A 30m Sub/Millimeter Survey Telescope to Probe Dusty, Star-Forming Galaxies into the Epoch of Reionization

The Reionization Epoch:
New Insights and Future Prospects

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S. Golwala (Caltech) for many others
What do dusty, star-forming galaxies have to do with reionization?

Reionization is a critical observable for constraining galaxy evolution.

- Must have enough star formation to produce ionizing photons.
- Must not form stars so quickly that dust too quickly begins to absorb UV photons.

Tracing the rise of DSFGs is necessary to piece together the puzzle of how galaxies reionized the universe.

A 30-m Sub/mm Survey Telescope to Probe DSFGs into the EoR

Robertson et al 2015

Redshift $z$
What is the history of DSFGs during and right after the epoch of reionization?

DSFGs dominate SFR density at epoch of peak SFR, $z \sim 1-3$

$$L_{\ast, IR} \approx 10^{12} L_{\odot}, \text{SFR} \sim 200 M_{\odot}/yr$$

hyperlum. starbursts: $> 2000 M_{\odot}/yr, 10^{13} L_{\odot}$

How did they arise during EoR and afterward?

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**Diagram:**

- **Lookback time (Gyr):** 0 to 12
- **Redshift:** 0 to 8
- **Log ψ (M_⊙ yr⁻¹ Mpc⁻³):** -2.4 to -0.8
- **Log L [L_⊙]:** 9 to 13

- **Points:** Various surveys and models
  - Le Floc’h+05 [$\alpha=1.23, \sigma=0.72$]
  - Caputi+07 [$\alpha=1.2, \sigma=0.39$]
  - Goto+10 [$a_1=-0.8, a_2=-2.0$]
  - Magnelli+11 [$a_1=-0.6, a_2=-2.20$]
  - Gruppioni+13 [$\alpha=1.2, \sigma=0.5$]
  - Magnelli+13 [$a_1=-0.6, a_2=-2.20$]
How quickly do DSFGs arise in/after EoR?

Important test cases exist!

**HFLS-3: Extraordinary:**
- $z \sim 6.3$
- $\text{SFR}_{\text{IR}} \sim 2900 \, M_{\odot}/\text{yr}$
- $L_{\text{IR}} \sim 4.2 \times 10^{13} \, L_{\odot}$
- $T_{\text{dust}} = 56 K$
- $\text{SFR}_{\text{UV}} \times 10^3$ smaller! Incredible dust content at end of EoR

These objects crucial
- Show the outer limits of what is possible at high $z$

Need to find many more to time birth of DSFGs, constrain rise of dust at $z > 6$
- Dimmer galaxies not visible to Herschel
- SED peak shifts to longer $\lambda$ at higher $z$

Also: tracers of extreme overdensities at high $z$
How do DSFGs connect to the galaxies that produce ionizing UV photons?

Standard IRX-β relation implies less dust in rest-frame UV galaxies at z > 3.5

Known deviations from IRX-β relation at high L_{IR}: UV and IR sightlines become mismatched

Maybe they are the same galaxies, with scatter in IRX from stochastic fluctuations in dust content into EoR (Bernhard et al 2014)?

Are they just different populations?

c.f. Reddy et al 2015 also
These studies require maps of 1000s of deg$^2$ to $10^{12}$ L$_{\text{Sun}}$

Various models (empirical, sim-based) indicate expected counts at $z > 3.5$

Driven by # of objects needed for UV-IR connection and detection of hyperluminous galaxies (extreme overdensities)

Cannot do this with ALMA: at same depth, ~0.1 deg$^2$ in 1000 hrs

<table>
<thead>
<tr>
<th>science</th>
<th># req’d</th>
<th>area req’d</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity function</td>
<td>$10^3$</td>
<td>1 deg$^2$, 20 deg$^2$, 200 deg$^2$</td>
</tr>
<tr>
<td>UV-IR connection</td>
<td>$10^4$</td>
<td>10 deg$^2$, 200 deg$^2$, 2000 deg$^2$</td>
</tr>
<tr>
<td>clustering</td>
<td>$5 \times 10^3$</td>
<td>5 deg$^2$, 100 deg$^2$, N/A (too sparse on sky)</td>
</tr>
<tr>
<td>clustering in M$_*$ or SFR bins</td>
<td>$5 \times 10^4$</td>
<td>50 deg$^2$, 1000 deg$^2$</td>
</tr>
<tr>
<td>clustering in (M$_*$, SFR) bins</td>
<td>$5 \times 10^5$</td>
<td>500 deg$^2$, 10$^4$ deg$^2$</td>
</tr>
<tr>
<td>hyperluminous (200x rarer)</td>
<td>50</td>
<td>10 deg$^2$, 200 deg$^2$, 2000 deg$^2$</td>
</tr>
</tbody>
</table>

$^\dagger$based on Bernhard et al 2014 model, which fits IR, UV data, predicts hyperluminous DSFGs
Chajnantor Sub/millimeter Survey Telescope

Low-cost, 30m, 850µm 1° FoV
Light, “minimal” mount

- Primary floats on single-point support at center-of-gravity
- Hexapod operates in balanced, “weightless” mode (except for wind & seismic): hexapod is repeatable
- 1 rad range-of-motion: 20,000 deg² at equator
- 1° diffraction-limited FoV at 850 µm at single forward instrument mount

Cheap materials, sophisticated design and controls

- Machined Al panels on steel truss
- Simple mechanisms: No cable wraps
- Light, exposed structure
- Active surface and offset guiding corrects wind and thermal deformations
Instrumentation Plan

First light: Simultaneous imager in 3-6 bands + 10-object MOS

- Provides the desired imaging survey; ~50,000 detectors
- Spectrometer to be built with existing technology
  - e.g., Z-Spec-style grating spectrometer
  - Only ~10,000 detectors in spectrometer

At $10^{12} \, L_{\text{Sun}}$ limit:

- $10^6$ imaging detections per year at $z > 4$
- $3000 \text{ SNR} = 5$ [CII] detections/yr

2nd generation instrument: 100-object MOS

- Requires more compact spectrometer technology
  - e.g., SuperSpec technology under development
  - few $\times 10^4$ [CII]/yr!

3rd generation: IFU with 100s to 1000s of beams

- Hundreds of thousands of [CII] detections/yr at $10^{12} \, L_{\text{Sun}}$
- Tomographic mapping down to $10^{11} \, L_{\text{Sun}}$
CSST provides required survey speed for DSFG clustering measurements into EoR

CSST maps 1000 deg$^2$/yr to $10^{12}$ L$_\odot$ 1000 hrs/yr with 1° FoV and excellent site: meets requirement for clustering measurements.

~100x higher for 30m than existing, comparable resolution telescopes.

Various models (empirical, sim-based) give consistent expectations for counts in z > 3.5 unexplored territory.

Accounts for weather, opacity
Assumes 100% survey operations

30m: 1000 deg$^2$/yr
First-Light Spectroscopic Capabilities

30m 3h  
$L_{\text{gal}} = 10^{12}$  
$L_{\text{sun}} = 5\sigma$ detection  

Bright fine structure lines are shown, with typical $L_{\text{line}}/L_{\text{IR}}$  
$R = 1000$ (300 km/s)  

$[\text{C II}]$ 158 µm ($1.5 \times 10^{-3}$)  

$[\text{O III}]$ 88 µm ($1.2 \times 10^{-3}$)  

$[\text{N II}]$ 122 µm ($3.1 \times 10^{-4}$)  

$[\text{N II}]$ 205 µm ($3.7 \times 10^{-4}$)  

$[\text{O I}]$ 145 µm ($1.1 \times 10^{-4}$)  

A 30-m Sub/mm Survey Telescope to Probe DSFGs into the EoR
Comparison to ALMA

For a single object, ALMA ~10x more sensitive than 30m

Both ALMA receivers and 30m spectrometers are photon background limited
ALMA more sensitive due to enormous collecting area (10x)

10-object MOS matches ALMA for dust-obscured source z-search

Those without O/IR counterpart and thus no photo-z
For z-search, ALMA requires 8 tunings = x8 in time; 30m requires no such tunings.
10-12 beams makes up another factor of 10 in time

10-object MOS effective in identifying objects for critical ALMA followup

1000 hrs/yr with 30m MOS (50% of available time) equivalent to 100 hrs/yr of ALMA
for sources with known z: 3000 [CII] SNR = 5 detections at $10^{12}$ L$_{\text{Sun}}$

use 30m [C II] to, e.g.:

define samples with range of SF spatial extents
find objects with anomalously low $L_{[\text{C II}]} / L_{\text{FIR}}$ (small spatial extent)
find objects with strong CH$^+$

use ALMA followup to

study [O I], [N II], [O III] to check [C II] calibration, measure effective stellar T in individual objects
study other tracers to measure morphology and kinematics of ionized and neutral gas
measure neutral outflows precisely using wings of [C II] (and CO)
Complementarity with other facilities

LSST/Euclid/VISTA/WFIRST
- Counterpart id to obtain photo-z
- $M_\star$, compl. SFR indicators (UV, Hα)
- Commensurate area

TMT, JWST
- UV/O/IR spectroscopic followup: HII region diagnostics
- Morphology, comparison of UV to FIR

JVLA, SKA
- Counterpart id
- Radio SFR indicators (synchrotron, free-free)

ALMA
- Lower-level fine-structure lines
- Morphology and kinematics
- Complementary area/depth surveys

FIR Surveyor
- Ideal for studying $z < 3.5$ population
- Use dropouts to id $z > 3.5$ sources

COSMOS $3.5 < z < 4.5$

At depth sufficient to detect comparable objects ($200$ MSun/yr), $<1$ src/30m 850 µm beam: counterpart id should be unambiguous (even for O/IR-obscured objects)
Trace the evolution of dusty, star-forming galaxies (DSFGs) from $z > 3.5$ to $z \approx 1-3$ when they dominate cosmic SFR by imaging 1000s of $\square{\degree}$ in multiple bands near 1 mm
~ten DSFGs known at $z > 3.5$; largely unexplored territory. We’ll find $>10^6$ DSFGs/yr at $z > 3.5$!

Connection between dusty galaxies at $z > 3.5$ and rest-frame UV population: same or different?
Use DSFGs to identify extreme overdensities at high $z$

w/O/IR photo-z’s, use clustering to tie DSFGs to DM halos to track time evolution along main sequence
Measure molecular gas masses for $z < 3.5$ galaxies to provide gas mass, fraction, connection to SFR

Detail the drivers and impacts of star formation using spectroscopy of 1000s of galaxies
the spatial extent of star formation
the physical conditions in the ionized and photodissociation regions around young stars
the characteristics of outflows and infall that are part of feedback loop that regulates SFR

Elucidate star formation locally by imaging nearby galaxies and large parts of our own
Map the fragmentation structure of molecular clouds and its connection to IMF
Study episodic accretion onto protostellar cores
Determine how rate and efficiency of star formation depend on $M_\odot$, environment, and galaxy morphology

Deepen our understanding of galaxy clusters and use them as cosmological tools via $SZ$
measure $P$, $T$, and $v$ in the ICM to constrain the role of mergers, accretion, and energy injection
measure the cosmological peculiar velocity field to constrain cosmo params and deviations from GR

Find the unexpected!