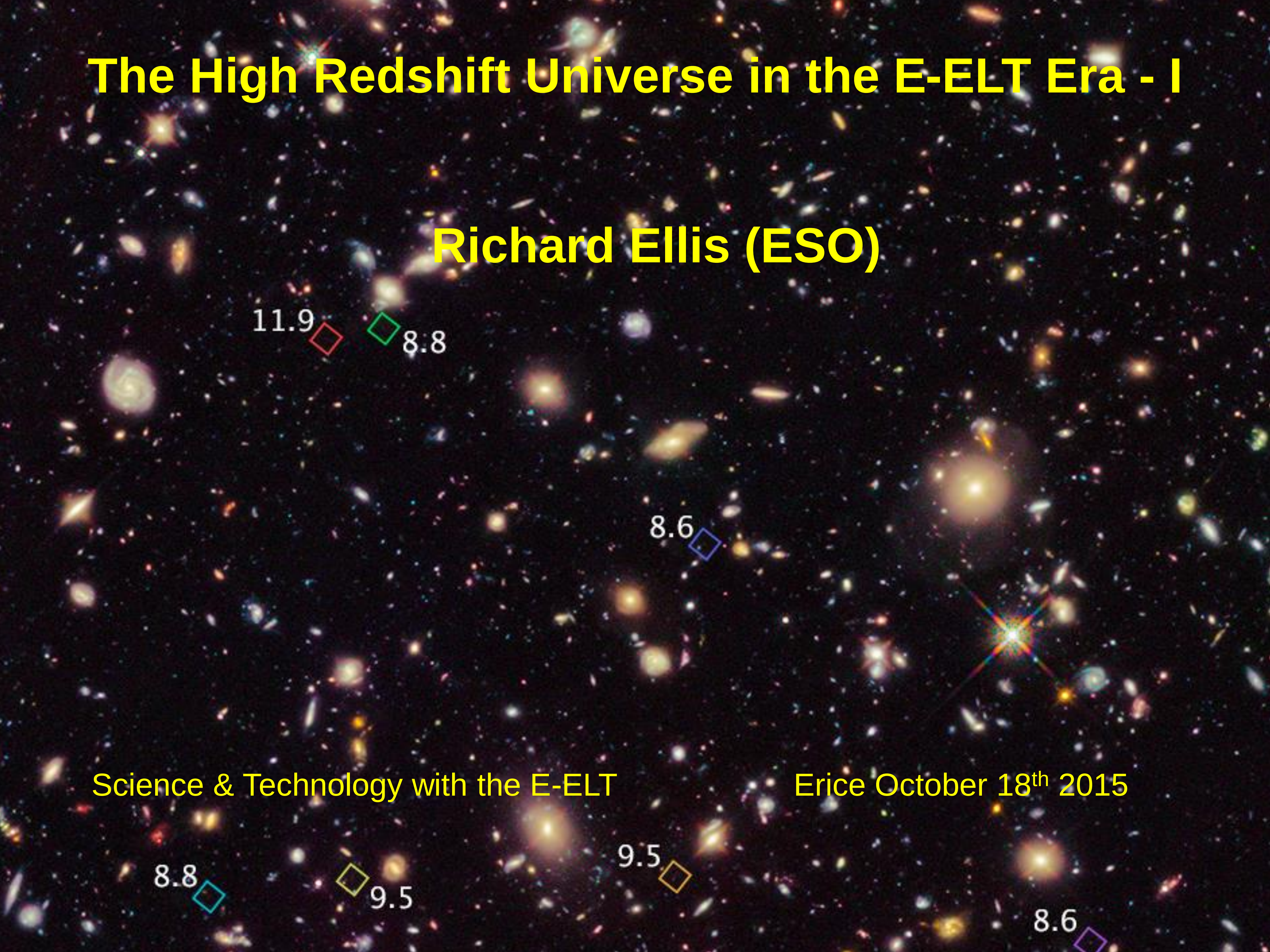
The High Redshift Universe in the E-ELT Era - I

Richard Ellis (ESO)



Science & Technology with the E-ELT

Erice October 18th 2015

Plan

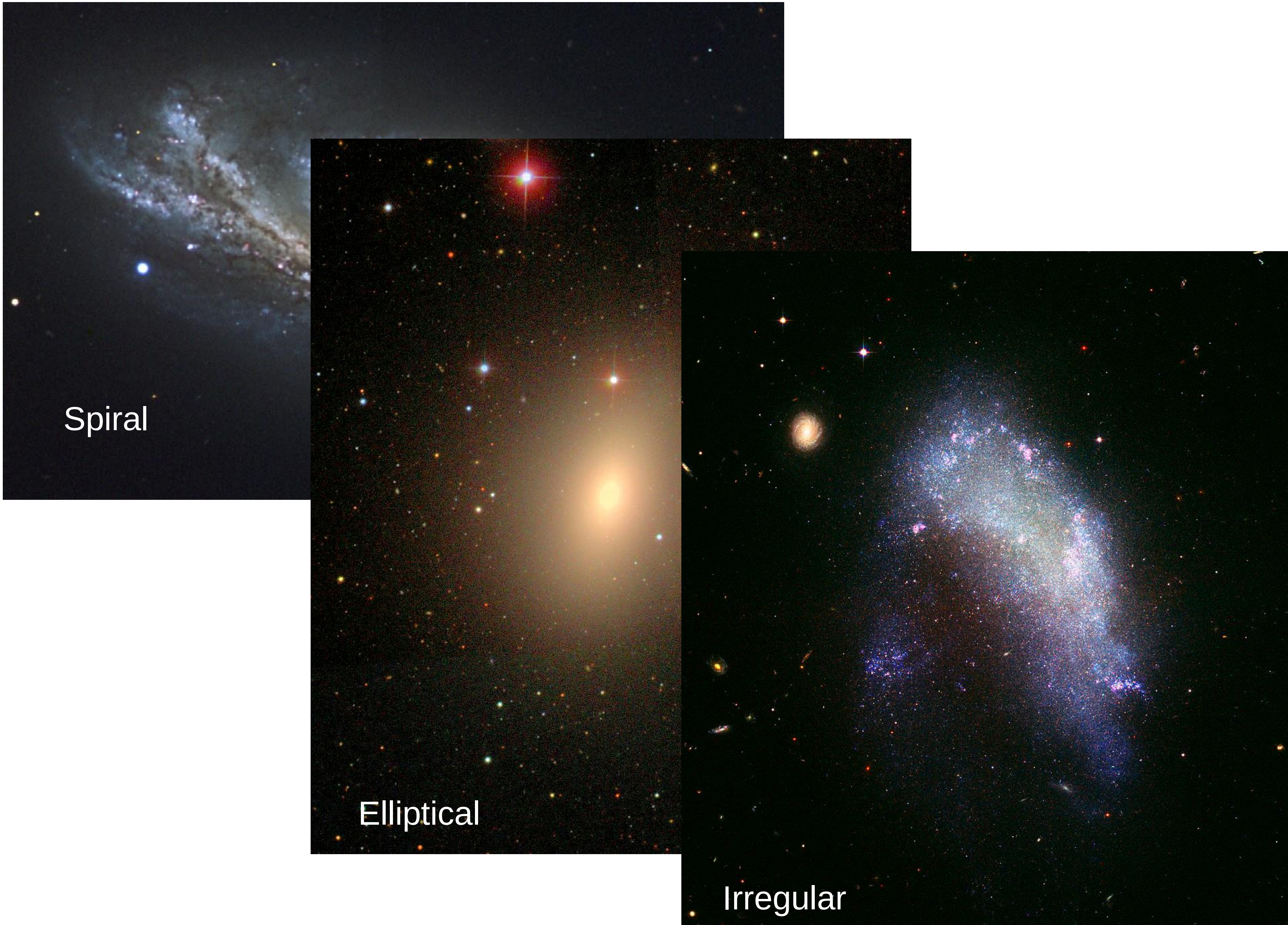
Lecture 1: Key Questions in Galaxy Evolution & Emerging Techniques

- The Hubble Sequence of Galaxies
- Cosmic Star Formation and Stellar Masses
- Theoretical Concepts: Hierarchical Assembly and Feedback
- The History of Disk Galaxies
- The Formation of Quiescent Galaxies
- Summary of Emerging Techniques in Context of E-ELT

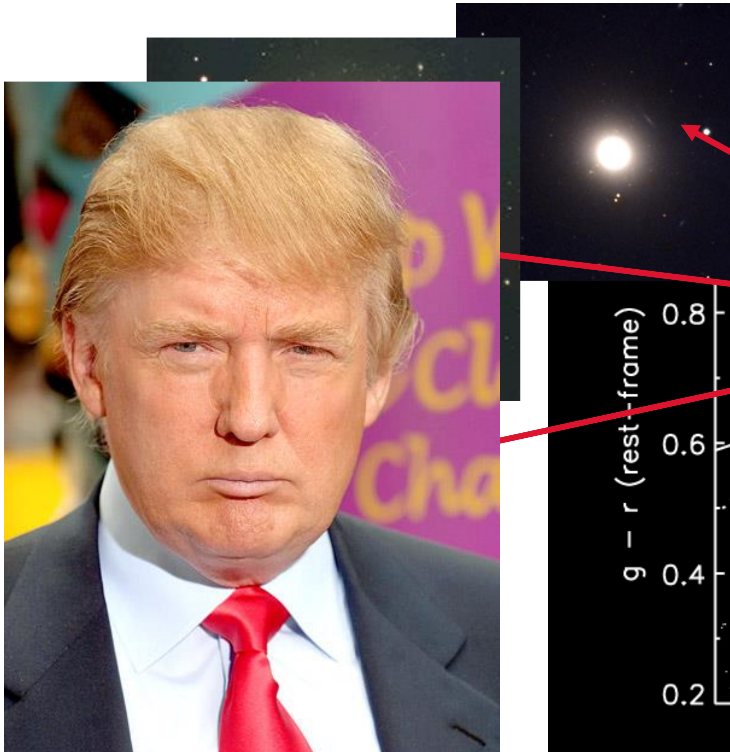
Lecture 2: Galaxies & Reionisation: Finalizing Cosmic History

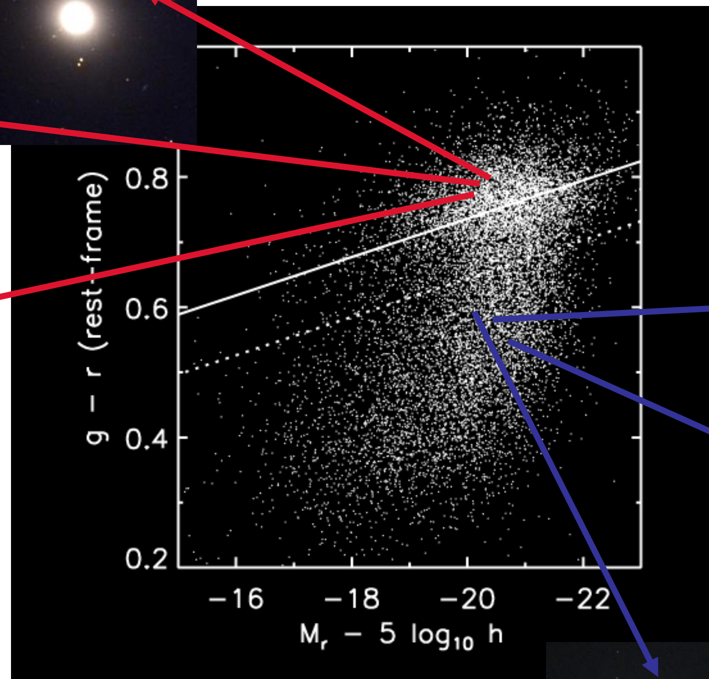
- What is Cosmic Reionisation
- When did Reionisation Occur?
- Were Star-Forming Galaxies Responsible?
- Challenges and Techniques
- JWST – E-ELT synergies

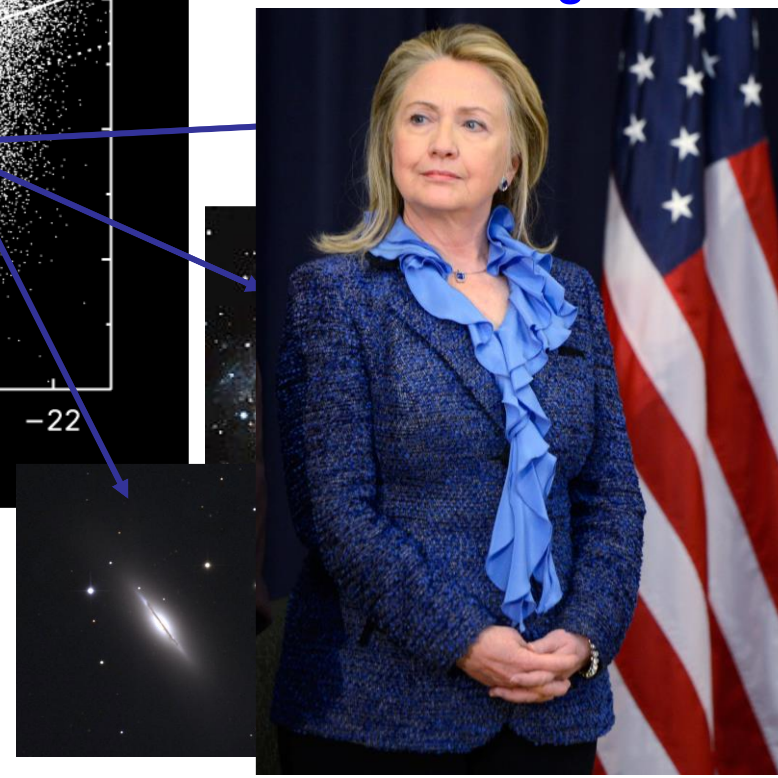
Hubble Sequence - Morphology



Hubble Sequence – Stellar Populations







Star forming
Blue
Late type
Young

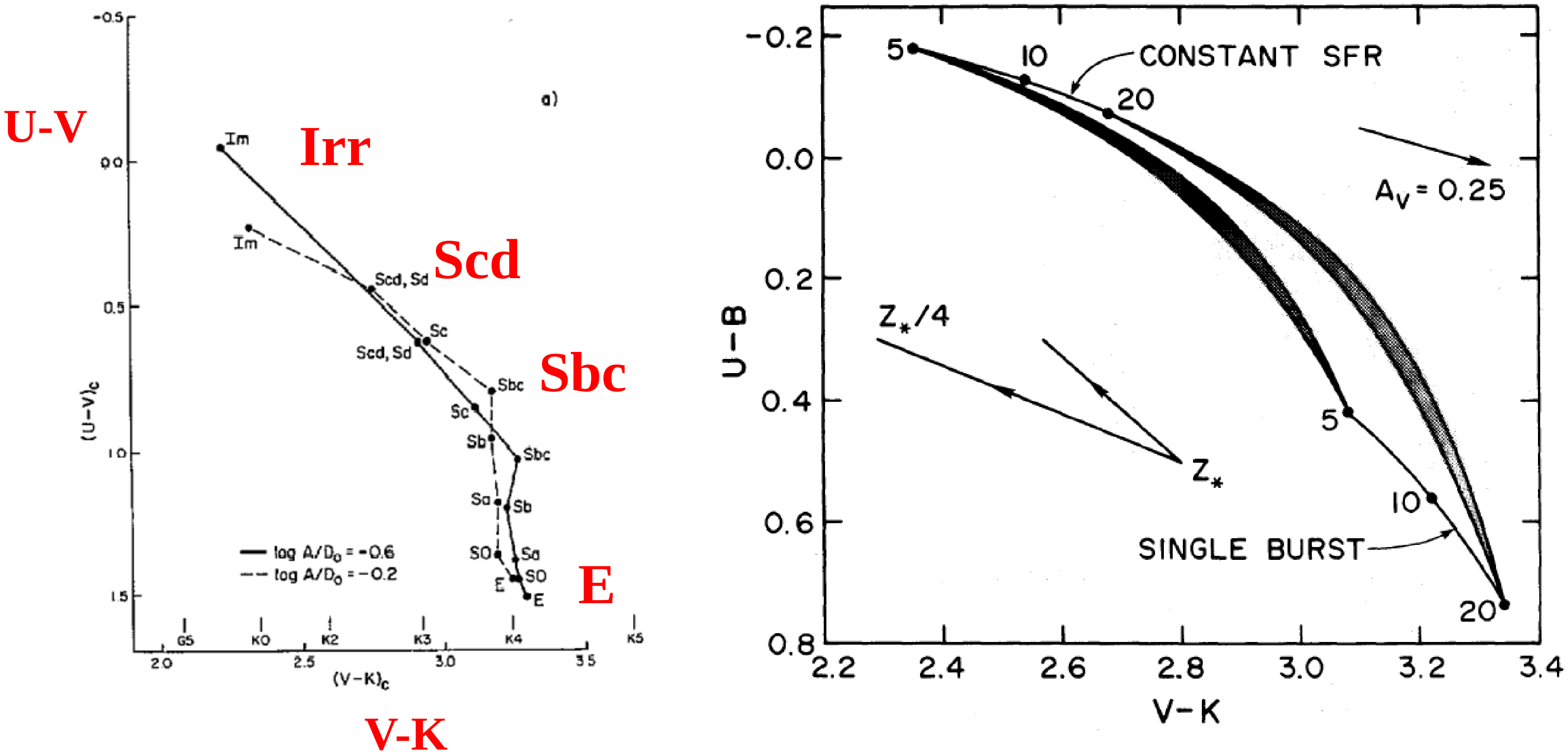
Passive
Red
Early type
Old

Bell et al. 2003

Hubble Sequence - morphology shows dynamically distinct populations

Gas content/integrated colors - different ages and star formation histories

Colors & Star Formation Histories



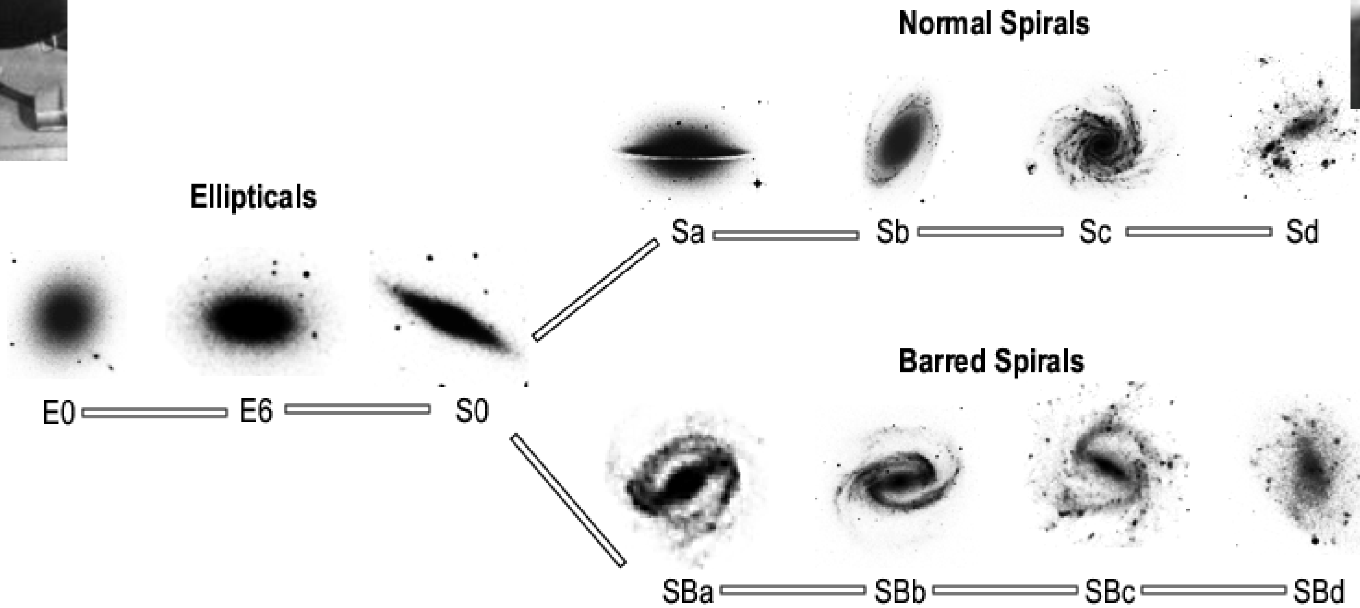
• Ellipticals and bulges – old stellar systems following an initial burst of formation; modest 'monolithic' collapse

• Spiral disks – significant dissipation during collapse, continuous star formation and younger mean stellar age

Tinsley & Danly 1980 Ap J 242, 435

The Hubble Sequence

"..describes a true order among the galaxies, not one imposed by the classifier" (Sandage 1994)



Distinguishes **dynamically distinct** structures:

spirals & S0s – rotating stellar disks

spheroids – ellipsoidal/triaxial systems with anisotropic dispersions

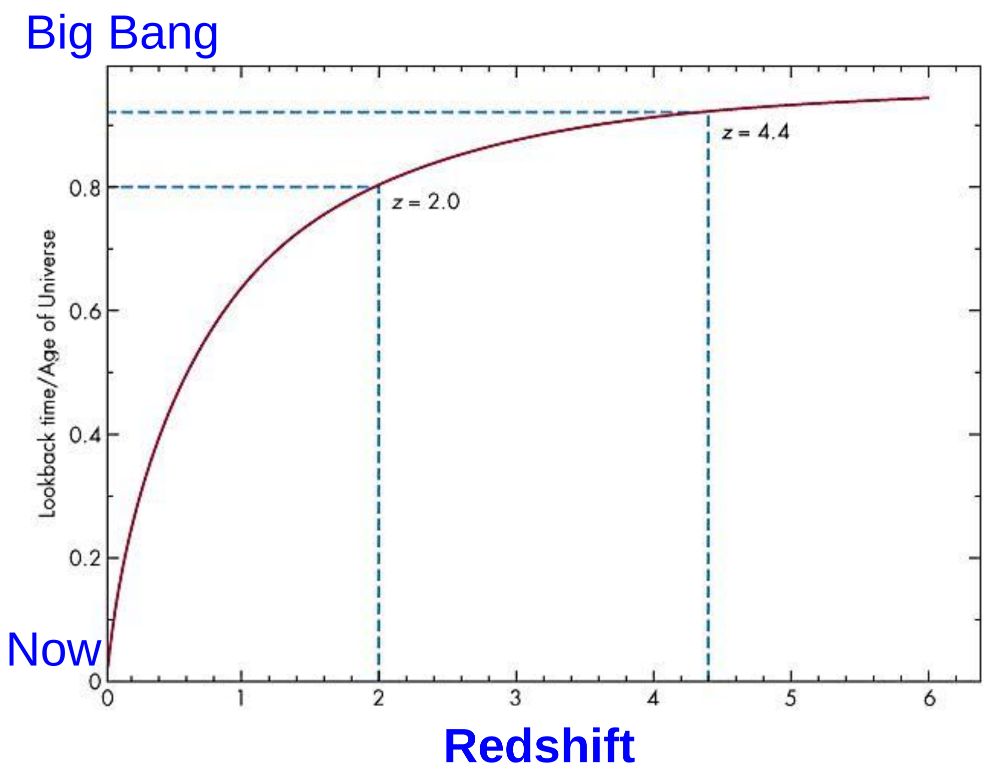
There exist **physical variables** that govern the sequence:

* gas content/integrated color $\rightarrow$ ratio of current to past average star formation rate

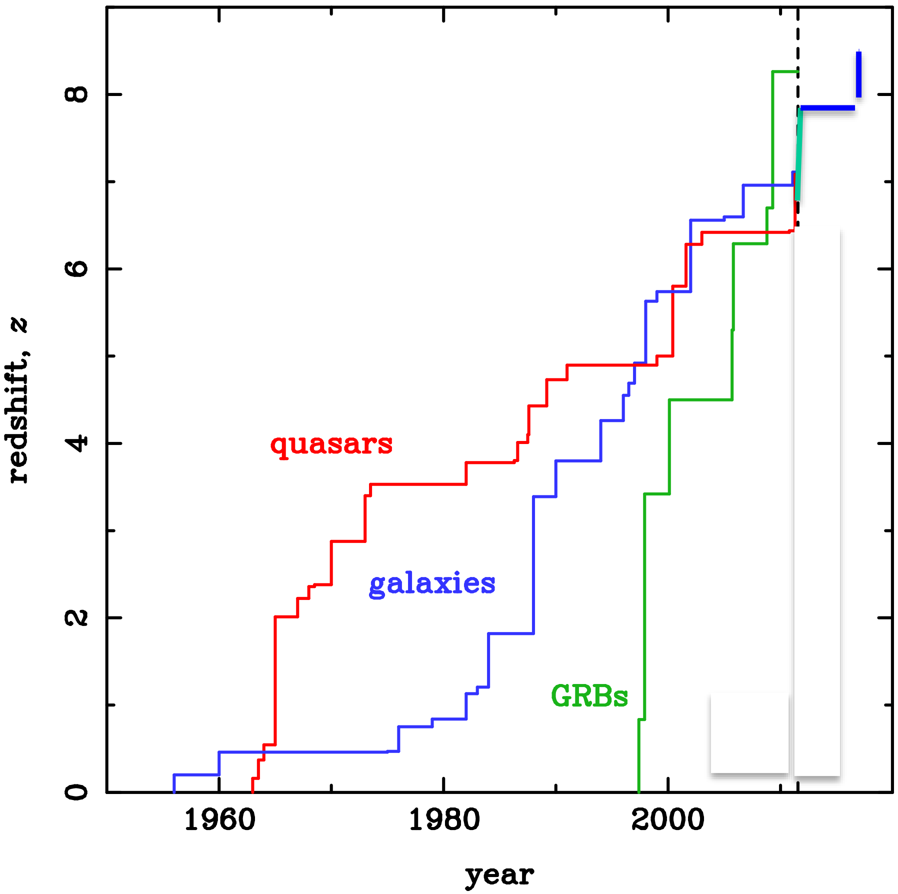
* inner structures $\rightarrow$ bulge/disk ratio

The Unique Advantage of Look-Back Time

Look-back time vs redshift



Most distant object



The challenge is to connect widely-different populations over a significant range in look-back time

Courtesy: Dan Mortlock

Cosmic Star Formation History

Various probes of the global SF rate: ρ_* (z) $M_\odot$ yr^{-1} comoving Mpc^{-3}

- UV continuum (GALEX, Lyman break galaxies)
- Hα and [O II] emission in spectroscopic surveys
- mid-IR dust emission
- 1.4GHz radio emission

No simple `best method': each has pros and cons (dust extinction, sample depth, z range and physical calibration uncertainties)

Each has different time-sensitivity to main sequence activity so if SFR not uniform do not expect same answers for the same sources

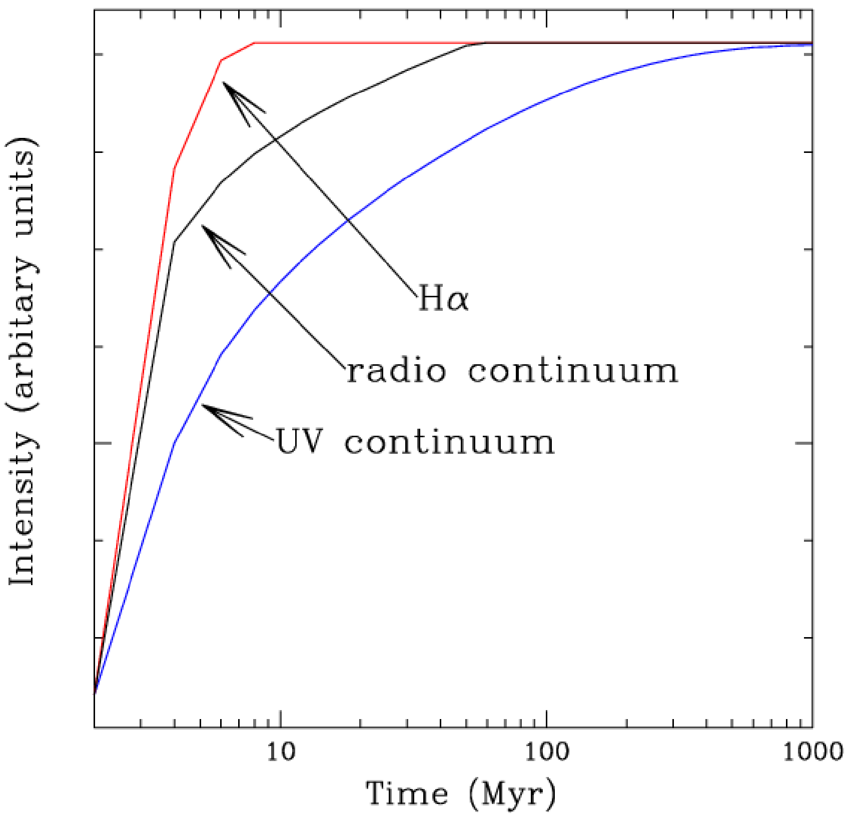
Would expect the integral of the past activity to agree with locally-determined stellar density (Fukugita & Peebles 2004)

Can also determine the stellar growth rate for comparison with the stellar mass assembly history

Recent review: Madau & Dickinson 2014 ARAA 52, 415

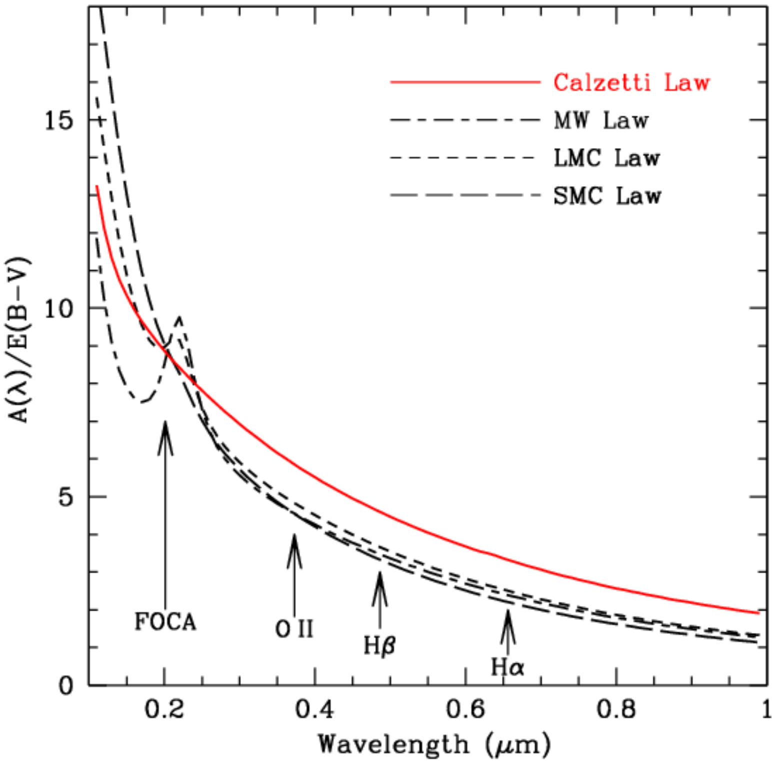
Two Important Uncertainties

Time-dependence of diagnostics



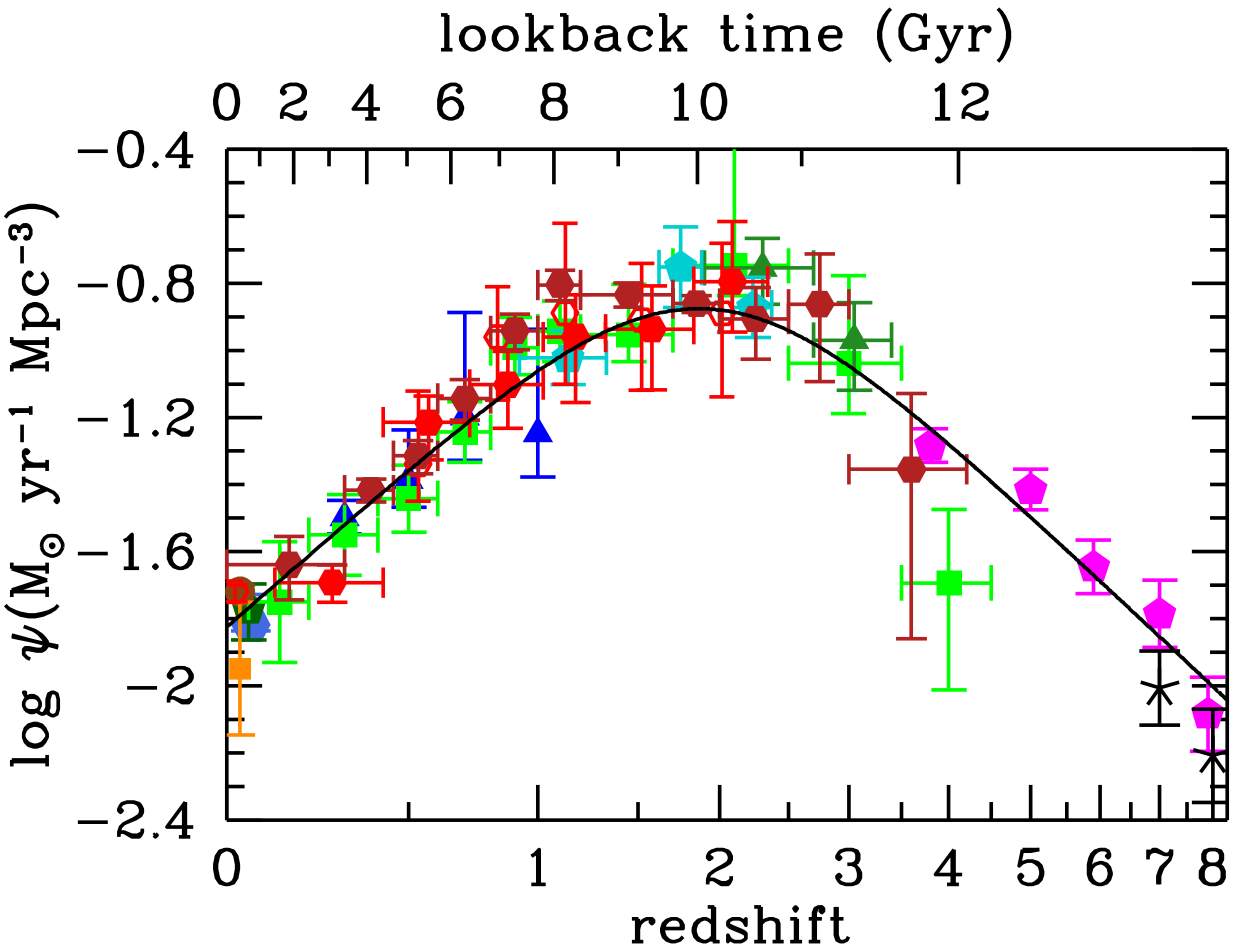
Each SF diagnostic arises from a part of the stellar population whose lifetime is different, so don't expect uniform results if SF is erratic

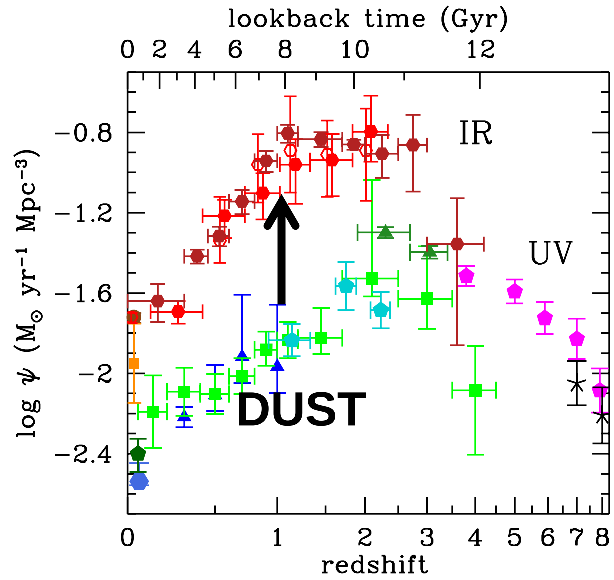
Dust extinction



Dust extinction clearly affects UV and optical diagnostics but the correction may itself be redshift or environmentally-dependent

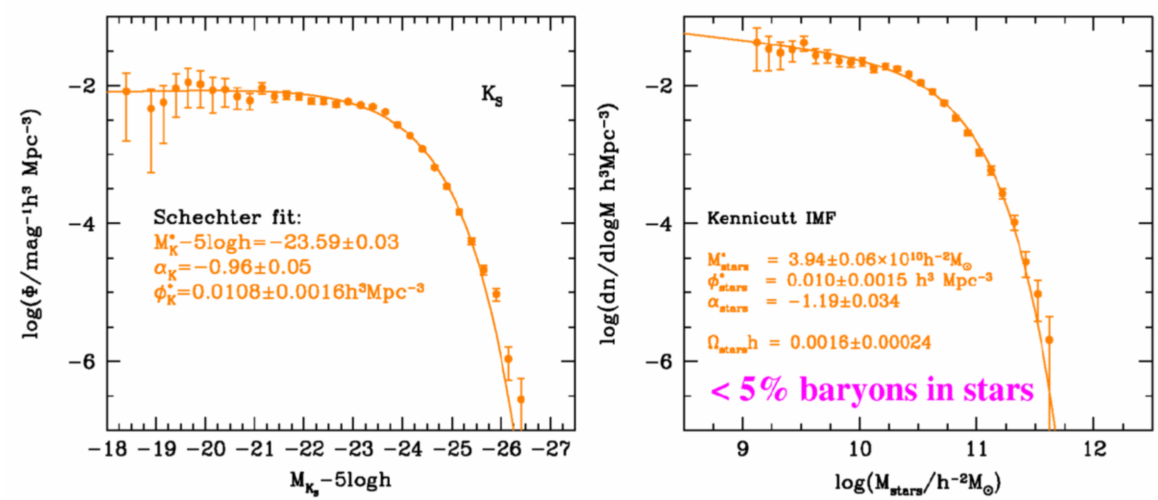
Cosmic Star Formation History





Madau & Dickinson 2014 ARAA 52, 415

Local Inventory of Stars



Stellar density: derives from **local infrared LF, Φ (L)** scaled by a **mean mass/light ratio (M/L_K)** which depends on initial mass function

Useful stellar density is that corrected for **fractional loss R of stellar material due to winds & SNe**: this should be integral of past SF history (e.g. R~0.28 for Salpeter IMF)

Cole et al find Ω_{stars} h = 0.0027 ± 0.00027; M/L_K = 1.32 (Salpeter)

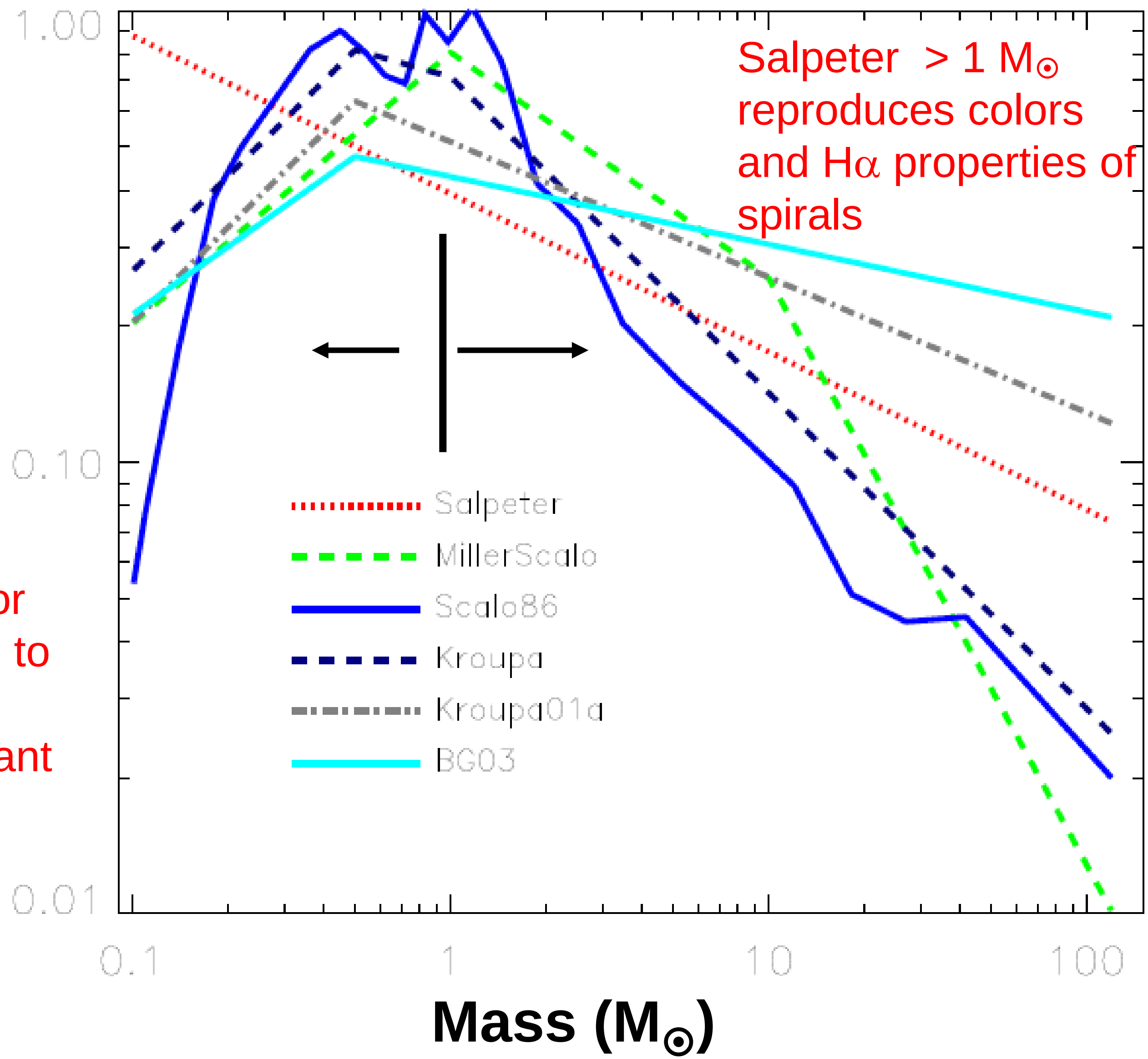
Fukugita & Peebles: Ω_{stars} h = 0.0027 ± 0.0005 (5% in brown dwarfs)

NB: < 6% of baryons are in stars!

Fukugita & Peebles 2004 Ap J 616, 643; Cole et al 2001 MNRAS 326, 255

Stellar Initial Mass Functions

Mass fraction per log mass bin

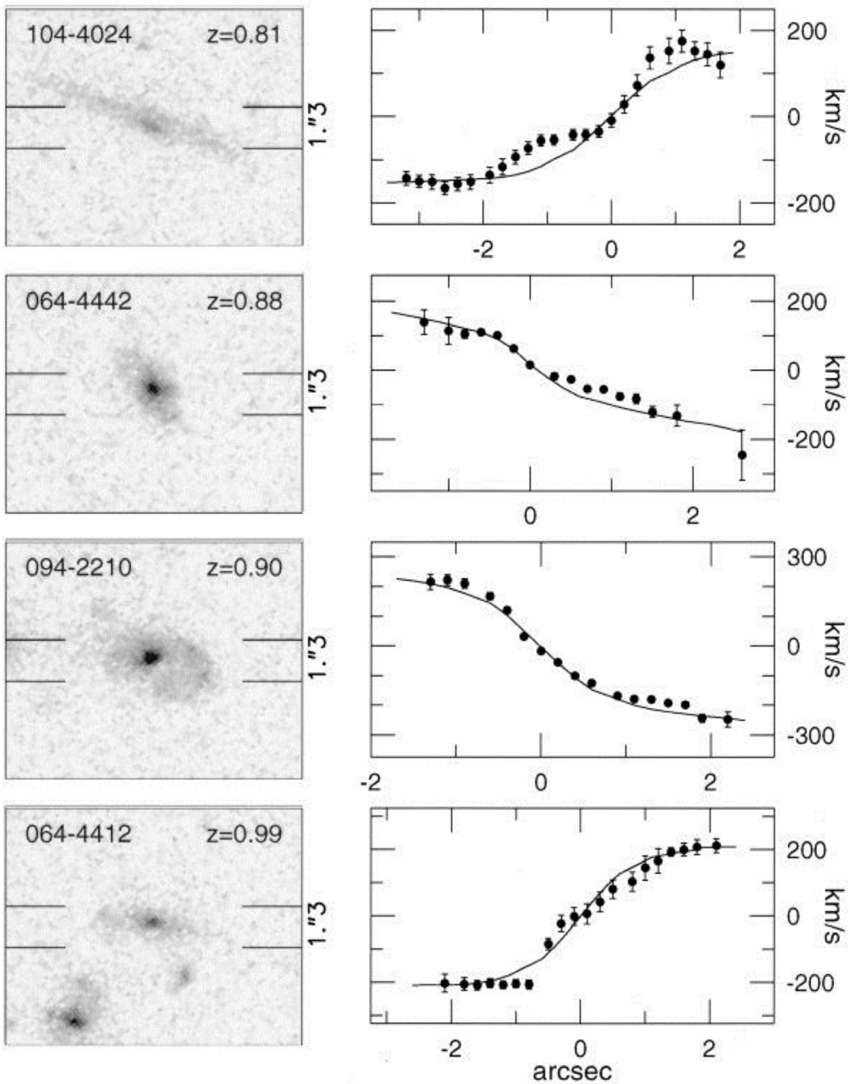


IMF < 1 M$_\odot$ makes minor contribution to light but is very important for mass inventory

Distant Galaxy Masses: what are the options?

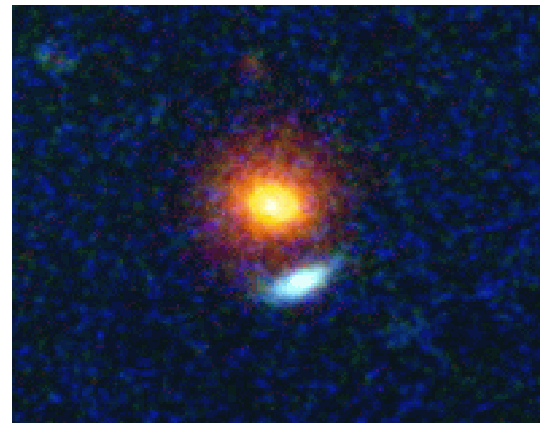
Dynamics: rotation & dispersions

(only for restricted populations)



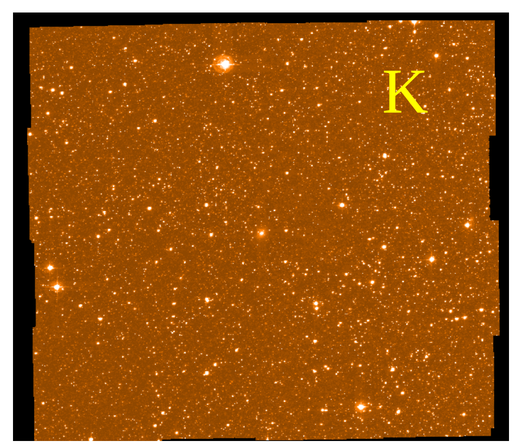
Gravitational lensing

(limited z ranges)



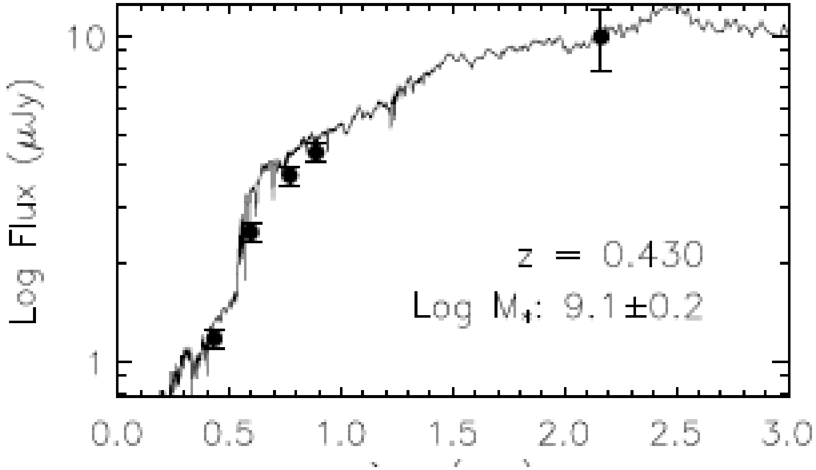
SED-based stellar masses

(universally effective 0<z<6)

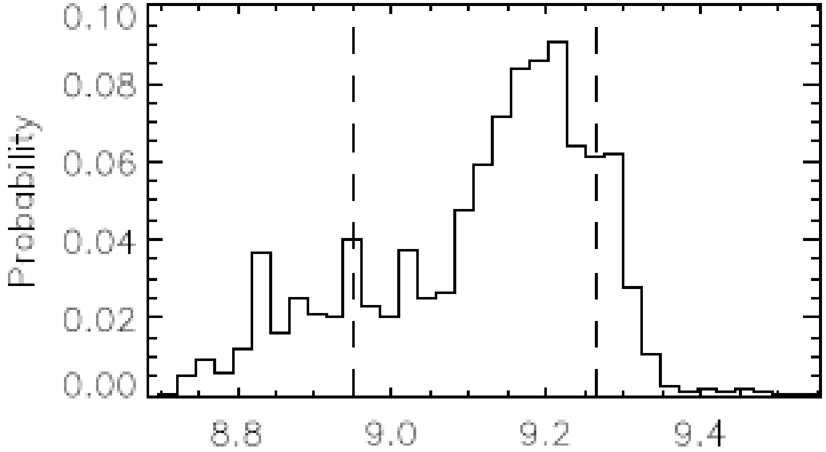


Stellar Masses from Multicolor Photometry

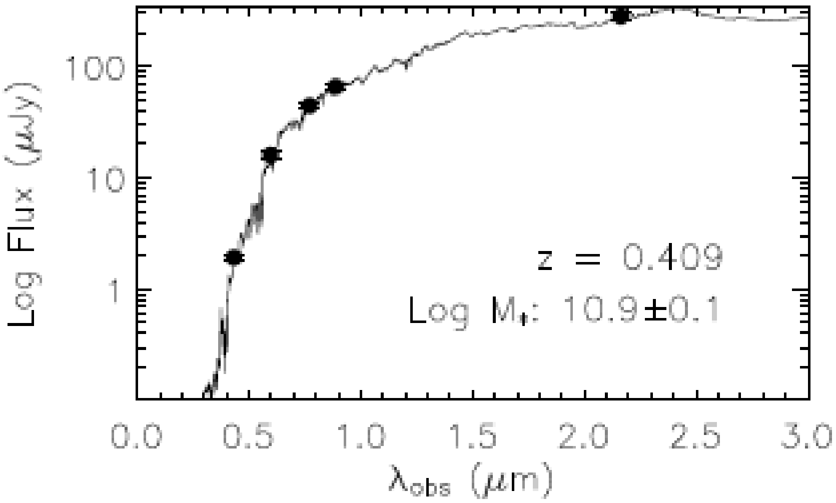
spectral energy distribution

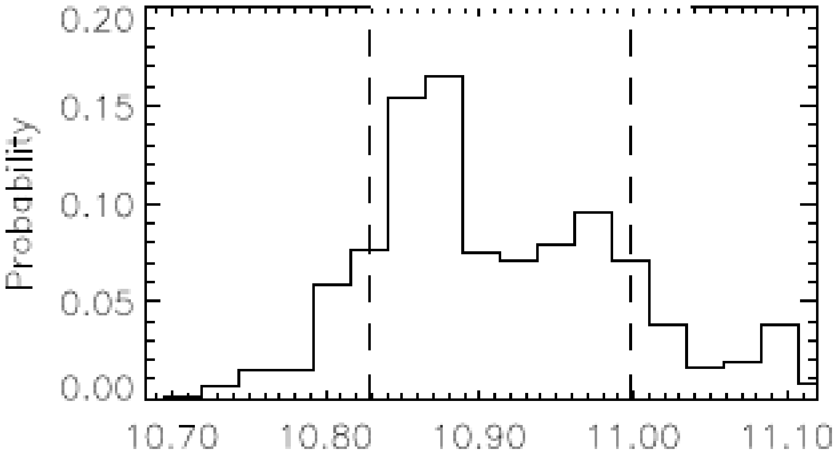


Mass likelihood function



log mass

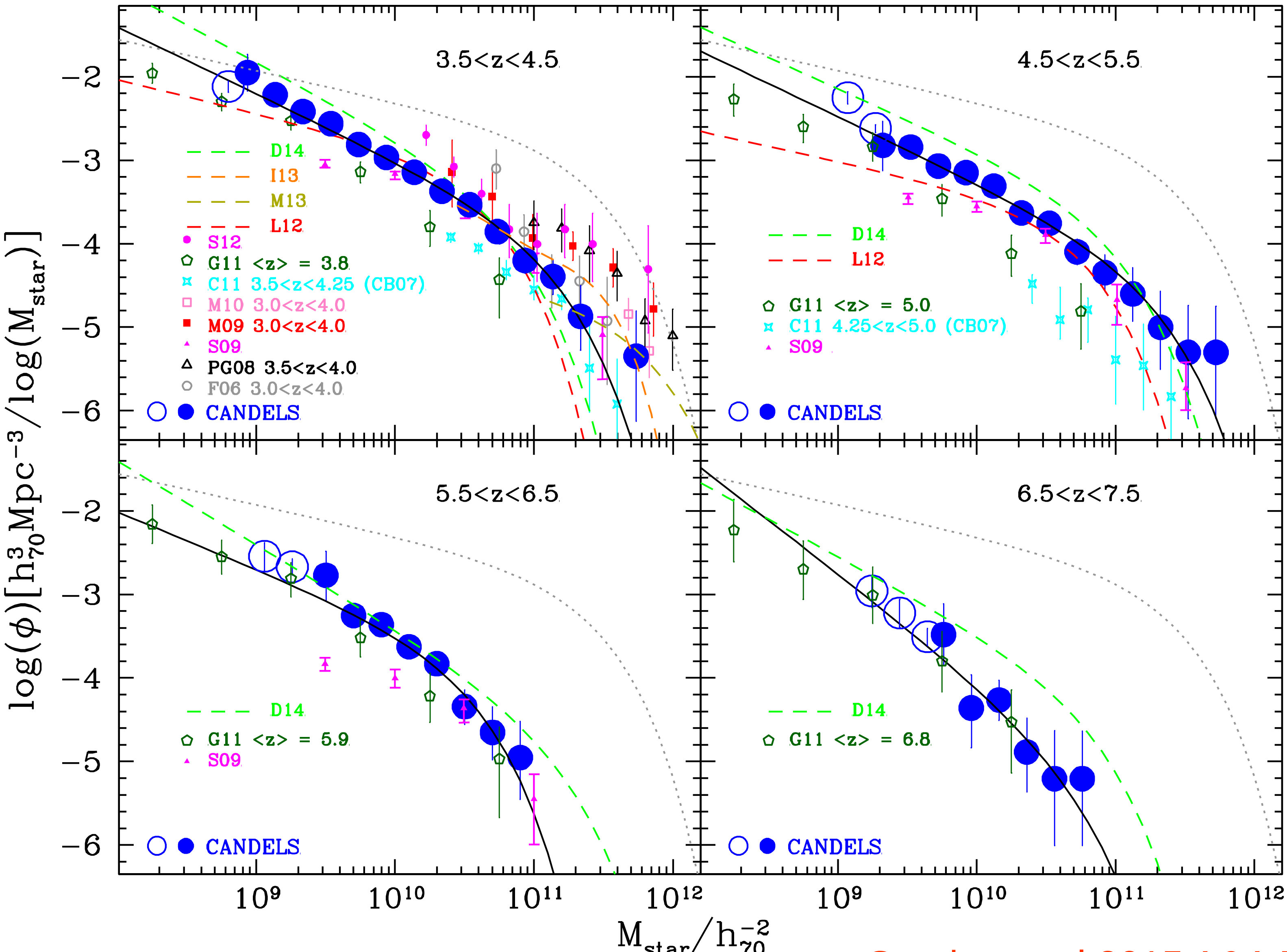




log mass

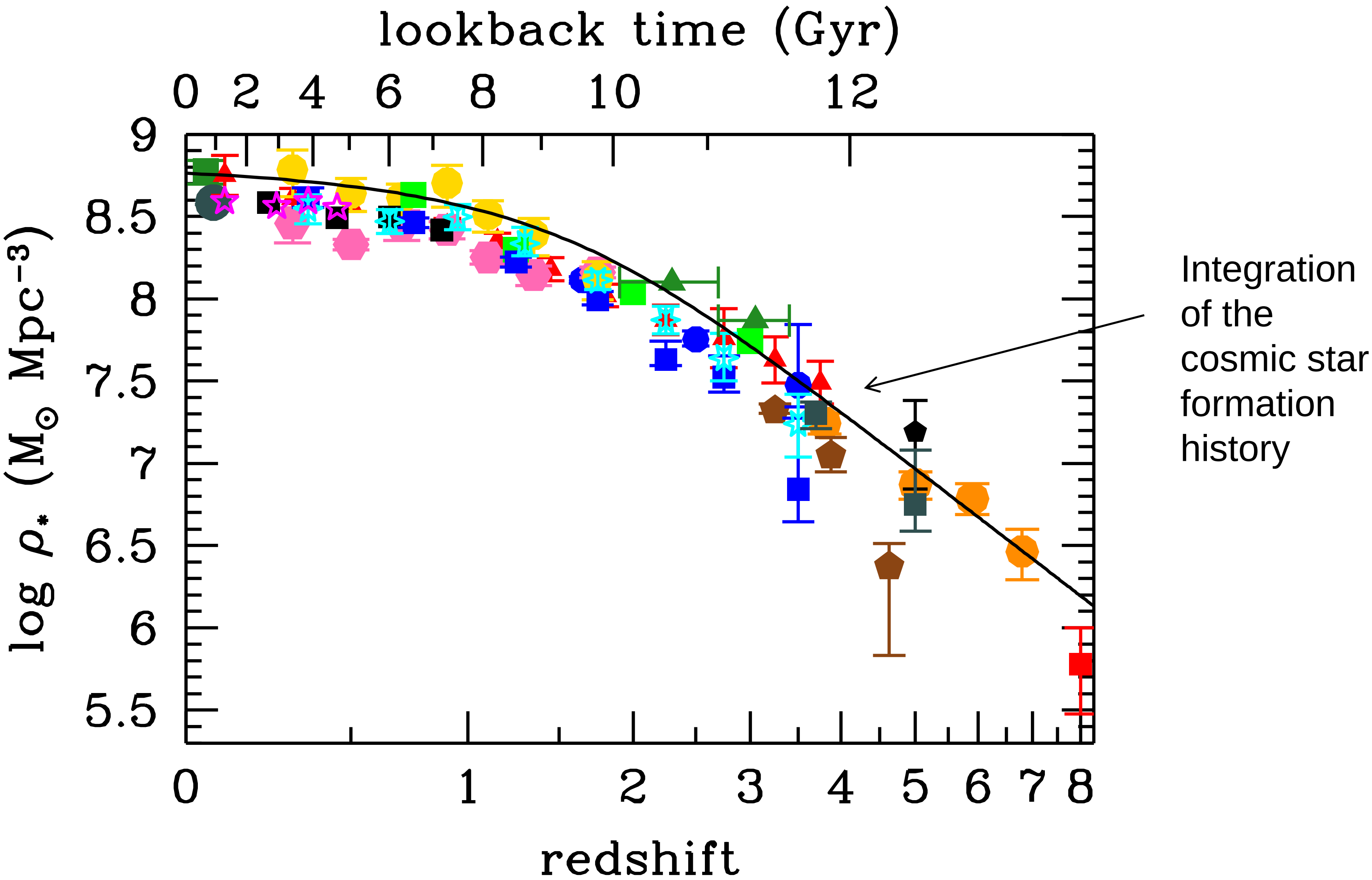
SED → $(M/L)_K$ Redshift → L_K hence stellar mass M

Recent Stellar Mass Functions



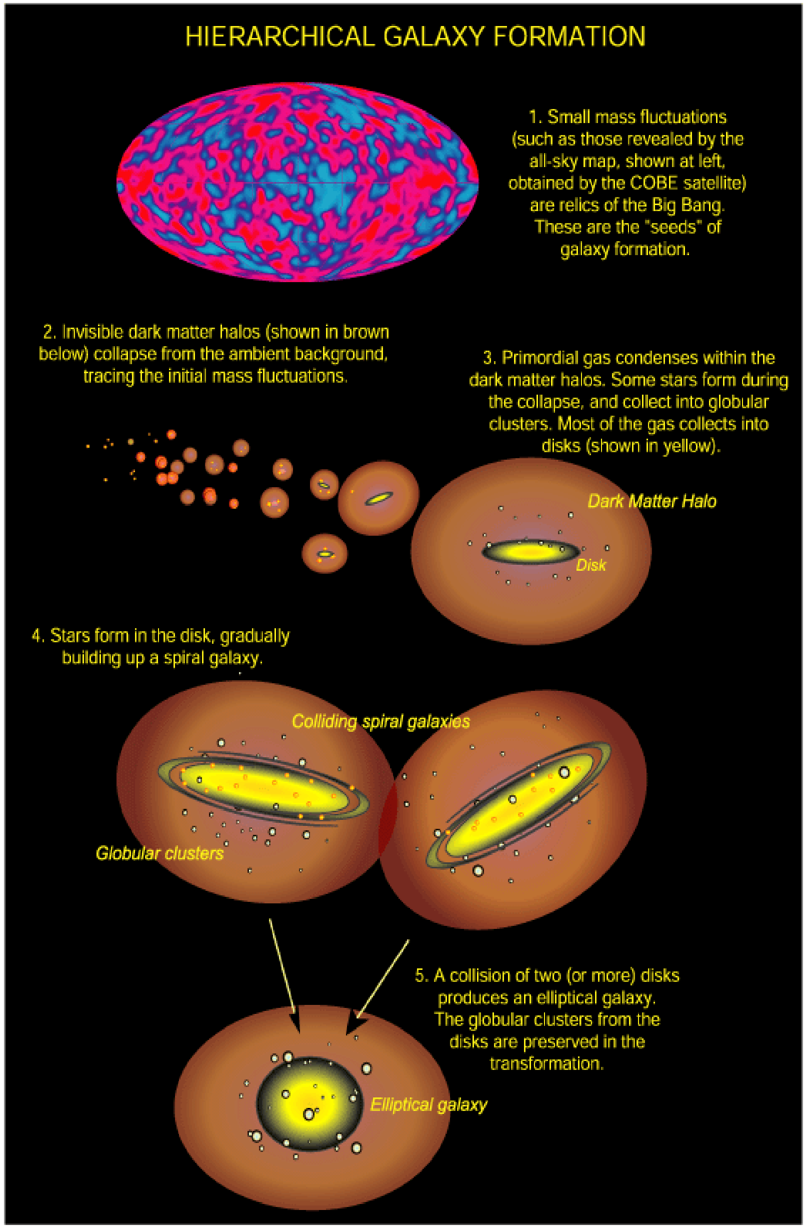
Grazian et al 2015 A&A 575, 96

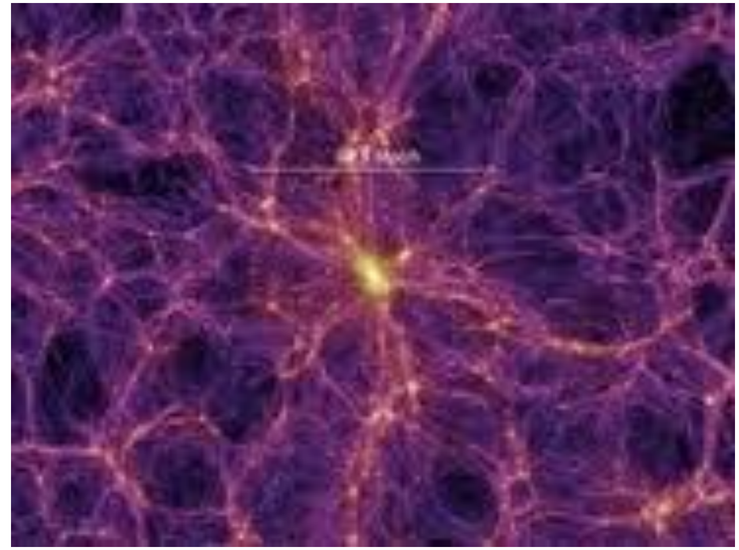
Evolution of the Stellar Mass Density



Madau & Dickinson 2014 ARAA 52, 415

Dark Matter & Galaxy Formation - I



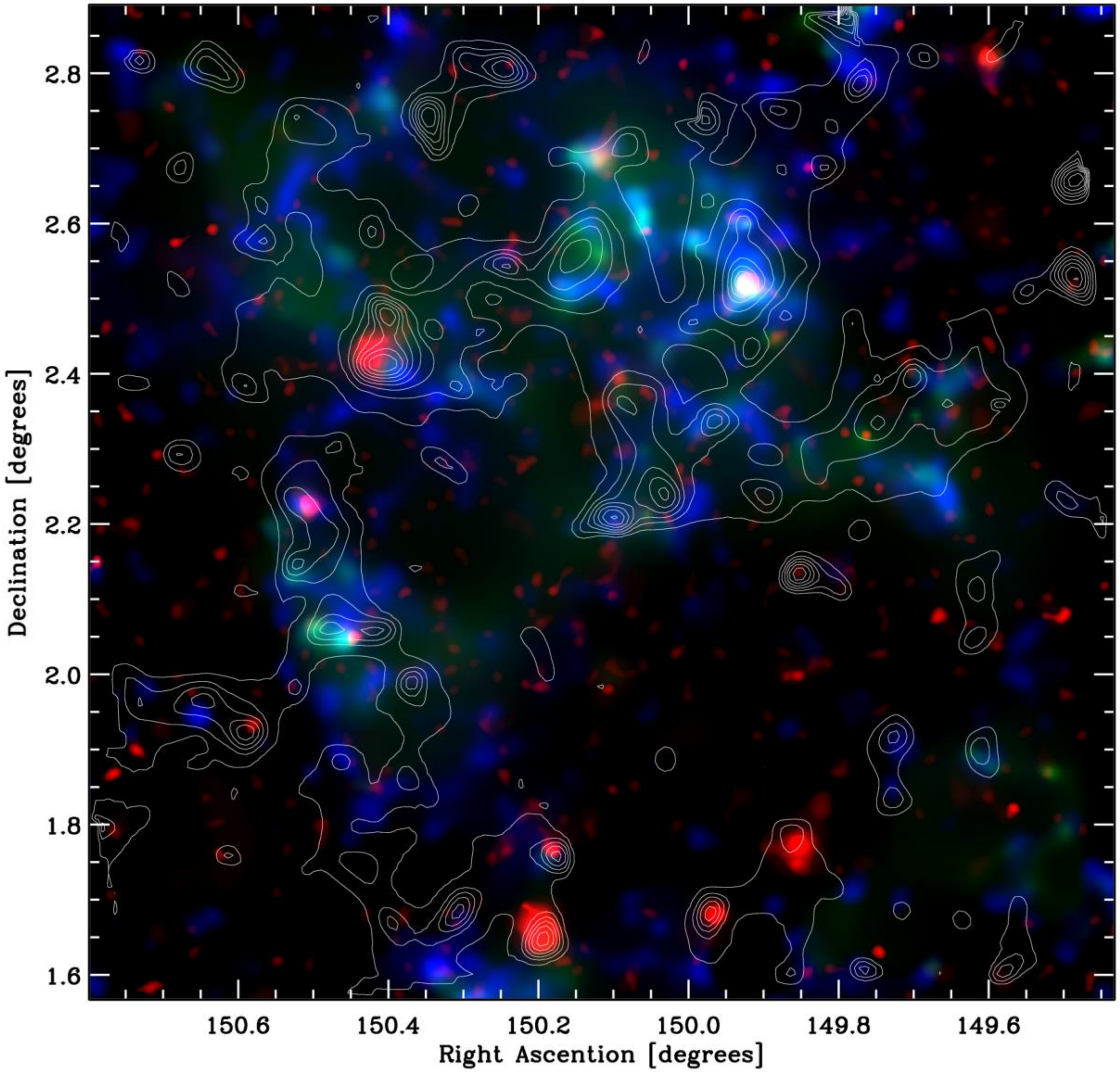


Numerical simulations based on a dominant gravitating component of cold (non-interacting) dark matter reproduces the large scale distribution of present-day galaxies (as probed by surveys such as SDSS and 2dF)

The theory successfully predicted an extended period of galaxy growth where evolution is governed by hierarchical merger of DM halos.

Springel et al 2005 Nature 435, 629

Dark Matter and Galaxy Formation - II



Wide field imaging with HST in the COSMOS field enabled the first weak lensing maps of how the DM is distributed.

It emerges the DM is indeed co-located with the baryons (as traced by stellar mass and X-ray emitting gas).

Clear evidence that DM is the `scaffolding' for the assembly of galaxies and larger structures

Massey et al 2007 Nature 445, 286

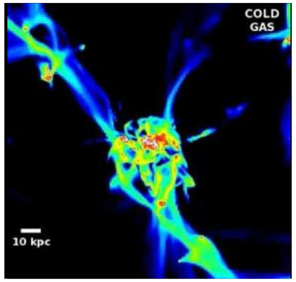
Where Next?

- Modulo a few uncertain assumptions (dust, IMF, incompleteness), we have a good global picture of the history of star formation and stellar mass assembly

- Moreover, galaxy assembly driven by the hierarchical merger of dark matter halos correctly predicted this extended mode of formation

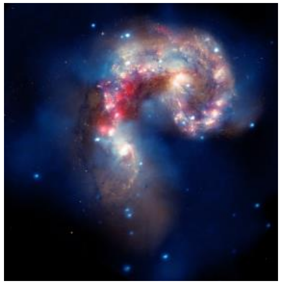
- However, by integrating over the entire population, we have not accounted for the diversity of the Hubble sequence

- Two problems showed how naïve our early dark matter models were in explaining the evolution and present properties of galaxies: baryonic physics is just as important



Accretion of cold gas

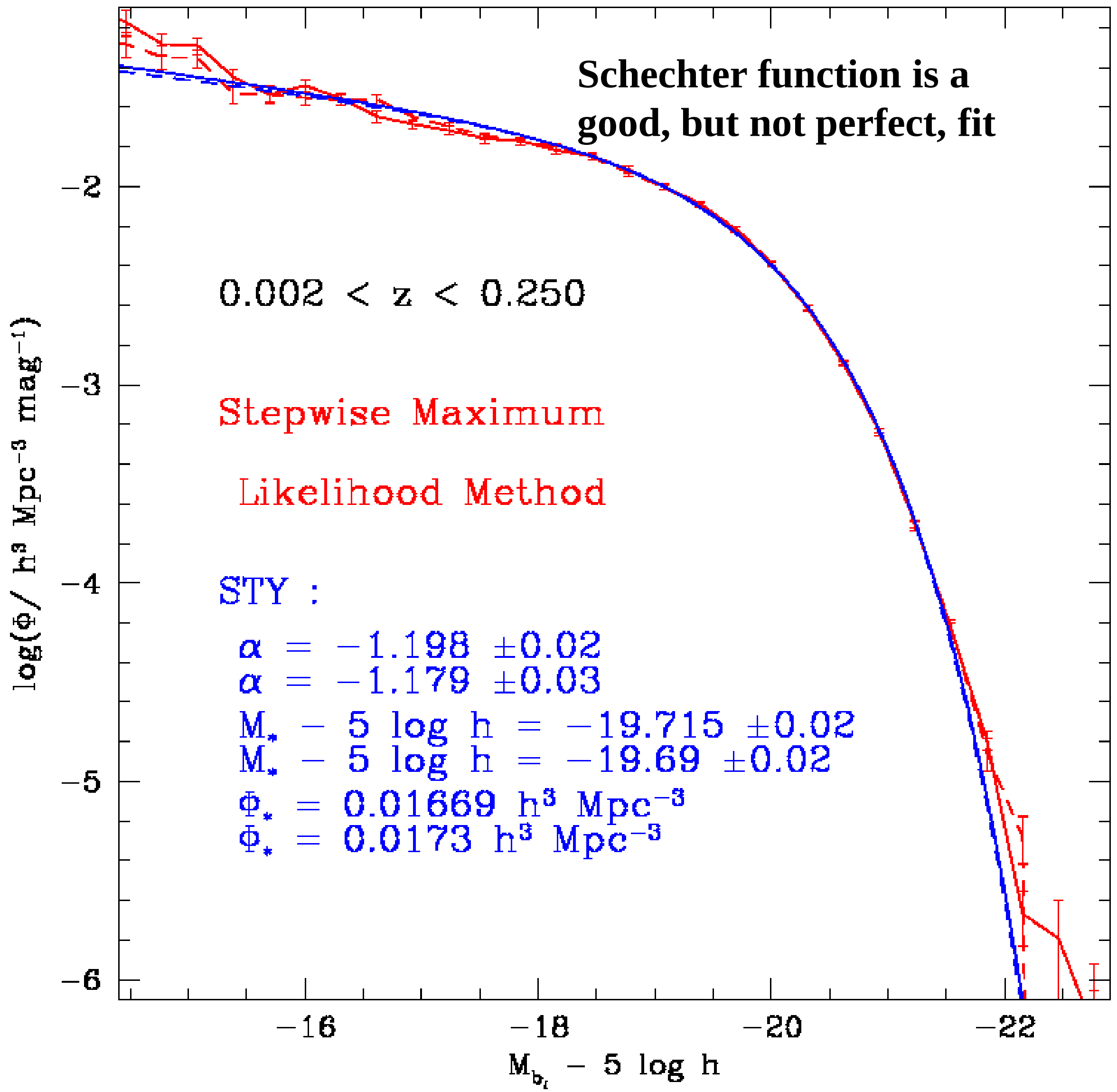
Outflows from energetic events



Mergers

- This motivates the need to move to a higher level of detail to examine the detailed history of star-forming and quiescent (non star-forming) galaxies

Issue #1 – The Local Luminosity Function

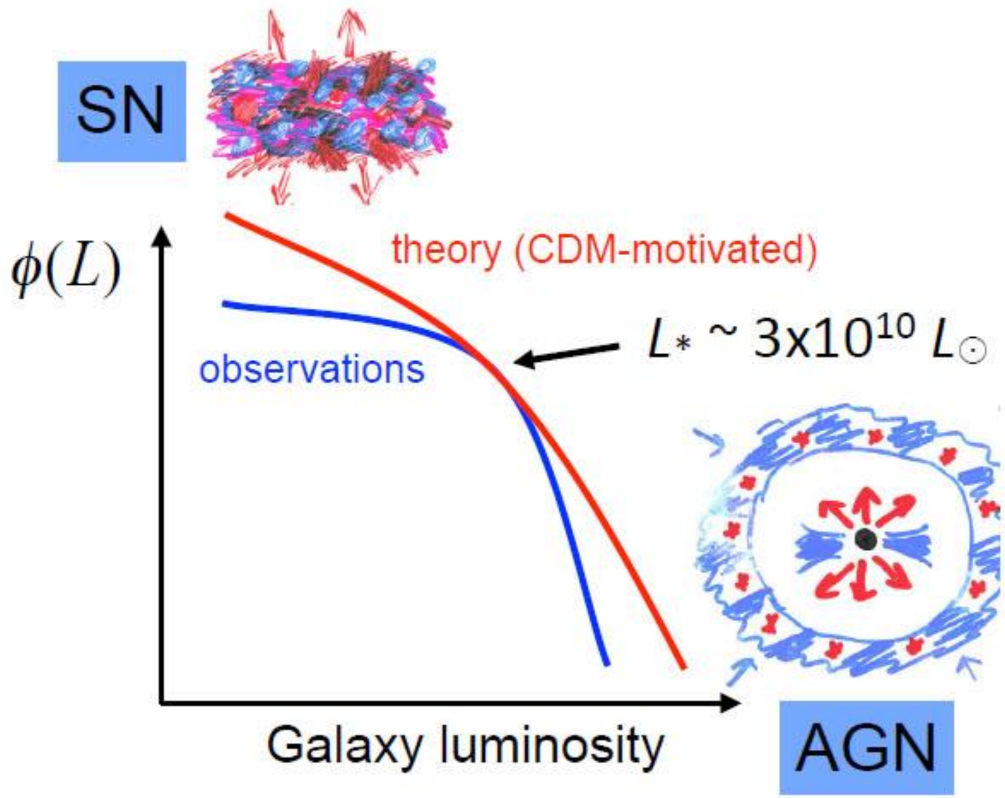


2dF Galaxy Redshift Survey N vs S   Norberg et al (2002) MN 336, 907

Galaxy Formation in CDM – Need Feedback

Semi-analytical models:

Numerical recipe for introducing baryons into DM N-body simulations and predicting observations using prescriptive methods for star formation & assembly. Over-produces luminous & feeble galaxies



Classic papers:

- Kauffmann et al 1993 MNRAS 264, 201
- Somerville & Primack 1999 MNRAS 310, 1087
- Cole et al 2000 MNRAS 319, 168

Feedback modes discussed by:

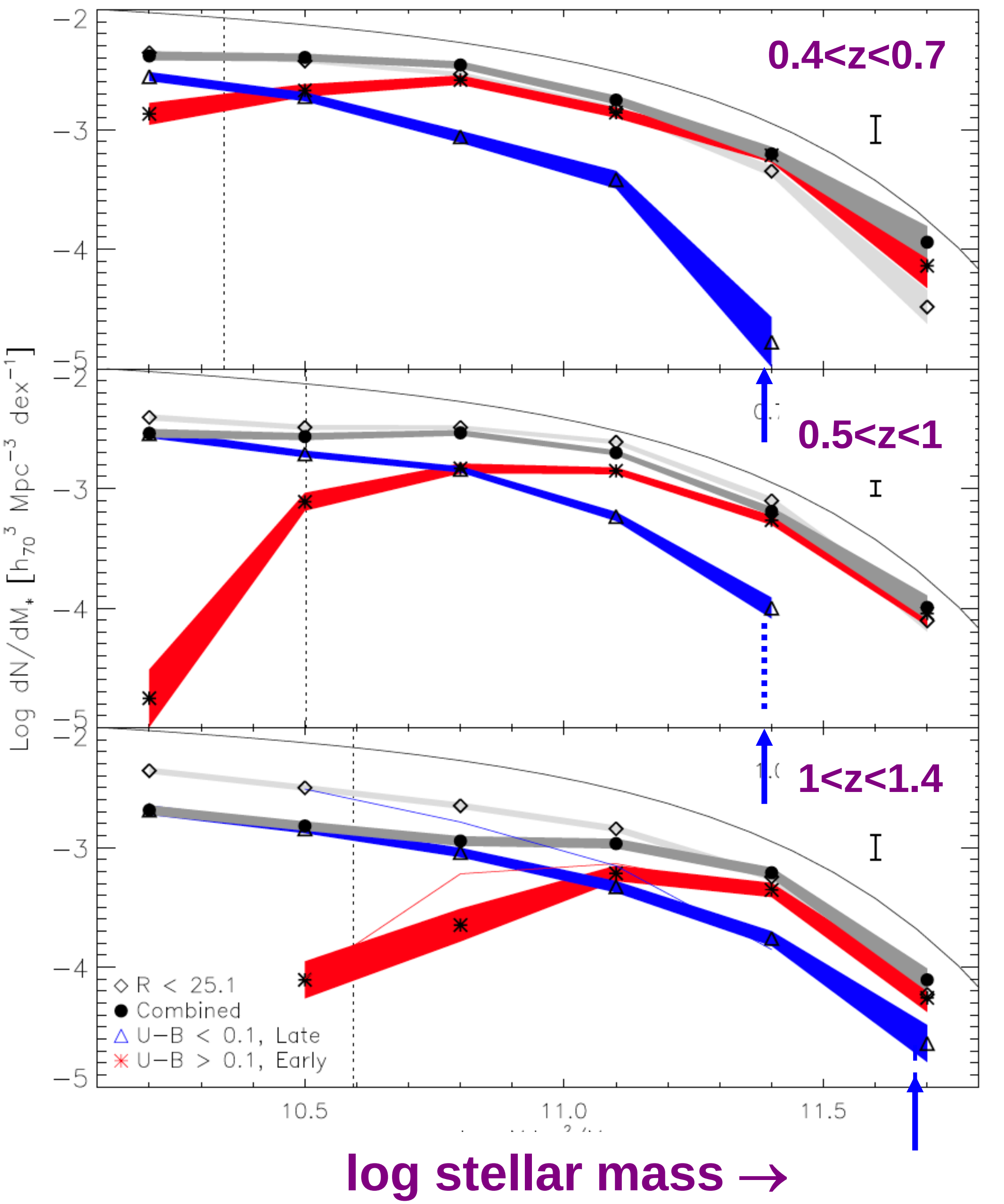
Benson et al (2003) Ap J 599, 38

Croton et al (2006) MNRAS 365, 11

De Lucia et al (2006) MNRAS 366, 499

Issue #2: `Downsizing'

- Stellar masses from Palomar K-band photometry for a large (8000g) spectroscopic sample (Keck DEEP2)
- Massive galaxy number density largely unchanged since z~1 whereas much growth in lower mass systems (`anti-hierarchical' behaviour or `downsizing')
- Using rest-frame U-B color as a SF discriminant, stellar mass functions reveal a threshold stellar mass above which SF is somehow quenched



Bundy et al Ap J 651, 120 (2006)

High Redshift Galaxy Populations

Can broadly break into 3 useful classes:

1. Lyman break galaxies (LBGs): colour-selected star-forming systems whose rest-frame UV luminosities imply SFRs ~10-100 $M_\odot$ yr^{-1}

   reviews: Giavalisco 2002 ARAA 40,579; Shapley et al 2011 ARAA 49, 525

2. Passive red galaxies: discovered later with IR detectors and subsequently confirmed to be quiescent with minimal SF; many are massive and surprisingly compact ("red nuggets")

   reviews: Renzini 2006 ARAA 44, 141

2. Sub-millimetre galaxies: located via intense redshifted dust emission whose negative k-correction offers visibility to very high z; thought to be transient with SFRs ~100-1000 $M_\odot$ yr^{-1}

   review: Lutz 2014 ARAA 52, 373

Key challenge: how to connect these populations into a coherent evolutionary story

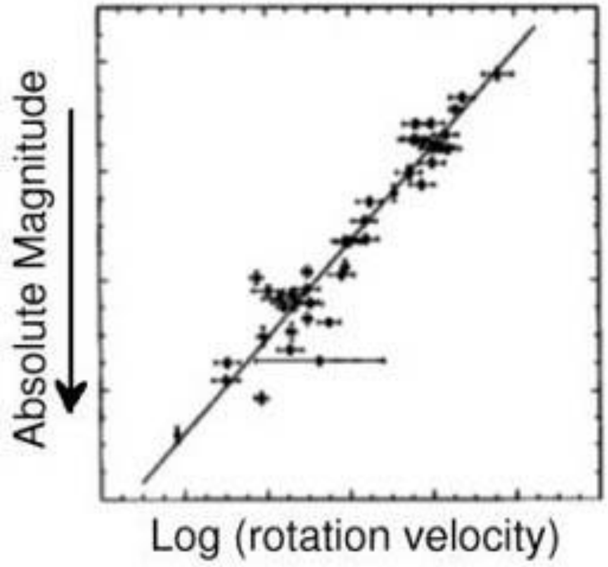
Evolutionary History of Disk Galaxies

Key questions:

1. When did rotating disks become established?

2. What governs star formation: infall of cold gas c.f. outflows from energetic events (AGN, SNe)?

Tools: Resolved kinematics and metallicities



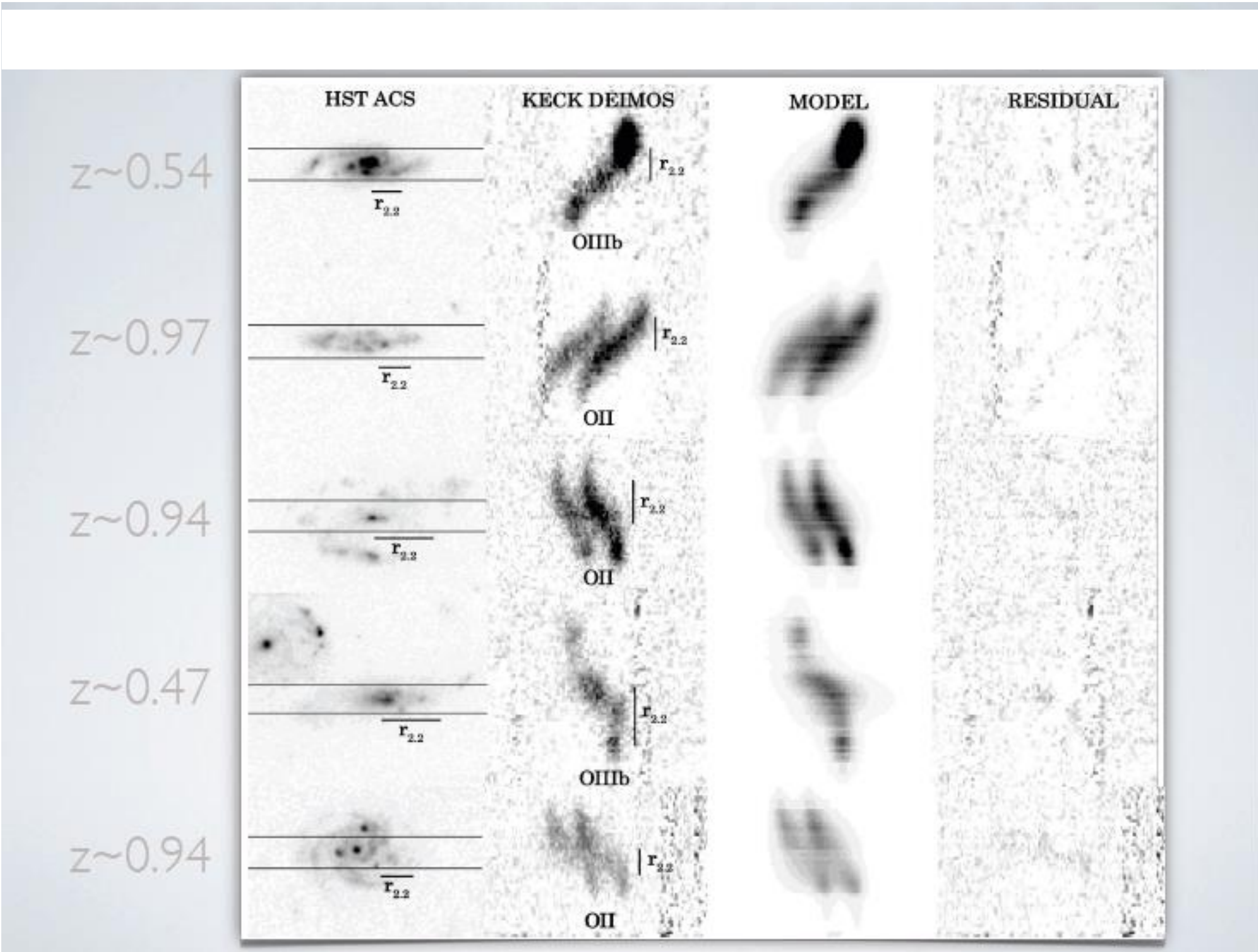
Classic paper: Tully & Fisher A&A 54, 661 (1977)

$$L \propto a(\lambda) \log v_{ROT}$$

where a ~ 8-10, consistent with M/L~const

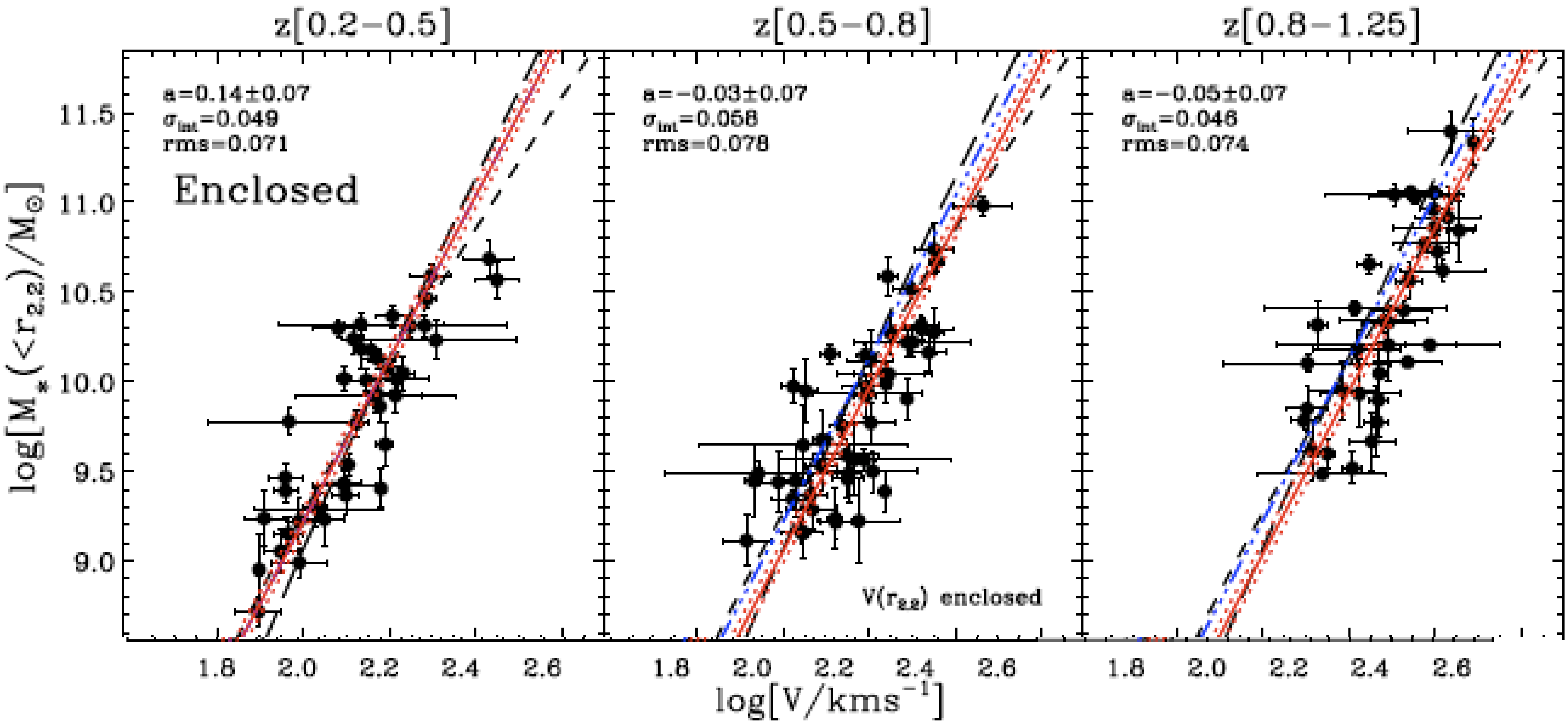
Rotation curves of distant spirals constrain evolution in L and/or M

Keck Rotation Curves of Galaxies (0.2<z<1.3)



Miller et al 2011 Ap J 741, 115

Stellar Mass Tully Fisher Relation 0.2 < z < 1.3+



Little evolution! Modest change over 0.2<z<1.3 and small scatter indicates disk formation largely complete by z~1.3

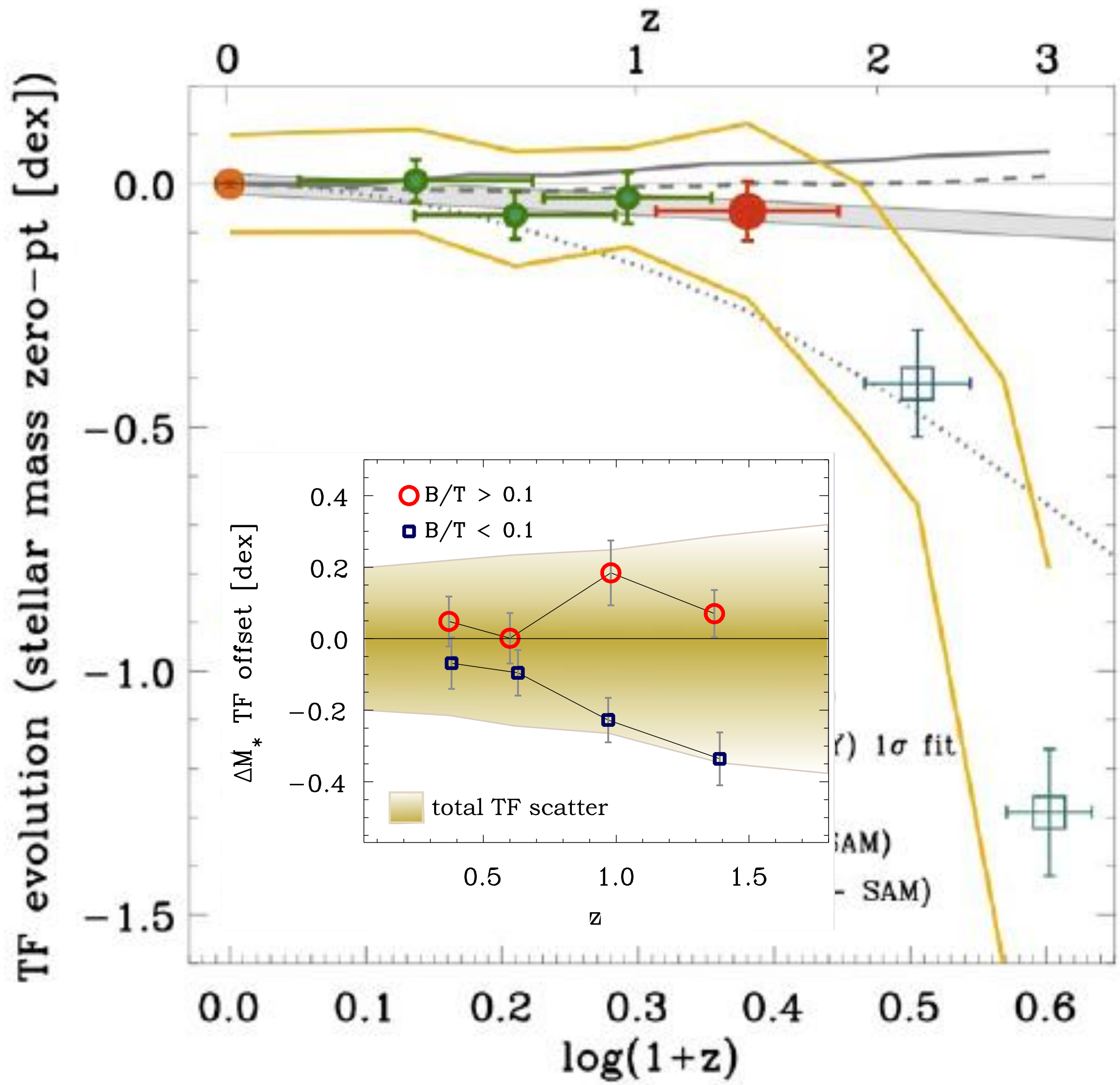
Miller et al (2011) Ap J 741, 115

Tully-Fisher Relationship over 1 < z < 2

It becomes harder to measure rotation curves with long-slit spectrographs beyond z~1

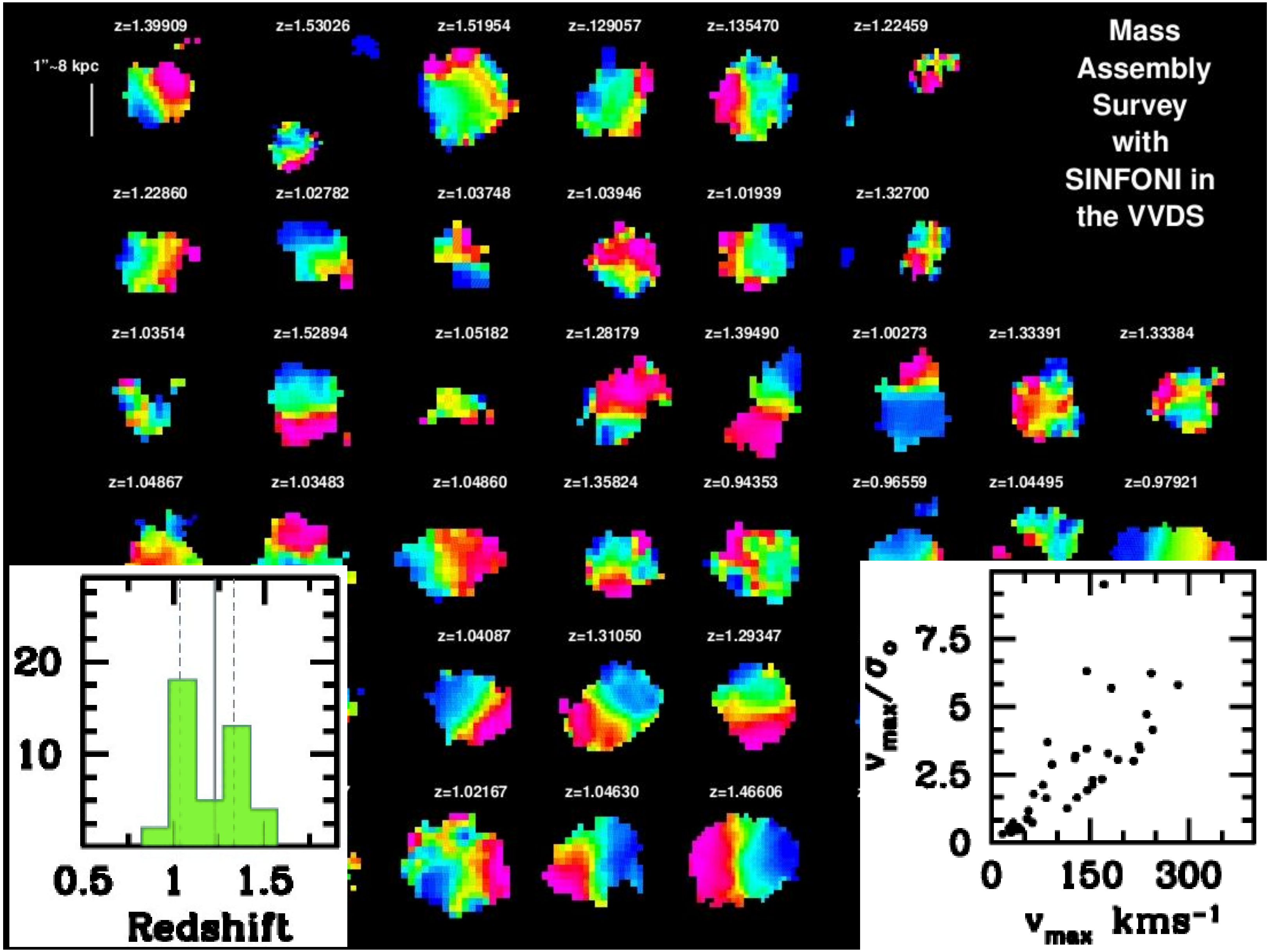
But evolution seems to be driven largely by the growth of bulges

Bulgeless galaxies mature onto the local TF relation much later than ones with prominent bulges



Miller et al (2012) Ap J 753, 74; Miller et al (2013) Ap J 762, L11

Emerging Tool: Resolved Spectroscopy 1<z<1.5

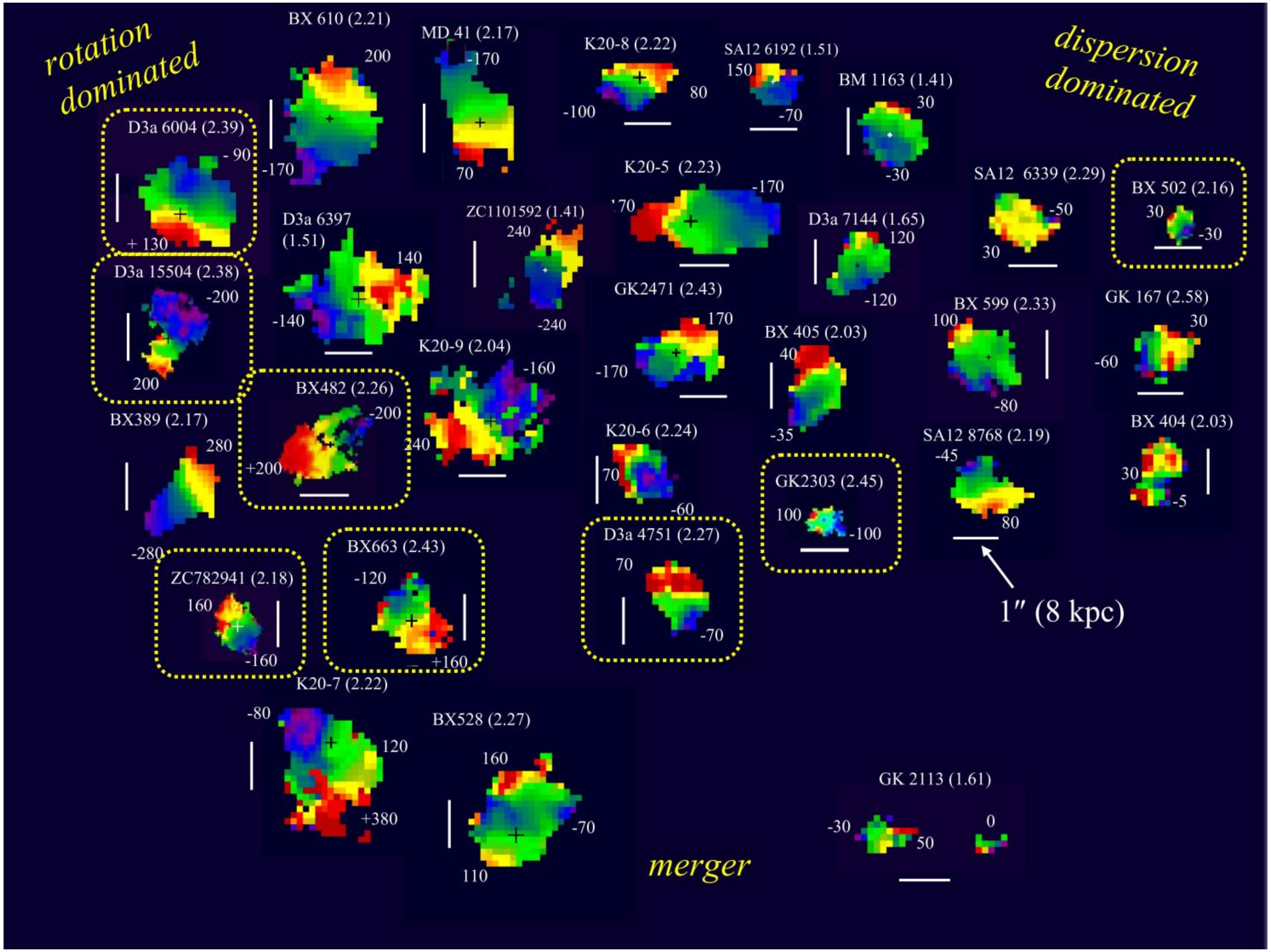


Vergani et al 2012 A&A 546, 118

Resolved Kinematics at Redshift z~2

SINFONI IFU measures of the kinematics of z~2 massive star forming galaxies using the Hα emission line:

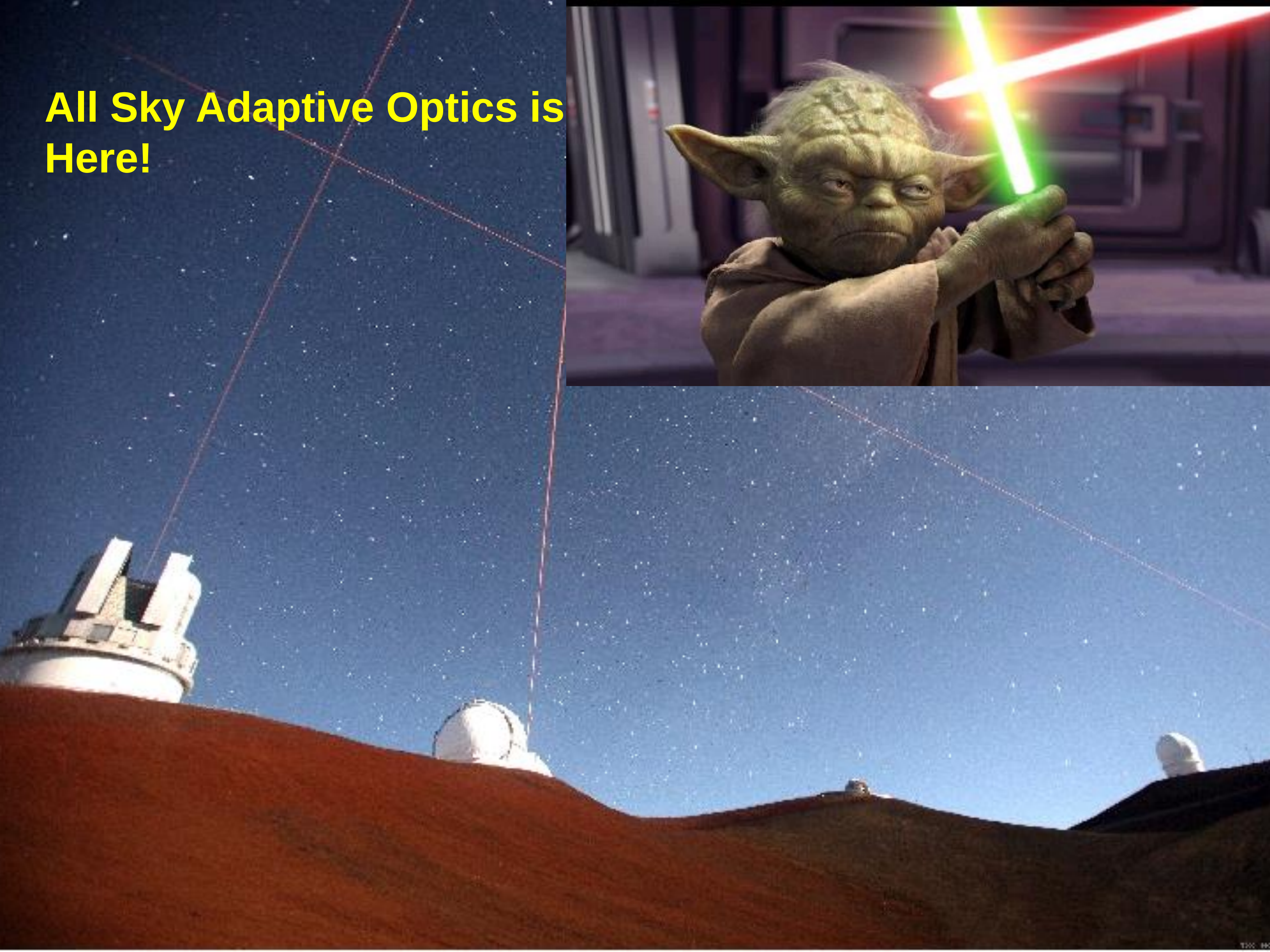
Key measure is the ratio of the rotational support V_{rot} to the random dispersion σ



← V_{rot}/σ

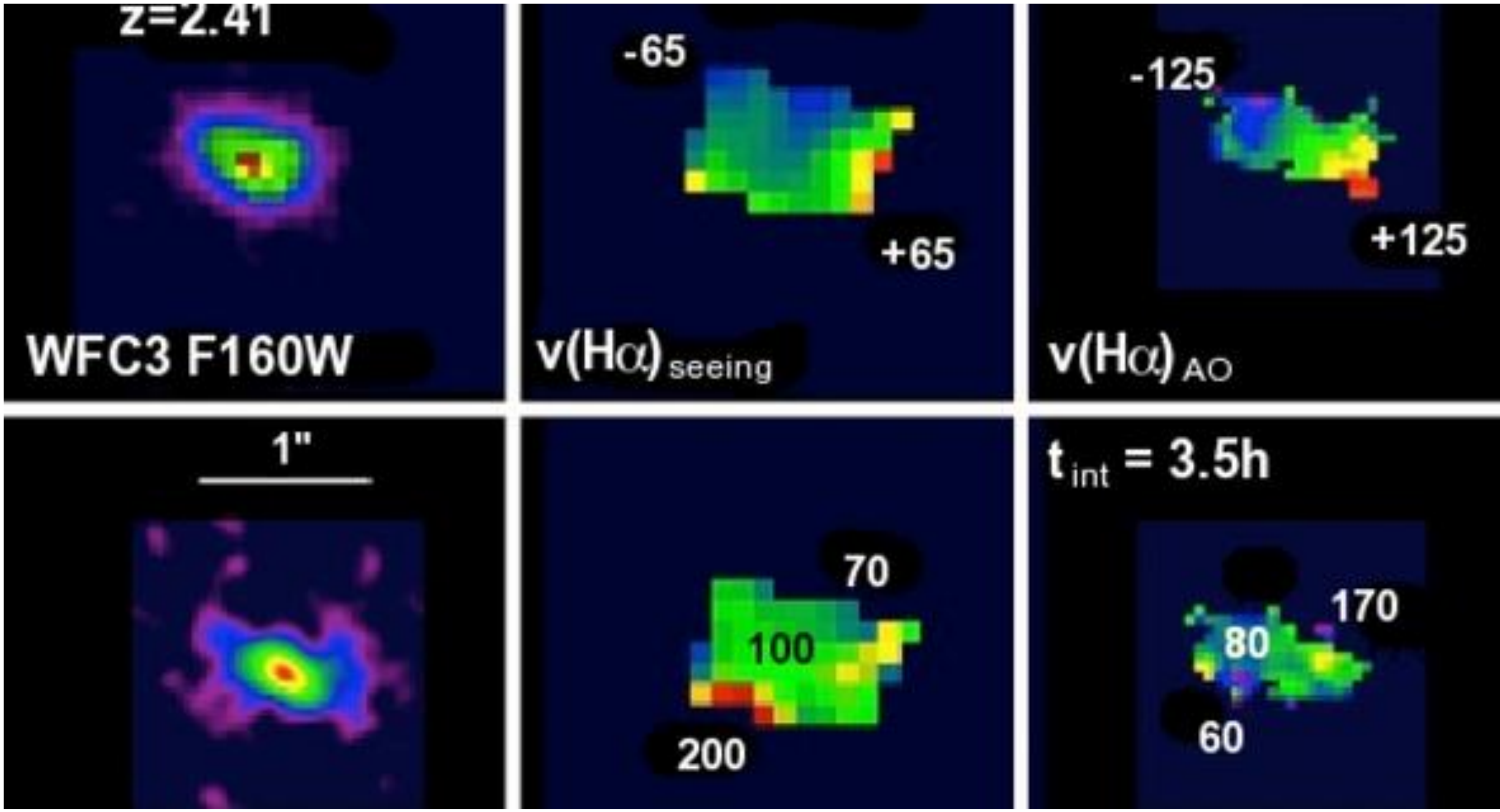
Forster-Schreiber et al 2009 Ap J 706, 1364

All Sky Adaptive Optics is Here!



AO Improvement in Kinematics

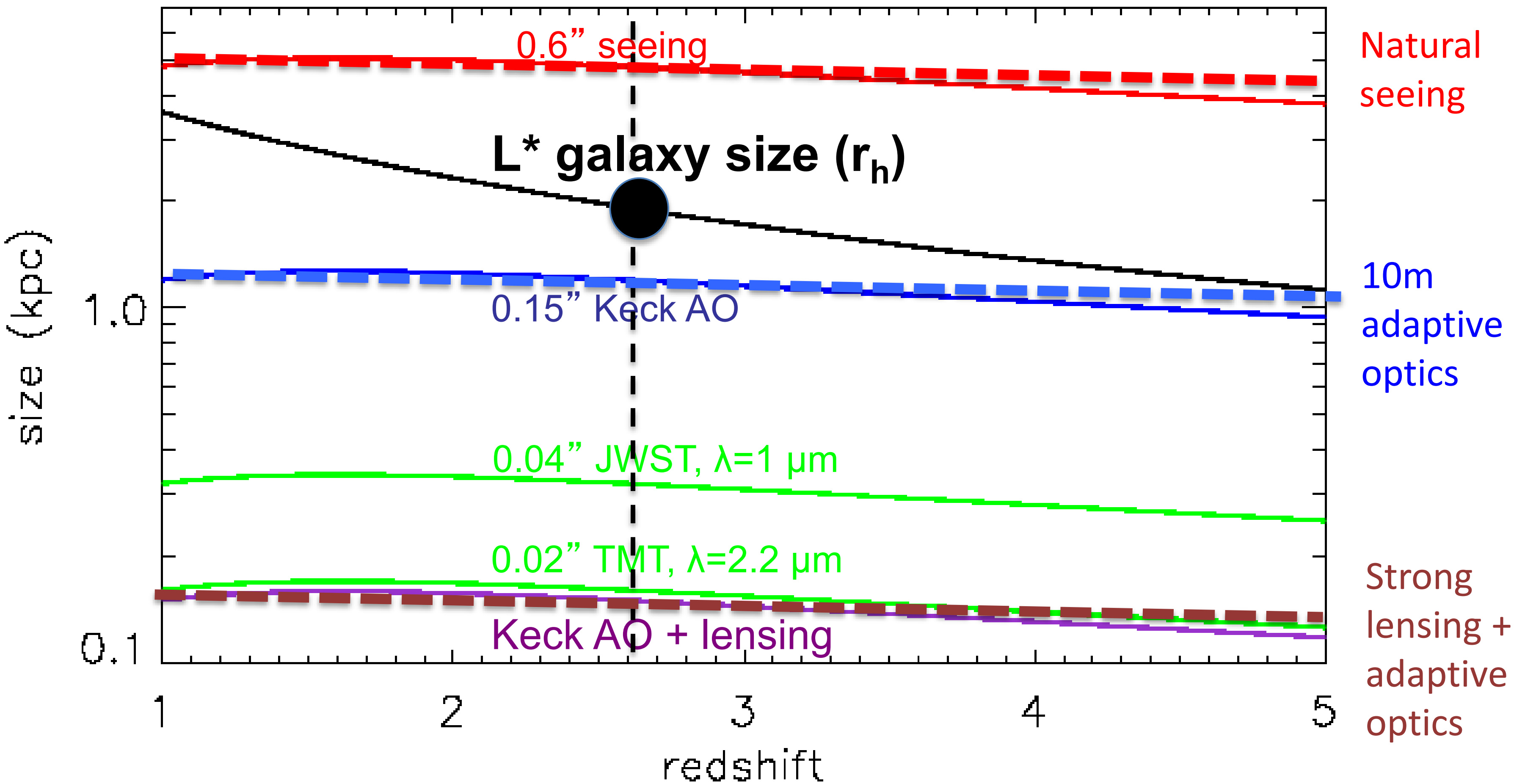
HST Image | **Seeing-limited Kinematics** | **AO Kinematics**



Question: Can reliable kinematics be secured for z>1.5 galaxies without AO (e.g. KMOS)?

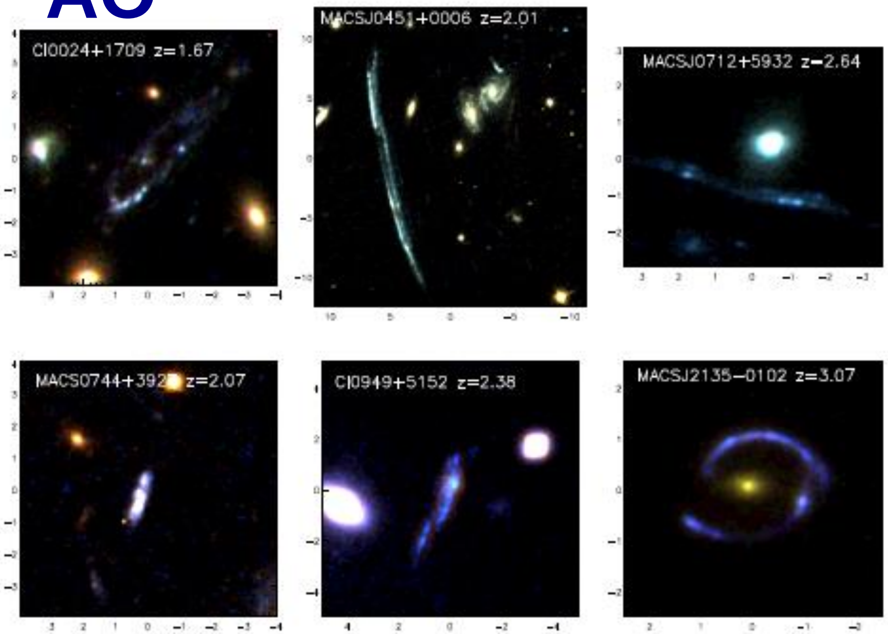
Newman et al 2013 Ap J 767, 104

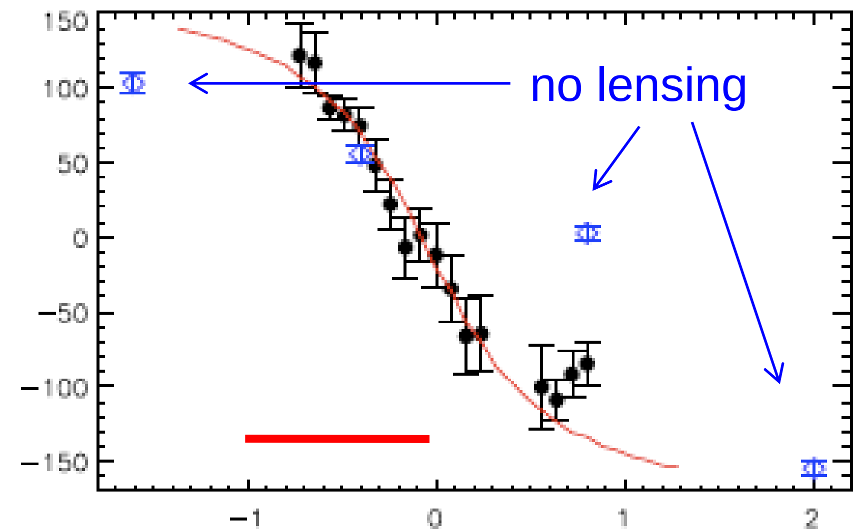
Typical (L*) Distant Galaxies are Very Small!

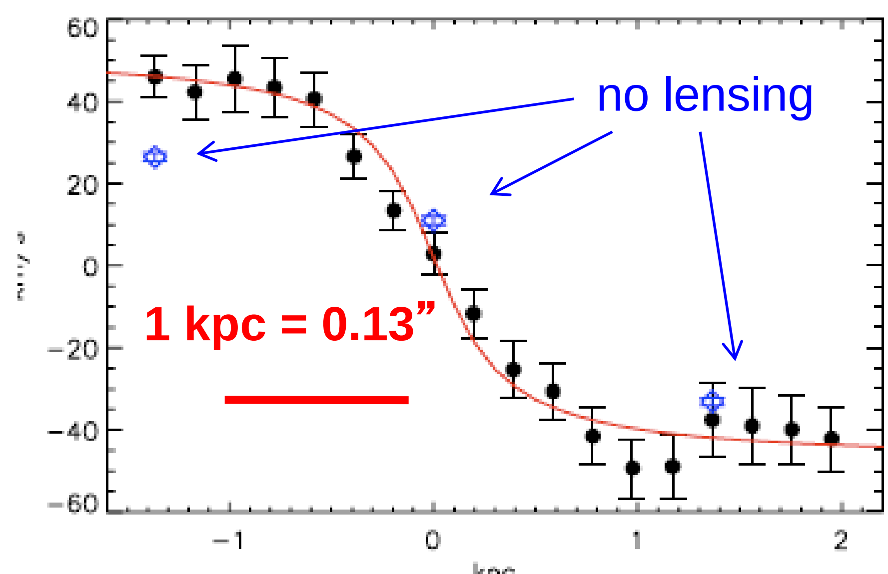


Conclusion: Even AO may not be enough; galaxies only partially resolved
Strong lensing + adaptive optics offers 200 pc resolution!

Resolved Dynamics (~100 pc) via Lensing & AO





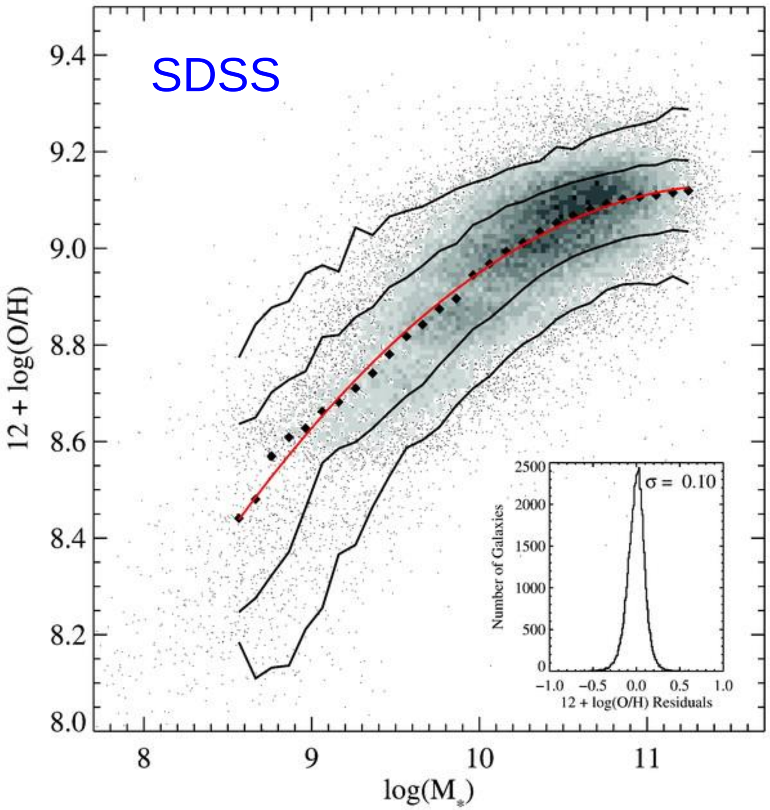


6 lensed galaxies 1.7 < z < 3.1
(linear magnification ~8-10)
revealing rotation in 5/6 cases

Rotation would not be accurately measured without lensing magnification

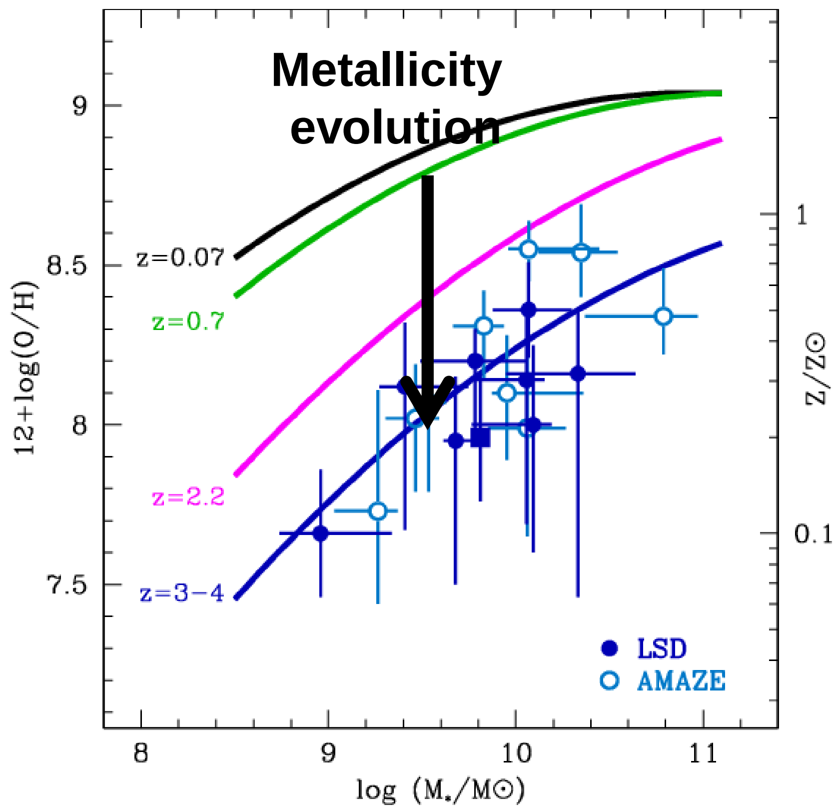
Jones et al 2010 MN 404, 1247

Evolving Mass-Metallicity Relation



First noticed in the 1970's, the gas-phase metallicity is higher in massive galaxies, presumably due to the larger gravitational potential retaining processed gas

Tremonti et al (2004) Ap J 613,898



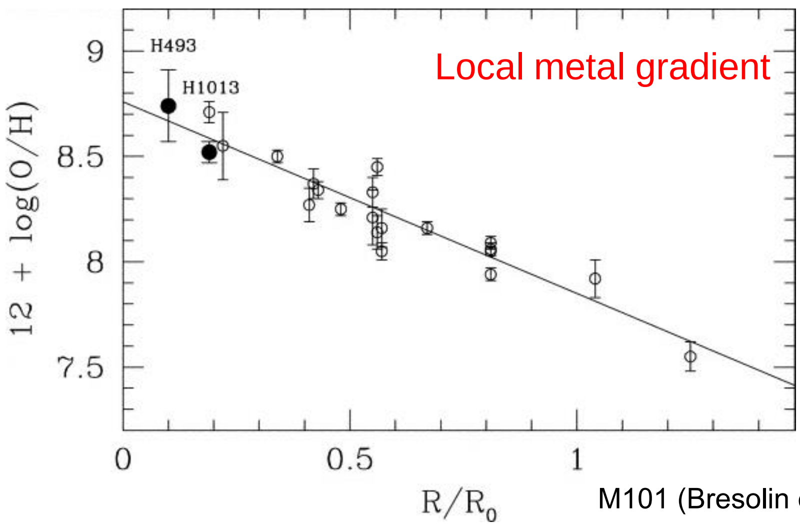
Evolution in the relationship is complex to interpret given uncertainties in the metal line diagnostics and since both the masses and star formation rates at high z are very different from those in local samples

Manucci et al (2010) MN 408, 2115

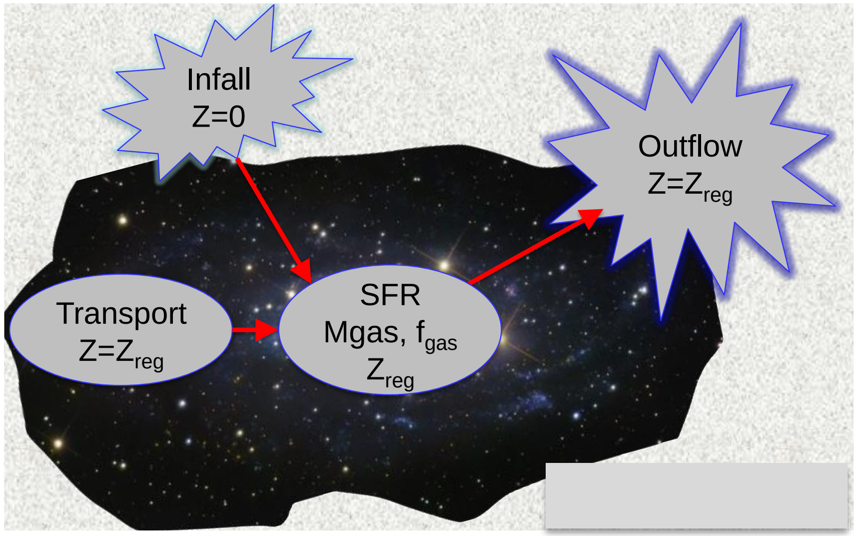
Importance of Metallicity Gradients

Resolved data offers much more insight into the mode of assembly, e.g.

1. Monolithic collapse (`outside-in' formation): initially weak gradient slowly steepens with time due to gravitational potential
2. Continuous cold accretion (`inside-out' formation): initially a very strong metal gradient that flattens with time
3. Mergers/interactions: gradients erased initially then slowly rebuild

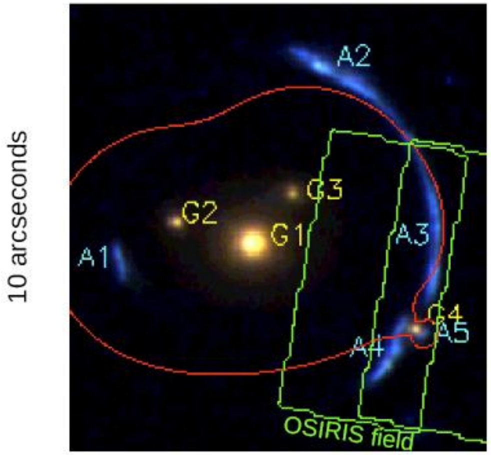


M101 (Bresolin et al 2006)



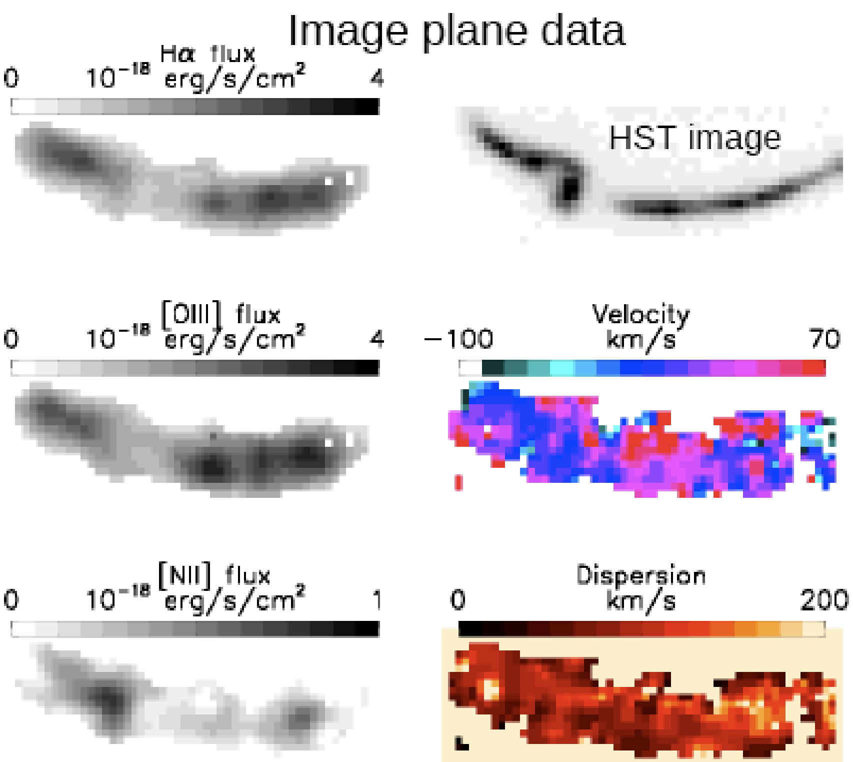
If metal-free infalling gas and processed outflowing gas are regulated by star formation, radial gradients are a natural byproduct of inward migration & radial dependent `mass loading factor' (effective outflow rate/SFR) whose time evolution can be predicted.

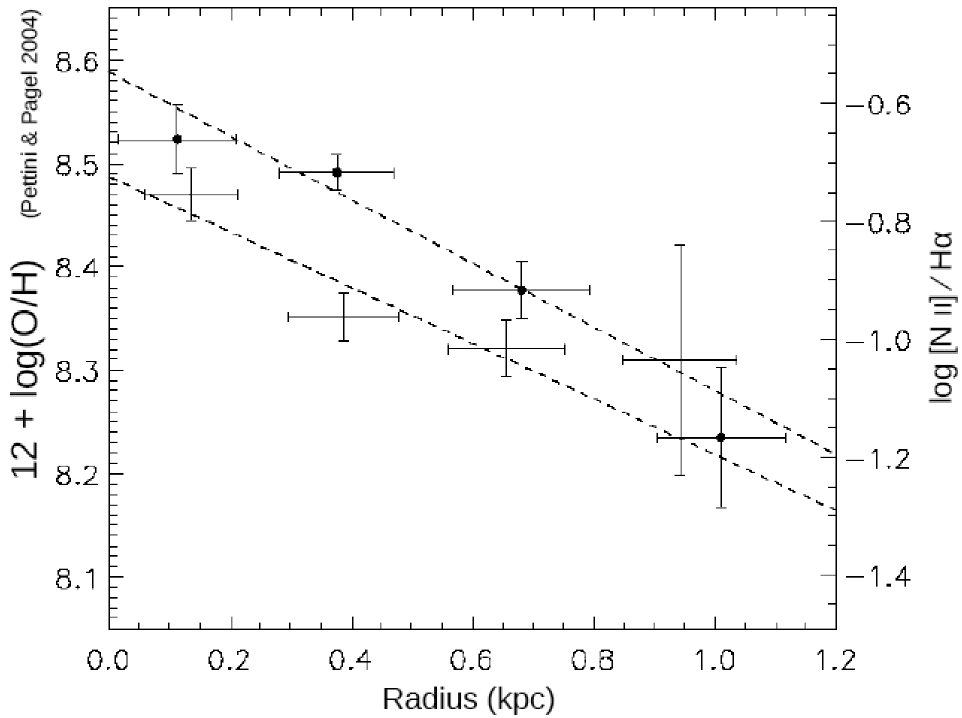
Resolved Metallicity Gradients



By combining [O II], [O III], Hα and [N II] measures, we can determine the metallicity gradient in z~3 galaxies

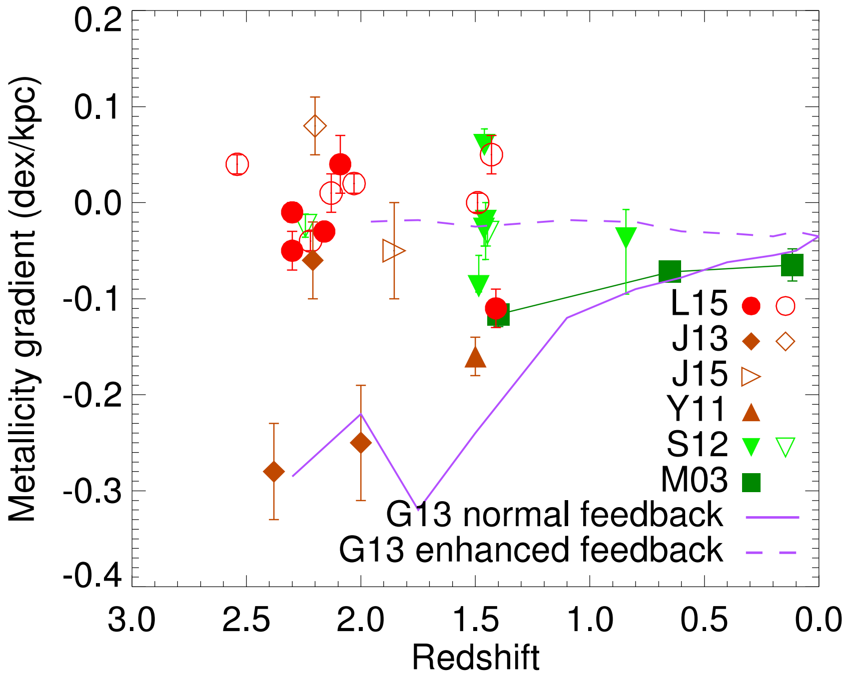
Appears steeper than in local spirals suggestive of inside-out growth

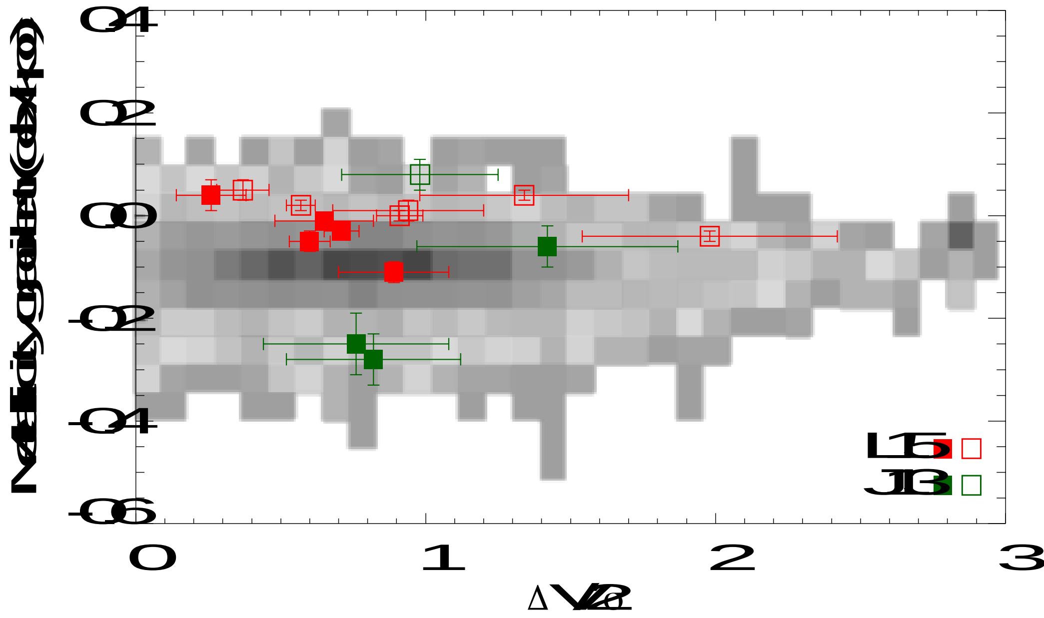




Jones et al Ap J 765, 48 (2013)

State of the Art in Metal Gradients





Considerable scatter is seen in the metallicity gradient in z~2-2.5 galaxies with no clear correlation with the kinematic state (as characterised by the degree of rotational support, ΔV/2σ)

Hydro simulations e.g Illustris, confirm these trends and suggest gradients are acutely sensitive to the amount of feedback.

Leethochawalit et al arXiv 1509.01279

z~2.3 Massive Red Galaxies

Discovery: FIRES VLT survey; colour selected

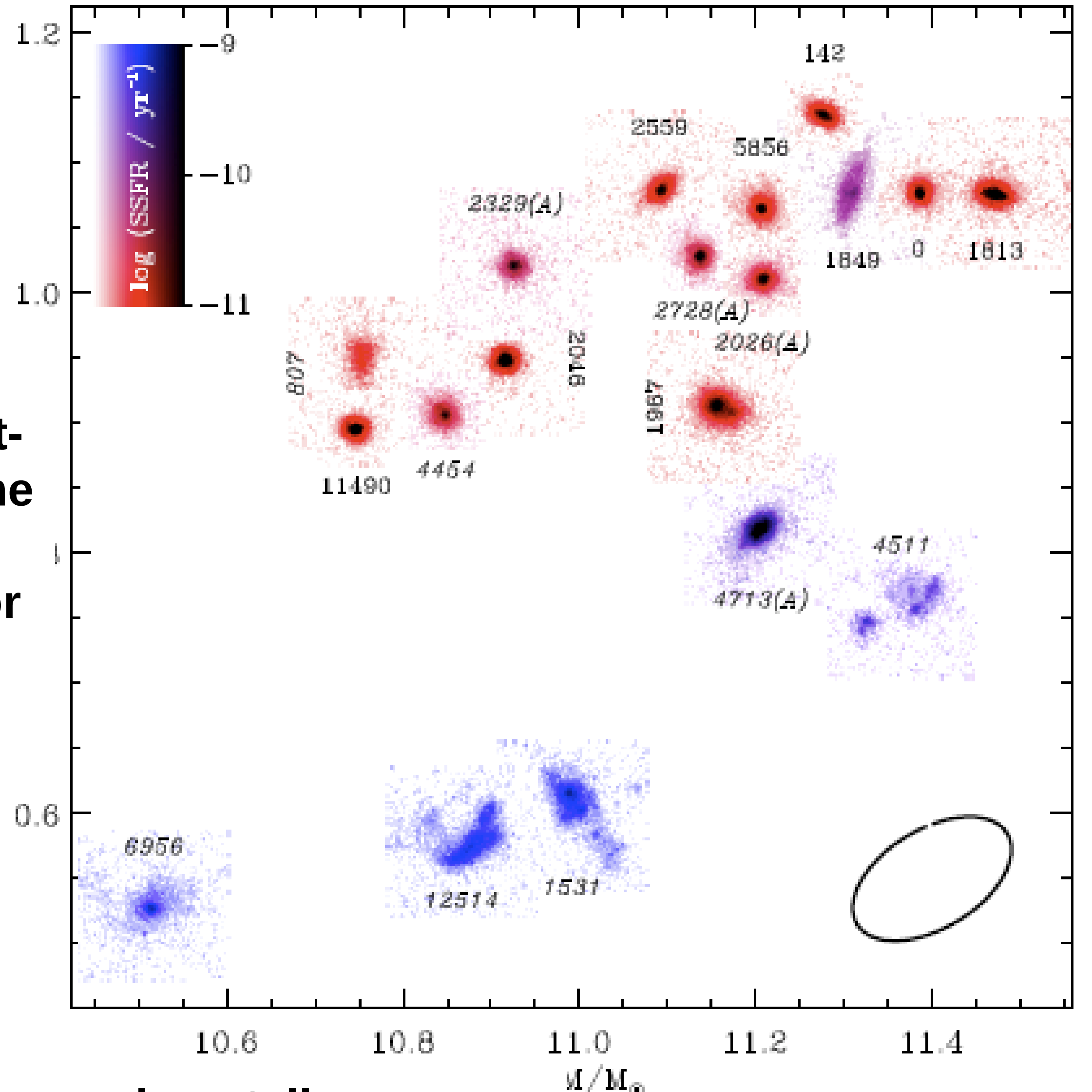
$2 < z_{photo} < 3$

Subsequently confirmed spectroscopically

Census of N~300 galaxies with masses $M > 10^{11} M_{\odot}$ in 400 arcmin^2

Most massive galaxies are DRGs (77%); LBGs constitute only 17%

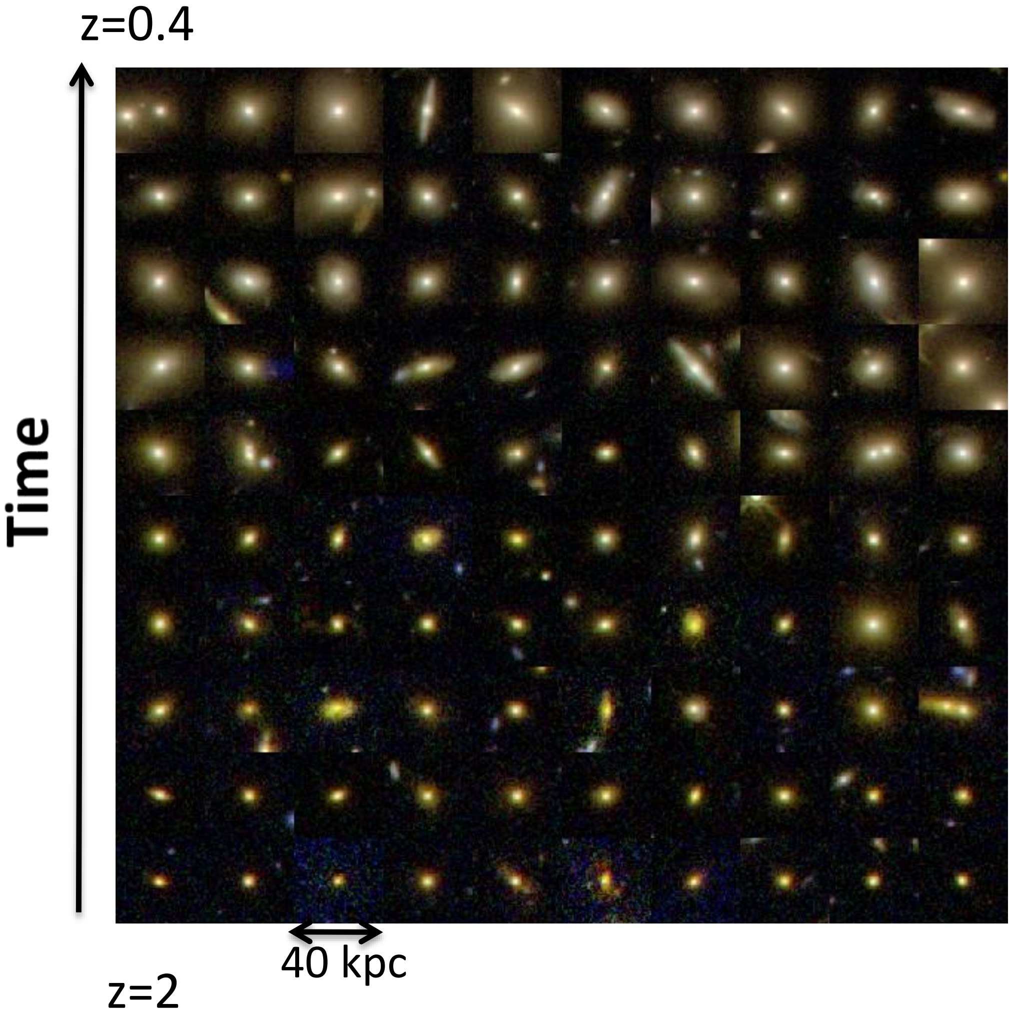
Rest-frame U-B color

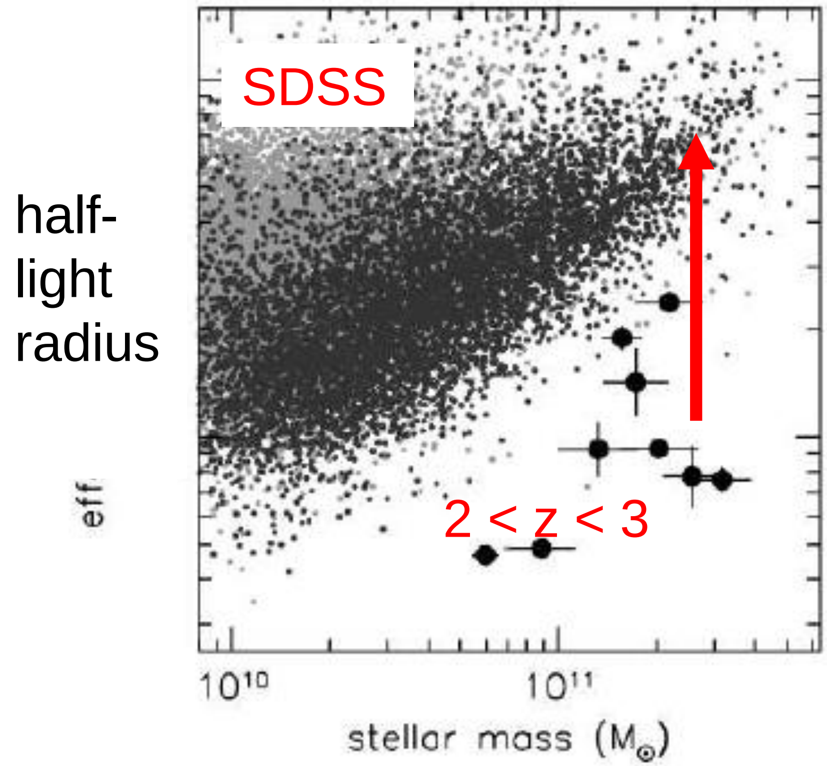


log stellar mass

Franx et al 2003 Ap J 587, L79 ; Kriek et al 2009 Ap J 705, L71

Distant Red Galaxies are Small!





HST NIC2 sizes of z~2-3 red galaxies with M >10^{11} $M_\odot$: r_e~0.9 kpc

2-5 times smaller than comparably massive z~0 ellipticals!

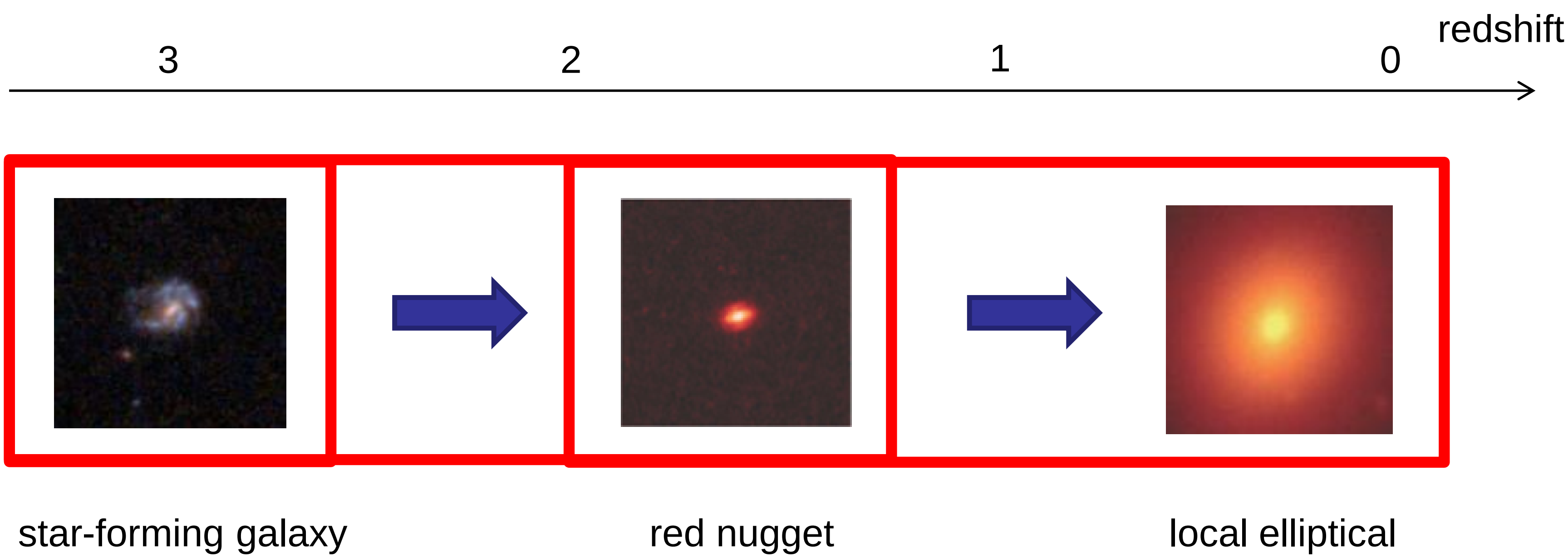
Growth in size but not mass?

van Dokkum et al 2008 Ap J 677, L5

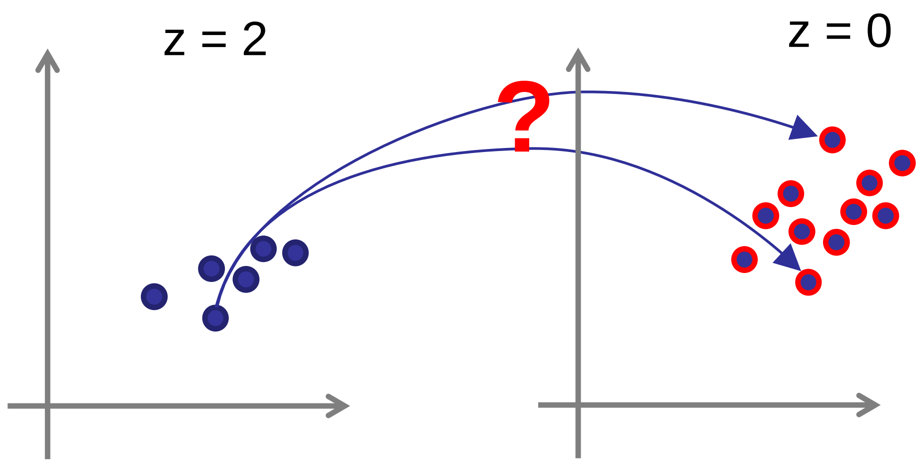
`Red Nuggets' Saga

Initial skepticism at observational claims: mass overestimated or size underestimated? Now confirmed, the key questions are:

1. How do compact galaxies grow in size?
2. What is the physical process responsible for quenching?
3. What are the progenitors of the compact red galaxies?

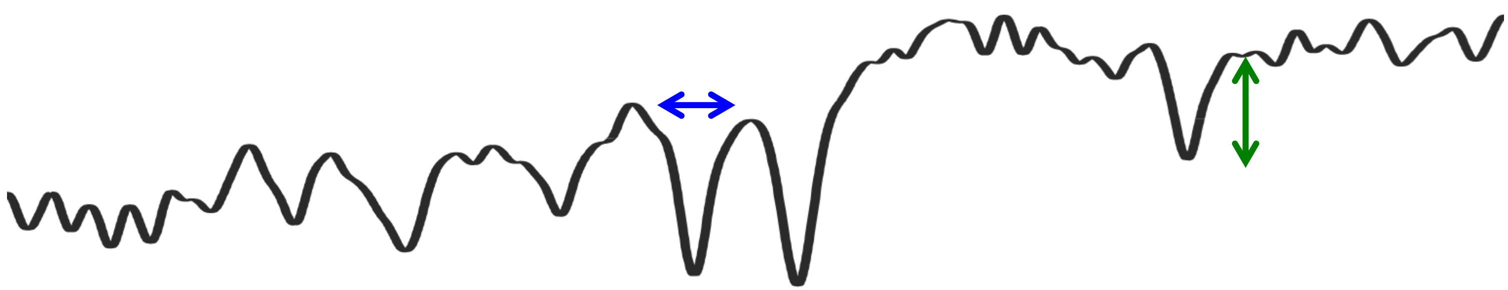


Emerging Tool: Absorption Line Spectroscopy!



Q: How to link progenitors and descendents?

- Dynamical masses from stellar velocity dispersions, σ: line widths
  - -- verify claimed high stellar masses from photometric data alone
  - – provides valuable proxy for tracing similar systems (since σ ~unaffected by many growth processes e.g. merging)
- Ages from stellar population analyses: line depths
  - - breaks degeneracy between long-lived and recently-quenched sources
  - – addresses key question of which galaxies evolved into red nuggets



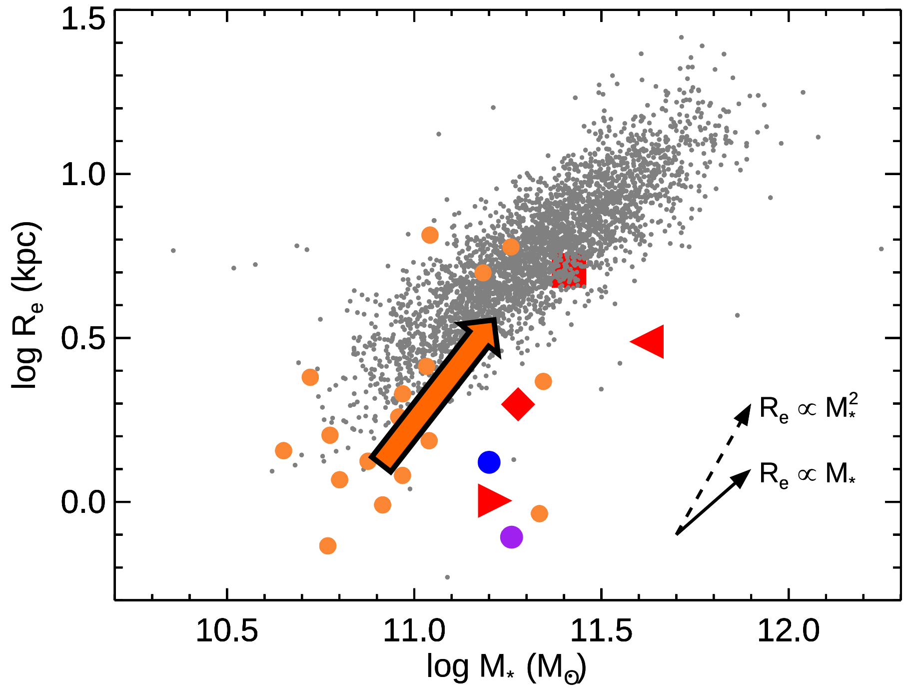
Mass and Size Growth at Fixed Dispersion σ

Velocity dispersion is largely unchanged during mergers so acts as label for connecting high and low z populations.

$$R \propto M^{\alpha}$$

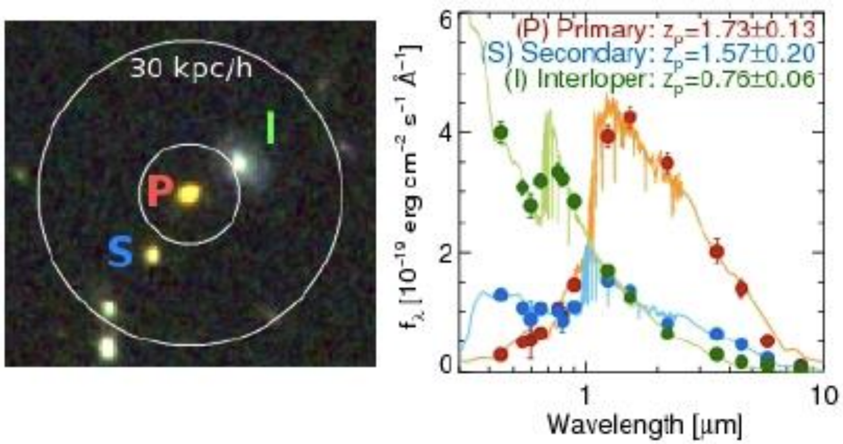
identical merger: α = 1

minor merger: 1 < α < 2

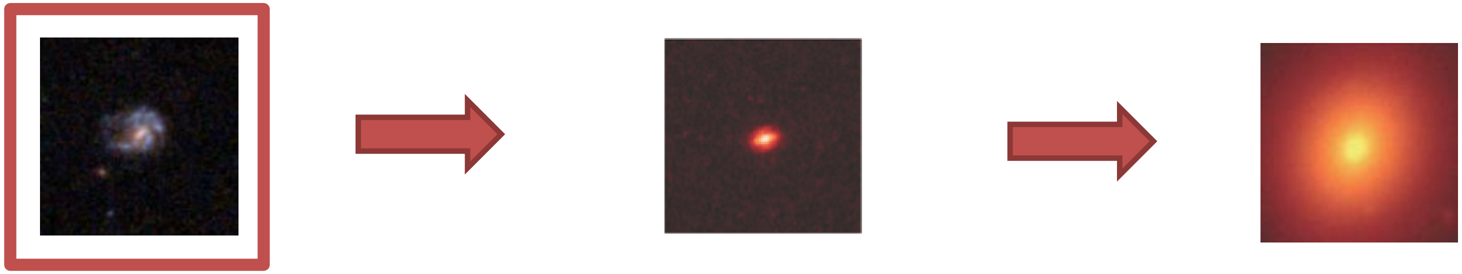


1 < z < 1.6: α = 1.4 ± 0.2

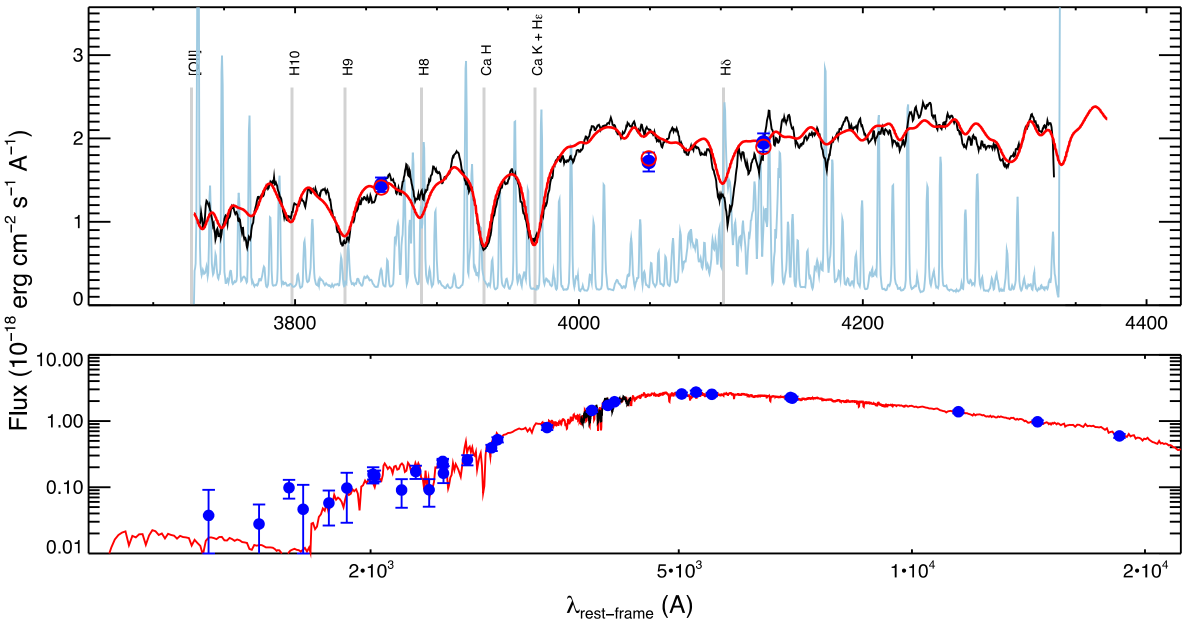
Consistent with minor merging



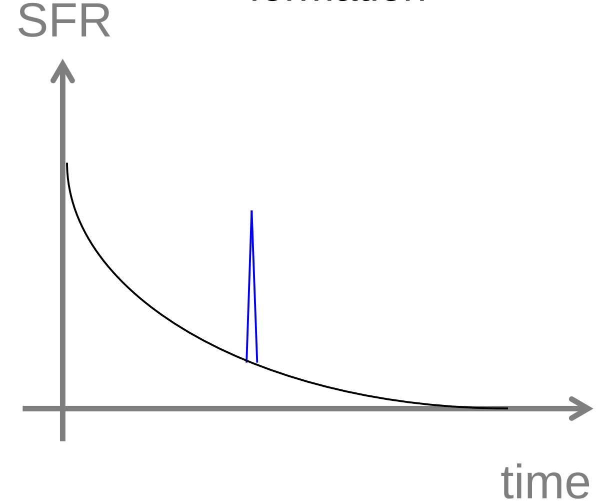
Age Dating z~2 Compact Galaxies



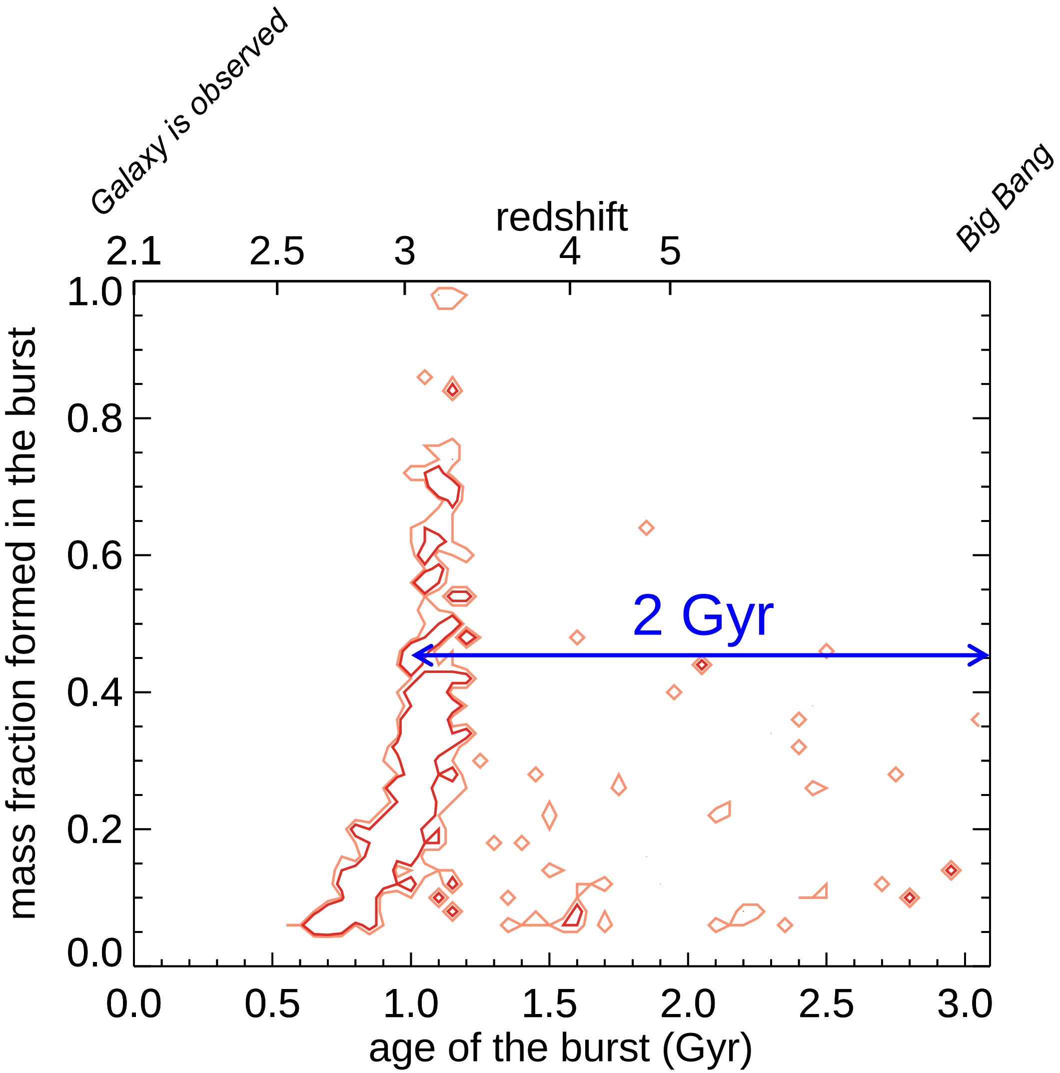
MOSFIRE spectrum: z = 2.09 (most massive in sample)



We add a **burst** to the tau model to constrain the most recent star formation



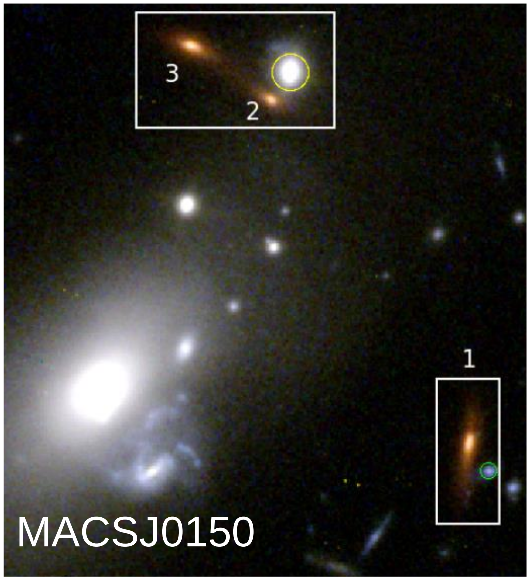
Constraining the Most Recent Star Formation



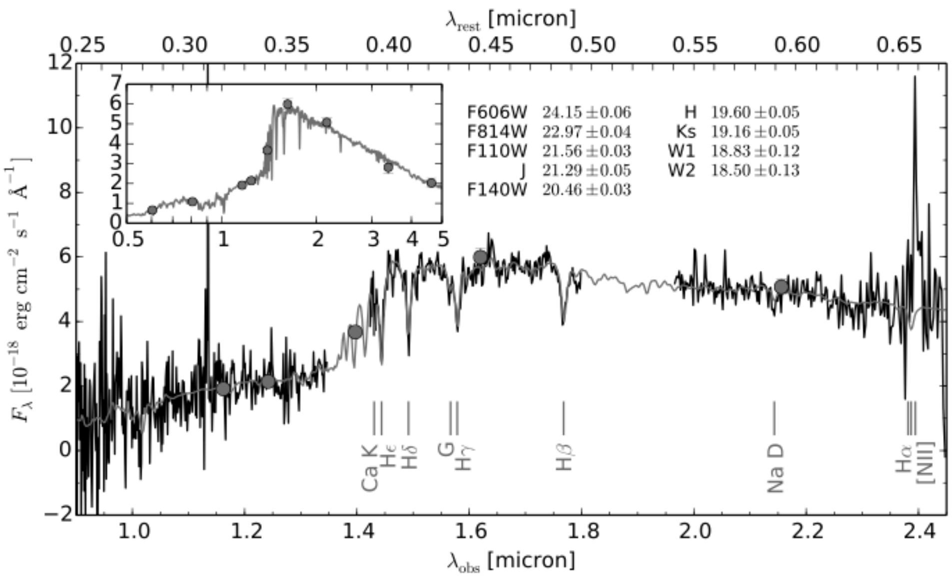
- Much of the stellar mass ($4 \cdot 10^{11}$ $M_\odot$) was formed at **z > 3**, in less than 2 Gyr
- SFR > 200 $M_\odot$/yr, similar to what found in **sub-mm galaxies** (e.g. Toft et al. 2014)
- Star formation ends very rapidly
- Constraint on the **progenitors** of quiescent galaxies, and on the **quenching** timescale

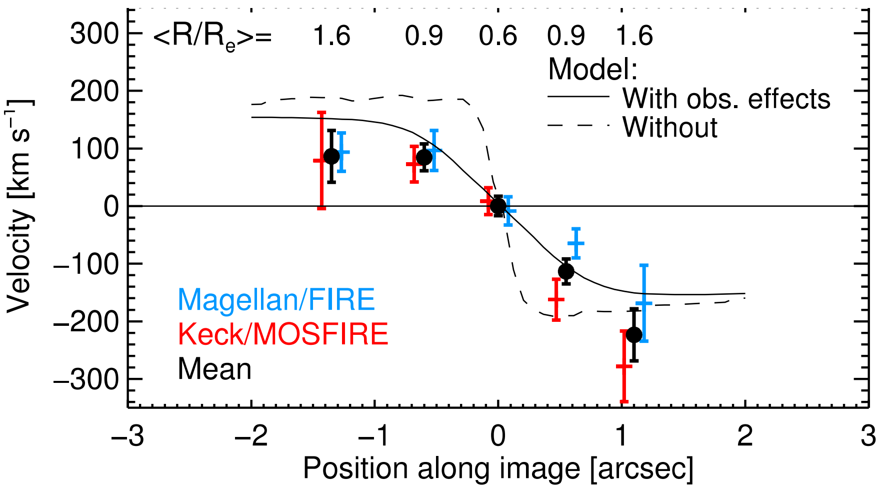
Next Step: Studying the Starlight

- Gas-phase metallicity probes many complex processes – infall/outflows and feedback; it utilises emission lines which are easier to measure (but difficult to interpret)
- Stellar abundances probe the chemical composition frozen in at the time of birth; together with ages, this is very powerful in connecting populations; but it is hard requiring high s/n absorption line spectra
- Resolved absorption line studies also probes kinematics of the stars – largely an unexplored tool



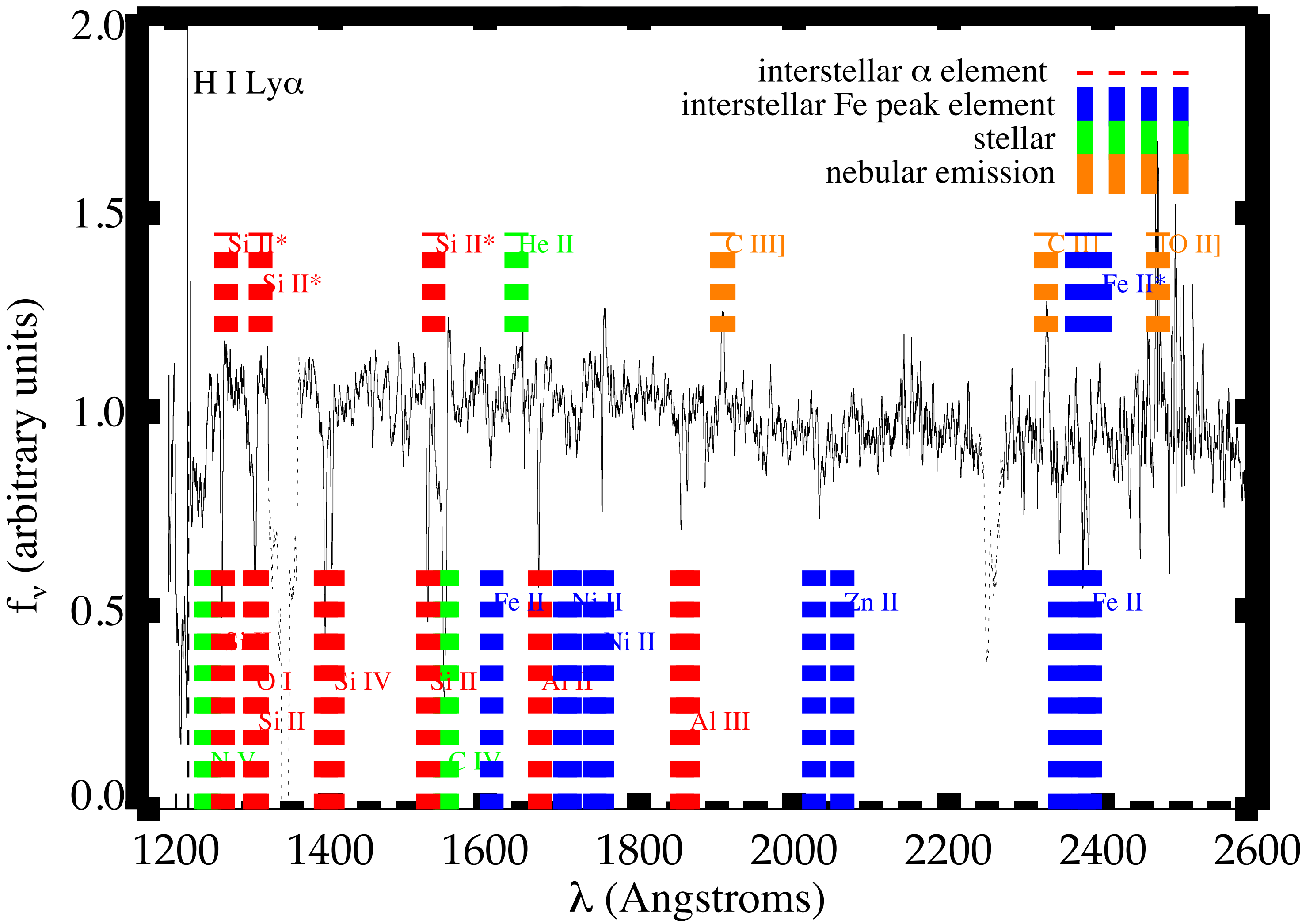
z=2.636 lensed red galaxy





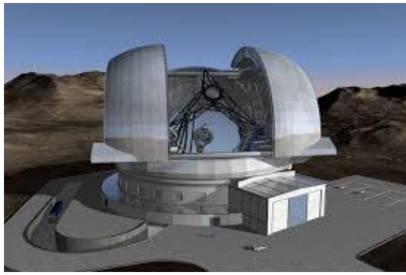
Newman et al arXiv 1509.04345

Separating Stars from the ISM



Quider et al 2009 MN 398, 1263

So How to Plan for the E-ELT?



- Galaxy evolution is rapidly advancing; projects that seemed impossible with present facilities 5 years ago are being undertaken now!

- Best to consider emerging tools and how they can be extended

- Two techniques have emerged as extremely powerful but their scope is severely limited with our present facilities:

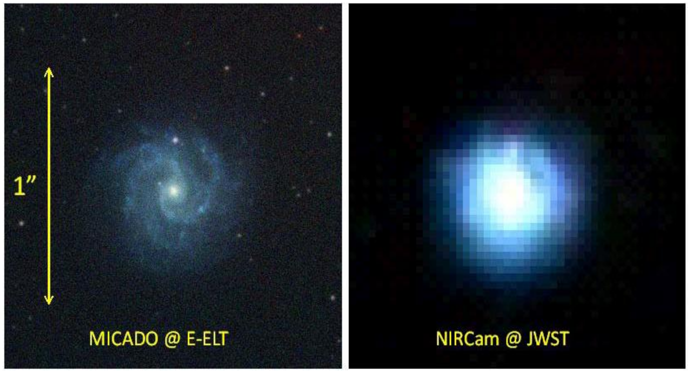
  (i) adaptive optics enabling resolved spectroscopic studies of the gas in z~2 galaxies ➔ 2-D maps of kinematics, star-formation, dust and metallicity

  (ii) absorption line spectroscopy probing the ages & composition of stellar populations and the nature of the ISM

- Current studies are limited to the most massive/large or lensed sources at z~2-3 E-ELT can extend these to more representative sources over 2<z<6 with higher spectral resolution

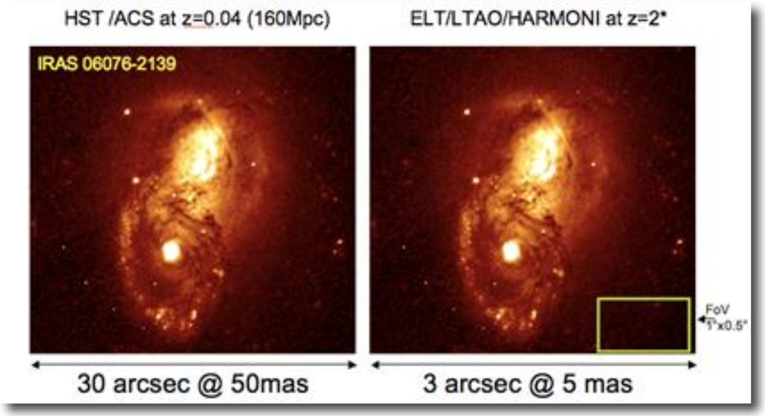
Attributes of Optical/NIR E-ELT Instruments

ELT-CAM
(MICADO)



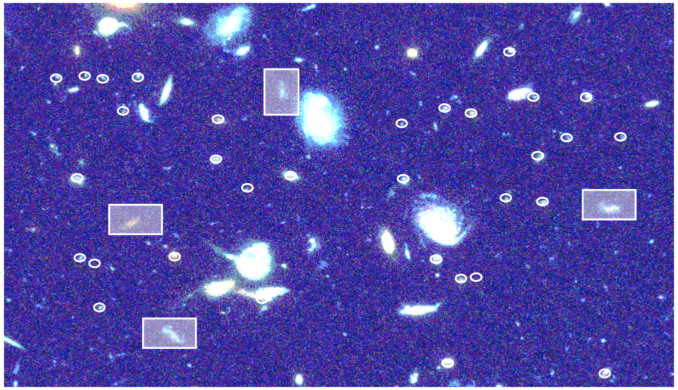
Rest-UV and nebular emission line mapping: internal distribution of star formation and dust in star-forming galaxies

ELT-IFU
(HARMONI)



2D kinematic and metallicity measures of gas at unprecedented spatial resolution

ELT-MOS
(MOSAIC)



High spectral resolution studies of starlight in passive and SF galaxies at rest-frame UV & optical wavelengths.