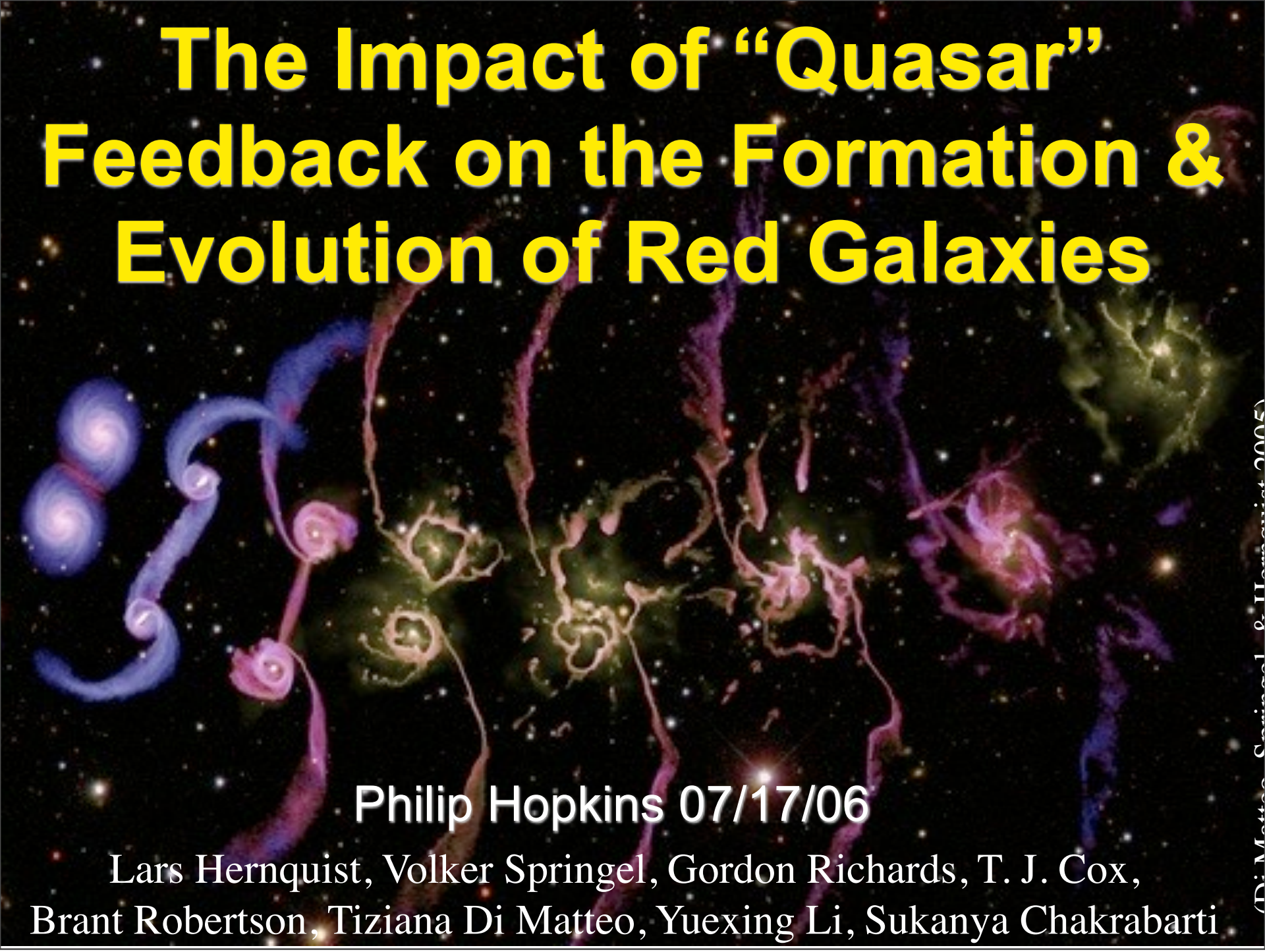
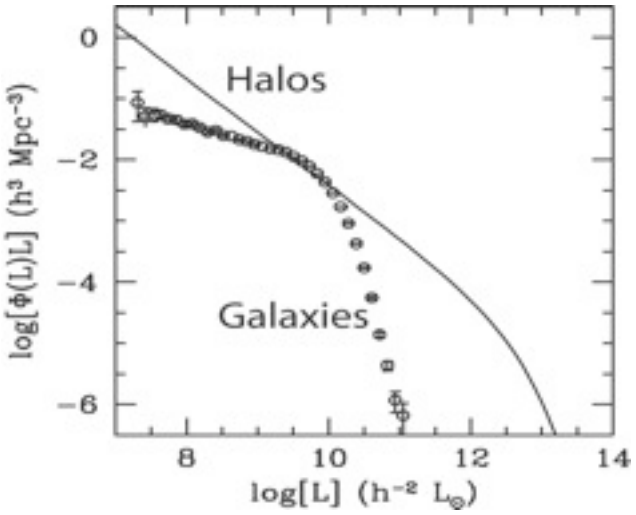
The Impact of "Quasar" Feedback on the Formation & Evolution of Red Galaxies

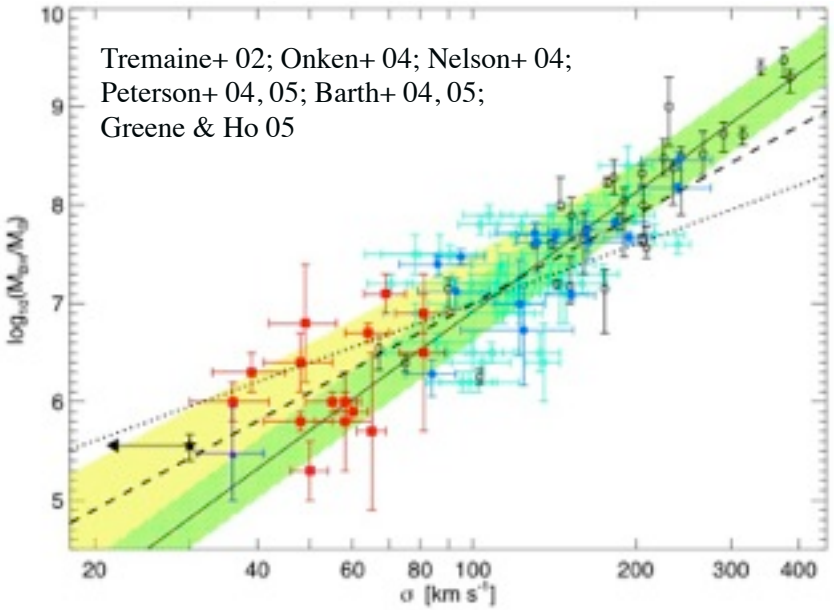


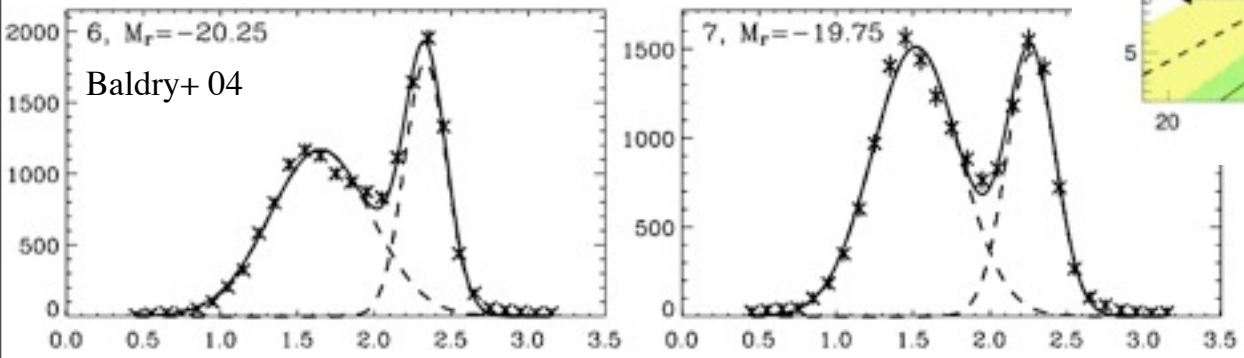
Philip Hopkins 07/17/06

Lars Hernquist, Volker Springel, Gordon Richards, T. J. Cox,
Brant Robertson, Tiziana Di Matteo, Yuexing Li, Sukanya Chakrabarti

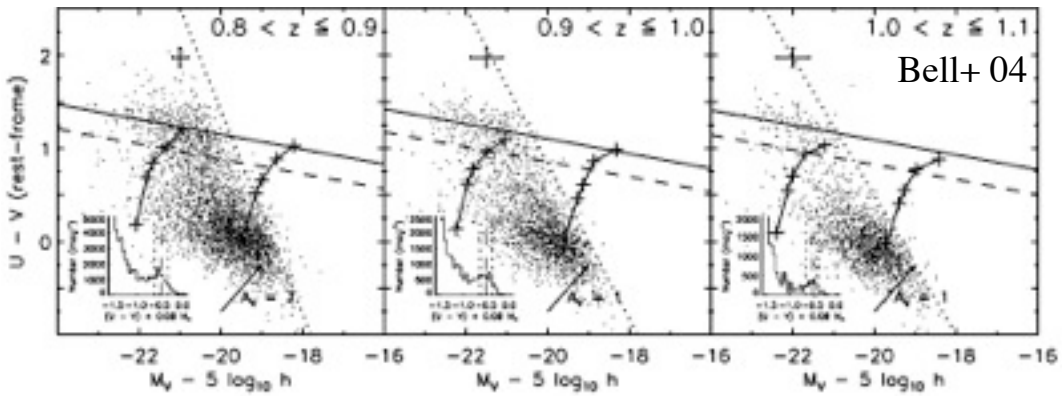
Motivation

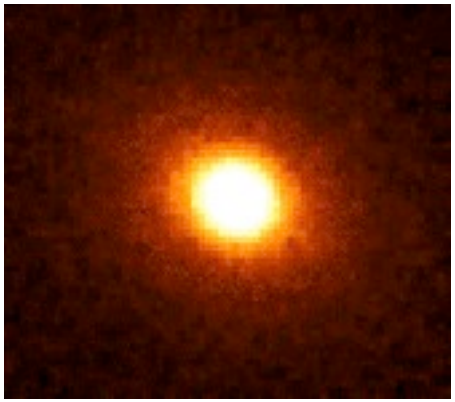




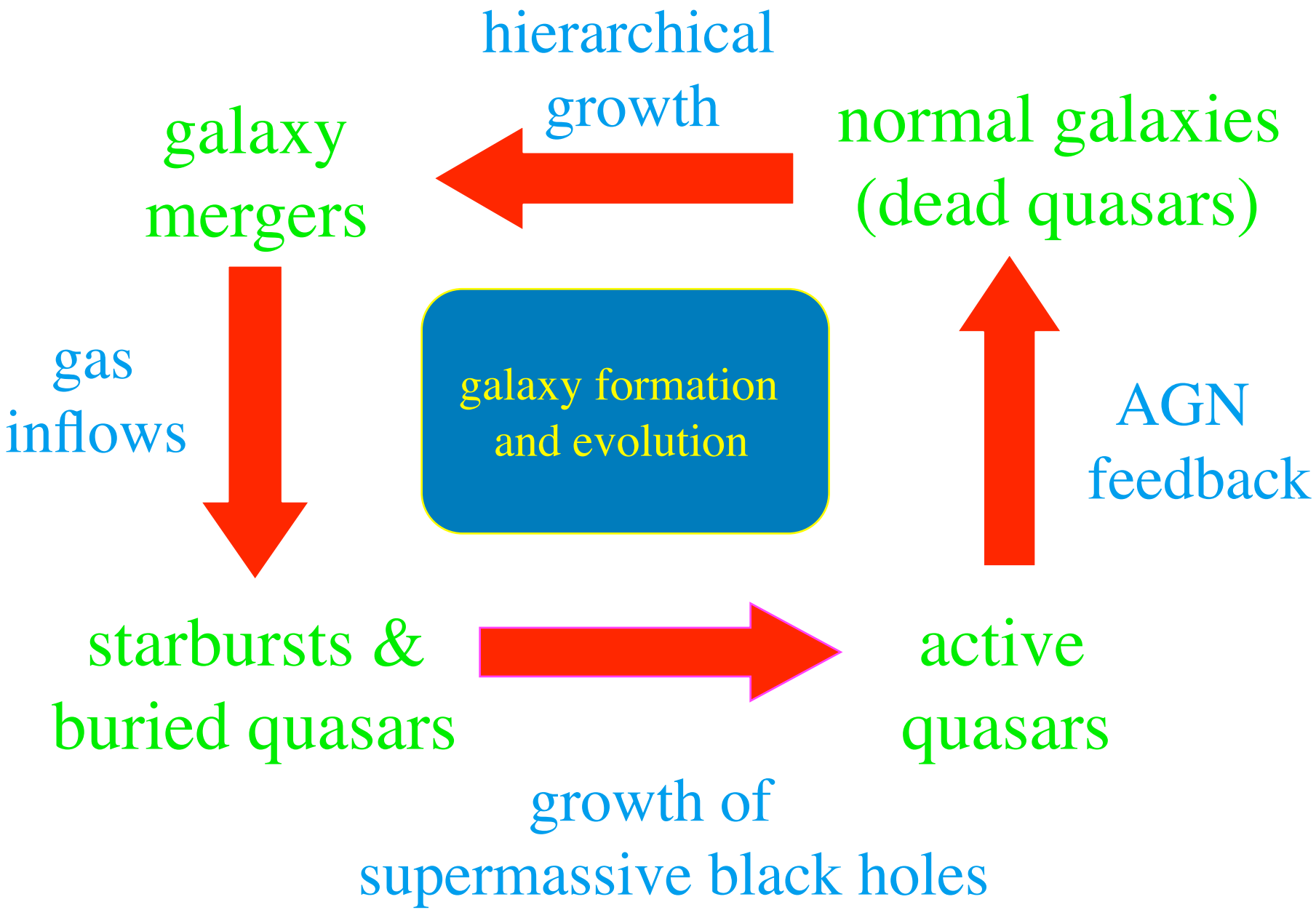


u-r



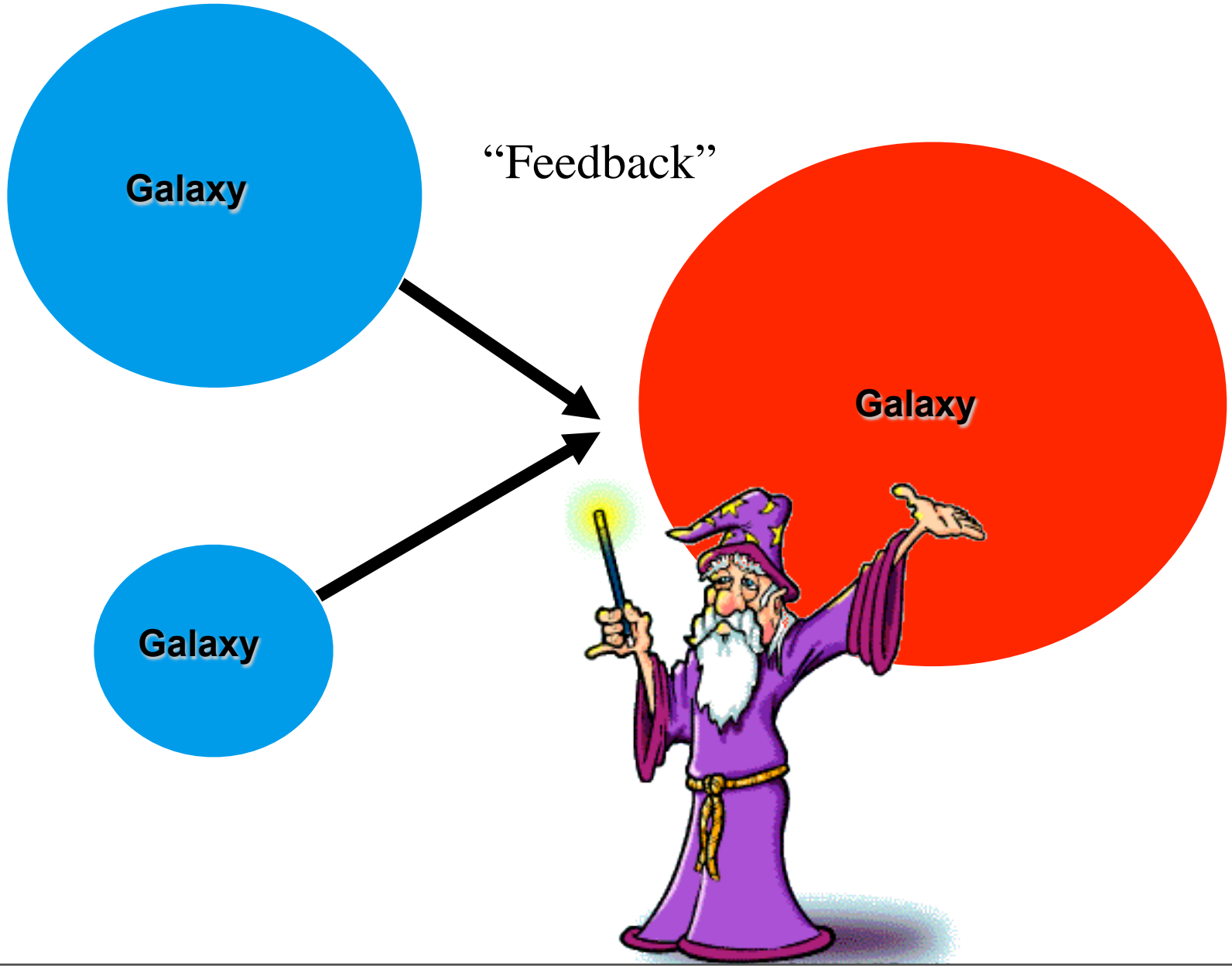


A General Framework...



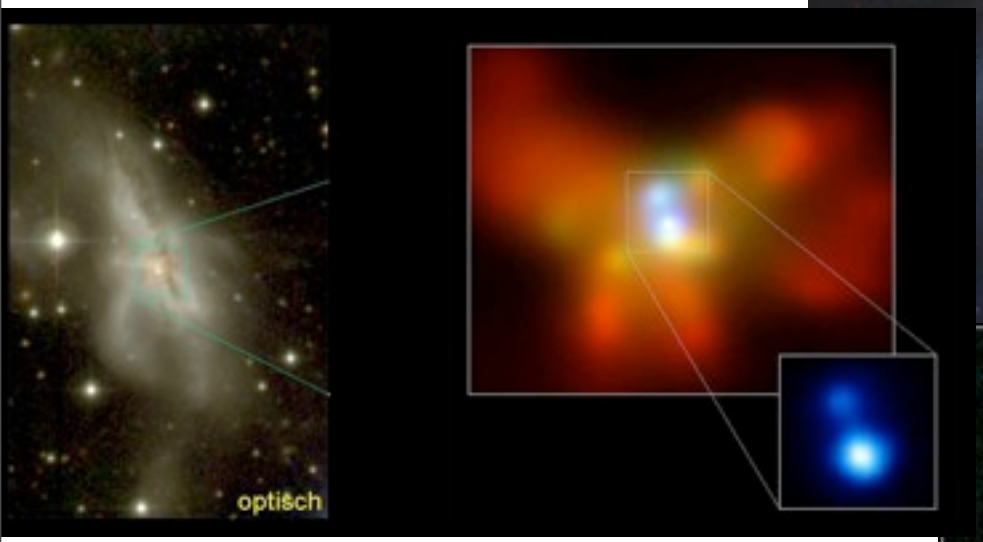
The Semi-Analytic Approach

The Semi-Analytic Approach



Real Systems Are Messy!

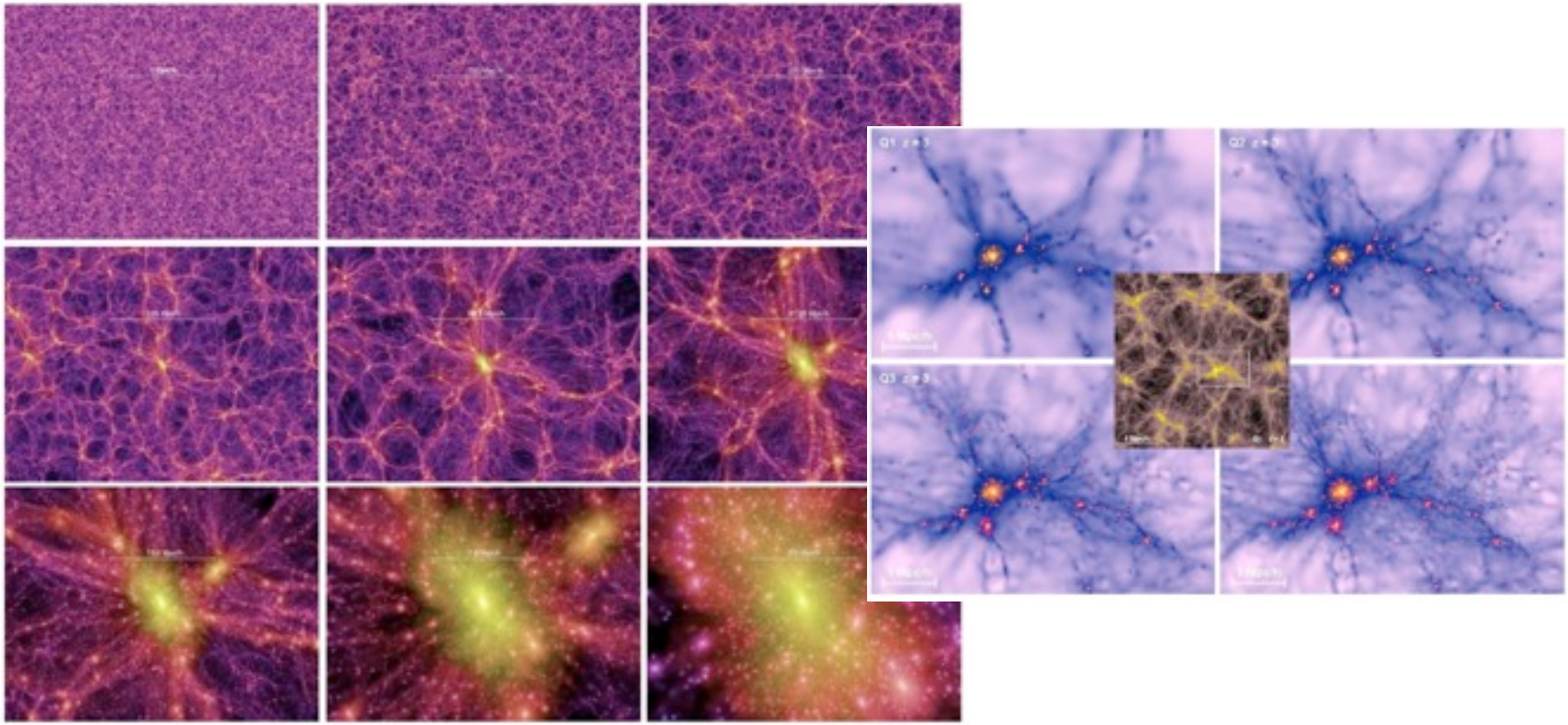
HUGE RANGE OF COMPLEX & UNCERTAIN PHYSICS



- Need to treat:
  - Orbits+torquing (3-D)
  - Star formation
  - Cooling
  - SNe Feedback
  - BH Feedback
  - Metal Enrichment
  - Shocks
  - Huge range of initial conditions

How to Model These Processes?

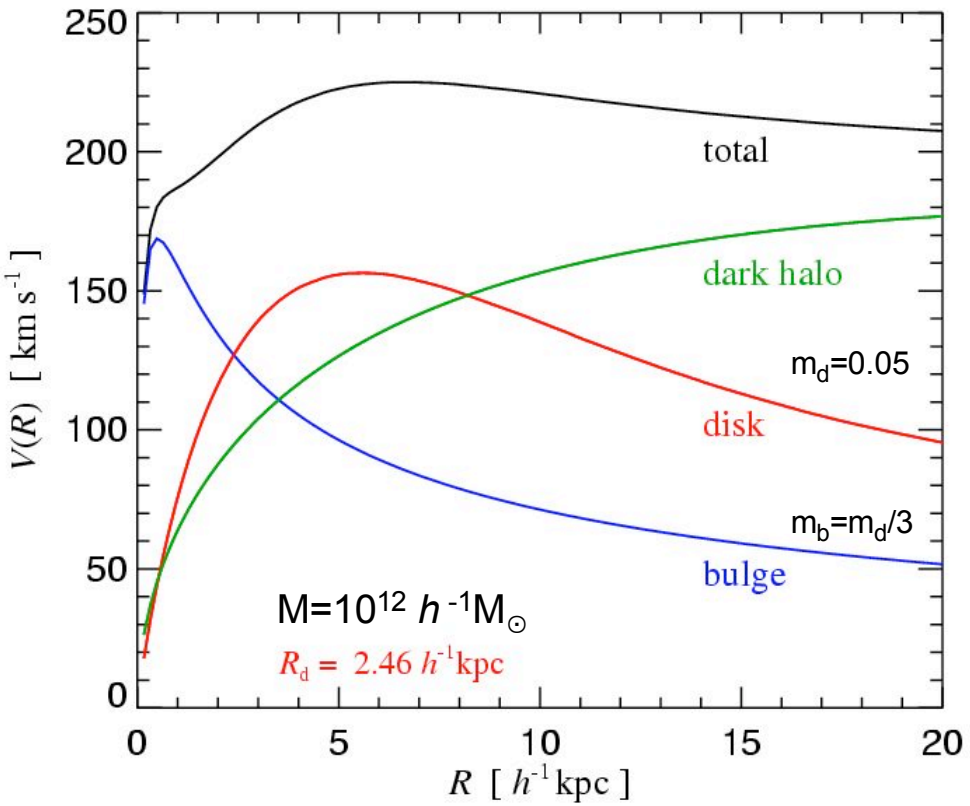
(HOW TO GET THE BEST BANG FOR YOUR SUPERCOMPUTING BUCK)



- Ideally, would use cosmological simulations:
  - Millenium run resolution ~ 5 h^-1 kpc
  - Adaptive mesh “zoom-in” runs similarly too expensive
  - What if the cosmological simulation doesn’t make disks?

The Simulations

INSTEAD, MODEL INDIVIDUAL GALAXY MERGERS AT HIGH RESOLUTION

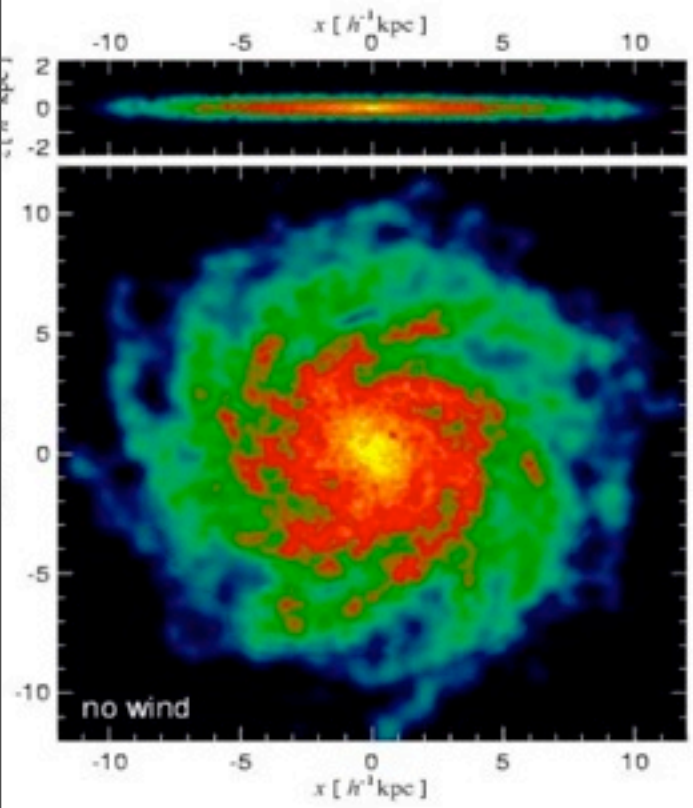


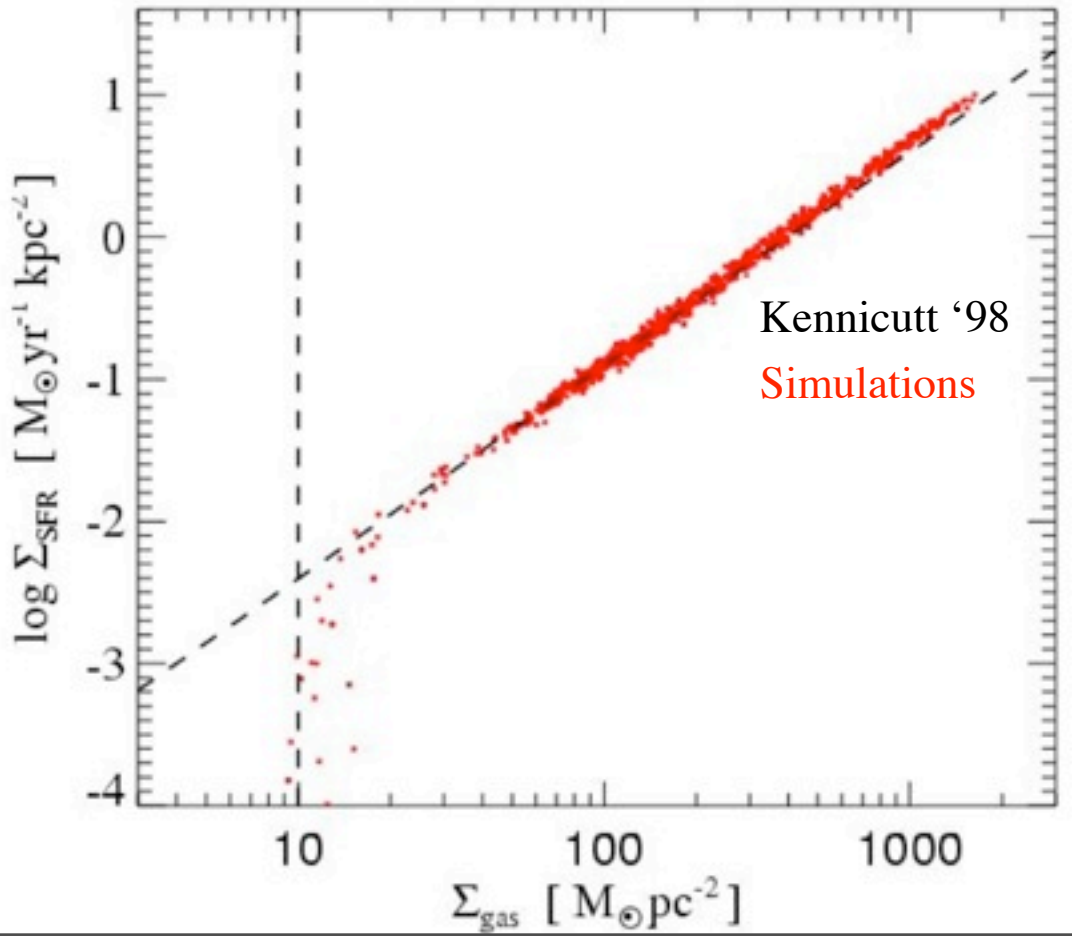
- Constuct initial disks in equilibium
  - DM (+gas) Halo
  - Gas+Stellar Disk (variable f_gas)
  - Bulge (variable size)
  - Seed BH
- Scalings derived from observations
  - Potential solved exactly, with pressure effects, etc.
- Put pairs on orbits & let them evolve
- Best cases:
  gas smoothing length ~ 20 pc
  - Stable
  - Numerical convergence

The Simulations

STILL, CAN'T RESOLVE EVERYTHING...

- Individual sites of star formation still << r_smooth
  - sub-resolution model for multi-phase ISM (e.g. McKee & Ostriker 1977)
  - cooling >> "sink" of molecular clouds >> star formation >> SNe feedback pressurizes hot phase & evaporates clouds

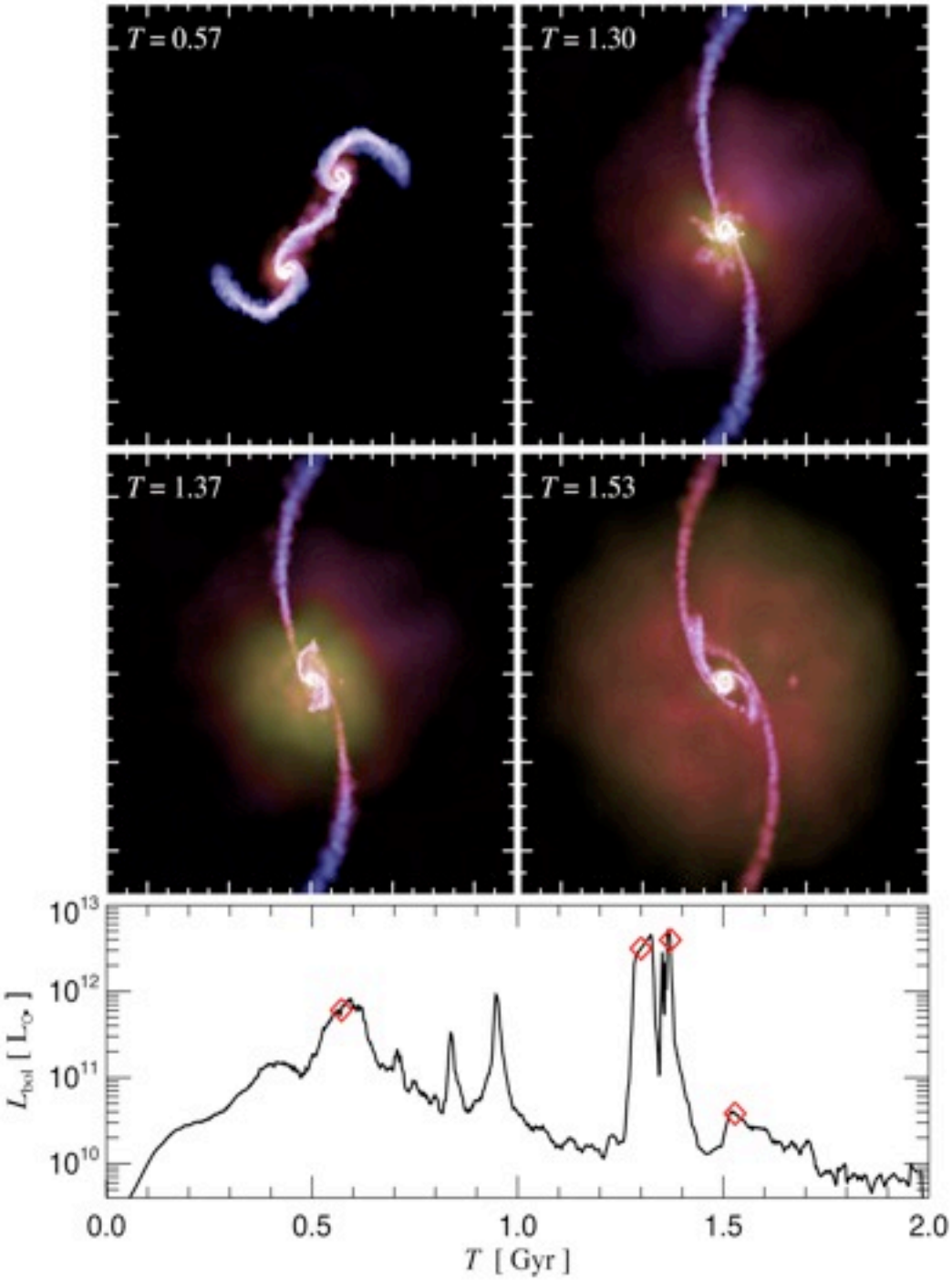




The Simulations

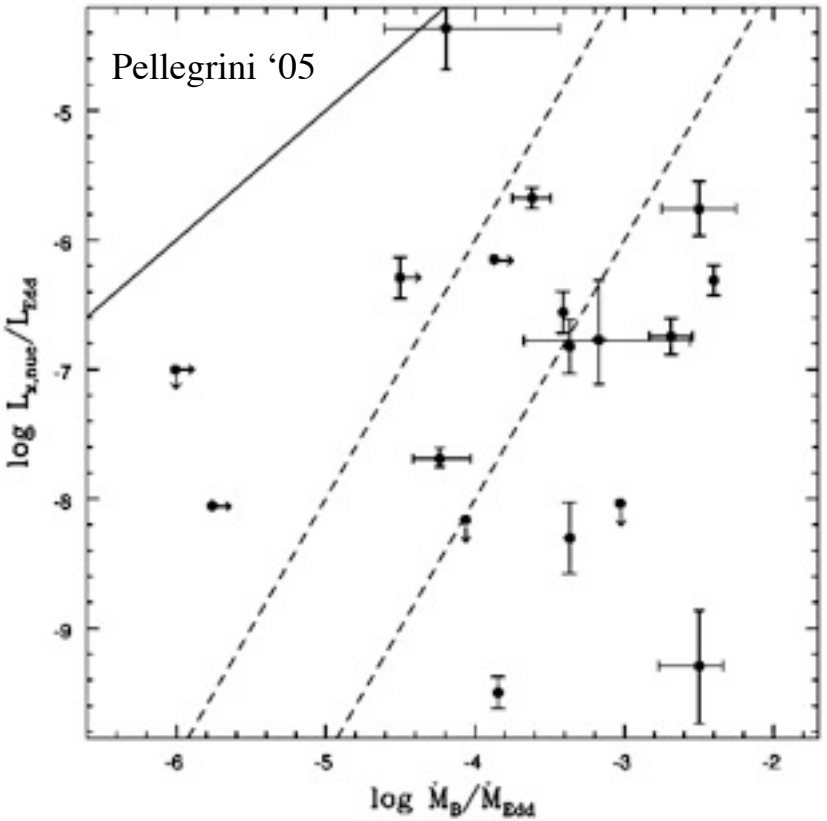
THE AGN...

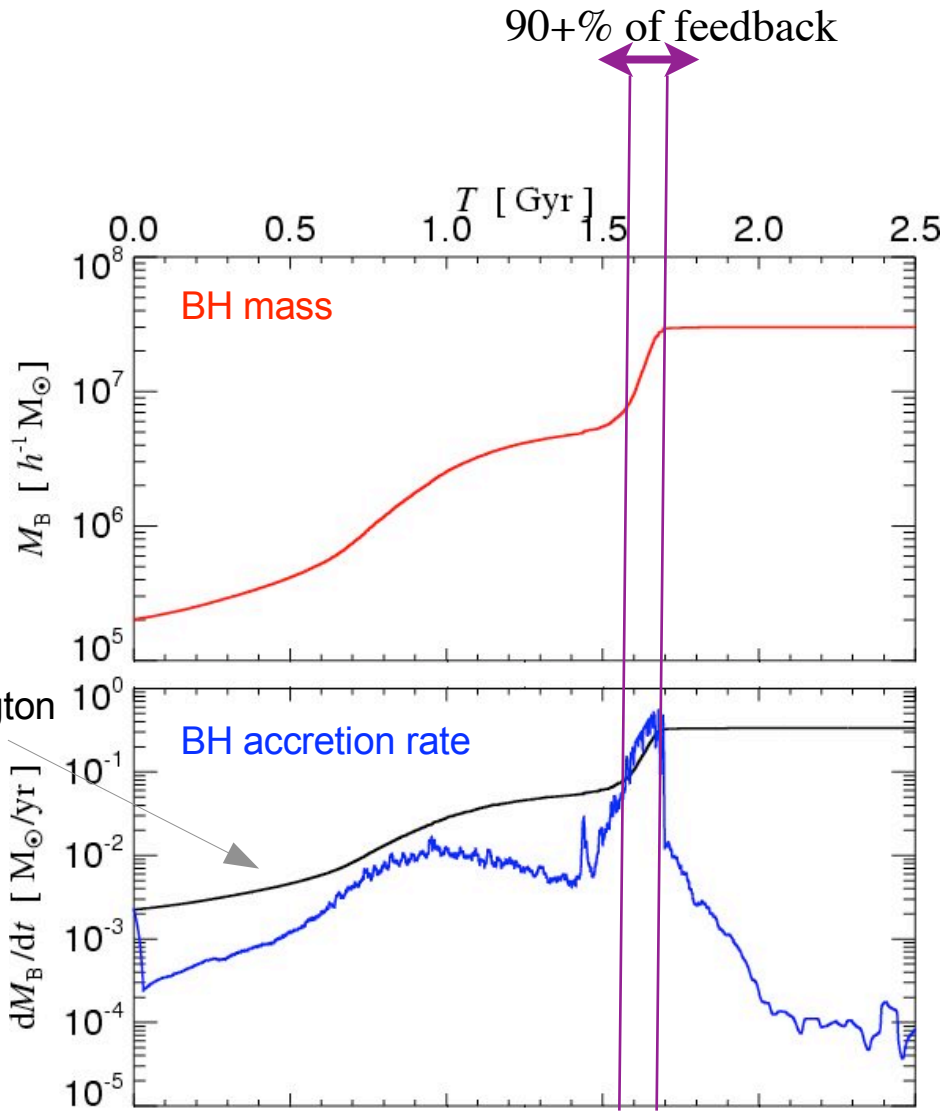
- R_sch ~ few AU ~ 10^-6 x our resolution
- R_Bondi ~ 10 pc (typical)
  - Bondi-Hoyle accretion rate (max Eddington)
  - ~0.1 radiative efficiency (high-mdot)
  - ~5% couples to local gas (thermally)



The Simulations

A CAUTION...



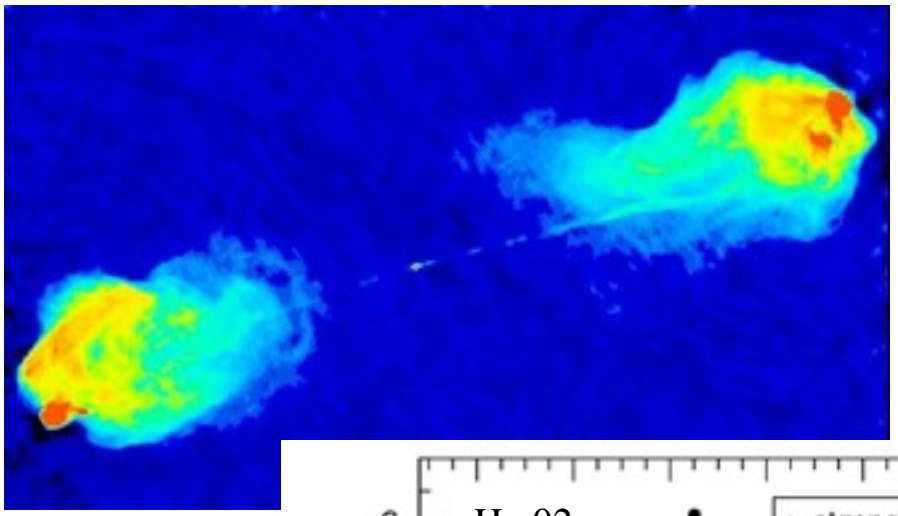


- But, feedback effects not sensitive to the accretion prescription!

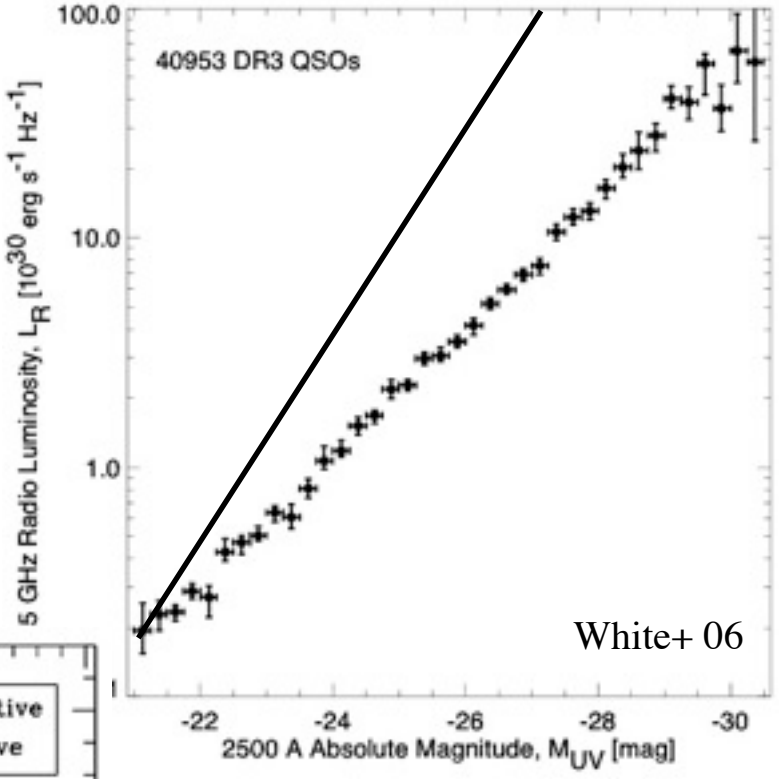
The Simulations

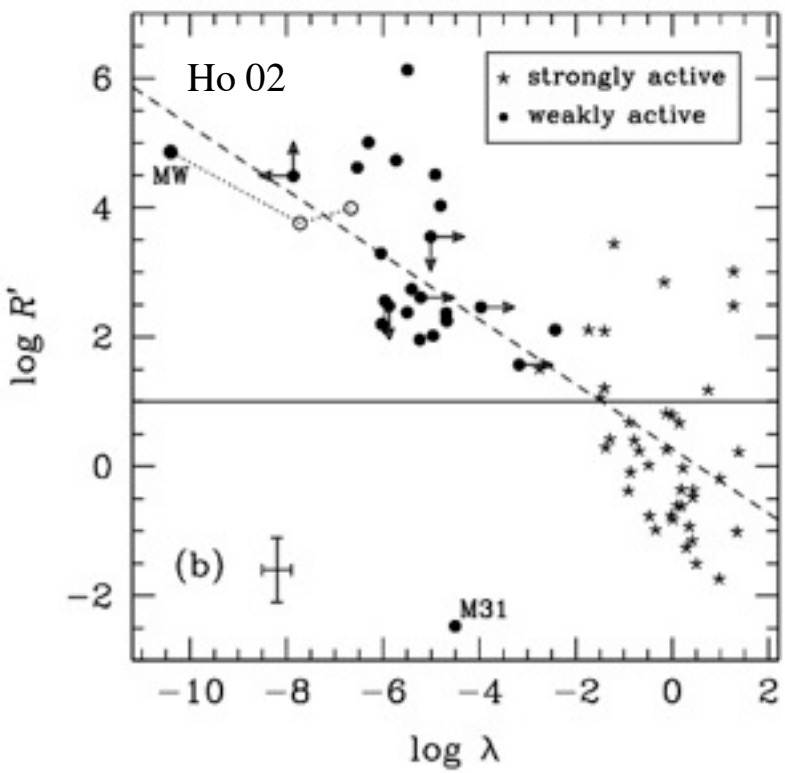
INITIAL, IMPULSIVE FEEDBACK VS. "MAINTENANCE"

We see today...



but...



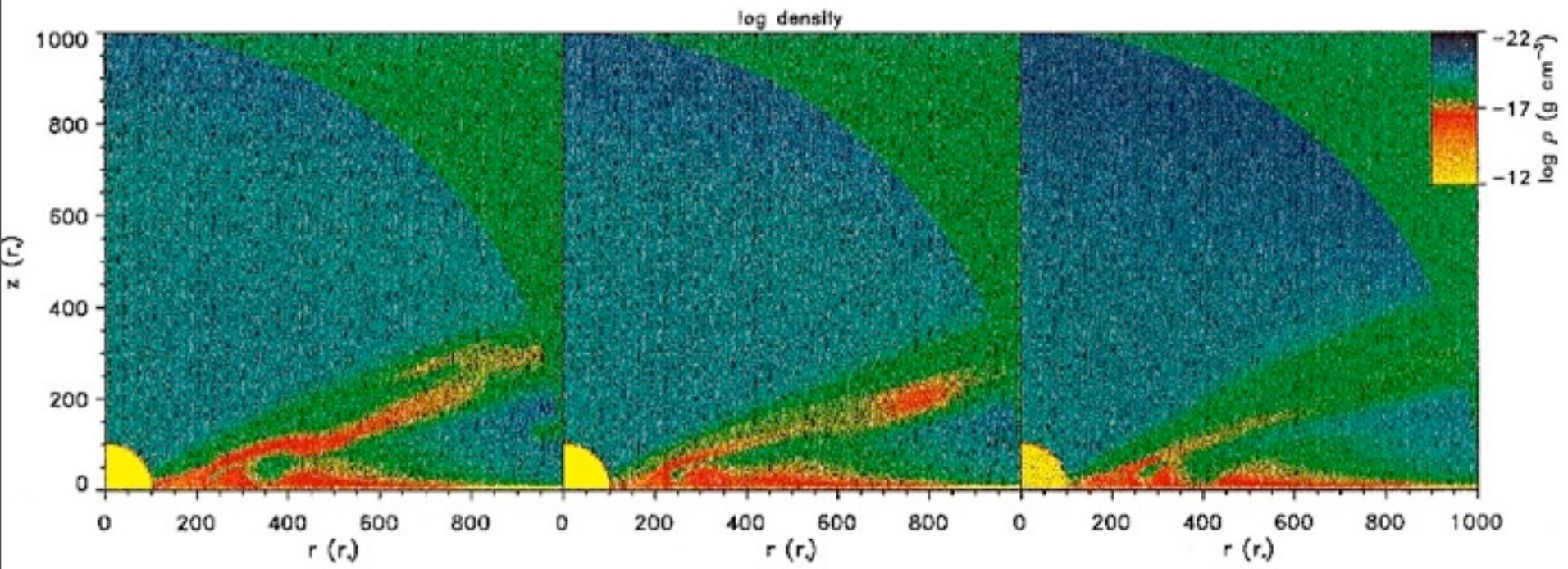


- Even with low (<10^-3) coupling efficiency, radio only important when L << L_edd & t ~ t_Hubble

The Simulations

WHAT ABOUT THE FEEDBACK PRESCRIPTION?

- Modeling “Quasar” Feedback
- ~5% to match observed M-sigma normalization (Silk & Rees ‘98)
  - Line opacities + AGN spectrum (Sazonov et al.)
  - Momentum driven winds (Murray et al.)
  - Disk wind simulations (Proga et al.)

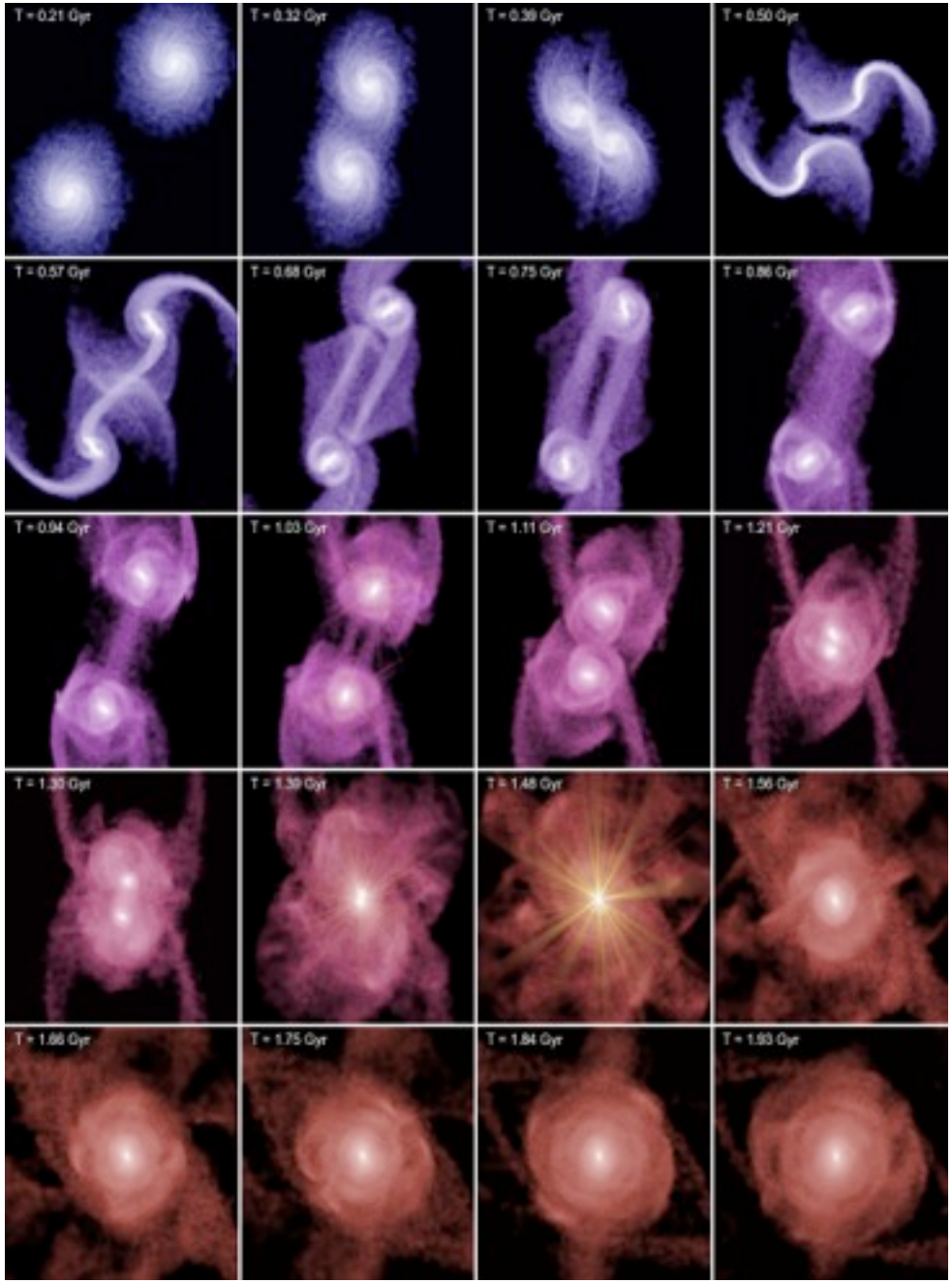


- Probably *not* radio jets

The Simulations

FINALLY, WHAT TO SIMULATE?

- Span the parameter space, varying:
  - Masses & mass ratios
  - Disk gas fractions
  - Redshift of formation & merger
  - Disk structural parameters
    - Bulge-to-disk ratio, concentration, scale lengths
  - ISM Feedback/Pressurization (isothermal > full multiphase)
  - BH accretion & feedback efficiency
  - Stellar winds : add/remove
    - Mass loading, energy-loading
  - Orbital parameters
    - Disk orientations
    - Angular momentum
    - Pericentric passage



- ~500+ simulations and counting (Robertson et al. 2005; Cox et al. 2004)

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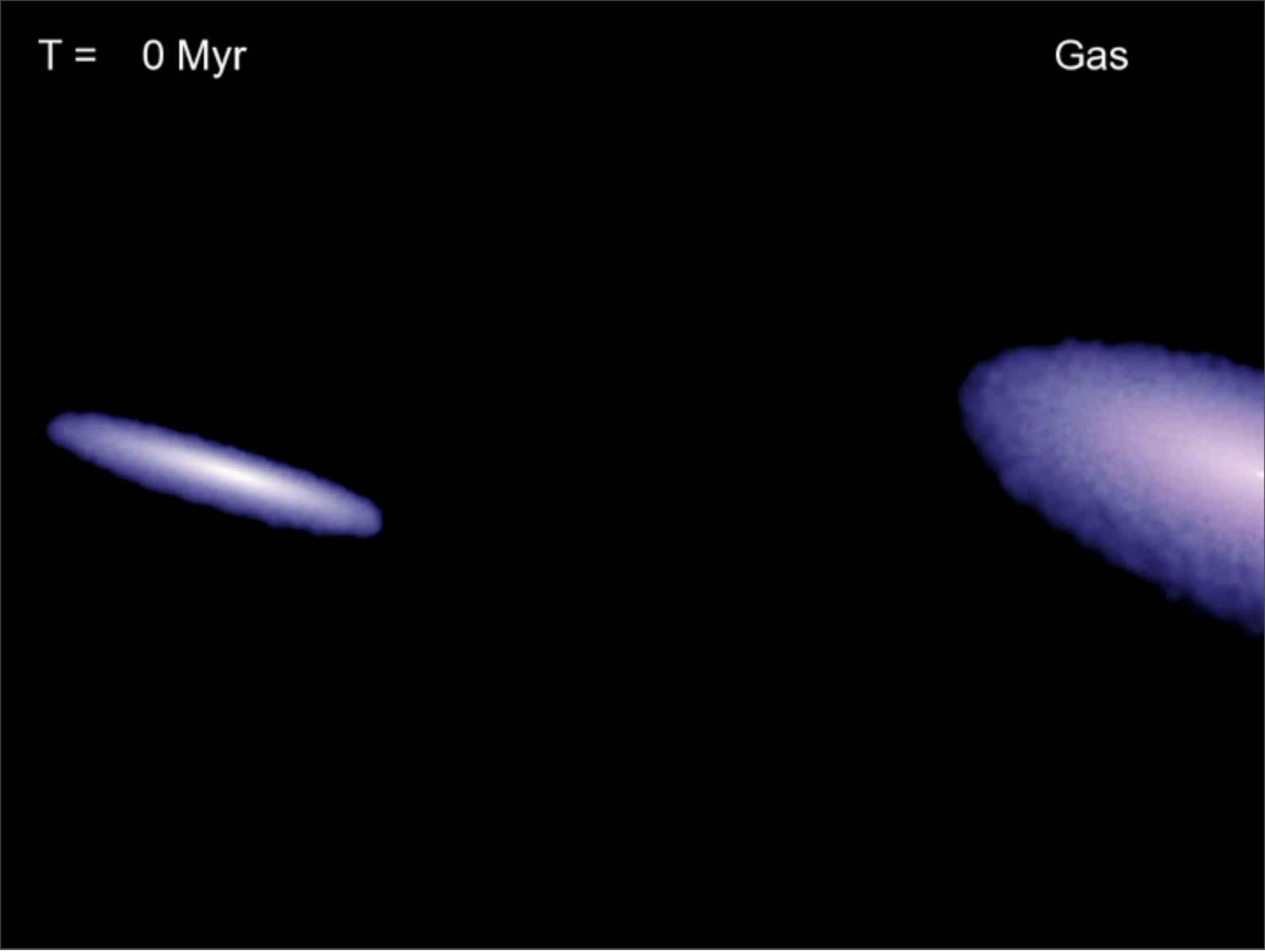
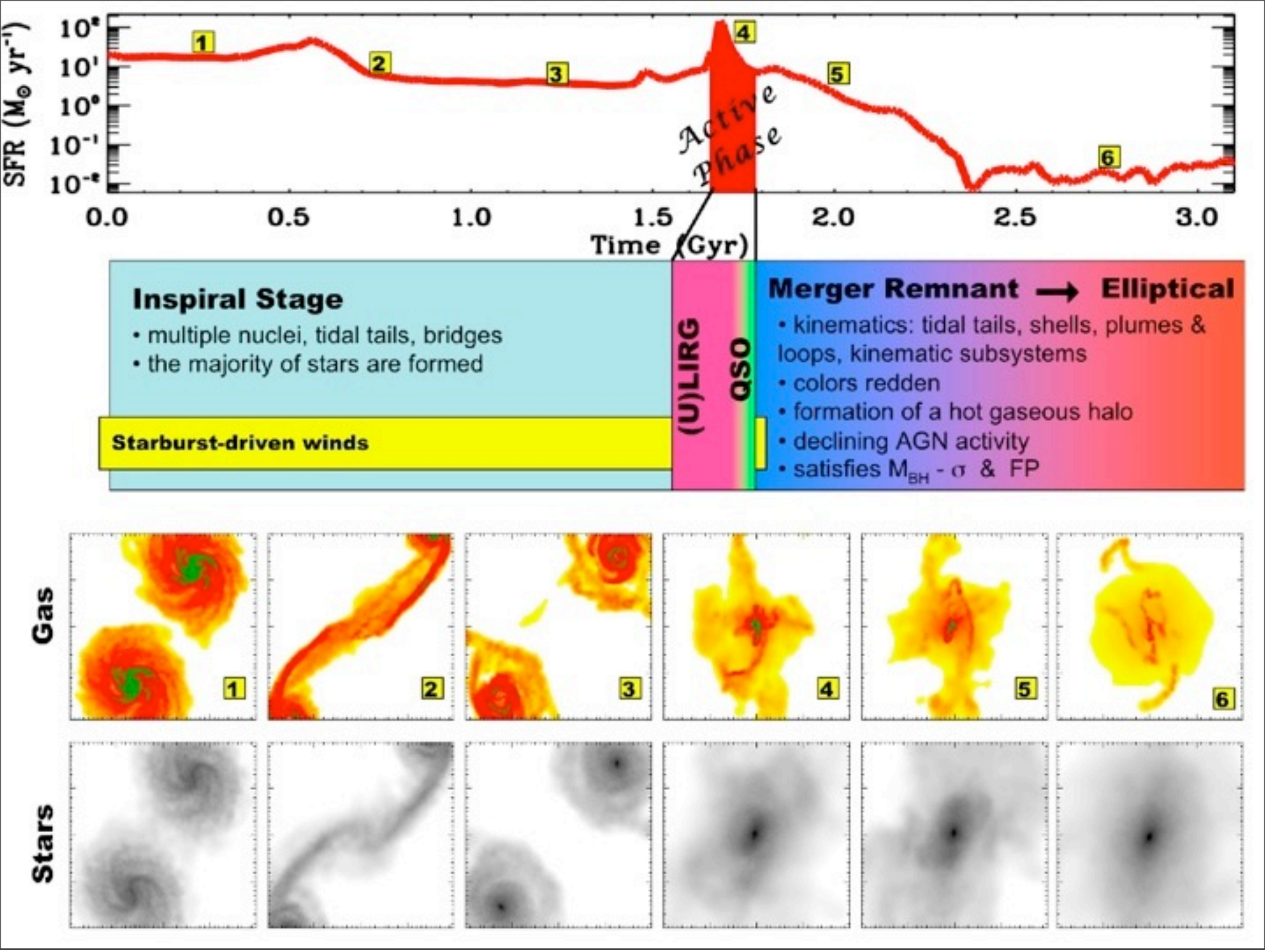
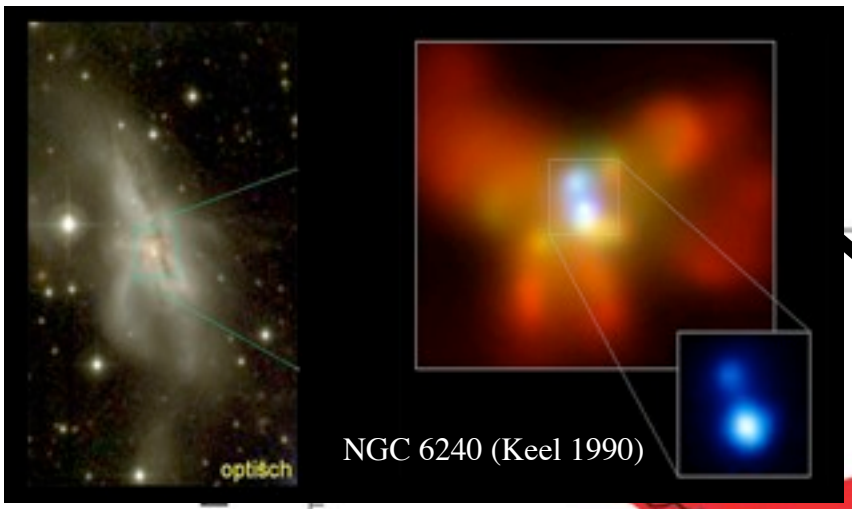
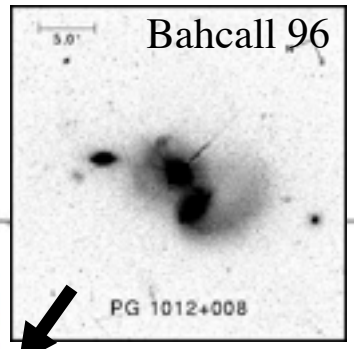

T = 0 Myr
Gas


SFR ($M_\odot$ yr^{-1})
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
1
2
3
4
5
6
Active Phase
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
Inspiral Stage
• multiple nuclei, tidal tails, bridges
• the majority of stars are formed
Starburst-driven winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

Quasar Growth:

GAS IS HEATED AND EXPELLED IN BLOWOUT, REVEALING A BRIEF, BRIGHT QUASAR





Column Densities

Bolometric

B-Band

"Blowout" phase

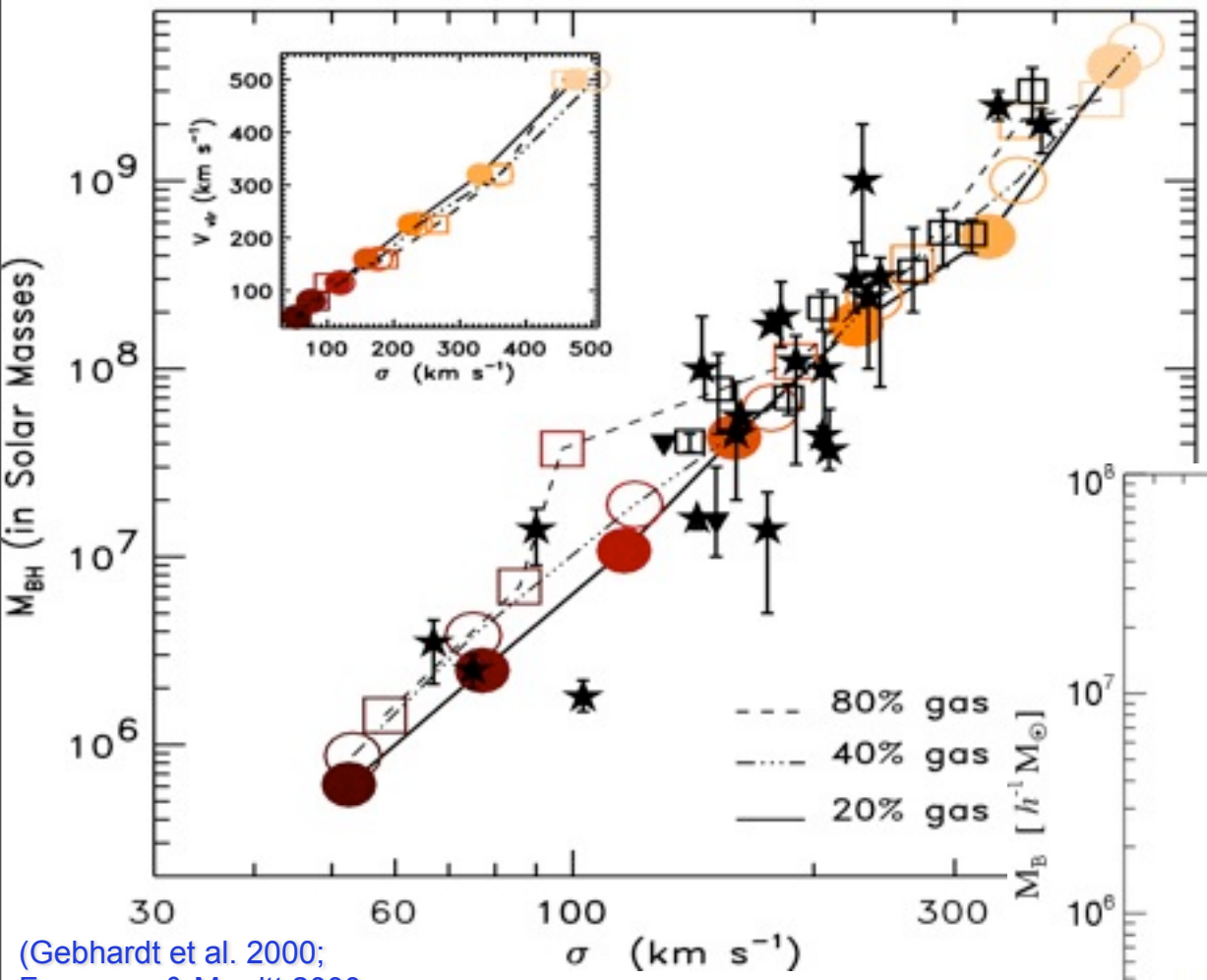
Luminosity

$\log_{10}$ L [L_{sun}]

Time [Gyr]

Feedback-driven "Blowout" Gives M-sigma Relation

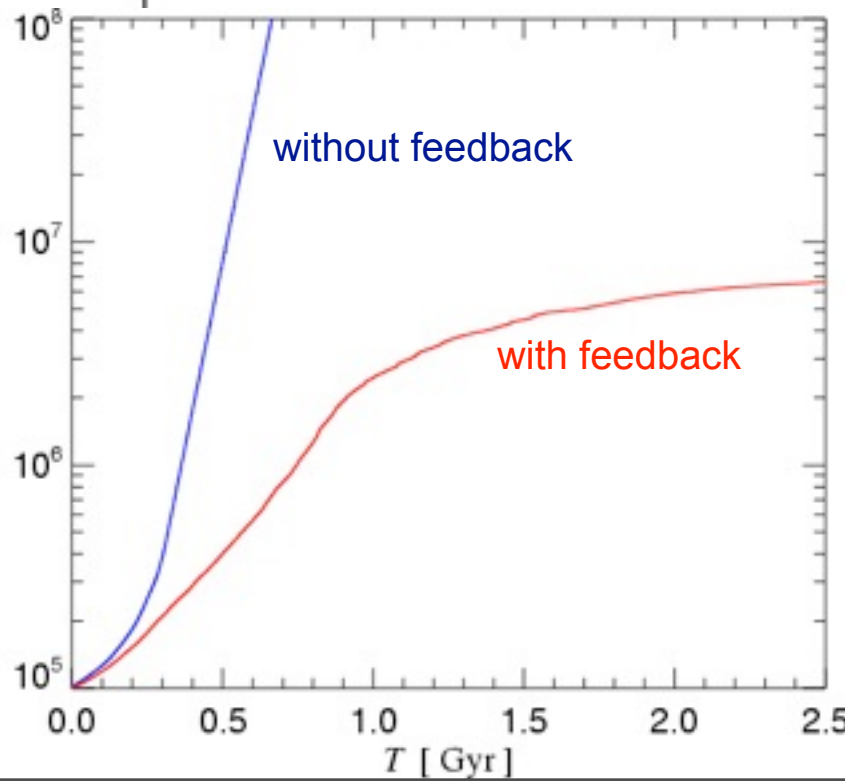
PREVENTS RUNAWAY BLACK HOLE GROWTH



(Gebhardt et al. 2000;
Ferrarese & Merritt 2000;
Tremaine et al. 2002)

Di Matteo et al. 2005

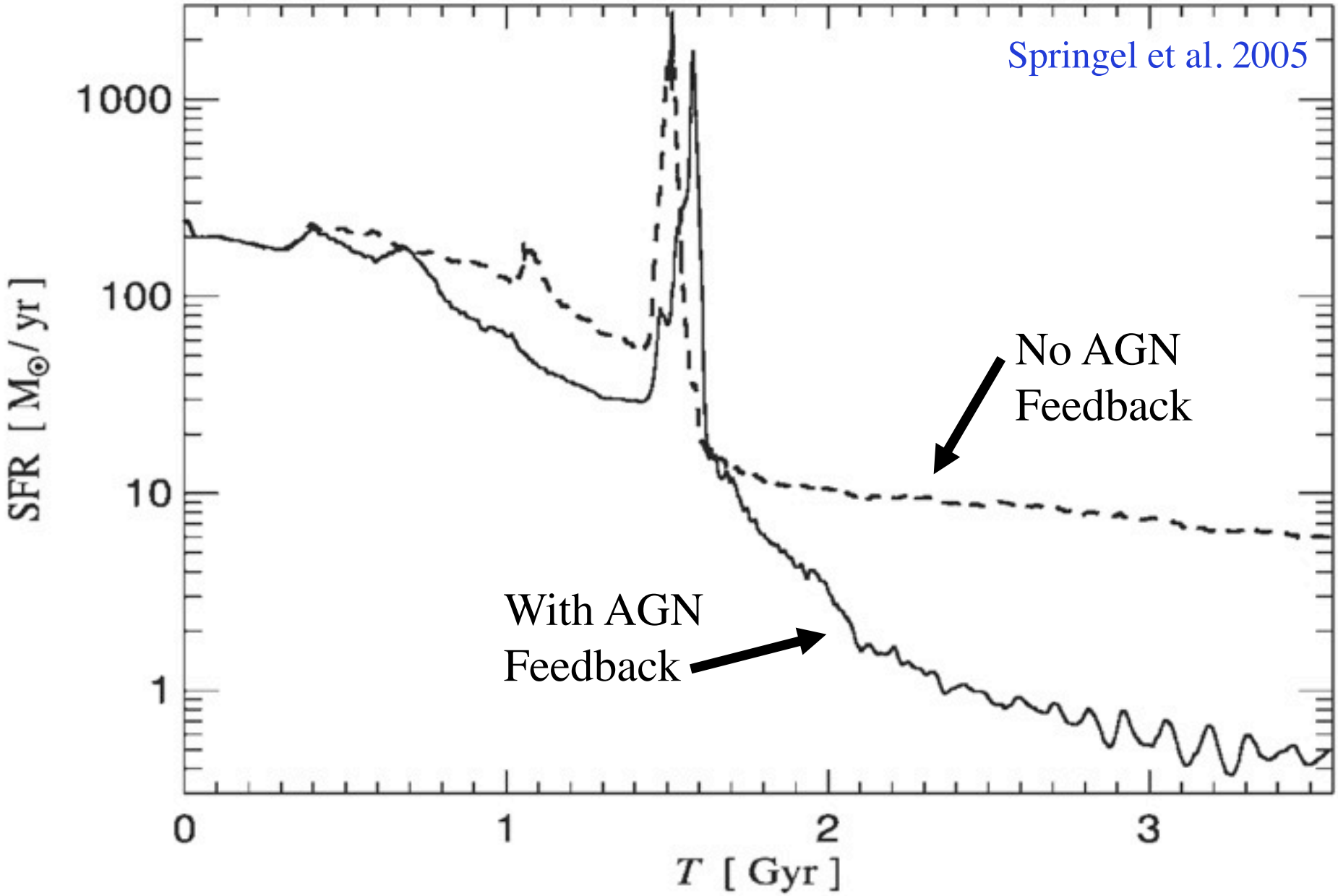
Black hole growth



Springel et al. 2004

Expulsion of Gas Turns off Star Formation

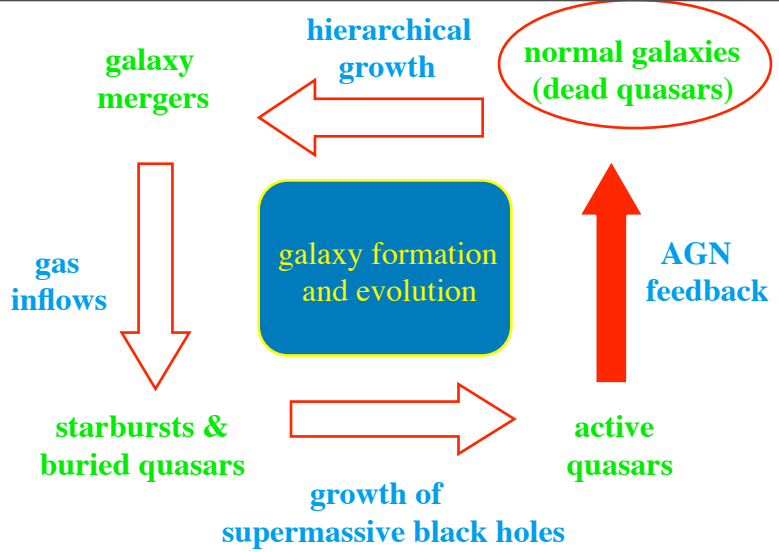
ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”



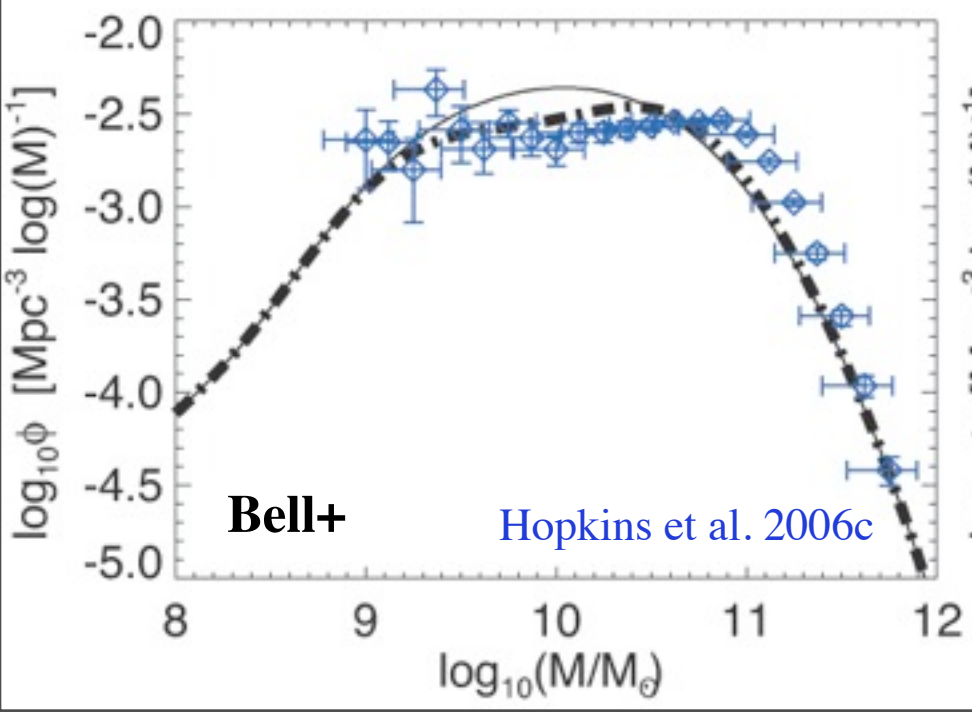
Every Quasar Has a Host

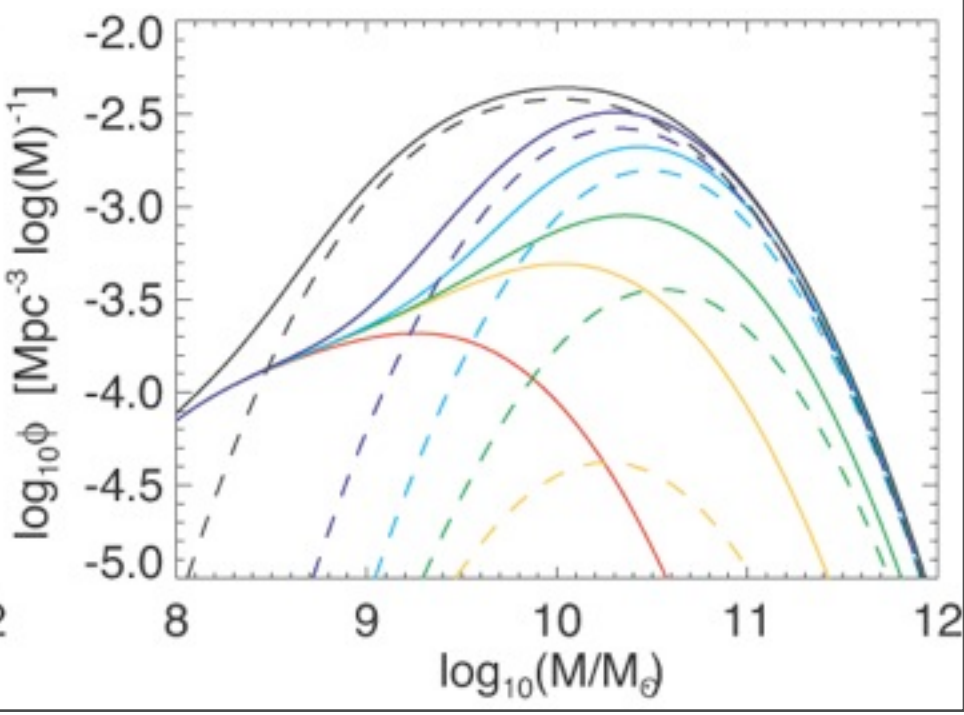
MAPPING BETWEEN MERGER DISTRIBUTIONS

- Spheroids + QSOs produced *together*
  - Hosts follow M-sigma (Di Matteo et al.), BH-bulge mass, Fundamental Plane (Robertson et al.), Kinematic/Morphological/Gas Properties (Cox et al.)
- Map each *quasar* to a *spheroid*



e.g. red galaxy mass function (dry mergers a small effect)





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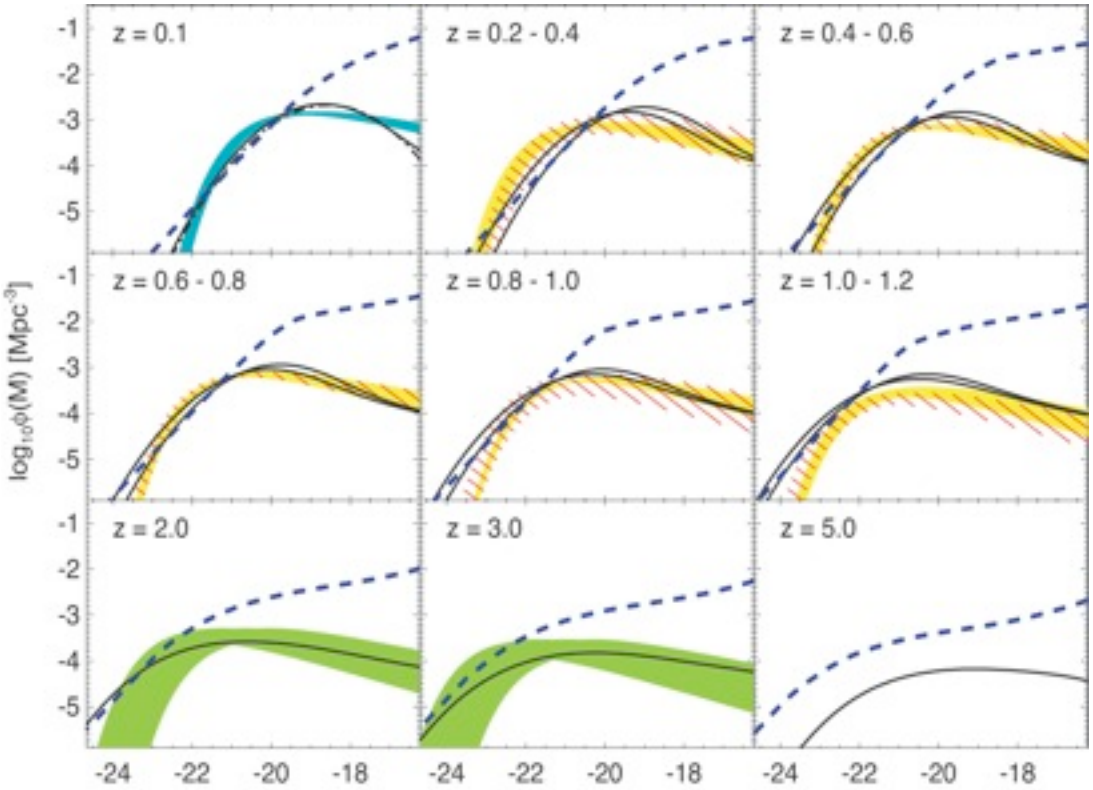
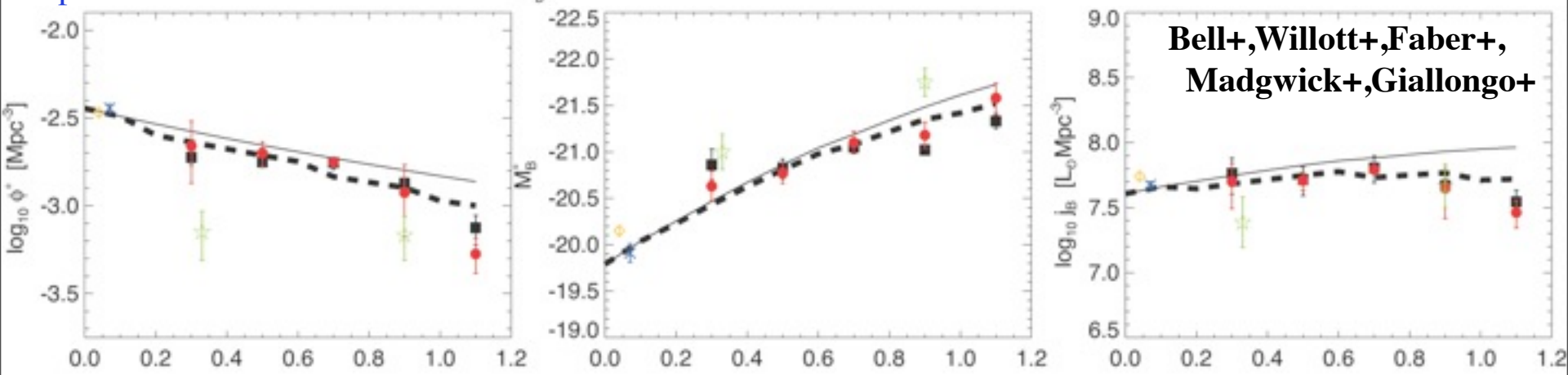
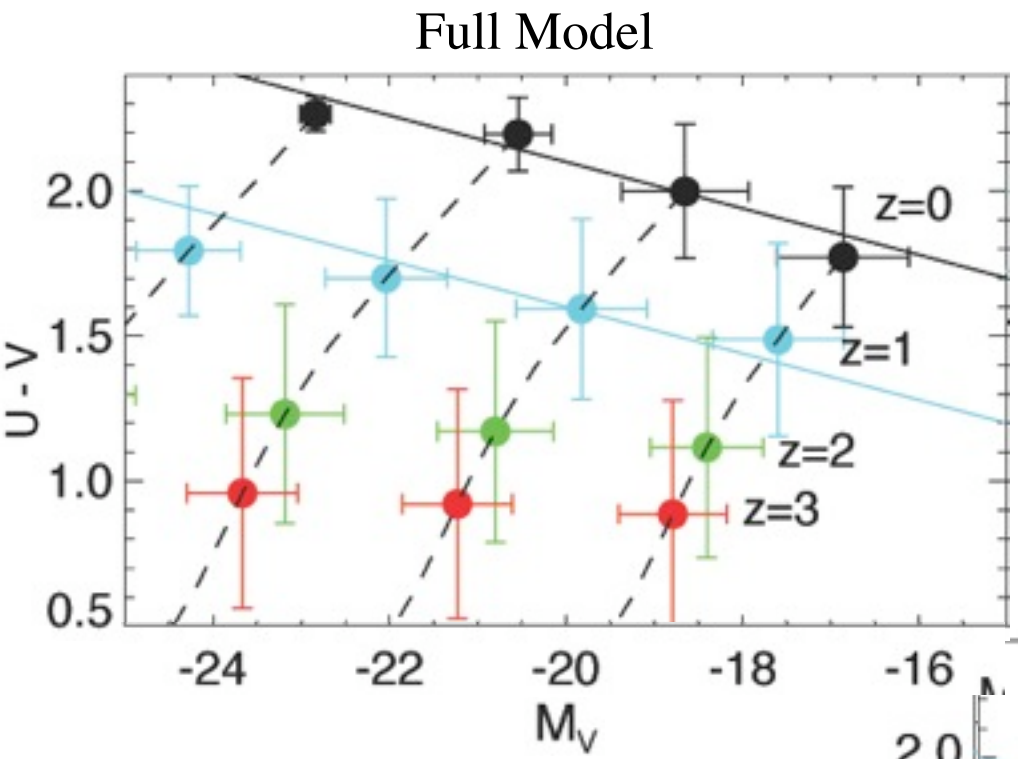


Hopkins et al. 2006c

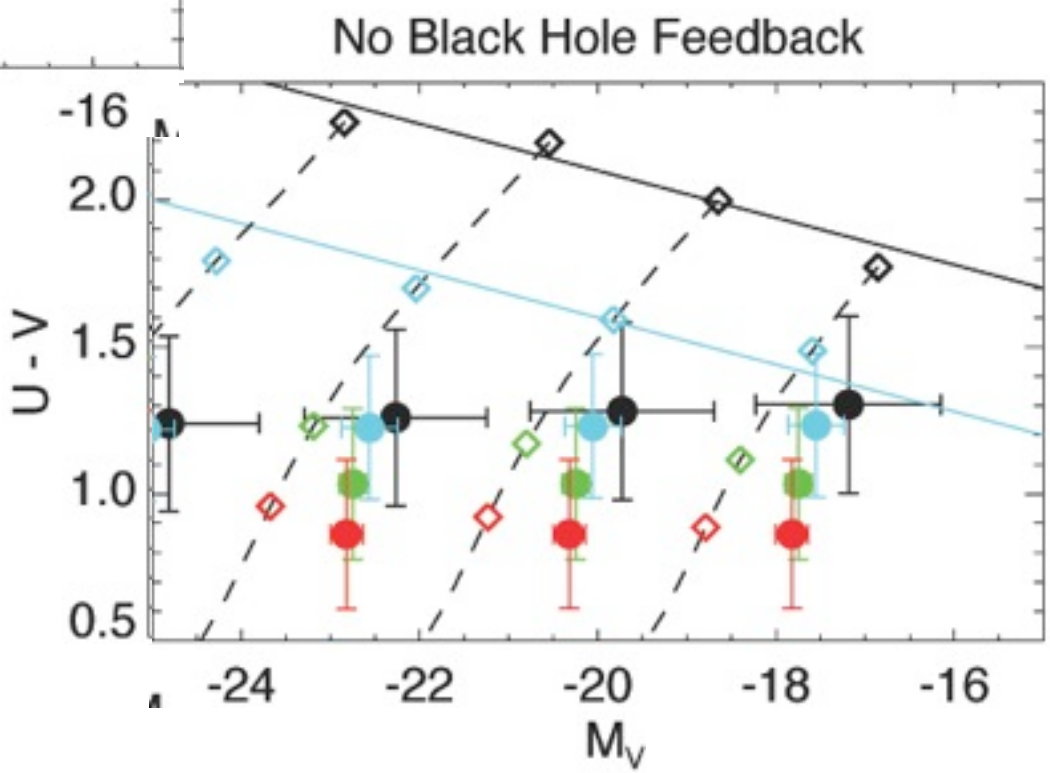
- Comparing with joint LFs (NUV,U,B,V,R,I,K) suggests reliable *empirical* model of population buildup



The Color-Magnitude Diagram



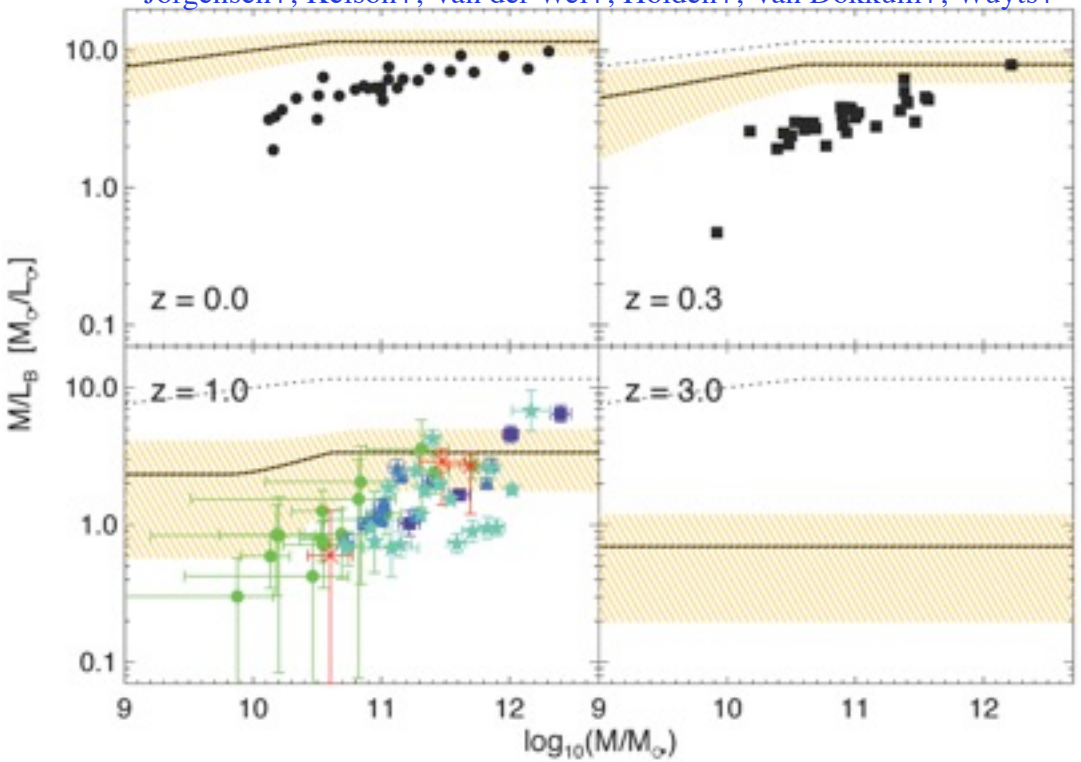
- More than one effect here!



Hopkins et al. 2006c (obs: Bell+; Faber+)

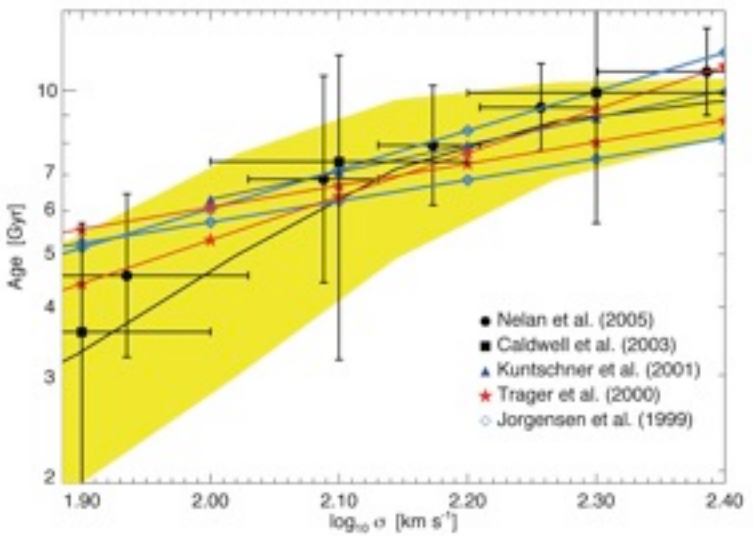
Multiple Age Measurements to Use as Checks

Jorgensen+; Kelson+; Van der Wel+; Holden+; Van Dokkum+; Wuyts+

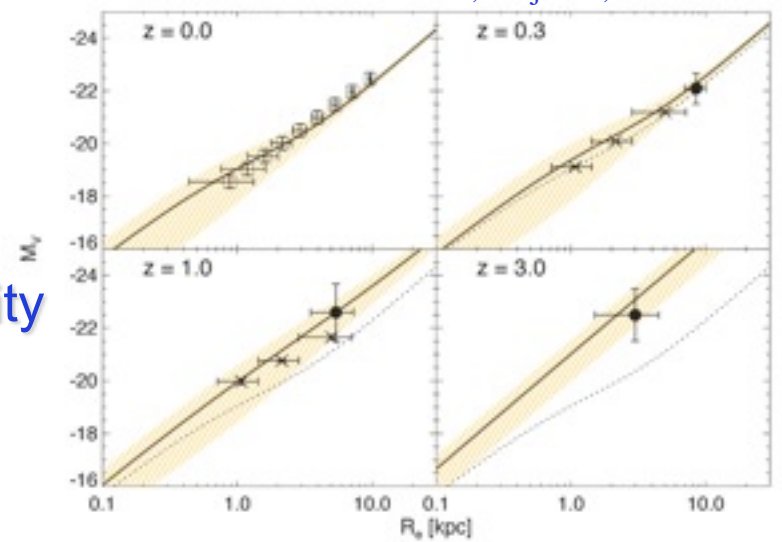


M/L Ratios

Age-sigma



Shen+; Trujillo+; McIntosh+



Size-Luminosity Relation

Hopkins et al. 2006c

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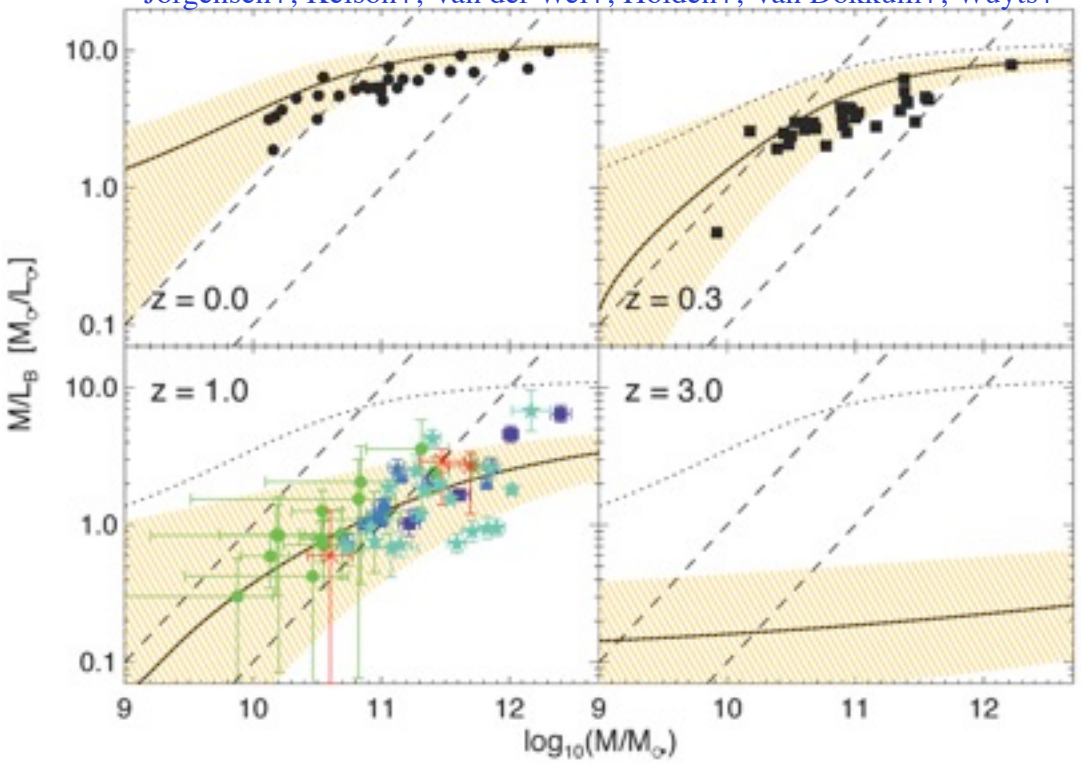
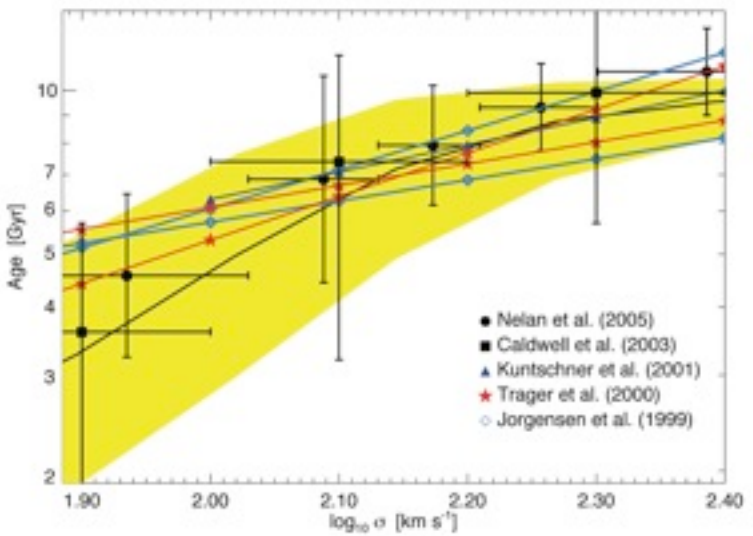


M/L Ratios

Age-sigma



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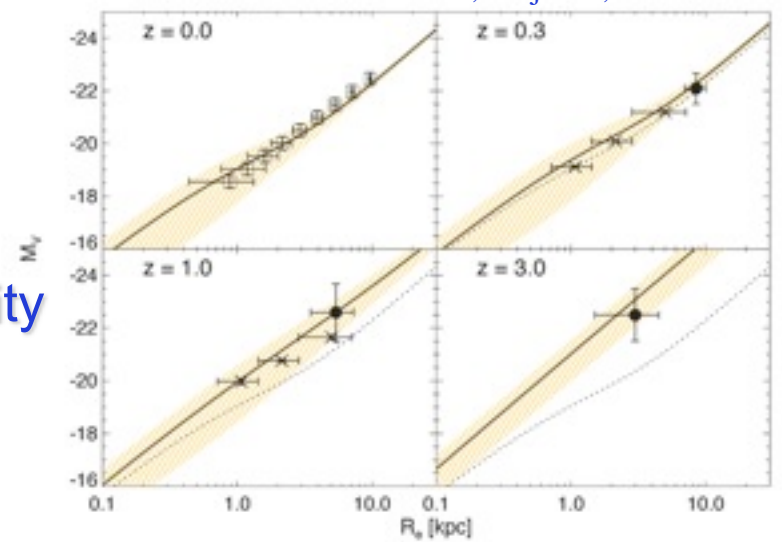


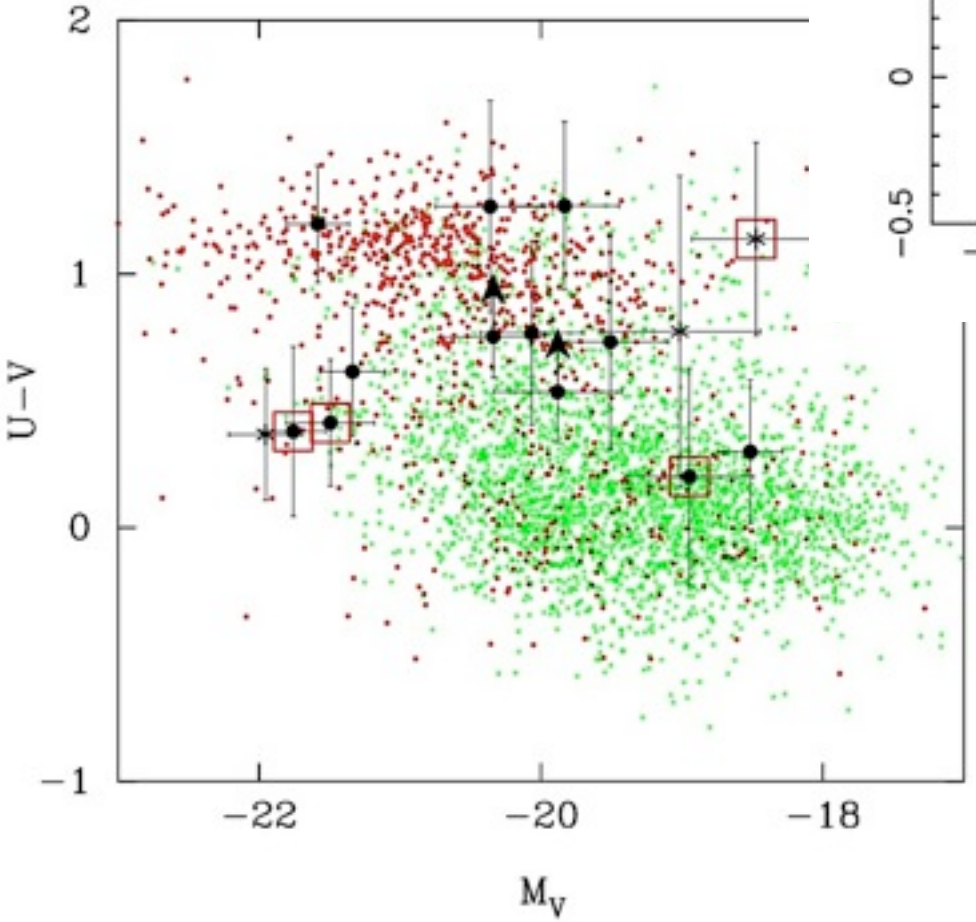
Size-Luminosity Relation

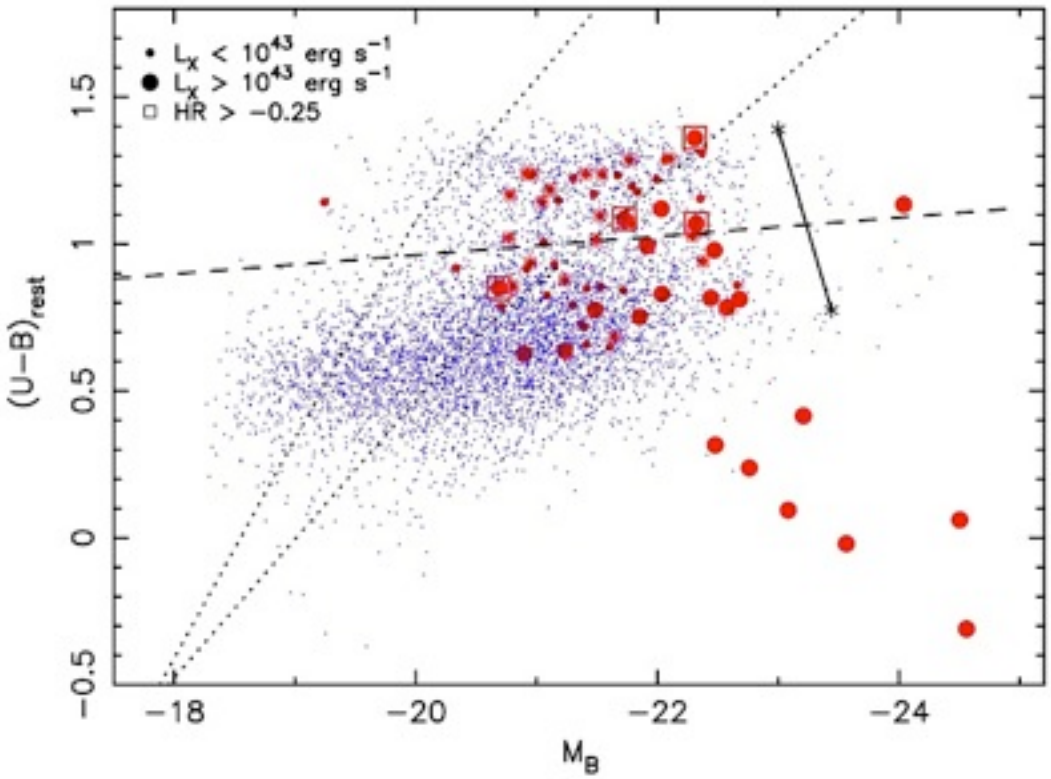
Hopkins et al. 2006c

Driving the Blue-Red Transition?

DIRECT OBSERVATIONS

Sanchez+ ‘05
GEMS
0.5 < z < 1.1
Optical QSOs





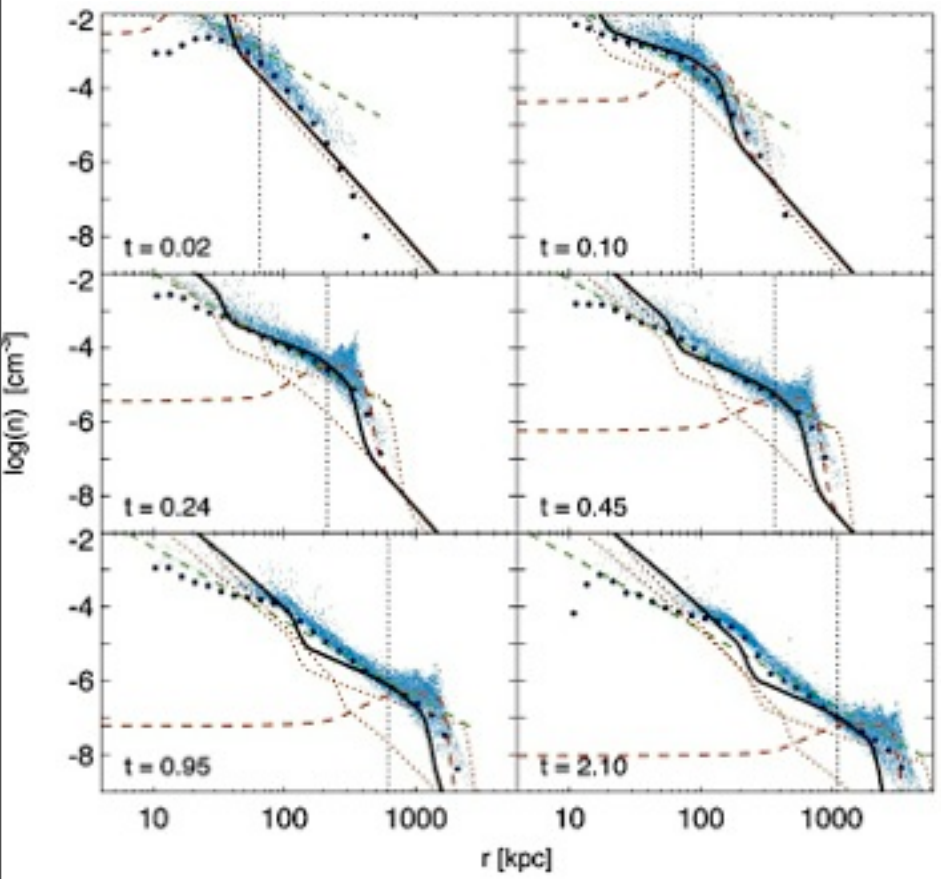
(also, Kauffmann+ 03;
local SDSS hosts)

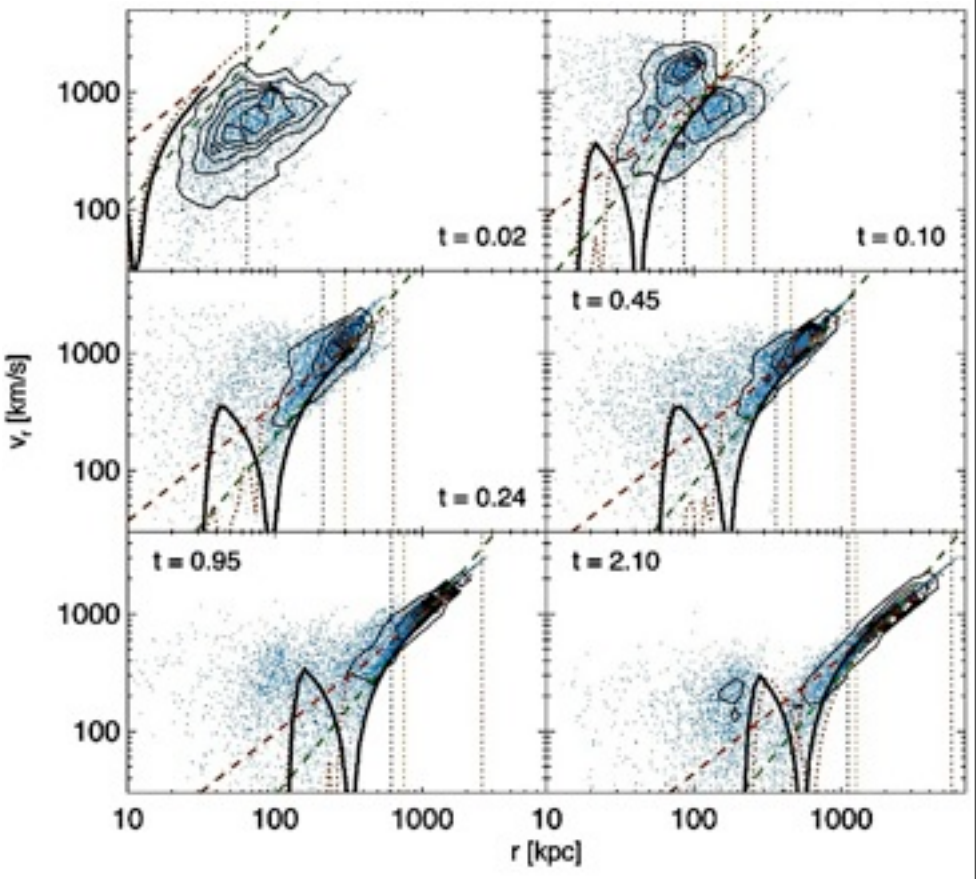
Nandra+ ‘06
DEEP2
0.7 < z < 1.4
X-ray QSOs

- Testing *how* color & accretion rate co-evolve can break model degeneracies

Feedback-Driven Winds

GENERAL PROPERTIES

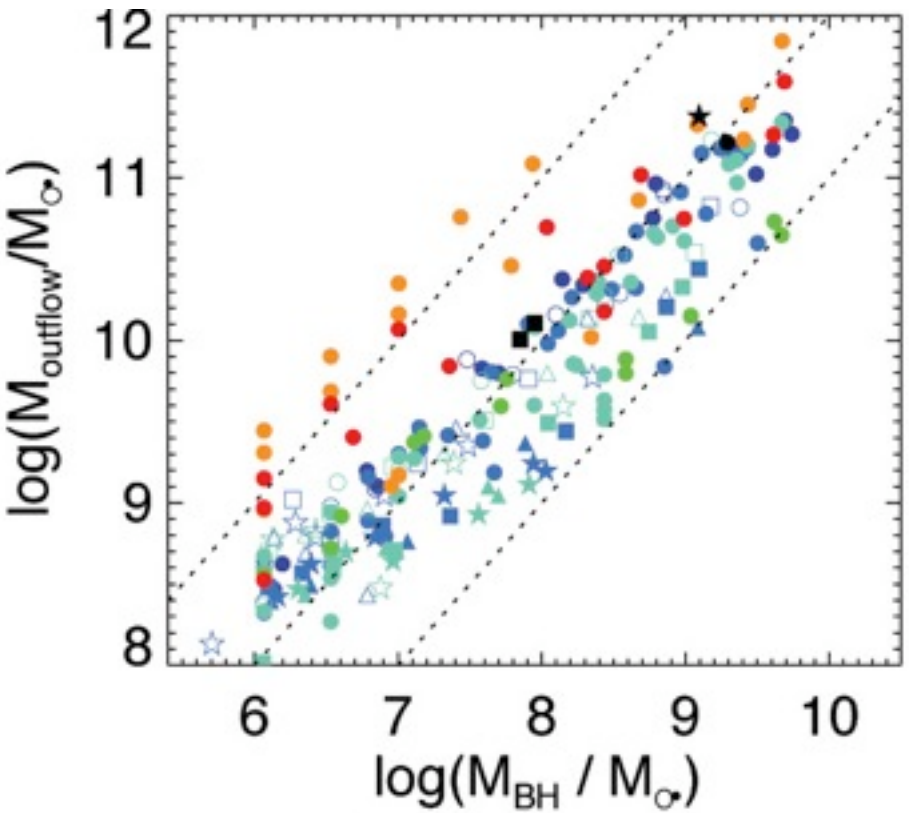




- Rapid growth (t_S<t_dyn)
- Point-like injection
- E~E_binding
  - Explosive outflow

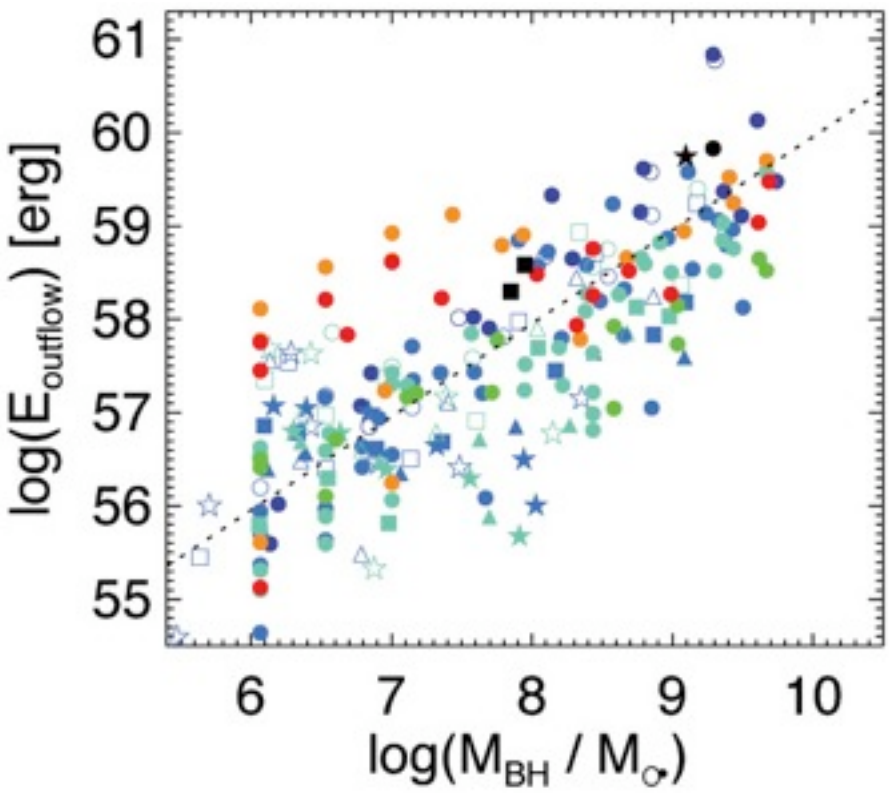
Feedback-Driven Winds

COMPARISON TO STARBURST-DRIVEN WINDS



Mass Loading

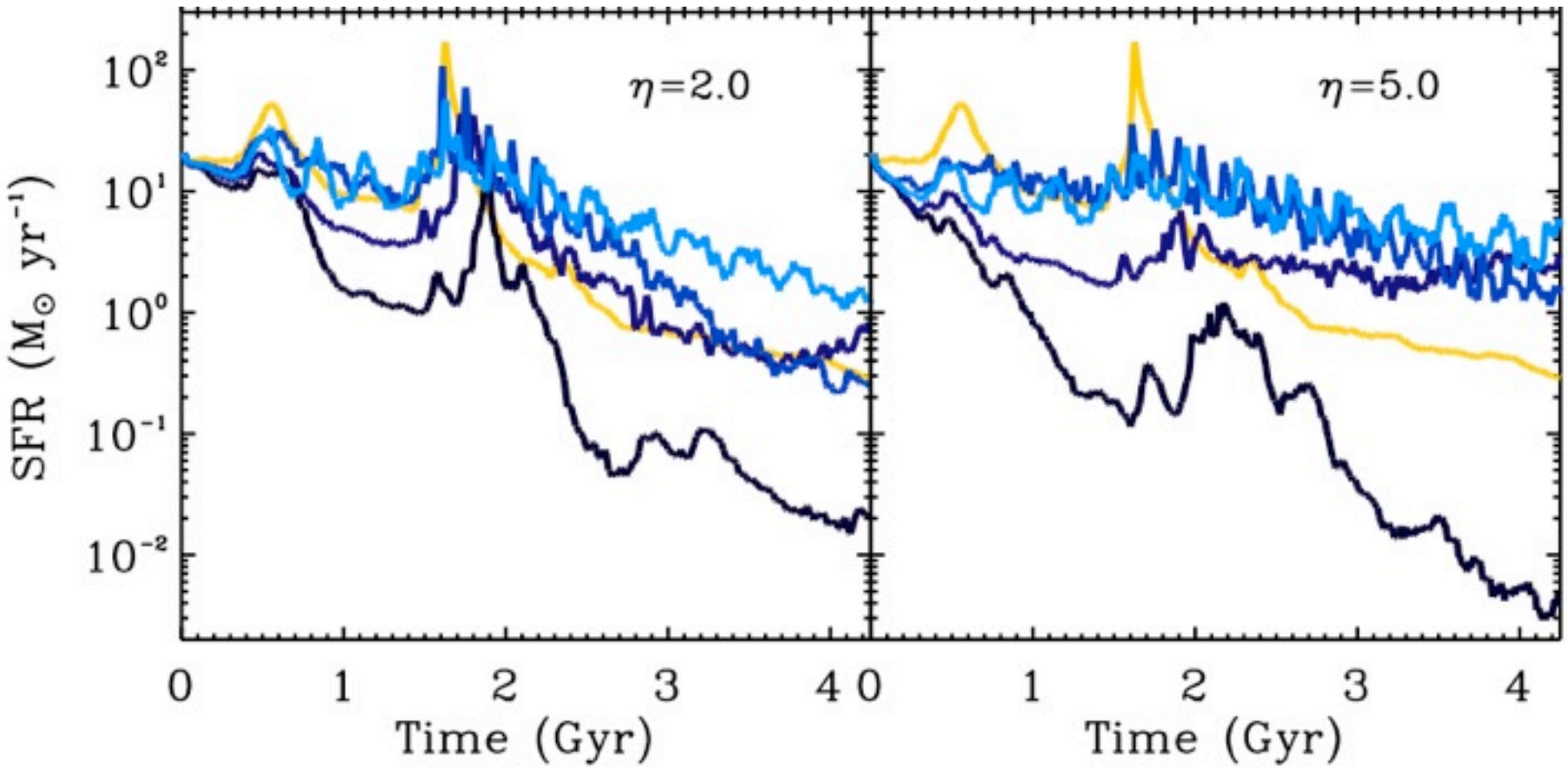
Energy Loading



- Wind *Structure* Similar
- Different Scales
- Different Efficiencies

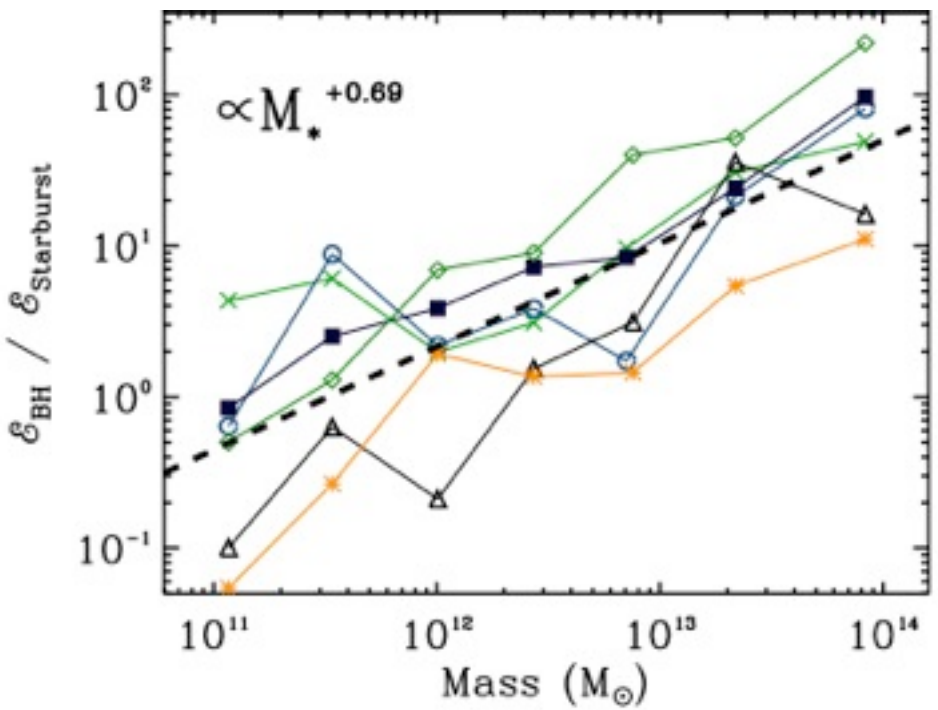
Feedback-Driven Winds

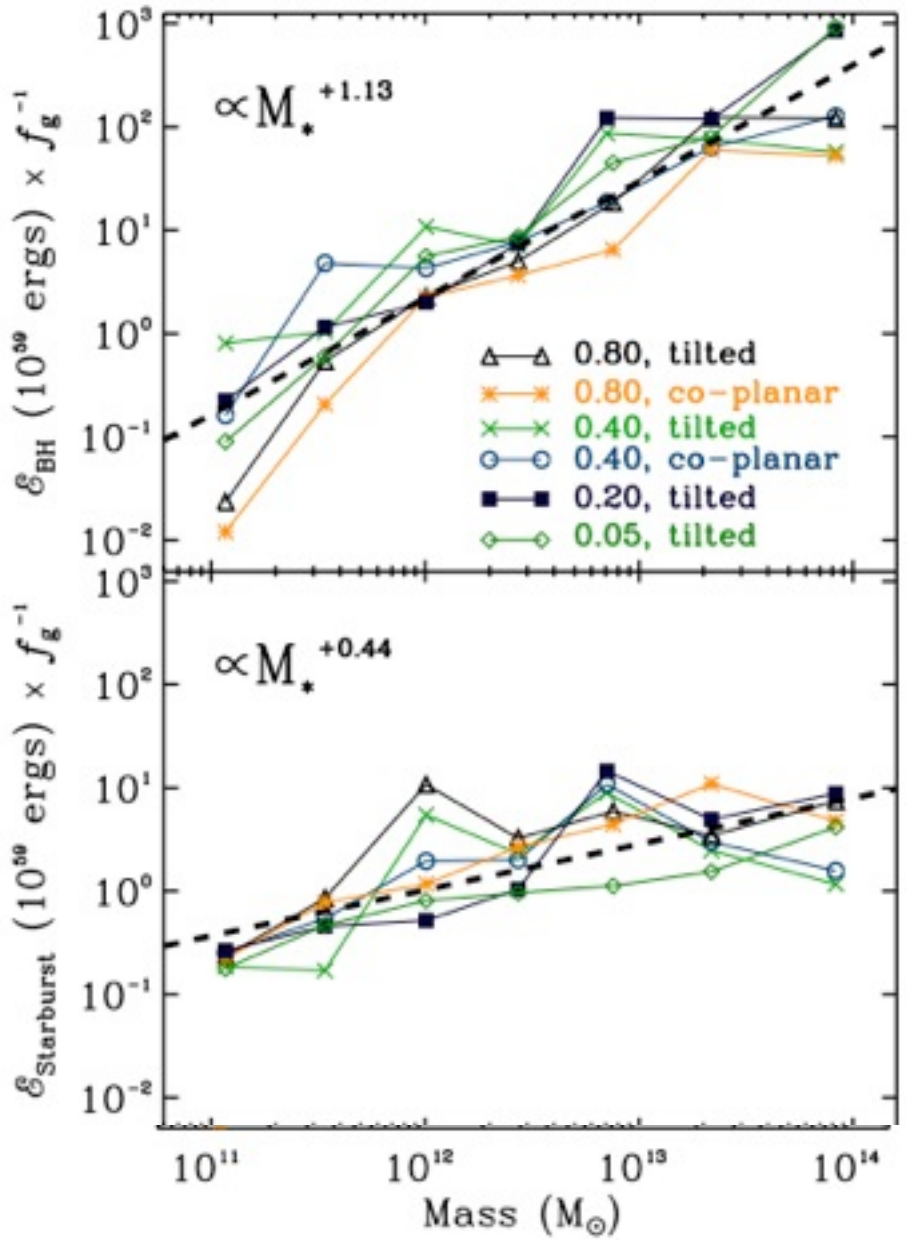
COMPARISON TO STARBURST-DRIVEN WINDS



Feedback-Driven Winds

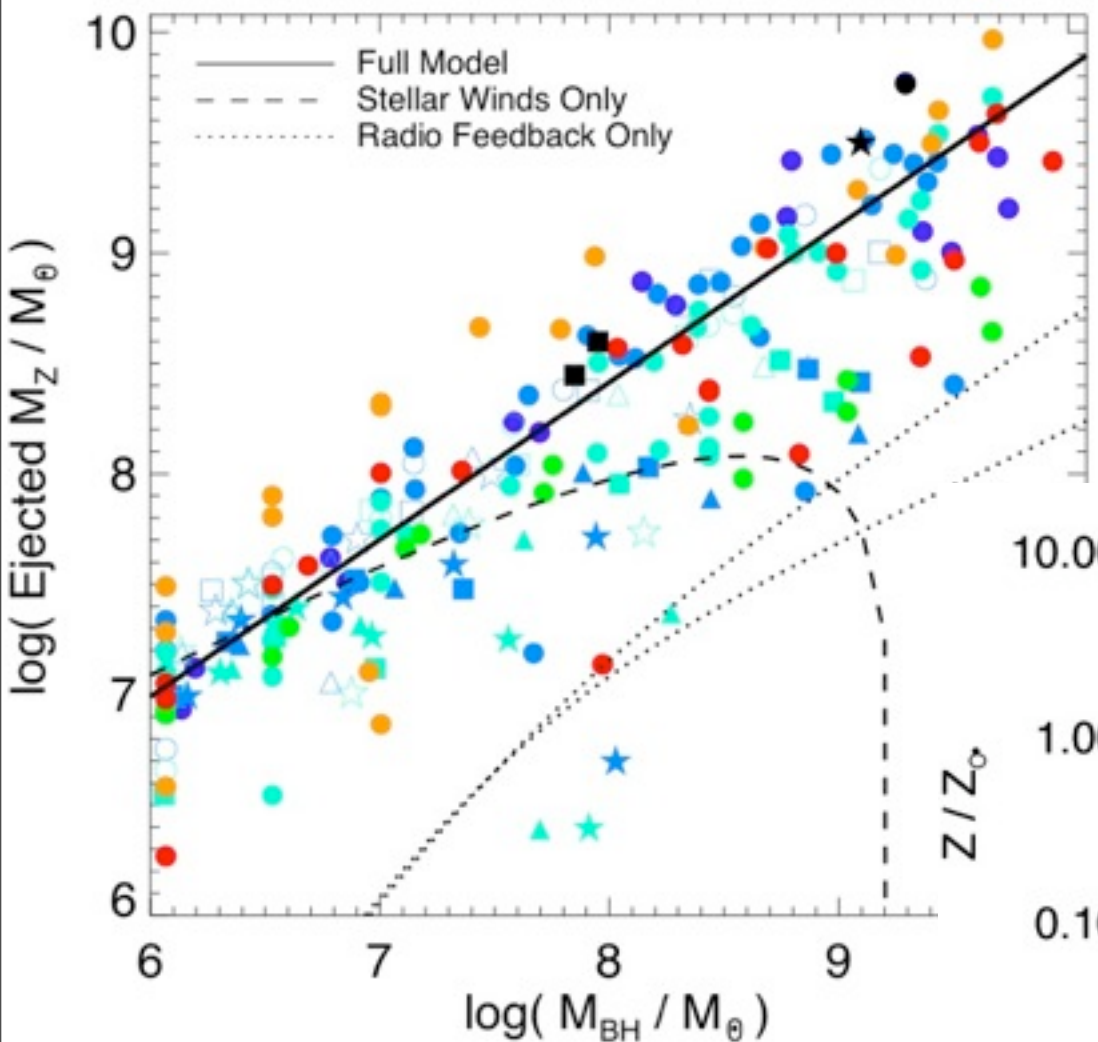
COMPARISON TO STARBURST-DRIVEN WINDS

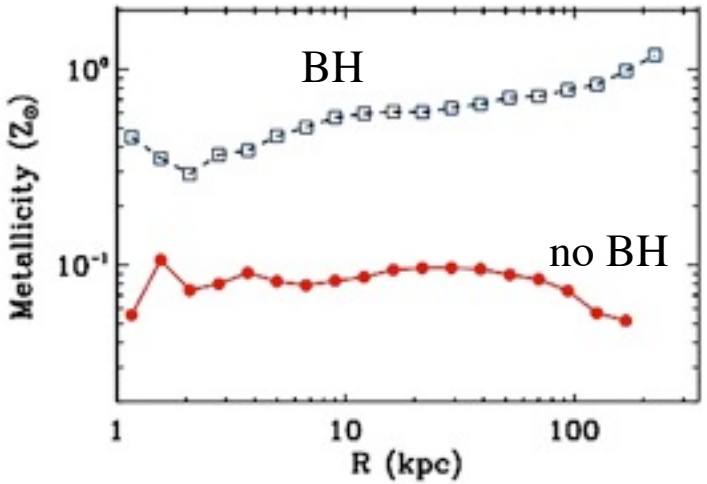


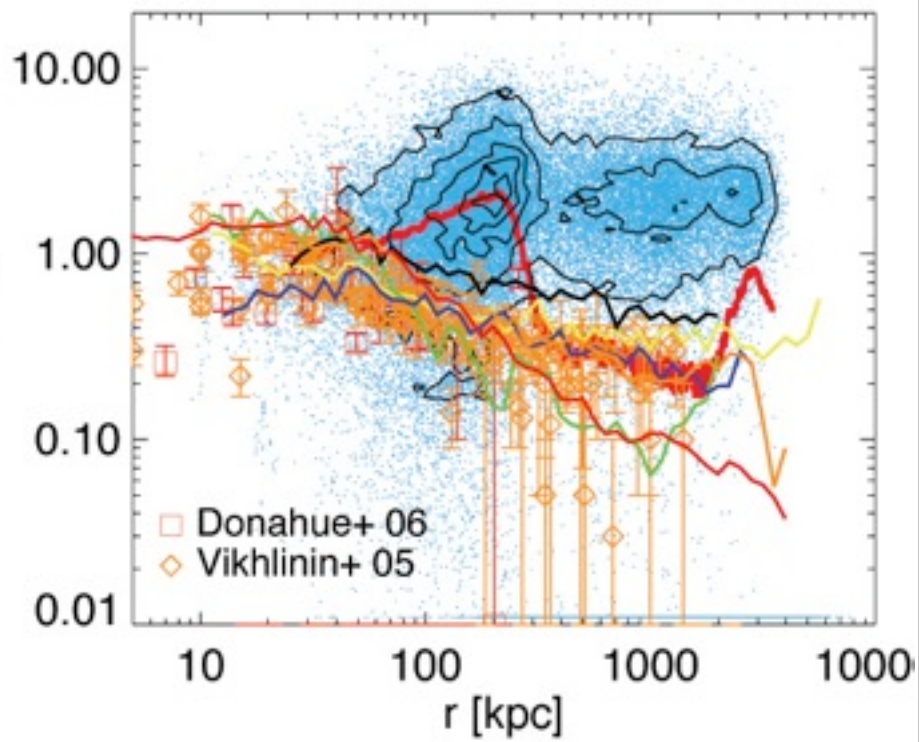


Feedback-Driven Winds

METAL ENRICHMENT

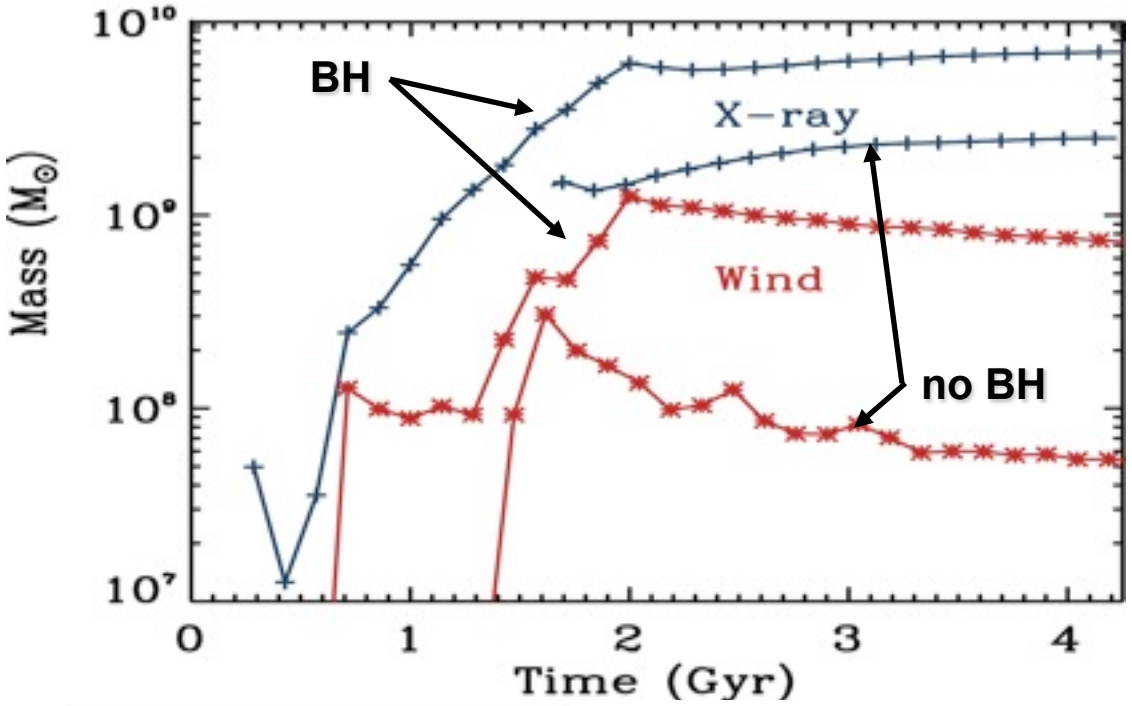


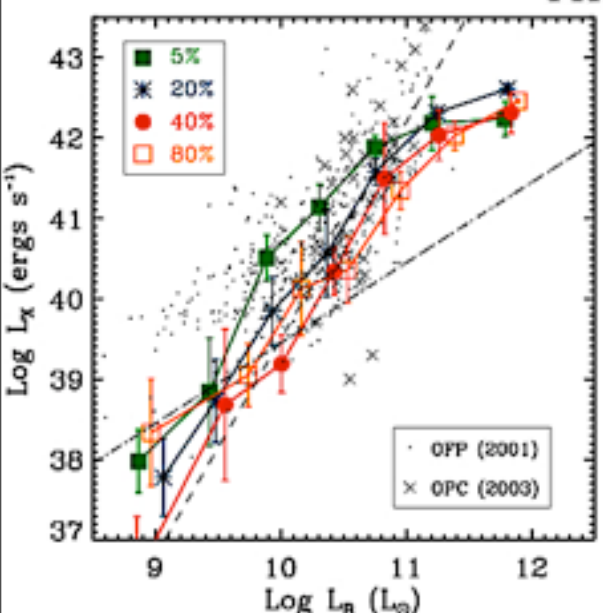


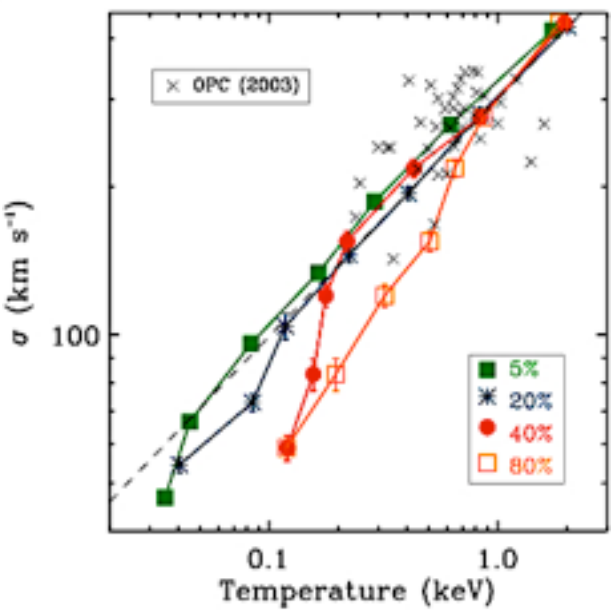


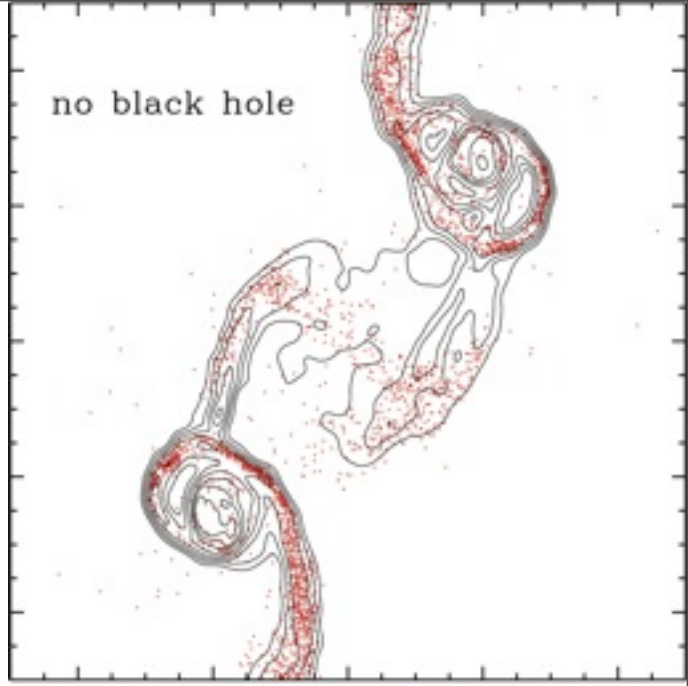
Feedback-Driven Winds

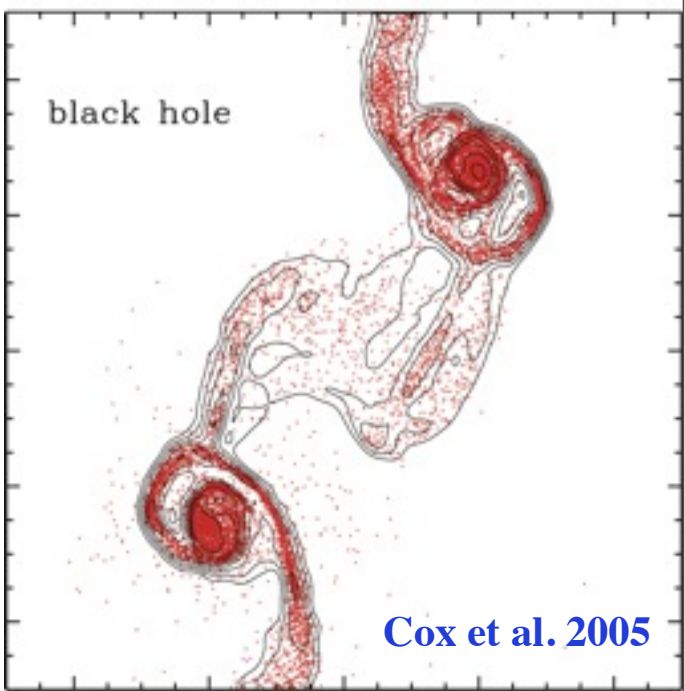
METAL ENRICHMENT & BUILDING THE X-RAY HALO







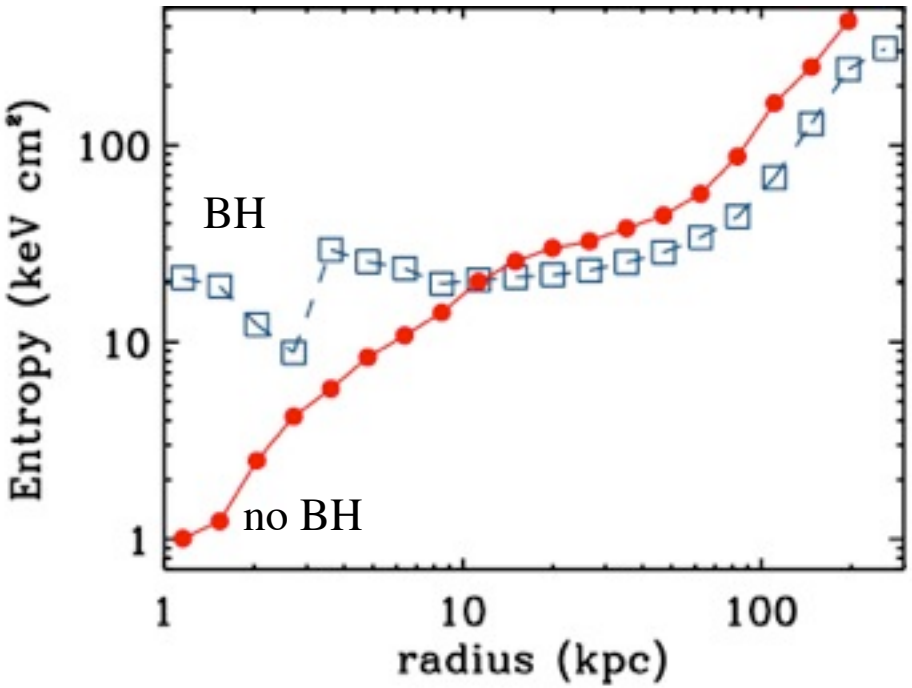


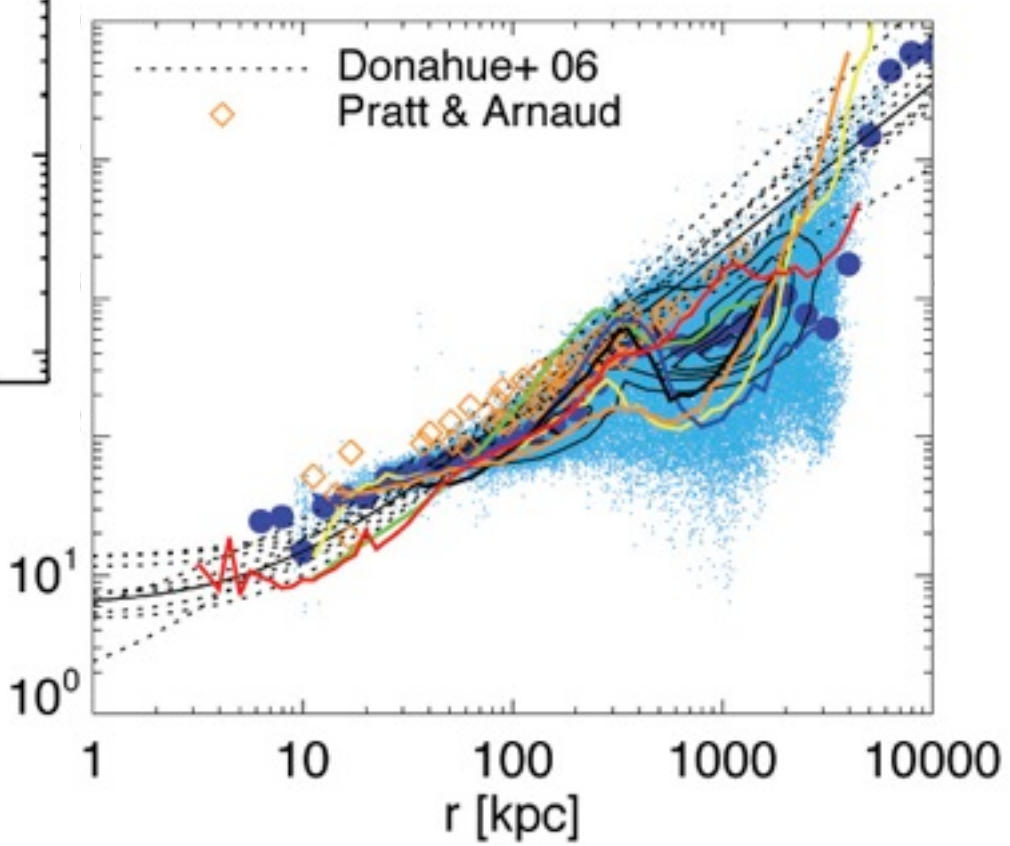


Feedback-Driven Winds

HEATING & ENTROPY

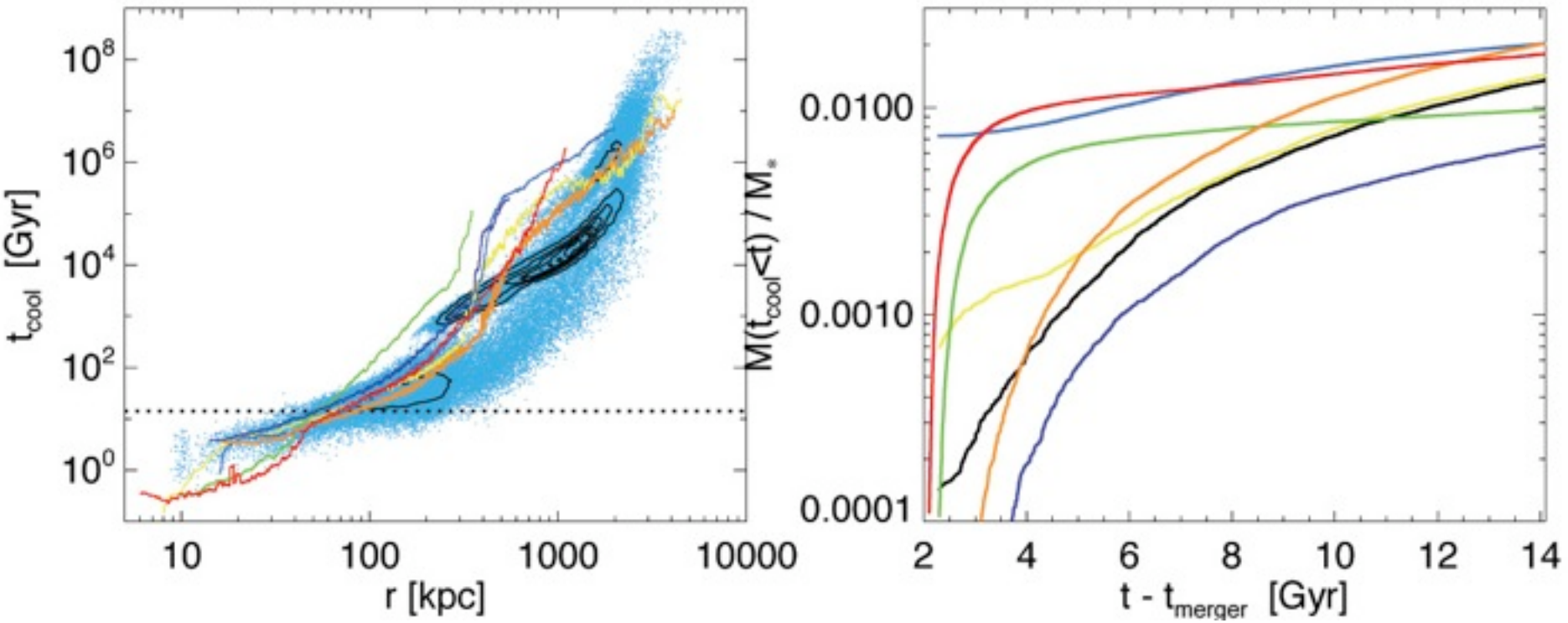
- Single, high-impact event can "set up" observed T/S profiles & correlations in ellipticals
  - Groups, even Clusters as well?





Feedback-Driven Winds
HEATING & ENTROPY

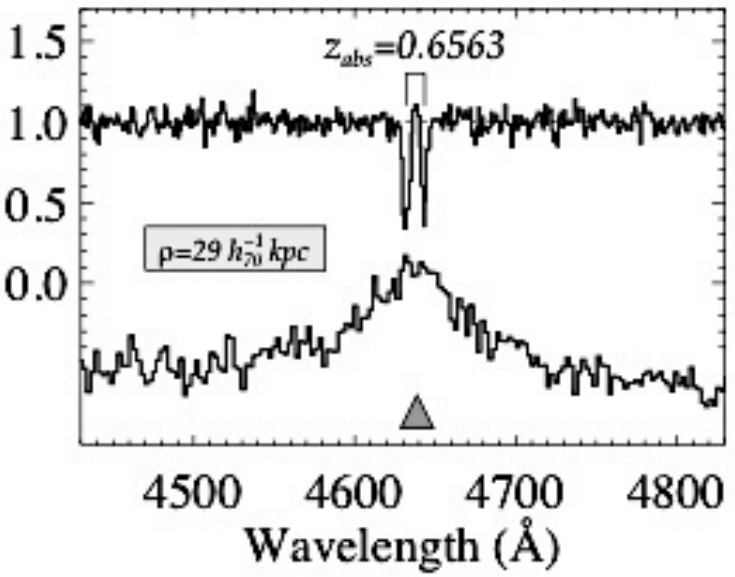
- Single episode heats enough gas to prevent a doubling of galaxy size:

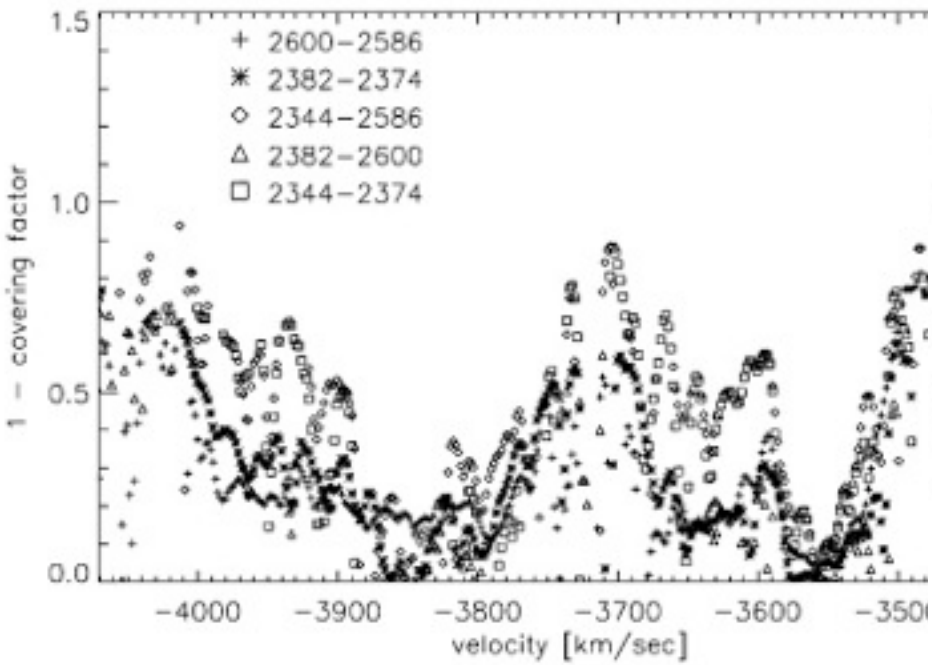


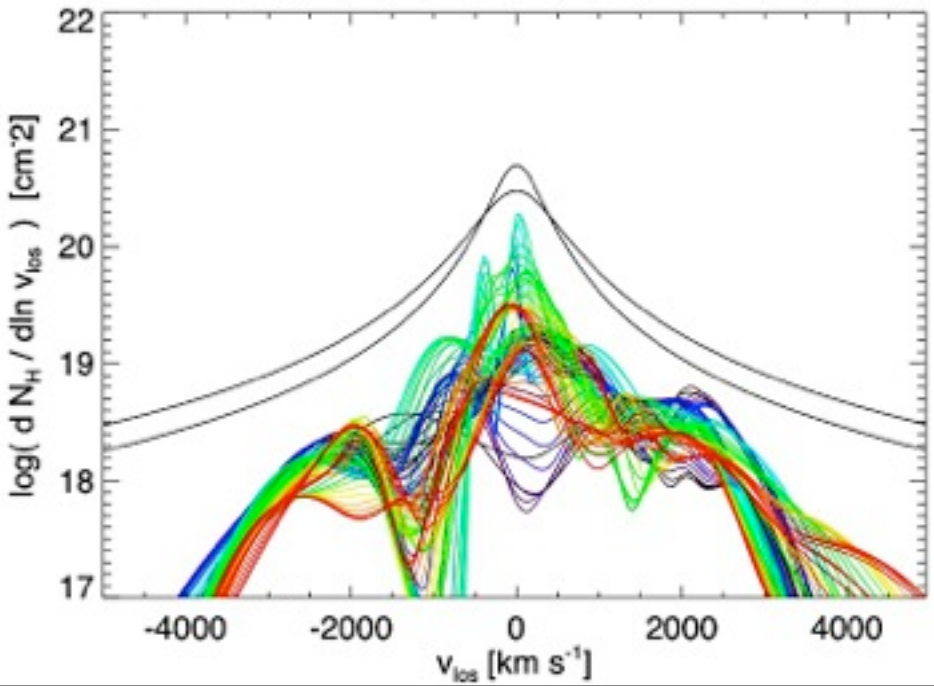
- Solution to cooling flows? Probably not, but supplements “radio mode”

Observational Prospects
"QUASAR" WINDS

- High-velocity outflows
  - >~ 1000 km/s at 1-1000 kpc
  - Local metal absorbers (Bowen+ 06)
  - BALs at "large distances" (deKool+ 01)
  - High-v outflow in non-BALs (Pounds 06)
- Clumpy substructure
- Preferentially w. high-Eddington ratio?

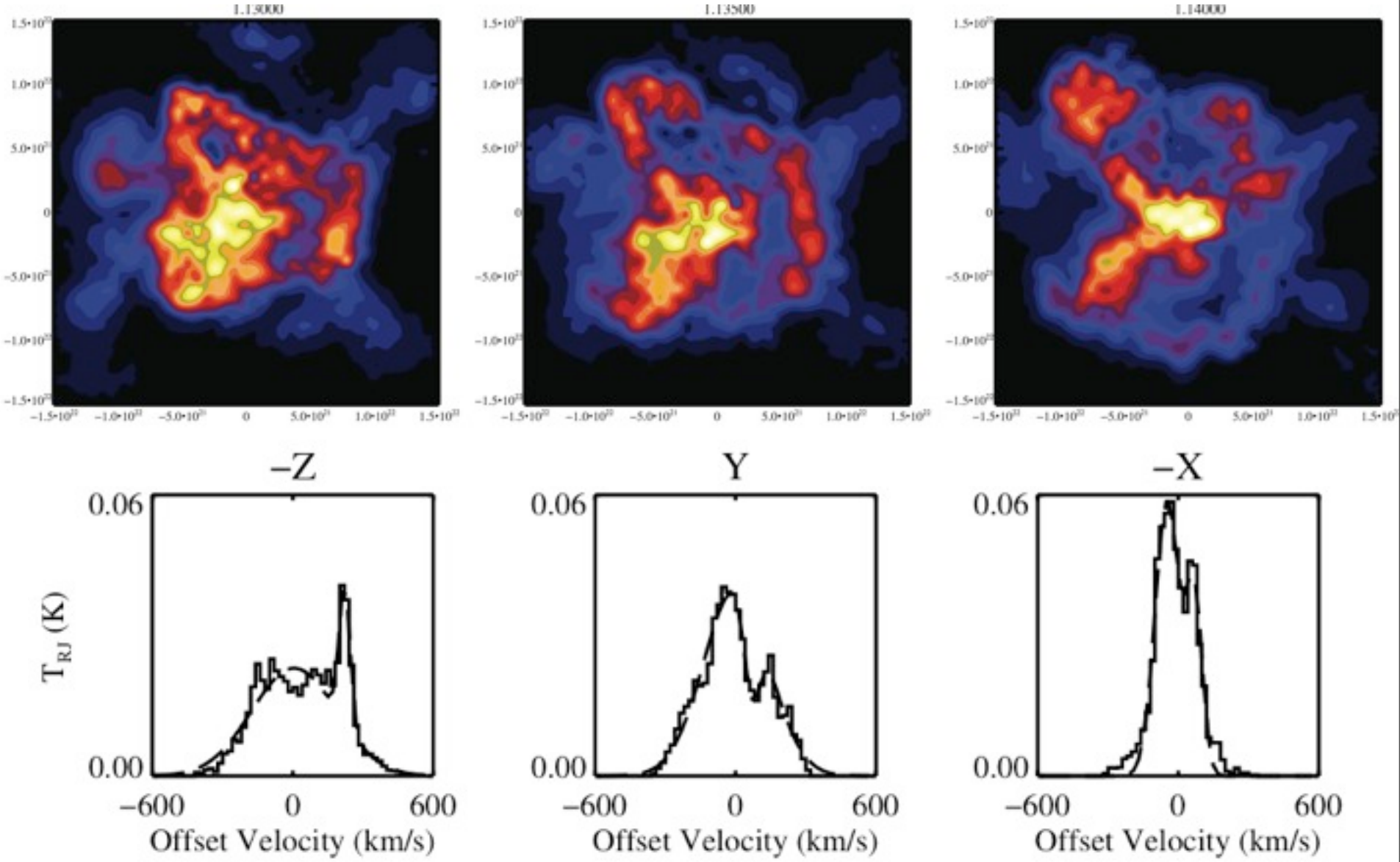




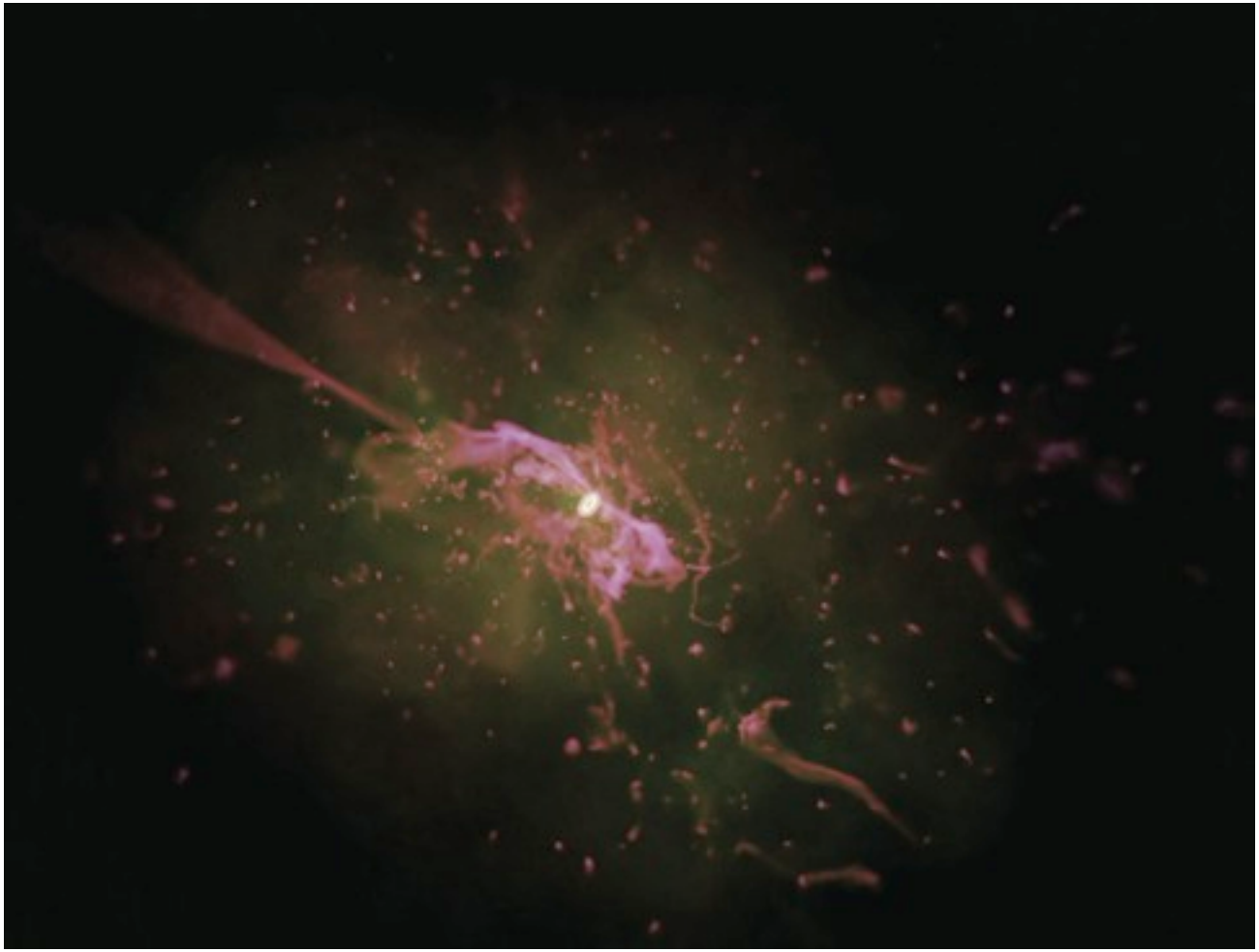


Observational Prospects
"QUASAR" WINDS

- CO outflows (Narayanan et al. 06)



Observational Prospects
INDIRECT EFFECTS



- Blue - Red transition :
  - colors/age of SB vs. Mdot
- Metal Enrichment
  - Abundance ratios (where/when are the metals from?)
  - Compare high-z merger profiles to local spheroids

Summary

- A number of lines of evidence argue for some form of “quasar” feedback
  - But need observations to
    (1) prove its there, and
    (2) actually begin to constrain its nature
- Much work to be done :
  - Modeling observations : covering factors, columns, velocity distributions, etc.
  - Self-consistently model feedback generation
  - Include radio and “quasar” mode feedback
  - Incorporate into cosmological models
- But there appears to be rapid progress!