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

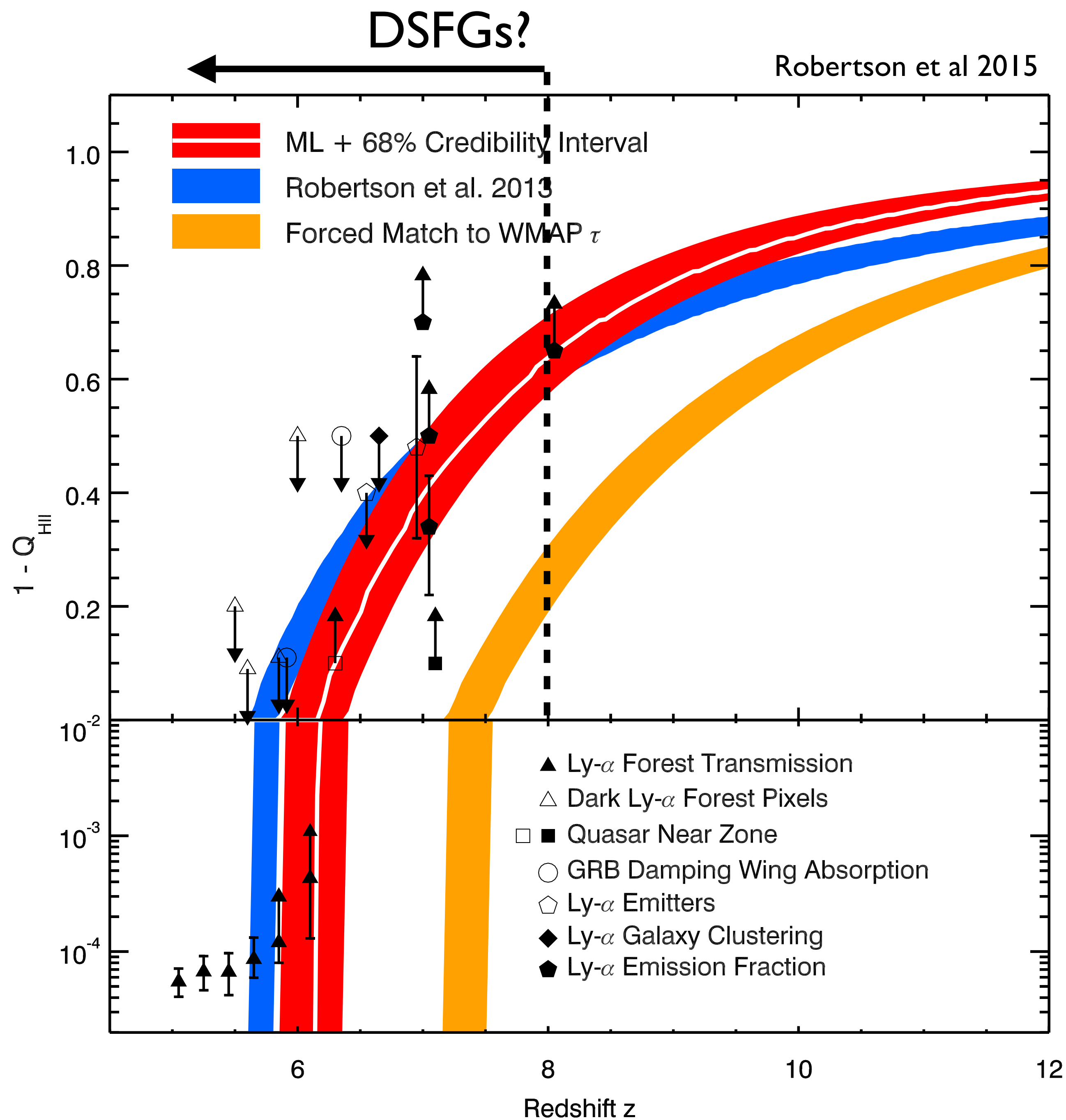
The Reionization Epoch:
New Insights and Future Prospects

2016/03/08

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

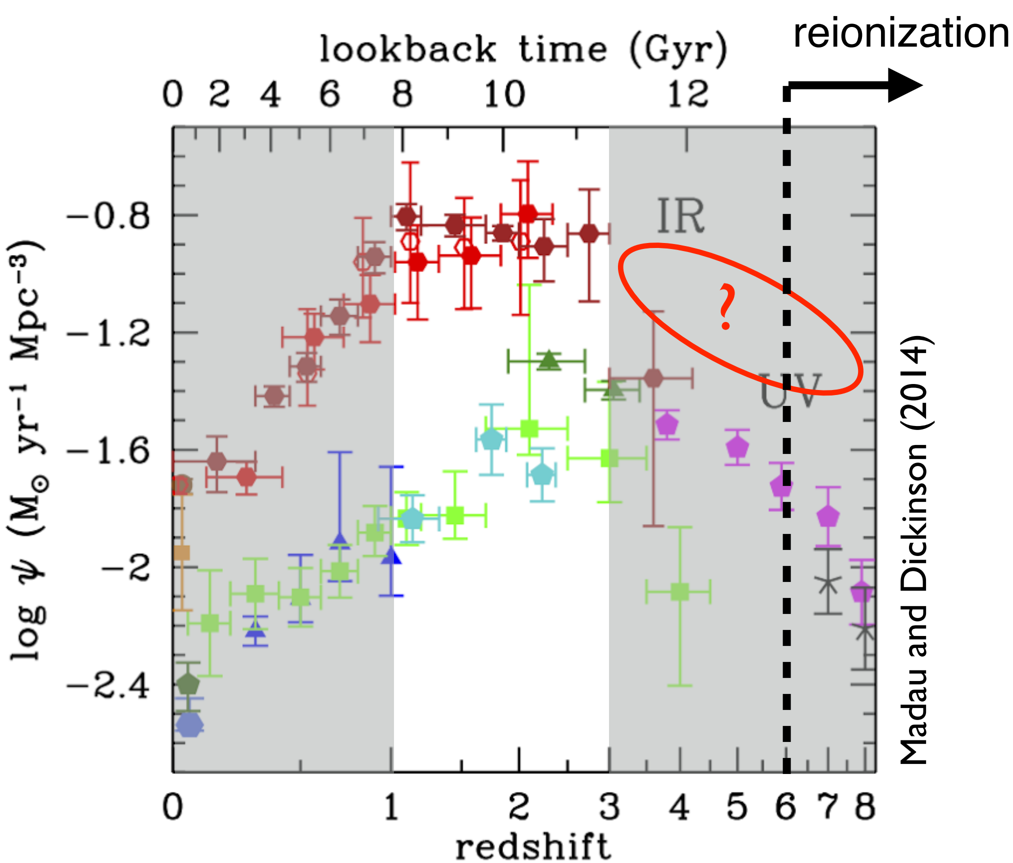


What is the history of DSFGs during and right after the epoch of reionization?

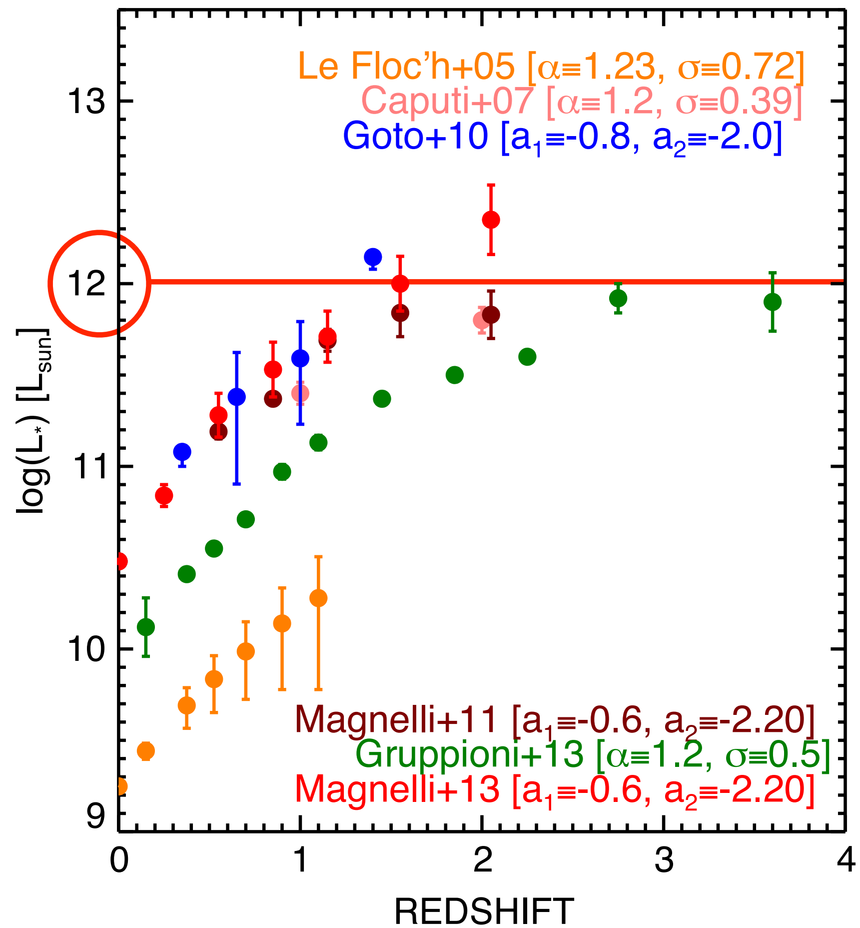
DSFGs dominate SFR density at epoch of peak SFR, z ~1-3

- $L_{*,IR} \approx 10^{12}\ L_{Sun}$, SFR ~ 200 M_{Sun}/yr
- hyperlum. starbursts: > 2000 M_{Sun}/yr, $10^{13}\ L_{Sun}$

How did they arise during EoR and afterward?



Madau and Dickinson (2014)



Casey et al 2014

How quickly do DSFGs arise in/after EoR?

Important test cases exist!

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

These objects crucial

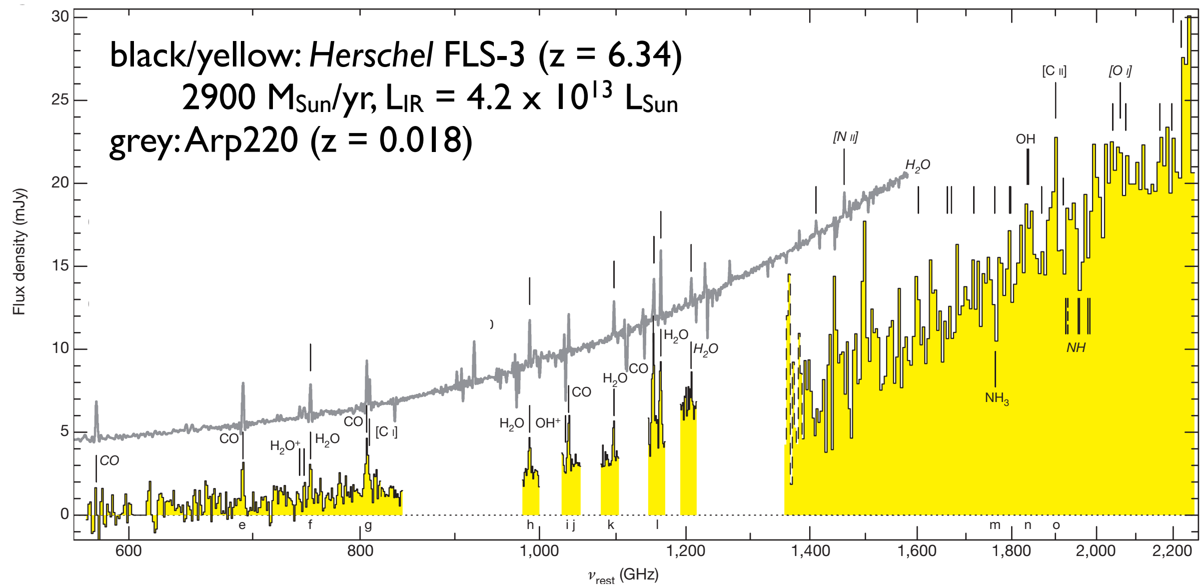
- Show the outer limits of what is possible at high z

Need to find many more to time birth of DSFGs, constrain rise of dust at z > 6

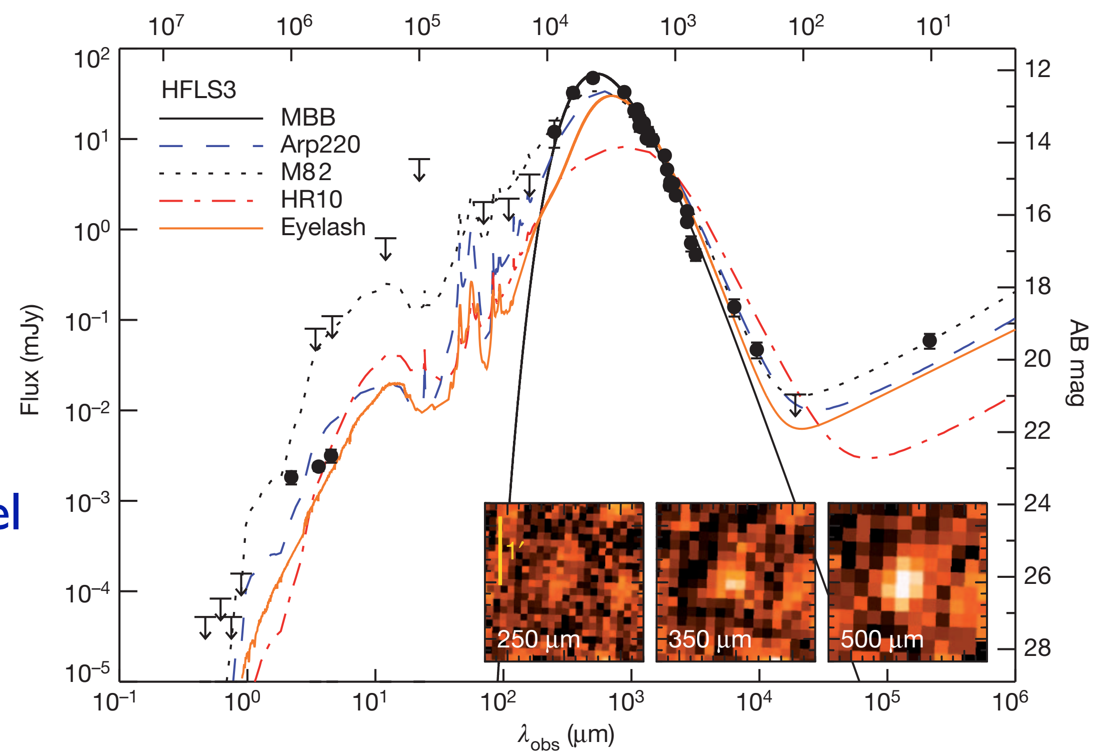
- Dimmer galaxies not visible to Herschel
- SED peak shifts to longer λ at higher z

Also: tracers of extreme over-densities at high z

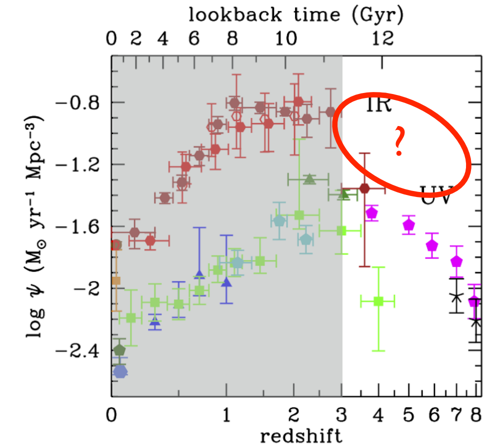
Riechers et al 2013



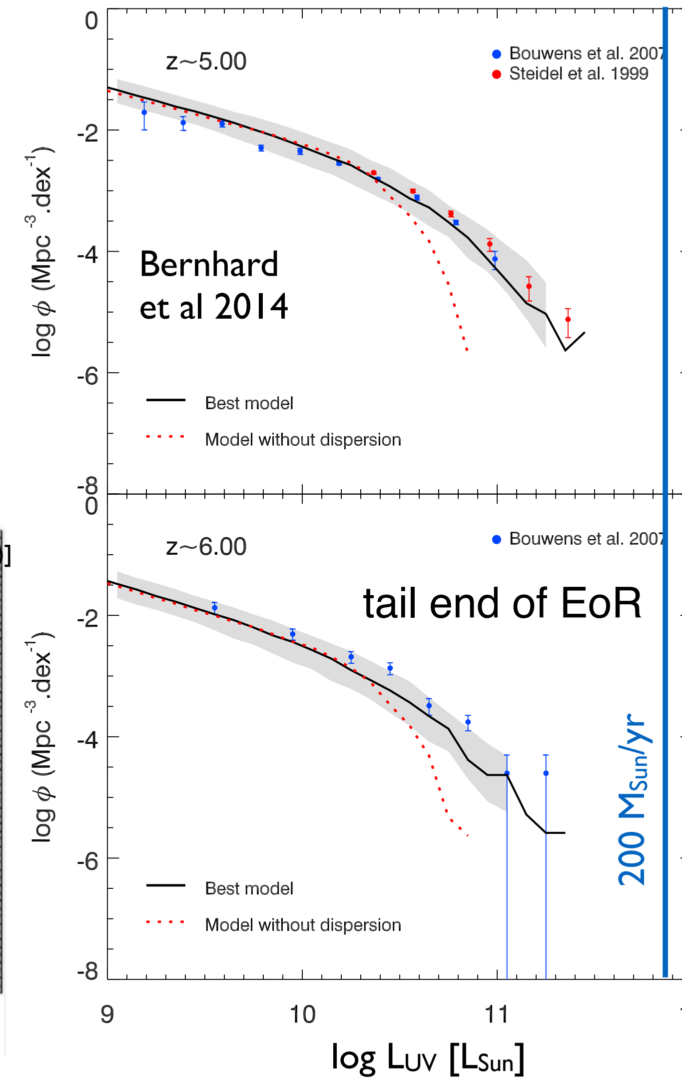
Riechers et al 2013



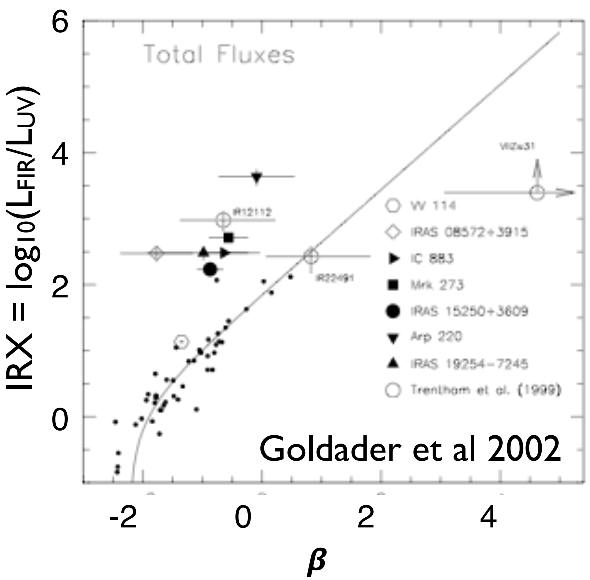
How do DSFGs connect to the galaxies that produce ionizing UV photons?

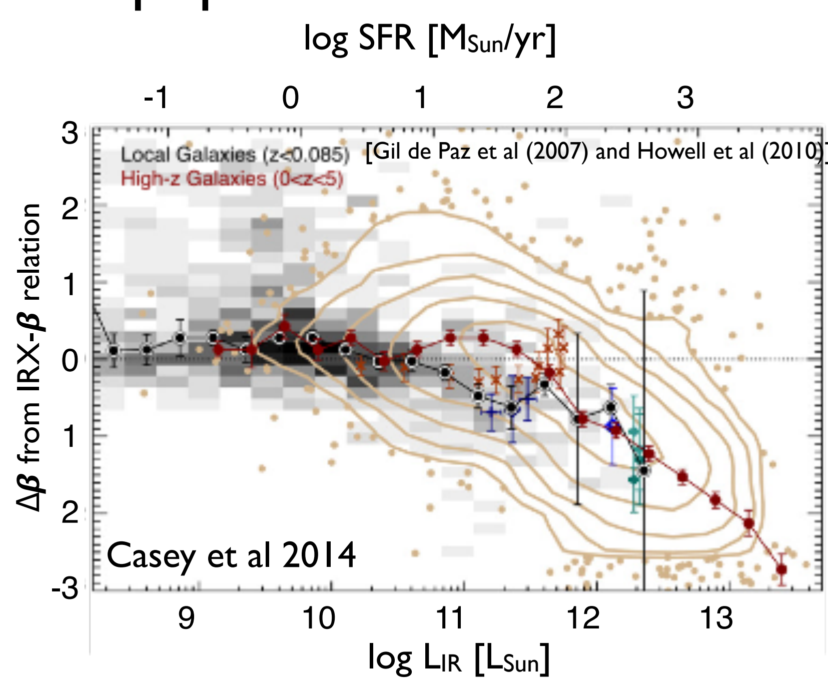


- Standard IRX-β relation implies less dust in rest-frame UV galaxies at z > 3.5
- Known deviations from IRX-β relation at high L_{IR}: UV and IR sightlines become mismatched
- Maybe they are the same galaxies, with scatter in IRX from stochastic fluctuations in dust content into EoR (Bernhard et al 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_{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

		$z \sim 4$	$z \sim 6$	$z \sim 7$
sky density† > 10^{12} L_{Sun}		1000/deg^2	50/deg^2	5/deg^2
science	**# req'd**	**area req'd**		
luminosity function	10^3	1 deg^2	20 deg^2	200 deg^2
UV-IR connection	10^4	10 deg^2	200 deg^2	2000 deg^2
clustering	5×10^3	5 deg^2	100 deg^2	N/A (too sparse on sky)
clustering in M_* or SFR bins	5×10^4	50 deg^2	1000 deg^2	
clustering in (M_*, SFR) bins	5×10^5	500 deg^2	10^4 deg^2	
hyperluminous (200x rarer)	50	10 deg^2	200 deg^2	2000 deg^2

†based on Bernhard et al 2014 model, which fits IR, UV data, predicts hyperluminous DSFGs

Chajnantor Sub/millimeter Survey Telescope

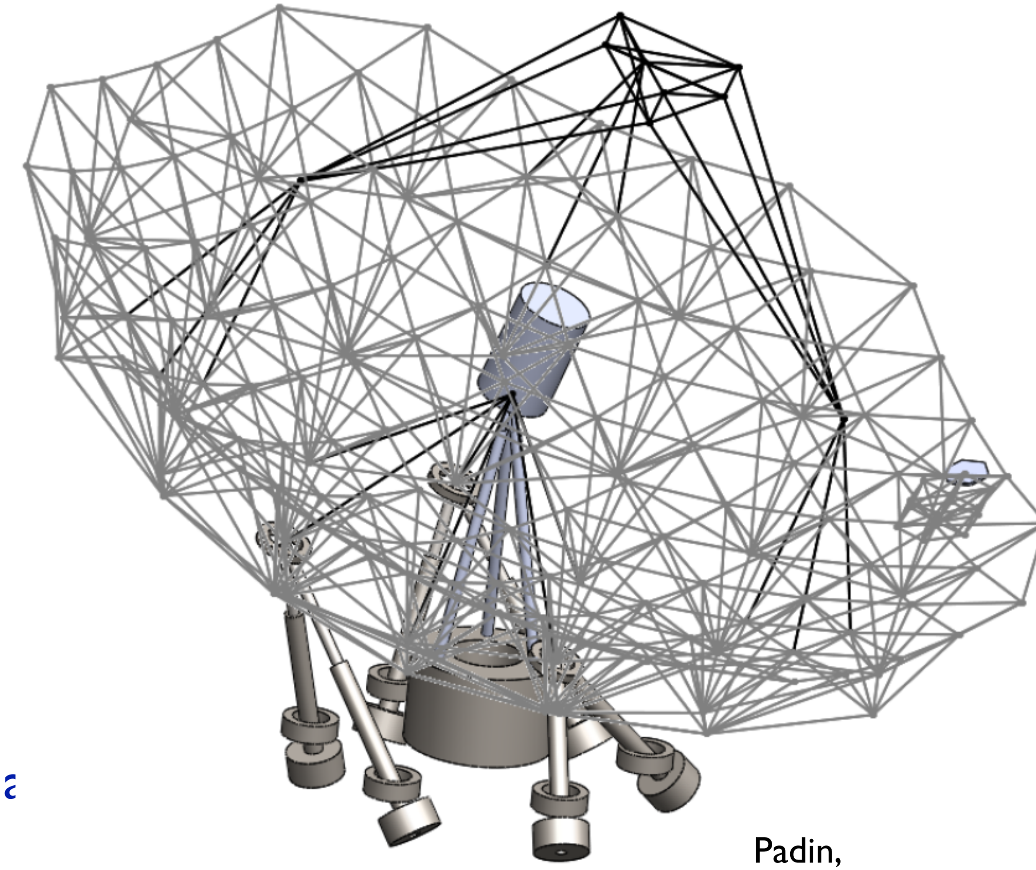
Low-cost, 30m, 850μm 1° FoV

Light, "minimal" mount

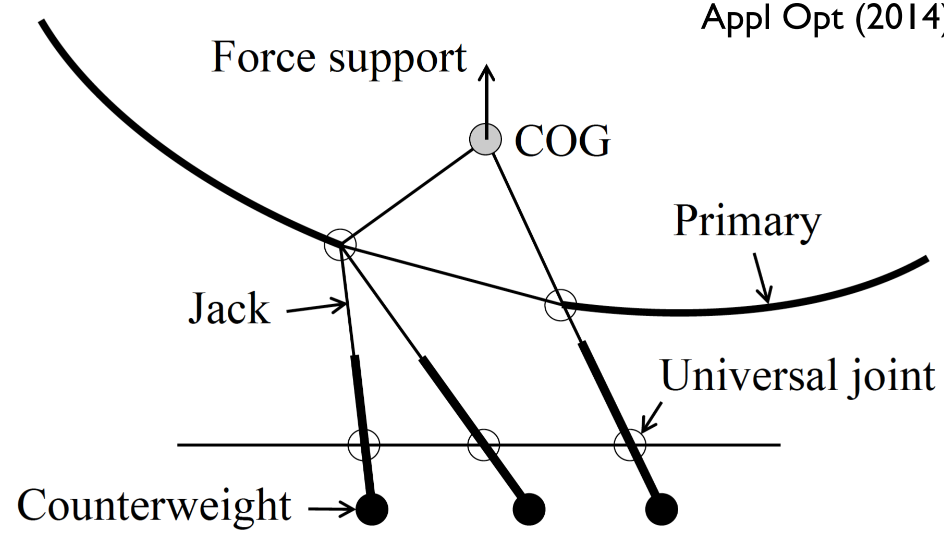
- Primary floats on single-point support at center-of-gravity
- Hexapod operates in balanced, "weightless" mode (except for wind & seismic): hexapod is repeatable
- 1 rad range-of-motion: 20,000 deg^2 at equa
- 1° diffraction-limited FoV at 850 μm at single forward instrument mount

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



Padin, Appl Opt (2014)



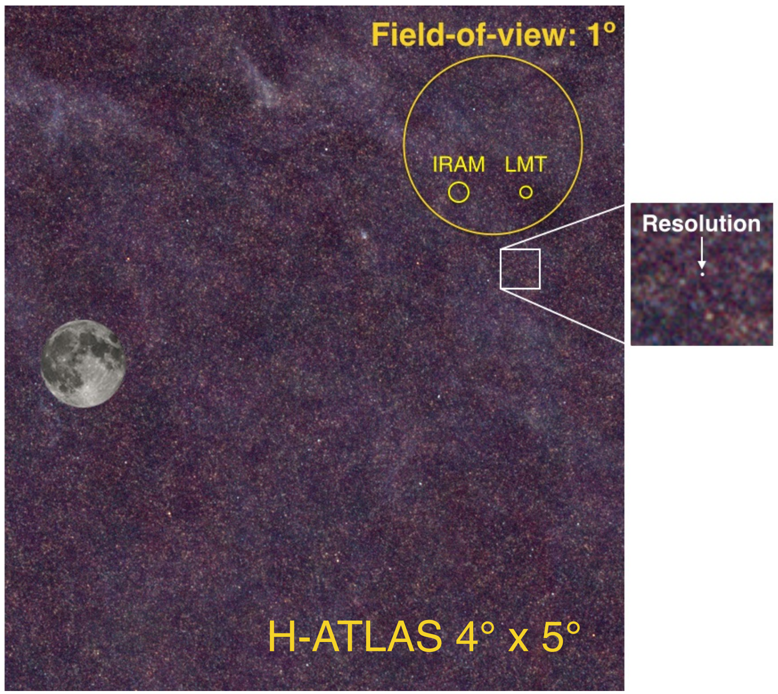
Instrumentation Plan

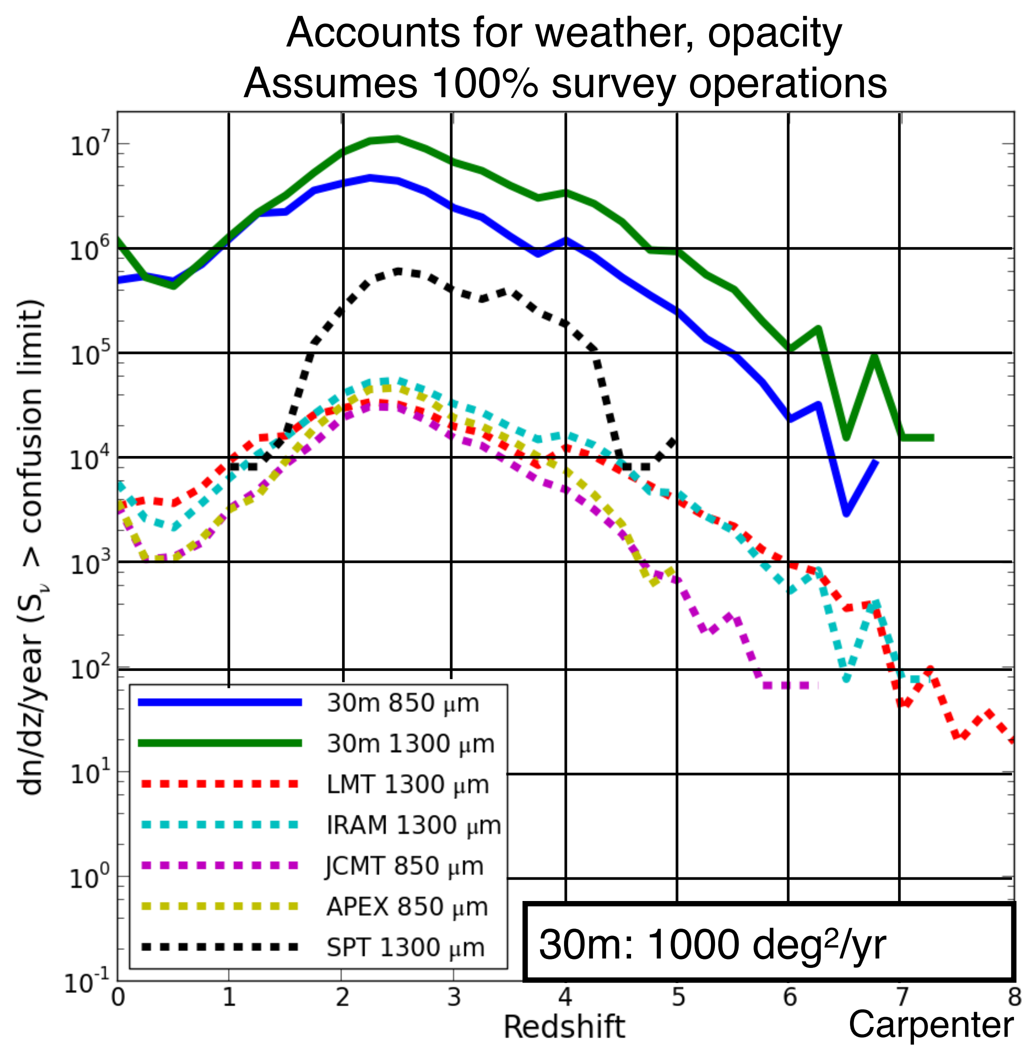
- First light: Simultaneous imager in 3-6 bands + 10-object MOS
  - Provides the desired imaging survey; ~50,000 detectors
  - Spectrometer to be built with existing technology
    - e.g., Z-Spec-style grating spectrometer
    - Only ~10,000 detectors in spectrometer
  - At 10^{12} L_{Sun} limit:
    - 10^6 imaging detections per year at z > 4
    - 3000 SNR = 5 [CII] detections/yr
- 2nd generation instrument: 100-object MOS
  - Requires more compact spectrometer technology
    - e.g, SuperSpec technology under development
  - few x 104 [CII]/yr!
- 3rd generation: IFU with 100s to 1000s of beams
  - hundreds of thousands of [CII] detections/yr at 10^{12} L_{Sun}
  - tomographic mapping down to 10^{11} L_{Sun}

CSST provides required survey speed for DSFG clustering measurements into EoR

CSST maps 1000 deg²/yr to 10^{12} L$_\odot$ 1000 hrs/yr with 1° FoV and excellent site: meets requirement for clustering measurements.

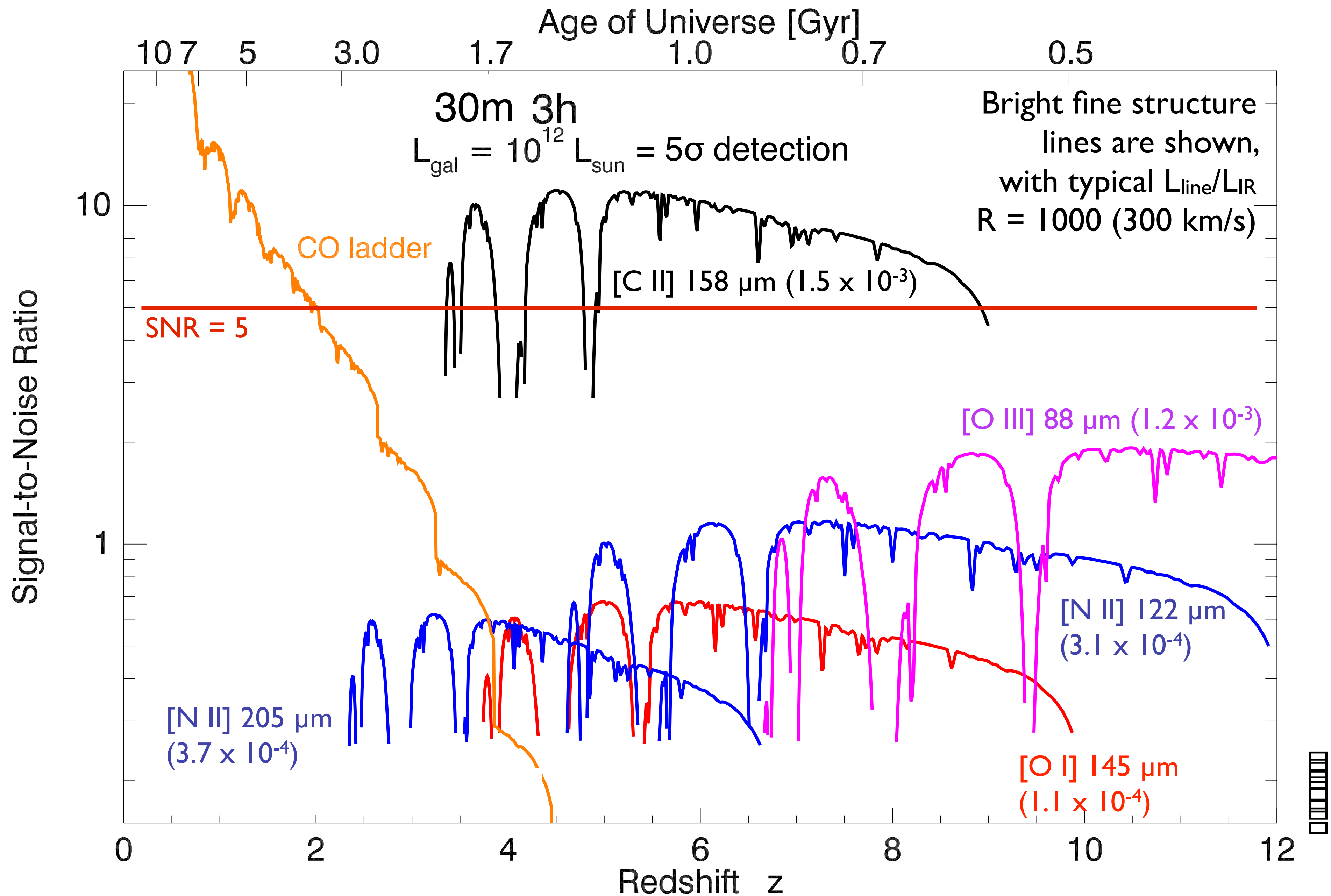
~100x higher for 30m than existing, comparable resolution telescopes





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

First-Light Spectroscopic Capabilities



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_{Sun}
  - use 30m [C II] to, e.g.:
    - define samples with range of SF spatial extents
    - find objects with anomalously low $L_{[C\ II]}/L_{FIR}$ (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_*, 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

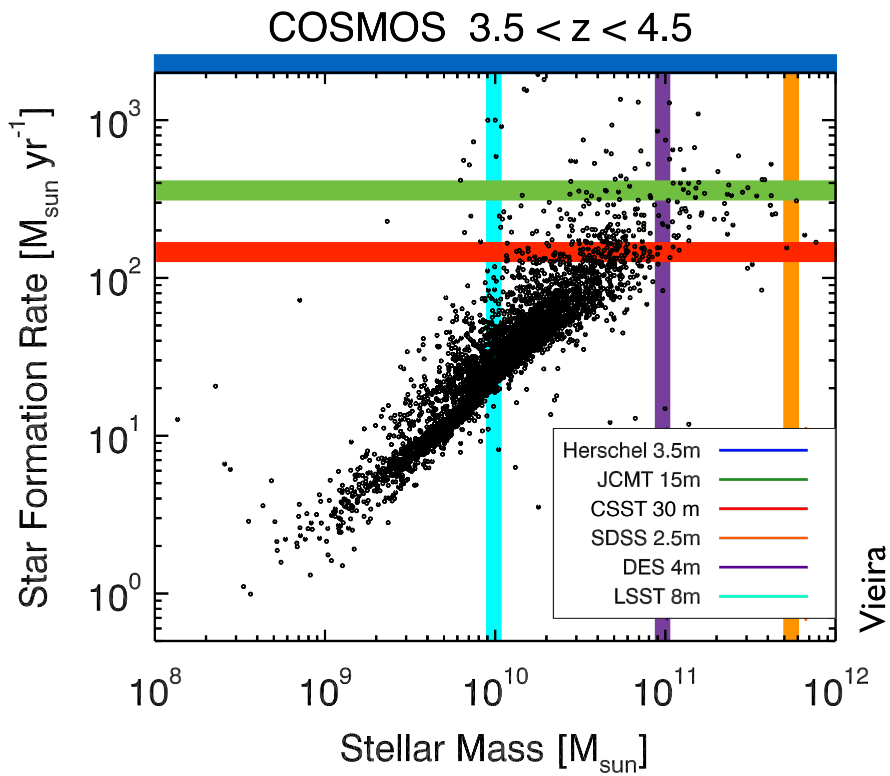
- Counterpart id
- Radio SFR indicators (synchrotron, free-free)

ALMA

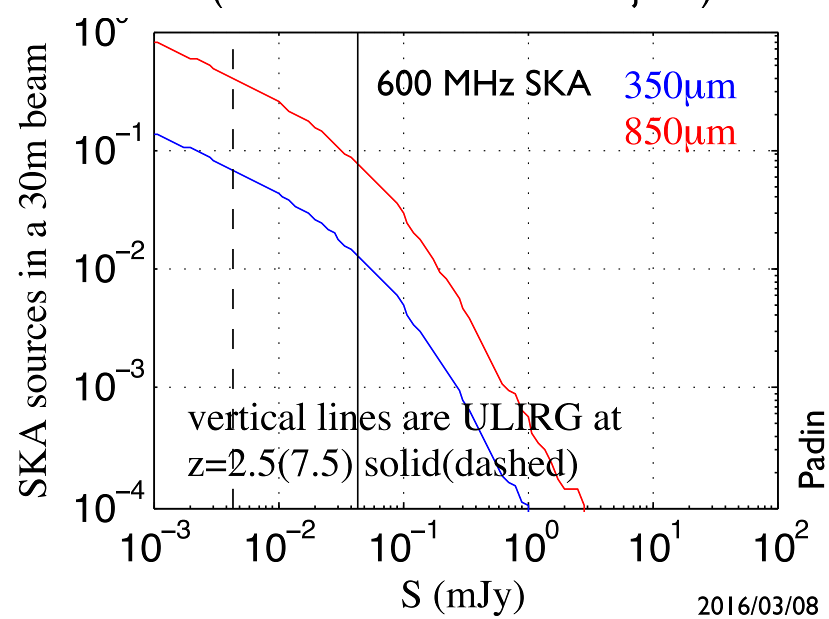
- Lower-level fine-structure lines
- Morphology and kinematics
- Complementary area/depth surveys

FIR Surveyor

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



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)



Science Capabilities of CSST

- 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 □° 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_*, 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!*