JWST and the Assembly of galaxies 2 < z < 7

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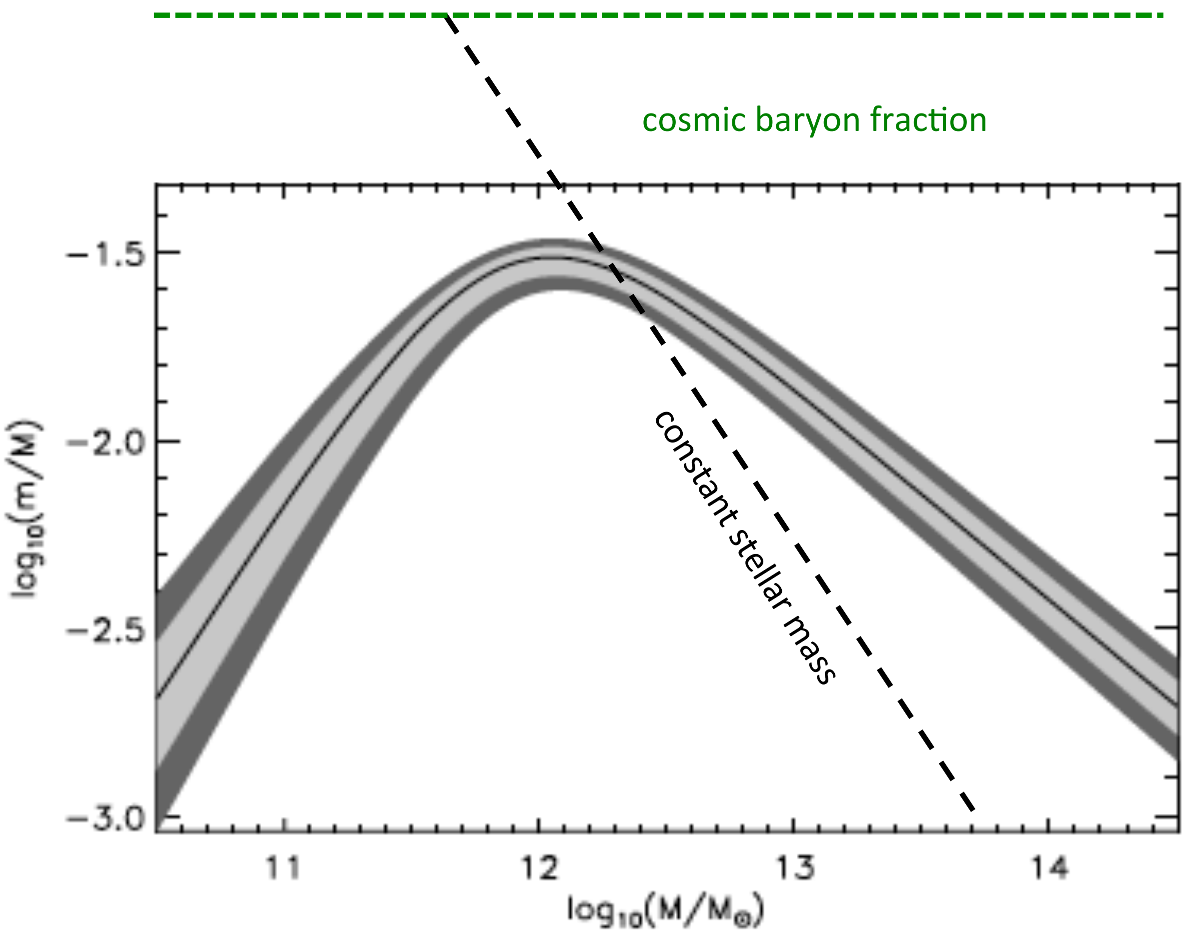
What we are trying to explain

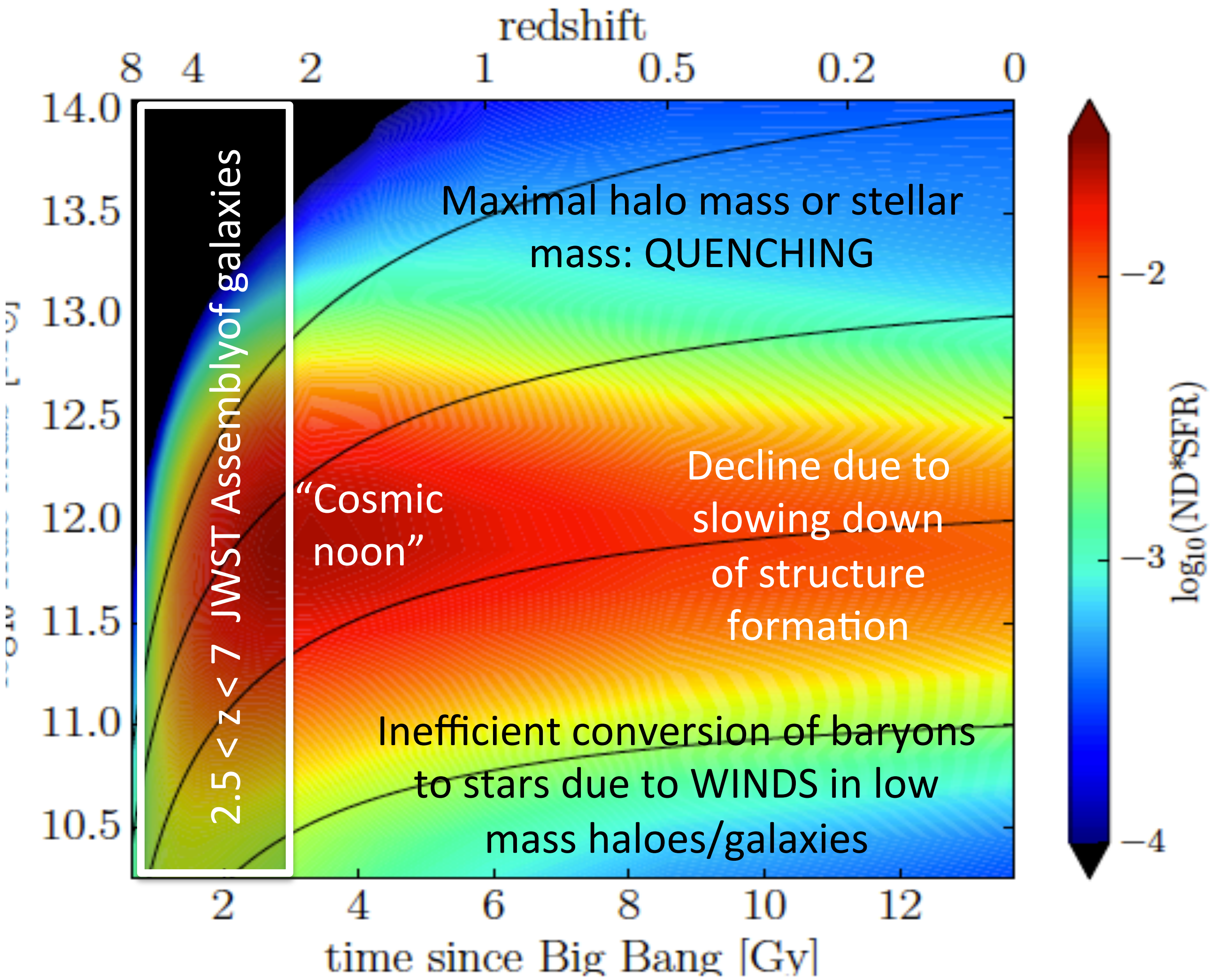


Moster et al (2010)

Conversion of baryons into stars as seen today

Peak conversion efficiency in DM haloes of 10^{12} $M_{\odot}$

What we are trying to explain



From Birrer, SJL et al 2014 toy-SAM, see also Behroozi et al 2013

Cosmic history of star-formation

Why 7 < z < 2.5 will be important for JWST

- Cosmologically: From re-ionization up to the peak in star-formation, galaxy evolution limited by available sites
- Operationally: Hα is at 2.3 < λ < 5 μm (i.e. inaccessible from ground): very strong non-resonant line relevant for SFR, kinematics, metallicities and diagnostics etc.

Questions for JWST (and everything else)

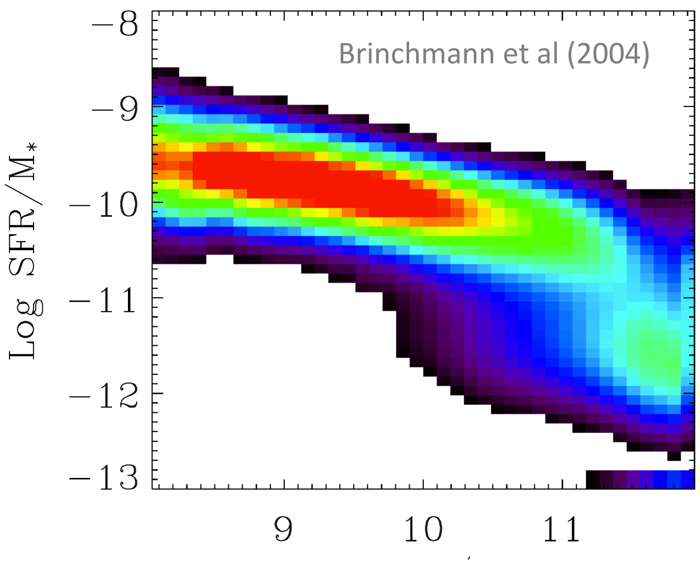
1. What is quenching star-formation in galaxies, and what is keeping them quenched?

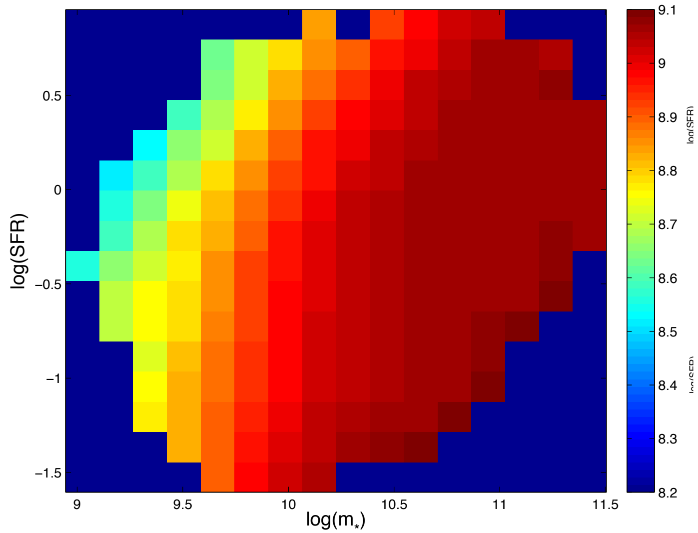
   Note: this happens at more or less the same mass at all epochs since z ~ 4!

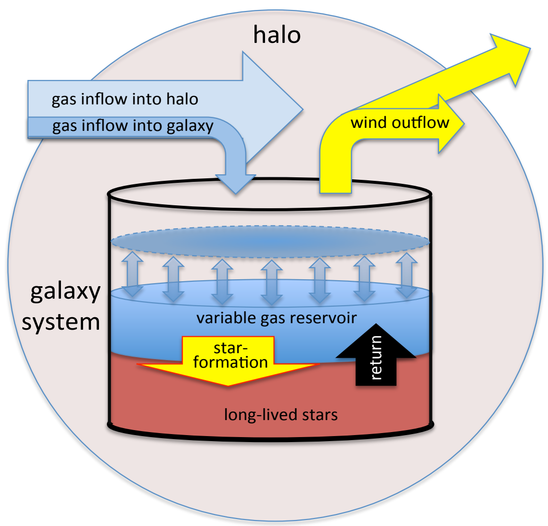
   - Halo quenching: i.e. heating of infalling gas in shocks, prevention of cooling, interruption of gas supply
   - AGN quenching: energy injection linked to SMBH ("quasar phase" and/or "radio phase"), ejection of gas from galaxies and/or heating of gas in haloes
   - Mergers leading to star-bursts (variant of AGN scenario?) and consumption/ejection of gas.
   - "morphological quenching", "gravitational quenching" : *internal* processes controlling star-formation efficiency related to stability of disks etc.

Questions for JWST (and everything else)

2. When is a Main Sequence established and what causes it?
   - The Main Sequence is diagnostic of quasi-steady-state SF vs. episodic star-burst SF and the regulation of star-formation
   - Is the MS regulated in the same way at high z >> 2 as locally? Metallicity as a diagnostic of regulation (e.g. Lilly+13)



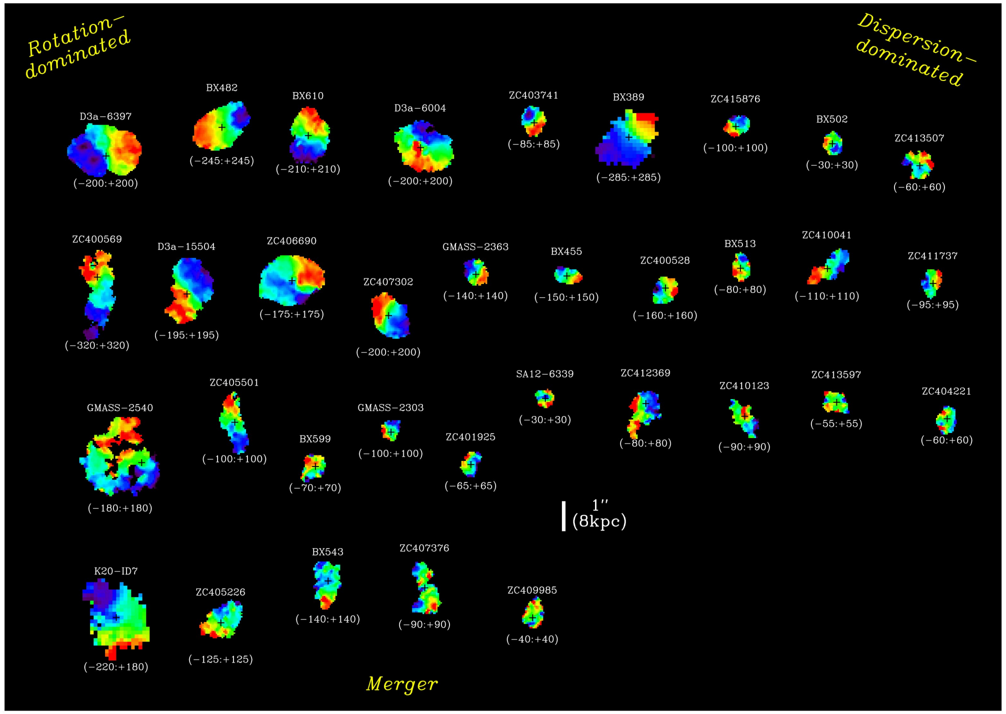




Questions for JWST (and everything else)

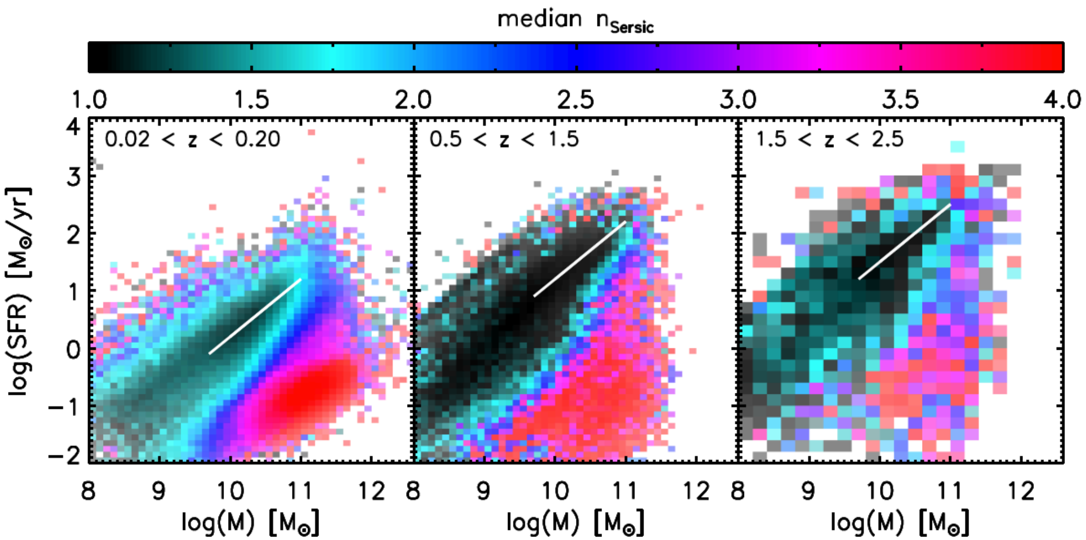
3. What is the relative importance of in situ star-formation and merging in adding mass to star-forming galaxies? And to most massive passive galaxies?
   - sMMR increases as sSFR, because both trace halo growth?
   - Prevalence of disks at $z < 2$. At higher redshift?
   - Size growth for passive early type galaxies

SINFONI AO Hα observations at VLT: SINS-zC survey: Genzel, Forster-Schreiber, SJL et al.



Questions for JWST (and everything else)

4. What is the role of galaxy structure and morphology?



Wuyts et al 2011 ApJ 742, 96

Basic problem: we do not really know how spheroids were formed

Tautological aspect

- Steady-state SF in disks!

A causal connection, but in which direction?

- Massive bulges quench star-formation (SMBH? or gravitational quenching?)
- Quenching produces massive bulges (through mergers?)

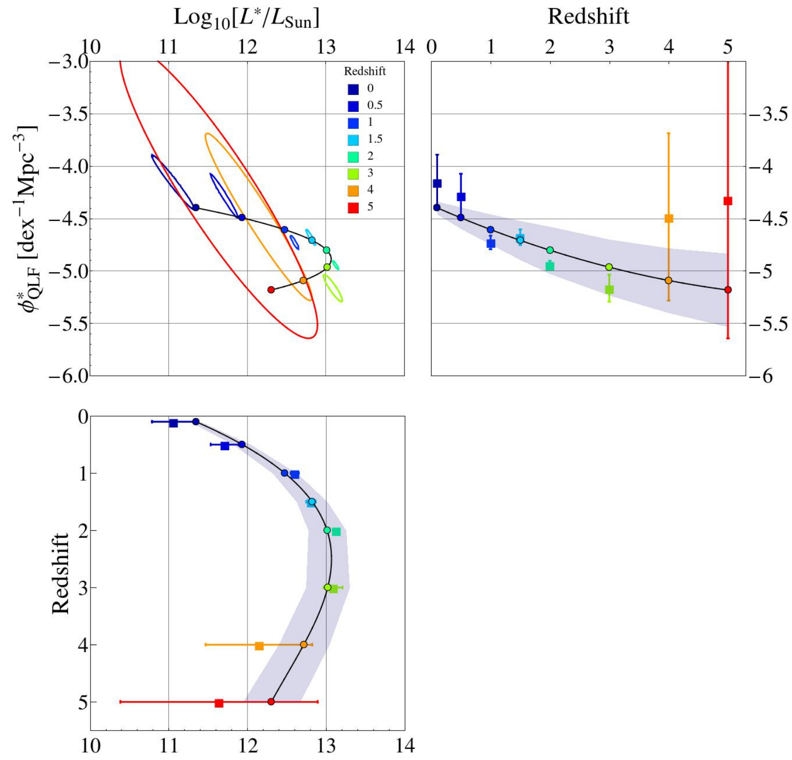
Or an indirect connection

- age-density-structure link

Questions for JWST (and everything else)

5. What is relationship between galaxies and their central supermassive black-holes?

- Local scaling relations of m_{BH} with galaxy properties: σ, m_{bulge}, m_{stars}….
- There is certainly broad "co-evolution", but also evidence for evolution in mean m_{BH}-m_{star} relation(s)
- Possible role of AGN in quenching star-formation in galaxies and maintaining quenched state.



Key questions **and emerging answers at 0 < z < 2.5**

How is stellar mass added to normal SF galaxies around M*?

- In situ SF — 80%
- Mergers — 10%
- Merger-induced star-bursts — 10%

What controls the (decline of the) SFR in most galaxies?

- Gas content driven by the accretion of gas from the halo

What changes m_{star}/m_{halo} as $f(m_{halo})$?

- SN-driven winds as evidenced by Z(m)

What physically quenches SF at M > M*?

Don't know: possibilities include

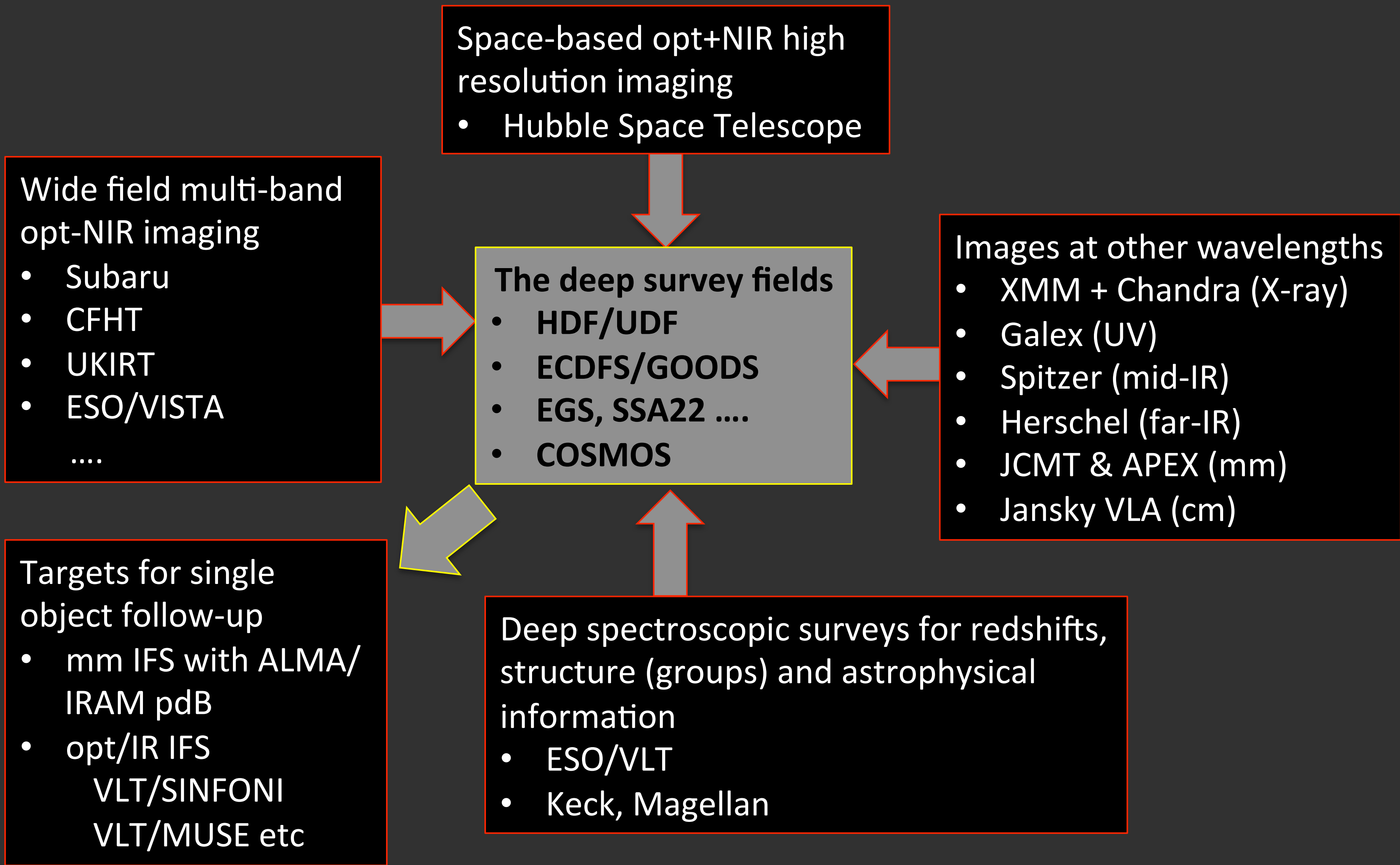
- AGN energy injection into halo gas
- Hot/cold accretion of gas driven by halo physics
- AGN or SN ejection of gas from galaxies
- Structural quenching

Origin and role of structure and morphology?

Clearly important but unclear:

- Most SF in rotating disks (but higher σ, clumpier, at high z)
- Dense old bulges present at z = 2.5
- SF galaxies (and quenched passives) denser at high z (as are their haloes)

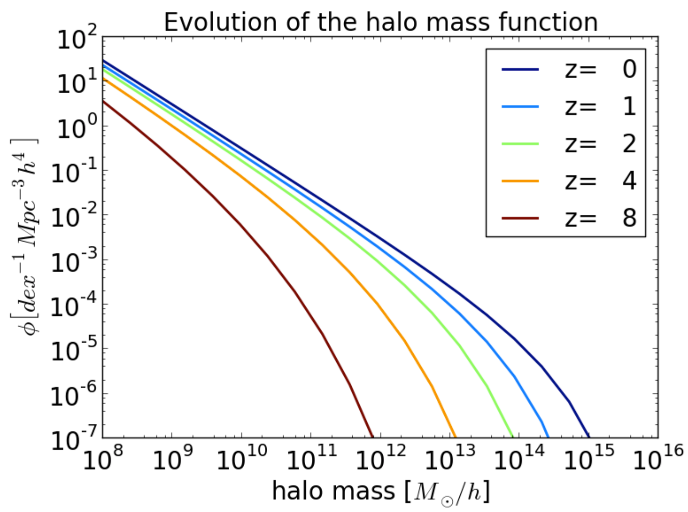
The global high-z multi-wavelength observatory "system"



But at least two reasons to expect z > 2.5 to be different

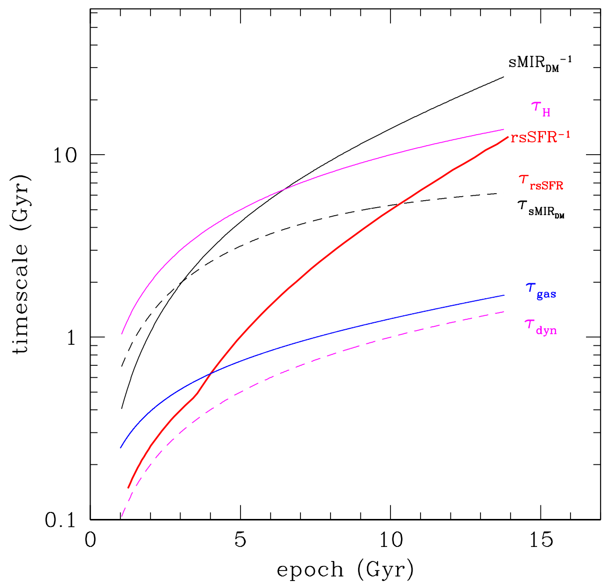
Halo mass M* is comparable to galaxy M*

- Biggest changes to halo φ(m) are occurring on galactic rather than group/cluster scales as later. Buildup in global SFRD due to increasing number of 10^{12} M haloes
- Distinction between mergers and accretion becomes blurred, increasing importance of mergers in build-up of mass (also BH mass vs. AGN?)
- Galaxy φ(m) set by halo φ(m) not by quenching
- "Environment" effects in $m_{halo} > 10^{12}$ increasingly unimportant



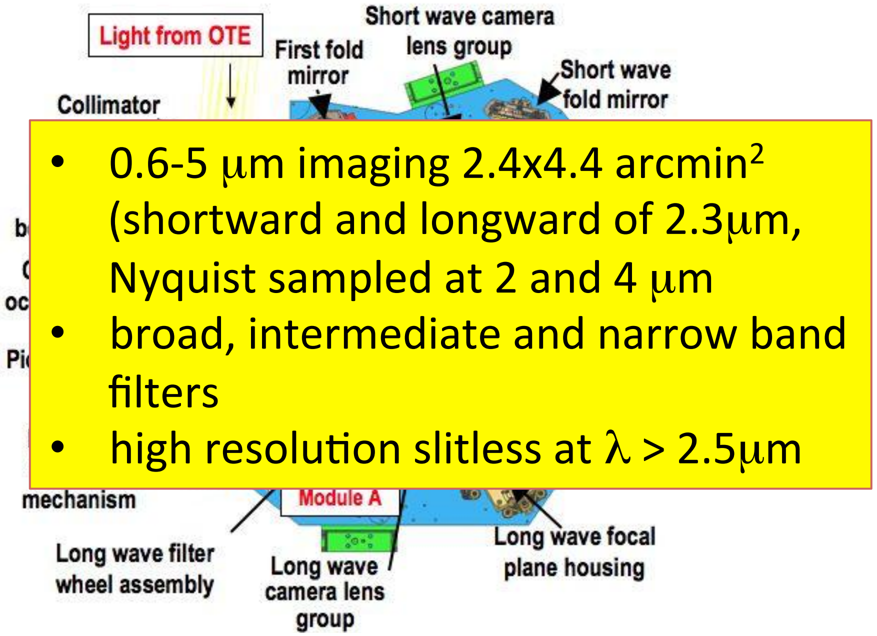
Gas depletion timescale (i.e. inverse of SF efficiency ε^{-1}) becomes comparable or longer to mass increase timescales, dynamical timescales etc.

- Simple gas regulator picture likely to break down
- Loss of "Main Sequence", more episodic SF?



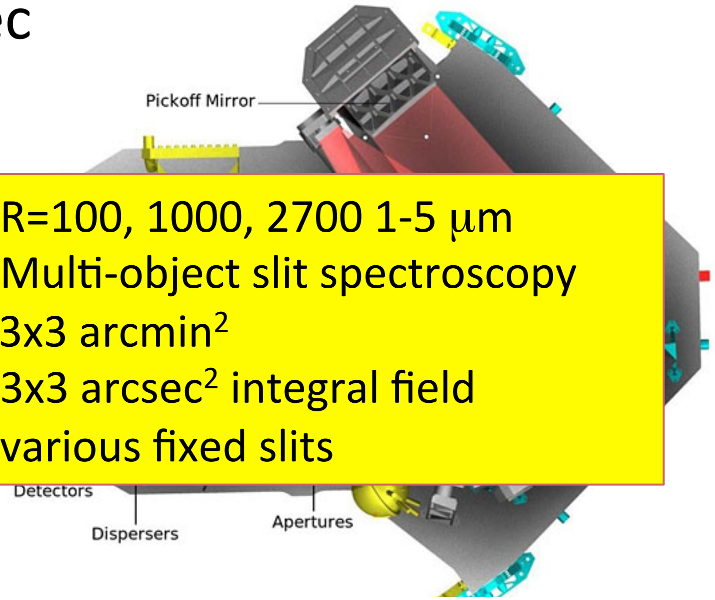
James Webb Space Telescope

NIRCam



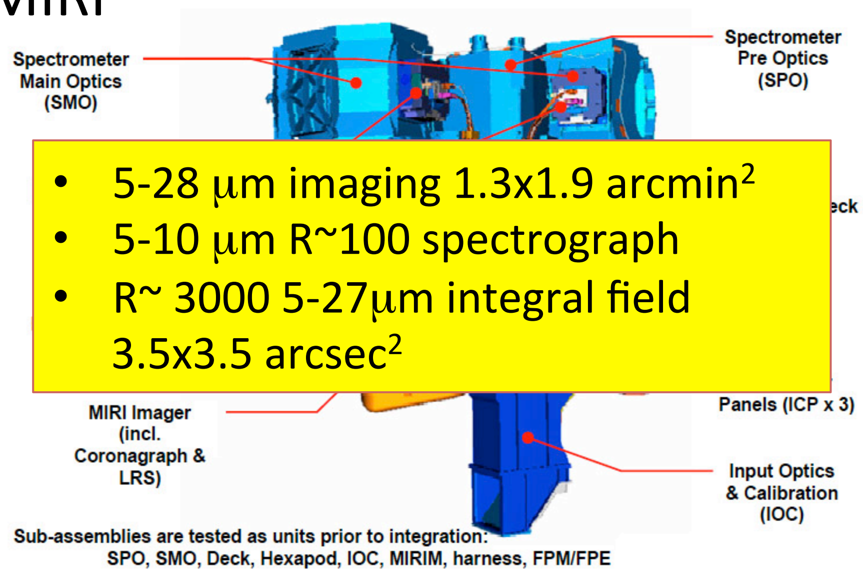
- 0.6-5 μm imaging 2.4x4.4 arcmin^2 (shortward and longward of 2.3μm, Nyquist sampled at 2 and 4 μm
- broad, intermediate and narrow band filters
- high resolution slitless at λ > 2.5μm

NIRSpec



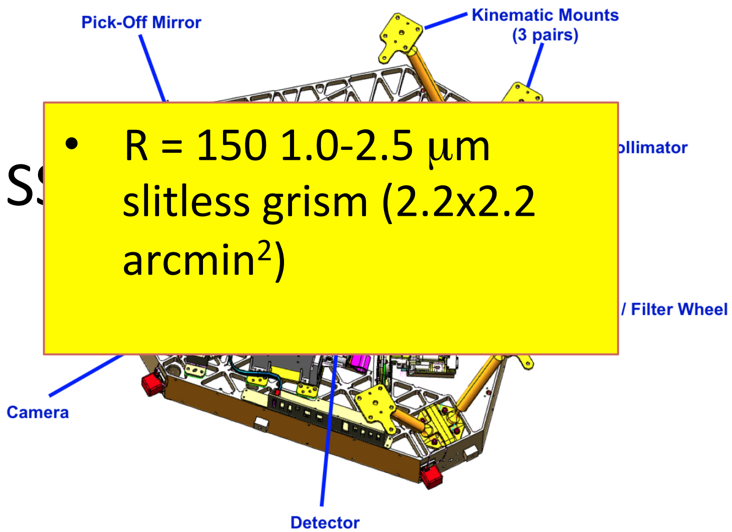
- R=100, 1000, 2700 1-5 μm
- Multi-object slit spectroscopy 3x3 arcmin^2
- 3x3 arcsec^2 integral field
- various fixed slits

MIRI



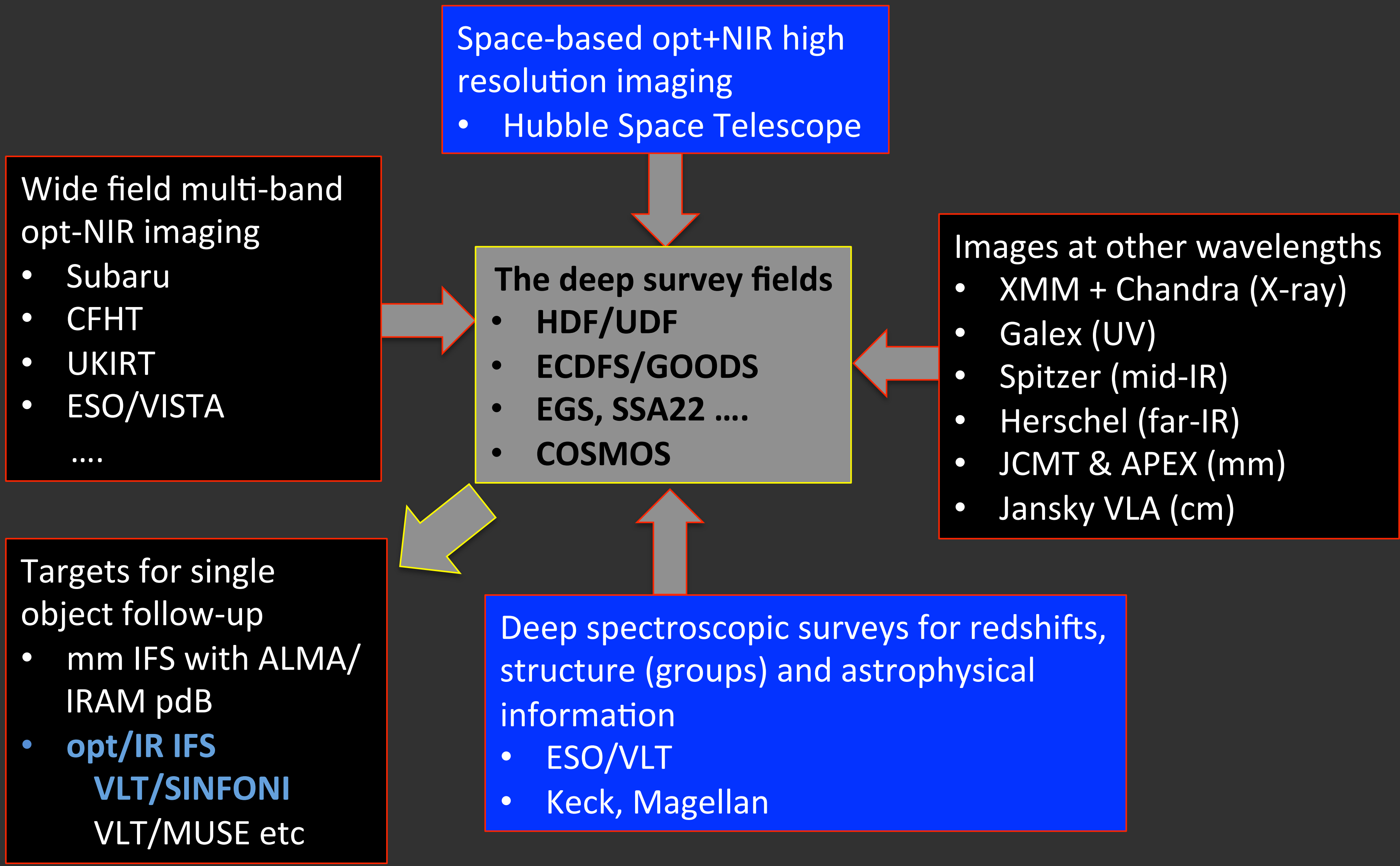
- 5-28 μm imaging 1.3x1.9 arcmin^2
- 5-10 μm R~100 spectrograph
- R~ 3000 5-27μm integral field 3.5x3.5 arcsec^2

NIRISS



- R = 150 1.0-2.5 μm slitless grism (2.2x2.2 arcmin^2)

The global high-z multi-wavelength observatory "system"



Observational Goals for Assembly of Galaxies

(-) Redshifts

- Photo-z from multi-colour photometry
- Single line(?) spectroscopy

(A) Build up of structural components, i.e. Spatially resolved stellar populations and galactic structure, star-formation efficiencies, and metallicity as diagnostic

- Multi-color kpc-scale imaging above and below 4000 A
- Kpc scale Hα and molecular gas distribution (e.g. ALMA)
- Spatially resolved em. line ratio maps
- Spatially resolved atomic (and molecular) gas kinematics (R > 1000)
- Spatially resolved absorption lines
- Atomic H content

(B) Outflows

- Kpc-scale Hα (+CO?) gas kinematics (R > 1000) also uv/opt absorption-lines

(C) Merging

- Multi-color kpc-scale imaging above and below 4000 A
- Low resolution em. line and molecular gas kinematics

(D) Inflows

- Mostly Lyman α emission and absorption (e.g. MUSE/VLT)

(E) AGN

- Emission line ratios and diagnostics
- Deep X-ray (and radio) catalogues

Obvious extragalactic survey programs

There will certainly be Wedding Cake imaging surveys in well-known extragalactic fields

- UDF
- 0.04 deg2 GOODS-S
- 0.2 deg^2 total CANDELS
- 2 deg^2 COSMOS? (will require a *lot* of time, of order 1000 NIRCam pointings)

With more limited areas for deep spectroscopic follow-up

Note: GTO programs (currently being defined) will only be a start (probably focusing on deeper observations of small areas rather than large "public surveys")

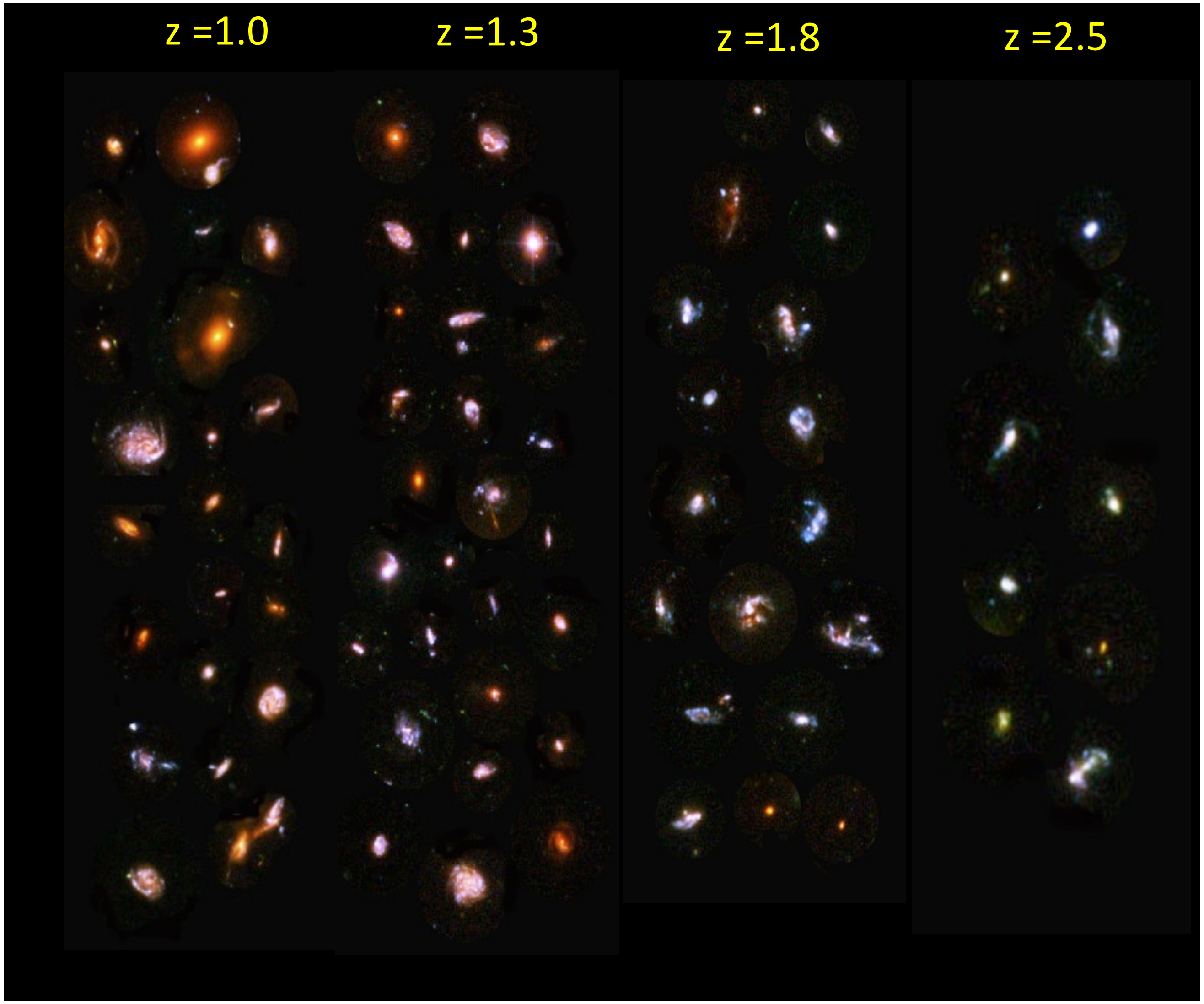
A few general thoughts

Similarities:

We will be doing everything we have been doing with HST in imaging and slitless spectroscopy at much higher redshift with JWST

Factor of 2.5 in mirror diameter → same resolution at 2.5x longer wavelength (i.e. rest-V is 1.6μm @ z = 2 and 4μm @ z = 6.5)

→ effective gain in sensitivity 1.6 mag (incl. lower zodi) c.f. ΔDM = 2.2 (z = 2.5 to z = 6)



courtesy Alan Dressler

A few general thoughts

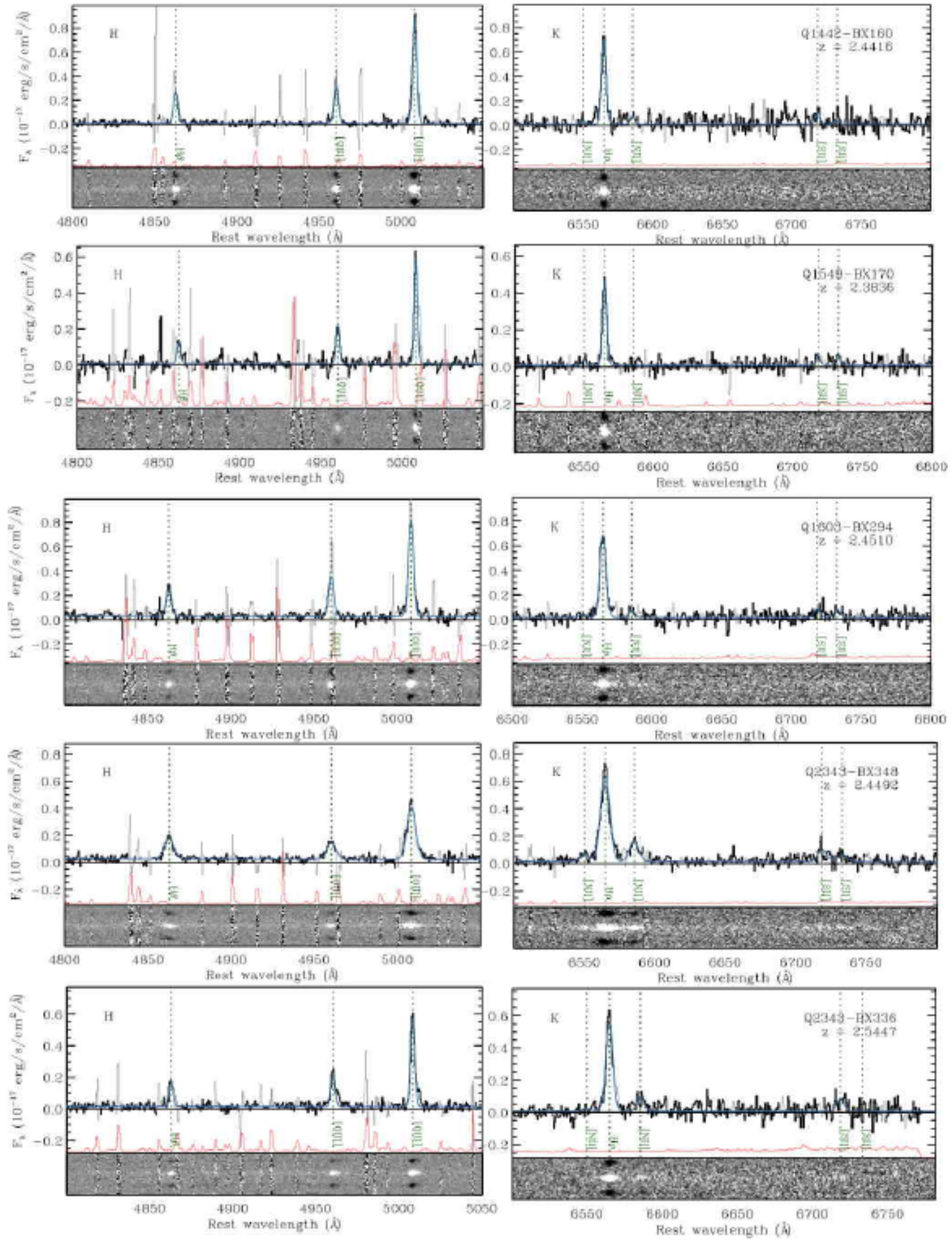
Differences

JWST spectroscopy will be much more important than HST spectroscopy has been (outside of the ultraviolet).

Ground-based deep spectroscopy from the ground (so far $\lambda < 2.5$ μm) is possible with 8-m but is very painful

NIRSpec will provide

- "large-scale" surveys of emission line redshifts and line diagnostics/metals with a high completeness out to 5 μm
- detailed "SINFONI-like" kinematic and diagnostic/metal maps out to 5 μm with NIRSpec and longer with MIRI



Challenges

The (only?) observational challenge

JWST will have a much wider effective spectral range than HST.
Interpretation of 2-d information from photometry and spectroscopy will require careful treatment of variable psf

The main challenge

How to synthesize the new information to give convincing astrophysical answers to long-standing questions?

Summary

- JWST will form an enabling component of the global system of facilities for studying galaxies at high redshift ($2 < z < 7$)

- Longer wavelength imaging with same (kpc) resolution as HST and with commensurate gains in sensitivity enables $z \sim 2$ studies out to $z \sim 6$

- We still have more questions than answers in this field. JWST will produce a mass of new "information": Much improved
  - galaxy internal structures (mass, SFR history etc across galaxies)
  - kinematic maps
  - metallicities and other astrophysical diagnostics

  Challenge will be to synthesize this into astrophysical understanding