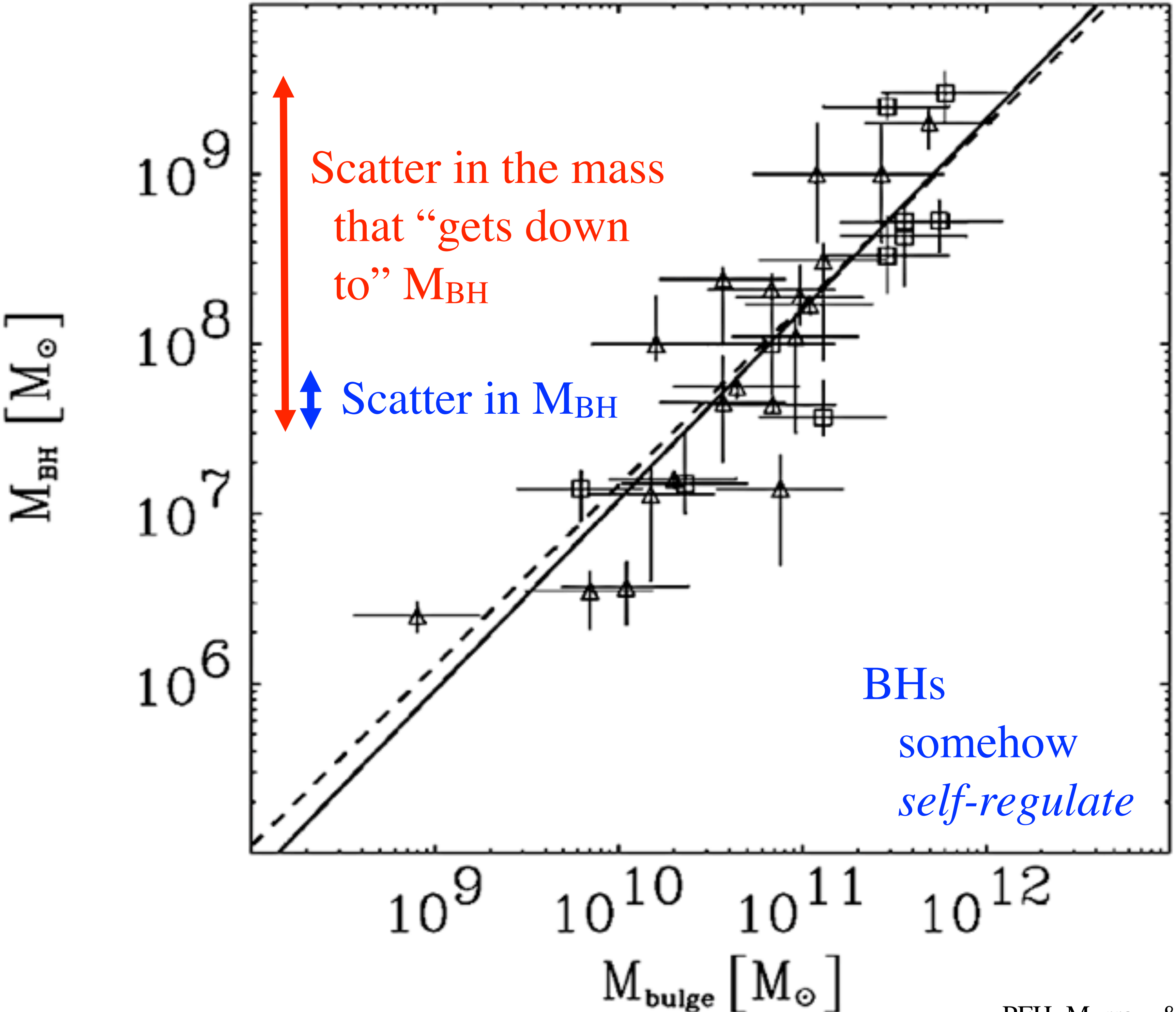
How Do Black Holes Get (Rid Of) Their Gas?

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



Gebhardt et al.
Ferrarese et al.
Haring & Rix
Tremaine
Marconi & Hunt

PFH, Murray, & Thompson 2009

Feedback Energy:

SILK & REES '98

$$L = \epsilon_r \, \dot{M}_{\rm BH} \, c^2 \qquad (\epsilon_r \sim 0.1)$$

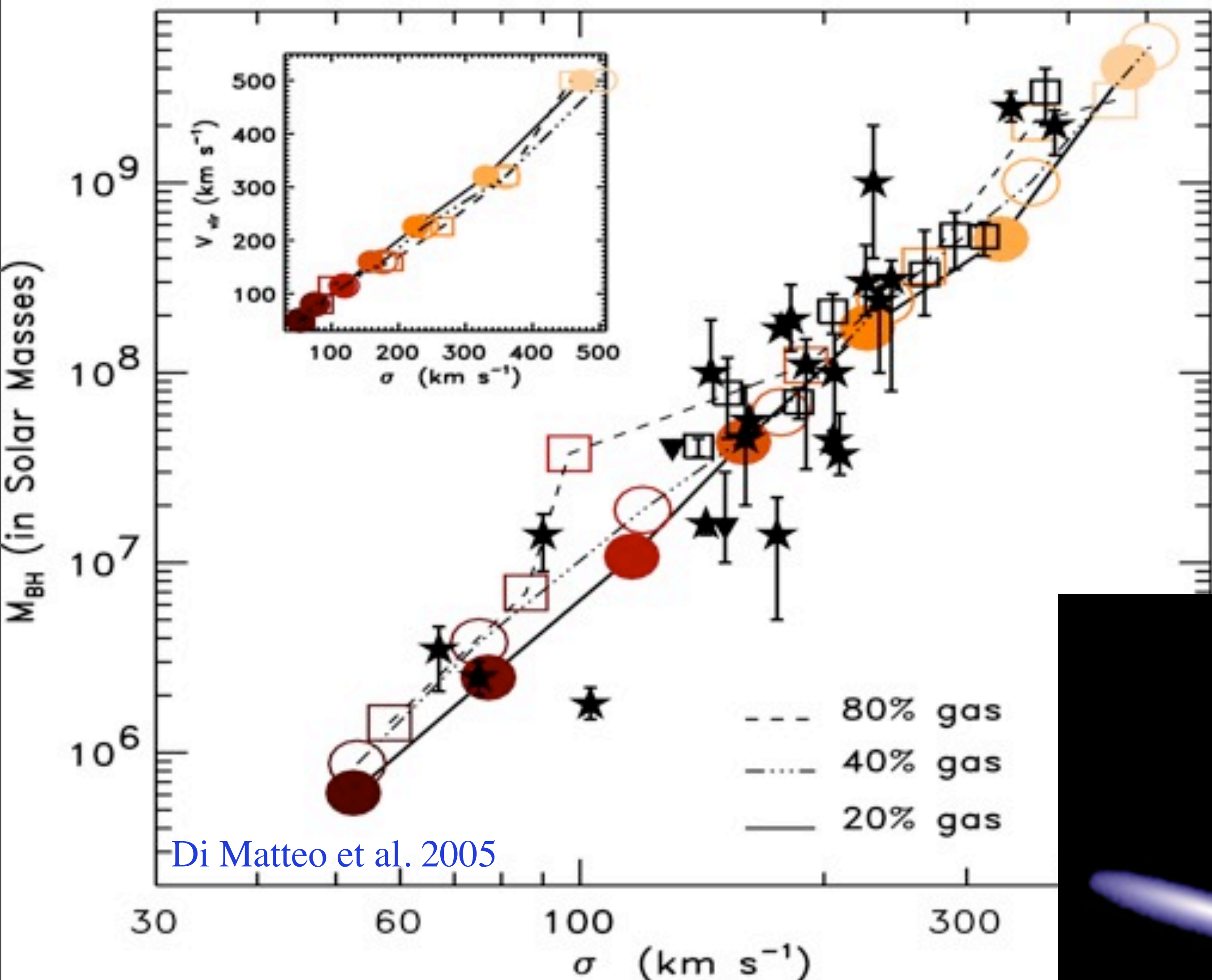
$$\rightarrow E_{\rm rad} \sim 0.1 \, M_{\rm BH} \, c^2 \sim 10^{61} \, {\rm erg}$$

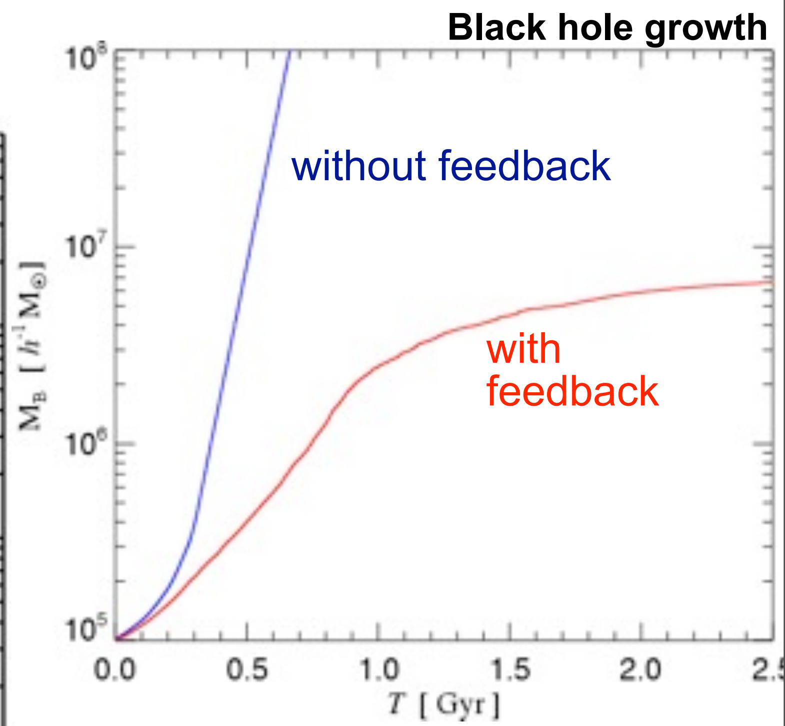
$$(M_{\rm BH} \sim 10^8 \, M_\odot)$$

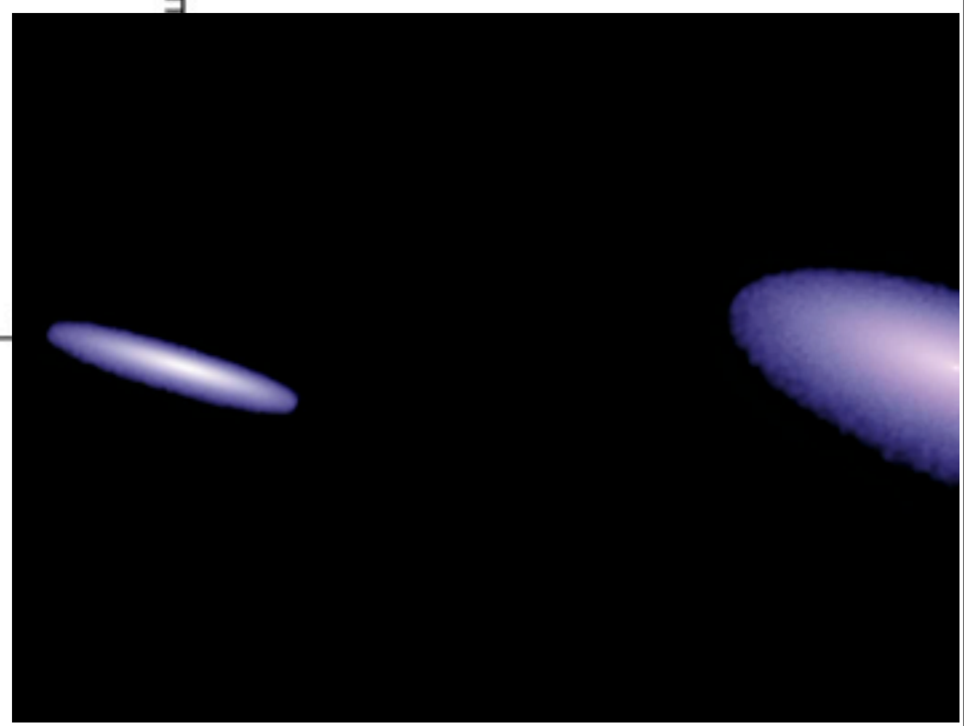
$$E_{\rm gal} \sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_\odot) \, (200 \, {\rm km/s})^2 \sim 10^{59} \, {\rm erg}$$

M-sigma Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



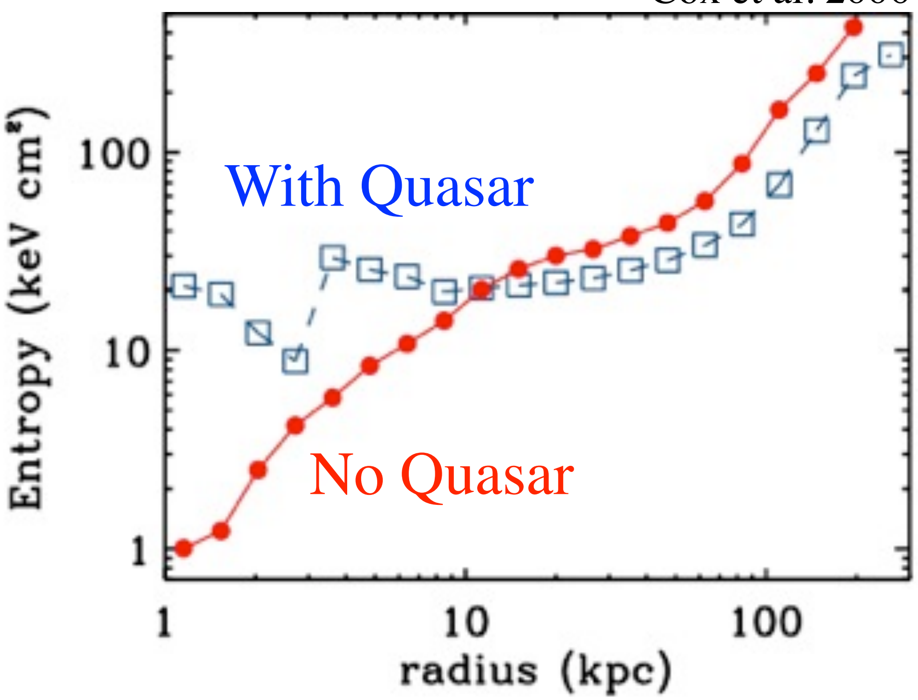




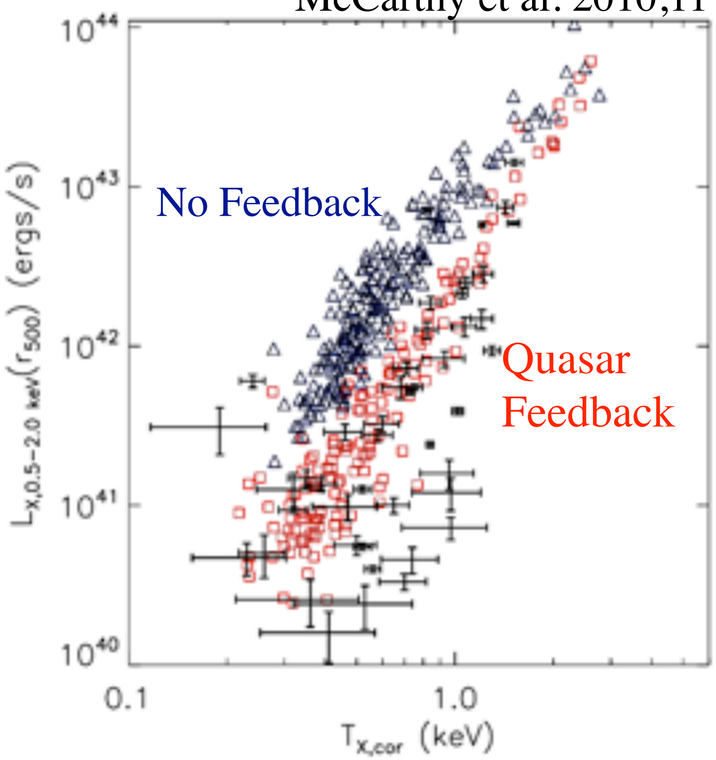
Quasar Outflows: Heating Halo Gas

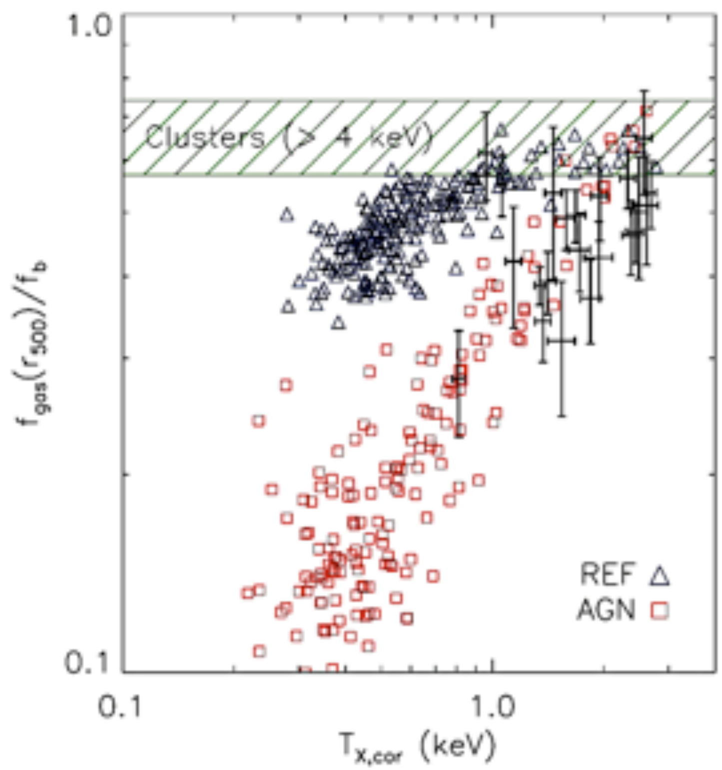
SHUT DOWN COOLING AND/OR "SET UP" RADIO MODE

Cox et al. 2006



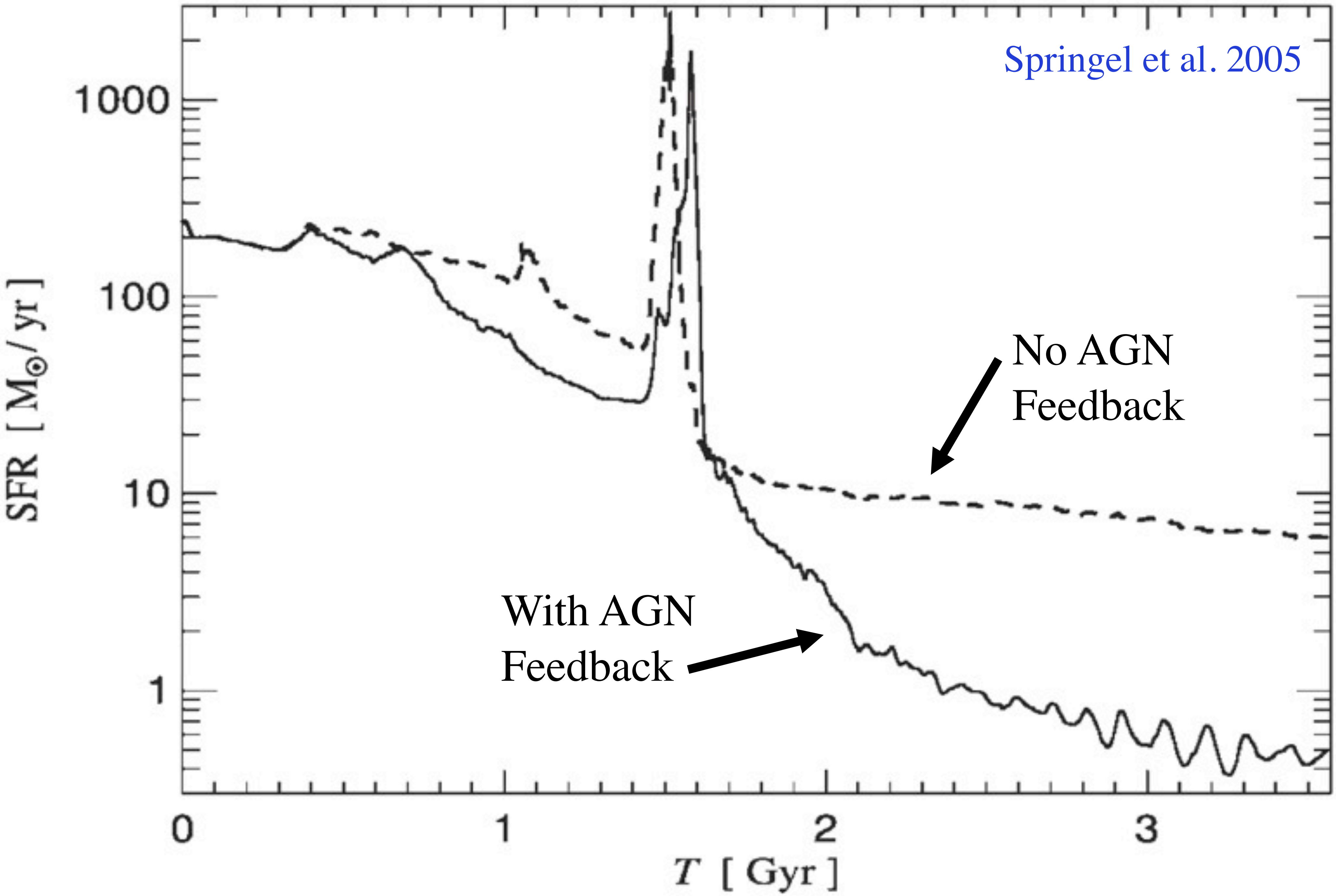
McCarthy et al. 2010,11





Expulsion of Gas Turns off Star Formation

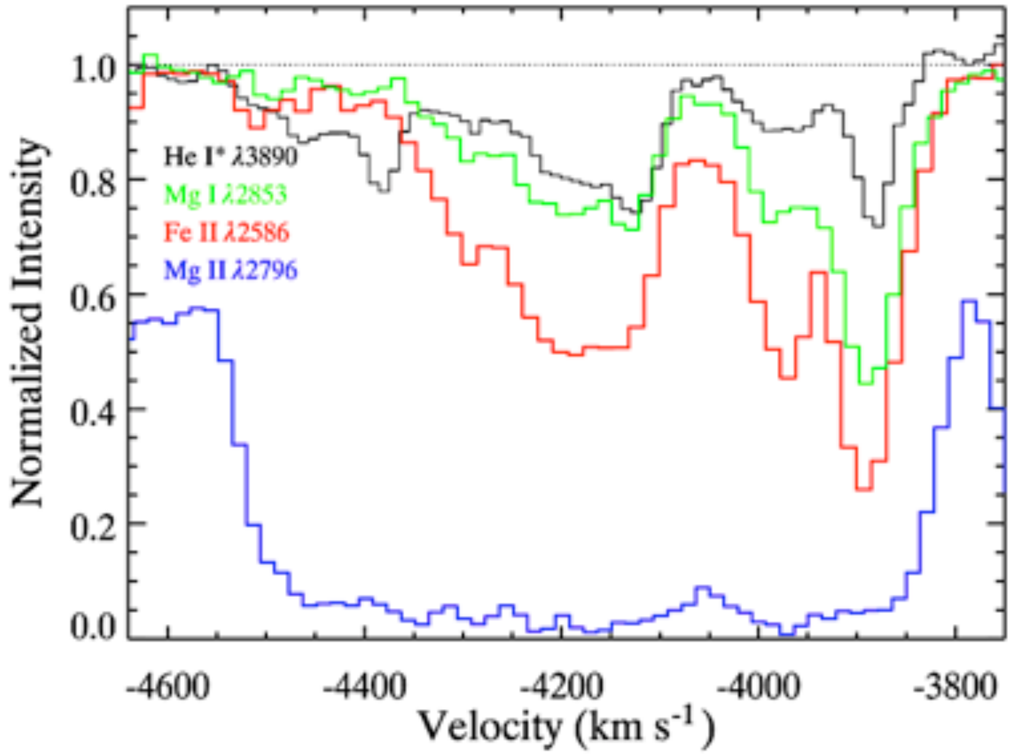
ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



But Does Quasar Mode Feedback Exist?

Broad Absorption Line Quasars

- Preferentially in high-L quasars
- Covering factor ~20%



- ~12 (16) objects now,
  10/12 confirmed:

$$\dot{M}_{\rm wind}\, v \gtrsim L_{\rm AGN}/c$$
$$L_{\rm wind} \gtrsim 0.01\, L_{\rm AGN}$$

$$R_{\rm wind} \sim 1 - 20\,{\rm kpc}$$
$$v \gtrsim 1000\,{\rm km\,s^{-1}}$$
$$\dot{M}_{\rm wind} \sim 100 - 600\, M_{\odot}\,{\rm yr}^{-1}$$

Arav et al.
Wampler et al. 1995
Hamann et al. 2001
de Kool et al. 2001&2
Korista et al. 2008
Moe et al. 2009
Dunn et al. 2010
Aoki et al. 2011
Kaastra et al. 2011

“Broad wings in Narrow Lines” in Type-2 (Narrow-Line) *Quasars*

Laor et al., Crenshaw et al.
(lower-luminosity, v ~ 100-400 km/s)

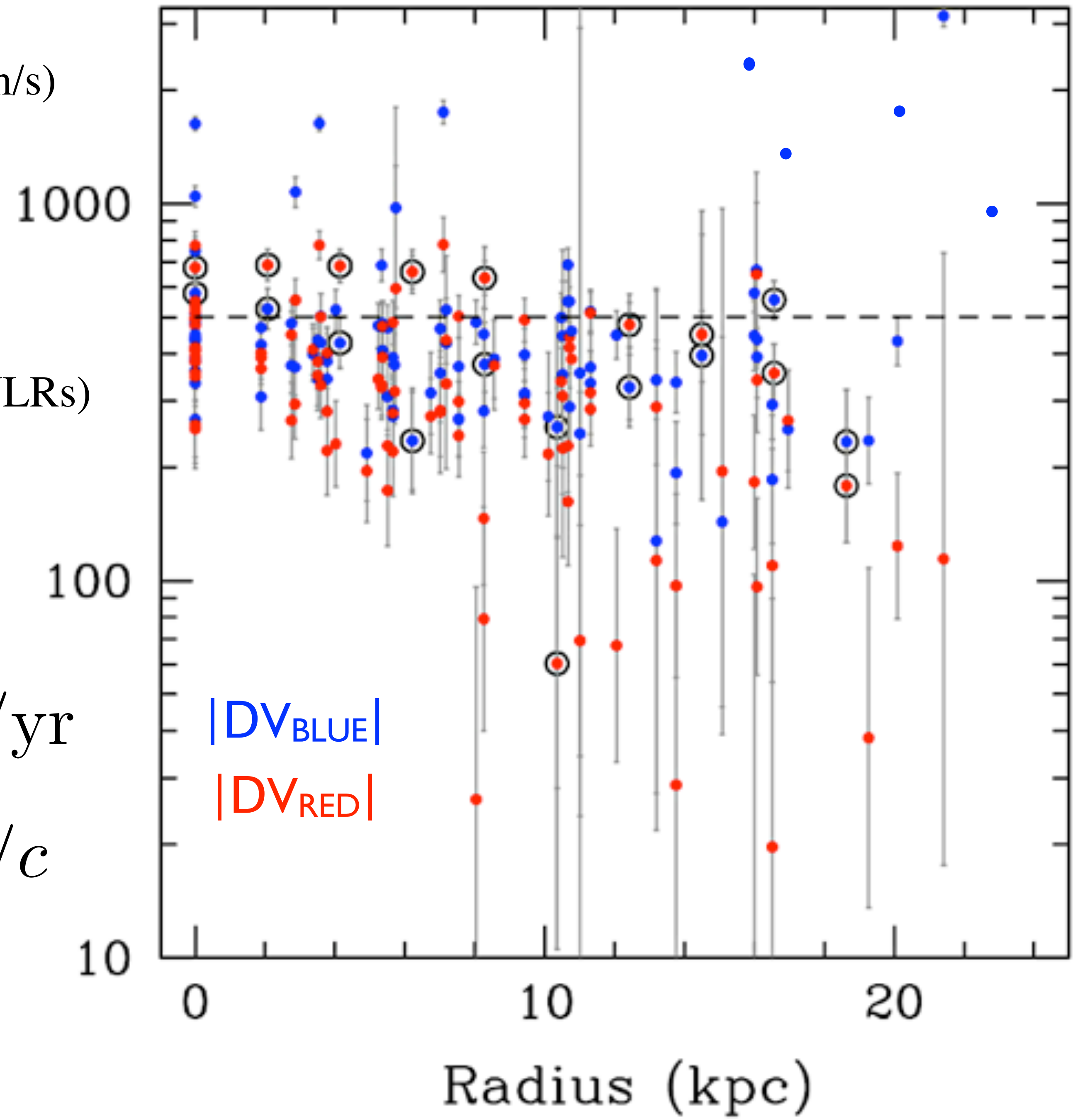
Humphrey et al. 2010
Green & Zakamska et al. 2011

Shen et al. 2011 (Double-Peaked NLRs)

$$\dot{M} \sim 50 - 1000\, M_\odot/\mathrm{yr}$$

$$\dot{M}\, v \sim 1 - 30\, L_{\mathrm{AGN}}/c$$

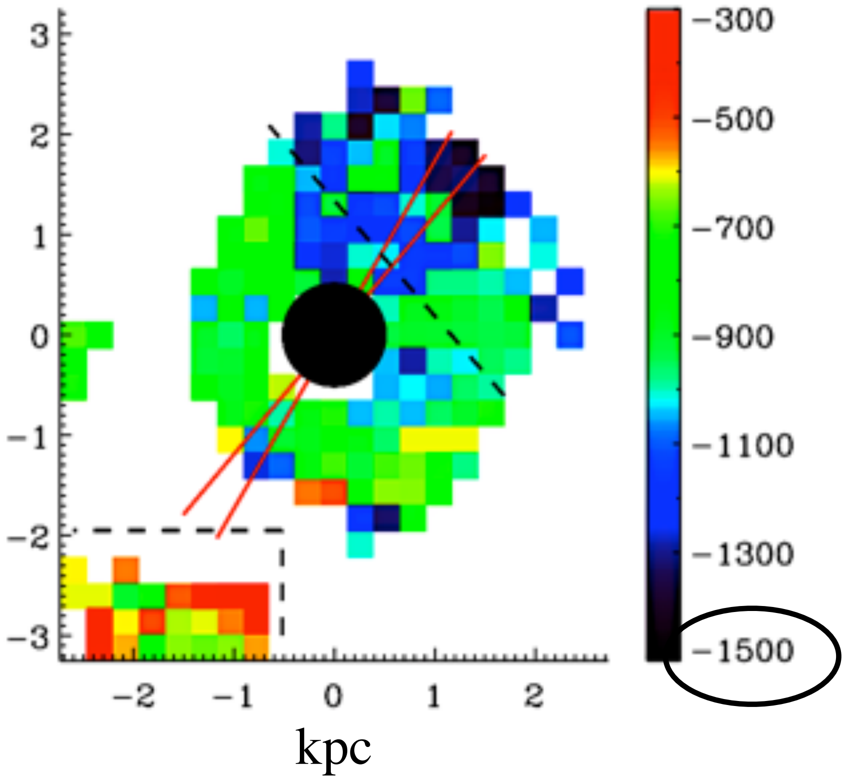
$$L_{\mathrm{wind}} \sim 0.01\, L_{\mathrm{AGN}}$$



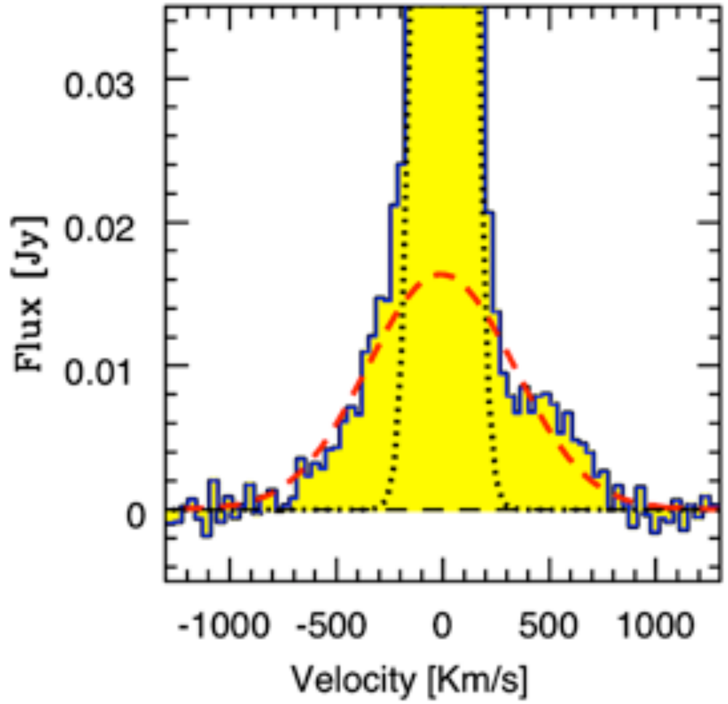
Molecular Outflows in AGN ULIRGs

Rupke & Veilleux 2005,2011
Fischer et al. 2010 (Mrk 231)
Feruglio et al. 2010 (Mrk 231)
Alatalo et al. 2011 (NGC 1266)

Molecular+Ionized Outflows:



CO:



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

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

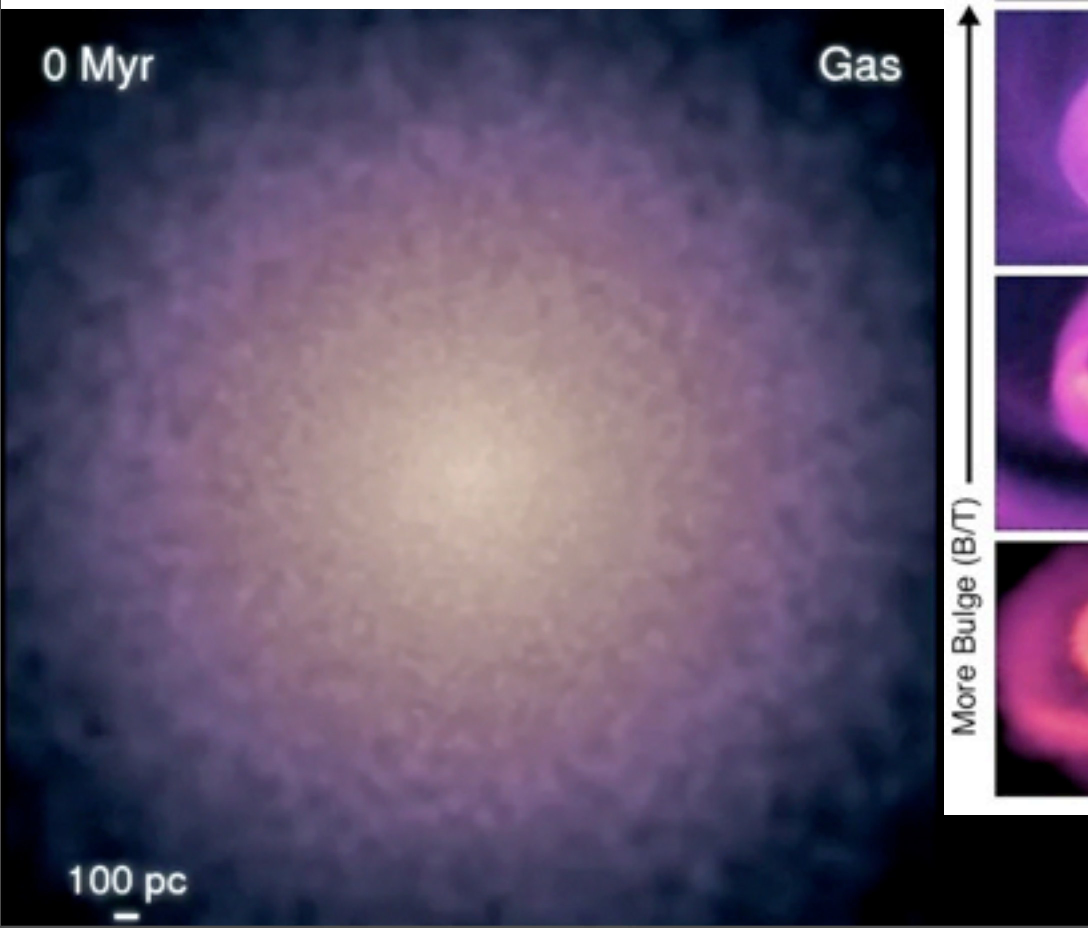
$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr}^{-1}$$

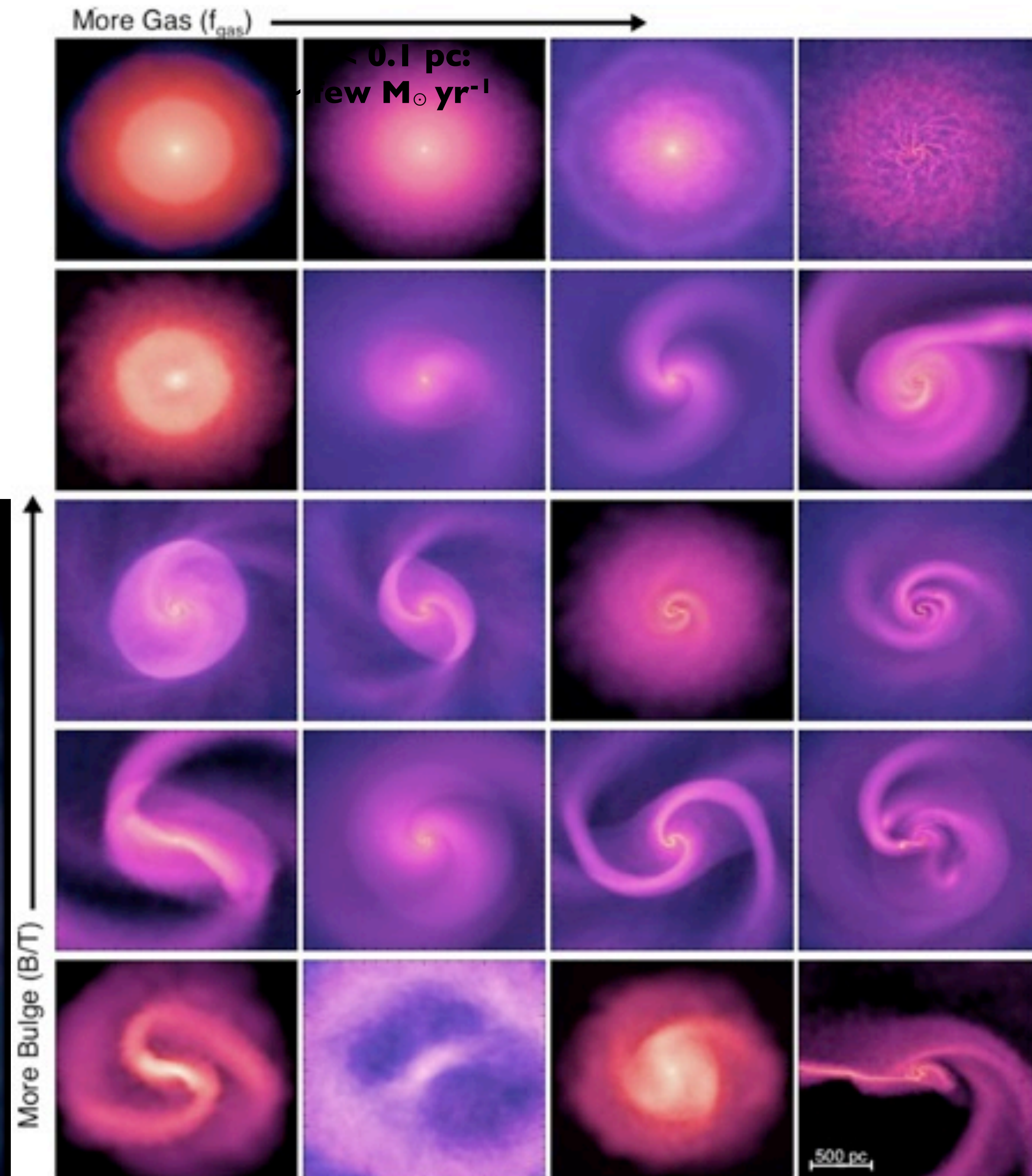
Where to now? How Do We Model This?

Step 1: Inflow

- Beginning to directly follow inflow to sub-pc scales

PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10





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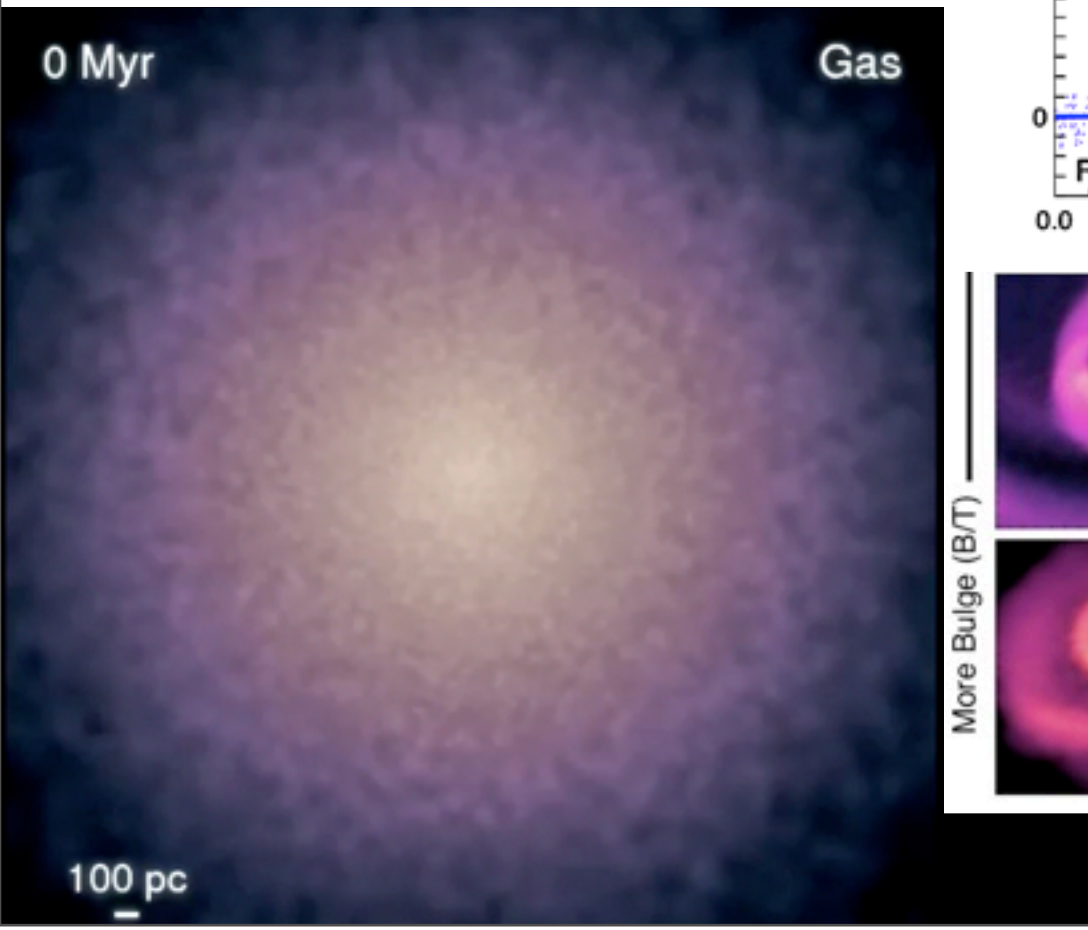
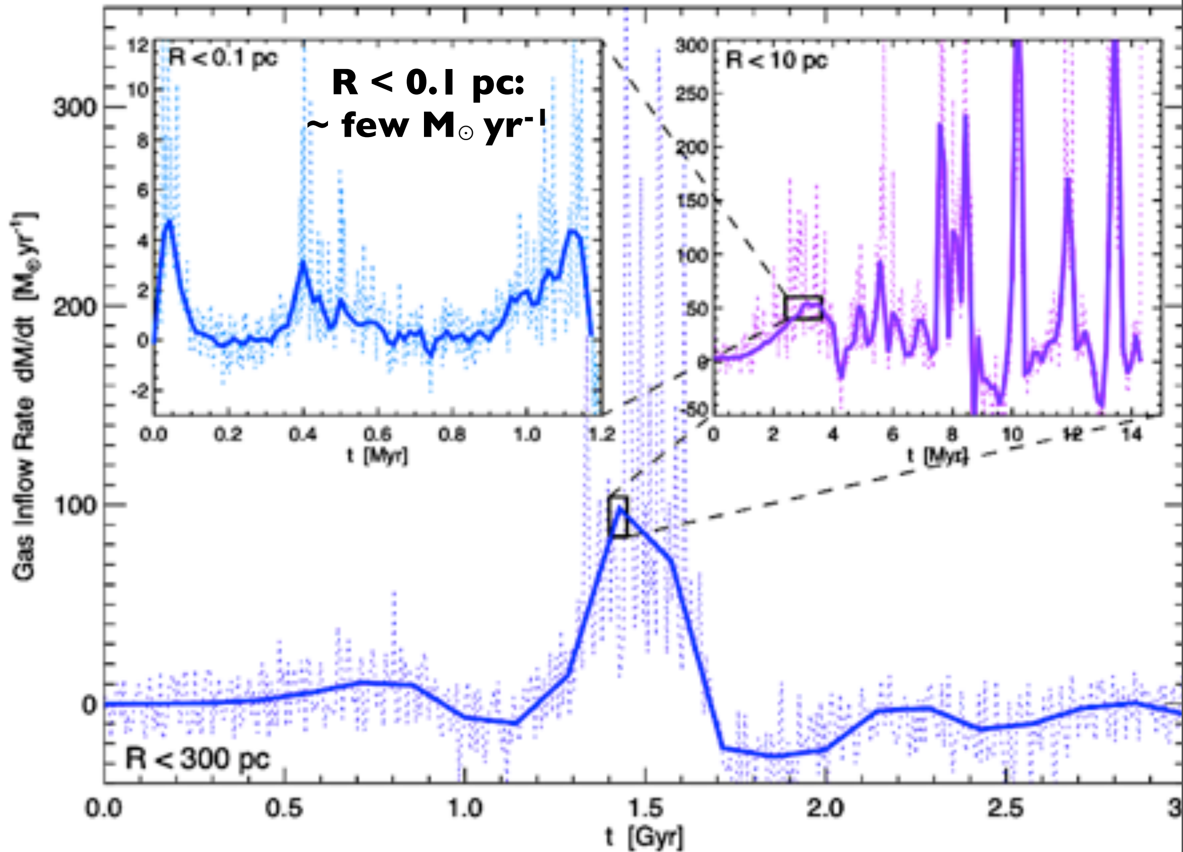
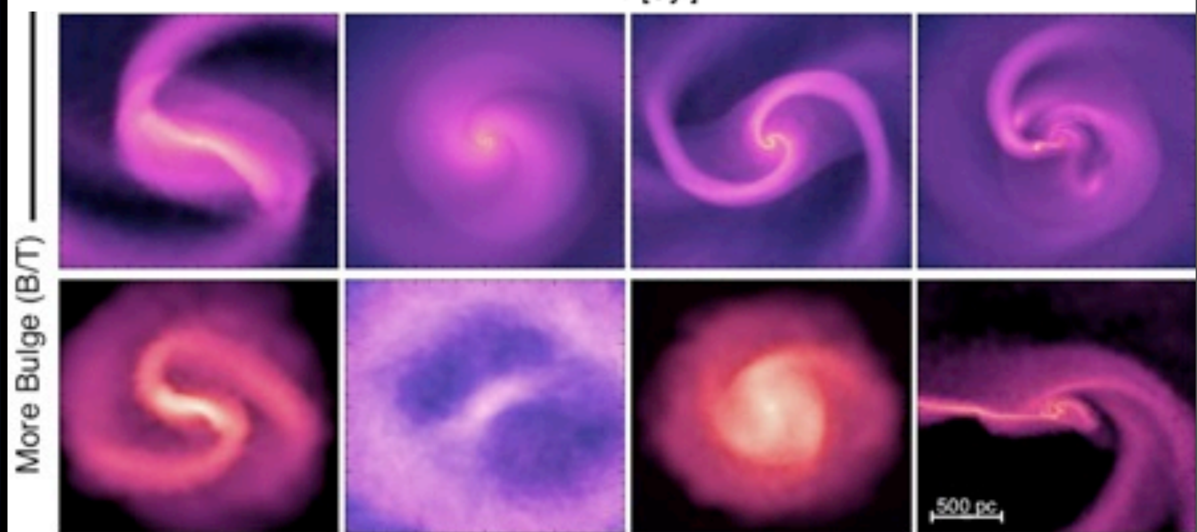
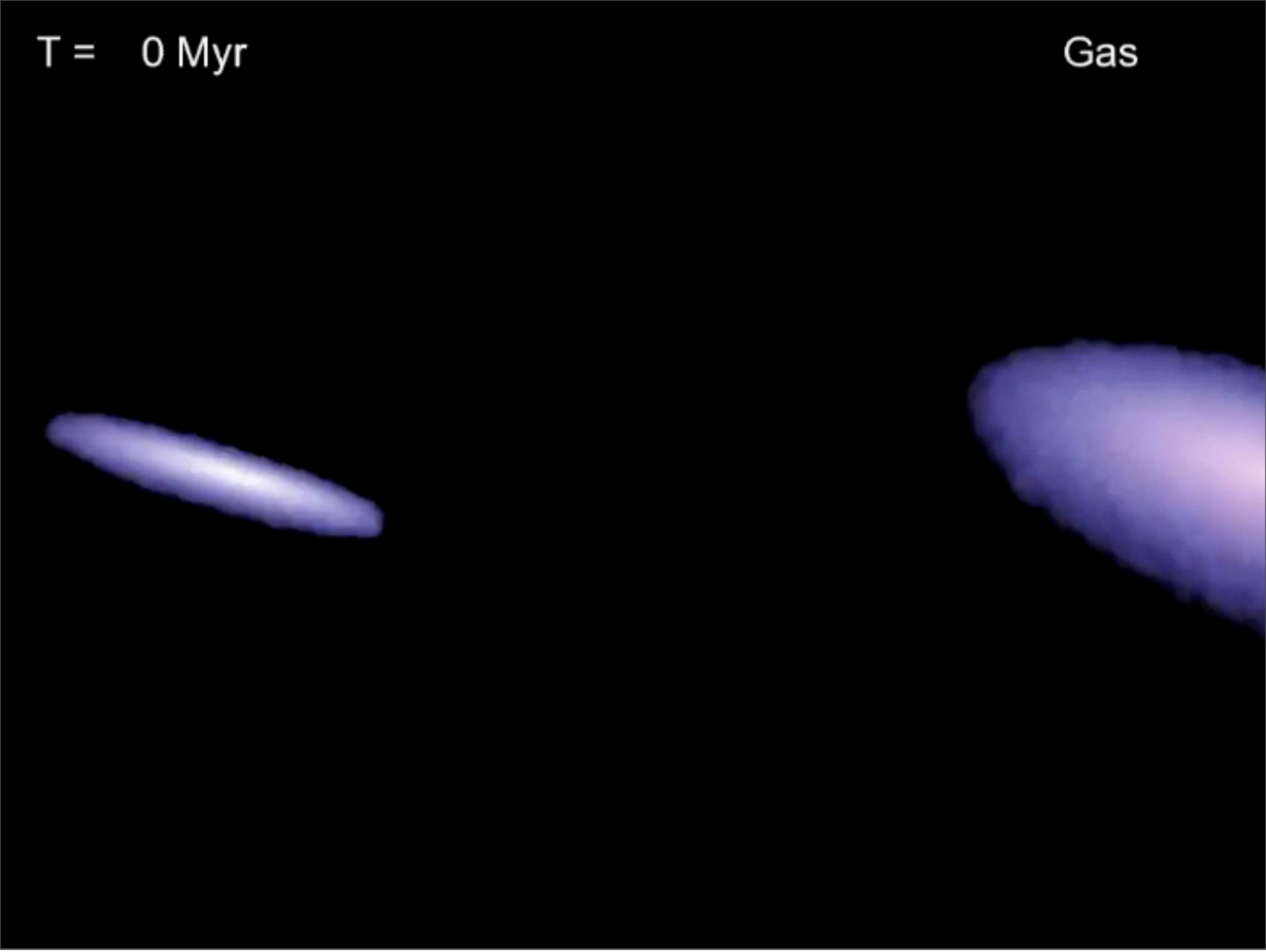
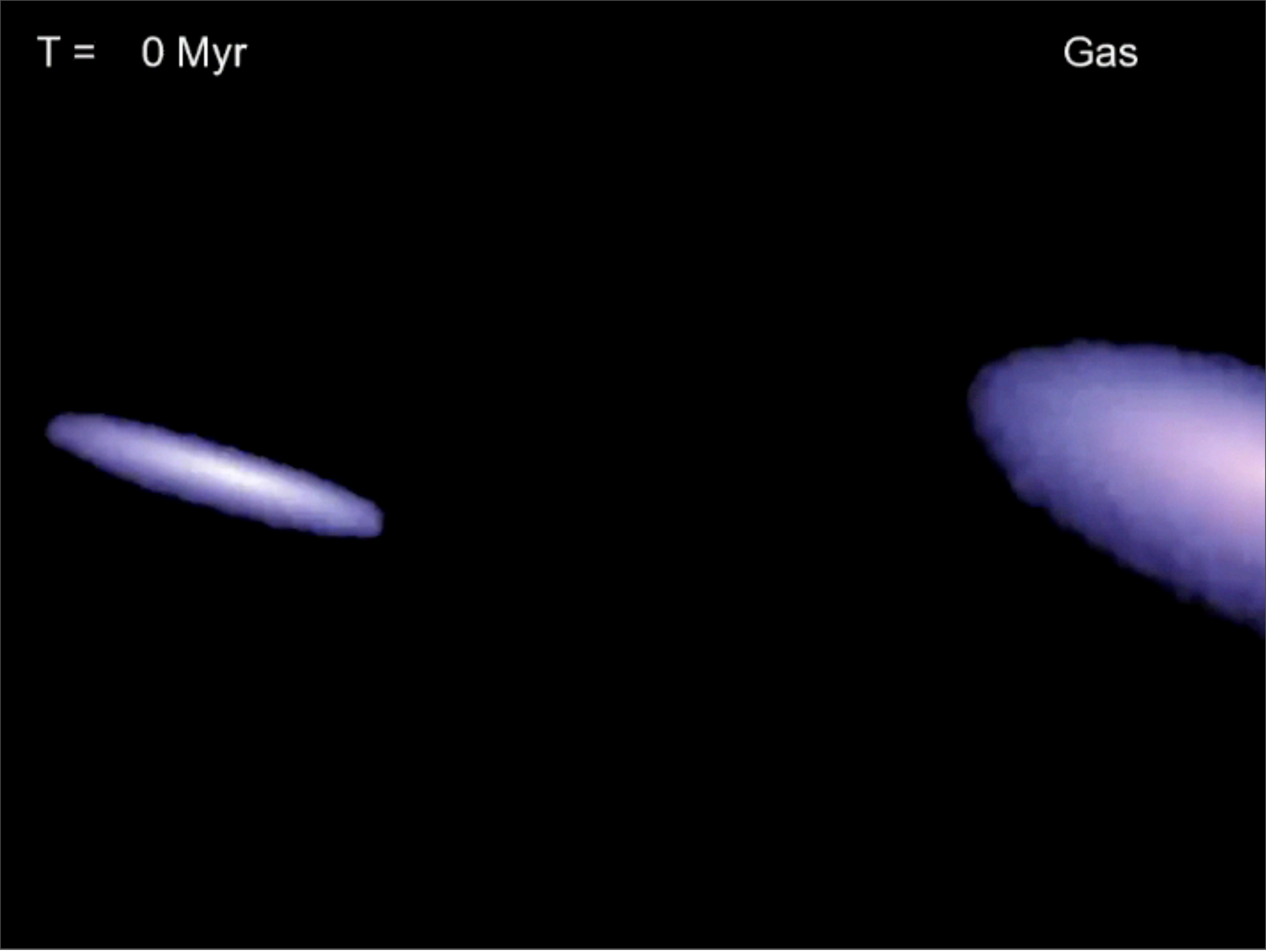







T = 0 Myr
Gas

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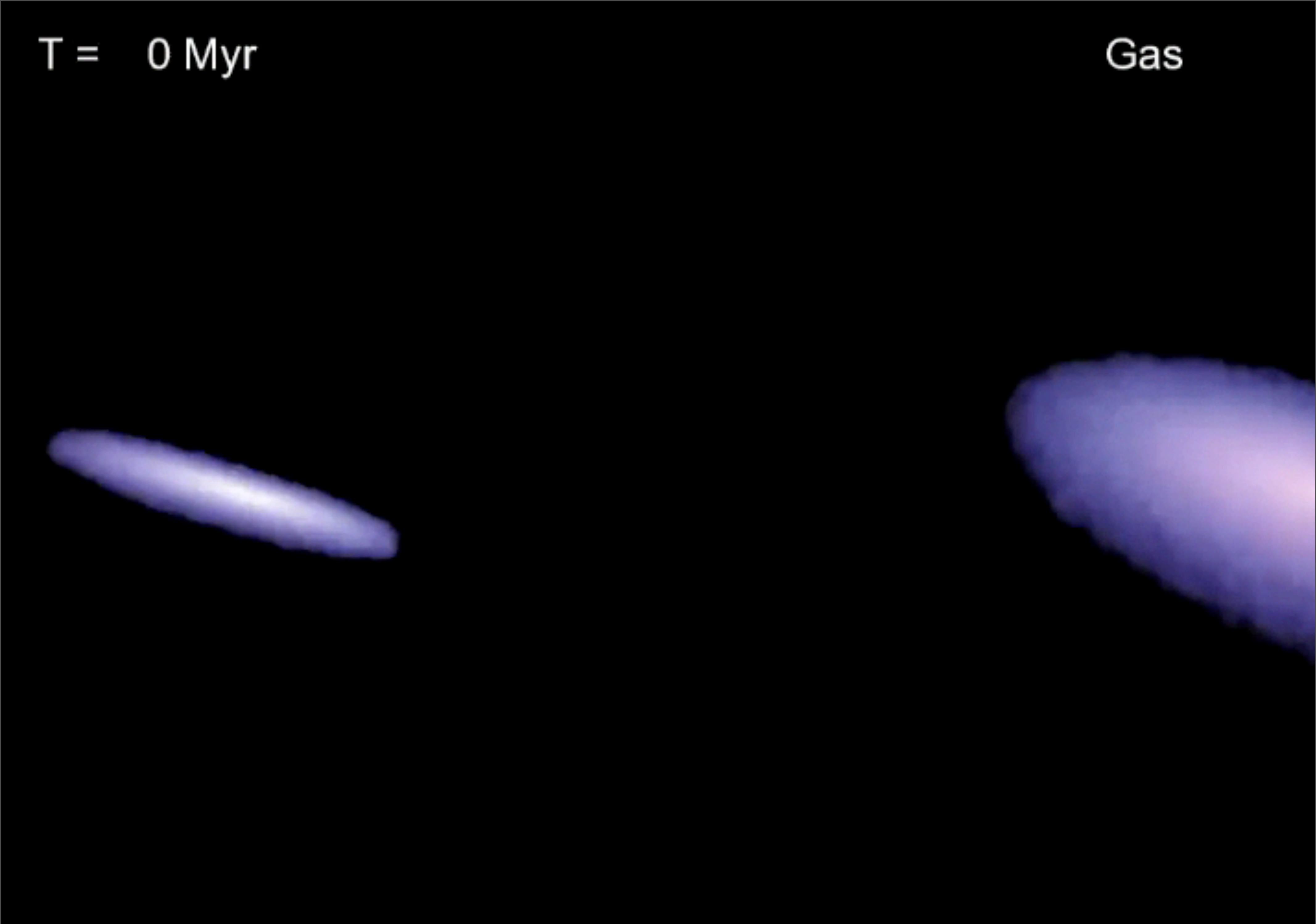
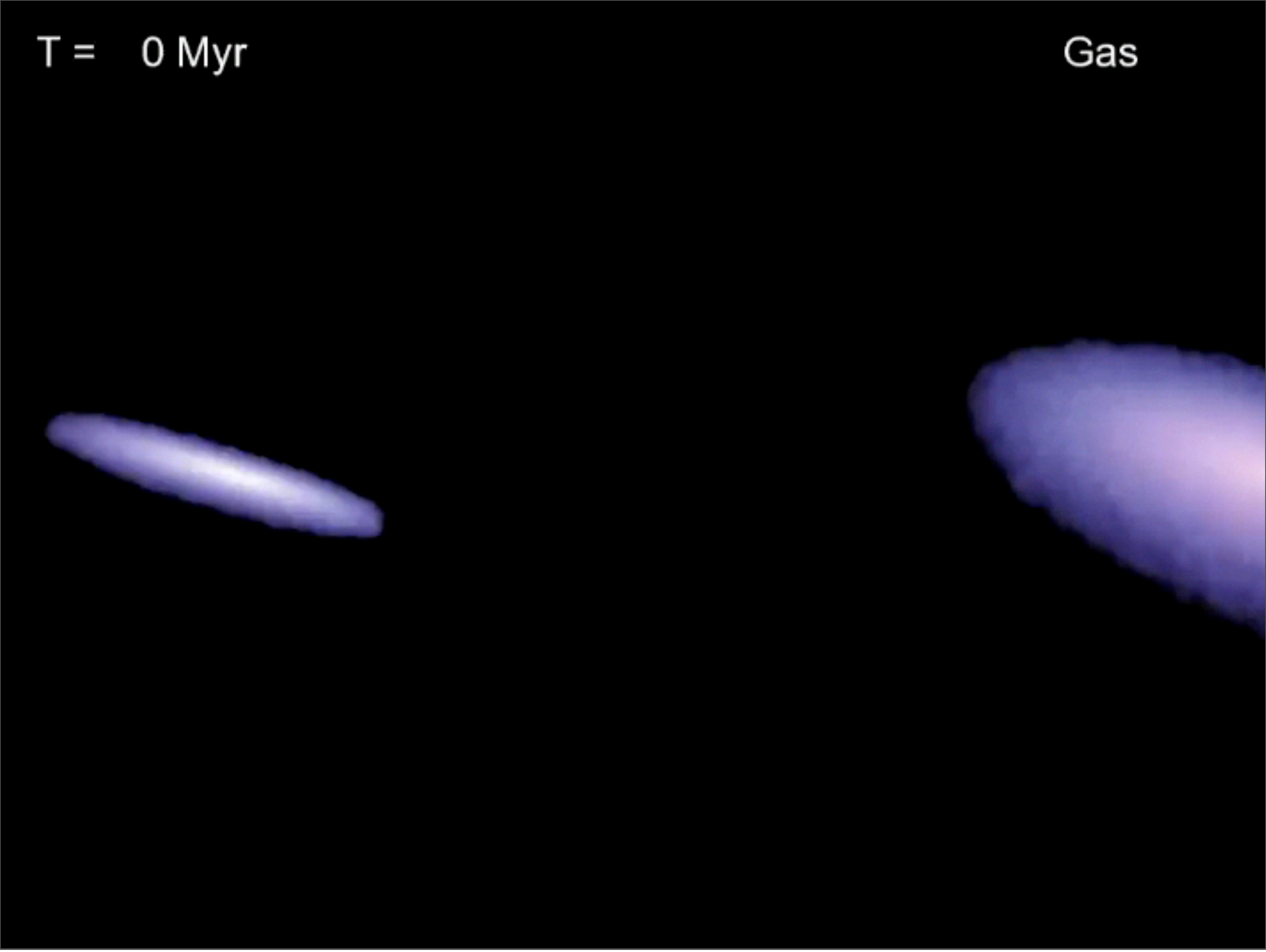
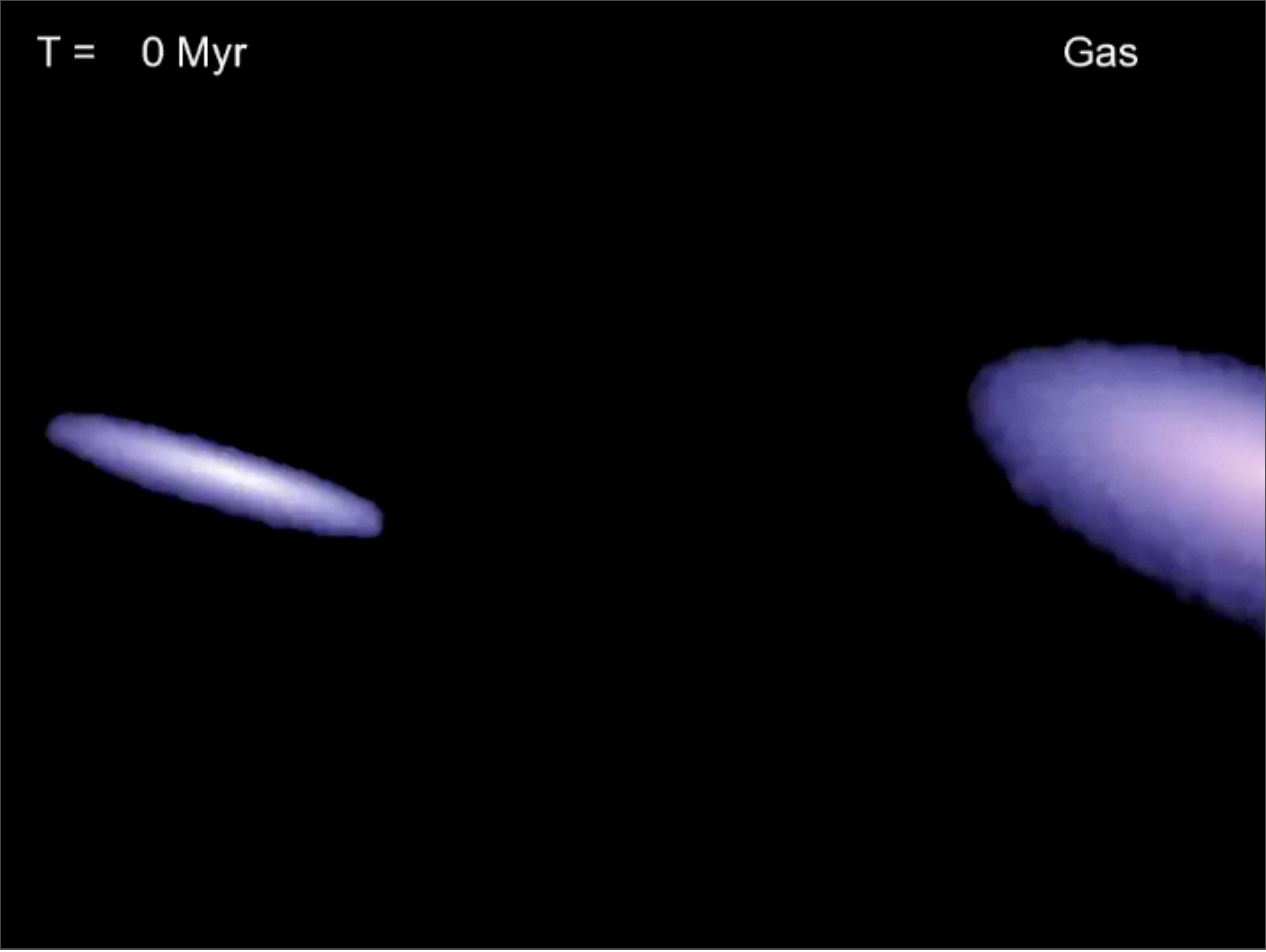


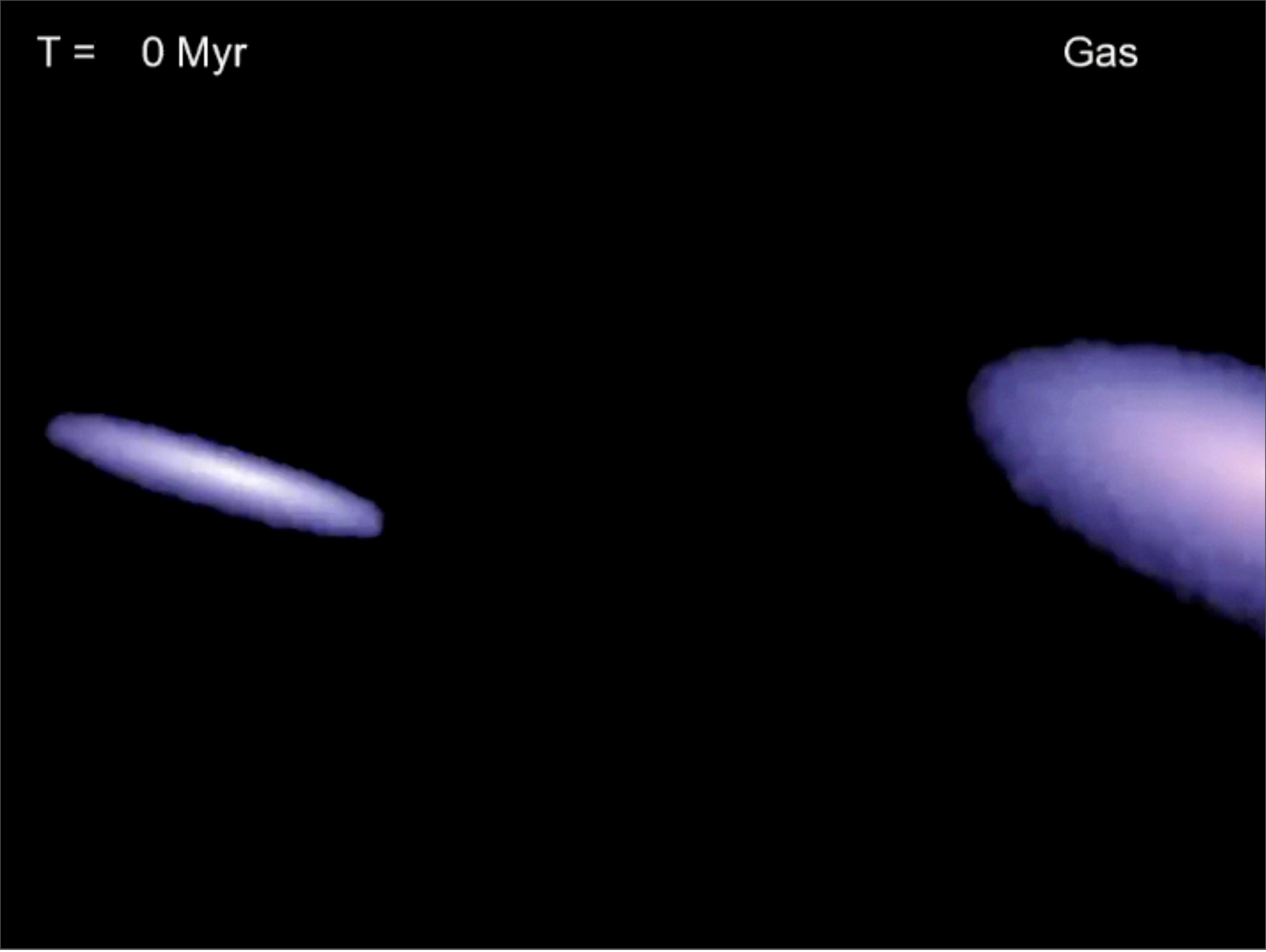
Triggers Starbursts (e.g. Mihos & Hernquist 1996)

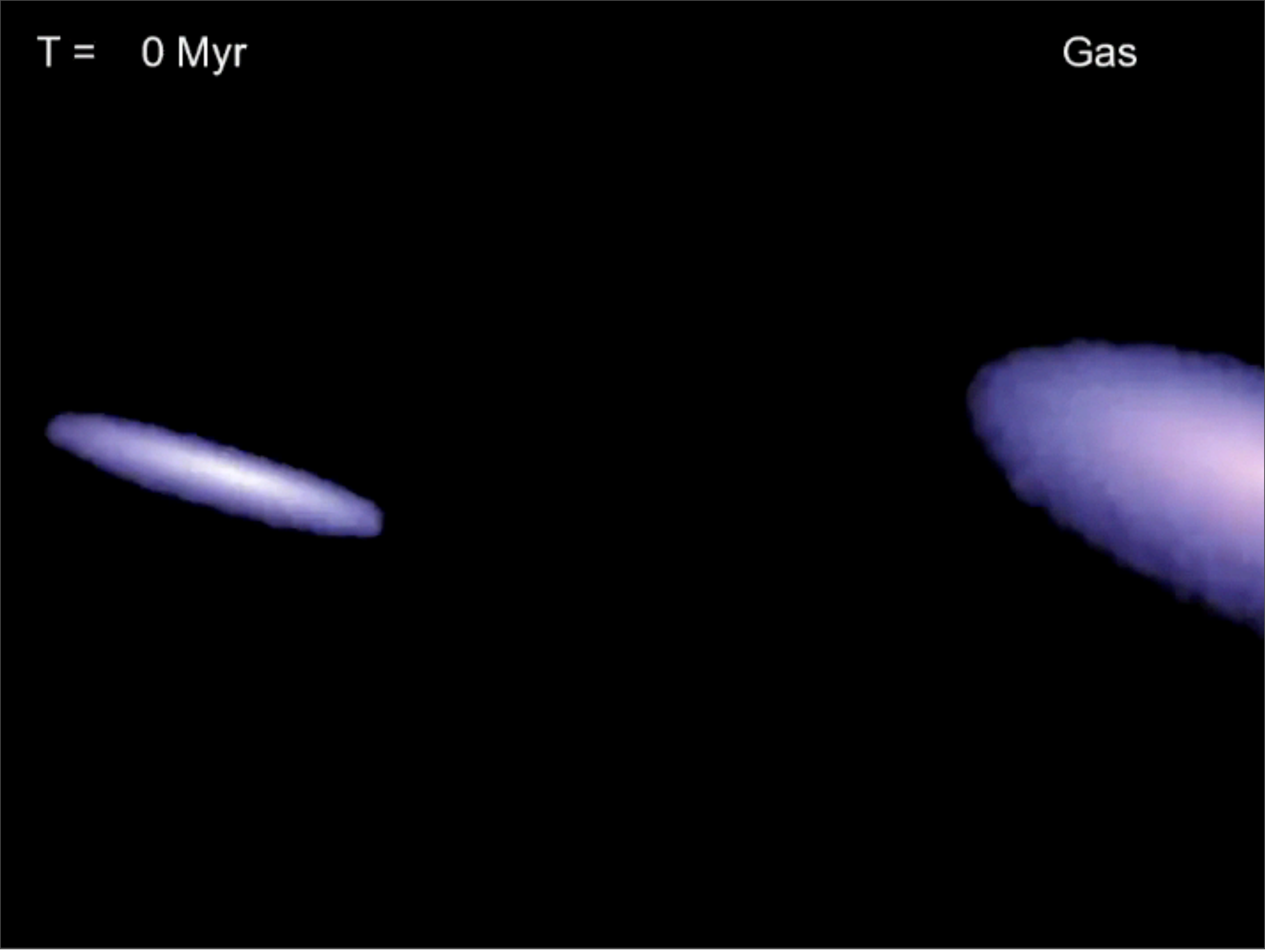

T = 0 Myr
Gas

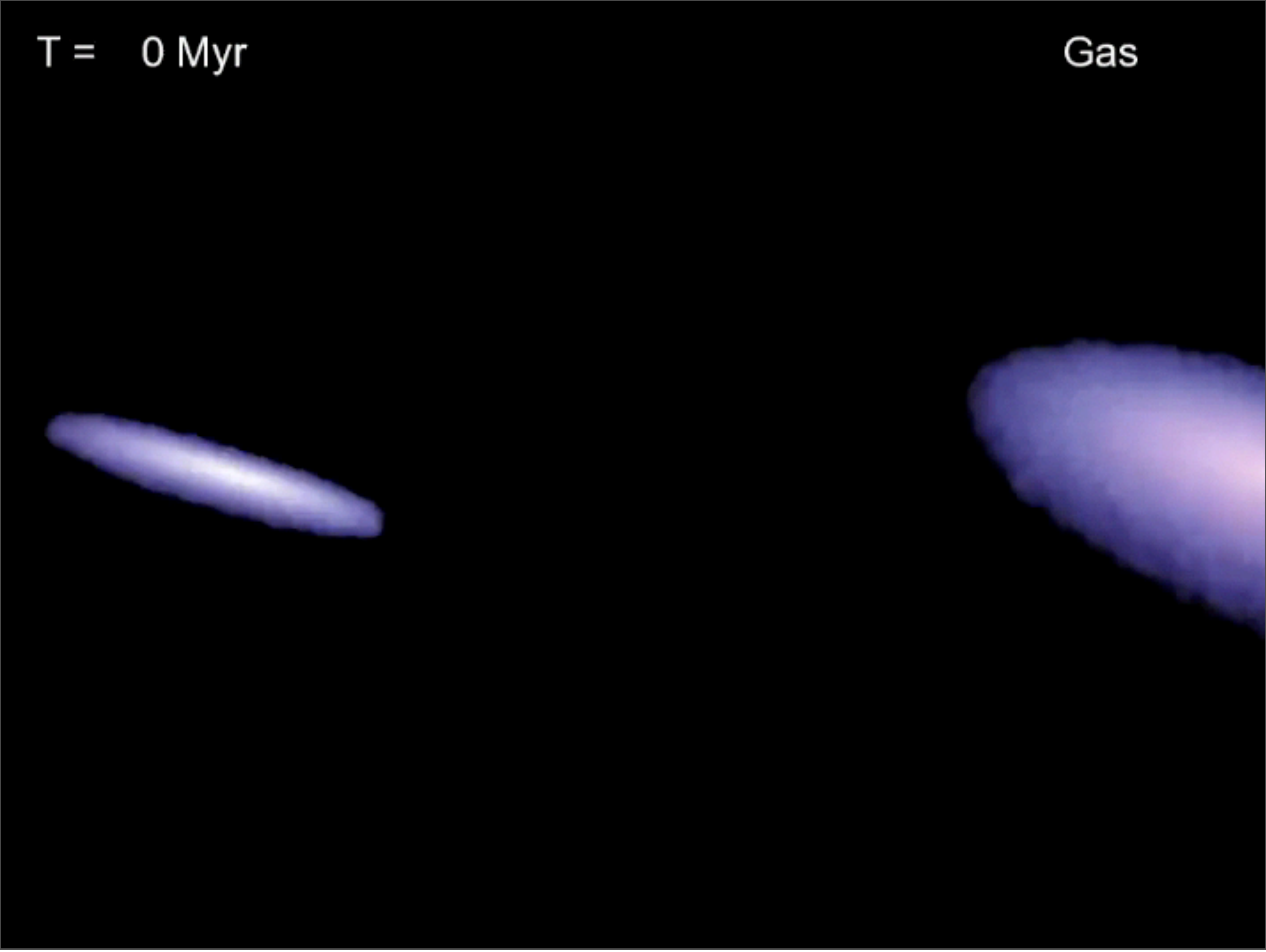
Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)


T = 0 Myr
Gas

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


T = 0 Myr
Gas


T = 0 Myr
Gas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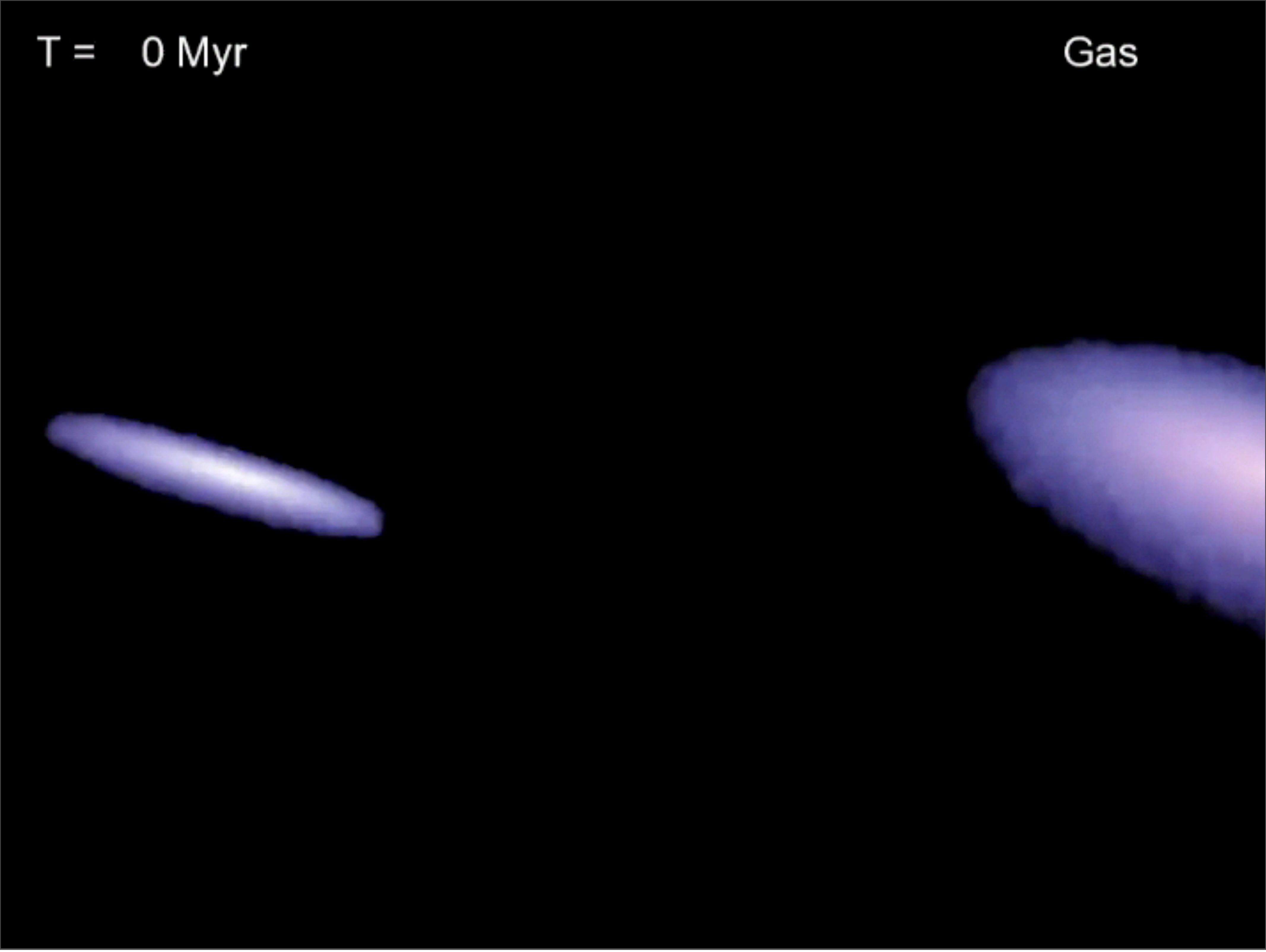
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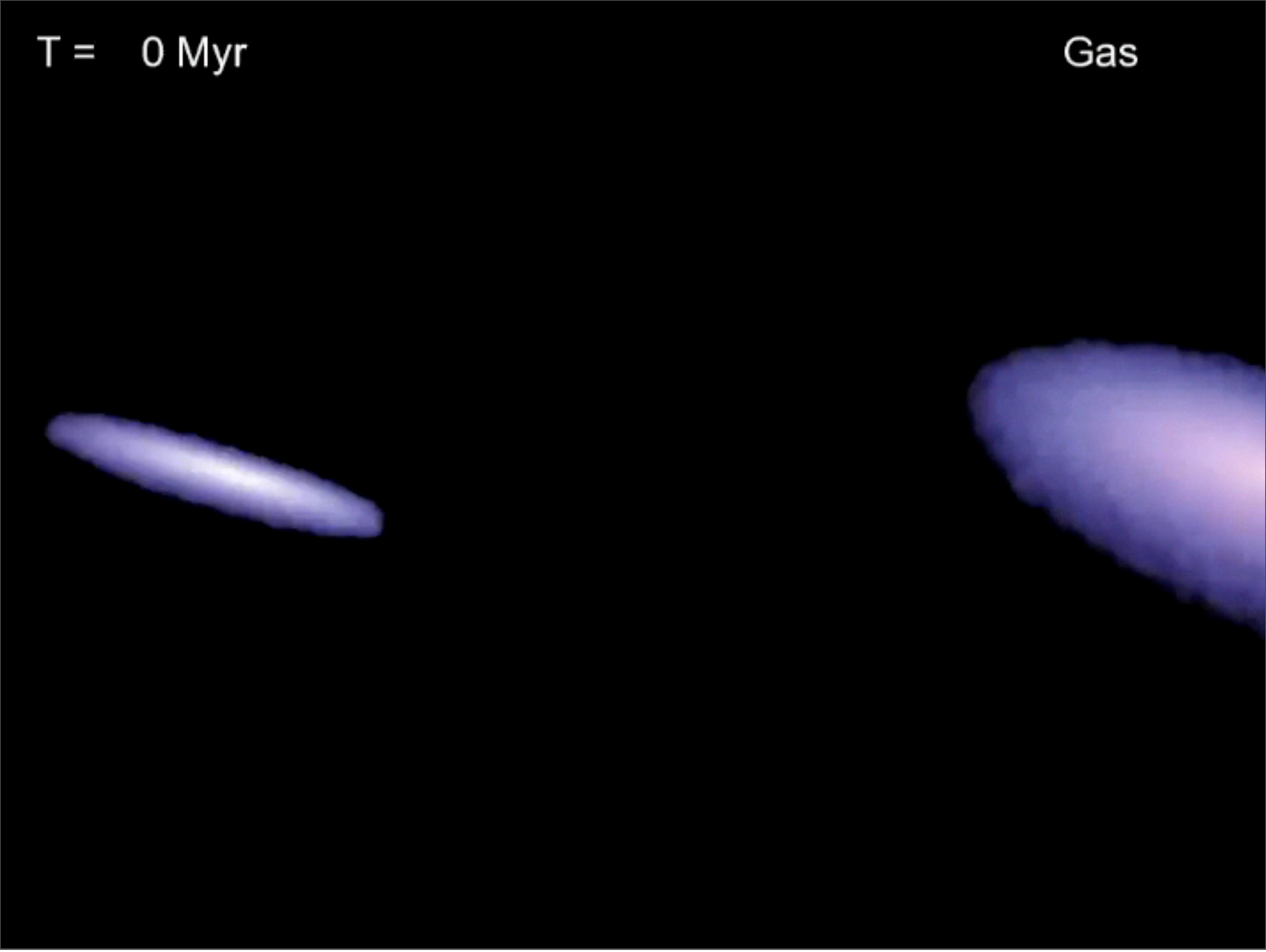
T = 0 Myr
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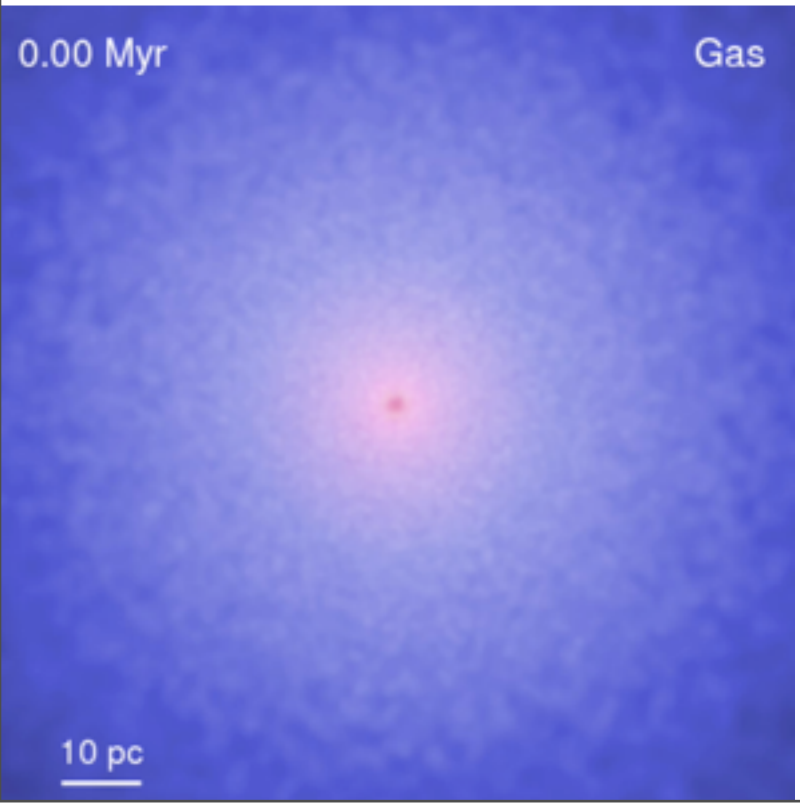
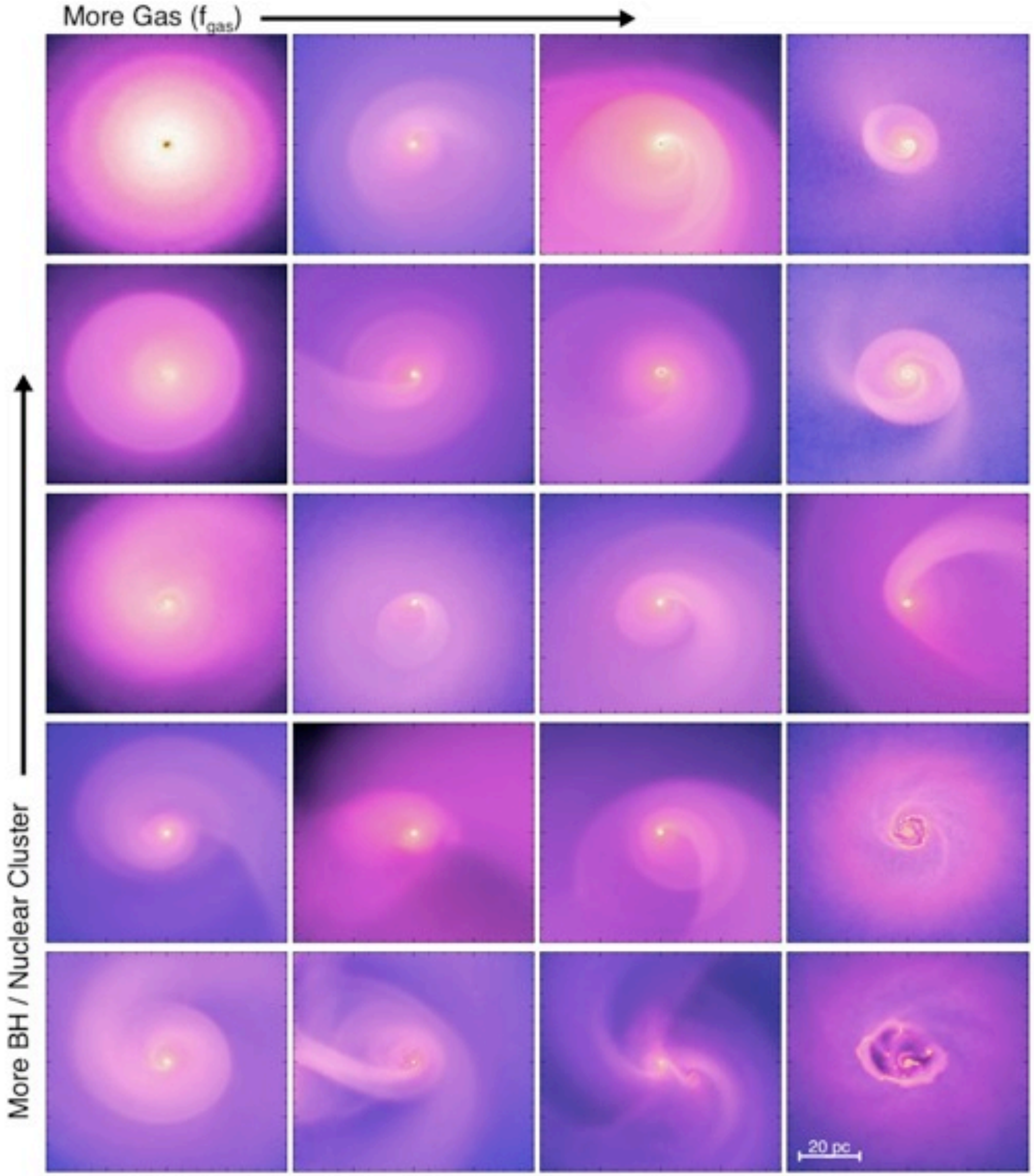
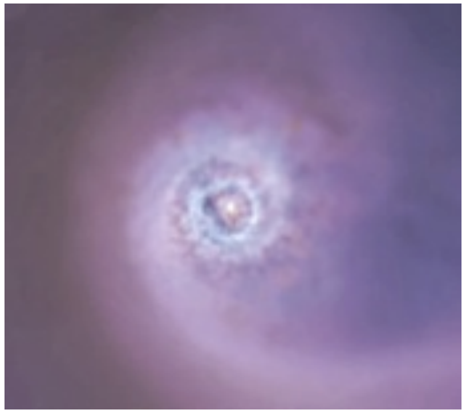
~10 pc scales: Nuclear eccentric disks

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

- Need *both* star formation and self-gravity





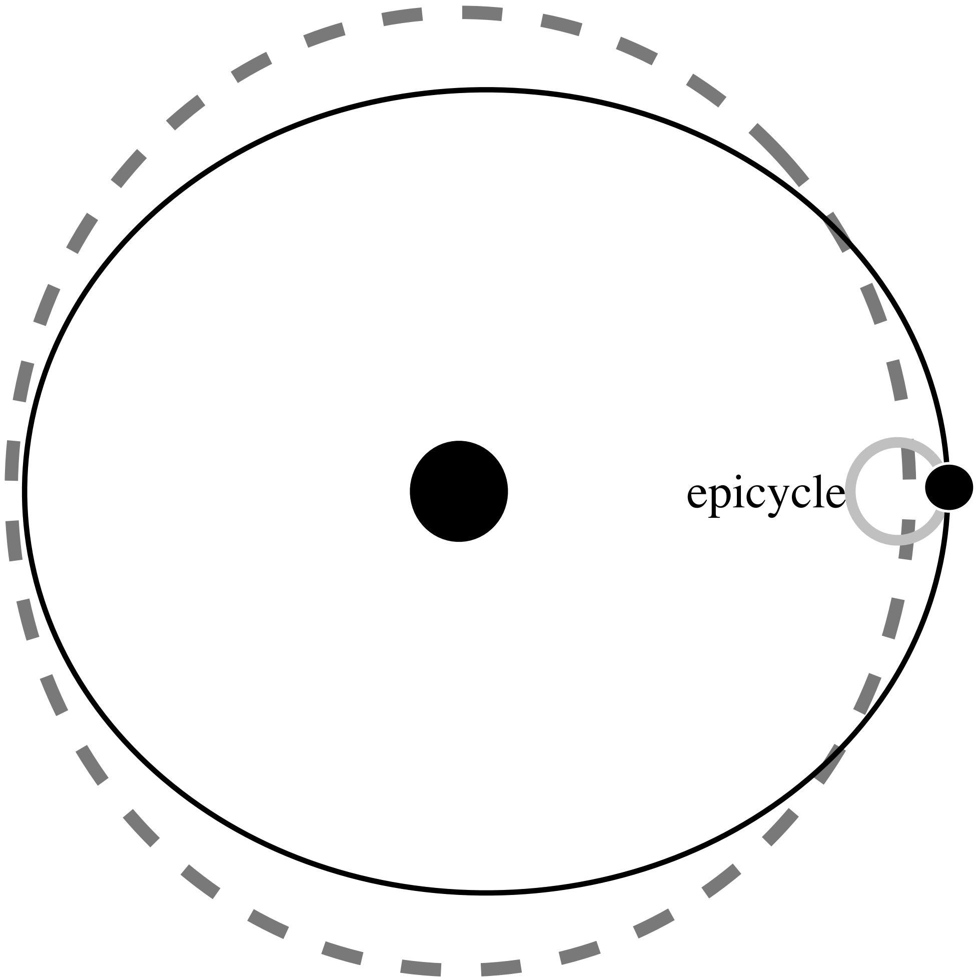


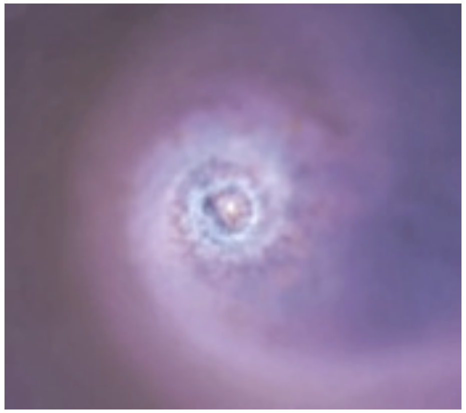
Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential

Keplerian potentials are special:

$$\kappa = \Omega$$

Hence, closed elliptical orbits!

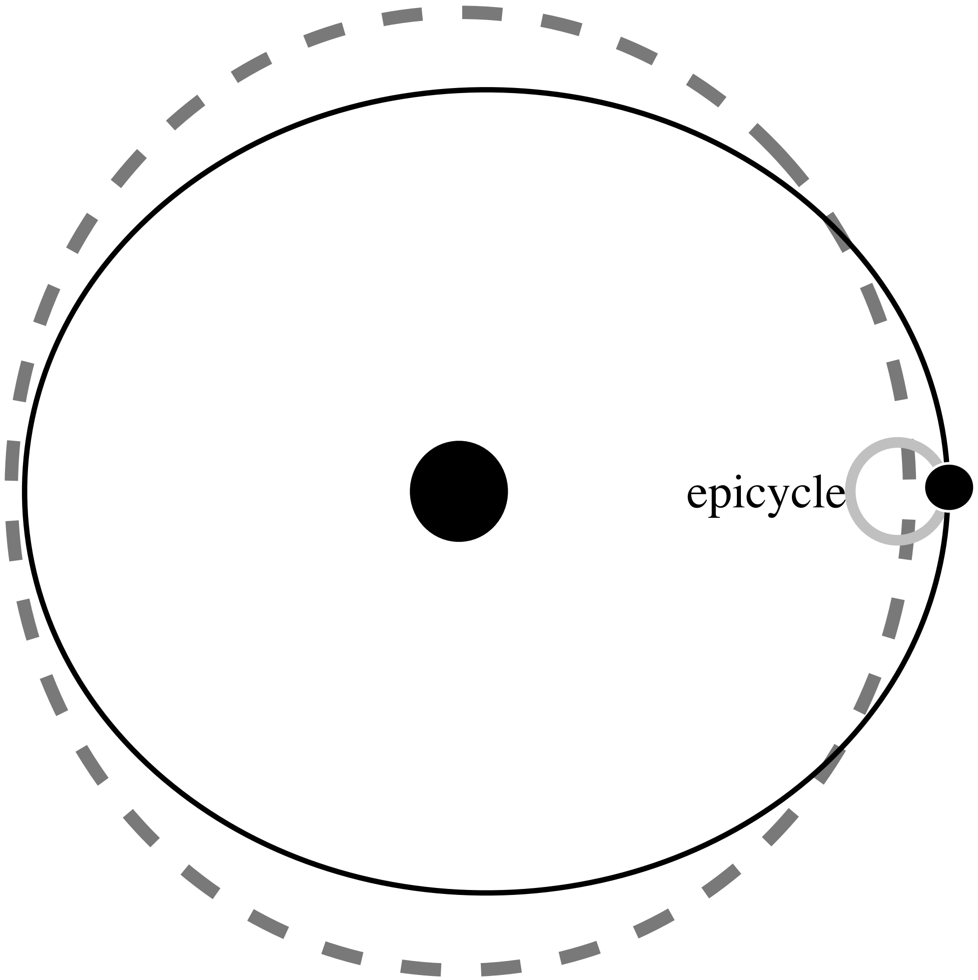


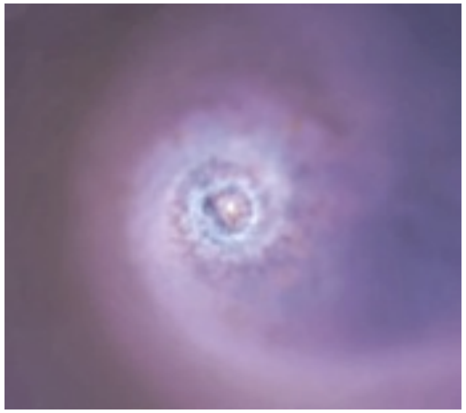


Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential

Disturb the stars with some perturbation in the disk:

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





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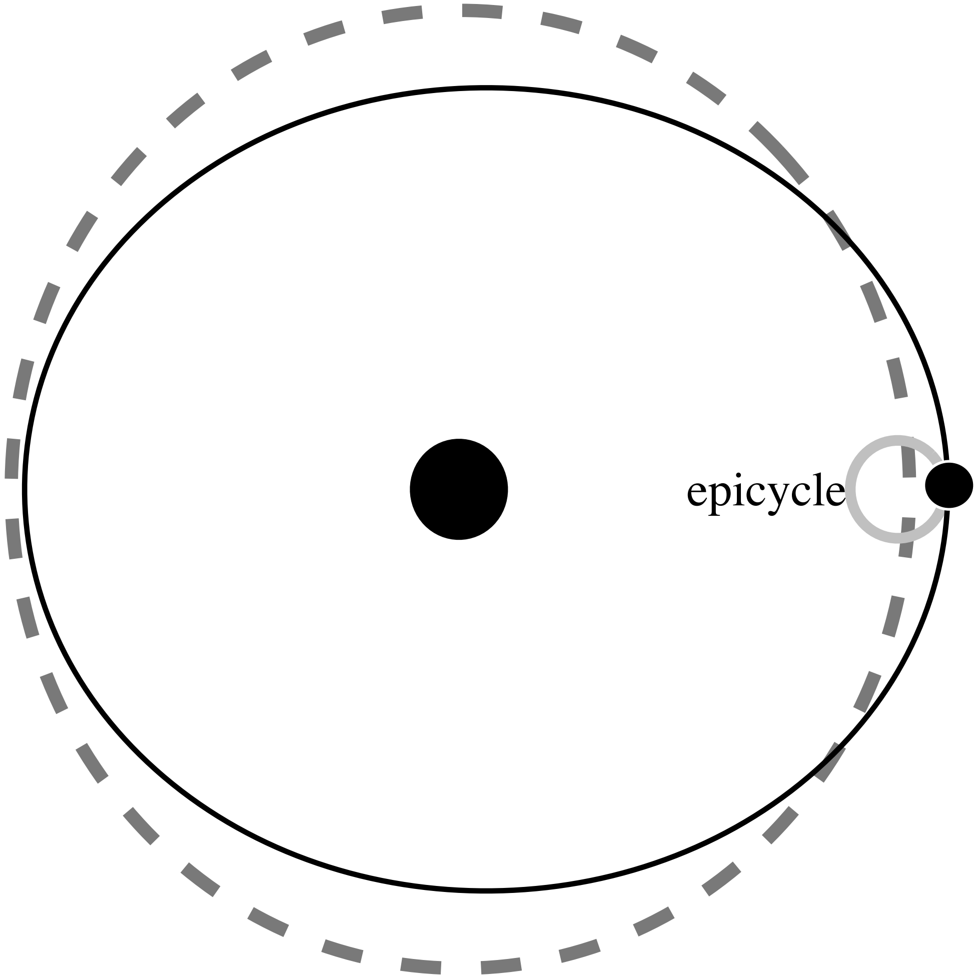
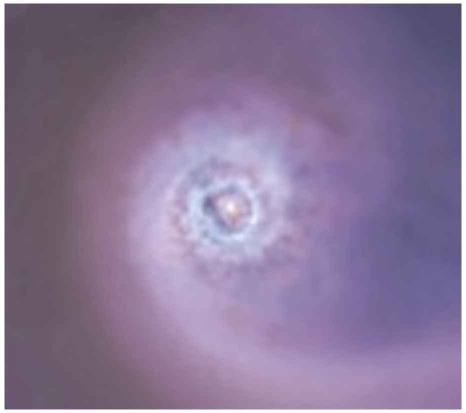
$$\left|\frac{\delta v}{V_c}\right| \sim \left(\frac{\delta\Sigma}{\Sigma}\right)\frac{M_{\rm disk}(<r)}{M_{\rm BH}}$$





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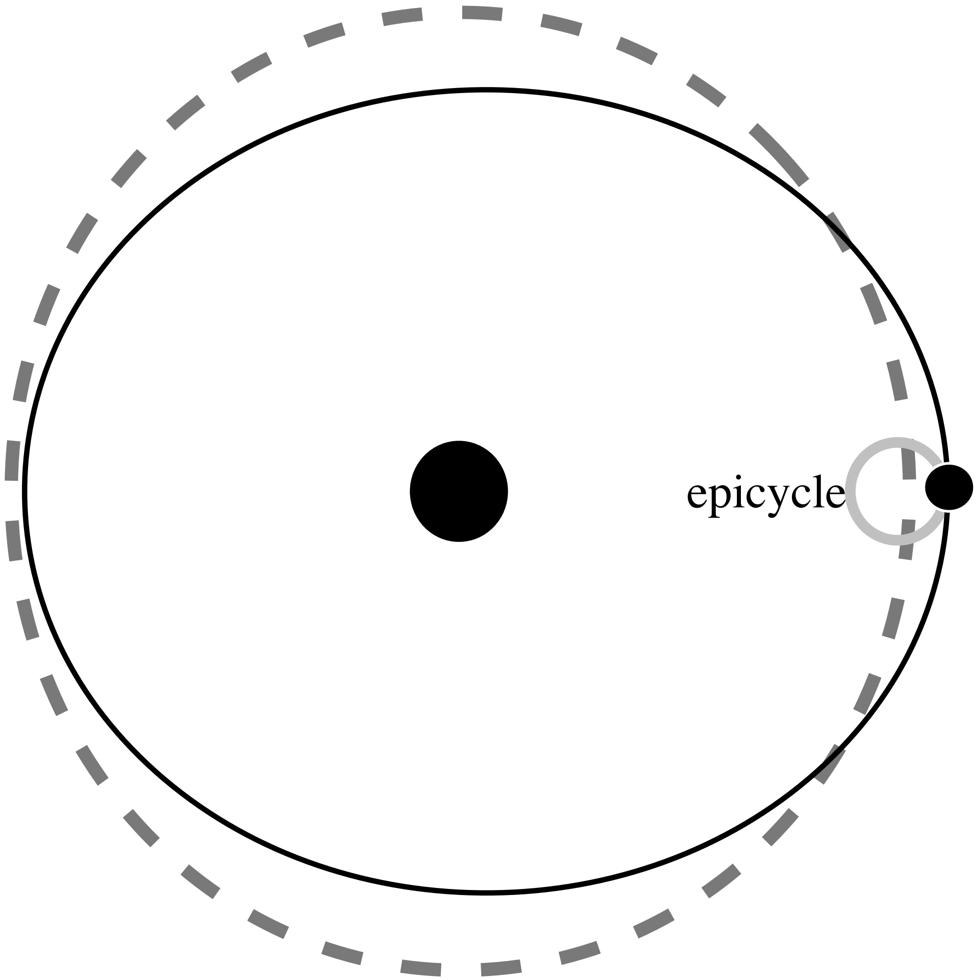
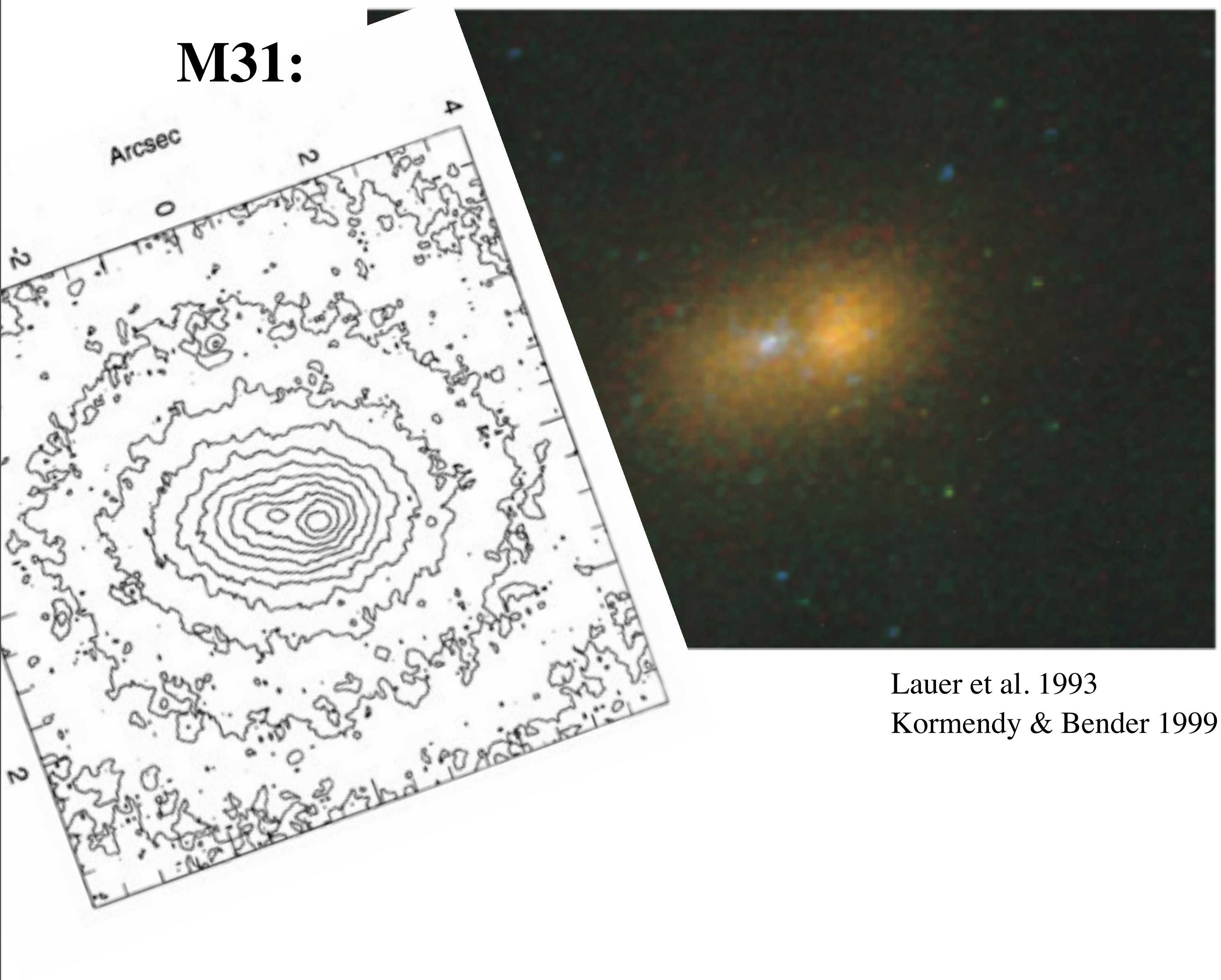
But, if (and *only* if) m=1:

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

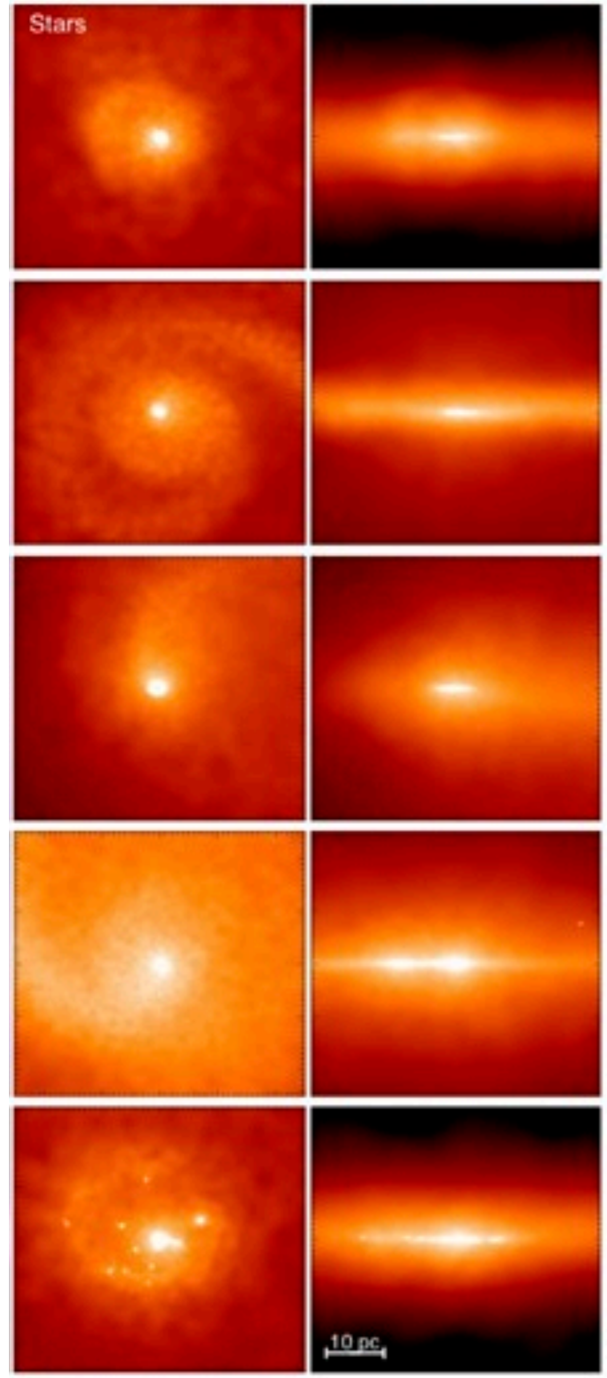


- These are observed!
  M31, NGC4486B, many candidates
  (NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)

M31:



Lauer et al. 1993
Kormendy & Bender 1999



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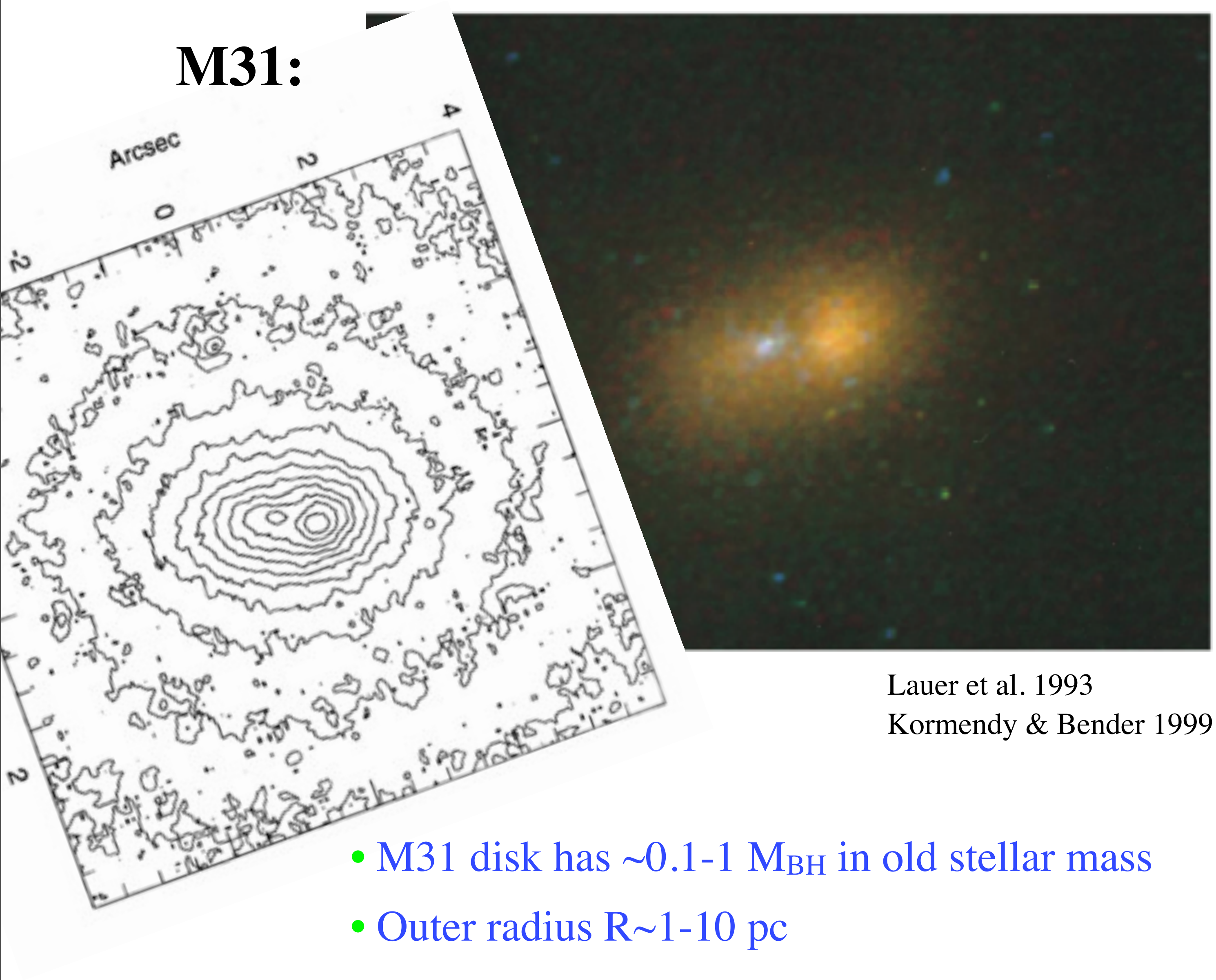
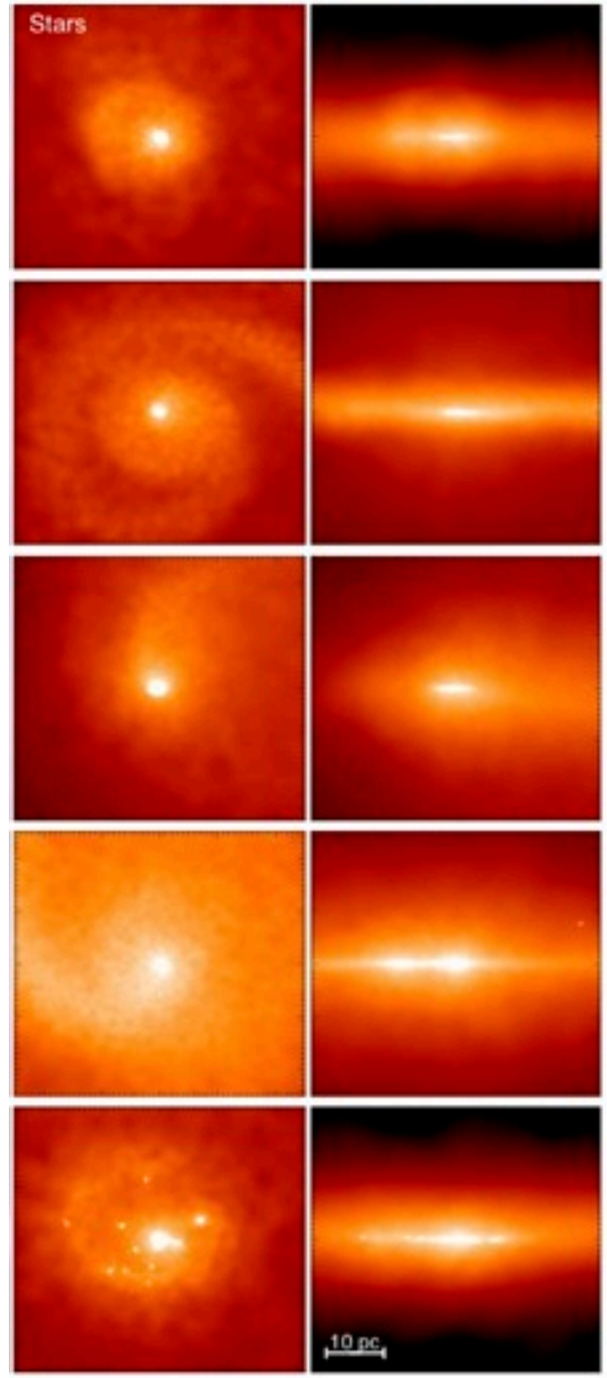


Lauer et al. 1993
Kormendy & Bender 1999

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



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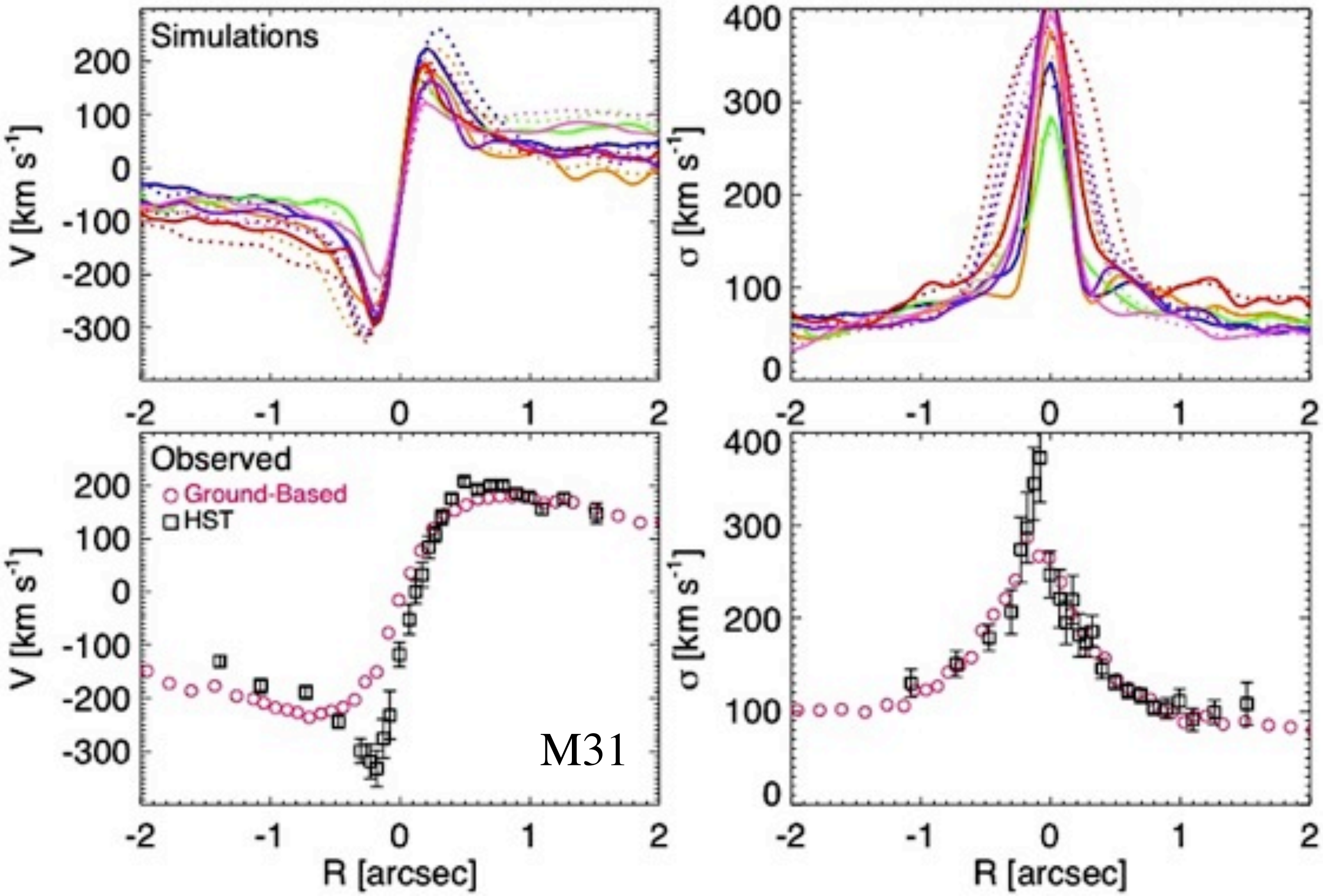
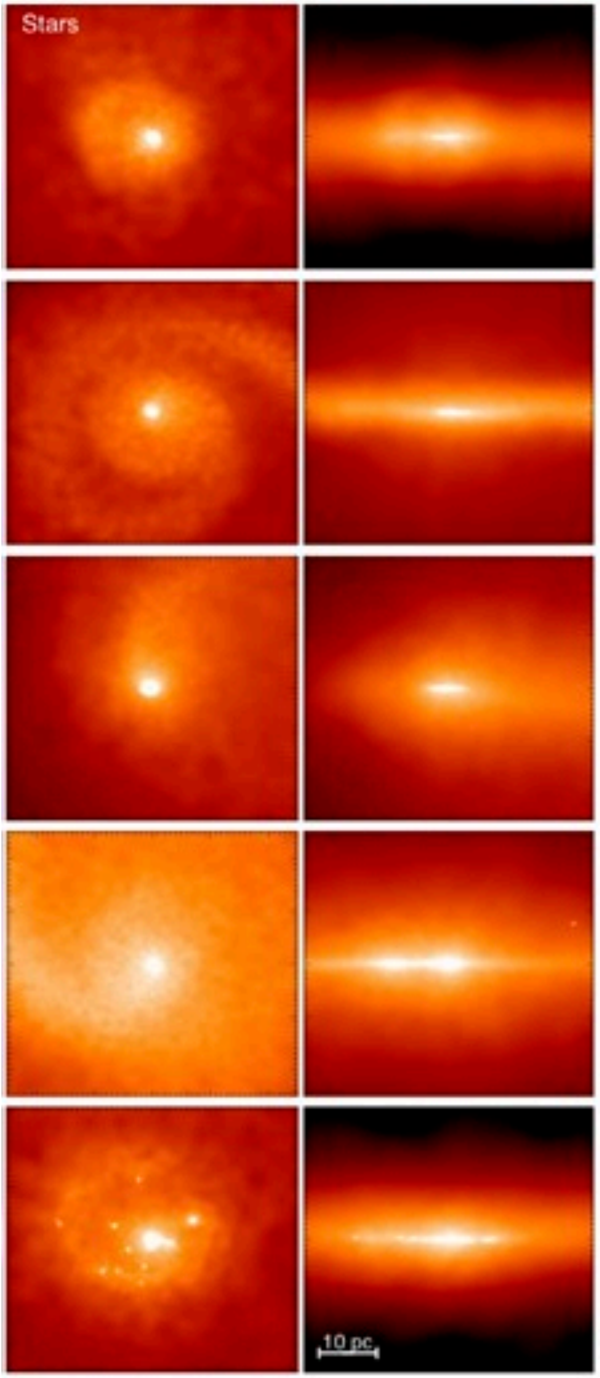
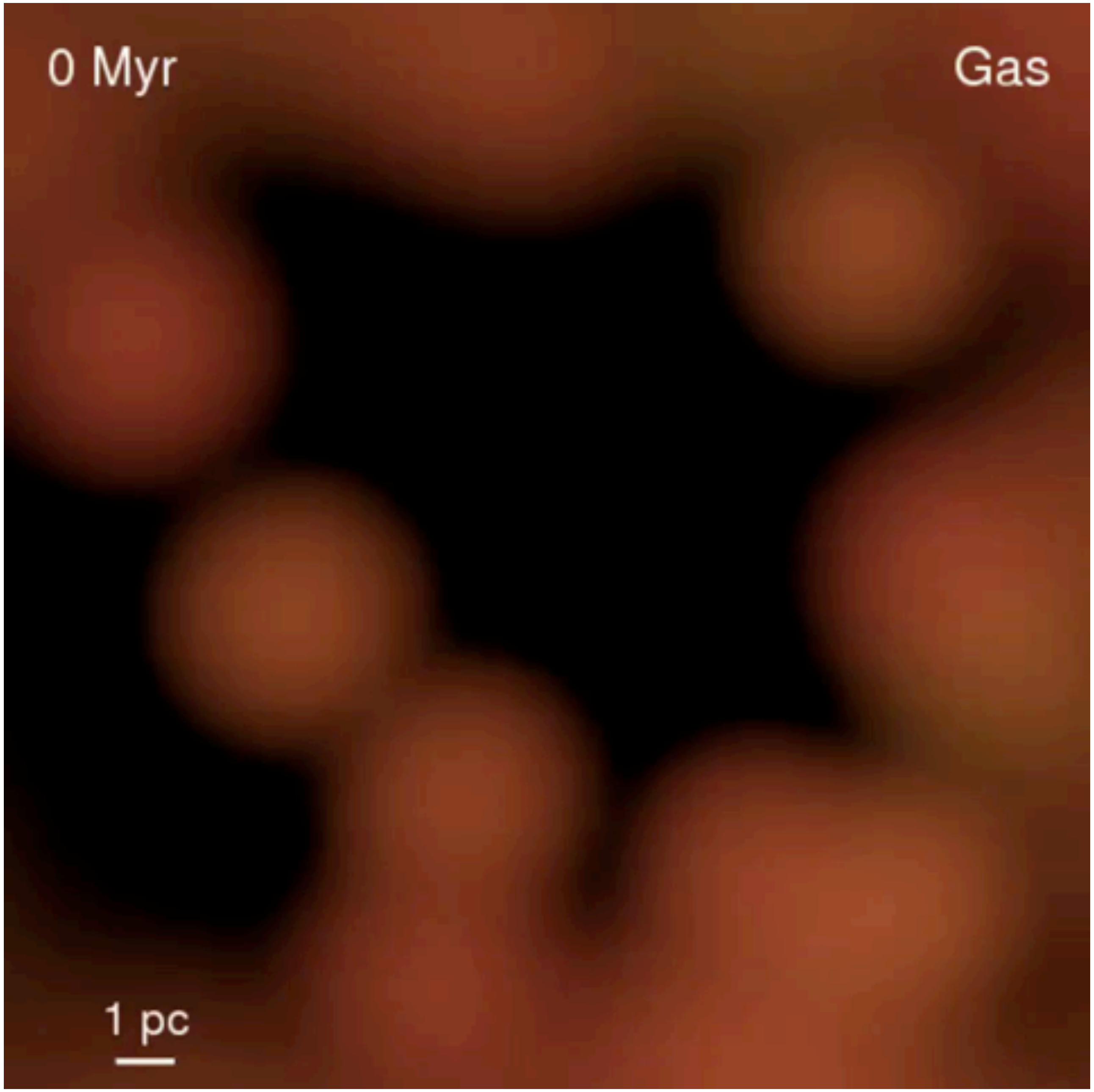




- "run backwards": the M31 disk implies accretion at
  ~0.5-3 M_{sun}/yr (~L_{Edd}) for ~100 Myr (~ M_{BH}) !

Step 2: *Stellar* Feedback & the ISM

- High-resolution (~1pc), molecular cooling (<100 K),
  SF only at highest densities (n_H>1000 cm^{-3})



- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

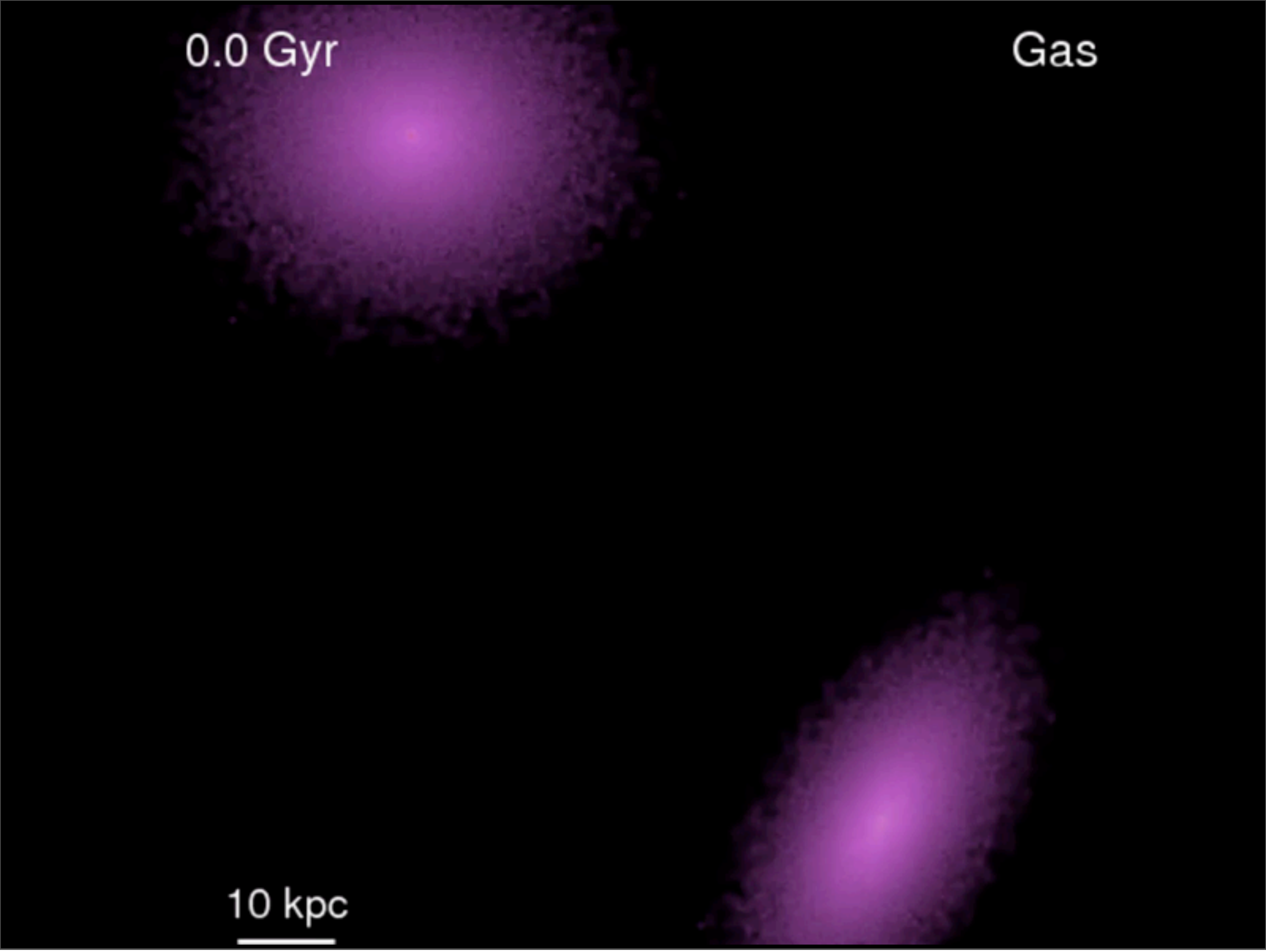
    $$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

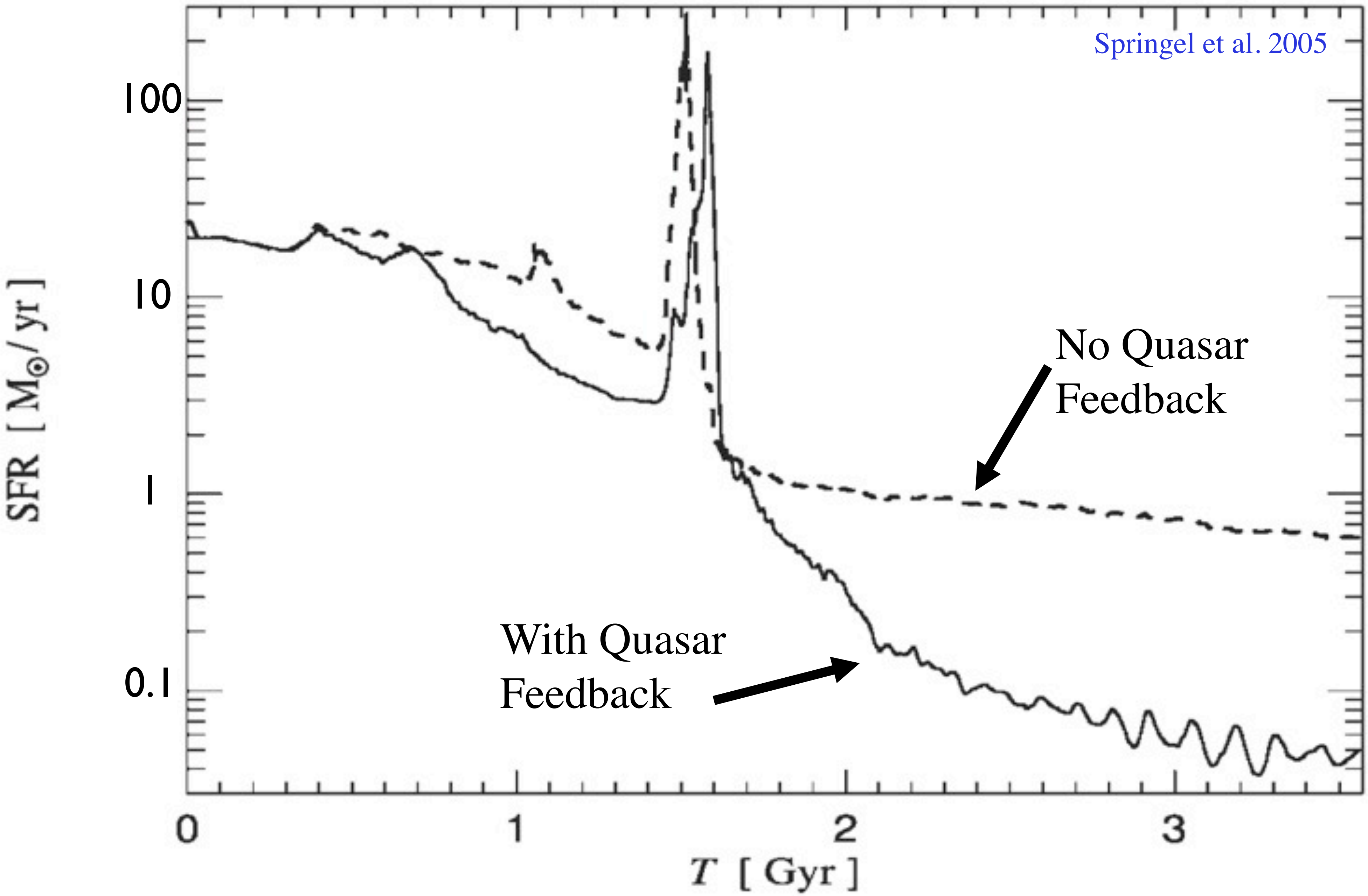
    $$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\,v_{\rm ejecta}^{-1}$$

  - Stellar Winds

    $$\dot{P}_{\rm W} \sim \dot{M}\,v_{\rm wind}$$


0.0 Gyr
Gas
10 kpc

Do we still need 'Quasar Mode' Feedback?



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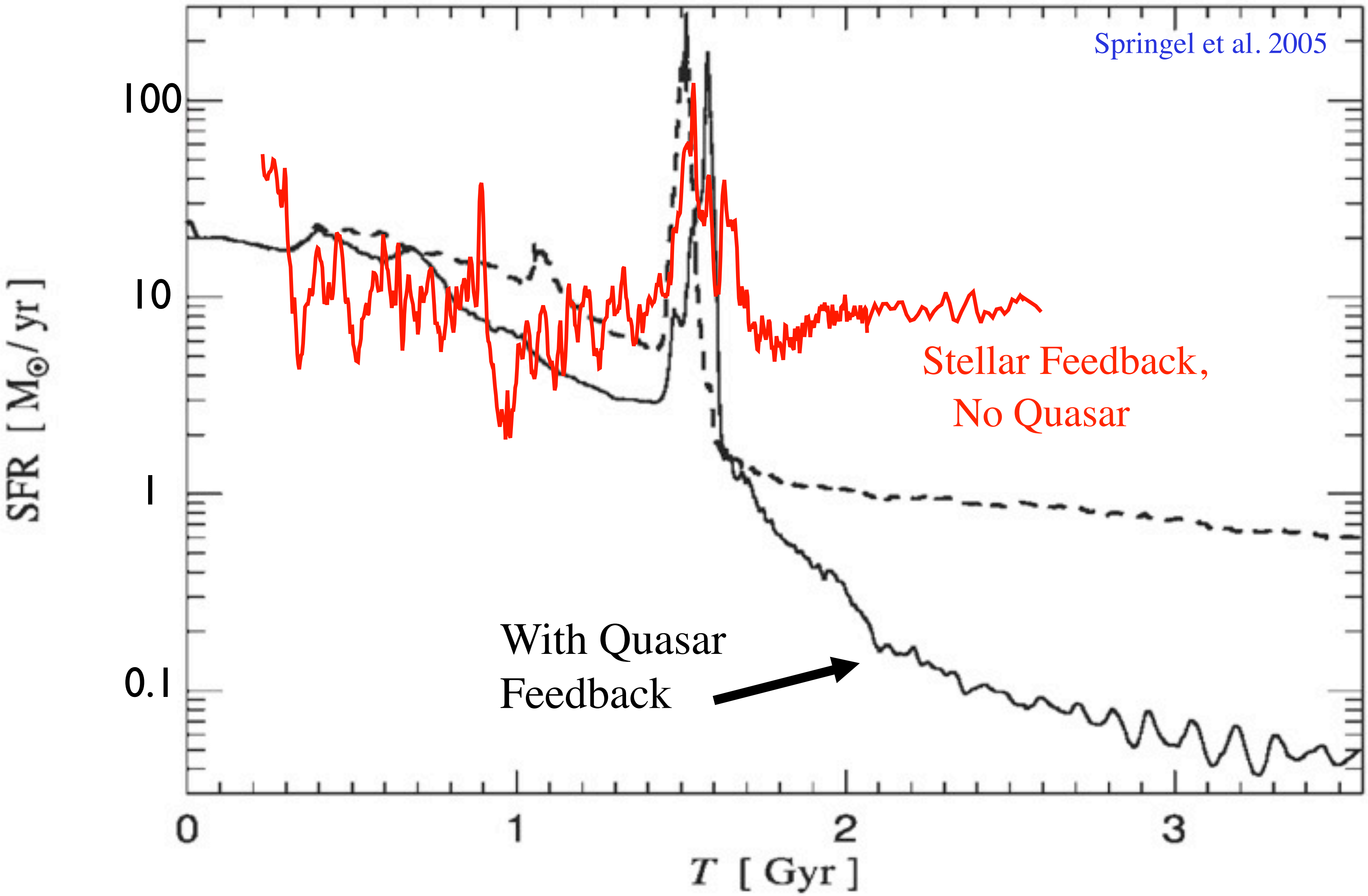


Step 3: Physical Sources of AGN Feedback

mechanical (jets & winds) & **radiative**

Jets

heat IGM/ICM (low ρ), but not dense ISM

Winds

BAL-QSO winds

equatorial

$\dot{P}$ up to ~ 5L/c (Arav+)

Photons

UV: $\dot{P}$ ~ L/c (absorbed by dust): $\kappa_{UV} \sim 10^3\ \mathrm{cm}^2\ \mathrm{g}^{-1} \sim 10^3$ e scatt

FIR: $\dot{P} \sim \tau L/c$ (τ ~ dust FIR optical depth ~ 10-100): $\kappa_{FIR} \sim 10$ e scatt

Compton Heating (only low density gas)

Outstanding Problem: Which Dominates?

Different physics in ISM & IGM

Step 2: Feedback

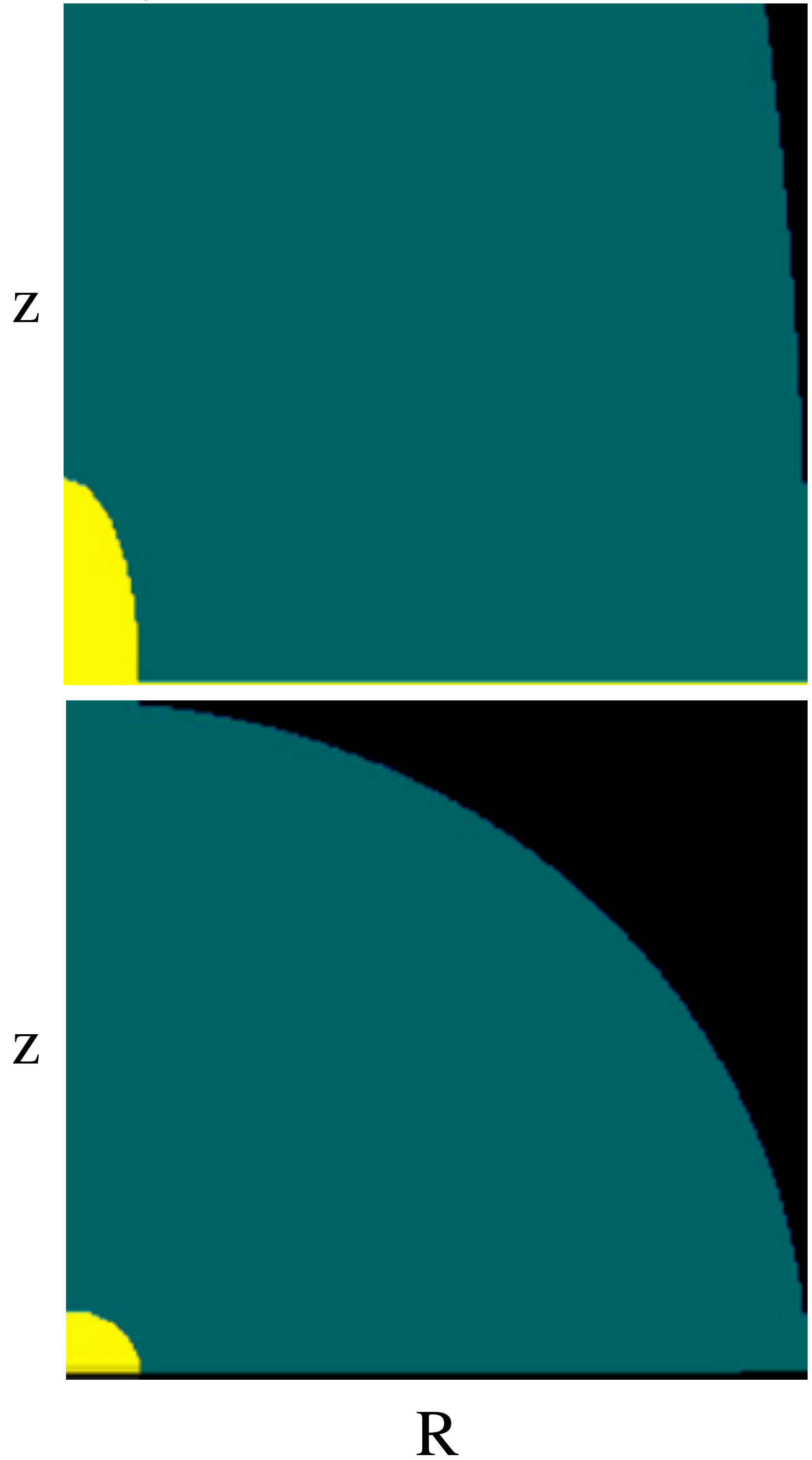
Proga et al. 00-07; Kurosawa et al. 08-11

- L/L_{Edd} >~ 0.1
- Covering factor ~10-30%

- Launched at < pc

$$\dot{M}_{\rm launch} \sim \dot{M}_{\rm BH}$$

$$v_{\rm launch} \sim 30,000\,{\rm km/s}$$

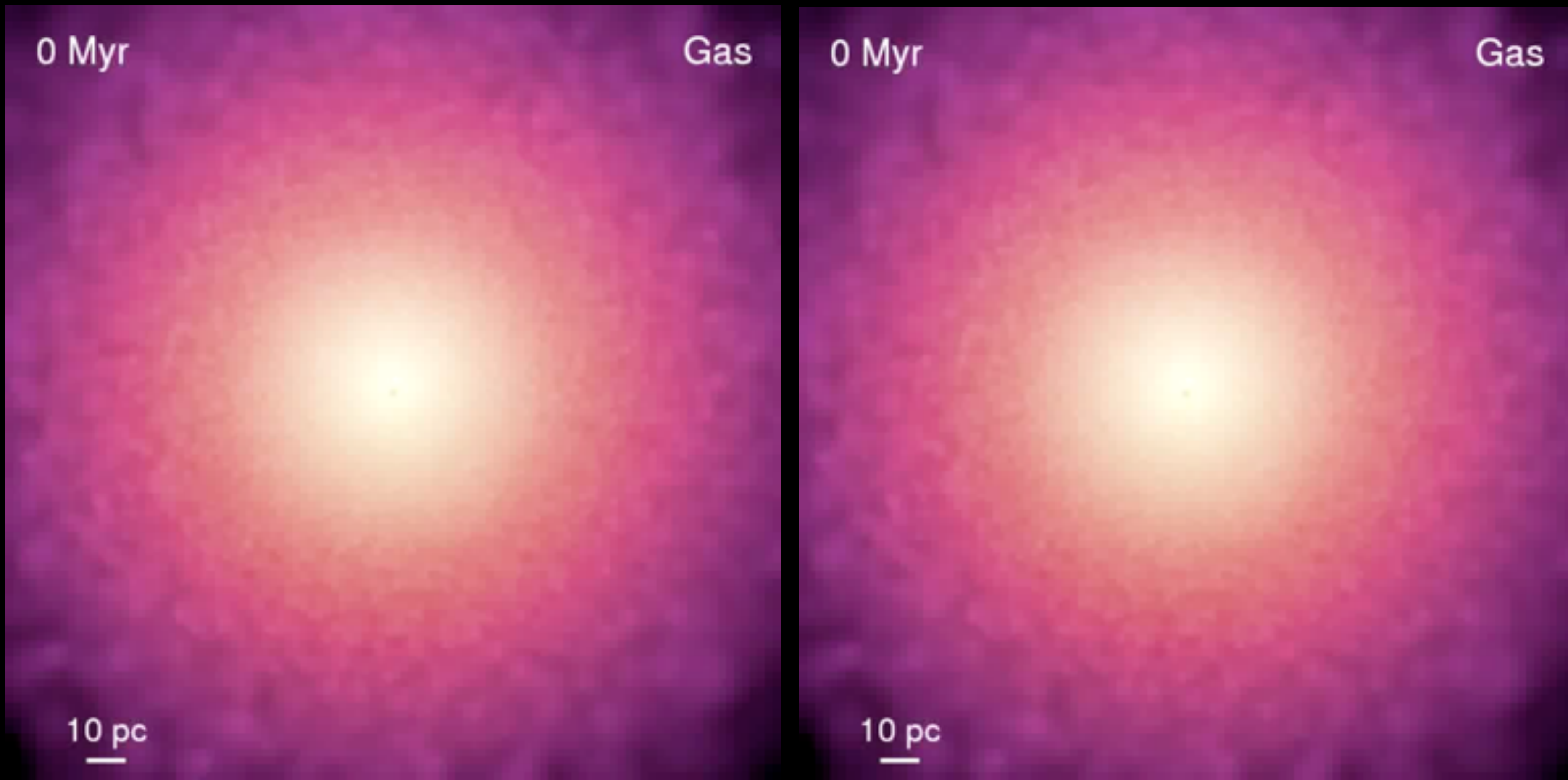


BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds

With BAL Winds



$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

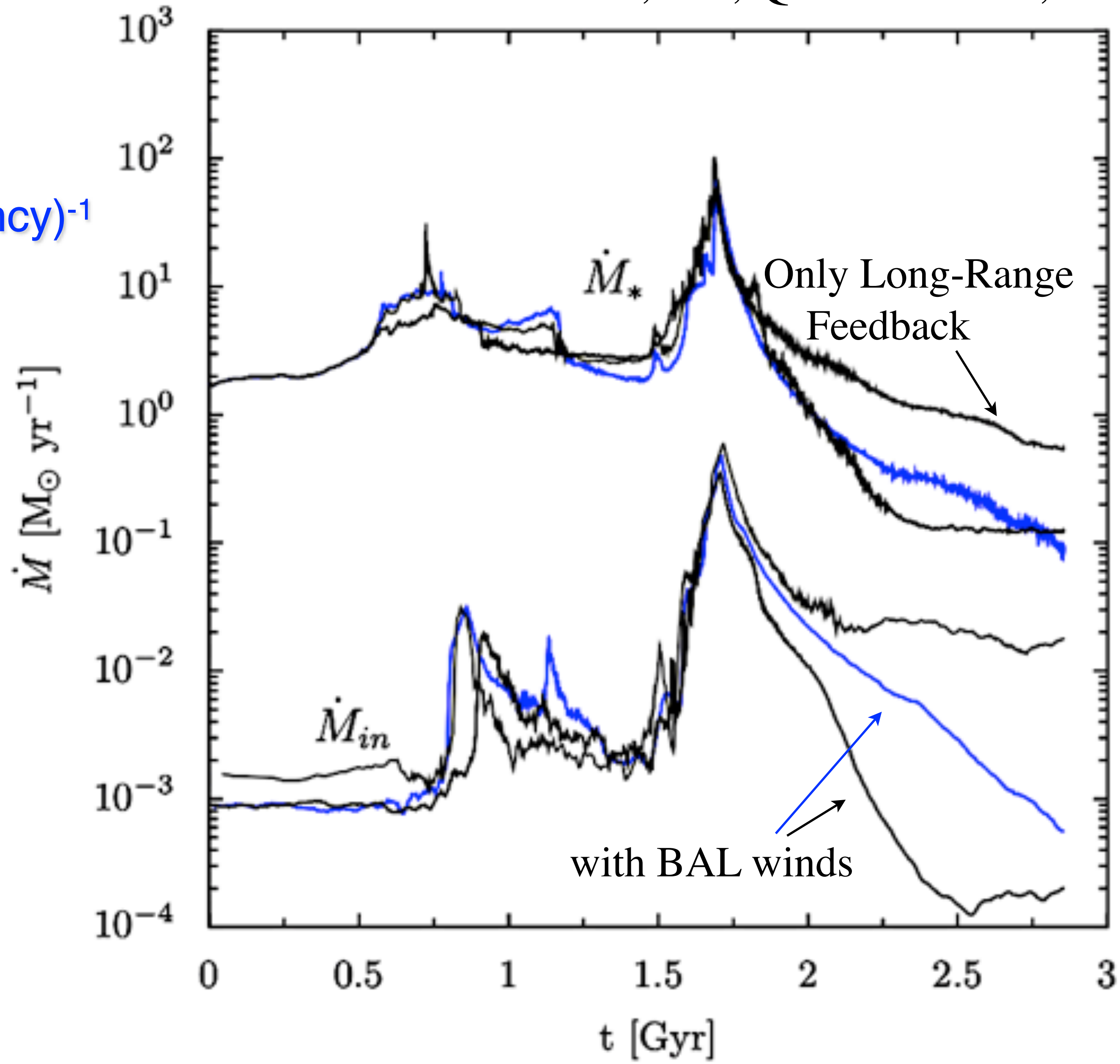
BAL Winds on Galactic Scales

CAN IT REALLY AFFECT STAR FORMATION?

Novak et al. 2010,11

Debuhr, Ma, Quataert 2010,11

- Recover M-s
  - Normalization ~ (efficiency)$^{-1}$
- Launch ~1000 km/s "tail" in winds
- Suppress SFR



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

$$\dot{M}_{\rm BH} \propto f({\rm B/T})\, M_{\rm gas}(R)/t_{\rm dyn}$$

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

- Quasar feedback is here to stay:
  - BAL Winds:
    - *CAN* explain M_{BH}-σ
    - *WILL* suppress SFRs
    - *SHOULD* heat & help clear IGM & Proto-Group Environments