Studying Galaxy Evolution with GMT plus Other Powerful New Facilities

Alan Dressler
Carnegie Observatories
First Annual GMT Community Science Meeting
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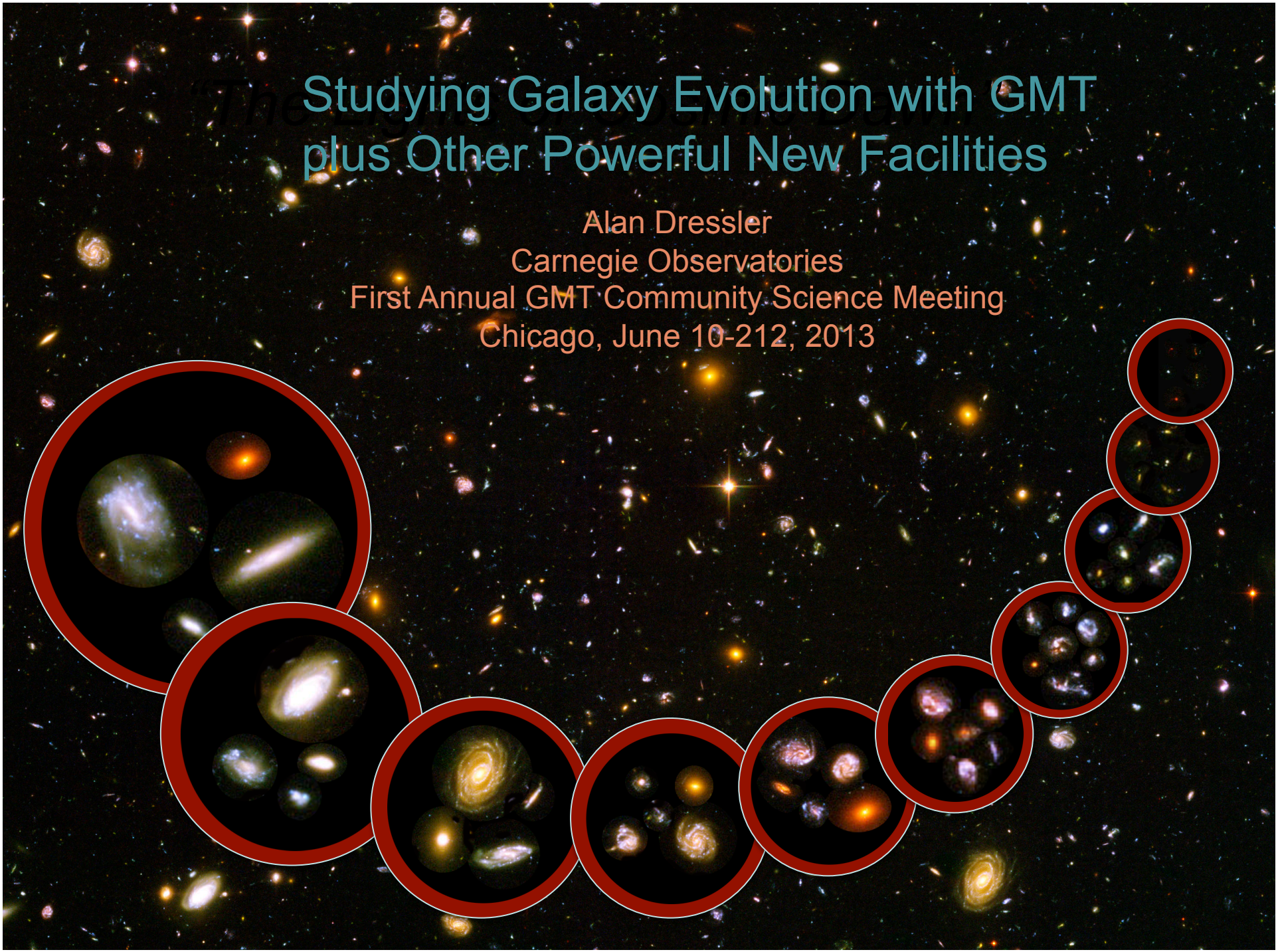


Six Themes in the Study of Galaxy Evolution

(1) The chemical evolution of the Universe, from BBN to today

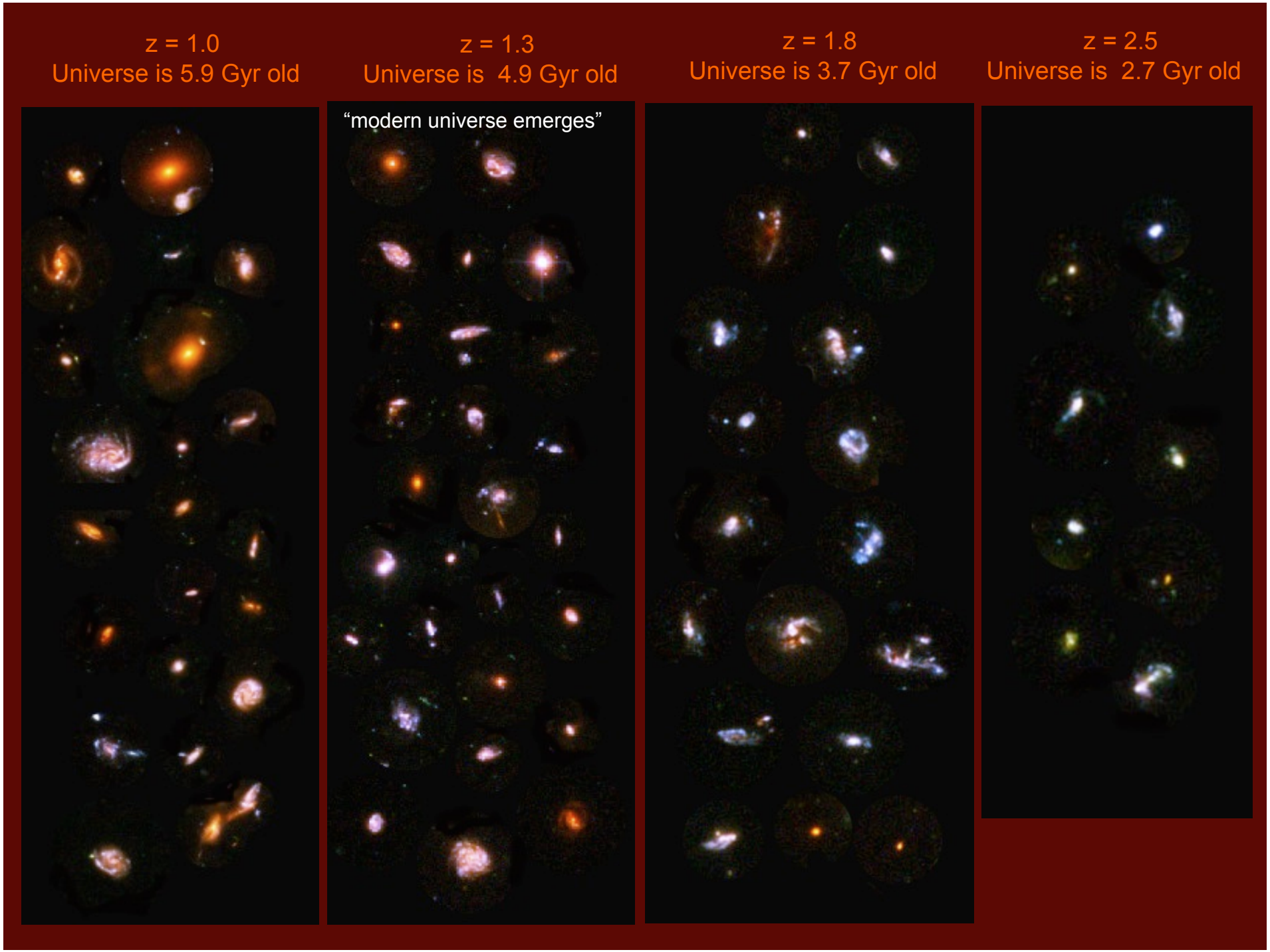
(2) The formation of proto- galaxies and supermassive black holes at $4 < z < 20$, and the role of stars and AGN in reionization of the IGM $6 < z < 20$

(3) The epoch of galaxy growth and assembly $1 < z < 3$

(4) The emergence of the modern universe $z < 1.5$

(5) The fossil record of galaxy formation through the stellar populations in local galaxies

(6) The co-evolution of galaxies and supermassive black holes


z = 1.0
Universe is 5.9 Gyr old
z = 1.3
Universe is 4.9 Gyr old
“modern universe emerges”
z = 1.8
Universe is 3.7 Gyr old
z = 2.5
Universe is 2.7 Gyr old

James Webb Space Telescope

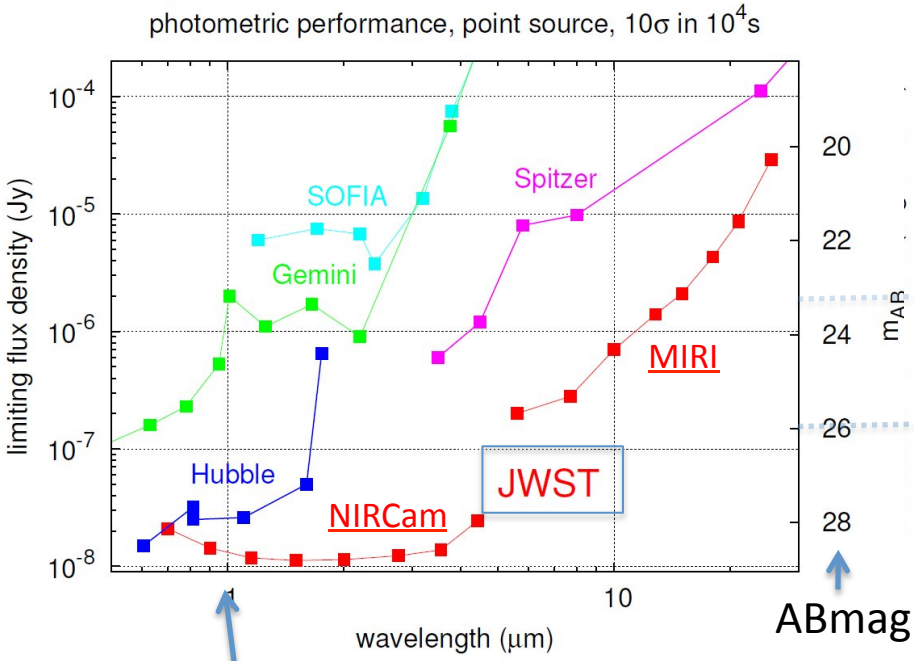
Aperture 6.6-m, T ≈ 40K
Wavelength range 0.6μm < λ < 28μm; PSF = 75 milliarcsec (0.075") @ 2.0μm

NIRCam
Wavelength range 0.6μm < λ < 5.0μm
FOV = 2.2' x 4.4' simultaneously at 2 wavelengths (0.6-2.2μm, 2.3-5.0μm)
Sampling 0.0317" and 0.0648"
10,000 s @10σ point source detection → AB = 29 @2μm, AB = 28 @ 4.4μm

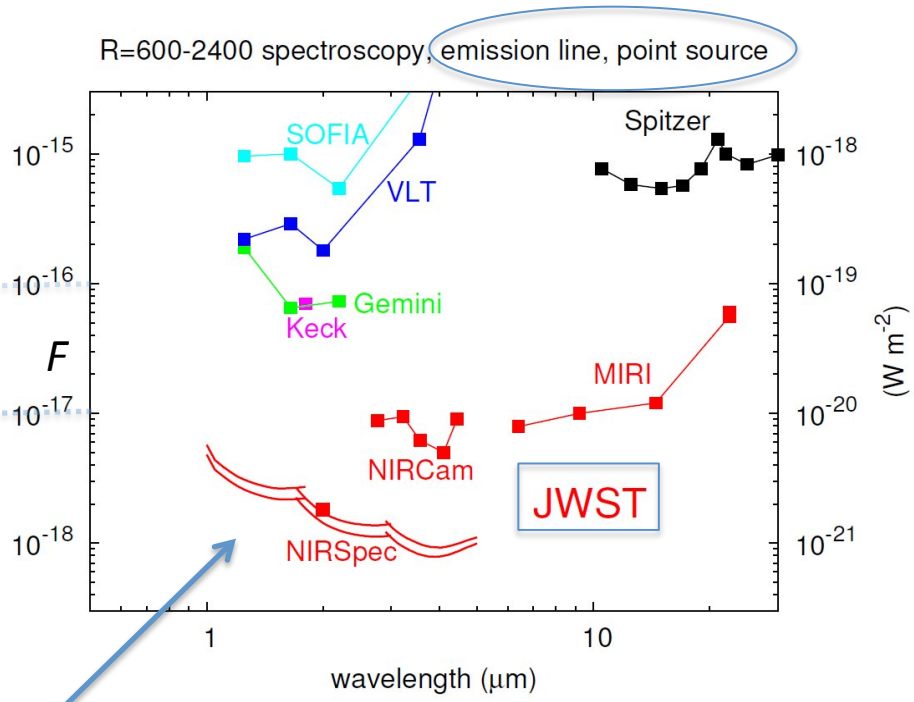
NIRSpec
Wavelength range 0.6μm < λ < 5.0μm
FOV ≈ 3' x 3', N ≈ 100 multislits (from 62,000 "micro-shutters"} and a 3" x 3" IFU
Spectral Resolutions = 100, 1000, 2700
S/N = 10, 10,000 s exposure → AB = 26.7 (2μm, R=100), AB = 25.1 (4.4 μm, R=100)
" " " → AB = 25.4 (2μm, R=1000), AB = 24.3 (4.4 μm, R=1000)
" " " → AB = 24.0 (2μm, R=2700), AB = 23.8 (4.4 μm, R=2700)
" " " line flux sensitivities in the range 10^{-18} to 10^{-19} ergs s^{-1} cm^{-2}

MIRI
Wavelength Range 5.8 < λ < 28.0μm
FOV = 1.3' x 1.9' imaging
Spectroscopy at R = 100 (single object) and R = 3000 IFU, 3.6" sq to 7.6"
S/N = 10, 10,000 s , AB ≈ 24.0 @10μm (Spitzer=21), AB=22.0 @21μm

Photometry (R ≈ 5)



Spectroscopy (R ≈ 600-2400)



JWST will go deeper in the visible-NIR than Hubble but the main difference is the spectroscopic capability

JWST will go much deeper in the near-to-mid IR, and have much higher spatial resolution, than Spitzer

WFIRST2.4 (AFTA)

Aperture 2.4-m (with 4% center obscuration)
Wide-Field near-IR camera 0.6μm < λ < 2.0μm
16 4K x 4K H4RG-10 detectors → 0.28 sq deg
PSF = 0.11" (EE50) at 1.0μm – pixels are 0.11" sq
Slitless grism spectroscopy R ≈ 600
3"x3" R=100 IFU (for DE supernovae)

AFTA will produce a 2000 sq deg 4-band near-IR
HLS: High Latitude Survey
2000 sq deg → Y, J, H ≈ 26.8, F184 ≈ 26.2
line flux 5 x 10^{-17} at 1.65μm (Hα @ z=1.5)

GO observations (deeper fields)
reach AB ≈ 27.1 in 2 hours per field (5 bands)
AB ≈ 29.0 in 3 days " "
Grism R ≈ 600 S/N ≈ 10 at AB ≈ 25.0 in ≈ 1 day
z = 2: 4000A bk @ 1.2μm; Hα @ 1.97μm
→ 5000 L*+1 galaxies per field

Yield of ≈300 L* galaxies at z ≈ 3 (4000A bk)
probable inclusion of K-band pushes z (Hα) to 3

0.28 sq deg = 200 x WFC3!

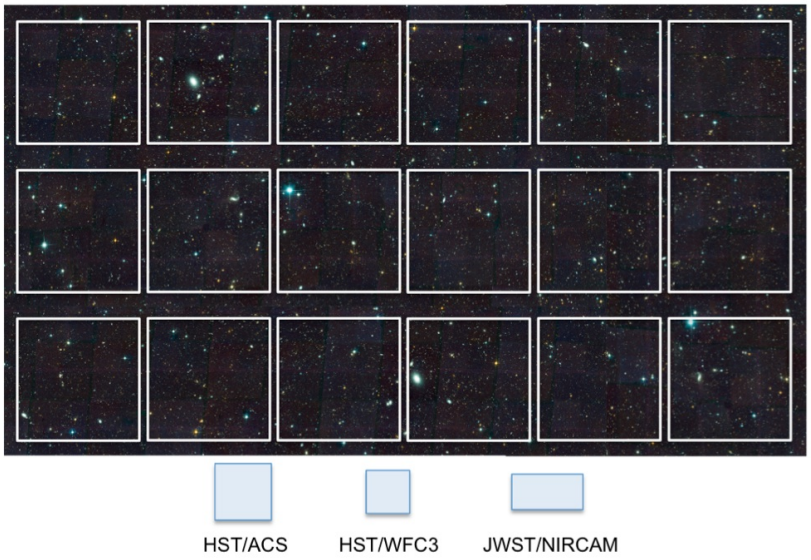
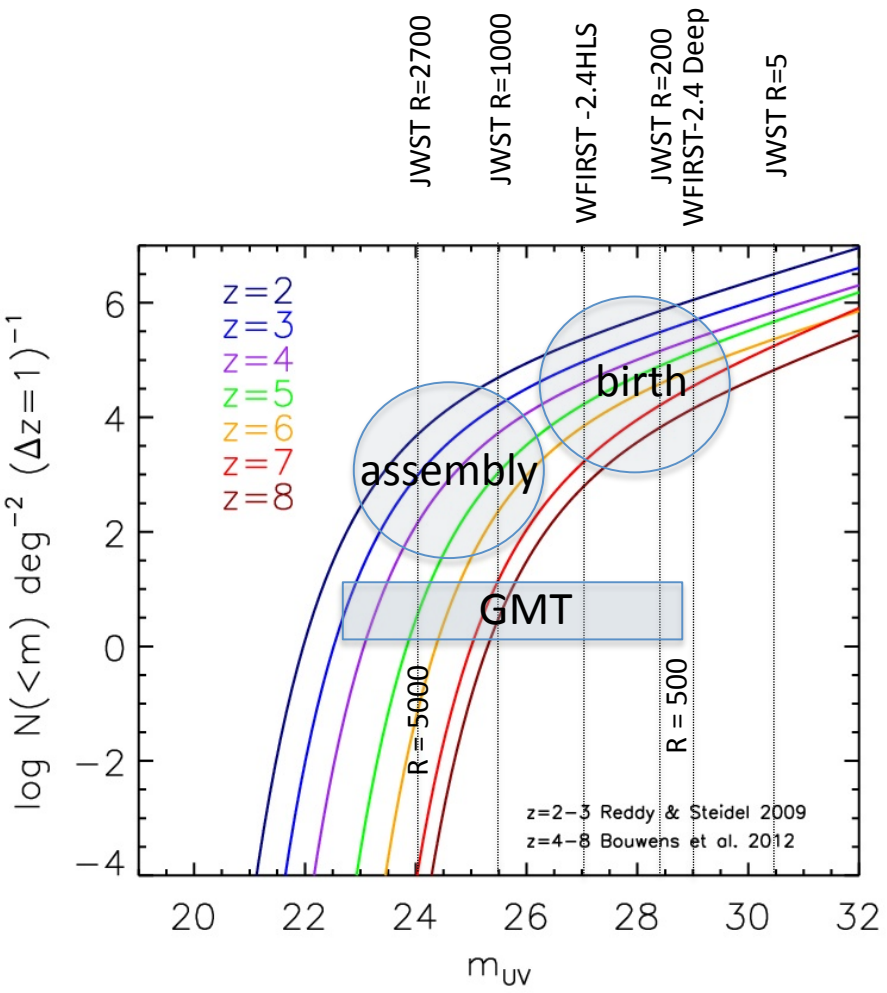
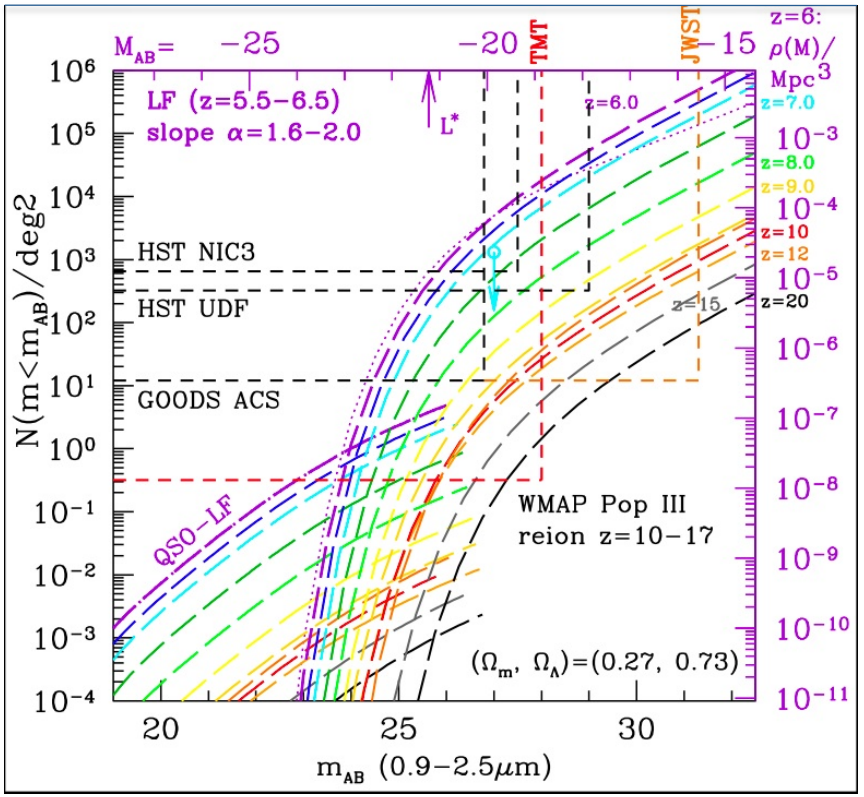


Figure 1-1: Field of view comparison, to scale, of the WFIRST-2.4 wide field instrument with wide field instruments on the Hubble and James Webb Space Telescopes. Each square is a 4k x 4k HgCdTe sensor array. The field of view extent is about 0.79 x 0.43 degrees. The pixels are mapped to 0.11 arcseconds on the sky.

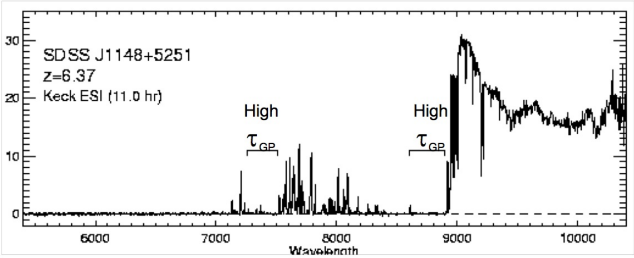
← 1 day survey


JWST R=2700
JWST R=1000
WFIRST -2.4HLS
JWST R=200
WFIRST-2.4 Deep
JWST R=5
z=2
z=3
z=4
z=5
z=6
z=7
z=8
assembly
birth
GMT
R = 5000
R = 500
z=2−3 Reddy & Steidel 2009
z=4−8 Bouwens et al. 2012
log N(<m) deg^{-2} (Δz=1)$^{-1}$
m_{UV}


M_{AB}= −25
−20
TMT
JWST
−15
z=6:
ρ(M)/
Mpc^3
LF (z=5.5−6.5)
slope α=1.6−2.0
L*
z=6.0
z=7.0
z=8.0
z=9.0
z=10
z=12
z=15
z=20
HST NIC3
HST UDF
GOODS ACS
QSO−LF
WMAP Pop III
reion z=10−17
(Ω$_m$, Ω$_Λ$)=(0.27, 0.73)
N(m<m$_{AB}$)/deg2
m$_{AB}$ (0.9−2.5μm)

Using z > 6 QSOs to probe the epoch of reionization

Gunn-Peterson Effect & Reionization Topology

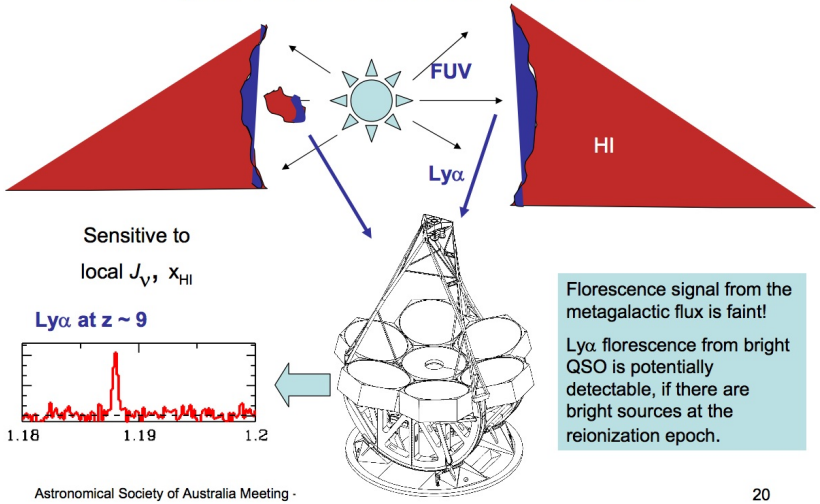


White et al. 2003

11-hour exposures with Keck 10m

Larger aperture needed to sample more sight-lines

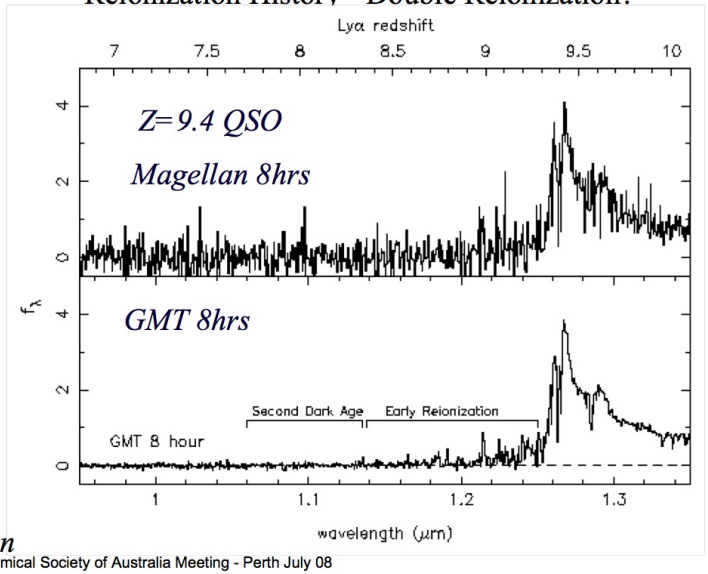
Lyα Florescence at the EOR?



Florescence signal from the metagalactic flux is faint!

Lyα florescence from bright QSO is potentially detectable, if there are bright sources at the reionization epoch.

Reionization History - Double Reionization?



This requires a near-IR spectrograph – GMTIFS – but IFU and AO not required. Need a J-band channel on GMACS!

X. Fan

The First QSO's with WFIRST-2.4

Survey	Area (deg^2)	Depth (5-sigma, AB)	z>7 QSO's	z>10 QSO's
UKIDSS-LAS	4000	Ks=20.3	8	-
VISTA-VHS	20,000	H=20.6	40	-
VISTA-VIKING	1500	H=21.5	11	-
VISTA-VIDEO	12	H=24.0	1	-
Euclid	15,000	H=24.0	1359	22
WFIRST SDT DRM1	3,400	K=26.0	1377	24
WFIRST-2.4 (AFTA, HLS)	2,000	H=26.7	1240	24

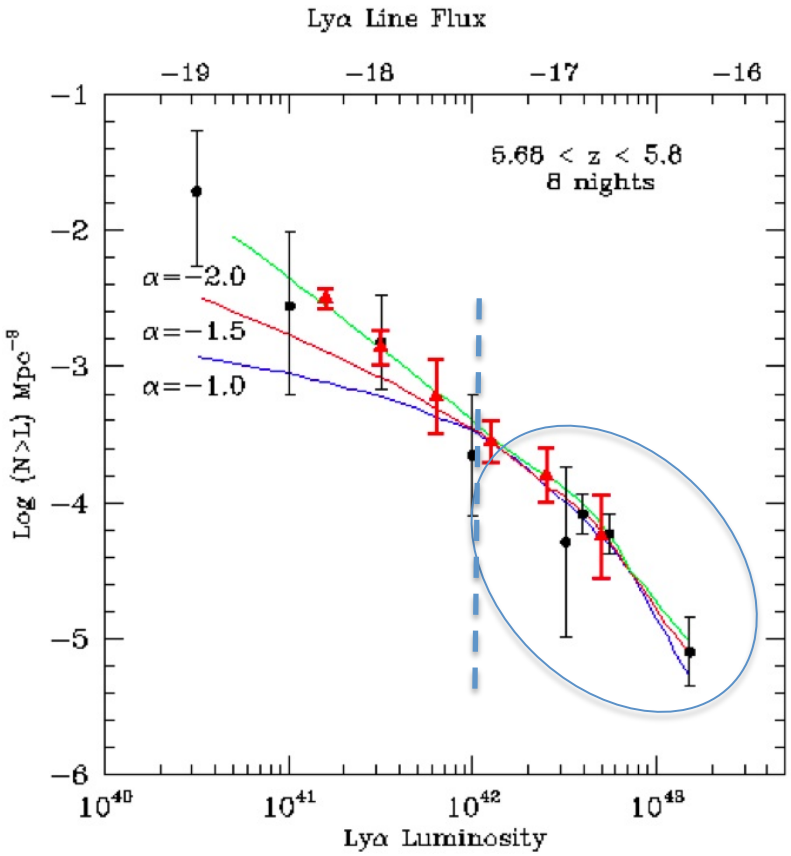
Table 3: Number of very high-redshift quasars predicted for various ground- and space-based near-infrared surveys, based on the quasar luminosity function of Willott et al. (2010). Note: 6.6% of the Euclid wide survey will have two or fewer dithered exposures per sky position. Such data will lack the redundancy required to robustly identify rare objects, and thus have been omitted in the above calculations.

Estimates from Dan Stern (JPL) on the QSO yield from the High Latitude Survey of WFIRST-2.4

z = 6-7 --- 3500
z = 7-8 --- 900
z = 8-9 --- 240
z = 9-10 --- 66
z > 10 --- 10

Using z > 6 Lyman-break and Lyα emitters to probe the epoch of reionization

Mock Lyα Luminosity Function at z ~ 6 with GMT



Are their enough Lyman continuum photons to account for reionization? Need to measure LF slope down to 10^{41}

Dressler et al. (McCarthy) 2011 ApJ, 740, 71

≈100 candidates for falint LAEs at z = 5.75

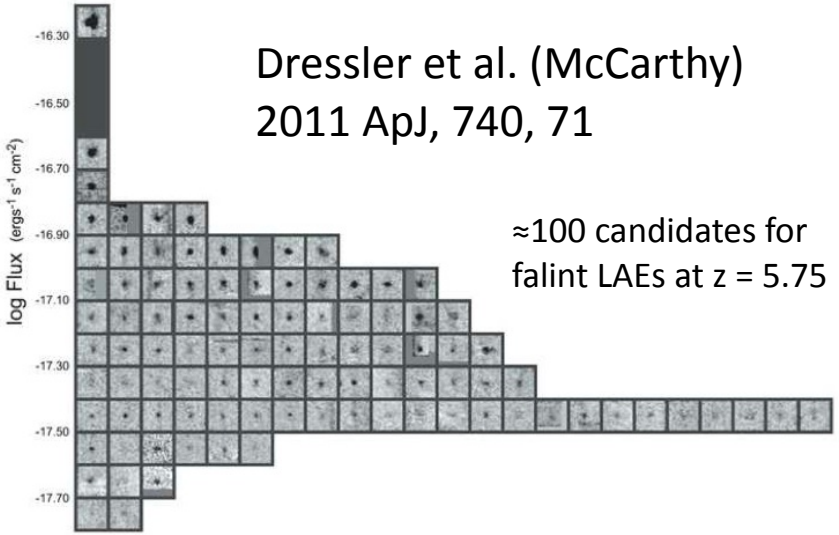
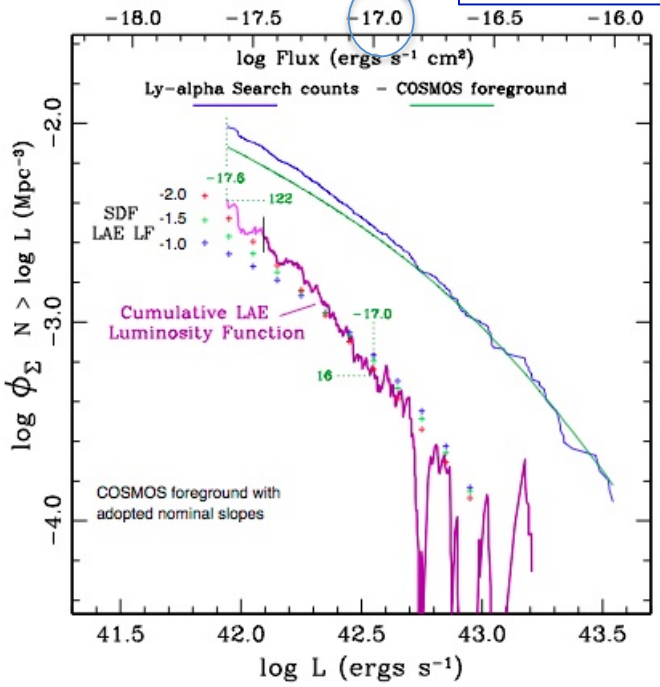


Fig. 1. Mosaic of $5'' \times 50$ Å boxes (spatial – horizontal, wavelength – vertical) of the sample of SELs (single-emission-line without blue continuum) sources in the 10h (COSMOS) field. A flux of $F = 10^{-17}$ ergs s^{-1} cm^{-2}, a natural limit for narrow-band photometric studies, is easily reached with these data, at the $\sim 10\sigma$ level. A flux of $F = 3 \times 10^{-18}$ ergs s^{-1} cm^{-2} is detected at the $\sim 3-4\sigma$ level. The number of sources rises rapidly with decreasing flux, as described in the text. Strong artifacts (eg., cosmic rays, bad pixels, and sky subtraction problems) have been blanked out in some cases.

Limit of narrow band Subaru searches



Henry et al. (McCarthy) 2012 ApJ, 744, 149

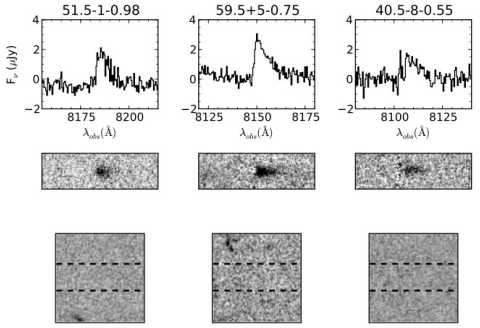


FIG. 2.— Spectra of high confidence, confirmed LAEs are shown in one dimension (top row) and two dimensions (middle row; dispersion in the horizontal direction). The bottom row shows $5''$ I_{814} cutouts from the COSMOS ACS observations (Koekemoer et al. 2007). The detection threshold in these images depends on the sizes of galaxies, but we can estimate that undetected sources have $I_{814} \gtrsim 27$ (Taniguchi et al. 2009; Henry et al. 2009). The dashed lines show the location of our 1.″5-wide slits.

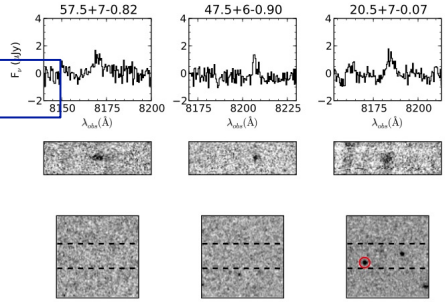


FIG. 3.— Same as Figure 2 but for less certain Lyα identifications. The $i-$ dropout near 20.5+7-0.07 (see text) is circled in red.

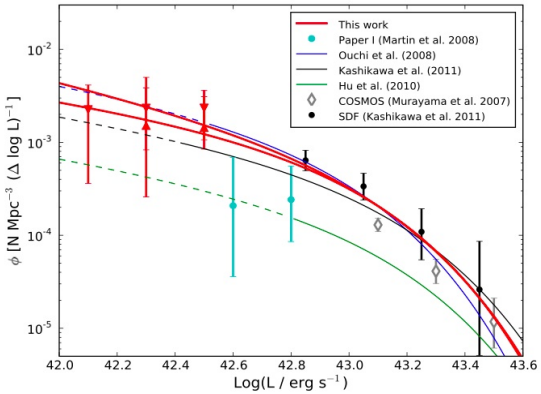
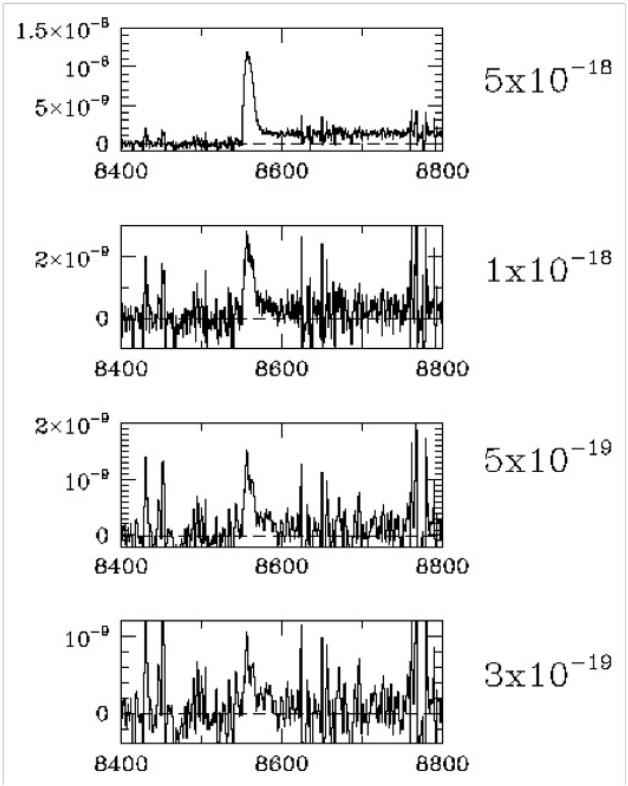


FIG. 7.— Best-fit LFs to the inferred LAE counts (high and low), shown in red, are compared to other derivations of the redshift 5.7 luminosity function. Curves are dashed at luminosities where they are extrapolated beyond the data in their various studies. For the Ouchi et al. (2008); Kashikawa et al. (2011) and Hu et al. (2010) studies we show the fits for $\alpha \equiv -1.5$, which is intermediate to the values favored by our data.

Use Case: Lyα Luminosity Function at z ~ 6



500 km/s FWHM

W_λ = 100Å

30hr integration with GMACS using 0.5" slits in 0.5" seeing

30% throughput

Gemini sky spectrum

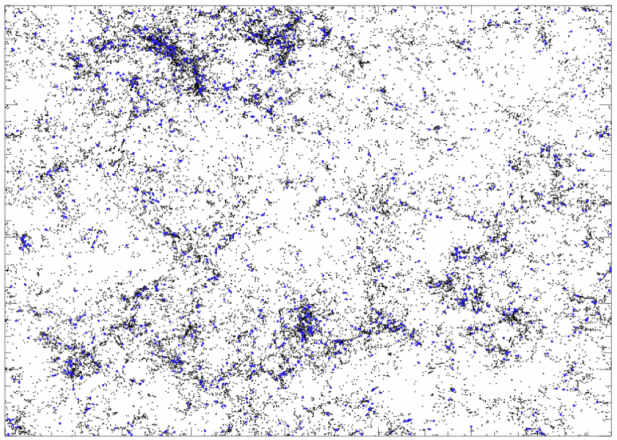
Nod & Shuffle sky rejection

R = 5000 rebinned to

R = 1200, Gaussian smoothing

How do we extend this to z > 8?

Move to the near-IR, but fields of view are smaller, so must target fields using HI maps



…much structure on degree scales

But, WFIRST-2.4 will provide 6 < z < 9 "dropout" maps

Visible Halos at z ~ 9

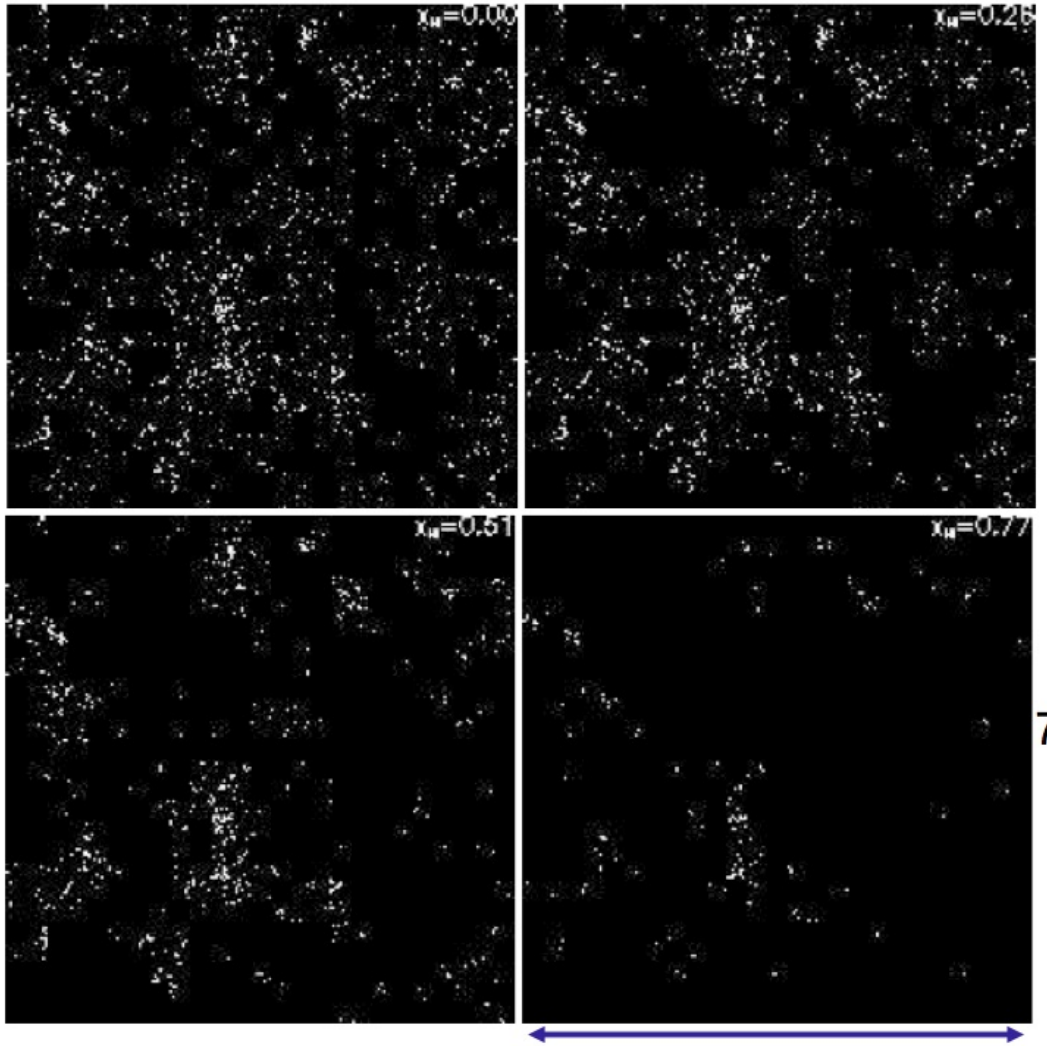
Fully Ionized

Lyα LF & distribution provides a probe of the neutral faction at high z

Scales are very large - impractical at z > 7?

50% Neutral

Damping wings are primary escape path for Lyα photons



25% Neutral

75% Neutral

250Mpc = 15 degrees!

GMACS needs a J-band channel!
1.25µm ➔ z = 9.3

Lyα Spectroscopy in the Near-IR

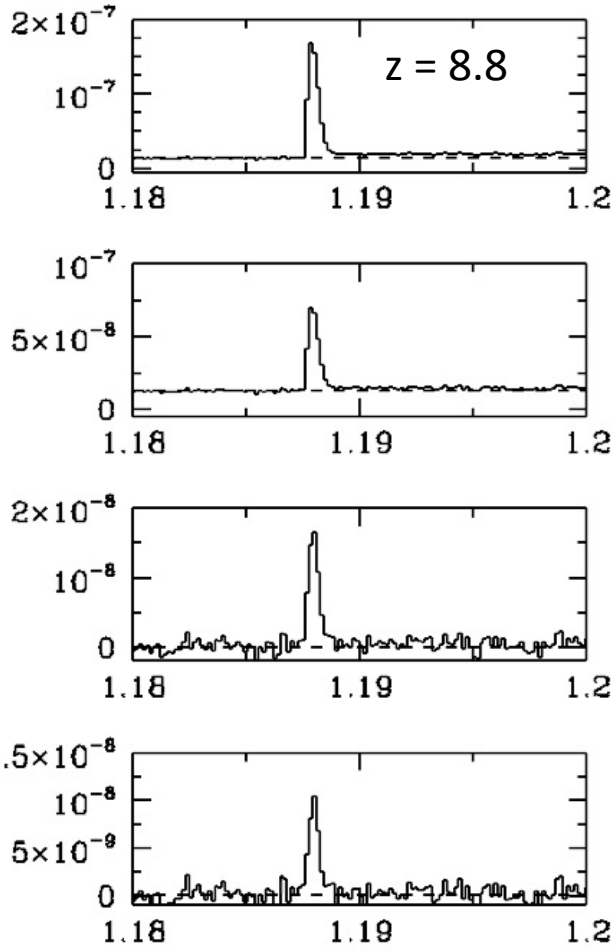
NIRMOS Properties with OH Suppression and low-noise Near-IR detectors

200 km/sec line widths

25 hour exposures

7′ x 7′ field of view

With OH suppression



$5x10^{-18}$
$5x10^{42}$

$2x10^{-18}$
$2x10^{42}$

$5x10^{-19}$
$5x10^{41}$

$3x10^{-19}$
$3x10^{41}$

Using strong lensing by rich clusters to probe the reionization epoch

Zheng et al. 2013, Nature, 489, 406

SOURCE PLANE RECONSTRUCTION OF THE BRIGHT LENSED GALAXY RCSGA 032727-132609*

KEREN SHARON[1], MICHAEL D. GLADDERS[1,2], JANE R. RIGBY[3], KECK WUESTER[1,2], BENJAMIN P. KOESTER[2], MATTHEW B. BAYLISS[1,2], L. FELIPE BARRIENTOS[5]

ACCEPTED TO APJ: *2011, December 17*

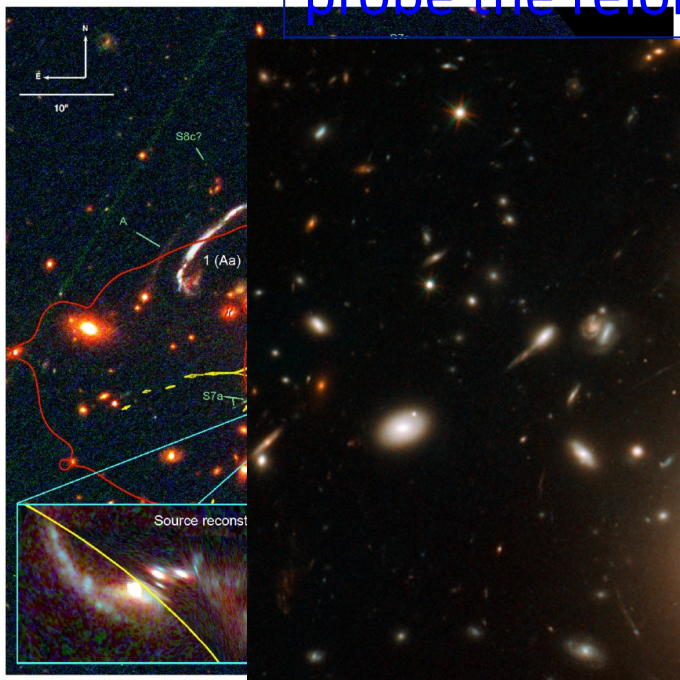
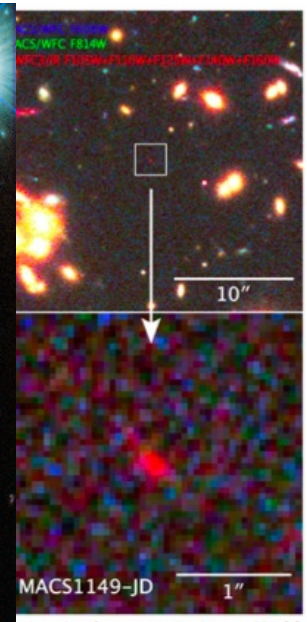


FIG. 2.— *HST*/WFC3 image of the core of RCS
critical curves of the best-fit model are overplotted
its location in the source plane are indicated by t
the source. The giant arc and additional arc candi



by the foreground cluster MACS
IR camera (Zheng et al. 2012). This

Gladders & collaborators study shows
power for studying galaxy assembly

Postman & collaborators:
CLASH clusters

Slice of Millennium simulation 500 x 500 x 30 Mpc
Red dots represent HLS survey clusters M > $5 \times 10^{13}\ M_{\odot}$
<u>WFIRST finds 40,000 such clusters</u>

HLS clusters | Dark matter | Euclid depth

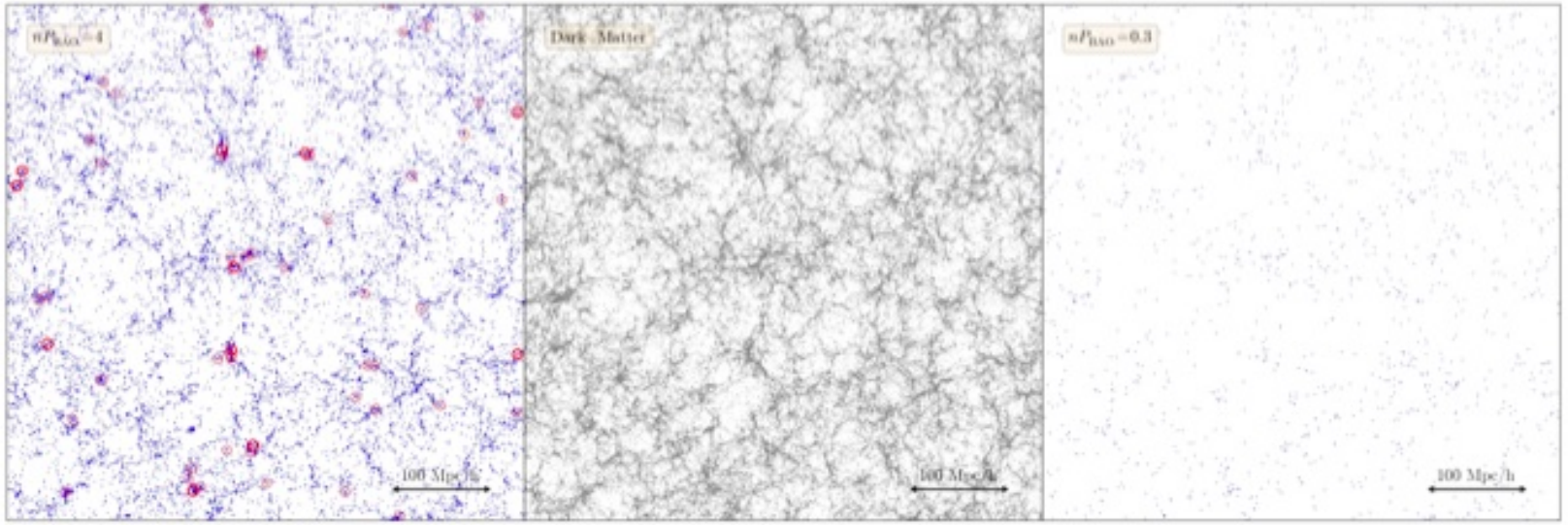


Figure 2-6: Slices 500 h^{-1} Mpc on a side and 30 h^{-1} Mpc thick from the Millenium simulation at z = 1.5. Points in the left panel show semi-analytic galaxies[17] selected at a luminosity threshold that yields our predicted space density for WFIRST-2.4. Thin and thick red circles mark clusters with virial mass exceeding $5 \times 10^{13}\ M_{sun}$ and $10^{14}\ M_{sun}$, respectively. The middle panel shows the dark matter density field, based on mass-weighting the full dark matter halo population. The right panel shows the galaxy distribution with a higher luminosity threshold that yields the space density predicted for the Euclid GRS at this redshift. At z = 1.5 this slice would subtend a solid angle (9.2 × 9.2) deg^2 with redshift depth $\Delta z = 0.022$, so it represents a minuscule fraction (~ 10^{-3}) of the GRS survey volume. Figure courtesy of Ying Zu.

Strong lensing with WFIRST-2.4 provides a bounty of galaxies in the reionization epoch!

With the amplification the lensing provies, some of these will be bright enough for moderate-resolution GMT spectroscopy.

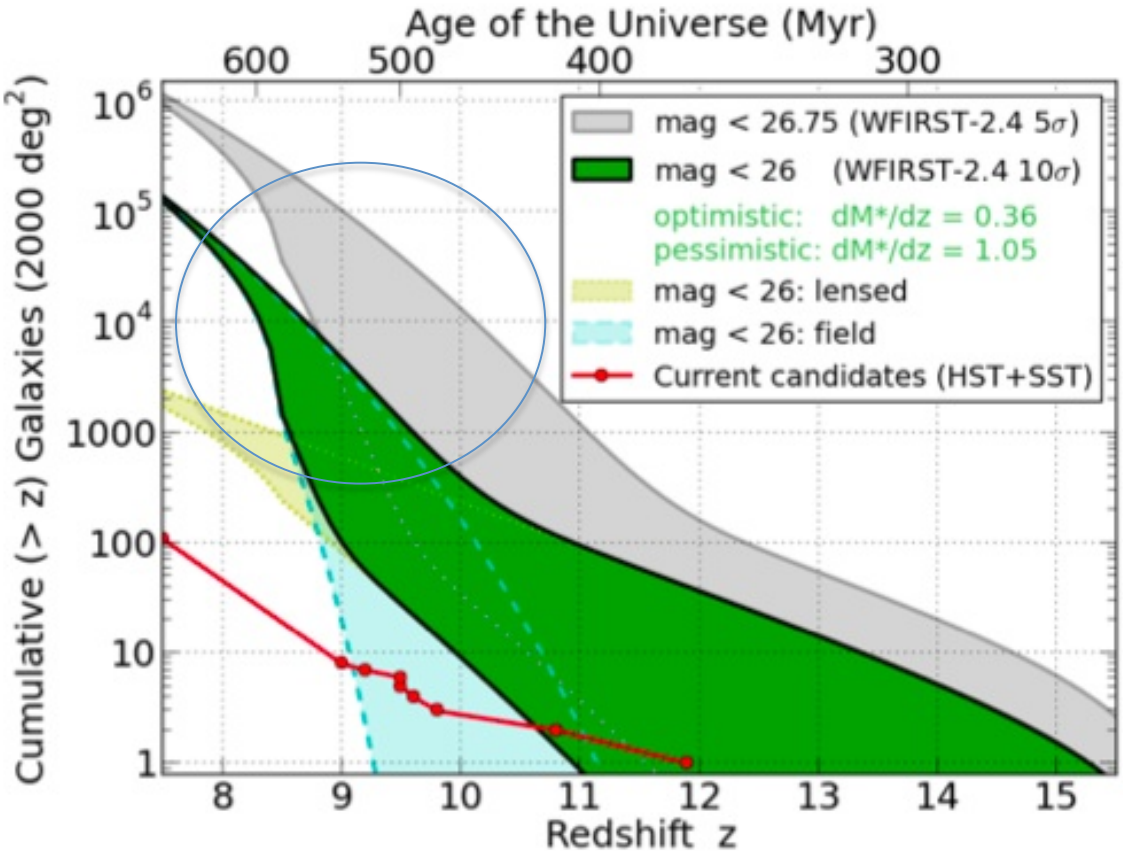
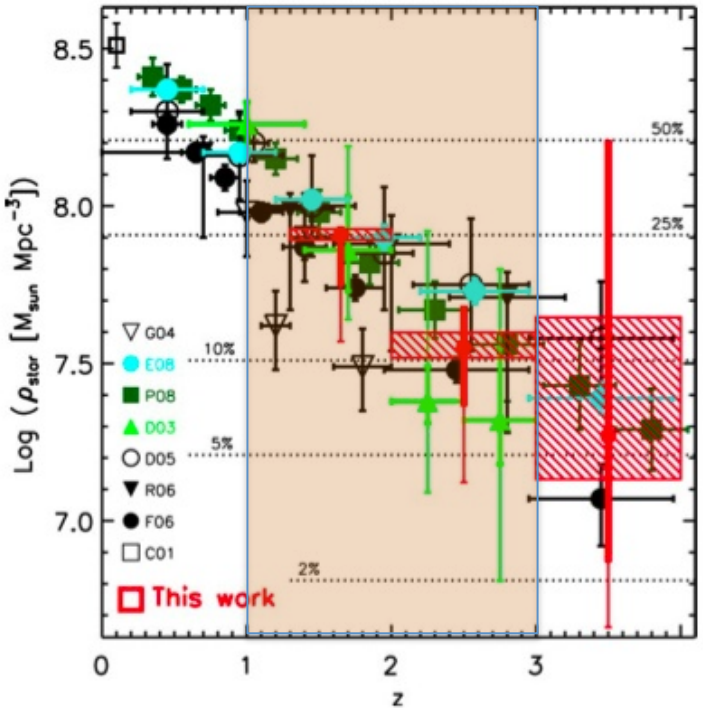


Figure 2-10: Cumulative number of high-z galaxies expected in the HLS. JWST will be able to follow-up on these high z galaxies and make detailed observations of their properties. For understanding the earliest galaxies, the synergy of a wide-field telescope that can discover luminous or highly magnified systems and a large aperture telescope that can characterize them is essential; WFIRST-2.4 and JWST are much more powerful than either one alone.

1 < z < 3 is the epoch of galaxy growth and assembly. Detailed measurements of this buildup, including chemical abudances and kinematics, will be one of GMT's most important contributions to the study of galaxy evolution .



Buildup of stellar mass in galaxies. Compilation of data by Marchesini et al. (2009)

Figure 5.3 Evolution of the stellar mass density history from z ~ 4 to the present compiled from a variety of surveys, as reported in Marchesini et al. (2009). The steady build up of stellar mass in galaxies is clear, but discrepancies between the integral of the star formation rate and the stellar mass history remain.

GMACS + GMTIFS can observe 1<z<3 range fully OII to Ha (with gaps)

WFIRST-2.4 HLS grism survey yield

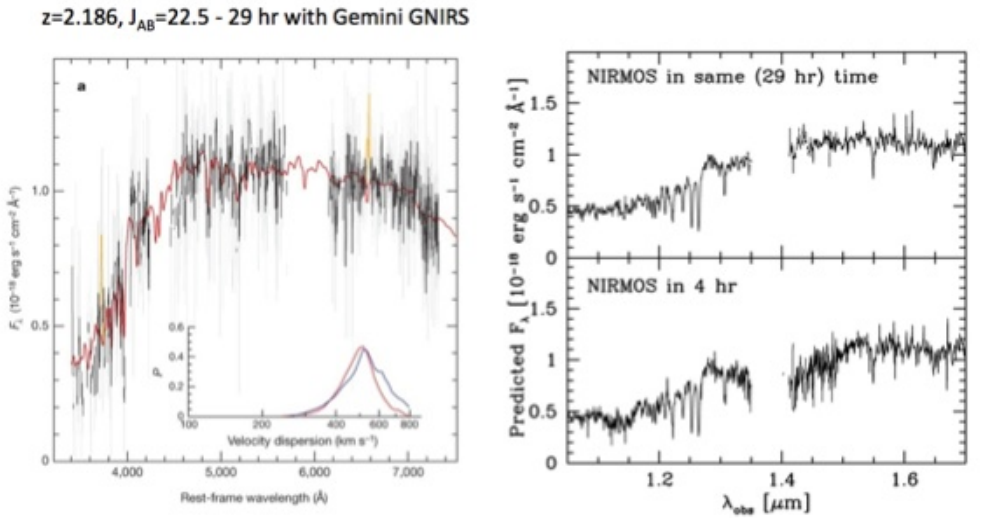
z	n (Mpc^{-3})	dN/dz/dA (deg^{-2})
1.10	1.17E-03	10623
1.15	1.25E-03	11776
1.20	1.32E-03	12814
1.25	1.38E-03	13877
1.30	1.43E-03	14719
1.35	1.47E-03	15527
1.40	1.50E-03	16244
1.45	1.53E-03	16890
1.50	1.51E-03	16965
1.55	1.37E-03	15759
1.60	1.25E-03	14536
1.65	1.13E-03	13305
1.70	1.01E-03	12110
1.75	9.02E-04	10918
1.80	8.00E-04	9789
1.85	7.05E-04	8697
1.90	6.17E-04	7686
1.95	5.36E-04	6718
2.00	1.33E-04	1678
2.10	1.21E-04	1541
2.20	1.15E-04	1477
2.30	9.72E-05	1258
2.40	8.12E-05	1054
2.50	6.66E-05	866
2.60	5.35E-05	696
2.70	4.28E-05	556
2.80	3.27E-05	424

Table 2-2: Comoving space density of galaxies, in comoving Mpc^{-3} and number per unit z per deg^2, expected in the WFIRST-2.4 GRS. We include only Hα emitters at z < 2 and only [OIII] emitters at z ≥ 2.

High Latitude Survey will produce
10^7 Hα redshifts z = 1-2
2 x 10^6 [O III] redshift z = 2-3

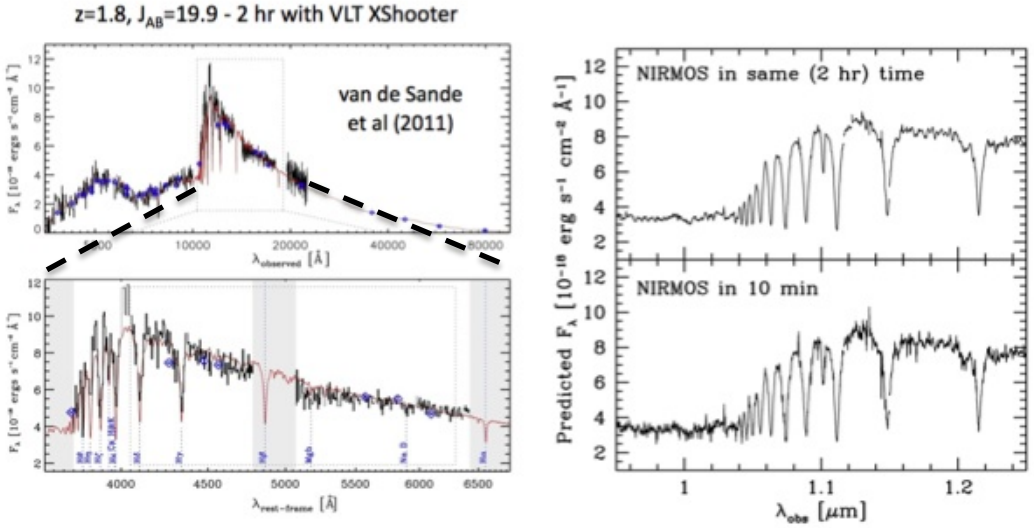
WFIRST-2.4 will produce an enormous sample for studying galaxy assembly 1 < z < 3

L*+ galaxy (AB=22.5) at z=2.2, 29 hr with Gemini GNIRS



4 hr GMT

Unusually bright (AB=19.9) starforming galaxy at z=1.8, 2 hr with VLT XShooter



10 min GMT

Figure 5.4 Comparisons between state-of-the-art spectra of red galaxies with simulated spectra from NIRMOS on GMT. The left panels show Gemini/GNIRS (van Dokkum et al. 2009) spectra and VLT/XShooter spectra (van de Sande et al. 2011) of red galaxies with J = 22.5 and 19.9, respectively.

Hsiao-Wen Chen: QSO-backlit circumgalactic gas – MgII abs with MAGE

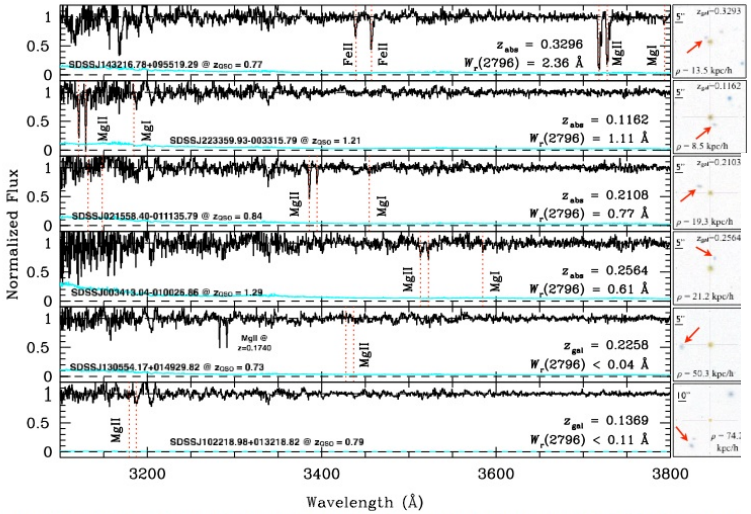
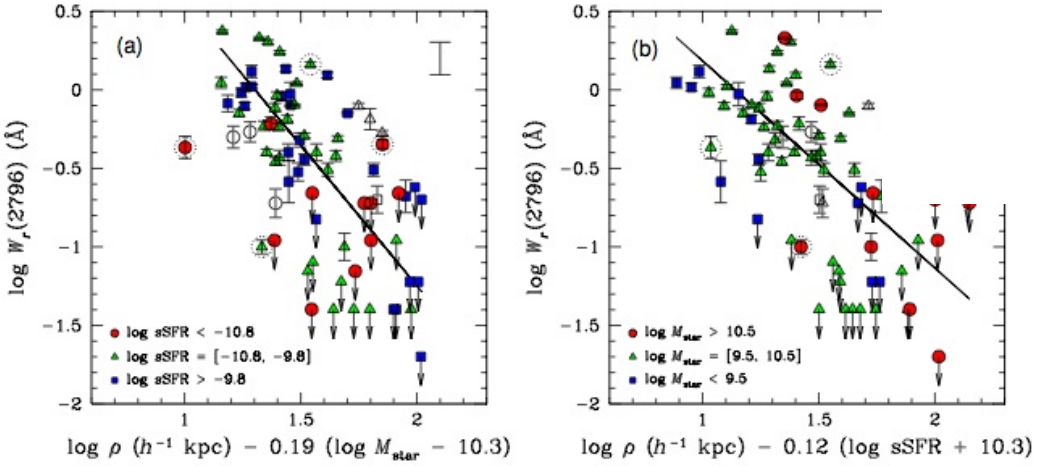
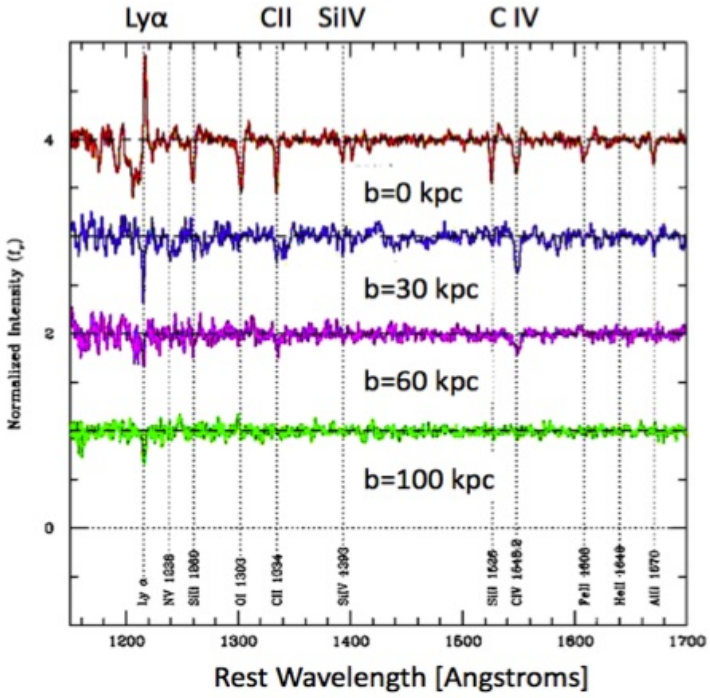


Figure 6. Examples of the galaxy–Mg II absorber pairs in our sample. For each field, we present the QSO spectrum in the left panel and the corre image centered at the QSO in the right panel. The galaxies in our survey with confirmed spectroscopic redshifts are indicated by the arrow. The proje the QSO is shown in the lower right corner of each image panel. The absorption features corresponding to the redshifts of the galaxies are indicated in the left panels. The absorber redshift is shown in the lower right corner of each spectrum. For non-detections in the bottom two panels, we note th galaxy and the 2σ upper limit of $W_r(2796)$.



GAS & GALAXIES: "Feeback"

Steidel+ (2010) composite spectra showing CII and CIV absorption from 512 foreground/background pairs



The huge photo-z sample from the WFIRST-2.4 HLS will provide multiple foreground/background pairs per GMACS field.

DEMOGRAPHICS AND PHYSICAL PROPERTIES OF GAS OUT/INFLOWS AT $0.4 < Z < 1.4$

Crystal L. Martin[1] Alice E. Shapley[2,8] Alison L. Coil[3,9] Katherine A. Kornei[2] Kevin Bundy[4] Benjamin J. Weiner[5] Kai G. Noeske[6] David Schiminovich[7]

Submitted June 22, 2012; Accepted October 12, 2012

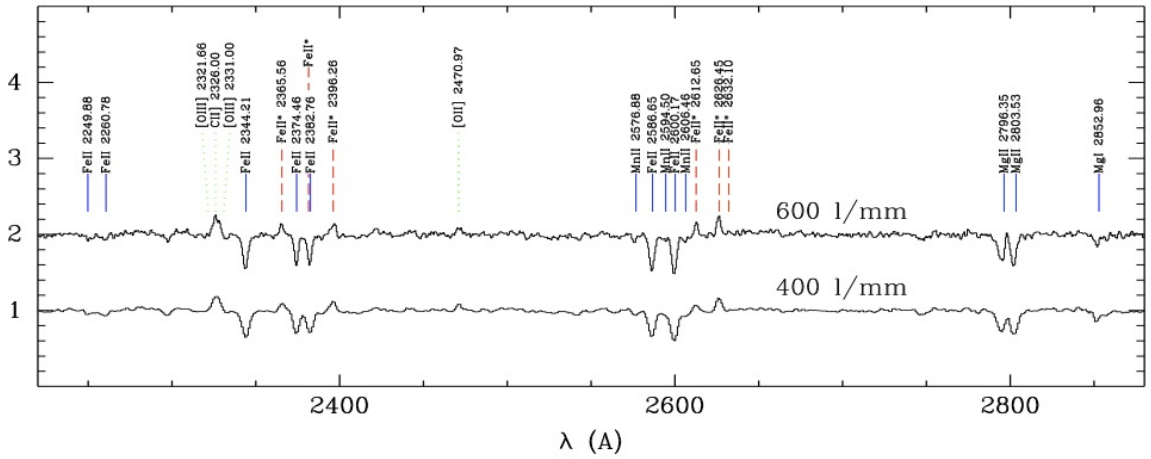
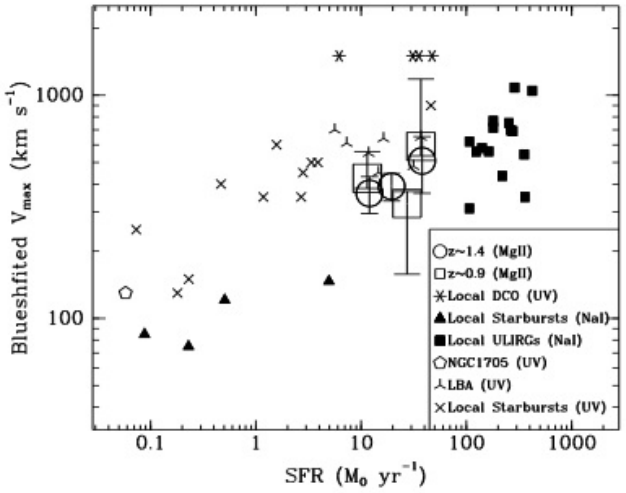
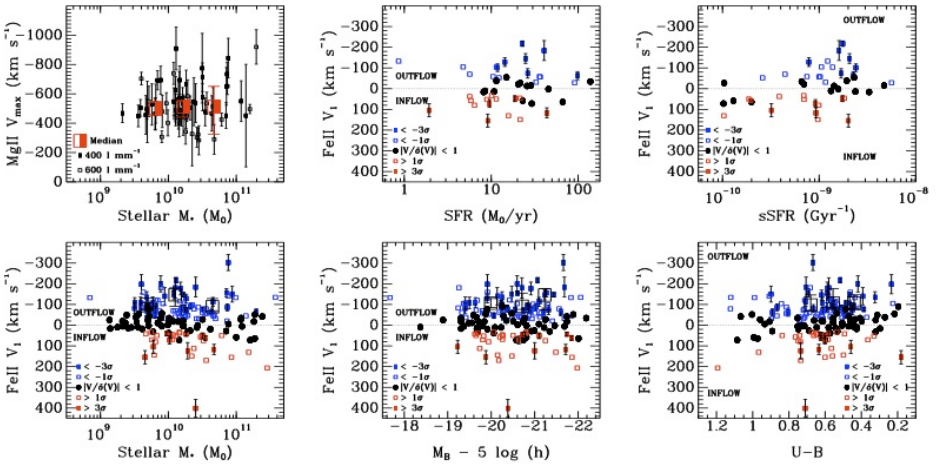
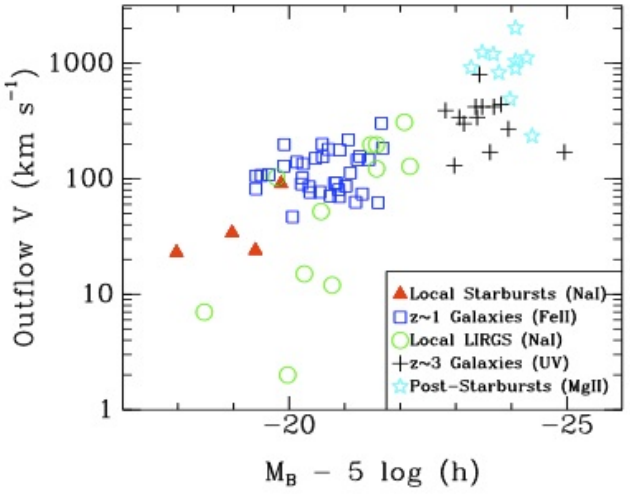


FIG. 2.— Composite, near-ultraviolet spectra of star-forming galaxies at $z \sim 1$. The continuum level has been normalized to unity. The lower spectrum in Figure 2 shows the addition of all 208 continuum normalized spectra after smoothing them to a common resolution of 435 km s^{-1} FWHM. The upper spectrum is the average of 63 spectra observed at a resolution of 282 km s^{-1} FWHM. Vertical blue (solid), red (dashed), and green (dotted) lines mark, respectively, resonance absorption lines, fluorescent emission lines, and nebular emission lines. The unlabeled Fe II* transition is a weak line at λ2381.49; see Martin et al. (2012b, in prep.) for a tabular linelist.







One of the primary goals of the 2020s:
Spatially resolved chemical composition (R ≈ 1000) and kinematics (R ≥ 5000) of galaxies in assembly 1 < z < 3

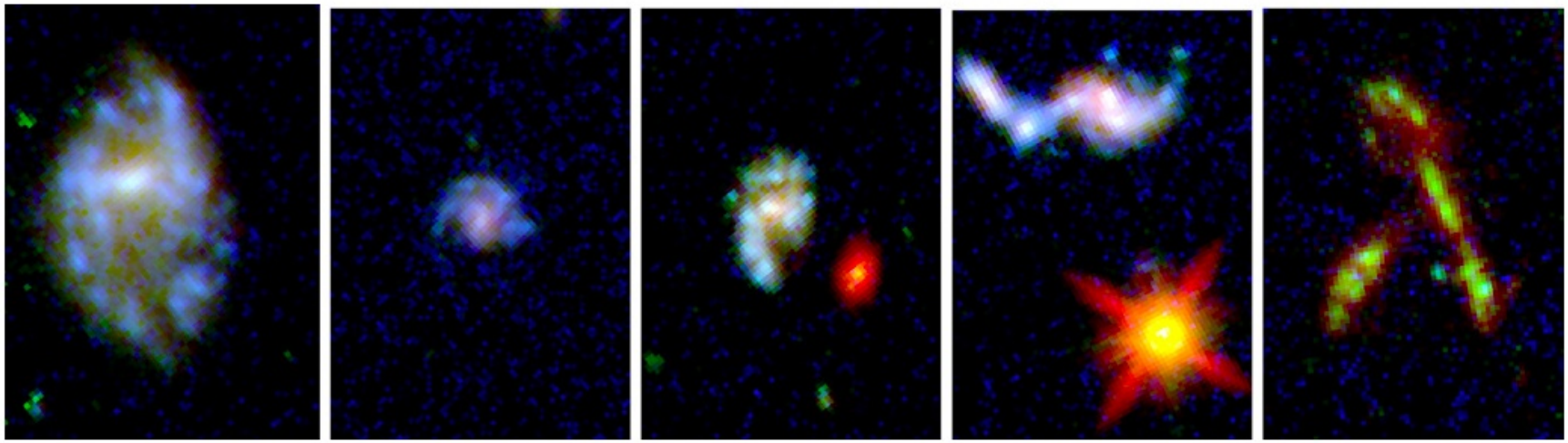
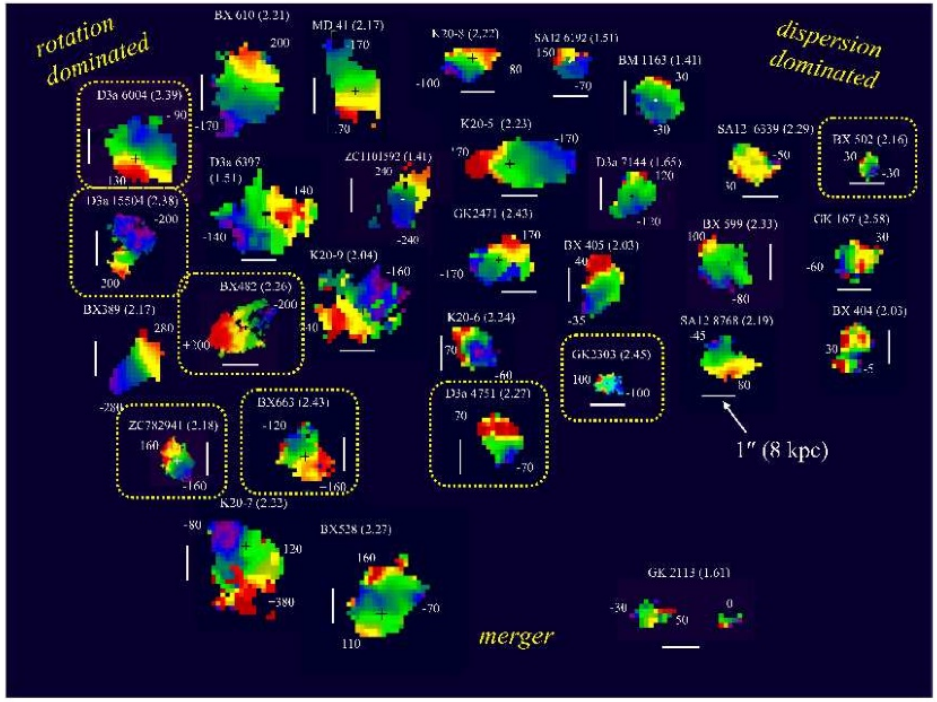


Figure 14. Panchromatic postage stamps of objects with interesting morphological structure in the 10-band ERS color images of the GOODS-South field: from left to right, high signal-to-noise detections of ERS galaxies resembling the main cosmological parameters H_0, Ω, ρ_o, w, and Λ, respectively. These images illustrate the rich and unique morphological information available in the 10-band panchromatic ERS data set.

THE SINS SURVEY: SINFONI INTEGRAL FIELD SPECTROSCOPY OF $Z \sim 2$ STAR-FORMING GALAXIES [1]

N. M. FÖRSTER SCHREIBER[2], R. GENZEL[2,3], N. BOUCHÉ[2], G. CRESCI[2], R. DAVIES[2], P. BUSCHKAMP[2], K. SHAPIRO[4], L. J. TACCONI[2], E. K. S. HICKS[2], S. GENEL[2], A. E. SHAPLEY[5], D. K. ERB[6], C. C. STEIDEL[7], D. LUTZ[2], F. EISENHAUER[2], S. GILLESSEN[2], A. STERNBERG[8], A. RENZINI[9], A. CIMATTI[10], E. DADDI[11], J. KURK[12], S. LILLY[13], X. KONG[14], M. D. LEHNERT[15], N. NESVADBA[16], A. VERMA[17], H. MCCRACKEN[18], N. ARIMOTO[19], M. MIGNOLI[10], M. ONODERA[11,20]

Kinematic maps with VLT SINFONI IFU showing rotation-dominated, and dispersion-dominated galaxies at z ≈ 2



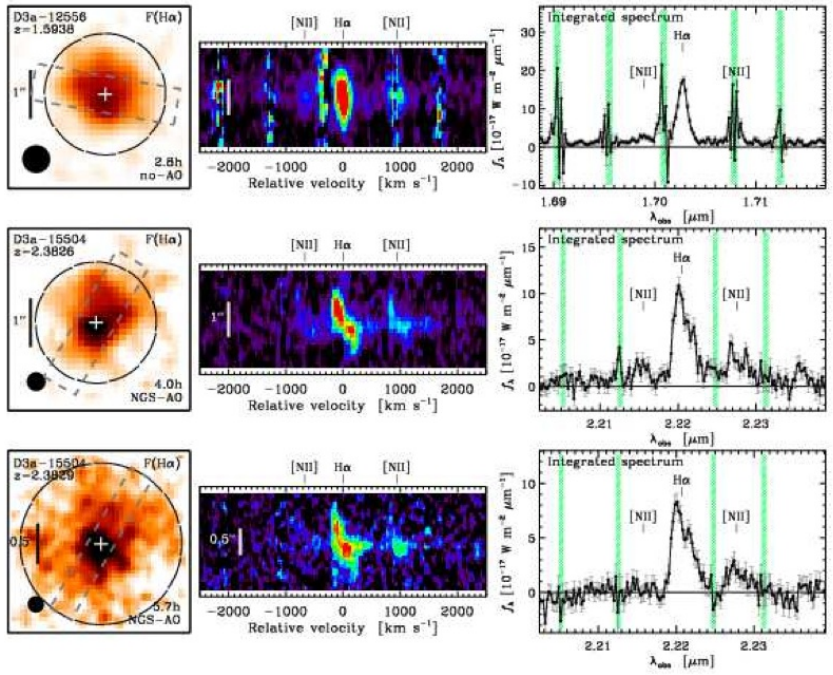


FIG. 17.— Velocity fields for 30 of the 62 galaxies of the SINS Hα sample. The velocity fields correspond to that derived from the Hα line emission as described in § 5.1 (the exception is K20 – ID5 for which it was obtained from the [O III] λ5007 line instead). The colour-coding is such that blue to red colours correspond to the blueshifted to redshifted line emission with respect to the systemic velocity. The minimum and maximum relative velocities are labeled for each galaxy (in km s^{-1}). All sources are shown on the same angular scale; the white bars correspond to 1″, or about 8 kpc at $z = 2$. The galaxies are approximately sorted from left to right according to whether their kinematics are rotation-dominated or dispersion-dominated, and from top to bottom according to whether they are disk-like or merger-like as quantified by our kinemetry (Shapiro et al. 2008). Galaxies observed with the aid of adaptive optics (both at the 50 and 125 mas pixel^{-1} scales) are indicated by the yellow rounded rectangles.

Example data: reconstructed images (left) and spectra

HST has pioneered in slitless grism spectroscopy to map SFRs, gas-phase chemical abundances (HST-3D, WISP…) WFIRST-2.4 will carry on such studies with 100-200 times the field area per exposure, for Hα to z=2 and [O III/Hβ to z = 3. GMTIFS can build on this work by concentrating on the most interesting galaxies to higher spatial/spectral resolution for SFRs, abundances, and adding detailed kinematics.

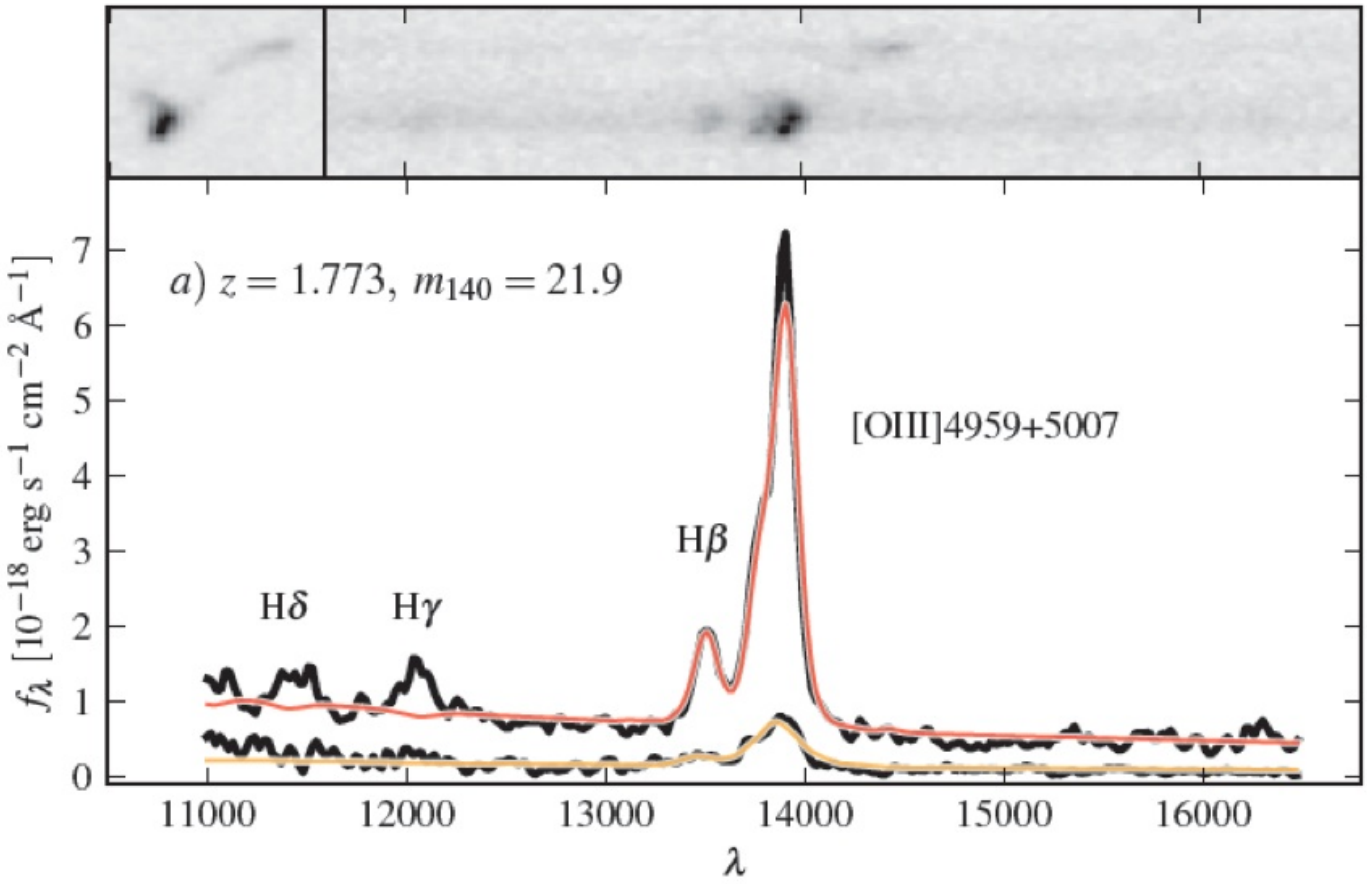


Figure 2-16: The grism image (top) and the extracted spectrum of a z=1.77 star-forming galaxy. The WFIRST-2.4 grism will allow us to detect thousands of such galaxies in the HLS area.

SPATIALLY RESOLVED Hα MAPS AND SIZES OF 57 STRONGLY STAR-FORMING GALAXIES AT $z \sim 1$ FROM 3D-HST: EVIDENCE FOR RAPID INSIDE-OUT ASSEMBLY OF DISK GALAXIES

Erica June Nelson[1], Pieter G. van Dokkum[1], Gabriel Brammer[2], Natascha Förster Schreiber[3], Marijn Franx[4], Mattia Fumagalli[4], Shannon Patel[4], Hans-Walter Rix[5], Rosalind E. Skelton[1], Rachel Bezanson[1], Elisabete Da Cunha[5], Mariska Kriek[6], Ivo Labbé[4], Britt Lundgren[1], Ryan Quadri[7], and Kasper B. Schmidt[5]

SFRs based on Hα grism observations – "inside-out galaxy building"

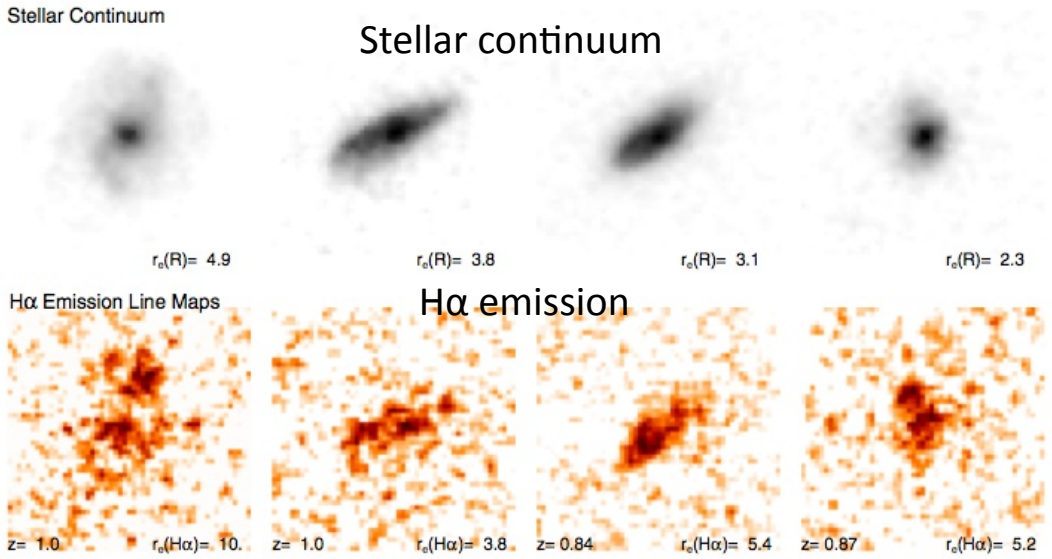
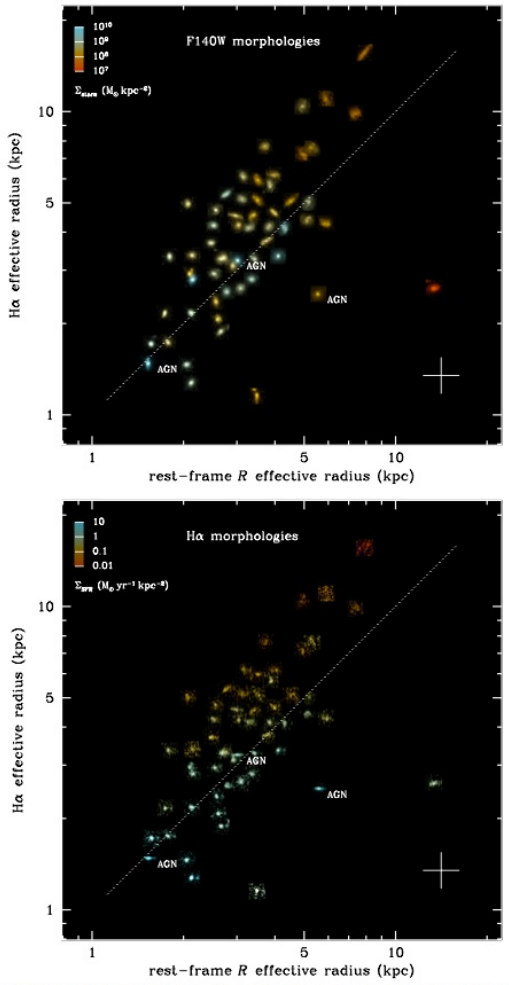


Figure 2. Examples of galaxies in the survey. Each panel shows the continuum emission, as traced by the F140W filter (rest-frame *R*), and the Hα emission line map. (A color version of this figure is available in the online journal.)



half-light radius of the Hα emission and the half-light radius of the stellar continuum radiation (as described by t
y in F140W (top panel) and in Hα (bottom panel). The Hα size scales with the rest-frame optical size but is typi
re is available in the online journal.)

GMACS will have the spectral resolution (R ≈ 2000) needed for mapping chemical abundance (OIII to z < 1.5) Kinematics information will require ≤ 30 km s^{-1} which GMACS also has. However, the small sizes of these 1 < z < 3 galaxies, typically 2 arcsec) means that an AO capability is required, i.e. GMTIFS. GLAO at 0.3" would make a good start, but ≤ 0.1" resolution (LTAO) is really required.

JWST can make a big contribution to such studies, but time will be limited, the smaller aperture makes it challenging, and spectral resolution is insufficient (R =2700) for detailed kinematic studies. GMTIFS is a necessity!

Rest-frame UV stellar continuum

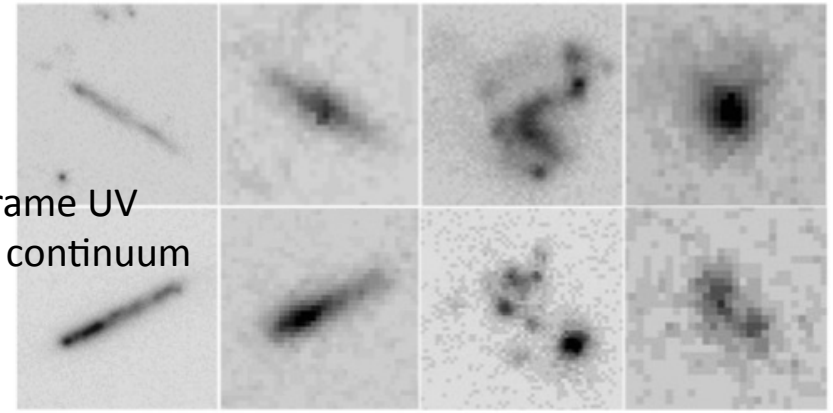


Figure 5.5 Examples of rest frame UV/optical images of four galaxies from the *HST* UDF, ACS *V* (left of each pair) & NICMOS *H* (right of each pair), from Elmegreen et al. (2008) showing the clumpy structure of high-redshift galaxies with (upper) and without (lower) clearly defined bulge structures. Observations at the limit of modern instrumentation show tantalizing hints of fundamental structural building blocks of galaxies at this key epoch, but only ELTs will provide the critical combination of sensitivity and resolution necessary to probe these unit building blocks.

Velocity slices (channel maps)

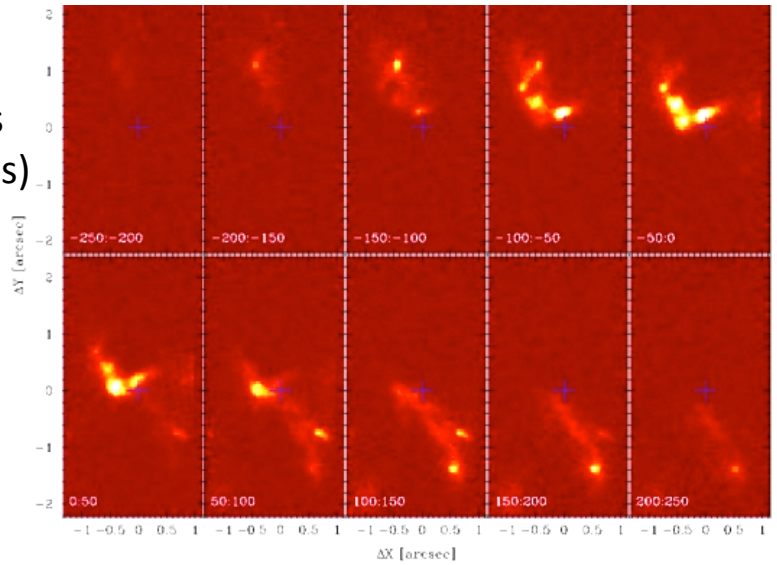
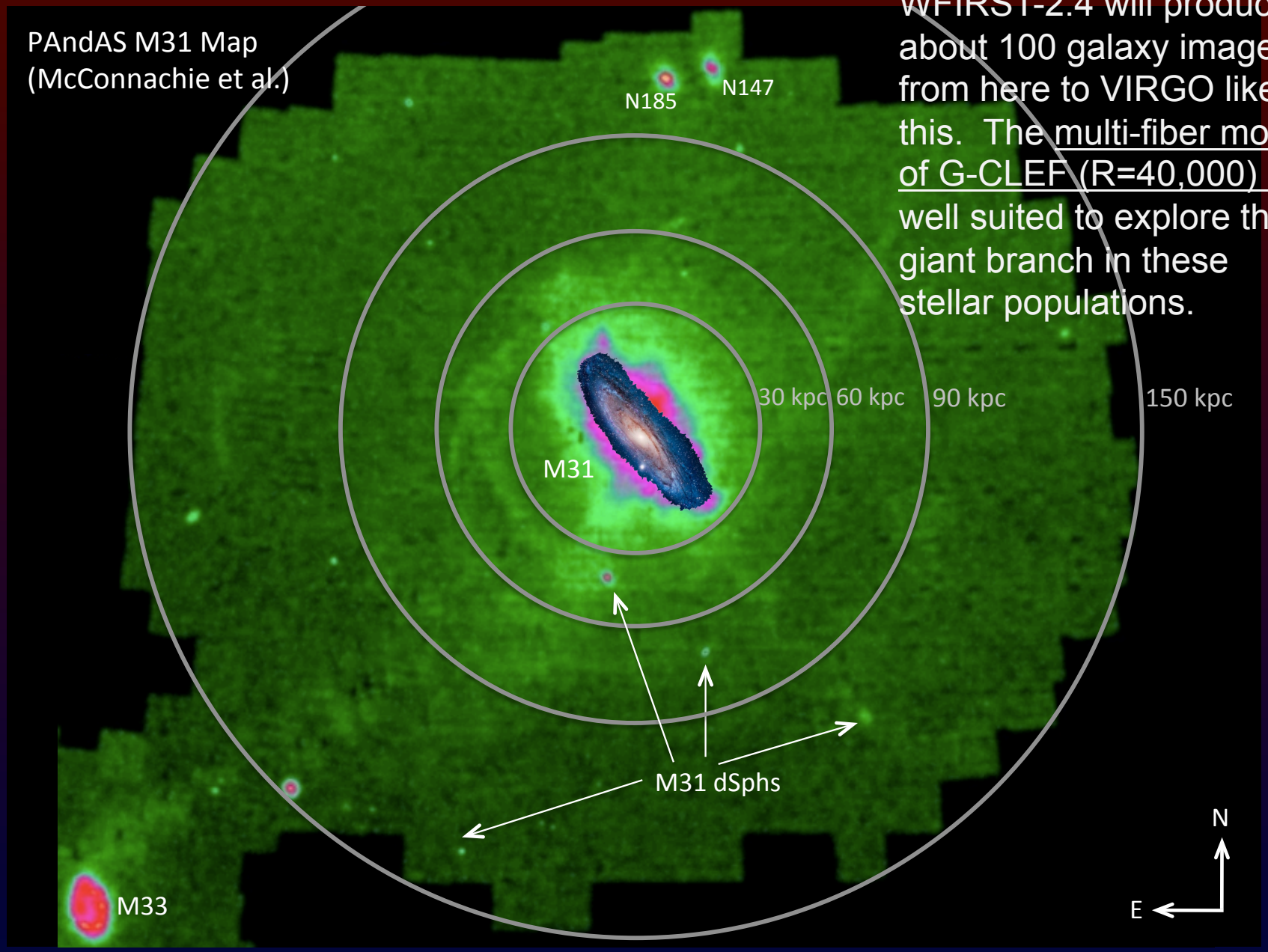


Figure 5.6 Simulated velocity channel maps from an observation of a z = 1.5 galaxy with the GMTIFS instrument on the GMT. An ordered velocity field with an amplitude of +/- 200km/sec was imposed on an ACS i-band image from the Hubble Ultra Deep Field. This simulation uses data obtained by Bournaud et al. (2008) and assumes 50mas spatial elements and a total line flux of 1.1×10^{-16} erg cm^{-2} s^{-1} (Bournaud et al. 2008) observed over a period of 12h (9h on source +3h on sky).



WFIRST-2.4 will produce about 100 galaxy images from here to VIRGO like this. The multi-fiber mode of G-CLEF (R=40,000) is well suited to explore the giant branch in these stellar populations.

Program	Each pointing (sq deg)	# Targets	Comment
Embedded star formation < 1 kpc (Tau, Oph, Ser, Per, Ori)	1 – 30	~10	IMF: substellar to intermediate masses: calibrating models
10-100 Myr open clusters (Pleiades, NGC clusters)	~1	~10	Mass Function to substellar masses, evolution, dynamics, brown dwarfs
Dense embedded star formation > 1 kpc (NGC 7538, W3, Gal Ctr)	~ 0.25 (1 field)	~15	IMF: high mass end
Globular Clusters	0.25	12	Calibrate IR CMD with metallicity
Stellar populations of Galactic bulge, halo, satellites	HLS microlensing	HLS microlensing	Substructure, tidal streams, AGB ages from HLS and microlensing data
Ultra-faint MW dwarf galaxies including S/LMC	0.25 – 4	>10	Star formation histories, metal-poor IMF, kinematics of LSST discoveries
Map local group galaxies (M31, M33, dwarf ellipticals)	~2 - 20	~6	Resolve disk structure, extinction maps, cluster dissolution to field
Mapping nearby galaxy thick disks and halos beyond local group	~1	> 24	Halo substructure, population gradients, test dark matter, kinematics
Mapping the core of Virgo cluster	~100	1	Morphologies, luminosity function, superstar clusters, intracluster objects
AGN host galaxies (coronagraph)	1E-6	> 10	Stellar populations, comparison to normal galaxies
Galaxy cluster (HLS) followup	0.25	> 24	High z lensed objects, structure growth, interactions & dark matter
LSST Deep Drilling Fields	0.25	1-4	Galaxy Luminosity Function out to reionization epoch (z from dropouts)
QSOs as probes of cosmic dawn	HLS	HLS	Epoch, speed, patchiness of reionization using QSO spectra

Table 2-3: Examples of GO programs.

Galaxy Evolution with GMACS (including J-band channel)

(1) SFRs, chemical evolution, kinematics for galaxies $z < 1.5$ efficiently through multislit spectroscopy

(2) Galaxy assembly with feedback: circumstellar gas through absorption line studies with foreground/background pairs (Lyα, MgII, CIV) up to $z \approx 4$

(3) Galaxy evolution through UV/optical spectroscopy of lensed galaxies found in WFIRST-2.4 identified strong-lensing clusters

(4) Supermassive black holes $10^4 - 10^6$ $M_\odot$ in Milky Way neighbor galaxies through $R \approx 5000$ of nuclear star clusters

Galaxy Evolution with G-CLEF using the 40-fiber R=40,000 mode

(1) Stellar populations in Milky Way halo and Local Group
(2) Mapping halo structure through TGB spectra in 100 WFIRST2.4 galaxy maps
(3) Age/metallicity of globular star clusters (integrated light) out to Virgo cluster

Galaxy Evolution with GMTIFS (lacking NIRMOS)

(1) Structure of the IGM at the epoch of reionization – GRBs and bright QSOs with GMTIFS

(2) Follow the feedback process in the formation of massive galaxies at $3 < z < 6$. Absorption- and emission-line maps and kinematics – again, challenging without AO

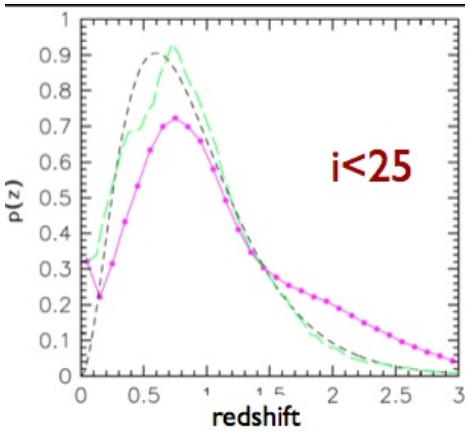
(3) Galaxy assembly: follow-up at higher angular and spectral resolution of JWST/WFIRST-2.4 identified high-z galaxies. Techniques: Lyα emission; Hα kinematics; chemical evolution through emission-line ratios; buildup of stellar component

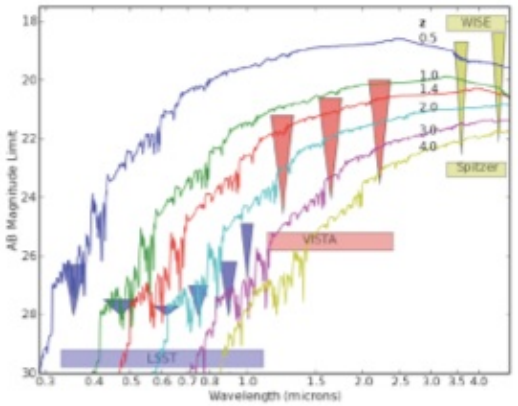
(4) Largest supermassive black hoes: detect $10^9 – 10^{10}$ $M_\odot$ black holes up to $z \approx 1$ through emission (gas disks) and stellar kinematics (continuum absorption lines)

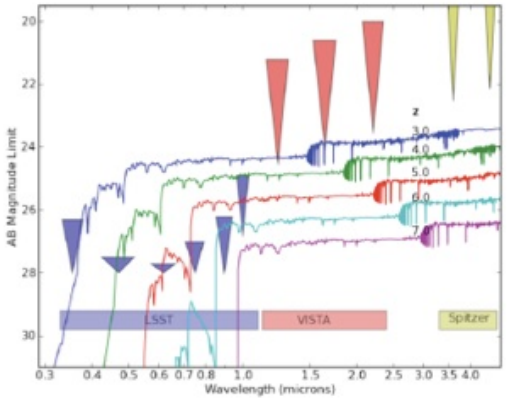
LSST – Large Synoptic Survey Telescope

8.4-m aperture telescope with 3.5 deg FOV
Opt-NIR 120 Mpix mosaic CCD camera sampling 0.2" pix^{-1}
Surveys the southern sky every 4 nights, 30 s exposures in
6 colors – u, g, r, i, z, y
Each scan reaches AB ≈ 23 ± 1 → AB ≈ 27 ± 1 (10's μJy) after 10 years

Photometric redshifts for 10^7 galaxies, reaching z ≈ 2.5, but most z < 1 --- not an interesting sample for GMT



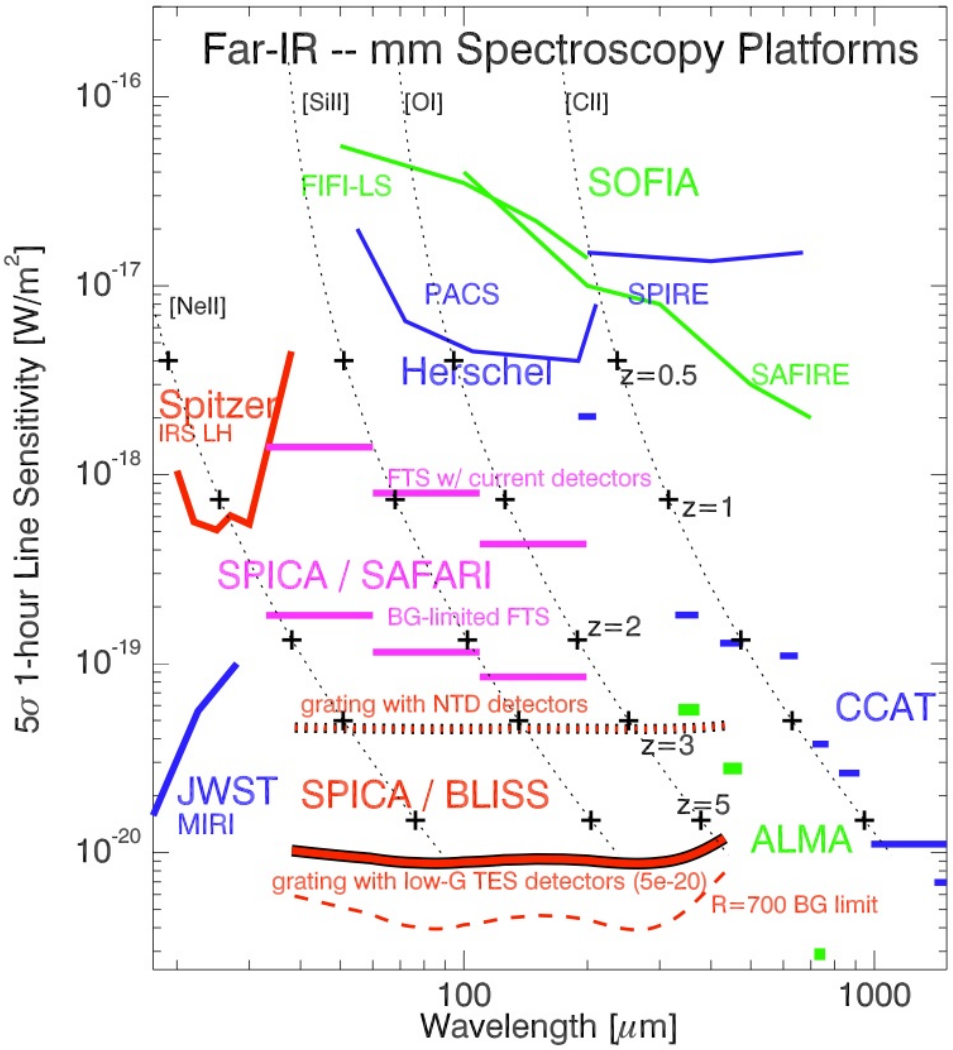




GMT can be a primary tool for following up variable sources, LSST's "prime directive" including supernova out to cosmological distances. How many will require the power of GMT?

Also, for galaxy evolution, LSST will make unprecedented maps of Galactic structure that GMT will follow up for evidence of the evolution of the Galaxy, Including high-dispersion spectra of faint halo stars (and streams).

Leading Far-IR – Submm – Millimeter – Radio Facilities of the 2020s



"By combining the results of deep optical and ultraviolet observations with measurements made in the far-infrared and submillimeter wavebands using the COBE satellite, the amount of energy that has been released by galaxies over the history of the Universe has been assessed"

ALMA is essential because all other 100-micron observations are confusion limited.

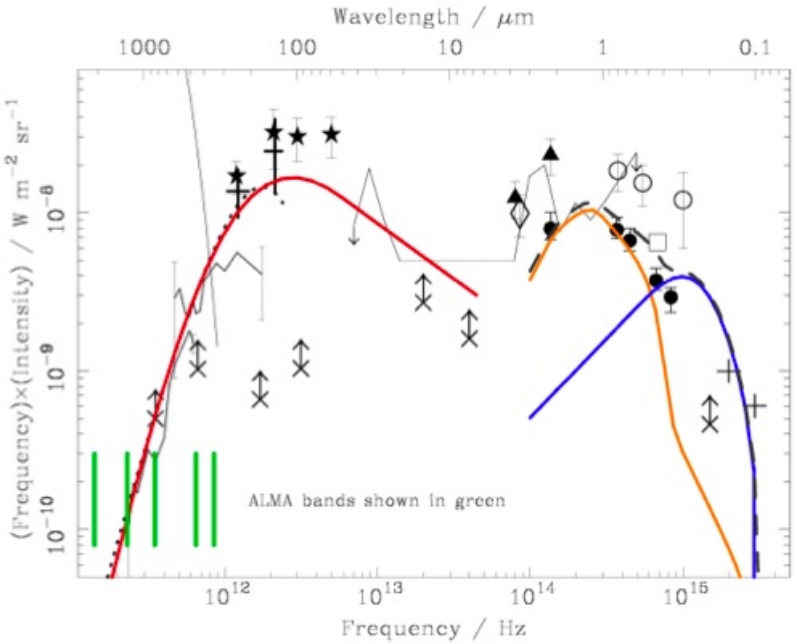


Figure 7: A wide range of measurements of the background radiation from galaxies. The region of the spectrum that will be probed by ALMA is highlighted. The amount of energy emitted from galaxies over the Universe's history in the far-infrared (red line) and optical/ultraviolet (blue line) wavebands are comparable, and so observations of submillimeter and redshifted far-infrared radiation from galaxies using ALMA are important if we are to fully understand the process of galaxy evolution.

SPICA – Space Infrared Telescope for Cosmology & Astrophysics

-- a joint JAXA-ESA mission with proposed US collaboration (BLISS spectrograph)

A 3.5-m telescope cooled to 5K for far-IR to submm photometry and spectroscopy
"…complete far-IR spectra thousands of dust-obscured galaxies out to z = 6"
"…the history of star formation, black hole growth, and organic element production"

SPICA probes: star formation through fine-structure lines in HII regions, Ne^{+} Ne^{++} O^{++} N^{+} N^{++} S^{++}
extremely high-ionization regions (AGN, starbursts), Ne^{4+} and O^{3+}
HI in photo-dissociated gas between HII regions and molecular clouds, Si^{+} C^{+} O^{0}
Dust through the PAH lines 6.2, 7.7, 8.6, 11.3, 12.7, 17µm

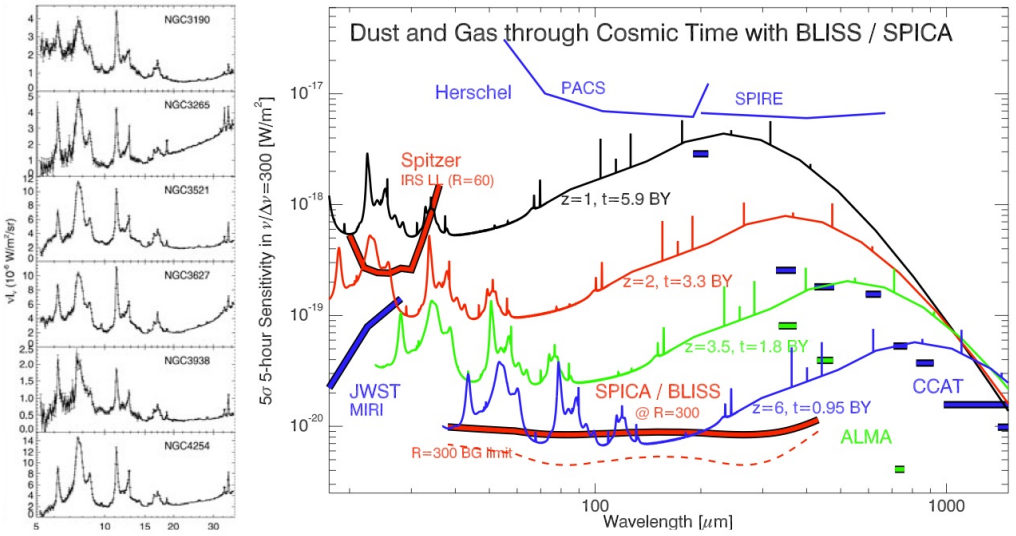


Figure 3: LEFT: Spitzer SINGS mid-IR spectra of nearby galaxies showing the powerful emission features from polycylic aromatic hydrocarbons (PAHs) [13]. RIGHT: the BLISS / SPICA sensitivity and redshifted galaxy spectra using the local-universe template and assuming $L = 10^{12}$ $L_{\odot}$. The mid-IR PAH features and the bright fine-structure lines are accessible for galaxies as early as 1 GY after the Big Bang.

…but, spatial resolution is only PFS ≈ 10 arcsec

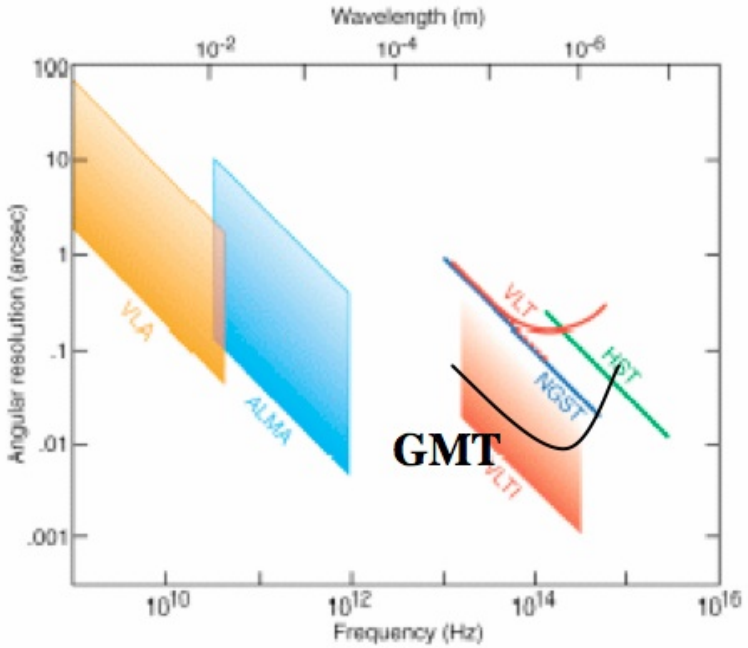
ALMA -- Atacama Large Millimeter Array

An array of 50 x 12-m antennae, plus
4 x 12-m and 12 x 7-m "compact array")
Sensitive to all atmospheric windows
320μm (950Ghz) to 3.6mm (84Ghz)
Antennae spacings from 150-m to 14 km

→ Resolution tens of milliarcseconds over FOV = 9" (690Ghz) to 25" (115Ghz)
--- a mapper, but not a surveyor!

Typical "3-day" survey with ALMA:
tile 4' x 4' at 300 Ghz (λ =1.0 mm) (140 pointings)

→ Would reach 0.1mJy and detect about
100-300 dusty galaxies (2 < z < 4)
Adding this to an 8-day 100 Ghz (3mm) survey,
flux ratios would give "photometric redshifts"
and expect to detect CO lines in all sources.



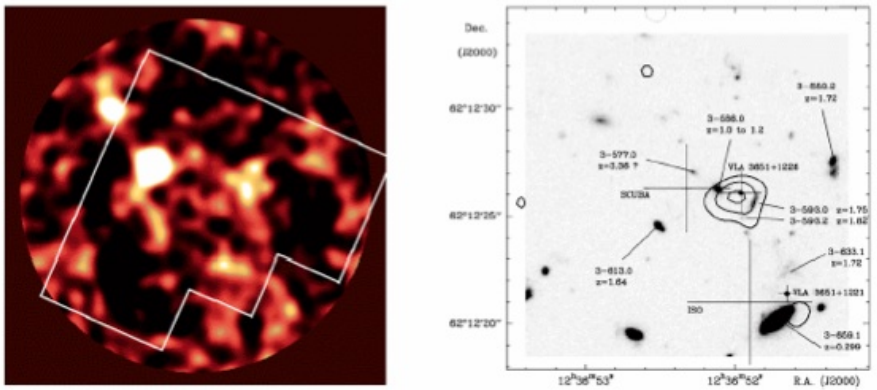


Figure 5. The HDF as imaged with SCUBA and the Hubble Space Telescope. ALMA will have greater sensitivity than SCUBA and higher angular resolution that HST, allowing it to detected lower luminosity objects at high redshift. The GMT will have the sensitivity needed for redshift determinations and detailed structural and dynamical studies on angular scales of 10-20mas.

ALMA is sensitive to galaxies with vigorous star formation -- a large fraction of the z>3 population. GMT will have spatial resolution similar to ALMA. Deep K-band images showing stellar continuum combined with ALMA observations of sites of star formation.

Modest-area surveys with ALMA (arcminutes) are well matched to GMACS multislit observations (spatially integrated light, R~26 in several hours), and objects targeted with deep ALMA maps through GMTIFS + AO (J,H,K point sources ~ 25?)

The complementarity of observations made using optical and submillimeter-wave radiation. The Antennae are a well known pair of interacting low-redshift galaxies [Wilson et al. 2000, Mirabel et al. 1998]. Only by comparing their appearance in CO emission (contours) and the *Hubble Space Telescope* image can the starlight absorbed by dust and reradiated at long wavelengths be accurately accounted for.

Figure 4: Optical and submillimeter views of a star forming galaxy

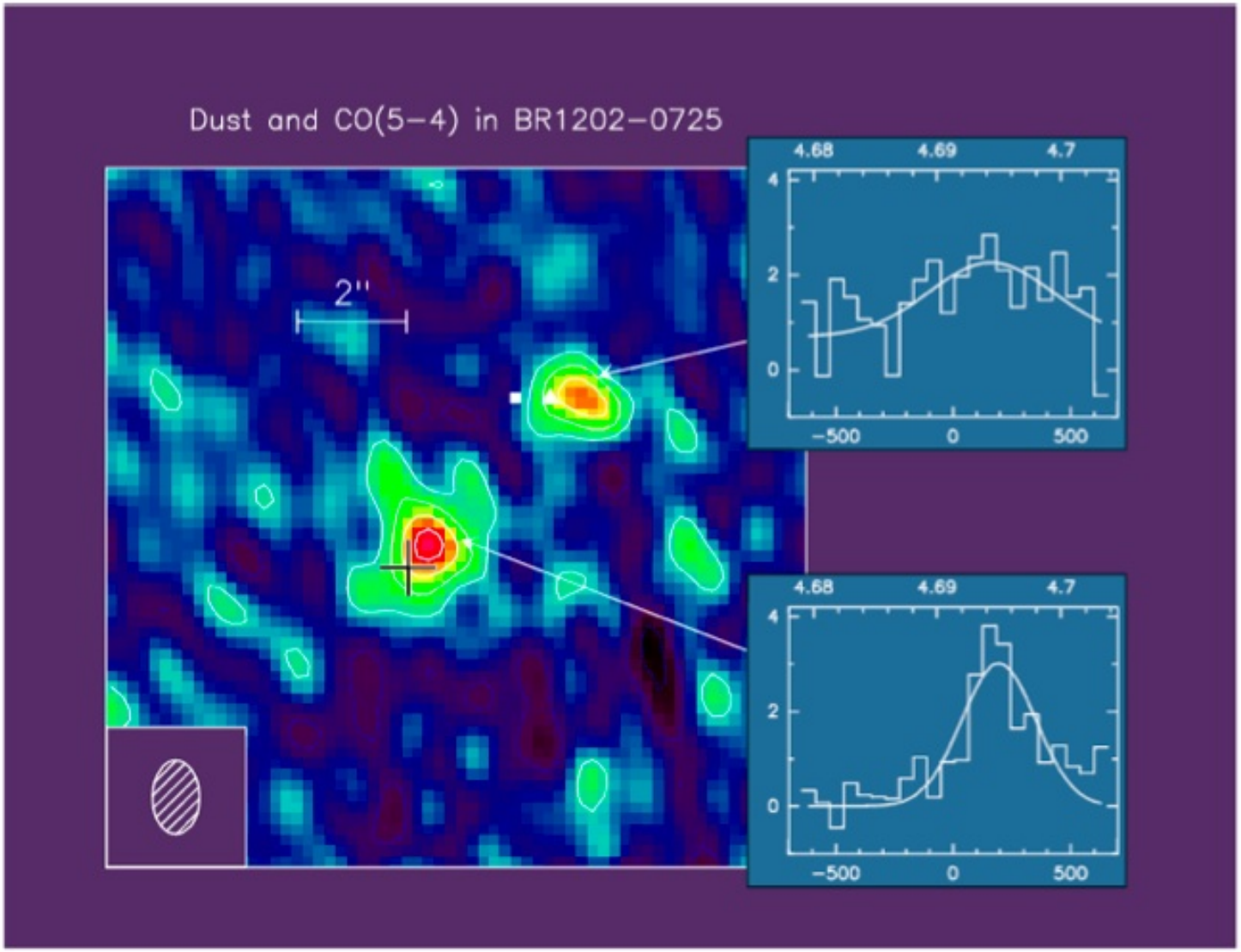
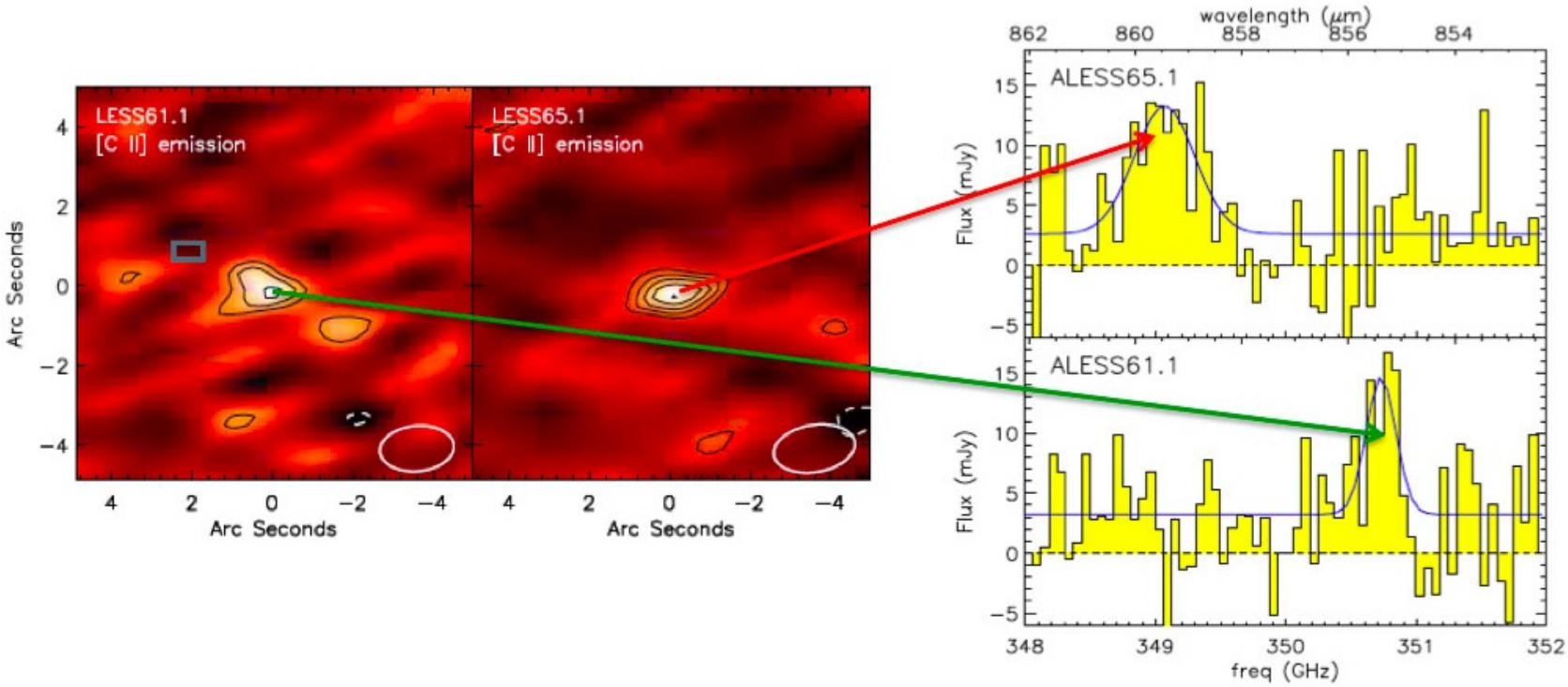


Figure 3: The quasar BR1202-07 at $z = 4.69$, mapped in the dust continuum at 1.3 mm with the IRAM interferometer. The insets show the CO(5-4) spectra of each component [Omont et al. 1996]



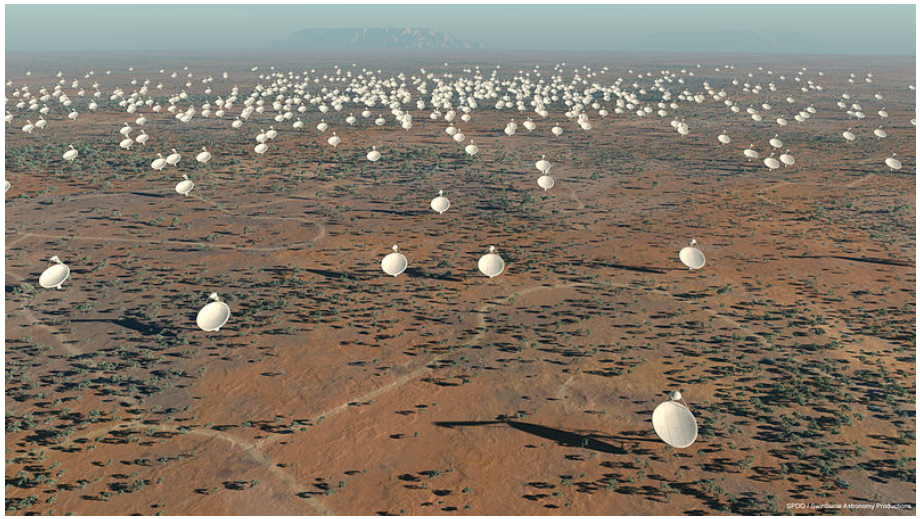
Swinbank et al (2013): **ALMA 870μm (345 GHz) observations of 2 submillimeter galaxies (SMGs) drawn from an ALMA study of the 126 SMGs in the LABOCA Extended Chandra Deep Field-South Survey. These ALMA data identify the counterparts to these previously unidentified submm sources and serendipitously detect bright emission lines that are most likely [CII] 158 μm emission, yielding redshifts z = 4.42 and 4.44. The volume probed by this ALMA survey demonstrates that the bright end of the [CII] luminosity function evolves strongly between z = 0 and ~ 4.4, reflecting the increased interstellar medium cooling in galaxies as a result of their higher star formation rates. Even with short integrations, ALMA is able to detect the dominant fine-structure cooling lines from high-z ULIRGs, measure their energetics, spatially resolve key properties, and trace their evolution with redshift.**

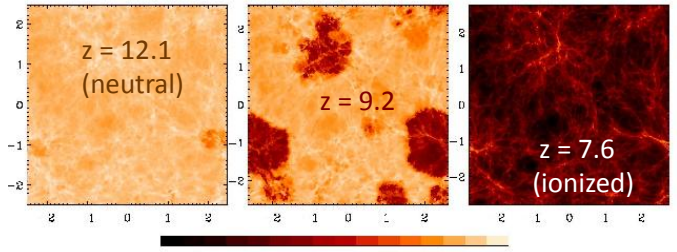
SKA -- Square Kilometer Array

An Australian-South African (+ others) collaboration to build a distributed "million square meter" radio telescope operating in 70 Mhz (4.26 m ➔ z = 20 for HI 21cm) to 10 Ghz (3 cm)

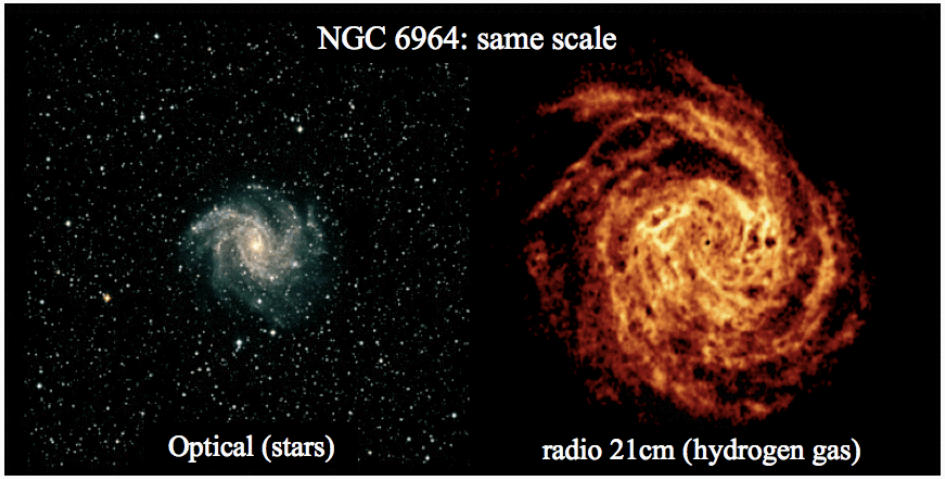
About 3000 15-m antennae with spacings from 100s of meters to 3000 km (VLBI)

FOV 1 sq deg with 0.1" resolution @1.4 Ghz

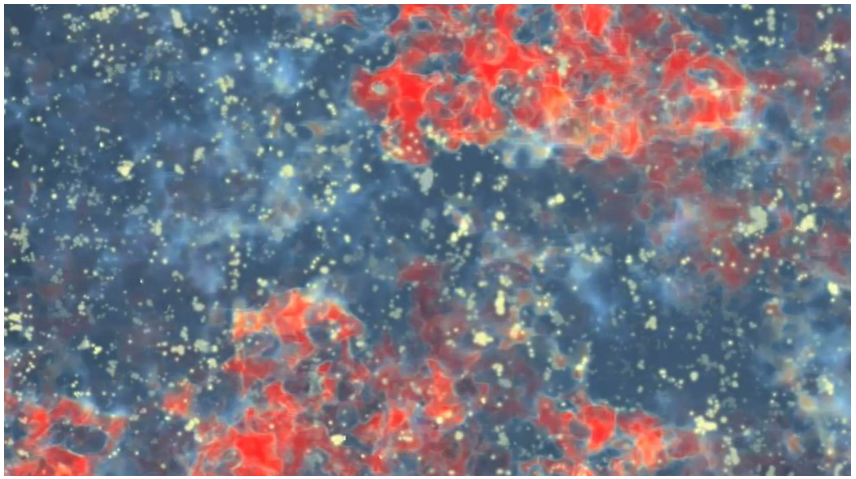




Observe HI gas in galaxies at cosmological distances



Map HI gas in the epoch of reionization



Missing Pieces – Will they be there before 2030?

1) "EXIST" – Gamma Ray bursts in Reionization epoch a great source for GMT G-CLEF spectroscopy

2) "IXO" – A large aperture X-ray mission to probe hotter circumgalactic/intergalactic gas (spreading heavy elements through the IGM)

3) "ATLAST" – A large-aperture UV-optical telescope to probe the warm circumgalactic medium for studies of outflows and inflows in the immediate IGM of a galaxy

4) **CCAT** – Compared to SPICA, higher sensitivity, much better spatial resolution mid-to-far IR for studies of star formation through dust and gas – Highest rank "mid-scale" facility in NWNH. Will the NSF be able to ramp up the mid-scale program sufficiently?

Conclusion: There really is a lot to do in studying galaxy evolution with GMT!