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

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11/16/10

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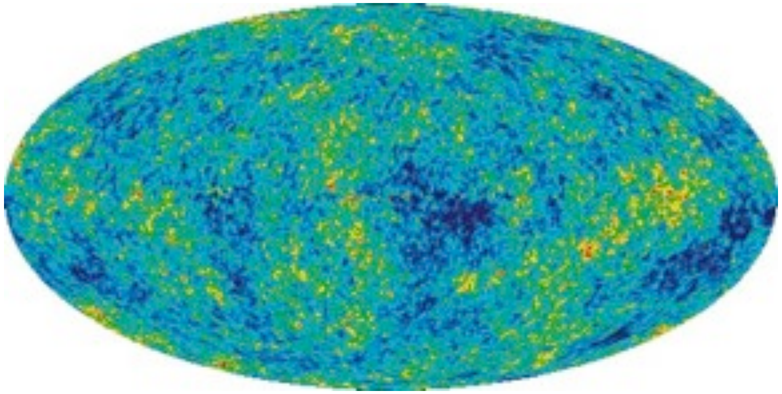

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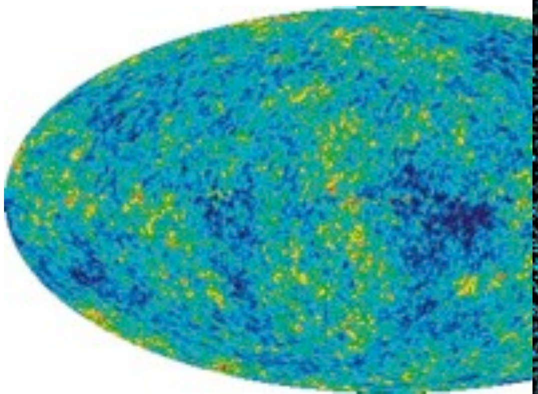
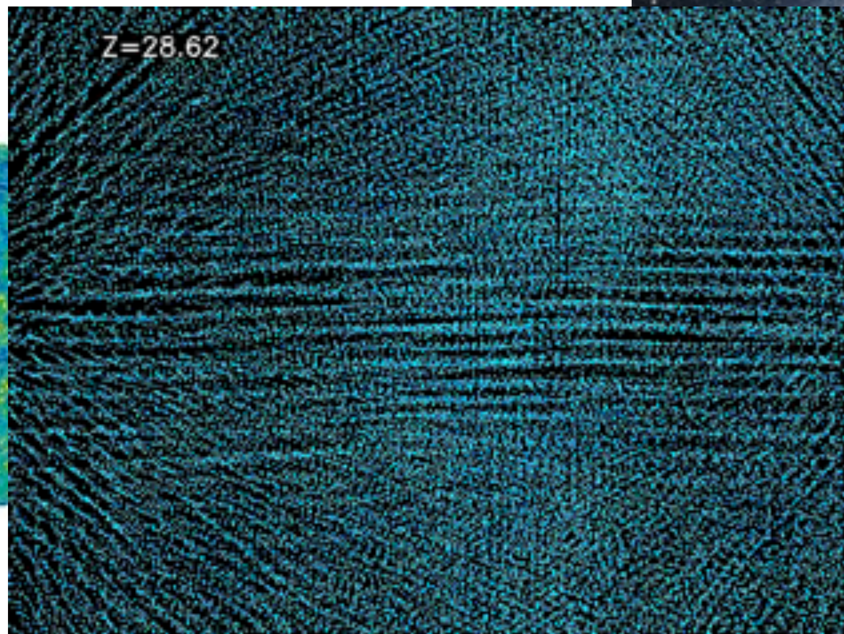
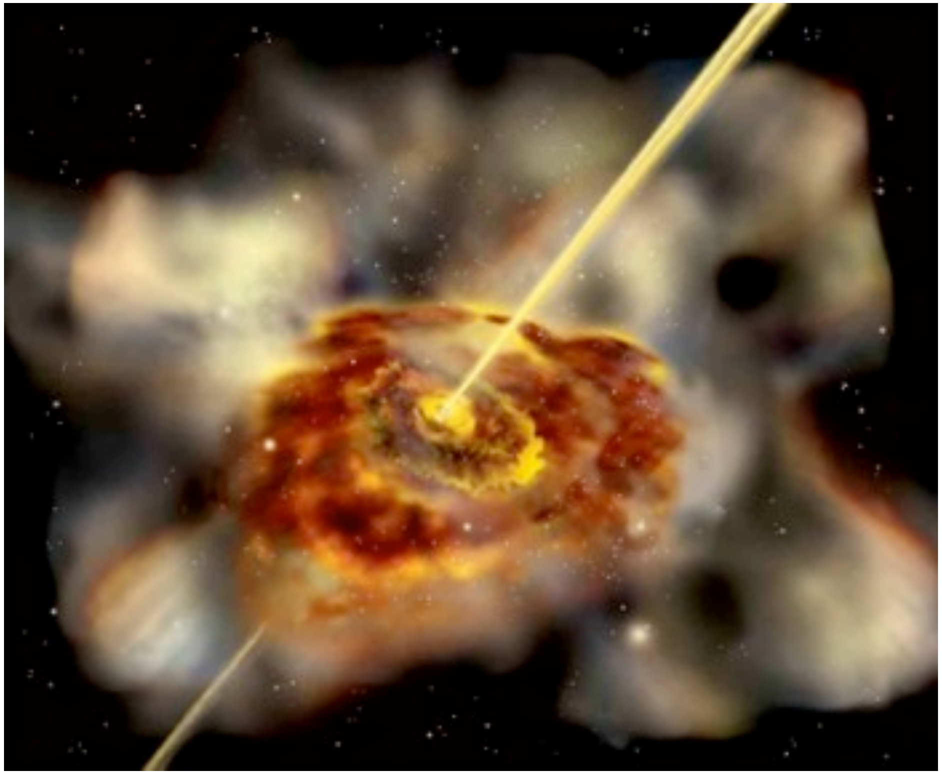


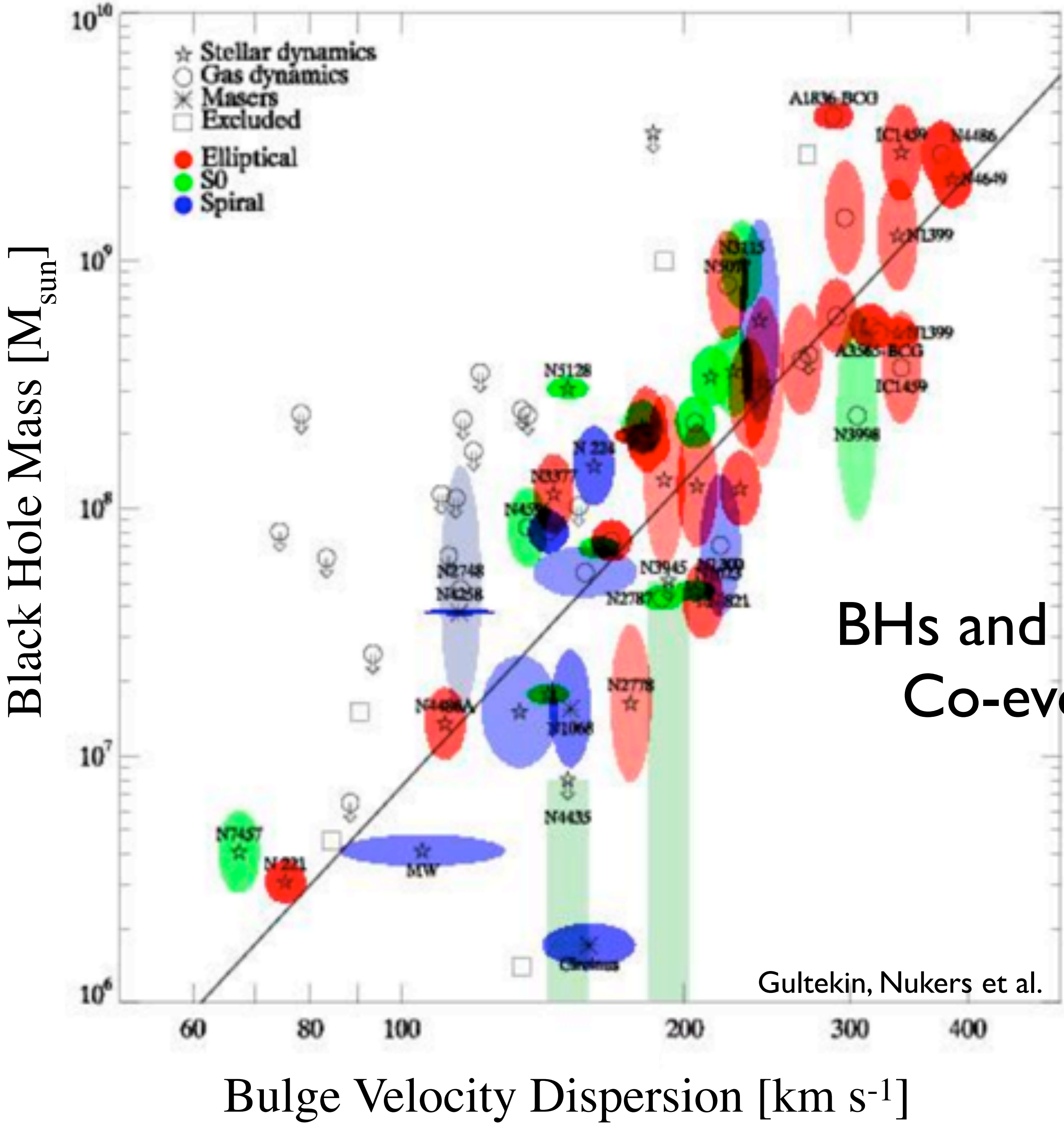


Z=28.62

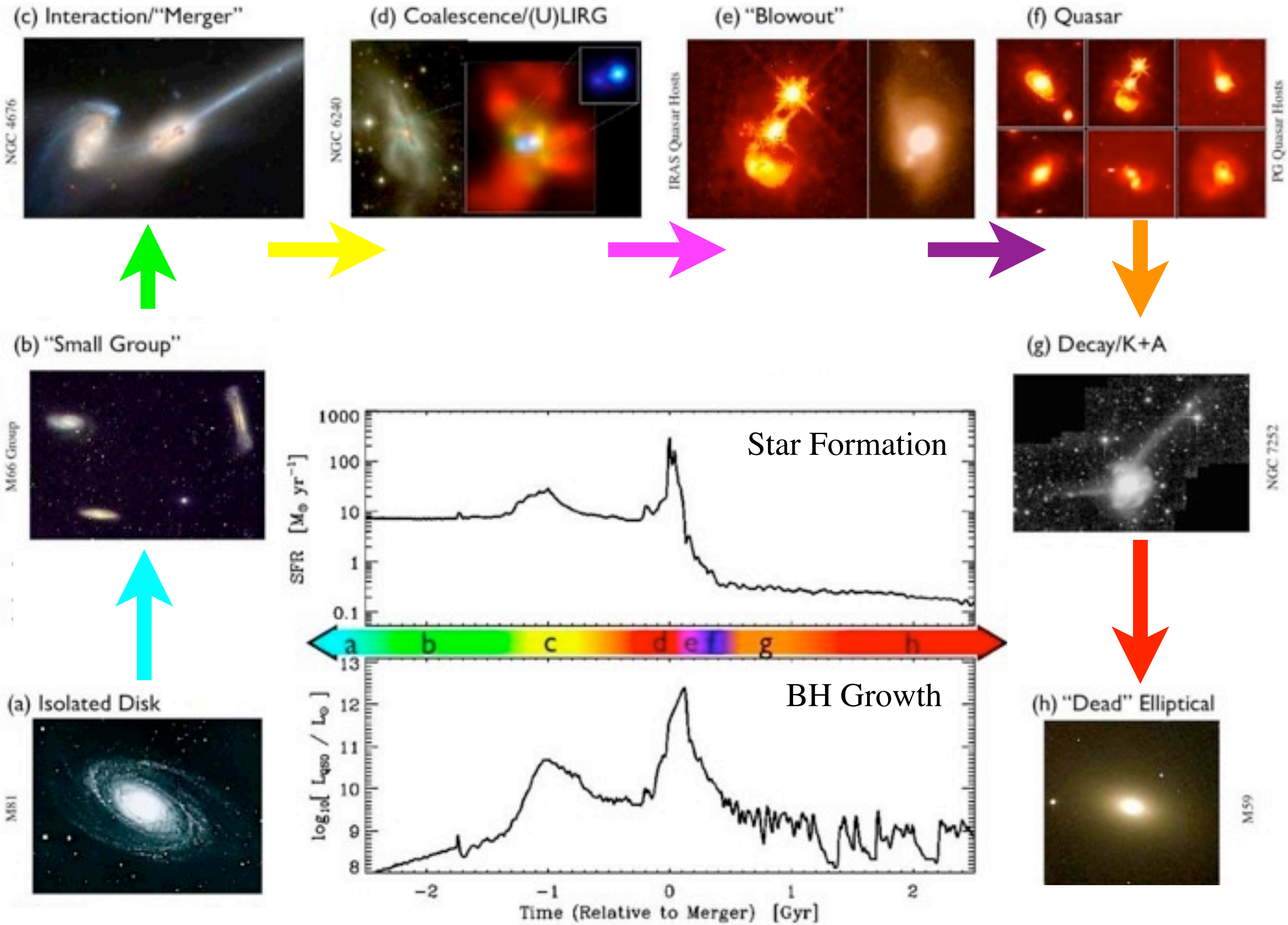
- Every massive galaxy hosts a supermassive black hole



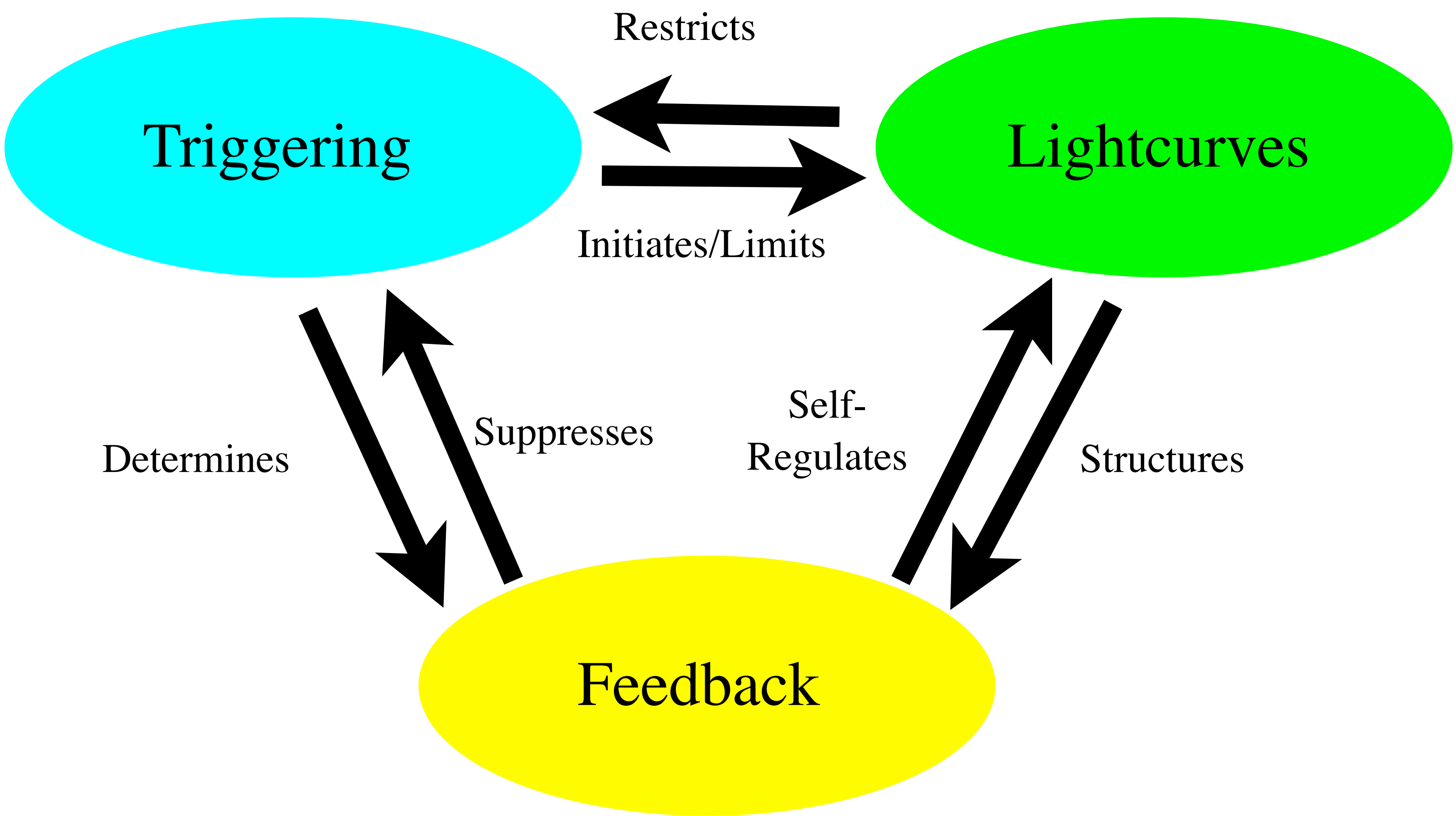
- These BHs are “fossil” quasars



BHs and Bulges Co-evolve


(c) Interaction/"Merger"
NGC 4676
(d) Coalescence/(U)LIRG
NGC 6240
(e) "Blowout"
IRAS Quasar Hosts
(f) Quasar
PG Quasar Hosts
(b) "Small Group"
M66 Group
(g) Decay/K+A
NGC 7252
(a) Isolated Disk
M81
(h) "Dead" Elliptical
M59
Star Formation
SFR $[M_\odot\ yr^{-1}]$
BH Growth
$\log_{10}[\ L_{QSO}\ /\ L_\odot\ ]$
a b c d e f g h
Time (Relative to Merger) [Gyr]

Outstanding (Inseparable?) Questions:



How Do Massive BHs Get Their Gas?

Some things to remember...

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

- Here: Focus on most luminous AGN (quasars)
  - Most BH mass accreted, most energy/momentum released
  - Fueling is hard: ~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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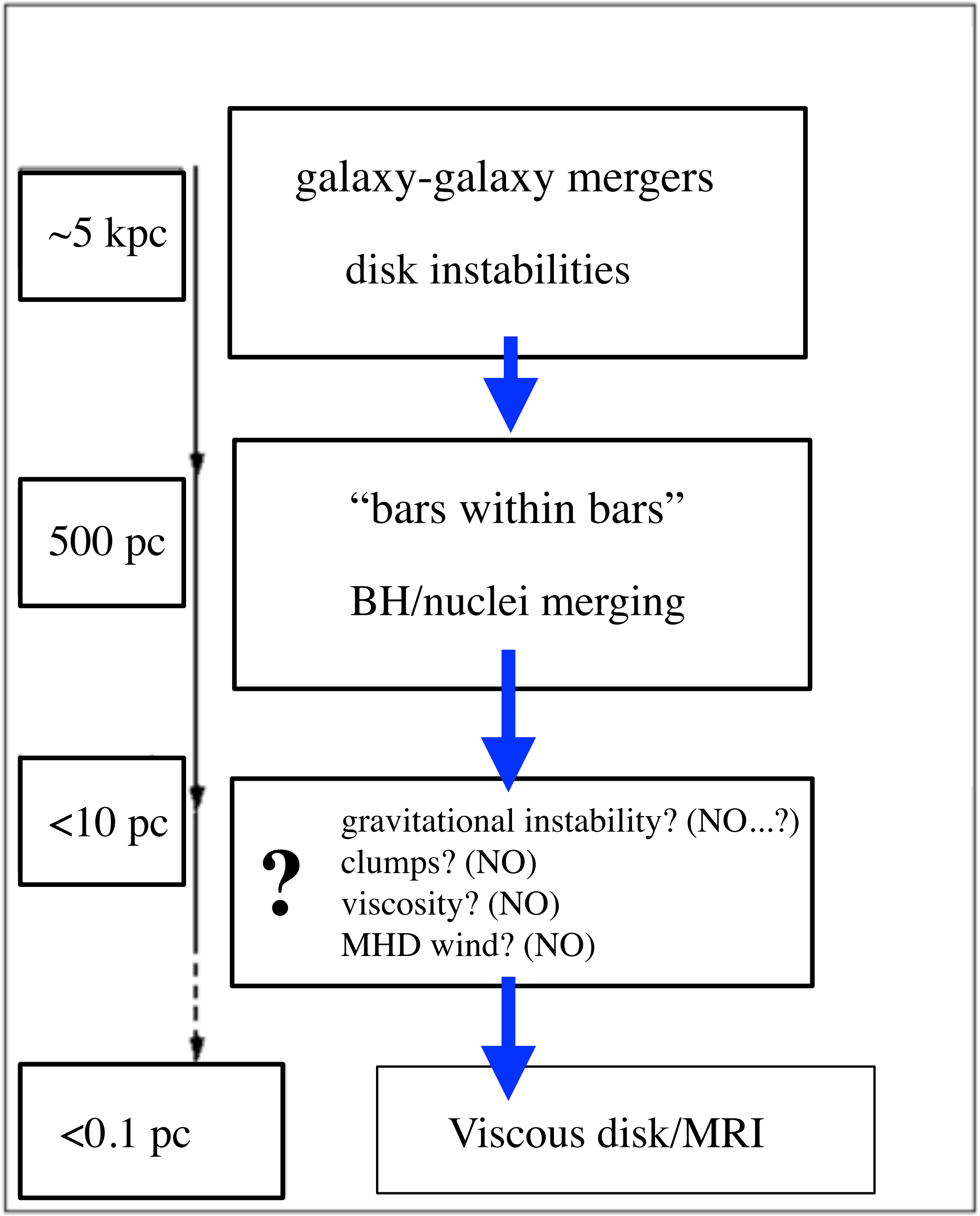
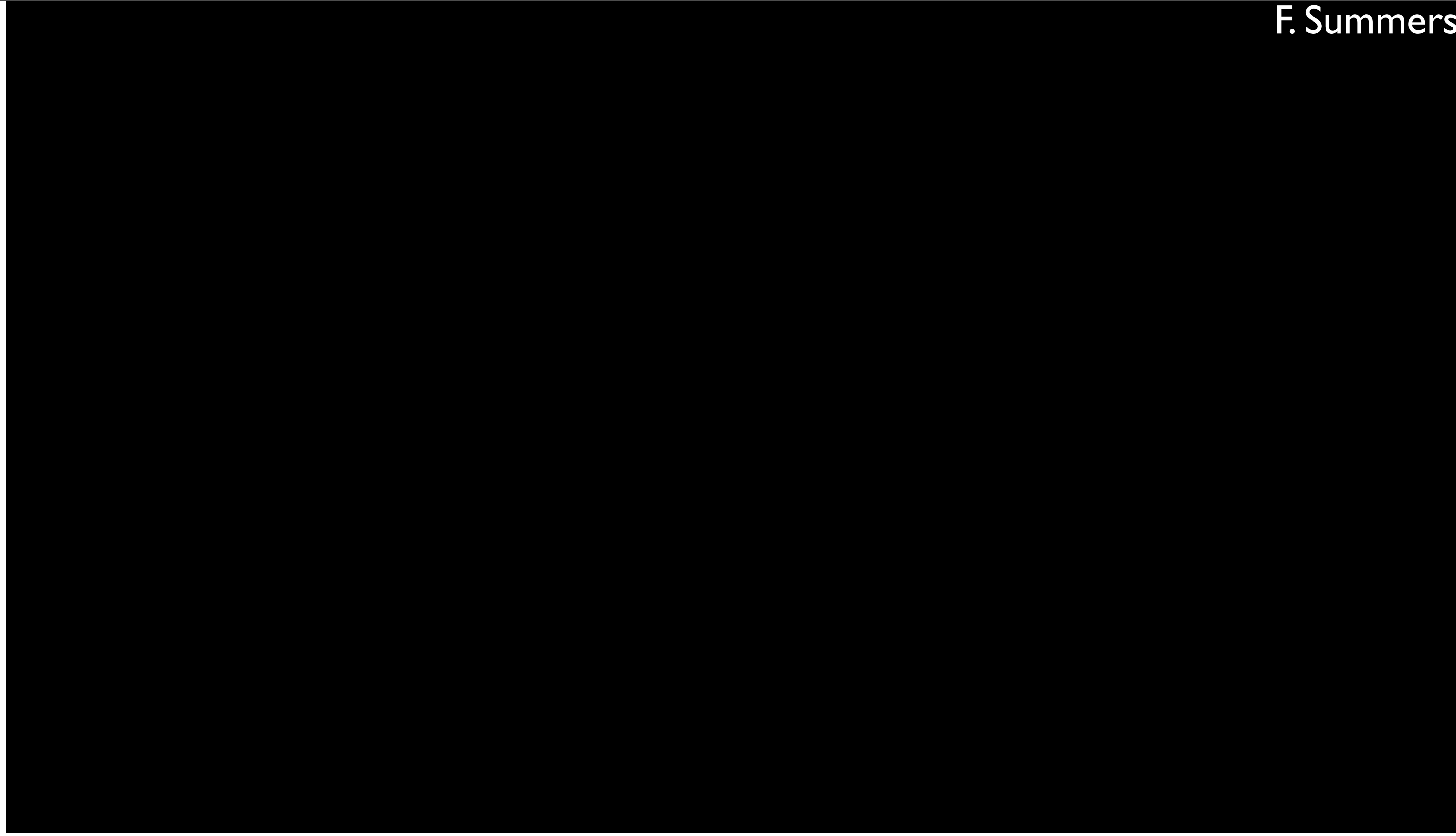
- Focus: Most luminous QSOs (~1-10 M_{sun}/yr)
- 'Bottleneck' at <10-50pc: BH begins to dominate the potential

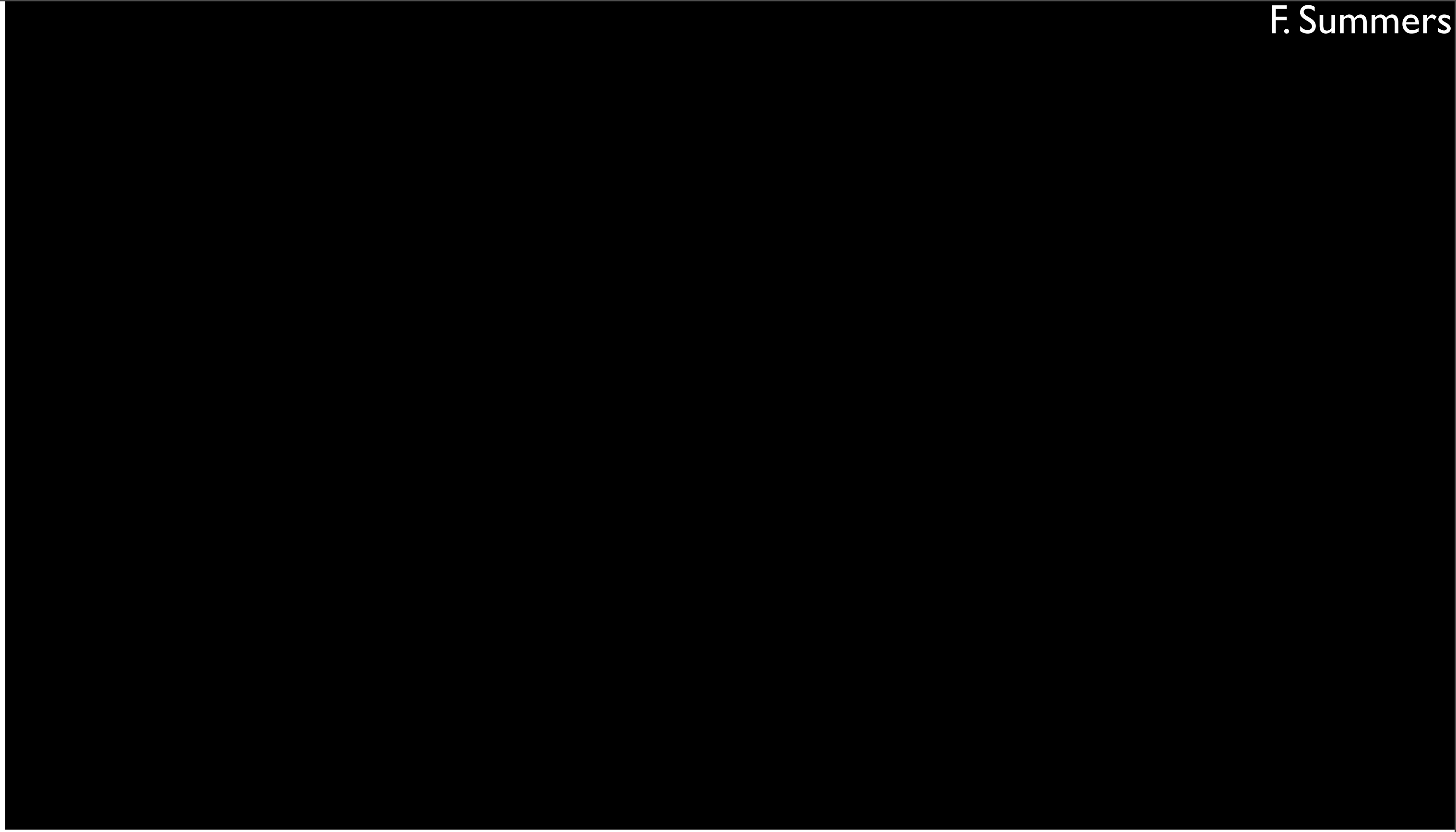
(e.g. Goodman et al., Jogee et al., Martini et al.)





- Galaxy merger: good way to get lots of gas to small scales!

- *If* BHs trace spheroids, then *most* mass added in violent events that also build bulges



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

- Solution 1: simple prescription

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

- Here: Focus on *robust* conclusions

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    - Gas+Stars

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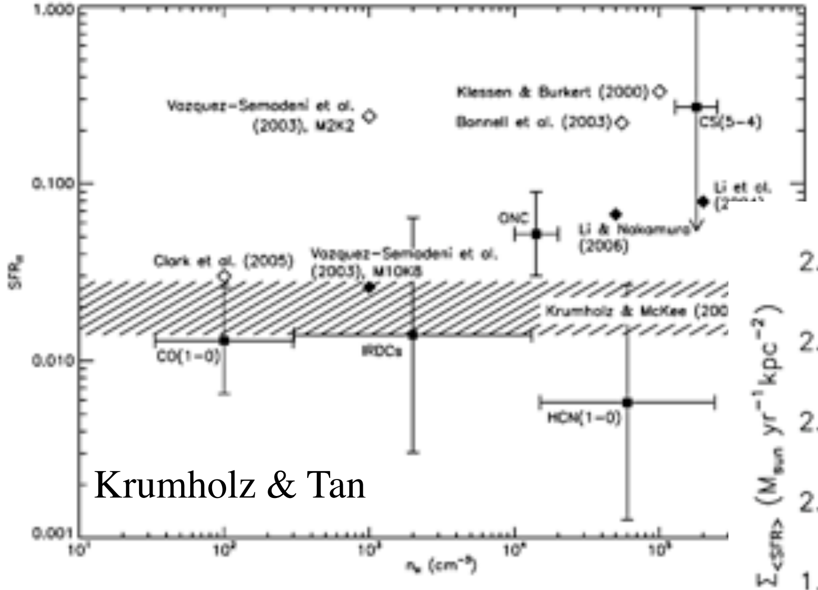
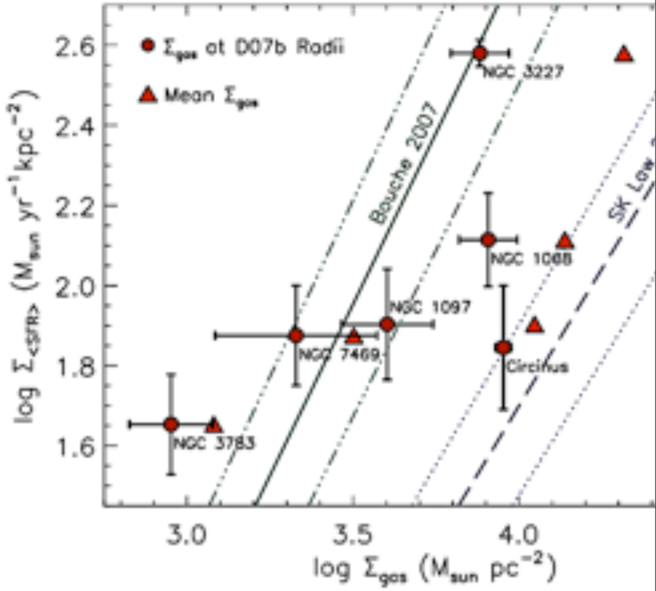


Hicks et al.



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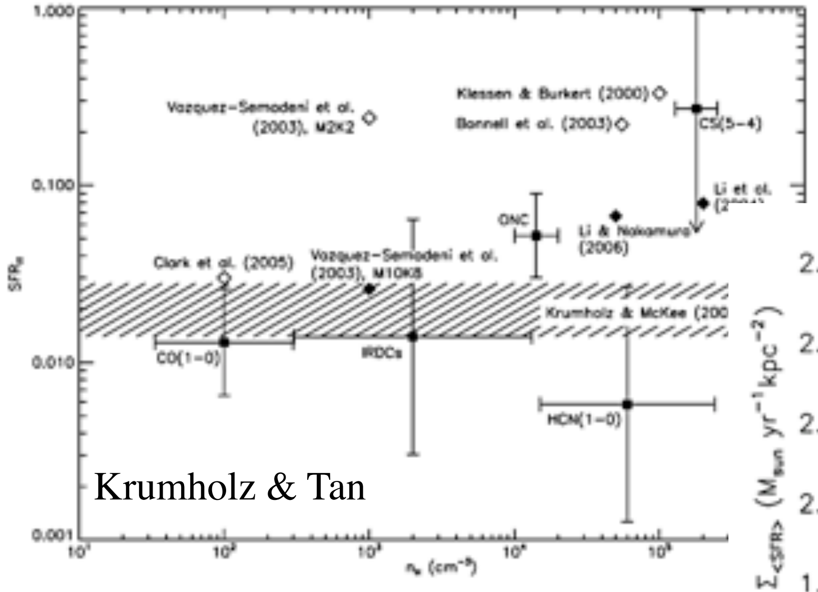
  - ‘Feedback’ (Stars, not AGN)
    - Admit we don’t understand it!



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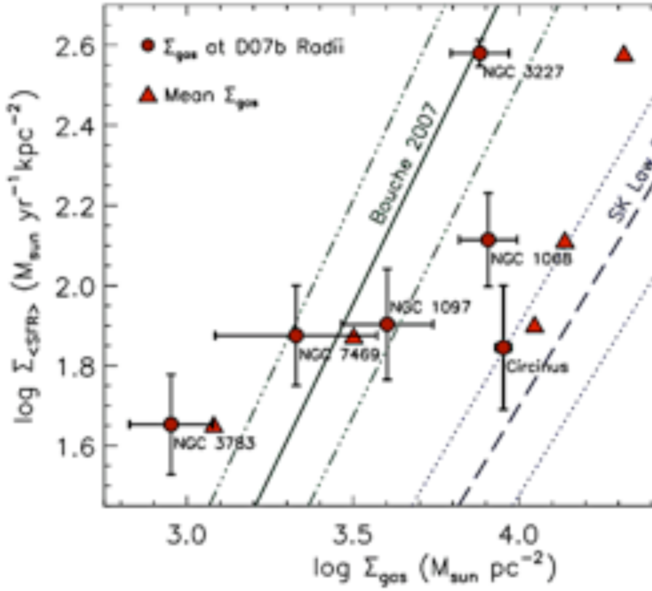

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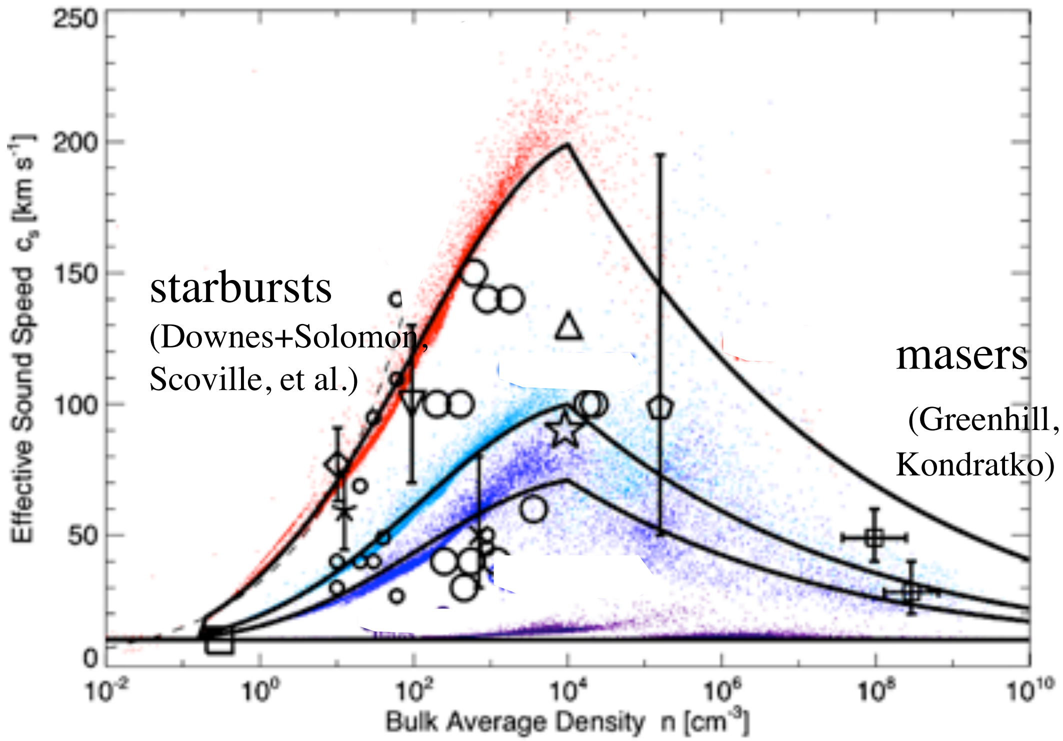

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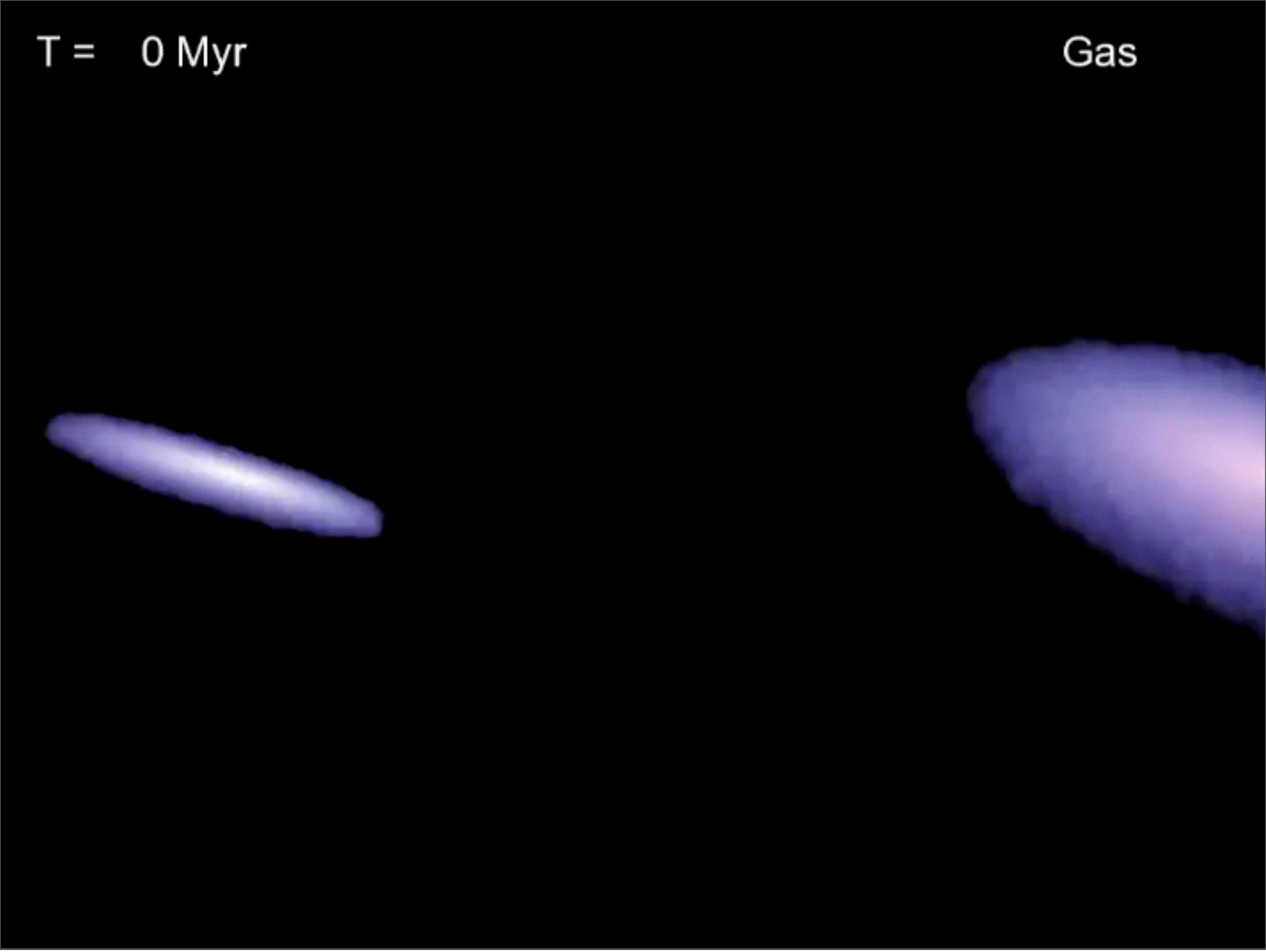
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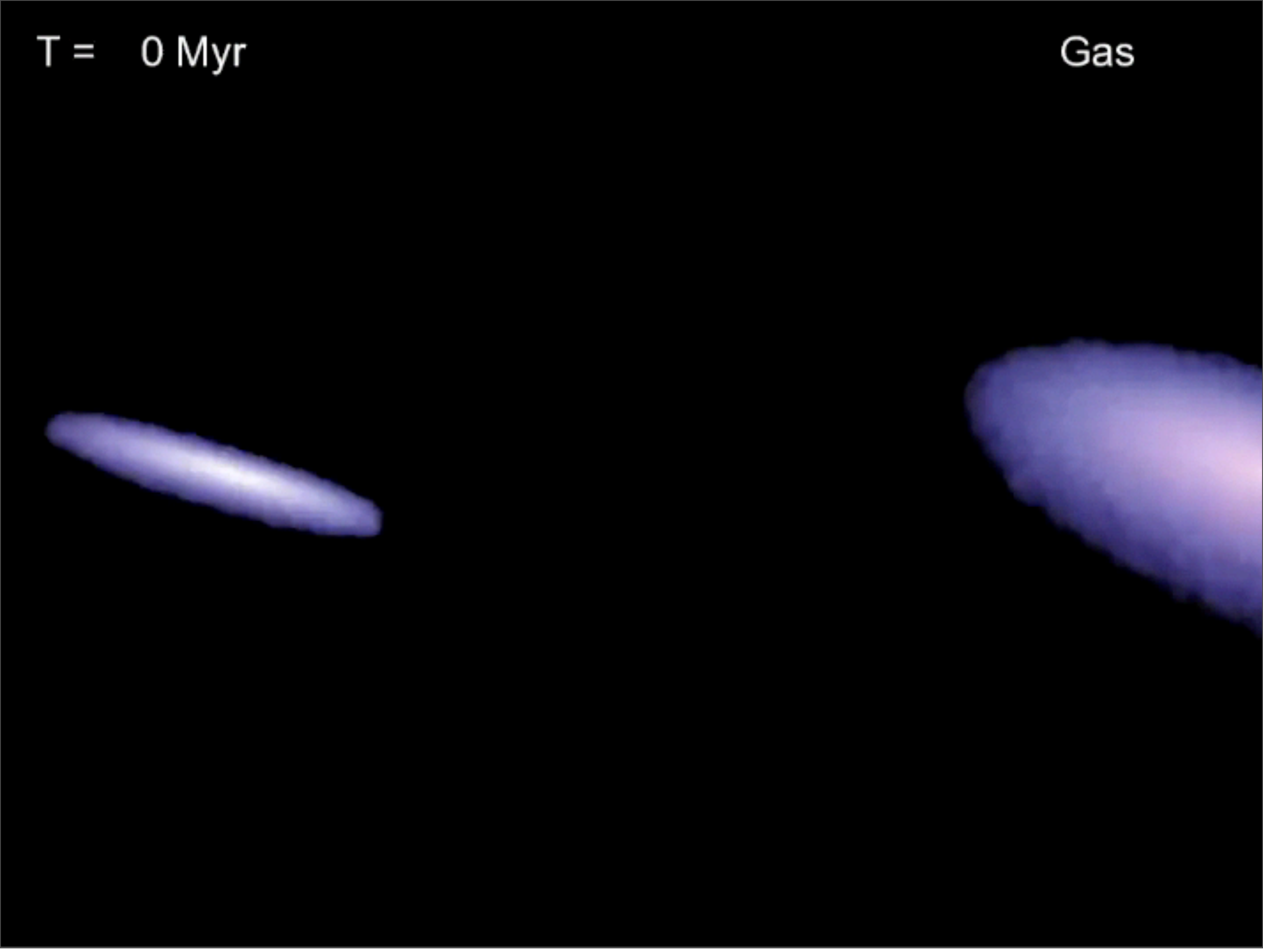
Gas

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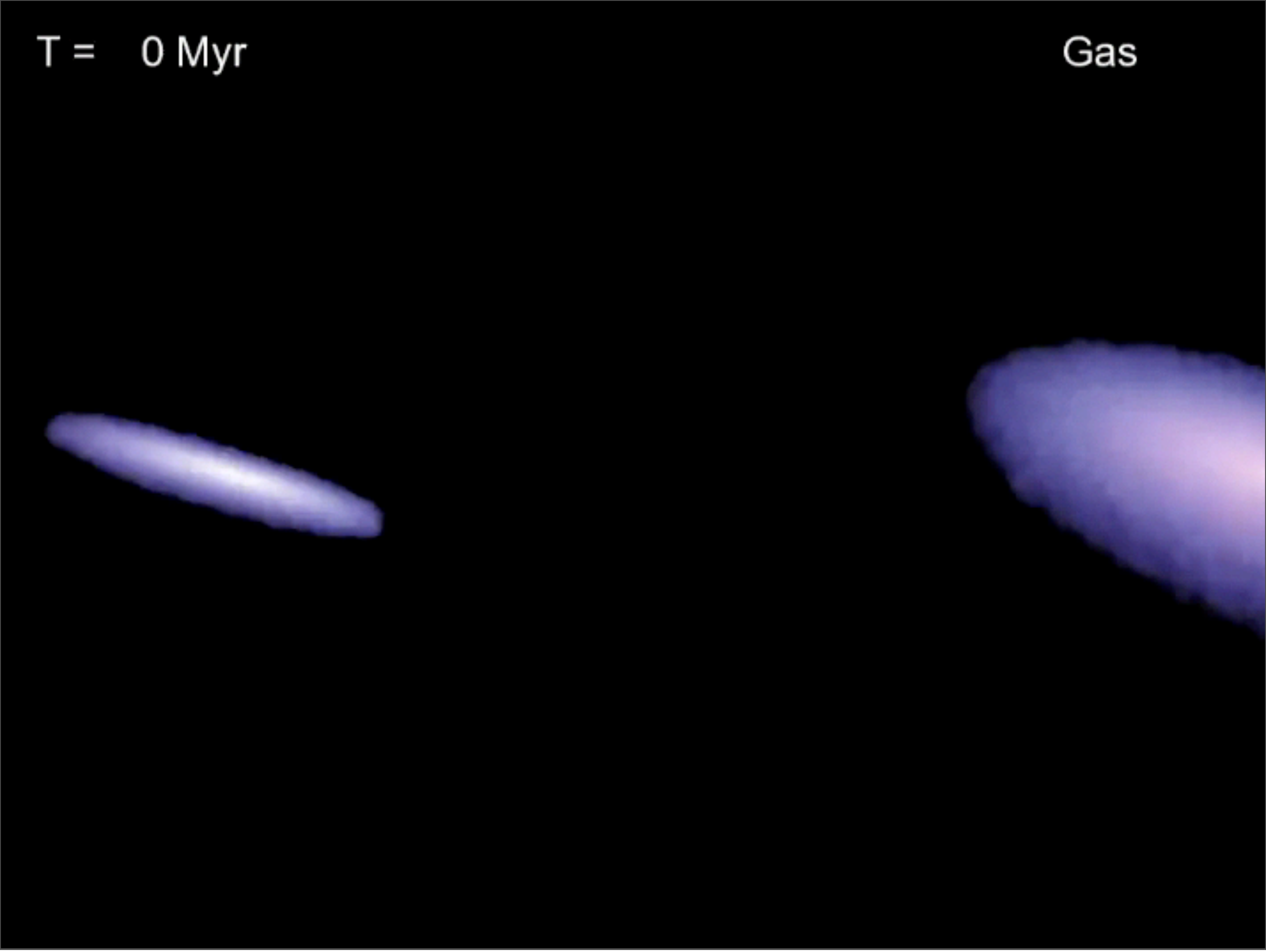
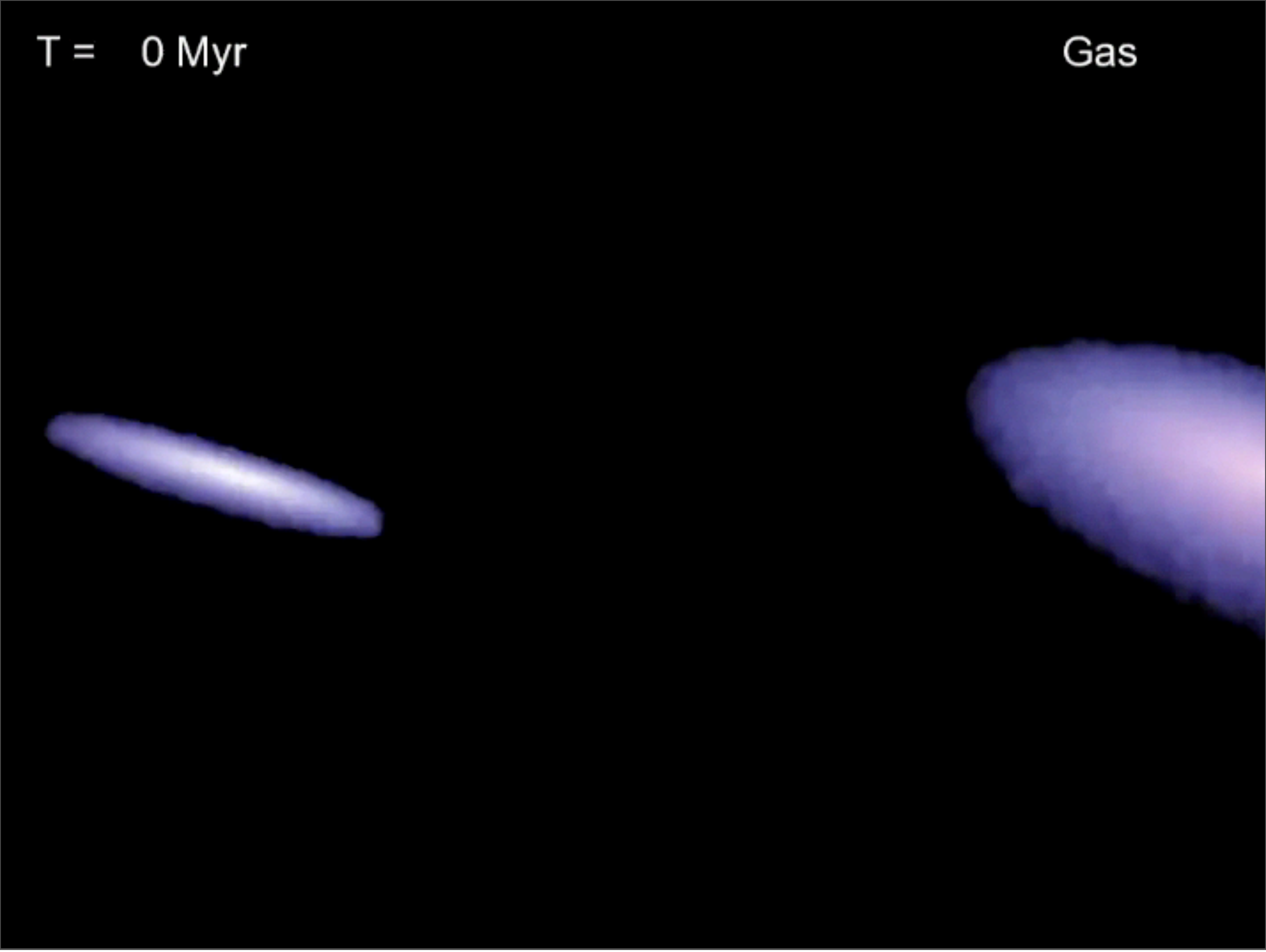
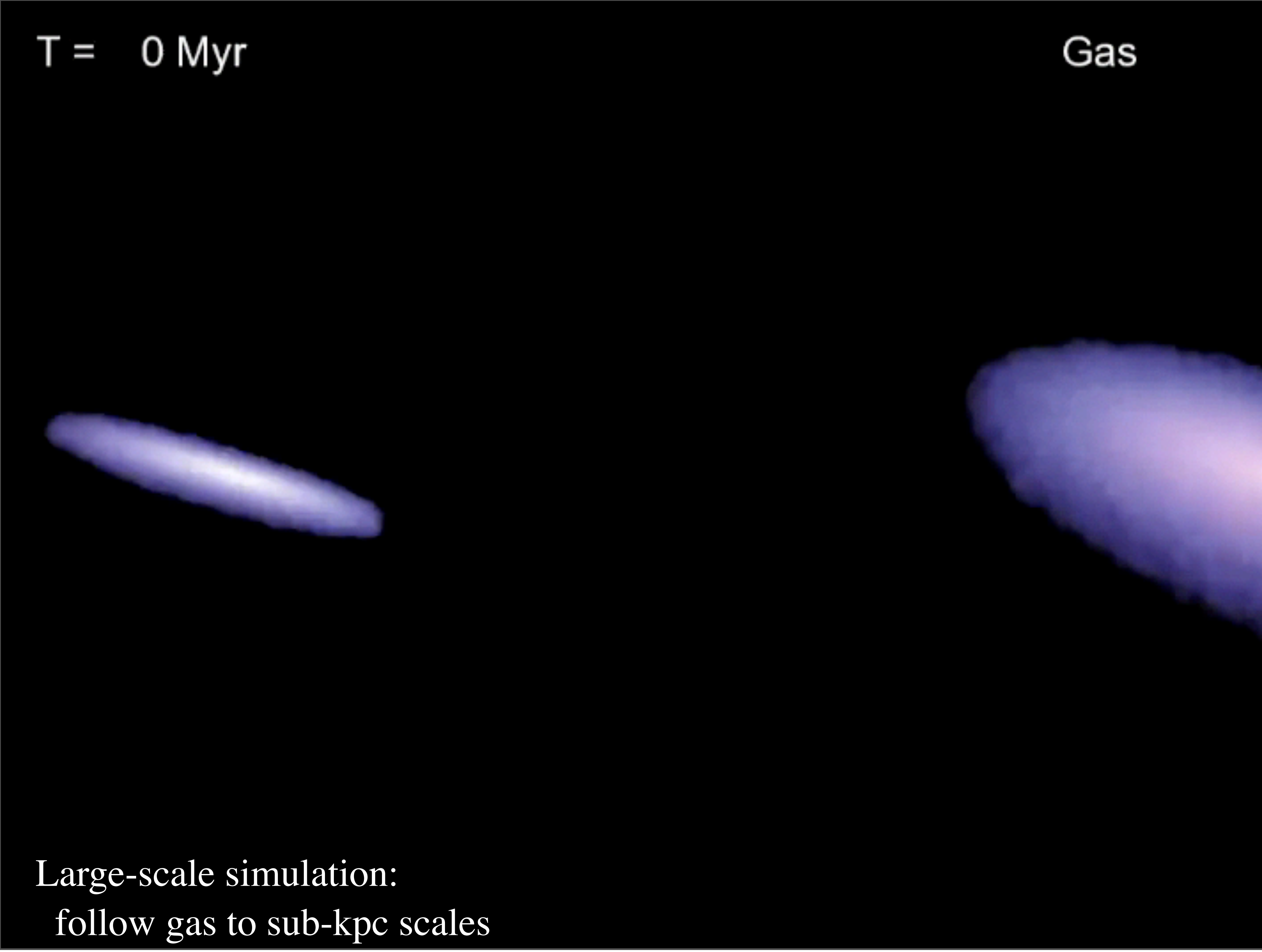
Triggers Starbursts (e.g. Mihos & Hernquist 1996)

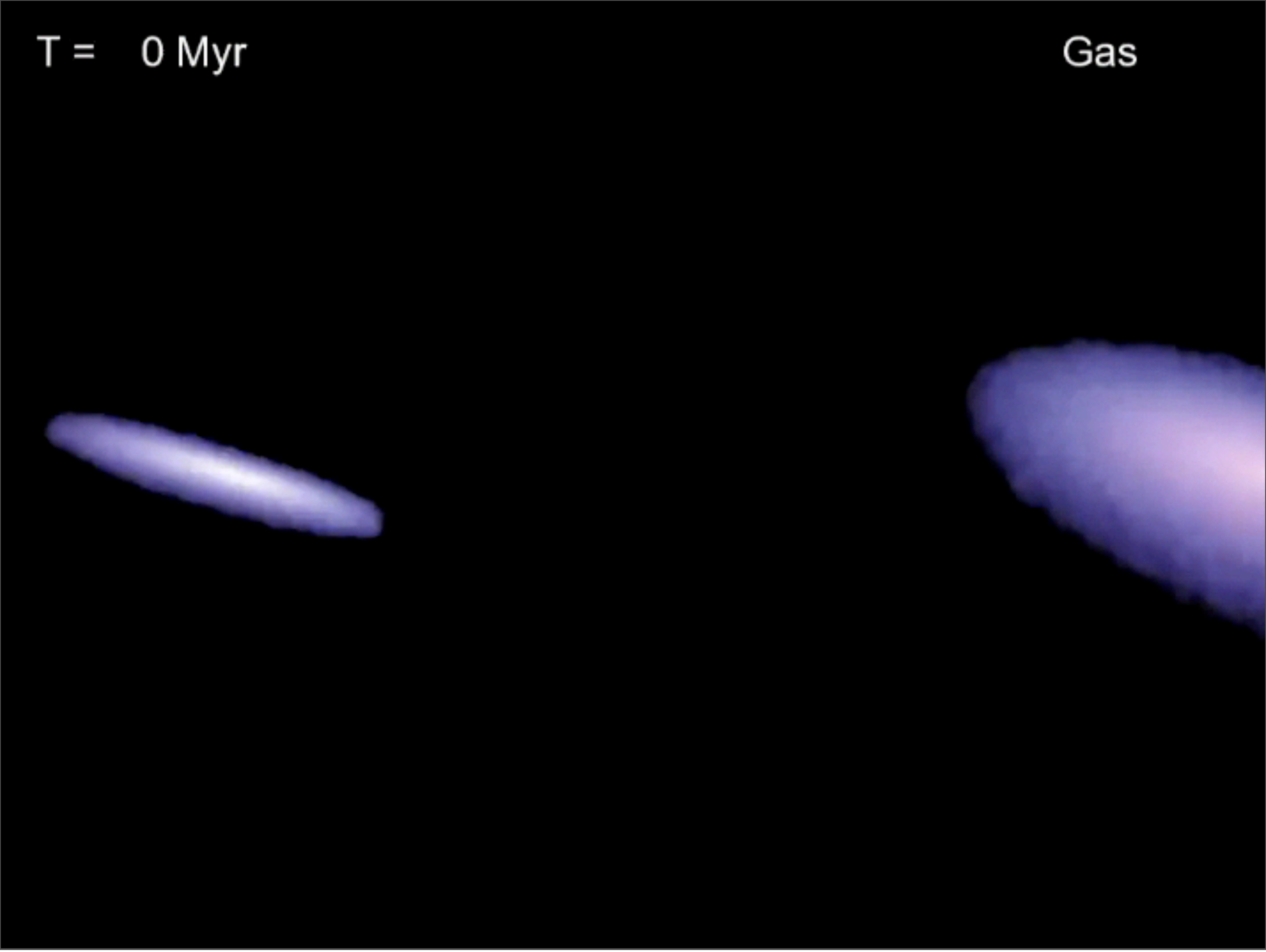

T = 0 Myr
Gas

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
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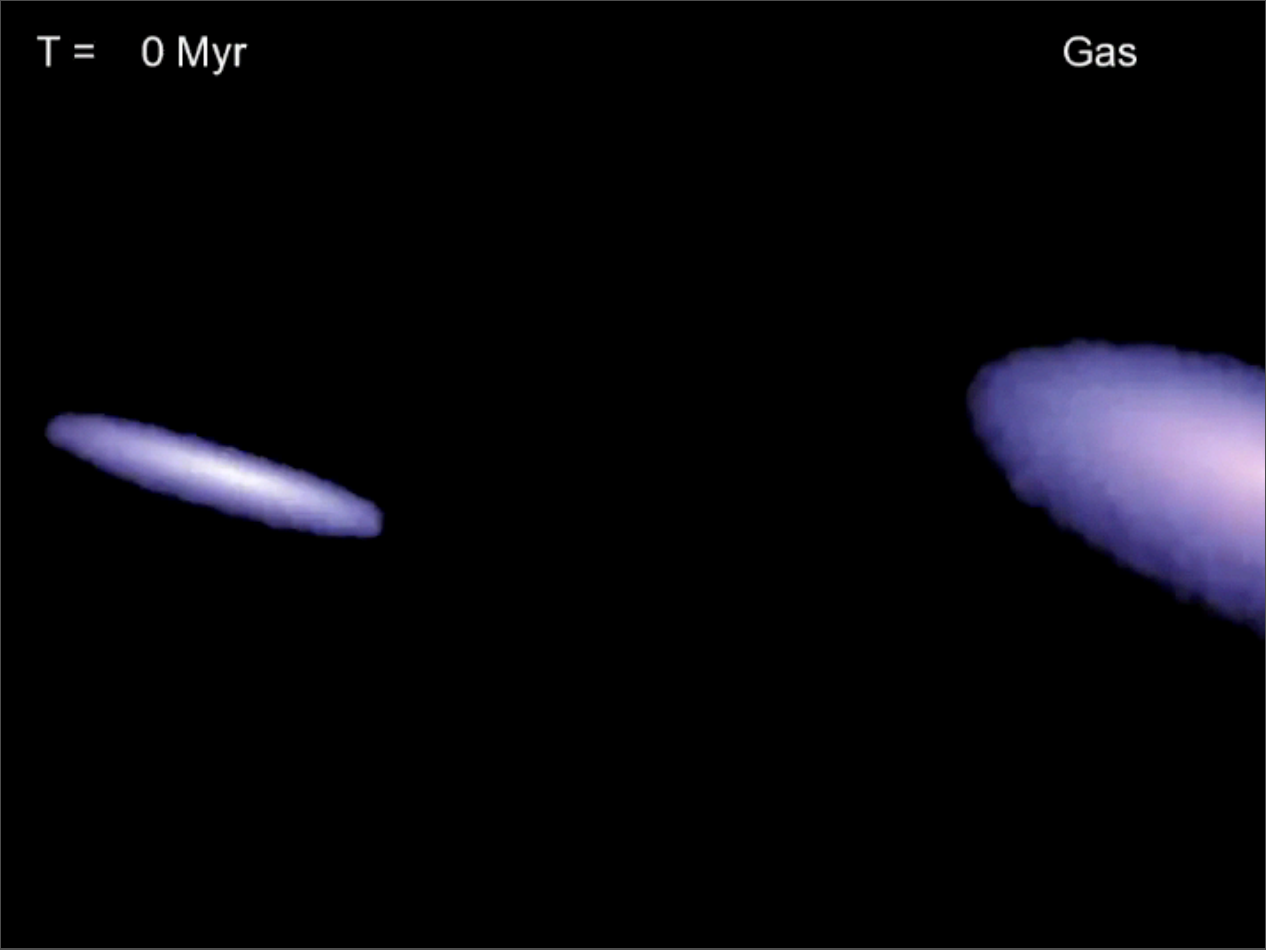
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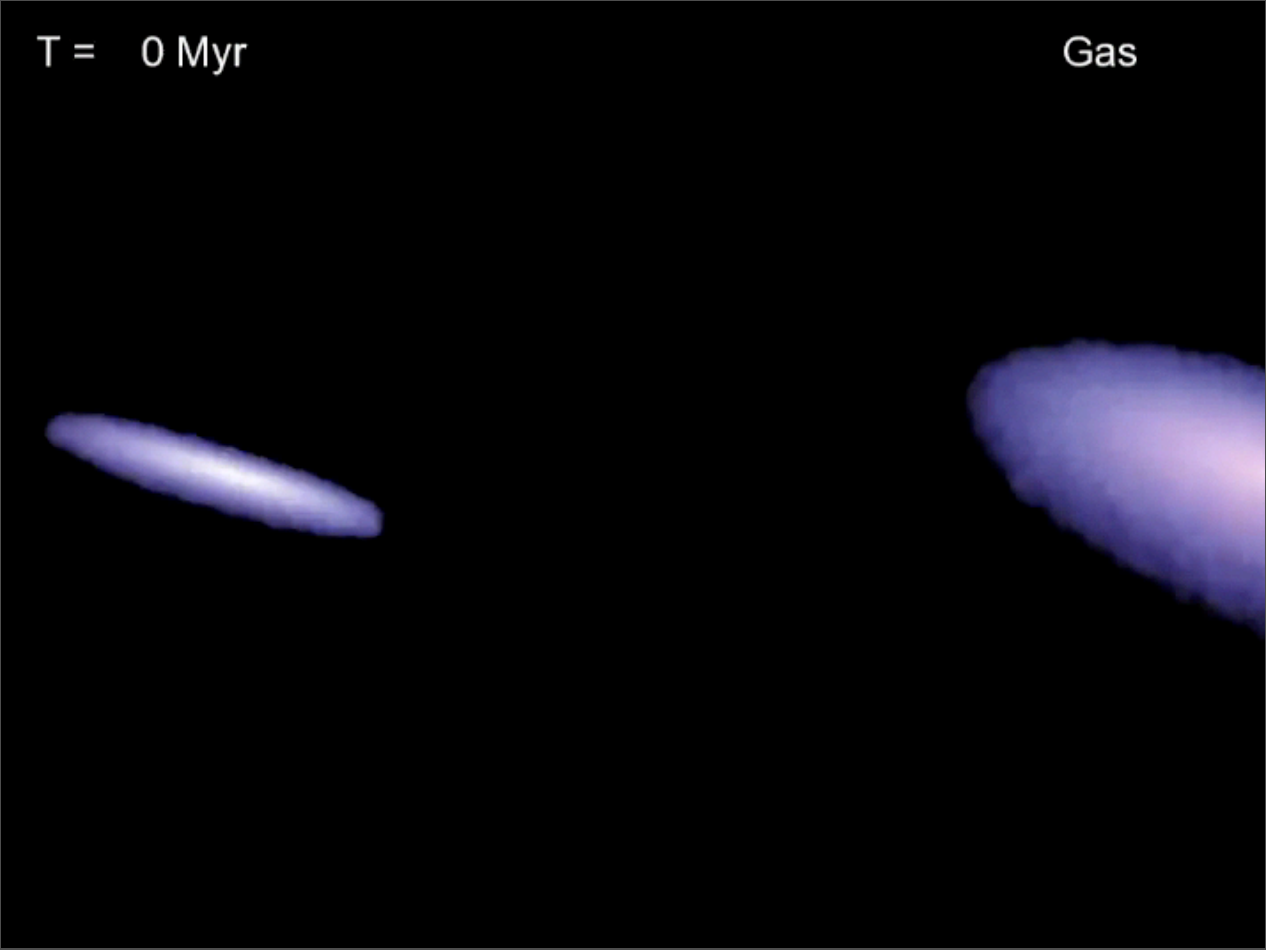
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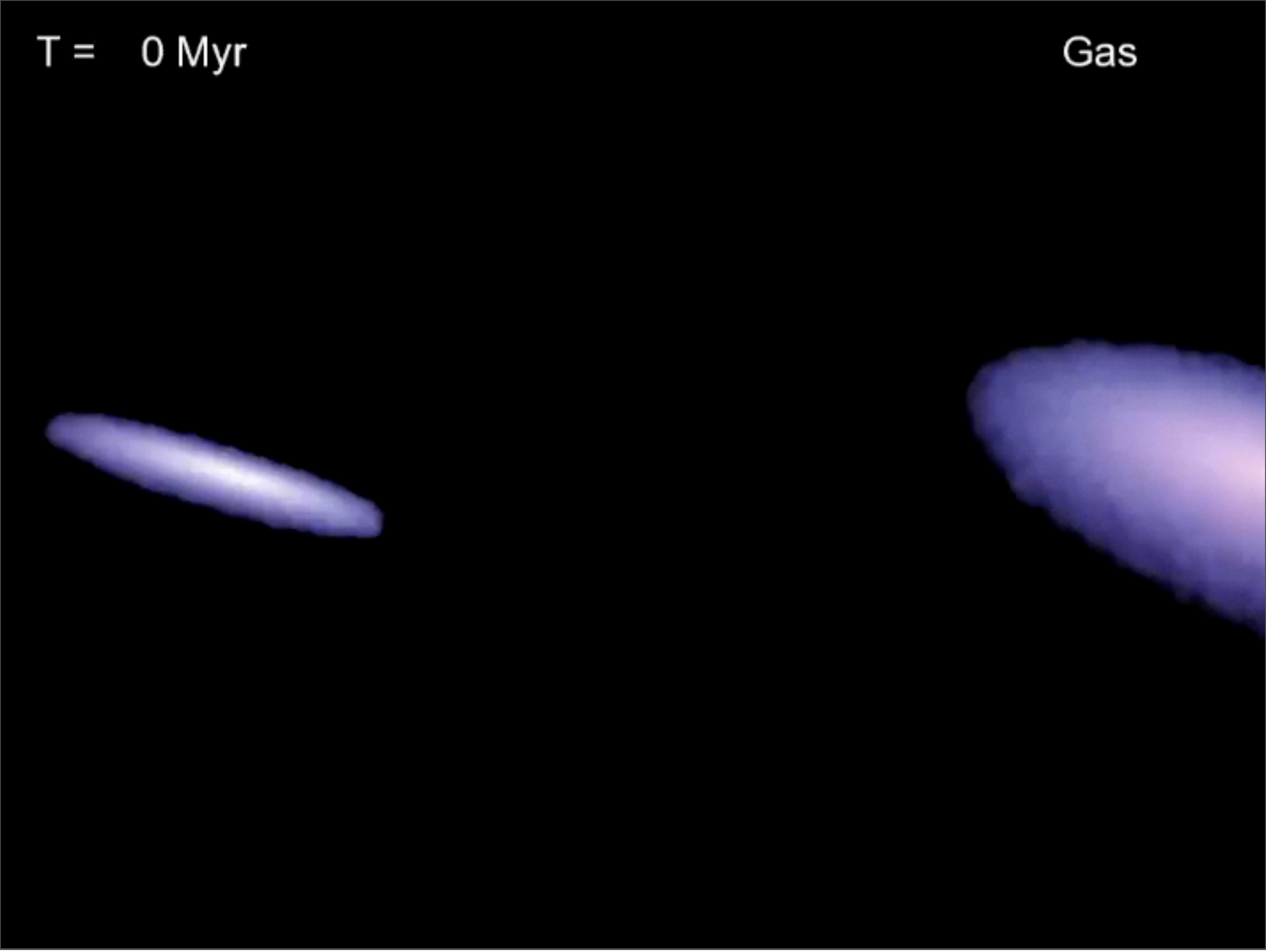
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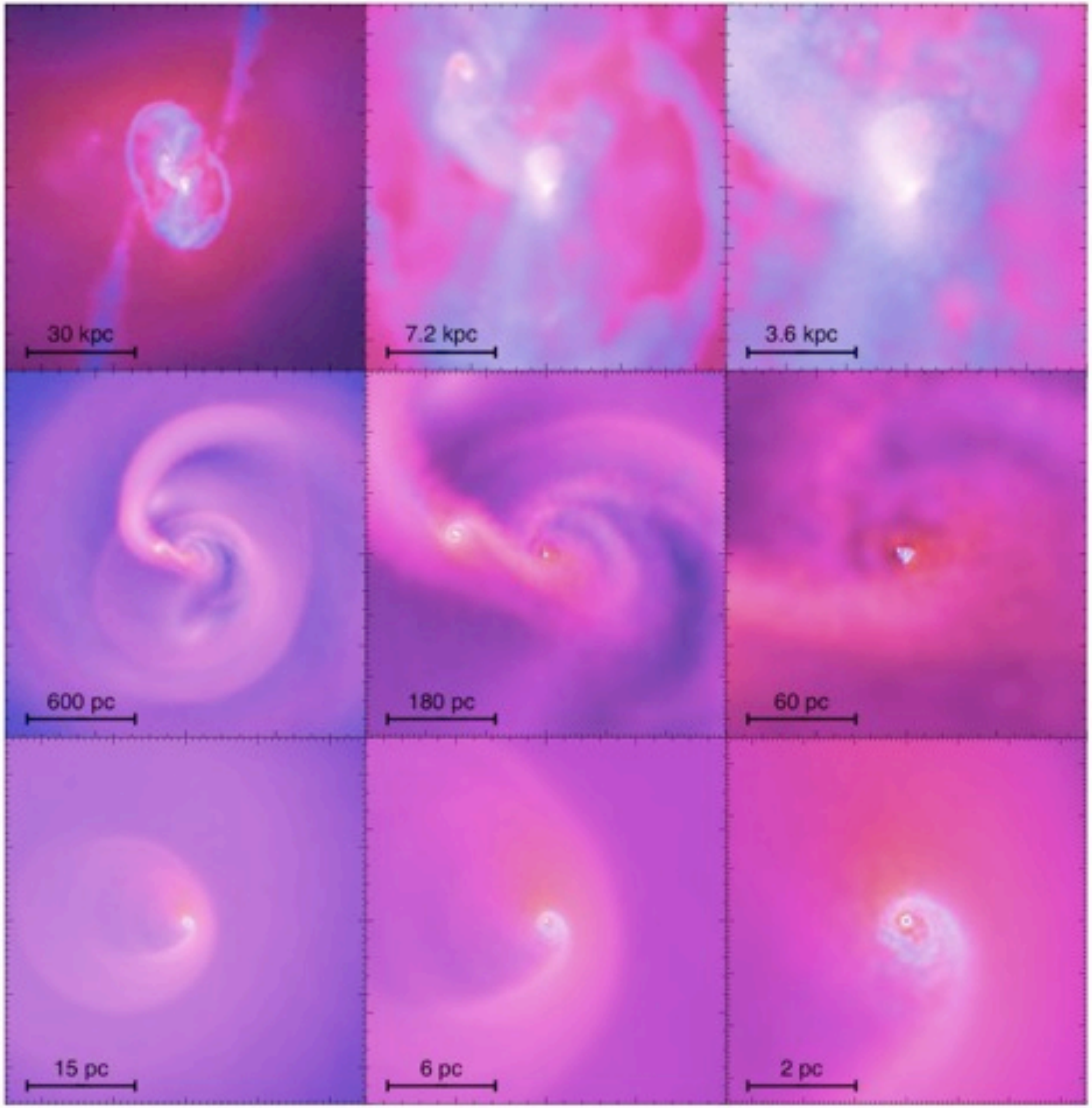
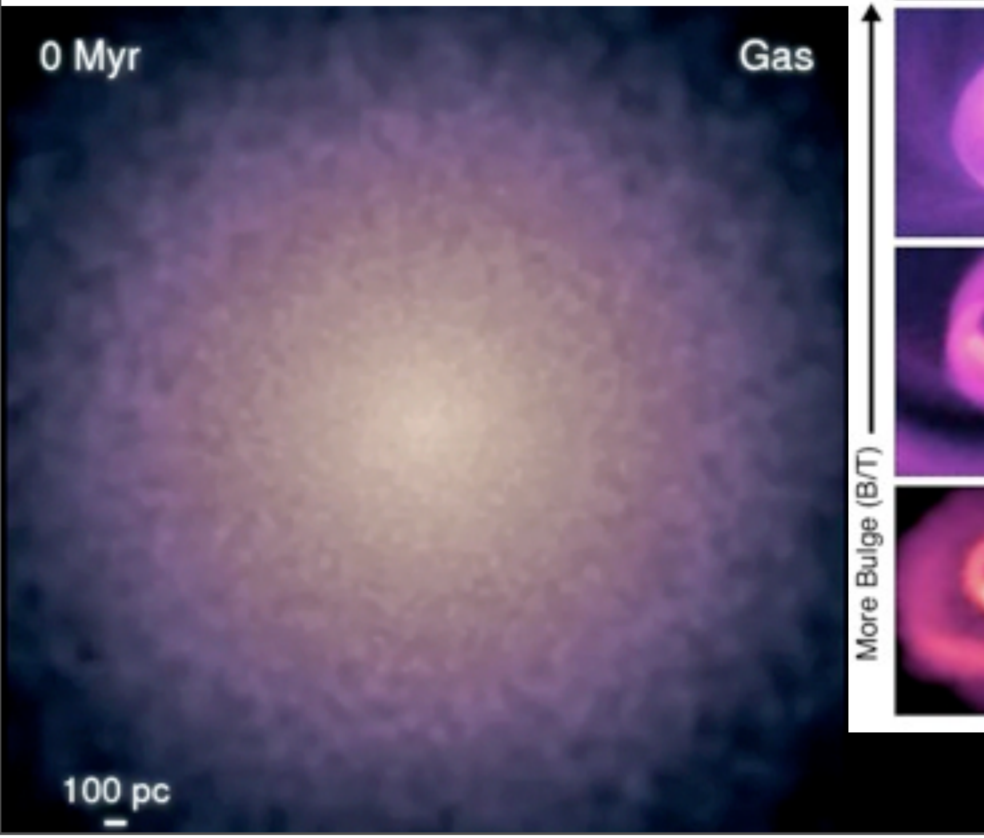
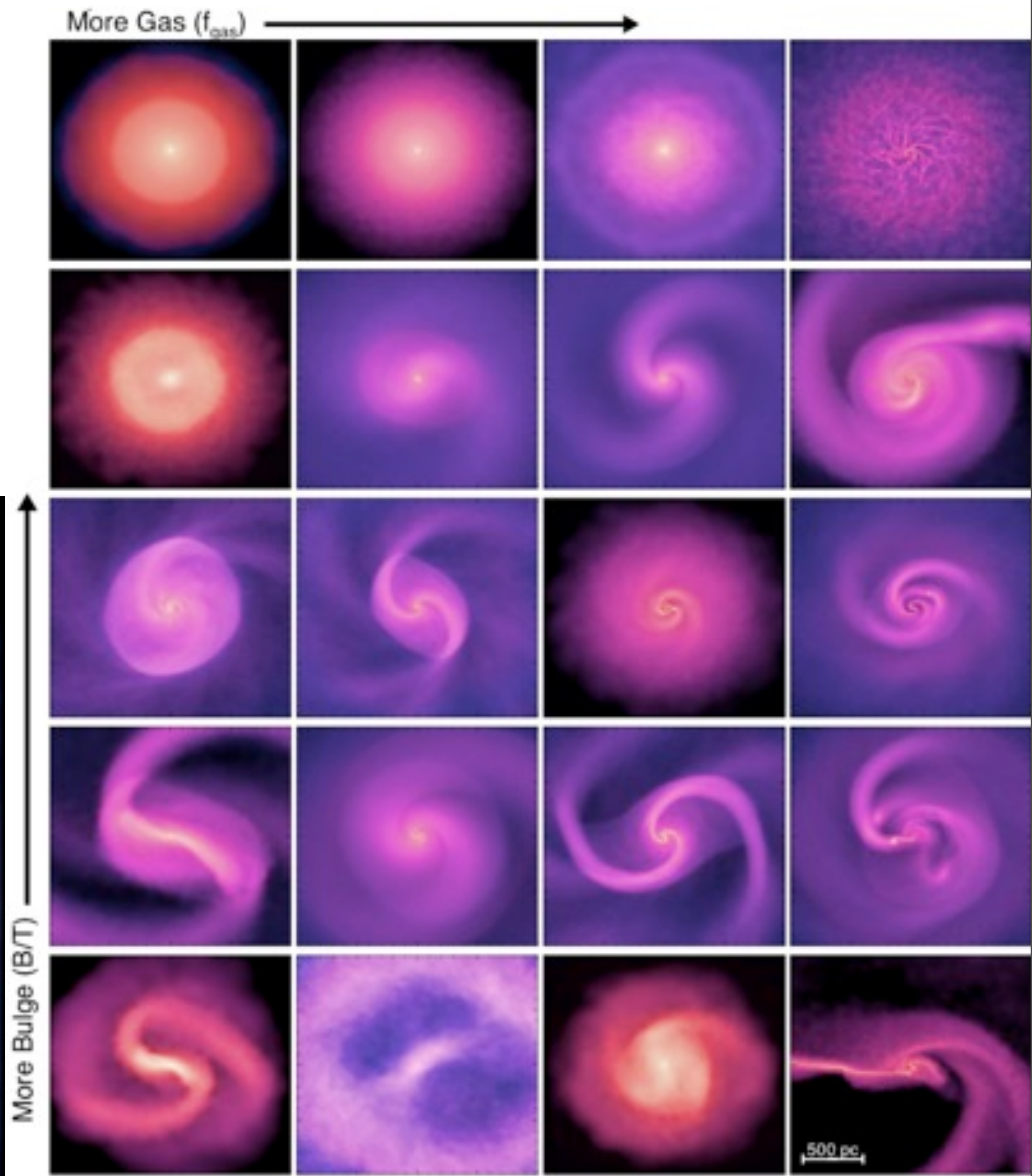


- Cascade of instabilities: merger not efficient inside ~kpc
- *Any* mechanism that gets to similar densities at these scales will do the same
- Instabilities change form at BH radius of influence

Sub-kpc scales: "Stuff within Stuff"

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





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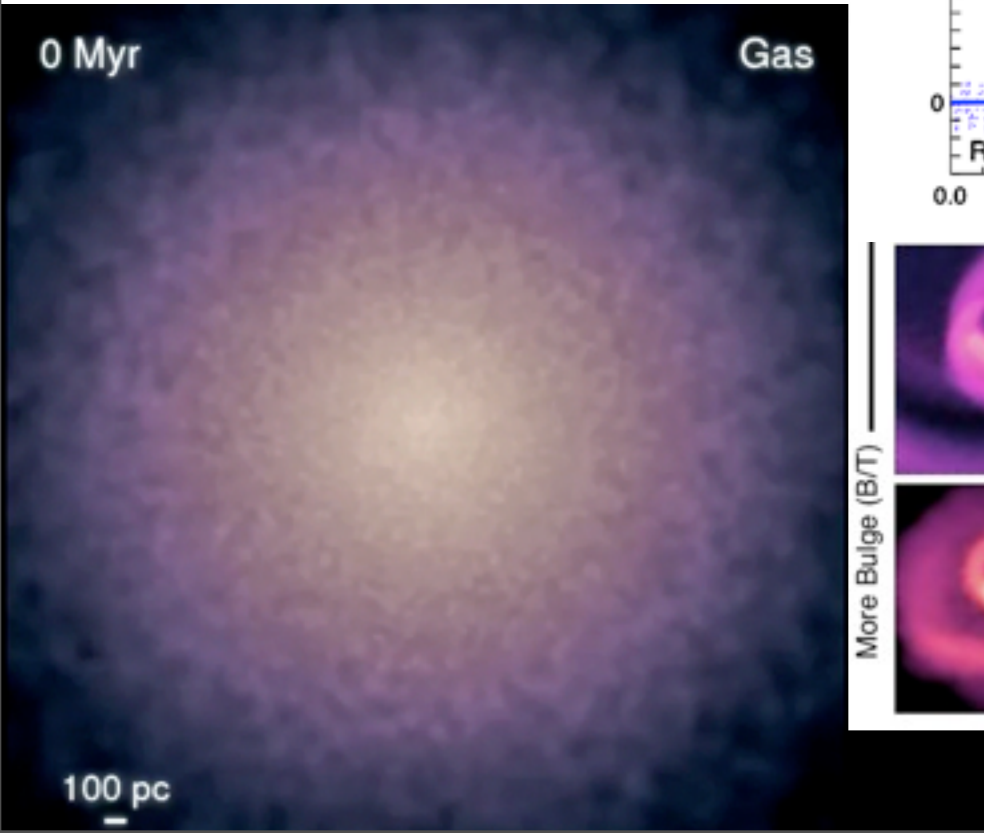
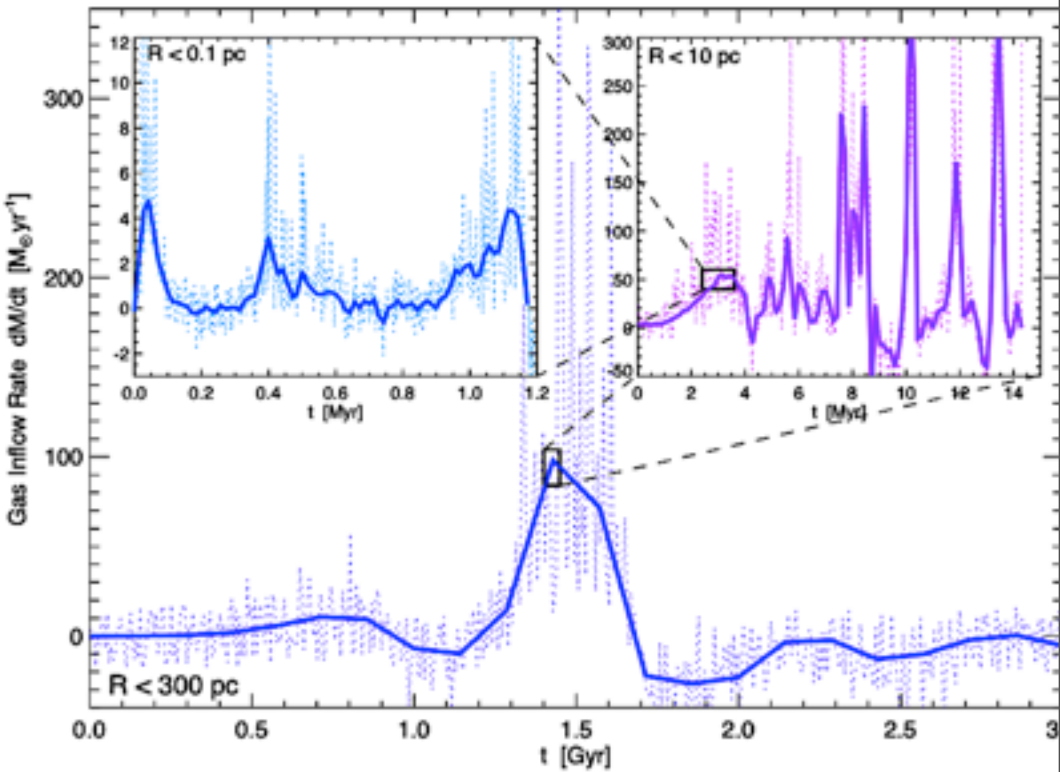
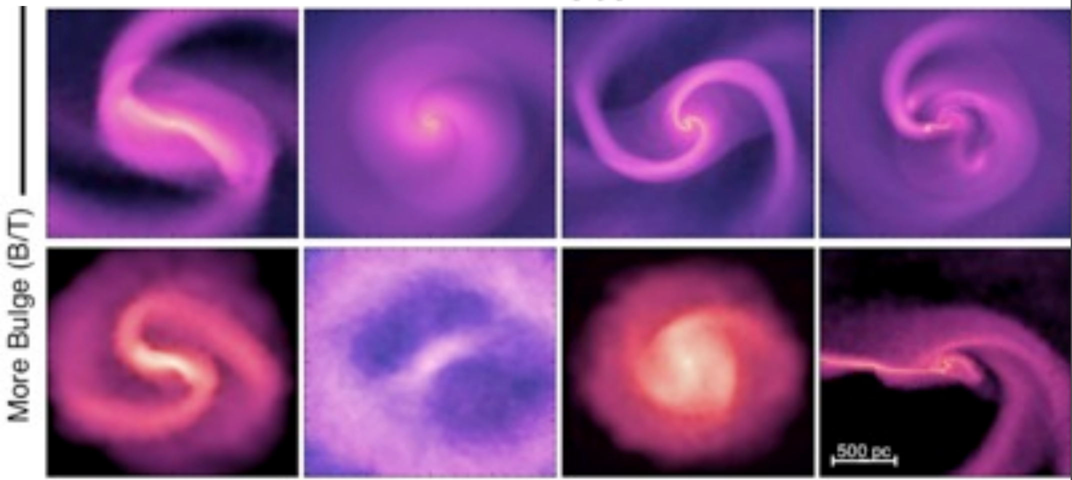
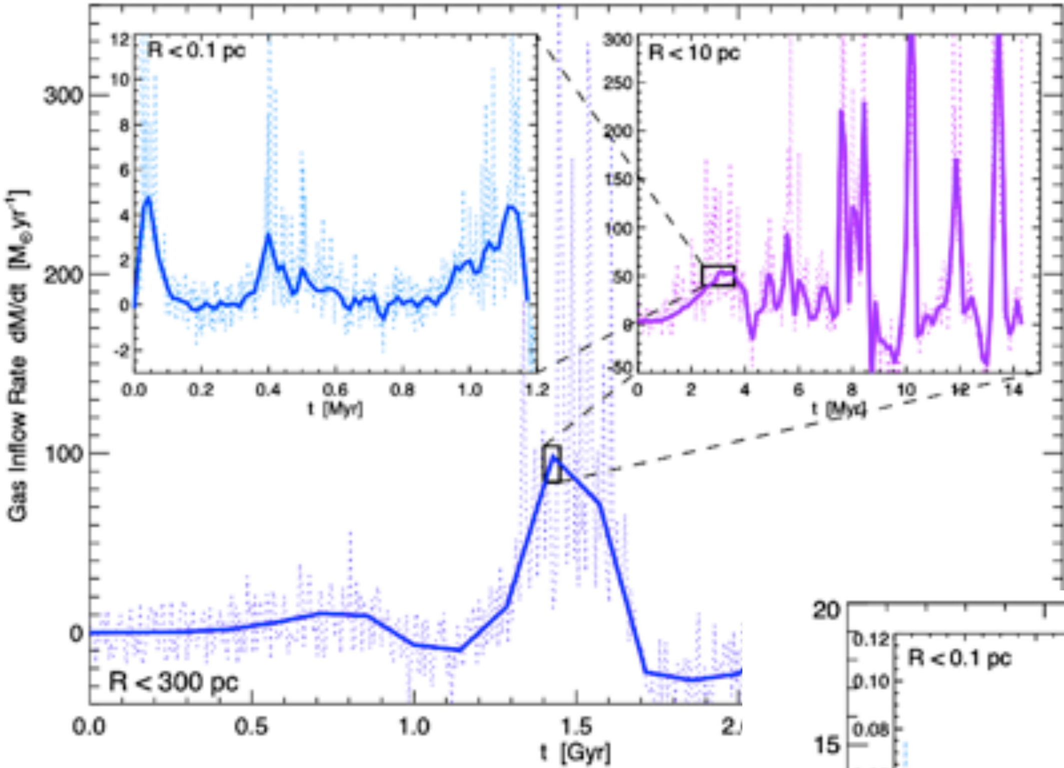


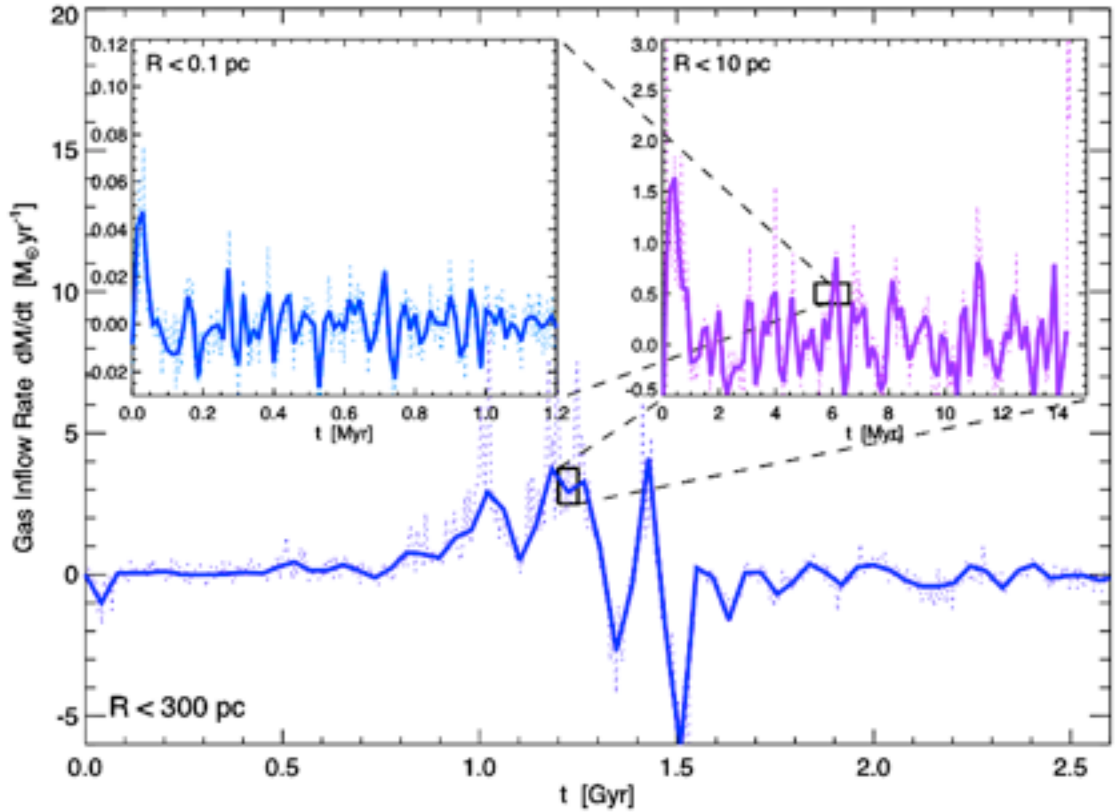




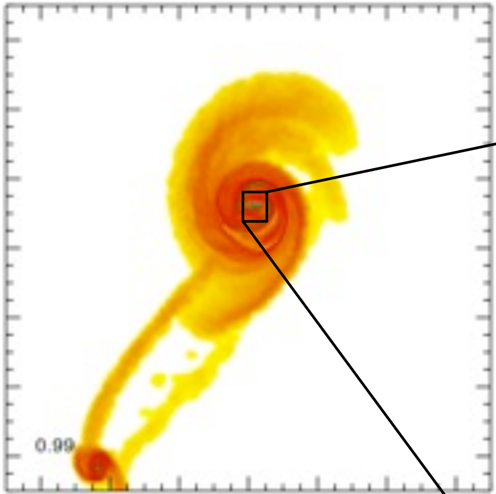


Gas-rich merger
(lots of inflow)

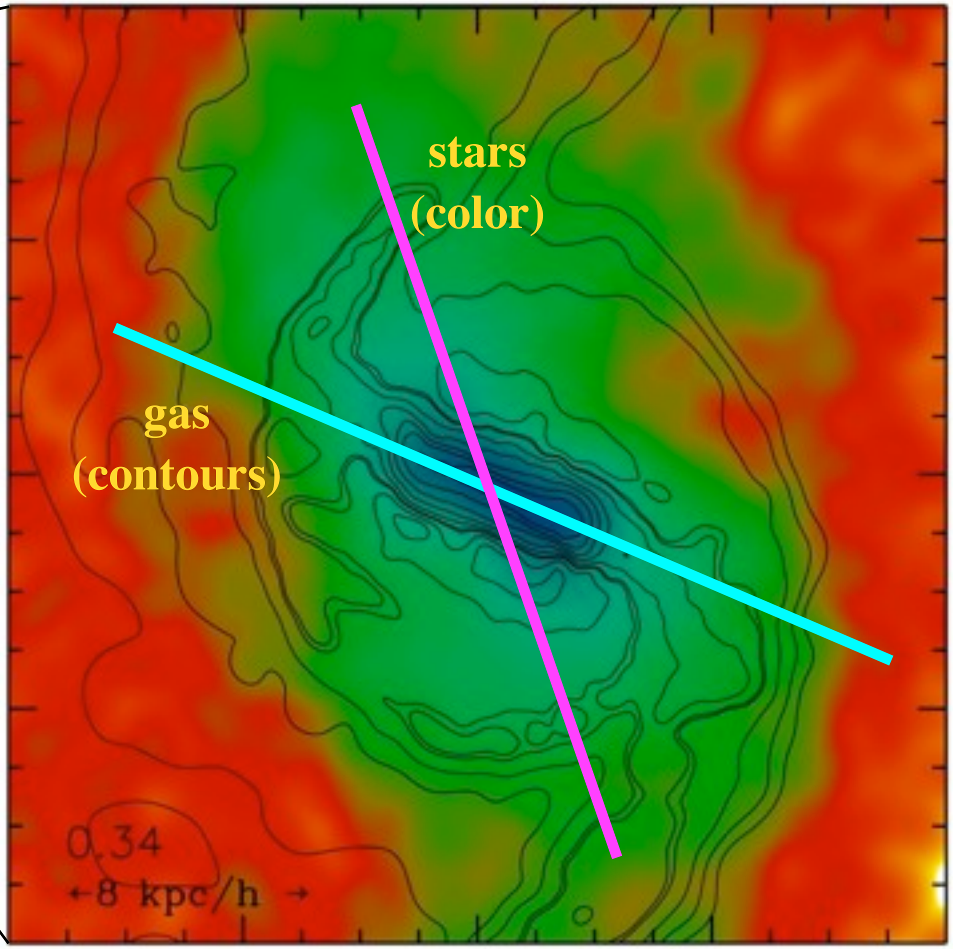
Weakly bar-unstable disk
(less inflow)



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



- *Stars* torquing on *gas*



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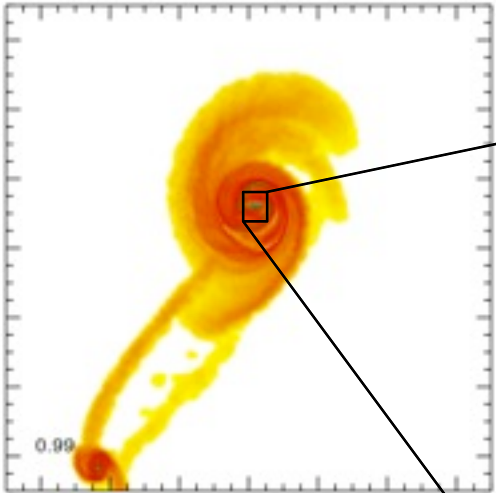

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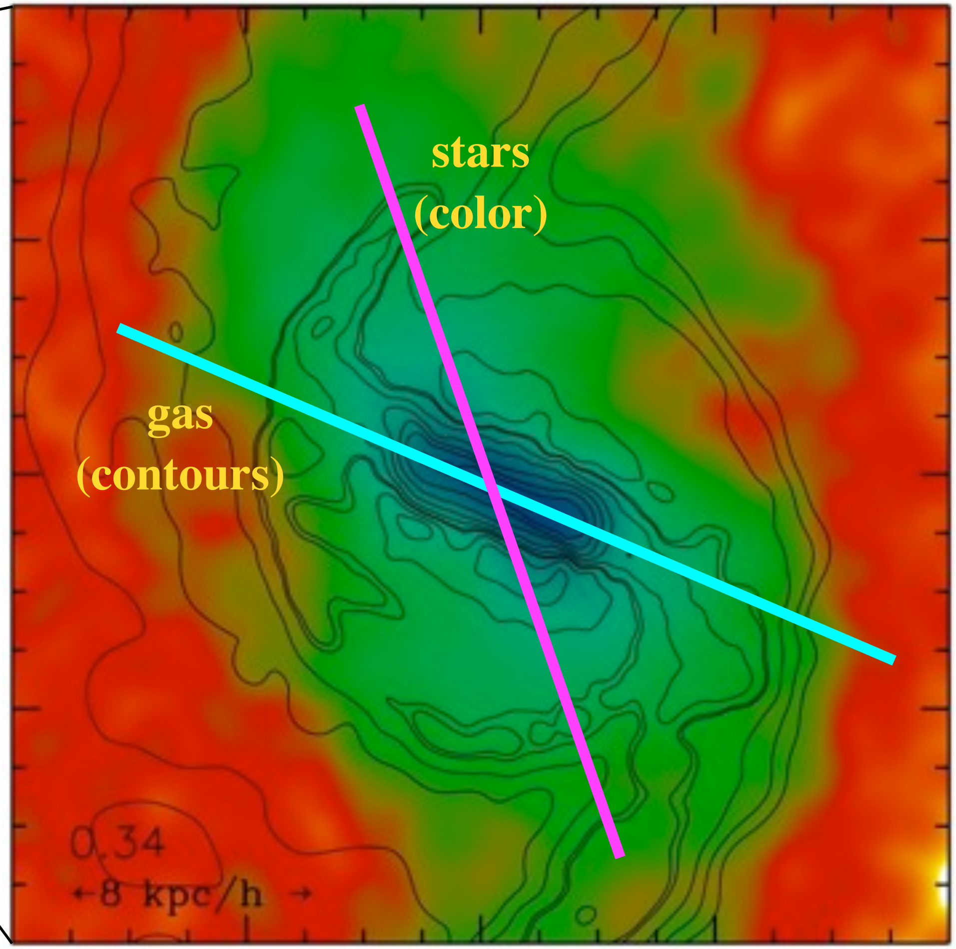
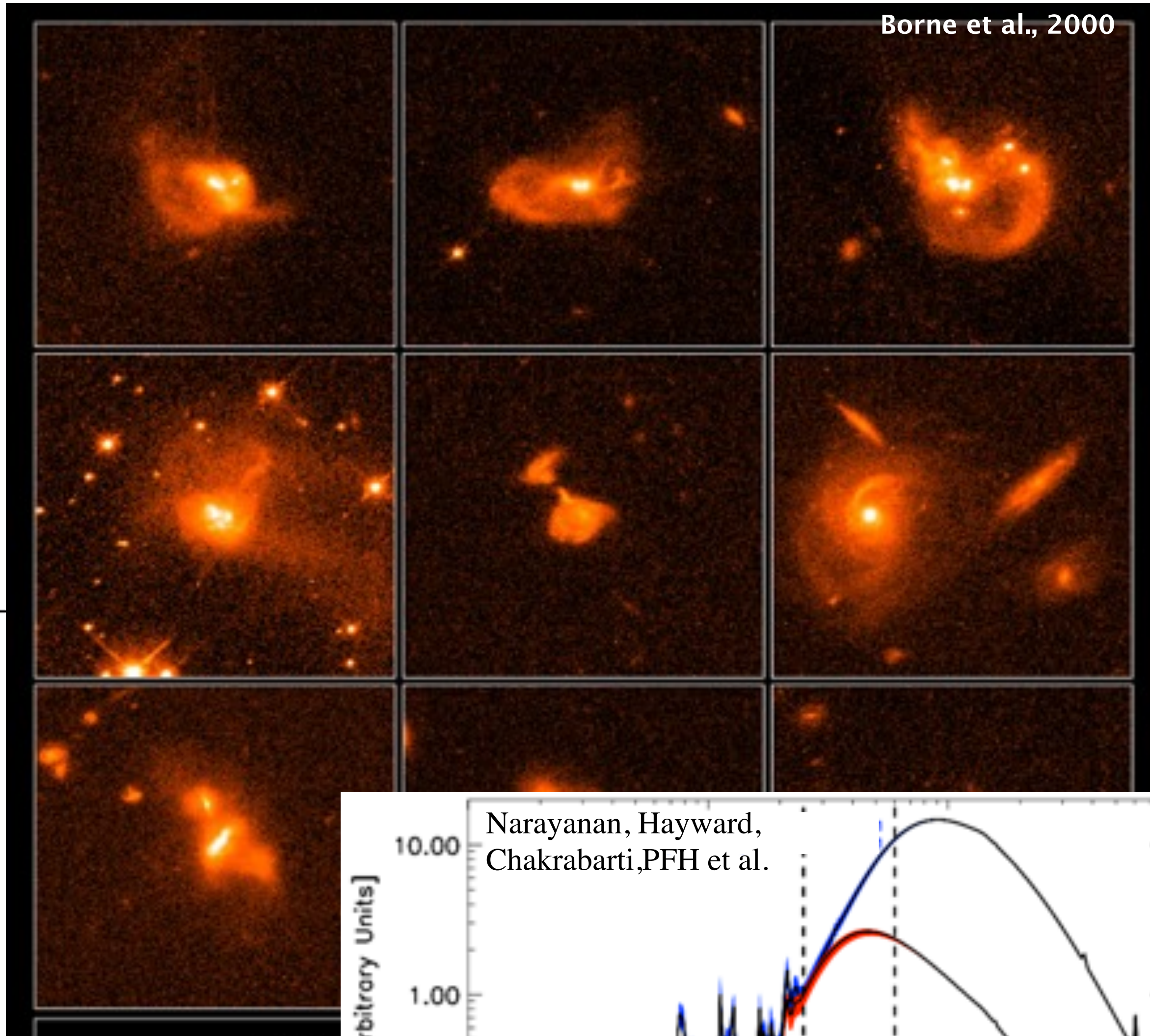


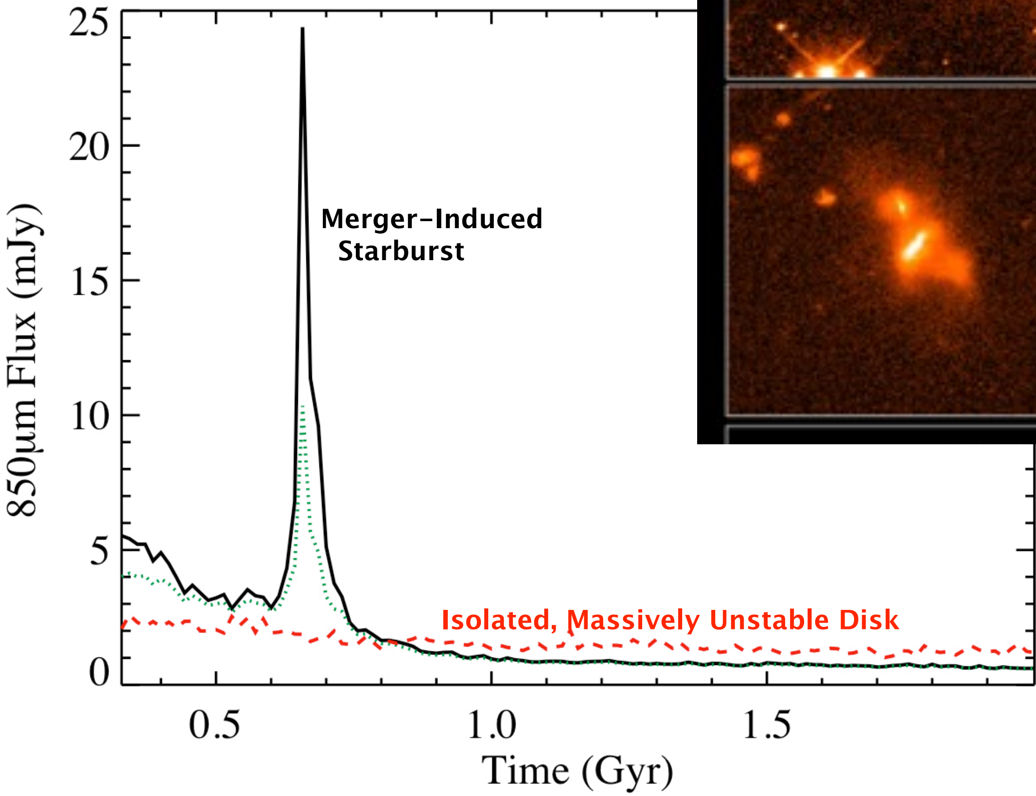
Derive ‘Instability’ Rate:

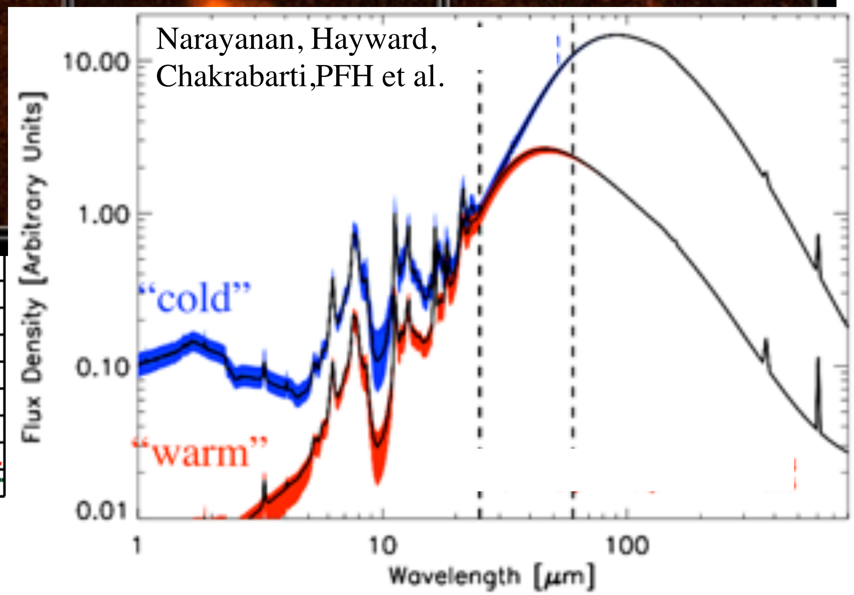
$$\dot{M} \approx 10\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{\mathrm{Disk}}{\mathrm{Total}}\right)^{5/2} M_{\mathrm{BH},\,8}^{-1/6}\, M_{\mathrm{gas},\,9}\, R_{0,100}^{-3/2}$$

Starbursts at kpc-scales:

- Compare local starburst ULIRGs: SFR>100 M_{sun}/yr
  - AGN & cold-warm transition?
- Sub-millimeter galaxies







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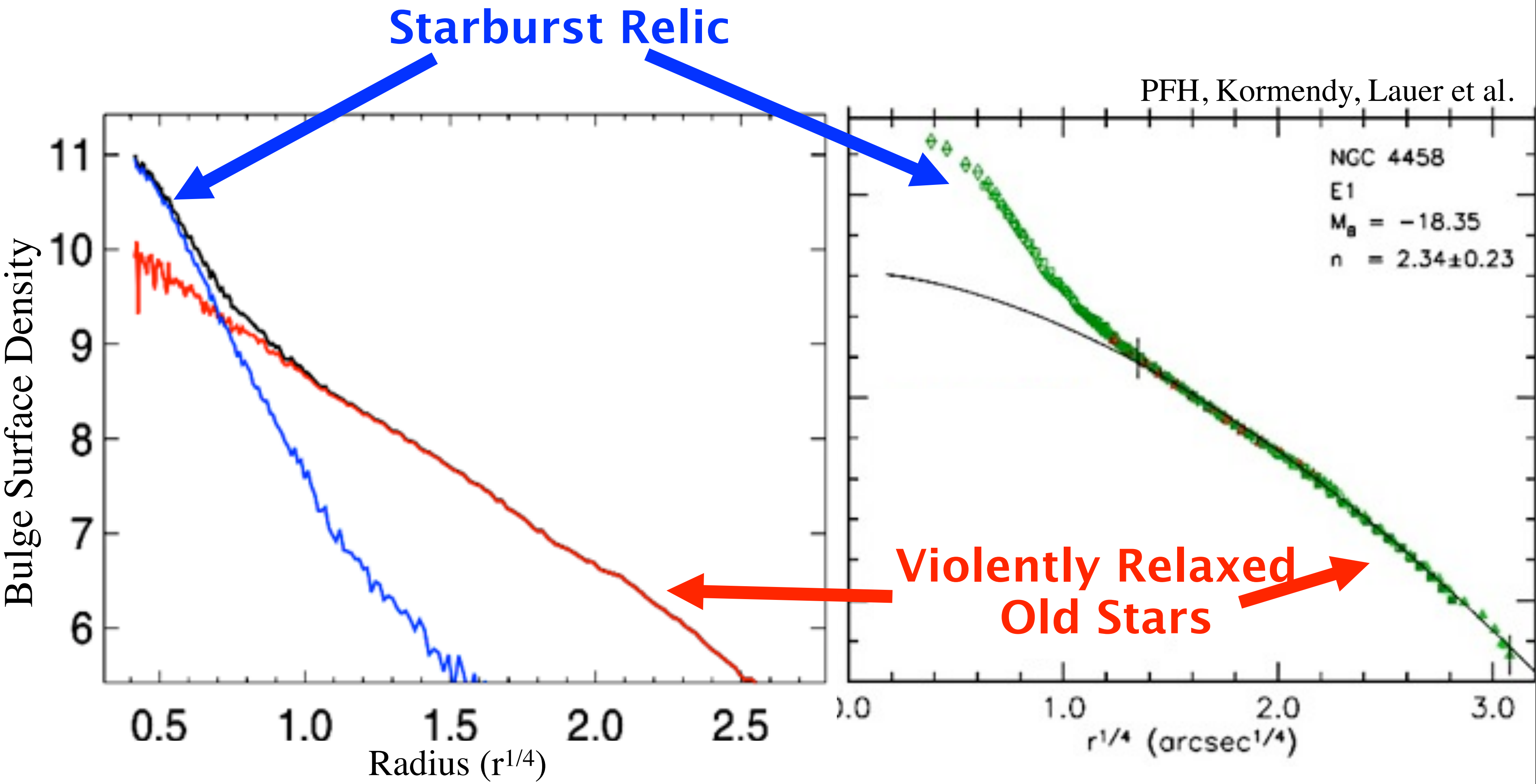

– Dominant effect on bulge structure/formation!

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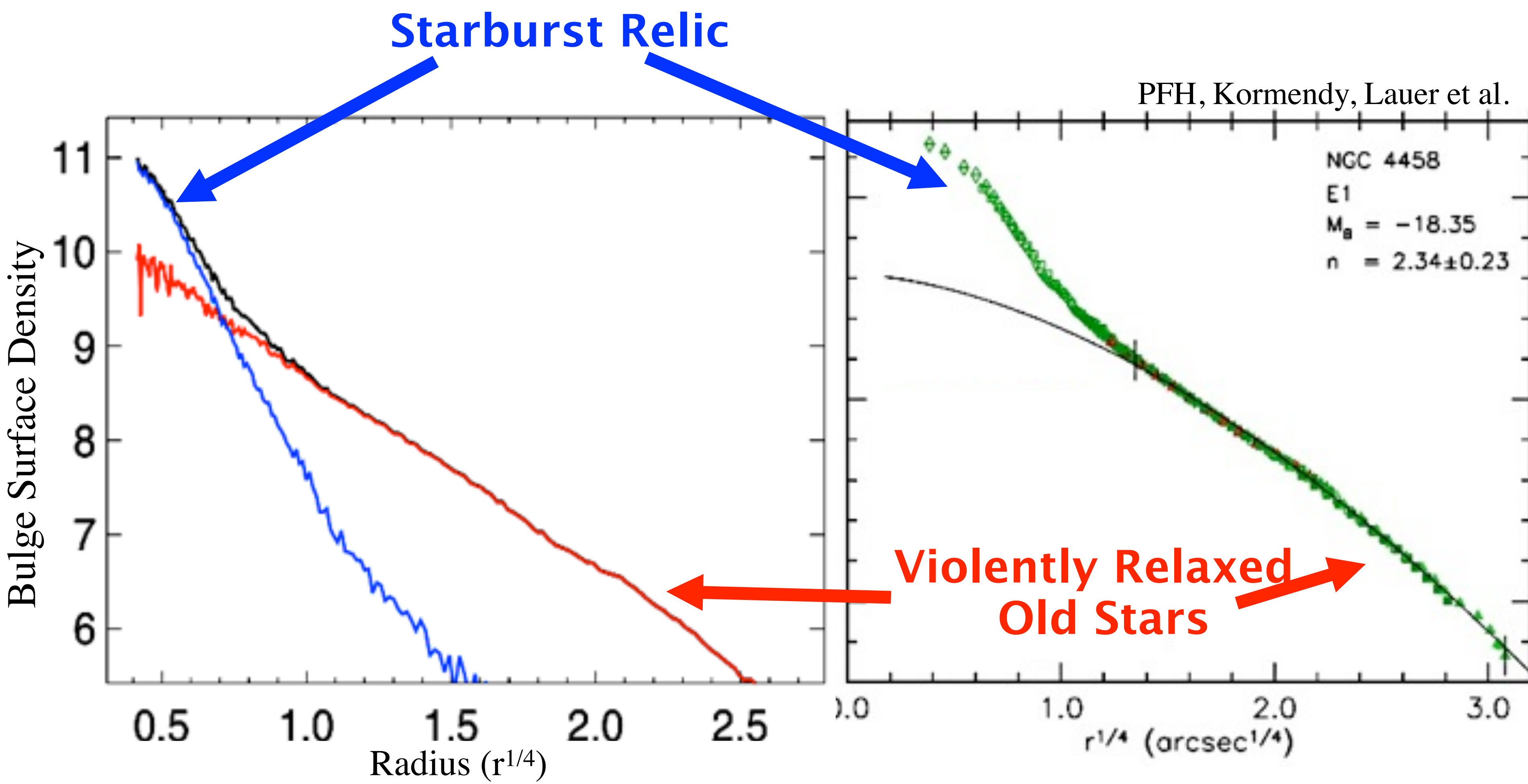


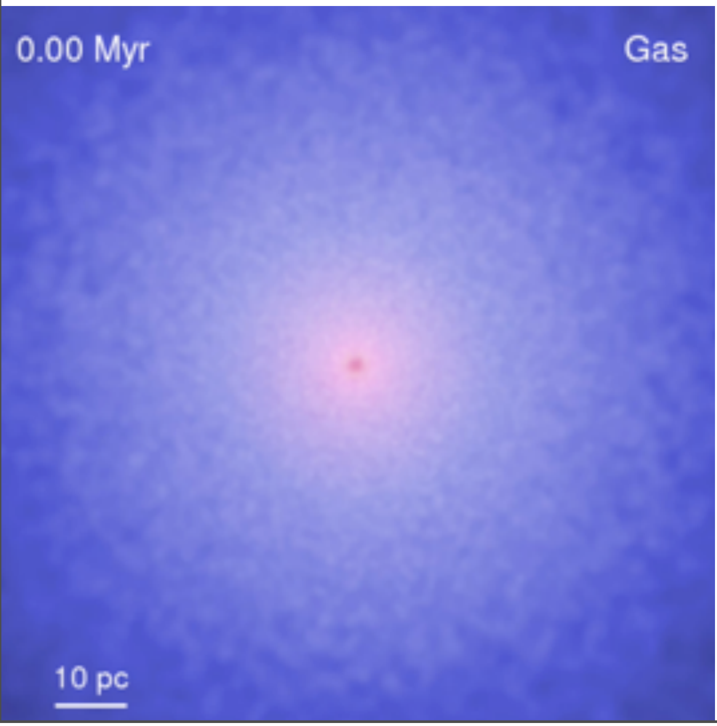
- Dominant effect on bulge structure/formation!
  - kinematics
  - substructure
  - sizes
  - shapes
  - phase-space densities
  - metallicities (+profiles)
  - fundamental plane
  - redshift evolution

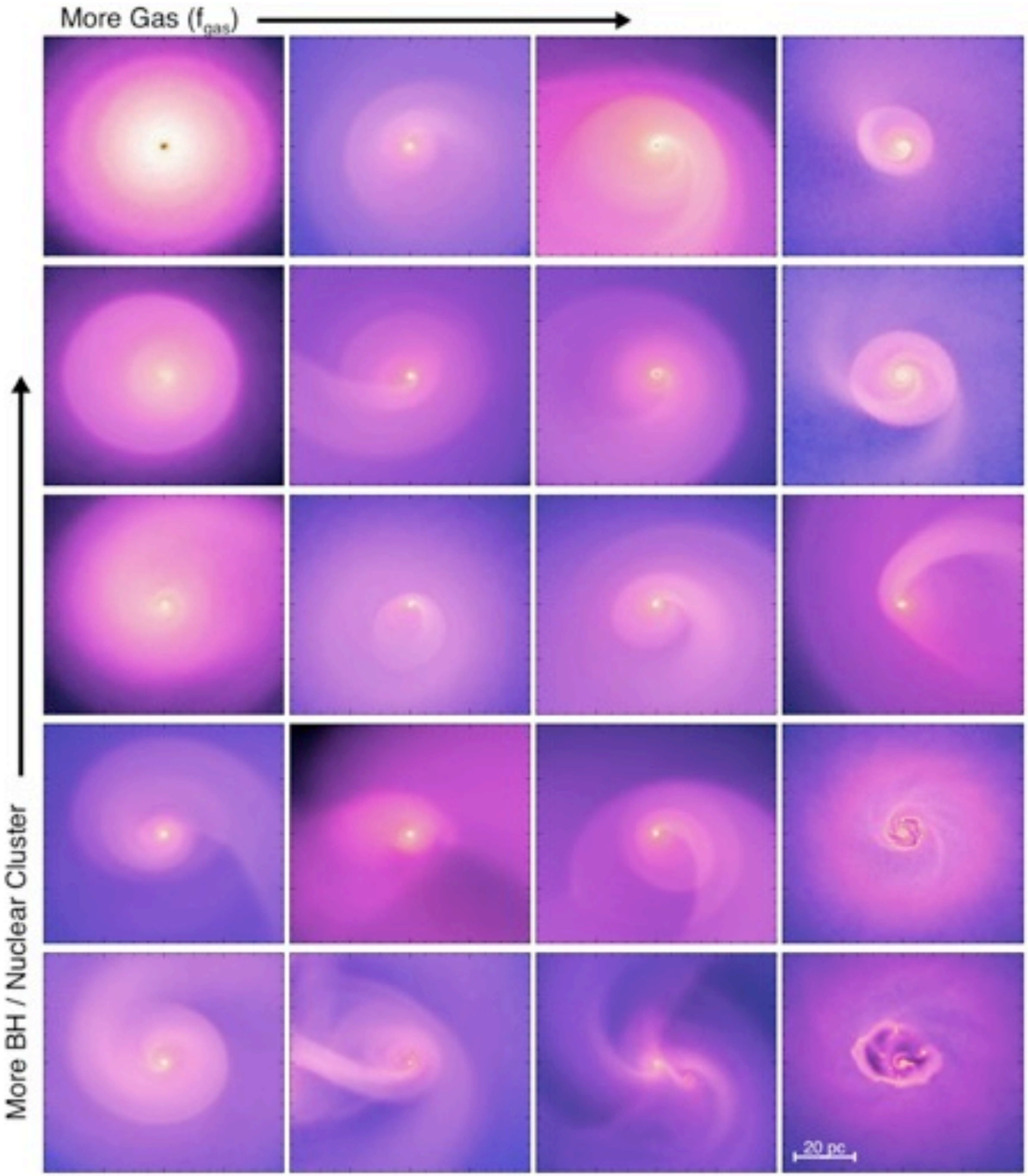
So, what about the “small” scales

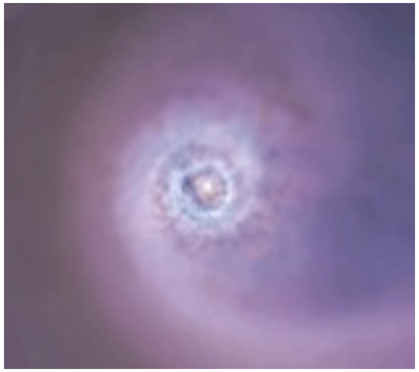
near the BH?

~10 pc scales:
Nuclear eccentric disks

- Inside BH radius of influence: eccentric, precessing disks





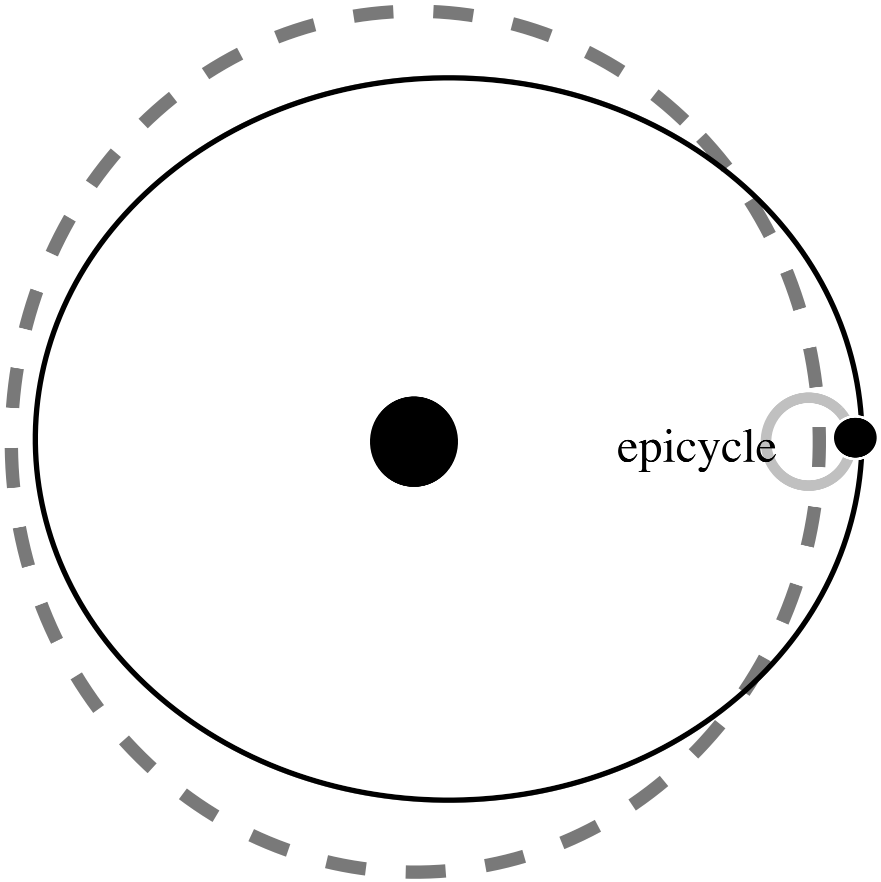


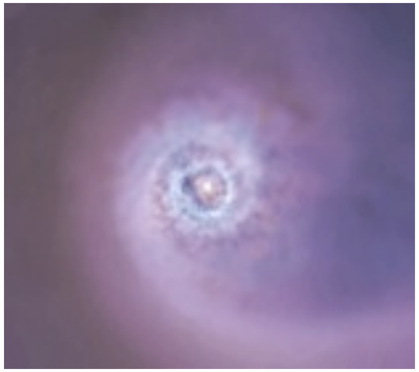
Eccentric/lopsided disks (m=1 modes) are special in a near-Keplerian potential

Keplerian potentials are special:

$$\kappa = \Omega$$

Hence, closed elliptical orbits!





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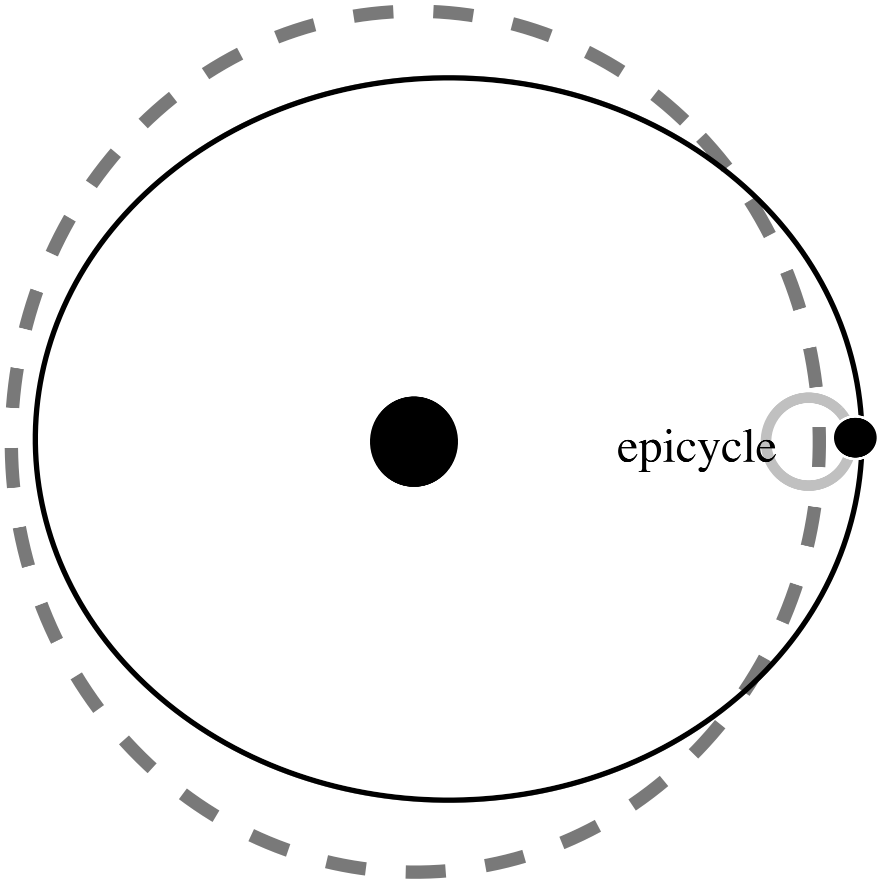
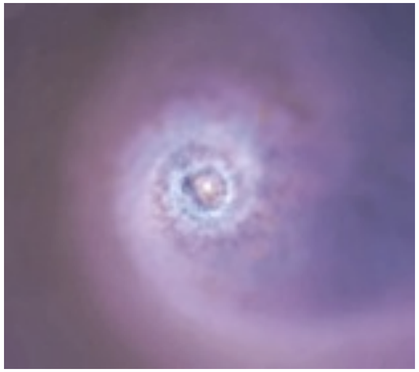
Disturb the stars with some perturbation in the disk:

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





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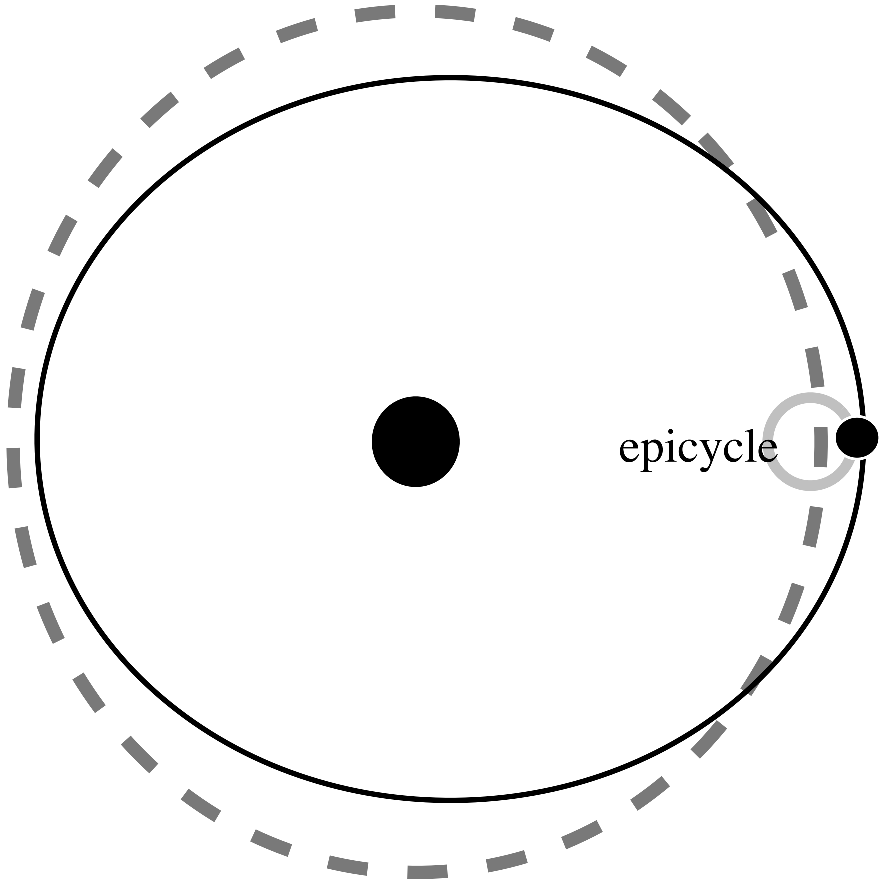
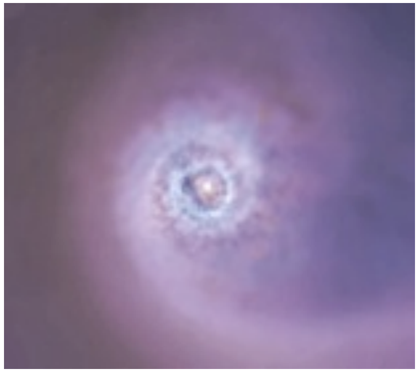
$$\left|\frac{\delta v}{V_c}\right| \sim \left(\frac{\delta\Sigma}{\Sigma}\right) \frac{M_{\rm disk}(<r)}{M_{\rm BH}}$$





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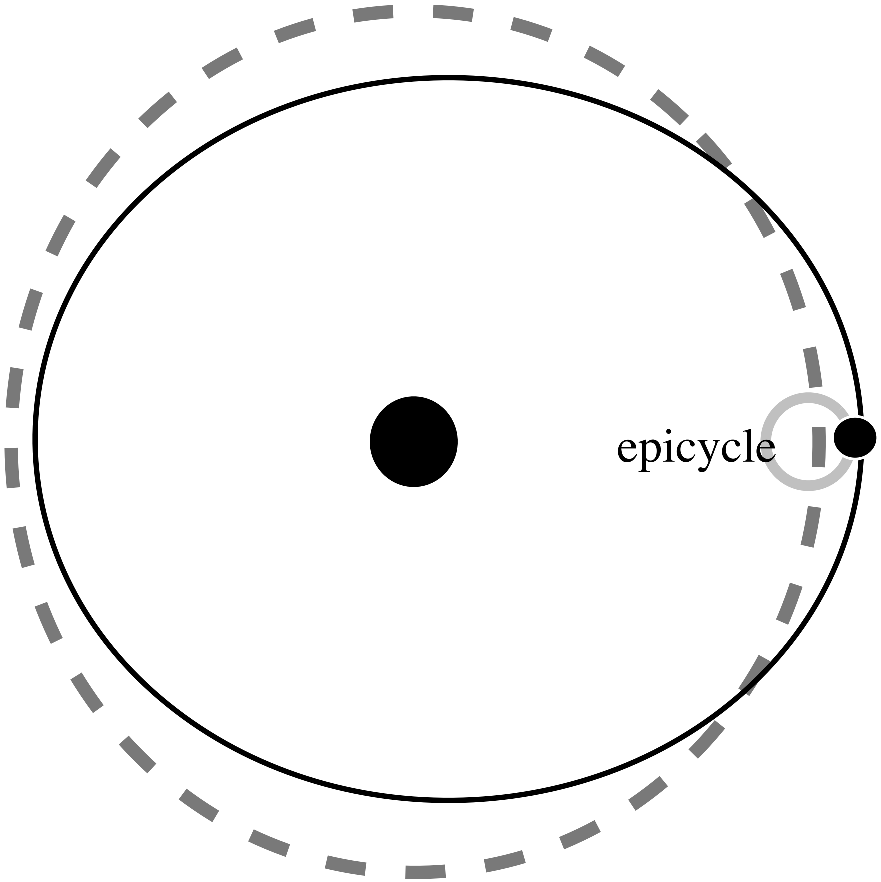
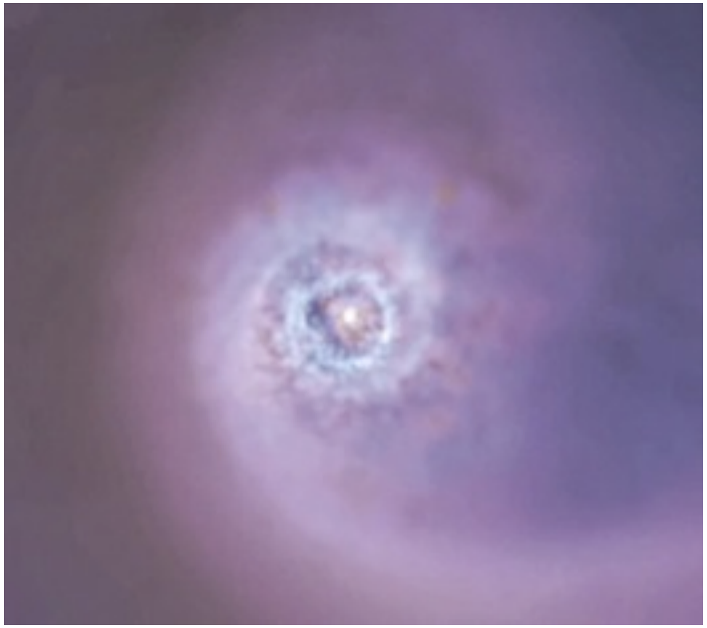
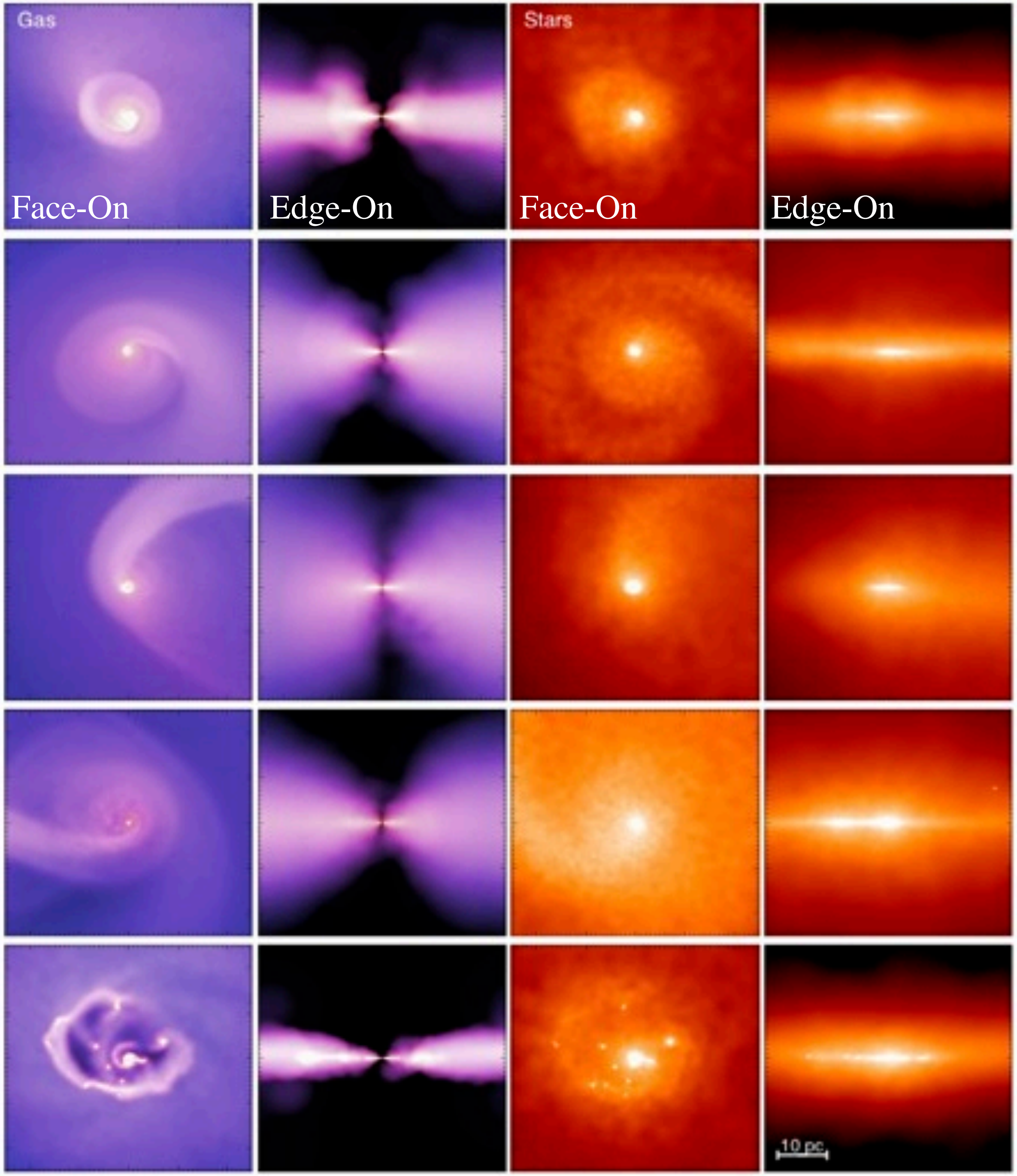
But, if (and *only* if) m=1:

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





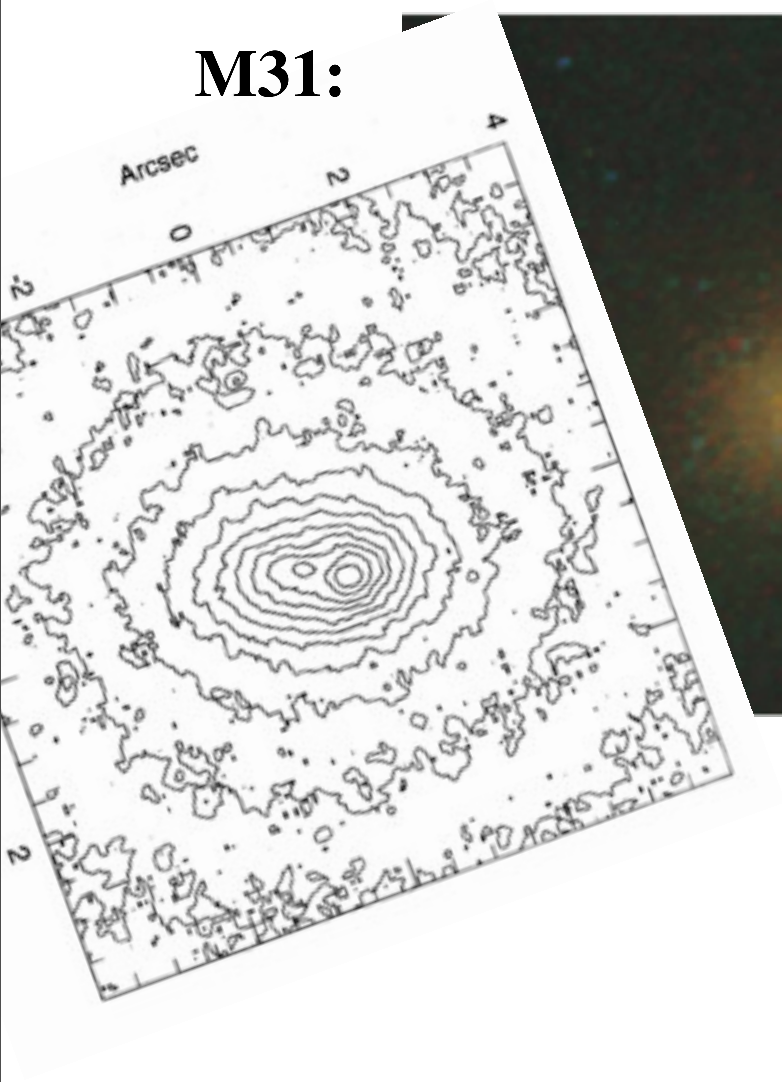


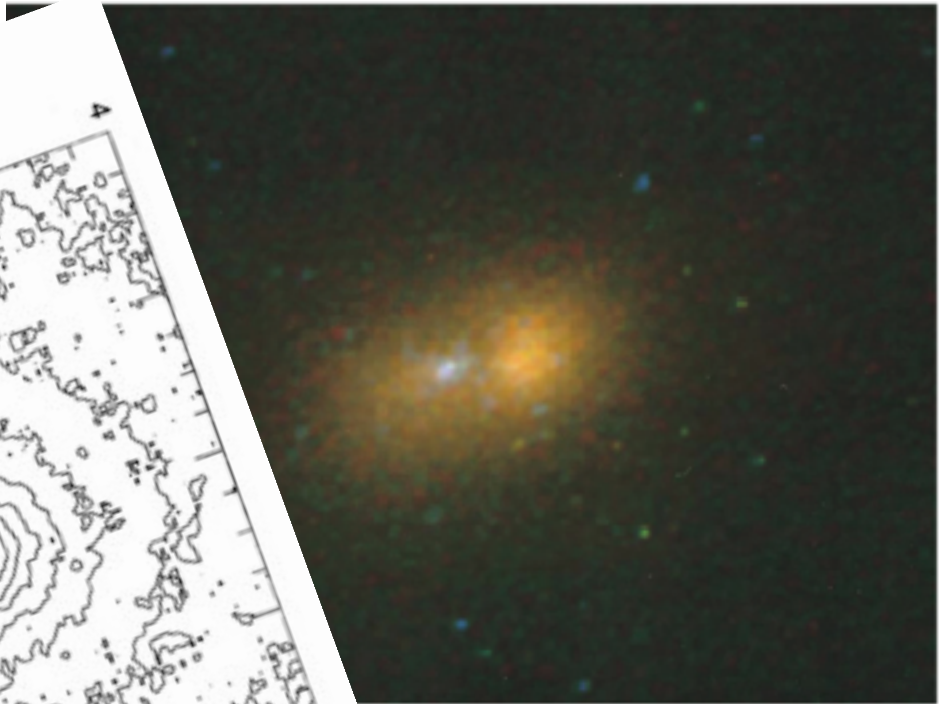
- Torques
  drive up to ~10 M_{sun}/yr
  inflow rates!

- Leave relic stellar disks?

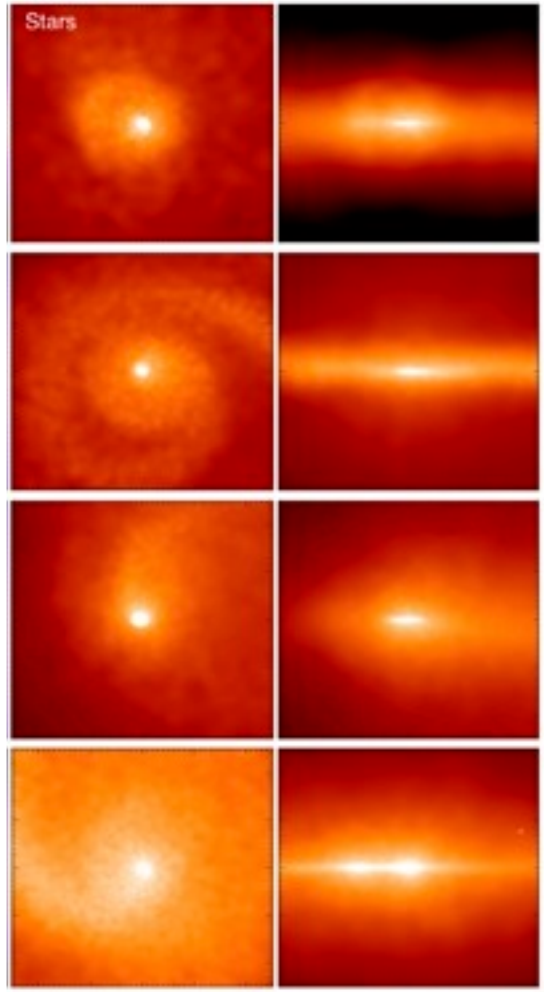
- These are observed!
  M31, NGC4486B, many candidates
  (NGC 404,507,1374,3706,4073,4291,4382,5055,5576,7619, VCC128, M32,83)

M31:





Lauer et al. 1993
Kormendy & Bender 1999



- 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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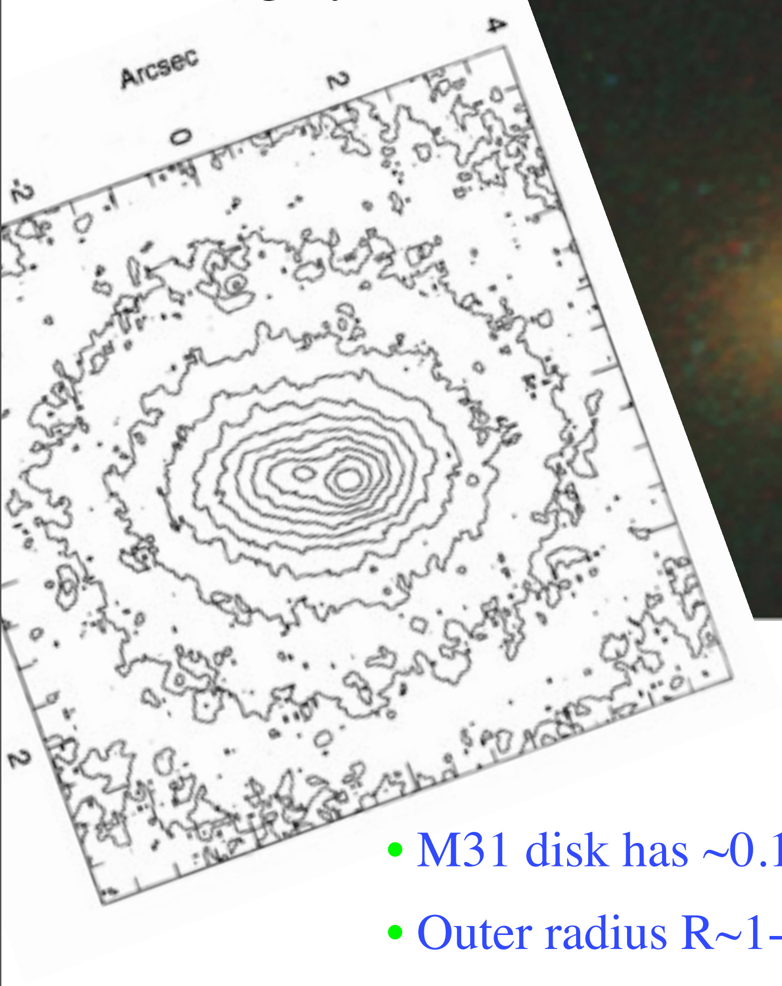
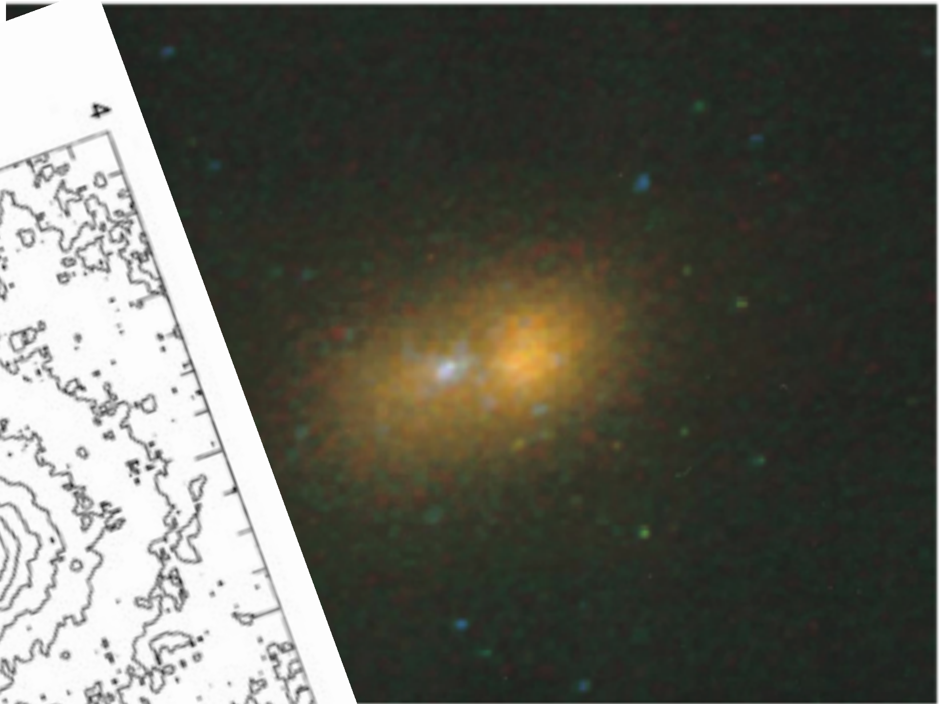
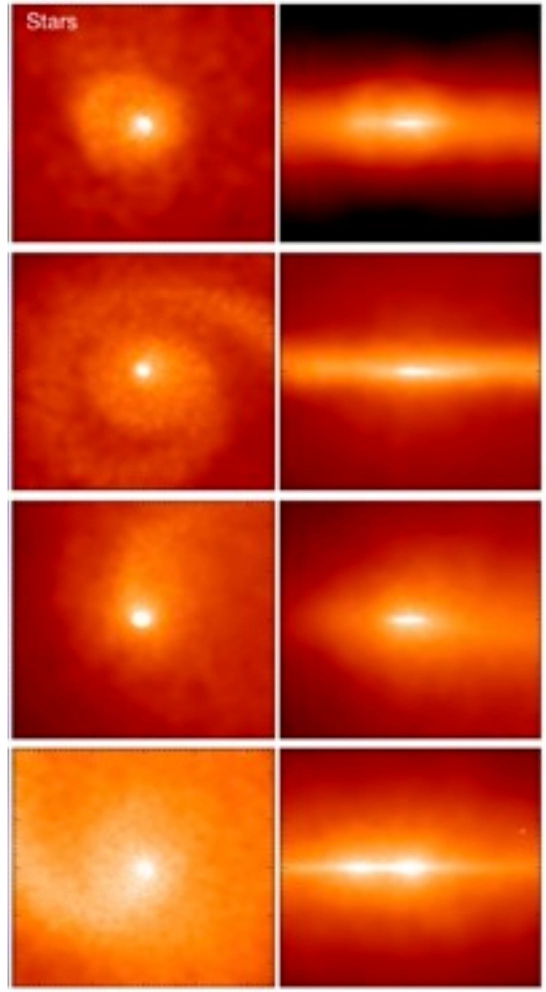


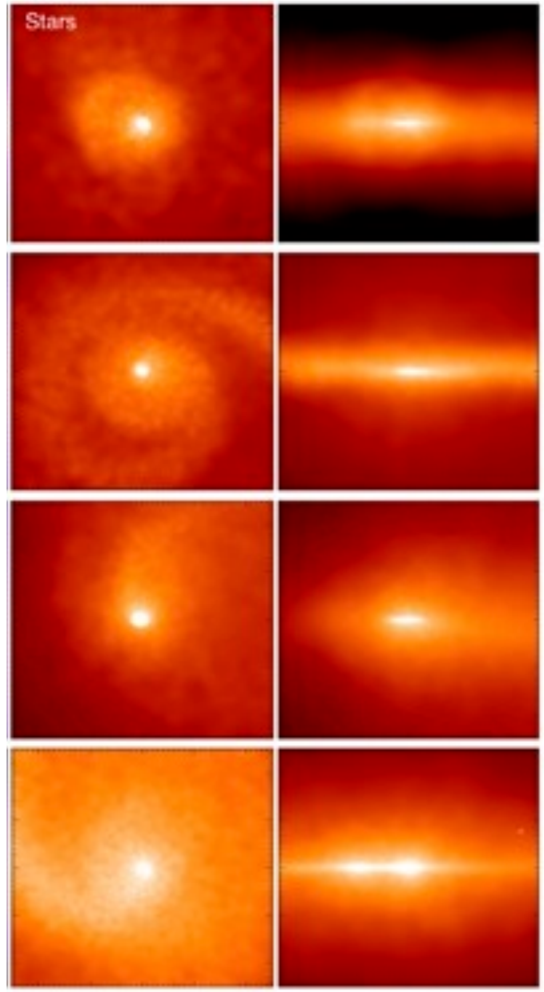




Lauer et al. 1993
Kormendy & Bender 1999

- 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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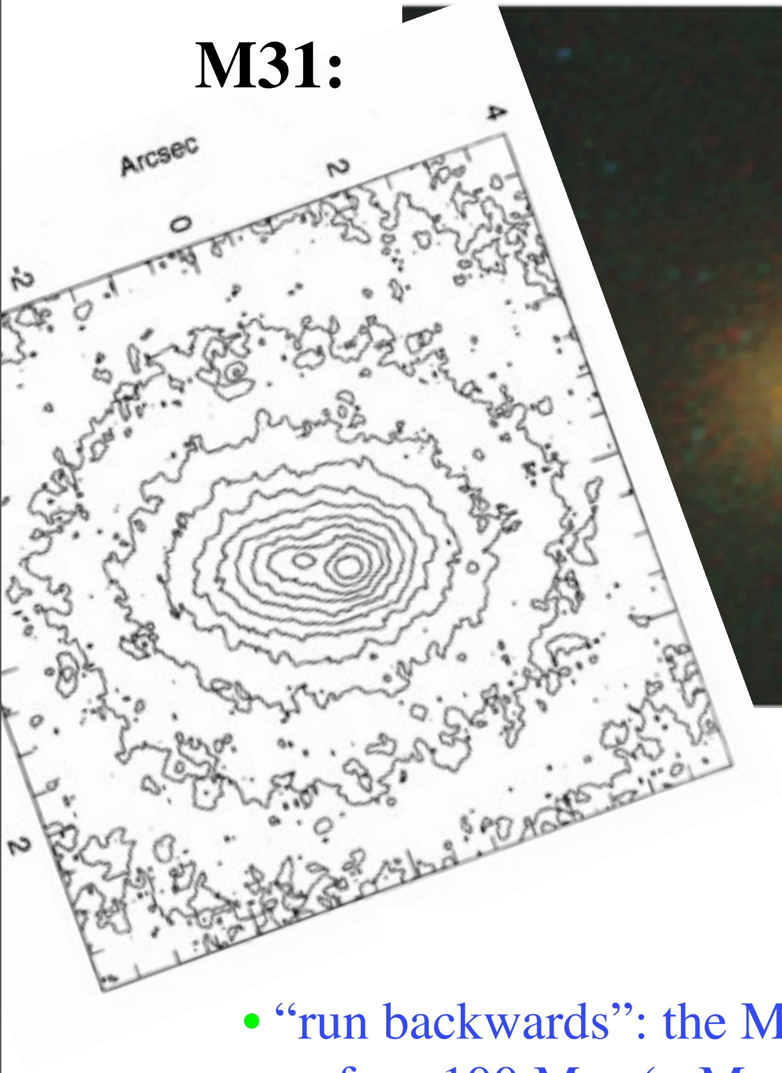
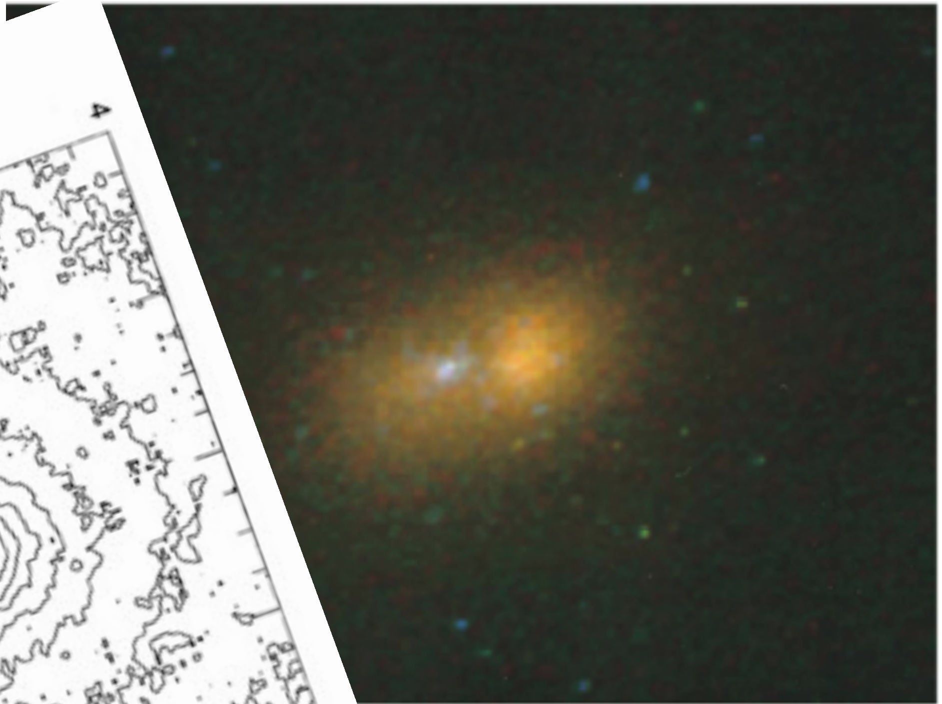
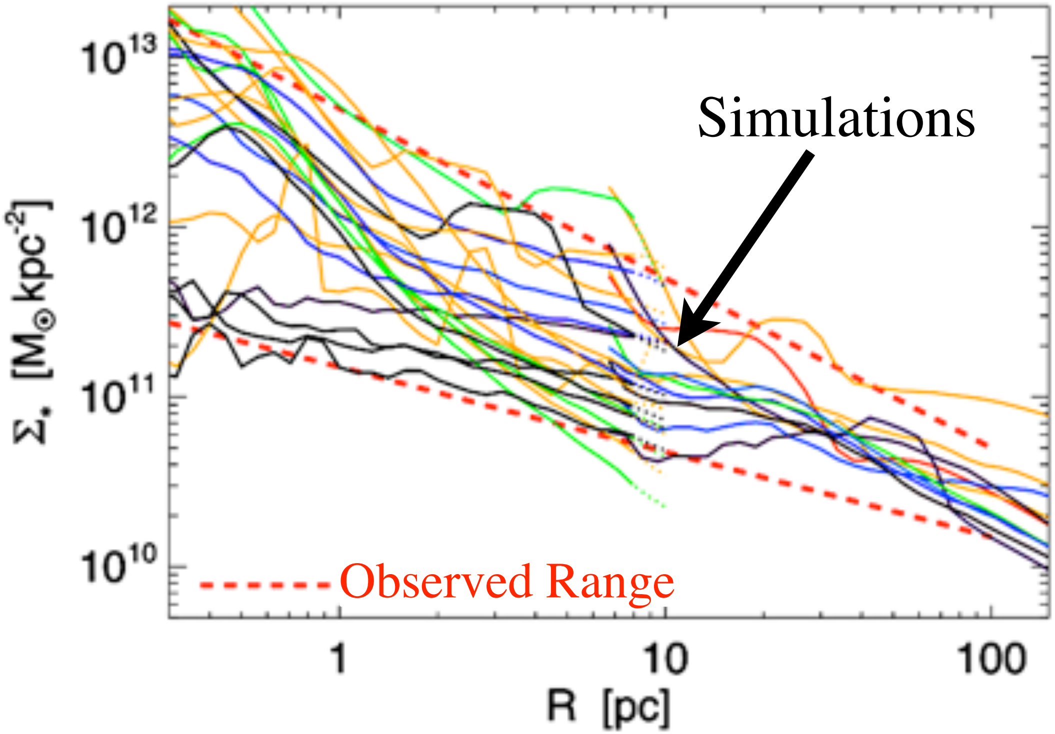




Lauer et al. 1993
Kormendy & Bender 1999

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

Naturally explains the nuclear slopes of ‘cuspy’ ellipticals



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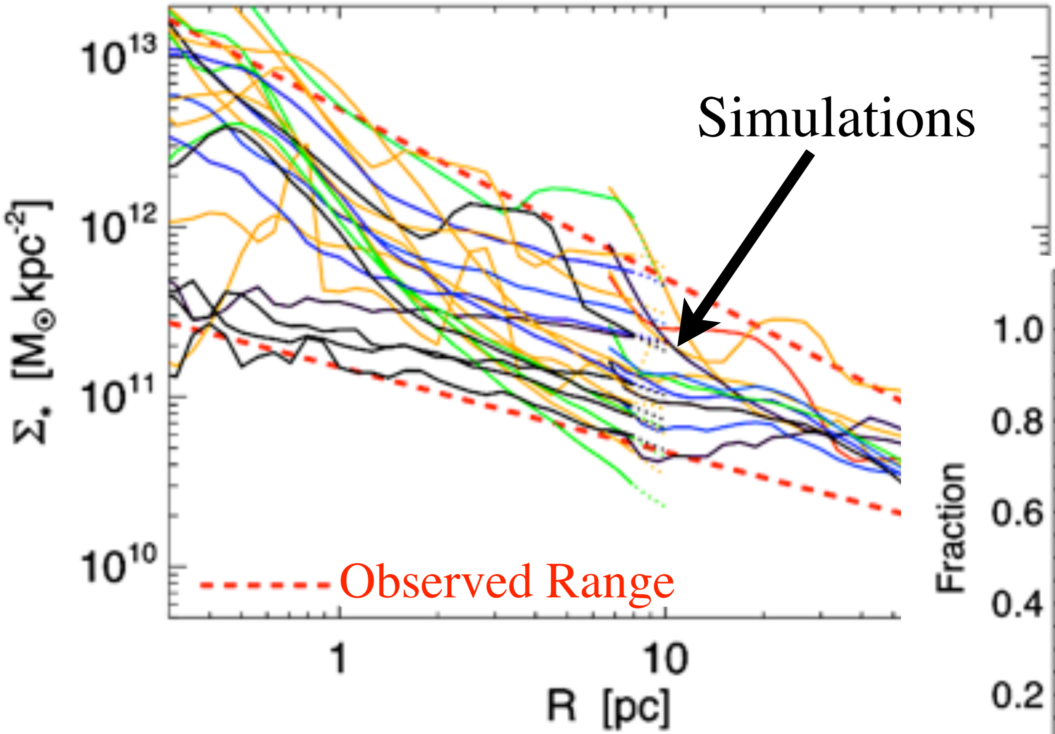

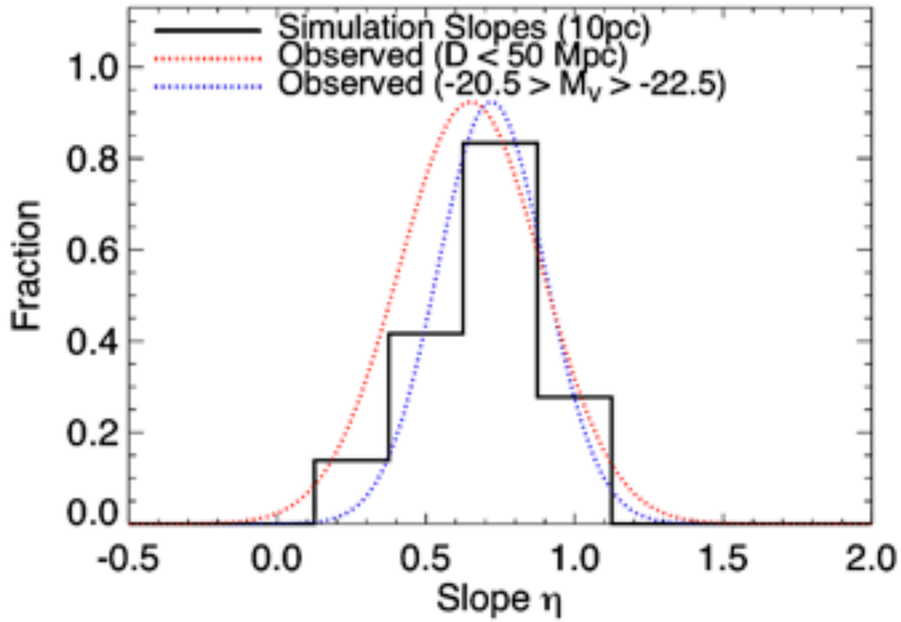

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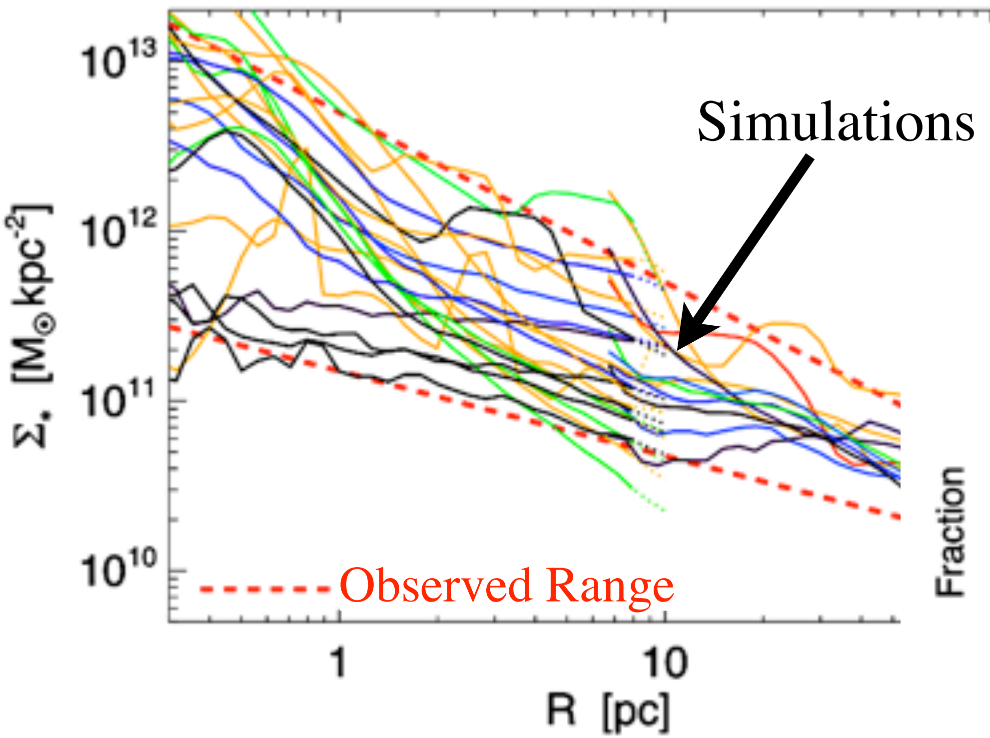
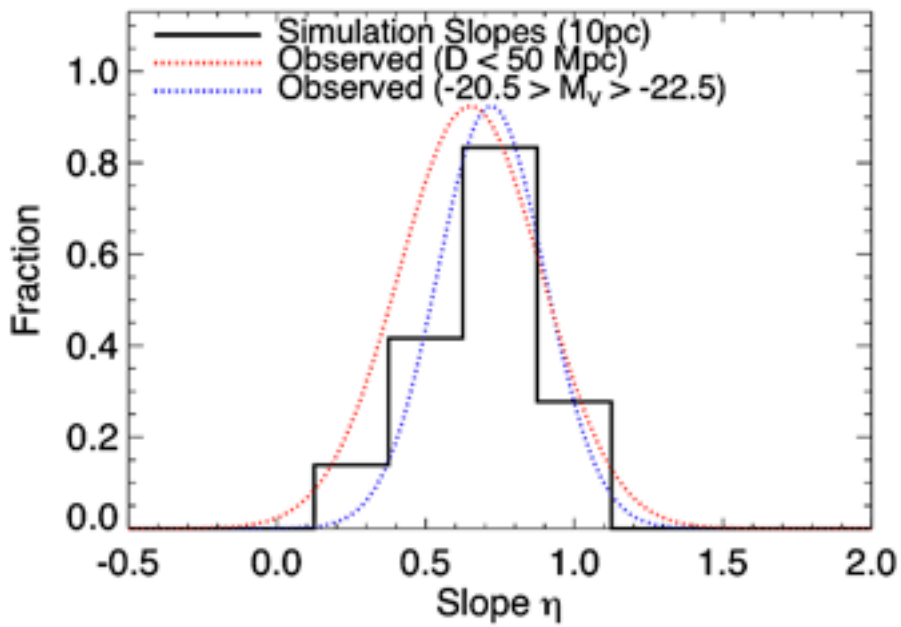
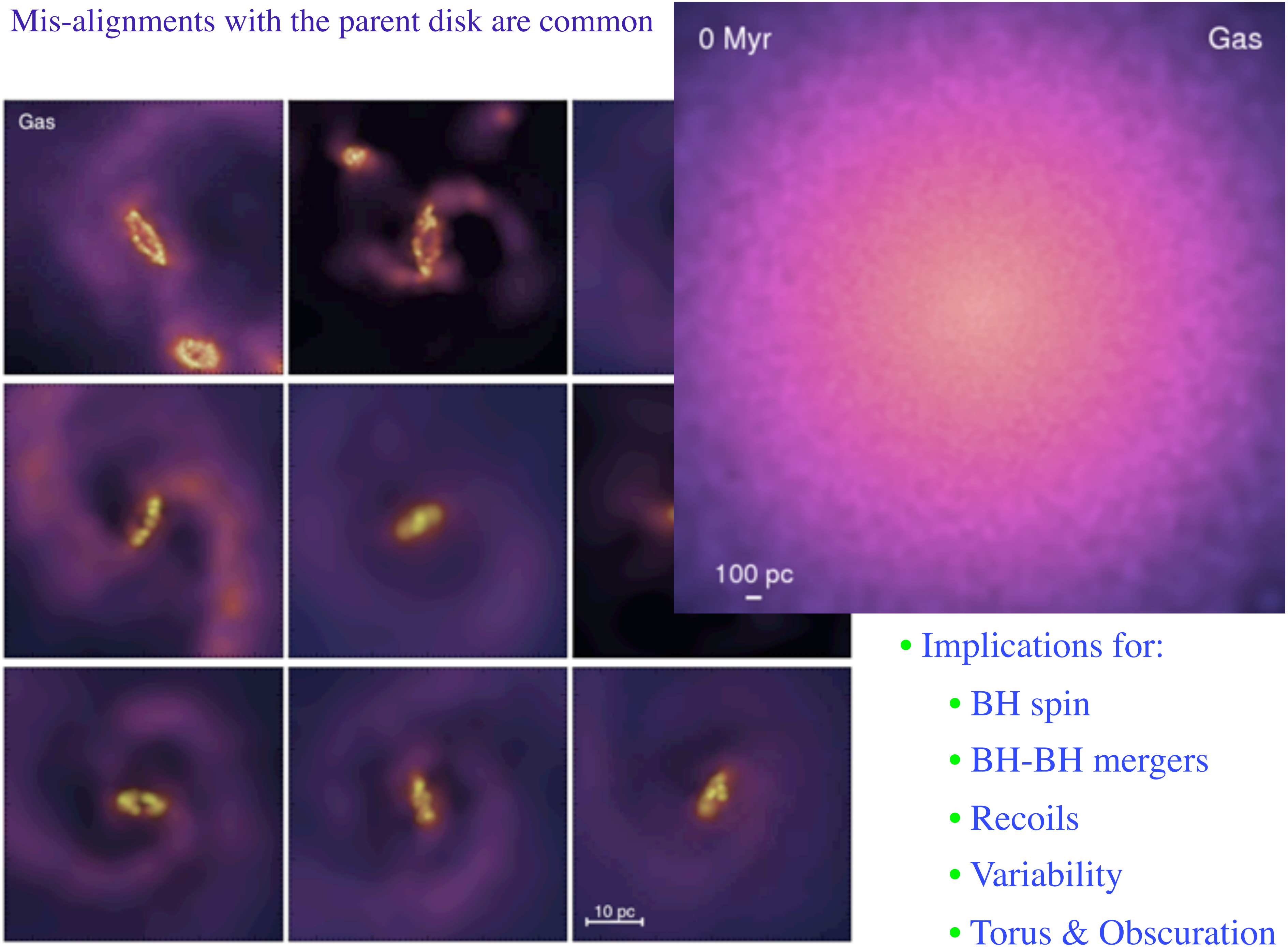




• Self-gravity for modes to propagate drives you to:

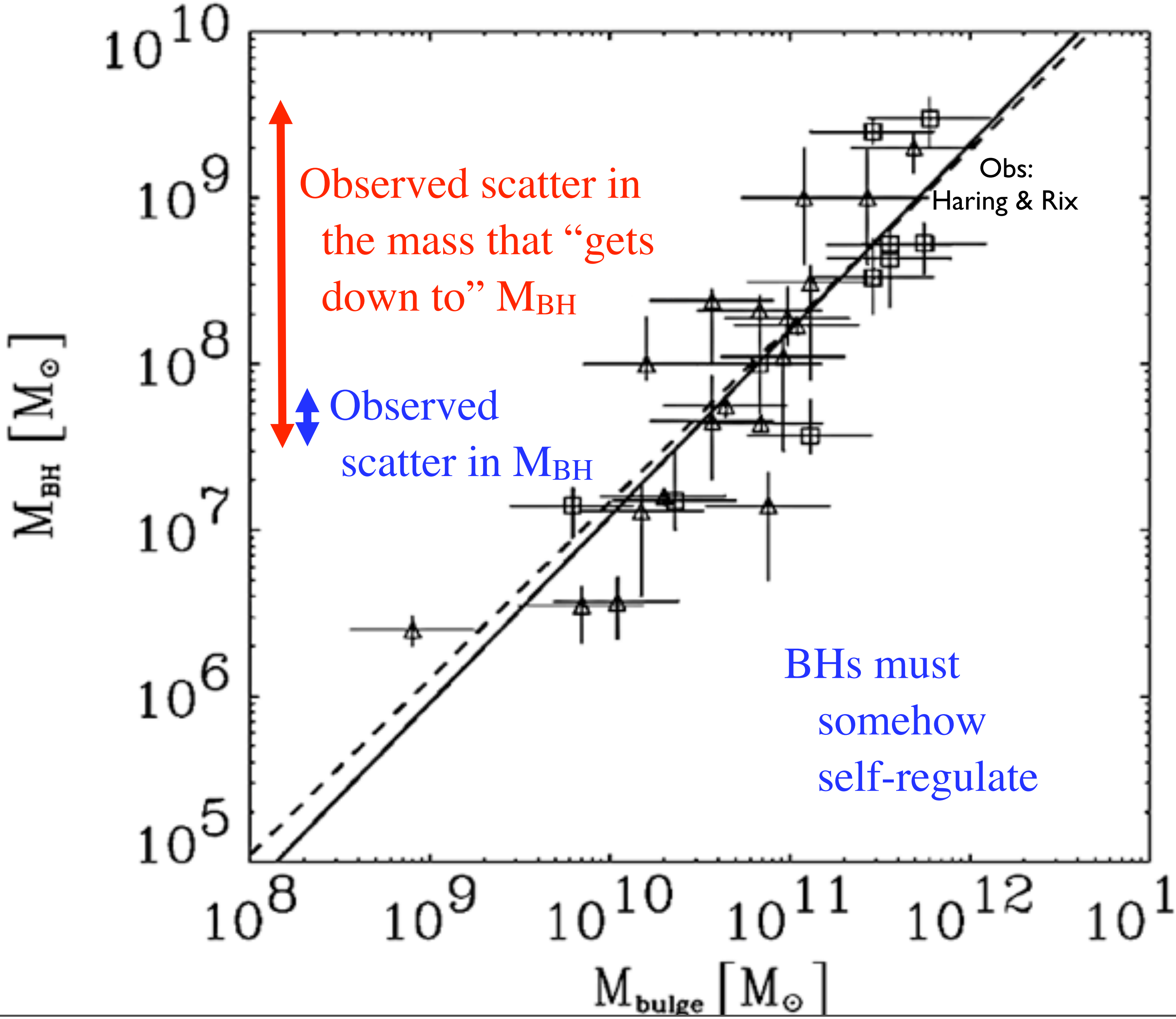
$$\Sigma(R) \propto R^{-\eta} : \qquad 1/2 < \eta < 1$$

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” MBH
Observed scatter in MBH
Obs: Haring & Rix
BHs must somehow self-regulate
MBH [M⊙]
Mbulge [M⊙]
10^10
10^9
10^8
10^7
10^6
10^5
10^8
10^9
10^10
10^11
10^12
10^1

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

- Accretion disk radiates:

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

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

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

- Compare to gravitational binding energy of galaxy:

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

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

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

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

- 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)

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

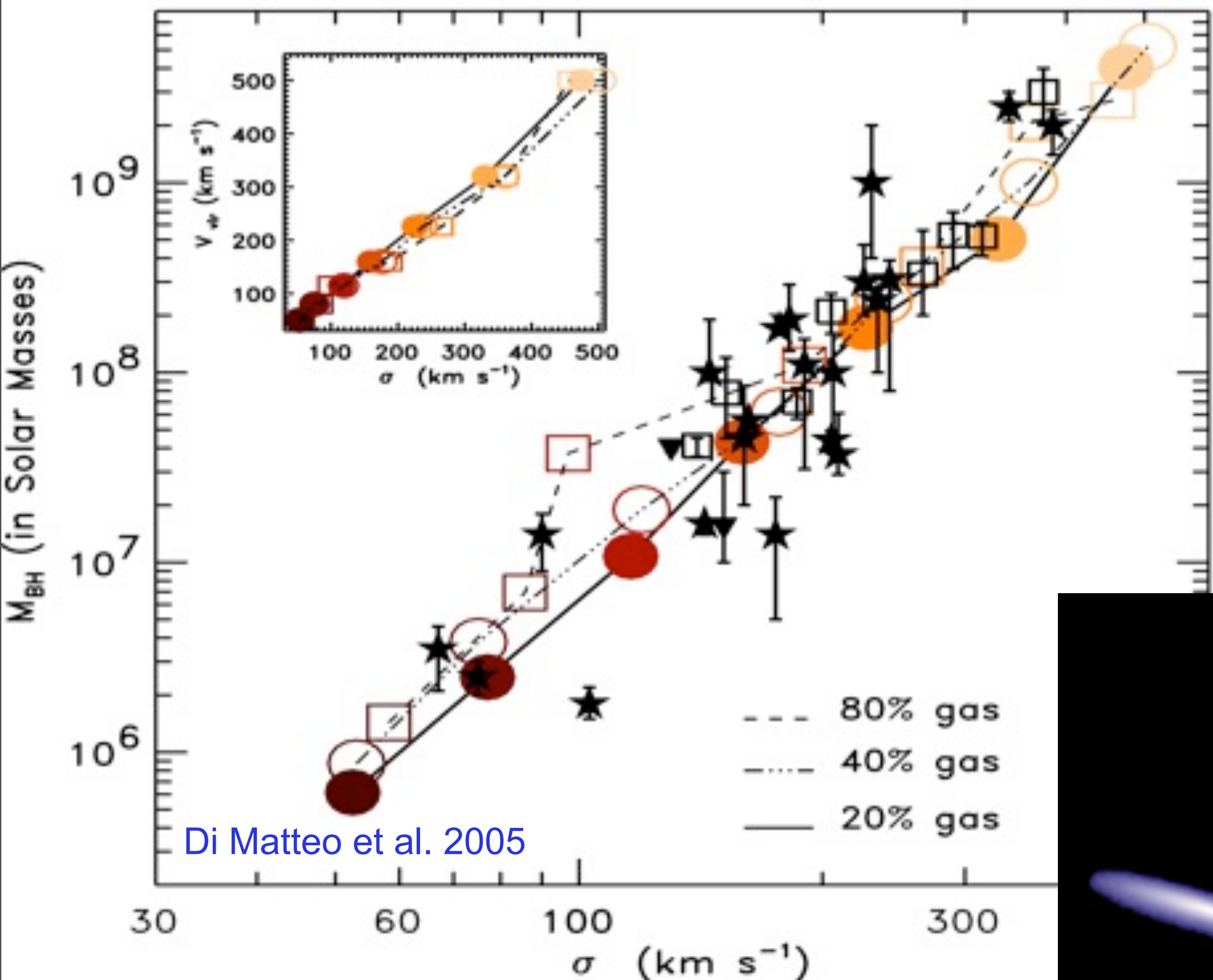
(DeBuhr et al. 2009)

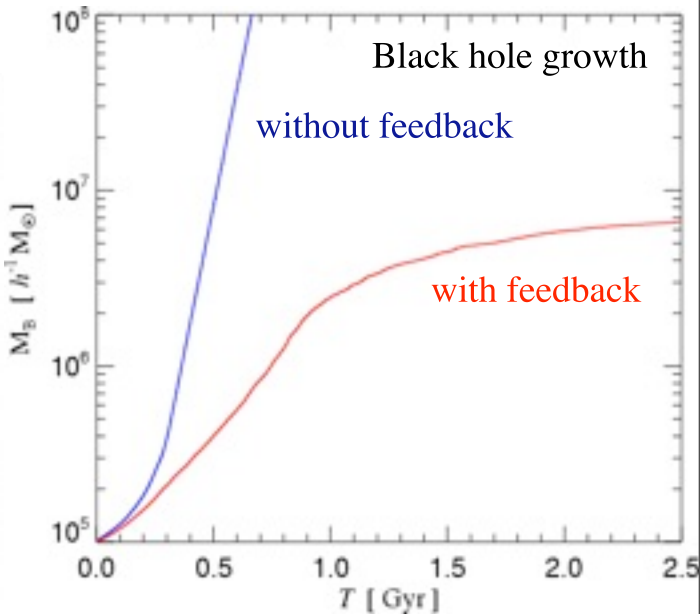
$$\dot{M}_{\rm Edd} \propto M_{\rm BH}$$

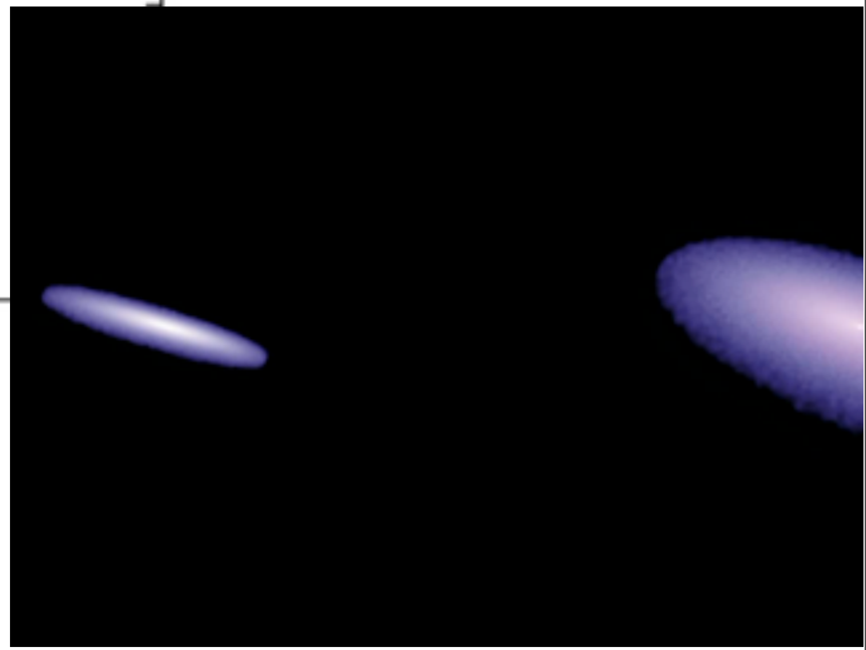
Predict similar "impact" of feedback

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

Self-Regulated BH Growth:

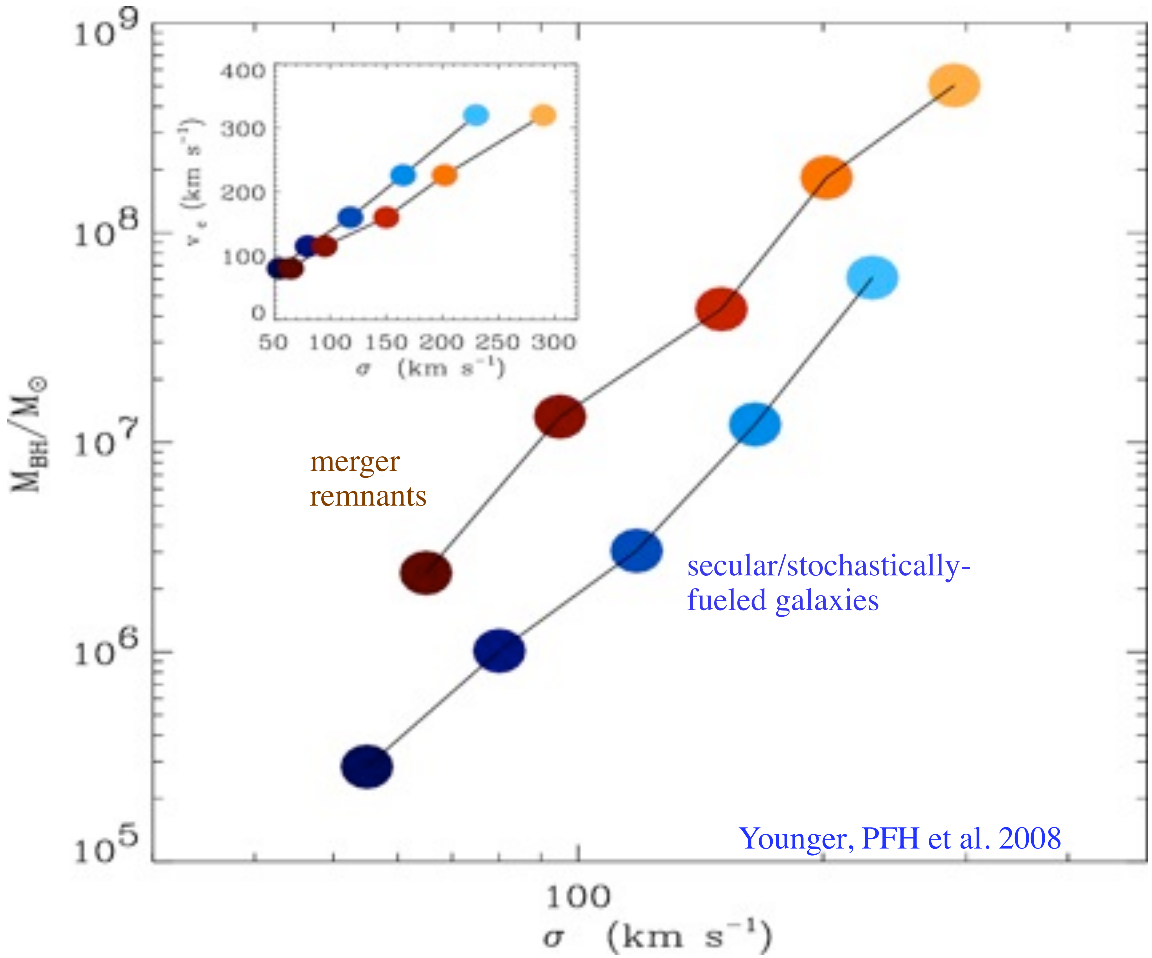






Predictions?

- “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.)

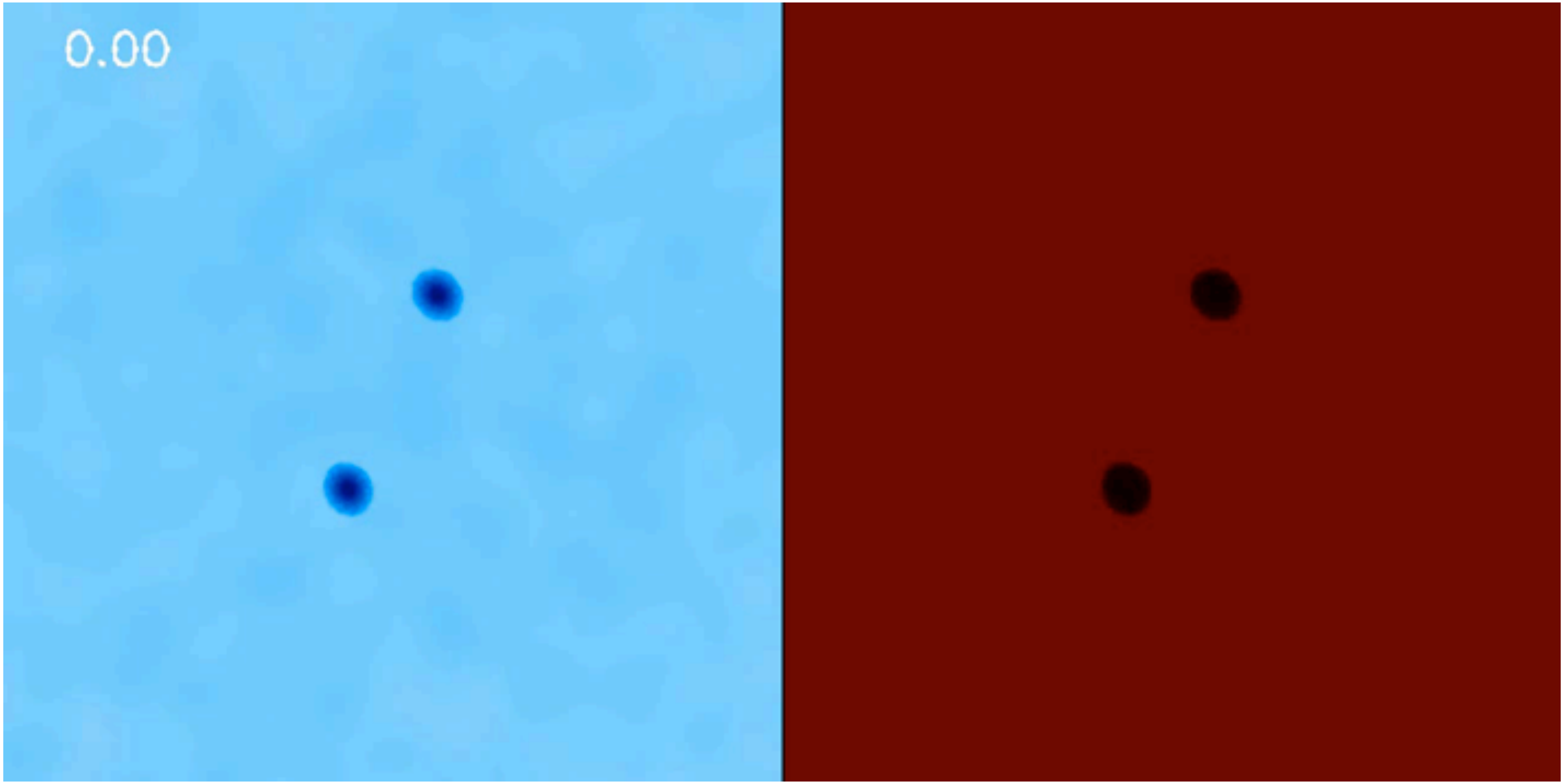


- Redshift evolution: as galaxy properties change (Peng et al., Shields et al., Walter et al.)

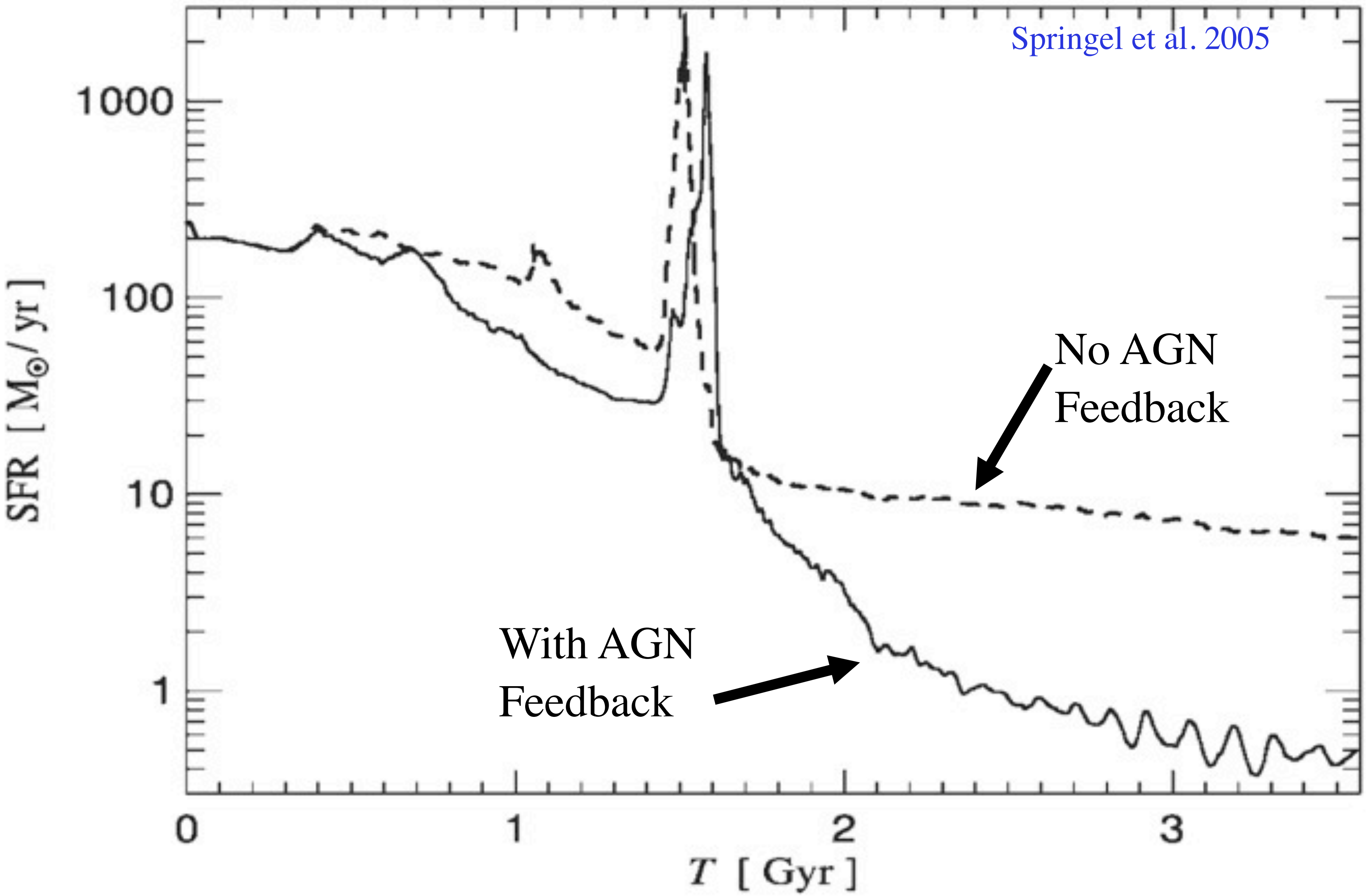
Feedback Part 2: What Does This Mean for the Host Galaxy?

Can AGN Feedback Prevent Star Formation?

Gas Density **Gas Temperature**

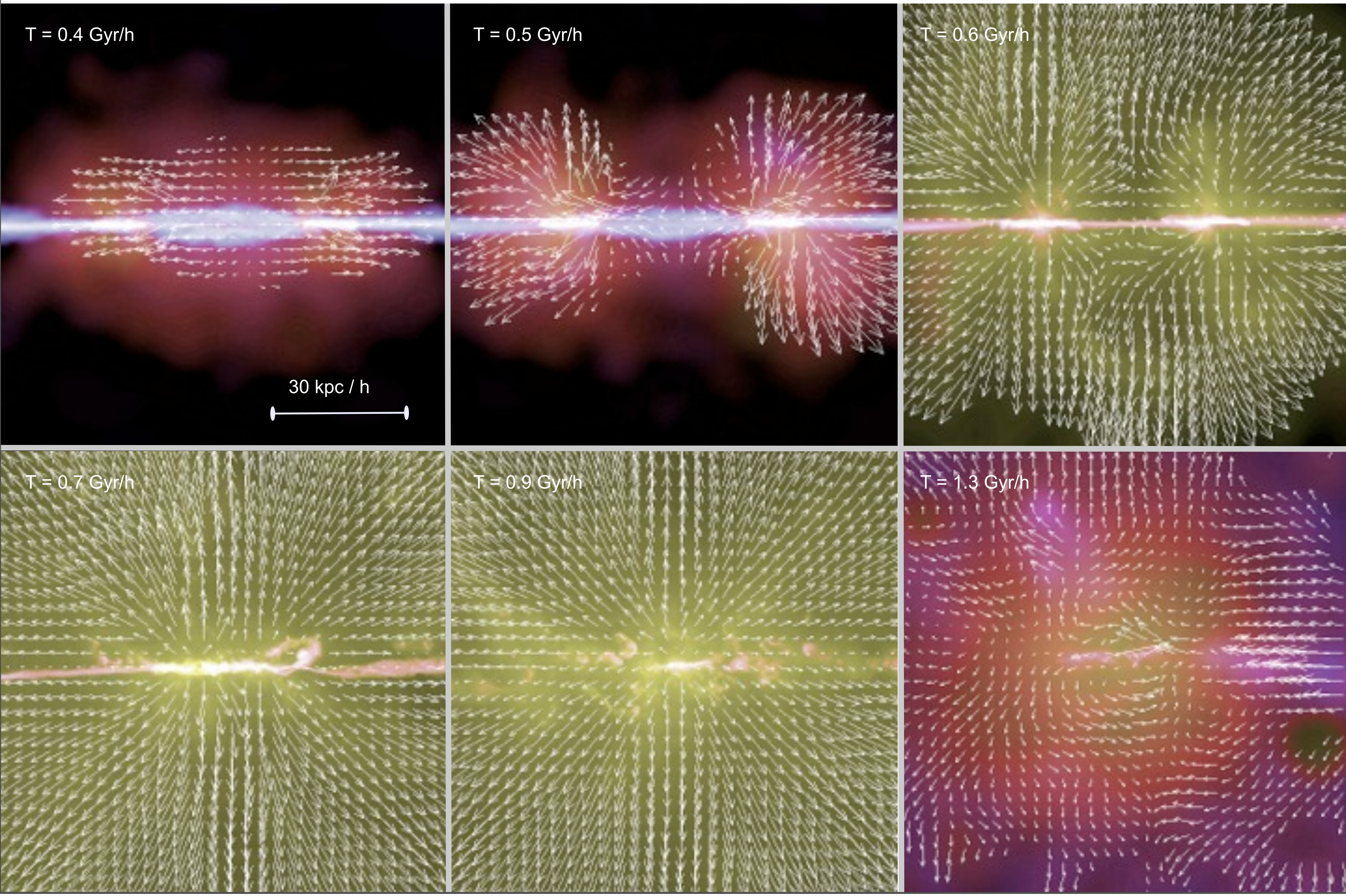


Helps Ensure Ellipticals are “Red and Dead”



Do We See It?

(speeds up to ~2000 km/s)



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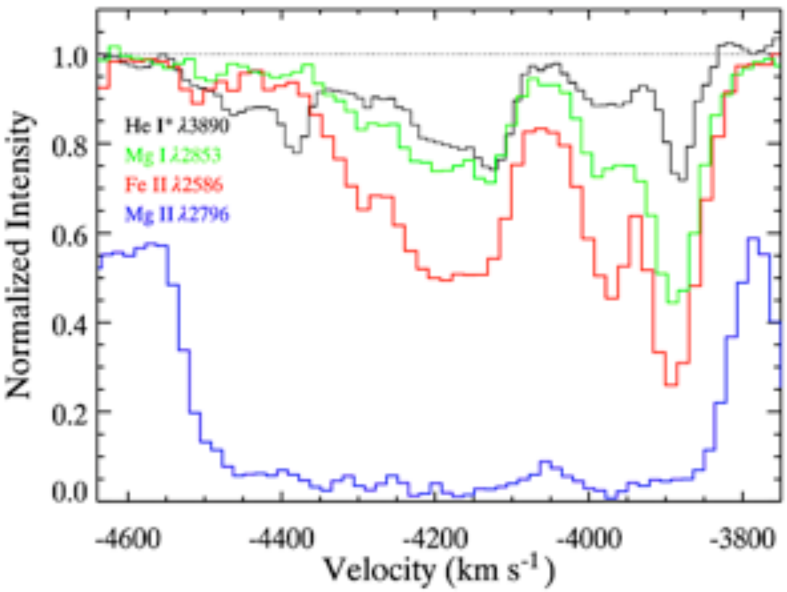


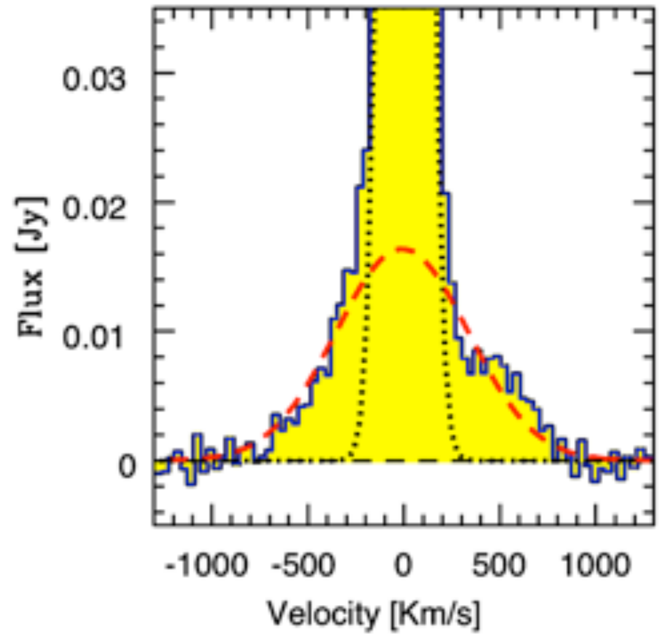
Arav et al.

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:

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

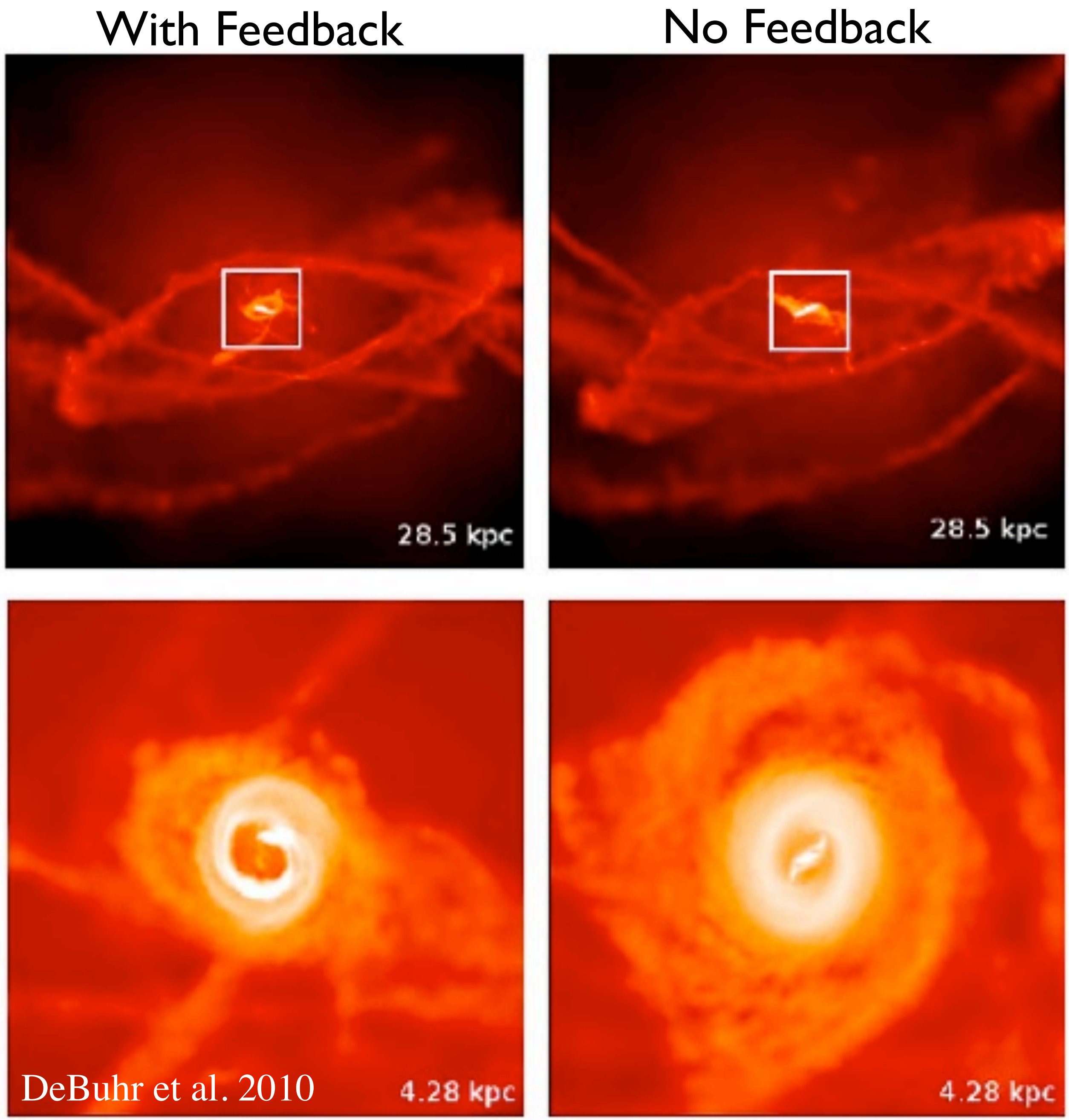
$$v > 500\,{\rm km\,s^{-1}}$$

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

But:

Momentum-Driven
(vs Energy-Driven)
Winds:

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



DeBuhr et al. 2010

Where to from here?

Future Directions:

1) Radiative Transfer:

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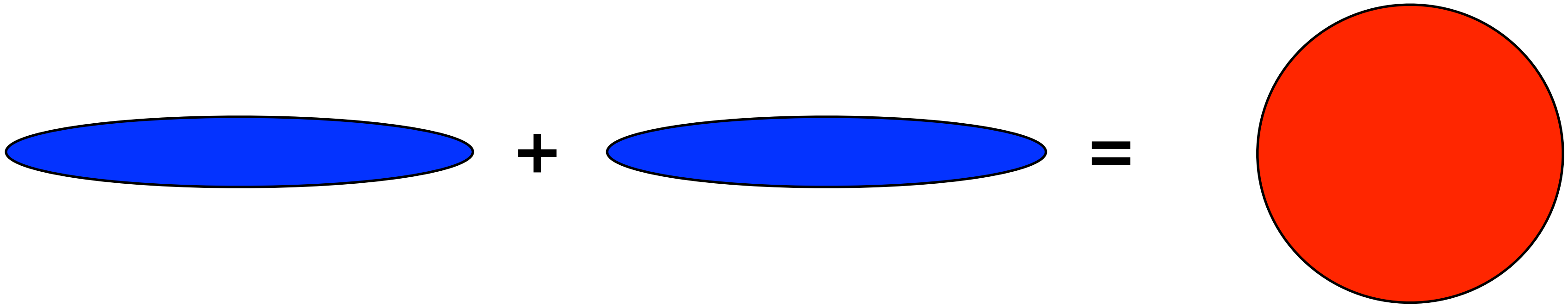
- Quantitative tests of Feedback Models

Future Directions:

1) Radiative Transfer:

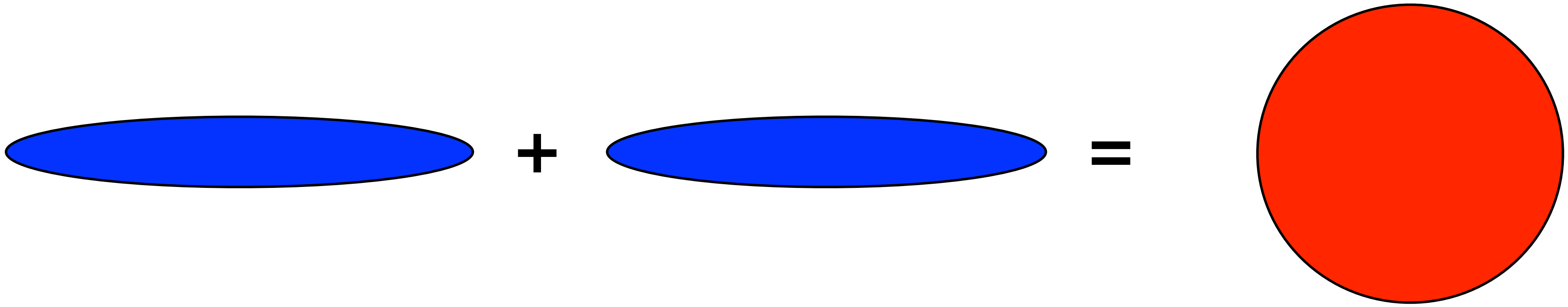
- Quantitative tests of Feedback Models
- Actual Feedback Physics!

2) How Do We Make Disks In the First Place?



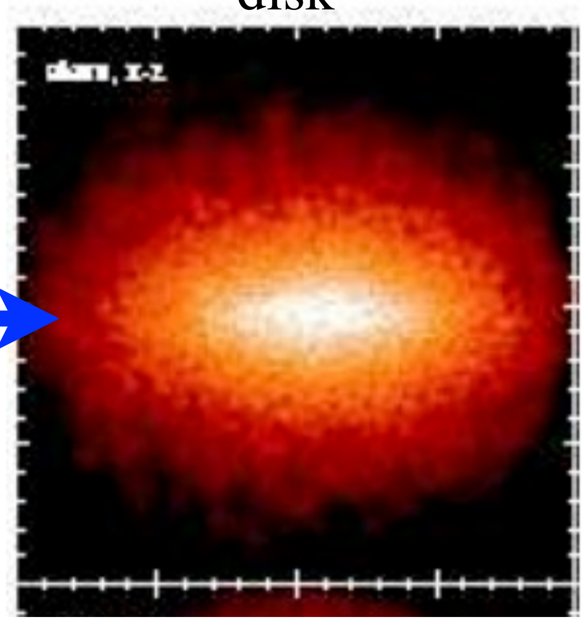
- Cosmologically, need to make disks *first*, but:

2) How Do We Make Disks In the First Place?

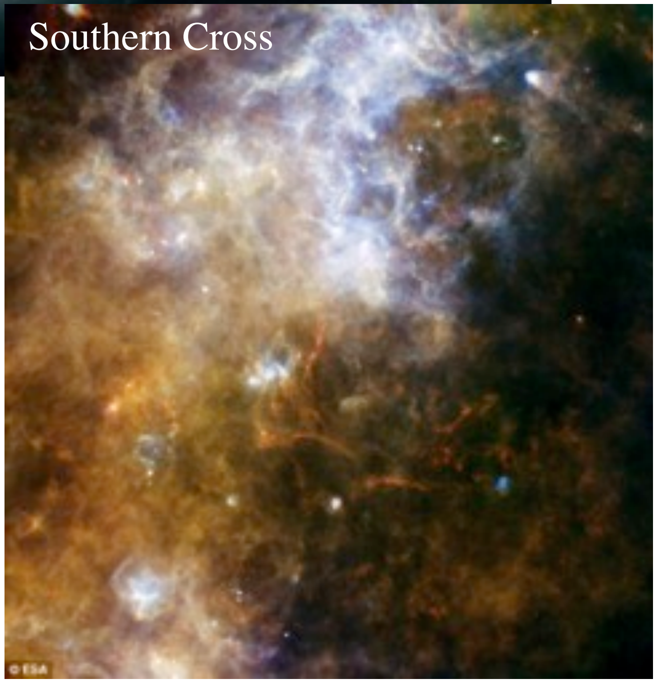


- Cosmologically, need to make disks *first*, but:

“disk”

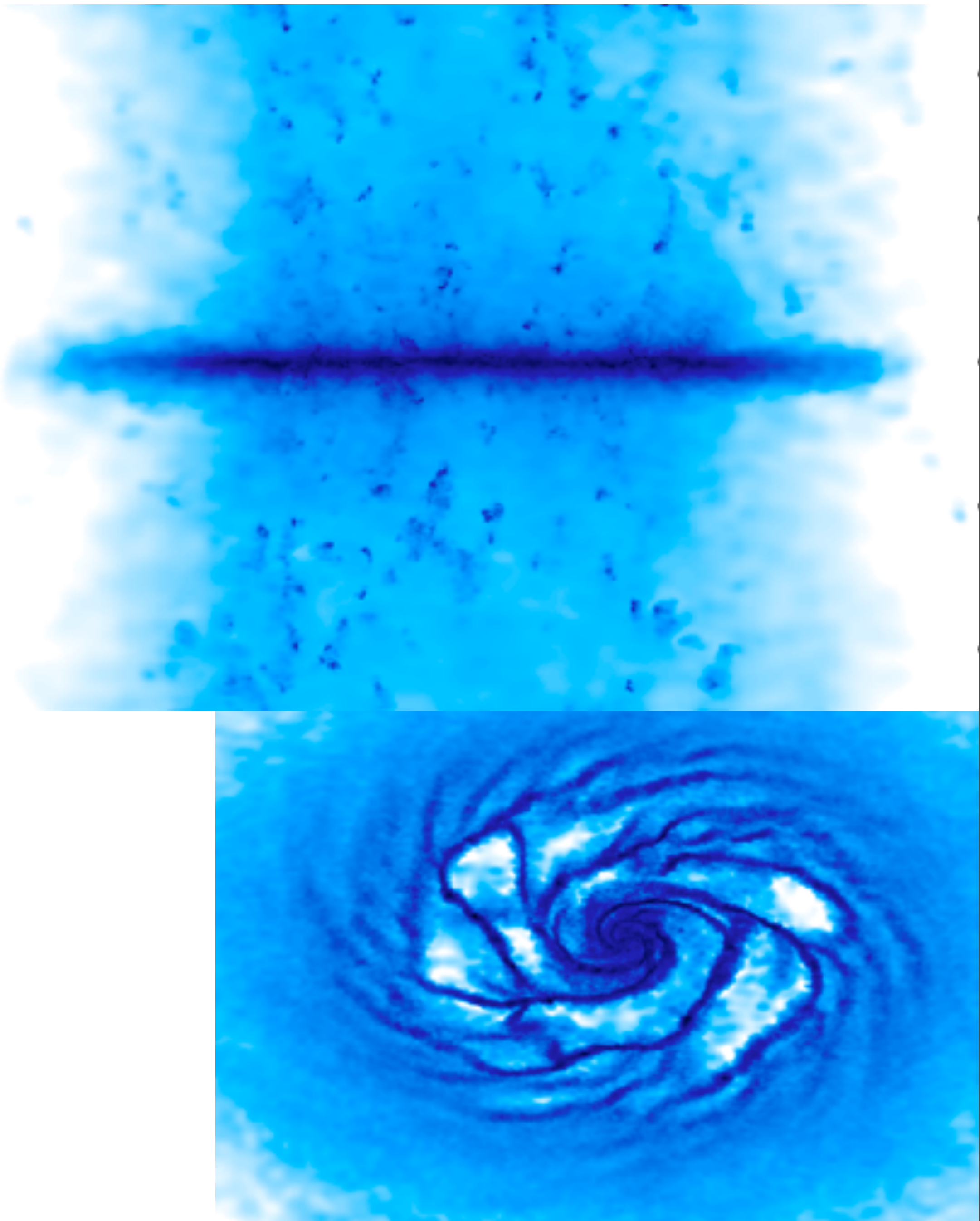


3) What about the small-scale ISM phase structure?



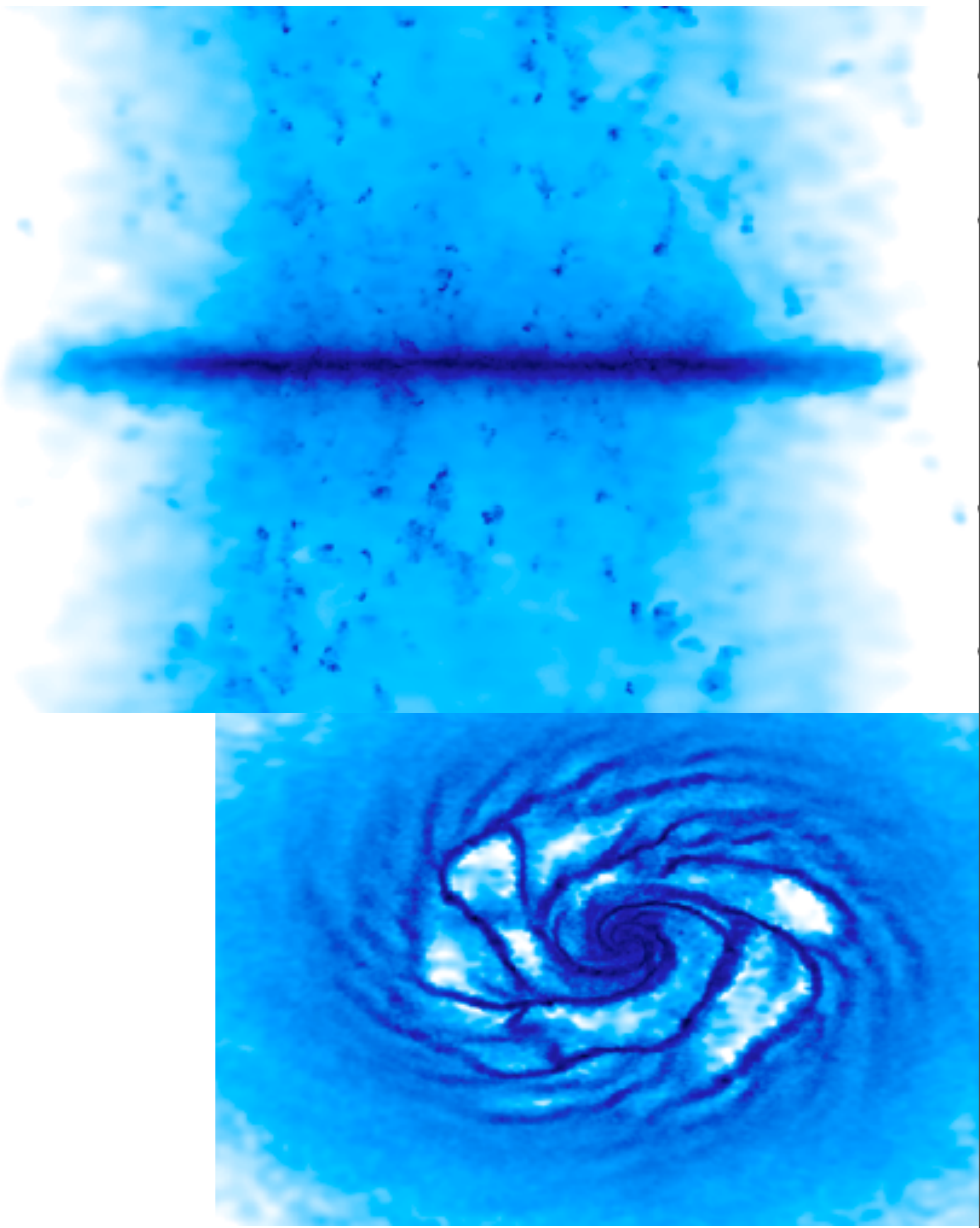
- "GMC-scale" sub-grid instead of galaxy-scale sub-grid
  - Resolve ~1pc
  - Cool to <100 K
  - Physically/empirically motivated SF in only dense clumps (n_H>>100cm^{-3})
  - Model radiative+SNe feedback explicitly from each young stellar cluster (vs age, Z)
  - Generate ISM turbulence & super-winds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

What about the small-scale ISM phase structure?



What about the small-scale ISM phase structure?

- SNe Heating: No Cooling Turnoff!



What about the small-scale ISM phase structure?

- SNe Heating: No Cooling Turnoff!
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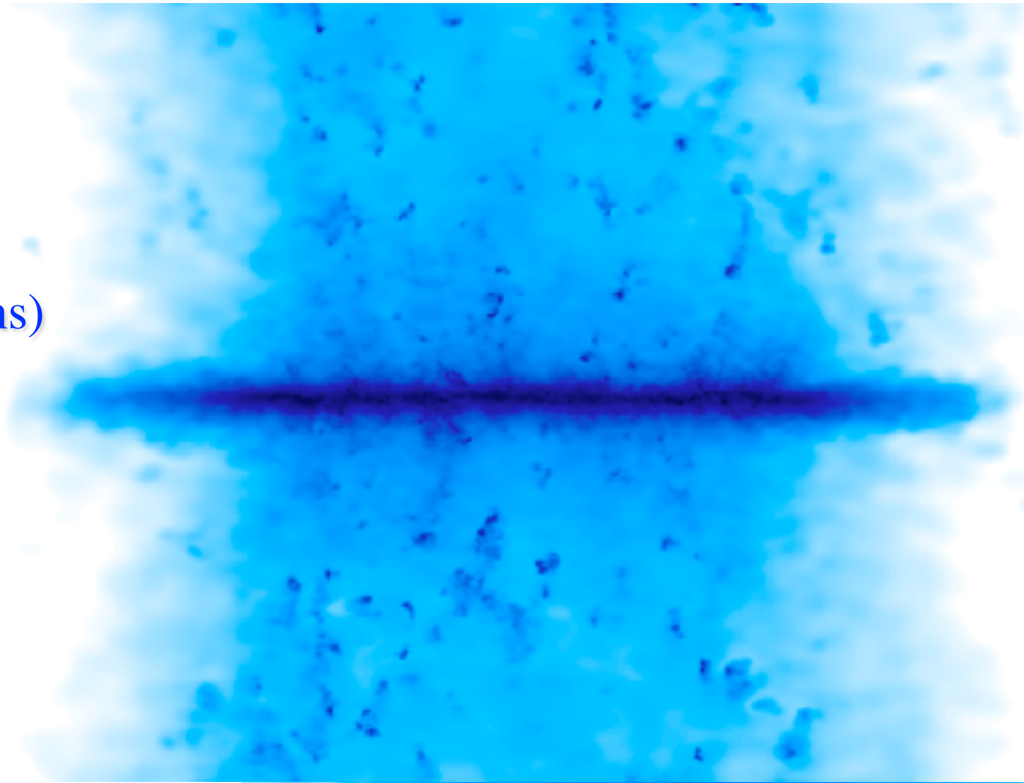

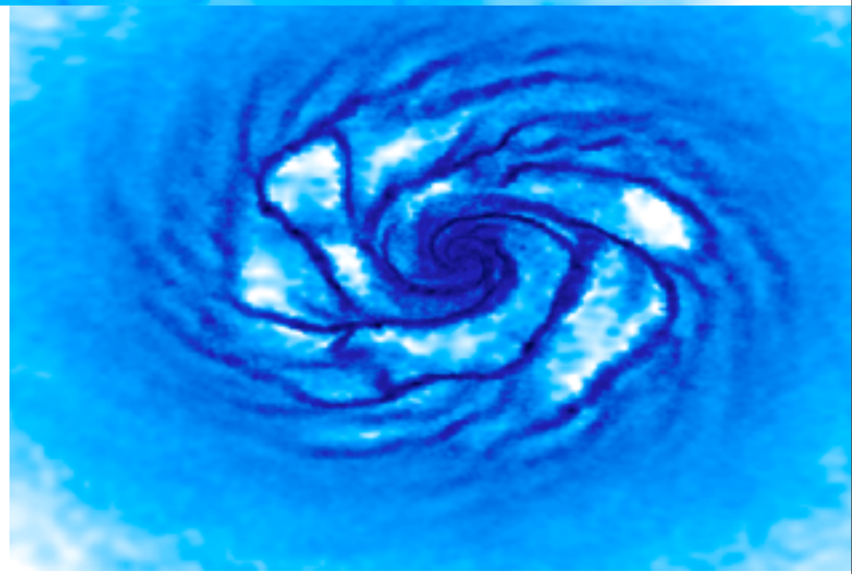

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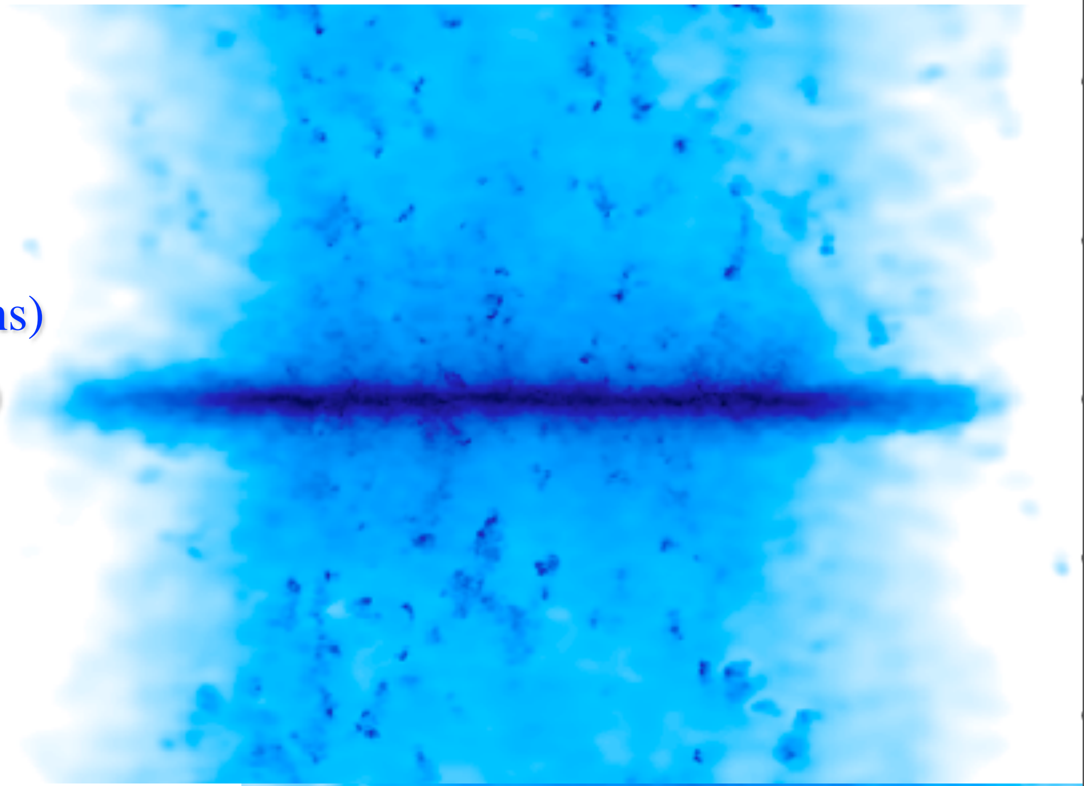

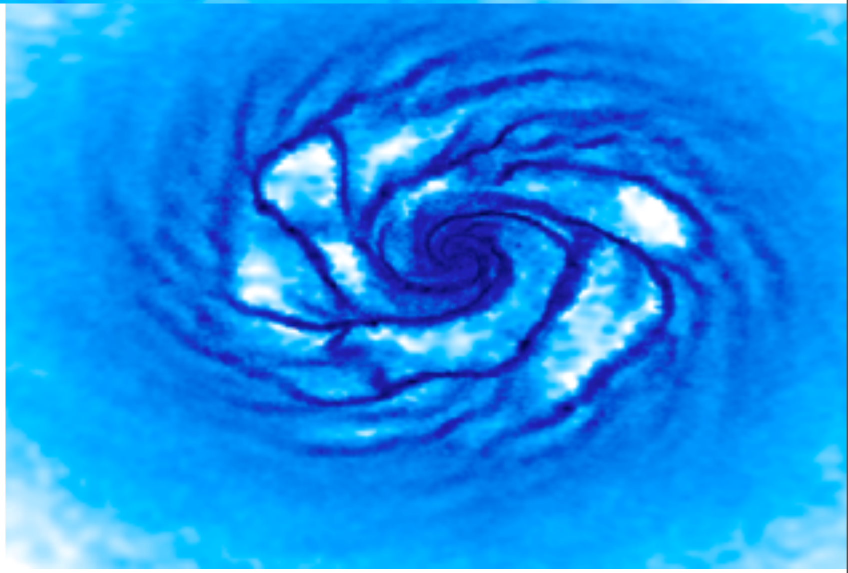

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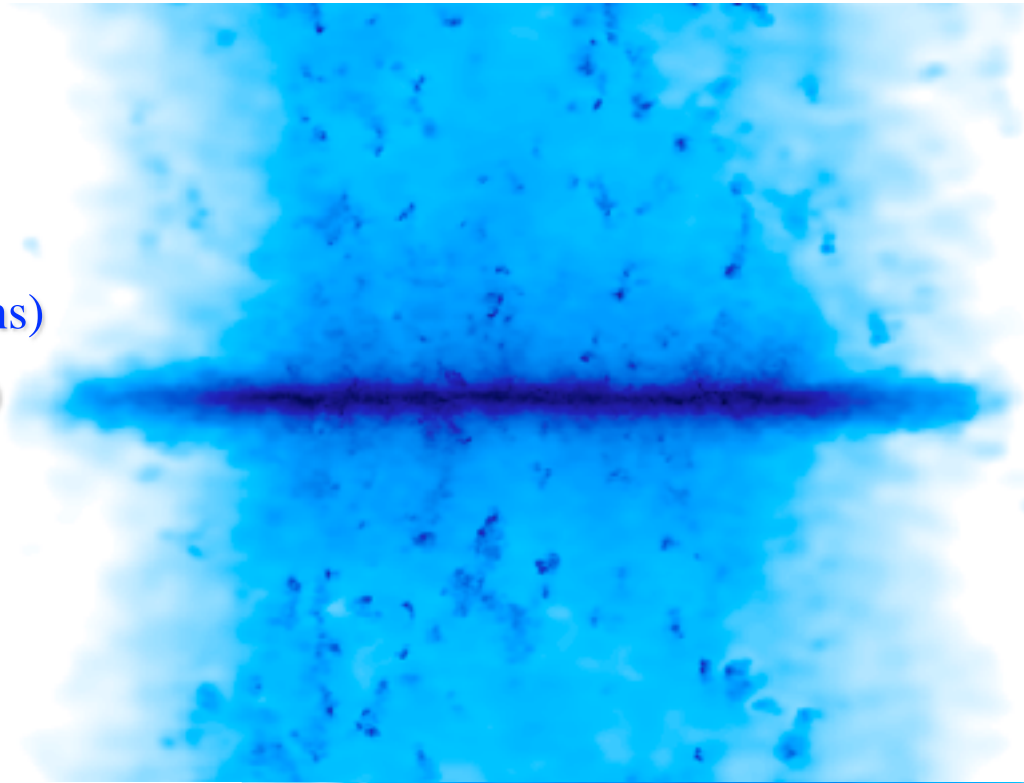

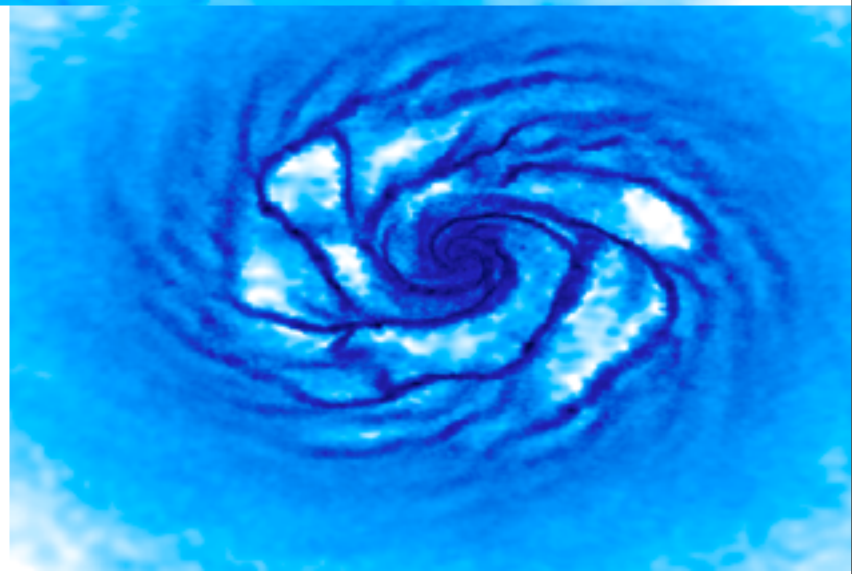

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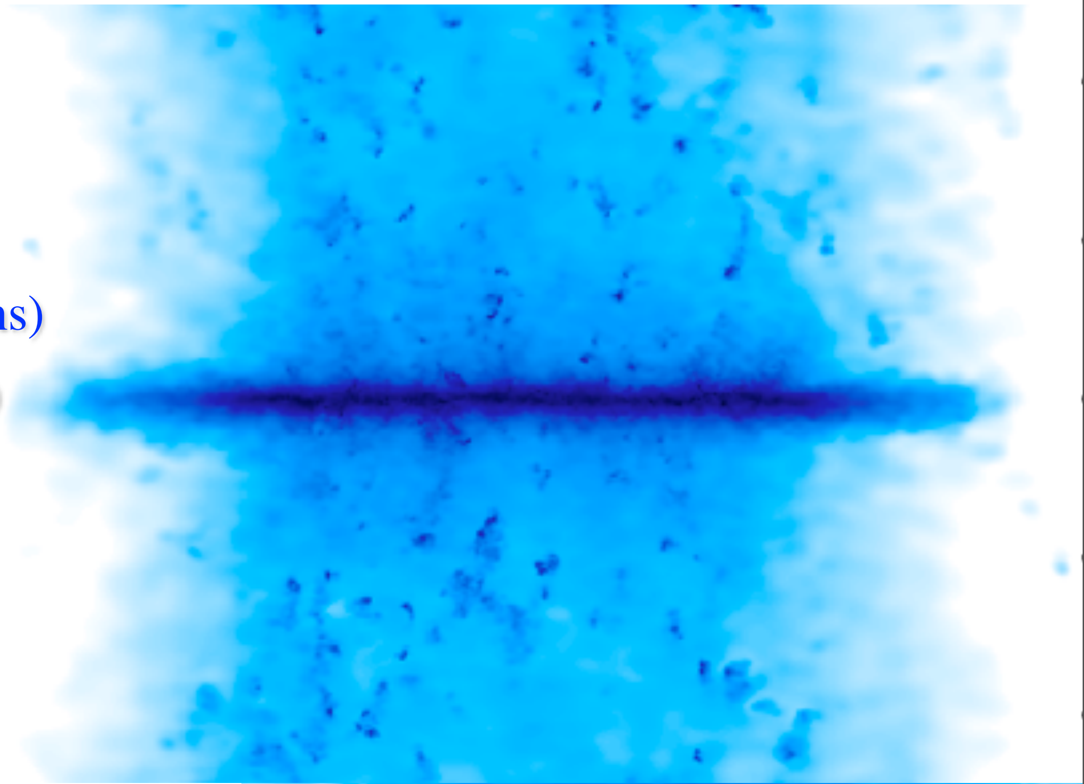

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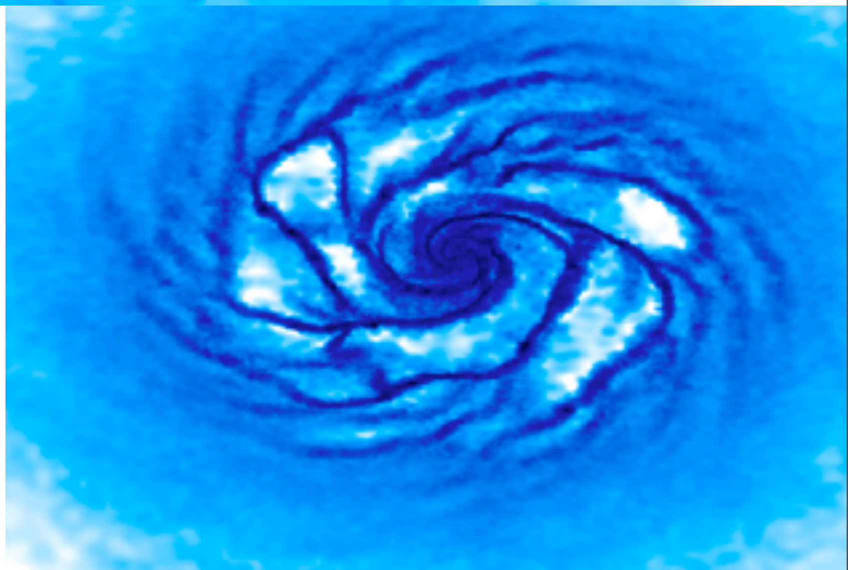
  - Radiation Pressure:
    $P_{dot} \sim (1+\tau)\, L / c$



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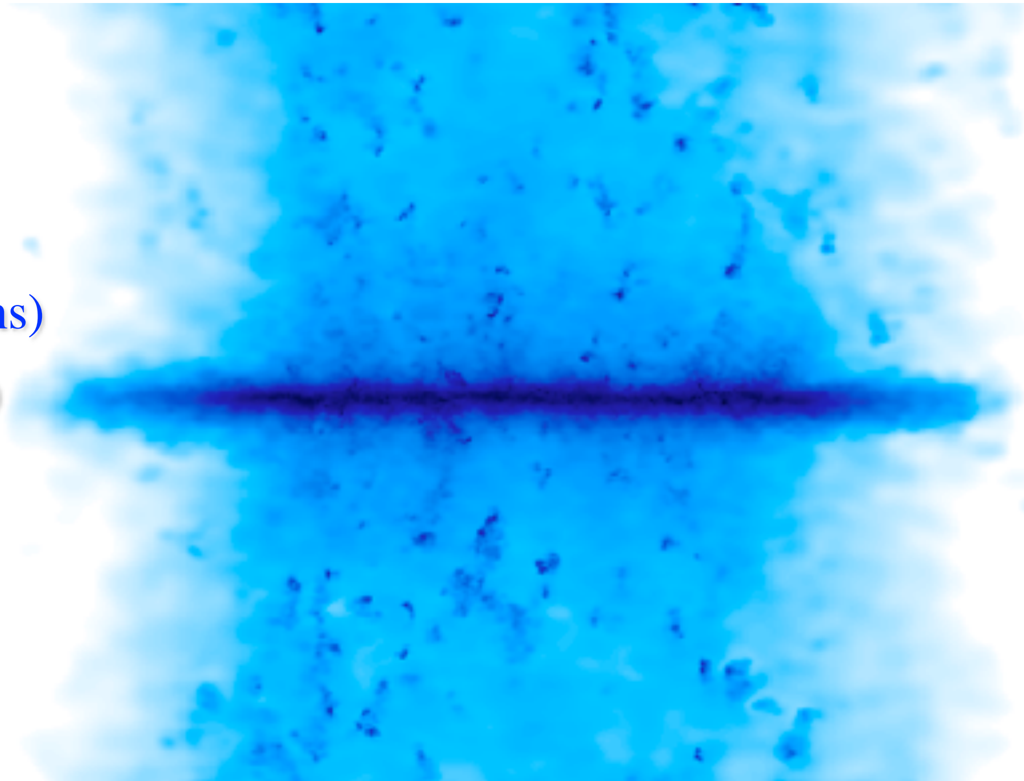

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- Explicit Momentum-Loading:
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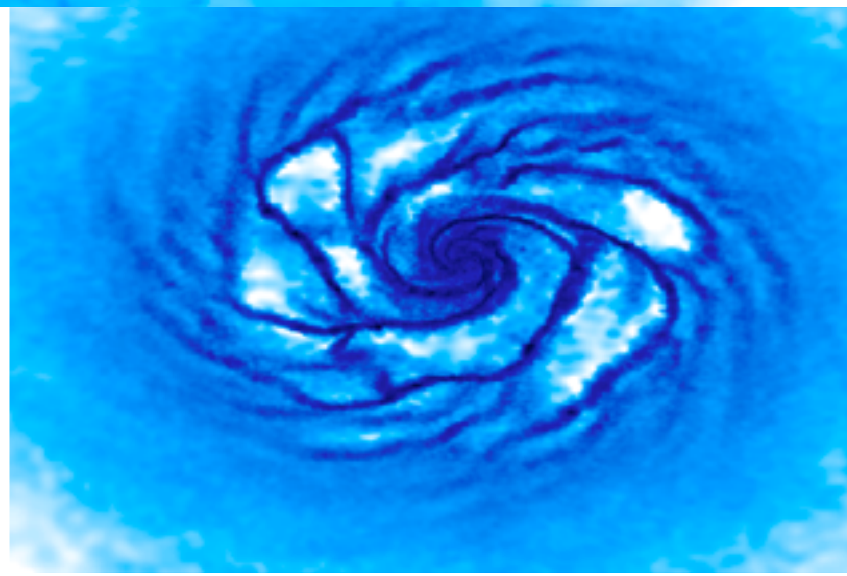
    $P_{dot} \sim (1+t)\ L / c$
  - Stellar Winds:

    $P_{dot} \sim M_{dot,w} v_{wind}$



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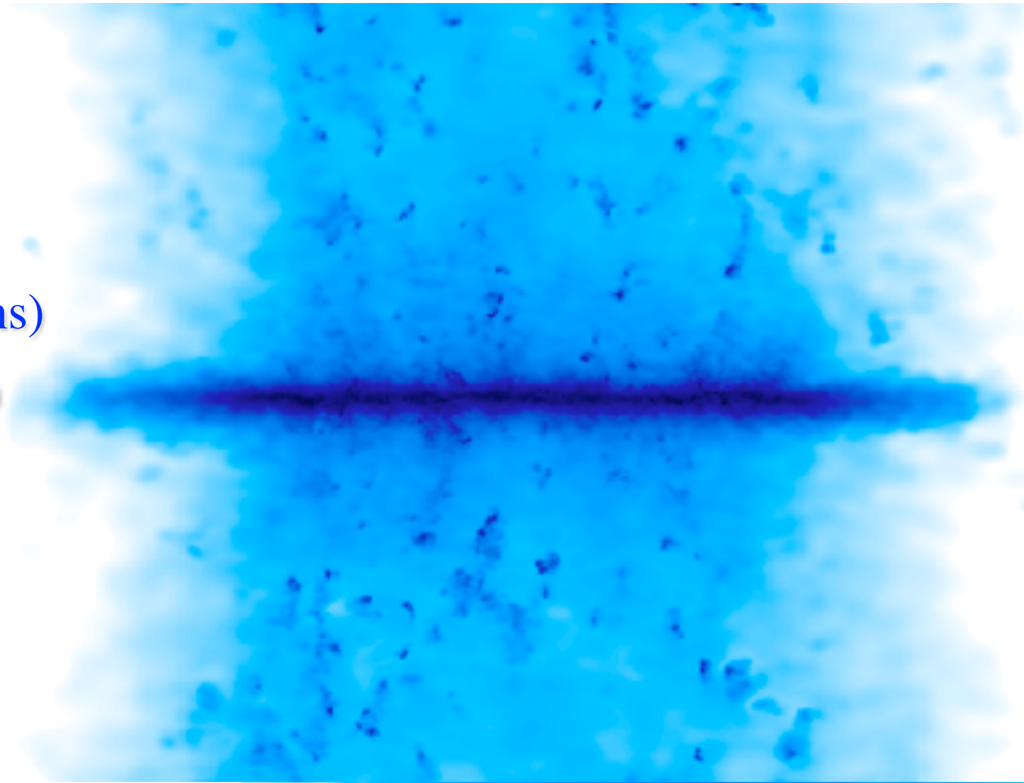
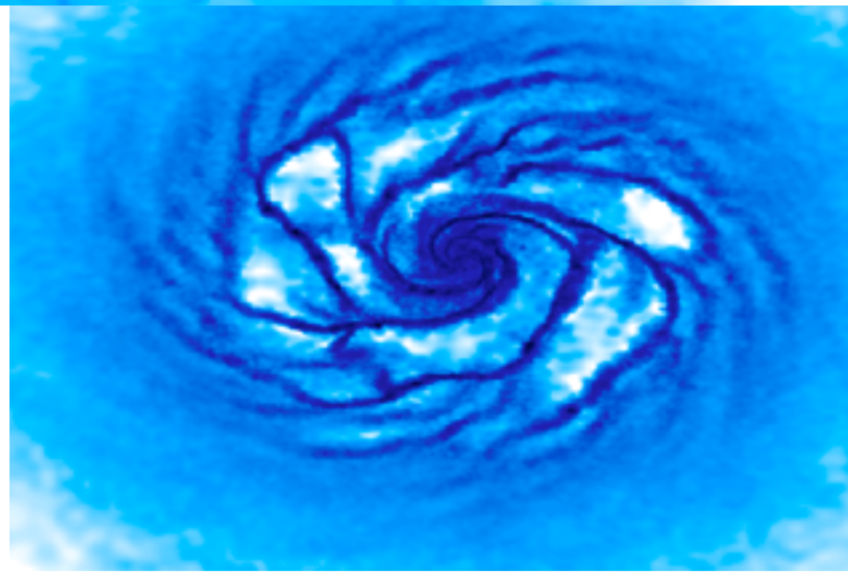
  - Stellar Winds:
    $P_{dot} \sim M_{dot,w} v_{wind}$
  - Supernovae:
    $P_{dot} \sim E_{SNe} / v_{ejecta}$





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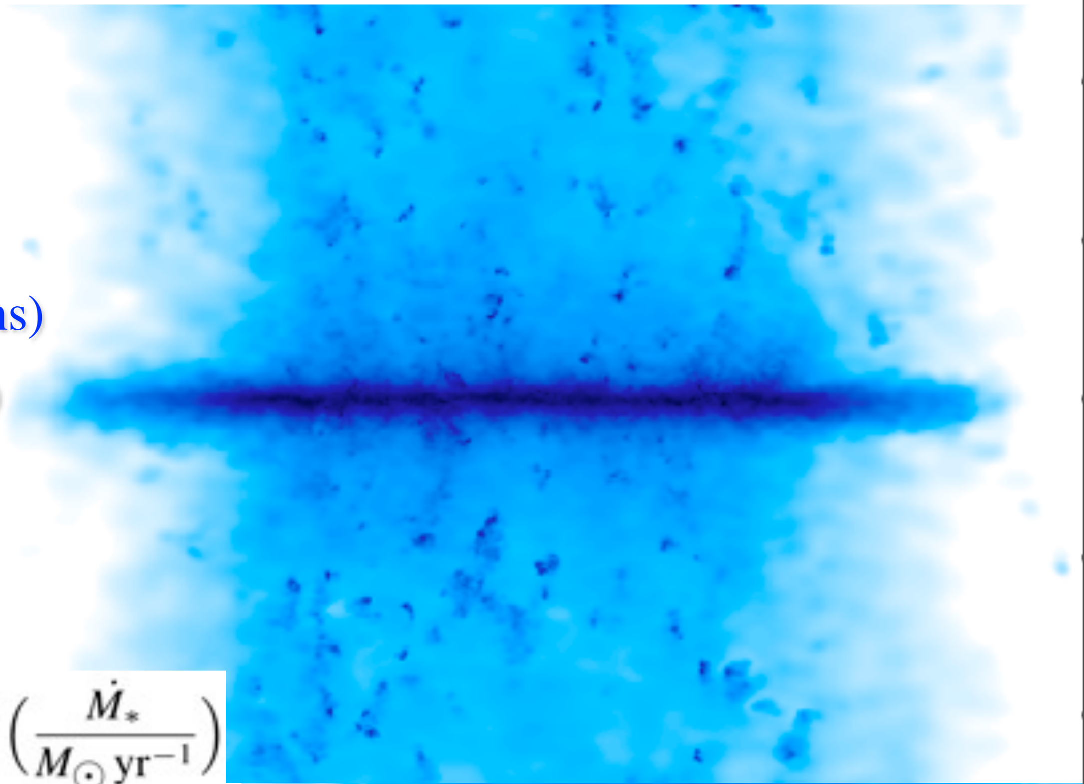

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- Explicit Momentum-Loading:
  - Radiation Pressure:

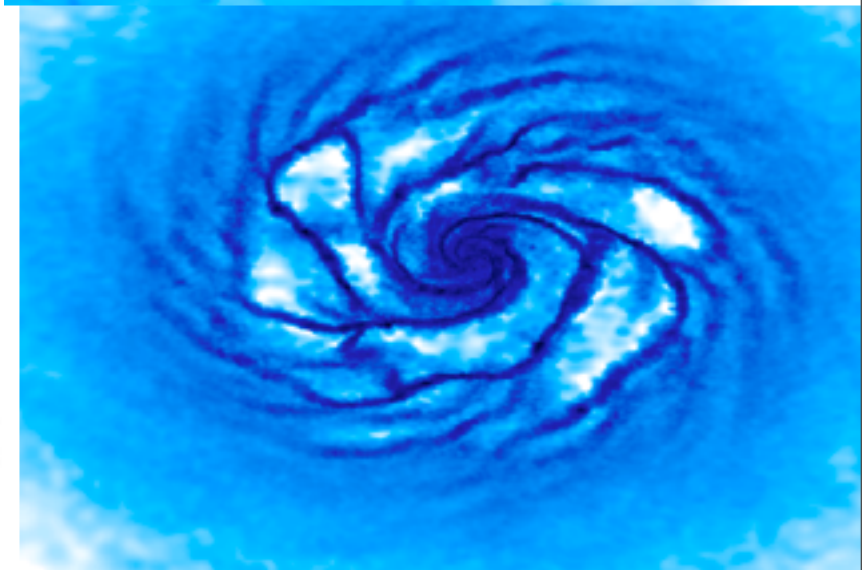
$$\frac{\dot{P}_{\rm rad}}{\rm g\,cm\,s^{-2}} \sim 2\times10^{33}\,\tau_{\rm eff}\left(\frac{M/L_{\rm Salpeter}}{M/L}\right)\left(\frac{\dot{M}_*}{M_\odot\,{\rm yr}^{-1}}\right)$$

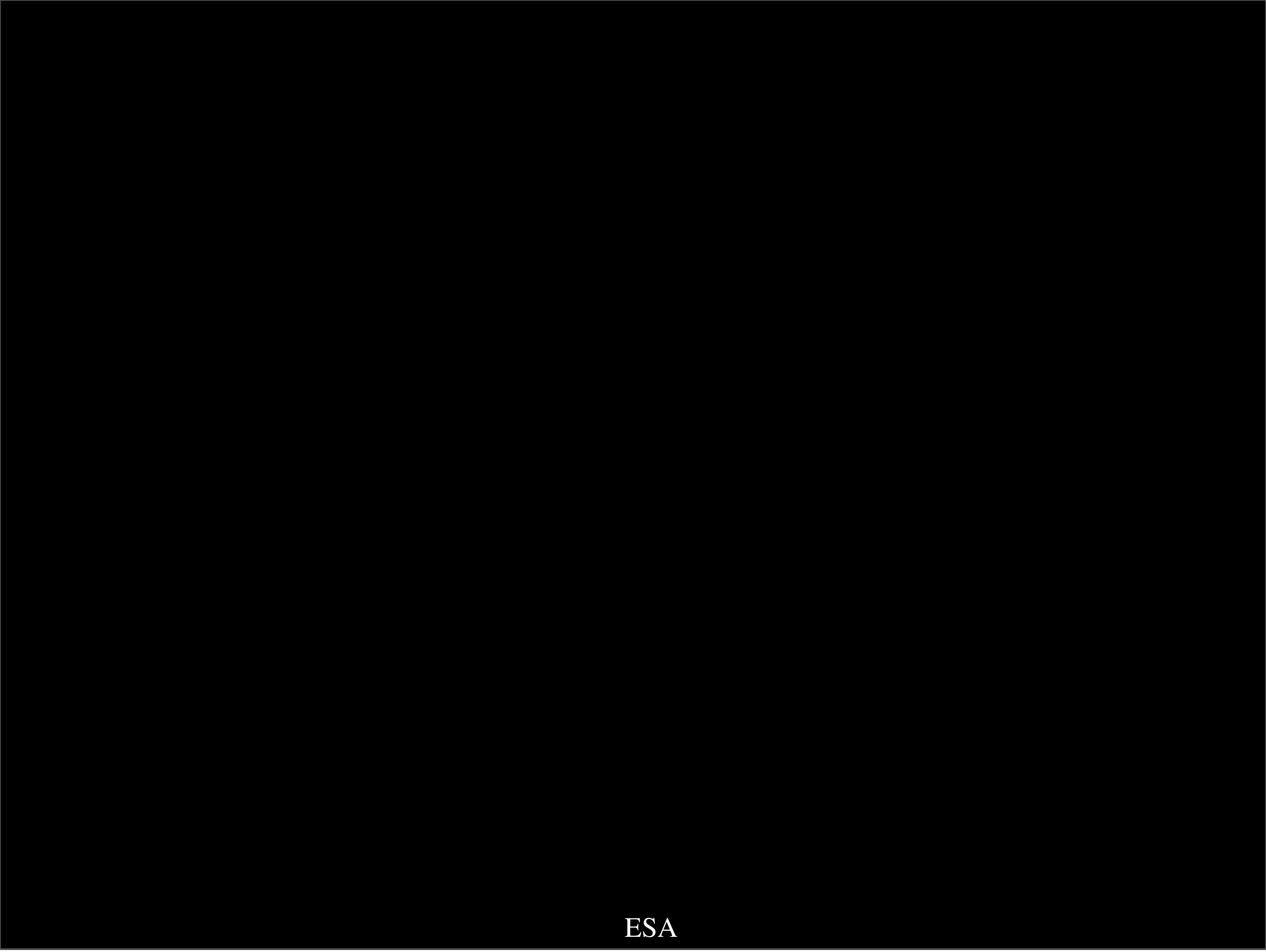
  - Stellar Winds:

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

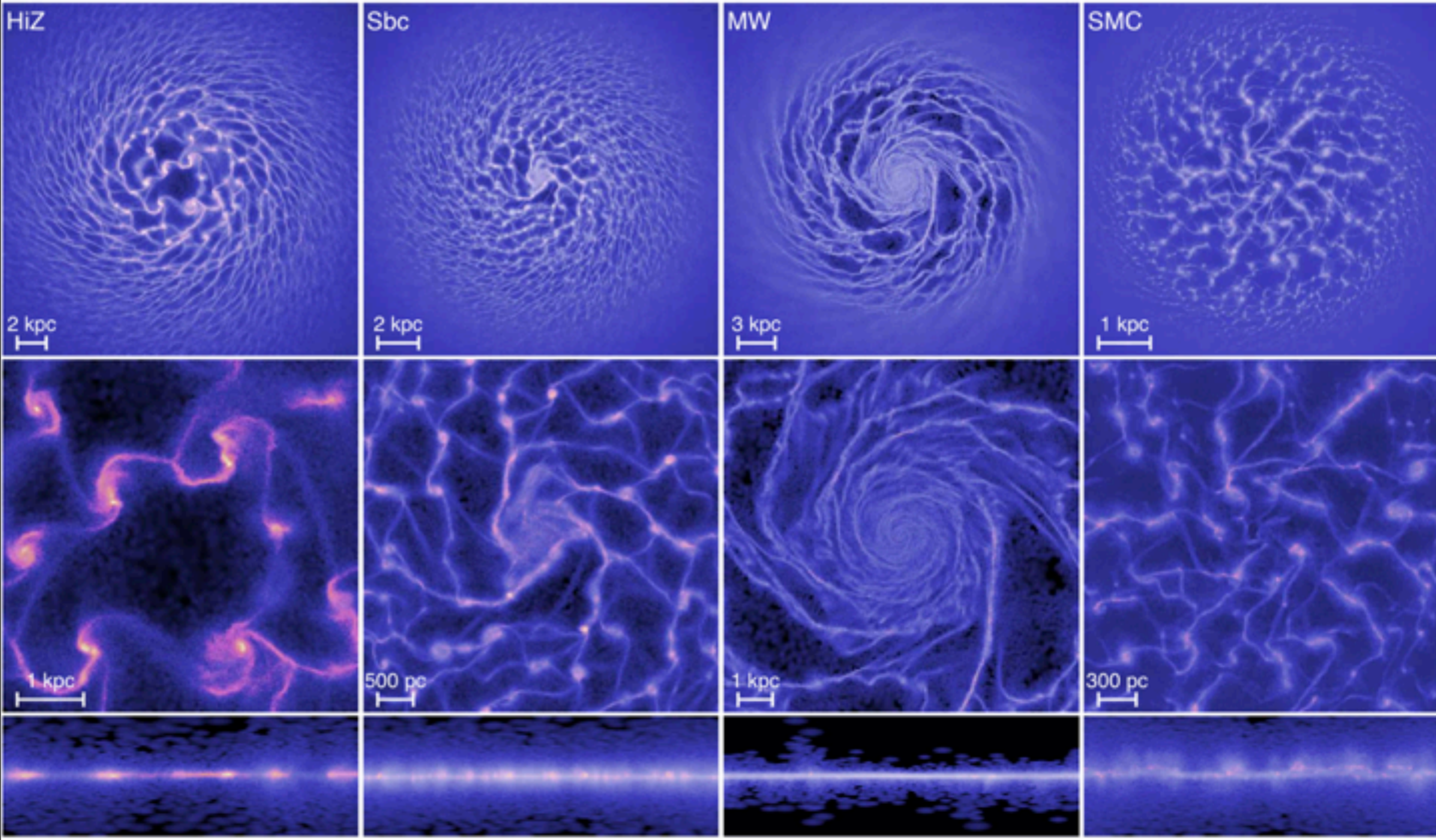
  - Supernovae:

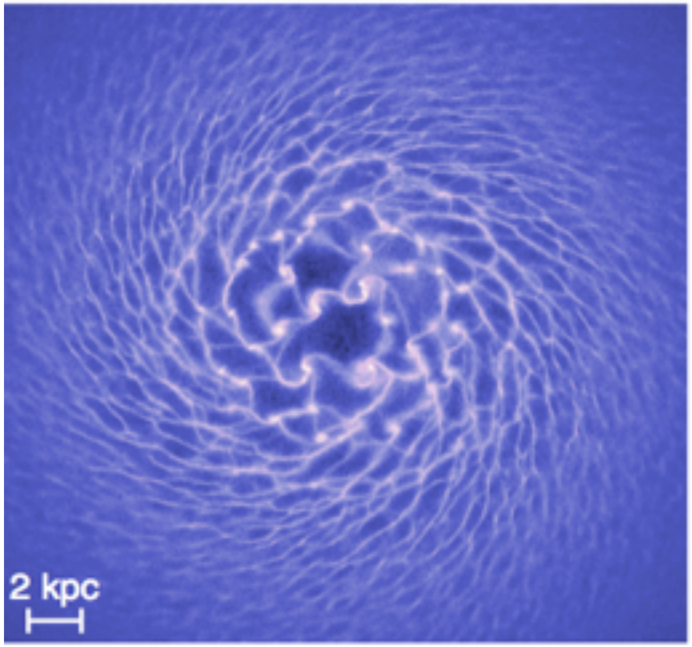
$$\frac{\dot{P}_{\rm SN}}{\rm g\,cm\,s^{-2}} \sim 2\times10^{33}\left(\frac{v_{\rm launch}}{3000\,{\rm km\,s^{-1}}}\right)\left(\frac{\dot{M}_*}{M_\odot\,{\rm yr}^{-1}}\right)$$

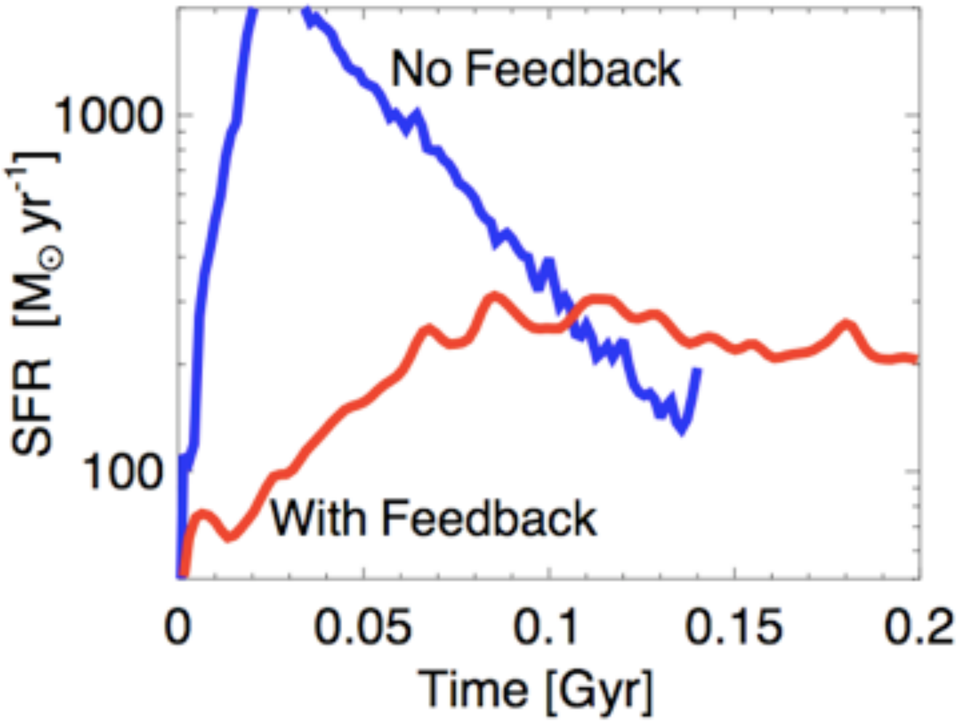


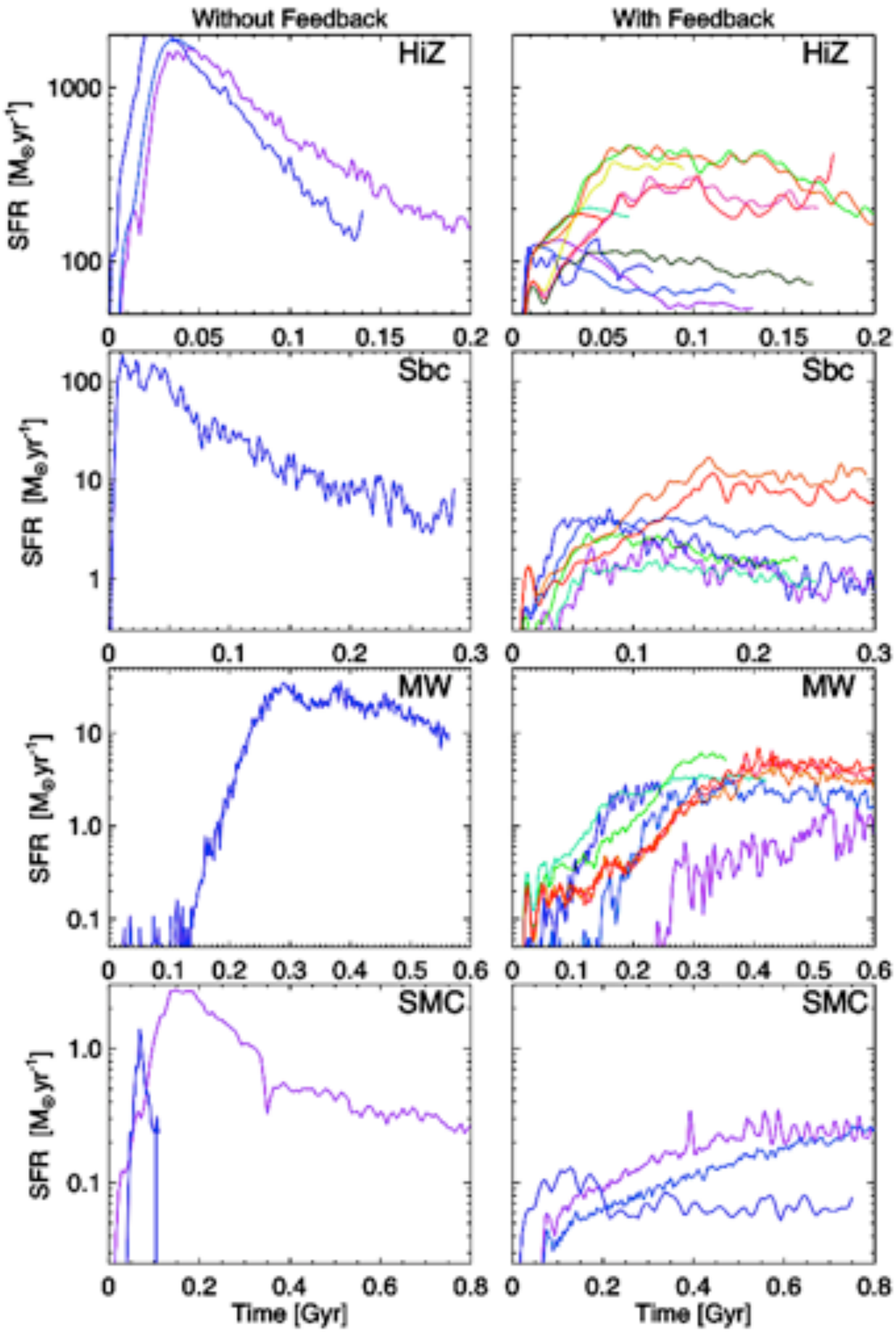


ESA

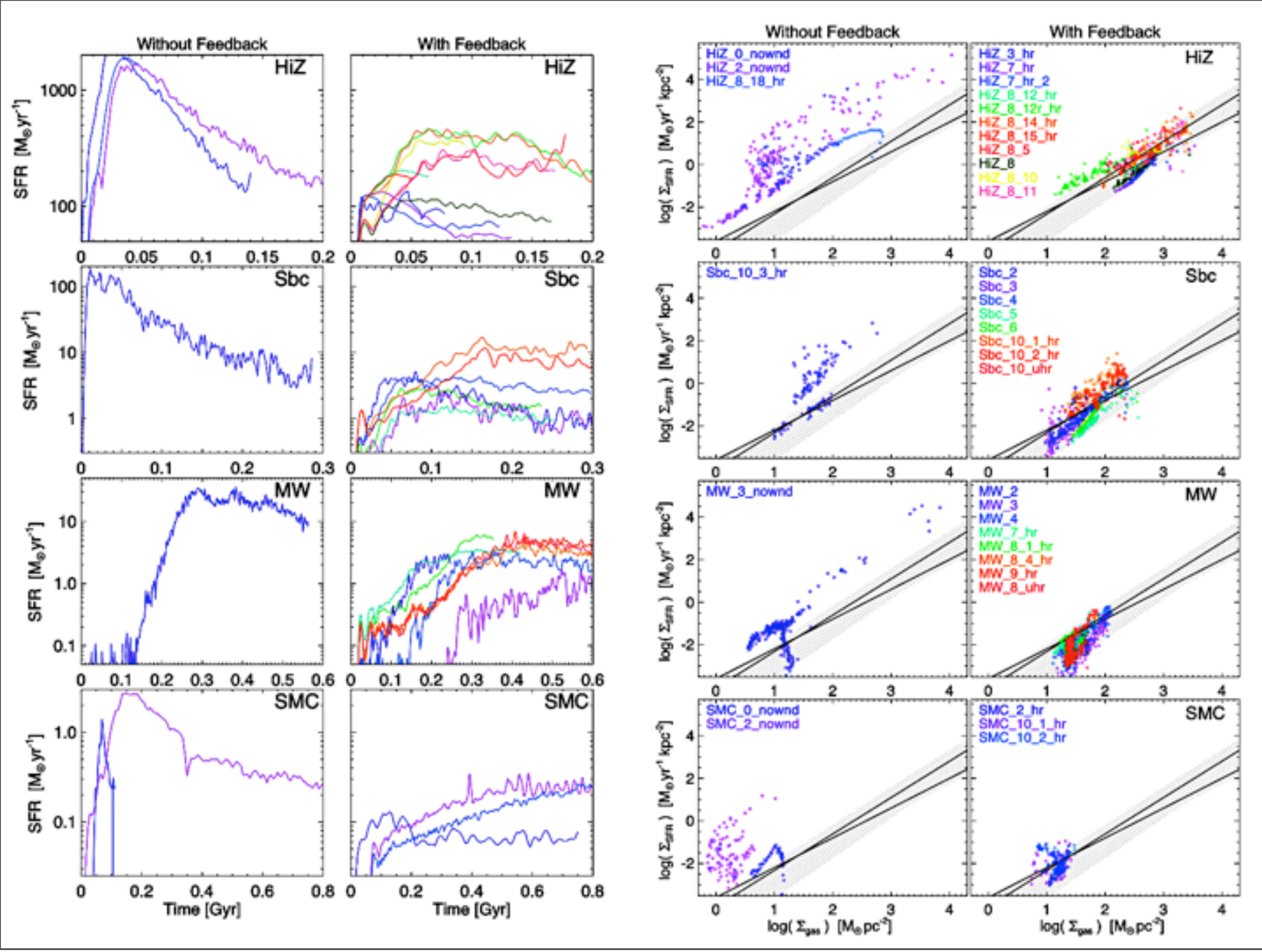

HiZ
Sbc
MW
SMC
2 kpc
2 kpc
3 kpc
1 kpc
1 kpc
500 pc
1 kpc
300 pc


2 kpc


No Feedback
With Feedback
1000
100
SFR [M$_\odot$ yr^{-1}]
0
0.05
0.1
0.15
0.2
Time [Gyr]

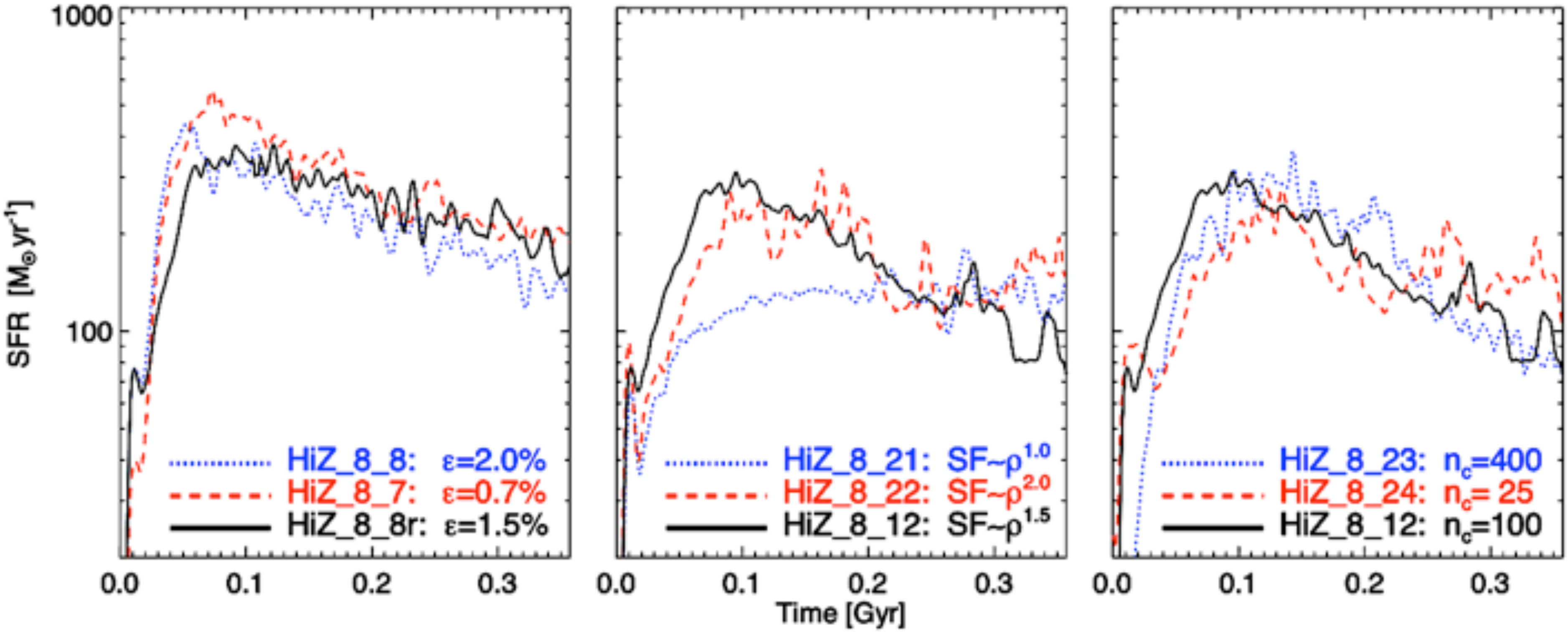


Without Feedback
With Feedback
HiZ
Sbc
MW
SMC
SFR [M⊙yr⁻¹]
Time [Gyr]

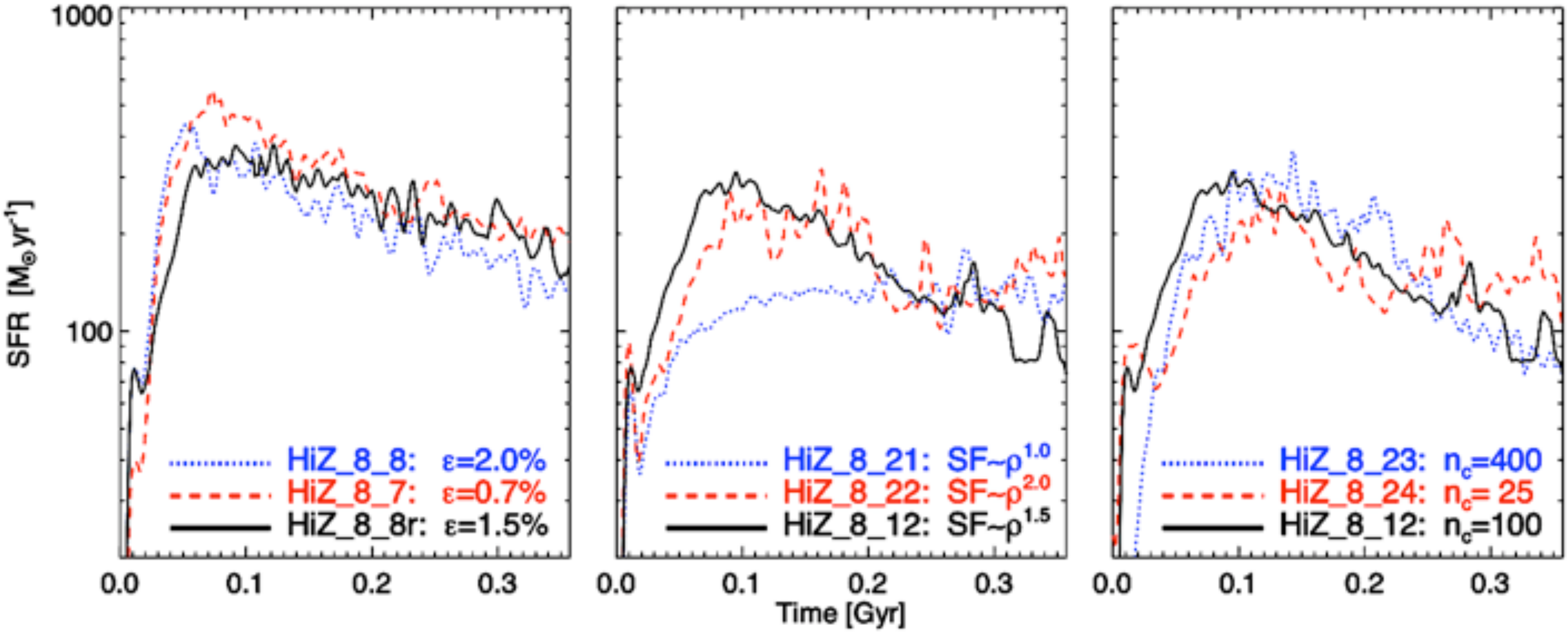


Without Feedback
With Feedback
HiZ
Sbc
MW
SMC
SFR [M⊙yr⁻¹]
Time [Gyr]
log(Σ_SFR) [M⊙yr⁻¹ kpc⁻²]
log(Σ_gas) [M⊙pc⁻²]
HiZ_0_nownd
HiZ_2_nownd
HiZ_8_18_hr
HiZ_3_hr
HiZ_7_hr
HiZ_7_hr_2
HiZ_8_12_hr
HiZ_8_12r_hr
HiZ_8_14_hr
HiZ_8_15_hr
HiZ_8_5
HiZ_8
HiZ_8_10
HiZ_8_11
Sbc_10_3_hr
Sbc_2
Sbc_3
Sbc_4
Sbc_5
Sbc_6
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

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



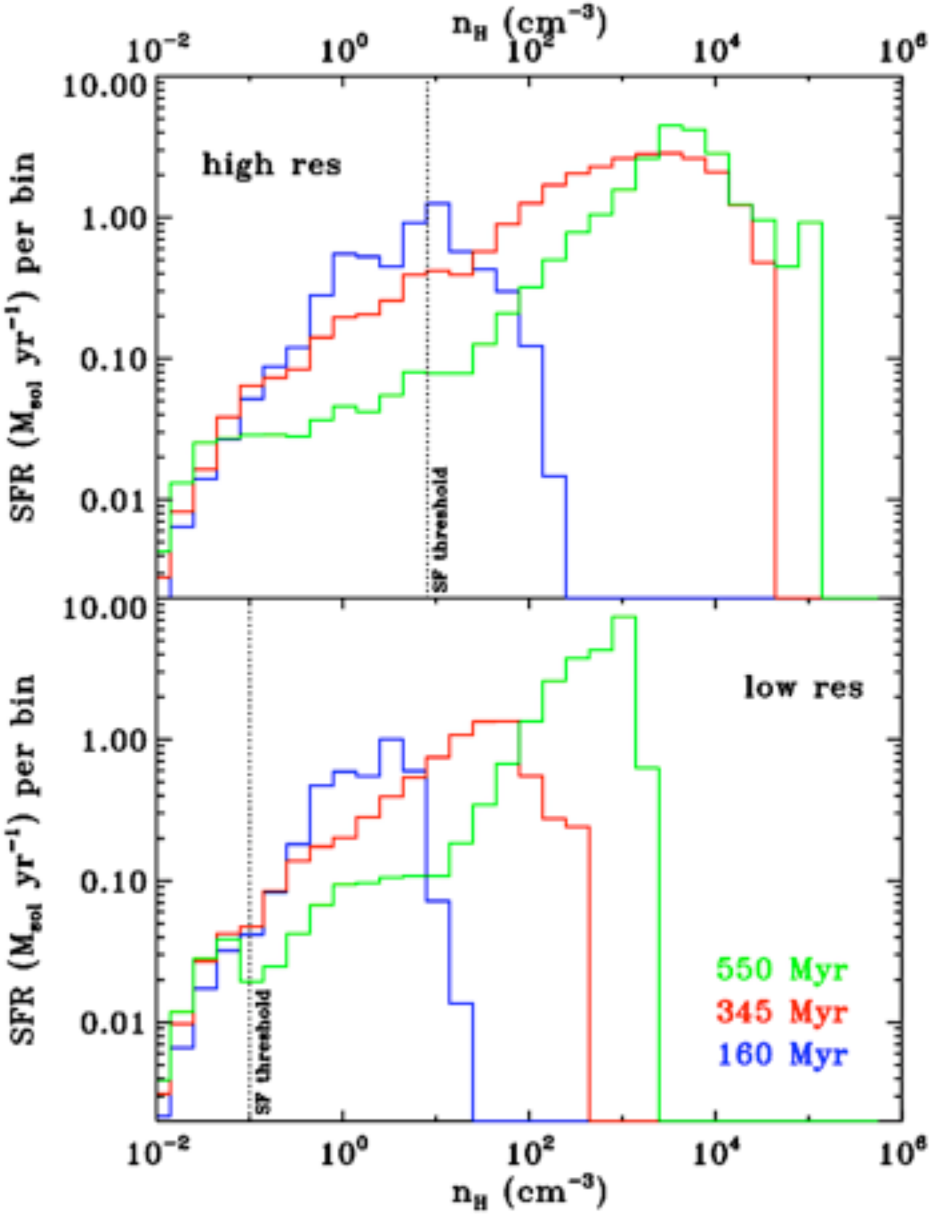
Schmidt-Kennicutt Law Emerges *INDEPENDENT* of Local SF Law



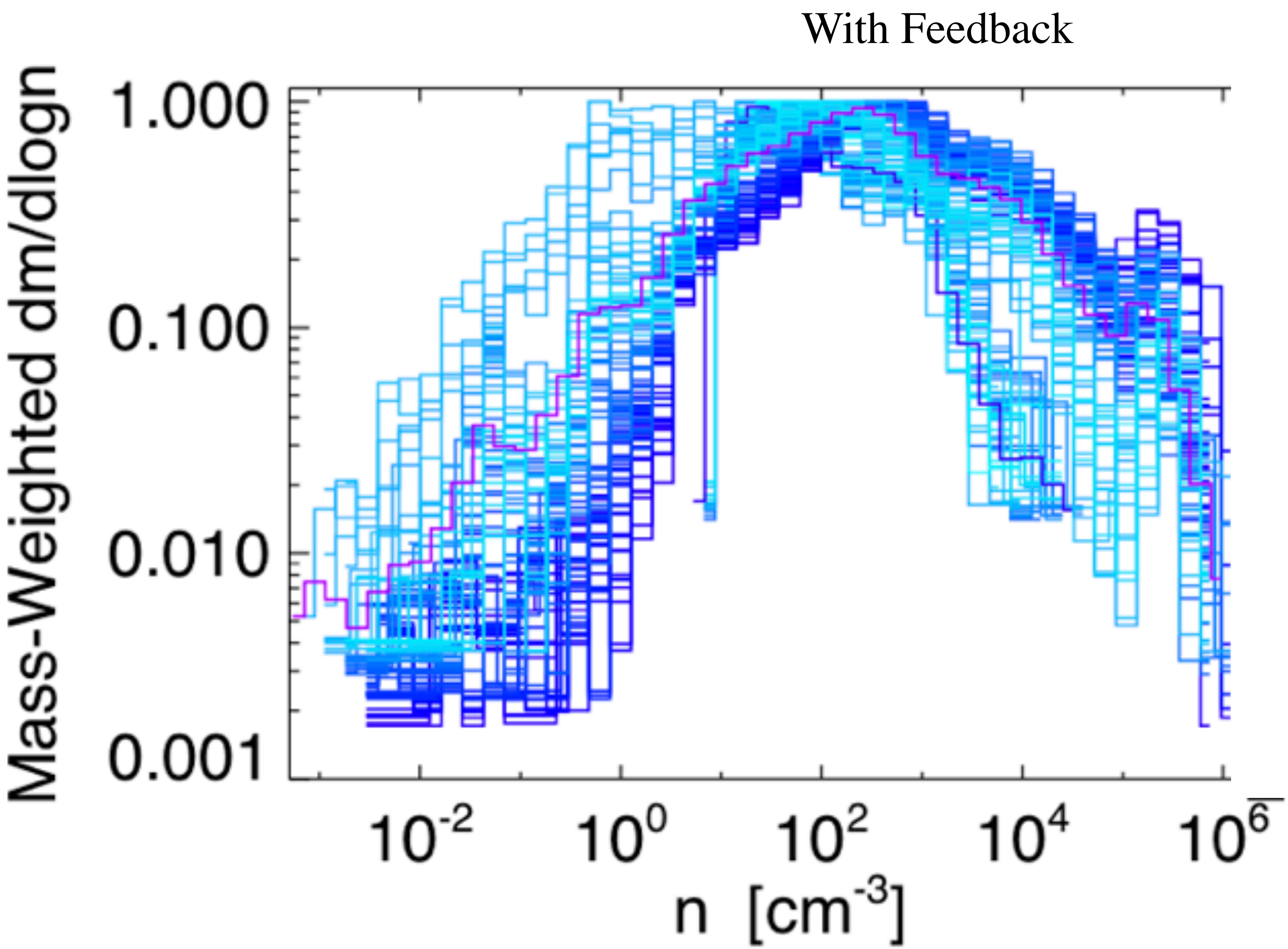
- Set by feedback (i.e. SFR) needed to maintain marginal stability

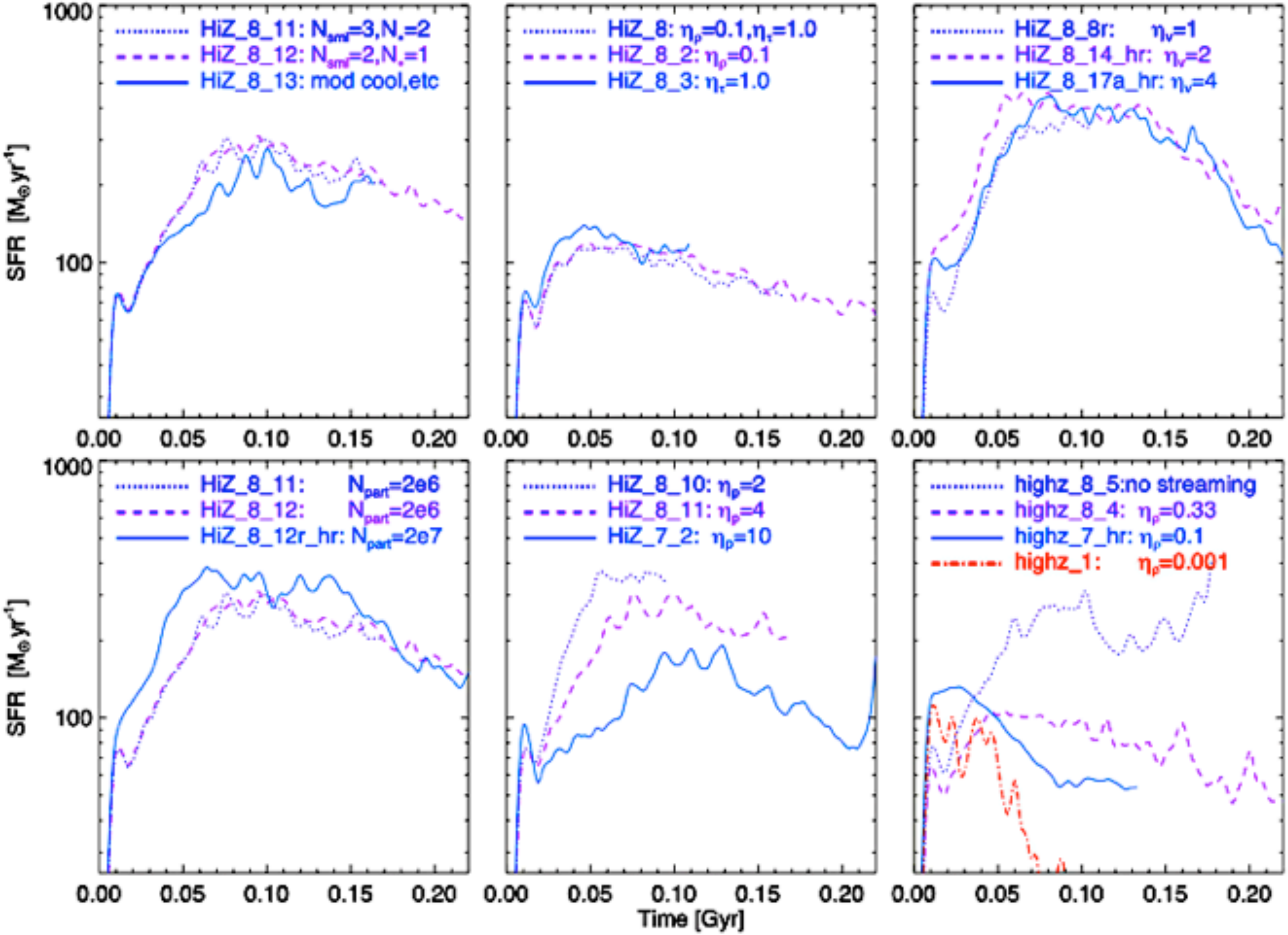
Summary

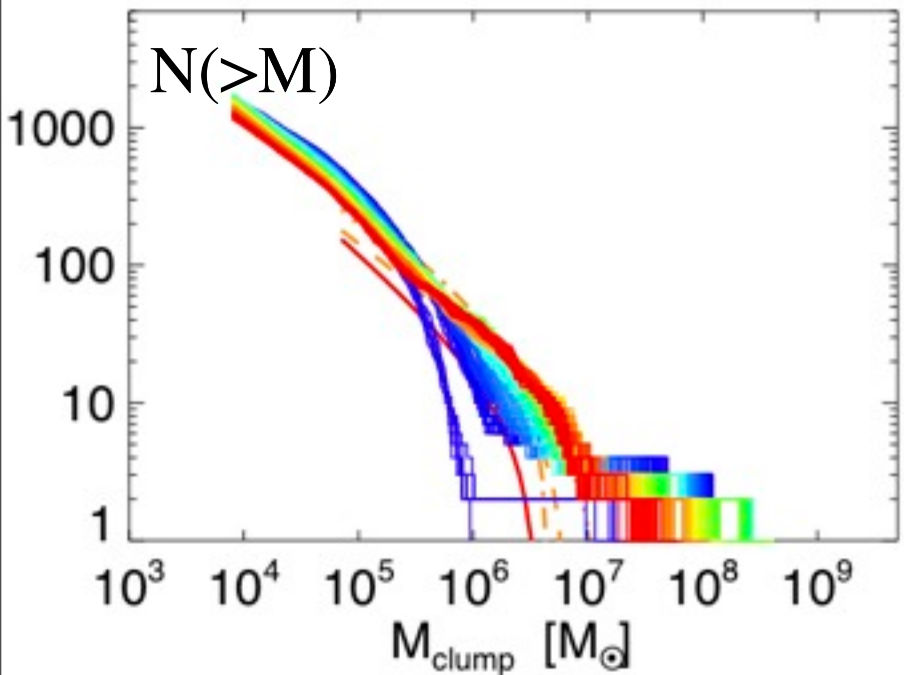
- Fueling Most Luminous BHs:
  Global gravitational instabilities CAN power ~10 M_{sun}/yr! Really!
  - New Mdot estimator: neither viscous nor Bondi
- "Stuff within Stuff": Cascade of instabilities with diverse morphology
  - Nuclear starbursts & powering of SMGs & ULIRGs
  - Determines structure & kinematics of elliptical galaxies
- Accretion rates & orientations are stochastic: spin too?
- Stellar nuclear disk 'relics': M31 & 4486b:
  Can we directly observe the 'fossil' of the accretion driver & torus ?
- M_{BH} traces spheroid $E_{binding}$: *self-regulated* BH growth
  - BH 'fundamental plane': depth of potential, not just M* or sigma
    - differences with redshift & bulge type
- Future work:
  - Better direct observational tests
  - More physics of star formation & stellar feedback
  - No more artificial separation of feedback from stars/quasar mode/radio mode

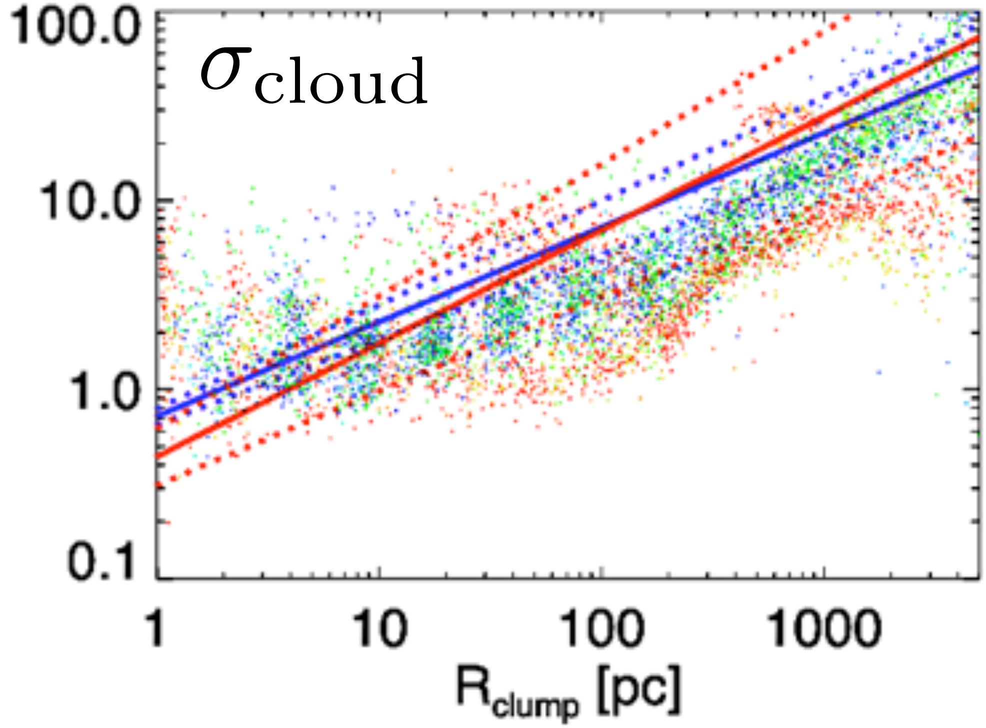


Without Feedback


With Feedback
Mass-Weighted dm/dlogn
1.000
0.100
0.010
0.001
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
n [cm^{-3}]

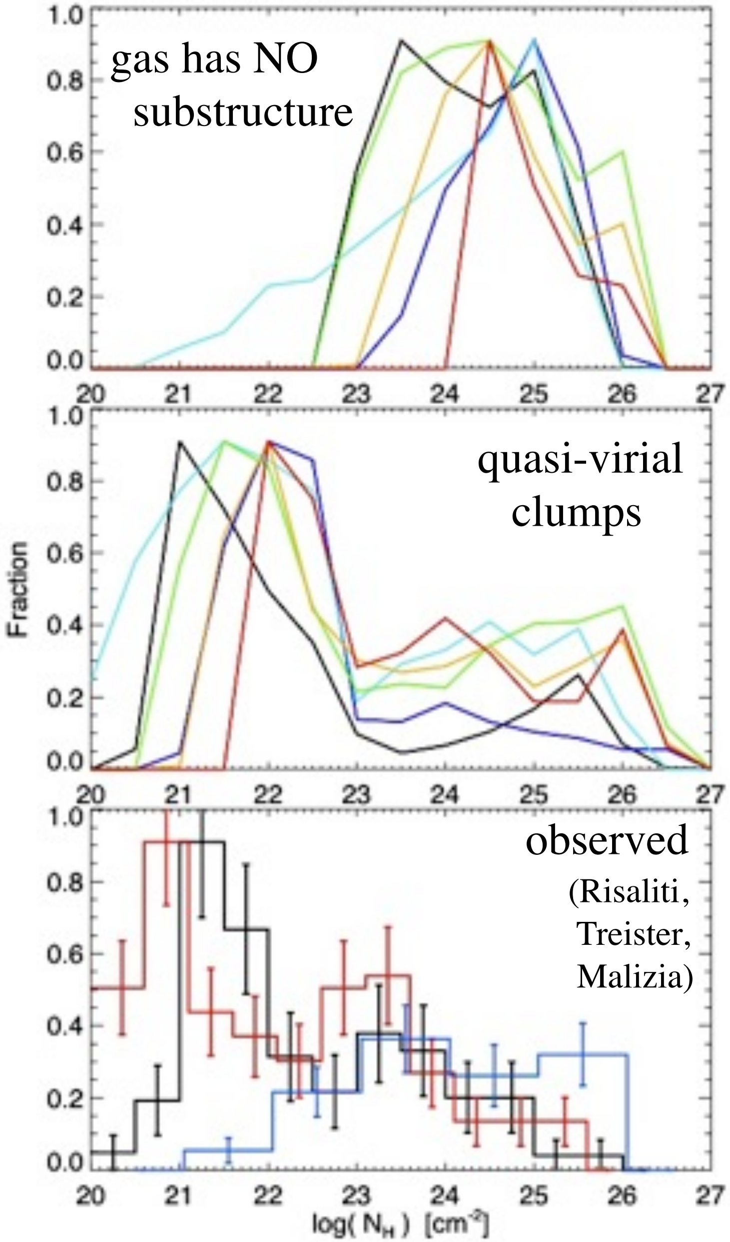

HiZ_8_11: N_{sml}=3,N_*=2
HiZ_8_12: N_{sml}=2,N_*=1
HiZ_8_13: mod cool,etc
HiZ_8: η_ρ=0.1,η_τ=1.0
HiZ_8_2: η_ρ=0.1
HiZ_8_3: η_τ=1.0
HiZ_8_8r: η_v=1
HiZ_8_14_hr: η_v=2
HiZ_8_17a_hr: η_v=4
HiZ_8_11: N_{part}=2e6
HiZ_8_12: N_{part}=2e6
HiZ_8_12r_hr: N_{part}=2e7
HiZ_8_10: η_ρ=2
HiZ_8_11: η_ρ=4
HiZ_7_2: 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
SFR [$M_\odot\,yr^{-1}$]
1000
100
0.00
0.05
0.10
0.15
0.20
Time [Gyr]

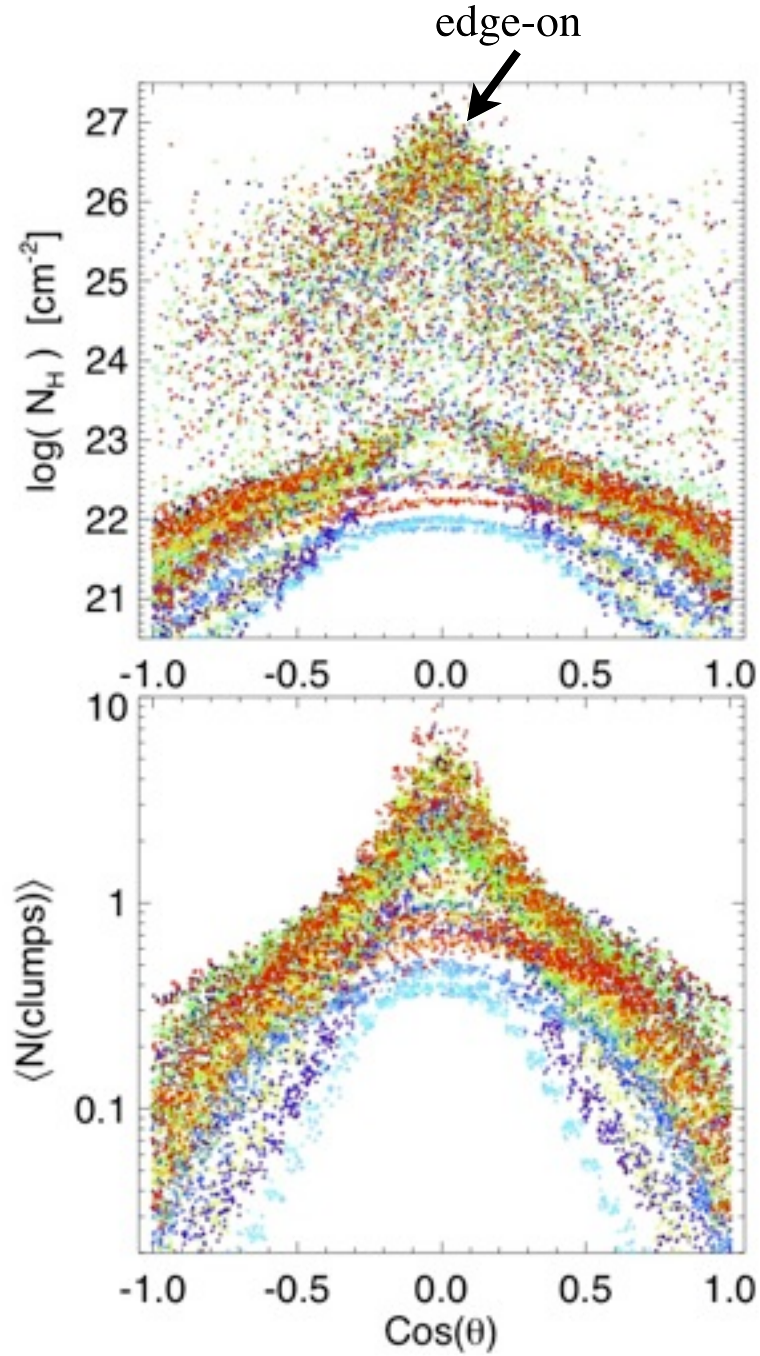




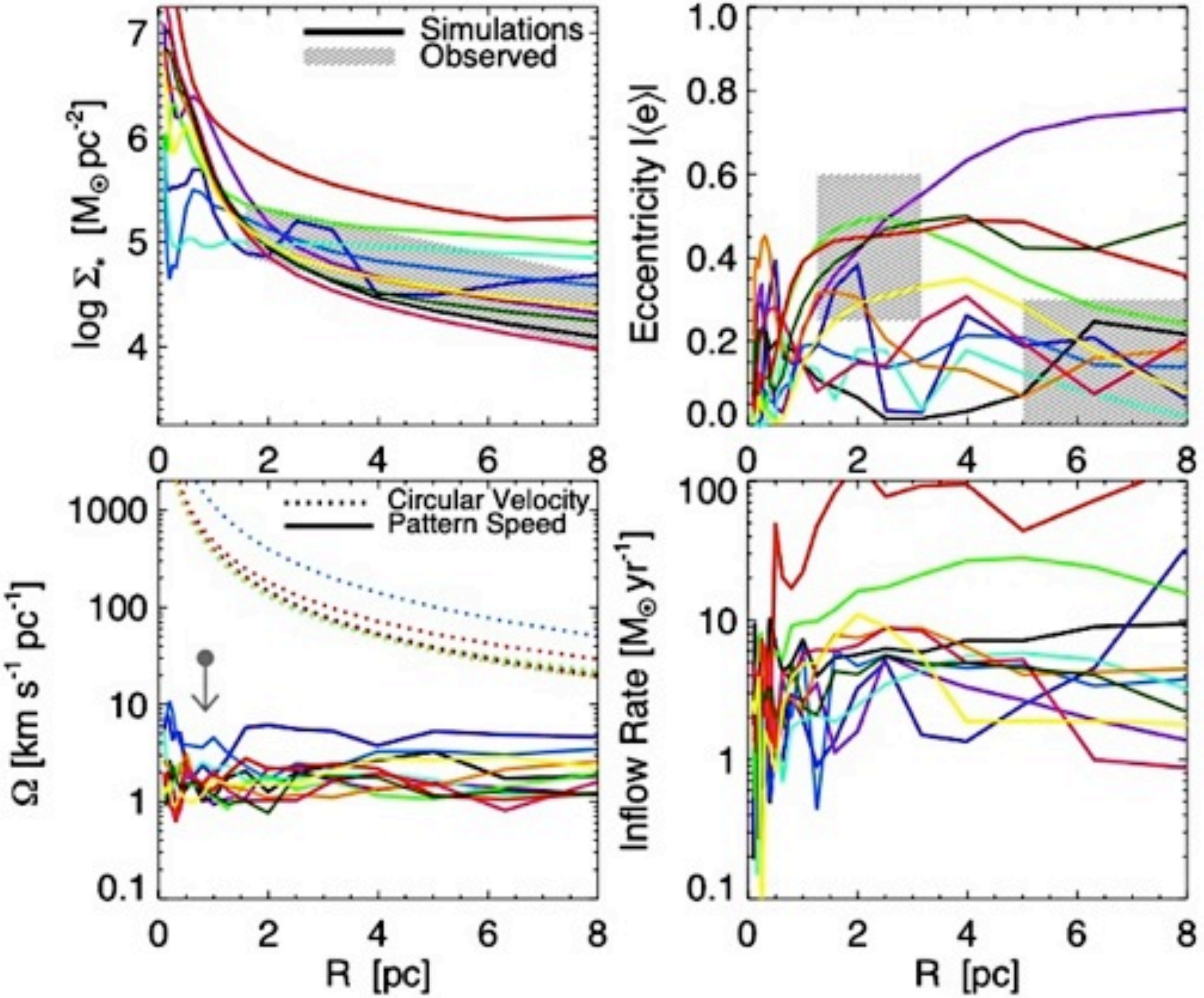
Some GMC Properties Emerge Generically from Feedback-Regulated Turbulence

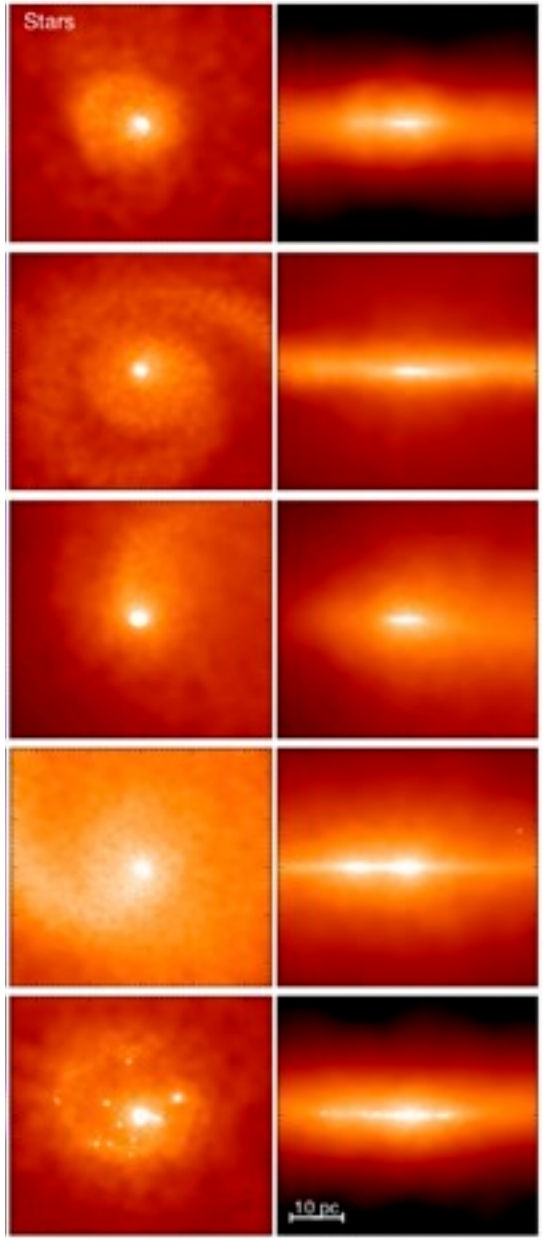
• Compare column density distributions:





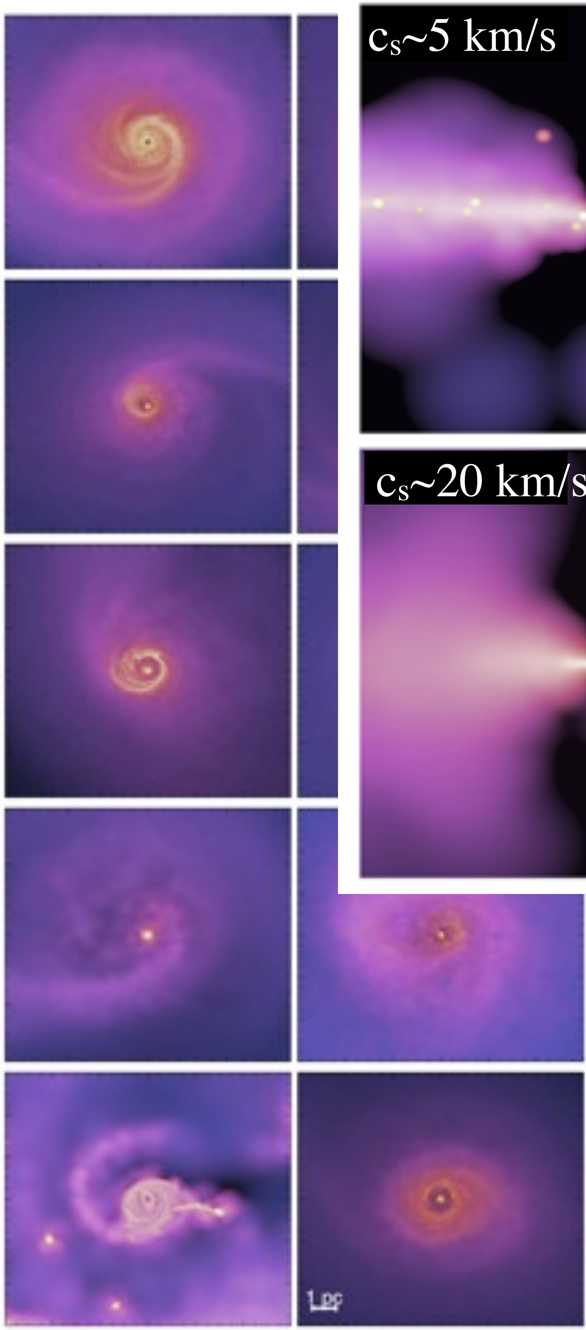
- These are observed!
  M31, NGC4486B, many candidates

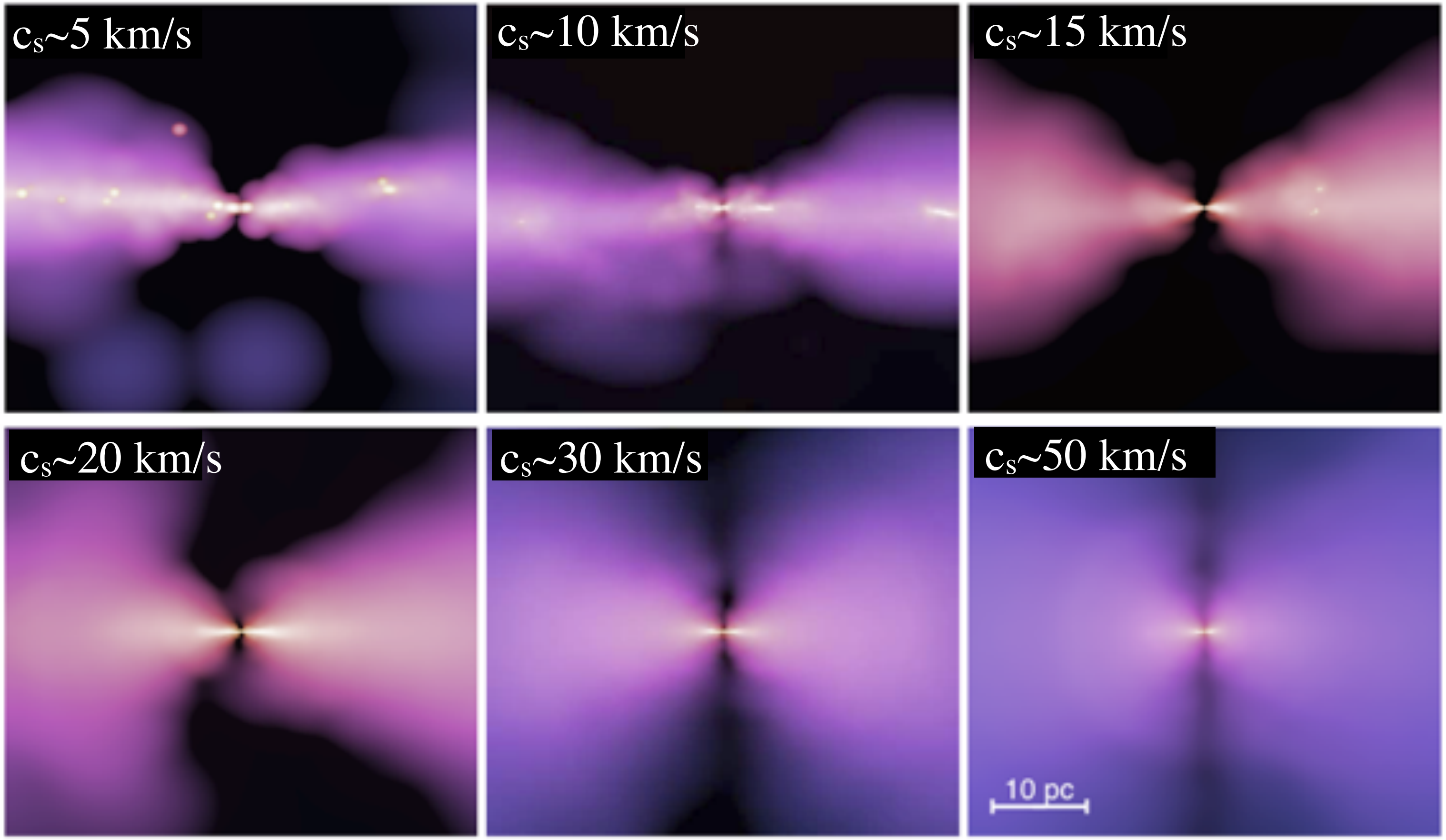




- "run backwards": the M31 disk implies accretion at ~0.5-3 M_{sun}/yr (~L_{Edd}) for ~100 Myr (~ M_{BH}) !

What about the obscuration from these disks?

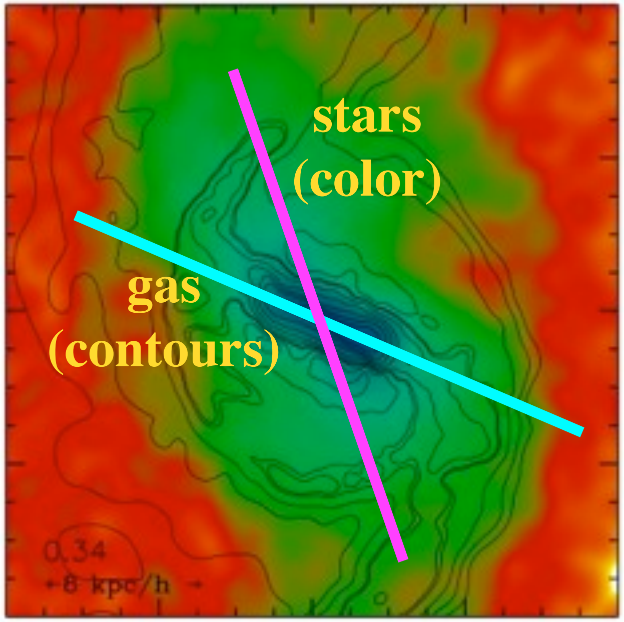




- The eccentric disk IS the torus
- Occurs even if allow cooling and no stellar feedback!
  - Heating by bending/warping modes, themselves excited *by the eccentric pattern*

How does this work?

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



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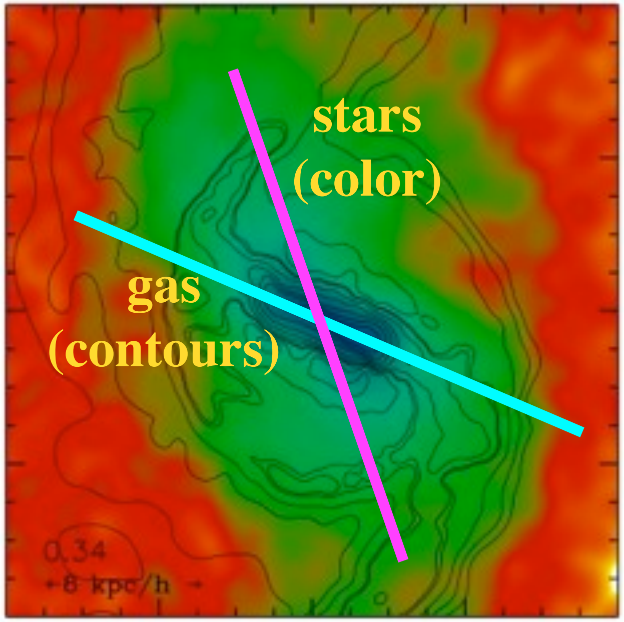

standard (dissipationless) formulation: spiral waves carry the angular momentum: (Lynden-Bell & Kalnajs '72)

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

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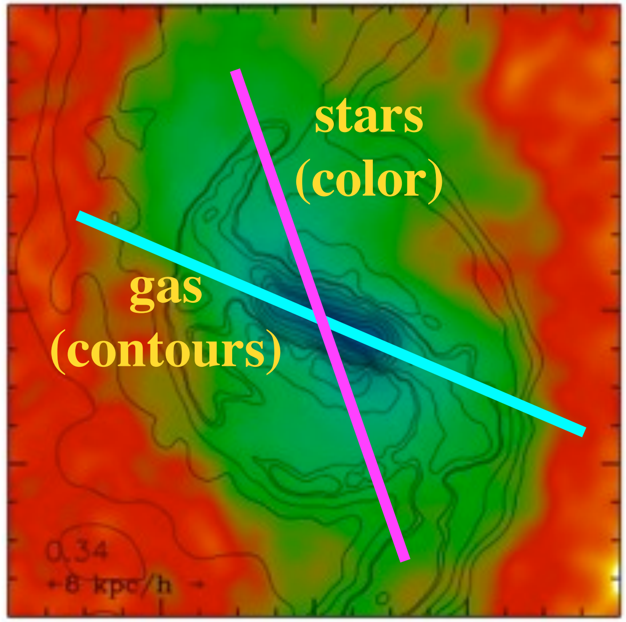

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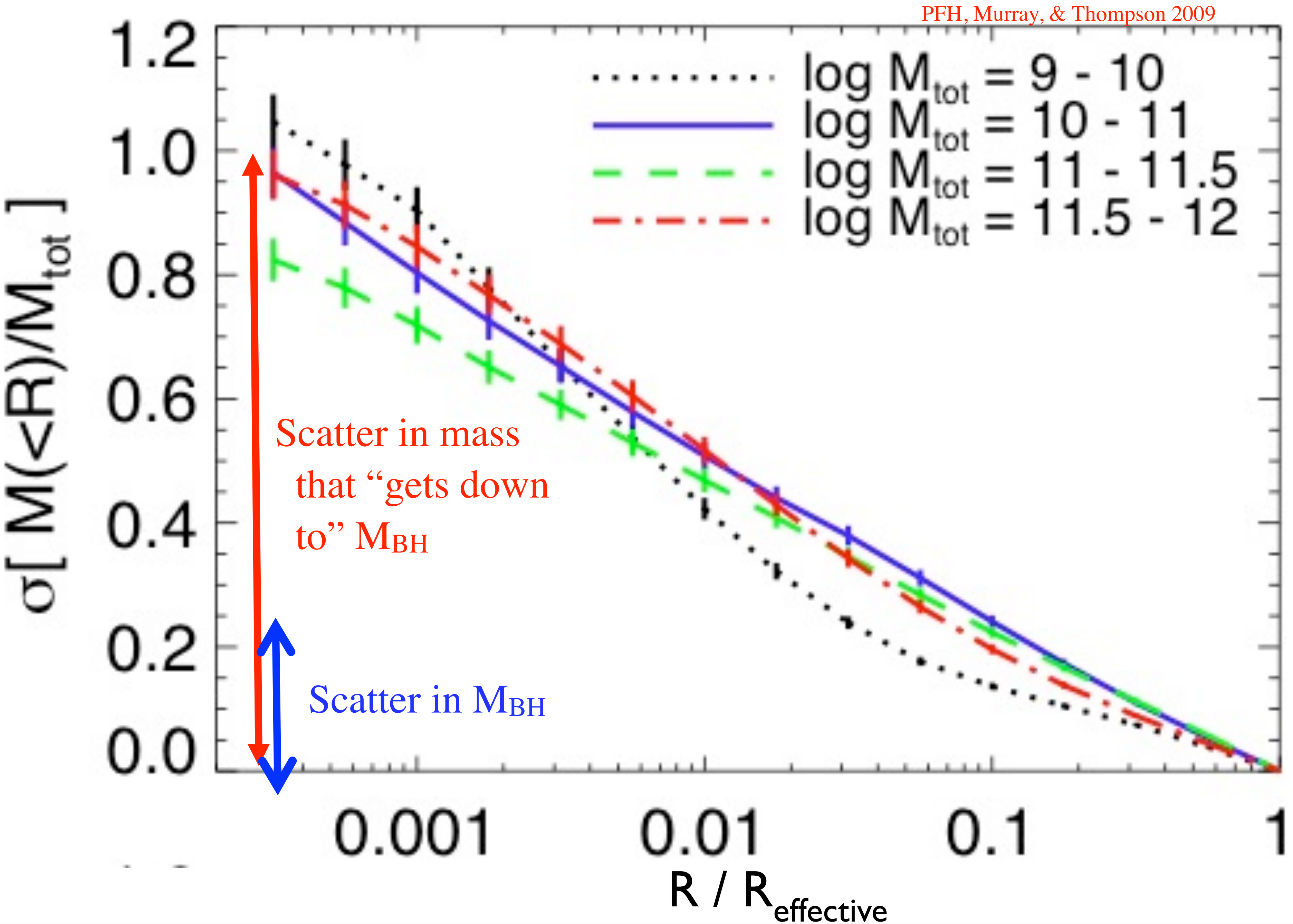
with shocks & dissipation:

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

>100x larger!!!

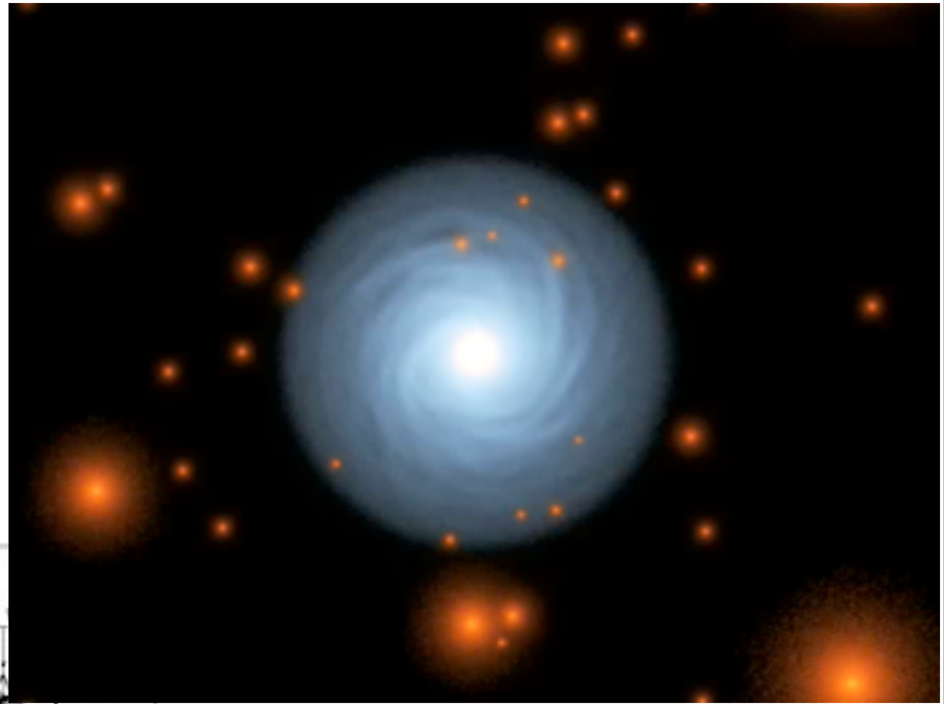
BHs appear to "know more" about the galaxy than nuclear stars...

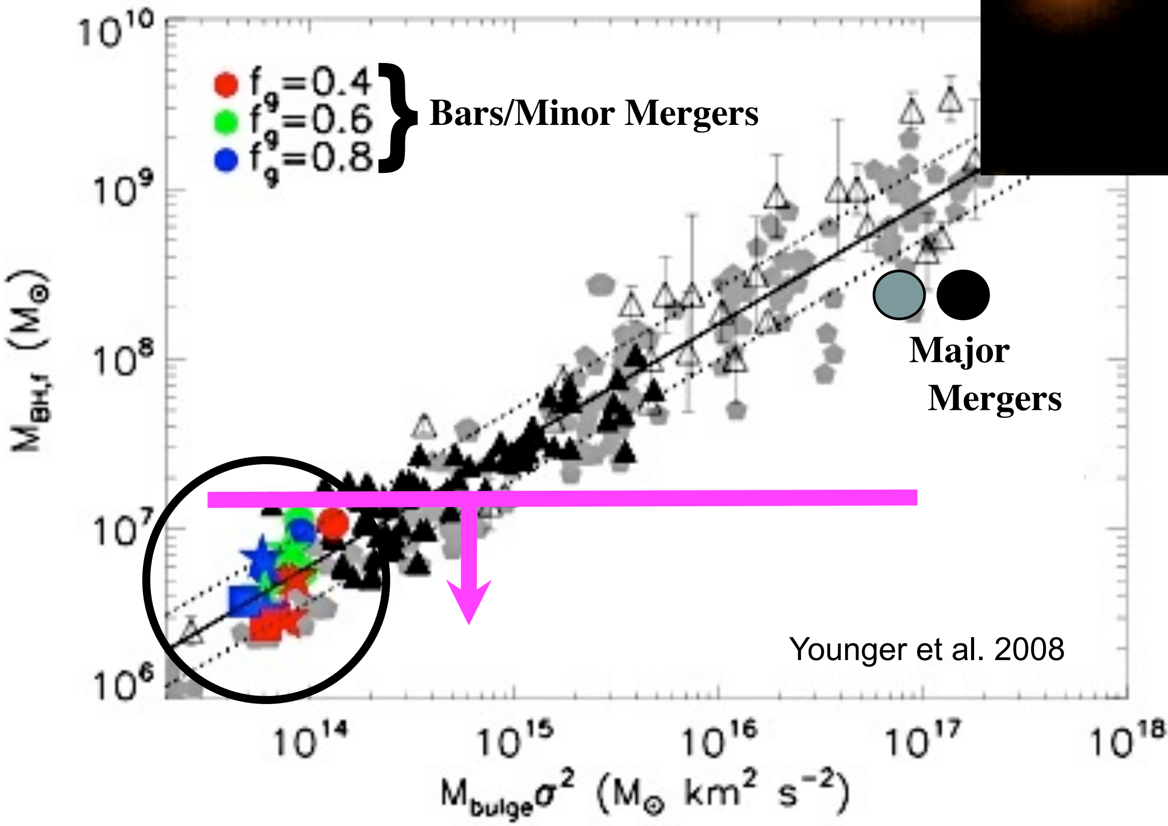


Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

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



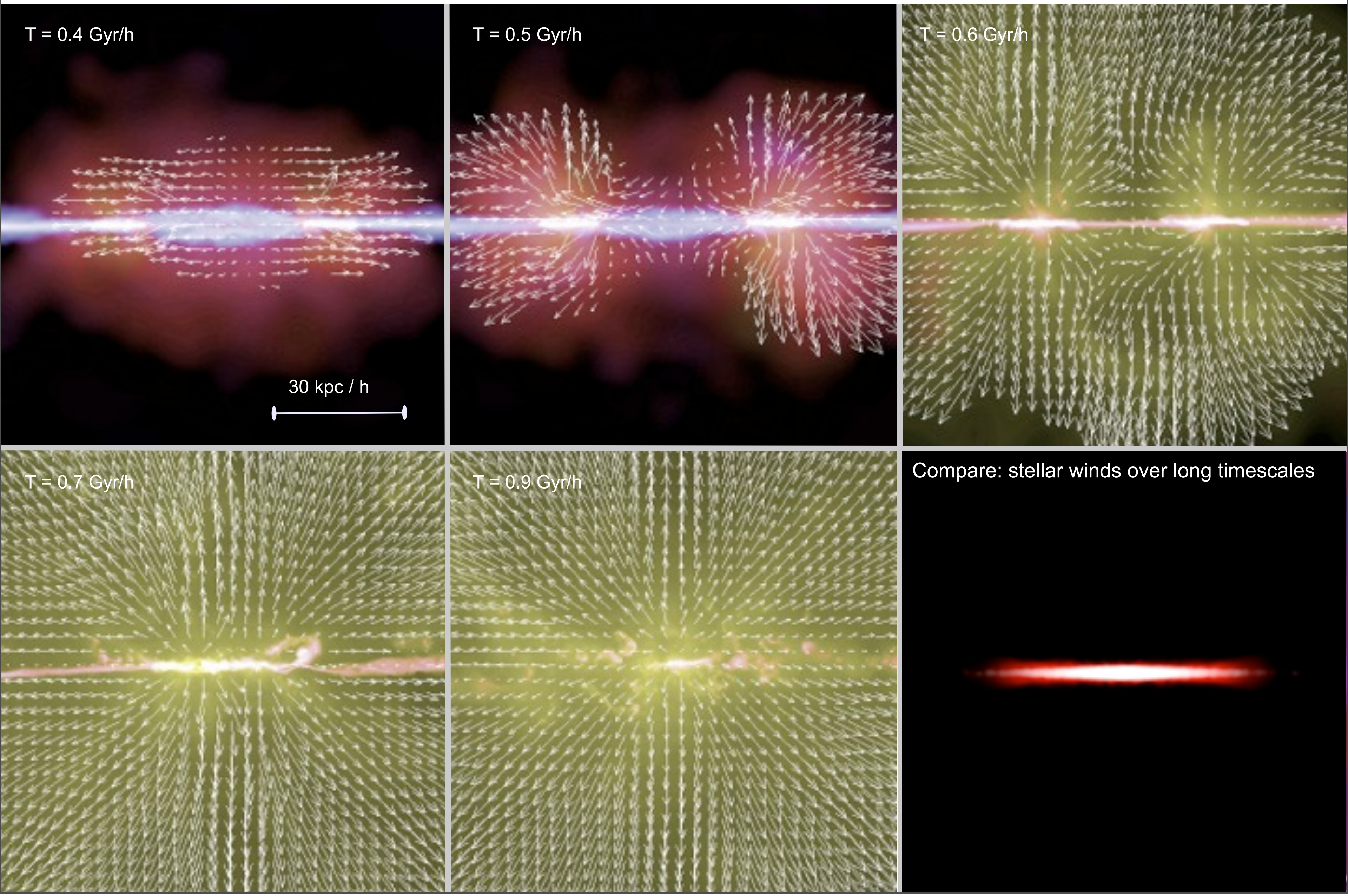


- If you don't build massive bulges, getting gas in *is not enough*!

Where Does the Energy/Momentum Go?

QUASAR-DRIVEN OUTFLOWS?

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



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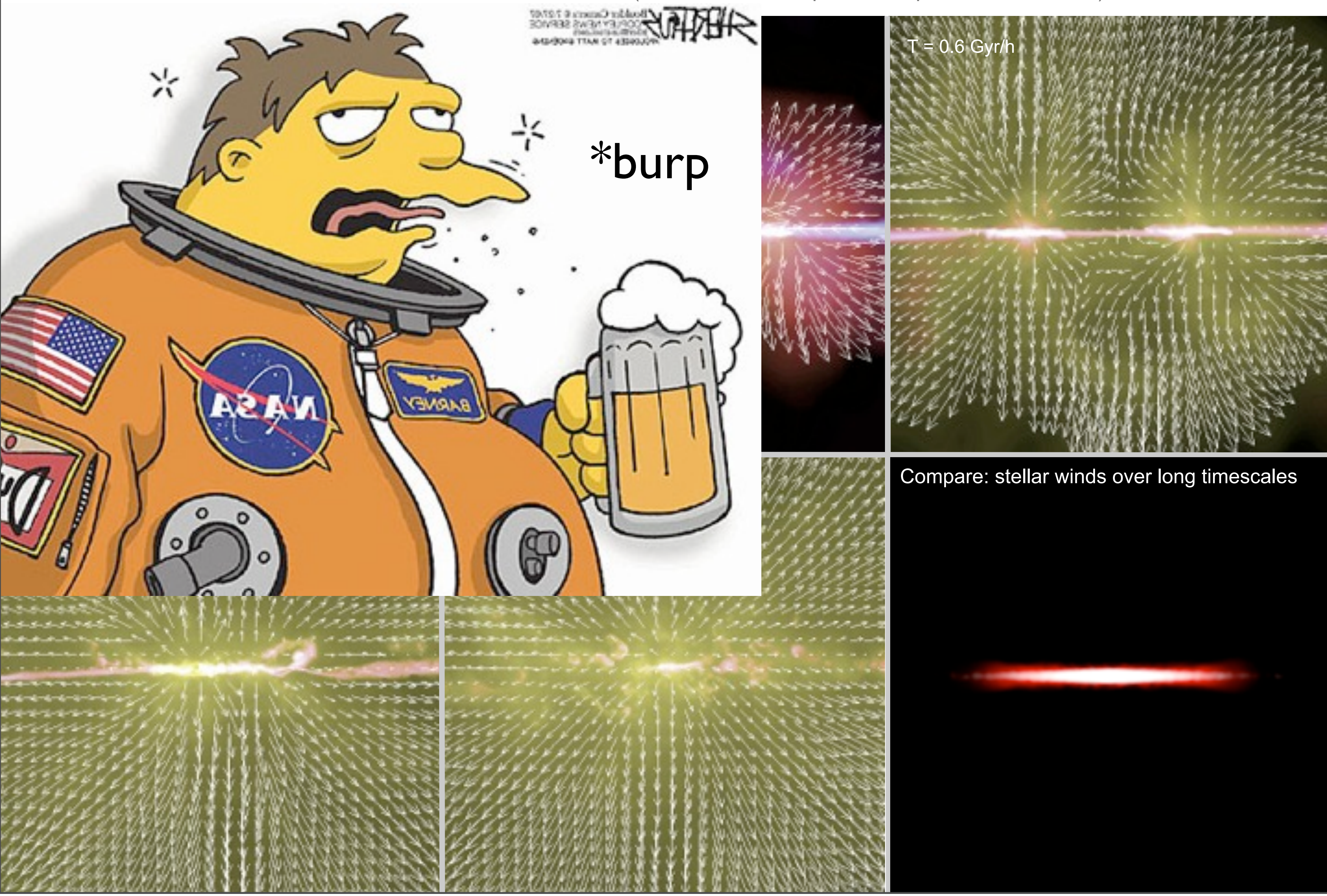

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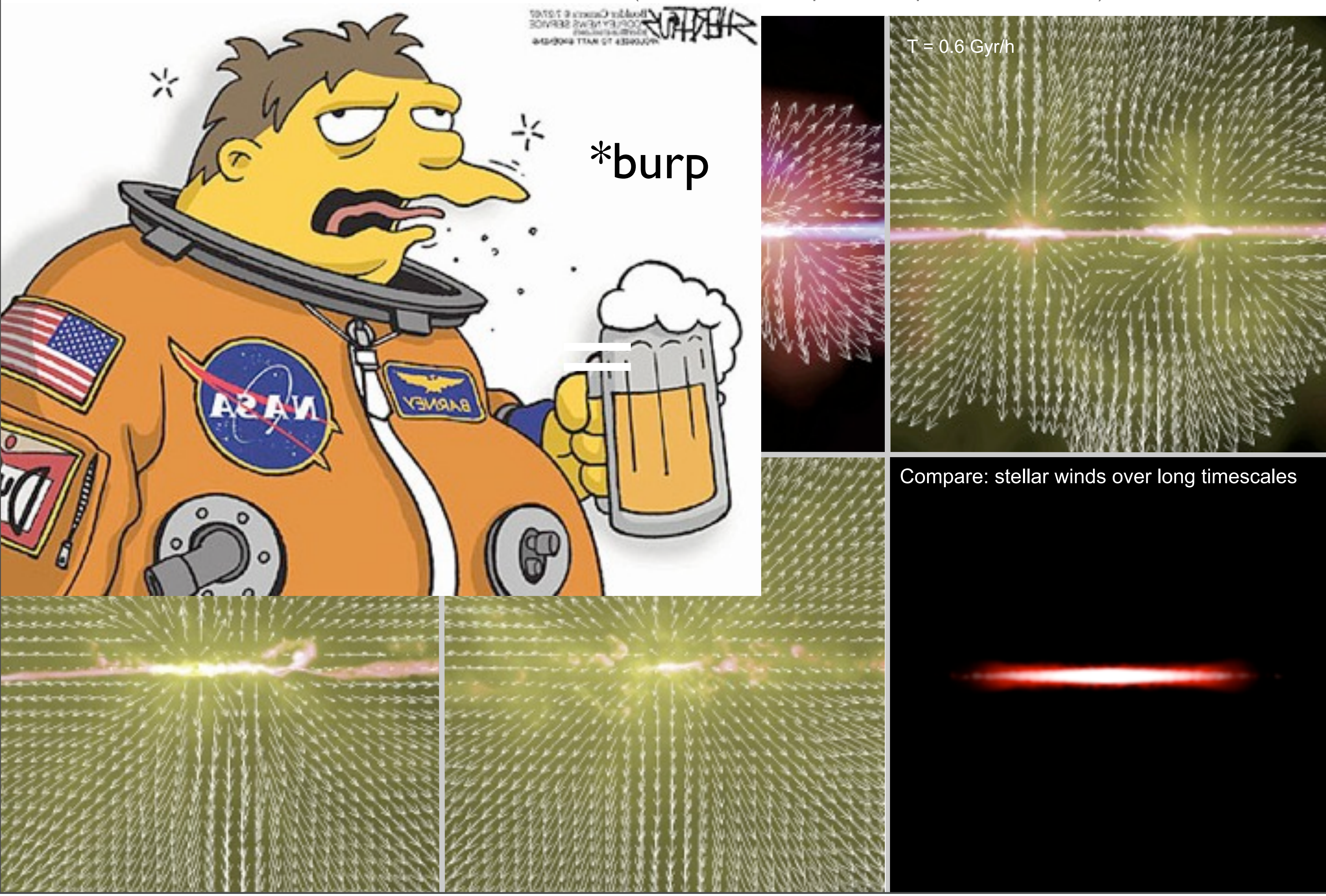

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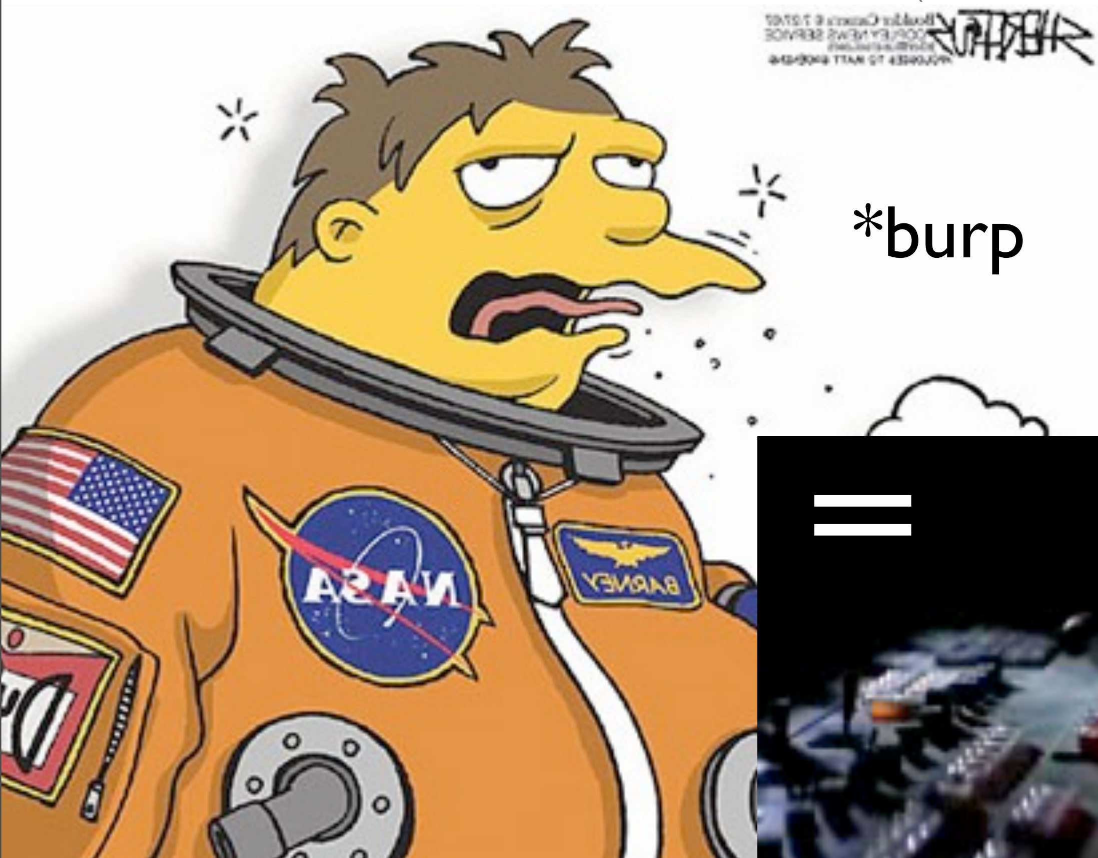
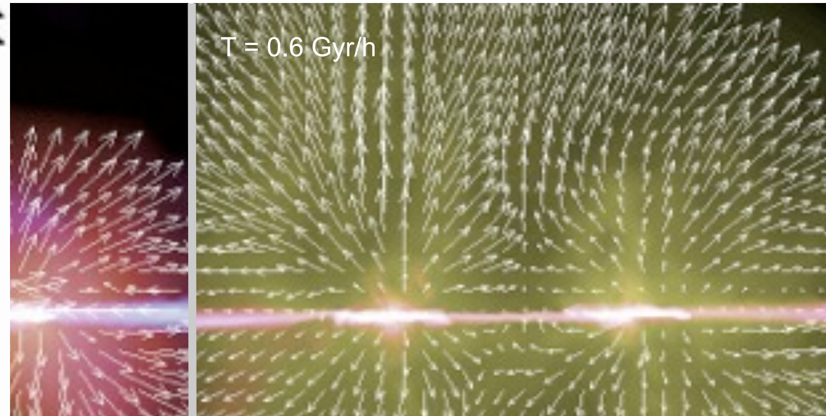
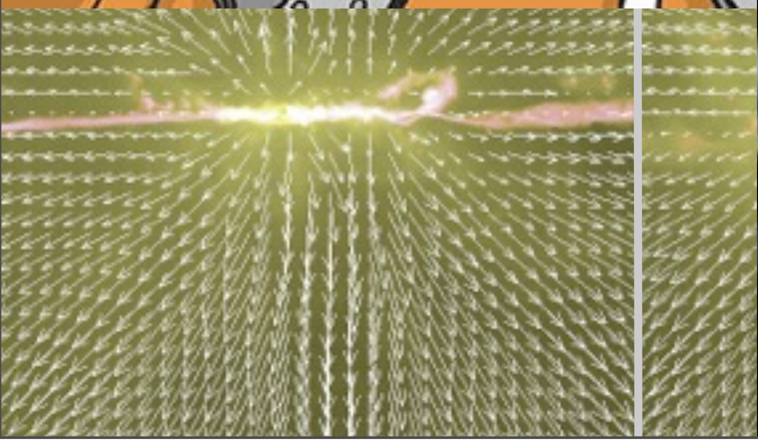
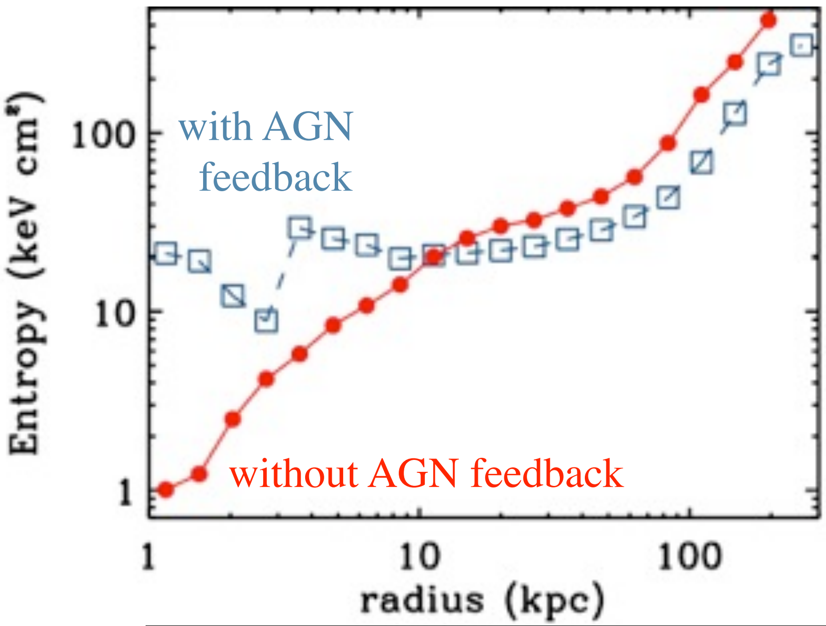


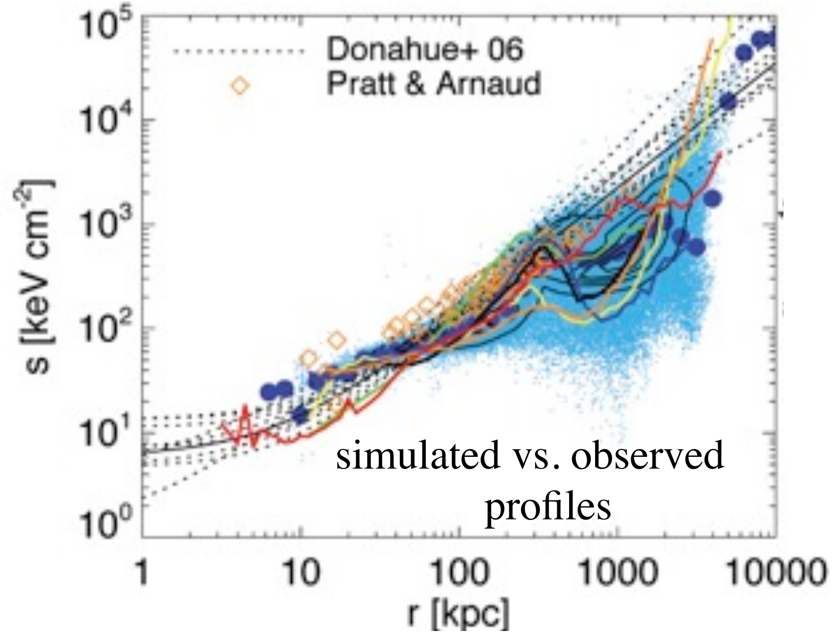


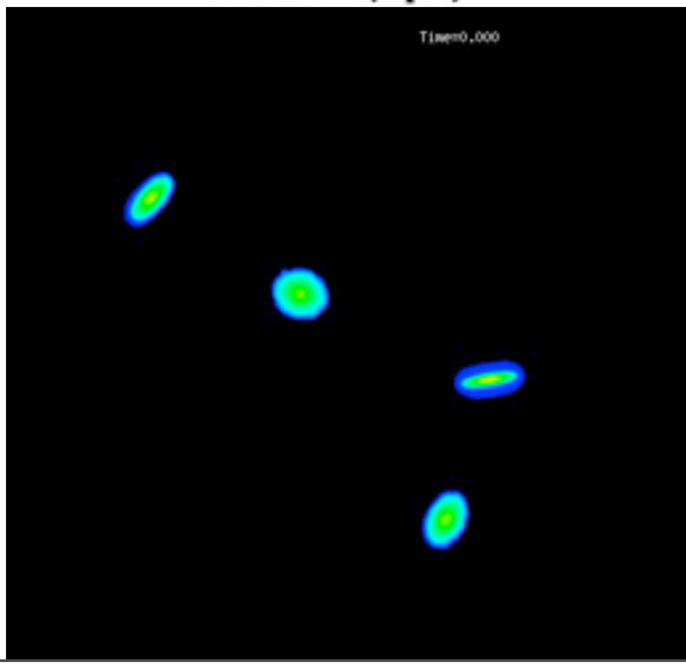


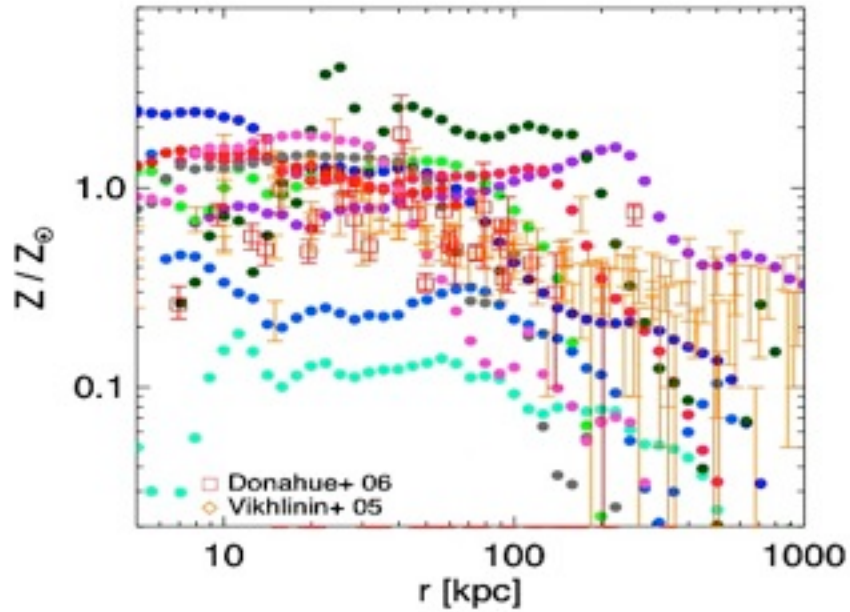
Quasar Outflows May Be Significant for the ICM & IGM

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





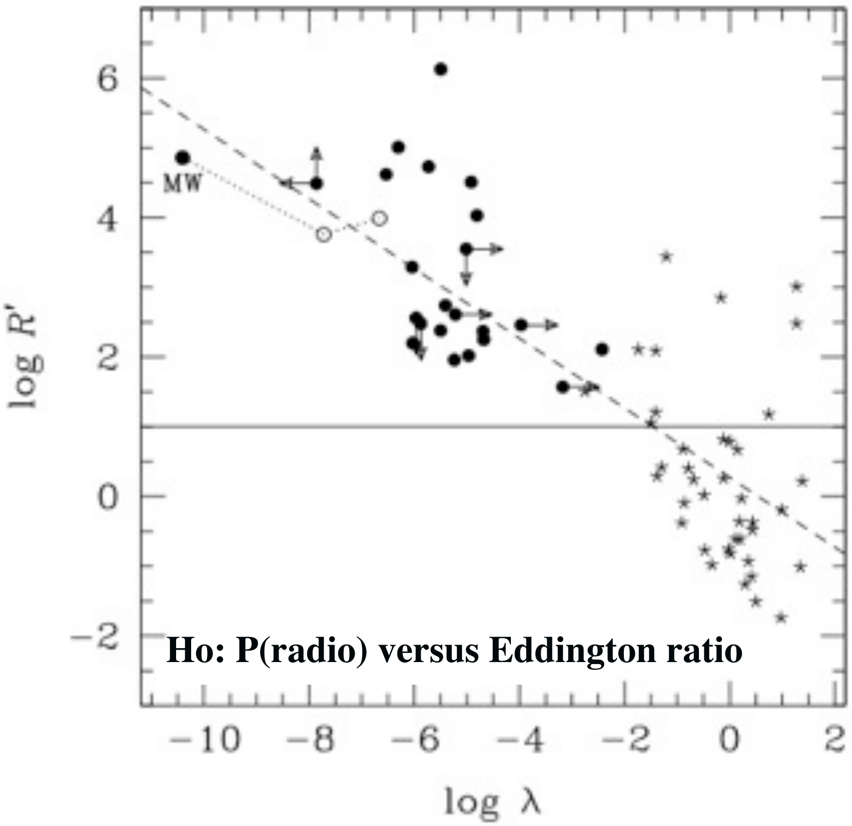




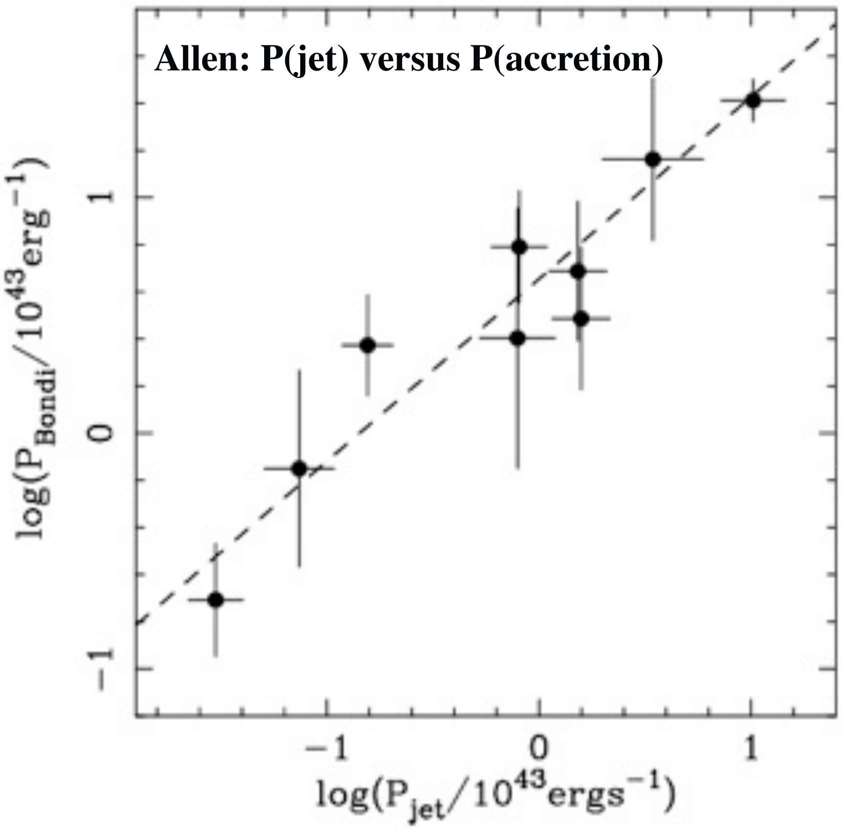
Maintenance Mode

HOW DOES IT FIT IN THIS PICTURE?

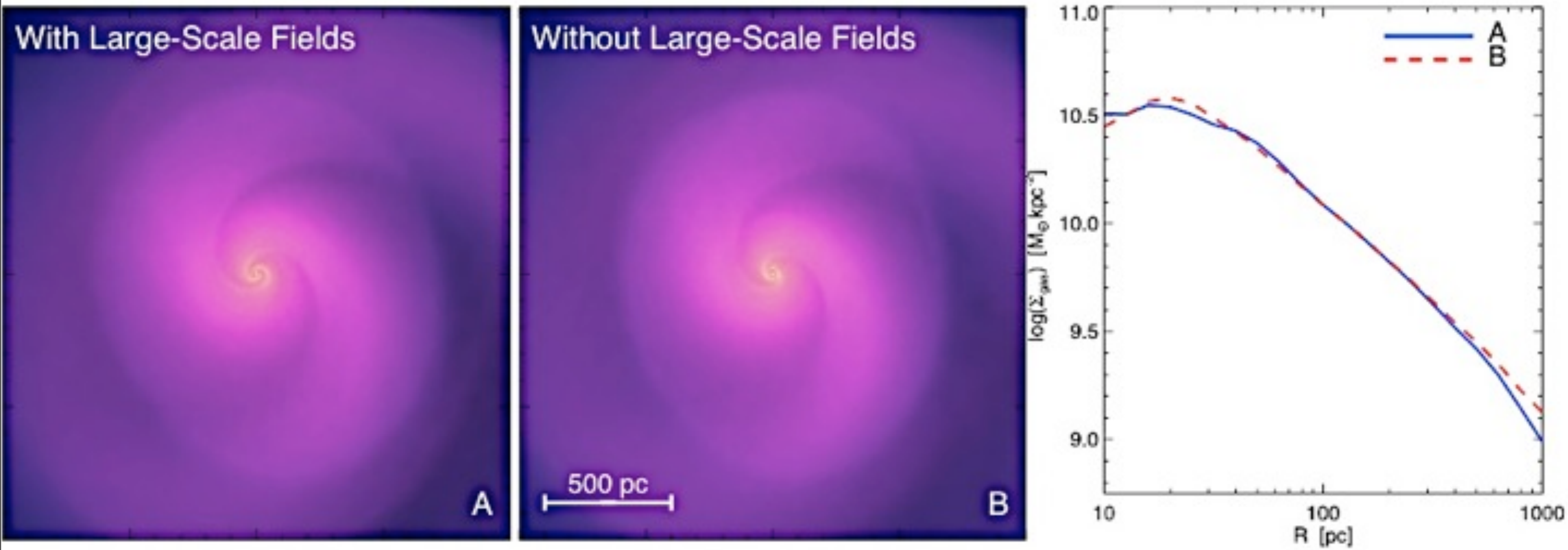
- Dominated by low accretion rates: does it “follow from” the bright-mode decay?



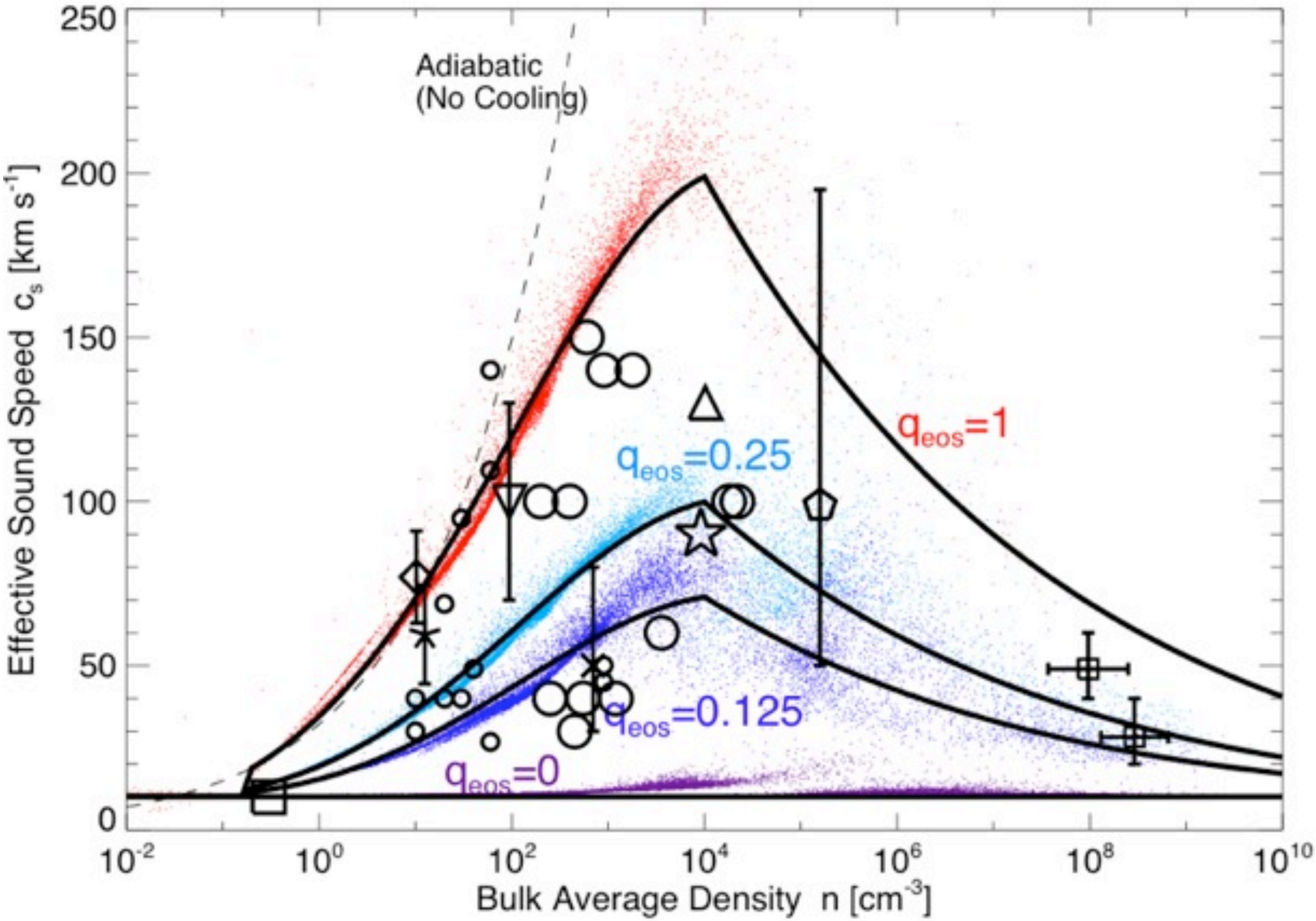
- Is Bondi accretion actually going to work for once?



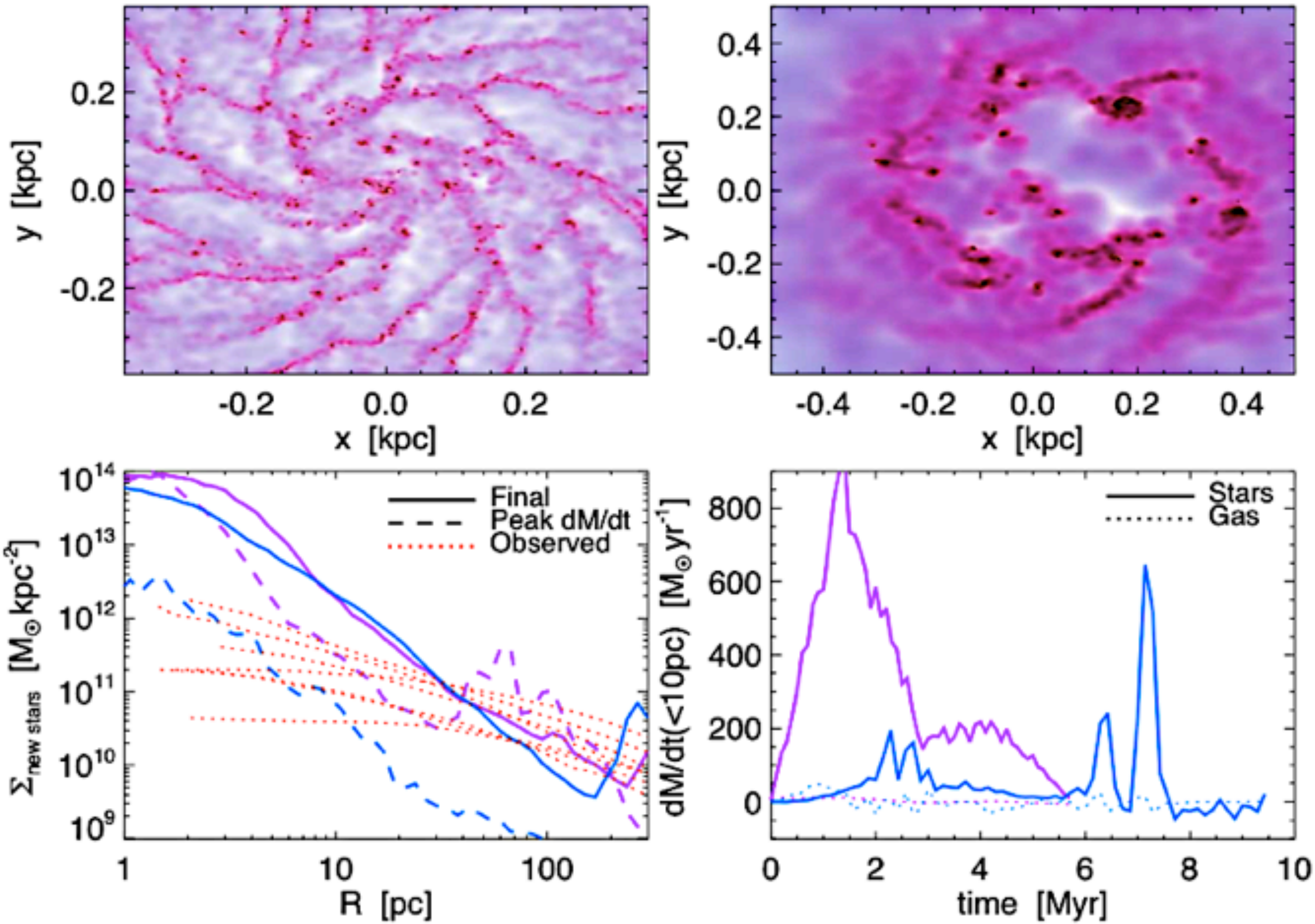
Large-Scale Tides are Not Important for AGN:



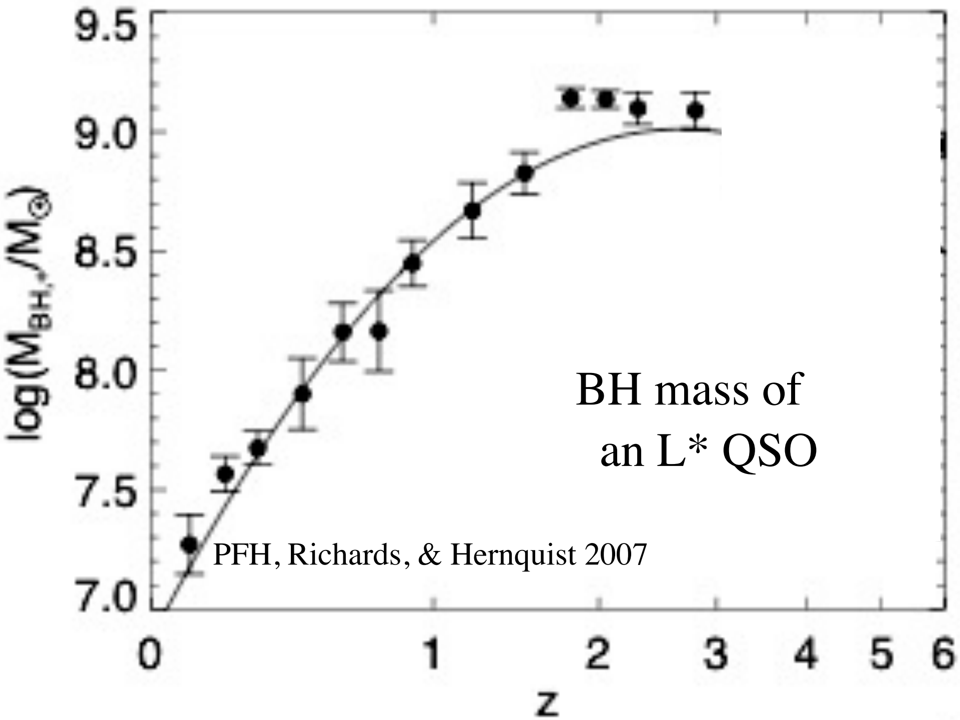
The Effective Stellar Feedback on Small Scales:
(REQUIRE SOME SUB-RESOLUTION MODEL)



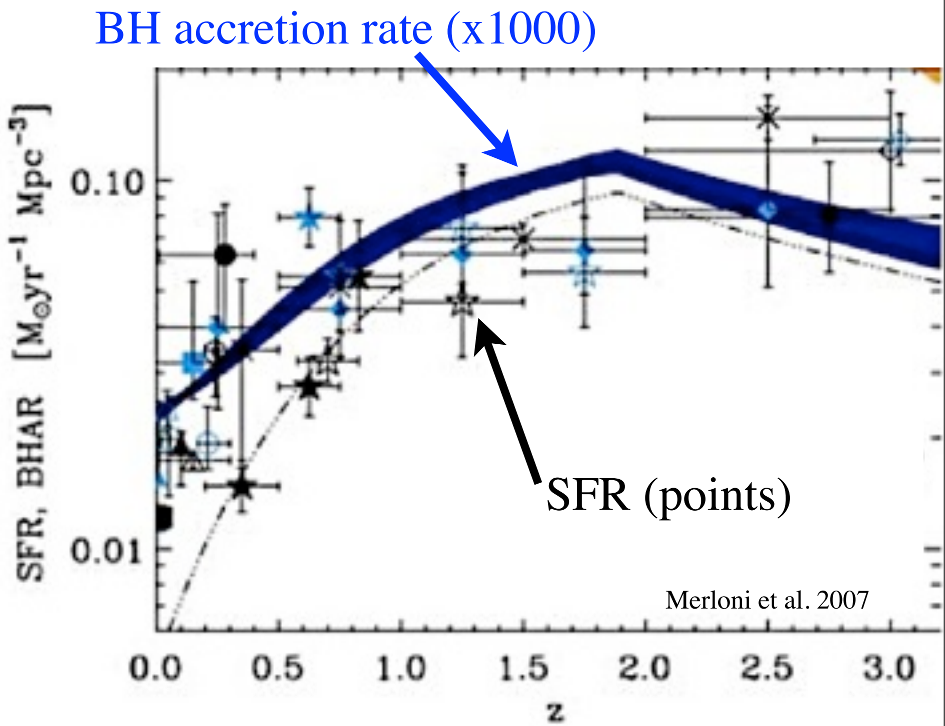
A “No Feedback” ISM is Ruled Out on Small Scales:

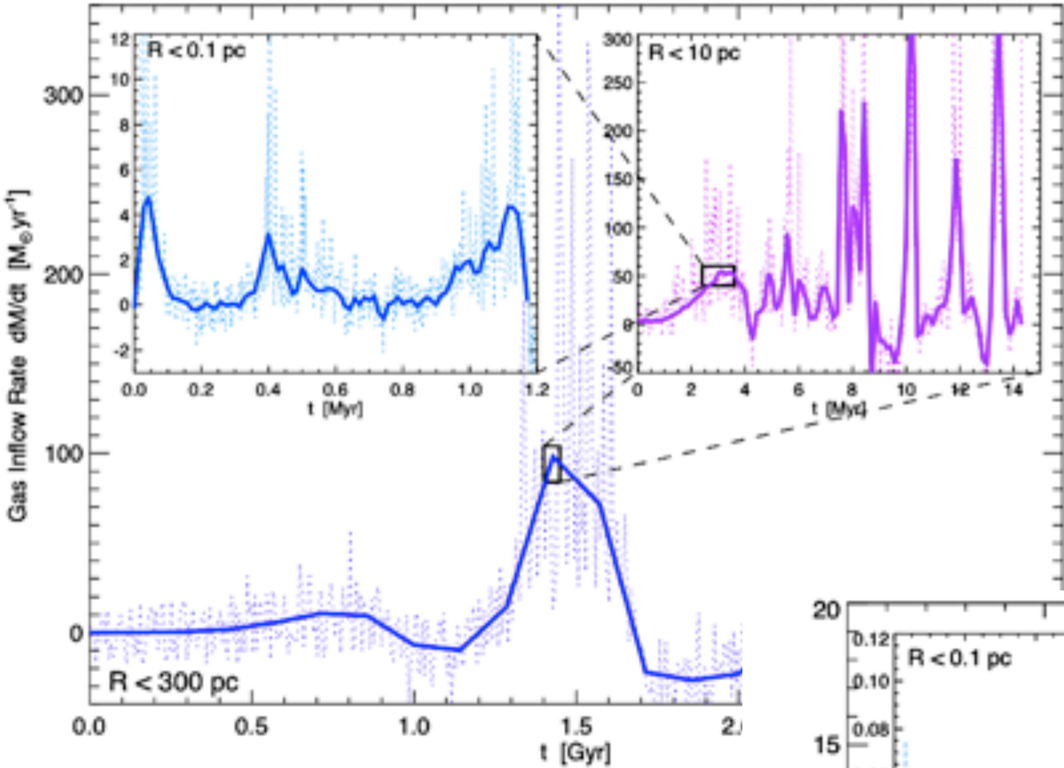


“Downsizing” in BHs and Active Galaxies:



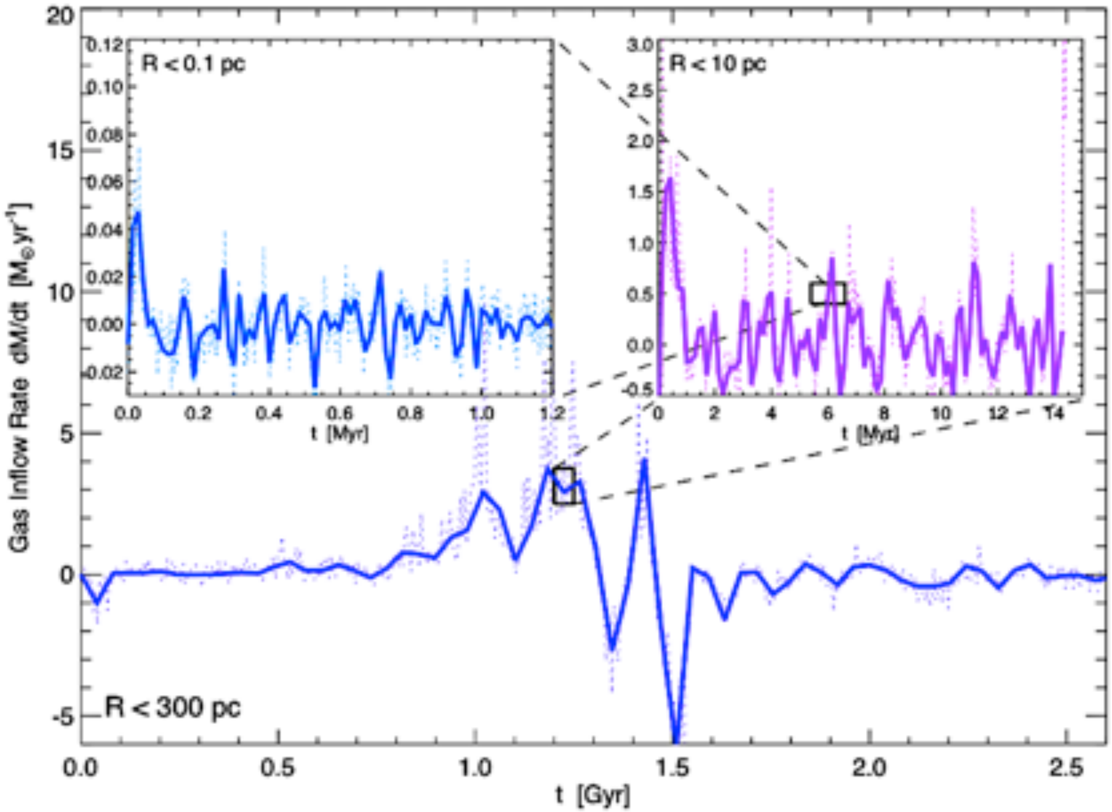
BH Growth Tracks the Universe’s Star Formation History:

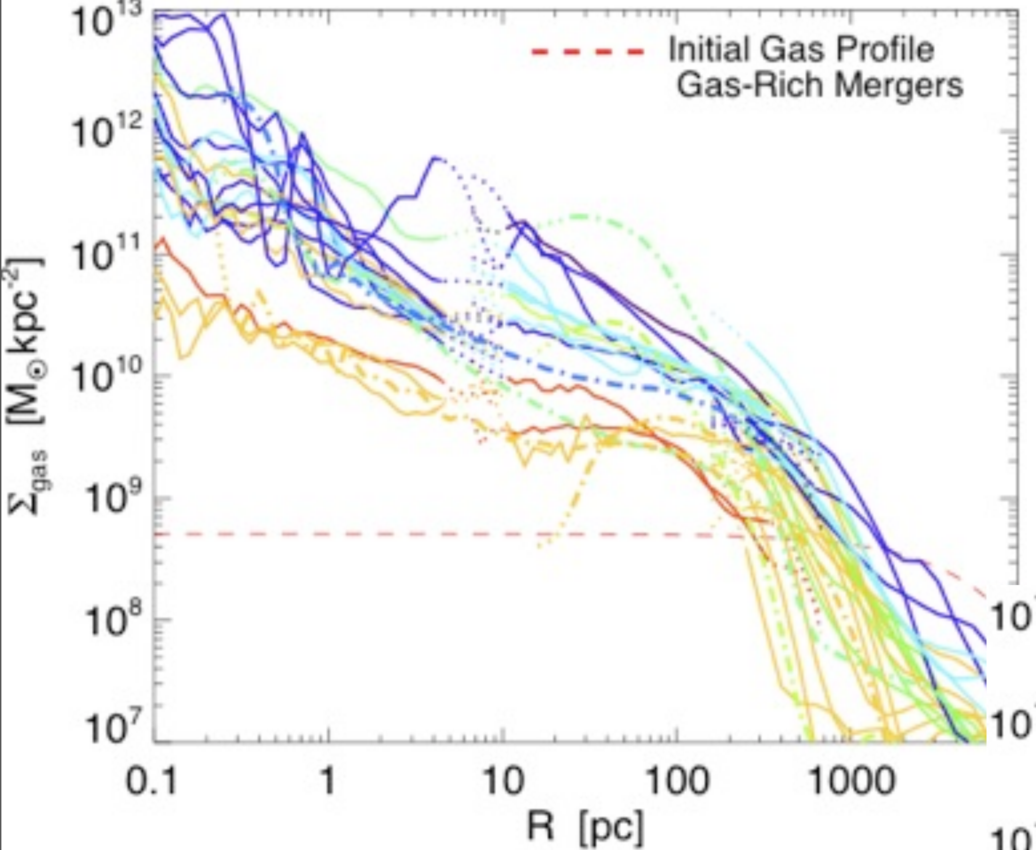




Gas-rich merger
(lots of inflow)

Weakly bar-unstable disk
(less inflow)





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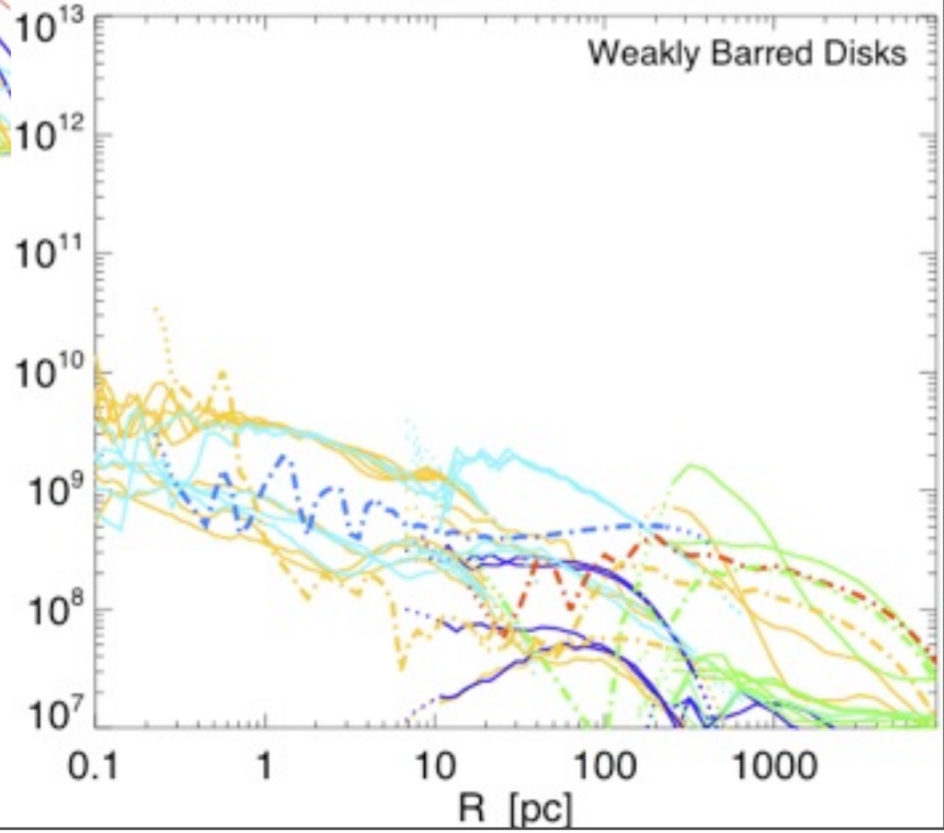
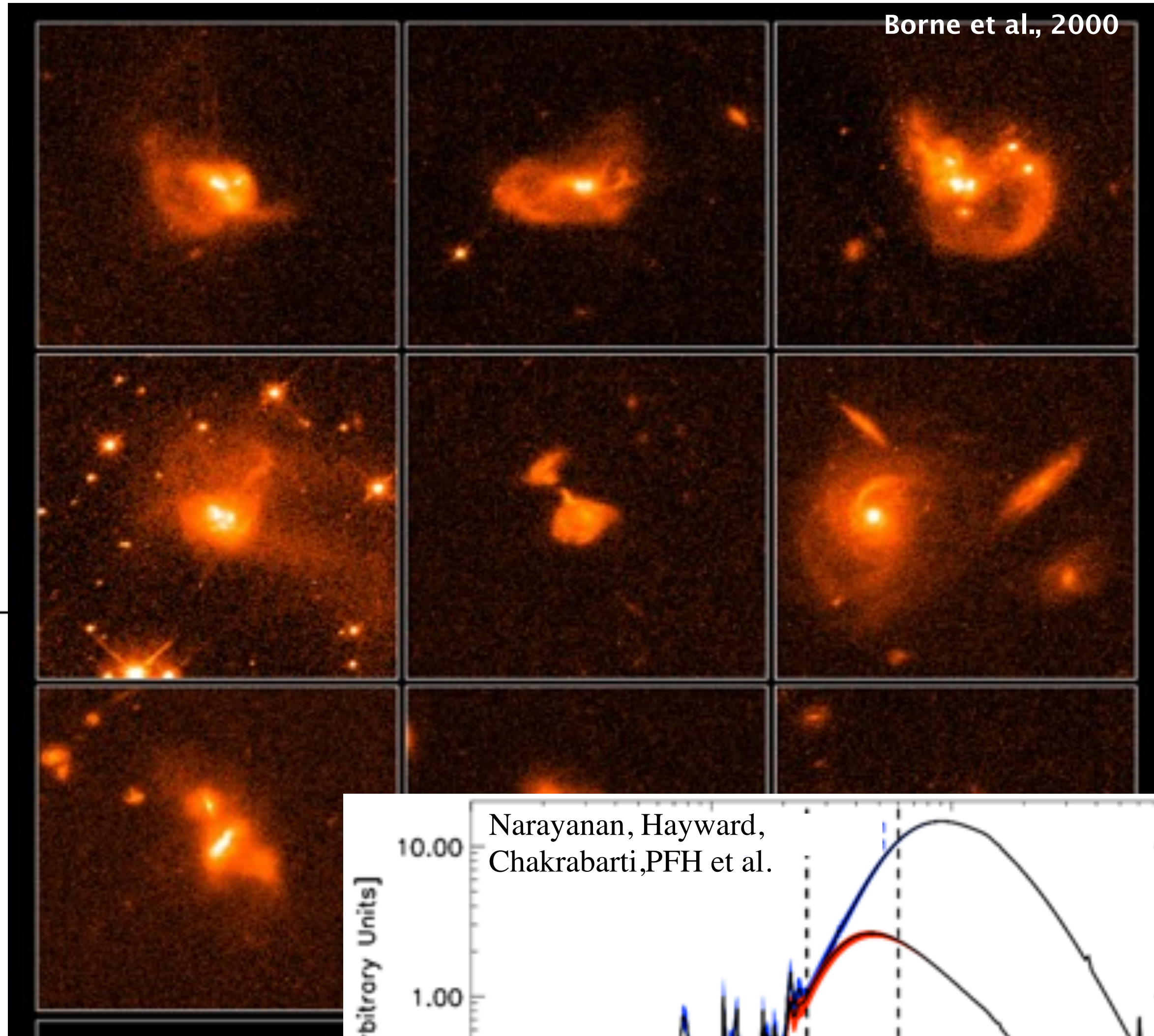
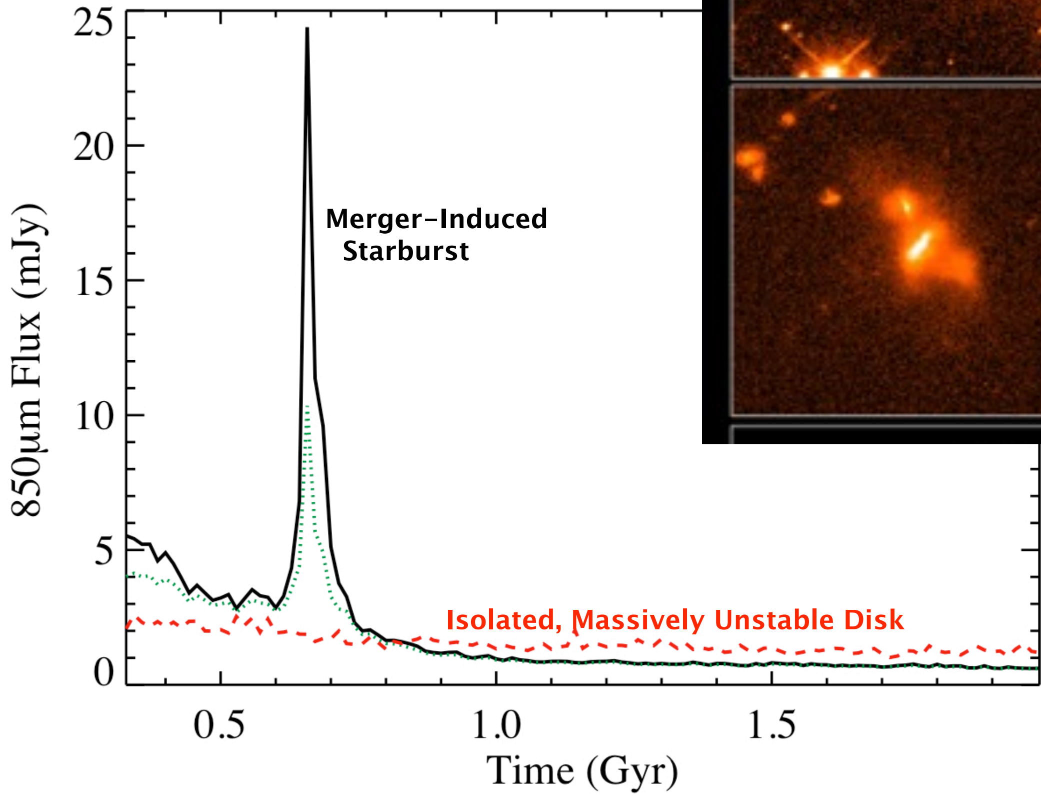
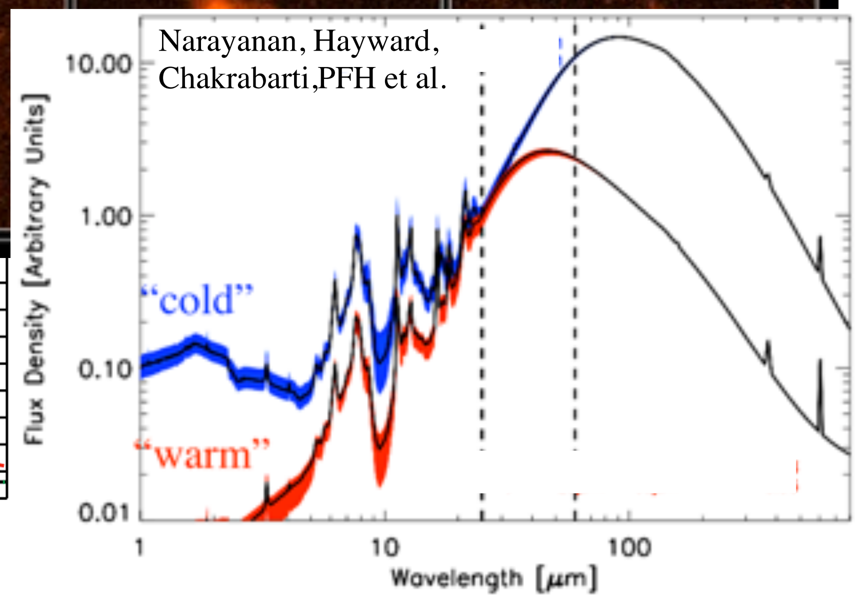


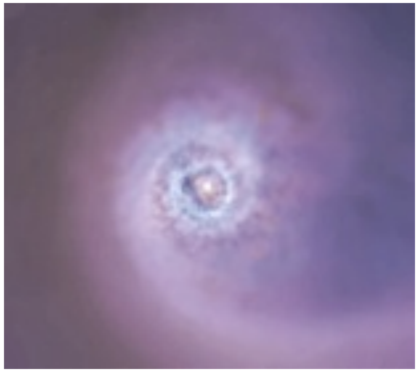
Starbursts at kpc-scales:

- Compare local starburst ULIRGs: SFR>100 M_{sun}/yr
  - AGN & cold-warm transition?
- Sub-millimeter galaxies



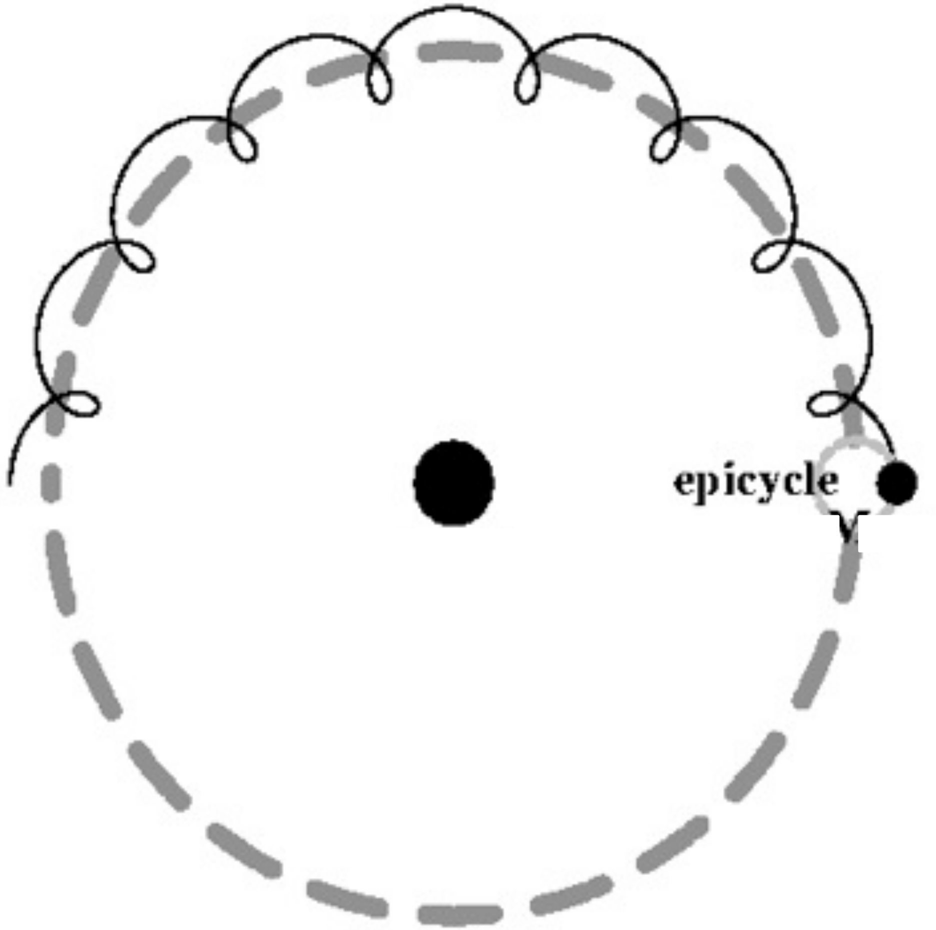


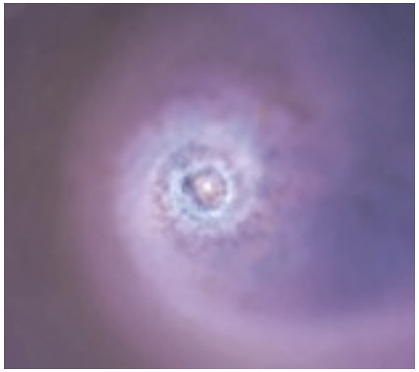




- m=1 ‘slow’ modes are special in a near-Keplerian potential

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





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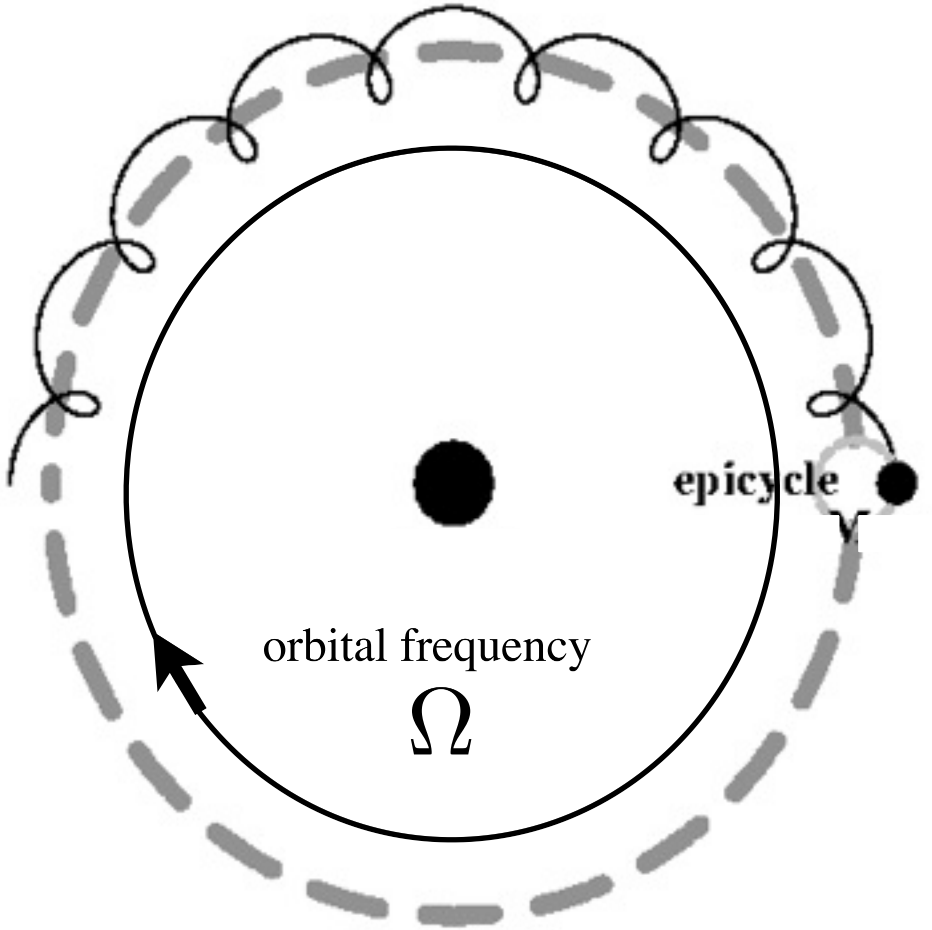

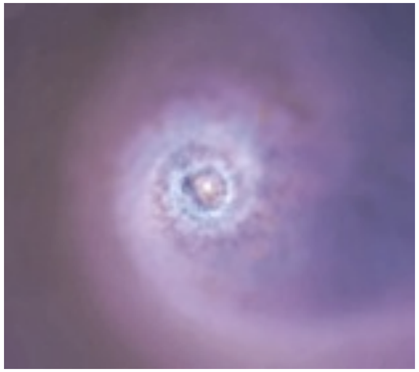

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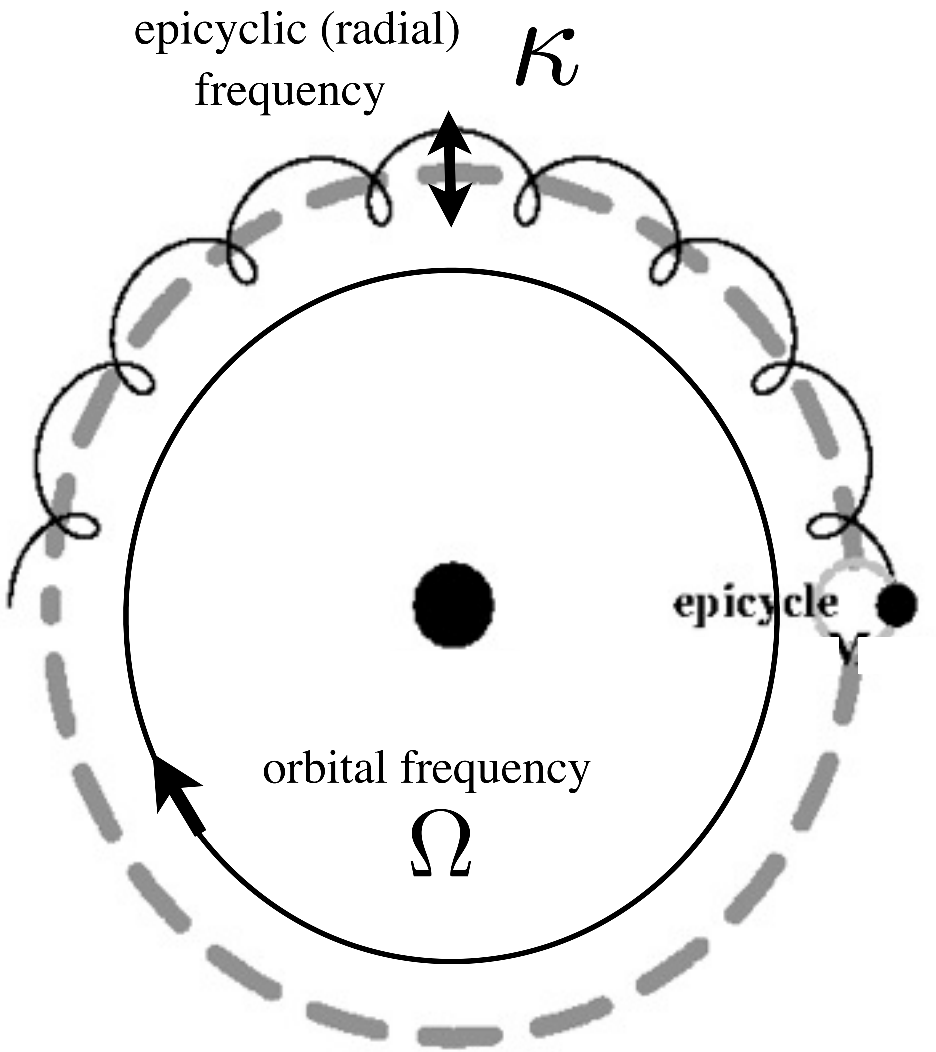
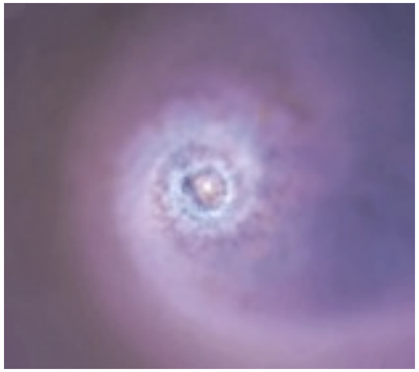


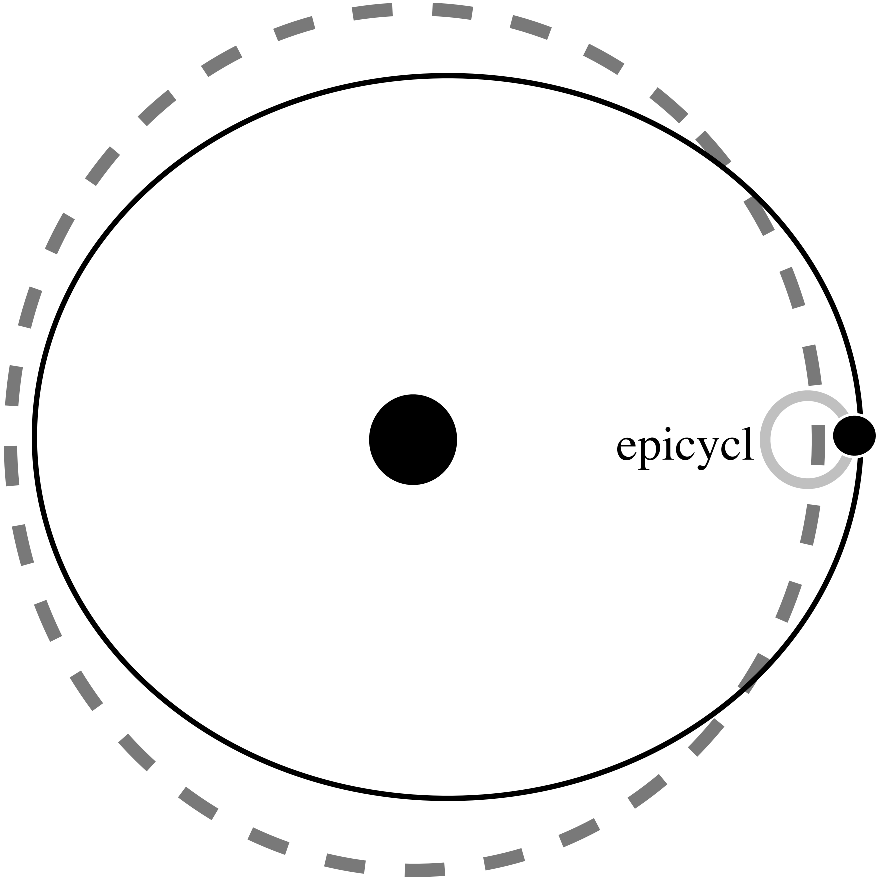


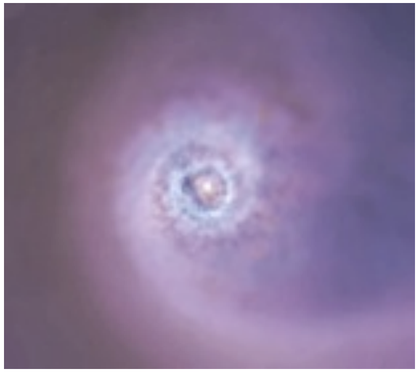
- m=1 'slow' modes are special in a near-Keplerian potential

Keplerian potentials
are special:

$$\kappa = \Omega$$

Hence, closed
elliptical orbits!



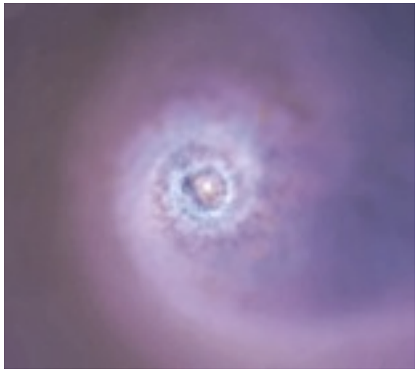


- m=1 'slow' modes are special in a near-Keplerian potential

Disturb the stars with some perturbation in the disk:

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

number of 'arms'



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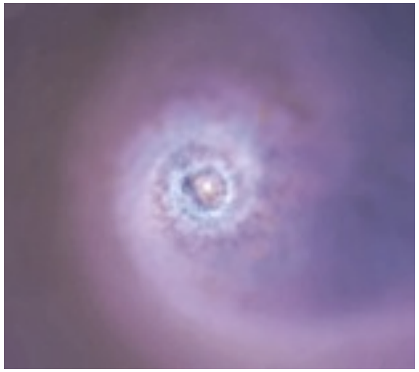
number of 'arms'

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

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



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

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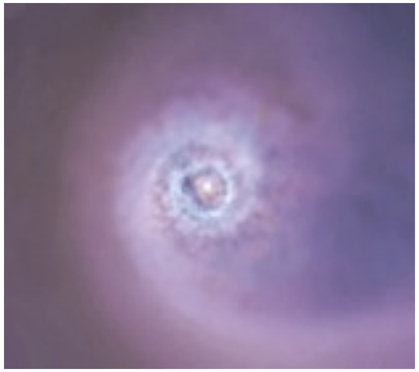

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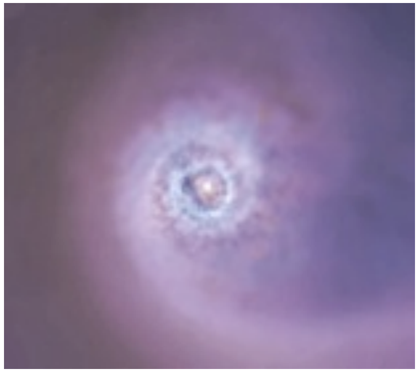
$$m \neq 1 :$$

Near a BH:

$$\frac{1}{\Delta} \rightarrow \frac{1}{(1-m)\Omega^2}$$

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

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



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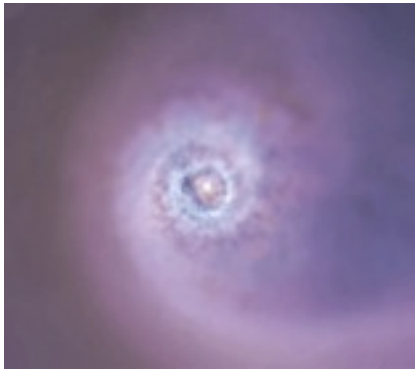

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Response: $$|\mathbf{e}| \propto \frac{1}{\Delta}$$

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

$$m = 1:$$

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

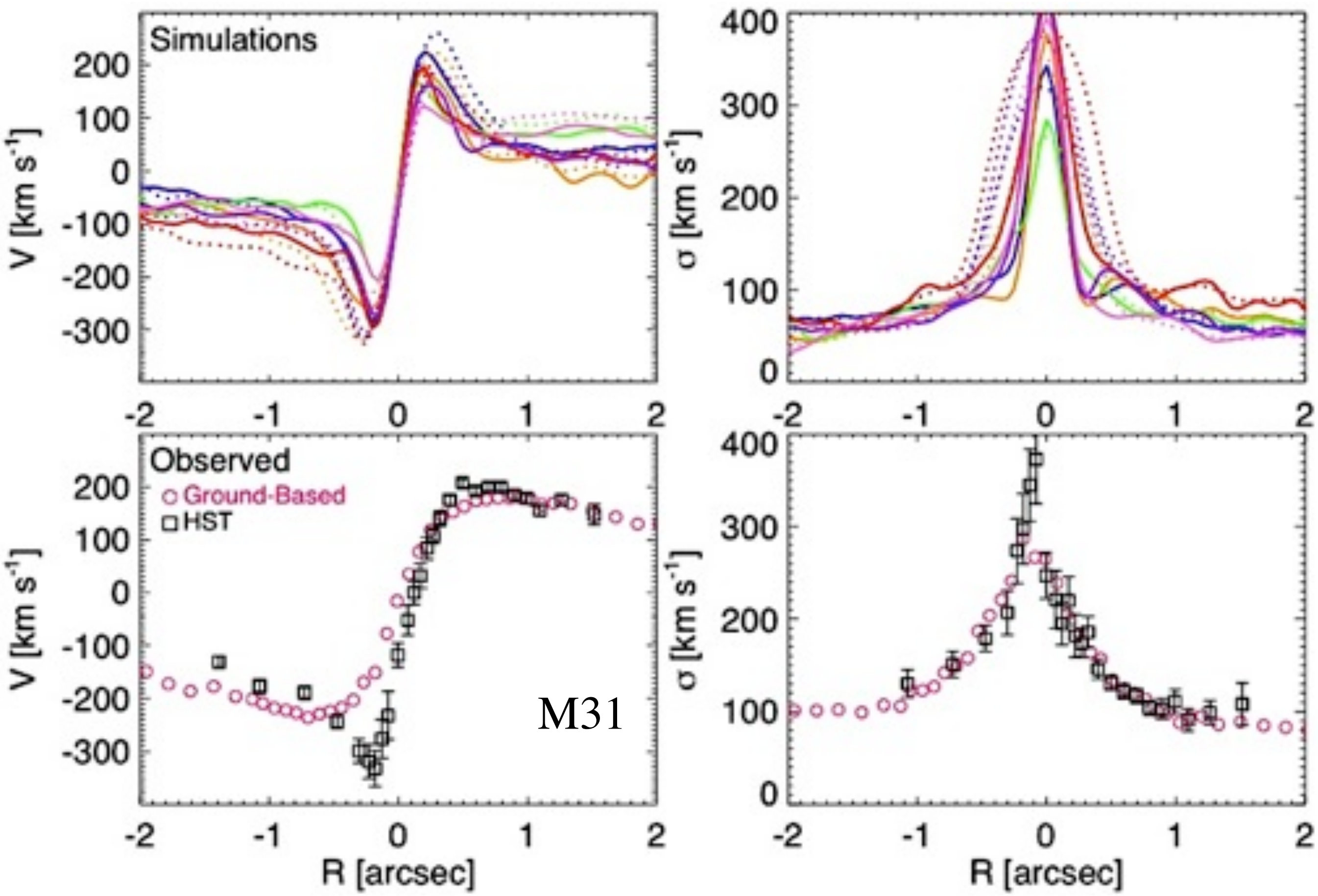
$$|\mathbf{e}| \sim \frac{\delta\Sigma}{\Sigma}$$

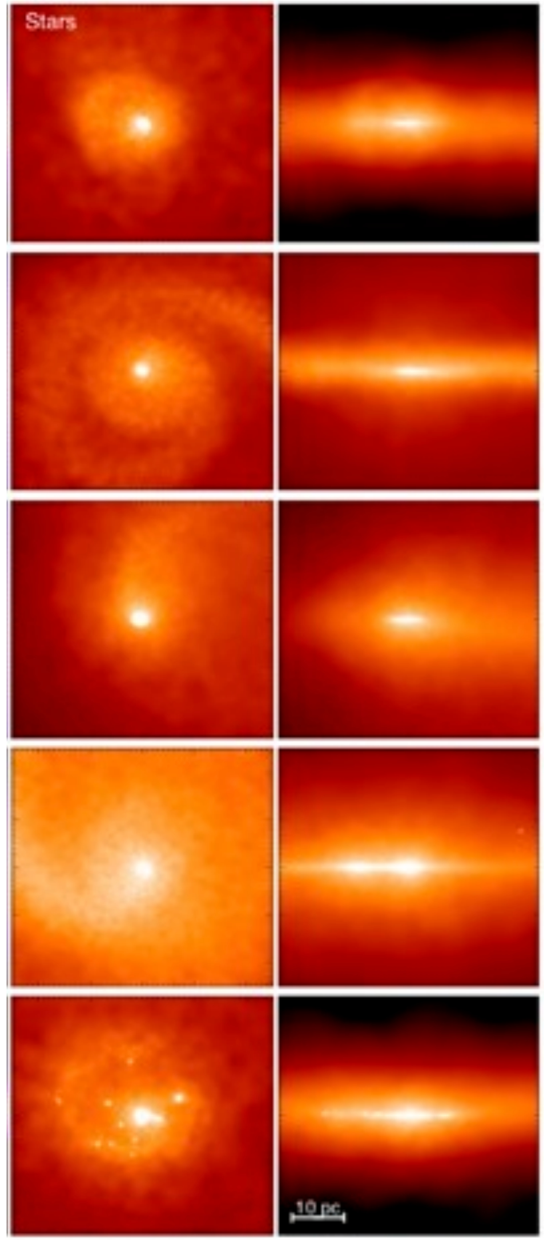
Near a BH: $$\frac{1}{\Delta} \to \frac{1}{(1-m)\Omega^2}$$

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

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

- 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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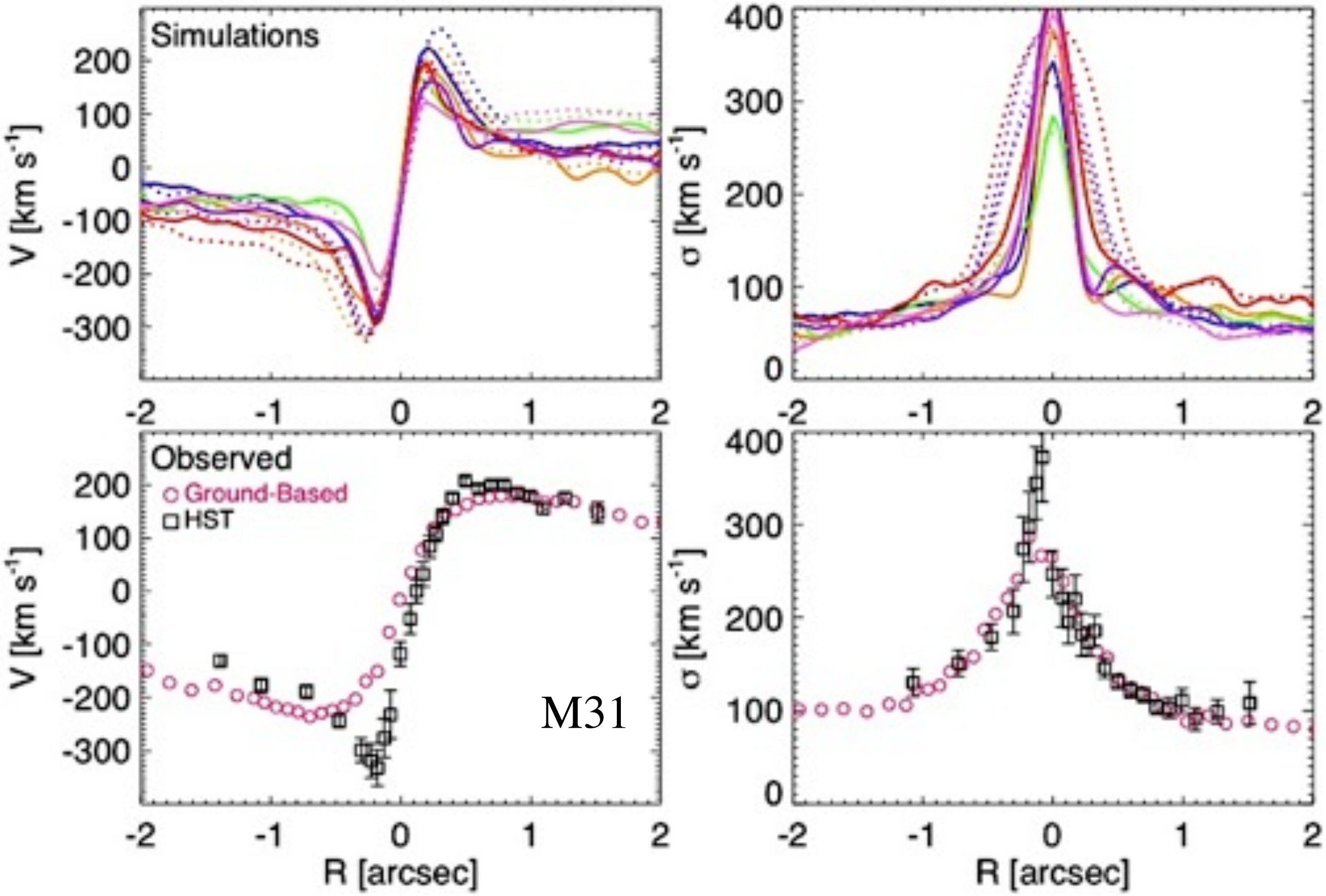
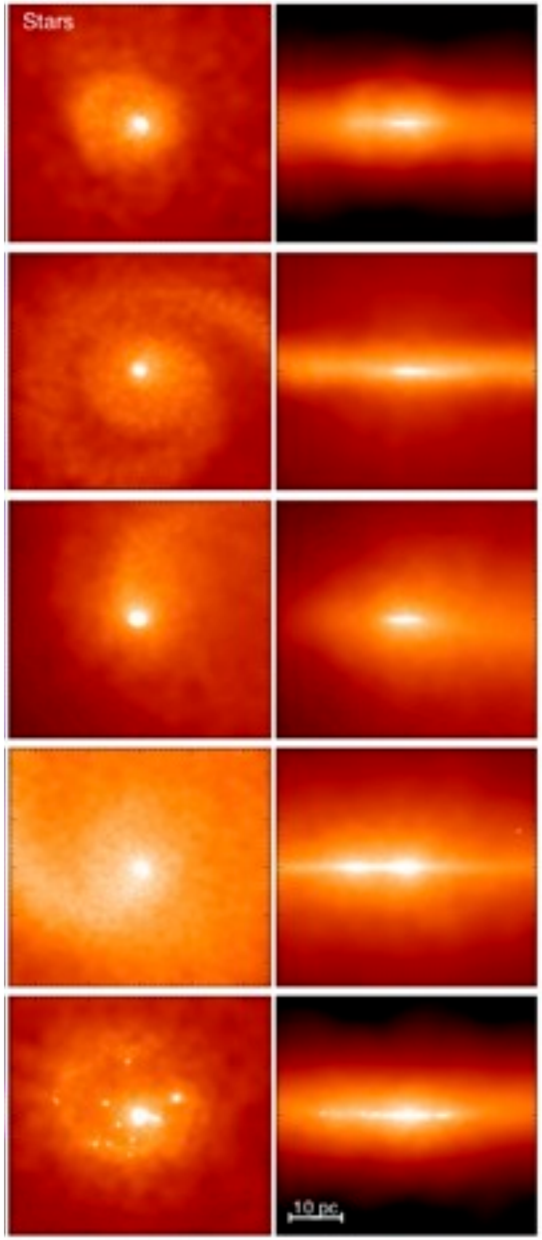
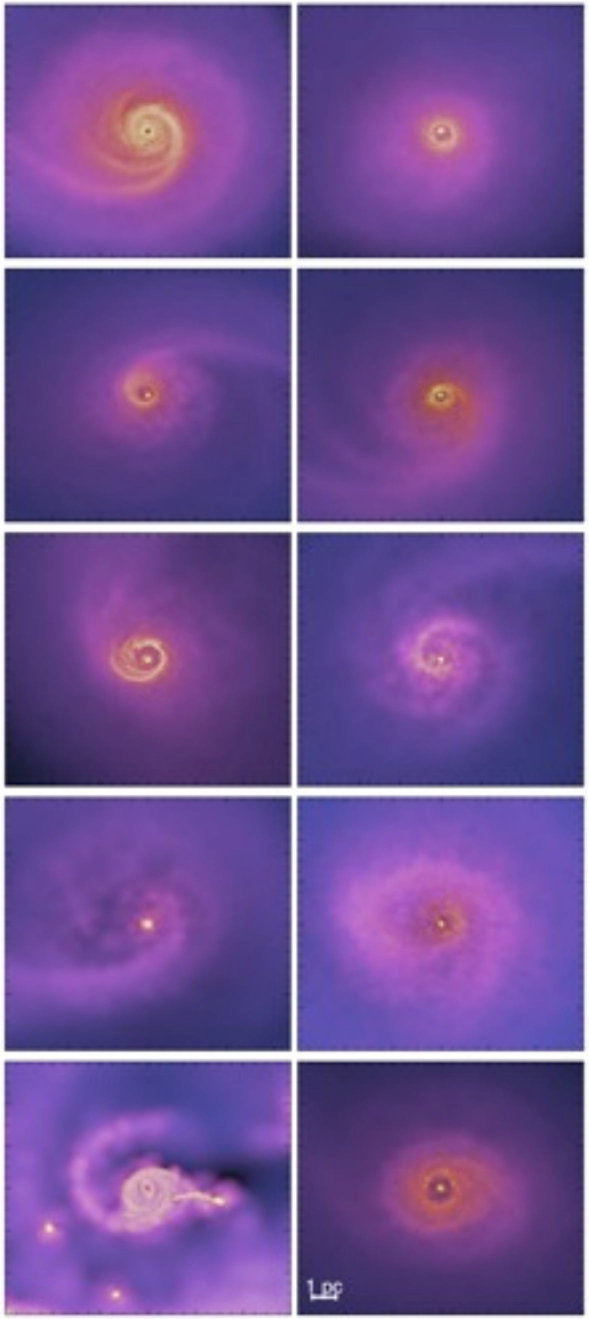




- "run backwards": the M31 disk implies accretion at ~0.5-3 M_{sun}/yr (~L_{Edd}) for ~100 Myr (~ M_{BH}) !

What about the obscuration from these disks?



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

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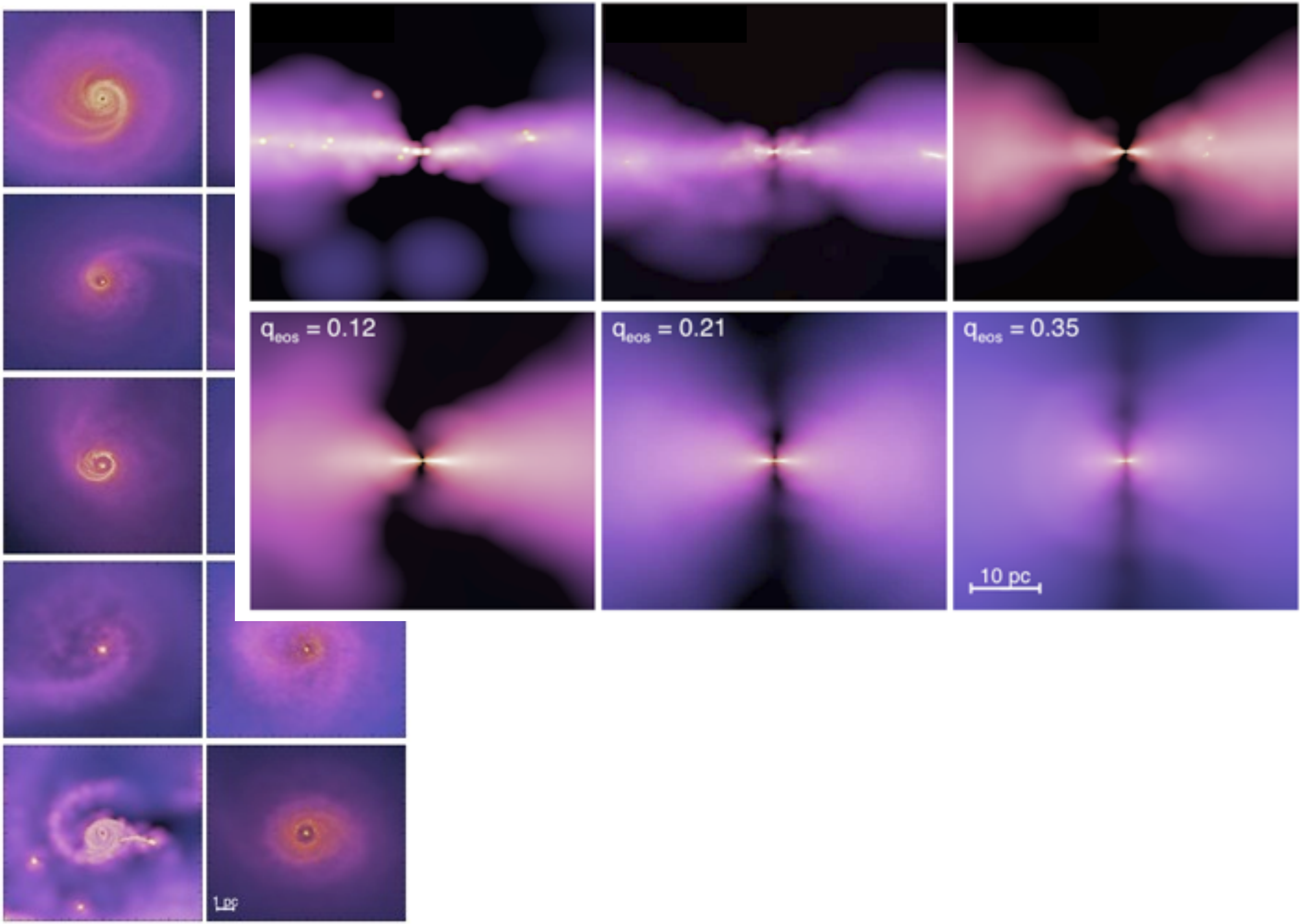

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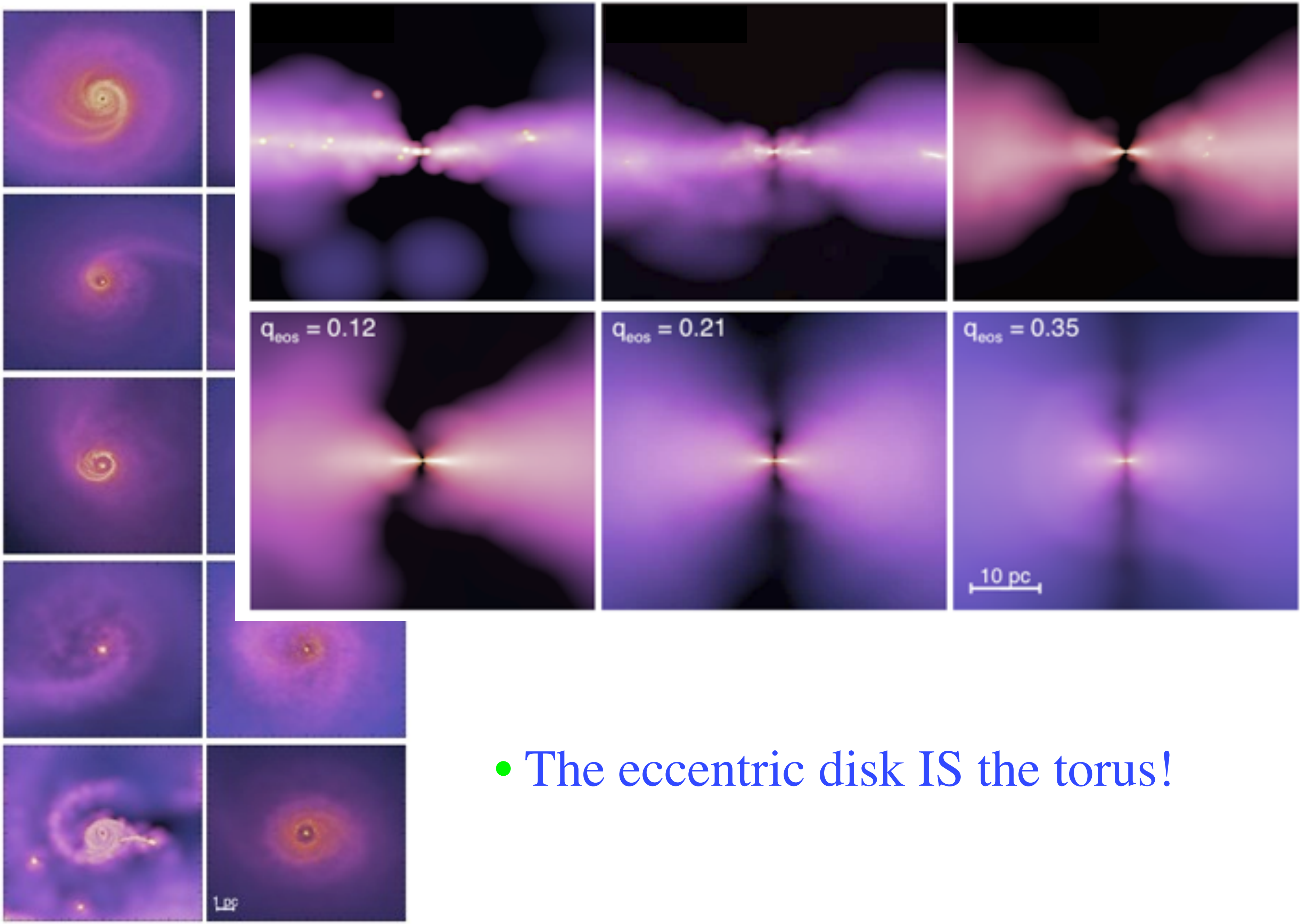


- The eccentric disk IS the torus!

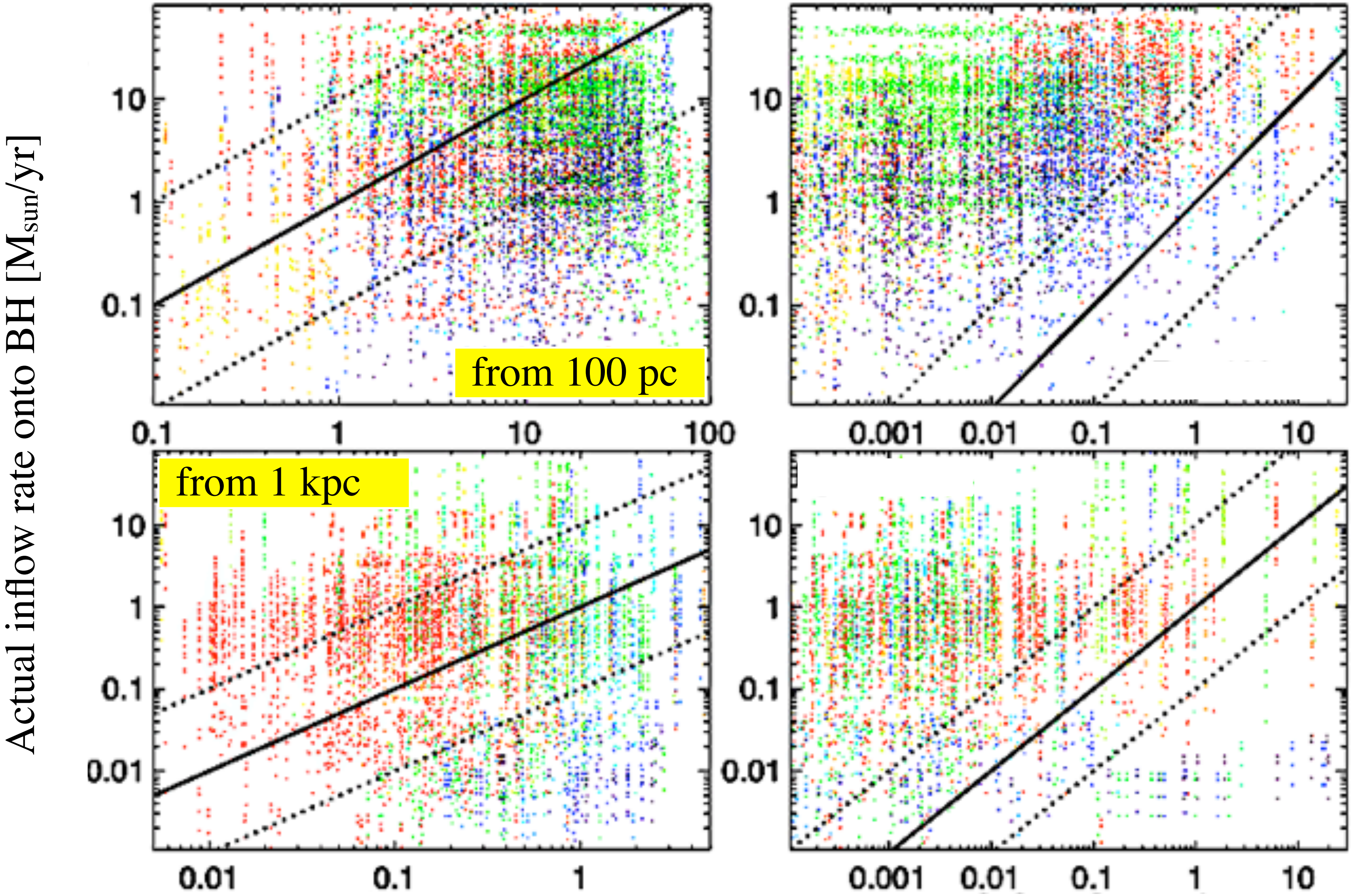
How do we step back, to

see the effects of feedback?

How do we step back, to see the effects of feedback?

- Need to be able to approximate the accretion rate while simulating >>kpc scales in a cosmological context

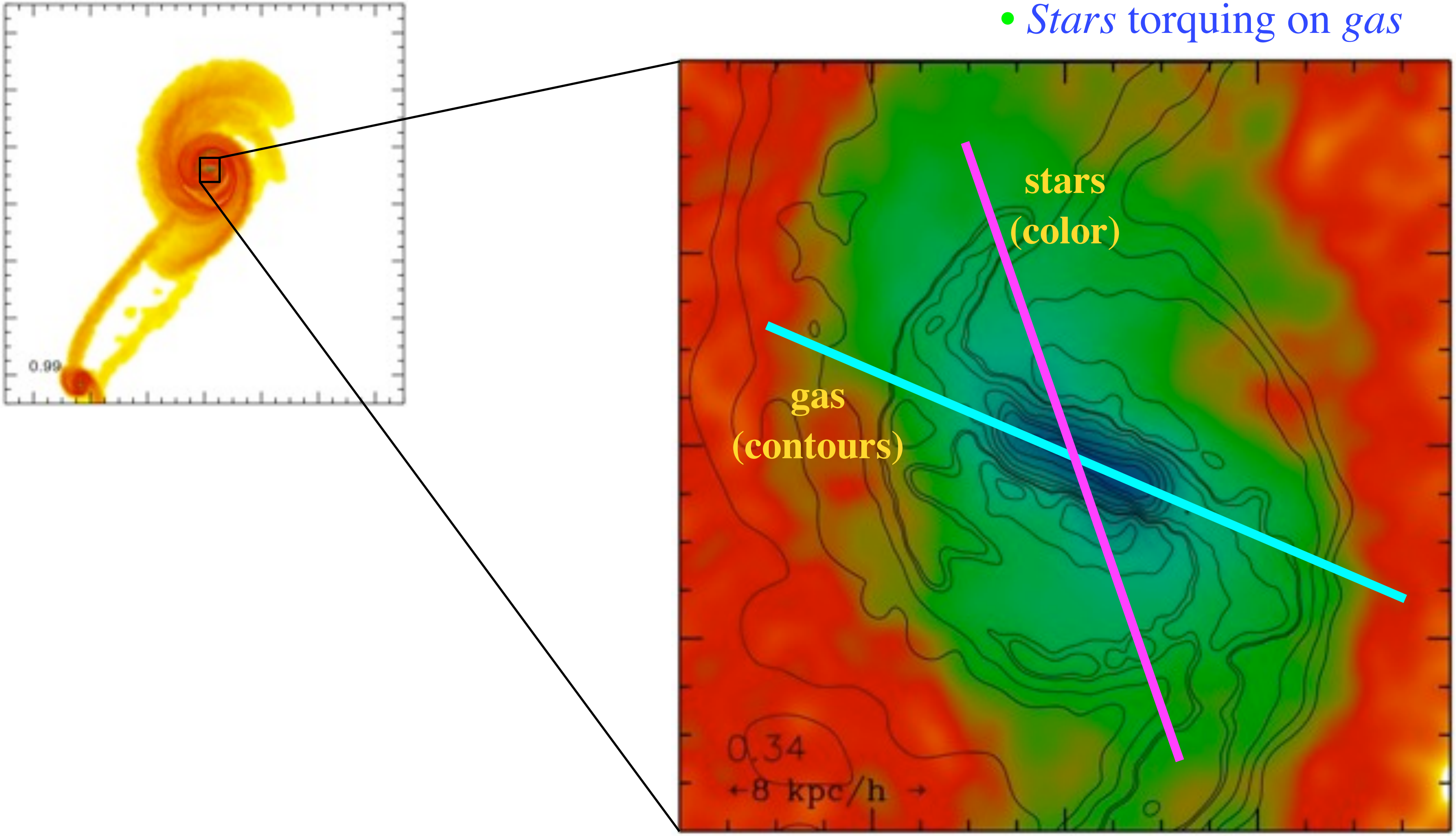
Typically, viscous or Bondi-Hoyle prescription adopted:



Viscous: $\sim c_s^2\, \Sigma_{\rm gas}\, \Omega^{-1}$ Bondi: $\sim G^2\, M_{\rm BH}^2\, \rho\, c_s^{-3}$

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

- *Stars* torquing on *gas*



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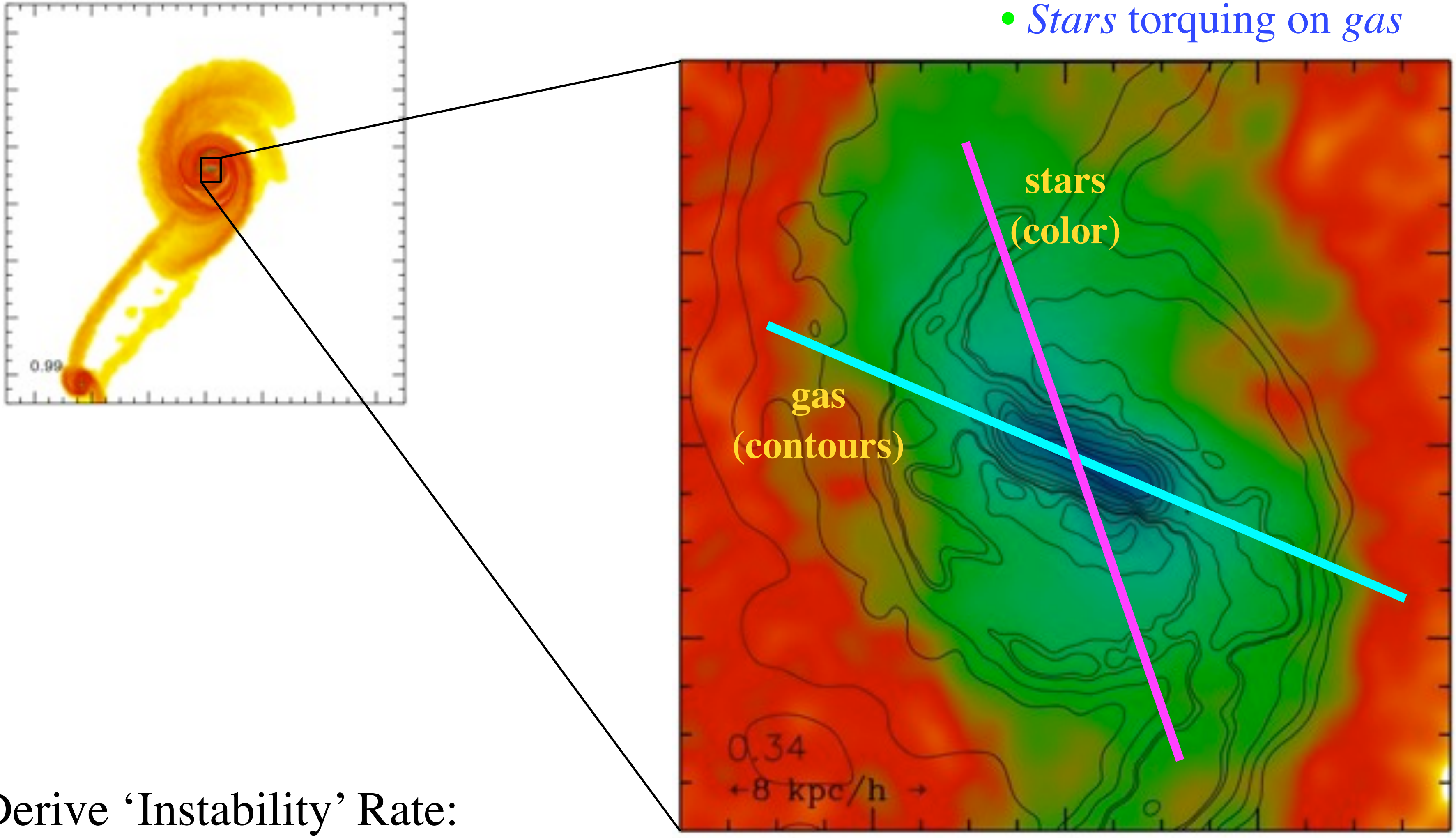
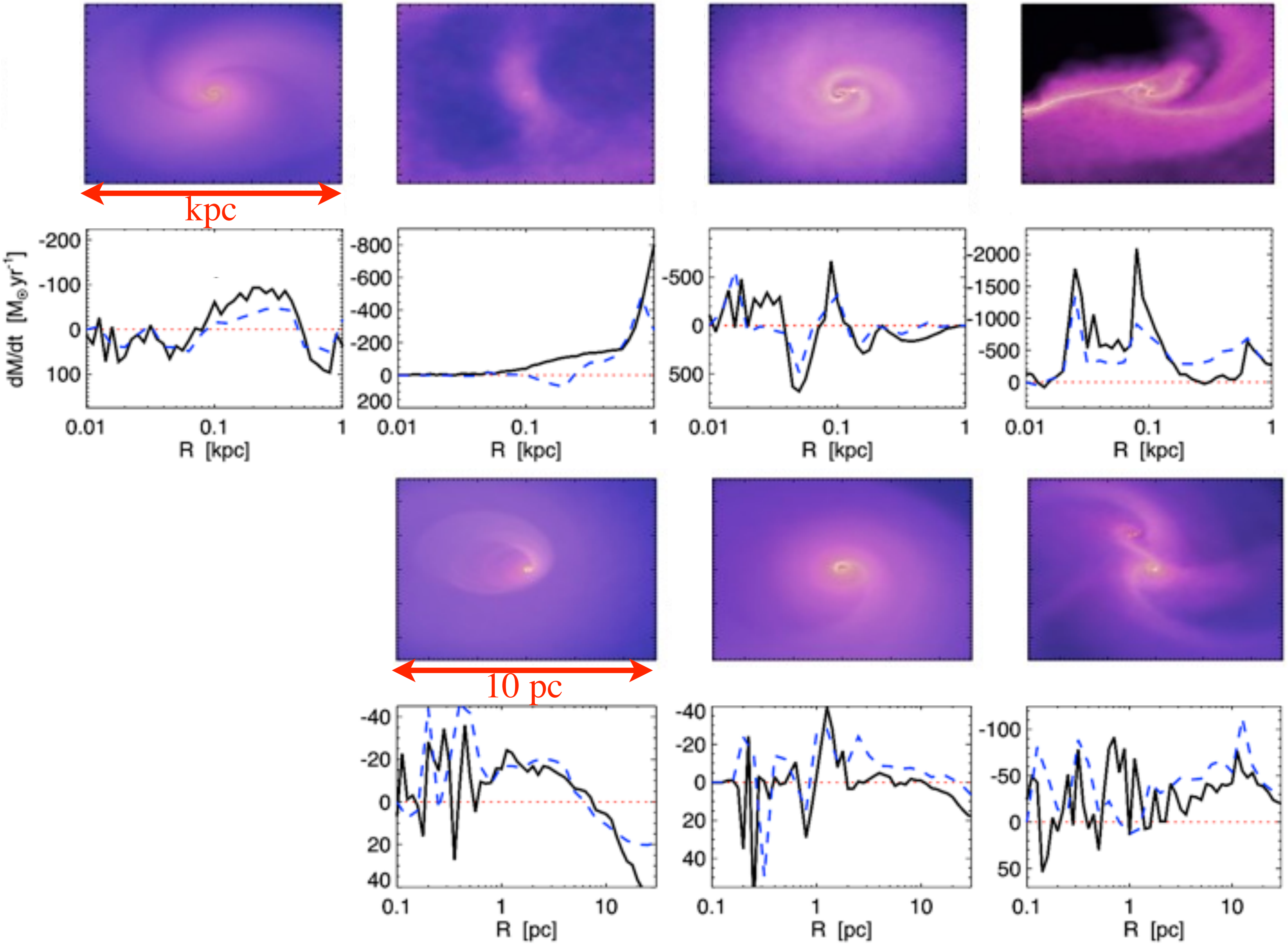
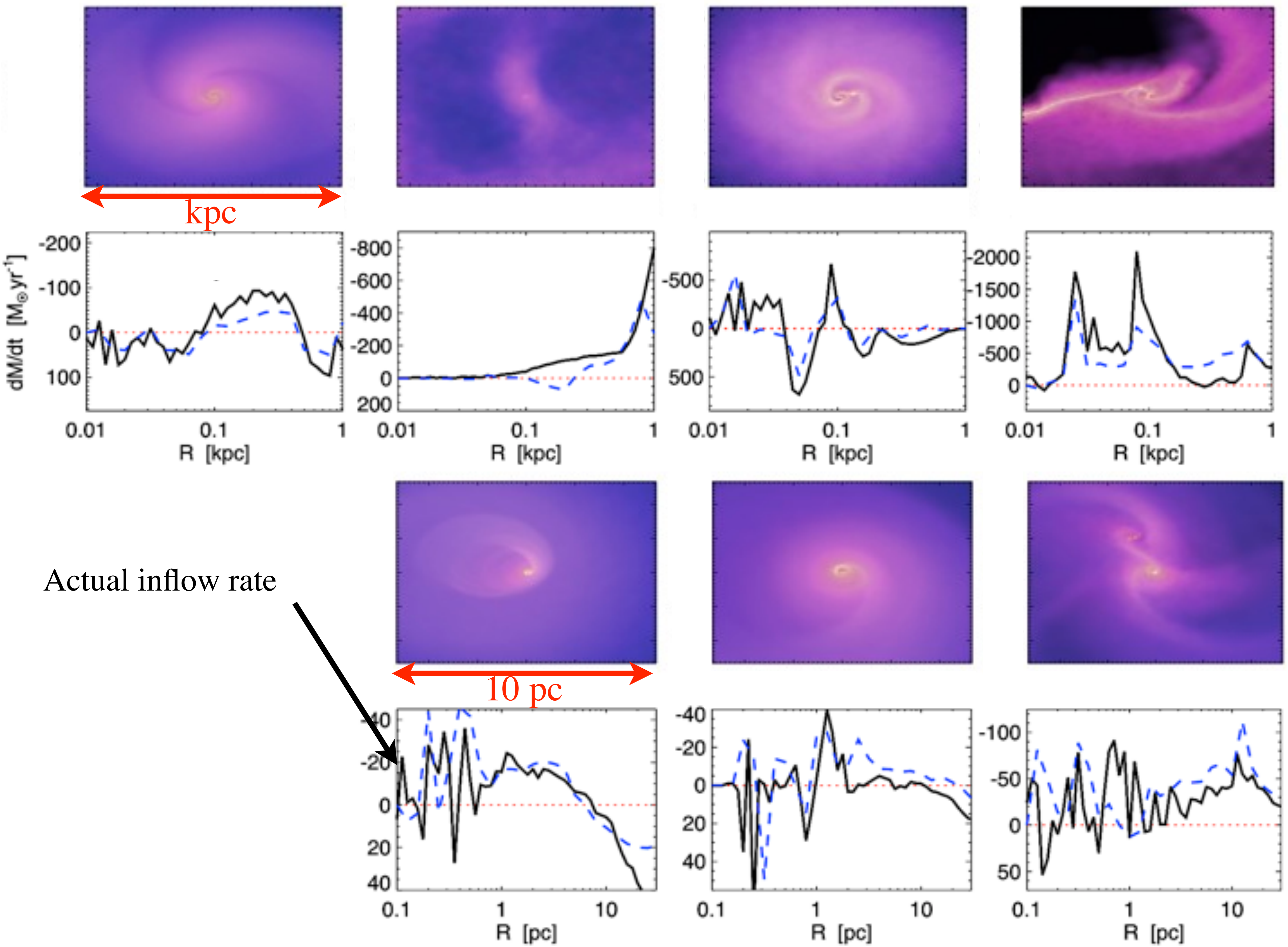


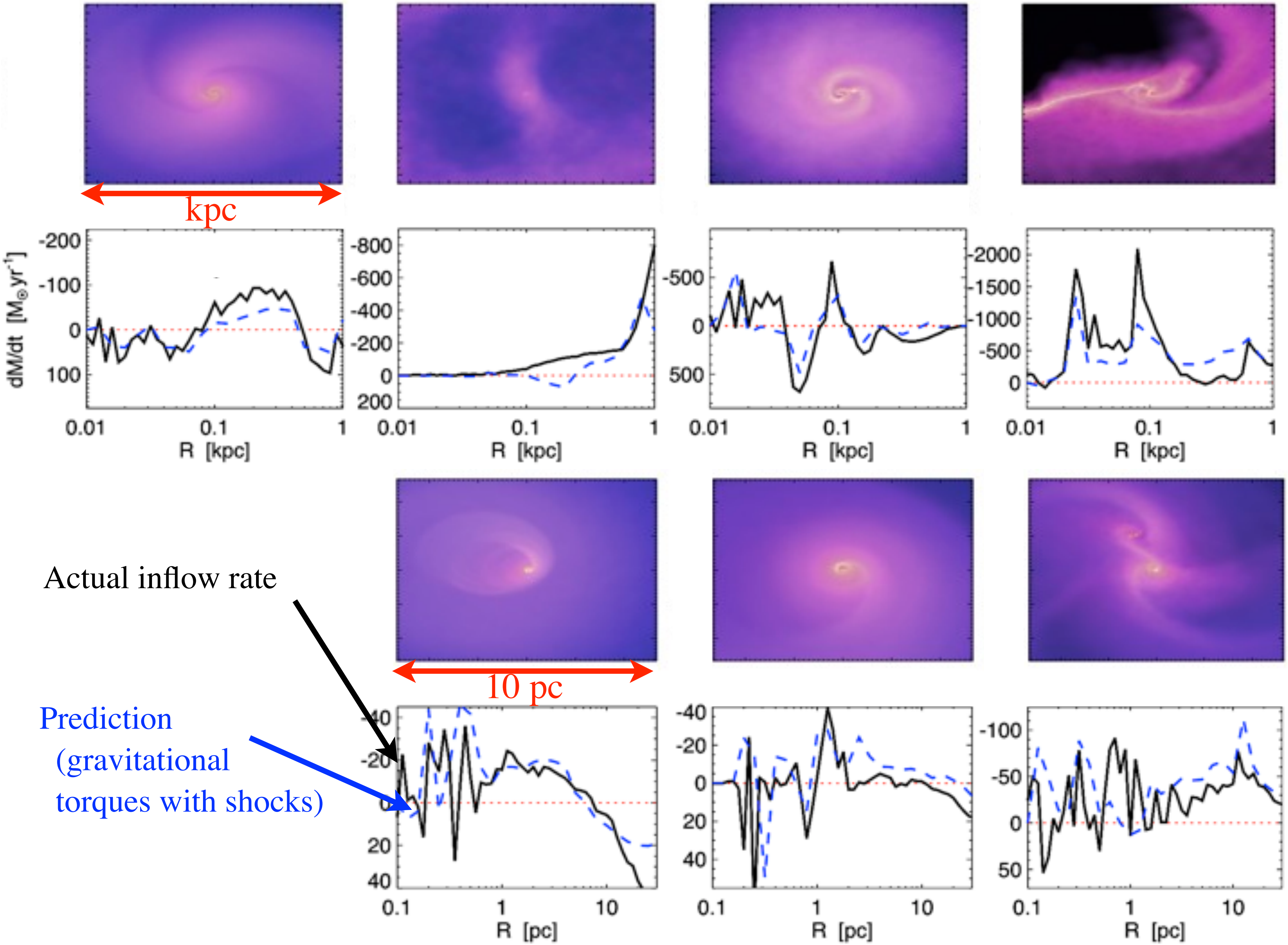
Derive 'Instability' Rate:

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

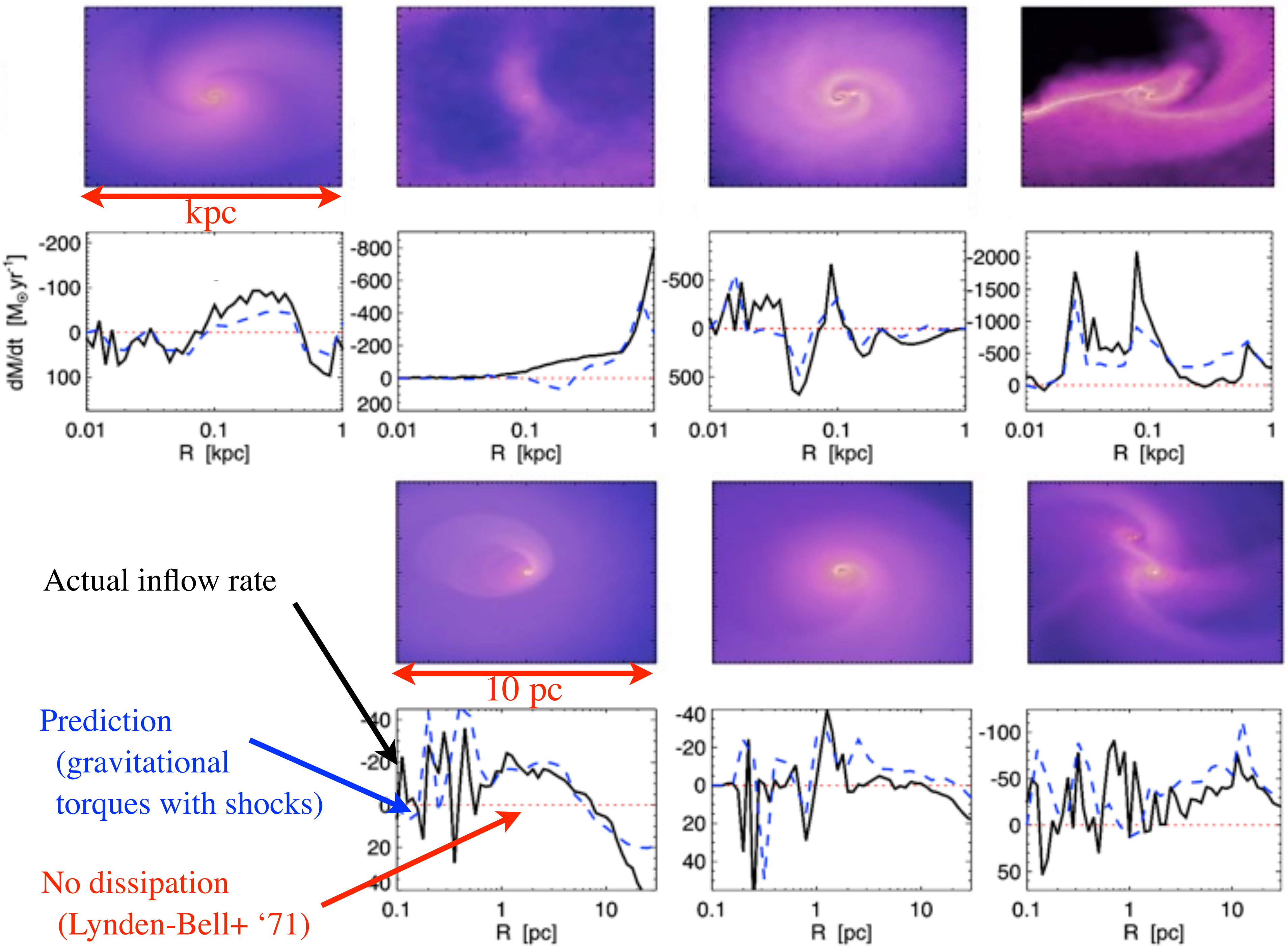


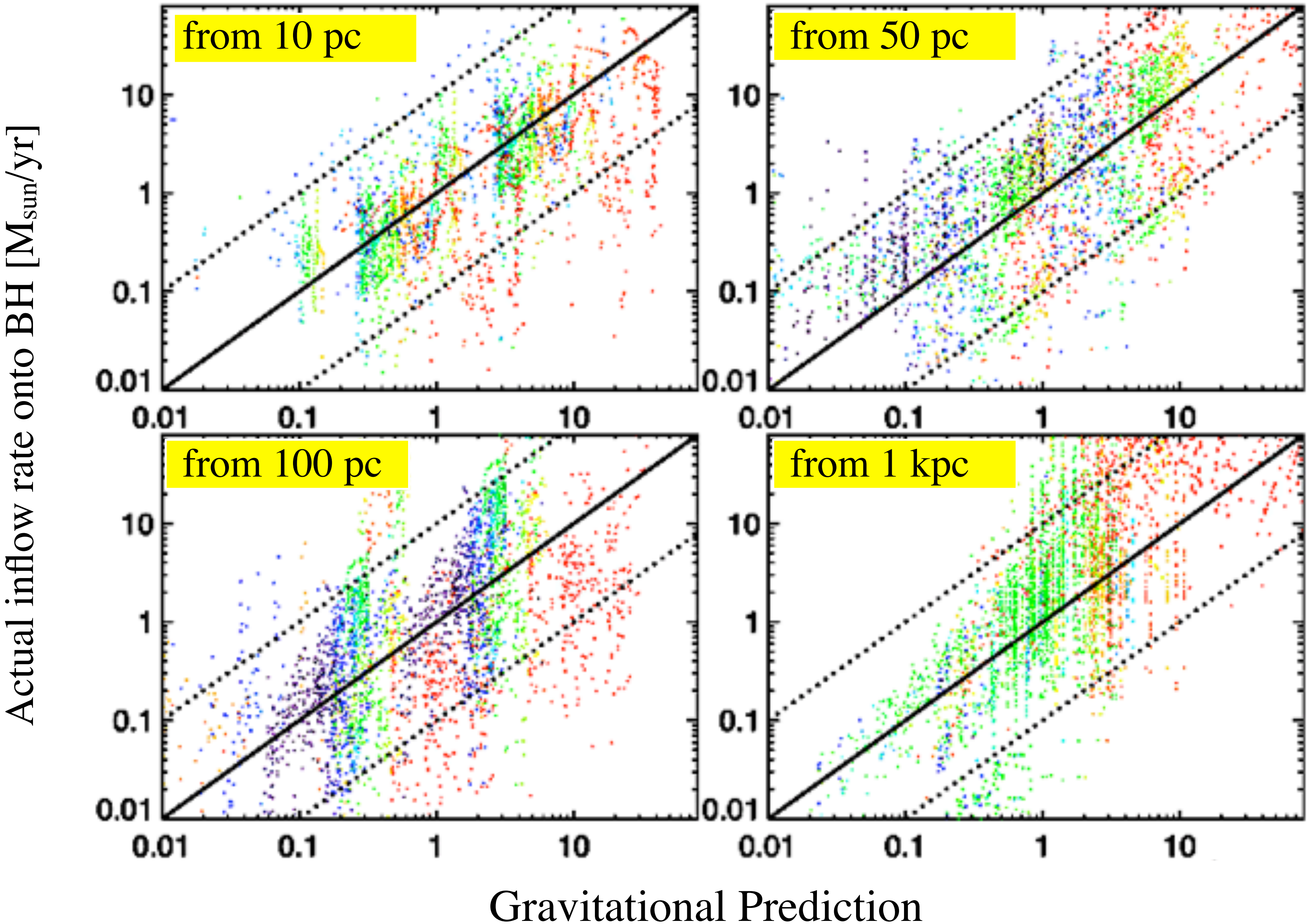
Tuesday, December 25, 12

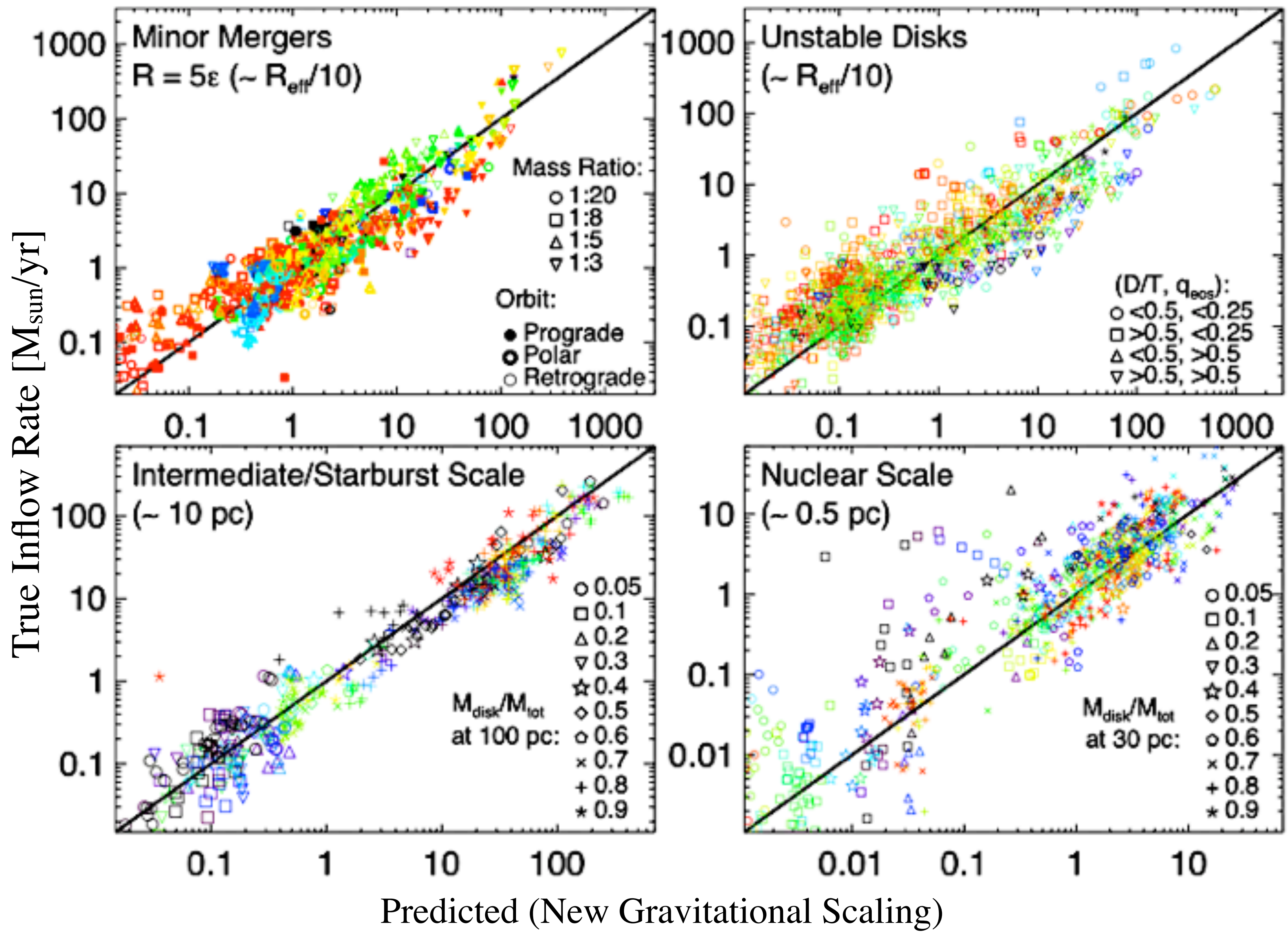

kpc
dM/dt [M☉ yr⁻¹]
R [kpc]
R [kpc]
R [kpc]
R [kpc]
Actual inflow rate
10 pc
R [pc]
R [pc]
R [pc]



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

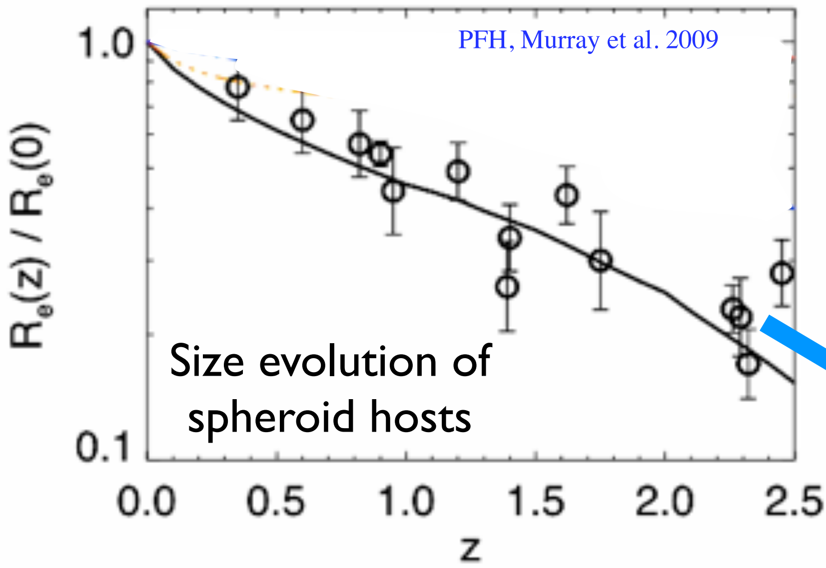

kpc
dM/dt [M⊙ yr⁻¹]
R [kpc]
10 pc
R [pc]
Actual inflow rate
Prediction
(gravitational
torques with shocks)
No dissipation
(Lynden-Bell+ '71)

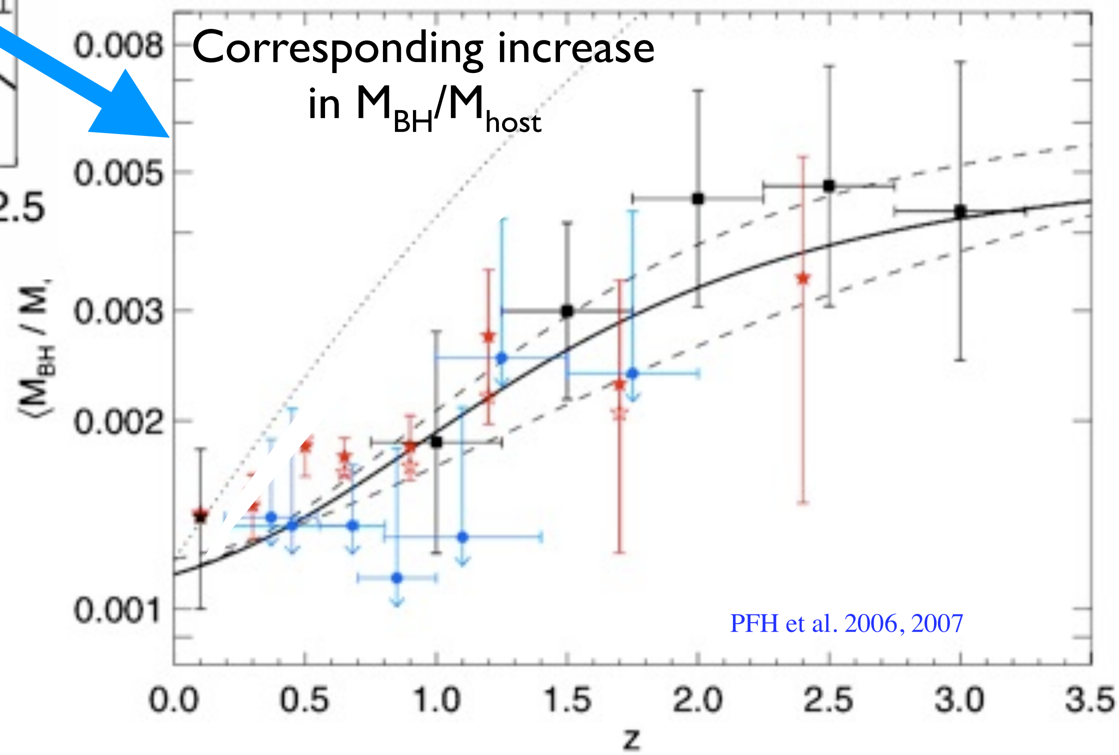

from 10 pc
from 50 pc
from 100 pc
from 1 kpc
Actual inflow rate onto BH [M_{sun}/yr]
Gravitational Prediction
0.01
0.1
1
10


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

Predictions?

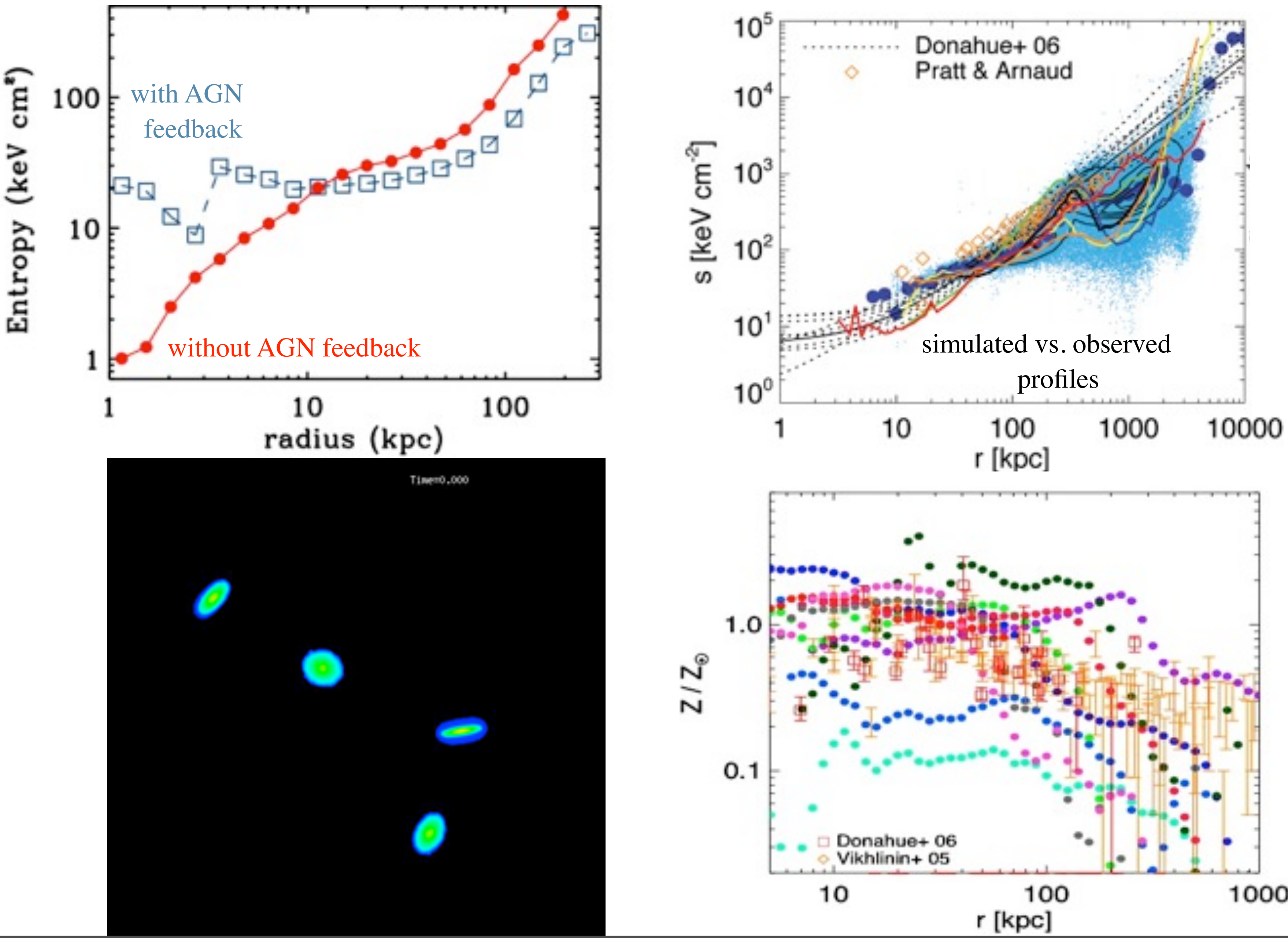
- M_{BH}-σ evolution:
  - Hosts more gas rich/compact at high-z ➔ more "work" for the BH before self-regulation





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

May Be Significant for the ICM & IGM (Pre-Heating?)



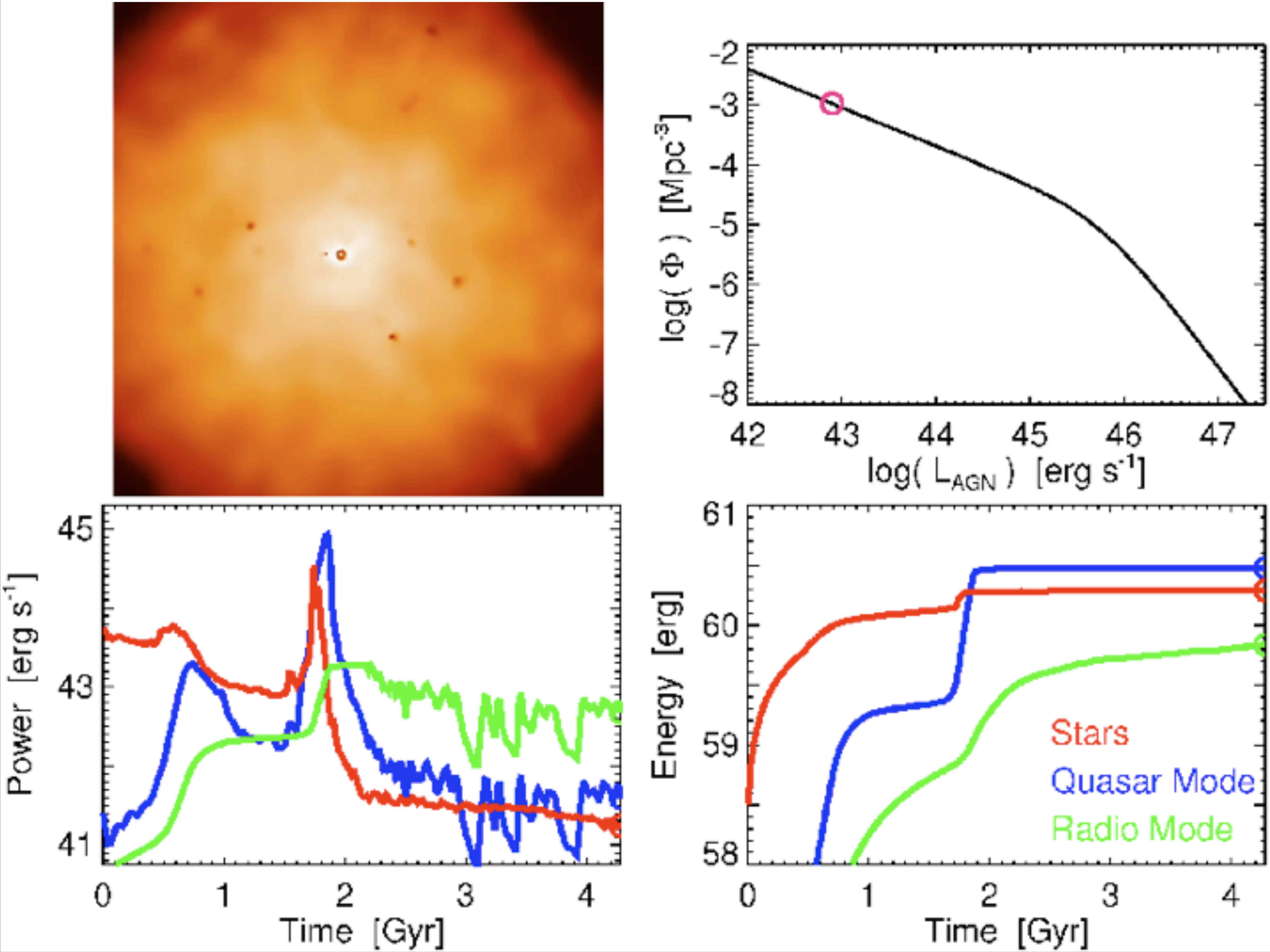
But What If We Change the Model?

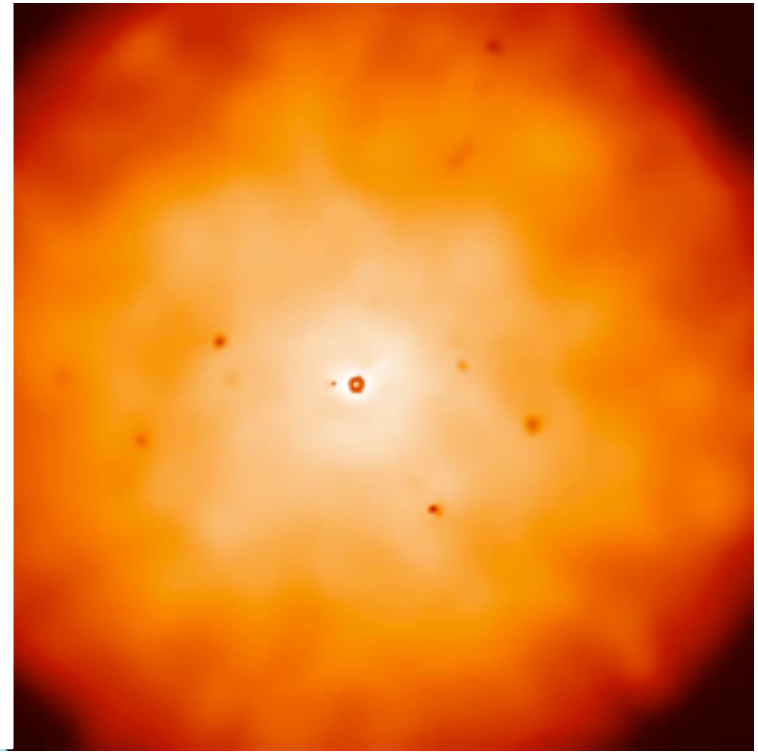
Dust in host absorbs radiation

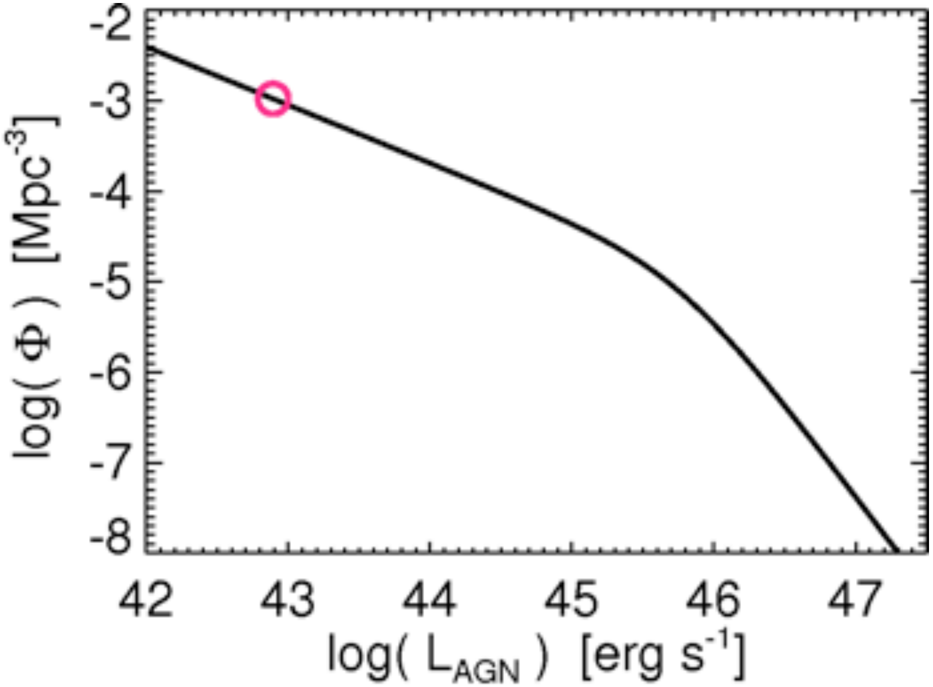
$$F_{\rm rad} = \tau \, \frac{L}{c}$$

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

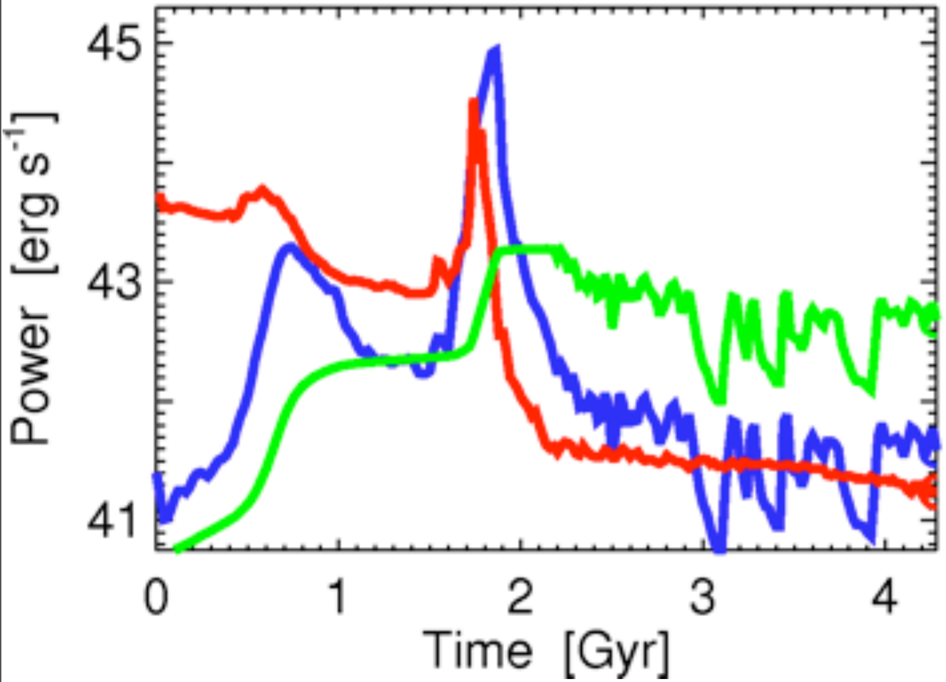
$$L_{\rm max} \sim \frac{4\, f_{\rm gas}\, \sigma^4\, c}{G}$$


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

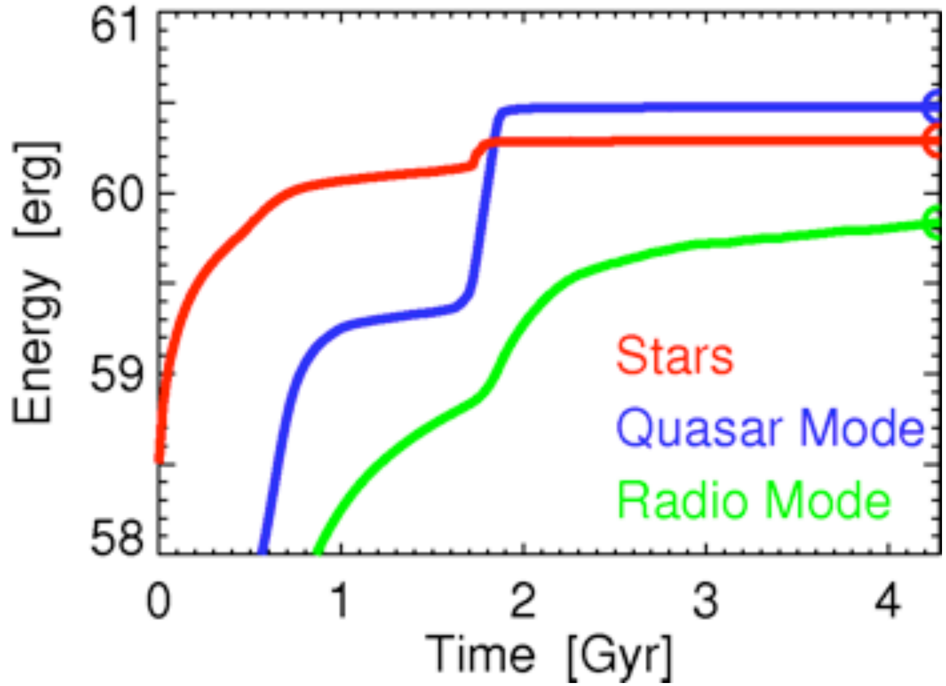




log(Φ) [Mpc^{-3}]
log(L_{AGN}) [erg s^{-1}]



Power [erg s^{-1}]
Time [Gyr]



Energy [erg]
Time [Gyr]
Stars
Quasar Mode
Radio Mode