# Open Questions in Galaxy Evolution

# A Subaru GLAO perspective

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# Outline

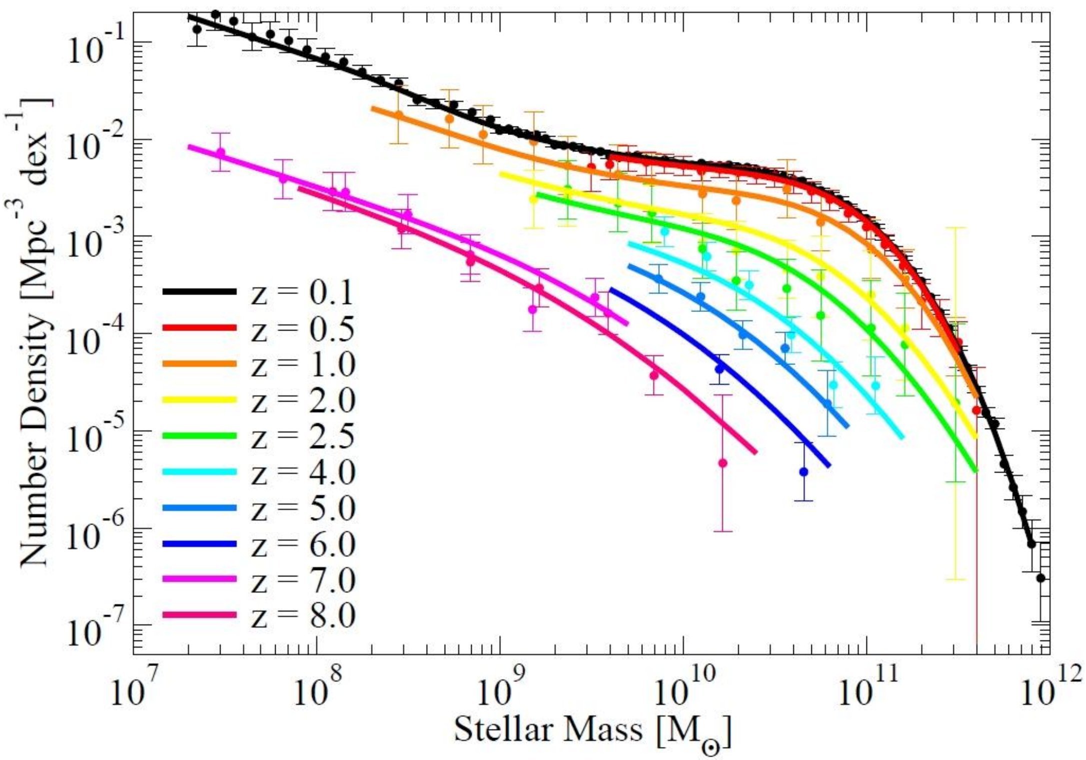
1. Current picture of galaxy evolution
2. Some unanswered questions
3. The role of Subaru GLAO
    - High-resolution IR imaging
    - Spectroscopy or NB imaging?
    - A proposed survey

# What is galaxy evolution?

- Galaxy mass
  - NIR useful for z<1 but essential at z>2
  - Multiple filters required for SED fitting
  - Dynamical masses with IFU spectroscopy
- SFR
  - rest UV (uncertain dust corrections)
  - far-IR emission (only high-SFR galaxies)
  - Emission lines.  Sensitive and yield precise redshift
- Halo masses
  - HOD models
  - Abundance matching
  - Velocity dispersions of galaxy systems
- Merger rate
  - From close pair analysis
  - Morphological disturbance
- Sizes and morphologies
  - High resolution imaging, preferably in the rest NIR
- Metallicity
  - Gas phase from emission lines
  - Stellar from absorption lines

# Evolution of SMF

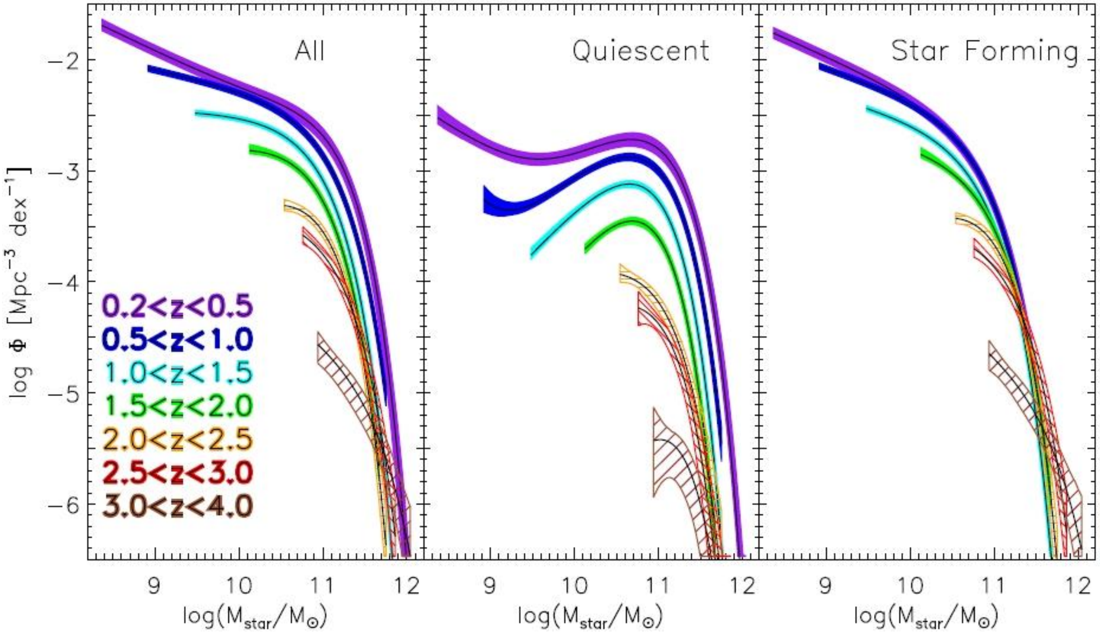
- Both massive and low-mass end poorly constrained at z>2

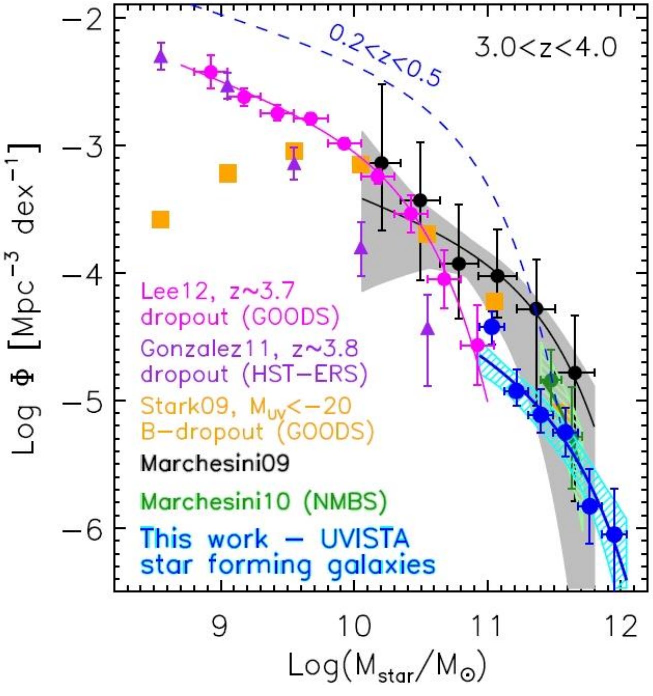



Behroozi et al. (2013)

# Evolution of SMF

- Most of the evolution in quiescent population



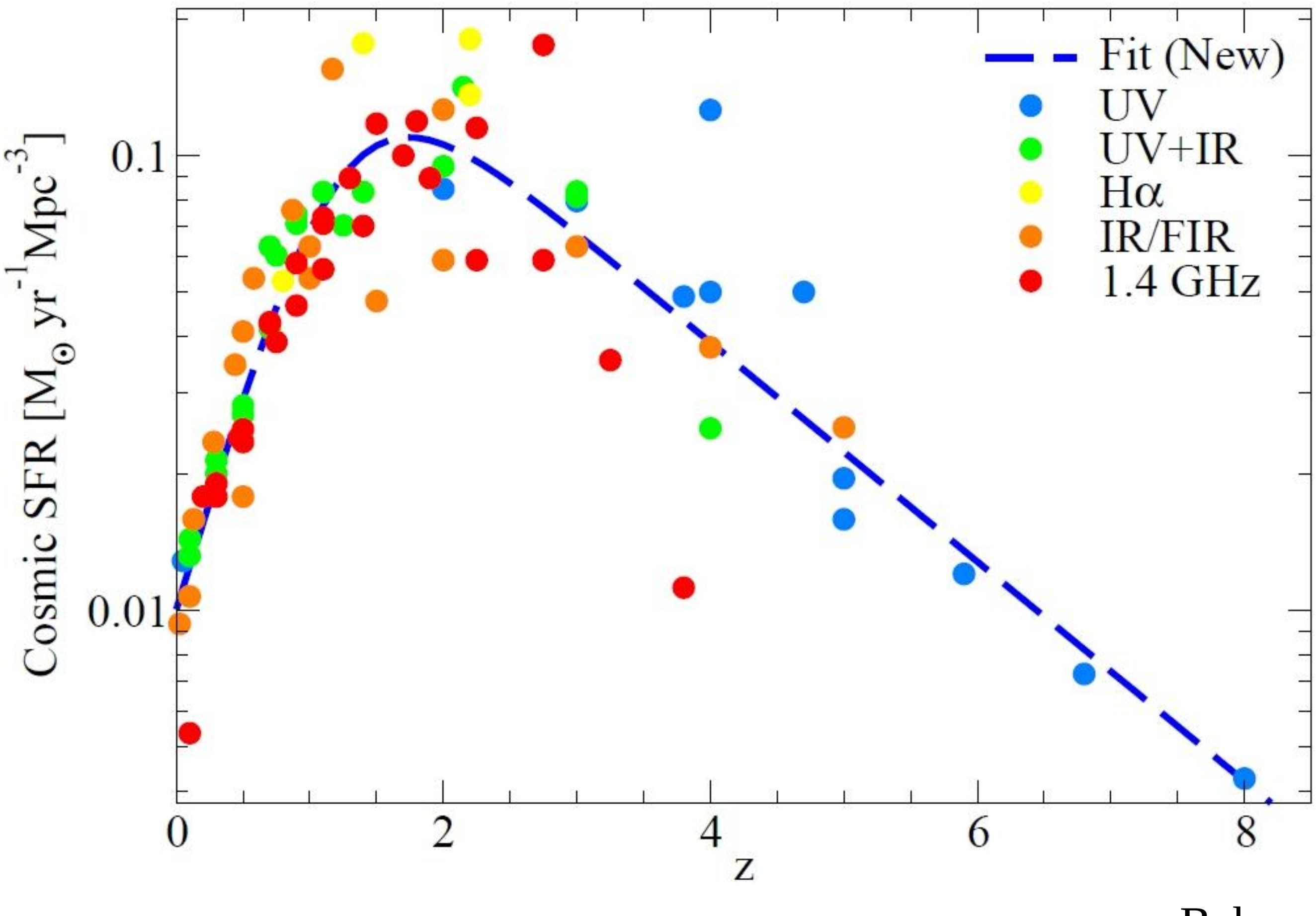




Ultravista: $K_{AB}$<24 over 1.6 sq deg

Muzzin et al. (2013)

# Evolution of cosmic SFR

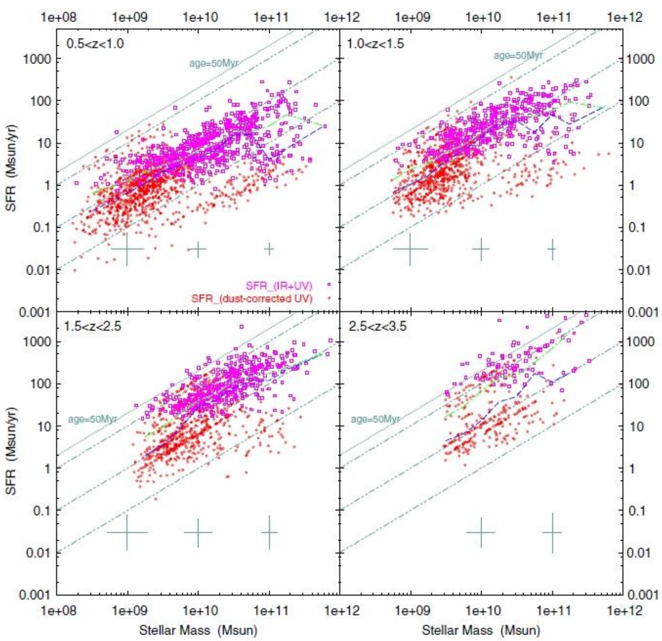
- Still poorly constrained at z>1.



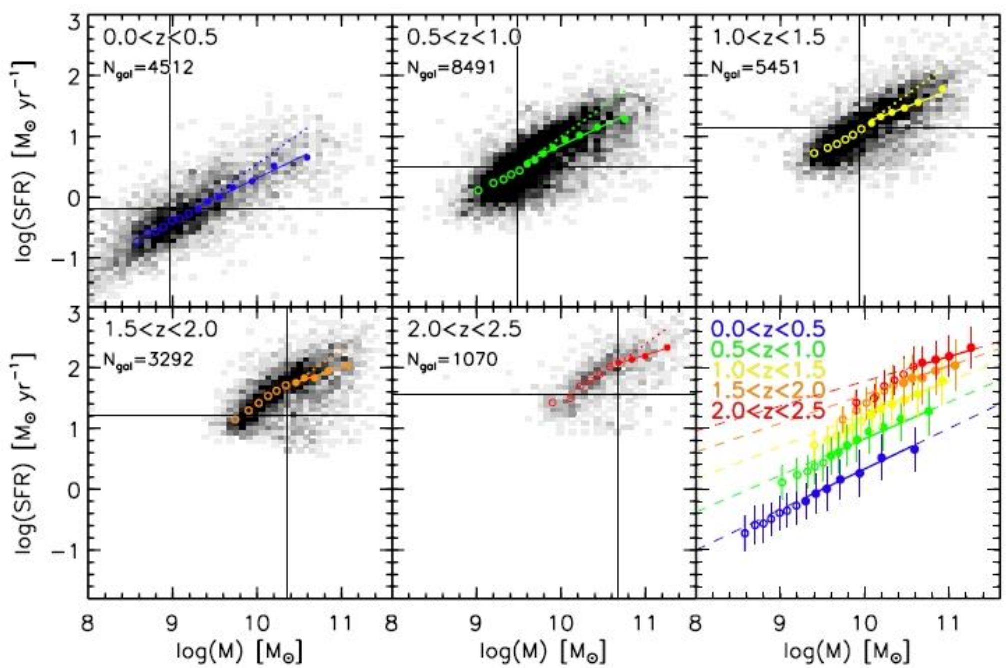

Behroozi et al. (2013)

# SFR-mass relation

- A key diagnostic. Low-mass end only constrained at low-z



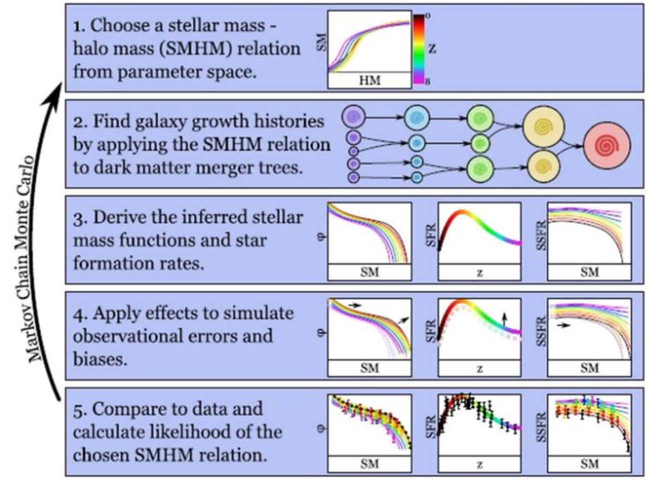

Kajisawa et al. (2010)

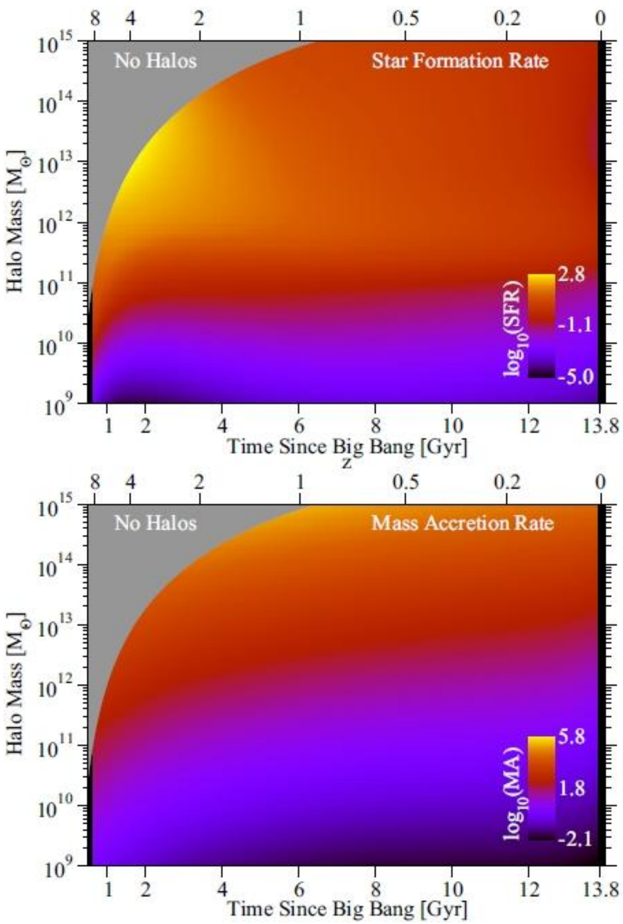


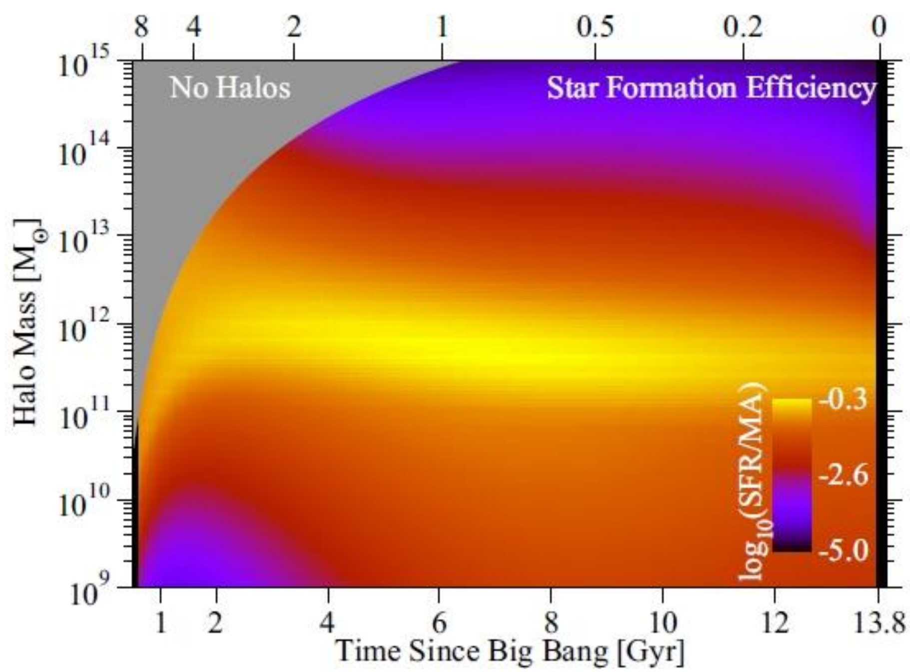

Whitaker et al. (2011)

# The halo model

- Shows star formation to be most efficient in Milky-Way mass haloes, at all times

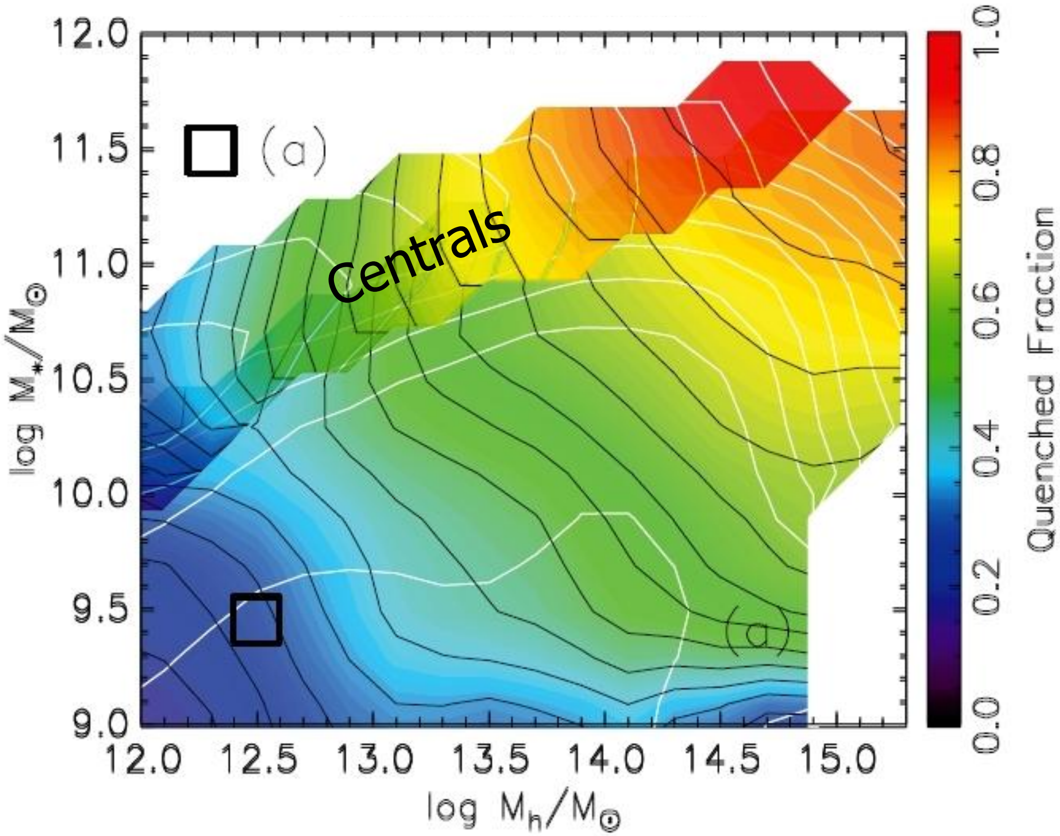


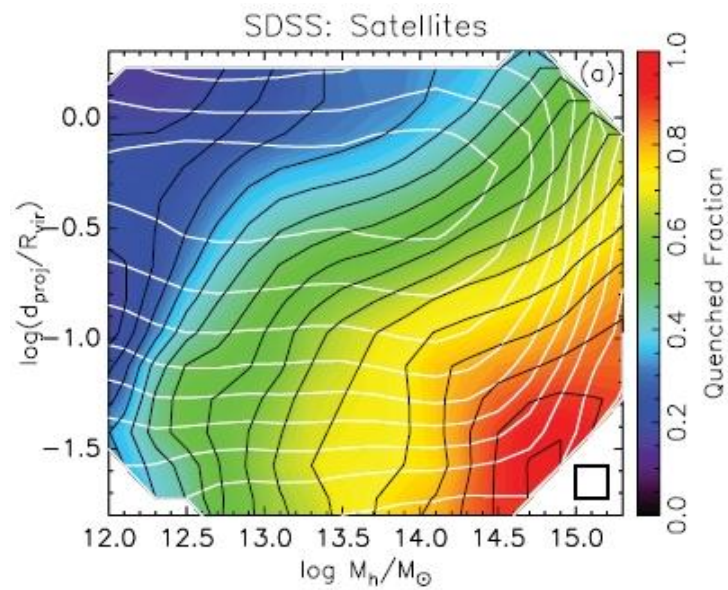

Behroozi et al. (2013)

# Satellite galaxies



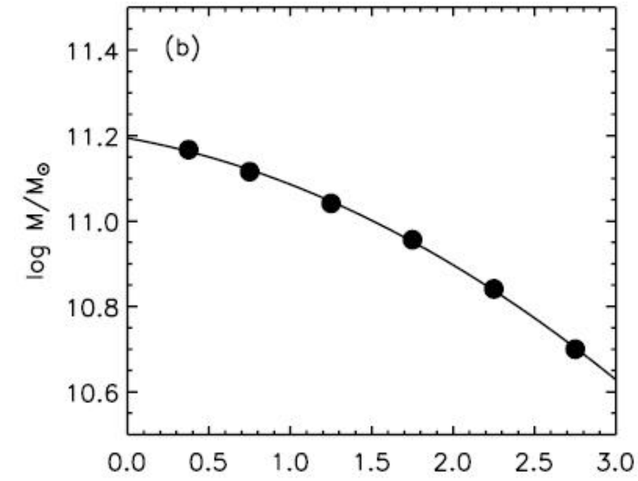

SDSS: Woo et al. (2013)

- Galaxies have a weak dependence on halo mass and location within a halo

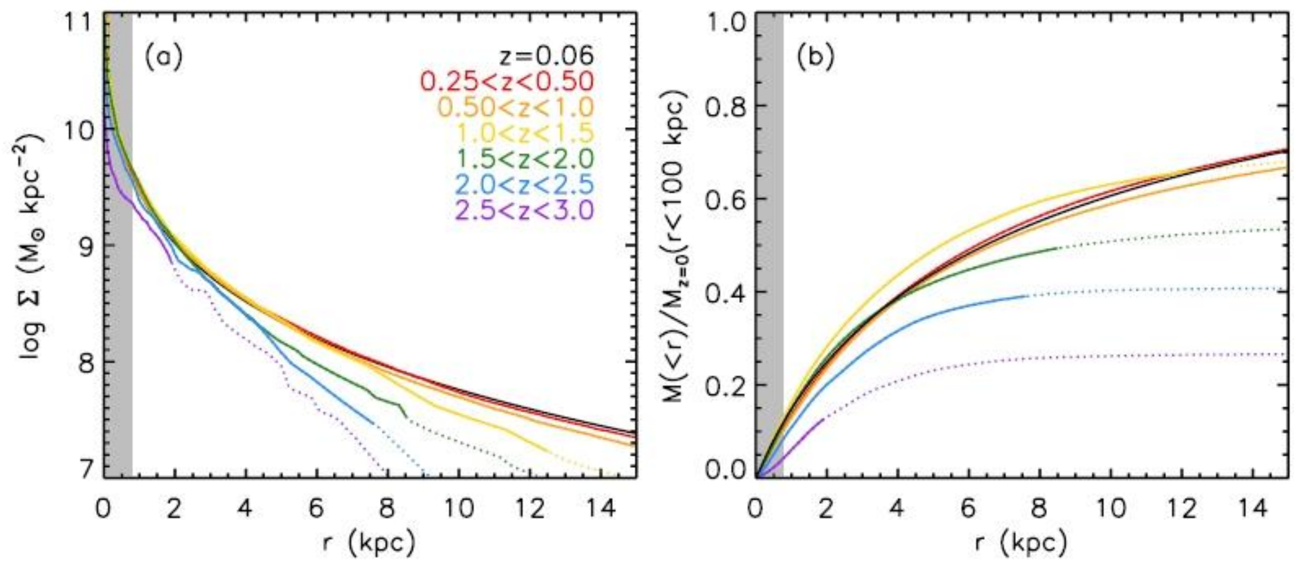


# Size growth of massive galaxies

- CANDELS: $H_{AB}$<26.5 over 0.2 sq degrees
- Match galaxies at fixed space density




- Massive galaxies grow inside-out, suggesting minor mergers




Patel et al. (2013)

# Some outstanding Questions

## What is the physical meaning of these observations?

- Why do low-mass galaxies form so much later than predicted by ab-initio models?
- What drives quenching?
- What drives the scatter in $M_{star}$-$M_{halo}$ relation?

## Are our assumptions correct?

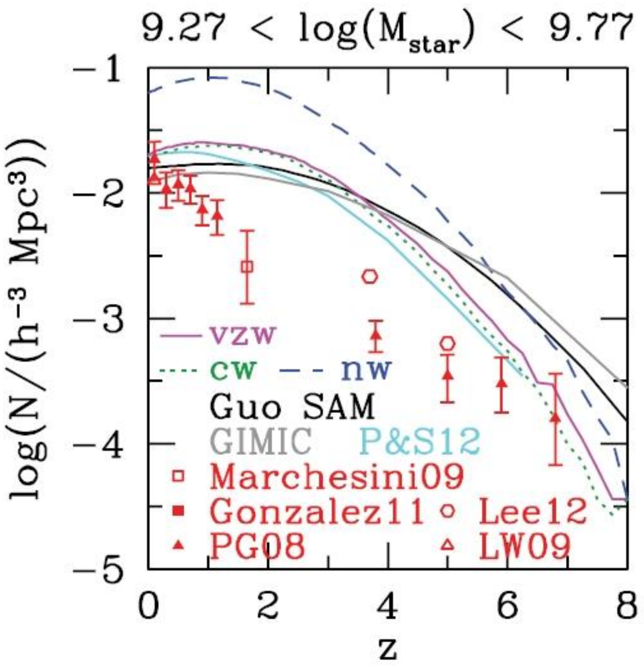
- Is galaxy evolution really driven by a single parameter? Is it stellar mass, velocity dispersion, or something else?
- Is the IMF universal?
- Is the central/satellite distinction correct?

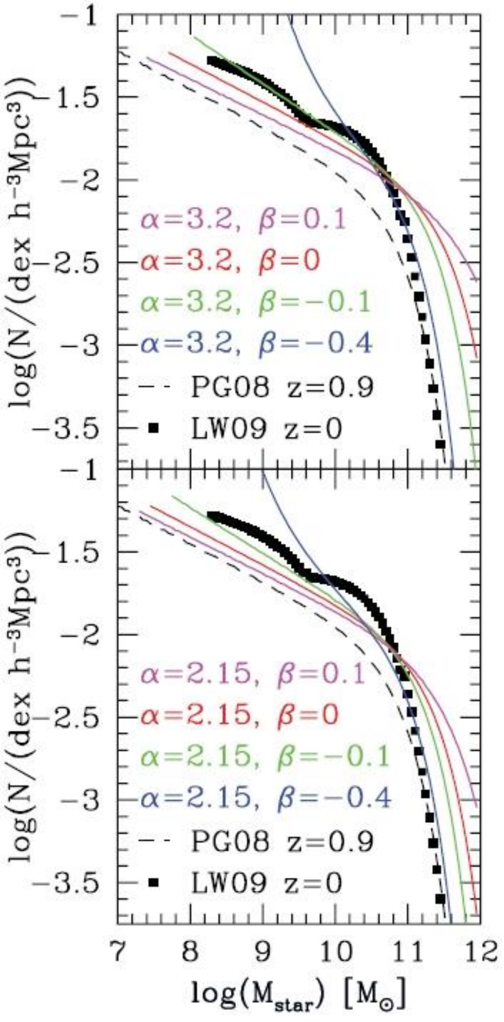
## Can we observationally test predictions of the HOD/AM models?

- What is the merger rate as a function of mass and time?
- What does the $M_{star}$-$M_{halo}$-SFR relationship look like at $z>0$?
- What are the gas-phase and stellar abundances of $z>2$ galaxies?
- What is the SFH of satellite galaxies? Is there a role of galaxy or halo dynamics?

# Why do low-mass galaxies form so much later than predicted by ab-initio models?

- Closely linked to slope of SFR-mass relation
- Requires either preventing gas from accreting, or efficiently expelling.

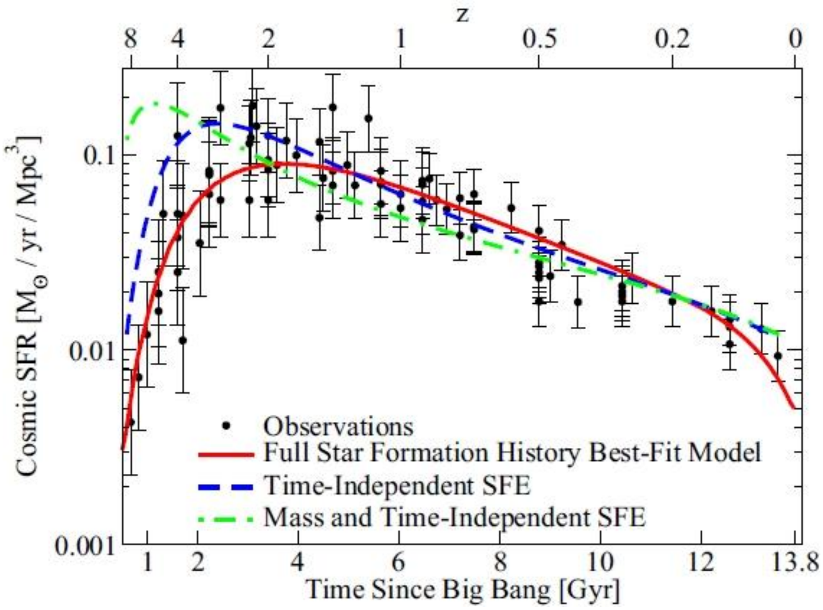



Weinmann et al. (2012)

# Low SFE in low-mass galaxies at high redshift

- At late times the decline in SFR is related to the declining infall rate.

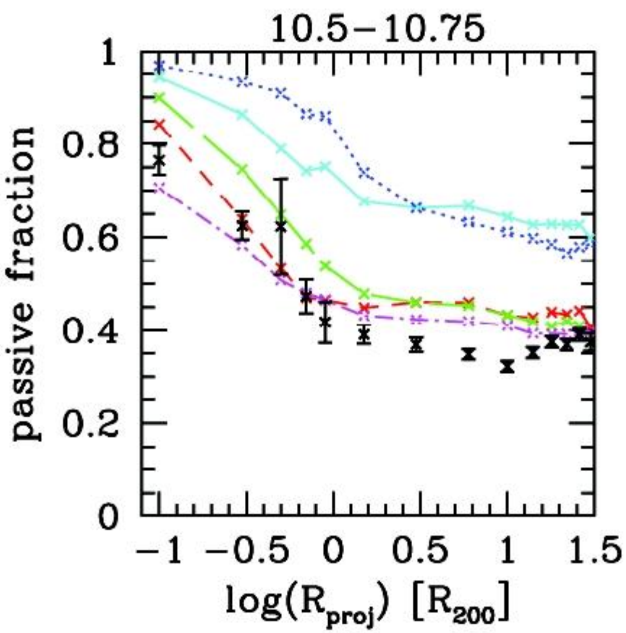


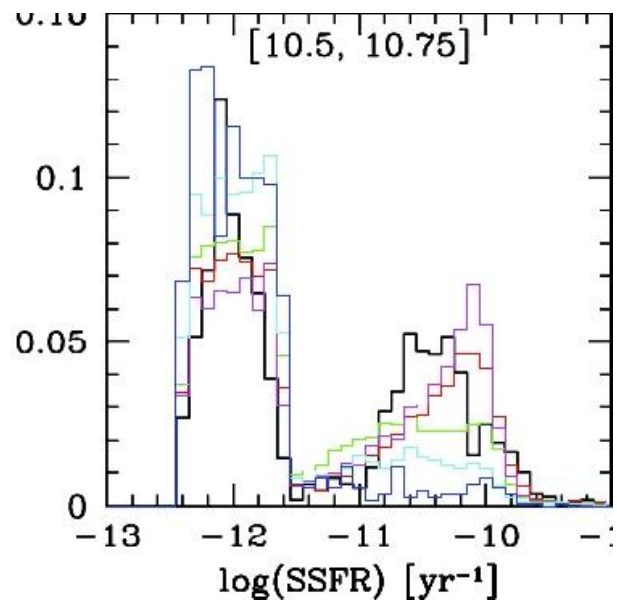

Behroozi et al. (2013)

- Cosmic SFR is sensitive to the physics of galaxy formation at z>2
- A constant efficiency leads to too much SF in low-mass galaxies at high redshift
- Star formation must be significantly decoupled from dark matter assembly

# Why does satellite quenching appear to be very efficient, yet not all satellites are quenched?

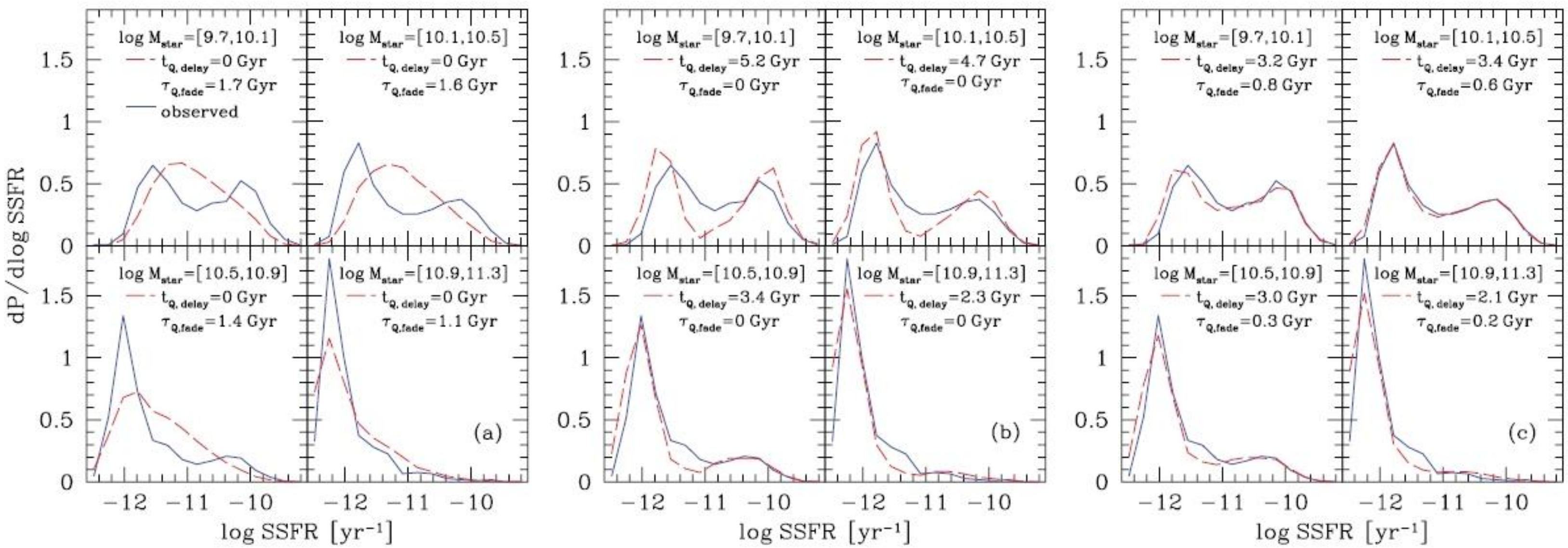
- Models which reproduce the observed quenched fraction do not reproduce the observed SFR distribution



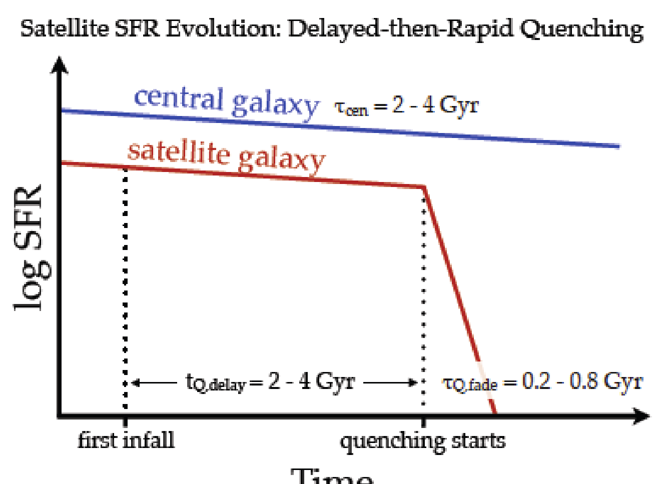

Weinmann et al. (2010)

# Satellite galaxy SFH

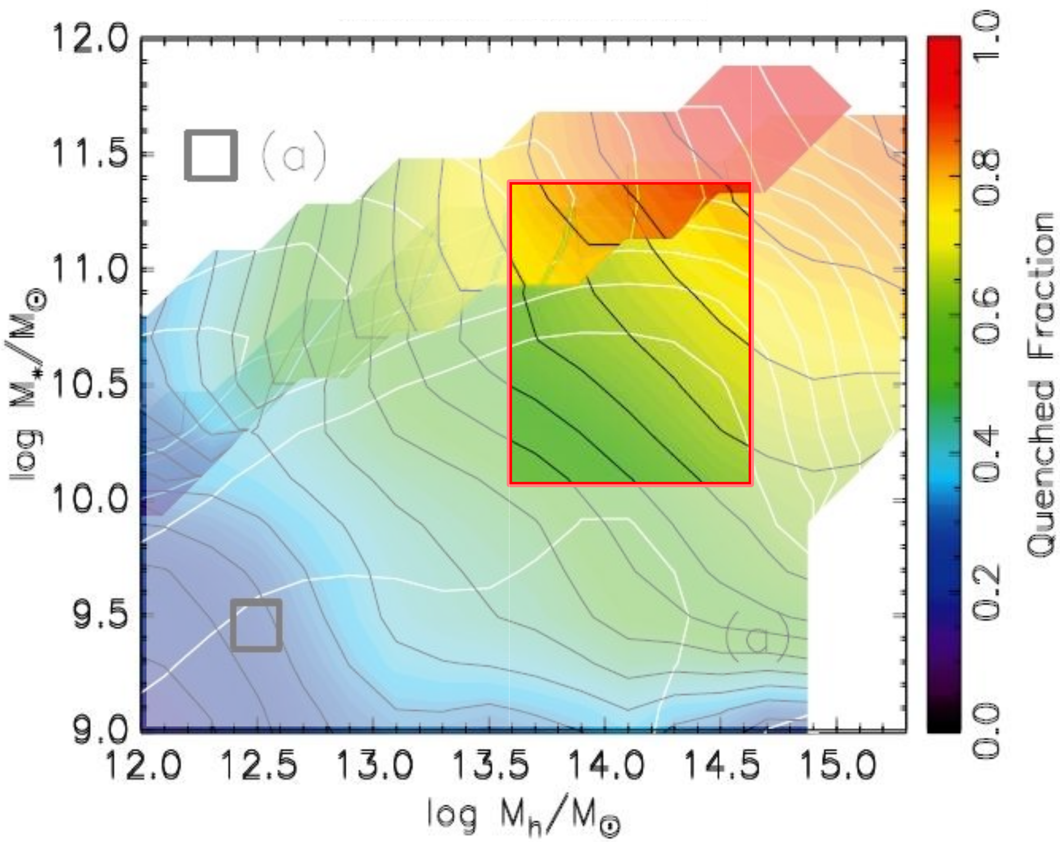



Wetzel et al. (2013)

- Matching detailed SFR distribution and quenched fraction simultaneously is difficult
- Success here with a delay+rapid quenching model
- Requires measuring SFR at <0.1 $M_{sun}$/year
- This cannot be constant with time (Mok et al. 2013)



# What do the established correlations at z=0 look like at higher redshift?




- We have only begun to sparsely sample the parameter space at z>0.5

# What do we need?

- Large statistical samples
  - Correlations between several key parameters and their scatter
- Depth
  - Need better understanding of low-mass galaxies and low SFRs.
- Good measurements of redshift, stellar mass, SFR, metallicity, merger rates

# Subaru GLAO: High Resolution Imaging

## Contributions

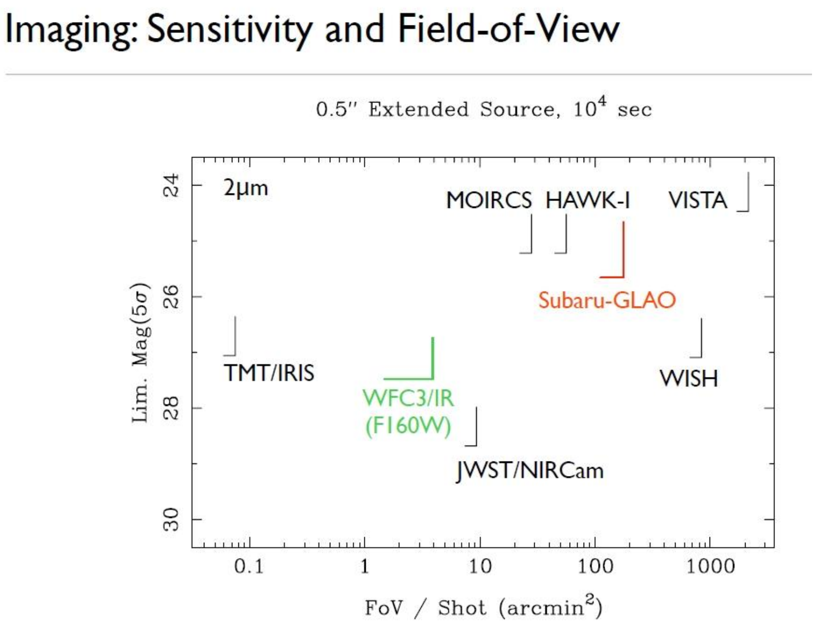
- Deep NIR imaging required for stellar mass estimates at z>2
- Can address merger rate directly (through asymmetries) and indirectly (size growth)
- Identify targets for JWST/TMT follow-up

## Competition

- CANDELS:
  - 668 sq arcmin H<26.5 (AB)
  - 120 sq arcmin H<27.2
  - 0.19″ spatial resolution
- Euclid (2018)
  - 20,000 sq deg K<24
  - 0.3″ pixels
- WISH (2020?)
  - 100,000 sq deg, K<27 (extended source)
  - 0.15″ sampling

# Subaru GLAO Broad-band imaging

- Reach CANDELS depth in ~5h exposures
  - Reproduce CANDELS in ~20h. Would need >200h to make an order of magnitude improvement in area
  - Or: cover 10 sq deg at AB=25.6, 1.6mag deeper than Euclid.
- Compare with HSC Deep: $r_{AB}$=27.2 over 30 sq deg.




Will be eclipsed by WISH. Even JWST will have superior mapping speed (though limited mission lifetime).

# NIR Spectroscopy

## Contributions

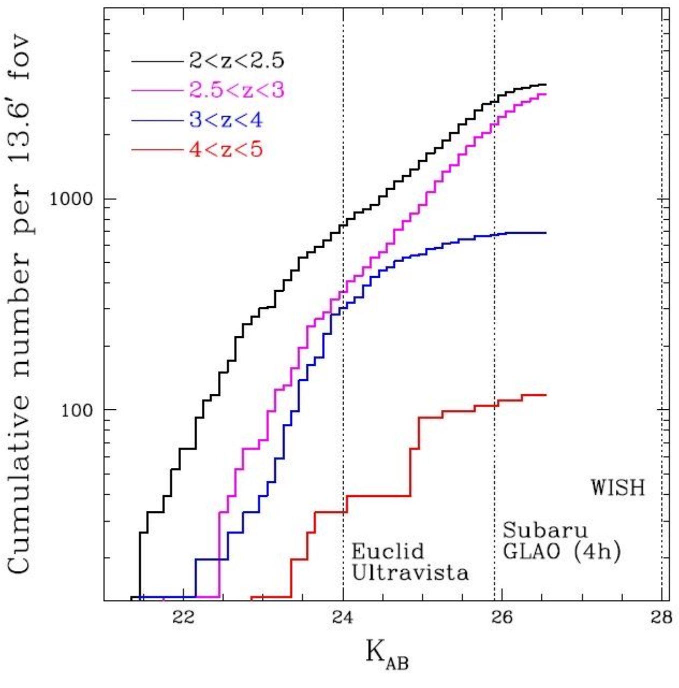
- Measurement of SFR-mass relation
  - Precise redshifts help remove biases
  - Emission lines are sensitive SFR measures
- Groups and clusters
  - dynamical halo masses
  - Satellite galaxy evolution
- Gas phase abundances
- Stellar abundances (hard from ground)

## Competition

- Extra depth and FOV gives advantage over Flamingos-2, MOSFIRE, KMOS
- TMT and JWST will do much better for individual objects

# Abundance of z>2 galaxies

- Number counts expected in a 13.6′ FoV
- Based on MOIRCS Deep survey (28h in K)

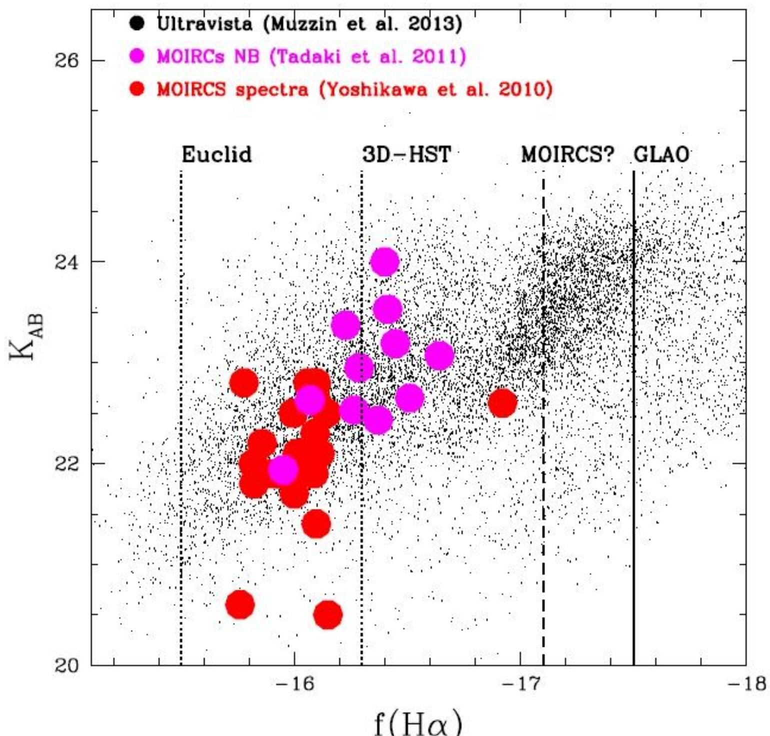


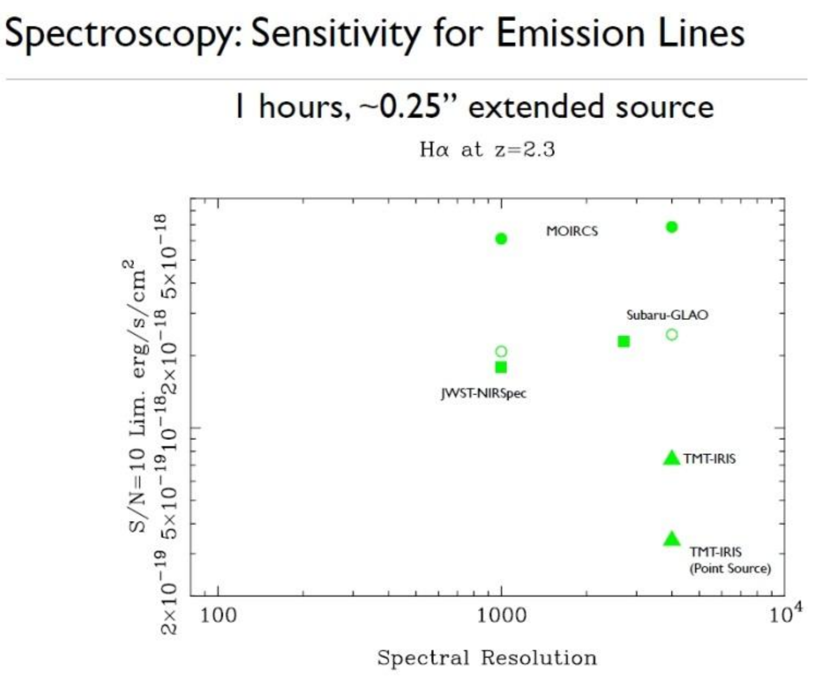

- About 700 galaxies per field at K<24
- Need 2-3 MOS masks per field to reach 50% completeness.

MODS: Kajisawa et al. (2011)

# Emission-line galaxies

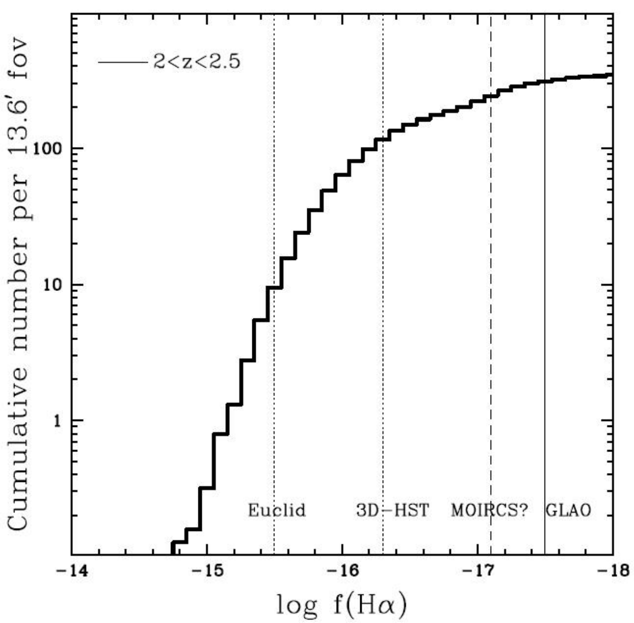
- Predict Hα and [OII] fluxes from Ultravista (K<24) SFRs
- Current MOIRCS spectroscopy does not probe the main sequence of SF



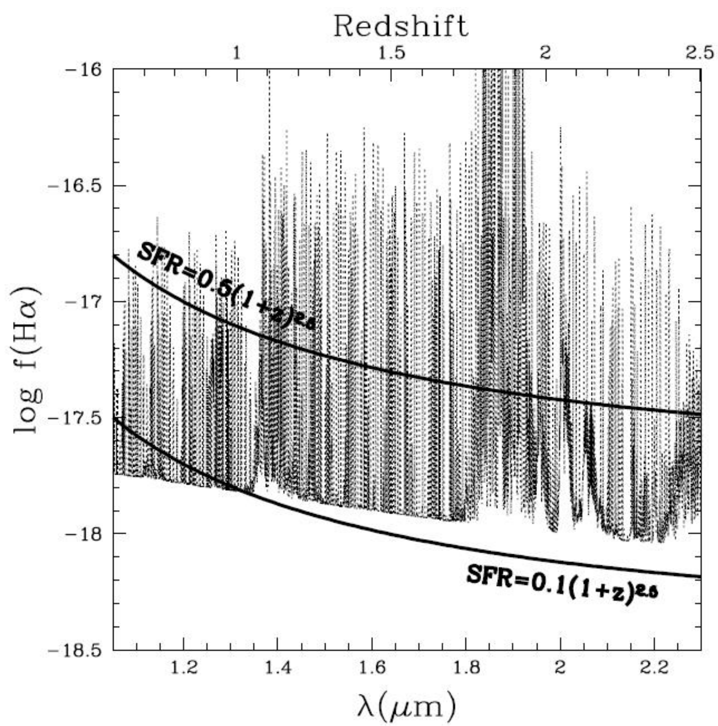



# Hα emission at 2<z<2.5

- Targets selected from K<24 survey
- 4h integration; very rough calculation.
- See yesterday's talk by Yusoke Minowa for more accurate numbers!



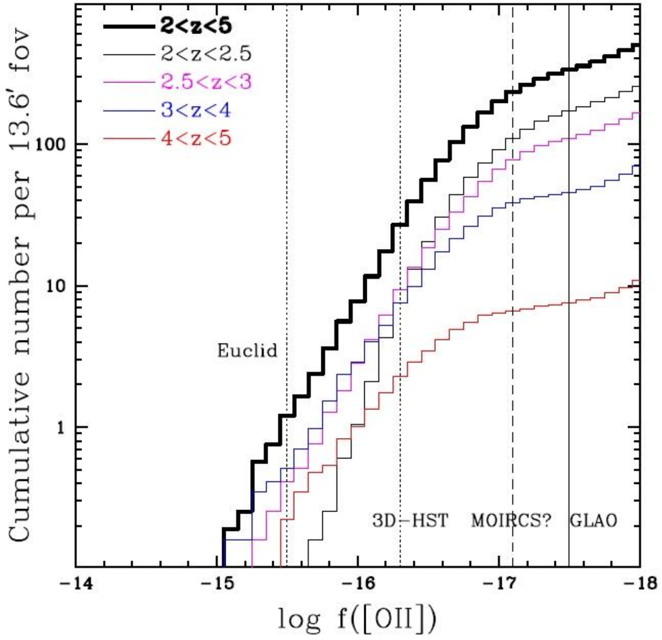

200-300 emitters per field. Fairly well matched to MOS if they can be efficiently preselected

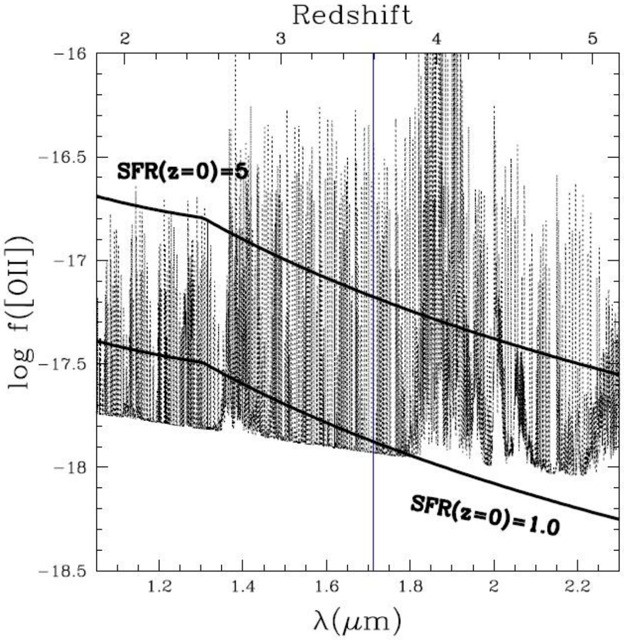



Can reach ~1 $M_{sun}$/year and sample well the main sequence of star formation

# [OII]-[OIII]

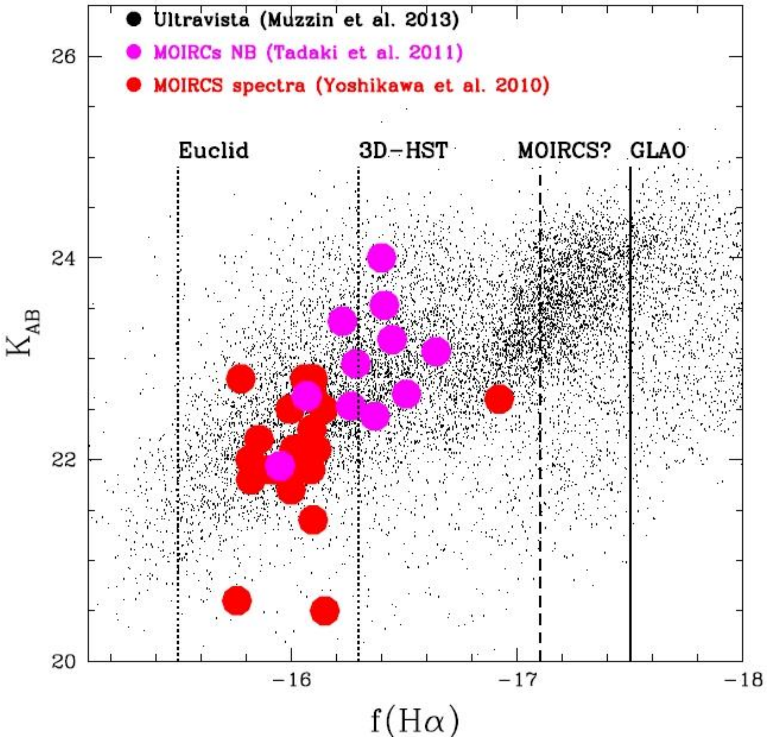
- Number of [OII] emitters per field at 2<z<5 is also reasonably matched to number of slits in a GLAO MOS.
- For 2<z<3.6, access to [OIII] and Hβ



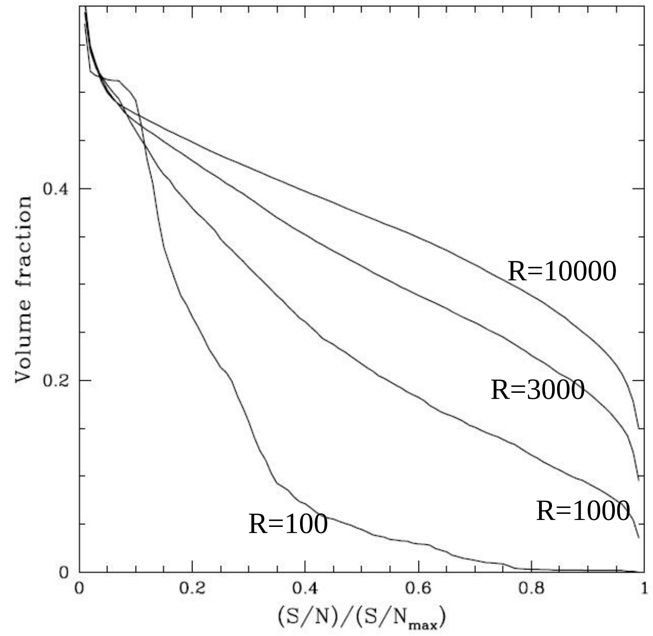
# Spectra or Narrow-band?

- At GLAO depths there will be many emitters with K>24
  - These might be more efficiently recovered with NB imaging; need sufficiently deep BB imaging as well.
- Source density will require 2-4 MOS masks to be complete

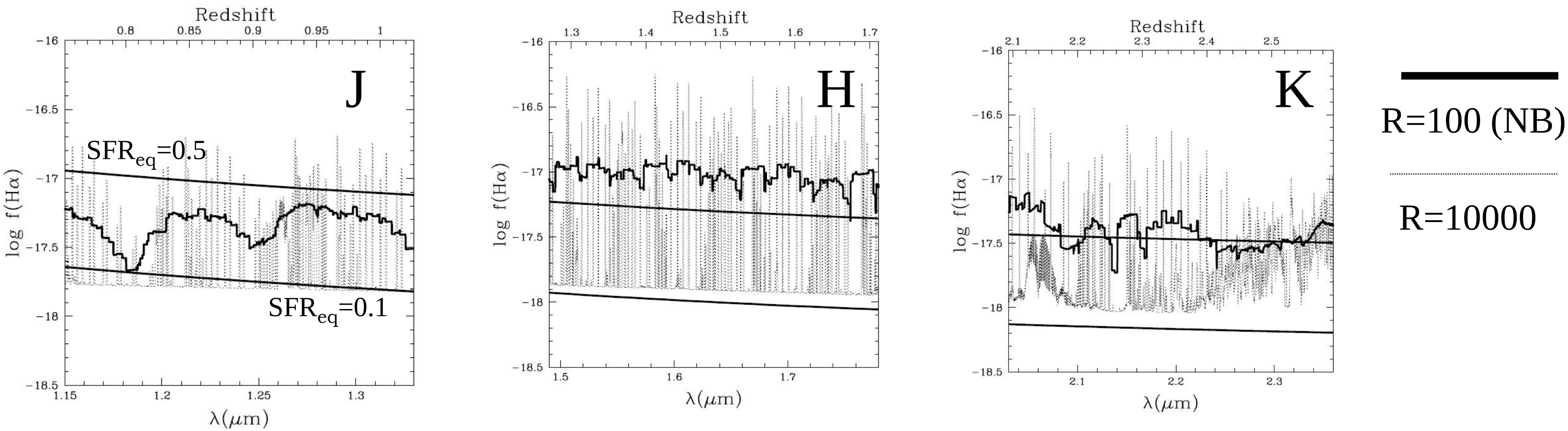


# Spectra or Narrow-band?

- Increasing resolution increases the amount of dark sky.
- For deepest limits moderate-resolution spectroscopy has an advantage
  - Caveats: slit losses and line widths




R=3000 provides 10% of the wavelength range at darkest levels. 10x volume probed by single 20nm NB filter.



# Proposed Survey

- Spectroscopic emission line survey.
  - 4h exposures to reach unprecedented depths
  - Target 2<z<5 galaxies with $K_{AB}<24$
    - $H\alpha$: 300/FoV with 2<z<2.5
    - [OII]: another 200/FoV
      - Will include $H\beta$, [OII] for z<3.6
    - Expect detection rate ~75%
  - Cover (e.g.) COSMOS (1.6 $deg^2$) in 25 pointings.
    - 2 masks in each pointing (~50% completeness).
    - 240h with overheads.
    - 5500 emission line detections (assuming 150 slits/mask).

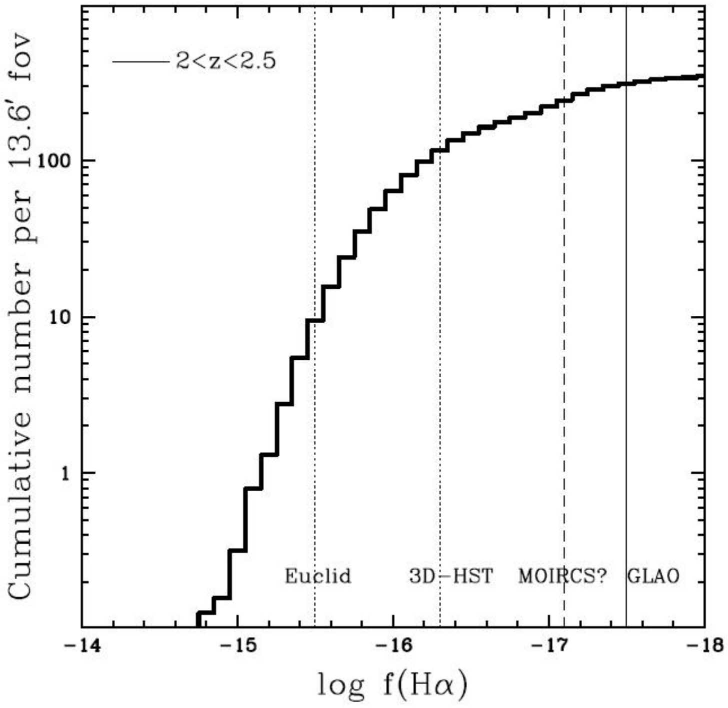
# Questions

1. Which instrument is essential?
   - Multi-object spectrograph. Provides most sensitive measurement of SFR, redshift. Unique.
     - Multi-IFU could be very beneficial if it improves overall throughput. But with only 24 IFUs it is poorly matched to the target density.
     - Narrow-band imaging or tunable filters could be a good alternative to obtain large samples of emission line galaxies. Needs a more careful analysis than I've done here.

# Questions

2. What is the optimal plate scale?

- Widest FoV so 0.1"/pix
- With MOIRCS FoV (4x6) only 10% of the area.
  - Source density might be a bit better matched to the smaller area (~40 objects per field) but same completeness reached with 3-4 masks over the larger field. Still wins.



# Questions continued

4. JWST/Euclid/WISH
   - Euclid/WISH/JWST will measure mass function well
     - Potentially good for providing targets, but GLAO survey unlikely to cover more than a few square degrees anyway
   - JWST follow-up for gas and stellar metallicity measurements (for example)
     - From the ground there is very limited redshift range over which multiple lines are visible to low levels.  Stellar absorption lines very difficult
   - NIRSPEC FoV is not small: 9 sq arcmin.  20 times smaller than ULTIMATE-Subaru but increased sensitivity makes up for that.
   - GMT NIRMOS
     - 5x7 arcmin MOS, 21.5m mirror with GLAO
     - Southern hemisphere

# Question 3&6: TMT

- Perfect sample of ~5500 from which to select good targets for TMT IFU follow up, to measure:
  - Kinematics
  - Distribution of emission line gas
  - AGN component (BH accretion rates)

# Summary

- Subaru GLAO will be an effective tool to map galaxy SFR over large area and to unprecedented depths
- Narrow-band, slit spectroscopy, and IFU are all potentially useful – tradeoffs need more careful study
- Potential to find thousands of targets from which to draw follow-up studies with TMT, JWST
- Competition from JWST and GMT is a concern.
    - Go for widest FoV possible. Is 20′ possible??
    - Maximize multiplex capability. What limits it to ~150? Combine NB+spectroscopy to achieve high multiplex?
    - JWST *could* cover large area to ground-based depths, but this does not seem like efficient use.
    - Remember there are >20000 sq degrees of sky visible from Subaru. *Flexibility is very valuable.*