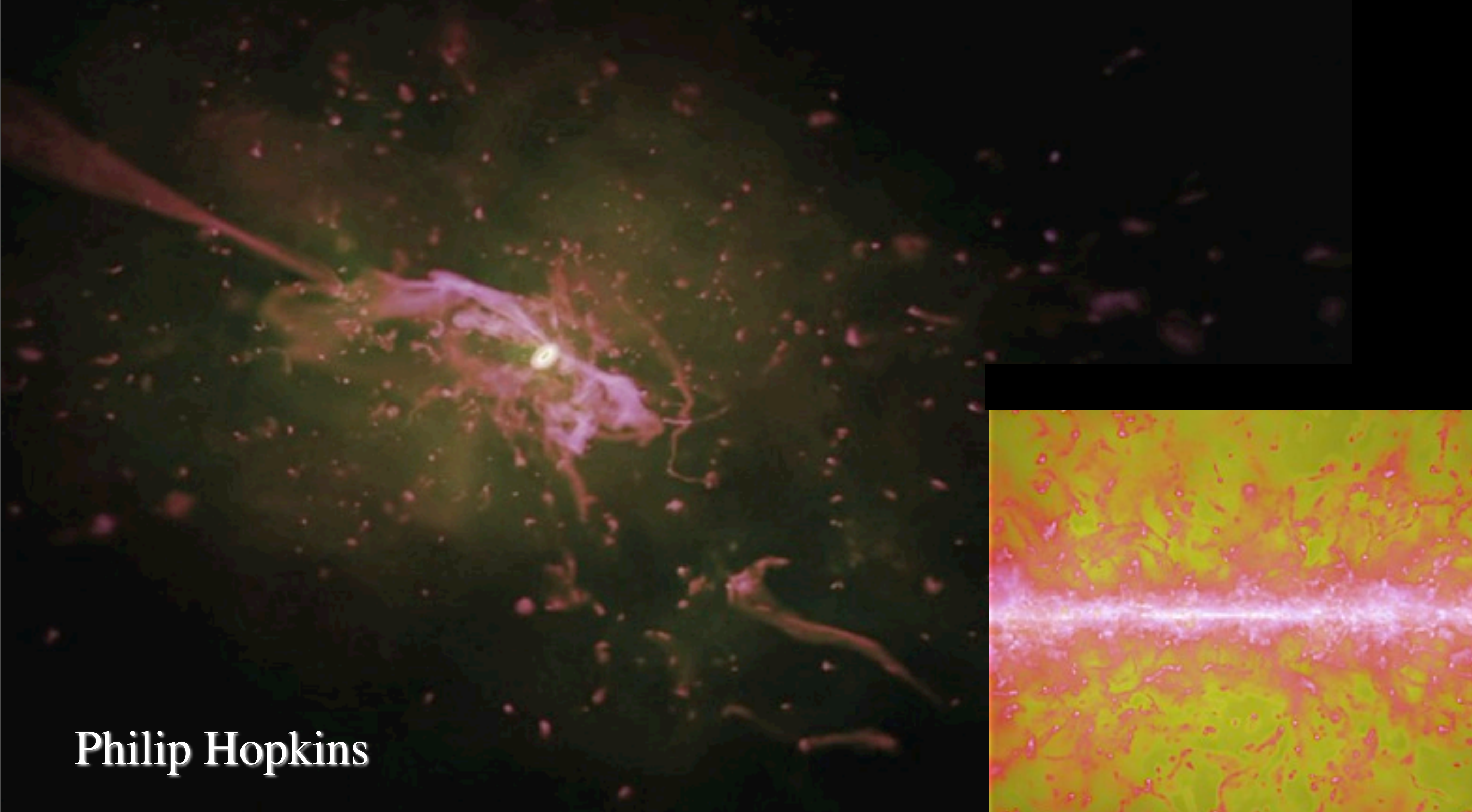
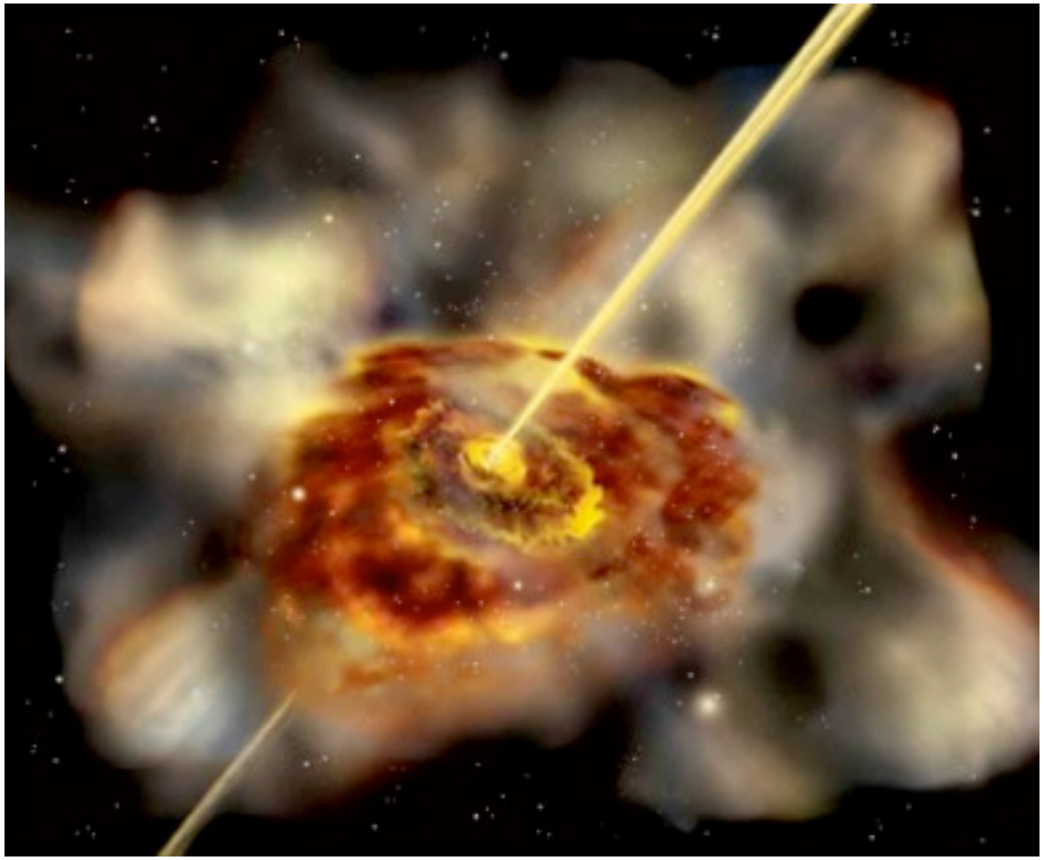
“Quasar” Feedback in Galaxies



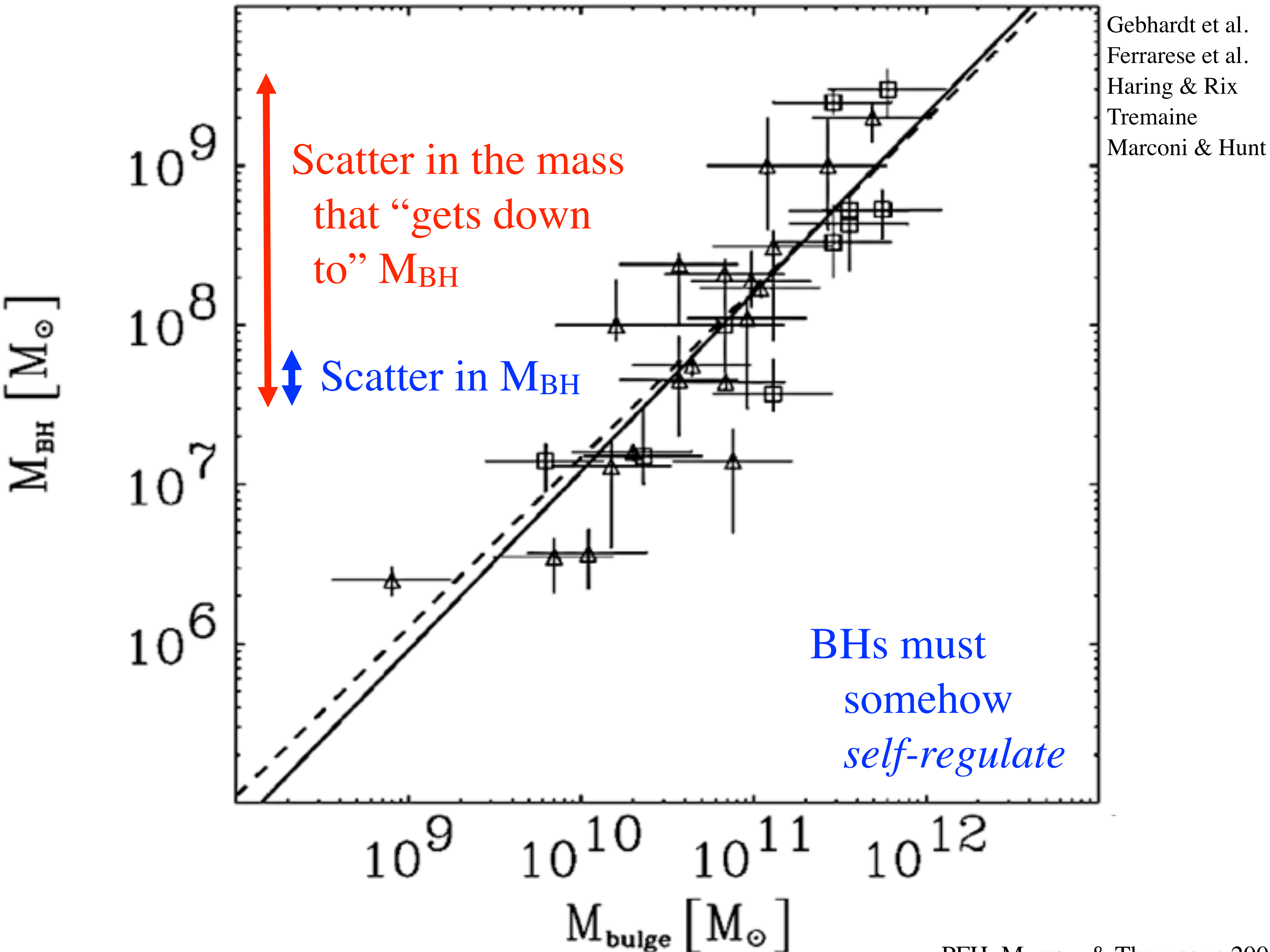
Philip Hopkins

Lars Hernquist, Norm Murray, Eliot Quataert,
Todd Thompson, Dusan Keres, Chris Hayward, Stijn Wuyts,
Kevin Bundy, Desika Narayanan, Ryan Hickox, Rachel Somerville, & more

- Every massive galaxy hosts a supermassive black hole

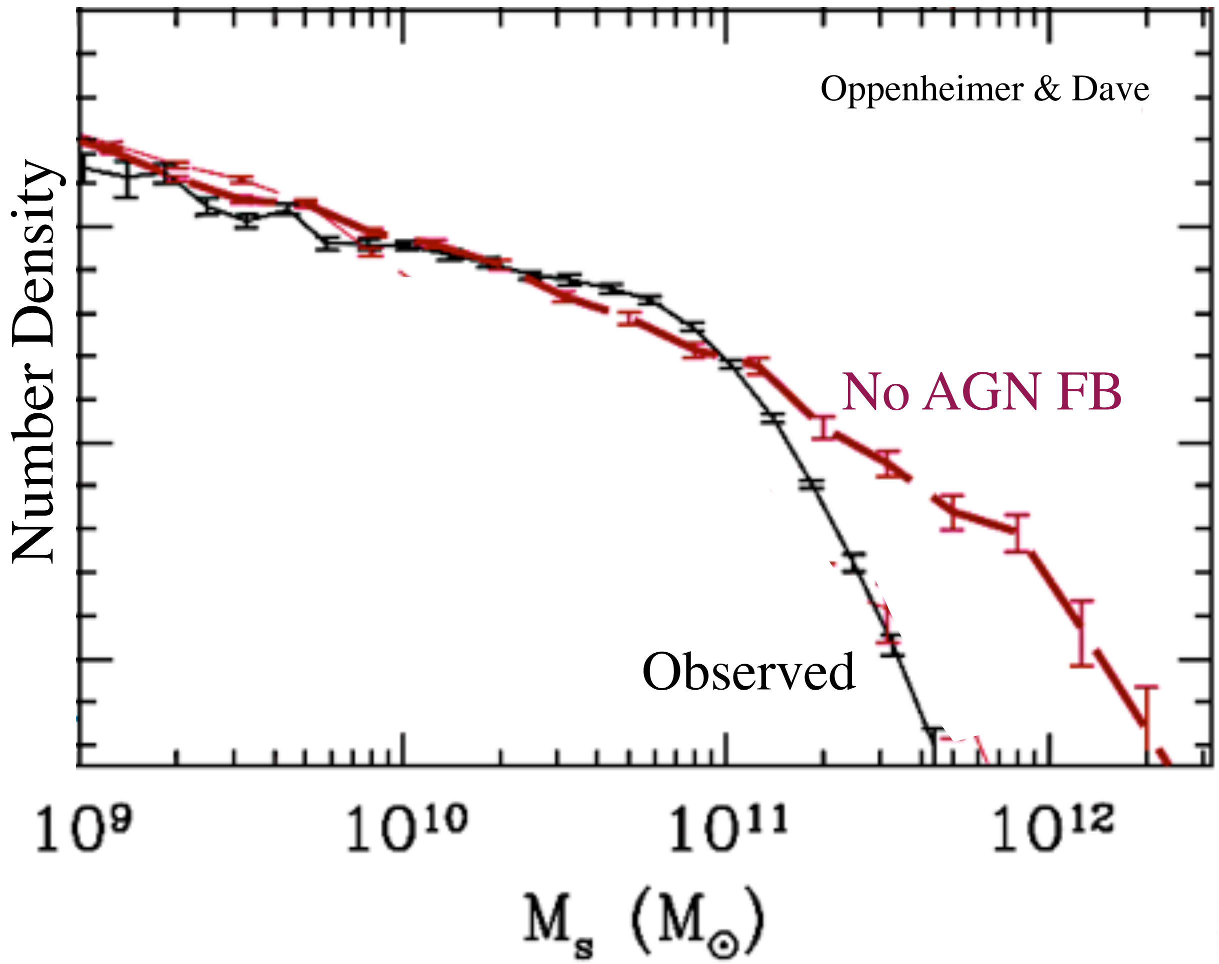


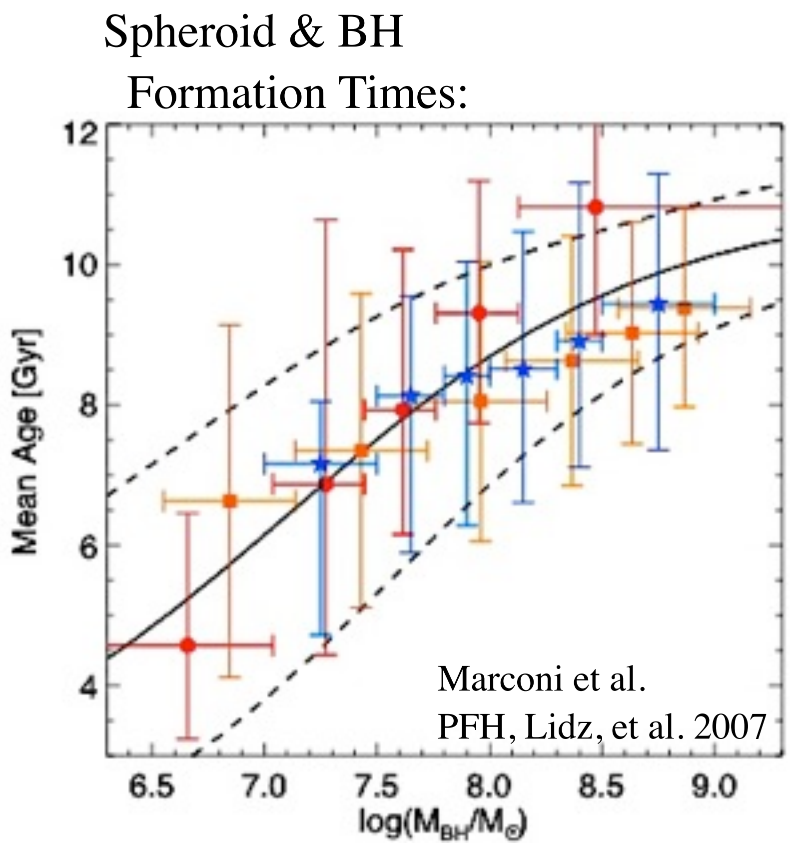
- Mass accreted in ~couple bright quasar phase(s)
  (Soltan, Salucci+, Tremaine+, Yu & Lu, PFH, Shankar, et al.)



PFH, Murray, & Thompson 2009

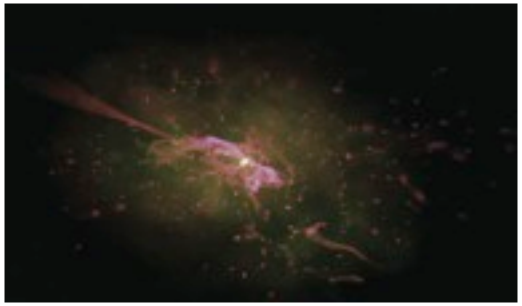
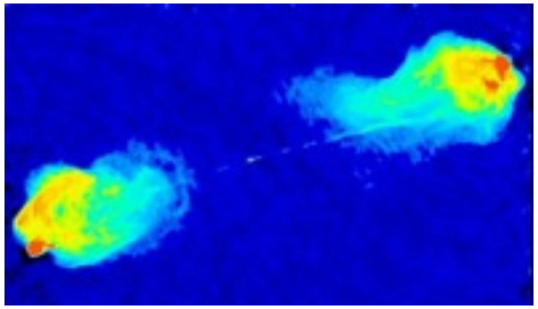
What can AGN Feedback Do For You?

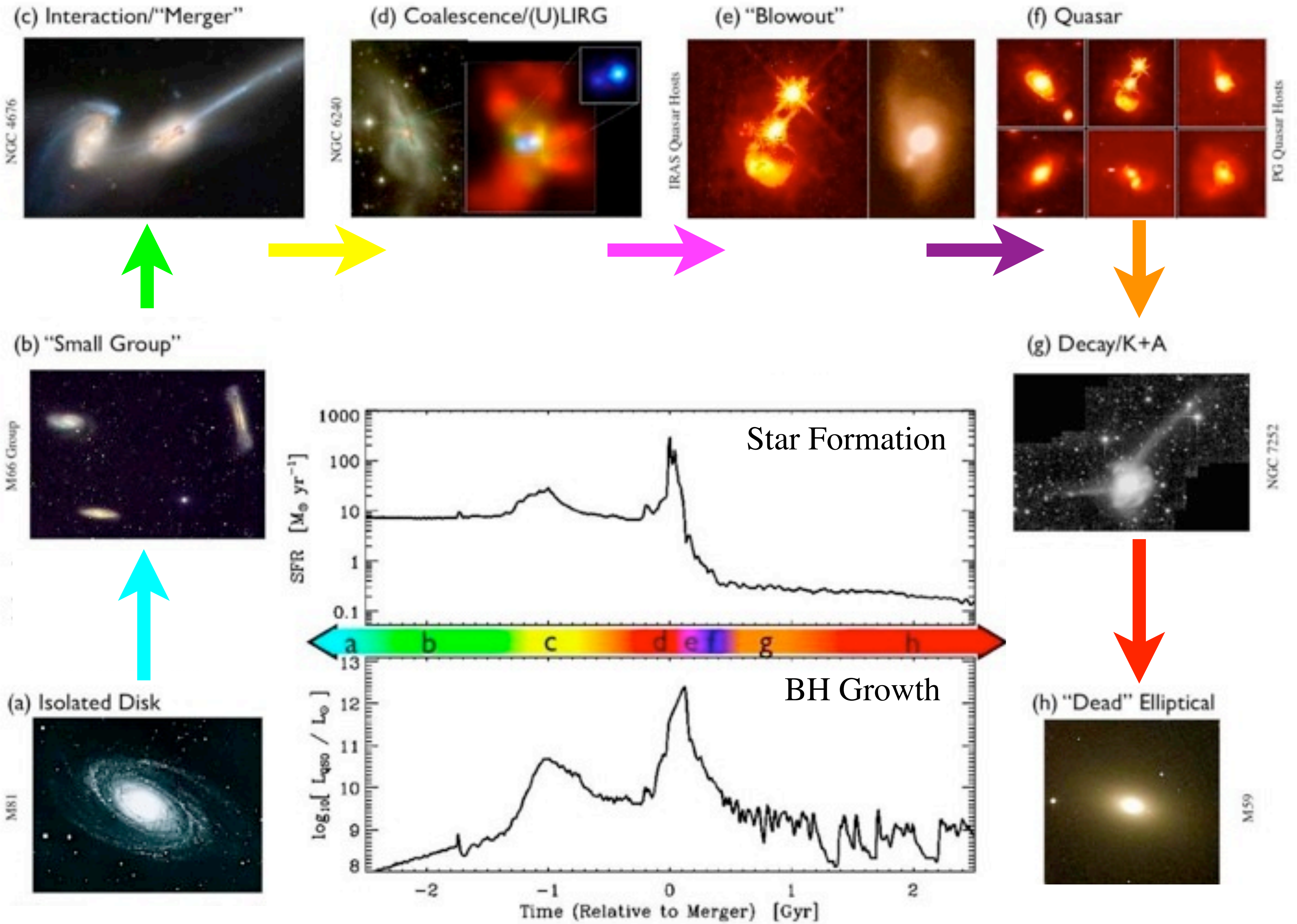




- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

“Transition” vs. “Maintenance”

“Transition”	“Maintenance”
“Quasar” mode (high mdot)	**“Radio”** mode (low mdot)
Move mass from Blue to Red?	Keep it Red
Rapid (~10^7 yr)	Long-lived (~Hubble time)
Small(er) scales (~pc-kpc)	Large (~halo) scales
Morphological Transformation	Subtle morphological change
Gas-rich/Dissipational Mergers?	Hot Halos & Dry Mergers
	
Regulates *Black Hole* Mass	Regulates *Galaxy* Mass



Sanders, Scoville, many subsequent

What Can Quasar Feedback Do?

Feedback Energy:

SILK & REES '98

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

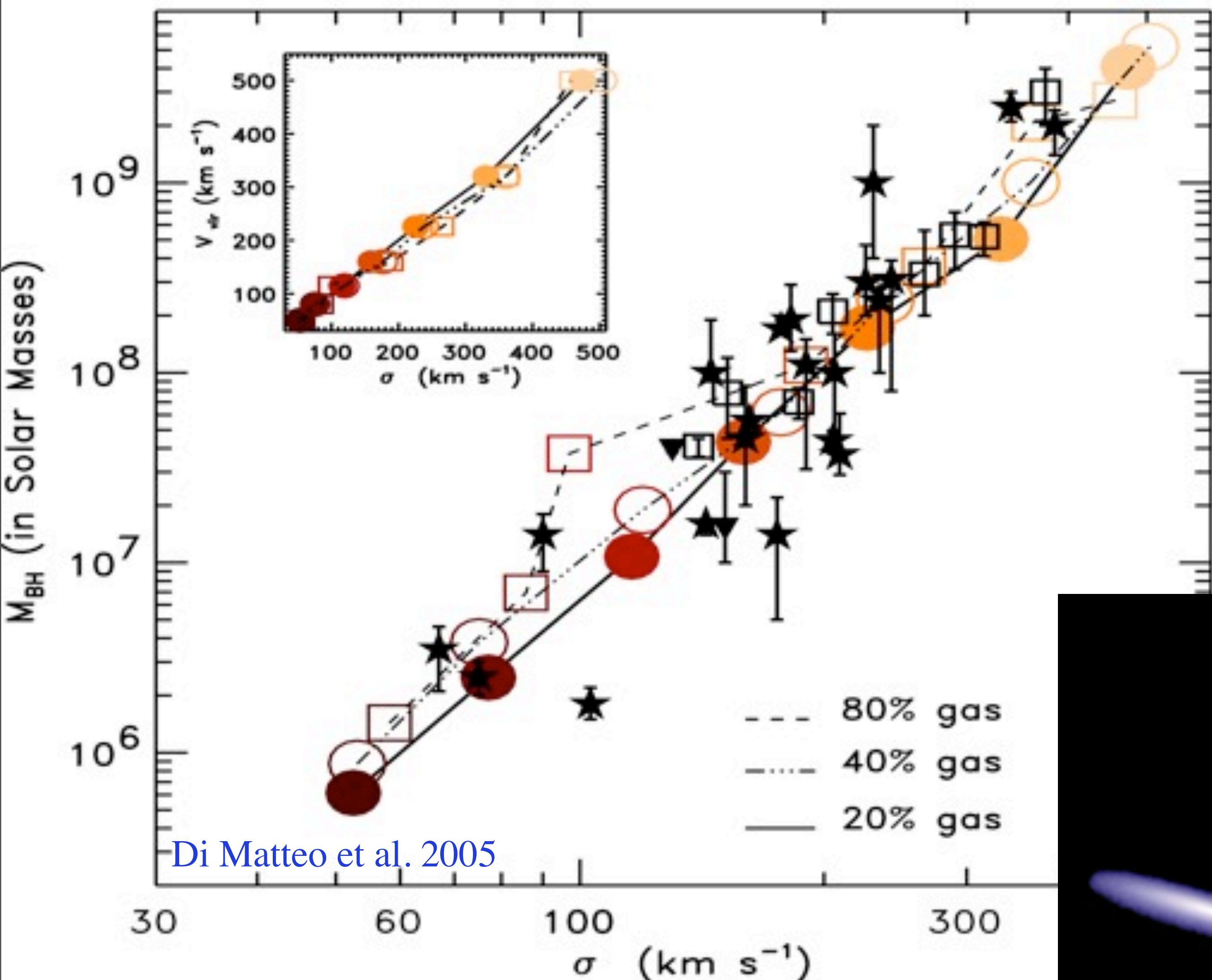
$$\rightarrow E_{\rm rad} \sim 0.1 \, M_{\rm BH} \, c^2 \sim 10^{61} \, {\rm erg}$$

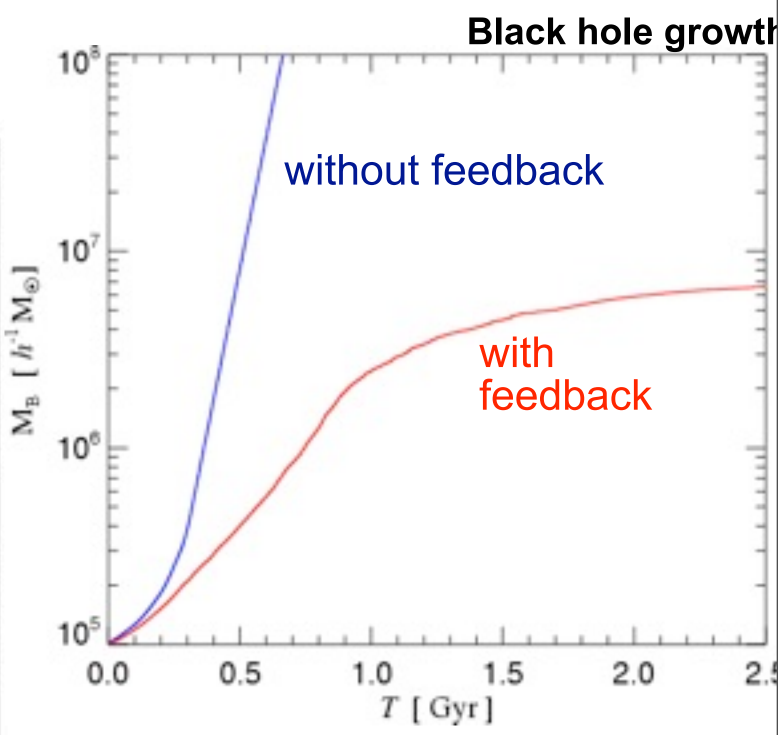
$$(M_{\rm BH} \sim 10^8 \, M_\odot)$$

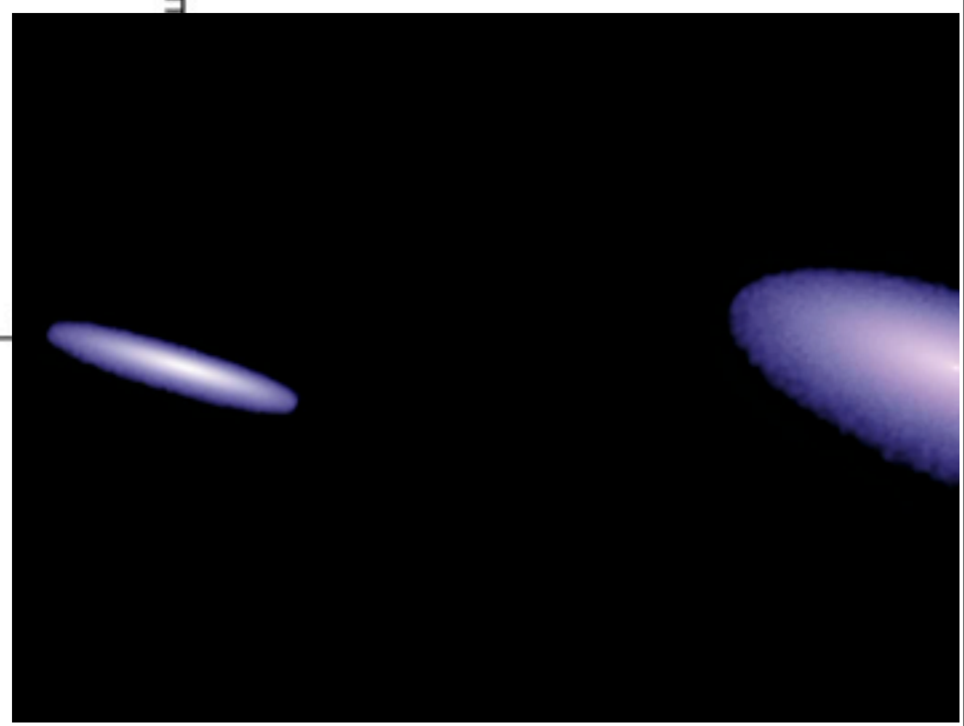
$$E_{\rm gal} \sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_\odot) \, (200 \, {\rm km/s})^2 \sim 10^{59} \, {\rm erg}$$

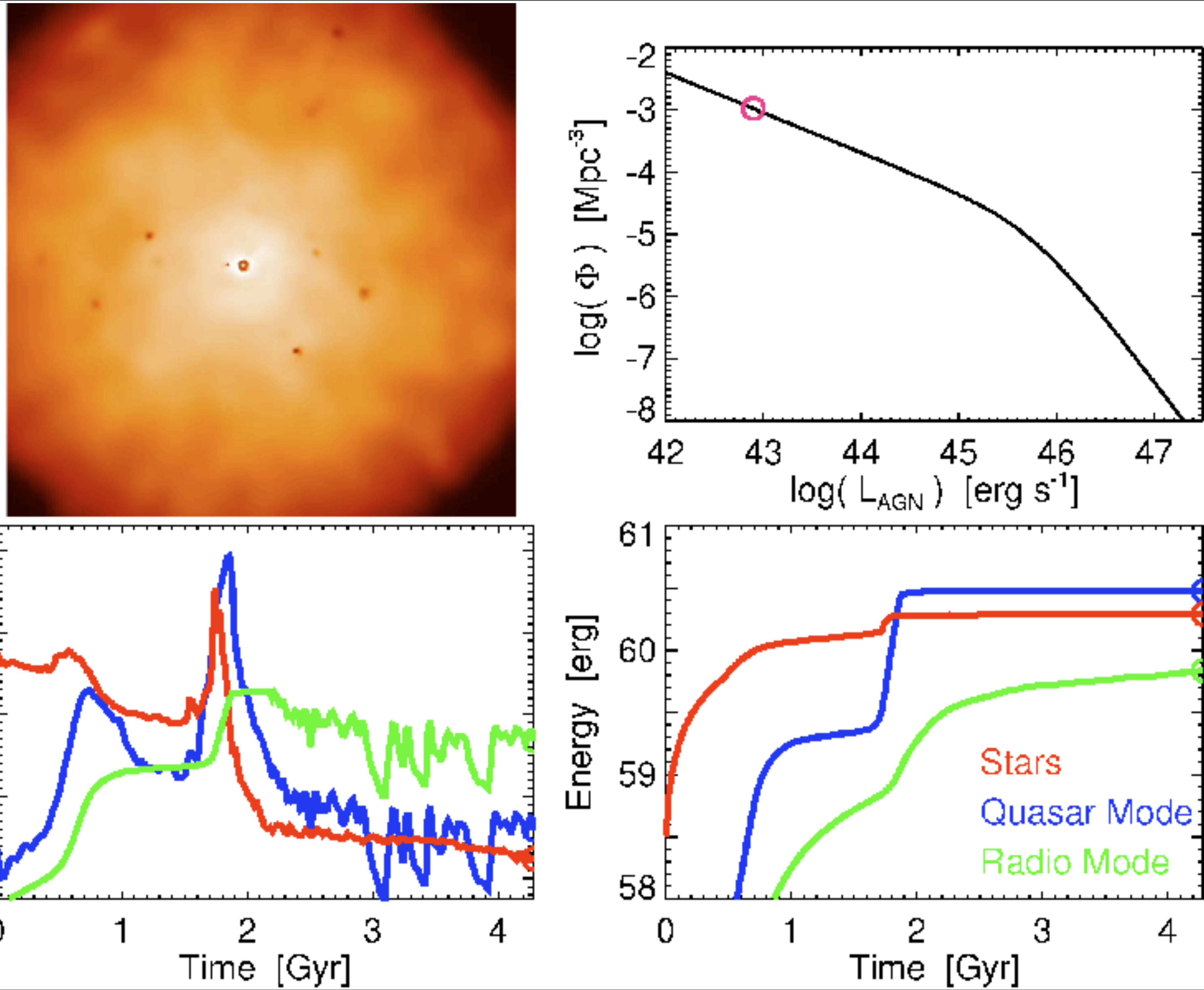
M-sigma Suggests *Self-Regulated* BH Growth

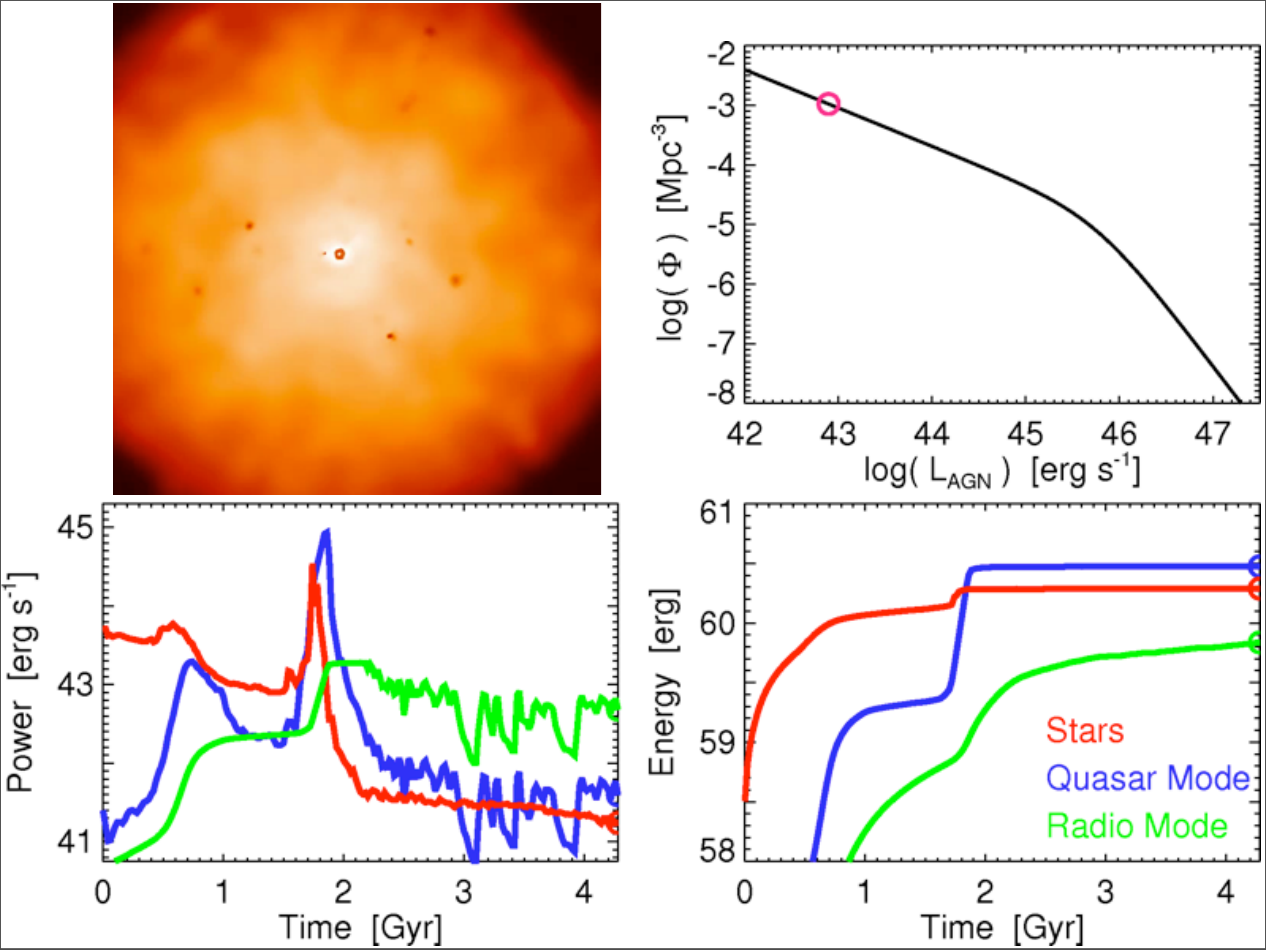
PREVENTS RUNAWAY BLACK HOLE GROWTH







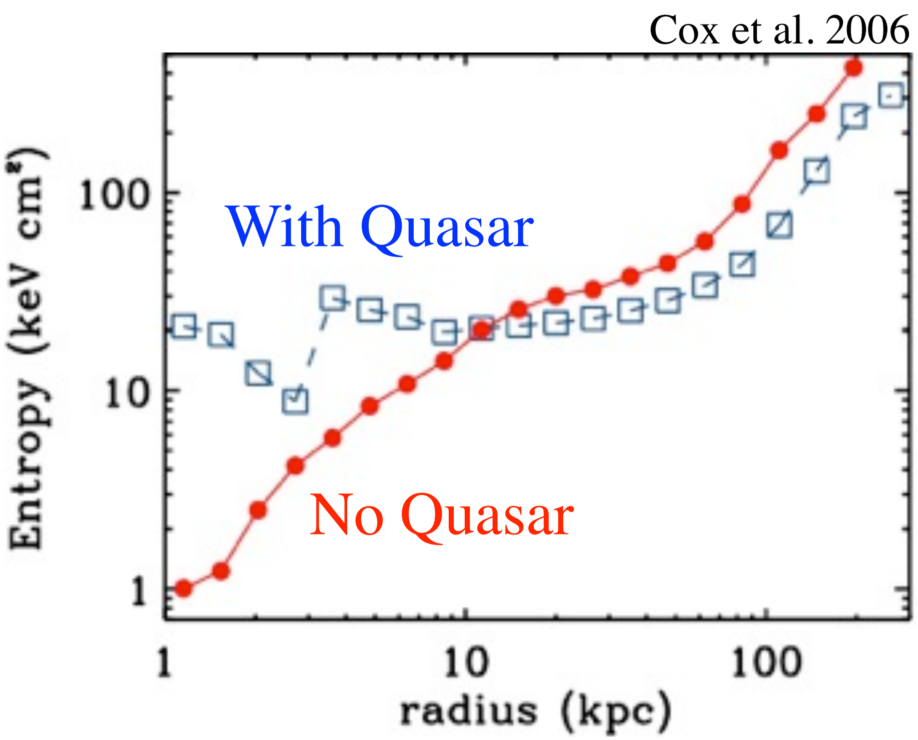

log(Φ) [Mpc^-3]
log(L_AGN) [erg s^-1]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
Power [erg s^-1]
45
43
41
Time [Gyr]
0
1
2
3
4
Energy [erg]
61
60
59
58
Stars
Quasar Mode
Radio Mode

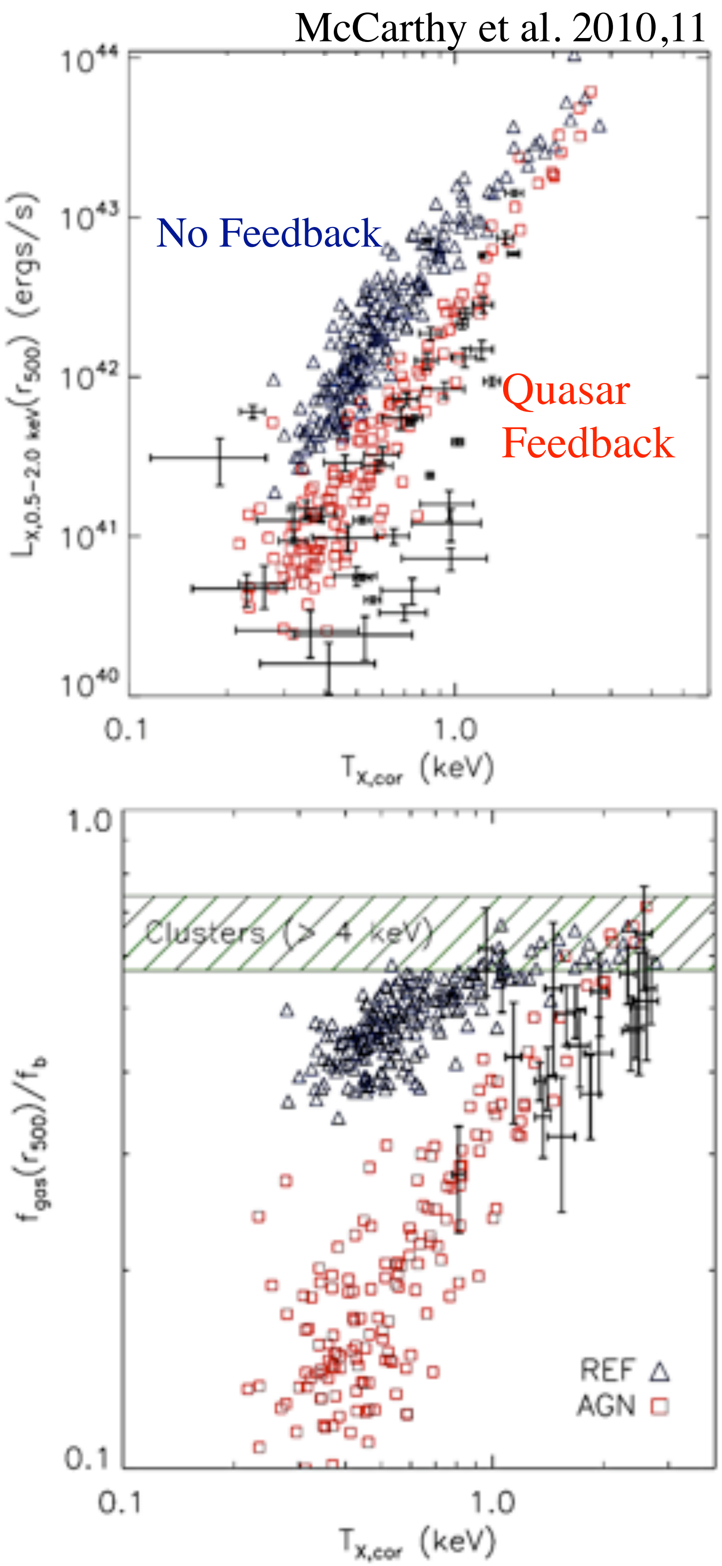


log(Φ) [Mpc^{-3}]
log(L_{AGN}) [erg s^{-1}]
Power [erg s^{-1}]
Time [Gyr]
Energy [erg]
Time [Gyr]
Stars
Quasar Mode
Radio Mode

Quasar Outflows: Heating Halo Gas

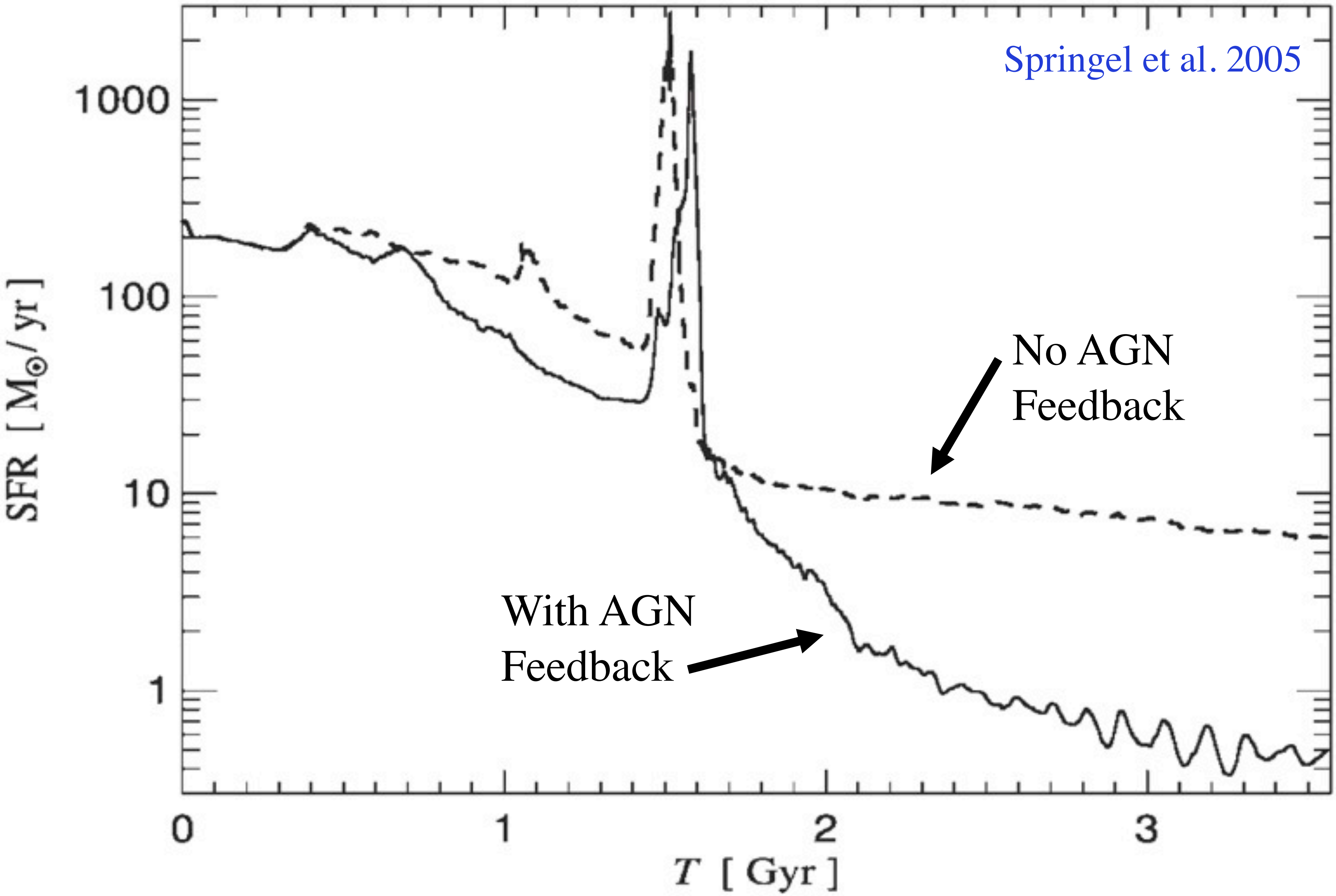
SHUT DOWN COOLING AND/OR "SET UP" RADIO MODE



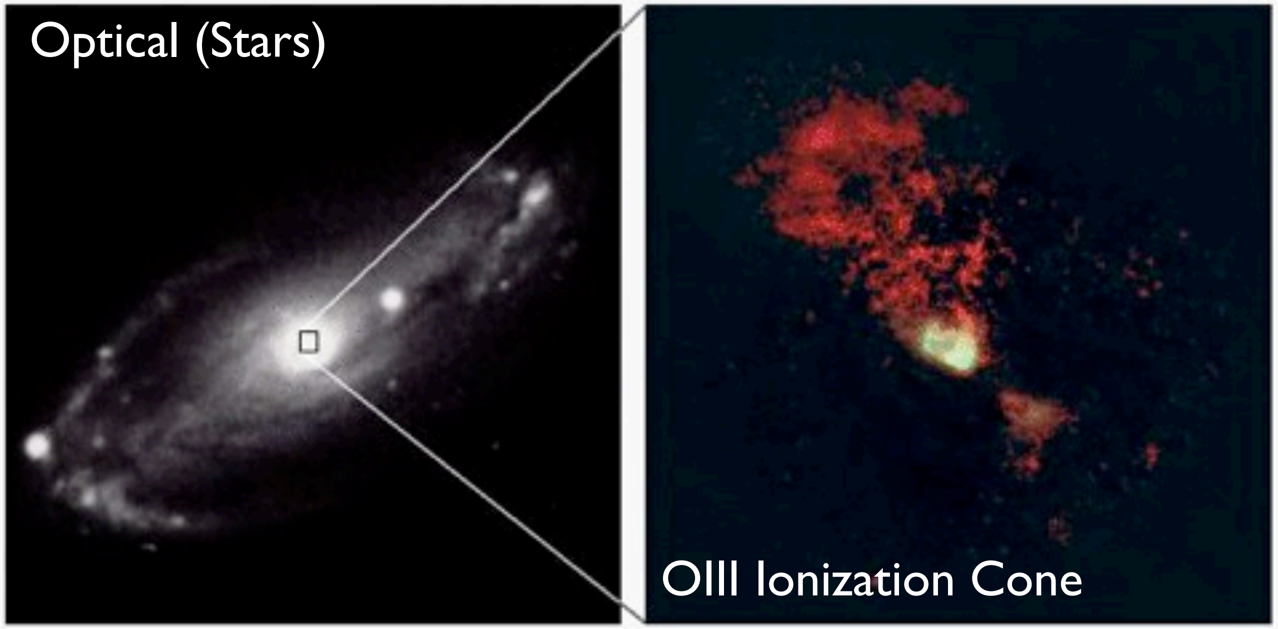


Expulsion of Gas Turns off Star Formation

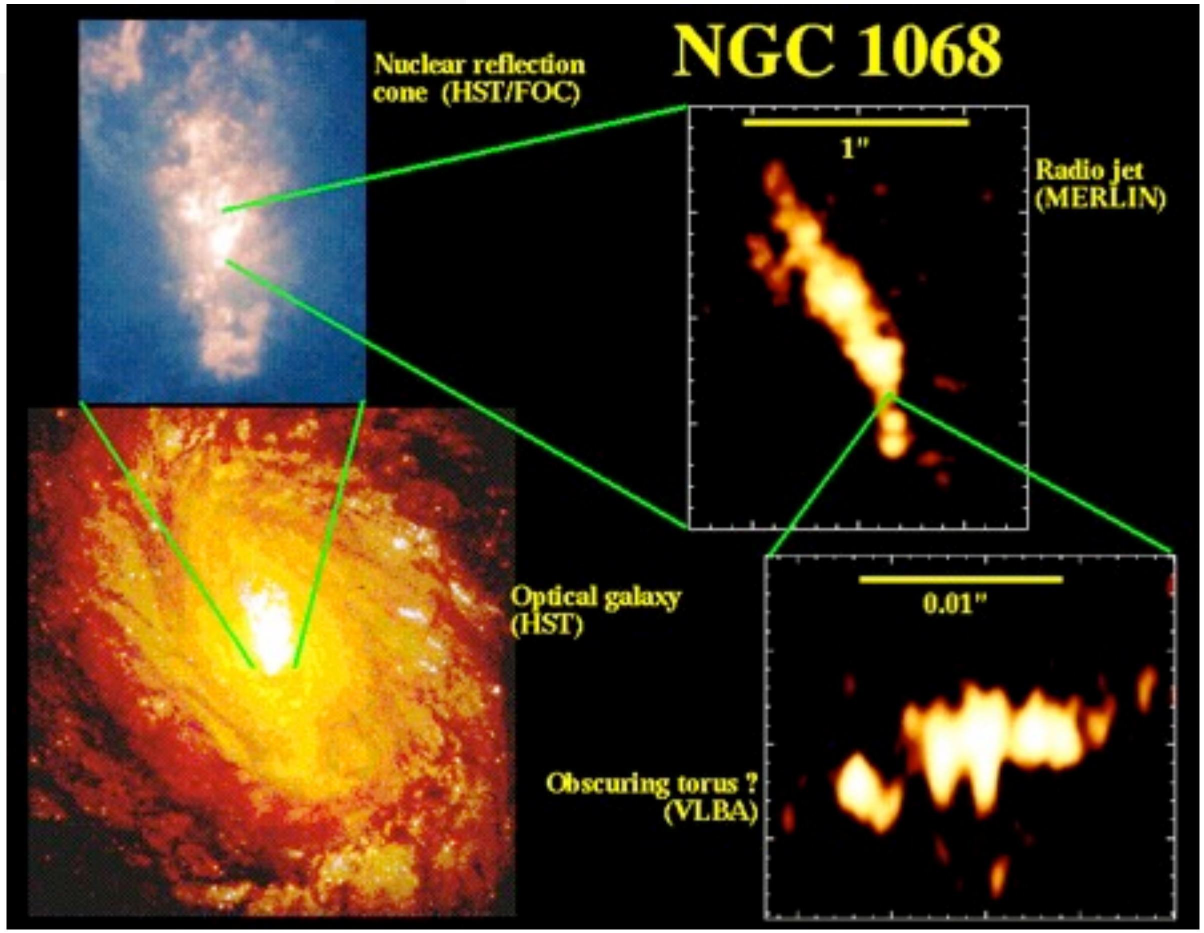
ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



But Does Quasar Mode Feedback Exist?


Optical (Stars)
OIII Ionization Cone

NGC 5728

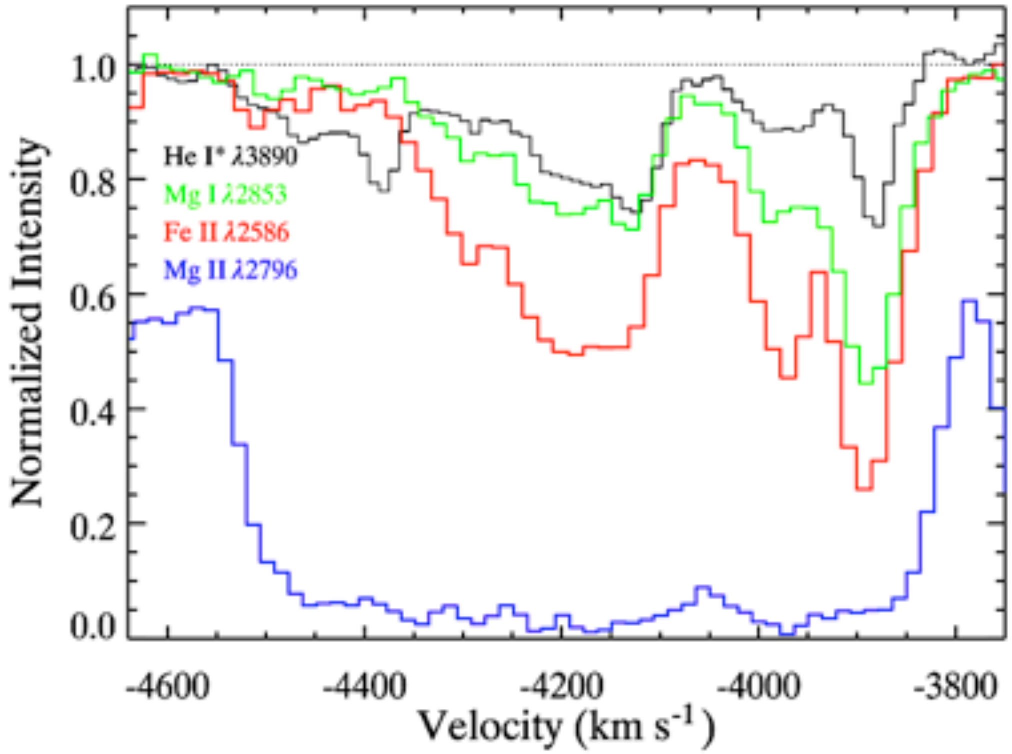

NGC 1068
Nuclear reflection cone (HST/FOC)
1"
Radio jet (MERLIN)
Optical galaxy (HST)
0.01"
Obscuring torus ? (VLBA)

Broad Absorption Line Quasars

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

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

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



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

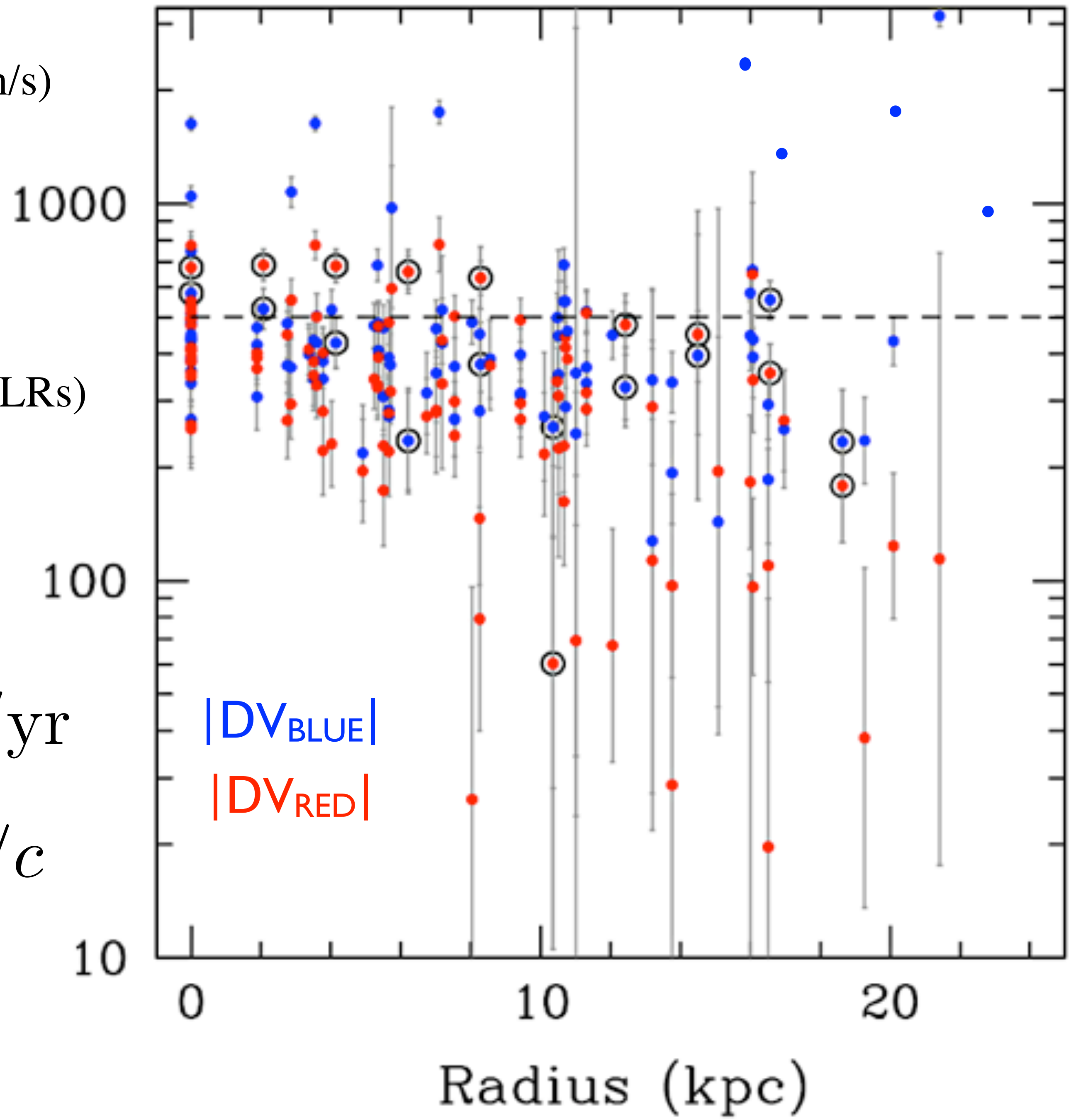
Arav et al.
Wampler et al. 1995
Hamann et al. 2001
de Kool et al. 2001&2
Korista et al. 2008
Moe et al. 2009
Dunn et al. 2010
Aoki et al. 2011
Kaastra et al. 2011

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

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

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

Shen et al. 2011 (Double-Peaked NLRs)



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

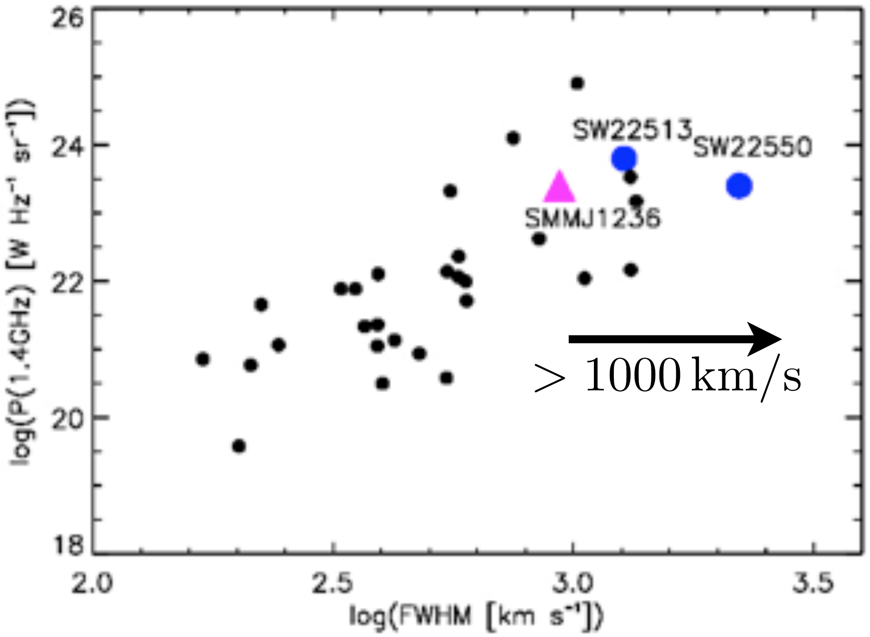
$$\dot{M}\, v \sim 1 - 30\, L_{\mathrm{AGN}}/c$$

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

Ionized Gas Tracers At High-Redshift

"Pushed" By Radio Jets

Lehnert et al. 2009,2011
Nesvadba et al. 2010,2011



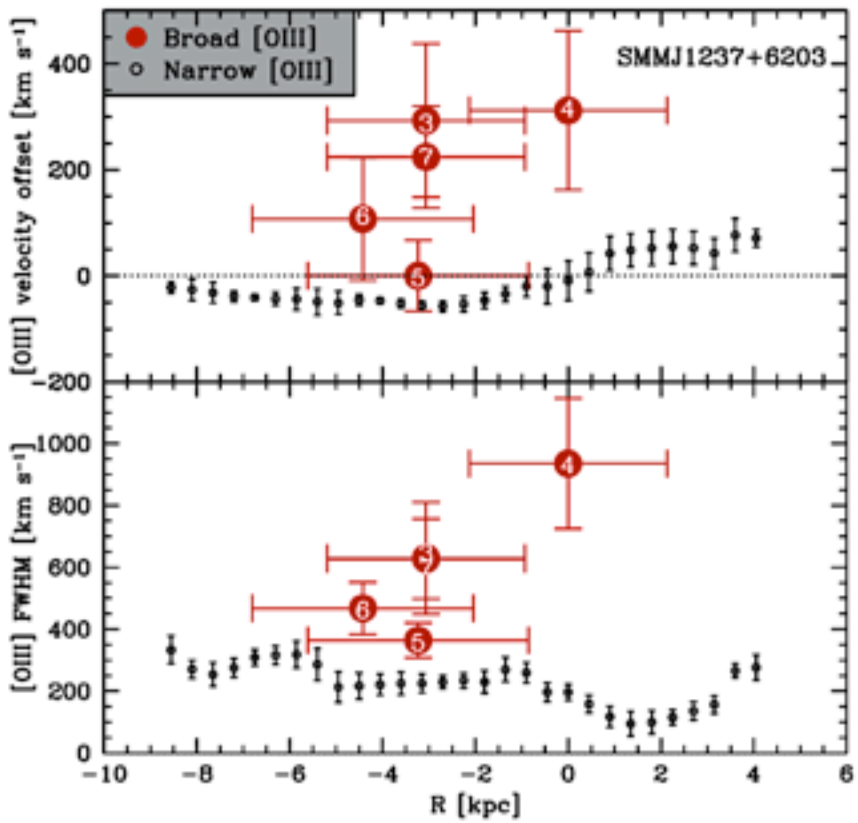
$$R_{\rm wind} \sim 5\,{\rm kpc}$$

$$v \sim 1000\,{\rm km/s}$$

$$L_{\rm wind} \sim 0.1\,L_{\rm AGN}$$

No Radio Jets / Radio Quiet

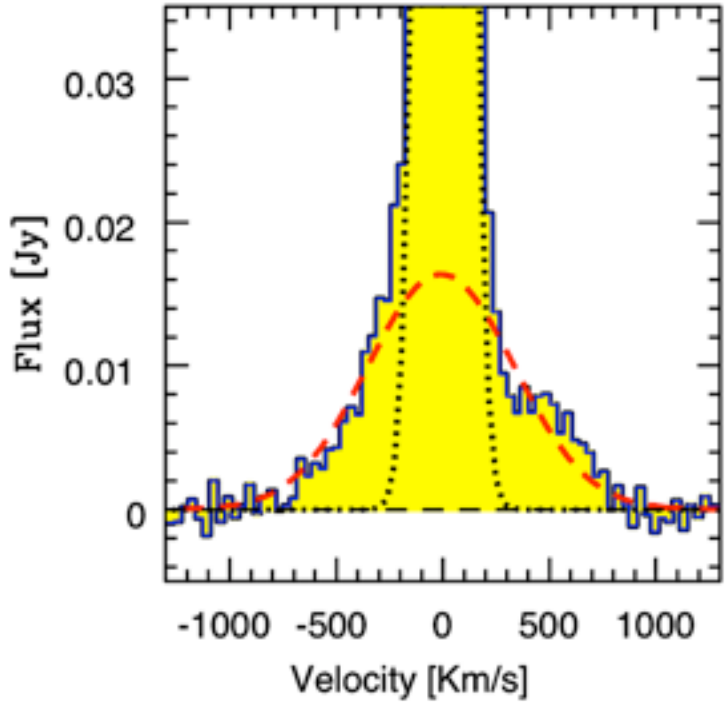
Alexander et al. 2010



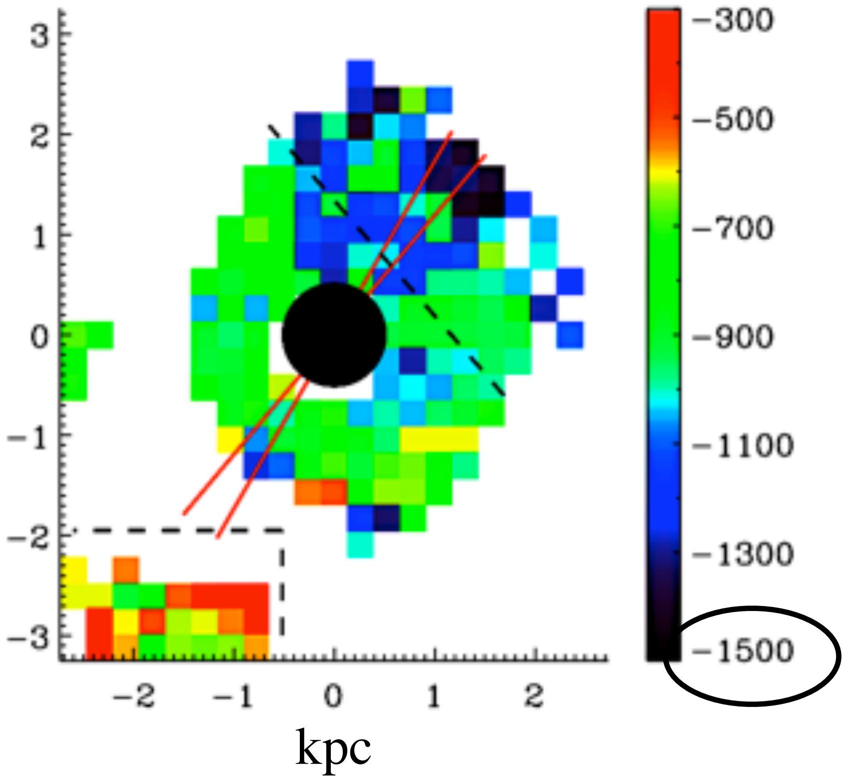
Molecular Outflows in AGN ULIRGs

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

CO:



Molecular+Ionized Outflows:



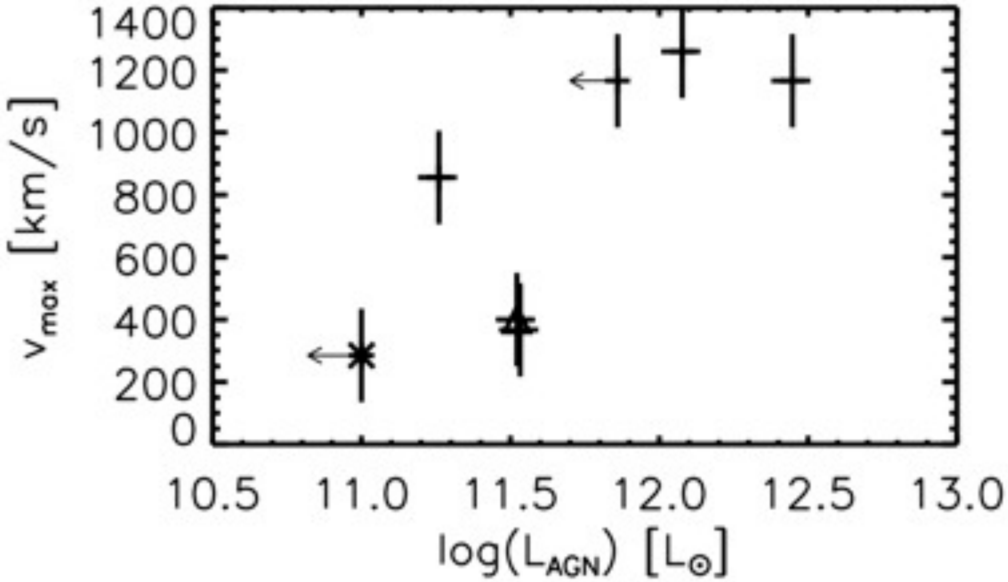
$$R_{\rm wind} \sim 1 - 4\,{\rm kpc}$$

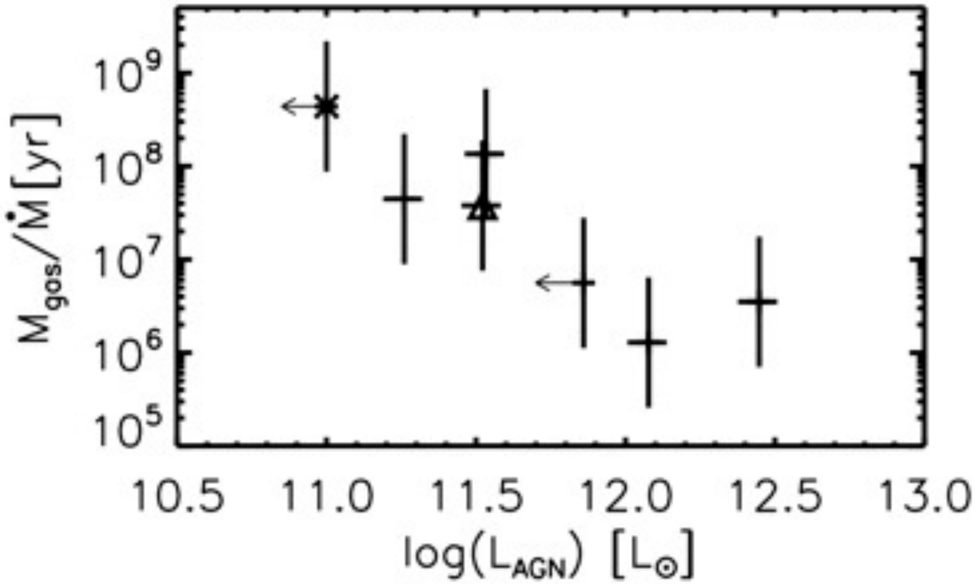
$$v > 500\,{\rm km\,s^{-1}}$$

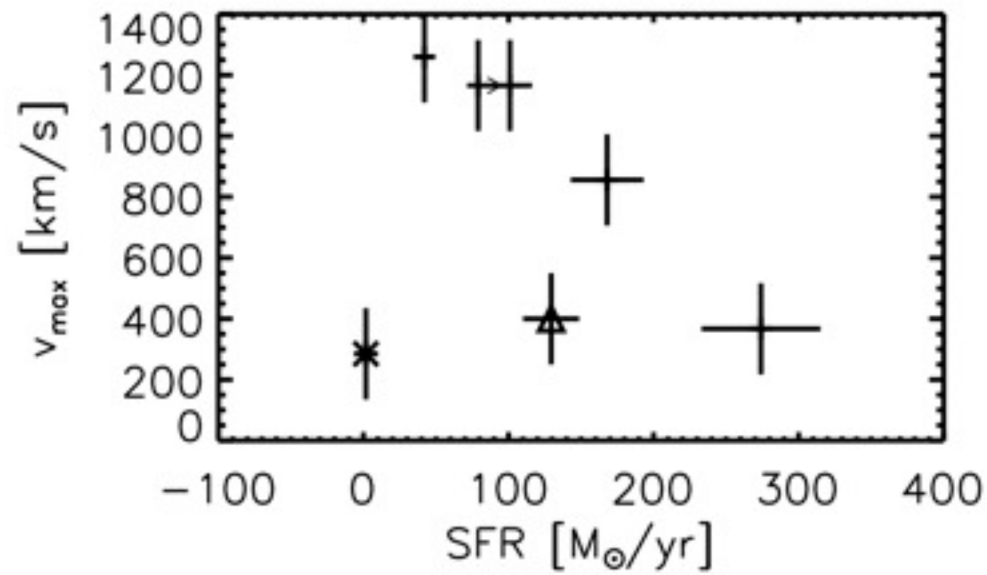
$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr^{-1}}$$

Molecular Outflows in AGN ULIRGs

Sturm et al. 2011:







$$\dot{M} \sim 100 - 1000 \, M_\odot/\mathrm{yr}$$

$$\dot{M} \, v \sim 5 - 30 \, L_{\mathrm{AGN}}/c$$

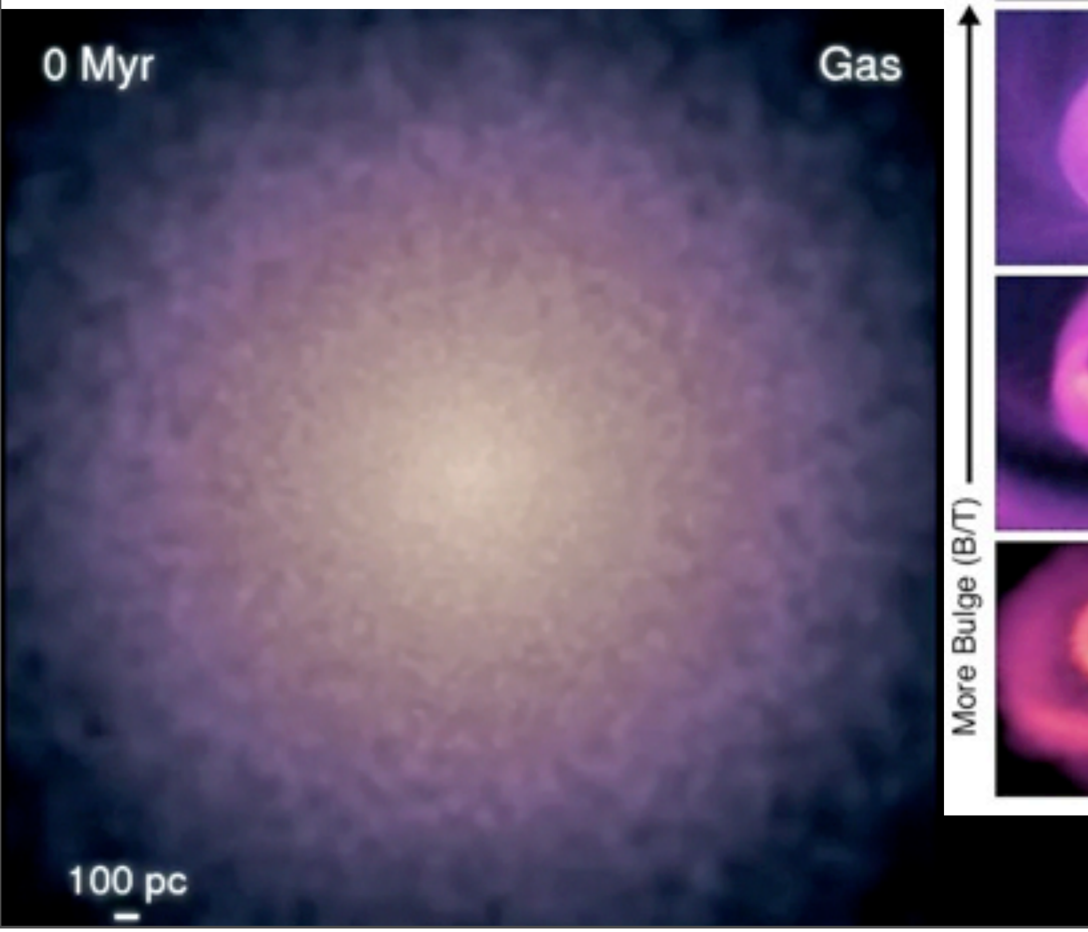
$$L_{\mathrm{wind}} \sim 0.03 - 0.10 L_{\mathrm{AGN}}$$

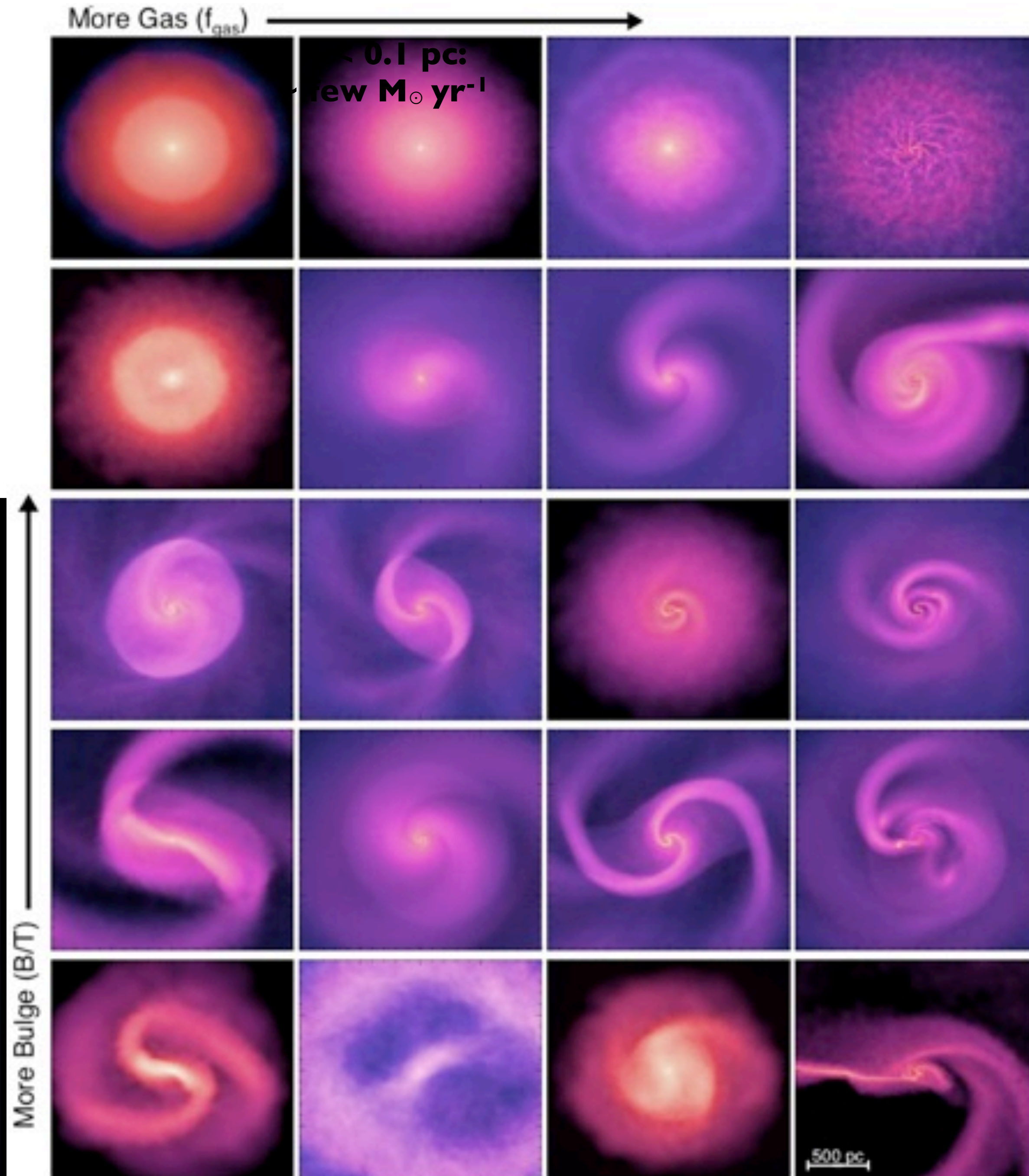
Where to now? How Do We Model This?

Step 1: Inflow

- Beginning to directly follow inflow to sub-pc scales

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





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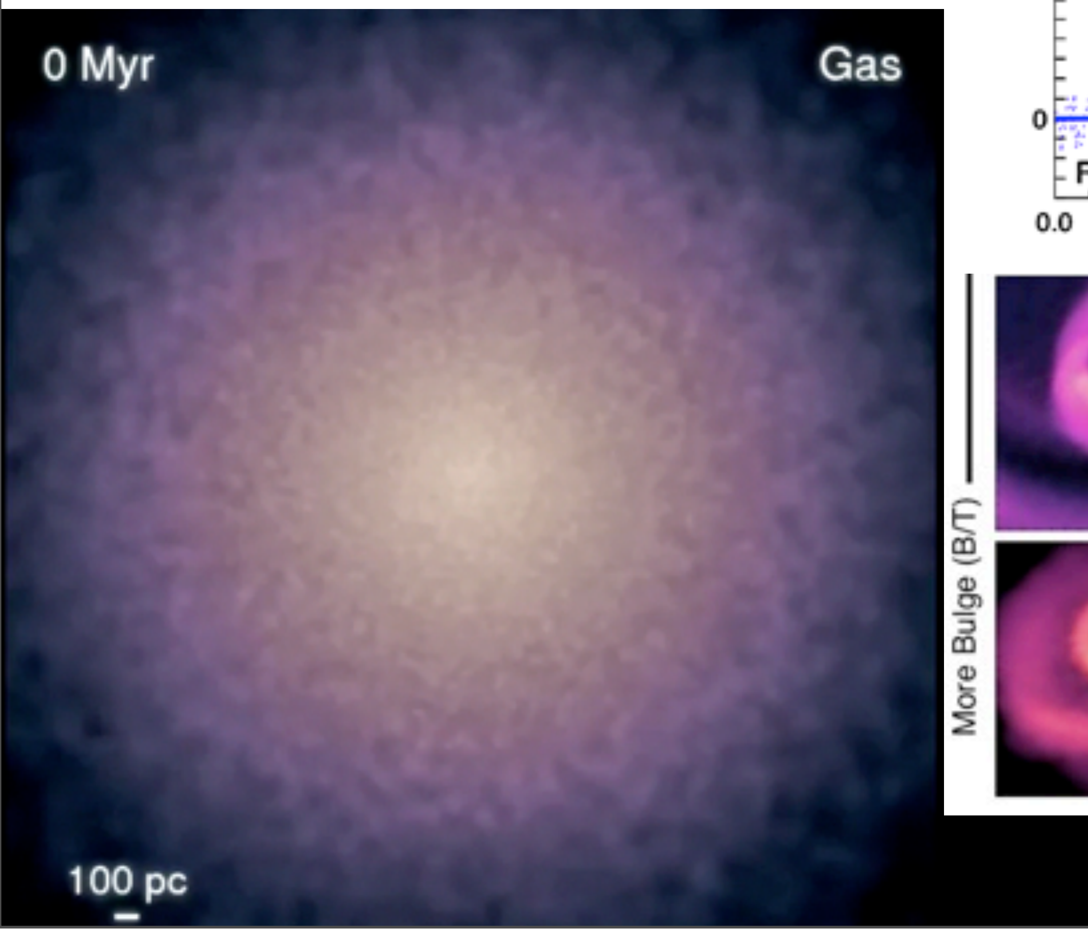

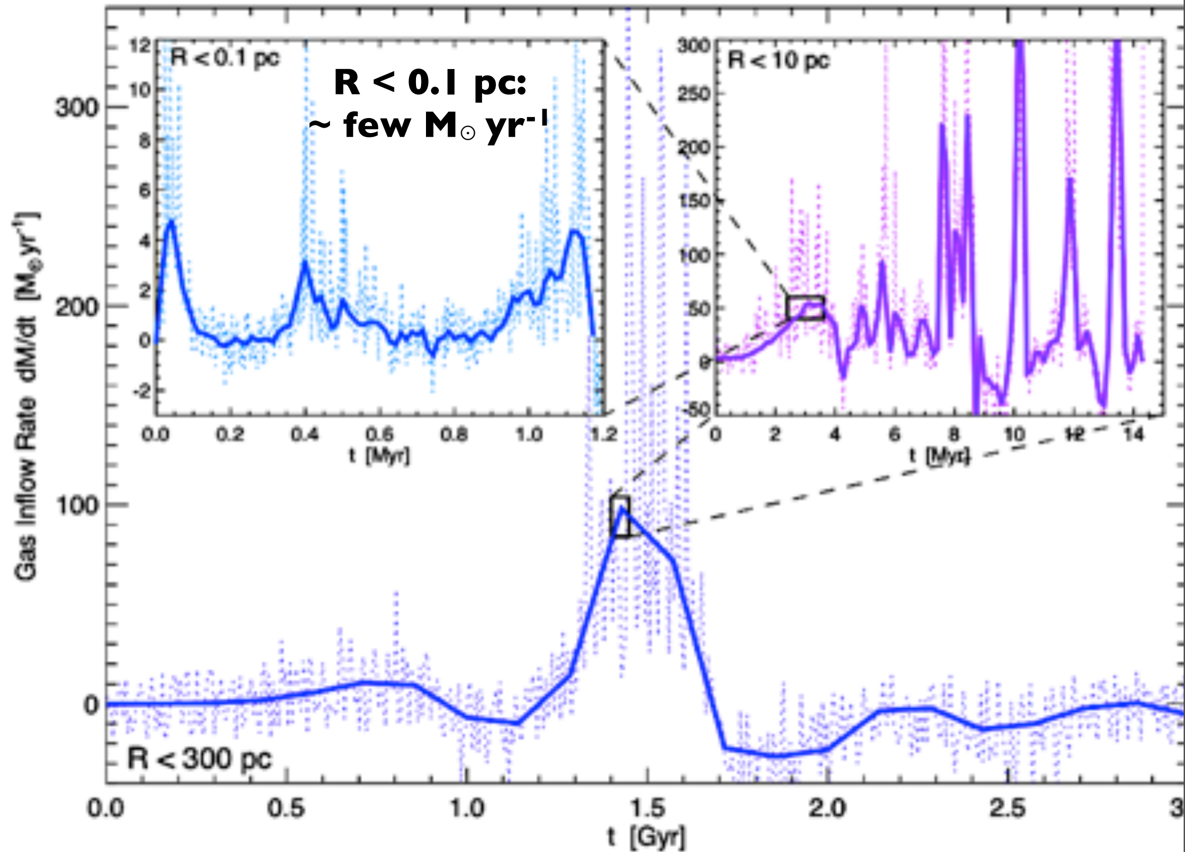

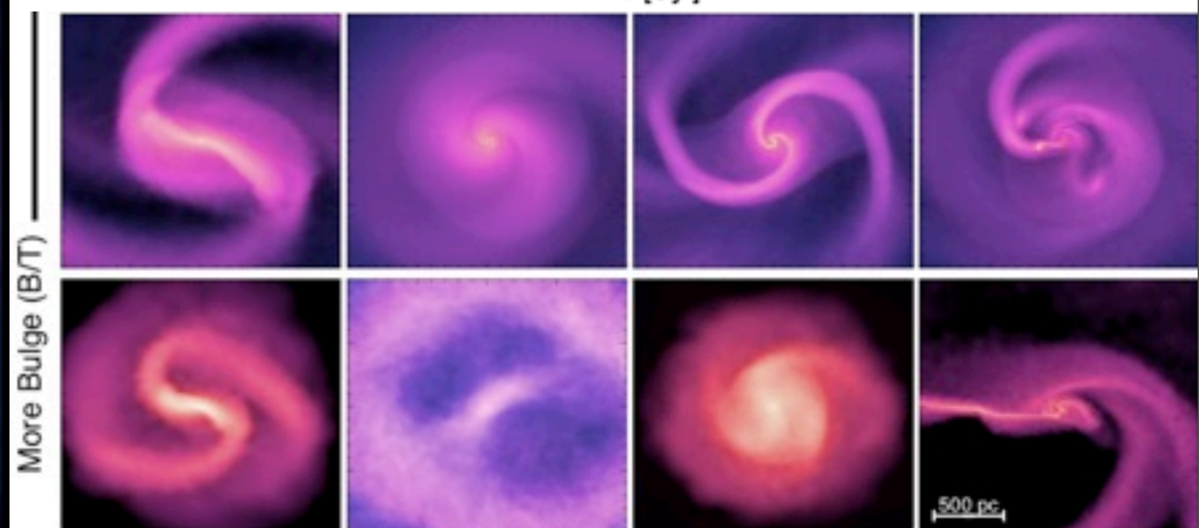

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”

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

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

More accurately ...

"It's Non-axisymmetric Features all the Way Down ..."

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

Step 2: *Stellar* Feedback & the ISM

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

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  - Stellar Winds
  - Photoionization (HII Regions)
- *Explicit* Momentum Flux:
  - Radiation Pressure

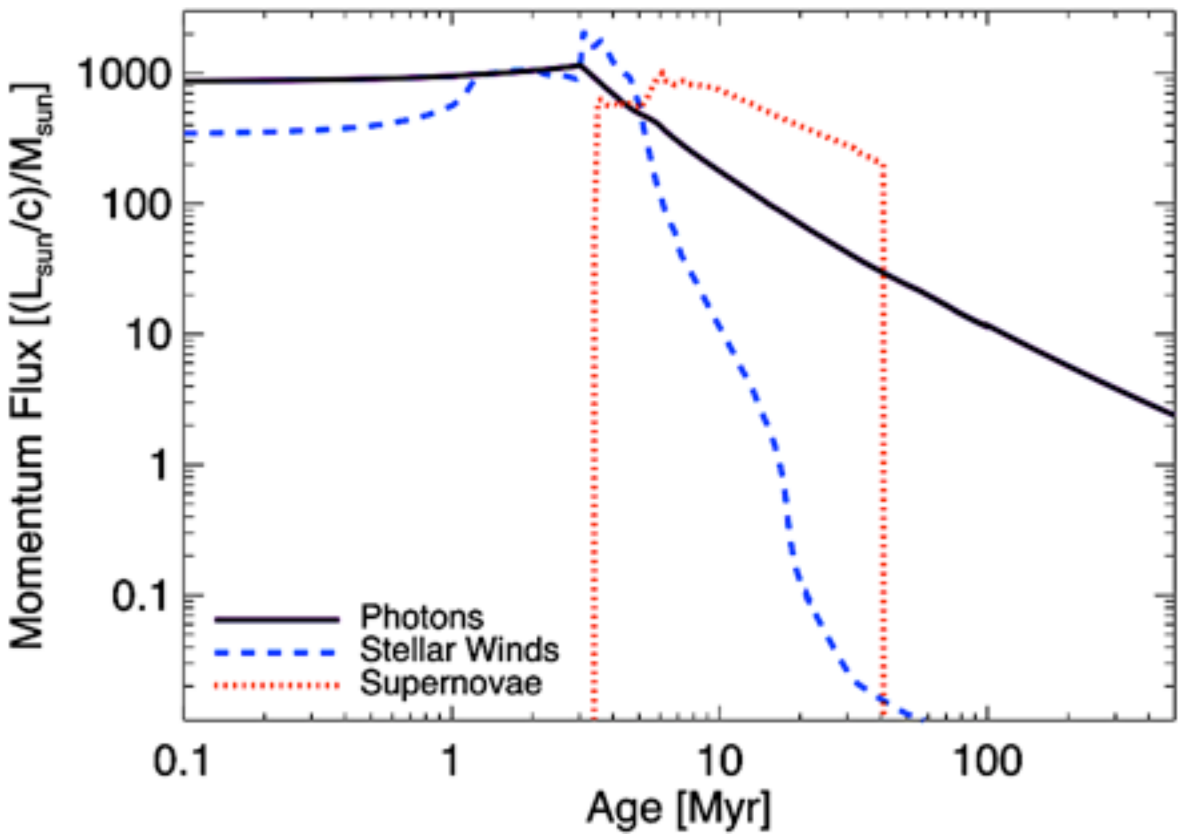
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

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



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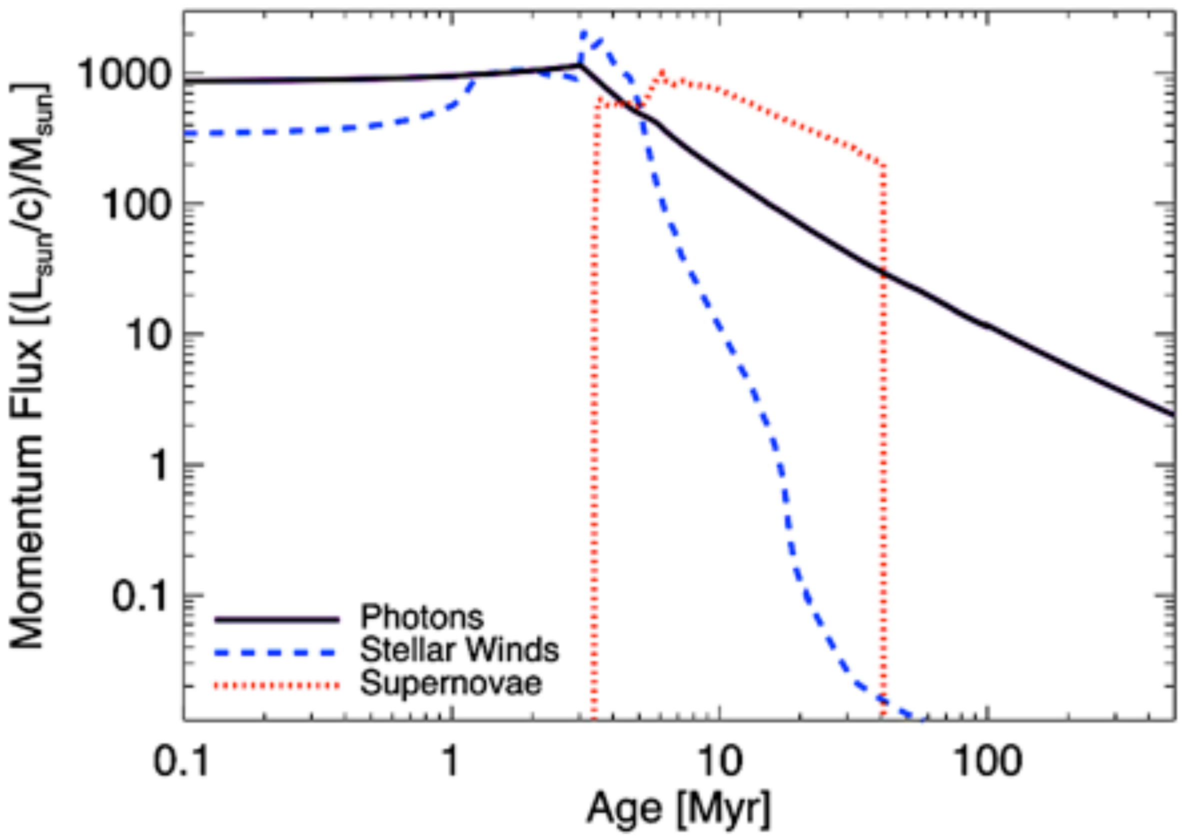
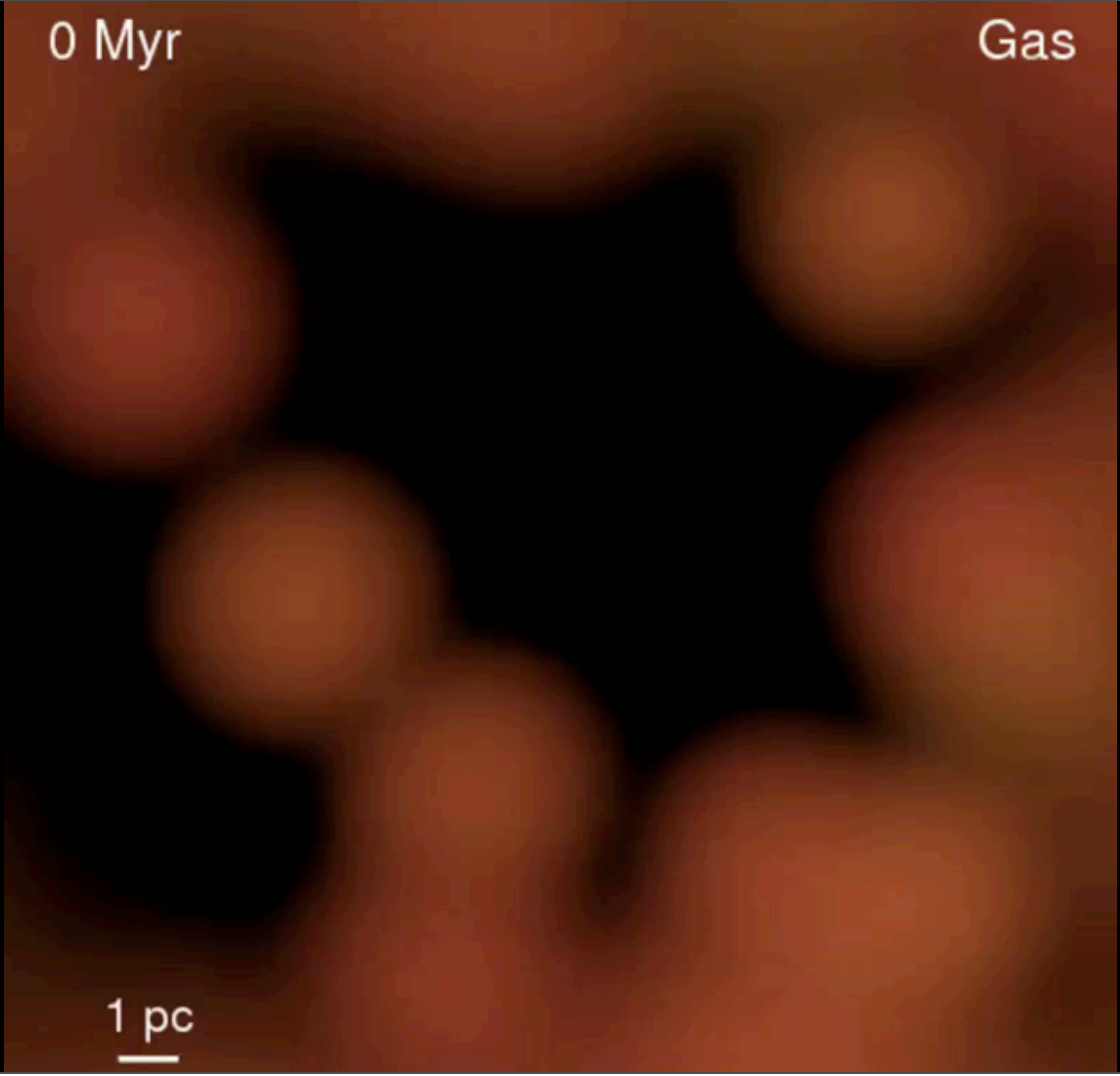
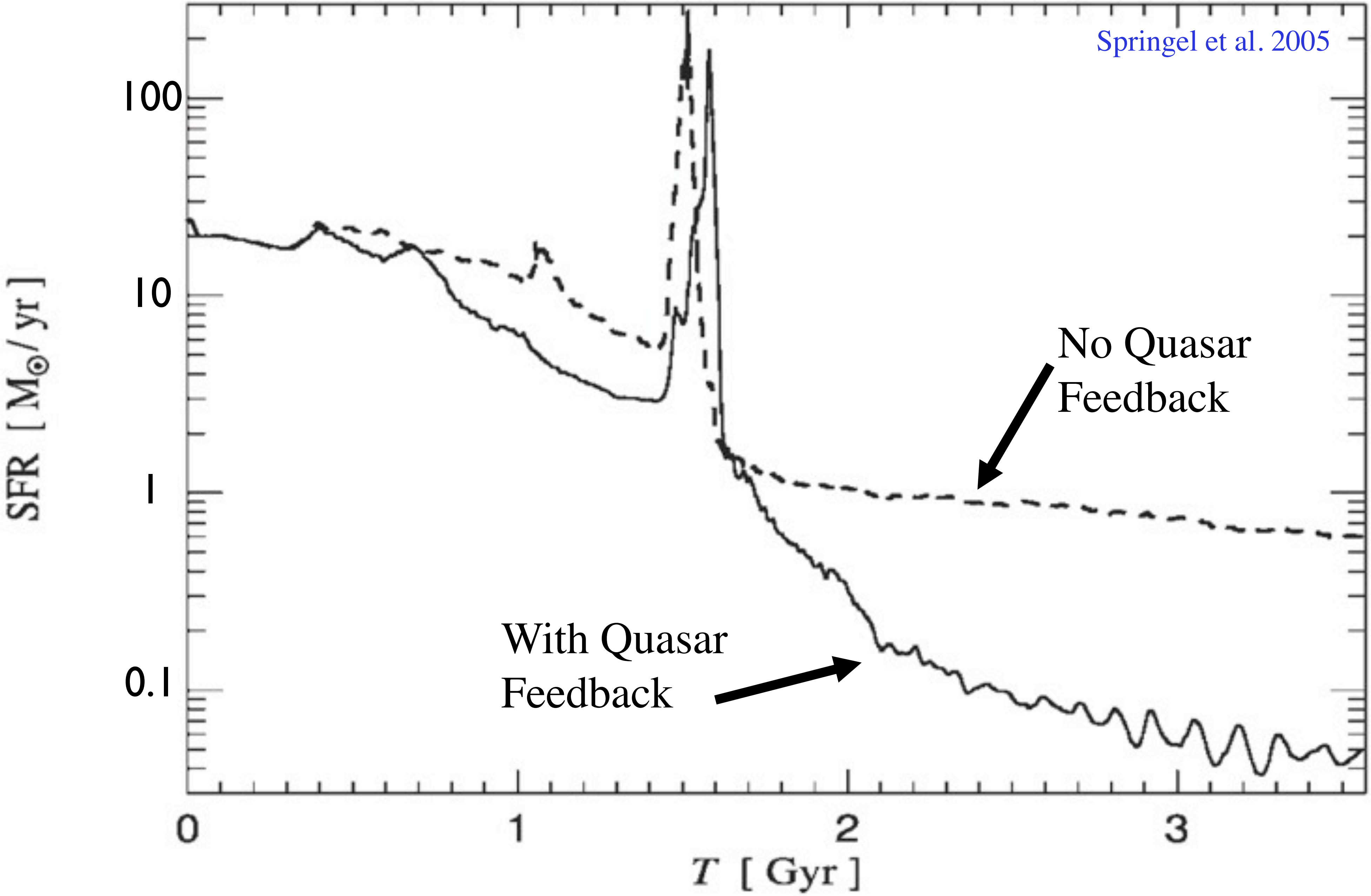
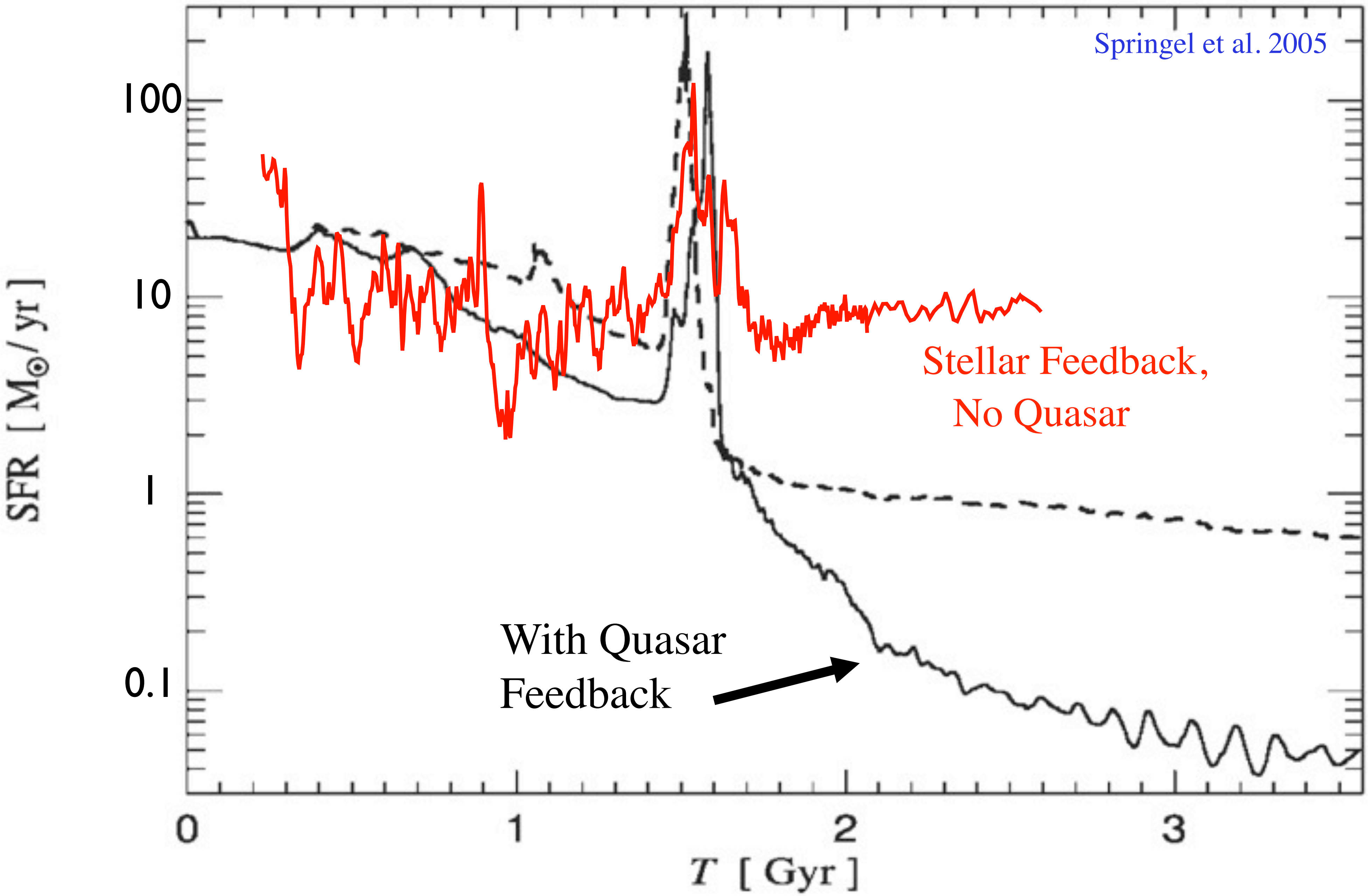



0 Myr
Gas
1 pc

Do we still need 'Quasar Mode' Feedback?



Do we still need 'Quasar Mode' Feedback?



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

Jets

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

Winds

BAL-QSO winds

equatorial

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

Photons

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

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

Compton Heating (only low density gas)

Outstanding Problem: Which Dominates?

Physics very difft for ISM & IGM

BAL Winds as a Quasar Feedback Mechanism

- L/L_{Edd} >~ 0.1
- Covering factor ~10-30%
- ~12 (16) objects now,
  10/12 confirmed:

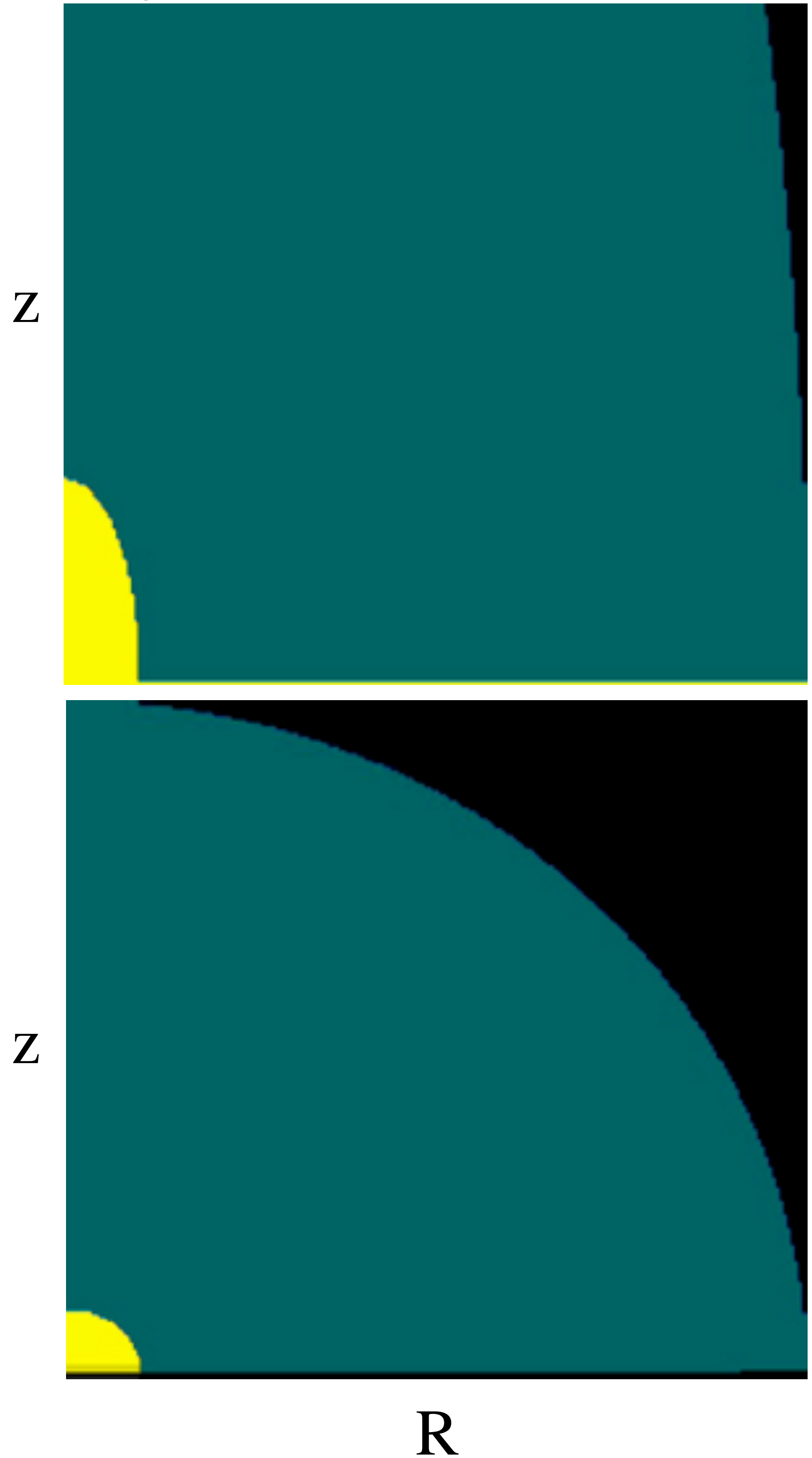
$$\dot{M}_{\rm wind}\, v \gtrsim L_{\rm AGN}/c$$
$$L_{\rm wind} \gtrsim 0.01\, L_{\rm AGN}$$

- Launched at < pc

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

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

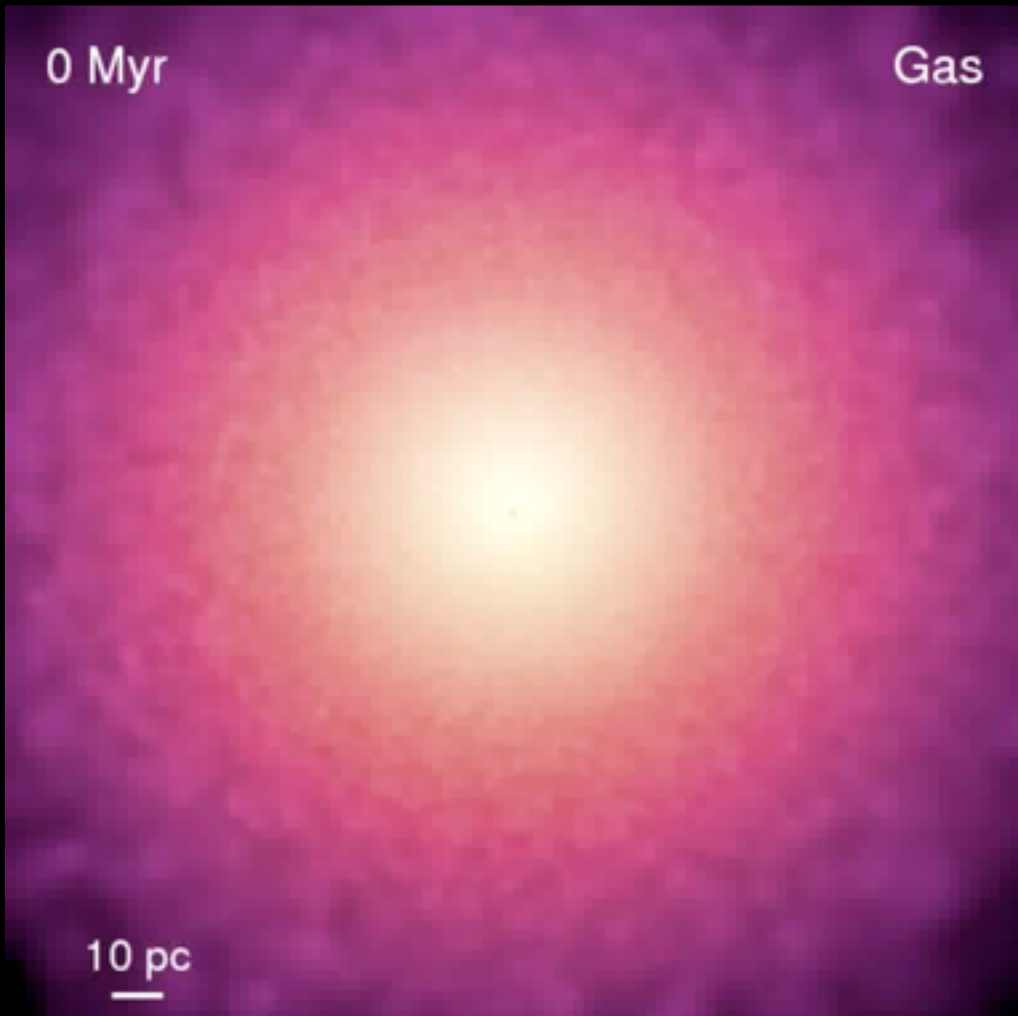
Proga et al. 00-07; Kurosawa et al. 08-11



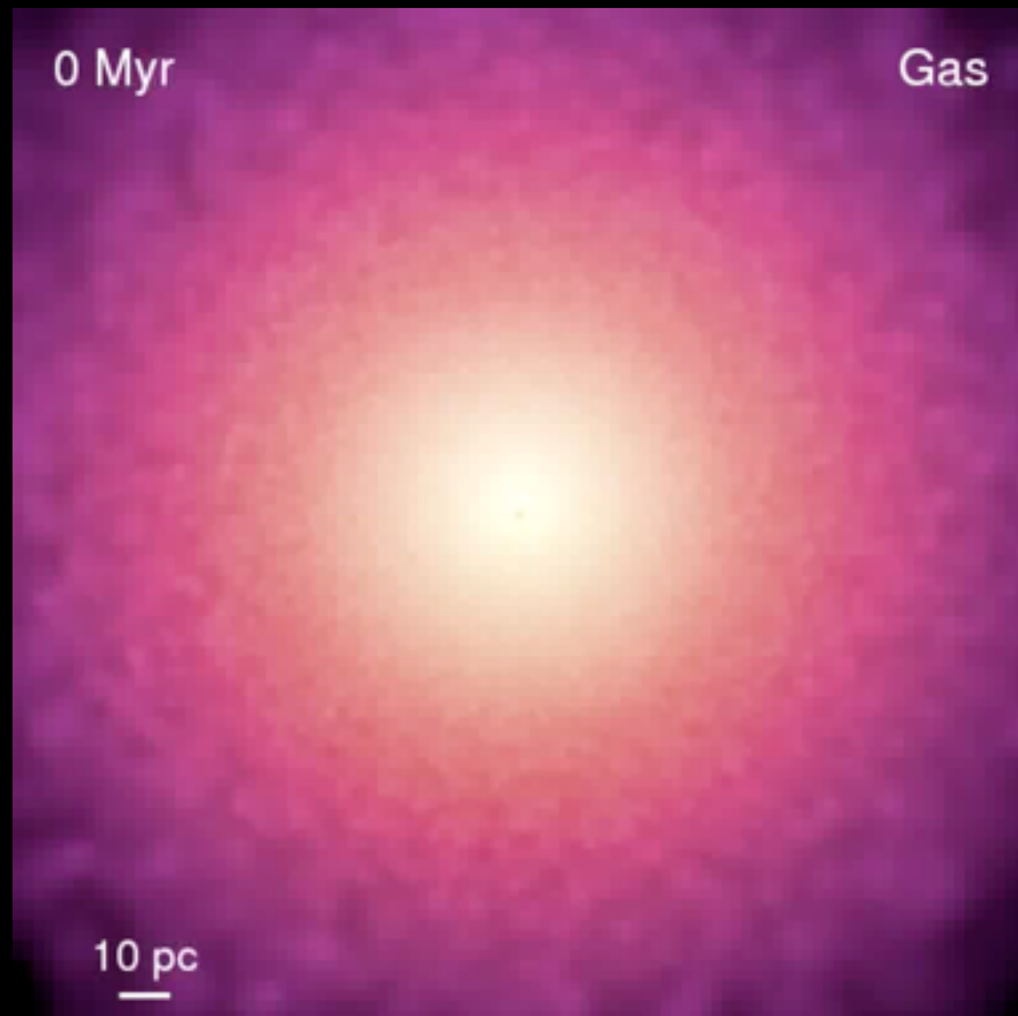
PFH in prep
Wada et al.

BAL Winds on ~1pc - 1kpc scales:

No BAL Winds



With BAL Winds

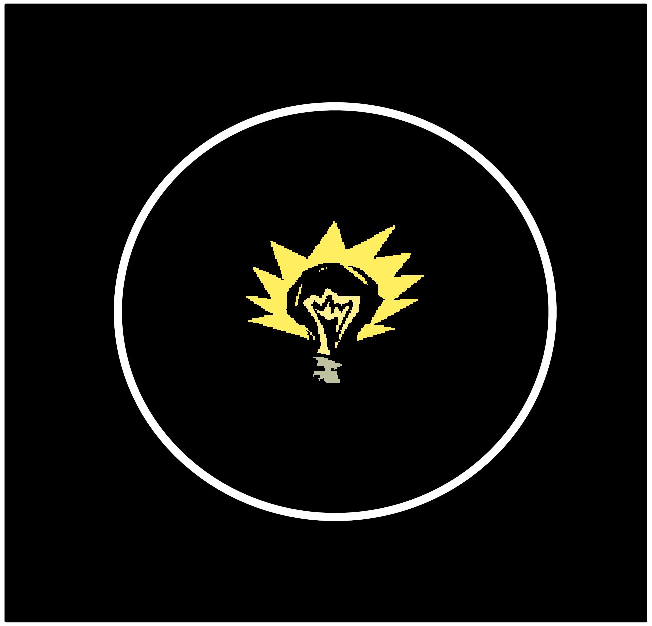


$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

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

BAL Winds as a Quasar Feedback Mechanism

SILK & REES 1998, MURRAY ET AL. 2005, MANY MORE



Momentum Flux:

$$\frac{L}{c} \gtrsim F_{\rm grav} \sim \frac{G\,M\,M_g}{r^2}$$

Shut Down Accretion When:

$$L_{\rm max} \propto M_{\rm BH} \propto \sigma^4$$

if momentum flux ~ few L/c, predicts *normalization* of M-s

$$M_{\rm BH} \sim 10^8\,M_\odot \left(\frac{\sigma}{200\,{\rm km/s}}\right)^4$$

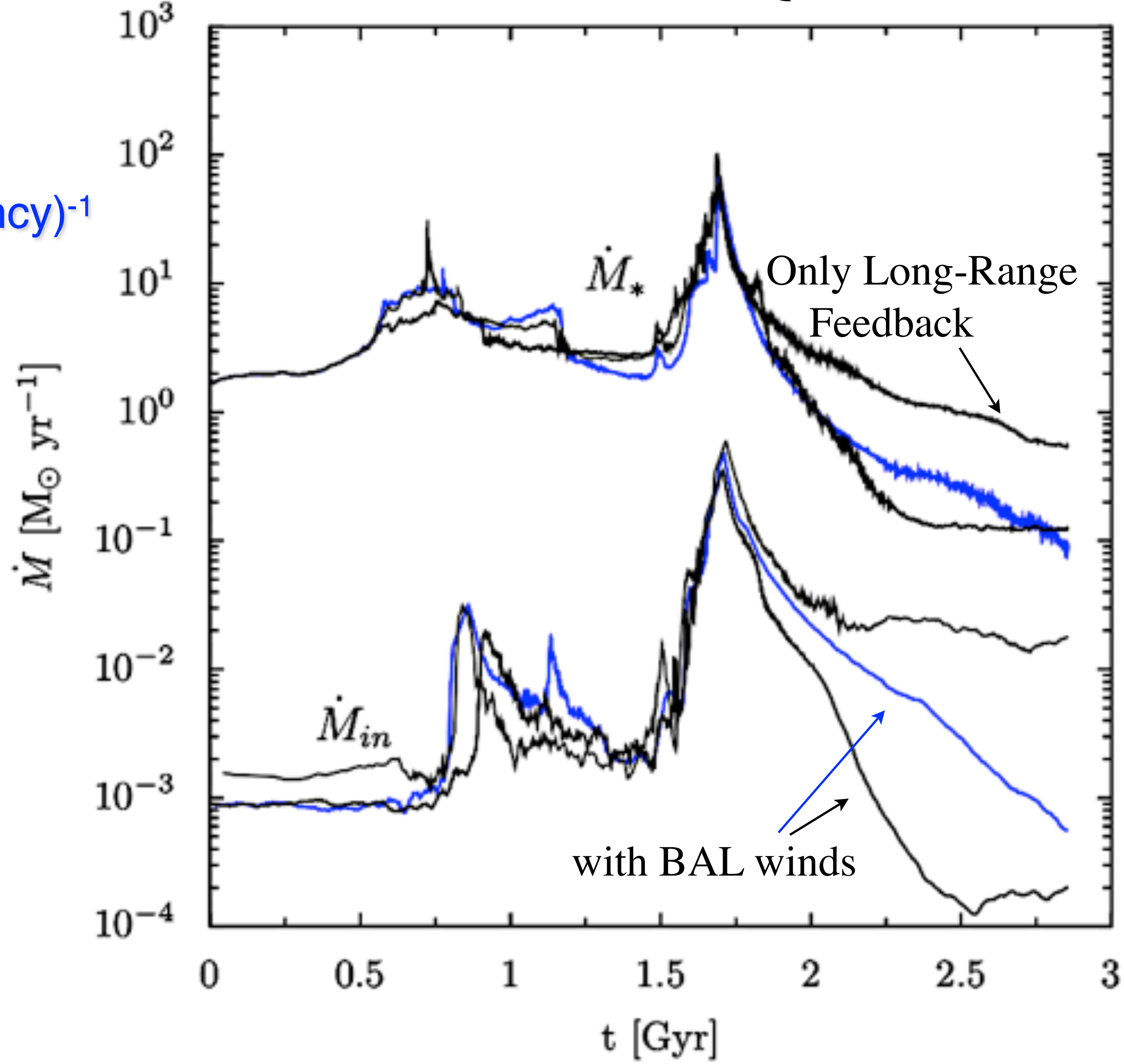
BAL Winds on Galactic Scales

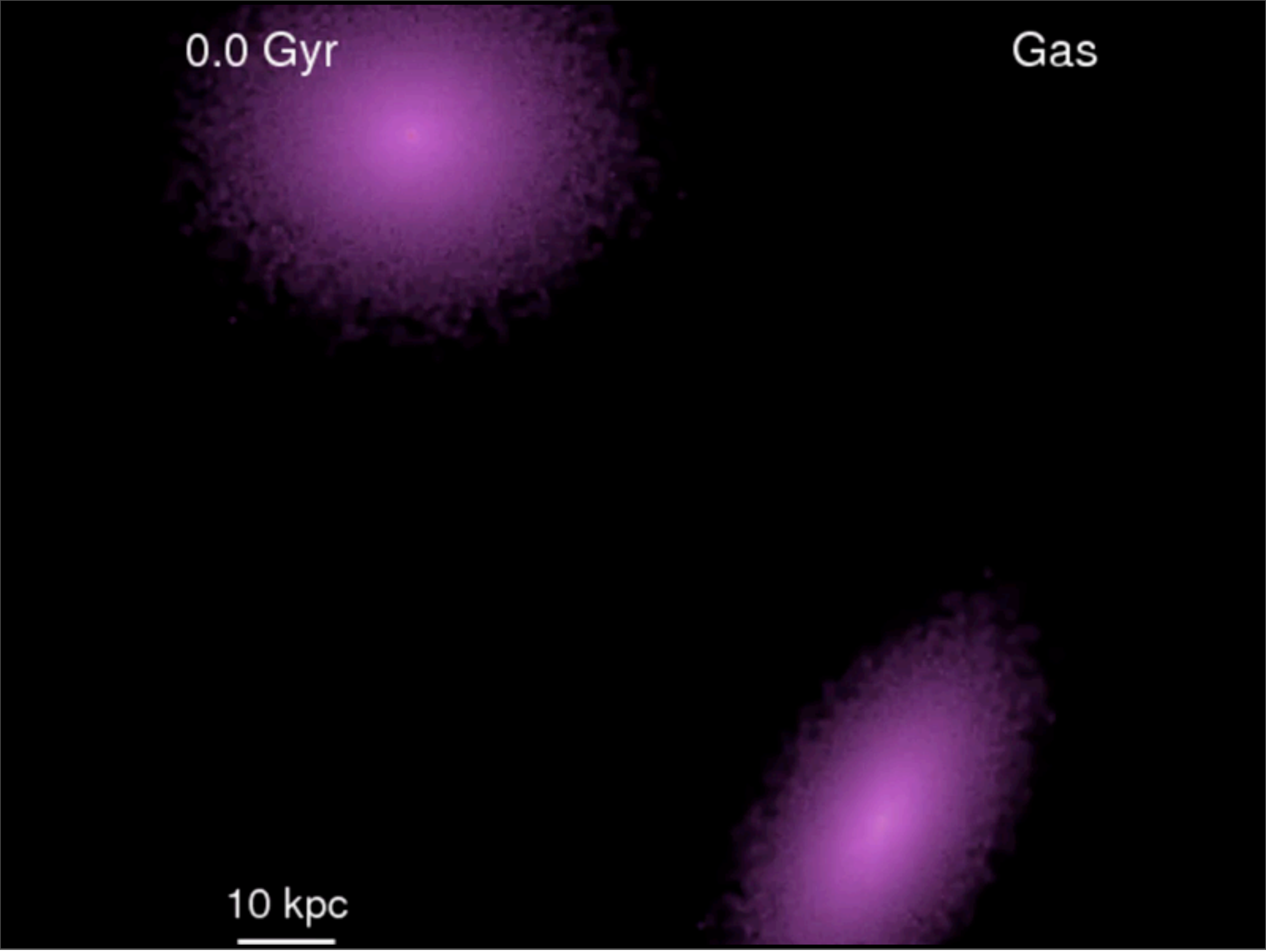
CAN IT REALLY AFFECT STAR FORMATION?

Novak et al. 2010,11

Debuhr, Ma, Quataert 2010,11

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




0.0 Gyr
Gas
10 kpc

Summary

- Quasar feedback is here to stay
  - BAL Winds + Jets + Radiation Pressure on Dust + ??? = ???
- Strong arguments that this regulates BH Mass: Sets M_{BH}-σ
  - Less clear how it impacts the galaxy
  - BUT, depletion times ~1 Myr are hard to ignore!
- Inflows: "Stuff within Stuff": Cascade of instabilities with diverse morphology
  - Nuclear starbursts & powering of SMGs & ULIRGs
  - Determines structure & kinematics of elliptical galaxies
- Outflows: Towards a *Predictive* Model
  - BAL Winds:
    - *CAN* explain M_{BH}-σ
    - *WILL* suppress SFRs
    - *SHOULD* heat & clear IGM & Proto-Group Environments
  - (Quasar) Jets:
    - *WHEN PRESENT*, probably even stronger effects
    - *Probably* jet-driven winds, not "direct" jet heating