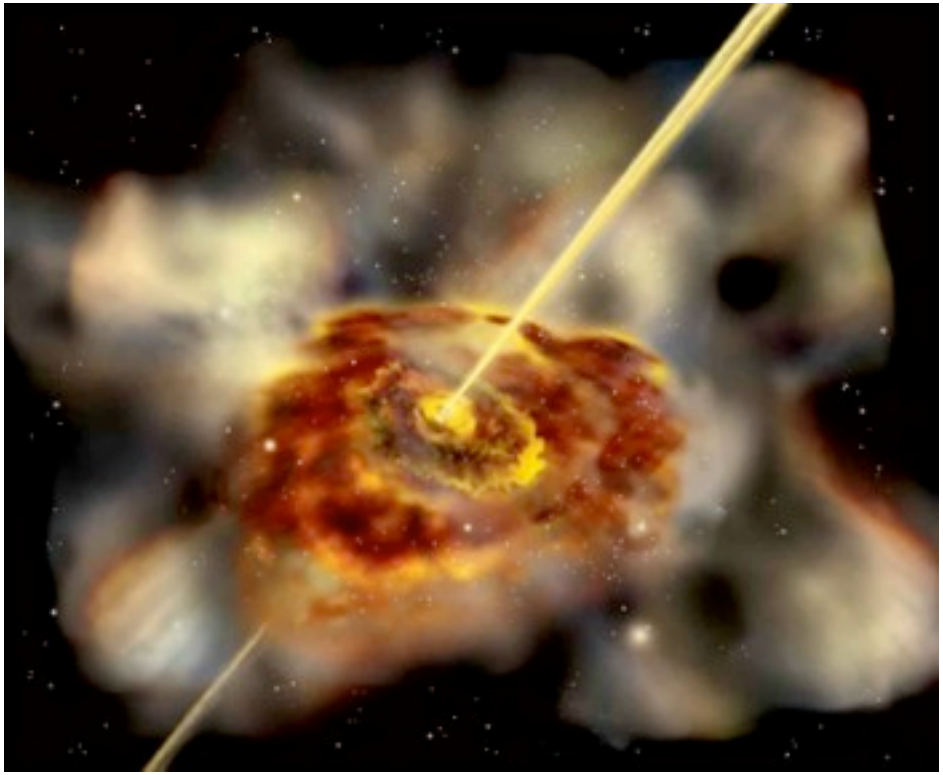
# How do Massive Black Holes Get their Gas? (and Get Rid of It?)

Philip Hopkins

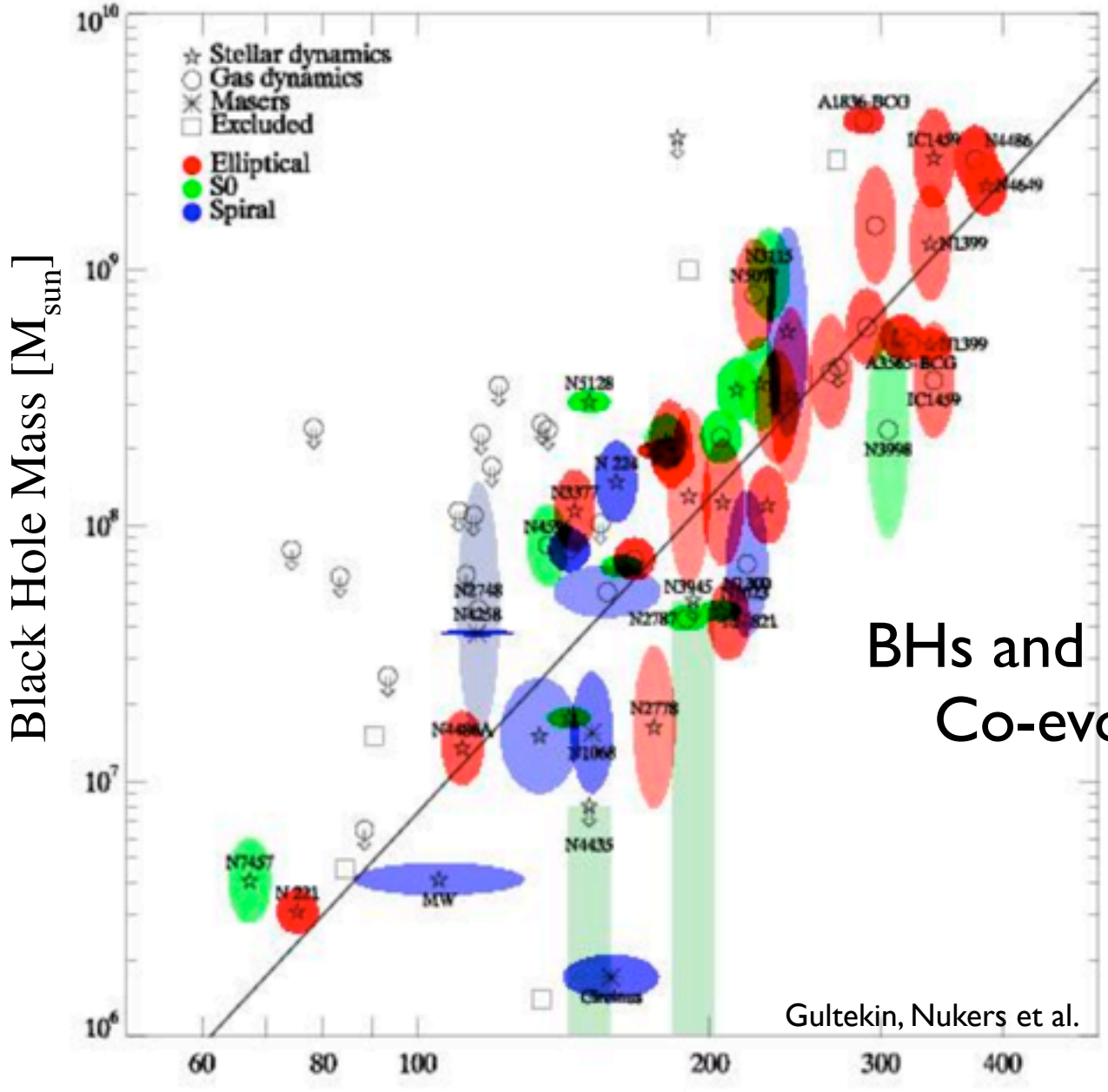
MGCT
11/09/10

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

- Every massive galaxy hosts a supermassive black hole




- These BHs are “fossil” quasars



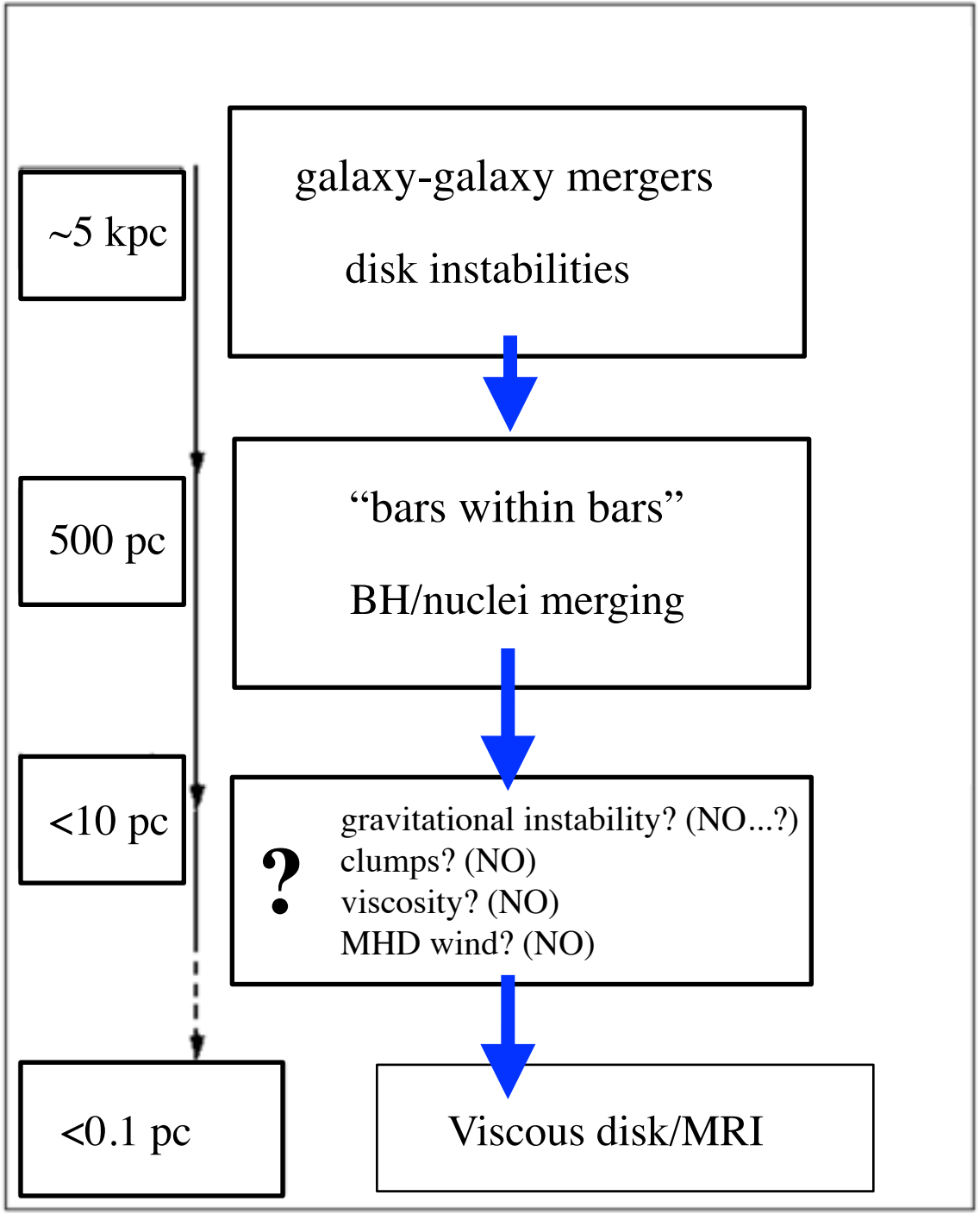

BHs and Bulges Co-evolve

# How Do Massive BHs Get Their Gas?

- 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.)



F. Summers

Komossa (NGC 6240)

- 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!

# FOLLOWING THE GAS IN...

- Here: Focus on *robust* conclusions

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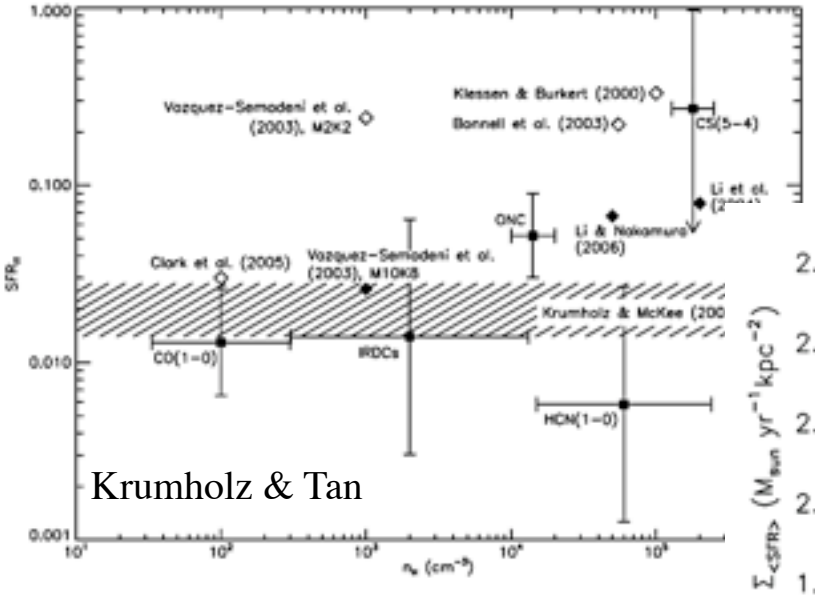
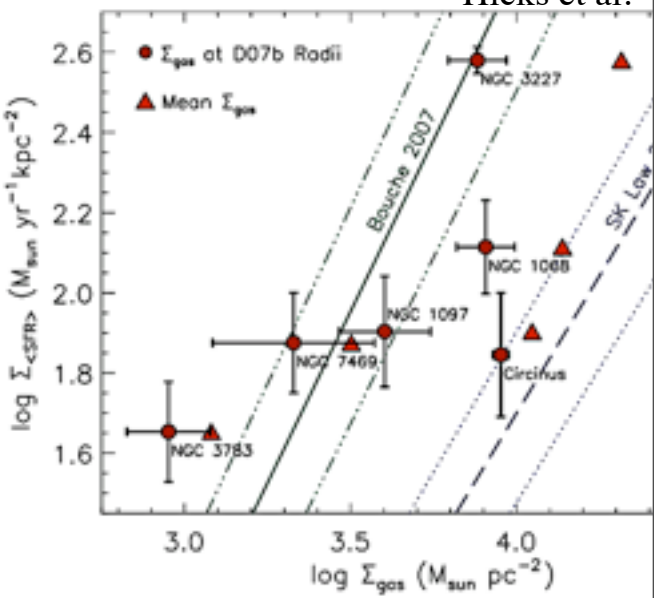



Krumholz & Tan

Hicks et al.

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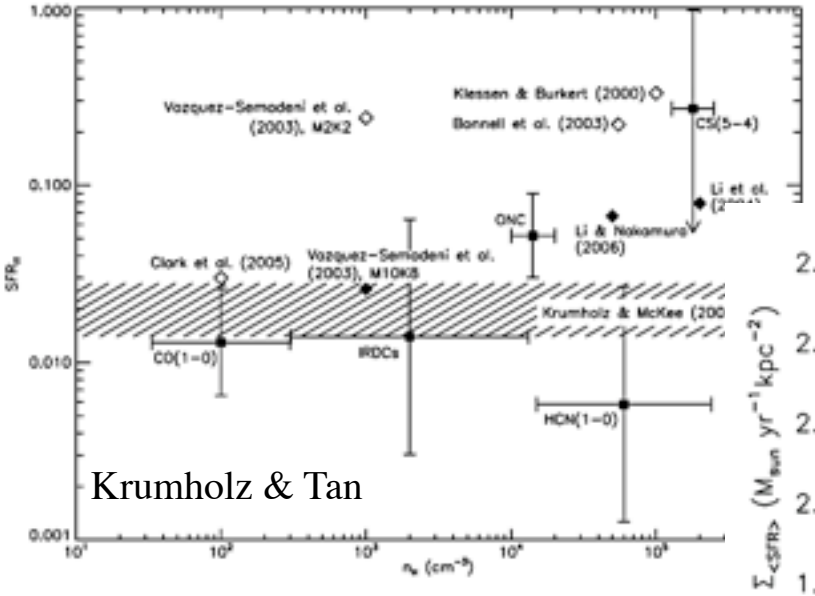

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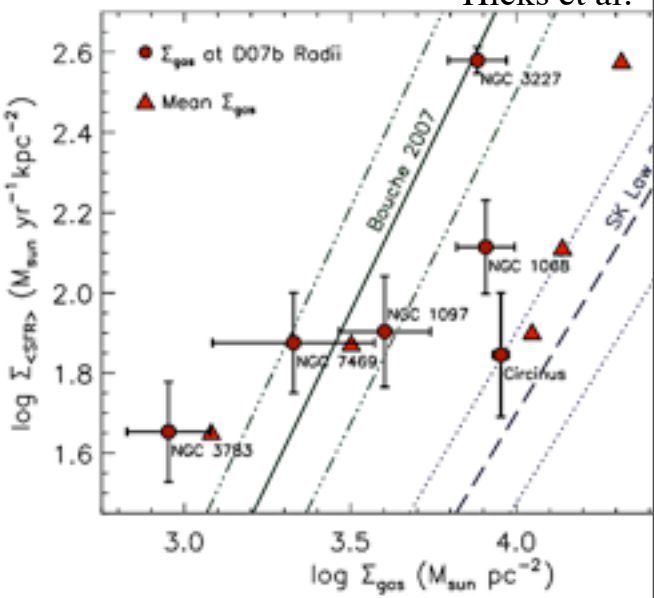


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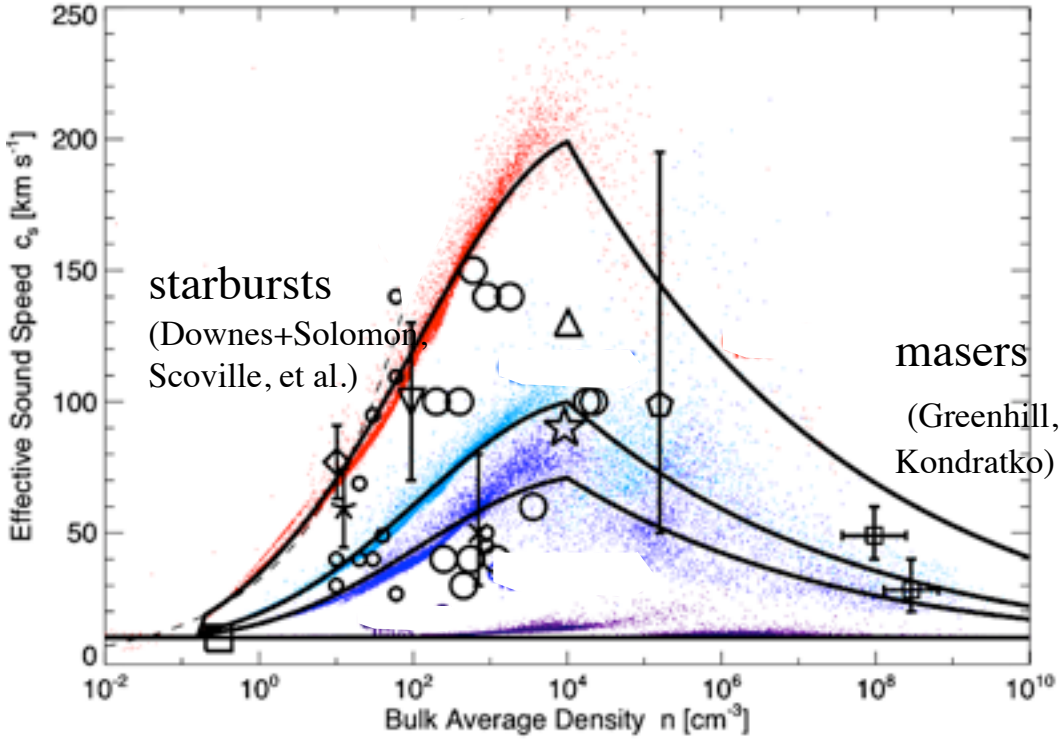


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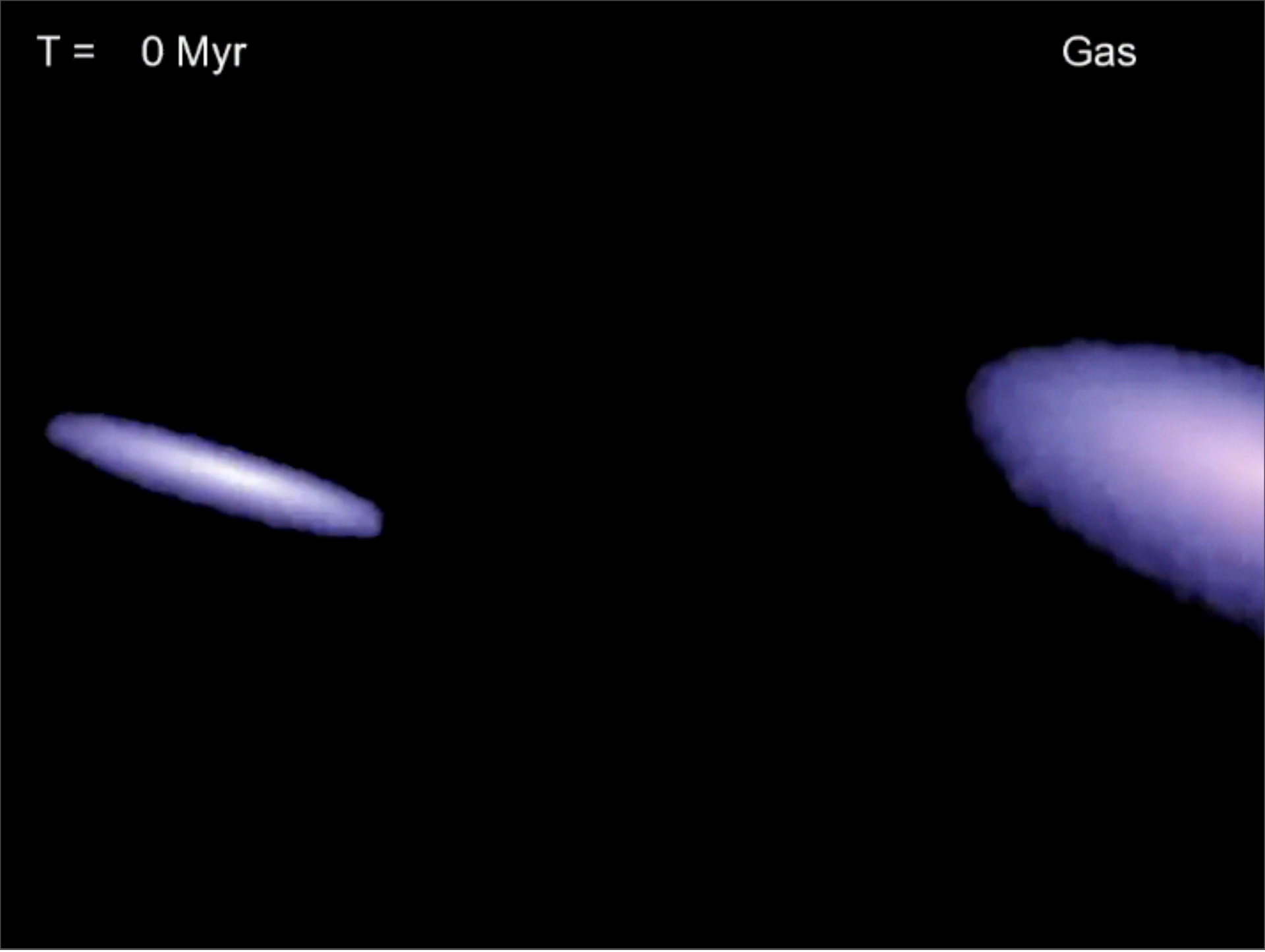
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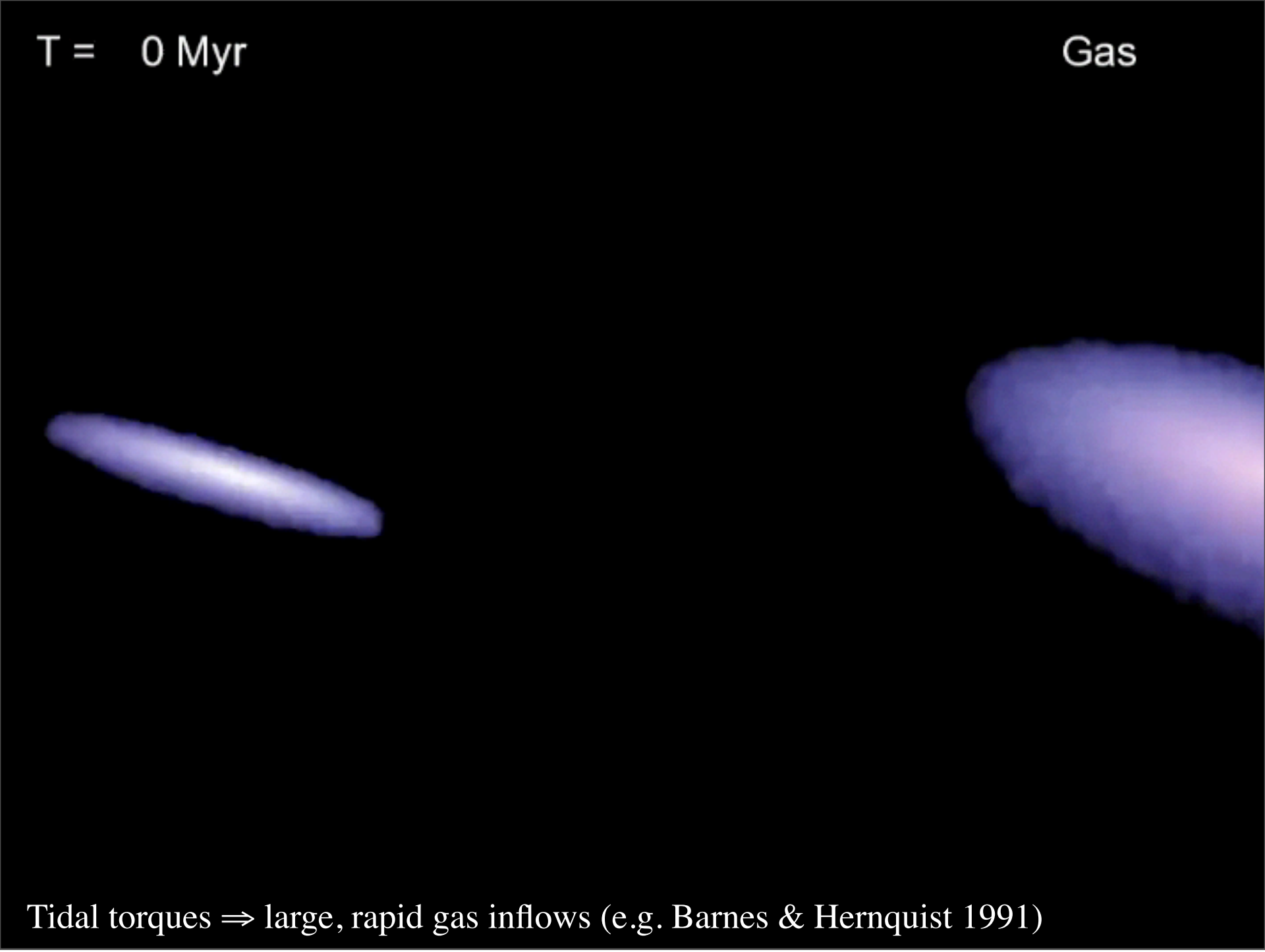
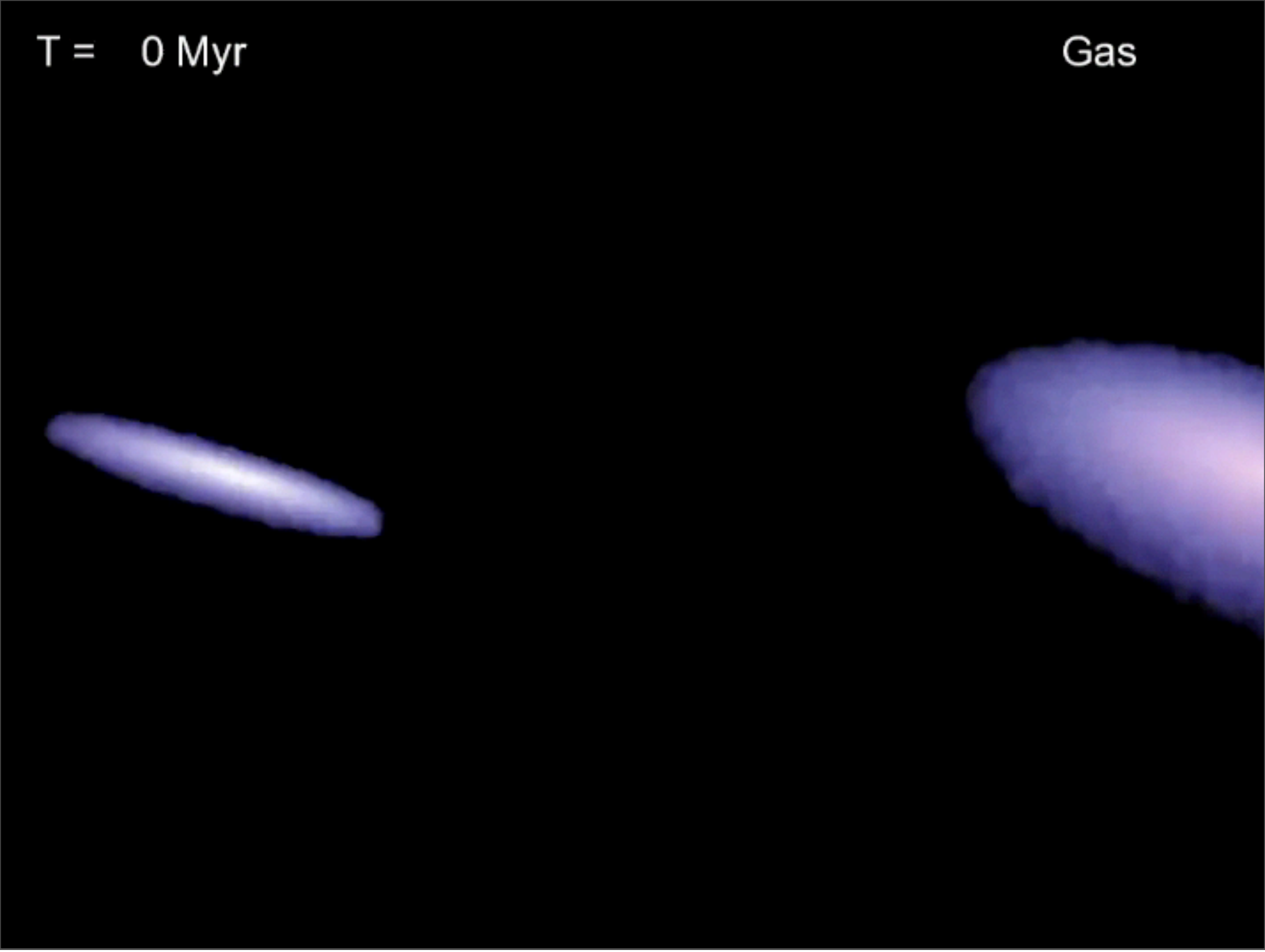
Gas




Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)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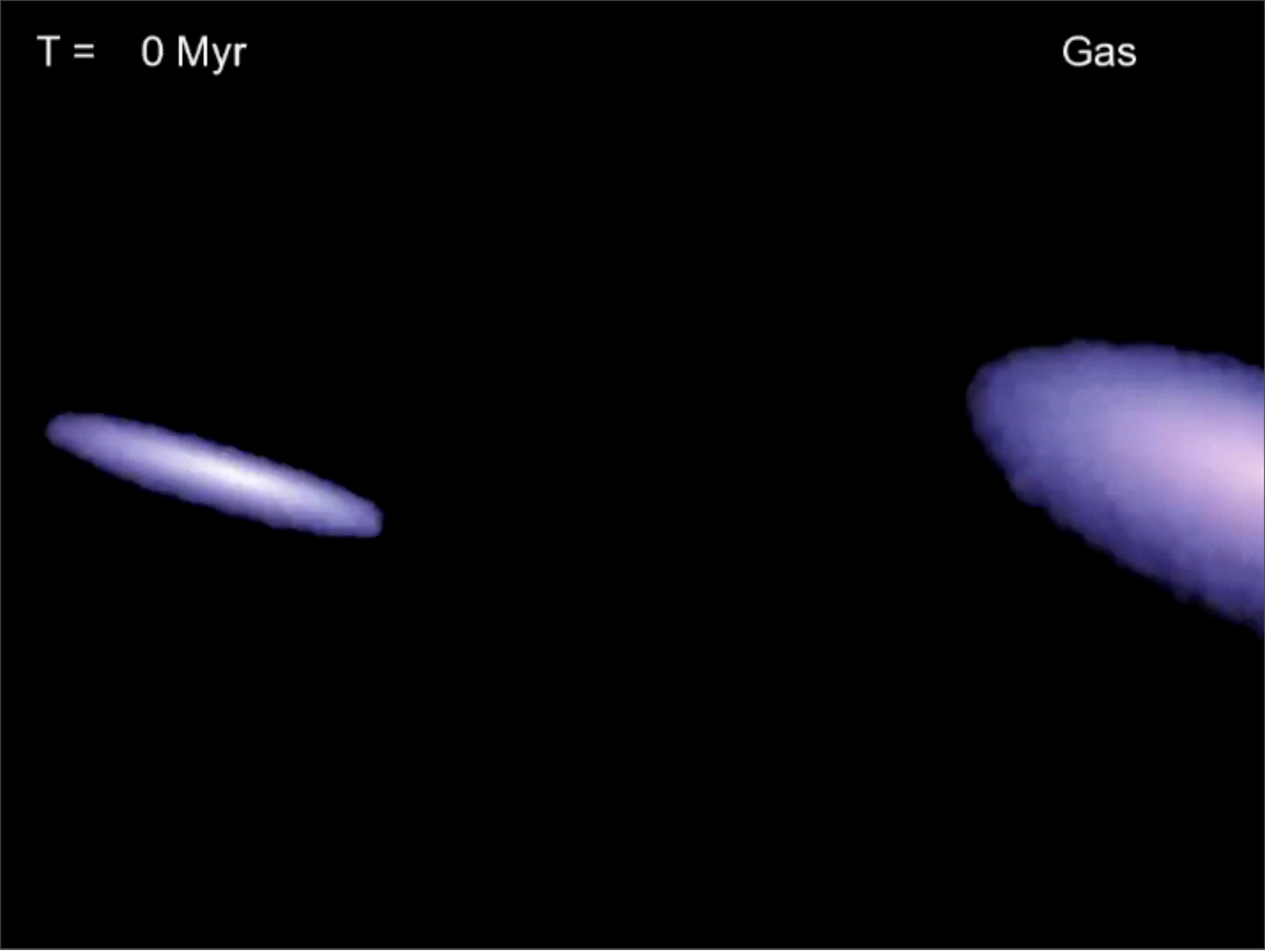
Triggers Starbursts (e.g. Mihos & Hernquist 1996)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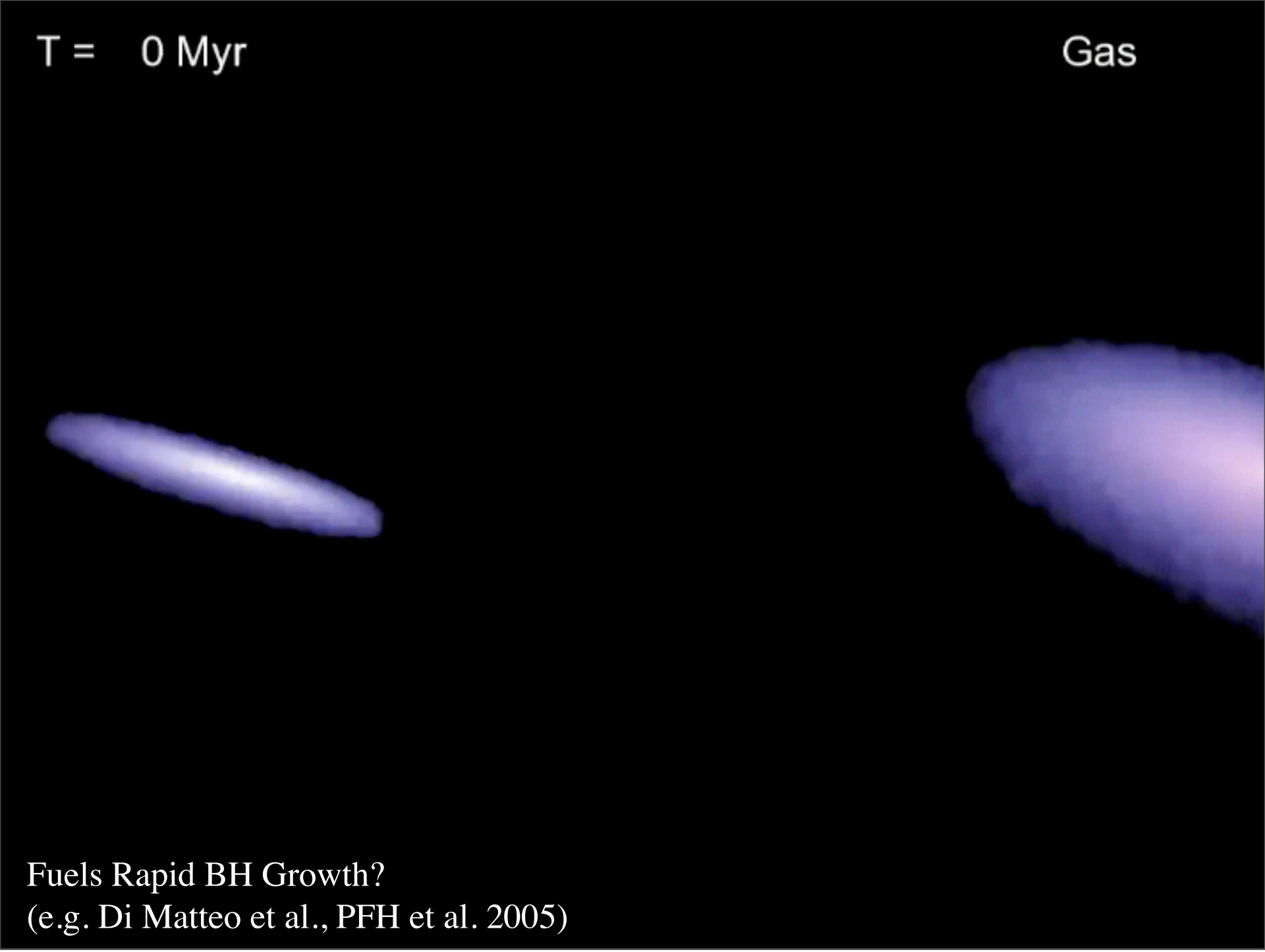
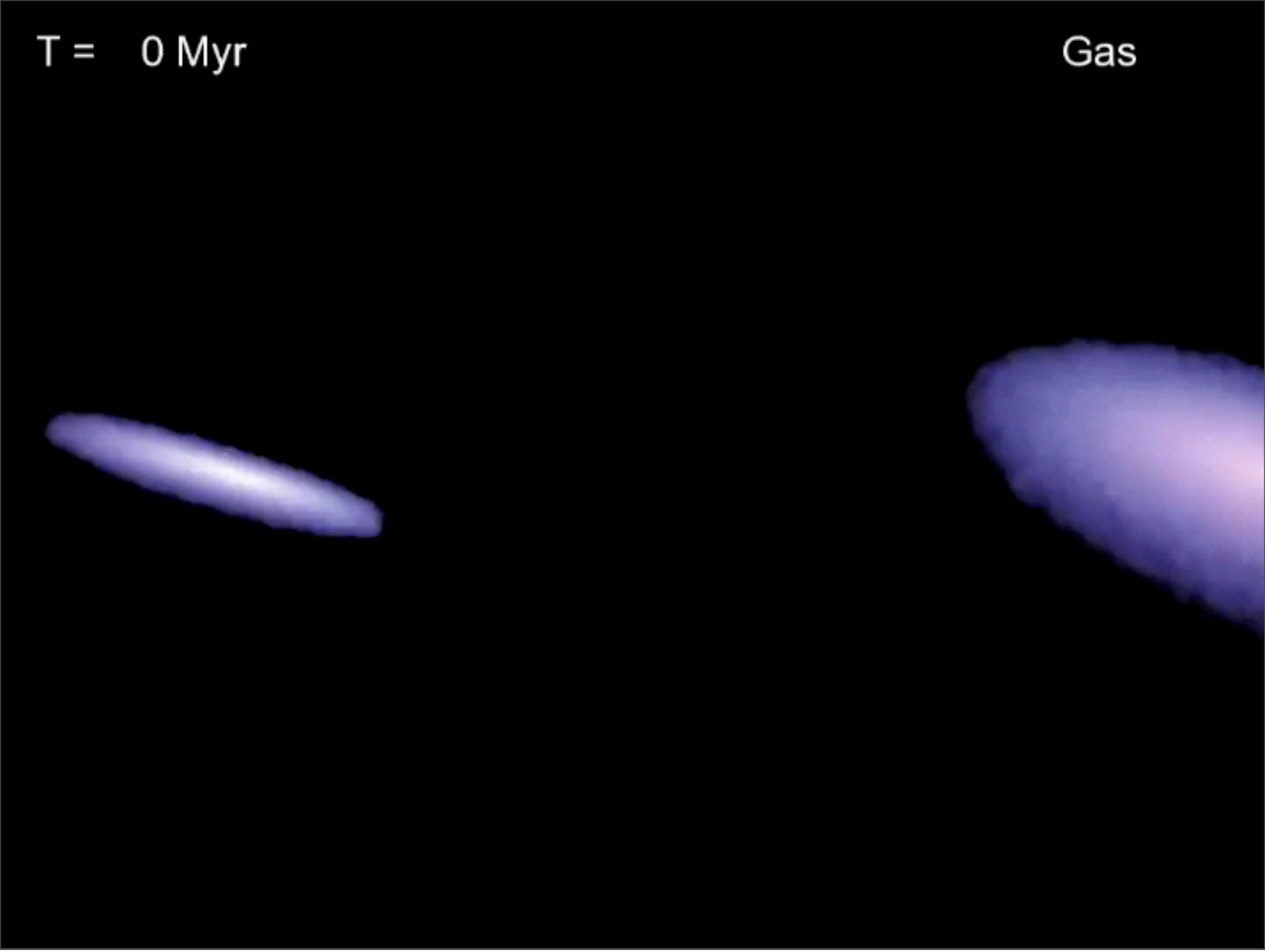



Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)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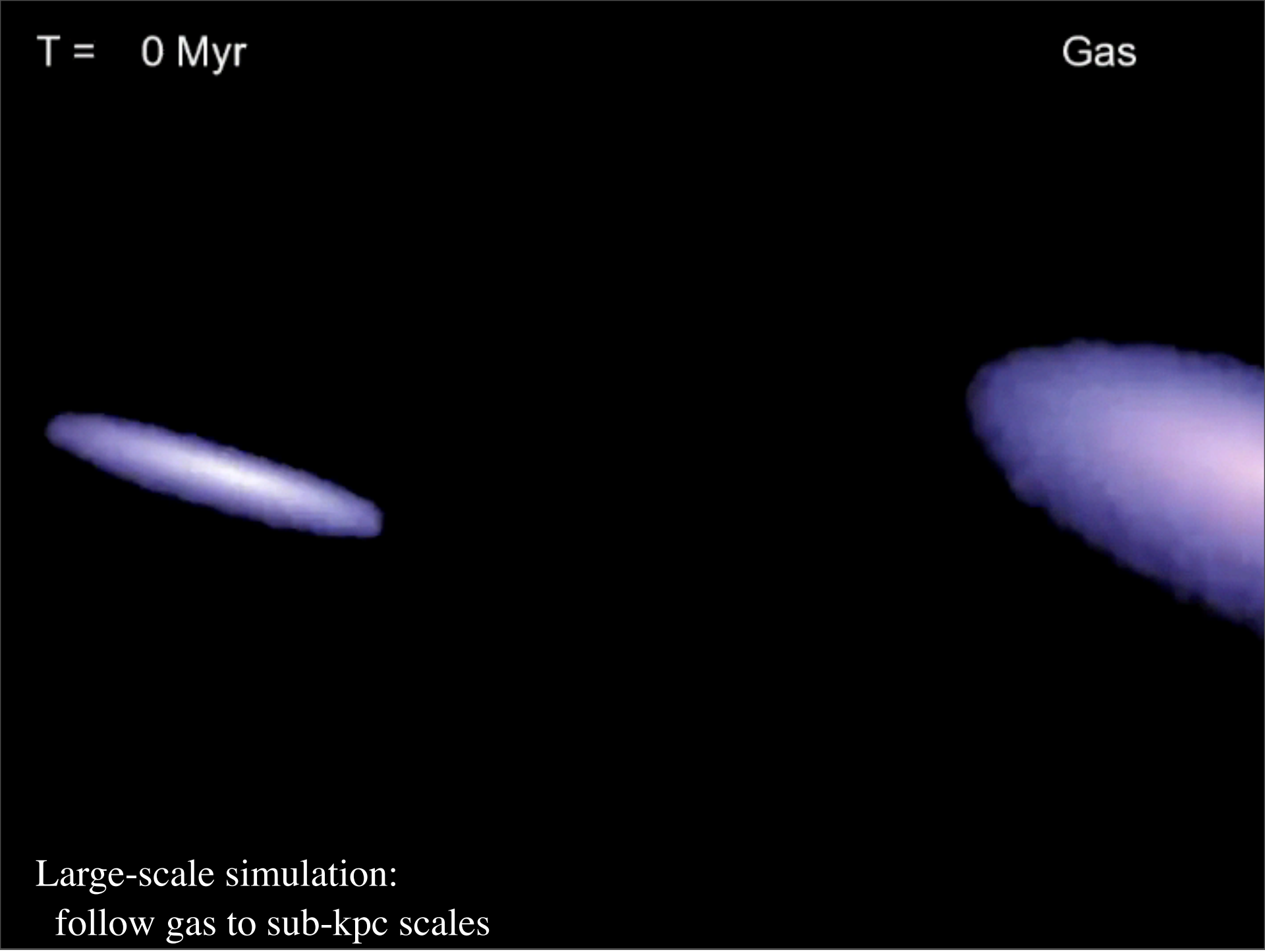
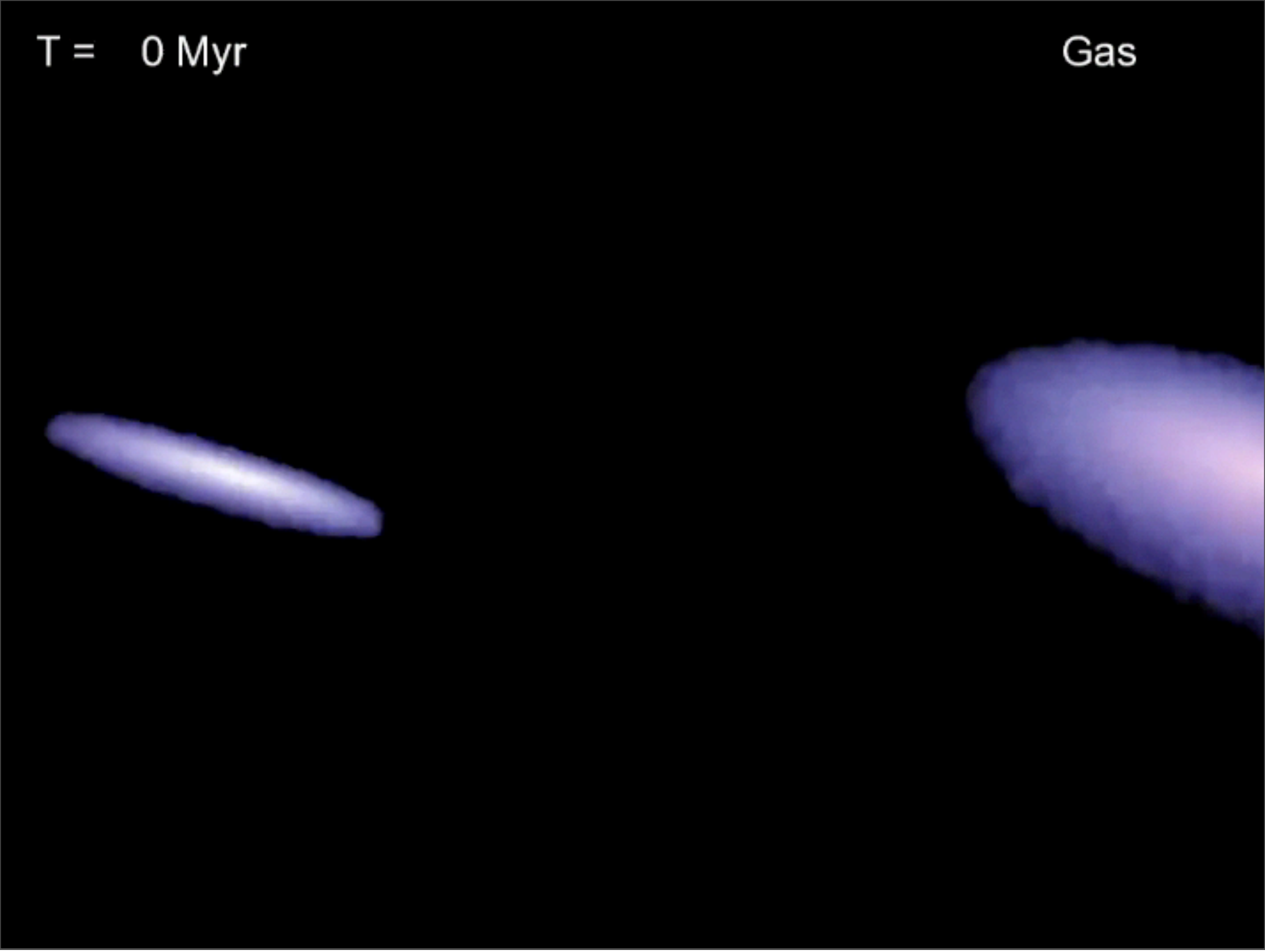



Large-scale simulation:
follow gas to sub-kpc scales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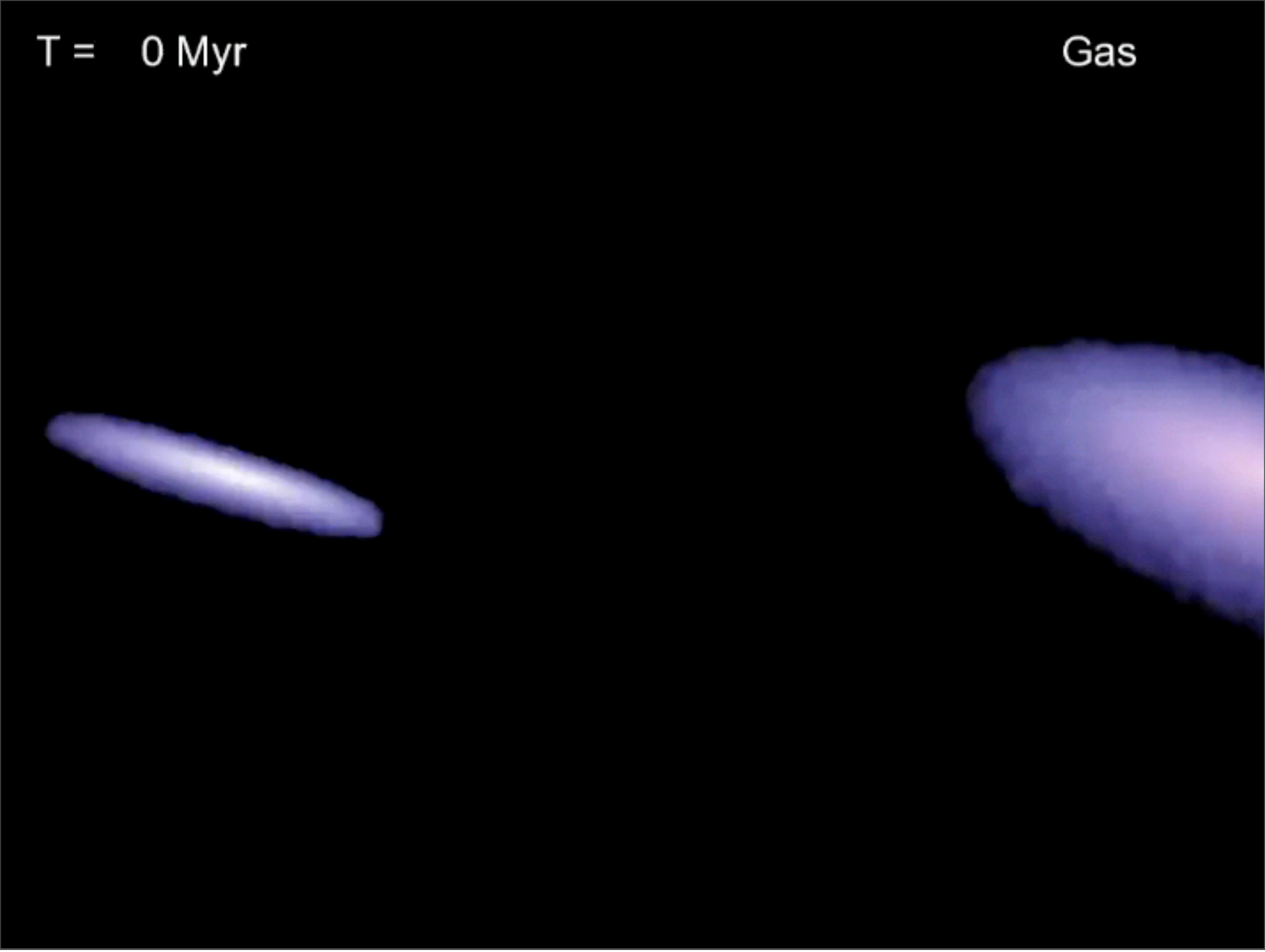
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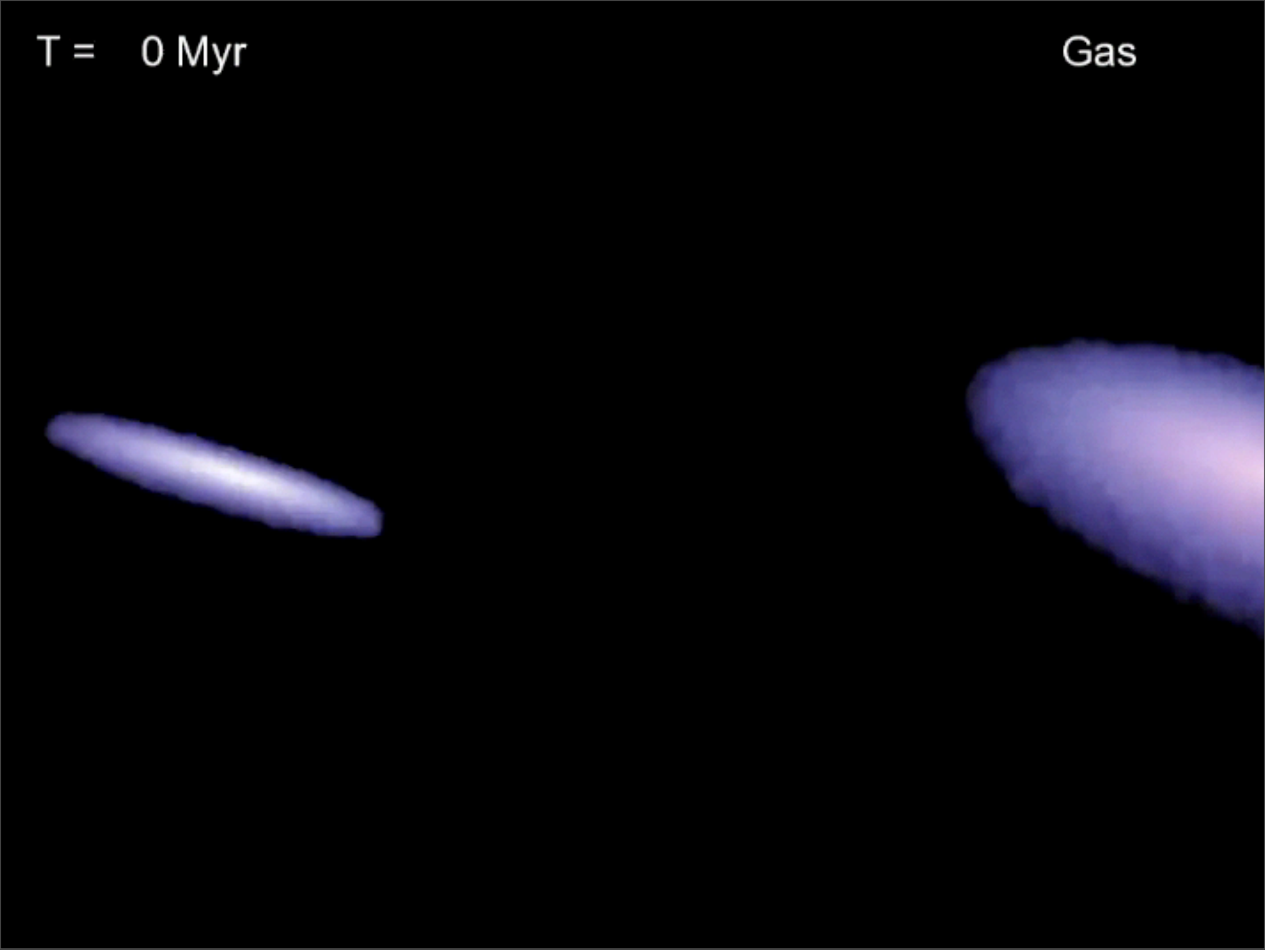
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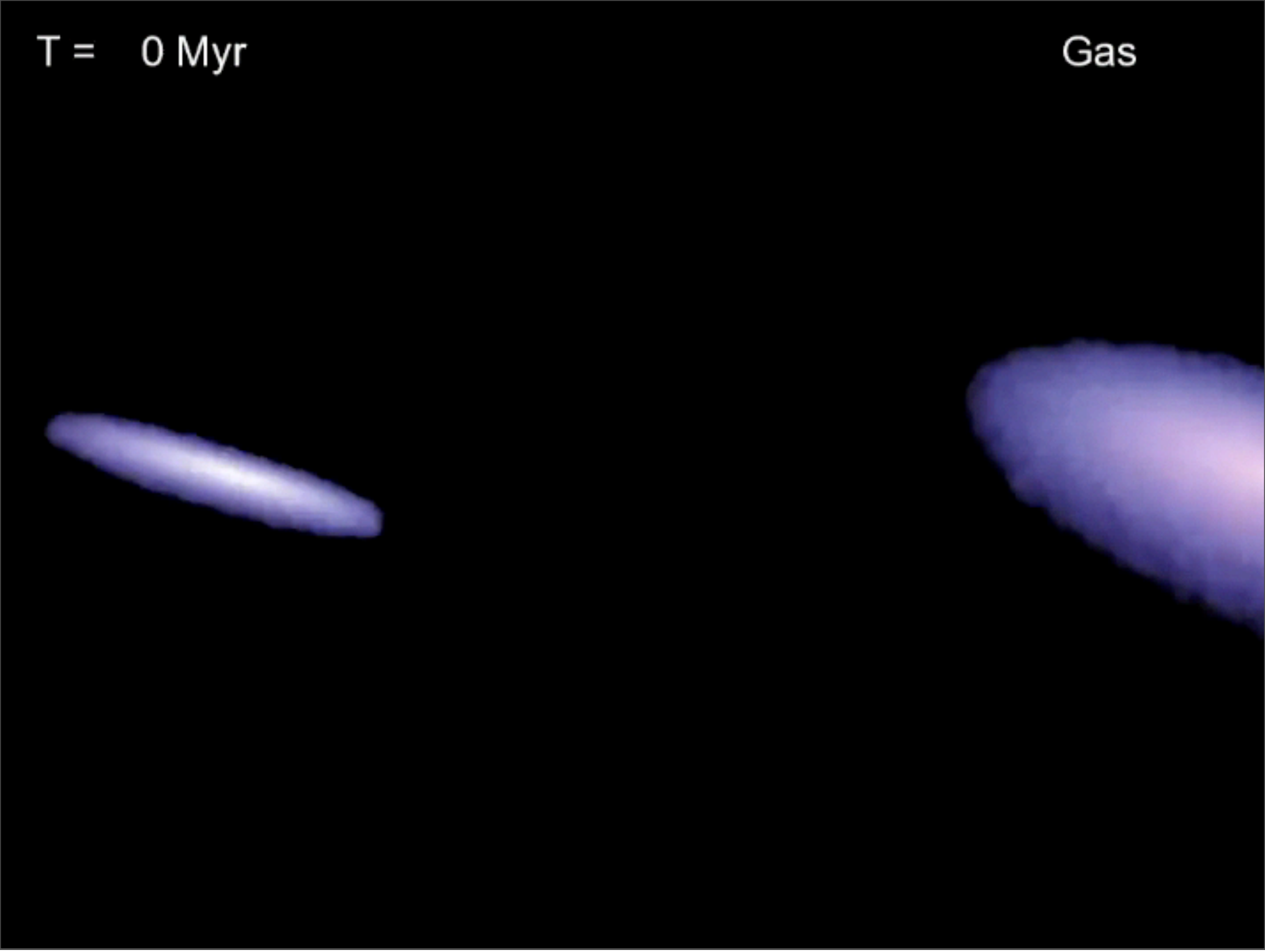
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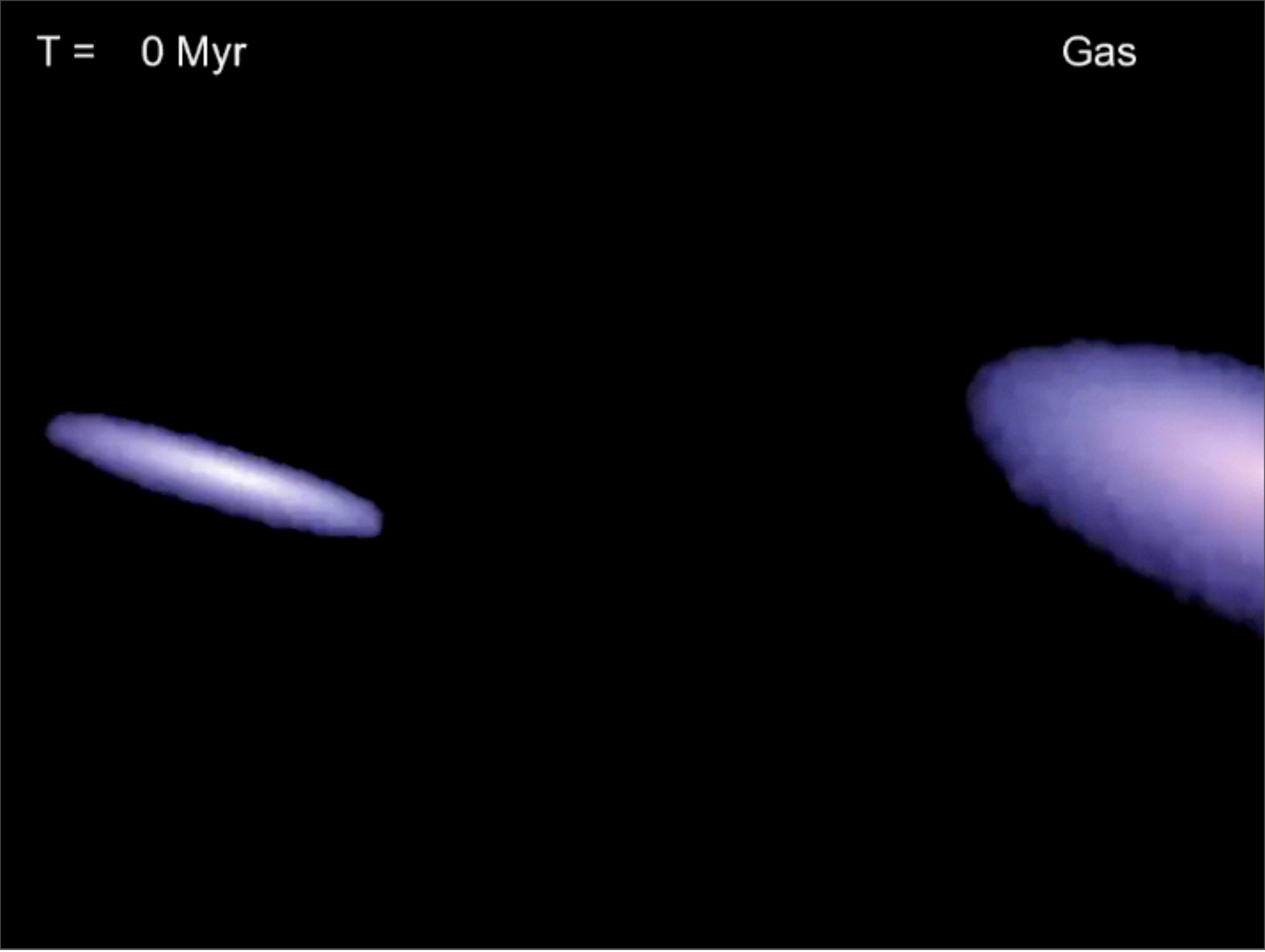
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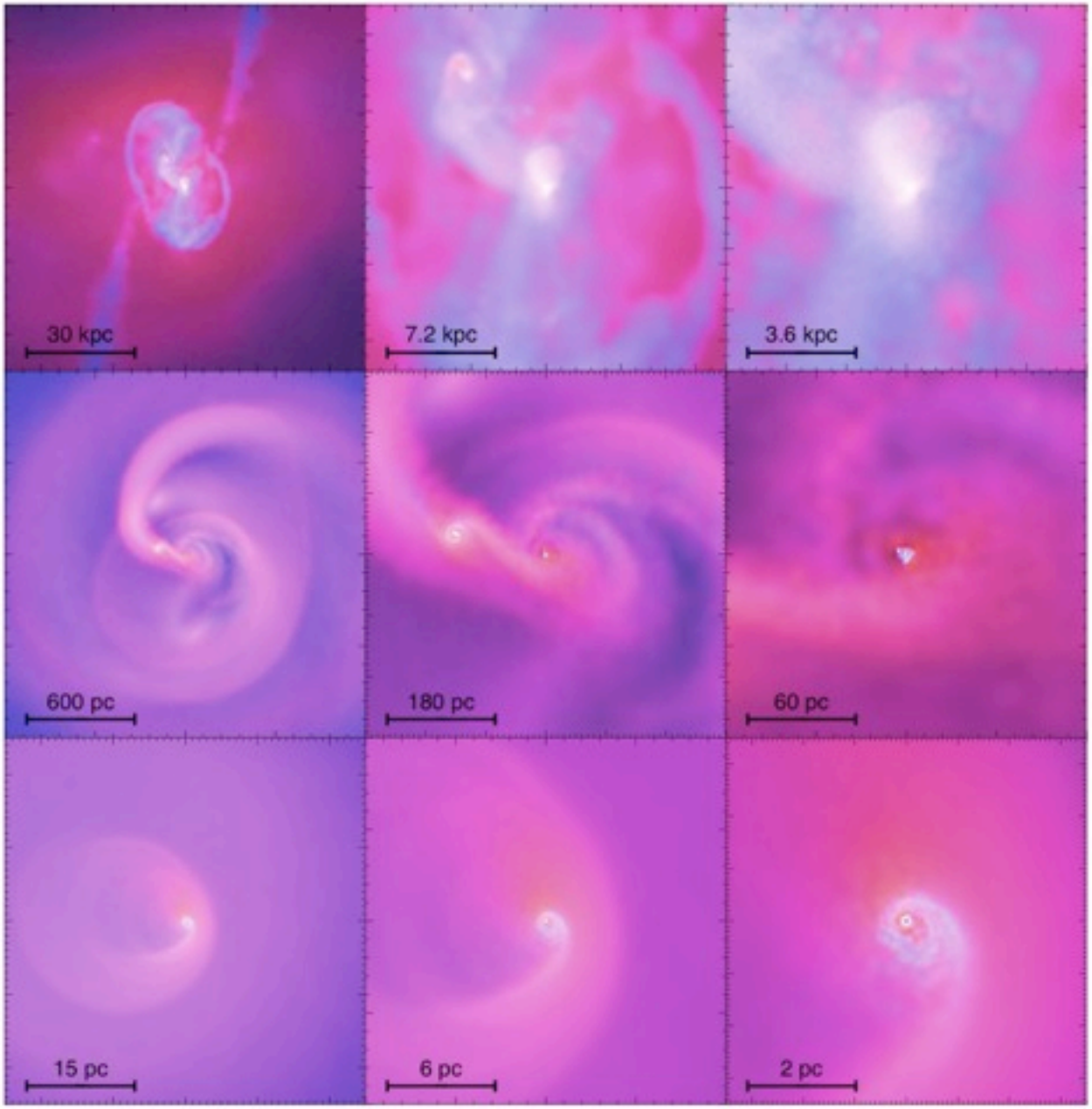
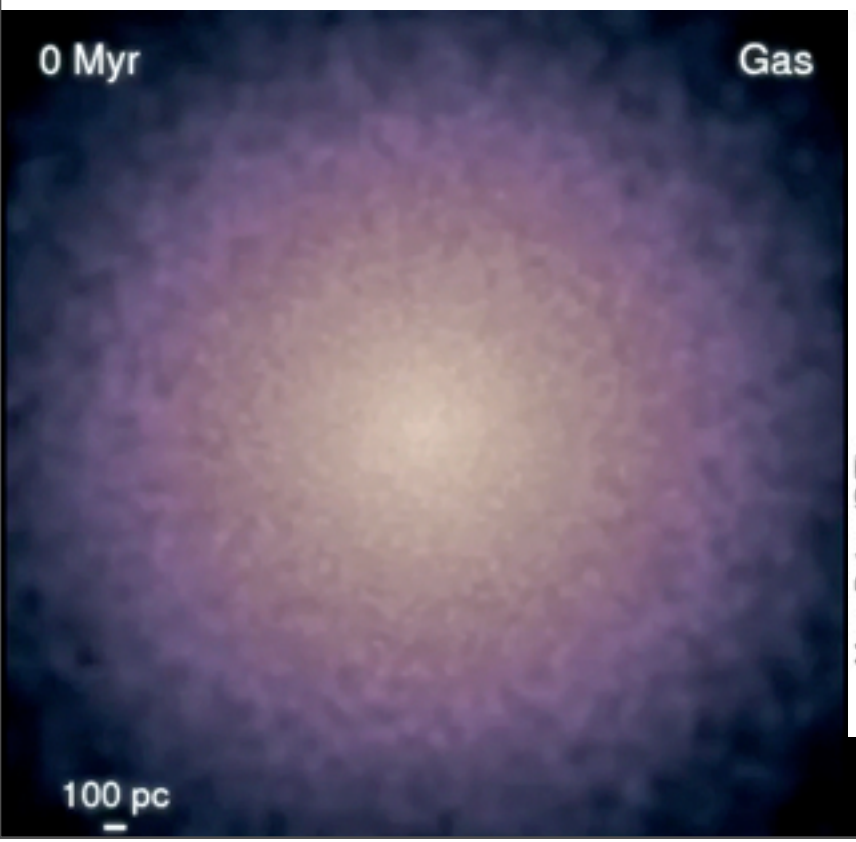
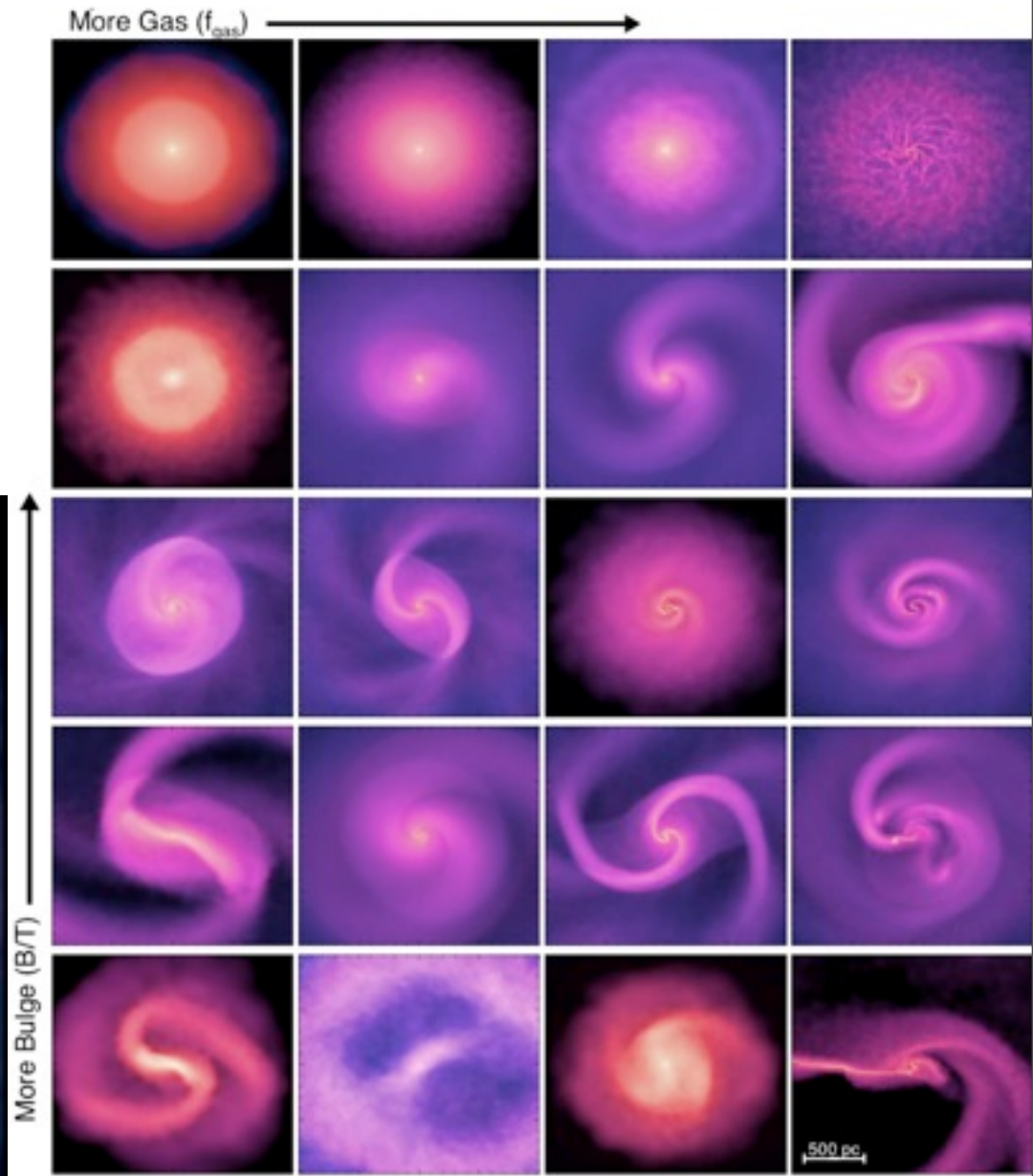



- Cascade of instabilities: merger not efficient inside ~kpc
- *Any* mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

# Sub-kpc scales: "Stuff within Stuff"

- Diverse morphologies: not just bars!
- Inflow is *not* smooth/continuous



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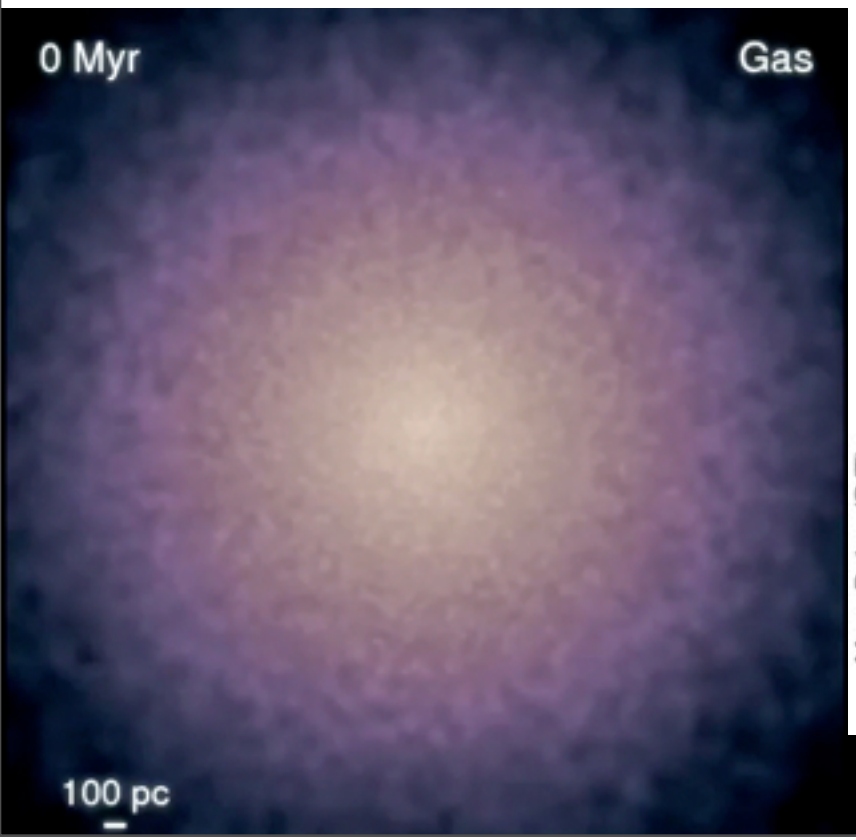
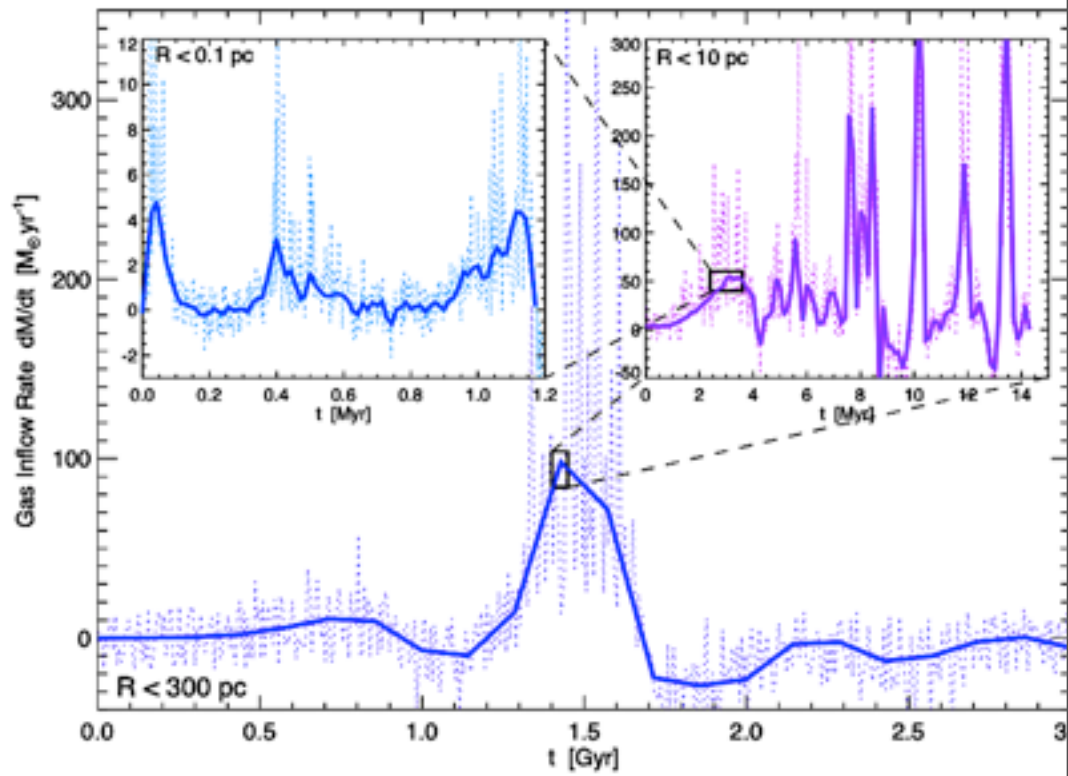
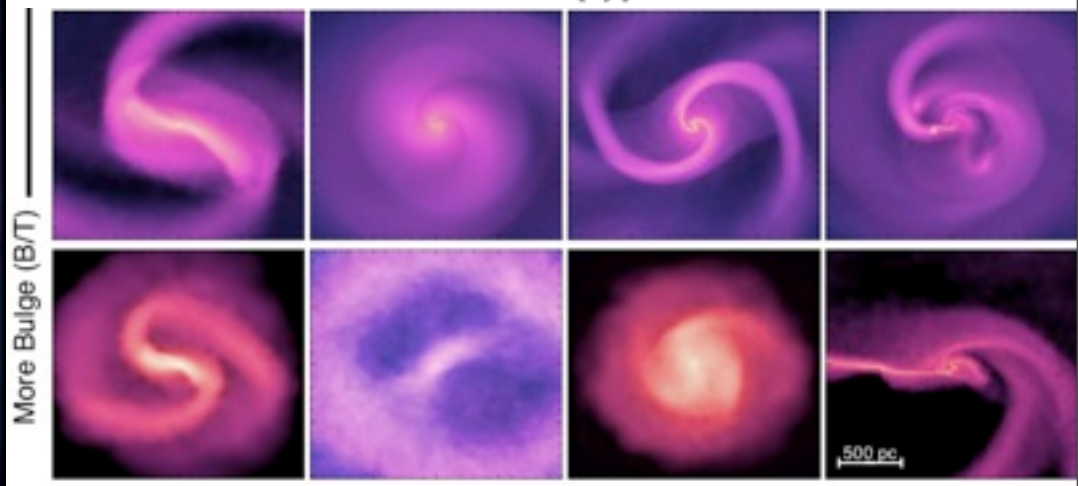
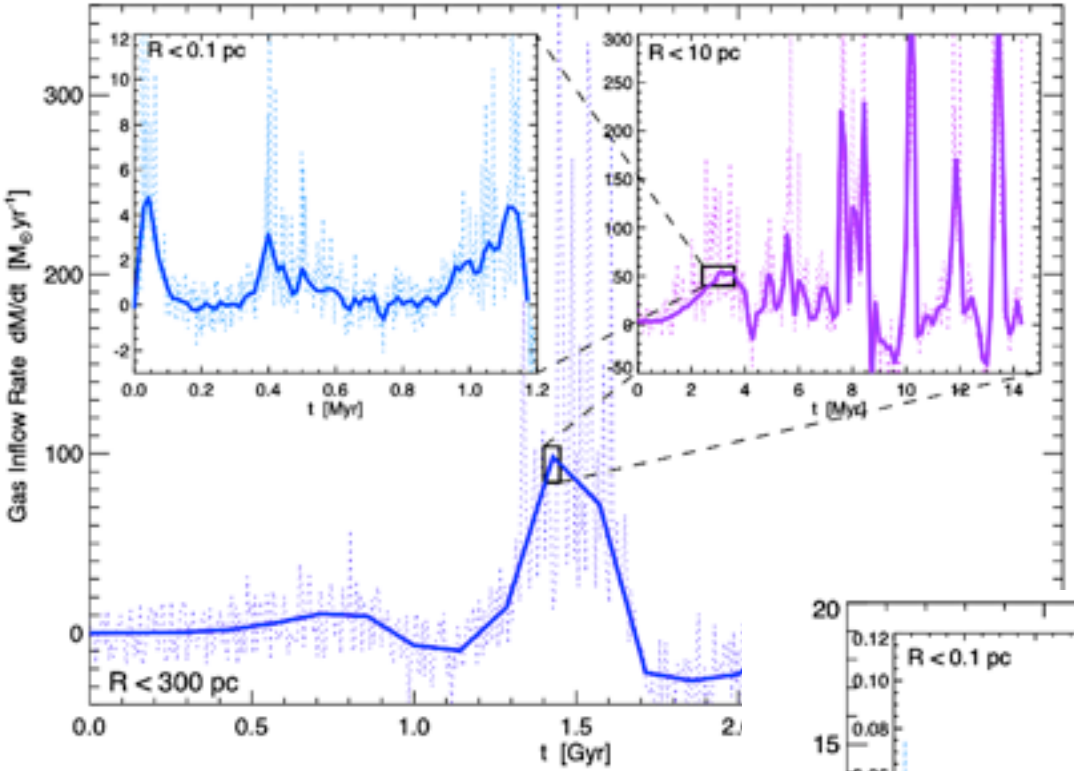


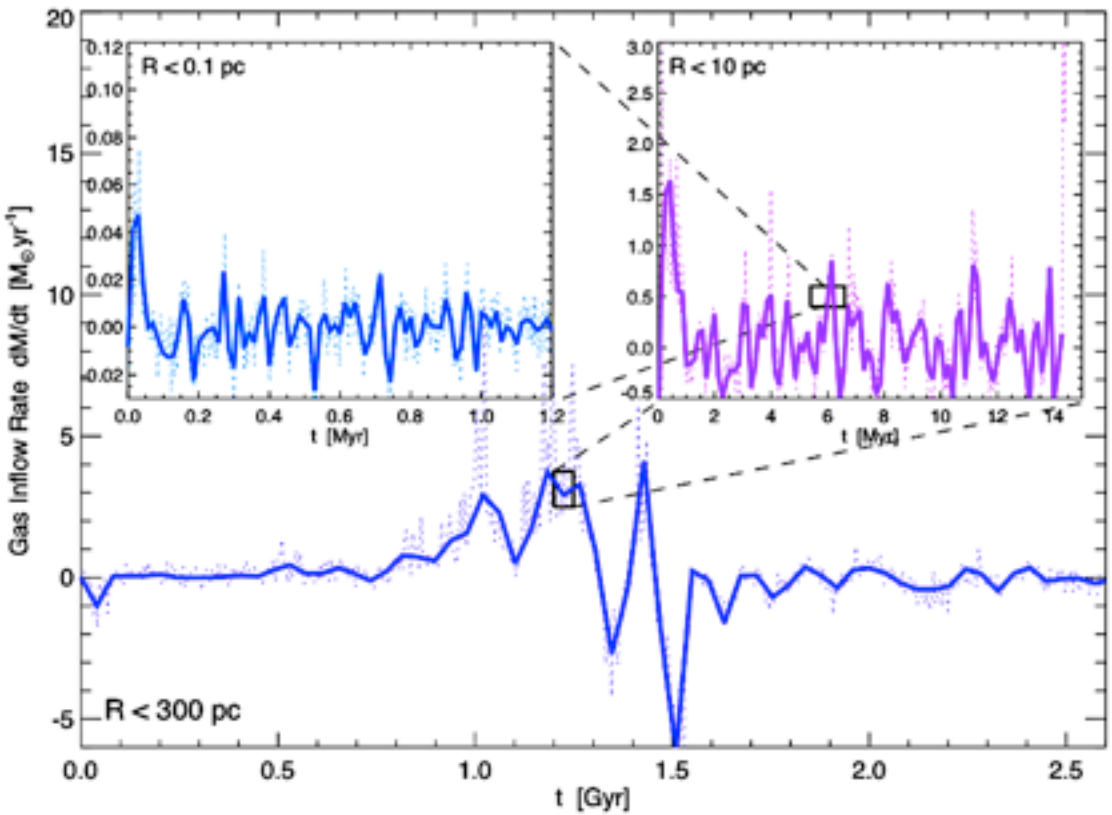



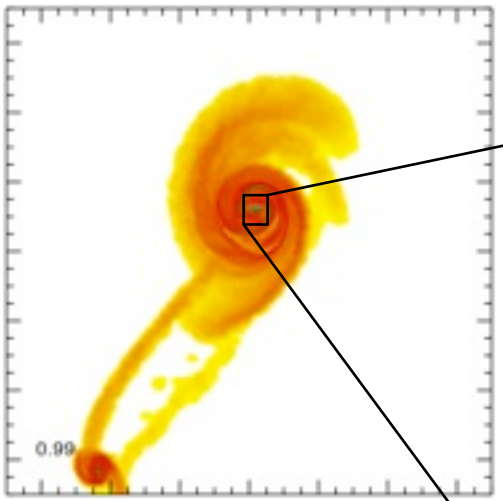



Gas-rich merger
(lots of inflow)

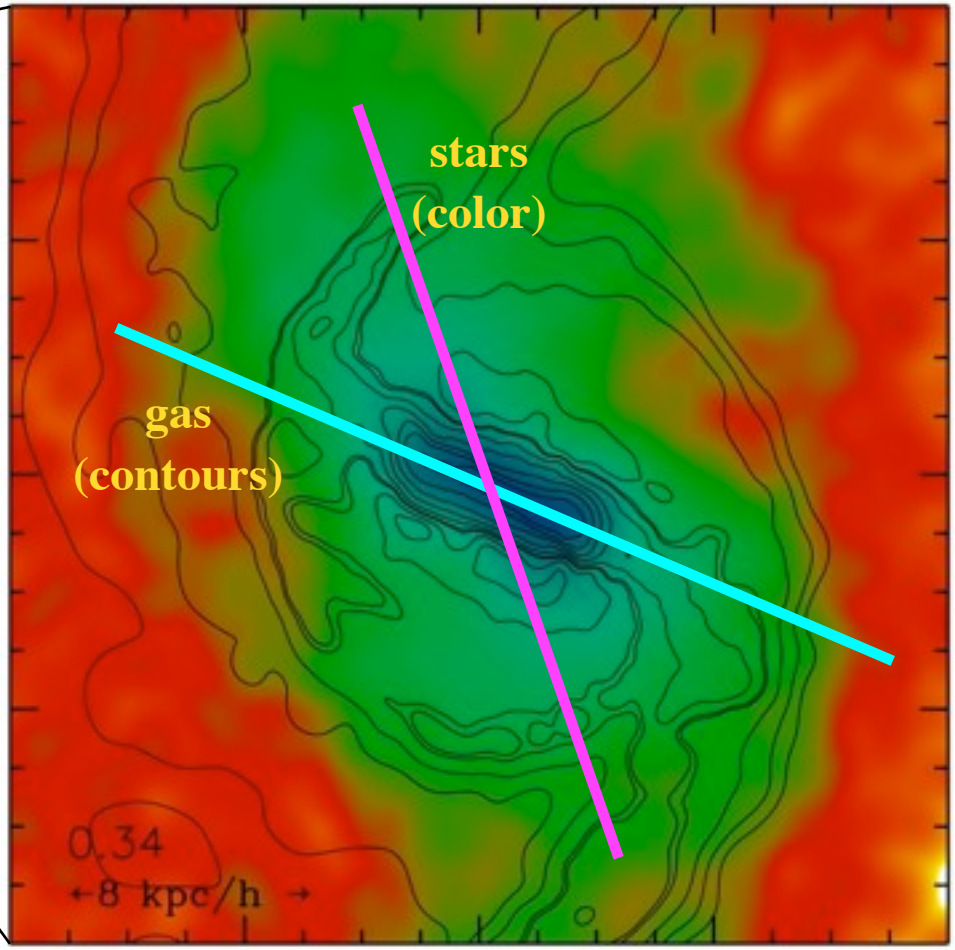
Weakly bar-unstable disk
(less inflow)



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




- *Stars* torquing on *gas*



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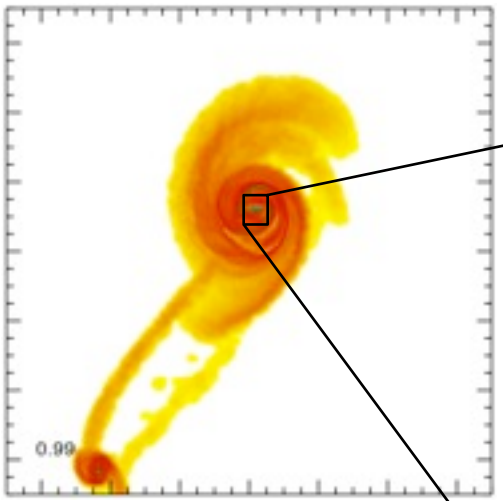


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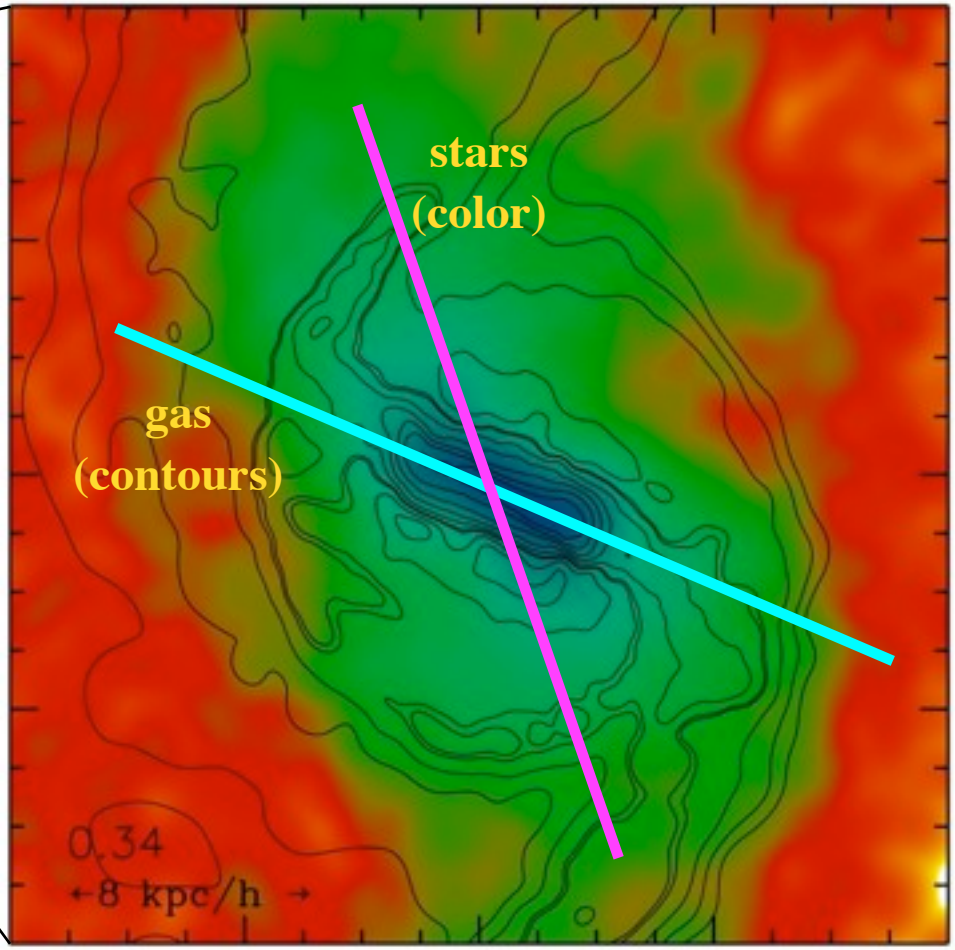



Derive 'Instability' Rate:

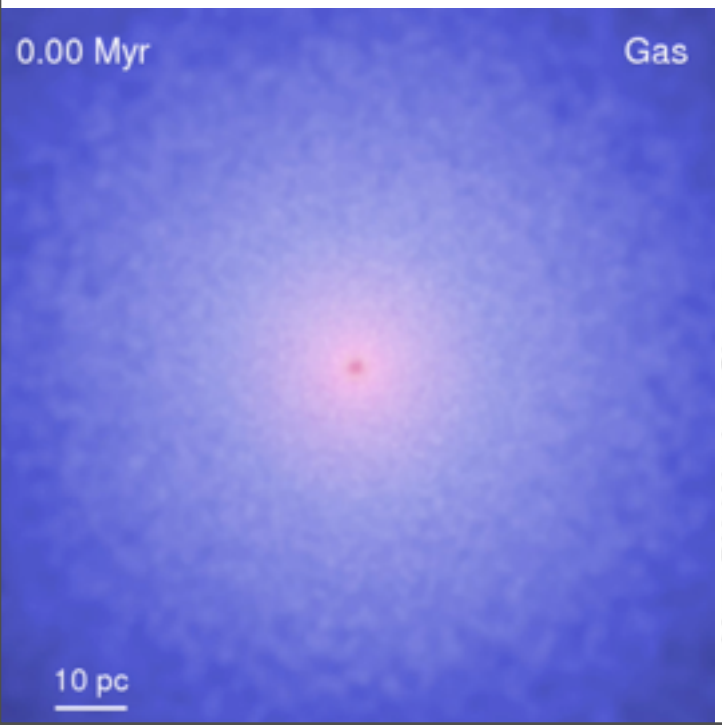
$$\dot{M} \approx 10\, M_{\odot}\, \mathrm{yr}^{-1} \left(\frac{\mathrm{Disk}}{\mathrm{Total}}\right)^{5/2} M_{\mathrm{BH},\,8}^{-1/6}\, M_{\mathrm{gas},\,9}\, R_{0,100}^{-3/2}$$

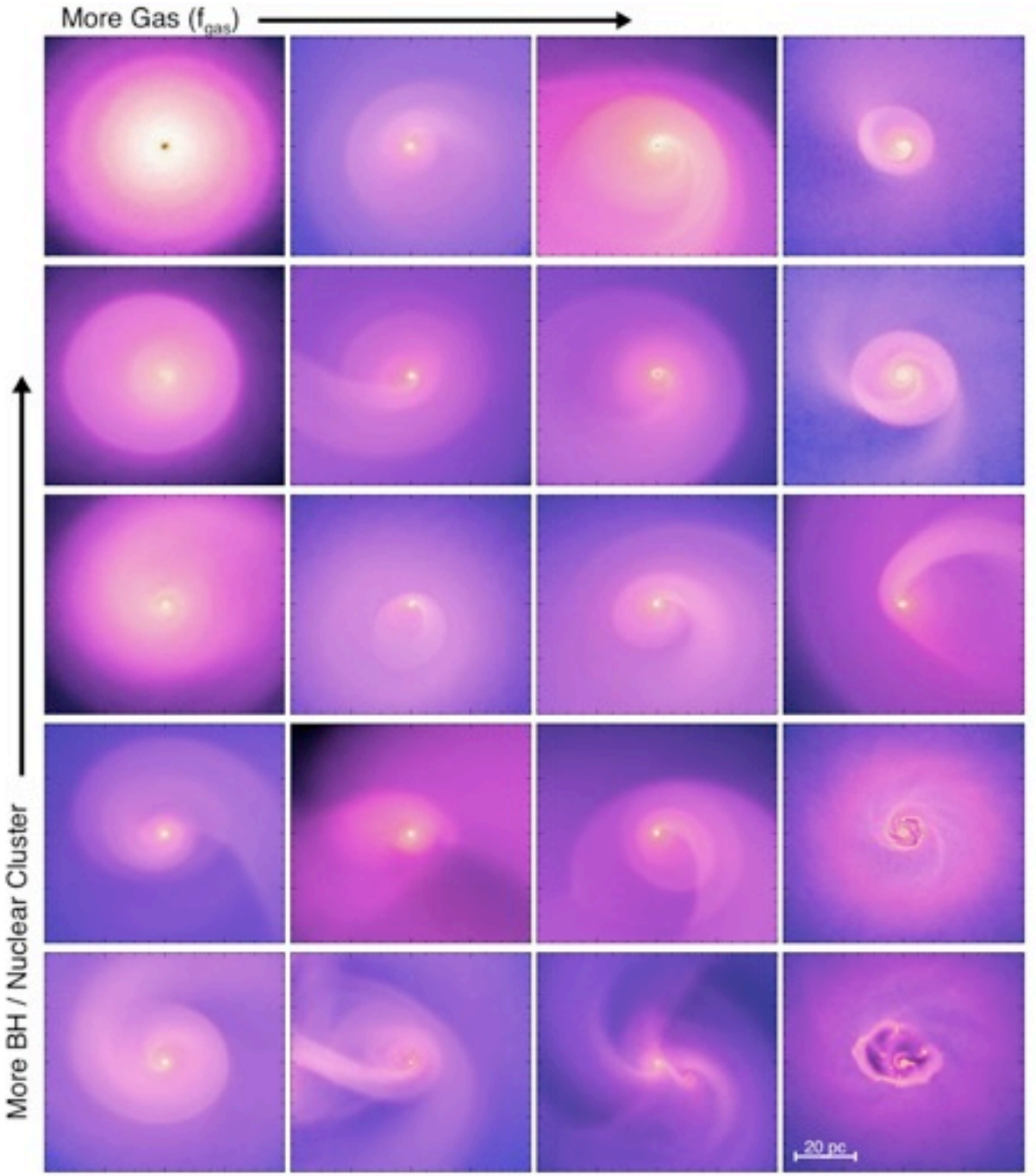
So, what about the “small” scales

near the BH?

~10 pc scales:
Nuclear eccentric disks

- Inside BH radius of influence: eccentric, precessing disks



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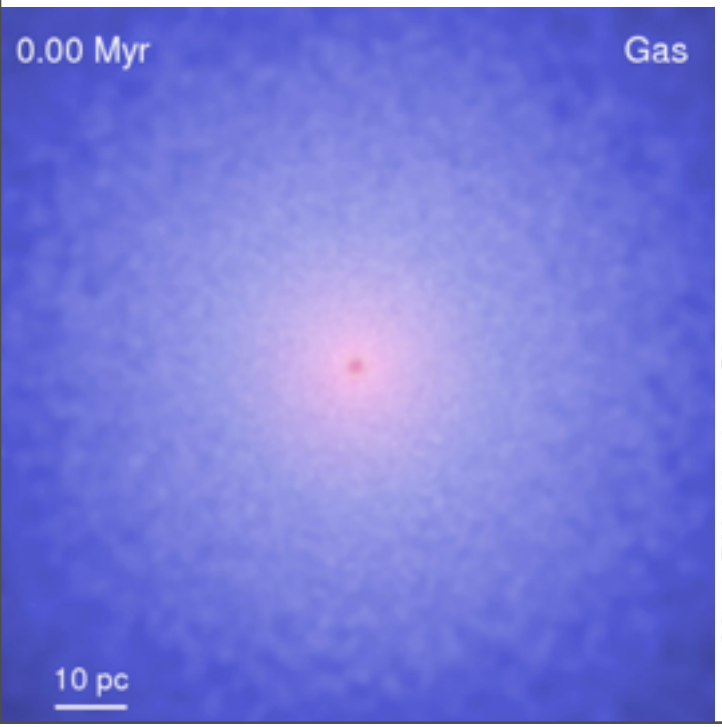
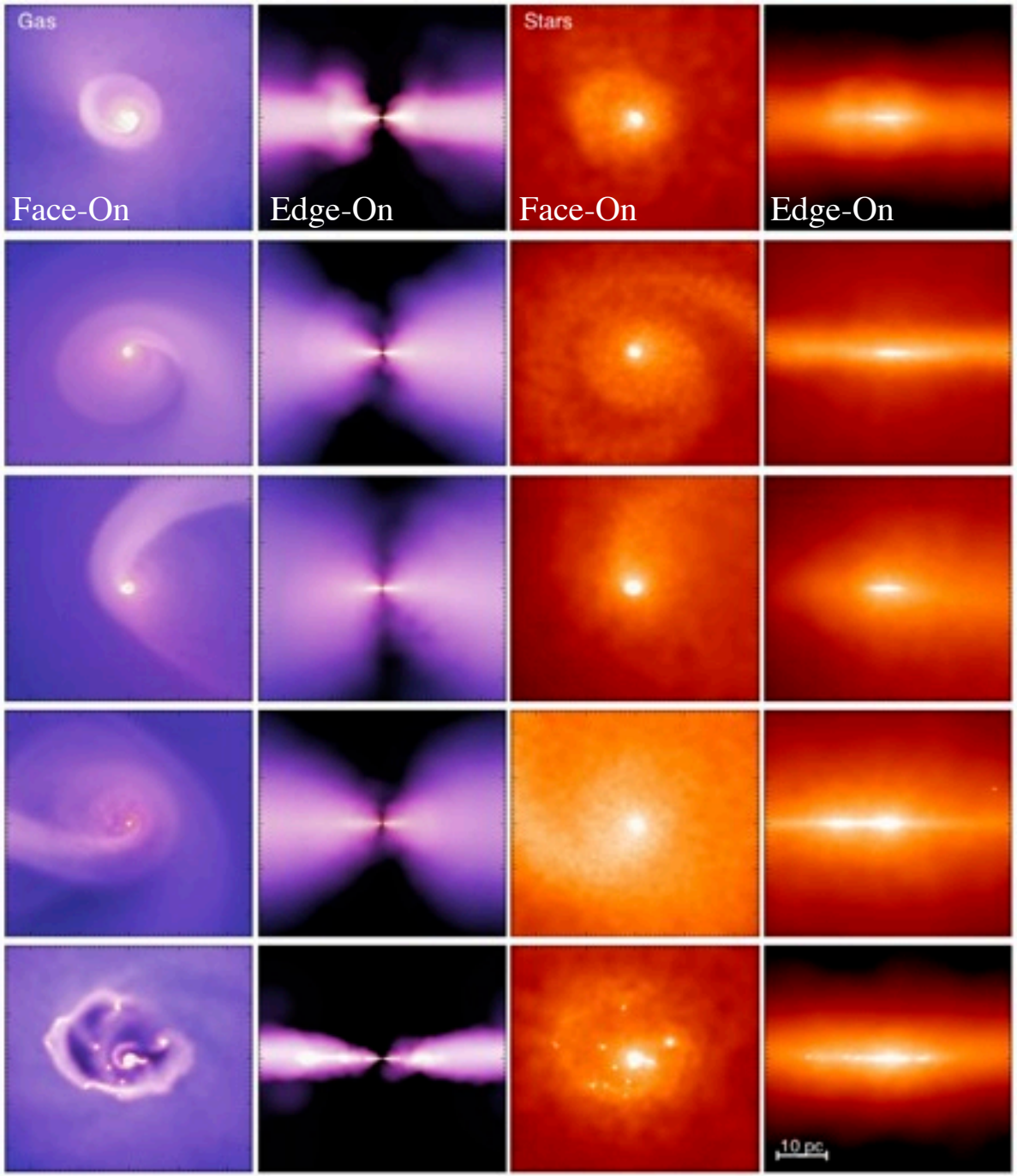


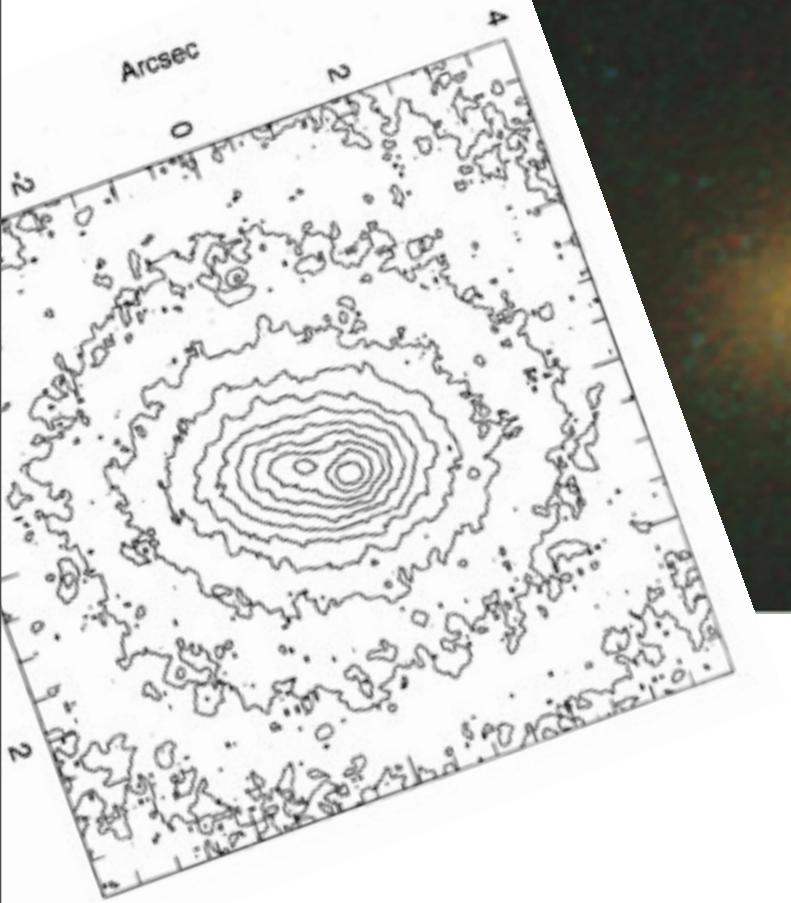



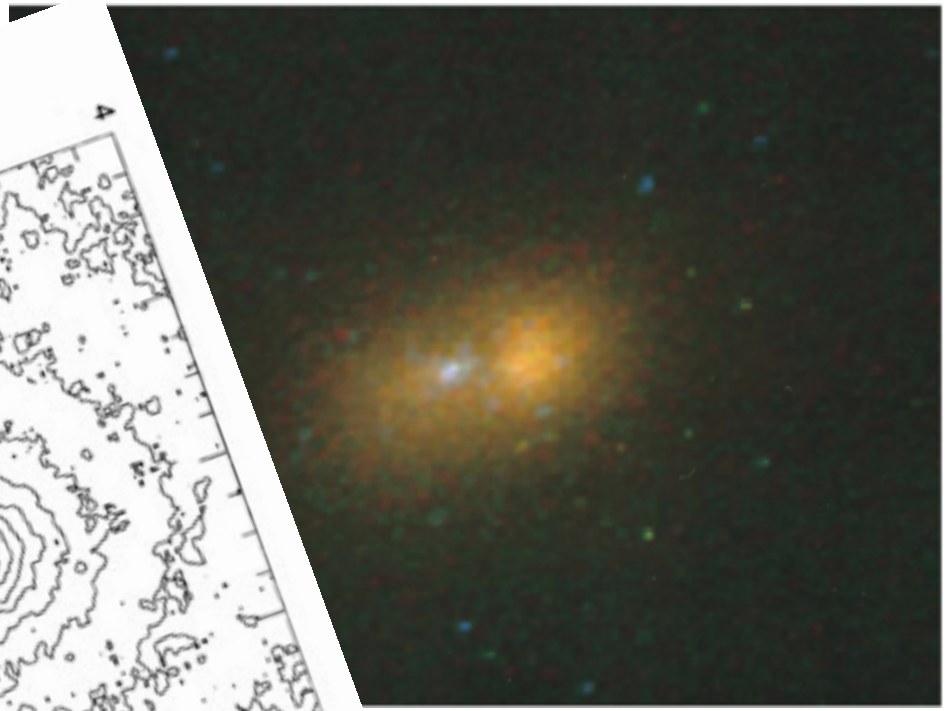
- These are observed!

  M31, NGC4486B, many candidates

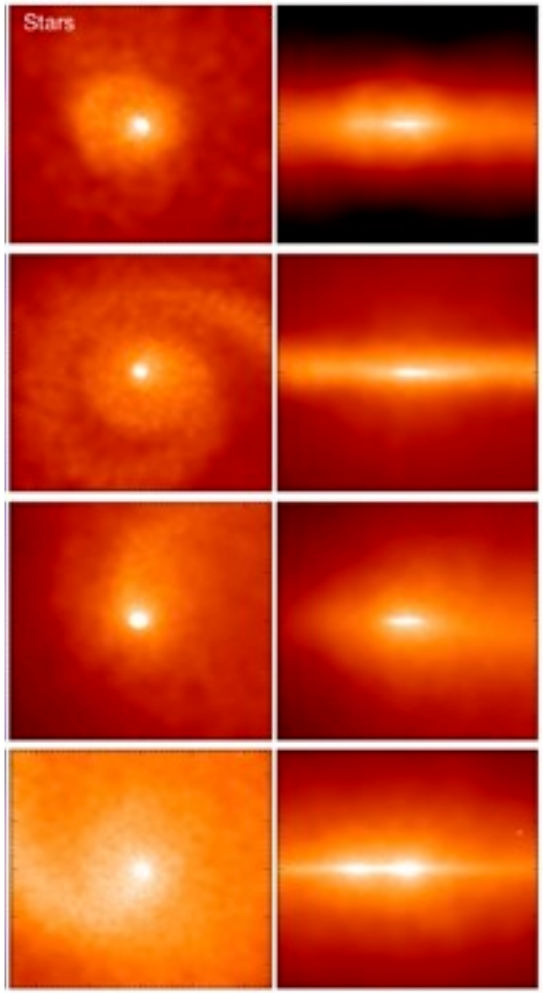
  (NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)

**M31:**



Lauer et al. 1993
Kormendy & Bender 1999



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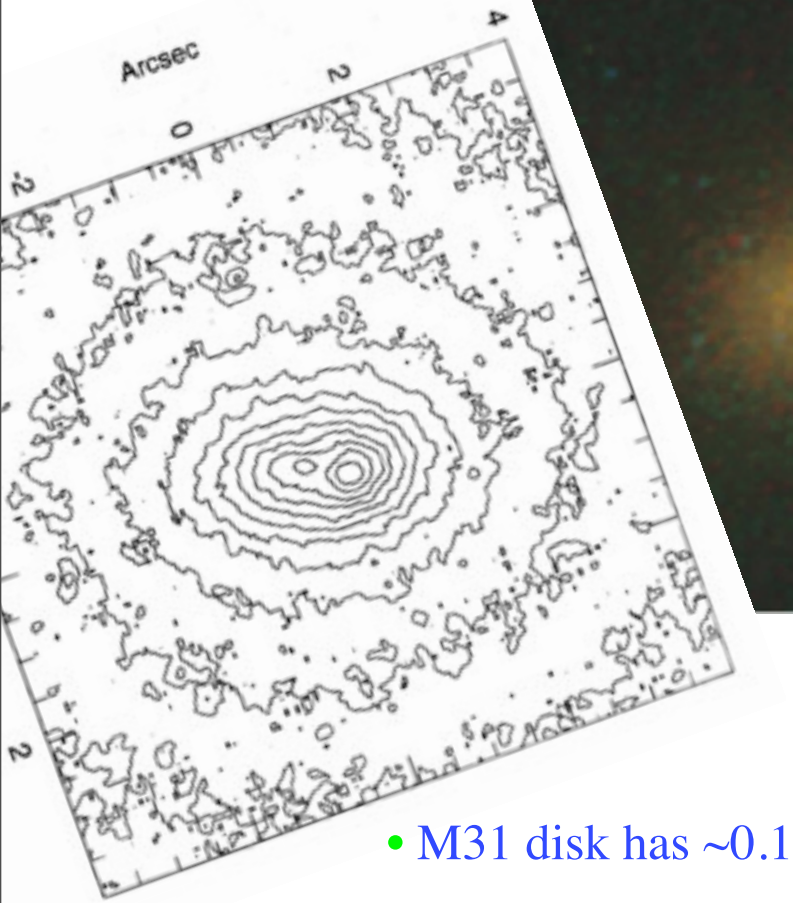


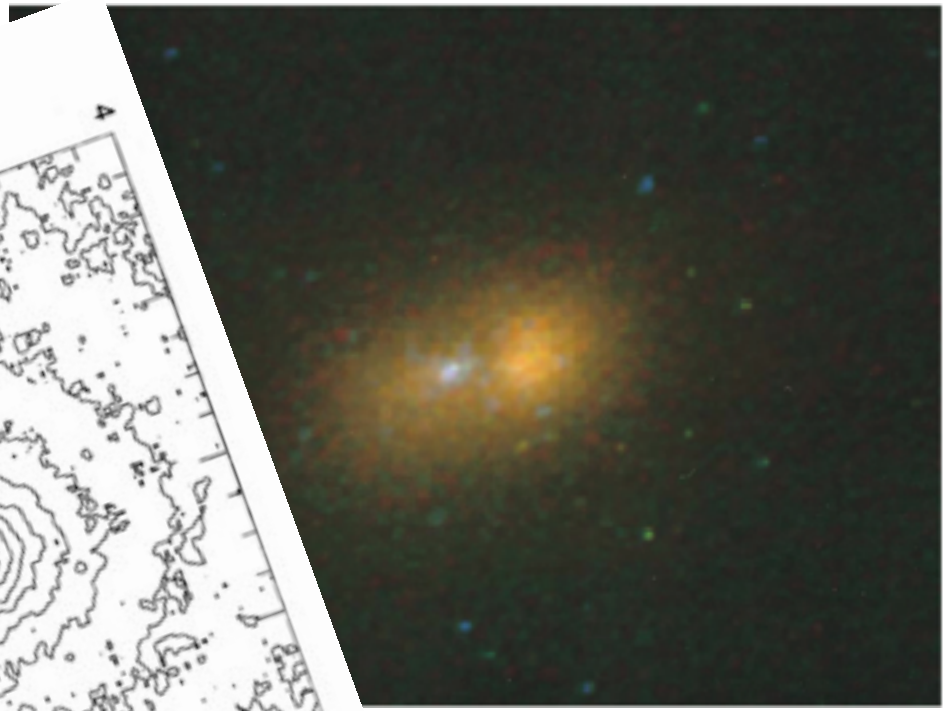

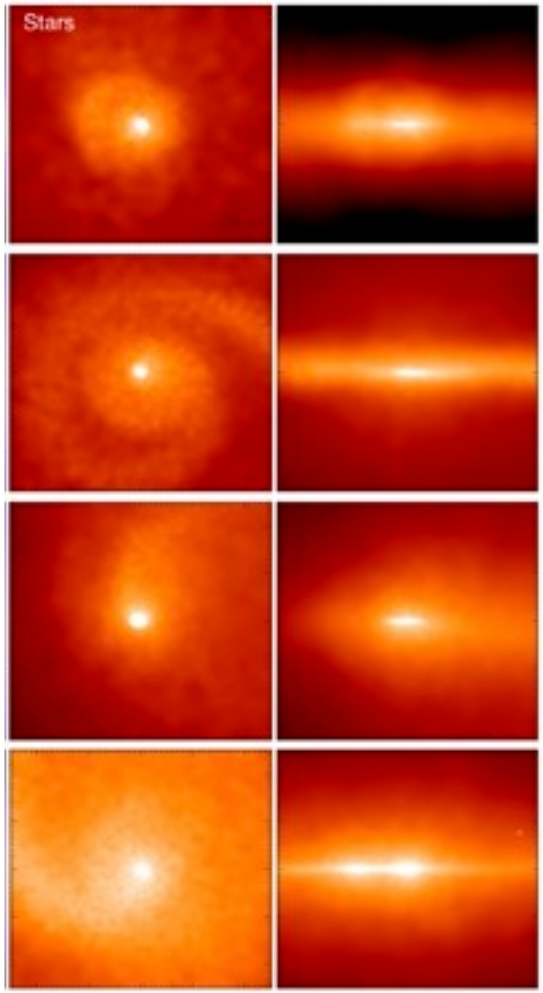


Lauer et al. 1993
Kormendy & Bender 1999

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

- These are observed!

  M31, NGC4486B, many candidates

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

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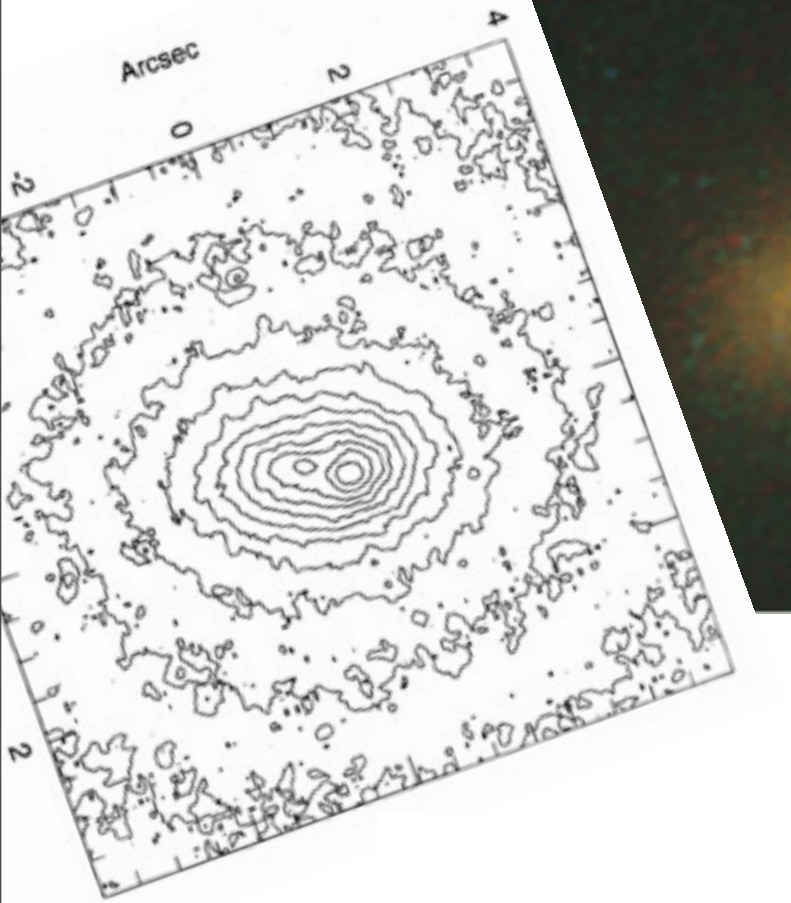


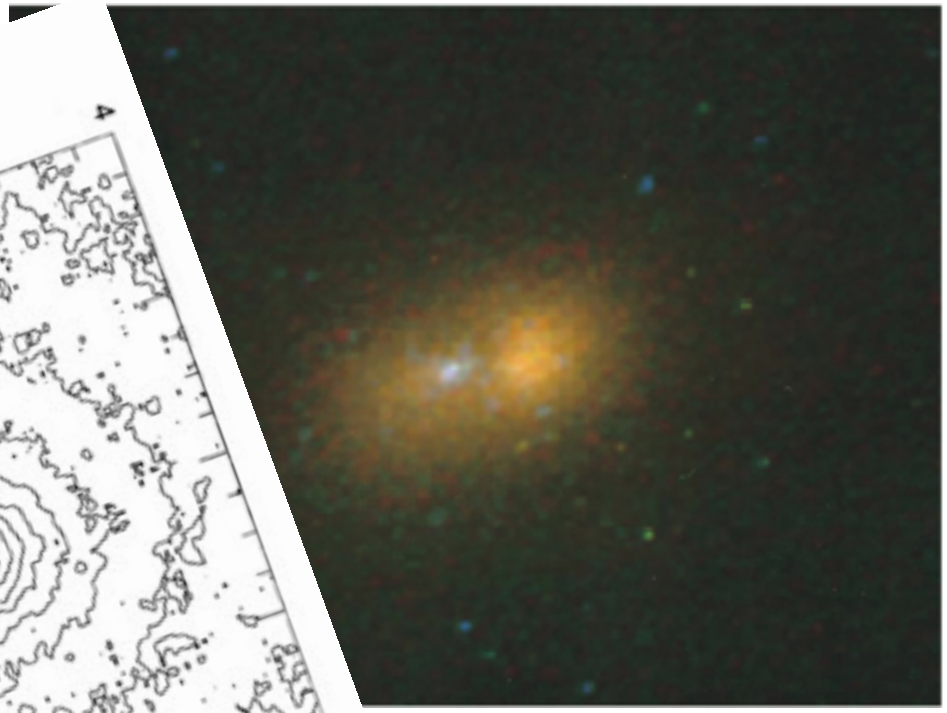

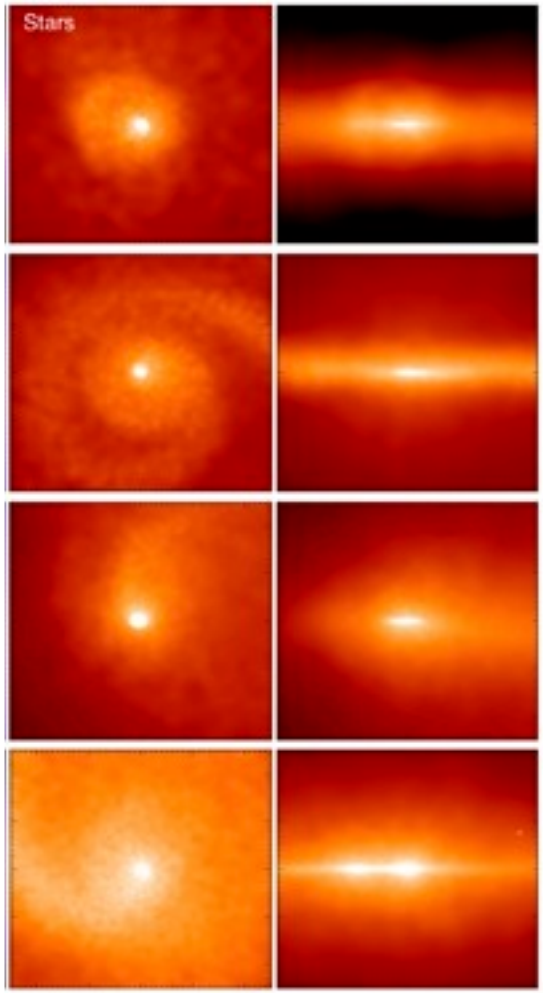


Lauer et al. 1993
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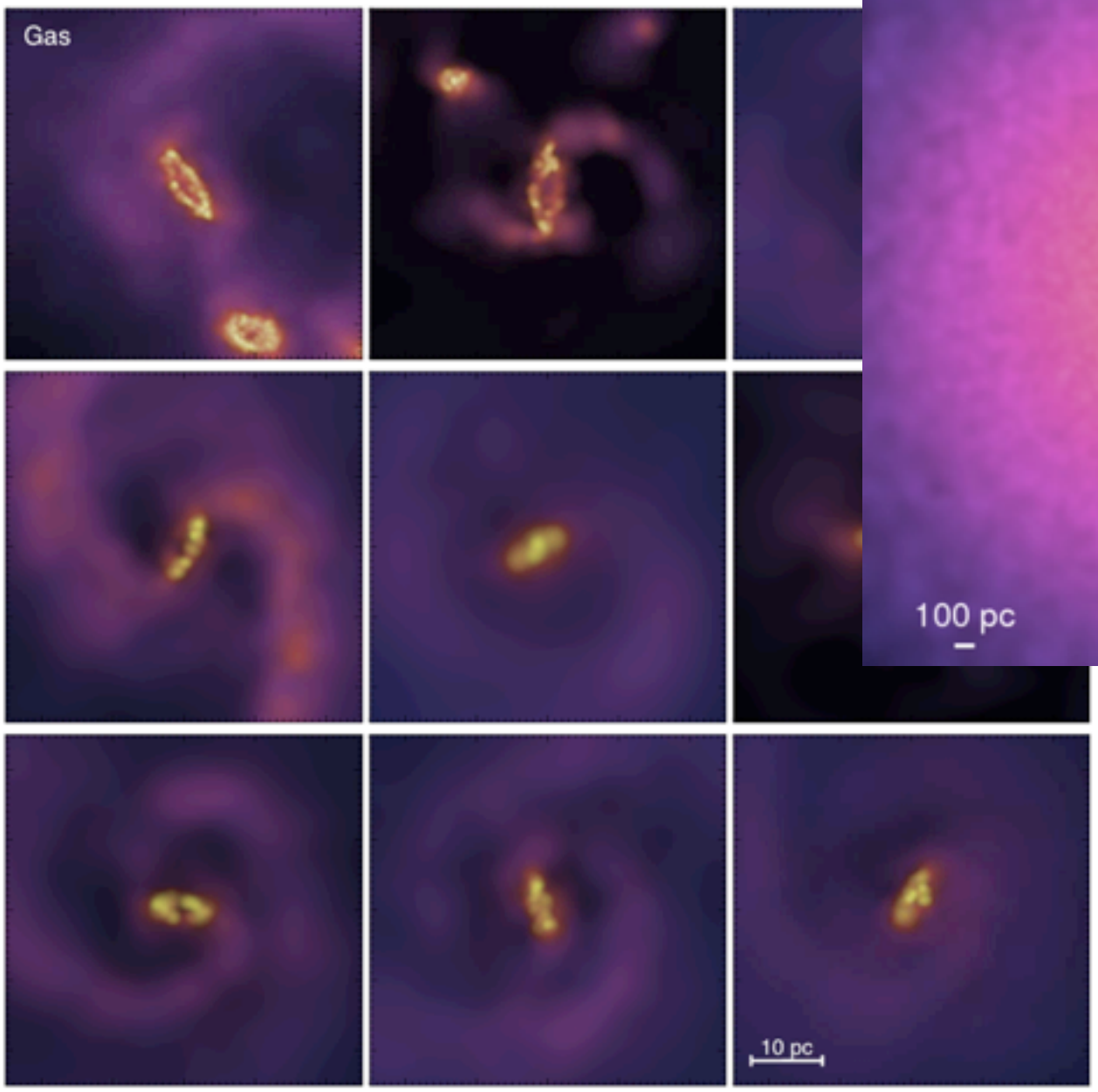
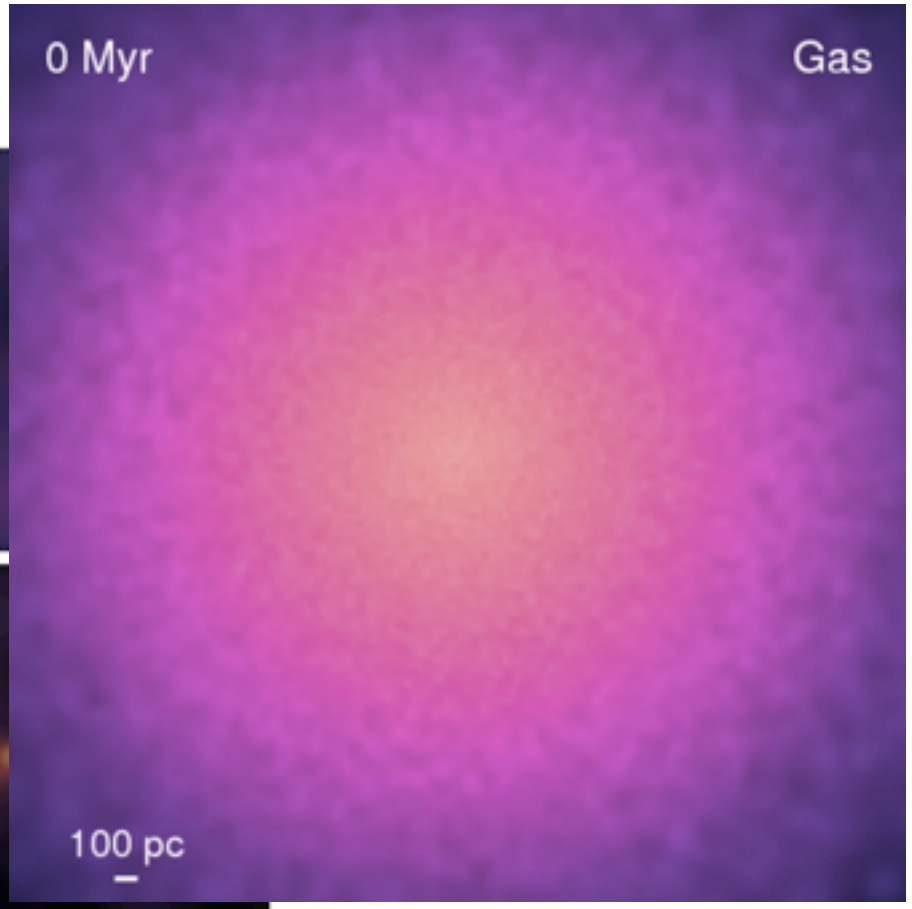
- "run backwards": the M31 disk implies accretion at ~0.5-3 $M_{sun}$/yr (~$L_{Edd}$) for ~100 Myr (~ $M_{BH}$) !

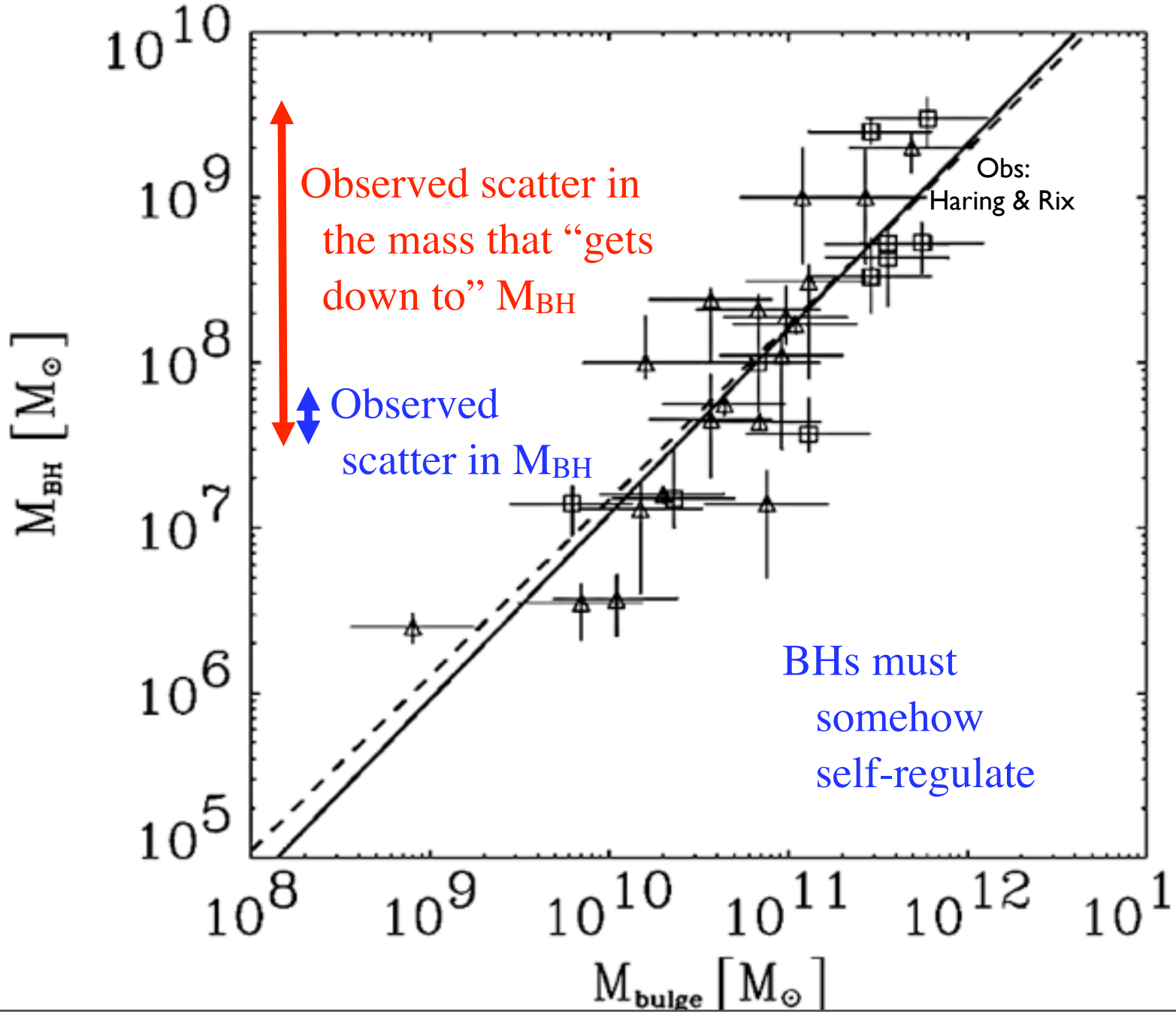
# Mis-alignments with the parent disk are common




- Implications for:
  - BH spin
  - BH-BH mergers
  - Recoils
  - Variability
  - Torus & Obscuration

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


Observed scatter in the mass that "gets down to" $M_{BH}$
Observed scatter in $M_{BH}$
Obs: Haring & Rix
BHs must somehow self-regulate
$M_{BH}$ [$M_\odot$]
$M_{bulge}$ [$M_\odot$]
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$10^{5}$
$10^{8}$
$10^{9}$
$10^{10}$
$10^{11}$
$10^{12}$
$10^{1}$

- Simplest model: ~few % energy injection

- 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)

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

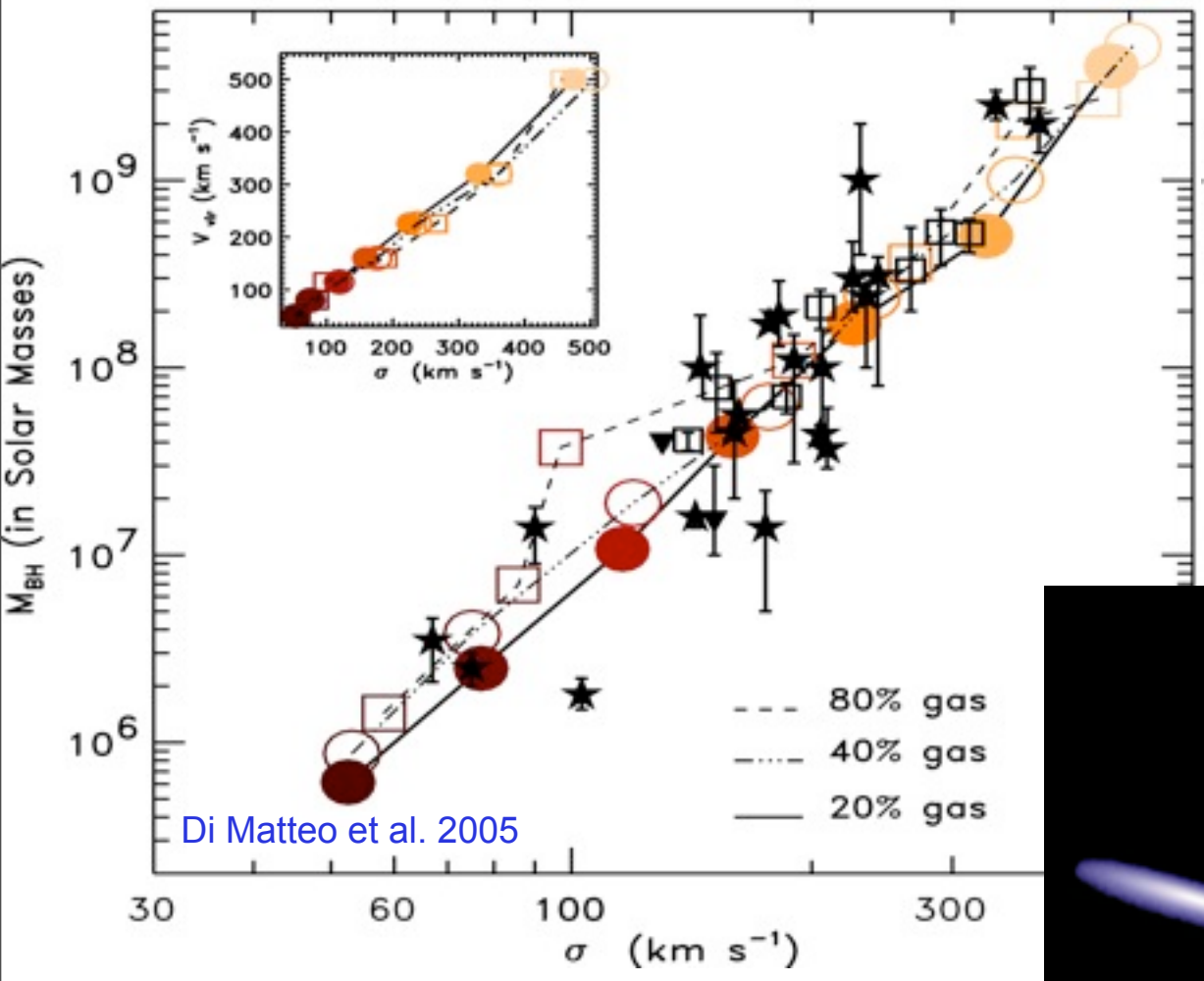
(DeBuhr et al. 2009)

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

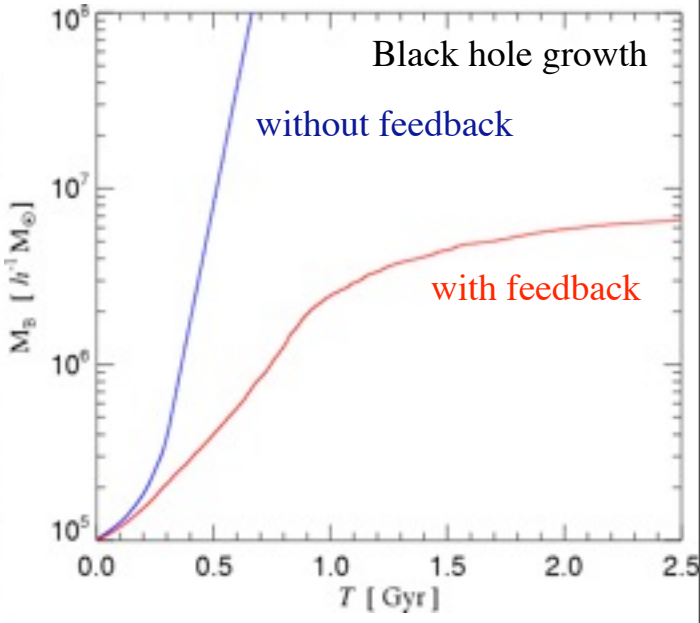
} Predict similar "impact" of feedback

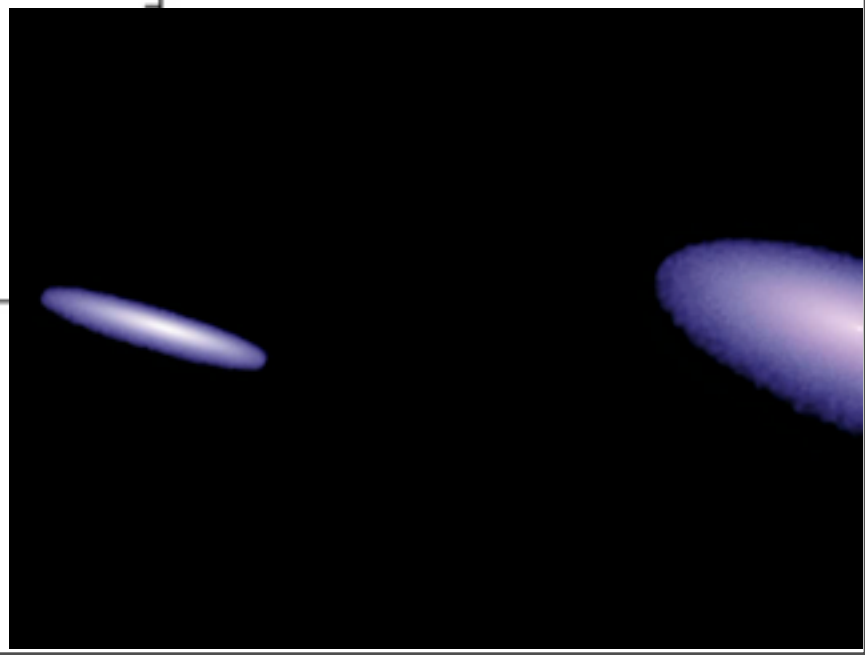
- Springel, Di Matteo, & Hernquist: 5% of $L_{bol}$ back in central ~10s of pc, as thermal energy

# *Self-Regulated* BH Growth:



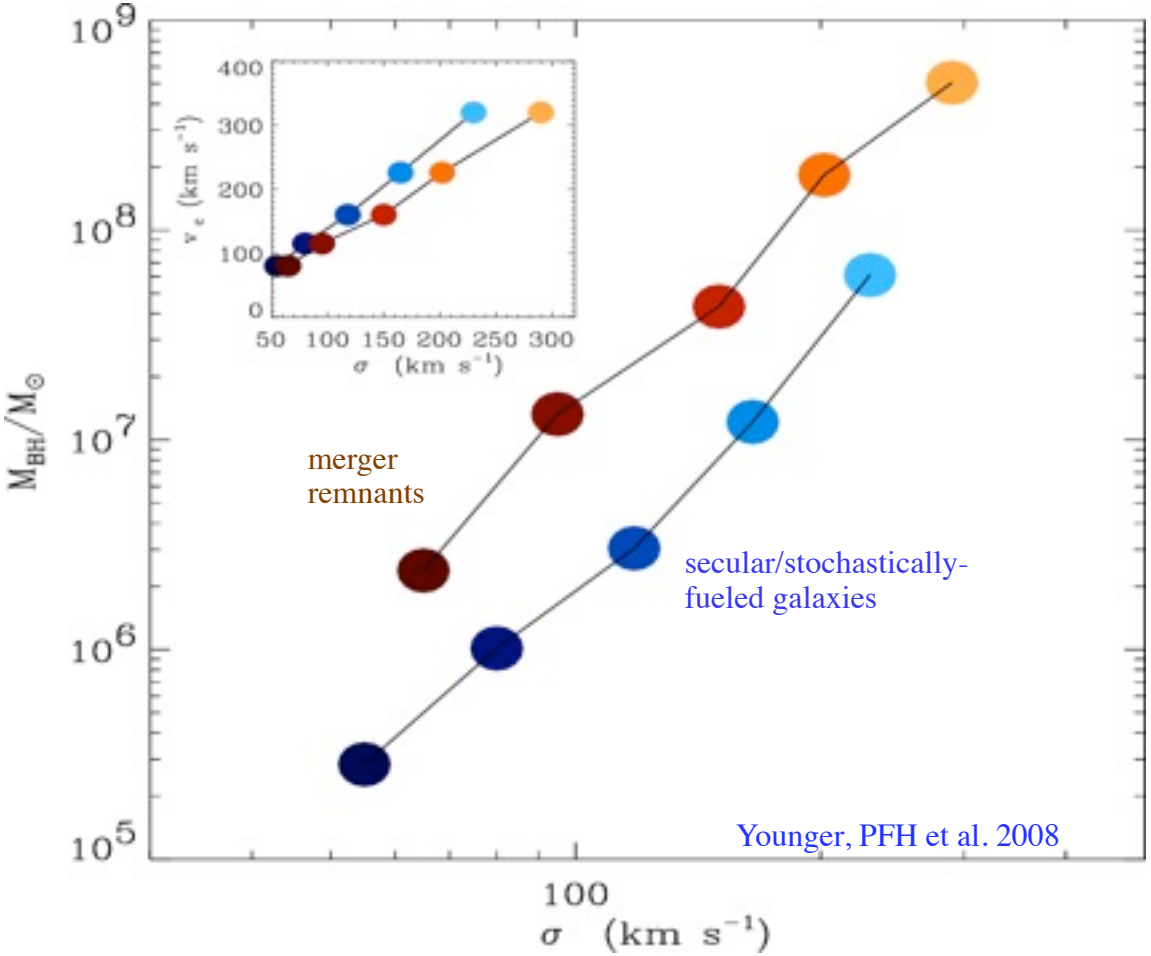

Di Matteo et al. 2005



# *Predictions?*

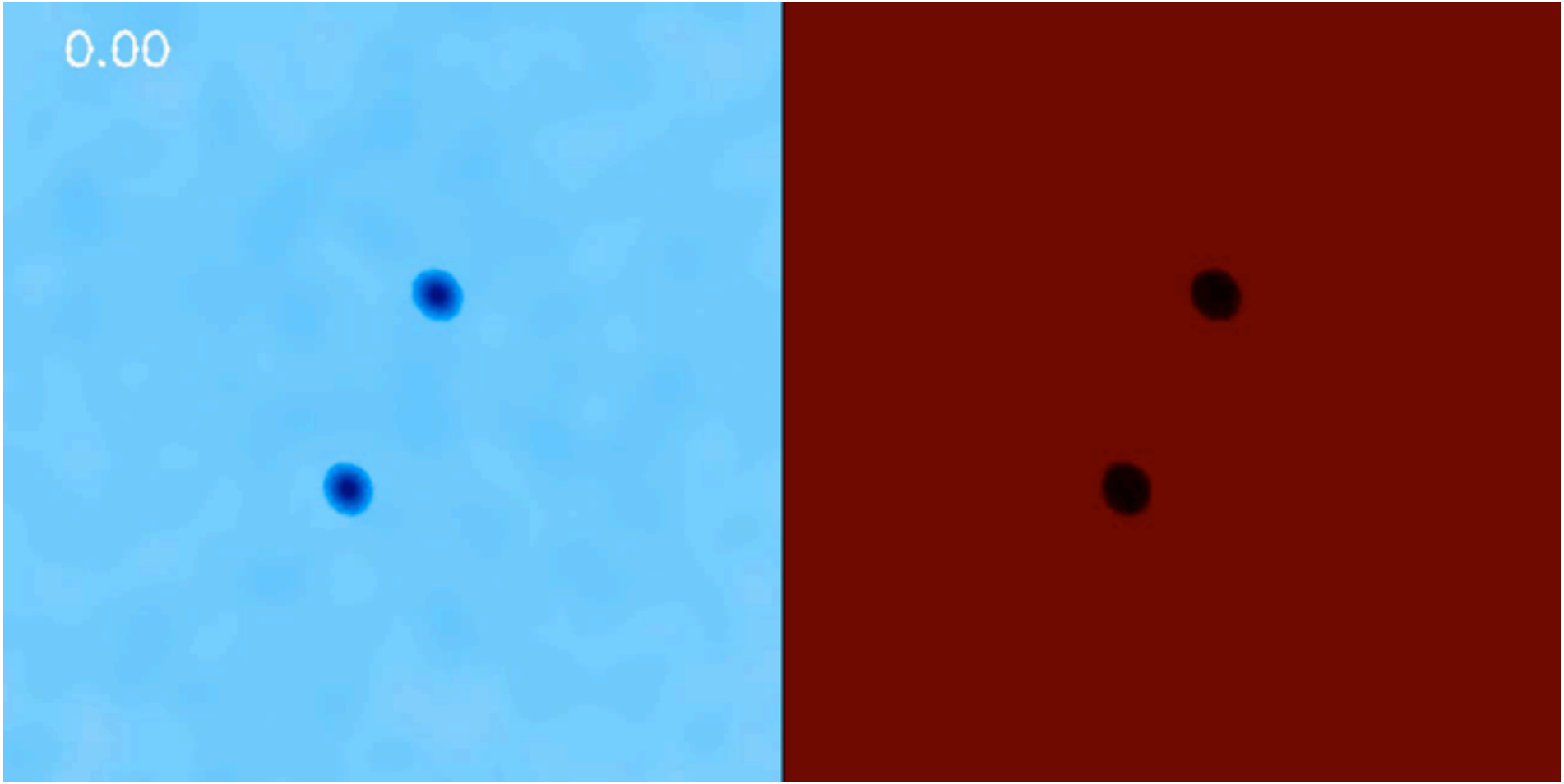
- "Fundamental" correlation? $M_{BH}$-$E_{binding}$ : BH "fundamental plane" (PFH et al.)
- Different correlation for "classical" and "pseudobulges"
  - Observed? (Aller & Richstone; Greene et al.; Hu; Gadotti et al.)



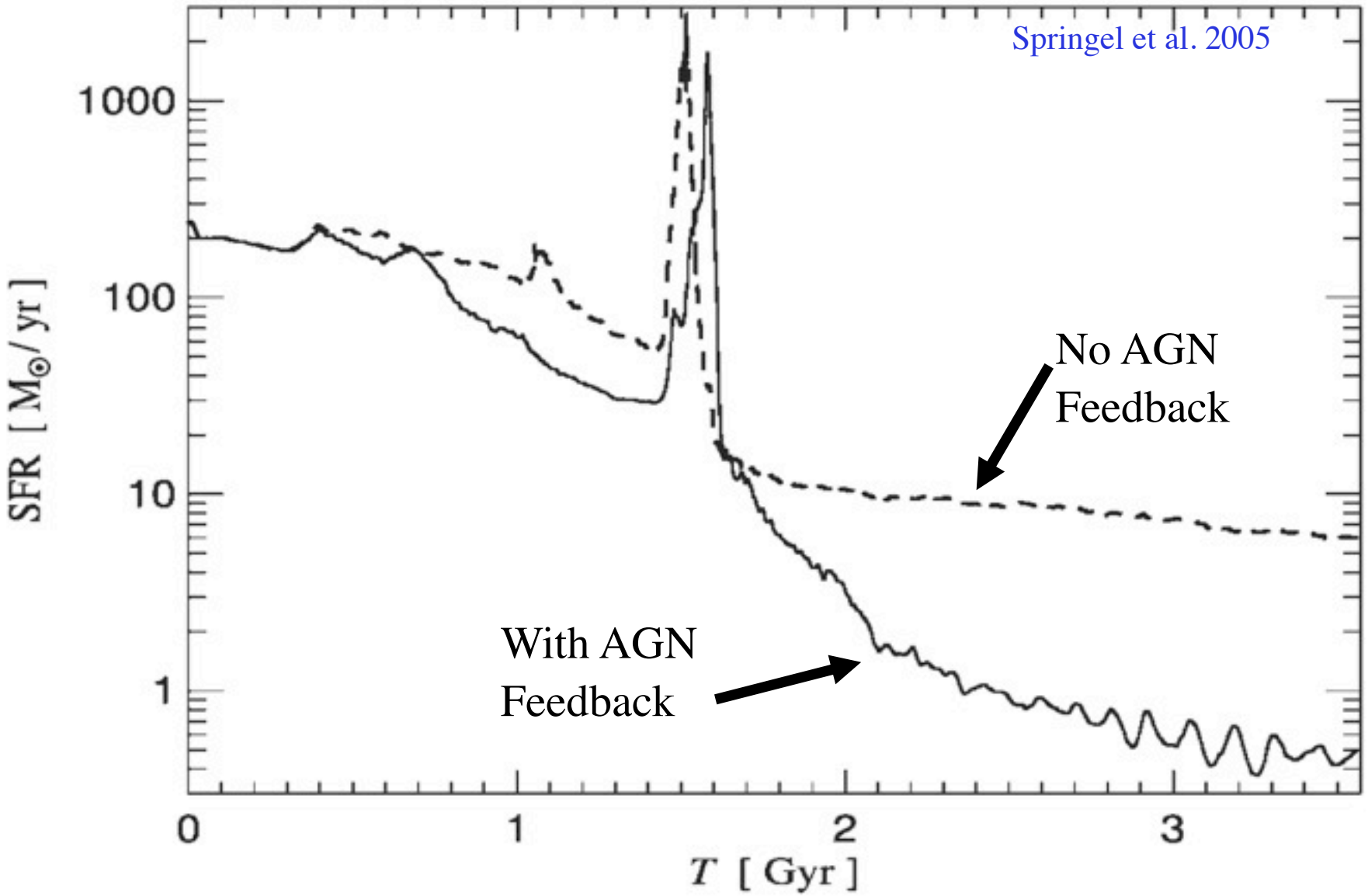

- Redshift evolution: as galaxy properties change (Peng et al., Shields et al., Walter et al.)

# *Can* AGN Feedback Prevent Star Formation?

**Gas Density** | **Gas Temperature**

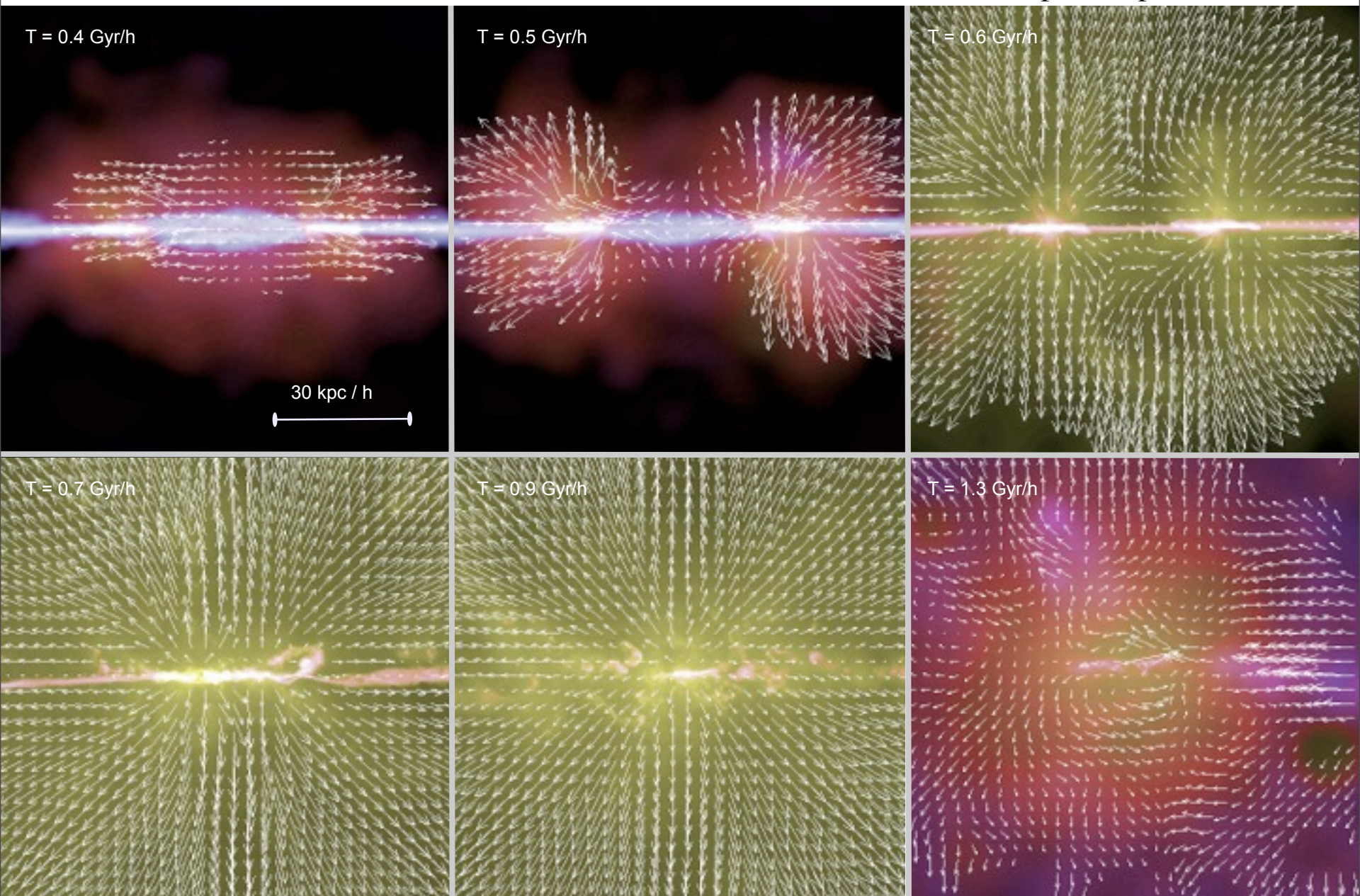


# Helps Ensure Ellipticals are "Red and Dead"



# Do We See It?

(speeds up to ~2000 km/s)

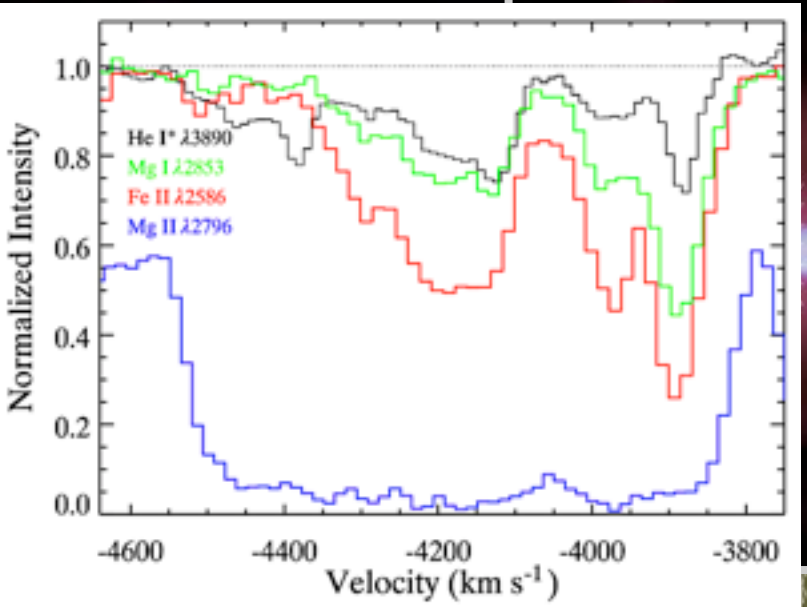


# Do We See It?

(speeds up to ~2000 km/s)

T = 0.4 Gyr/h

T = 0.5 Gyr/h



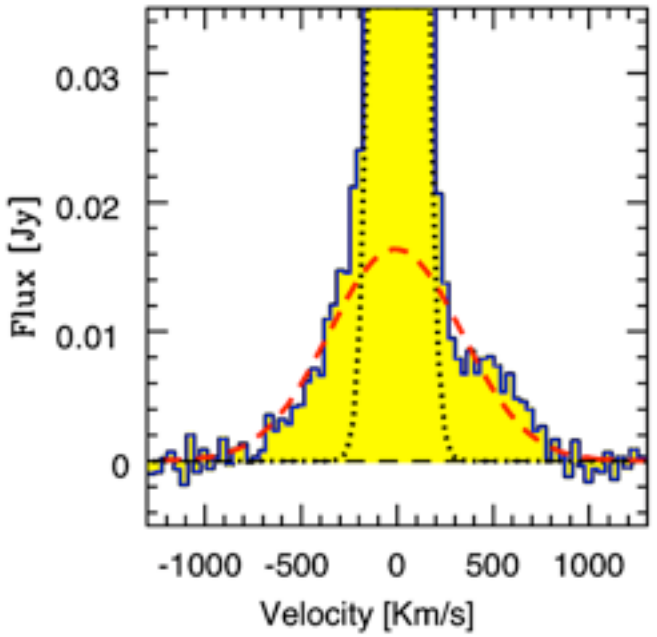

Arav et al.

BAL QSOs:

$$R_{\rm wind} \sim 1 - 20\,{\rm kpc}$$

$$v \gtrsim 1000\,{\rm km\,s^{-1}}$$

$$\dot{M}_{\rm wind} \sim 100 - 600\,M_\odot\,{\rm yr^{-1}}$$




Feruglio et al., Fischer et al.

Mrk 231 Molecular Outflows:

$$R_{\rm wind} \sim 1 - 4\,{\rm kpc}$$

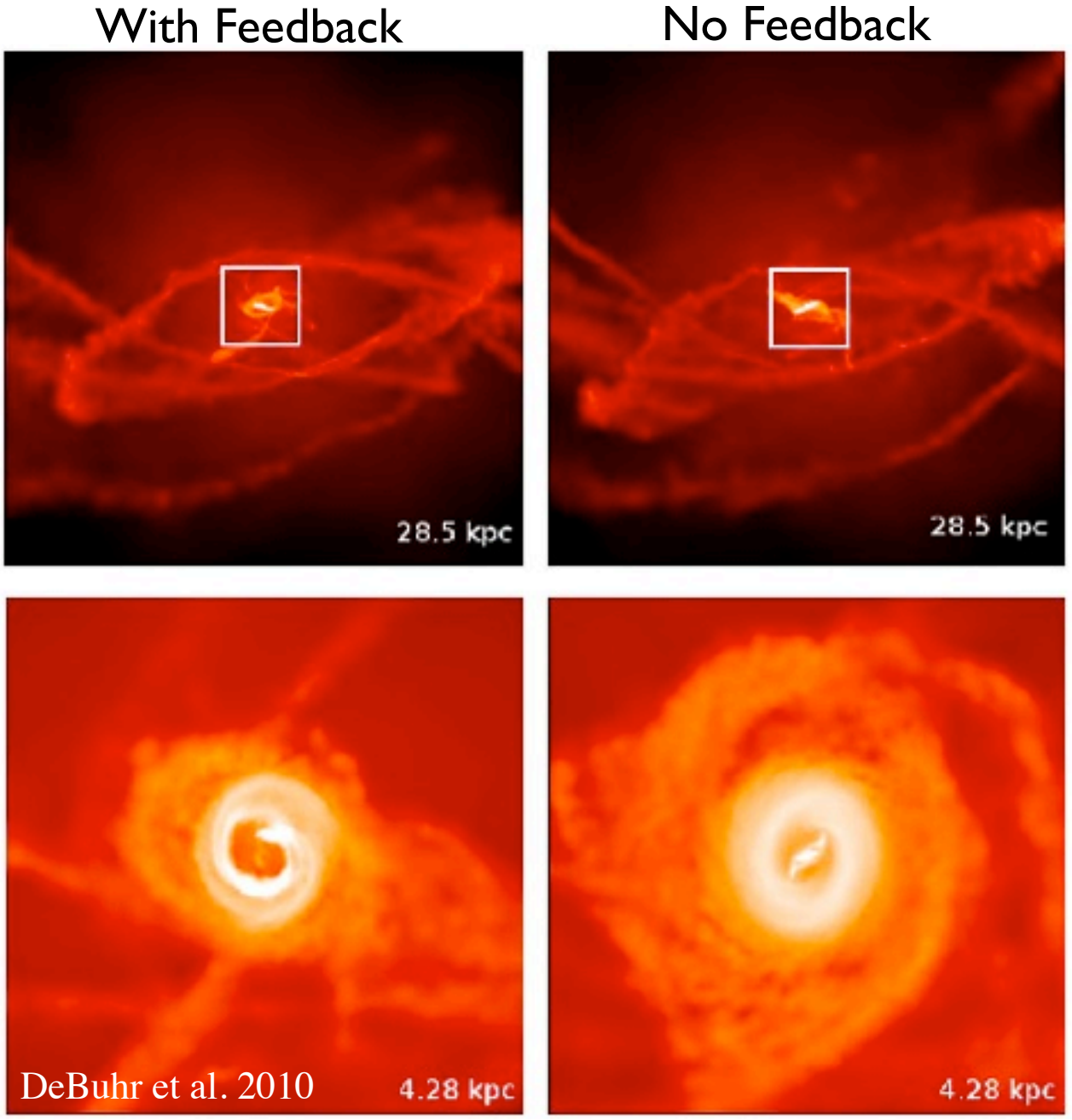
$$v > 500\,{\rm km\,s^{-1}}$$

$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr^{-1}}$$

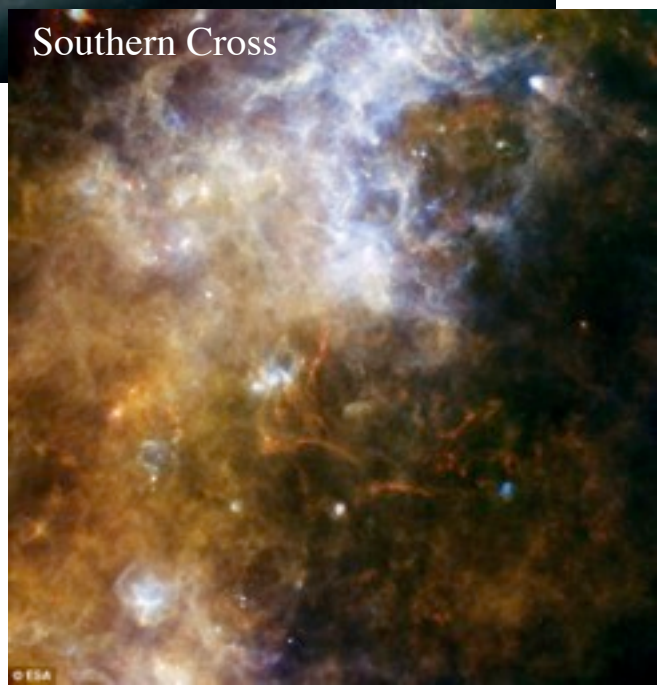
But:

Momentum-Driven (vs Energy-Driven) Winds:

- BH self-regulates, but no galaxy scale "blowout"



# What about the small-scale ISM phase structure?


- "GMC-scale" sub-grid instead of galaxy-scale sub-grid
  - Resolve ~1pc
  - Cool to <100 K
  - Physically/empirically motivated SF in only dense clumps ($n_H$>>100cm$^{-3}$)
  - Model radiative+SNe feedback explicitly from each young stellar cluster (vs age, Z)
  - Generate ISM turbulence & super-winds self-consistently?

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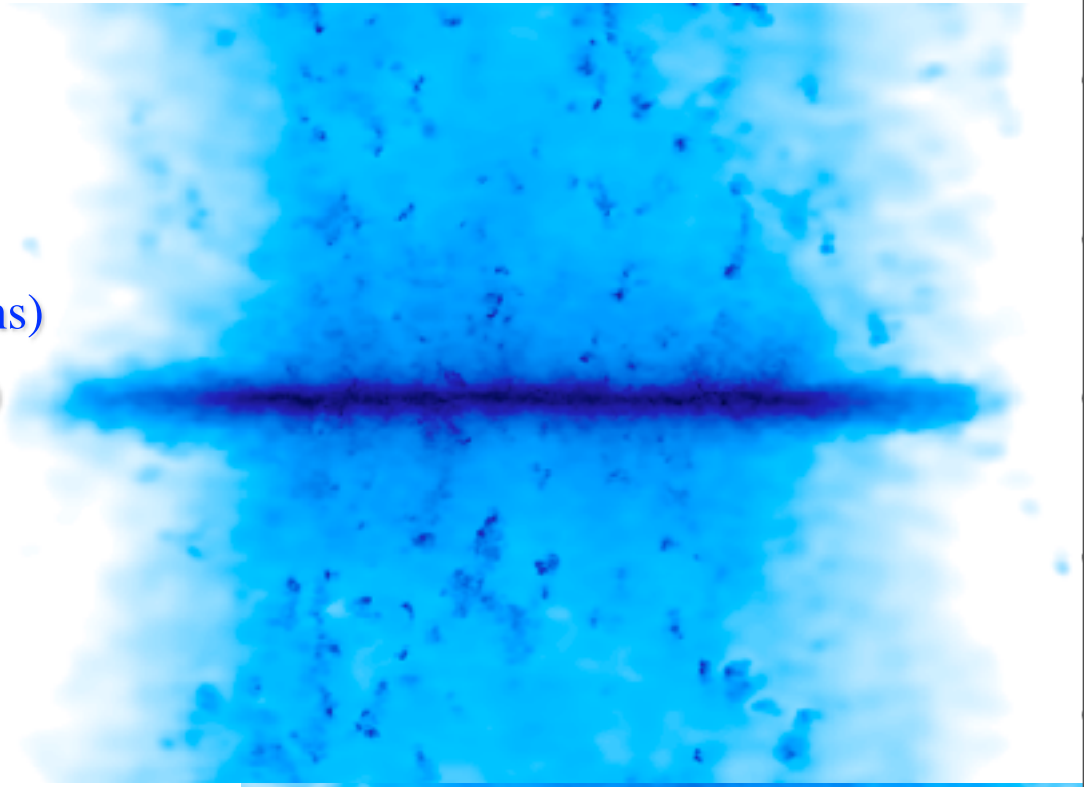
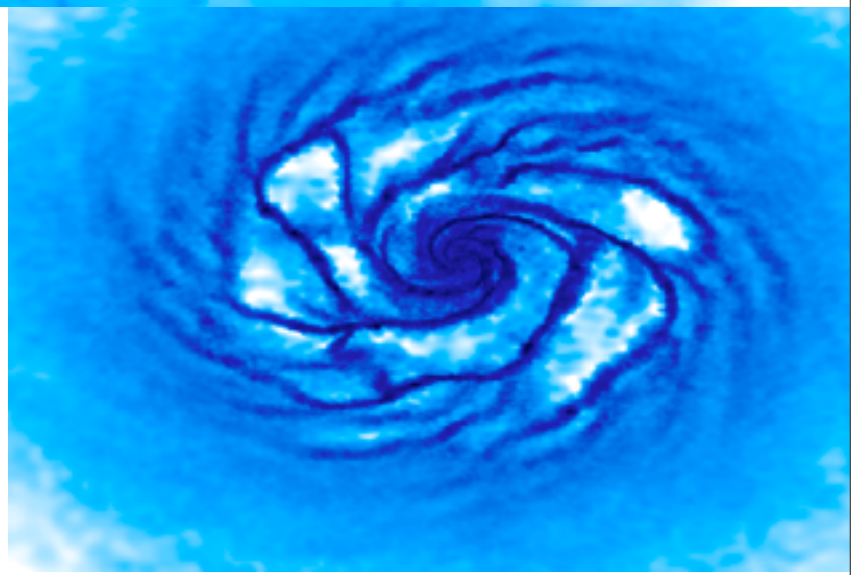


- SNe Heating: No Cooling Turnoff!
- Photoionization Heating (HII Regions)
- Stellar Winds (Mass Loss & Shocks)

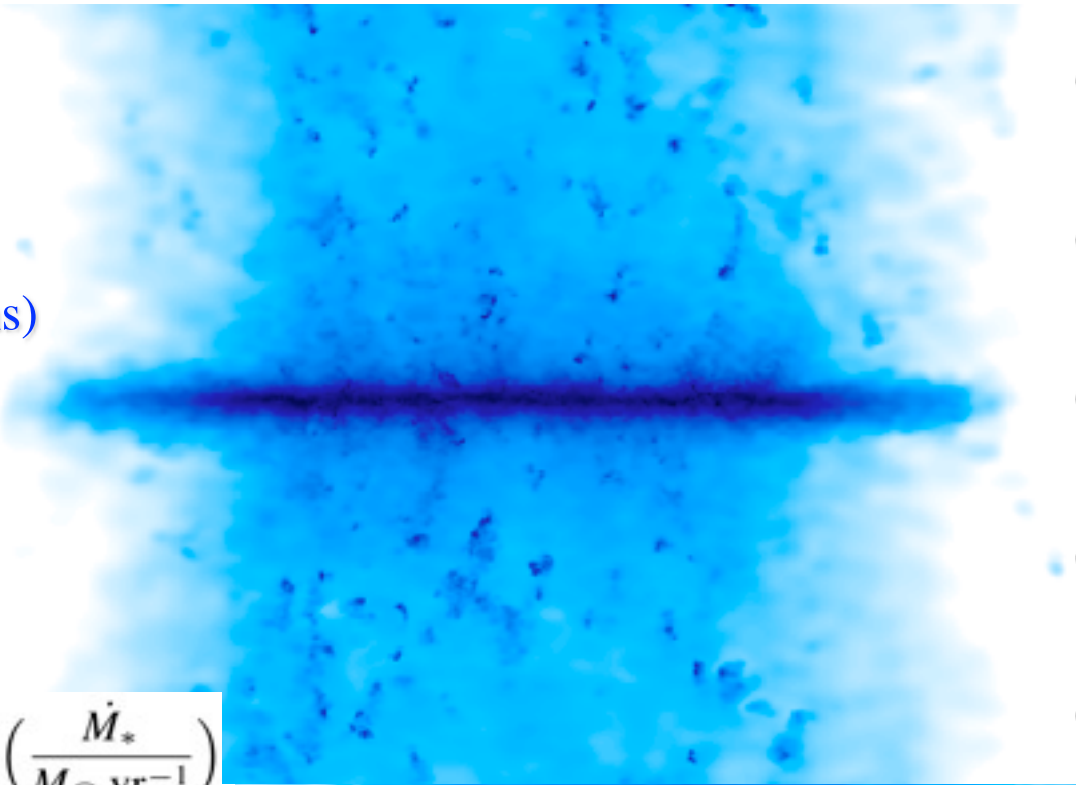
- Explicit Momentum-Loading:
  - Radiation Pressure:



  - Stellar Winds:

  - Supernovae:

# What about the small-scale ISM phase structure?



- SNe Heating: No Cooling Turnoff!
- Photoionization Heating (HII Regions)
- Stellar Winds (Mass Loss & Shocks)

- Explicit Momentum-Loading:
  - Radiation Pressure:

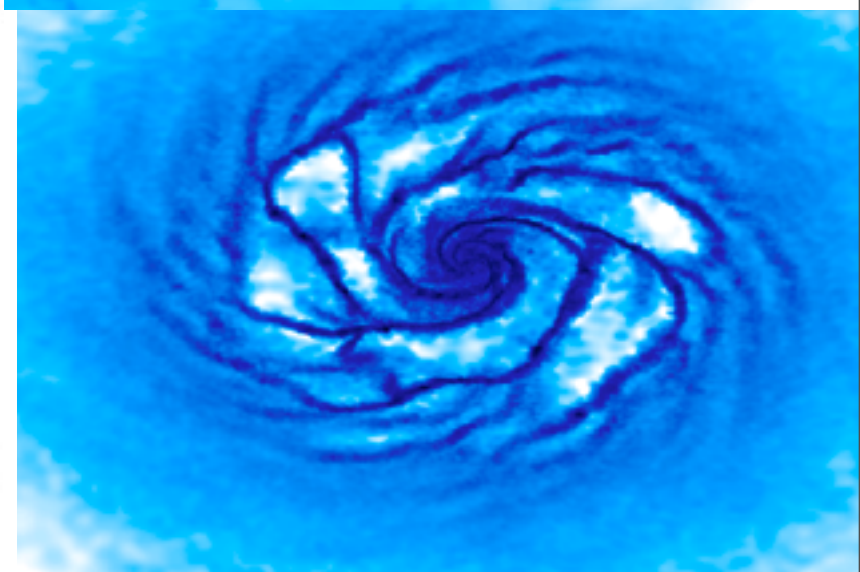
$$\frac{\dot{P}_{\rm rad}}{\rm g\,cm\,s^{-2}} \sim 2\times10^{33}\,\tau_{\rm eff}\left(\frac{M/L_{\rm Salpeter}}{M/L}\right)\left(\frac{\dot{M}_*}{M_\odot\,{\rm yr}^{-1}}\right)$$

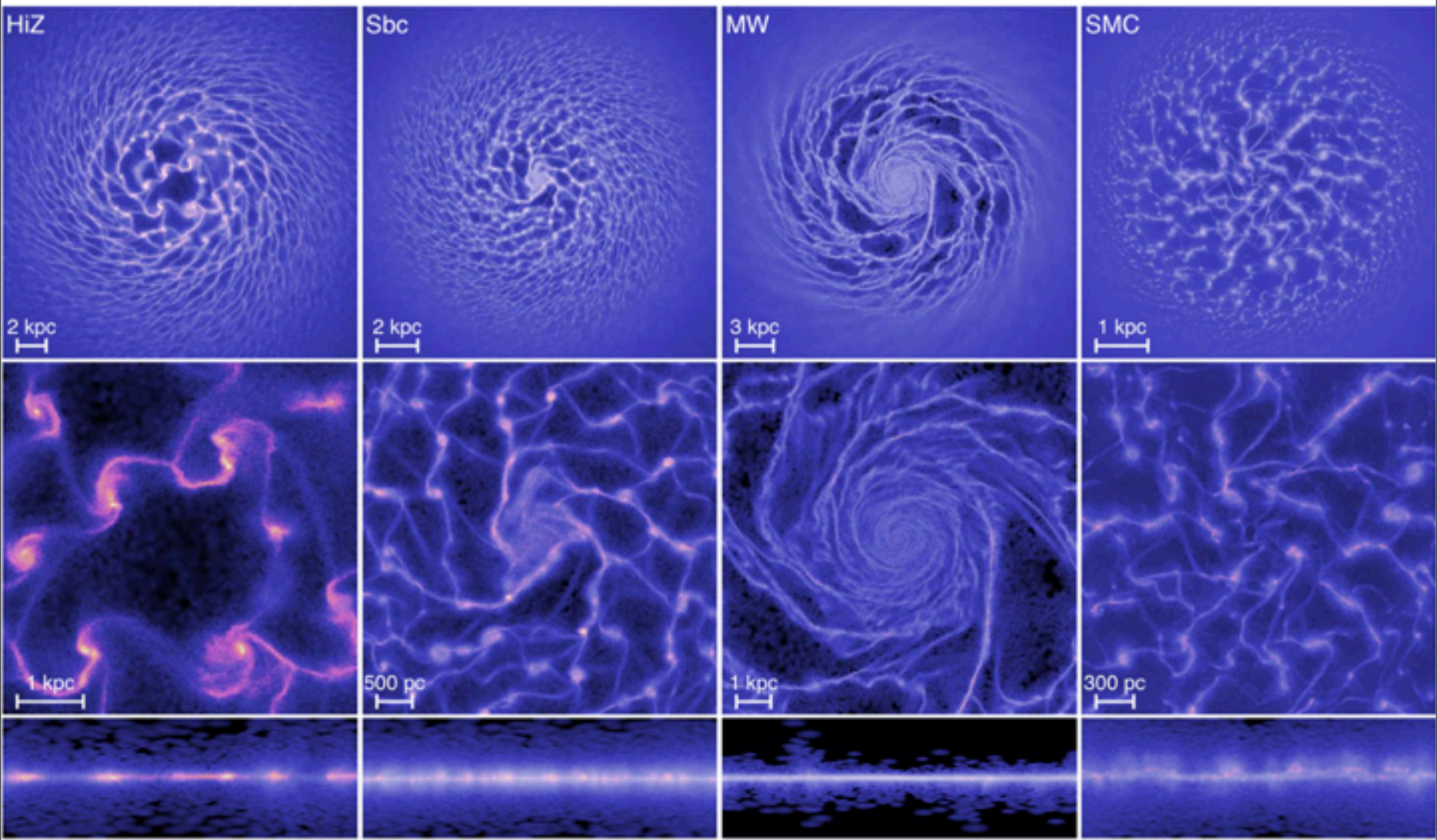
  - Stellar Winds:

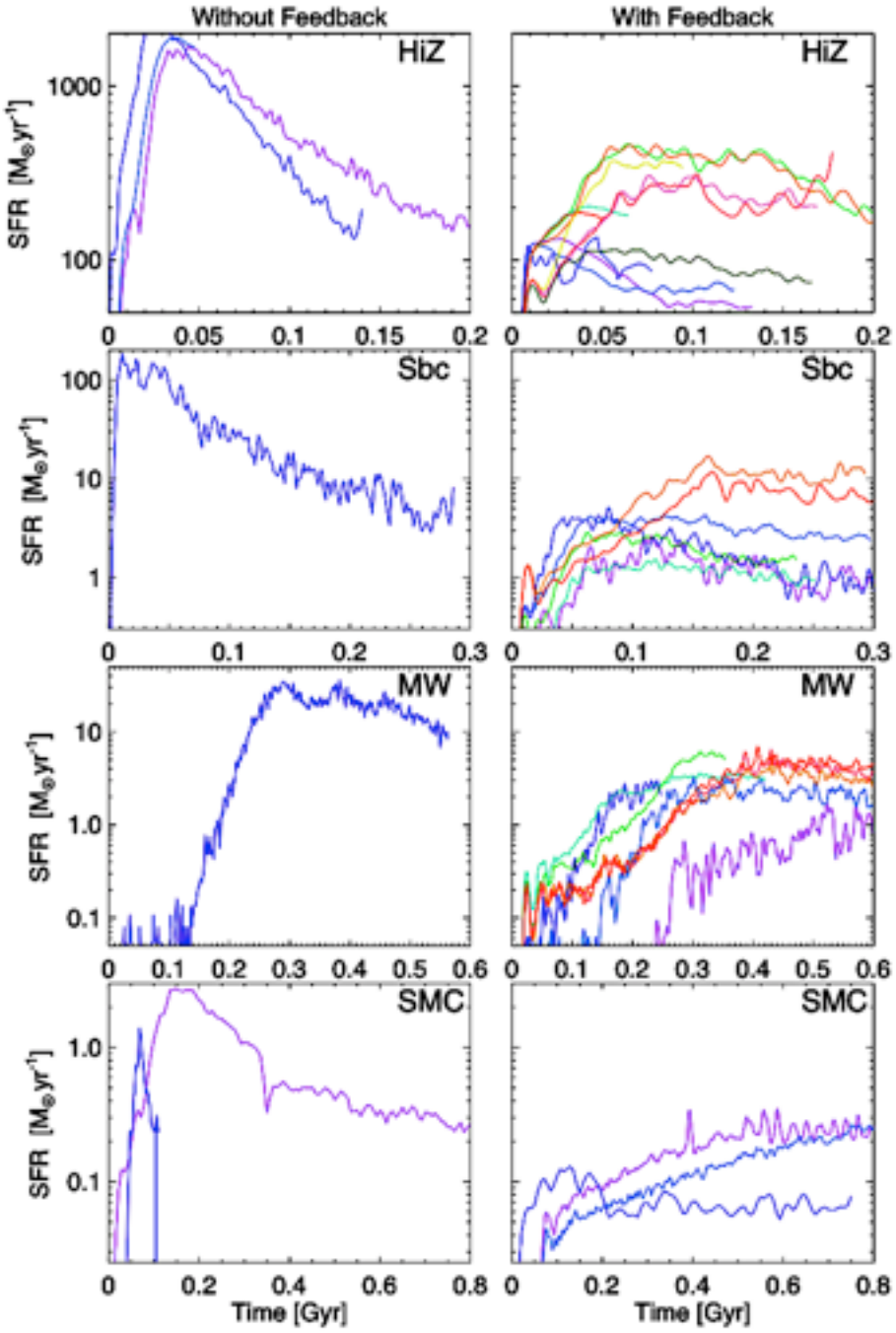
$$\frac{\dot{P}_{\rm w}}{\rm g\,cm\,s^{-2}} \sim 2\times10^{33}\left(\frac{v_{\rm w}}{500\,{\rm km\,s^{-1}}}\right)\left(\frac{\dot{M}_*}{M_\odot\,{\rm yr}^{-1}}\right)$$

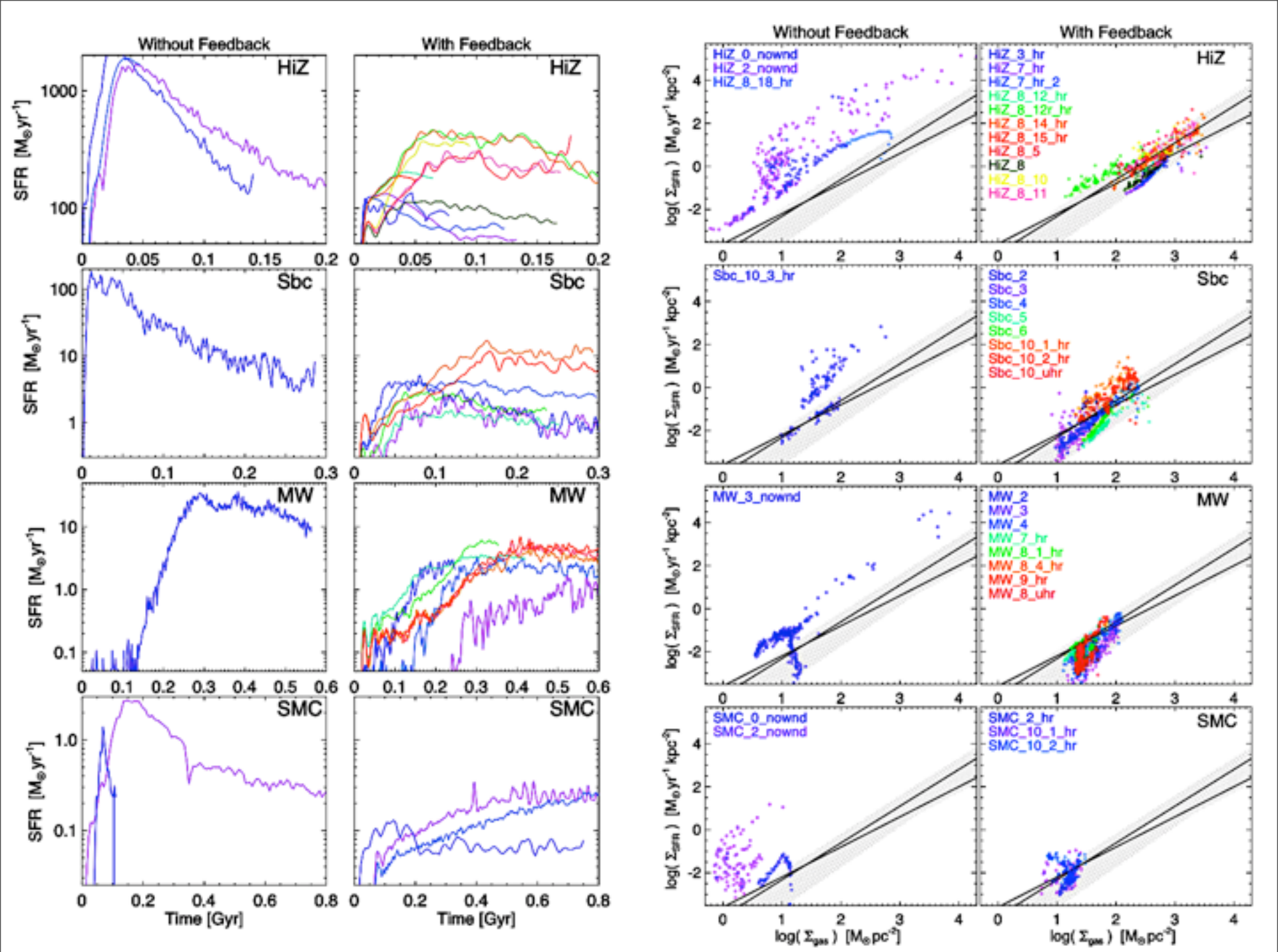
  - Supernovae:

$$\frac{\dot{P}_{\rm SN}}{\rm g\,cm\,s^{-2}} \sim 2\times10^{33}\left(\frac{v_{\rm launch}}{3000\,{\rm km\,s^{-1}}}\right)\left(\frac{\dot{M}_*}{M_\odot\,{\rm yr}^{-1}}\right)$$

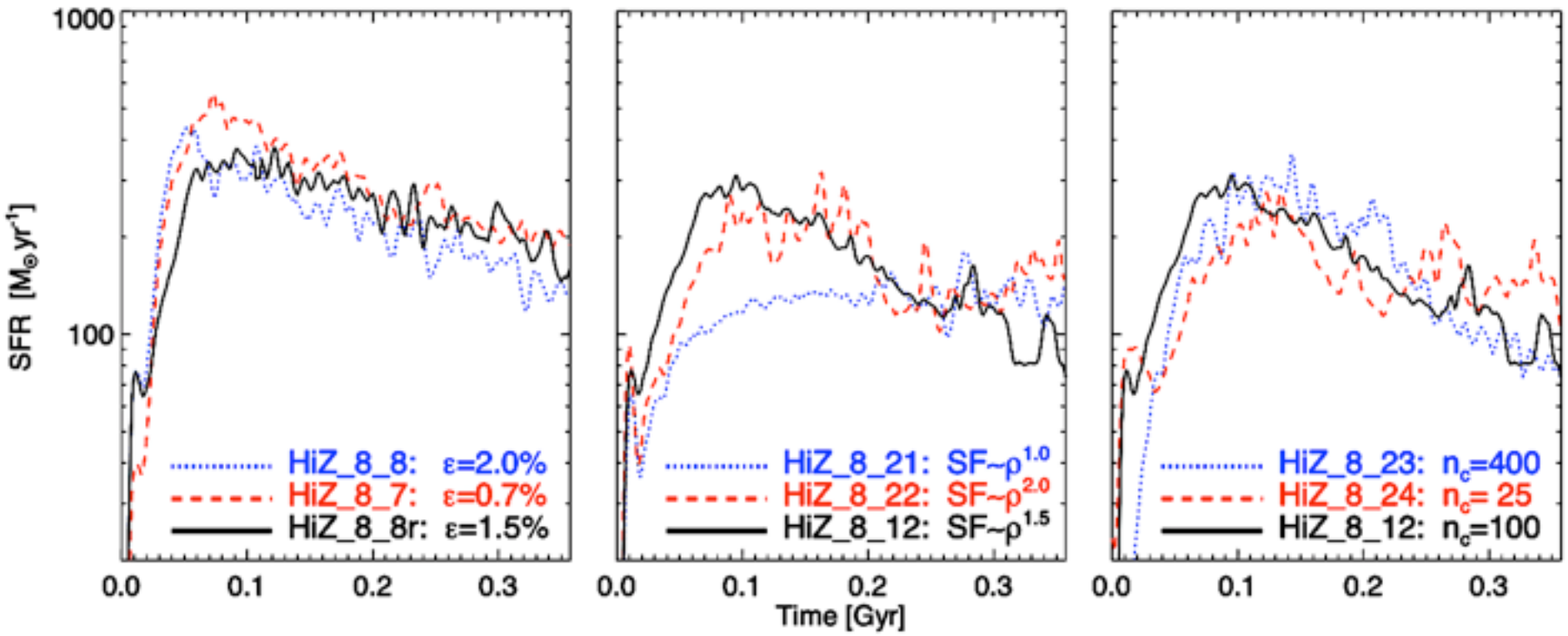



HiZ
Sbc
MW
SMC
2 kpc
2 kpc
3 kpc
1 kpc
1 kpc
500 pc
1 kpc
300 pc


Without Feedback
With Feedback
HiZ
Sbc
MW
SMC
SFR [M⊙yr⁻¹]
Time [Gyr]


Without Feedback
With Feedback
HiZ
Sbc
MW
SMC
SFR [M⊙yr⁻¹]
Time [Gyr]
HiZ_0_nownd
HiZ_2_nownd
HiZ_8_18_hr
HiZ_3_hr
HiZ_7_hr
HiZ_7_hr_2
HiZ_8_12_hr
HiZ_8_12r_hr
HiZ_8_14_hr
HiZ_8_15_hr
HiZ_8_5
HiZ_8
HiZ_8_10
HiZ_8_11
Sbc_10_3_hr
Sbc_2
Sbc_3
Sbc_4
Sbc_5
Sbc_6
Sbc_10_1_hr
Sbc_10_2_hr
Sbc_10_uhr
MW_3_nownd
MW_2
MW_3
MW_4
MW_7_hr
MW_8_1_hr
MW_8_4_hr
MW_9_hr
MW_8_uhr
SMC_0_nownd
SMC_2_nownd
SMC_2_hr
SMC_10_1_hr
SMC_10_2_hr
log( Σsfr ) [M⊙yr⁻¹ kpc⁻²]
log( Σgas ) [M⊙pc⁻²]

# Schmidt-Kennicutt Law Emerges *INDEPENDENT* of Local SF Law



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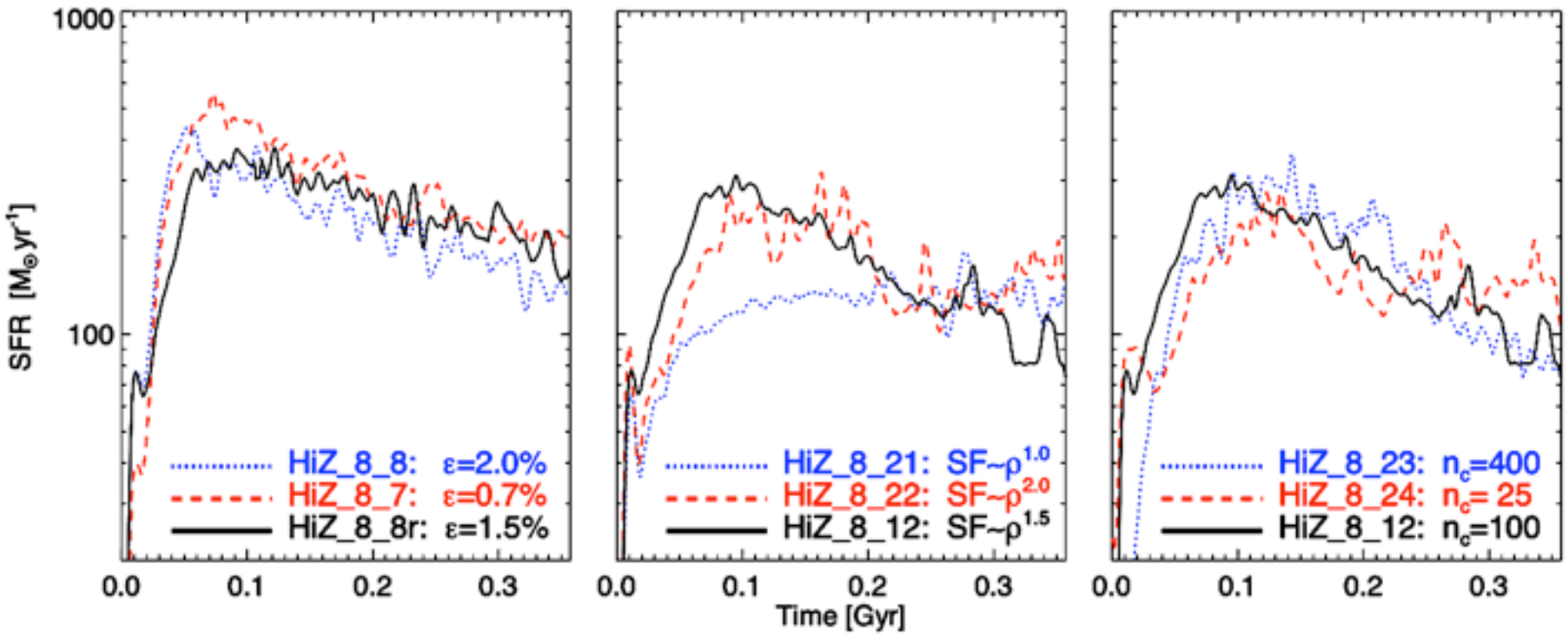



- Set by feedback (i.e. SFR) needed to maintain marginal stability

# Summary

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

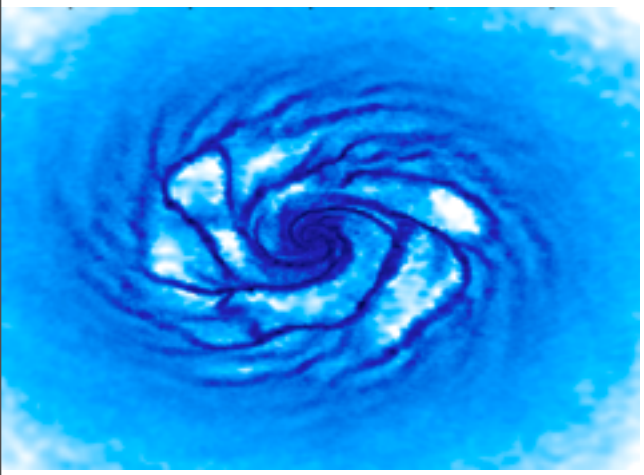
- "Stuff within Stuff": Cascade of instabilities with diverse morphology
- Accretion rates & orientations are stochastic

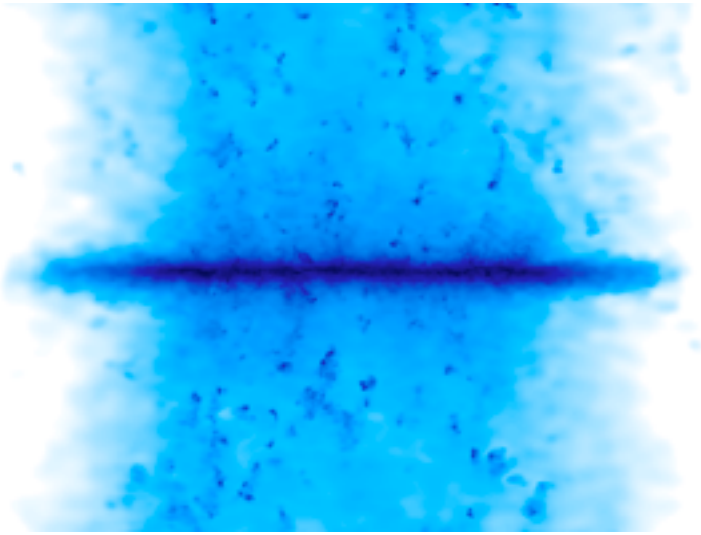
- See stellar nuclear disk 'relics': M31 & 4486b

- $M_{BH}$ traces spheroid $E_{binding}$: *self-regulated* BH growth
  - Consequences for *galaxies* depend on details of feedback model & ISM

- Next-Generation Simulations:
  - Resolve the ISM at the GMC-scale
  - Couple feedback self-consistently
    - *Momentum* matters, not just energy!
    - If you don't have feedback, you shouldn't get the Kennicutt Law

# 4) Modeling the small-scale ISM phase structure:





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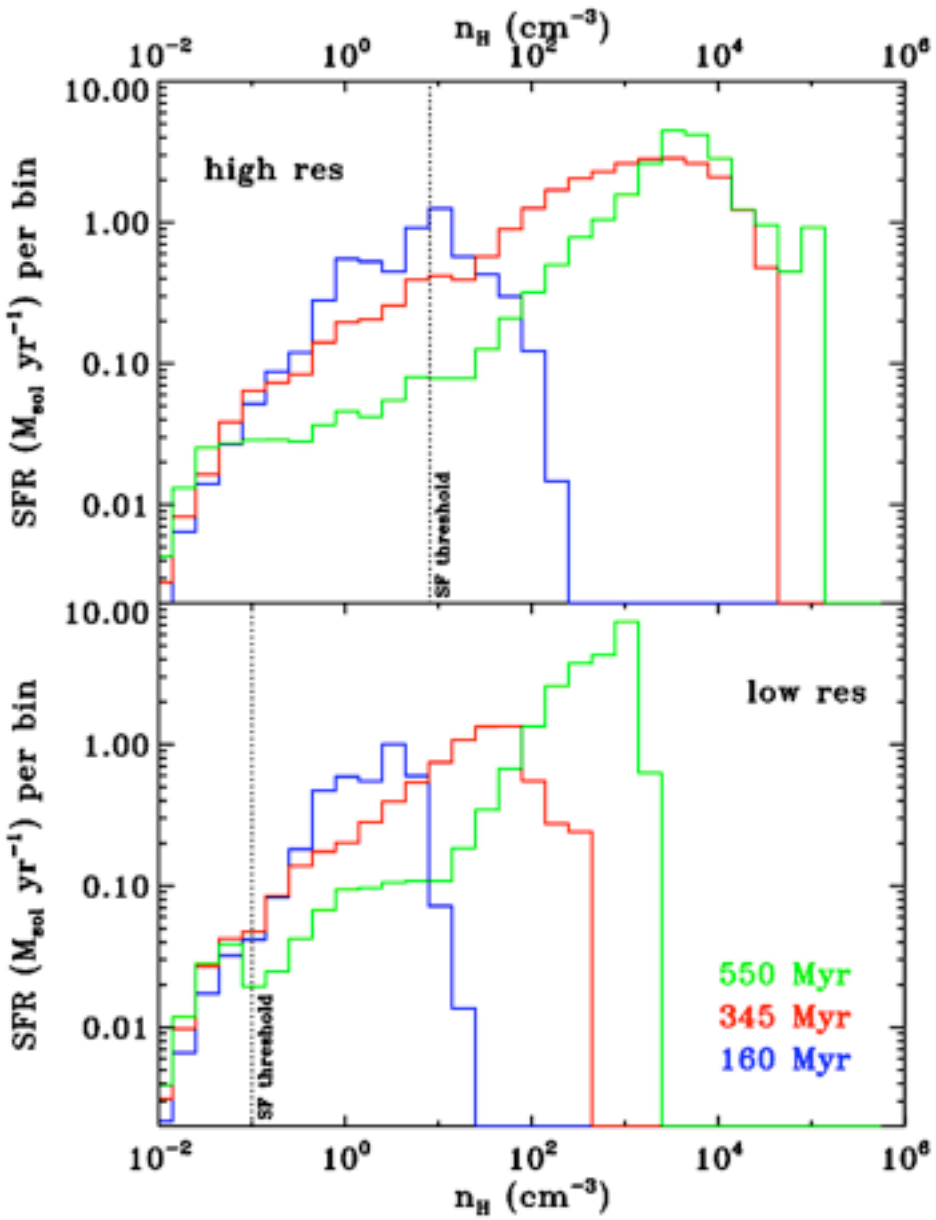
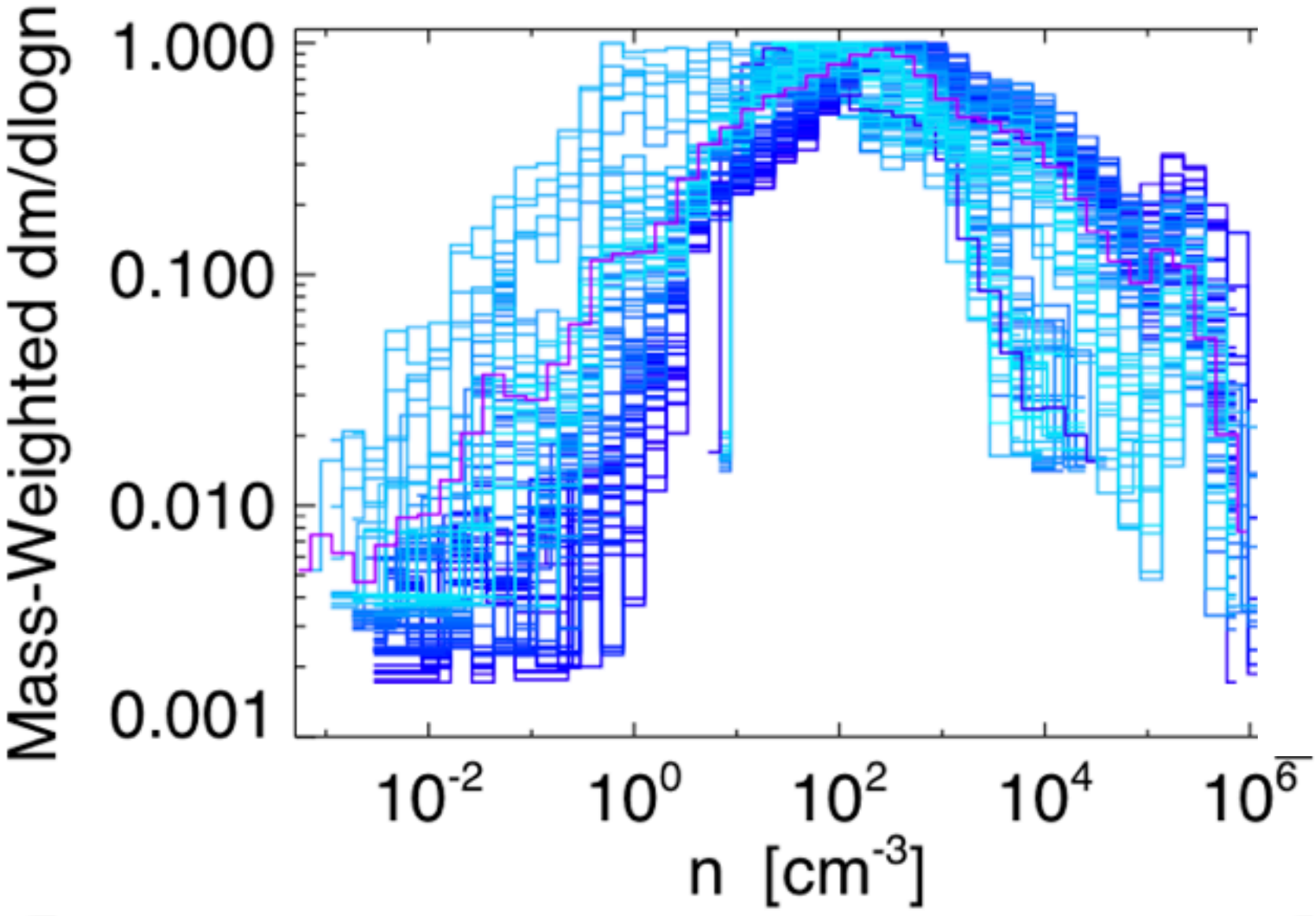
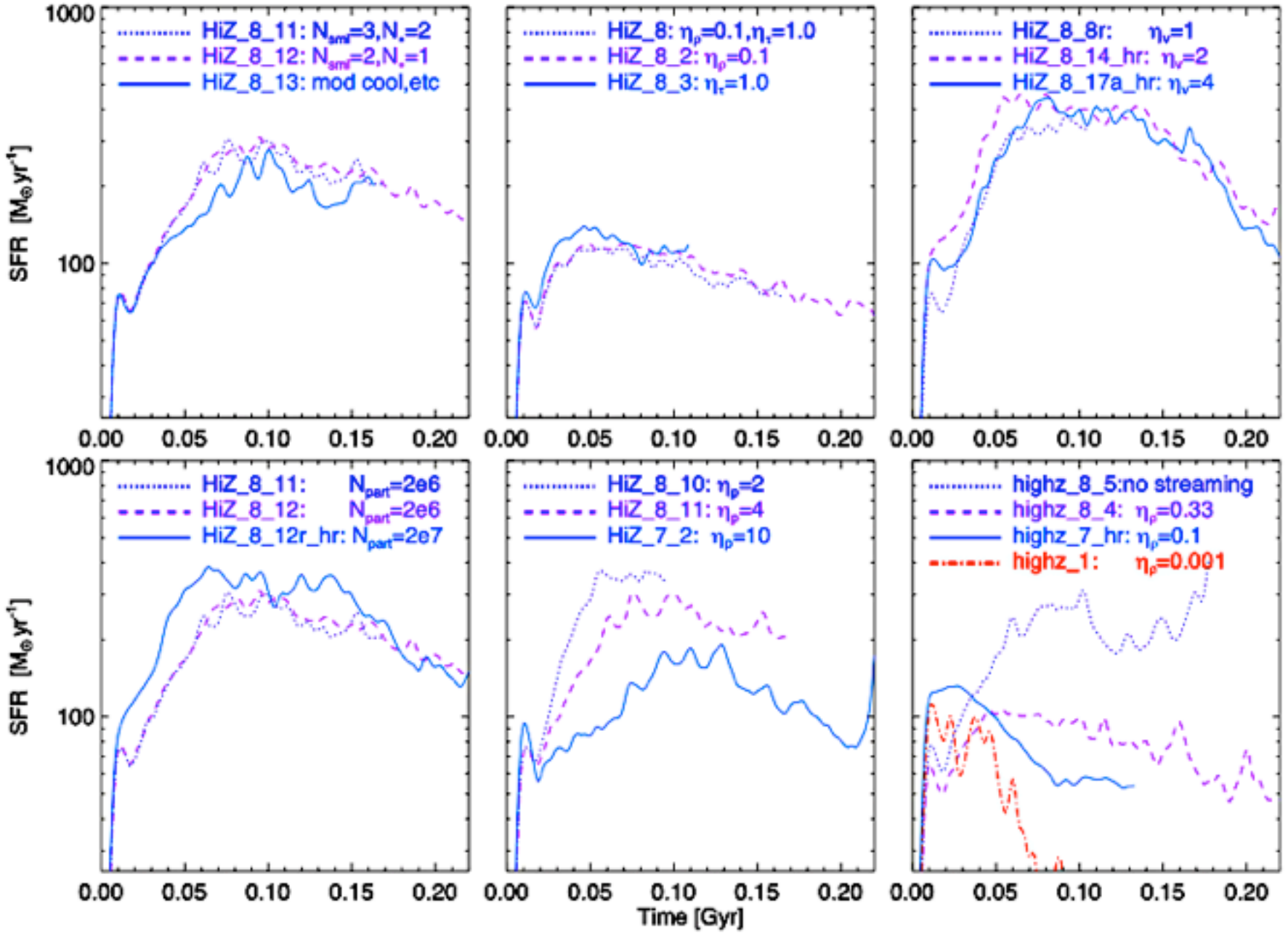
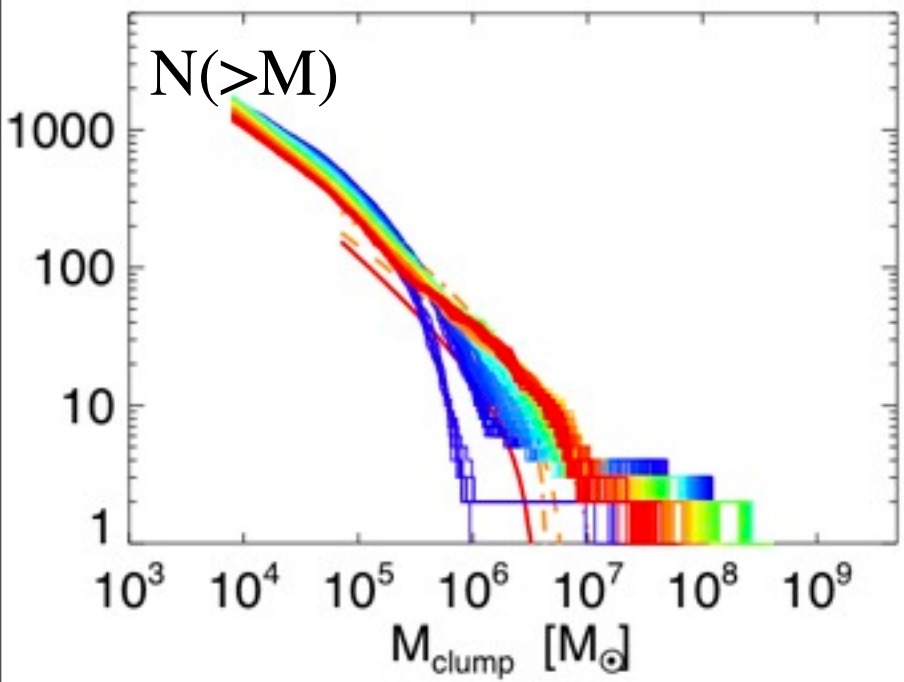


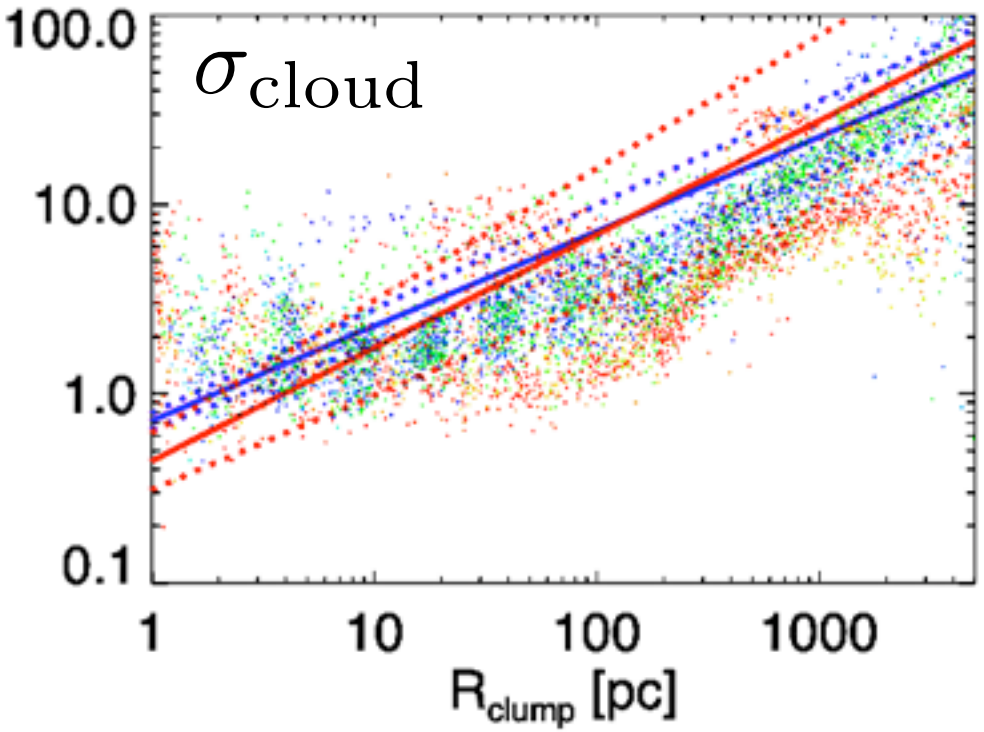

Without Feedback

With Feedback




1000
100
SFR [M⊙ yr⁻¹]
HiZ_8_11: N_sml=3,N*=2
HiZ_8_12: N_sml=2,N*=1
HiZ_8_13: mod cool,etc
HiZ_8: η_ρ=0.1,η_τ=1.0
HiZ_8_2: η_ρ=0.1
HiZ_8_3: η_τ=1.0
HiZ_8_8r: η_ν=1
HiZ_8_14_hr: η_ν=2
HiZ_8_17a_hr: η_ν=4
HiZ_8_11: N_part=2e6
HiZ_8_12: N_part=2e6
HiZ_8_12r_hr: N_part=2e7
HiZ_8_10: η_ρ=2
HiZ_8_11: η_ρ=4
HiZ_7_2: η_ρ=10
highz_8_5:no streaming
highz_8_4: η_ρ=0.33
highz_7_hr: η_ρ=0.1
highz_1: η_ρ=0.001
0.00
0.05
0.10
0.15
0.20
Time [Gyr]




Some GMC Properties Emerge Generically from Feedback-Regulated Turbulence