Context and Big Questions
Thousands of galaxies can be observed in a blank patch of sky with the size of the full moon.
In perspective...

Until only ~20 years ago, we had quite a sparse knowledge of galaxies at z>1.5

the connection between different galaxy populations was unclear

New facilities (*HST, Spitzer, ground-based 8m-diam. telescopes*) allowed us to create a more complete and clearer picture of the Universe at high z.
The cosmic SFR density

Galaxy formation and growth was much more efficient in the past

Behroozi et al. (2013); Madau & Dickinson (2014)
Massive galaxy formation at high z

When have massive galaxies formed and become massive?

Credit: McDonald Observatory
The sources of reionization

Understanding when first galaxies formed is one of ultimate goals
Selection of High z Galaxies
The highest \( z \) known galaxy over the last decades

<table>
<thead>
<tr>
<th>Date</th>
<th>Galaxy</th>
<th>( z )</th>
<th>Search Technique</th>
<th>Reference</th>
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Credit: http://ned.ipac.caltech.edu/level5/Sept04/Stern/Stern1.html

To date we know a few thousand galaxy candidates at \( z > 5-6 \) and a few at \( z \sim 10-11 \)
Selection of SF galaxies at z~2-3

Lyman-break selection technique

Introduced by Steidel et al. (1996) to select star-forming galaxies at z~3

Note: low-z contaminants can be 20-30% of sample

Picture Credit: http://www.astro.ku.dk/~jfynbo/LBG.html
Selection of SF galaxies at $z \sim 2-3$

Figure 1: (From Steidel et al. 2004) Two-color ($U - G$ vs. $G - R$) diagram from one of the UV-selected survey fields, demonstrating the UV-selection technique described in Section 2.2. The green and yellow shaded regions represent the $z \sim 3$ LBG color selection windows, while the cyan and magenta regions are used to select galaxies at $z \sim 2.0 - 2.5$ and $z \sim 1.5 - 2.0$, respectively.

Selection of SF galaxies at z~4-5

changing the set of filters, the technique can be extended to select higher-z galaxies

Caveat of this technique: biased against dusty galaxies!
The spectroscopic confirmation

Shapley et al. (2003)
Ly-break galaxies vs. Ly-alpha emitters

Lyman-break galaxies are not necessarily Lyman-alpha emitters

The Lyman-alpha line profile depends on the ability of Lyα photons to escape dusty/clumpy interstellar medium

**problem:** resonant scattering of photons with HI

**note:** if Lyα EW > 100 Å, then age < 50 Myr

*Pictures Credit: Verhamme et al. (2008); see also Neufeld (1990)*
Optical vs Near-IR Galaxy Surveys

for many years, the search of $z>1.5$ galaxies has been performed on optical images

but the advent of near-IR surveys showed that optical surveys miss a significant fraction of high-z galaxies

Why?
Optical vs Near-IR Galaxy Surveys

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Why?

Picture Credit: http://ned.ipac.caltech.edu/level5/Sept01/Malkan/Malkan2.html
Galaxy selection through photometric redshifts

Credit: STScI

Photometric redshift
Age
Dust Extinction
Stellar Mass

‘cheap’ alternative to spectroscopic redshifts
Spectroscopic surveys

Spectroscopic galaxy surveys require big telescope time investments necessary to confirm photometric techniques and for precision studies (e.g. study of galaxy pairs)

They usually require target pre-selection
Physics of High-z
Galaxy Evolution
Galaxy luminosities: theory vs. observations

under the assumption that dark matter halos host gas: need to find mechanisms why conversion to stars is less efficient in low and high mass systems

either gas can never cool or gas gets reheated/removed

e.g. Springel et al. (2005); Somerville et al. (2008)
Star formation: cold flows versus mergers

The relative importance of cold flows versus mergers is still under debate

Dekel et al. (2009)

Bournaud et al. (2010)
Starbursts may be more important than what it was thought a few years ago but needs to look for them among galaxies with lower stellar masses.
Searching for galaxy outflows

Evidence for outflows in spectra

Velocity offsets (em-abs)
- Redshifted Ly\(\alpha\)
- Blueshifted IS abs
- Avg offset is 650 km s\(^{-1}\) \((\Delta z=0.008) \rightarrow\) outflow
- Stellar photospheric features are too weak to detect, so we need to guess what the systemic redshift is

(Shapley et al. 2003)