Merger-Driven Co-Evolution of Quasars, Supermassive Black Holes & Elliptical Galaxies

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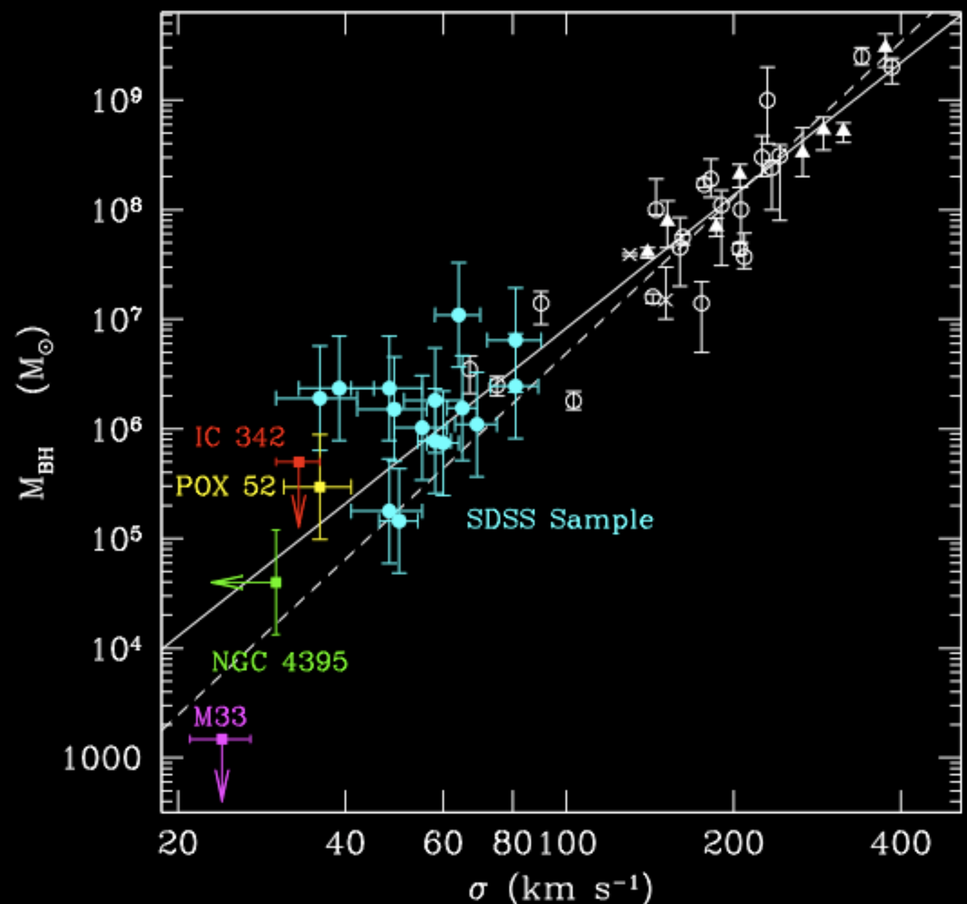
with: TJ Cox (Carnegie) & Phil Hopkins (Berkeley)

How are Quasars, Supermassive Black Holes, Elliptical Galaxies Connected?

- Black holes, spheroids correlated ⇒ formation related
- Most black hole mass in quasar phases (Soltan)
- Simplest picture: originate primarily in one event
- Is this sensible?



Barth, Greene & Ho (2004)

Requirements on Single "Event"

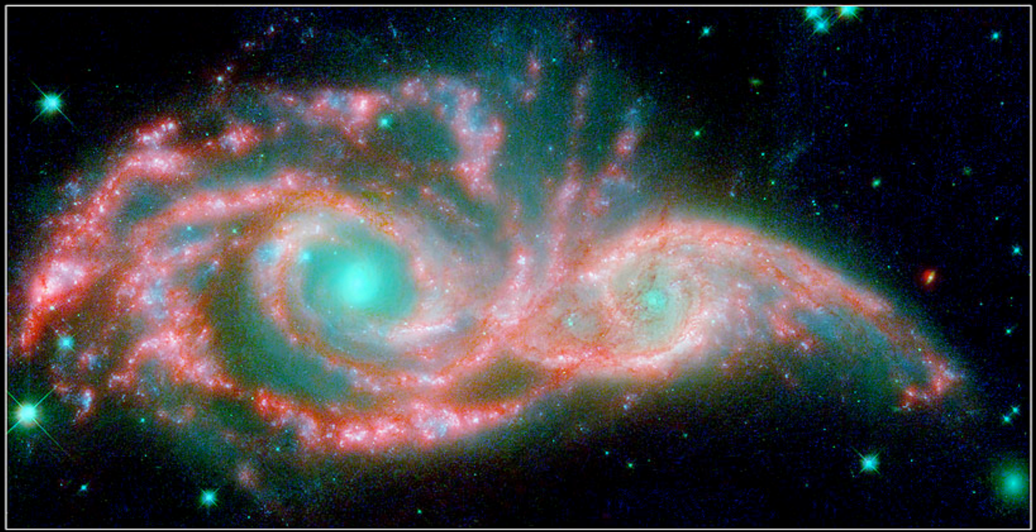
- Fast, violent
- Blend of gas & stellar dynamics
- Why?
  - * Soltan (1982): bulk of SMBH mass density grown through radiatively efficient accretion in quasars

    → gas dynamics; rapid (~ few 10^7 years)
  - * Lynden-Bell (1967): orbits of stars redistributed in phase space by large, rapid potential fluctuations

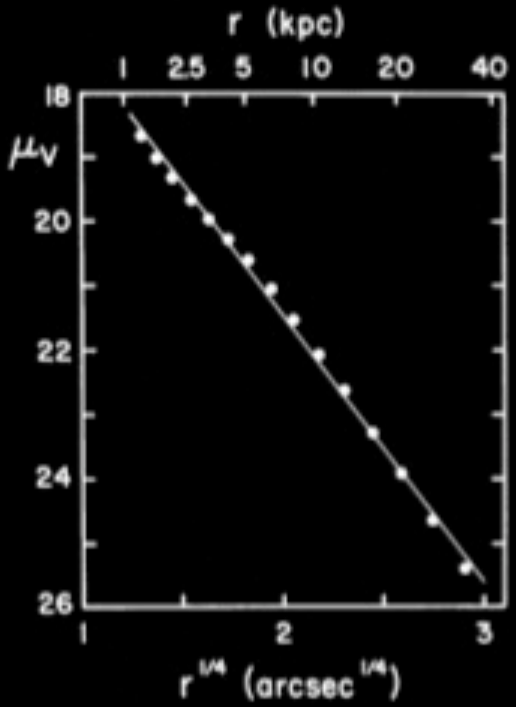
    → stellar dynamics; freefall timescale
- Need galaxy's supply of each: BH / host relations; structure of ellipticals

Candidate Process: Gas-Rich, Major Merger

- Locally, related to:
  - growth of spheroids
  - causing starbursts
  - fueling SMBH growth, quasar activity



Spitzer/Hubble View of NGC 2207 & IC 2163 Spitzer Space Telescope • IRAC
NASA, ESA / JPL-Caltech / STScI / D. Elmegreen (Vassar) ssc2006-11b



NGC 7252
Schweizer (1982)

Candidate Process: Gas-Rich, Major Merger

- Locally seen related to:
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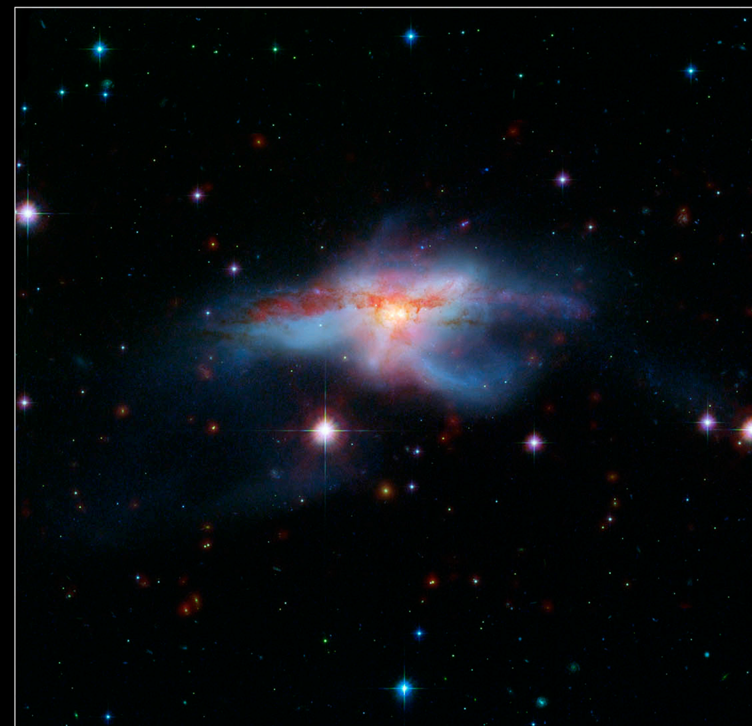
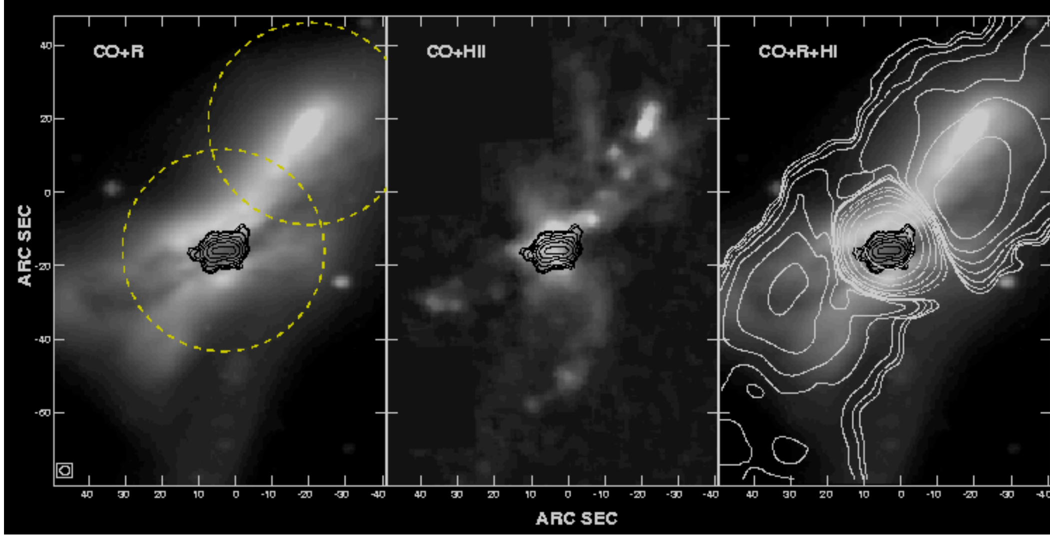
  - causing starbursts (ULIRGs)
  - fueling SMBH growth, quasar activity



Ultraluminous Galaxy Merger NGC 6240

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS

NASA / JPL-Caltech / STScI-ESA / S. Bush (Harvard-Smithsonian CfA) ssc2009-06a



Yun & Hibbard (2001)

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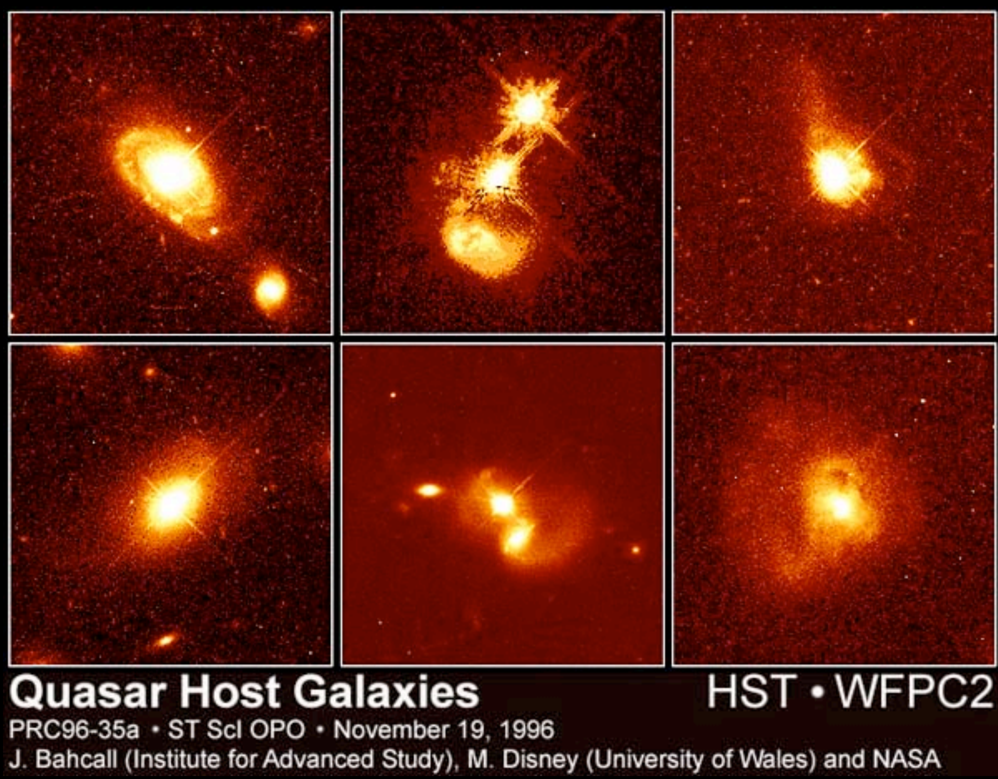
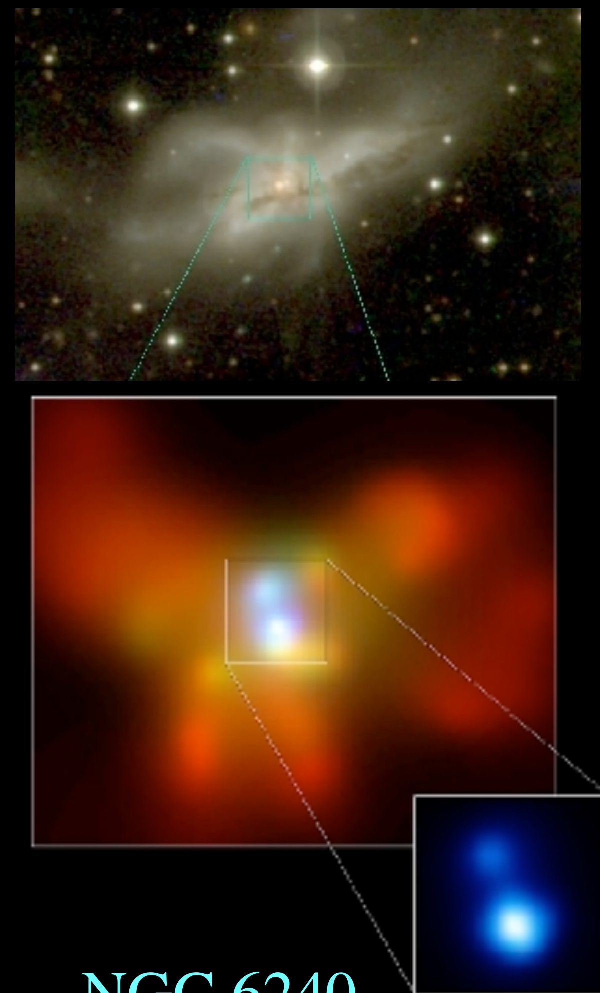
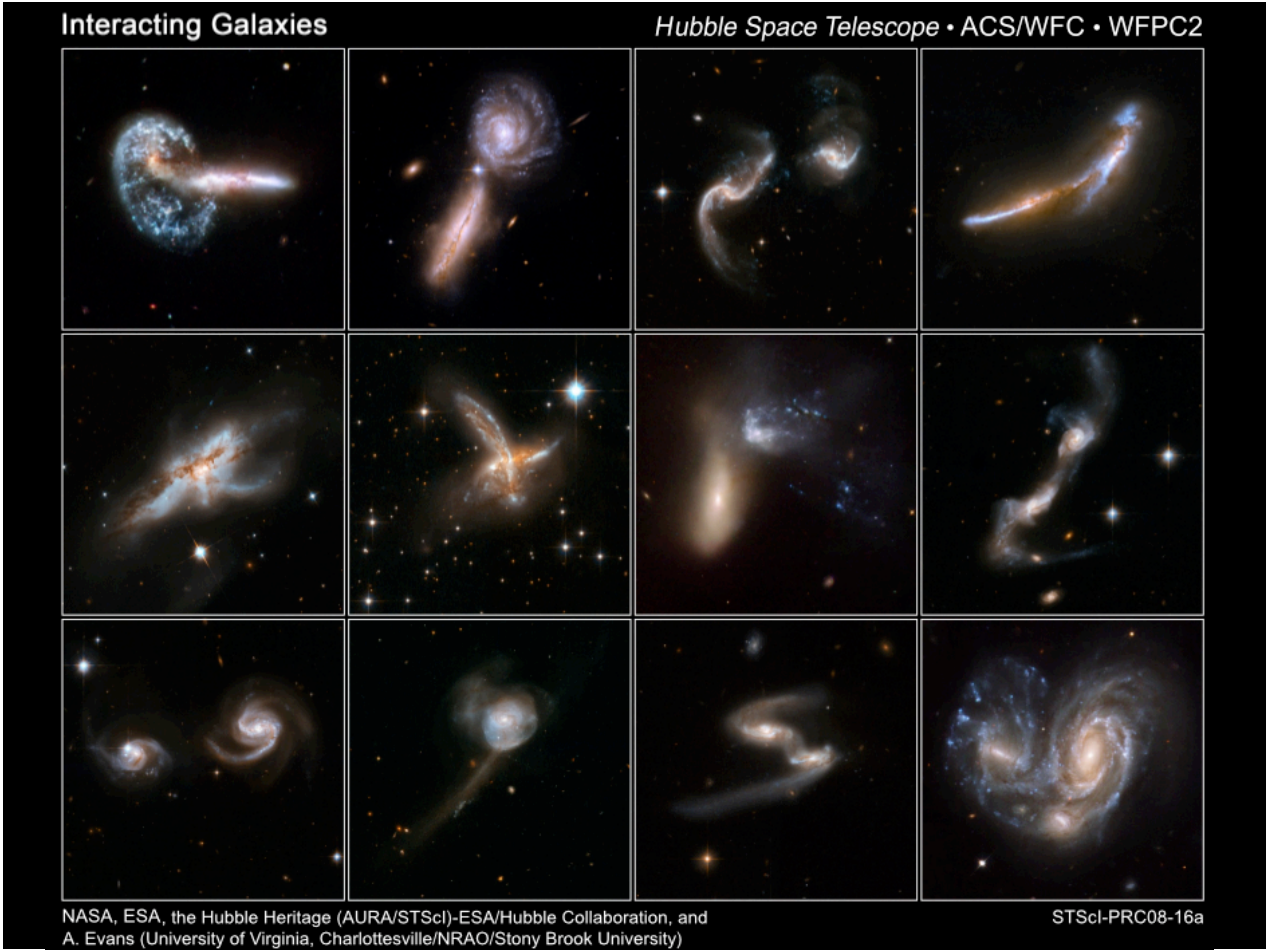


Komossa et al. (2003)



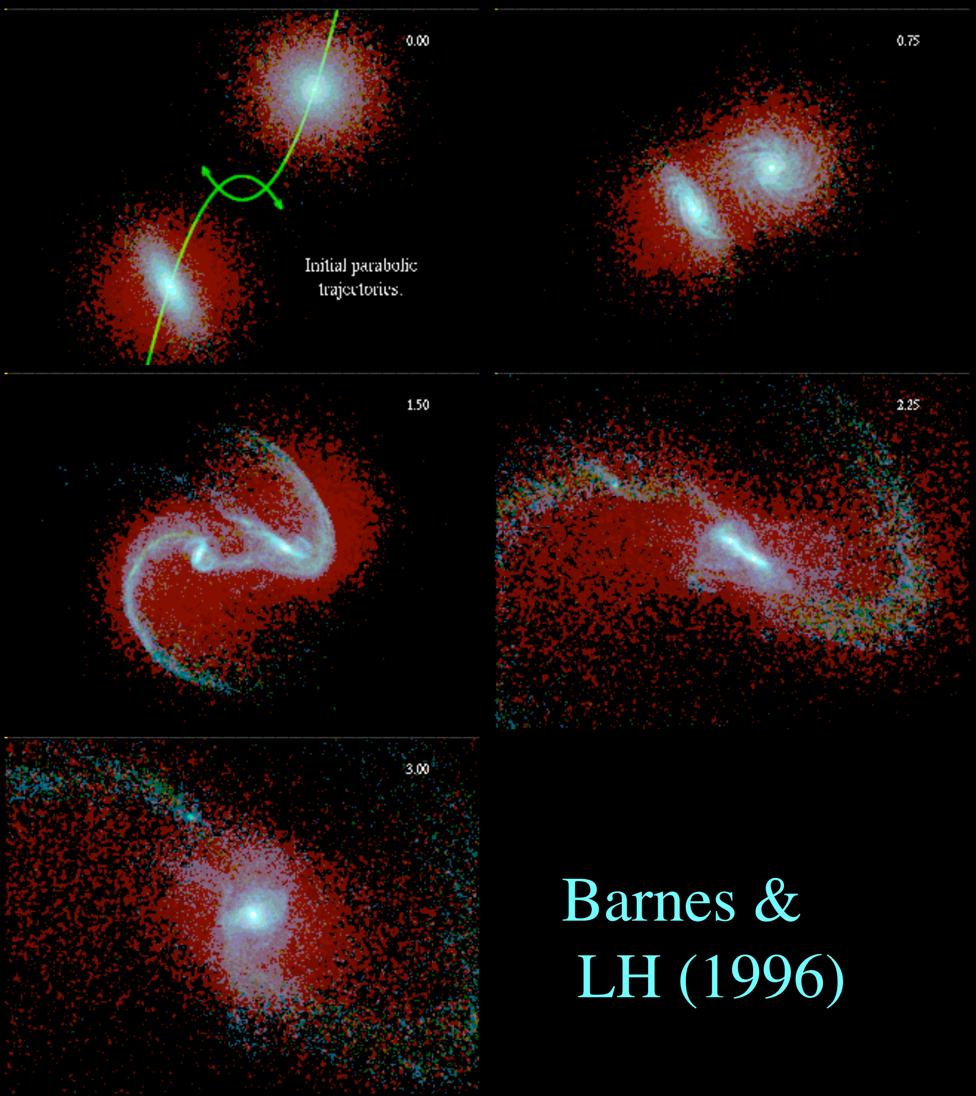
NGC 6240


Interacting Galaxies
Hubble Space Telescope • ACS/WFC • WFPC2
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)
STScI-PRC08-16a

Frank Summers (STScI)

Plausible Physical Mechanism

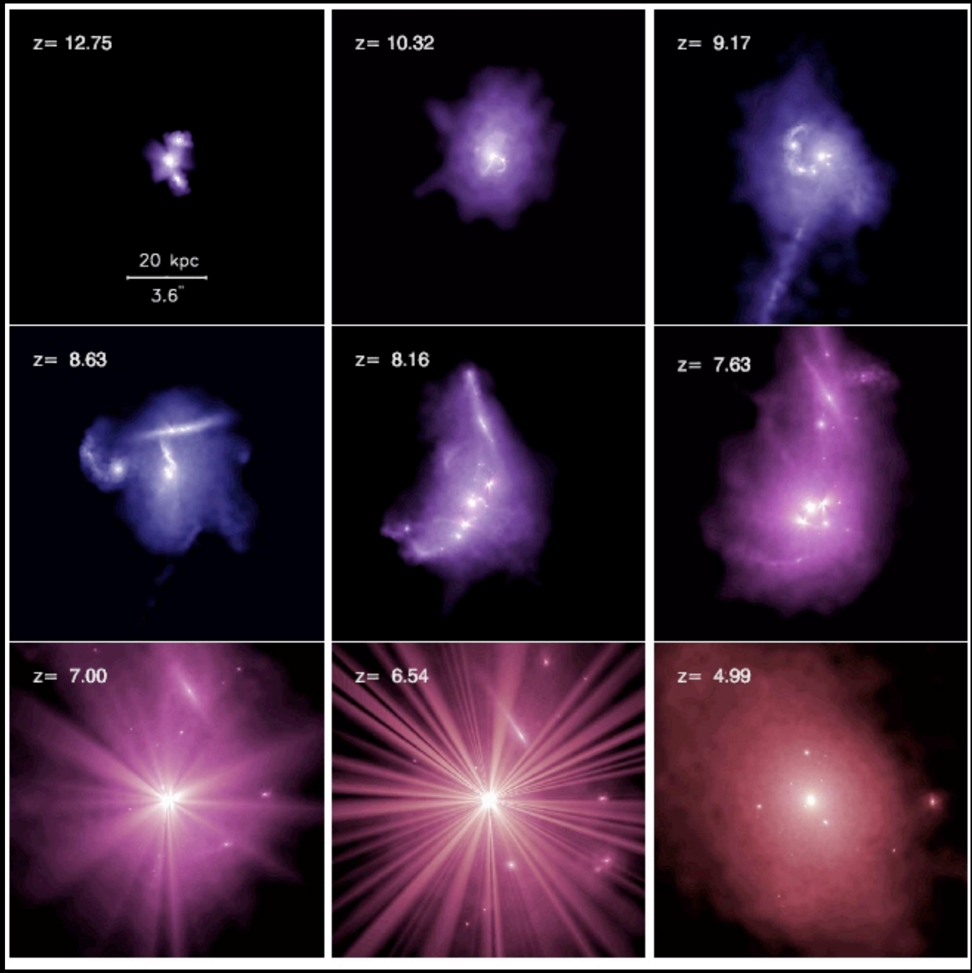
- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & LH 1991)
- Triggers starburst (e.g. Mihos & LH 1996)
- Feeds BH growth (e.g. Di Matteo et al. 2005)
- Merging stellar disks grow spheroid
- Requirements:
  - major merger
  - supply of cold gas ("cold" = rotationally supported)



Barnes & LH (1996)

Testing the Hypothesis

- Simulations: 3-D, time-dependence
- Consider:
  - single, multiple mergers
  - varying mass ratios
  - star formation, supernova feedback & winds (sub-resolution)
  - black hole growth, feedback (sub-resolution)
  - large gas fractions: made possible by SN feedback



Li et al. (2006)

QuickTime™ and a
decompressor
are needed to see this picture.

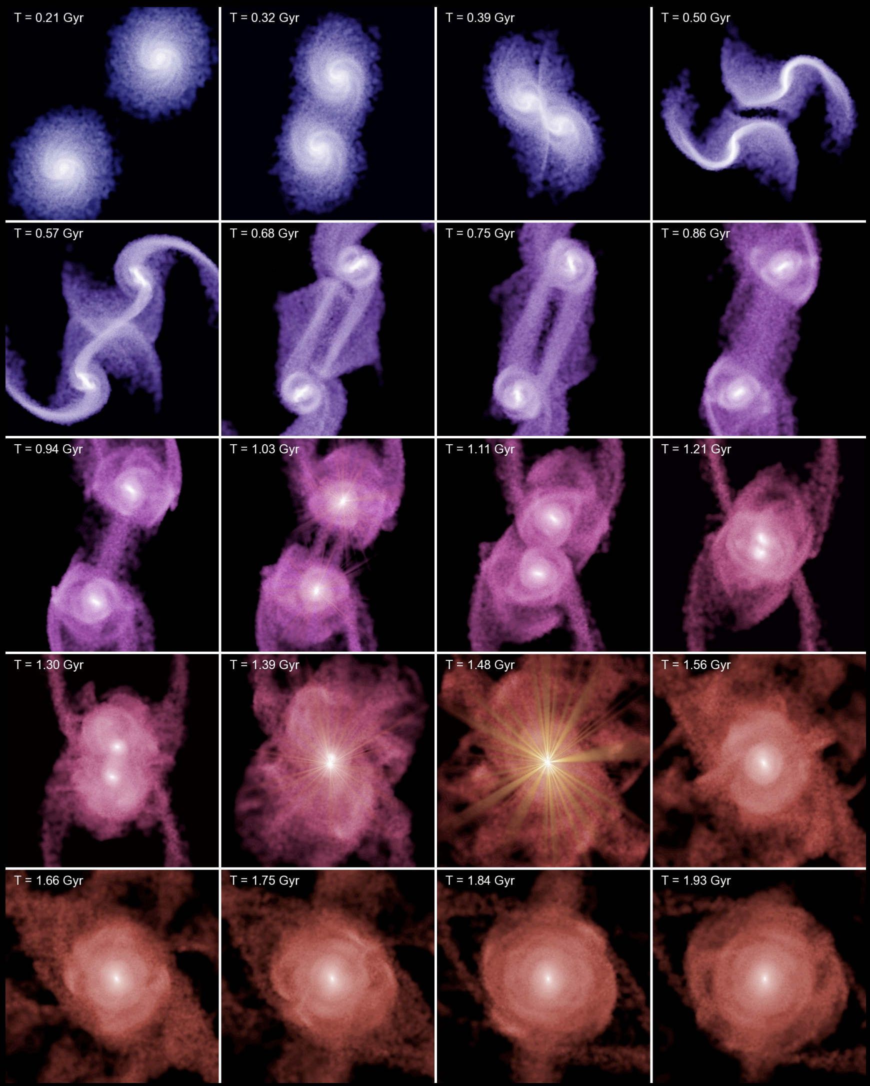
Stars

QuickTime™ and a
decompressor
are needed to see this picture.

Gas

Generic Outcome of Gas-Rich Mergers

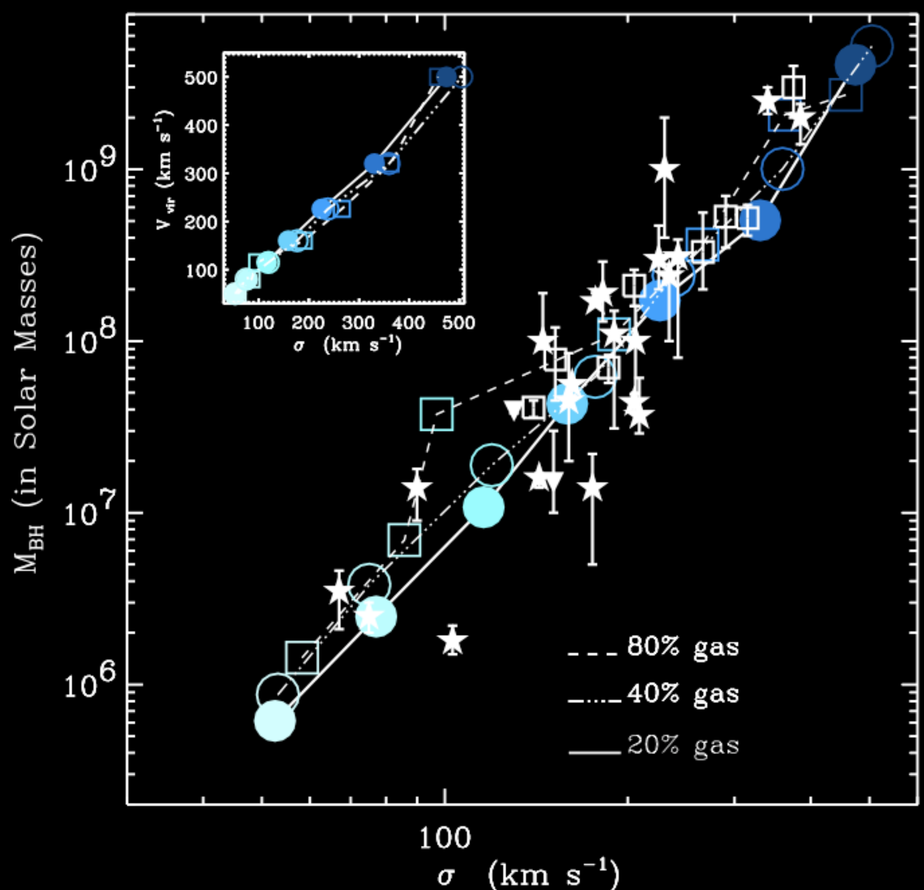
- Gas inflow → starburst
  - BH mainly buried in optical by gas & dust: obscured growth
- AGN feedback → dispersal
  - black hole briefly visible as optical quasar: blowout phase
- Remnant relaxes
  - quasar dies when gas supply runs out
  - spheroid satisfies M_{BH} - σ
  - little residual star formation (quickly reddens)



Hopkins et al., astro-ph/0506398

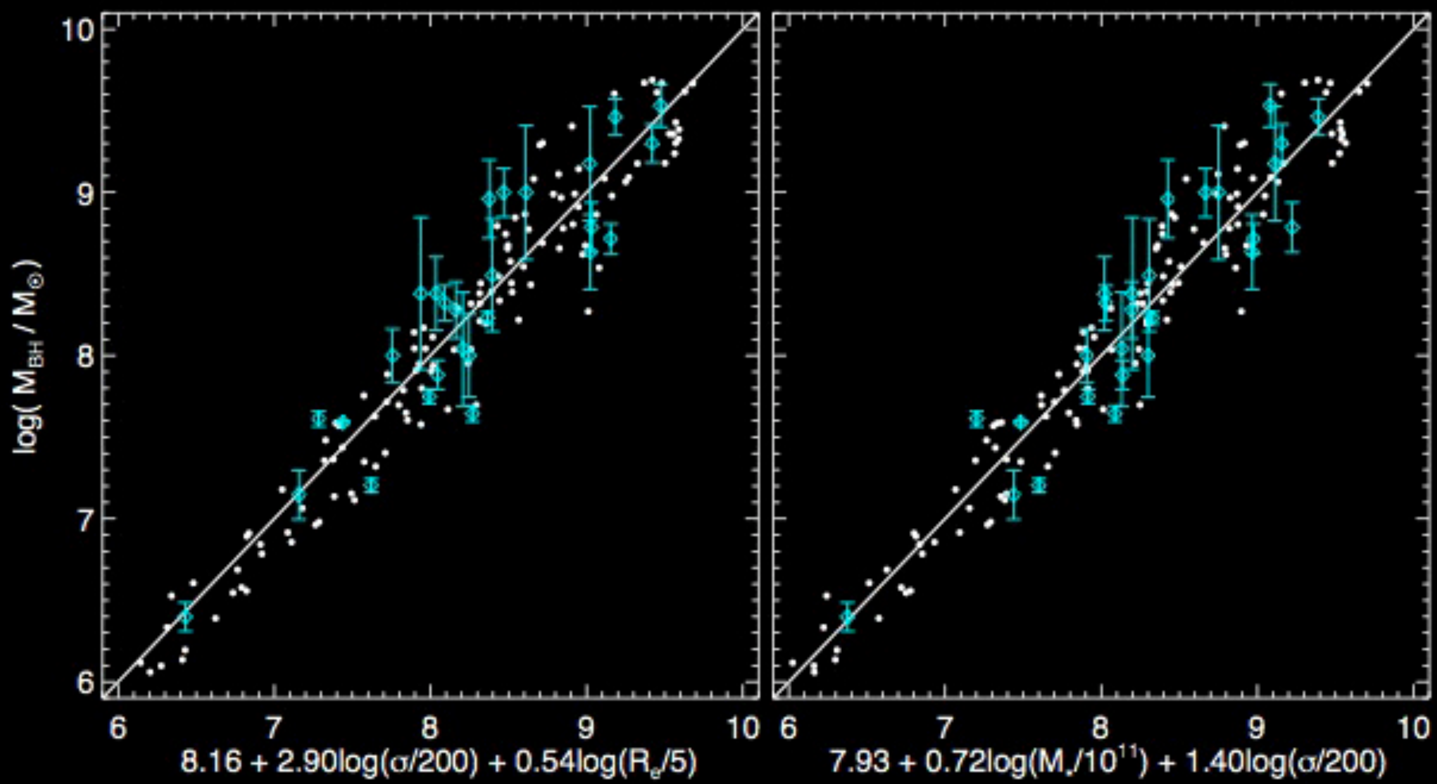
Relics: Black Hole - Host Correlations

- BH mass determined by feedback, gas cooling, potential well, gas dynamics
- BH growth self-regulated, fixing feedback efficiency $E_{feed} = \varepsilon_f M_{BH} c^2$ with $\varepsilon_f \sim 0.005$
- Match observed slope of M-σ relation
- Interpretation motivates more refined correlations



Di Matteo, Springel & LH (2005)

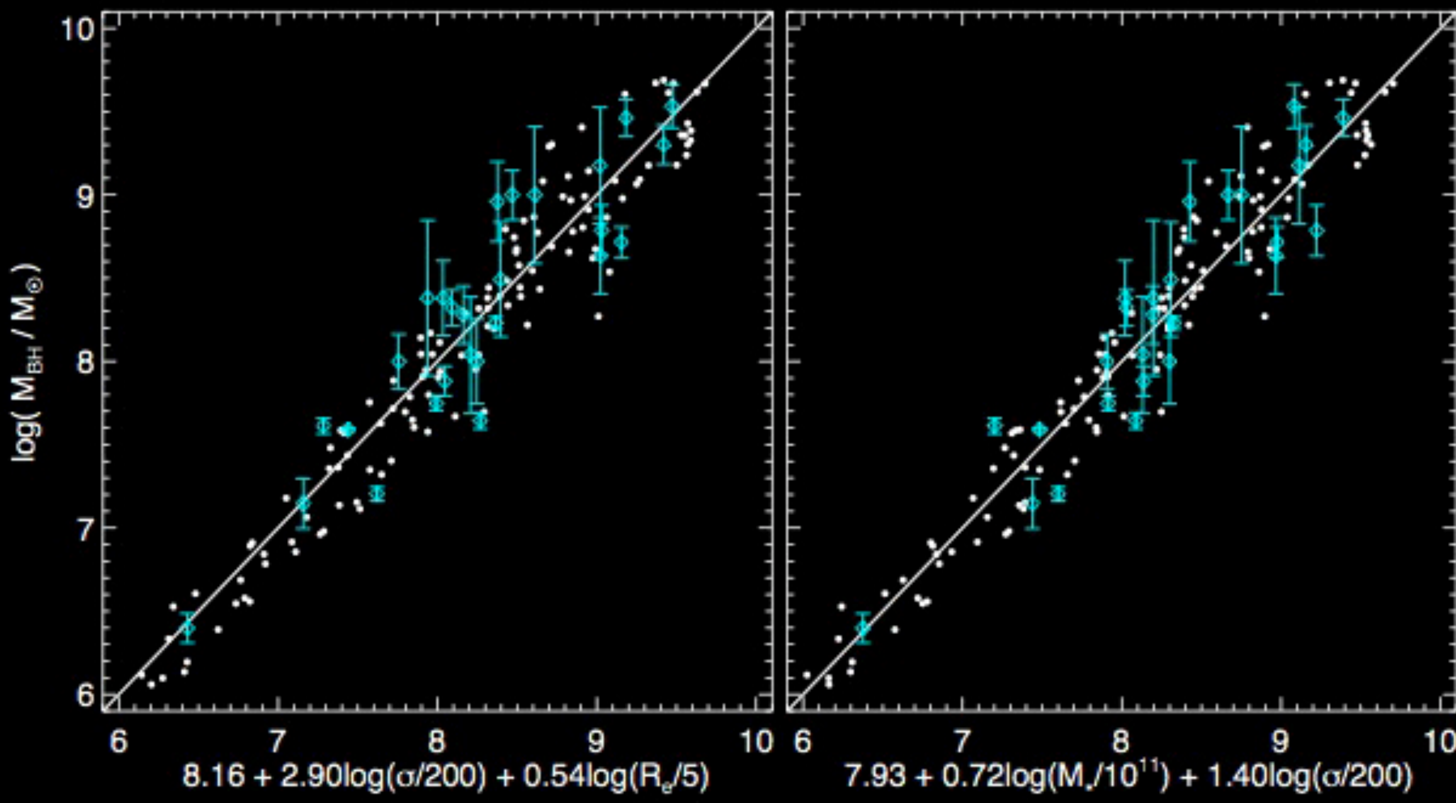
Self-Regulated Black Hole Growth



- "BH fundamental plane" (Hopkins et al. arXiv:0707.4005, 0701351):
  - energy input ∝ $dM_{BH}/dt \sim M_{BH}$
  - gas binding $\sim M_* \sigma^2$
  - data: $M_{BH} \sim (M_* \sigma^2)^{0.7}$ or $M_{BH} \sim \sigma^3 R_e^{0.5}$
  - pressure-driven outflow unbinds gas (Hopkins & LH 2006)

Self-Regulated Black Hole Growth

(Hopkins et al., arXiv / 0701351 & 070.4005)



- Resolves outliers in M_{BH} - σ and M_{BH} - M_* relations
- Predicts BHs more massive for fixed M_* at high z (deeper potentials):

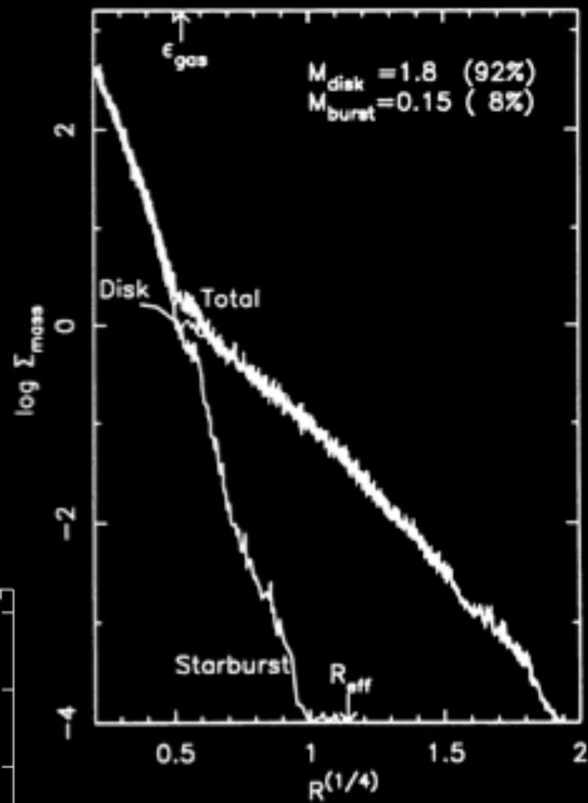
  $M_{BH} \sim M_*^{1.5} R_e^{-1.0}$

  Trujillo et al.: $R_e \sim (1+z)^{-0.4}$

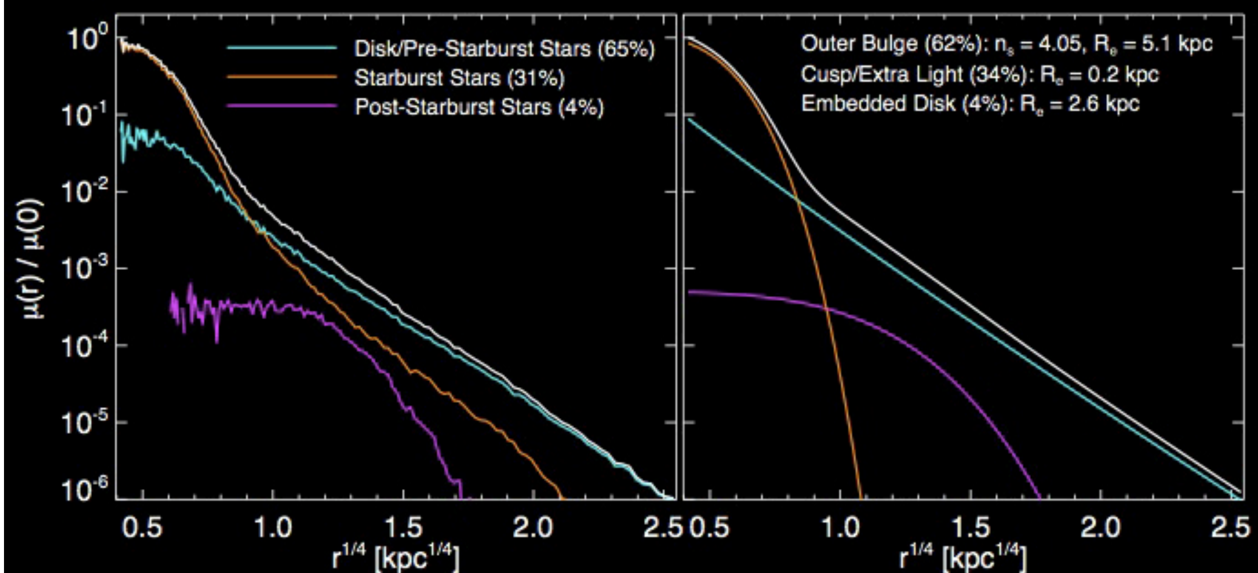
  expect: $M_{BH} / M_* \sim (1+z)^{0.5}$ (similar to e.g. Peng et al. 2006)

Relics: Two - Component Spheroids

- predicted theoretically:
  - outer "envelope" from pre-existing stars
  - inner relic "starburst" component
- verified by more general, more accurate simulations



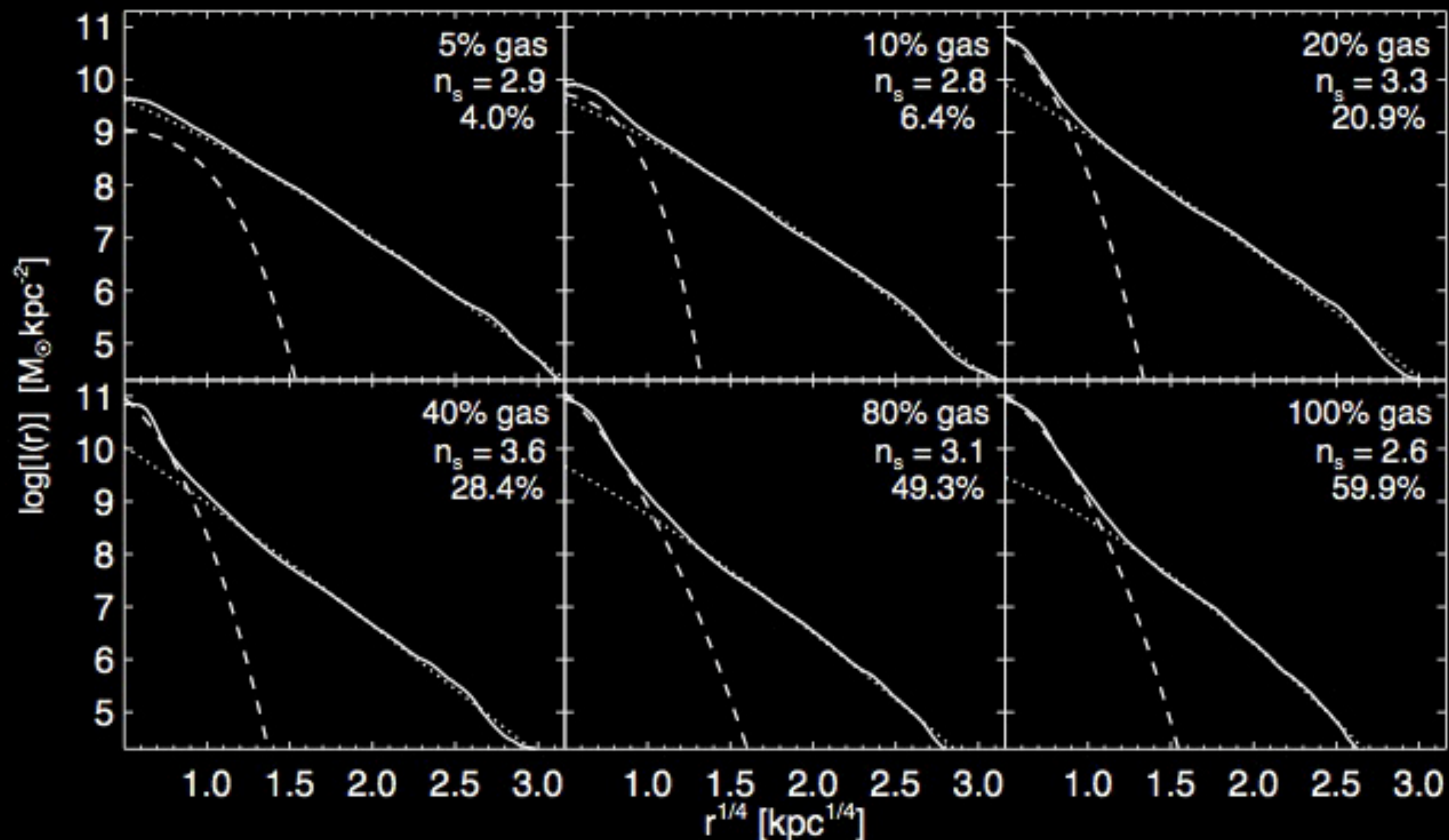
Mihos & LH (1994)



Hopkins et al. (2008), arXiv:0802.0508

Relics: Two - Component Spheroids

Fraction of starburst component determined by gas content



Hopkins et al. (2008), arXiv:0802.0508

Theoretical / Observational Analysis

(Hopkins et al., arXiv:0802.0508v2, 0805.3533v2, 0806.2325v2)

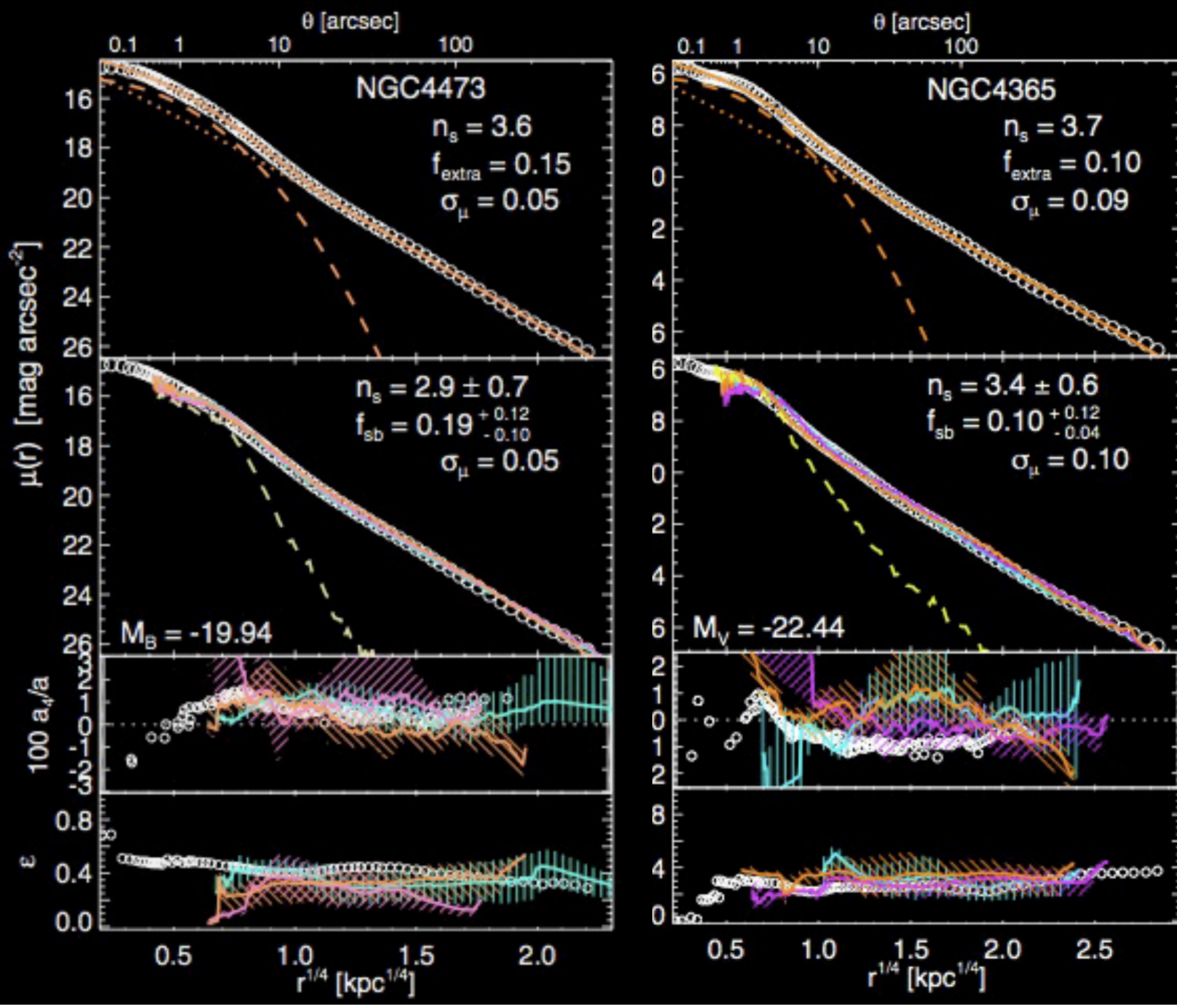
- Observations (span ≈ 0.01 L_* - 10 L_*):
  - ≈ 50 gas-rich mergers (Rothberg & Joseph)
  - ≈ 80 cusp ellipticals (Kormendy et al., Bender et al., Lauer et al.)
  - ≈ 110 core ellipticals (ibid.)
- Simulations - many hundreds:
  - vary: orbit, structure/masses of progenitors, gas content, star formation/feedback, black hole accretion/feedback, resolution
- Analysis:
  - best matching simulation
  - two-component Sersic fits: $I \propto \exp[-(r/r_0)^{1/n}]$ for n_{in} & n_{out} (note: n=1 → exponential; n=4 → $r^{1/4}$ law)

Theoretical / Observational Analysis

(Tabulated in arXiv: 0802.0508v2, 0805.3533v2, 0806.2325v2)

- two-component matches to all ellipticals (but at $L \approx 0.01\ L_*$)
- exclude dwarf spheroidals, S0s
- top: parameter fit
- middle: 3 best matching sims. (starburst = dash)

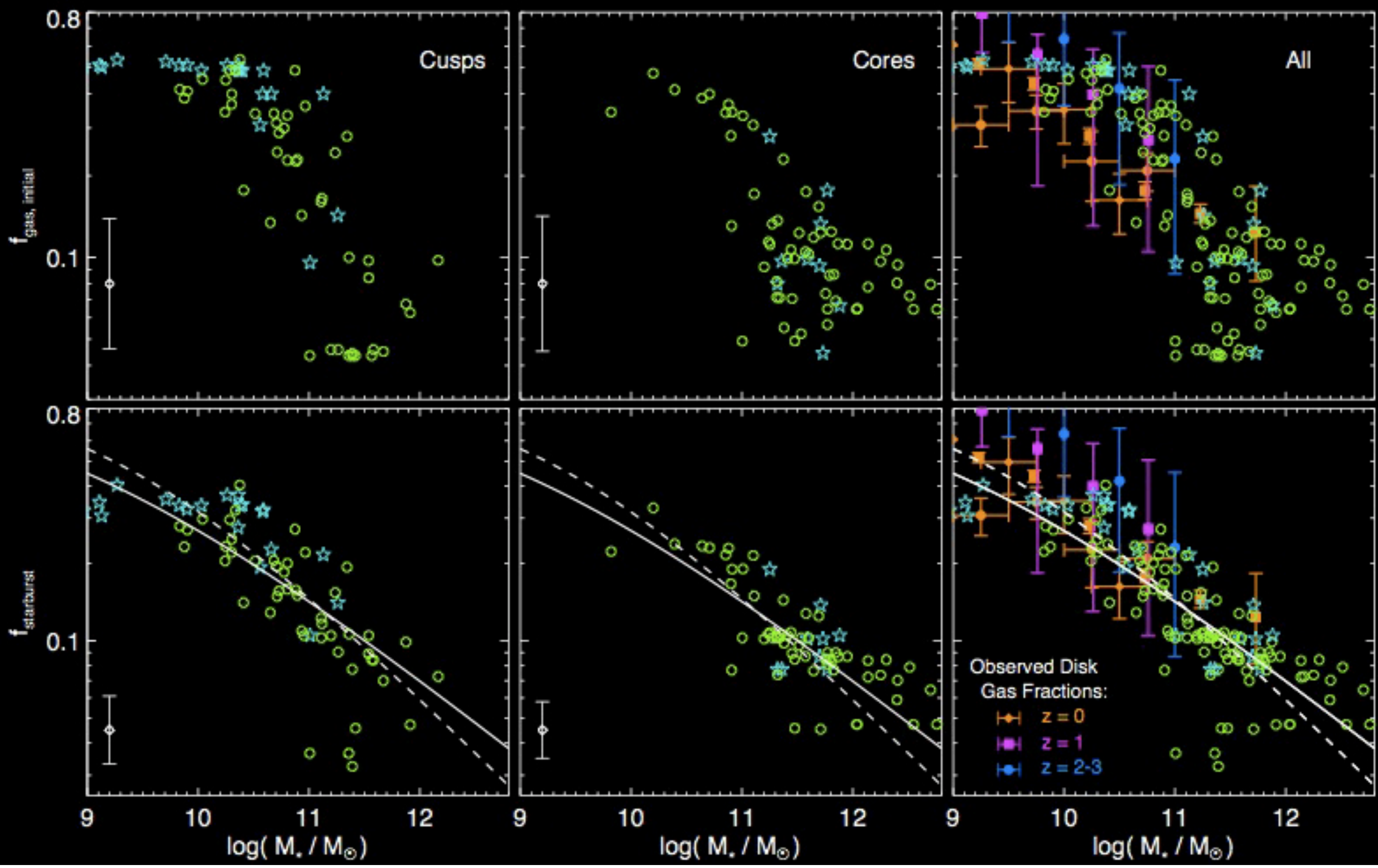
cusp E | core E



Theoretical / Observational Analysis

(Tabulated in arXiv: 0802.0508v2, 0805.3533v2, 0806.2325v2)

- starburst component declines with M: progenitor gas-richness → star formation more efficient in high mass disks (higher Σ_{gas})



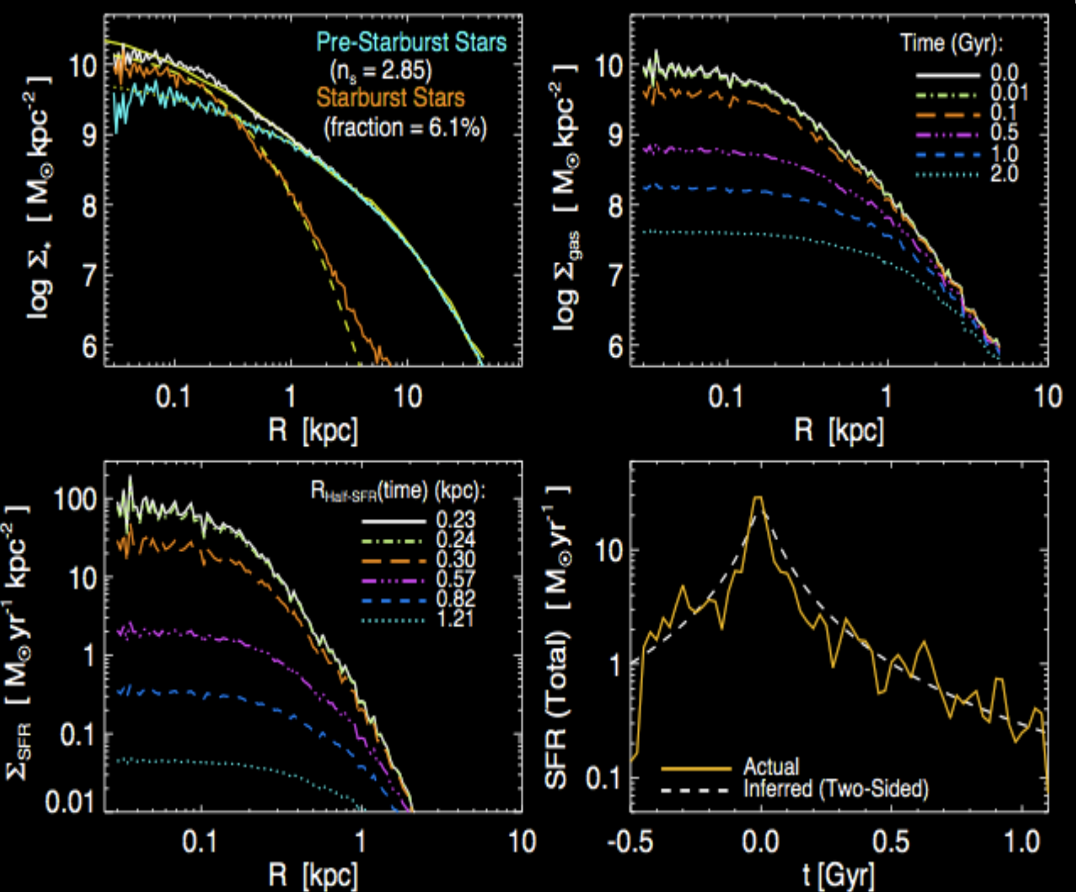
Inferring Starburst History of Universe

(Hopkins & Hernquist, MNRAS, submitted)

- Central component from starbursts; know Σ_{burst} (R)
- Assume:
  - gas collapses to center, forms stars in situ
  - Kennicutt-Schmidt Law
- Σ_{burst} (R) $\Rightarrow$ Σ_{gas} (R, t_0) $\Rightarrow$ d Σ_* (R, t_0) /dt (KS Law)

$$d\,\Sigma_*/dt \;=\; -d\,\Sigma_{gas} / dt \propto \Sigma_{gas}^{\;nK}$$

- Start at t=t_0 , integrate forward in time



Hopkins & Hernquist (2009)

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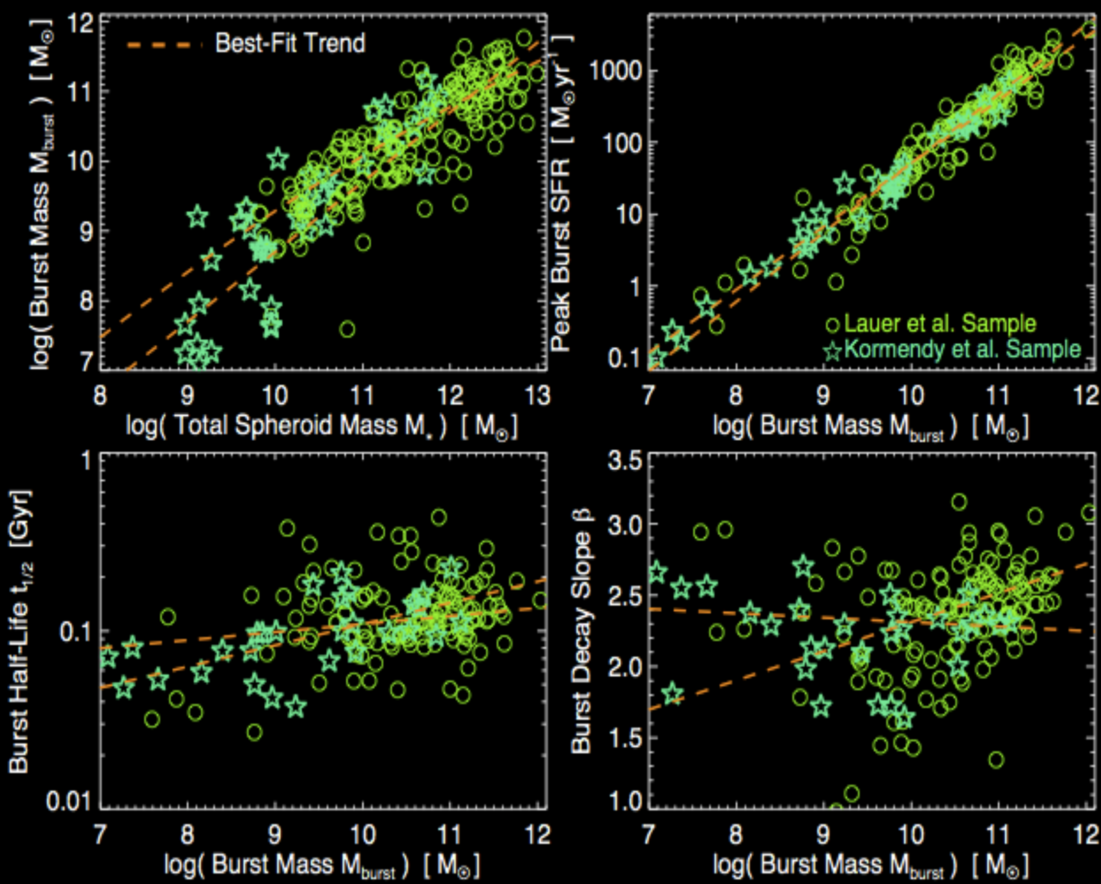
- Characterize starbursts in individual systems:
  - burst mass
  - peak burst SFR
  - burst timescale
  - spatial size
- Use empirical constraints on ages to assign (Monte Carlo) burst redshifts
- Use empirical relations between SFR and IR



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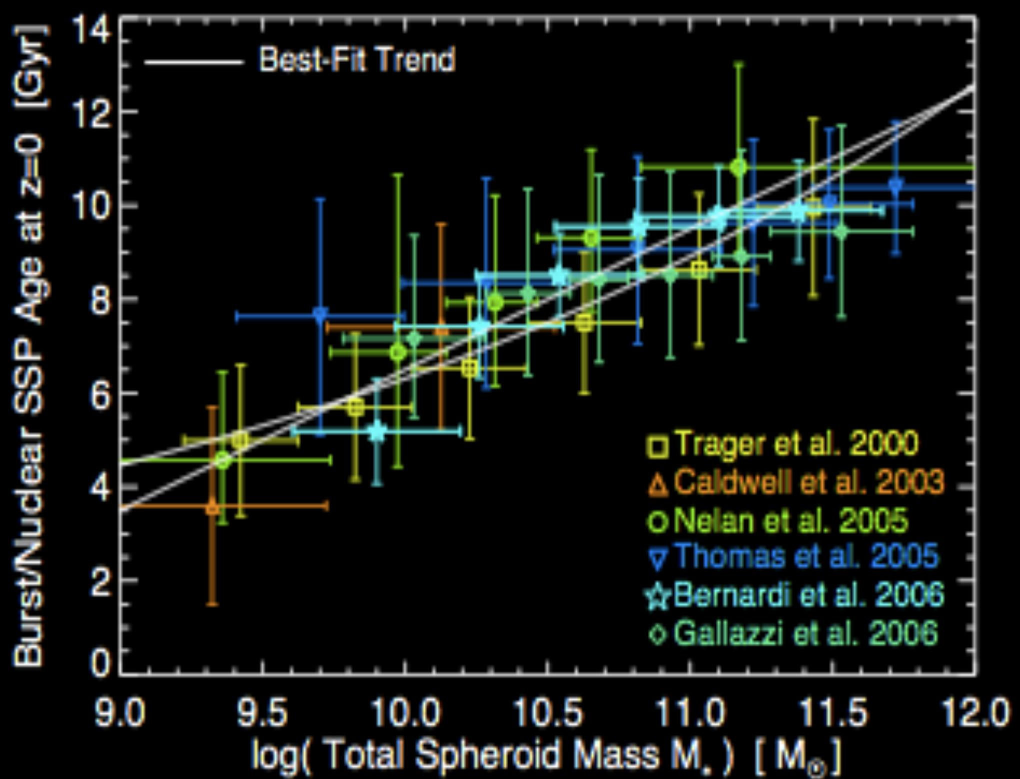
  - burst timescale
  - spatial size
- Use empirical constraints on ages to assign (Monte Carlo) burst redshifts, construct mock populations
- Use empirical relations between SFR and IR to get IR burst luminosity



Hopkins & Hernquist (2009)

Inferring Starburst History of Universe

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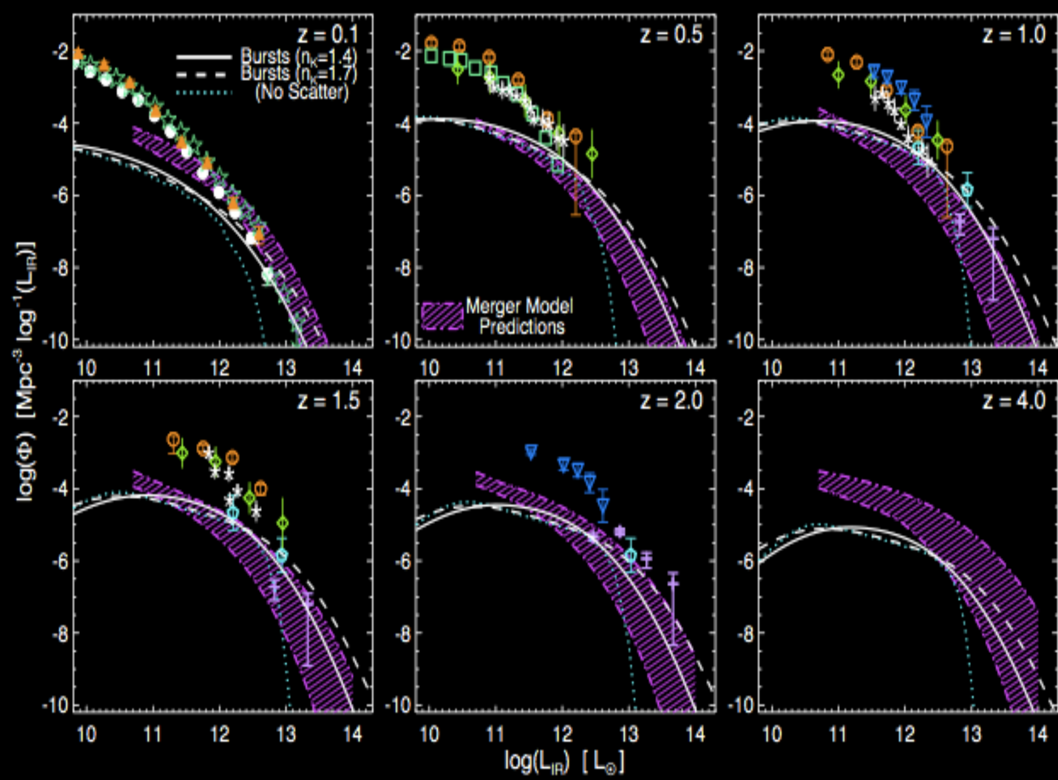
- Total (8 - 1000 μm) IR LFs:
  - reasonable agreement at bright end
  - bursts unimportant at faint end
  - transition: ULIRGs (z=0), HyLIRGs (z =2)
- At all z, bursts small fraction (~ 5 - 10 %) of total SFR or IR density



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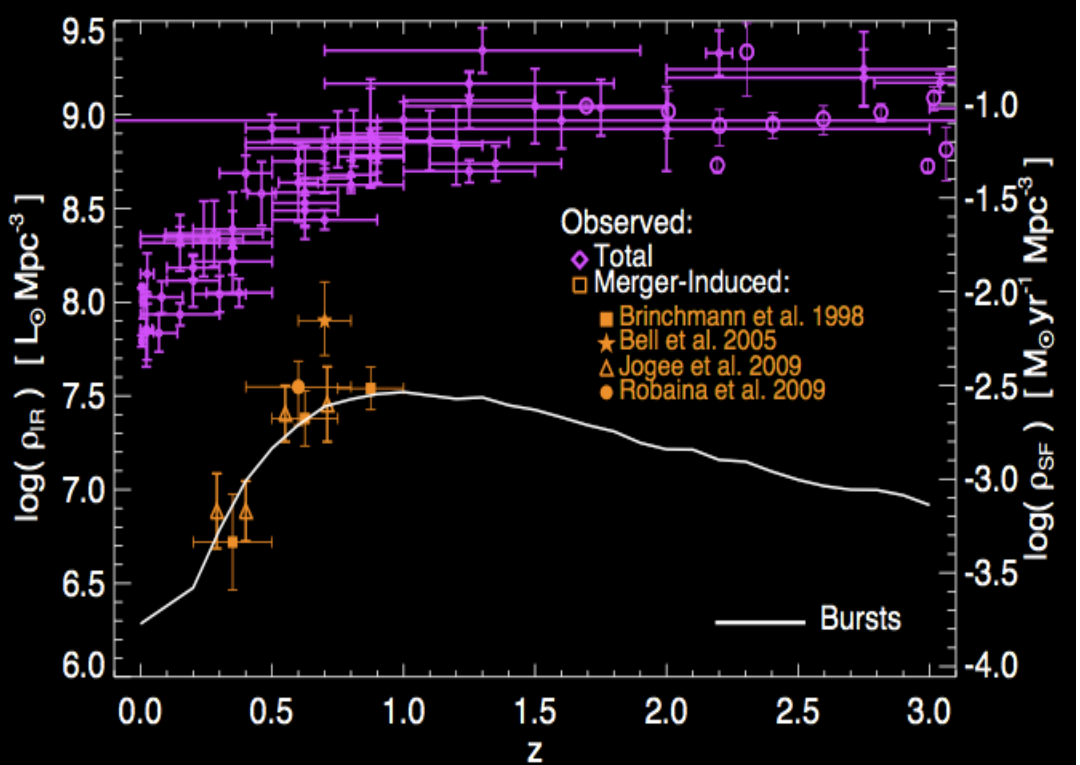
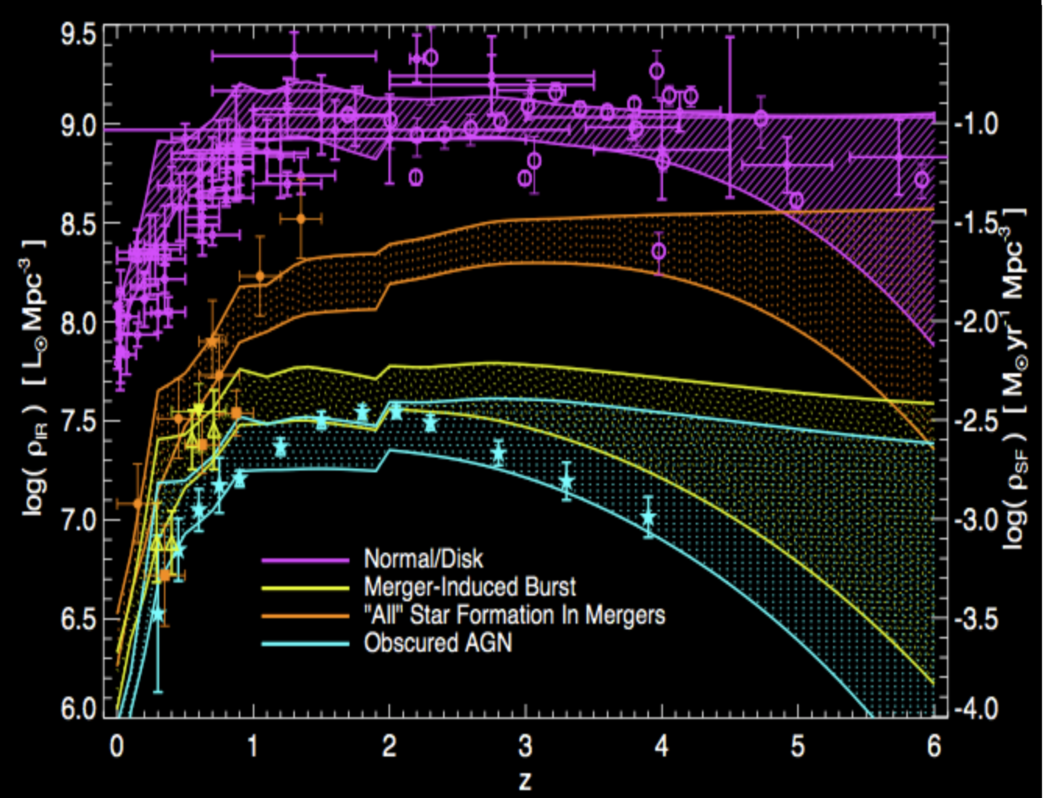


Hopkins & Hernquist (2009)

Inferring Starburst History of Universe

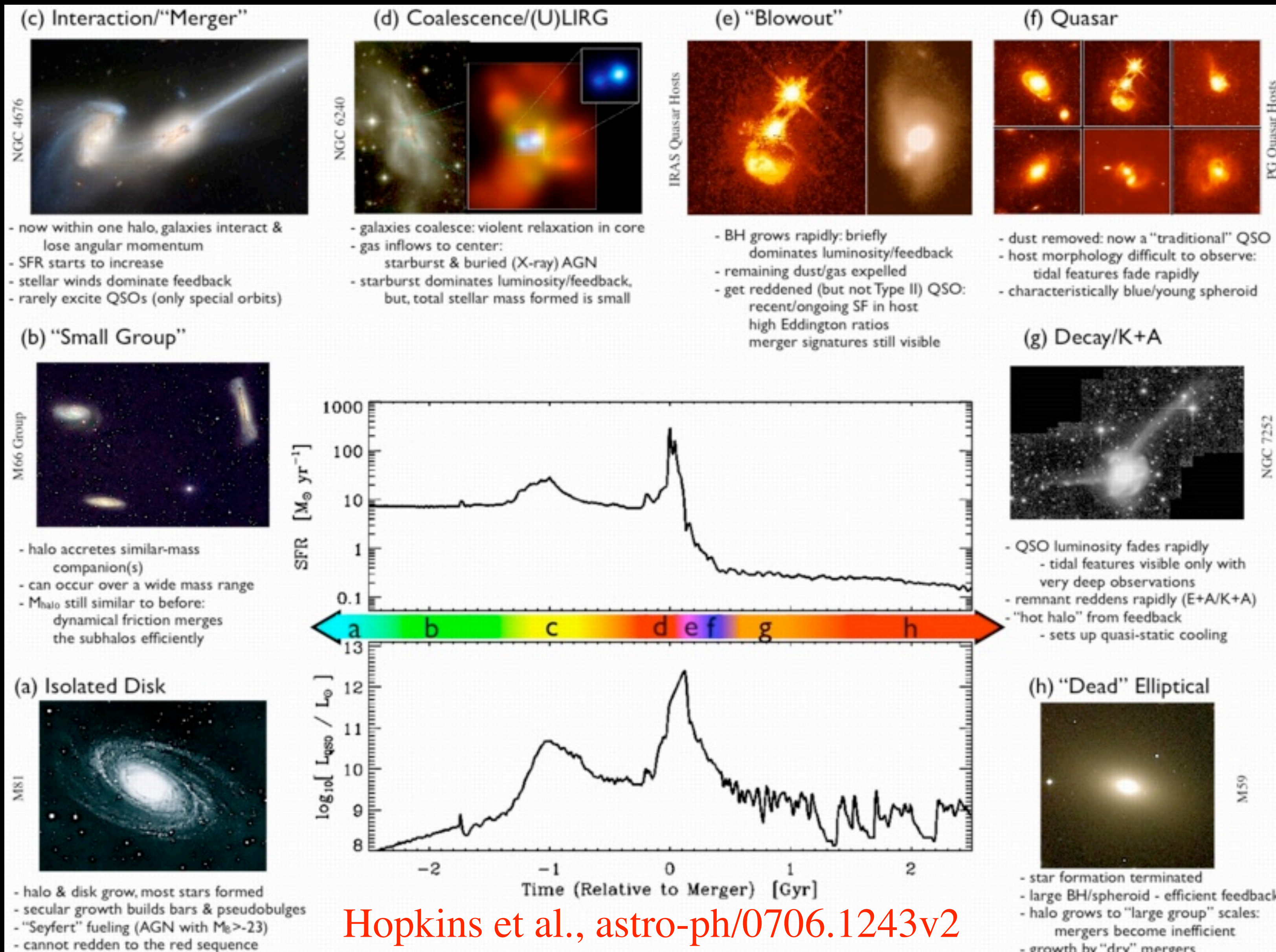
(Hopkins et al. 2009, MNRAS, submitted)

- Complementary approach: forward modeling from theory:
  - populate halos with galaxies using empirical constraints
  - track quiescent star formation
  - use simulations (light curves) for burst, quasars in mergers
- can estimate contribution from obscured AGN: smaller than bursts



Hopkins et al. (2009)

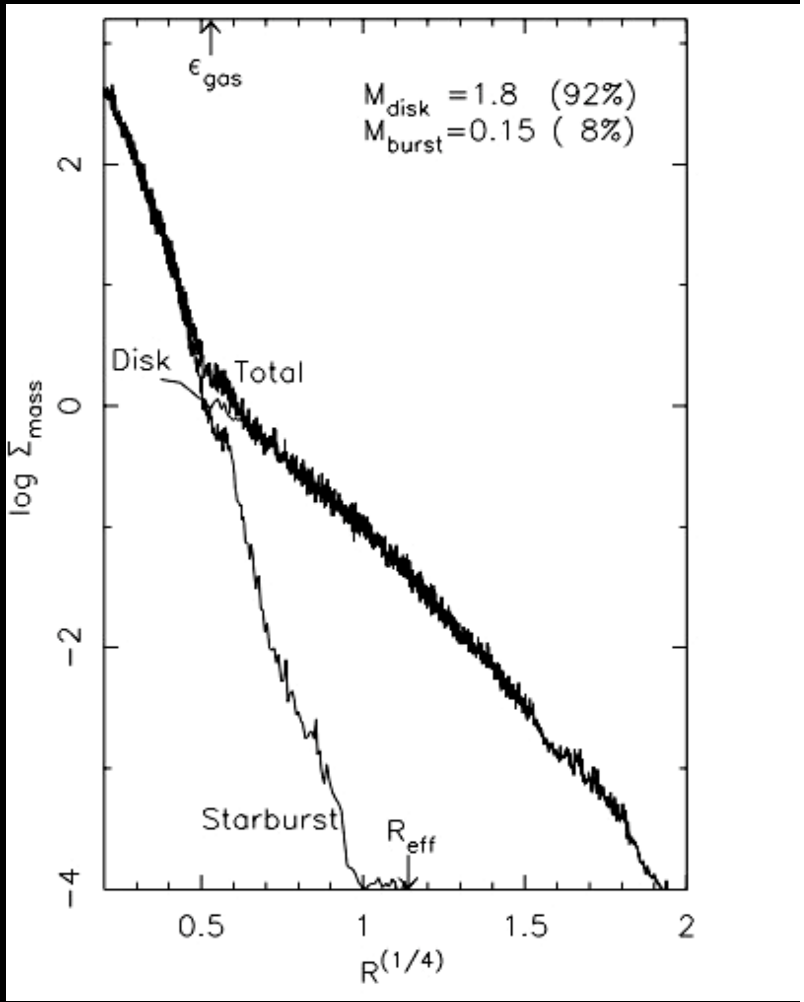
Unified Picture for Galaxy Evolution



Hopkins et al., astro-ph/0706.1243v2

Remnant Structure: Central Light Excess

- Remnant surface density like elliptical galaxies
- Gas-rich mergers → starbursts → ellipticals ⇒ multiple stellar populations
- Predict central light excess from starburst (Mihos & LH 1994; Springel & LH 2005)



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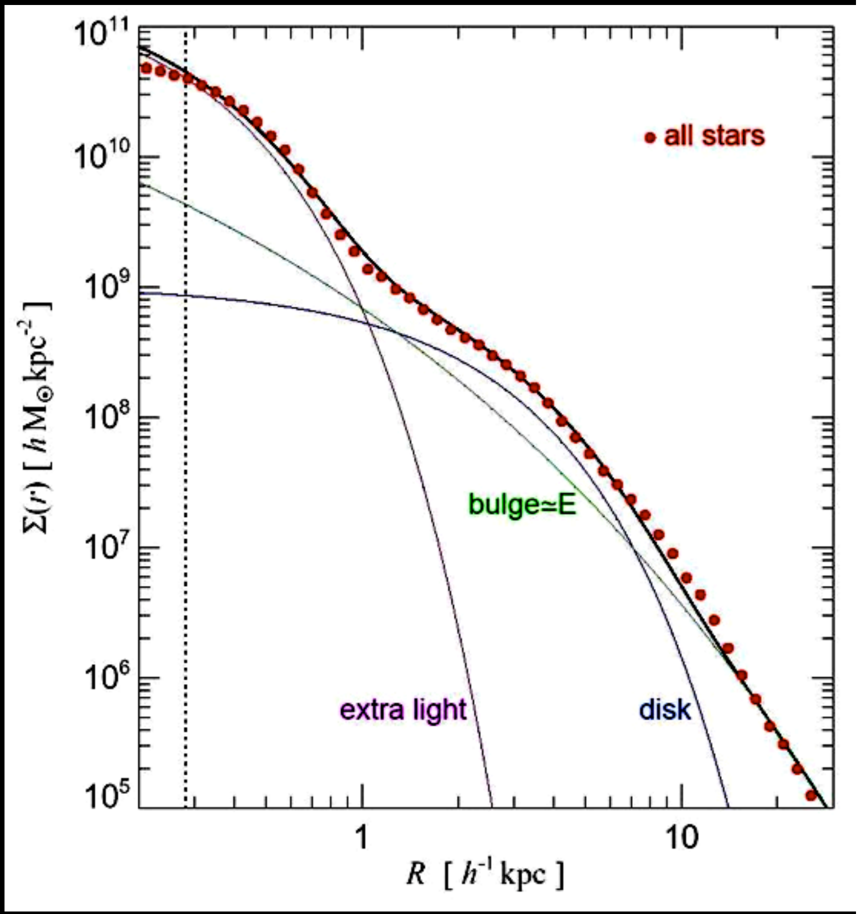
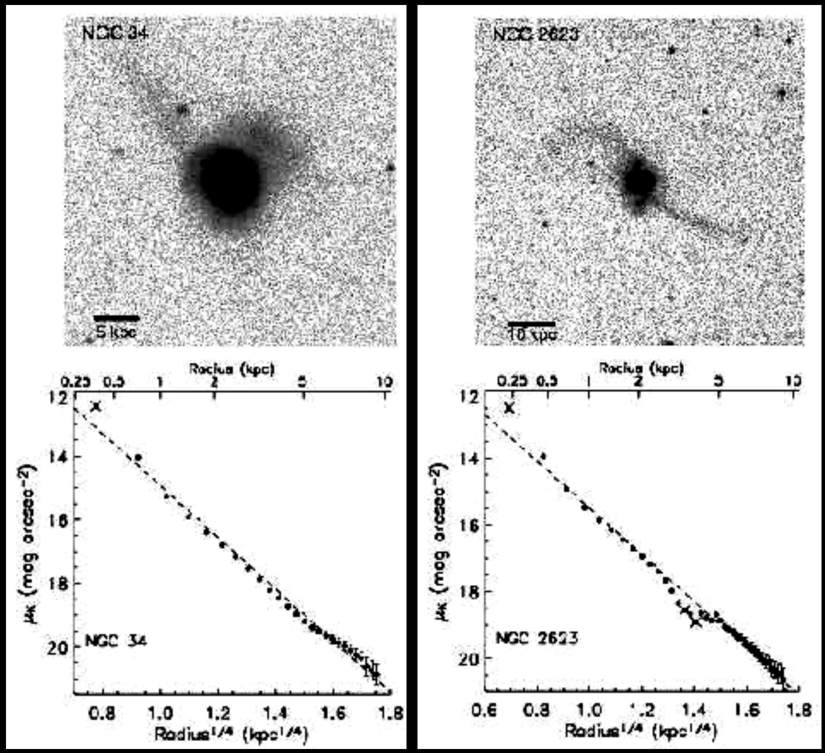


Springel & LH (2005)

Remnant Structure: Central Light Excess

- New observational evidence:
  - Rothberg & Joseph (2004, 2006): sample of gas-rich mergers
  - Kormendy et al. (2007): relaxed ellipticals
- Amount ~ 10^{10} L_{sun} (e.g. Rothberg & Joseph); similar to gas content of ULIRGs
- Relic starburst?



Rothberg & Joseph (2004)

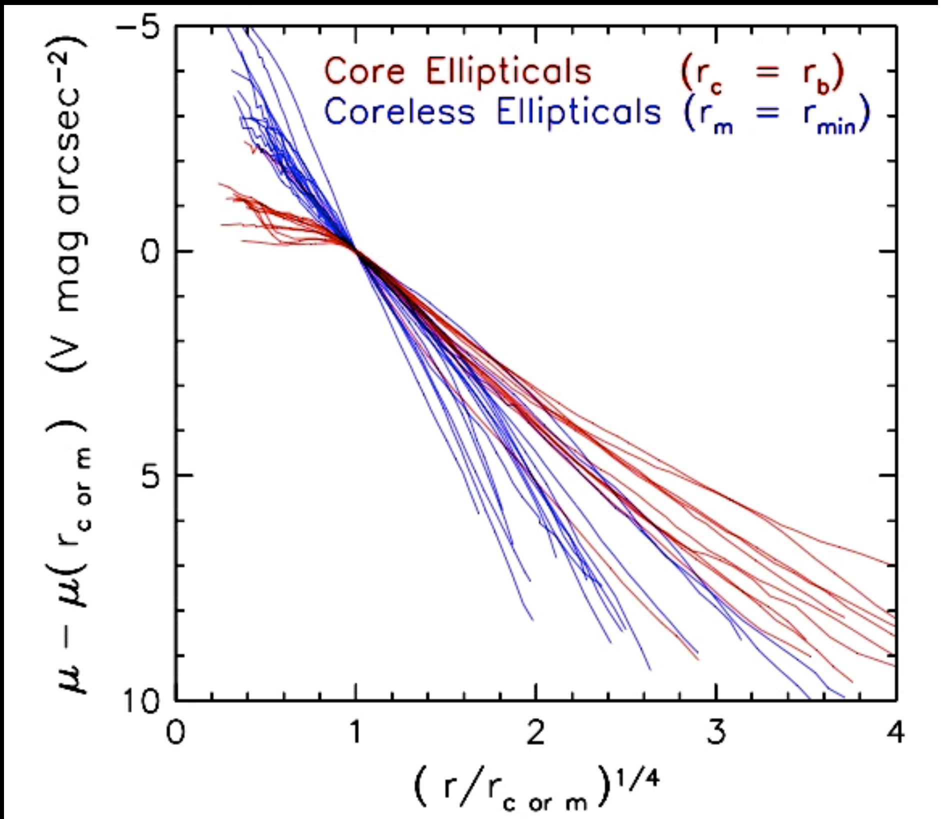
Central Light Excess: Theoretical / Observational Analysis

(Hopkins et al. 2007)

- Observations:
  - Rothberg & Joseph (2004, 2006): ≈ 50 gas-rich mergers
  - Relaxed ellipticals: Kormendy et al. (2007), Bender et al. (1998), Lauer et al. (2006)
    - ≈ 100 “cusp” ellipticals
    - ≈ 100 “core” ellipticals
  - Multiple observations of each object in various wavebands with different instruments
- Simulations:
  - Many hundreds: vary orbit, structure/masses of progenitors, gas content, star formation/feedback, black hole accretion/feedback, resolution, etc.

Two Families of Ellipticals?

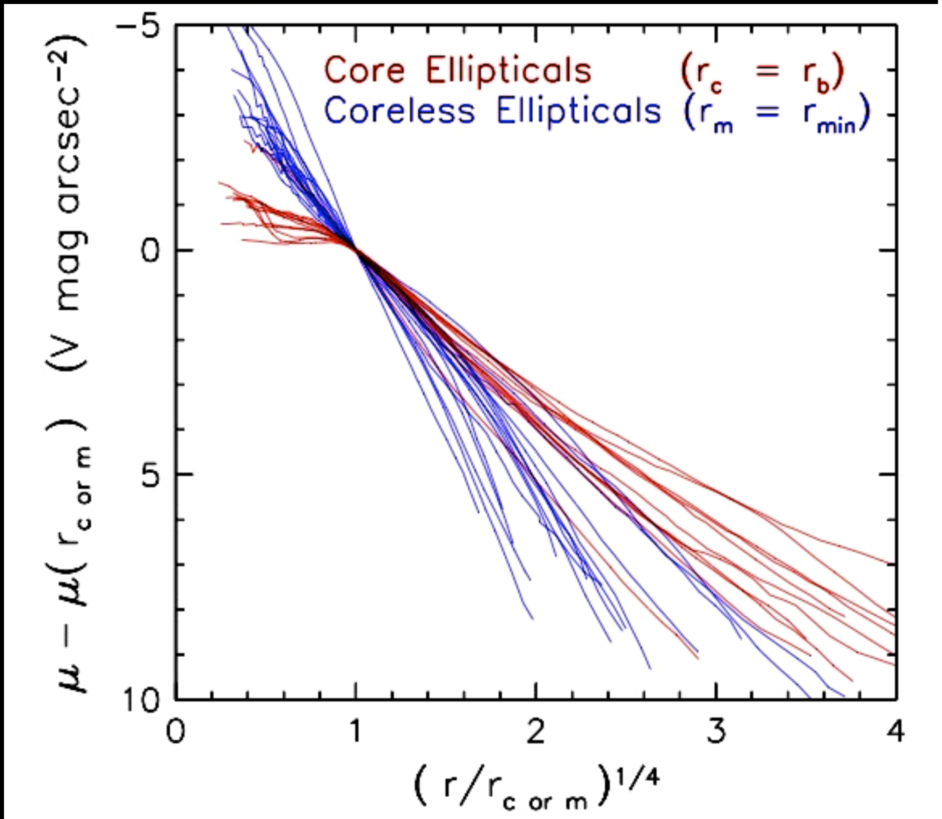
- “Coreless”: steep central profiles (lower mass Es)
- “Core”: shallow central profiles (higher mass Es)
- “Coreless ”: direct remnant of gas-rich merger
- “Core”: modified by subsequent gas-free merger; core from binary black hole?



Kormendy et al. (2007)

Two Families of Ellipticals?

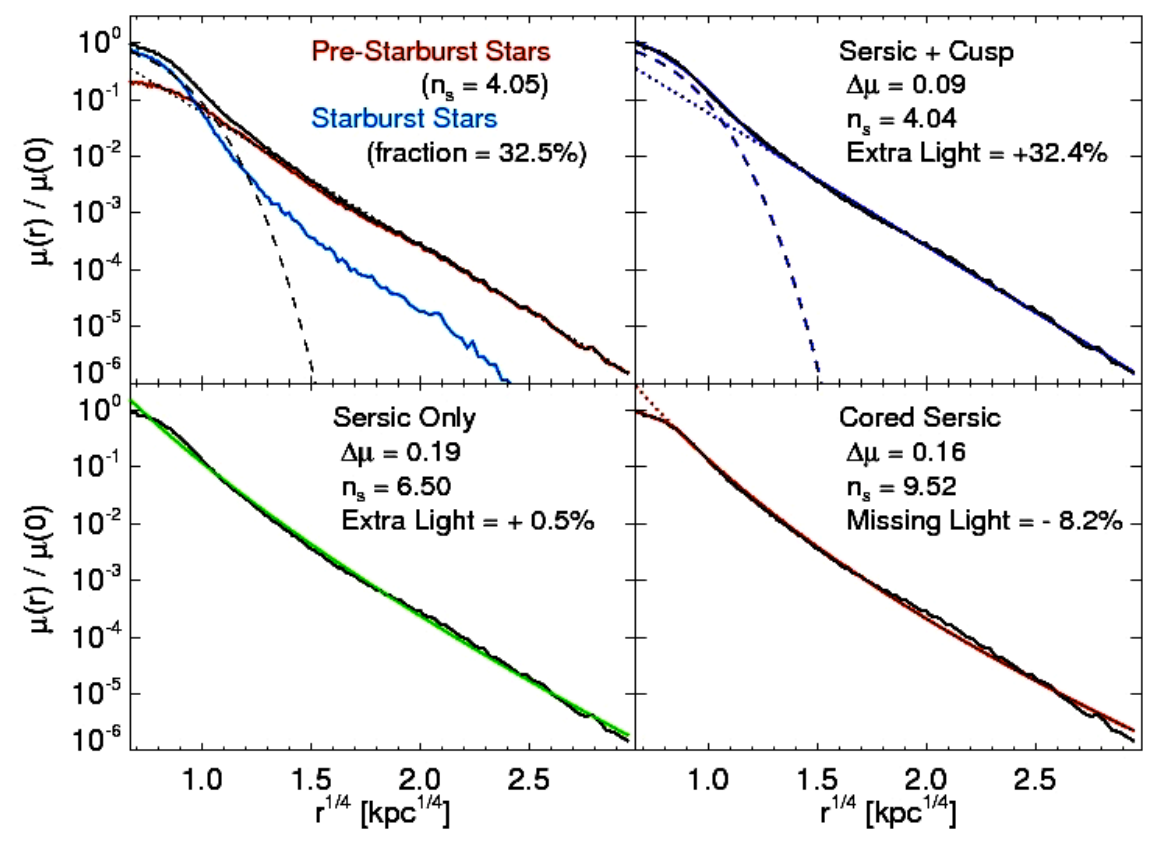
- “Coreless” vs. “core”: distinction on scales << relic starbursts
- Focus here on coreless ellipticals (analysis of core ellipticals in progress)
- Hypothesis: ellipticals, black holes originate via gas-rich mergers, some only later modified by gas-free mergers



Kormendy et al. (2007)

Two Component Luminosity Profiles

- Sersic profile:
  $I \propto \exp\left[- (r/r_0)^{1/n} \right]$
  exponential: $n = 1$
  $r^{1/4}$ - law: $n = 4$
- Simulations motivate multi-component fits:
  inner starburst ($n=1$)
  outer profile (n_s)
- Single component fits less accurate; physically misleading

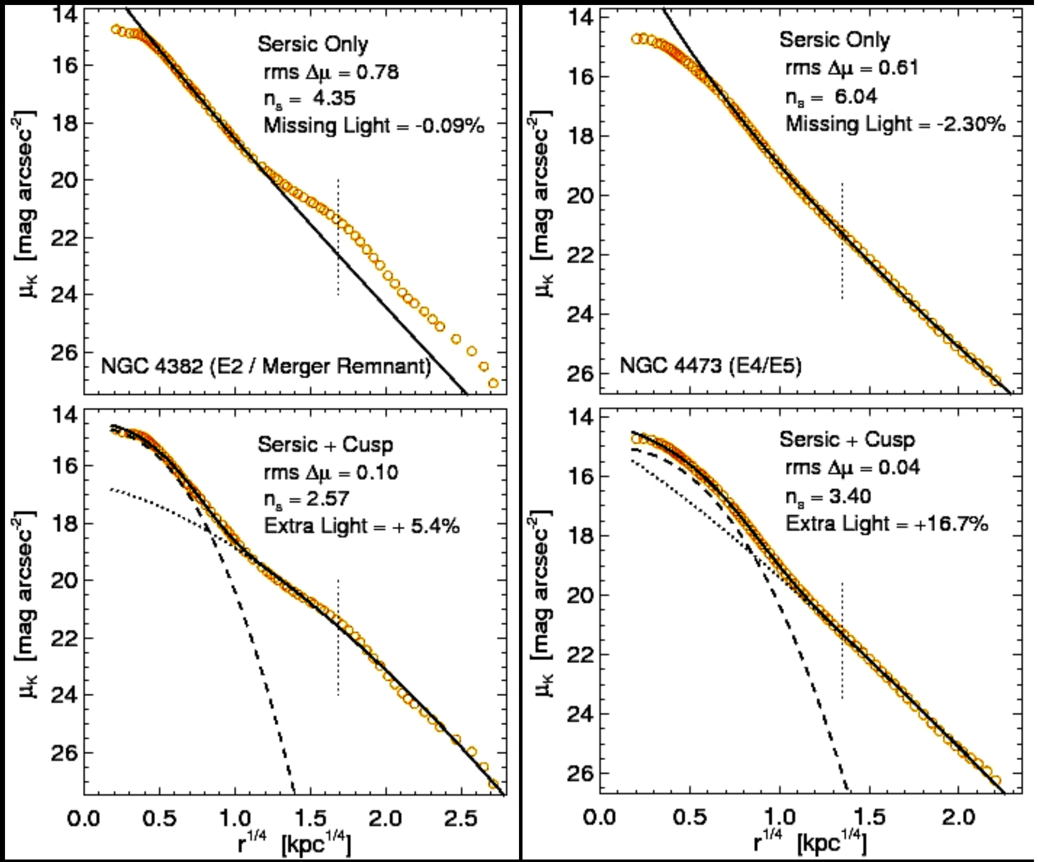


Hopkins et al. (2007)

Two Component Profiles: Observations

- Apply 2-component fits to observations: ≈ 50 gas-rich mergers (Rothberg & Joseph);

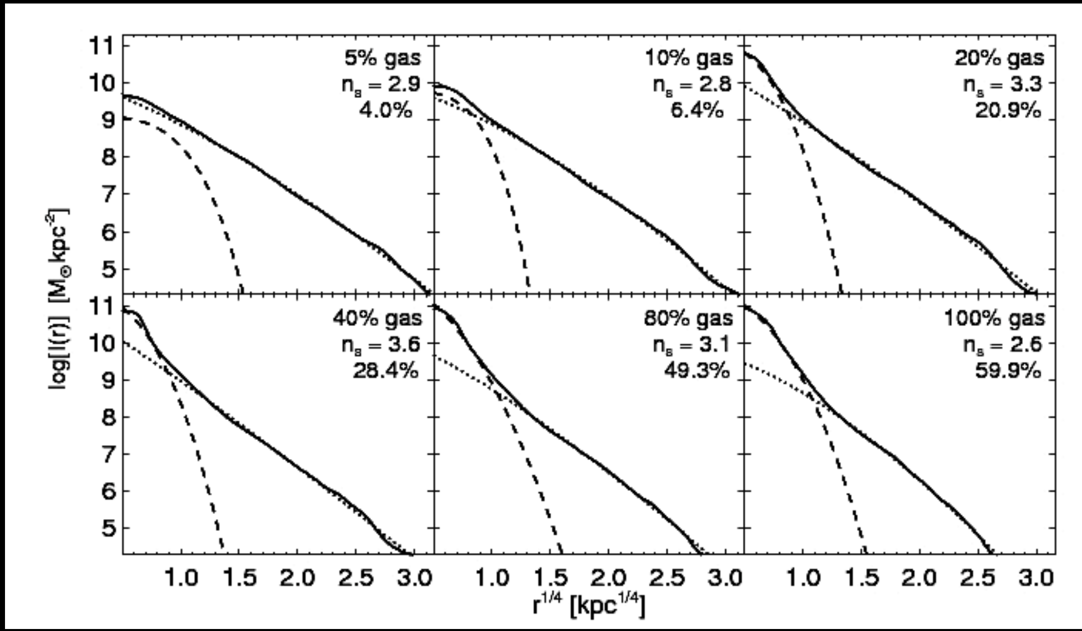
  ≈ 100 cusp ellipticals (Kormendy, Lauer, Bender)
- Superior matches to data in nearly each case
- Simulation analogs often provide even better fits
- For some objects, classification altered



Hopkins et al. (2007); from Kormendy et al. (2007)

Two Component Profiles: Merger Properties

- Dependence on nature of merger; e.g. gas fraction (all else equal): more extra light, similar outer profiles
- Depends also on galaxy mass, orbit; e.g. fixed initial gas fraction: $f_{sb} \propto M_*^{-0.15}$ (explains elliptical FP tilt)
- Extra light correlated with gas mass at end of merger
- Observed systems occupy similar location in e.g. extra light fraction vs. M_*



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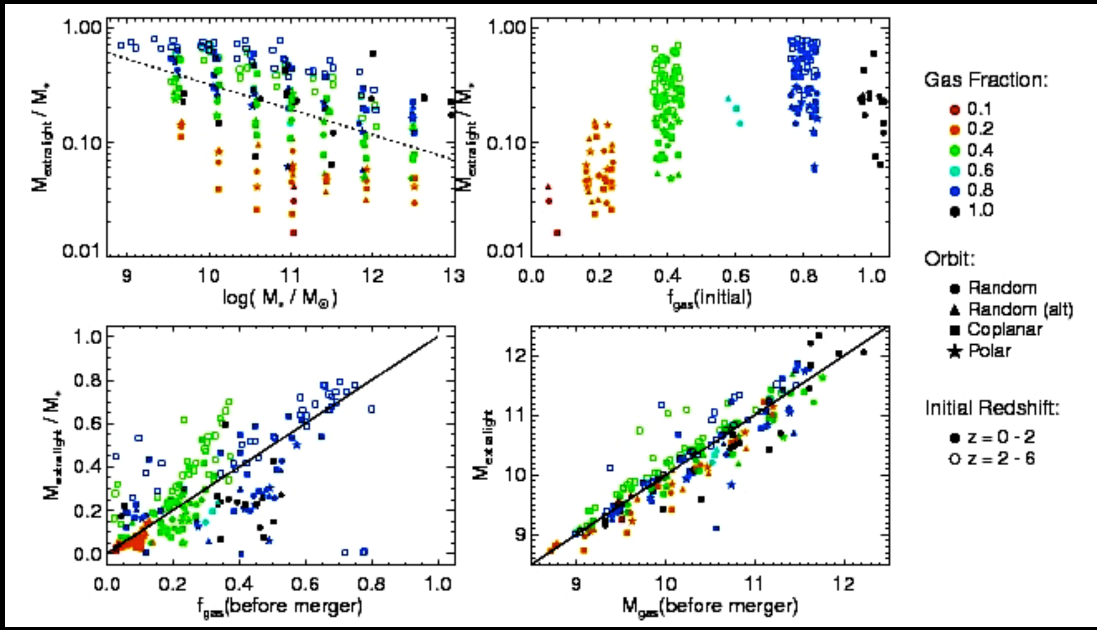

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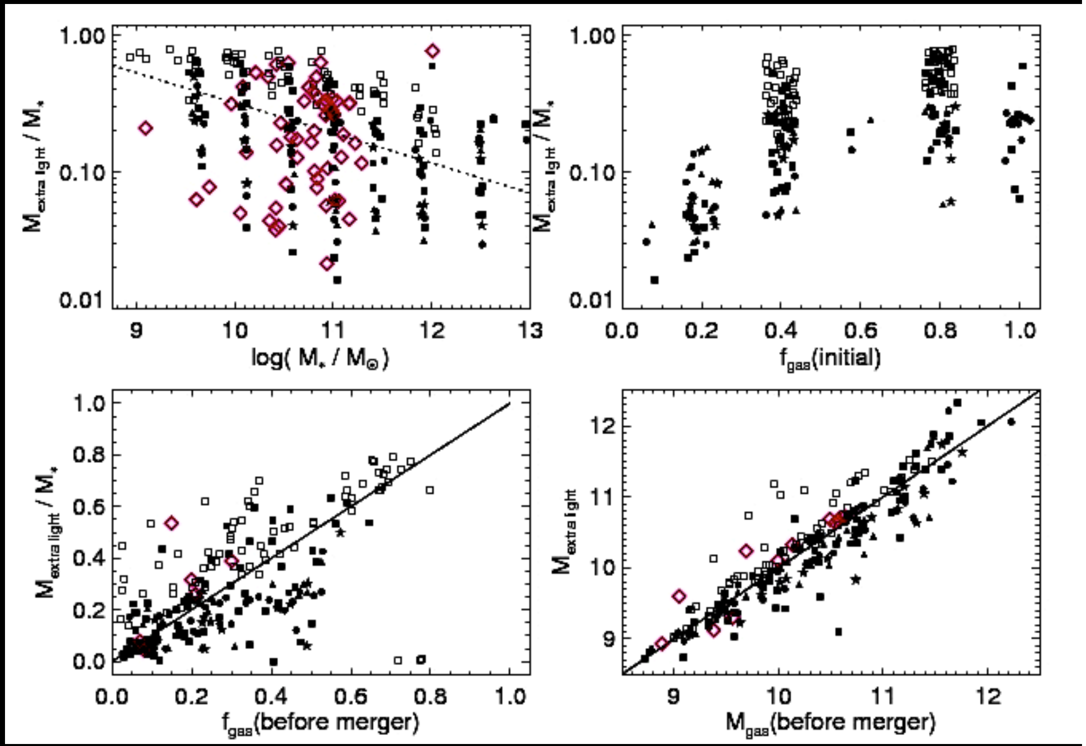
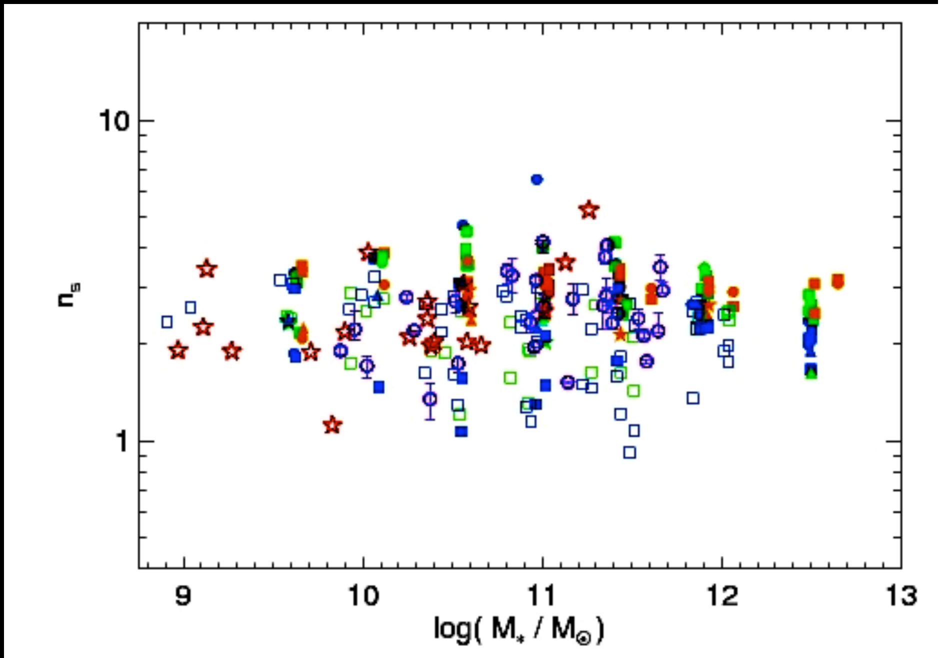


Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)

Outer Sersic Indices

- Match observations with fits, simulation analogs
- Compare statistically
- E.g. outer Sersic index: no strong dependence on mass
- Different from e.g. Graham (2001), Ferrarese et al. (2006), but with single component fits
- Expect similar outer profiles (violent relaxation/gravity)
- Slight offset ($\Delta n \sim 0.25$) may be resolution artifact in data



Hopkins et al. (2007); solid: simulations; open: observed; data from Kormendy et al. (2007)

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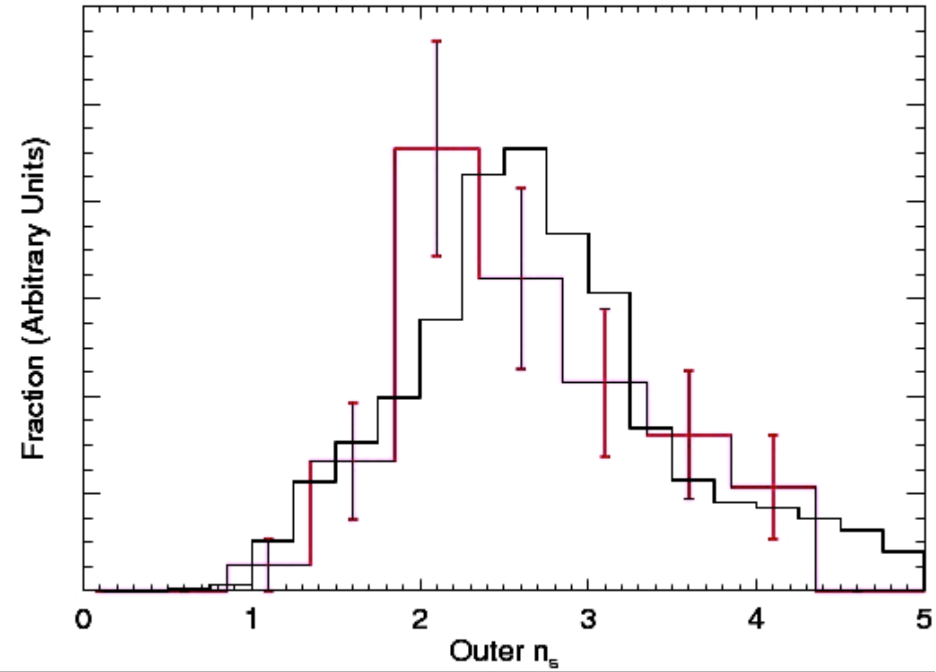
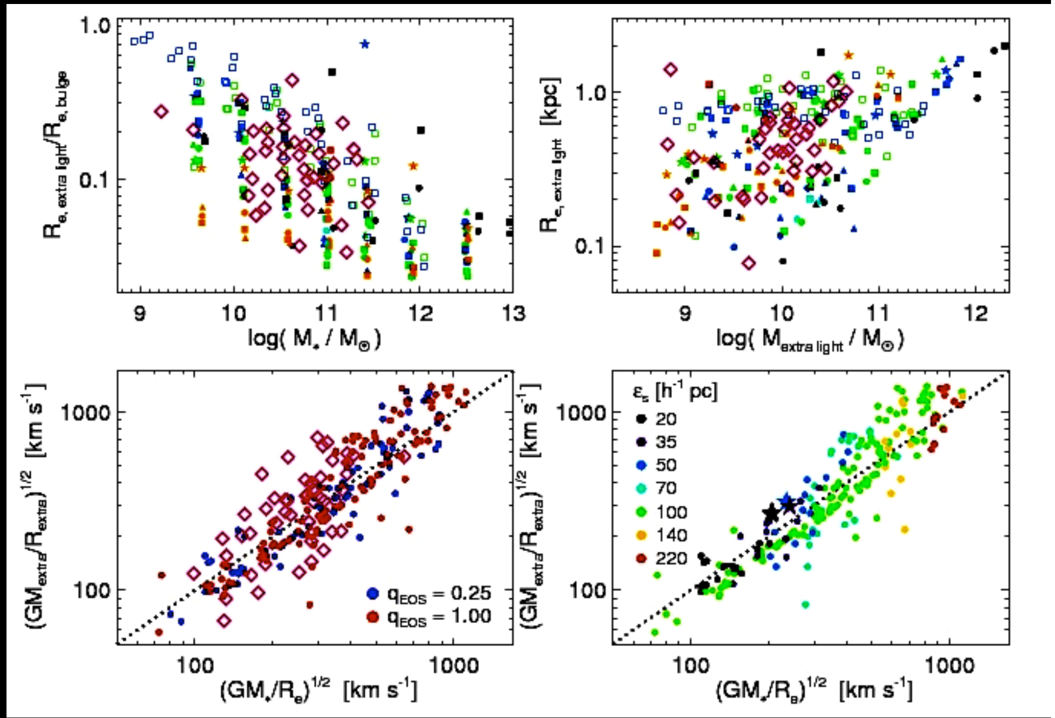


Hopkins et al. (2007); black: simulations; red: observed; data from Kormendy et al. (2007)

Spatial Extent of Extra Light

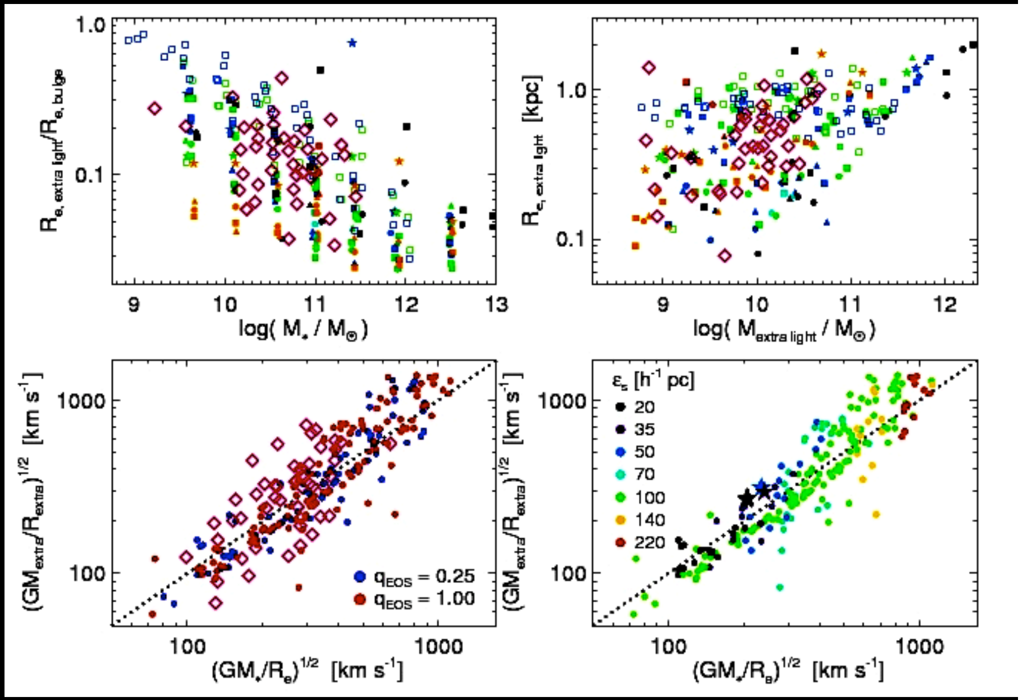
- Measure effective radii of inner, outer components
- Fractionally smaller in higher mass galaxies
- More massive galaxies have fractionally less extra light
- $R_{extra} \propto M_{extra}^{0.33}$



Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)

Spatial Extent of Extra Light

- Spatial extent: gas self gravity
- Scenario (Mihos & LH 1996):
  - gas loses angular momentum
  - gas enters free-fall
  - becomes self-gravitating
  - no longer free-falling, shocks
  - quasi-equilibrium: cooling offset by feedback from star formation
  - gas stalls, rapidly forms stars



Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)

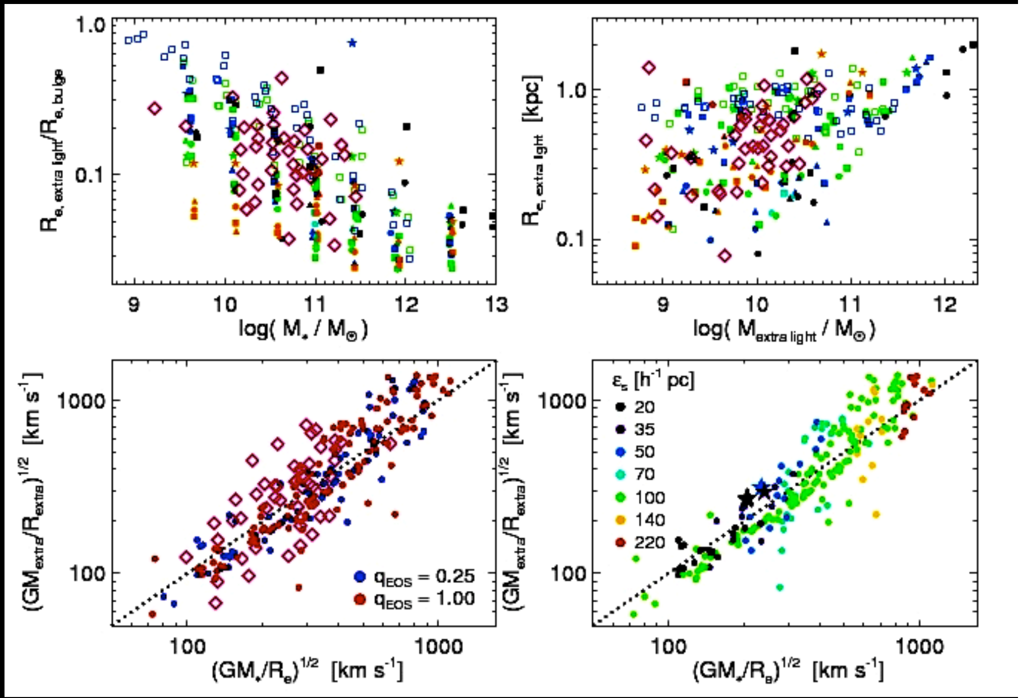
Spatial Extent of Extra Light

- Spatial extent: gas self-gravity
- Self-gravity condition:

$$G M_{extra} / R_{extra} = \alpha G M_* / R_e$$

$$(\alpha \sim 1)$$

- Describes simulations, data
- Independent of treatment of ISM, star formation, feedback
- Numerically converged spatially

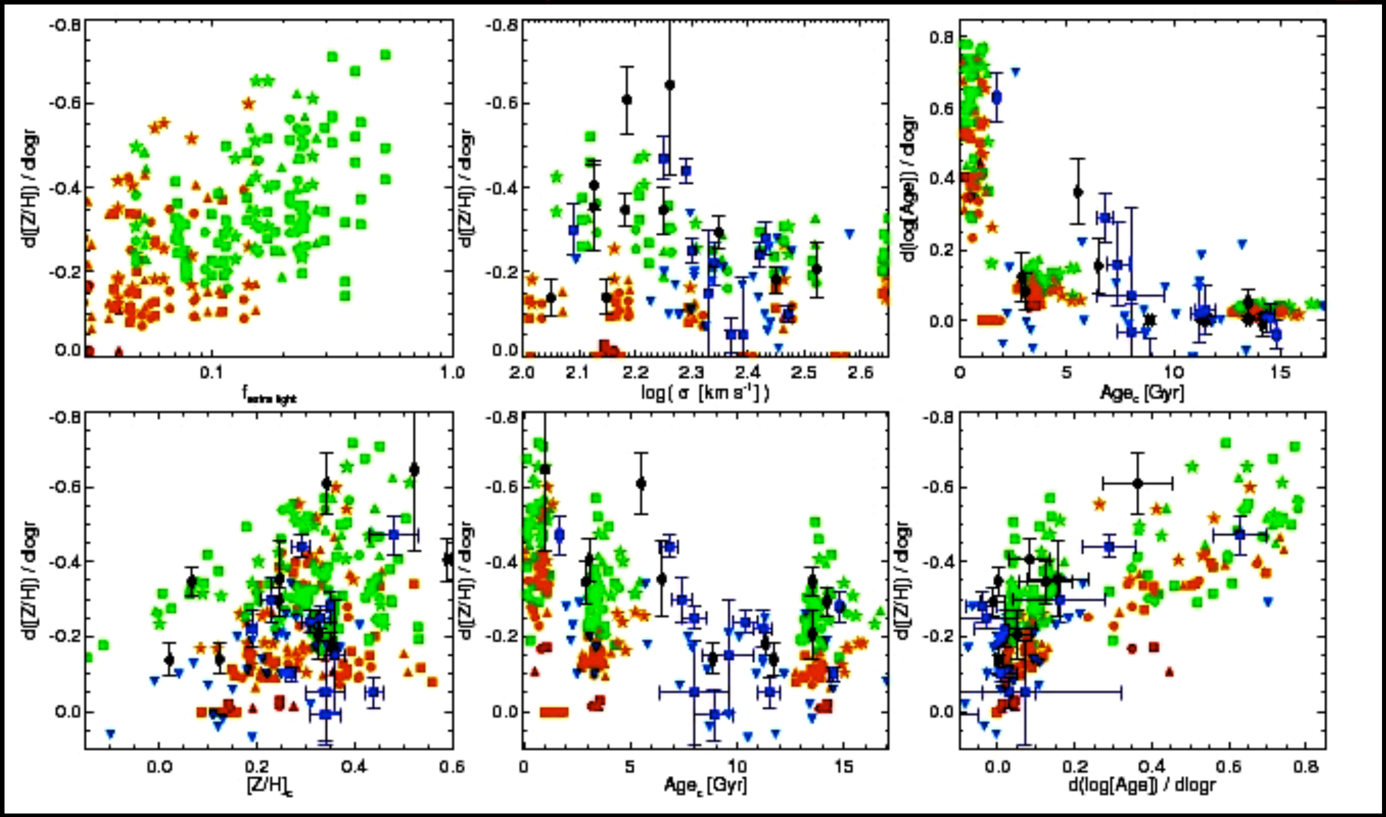


Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)

Other Properties

- Time evolution of profiles in various bands
- Stellar population gradients
- Age, metallicity gradients
- Color gradients:
  - early on, cores blue: young stars, age gradients dominate
  - later, cores red: metallicity gradients dominate
- Kinematic subsystems, embedded disks

Metallicity & Gradients in Ellipticals



Hopkins et al. (2007)

red = 0.1 gas
orange = 0.2 gas
green = 0.4 gas

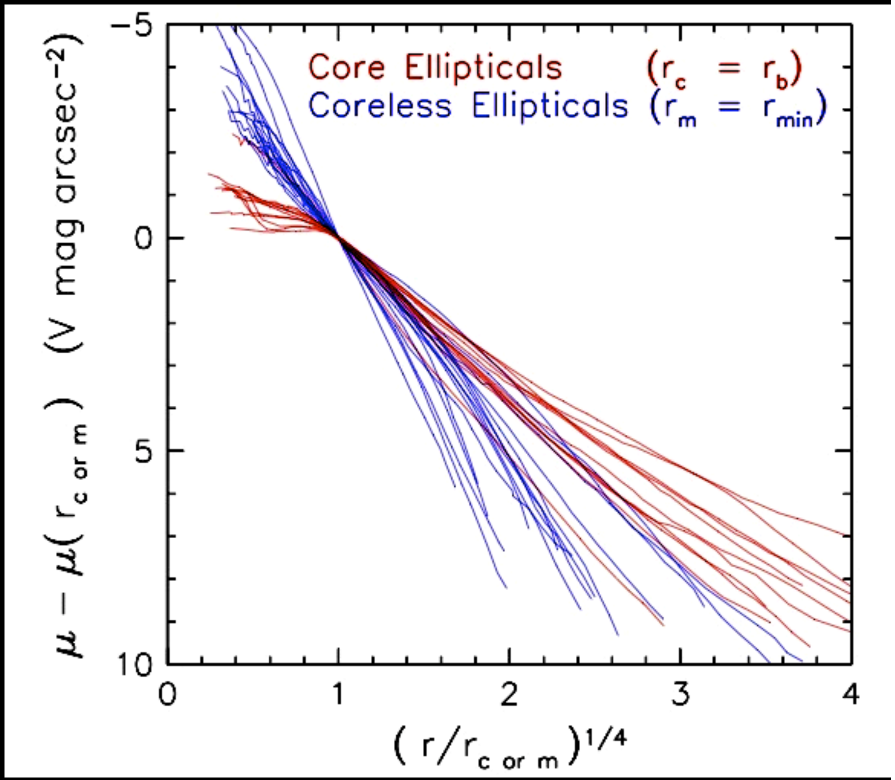
- Long-standing objection: metallicity, gradients in ellipticals too strong compared to present-day spirals (Ostriker 1980)
- Ignores dissipation: boosts central metallicity, gradients
- In fact, simulations, observations consistent (bottom left)
- N.B.: Z measured in R_e / 8 ⇒ not much self-enriched material

Gas-Rich Merger Origin of Ellipticals

- Explains structure: multi-component systems
- Provides physical basis for structure:
  - outer profile from violent relaxation (roughly self-similar)
  - inner component from dissipation, star formation (non-homology)
- Supports view that blend of stellar & gas dynamics required, with galaxy's supply of each
- Needed gas fractions ~ 10 - 30 %, similar to phase-space constraints (Hernquist, Spergel & Heyl 1993)
- Eliminates objections to (generalized) merger hypothesis
- Explains observed correlations (fundamental plane)
- Accounts for metallicity, gradients in ellipticals

Gas-Rich Merger Origin of Ellipticals

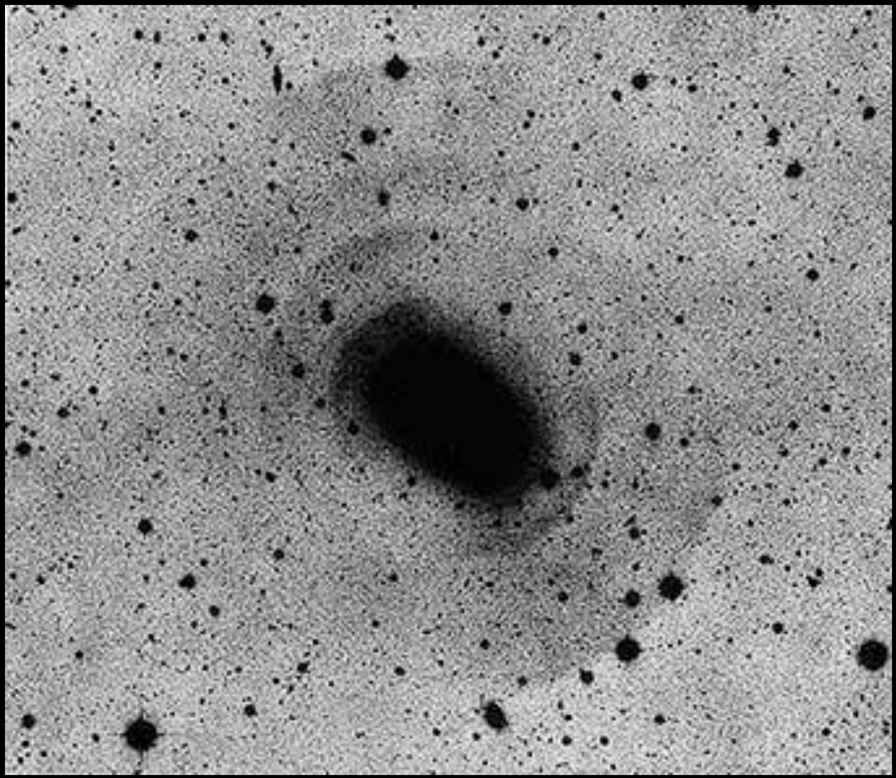
- Preliminary analysis: merger of cusp ellipticals → cores
- Basic properties of ellipticals, black holes set by gas-rich mergers
- Cusp/core dichotomy set on scales << inner component
- Kinematic anomalies, fine structure destroyed in secondary, gas-free mergers
- Predict presence of these features correlated with family type



Kormendy et al. (2007)

Remnants Properties: Fine Structure

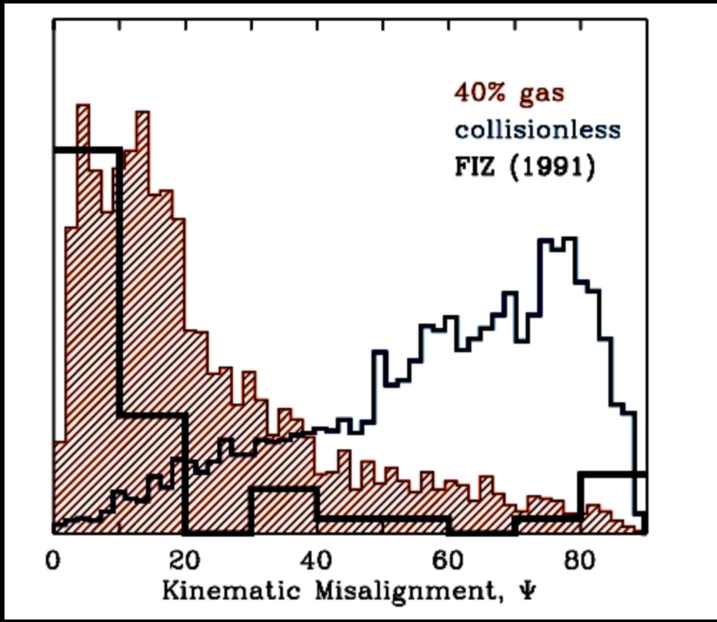
- Shells in ellipticals: phase-wrapping of “cold” stellar material (Quinn 1984; Quinn & LH 1986)
- From debris in tidal tails (LH & Spergel 1992)
- NOT signature of major mergers of spheroids, just the opposite!

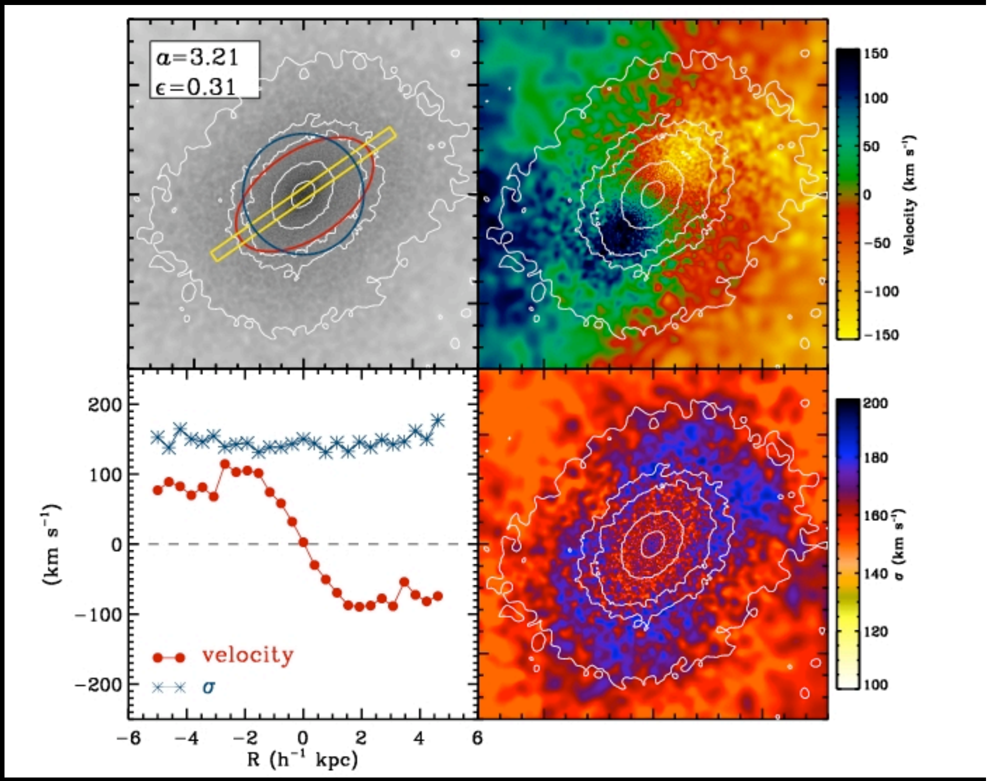


NGC 3923

Remnant Properties: Kinematics

- Measure $\tan \Psi = V_{min} / V_{maj}$
- Match elliptical kinematic misalignments if gas fraction > 25 - 30 % (little minor axis rotation)

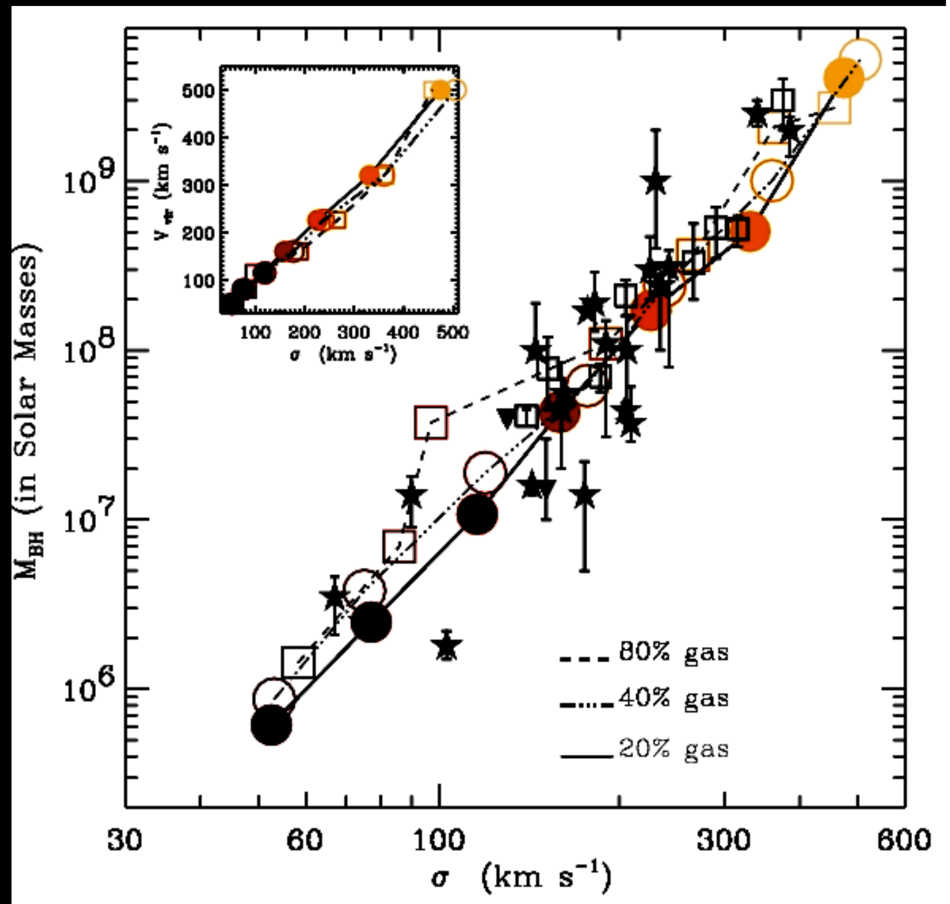




Cox et al. (2005)

Black Hole - Host Correlations

- BH mass determined by feedback, gas cooling, potential well, gas dynamics
- BH growth self-regulated, fixing feedback efficiency $E_{feed} = \varepsilon_f M_{BH} c^2$ with $\varepsilon_f \sim 0.005$
- Match observed slope of M-σ relation
- Interpretation motivates more refined correlations

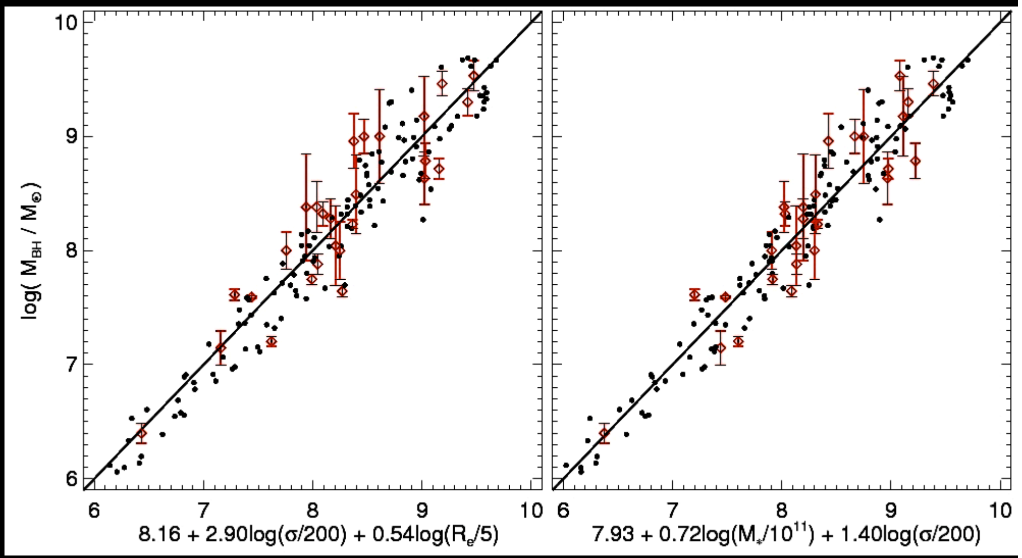


Di Matteo, Springel & LH (2005)

Black Hole Fundamental Plane

(Hopkins et al., astro-ph / 0701351 & 070.4005)

- Elliptical galaxy FP:
  $R_e \sim \sigma^{1.5}\, I^{-0.8}$ (K-band)
- Try: $M_{BH} \sim M_*^{\alpha}\, \sigma^{\beta}$
- From data: $M_{BH} \sim (M_*\, \sigma^2)^{\,0.5}$
- Condition for pressure-driven outflow to unbind gas (Hopkins & LH 2006)
- No evidence for curvature



Black Hole Fundamental Plane

(Hopkins et al., astro-ph / 0701351 & 070.4005)

- Resolves outliers in M_{BH} - σ and M_{BH} - M_* relations
- Predicts BHs more massive for fixed M_* at high z (deeper potentials):

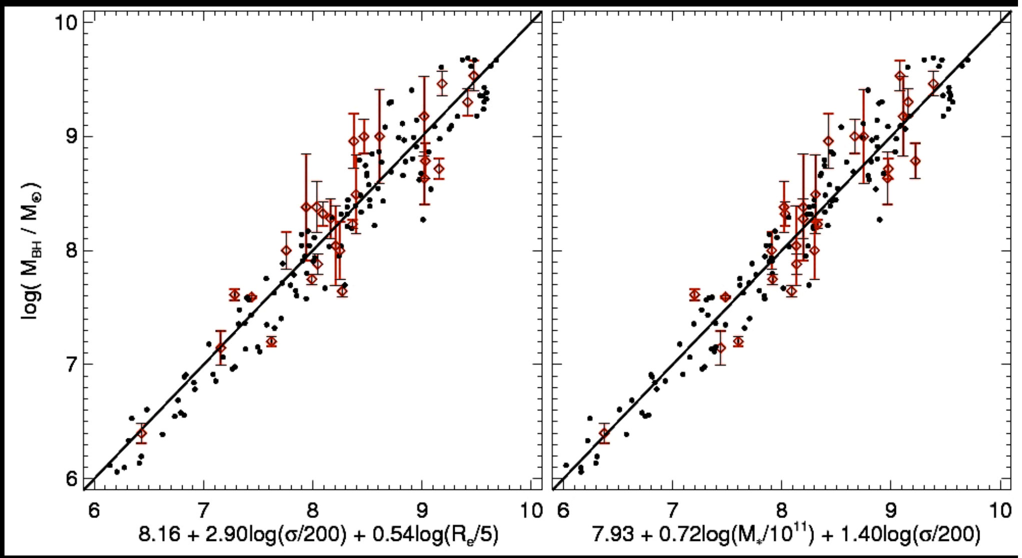
$M_{BH} \sim M_*^{1.5}\, R_e^{-1.0}$

Trujillo et al.: $R_e \sim (1+z)^{-0.45}$

so, expect:

$M_{BH} / M_* \sim (1+z)^{0.5}$

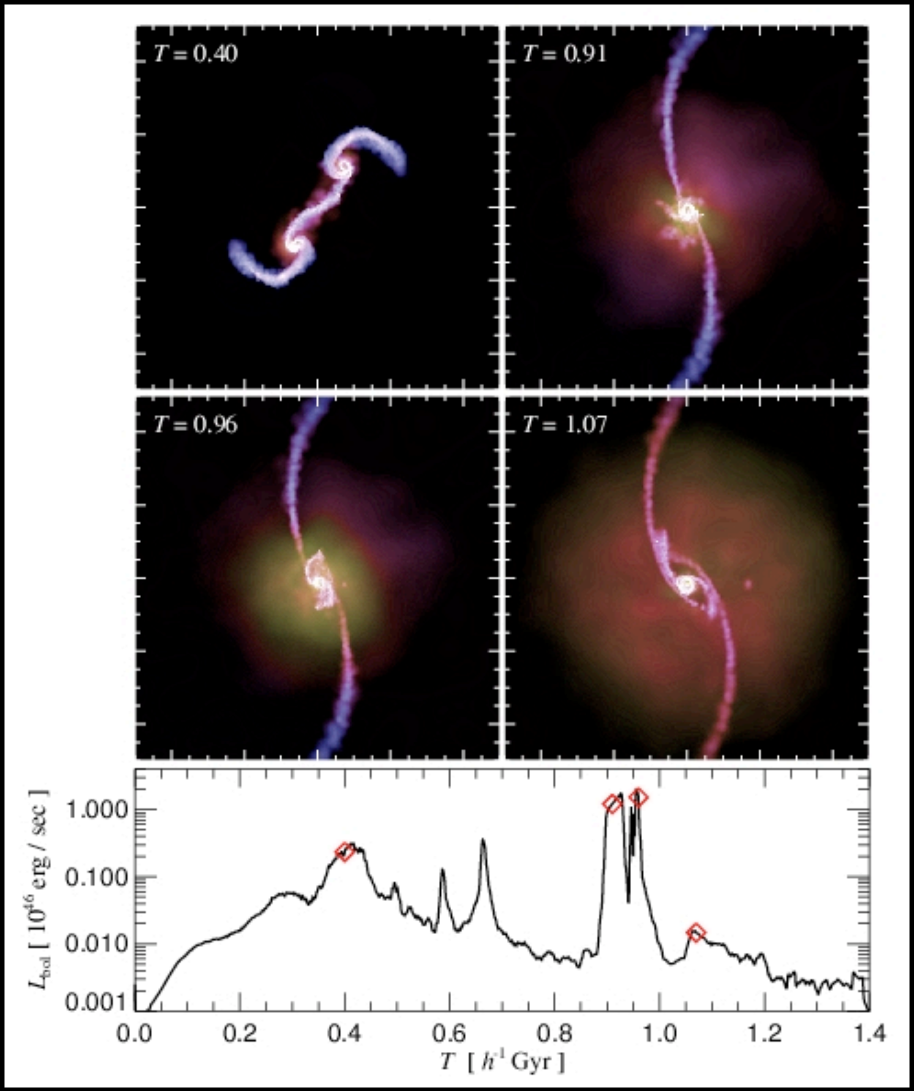
(similar to e.g. Peng et al. 2006)



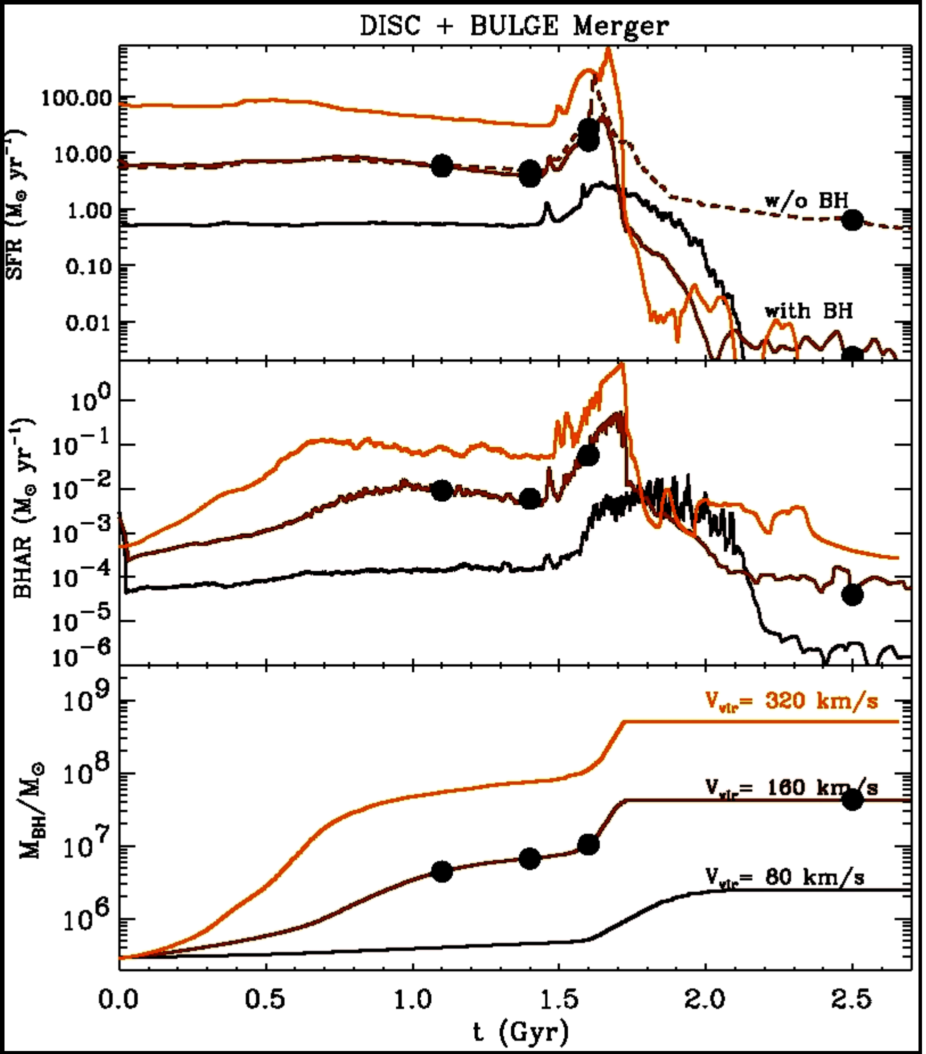
Quasars

- new picture for quasar evolution:
  - complex, evolving light-curves, lifetimes
  - evolving pattern of obscuration: increases with luminosity, drops during blowout
- new interpretation of quasar luminosity function
- self-consistent model for quasar population, cosmic X-ray background, supermassive black hole & galaxy spheroid population
- analytic model for low-luminosity AGN not fueled by mergers
- new description of quasar clustering
- explanation for “universal” quasar host halo mass

Quasar Evolution



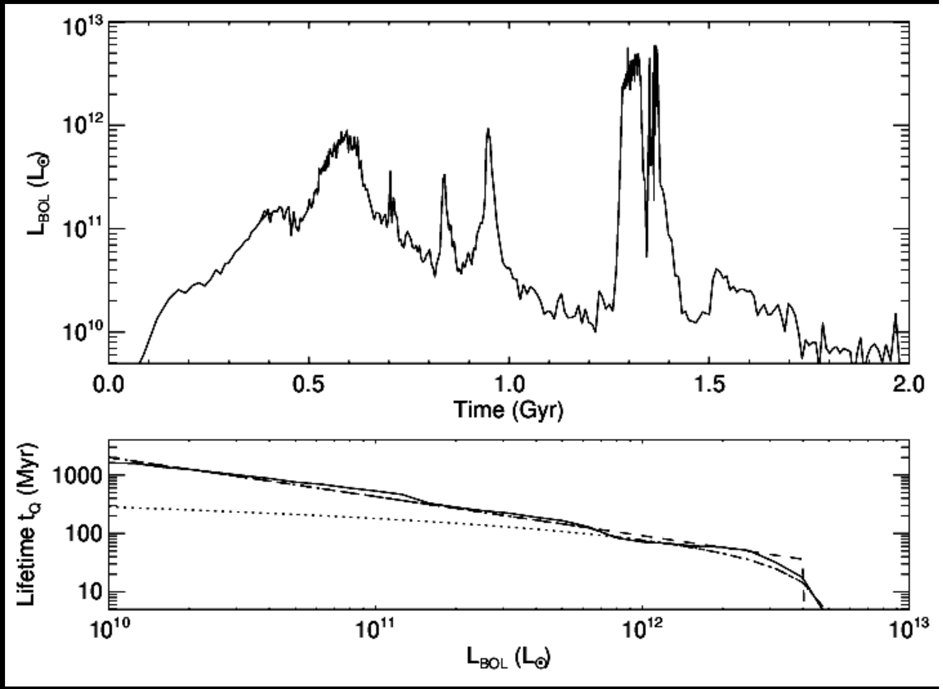
Hopkins et al. (2005)



DiMatteo et al. (2005)

Quasars: Light-curves & Lifetimes

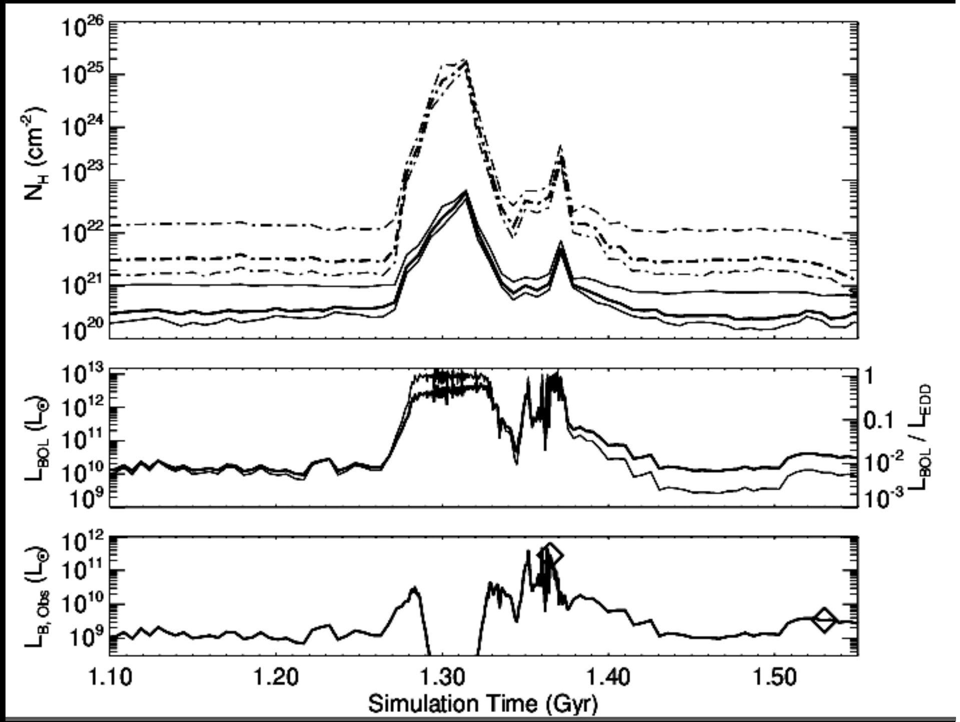
- luminosity evolves:
  - extended dim phases
  - Short peak phases (< 10^8 yrs)
- "lifetime" depends on both peak and instantaneous luminosities
- unlike "light bulb," pure exponential growth
- More time at faint L (e. g. Adelberger & Steidel 2005)



Hopkins et al. (2005)

Quasars: Absorbing Columns

- absorbing column evolves with time:
  - large spread in N_H with time
  - smaller spread at given time
- quasar phenomena mainly evolutionary?

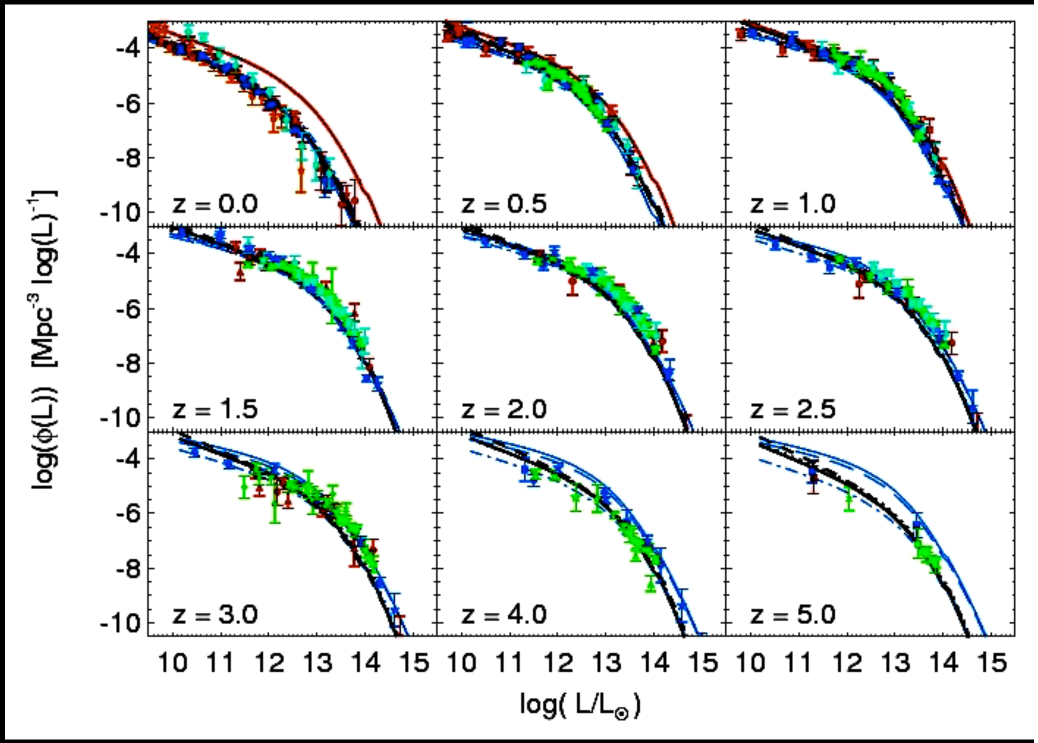


Hopkins et al. (2005)

Cosmological Context

(Hopkins et al. astro-ph / 0706.1243 & 0706.1246)

- Combine:
  - halo/sub-halo mass functions
  - halo occupation models
  - dynamical friction estimates
- Predict abundance, biasing of major gas-rich mergers vs. z
- Use quasar light curves from merger simulations
- Predict e.g. quasar LF, excess small-scale clustering, bias of quasars



bolometric QLF: points from data in various bands (Hopkins et al. 2007); red lines allow "dry" mergers to trigger quasars

Cosmological Context

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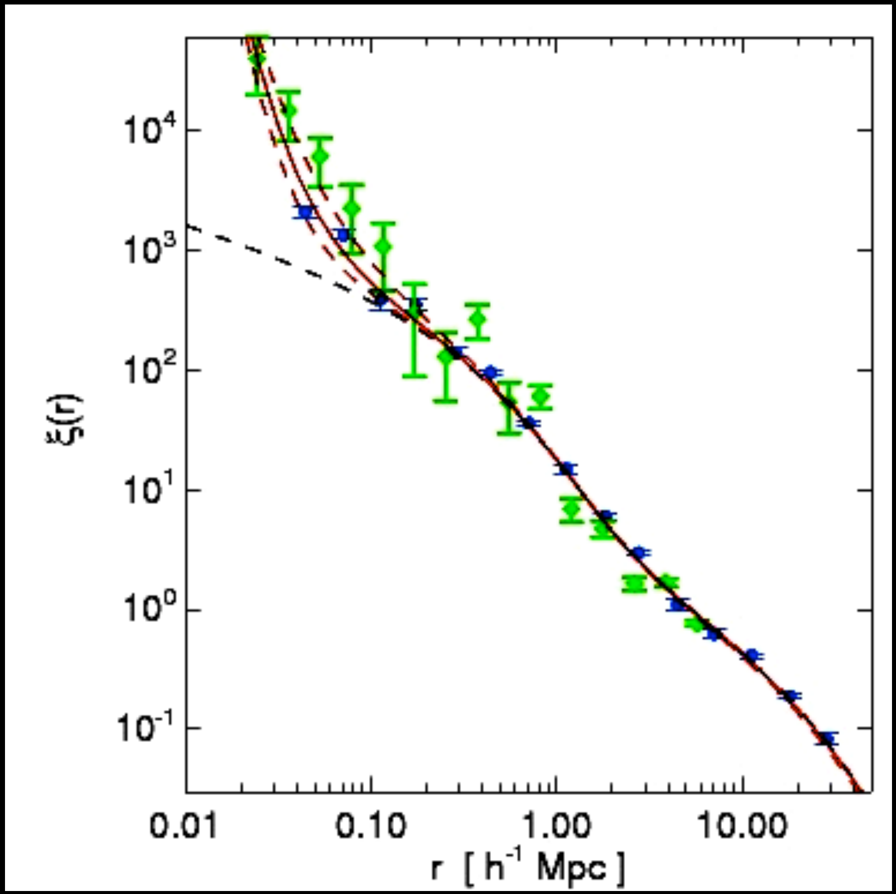
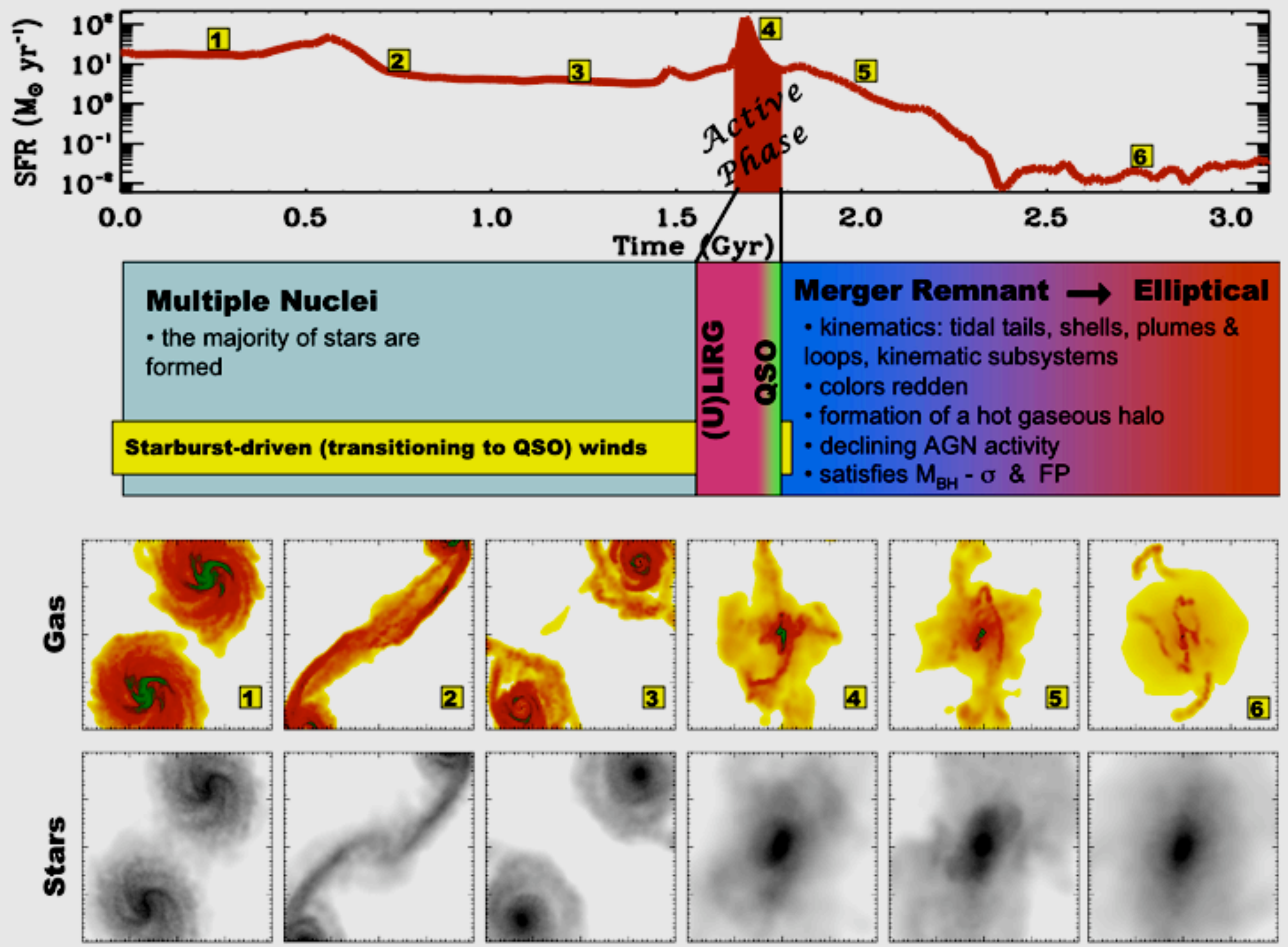


Observed points: Myers et al. (2006), Hennawi et al. (2006)

Origin of Quasars, Supermassive Black Holes & Elliptical Galaxies in Gas-Rich Mergers



Cox et al. (2006)

Origin of Quasars, Supermassive Black Holes & Elliptical Galaxies in Gas-Rich Mergers

- Explains:
  - Clustering, abundance, evolution of quasars
  - Growth, demographics of supermassive black hole population
  - Abundance, clustering, structure (profiles, kinematics, correlations) of elliptical galaxies
  - Properties of cosmic X-ray background
  - Nature of starburst galaxies (ULIRGs, SMGs)
  - Blue → red galaxy transition