Transforming Galaxies since z~3 via Mergers, Gas Accretion, and Secular Processes

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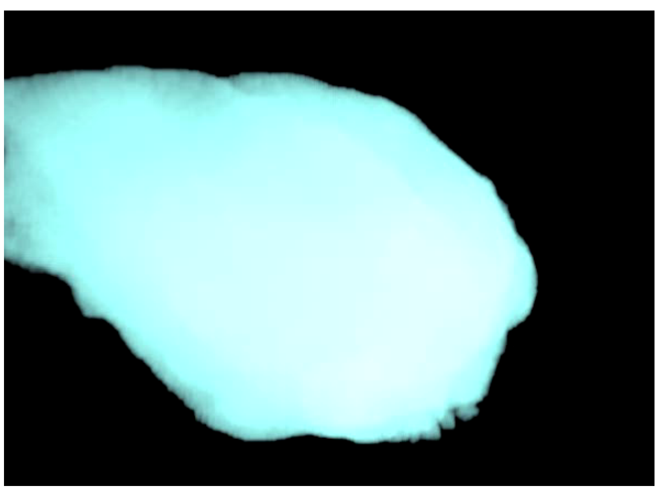
Science Collaborations: GEMS, GOODS-ACS, GOODS-NICMOS, STAGES, Coma HST Treasury survey, HETDEX, VENGA

Cartoon Simulation: Building a MW-type Spiral Galaxy over ~12 Gyr



Courtesy: Fabio Governato

N-bady + SPH
Gas= Green Cyan
New Stars = Dark Blue
Old Stars = Red
Movie frame ~ 80 kpc
Final mass $=10^{12}$ Mo

Galaxies grow via different processes whose relative importance have to be established:
- Gas Accretion (from halos and cosmological filaments)
- Major Mergers and Minor Mergers
- Internal Secular Processes (e.g. driven by stellar bars, dynamical friction in z~2 clumpy disks)
- Star Formation
- Feedback (from star formation and AGN activity)

Outline

- Overview of Growth Modes: Mergers, Gas Accretion, Secular Process

- Star Formation activity z~0-3: Contributions of Different Modes
- AGN Formation activity z~0-3: Contributions of Different Modes

- Bars: Frequency and impact on SF/AGN/Activity ??

- Tracing Assemby History via Structural Archeology
- Structural Evolution From Different Growth Modes (& Use of Structural Archeology)

- Galaxy Merger Rates as f(z): Empirical Constraints + Theoretical predictions
- Tensions with LCDM
- (Could combine these two into one : Challenges)

- Summary

Galaxy Major Mergers

Major Merger = merger of 2 galaxies of mass ratio M1/M2 < 1/4

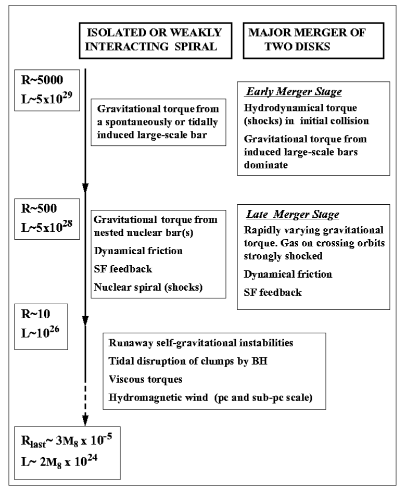
NGC 4736 / The Mice
Collision between 2 spiral galaxies 30 kpc apart.

(Credit: NASA/STScI/Hubble Heritage)

The Antennae
(NGC 4038/NGC 4039)

Transformational Effect of Major Mergers

- **Gas is driven into the inner kpc** due to shocks and gravitational torques (exerted by induced bars and by companion).



- These gas inflows
  → can fuel **high cental star formation rates**

→ may fuel central black holes by helping solve the angular momentum (Jogee 2006)

(Jogee 2006; astro-ph/0408383)

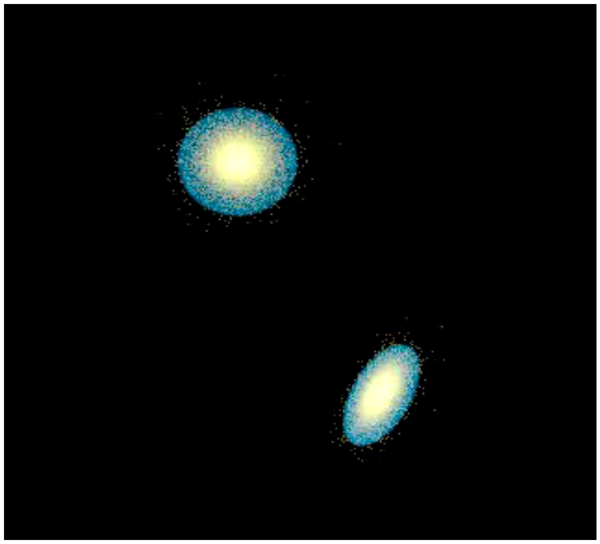
Transformational Effect of Major Mergers

- Due to rapid change in potential, violent relaxation destroys existing stellar disks (flat, rotation-dominated) to form classical bulges or ellipticals (spheroidal, dispersion-dominated).

Traditional view: Major merger of 2 spirals produces a classical bulge or elliptical).

New view: In extremely gas-rich mergers (f_{gas}> 60%) at very high redshifts, the remnant can host a significant (new) stellar disk, which forms from residual gas at late stages of the major merger, well after the onset of violent relaxation (e.g., Robertson+06; Hopkins+09; Naab+09)

Transformational Effect of Major Mergers



Data
The Toomre Sequence

Above = simulation of a major merger between 2 moderately gas-rich spirals
Mihos & Hernquist, Summers; Stars =yellow, gas= blue, Duration = 1 Gyr)

Minor Mergers

Minor mergers have a progenitor mass ratio 1/10 <M1/M2 <= ¼

During the minor merger of a spiral with a satellite we expect the following

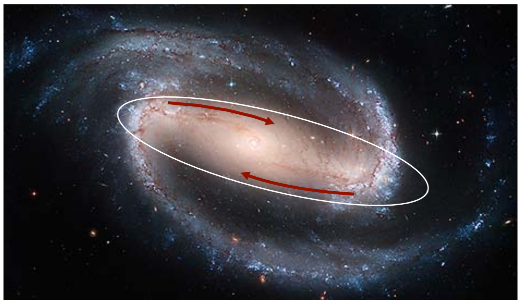
- The disk of the spiral thickens due to tidal heating, is tidally distorted with arcs and ripples, but it is not destroyed
- A stellar bar is often induced in the disk and drives gas inflows (Mihos & Hernquist 1995)
- Dynamical friction causes the core of the satellite to sink to the center of the spiral. The outer parts of the satellite can be tidally disrupted

NGC 2782: Minor merger of mass ratio ¼
(Jogee et al 1999; Smith et al 1999)

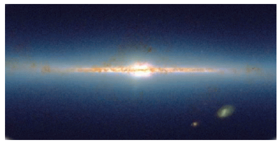
Internal Secular Processes

Stellar bars and ovals drive important internal secular processes (e.g., Kormendy+1993, 2004 ; Sakamoto+1999; Jogee+1999, 2005; Athanassoula 2005; Weinzirl+2009)

- Bars very efficiently drive gas from outer disk of a galaxy into the circumnuclear (CN) or inner kpc region via gravitational torques and shocks.
- Gas inflows raise the CN gas concentration, fuel CN star formation and build CN disks called pseudo-bulges

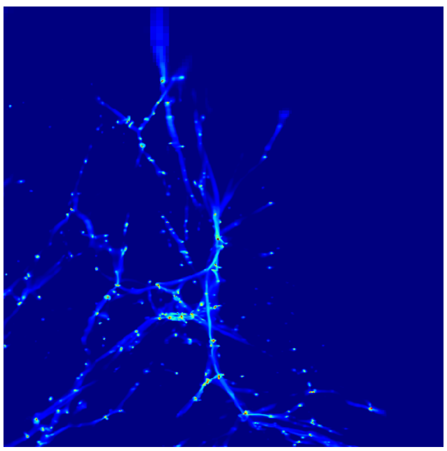


- Bars can form boxy/peanut bulges when its stars are driven to large scale heights (Combes+1990;Athanassoula 2005; Martinez-Valpuesta+2005)



- Bars postulated to drive secular evolution along part of Hubble Sequence (Scd-Sb)

Gas Accretion from halo and cold flows



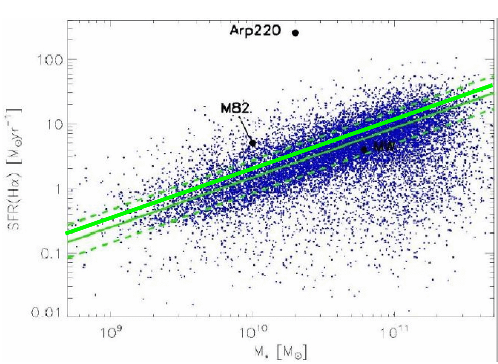
Courtesy: A. Dekel & R. Teyssier (200 Mpc, z=5 to 2)
Shown: The mass-weighted average density of galactic and intergalactic gas. Most of gas is at 10^4 K, while the diffuse gas is hotter

- As galaxies accrete gas, the gas shocks to the halo virial temperature T_{vir}
- Simulations suggest some accreted gas is unshocked ($T<T_{vir}$) and accretes along narrow streams called "cold" flows (Keres+05,+08; Dekel+06,+09; Brooks +09)
- Cold flows deliver unshocked gas close to the disk and this gas fuels SF after cooling. This is esp. important in high mass halos ($M>10^{12}\ M_o$) filled w/ hot gas.
- But importance of cold flows is debated (Vogelsberger et al. 2014)

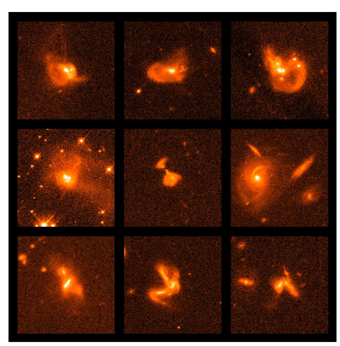
SF ACTIVITY

SFR at z~0: Contributions of Different Modes

- At a given redshift, the extreme systems (defined as systems with high sSFR= SFR/M_*) wrt to the average main sequence of star formation) tend to be have a larger fraction of interactions/mergers than typical systems on the main sequence
- At z~0, where average typical sSFR ~ few x 10^{-11} yr^{-1} (for $M_*=10^{11}$ M_o, SFR~ few M_o yr^{-1}), UILRS ($L_{IR} > 10^{12}$ L_o, SFR > 100 M_o yr^{-1}, sSFR ~ 10^{-9} yr^{-1}) are extreme systems amd most of them are mergers/interactions (Sanders & Mirabel 1996 & references; Veilleux+2002)



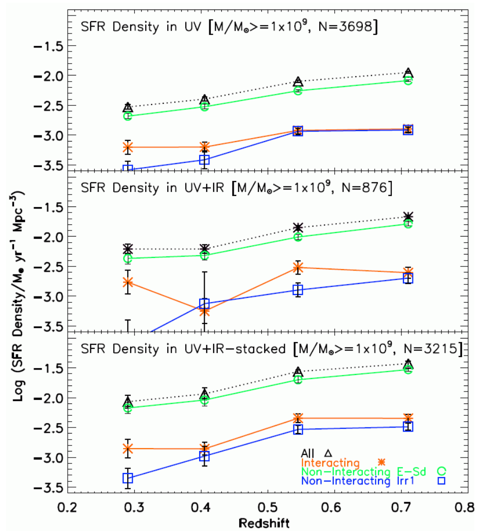
Brinchmann et al. 2004 SDSS z ~ 0



Credit:STScI

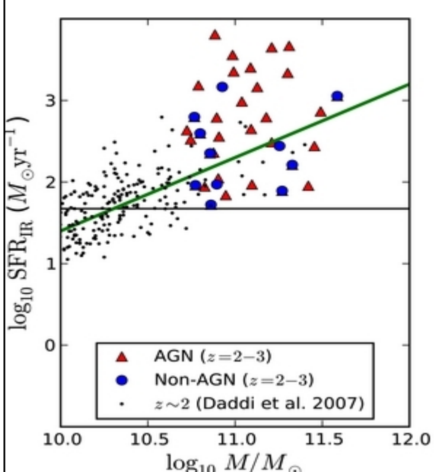
Out to z~1: at most 30% of the SFR density is in major mergers

- At most 30% of the cosmic star formation rate density over half of the age of the Universe stems from visible major mergers for (M_*>1 x 10^9 M_o) galaxies.
- Bulk of star formation occurs in fairly undisturbed systems
- Consistent with later empirical studies (e.g., Robaina et al. 2010; Lotz et al. 2011).



(Jogee & GEMS team 2009, ApJ)

SFR at z~2: Contributions of Different Modes

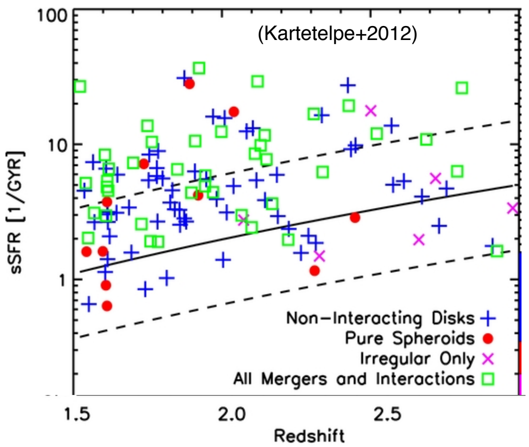


(Weinzirl Jogee & GNS team 2011)

- sSFRs considered extreme at z~0 can be typical at z~2: (e.g. M_*=$10^{11}$$M_o$, SFR~ 100 M_o yr^{-1}, sSFR ~ 10^{-9} yr^{-1})
- At z~2, extreme systems have sSFR <10^{-8} yr^{-1}) and include hyper-LIRGs (L_{IR} > $10^{13}L_o$, SFR > 1000 M_o yr^{-1}) some submm galaxies (SMGs)

SFR at z~2-3 in dusty ULIRGs/Hyper-LIRGs

WFC3 study of **galaxies detected at 60 and 160 micron** GOOD-S and GOODs-Herchel (biased toward FIR-bright dusty star-forming systems)   (Kataltepe 2012)



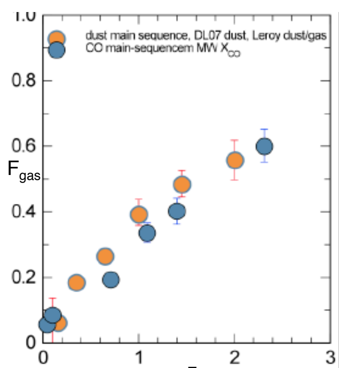
z~2: UILRGs (L_{IR}>$10^{12}L_0$) host 47% mergers/interactions and 25% **irregular disks**

Amongz~2 UILRGs, merger/int systems make up ~50% of starbursts (systems more than a factor of 3 above Main Sequence) and only only 24% of Main Seq systems

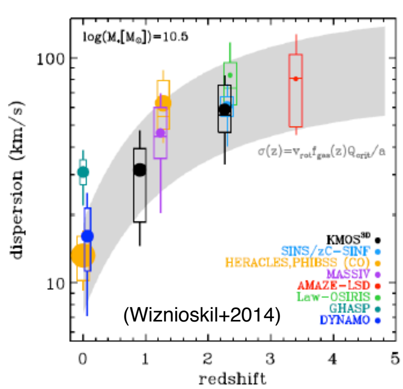
→ In z~2 UILRGs, disk instabilities + early-stage interactions, minor mergers may be important

Why are sSFR at z~2 on main sequence >> at z~0

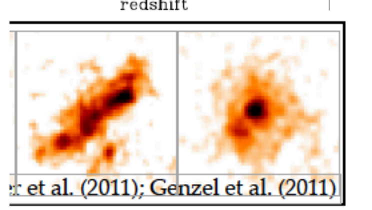
Star forming galaxy disks at z~2 differ from z~0   (higher gas fraction, higher turbulence and σ of ionized gas, clumpy ; see Foster-Scheider+2009, Wisnoski+2014, 2015)



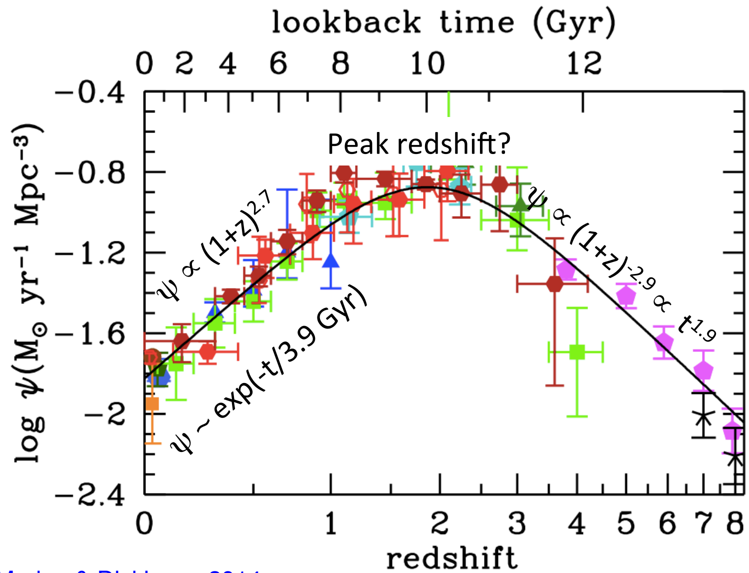
(Genzel+2014)



→ Extra pathway for SF and bulge buildng: massive gas clumps sink via dynamical friction   (Bournaud+2011 ; Elmegreen +2005)



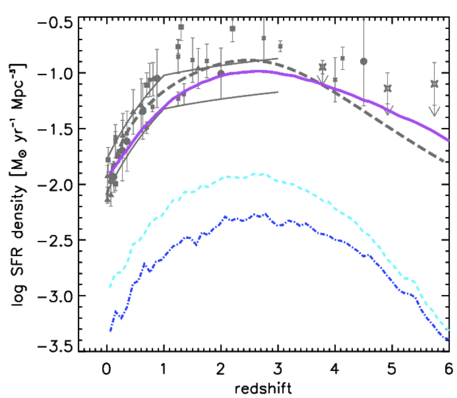
Cosmic Star Formation Histoy of Galaxies



Madau & Dickinson 2014

Contributions of Different Growth Modes to Cosmic SFRD

MODEL Purple=Total Blue=Major Merger Cyan =Major+Minor



(Based on Somerville+2011)

In many current models, major merger (blue) account for only a small fraction of the total cosmic SFR density (purple),which is mostly due to smooth accretion (in situ-SF).

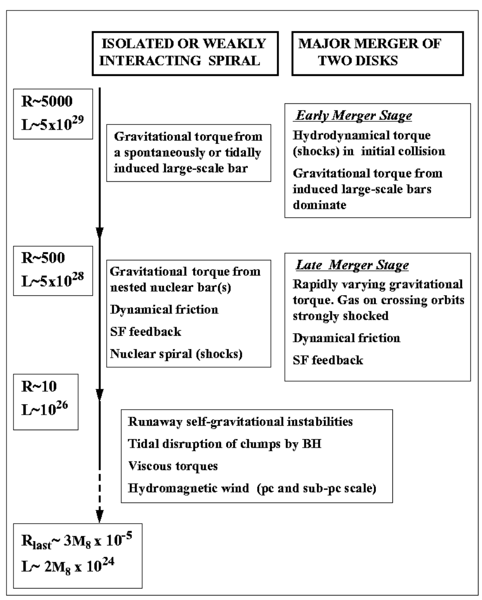
AGN ACTIVITY

Fueling the Central BH :The Angular Momentum Problem

Gas in the outer disk need its specific angular momentum L to be lowered by 10^5 before it can feed a BH

Bars help only down to r~few 100 pc as gas piles up in rings inside OILR

Interactions /mergers can channel gas down to lower r

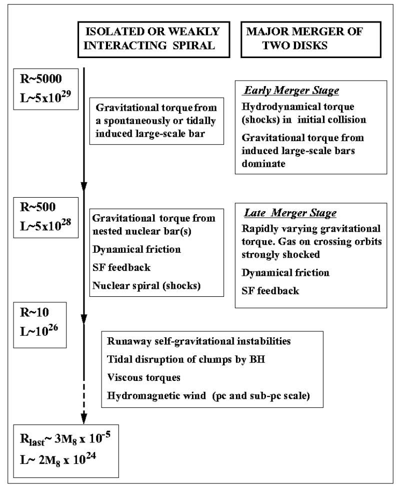


(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

Fueling the Central BH :The Angular Momentum Problem

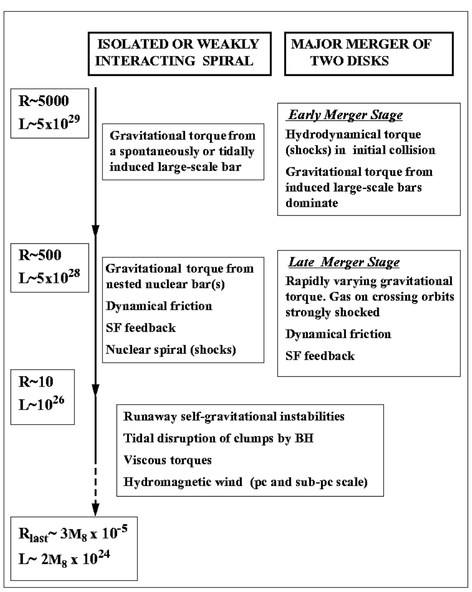
High Lum QSOs have large mass acc rate the gas mass fuel them over many duty cycles >> gas contenti in inner kpc. Hence they require **external gas accretion + transport of gas from outer region to inner parts**

Low lum AGN



(Jogee 2006, Ch6,; astro-ph/0408383)

Why are large-scale properties of AGN and non-AGN at z~2-3 similar?



In order to feed gas from tens of kpc down to an AGN, transport mechanisms on different scales must remove over 99% of its angular momentum

The AGN at z~2-3 have low estimated gas accretion rate dM/dt <= 1M_o yr^{-1}. The implied accreted gas mass (< 10^8 Mo) over a duty cycle is *much less than the typical gas content in inner kpc of most massive galaxies (except in some gas-starved ultra-compact galaxies).*

Thus. the AGN activity can be triggered by circumnuclear gas transport mechansims (e.g., dynamical friction on clumps, nuclear bars, shocks)

Large-scale transport or fueling mechanisms (e.g, mergers, large-scale bars) are not necessary conditions to fuel the AGN (but can grow the galaxy as a whole

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

AGN in Massive Galaxies at z~2-3

- AGN identified mainly via X-ray properties (L_x,G), and some from IR power-law SEDs (Donely+08) , IR-to-optical excess (Fiore+08)

  At z~2-3, 40% (31/77) of massive galaxies host a AGN

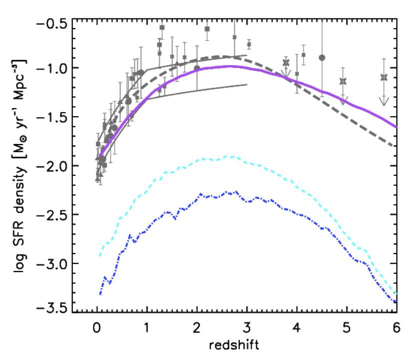
- The 20 AGN with X-ray detection are low luminosity Seyfert-type systems
  L_x = few x 10^{42} to 10^{44} erg s^{-1}
  L_{bol} = few x 10^{43} to 10^{45} erg s^{-1} (for L_{bol} / L_x ~20; Vasudevan & Fabian 2009)
  Mass Accretion rate < 1 M_o yr^{-1} (for e=0.1)
  (Complementary to high luminosity AGN --- Donley's talk]

- Number density

Low Luminosity AGN at z~2-3:	2 x 10^{-4} Mpc^{-3}
SMG at z~2-3:	2 x 10^{-6} Mpc^{-3}
QSO at z~2-3:	~10^{-6} Mpc^{-3} ,
High-z radio galaxies	~few times 10^{-8} Mpc^-3

Merger –AGN fuelling at z~0

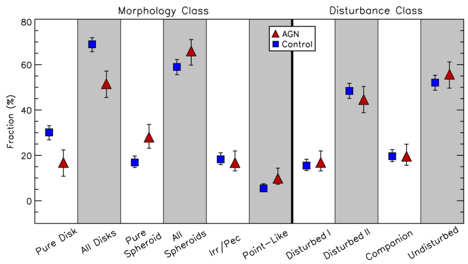
---- mergers and AGN
* Correlation expected at high end
* Low Lum AGN mostly in undistrurbed disks Weinz+2011
  high lum AGN



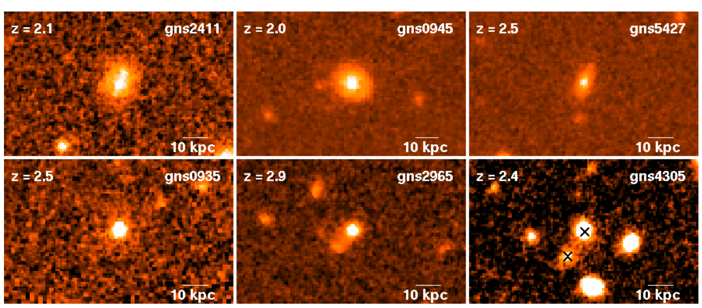
Merger –AGN fuelling at z~2

-1) For moderate lum AGN (L X ~ 1042-44 erg s-1) A
- AGNs host are no more likely to be involved in an ongoing merger or interaction relative to non-active galaxies of similar mass at z ~ 2. T

• Low Lum AGN mostly in undistrurbed disks Weinz+2011

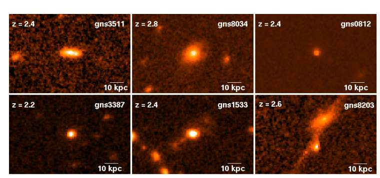


Only a small fraction of AGN & Non-AGN show visibly strong distortions



AGN

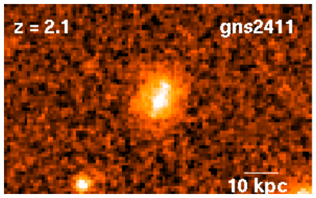
Both AGN and non-AGN hosts have a comparably low fraction (<15%) of strong visible morphological distortions

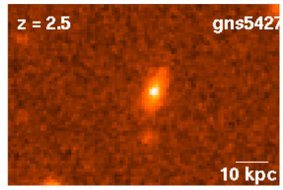


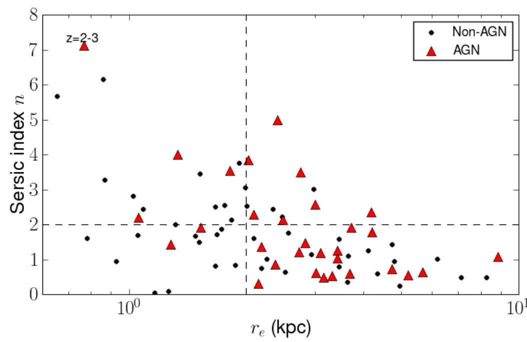
Non-AGN

However even best current datasets do not have resolution and sensitivity to detect late stages of major merger or minor mergers

Morphology of (Low-Luminosity) AGN hosts at z=2-3





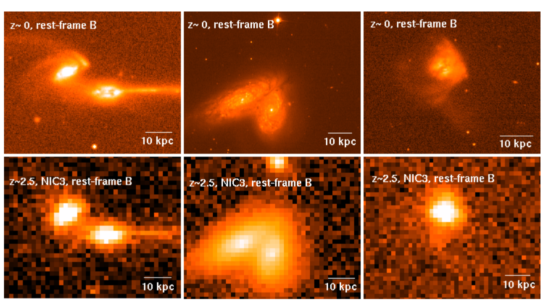


Most (65%) of AGN hosts are disky extended galaxies (just like the general population)

AGN hosts are ~3 times less likely than non-AGN to be ultra-compact (this is likely caused by the fact that many UC are undetected in SFR, gas starved and 'dead',)

Can we detect major & minor mergers with deep NIC3 data?

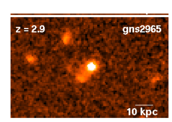
Artificially redshift rest-frame B light of mergers from z=0 to z=2.5 and re-observe with NIC3/F160W to depth of GNS survey.

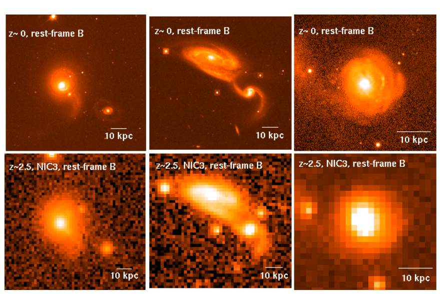


Major mergers

z=0, rest-frame B

z=2.5, rest-frame B (NIC3/F160W)





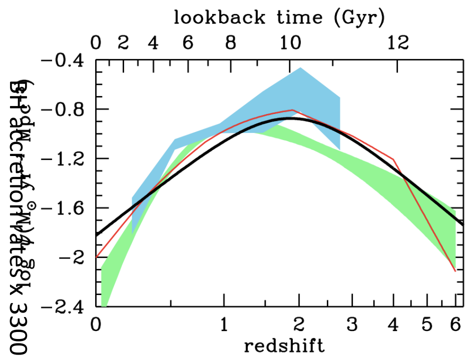
Minor mergers

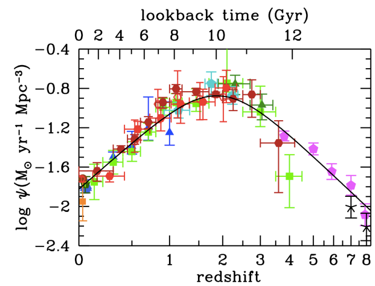
z=0, rest-frame B

z=2.5, rest-frame B (NIC3/F160W)

Cosmic AGN Accretion History

Recent estimates of the AGN accretion history vary and are not terribly precise, but
It is in broad agreement with the cosmic SF history.





Shankar+2009(optical + X-ray)

Aird+2010 (X-ray)

Delvecchio+2014 (infrared)

COULD DO A SEPARATE SECTION ON BARS : FREQ AND IMPACTS OF SF AND AGN ACTIVITY

REASON FOR SEPARATE: LESS INFO AVAILABLE AS REQUIRE RESOLVED INFO ON CIRCM SF …..

Bars and SF activity at z~0

--- slide

- at z~0 Bar show higher gas conc; + Starburst have higher bar frac than unbarrred

Bars and SF activity at higher z?

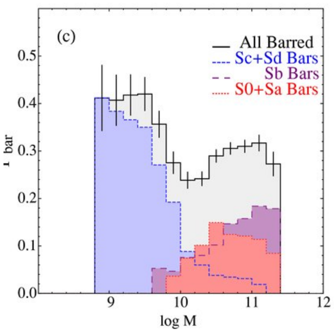
--- slide

- at z~2; bar-Sf is difficult as have on hig res IR tracer of CN SFR
- Herschel HeRS,

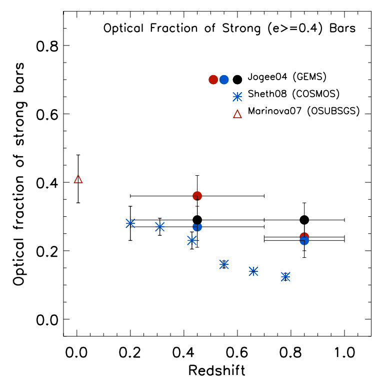
- GIVE SOME GENERAL INFO ON FREQ OF BARS HERE? j09, S08, 2010

Freq of Bars

- At z~0, the optical fraction of strong bars depends strongly on stellar mass (Barazza +2006; Nair & Abraham 2010).
- At z~0 the quantitative NIR-bar fraction is at least 1.3 times higher than in the optical due to obscuration by SF and dust (Laurikainen +04; Menendez-Delmestre+07; Marinova & Jogee 07; Weinzirl+09)



(Nair & Abraham 2010)



- At z~0.2-1, optically-strong bars (e>0.4) are frequent (~10% to 25%) over the last 8 Gyr -- an interval long enough to drive significant evolution ((Jogee+04; Sheth+08; Cameron+10)
- Progress requires NIR-based bar fraction as a function of M* from z~0 to 1.5 to get the unobscured fraction of strong or all bars.

Freq of Bars

- Add Cosmos results at z~2
- Talk here of models by Shlos and min mass of disk to support bar

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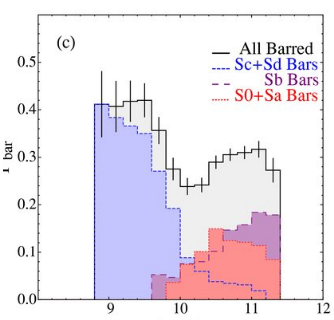


(Nair & Abraham 2010)

Structural Evolution From Different Growth Pathways
Or
Tracing Assemby History via Structural Archeology

Structural Archeology

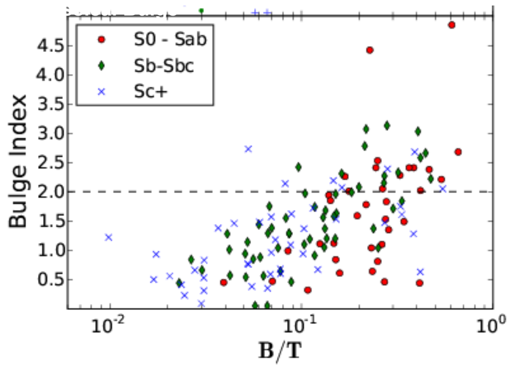
- In Galactic archeology, properties of stars (age, metallicity, kinematics) to infer the star formation history of our Milky Way (e.g., AU-led GALAH survey)
- In our structural archeology technique, the ratio of stellar masses of fundamentally different components (disk versus classical bulge/E) in a galaxy is used to constrain its past merger and gas accretion history. Unlike direct observations of distant merging systems, structural archeology is less affected by redshift-dependent systematics (surface brightness dimming, loss of spatial resolution)

1) Stellar disks : Flattened. Stars dominated by ordered motion Includes outer and central disks (called pseudo-bulges)
→ Forms from gas-rich dissipative events

2) Classical Bulges/Ellipticals: Puffed-up (spherical/spheroidal). Stars dominated by random motion
→ form from violent stellar processes (e.g., major merger of 2 stellar disks)

Most nearby massive field spirals do not have classical bulges!

- See details in Weinzirl, Jogee, Khochfar, Burkert, & Kormendy 2009, ApJ, 696, 411
  - Perform 2D bulge-disk and bulge-disk-bar decomposition on H-band images
  - Sample of 143 spirals ($M_* \geq 10^{10}$ M_o, S0/a to Sm, i< 70°) from OSUBGS (Eskridge+2002)



- Most nearby massive field spiral galaxies
  → have little mass in their bulges (66% with B/T< 0.2)
  → host bulges that are disks (pseudo-bulges) (77% with n<2) rather than classical bulges!

(See also Laurikainen et al. 2007; Graham & Worley 2008; Gadotti+09)

Comparing with Hierarchical Models of Galaxy Evolution

Models from Khochar & Burkert (2001), Khochfar & Silk (2006)

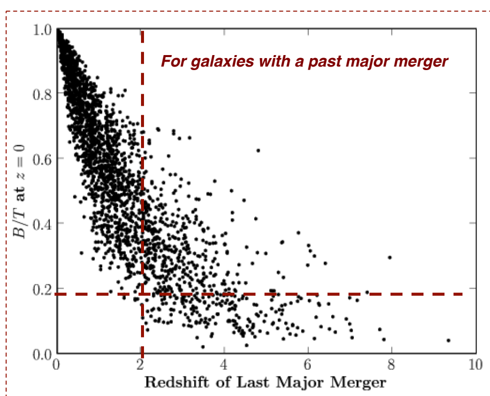
Standard approach

- ΛCDM cosmology assumed. Merger trees of DM halos derived from the EPS
- Galaxy merger timescale set by dynamical friction of satellite in halo of central galaxy
- Semi-analytic prescriptions for star formation (Cox+08) , cooling, Supernova feedback

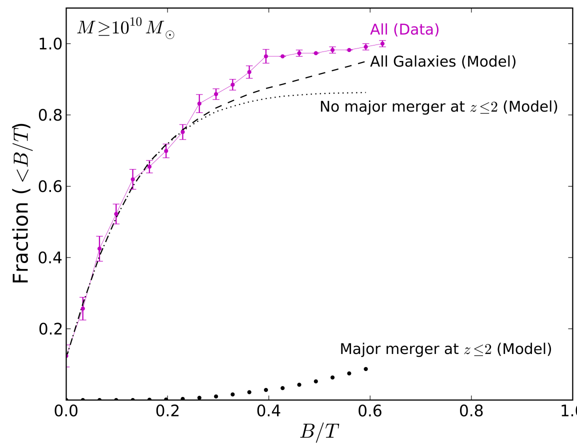
During major mergers (1:1 to 1:3).

A fraction of the gas forms stars, and all stars are converted into a spheroid giving B/T =1.After last major merger, B/T falls with time as an outer stellar disk grows (from accretion, residual gas, minor merger)

A low B/T<0.2 at z~0 is realized only if the last major merger was at z>2



Data imply quiescent major merger history for field spirals



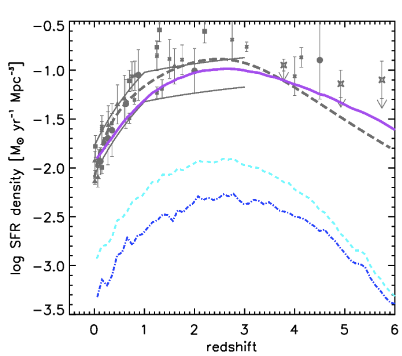
(Weinzirl, Jogee et al. 2009,)

- The fact that most massive nearby field spirals have low-mass, disky, non-classical bulges implies that most spirals have had no recent major merger over the last 10 Gyr (since z<2).
- This is in agreement with several theoretical models (SAMs by Khochfar & Slik 2006; Hopkins+2009) where only ~15% of massive field spirals had a major merger since z<2

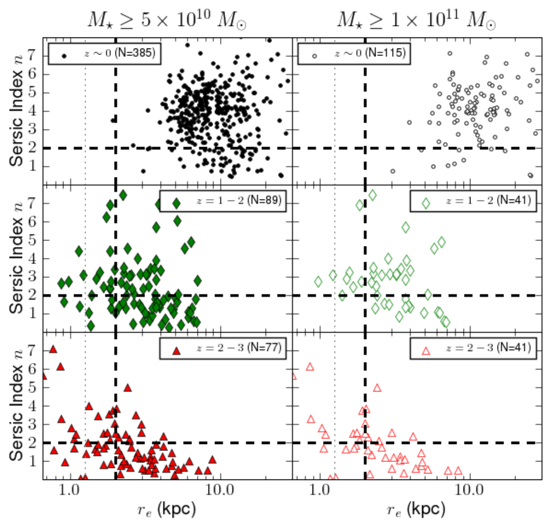
Brennan work

---- 1 slide

- Mention new growth mode at high z~2: massive clumps



Structure of Massive Galaxies at t~2-4 Gyr Differ Widely from Today

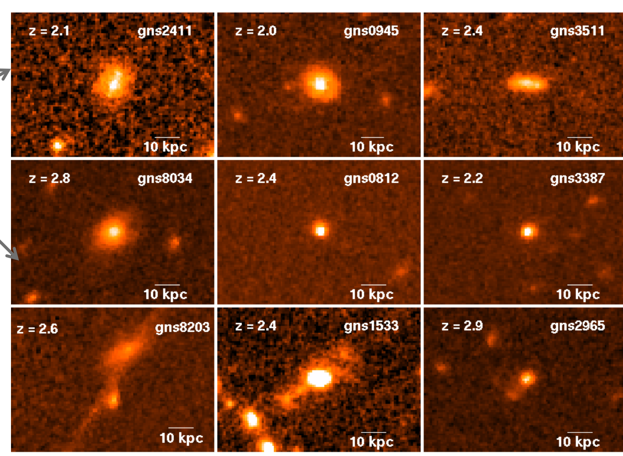


(Weinzirl, Jogee,Conselice + 2011, ApJ, 743)

- The fraction (40%) and relative number density of massive ultra-compact (r_e<2 kpc) sysyems is over 10 times larger at z~2-3 than at z~0.
- A large fraction (60%) of massive galaxies at z~2-3 have disky (n<2) stuctures They tend to be star forming

Rest-Frame Optical Structure of Massive Galaxies at z~2-3

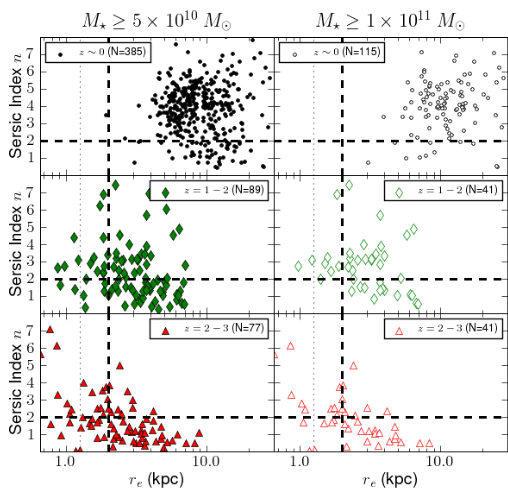
Disky, flattened extended

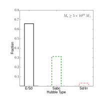


Ultra-compact Re<2 kpc

At z=2-3, among our 77 massive (M_*/M_0> = 5 x10^{10}) galaxies:
→ Most (65%) have extended (R_e>2 kpc), flattened/disky (n<2) morphologies
→ 40% are ultra-compact (Re<2 kpc)
→ A small fraction (<15 \%) have strong visible distortions

Rest-Frame Optical Structure of massive galaxies at z=2-3 vs z~0





At z~0, most massive (M_*/M_0> = 5 x10^{10}) systems are E,/S0 followed by Sab : typically high (n, R_e), extended, host classical bulges/E or pseudobulges

At z~2-3, massive galaxies have very different structures of lower (n, r_e)

- 65% have n<2 disk morphologies at z=2-3 vs 20% at z~0.
- 40% are ultra-compact (re<2 kpc) at z=2-3 vs <1% at z~0

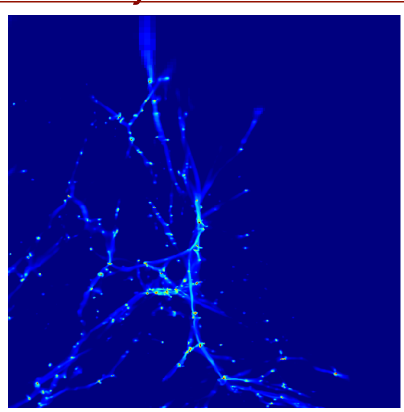
(Weinzirl, Jogee,Conselice et al. 2011, ApJ, 743)

Can Models Form Large Fraction of z~2 Disky Massive Galaxies?

- The large population of massive disky galaxies, with high stellar mass densities at z~2-3 must have developed through rapid gas dssispative processes at z>2:

  1) Gas accretion via cold flows helps build disks at z>2 (e.g., Keres+05; Dekel+09; Brooks+09)

  2) Gas-rich mergers (which do no make classical bulges)



Courtesy: A. Dekel & R. Teyssier
(200 Mpc, z=5 to 2)

→ EG disky boxy --> dry major mergers; Kormendy plot?

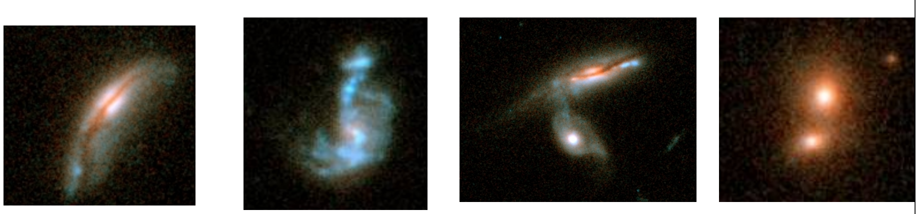
Galaxy Merger Rates as f(z): Empirical Constraints + Theoretical predictions (8)

Methods

1) Disturbed morphology identified via trained visual classification

a) Visual classification tailored by simulations of mergers (e.g. Le Fevre et al 2000; Jogee et al. 2009; Kartaltepe et al. 2012)

b) Automated crtieria : CAS (A> 0.35 and A >S) (Conselice 2003) or Gini-M20 (Lorz et al. 2008, 2011)



Jogee & the GEMS team 2009, ApJ

2) Close galaxy pairs with M1/M2 >1/10, z1~z2, r<20-30 kpc;1 or 2 galaxies disturbed

3) Structural archeology

Challenges for Empirical and Thoeretical Merger Rates

Empirical estimates of how galaxy merger rate evolves with z depend strongly

a) sample selection by mass or constant no density (Lotz 2011)

b) Mass ratio M1/M2 used to define mergers : halo, baryonic, or stellar mass ratio or flux ratio (e.g., see H10, W14)

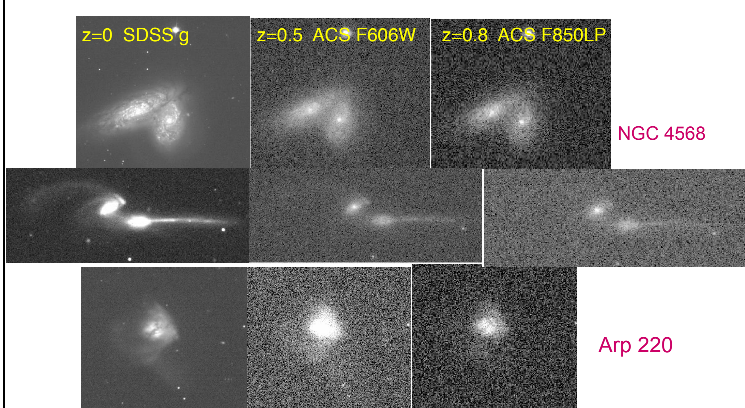
c) Assumed visibility timescale to covert merger fraction to rate R = fn/tvis
depends on mass ratio and gas fraction (J09; L11)
d) Impact on SB dimming and loss of resolution
e) the mass range involved M*>10^9 , M*>1e10, M*>1e11

Theoretical predictions of merger rate depend on

a) Mass ratio M1/M2 used to define mergers : halo, baryonic, or stellar mass ratio
b) treatment of Tdyn friction for satellites (J09 ; Hopkins 2010
c) The phase of the merger (infall, max) where mass ratio is measured Rodriguez-Gomez +2015

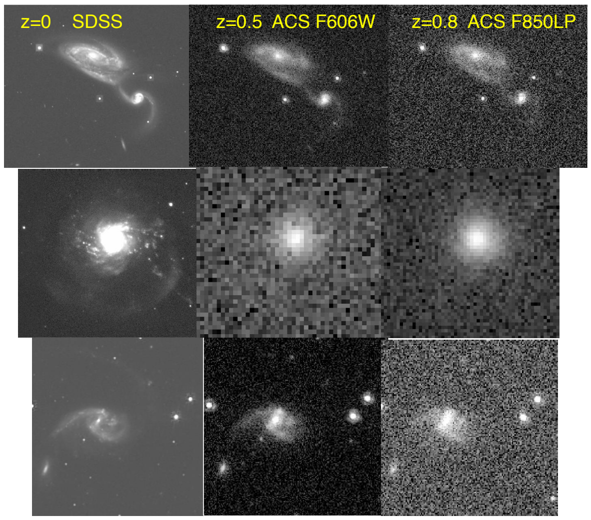
Challenge: Surface brightness Dimming + Loss of resolution

We artificially redshift optical images of present-day mergers to early epochs (z~1 pr t~6 Gyr) and re-observe with ACS camera on Hubble Space Telescope



Major mergers in early, middle and late phases

- At z>1 (t<6 Gyr) it it hard to detect
  - extended faint tidal features (due to SB dimming by a factor >16)
  - double nuclei of proto-typical merger Arp 220 (as HST resolution 0.1"= 700 pc)
- Giant Magellan Telescope's large aperture and resolution (30 m, 0.01") will help!



NGC 5395

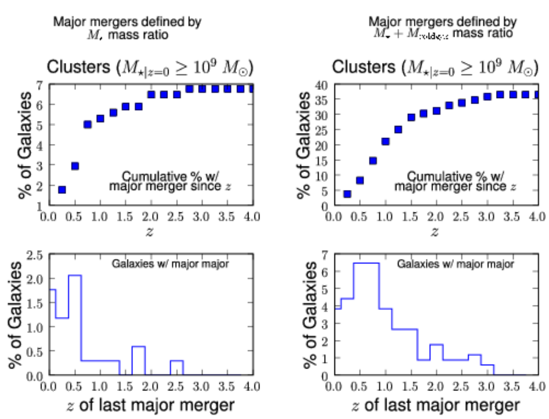
NGC 3310

NGC 5996

Minor mergers in early, middle and late phases

Challenge: Merger Rates Based on Stars vs Baryons Differ!

- Major and Minot mergers are defined based on mass ratio M1/M2
- One should ideally use the total galaxy mass from (dark matter halo + gas + stars), but observers cannot easily measure mass of dark matter or gas for large number of galaxies at high redshifts (early epochs). The most common proxy is to use stellar mass M_{star}



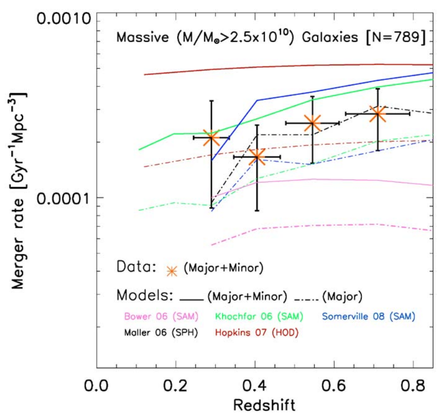
- But merger rates differ by over a factor of 5 depending on whether one use M_{star} or baryonic mass (M_{star} + M_{gas})
- Need ALMA and SKA to add M_{gas}

(Weinzirl, Jogee, Neistein Khochfar and Coma Treasury Team 2014, MNRAS)

Minor and Major Merger Rate out to z~1

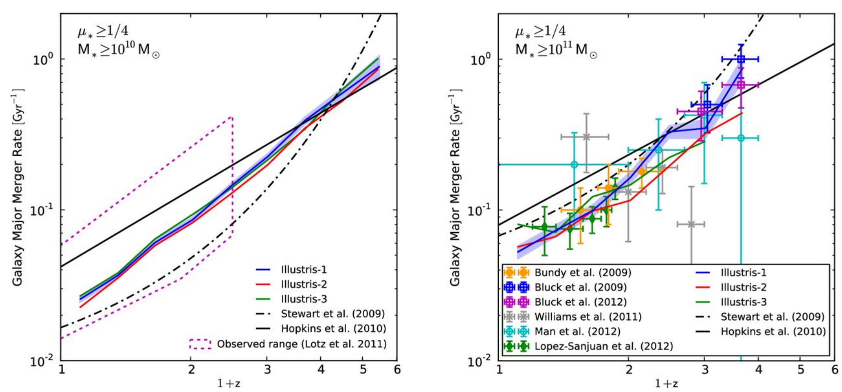
- Among high mass ($M_* > 2.5 \times 10^{10}$ M_o) galaxies over z~0.2 to ~1:
  - → Visible merger fraction varies from 3 %to 10%
  - → Minor merger are at least three times as frequent as major mergers (also Lotz+2011)
  - → Minor merger frequency is only a lower limit due to strong impact of SB dimming

- Theoretical simulations (SAM and hydro) of merger rates show a factor of 5 dispersion in their absolute values and bracket data within a factor of two.
- This led to subsequent paper by Hopkins+2010 on order of magnitude uncertainties in theoretical merger rates" !



(Jogee & GEMS team 2009, ApJ)

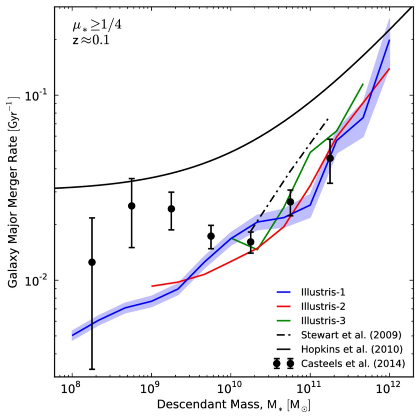
Evol of major merger rate as f(z); obs and theory



- Theoretical simulations (SAM and hydro) of merger rates show a factor of 5 dispersion in their absolute values and bracket data within a factor of two.

(Jogee & GEMS team 2009, ApJ)

galaxy major merger rate as a function of descendant stellar mass



- Theoretical simulations (SAM and hydro) of merger rates show a factor of 5 dispersion in their absolute values and bracket data within a factor of two.

(Jogee & GEMS team 2009, ApJ)

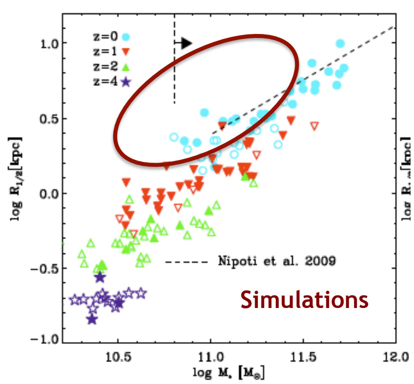
Chemical Evolution

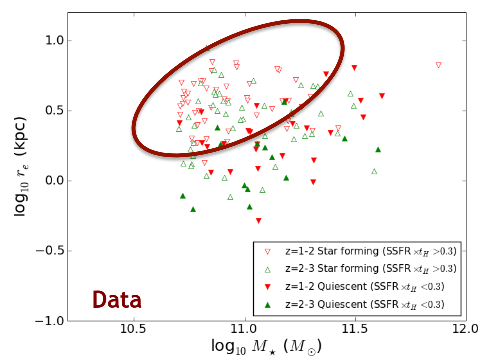
Tensions with LCDM

Can Models Form Large Fraction of z~2 Disky Massive Galaxies?

Cosmologically-motivated hydrodynamical simulations by Oser & Naab (2012) with cold streams, halo accretion, satellite accretion

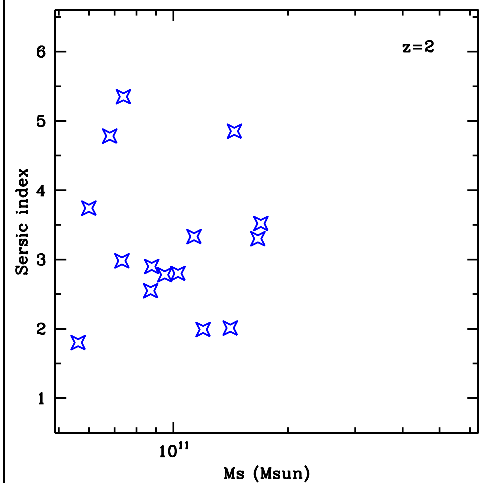
Data from Weinzirl, Jogee & GNS team 2011 + 2014



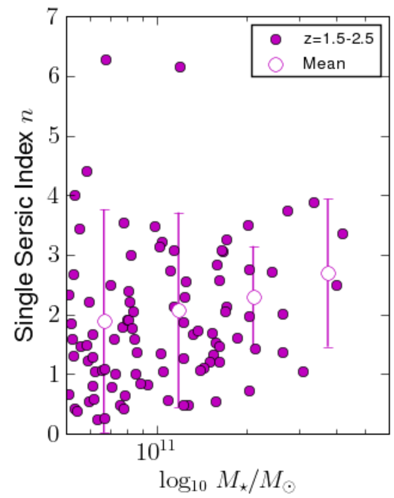


→ simulations fail to produce the large population of extended massive disk galaxies present 10 Gyr ago although they produce the compact systems well. This is reminiscent of the angular momentum problem

Can Models Form Large Fraction of z~2 Disky Massive Galaxies?



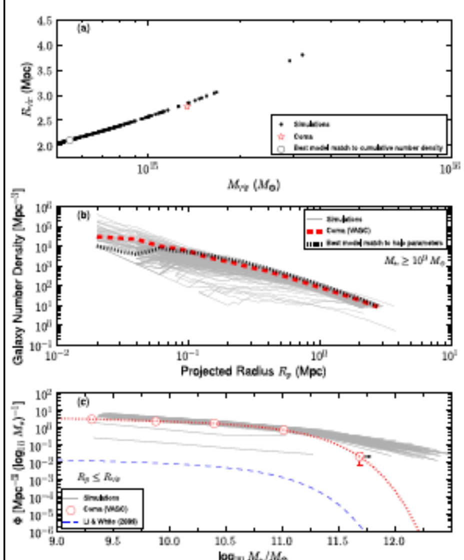
Simulations
(Ceverino+ 2011; Ceverino & Dekel in prep)



Data from NIC3/H GNS survey
(Weinzirl, Jogee,Conselice + 2011, ApJ, 743)

→ Simulations vastly underpredict the fraction of massive disky (n<2) galaxies at z~2

Need Improved Simulations of Galaxies in Clusters



The Coma cluster is often used as a benchmark for a nearby rich galaxy cluster. Yet, our comparison of its properties with a wide set of theoretical SAM models show that

→ No single SAM model can simultaneously match its main global properties (halo mass/ size, galaxy number density, galaxy stellar mass function)

→ SAMS have too many red massive galaxies.

(Weinzirl Jogee, Neistein + Coma Team 2014)

Models used are from Neistein+2010 (combine Millennium DM simulations + baryonic physics)

- Include cold/hot gas accretion, gas cooling, SF and SN feedback, strangulation t~4 Gyr
- Do not include ram pressure/ tidal stripping, AGN feedback, dynamical friction heating

Summary: Galaxy Growth Across Cosmic Time and Environments

Galaxy major mergers were once thought to dominate galaxy growth, but evidence shows more quiescent processes (minor mergers, gas accretion, and secular processes) play a central role:

- Over half of the age of the Universe, among massive galaxies, minor mergers are at least three times as frequent as major mergers, and at most 30% of the cosmic star formation rate density stems from major mergers.
- Structural archeology shows most z~0 massive field spiral galaxies host low-mass disky pseudo-bulges rather than classical bulges. This implies they have experienced no major merger over the last 10 Gyr, consistent with model predictions for field spirals.
- A surprisingly large fraction (>50%) of massive galaxies at early epochs (t=3 Gyr) are disky and star-forming. Cold flows and gas-rich mergers played a key role in their formation.

Theoretical models/simulations face challenges in reproducing the observed galaxy properties in present-day clusters; the correct mix of ultra-compact and extended disky galaxies at early epochs (t=3 Gyr); and the observed number of satellites.

In the next decade, transformational facilities (e.g., GMT, JWST, SKA) will provide a 10-to-100 fold increase in sensitivity, spatial resolution, spectroscopic capabilities, and dat volume: This will revolutionize our understanding of how galaxies grow their dark matter and baryons in a dark Universe.