Quasars, Feedback, (and Galaxy Formation)

Philip Hopkins

08/10/09

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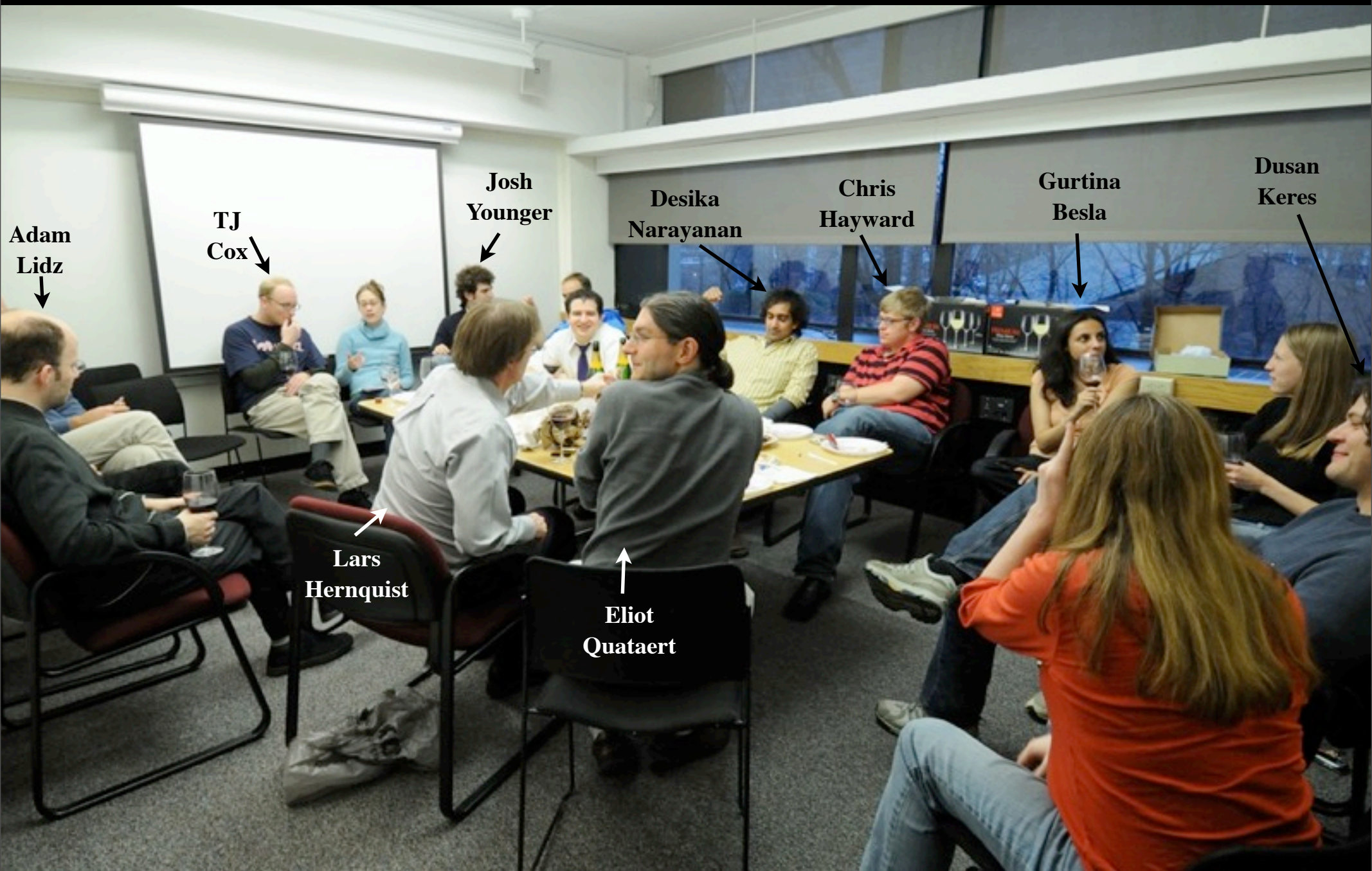
Adam Lidz
TJ Cox
Josh Younger
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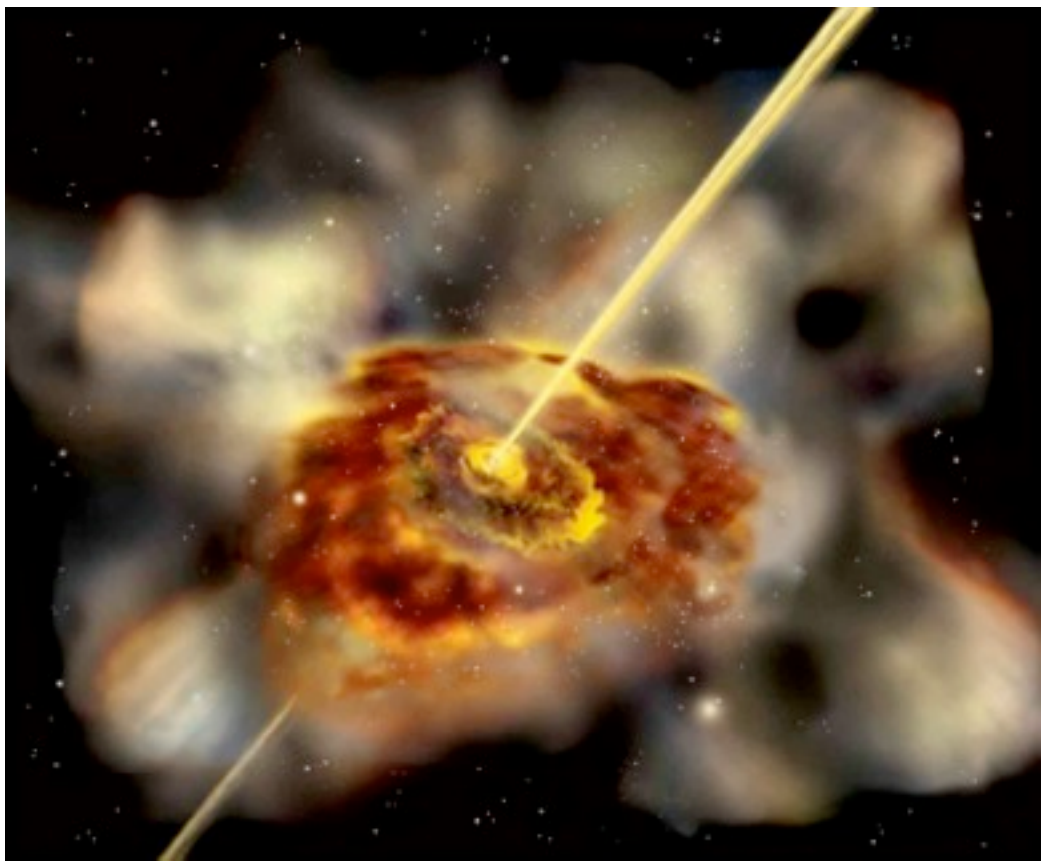
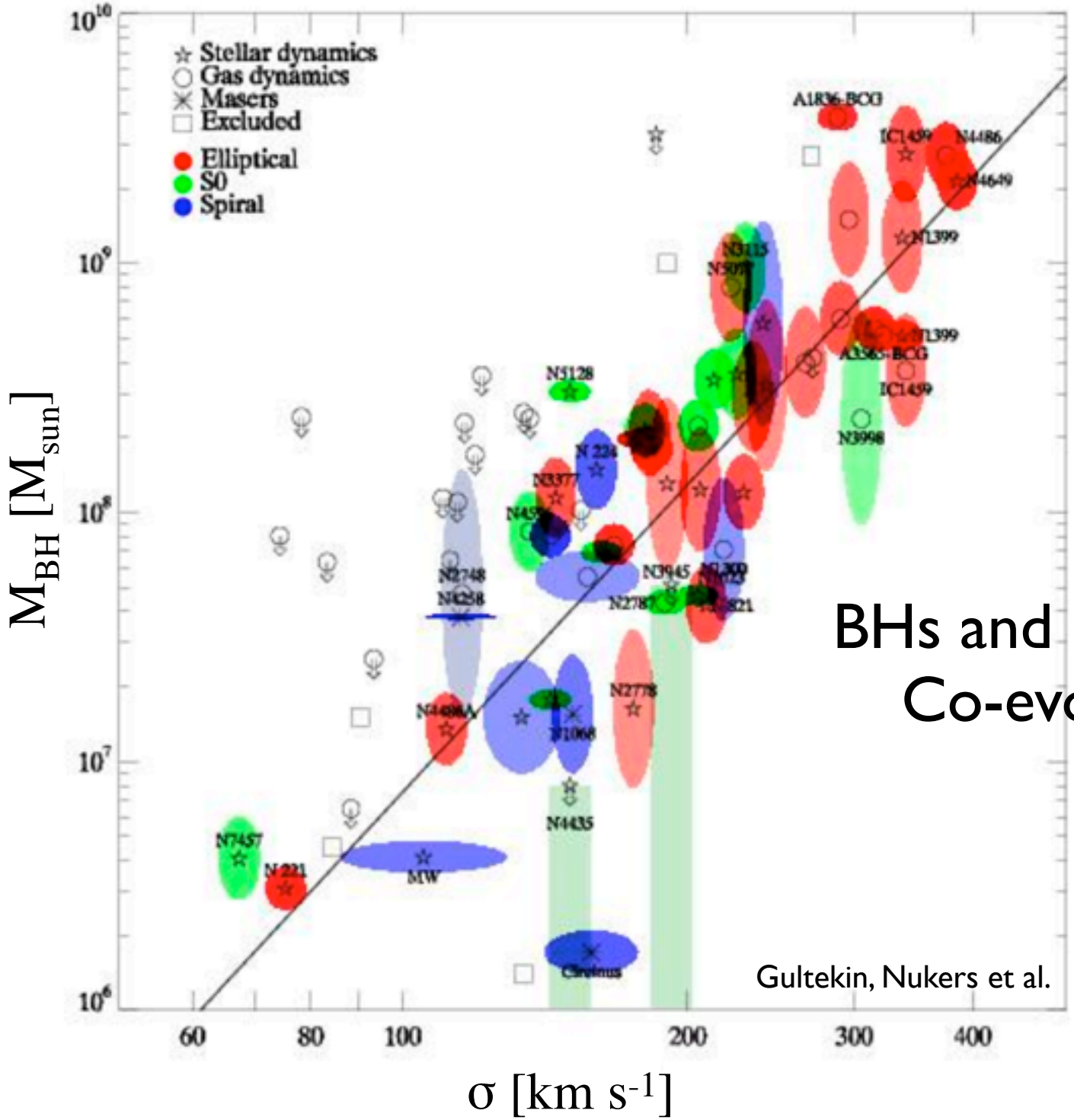
Motivation
WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Every massive galaxy hosts a supermassive black hole



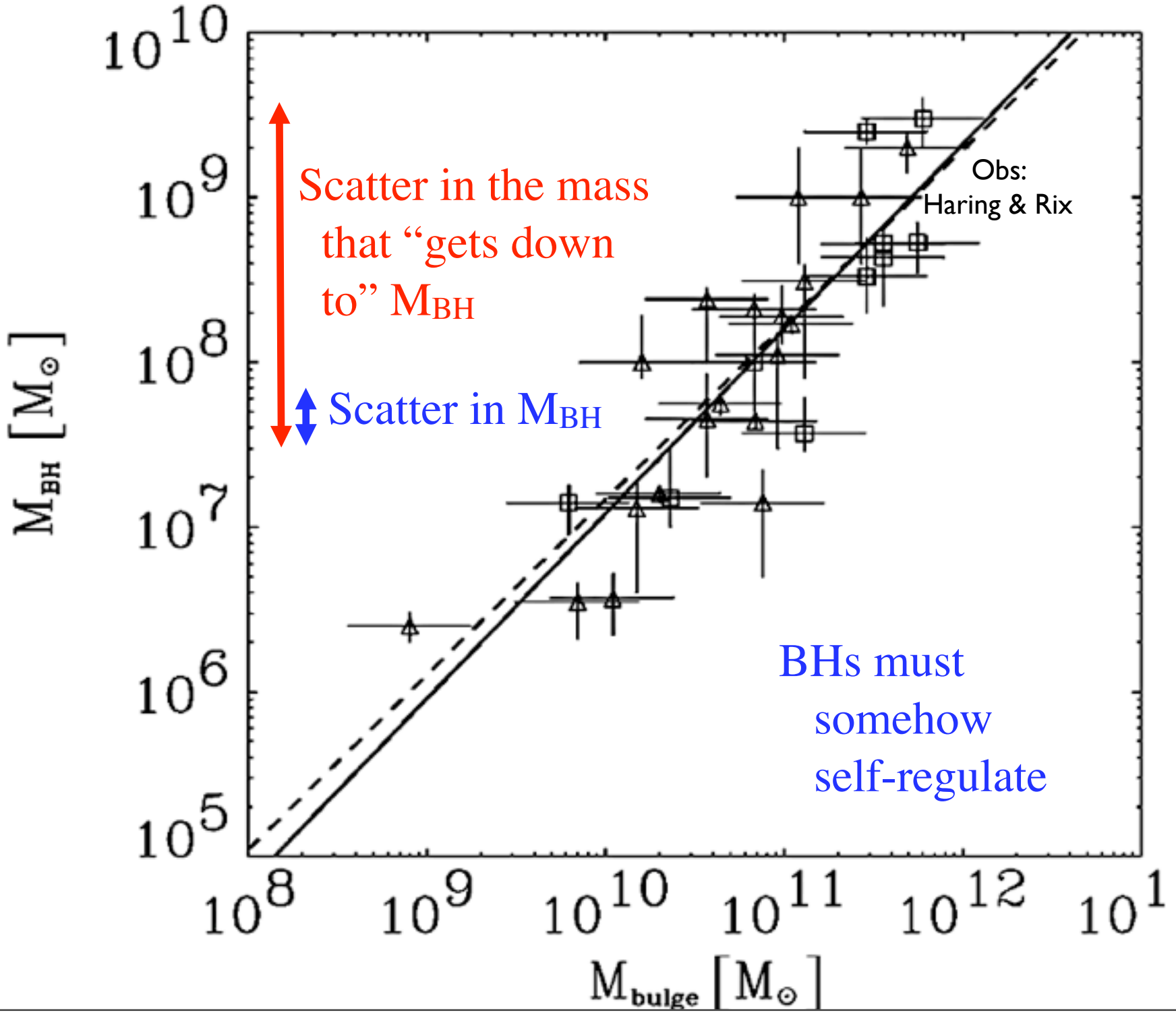
- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

Black Holes are Tightly Coupled to Bulge Properties...

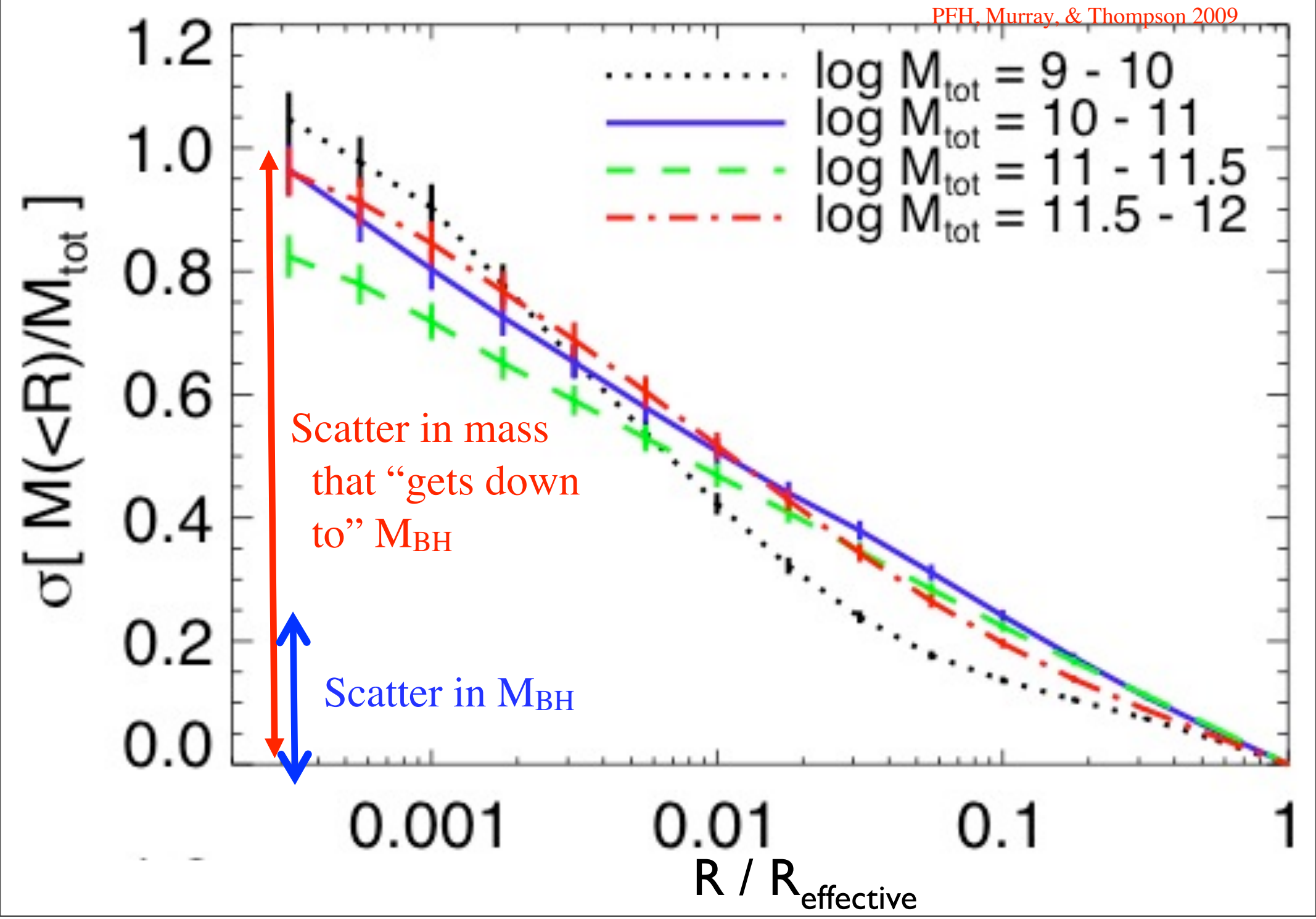


BHs and Bulges Co-evolve

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 $M_{\rm sun}$ 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!

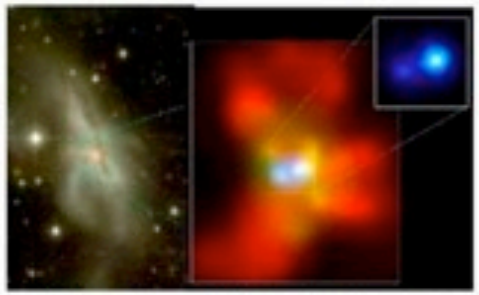
- Turn this around: *if* some fraction f ~ 1-5% of the luminosity can couple, then accretion stops when

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

(c) Interaction/"Merger"

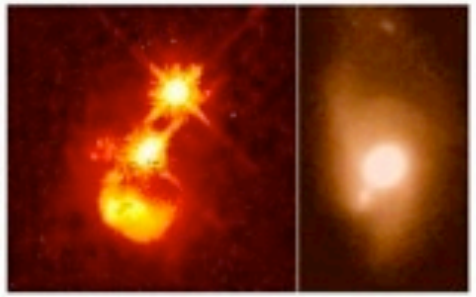
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG



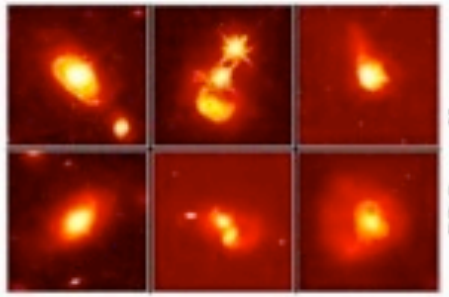
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) "Blowout"



- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible

(f) Quasar

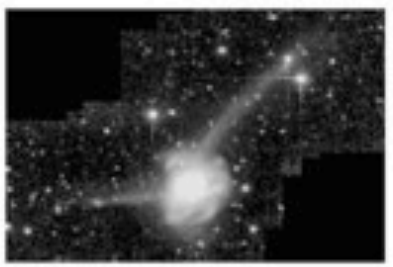


- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

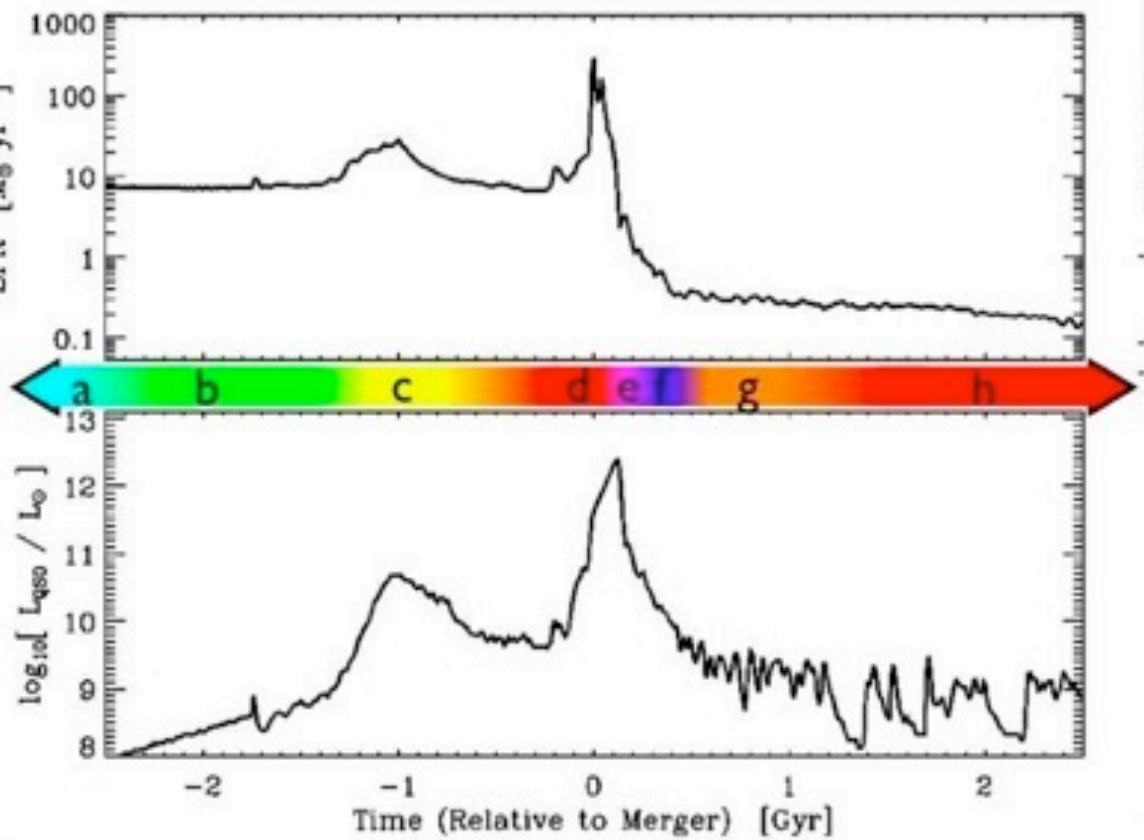
(b) "Small Group"

- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently

(g) Decay/K+A



- QSO luminosity fades rapidly
  - tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
  - sets up quasi-static cooling



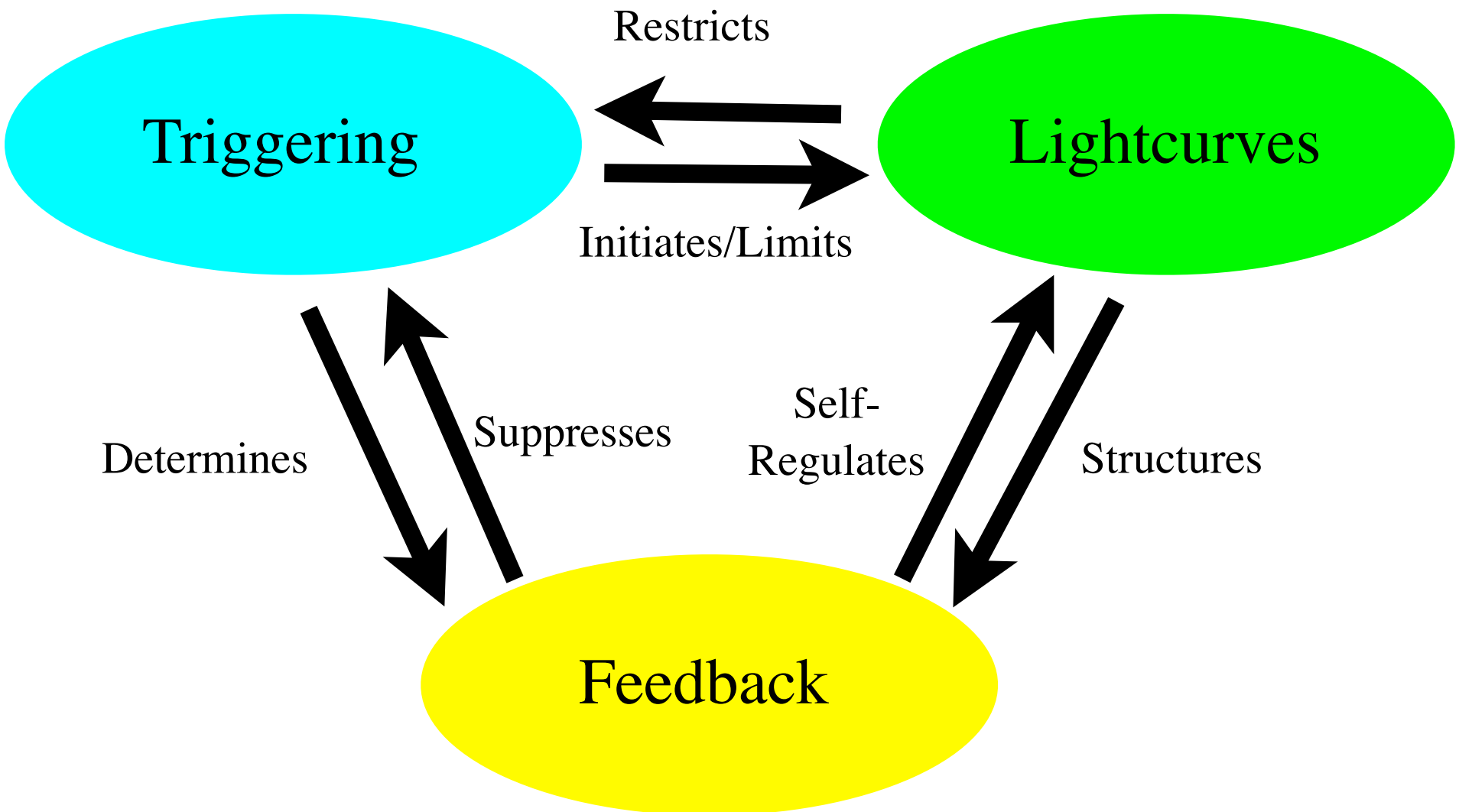
(a) Isolated Disk

- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence

(h) "Dead" Elliptical

- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

Three Outstanding (Inseparable?) Questions:



Triggering: How Do Massive BHs Get Their Gas?

AGN Fueling: Some General Notes

- *All* galaxies are AGN
- AGN are a *process*, not an "object"
  - 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: ~10 M_{sun}/yr to R<<pc, ~10^9 M_{sun} total

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} None of these come close

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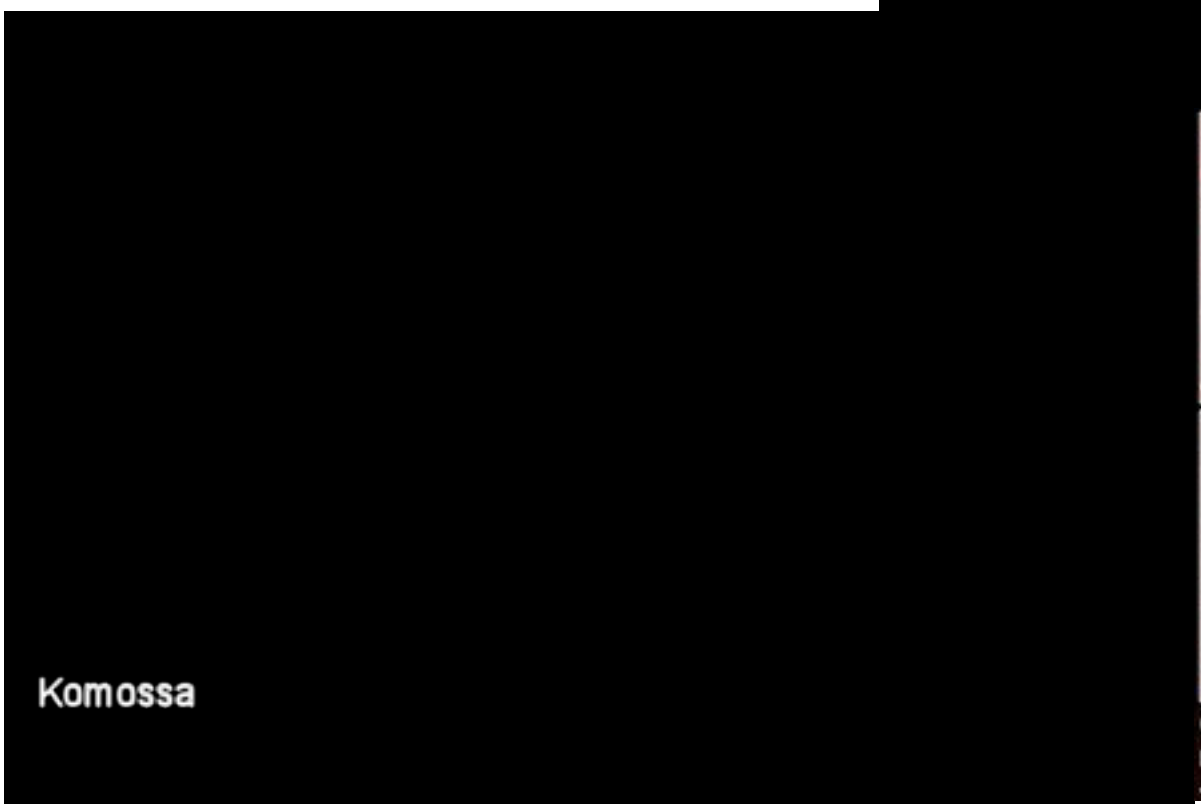
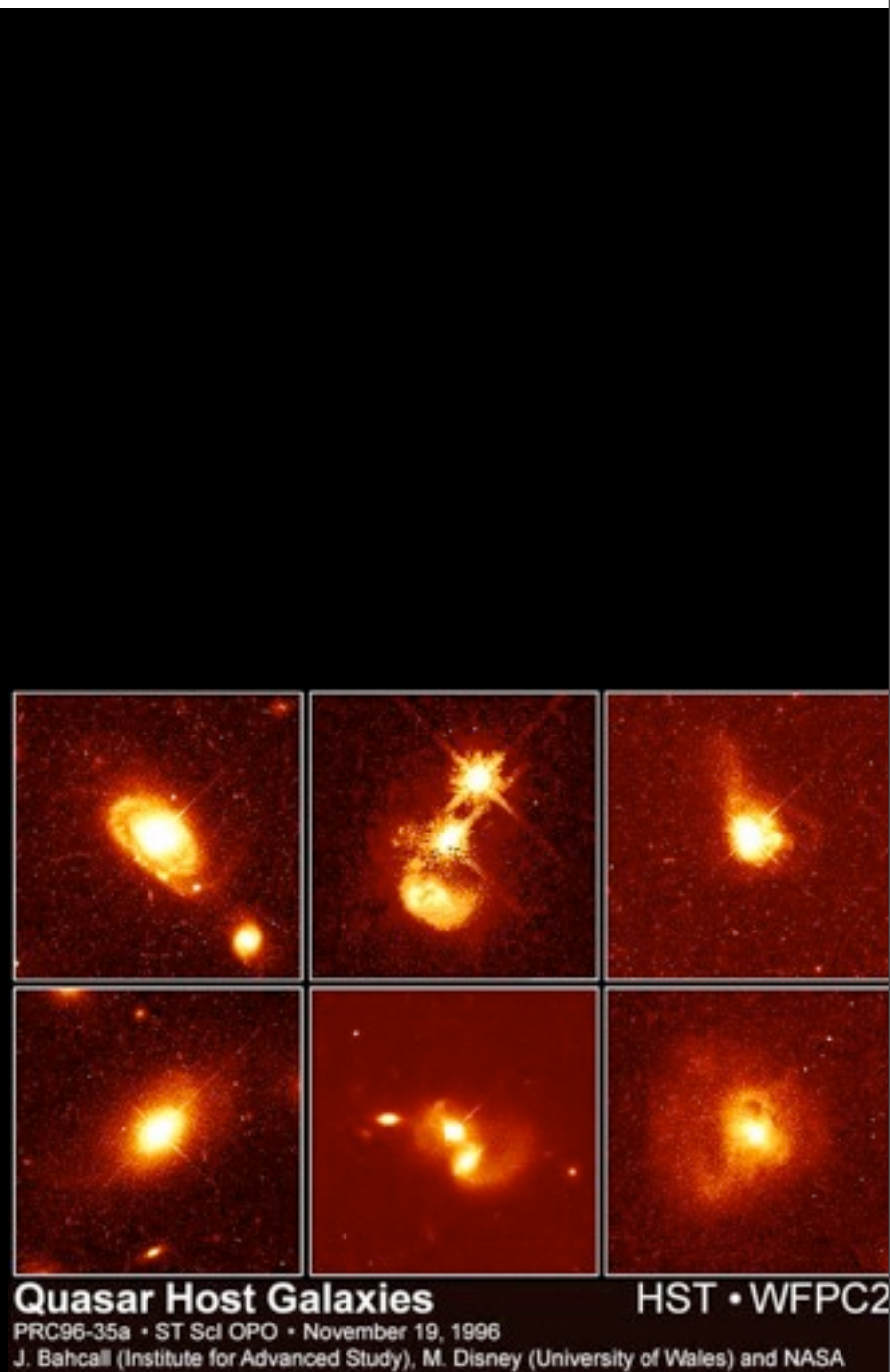
Implications for Fueling: "Feeding the Monster"

WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

- 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

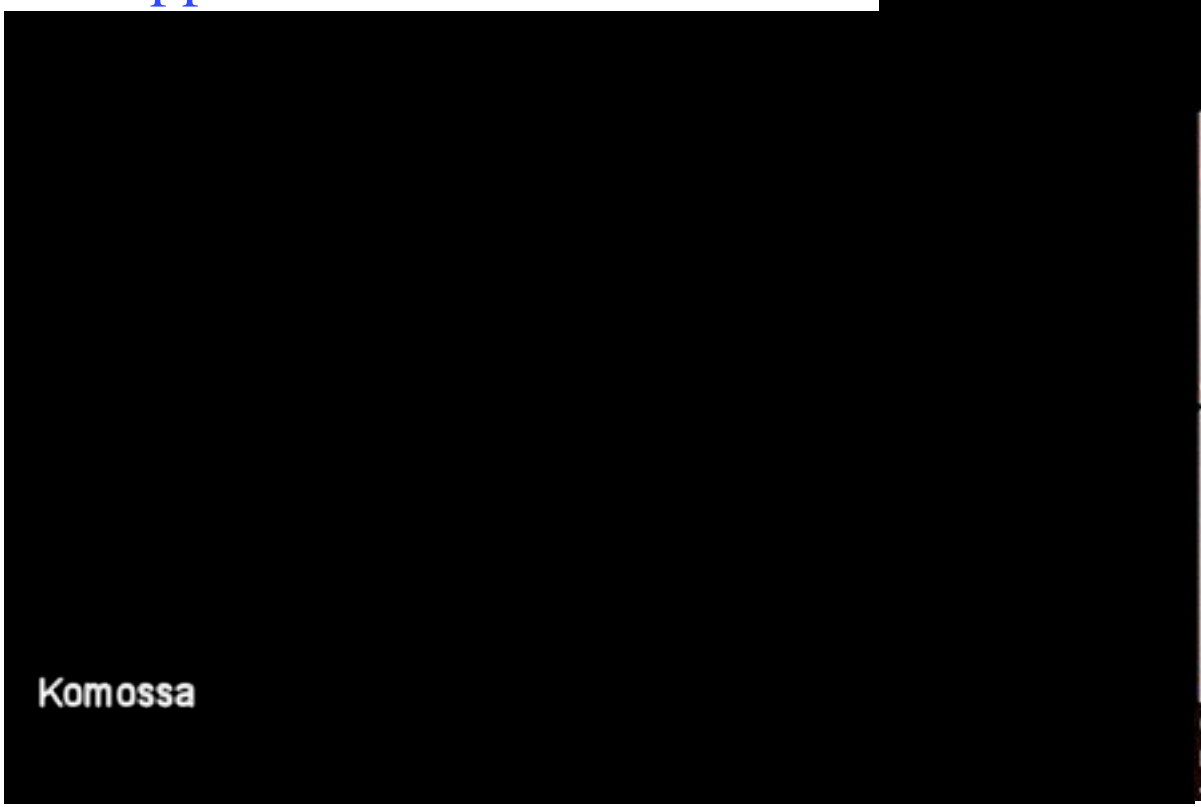


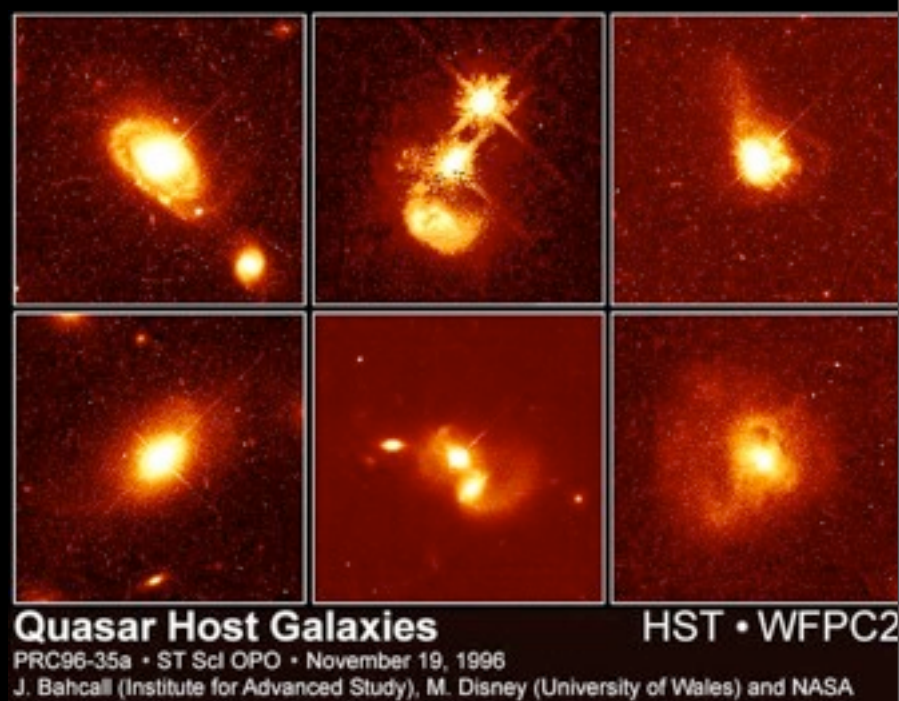


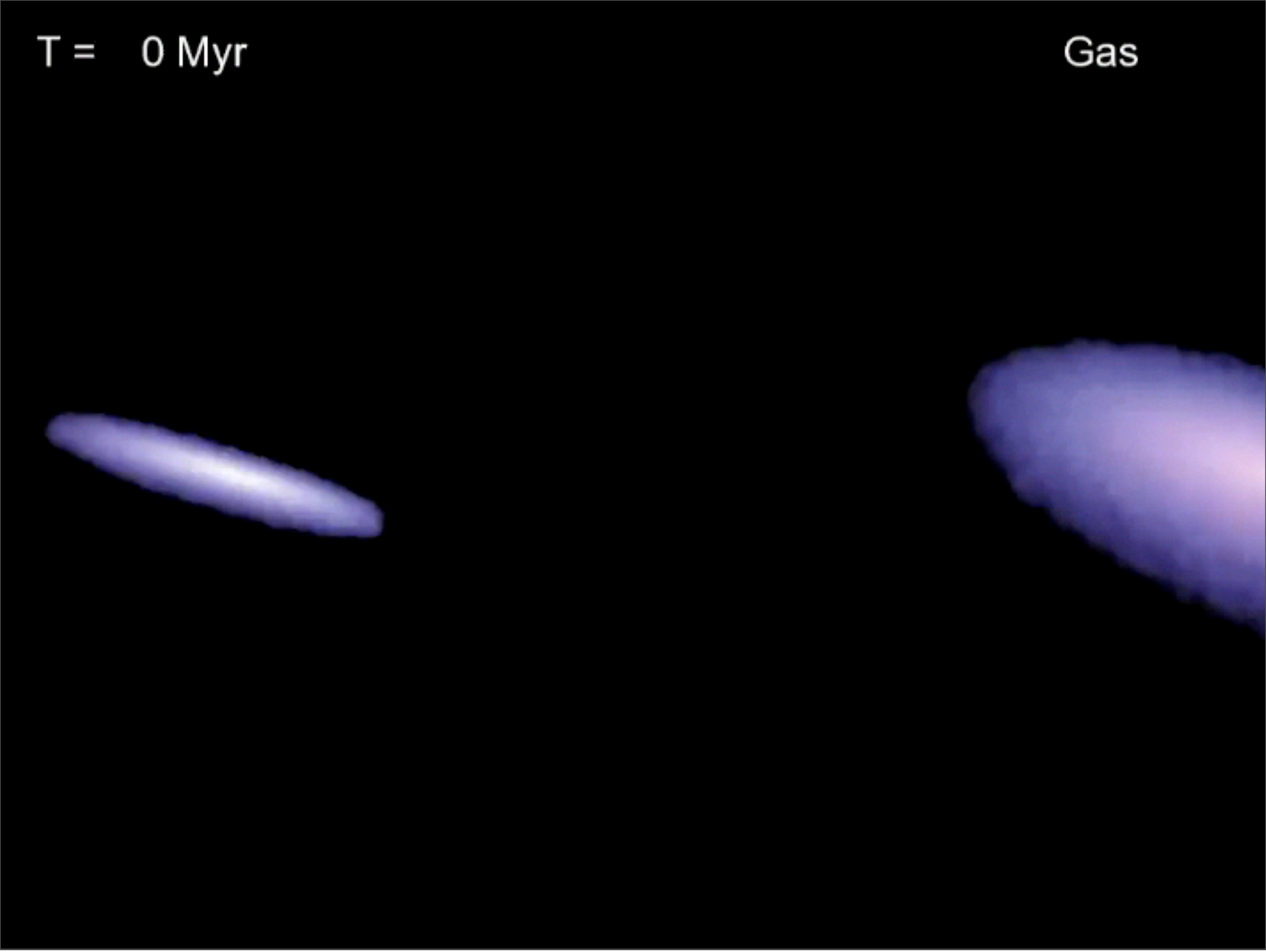
Implications for Fueling: "Feeding the Monster"

WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

- 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!



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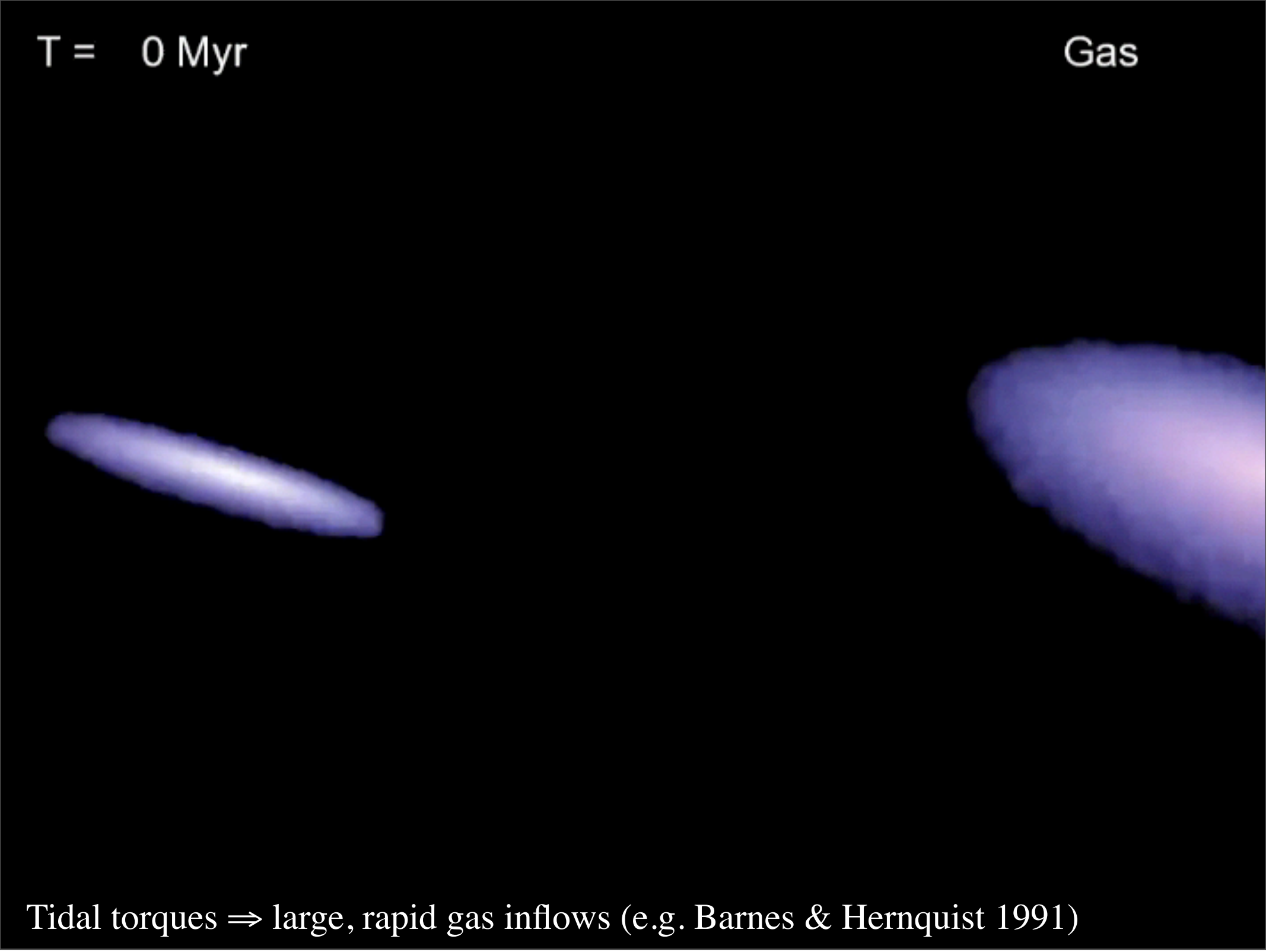
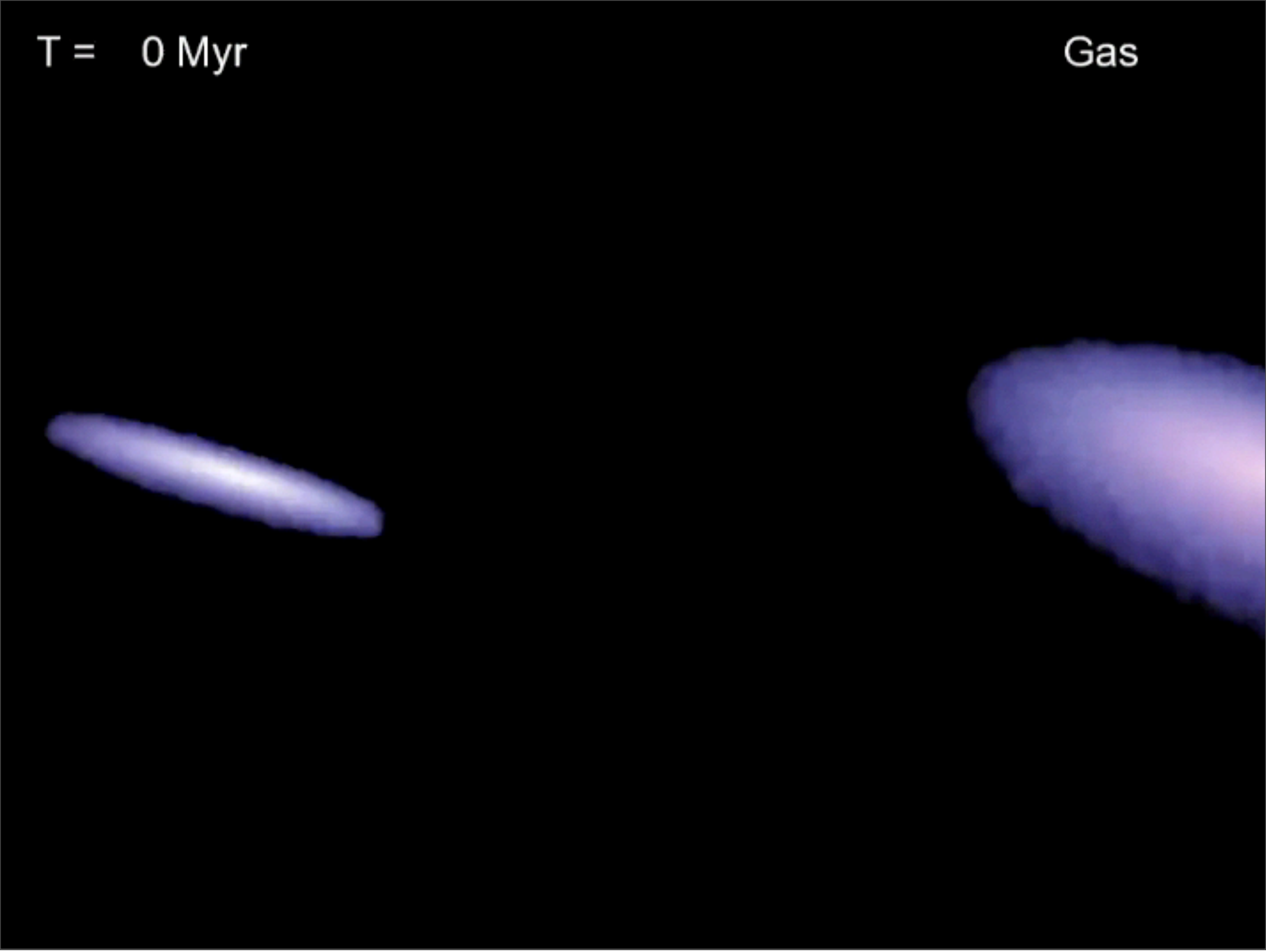
Gas



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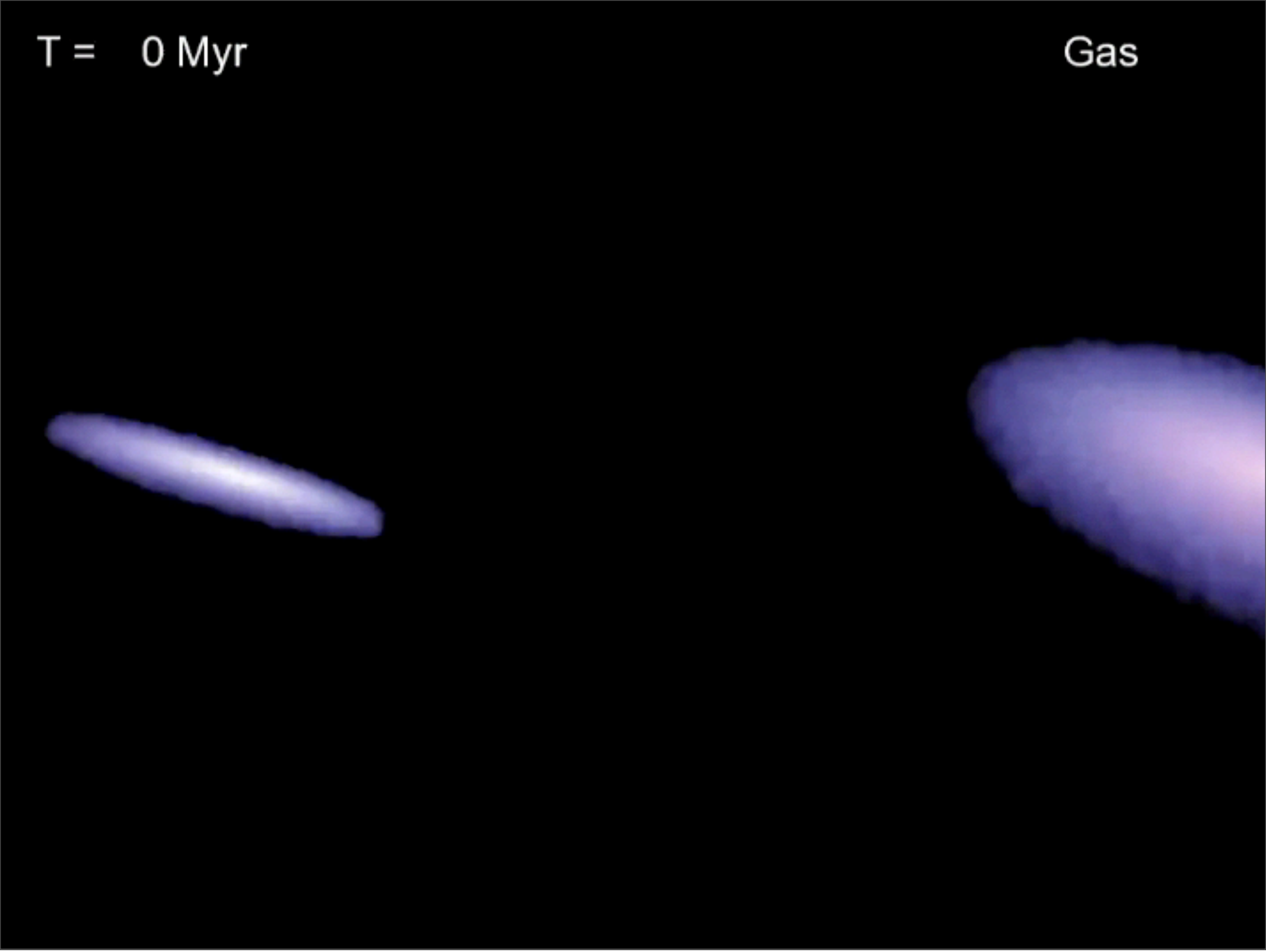
Triggers Starbursts (e.g. Mihos & Hernquist 1996)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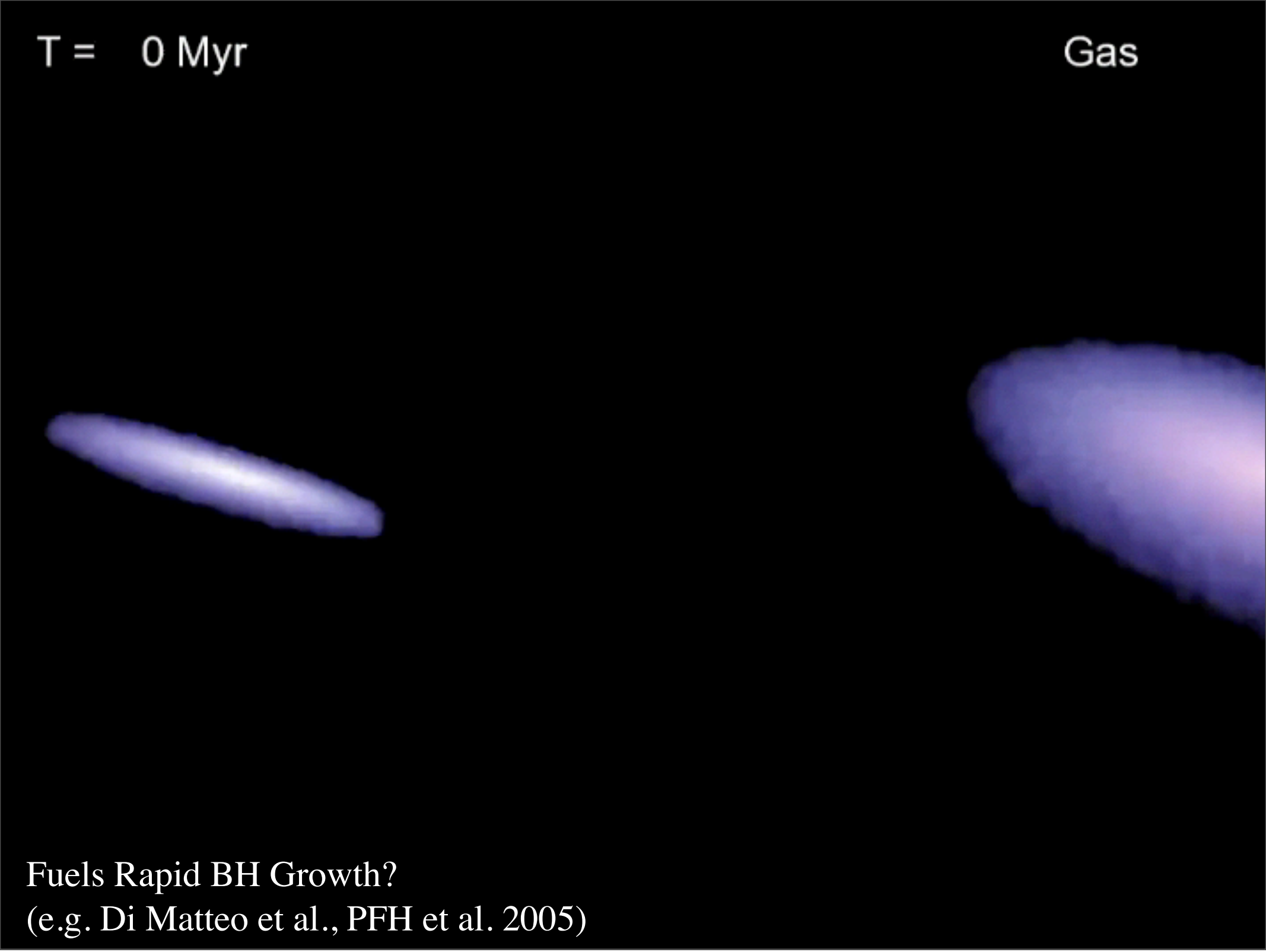
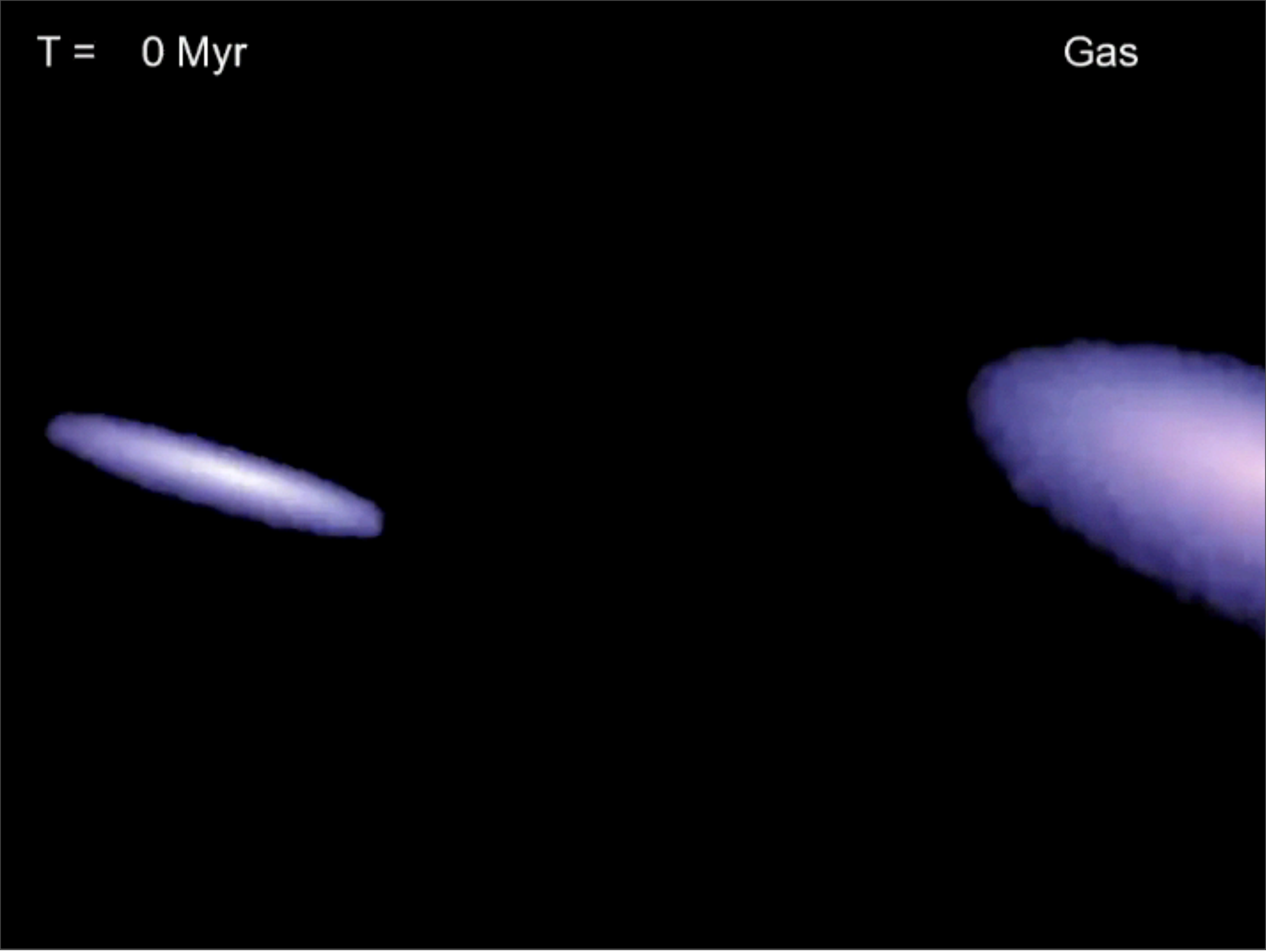


Fuels Rapid BH Growth?
(e.g. Di Matteo et al., PFH et al. 2005)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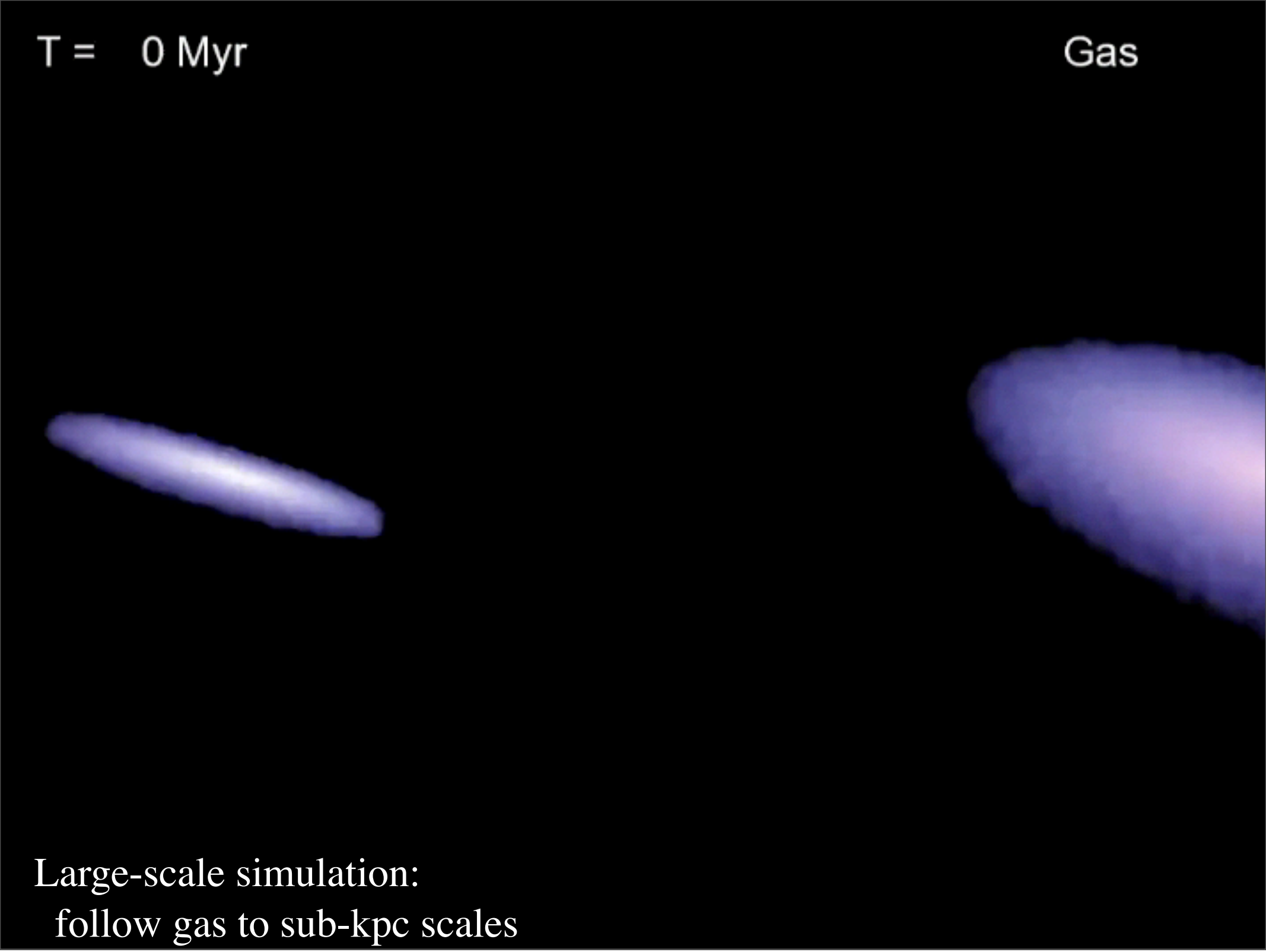
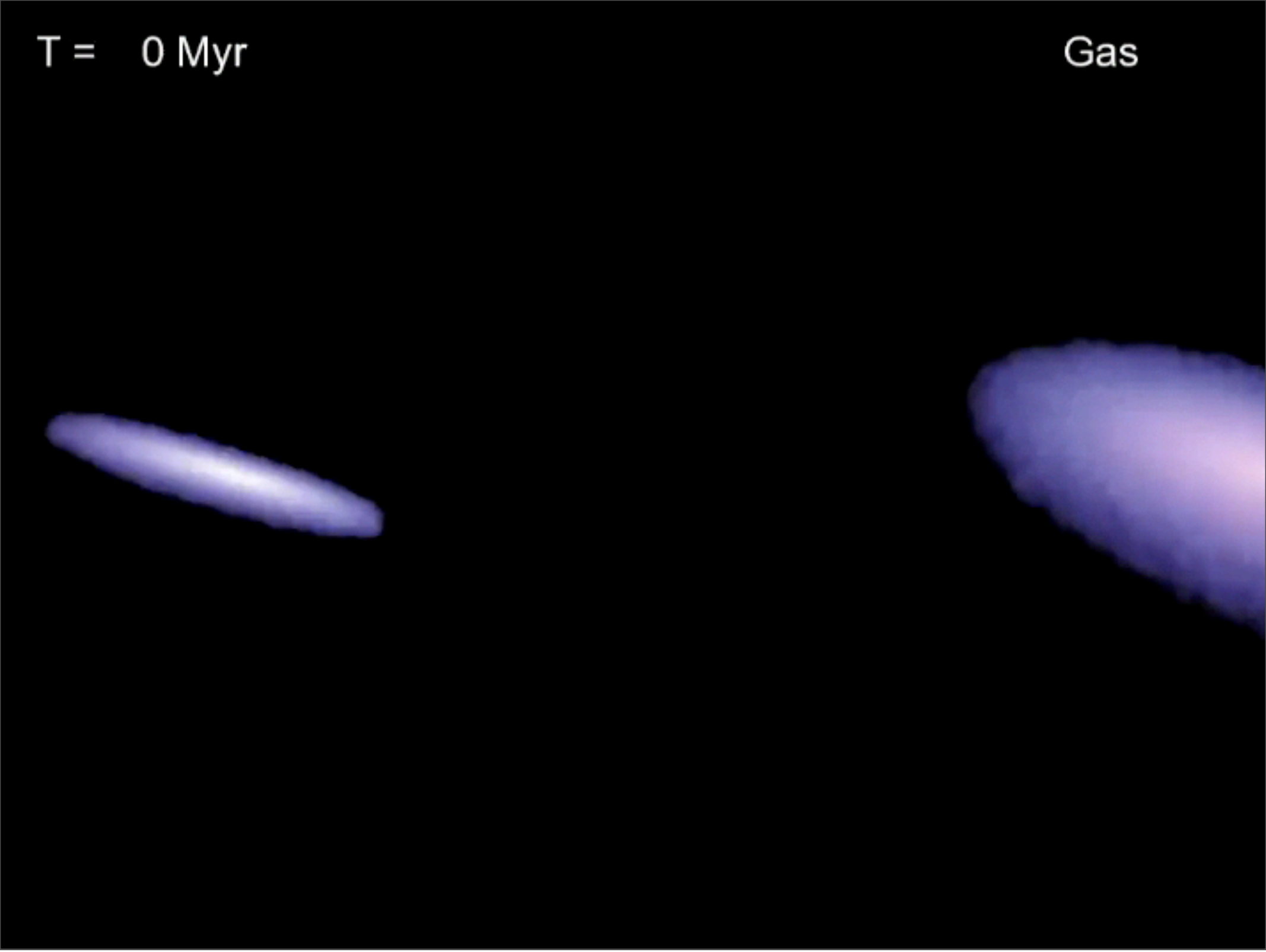


Large-scale simulation:
follow gas to sub-kpc scales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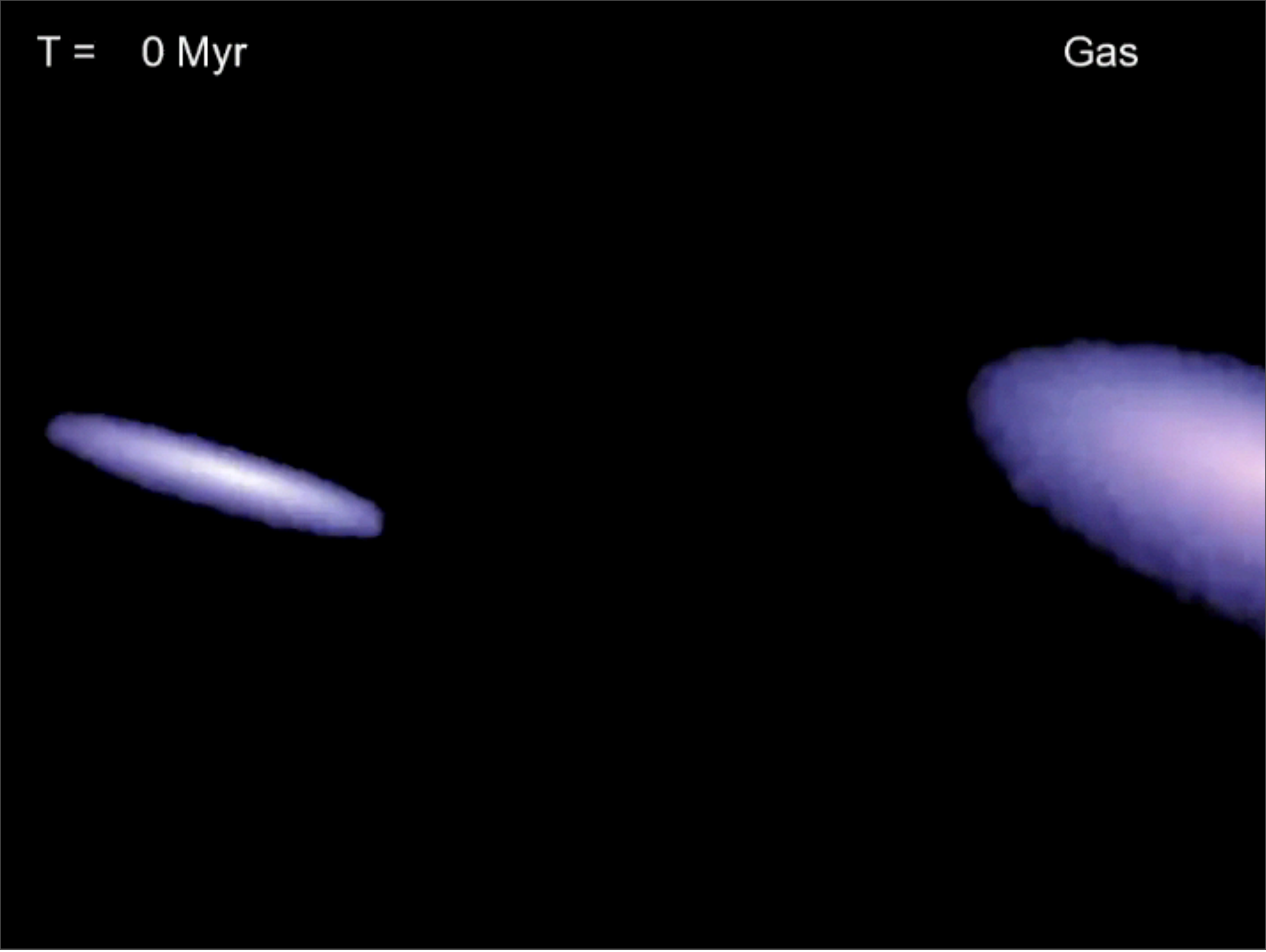
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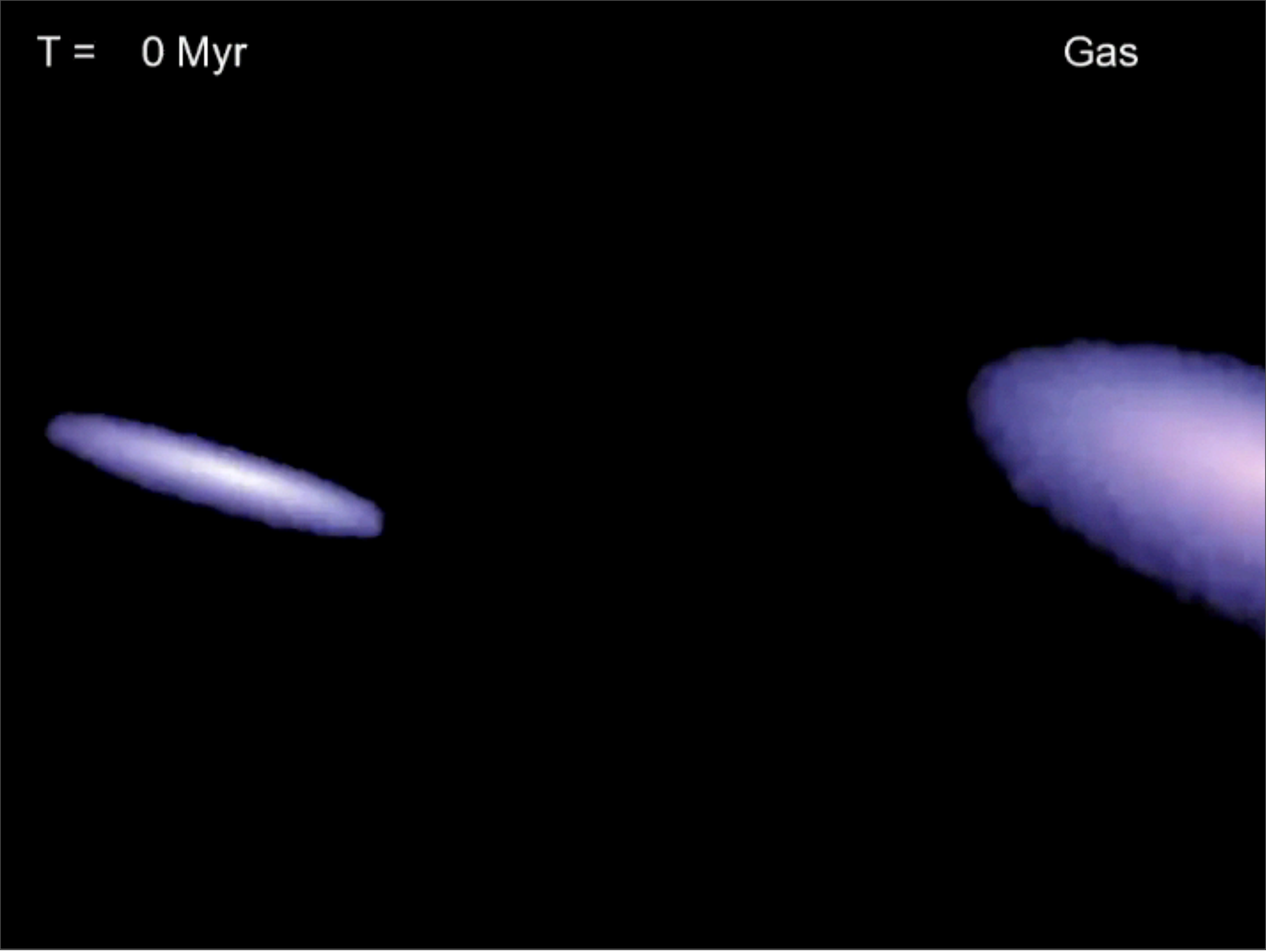
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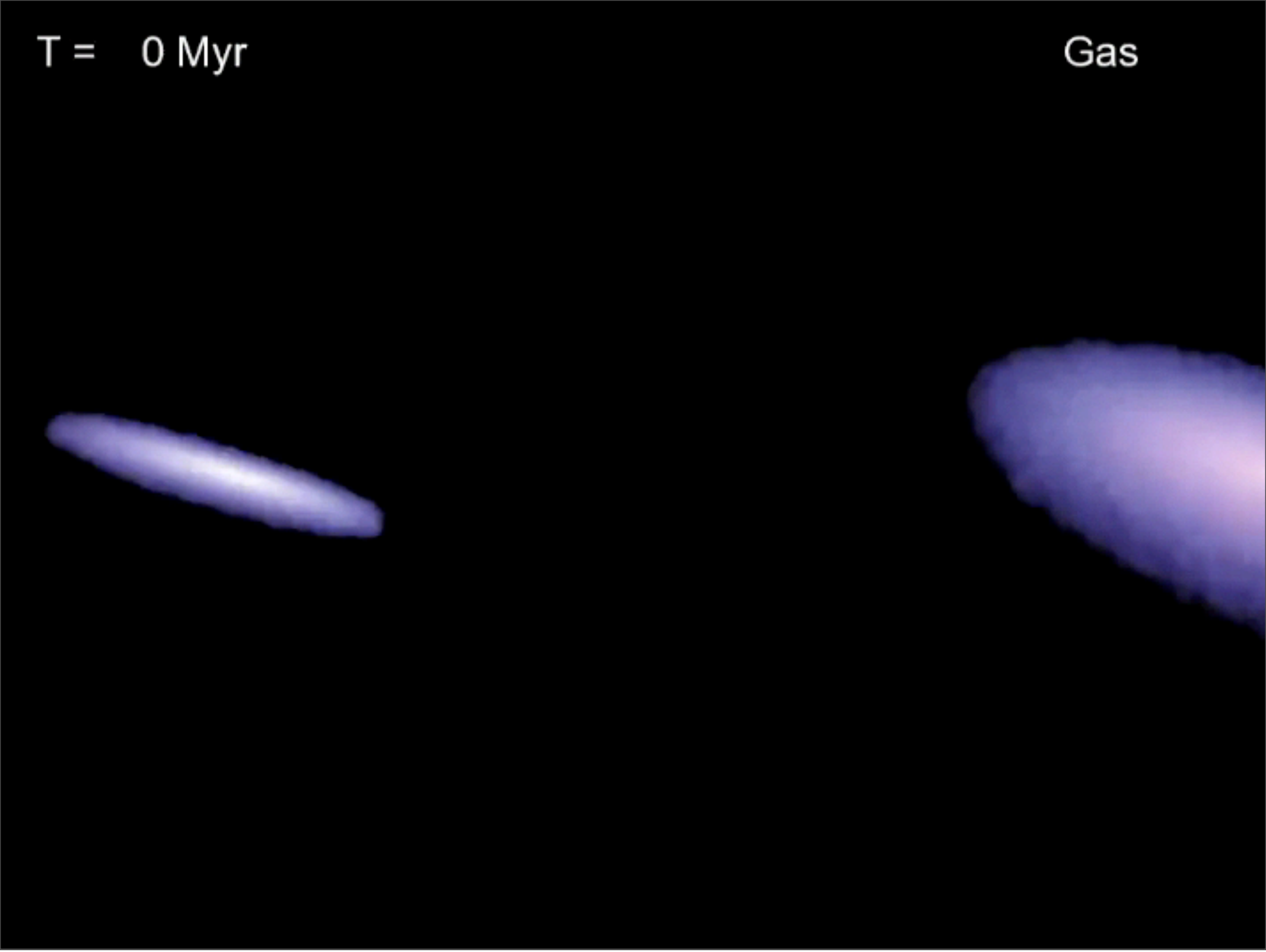
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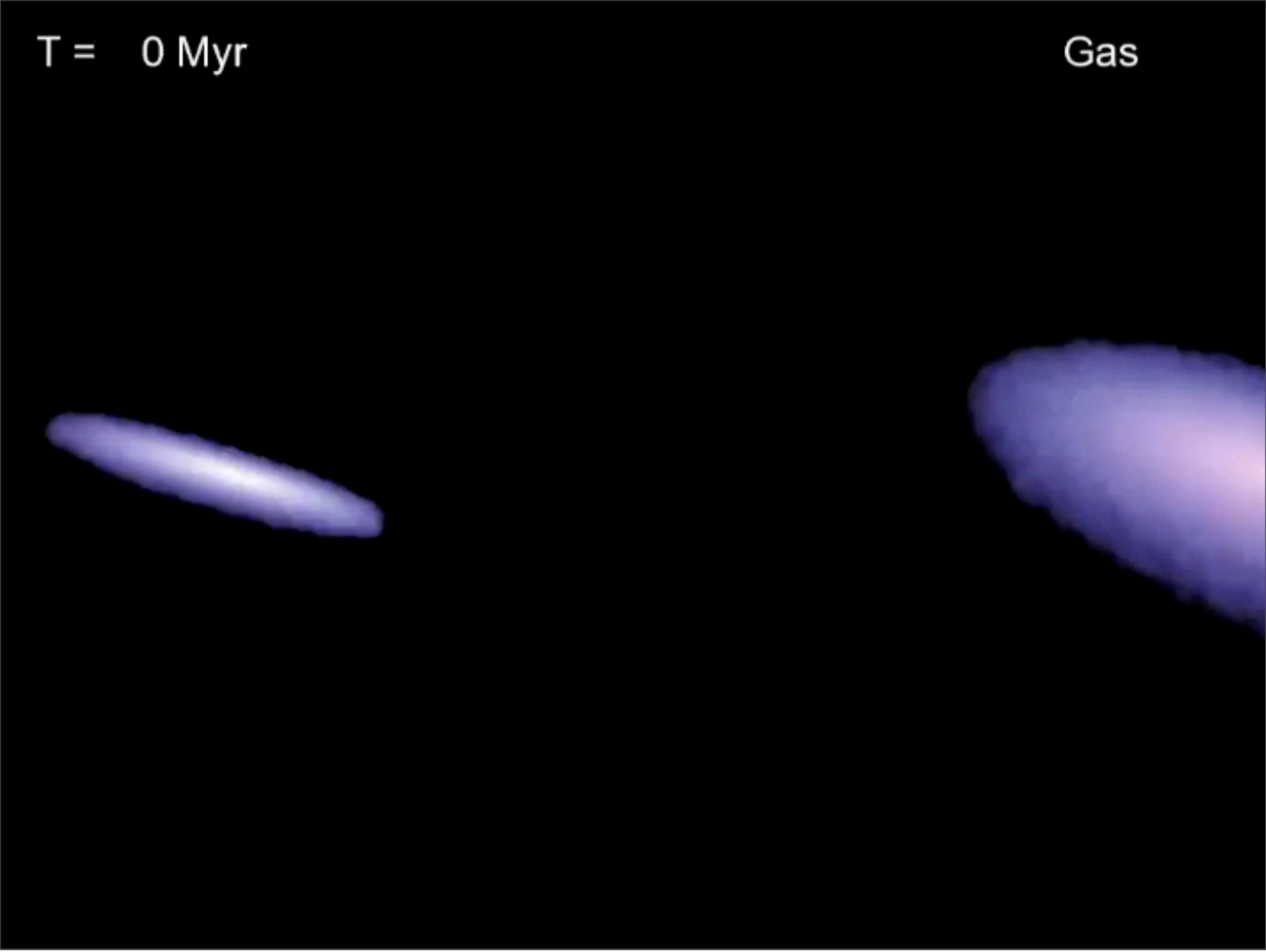
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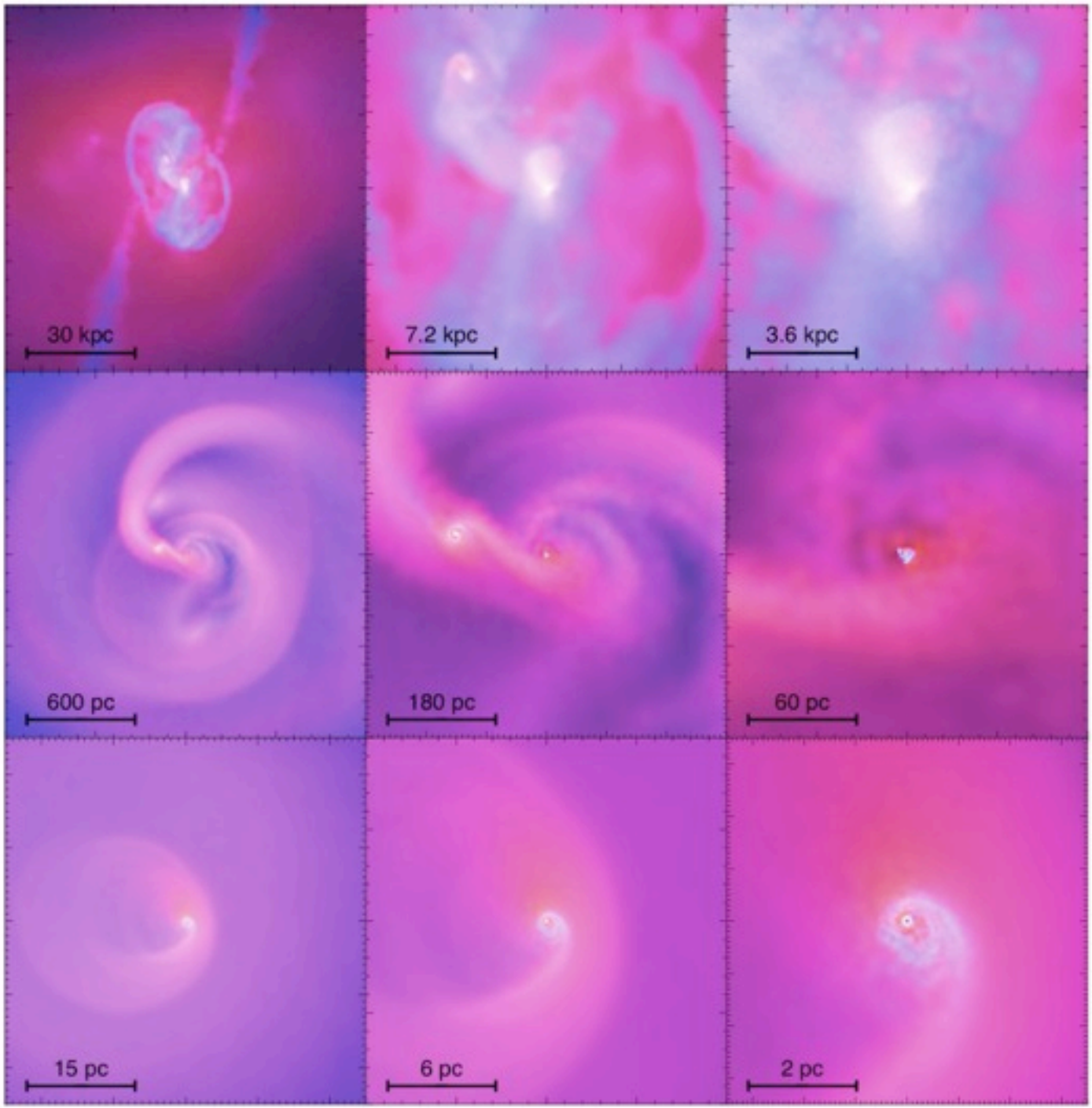
How do massive BHs get their gas?

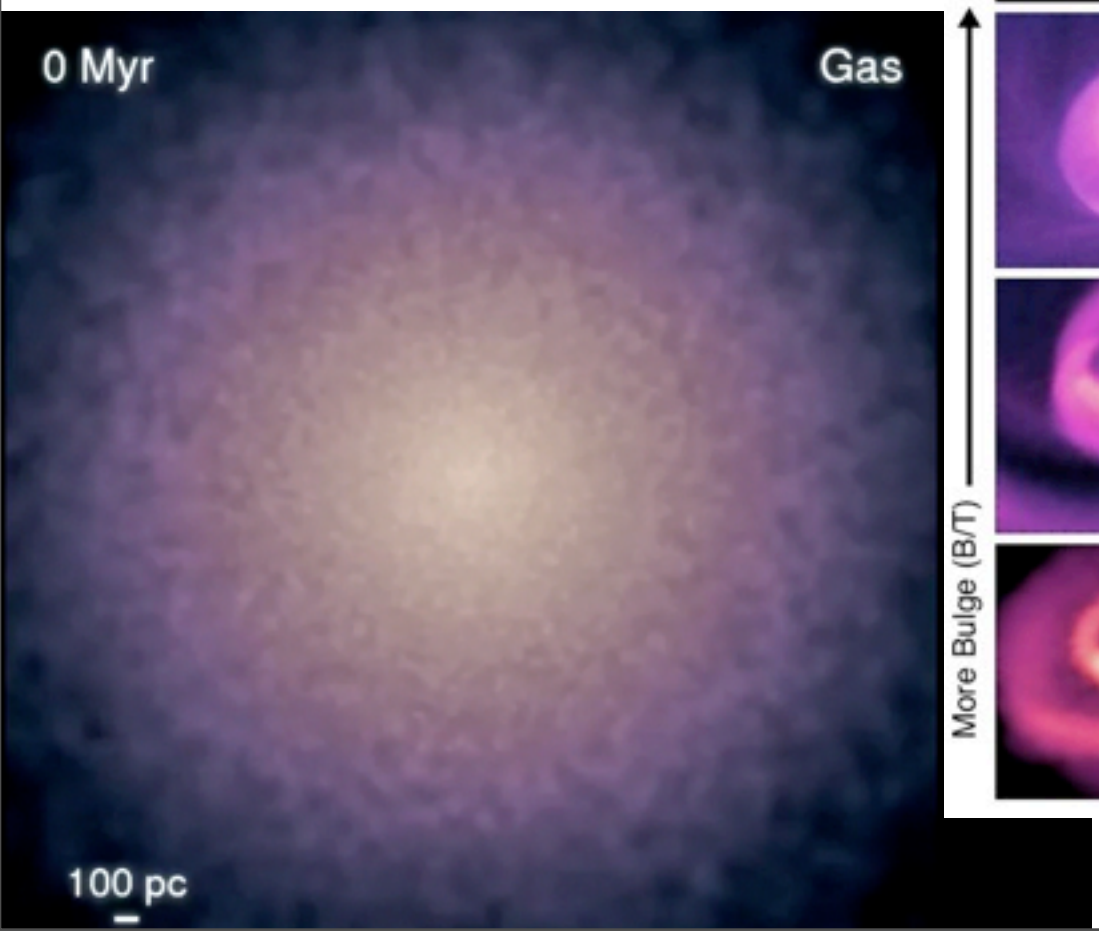
CAN WE FUEL THE MONSTER?

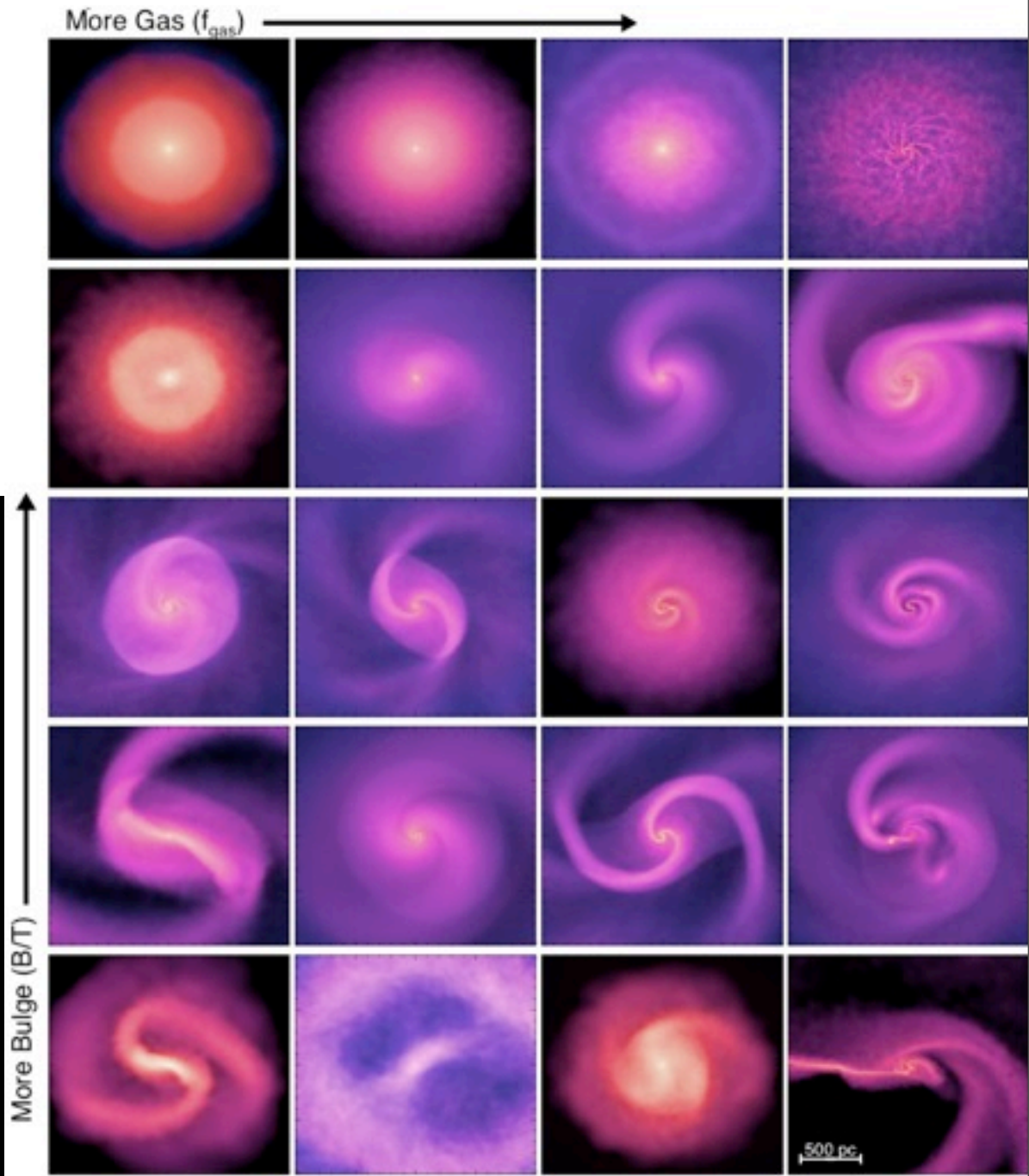


- Follow gas from 10s of kpc to ~0.1 pc
- Cascade of instabilities: merger is not efficient inside ~kpc
- *Any* mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

Sub-kpc scales: "Stuff within Stuff"

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





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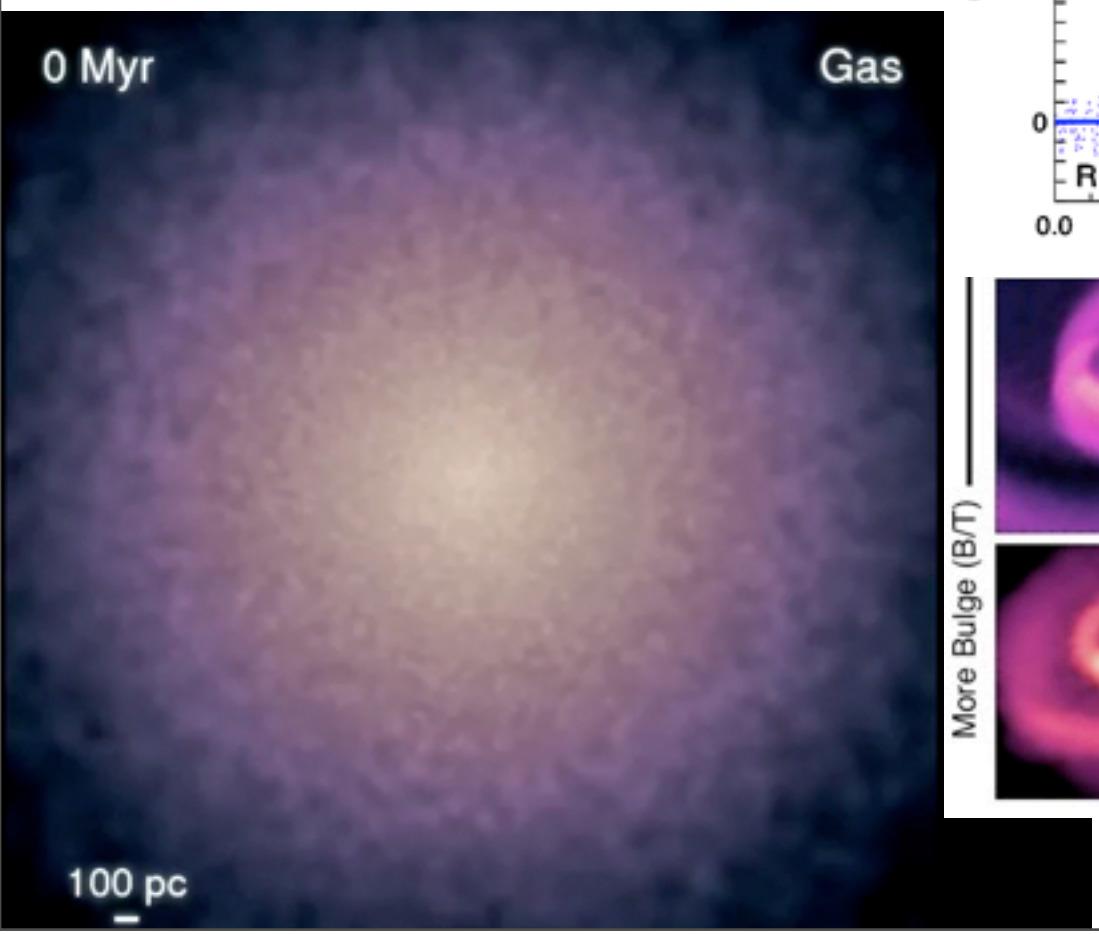
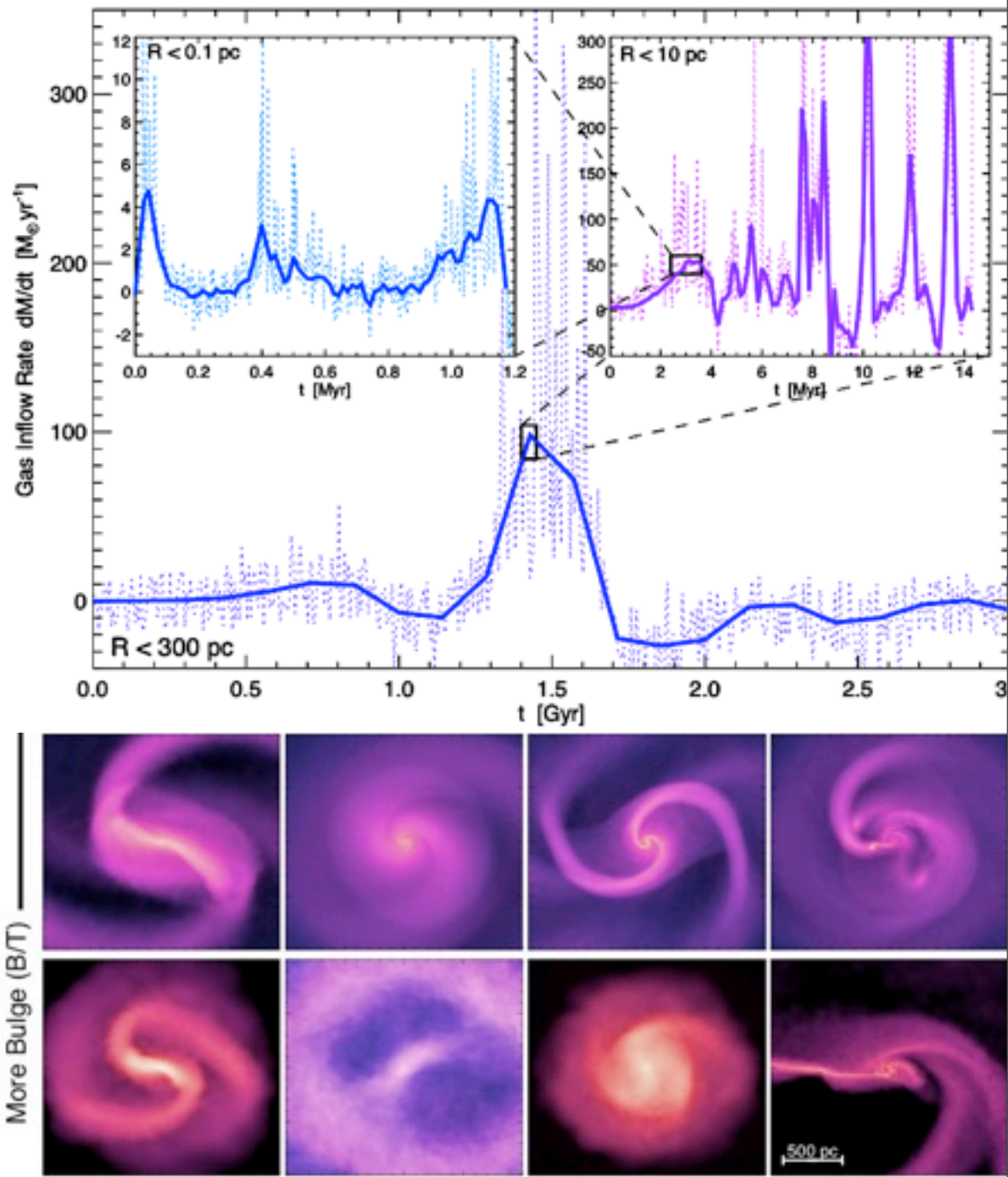
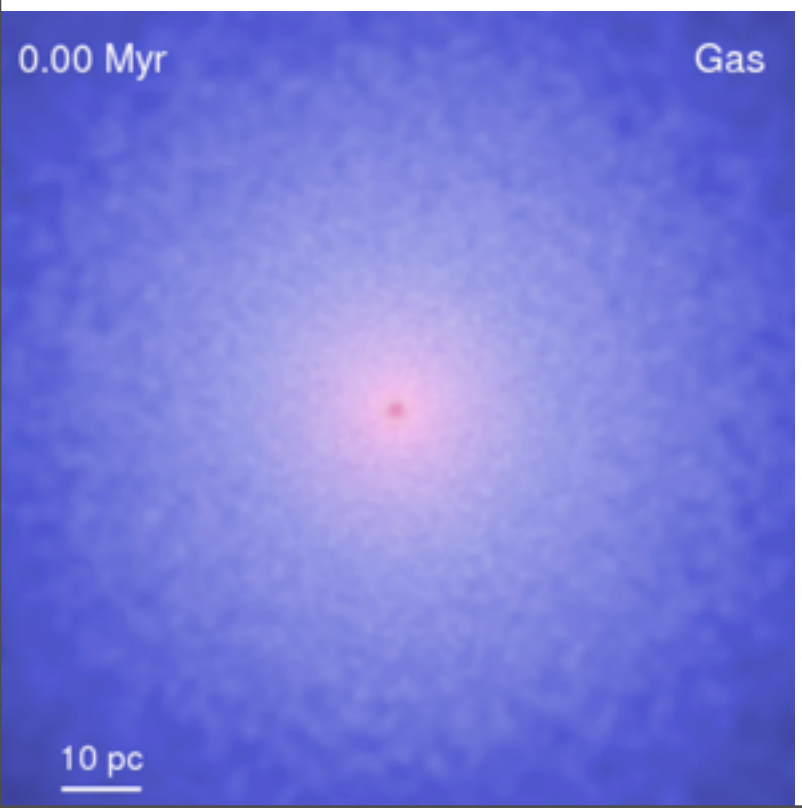
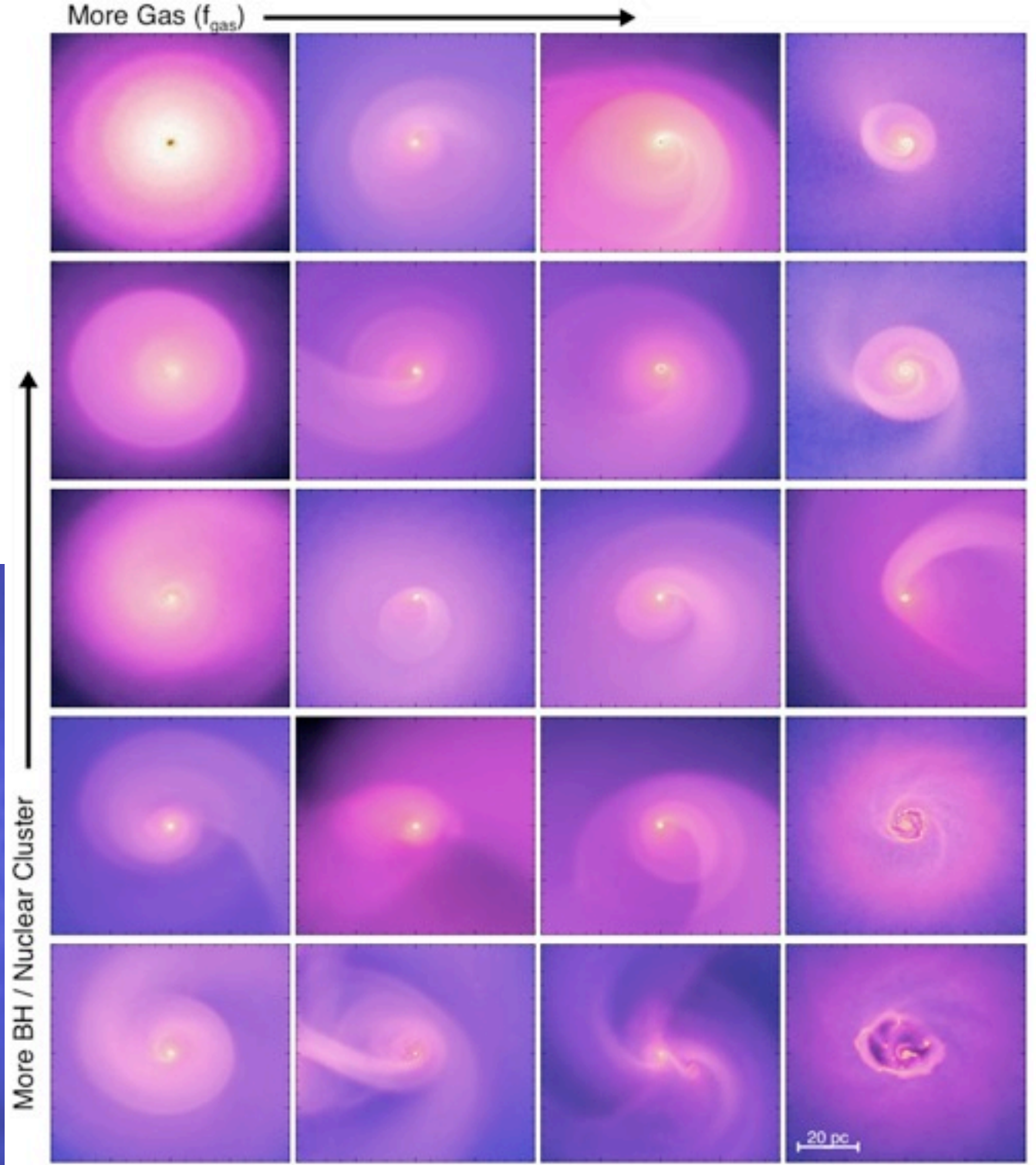




~10 pc scales: Nuclear eccentric disks

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





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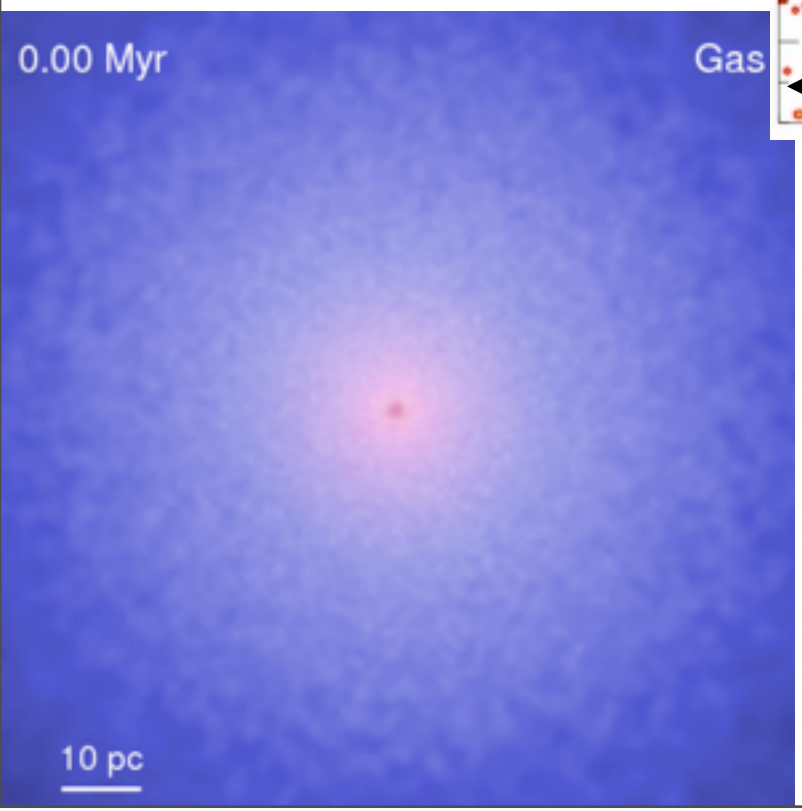

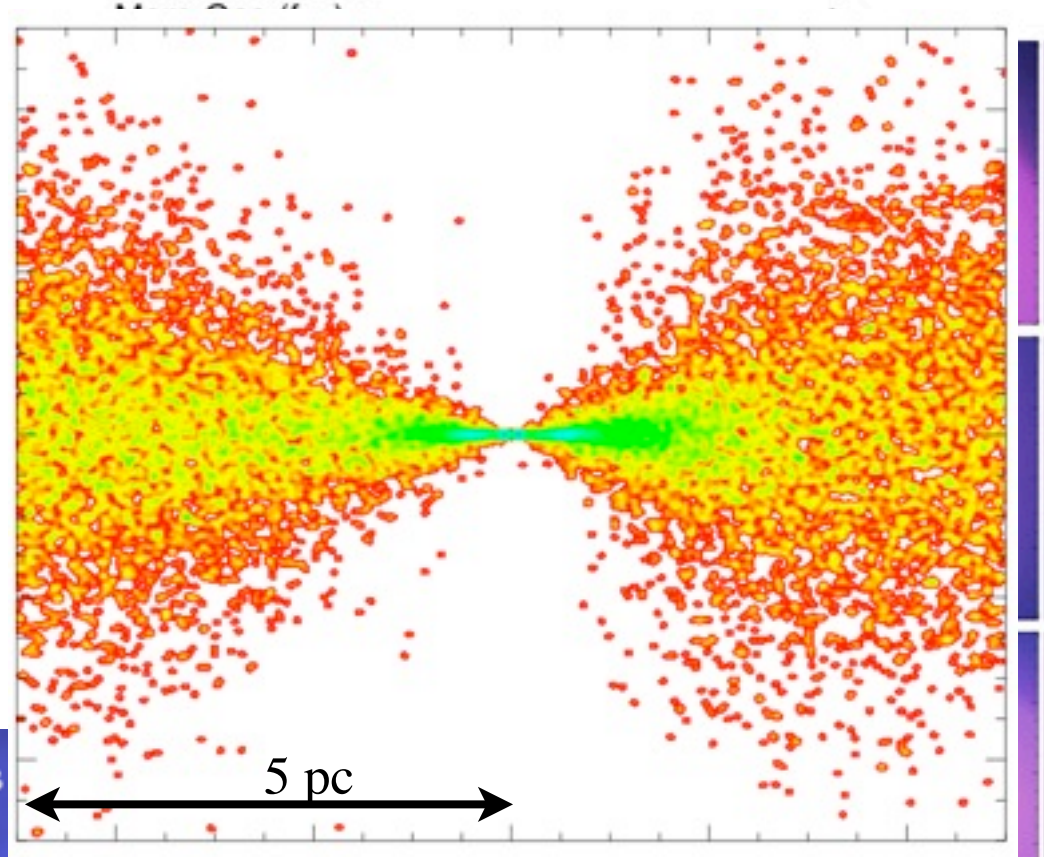

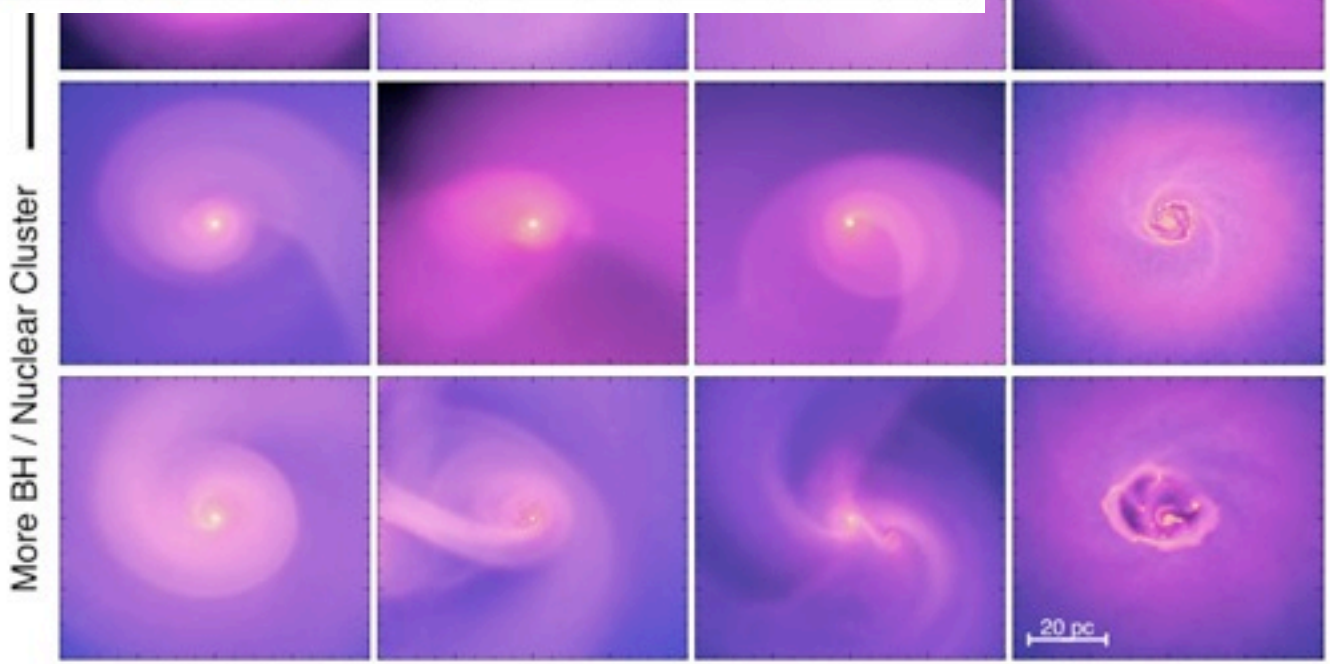

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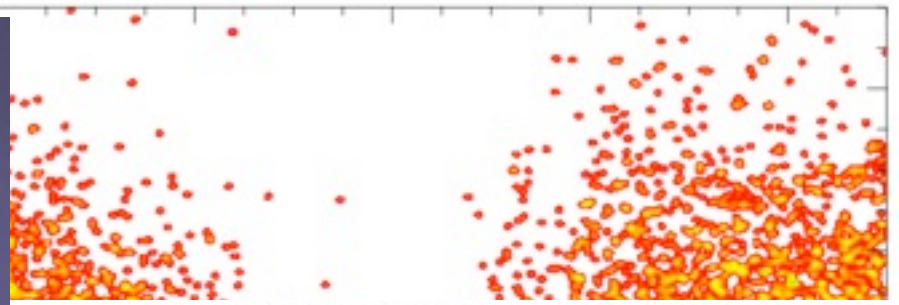
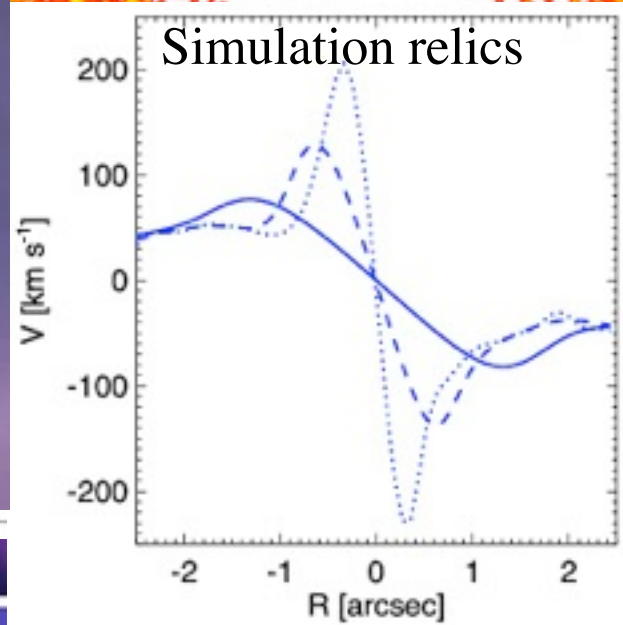
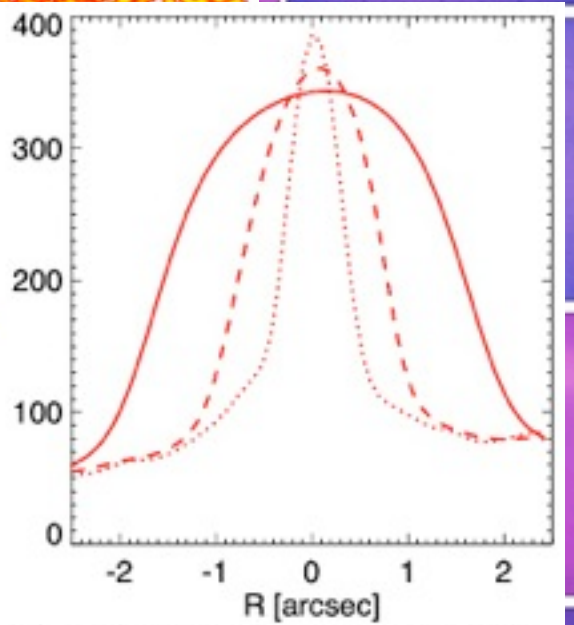
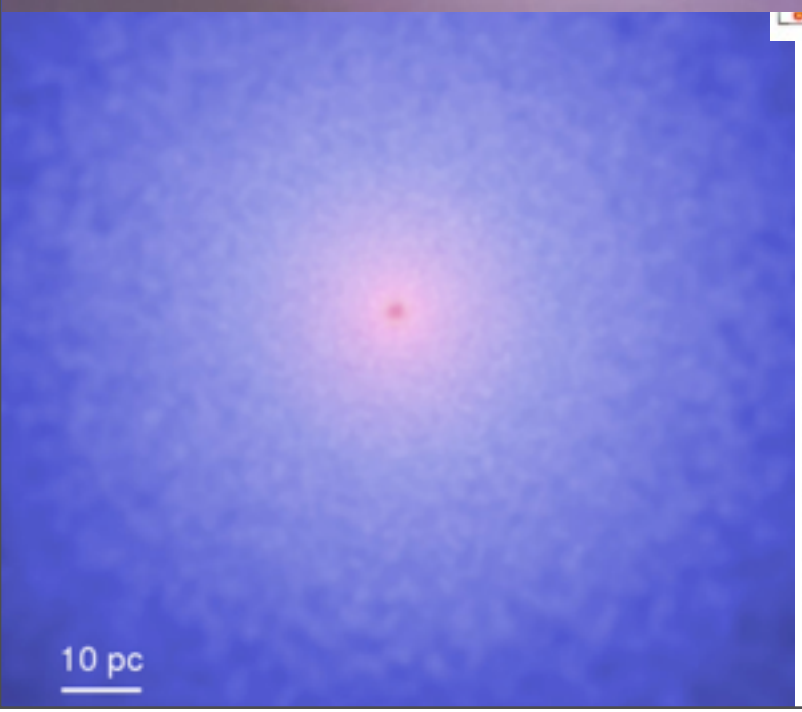
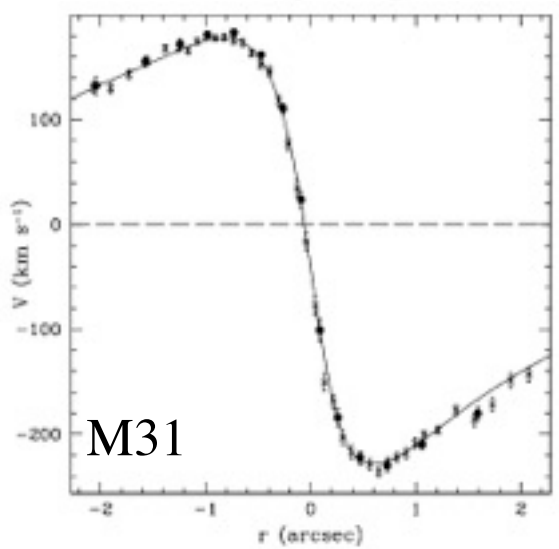


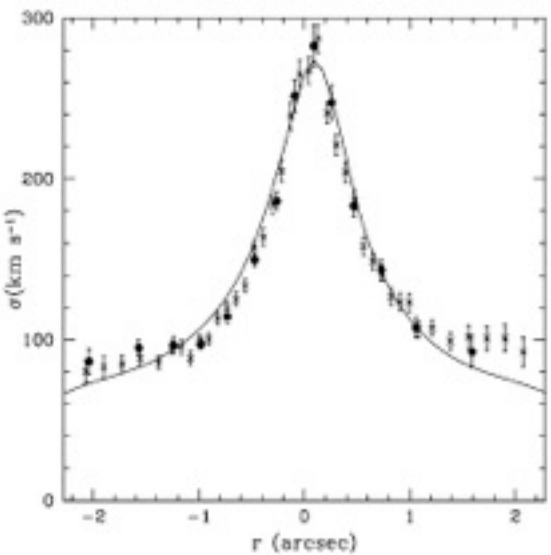




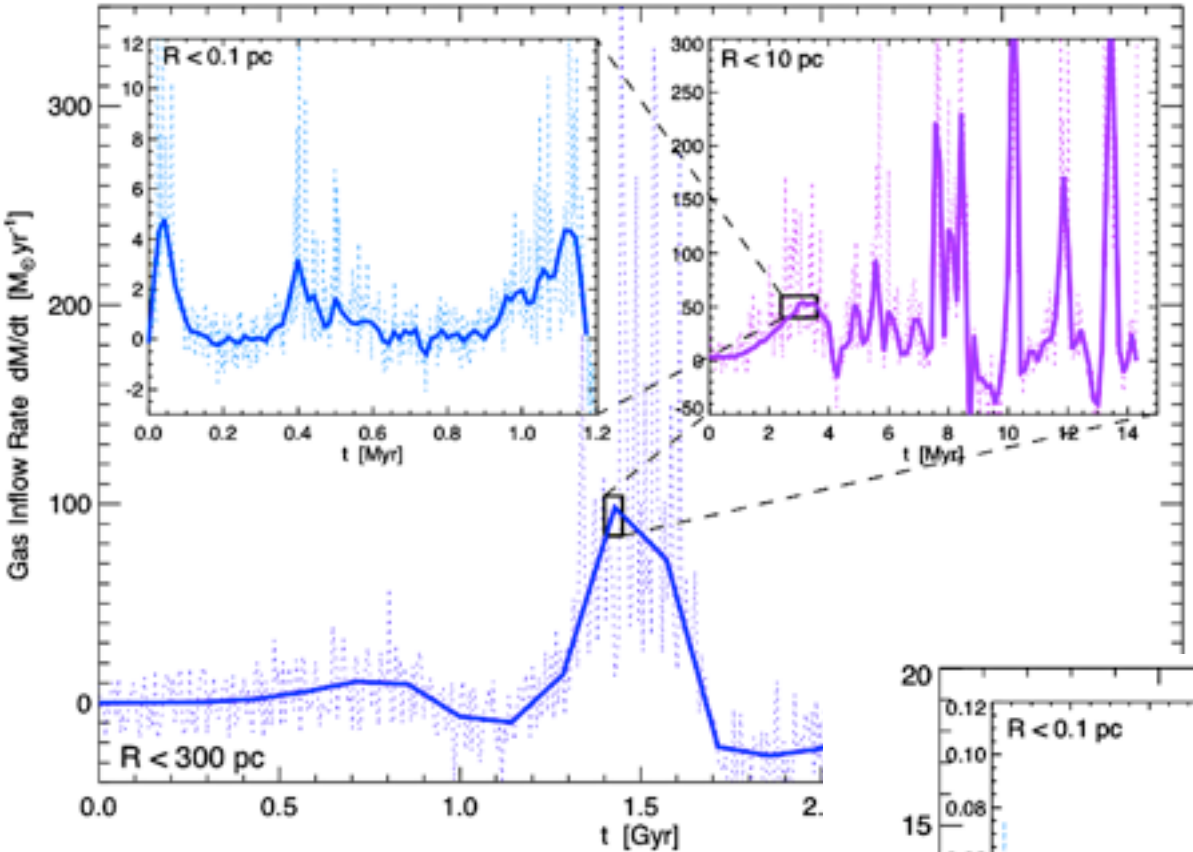


More BH / Nuclear Cluster

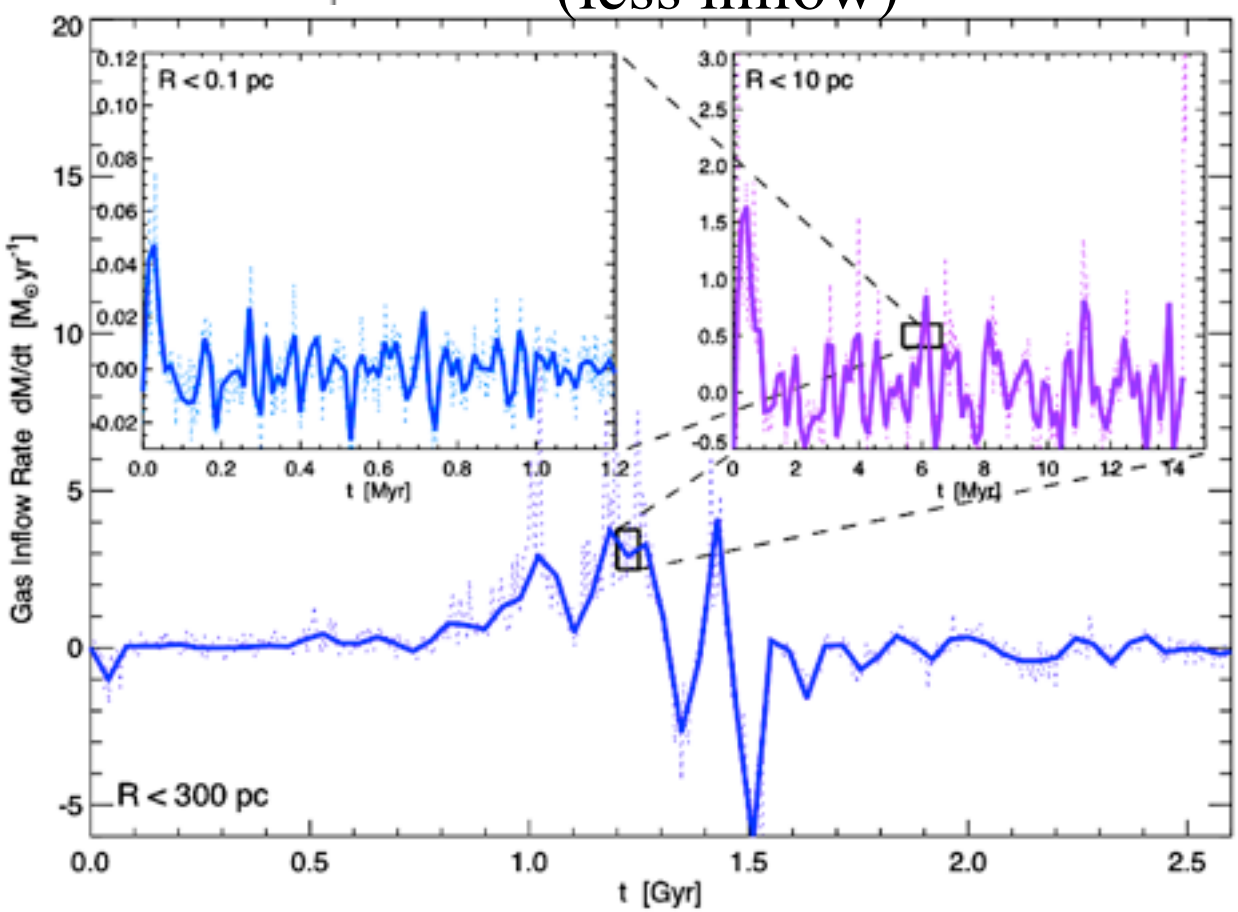




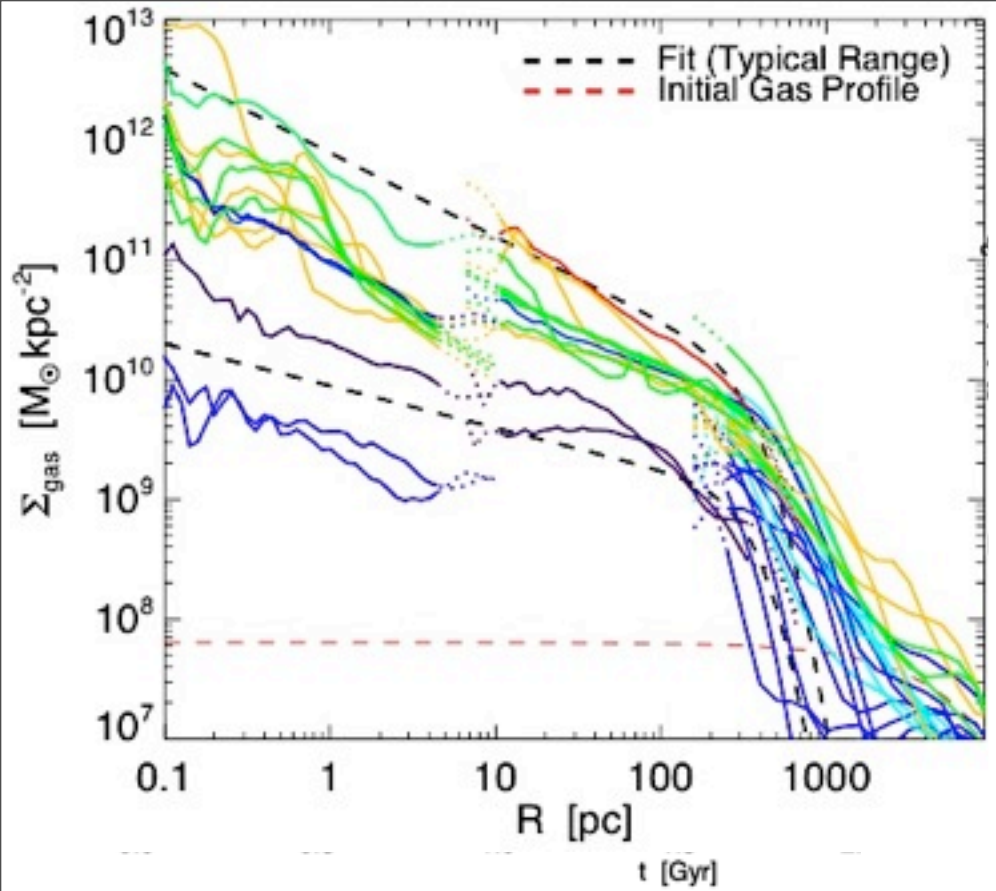
Gas-rich merger
(lots of inflow)



Weakly bar-unstable disk
(less inflow)



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



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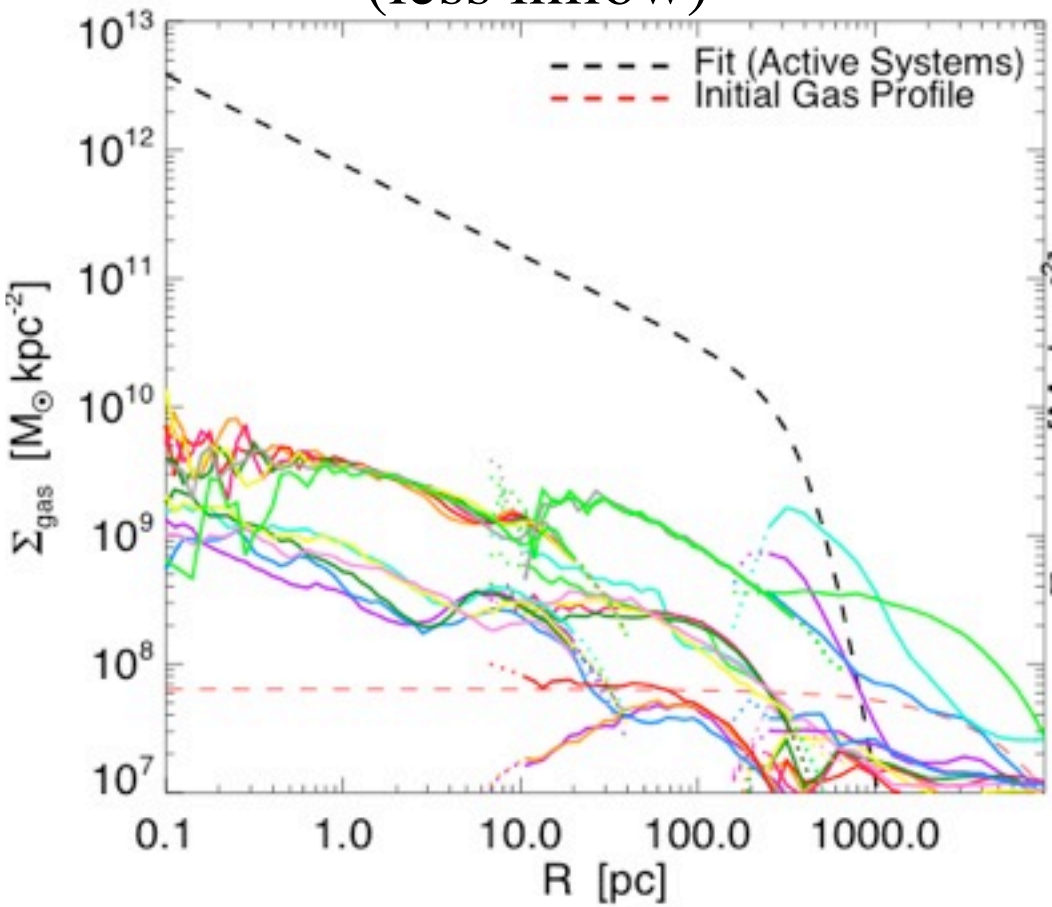

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  pre-existing bulge/BH mass

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

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, and feedback-regulated later

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

(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 et al. in prep)

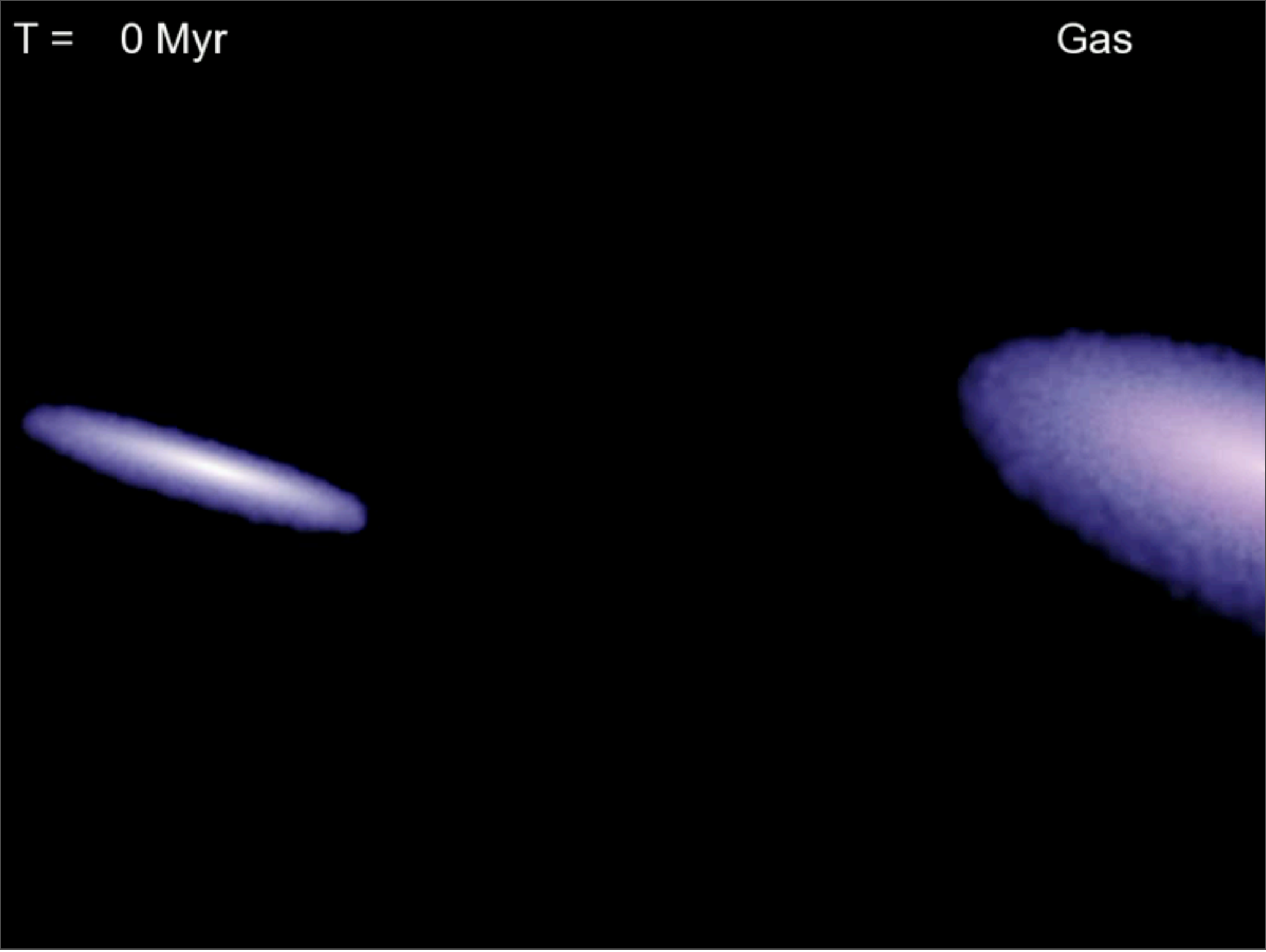
$$\dot{M}_{\rm viscous} \propto \frac{\Sigma_{\rm gas}\,c_s^2}{\Omega}$$

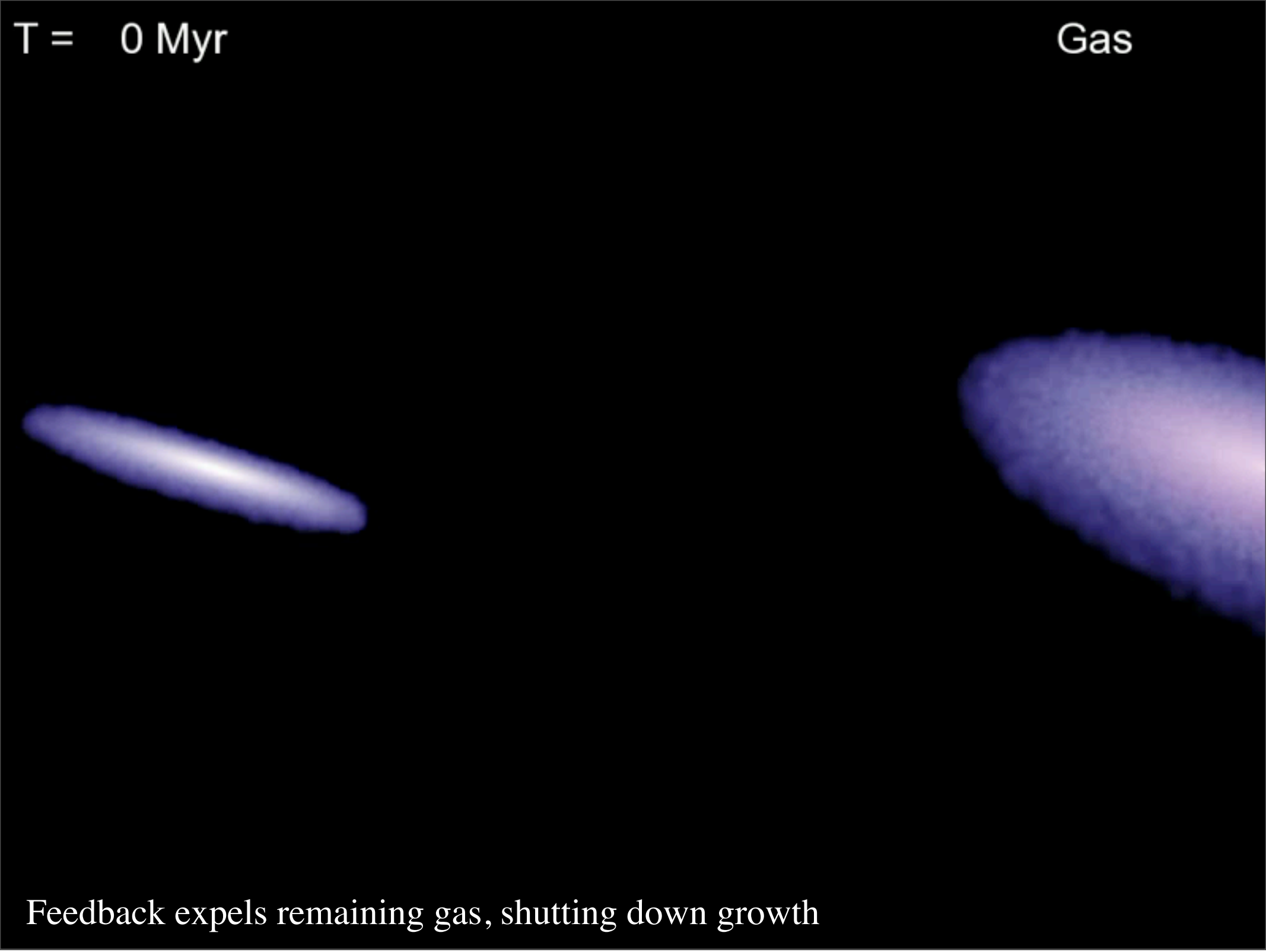
(DeBuhr et al. 2009)

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

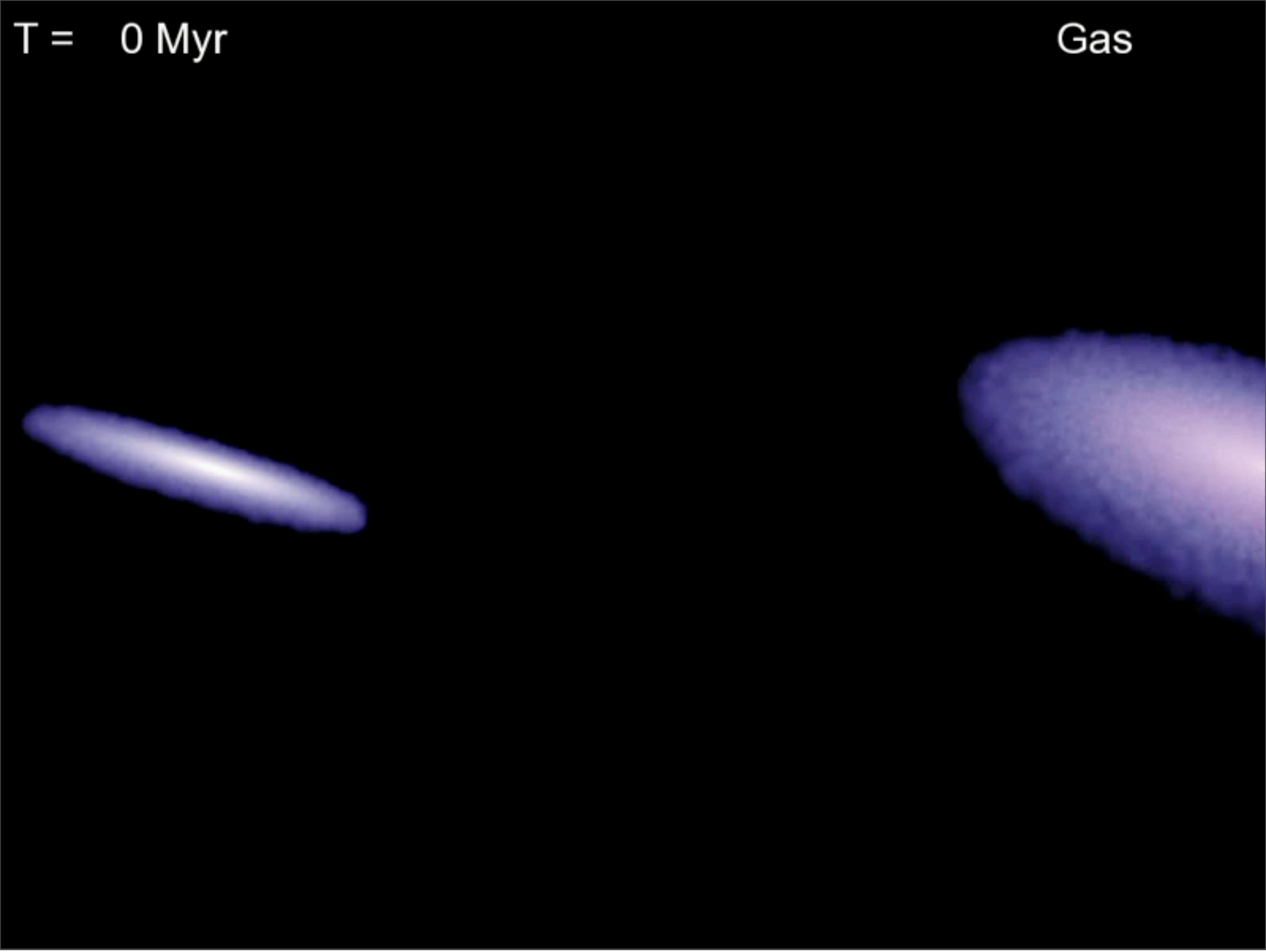
} Predict same "impact" of feedback

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


T = 0 Myr
Gas



Feedback expels remaining gas, shutting down growth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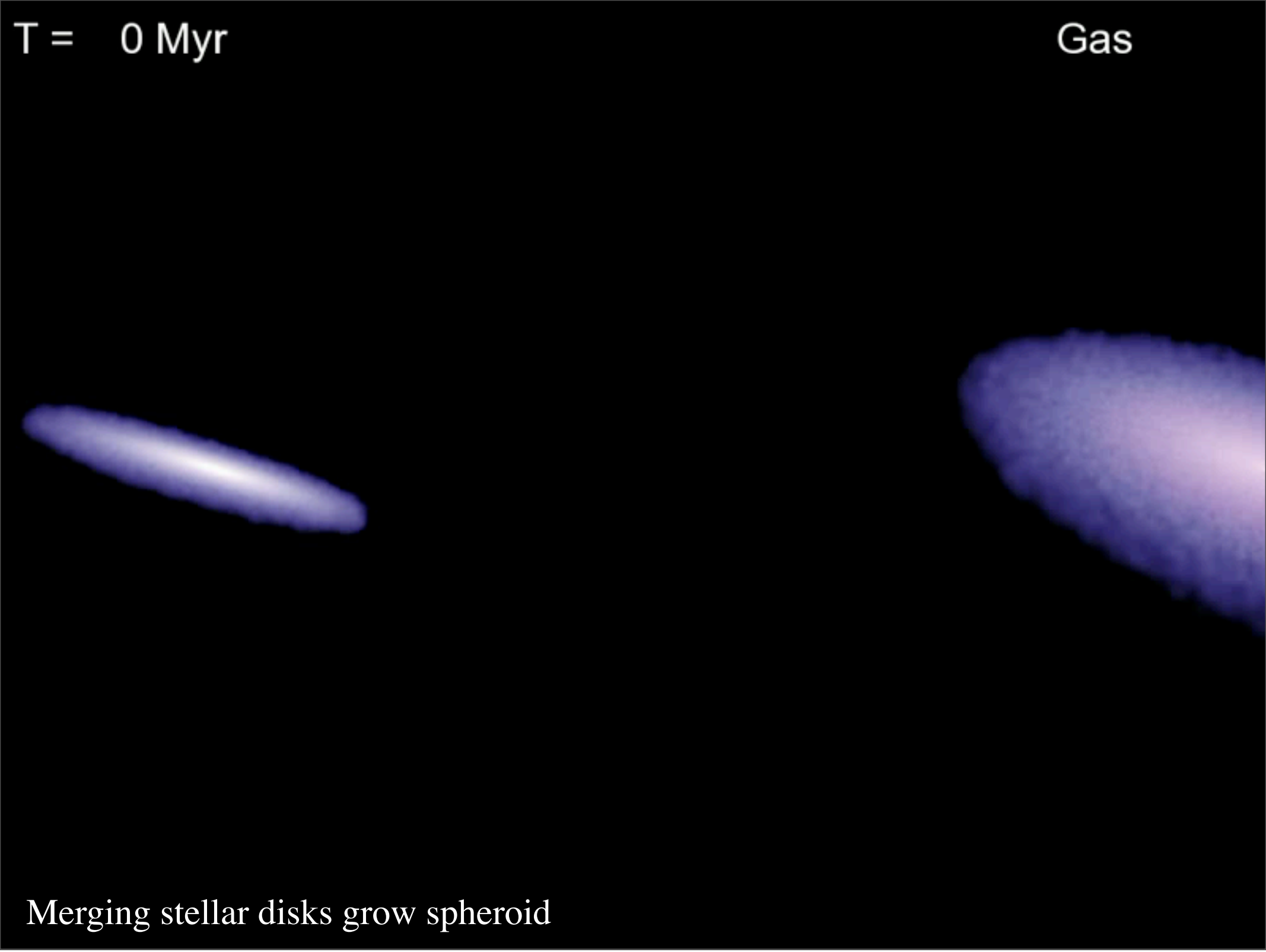
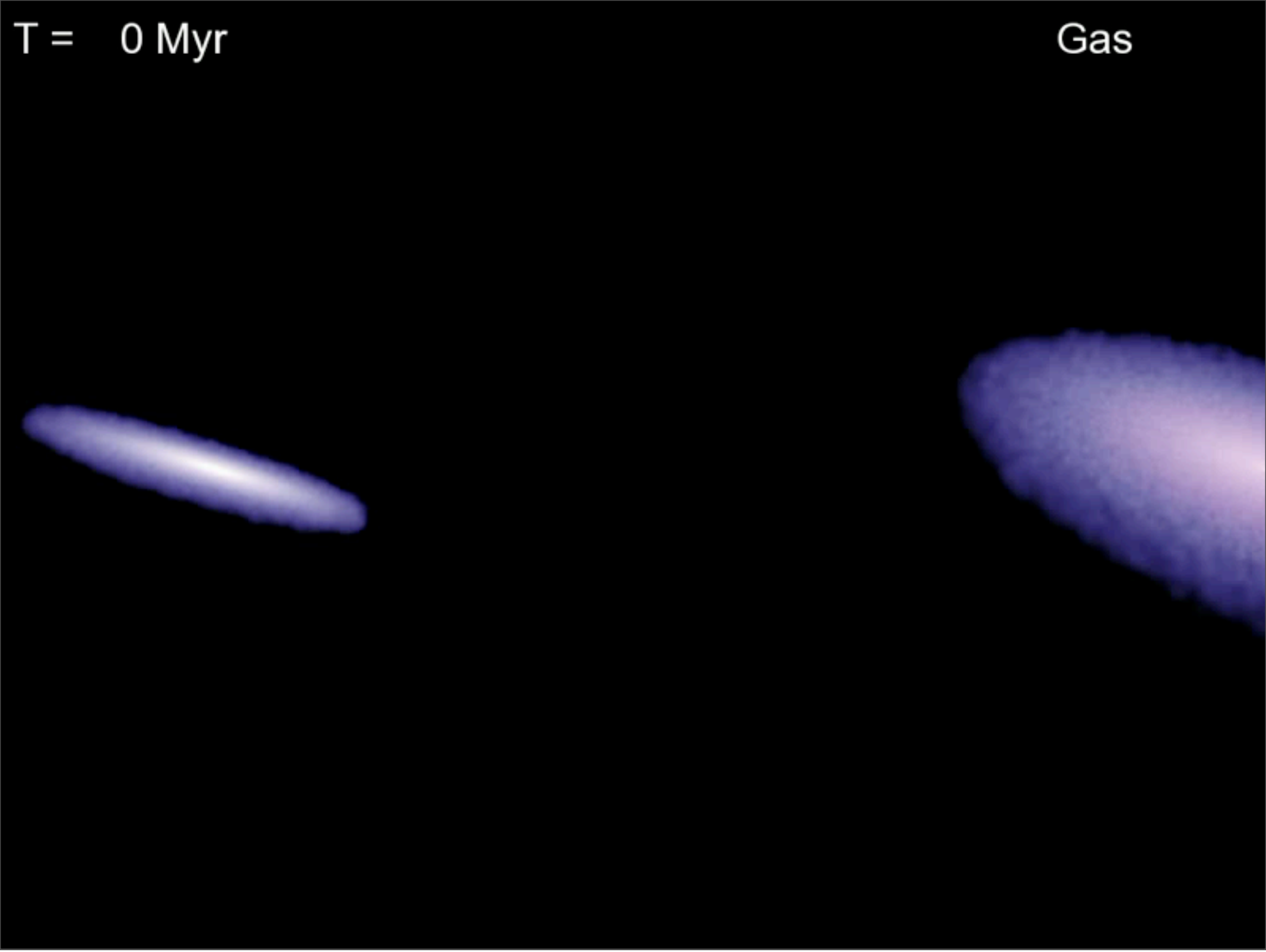
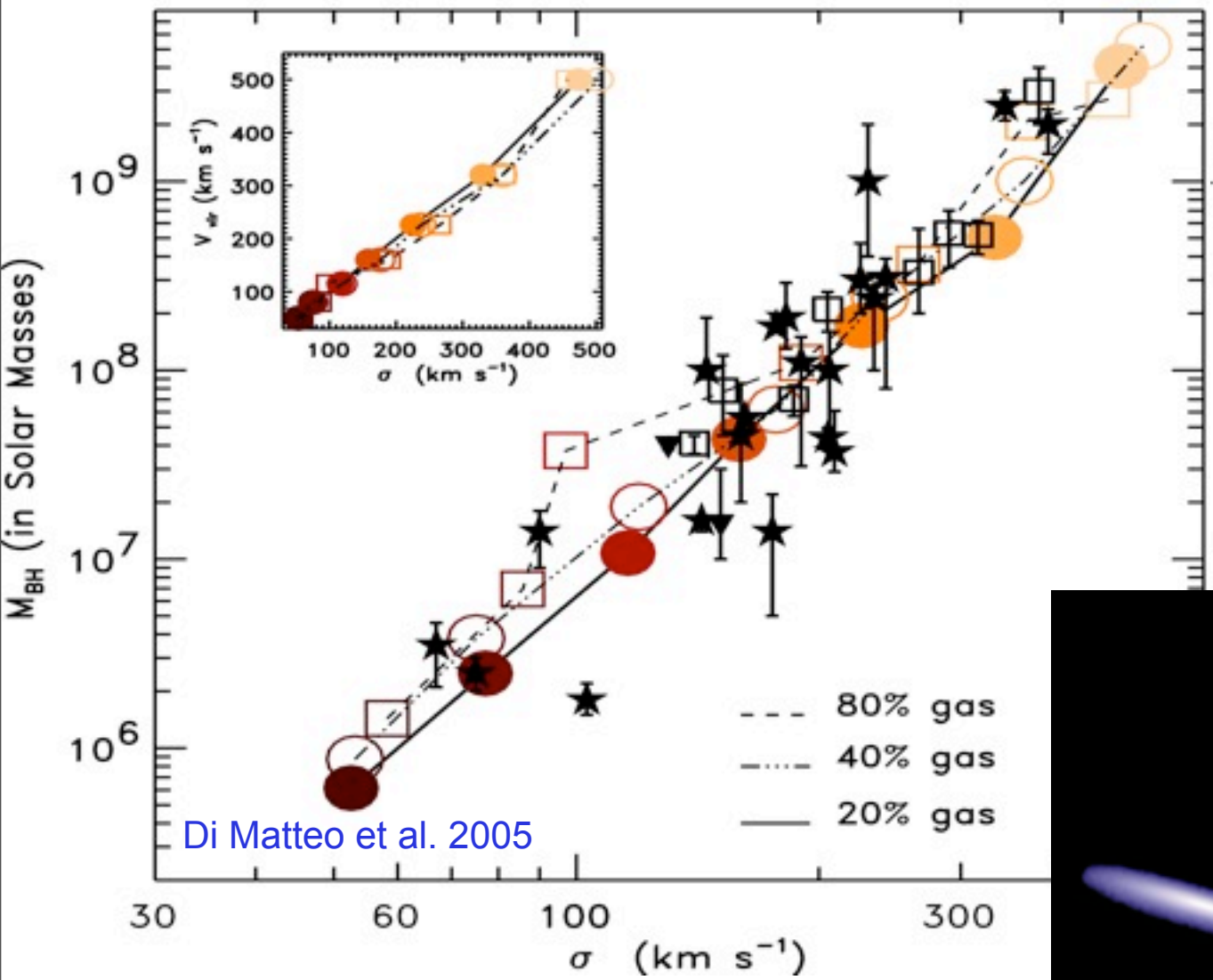


Merging stellar disks grow spheroid

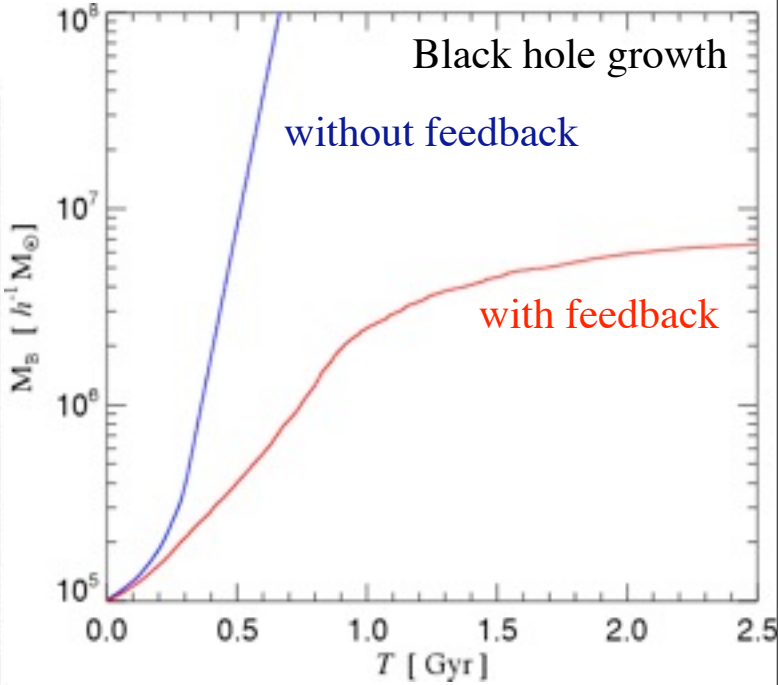

T = 0 Myr
Gas

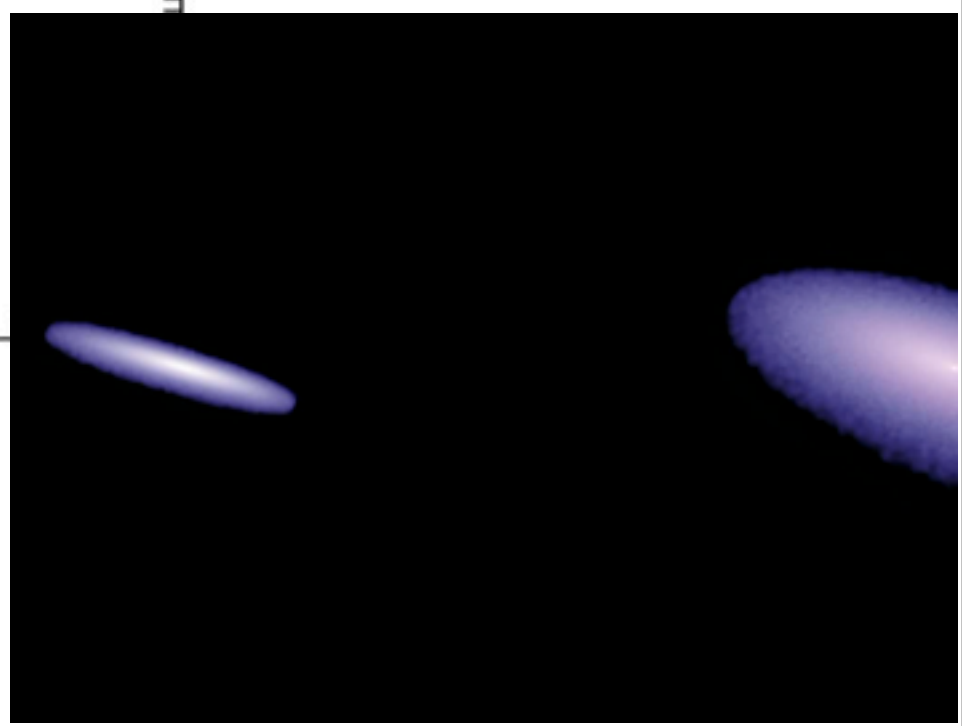
M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



Di Matteo et al. 2005

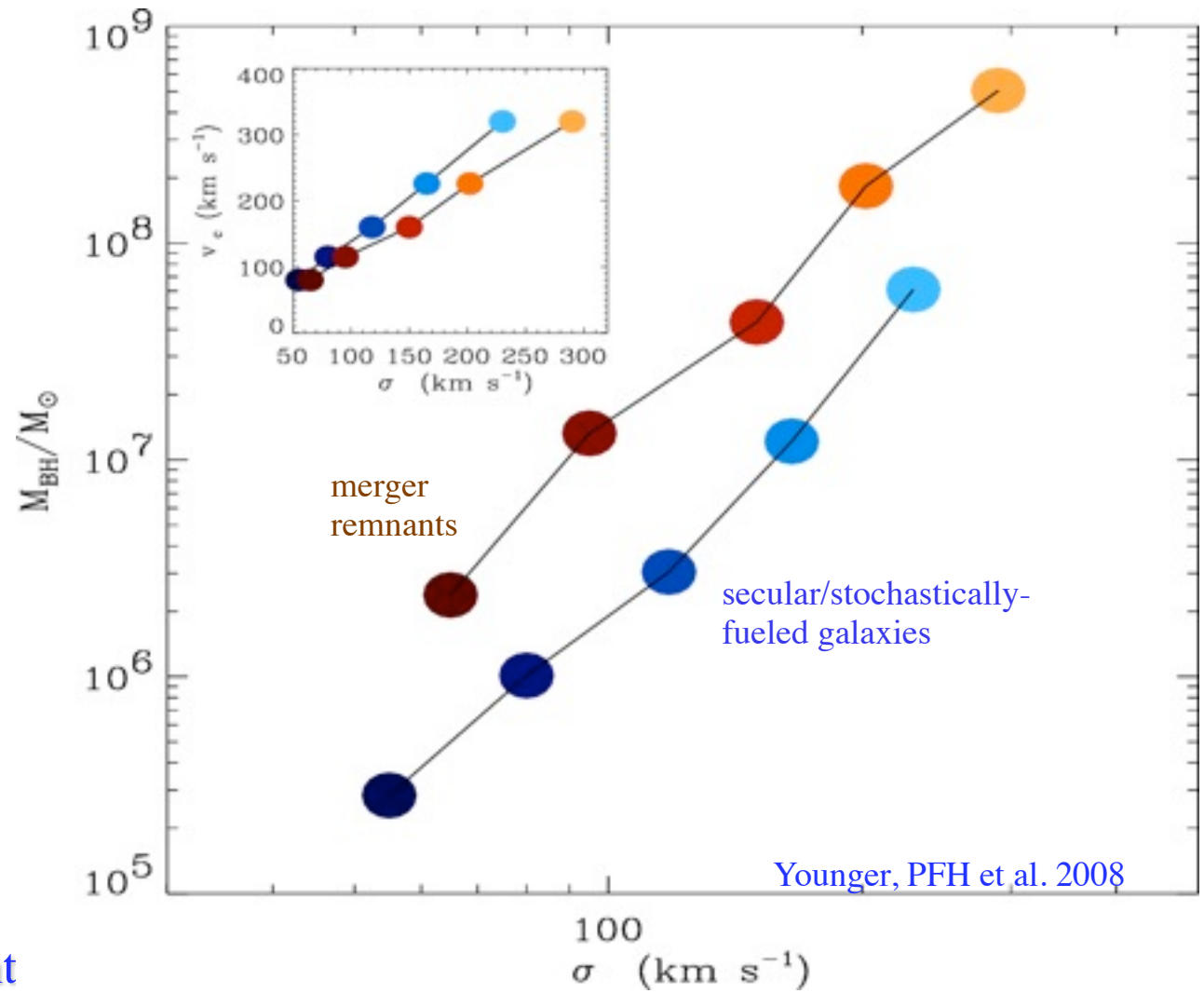




Observations & Simulations Suggest this Simple Picture Works

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.)

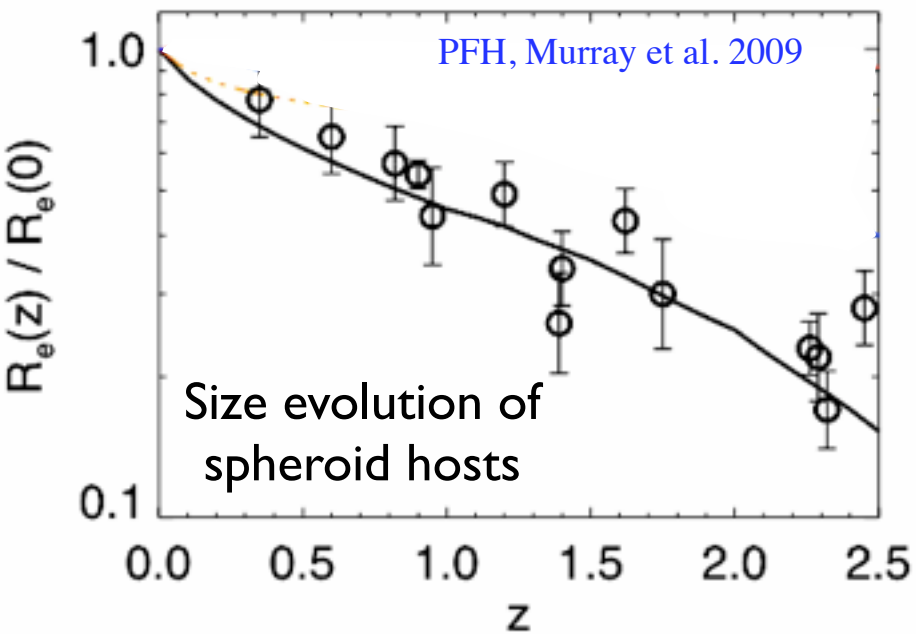


- Basic argument
  - BH feedback self-regulates growth in ~fixed potential

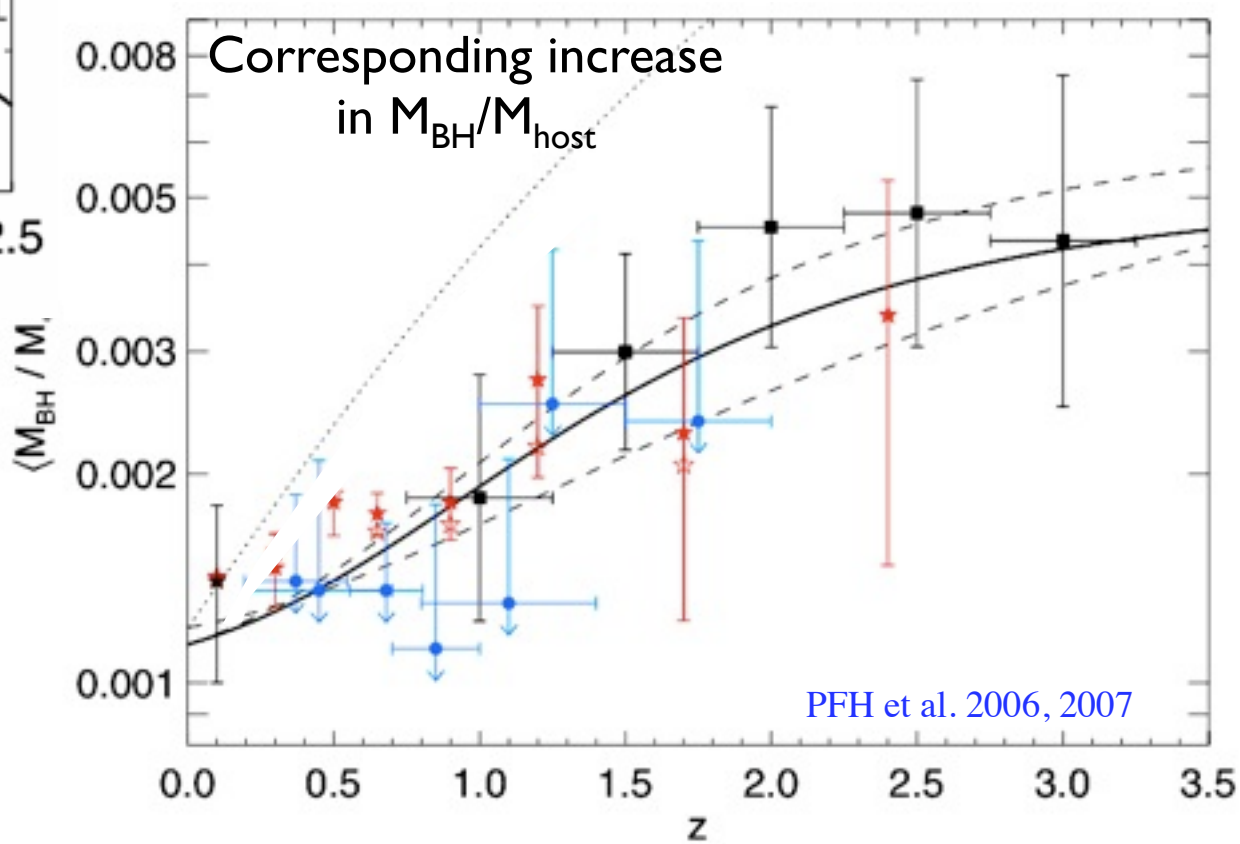
Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- Naturally predicts some evolution in BH-Host correlations:
  - Hosts more gas rich/compact at high-z → more "work" for the BH before self-regulation



- DOES NOT mean that BHs grew "before" their bulges

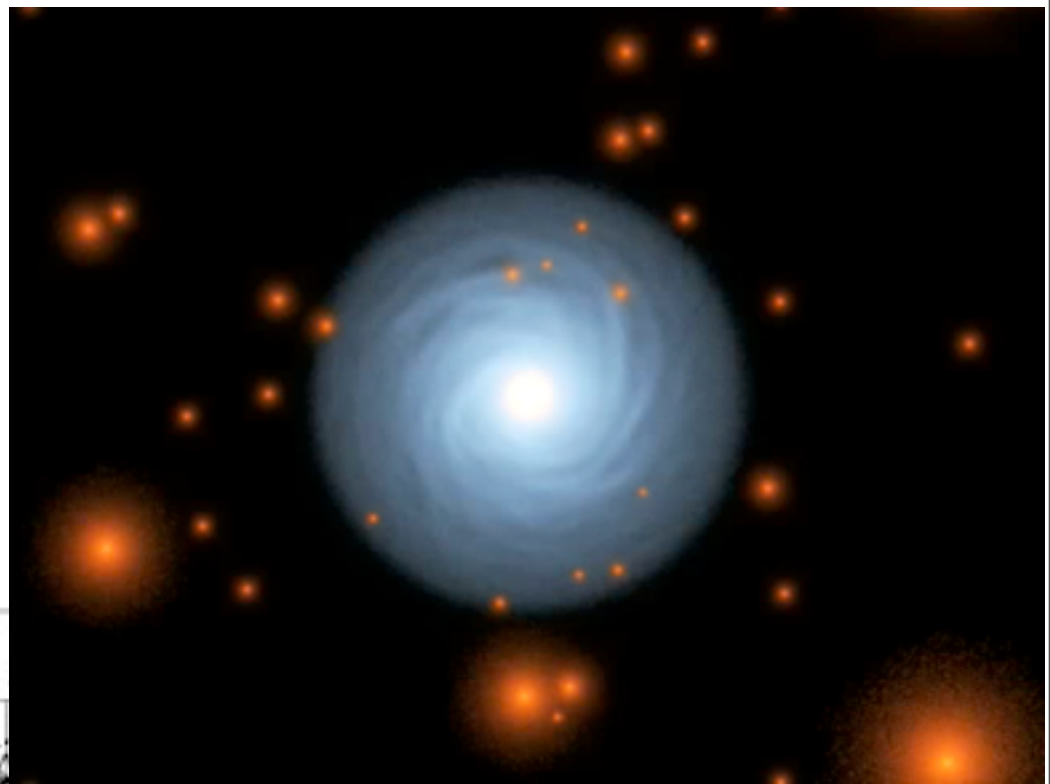


- "Catch up" via mergers with late-forming spheroids and gas-poor disks

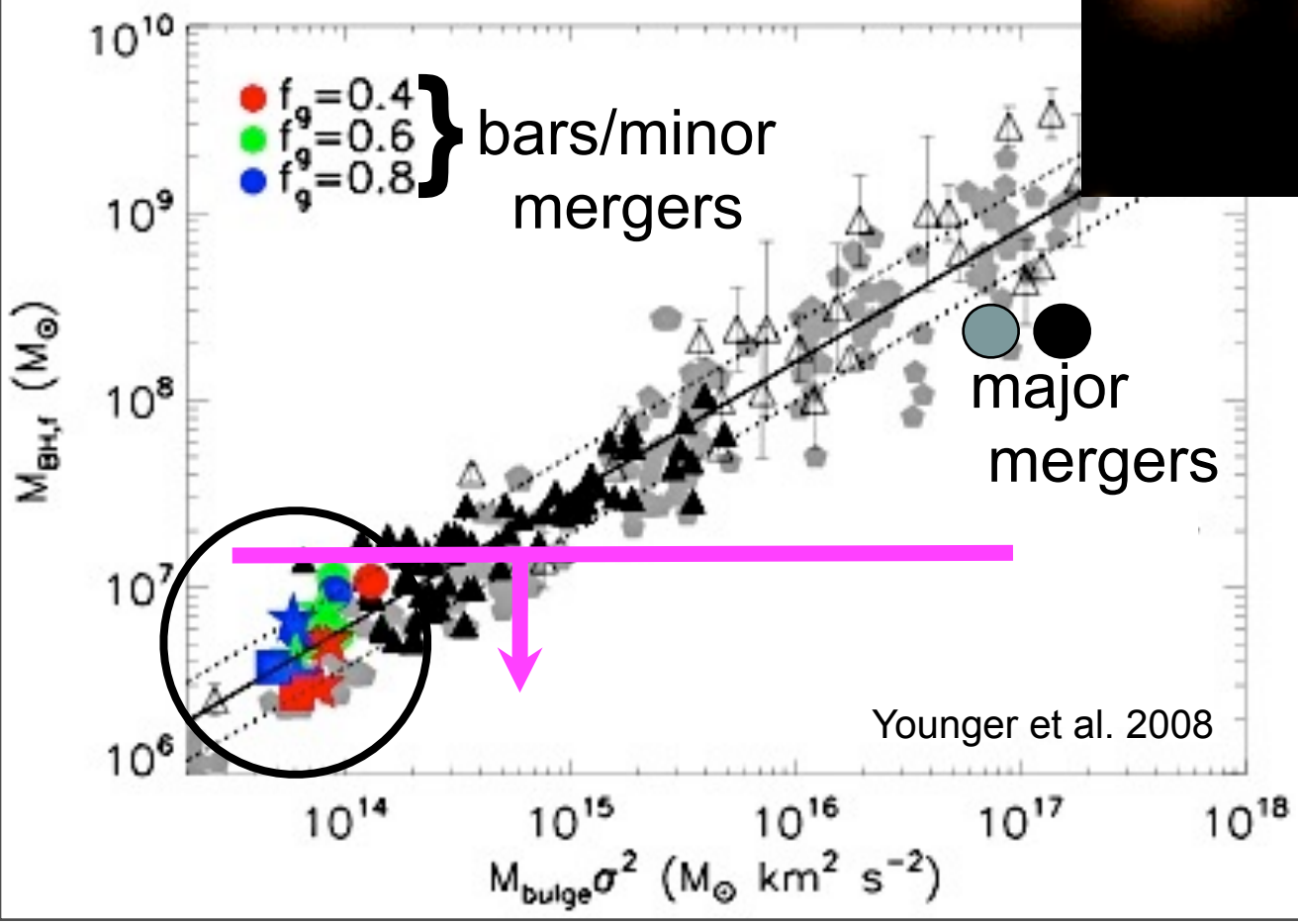
Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

- z~2 QSO: 10^{11} M_{sun} in <10pc in ~t_{dyn}
- Seyfert: only 10^{7-8} M_{sun} ~ GMC
- Minor mergers?
- Secular instabilities/bars?

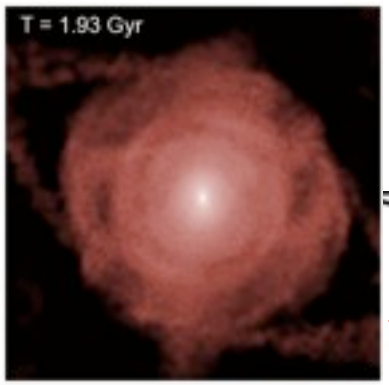


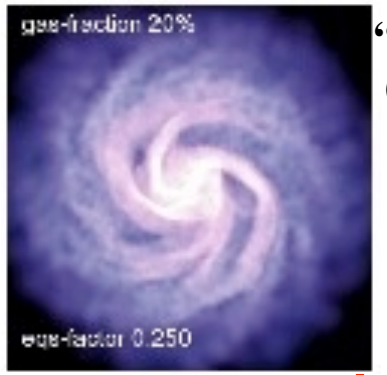
Dubinski



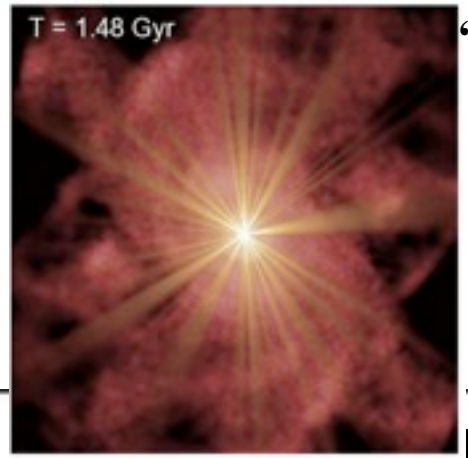
- If you don't build massive bulges, doesn't matter if you can get the gas in!

"Dead" Bulges (stellar wind/hot gas halo accretion)

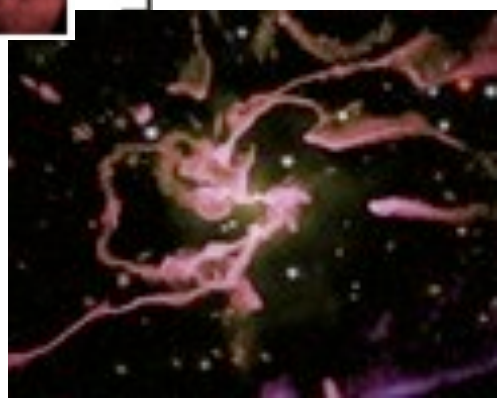




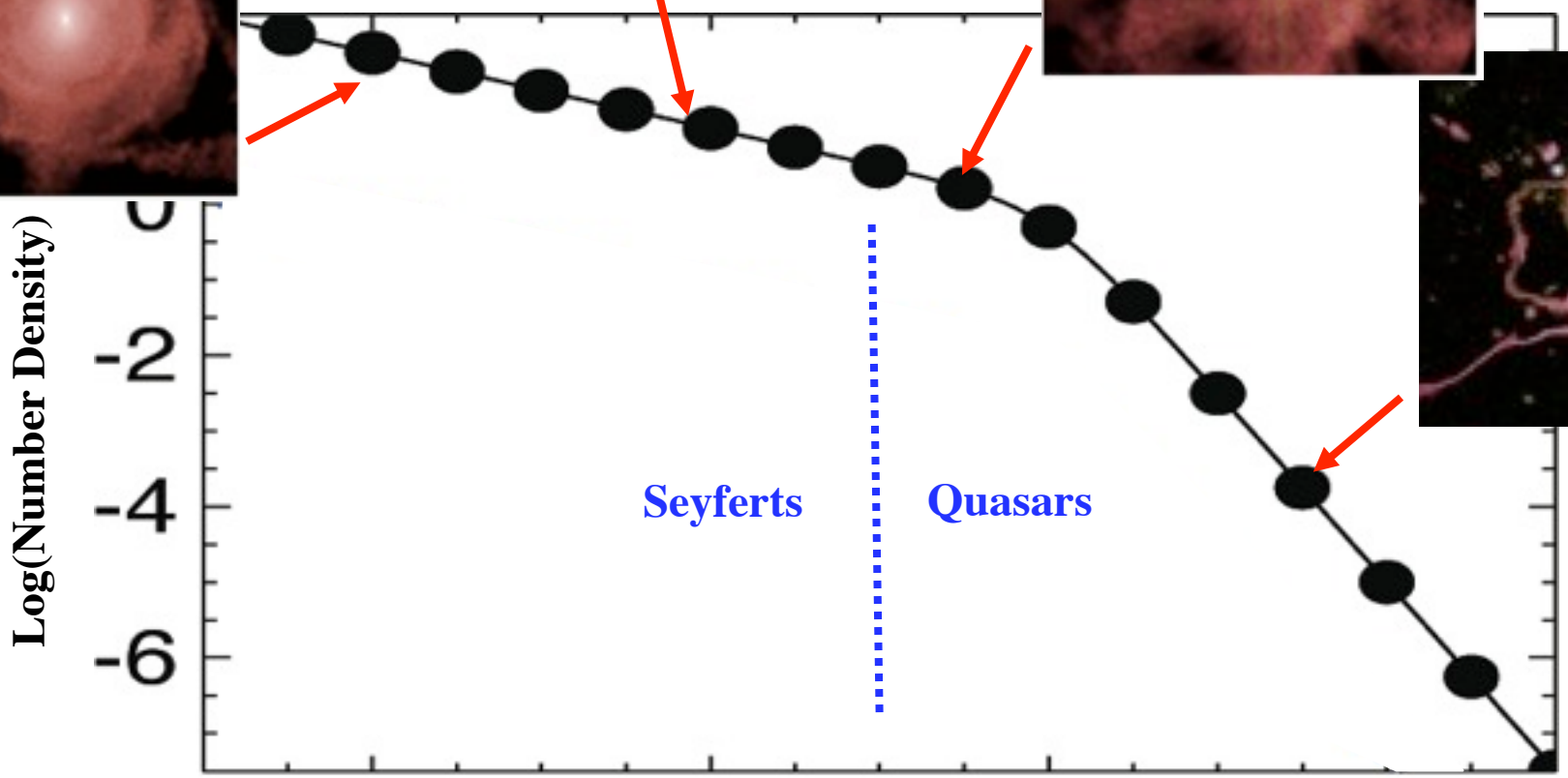
"Seyferts" (disk-dominated, secular/minor mergers)



"Fading" Mergers (post-starburst spheroids)

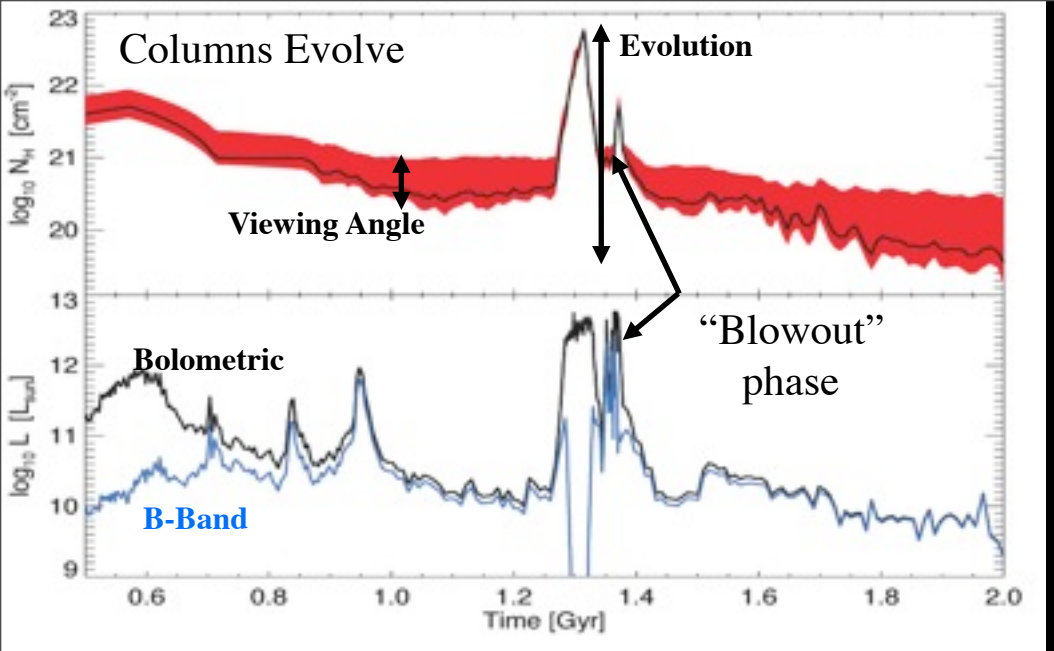


"Blowout" (Bright Mergers)



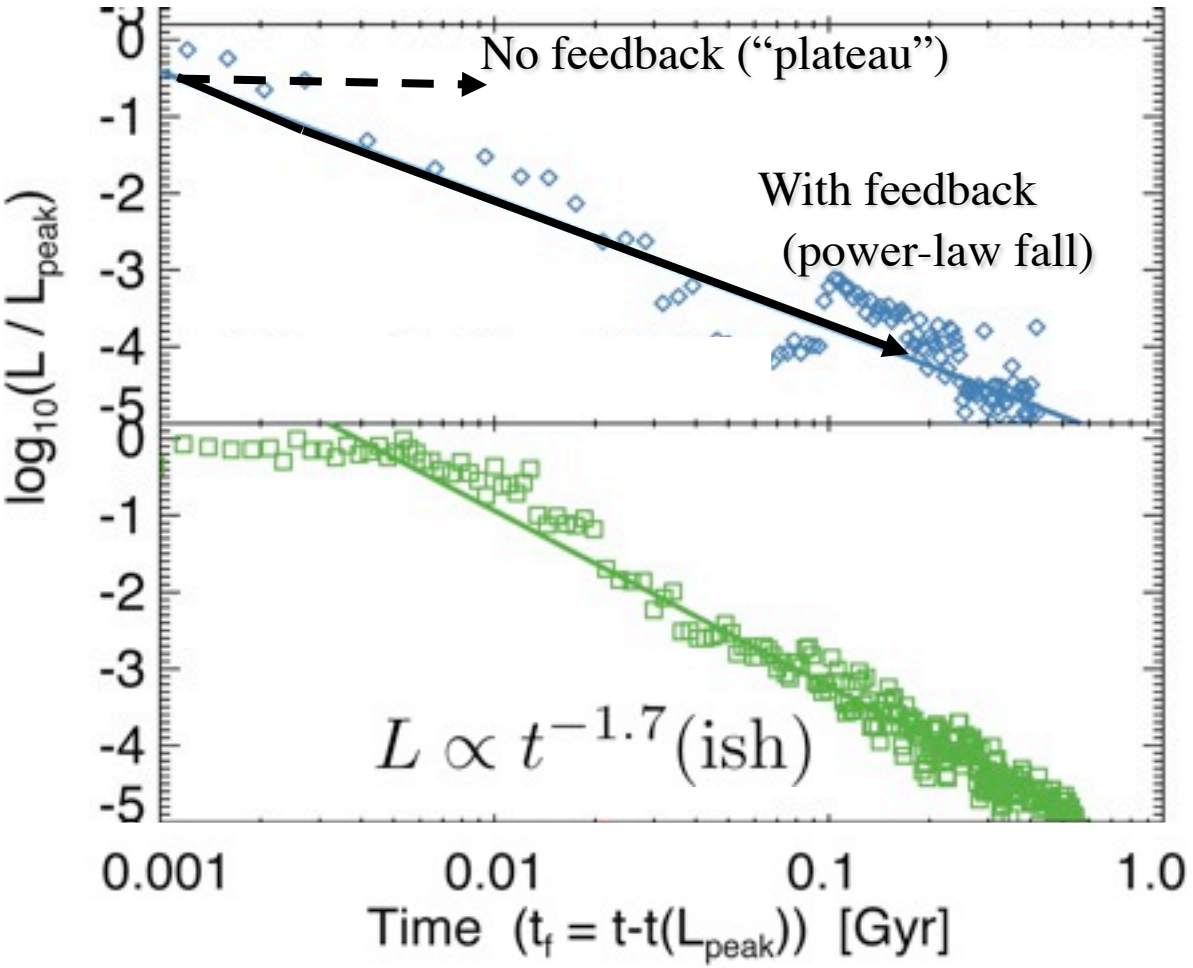
- Observed luminosity function: populations at different *evolutionary* stages

Lightcurves: How Does Feedback Affect How AGN Move *Along* the Luminosity Function?


Columns Evolve
Evolution
Viewing Angle
"Blowout" phase
Bolometric
B-Band
log10 NH [cm-2]
log10 L [Lsun]
Time [Gyr]
23
22
21
20
13
12
11
10
9
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Quasar Lightcurves and Lifetimes

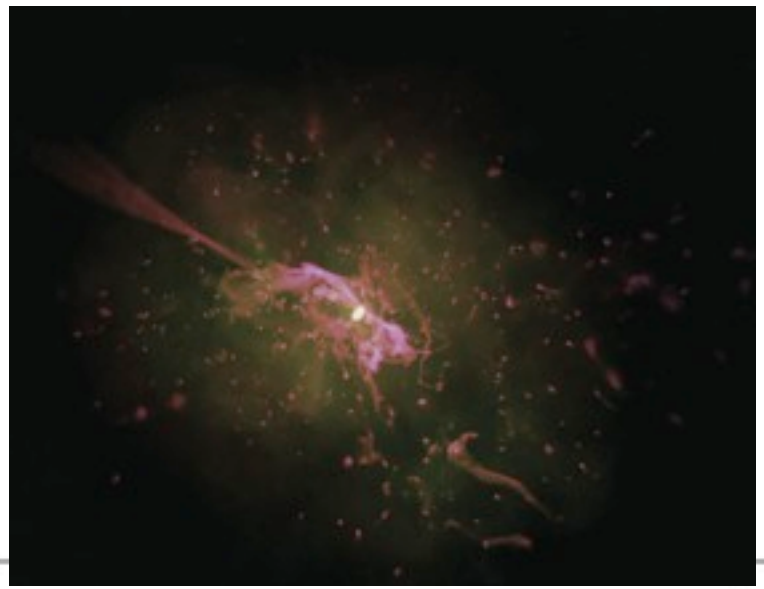
- Feedback determines the decay of the quasar light curve:

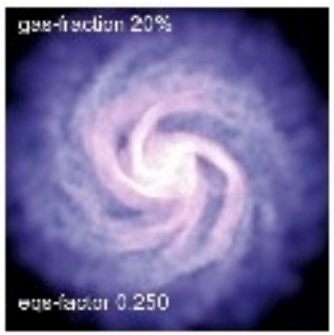


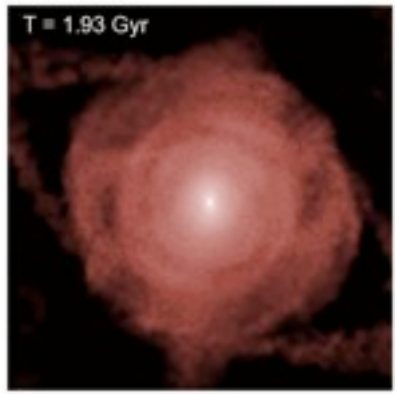
- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)
- Generic, if feedback is:
  - Point-like
  - Rapid
  - E ~ $E_{binding}$

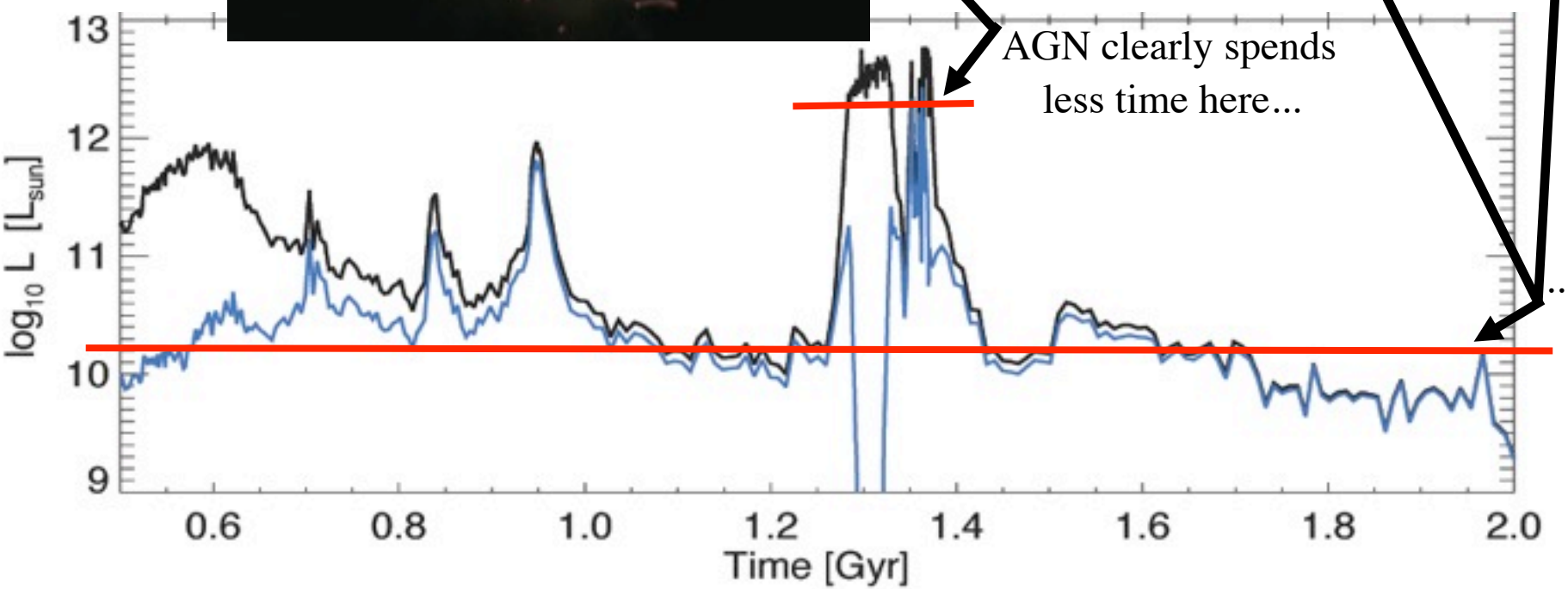
PFH et al. 2006a

So What Is the "Quasar Lifetime"?







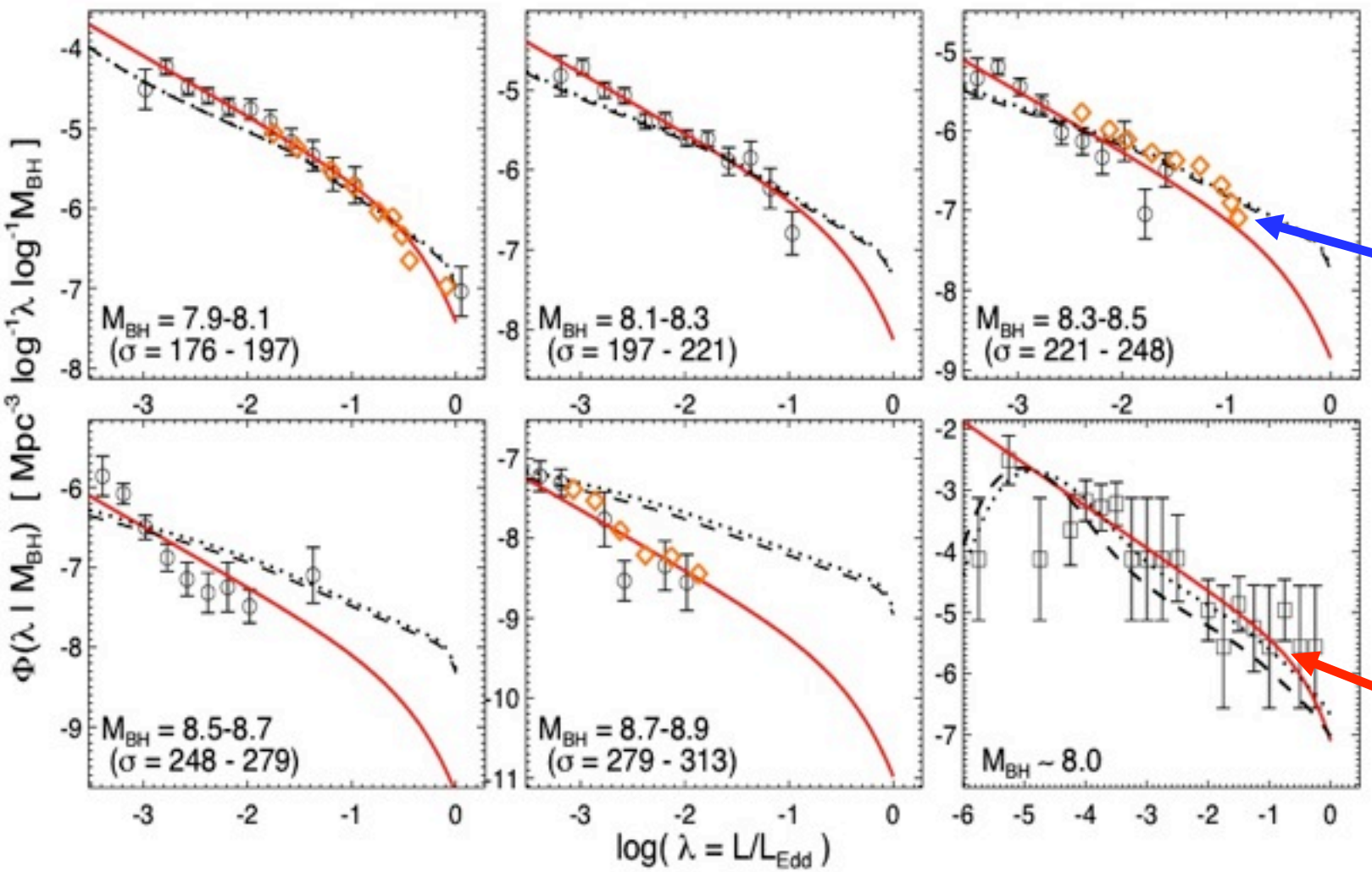


AGN clearly spends less time here...

... than here

- "Quasar Lifetime": a conditional, *luminosity-dependent* distribution

Can *See* This Behavior in Observed Eddington Ratio Distributions



Observed
(Kauffmann et al.,
Merloni et al.,
Li et al.)

Predicted
(Feedback model)

Observed L/L_{Edd} Distribution:

$$\frac{dt}{d\log L} = t_0 \left(\frac{L}{L_{peak}}\right)^{-\beta} \exp(-L/L_{peak})$$

Implies *Bright*-L Decay:

$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

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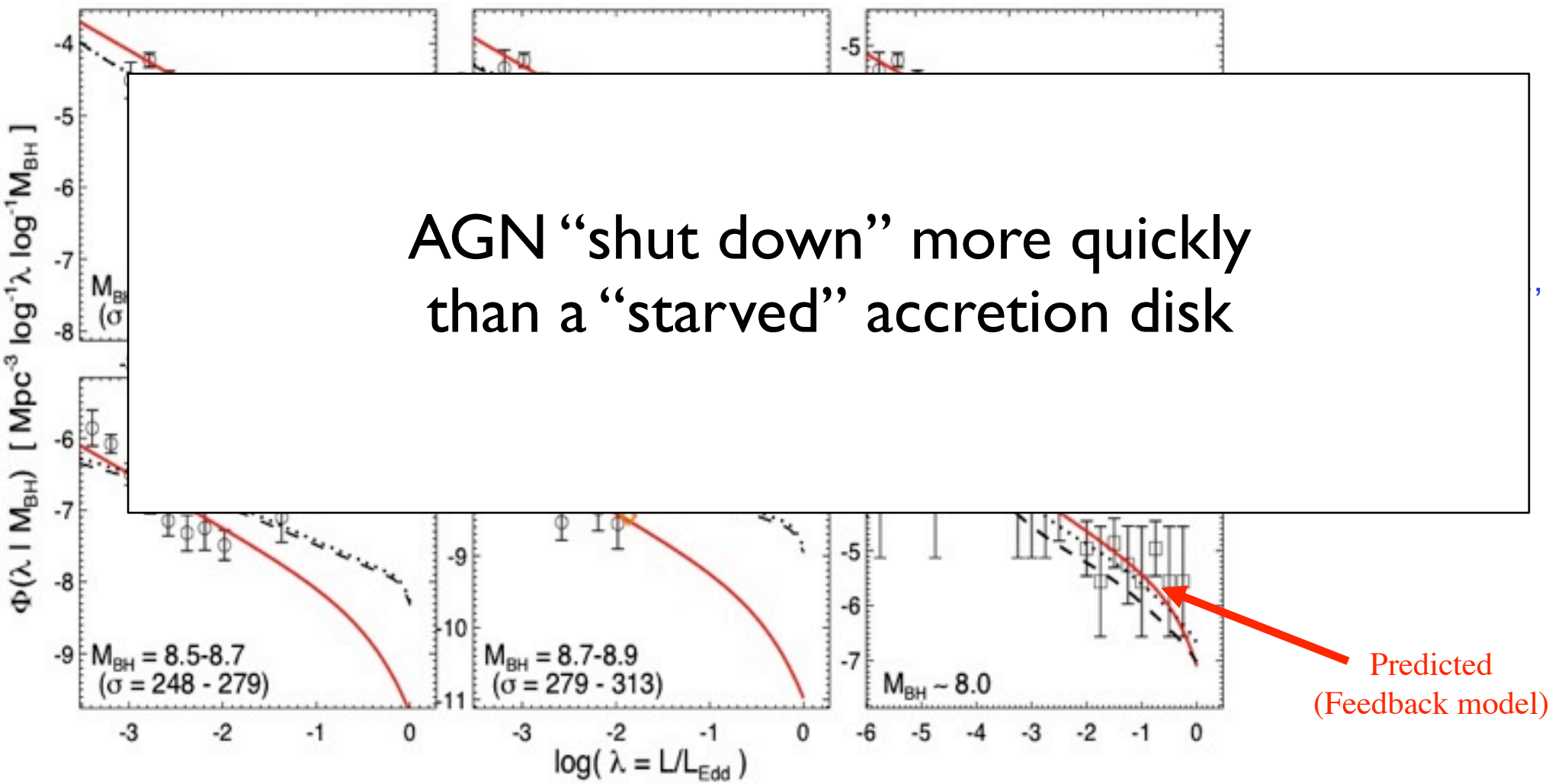

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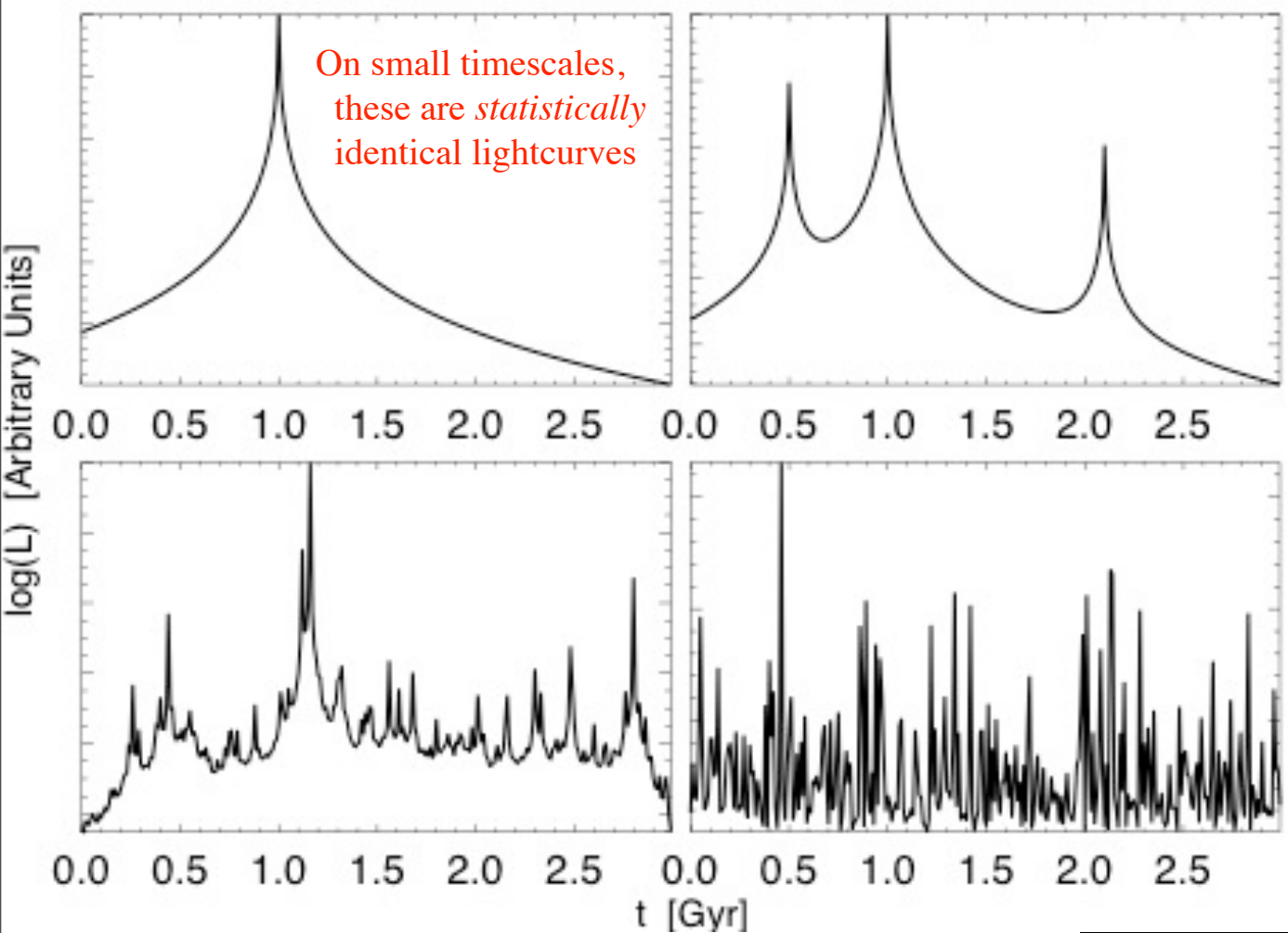
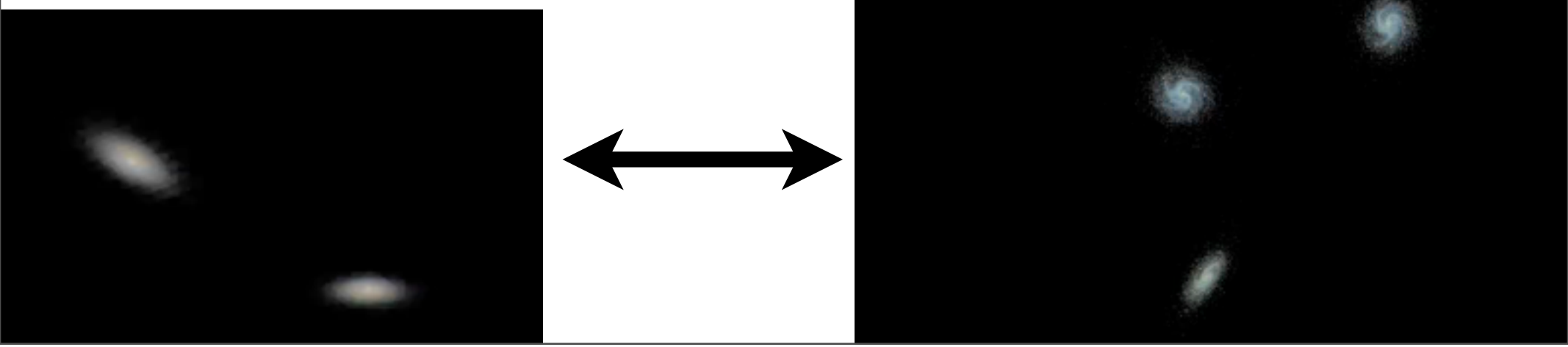
AGN Light-Curves are Self-Regulating in each "Event"



May be multiple "events," but AGN decay/regulation is self-similar!

- *BH*, not galaxy, determines lightcurve evolution



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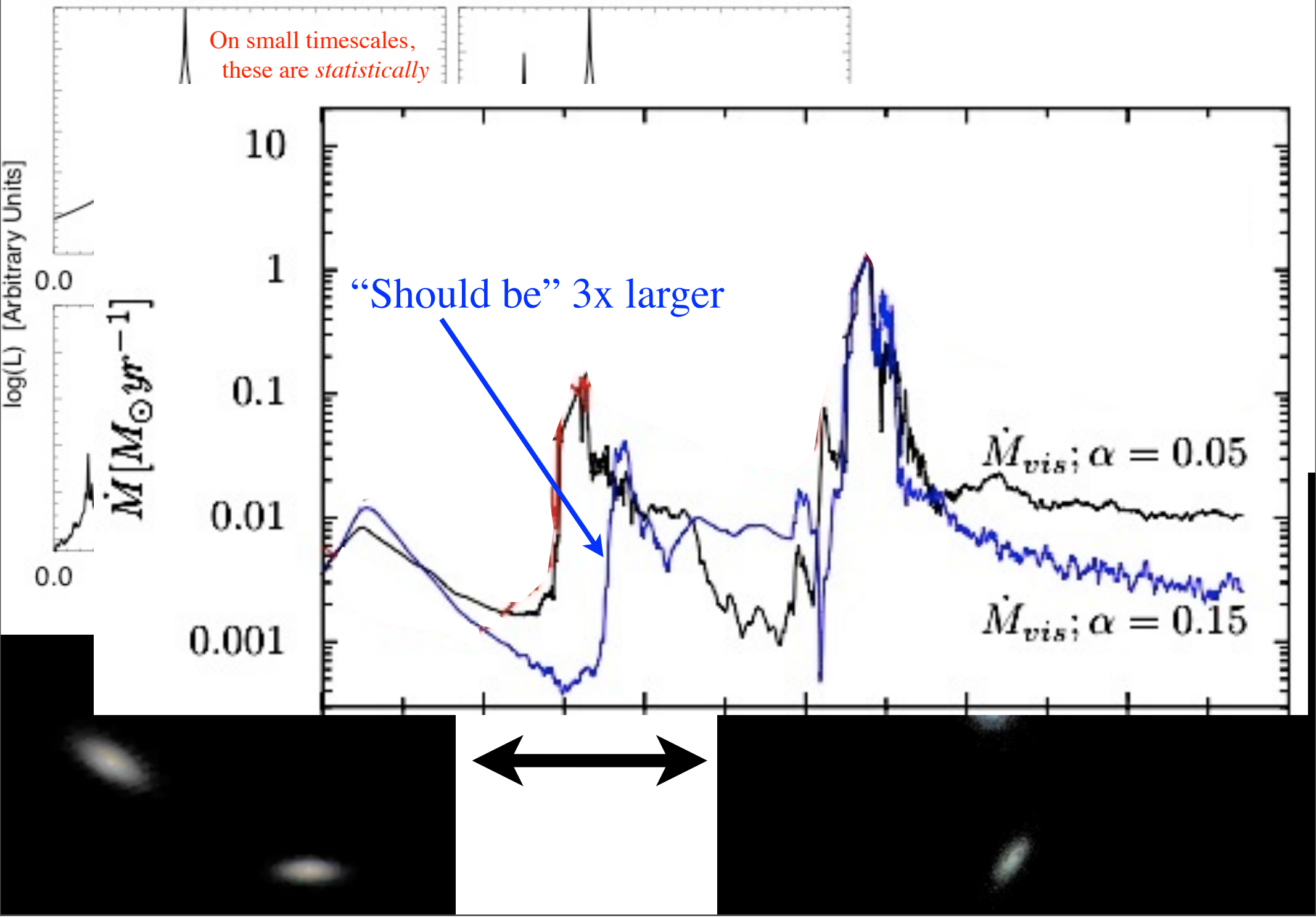
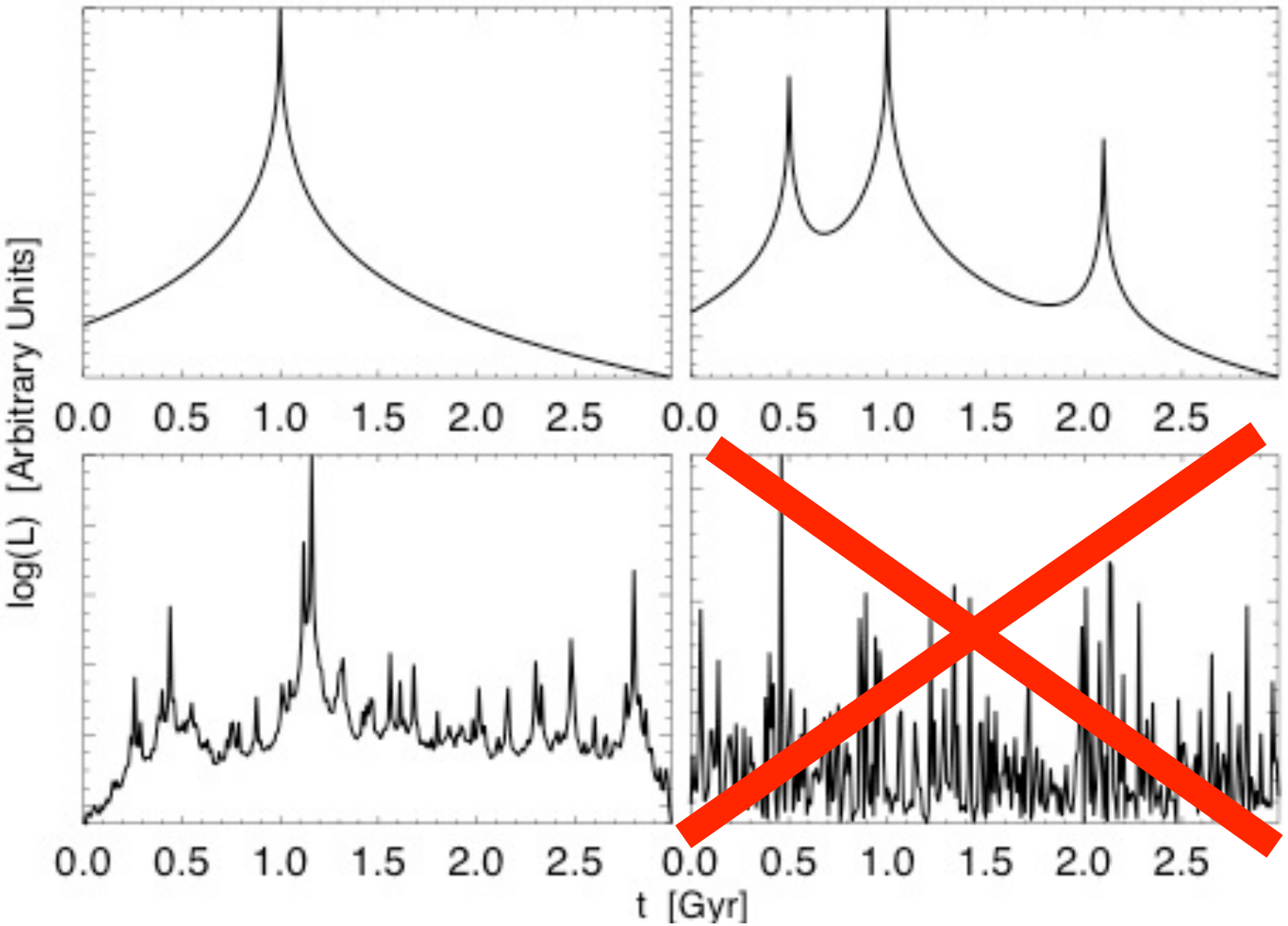


Combine with Other Constraints to Determine *Global* Evolution



Ruled out by transverse proximity effect

$t_{episodic} \sim t_{total}$

- Complimentary constraints from clustering (Meyers, Croom, Porciani, da Angela)

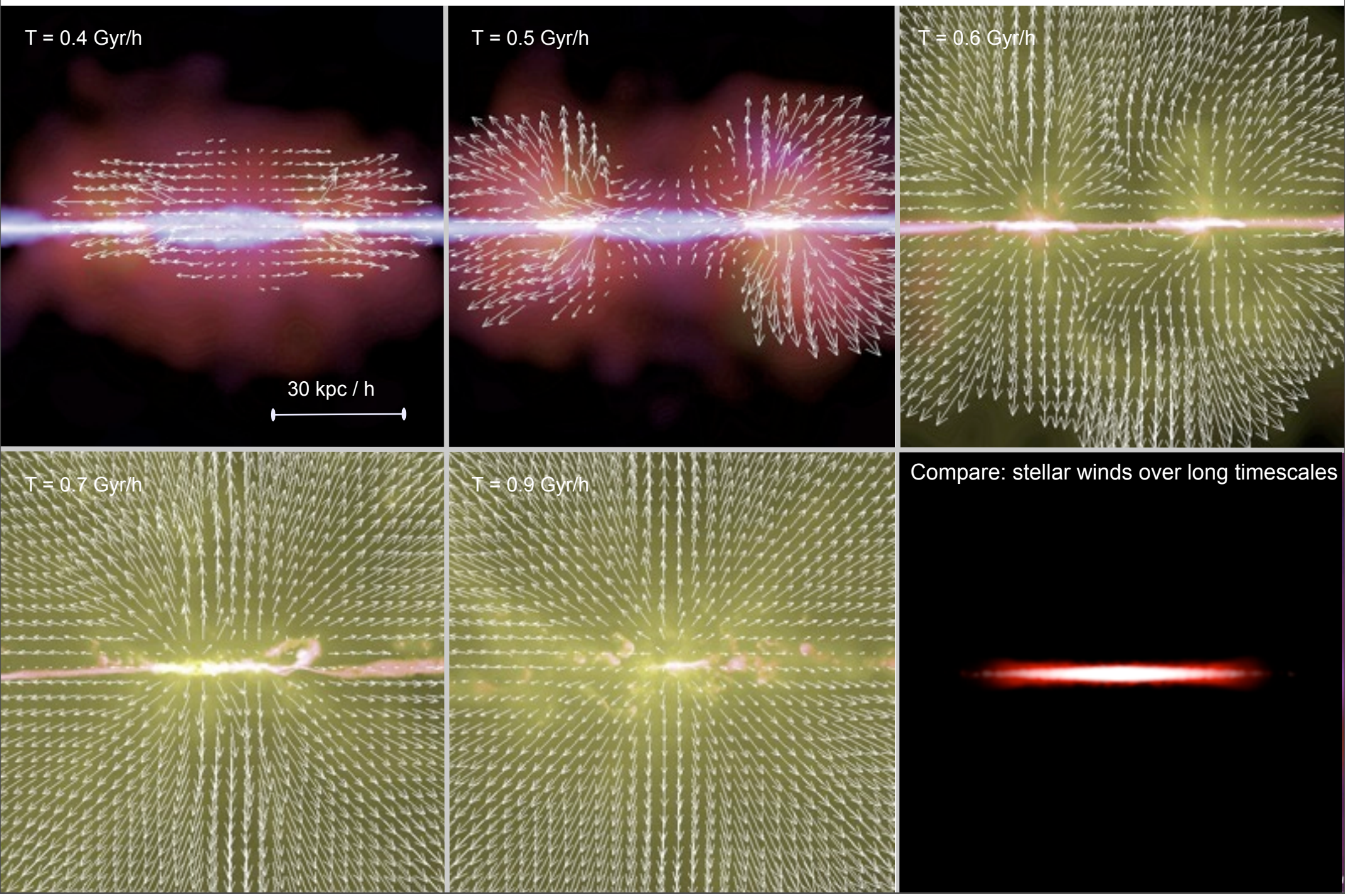
BHs gained their mass in just a couple of "major" events

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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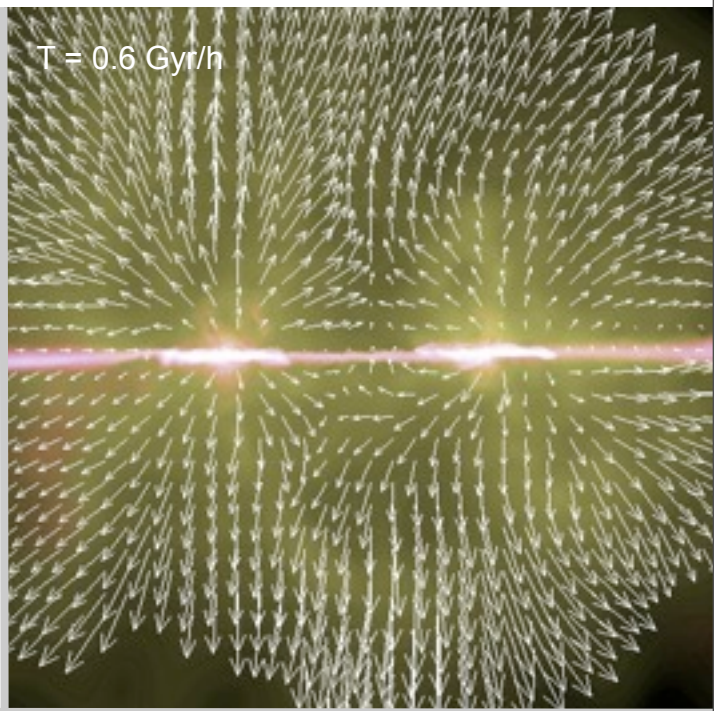

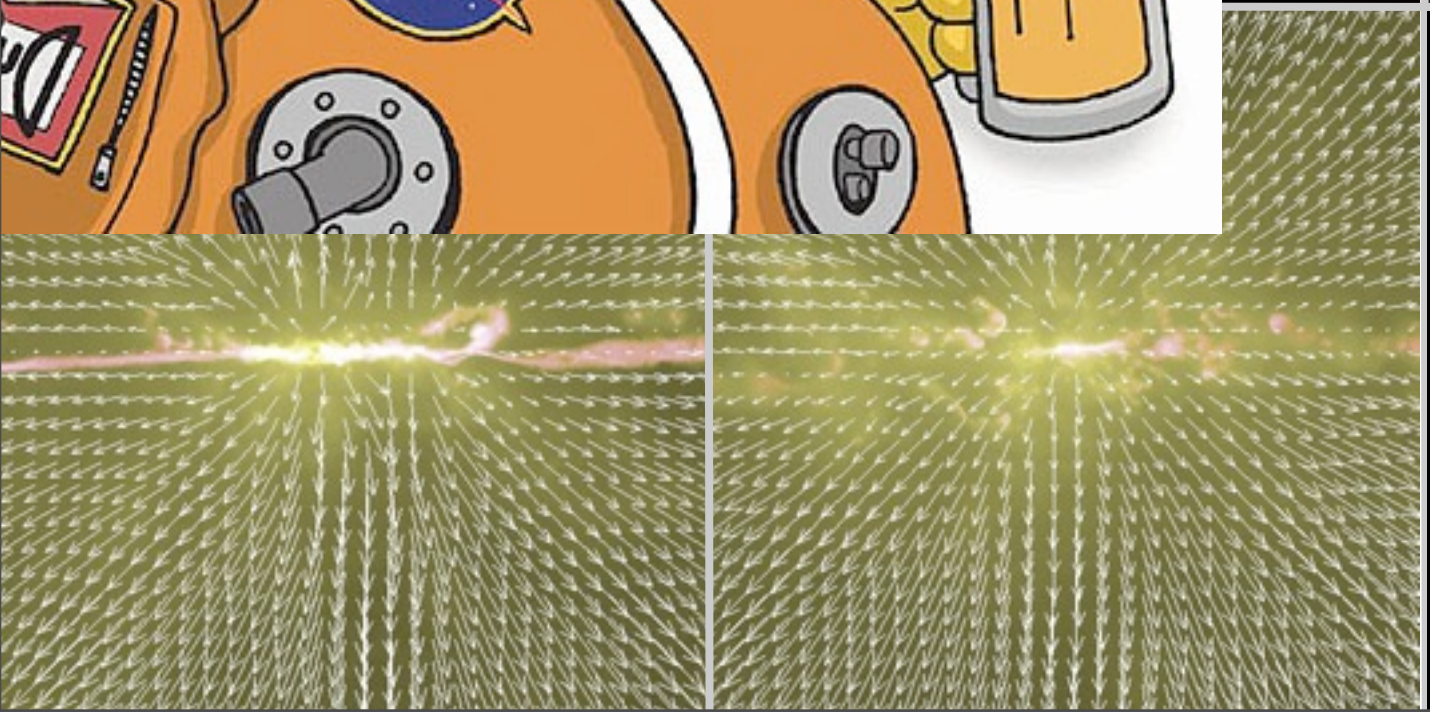

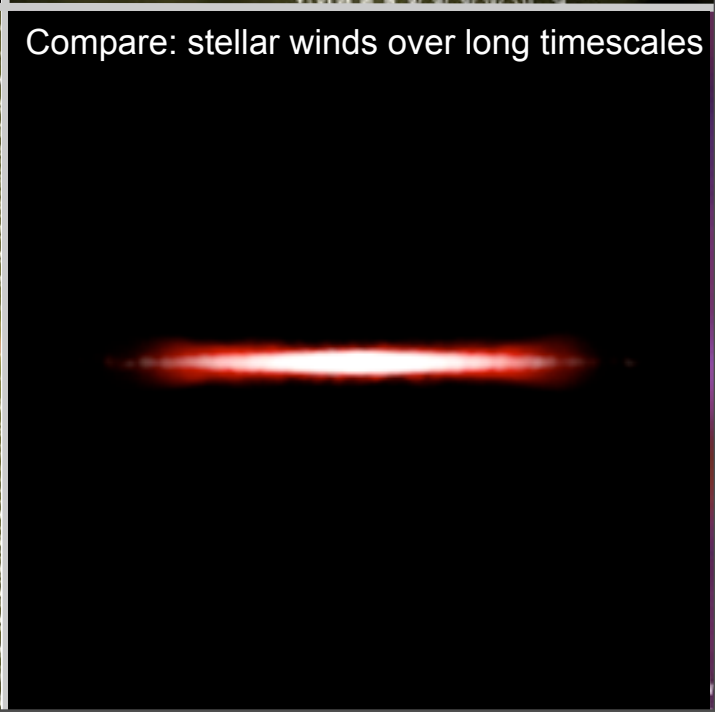

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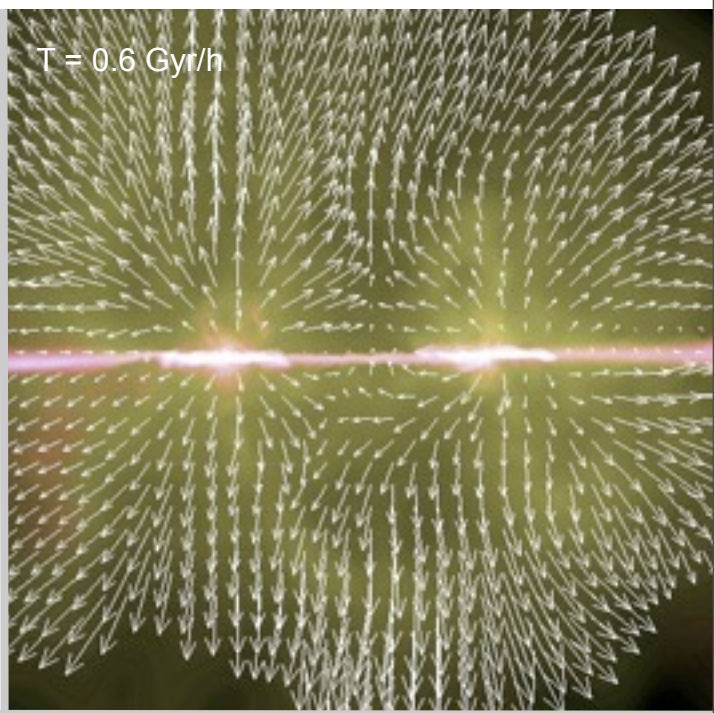

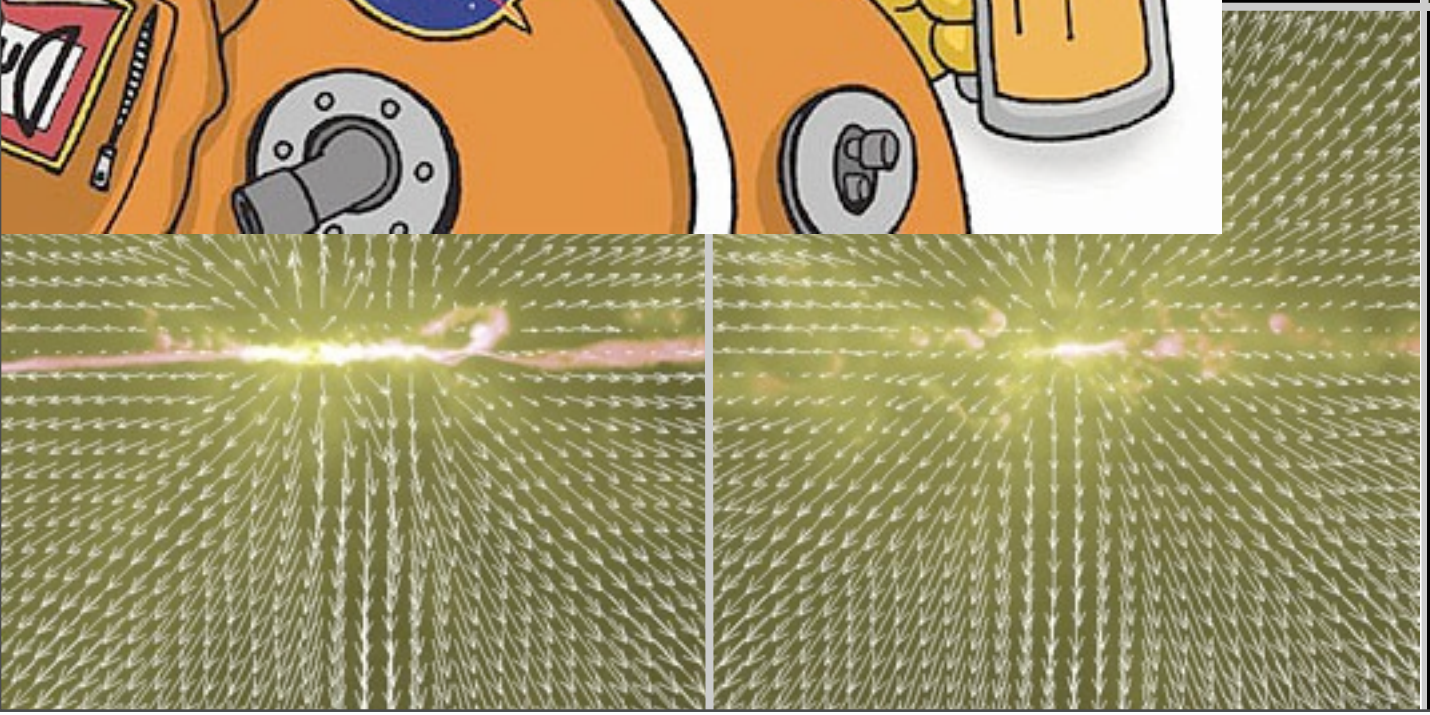

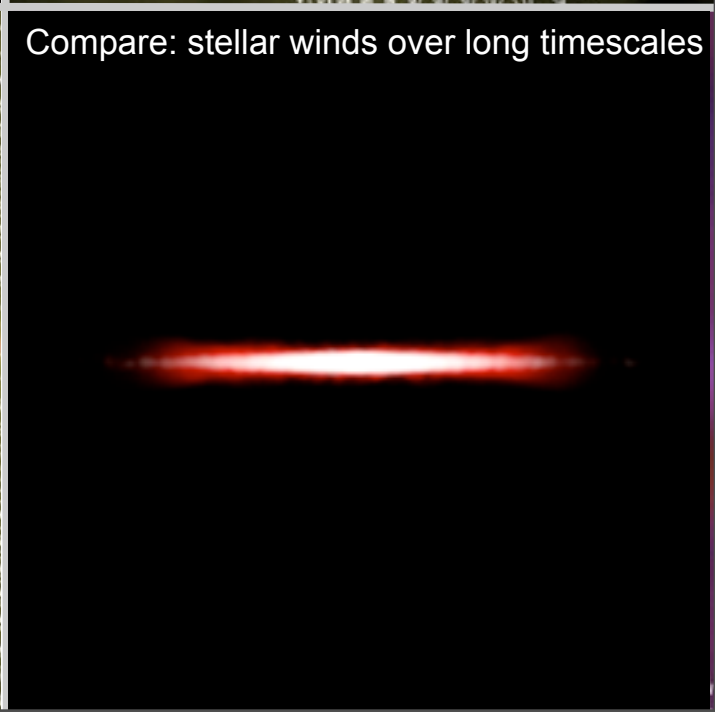

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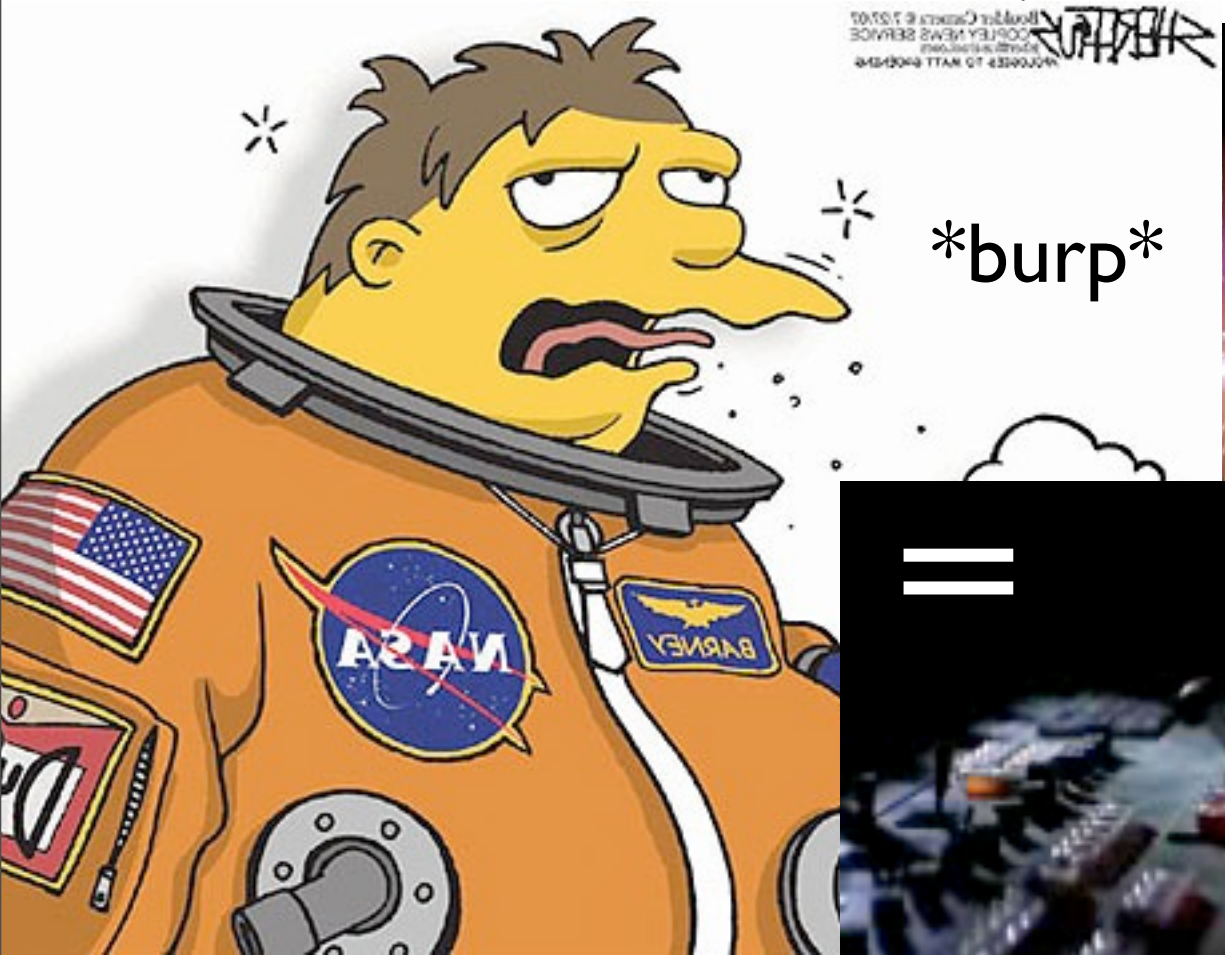
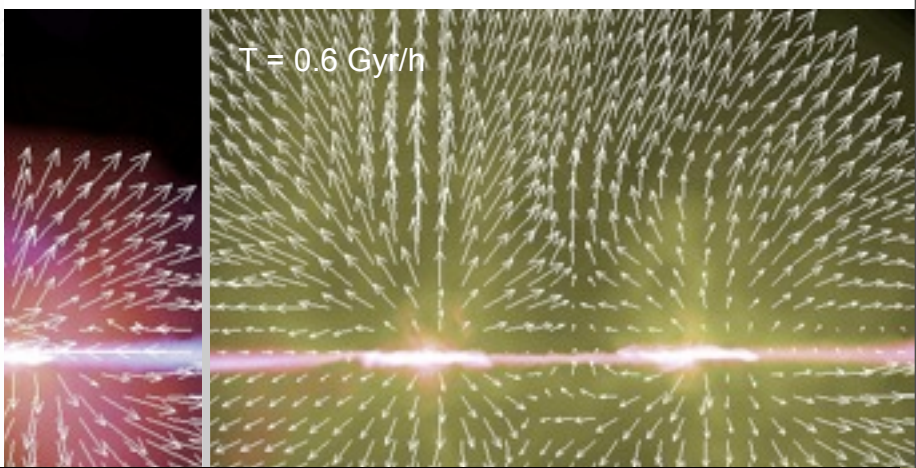


burp



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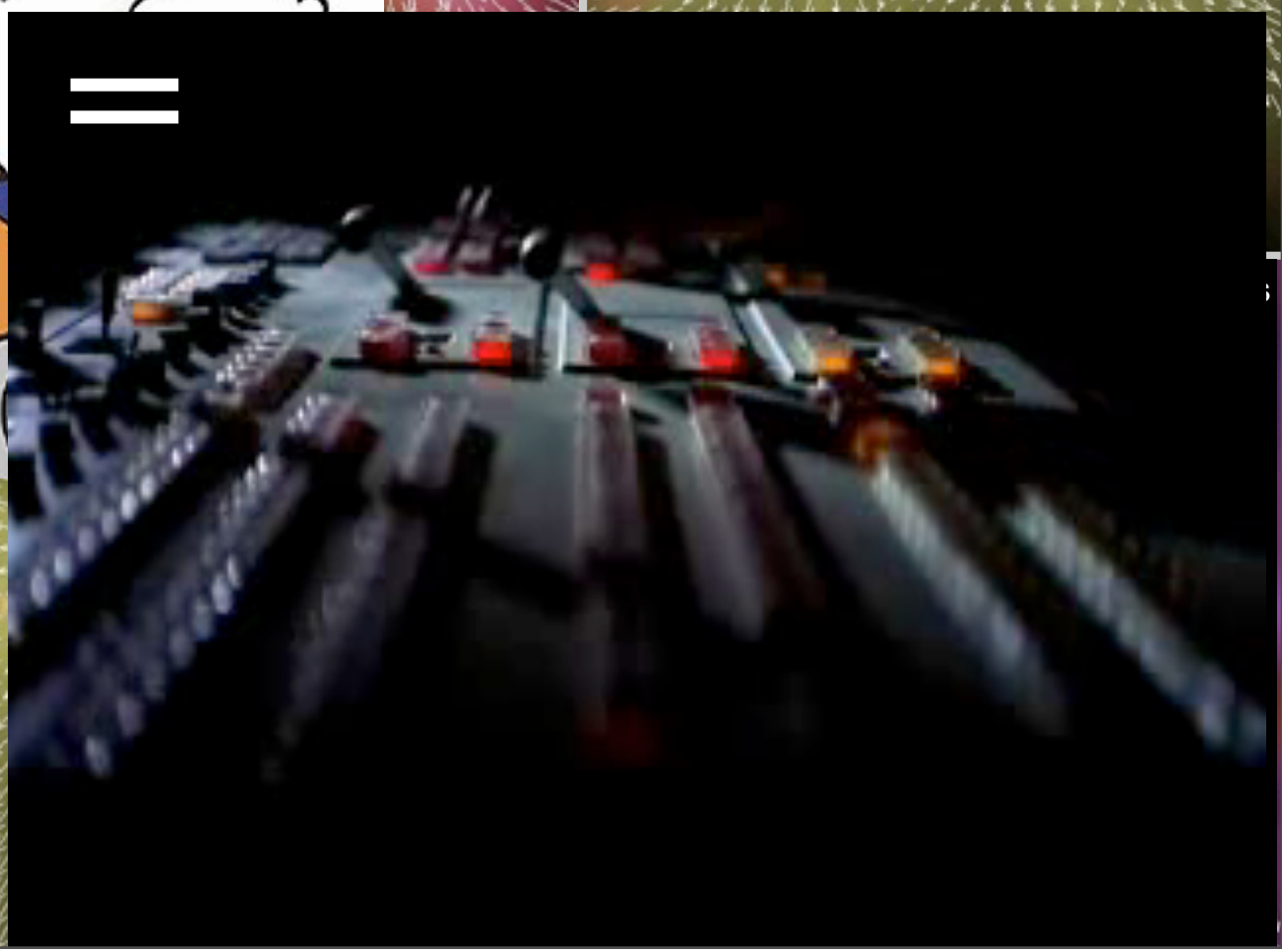
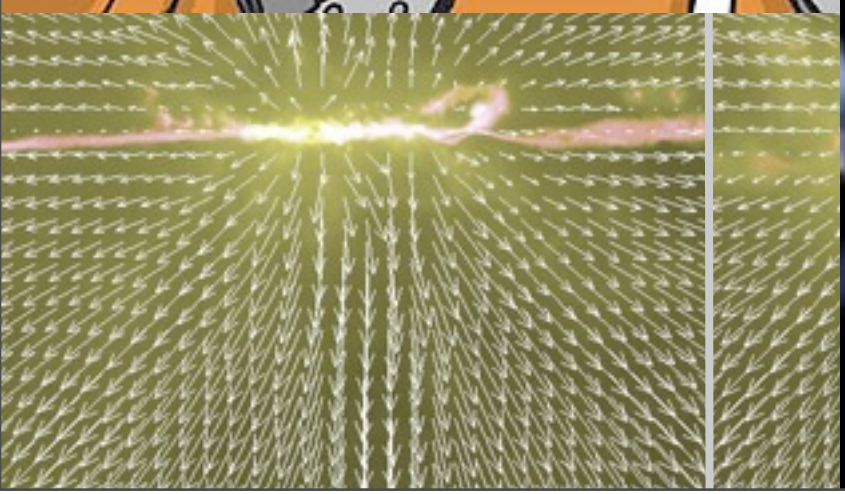
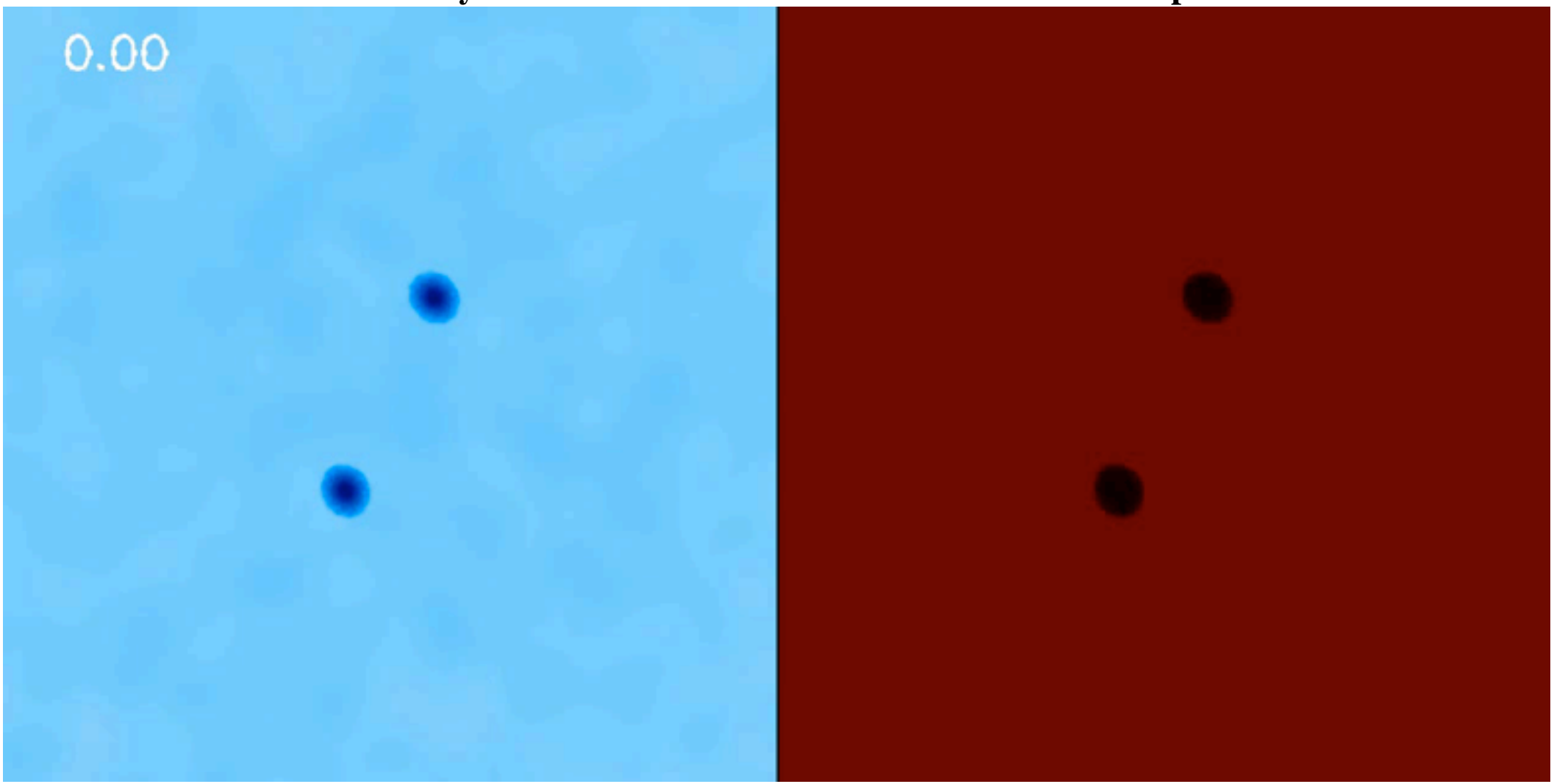




Quasar Outflows May Be Significant for the ICM & IGM

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

Gas Density **Gas Temperature**



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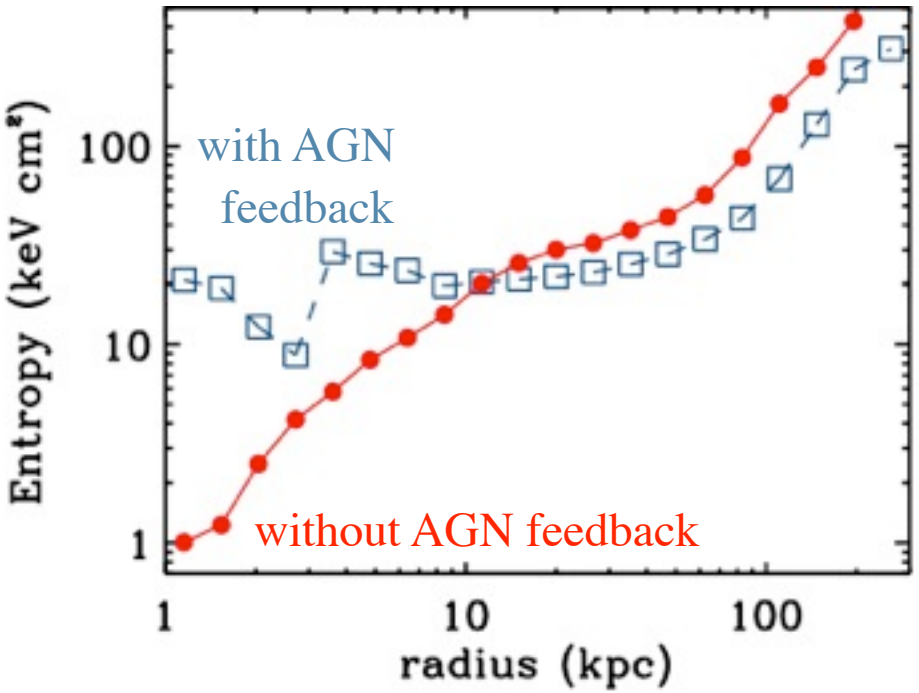
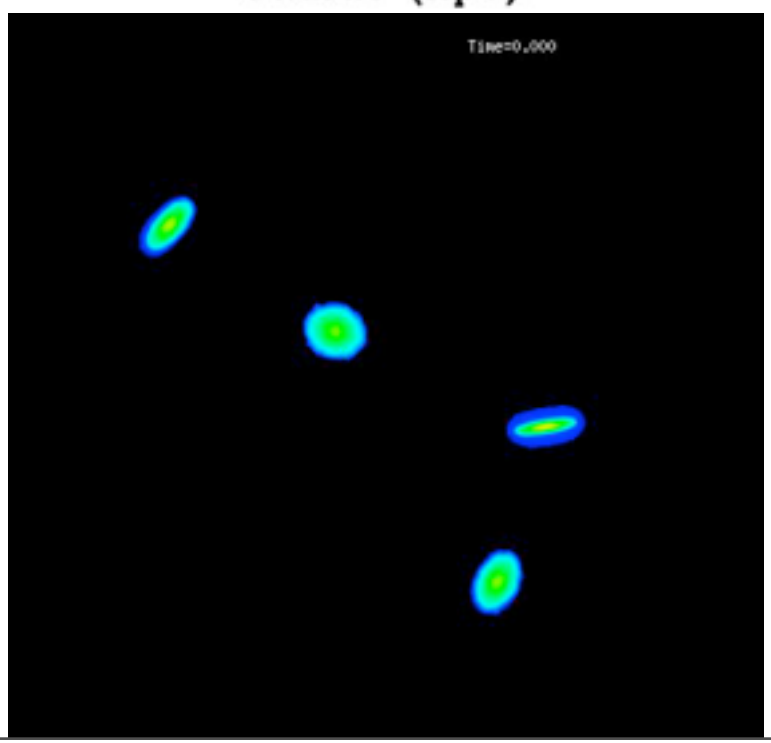
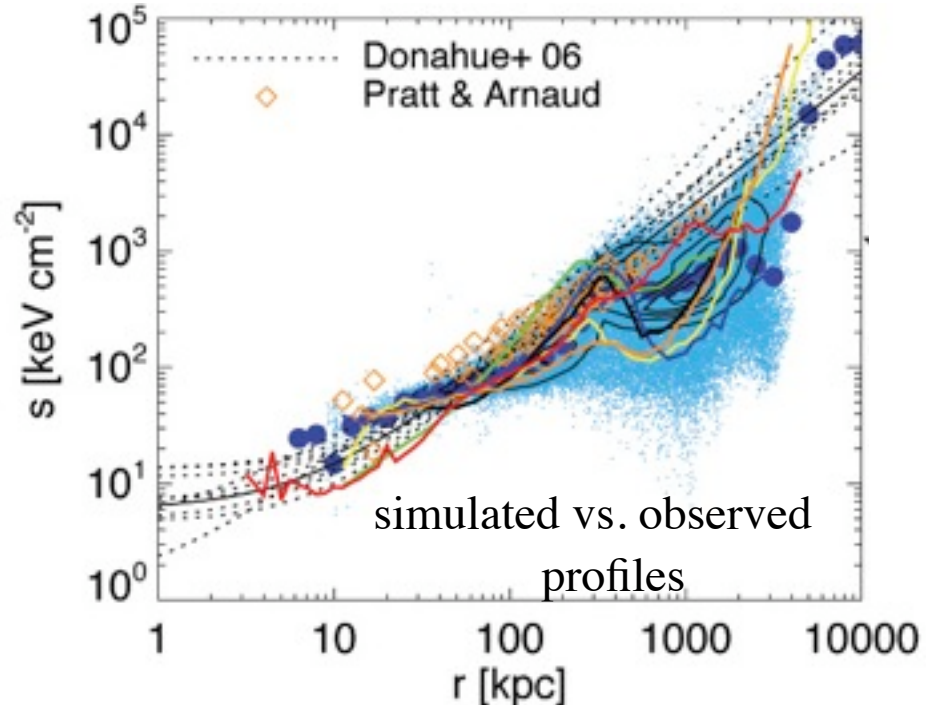
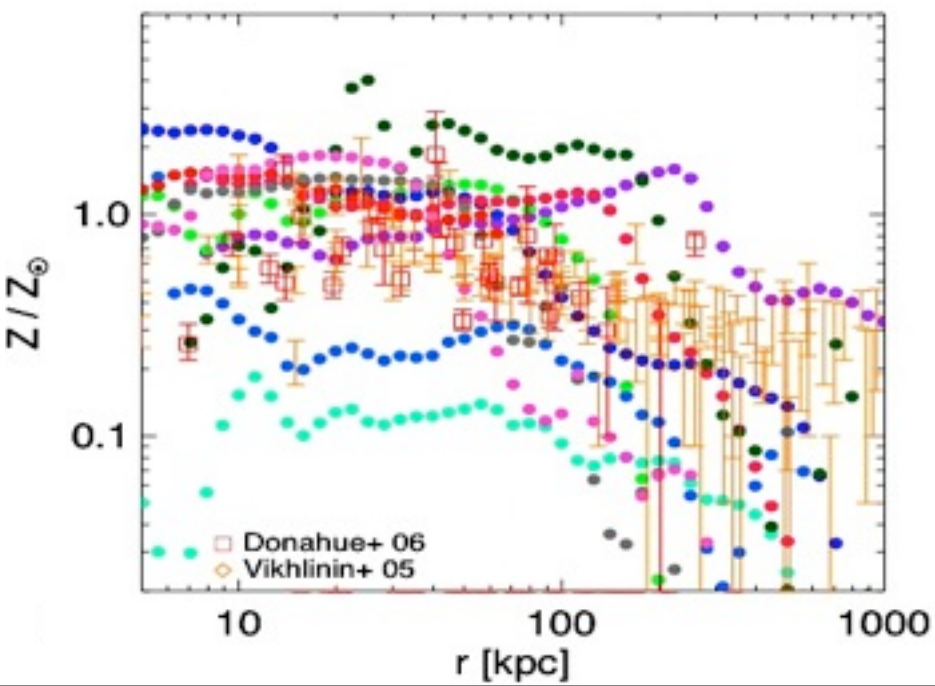


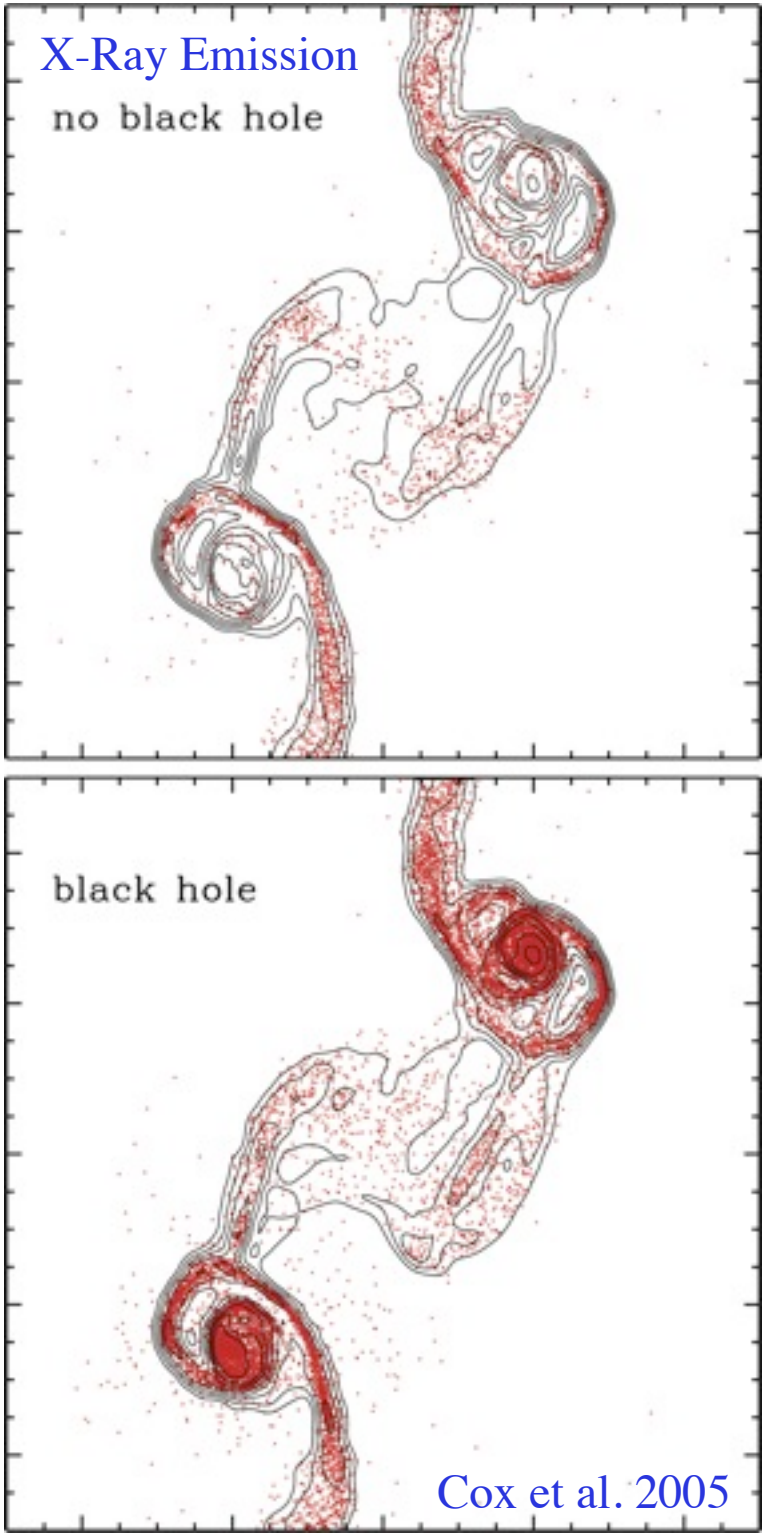






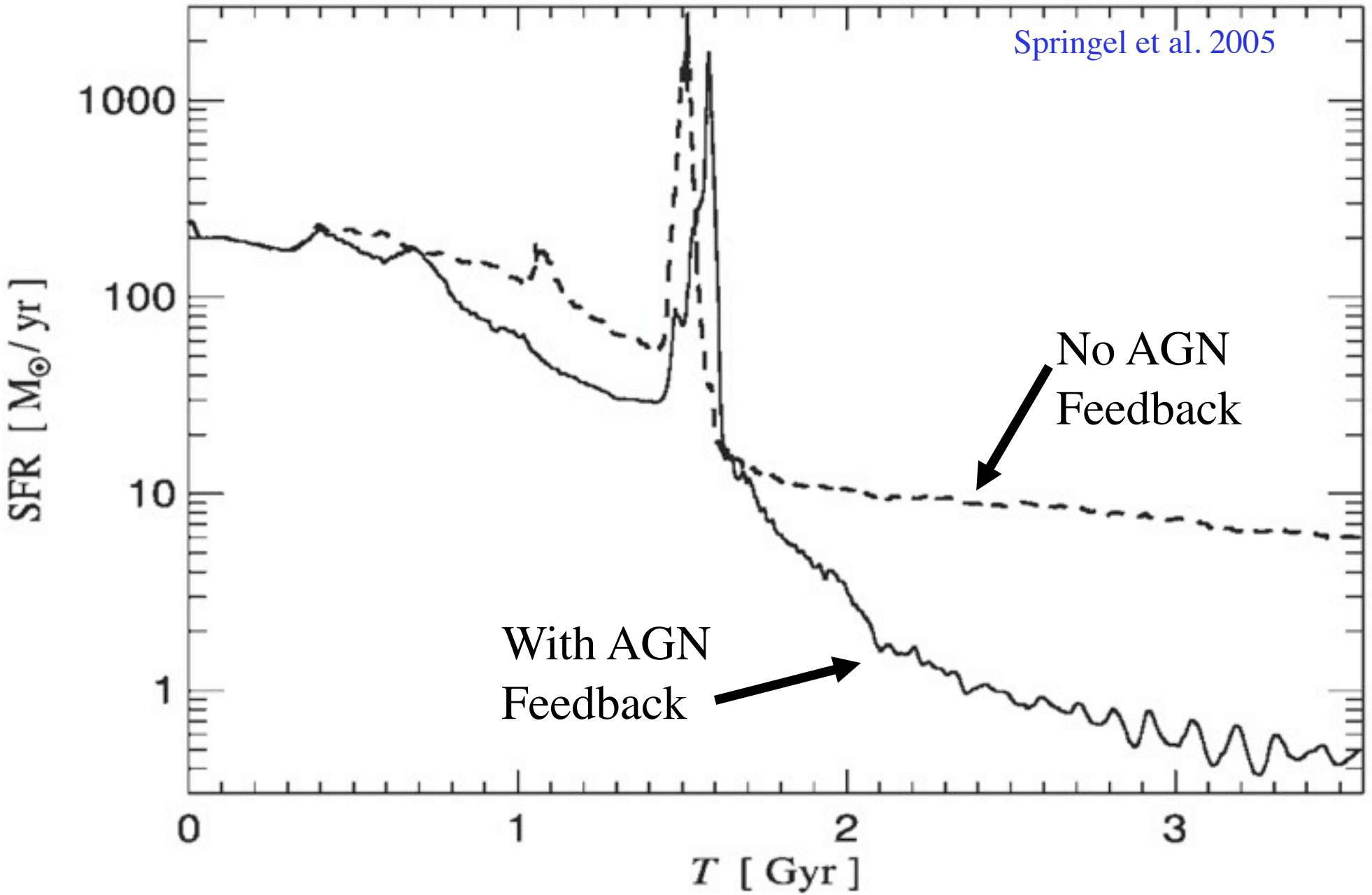
Feedback-Driven Winds

METAL ENRICHMENT & BUILDING THE X-RAY HALO



Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?

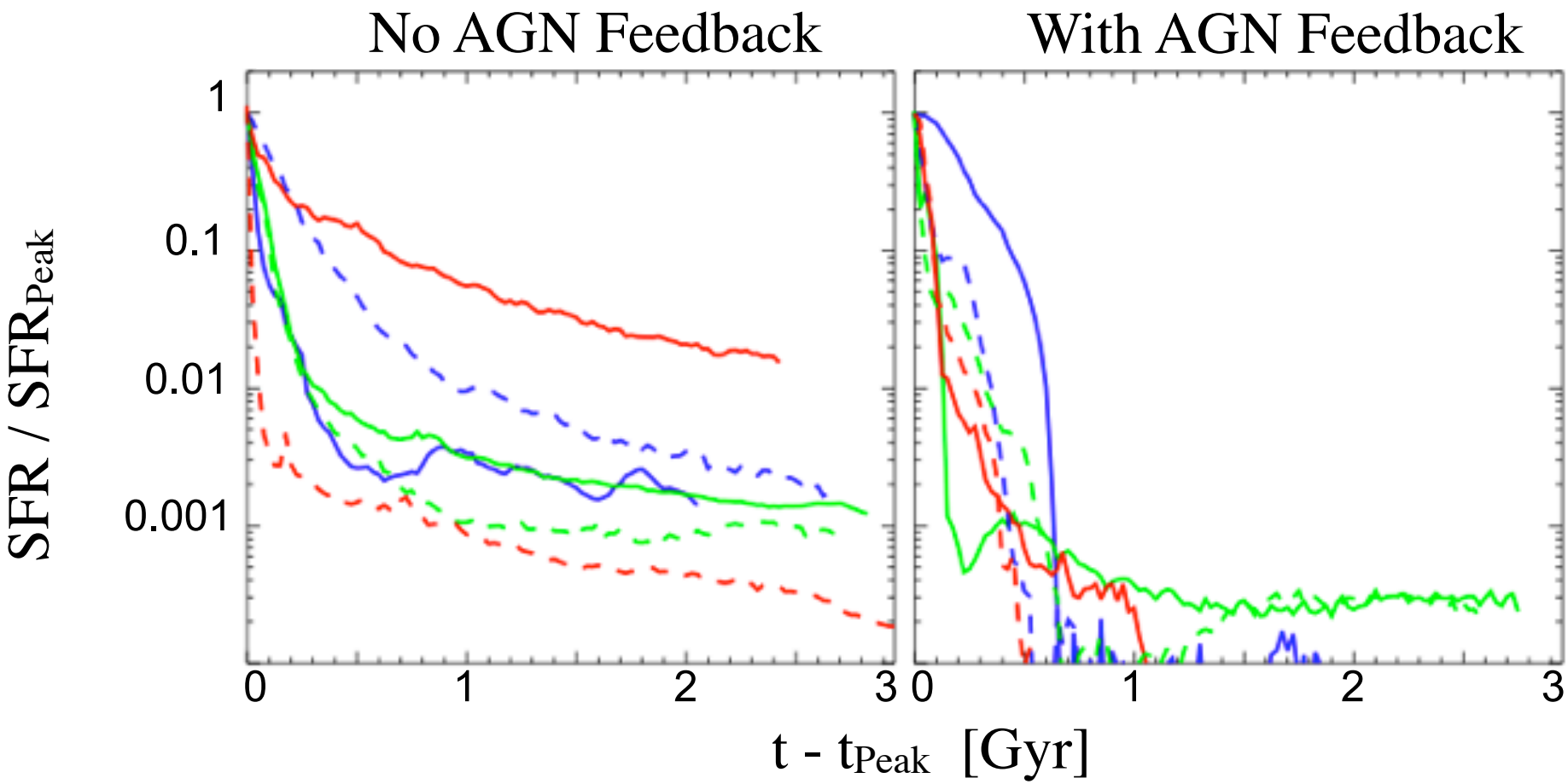


Expulsion of Gas Turns off Star Formation

PFH, Keres et al. 2008

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?

... but ...

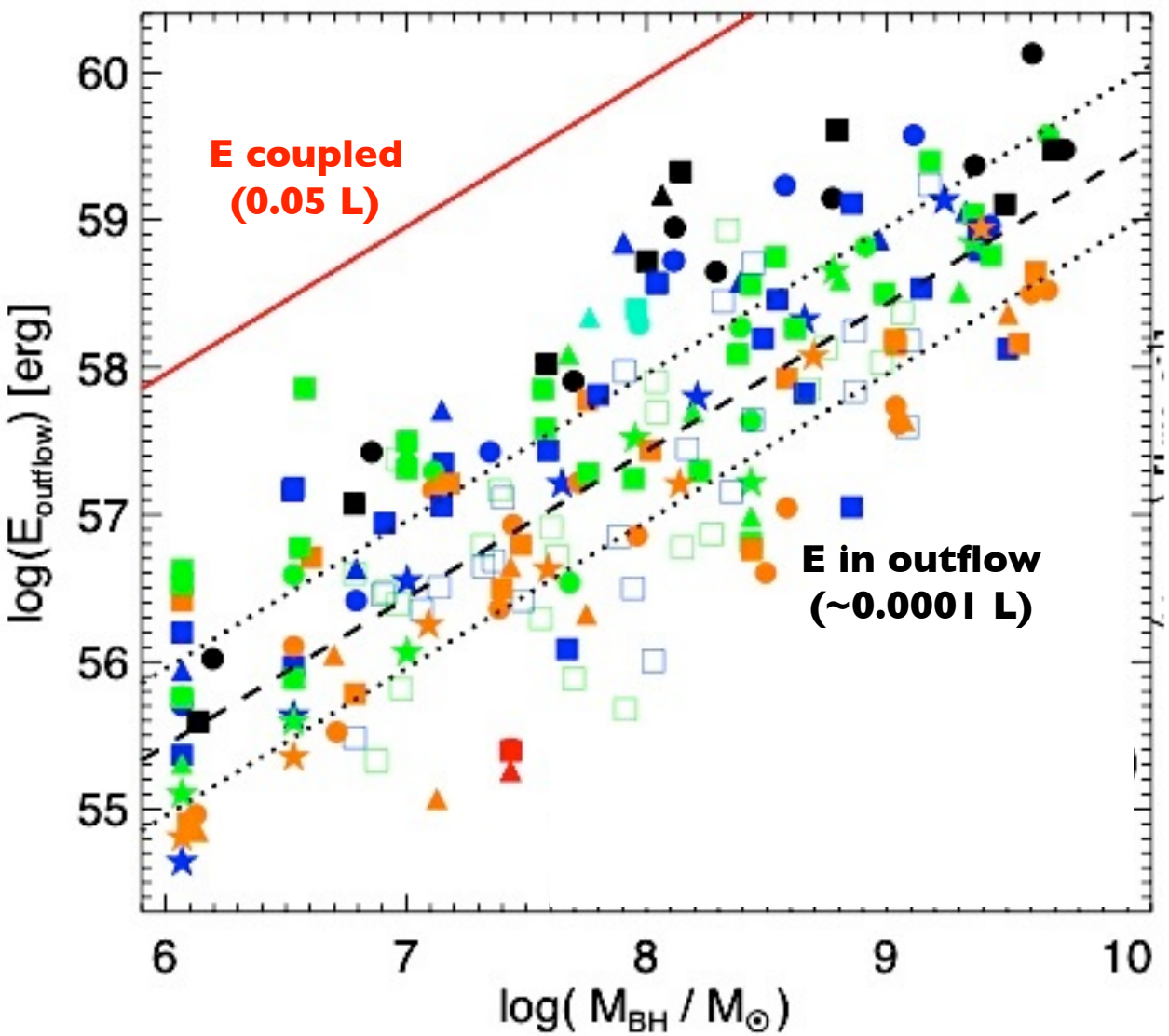


... MOST of the work is still done by star formation/stellar feedback

- but over a longer period of time -

CAUTION: Energy-Driven Outflows are *NOT* Energy-Conserving

MOMENTUM IS WHAT MATTERS ON LARGE SCALES!



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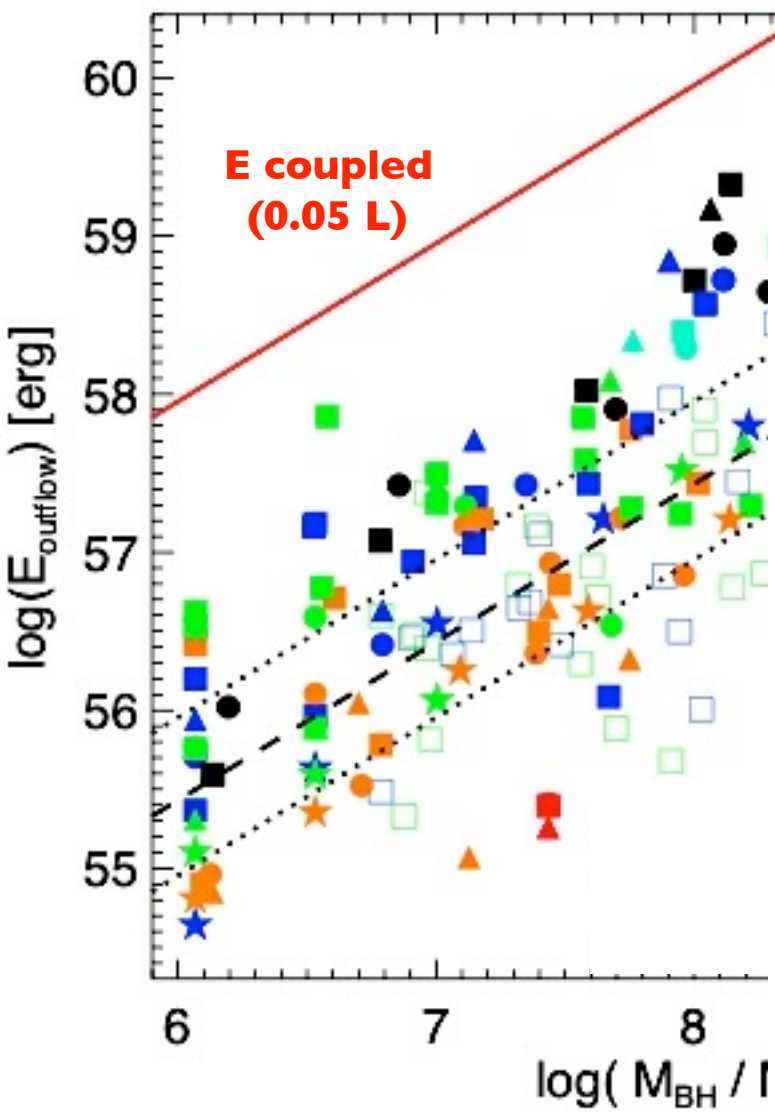
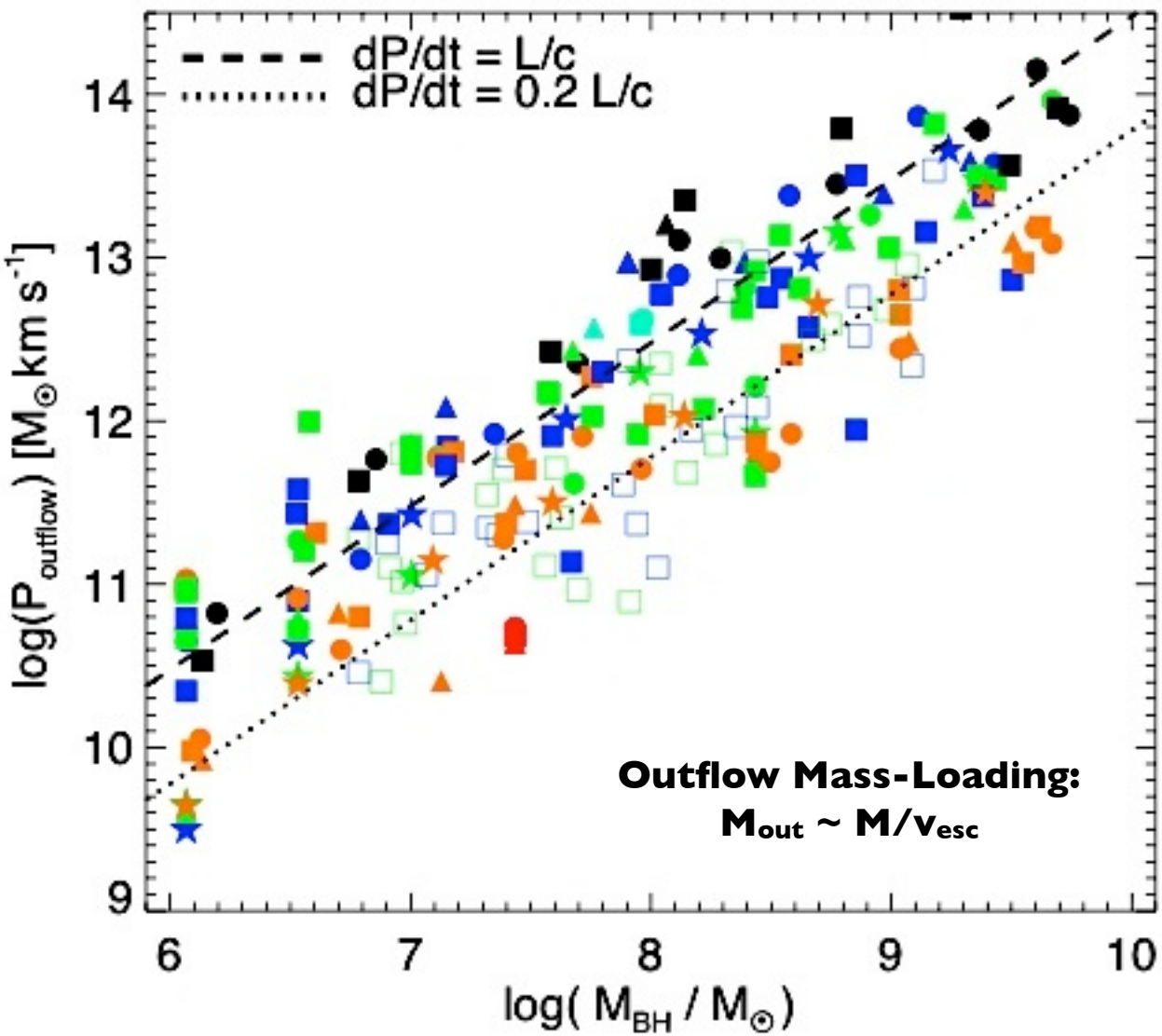




Why Not Just Couple the Momentum Directly?

EXPERIMENTS WITH RADIATION PRESSURE

- Problem: Cooling times at densities near BH ~ 0
- BUT, photons have an irreducible momentum

Dust in host absorbs radiation

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

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

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

Why Not Just Couple the Momentum Directly?

EXPERIMENTS WITH RADIATION PRESSURE

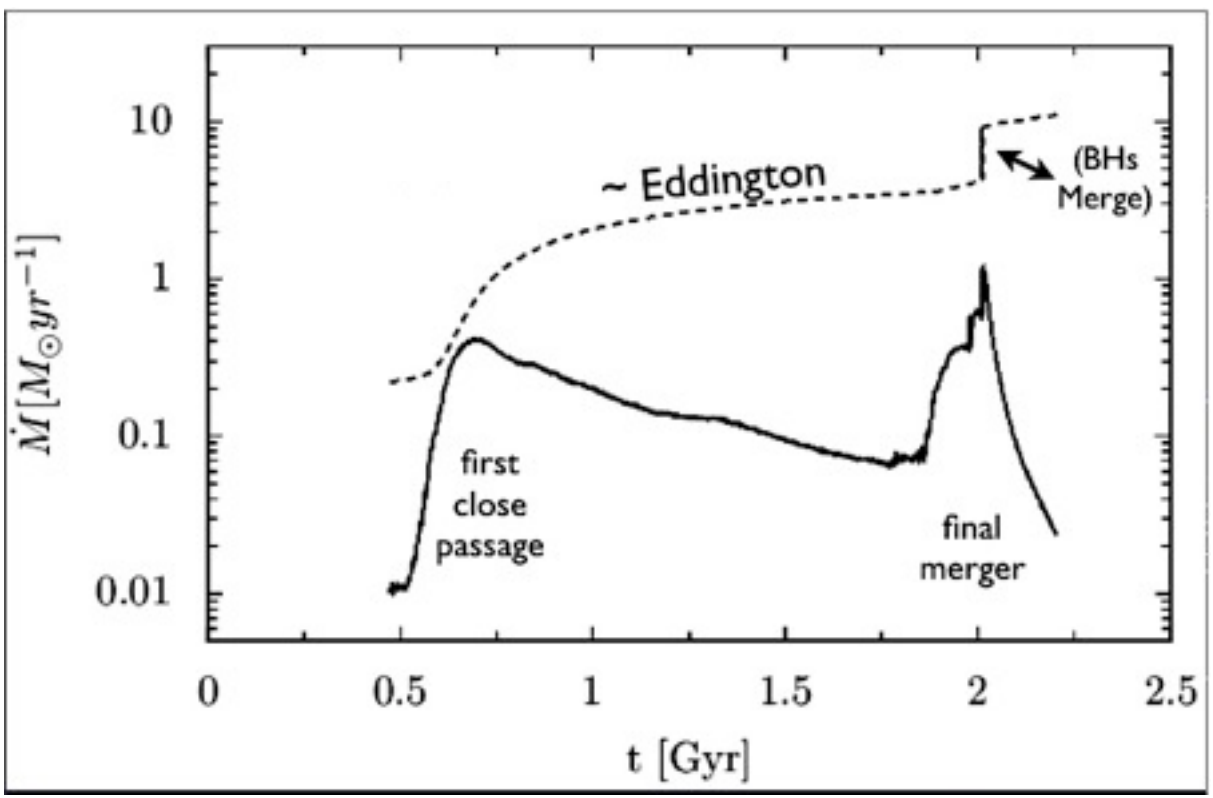
- New simulations in DeBuhr et al. 2009: add feedback force from radiation:

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

$\tau \sim 10$

Radial momentum flux

Couple to nearest ~500-2000 particles

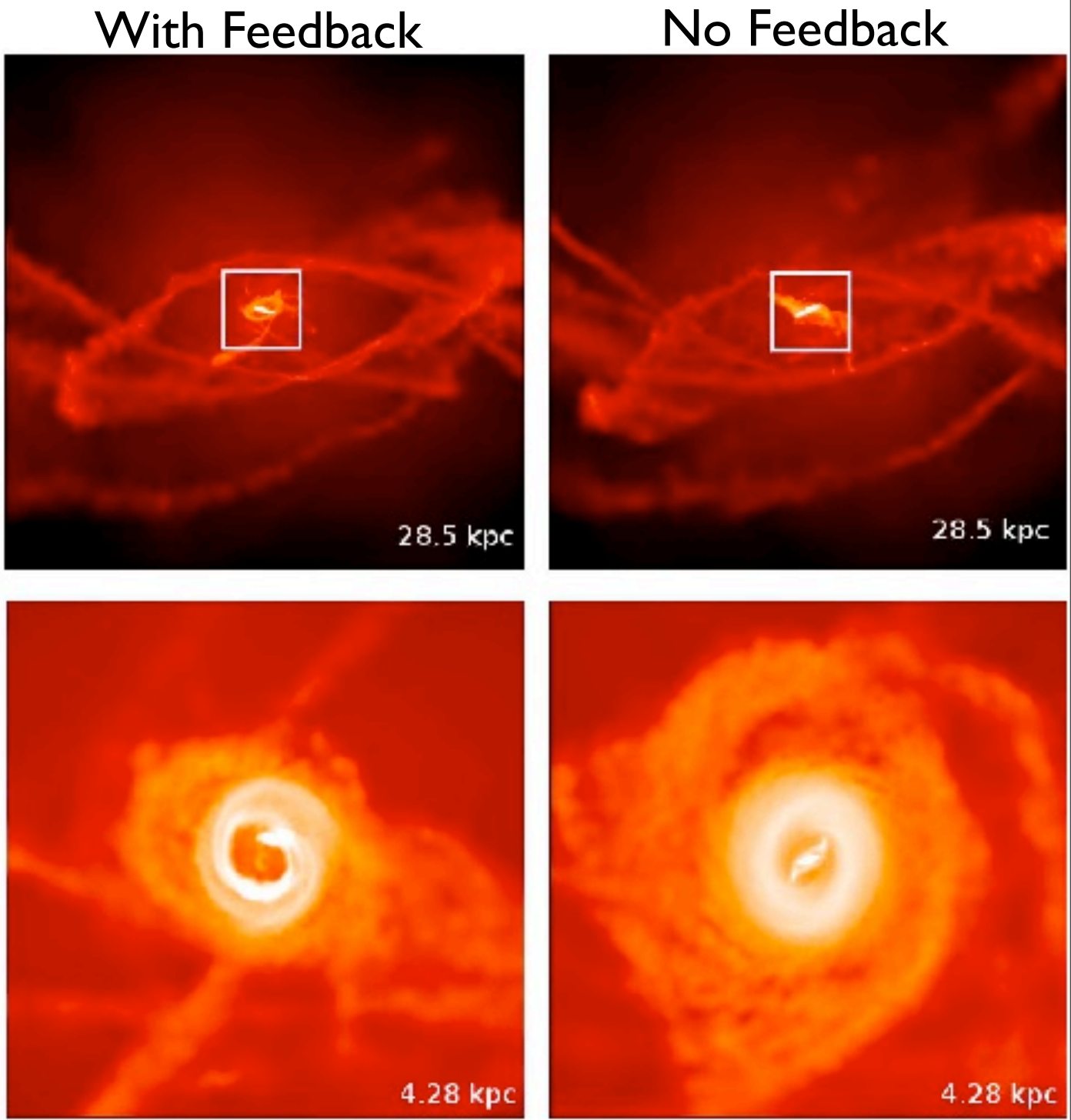


- Get self-regulated BH growth!

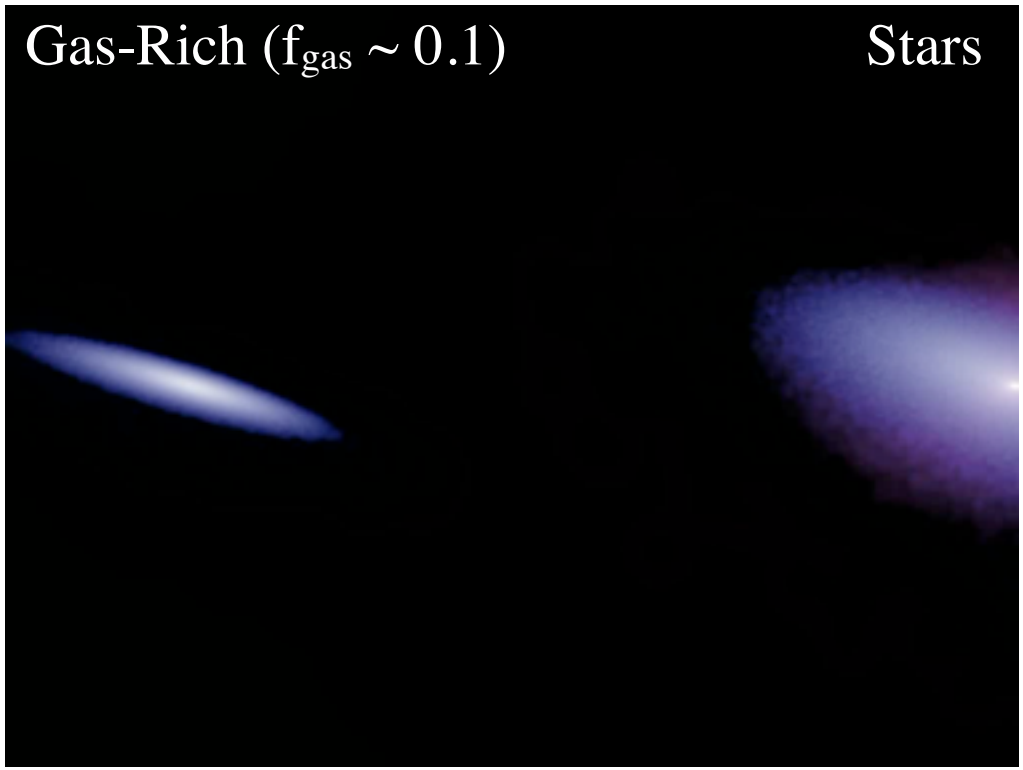
But.....

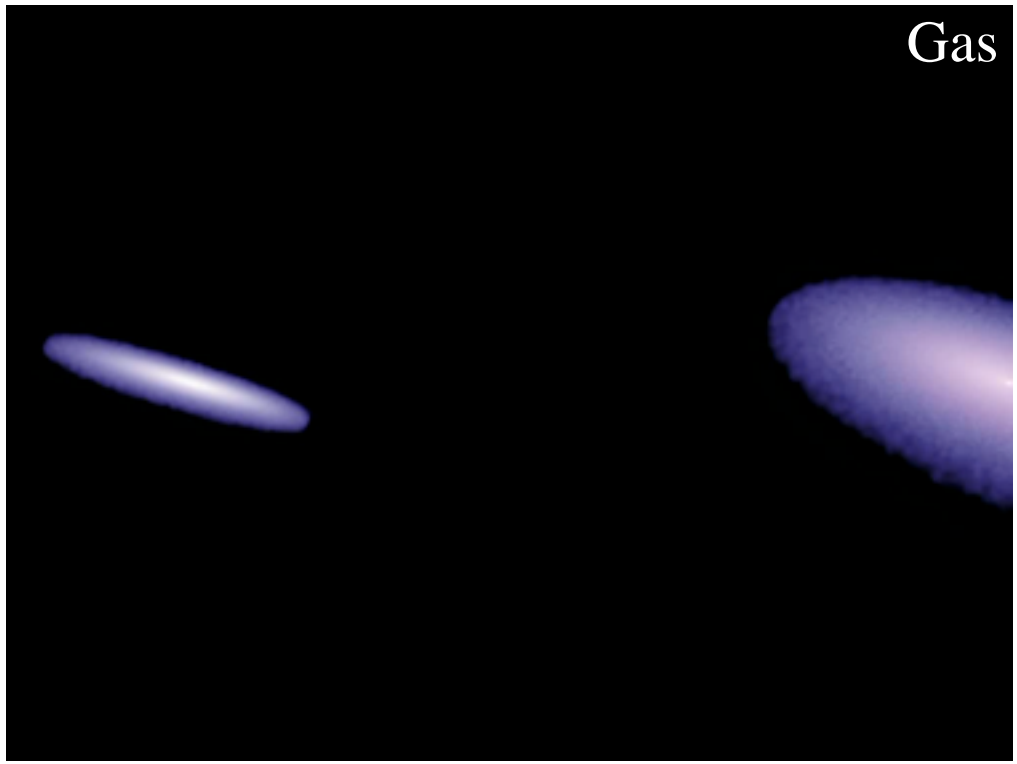
- BH growth self-regulates on ~kpc scales, but with no galaxy scale "blowout"!

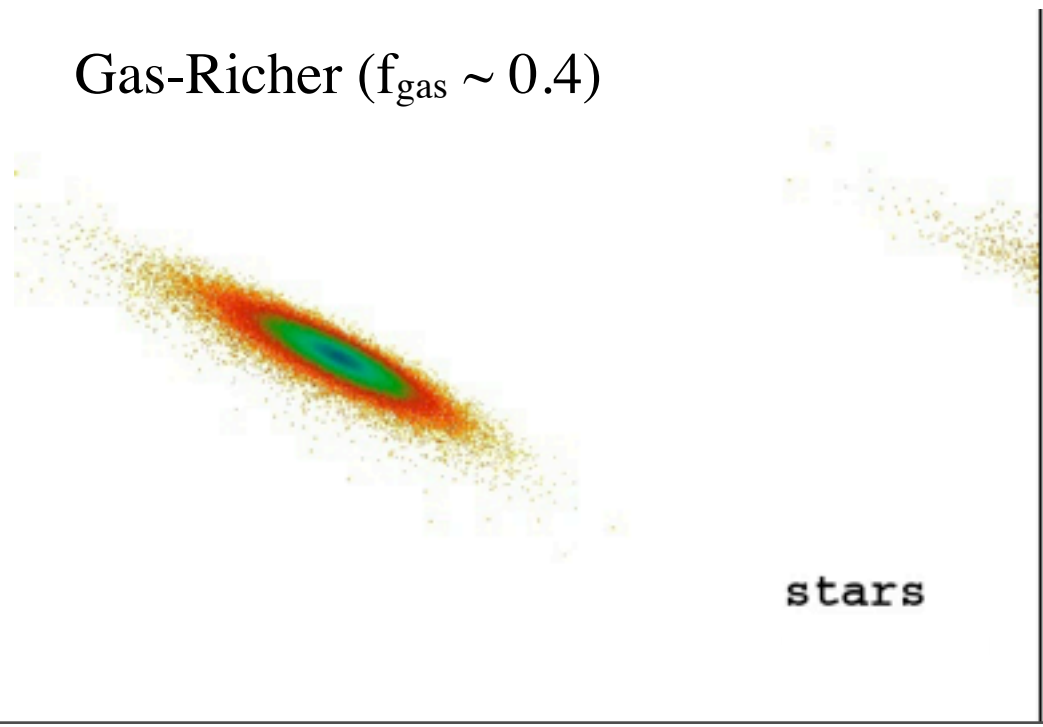
- Depending on FB & accretion rate couplings, can simply "hold up" the gas at intermediate scales

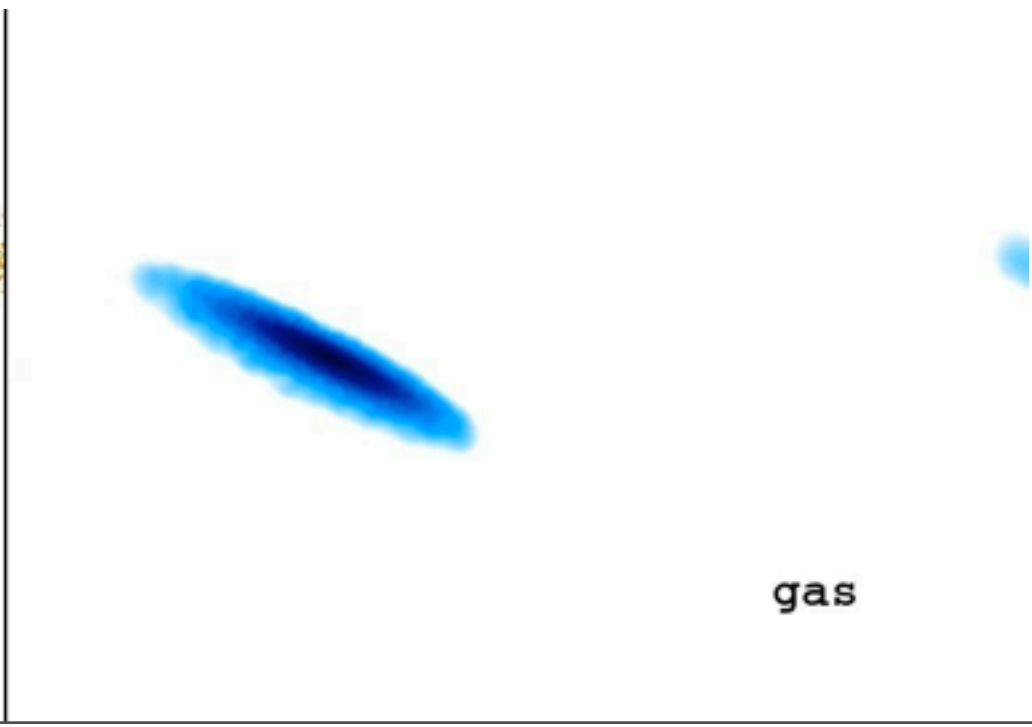


Even with Energy-Driven Feedback: THE AGN DOESN'T ALWAYS WIN!





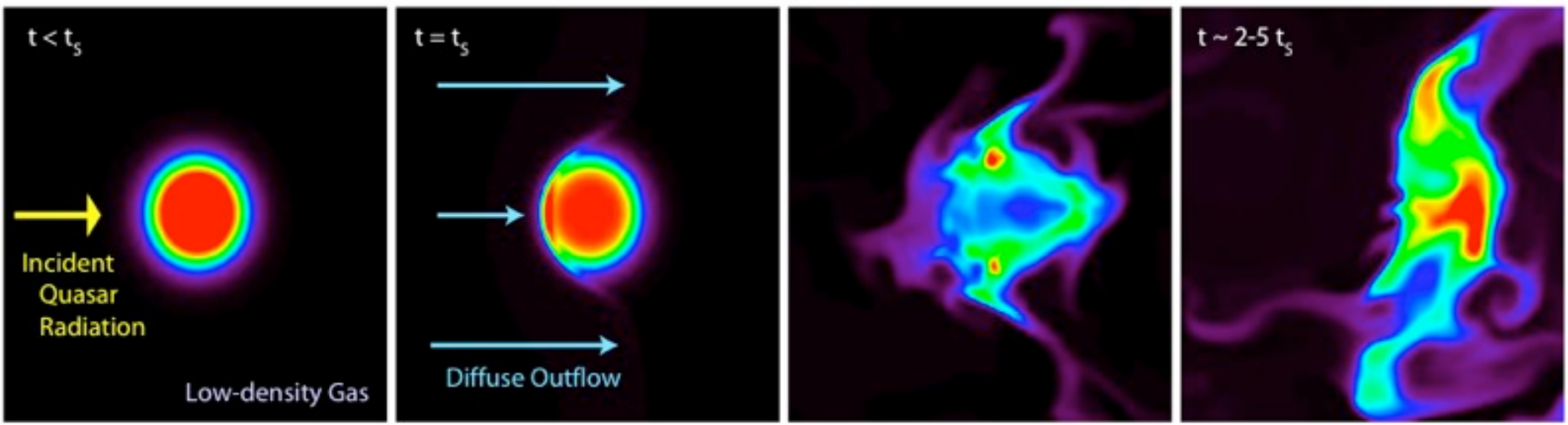




A Caution:
THE SCALES AFFECTED BY THE AGN DEPEND ON THE FORM OF FEEDBACK

- 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.

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?

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

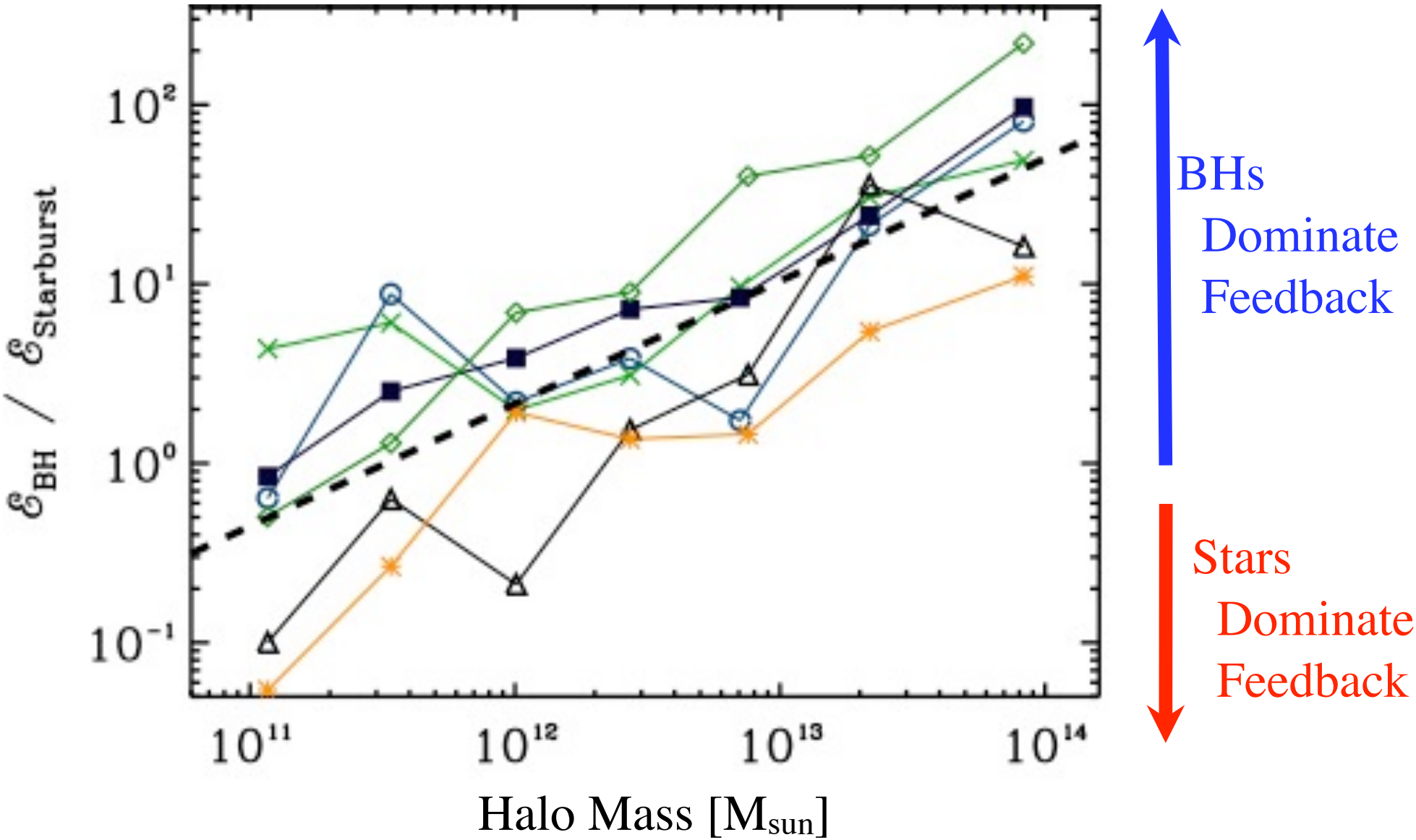
Total $E_{AGN} \sim E_{Supernovae}$ for a bulge-dominated galaxy.

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

PFH, Cox et al. 2007

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?



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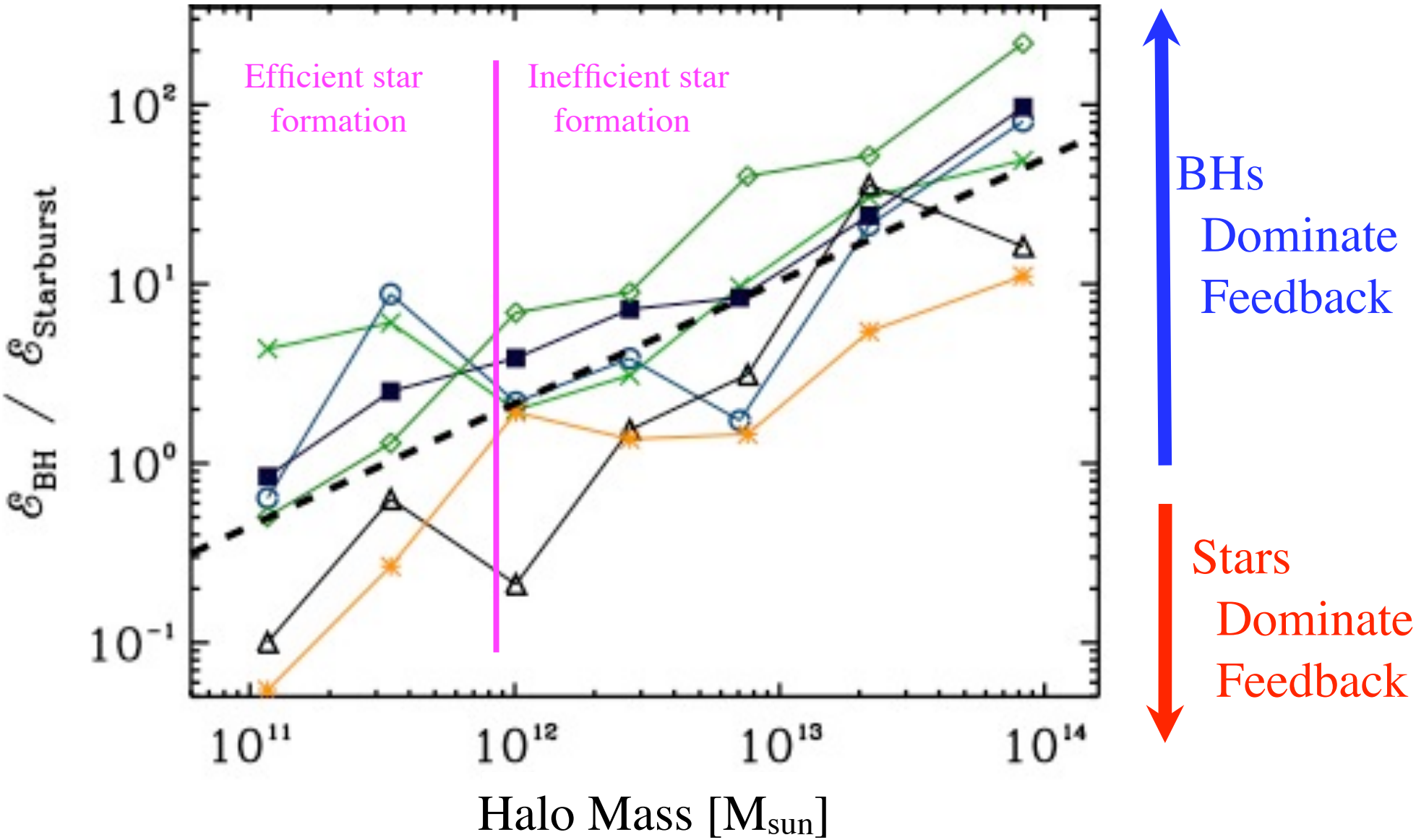

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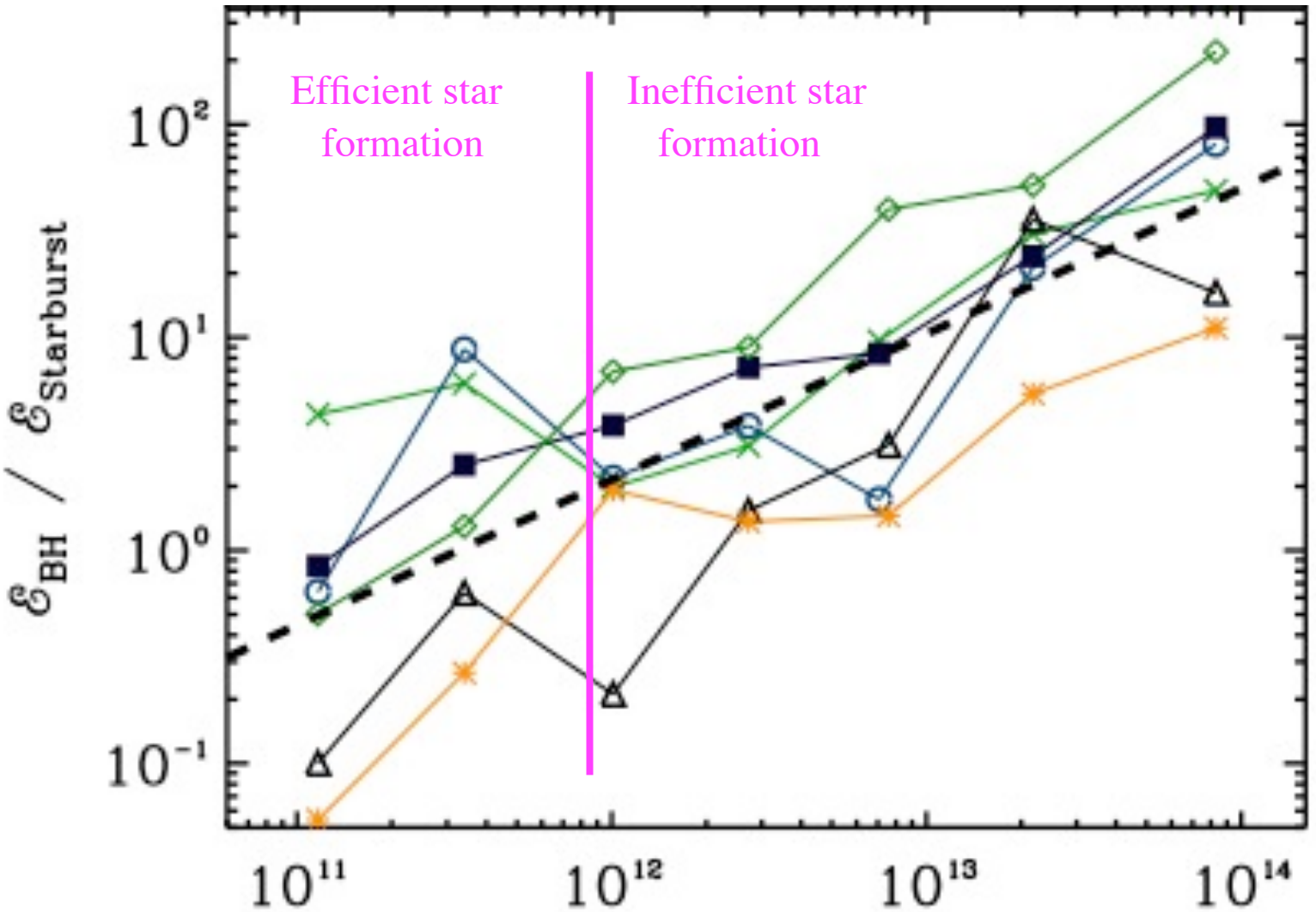


BHs Dominate Feedback

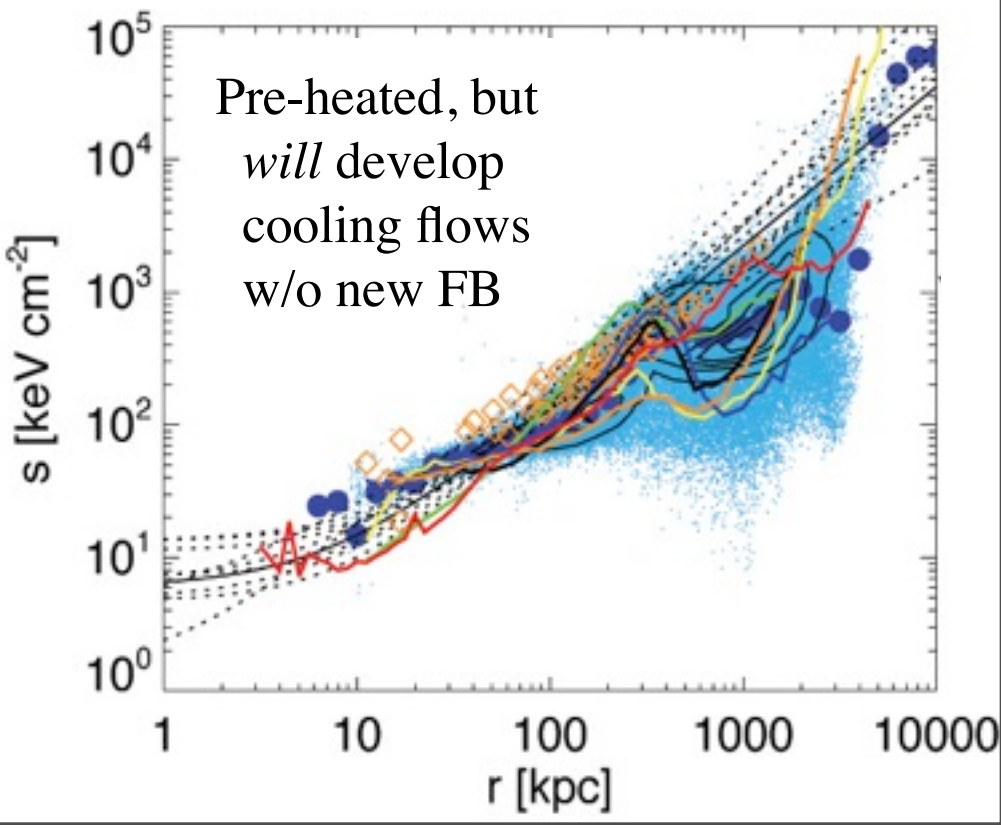
Stars Dominate Feedback

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



"Transition" vs. "Maintenance"

- Move mass from Blue to Red
- Rapid
- Small scales
- "Quasar" mode (high mdot)
- Morphological Transformation
- Gas-rich/Dissipational Mergers

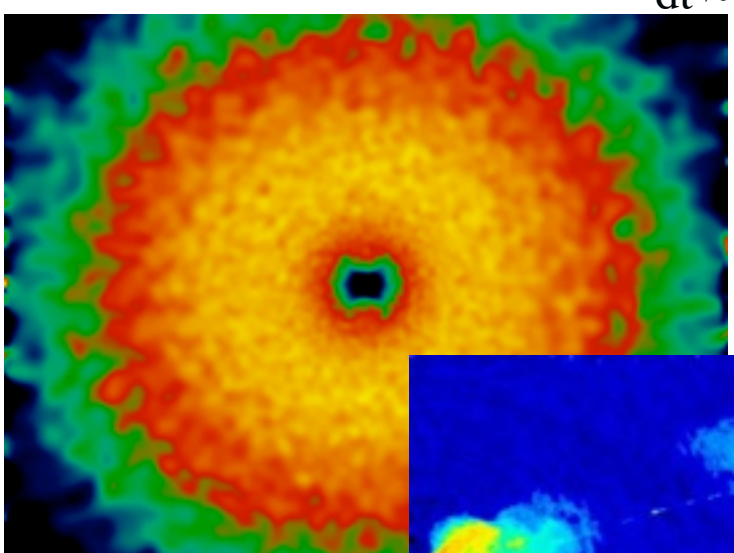
Proga et al.

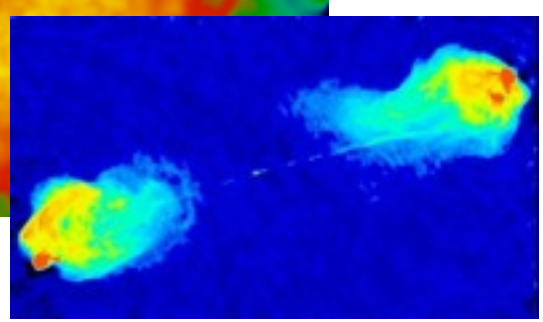
dt ~ 10^6 yr

- Regulates Black Hole Mass

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

dt ~ 10^{10} yr





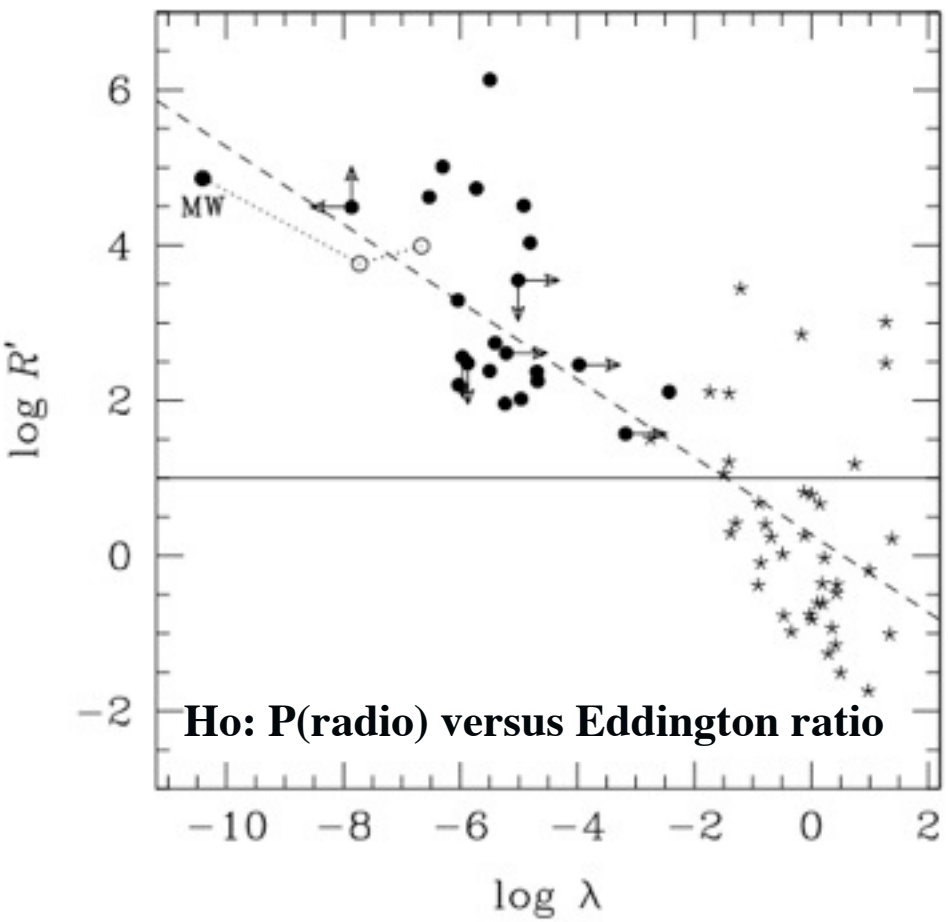
Sijacki et al.

- Regulates Galaxy Mass

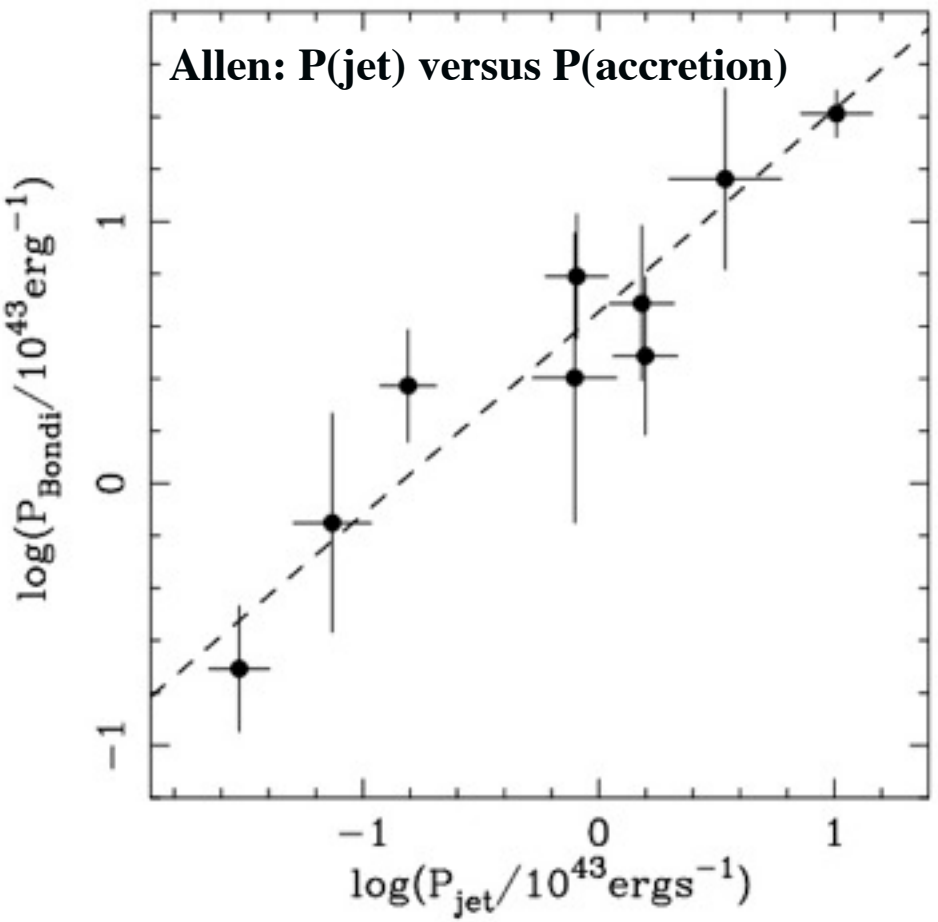
Maintenance Mode

HOW DOES IT FIT IN THIS PICTURE?

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



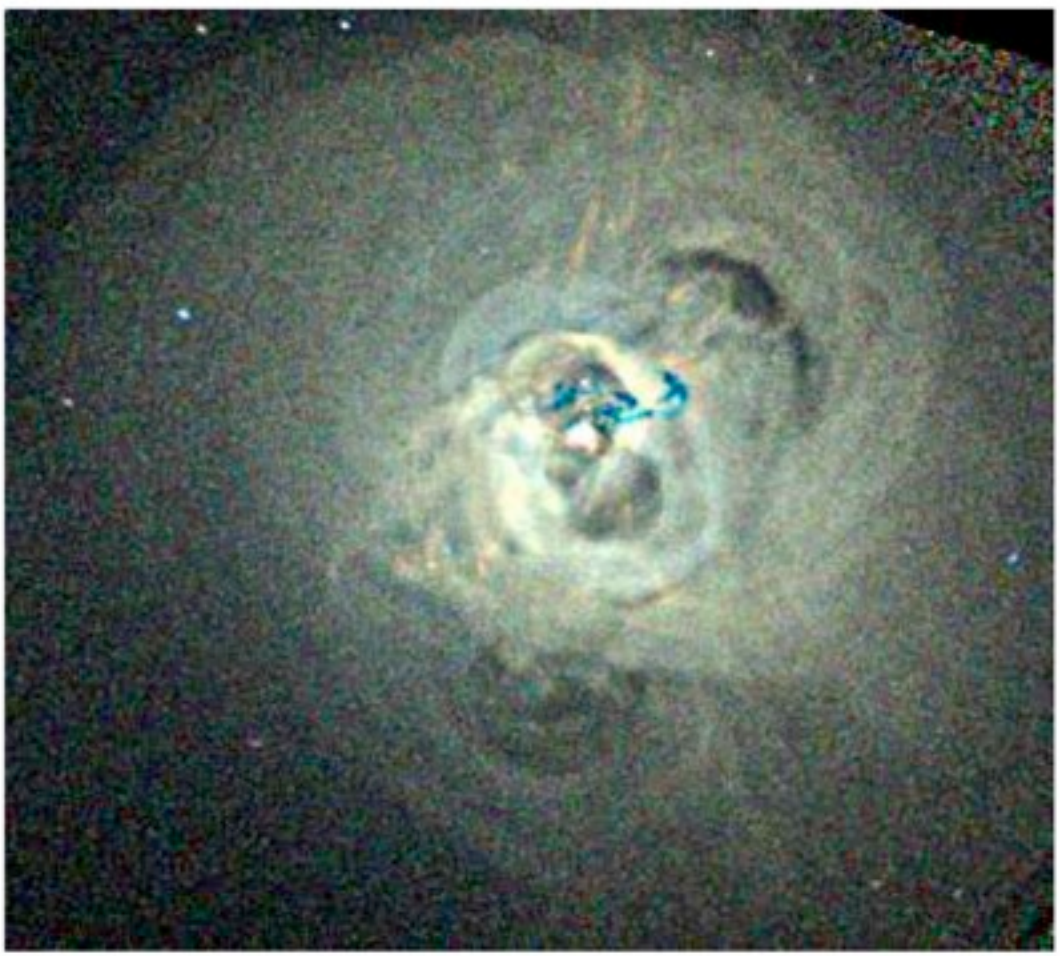
- Is Bondi accretion actually going to work for once?



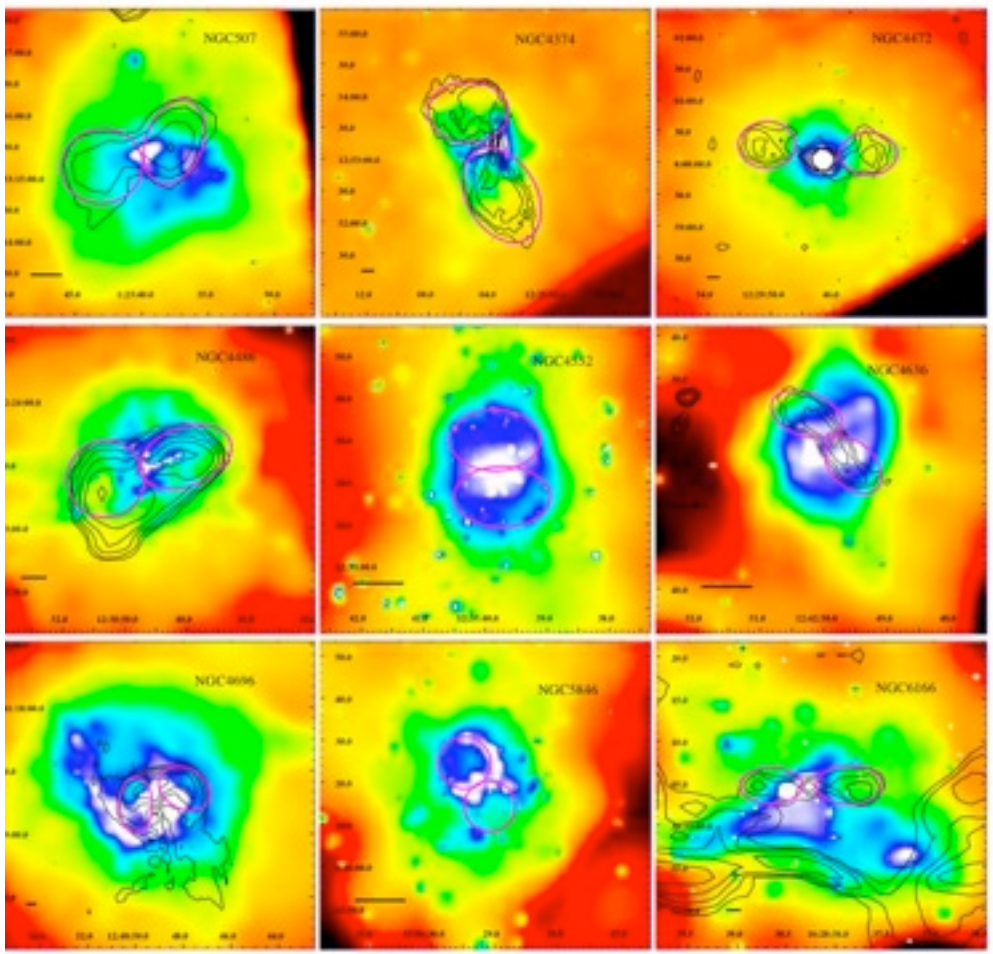
Maintenance Mode

HOW DO WE FIT THIS INTO OUR PICTURE?

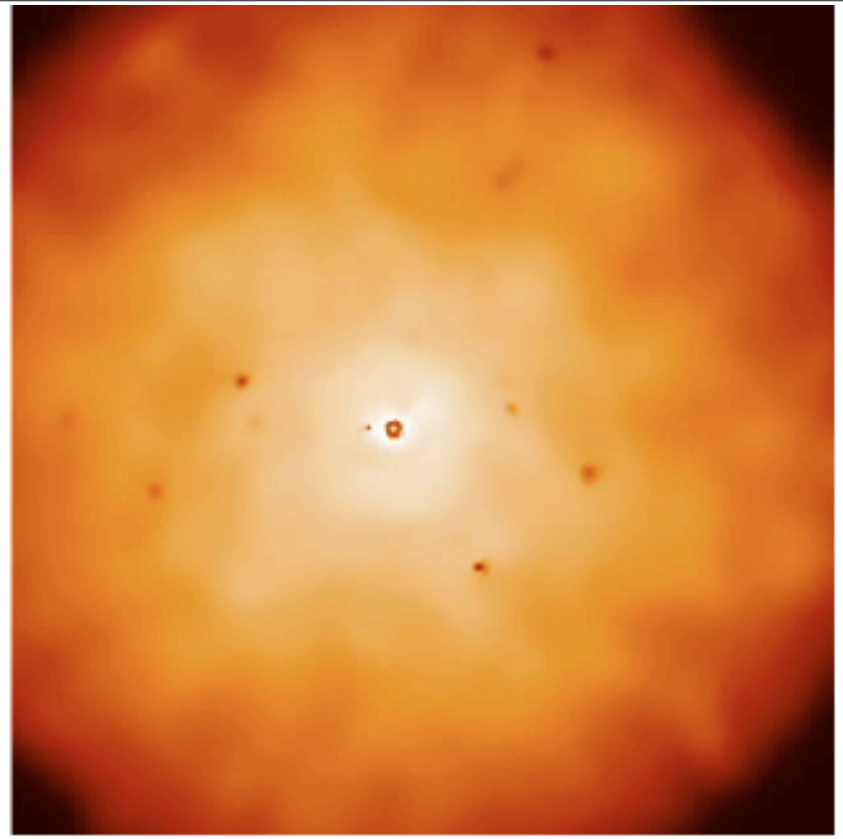
- Is pre-heating relevant for cooling flows? Can we solve the problems in isolation?
- Do we only care about Perseus? Or do we care about moderate-mass Es with radio jets, in ~ 10^{13} M_{sun} halos?

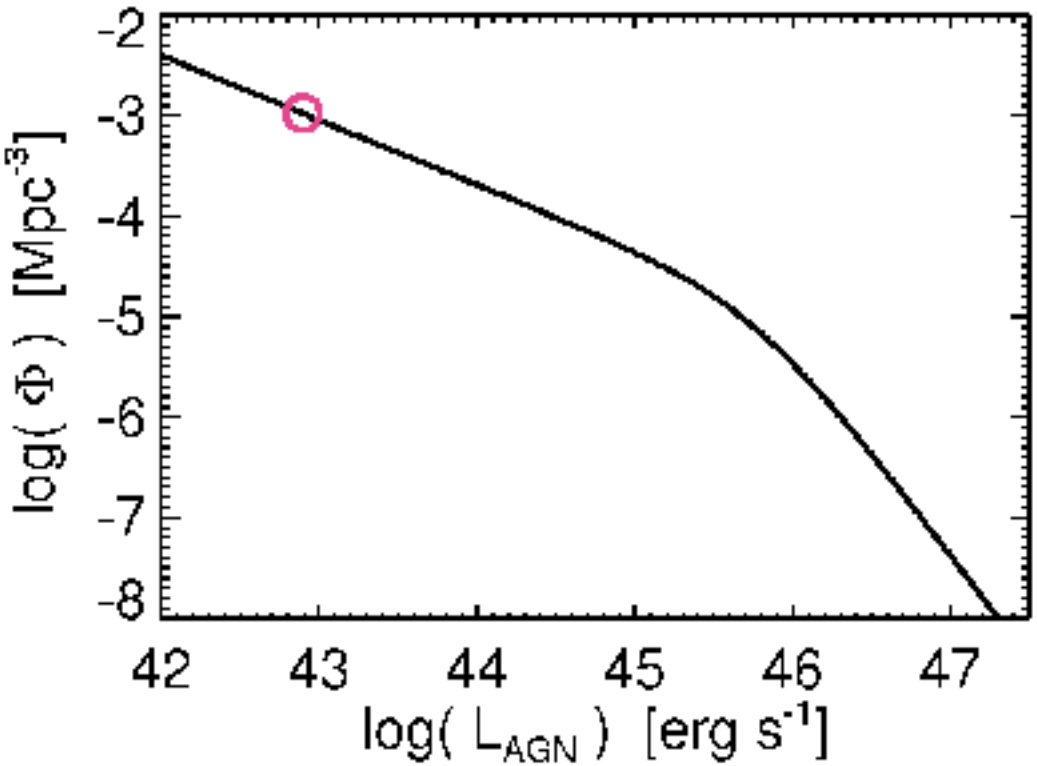


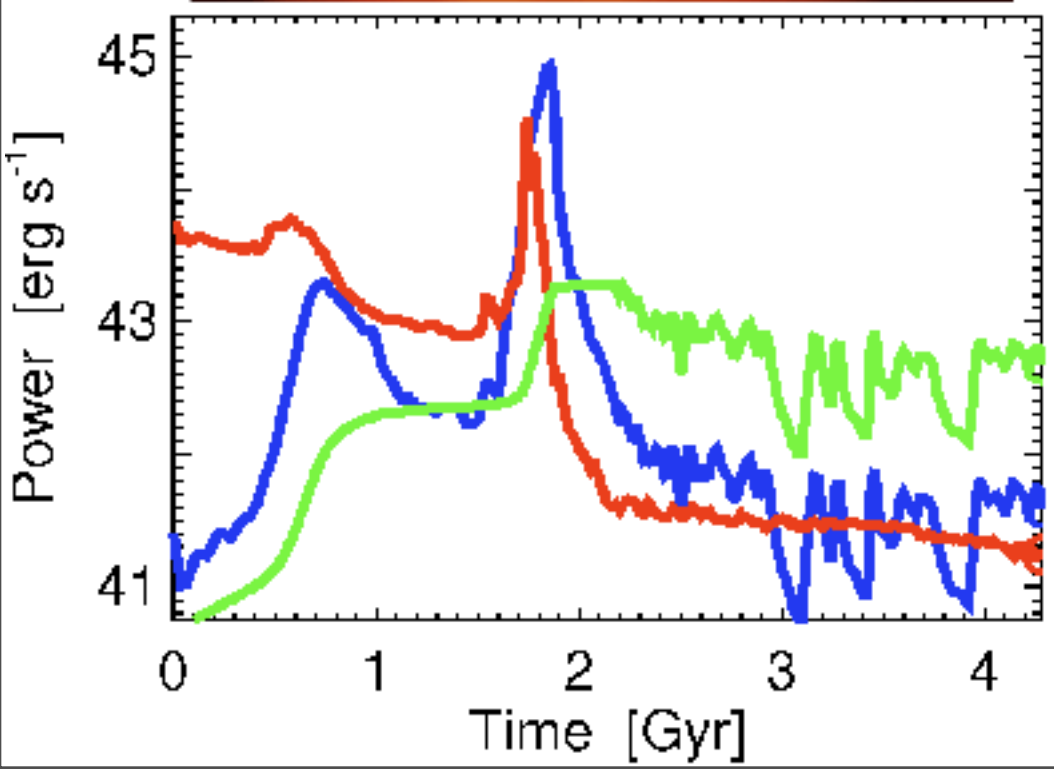
Fabian (Perseus Cluster)

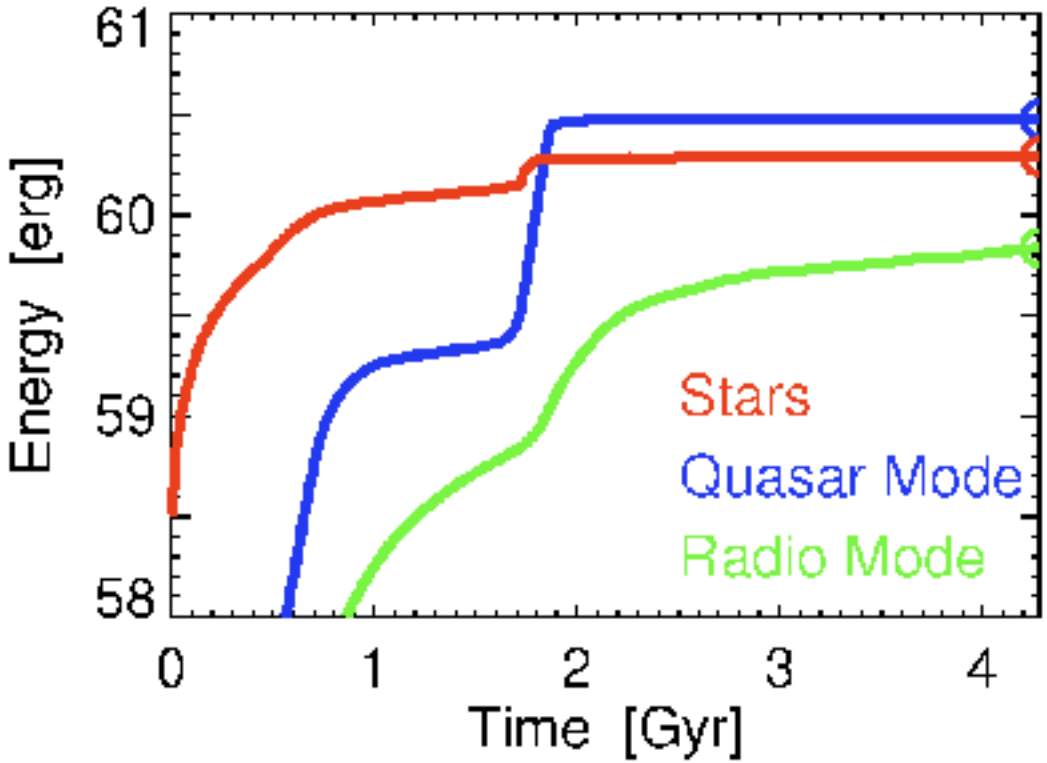


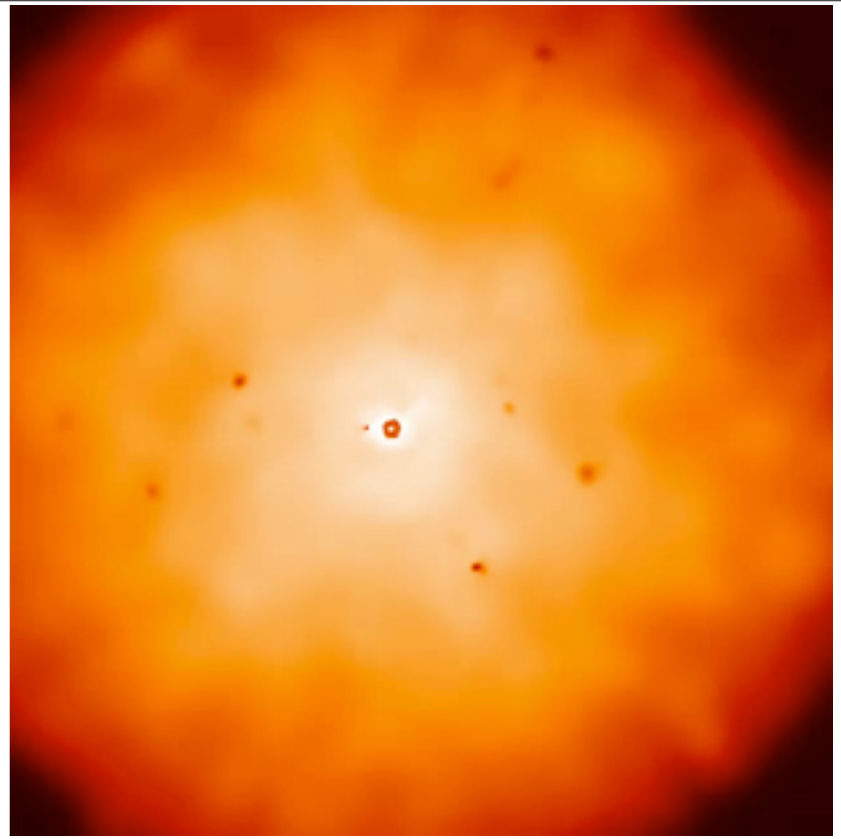
Allen (X-ray Ellipticals)

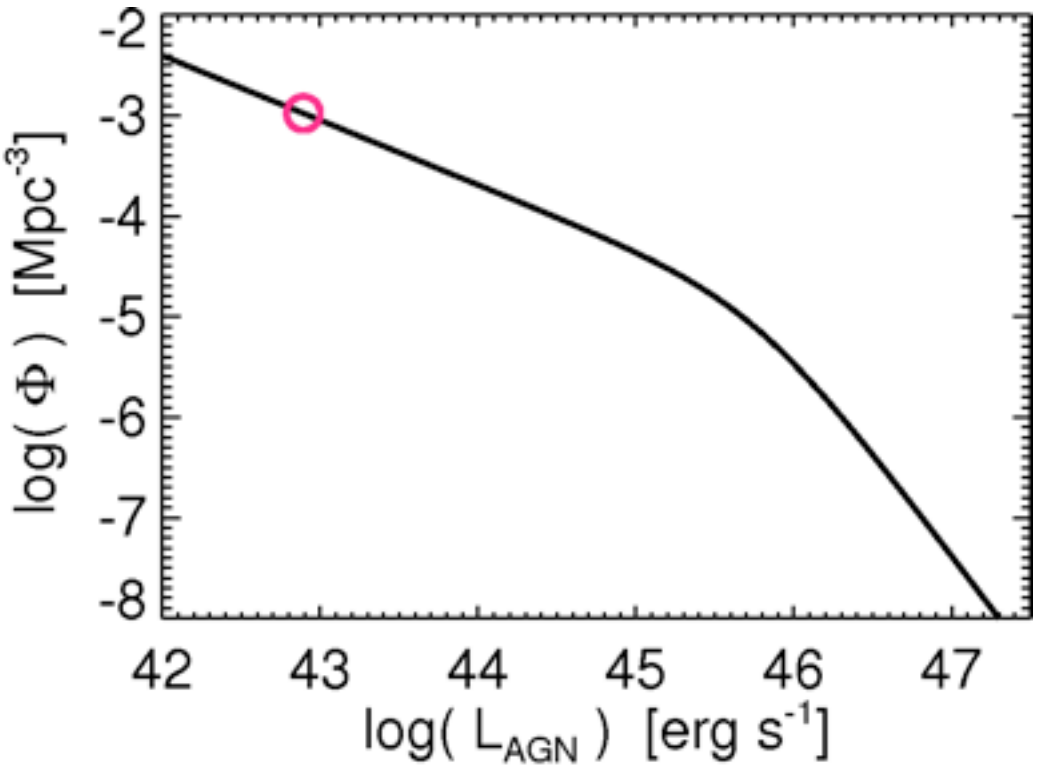



log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]


Power [erg s^{-1}]
45
43
41
0
1
2
3
4
Time [Gyr]


Energy [erg]
61
60
59
58
0
1
2
3
4
Time [Gyr]
Stars
Quasar Mode
Radio Mode

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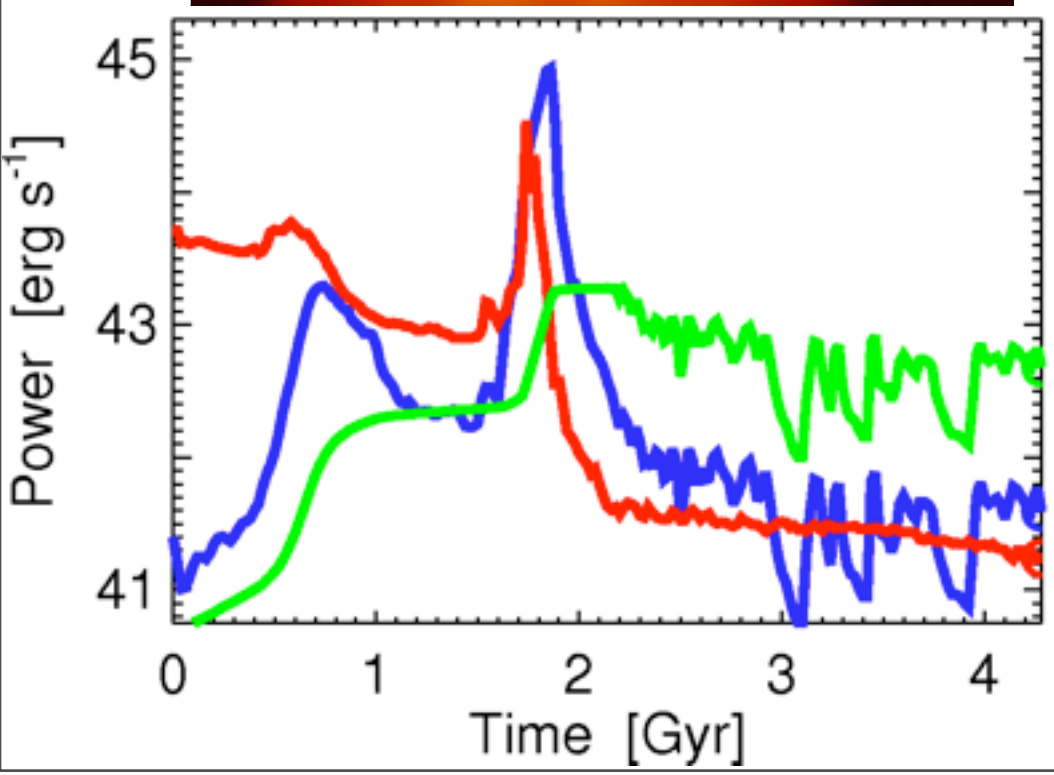
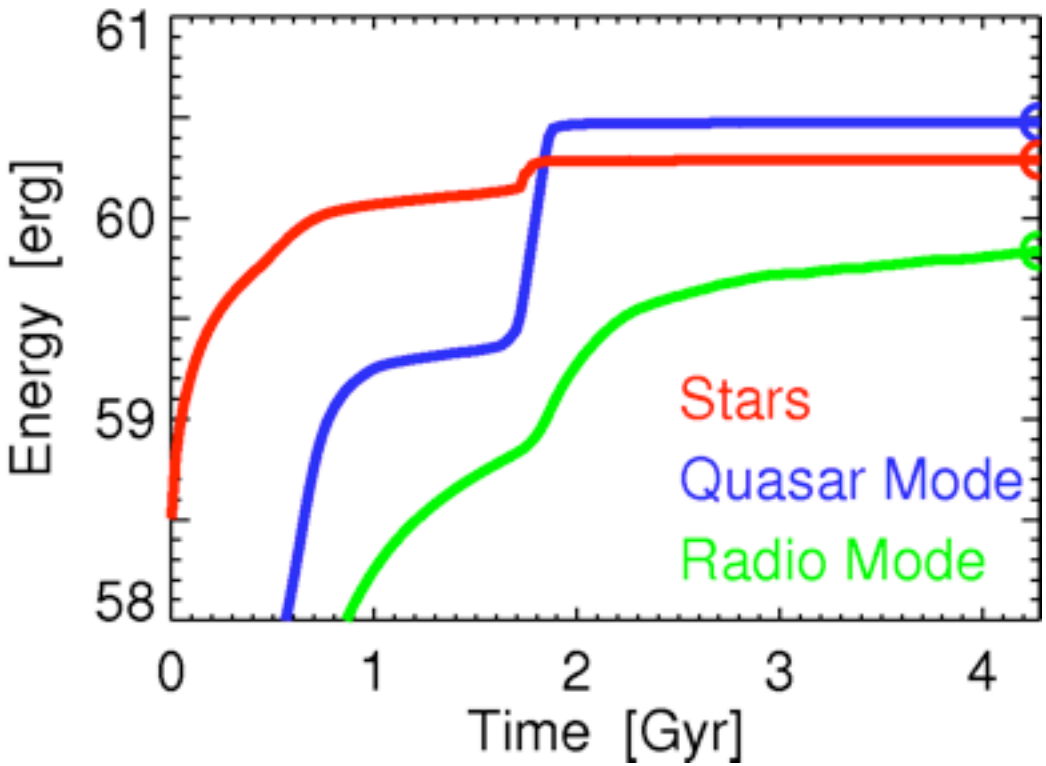

45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]


61
60
59
58
Energy [erg]
0
1
2
3
4
Time [Gyr]
Stars
Quasar Mode
Radio Mode

Summary

- Fueling Most Luminous BHs: Require global gravitational instabilities
  - "Stuff within Stuff": Cascade of instabilities with diverse morphology
    - Accretion rates, even orientations are stochastic
    - Can get ~10 M_{sun}/yr: May self-consistently yield the torus & nuclear disks
- "Are AGN mergers?" is the wrong question (even in merger-driven models!)
  - Should ask: "Where (as a function of L, z, d) do mergers vs. non-mergers dominate "getting gas down to" sub-kpc scales
- M_{BH} traces spheroid $E_{binding}$
  - Suggests *self-regulated* BH growth
    - You CAN'T build very big BHs without making bulges first
    - Which mechanisms dominate BH feedback? When/where?
- If self-regulated, this feedback may be radically important:
  - Self-regulated decay of QSO luminosity
  - Heating gas, ejecting metals, shutting down SF
    - Depends on feedback mode! Radiation pressure = no blowout?
  - Where/what is the transition/maintenance mode role?
    - Function of Eddington ratio? What does each "phase" do?