Feedback from Radiation Pressure during Galaxy Formation

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w/ Norm Murray, Jackson Debuhr, Phil Hopkins....

Spitzer's view of Carina

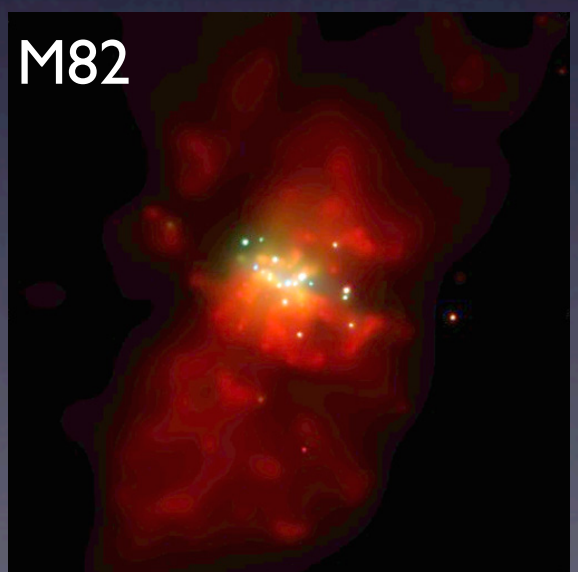
Outline

- Feedback: What is it good for?
  - Absolutely Everything ....
- Feedback 101: the Physics of Feedback
  - Energy vs Momentum
- Feedback from momentum (rad pressure) during
  - Star Formation
  - The Growth of Massive Black Holes

Feedback 101

Energy
(dilute gas)

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

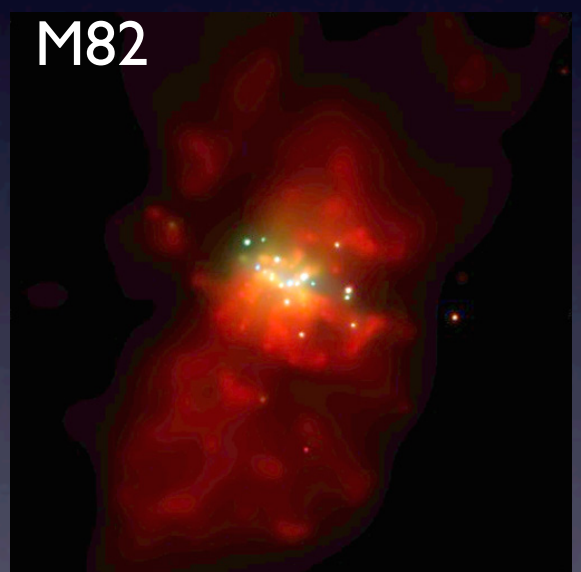


Momentum
(dense gas; energy radiated)

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

Feedback 101

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

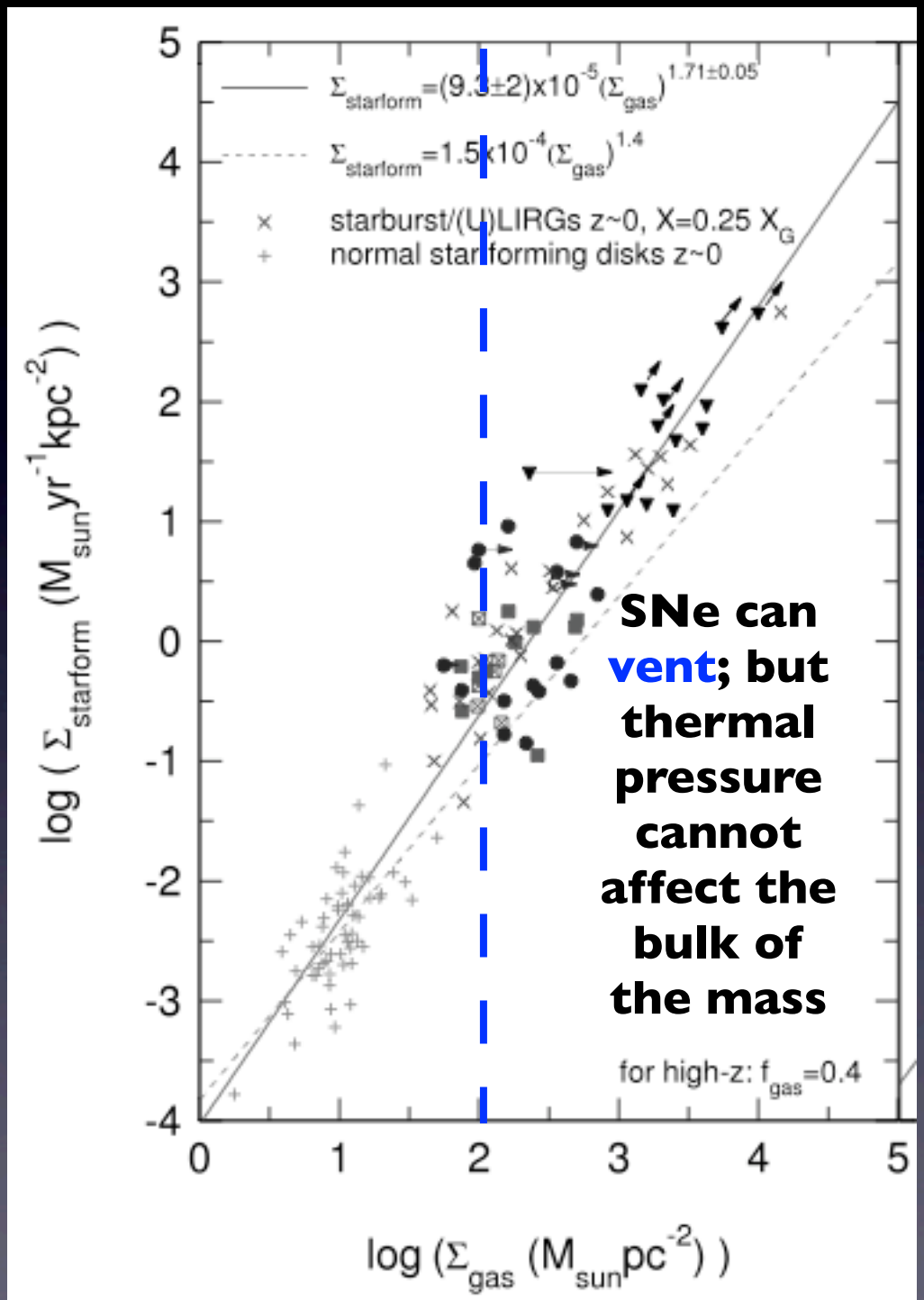


Σ_g (cold gas)

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



Bulk of the Mass Stirred up by ***Momentum*** (photons, radiative SNe, CRs)

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

Driving Turbulence in Dense Gas

GMC w/ embedded star cluster

Analytic Studies:

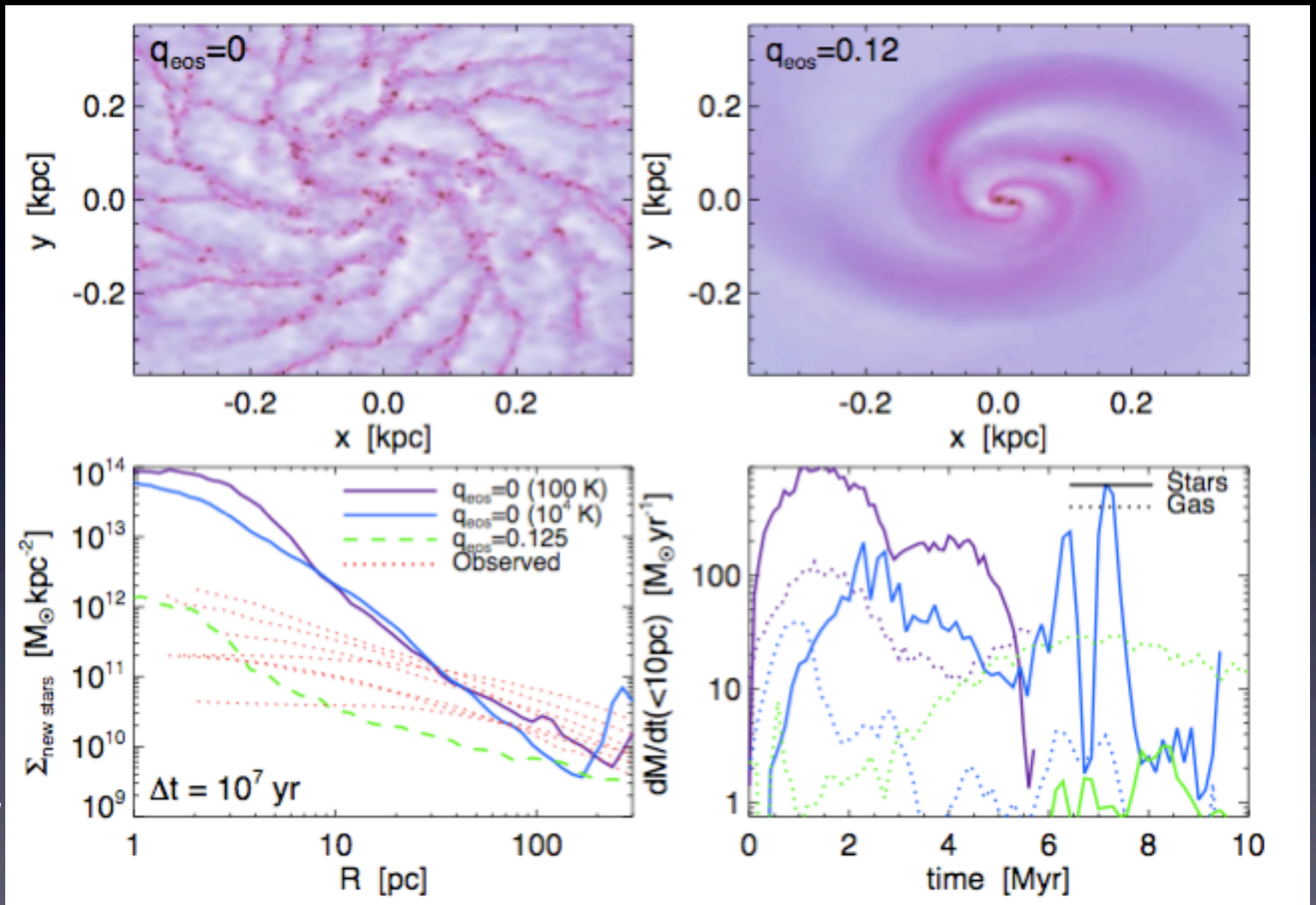
Rad Pressure contributes significantly to GMC destruction & ISM turbulence (from MW to ULIRGs)

Krumholz+; MQT

Why is this Important? Gas Inflow in Galaxies

Isothermal EOS: T ~ 100 K

Stiffer EOS



PH & EQ

Both of these Sims are Wrong

Need to both form and disrupt GMCs (e.g., Genel+)

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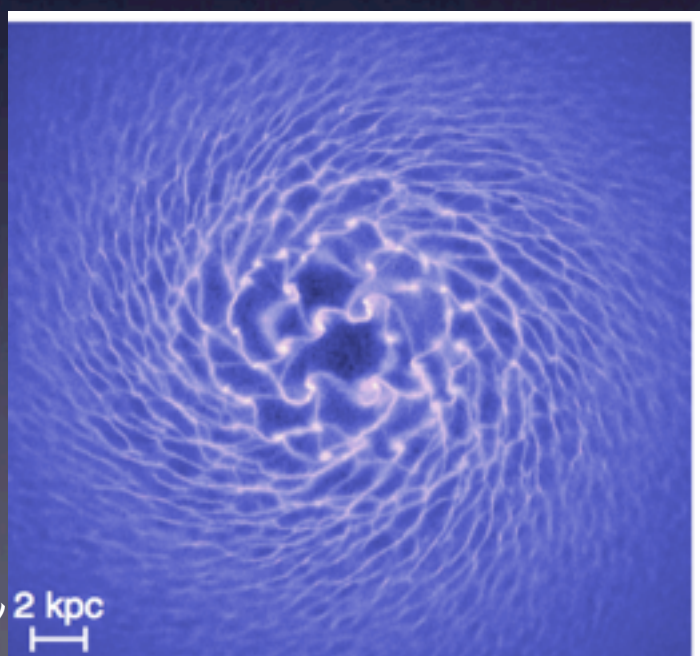
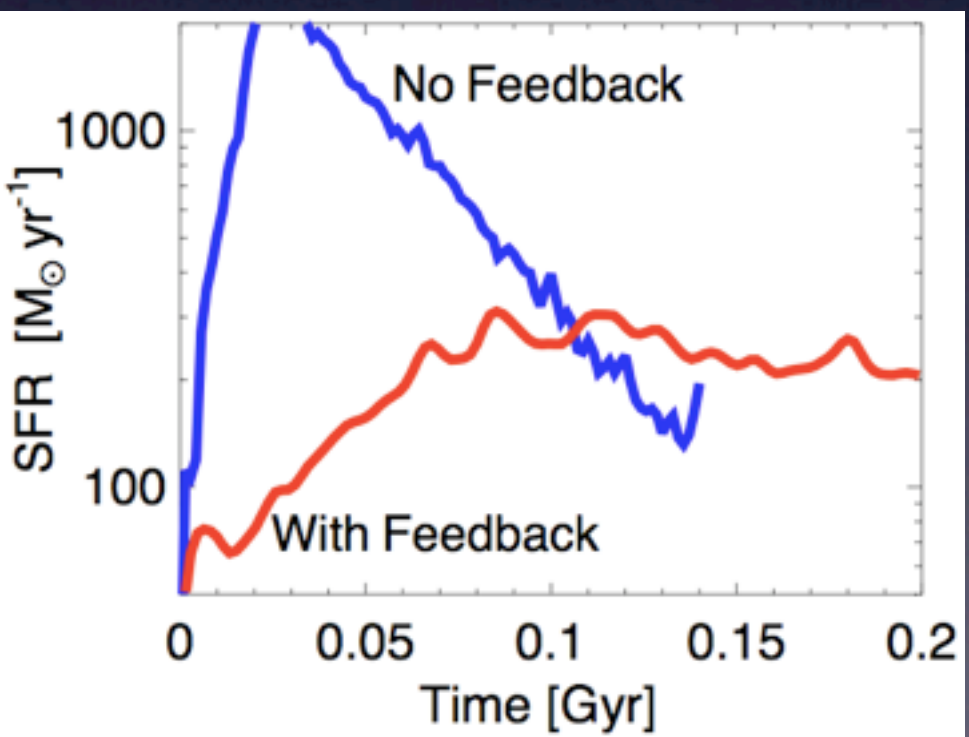


gas-rich z ~ 2 galaxy (isolated)

PH & EQ



Feedback from the Central AGN

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

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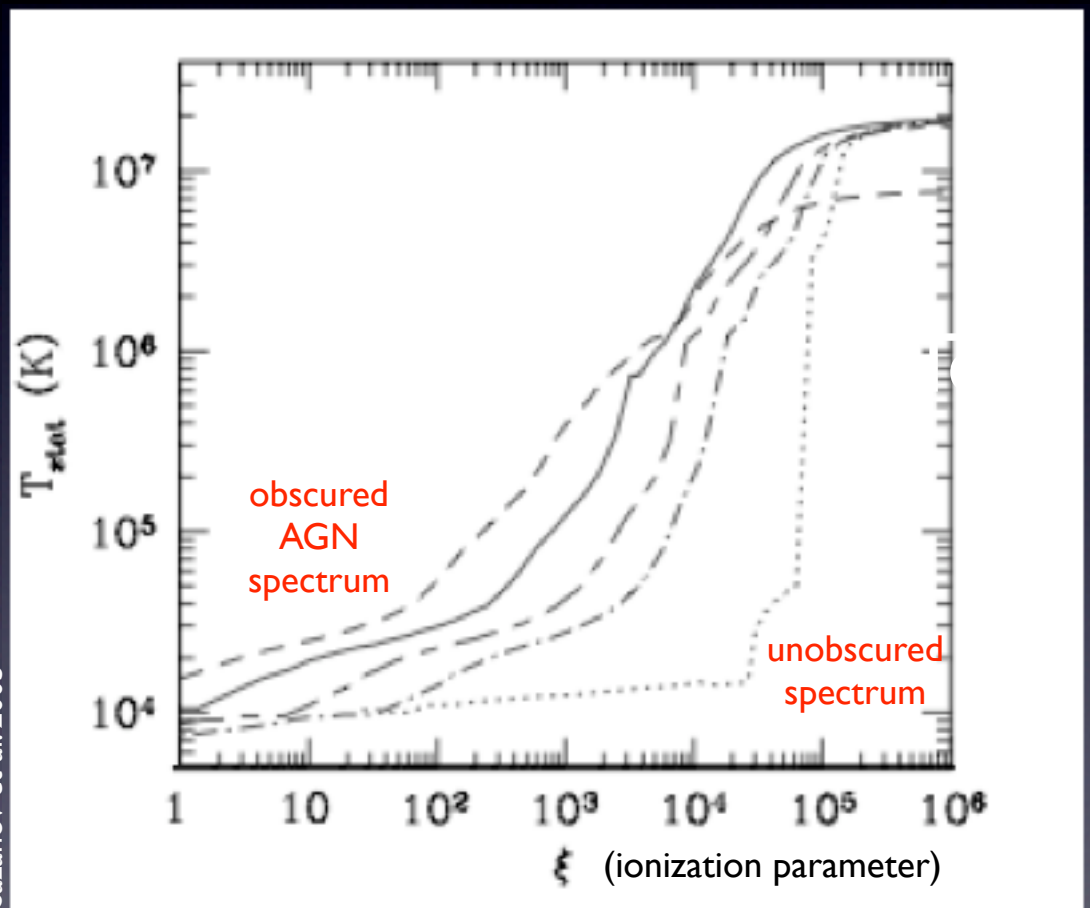

Sazanov et al. 2005

Atomic cooling only; molecular gas/dust mix would cool to T < 100 K for low/moderate ξ

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

(ξ ind of r for Q ~ 1)

→ no AGN "heating" but momentum is imparted

Feedback from the Central AGN

Dust in the host Galaxy absorbs the AGN's radiation

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

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

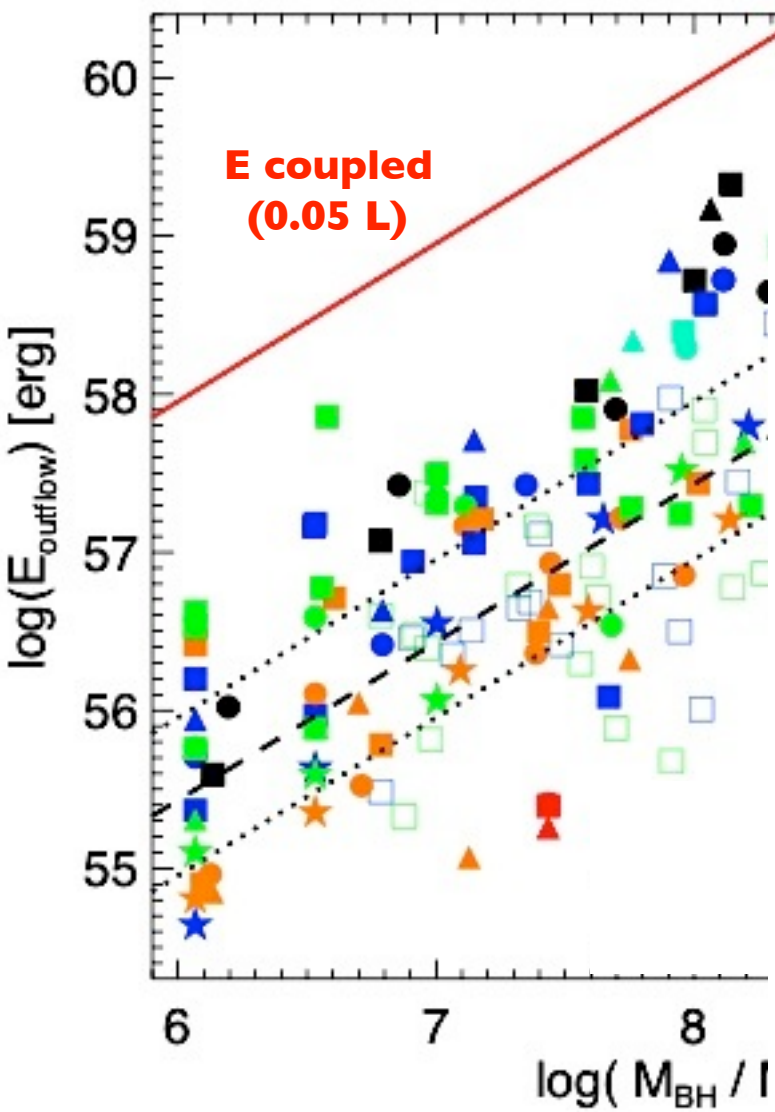
For L > L_M momentum injection is sufficient to blow away all of the gas in a galaxy

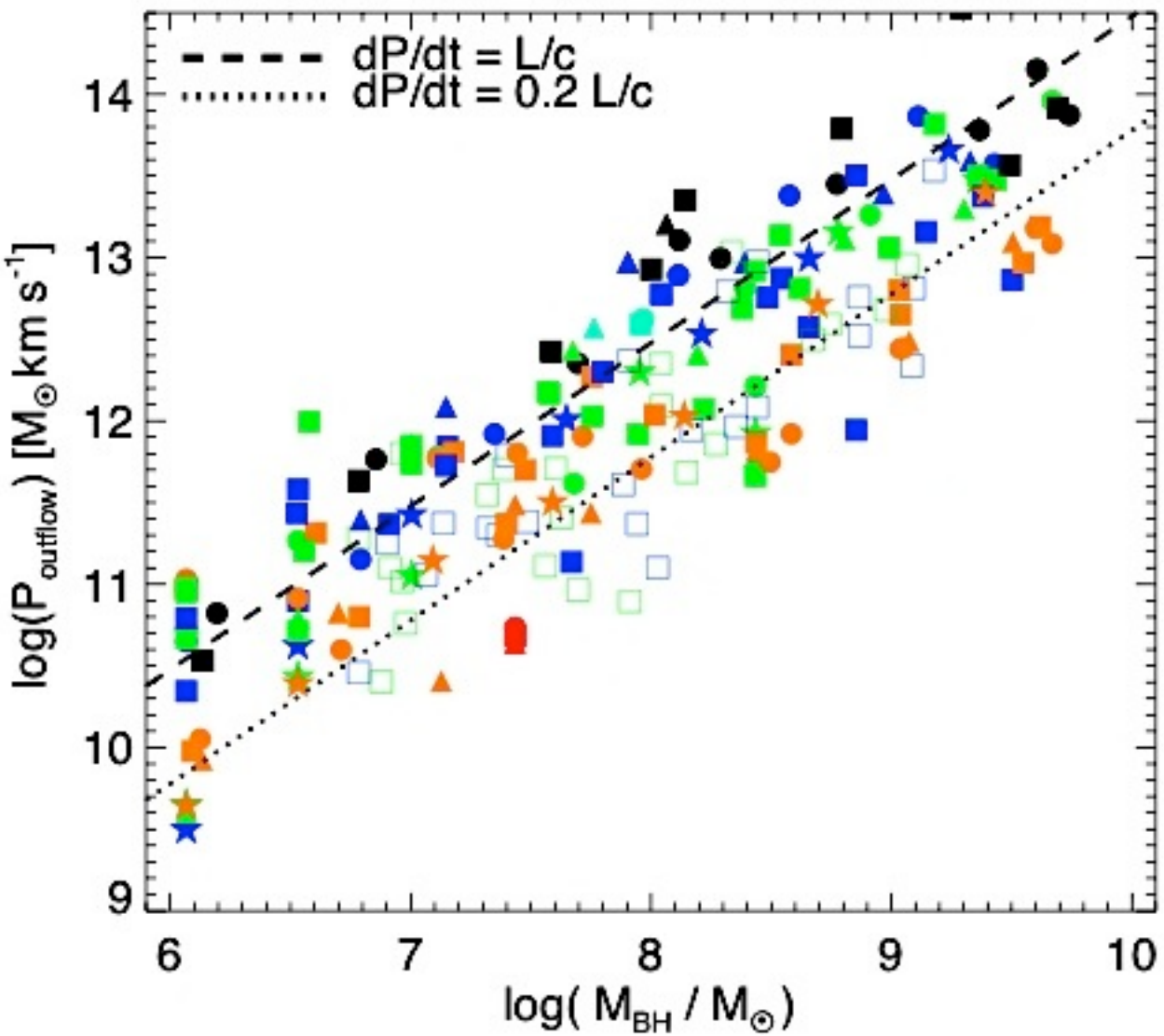
$$L_M \sim \frac{4f\sigma^4 c}{G} \sim 3 \times 10^{46}\, f_{0.1}\, \sigma_{200}^4\, \mathrm{ergs\,s^{-1}}$$

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

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

MOMENTUM IS WHAT MATTERS ON LARGE SCALES!





Slide From Phil Hopkins

BH Growth & AGN Feedback in Numerical Simulations

(Jackson Debuhr, EQ, Phil Hopkins, Chung-Pei Ma)

- SPH sims w/ Gadget
  - isolated galaxies; mergers, ...
- BHs: accreting sink particles
  - **How do BHs get their gas?**
- "Radiative" Feedback
  - Simple model: addtl force ∋ τL/c absorbed by nearest N ~ $10^{3\text{-}4}$ particles
    - Results weakly dependent on N (pressure redistributes momentum)

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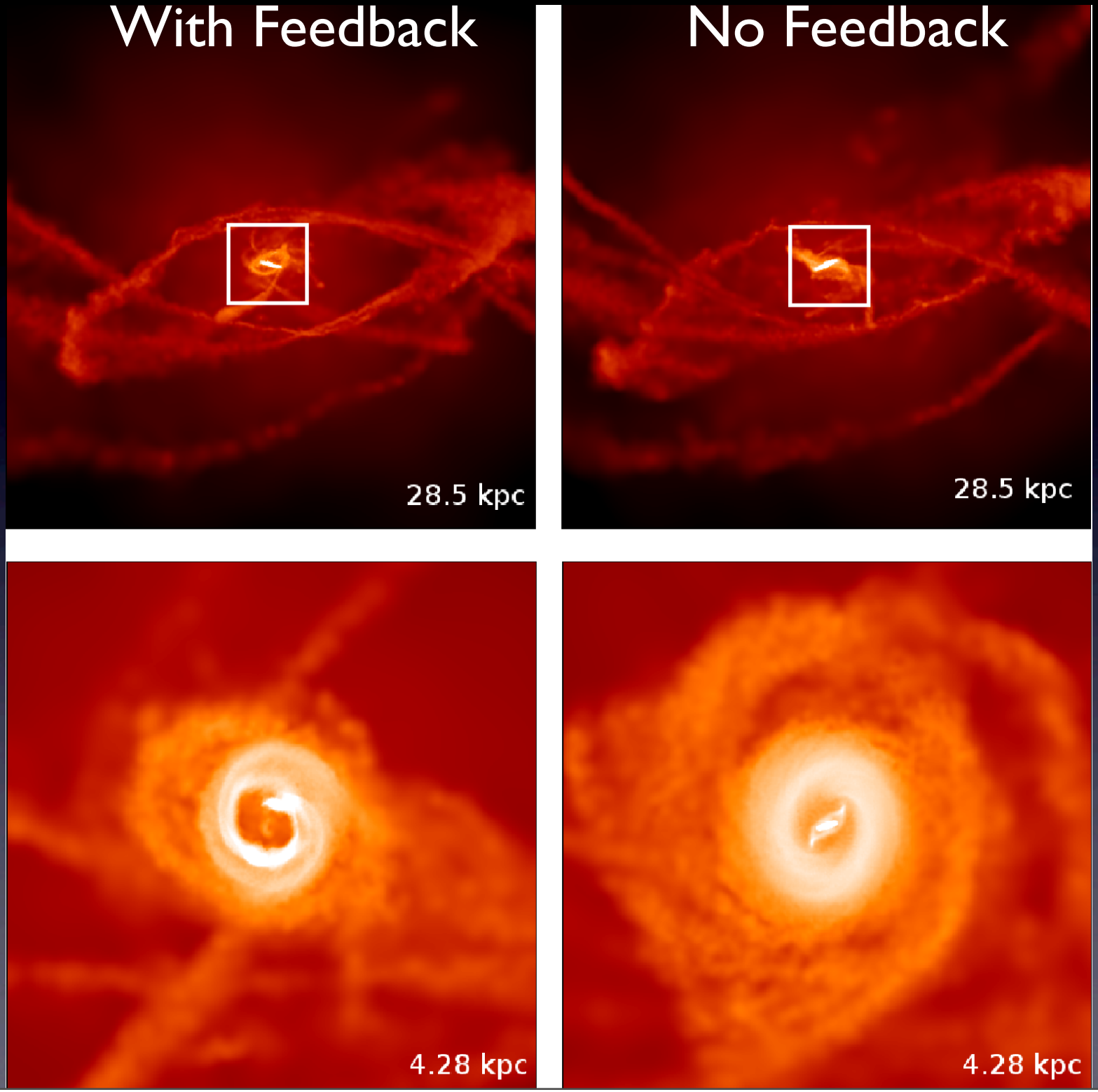
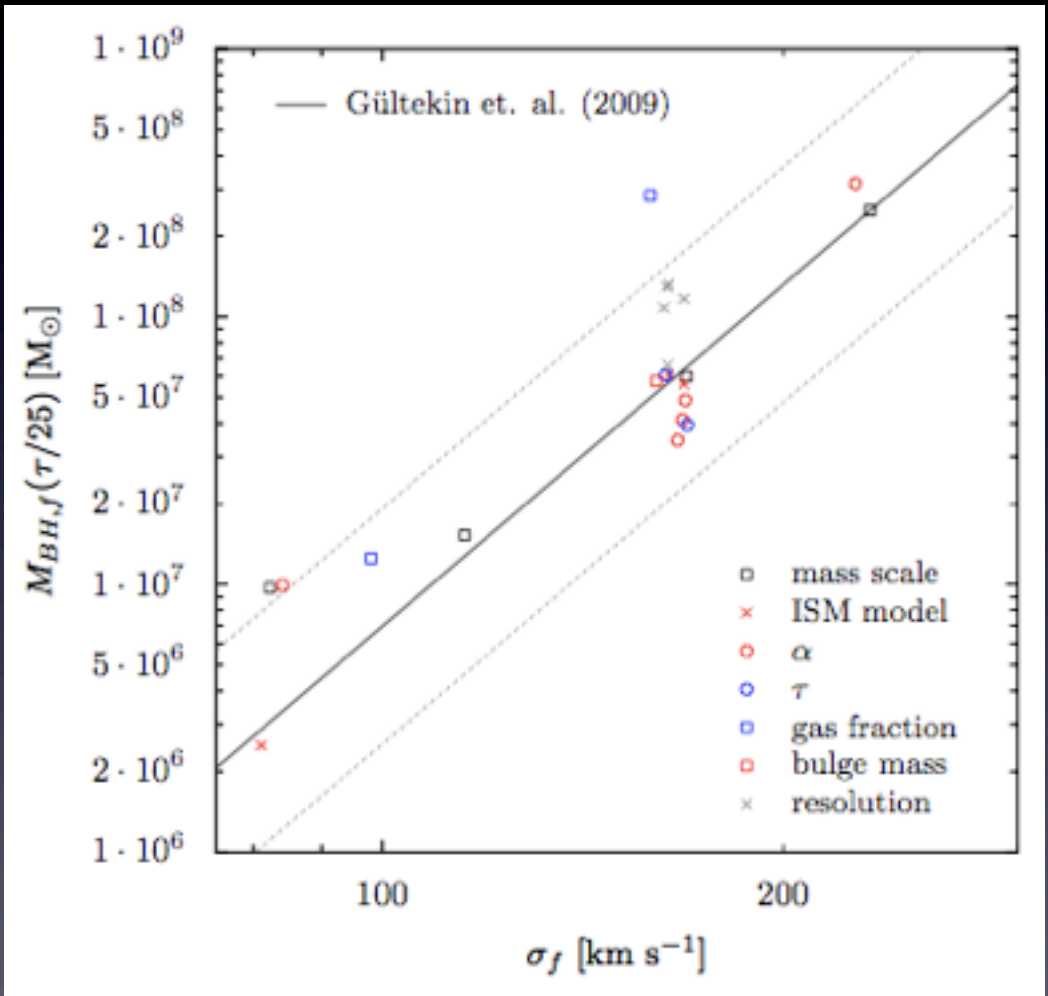


Merger of 2
~ 10^{11} $M_\odot$
(baryonic)
galaxies

BH impacts the central ~ kpc but no Galaxy-scale effects

no large-scale blow out of gas

What sets M_{BH} & M_{star} in galaxy mergers (sims)?



AGN feedback has ...

little effect on stellar mass formed

strong effect on BH mass: sets M_{BH}-σ

M_{BH}-σ reqs τ ~ 25, i.e, $\dot{P} \sim 25\ L/c$

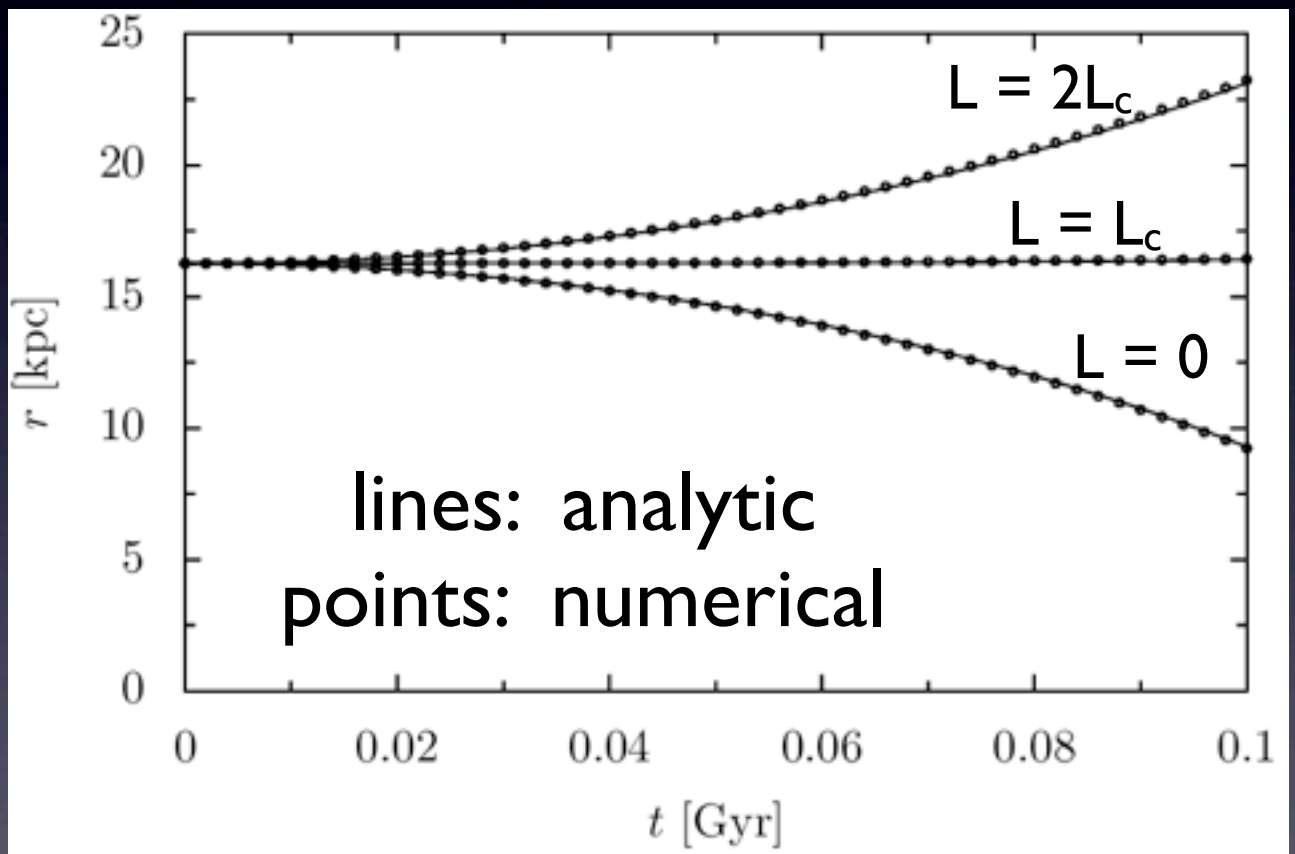
(similar to $\dot{E} \sim 0.05\ L$ in Di Matteo+ 05)

reproducing this efficient coupling very non-trivial

Summary

- Feedback is important for a wide variety of problems in galaxy formation (although likely not as many as it is invoked for!)
- "Pushing" (momentum), rather than "heating" (energy), dominates feedback for dense gas, i.e., for most of the mass
  - impt in both star forming units (molecular clouds) & larger scales
- AGN Feedback in the dense ISM: Momentum, not Energy
  - BH growth self-regulates on sub-kpc scales: M-σ relation
    - reqs very efficient coupling: $\tau \sim 25$ (during mergers)
  - Little effect on star formation; not nec. galactic-scale blowout

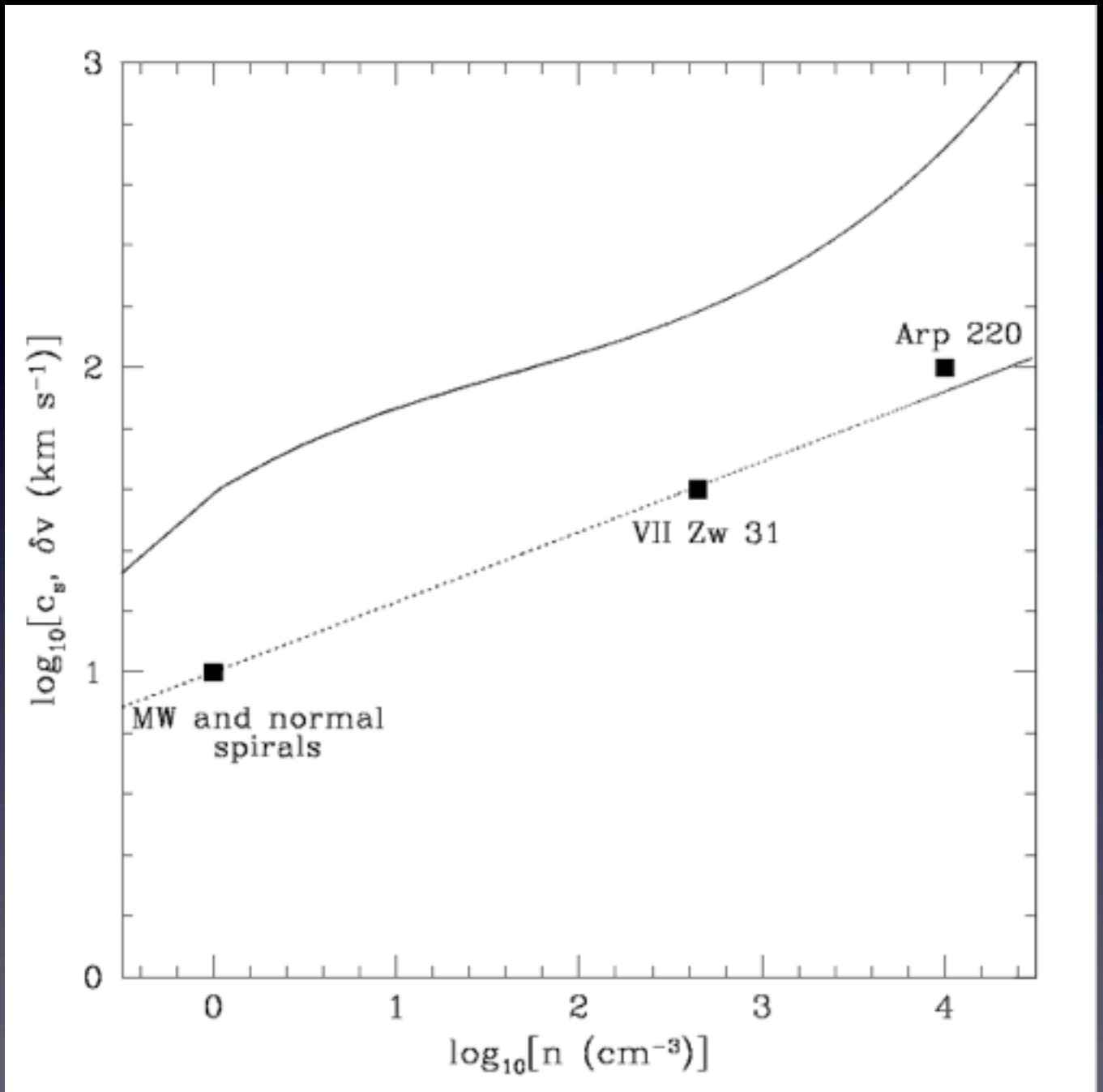
Test of Extra Force



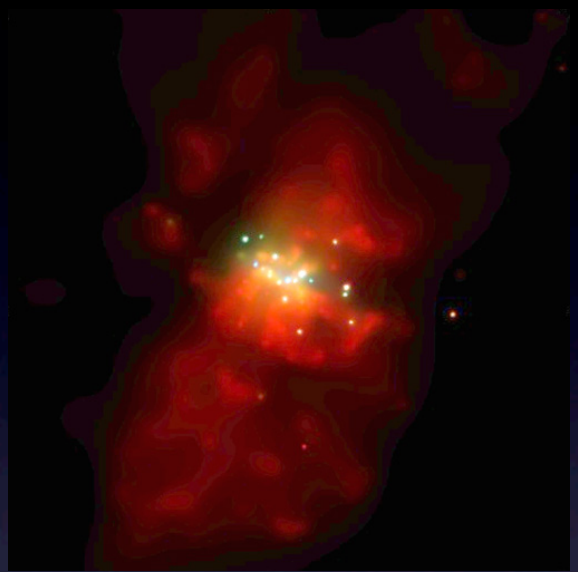
spherical isothermal potential

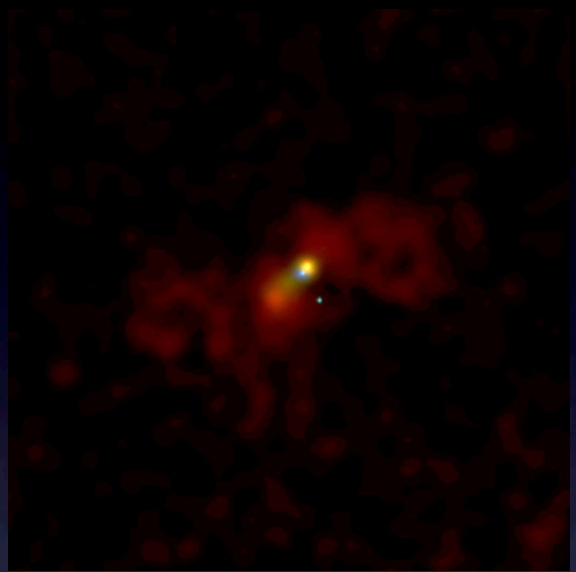
spherical shell of mass M_g

$$\frac{L_c}{c} \equiv \frac{GMM_g}{r^2}$$

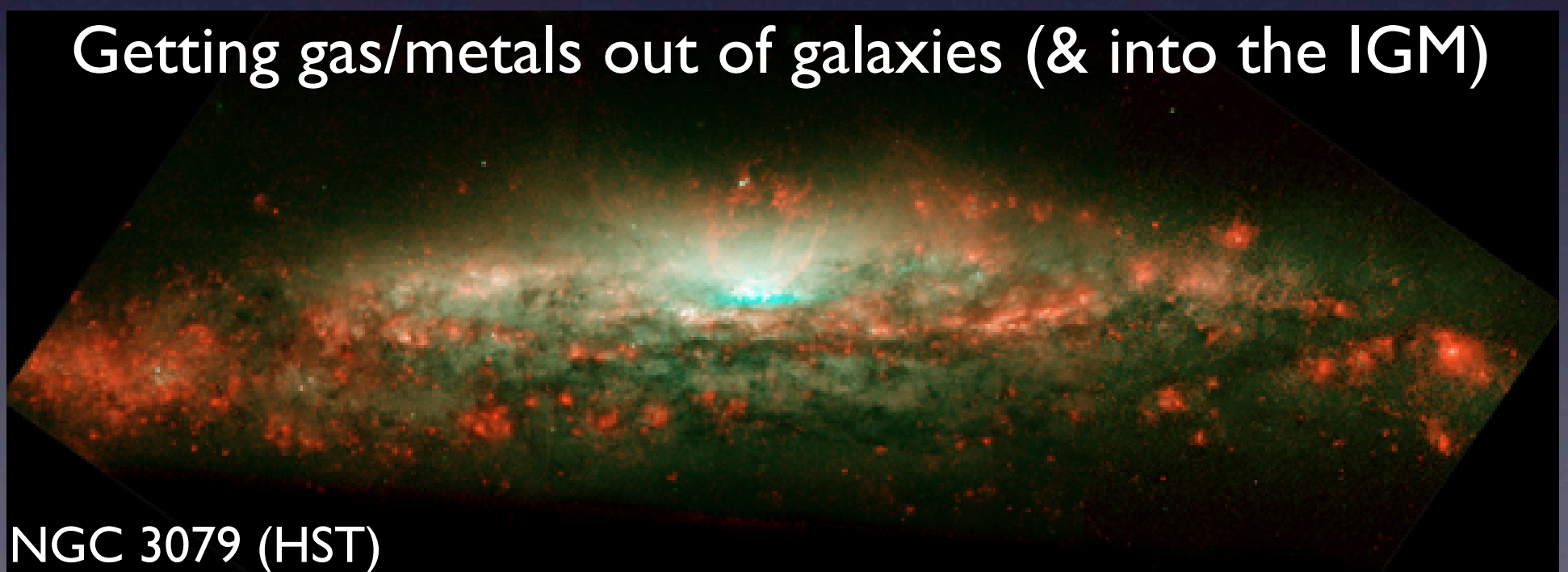

3
2
1
0
0
1
2
3
4
$\log_{10}[c_s,\ \delta v\ (\mathrm{km\ s^{-1}})]$
$\log_{10}[n\ (\mathrm{cm^{-3}})]$
Arp 220
VII Zw 31
MW and normal
spirals

What is it Good For?





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



NGC 3079 (HST)

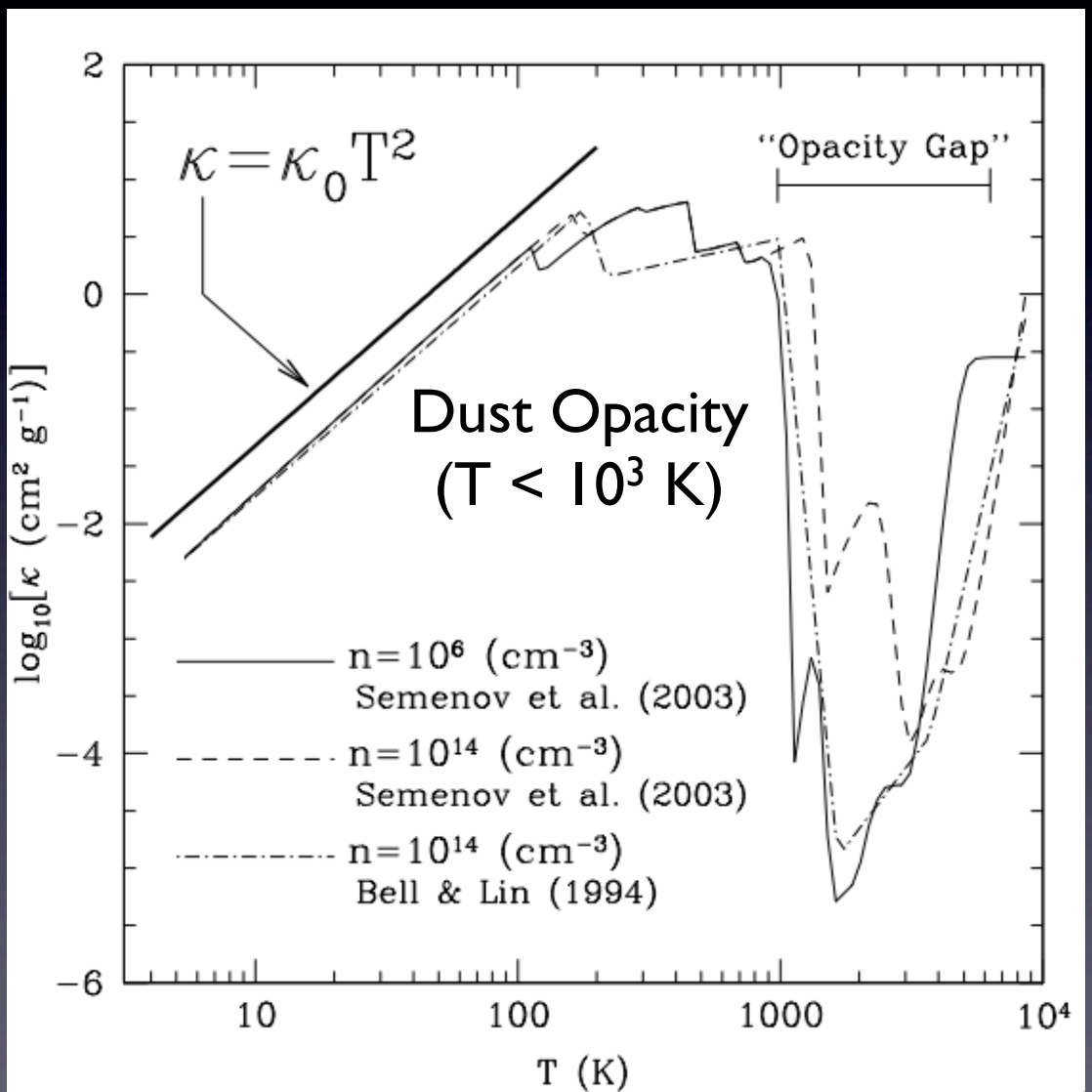
The Schmidt Law(s)

- Observed: $\dot{\Sigma}_* \sim 0.02\Sigma\Omega$ and $\dot{\Sigma}_* \propto \Sigma^{1.5}$

$$Q \sim 1 \rightarrow \rho \sim \Omega^2/2\pi G$$

$$\mathrm{H} \sim \mathrm{constant} \rightarrow \delta v \propto \Sigma^{1/2}$$

Opacity


$\kappa = \kappa_0 T^2$
"Opacity Gap"
Dust Opacity
(T < 10³ K)
n=10⁶ (cm⁻³)
Semenov et al. (2003)
n=10¹⁴ (cm⁻³)
Semenov et al. (2003)
n=10¹⁴ (cm⁻³)
Bell & Lin (1994)
log₁₀[κ (cm² g⁻¹)]
T (K)
2
0
−2
−4
−6
10
100
1000
10⁴