Spectroscopy of
Very Early Quiescent Galaxies

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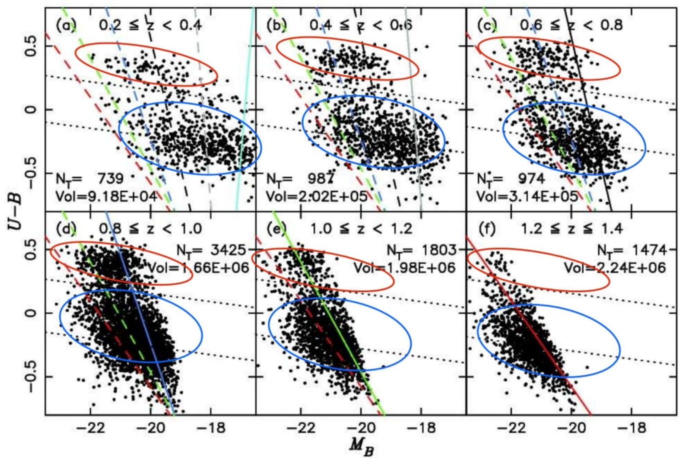
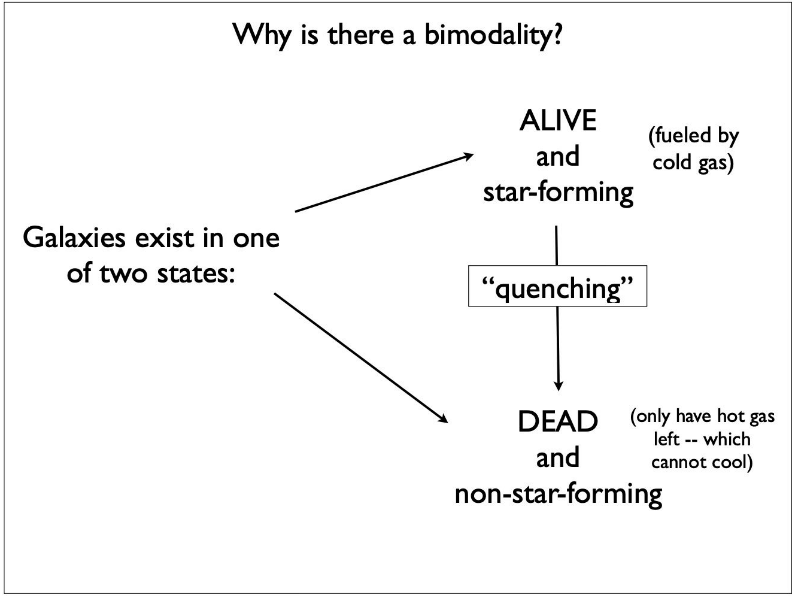
Galaxy bimodality

One of the most interesting aspects of the evolution of galaxies with cosmic time are changes to the "red sequence" and "blue cloud":



One can see the existence of the red-sequence out to z~1

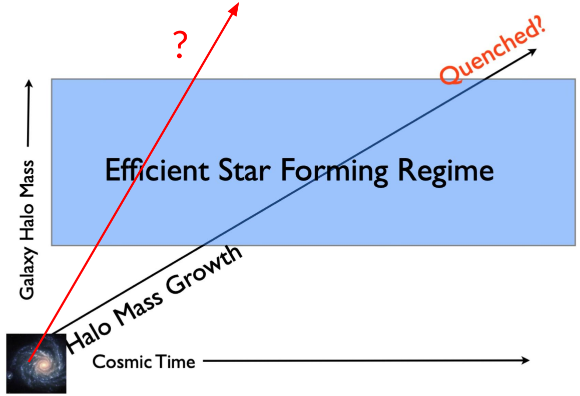


Why early quiescent galaxies matter?

z>3 (age of the universe <~2Gyr), stellar mass ~10^{11} M☉

Stopped forming stars within 1–2 Gyr after the Big Bang

- Their existence requires rapid growth and quenching, challenging current theories.
- Steinhardt et al. (2016): THE IMPOSSIBLY EARLY GALAXY PROBLEM

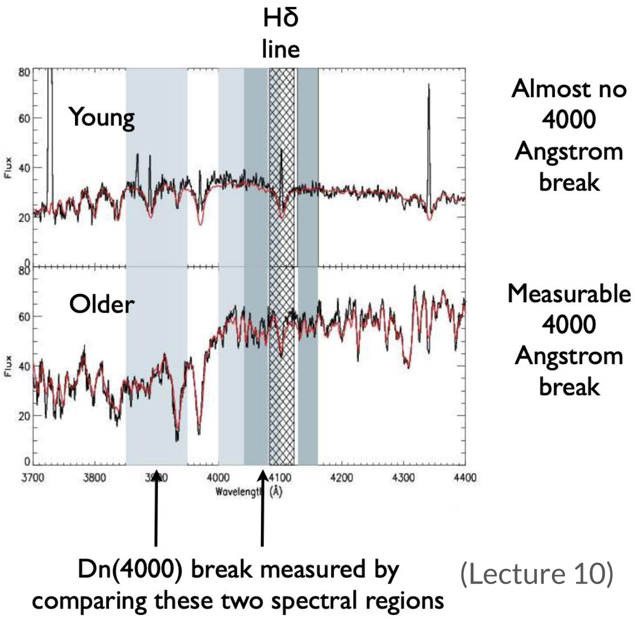


Noekse+2007; Salim+2006

(Lecture 13)

Observational challenges

- Photometric selection is subject to contamination by dusty objects. We need **spectroscopy**.
- At z>3, the age indicators **Balmer/D4000 break** shifts to observed wavelengths >1.6 µm
- Ground-based observations are restricted by
  - Atmosphere windows
  - Sensitivity floor: bias towards younger and brighter objects
- JWST brings new opportunity:
  - Paper 1: confirmation of 12 HST-selected QGs at 3<z<4 (Nanayakkara et al., 2024)
  - Paper 2: discovery of an QG at z~7 (Weibel et al., 2025)

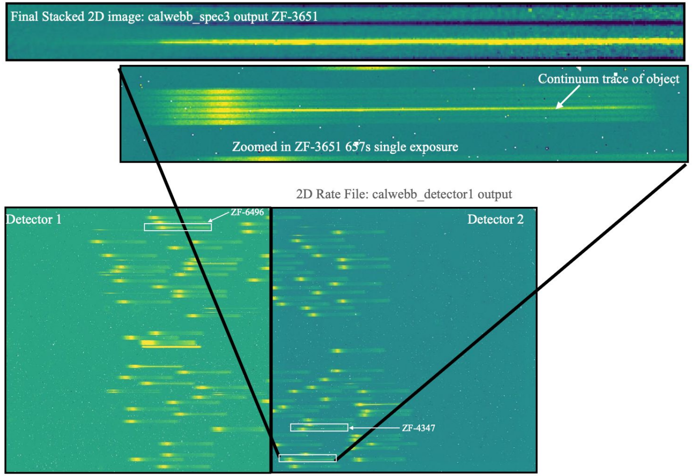


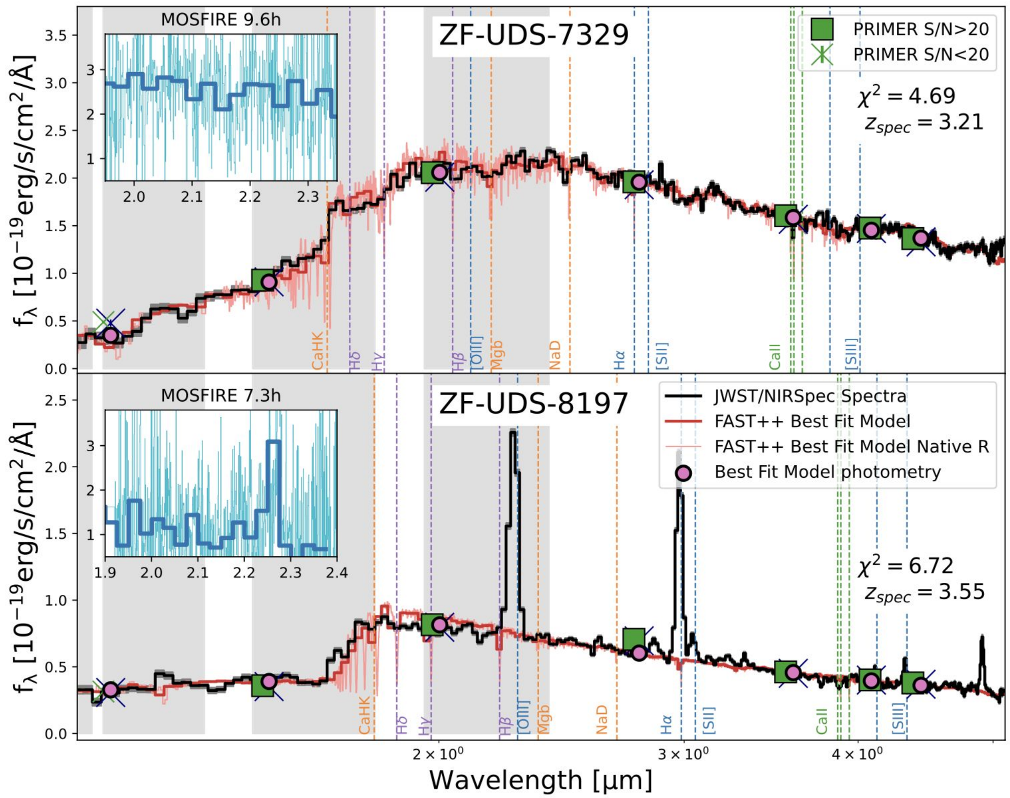
(Lecture 10)

Paper 1: Sample and observations

- Sample: 12 massive quiescent galaxy candidates at z ~ 3–4
  - selected from Schreiber+18 using rest-frame U−V vs V−J color selection on HST imaging
  - 10 of 12 had no prior spectroscopic confirmation (too faint)
- Observation setup:
  - JWST NIRSpec MSA (multi-shutter array)
  - PRISM/CLEAR mode (R ~ 50–500, covering 0.6–5.3 μm)
  - 3 dither positions × 657s each = **~33 min total per target**

- Confirmed that all 12 sources are at z>3, and 11 are post-starburst with spectral breaks.





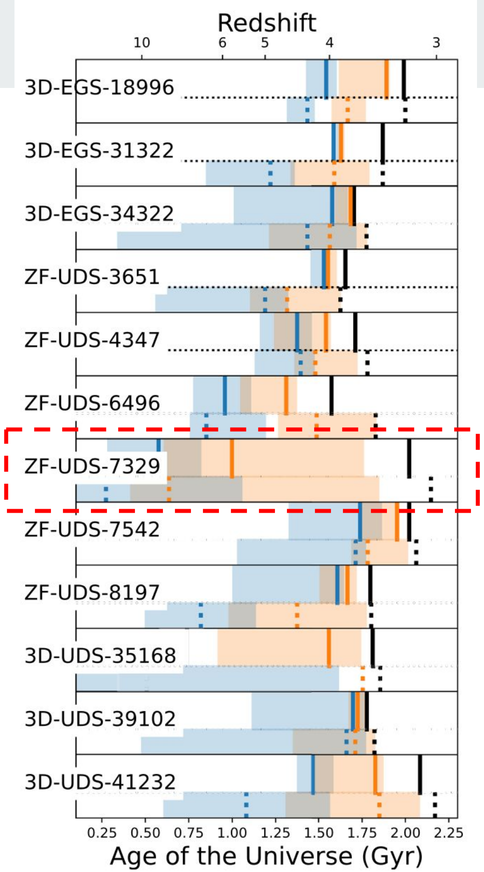
ZF-UDS-7329
MOSFIRE 9.6h
PRIMER S/N>20
PRIMER S/N<20
$\chi^2 = 4.69$
$z_{spec} = 3.21$
ZF-UDS-8197
MOSFIRE 7.3h
JWST/NIRSpec Spectra
FAST++ Best Fit Model
FAST++ Best Fit Model Native R
Best Fit Model photometry
$\chi^2 = 6.72$
$z_{spec} = 3.55$
CaHK
Hδ
Hγ
Hβ
[OIII]
Mgb
NaD
Hα
[SII]
CaII
[SIII]
f_λ [10^{-19}erg/s/cm^2/Å]
Wavelength [μm]
2×10^0
3×10^0
4×10^0

Reconstructed SFH with SED fitting

- SED fitting set up:
  - FAST++, BC03 stellar library, Chabrier IMF, Calzetti dust law, 20%–250% Z☉
  - SFH parameterization from Schreiber+18
  - NIRSpec spectra + NIRCam photometry fitted simultaneously

$$SFR_{\rm Base}(t) \propto \begin{cases} e^{(t_{\rm burst}-t)/\tau_{\rm rise}} & \text{for } t > t_{\rm burst}, \\ e^{(t-t_{\rm burst})/\tau_{\rm decl}} & \text{for } t \leq t_{\rm burst}, \end{cases}$$

$$SFR(t) = SFR_{\rm Base}(t) \times \begin{cases} 1 & \text{for } t > t_{\rm free}, \\ R_{SFR} & \text{for } t \leq t_{\rm free}. \end{cases}$$



50% of mass has formed

SFR fall below 10% of its primary SFR episode

observation

Observation v.s. Simulation

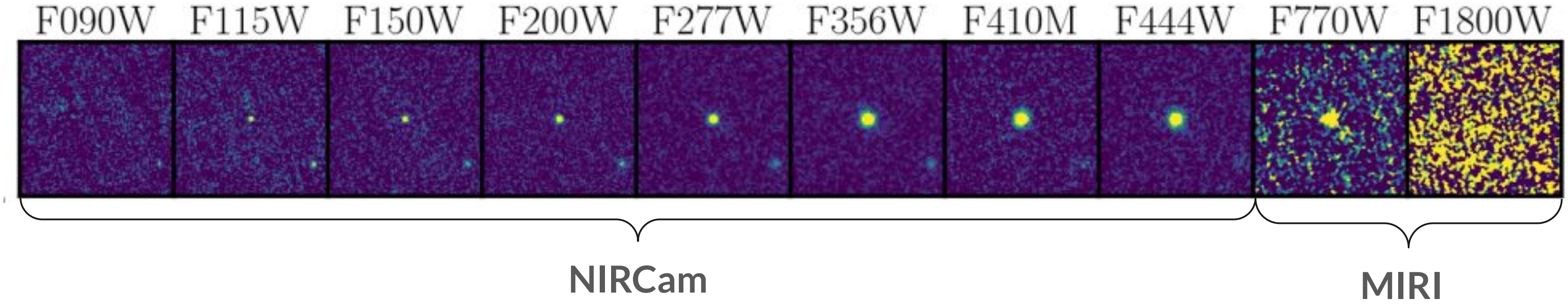
- Observation
  - Number density estimate: **~1.1 (±0.3) × 10^{-5} Mpc^{-3}** for quiescent galaxies at z ~ 3–4
  - Extreme case: ZF-UDS-7329 formed **~10^{11} M$\odot$** of mass within the **first few hundred Myr** after the Big Bang and is quenched **~2 Gyr** after the Big Bang (at z ~ 3.2)
- Simulations
  - Able to reproduce the number density at z ~ 3–4: Illustris-TNG 100, SHARK v2.0, Magneticum
  - The ages and formation timescales are still problematic: **observed galaxies formed earlier and faster**
- Future
  - updated galaxy evolution models (e.g., AGN feedback)
  - tighter constraints to galaxy formation and mass build-up mechanisms at z > 6

Paper 2: What does Weibel add?

- **Same question: How early can massive quiescent galaxies can form?**
  - Focuses on one galaxy RUBIES-UDS-QG-z7
  - The galaxy is at $z_{spec} = 7.29 \pm 0.01$
  - This is the farthest quiescent galaxy ever recorded
  - How can this be possible?

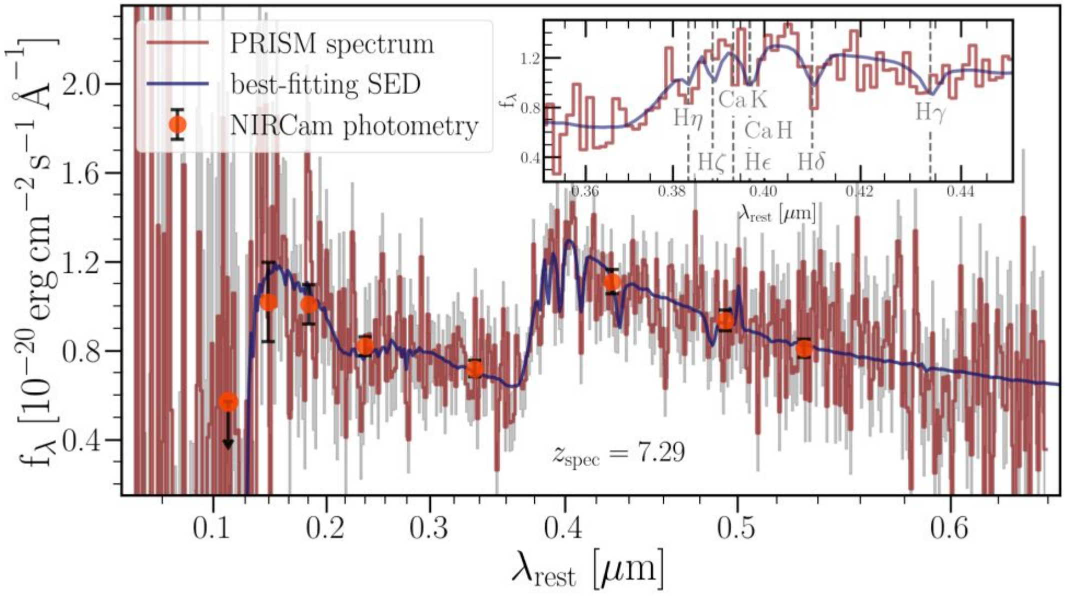
How it was observed?

- RUBIES
  - JWST/NIRSpec survey targeting bright red galaxies
  - 8 NIRCam bands (F090W–F444W)
  - 2 MIRI Photometry bands (F770W/F1800W)
  - MIRI is used as $z_{spec} = 7.29 \pm 0.01$ redshifts the object into near/mid-infrared



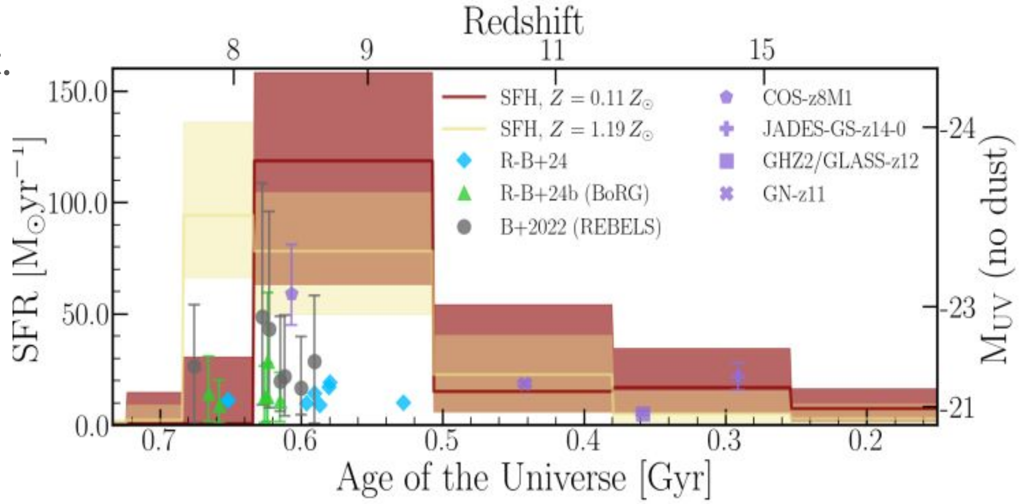
Spectroscopic evidence: why it is quiescent?

- **PRISM:** low-resolution NIRSpec mode
- **Prospector:** Combines both PRISM data and photometry to create SED
- **Lyman break:** finds the galaxy redshift
- **Balmer Brake:** Proves that the stellar population is evolved.



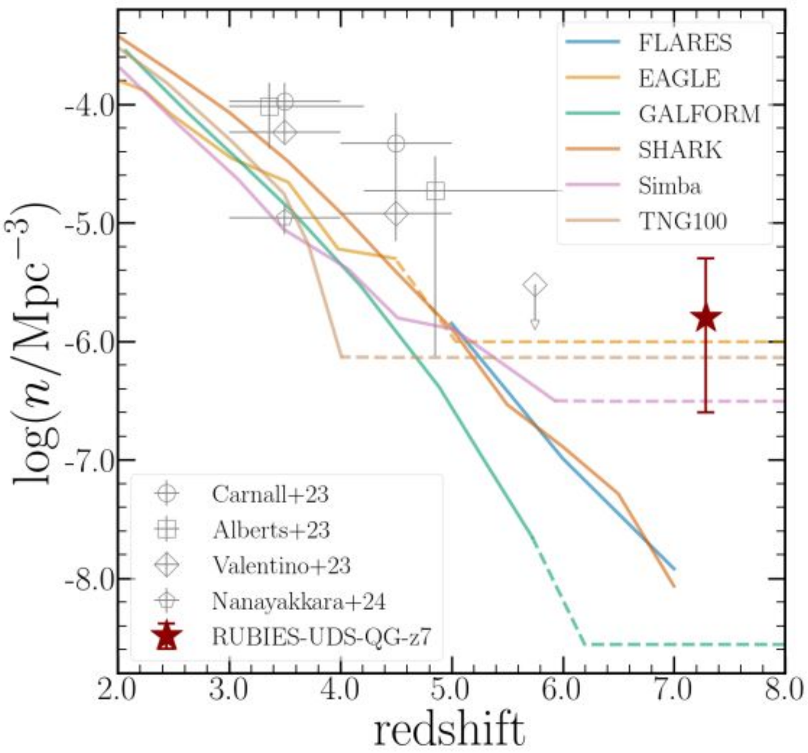
Star Formation History (SFH):

- **Red Shade:** Low metallicity fit.
- **Yellow Shade:** High metallicity fit.
- **Both fits show the same main history:**
  - SFR rises and peaks at z~8−9
  - Star formation then drops rapidly around z~8
  - little/no star formation in the last ≳50 Myr



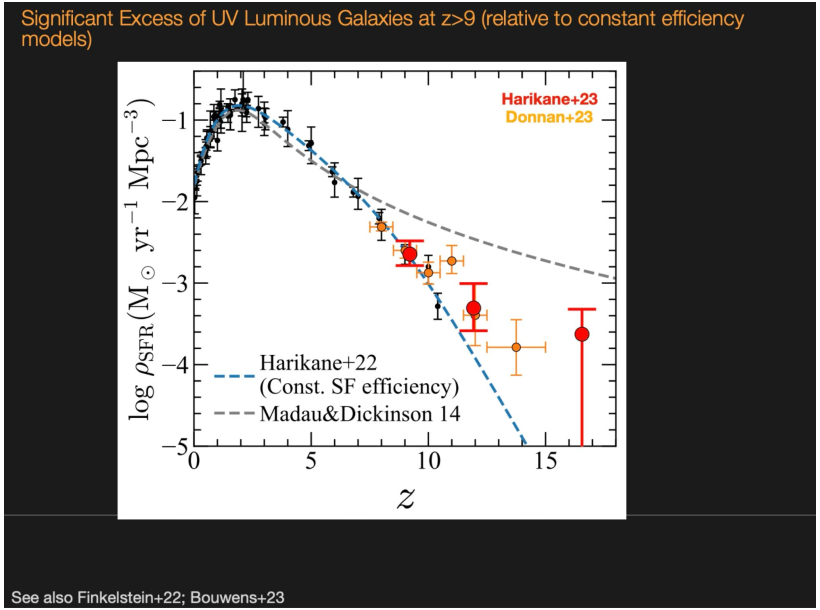
Result and importance

- Challenges early galaxy formation models
- Suggests more efficient star formation in the first billion years
- Shows quenching can happen much earlier than expected
- Points to missing physics: feedback, gas removal, or rapid depletion
- Suggests massive galaxy cores may already exist at very high redshift



Summary and Discussion

- JWST revolutionized our understanding of early massive quiescent galaxies by spectroscopically confirming larger samples and more extreme cases.
- Possible explanations
  - Extreme star formation efficiency
  - Top-heavy IMF
  - Modified cosmological model



(Lecture 13)