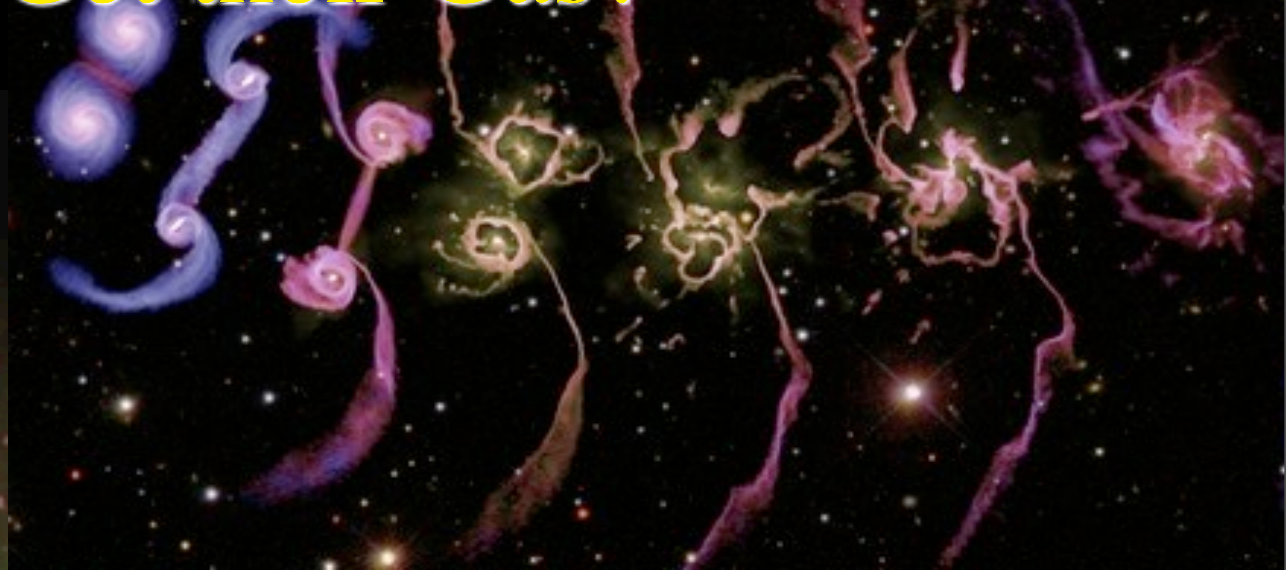
How do Massive Black Holes Get their Gas?



Philip Hopkins

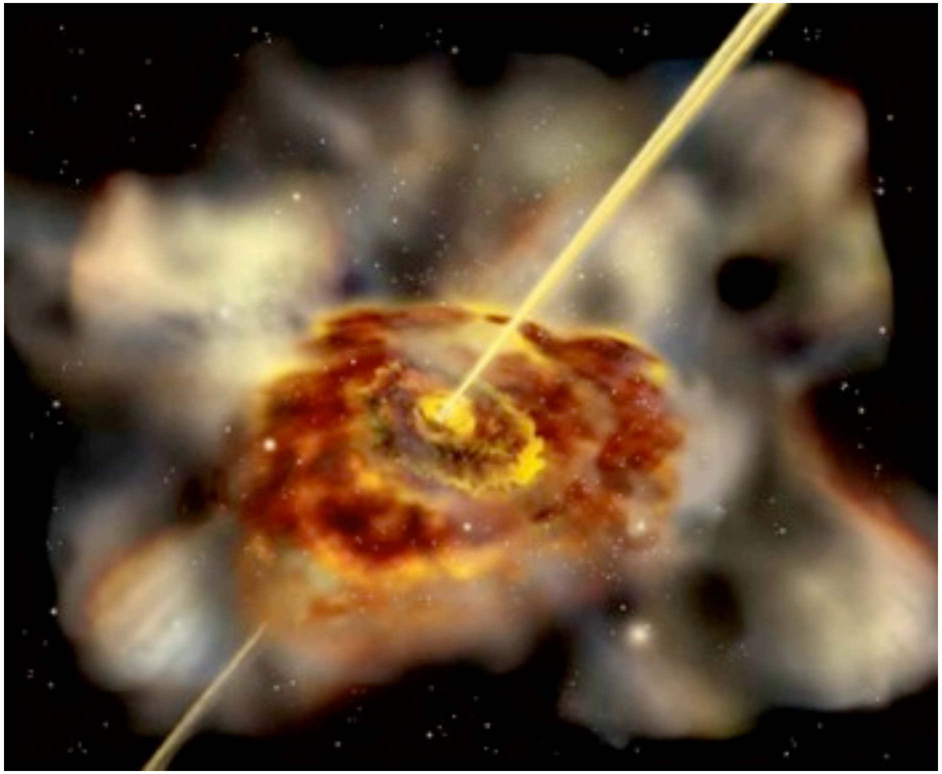
Eliot Quataert, Lars Hernquist, T. J. Cox, Kevin Bundy, Jackson DeBuhr, Volker Springel, Dusan Keres, Gordon Richards, Josh Younger, Desika Narayanan, Paul Martini, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Alison Coil, Adam Myers, Patrik Jonsson, Chris Hayward


Adam
Lidz
TJ
Cox
Josh
Younger
Desika
Narayanan
Chris
Hayward
Gurtina
Besla
Dusan
Keres
Lars
Hernquist
Eliot
Quataert

Motivation

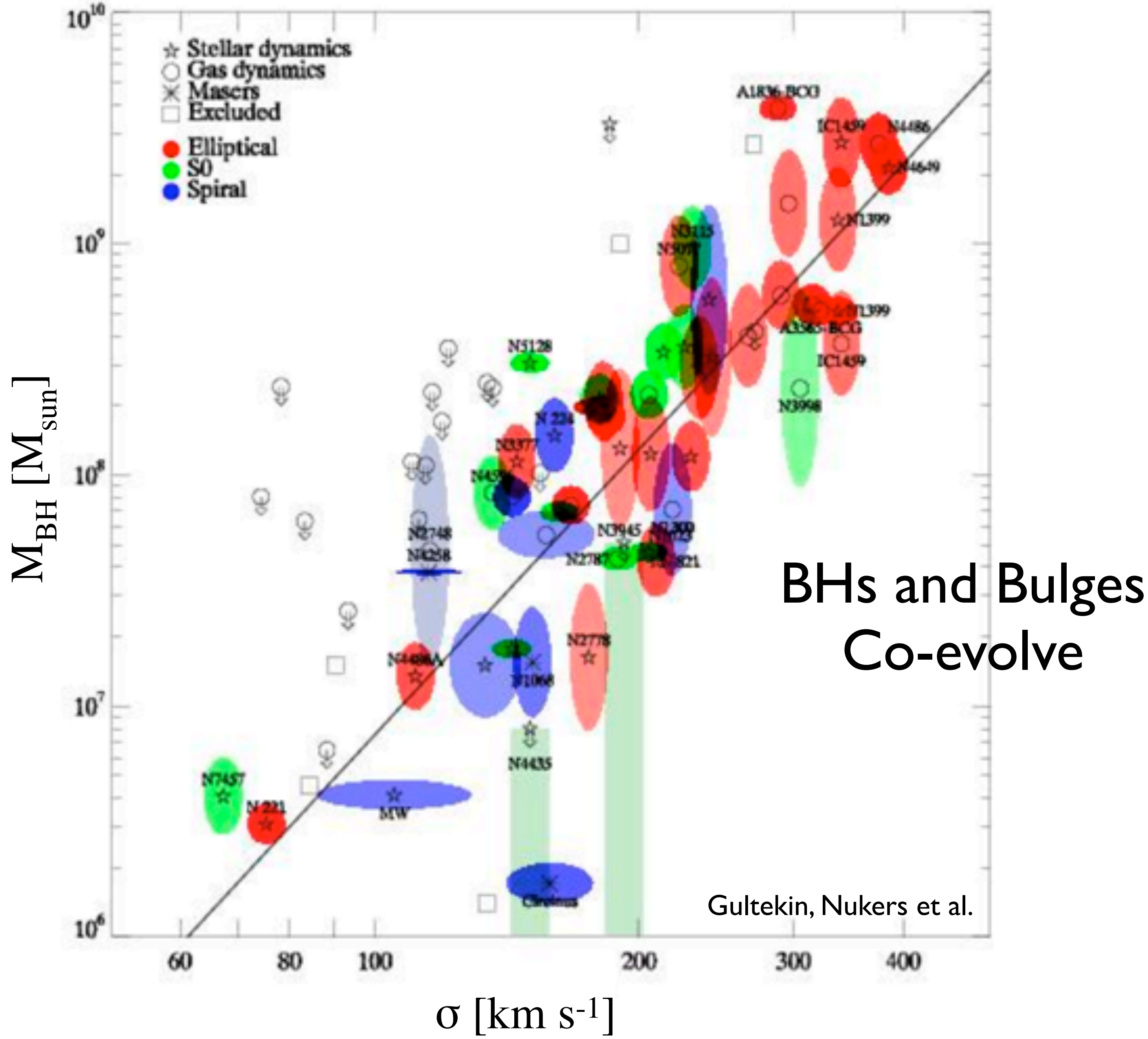
WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Every massive galaxy hosts a supermassive black hole

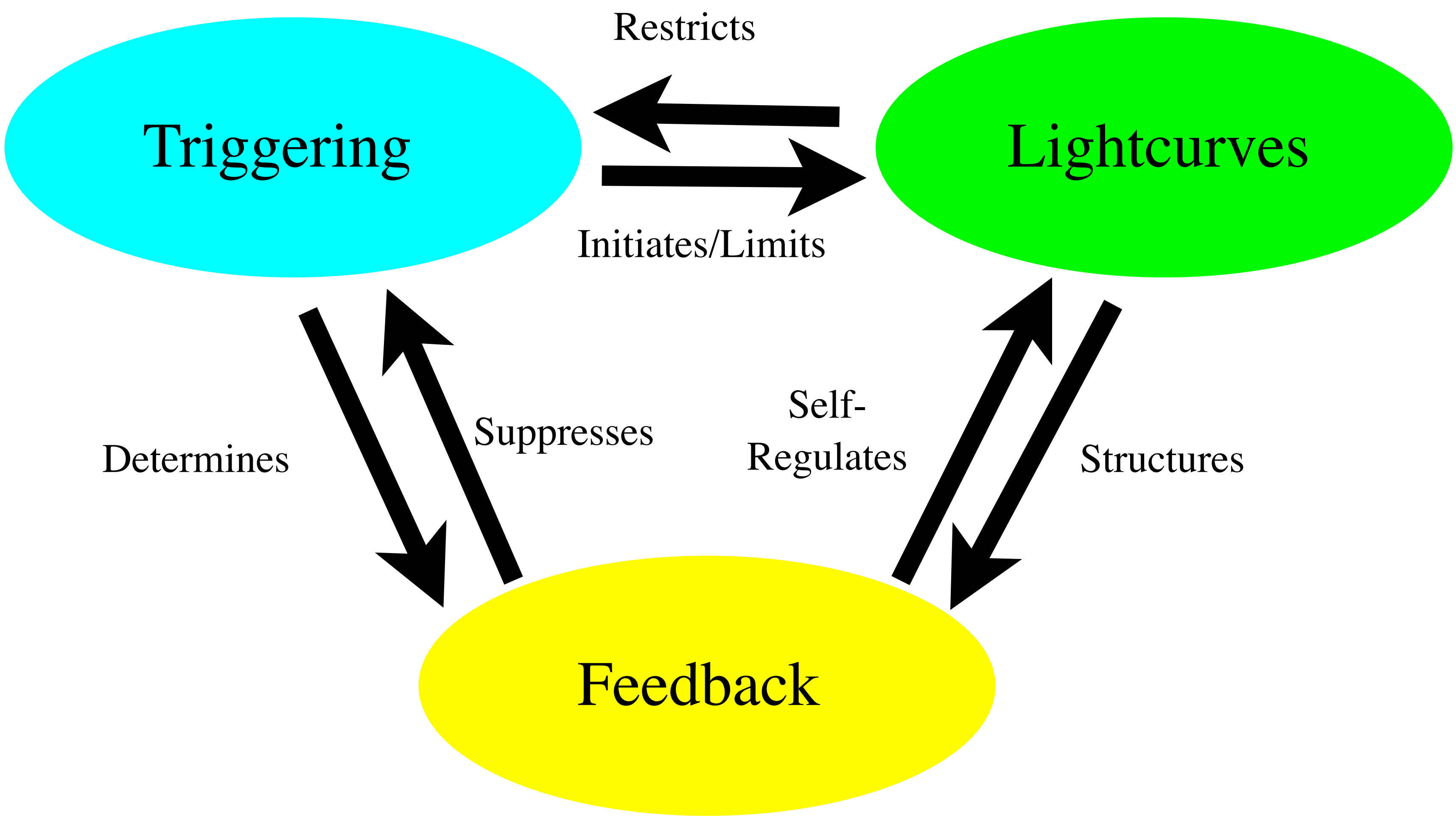


- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

Black Holes are Tightly Coupled to Bulge Properties...



Outstanding (Inseparable?) Questions:



How Do Massive BHs Get Their Gas?

Some things to remember...

- *All* SMBH are 'AGN' (on some level)
- "BHs are objects, AGN are a process"
  - Gas around BH = AGN
- Many ways to fuel: they will all happen
  - Stellar winds/mass loss
  - Diffuse/hot accretion (Bondi-Hoyle)
  - Tidal disruption of stars
  - Stochastic collisions with molecular clouds
  - Gravitational instabilities

- Here: Focus on most luminous AGN (quasars)
  - Most BH mass accreted, most energy/momentum released
  - Fueling is hard: $\sim 10\ M_{sun}/yr$ to $R \ll pc$, $\sim 10^9\ M_{sun}$ total

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None of these come close

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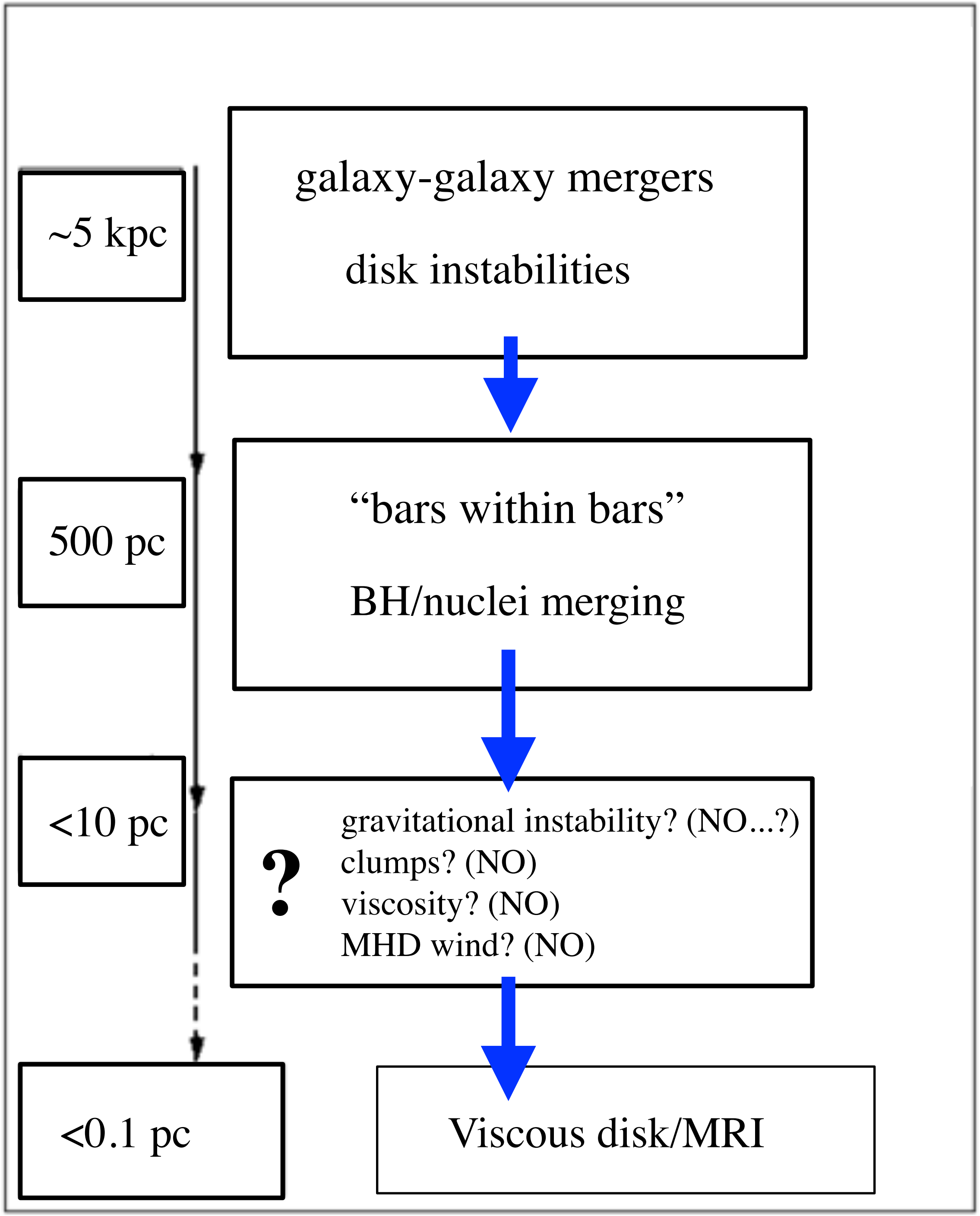
- Focus: Most luminous QSOs
  (~1-10 M_{sun}/yr)

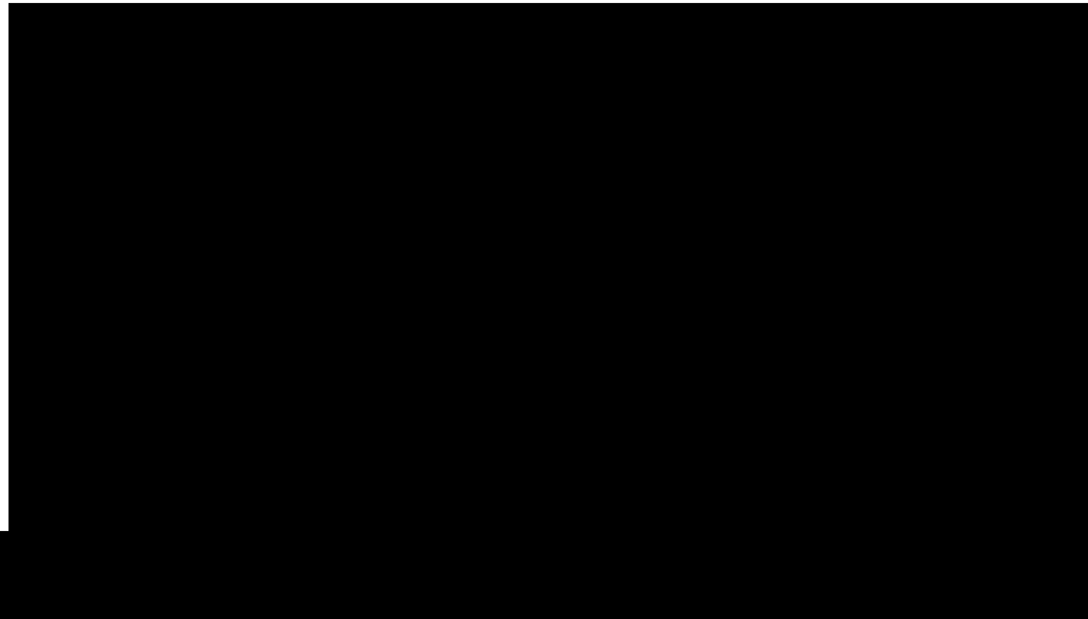
- 'Bottleneck' at
  <10-50pc: BH begins
  to dominate the potential

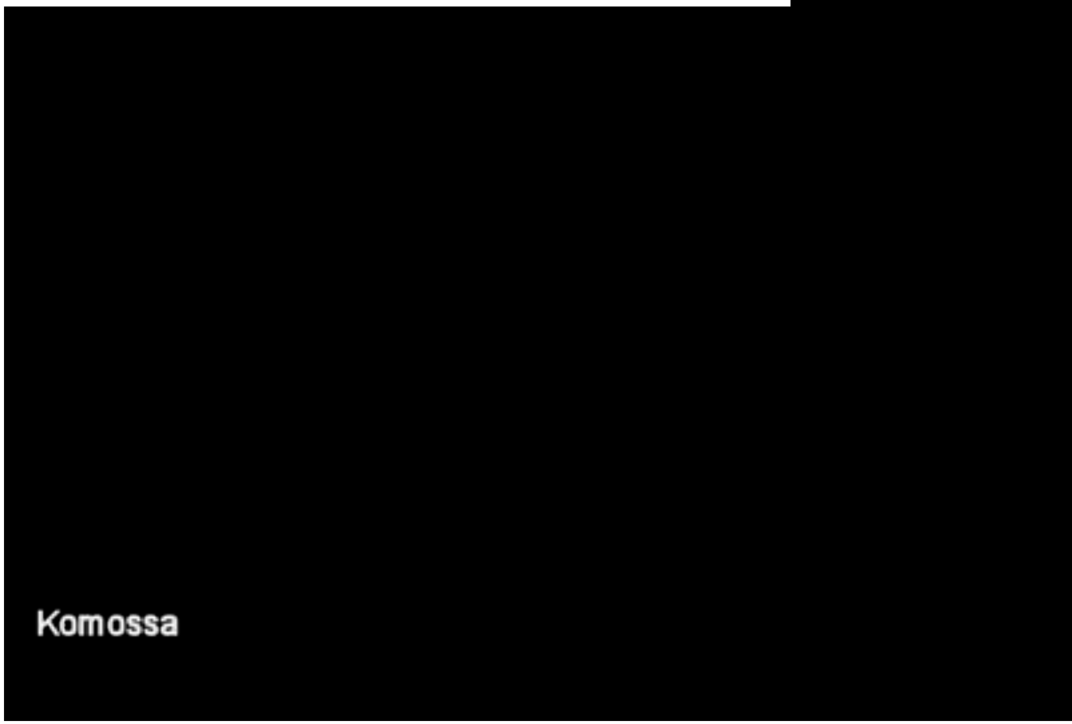
  (e.g. Goodman et al.,
  Jogee et al., Martini et al.)



- 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:

FOLLOWING THE GAS IN...

- Need to include:

- Here: Focus on *robust* conclusions

Simulations:

FOLLOWING THE GAS IN...

- Need to include:
    - Gas+Stars

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Simulations:

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- Need to include:
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Simulations:

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Simulations:

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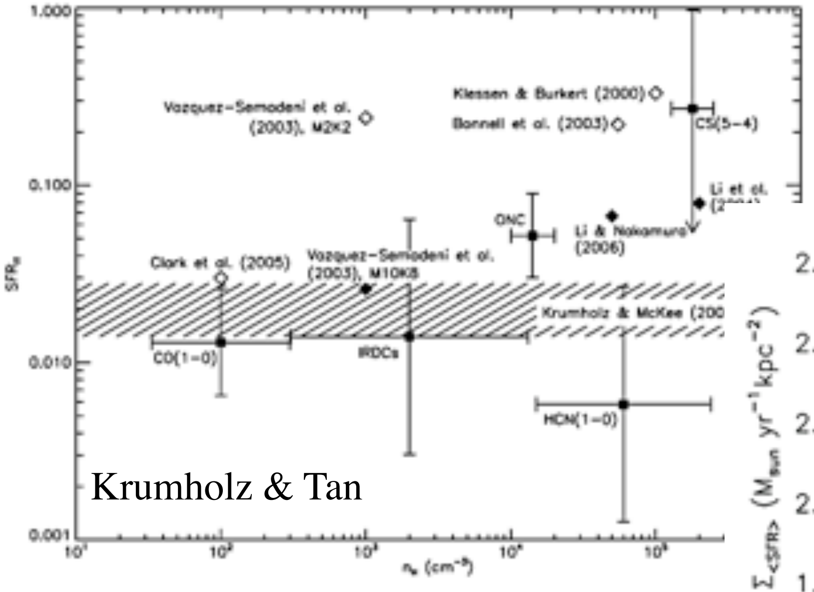
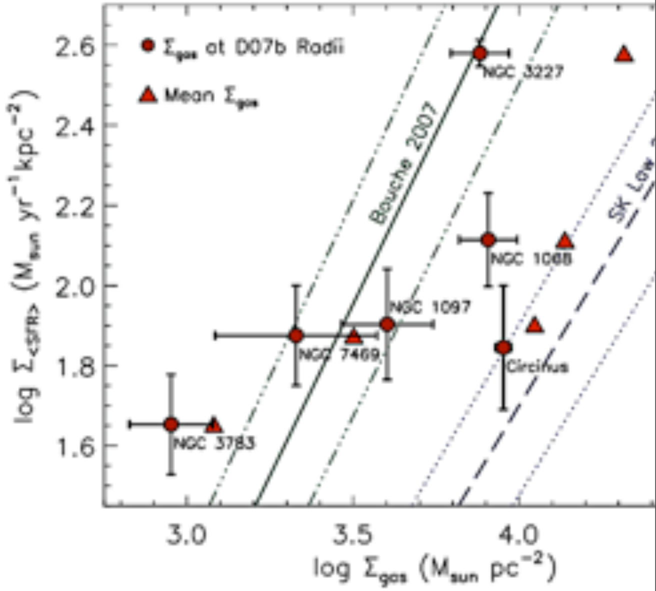


Hicks et al.



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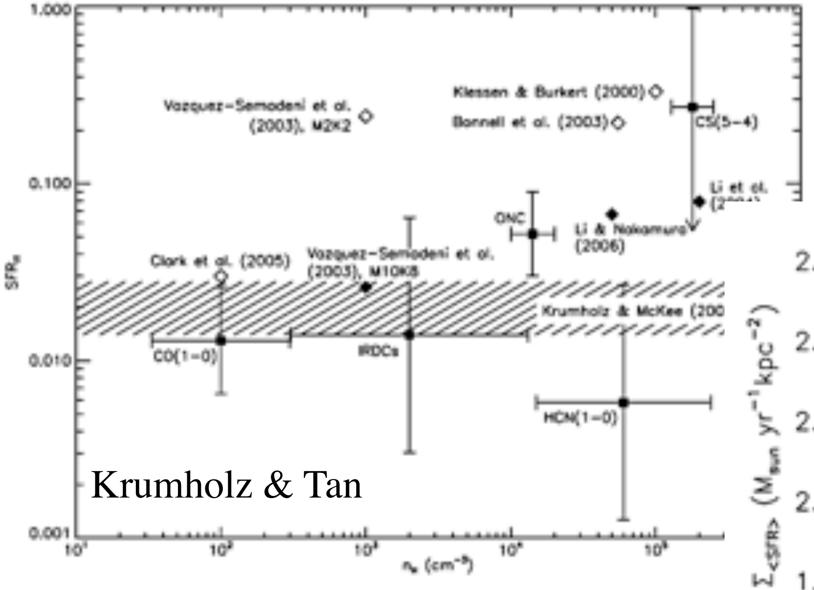
  - ‘Feedback’
    - Admit we don’t understand it!



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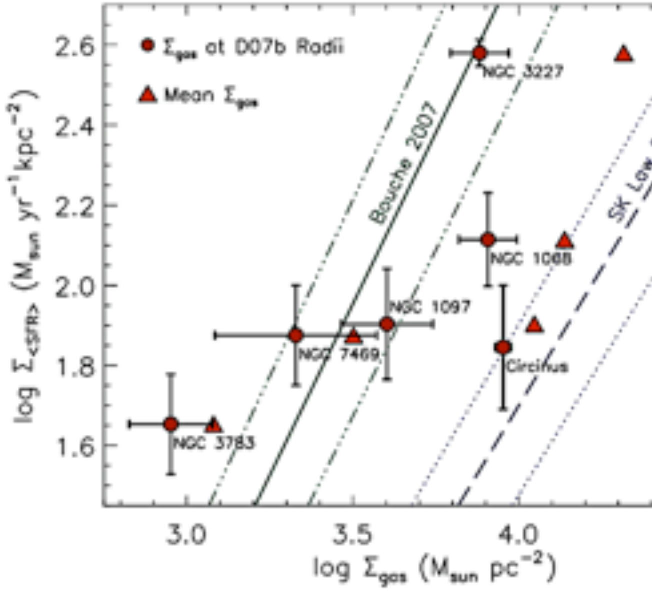

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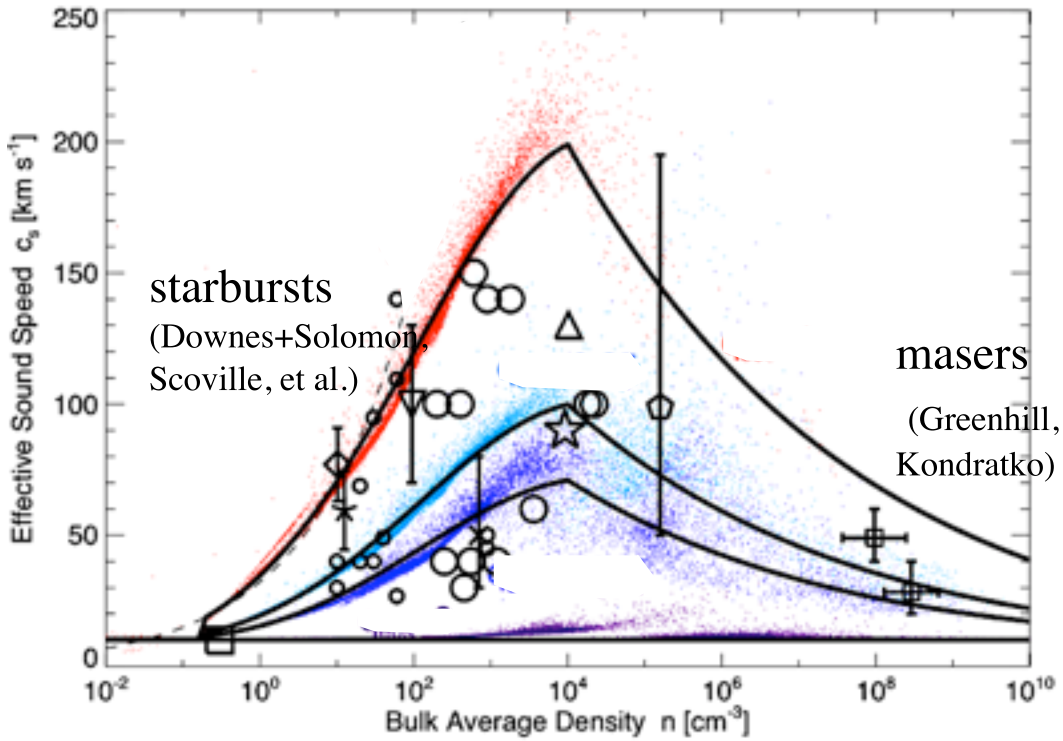

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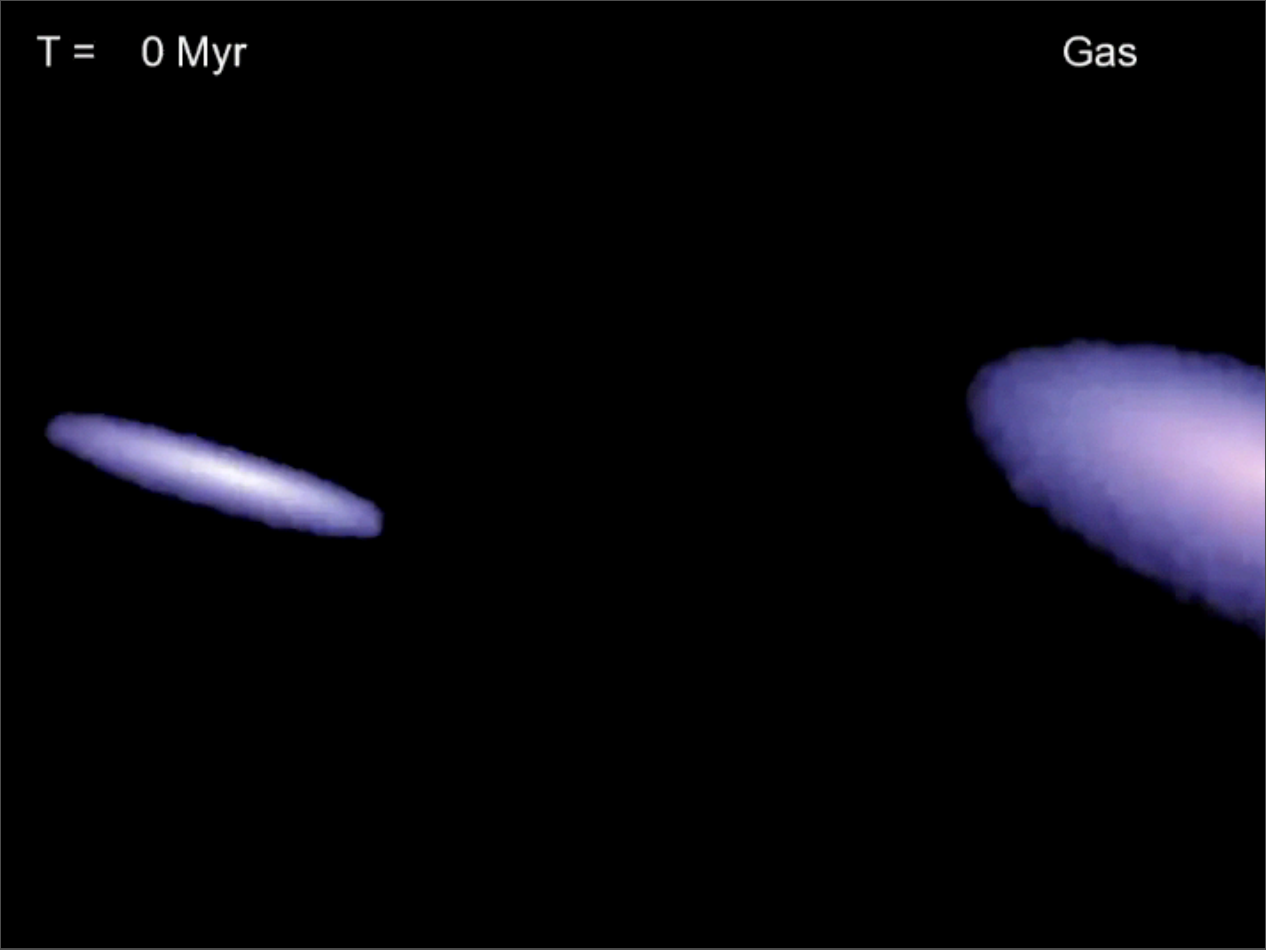
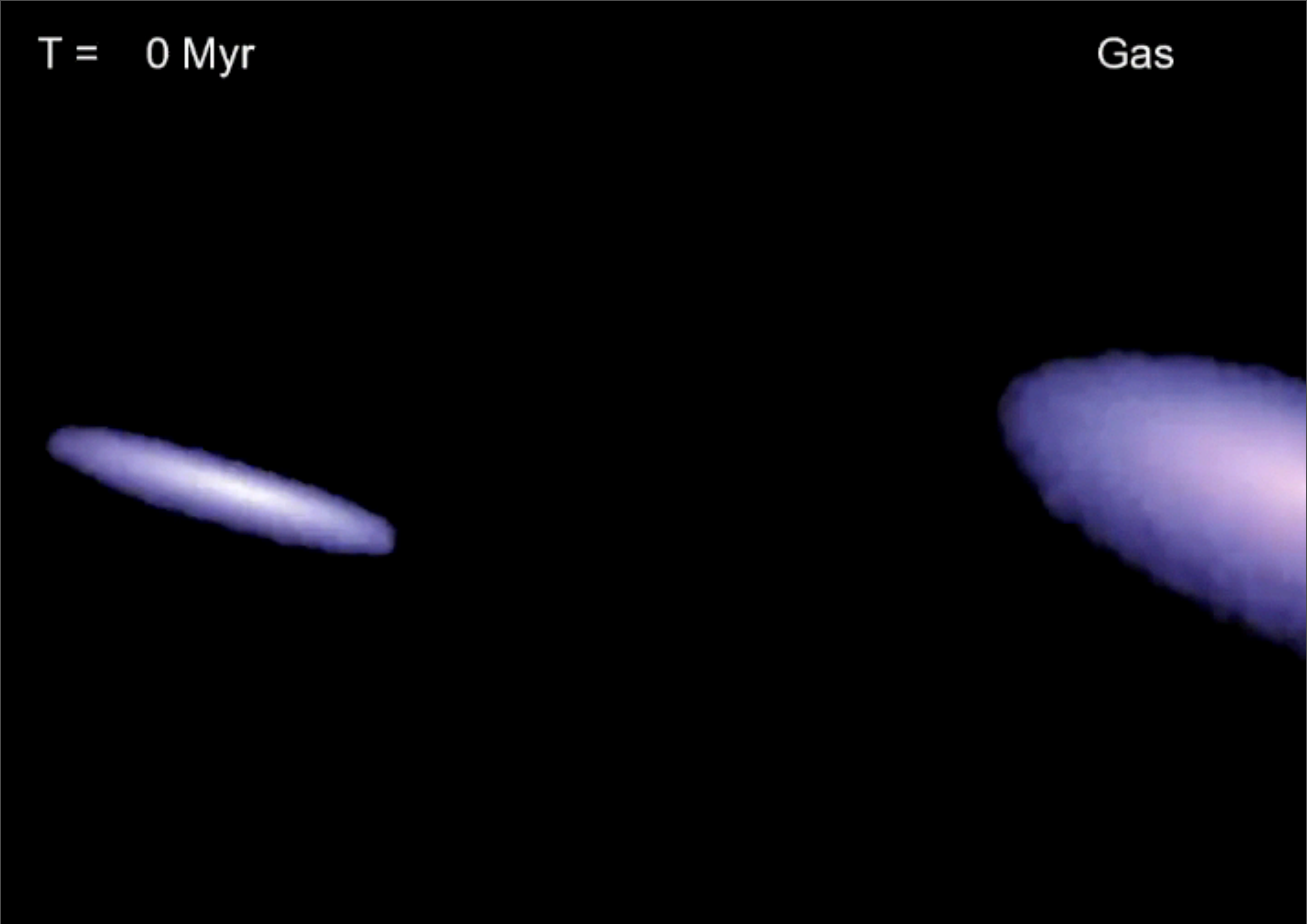
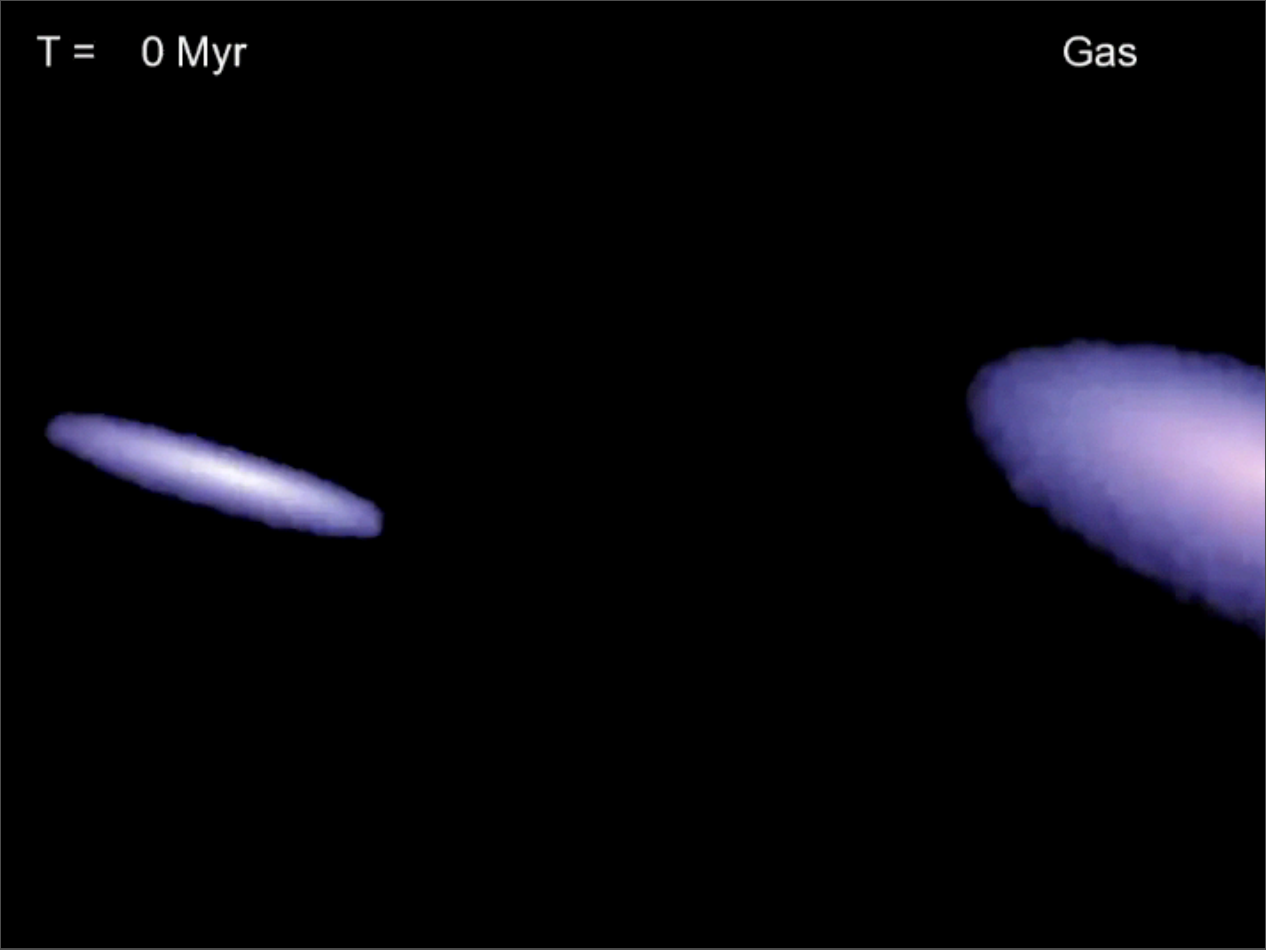

T = 0 Myr
Gas



Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)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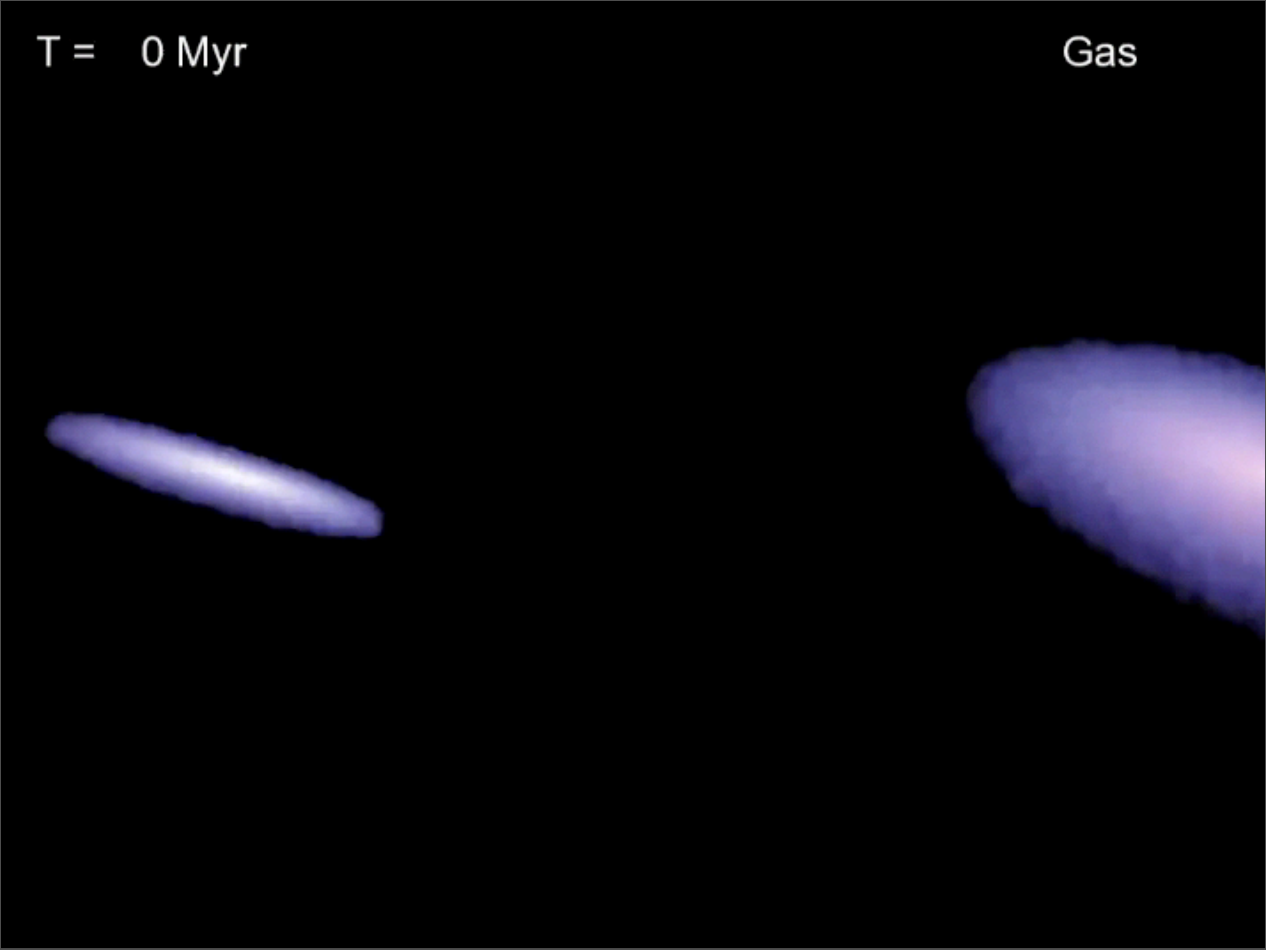
Gas

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


T = 0 Myr
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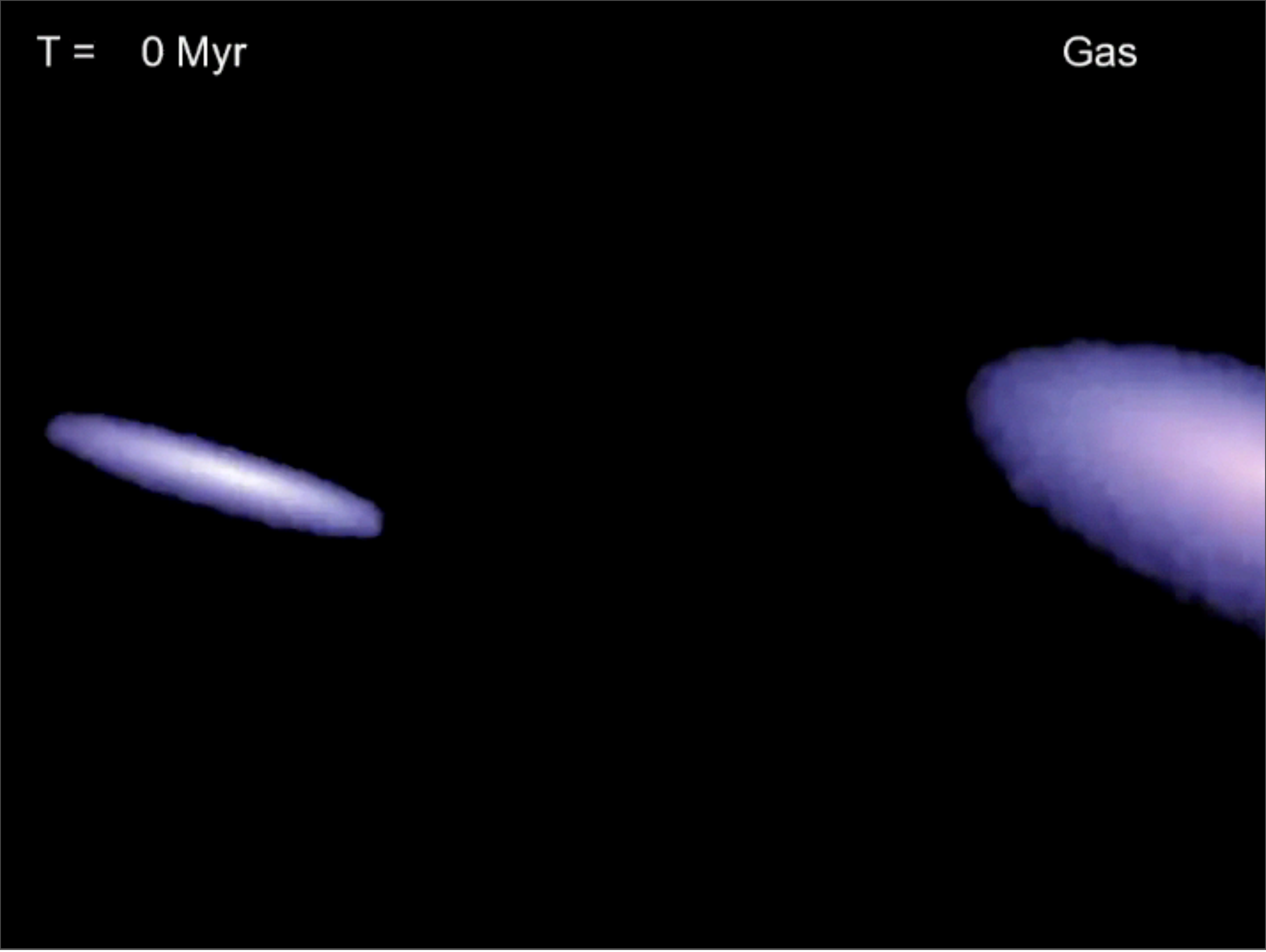
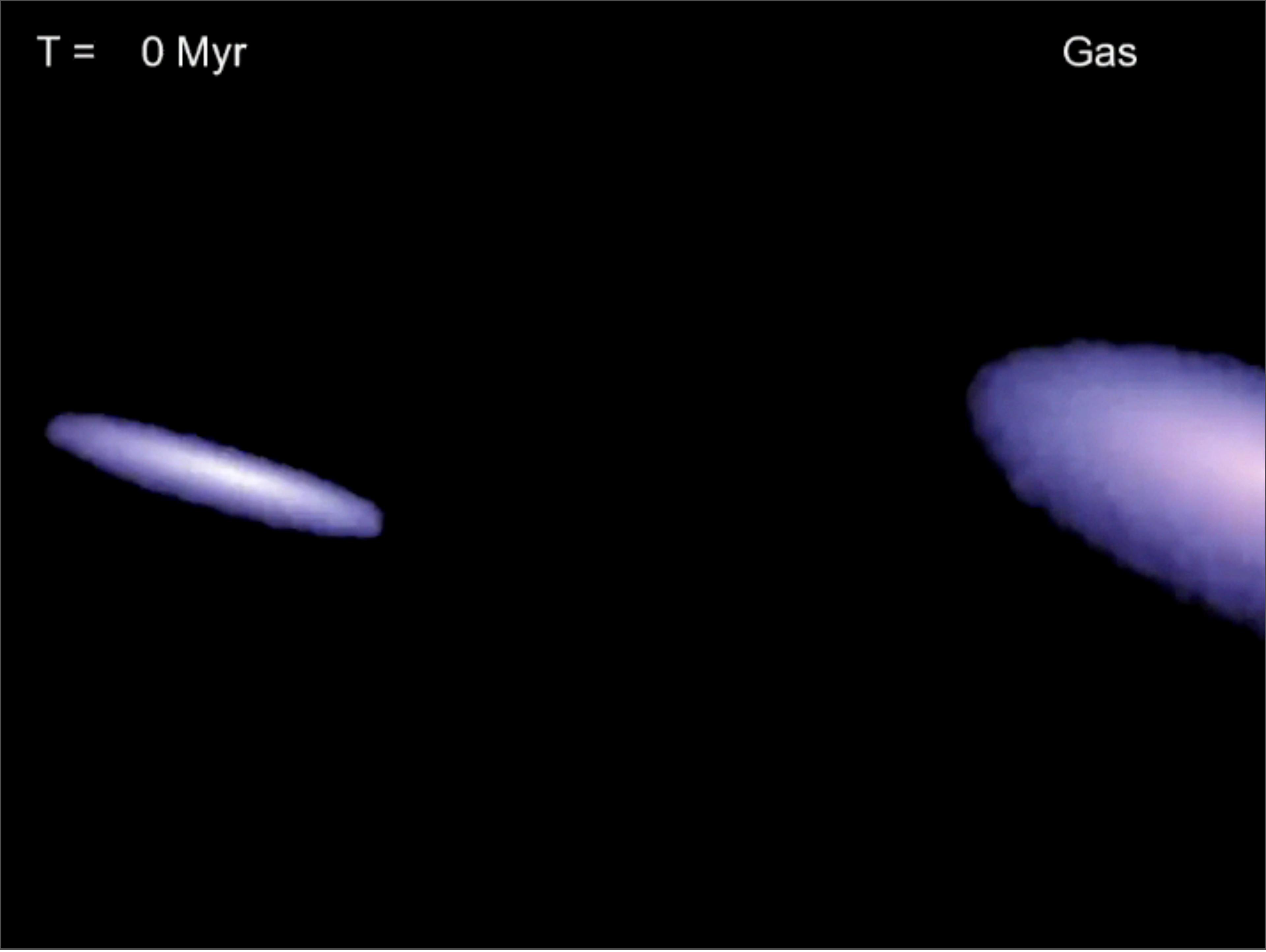
Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)


T = 0 Myr
Gas

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


T =   0 Myr
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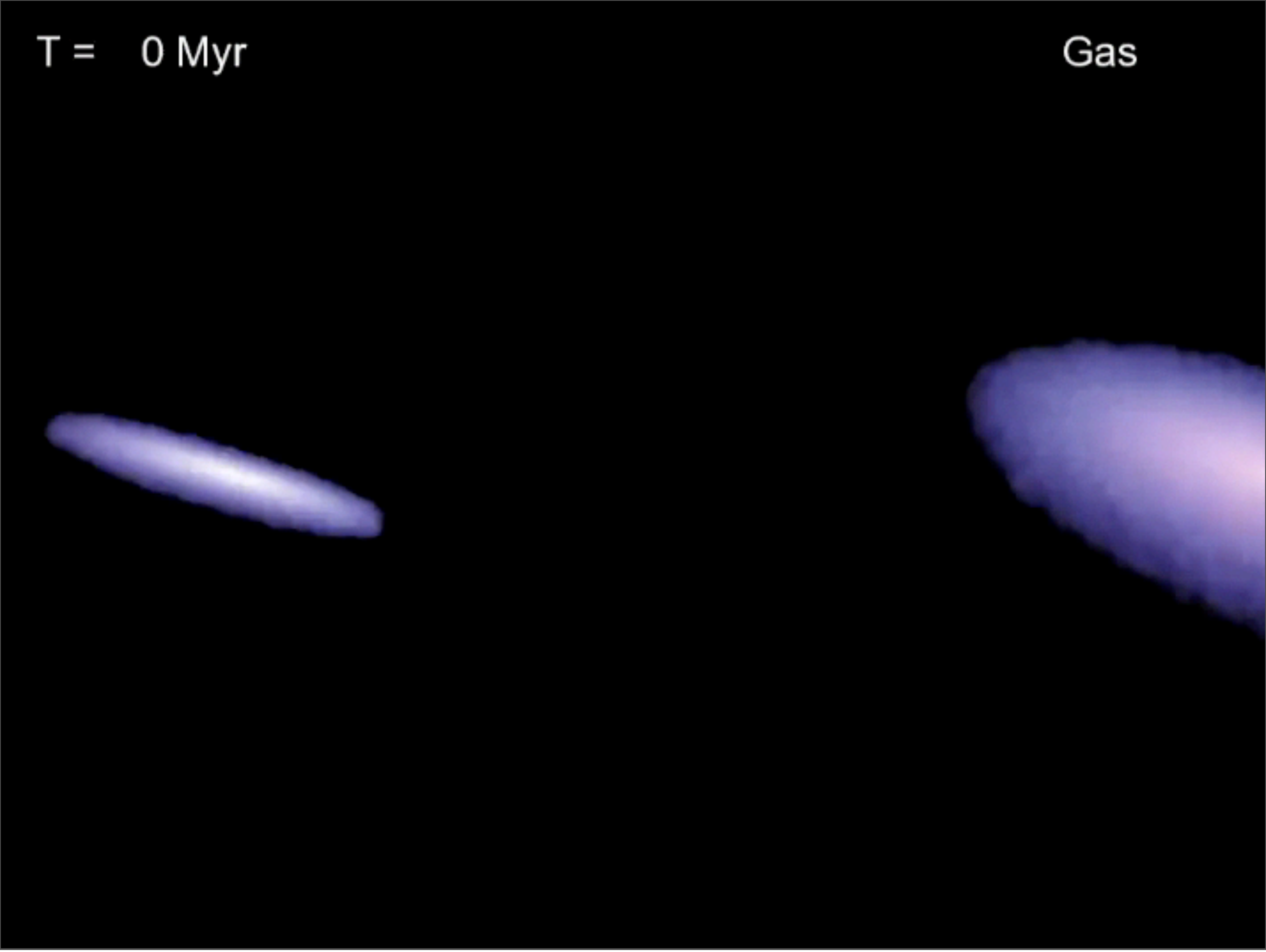
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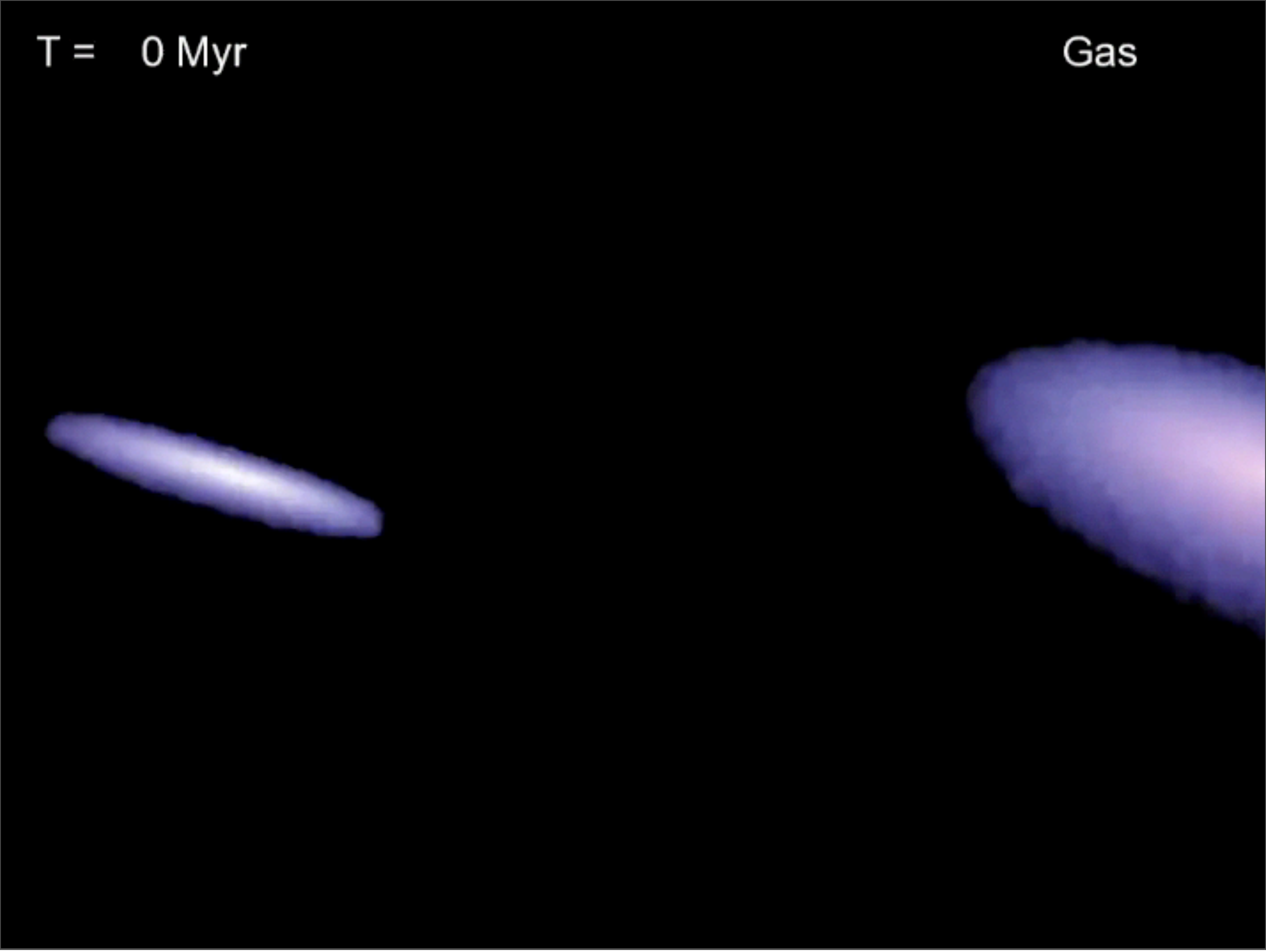
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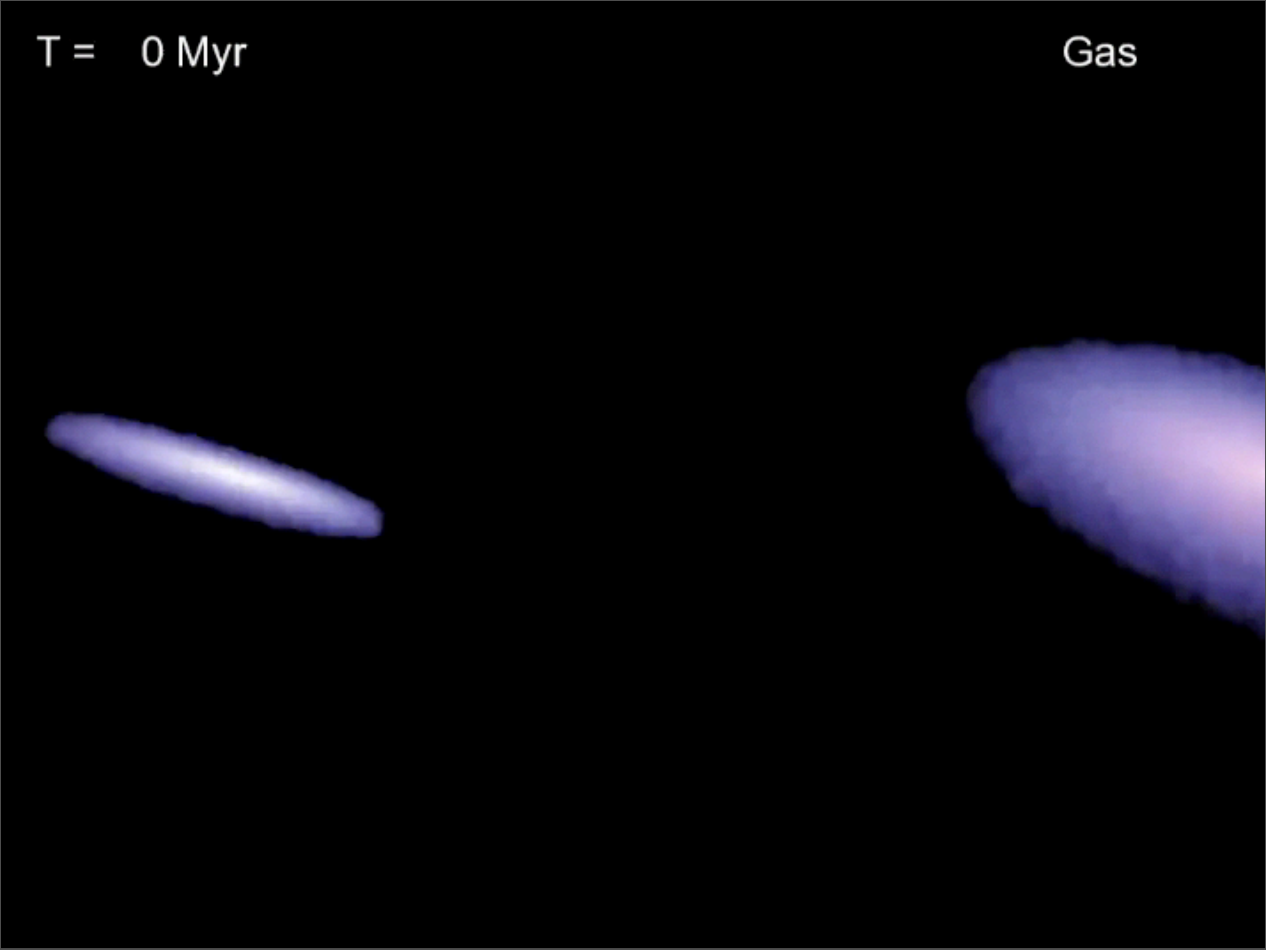
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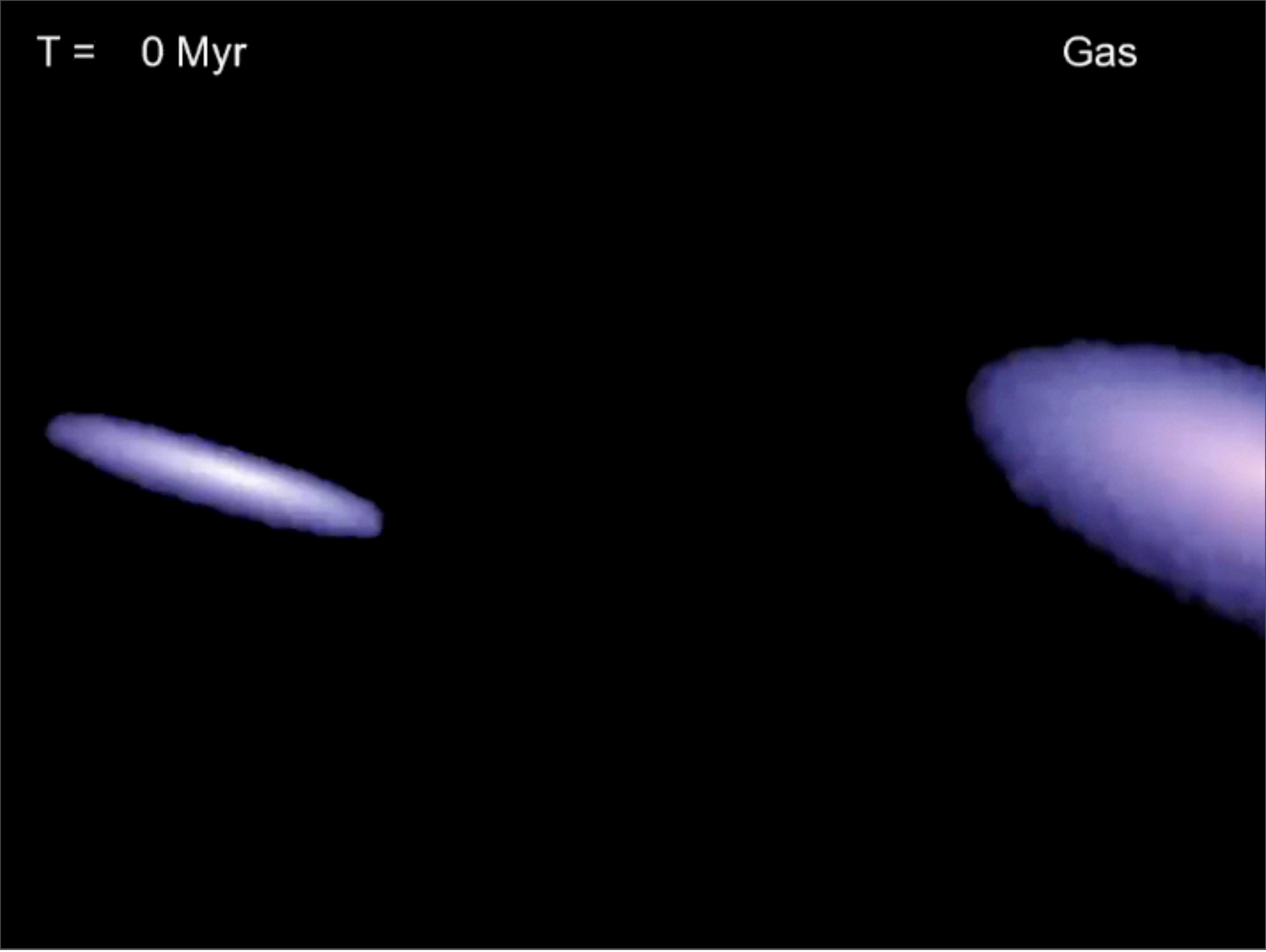
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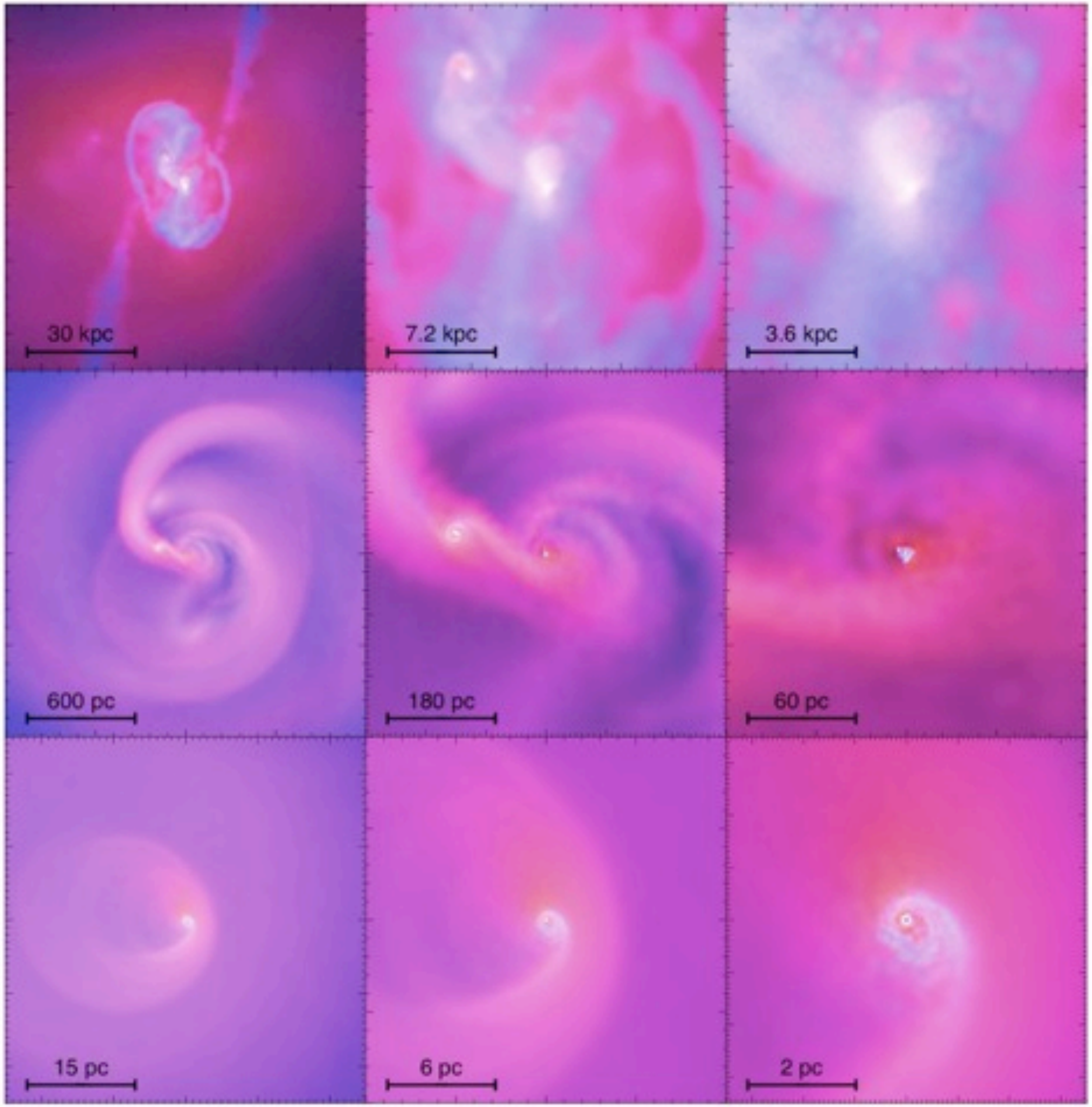
Gas

How do massive BHs get their gas?

CAN WE FUEL THE MONSTER?

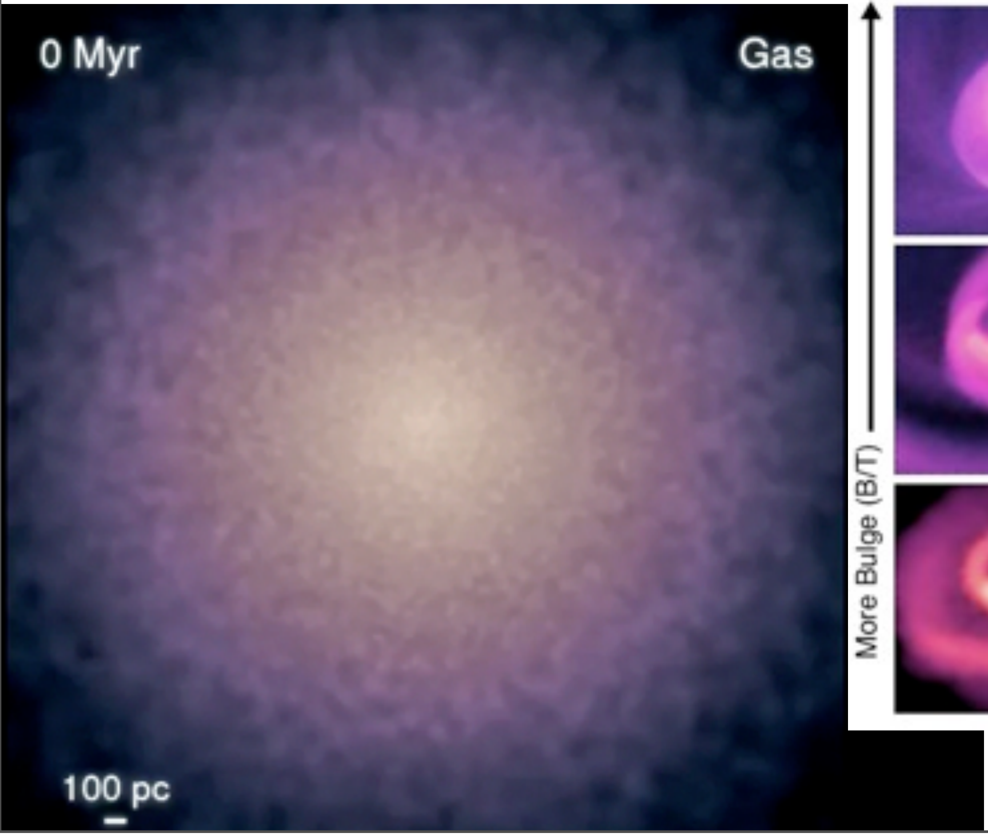


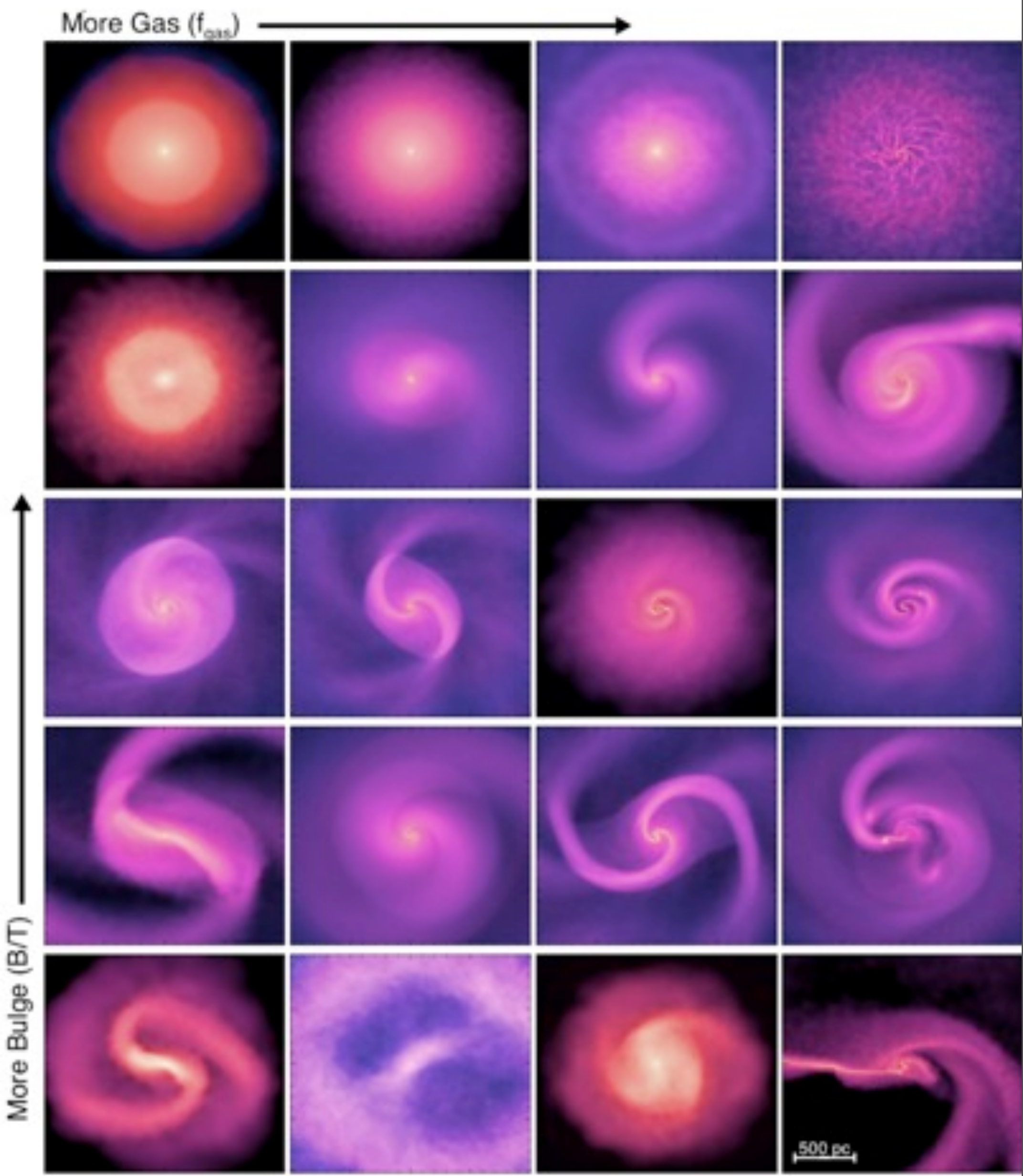
- Cascade of instabilities: merger not efficient inside ~kpc
- *Any* mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

Sub-kpc scales: "Stuff within Stuff"

- Diverse morphologies on sub-kpc scales: not just bars!

- Inflow is *not* smooth/continuous





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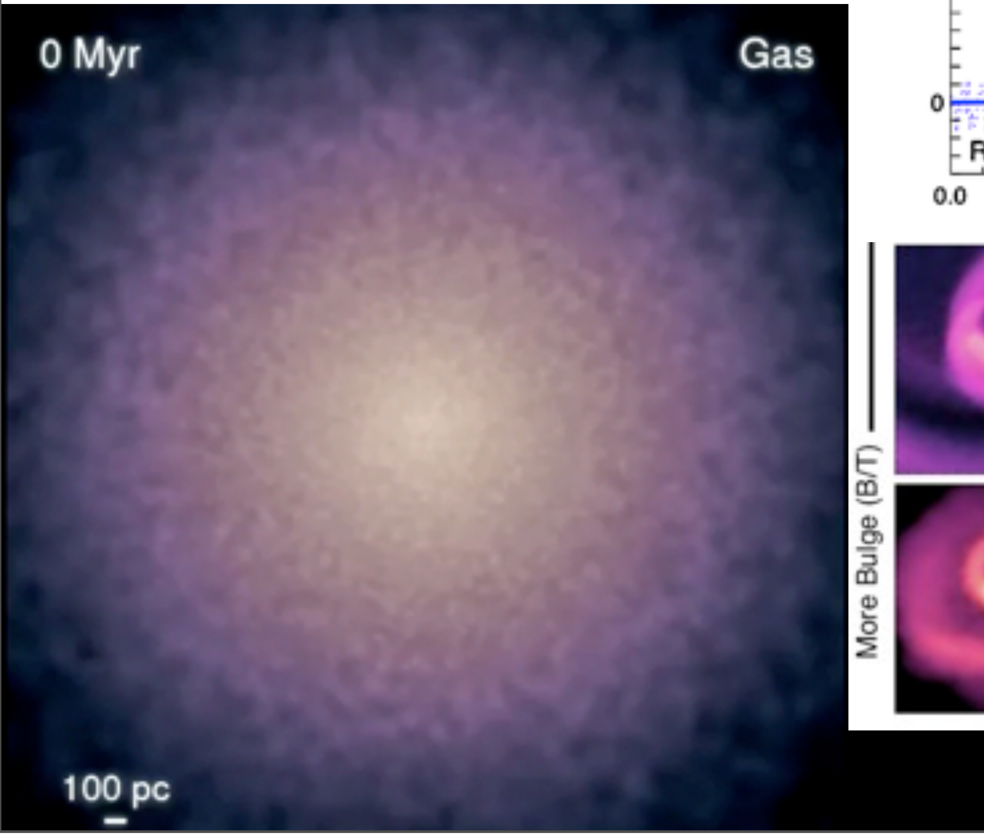
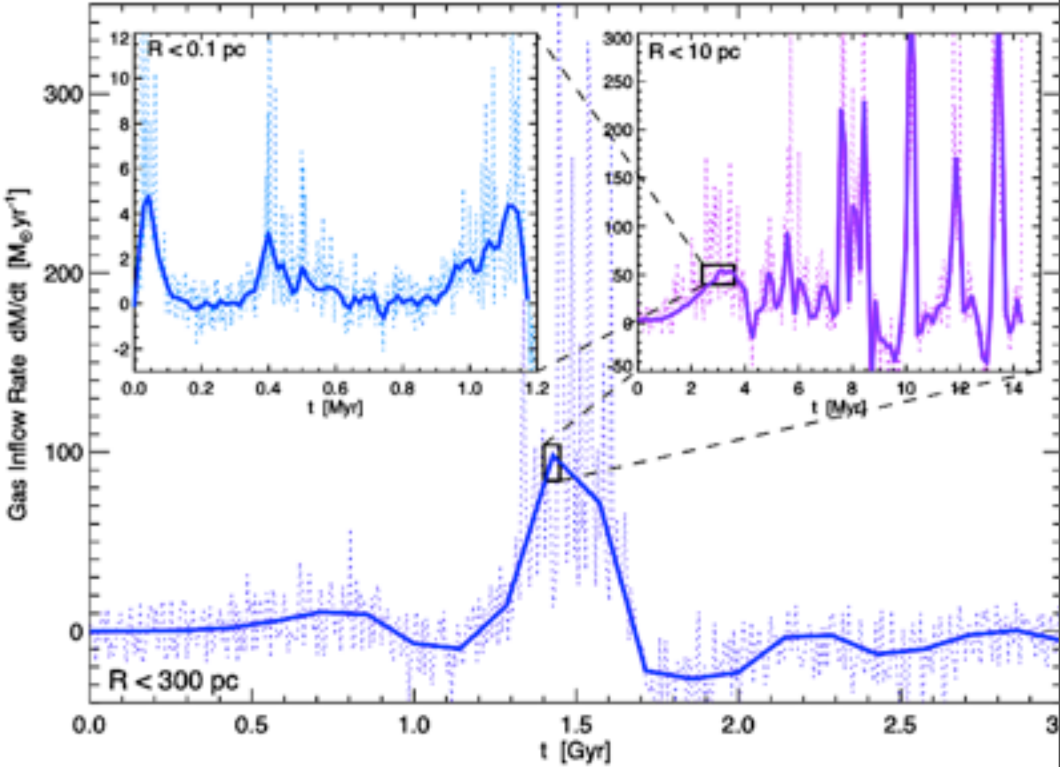
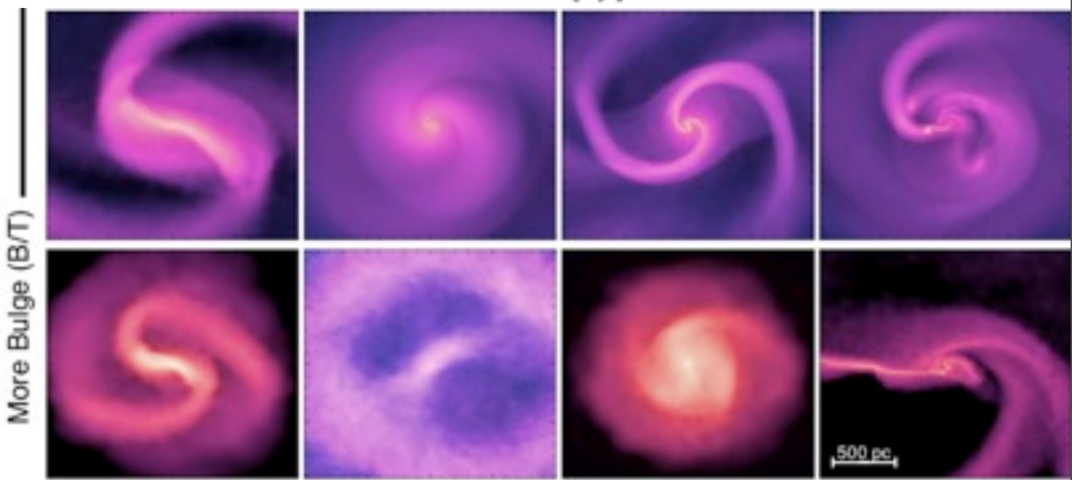
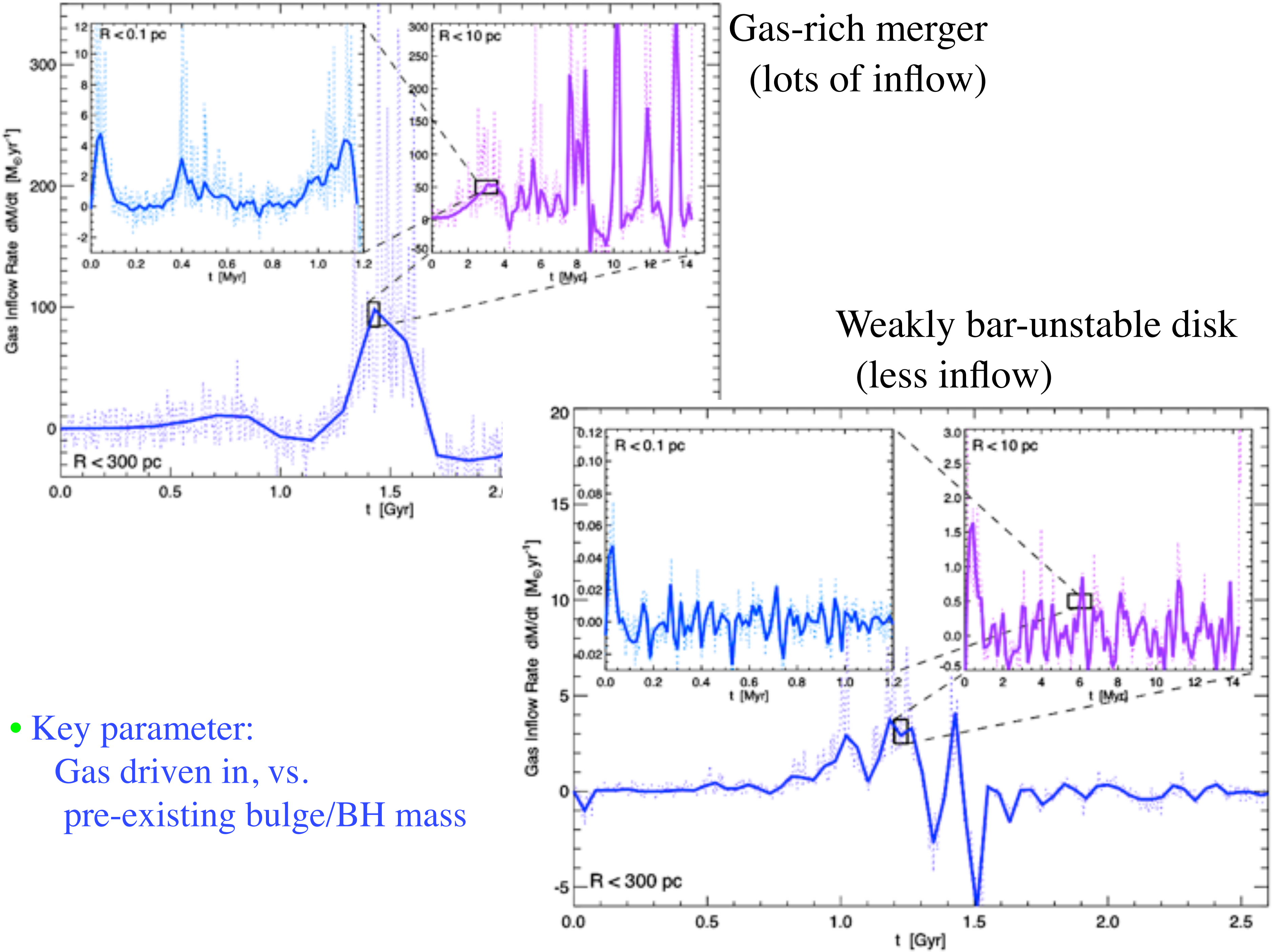






Gas-rich merger (lots of inflow)

Weakly bar-unstable disk (less inflow)



- Key parameter:
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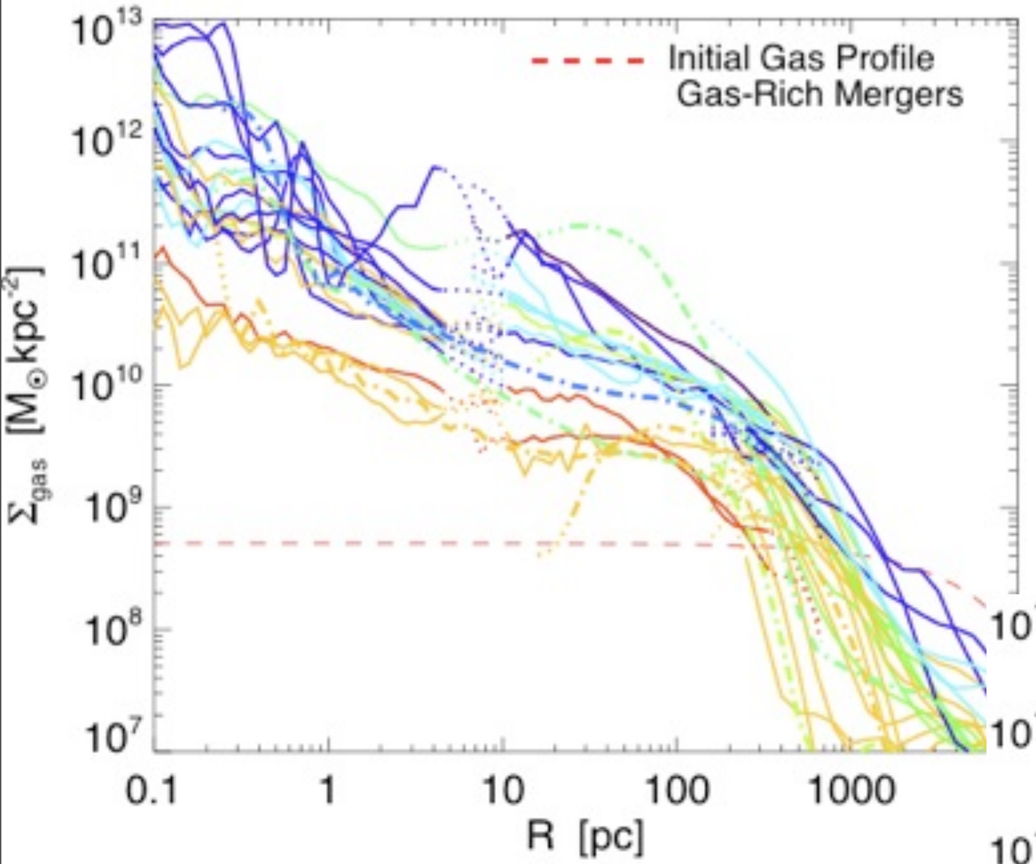

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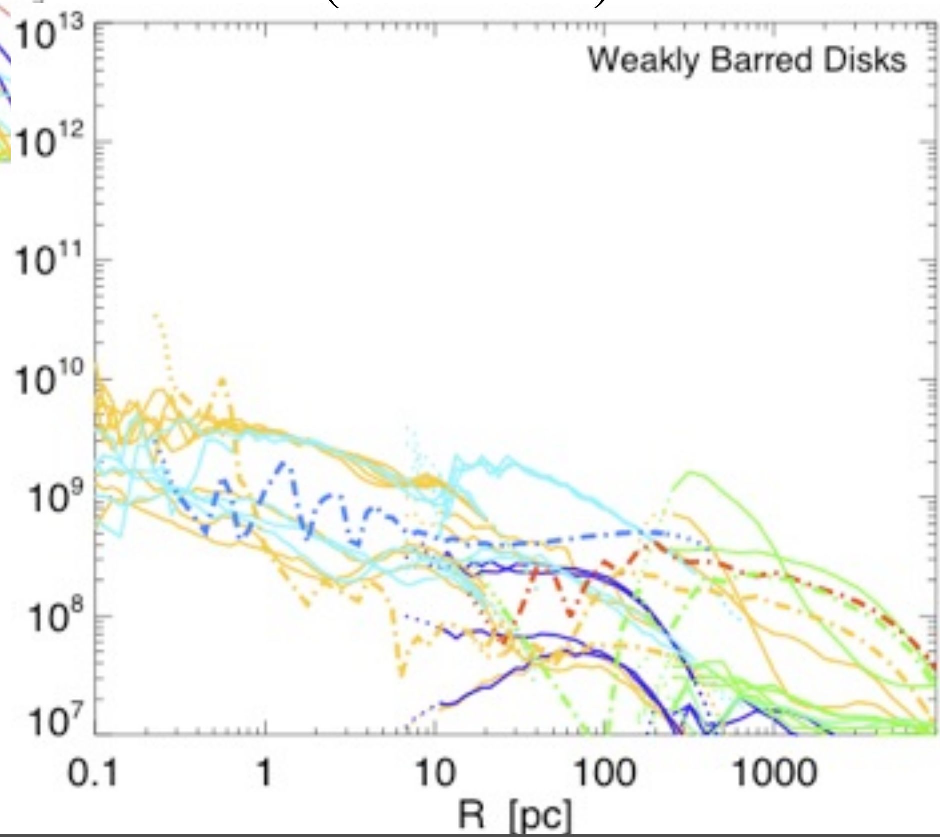

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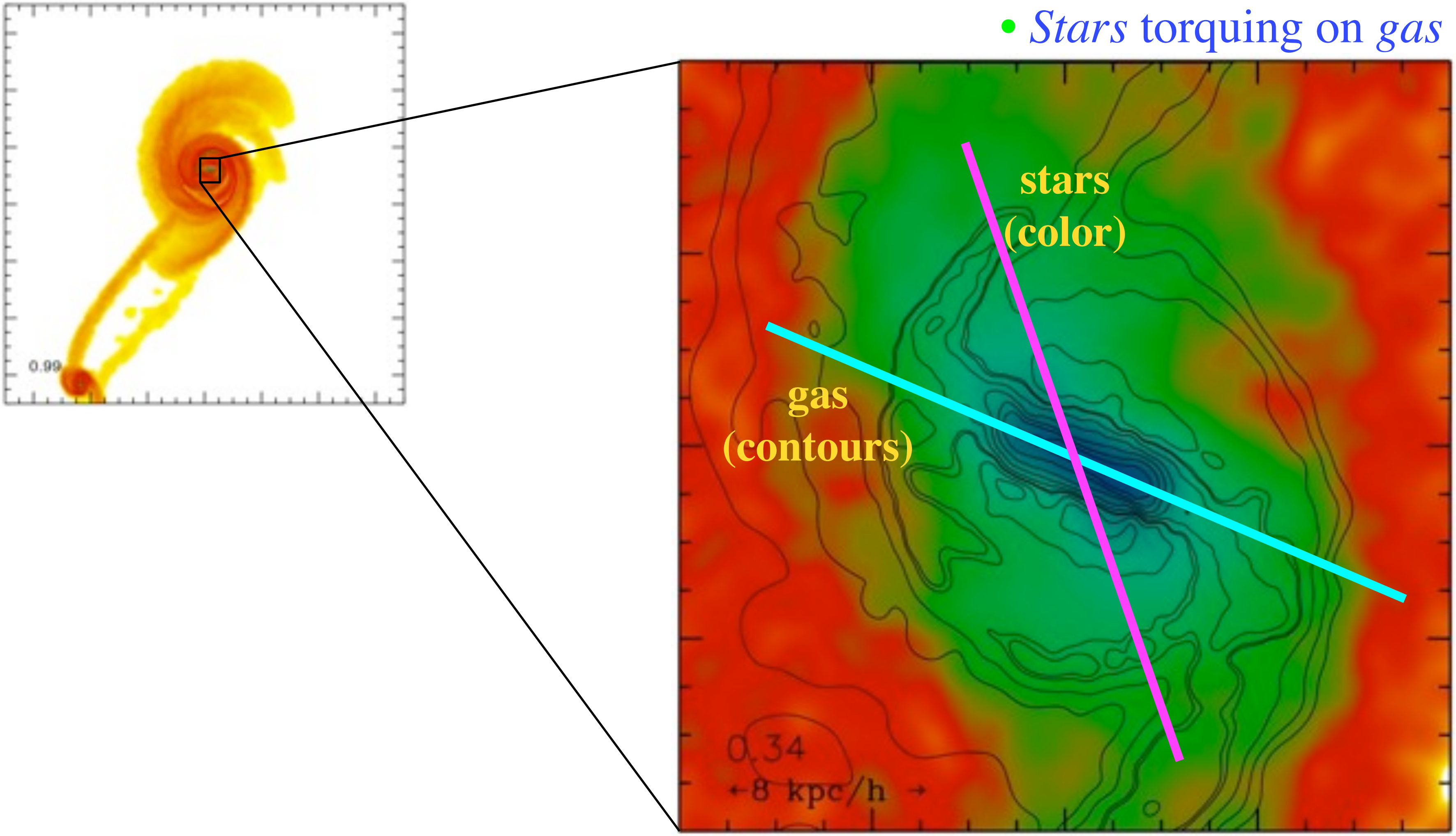
- Gravity dominates torques from 0.1 - 10,000 pc:

- *Stars* torquing on *gas*



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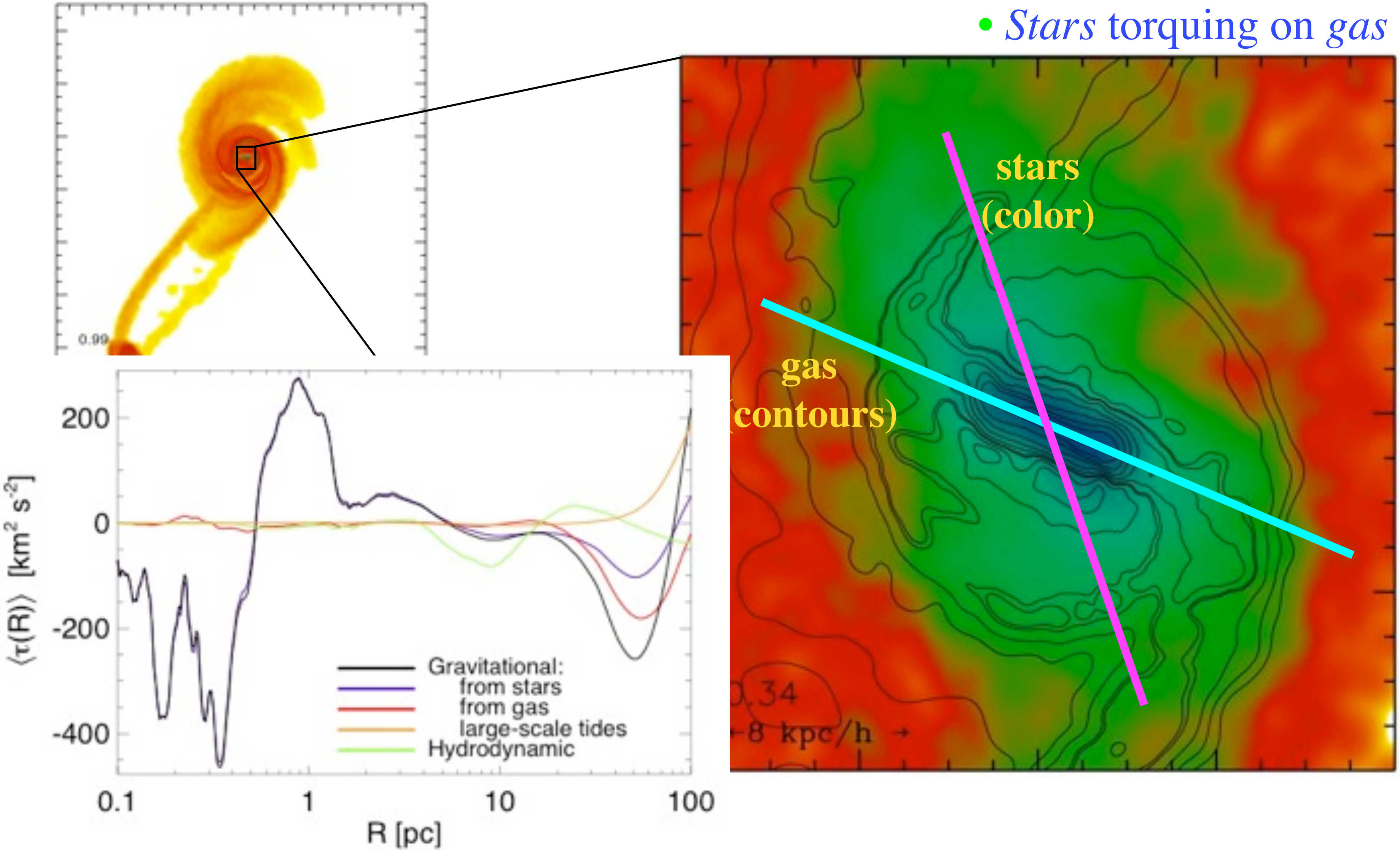
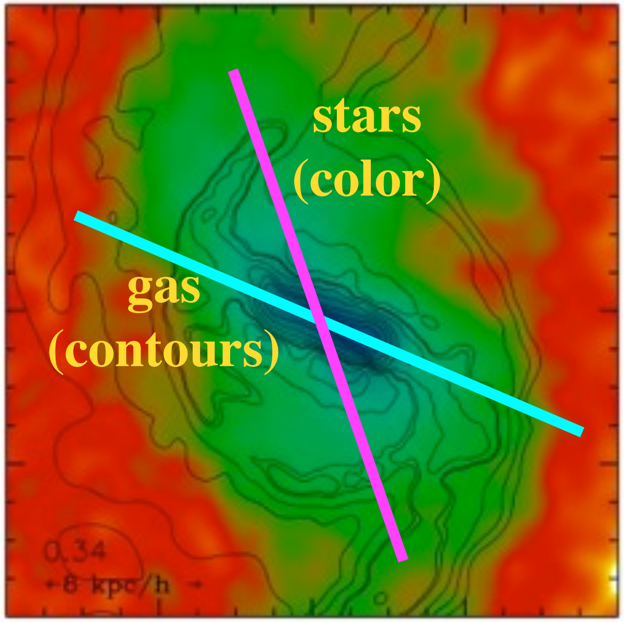


How does this work?

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



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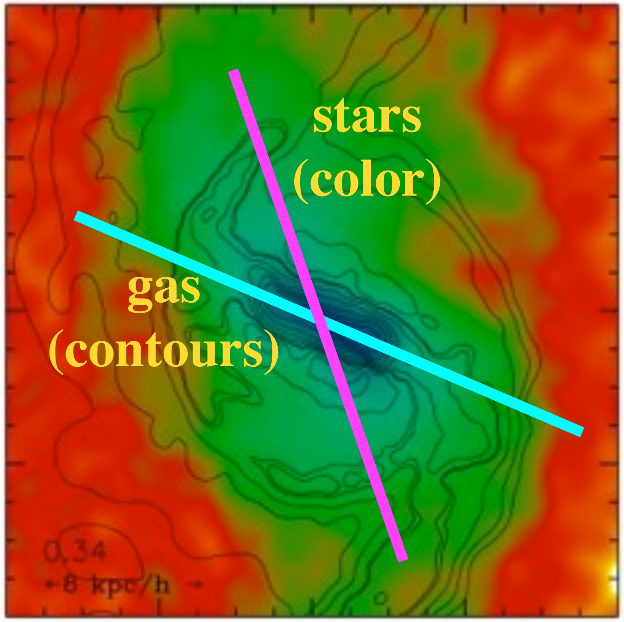

standard (dissipationless) formulation: spiral waves carry the angular momentum: (Lynden-Bell & Kalnajs '72)

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

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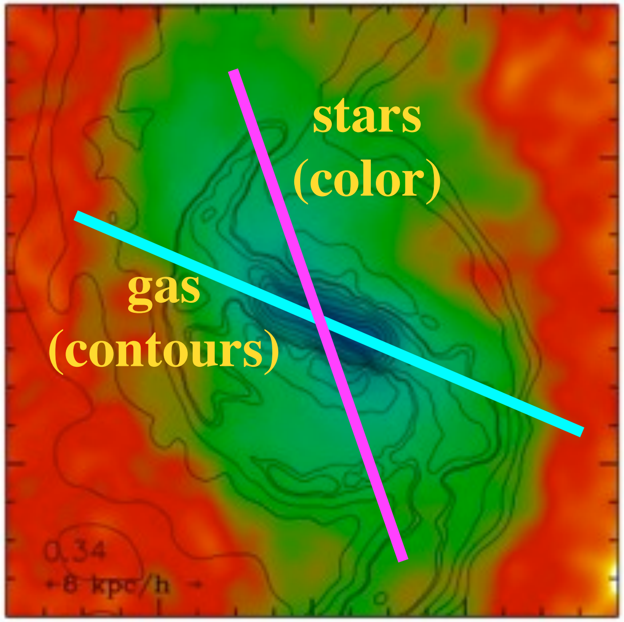

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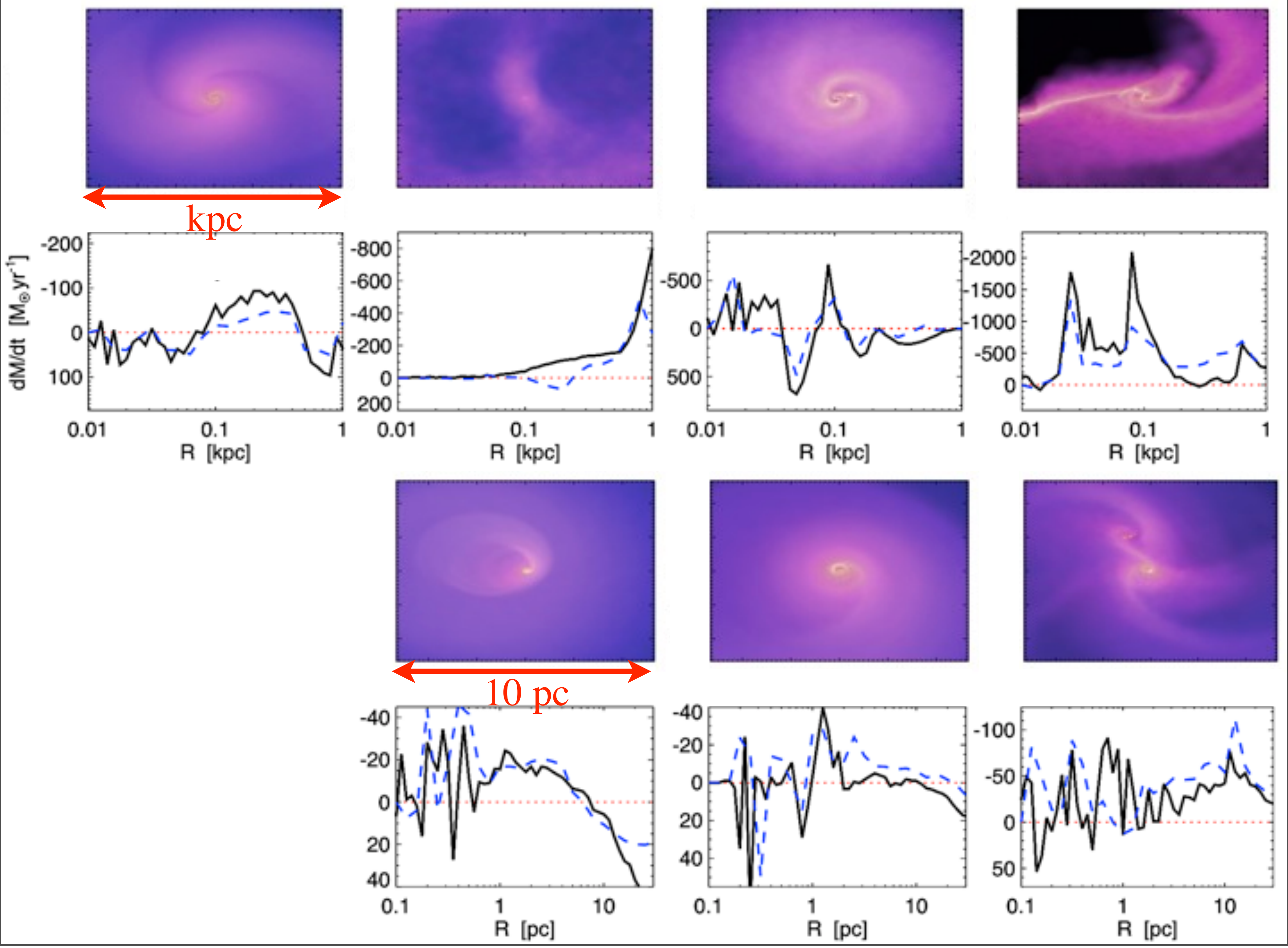
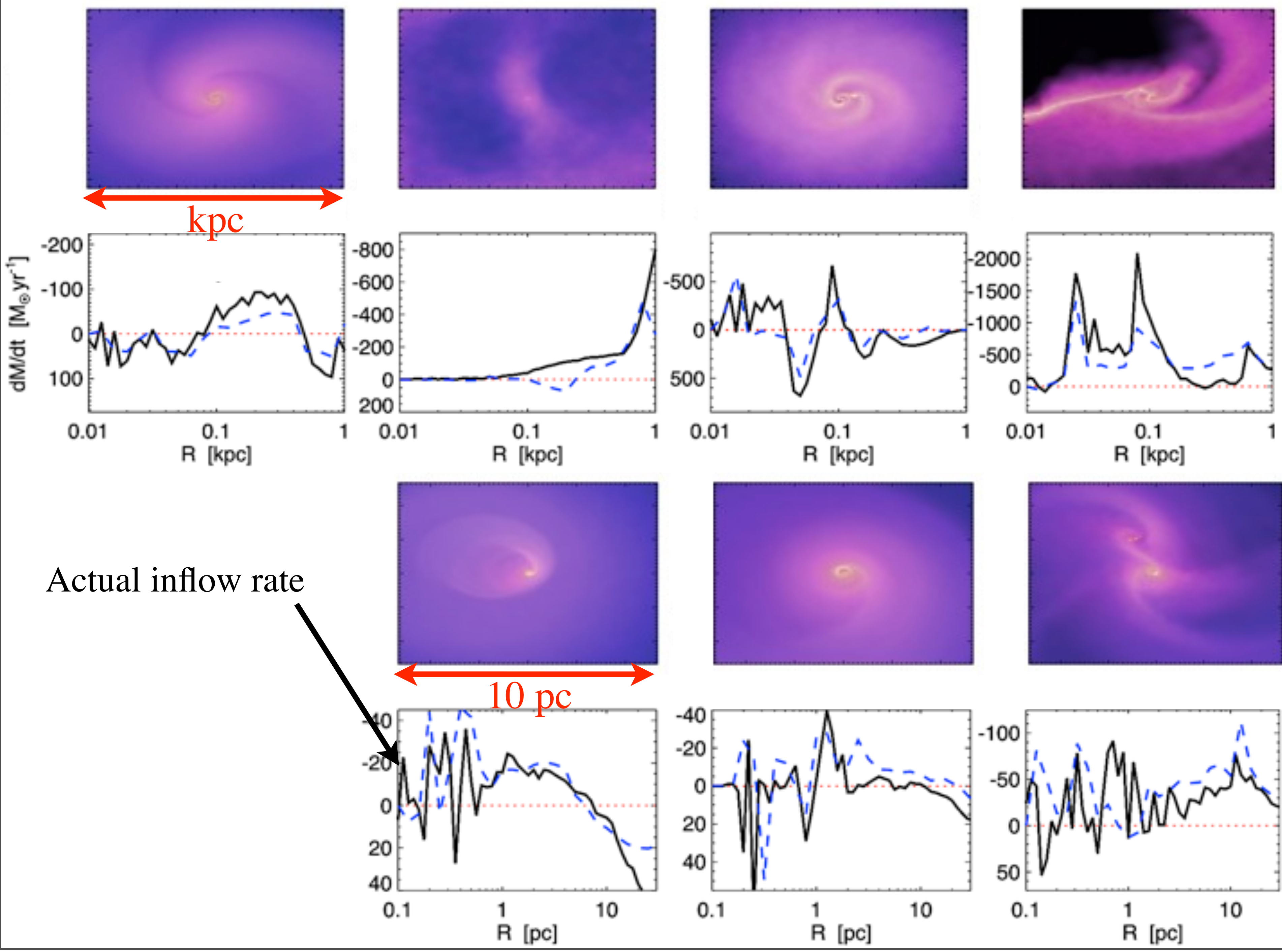
with shocks & dissipation:

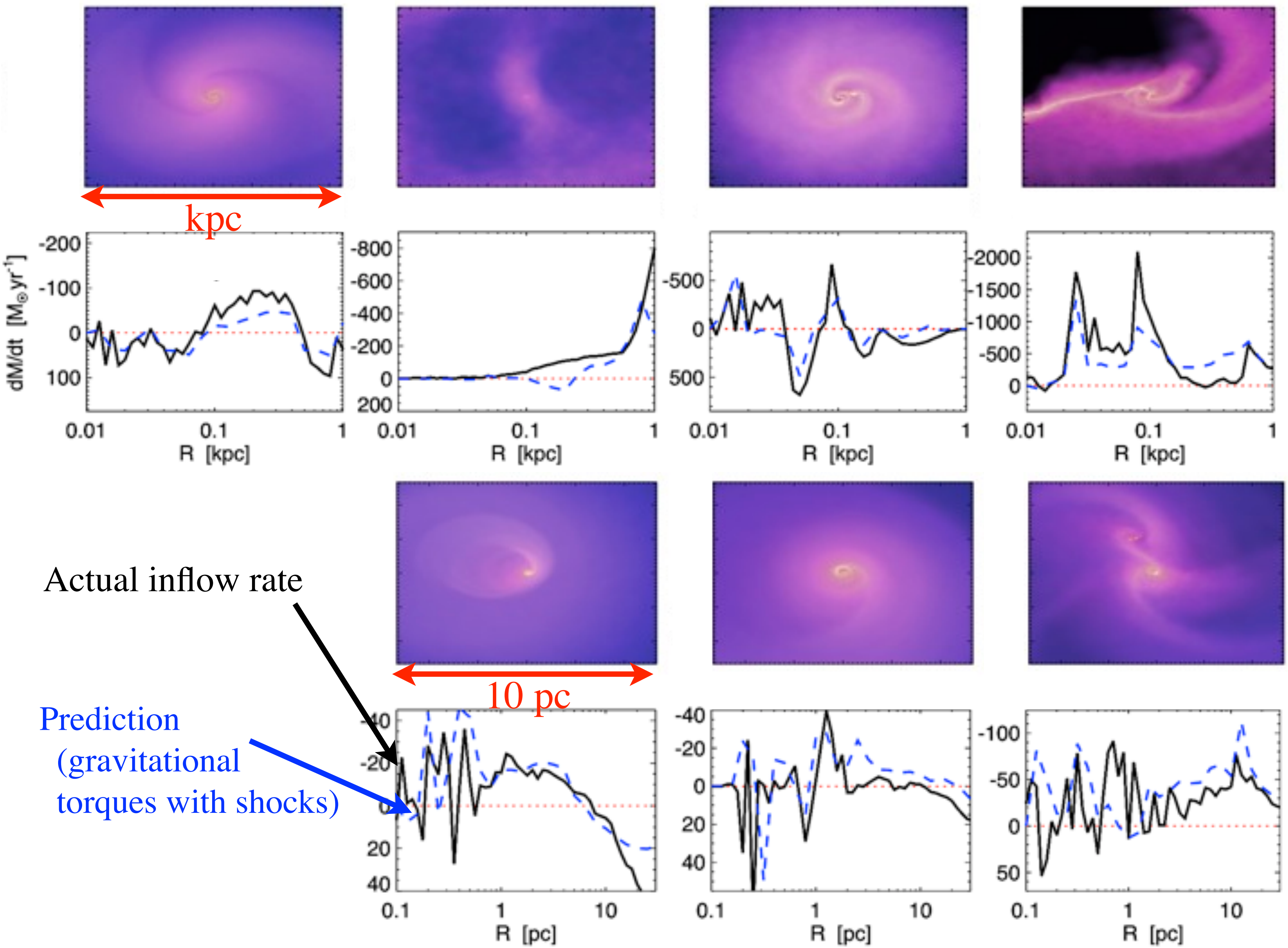
$$\dot{M}_{\rm inflow} = \Sigma_{\rm gas}\, R^2\, \Omega \left|\frac{\Phi_1}{V_c^2}\right| \frac{m\,{\rm sign}(\Omega - \Omega_p)}{1 + \partial \ln V_c / \partial \ln R} F(\zeta) \sim |a|\, \frac{M_{\rm gas}}{t_{\rm dyn}}$$

>100x larger!!!

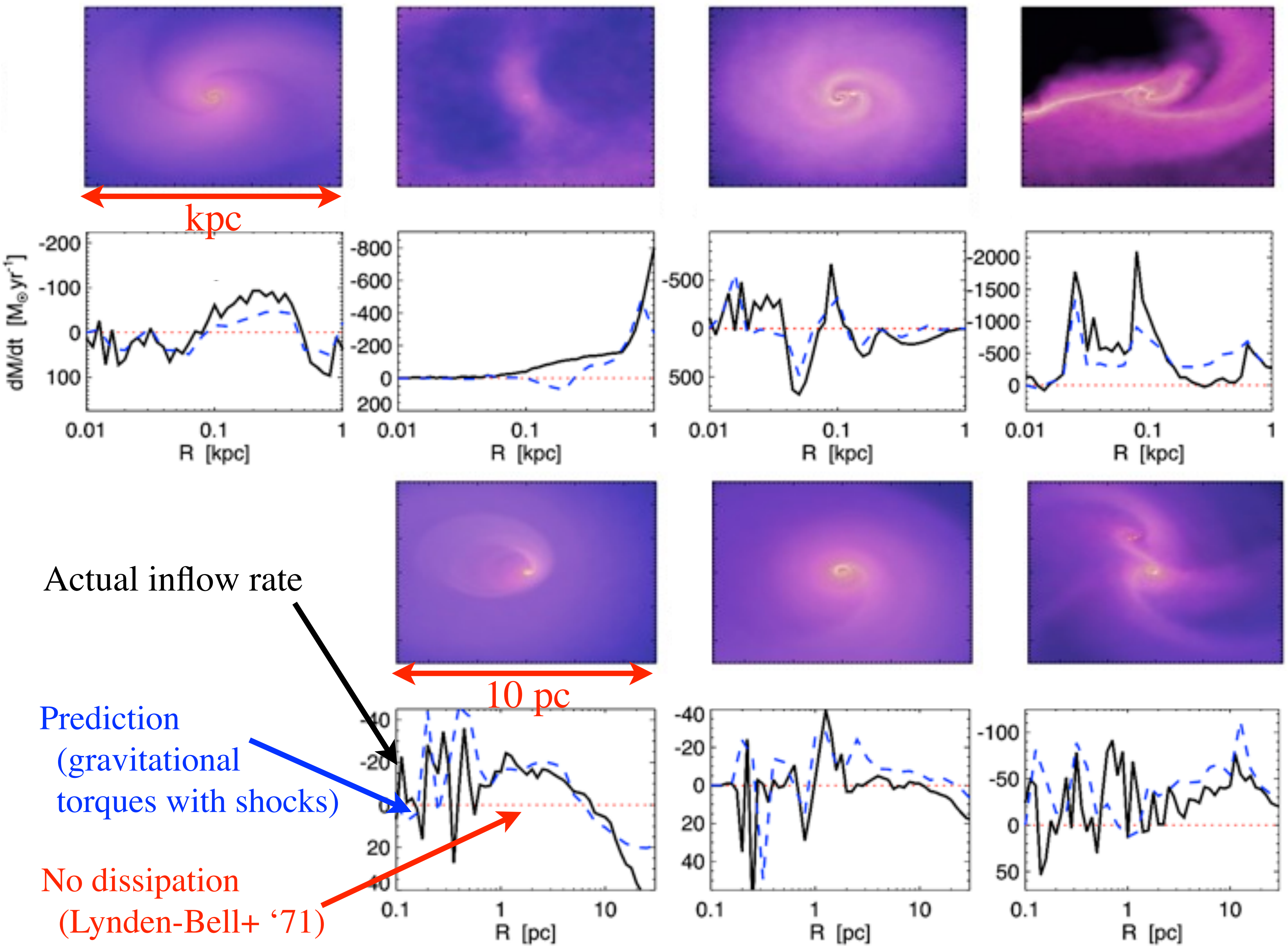


kpc
10 pc
dM/dt [M⊙yr⁻¹]
-200
-100
0
100
-800
-600
-400
-200
0
200
-500
0
500
-2000
-1500
-1000
-500
0
0.01
0.1
1
R [kpc]
-40
-20
0
20
40
-100
-50
0
50
0.1
1
10
R [pc]


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



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


kpc
dM/dt [M⊙yr⁻¹]
R [kpc]
Actual inflow rate
Prediction
(gravitational
torques with shocks)
No dissipation
(Lynden-Bell+ '71)
10 pc
R [pc]

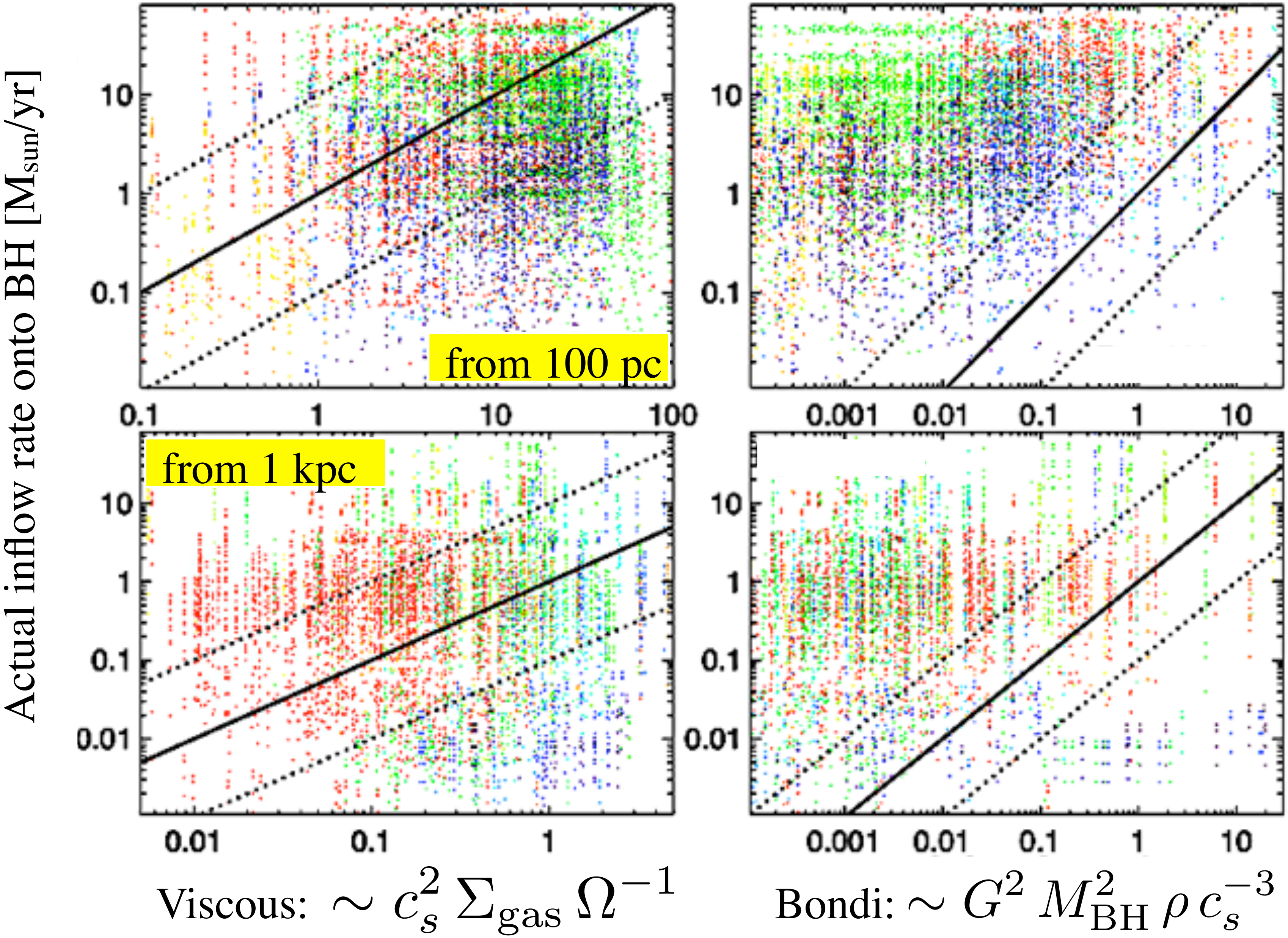
Can we build a better accretion rate estimator?

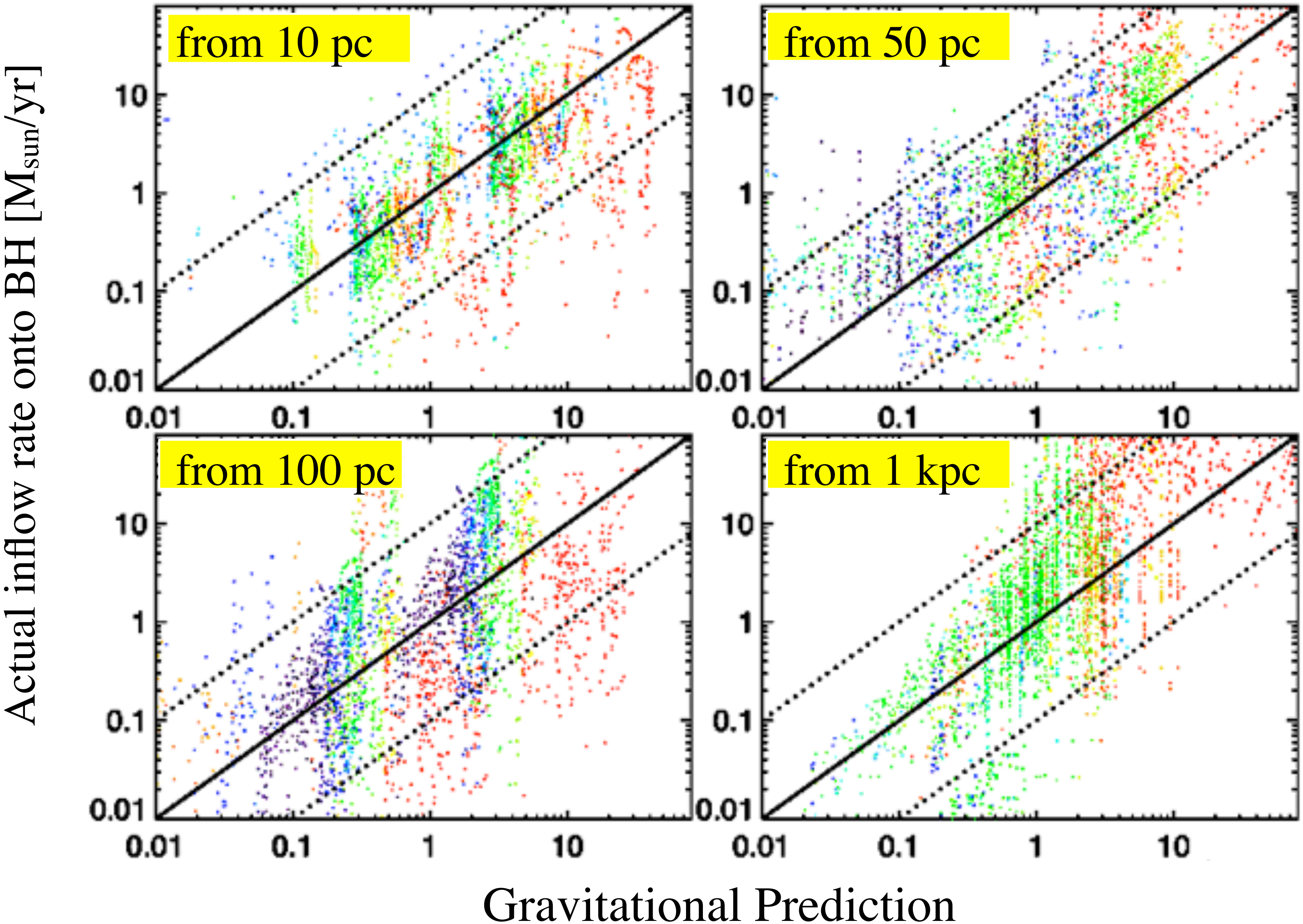
Can we build a better accretion rate estimator?

Derive ‘Gravitational Torque’ Rate:

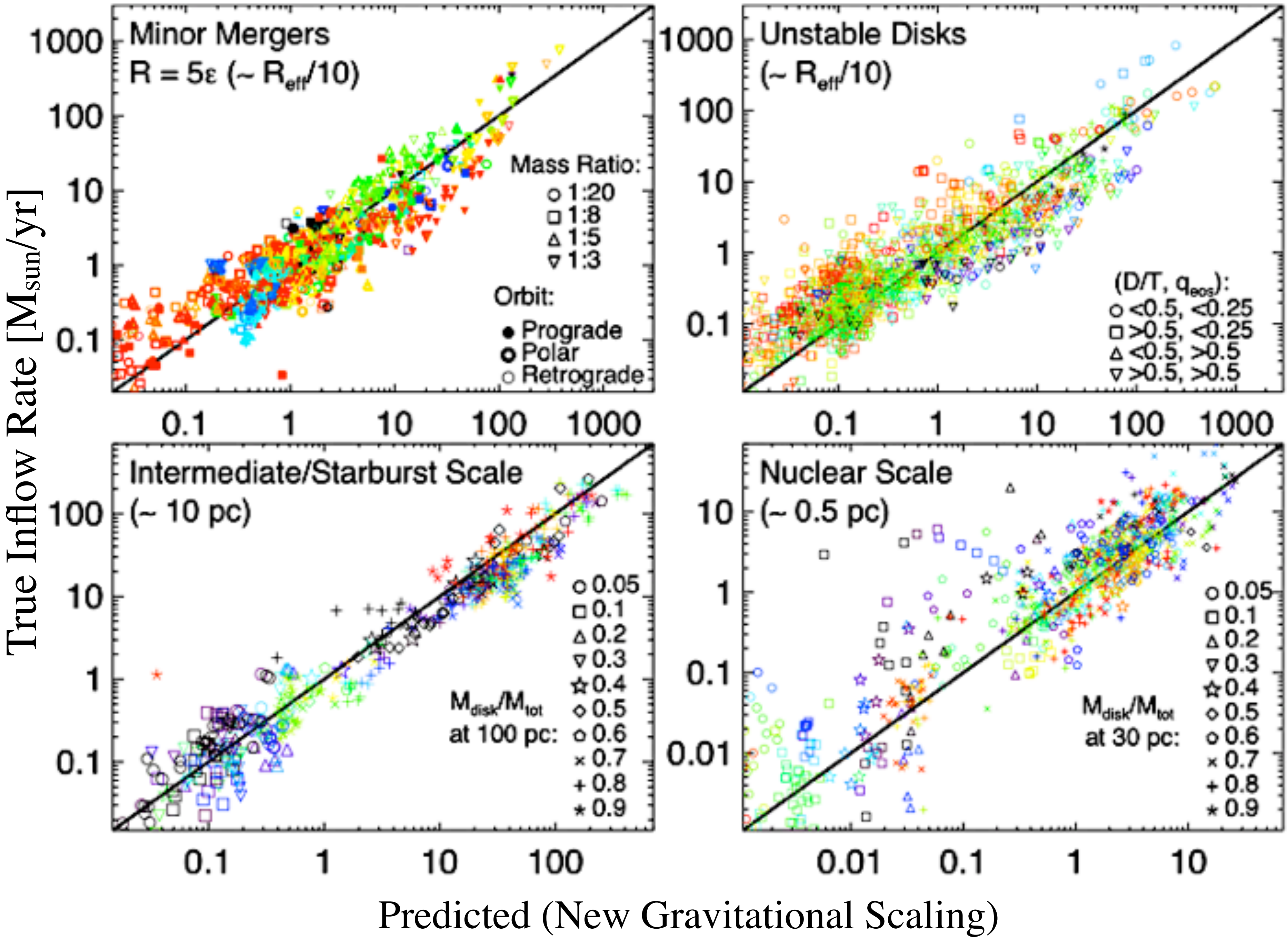
$$\dot{M} \approx 10\,M_{\odot}\,\mathrm{yr}^{-1}\left(\frac{\mathrm{Disk}}{\mathrm{Total}}\right)^{5/2} M_{\mathrm{BH},\,8}^{-1/6}\,M_{\mathrm{gas},\,9}\,R_{0,100}^{-3/2}$$

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)

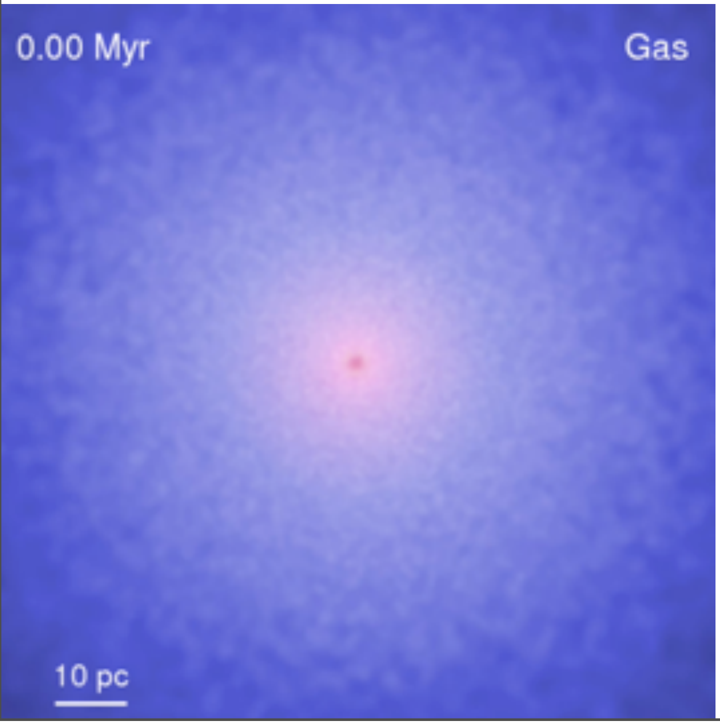
So, what about the “small” scales

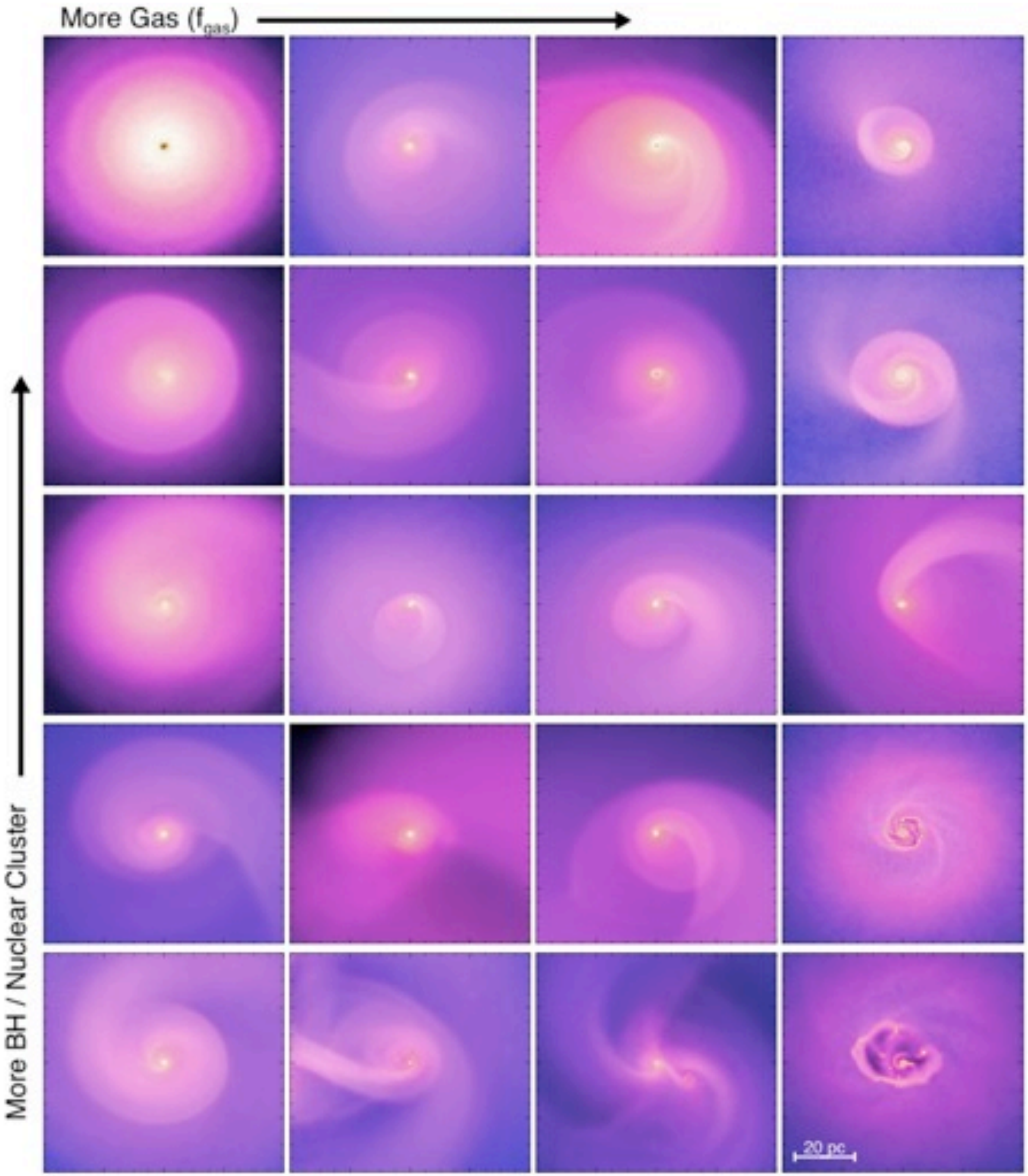
near the BH?

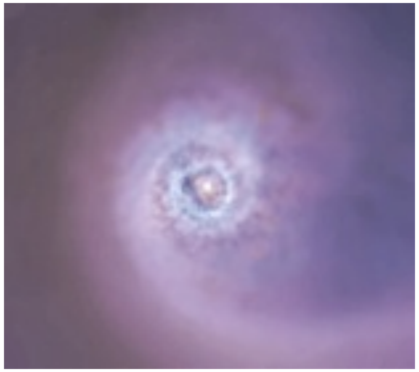
~10 pc scales: Nuclear eccentric disks

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

- Need *both* star formation and self-gravity

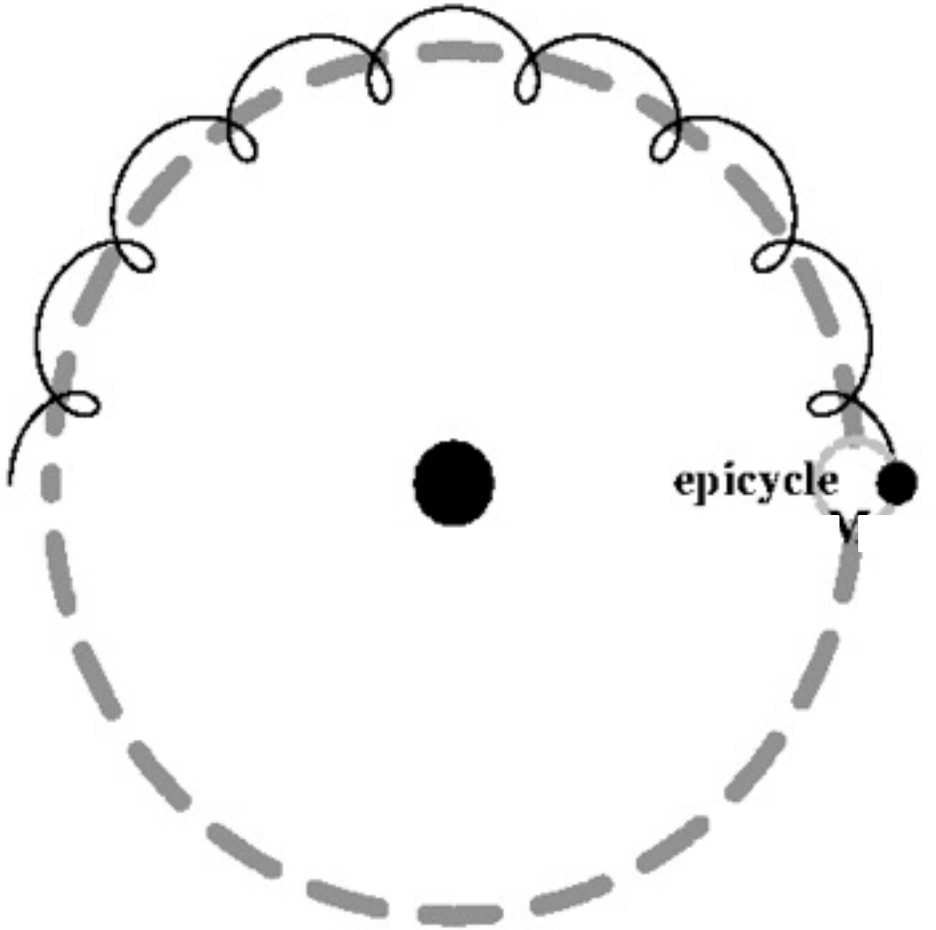


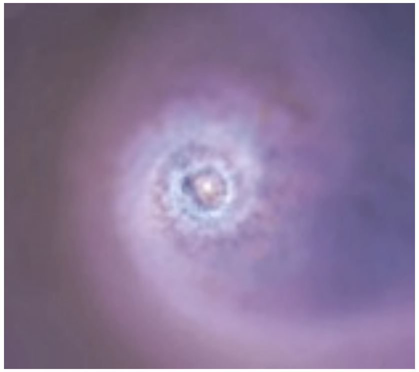




- m=1 ‘slow’ modes are special in a near-Keplerian potential

Remember,
poke a circular orbit, and
you can approximate the
result with epicycles:





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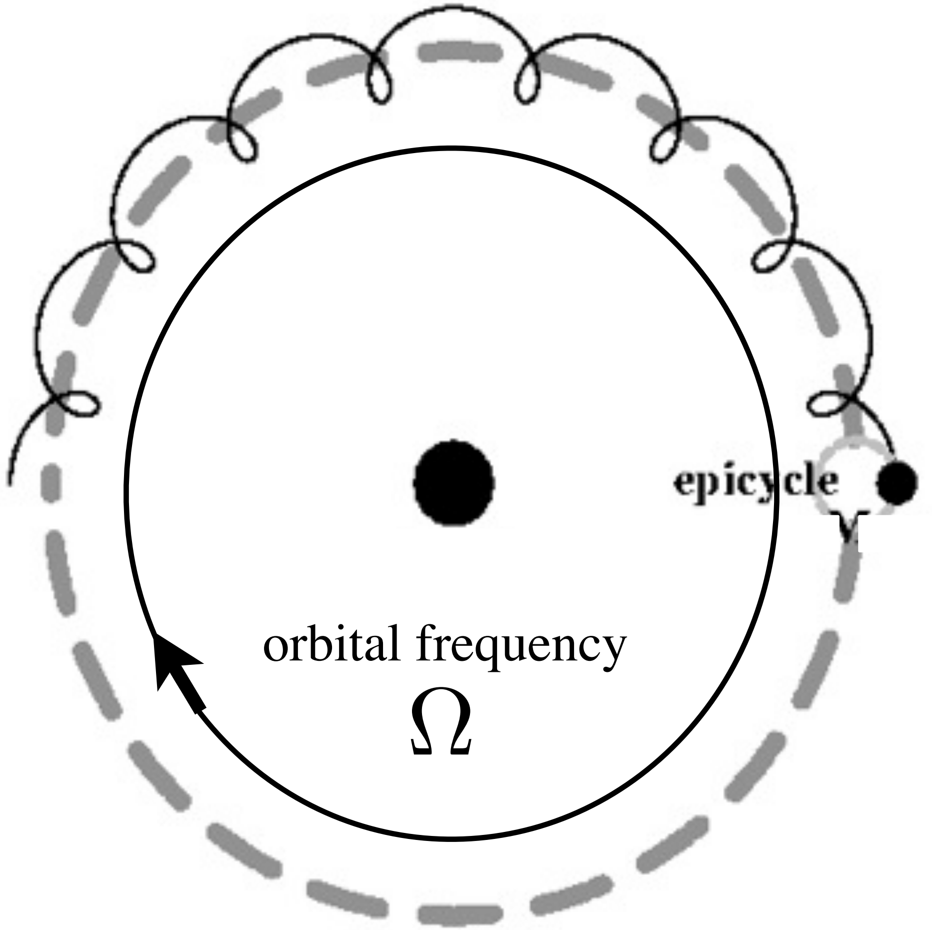
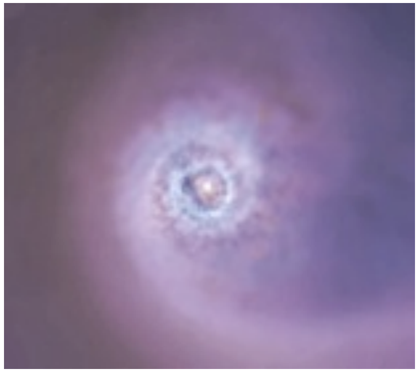
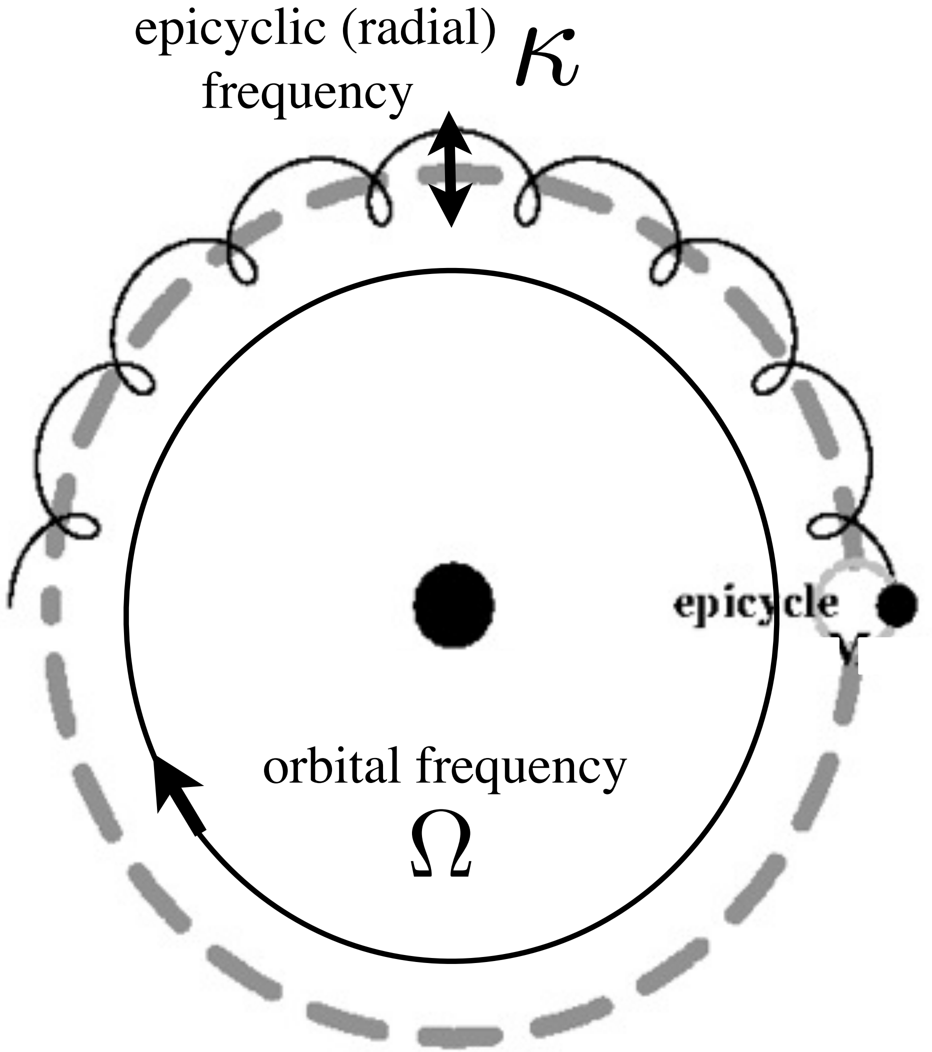
result with epicycles:

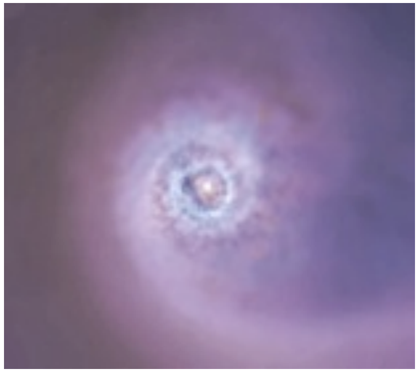




• m=1 'slow' modes are special in a near-Keplerian potential

Remember,
poke a circular orbit, and you can approximate the result with epicycles:



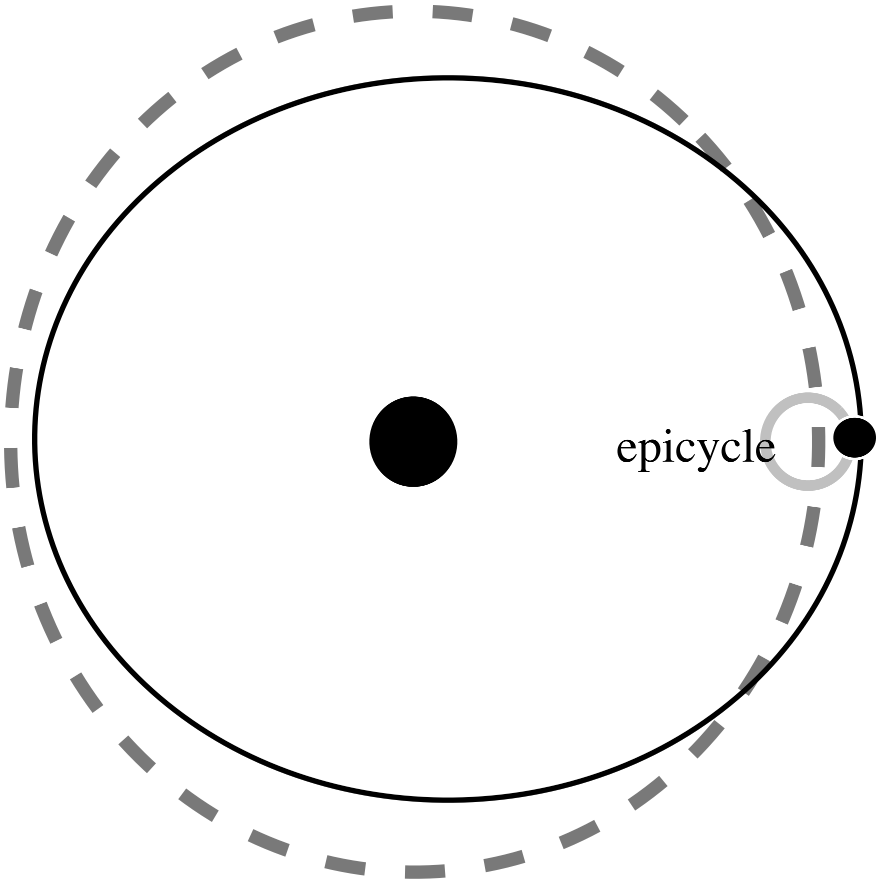


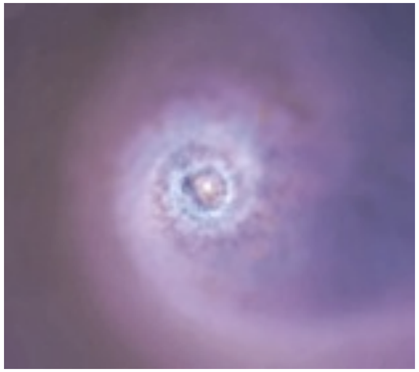
• m=1 'slow' modes are special in a near-Keplerian potential

Keplerian potentials are special:

$$\kappa = \Omega$$

Hence, closed elliptical orbits!



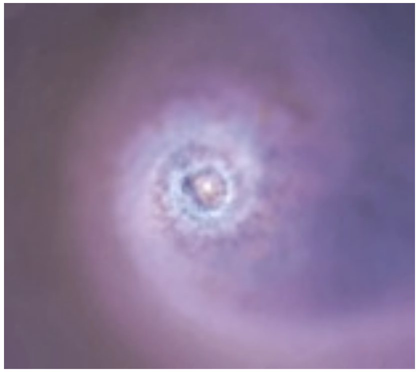


- m=1 ‘slow’ modes are special in a near-Keplerian potential

Disturb the stars with some perturbation in the disk:

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

number of ‘arms’



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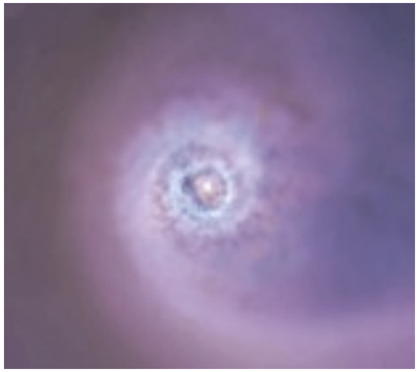
$$\Delta = \kappa^2 - m\Omega^2$$



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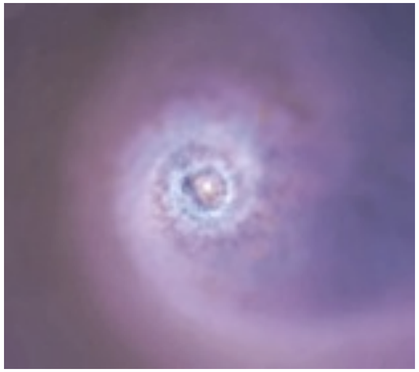
Near a BH: $\dfrac{1}{\Delta} \rightarrow \dfrac{1}{(1-m)\Omega^2}$



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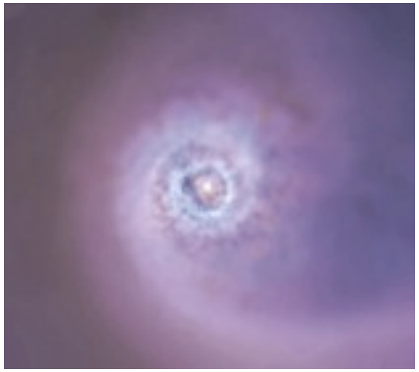
$$\Delta = \kappa^2 - m\Omega^2$$

$$m \neq 1 :$$

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

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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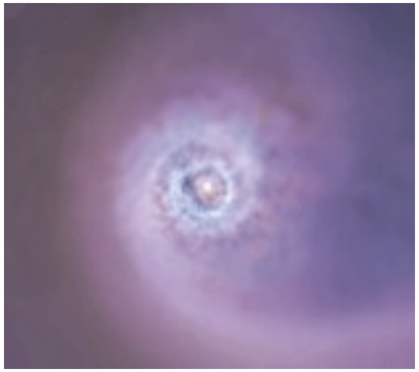

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$$\delta\Sigma \propto \cos m\phi$$

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Response: $$|\mathbf{e}| \propto \frac{1}{\Delta}$$

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

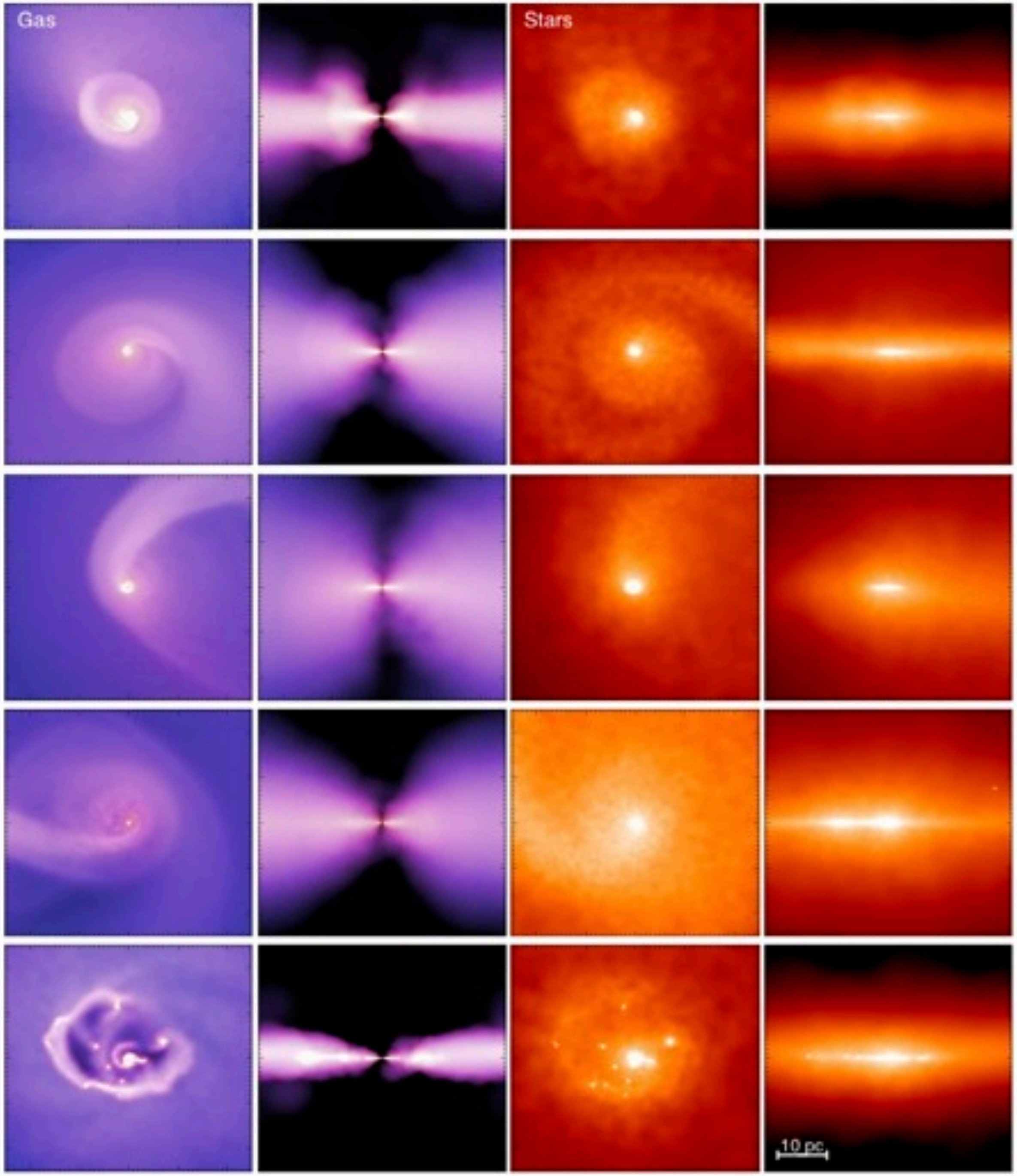
$$m = 1 :$$

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

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

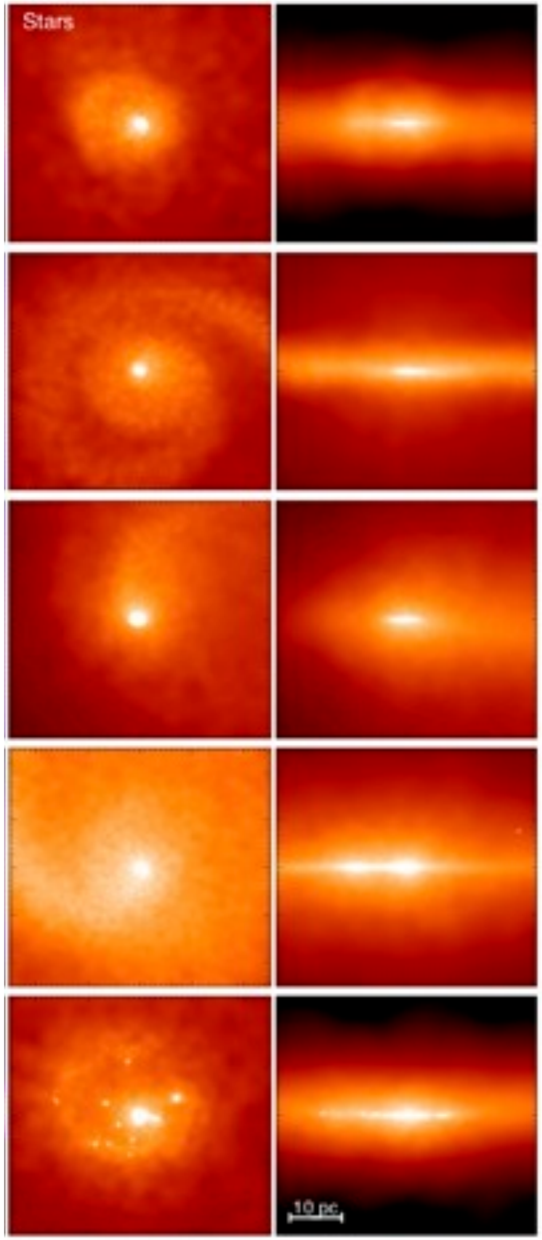
$$|\mathbf{e}| \sim \frac{\delta\Sigma}{\Sigma}$$

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

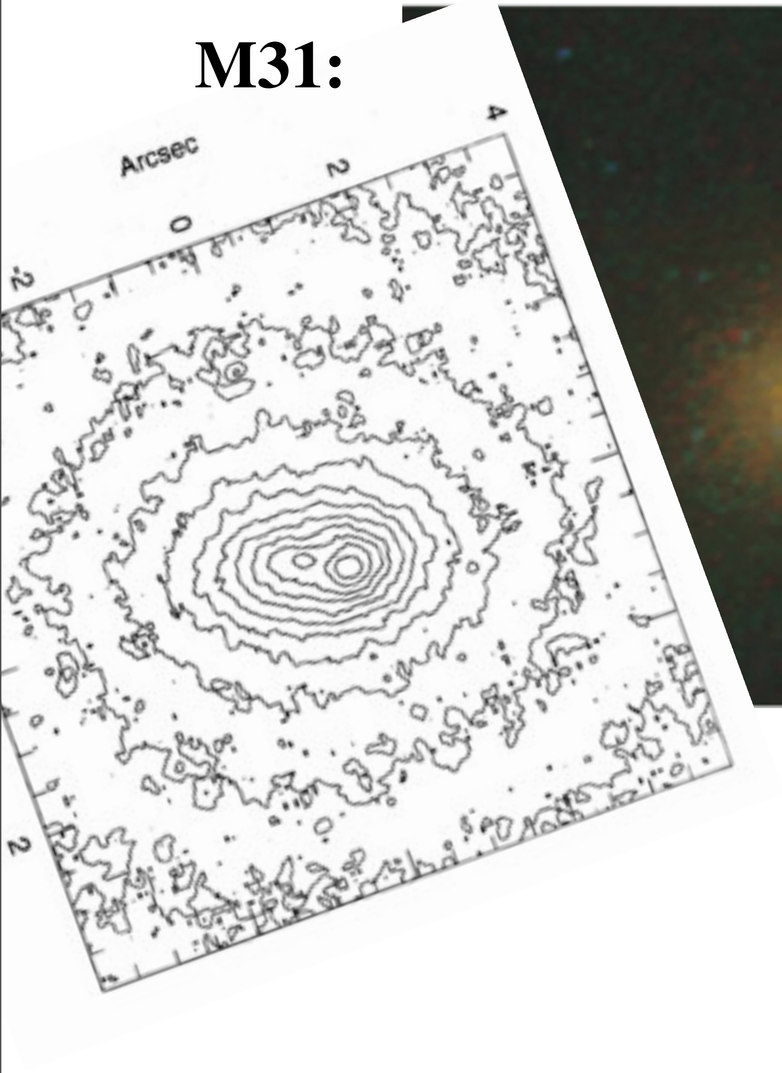


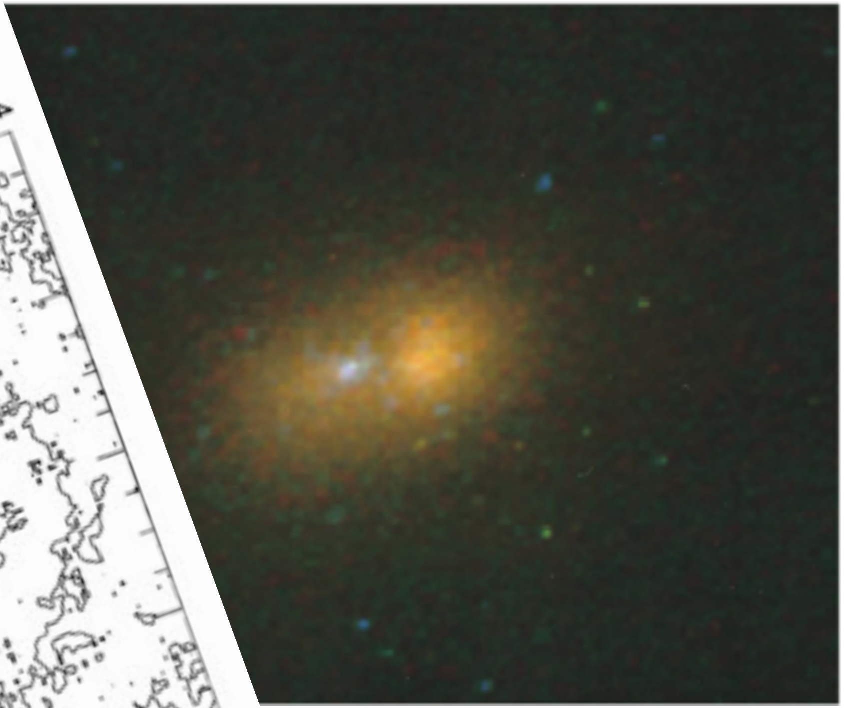
- Gas-stellar exchange can dramatically enhance torques
- Drives up to ~10 M_{sun}/yr inflow rates
- Leave relic stellar disks?

- 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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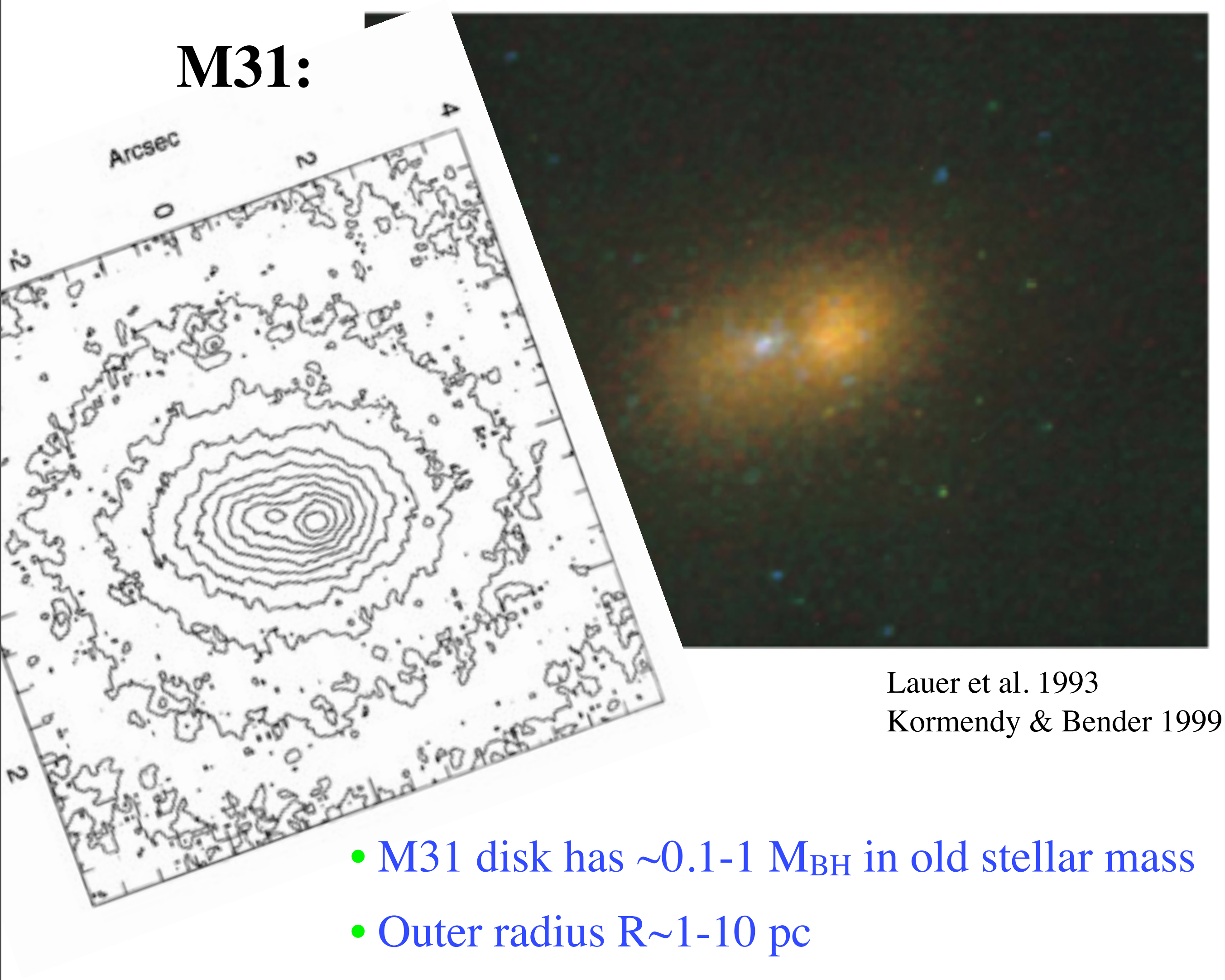
M31:



Lauer et al. 1993
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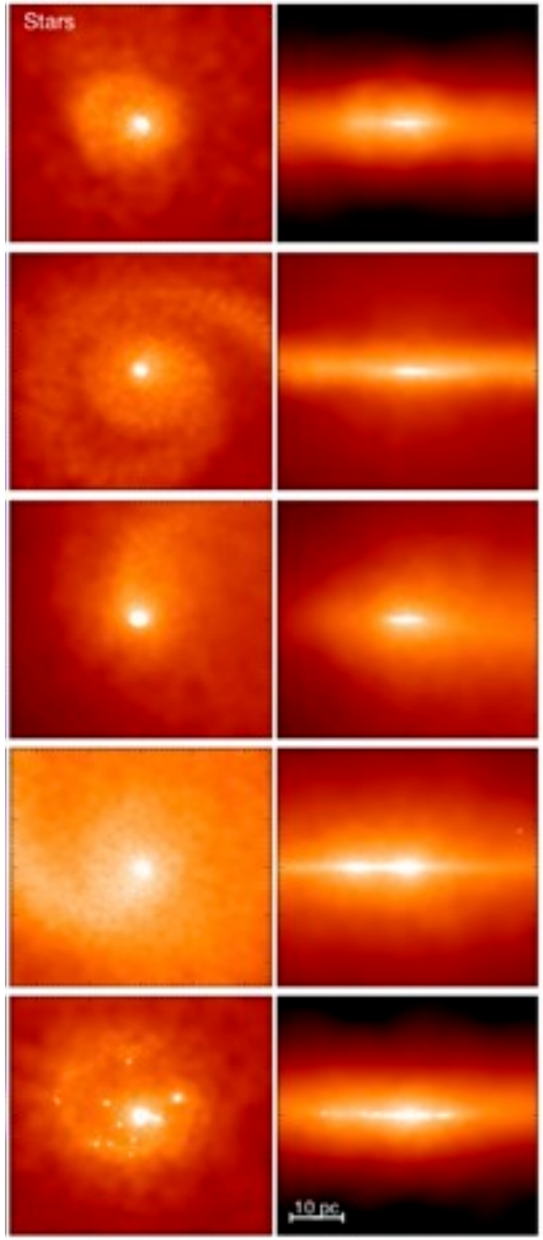
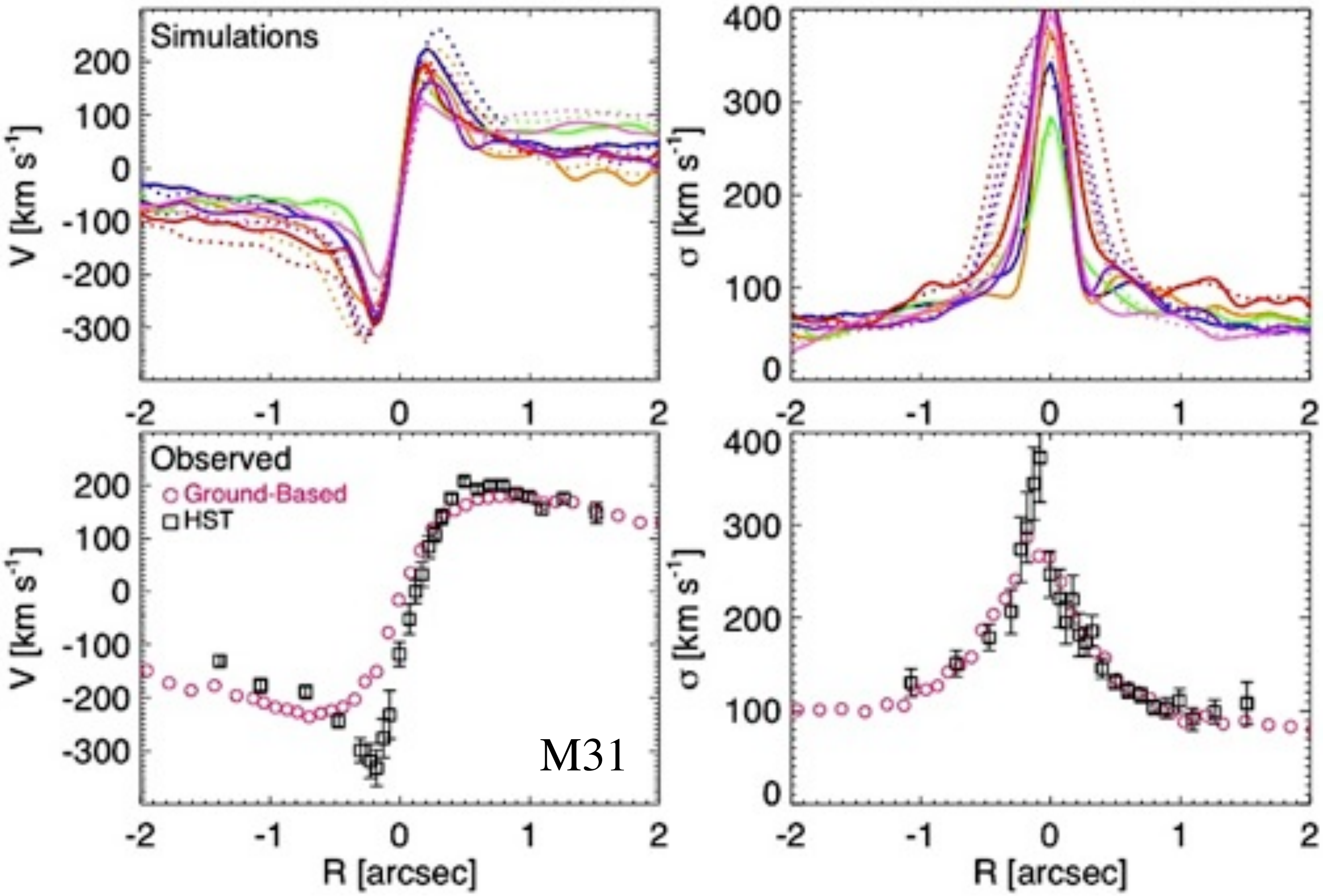
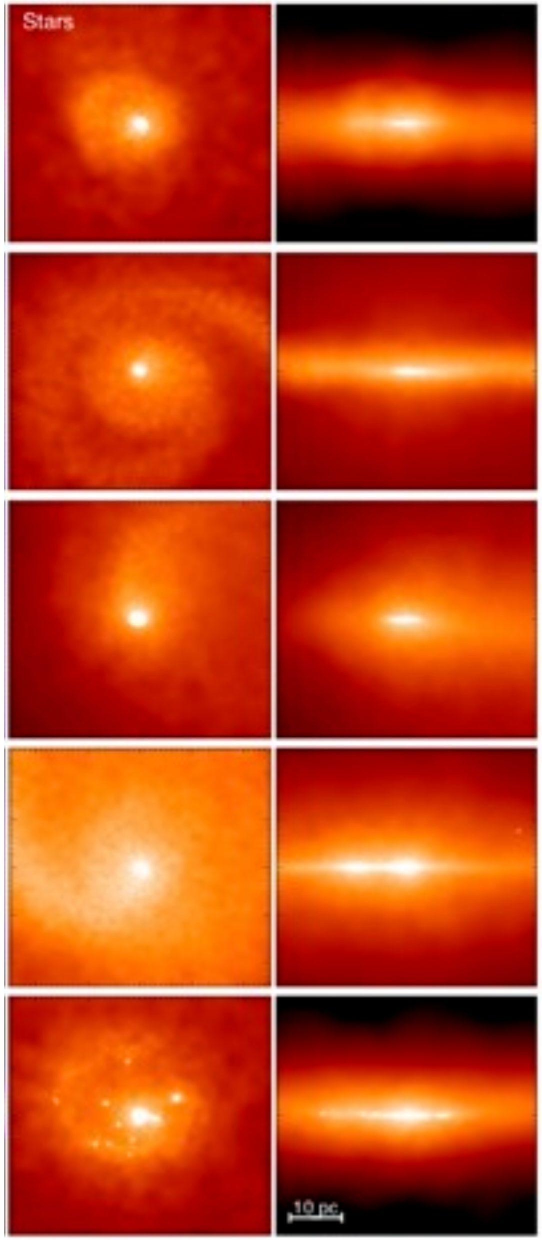


- M31 disk has ~0.1-1 M_{BH} in old stellar mass
- Outer radius R~1-10 pc
- Moderate thickness, high eccentricity

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





- These are observed!
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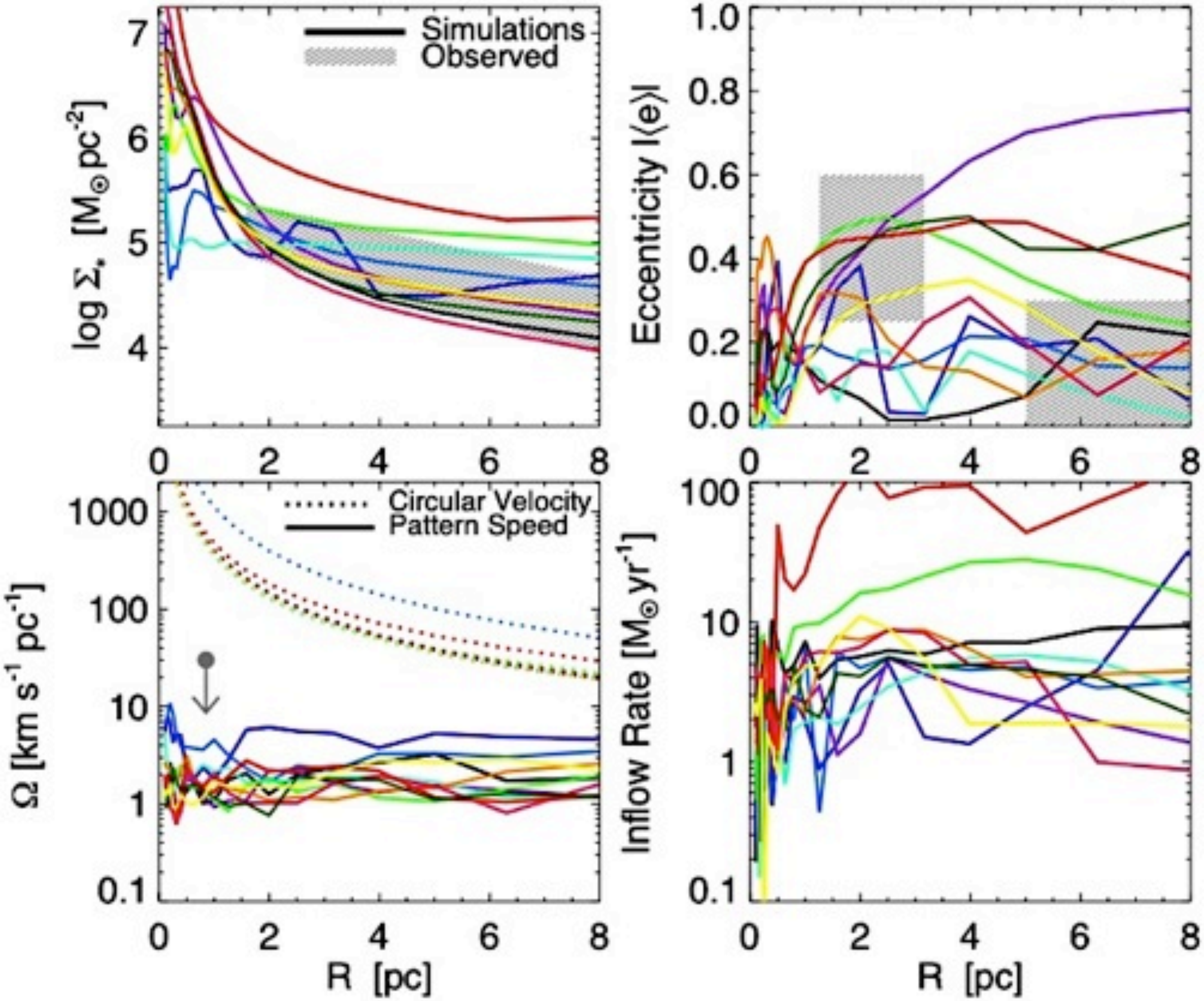
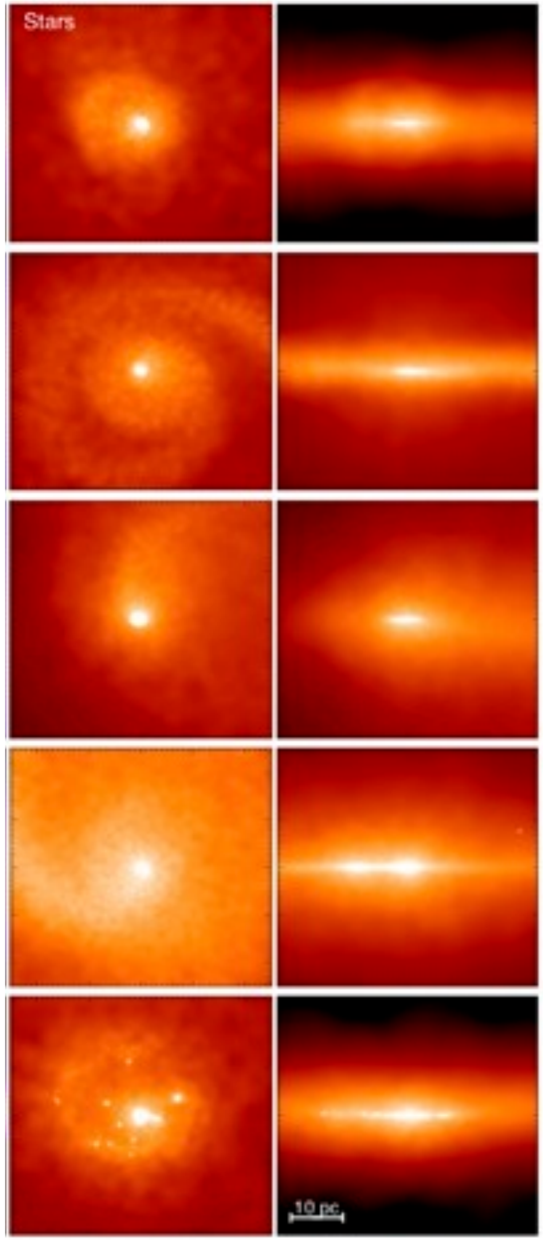
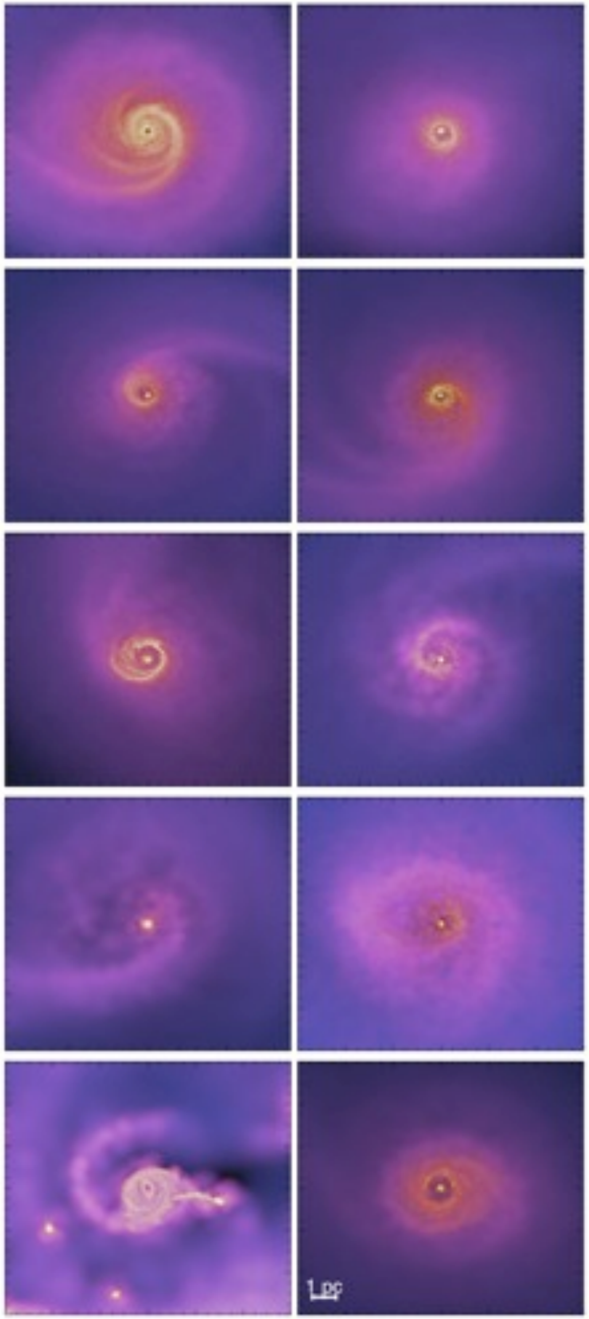




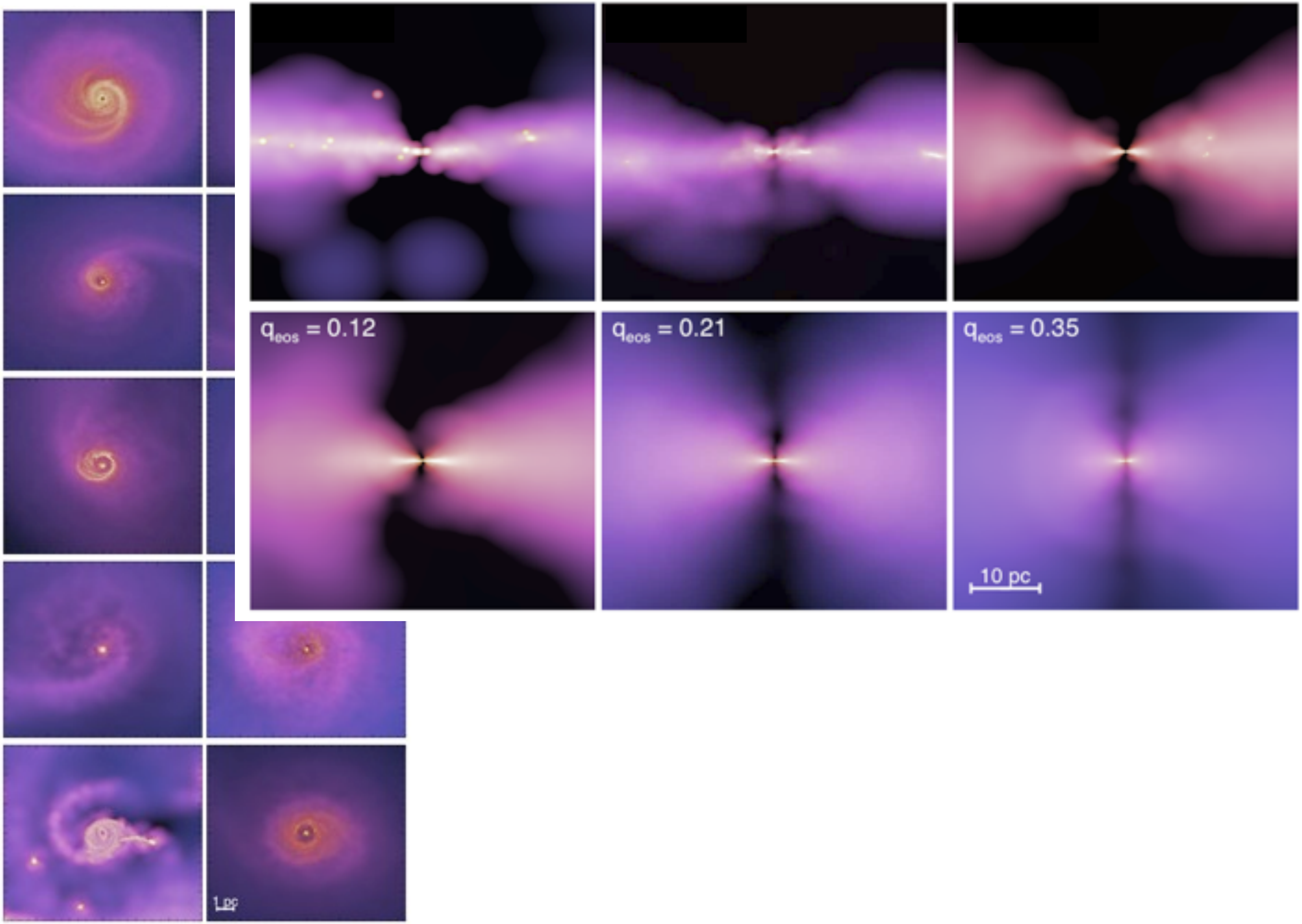
- "run backwards": the M31 disk implies accretion at ~0.5-3 M_{sun}/yr (~L_{Edd})
  for ~100 Myr (~ M_{BH}) !

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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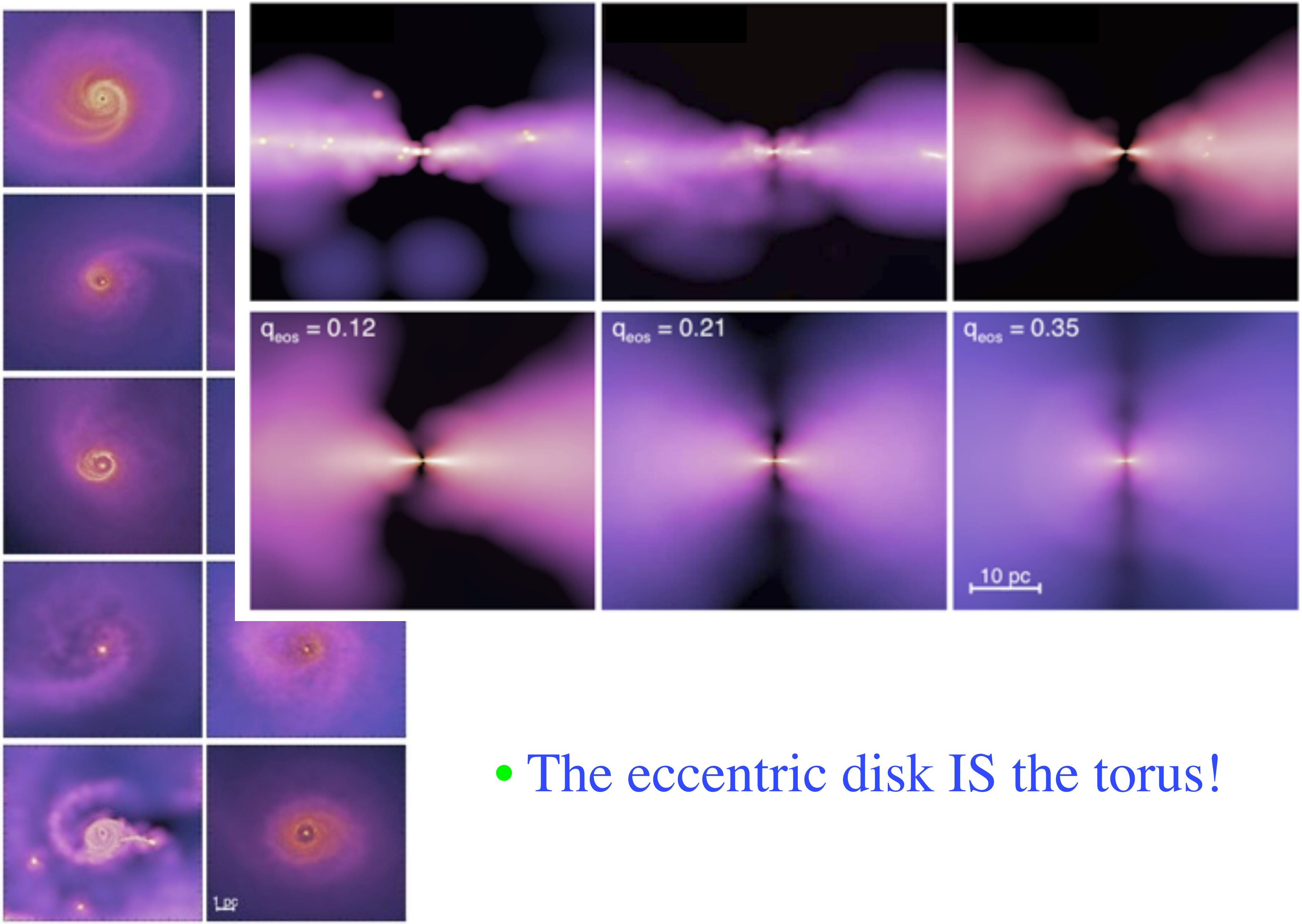

- The eccentric disk IS the torus!

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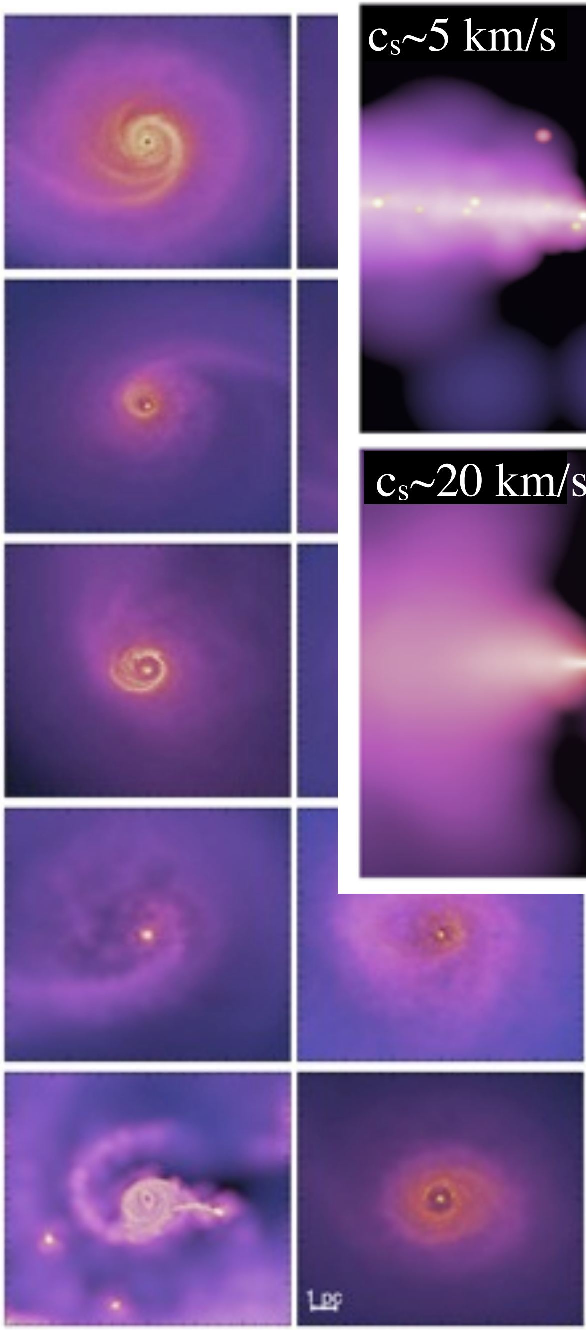
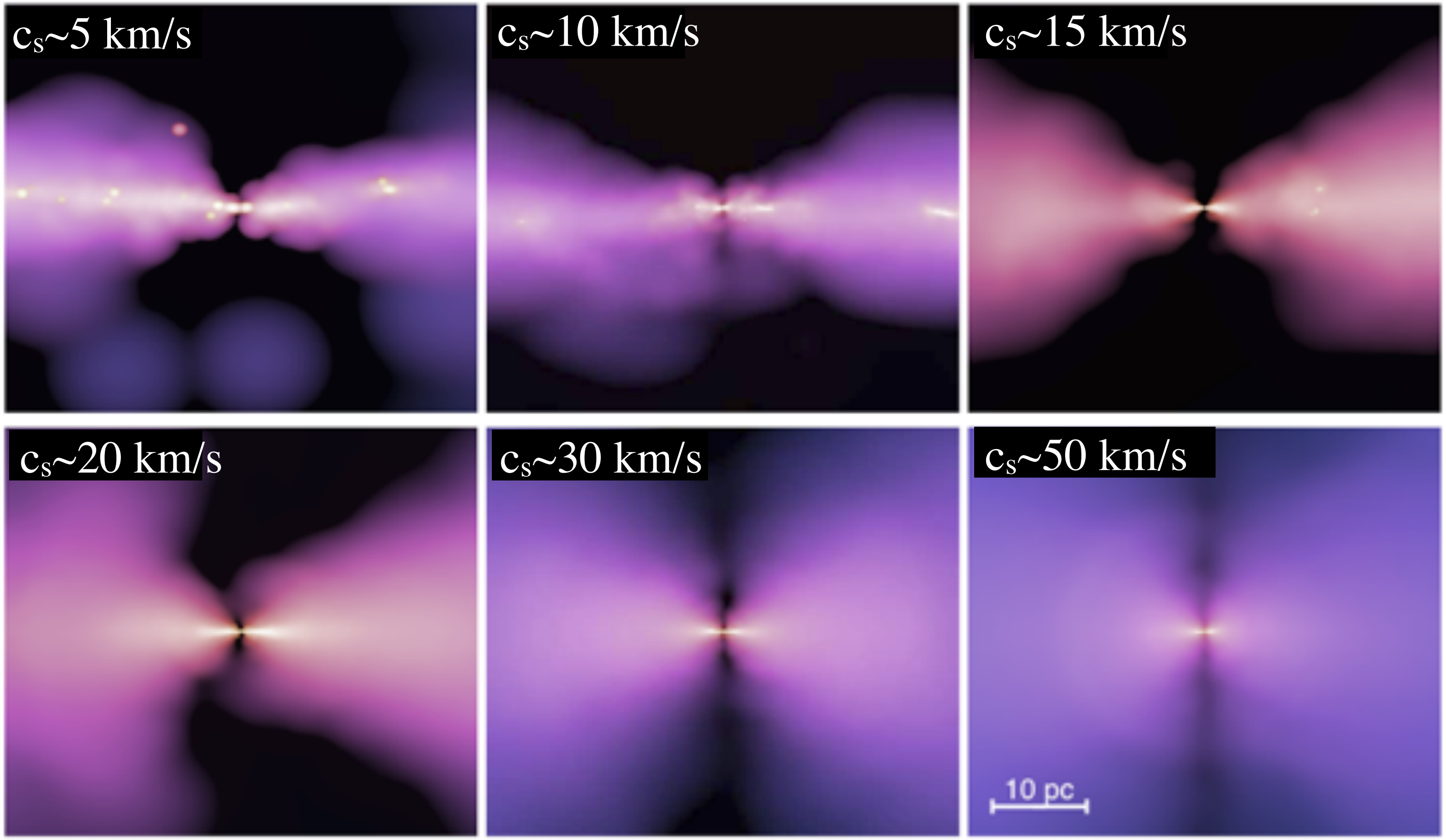
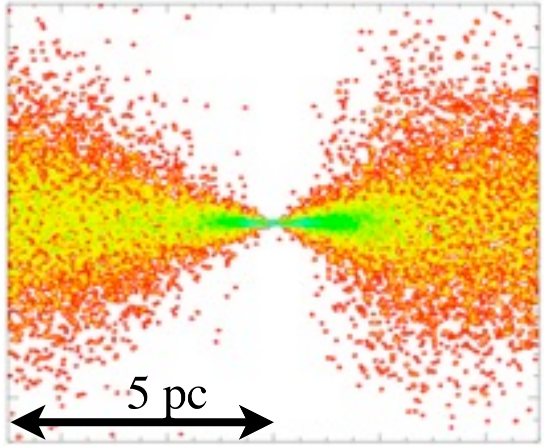




- The eccentric disk IS the torus
- Occurs even if allow cooling and no stellar feedback!
  - Heating by bending/warping modes, themselves excited *by the eccentric pattern*

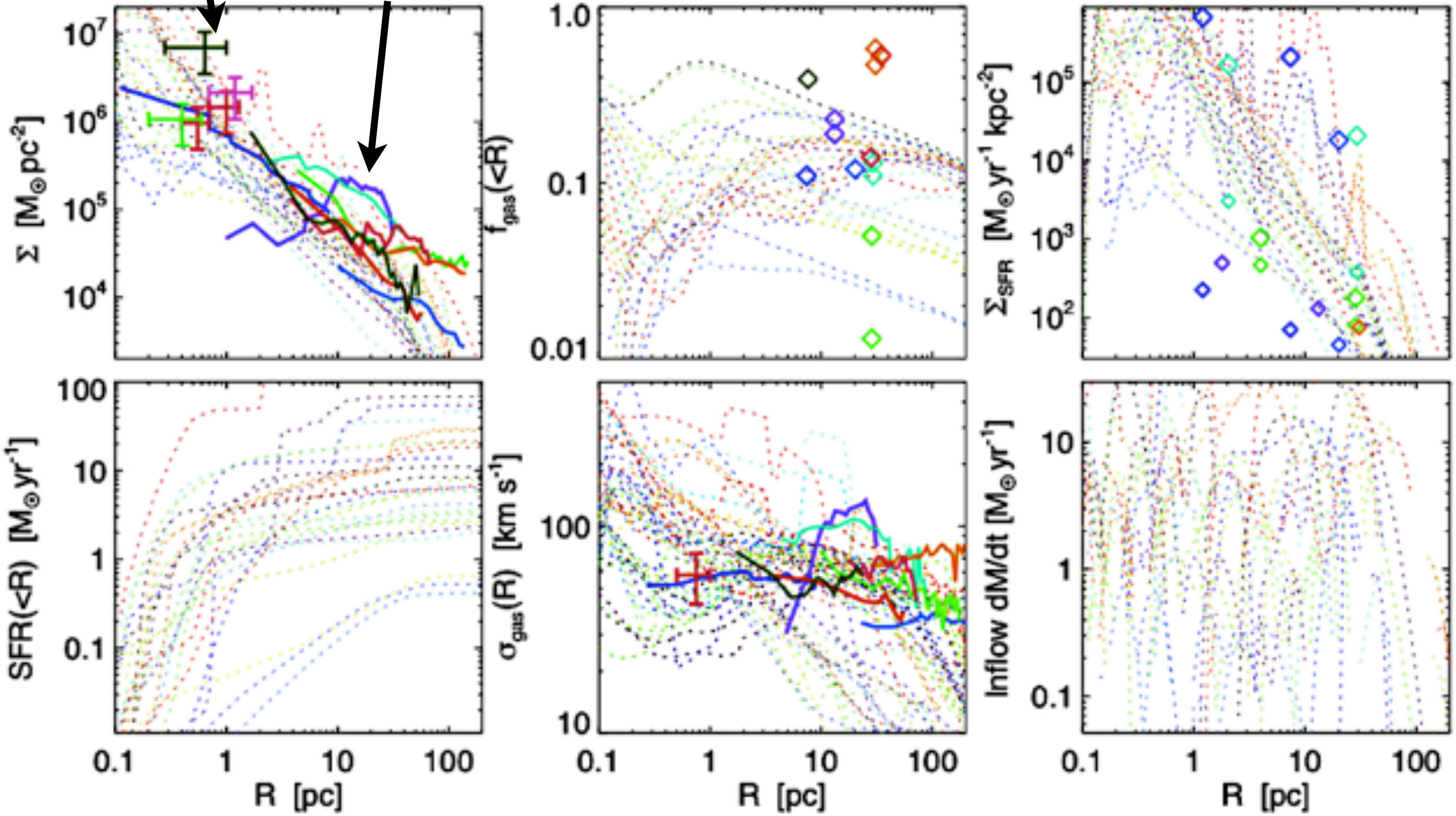
Obscuration and the 'torus'



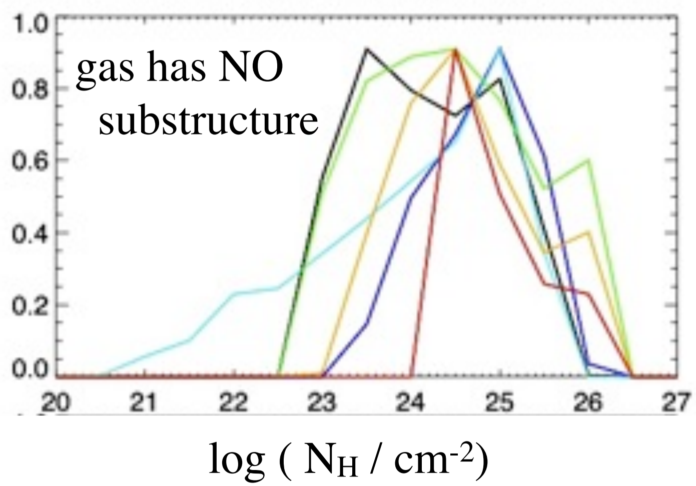
- Observed surface densities and kinematics arise naturally

Masers (Kondratko, Greenhill, et al.)

AO (Hicks, Davies, et al.)

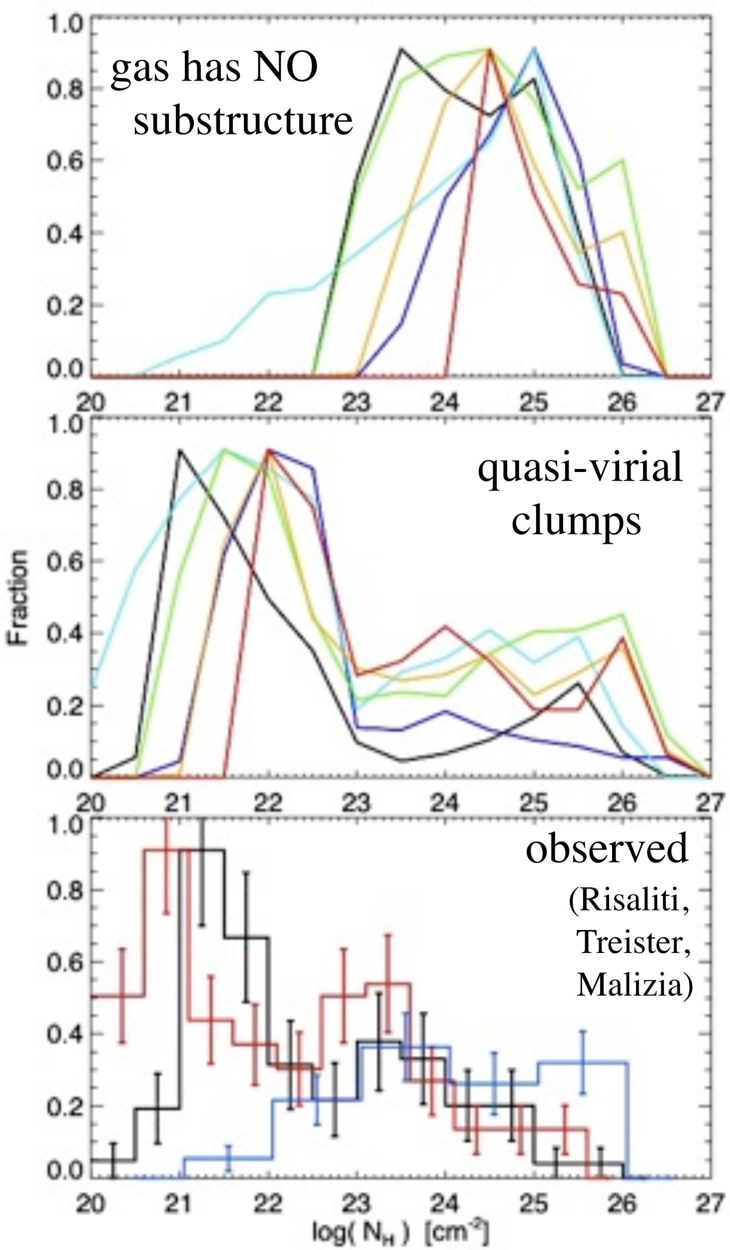


• Compare column density distributions:



• Cannot *simultaneously* match observed gas masses/kinematics & columns with *perfectly smooth* gas

• Compare column density distributions:

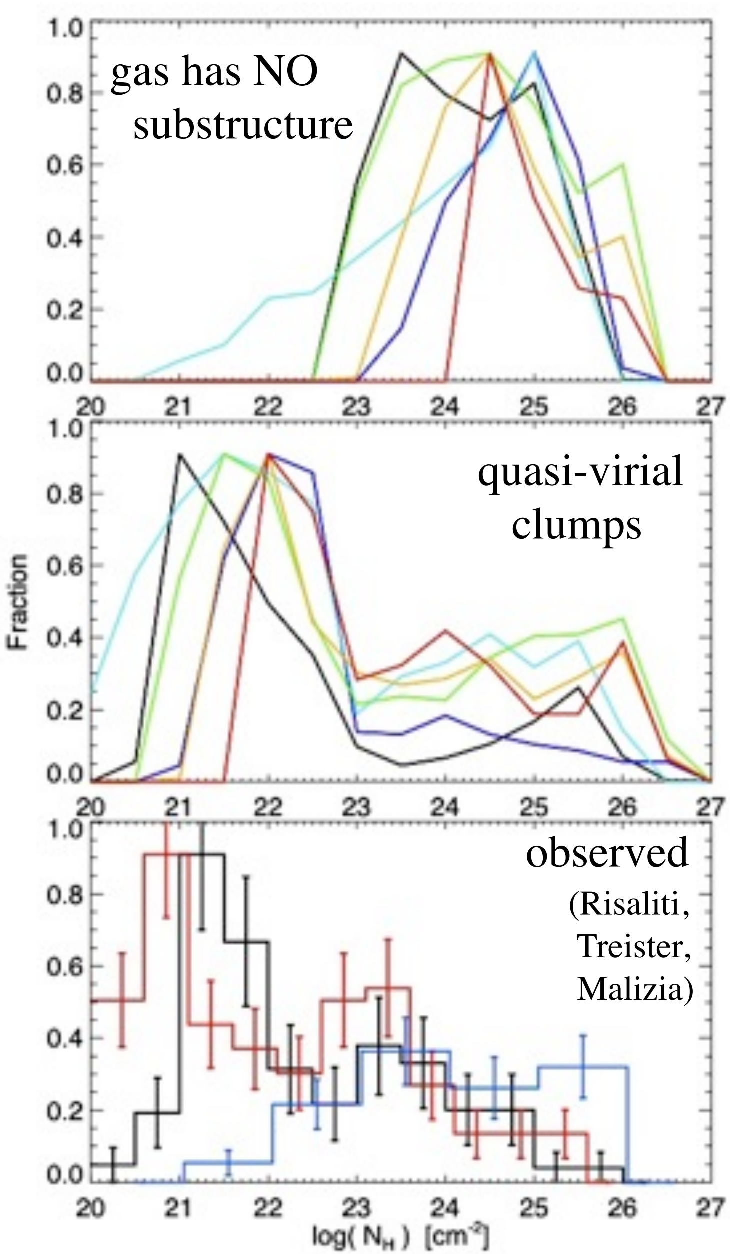


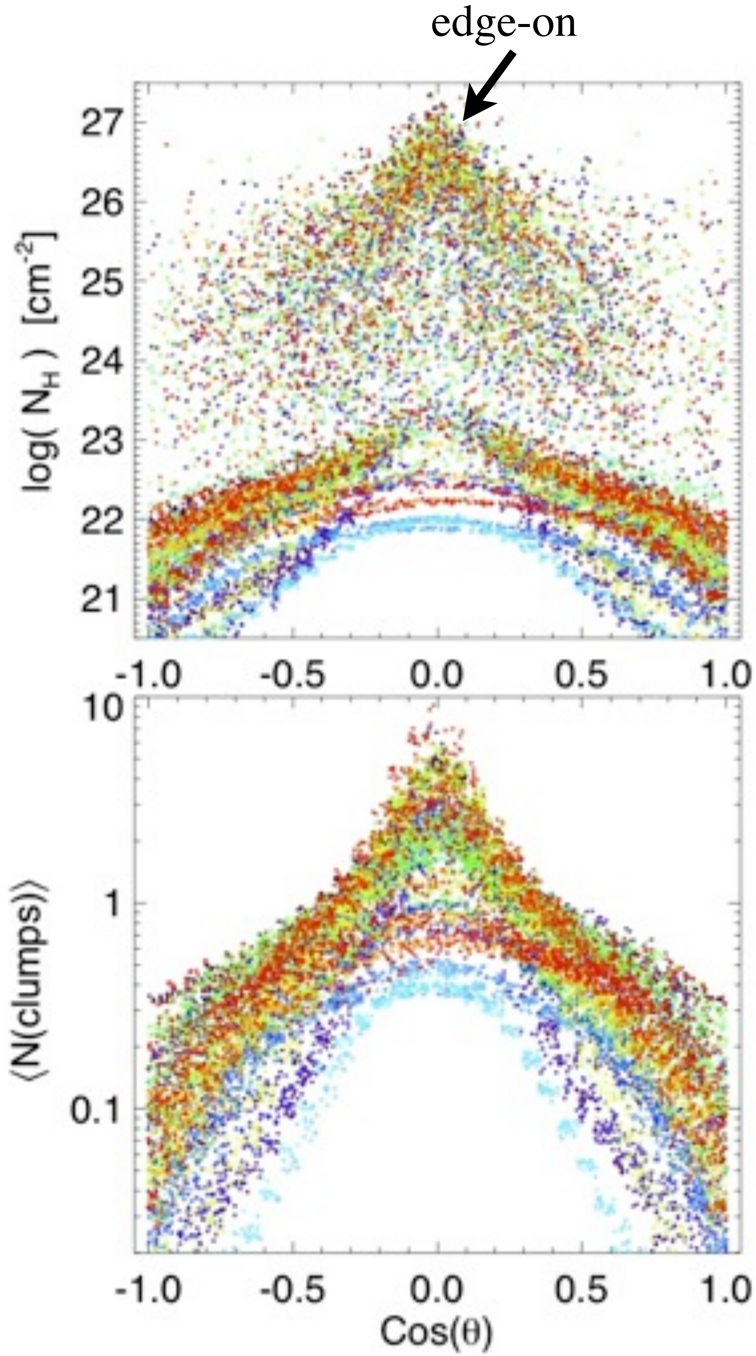
• Cannot *simultaneously* match observed gas masses/kinematics & columns with *perfectly smooth* gas

• 'Simplest' assumption: sub-resolution clumps are quasi-virial and in pressure equlibrium

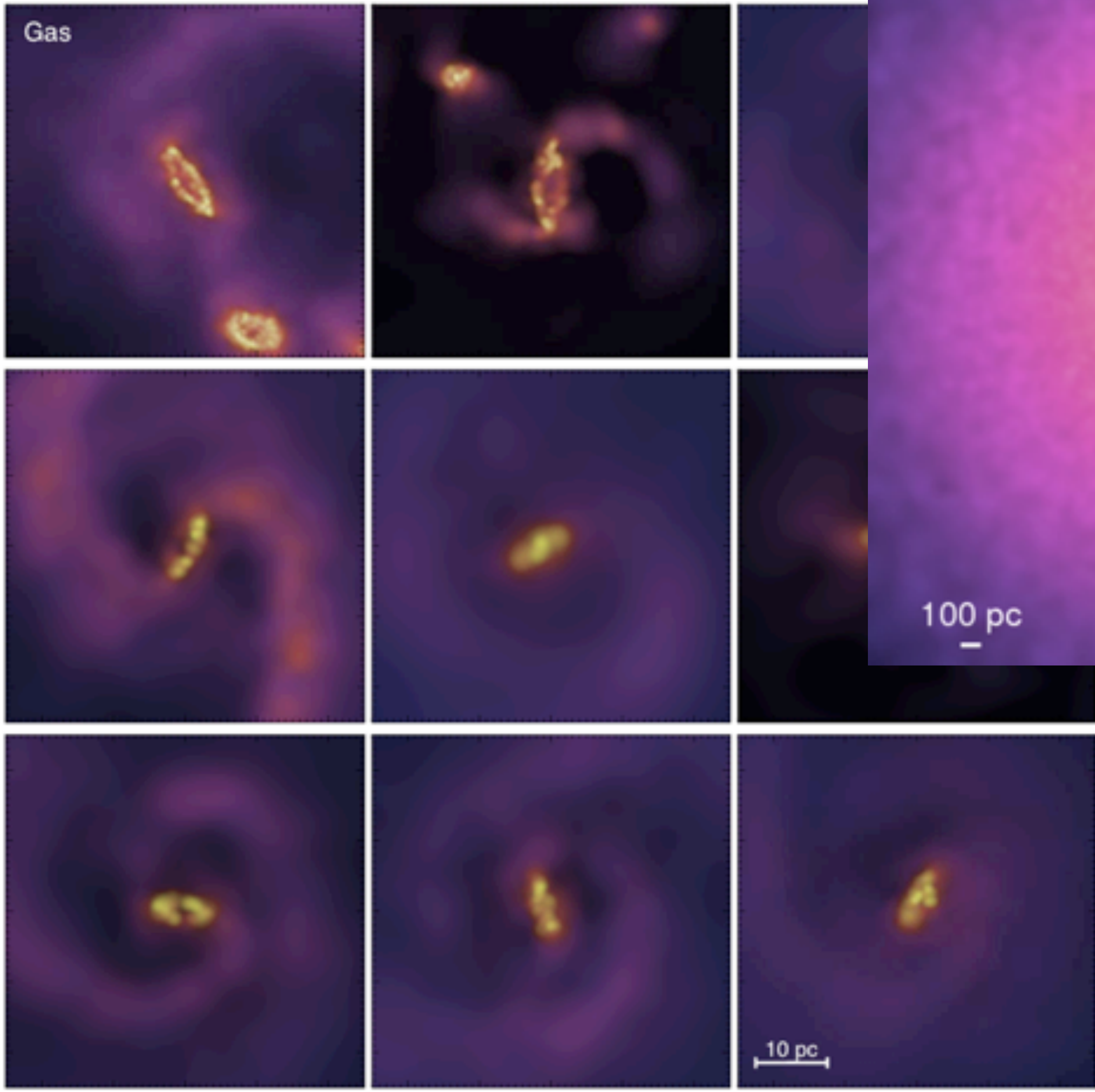
  • Completely determines N_H distribution (independent of clump mass/size spectrum)

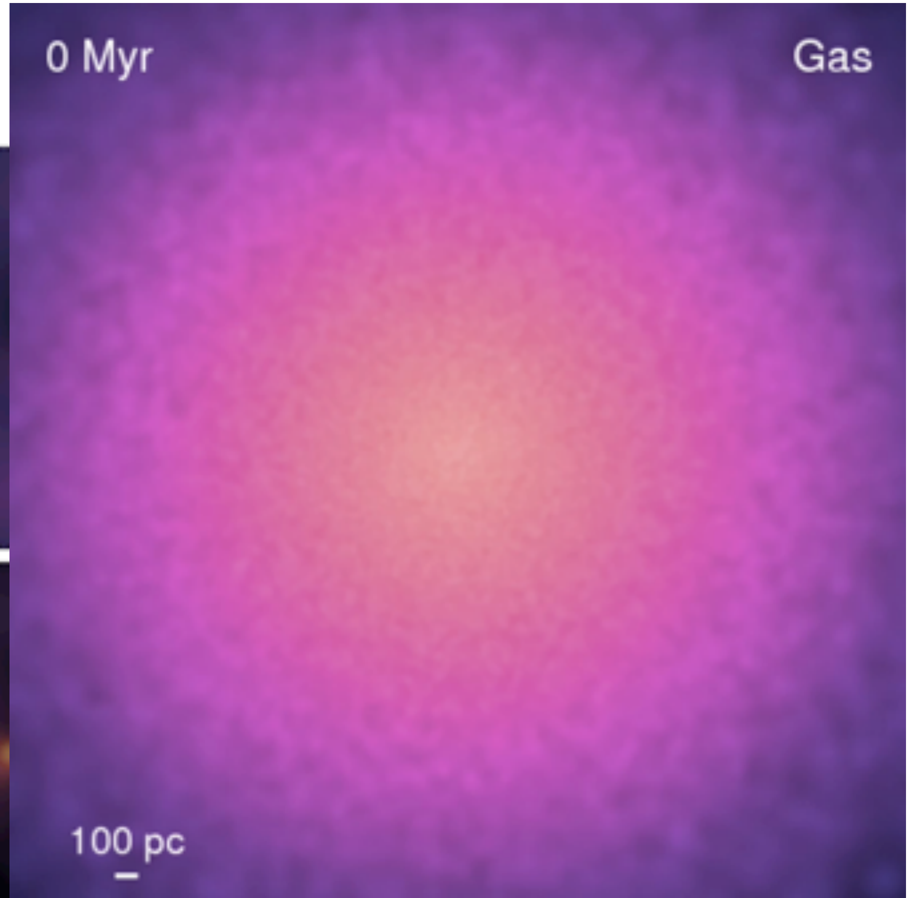
• Compare column density distributions:





Mis-alignments with the parent disk are common

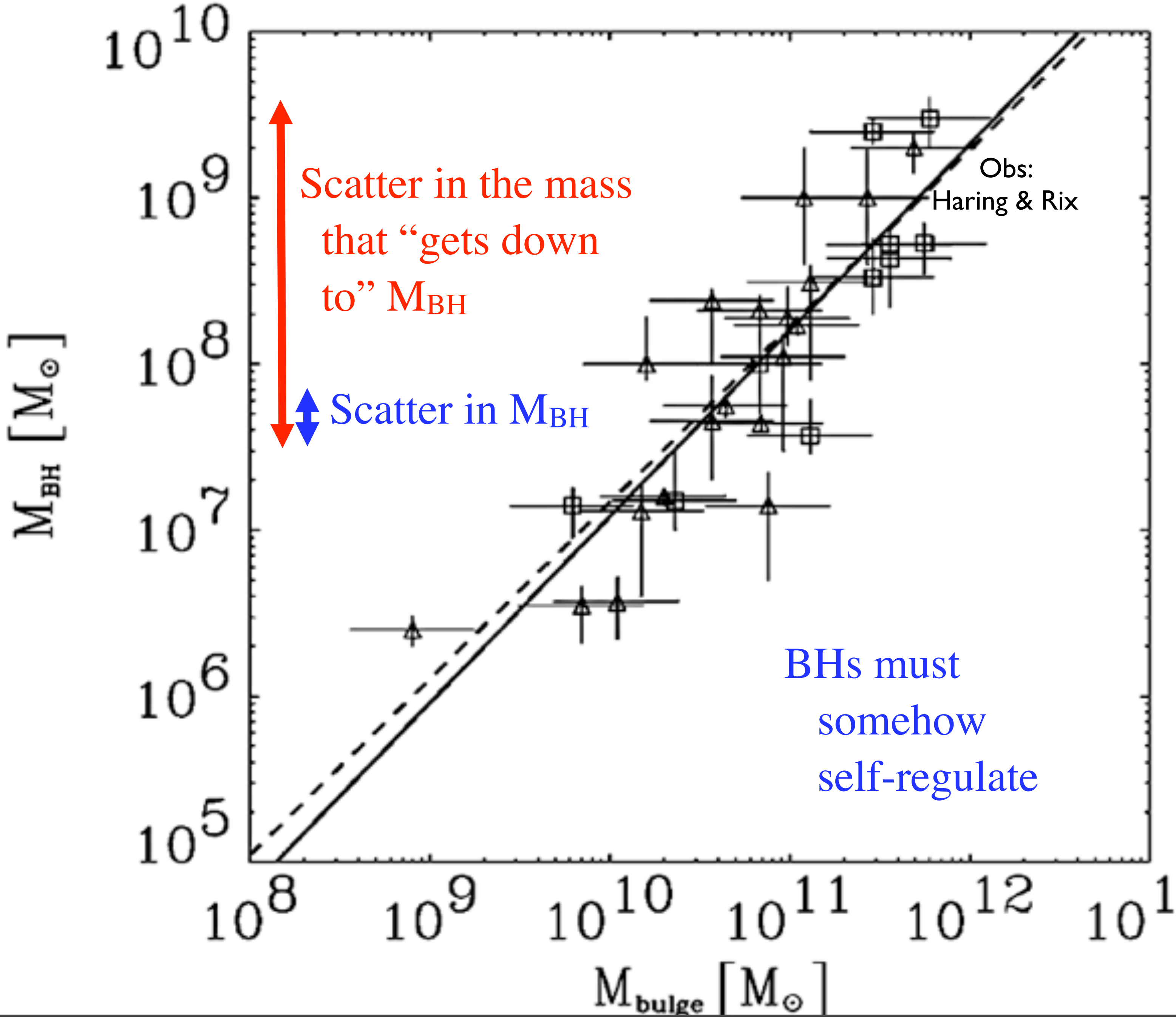




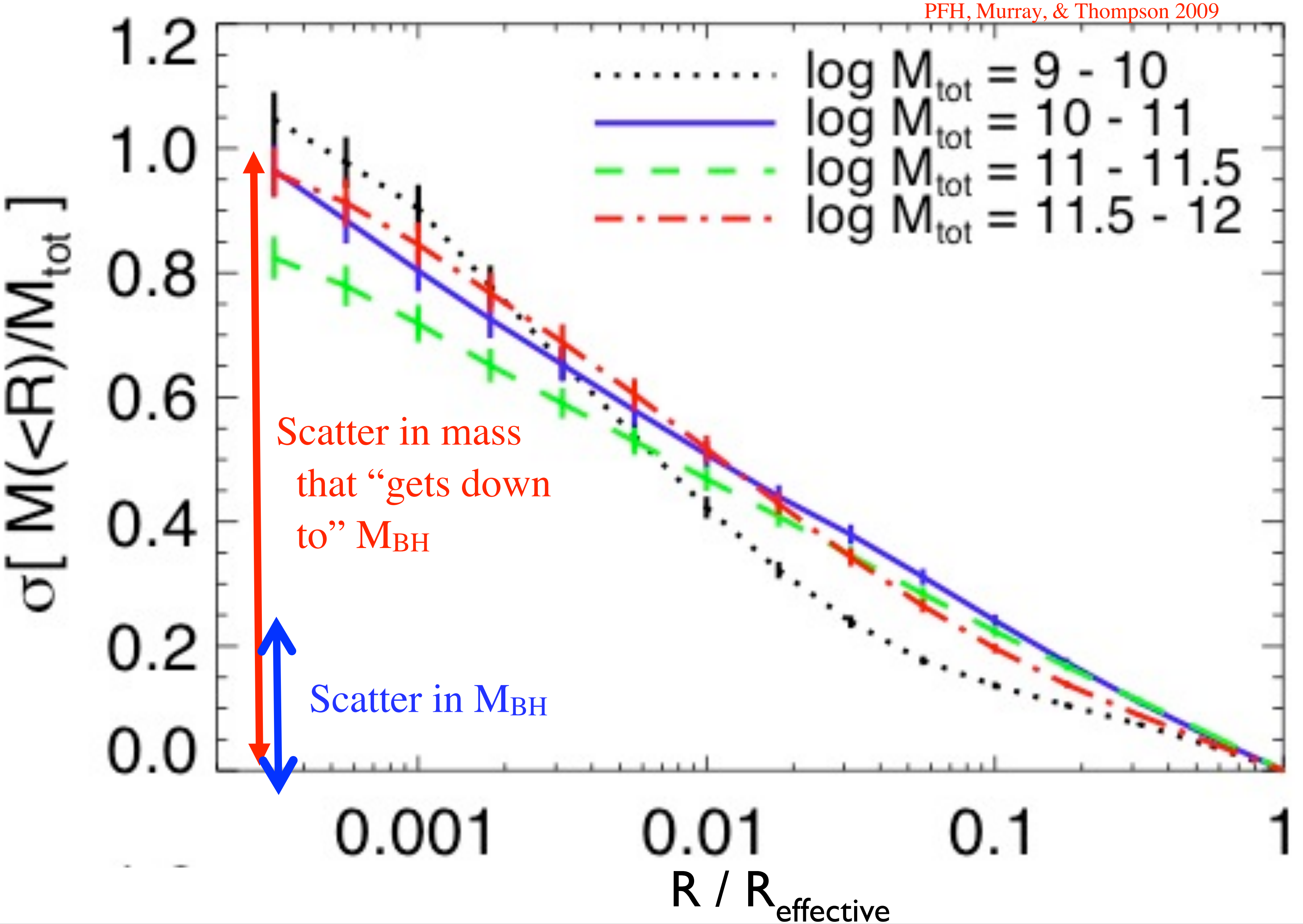
- Implications for:
  - BH spin
  - BH-BH mergers
  - Recoils
  - Variability

Feedback: How Does the Black Hole Know When to Stop?

And this is NOT the simplest expectation!



BHs appear to "know more" about the galaxy than nuclear stars...



Simplest Idea:

FEEDBACK ENERGY/MOMENTUM BALANCE (SILK & REES '98)

- Accretion disk radiates:

$$L = \epsilon_r \,(\mathrm{d}M_{\rm BH}/\mathrm{d}t)\, c^2 \quad (\epsilon_r \sim 0.1)$$

- Total energy radiated (typical ~10^8 M_{sun} system)

$$\sim 0.1\, M_{\rm BH}\, c^2 \sim 10^{61}\,\mathrm{ergs}$$

- Compare to gravitational binding energy of galaxy:

$$\sim M_{\rm gal}\,\sigma^2 \sim (10^{11}\,M_{\rm sun})\,(200\,\mathrm{km/s})^2 \sim 10^{59}\,\mathrm{erg}$$

- If only a few percent of the luminous energy coupled, it would unbind the baryons!

- Turn this around: *if* some fraction f ~ 1-5% of the luminosity can couple, then accretion stops when

$$M_{\rm BH} \sim (1/f\epsilon_r)\,M_{\rm gal}\,(\sigma/c)^2 \sim 0.002\,M_{\rm gal}$$

AGN Fueling: Some General Notes

- Recall: simplest model is ~few % energy injection

- Since need to see feedback on large scales, can't zoom-in: estimate BHAR from gas on ~100 pc scales
  - Good news: It's near Eddington at peak

$$\dot{M}_{\rm Bondi} \propto \frac{M_{\rm BH}^2\,\rho}{(c_s^2+v^2)^{3/2}}$$

(Springel, Di Matteo et al. 2005)

$$\dot{M}_{\rm dyn} \propto \Sigma_{\rm gas}\,R^2\,\Omega\,f\{\frac{\sigma}{V_c},\,\frac{B}{T}\}$$

(PFH & Quataert 2010)

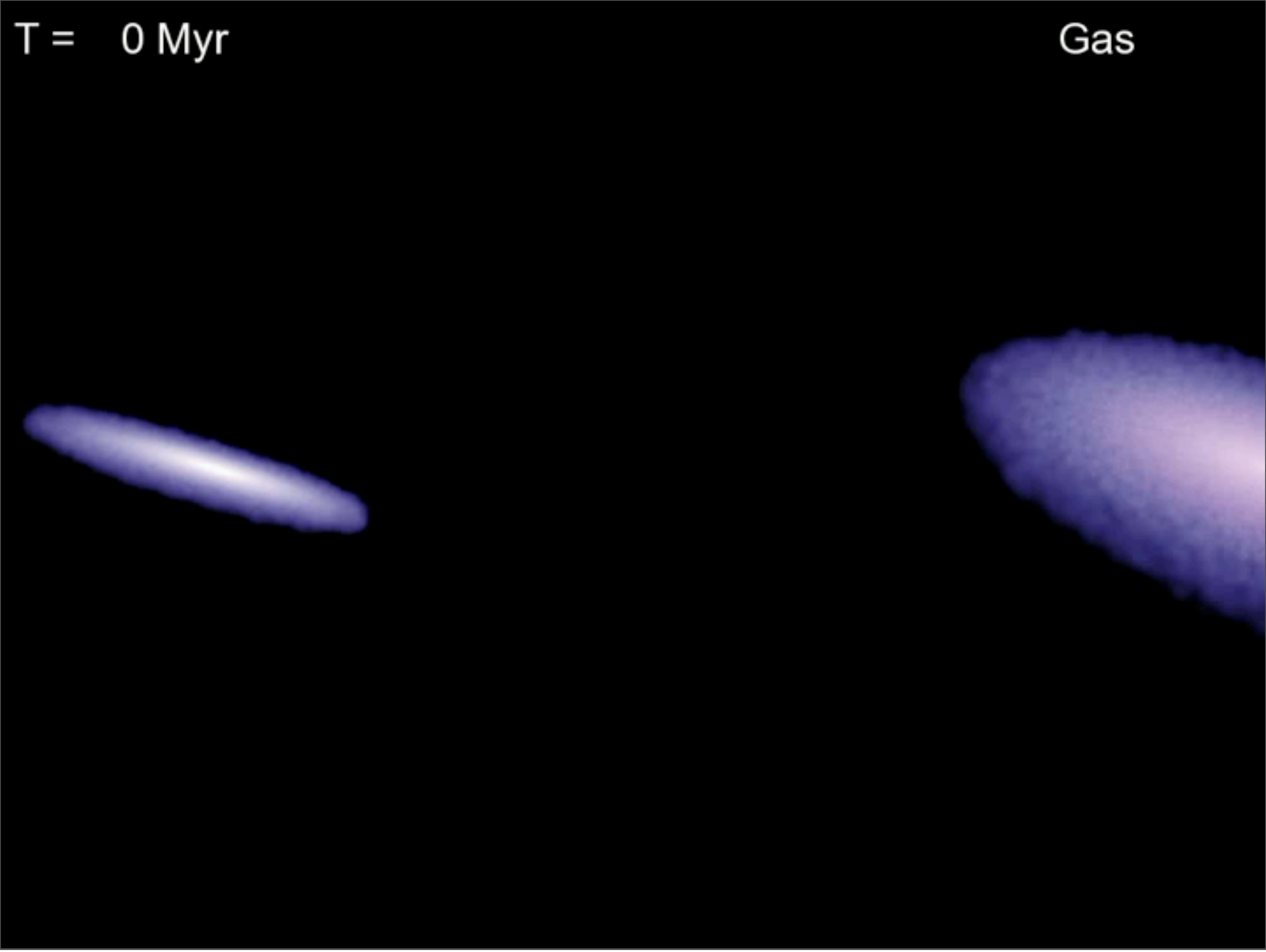
$$\dot{M}_{\rm viscous} \propto \frac{\Sigma_{\rm gas}\,c_s^2}{\Omega}$$

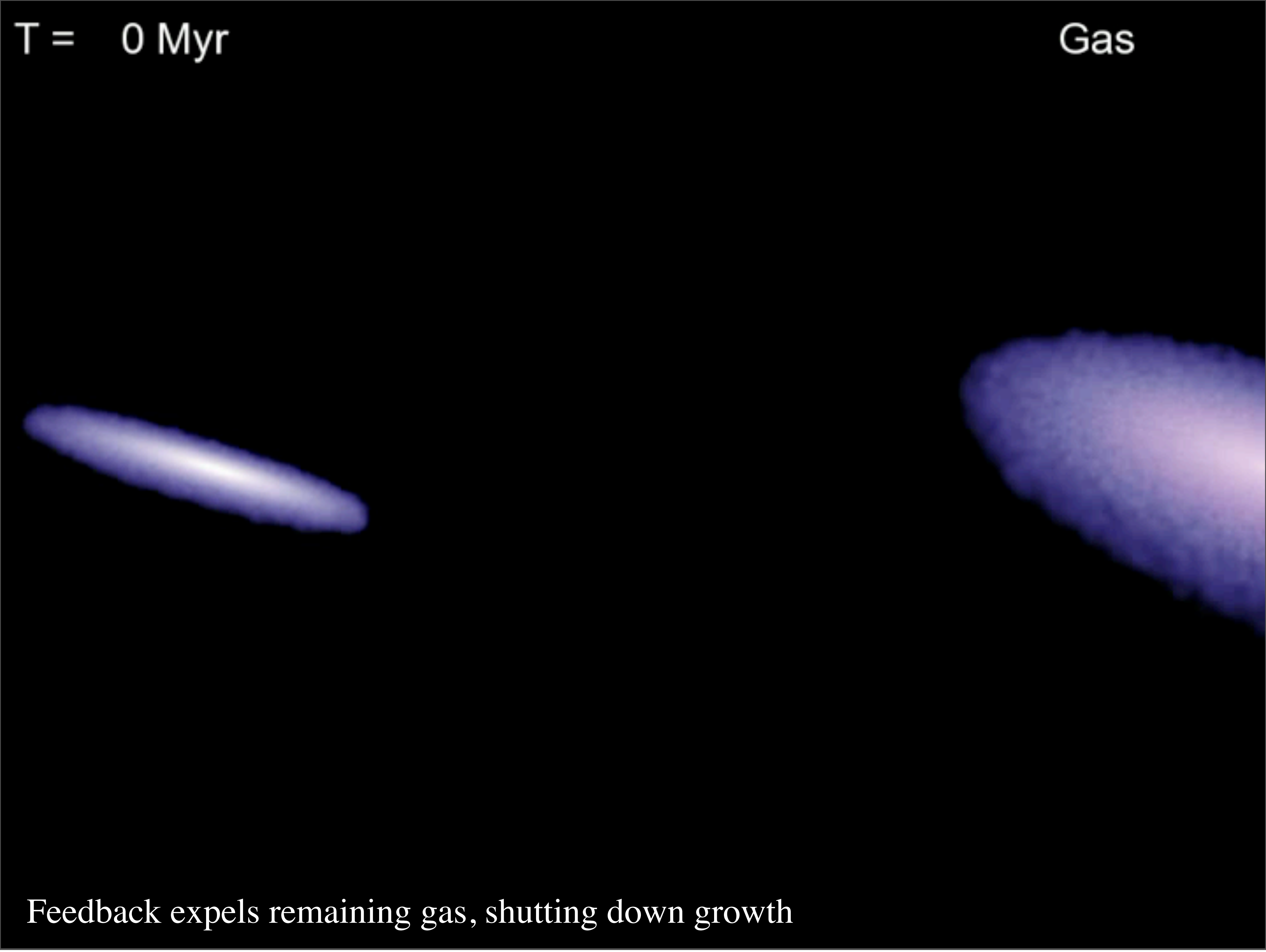
(DeBuhr et al. 2009)

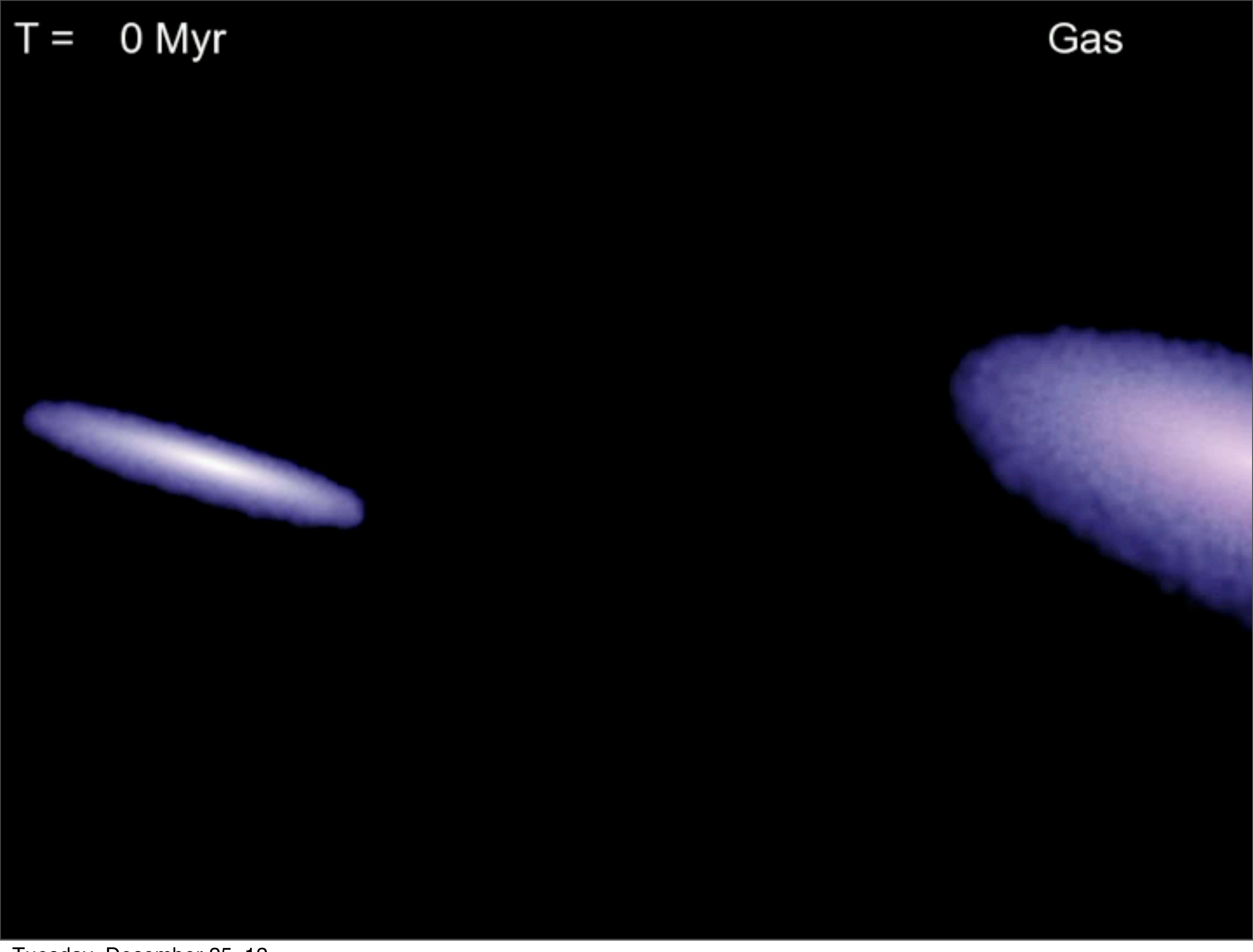
$$\dot{M}_{\rm Edd} \propto M_{\rm BH}$$

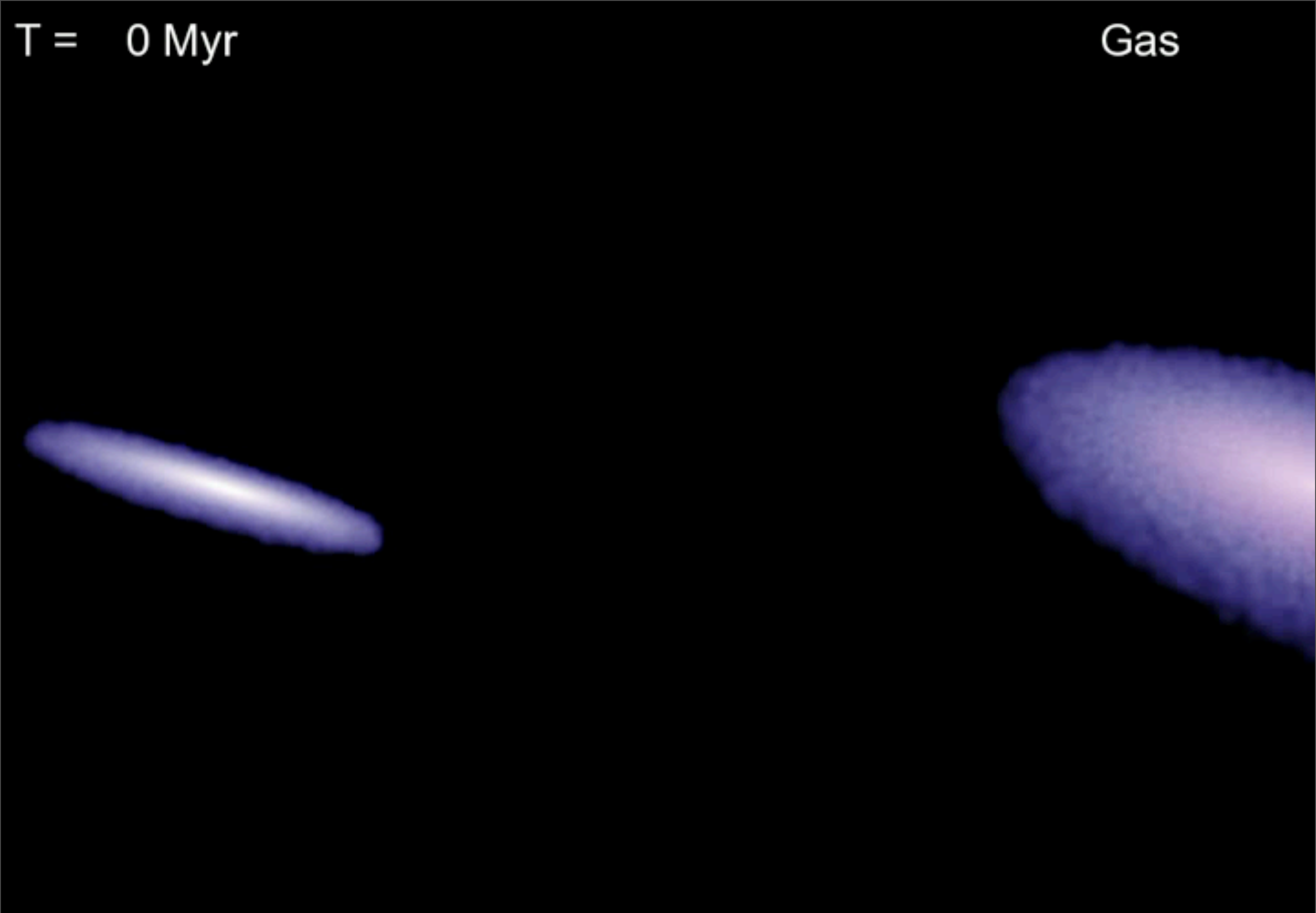
Predict similar "impact" of feedback

- Springel, Di Matteo, & Hernquist: 5% of $L_{\rm bol}$ back in central ~10s of pc, as thermal energy

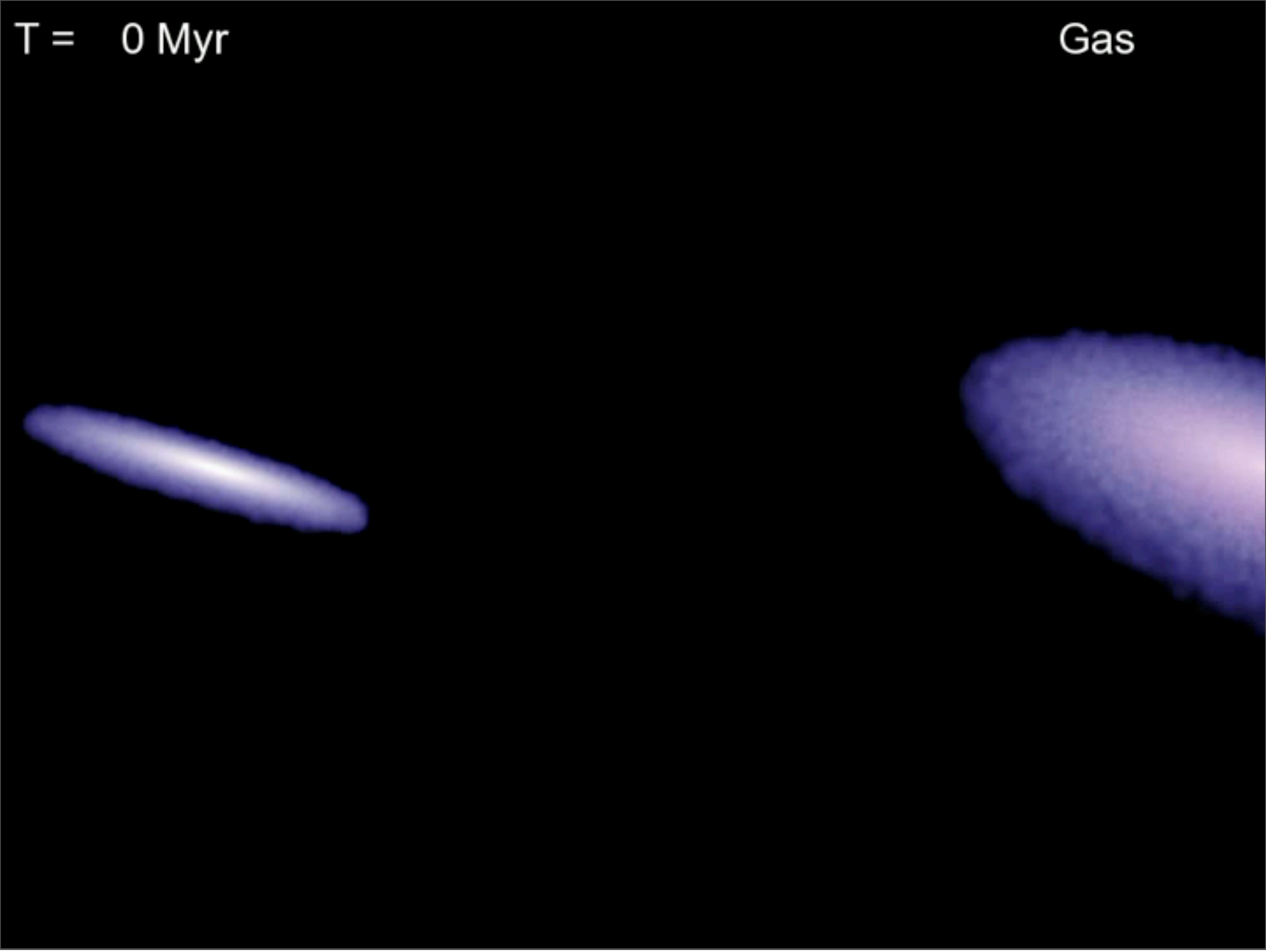

T = 0 Myr
Gas


T = 0 Myr
Gas
Feedback expels remaining gas, shutting down growth


T = 0 Myr
Gas

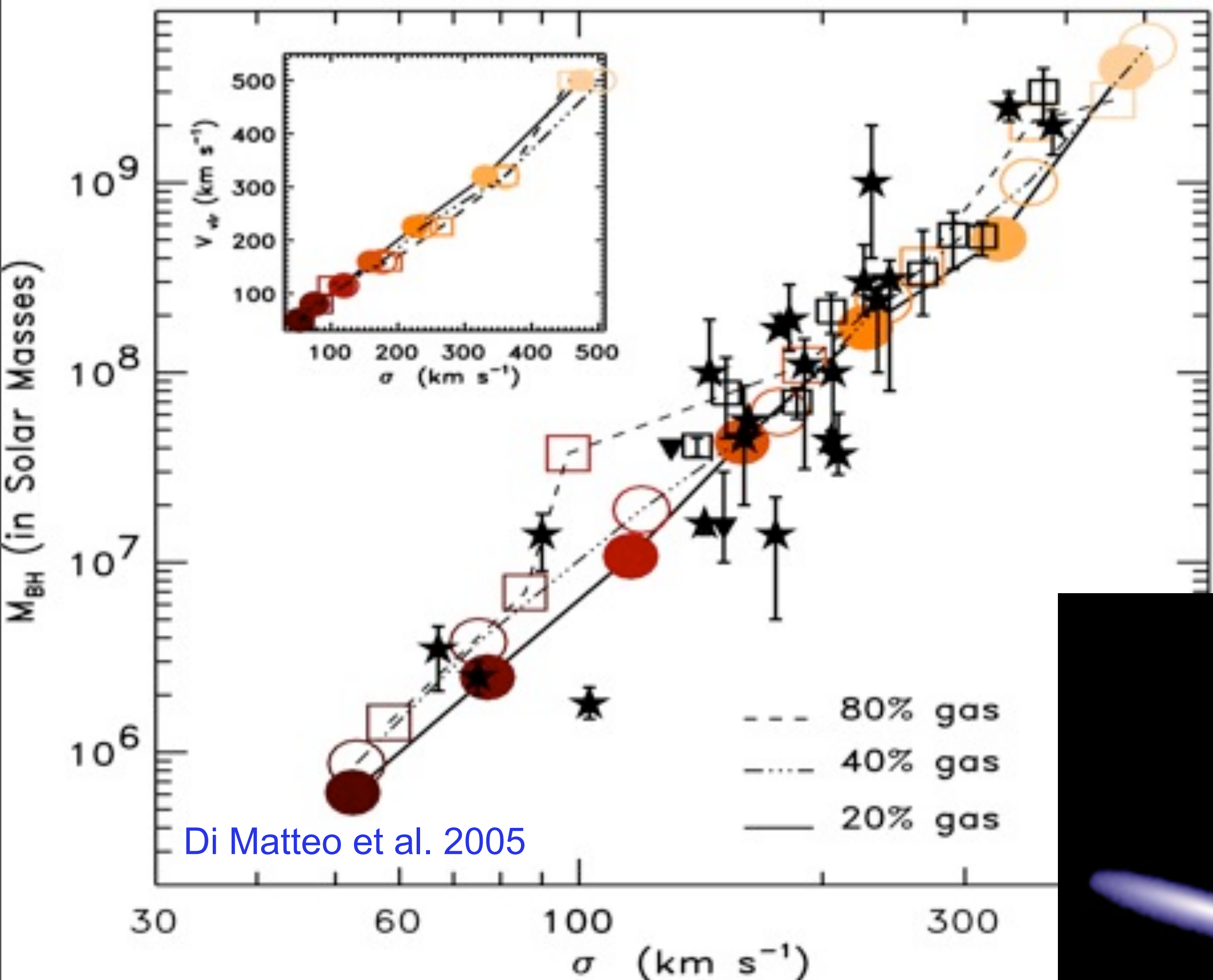


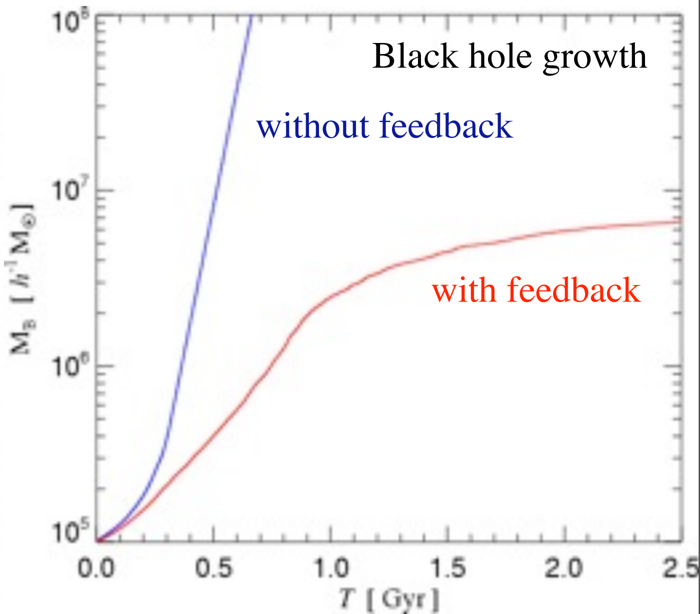
Merging stellar disks grow spheroid

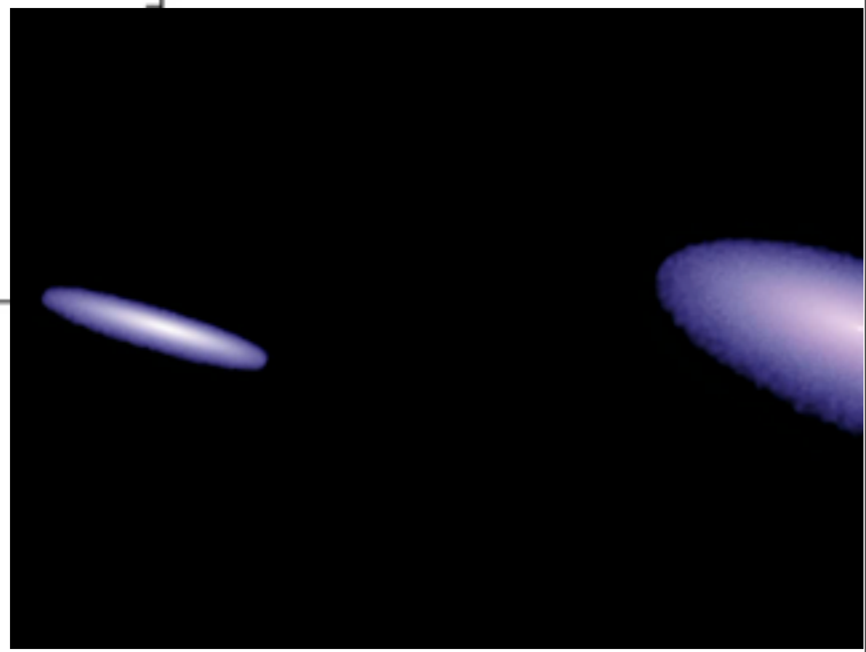

T = 0 Myr
Gas

M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



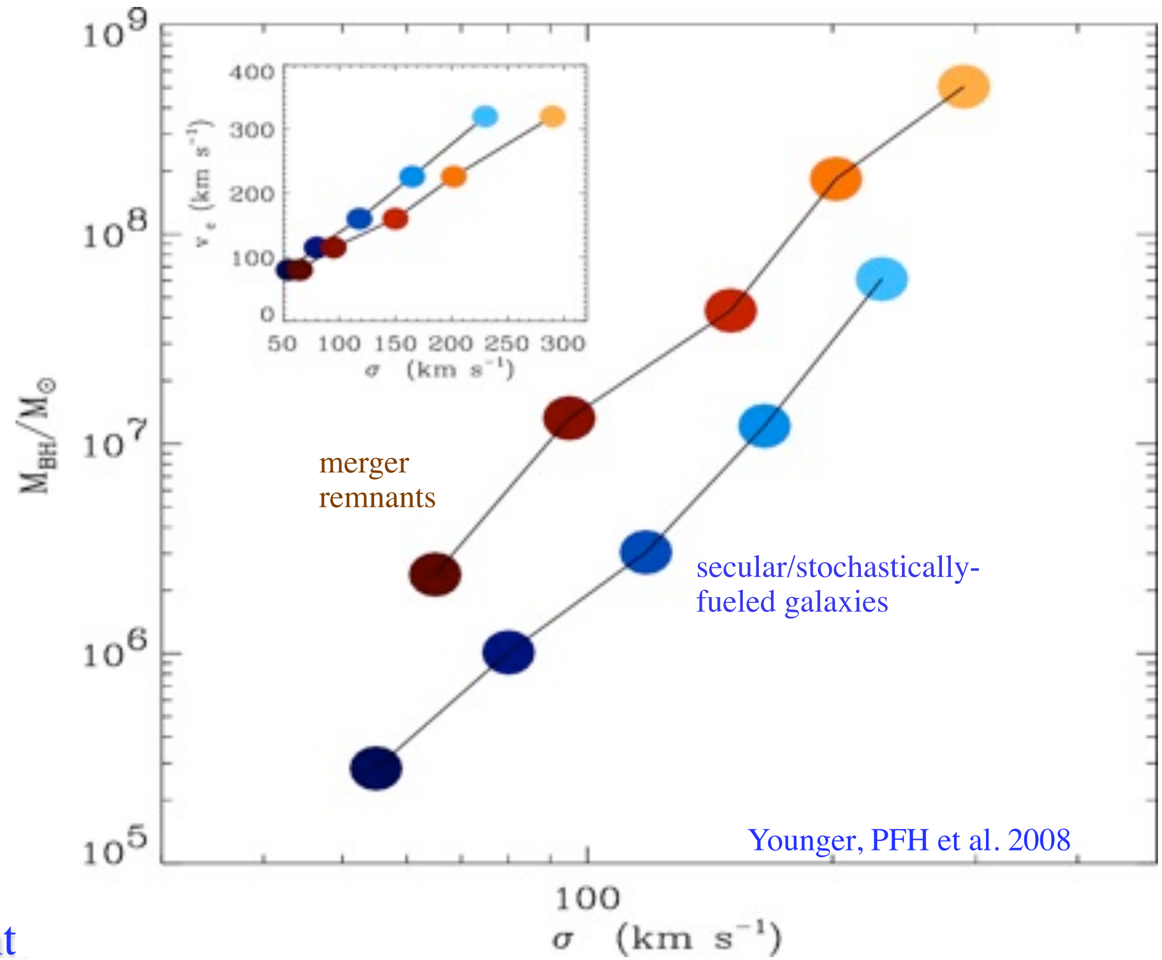




Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- What is the "fundamental" correlation? M_{BH}-$E_{binding}$: BH "fundamental plane" (PFH et al.)
- Different correlation for "classical" and "pseudobulges"
- Both tentatively observed (Aller & Richstone; Greene et al.; Hu; Gadotti et al.)

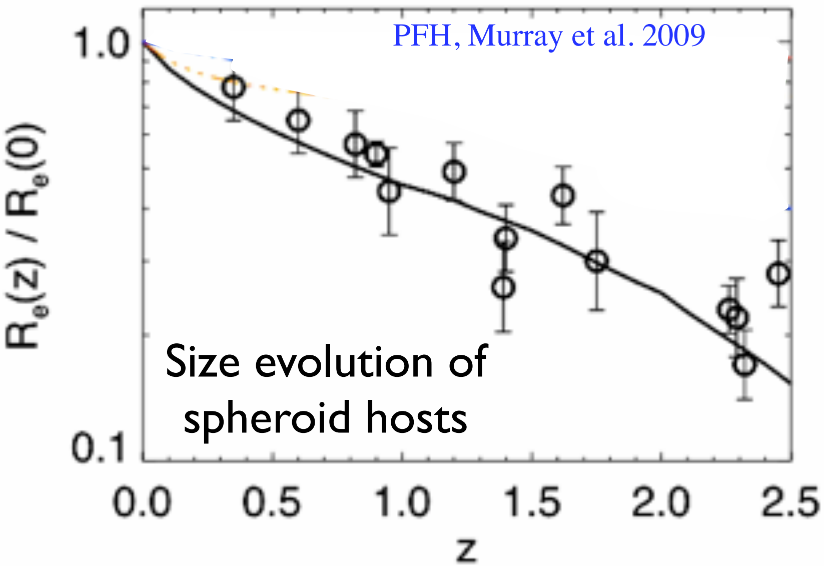


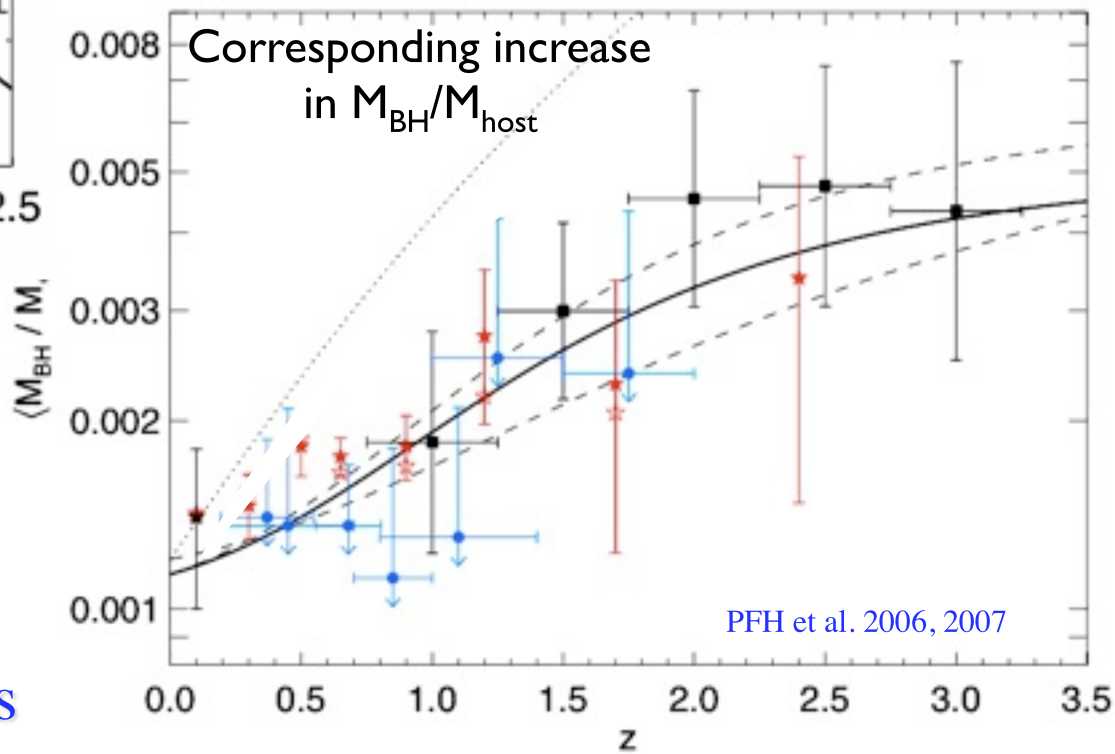
- Basic argument
  - BH feedback self-regulates growth in ~fixed potential

Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- Predict some M-sigma evolution:
  - Hosts more gas rich/compact at high-z ➔ more "work" for the BH before self-regulation



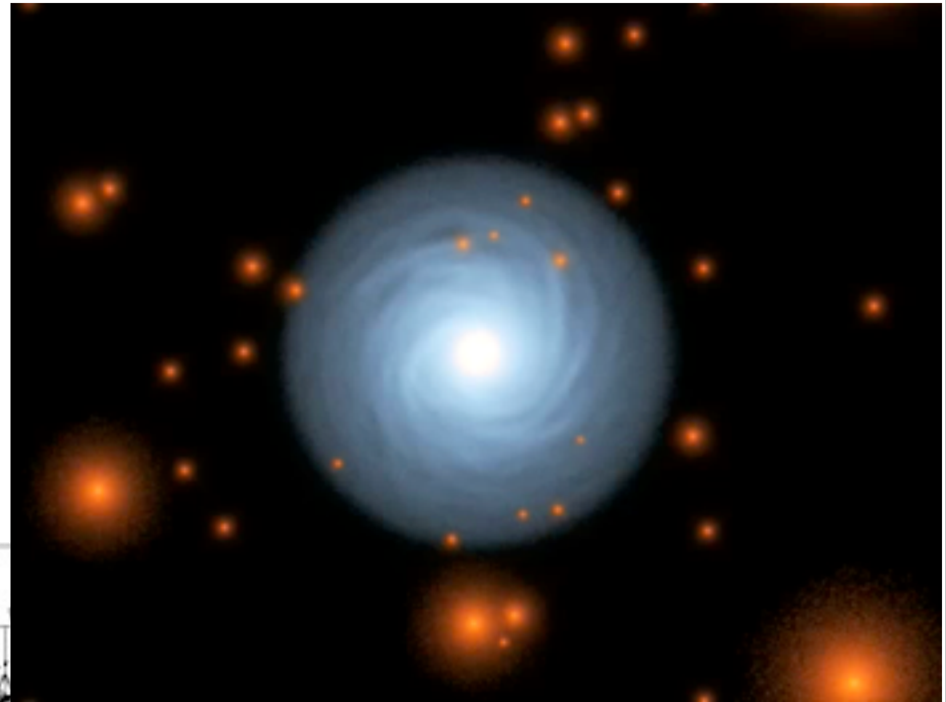


- Doesn't mean that BHs grew "before" their bulges

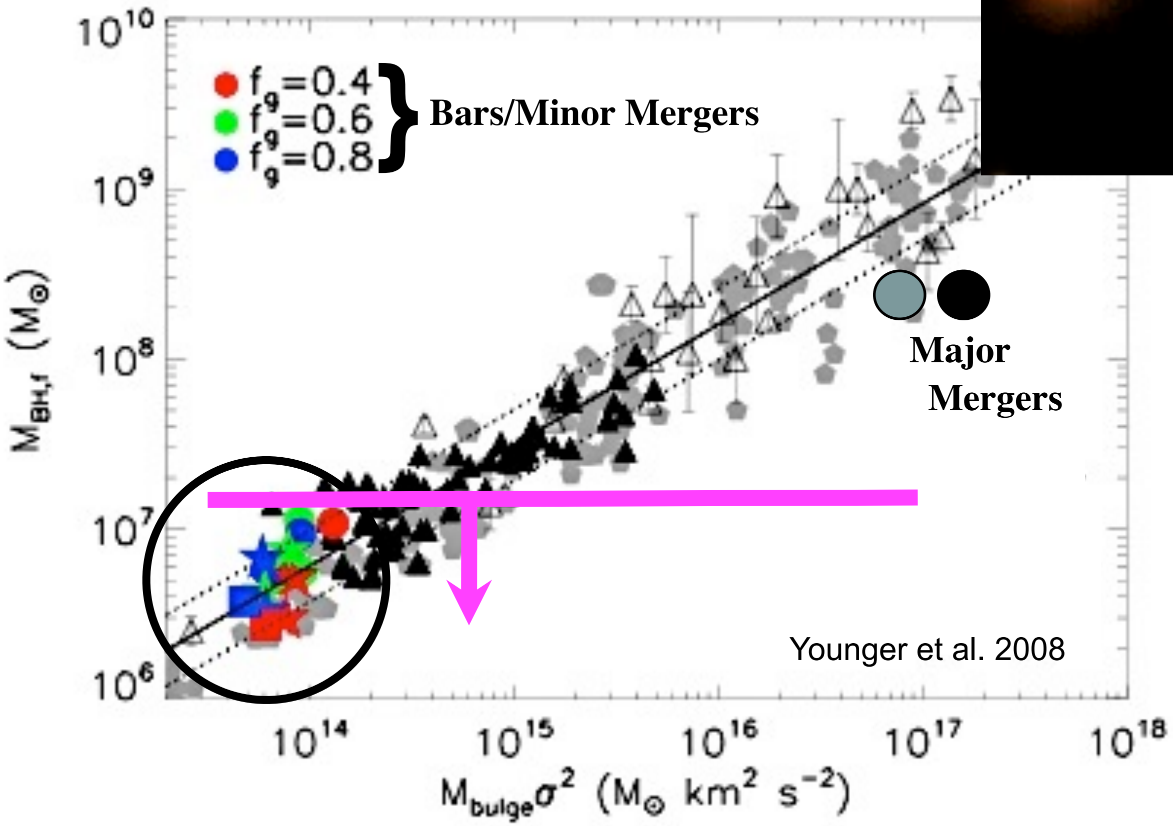
Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

- Seyfert: only $10^{7\text{-}8}$ M_{sun} ~ GMC
- Minor mergers?
- Secular instabilities/bars?



Dubinski

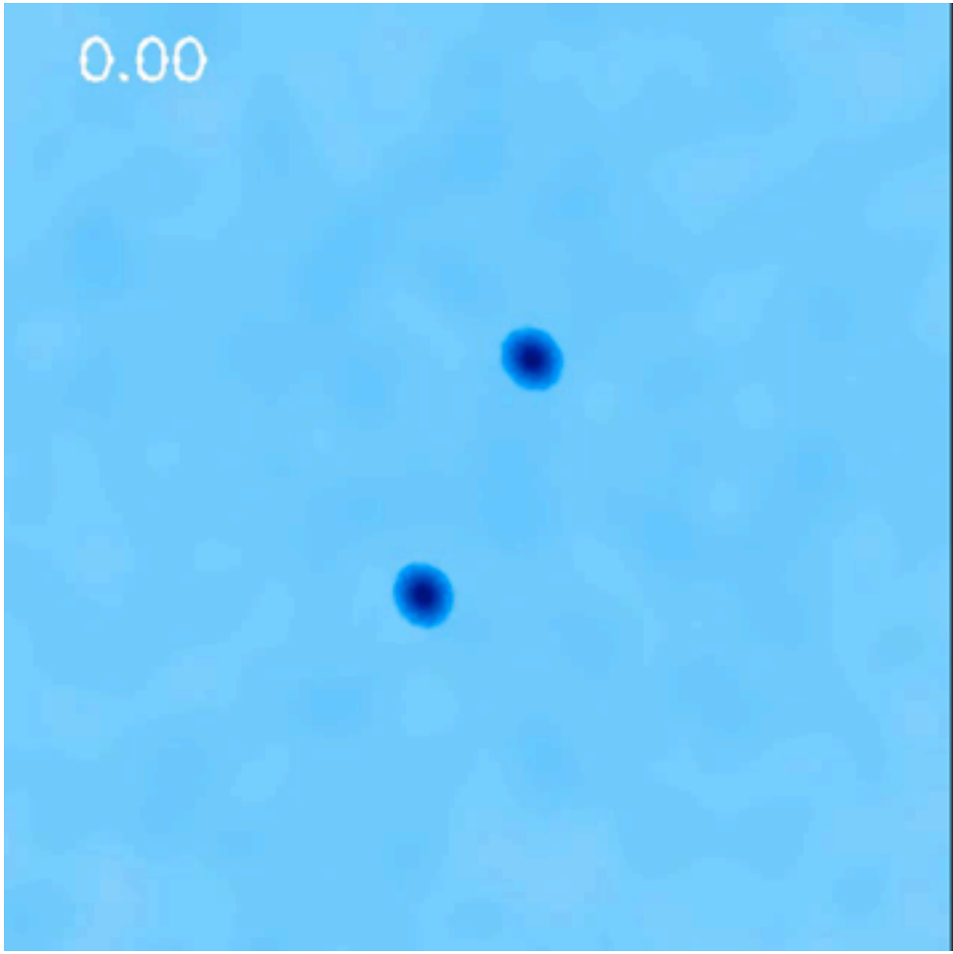


- If you don't build massive bulges, getting gas in *is not enough*!

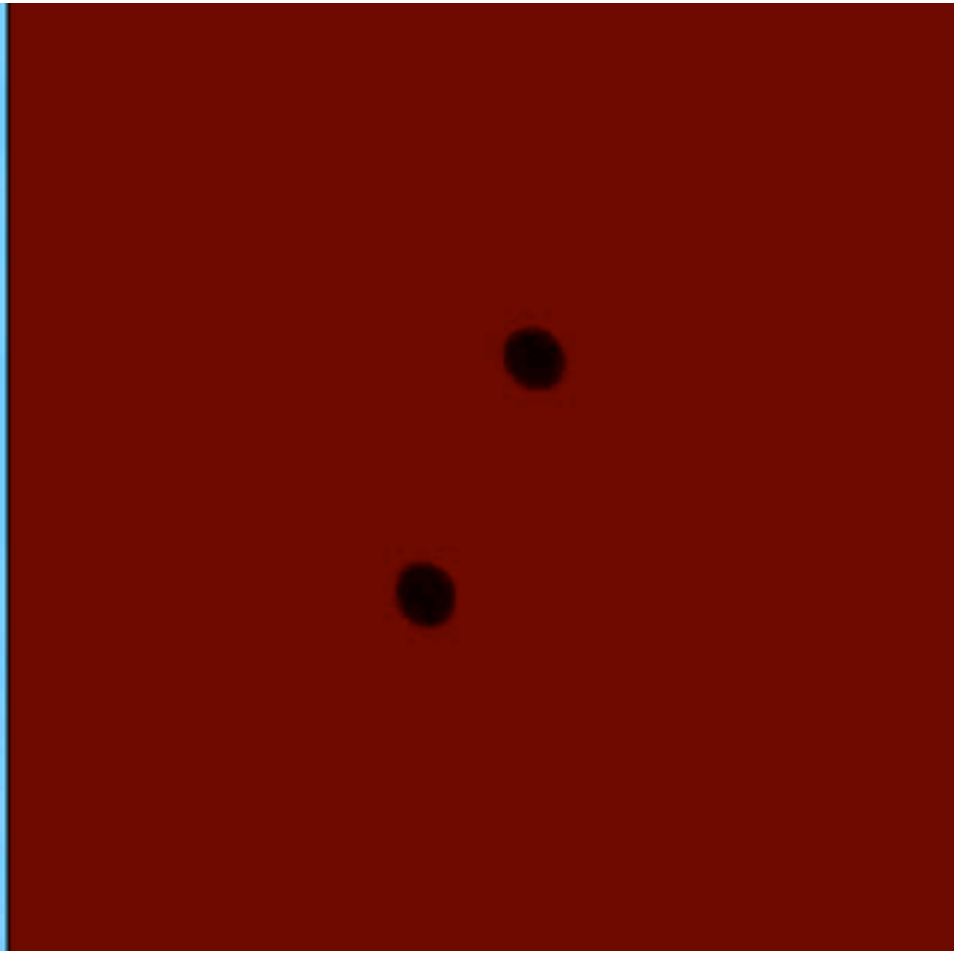
Quasar Outflows May Be Significant for the ICM & IGM

SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?

Gas Density



Gas Temperature



Why Not Just Couple the Momentum Directly?

EXPERIMENTS WITH RADIATION PRESSURE

Dust in host absorbs radiation

$$F_{\rm rad} = \tau\,\frac{L}{c}$$

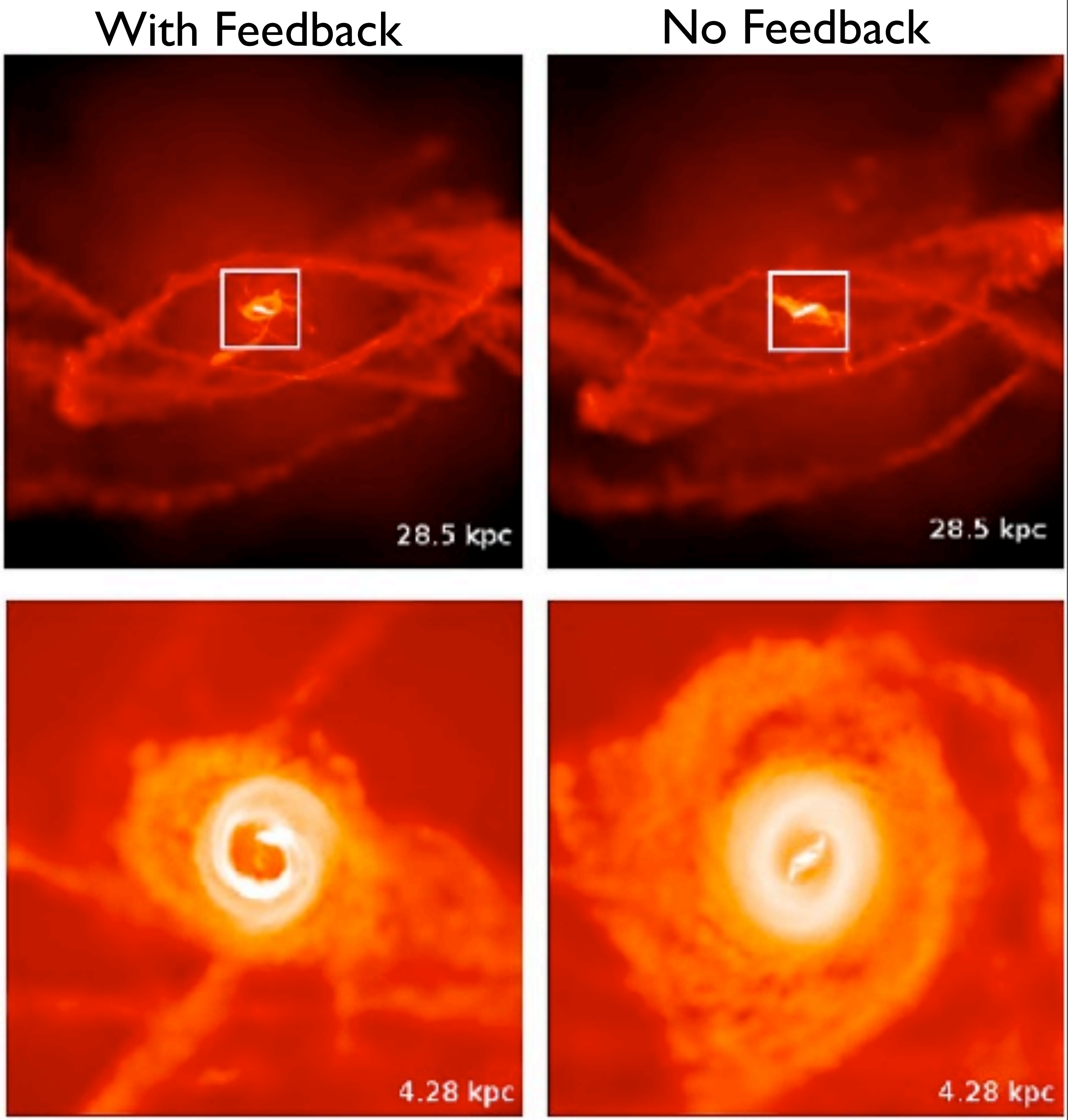
Set equal to $F_{\rm gravity}$, get a galaxy-scale Eddington limit:

$$L_{\rm max} \sim \frac{4\,f_{\rm gas}\,\sigma^4\,c}{G}$$

But..........

- BH growth self-regulates on ~kpc scales, but with no galaxy scale “blowout”!

- Different feedback mechanisms may do *very* different things to the host galaxy!



"Transition" vs. "Maintenance"

- Move mass from Blue to Red
- Rapid
- Small scales
- "Quasar" mode (high mdot)
- Morphological Transformation

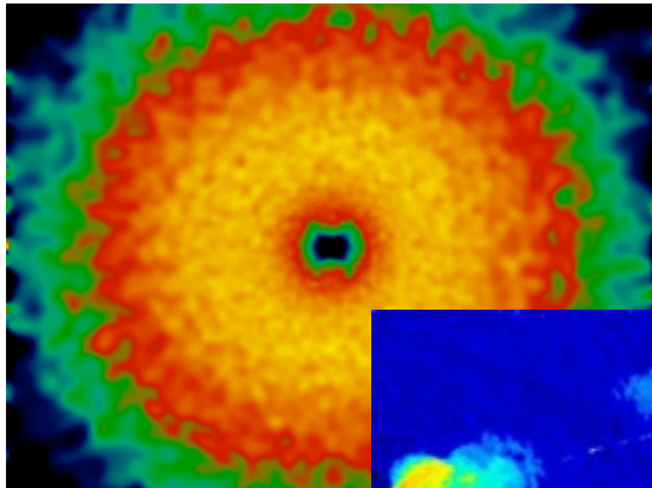
Proga et al.

dt ~ 10^6 yr

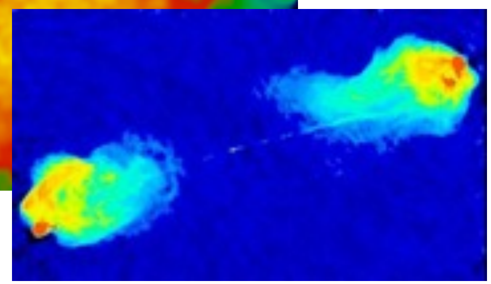
- Regulates Black Hole Mass

- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- "Radio" mode (low mdot)
- Subtle morphological change

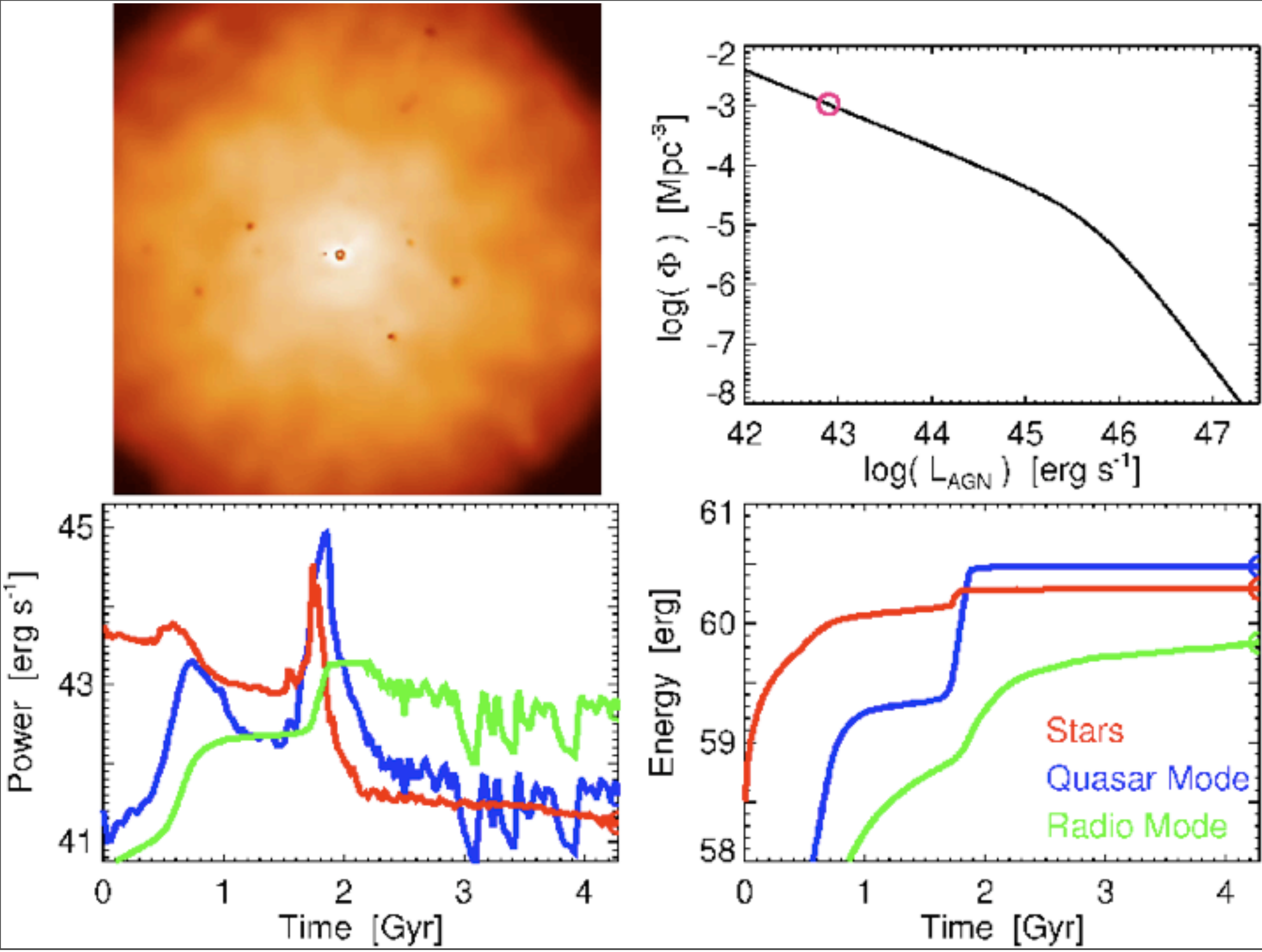
dt ~ 10^{10} yr

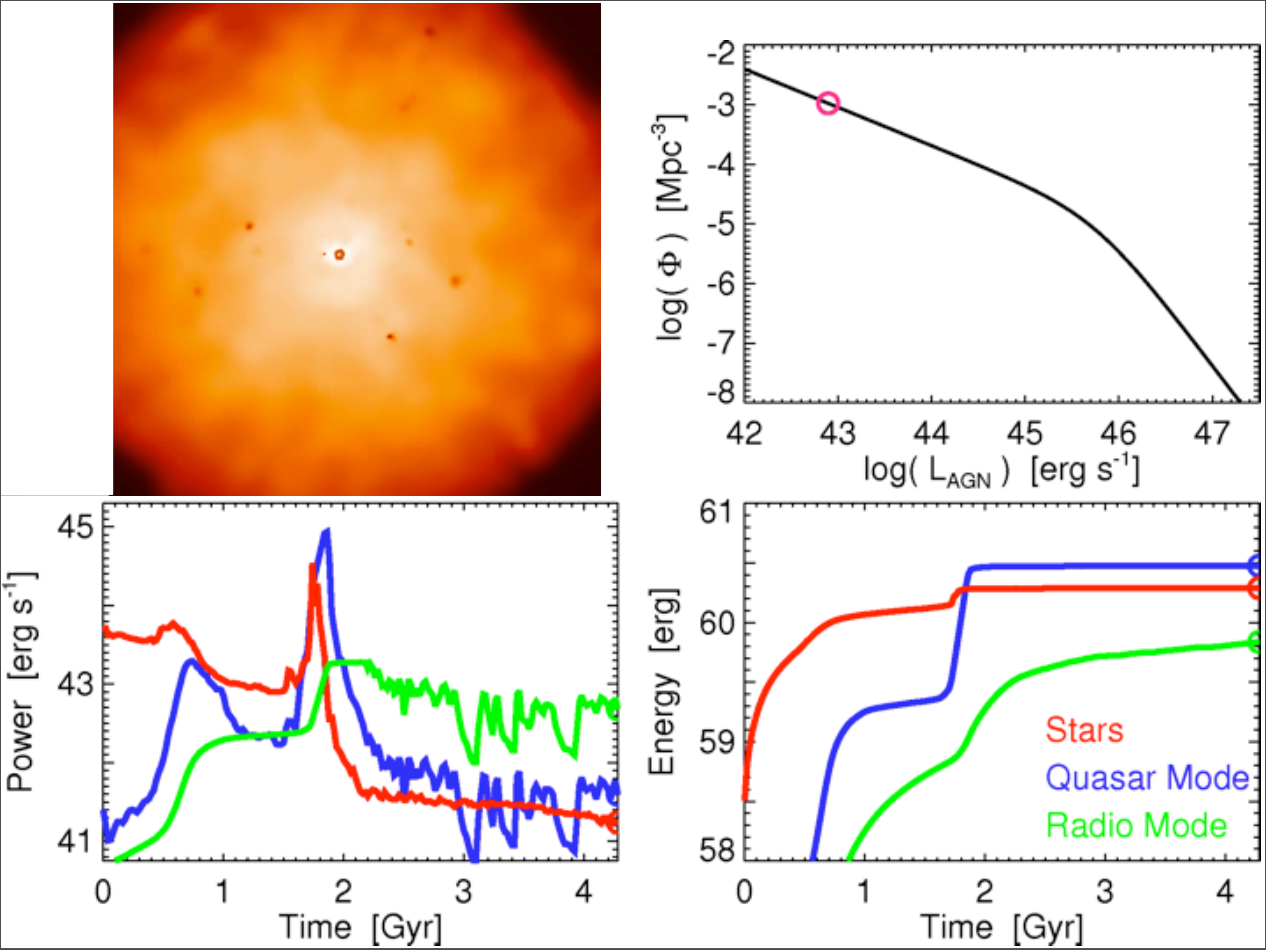


Sijacki et al.



- Regulates Galaxy Mass


log(Φ) [Mpc-3]
log(LAGN) [erg s-1]
-2 -3 -4 -5 -6 -7 -8
42 43 44 45 46 47
Power [erg s-1]
45 43 41
Time [Gyr]
0 1 2 3 4
Energy [erg]
61 60 59 58
Time [Gyr]
0 1 2 3 4
Stars
Quasar Mode
Radio Mode



log(Φ) [Mpc^{-3}]
log(L_{AGN}) [erg s^{-1}]
Power [erg s^{-1}]
Time [Gyr]
Energy [erg]
Stars
Quasar Mode
Radio Mode

Summary

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

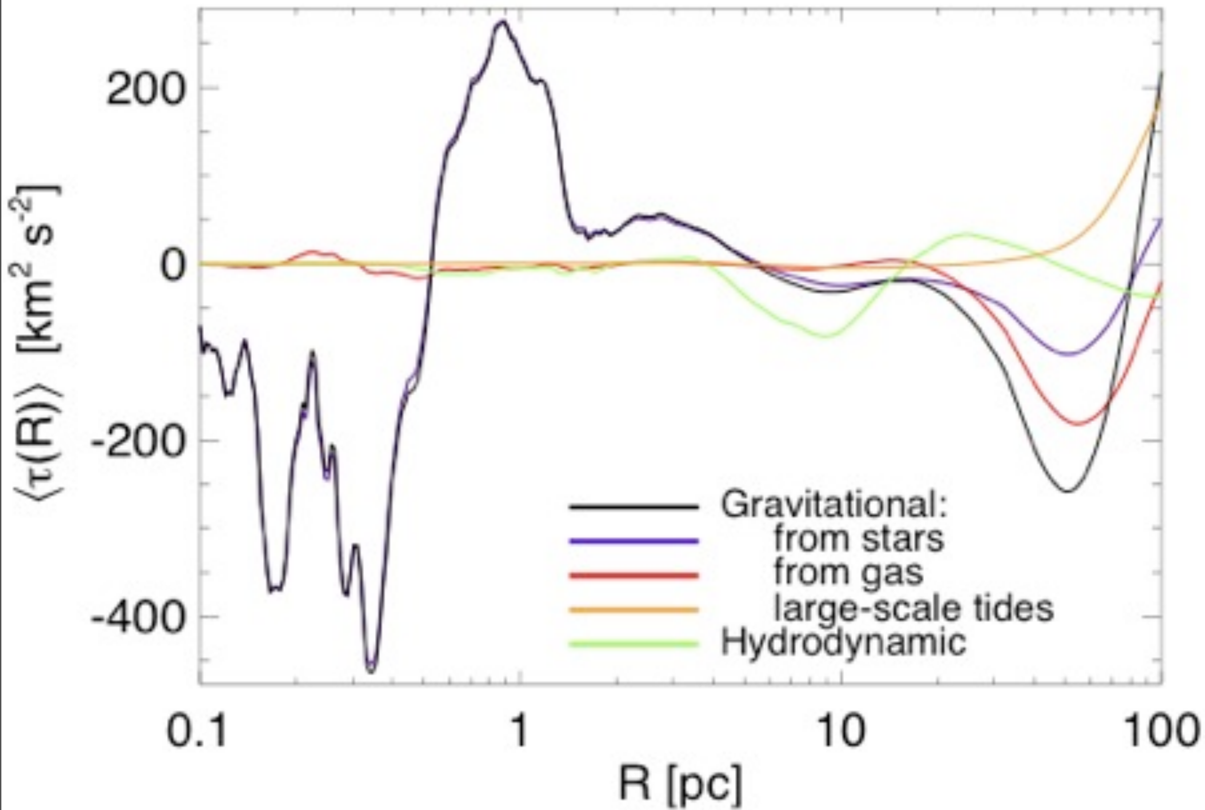
- "Stuff within Stuff": Cascade of instabilities with diverse morphology
    - Doesn't matter how *first* 'get down' from large scales

- Accretion rates & orientations are stochastic
    - Vary on *all* timescales
    - Angular momentum changes rapidly - no correlation with host disk

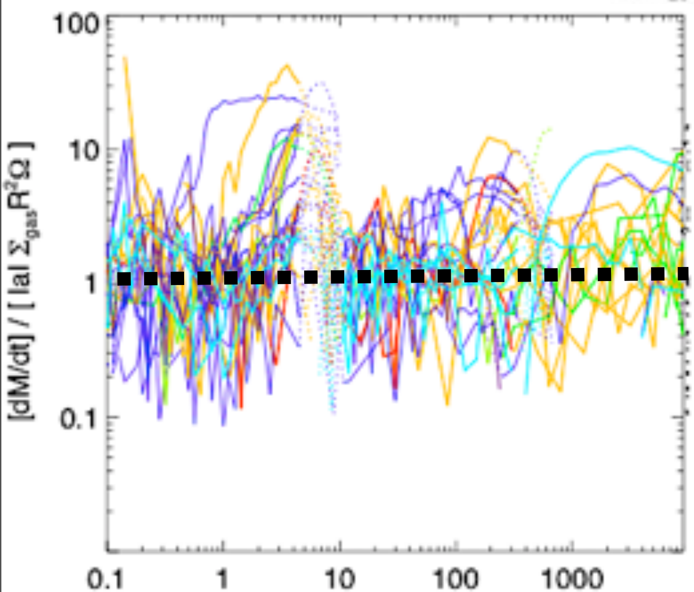
- The torus is the disk: a dynamical accretion driver
    - Bending/warping instabilities: thick even without stellar feedback

- Stellar nuclear disk 'relics': M31 & 4486b:
  Can we directly observe the 'fossil' of the accretion driver & torus ?

- M_{BH} traces spheroid $E_{binding}$: *self-regulated* BH growth
    - Global 'integral-quantity' prescriptions non-unique
    - BH 'fundamental plane': depth of potential, not just M* or sigma
      - differences with redshift & bulge type

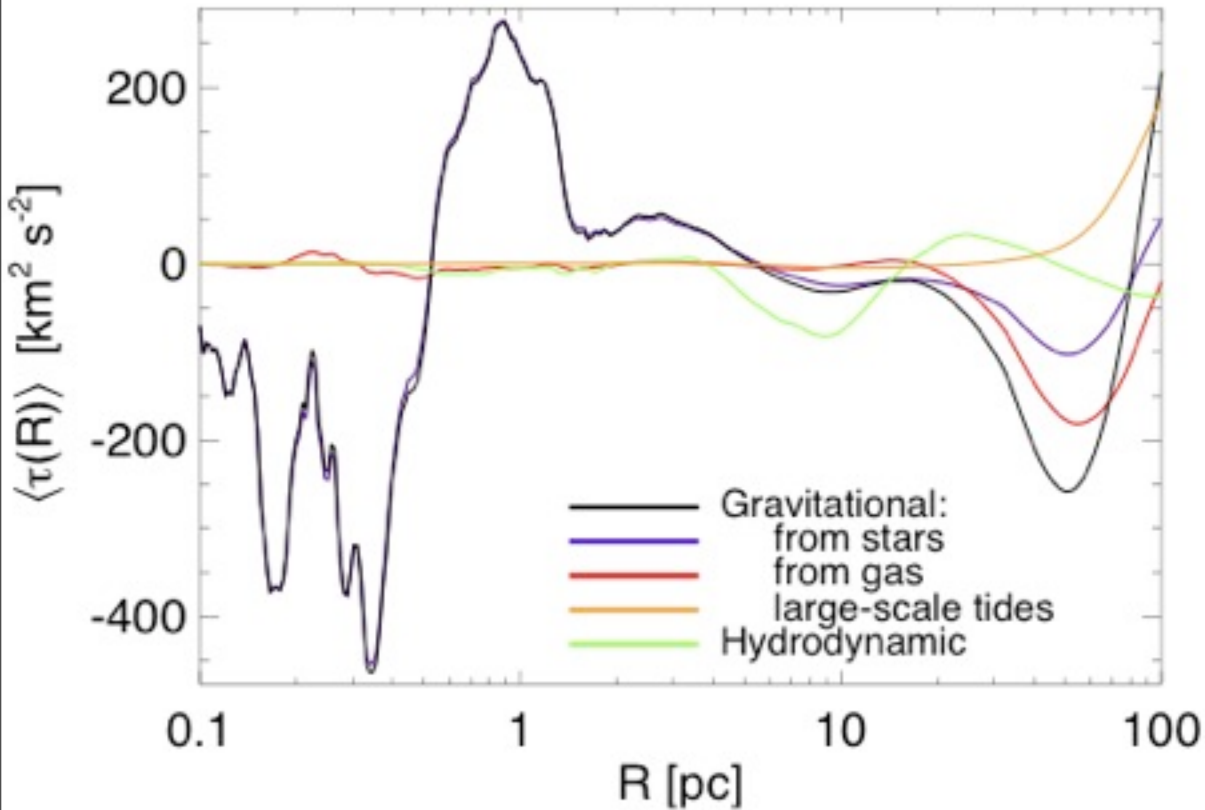


- Gravity dominates all the way down to <0.1 pc



Compare true inflow rate vs gravitational torque:

$$\dot{M}_{grav} \sim |a_m|\,\Sigma_{\rm gas}\,R^2\,\Omega$$



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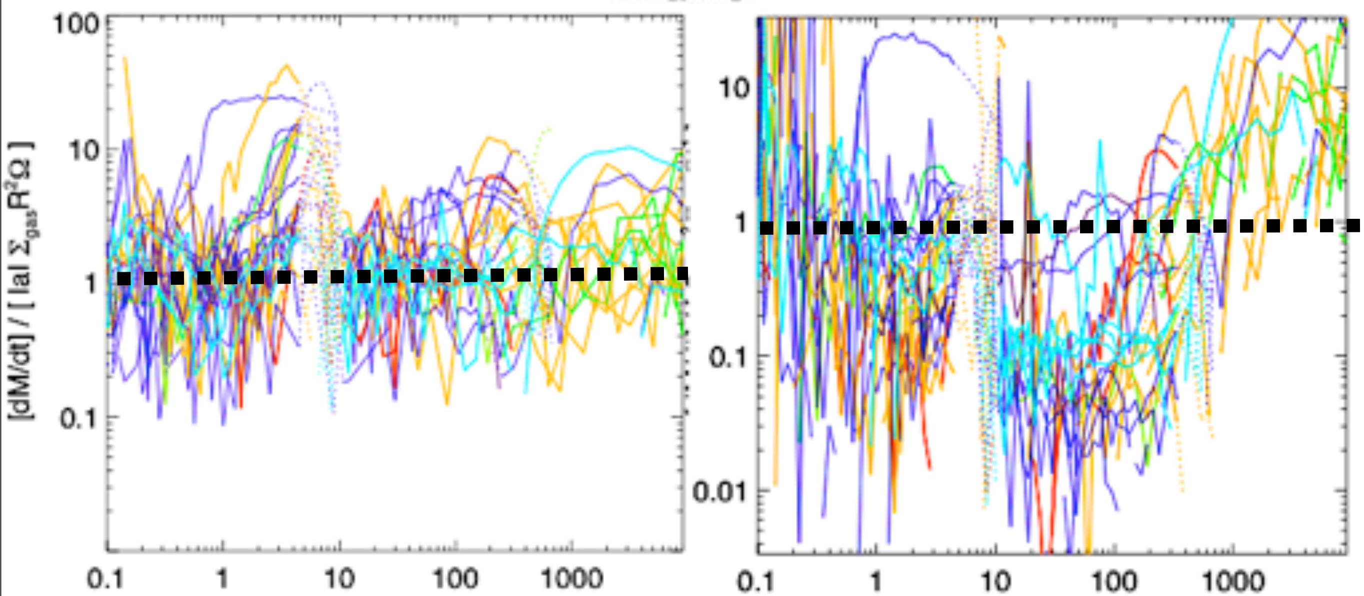
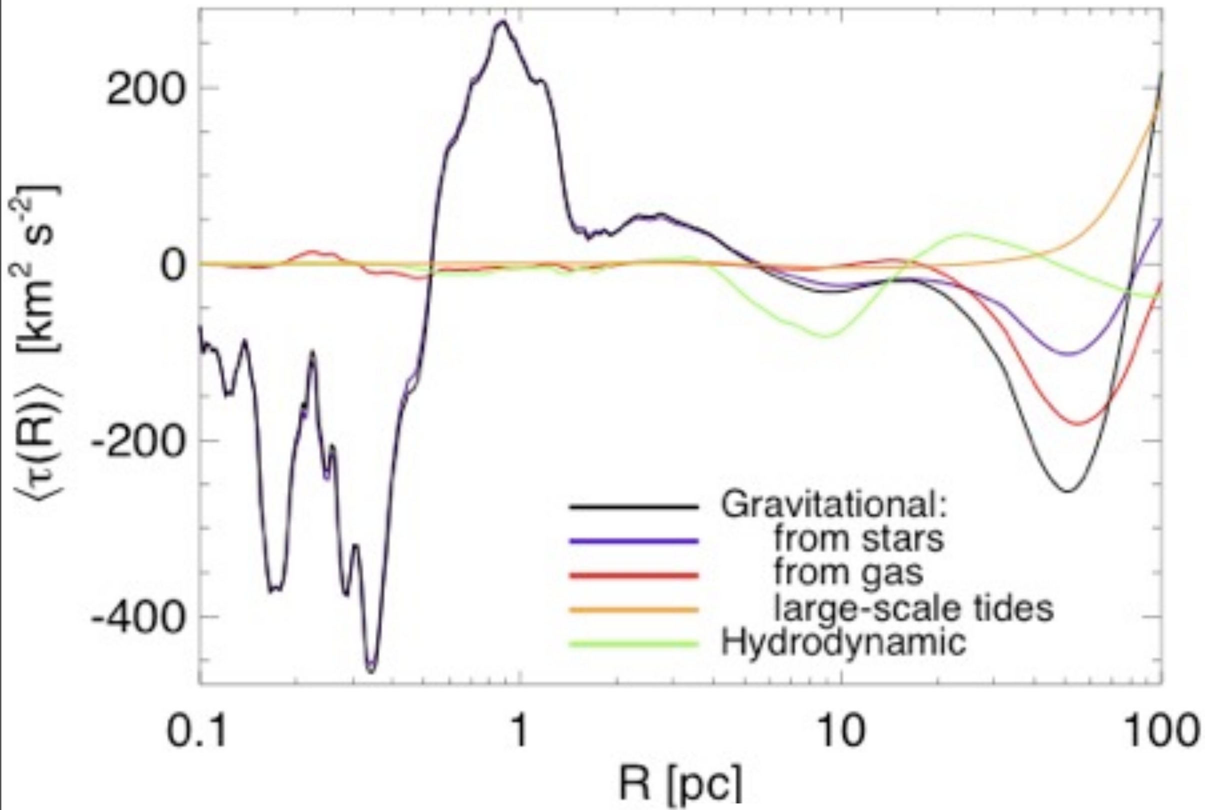


vs viscous torques?

$$\dot{M}_{\rm visc} \sim 3\pi\alpha\, c_s^2\, \Sigma_{\rm gas}\, \Omega^{-1}$$



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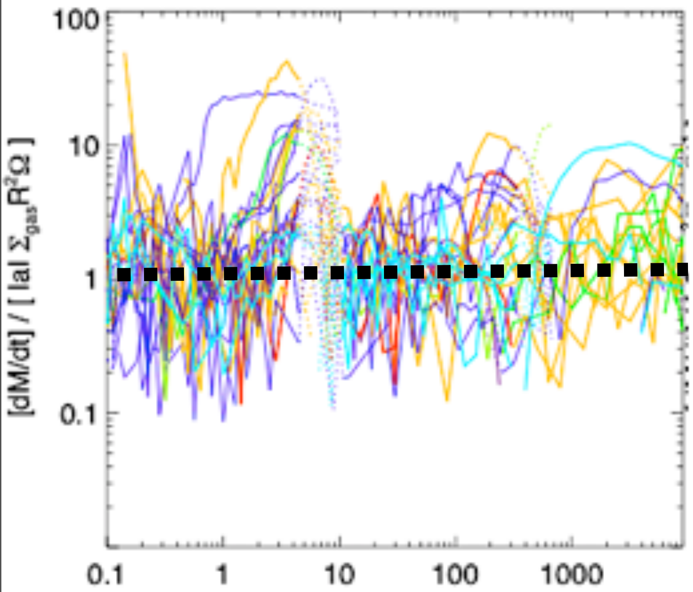
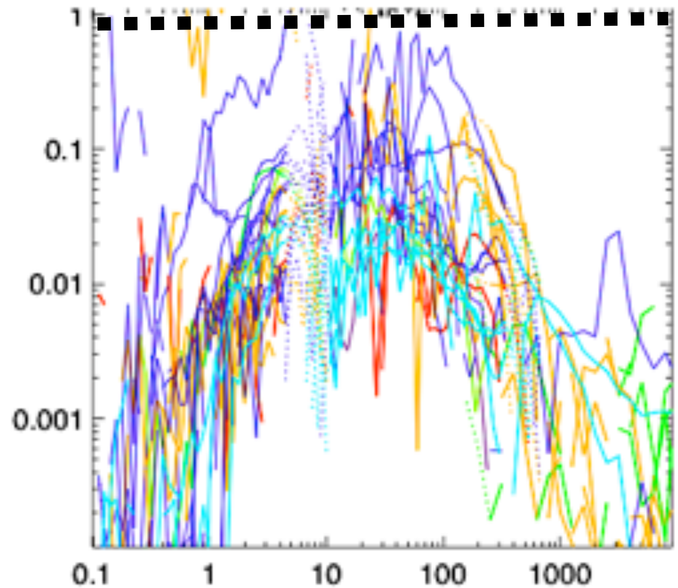


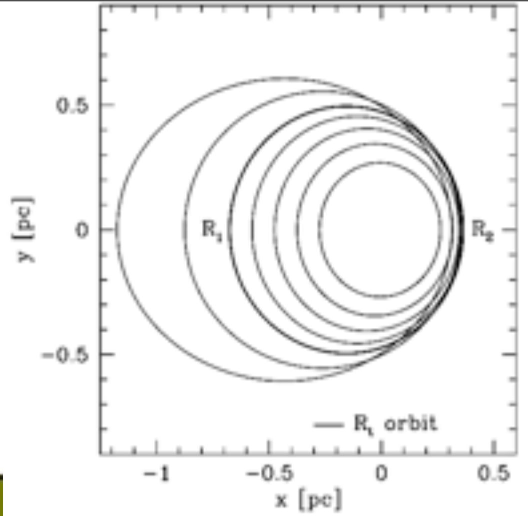


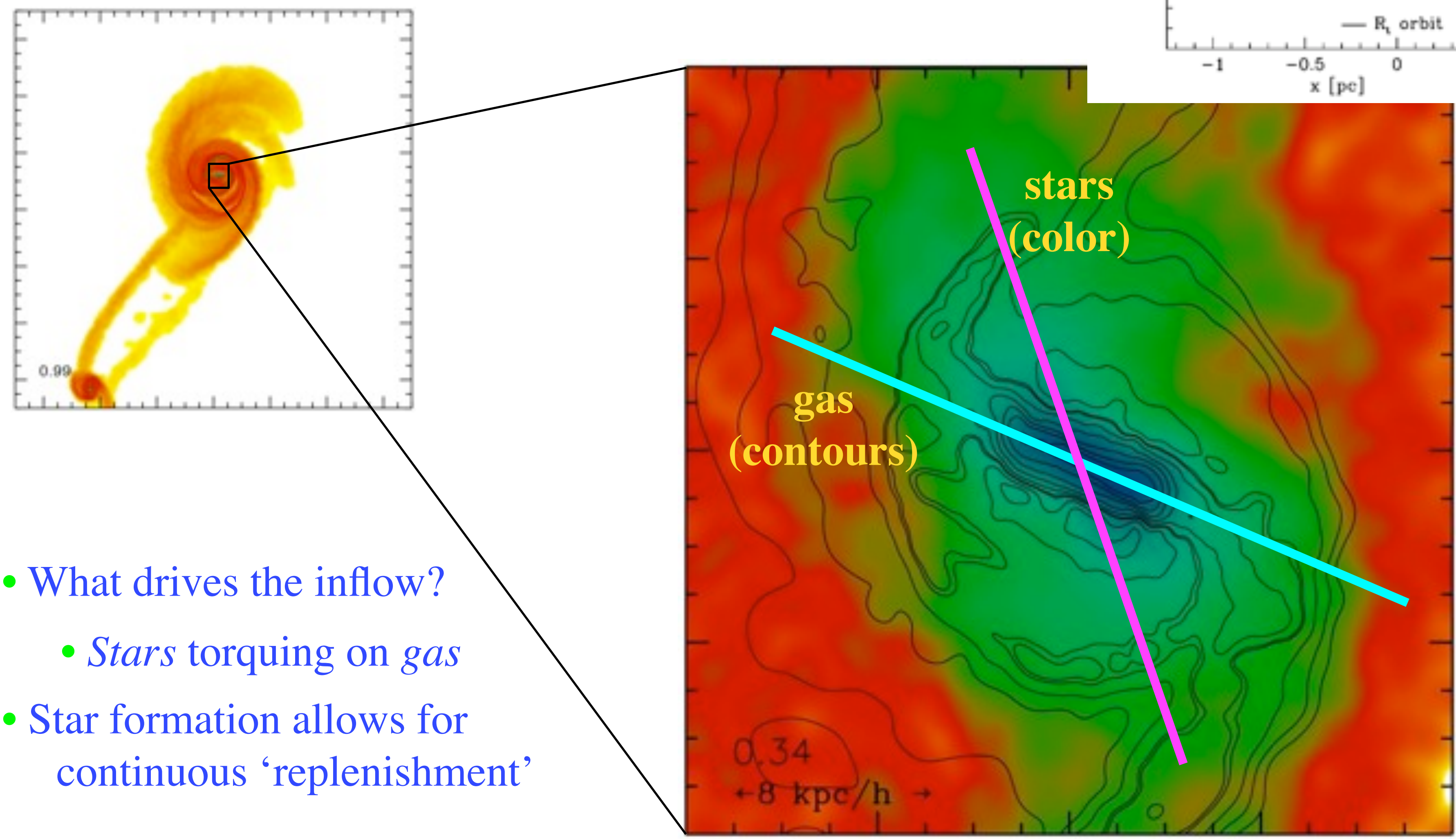
vs Bondi?

$$\dot{M}_{\rm Bondi} \sim 4\pi G^2 M_{\rm enc}^2 \rho\, c_s^{-3}$$

How does this work?

Example: Stars in eccentric disk drive gas to crossing orbits -- shocks -- dissipation -- inflow (e.g. Barnes & Hernquist 96, Hopkins et al. 09)

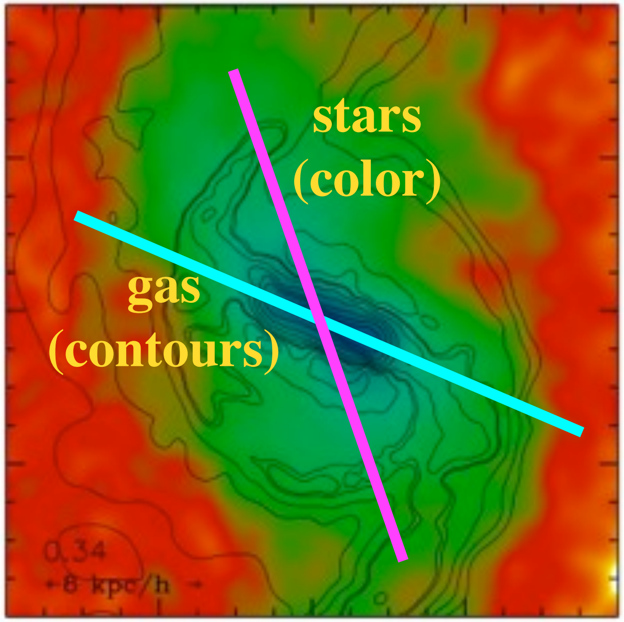




- What drives the inflow?
  - *Stars* torquing on *gas*
- Star formation allows for continuous 'replenishment'

How does this work?

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



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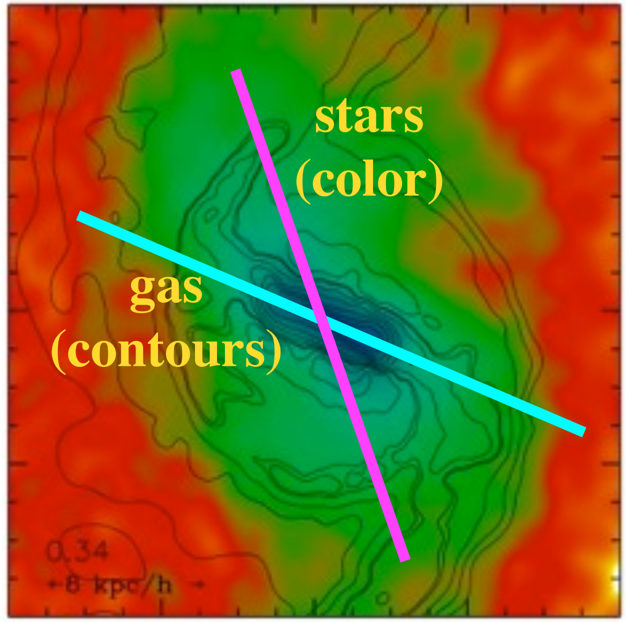

standard (dissipationless) formulation: spiral waves carry the angular momentum: (Lynden-Bell & Kalnajs '72)

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

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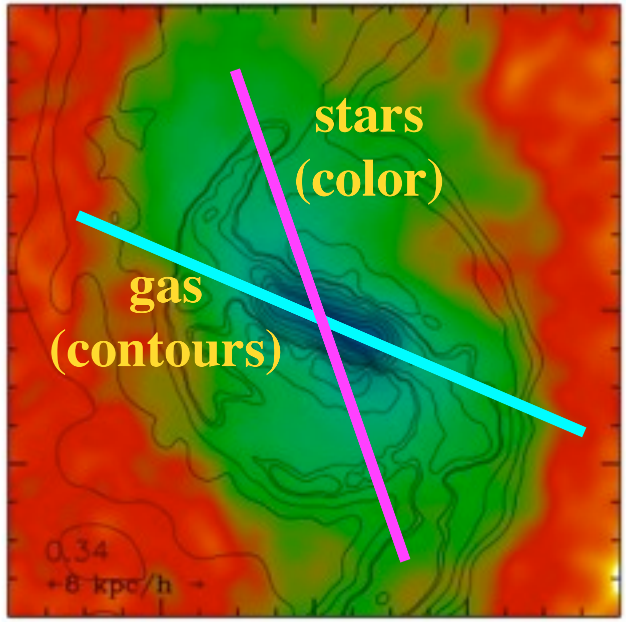

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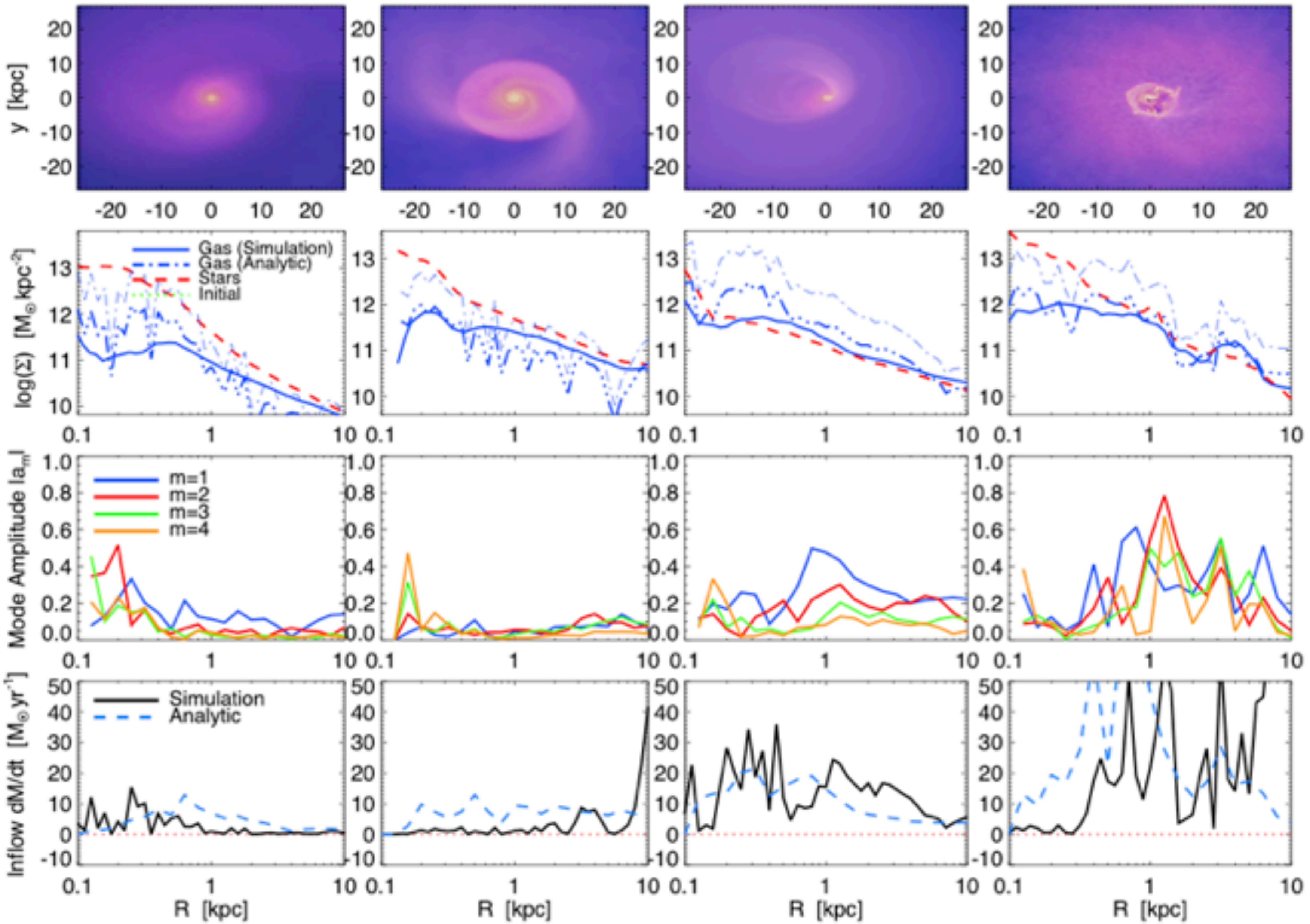
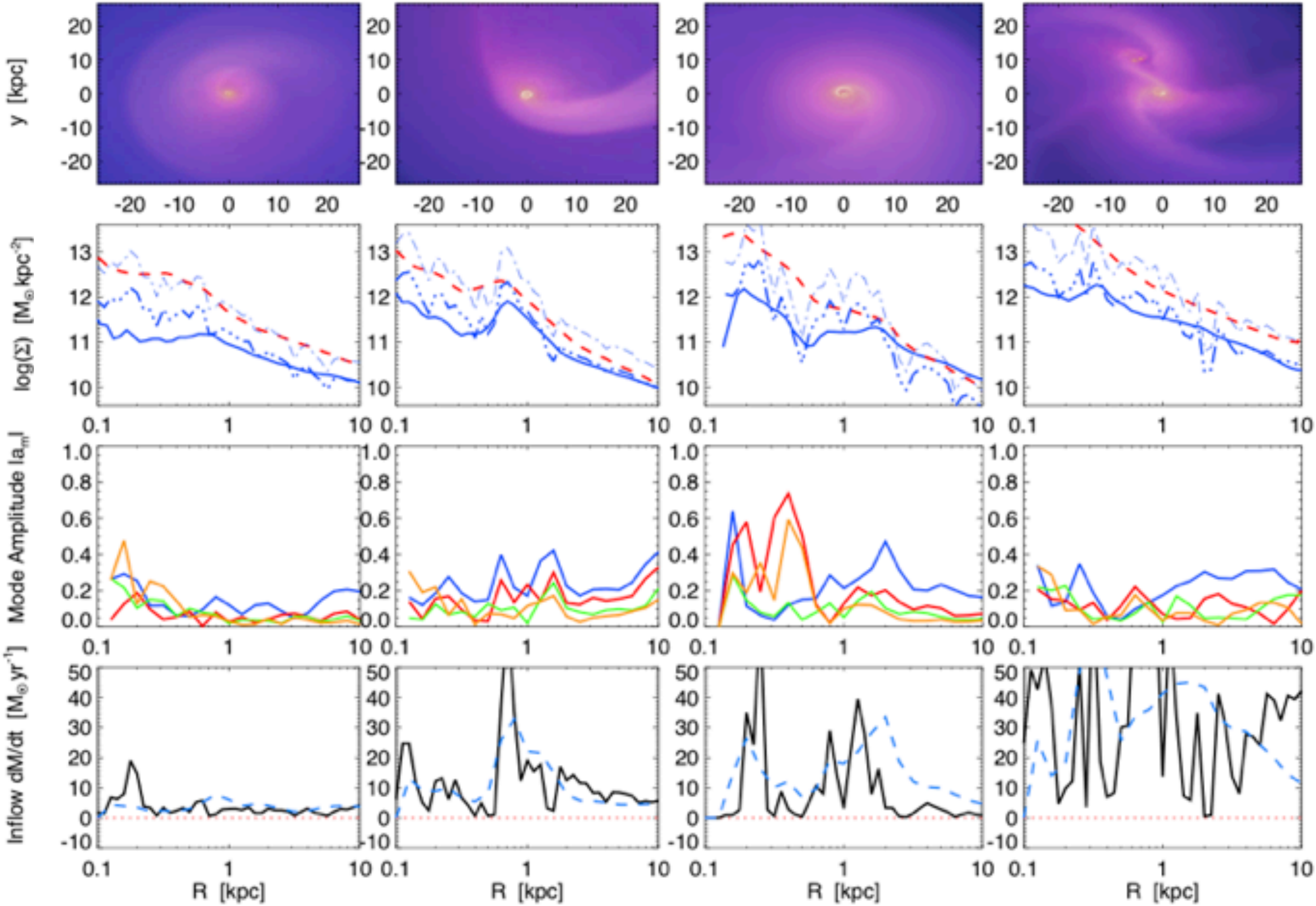
with shocks & dissipation:

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

Typically >100x larger!!!


y [kpc]
log(Σ) [M☉ kpc⁻²]
Gas (Simulation)
Gas (Analytic)
Stars
Initial
Mode Amplitude |a_m|
m=1
m=2
m=3
m=4
Inflow dM/dt [M☉ yr⁻¹]
Simulation
Analytic
R [kpc]



y [kpc]
log(Σ) [$M_\odot$ kpc^{-2}]
Mode Amplitude $|a_m|$
Inflow dM/dt [$M_\odot$ yr^{-1}]
R [kpc]

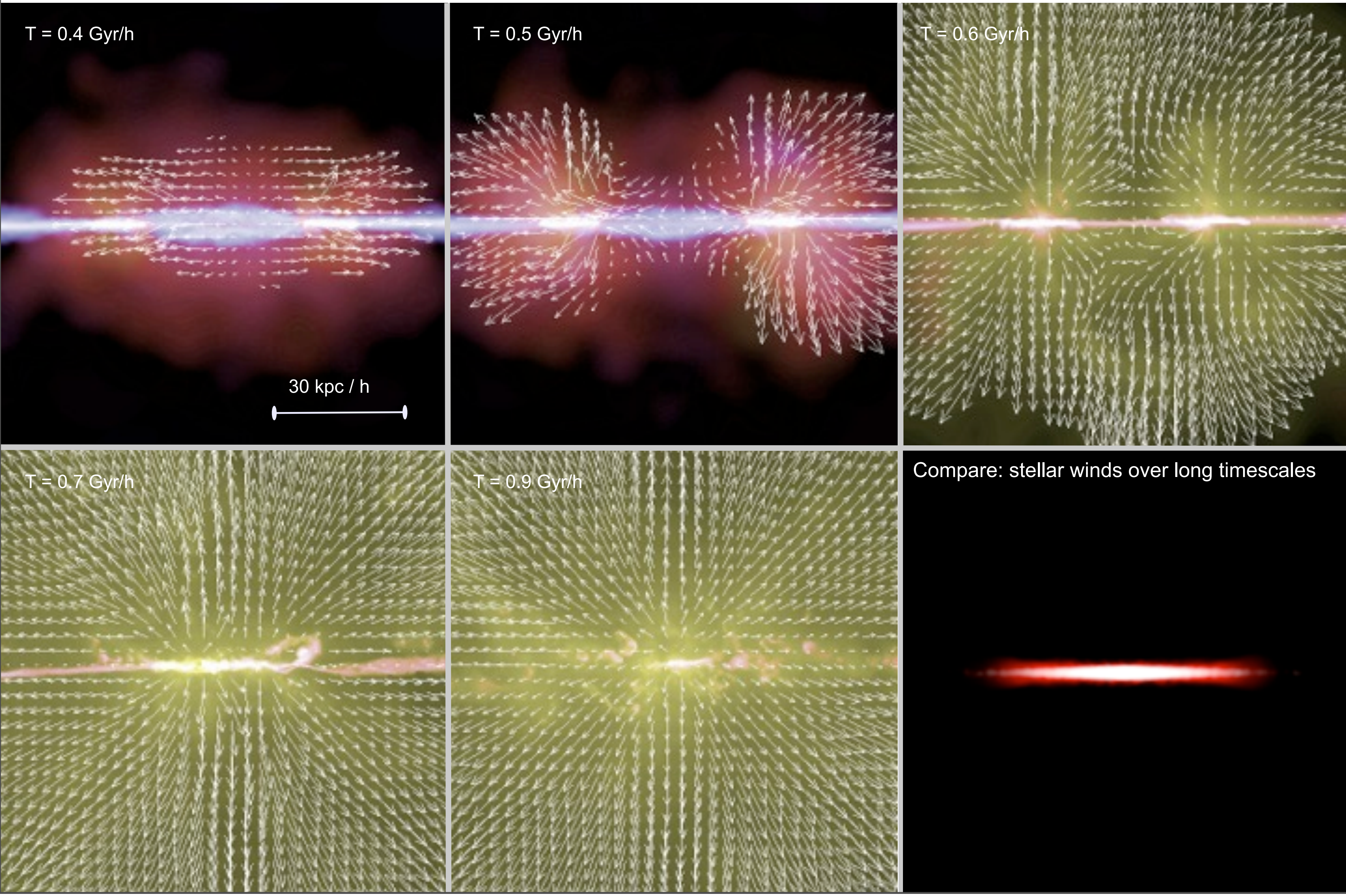
So, what about the small scales near the BH?

Feedback Part 2: What Does This Mean for the Host Galaxy?

Where Does the Energy/Momentum Go?

QUASAR-DRIVEN OUTFLOWS?

(outflow reaches speeds of up to ~1800 km/sec)



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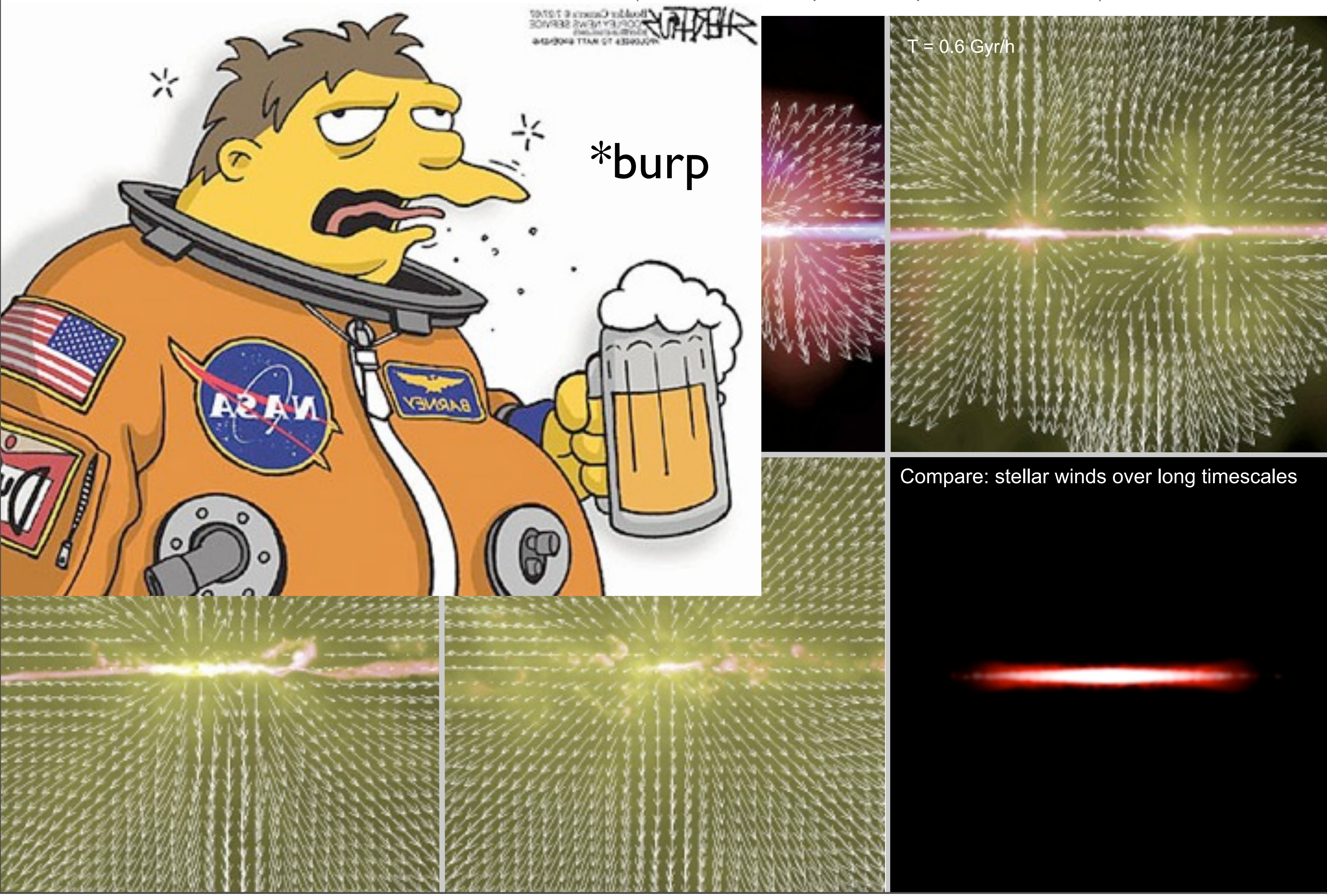

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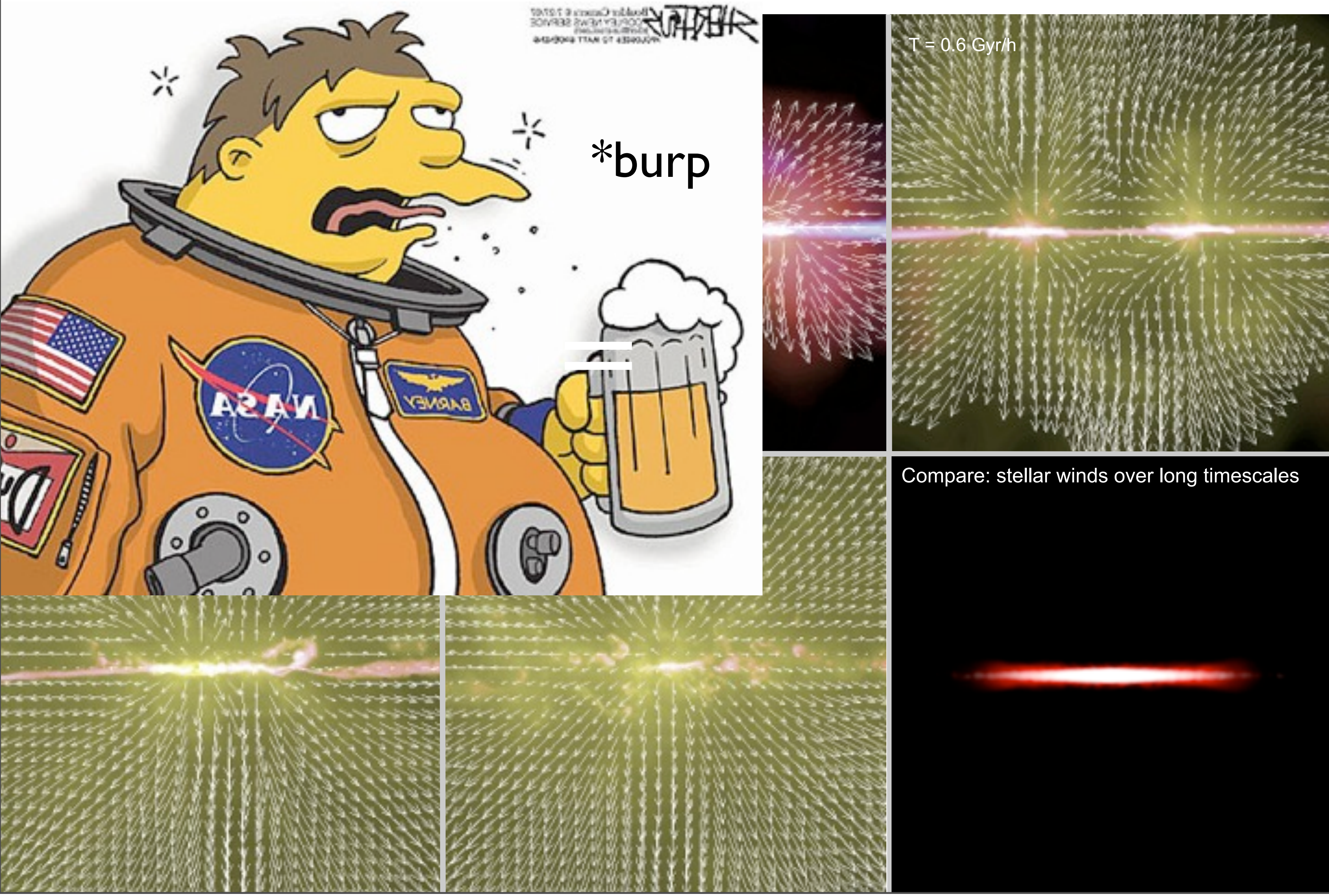

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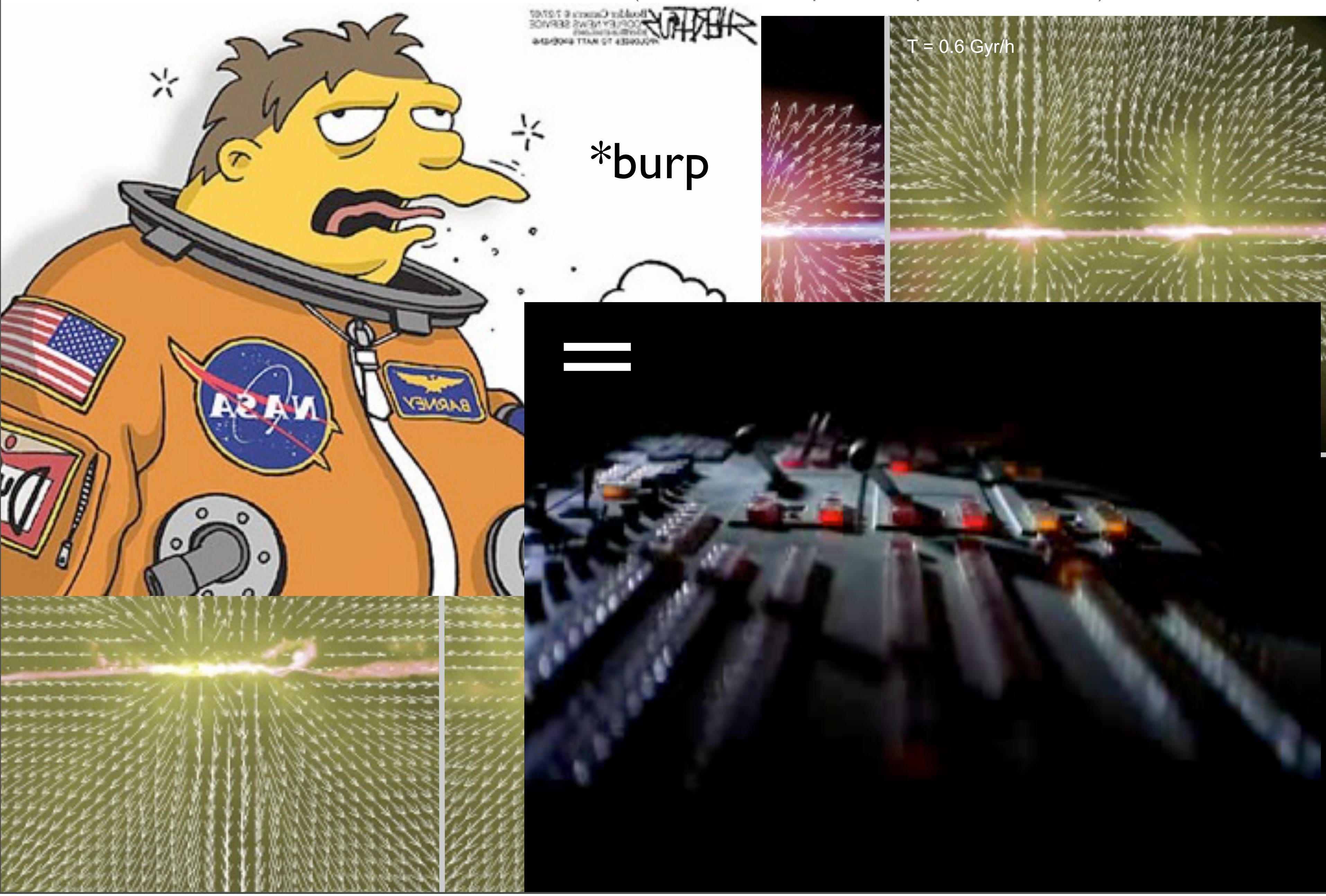
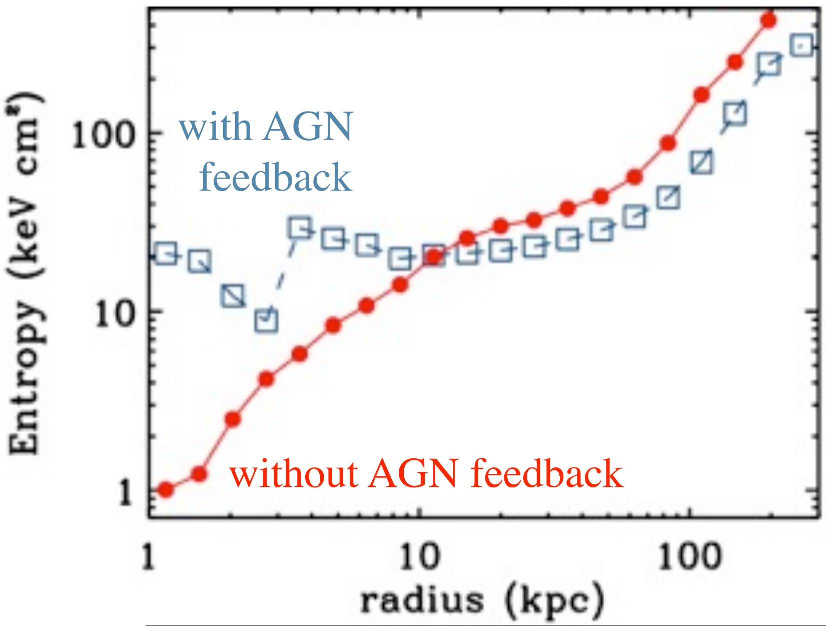
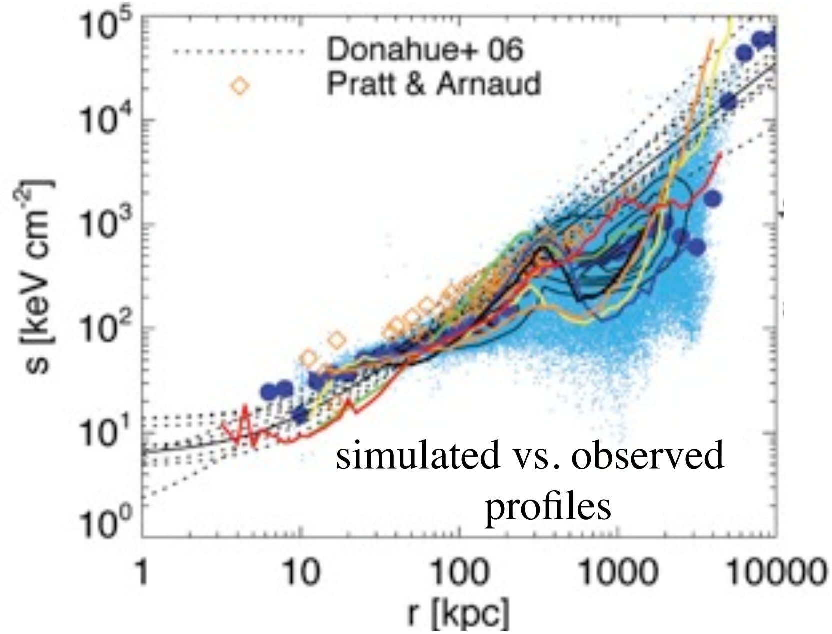
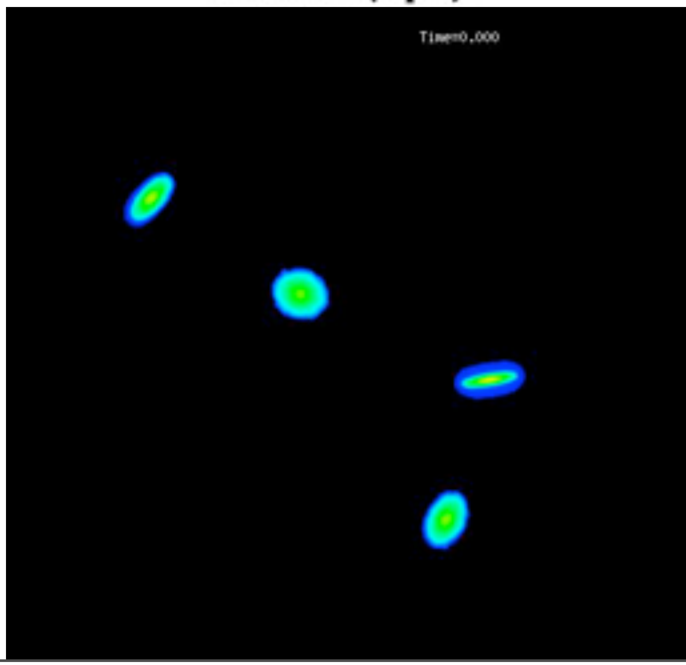


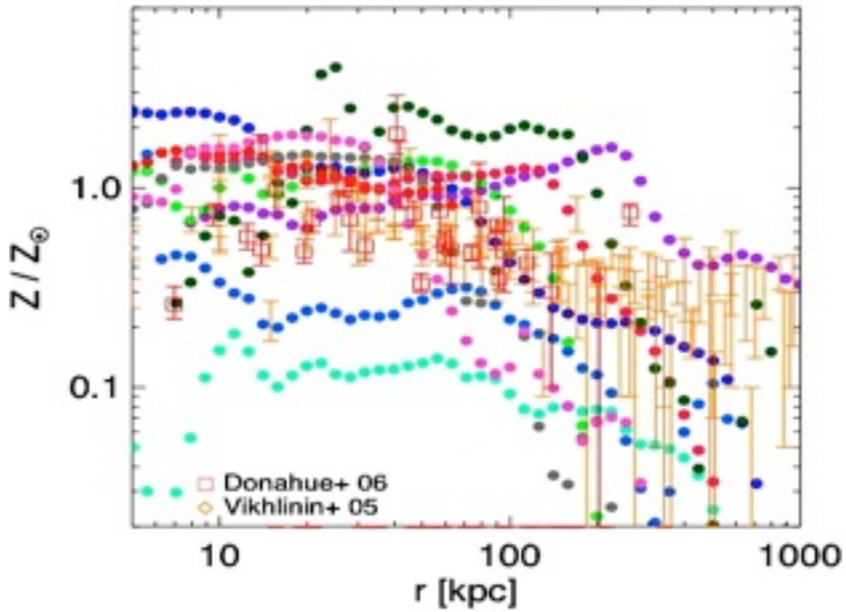
Quasar Outflows May Be Significant for the ICM & IGM

SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



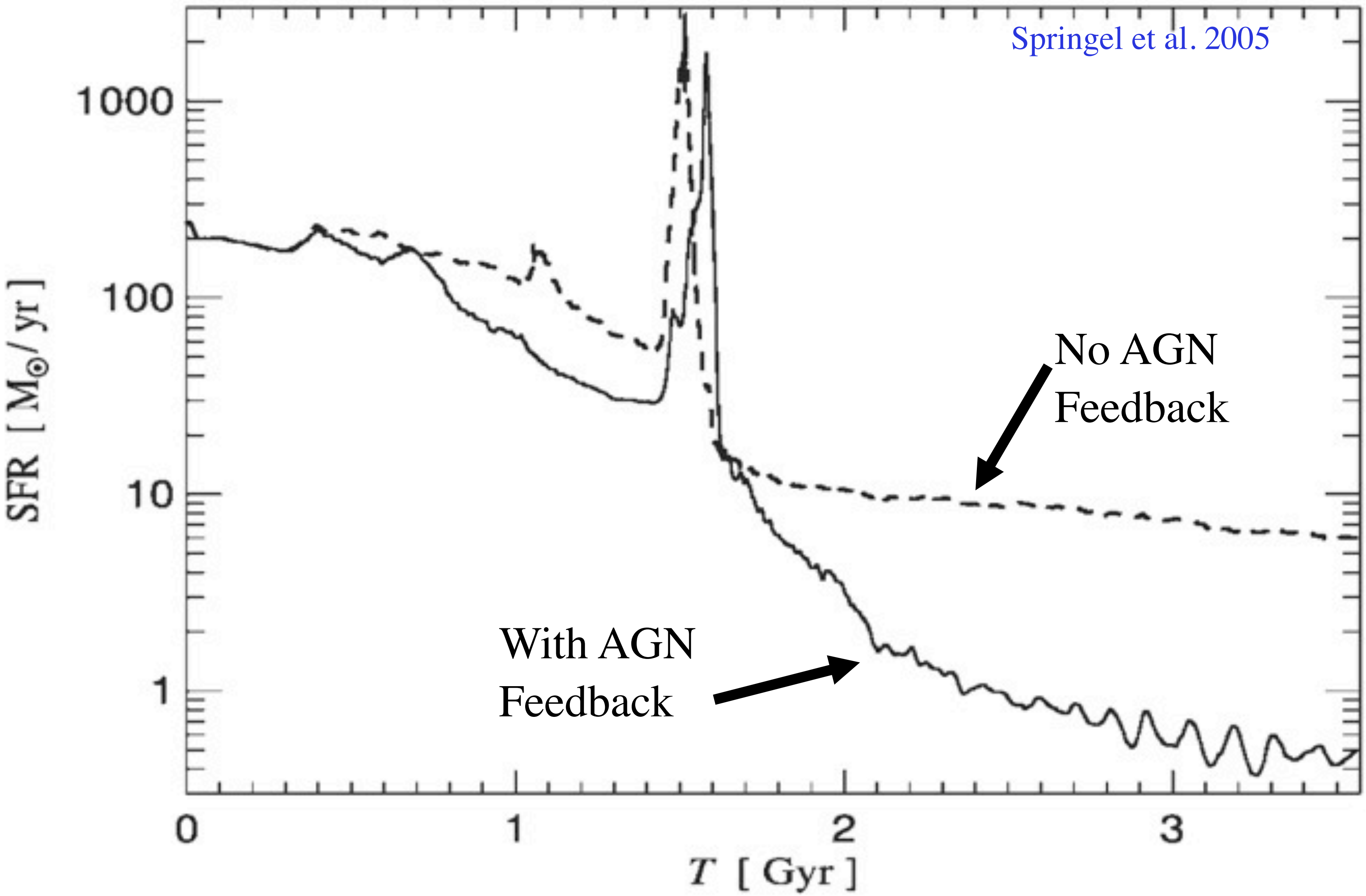






Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



Why Not Just Couple the Momentum Directly?

EXPERIMENTS WITH RADIATION PRESSURE

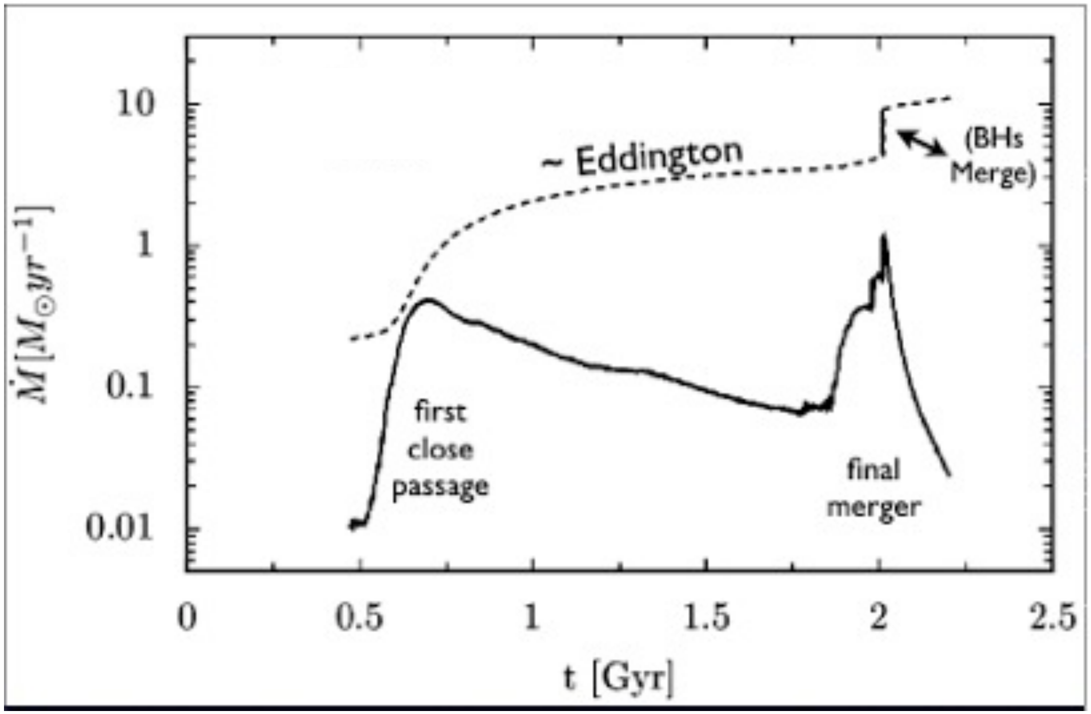
- New simulations in DeBuhr et al. 2009: add feedback force from radiation:

$$F_{\rm rad} = \tau \frac{L}{c}$$

$\tau \sim 10$

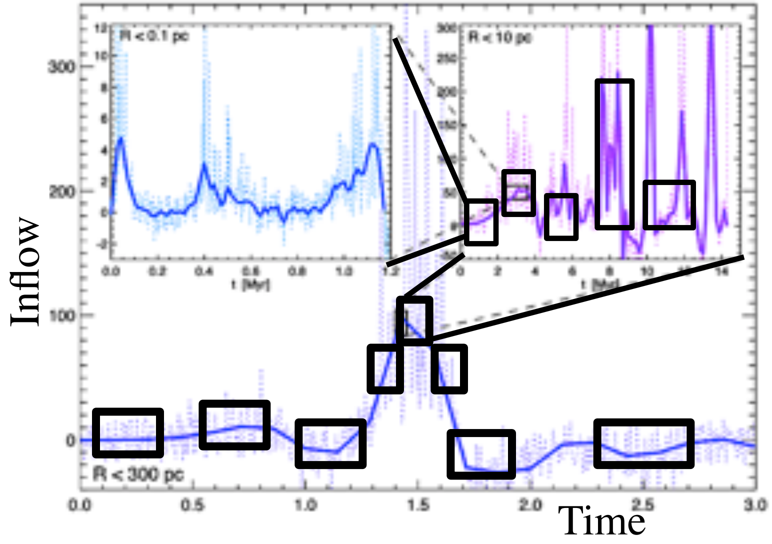
Radial momentum flux

Couple to nearest ~500-2000 particles



- Get self-regulated BH growth!

Strategy: a General Note



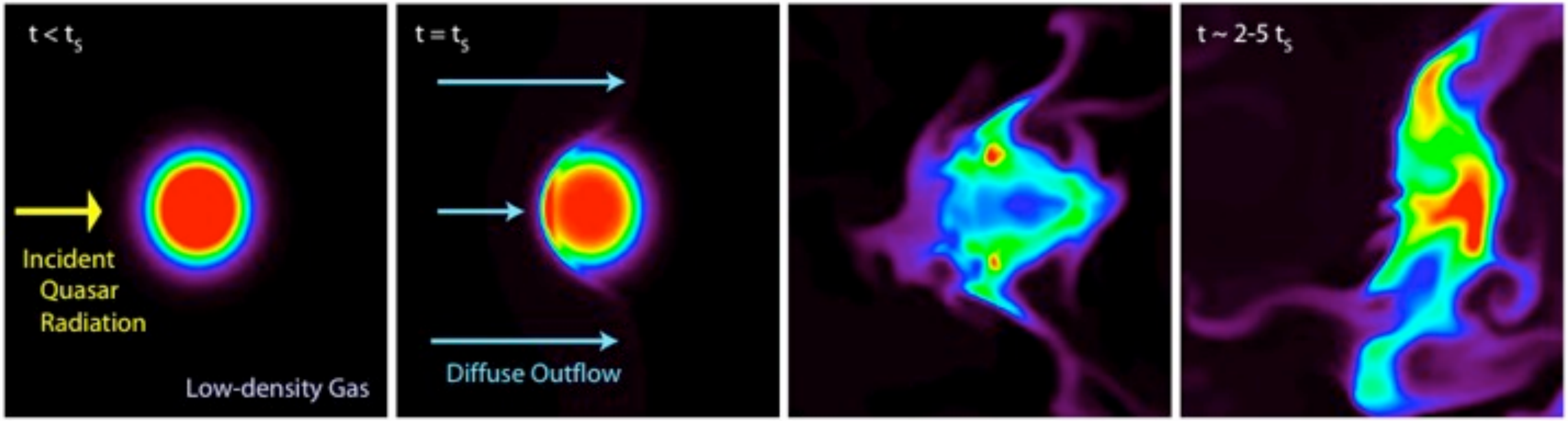
- Circum-BH dynamical times are ~100-1000 yr
  No code can follow for ~10^9 yr
- Only a couple of previous attempts
  (Levine et al., Escala et al., Mayer et al.)
  - All disabled key physics (cooling, self-gravity, star formation)
  - Typically evolved ~1-2 local t_{dyn} -- only an instantaneous response to a given inflow
- Our strategy: use a large suite to pick many interesting times
  - Simulate each for many dynamical times
  - Use them as new ICs for subsequent inflows
  - Mix up ICs & structure as much as possible!
- ~100+ nuclear-scale simulations: can 'stitch together' appropriate responses for arbitrary inflow histories

A Caution:

THE SCALES AFFECTED BY THE AGN DEPEND ON THE FORM OF FEEDBACK

- These are still toy models – almost certainly have "mixed" scenarios:

Hopkins & Elvis 2009



Cloud is "too dense": resists radiation pressure

Stripping/mixing increases cross section by factor ~50; now easily "blown out"

- Hot outflow "pre-processes" cold clouds – makes them order-of-magnitude more receptive to radiation flux
  - Enhance feedback efficiency by order-of-magnitude (only need ~0.003 L_{QSO} to couple); but will "look like" stellar winds

Q. Despite this, can we say some global things about AGN feedback and galaxies?

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A. Yes.

Q. Despite this, can we say some global things about AGN feedback and galaxies?

A. Yes.   I Think.

1. Even with the most optimistic assumptions, stellar FB dominates over AGN FB in star-forming, disk-dominated galaxies

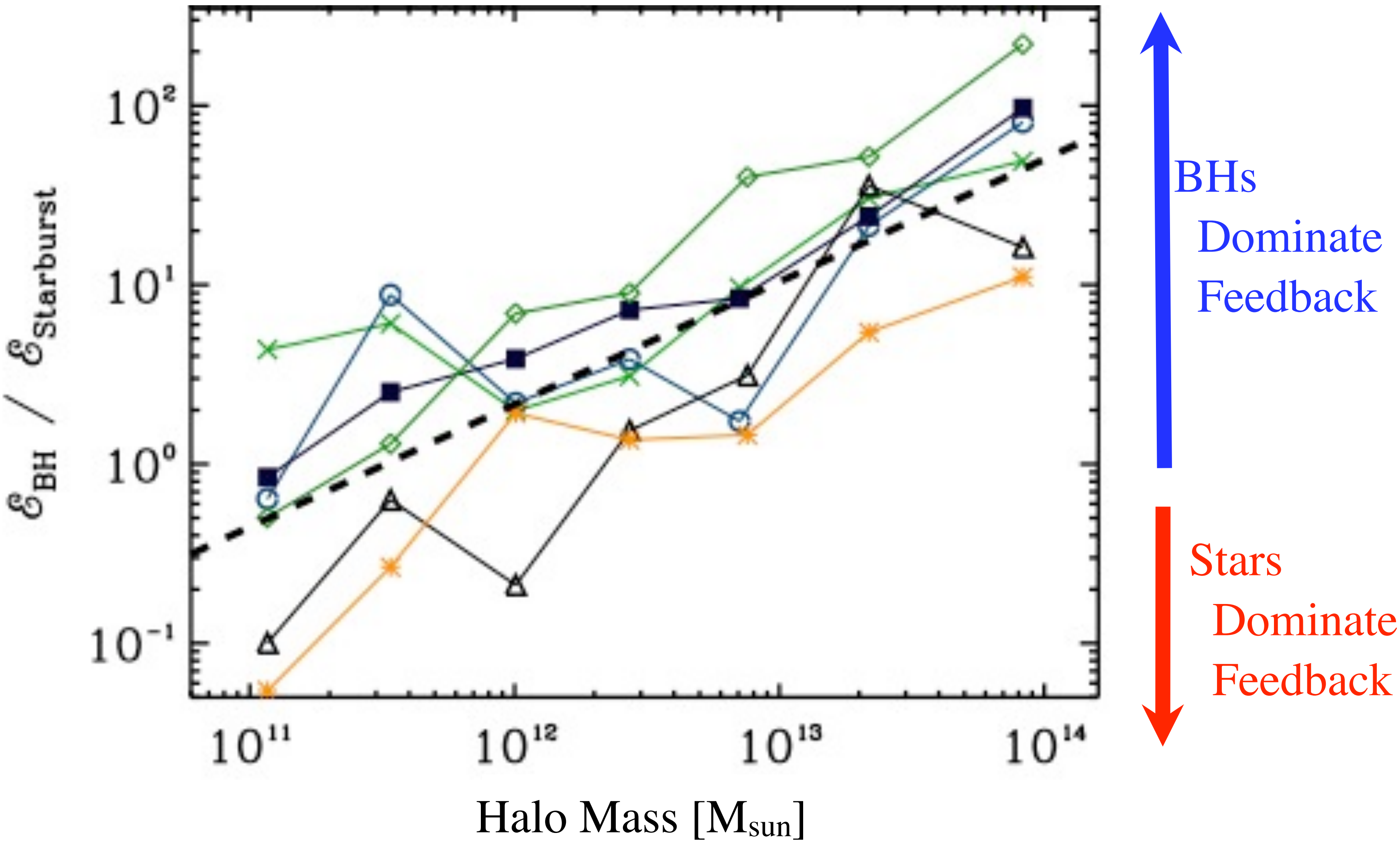
Total $E_{AGN} \sim E_{Supernovae}$ for a bulge-dominated galaxy.

But the E_{AGN} comes in a very short burst

PFH, Cox et al. 2007

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?



PFH, Cox et al. 2007

AGN or Starburst-Driven Winds?

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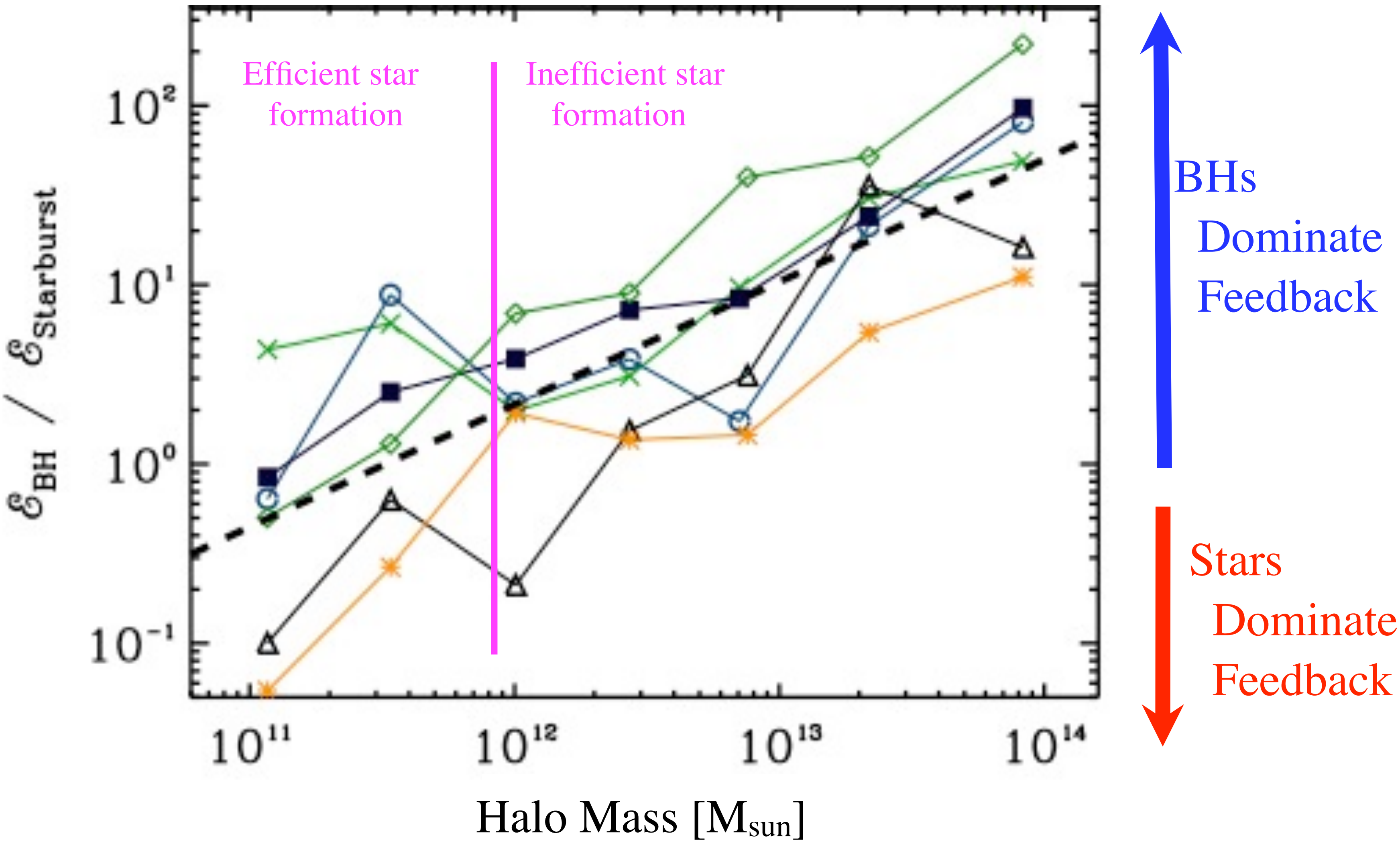

PFH, Cox et al. 2007

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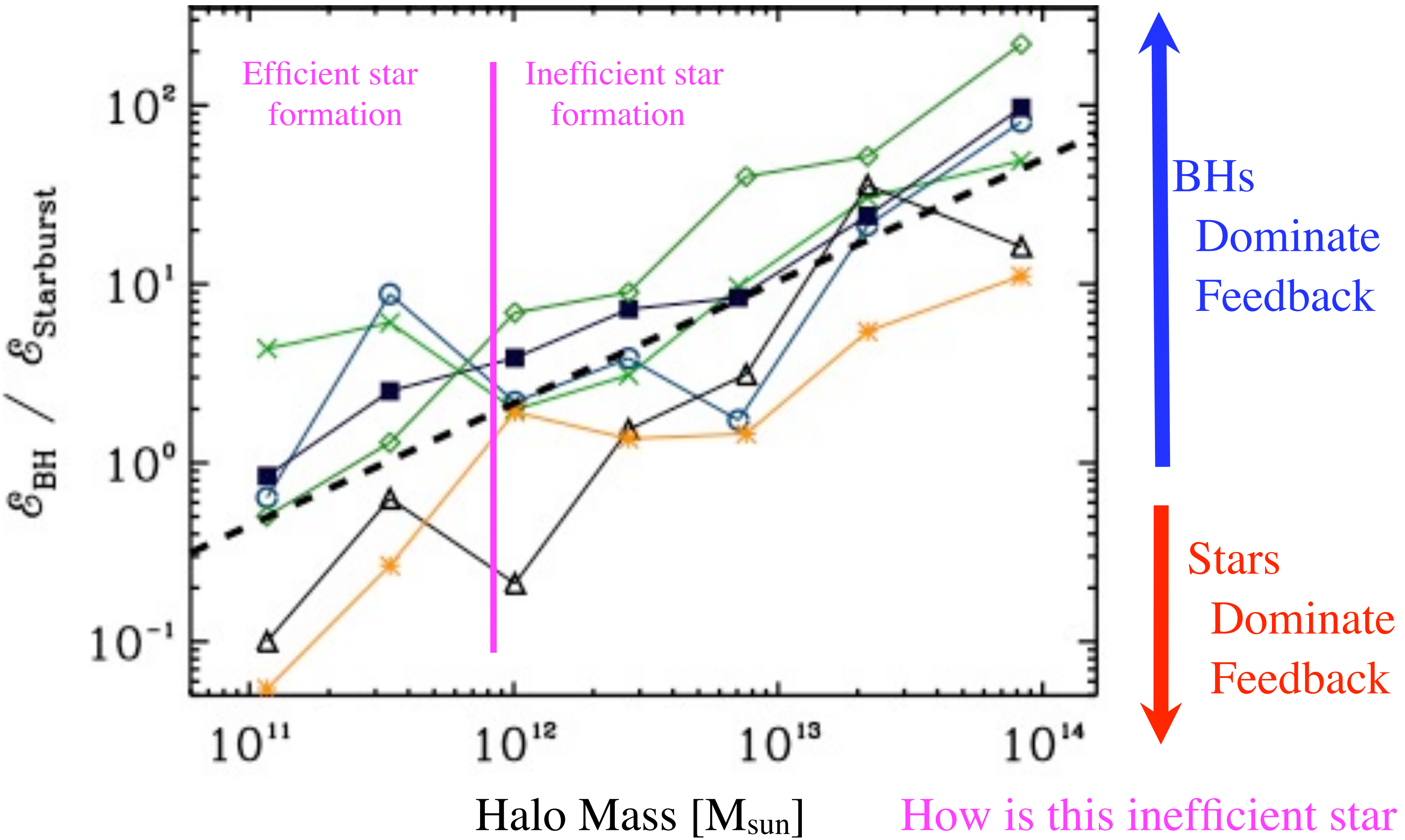
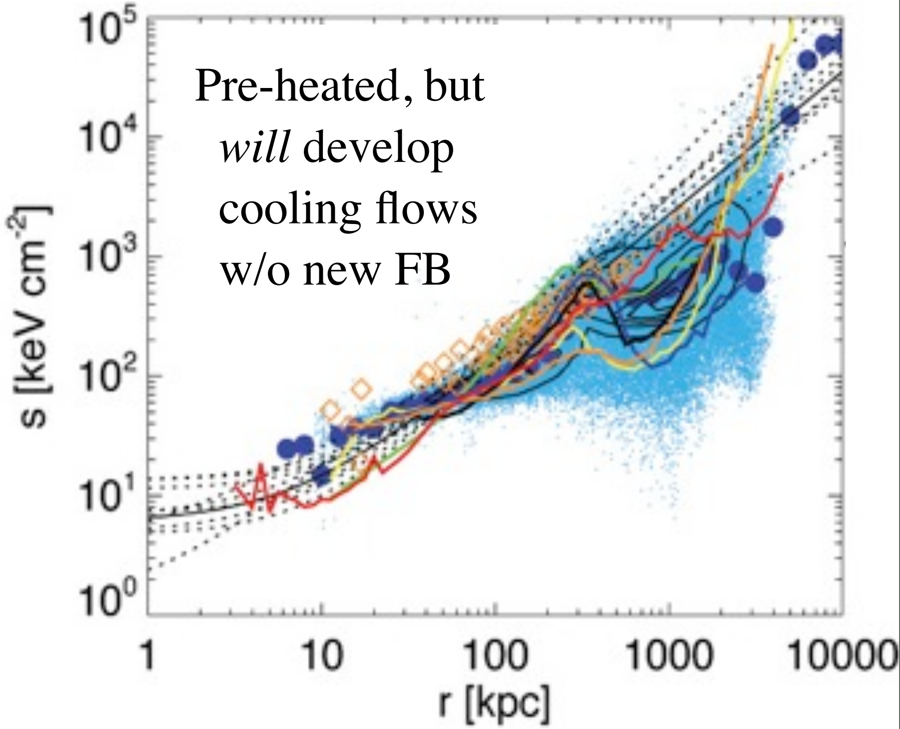


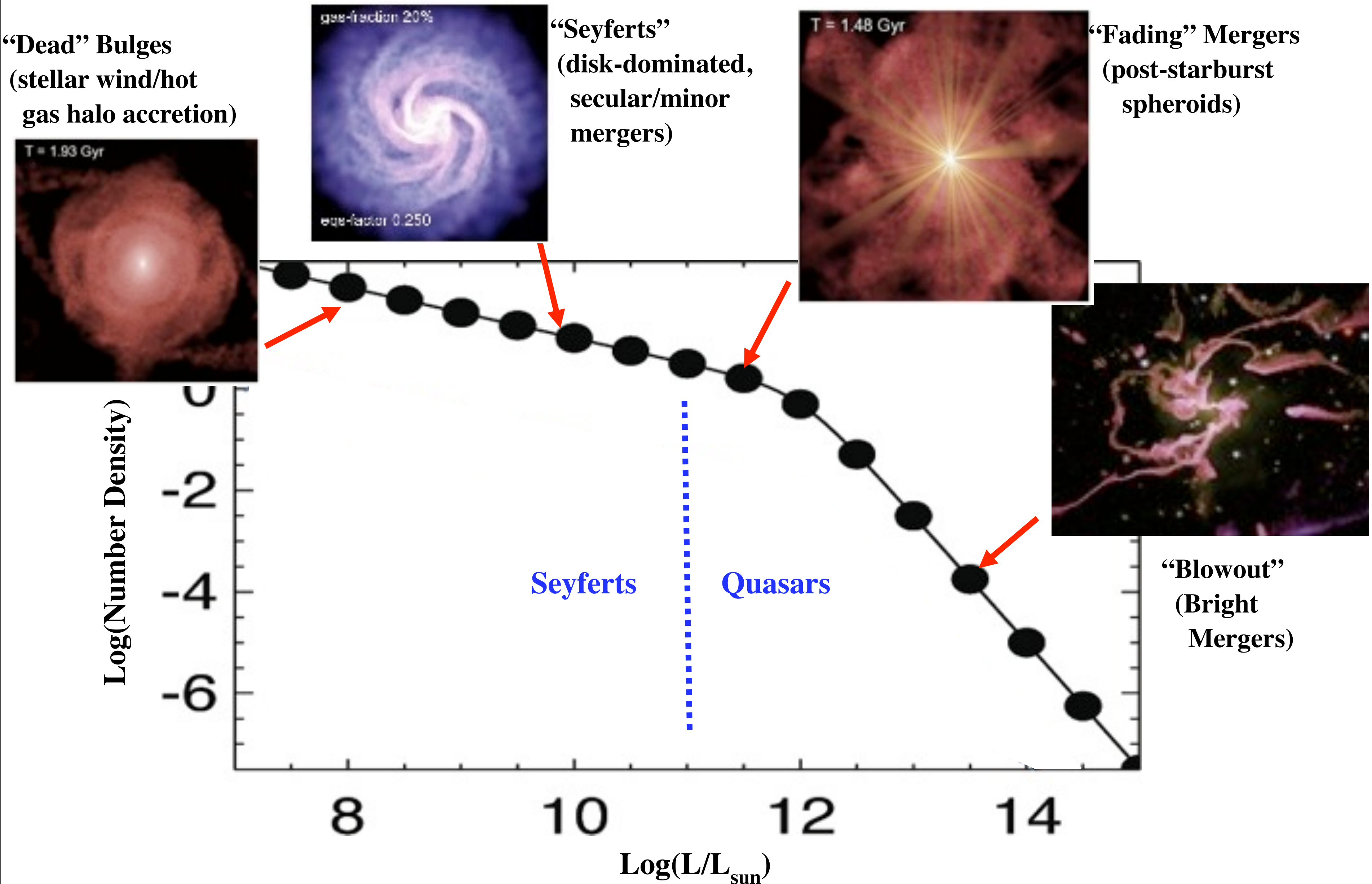
How is this inefficient star formation *maintained*?

2. Quasar-mode feedback will not solve the cooling-flow problem

Clusters with cooling flows do *not* have quasars!

Even optimistic models cannot halt ~10 Gyr of future cooling



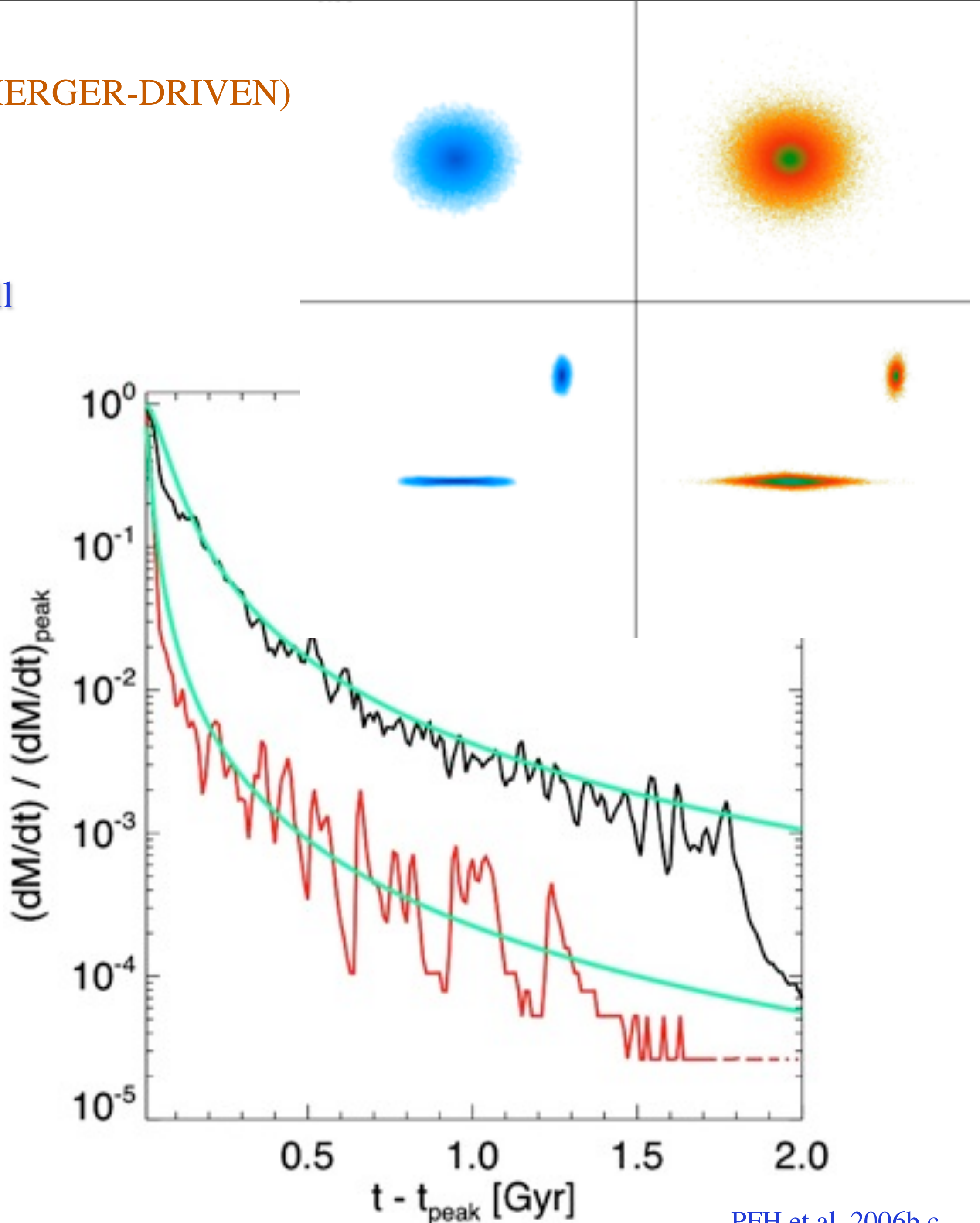


- Observed luminosity function: populations at different *evolutionary* stages

This is Very General:

(EVEN THOUGH NOT ALL AGN ARE MERGER-DRIVEN)

- Almost any (ex. radio) AGN feedback will share key properties:
  - Point-like
  - Short input (~ $t_{Salpeter}$)
  - $E \sim E_{binding}$
- Simple, analytic solutions:
  - $L \sim (t / t_Q)^{-1.7(ish)}$
  - Agrees well with simulations!
- Generalize to "Seyferts"
  - Disk-dominated galaxies with bars
  - Minor mergers

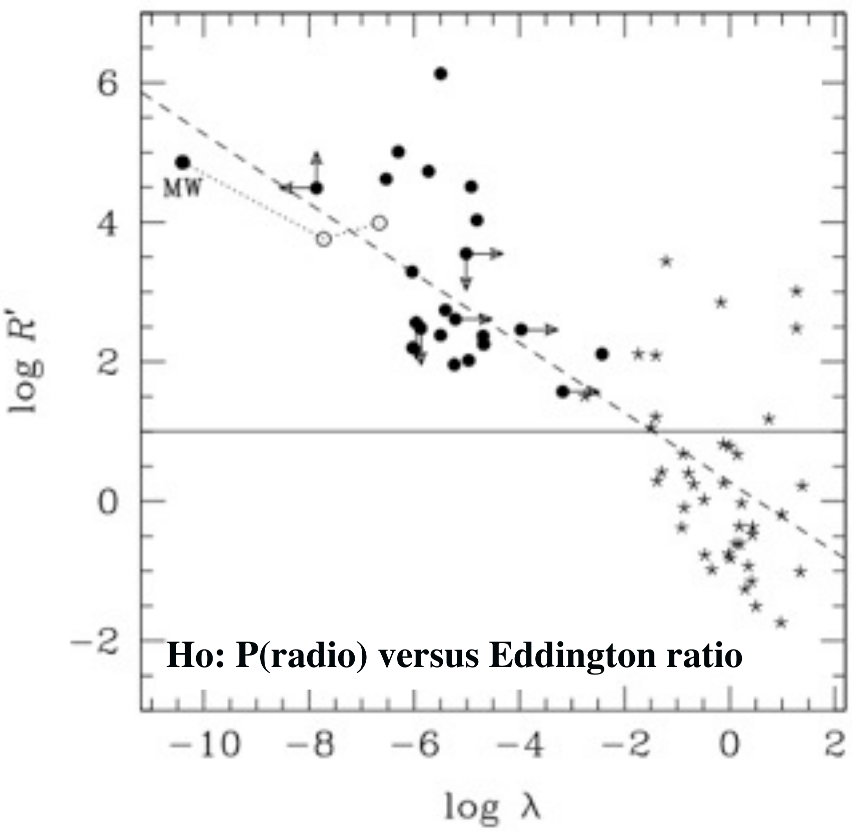


PFH et al. 2006b,c

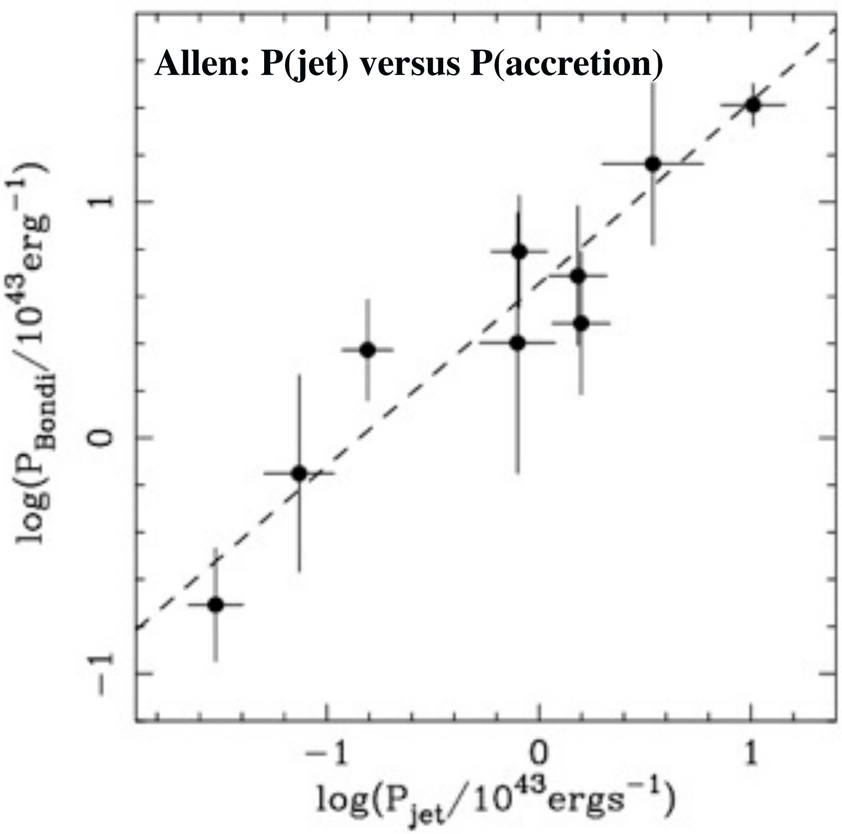
Maintenance Mode

HOW DOES IT FIT IN THIS PICTURE?

- Dominated by low accretion rates: does it "follow from" the bright-mode decay?



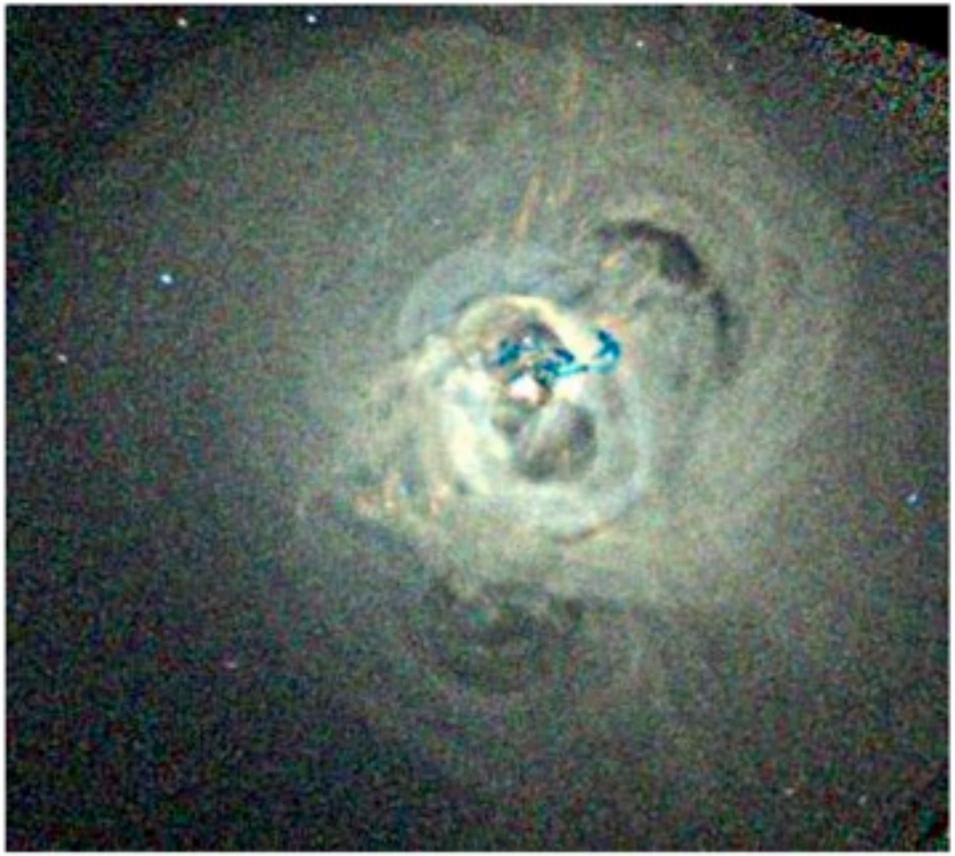
- Is Bondi accretion actually going to work for once?



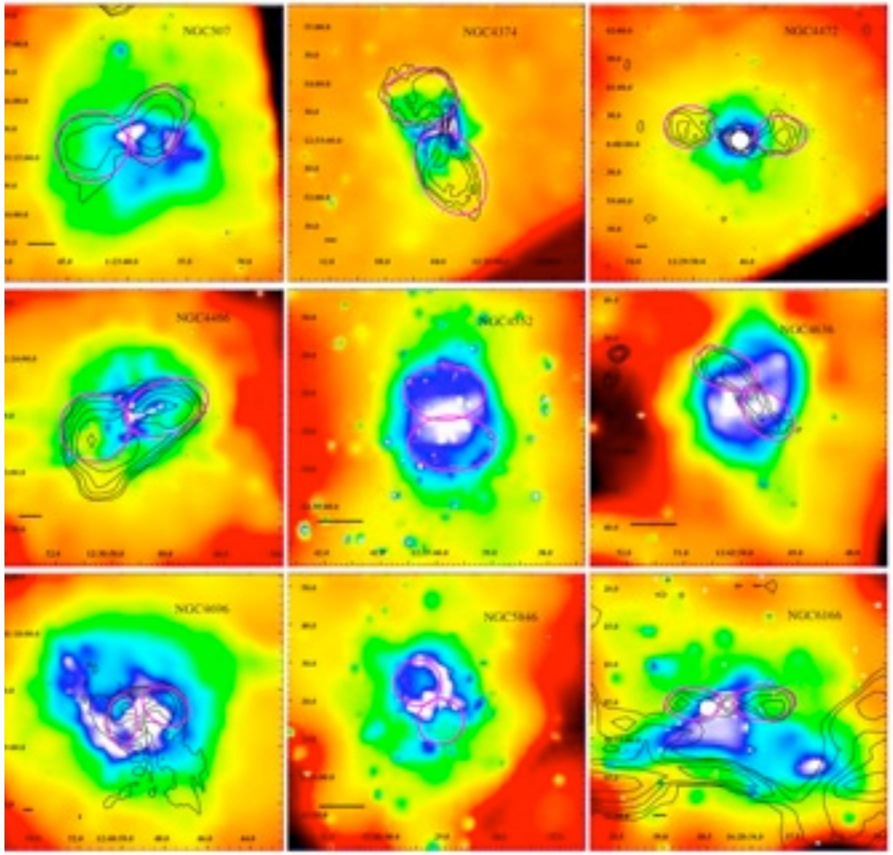
Maintenance Mode

HOW DO WE FIT THIS INTO OUR PICTURE?

- Is pre-heating relevant for cooling flows? Can we solve the problems in isolation?
- Do we only care about Perseus? Or do we care about moderate-mass Es with radio jets, in ~ 10^{13} M_{sun} halos?

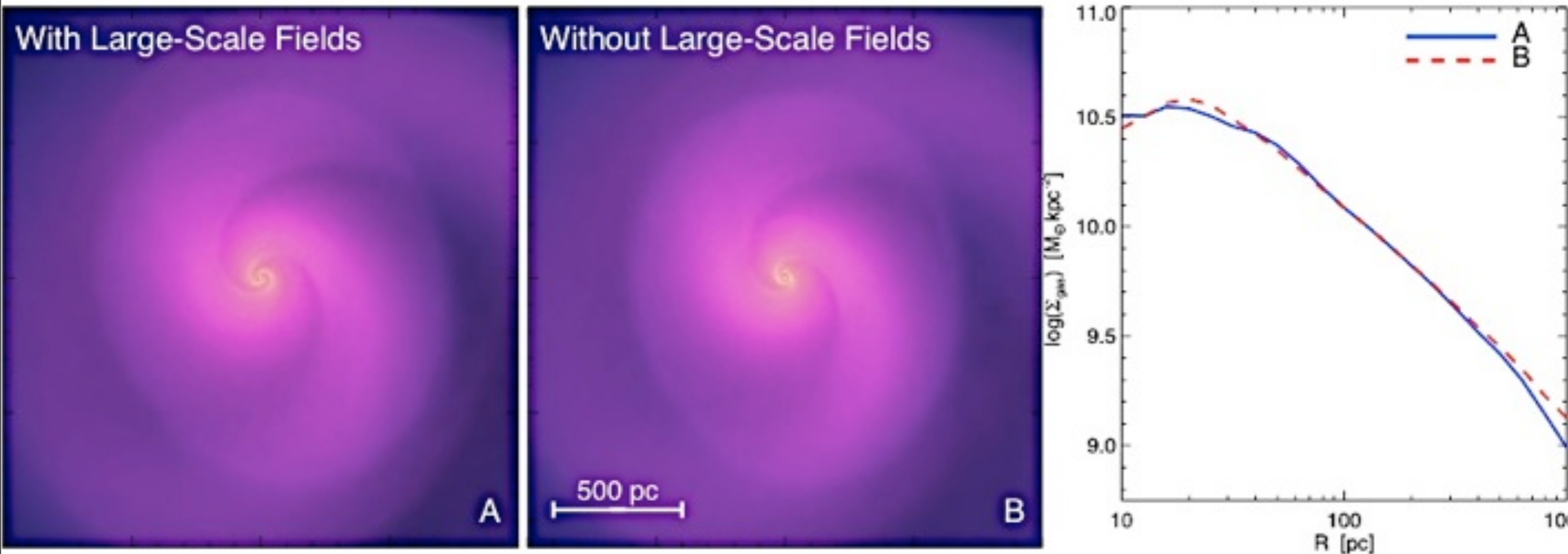


Fabian (Perseus Cluster)

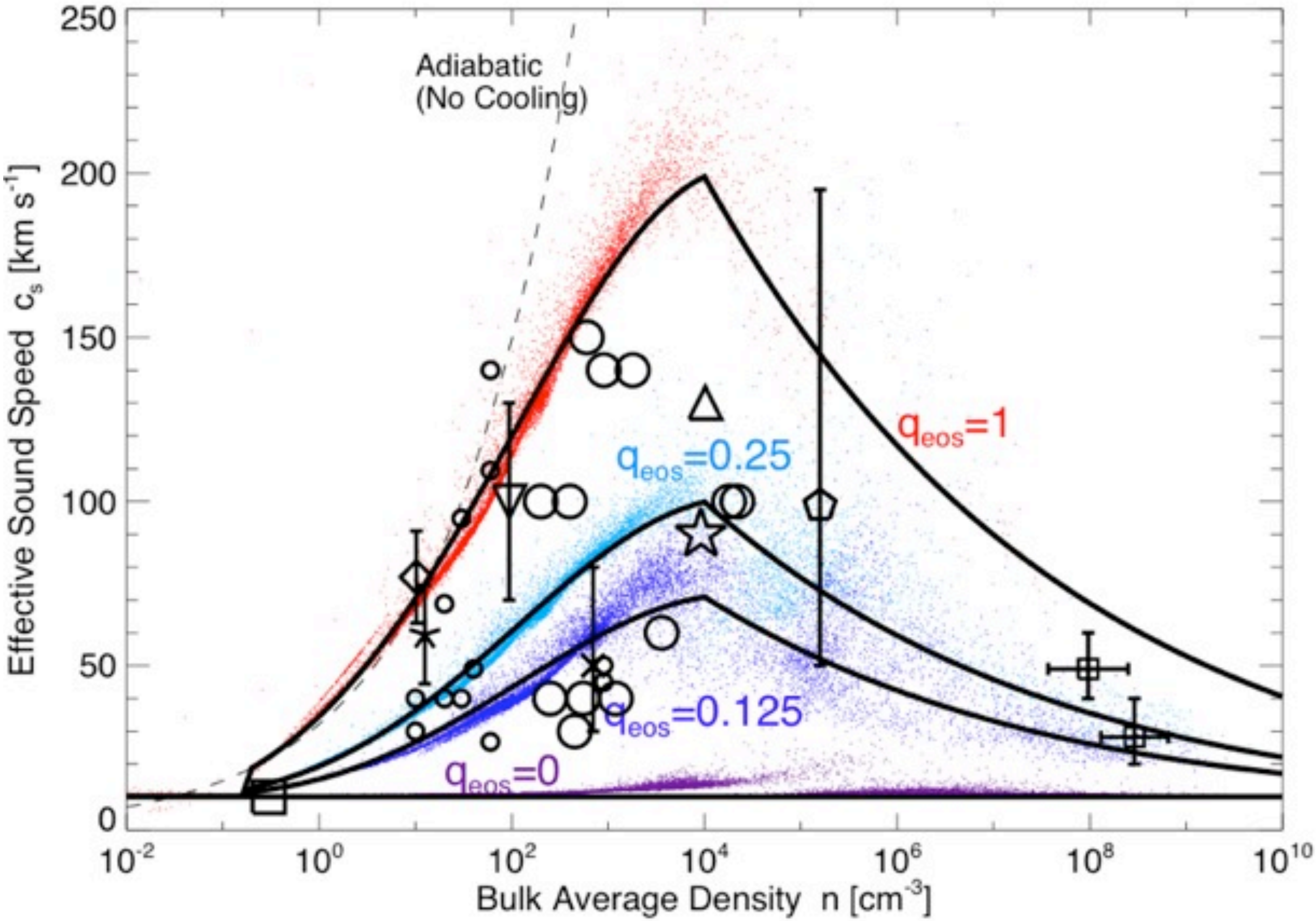


Allen (X-ray Ellipticals)

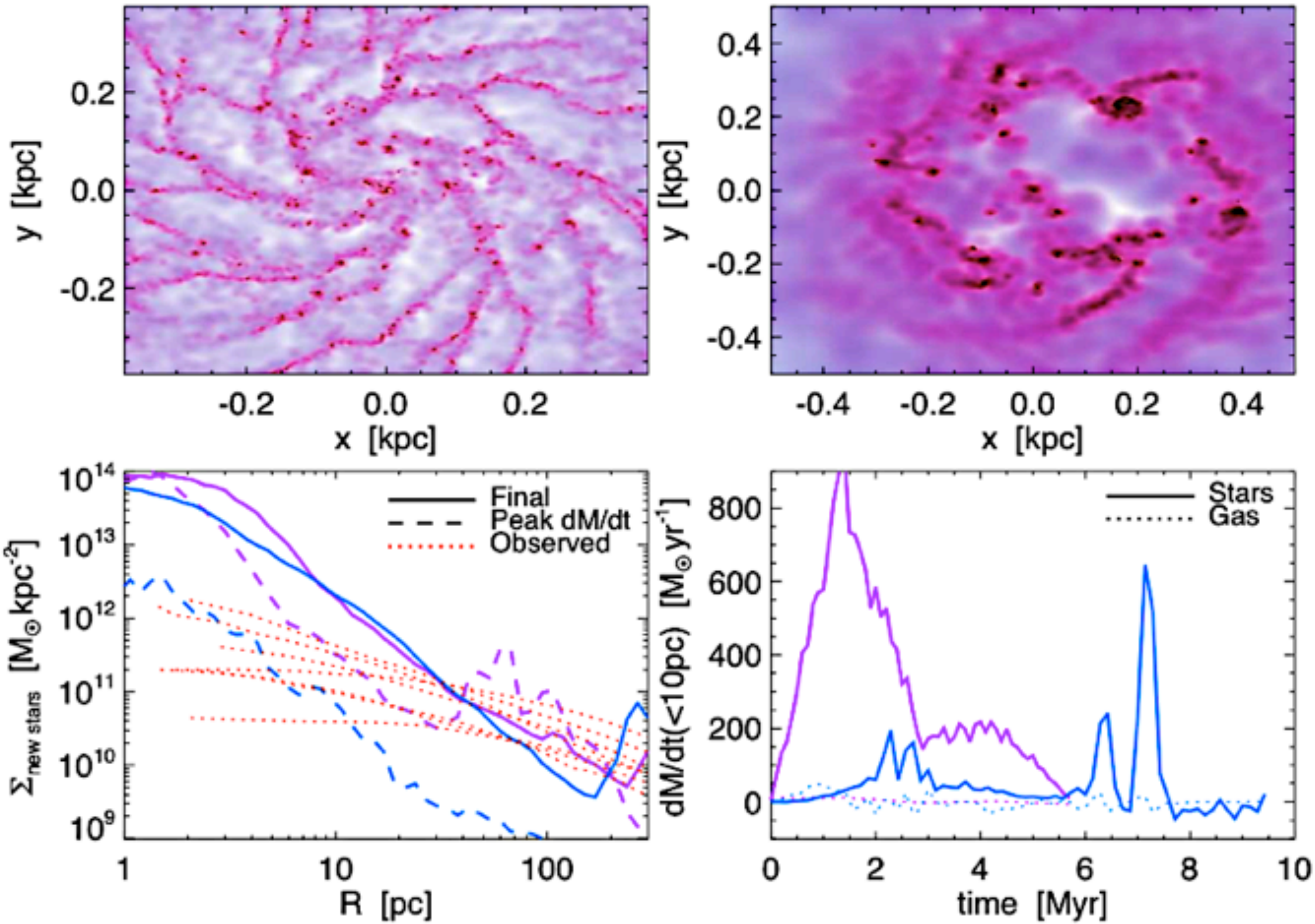
Large-Scale Tides are Not Important for AGN:



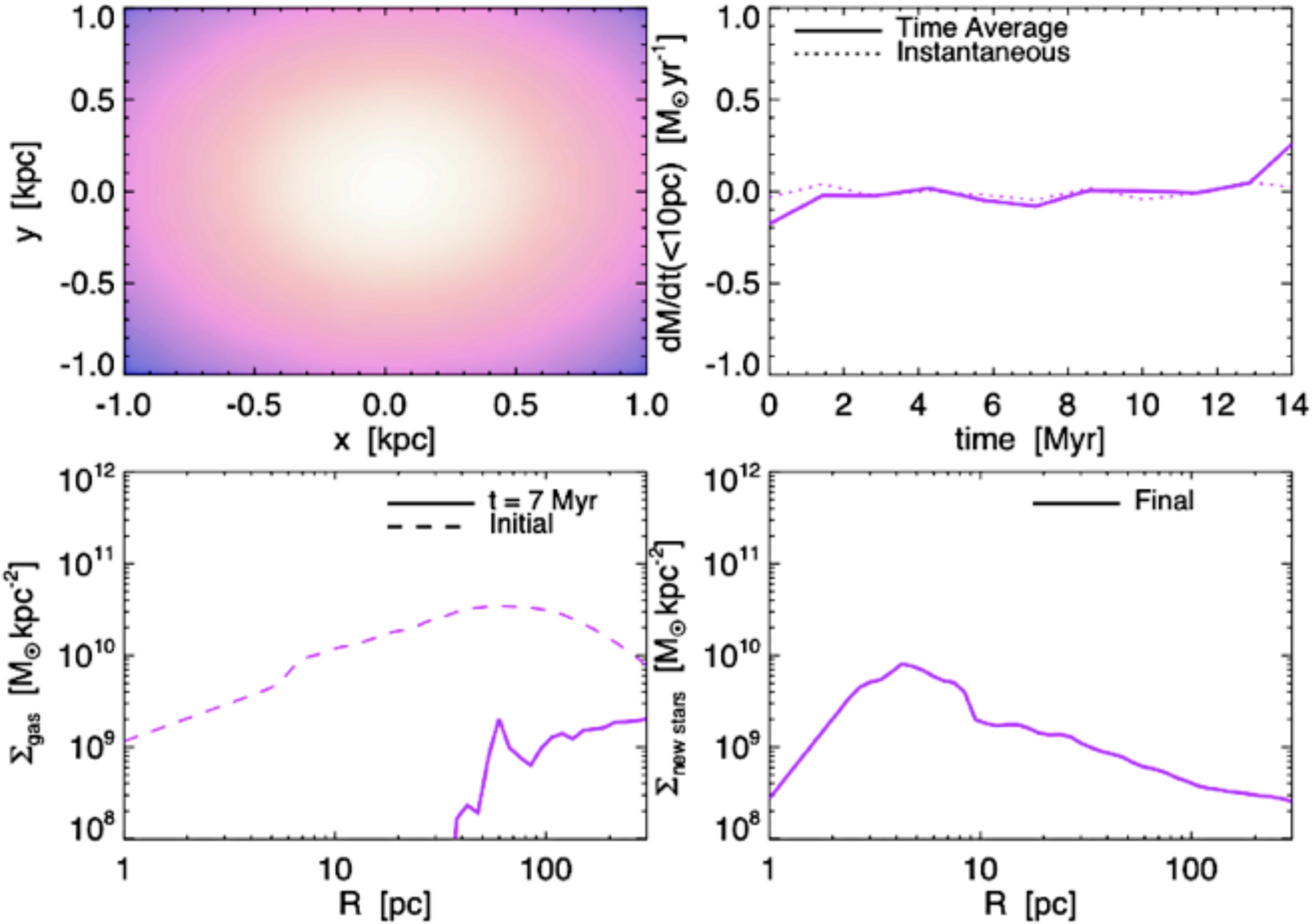
The Effective Stellar Feedback on Small Scales:
(REQUIRE SOME SUB-RESOLUTION MODEL)



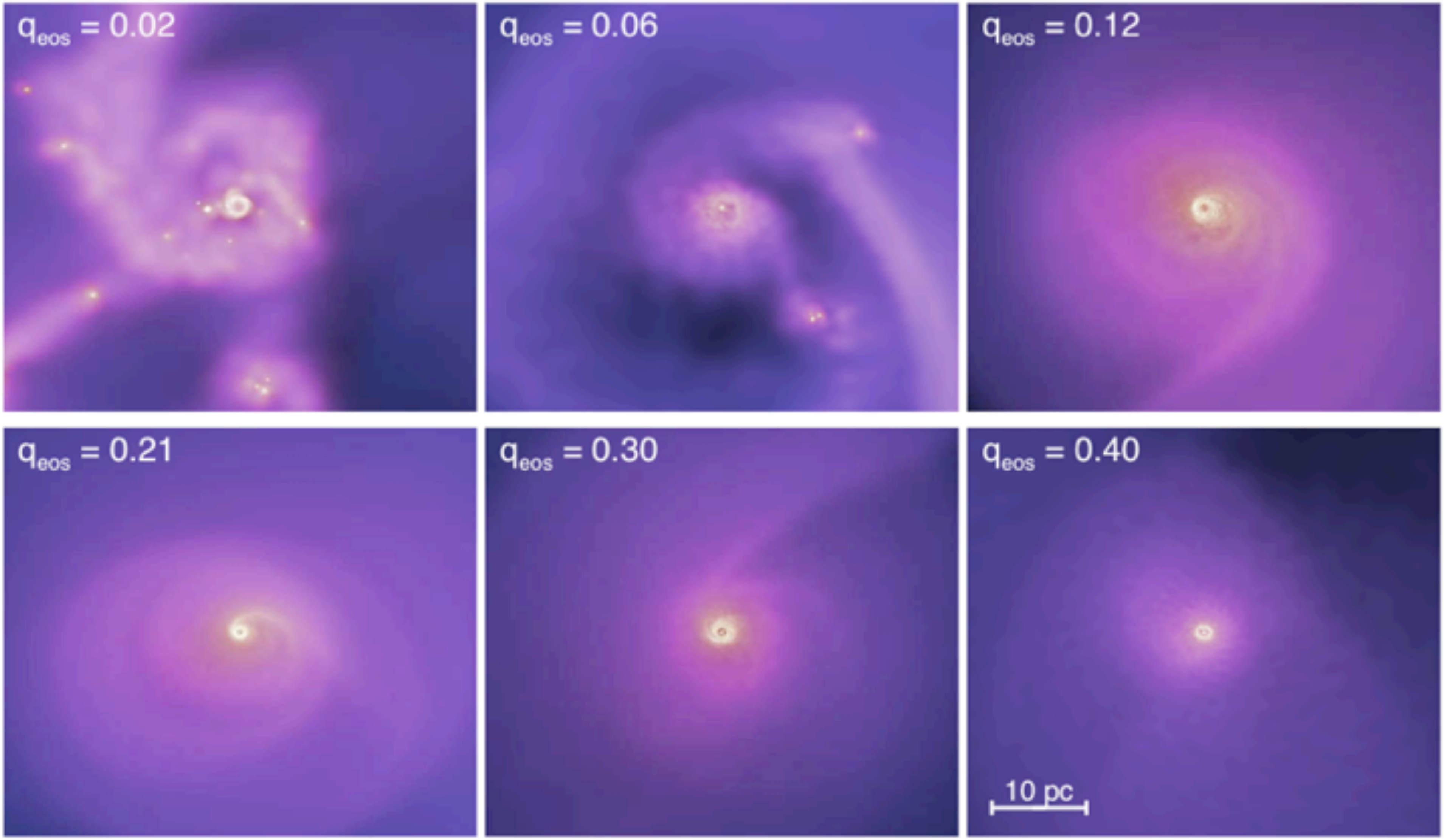
A “No Feedback” ISM is Ruled Out on Small Scales:

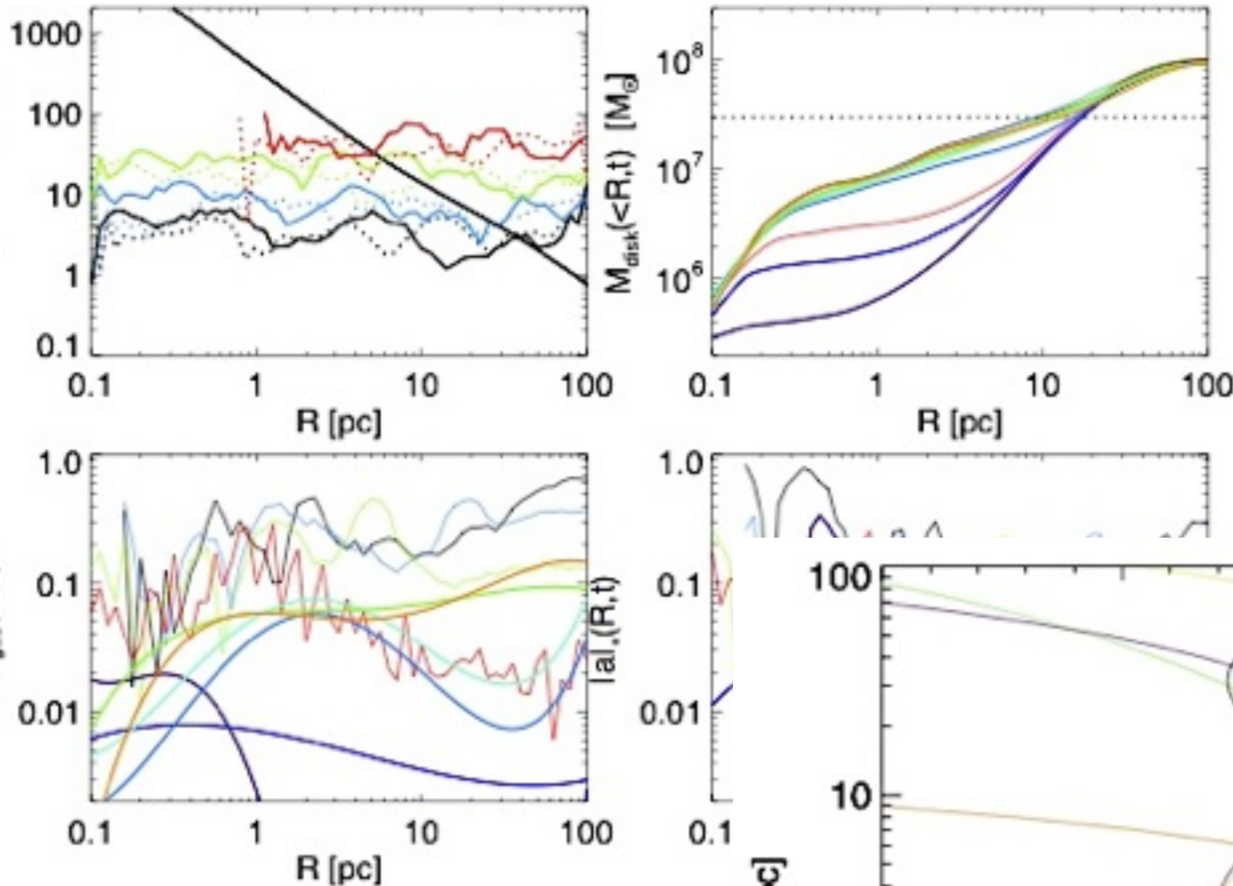


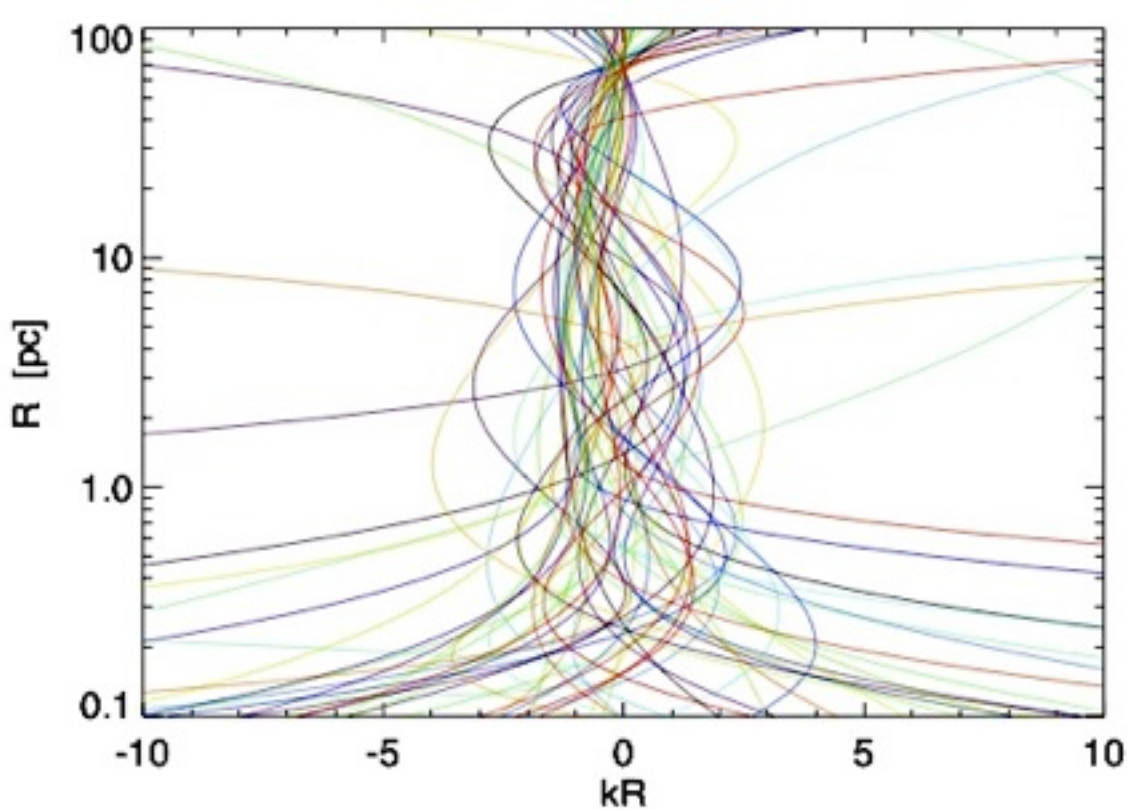
A “Maximal Feedback” ISM is Also Ruled Out on Small Scales:



But qualitative conclusions are insensitive to the gas microphysics







How do the m=1 modes arise?

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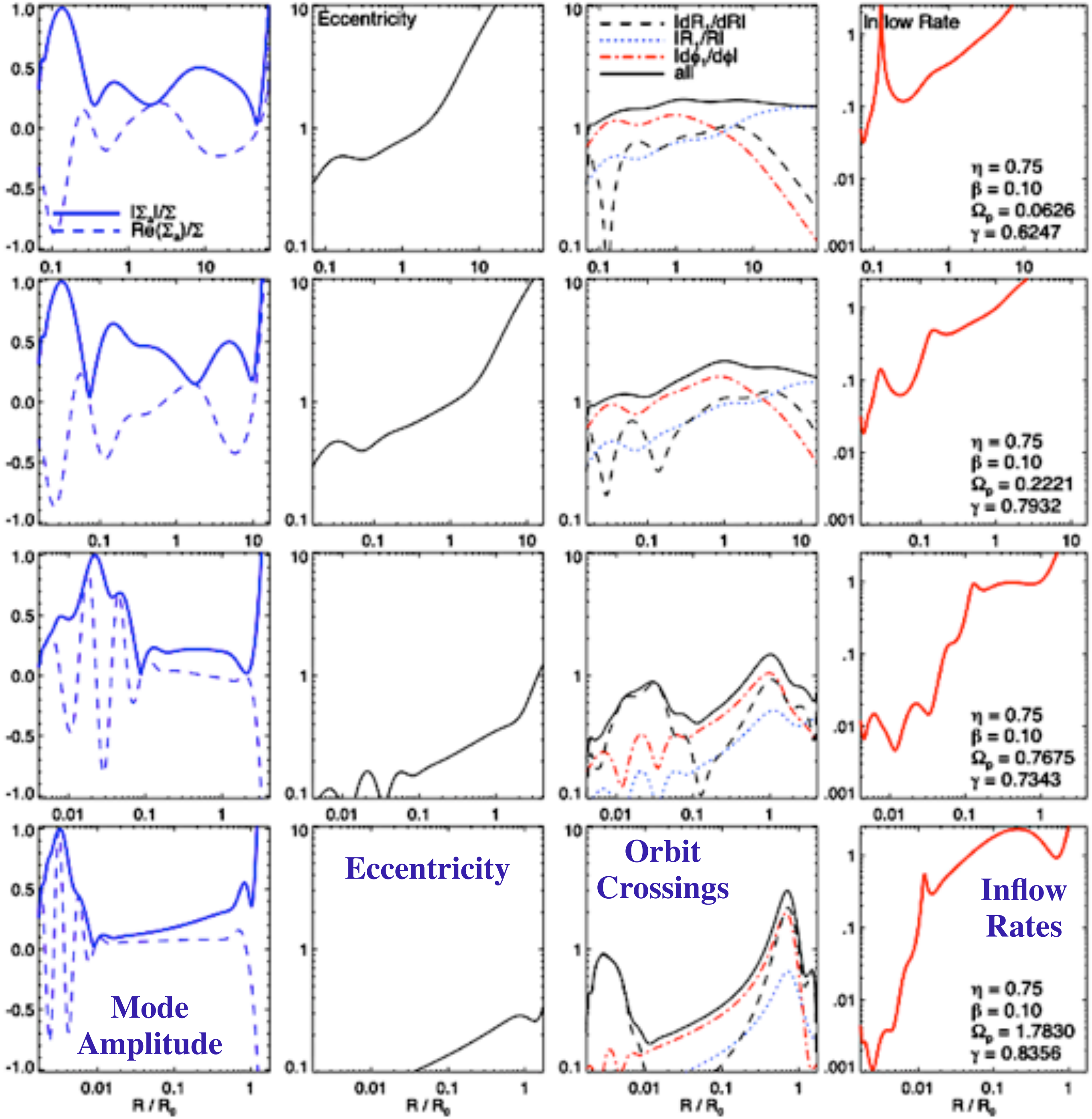
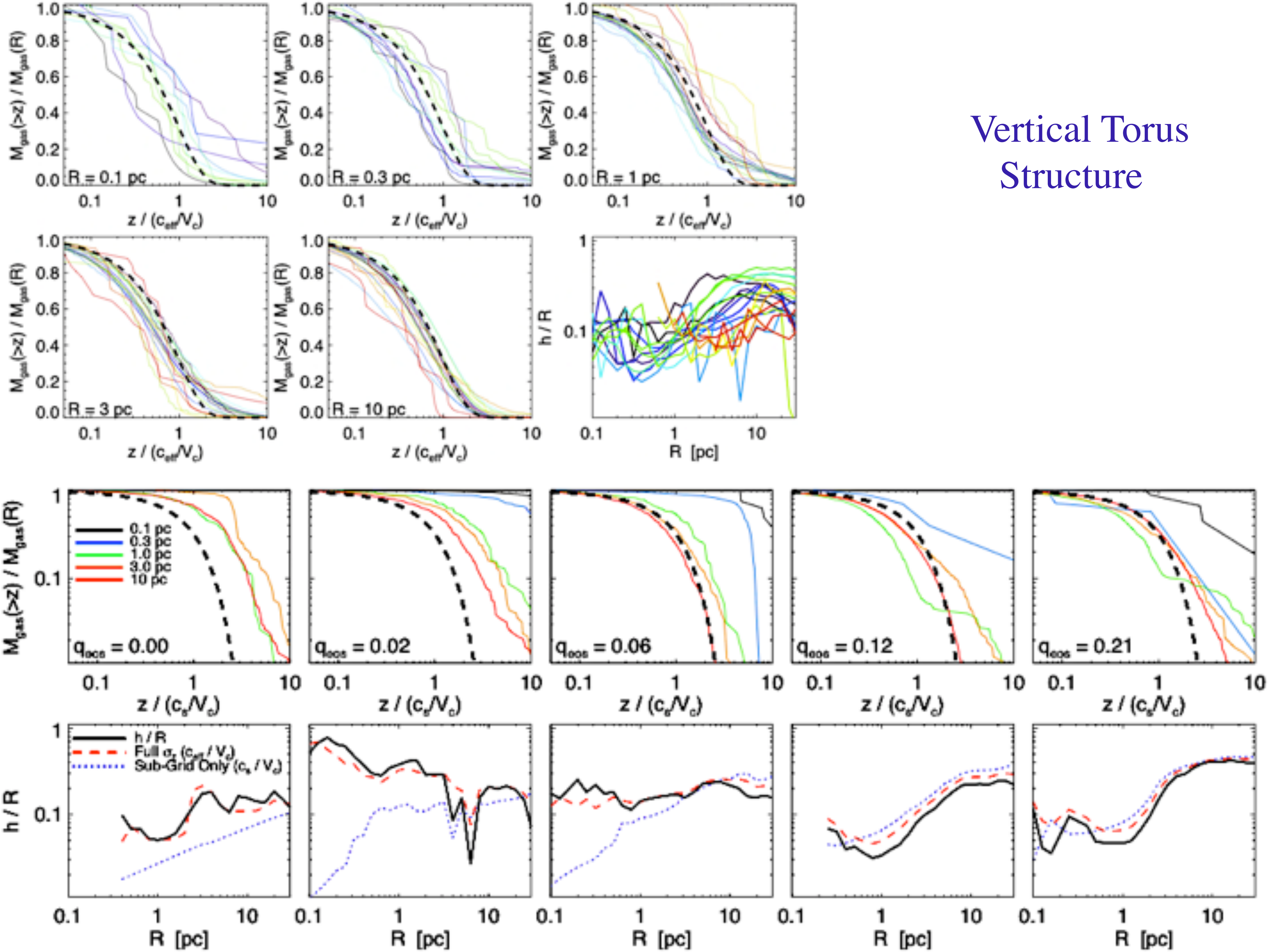
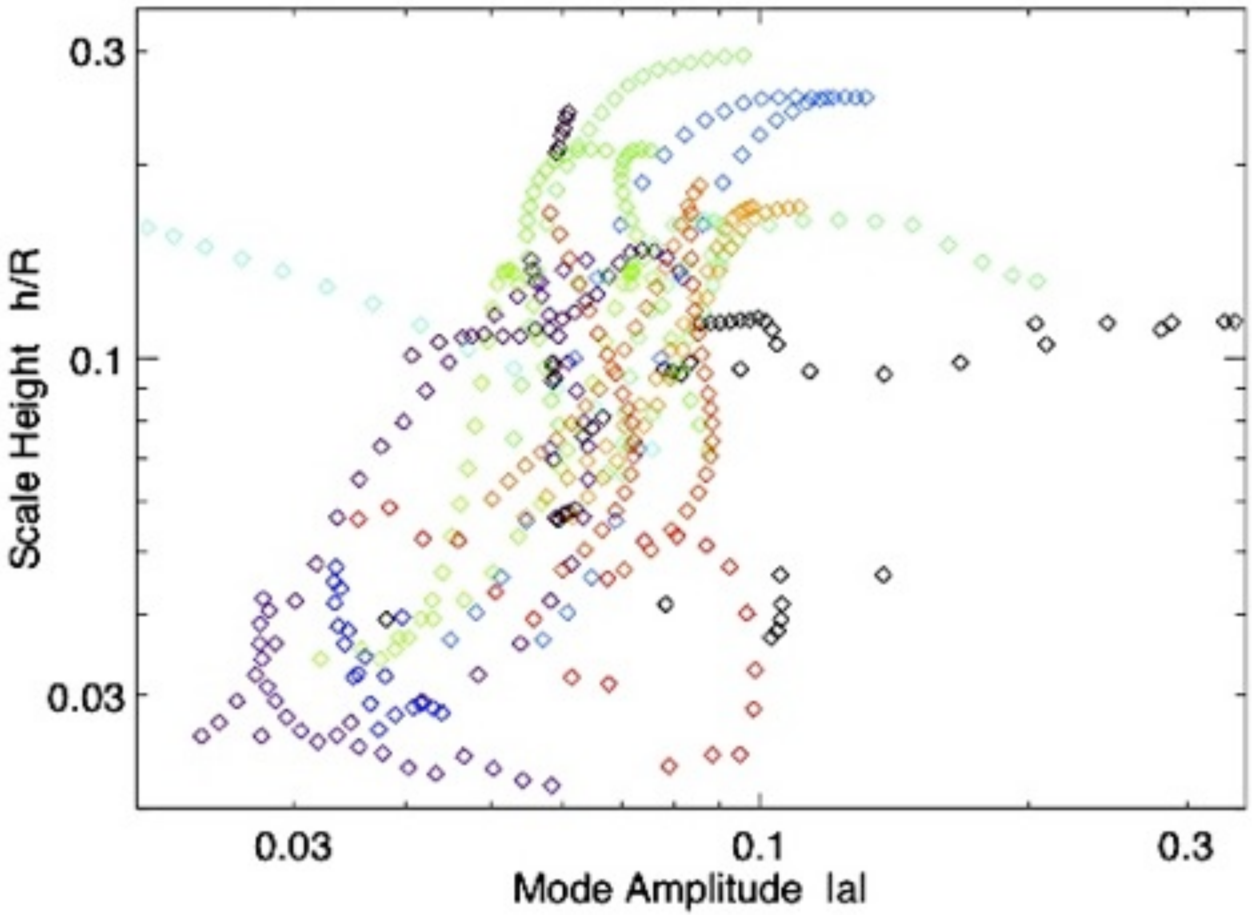
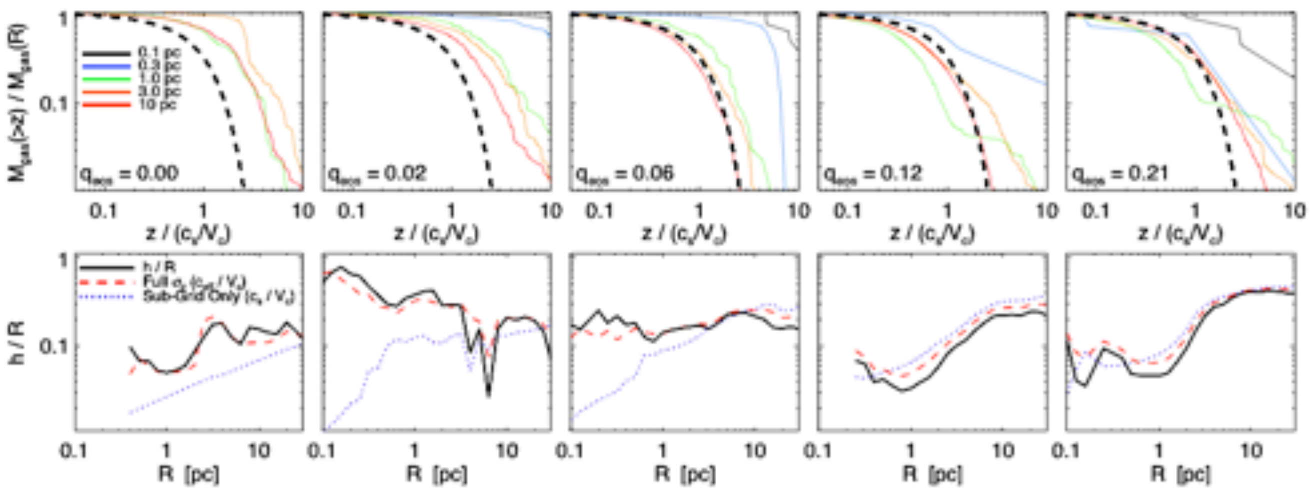


Vertical Torus Structure







Vertical Torus Structure

Torus-Host disk misalignments: