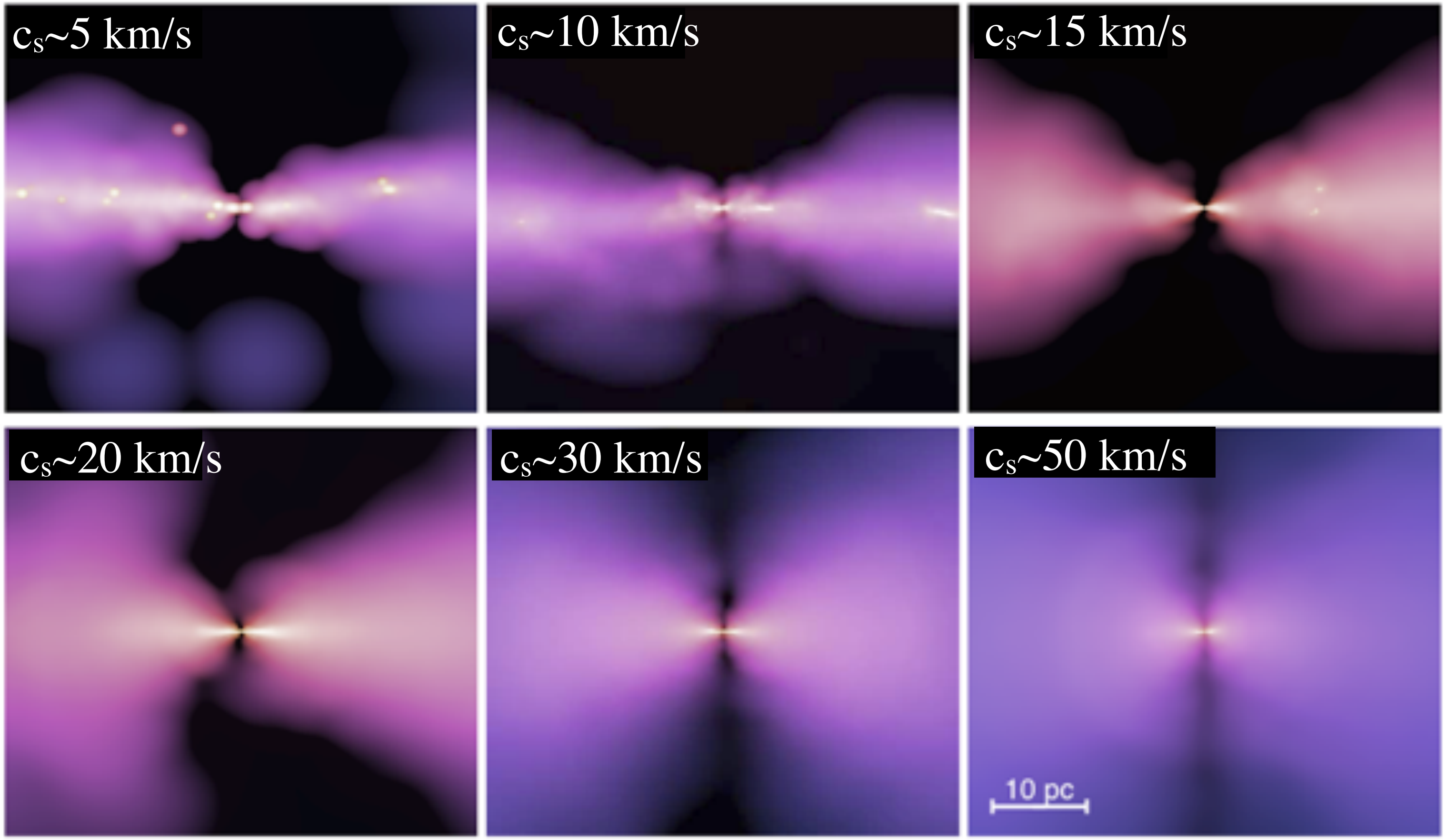




- The eccentric disk IS the torus
- Occurs even if allow cooling and no stellar feedback!
  - Heating by bending/warping modes, themselves excited *by the eccentric pattern*

Summary

- Fueling Most Luminous BHs:
  Global gravitational instabilities CAN power ~10 M_{sun}/yr! Really!
  - New Mdot estimator: neither viscous nor Bondi

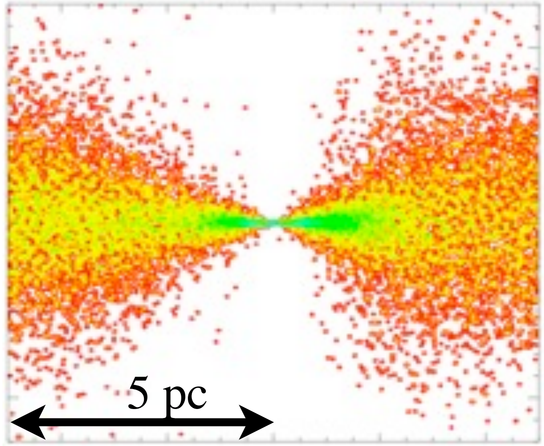
- "Stuff within Stuff": Cascade of instabilities with diverse morphology
  - Doesn't matter how *first* 'get down' from large scales

- 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 ?

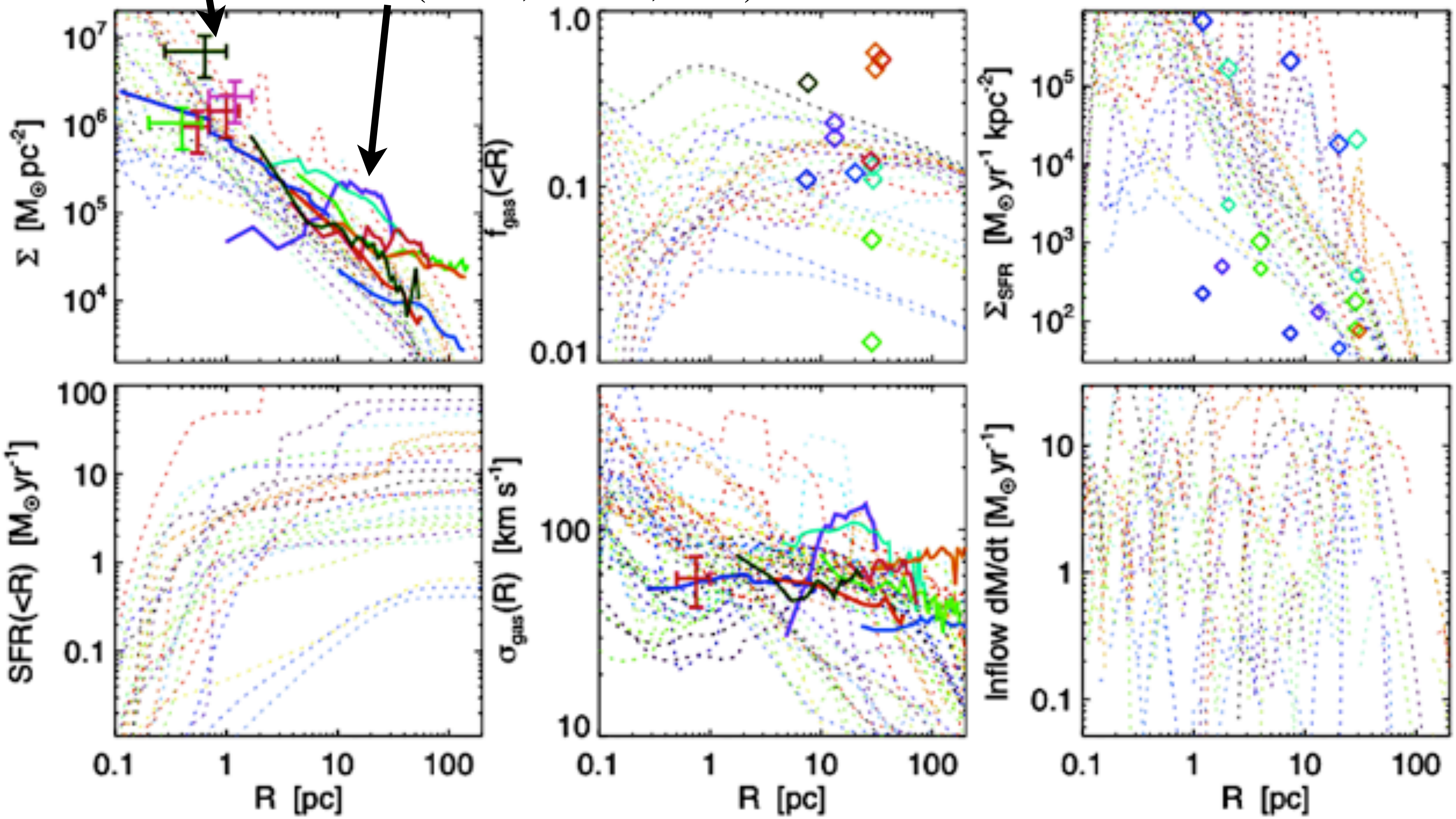
Obscuration and the 'torus'



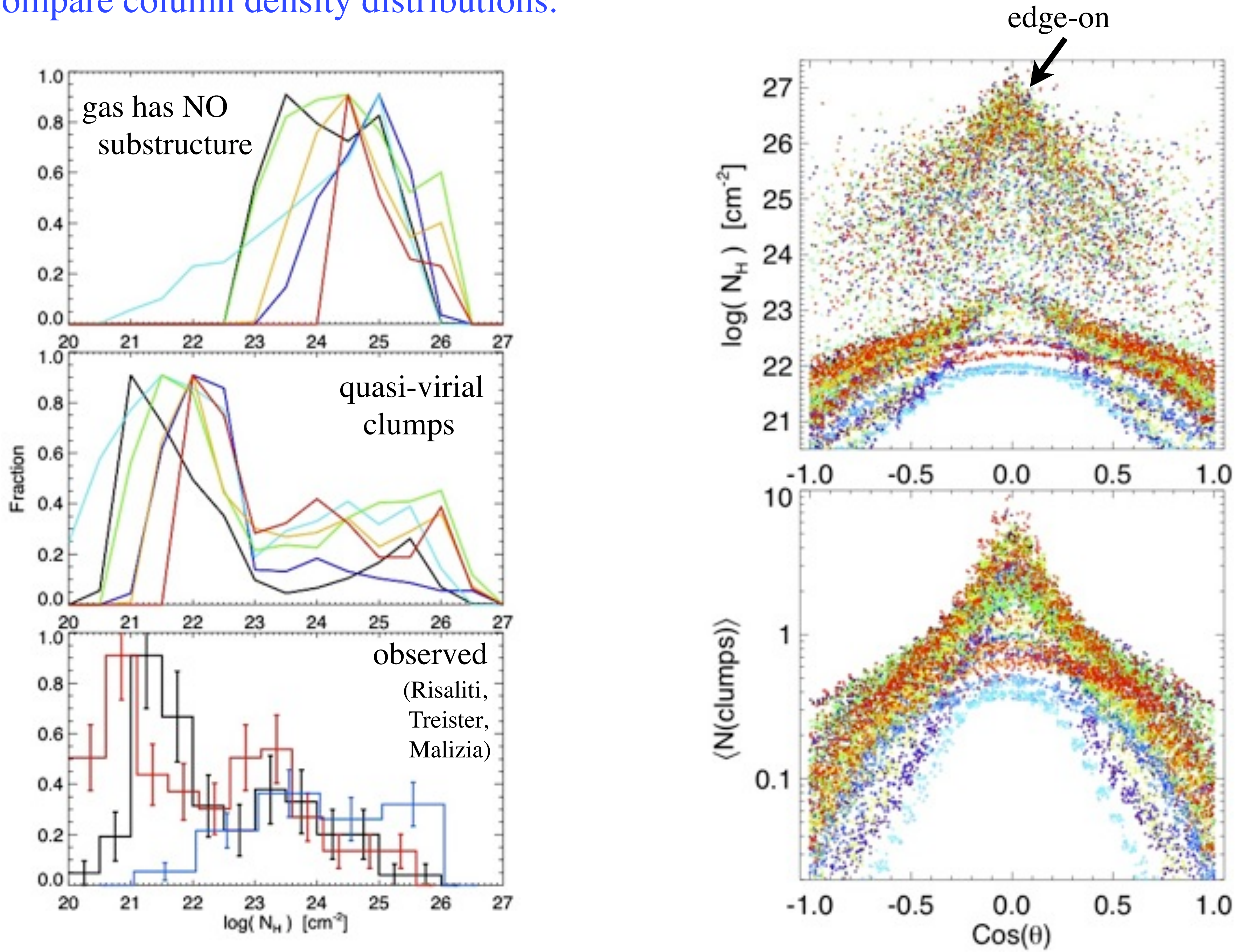
- Observed surface densities and kinematics arise naturally

Masers (Kondratko, Greenhill, et al.)

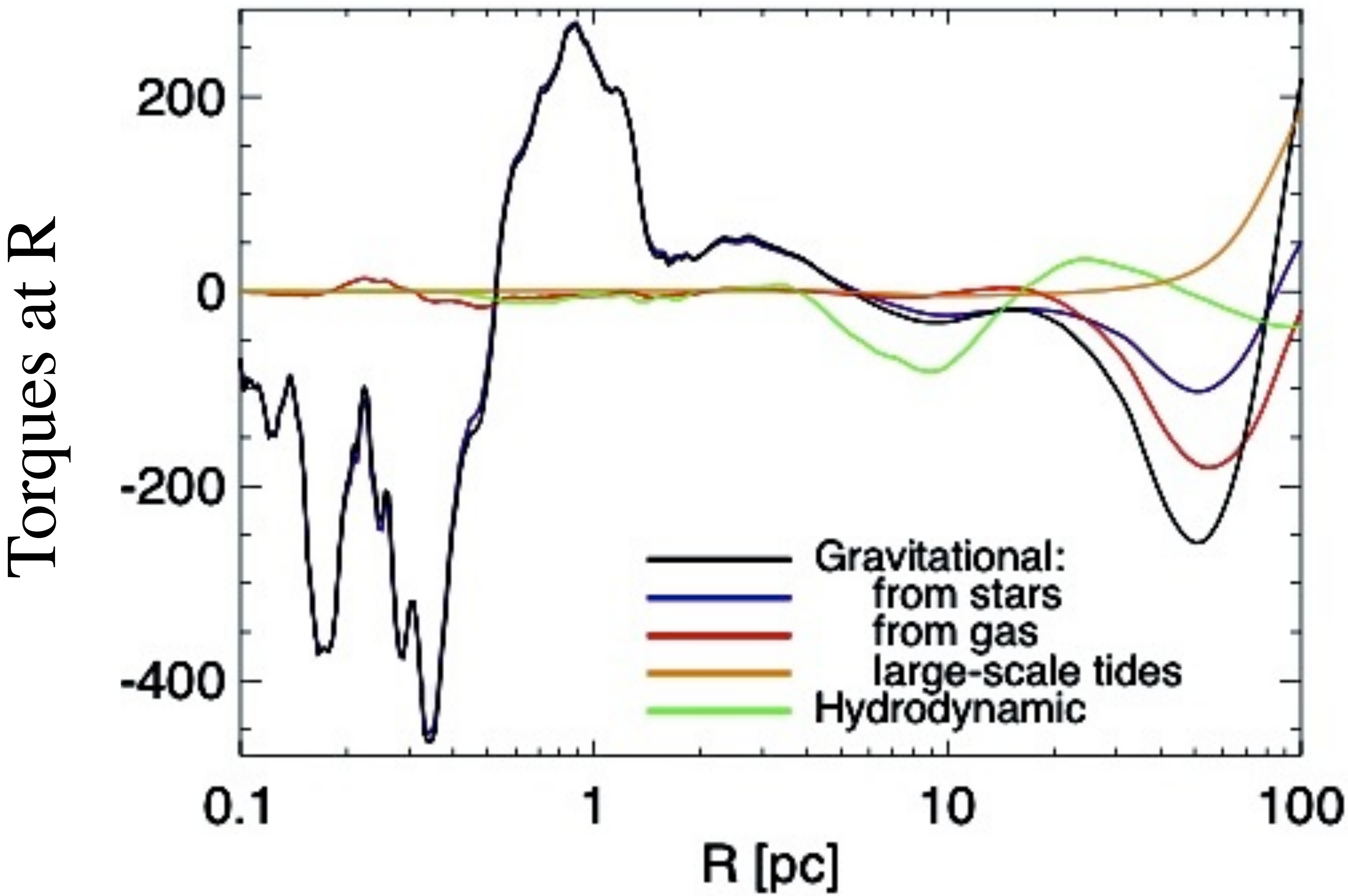
AO (Hicks, Davies, et al.)

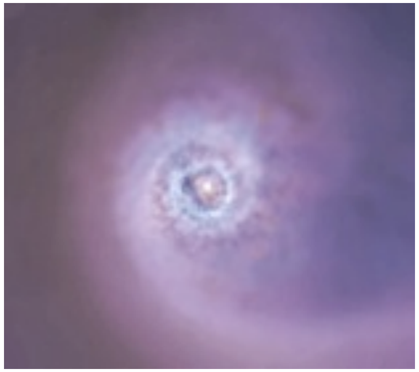


• Compare column density distributions:



- Gravity dominates torques from 0.1 - 10,000 pc



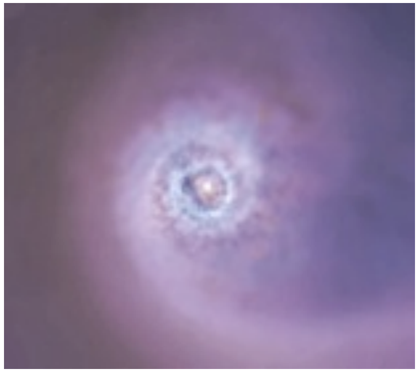


- m=1 'slow' modes are special in a near-Keplerian potential

Disturb the stars with some perturbation in the disk:

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

number of 'arms'



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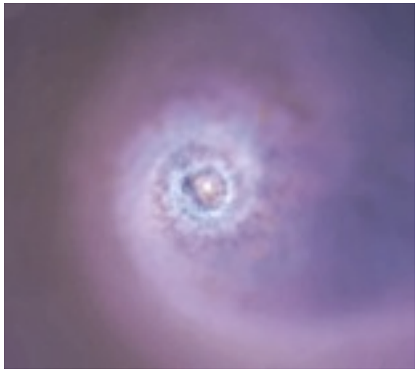
$$\Delta = \kappa^2 - m\Omega^2$$



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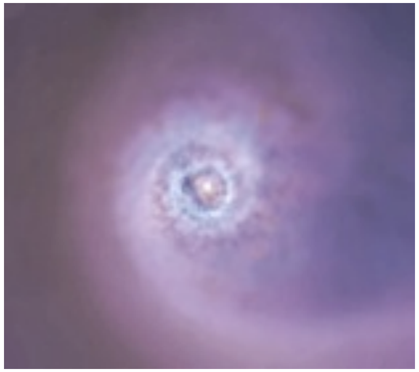

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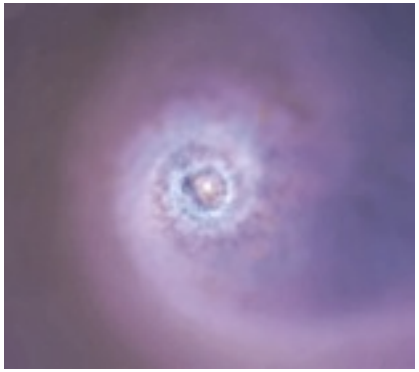
$$\Delta = \kappa^2 - m\Omega^2$$

$$m \neq 1 :$$

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

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

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



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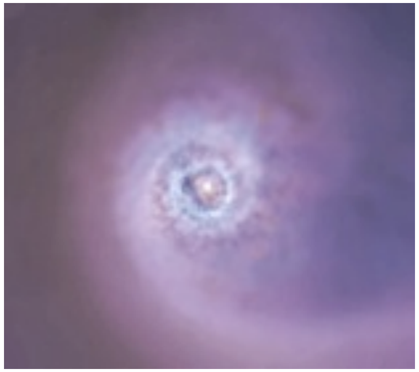

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$$m = 1 :$$

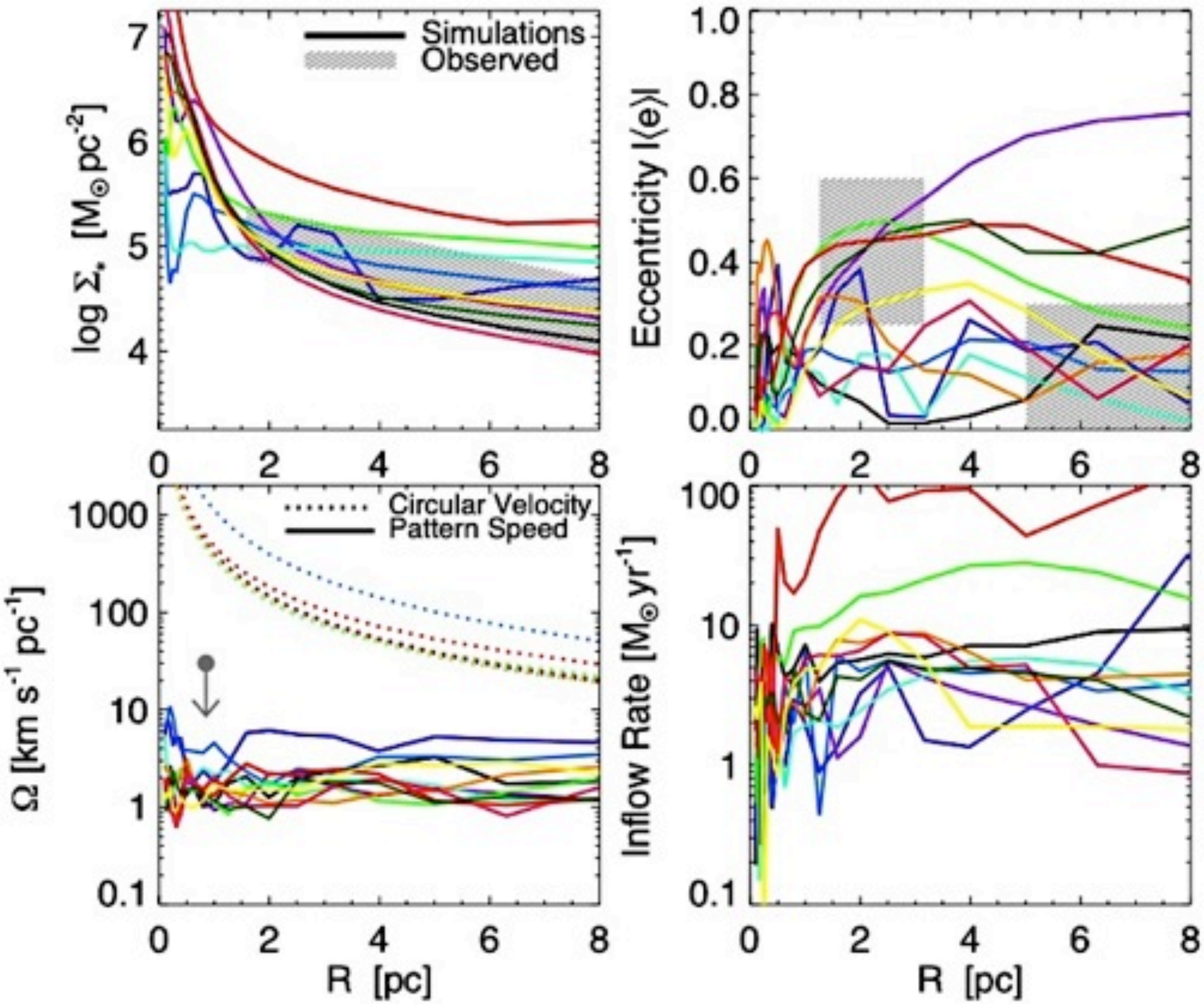
$$\Delta \to 0 \;\text{(resonance)}$$

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

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

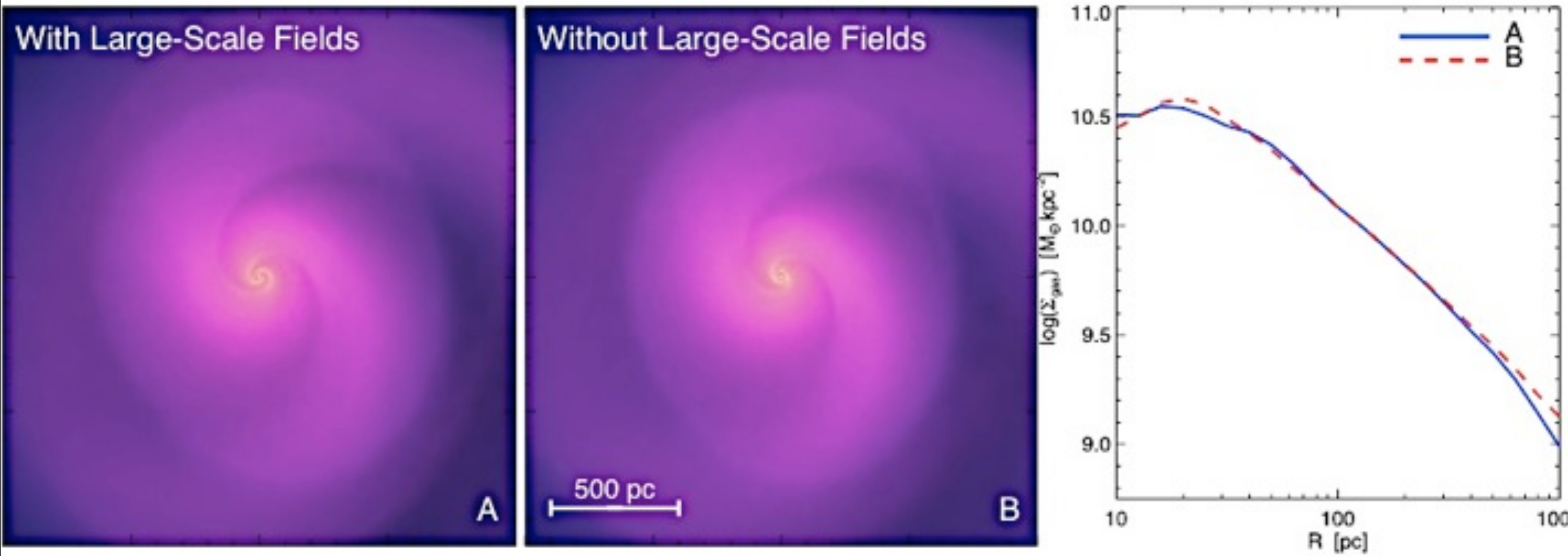
- Strong torques can propagate to all r (even << 0.1pc)

INDEPENDENT of $M_{disk}(<r)/M_{BH}$



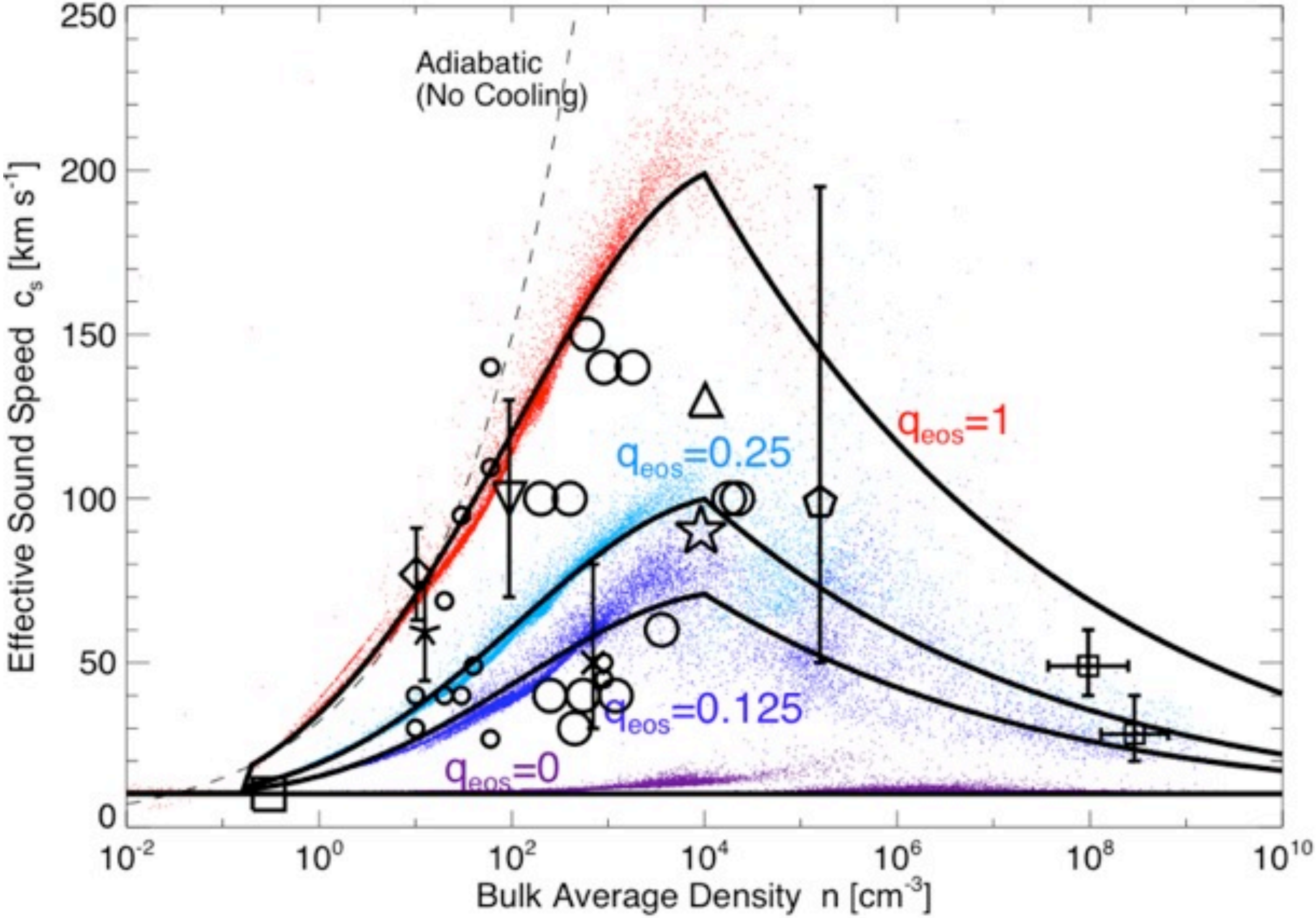
Simulations
Observed
log Σ* [M☉ pc⁻²]
Eccentricity |⟨e⟩|
Circular Velocity
Pattern Speed
Ω [km s⁻¹ pc⁻¹]
Inflow Rate [M☉ yr⁻¹]
R [pc]
R [pc]

Large-Scale Tides are Not Important for AGN:

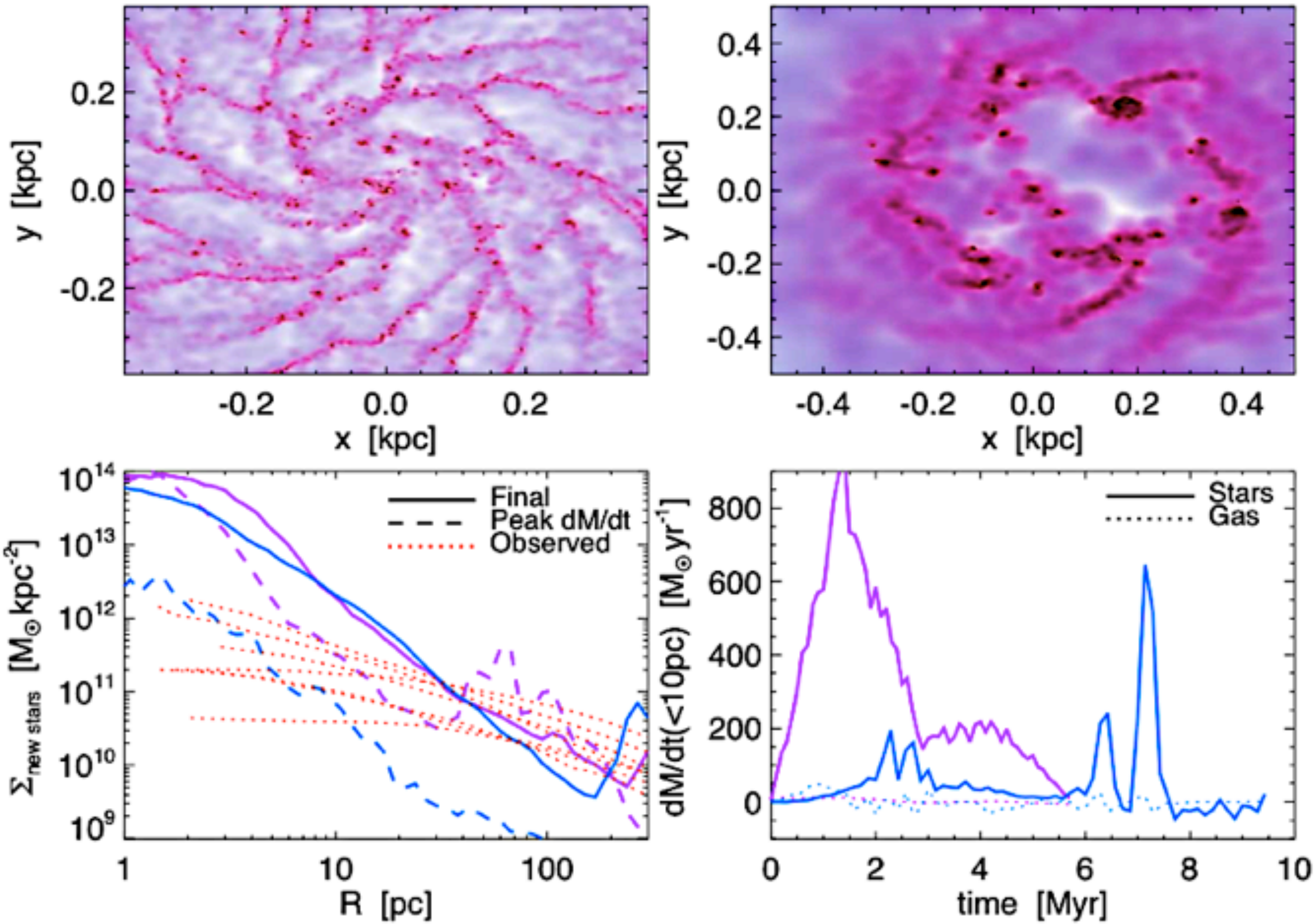


The Effective Stellar Feedback on Small Scales:

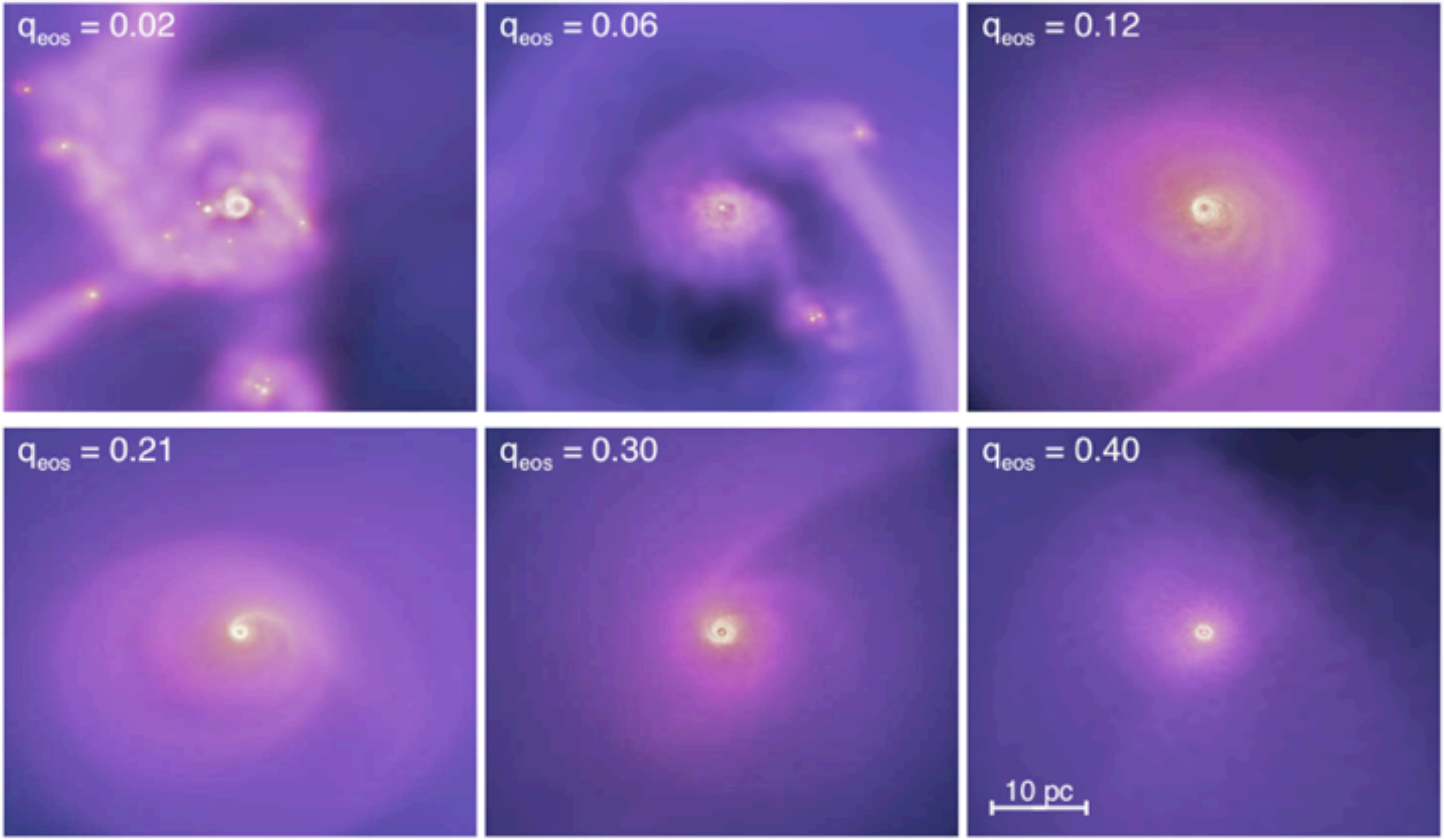
(REQUIRE SOME SUB-RESOLUTION MODEL)



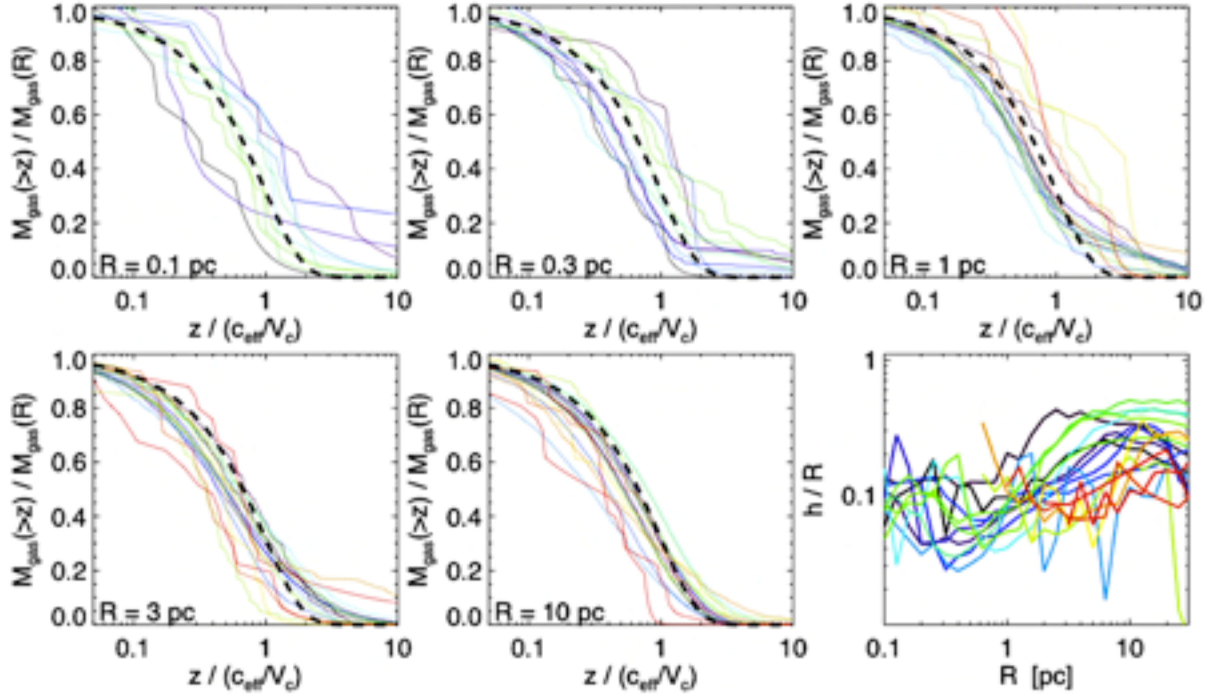
A "No Feedback" ISM is Ruled Out on Small Scales:

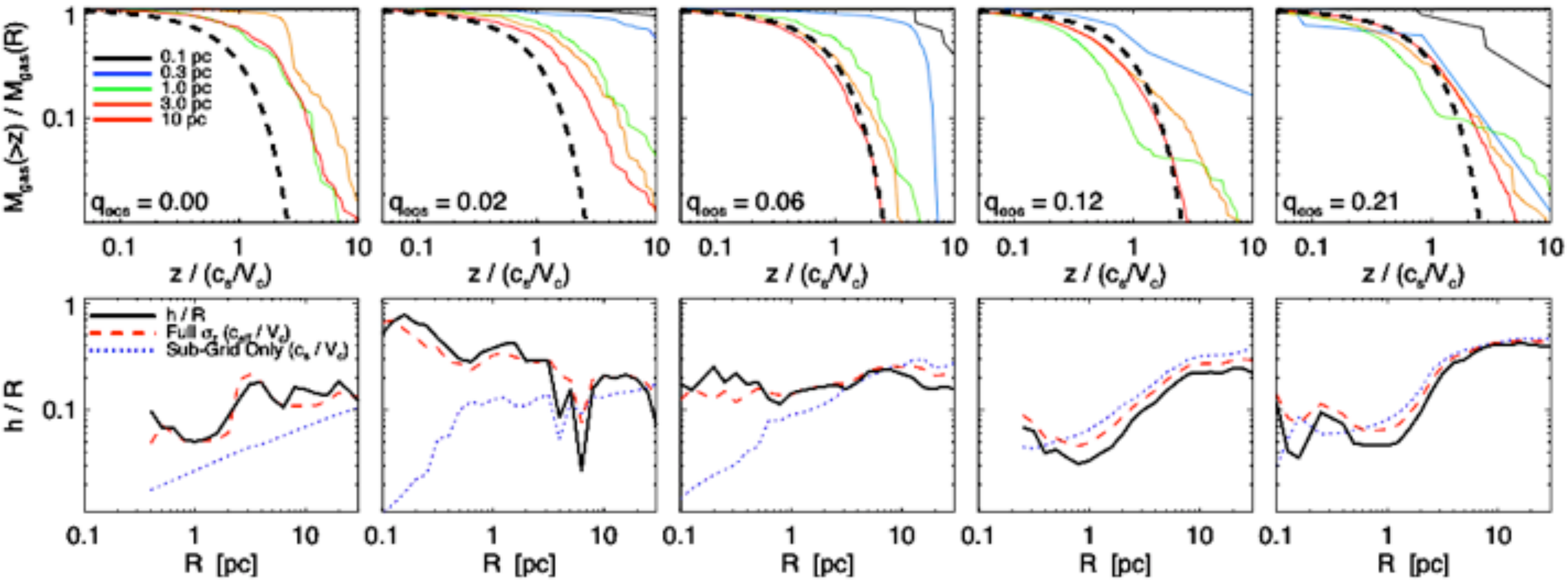


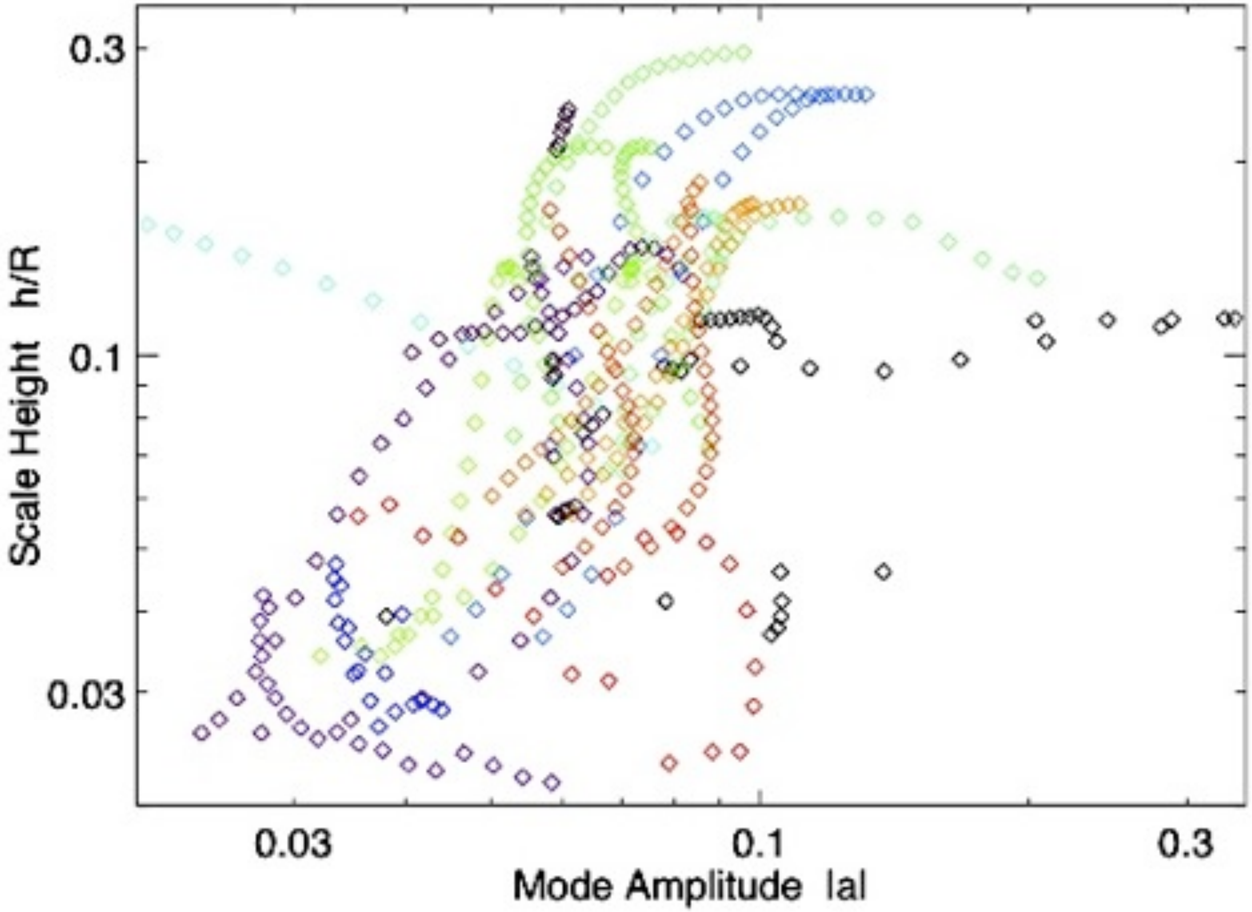
But qualitative conclusions are insensitive to the gas microphysics

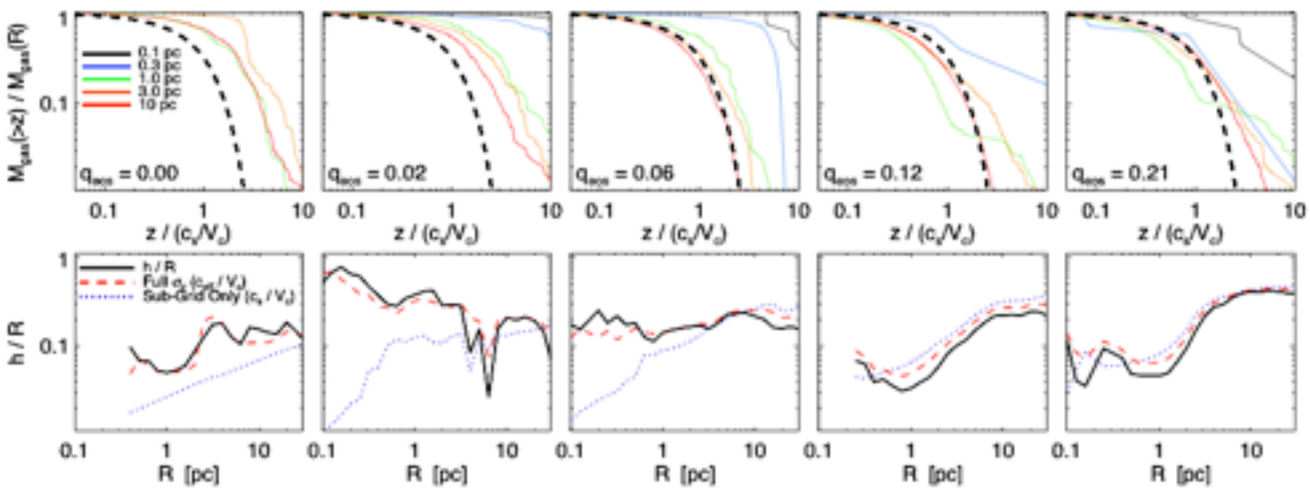


Vertical Torus Structure



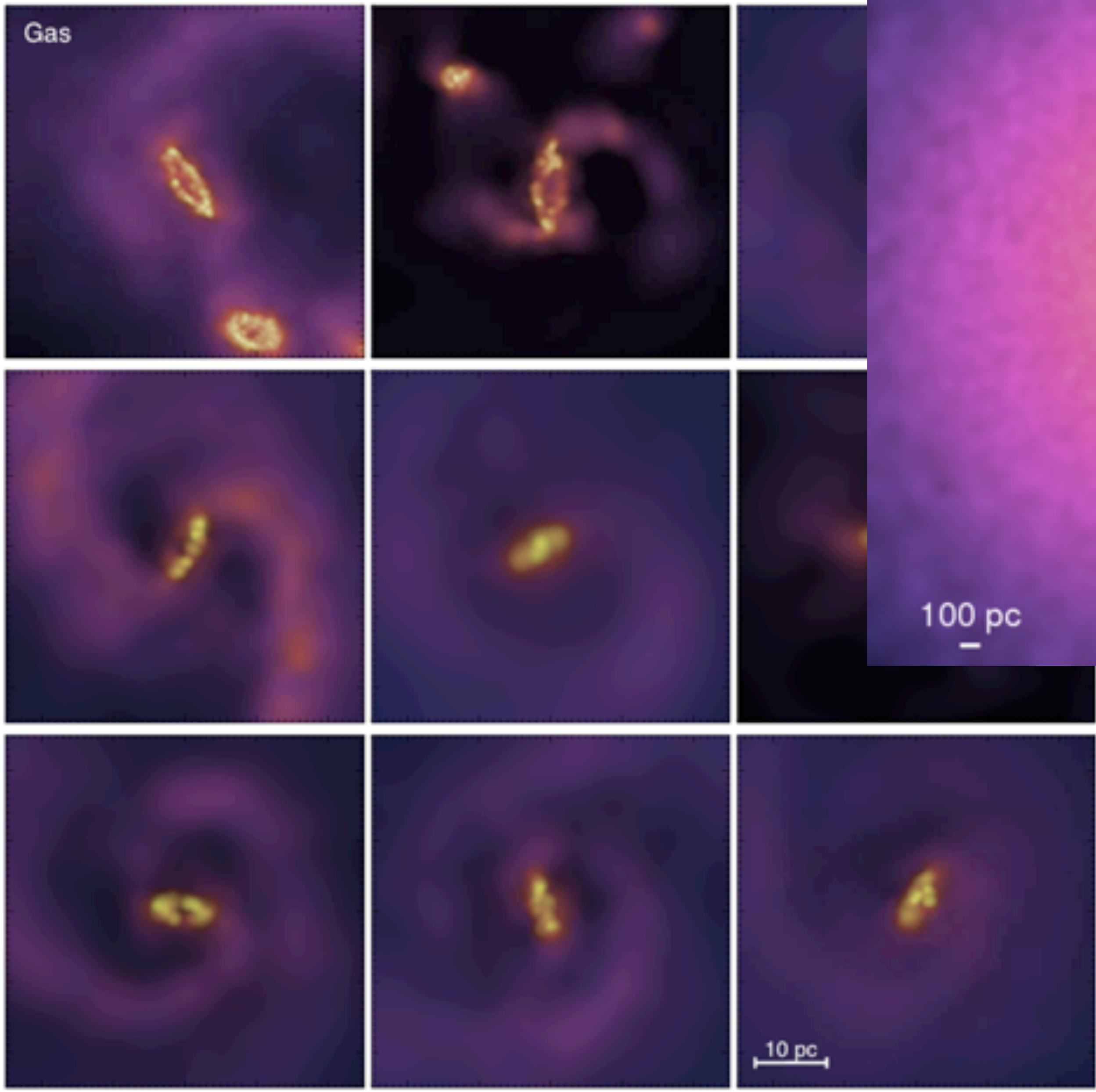


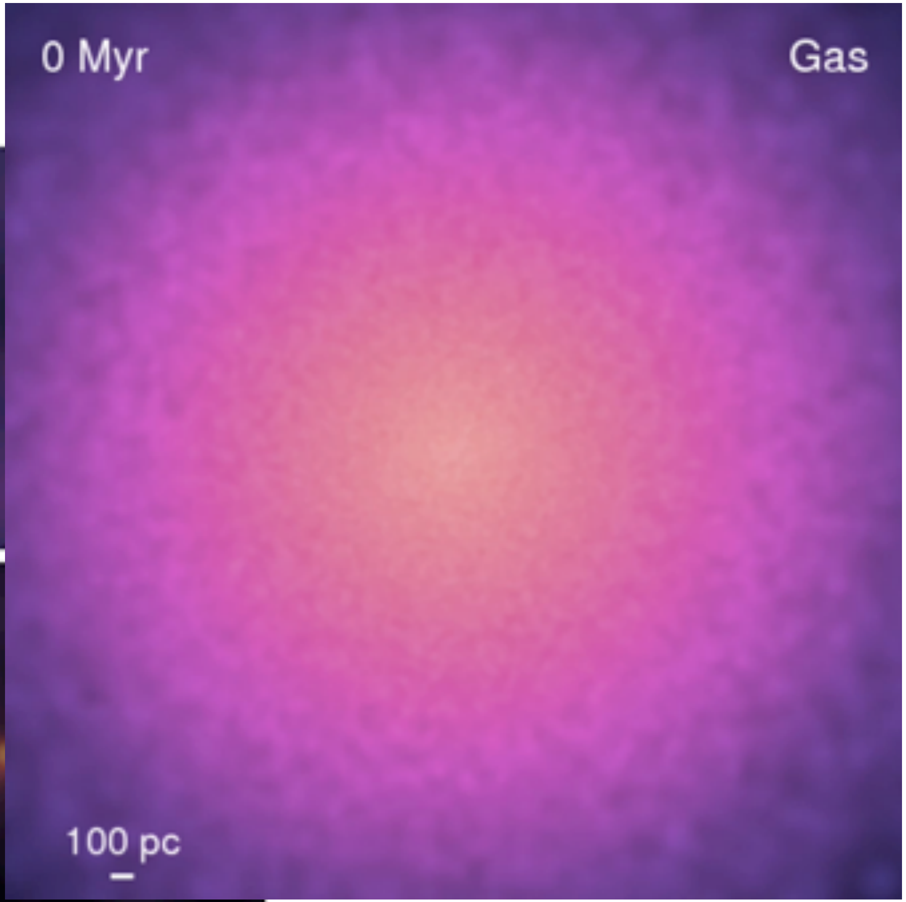




Vertical Torus Structure

Mis-alignments with the parent disk are common





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

Torus-Host disk misalignments: