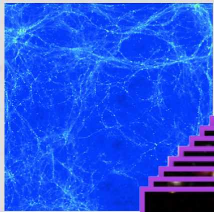
The frontier of galaxy formation and evolution

HST Frontier Fields



WFC3
BoRG
SURVEY

HUBBLE UDF ULTRA DEEP FIELD

GLASS

Present and Future

Kavli Institute for Cosmology Cambridge KICC

Michele Trenti

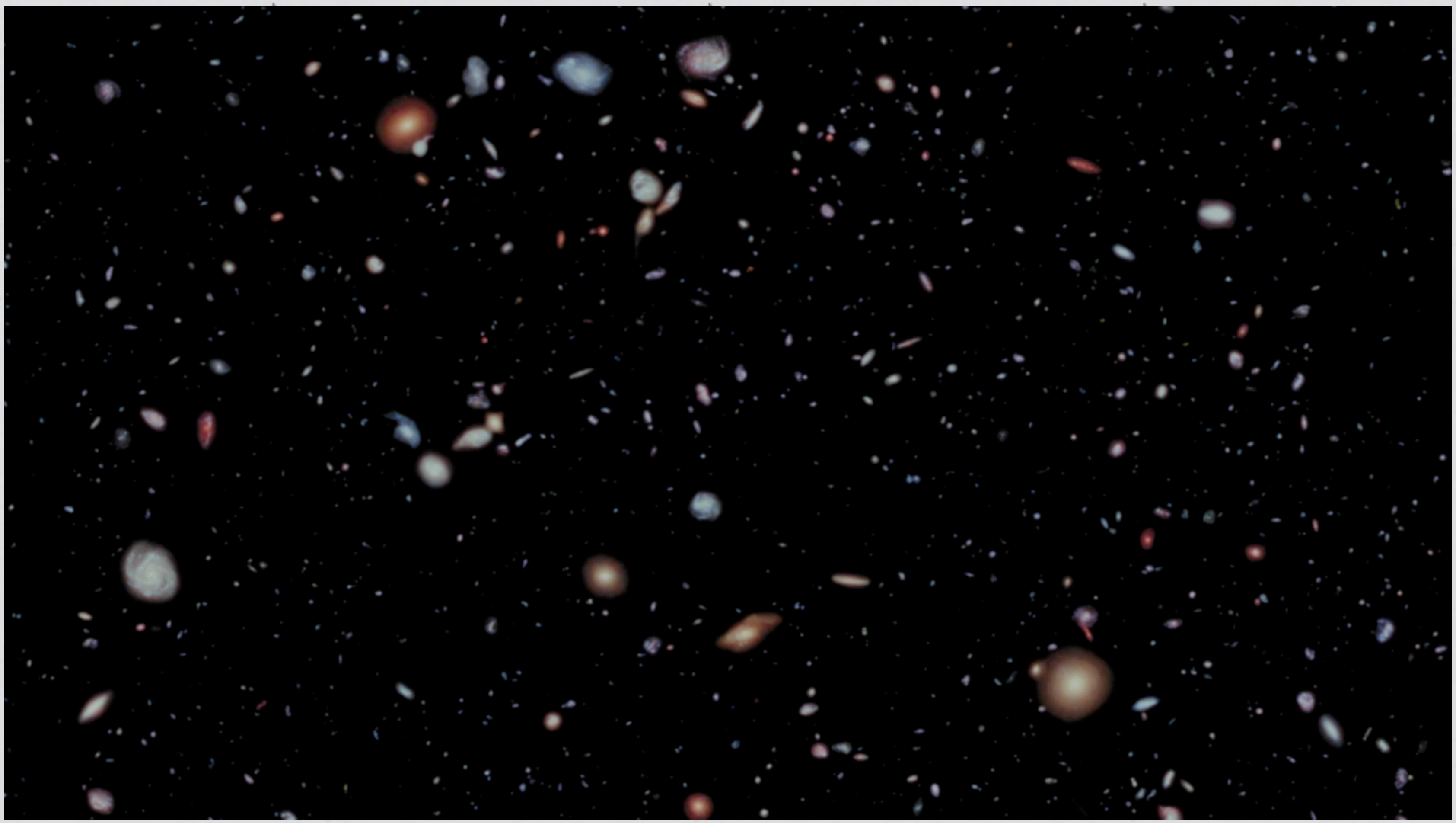
Kavli Institute Fellow

Marie Curie Career Integration Fellow

IoA UNIVERSITY OF CAMBRIDGE

Reaching the frontier

★ **Finite speed of light: most distant = earliest time**

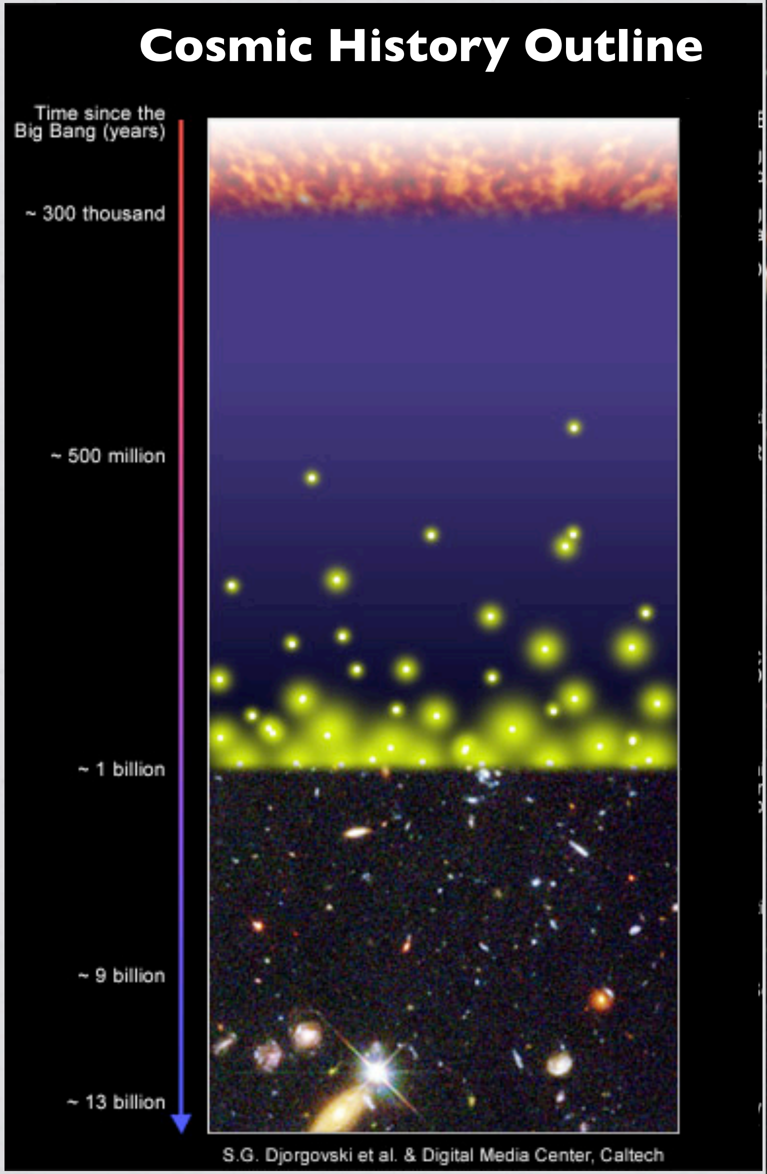


NASA/ESA, XDF team (w/MT)

The first stars and galaxies

Where are we coming from?

- ★ When and how are the first generations of galaxies formed?
- ★ How they affect the intergalactic medium (radiation and metals)?
- ★ What is connection between galaxies and dark-matter?



Finding the first galaxies

★ Very faint: Approximate techniques needed, color based (light from distant objects is redshifted)

NASA, ESA, M. Trenti (University of Colorado, Boulder and University of Cambridge), L. Bradley (STScI), and the BoRG team

Finding the first galaxies

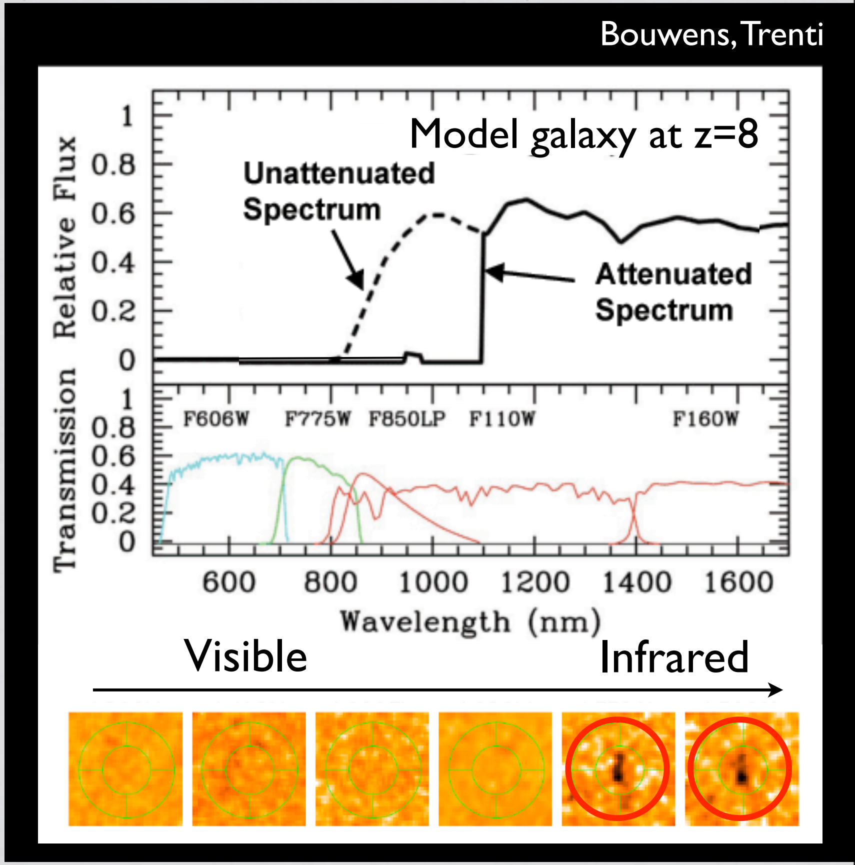
★ **Dropout (Lyman-break) technique** (Steidel et al. 1996)

★ Multiband imaging of a field

★ Intergalactic Medium optically thick at λ<121.6 (1+z)nm

★ High-z galaxies detected in red bands only

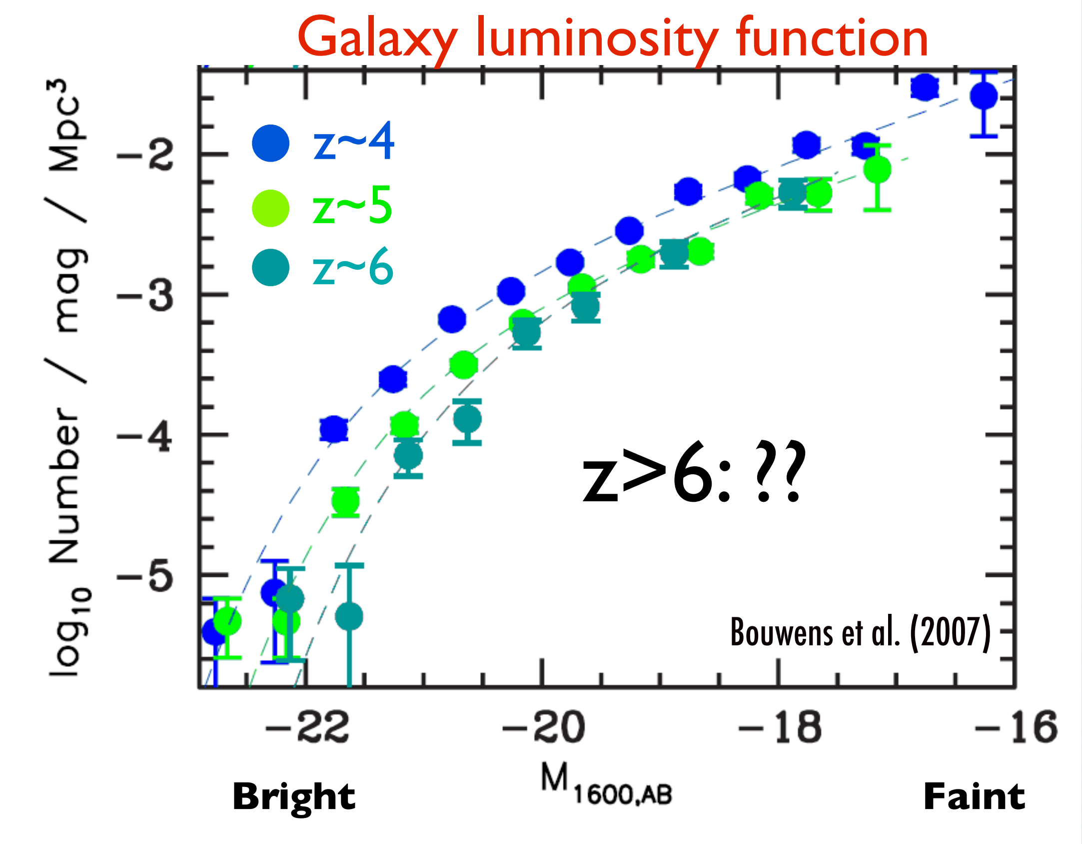
★ Approximate but reliable redshift (*spectroscopic confirmation to z~7)*



Hubble's high-z galaxy surveys
(pre-2009)

★ ~5000 Lyman Break galaxies identified at z~4-6 (~1.5 to 1 Gyr)

★ **BUT: Only handful of sources at z>6.5** (e.g. 4 sources in 2007)



Hubble's high-z galaxy surveys

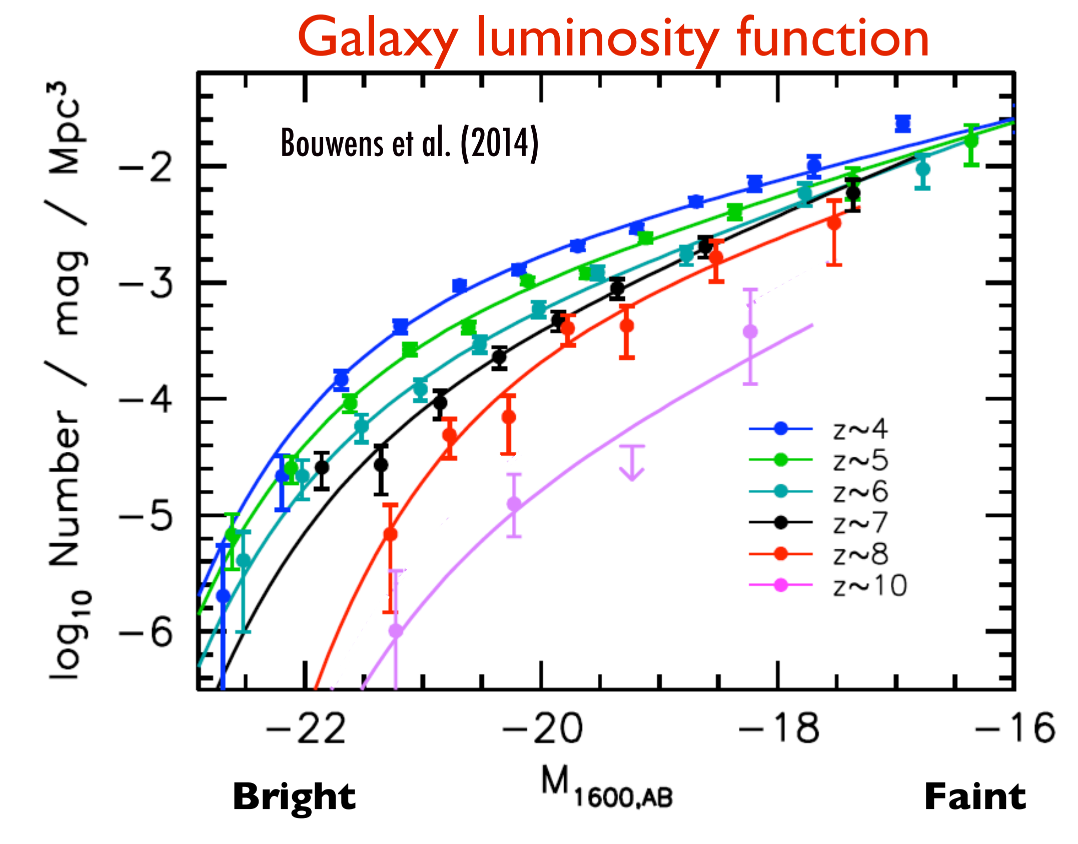
(the present)

HST/WFC3 (near-IR camera) transformed the field

★ Diverse & synergic galaxy searches at z≳7:

n>800 objects found

- ★ Faint & abundant
  - ★ HUDF09/12 (PI Illingworth/Ellis)
- ★ Bright & rare
  - ★ CANDELS (PI Faber/Ferguson)
  - ★ BoRG (PI Trenti)

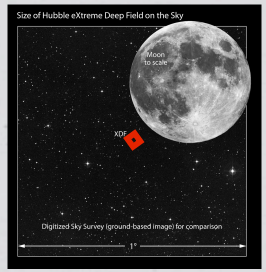


The nearIR Hubble Ultradeep Field

★ Hubble Ultradeep Field [2013]:

- ~2,000,000 s (optical+near-IR) m_{lim}~30 (5σ)
  [29 papers by our team]

~4 arcmin^2

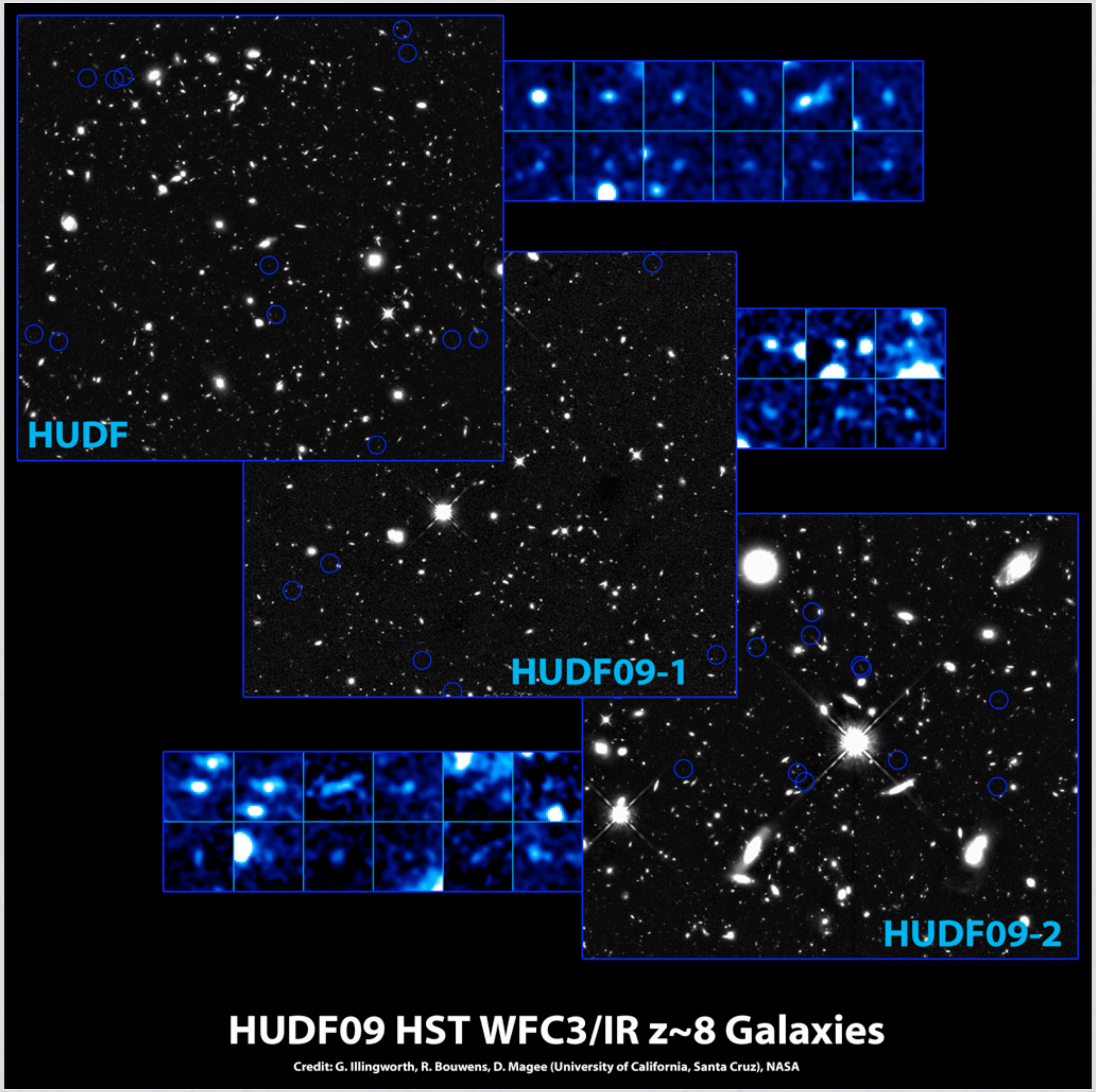


The nearIR Hubble Ultradeep Field

★Hubble Ultradeep Field [2013]:

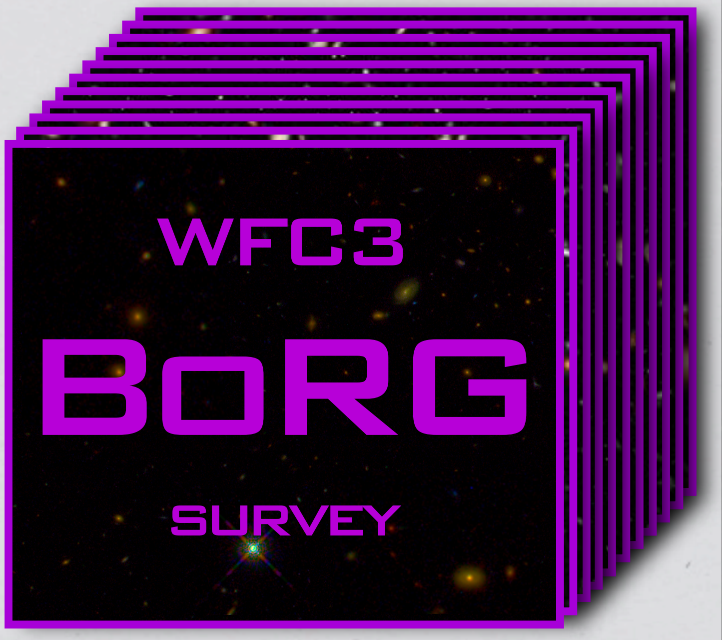
- ~2,000,000 s (optical+near-IR) m_{lim}~30
  [29 papers by our team]

★30 **faint (m ≳ 26.5)** galaxies at z~8 (~650 Myr)



The Brightest of Reionizing Galaxies Survey

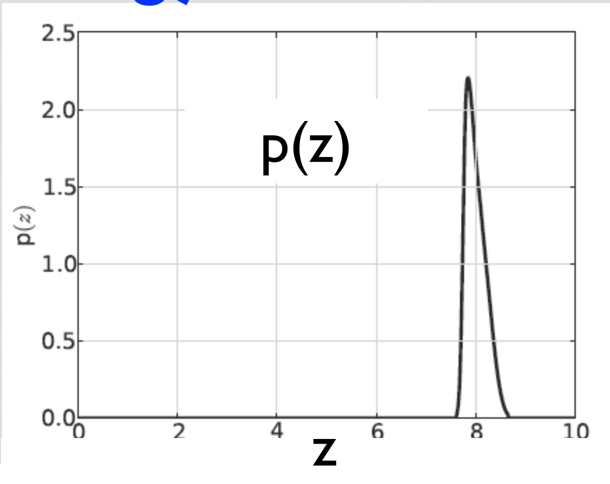
- **Primary goal: photometric identification of rare galaxies at z~8 (~650Myr after Big Bang)**
- 74 WFC3 **independent** pointings
  ~350 arcmin^2, >400 hours
  (PI Trenti, Cycles 17+19+20)
- 4 filters (optical+near-IR):
  V, Y, J, H
- 4-6 hours/field:
  5σ sensitivity: m_{lim}~27



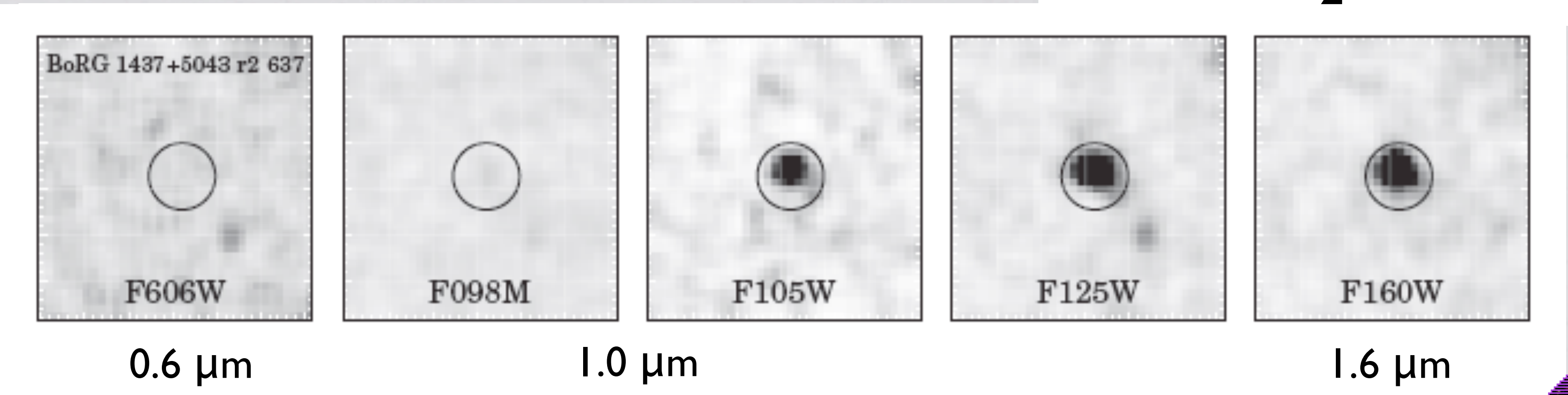
The Brightest of Reionizing Galaxies Survey

★ **BoRG (10x HUDF area) finds most luminous z~8 galaxies (~650 Myr after Big Bang):**

- n=10 at S/N>8 (m<26.5)
- n=28 at S/N>5 (m~27)



Best BoRG source: m_J=25.9 (S/N>20)



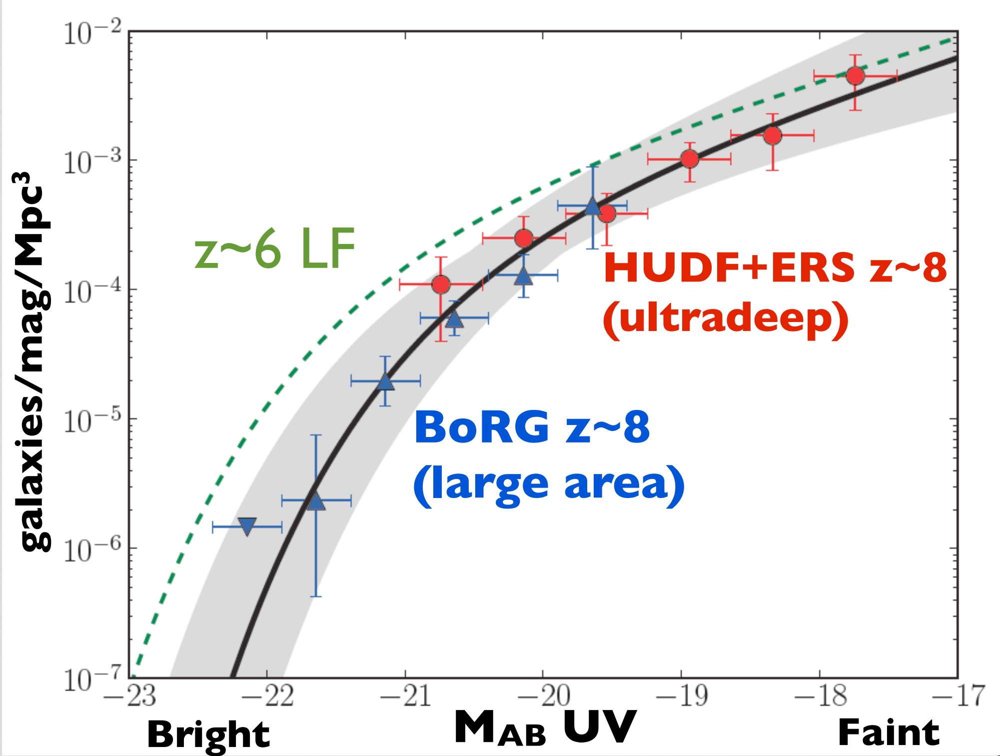
Trenti et al. (2011, 2012a); Bradley et al. (2012); Schmidt et al. (2014)

The luminosity function at z~8

Large area (~350 arcmin²) determination

- ★ BoRG+HUDF/ERS:
  97 Y-dropout galaxies
  - ★ **None known preWFC3!**
- ★ LF well described by Schechter form
  - ★ Less sources at high-z: Galaxy density evolution from z~6 to z~8 at 99.995% confidence

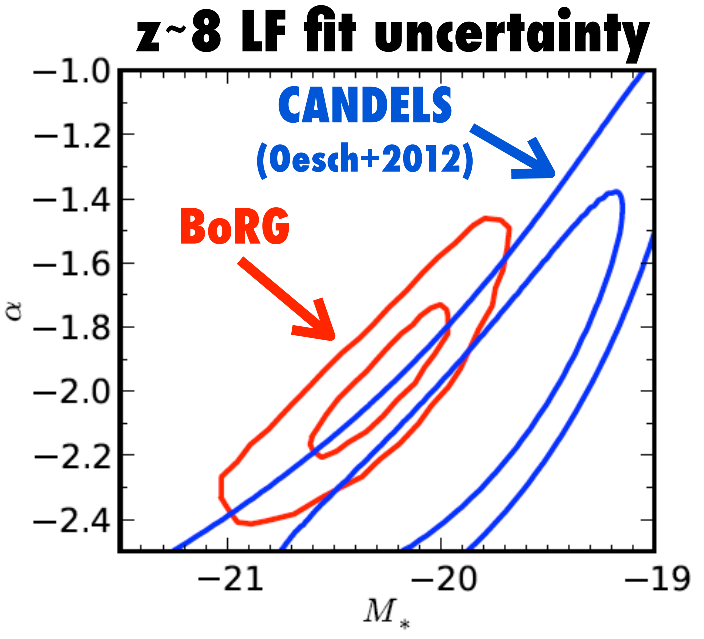
$$\phi(L) = \phi_0 (L/L_*)^\alpha \exp(-L/L_*)$$



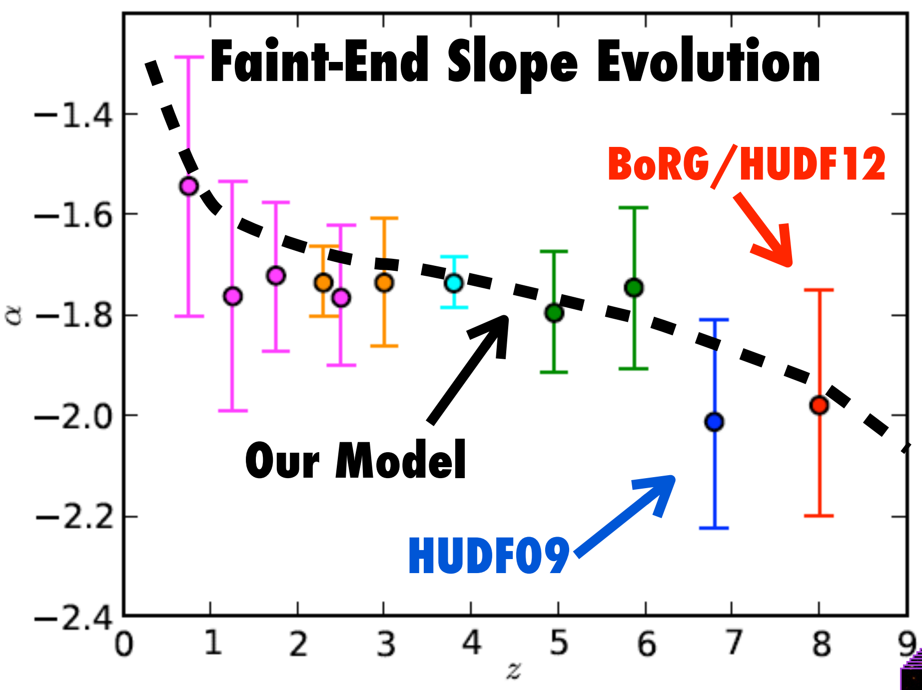
Bradley, Trenti et al. (2012); Schmidt et al. (2014)

Very steep z~8 luminosity function

- Best fit gives α= -1.98±0.2 (log divergent!)
- Steepening of the LF at z>7:
  Majority of light produced by faint sources



Bradley, Trenti et al. (2012)

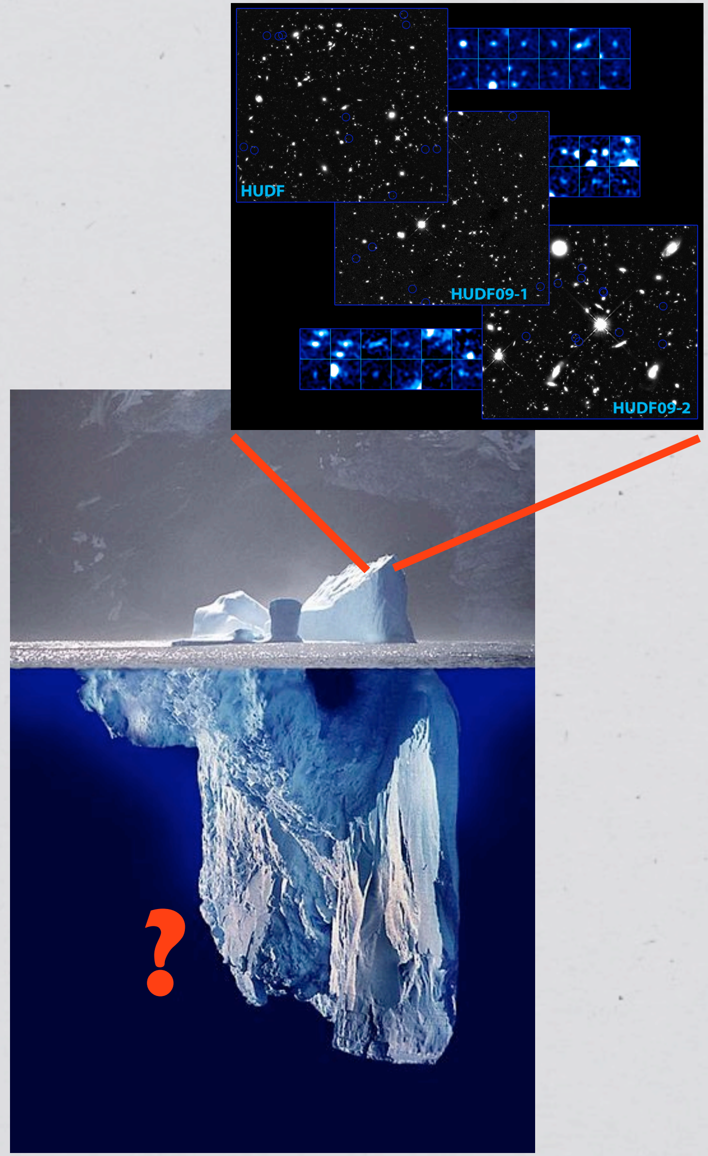


from Tacchella, Trenti & Carollo (2013)

Only the tip of the iceberg

- ★ Modeling galaxy-dark matter connection predicts that Hubble sees only brightest z>7 galaxies (~20% of light) (Trenti et al. 2010, 2013, Tacchella, Trenti & Carollo 2013)

- ★ **How can we probe what lies hidden below our galaxy detection limit?**



Star formation beacons

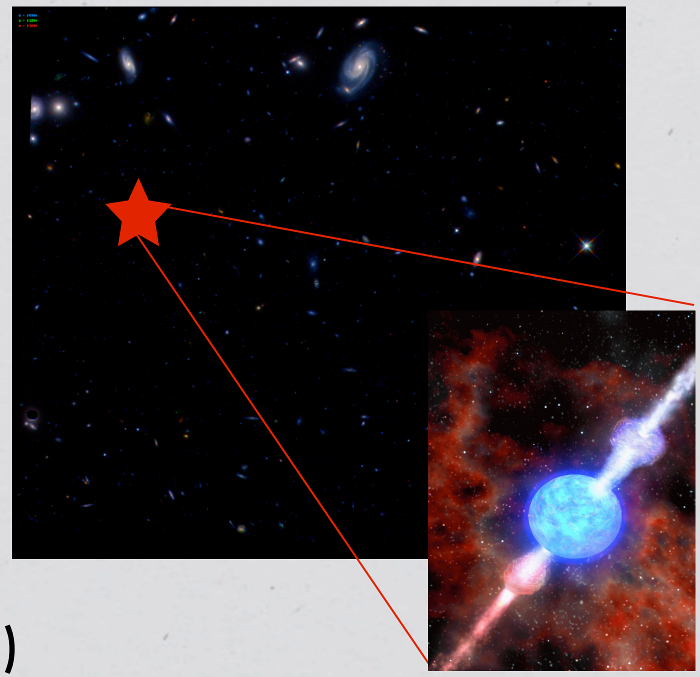
★ Gamma Ray Bursts [~10^{52} ergs s^{-1}] emitted by dying massive stars rare but detectable at all redshifts

- ★ *Pinpoint sky locations with star formation (from bright optical/IR afterglow)*

★ Follow-up to probe host galaxy

- ★ Upper limits only from HST ultra-deep data on 6 GRBs at z>5
  - ★ Galaxy LF extends to 10x fainter than observed

(Trenti et al. 2012b,2013, Tanvir et al. 2012)



High-z galaxies: Extending the frontier

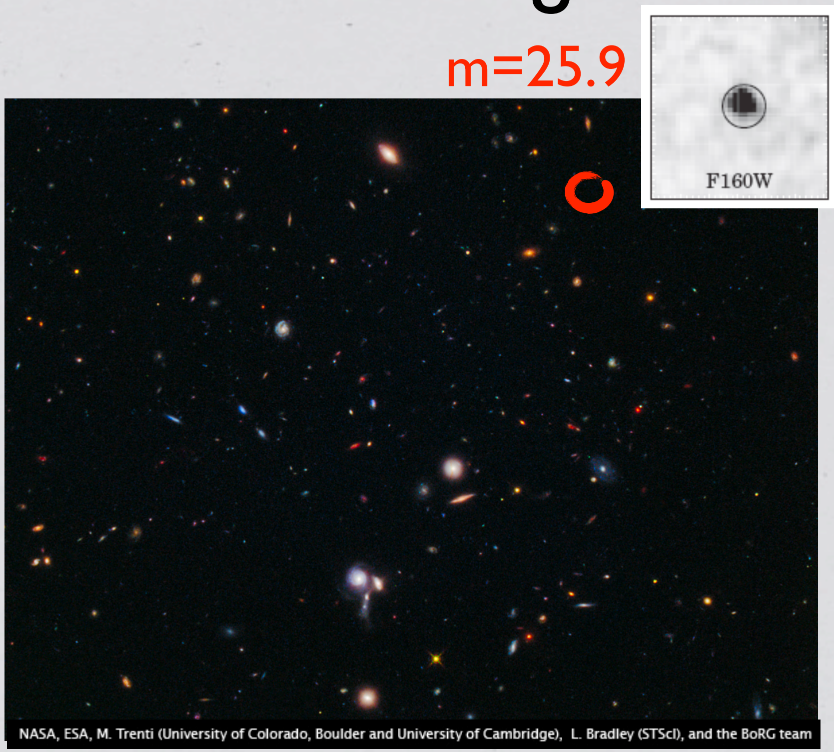
★ WFC3/HST: Galaxies found at z~7-10 (2010-2013)

★ Next step: Characterize their properties

★ Brightest z>8 galaxies: *rare but ideal targets*

★ Easiest to follow-up!

★ Earlier assembly expected: z>13 [~300 Myr!!]
Probes of earliest star formation and reionization



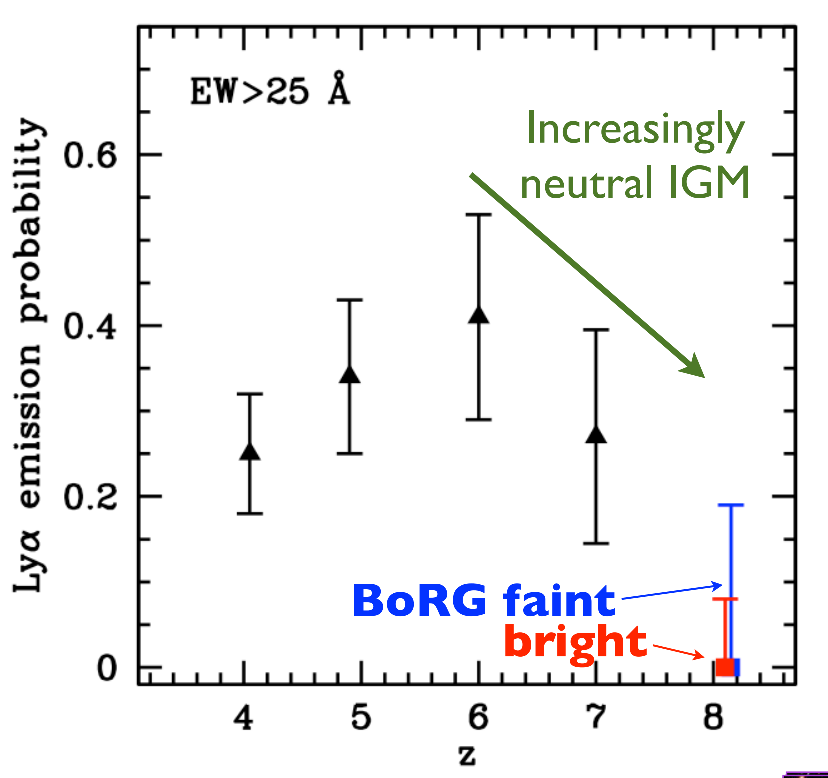
Galaxy properties: Lyα emission

★ BoRG follow-up: Keck (~32h) & VLT (~12h)

★ 15 galaxies observed, **no Lyα emission detected** (EW>25A)

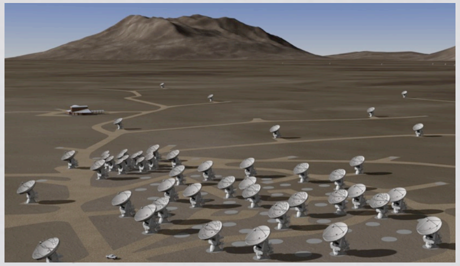
- ★ Dramatic evolution of intergalactic medium from z~8 to z~6: Reionization in progress
- ★ BoRG z~8 limits crucial to establish trend previously hinted by z~7 spectroscopy

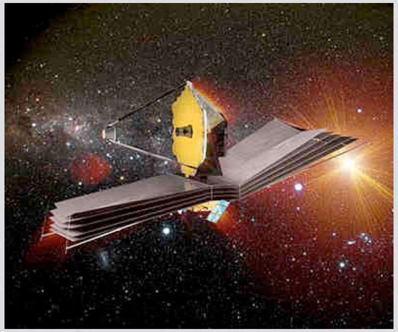
Probability of Lyα emission



Treu, Trenti et al. (2012, 2013)

Outlook for the future





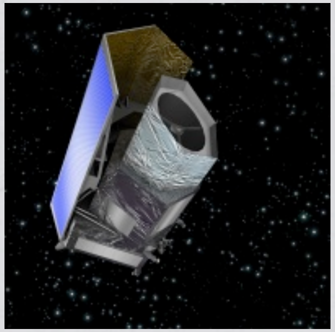
Hubble

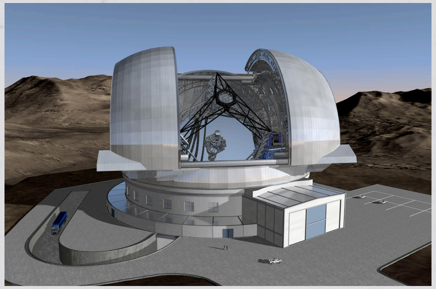
ALMA

James Webb

EUCLID

E-ELT





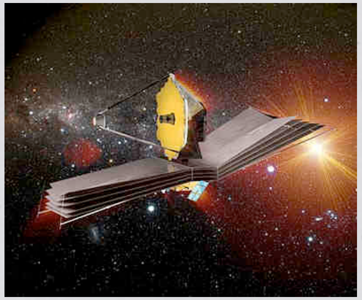
Hubble Space Telescope

★ HST is photon and wavelength limited to z~10 but key facility for short-term progress:

- ★ "Frontier Fields" [public survey] is using gravitational lenses to identify intrinsically fainter sources
- ★ GLASS survey [Treu PI, Trenti CoI] will provide spectra of faint z≲8 sources (synergic with BoRG)

★ BoRG-like survey targeted at z~9 to find rare bright catches (easiest to follow-up)

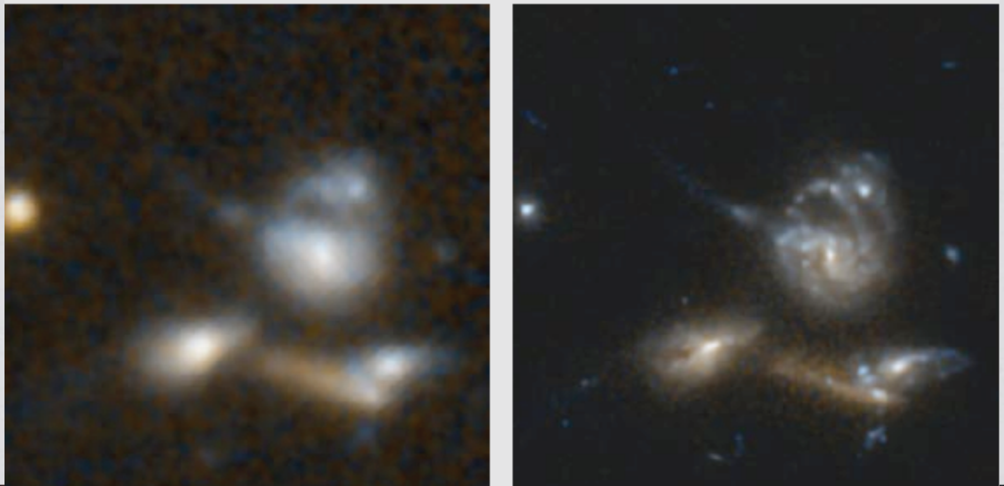
Beyond Hubble: JWST (2018)



★James Webb next giant leap

- Better sensitivity, resolution, IR coverage
- **Spectra of all galaxies seen by Hubble**
- **Detection of first generation of galaxies out to ~300 million years after Big Bang (z~15)**

Hubble
H band



JWST
H band

image simulation by
M. Stiavelli, STScI

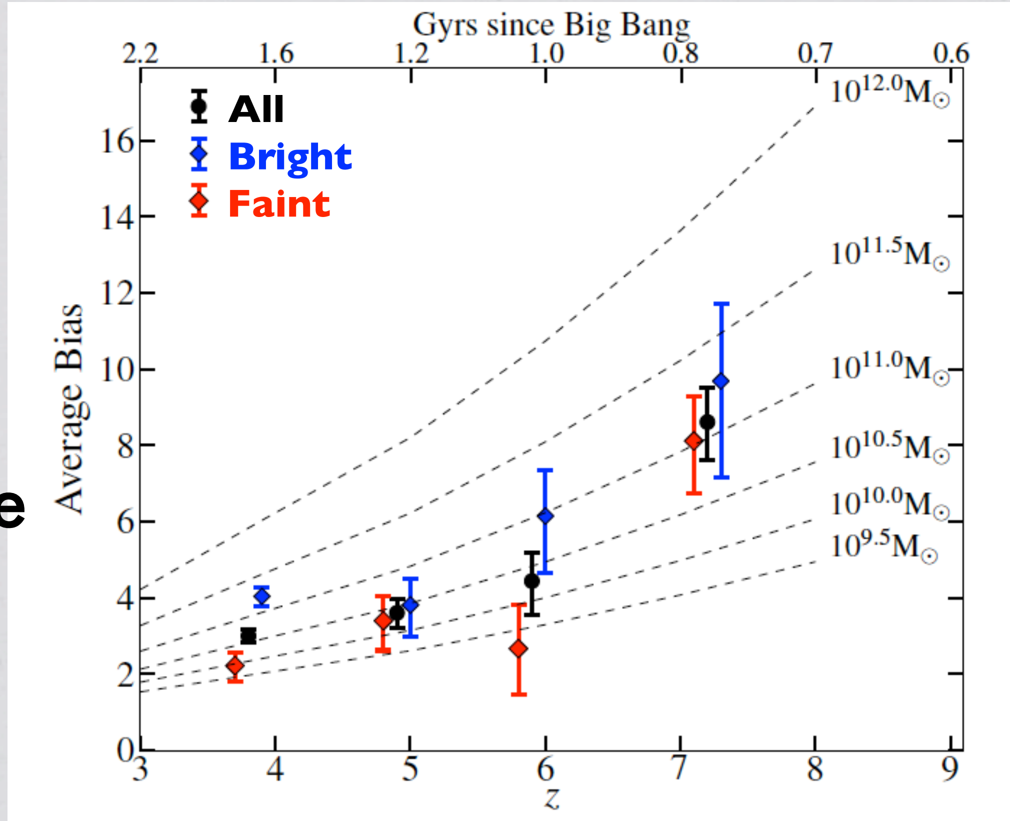
Summary

- **Hubble's WFC3 transformed our view of galaxy evolution in the first 700 Myr**
  - Combination of ultradeep and wide area observations is characterizing star forming galaxies at earliest times and their role in reionization
- Exciting new results coming from Hubble in the short term
- Next leap to first generation objects just behind the corner: James Webb will amaze with unprecedented deep observations in the infrared!

Galaxy clustering and halo masses

Clustering analysis validates scenario with fainter than seen galaxies

Bias: galaxies vs. DM halos



- ★ Derived DM halos ~$10^{11}M_{sun}$
  - ★ Galaxies at z>7 expected in the more abundant halos with 10^8-10^{10} Msun!

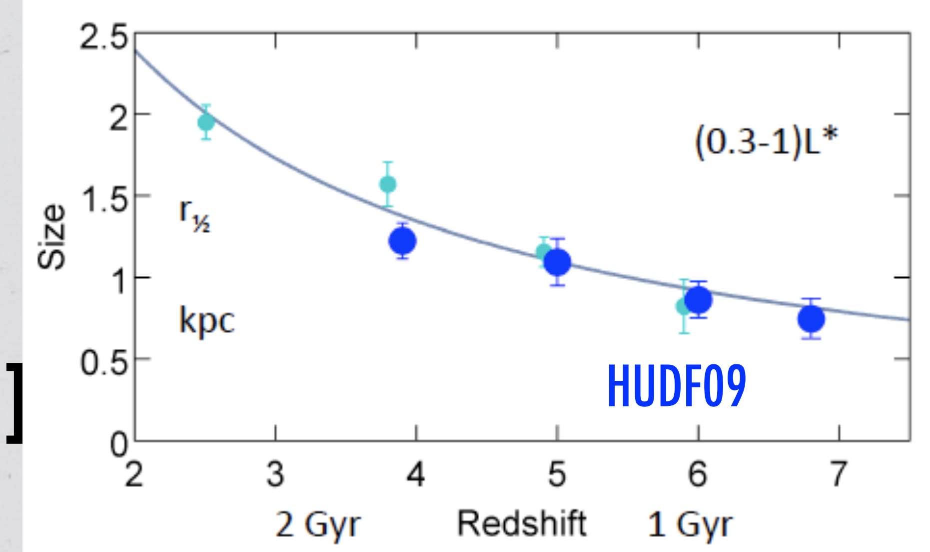
Barone-Nugent, Trenti et al. (submitted)

Smaller and smaller galaxies

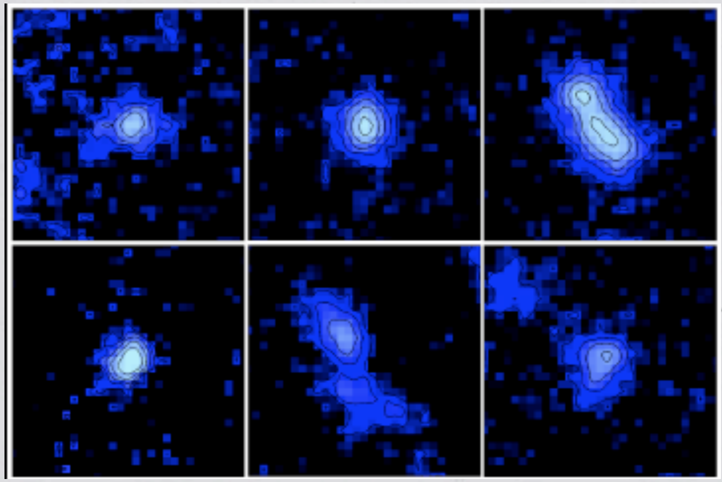
★Galaxies become smaller at high z:

- $(1+z)^{-m}$, m=1.12±0.17 [constant comoving size]
- consistent with theoretical modeling (Wyithe & Loeb 2010)

★z~7 galaxies have significant substructure



Oesch et al. (2010b)

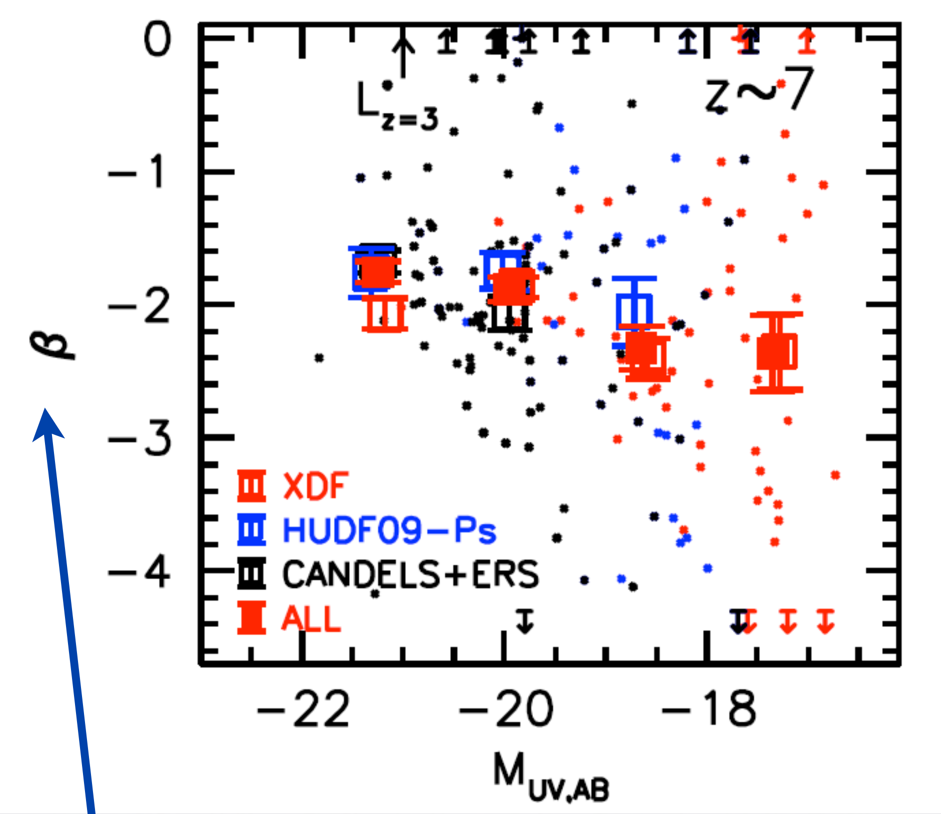


z~7
1.8″x1.8″

Blue galaxies

★ UV Continuum slope depends on IMF, age, metallicity, dust content of stellar population

- steep slopes imply little or no-dust & low-metallicity



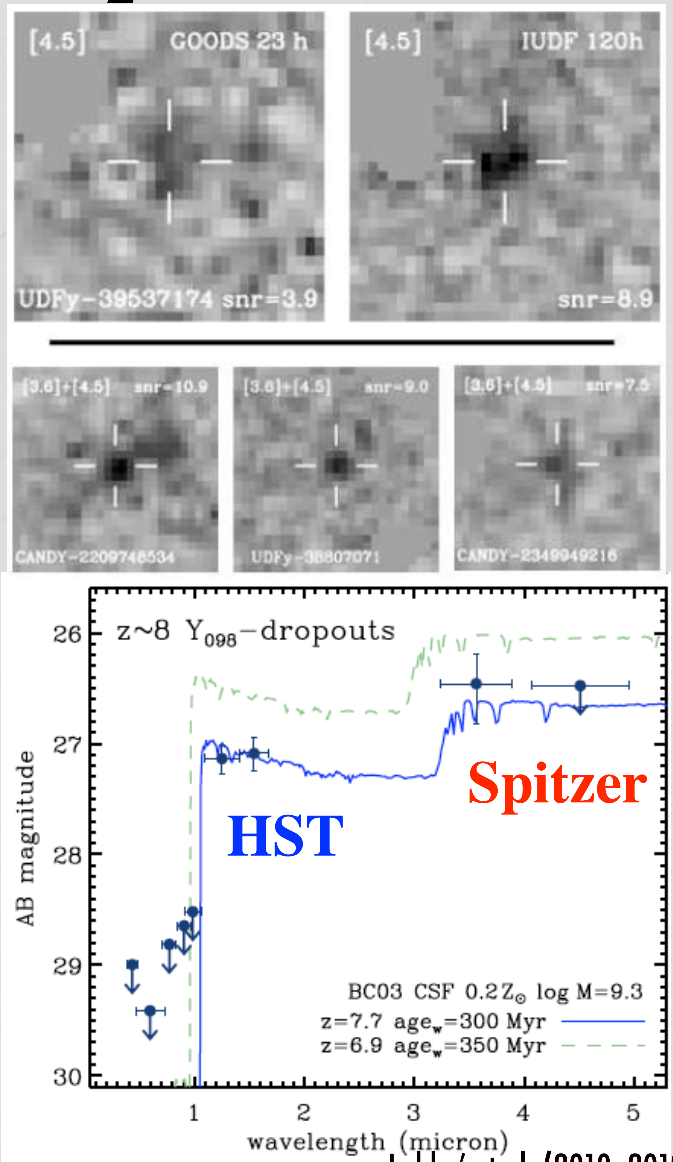
Power law slope of UV continuum: $f_\lambda \sim \lambda^\beta$

Bouwens et al. (2012,2014)

Assembly at very early time

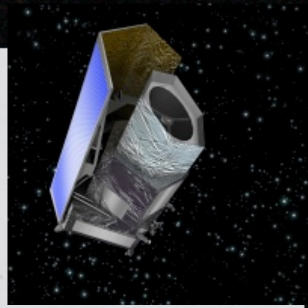
★ Age/stellar mass constrained by ultradeep Spitzer IRAC data (3.6-4.5 μm)

- Estimated stellar mass per z~8 galaxy: $>10^9$ M_{sun}
- z~8 galaxies [~650 Myr] already ~300Myr old
  - **Formation at z>12**



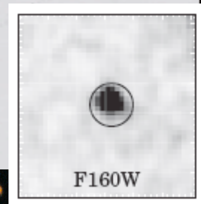
Labbe' et al. (2010, 2012)

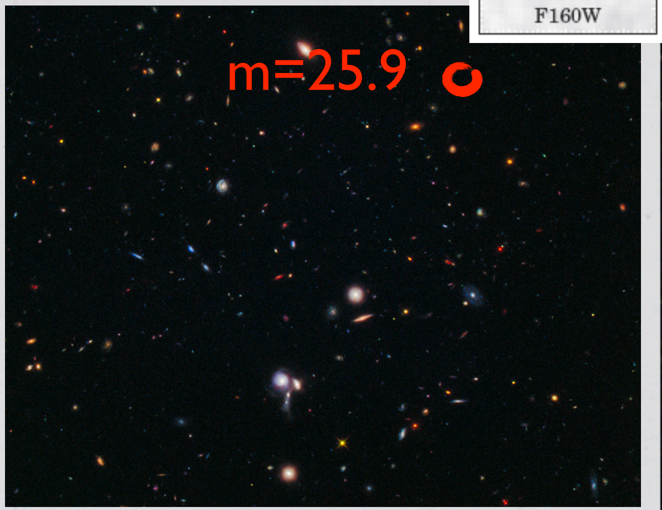
Beyond Hubble: EUCLID (2020)



★EUCLID deep field (40 deg^2; m_{lim}=26 [5σ]):

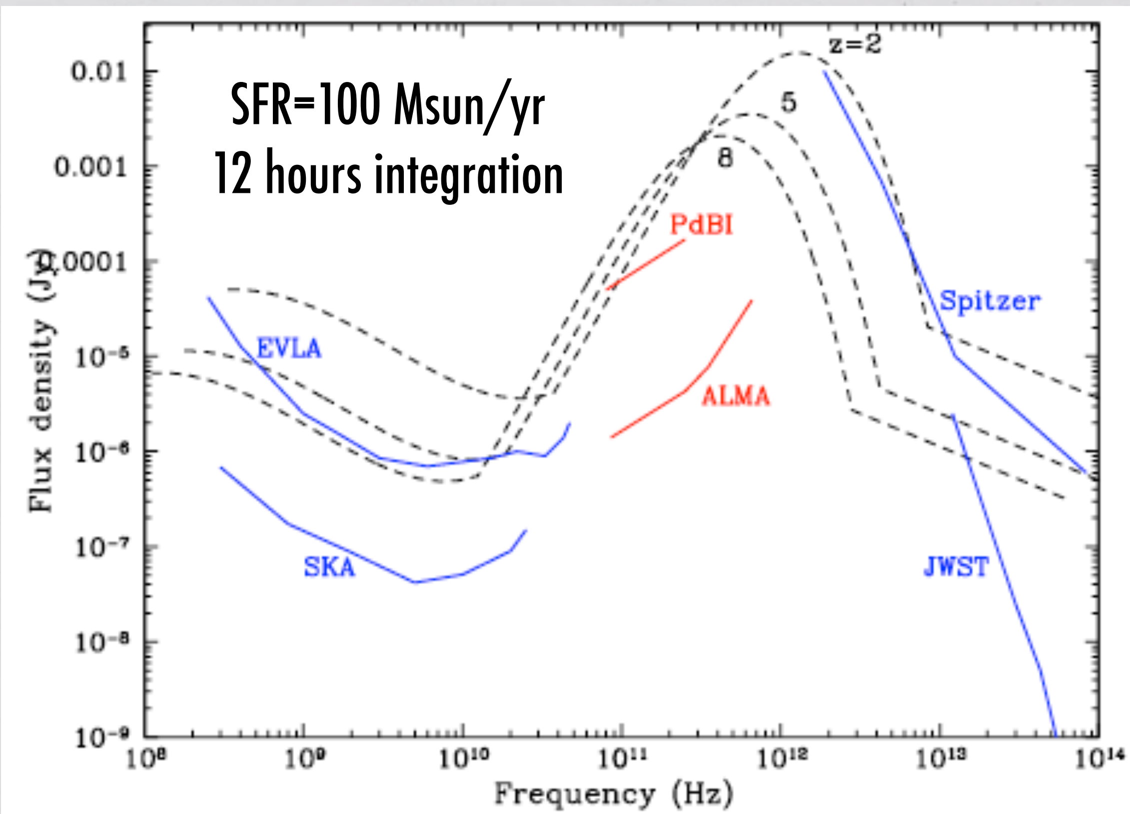
- First census of ultra-bright (m_{AB}~25-26) galaxies at z~8-10
  - ~800 expected at z~8 from BoRG LF
  - Handful at z~10 possible
- Ideal follow-up targets for ALMA/30m class telescopes:
  - Testbeds to investigate topology of reionization





Future galaxy surveys

★ ALMA will be able to detect continuum (and lines) from z~8 BoRG galaxies (SFRs of ~10 M_{sun}/yr)



Carilli et al. (2008)