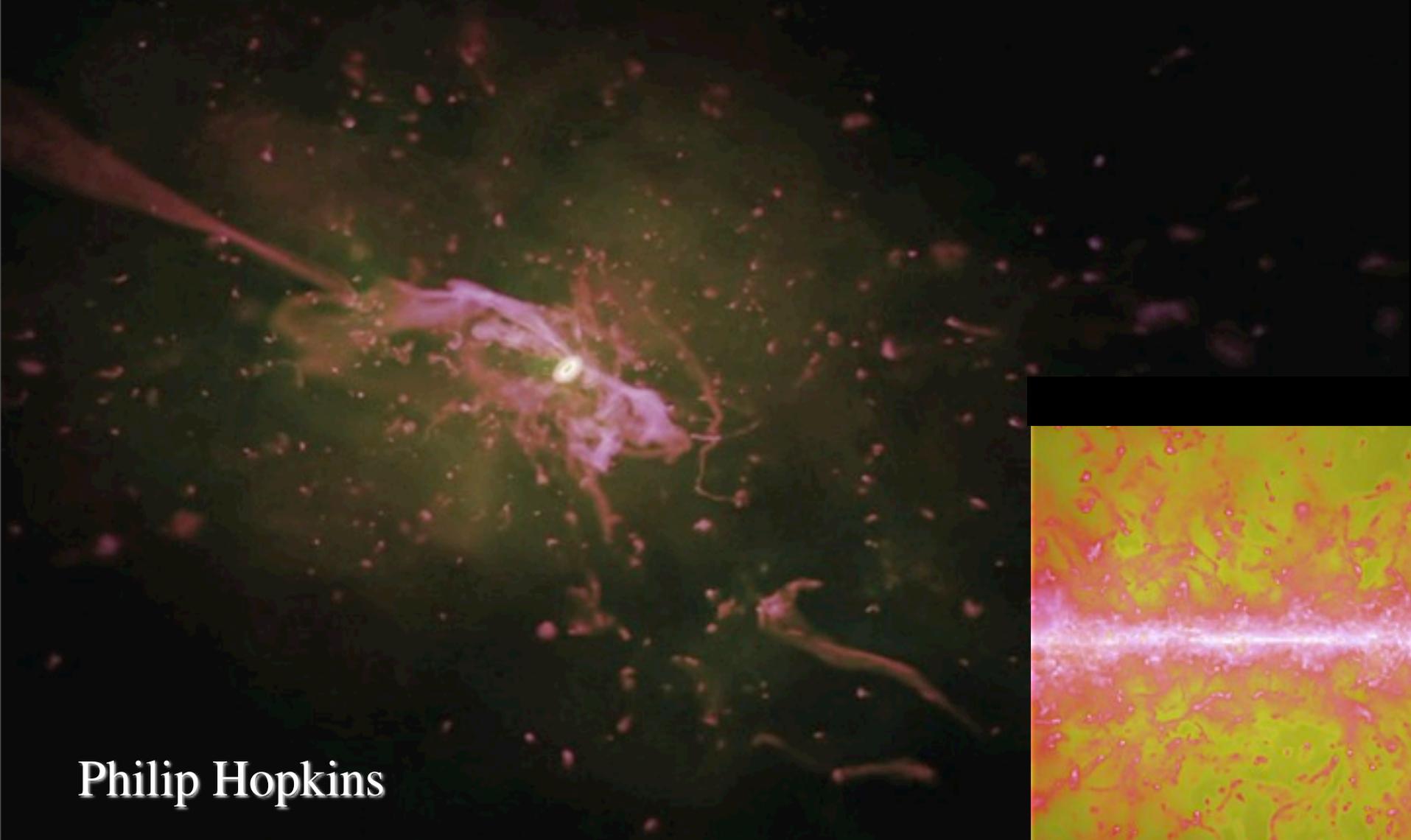


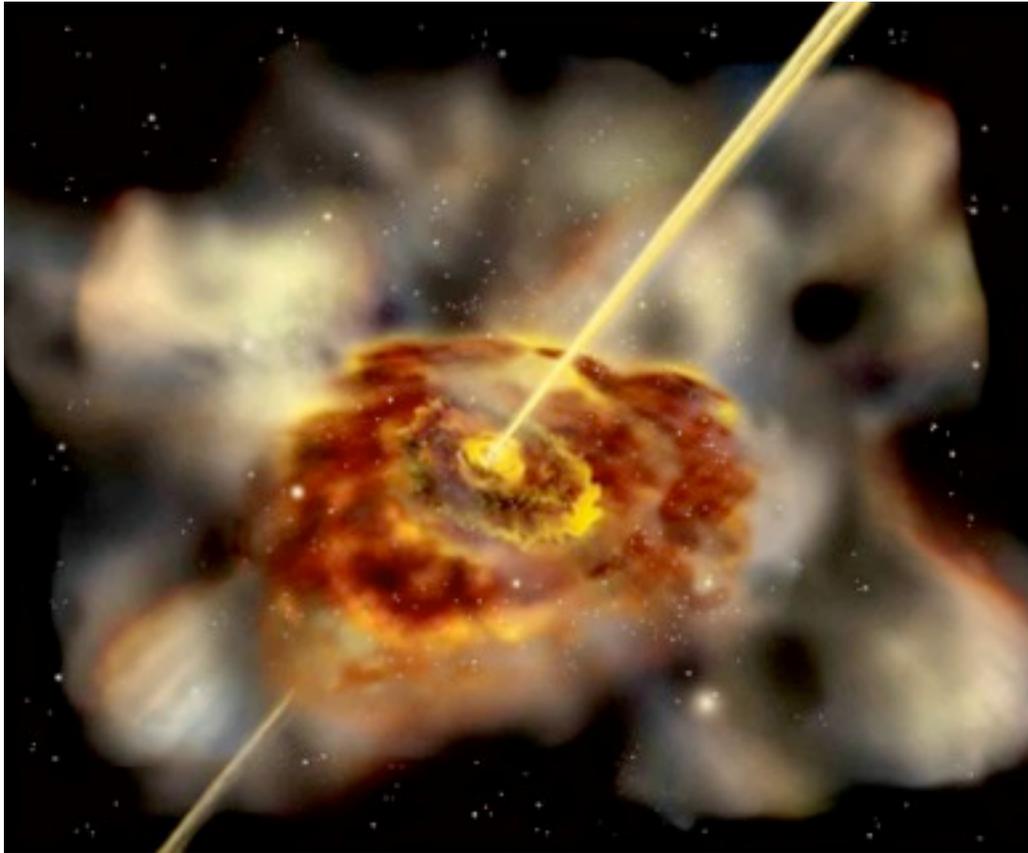
“Quasar” Feedback in Galaxies



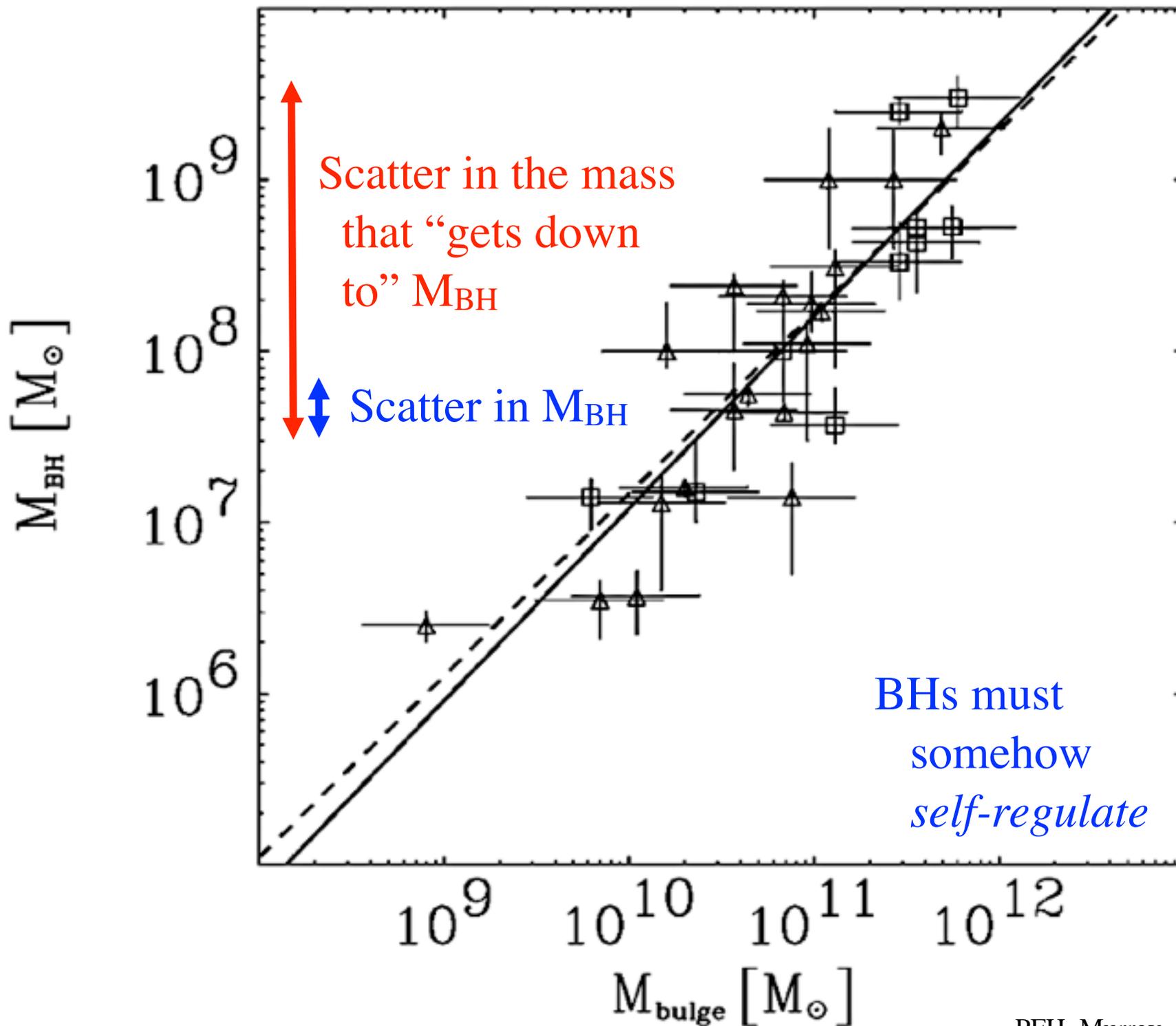
Philip Hopkins

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

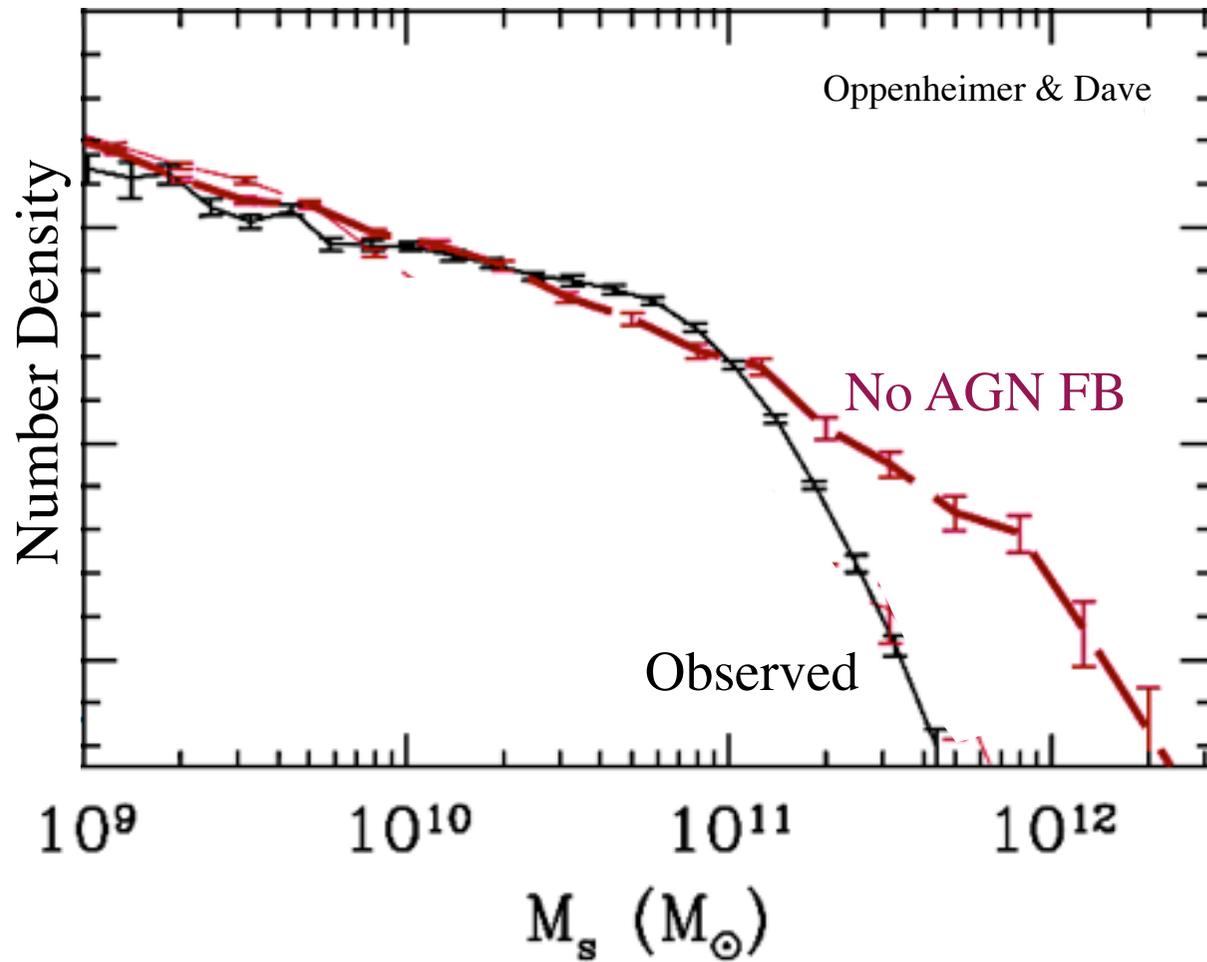


- Mass accreted in ~couple bright quasar phase(s)
(Soltan, Salucci+, Tremaine+, Yu & Lu, PFH, Shankar, et al.)



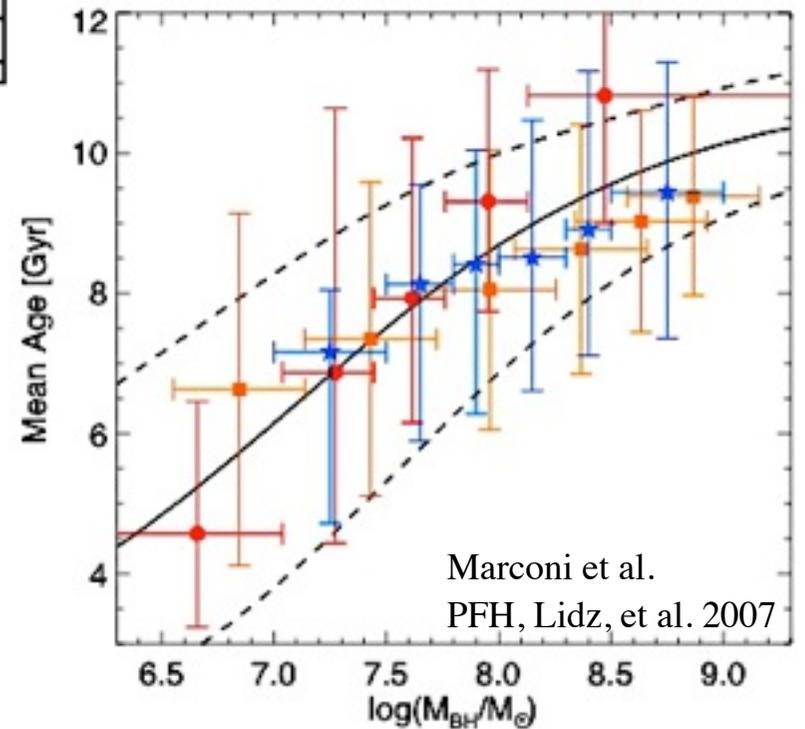
Gebhardt et al.
 Ferrarese et al.
 Haring & Rix
 Tremaine
 Marconi & Hunt

What can AGN Feedback Do For You?



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

Spheroid & BH Formation Times:

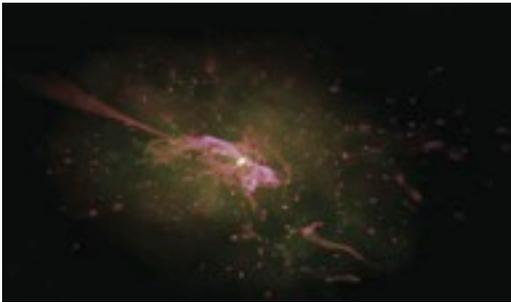


“Transition”

vs.

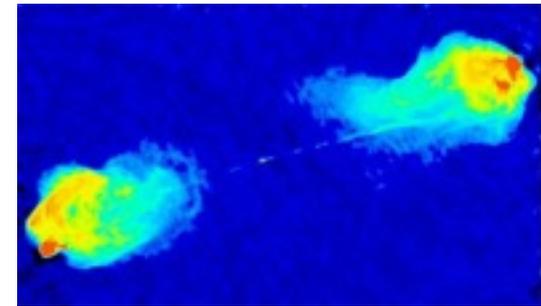
“Maintenance”

- “**Quasar**” mode (high \dot{m})
- Move mass from Blue to Red?
- Rapid ($\sim 10^7$ yr)
- Small(er) scales (\sim pc-kpc)
- Morphological Transformation
- Gas-rich/Dissipational Mergers?



- Regulates *Black Hole* Mass

- “**Radio**” mode (low \dot{m})
- Keep it Red
- Long-lived (\sim Hubble time)
- Large (\sim halo) scales
- Subtle morphological change
- Hot Halos & Dry Mergers

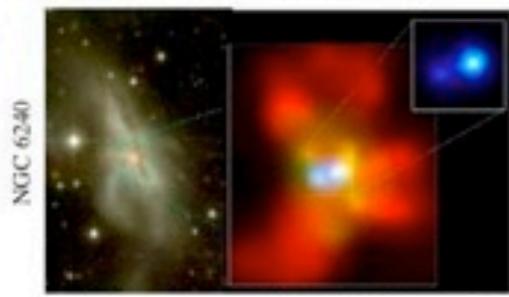


- Regulates *Galaxy* Mass

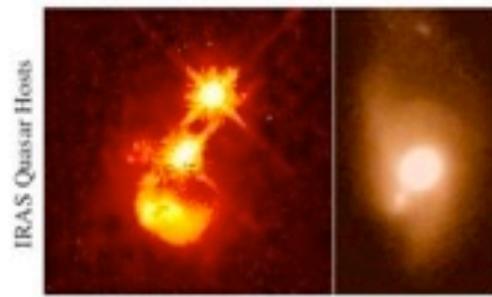
(c) Interaction/"Merger"



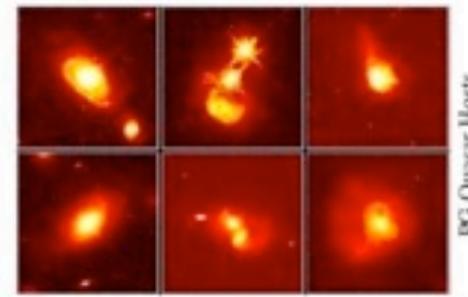
(d) Coalescence/(U)LIRG



(e) "Blowout"



(f) Quasar



(b) "Small Group"



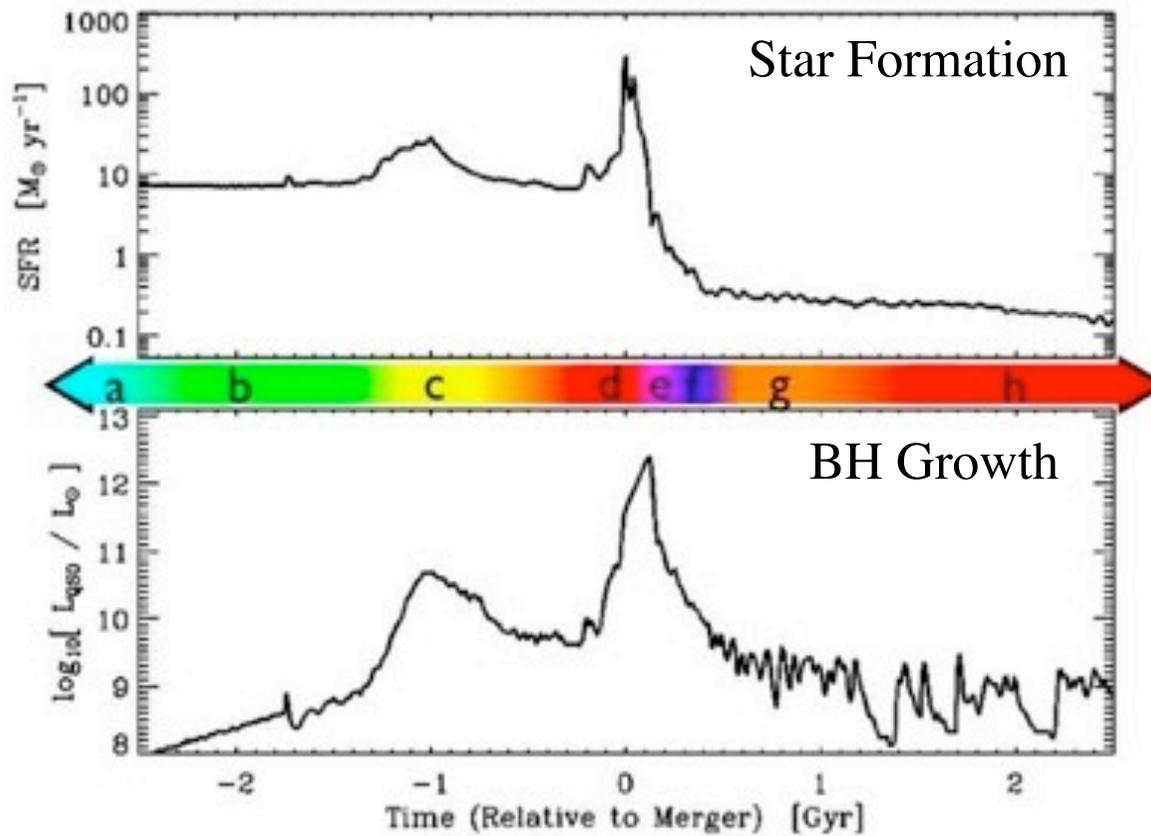
(g) Decay/K+A



(a) Isolated Disk



(h) "Dead" Elliptical



Sanders, Scoville, many subsequent

What Can Quasar Feedback Do?

Feedback Energy:

SILK & REES '98

$$L = \epsilon_r \dot{M}_{\text{BH}} c^2 \quad (\epsilon_r \sim 0.1)$$

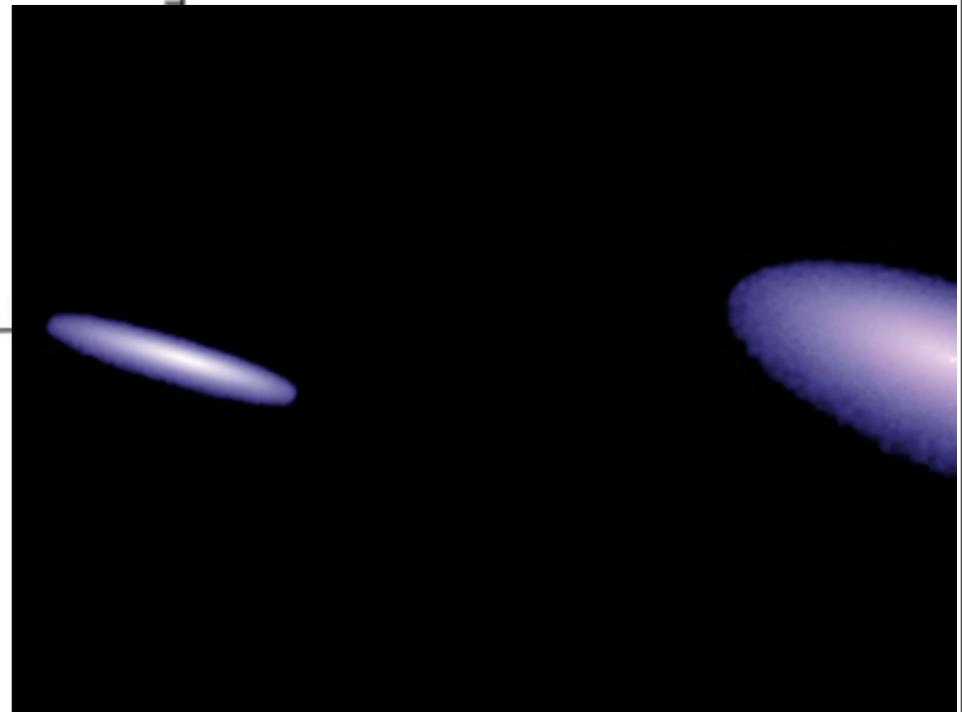
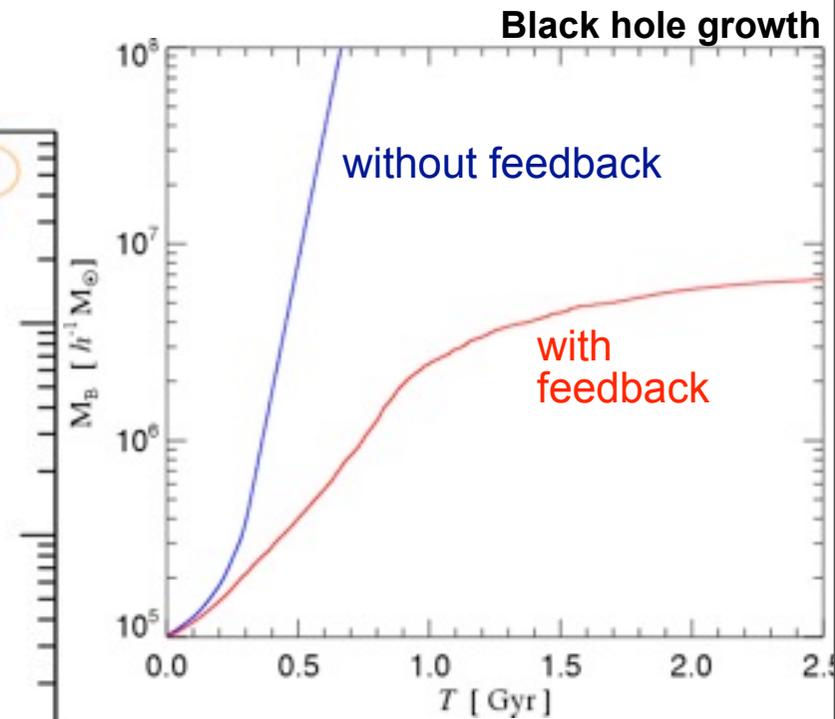
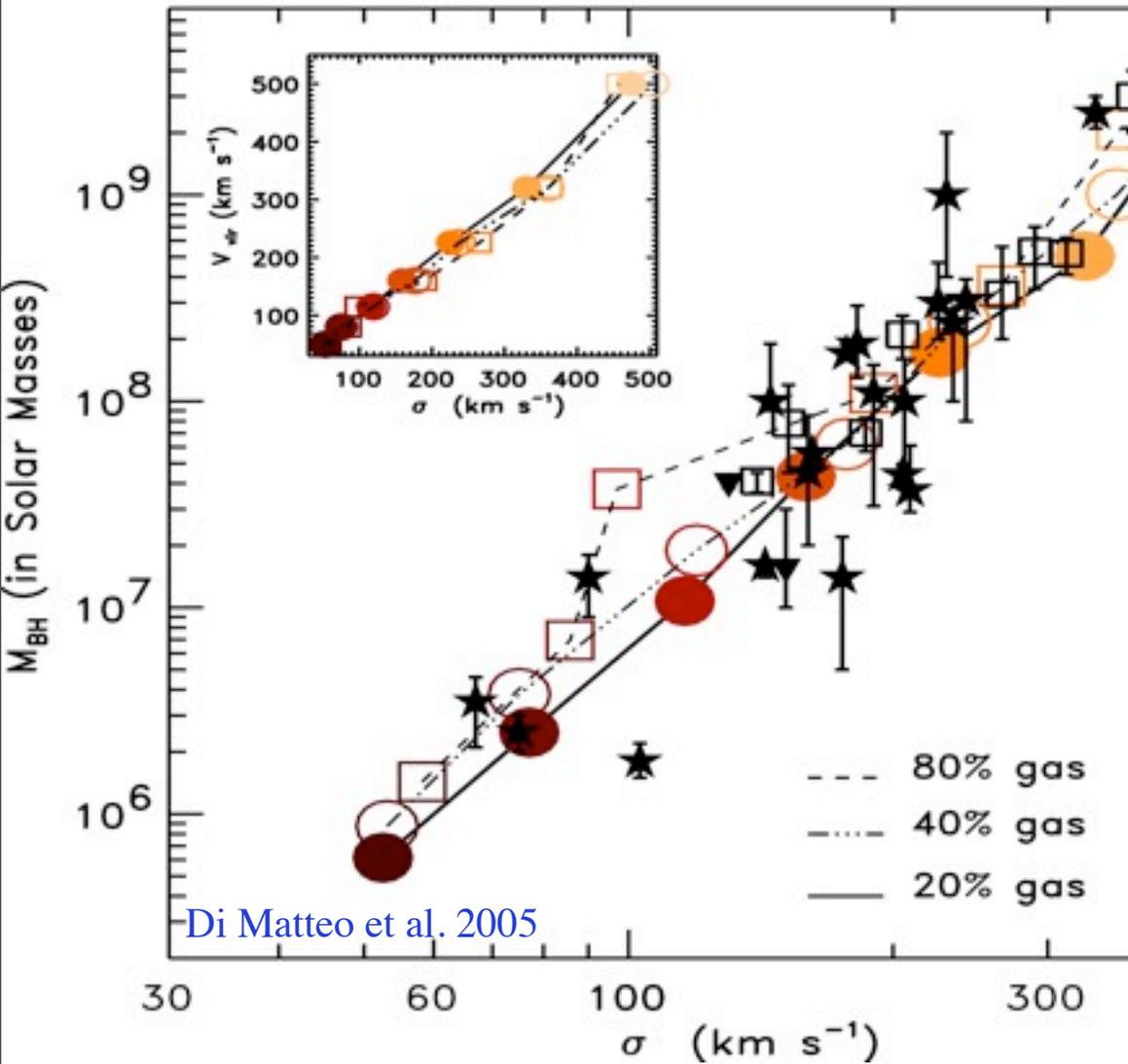
$$\rightarrow E_{\text{rad}} \sim 0.1 M_{\text{BH}} c^2 \sim 10^{61} \text{ erg}$$

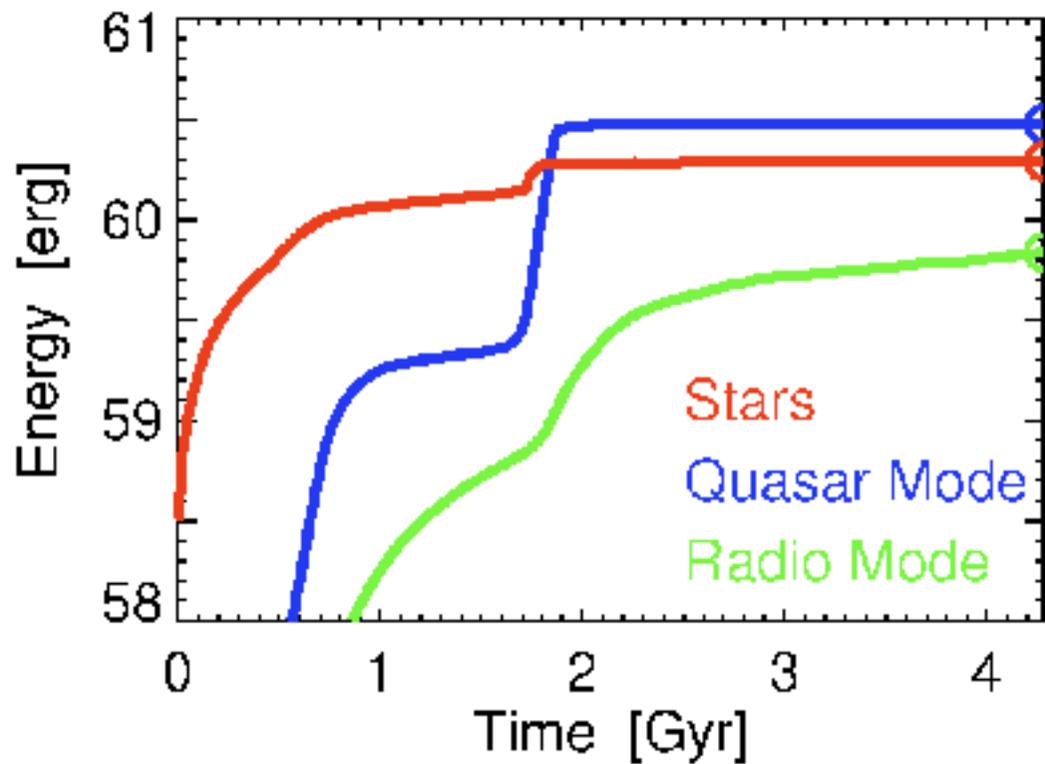
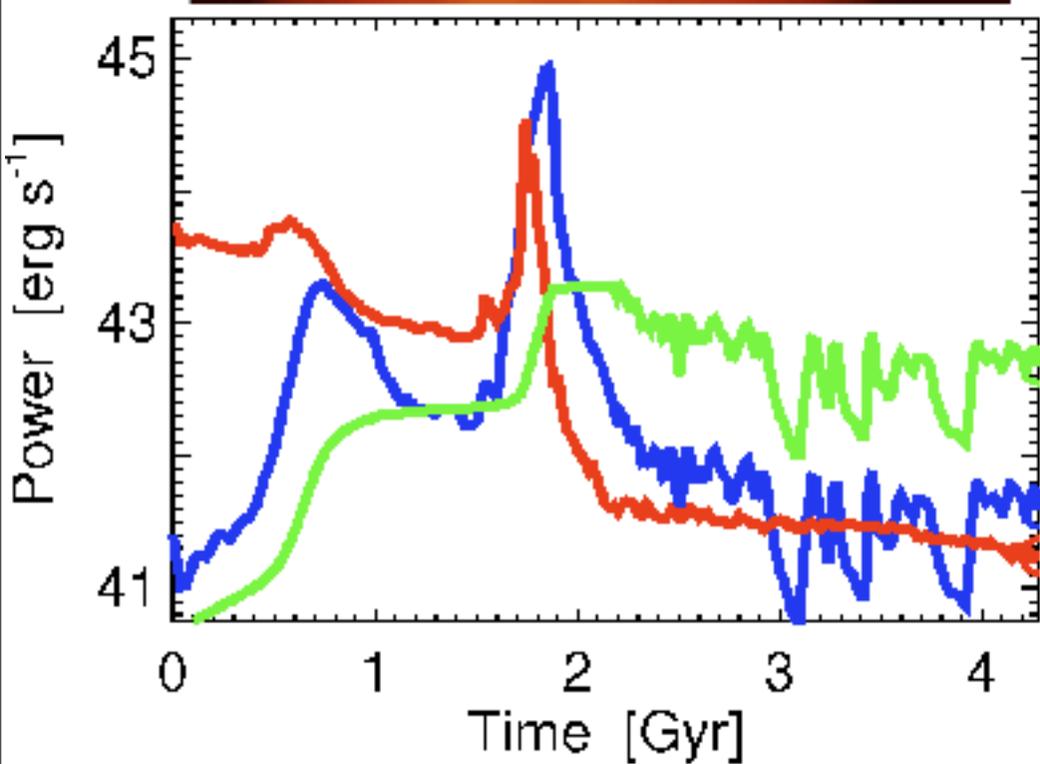
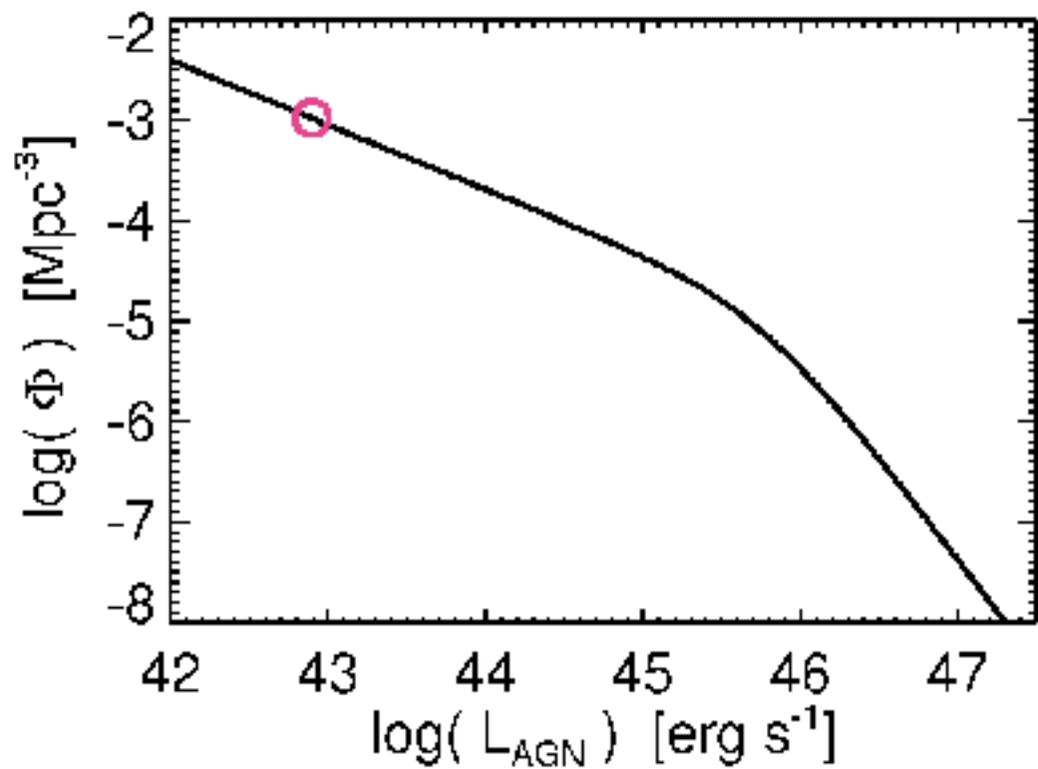
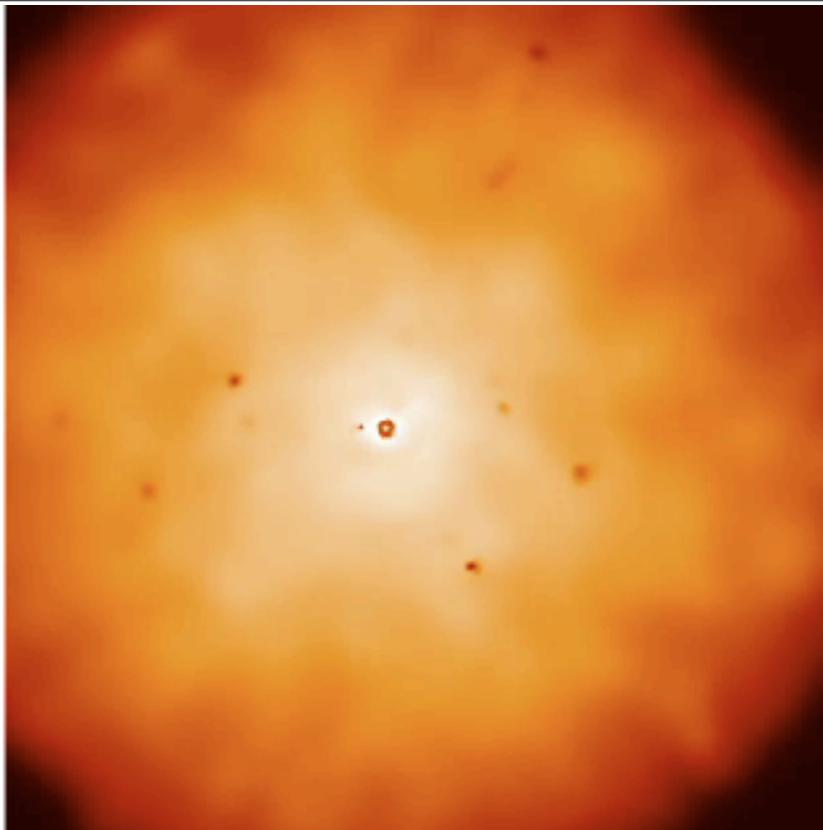
$(M_{\text{BH}} \sim 10^8 M_{\odot})$

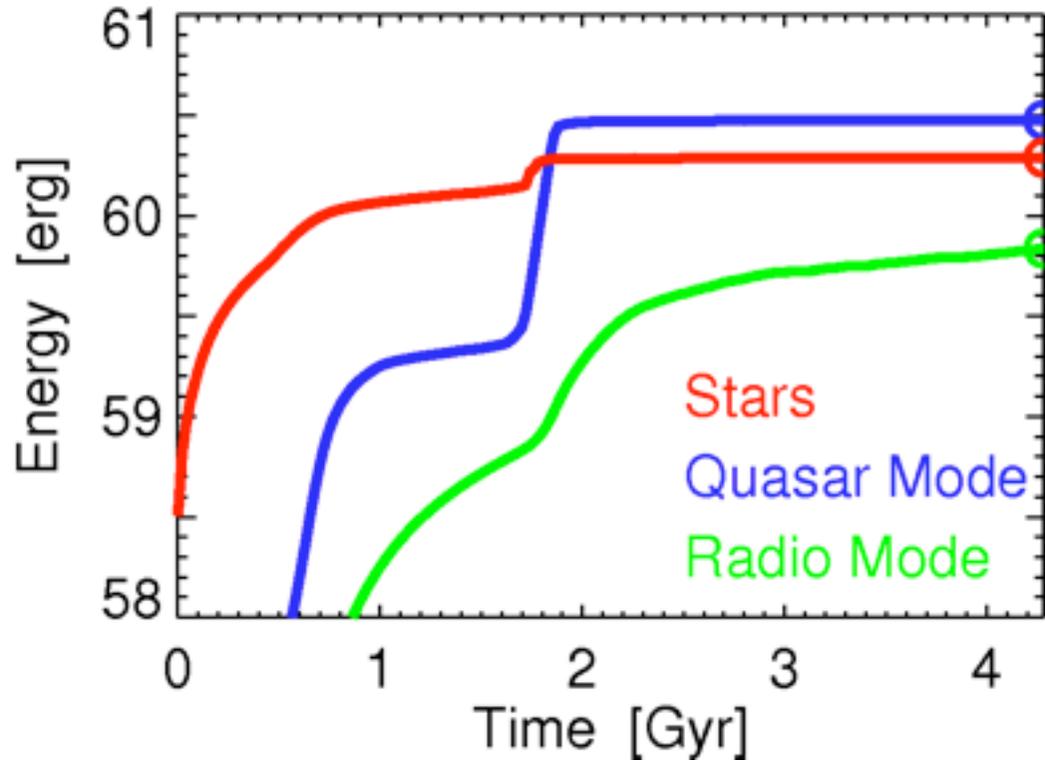
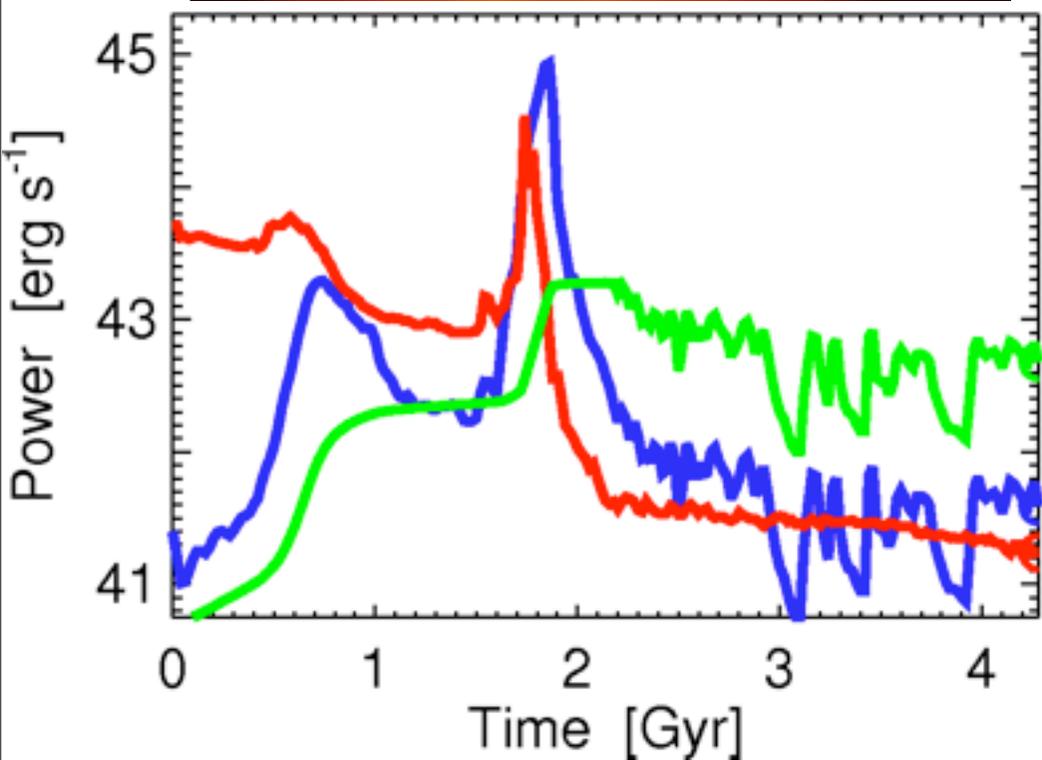
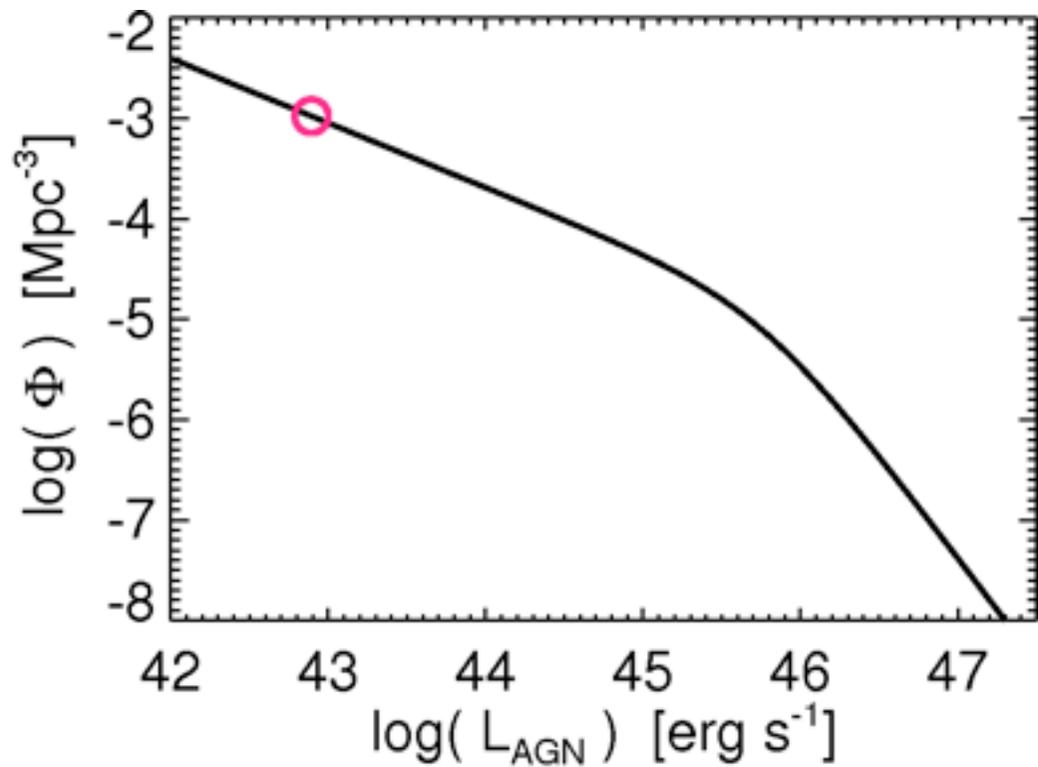
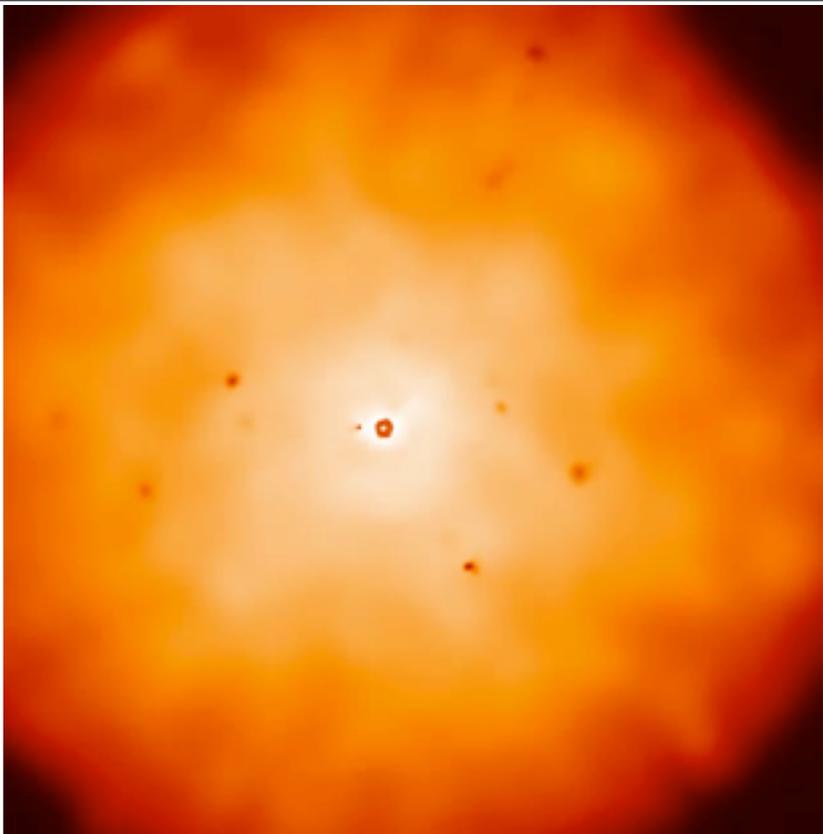
$$E_{\text{gal}} \sim M_{\text{gal}} \sigma^2 \sim (10^{11} M_{\odot}) (200 \text{ km/s})^2 \sim 10^{59} \text{ erg}$$

M-sigma Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



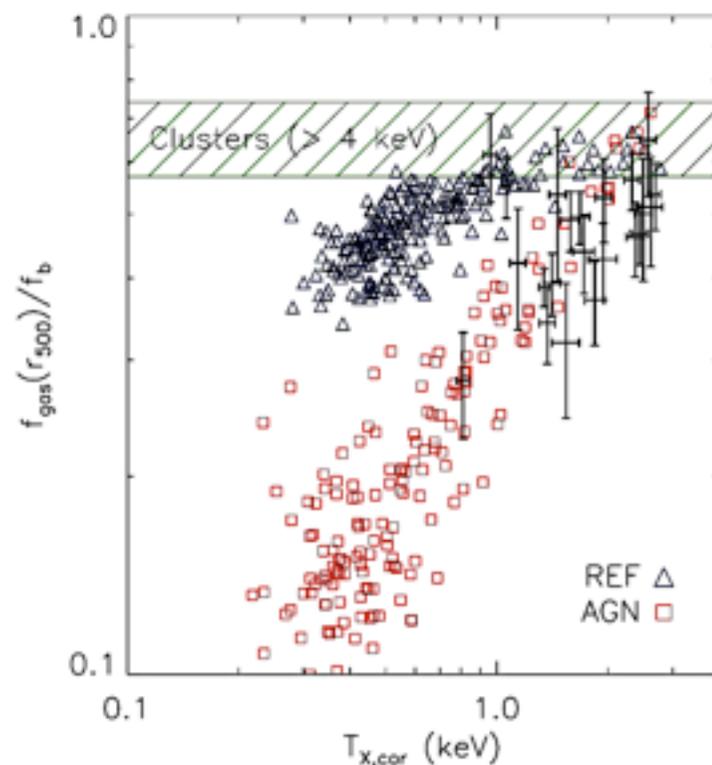
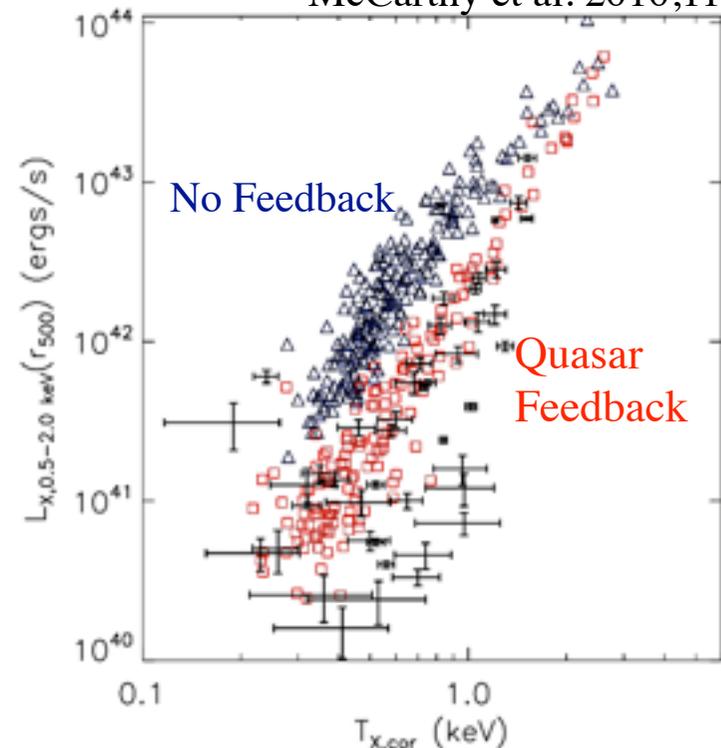
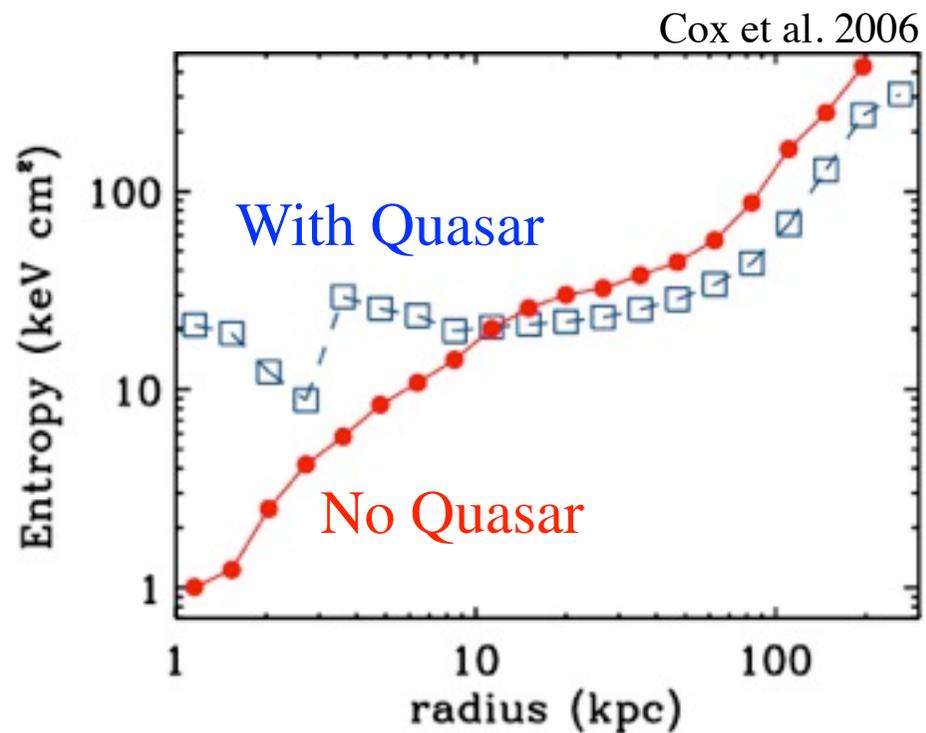




Quasar Outflows: Heating Halo Gas

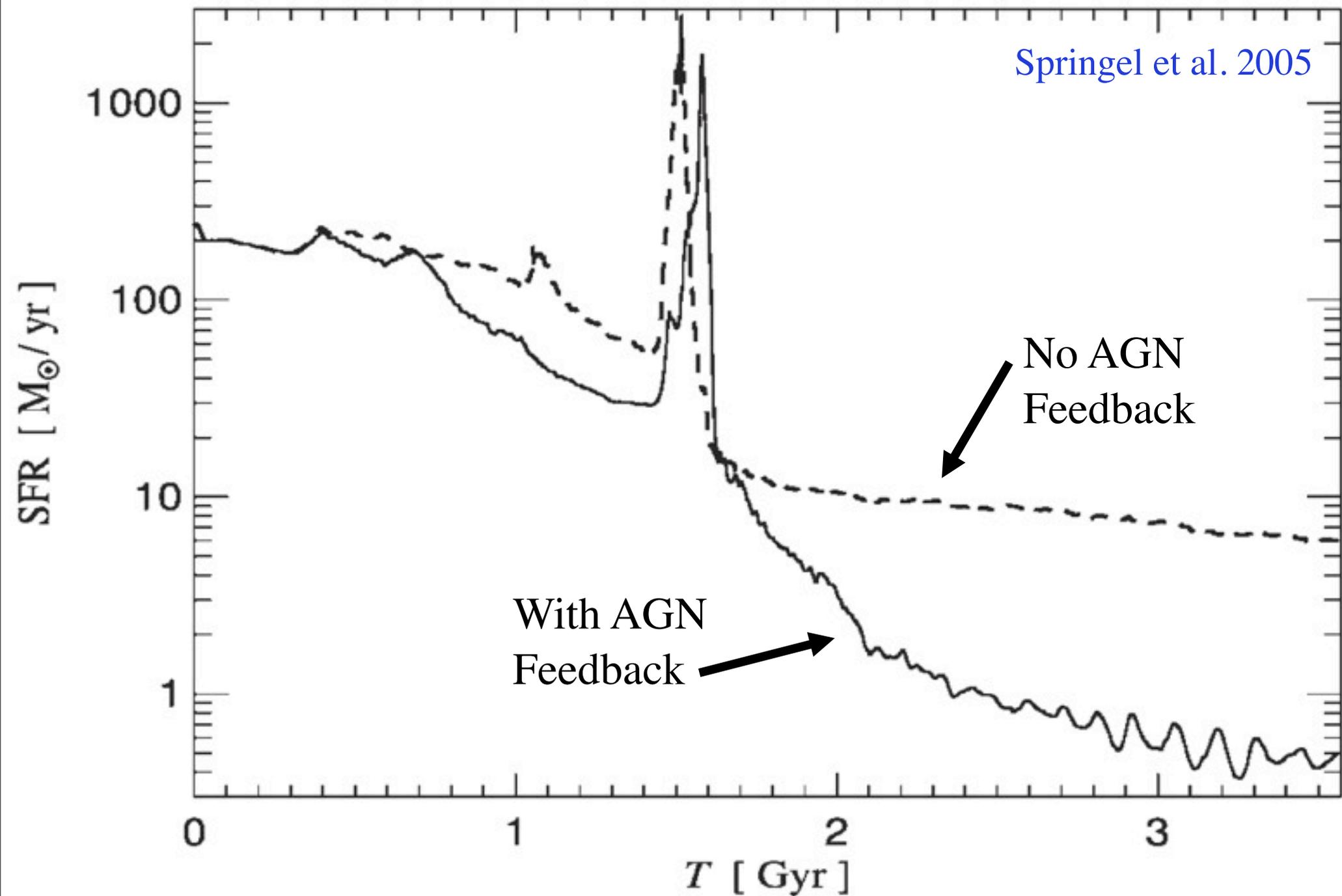
SHUT DOWN COOLING AND/OR "SET UP" RADIO MODE

McCarthy et al. 2010,11



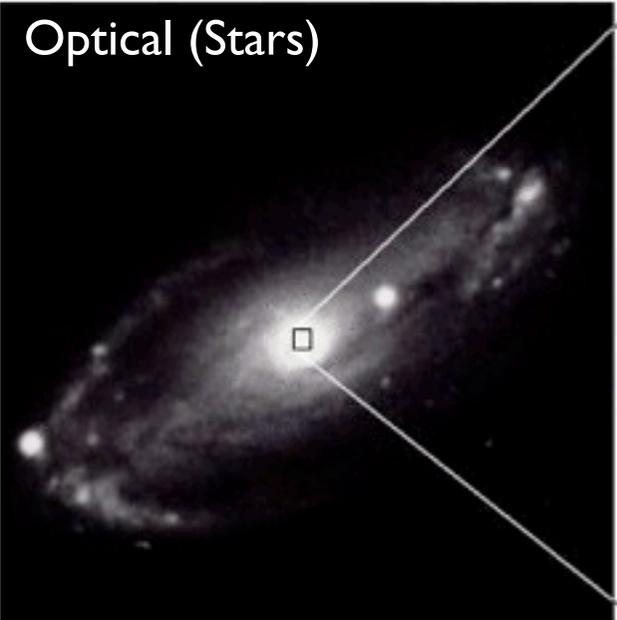
Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?

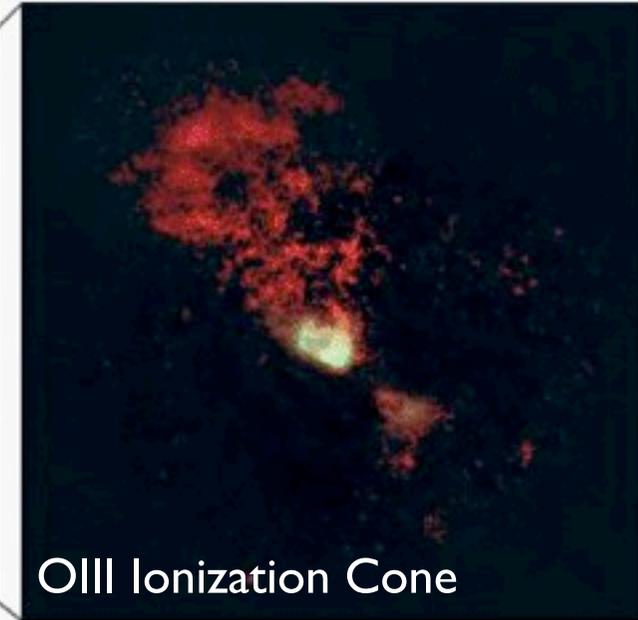


But Does Quasar Mode Feedback Exist?

Optical (Stars)

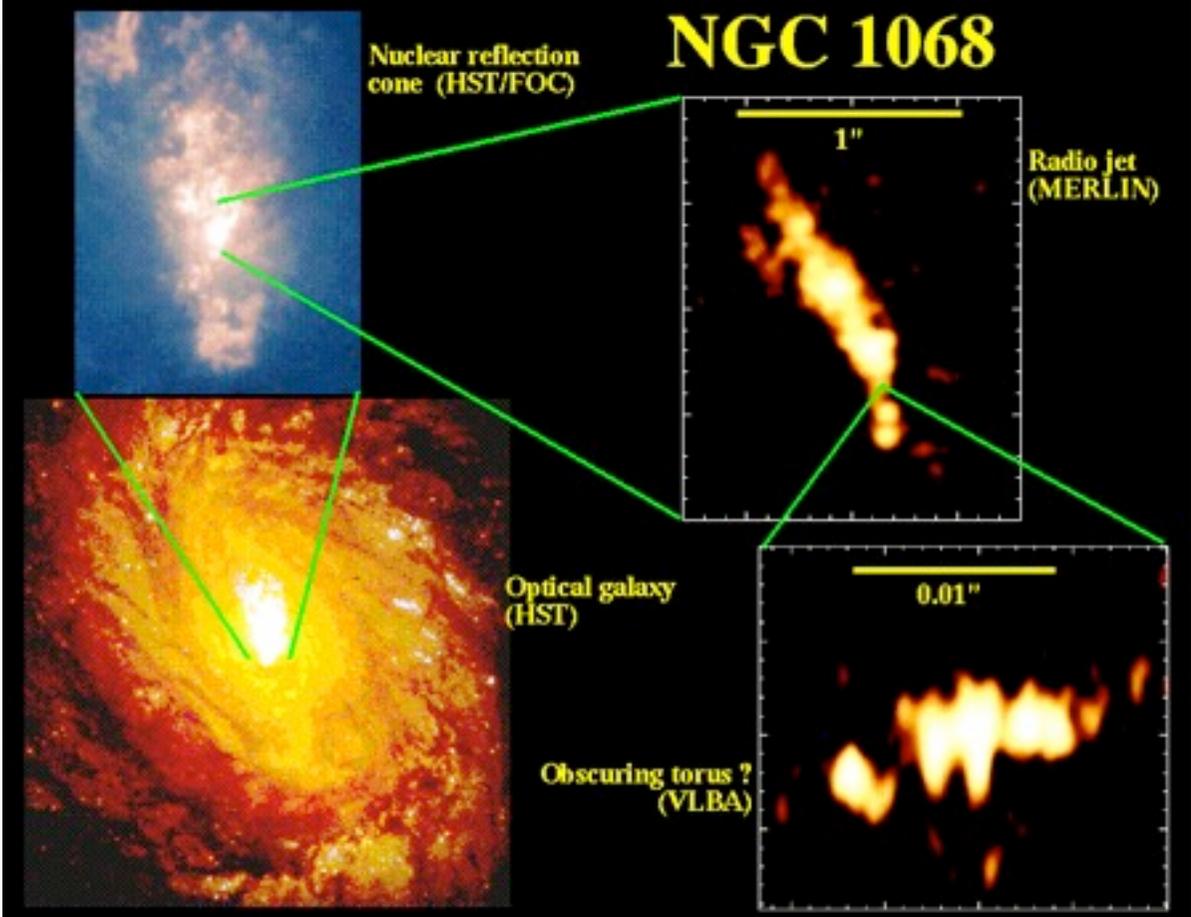


OIII Ionization Cone



NGC 5728

NGC 1068



Nuclear reflection cone (HST/FOC)

Radio jet (MERLIN)

Optical galaxy (HST)

Obscuring torus? (VLBA)

1''

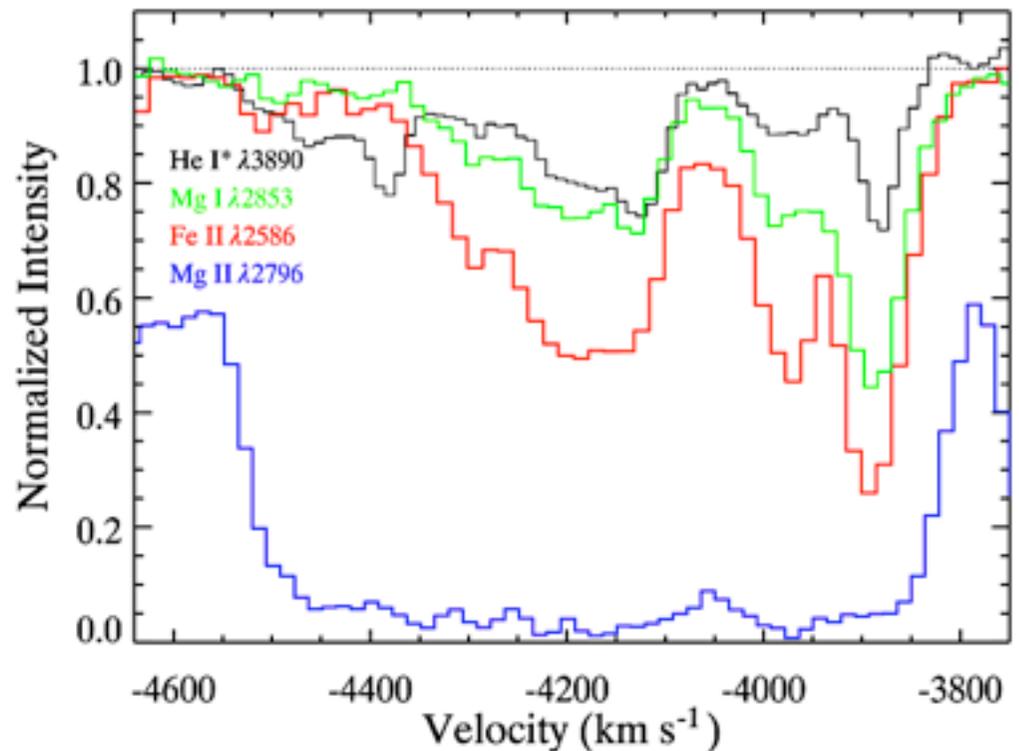
0.01''

Broad Absorption Line Quasars

- Preferentially in high-L quasars
- Covering factor $\sim 20\%$

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

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



$$R_{\text{wind}} \sim 1 - 20 \text{ kpc}$$

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

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

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, $v \sim 100\text{-}400$ km/s)

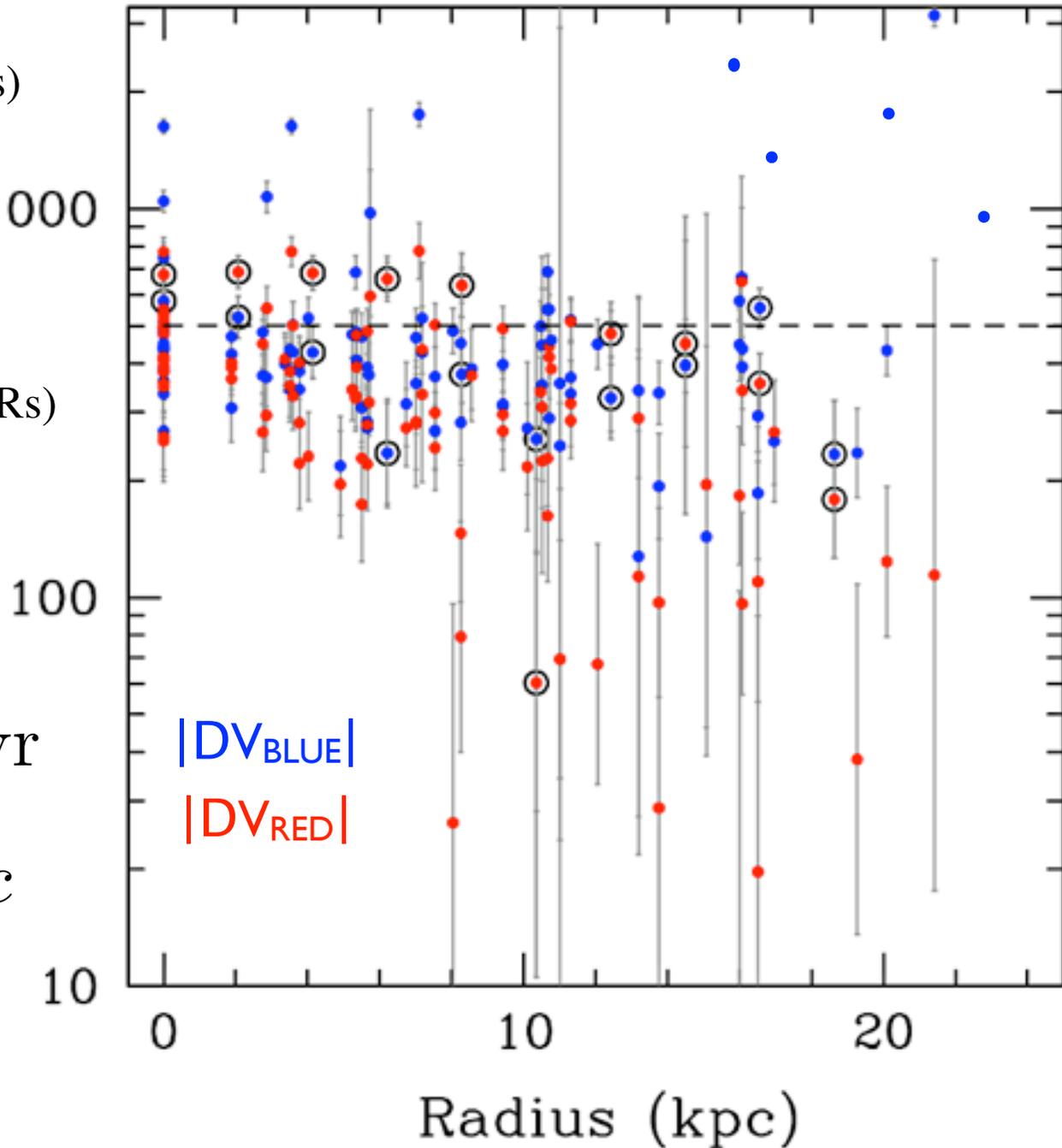
Humphrey et al. 2010
Green & Zakamska et al. 2011

Shen et al. 2011 (Double-Peaked NLRs)

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

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

$$L_{\text{wind}} \sim 0.01 L_{\text{AGN}}$$

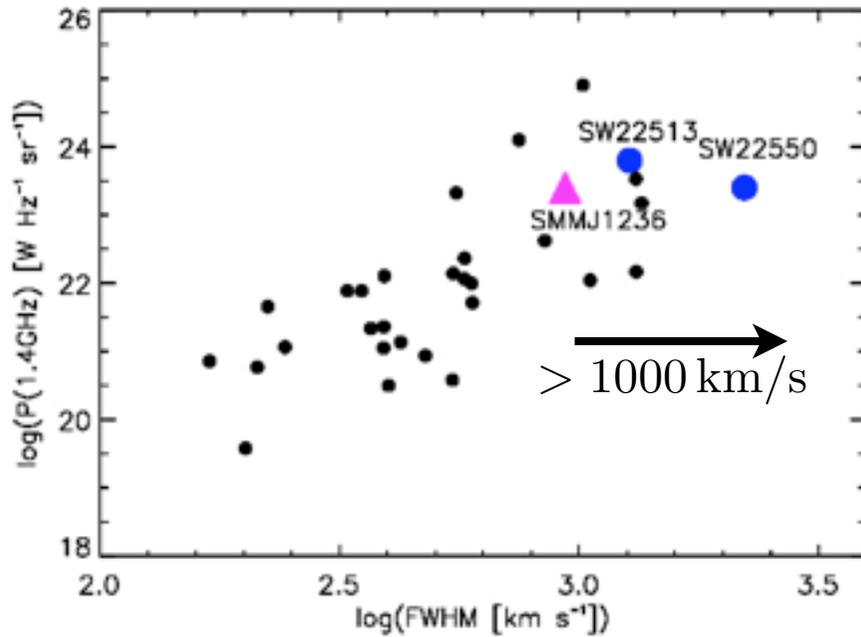


Ionized Gas Tracers At High-Redshift

“Pushed” By Radio Jets

Lehnert et al. 2009,2011

Nesvadba et al. 2010,2011



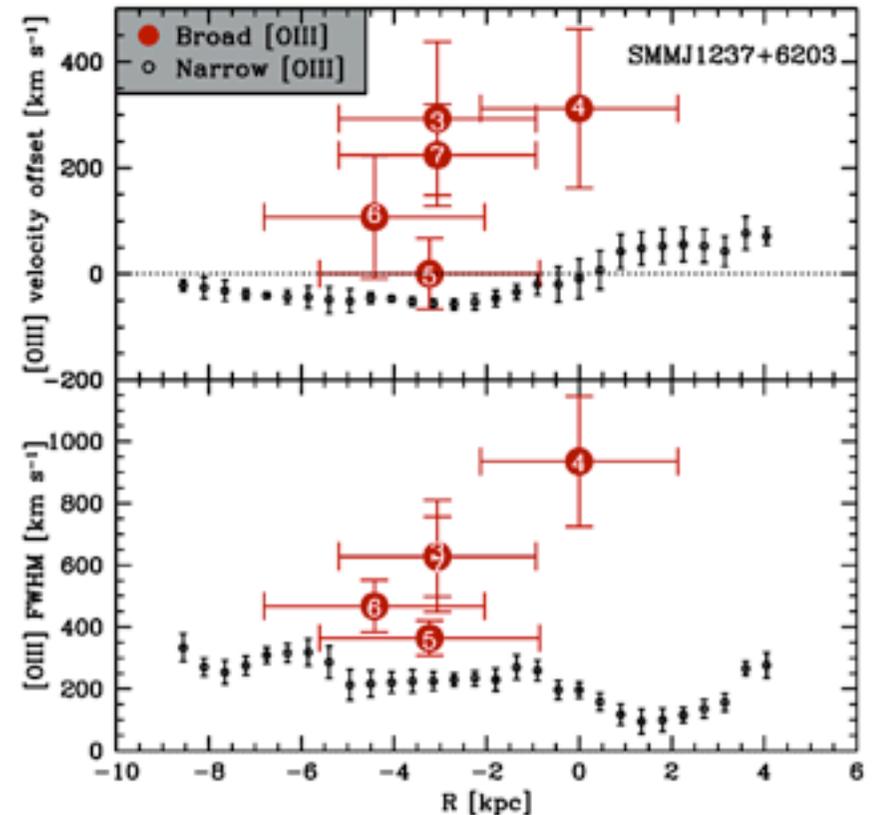
$$R_{\text{wind}} \sim 5 \text{ kpc}$$

$$v \sim 1000 \text{ km/s}$$

$$L_{\text{wind}} \sim 0.1 L_{\text{AGN}}$$

No Radio Jets / Radio Quiet

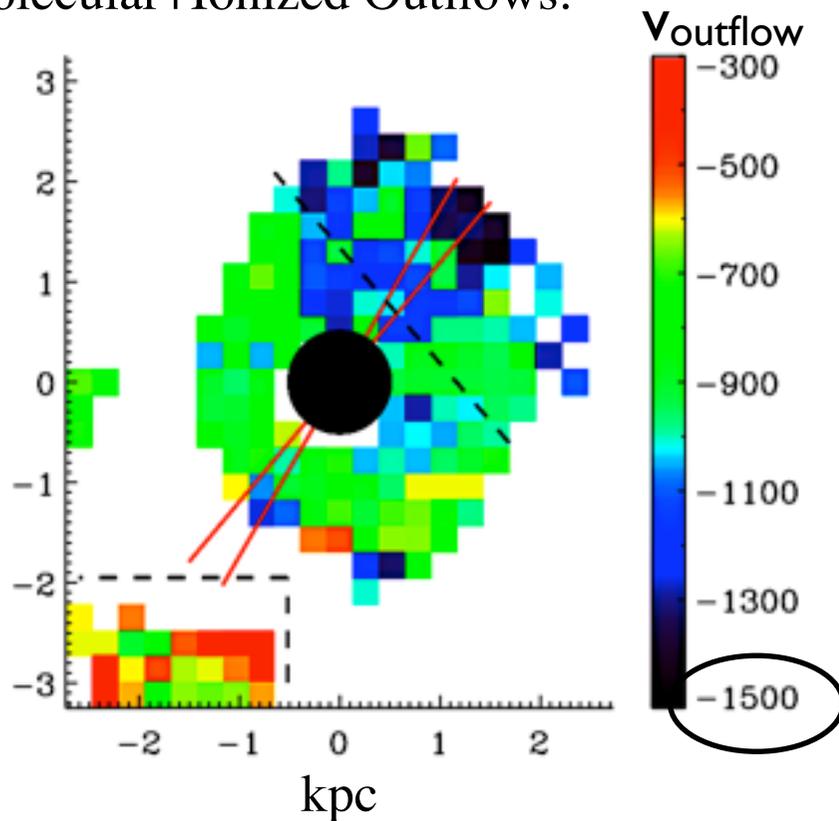
Alexander et al. 2010



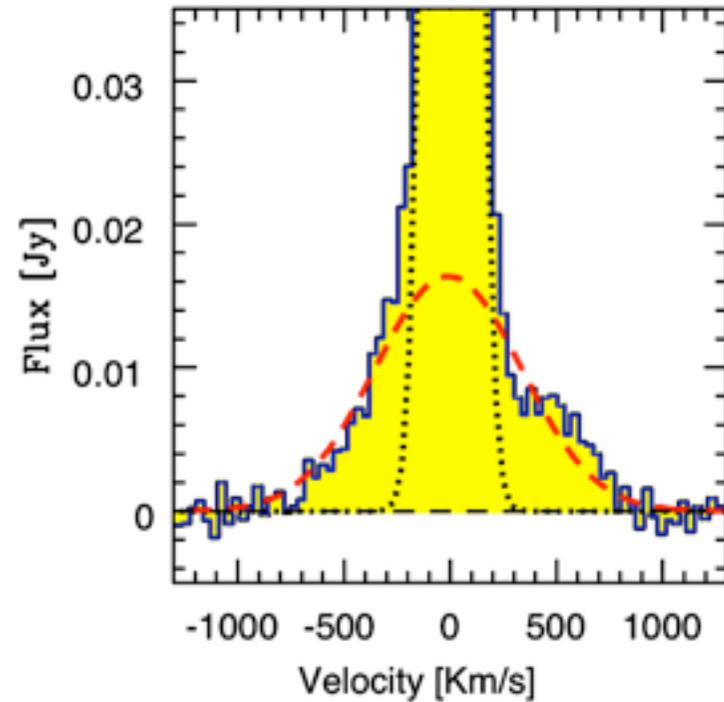
Molecular Outflows in AGN ULIRGs

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

Molecular+Ionized Outflows:



CO:



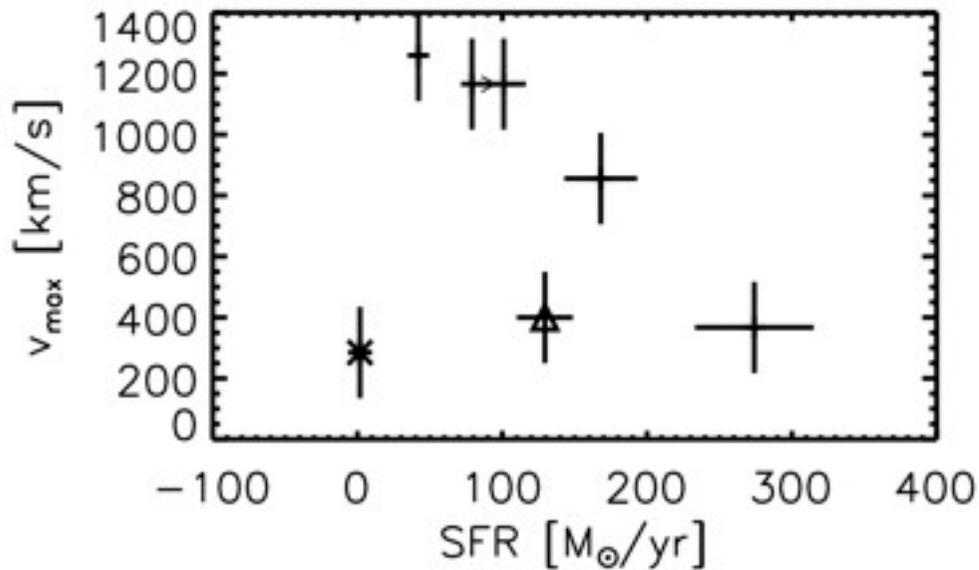
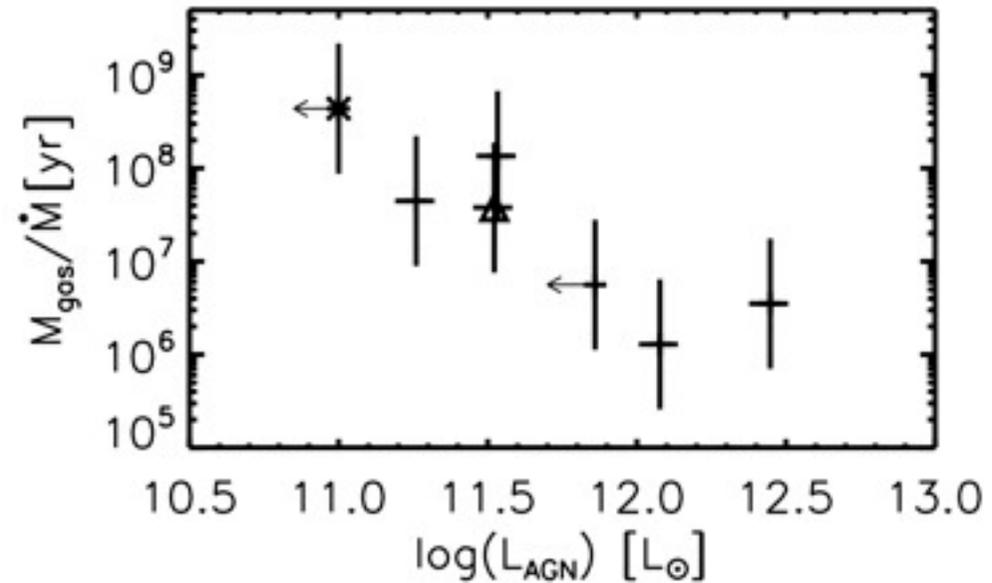
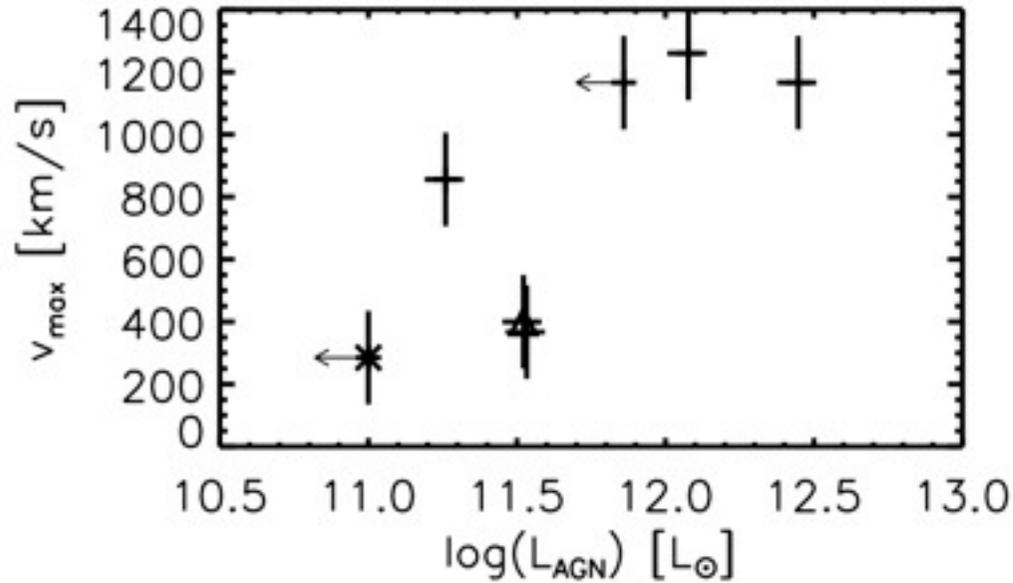
$$R_{\text{wind}} \sim 1 - 4 \text{ kpc}$$

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

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

Molecular Outflows in AGN ULIRGs

Sturm et al. 2011:



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

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

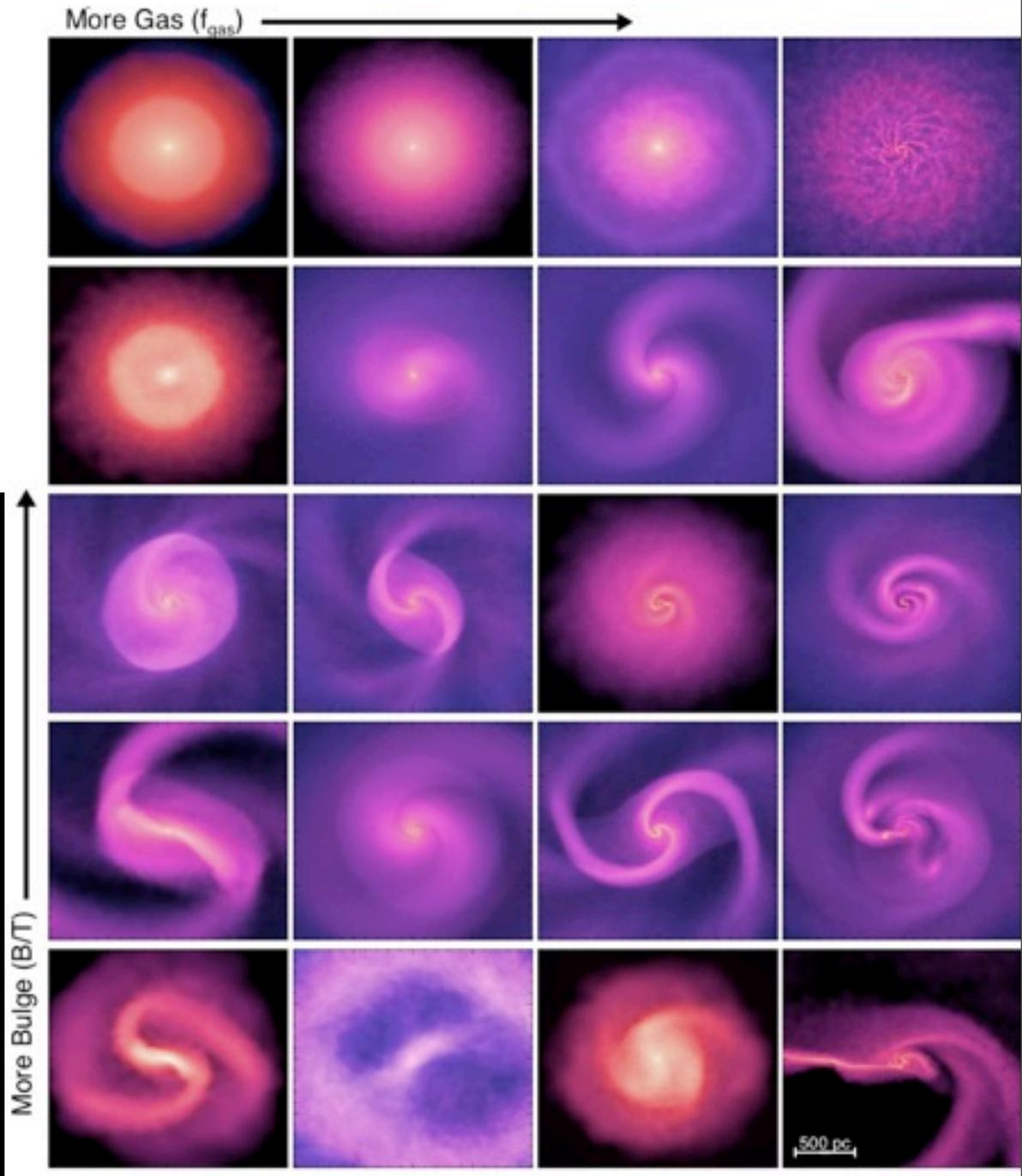
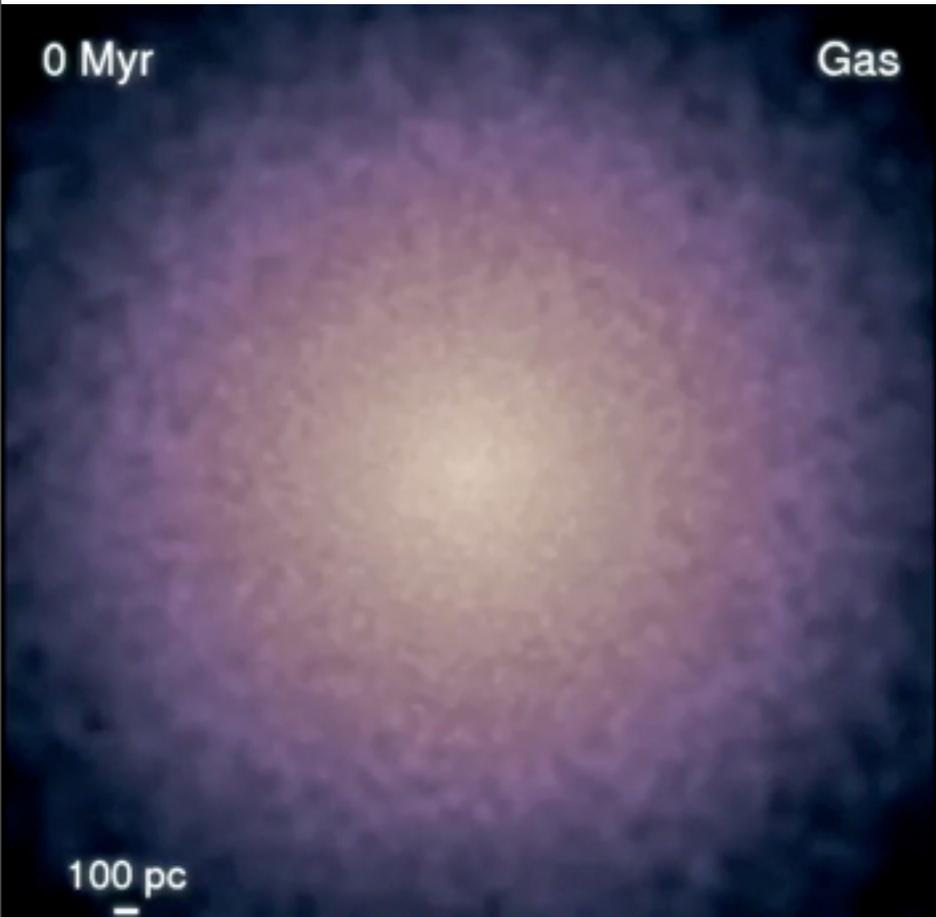
$$L_{\text{wind}} \sim 0.03 - 0.10 L_{\text{AGN}}$$

Where to now? How Do We Model This?

Step 1: Inflow

- Beginning to directly follow inflow to sub-pc scales

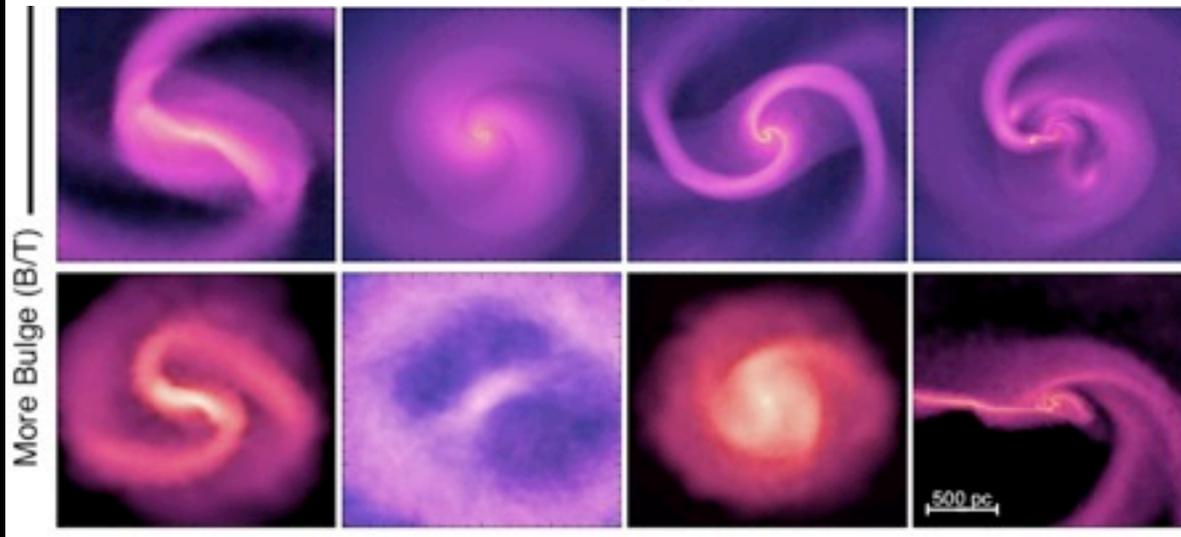
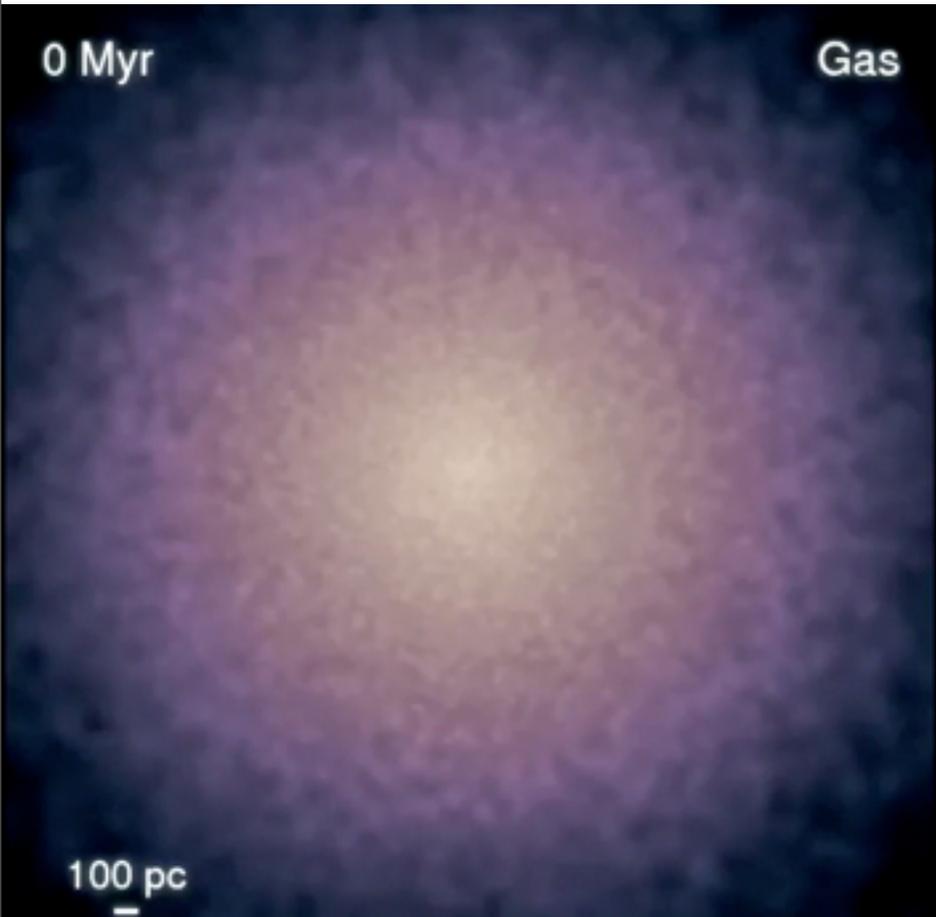
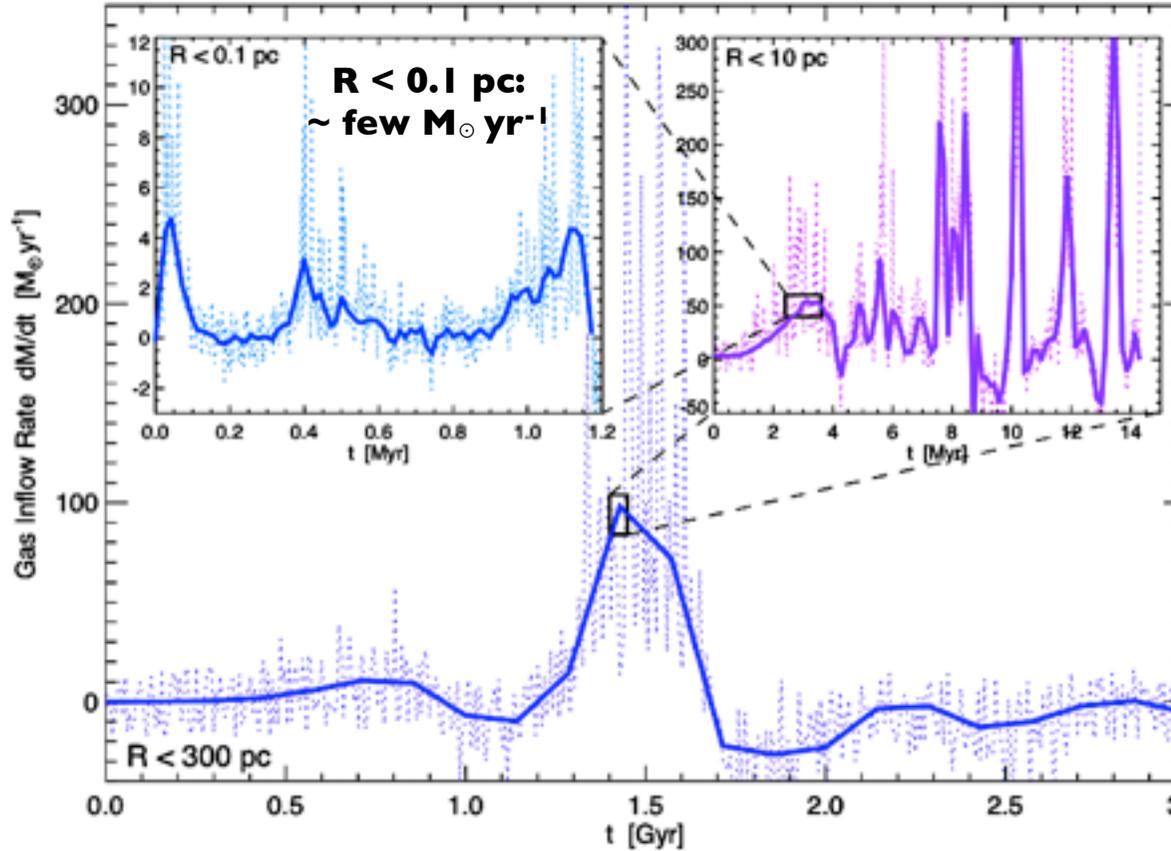
PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10



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



Bars w/in Bars

(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”



Bars w/in Bars

(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”



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



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 ...”

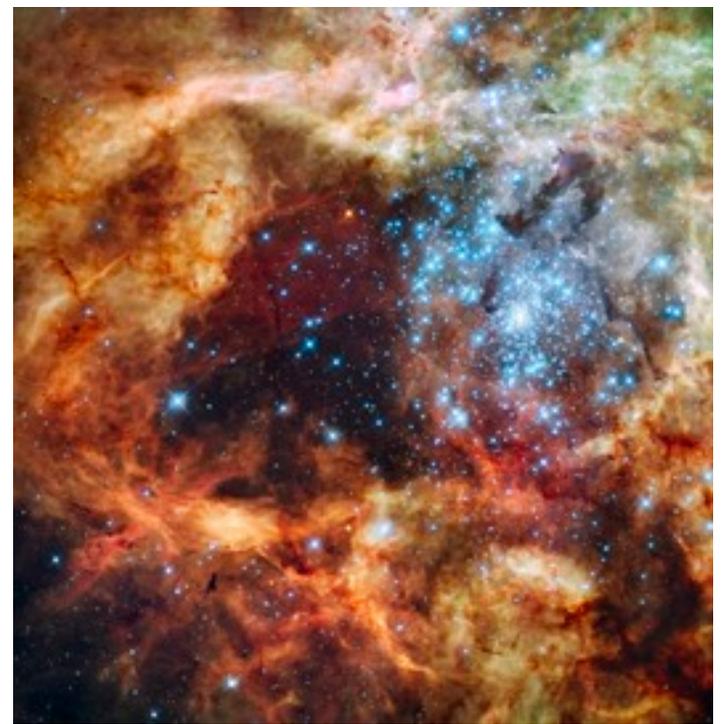
$$\dot{M} \approx 10 M_{\odot} \text{ yr}^{-1} \left(\frac{\text{Disk}}{\text{Total}} \right)^{5/2} M_{\text{BH}, 8}^{-1/6} M_{\text{gas}, 9} R_{0,100}^{-3/2}$$

Step 2: *Stellar* Feedback & the ISM



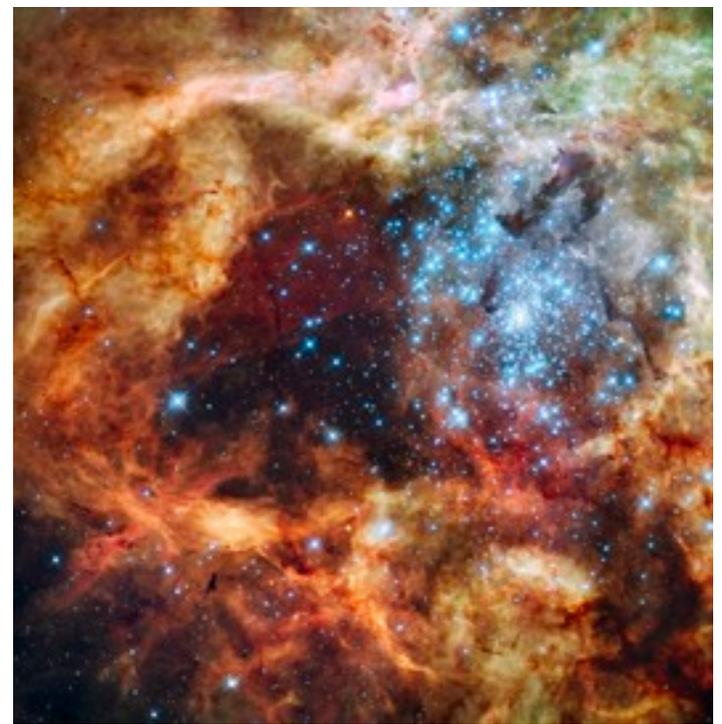
Step 2: *Stellar* Feedback & the ISM

- High-resolution ($\sim 1\text{pc}$), molecular cooling ($<100\text{ K}$), SF only at highest densities ($n_{\text{H}} > 1000\text{ cm}^{-3}$)



Step 2: *Stellar* Feedback & the ISM

- High-resolution ($\sim 1\text{pc}$), molecular cooling ($<100\text{ K}$), SF only at highest densities ($n_{\text{H}} > 1000\text{ cm}^{-3}$)
- Heating:
 - SNe (II & Ia)
 - Stellar Winds
 - Photoionization (HII Regions)



Step 2: *Stellar* Feedback & the ISM

- High-resolution ($\sim 1\text{pc}$), molecular cooling ($<100\text{ K}$), SF only at highest densities ($n_{\text{H}} > 1000\text{ cm}^{-3}$)
- Heating:
 - SNe (II & Ia)
 - Stellar Winds
 - Photoionization (HII Regions)



- *Explicit* Momentum Flux:

- Radiation Pressure

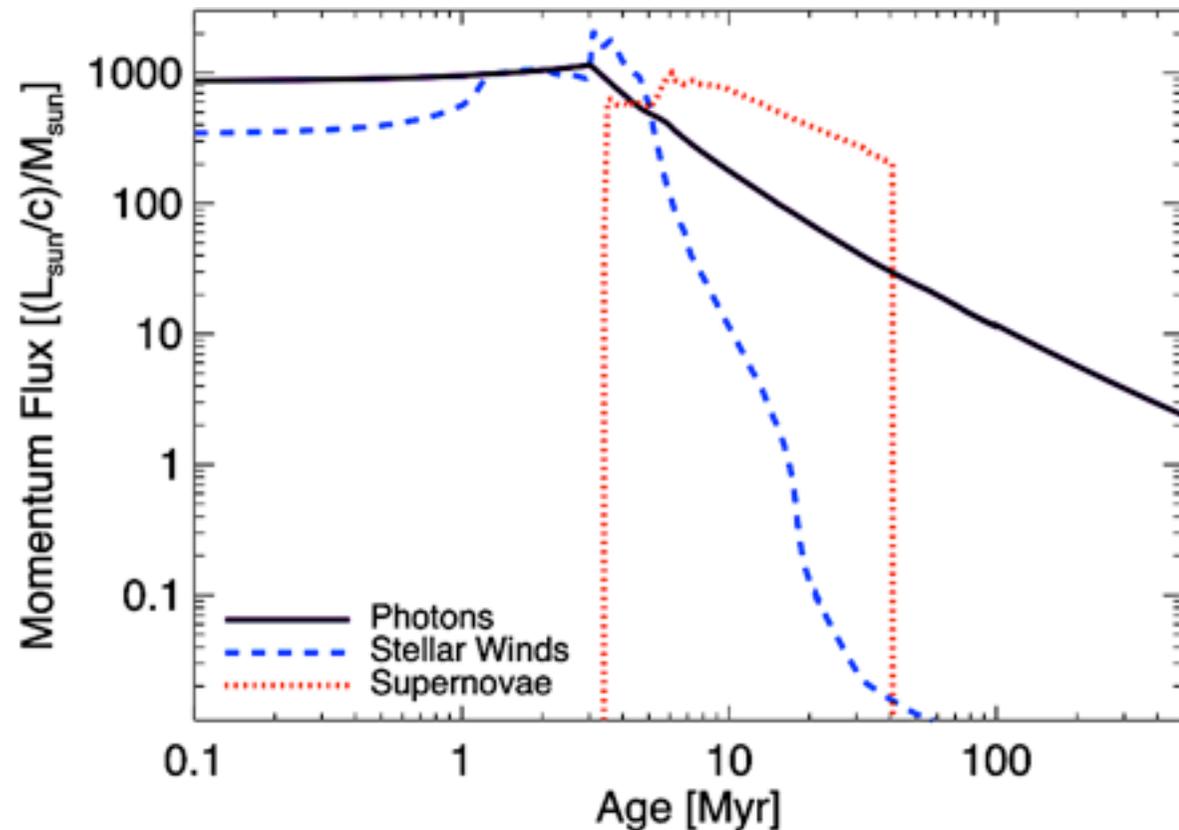
$$\dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}})$$

- SNe

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

- Stellar Winds

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

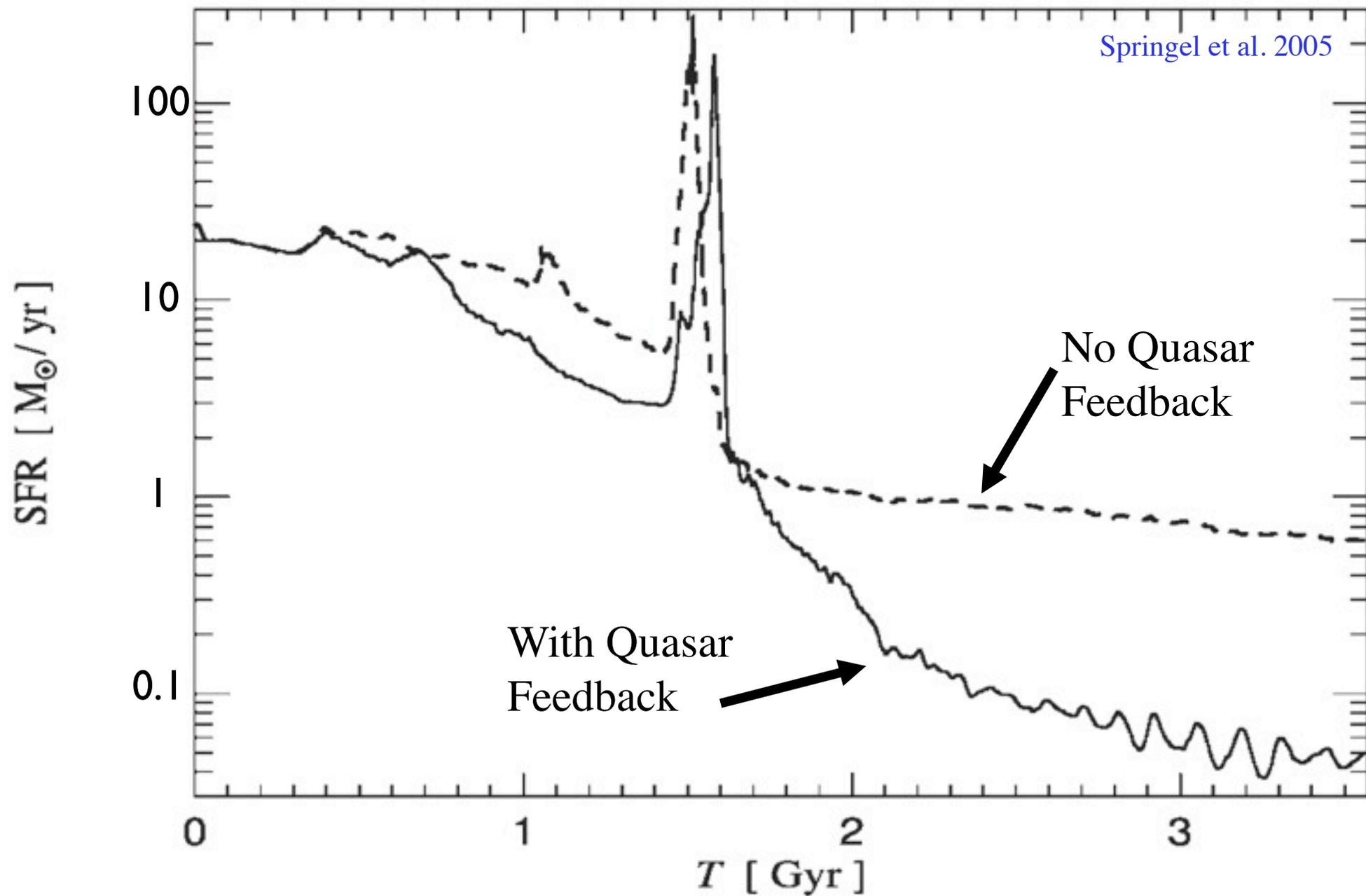


0 Myr

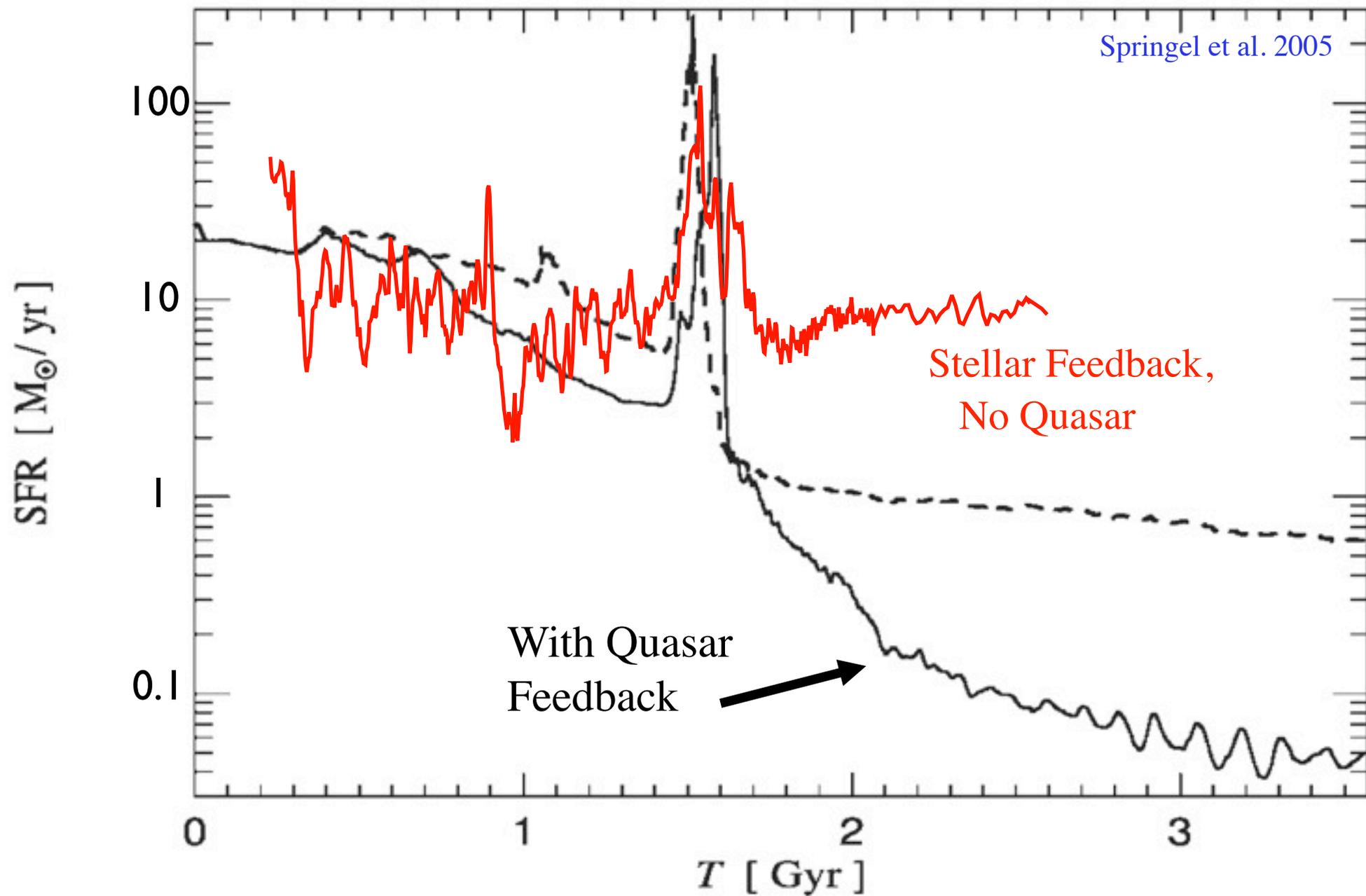
Gas

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 $\sim 5L/c$ (Arav+)

Photons

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

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

Compton Heating (only low density gas)

Outstanding Problem: Which Dominates?

Physics very diff for ISM & IGM

BAL Winds as a Quasar Feedback Mechanism

- $L/L_{\text{Edd}} > \sim 0.1$
- Covering factor $\sim 10\text{-}30\%$

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

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

- Launched at $< \text{pc}$

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

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

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

Z

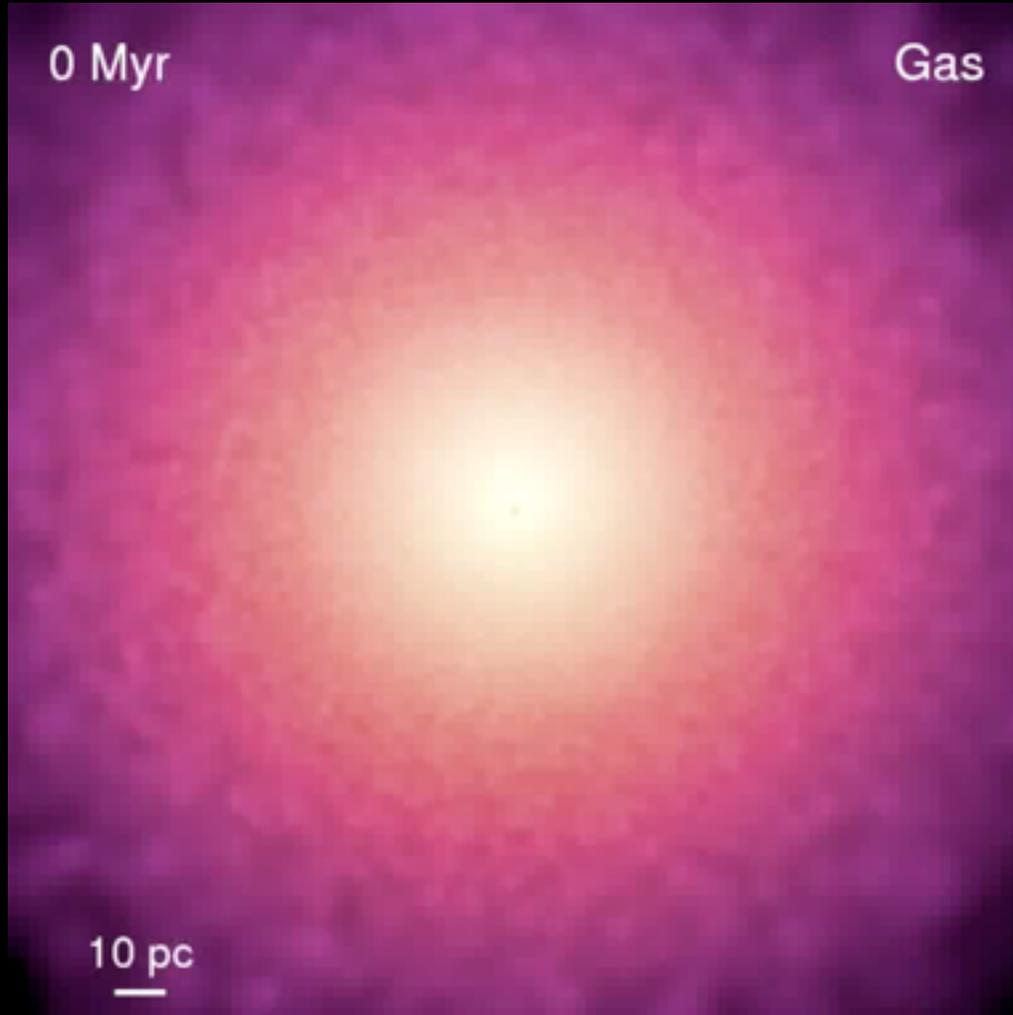


Z

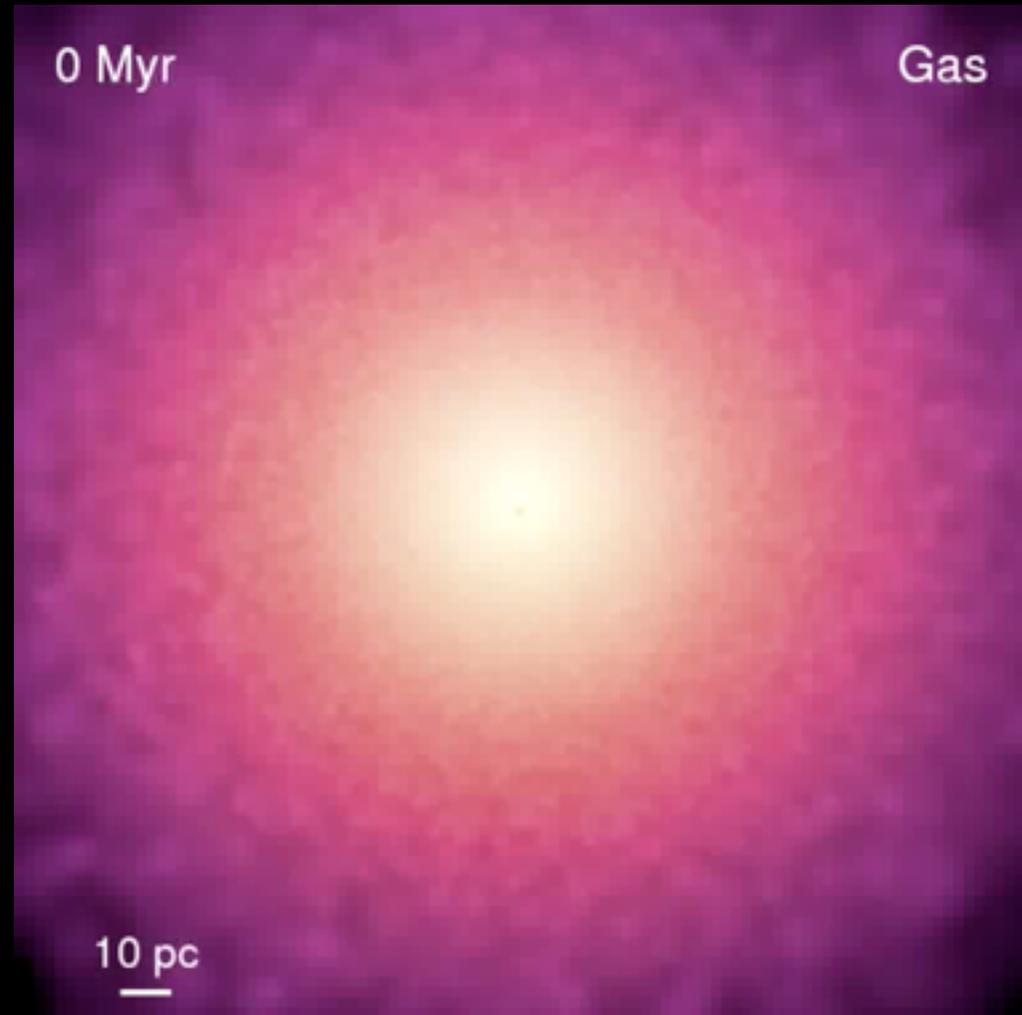


R

No BAL Winds



With BAL Winds



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

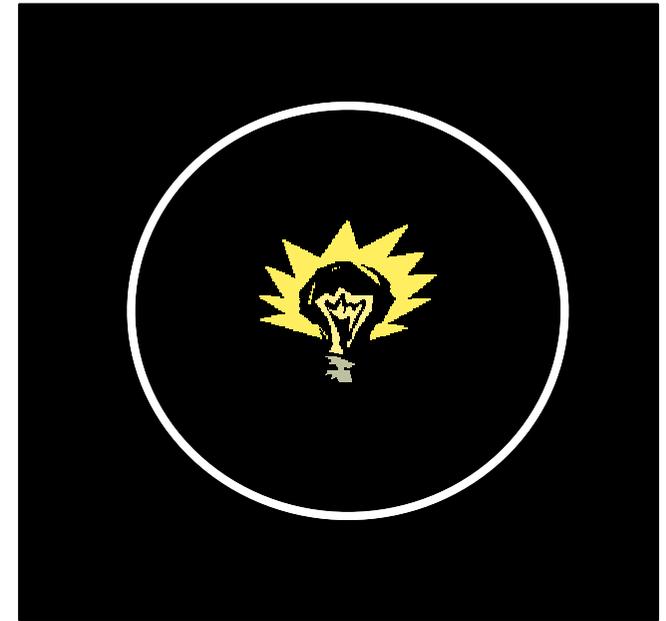
$$v_{\text{launch}}(0.1 \text{ pc}) = 10,000 \text{ km/s}$$

BAL Winds as a Quasar Feedback Mechanism

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

Momentum Flux:

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



Shut Down Accretion When:

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

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

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

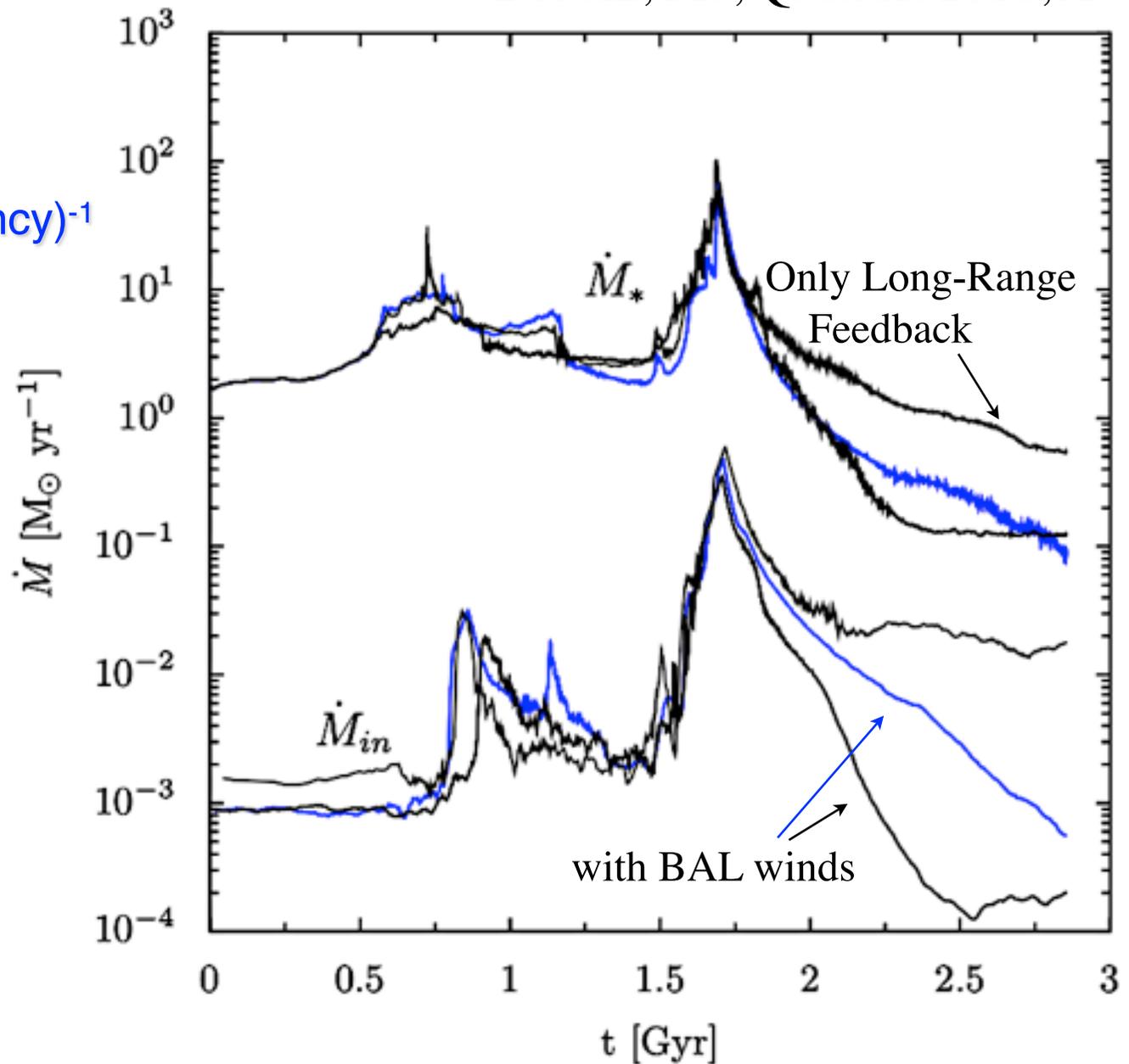
BAL Winds on Galactic Scales

CAN IT REALLY AFFECT STAR FORMATION?

Novak et al. 2010,11

Debuhr, Ma, Quataert 2010,11

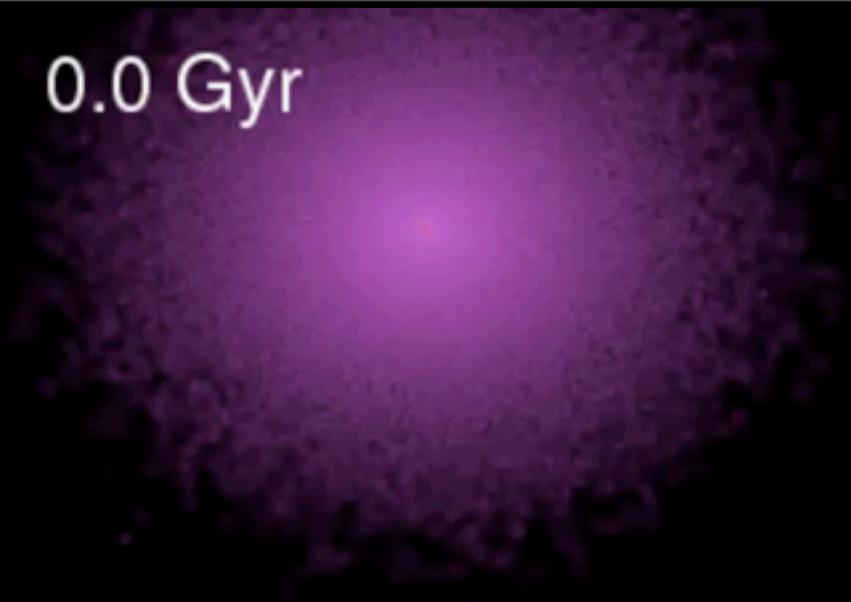
- Recover M-s
- Normalization $\sim (\text{efficiency})^{-1}$
- Launch ~ 1000 km/s “tail” in winds
- Suppress SFR



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 $M_{\text{BH-S}}$
 - 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 $M_{\text{BH-S}}$
 - 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