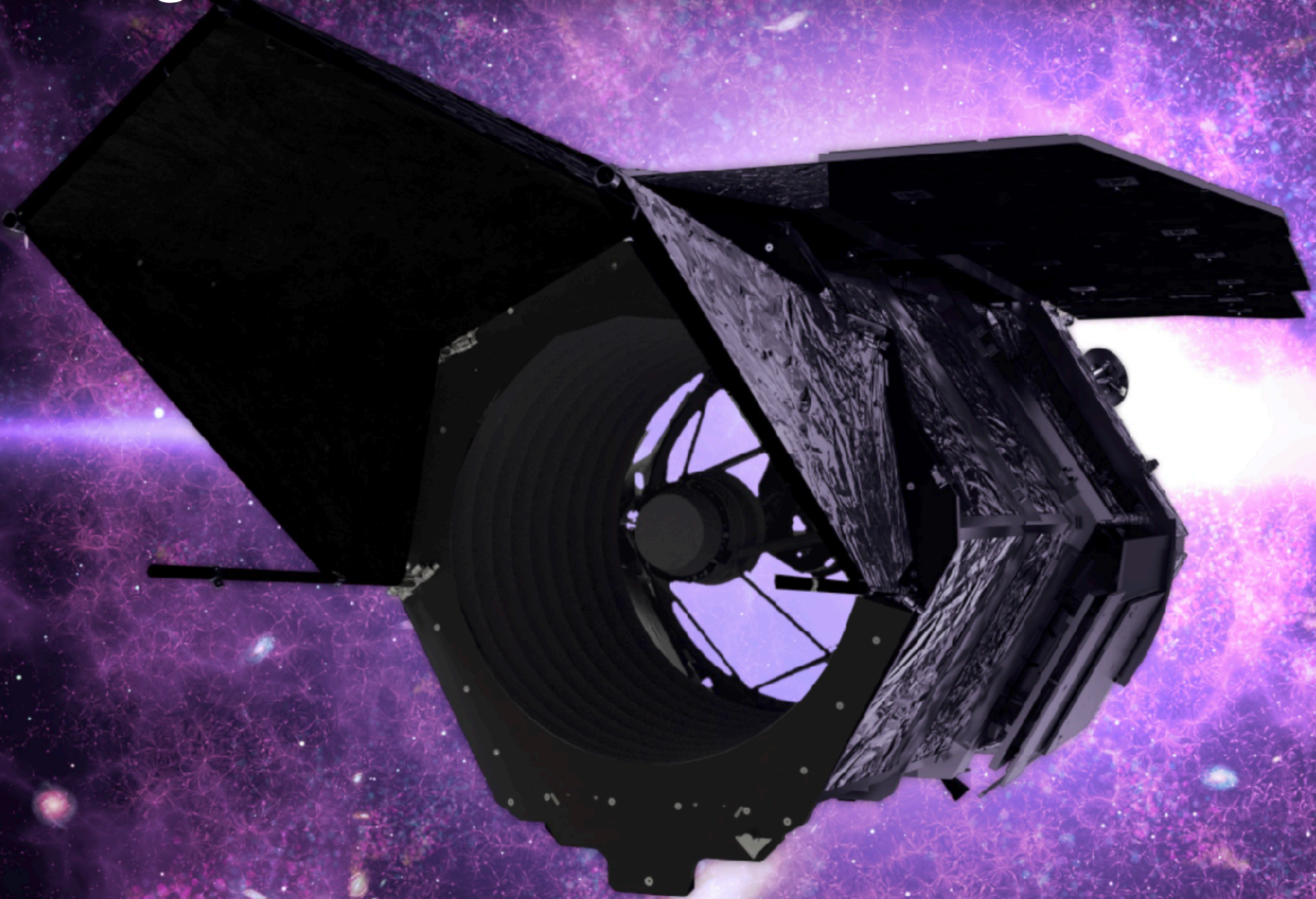
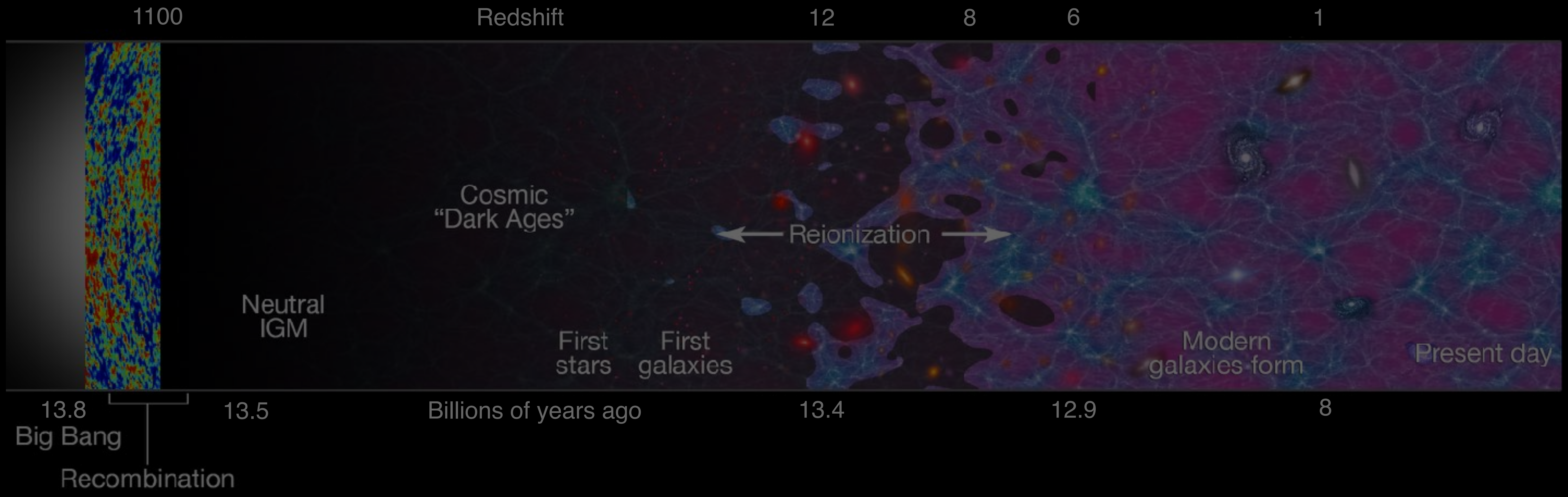
Distant Extragalactic Science with Roman



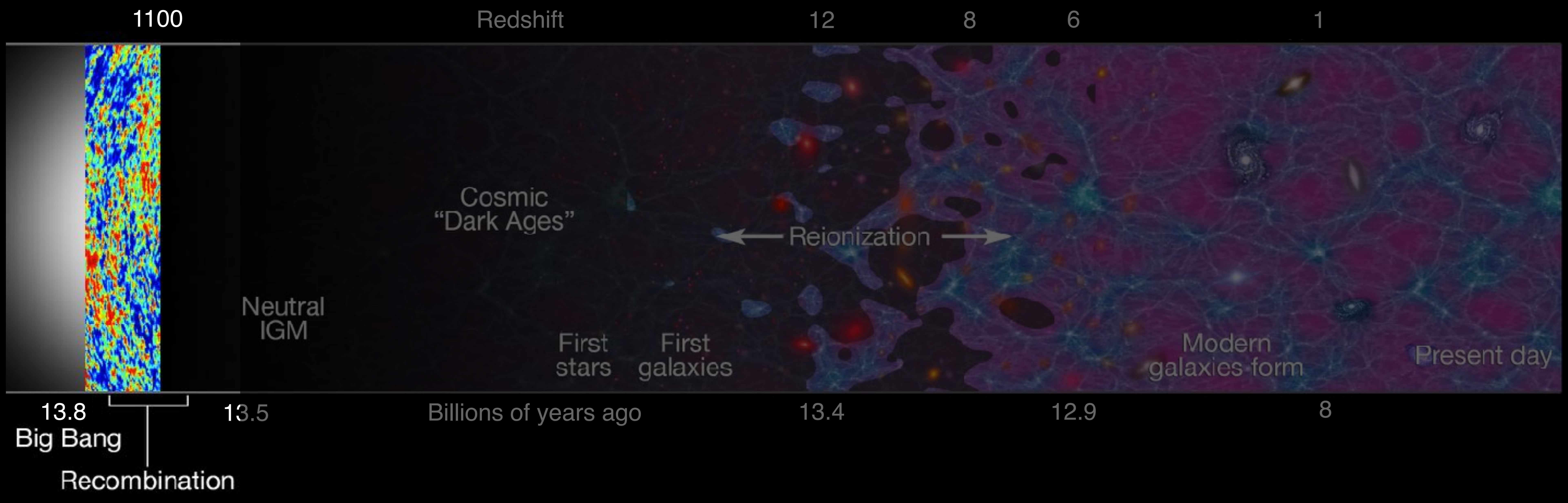
Dan Stark (University of Arizona)
and the Roman Extragalactic Potential Observations (EXPO)
Science Investigation Team (PI: Brant Robertson)

Brief Observable History of the Universe



Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

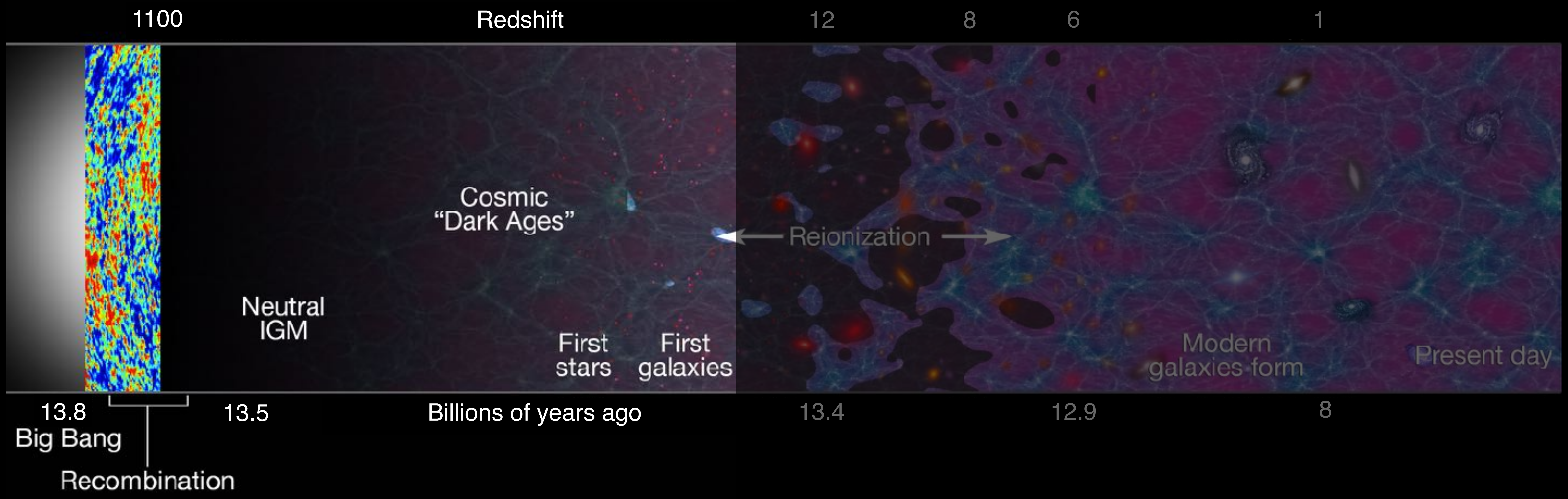
Brief Observable History of the Universe



Recombination (z~1100)

Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

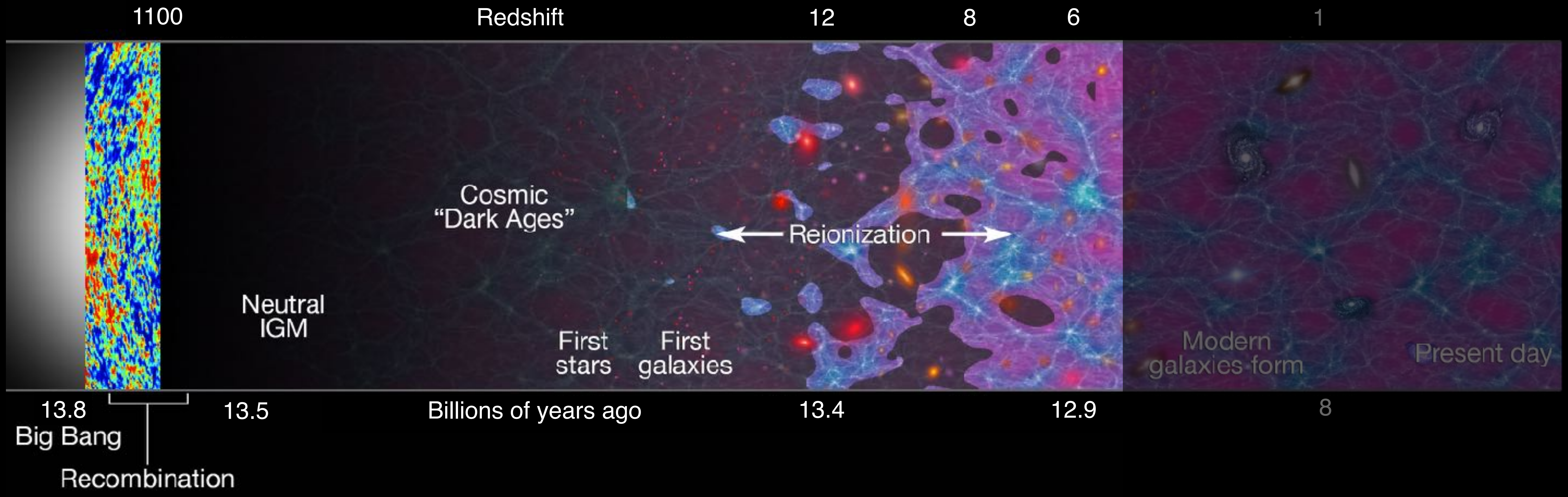
Brief Observable History of the Universe



First Galaxies Form (z~15-30)

Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

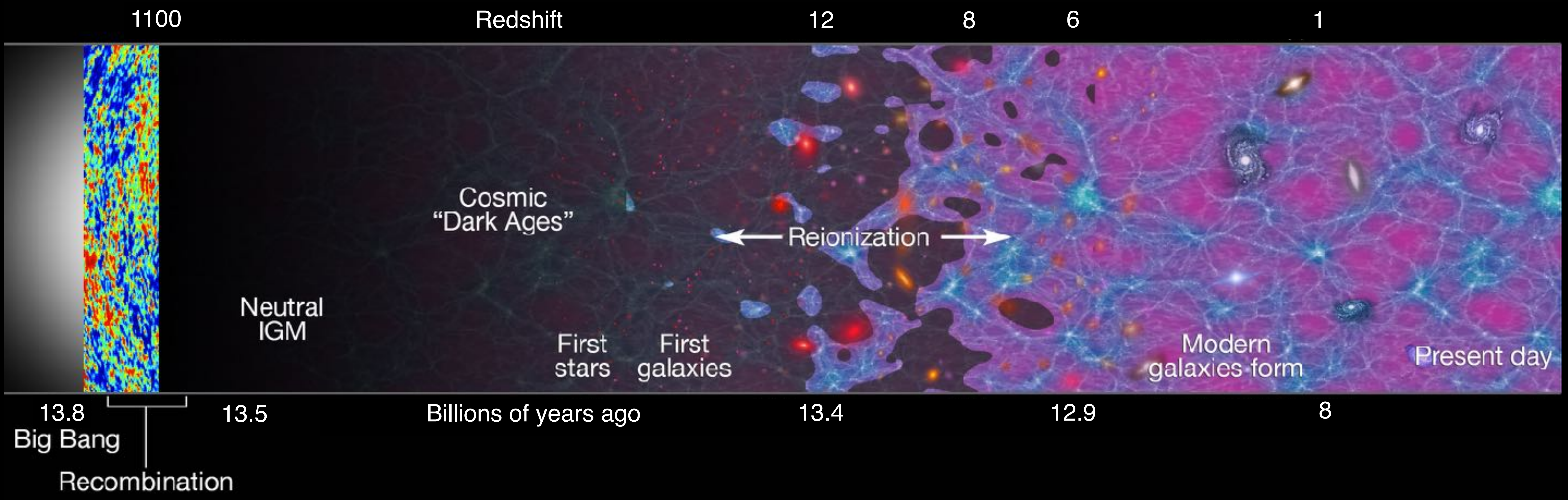
Brief Observable History of the Universe



Reionization (z~6-15)

Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

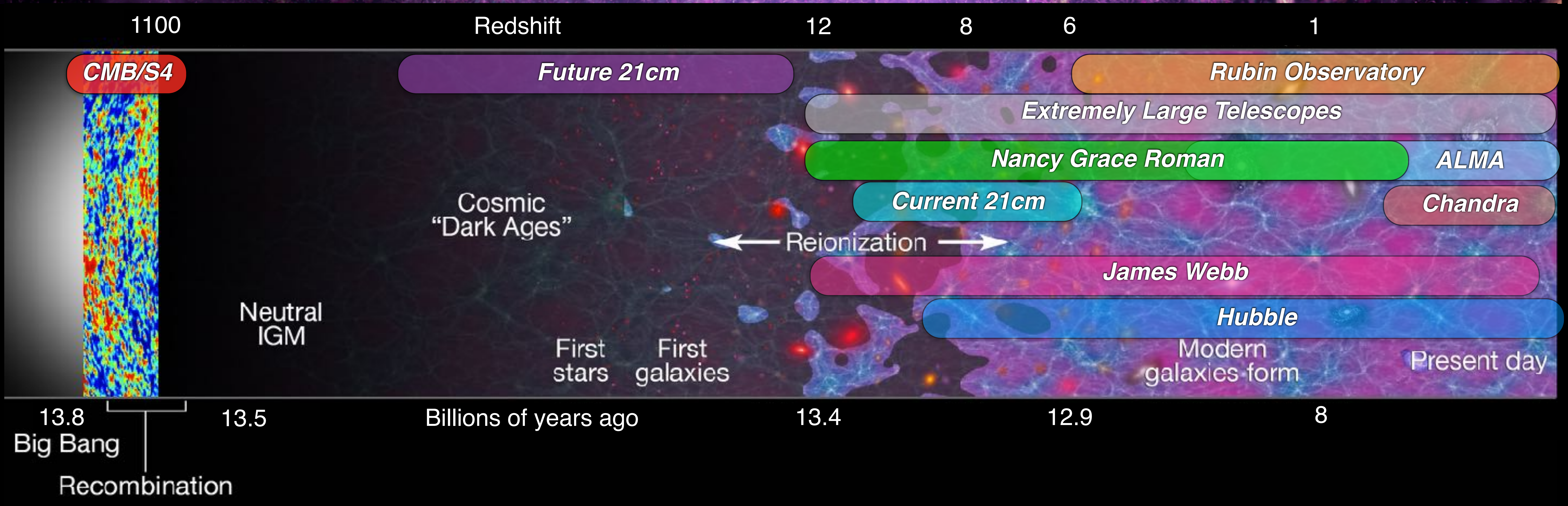
Brief Observable History of the Universe



Modern Galaxies Form (z~0-2)

Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

A New “Golden Age” for Extragalactic Astronomy



Observations with Nancy Grace Roman Space Telescope, ALMA, JWST, Rubin, and the ELTs will drive astronomical discoveries over the next decade.

Adapted from Robertson et al., *Nature*, **468**, 49 (2010)

Roman Extragalactic Potential Observations (EXPO) Science Investigation Team


Mark Dickinson
(NOIR Lab)


Harry Ferguson
(STScI)


Steve Furlanetto
(UCLA)


Jenny Greene
(Princeton)


Piero Madau
(UCSC)


Dan Marrone
(Arizona)


Brant Robertson
(UCSC; PI)


Alice Shapley
(UCLA)


Dan Stark
(Arizona)


Risa Wechsler
(Stanford)


Stan Woosley
(UCSC)

Roman Distant Galaxy Science Questions

- Can we quantify the importance of galaxies and AGNs for reionization through the statistical samples finally delivered by *Roman*?
- Can we use the grism on Roman to map the ionized bubbles created by the first galaxies and quasars?

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- What will *Roman* spectroscopy teach us about galaxy properties and evolution during the peak era of cosmic star formation?

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- How will *Roman* help us understand galaxy properties in the context of their environments over cosmic time?
- What will *Roman* spectroscopy teach us about galaxy properties and evolution during the peak era of cosmic star formation?
- How can we leverage *Roman* to discover and characterize rare AGN and quasars?

Notional *Roman* Surveys

- *Roman* High Latitude Survey (Mission)

  ~2000 deg^2, YJH~26.7AB, g~10^{-16} ergs/s/cm^2

x-scale: 2x width == 100x area
y-scale: 2x width == 2x flux

HLS

Notional *Roman* Surveys

- *Roman* High Latitude Survey (Mission)
  ~2000 deg^2, YJH~26.7AB, g~10^{-16} ergs/s/cm^2

- *Roman* Medium Deep Survey (Mission+GO)
  ~20 deg^2, ZYJH~28.5AB, g~1.6×10^{-17} ergs/s/cm^2

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- *Roman* Medium Deep Survey (Mission+GO)
  ~20 deg^2, ZYJH~28.5AB, g~1.6×10^{-17} ergs/s/cm^2
- *Roman* Ultra Deep Survey (GO)
  ~0.28 deg^2, ZYJH~29.5AB, g~10^{-17} ergs/s/cm^2

x-scale: 2x width == 100x area
y-scale: 2x width == 2x flux

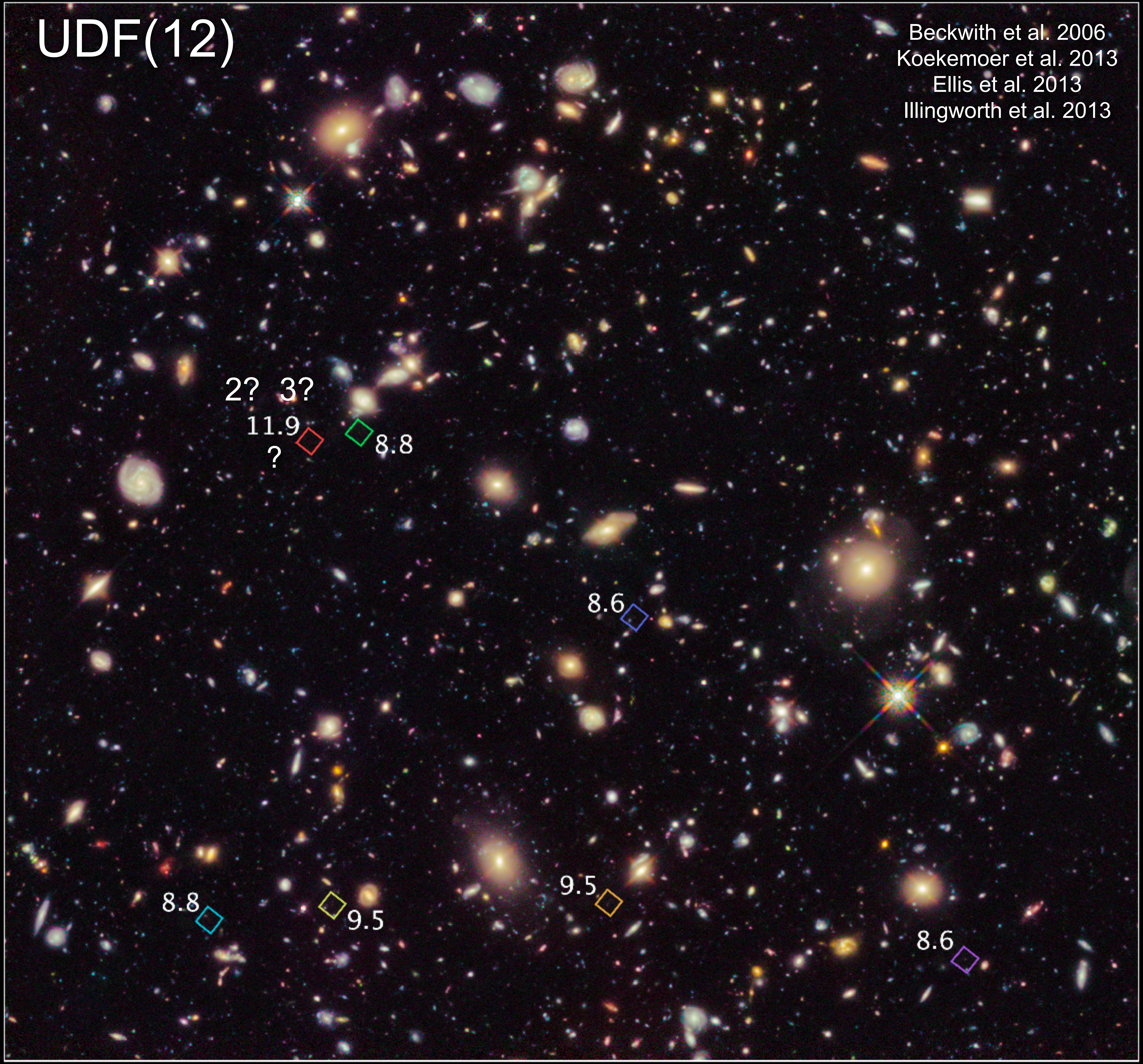
Ultra Deep

Medium Deep

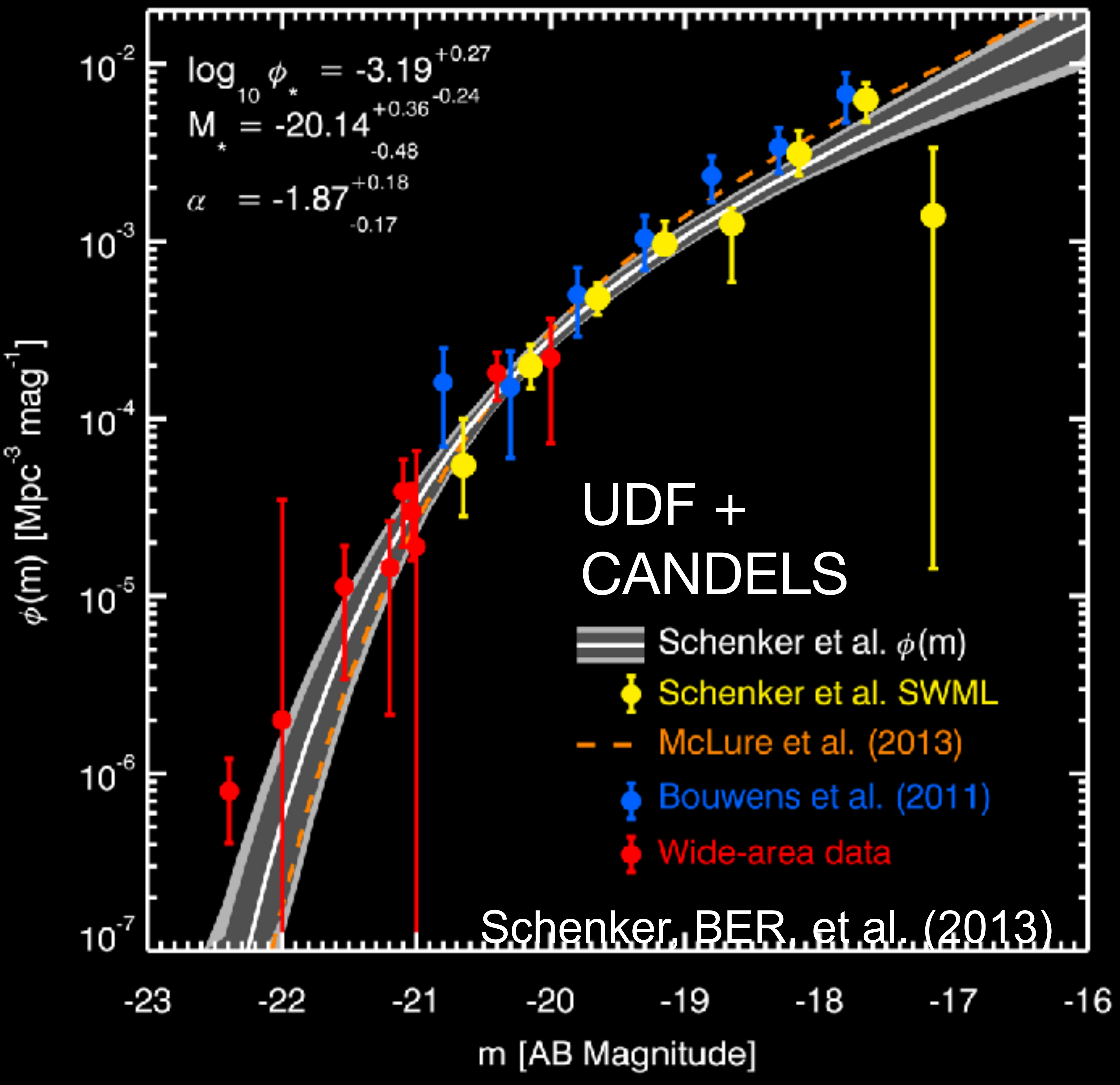
HLS

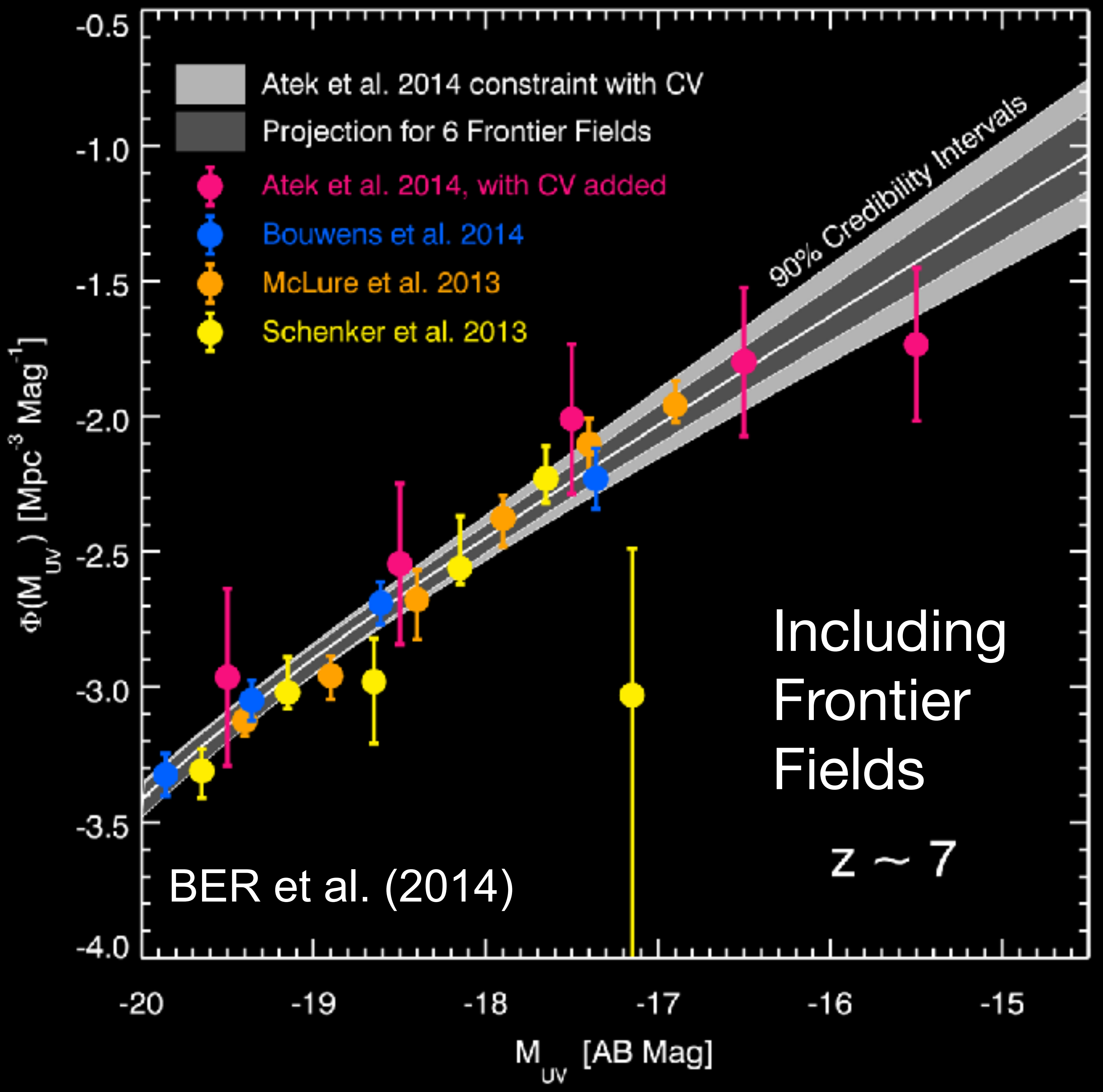
Reionization Science with *Roman*

- Can we quantify the importance of galaxies and AGNs for reionization through the statistical samples finally delivered by *Roman*?


UDF(12)
Beckwith et al. 2006
Koekemoer et al. 2013
Ellis et al. 2013
Illingworth et al. 2013
2?
3?
11.9
?
8.8
8.6
8.8
9.5
9.5
8.6

UV Luminosity Function @ z~7



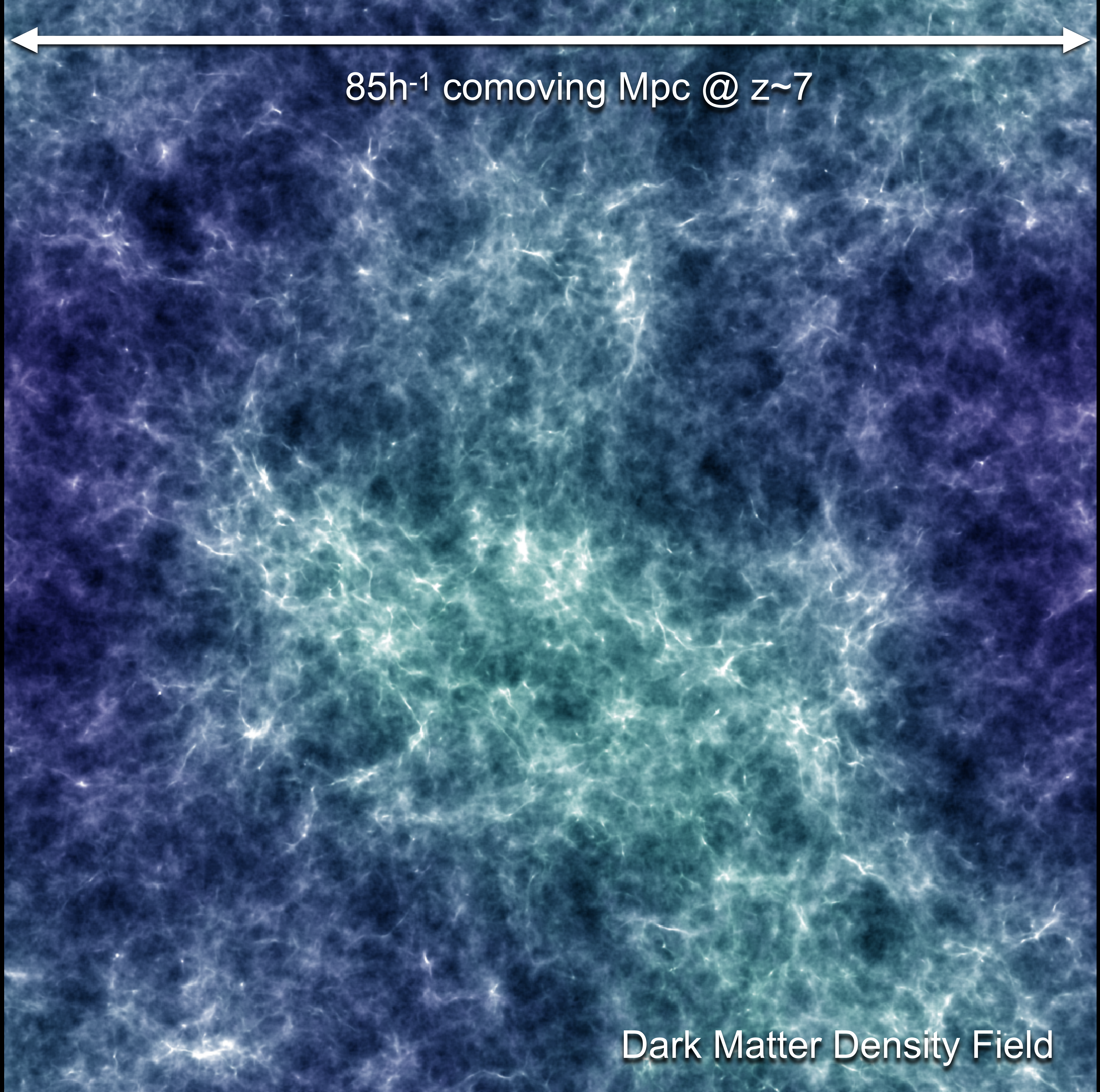


- The z~7 luminosity function of galaxies has a steep faint-end slope ~-2, meaning most of the light and ionizing radiation are contributed by faint galaxies.
- Very deep view of early galaxies, but current deep surveys probe very small volume.
- Uncertainties dominated by limited volume / cosmic variance.

Roman Surveys Enormous Areas

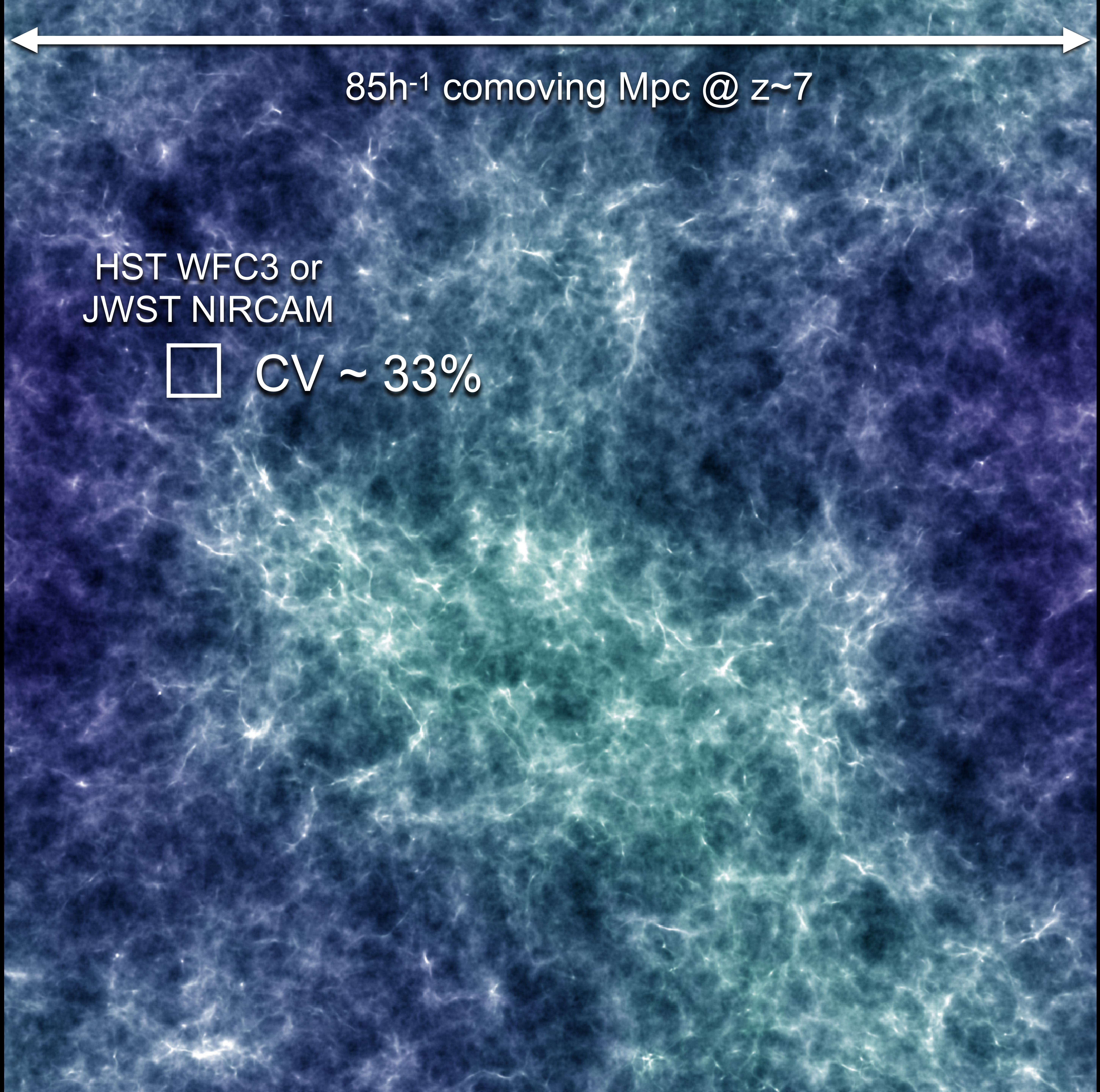
Roman field of view is ~100x *HST* WFC3, with similar sensitivity.

Cosmic Variance



Adapted from Robertson, ApJ, 713, 1266 (2010)

Cosmic Variance



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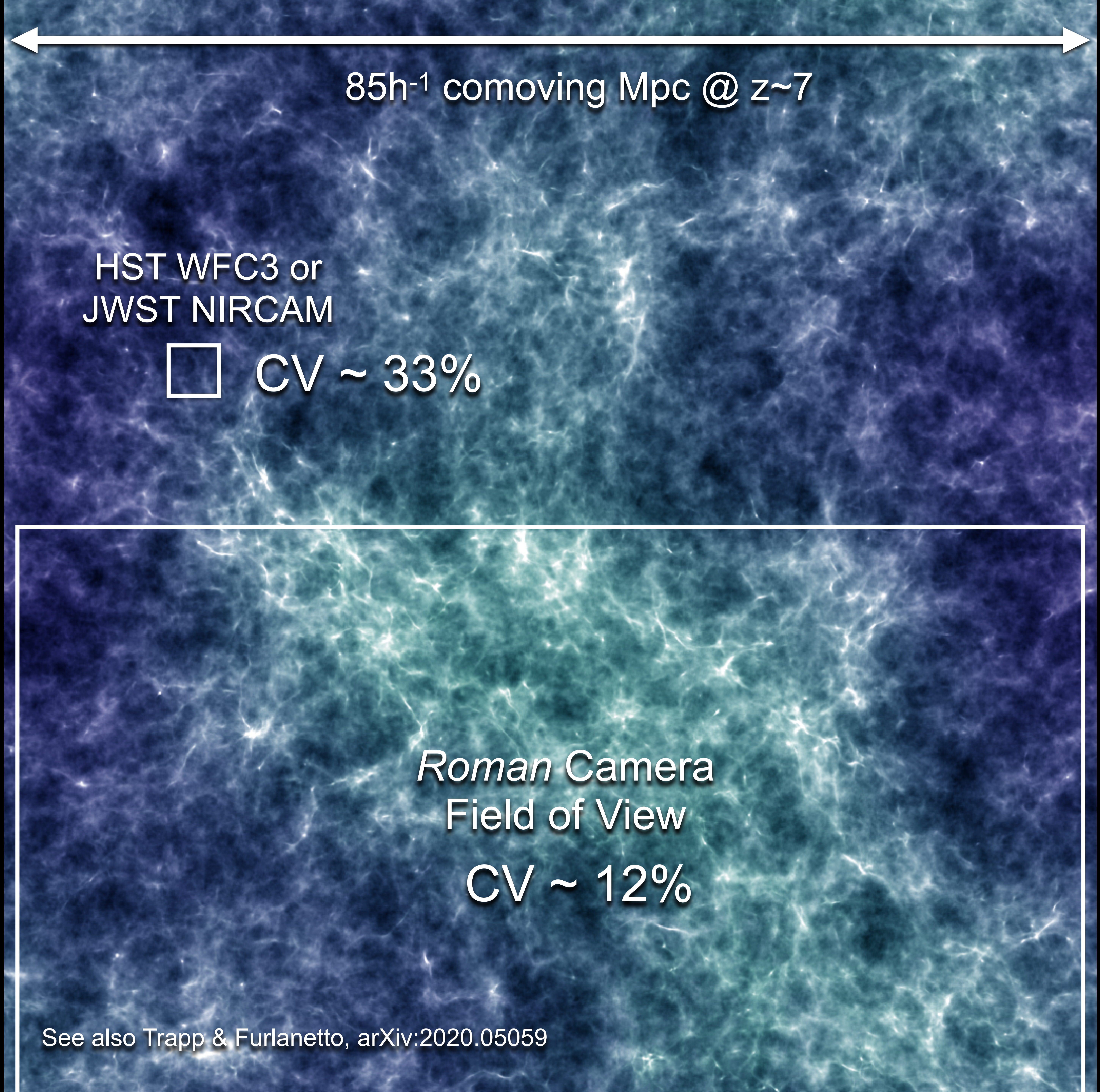
Cosmic Variance



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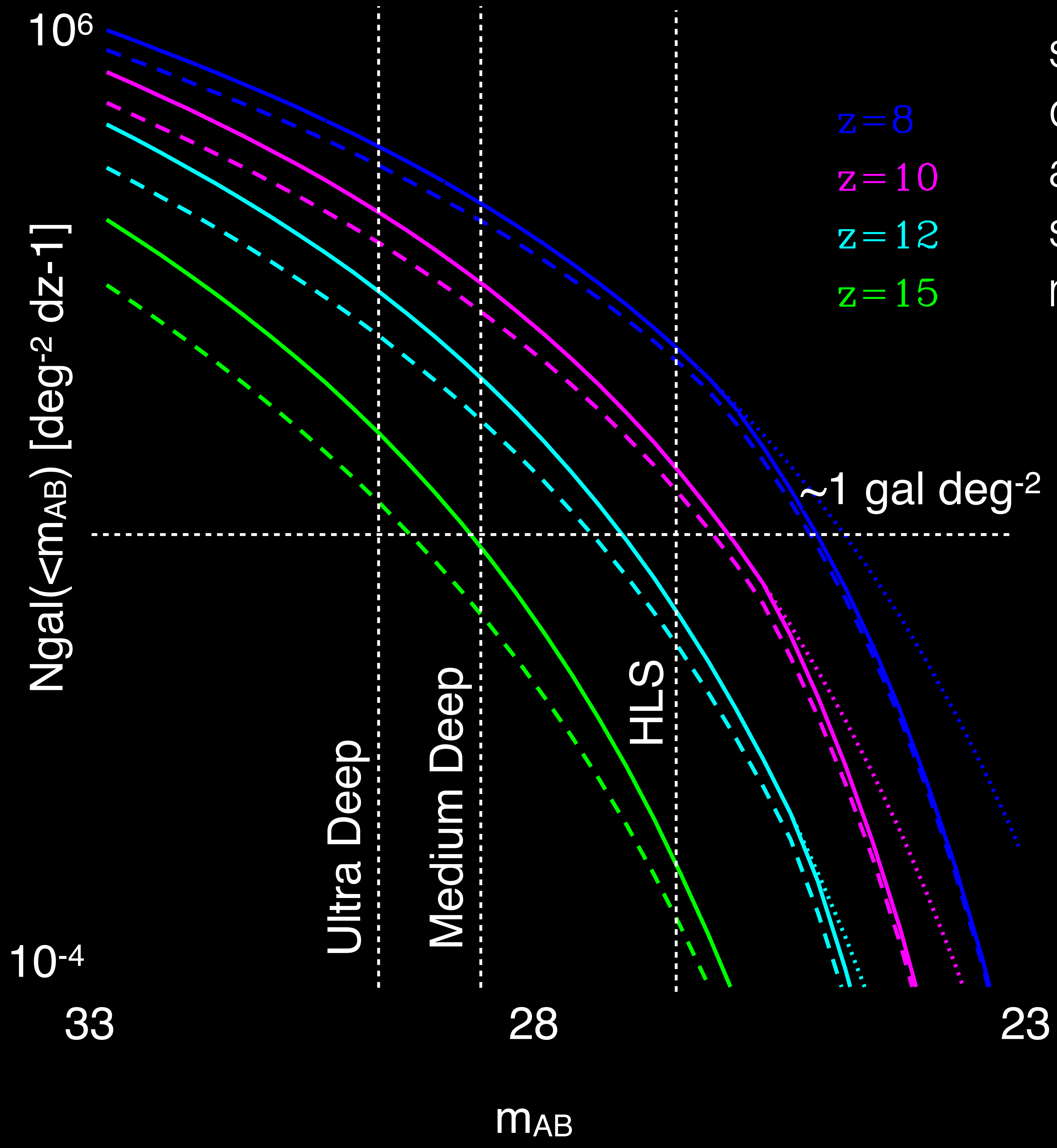
Roman will provide enormous samples of z>8 galaxies

HLS will detect $>10^5$ to 10^6 galaxies at z>8 constraining bright end of luminosity function at z~8-10.



solid/dashed/dotted curves are different star formation models.

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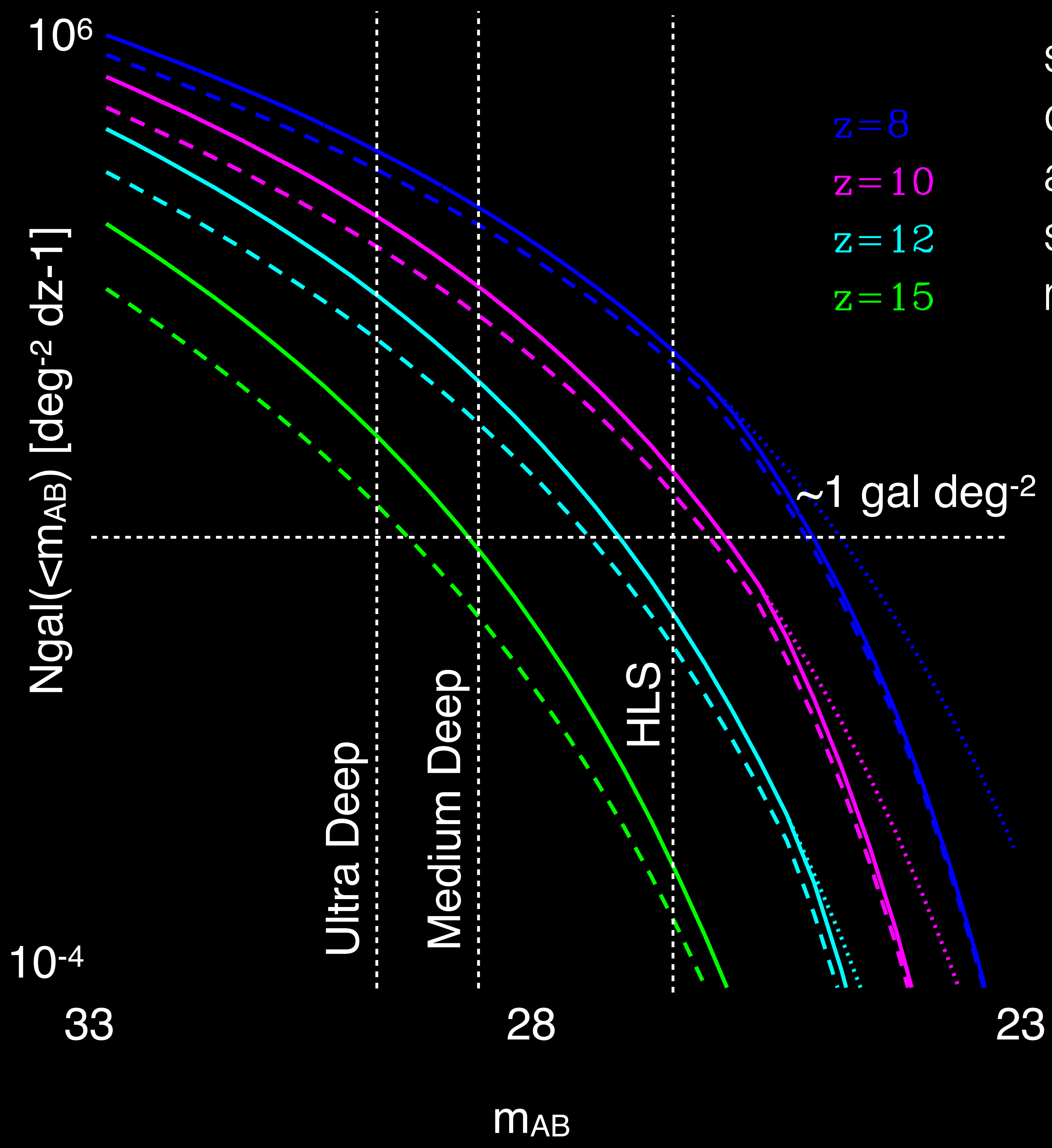
Bulk of UV output thought to be produced by fainter galaxies.



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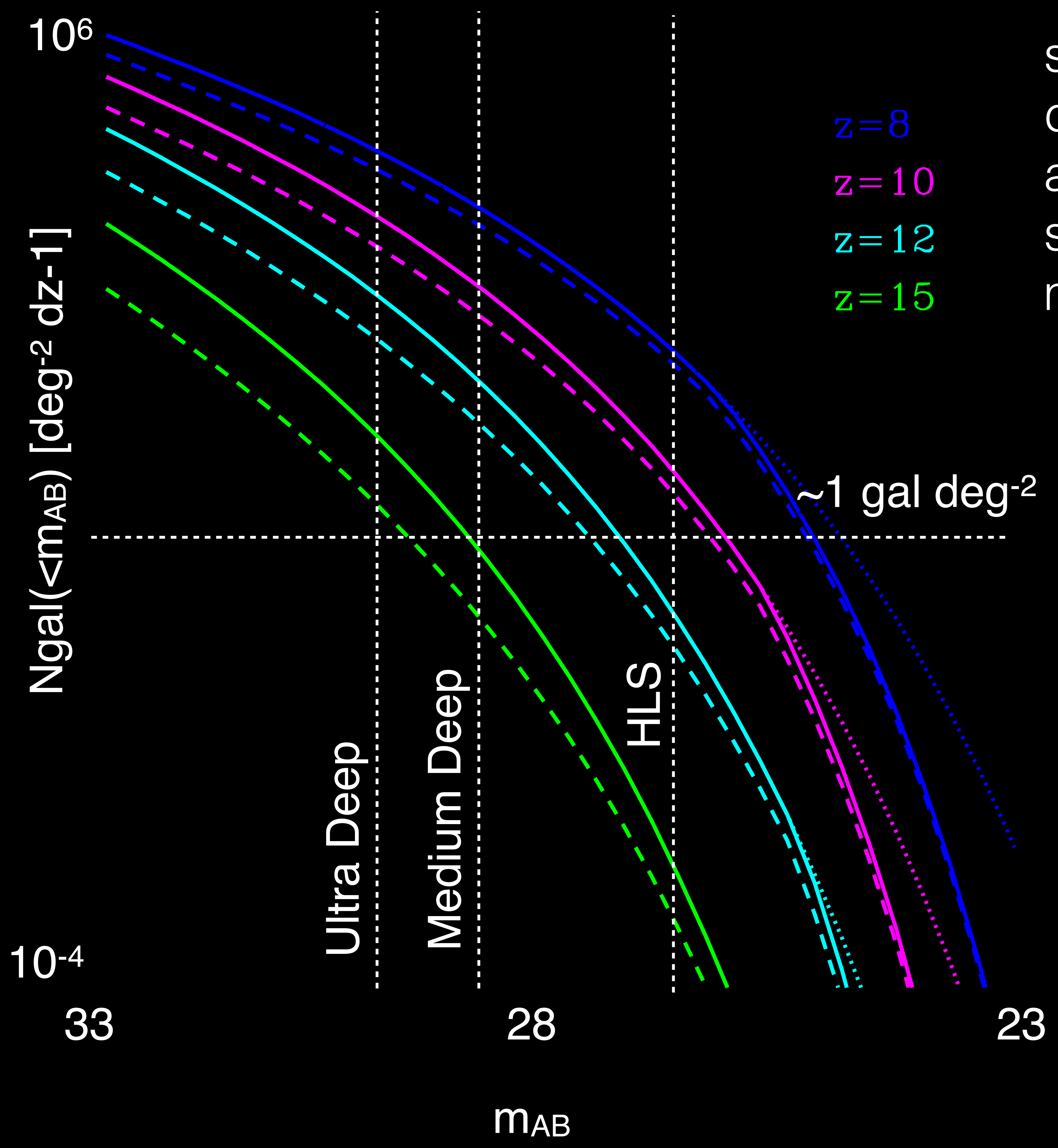
Bulk of UV output thought to be produced by fainter galaxies.

Medium and Ultra Deep surveys probe fainter galaxies at 6<z<10, also detecting more than 10^5 galaxies.



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Roman will provide enormous samples of z>8 galaxies

HLS will provide largest samples but will only probe down to L* at z~8.

Medium and UltraDeep components provide somewhat smaller samples but are needed to identify the more typical faint galaxies which dominate UV output.

SDSS-like survey for high redshift galaxies.

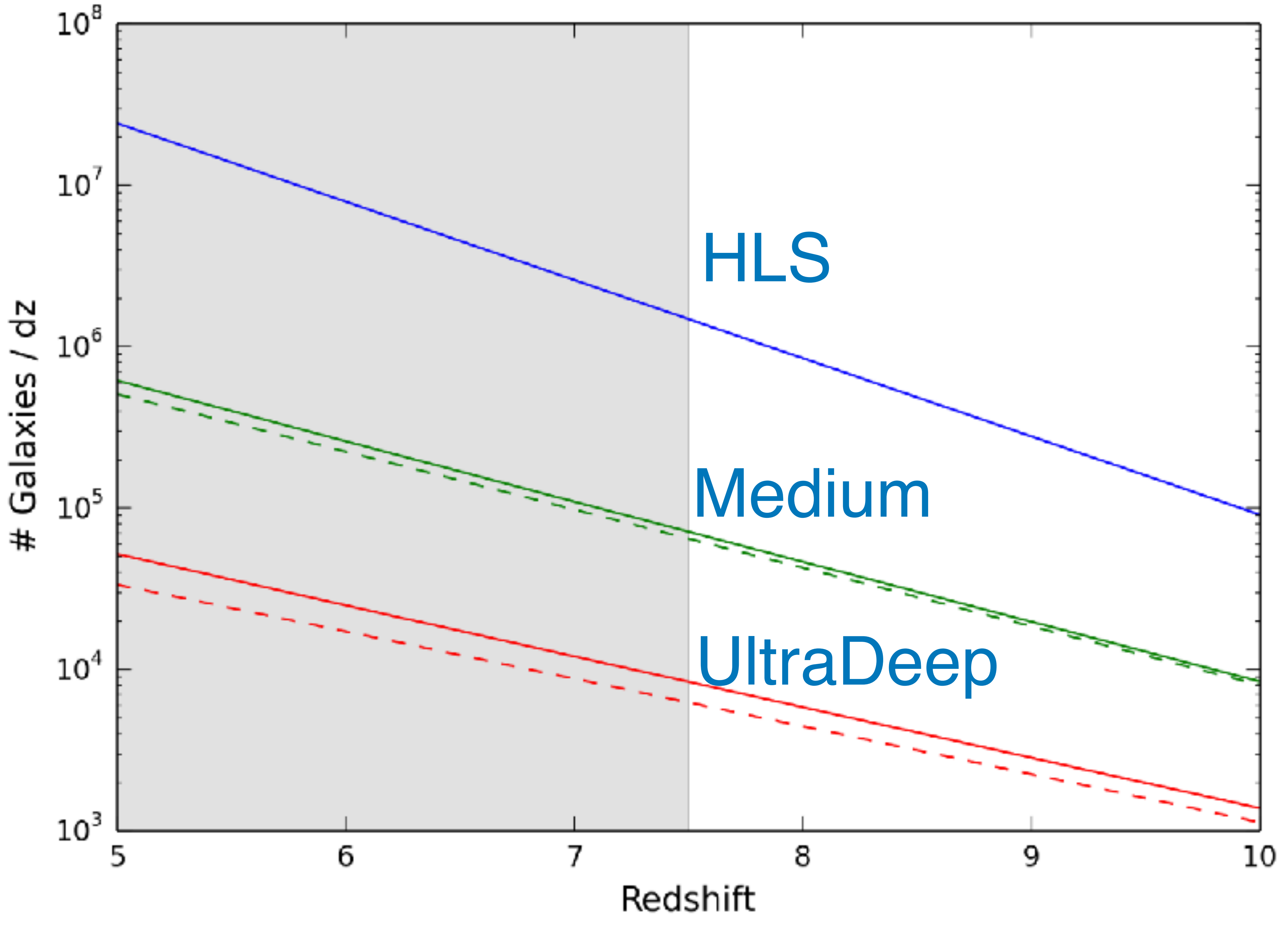

Figure 3.1: Source counts for our fiducial HLS (blue), Medium Deep (green) and Ultra Deep (red) surveys. Solid lines show source counts to the limiting depth of the survey, while dotted lines show source counts fainter than the limiting magnitude of the next larger survey (Medium Deep vs. HLS, and Ultra Deep vs. Medium Deep).

courtesy of B. Robertson and EXPO team

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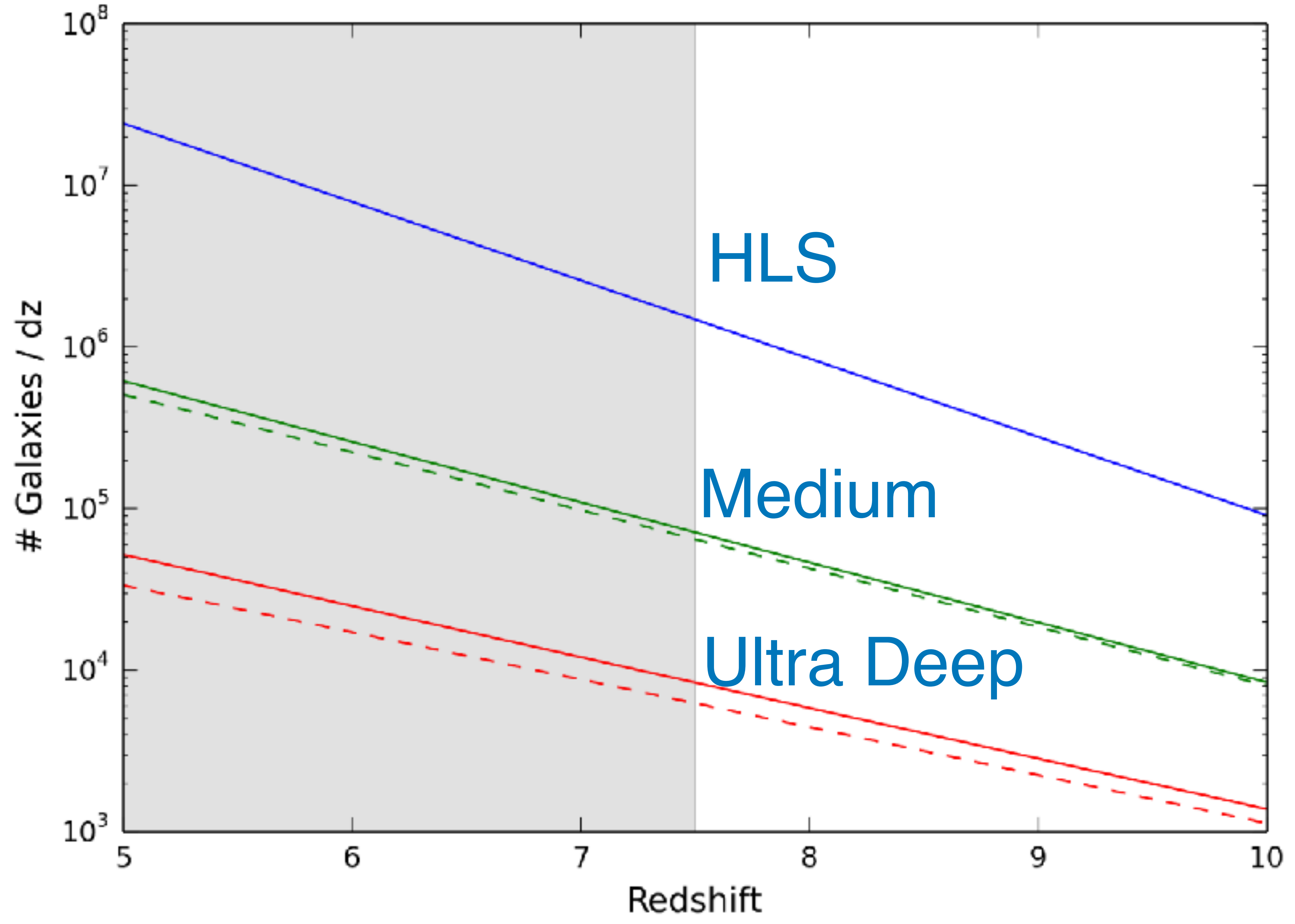
SDSS-like survey for high redshift galaxies.

- Luminosity function establishes relative role of bright/faint galaxies in reionization.
- Angular clustering establishes galaxy/halo connection.
- Brightest gravitationally lensed galaxies at z>8 for detailed spectroscopic study.
- Rare overdense regions easily identifiable. Earliest sites of structure formation.



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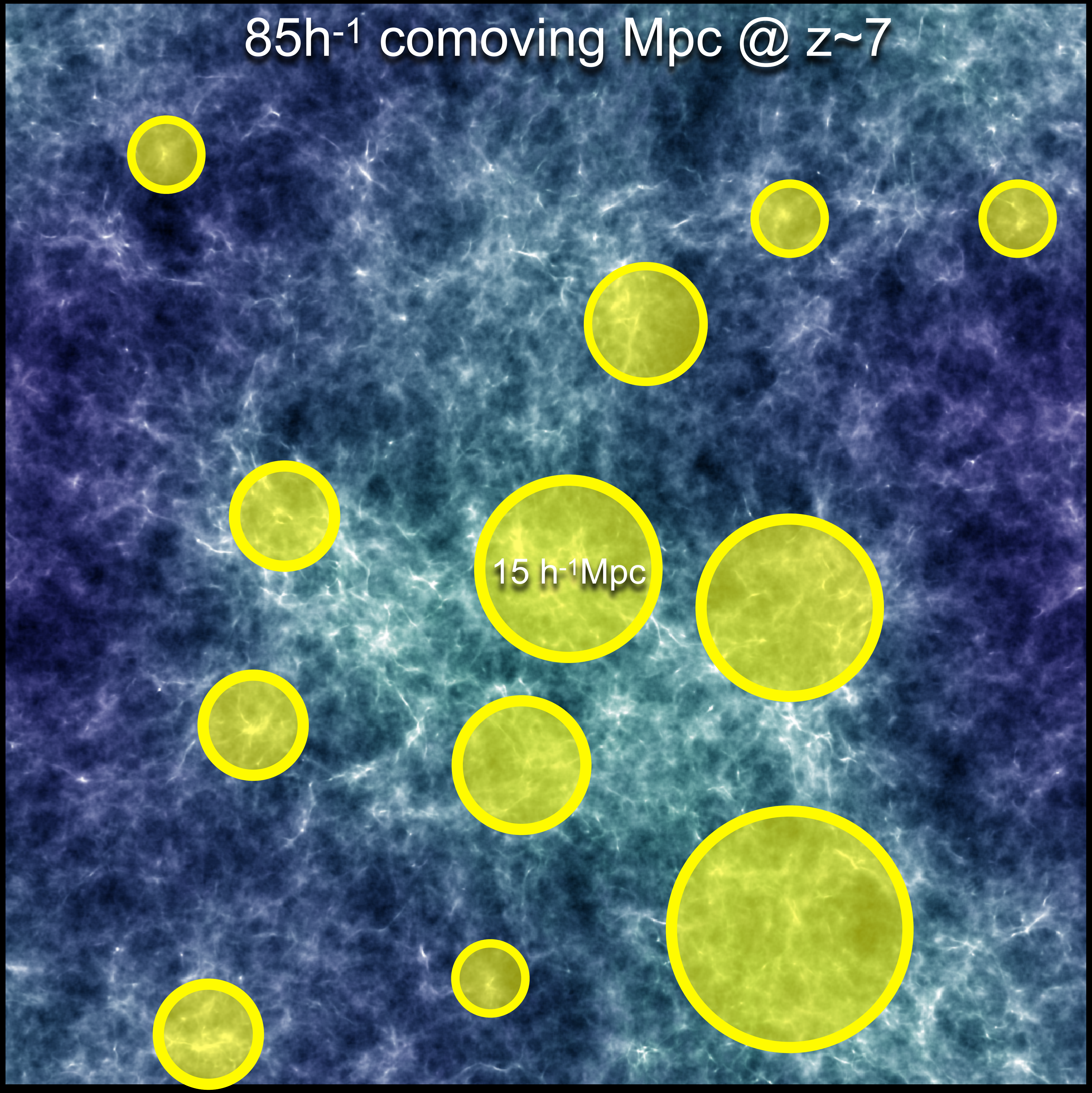
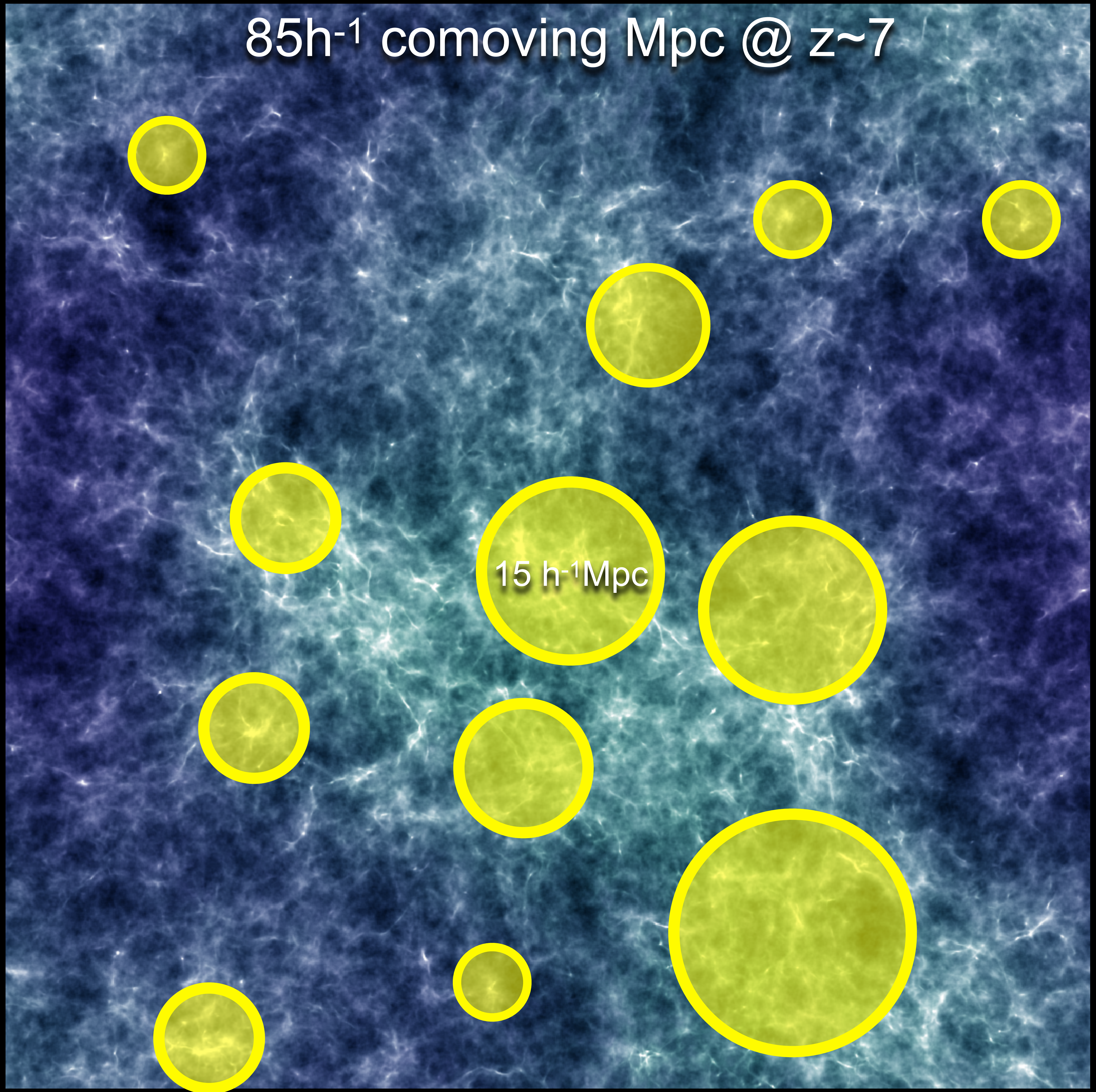
Roman and Ionized Bubbles



- Reionization begins around largest overdensities, with large ionized bubbles growing over time at $6<z<10$.

Roman and Ionized Bubbles



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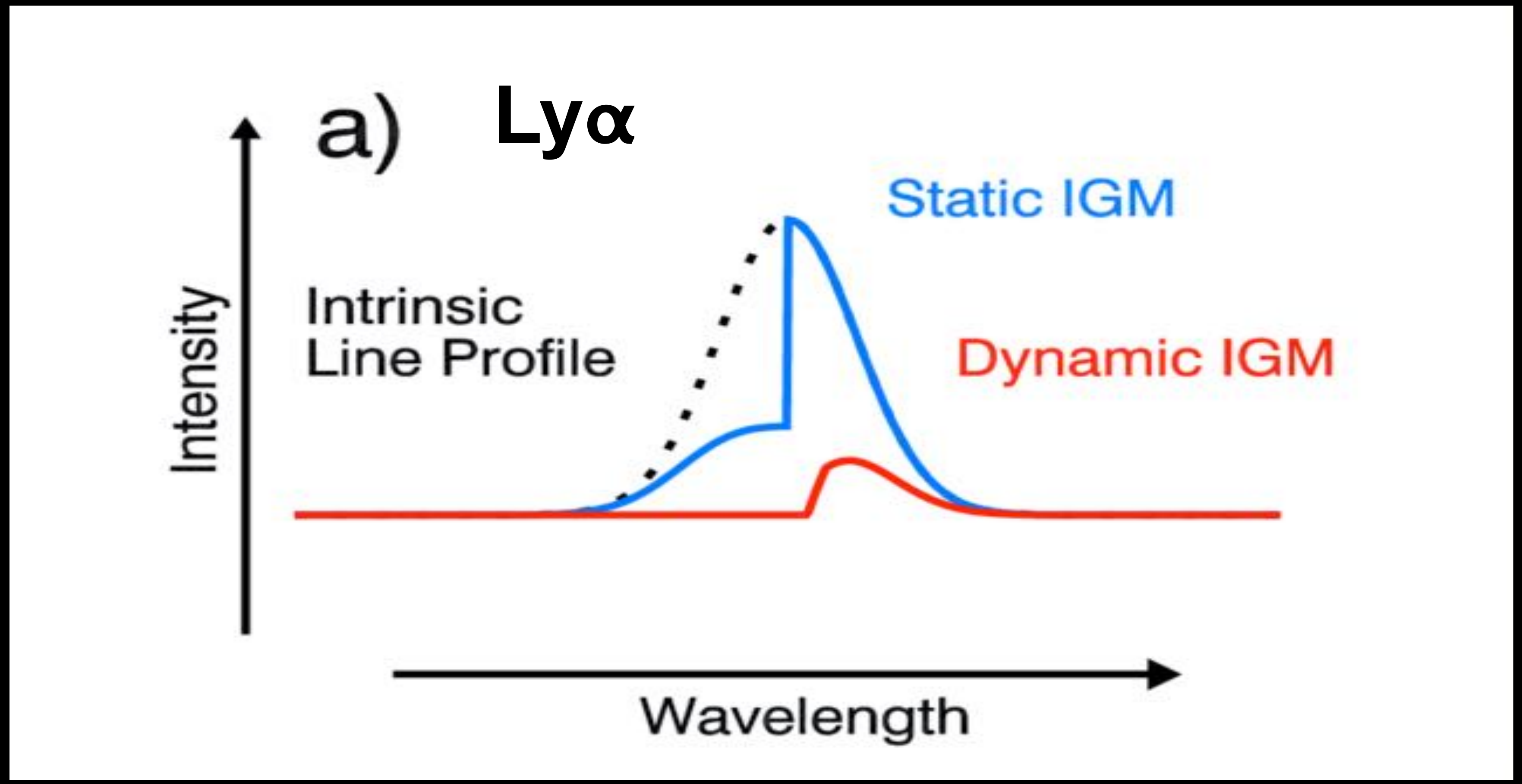

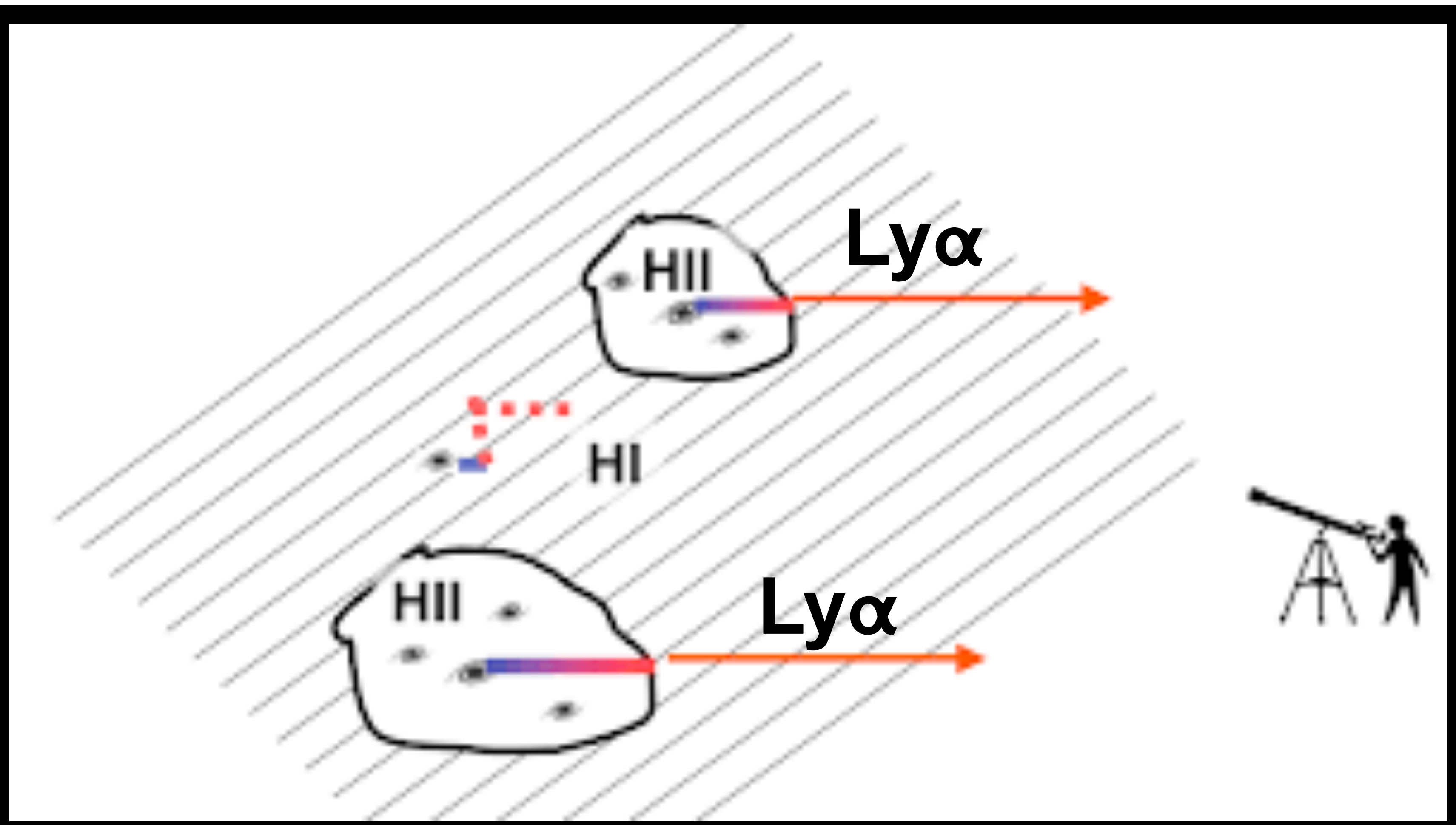

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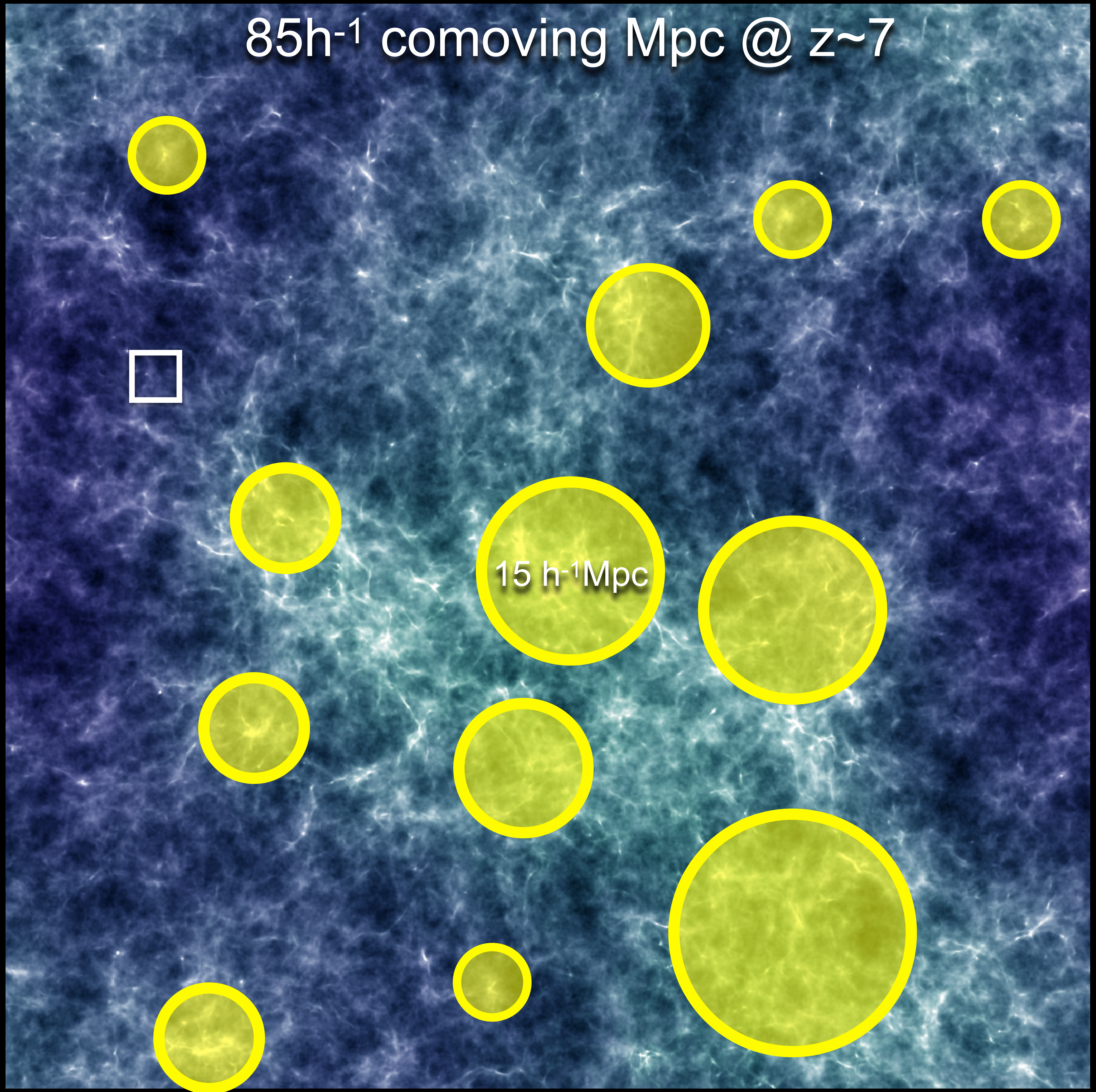
- Lyman alpha spectroscopy provides means of identifying bubbles. *Lyman alpha weakened by neutral IGM. Lyman alpha emitters likely to be located in bubbles, providing signpost of largest ionized regions.*

Roman and Ionized Bubbles



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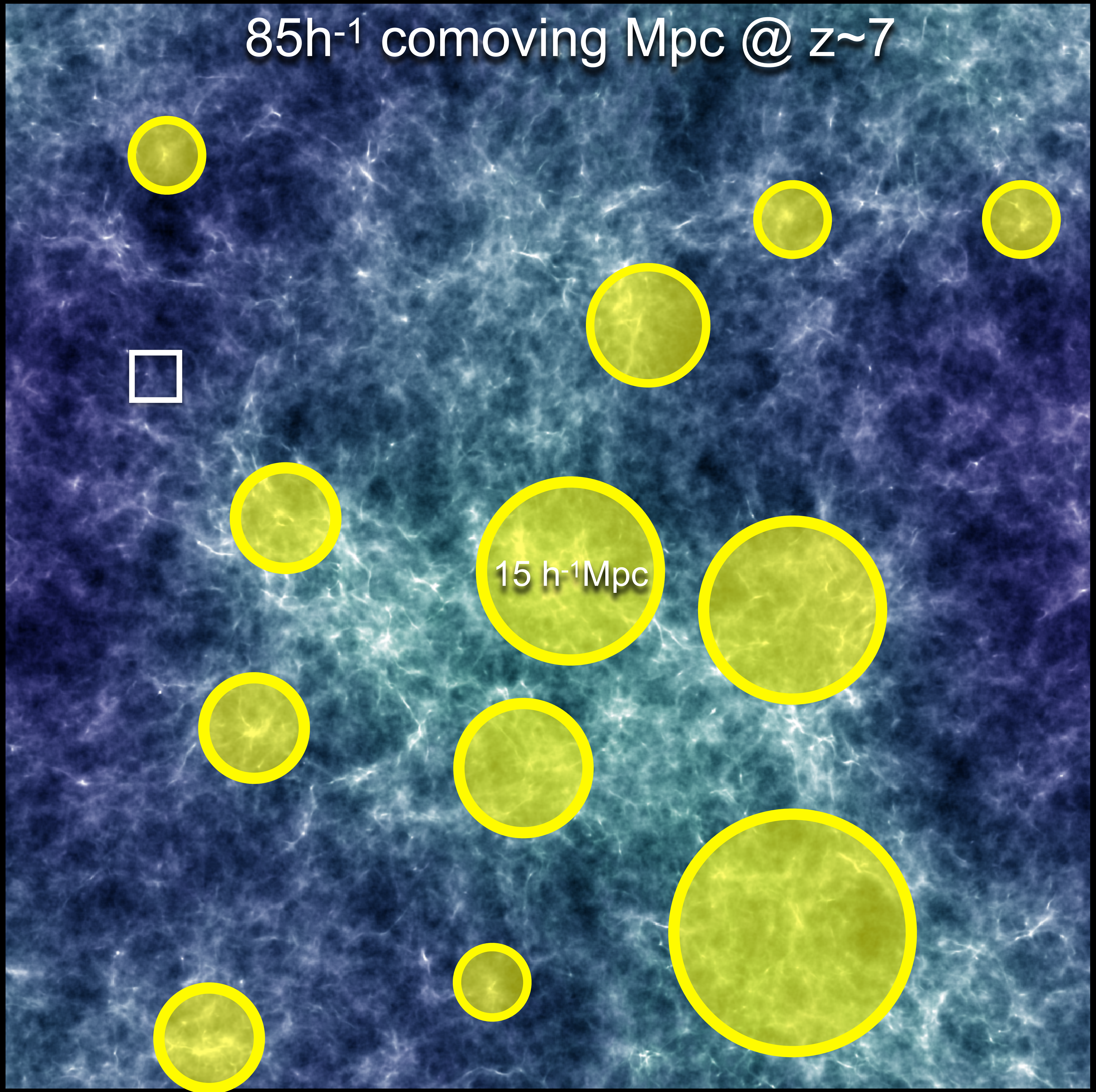

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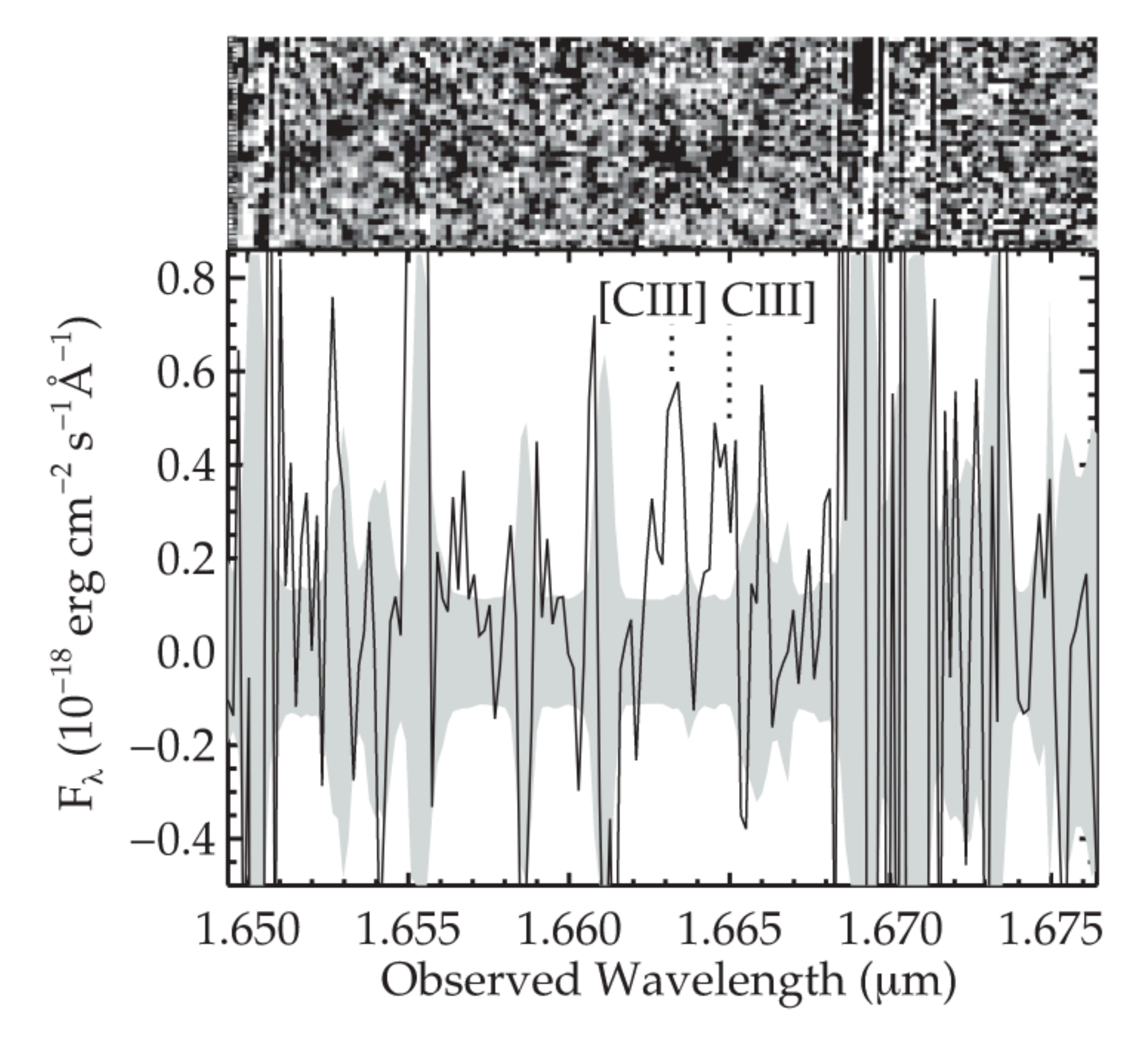
- Lyman alpha spectroscopy provides means of identifying bubbles.
- Ionized regions are big (~10-15 arcminutes), requiring large fields of view. JWST and ELTs ill-suited to this task.
- Roman grism spectra in medium survey can reach requisite flux level to identify Lyman alpha in H=24 (EW>7Å) and H=26 (EW>35Å) — can identify and map size of ionized bubbles.

Roman grism reveals nature of early galaxies



Stark et al. 2017

In addition to Lyman alpha, the Roman grism is sensitive to a suite of fainter lines in the far UV (NV, CIV, He II, OIII], CIII]).

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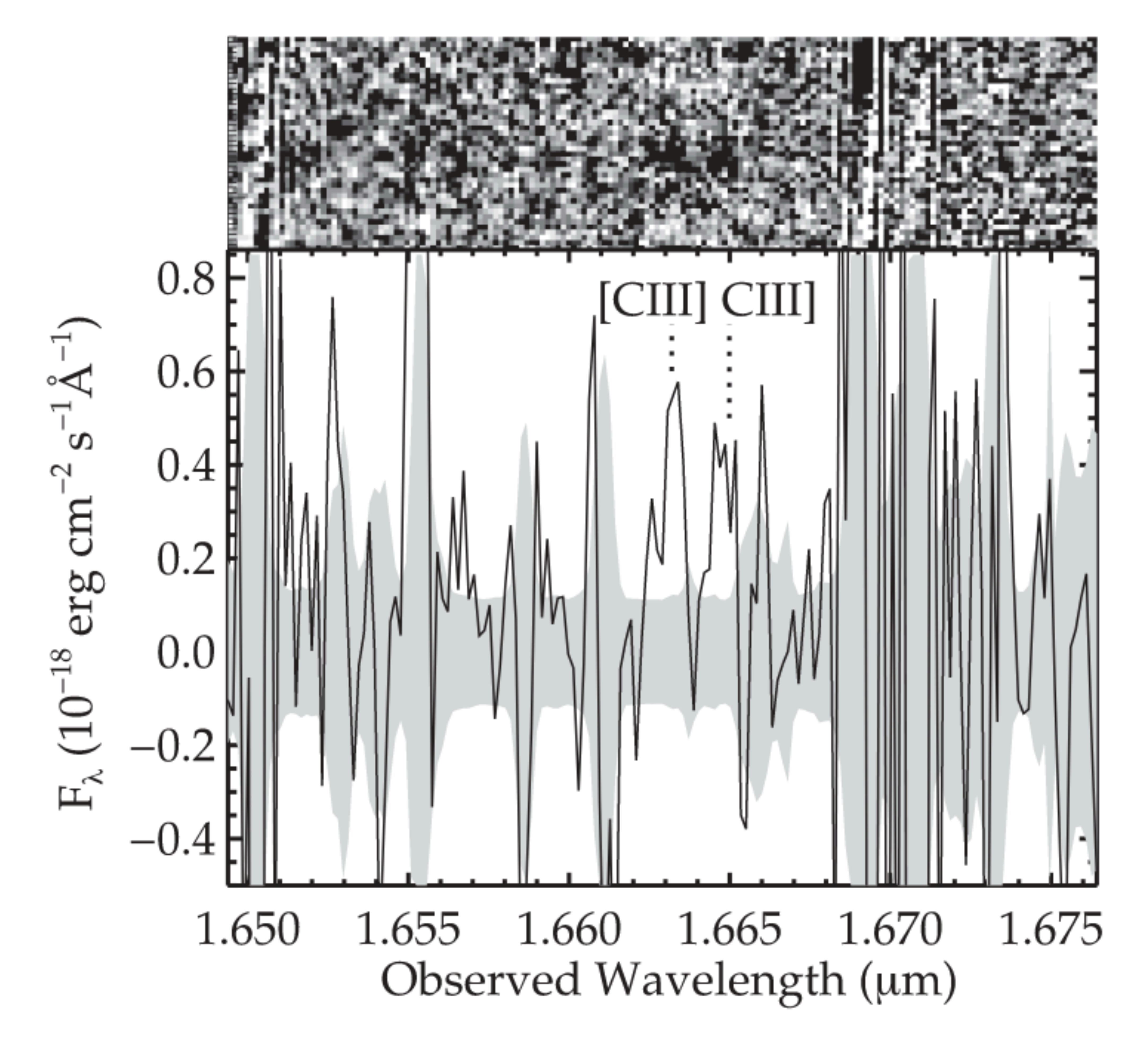

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Lines are faint but detectable in bright galaxies (and have already been detected with HST/WFC3 grism; Tilvi et al. 2016, Schmidt et al. 2017).

EW=20Å detectable at H~25 for medium depth grism survey.

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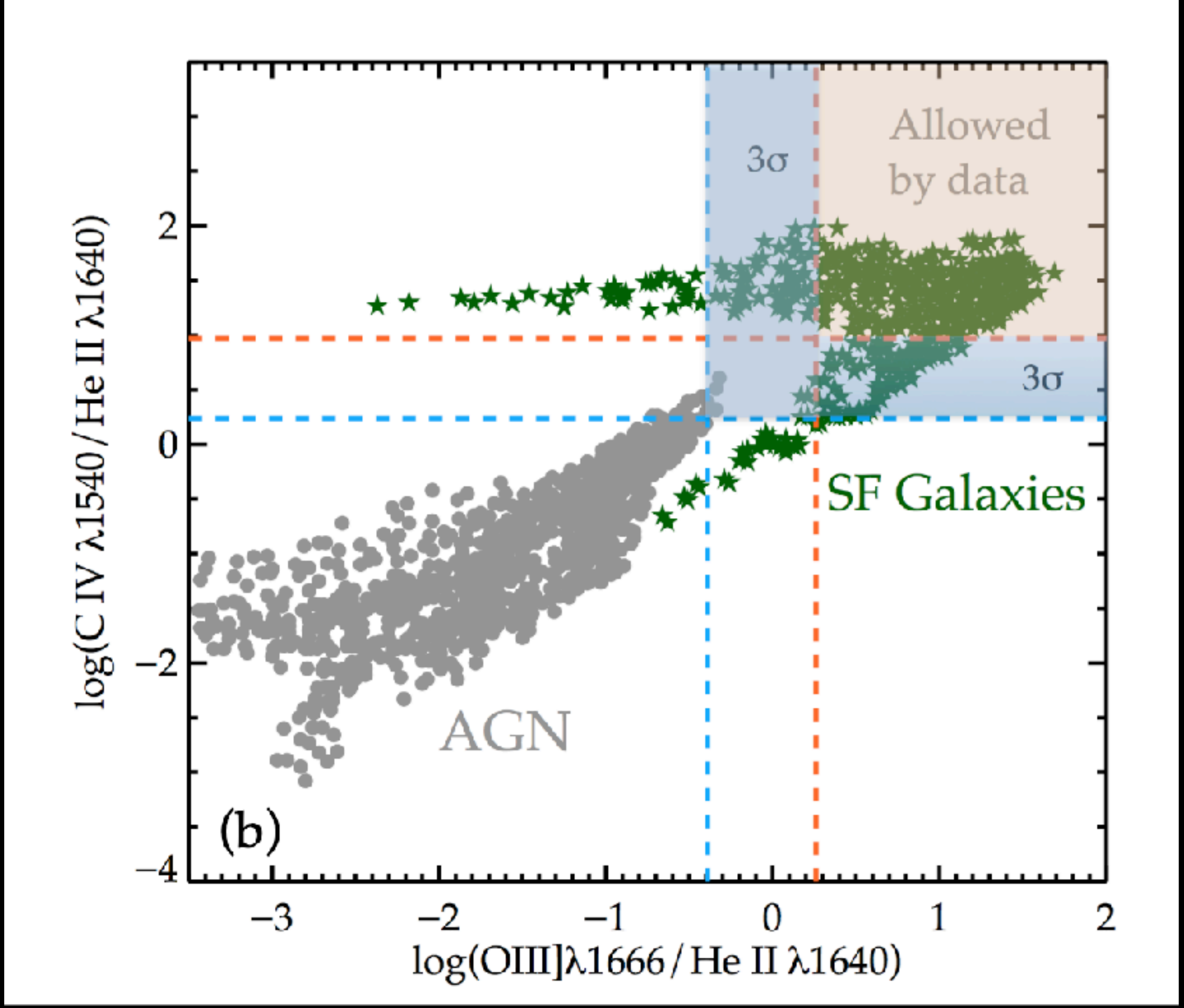

Mainali et al. 2017

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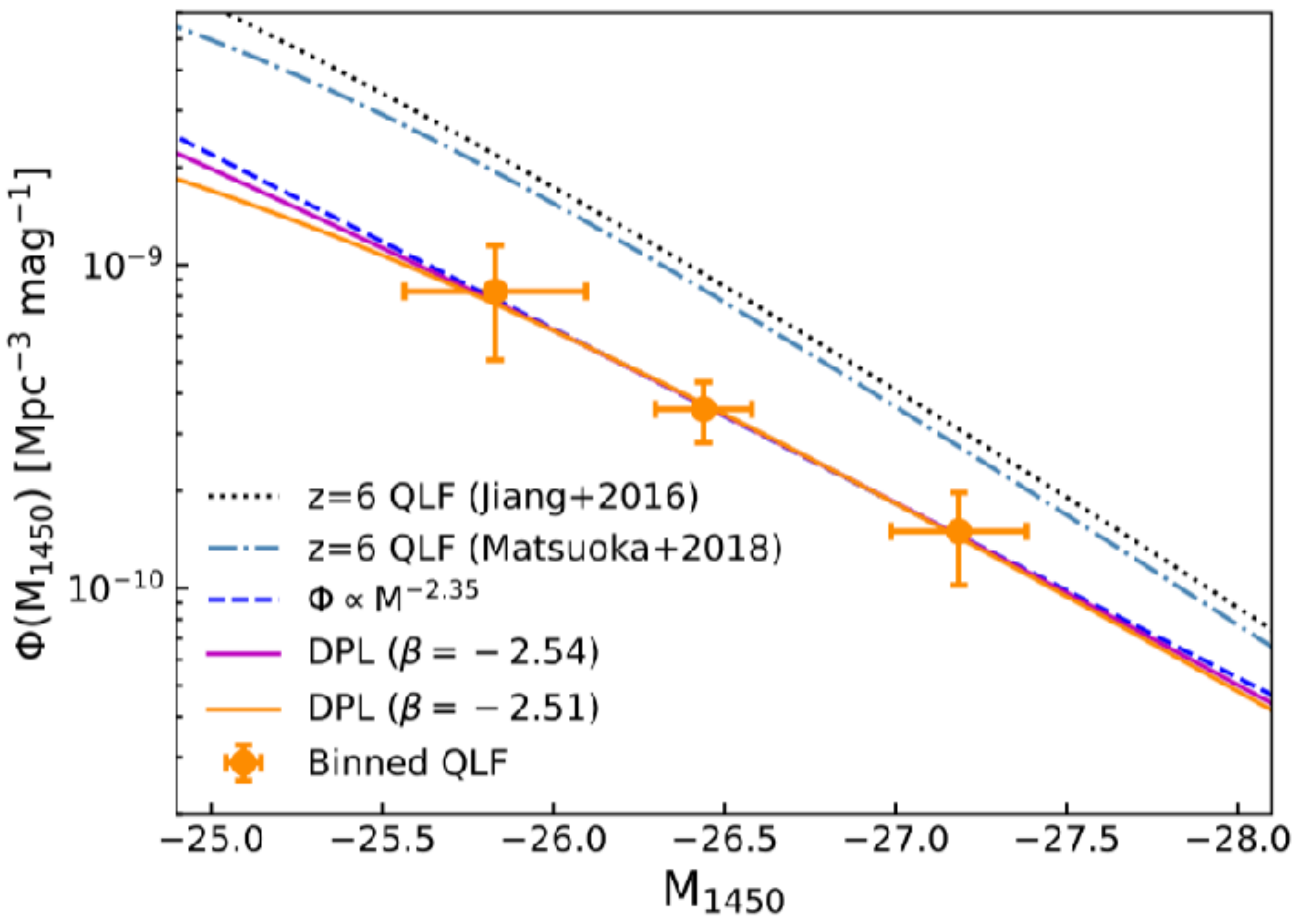
EW=20Å detectable at H~25 for medium depth grism survey.

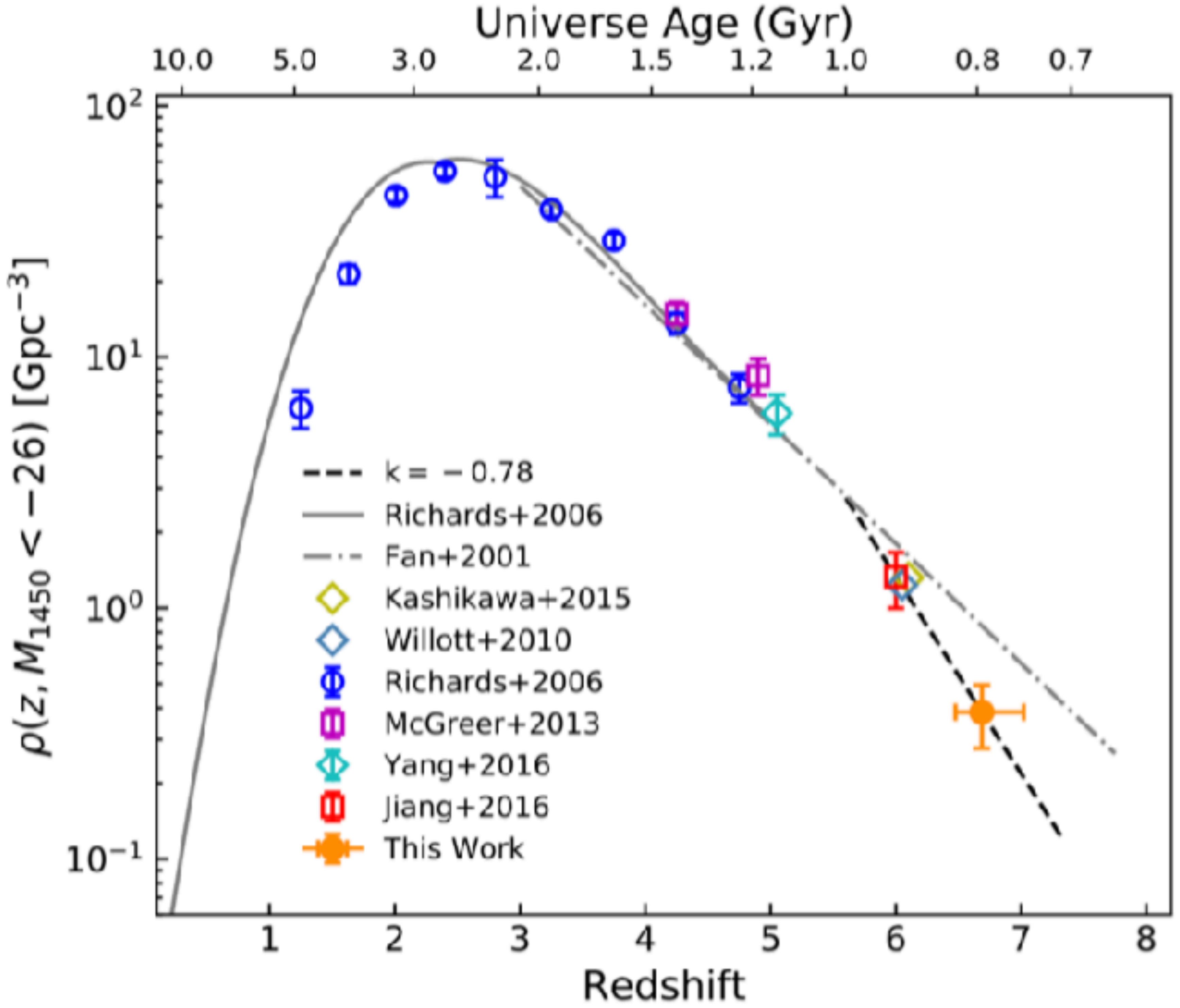
Low luminosity AGN can cleanly be selected via line ratios, revealing their role in reionization.

AGN and Quasars with *Roman*

- How can we leverage *Roman* to discover and characterize rare AGN and quasars?

AGN and Quasars with *Roman*



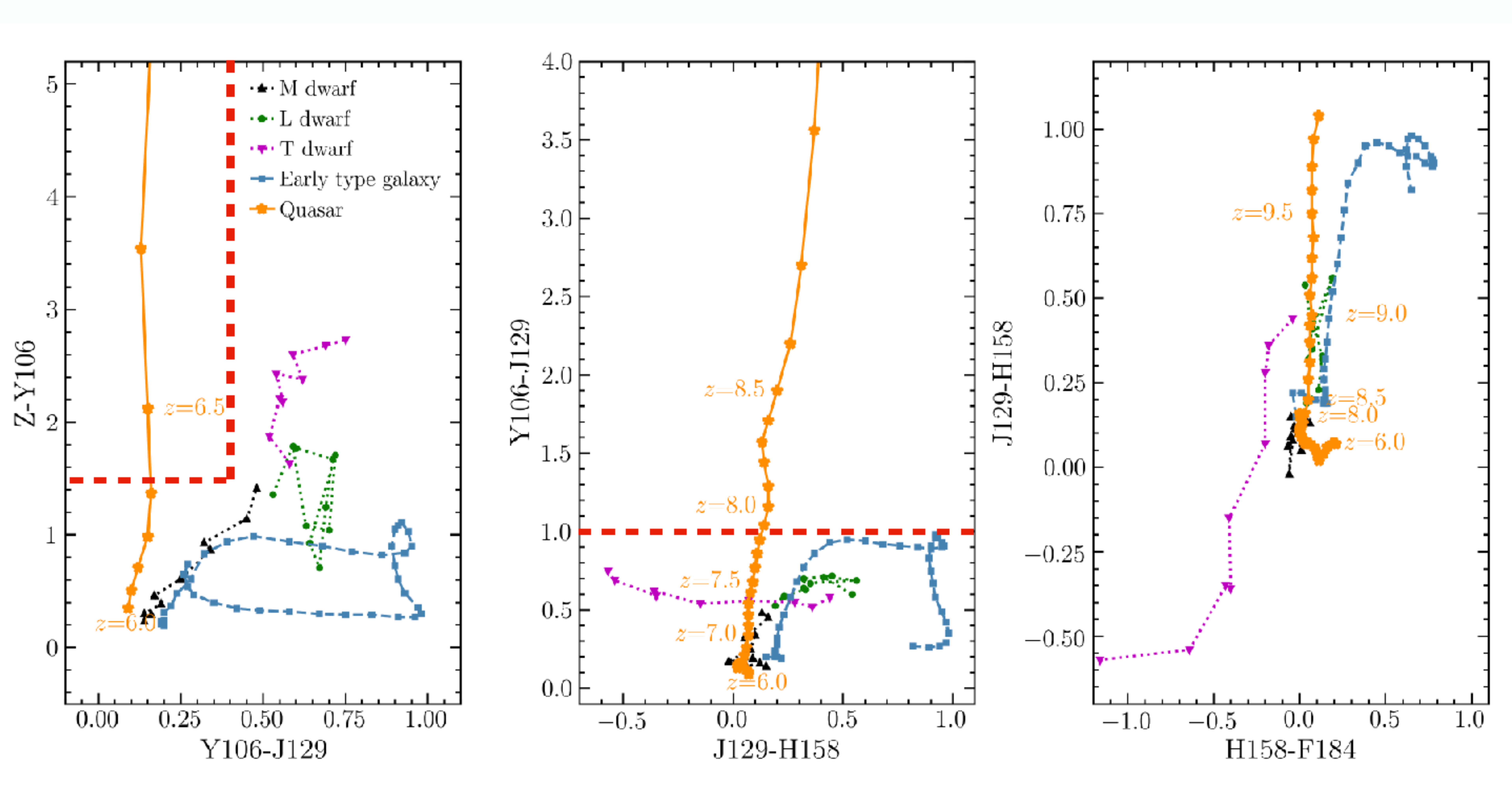


$$\Phi(M,z) = \frac{\Phi^{*}(z)}{10^{0.4(\alpha+1)} + 10^{0.4(\beta+1)(M-M^{*})}}$$

$$\rho(M<-26,\, z\sim 6.7) = (0.39 \pm 0.11)\,\mathrm{Gpc}^{-3}$$

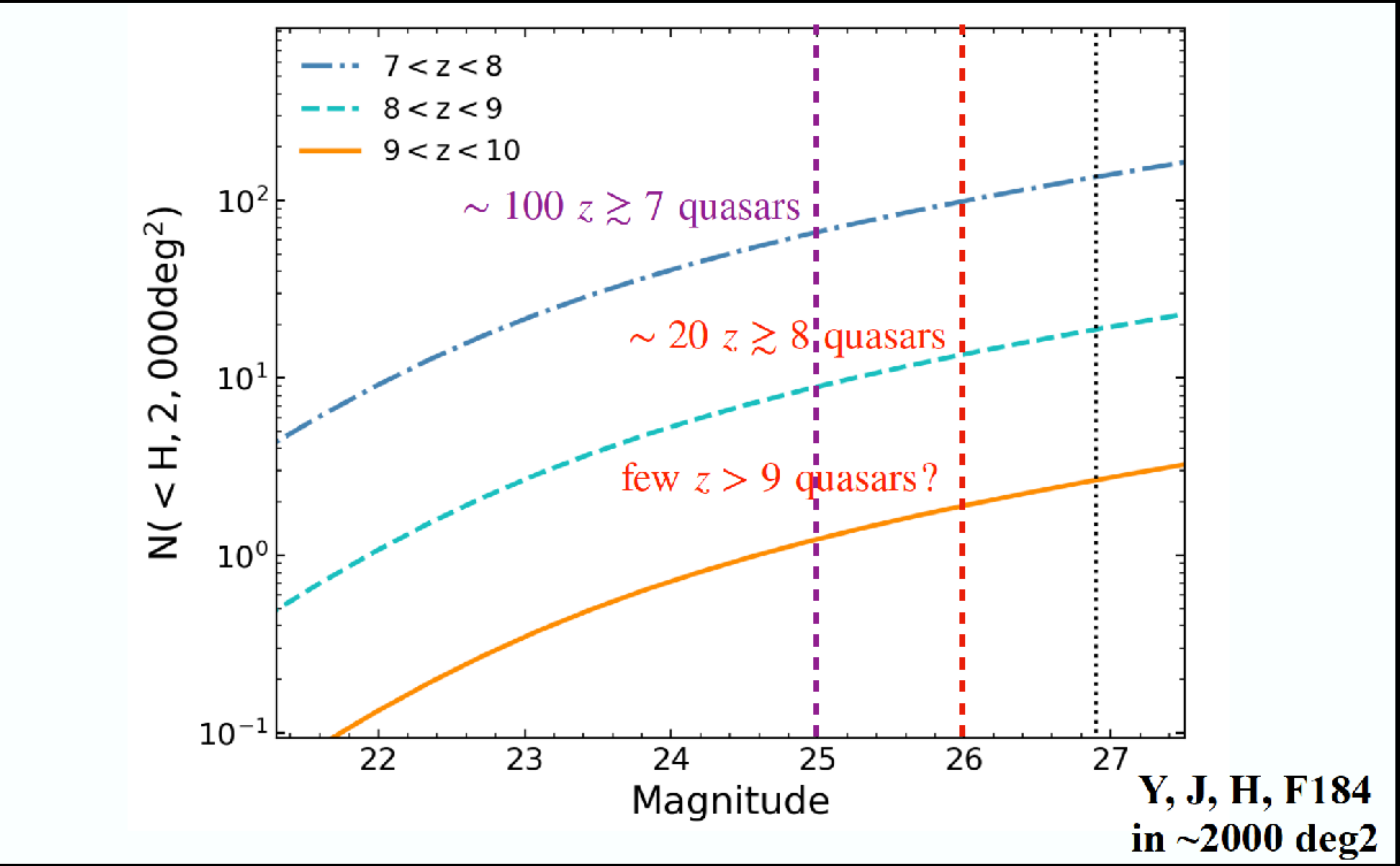
Wang et al. 2019b

AGN and Quasars with *Roman*



Slide courtesy of Feige Wang

AGN and Quasars with *Roman*



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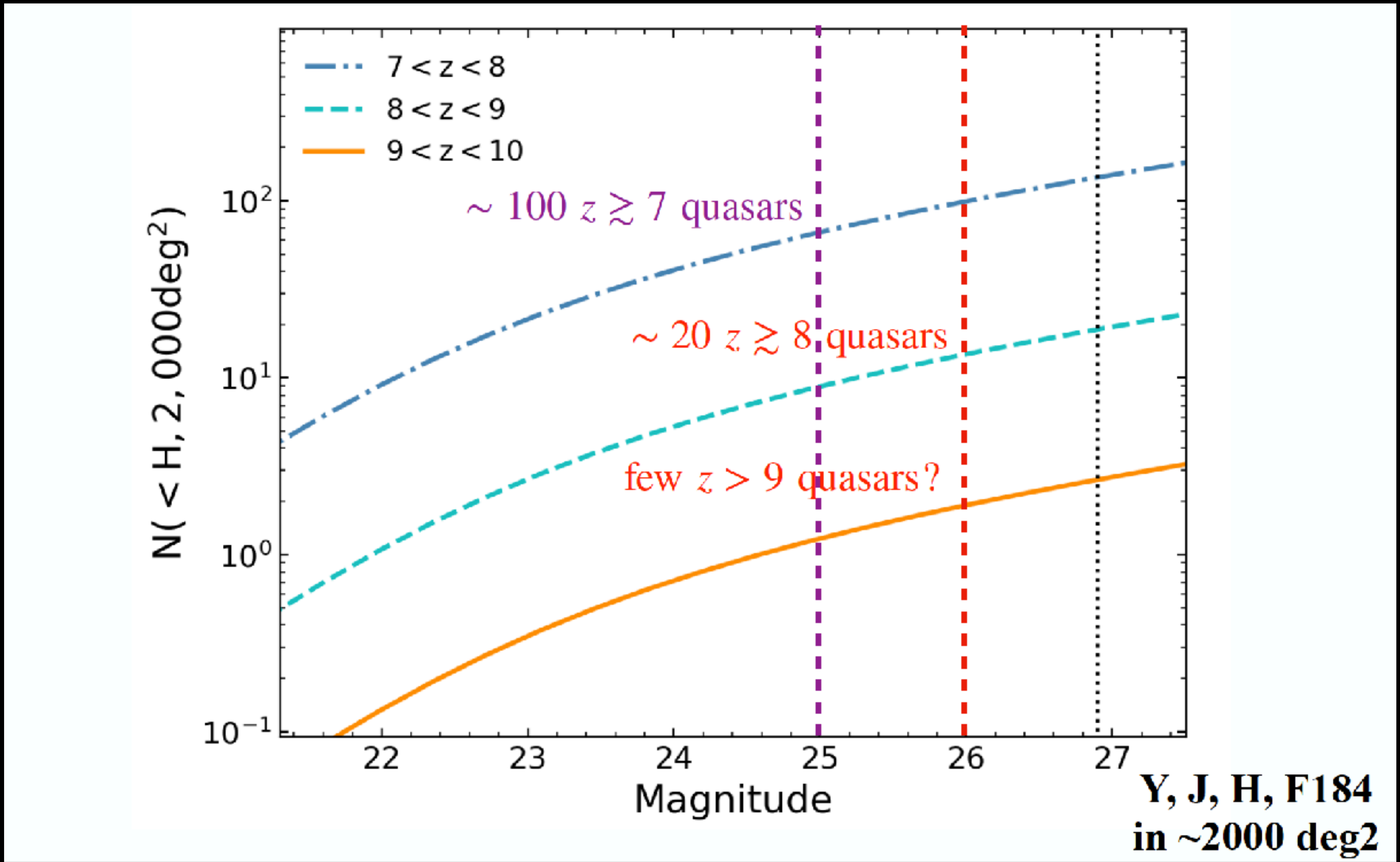
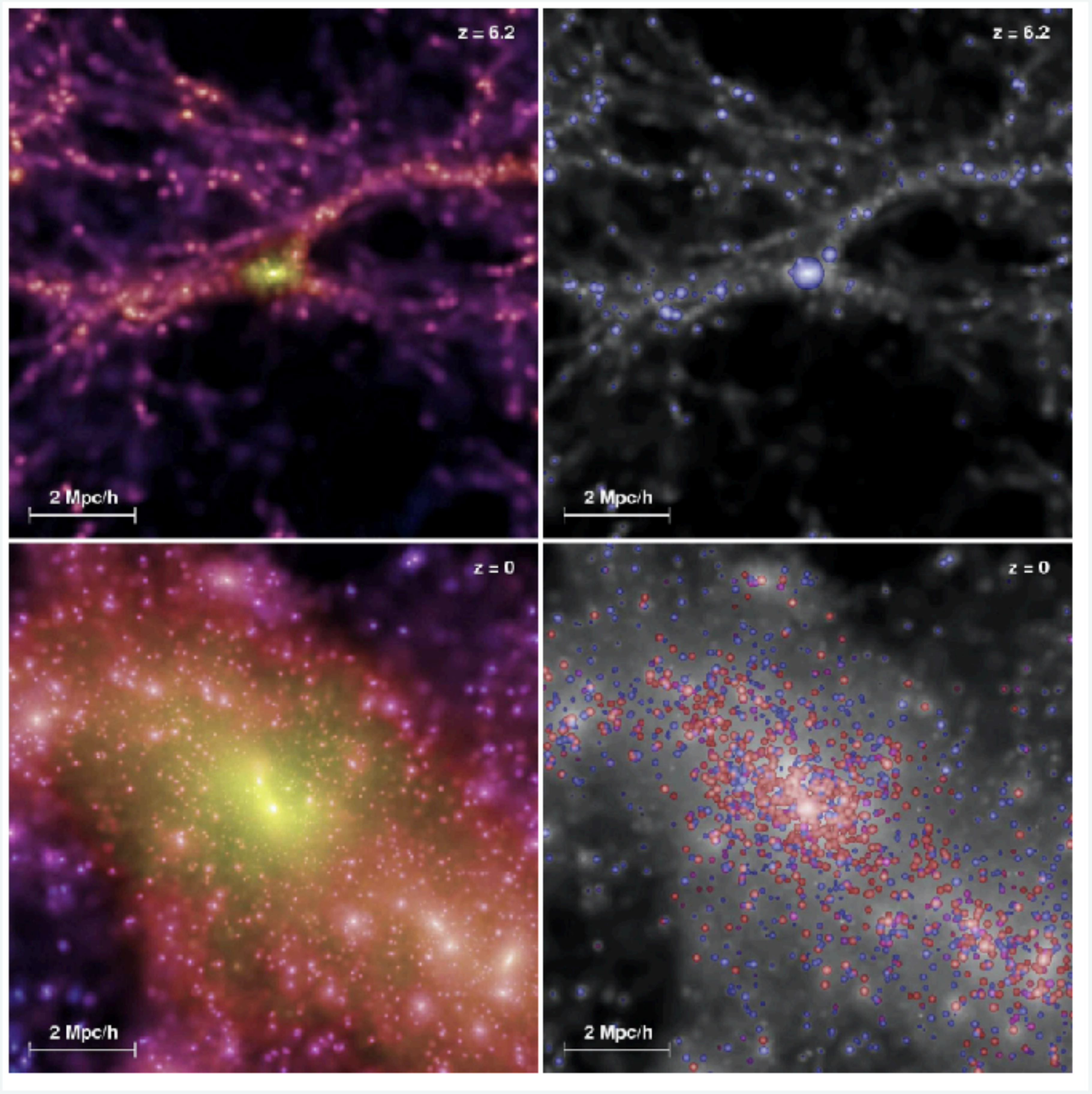
AGN and Quasars with *Roman*



Slide courtesy of Feige Wang

- **Many science cases to follow discovery of quasar samples:**
  - Quasar LF at z>7
  - Gravitationally lensed quasars
  - Quasar host galaxies
  - Obscured AGN
  - AGN variability
  - Environment of quasars

High z Quasar Environment with *Roman*



$$L_{\rm bol} \propto M_{\rm BH}$$
$$M_{\rm BH} \propto M_{\rm gal}$$
$$M_{\rm gal} \propto M_{\rm halo}$$

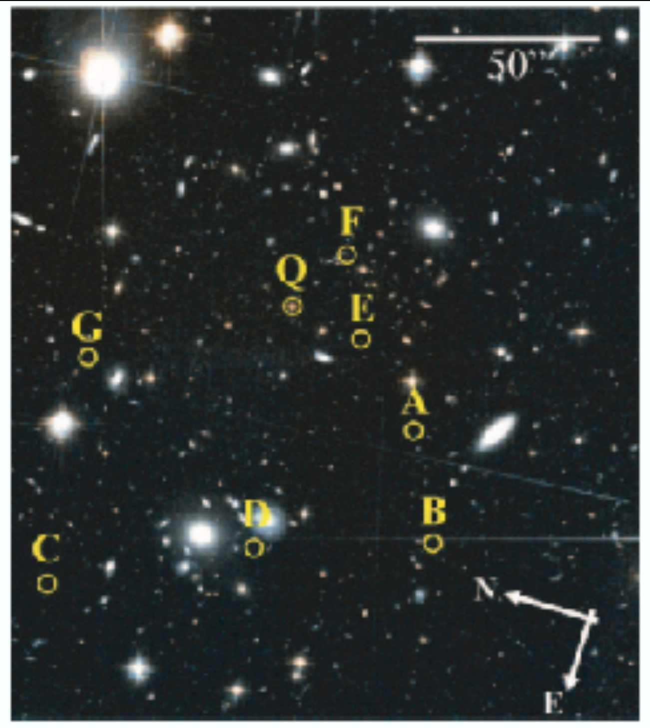
↓

Luminous quasars reside in the most overdense region of the Universe

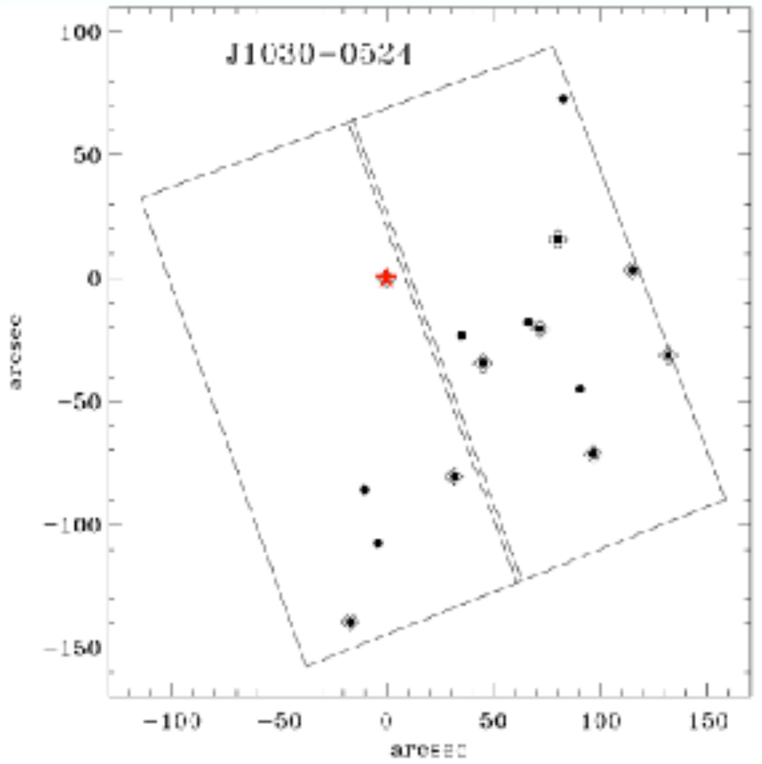
e.g. Springel et al. 2005

Slide courtesy of Feige Wang

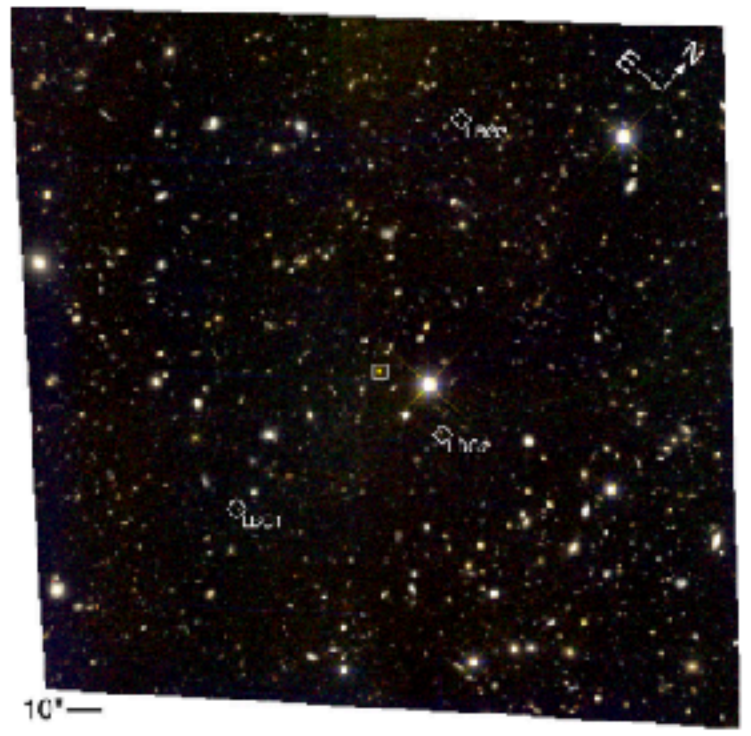
High z Quasar Environment with *Roman*



J0836+0054, z=5.81,
Zheng et al. 2006



J1030+0524, z=6.28
Stiavelli et al. 2005;
Kim et al. 2009

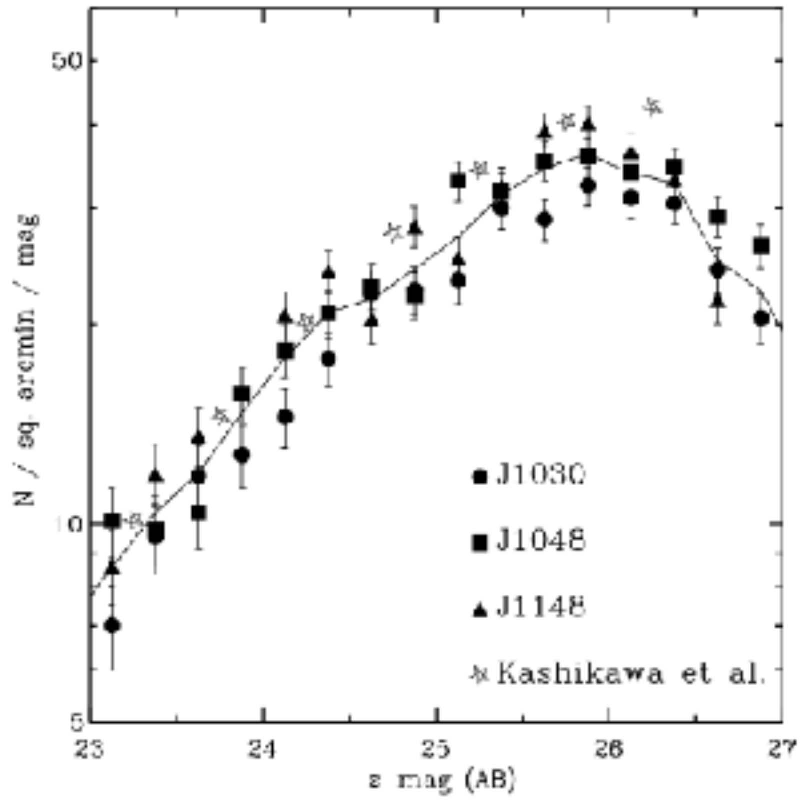


J1120+0641, z=7.085
Simpson et al. 2014

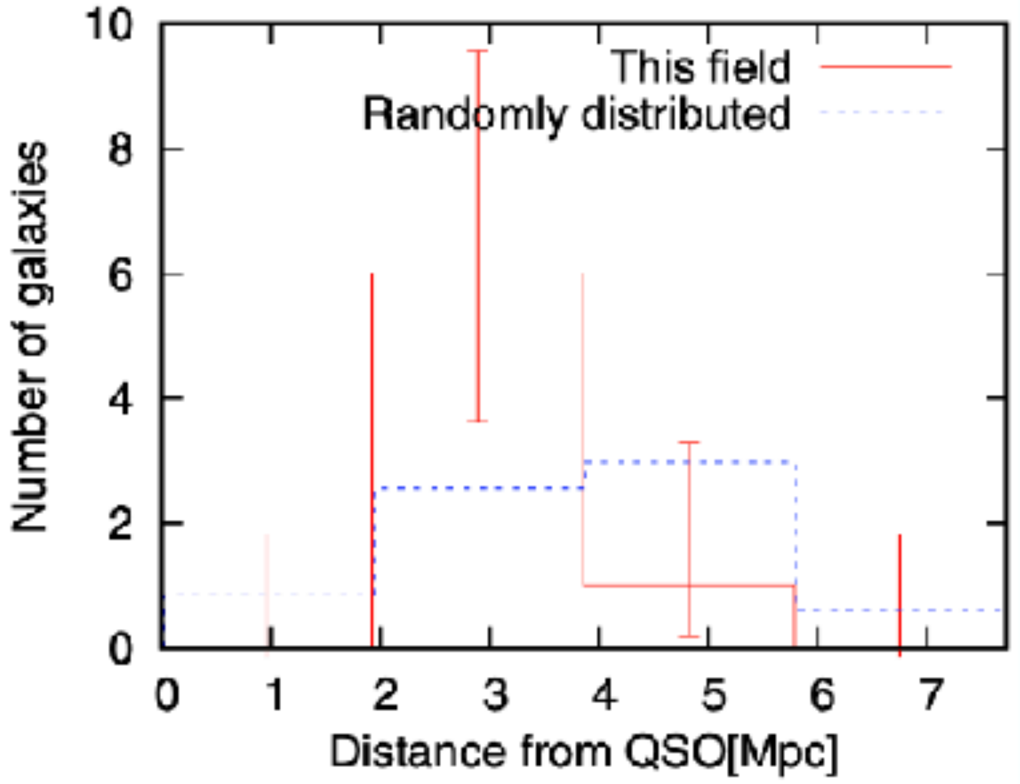
J1048+4637, z=6.23
J1148+5251, z=6.41
J1306+0356, z=5.99
J1630+4012, z=6.05
Kim et al. 2009

$3.4' \times 3.4'$

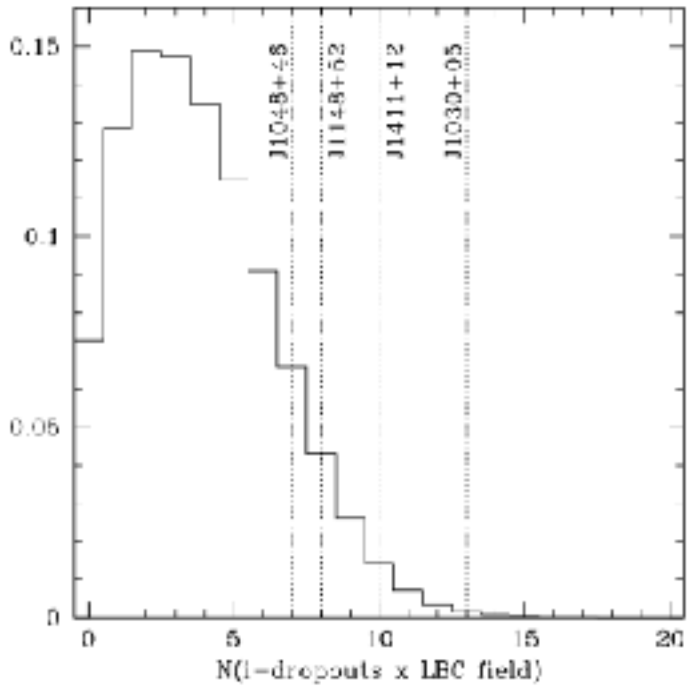
$1.1\ \mathrm{Mpc} \times 1.1\ \mathrm{Mpc}$



J1030+0524, z=6.28
J1048+4637, z=6.23
J1148+5251, z=6.41
Willott et al. 2005



J2329-0301, z=6.43
Utsumi et al. 2010



J1030+0524, z=6.28
J1048+4637, z=6.23
J1148+5251, z=6.41
J1411+1217, z=5.95
Morselli et al. 2014
Badmaverde et al. 2017

- Overdensity
- No overdensity

Slide courtesy of Feige Wang

High z Quasar Environment with *Roman*

- **Difficulties:**
  - HST/ACS FoV is too small
  - Ground based imaging is too shallow
  - Cosmic variance
- **Solutions:**
  - ✓ Deep and wide field imaging
  - ✓ Large quasar sample

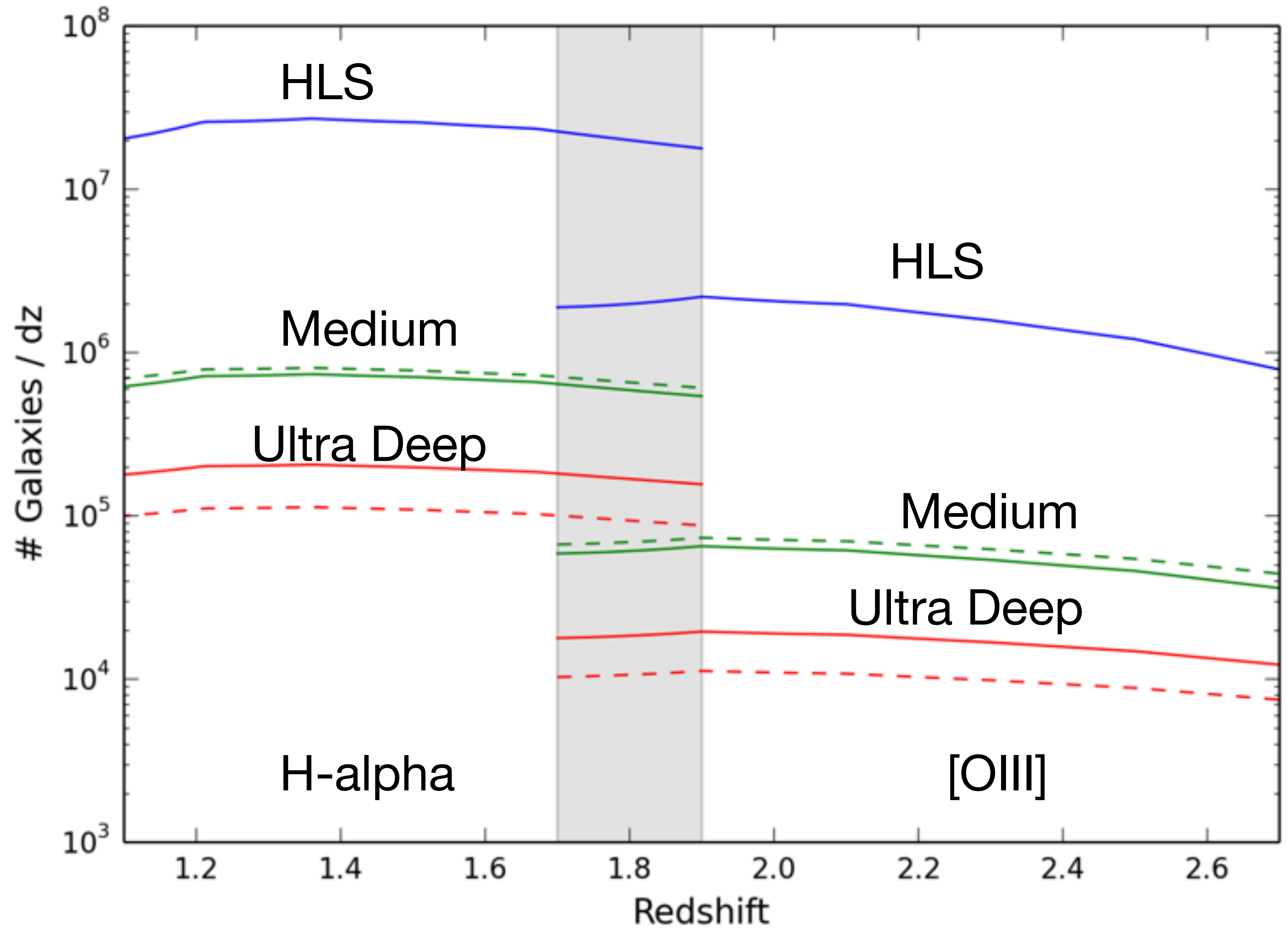
RST !

Slide courtesy of Feige Wang

Galaxy Formation and Environment with *Roman*

- What will *Roman* spectroscopy teach us about galaxy properties and evolution during the peak era of cosmic star formation? How will *Roman* help us understand galaxy properties in the context of their environments over cosmic time?

Galaxy Formation and Environment with *Roman*

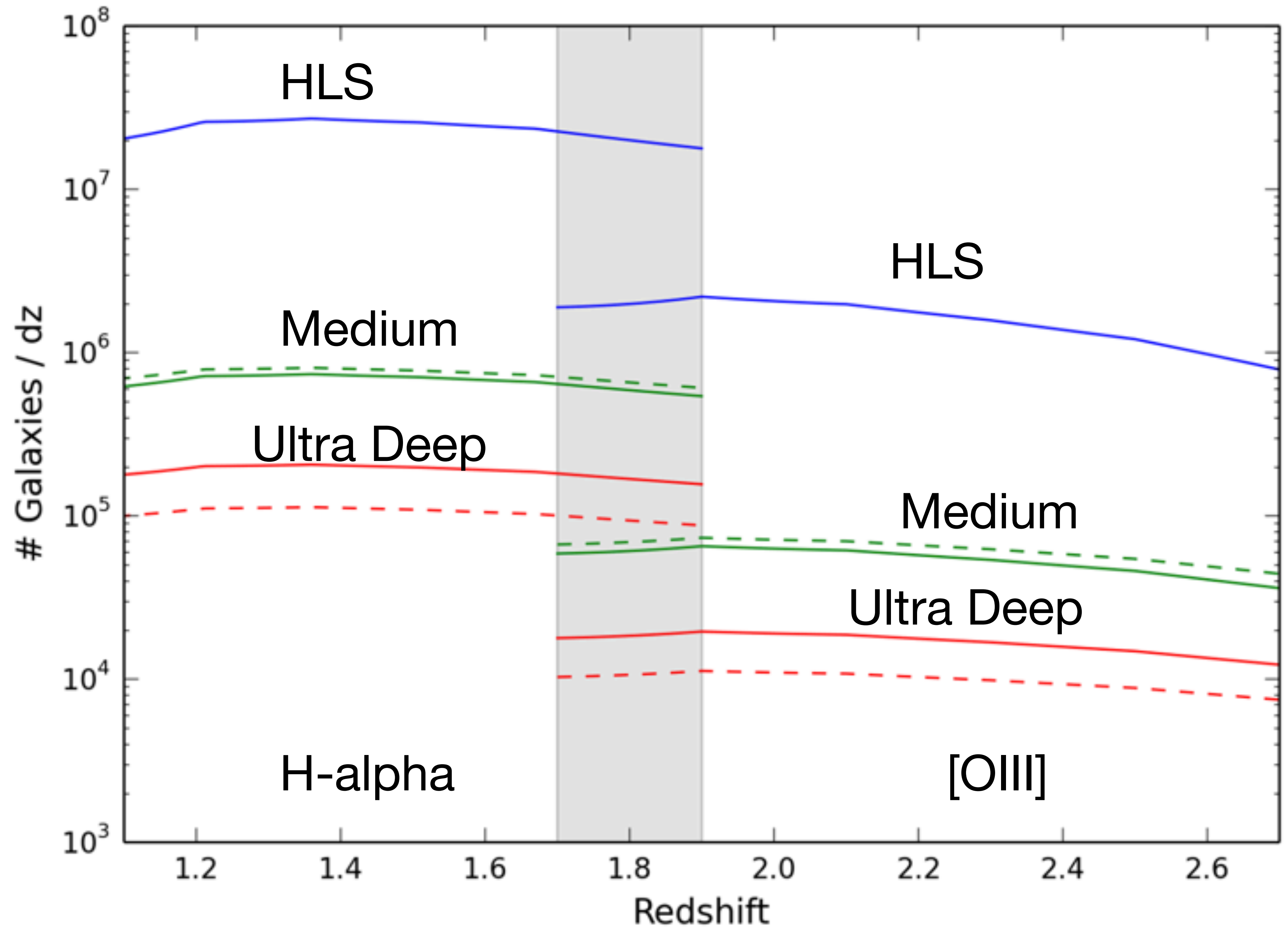


courtesy of B. Robertson and EXPO team

Figure 4.1: Spectroscopic counts for our fiducial HLS (blue), Medium Deep (green) and Ultra Deep (red) grism surveys. Below $z \lesssim 1.9$, the source counts represent Hα source counts, while at $z \gtrsim 1.7$ the source counts reflect O[III] source counts. Both sets of number counts reflect the models used in the SDT report (Spergel et al. 2015). Solid lines show source counts to the limiting depth of the survey, while dotted lines show source counts fainter than the limiting magnitude of the next larger survey

- Current state of the art grism survey: the 3DHST Survey (Brammer et al. 2012) has provided WFC3 G141 spectra for 10,000s galaxies (Momcheva et al. 2015).

Galaxy Formation and Environment with *Roman*

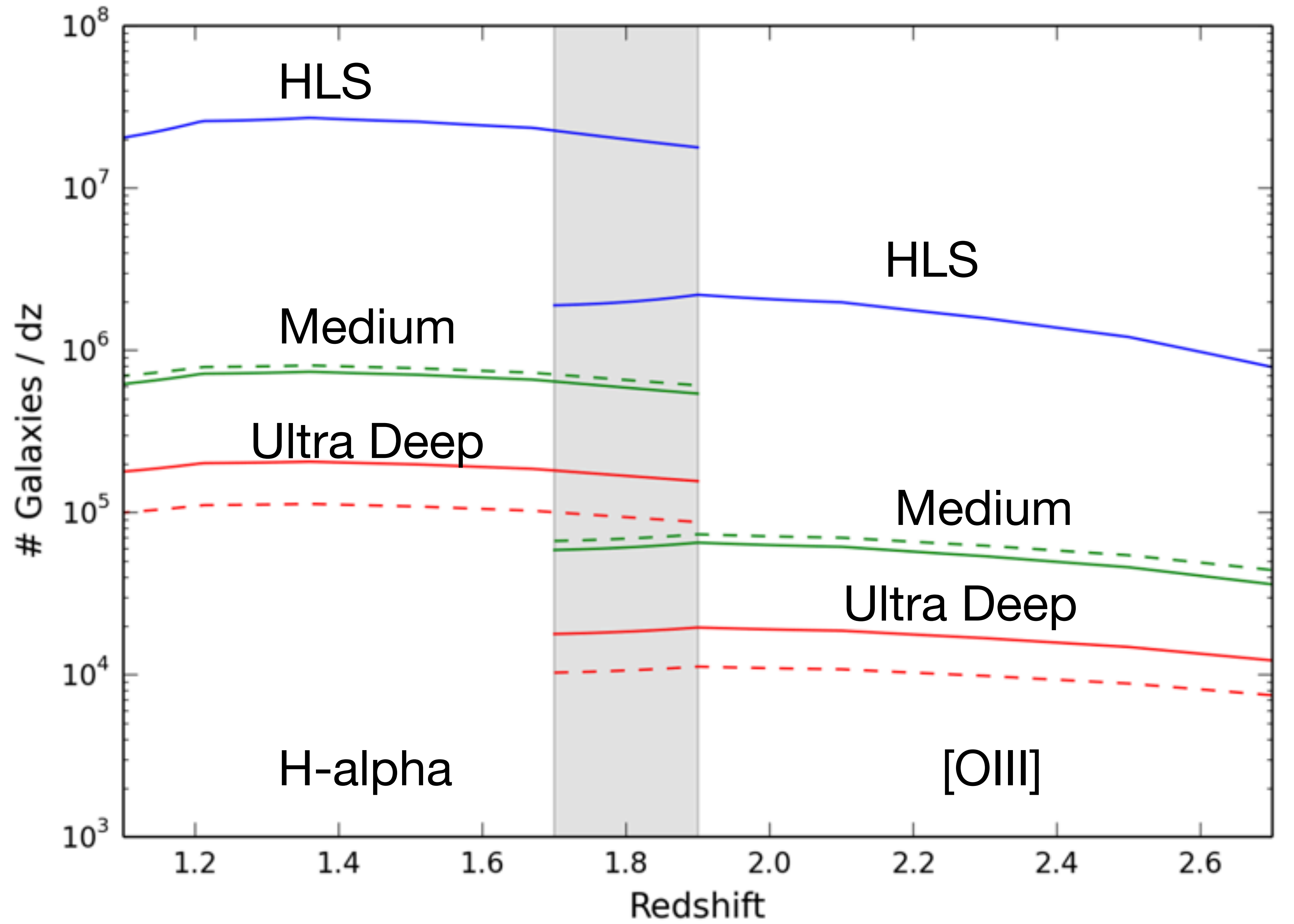


courtesy of B. Robertson and EXPO team

Figure 4.1: Spectroscopic counts for our fiducial HLS (blue), Medium Deep (green) and Ultra Deep (red) grism surveys. Below $z \lesssim 1.9$, the source counts represent Hα source counts, while at $z \gtrsim 1.7$ the source counts reflect O[III] source counts. Both sets of number counts reflect the models used in the SDT report (Spergel et al. 2015). Solid lines show source counts to the limiting depth of the survey, while dotted lines show source counts fainter than the limiting magnitude of the next larger survey

- Current state of the art grism survey: the 3DHST Survey (Brammer et al. 2012) has provided WFC3 G141 spectra for 10,000s galaxies (Momcheva et al. 2015).
  - *Roman* will deliver orders of magnitude larger spectroscopic samples, with over 10 million in HLS.
  - Galaxies in medium and ultra deep probe different luminosity regime and provide improved image quality for resolved morphological studies at z~1-3.

Galaxy Formation and Environment with *Roman*



courtesy of B. Robertson and EXPO team

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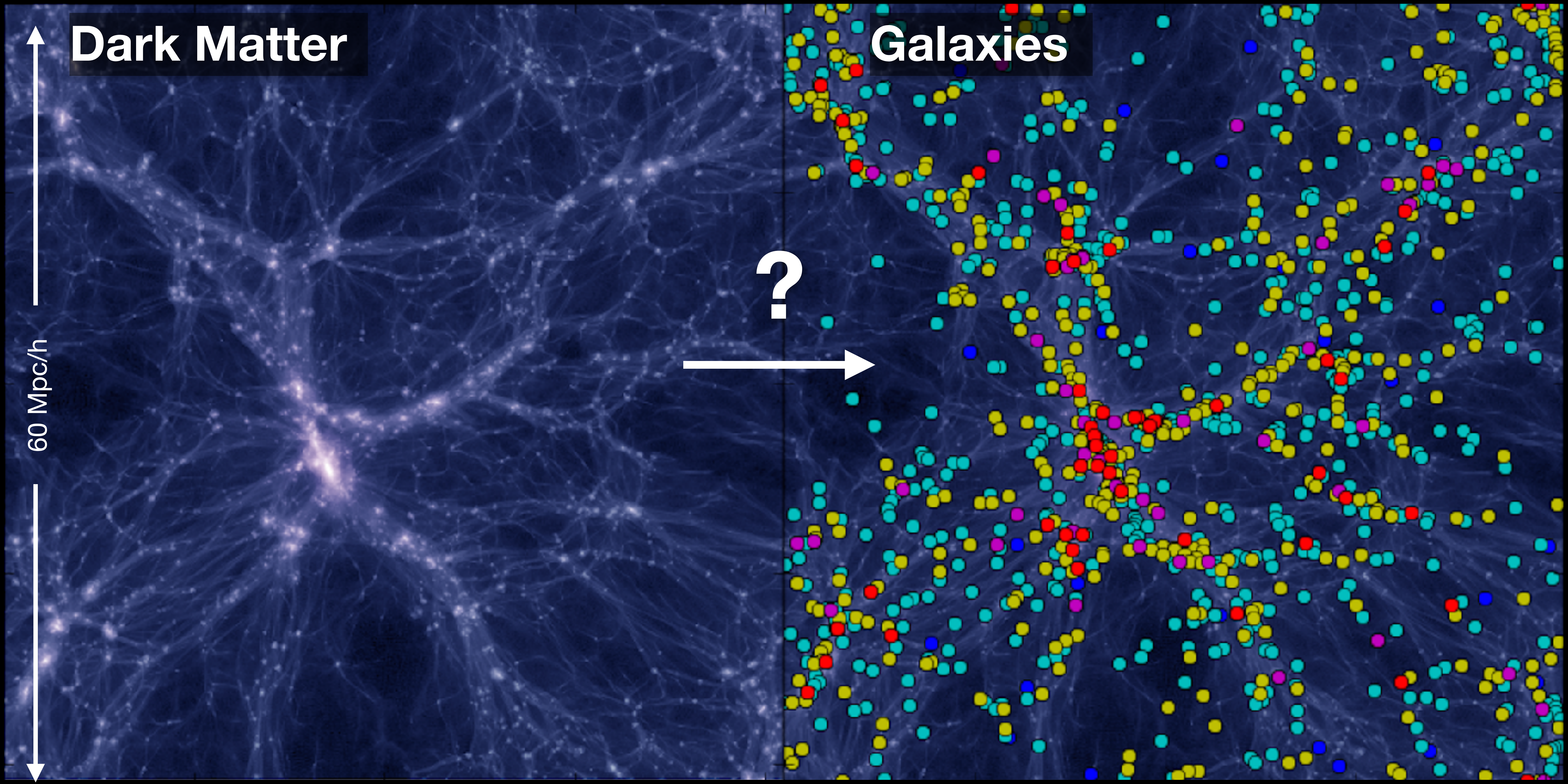
  - Galaxies in medium and ultra deep probe different luminosity regime and provide improved image quality for resolved morphological studies at z~1-3.
  - Galaxies span wide areas and range of environments, enabling many new science cases.

Roman Provides Cosmic Context



Roman wide areas and large samples will establish galaxy-halo connection via (i) clustering and (ii) weak lensing measurements.

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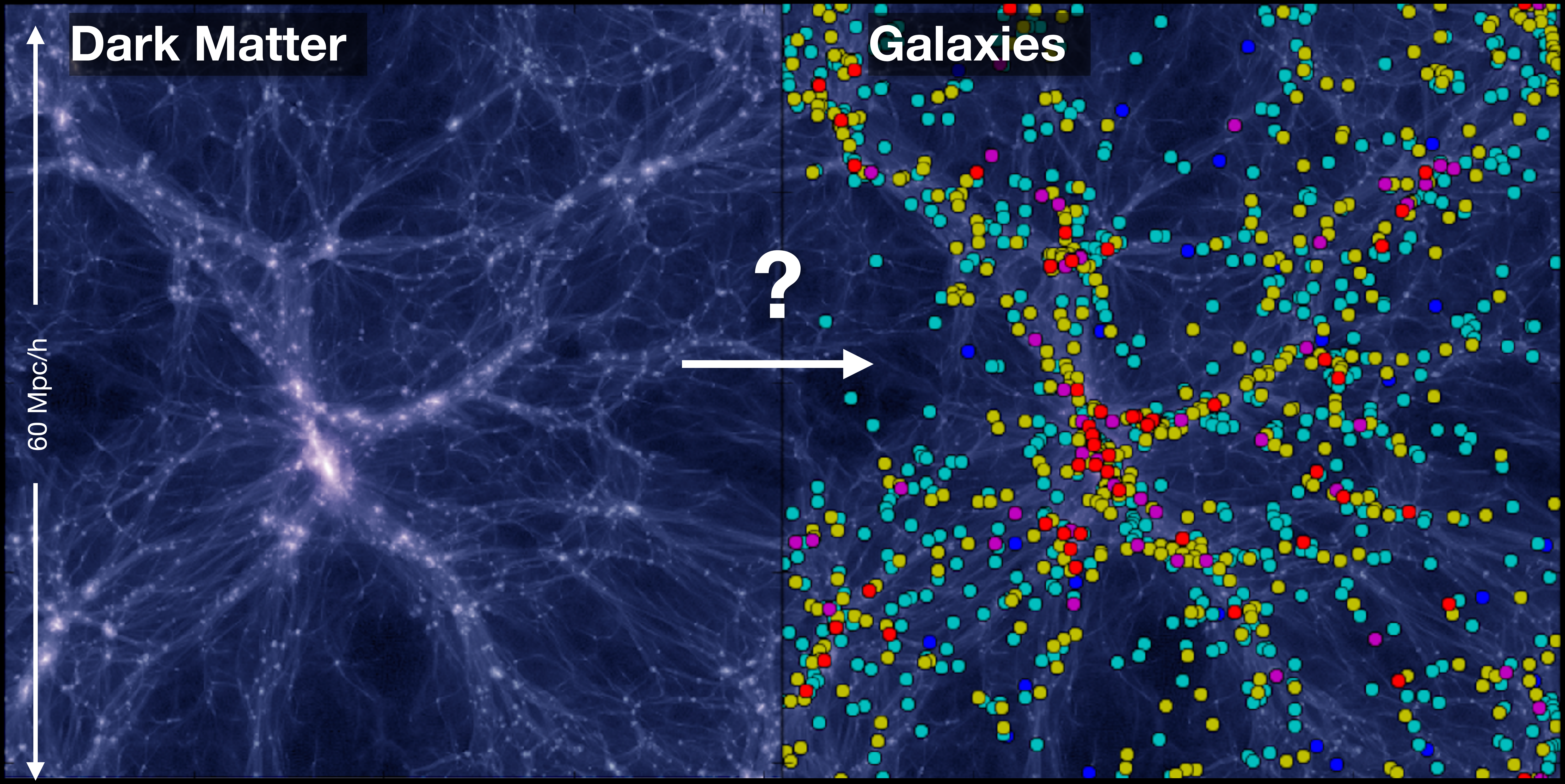

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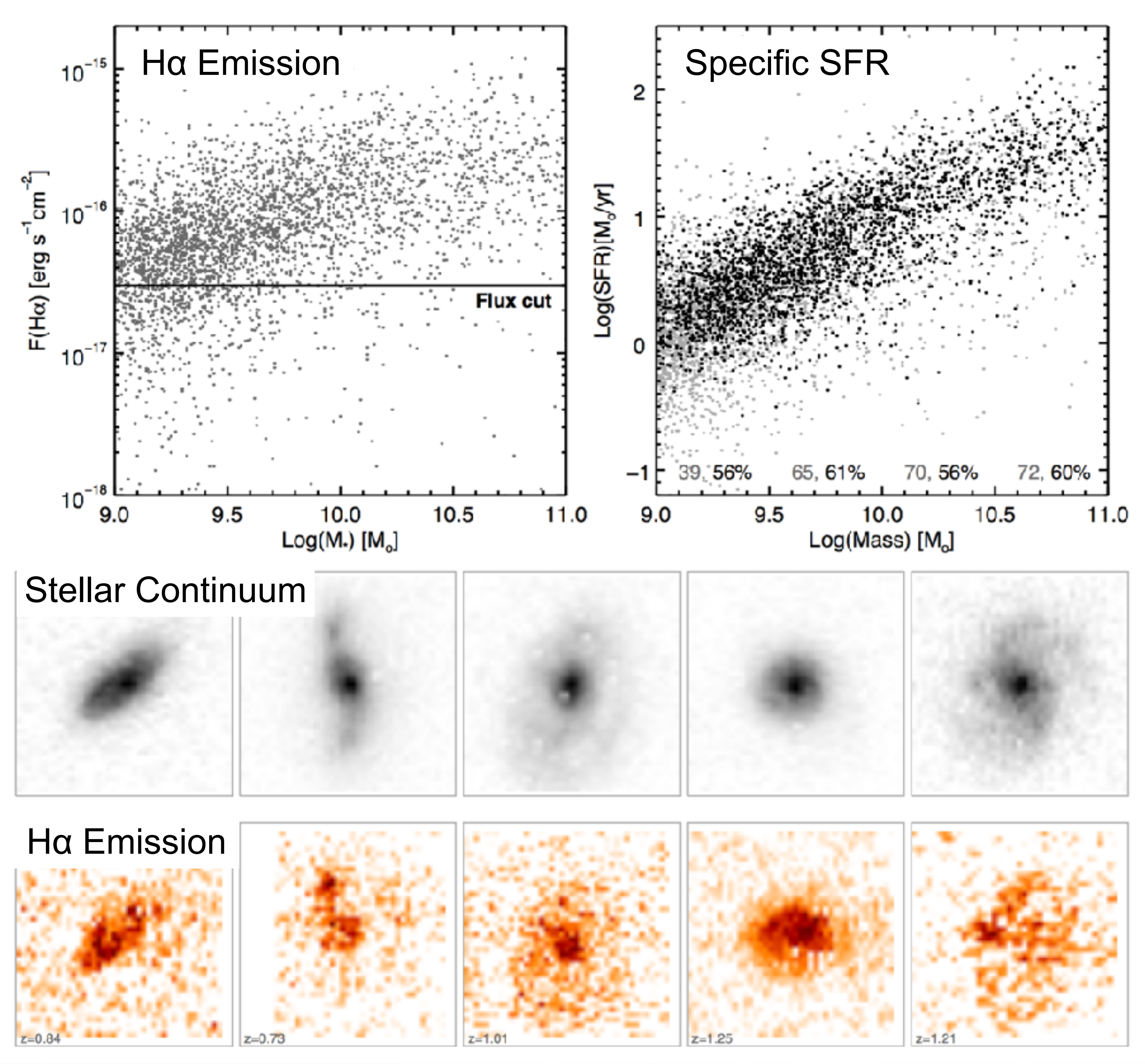
Establish how galaxy properties map onto dark matter structures.

And how cosmic environment affects galaxy evolution.

Roman Can Revolutionize z~1-2 Galaxy Surveys



Nelson et al. (2015)

- Currently only ~3% of 3D-HST galaxies are star forming with sufficient fluxes to measure both stellar morphologies and resolved Hα emission.
- Enables measures of the SFR vs. stellar mass in z~2 galaxies, and SFR maps (usually stacked).

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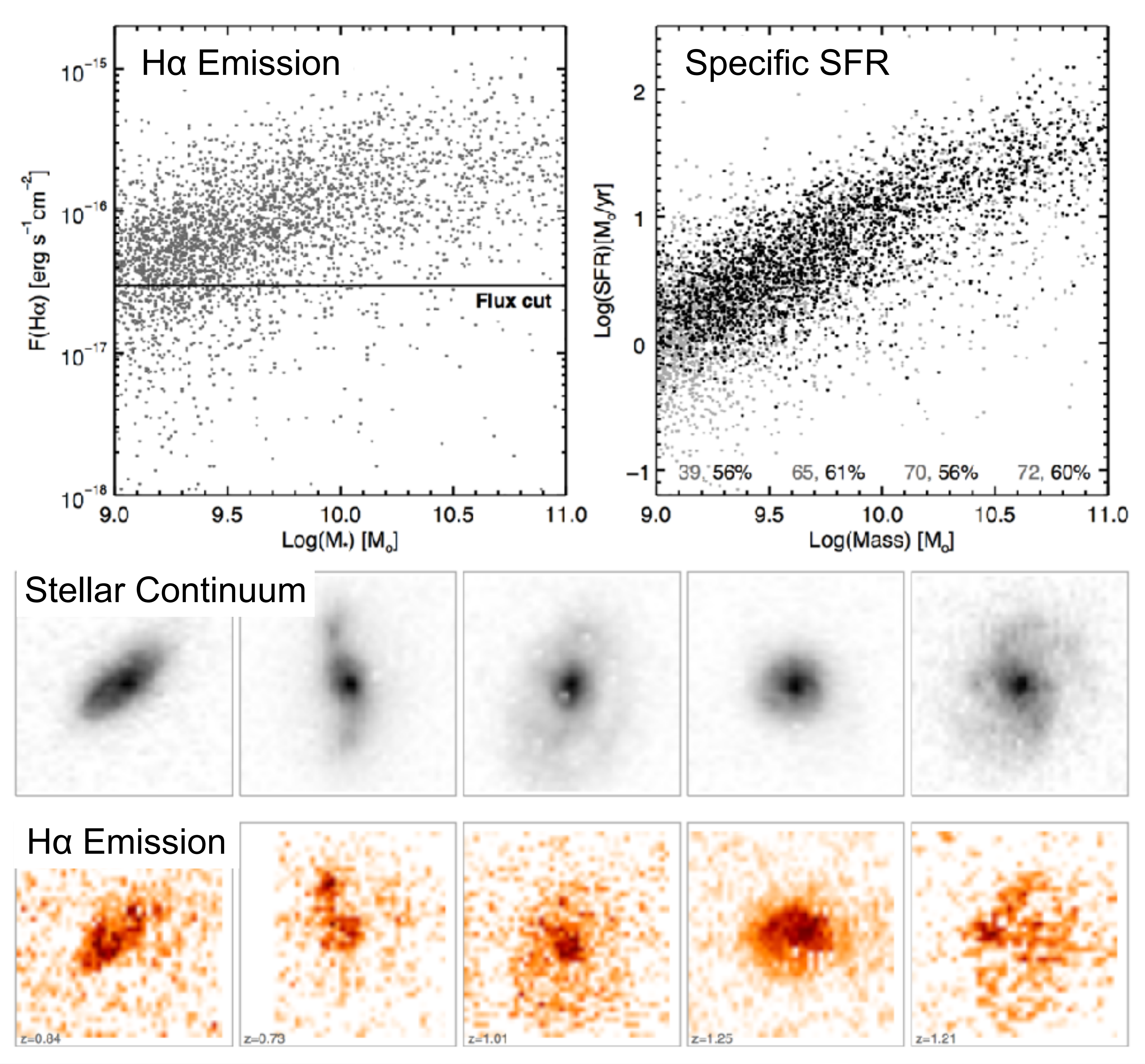

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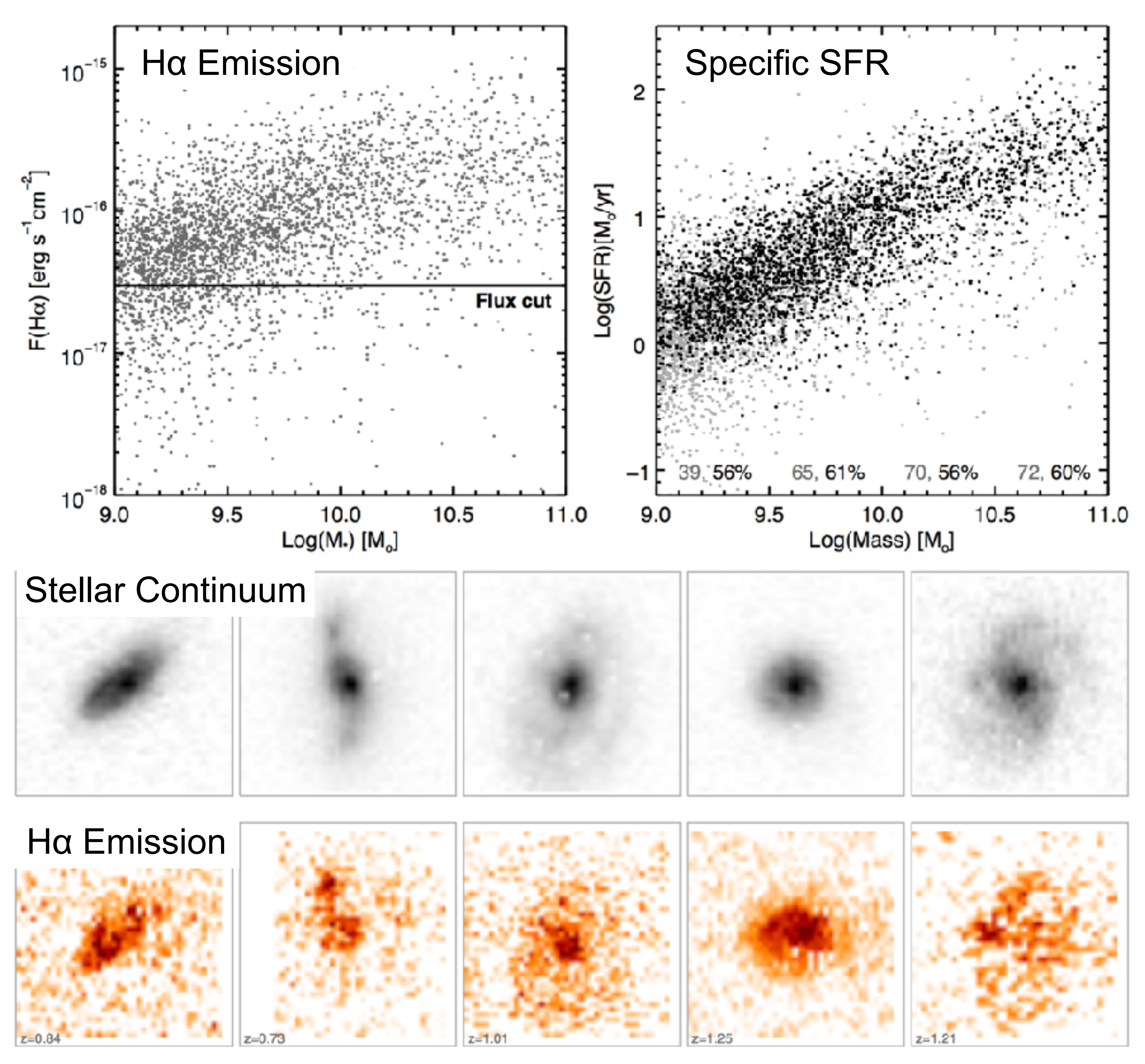

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- Gravitationally lensed galaxies in HLSS will complement these field studies, revealing metallicity and excitation gradients at z~1-2.

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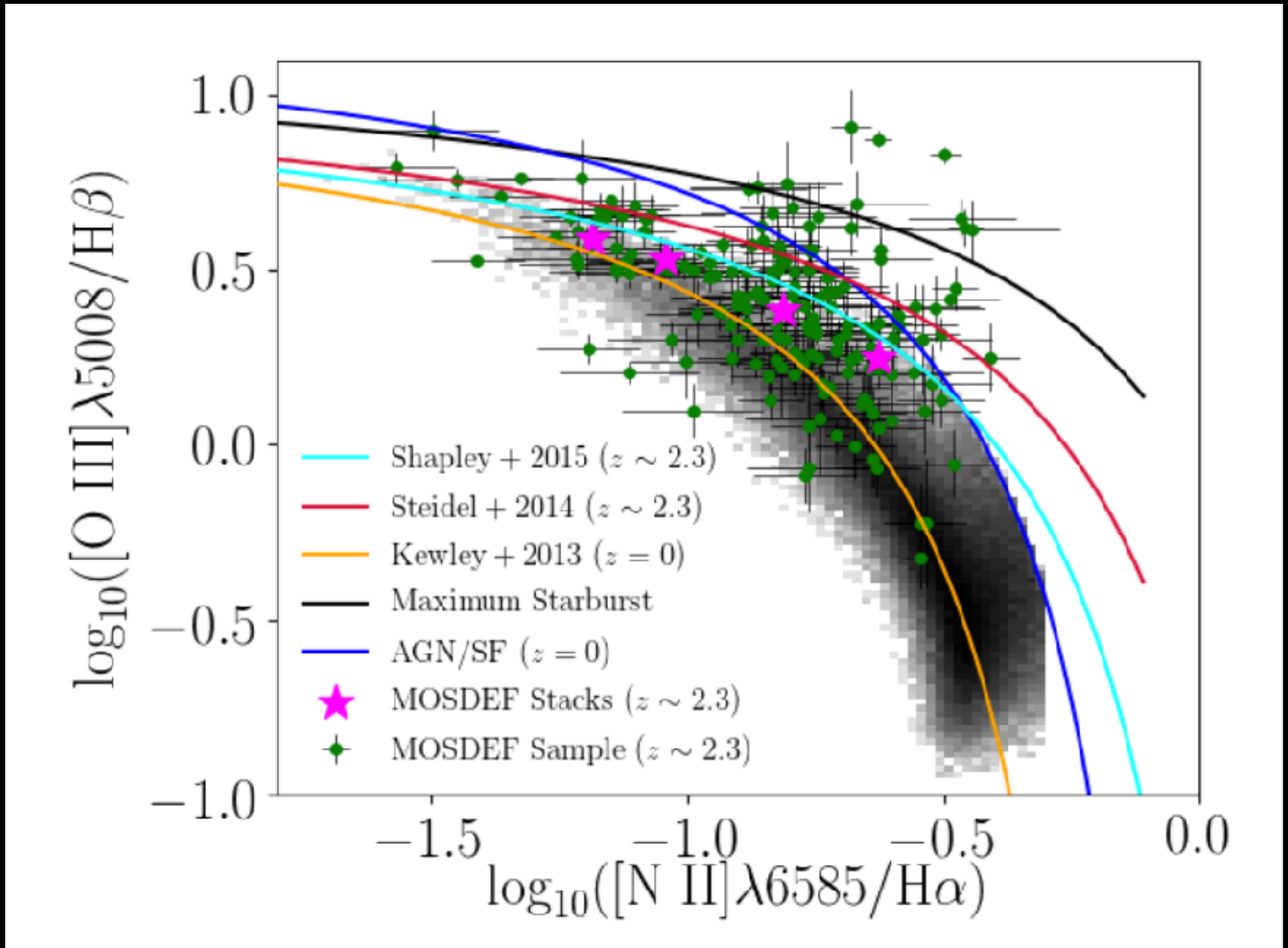
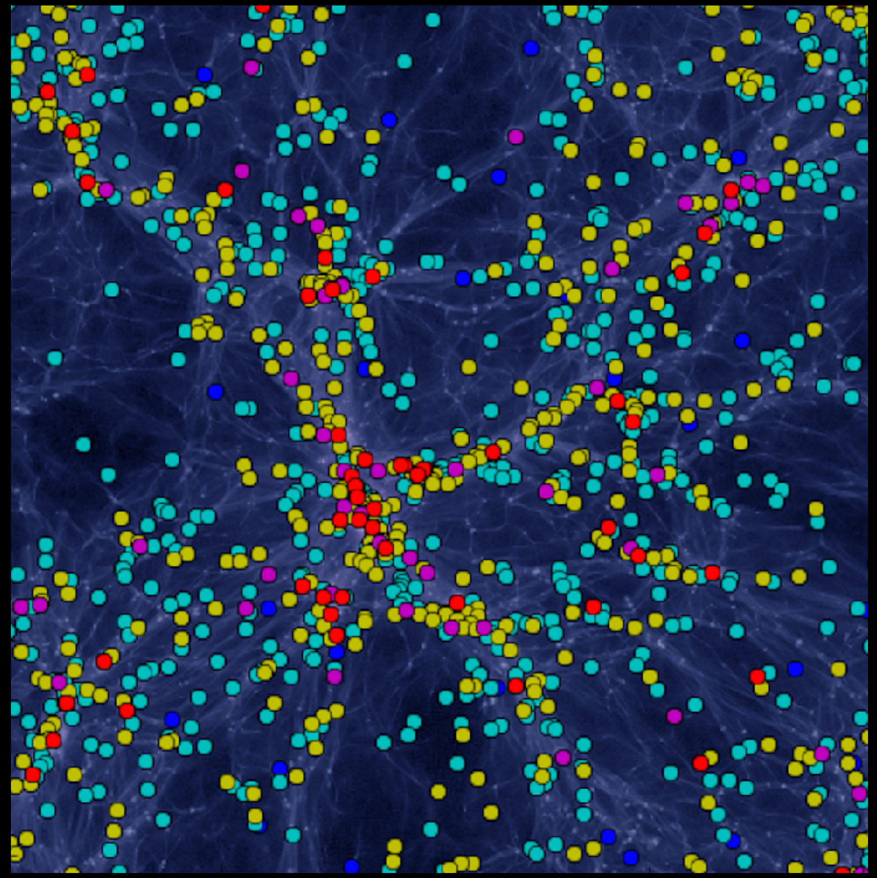
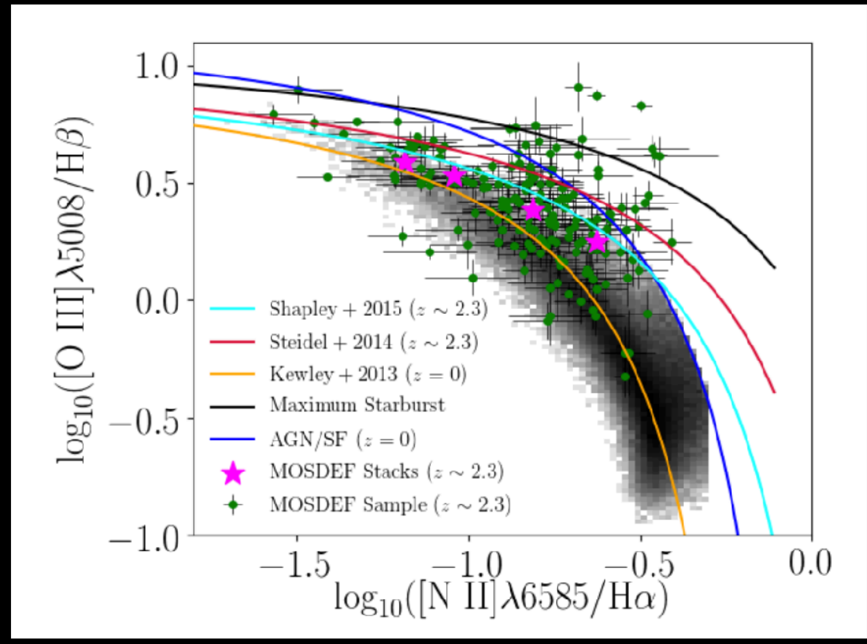


Runco et al. 2021, MNRAS, 502, 2600

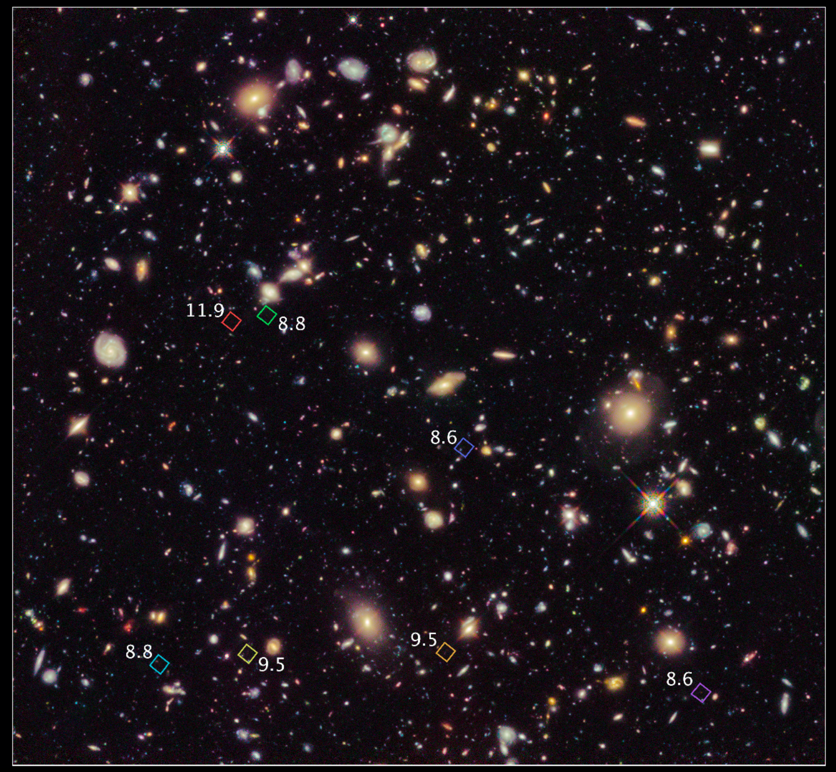
- Roman grism programs will detect key rest-frame optical emission lines (H-alpha, H-beta, [OIII], [NII) at z~1.1-1.9. Given redshift range and flux limits, expect ~100x greater sample size than current surveys (i.e., MOSDEF).
- Track galaxy physical conditions (i.e., metallicity, ionizing spectra, AGN content) with environment.

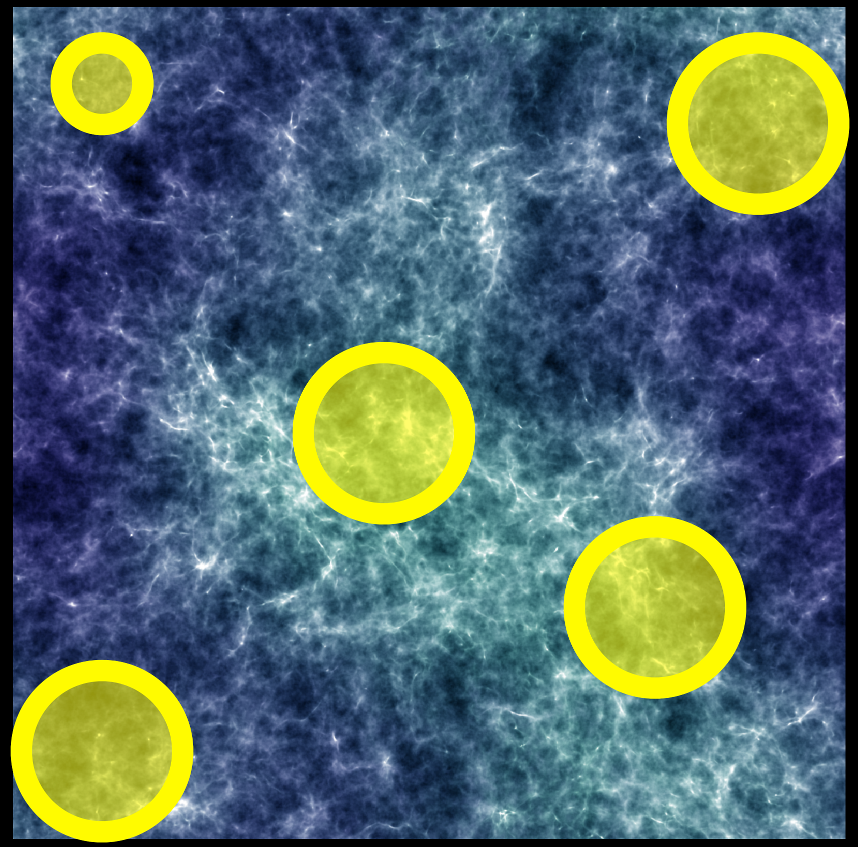
Summary: High Redshift Science with *Roman*



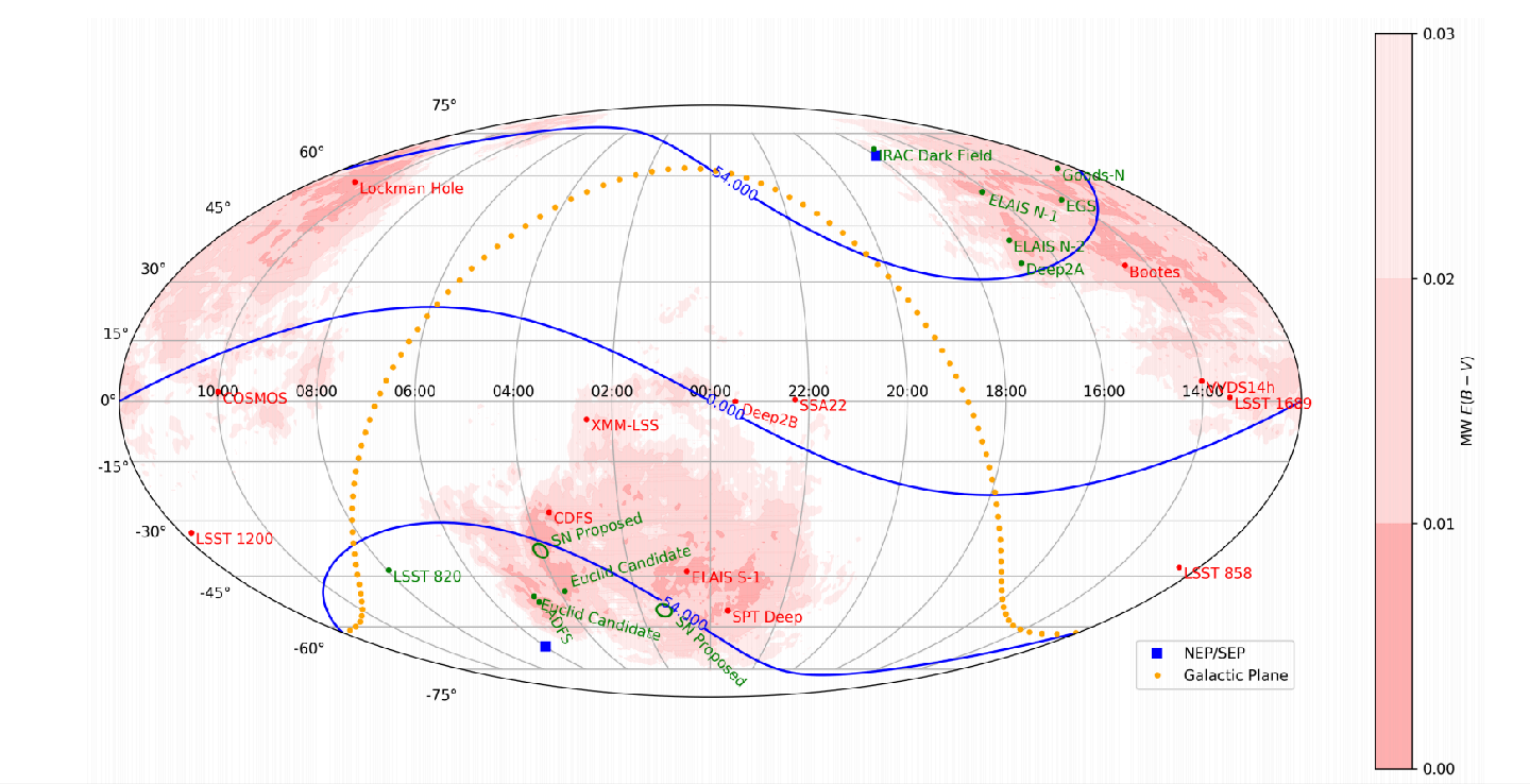


- ***Roman*** will be transformative for deep field studies of galaxy evolution and formation.
- ***Roman*** will provide improved statistical samples for studying early galaxy and quasar populations that cause cosmic reionization.
- ***Roman*** will provide unprecedented spectroscopic samples during the peak of galaxy formation.
- ***Roman*** can teach us about the connection between galaxy evolution and cosmic environment.





Roman Deep Survey Field Choice



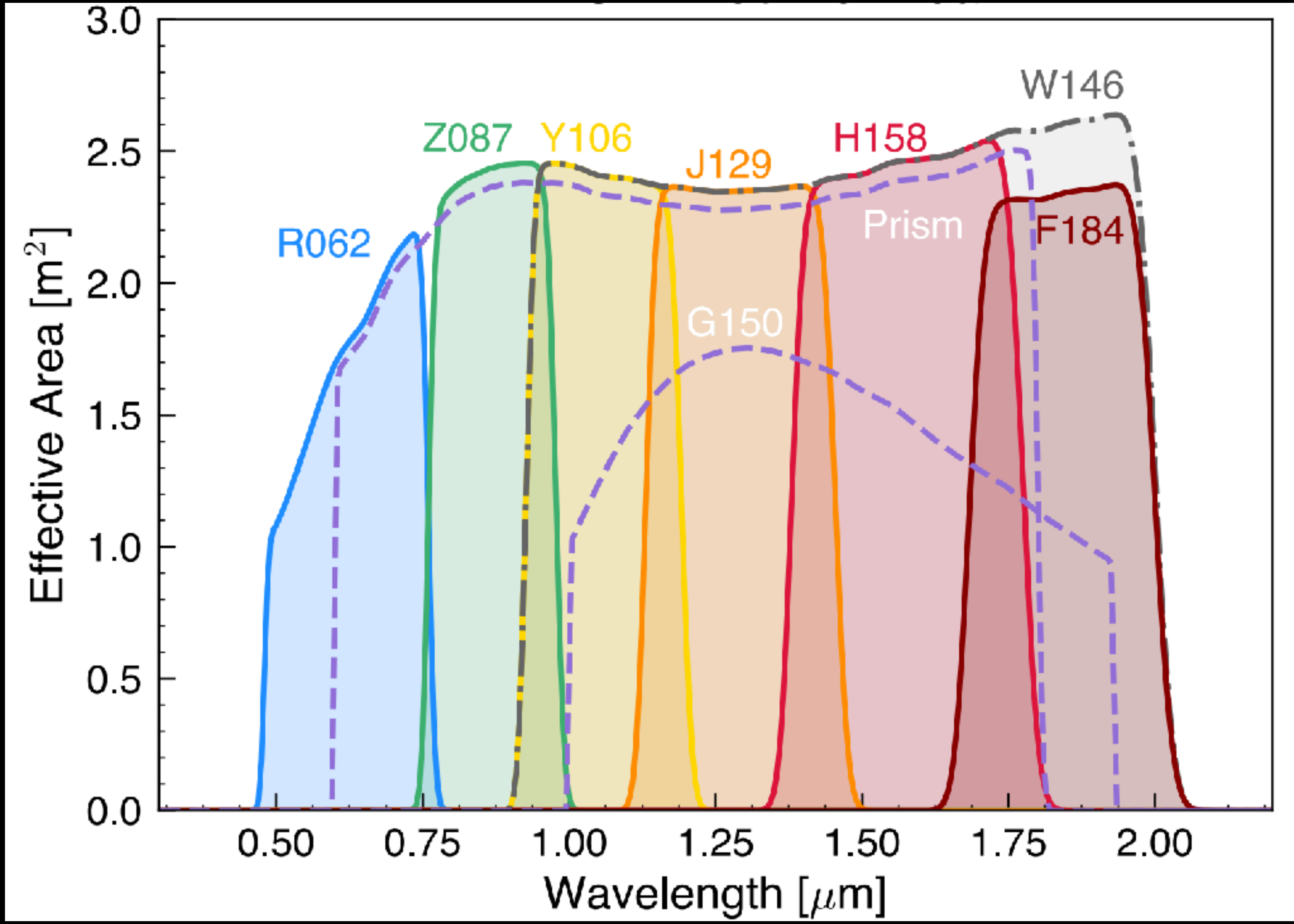
Koekemoer et al. (2019), arXiv:1903.06154

Field Visibility with *Roman*

Field	R.A.	Dec.	Ecl. Lat.	Area (deg^2)	E(B-V)	Rel. Zodi	Days/yr
Polar fields ($< 36°$):							
IRAC Dark Field	17:40	+69:00	+87	0.2	0.043	1.0	365
Extended Groth Strip	14:17	+52:30	+60	0.2	0.009	1.2	365
GOODS-N	12:36	+62:13	+57	0.25	0.012	1.2	365
Deep2A	16:52	+34:55	+57	1	0.018	1.2	365
ELAIS N-2	16:46	+41:01	+63	5	0.014	1.1	365
ELAIS N-1	16:11	+55:00	+73	9	0.008	1.0	365
Akari Deep Field South	04:44	−52:20	−73	12	0.008	1.0	365
JWST-NEP-TDF	17:22	+65:49	+86	0.2	0.042	1.0	365
NEP-Spitzer	18:00	+66:33	+90	10	0.046	1.0	365
SEP-Spitzer	06:00	−66:33	−90	10	0.062	1.0	365
Equatorial fields:							
CDFS	03:32	−27:48	−45	0.3	0.008	1.4	229
Deep2B	23:30	+00:00	+3	1	0.044	19	146
SSA22	22:17	+00:24	+10	4	0.056	5.6	149
COSMOS	10:00	+02:12	−9	2	0.018	6.0	148
VVDS14h	14:00	+05:00	+16	4	0.026	3.6	153
ELAIS S-1	00:35	−43:40	−43	7	0.008	1.5	215
Bootes	14:32	+34:16	+46	9	0.016	1.4	236
Lockman Hole	10:45	+58:00	+45	11	0.011	1.4	229
XMM-LSS	02:31	−04:30	−18	11	0.024	3.2	155
SPT Deep	23:30	−55:00	−46	100	0.010	1.4	236
HERA	07:00	−30:43		1200			

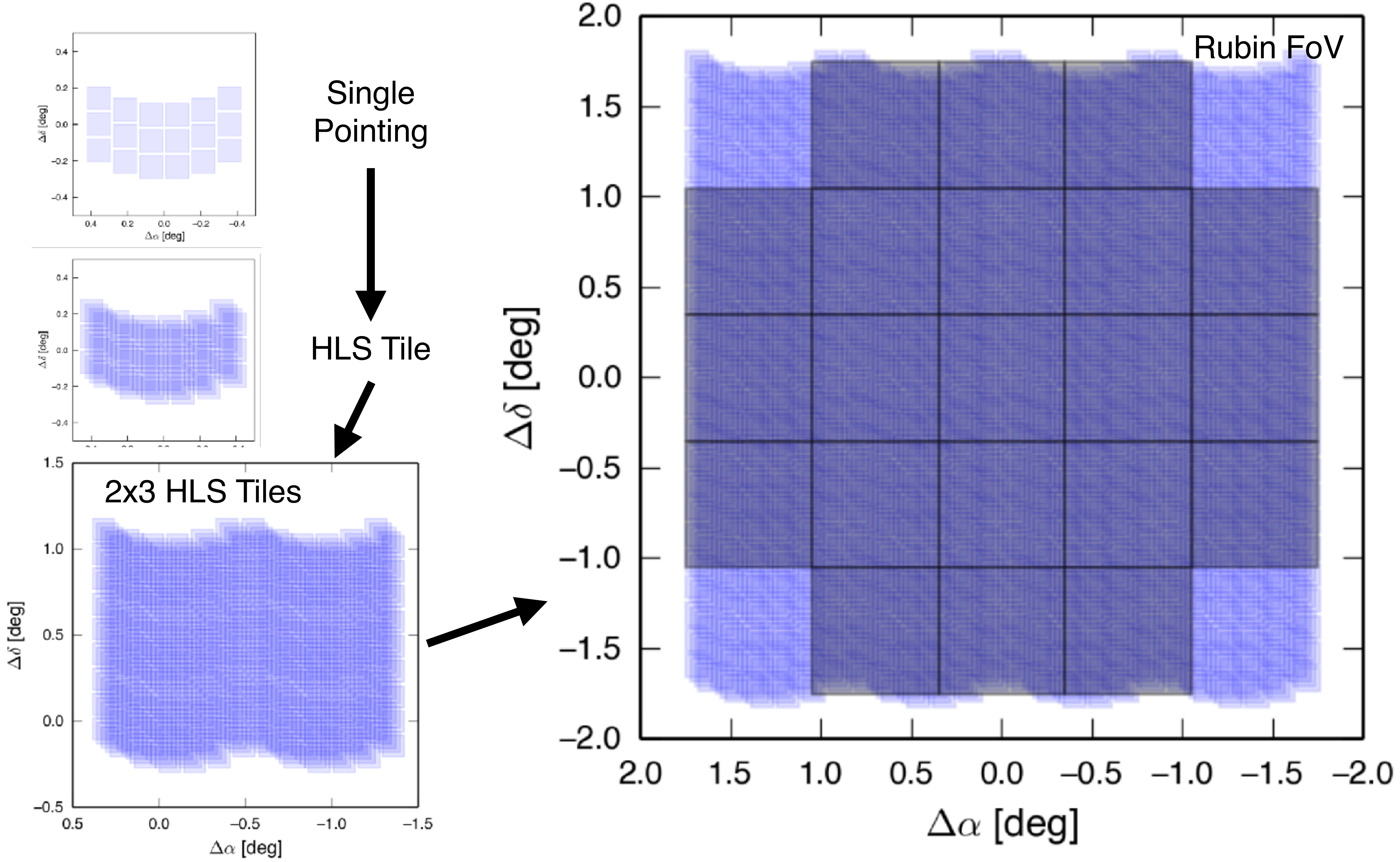
Koekemoer et al. (2019), arXiv:1903.06154

Roman Deep Field Filter Considerations



Akeson et al. (2019), arXiv:1902.05569

Modeling *Roman* Surveys



Example *Roman* Deep Survey