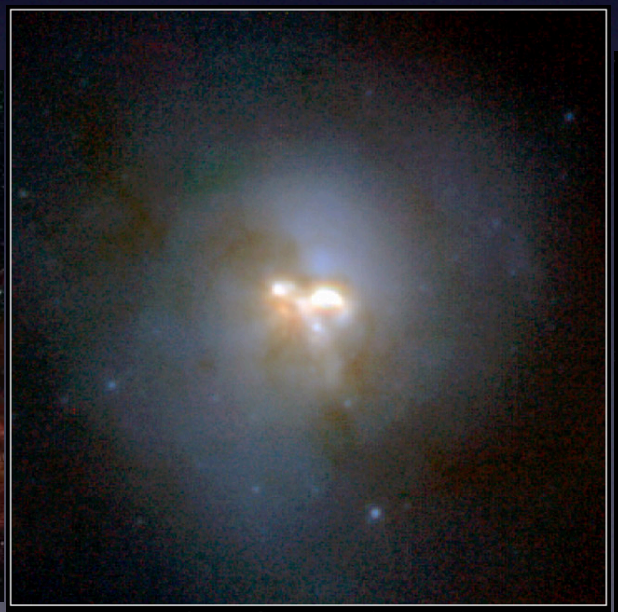
The Biermann Lectures: Adventures in Theoretical Astrophysics

II Feedback during Galaxy Formation

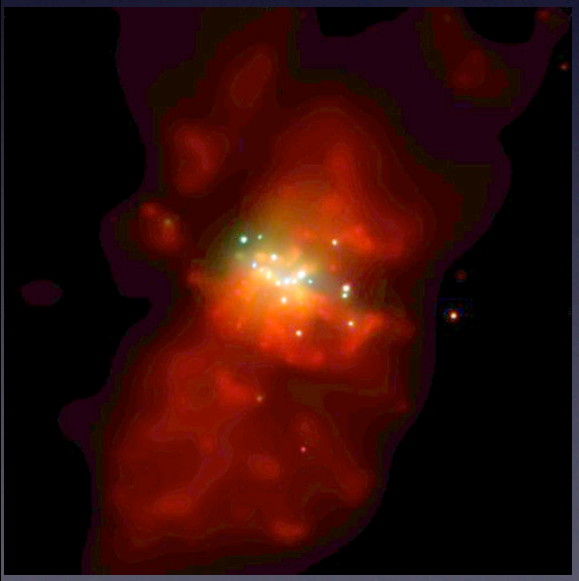
Eliot Quataert (UC Berkeley)

w/ Norm Murray, Phil Hopkins, Jackson Debuhr, Todd Thompson, Chung-Pei Ma ....

Spitzer's view of Carina



Ultraluminous Infrared Galaxy Arp 220 HST • NICMOS
PRC97-17 • ST ScI OPO • June 9, 1997
R. Thompson (University of Arizona),
N. Scoville (California Institute of Technology) and NASA



M82 (Chandra)

Outline

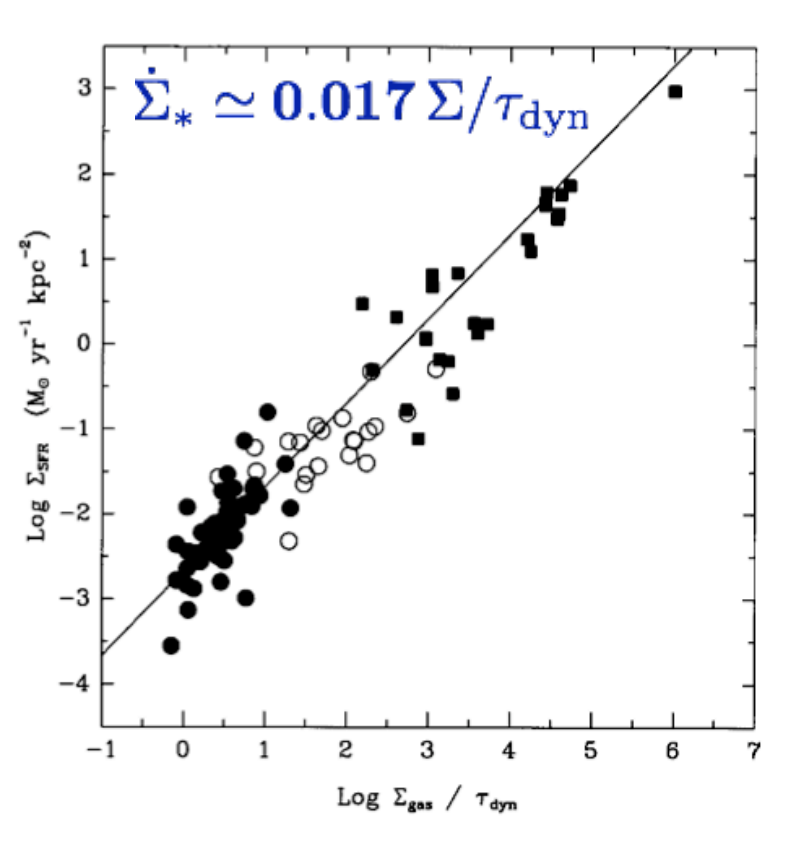
- Feedback: What is it good for?
  - Absolutely Everything ...
- Feedback 101: Energy vs Momentum
- Feedback during

  1. Star Formation (KS, Galactic Winds, Clumps, ..)

  2. BH Growth (M_{BH}-σ, Winds, ..)

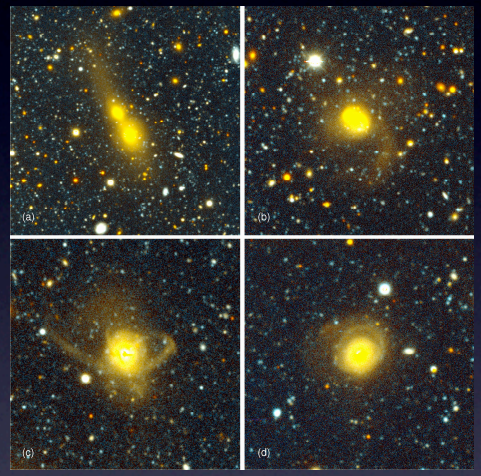
What is it Good For?

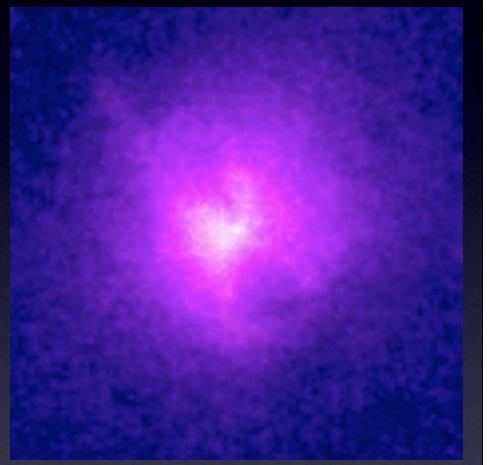
Slowing Down Star Formation in Galaxies



Kennicutt 1998

Shutting off Star Formation in E's & Cooling in Clusters

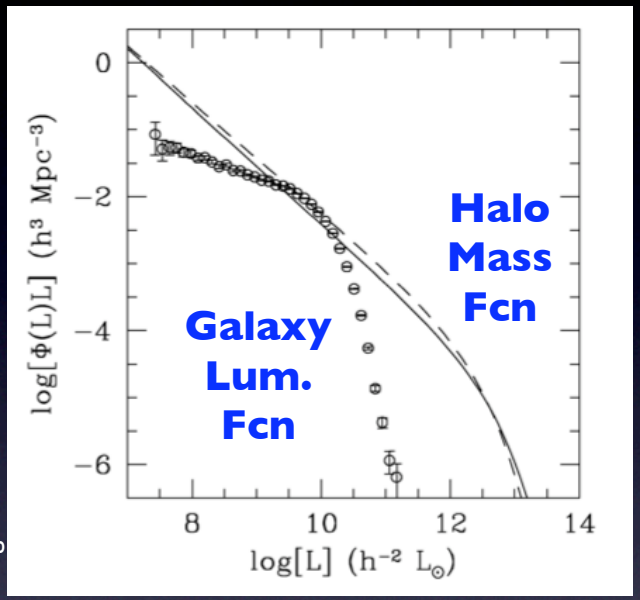




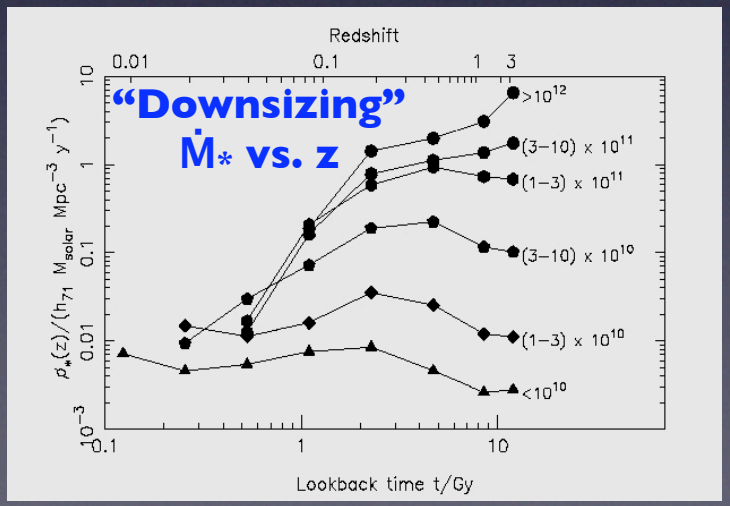
Getting gas/metals out of galaxies (& into the IGM)

NGC 3079 (HST)

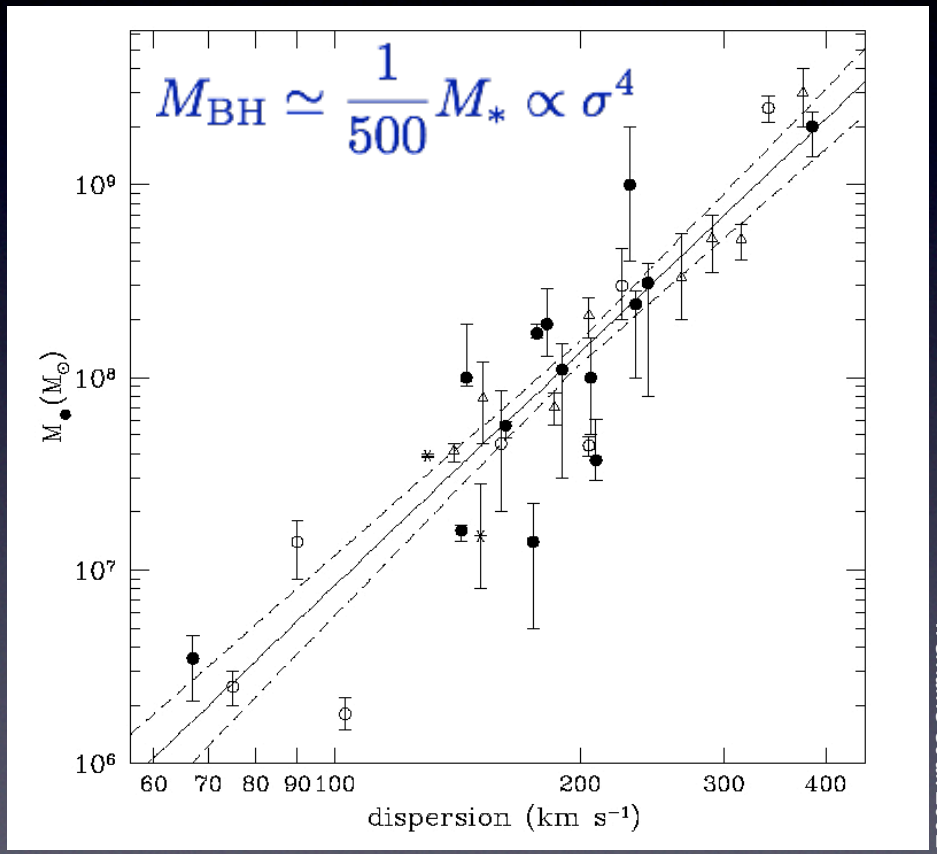
What is it Good For?



Yang et al. 2003



Heavens et al. 2004

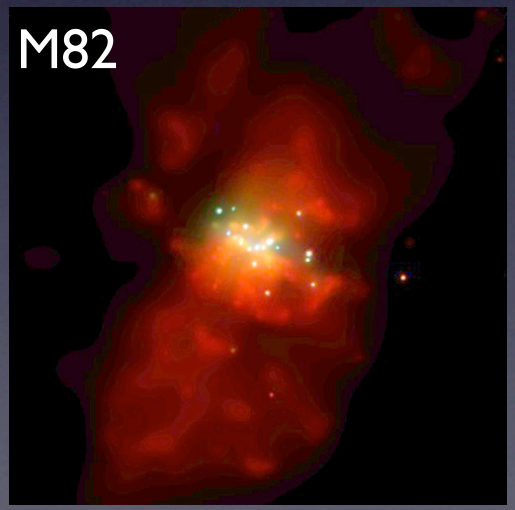


Tremaine et al. 2002

Feedback 101

Energy
(dilute gas)

Gas heated up to
$C_s > V_{esc}$ & then unbound
eg: solar wind
SN-heated galactic wind



Momentum
(dense gas; energy radiated)

force induces δV
if ~ V_{esc}, gas blown out
eg: molecular gas δV's
O star winds

Feedback associated with Star Formation

Major Science Questions

- What is the Multiphase (Turbulent) Structure of the ISM of Galaxies? Key to
  - Gas inflow in galaxies and growth of bulges (diffuse gas inflow along bars? cluster inspiral? ...)
  - Effect of AGN Feedback on ISM (porous ISM? smooth? ...)
  - Producing realistic disk galaxies
    (Agertz+; Governato+)

- Physical origin of Galactic Winds & Scaling w/ Global Galaxy Properties
  - partially constrained at z ~ 0-2 but not fully understood
  - which wind phase carries most of the mass, momentum, energy, metals?
  - does $\dot{M}_{wind}/\dot{M}_{*} \uparrow$ as $M_{halo} \downarrow$?

Feedback associated with Star Formation

- Direct Momentum & Energy Input
  - Momentum: $\dot{P}_{photons} \sim \dot{P}_{SNe} \sim \dot{P}_{* winds} \sim L/c$
  - Energy: $\dot{E}_{SNe} \sim 10^{-2} L \sim 10\ \dot{E}_{CR} \sim 10\ \dot{E}_{* winds}$; $\dot{E}_{ionization} \sim 0.3\ L$ ($T \sim 10^4$ K in HII regions)
- Interaction with Ambient ISM
  - $\dot{P}$ (force) imparted can ↑ (work done bec. energy builds up)
  - $\dot{E}$ ↓ (energy radiated away, particularly in dense ISM)

Feedback associated with Star Formation

- Interaction with Ambient ISM
  - $\dot{P}$ (force) imparted can ↑ (work done bec. energy builds up)
  - $\dot{E}$ ↓ (energy radiated away, particularly in dense ISM)

$$\text{Photons}: \quad \dot{P} \simeq \frac{L}{c}\left(1 - \exp[-\tau_{UV}]\right) + \frac{L_{FIR}}{c}\tau_{FIR} \sim \frac{L}{c}\left(1 + \tau_{FIR}\right)$$

UV degraded into FIR ($\kappa_{UV} \sim 10^3\ \kappa_{es}$) FIR absorption ($\kappa_{FIR} \sim$ 1-10 κ_{es})

$$\text{SNe}: \quad \dot{P} \simeq \frac{L}{c}\,\text{Max}[1\,,\,8\,n_{ISM}^{-1/4}]$$

Work done during Sedov-Taylor Phase

$$\text{CR Pressure} \sim \frac{\dot{E}_{CR}\,t_{escape}}{V_{CR}} \quad (\sim B^2/8\pi \sim \text{turbulent pressure in MW})$$

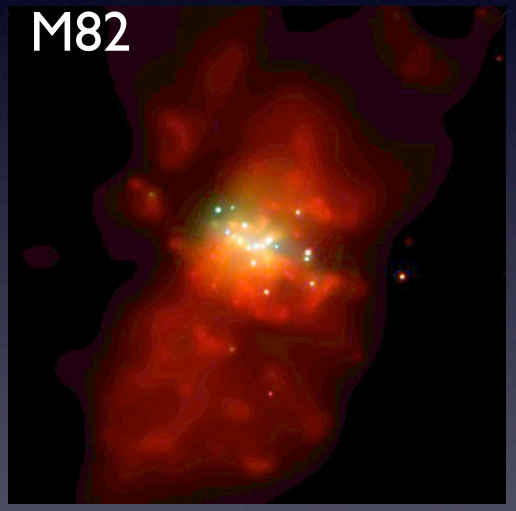
Typical Feedback in Galaxy Formation Sims:
none (artificial pressure floor) or $\dot{E}_{SNe}$ (thermal) but not $\dot{P}$

SN-heated galactic wind in formation of MW-like galaxy

Teyssier et al. (related work by Governato +)

The Role of the Hot ISM in Galaxies

- Hot ISM in galaxies (shock heated by SNe)
  - hot gas can push around most of the mass iff $p_{\rm hot} \gtrsim \pi G \Sigma_g^2$



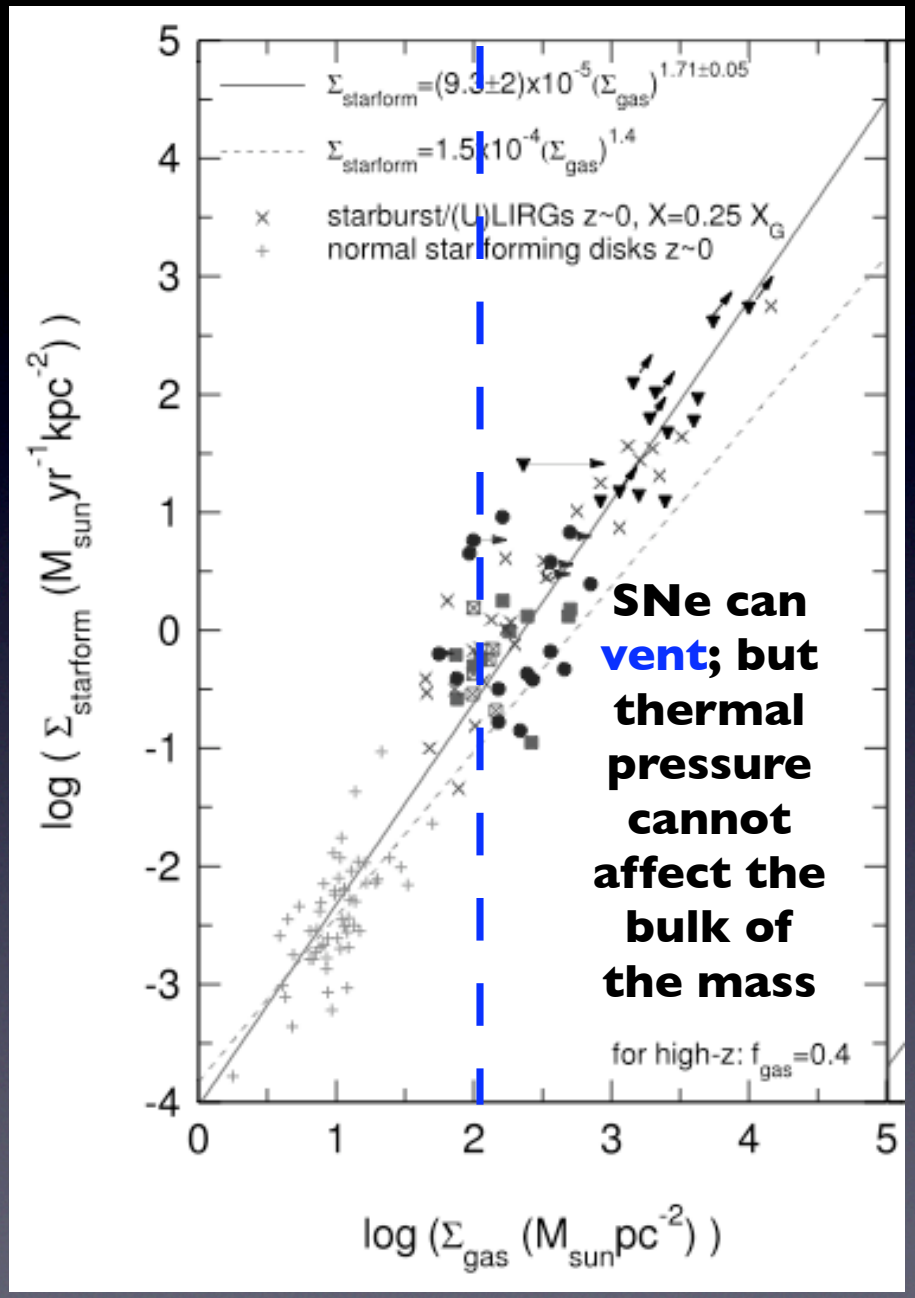
Σ_g (cold gas)

Hydro Equil:
$P = \pi G \Sigma_g^2$

$$p_{\rm hot} \gtrsim \pi G \Sigma_g^2 \rightarrow \dot{E}_{\rm cool} \gtrsim L_X \text{ for } \Sigma_g \gtrsim 0.03\,{\rm g\,cm^{-2}}$$

(observed: $L_X \sim 10^{-4} L_{FIR}$)

Bouche et al.

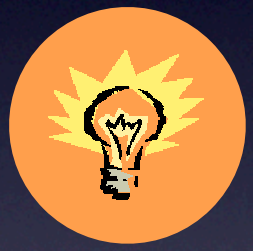


Bulk of the Mass in Galaxies Stirred up by ***Momentum***
(Photons, $\dot{P}$ of SNe, ...)

in MW today, SN-heated hot ISM ~ 10% of pressure

The Importance of Radiation Pressure in Dense Gas

Σ_g (e.g., GMC)



Hydro Equil:
$P = \pi G \Sigma_g^2$

$$\text{SNe}: \quad \dot{P} \simeq \frac{L}{c}\,\text{Max}[1\,,\,8\,n_{ISM}^{-1/4}]$$

$$\text{Photons}: \quad \dot{P} \simeq \frac{L}{c}\,(1+\tau_{FIR}) \propto L\,\kappa_{FIR}\,\Sigma_g$$

$\dot{P}_{rad}$ ↑ as density ↑, unlike all other feedback mechanisms

⇒ $\dot{P}_{rad}$ dominates at high density

⇒ can approach $L \sim L_{Edd}$ on dust

Feedback associated with Star Formation

Need to include **both** $\dot{P}$ and $\dot{E}$

$\dot{P}$

impt in dense gas

star forming regions w/in galaxies
massive galaxies
galactic nuclei (BH growth)

$\dot{E}$

impt in rarified gas

dilute phases of ISM (& ICM)
less massive galaxies (dwarfs)

intimately connected

dwarfs → massive galaxies
fraction of dense/dilute gas depends on $\dot{E}$ & $\dot{P}$

physically reasonable modeling reqd for both disk & bulge formation

Feedback associated with Star Formation

- Direct Momentum & Energy Input
  - $\dot{P}_{photons} \sim \dot{P}_{SNe} \sim \dot{P}_{*\ winds} \sim L/c$ **$\dot{E}_{SNe} \sim 10^{-2}\ L$** $\sim 10\ \dot{E}_{*\ winds}$; $\dot{E}_{ionization}$
- Interaction with Ambient ISM
  - $\dot{P}$ can ↑ (work done) while $\dot{E}$ ↓ (energy radiated away)

$$\text{Photons}: \quad \dot{P} \simeq \frac{L}{c}\left(1 - \exp[-\tau_{UV}]\right) + \frac{L_{FIR}}{c}\tau_{FIR} \sim \frac{L}{c}\left(1 + \tau_{FIR}\right)$$

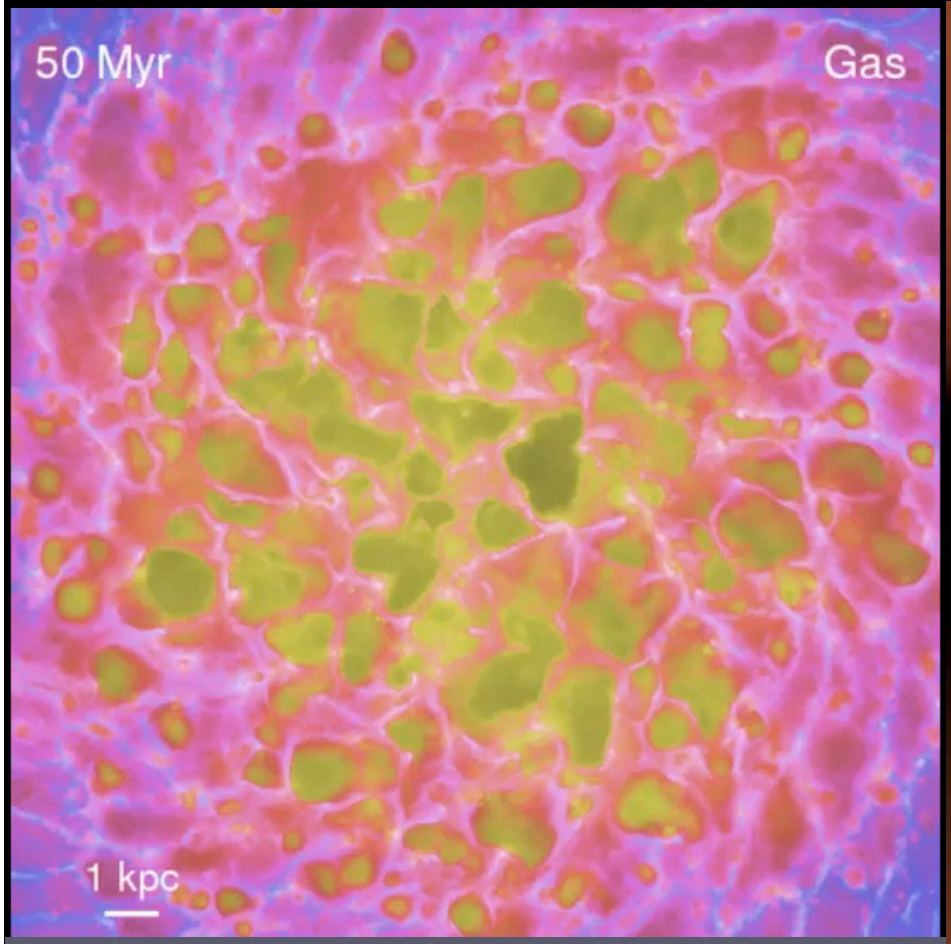
UV degraded into FIR — FIR scattering/absorption

(very approx implementation; see HQM 2011)

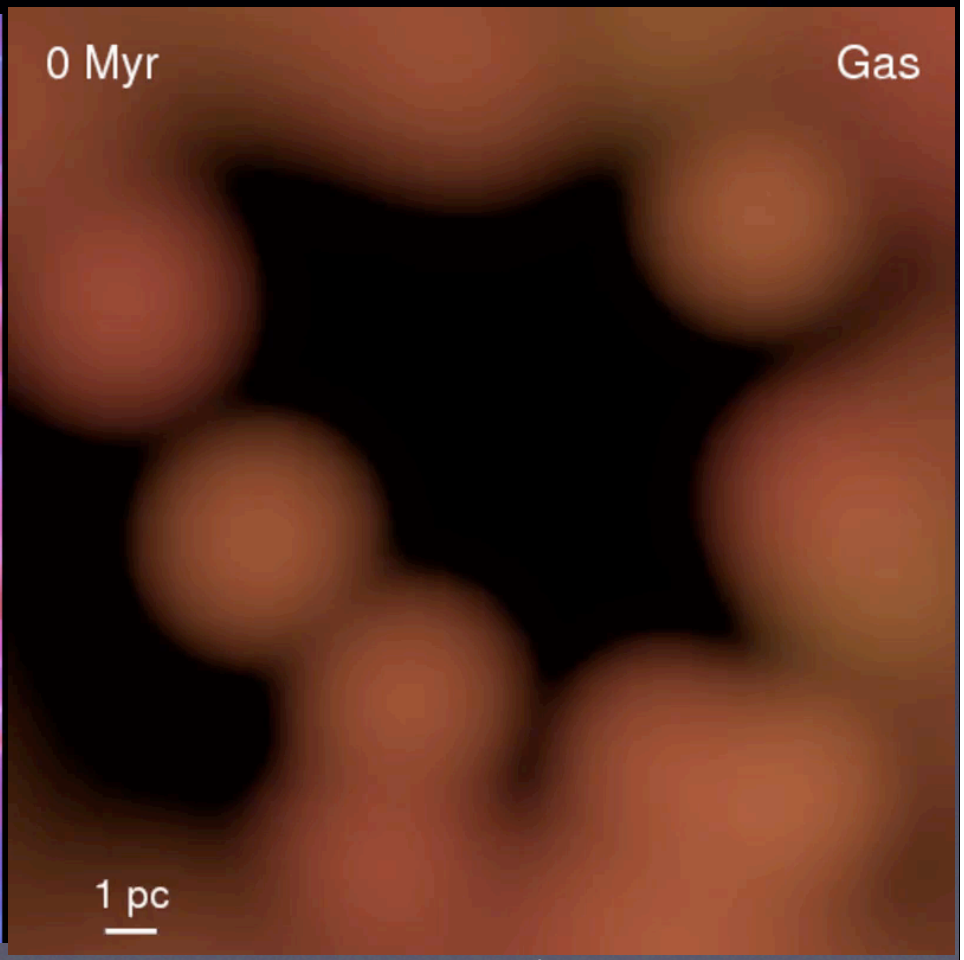
Typical Feedback in Sims:
none (just pressure floor) or SNe $\dot{E}$ (thermal) but not $\dot{P}$

SPH Sims of Isolated Galaxies w/ Momentum & Energy Feedback

massive "z ~ 2" star-forming disk



SMC-like dwarf

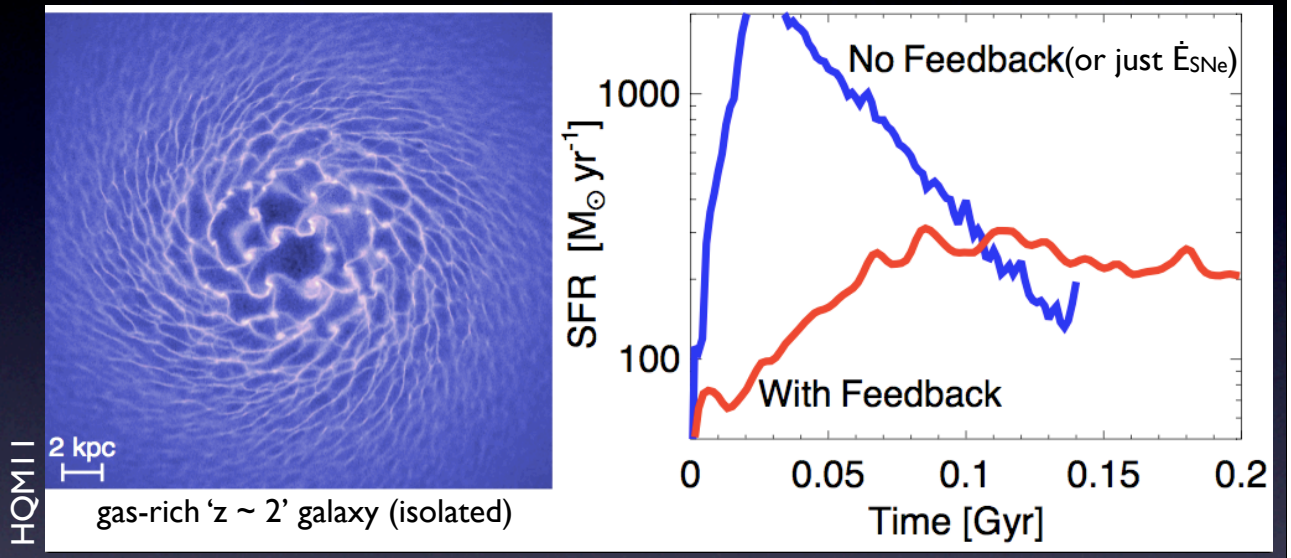


w/ Phil Hopkins & Norm Murray

Inhomogeneous 'turbulent' ISM self-consistently created

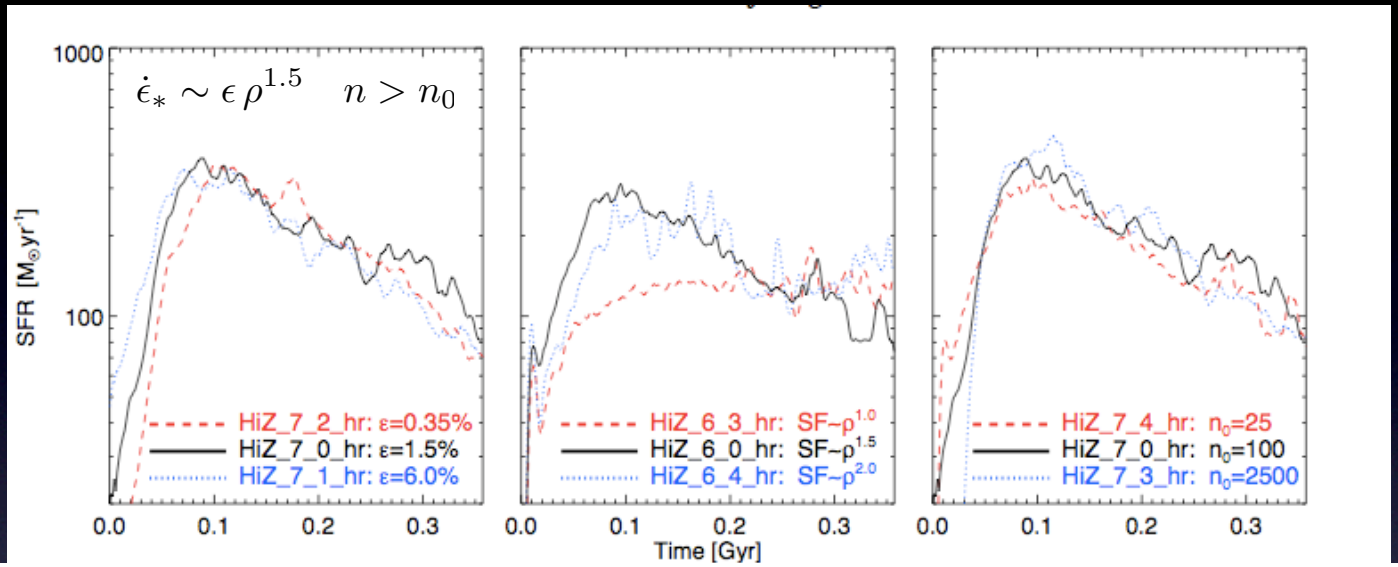
SPH Sims of Isolated Galaxies w/ Momentum & Energy Feedback

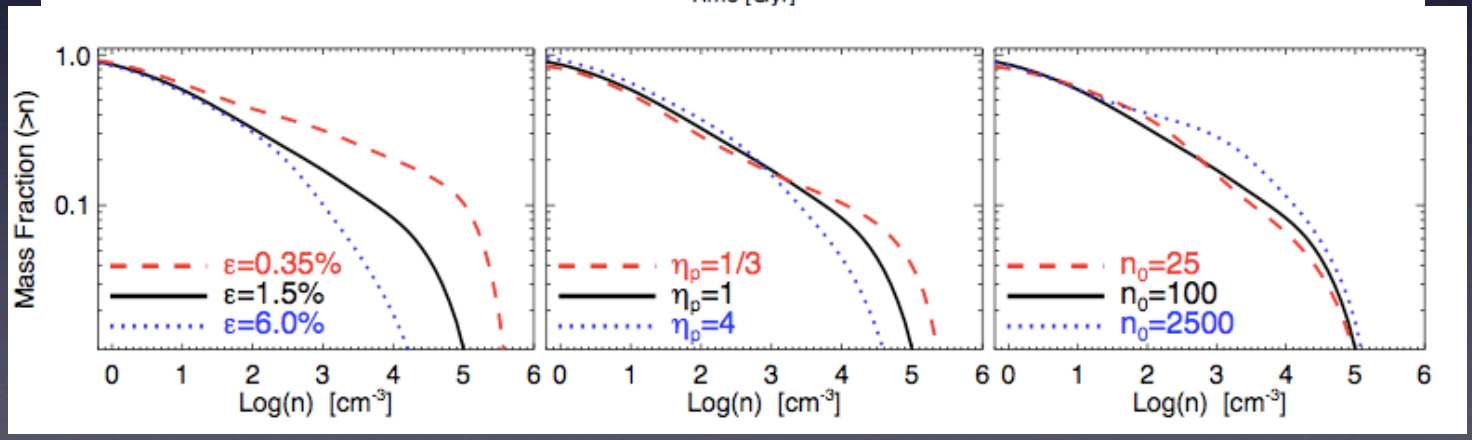
GMCs form when $Q \lesssim 1$
GMCs unbound by P_{rad} of star clusters
(or HII regions in low mass systems)



- Inhomogeneous 'turbulent' ISM self-consistently created
- SFR & Feedback adjust to maintain $Q \sim 1$
  - Global SFR consistent w/ Kennicutt Laws
  - SFR weakly dependent on subgrid star formation law (gas mass at high ρ adjusts)
- Can begin to quantitatively predict wind properties

The Role of Feedback in Dense Gas

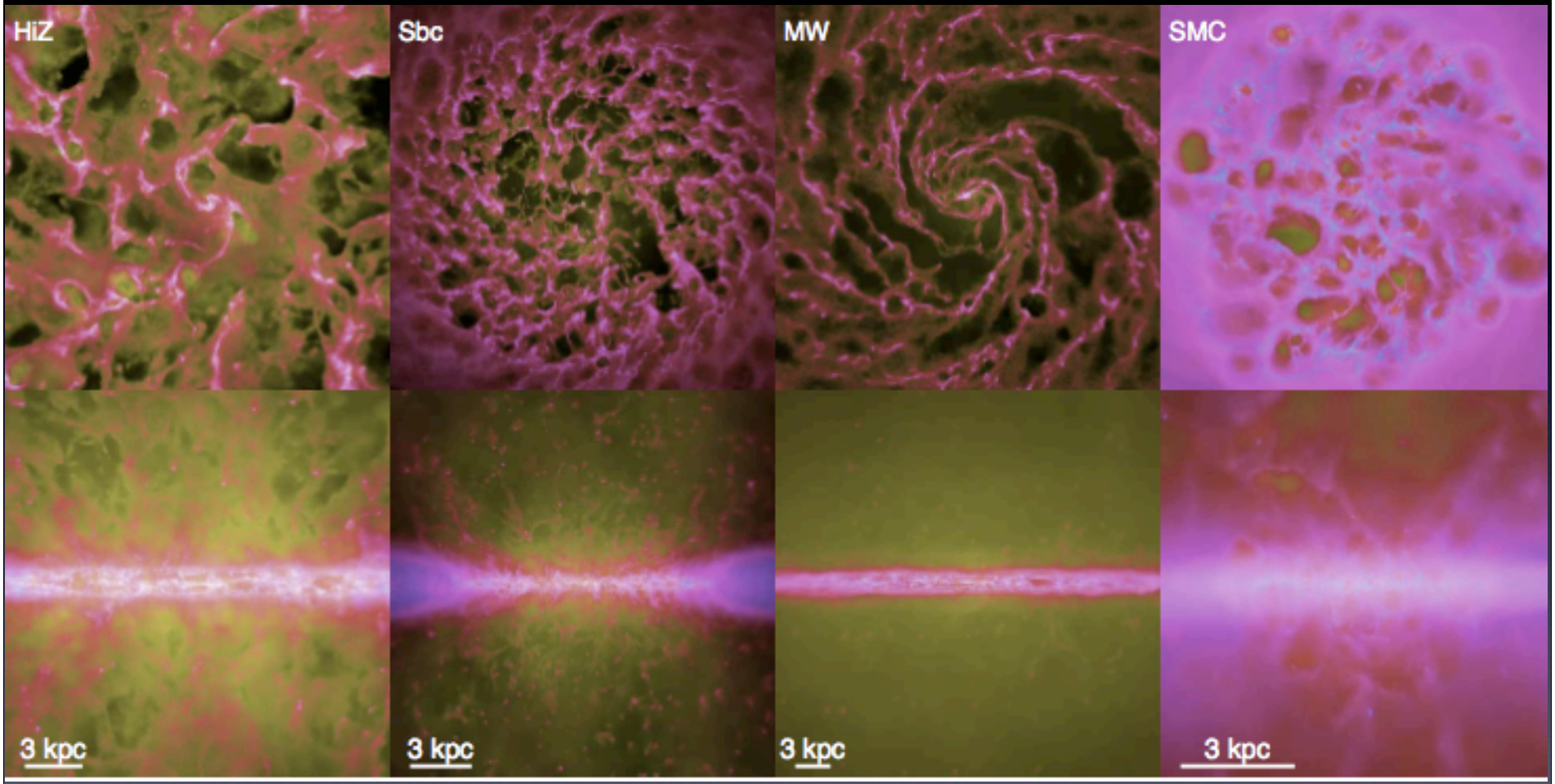




- Global SFR weakly dependent on subgrid star formation law (nice feature)
- Gas Density at high ρ adjusts to maintain SFR & Feedback ∋ Q ~ 1

Why is the treatment of Feedback within Galaxies Important?

Galactic Winds



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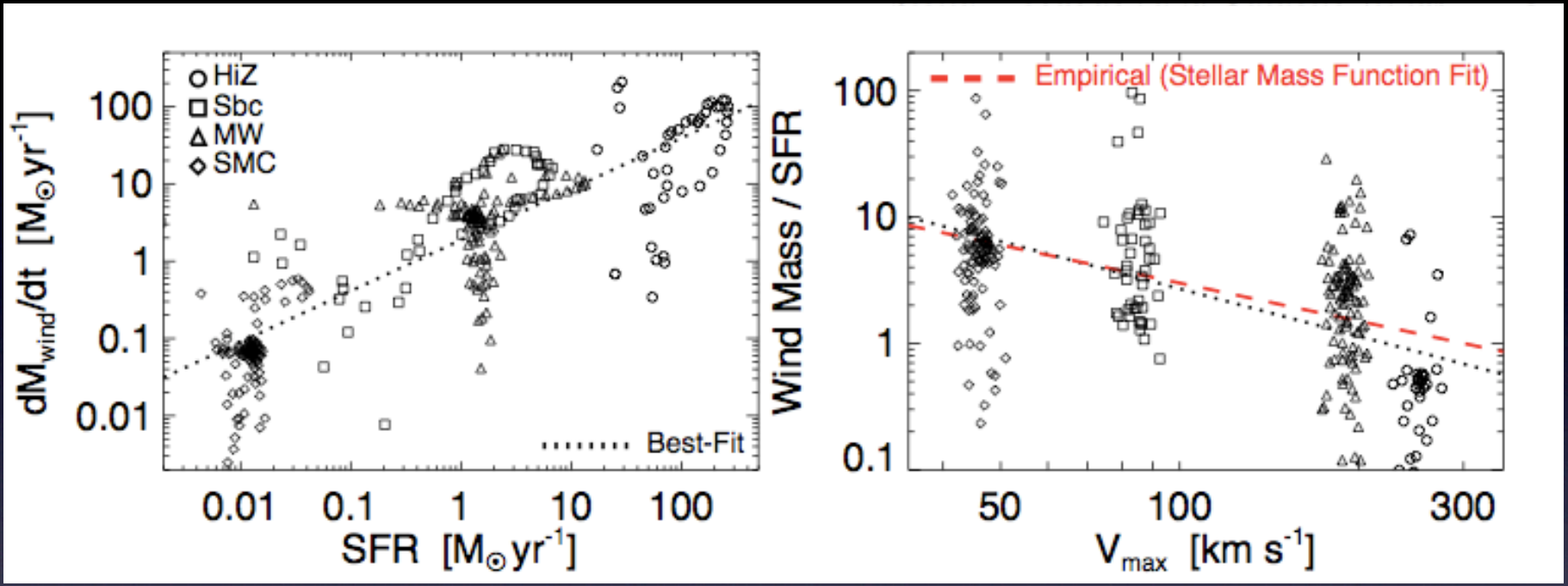


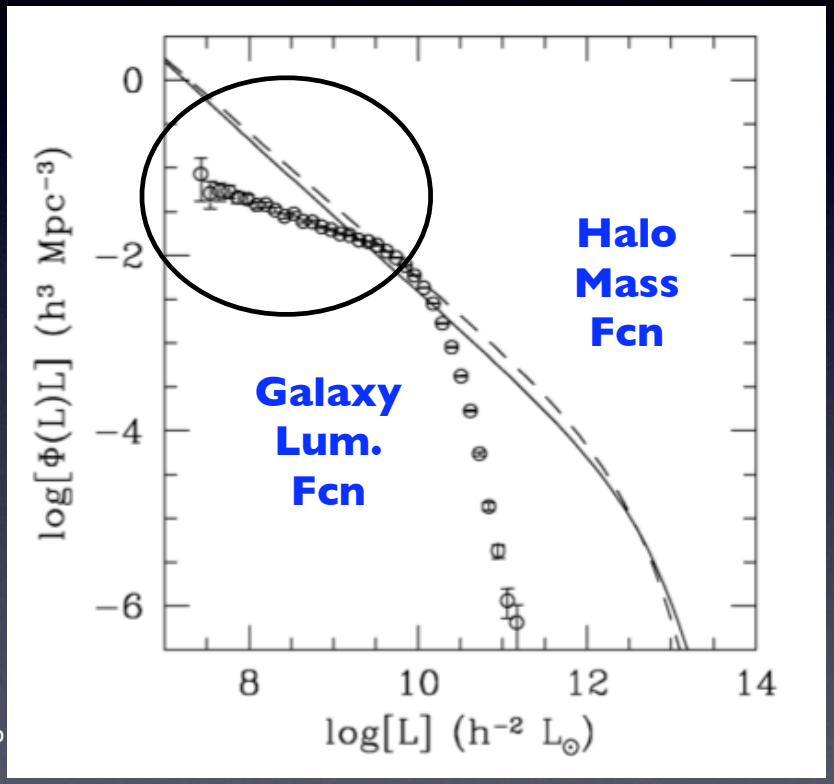
momentum conservation

$$\dot{M}_{wind} V_{wind} \sim \frac{L}{c} \rightarrow \dot{M}_{wind} \propto \dot{M}_* V_{max}^{-1}$$

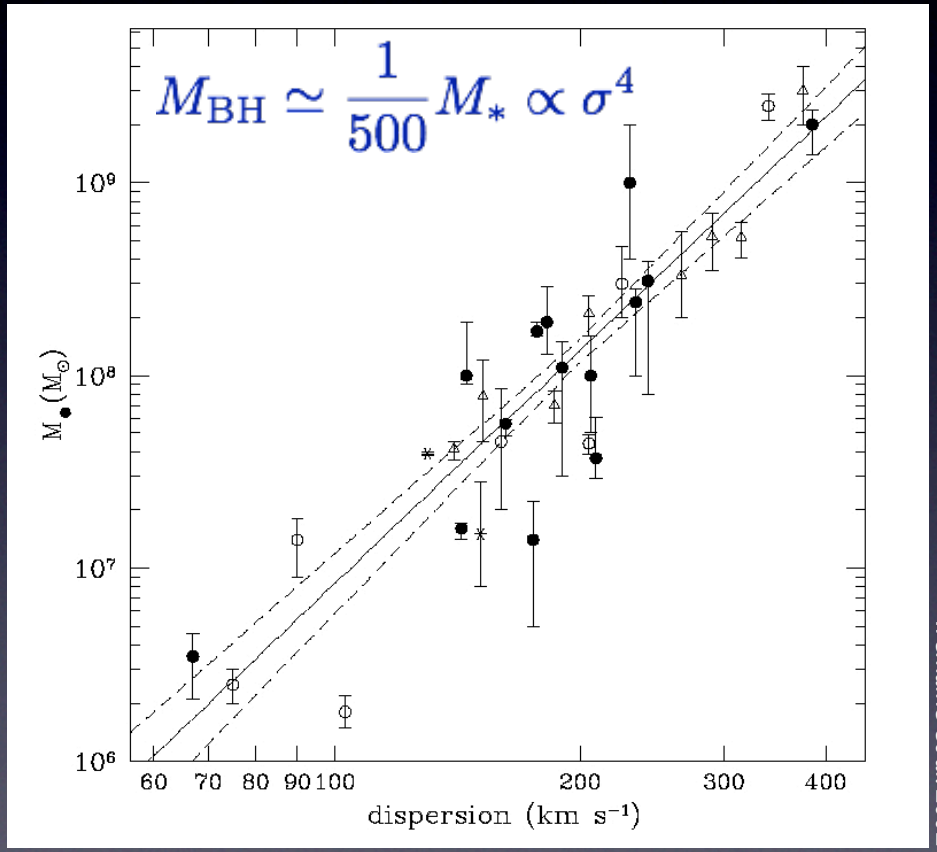
Best-Fit to Sims

$$\dot{M}_{wind} \sim 10\,\dot{M}_* \left(\frac{V_{max}}{100\,\mathrm{km\,s^{-1}}}\right)^{-1} \left(\frac{\Sigma_{gas}}{10\,M_\odot\,pc^{-2}}\right)^{-1/2}$$

What is it Good For?



Yang et al. 2003



Tremaine et al. 2002

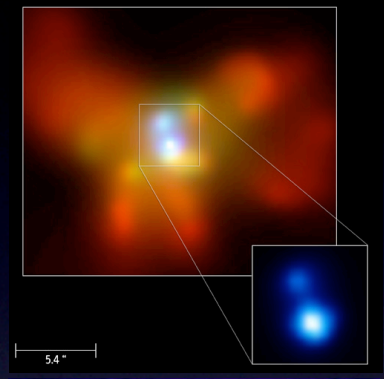
Feedback from a Central AGN

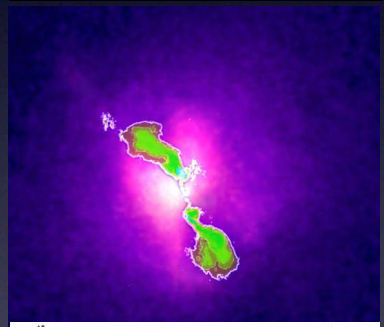
Major Science Questions

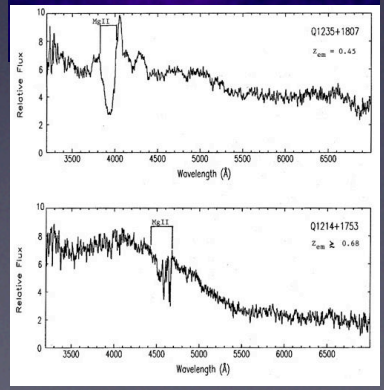
- Can quasars suppress/quench star formation in galaxies?
  - Which physical mechanisms dominate (radiation, winds, jets, ...)
- What determines the M_{BH}-σ relation? Feedback or Fueling?
- What htg balances radiative losses in massive halos?
  - Radio-loud AGN (i.e., jets)? What about at ~ $10^{12\text{-}13}\ M_\odot$ halos?
- How much does large-scale structure formation determine properties/evolution of BH population?

Feedback from a Central AGN

- Photons
  - UV: $\dot{P} \sim L/c$ (absorbed by dust): $\kappa_{UV} \sim 10^3\ cm^2\ g^{-1} \sim 10^3$ e scatt
  - FIR: $\dot{P} \sim \tau_{FIR} L/c$ ($\tau_{FIR} \sim$ 10-100 in galactic nuclei)
  - Compton Heating (low density gas)
- Jets
  - $\dot{E}_{jet} \sim L$ in radio loud objects
  - heat IGM/ICM (low ρ), but not dense ISM
- Winds
  - BAL-QSO winds
    - seen in ~ 40% of quasars (IR-selected); quasi-equatorial
    - $\dot{P} \sim$ few L/c (Arav+); $v \sim 10^4$ km/s; $\dot{E} \sim 0.02$ L







Di Matteo, Springel, Hernquist, Hopkins, ...

The Quasar Bomb

$\dot{E} \sim 0.05\ L$ (thermal htg)

quenches star formation

observationally very successful

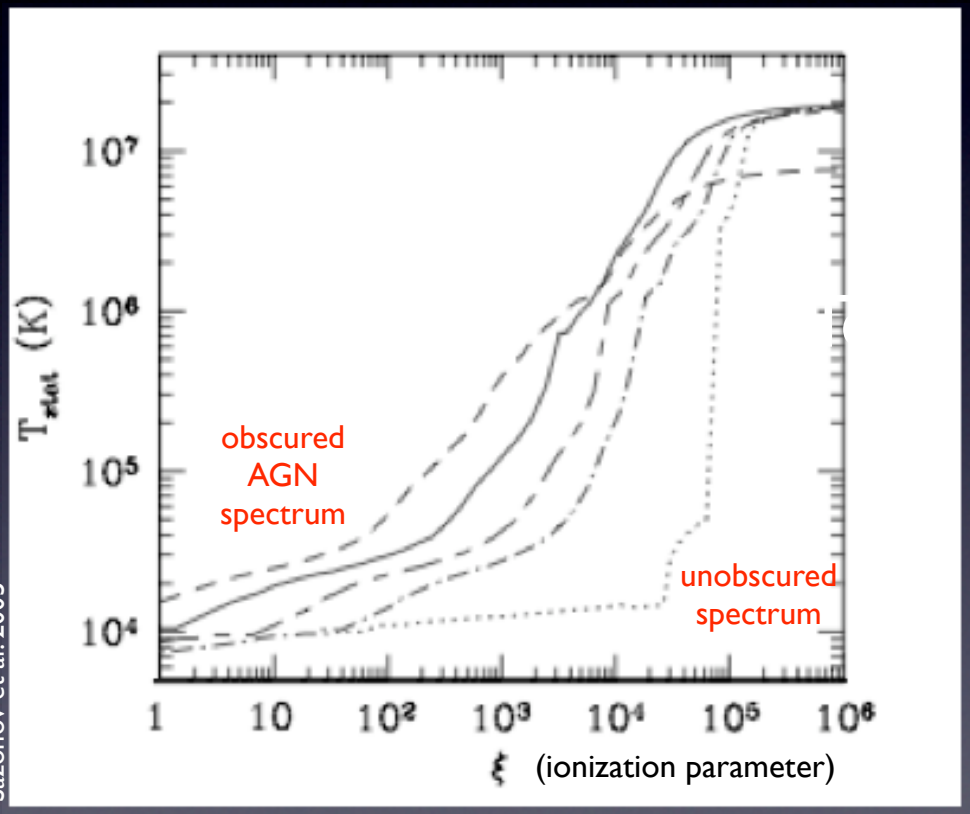
what is the underlying physics?

is it robust? or do the results

depend on σ? fg? metallicity? ...

Feedback from a Central AGN

radiative impact of AGN



Sazonov et al. 2005

Atomic cooling only; molecular gas/dust mix would cool to T < 100 K for $\xi \lesssim 10^{2\text{-}3}$

$$\xi \equiv \frac{L}{nr^2} \simeq 10 \left(\frac{L}{L_{\rm Edd}}\right) \times \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right) \left(\frac{n}{10^4\,{\rm cm}^{-3}}\right)^{-1} \left(\frac{r}{100\,{\rm pc}}\right)^{-2}$$

(ξ ind of r for Q ~ 1)

→ no AGN "heating" but momentum is imparted

Feedback from a Central AGN

Dust in the host Galaxy absorbs the AGN's radiation

$$\frac{\mathrm{L}}{\mathrm{c}} > \frac{GMM_g}{r^2}$$

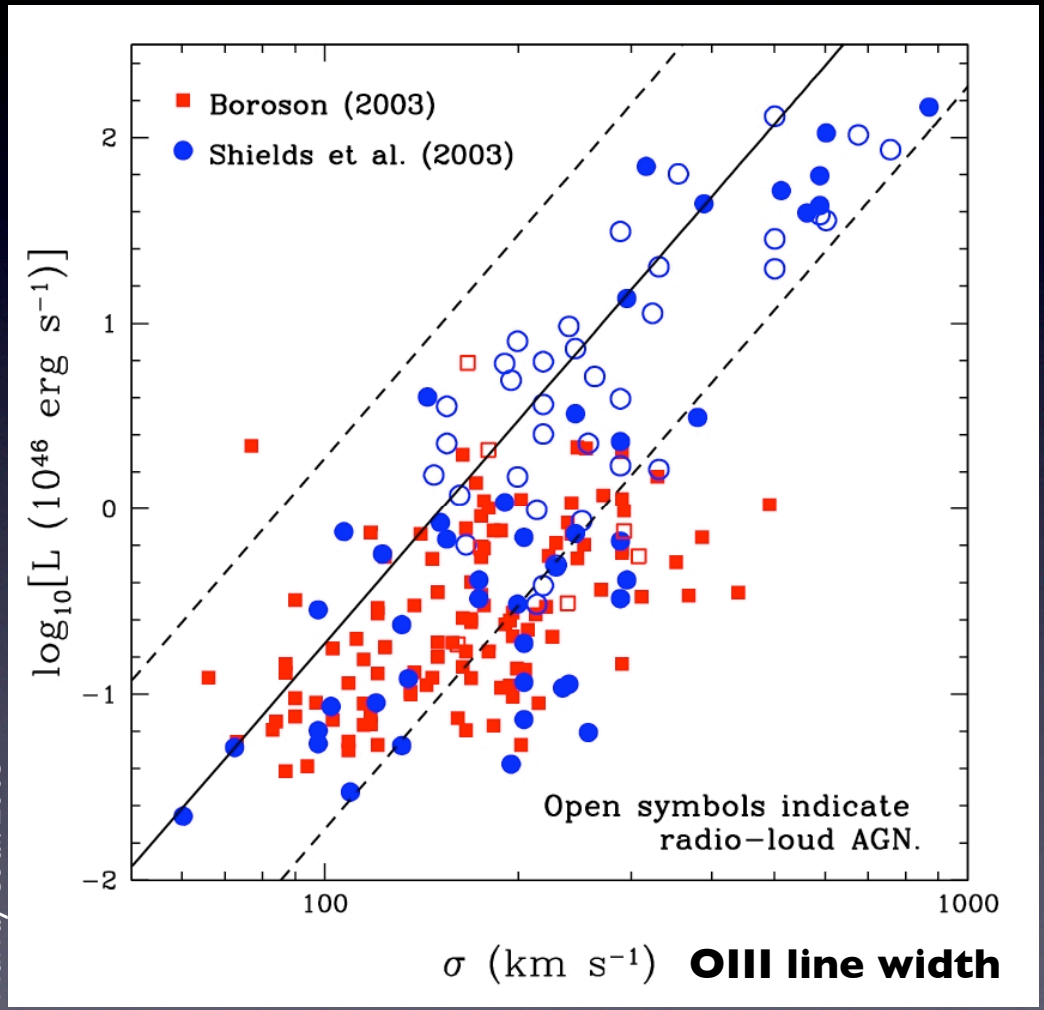
$$M(r) = \frac{2\sigma^2 r}{G} \quad M_g = fM \quad (\sigma \sim \text{constant})$$

For L > L_M momentum injection is sufficient to blow away all of the gas in a galaxy

$$L_M \sim \frac{4f\sigma^4 c}{G} \sim 3 \times 10^{46}\, f_{0.1}\, \sigma_{200}^4\, \mathrm{ergs\,s^{-1}}$$

Conjecture: L_M is an upper limit to the luminosity of an accreting BH; systems that reach L_M self-regulate and L does not increase further

The Maximum Luminosity of Quasars

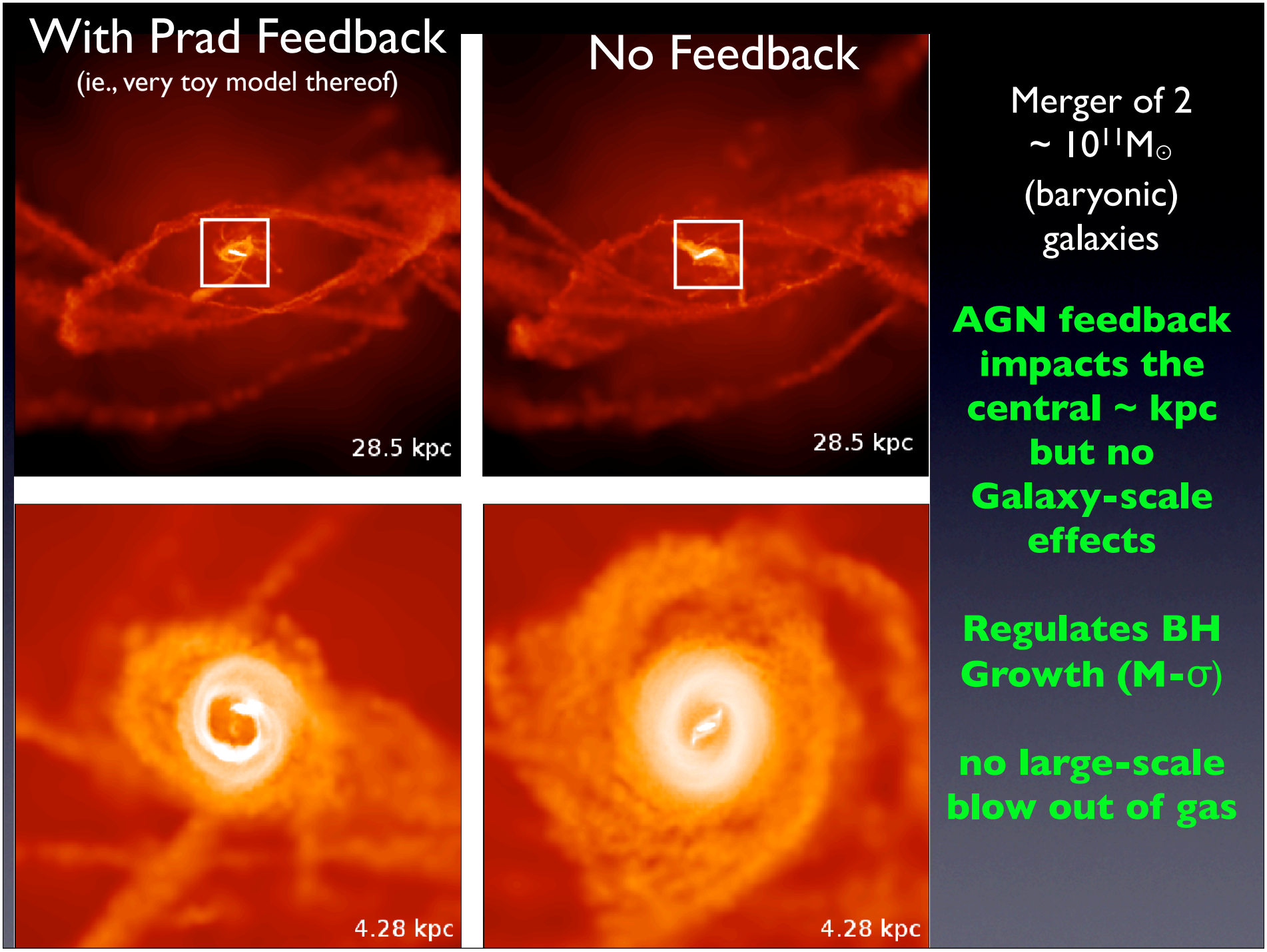


Murray et al. 2005

AGN reach ~ L_M when

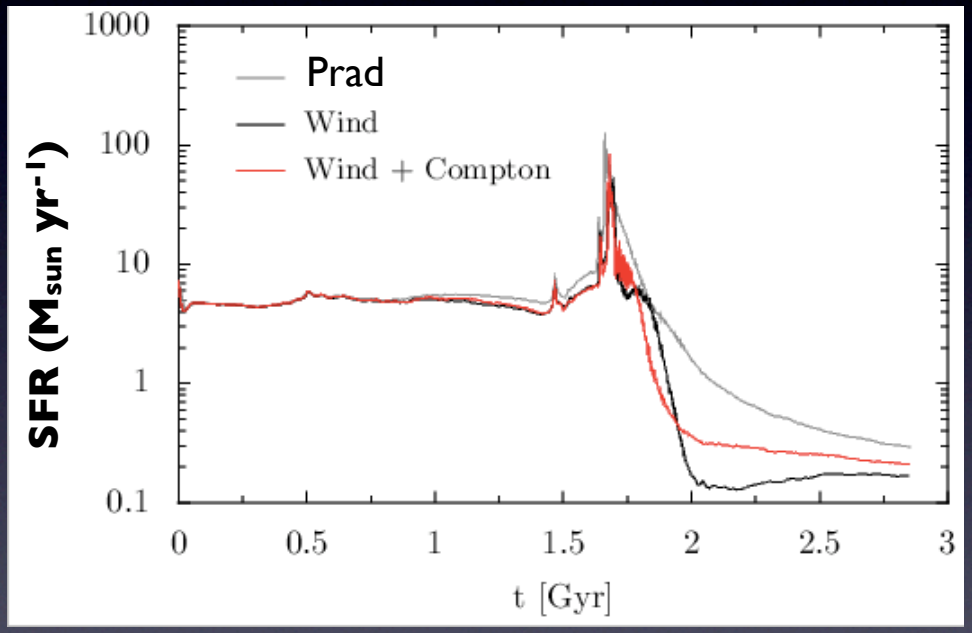
$$M_{\rm BH} \sim 10^8\, f_{0.1}\, \sigma_{200}^4\, M_\odot$$

in agreement
w/ observed
M_{BH}-σ relation


With Prad Feedback
(ie., very toy model thereof)
No Feedback
28.5 kpc
28.5 kpc
4.28 kpc
4.28 kpc
Merger of 2
~ $10^{11} M_\odot$
(baryonic)
galaxies
AGN feedback impacts the central ~ kpc but no Galaxy-scale effects
Regulates BH Growth (M-σ)
no large-scale blow out of gas

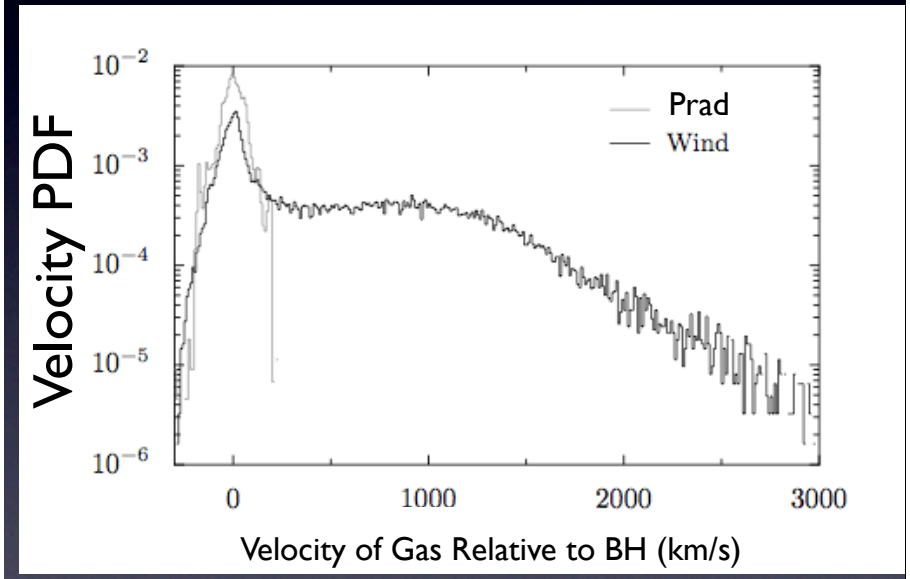
(Partially) Suppressing Star Formation via BAL Quasar Winds

- BAL-QSO wind seen in ~ 40% of quasars -- plausibly present in all
- ~ equatorial with $\dot{P} \sim L/c$ (Arav+); $v \sim 10^4$ km/s; $\dot{E} \sim 0.02\ L$
- Believed to be launched at ~ $10^{3\text{-}4}$ Schwarzschild radii = subgrid!



Effects of QSO wind
during major merger
(with & without Compton htg)

partially stifles star formation for BHs at ~ M_{BH}-σ
(though small dense nuclear disk always remains ...)



Interaction btw. QSO wind & ISM drives
galactic wind: v ~ 1000 km/s, $\dot{M}_{wind} \sim \dot{M}_*$

origin of molecular (OH, CO) outflows
observed in local ULIRGs (Sturm+, Maiolino+)?

Normalization of M_{BH}-σ

- Di Matteo et al.: $\dot{E} \sim 0.05$ L Required
- Our work: $\dot{P} \sim 10$ L/c ($\dot{E} \sim \dot{P}\sigma \sim 0.01$ L)
  - Good: not totally dissimilar ...
  - Bad: Pretty Efficient Feedback
    - $\tau_{FIR} \sim$ 10-100 in ULIRGs
- Reality: CO/OH outflows have $\dot{P} \sim 10\ L_{AGN}/c$

Summary

- Feedback is important for a wide variety of problems in galaxy formation (although likely not as many as it is invoked for!)
- Dense Gas: "Pushing" dominates (momentum), not "heating" (energy)
  - $\dot{P}_{radiation} \Rightarrow$ reasonable 'cycle' of GMC formation & destruction; Kennicutt Laws ....
  - $\dot{P}$ & $\dot{E} \Rightarrow$ galactic winds ~ those observed; $\dot{M}_{wind} >> \dot{M}_{*}$ in low mass galaxies
- AGN Feedback in the dense ISM: largely $\dot{P}$, not $\dot{E}$
  - M-σ reqs very efficient coupling: $\dot{P} \gtrsim 10\ L/c$ (τ_{FIR} ~ 10-100 in galactic nuclei)
  - BAL-QSO winds help quench star formation $\Rightarrow$ galactic winds ~ ULIRG molecular outflows

Next Time