Studying Galaxy Evolution with GMT plus Other Powerful New Facilities

Alan Dressler
Carnegie Observatories
First Annual GMT Community Science Meeting
Chicago, June 10-212, 2013
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

$z = 1.8$
Universe is 3.7 Gyr old

$z = 2.5$
Universe is 2.7 Gyr old

“modern universe emerges”
James Webb Space Telescope

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

NIRCam
Wavelength range $0.6 \mu m < \lambda < 5.0 \mu m$
FOV = 2.2’ x 4.4’ simultaneously at 2 wavelengths (0.6-2.2μm, 2.3-5.0μm)
Sampling 0.0317” and 0.0648”
$10,000 \text{ s} @ 10\sigma$ point source detection $\rightarrow$ AB = 29 @2μm, AB = 28 @ 4.4μm

NIRSpec
Wavelength range $0.6 \mu m < \lambda < 5.0 \mu m$
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 $\rightarrow$ AB = 26.7 (2μm, R=100), AB = 25.1 (4.4 μm, R=100)
“ “ “ $\rightarrow$ AB = 25.4 (2μm, R=1000), AB = 24.3 (4.4 μm, R=1000)
“ “ “ $\rightarrow$ 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 $5.8 < \lambda < 28.0 \mu m$
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
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 $0.6\mu m < \lambda < 2.0\mu m$
16 4K x 4K H4RG-10 detectors $\rightarrow 0.28$ sq deg
PSF = 0.11” (EE50) at 1.0$\mu$m – pixels are 0.11” sq
Slitless grism spectroscopy $R \approx 600$

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 $\rightarrow$ Y, J, H $\approx 26.8$, F184 $\approx 26.2$
line flux $5 \times 10^{-17}$ at 1.65$\mu$m (H$\alpha$ @ $z=1.5$)

GO observations (deeper fields)
reach AB $\approx 27.1$ in 2 hours per field (5 bands)
AB $\approx 29.0$ in 3 days """
Grism $R \approx 600$ S/N $\approx 10$ at AB $\approx 25.0$ in $\approx 1$ day
$z=2$: 4000A bk @ 1.2$\mu$m; H$\alpha$ @ 1.97$\mu$m
$\Rightarrow 5000$ L*+1 galaxies per field

Yield of $\approx 300$ L* galaxies at $z \approx 3$ (4000A bk)
probable inclusion of K-band pushes $z$ (H$\alpha$) to 3
Using $z > 6$ QSOs to probe the epoch of reionization.

This requires a near-IR spectrograph – GMTIFS – but IFU and AO not required. Need a J-band channel on GMACS!
Estimates from Dan Stern (JPL) on the QSO yield from the High Latitude Survey of WFIRST-2.4

\[ z = 6-7 \quad --- \quad 3500 \]
\[ z = 7-8 \quad --- \quad 900 \]
\[ z = 8-9 \quad --- \quad 240 \]
\[ z = 9-10 \quad --- \quad 66 \]
\[ z > 10 \quad --- \quad 10 \]
Using $z > 6$ Lyman-break and Ly$\alpha$ emitters to probe the epoch of reionization

Are there enough Lyman continuum photons to account for reionization? Need to measure LF slope down to $10^{41}$
Dressler et al. (McCarthy)  

≈100 candidates for faint LAEs at z = 5.75

Henry et al. (McCarthy)  

Limit of narrow band Subaru searches
Use Case: Lyα Luminosity Function at $z \sim 6$

- Much structure on degree scales

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

How do we extend this to $z > 8$?

- 500 km/s FWHM
- $W_\lambda = 100\,\AA$
- 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

Astronomical Society of Australia Meeting - Perth July 08

...much structure on degree scales

But, WFIRST-2.4 will provide $6 < z < 9$ "dropout" maps
Visible Halos at $z \sim 9$

- Fully Ionized
- Ly$\alpha$ 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 Ly$\alpha$ photons

- 25% Neutral
- 75% Neutral

250 Mpc = 15 degrees!
GMACS needs a J-band channel!

1.25μm $\Rightarrow$ $z = 9.3$

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

Astronomical Society of Australia Meeting - Perth July 08
Gladders & collaborators: study shows power for studying galaxy assembly. Postman & collaborators: CLASH clusters probe the reionization epoch.
Slice of Millennium simulation 500 x 500 x 30 Mpc
Red dots represent HLS survey clusters $M > 5 \times 10^{13} M_\odot$
WFIRST finds 40,000 such clusters

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 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 $5 \times 10^{13} M_{\text{sun}}$ and $10^{14} M_{\text{sun}}$, 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 $(9.2 \times 9.2)$ deg$^2$ with redshift depth $\Delta z = 0.022$, so it represents a minuscule fraction ($\sim 10^{-3}$) 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 abundances and kinematics, will be one of GMT’s most important contributions to the study of galaxy evolution.

GMACS + GMTIFS can observe $1 < z < 3$ range fully OII to Ha (with gaps)
High Latitude Survey will produce $10^7$ Hα redshifts $z = 1-2$

$2 \times 10^6$ [O III] redshift $z = 2-3$

WFIRST-2.4 HLS grism survey yield

<table>
<thead>
<tr>
<th>$z$</th>
<th>$n$ (Mpc$^{-3}$)</th>
<th>$dN/dz/dA$ (deg$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10</td>
<td>1.17E-03</td>
<td>10623</td>
</tr>
<tr>
<td>1.15</td>
<td>1.25E-03</td>
<td>11776</td>
</tr>
<tr>
<td>1.20</td>
<td>1.32E-03</td>
<td>12814</td>
</tr>
<tr>
<td>1.25</td>
<td>1.38E-03</td>
<td>13877</td>
</tr>
<tr>
<td>1.30</td>
<td>1.43E-03</td>
<td>14719</td>
</tr>
<tr>
<td>1.35</td>
<td>1.47E-03</td>
<td>15527</td>
</tr>
<tr>
<td>1.40</td>
<td>1.50E-03</td>
<td>16244</td>
</tr>
<tr>
<td>1.45</td>
<td>1.53E-03</td>
<td>16890</td>
</tr>
<tr>
<td>1.50</td>
<td>1.51E-03</td>
<td>16985</td>
</tr>
<tr>
<td>1.55</td>
<td>1.37E-03</td>
<td>15759</td>
</tr>
<tr>
<td>1.60</td>
<td>1.25E-03</td>
<td>14536</td>
</tr>
<tr>
<td>1.65</td>
<td>1.13E-03</td>
<td>13305</td>
</tr>
<tr>
<td>1.70</td>
<td>1.01E-03</td>
<td>12110</td>
</tr>
<tr>
<td>1.75</td>
<td>9.02E-04</td>
<td>10918</td>
</tr>
<tr>
<td>1.80</td>
<td>8.00E-04</td>
<td>9769</td>
</tr>
<tr>
<td>1.85</td>
<td>7.05E-04</td>
<td>8697</td>
</tr>
<tr>
<td>1.90</td>
<td>6.17E-04</td>
<td>7666</td>
</tr>
<tr>
<td>1.95</td>
<td>5.36E-04</td>
<td>6718</td>
</tr>
<tr>
<td>2.00</td>
<td>1.33E-04</td>
<td>1678</td>
</tr>
<tr>
<td>2.10</td>
<td>1.21E-04</td>
<td>1541</td>
</tr>
<tr>
<td>2.20</td>
<td>1.15E-04</td>
<td>1477</td>
</tr>
<tr>
<td>2.30</td>
<td>9.72E-05</td>
<td>1258</td>
</tr>
<tr>
<td>2.40</td>
<td>8.12E-05</td>
<td>1054</td>
</tr>
<tr>
<td>2.50</td>
<td>6.66E-05</td>
<td>866</td>
</tr>
<tr>
<td>2.60</td>
<td>5.35E-05</td>
<td>696</td>
</tr>
<tr>
<td>2.70</td>
<td>4.28E-05</td>
<td>556</td>
</tr>
<tr>
<td>2.80</td>
<td>3.27E-05</td>
<td>424</td>
</tr>
</tbody>
</table>

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 $z \geq 2$. WFIRST-2.4 will produce an enormous sample for studying galaxy assembly $1 < z < 3$. 
Unusually bright (AB=19.9) starforming galaxy at z=1.8, 2 hr with VLT XShooter

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

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

GAS & GALAXIES: “Feedback”

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, Alice E. Shapley, Alison L. Coil, Katherine A. Korner, Kevin Bundy, Benjamin J. Weiner, Kai G. Noeske, David Schiminovich

Submitted June 22, 2012; Accepted October 12, 2012

Fig. 2: Composite, near-ultraviolet spectra of star-forming galaxies at z ~ 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 855 km s^{-1} FWHM. The upper spectrum is the average of 60 spectra observed at a resolution of 202 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 unshaded Fe II transition is a weak line at 2380.49; see Martin et al. (2012b, in prep.) for a tabular list.

Fig. 3: Bluestripped V vs. SFR (M_{\odot} yr^{-1}).
One of the primary goals of the 2020s:
Spatially resolved chemical composition \((R \approx 1000)\) and
kinematics \((R \geq 5000)\) 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 \(H_0, \Omega, \rho_0, w,\) and \(\Lambda,\) 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 ~ 2 STAR-FORMING GALAXIES ¹

N. M. FORSTER SCHREIBER², R. GENZEL², N. BOUCHE², G. CRESCI², R. DAVIES², P. BUSCHKAMP², K. SHAPIRO², L. J. TACCONI², E. K. S. HICKS², S. GENEL², A. E. SHAPLEY², D. K. ERB², C. C. STEIDEL², D. LUTZ², F. EISENHAUER², S. GILLESSEN², A. STERNBERG⁵, A. RENZINI⁵, A. CIMATTI⁷, E. DADDI⁷, J. KURKⁱ², S. LILLY⁷, X. KONG⁷, M. D. LEHNERT⁷, N. NESVADBA⁶, A. VERMA⁷, H. MCCracken⁷, N. ARIMOTO¹⁰, M. MIGNOLI¹⁰, M. ONODERA¹¹,²⁰

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

Example data: reconstructed images (left) and spectra

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–IDS for which it was obtained from the [O III] λ5007 line instead). The colour-coding is such that blue to red colours correspond to 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 (Shapins 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.
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.
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.)
GMACS will have the spectral resolution ($R \approx 2000$) needed for mapping chemical abundance (OIII to $z < 1.5$). Kinematics information will require $\leq 30 \text{ km s}^{-1}$ which GMACS also has. However, the small sizes of these $1 < z < 3$ galaxies, typically $2 \text{ arcsec}$) means that an AO capability is required, i.e. GMTIFS. GLAO at $0.3''$ would make a good start, but $\leq 0.1''$ 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!
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.
<table>
<thead>
<tr>
<th>Program</th>
<th>Each pointing (sq deg)</th>
<th># Targets</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embedded star formation &lt; 1 kpc (Tau, Oph, Ser, Per, Ori)</td>
<td>1 – 30</td>
<td>~10</td>
<td>IMF: substellar to intermediate masses: calibrating models</td>
</tr>
<tr>
<td>10-100 Myr open clusters (Pleiades, NGC clusters)</td>
<td>~1</td>
<td>~10</td>
<td>Mass Function to substellar masses, evolution, dynamics, brown dwarfs</td>
</tr>
<tr>
<td>Dense embedded star formation &gt; 1 kpc (NGC 7538, W3, Gal Ctr)</td>
<td>~ 0.25 (1 field)</td>
<td>~15</td>
<td>IMF: high mass end</td>
</tr>
<tr>
<td>Globular Clusters</td>
<td>0.25</td>
<td>12</td>
<td>Calibrate IR CMD with metallicity</td>
</tr>
<tr>
<td>Stellar populations of Galactic bulge, halo, satellites</td>
<td>HLS microlensing</td>
<td>HLS microlensing</td>
<td>Substructure, tidal streams, AGB ages from HLS and microlensing data</td>
</tr>
<tr>
<td>Ultra-faint MW dwarf galaxies including S/LMC</td>
<td>0.25 – 4</td>
<td>&gt;10</td>
<td>Star formation histories, metal-poor IMF, kinematics of LSST discoveries</td>
</tr>
<tr>
<td>Map local group galaxies (M31, M33, dwarf ellipticals)</td>
<td>~2 - 20</td>
<td>~6</td>
<td>Resolve disk structure, extinction maps, cluster dissolution to field</td>
</tr>
<tr>
<td>Mapping nearby galaxy thick disks and halos beyond local group</td>
<td>~1</td>
<td>&gt; 24</td>
<td>Halo substructure, population gradients, test dark matter, kinematics</td>
</tr>
<tr>
<td>Mapping the core of Virgo cluster</td>
<td>~100</td>
<td>1</td>
<td>Morphologies, luminosity function, superstar clusters, intracluster objects</td>
</tr>
<tr>
<td>AGN host galaxies (coronagraph)</td>
<td>1E-6</td>
<td>&gt; 10</td>
<td>Stellar populations, comparison to normal galaxies</td>
</tr>
<tr>
<td>Galaxy cluster (HLS) followup</td>
<td>0.25</td>
<td>&gt; 24</td>
<td>High z lensed objects, structure growth, interactions &amp; dark matter</td>
</tr>
<tr>
<td>LSST Deep Drilling Fields</td>
<td>0.25</td>
<td>1-4</td>
<td>Galaxy Luminosity Function out to reionization epoch (z from dropouts)</td>
</tr>
<tr>
<td>QSOs as probes of cosmic dawn</td>
<td>HLS</td>
<td>HLS</td>
<td>Epoch, speed, patchiness of reionization using QSO spectra</td>
</tr>
</tbody>
</table>

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 ≈ 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: Ly$\alpha$ emission; H$\alpha$ kinematics; chemical evolution through emission-line ratios; buildup of stellar component

(4) Largest supermassive black holes: 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 \(\rightarrow\) 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第十 Ne第十第十 O第十 第十 N第十 N第十第十 S第十
extremely high-ionization regions (AGN, starbursts), Ne第四 and O第三
HI in photo-dissociated gas between HII regions and molecular clouds, Si第十 C第十 O零
Dust through the PAH lines 6.2, 7.7, 8.6, 11.3, 12.7, 17μm

...but, spatial resolution is only PFS ≈ 10 arcsec

---

Figure 3: LEFT: Spitzer SINGS mid-IR spectra of nearby galaxies showing the powerful emission features from polycyclic aromatic hydrocarbons (PAHs) [13]. RIGHT: the BLISS / SPICA sensitivity and redshifted galaxy spectra using the local-universe template and assuming L = 10^{12} L阳. The mid-IR PAH features and the bright fine-structure lines are accessible for galaxies as early as 1 GY after the Big Bang.
**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.
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 $\sim 4.4$, 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 $\Rightarrow$ $z = 20$ 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

**NGC 6964: same scale**

Optical (stars) radio 21cm (hydrogen gas)
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!