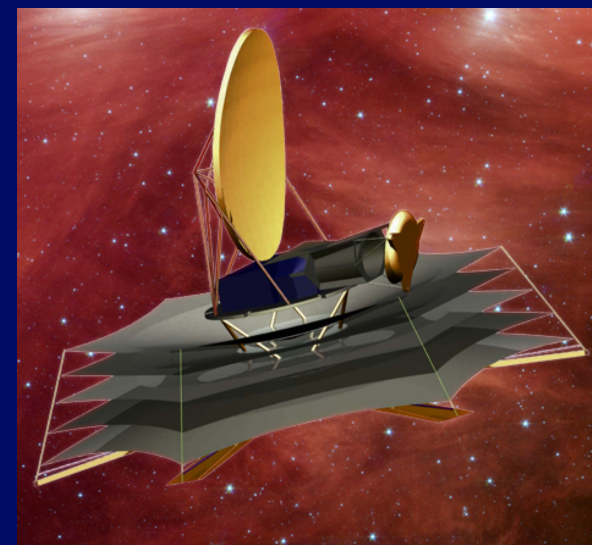
Some Cosmology Possibilities for Next-Generation Far-Infrared



Asantha Cooray

UCIrvine
University of California, Irvine

Quick summary of some key Herschel (cosmology/LSS results)

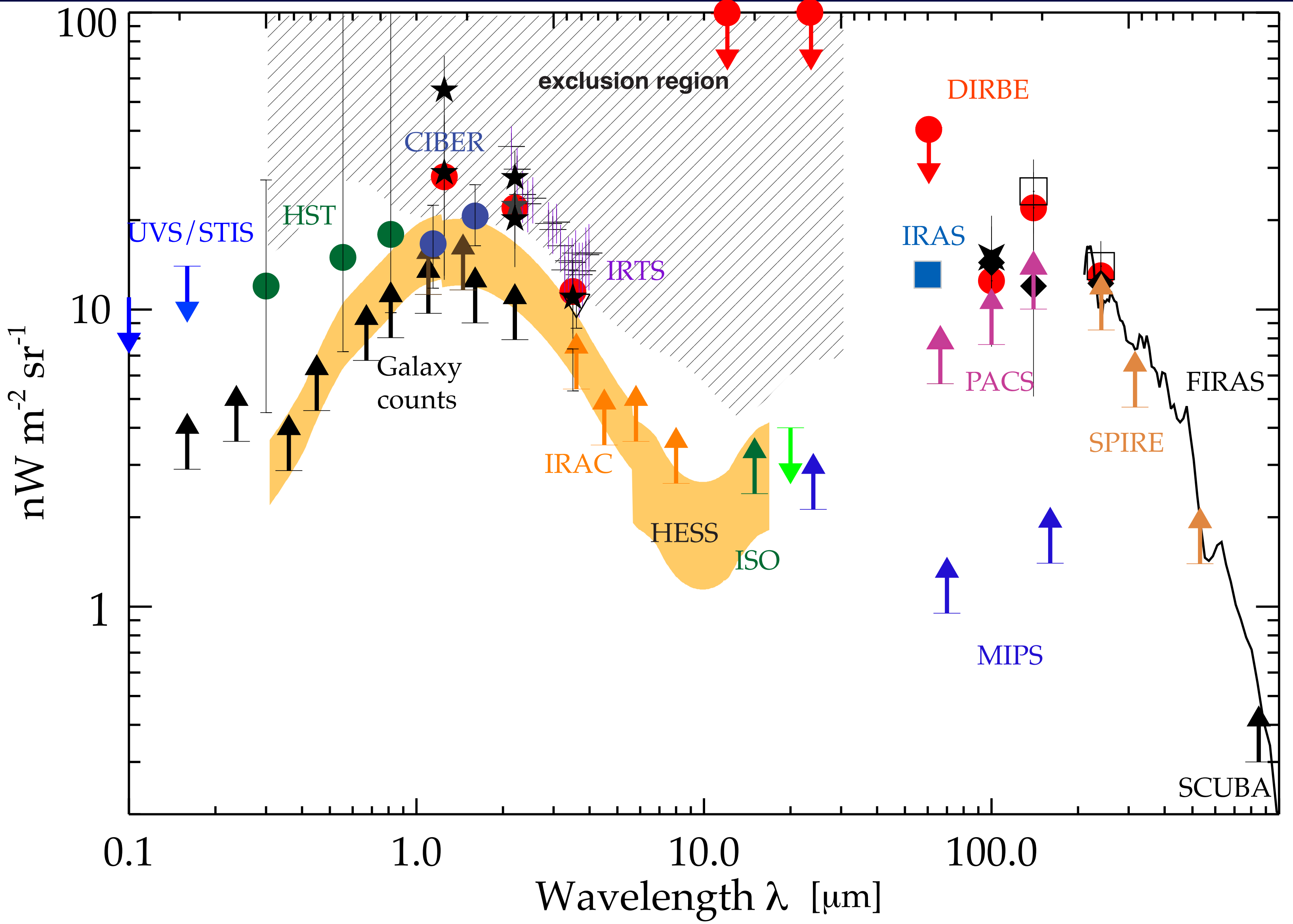
2D anisotropies to 3D spectral line intensity mapping

Far-infrared probes of reionization
(especially molecular Hydrogen 6 < z < ~15)

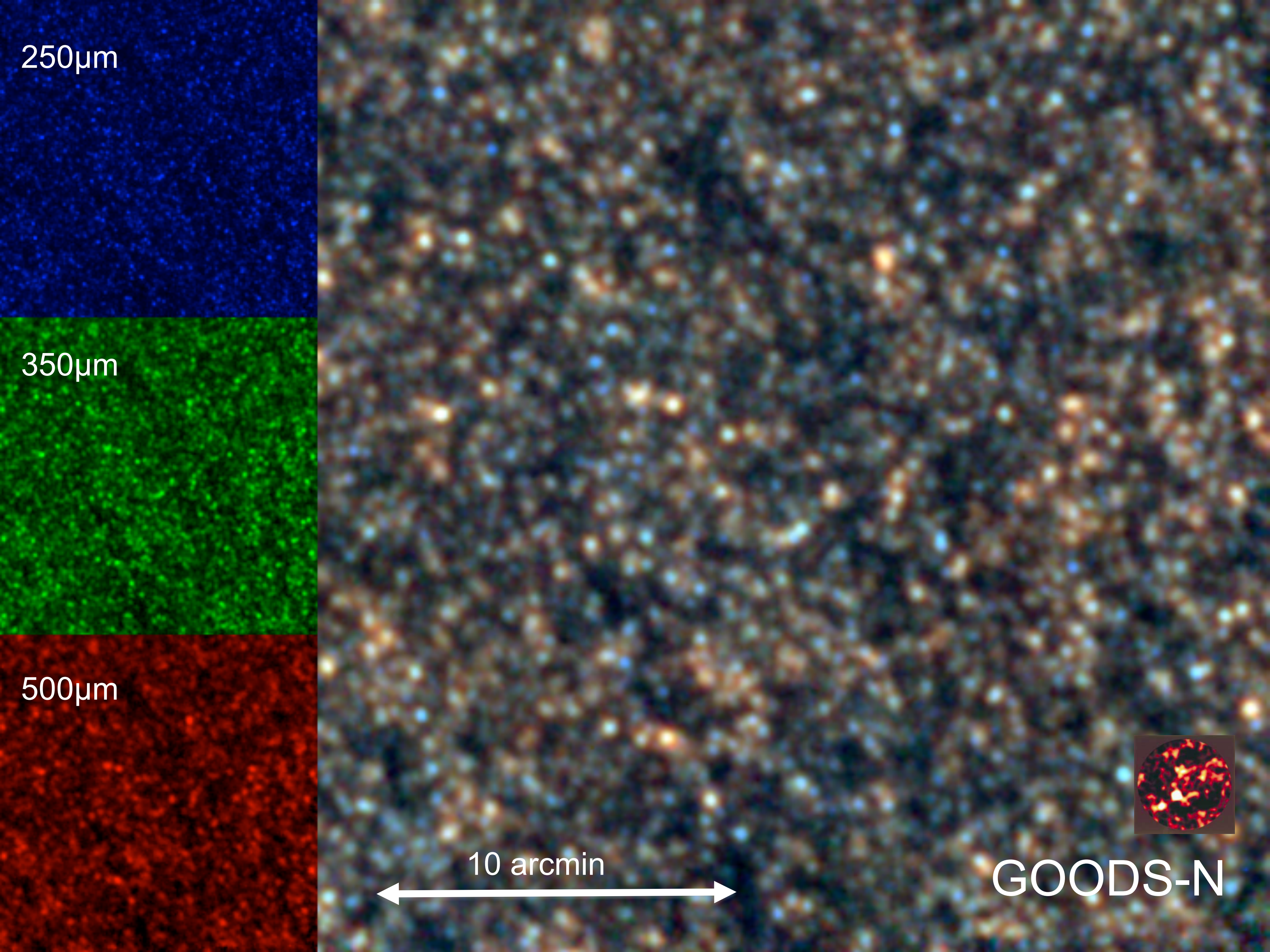
(Some mention of PIXIE - a 2-5 degree resolution all-sky CMB/far-IR explorer concept between 60 microns to 10 cm at 15 GHz spectral resolution with a FTS)

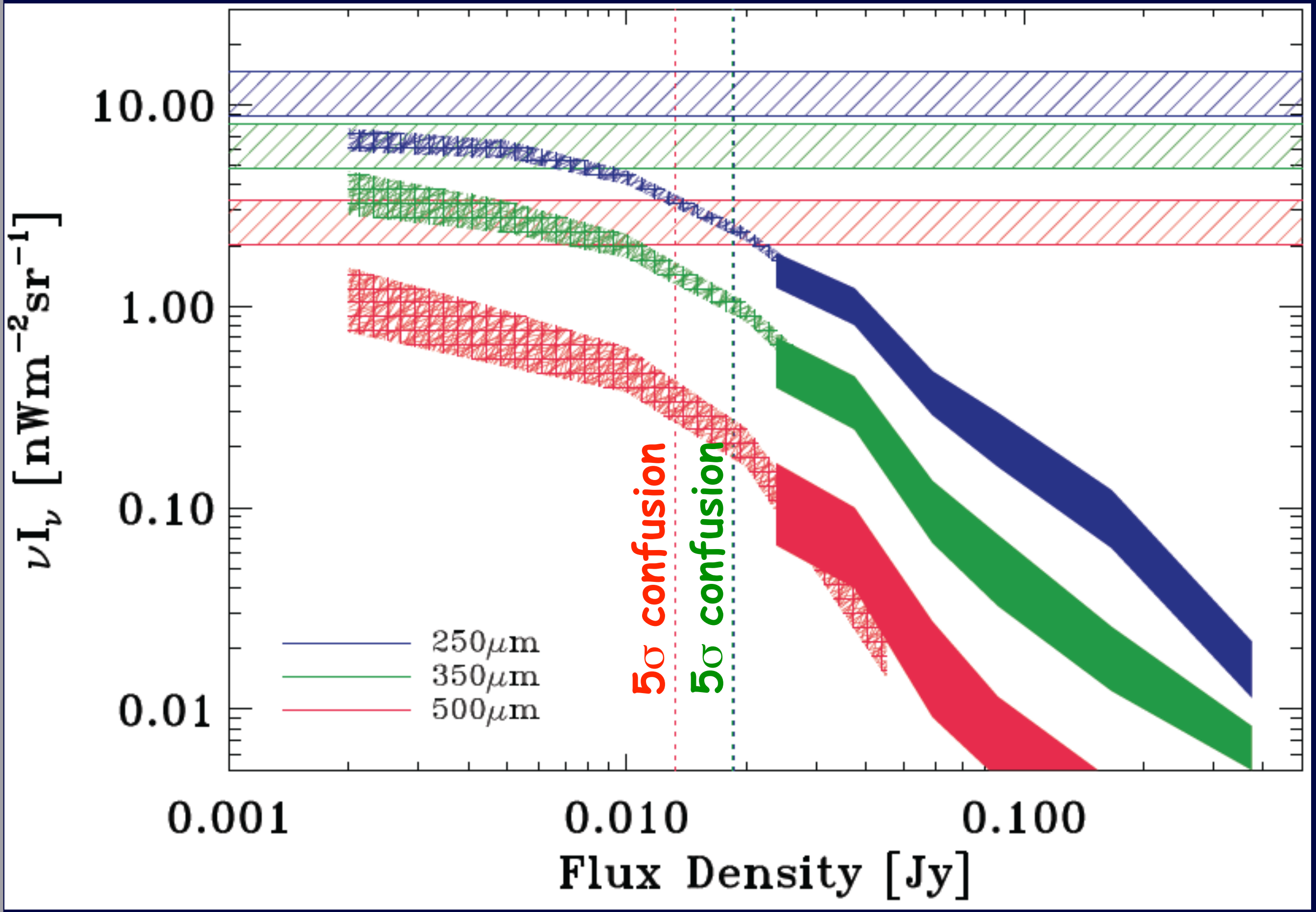
A cool review of dusty star-forming galaxies Casey+ arXiv.org*:1402.1456*

Outline



The extragalactic background spectrum

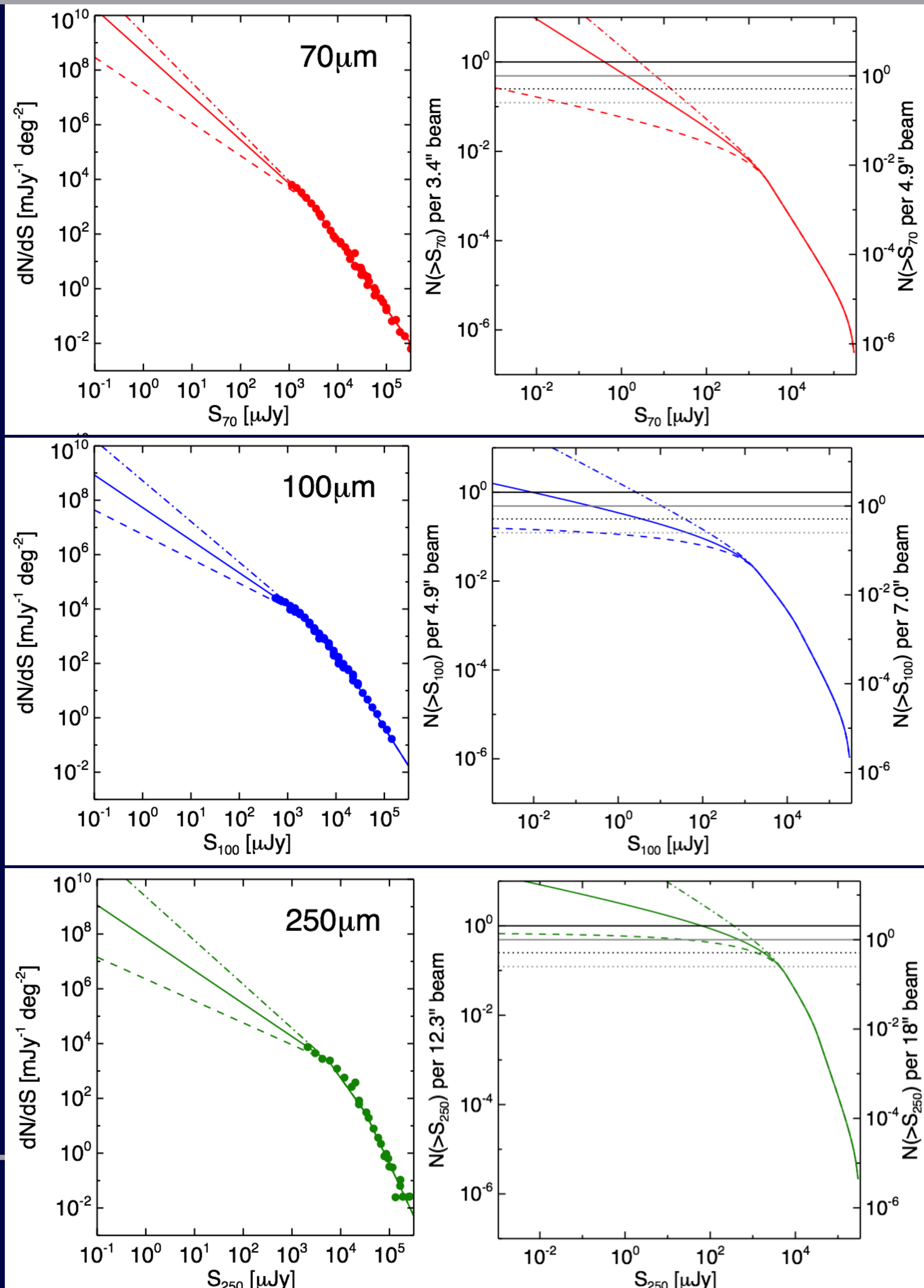

250μm
350μm
500μm
10 arcmin
GOODS-N



- Source Counts
  250, 350, 500 μm
  15%, 10%, 6%
- P(D)
  250, 350, 500 μm
  65%, 60%, 45%
- Stacking:
  250, 350, 500 μm
  80%, 80%, 85%

Of course: The remainder are the most interesting sources!
E.g. z > 3 galaxy populations

Resolving the extragalactic background spectrum

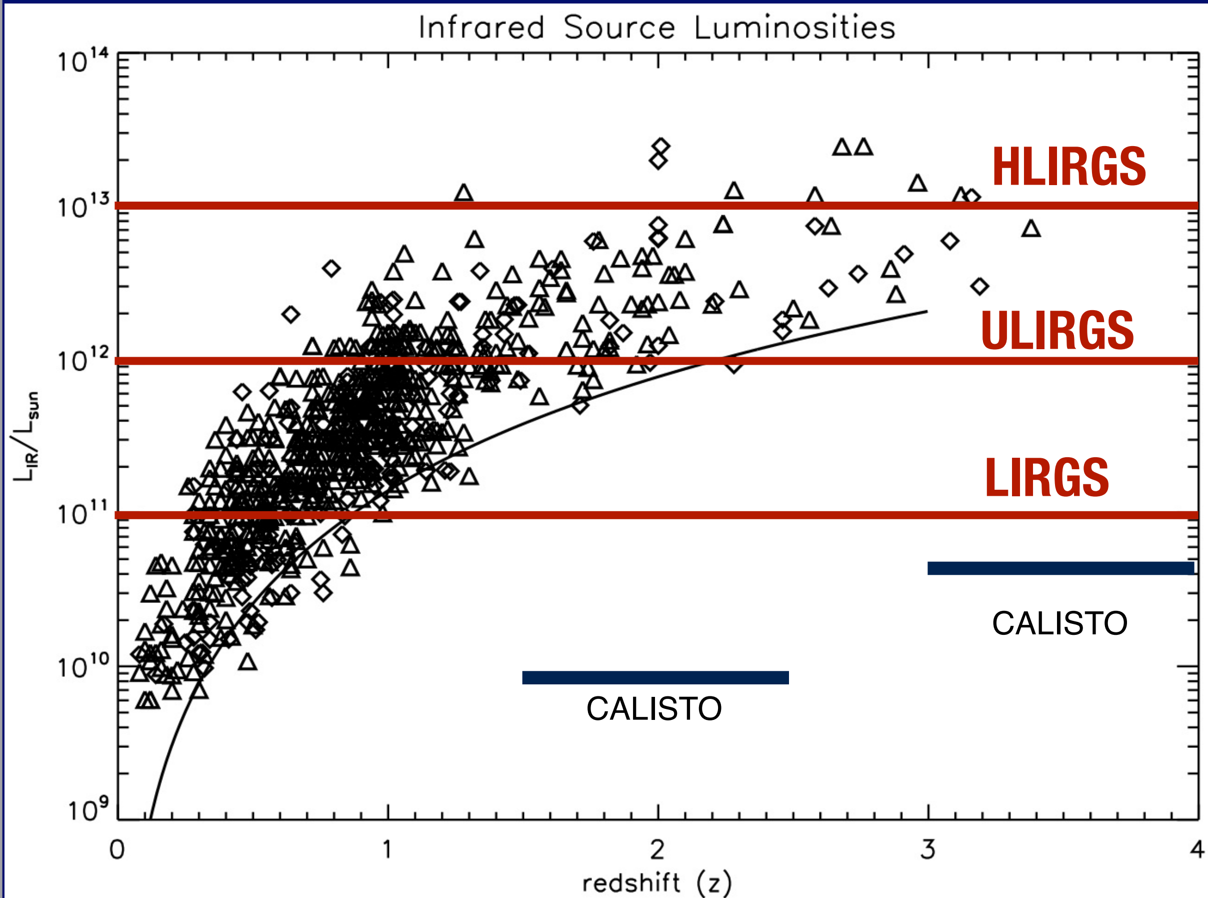


- CALISTO will

- 1. Directly resolve more of
- the background.

- 2. 5m can resolve x3 deeper
- at 70 microns and x10 deeper
- at 100 and 250 microns

- (Casey et al. white paper)



2000

200

20

2 (~Milky-way SFR)

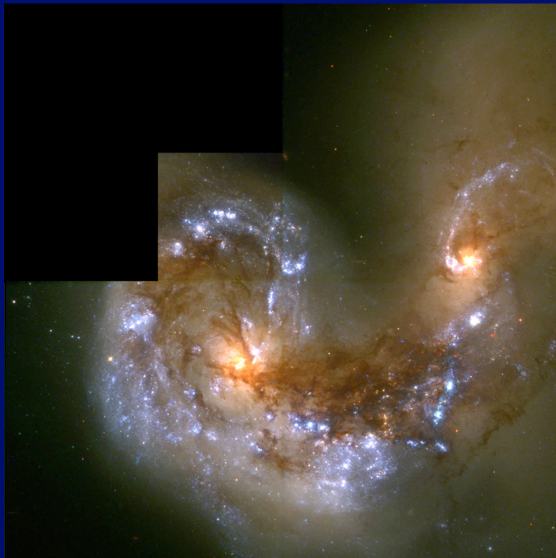
Star-Formation Rate in solar masses per year

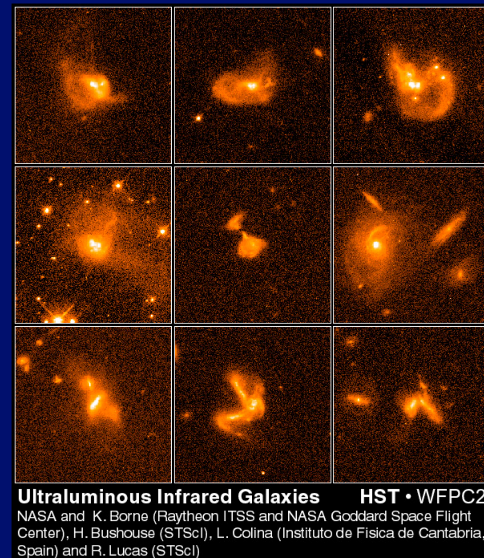
(i) ULIRGS/HyLIRGS typically have about ~10^{10} solar masses in stars

(ii) So the time scale for star-formation is [M*/(dM*/dt)] ~ 5 to 100 Million years

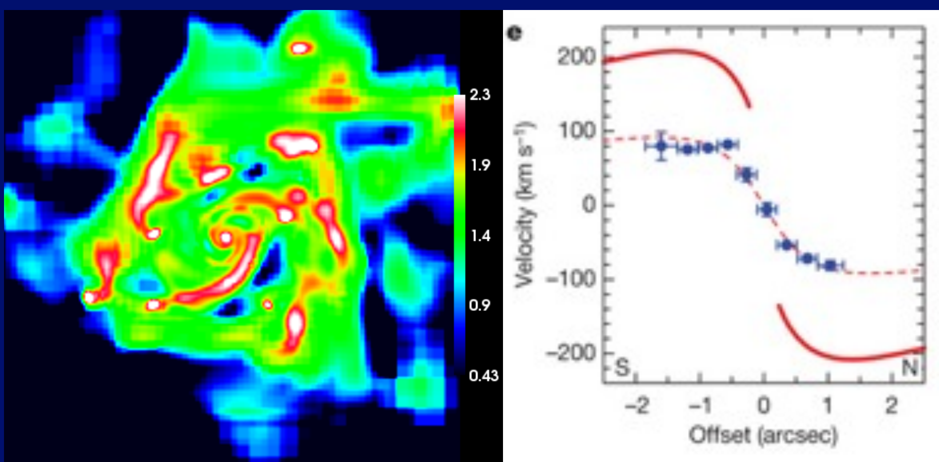
(star-bursting galaxies!)

What kind of galaxies do we detect with Herschel?





In the local Universe ~100% of starbursts are driven by gas-rich galaxy mergers.



But at z ~ 1 to 2, observations show that some starburst galaxies are simple disks.

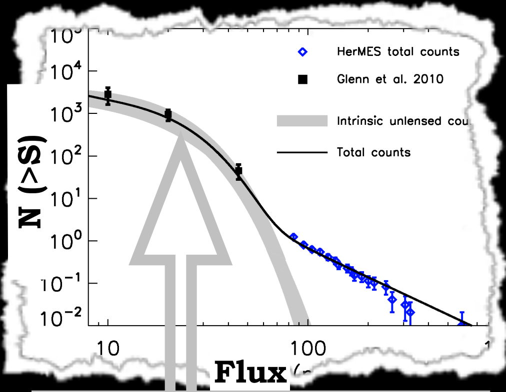
Is there a different mechanism to trigger a starburst at high redshifts?
(theorists: cold accretion mode)

Tacconi, L. J. et al. 2008, ApJ, 680, 246
Dekel, A. et al. 2009, ApJ, 703, 785

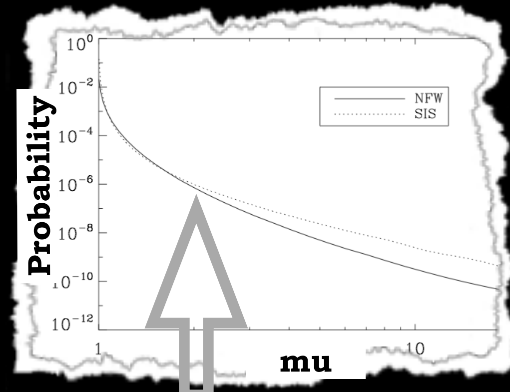
(a) What fraction of starbursts are mergers vs. cold flows?
(b) Do the mergers evolve differently from cold flows? what stops the starburst?

What are Dusty Star Forming Galaxies (DSFGs)?

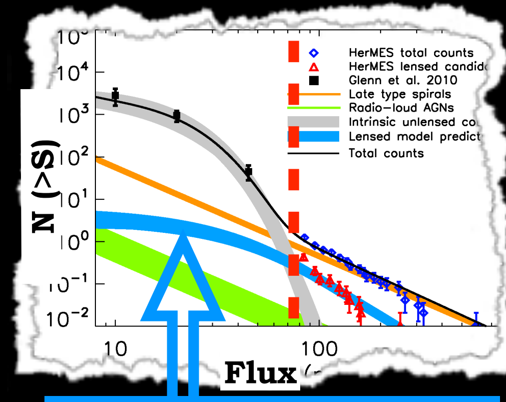
LOCAL ULIRGS REVIEW: SANDERS, D. AND MIRABEL, I. 1996, ARAA, 34, 749



Intrinsic Source Count

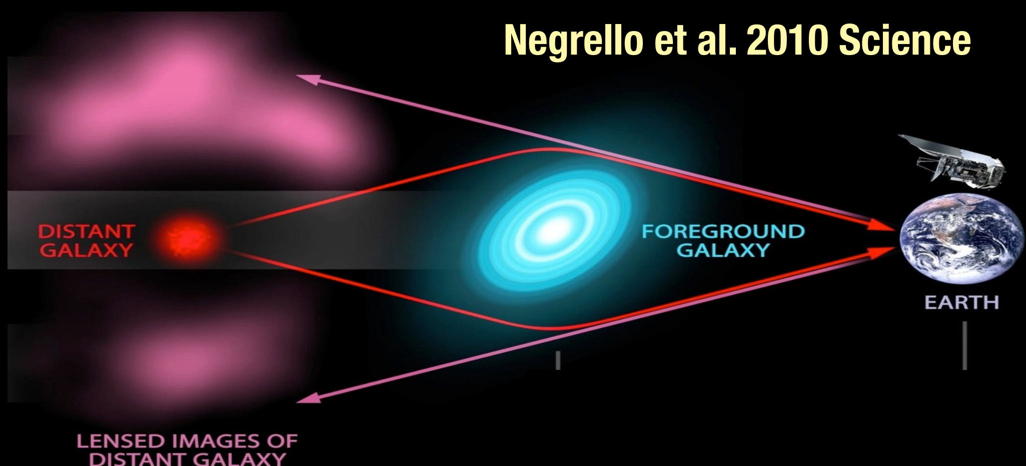


Magnification Cross Section



Lensed Source Count

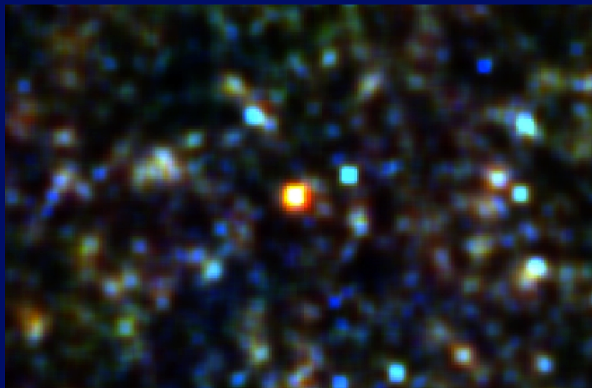
Negrello et al. 2010 Science



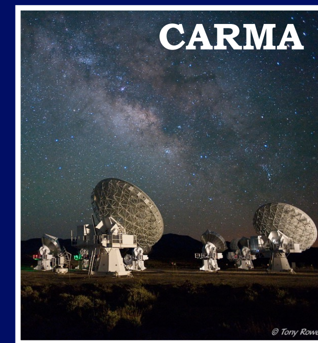
Julie Wardlow et al. 2013, ApJ

<u>Lensing galaxy selection at sub-mm wavelengths > 95% efficient</u>

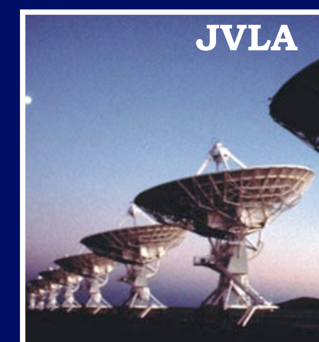
The Nature of Brightest high-z Herschel Galaxies



Source CO Redshift



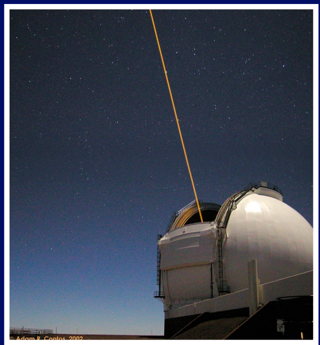
High-Resolution Imaging



1200 deg2 of Herschel should have 300 bright lensed galaxies.

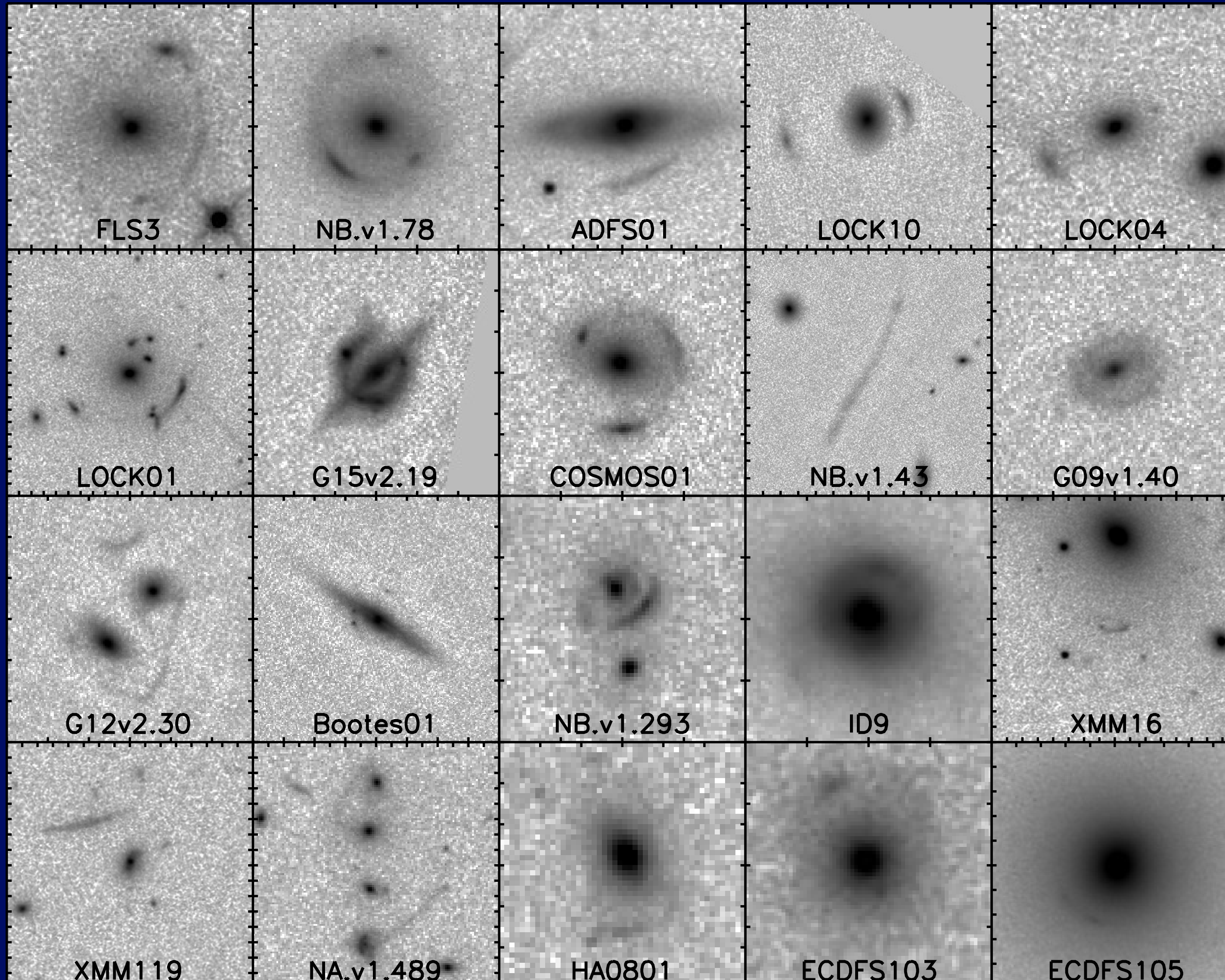
[All of optical surveys (since late 1970s) have detected about 300 lensed galaxies.]

Extensive Ground-based Follow-up Observations



Jae Calanog
UCI PhD 2014

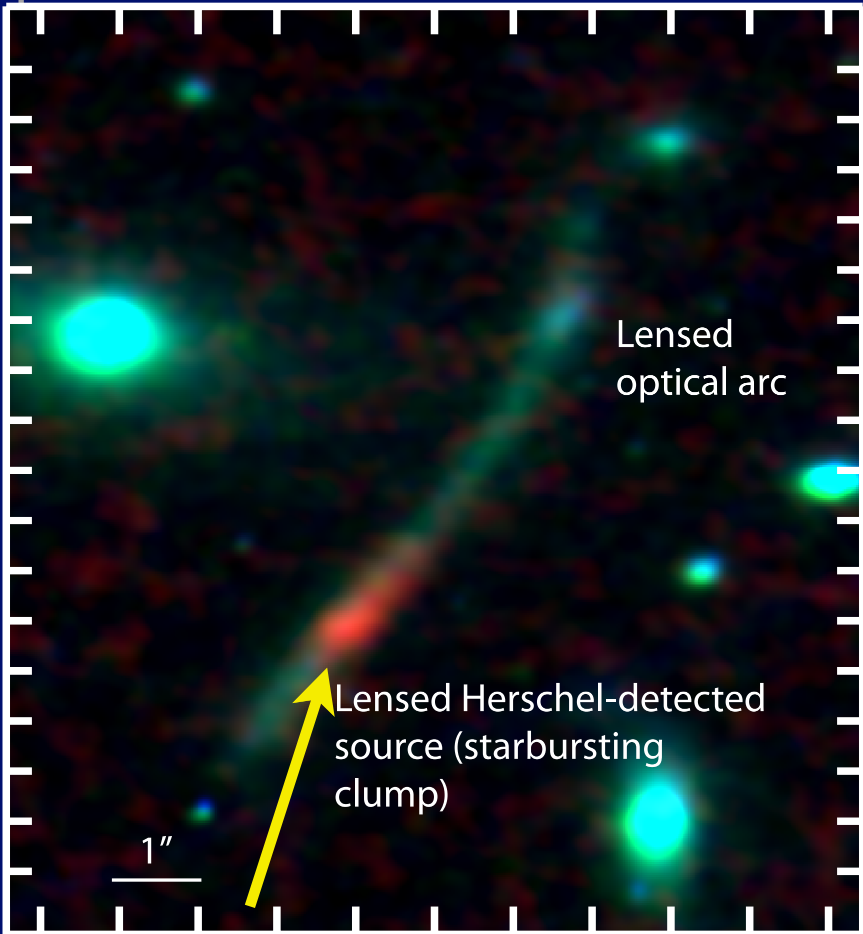
We now have 60 images like these in total with Keck/LGS AO

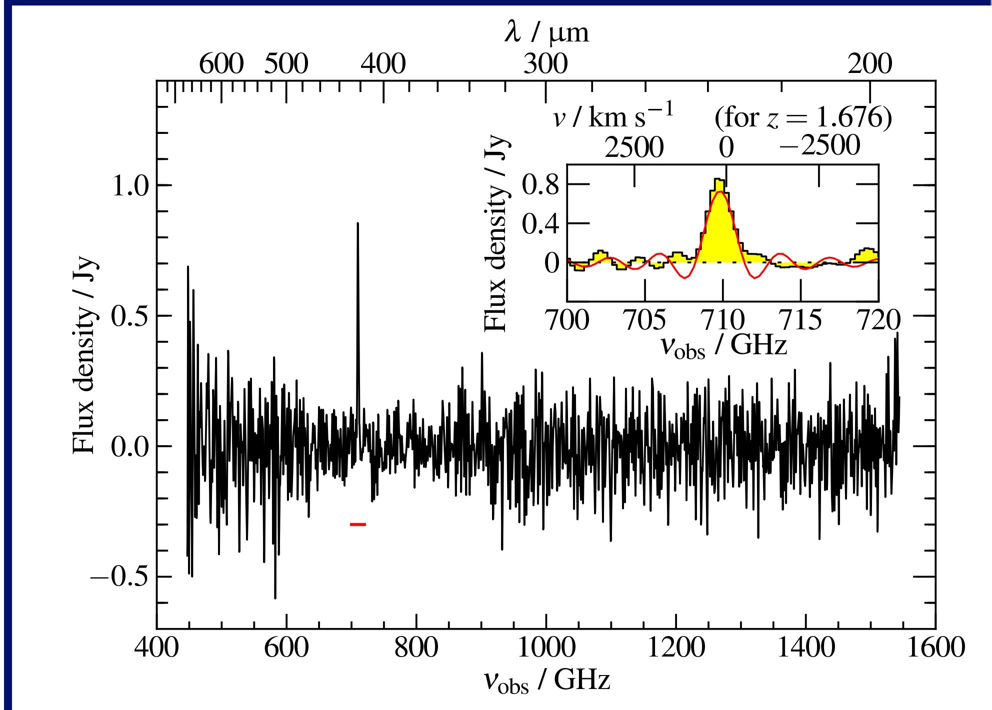


Keck LGS-AO Imaging (~20+ nights)

Fu et al. 2012; Bussmann et al. 2012; Fu et al. 2013; Calanog et al. 2014; Timmons et al. in prep

H-ATLAS: 650 sq. degrees. ~2 lensed Planck CSC sources. One in HerMES over 370 sq. degrees.





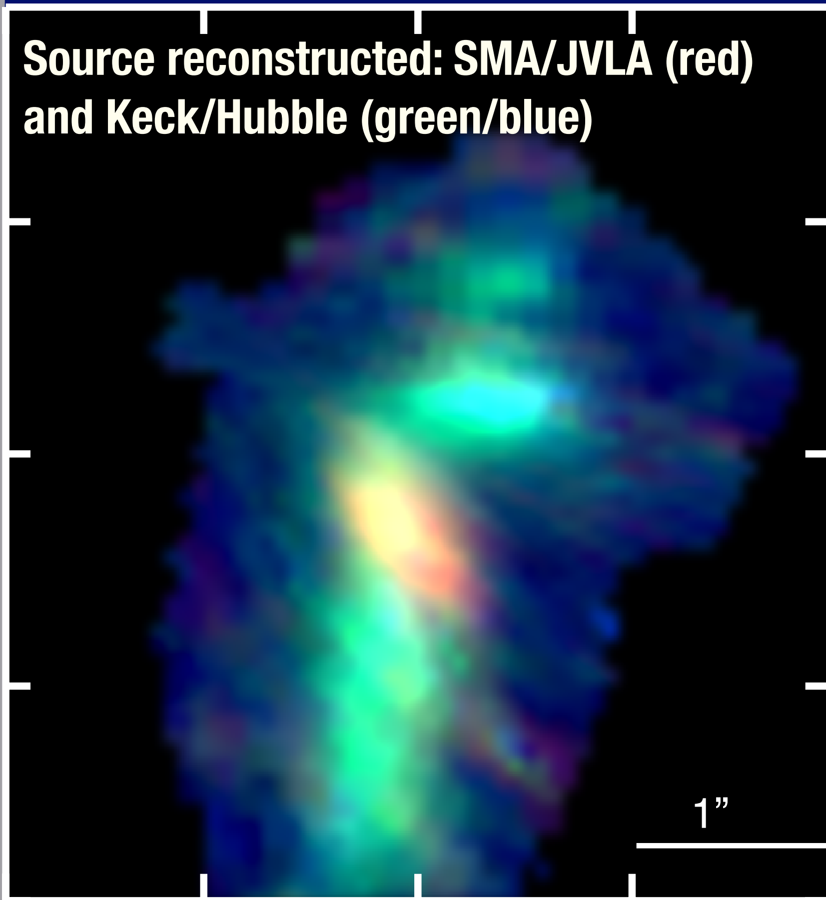
Starbursting knot in a spiral galaxy. Disk is mostly an old stellar population.

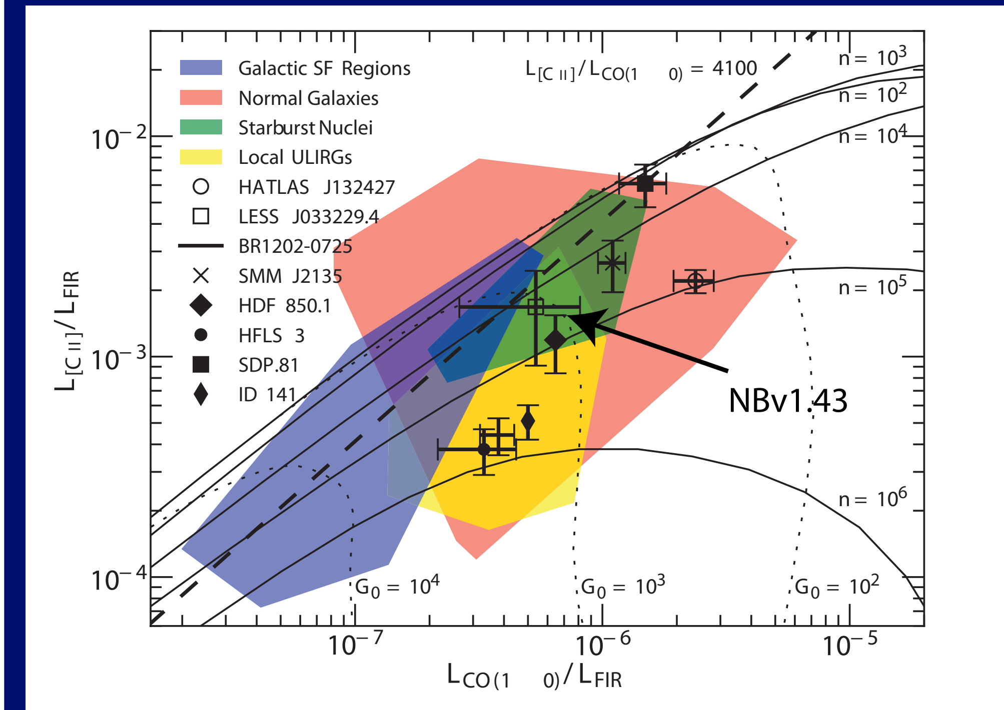
z=1.68, z determined from the Herschel-SPIRE/FTS spectrum with the 158 micron CII line

George et al. 2014

Herschel Lensed Sources

H-ATLAS: 650 sq. degrees. ~2 lensed Planck CSC sources. One in HerMES over 370 sq. degrees.

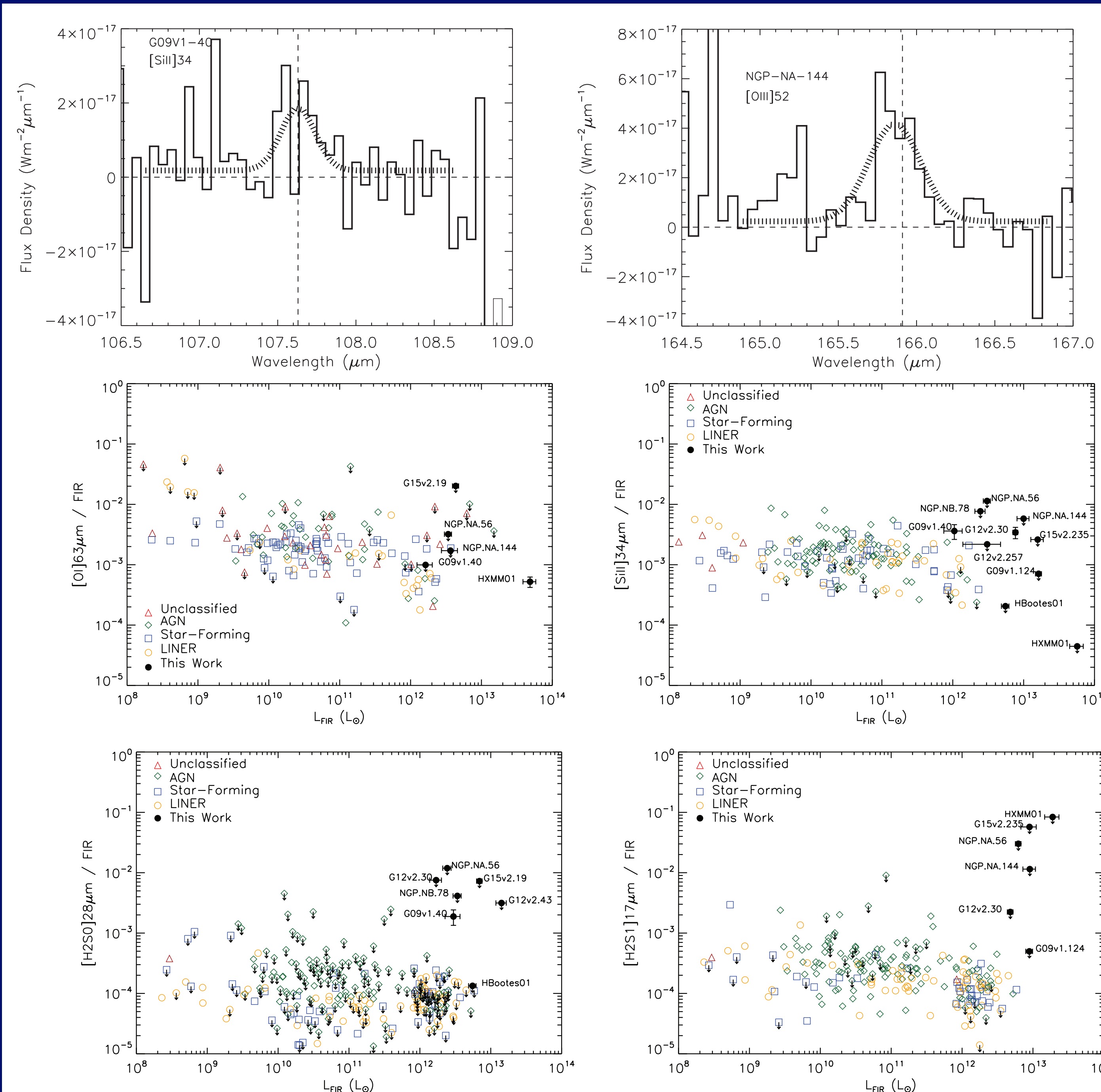




z=1.68, determined from the Herschel-SPIRE/FTS spectrum detecting the 158 micron CII line

George et al. 2014

Herschel Lensed Sources

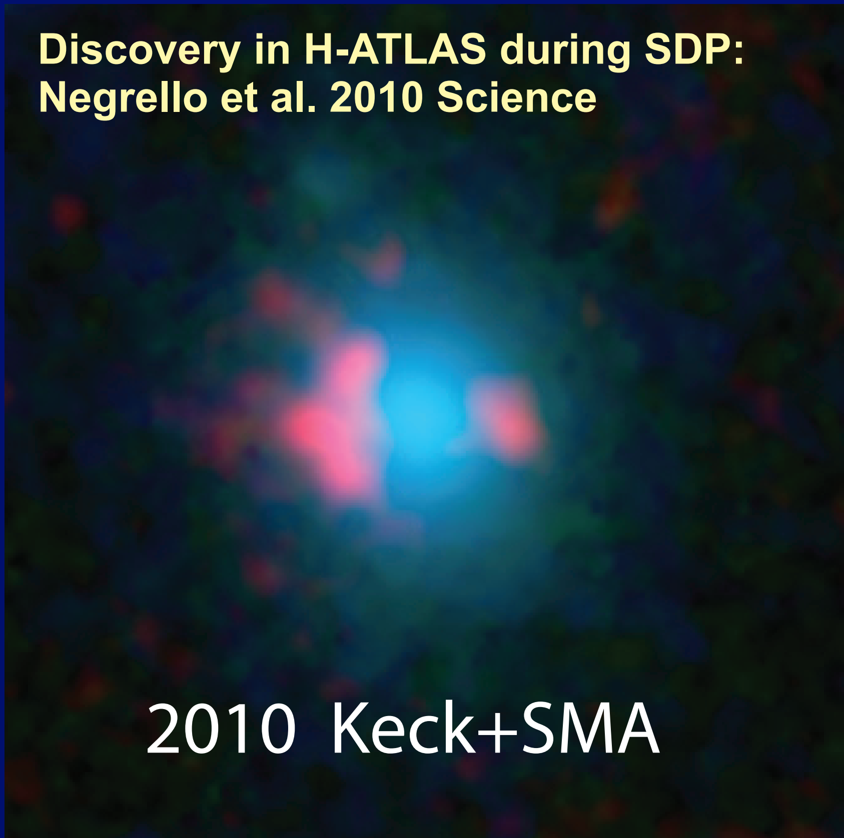


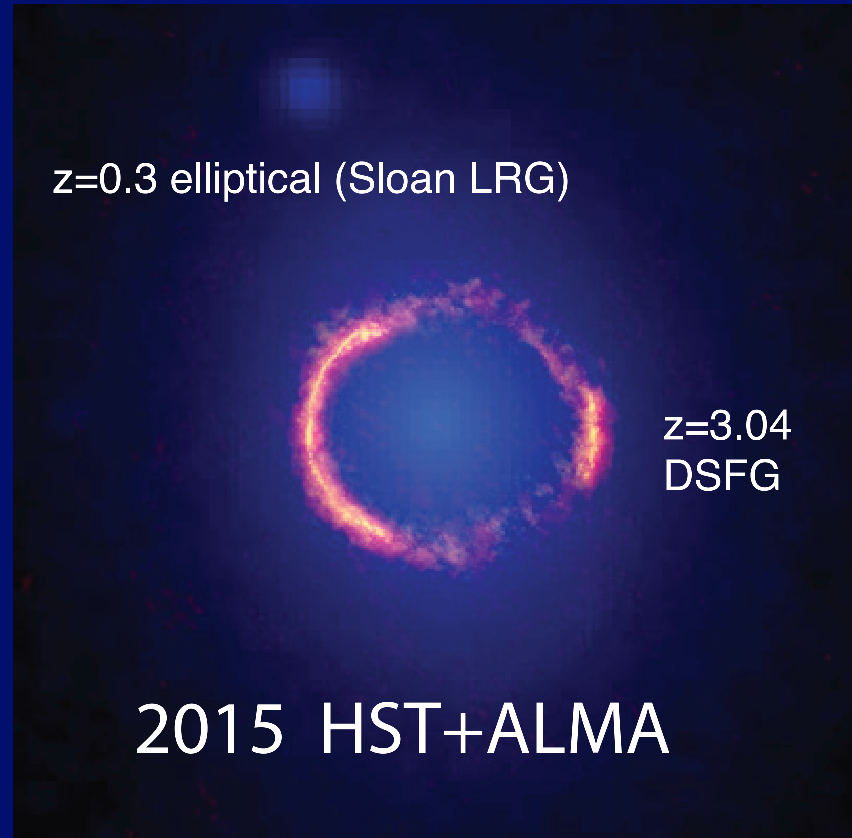
PACS spectroscopy of z > 1 galaxies

- mainly lensed galaxies
- about 50 targets
- Mostly undetected
- detections are at best 3 to 5 sigma

70 to 500 micron spectroscopy was not easy with Herschel - tons of upper limits over close to 500 hours unpublished.

Wardlow et al. in prep (Includes a molecular H2 detection at z of 2.1)



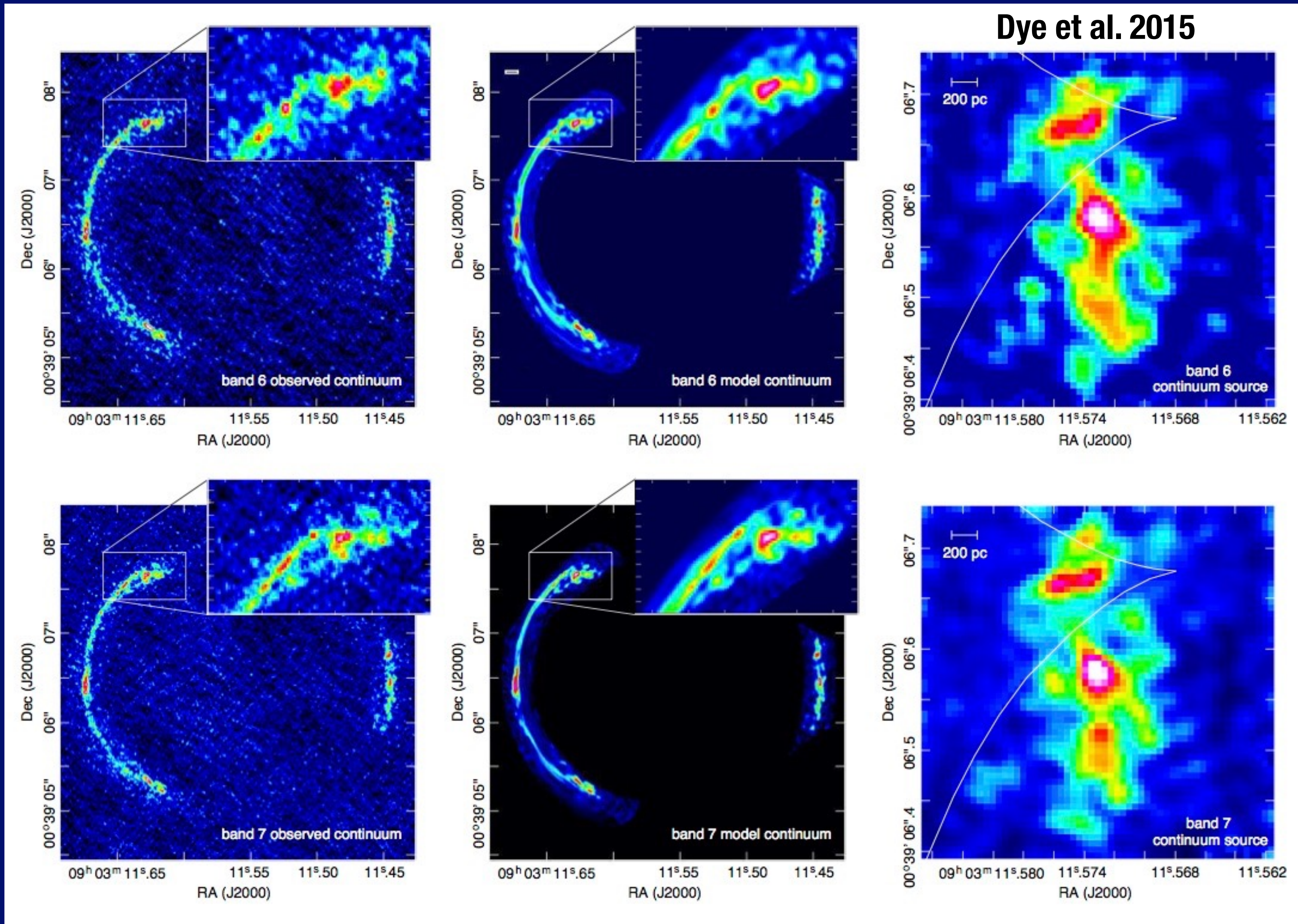


ALMA SV data Vlahakis et al. 2015; Results so far in 6 papers + at least 2 more in prep

1.0, 1.3 and 2.0mm continuum; CO(5-4), 8-7, 10-9 and $H_2$0 (2_{02}-1_{11}) maps

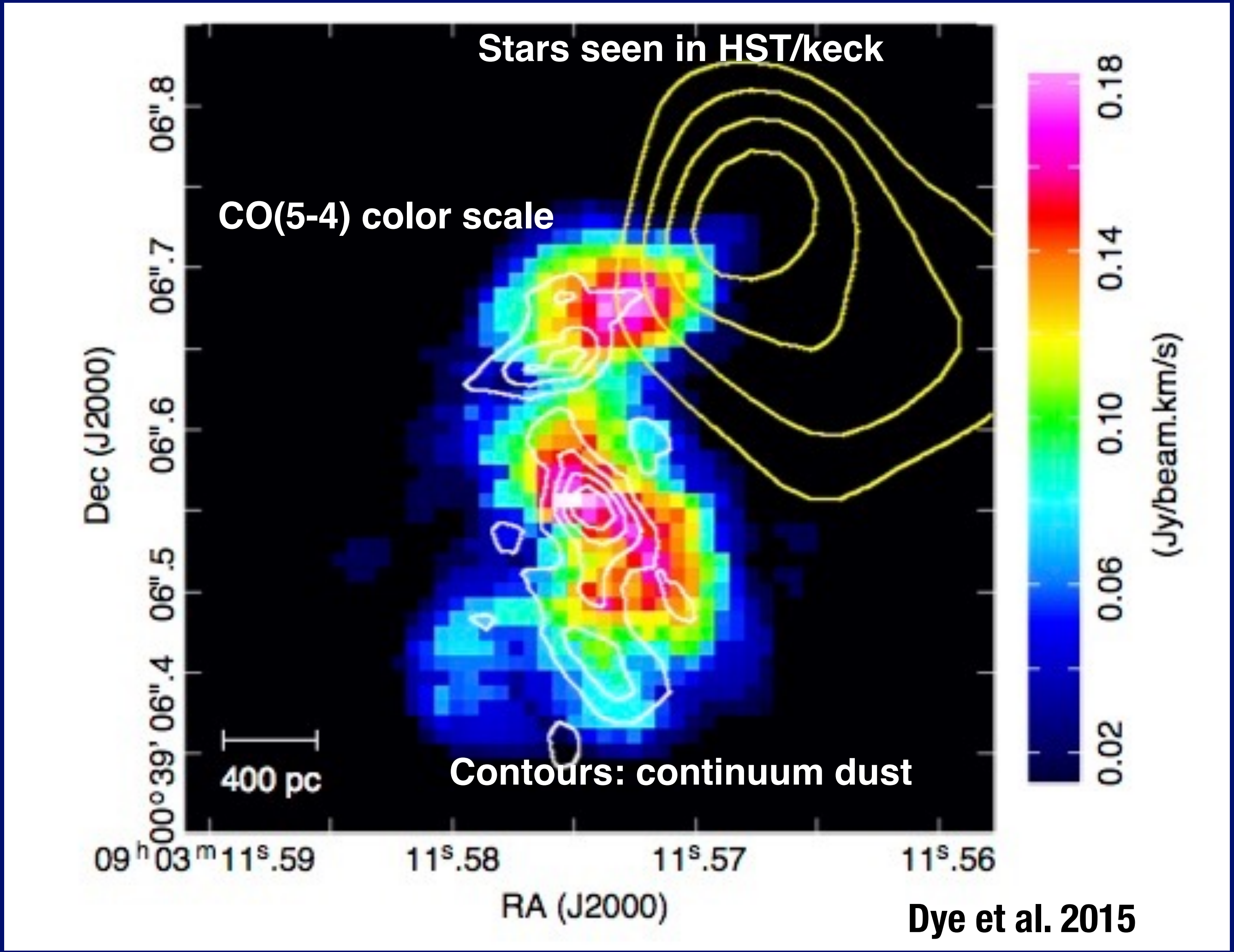
total of 30 hours, on source 16 hours; 300+ GB of data

Ring of Fire: ALMA superstar, SDP.81



Ring of Fire: ALMA superstar, SDP.81

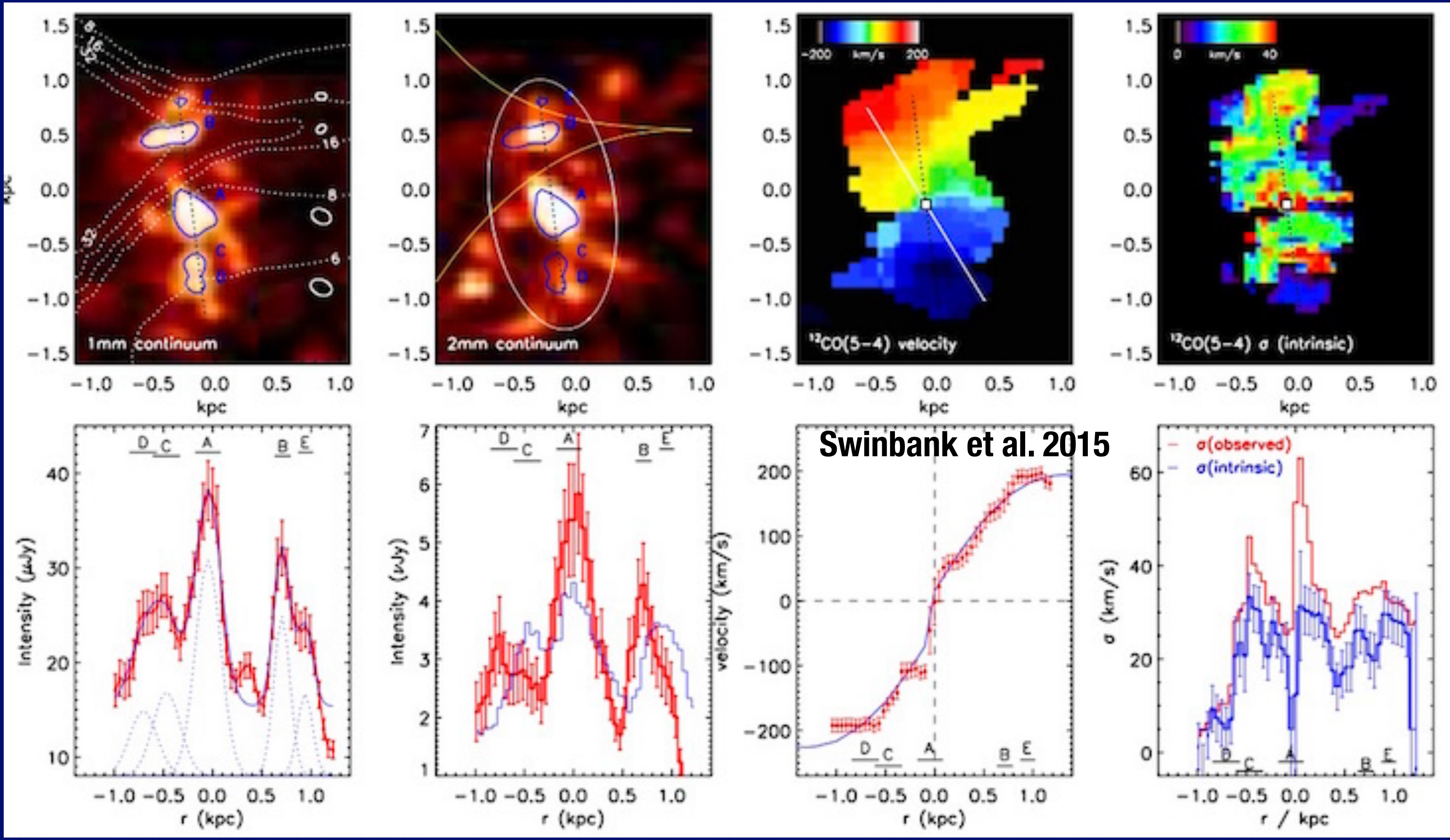
Negrello et al. 2010; Vlahakis et al. 2015; Dye et al. 2015; Swinbank et al. 2015;… (6 papers with ALMA)



Thanks to lensing+ALMA 50 pc resolution at z of 3 in a star-forming galaxy

Ring of Fire: ALMA superstar, SDP.81

Negrello et al. 2010; Vlahakis et al. 2015; Dye et al. 2015; Swinbank et al. 2015;… (6 papers with ALMA)



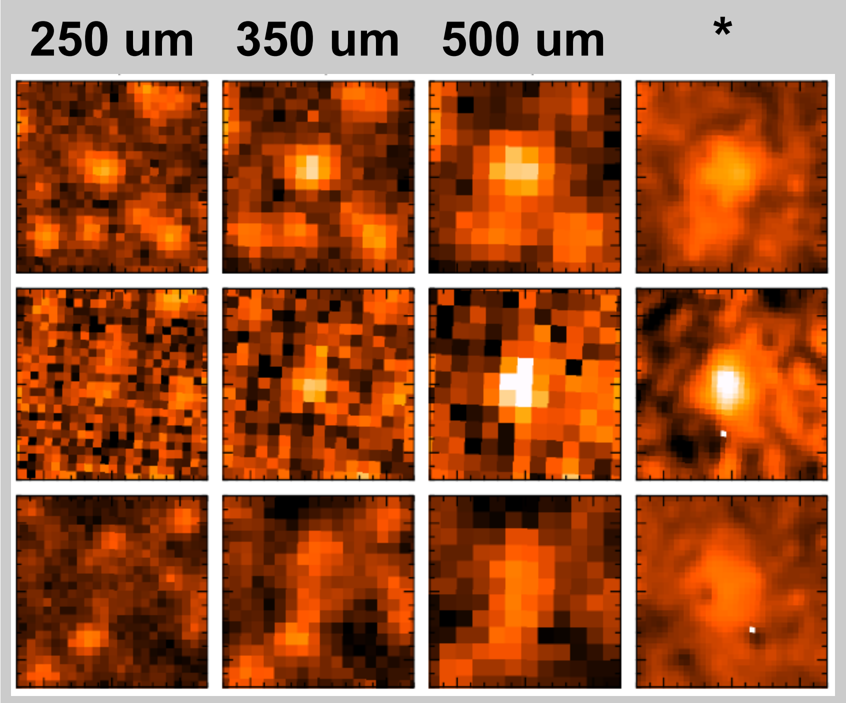
Toomre unstable gas disk Q~0.3 +/- 0.1; gas fraction 70-90%; Jeans length of 130-200pc

Ring of Fire: ALMA superstar, SDP.81

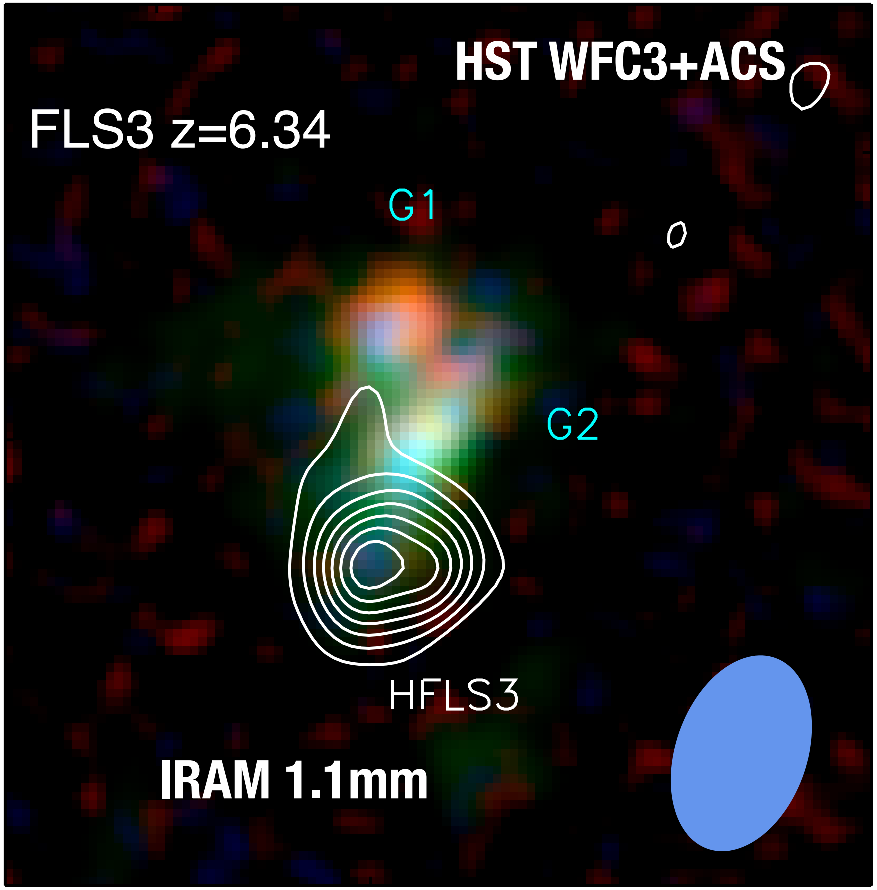
Negrello et al. 2010; Vlahakis et al. 2015; Dye et al. 2015; Swinbank et al. 2015;… (6 papers with ALMA)

500 um peaked sources $S_{250} < S_{350} < S_{500}$: z > 4?

*Confusion reduced S(500) – fS(250)

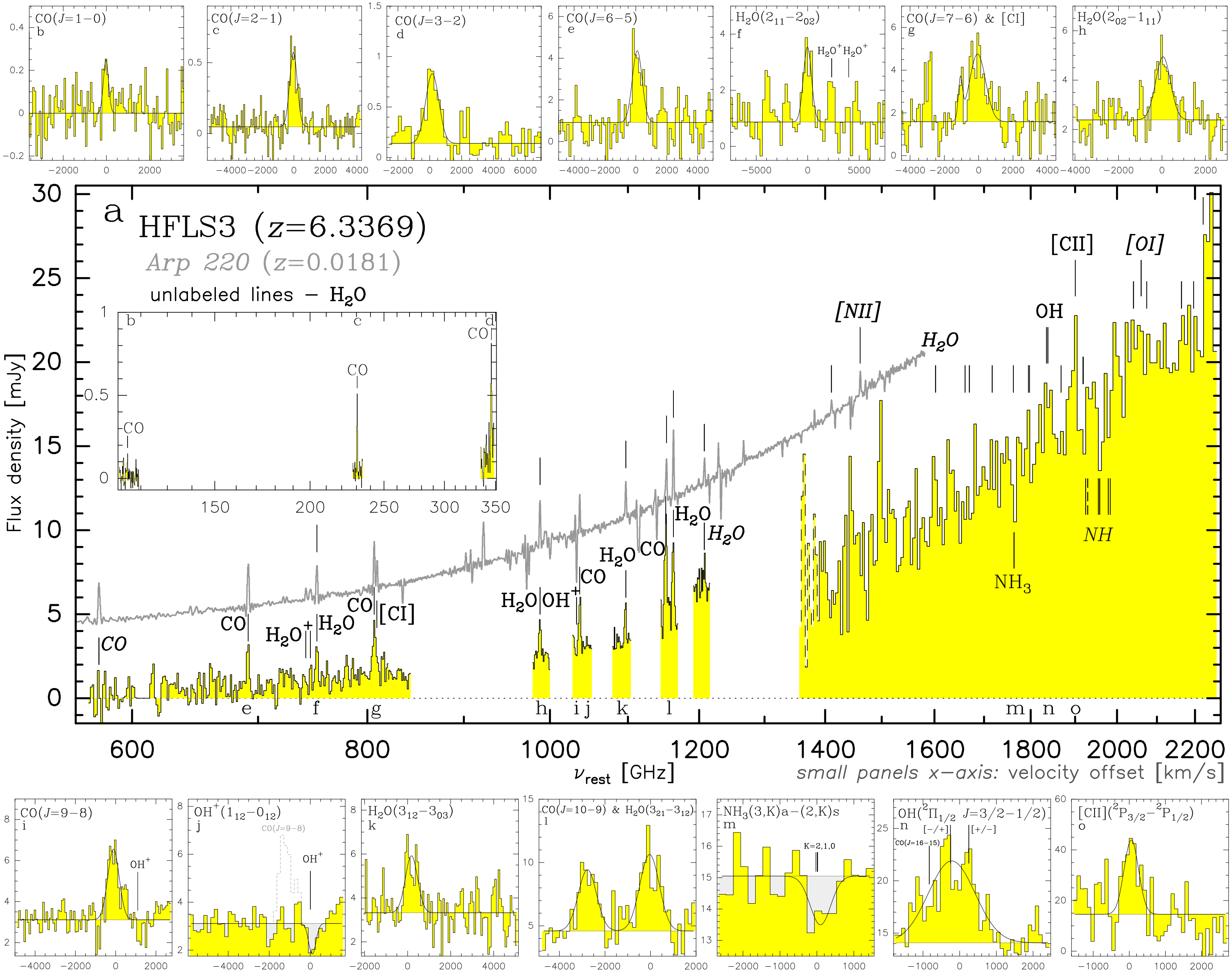


Dowell et al. 2014 ApJ technique

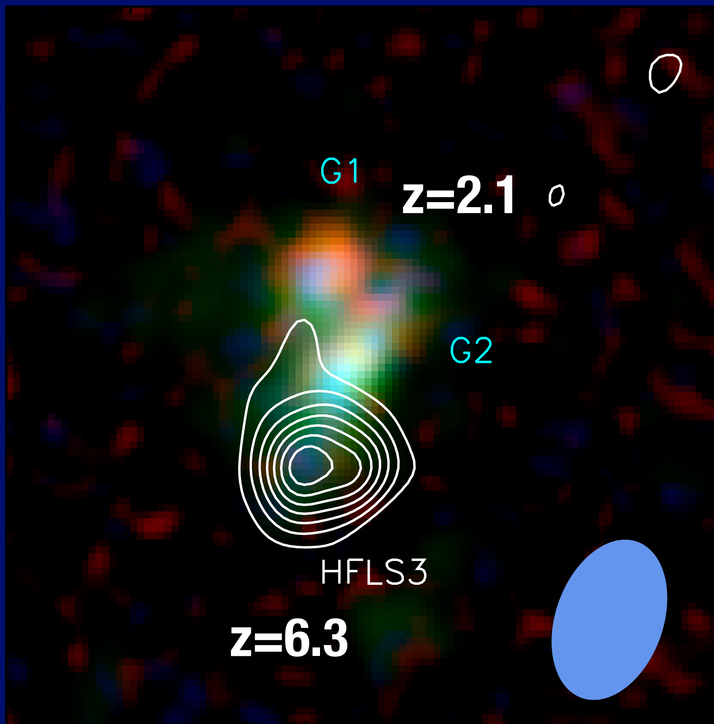


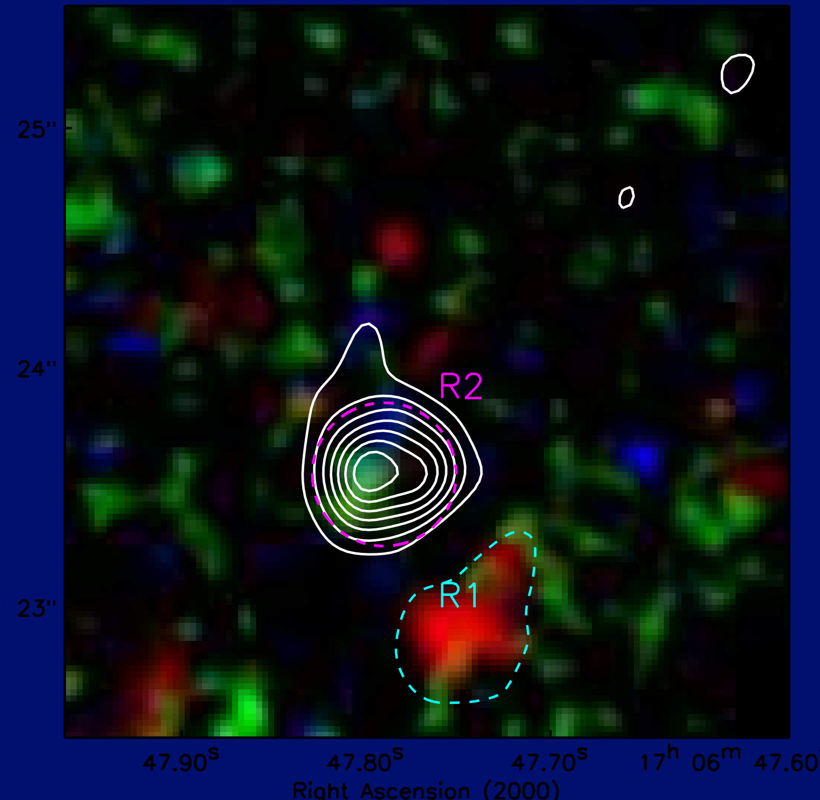
z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014



a
HFLS3 (z=6.3369)
Arp 220 (z=0.0181)
unlabeled lines – H2O
Flux density [mJy]
ν rest [GHz]
small panels x-axis: velocity offset [km/s]
CO(J=1−0)
CO(J=2−1)
CO(J=3−2)
CO(J=6−5)
H2O(211−202)
CO(J=7−6) & [CI]
H2O(202−111)
CO(J=9−8)
OH+(112−012)
H2O(312−303)
CO(J=10−9) & H2O(321−312)
NH3(3,K)a−(2,K)s
OH(2Π1/2 J=3/2−1/2)
[CII](2P3/2−2P1/2)
[CII]
[OI]
[NII]
OH
NH3
NH
CO
[CI]
OH+





Weakly lensed by two z=2.1 galaxies with magnification 1.6 +/- 0.3

[G2 identification in R13 as K-band ID of FLS3 incorrect]

$L_{FIR} = 6X10^{12}\ L_\odot$

<u>SFR ~ 1300 $M_\odot$/yr</u>

$T_{DUST} = 55 \pm 10$ K

$M_{DUST} > 10^9\ M_\odot$

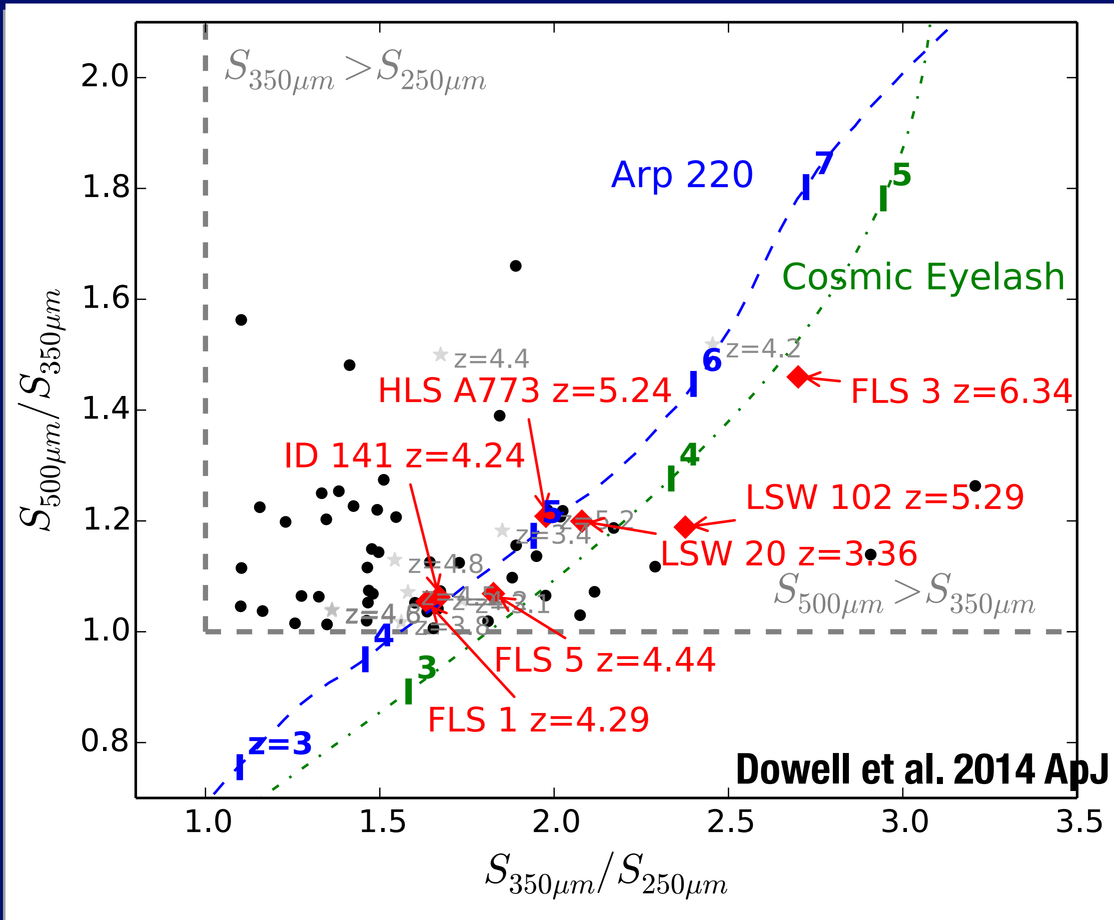
$M_{STARS} \sim 5X10^{10}\ M_\odot$

$M_{GAS} \sim 10^{11}\ M_\odot$

No evidence for a quasar/massive AGN!

z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014



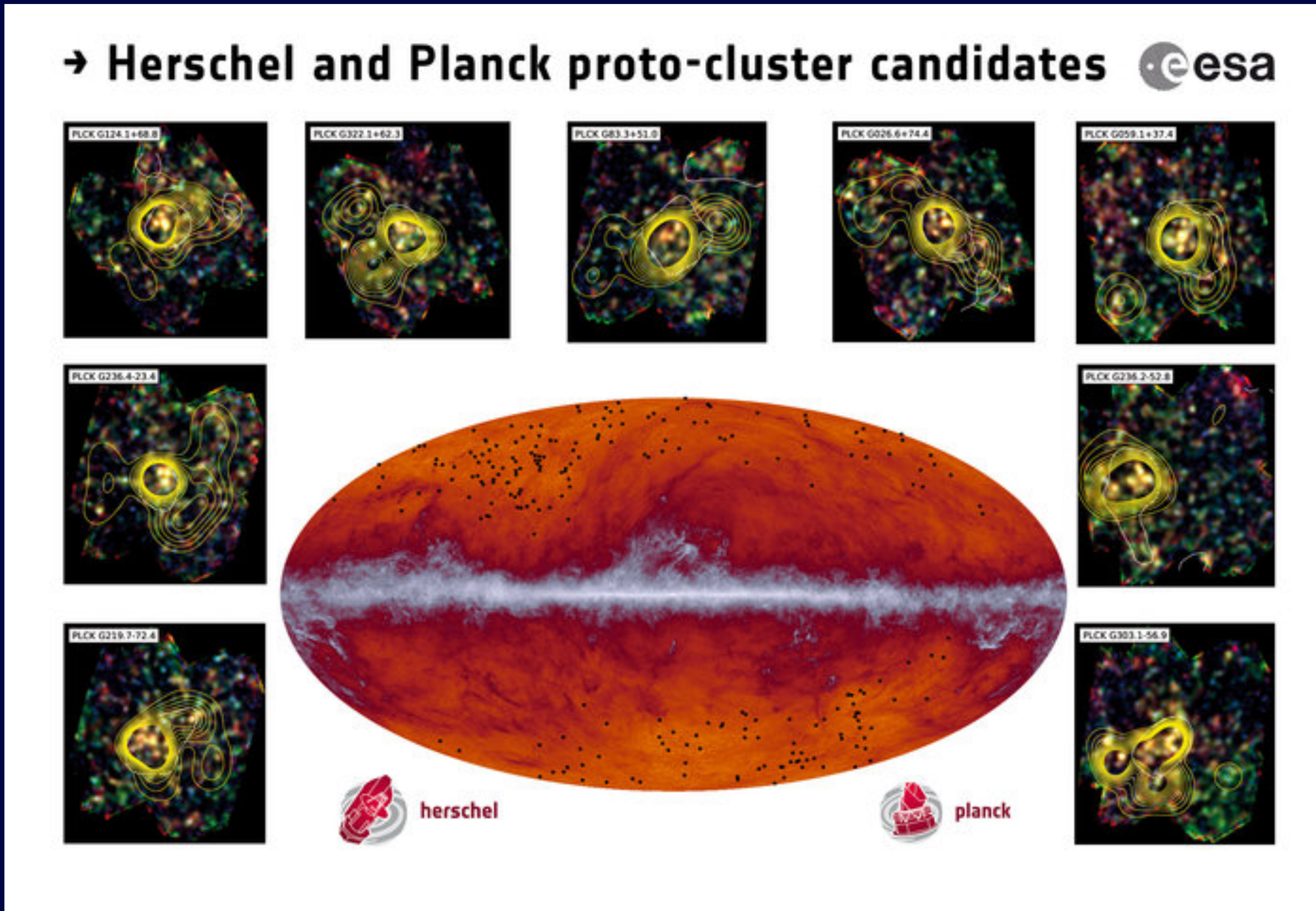
z > 6 galaxies can be discovered with just 100 to 600 micron coverage.

Need a survey area of around 1000 deg2 for statistically interesting number of targets.

[How angular resolution improvement with CALISTO increases or enhances identification of z > 5 galaxies with far-IR alone?]

"red" galaxies in Herschel

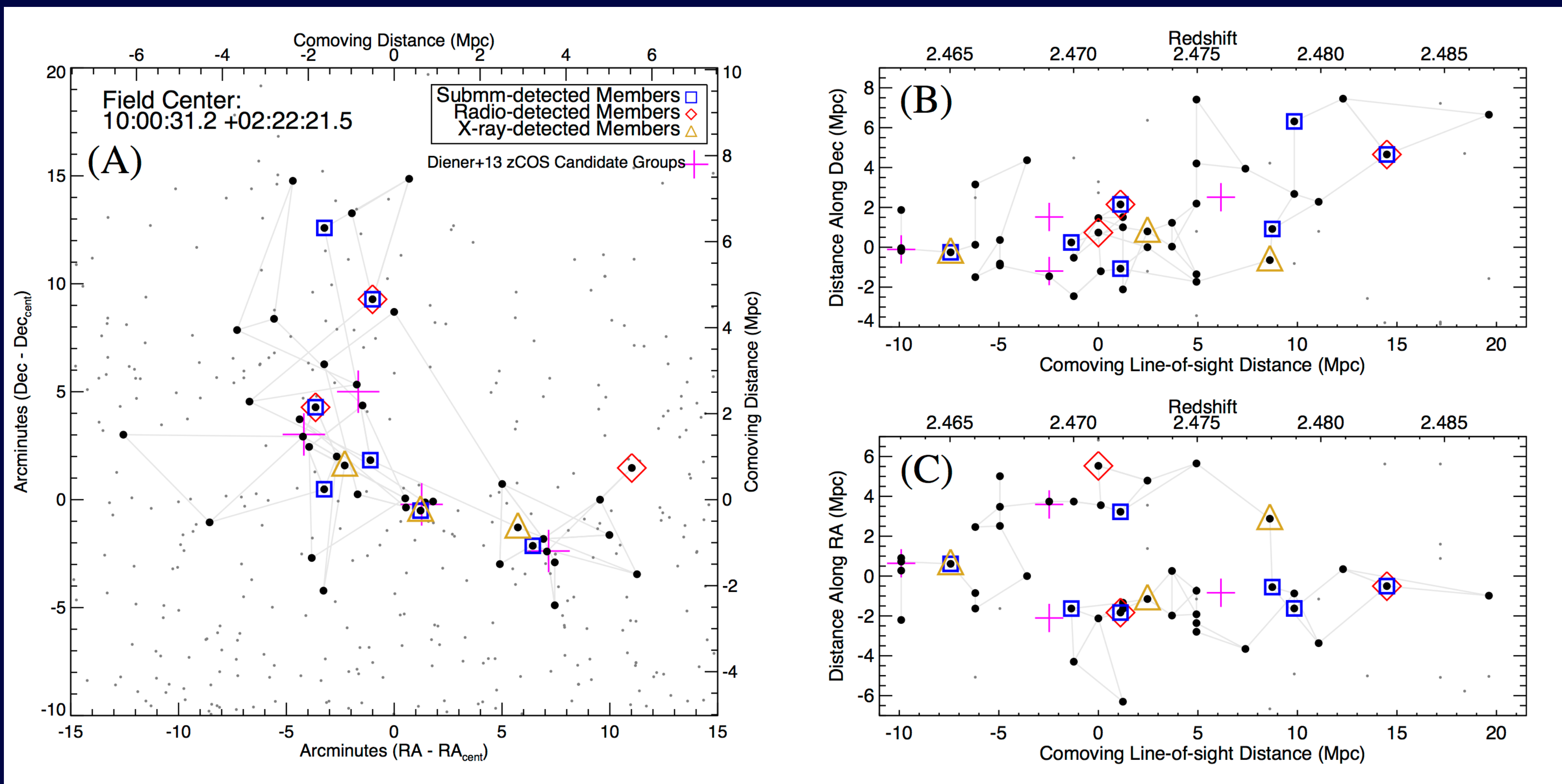
Galaxy proto-clusters at z >2
(before clusters “virialized” and bright in X-rays and SZ)



Galaxy proto-clusters at z >2

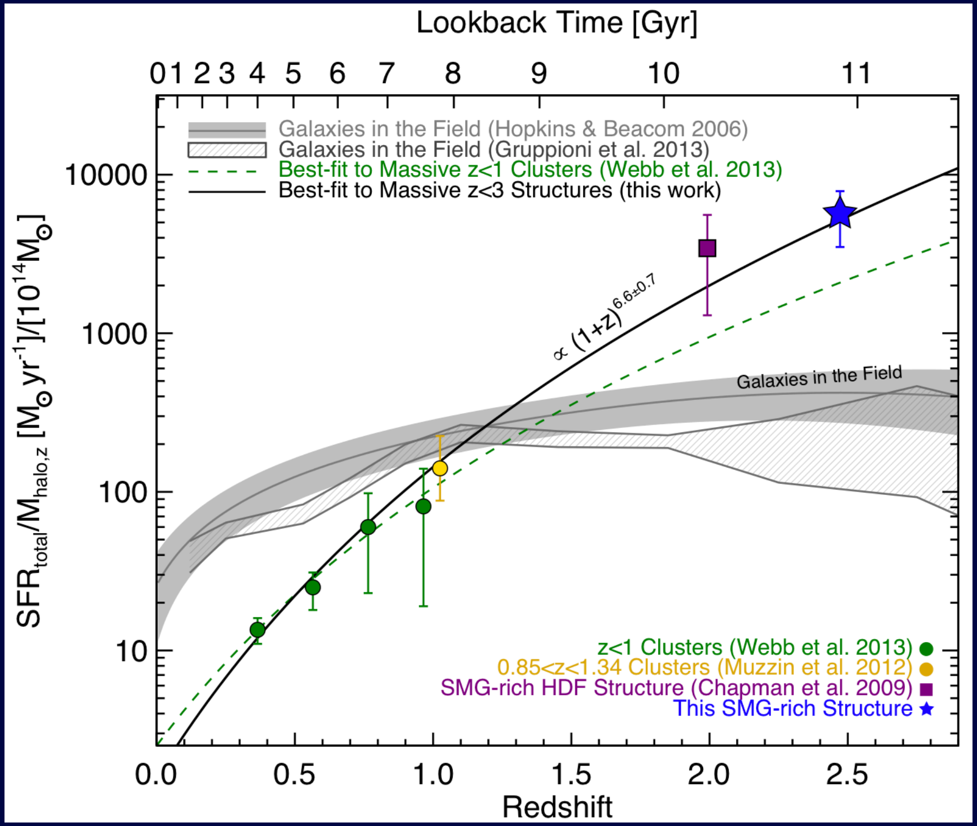
Casey et al. 2015: Herschel/SCUBA-2 + redshifts from Keck/MOSFIRE

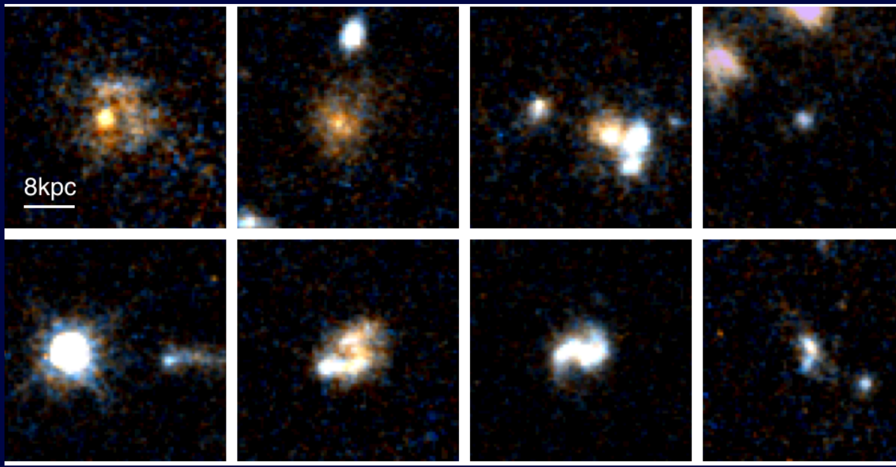
z=2.47, 8 dusty, starbursting galaxies and 40+ Lyman-break galaxies + radio + AGNs

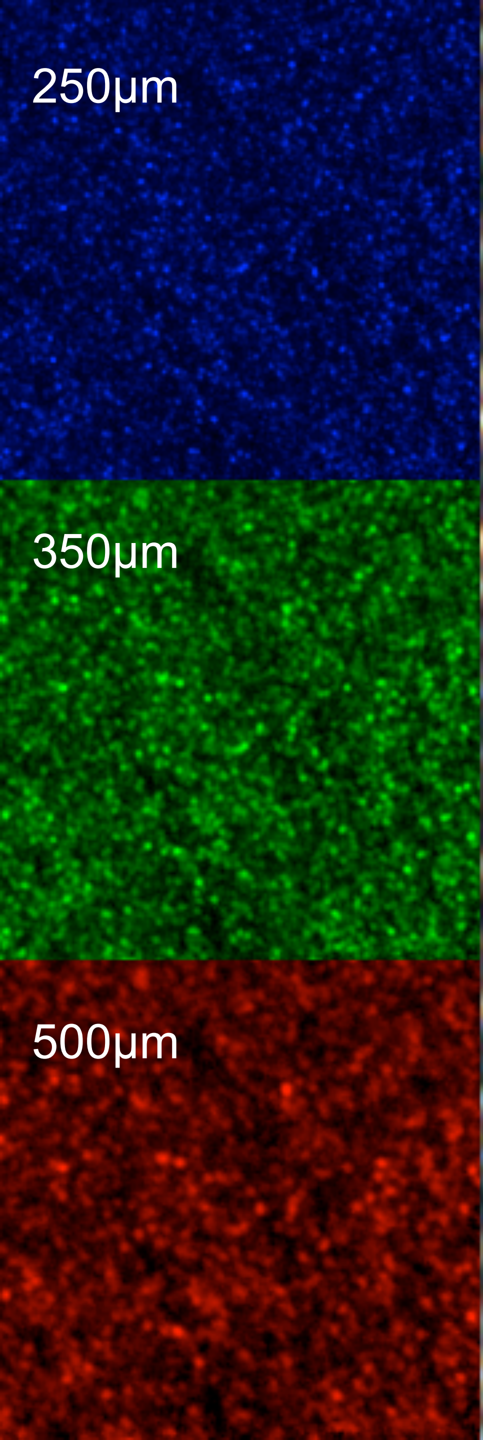


Galaxy proto-clusters at z >2

CALISTO surveying over 1000 deg2 will find many 100s of these things - no follow-up as automatic redshifts

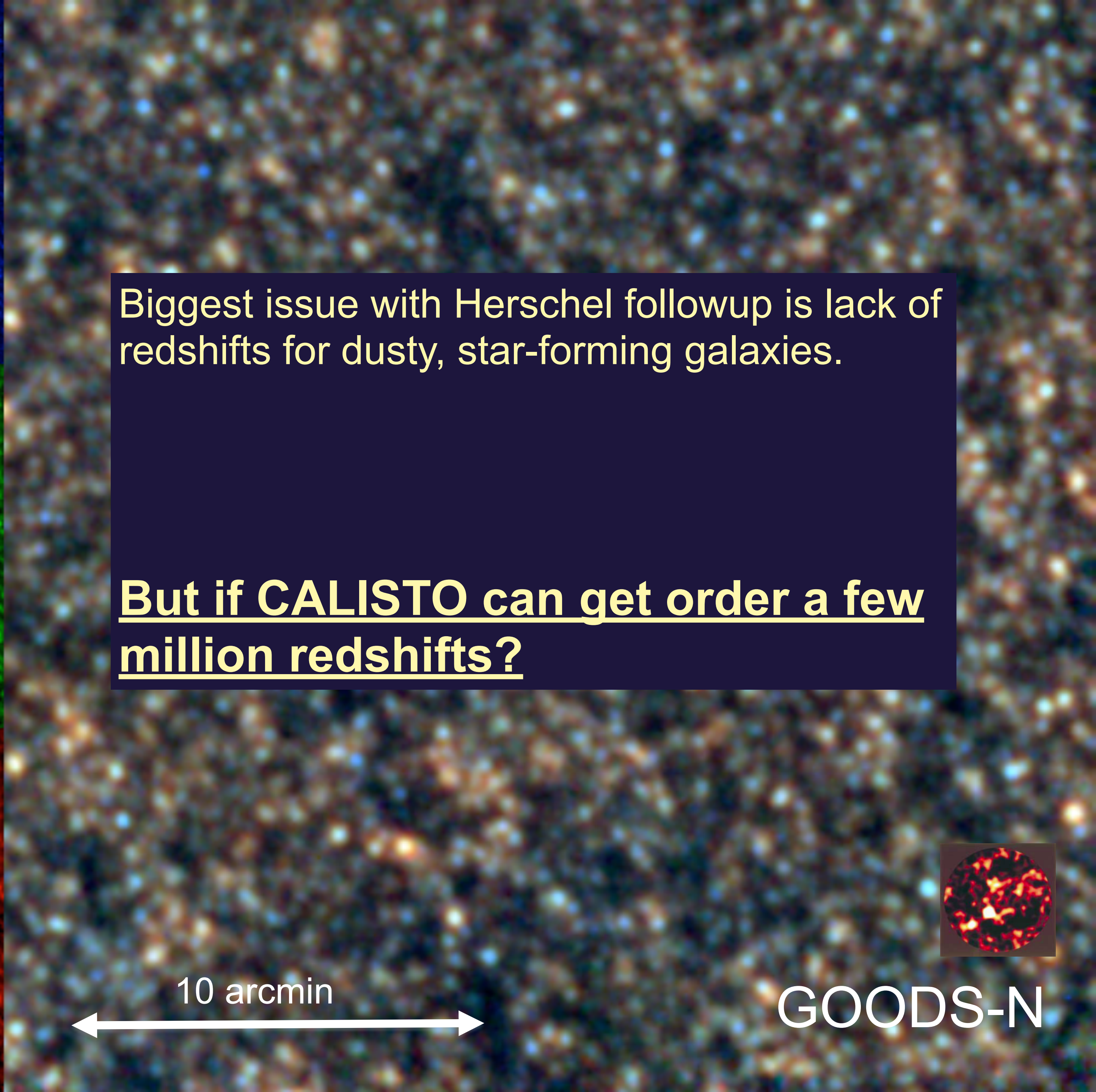




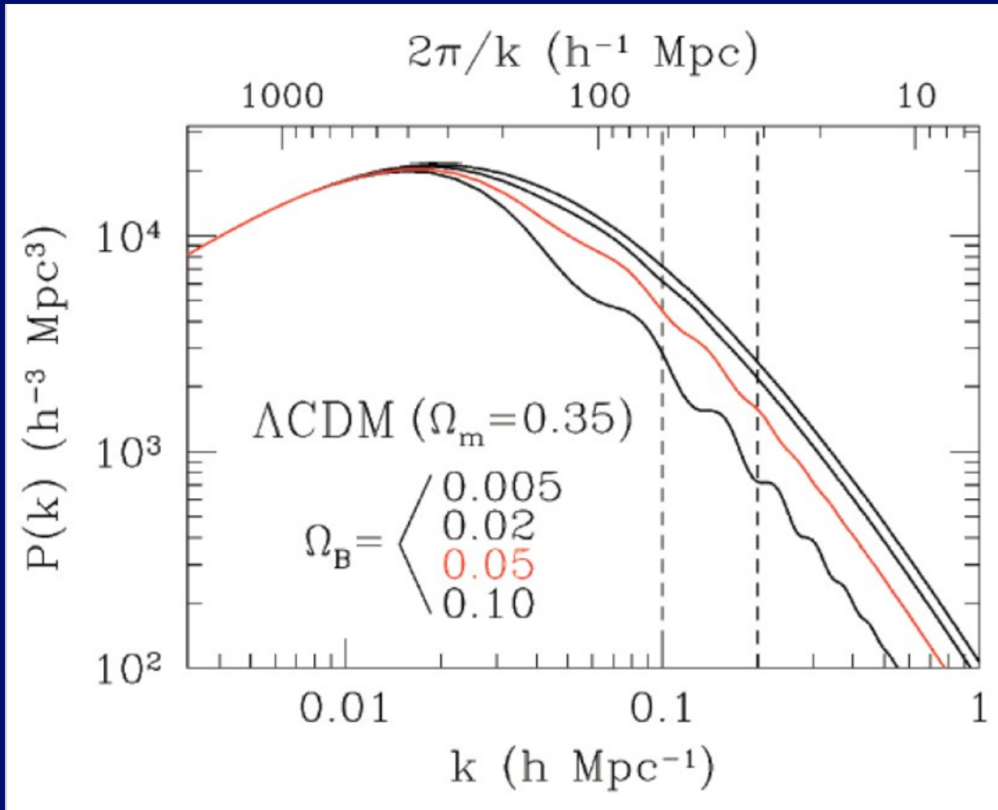


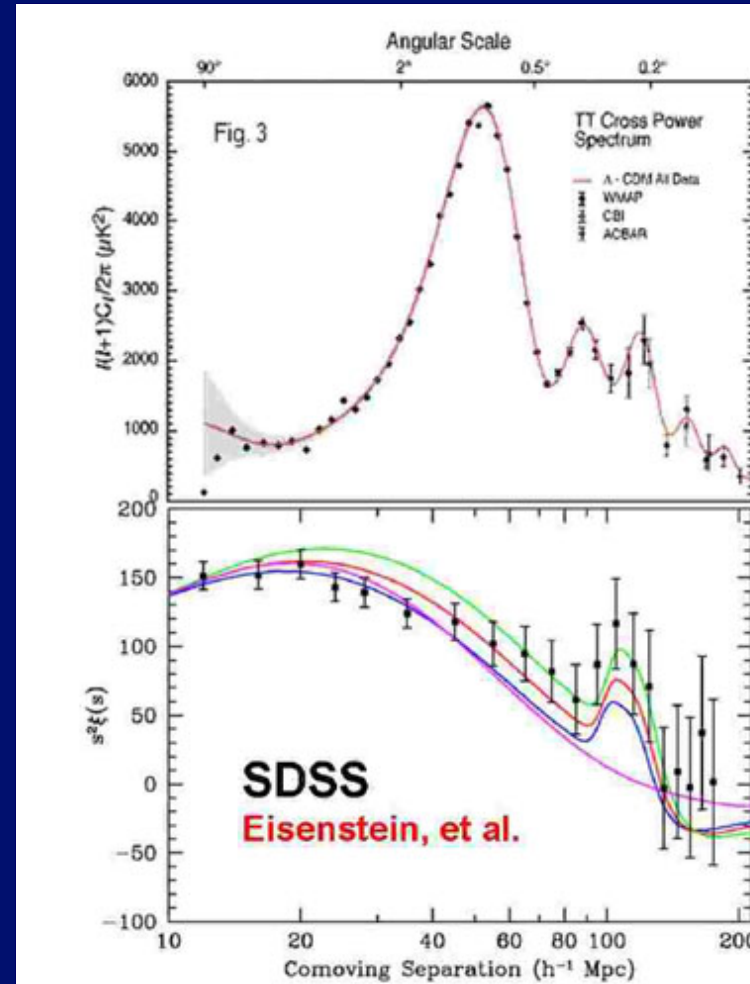
Biggest issue with Herschel followup is lack of redshifts for dusty, star-forming galaxies.

But if CALISTO can get order a few million redshifts?



3D Correlations or Power Spectrum

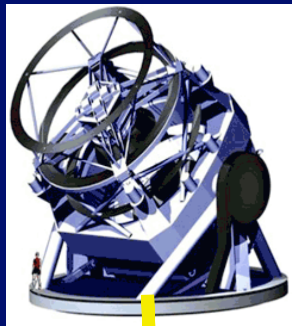


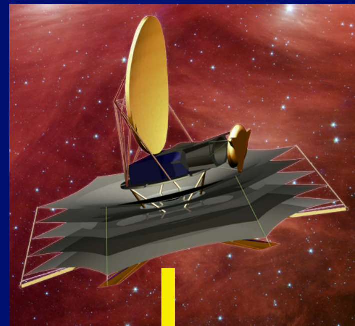


The projected wavenumber provides a measurement of the ang diameter distance, which in return probes cosmology.

What's next in far-IR in terms of cosmology?

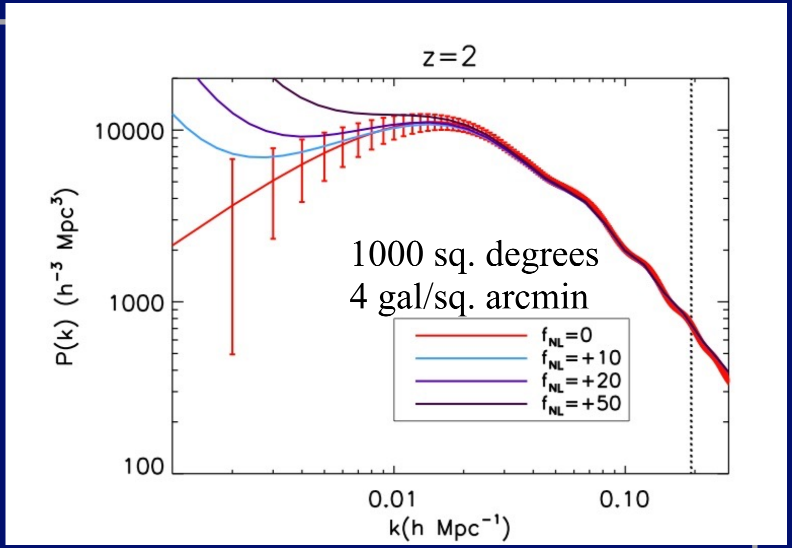
3D Correlations or Power Spectrum

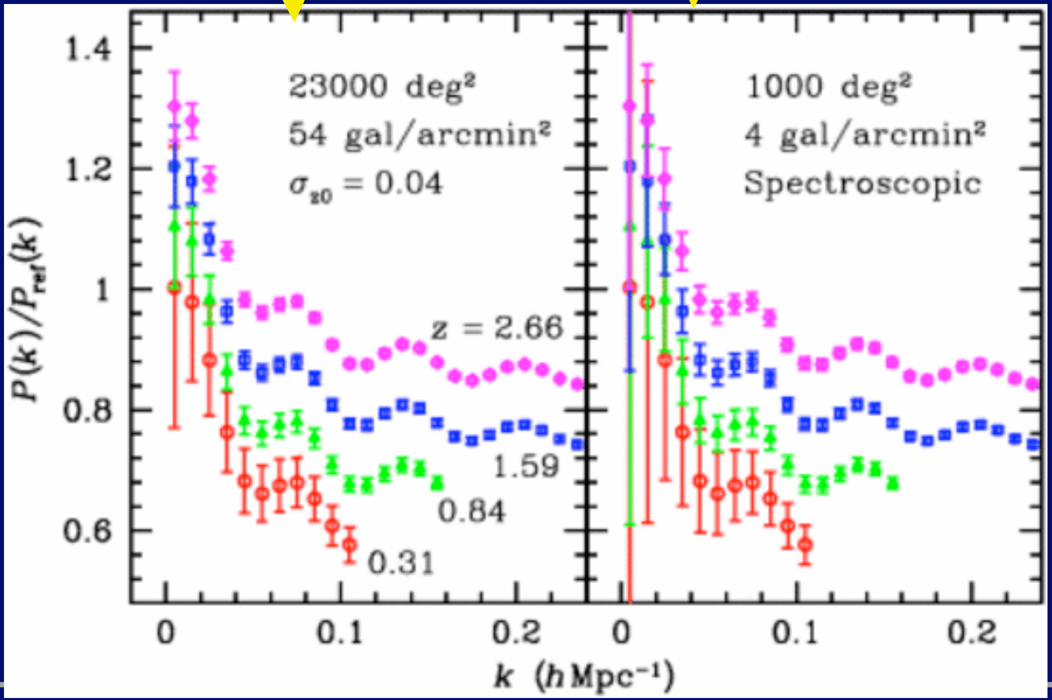


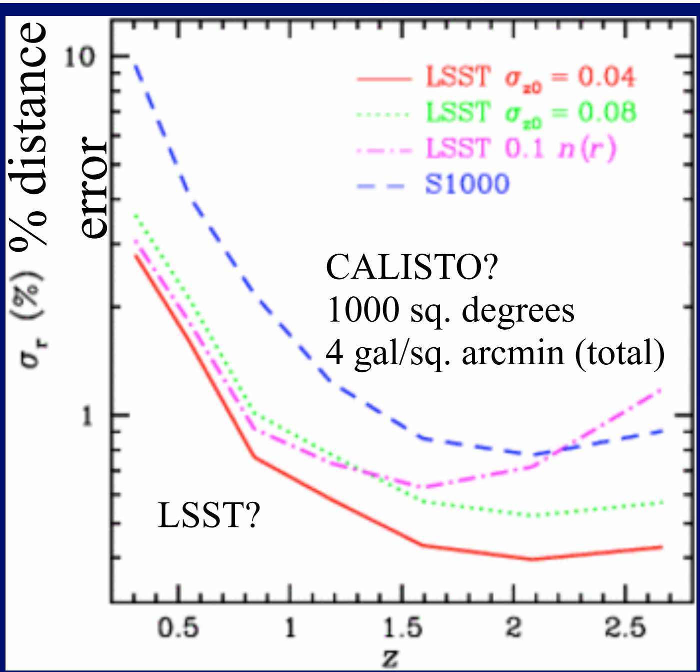


LSST+WFIRST

CALISTO?

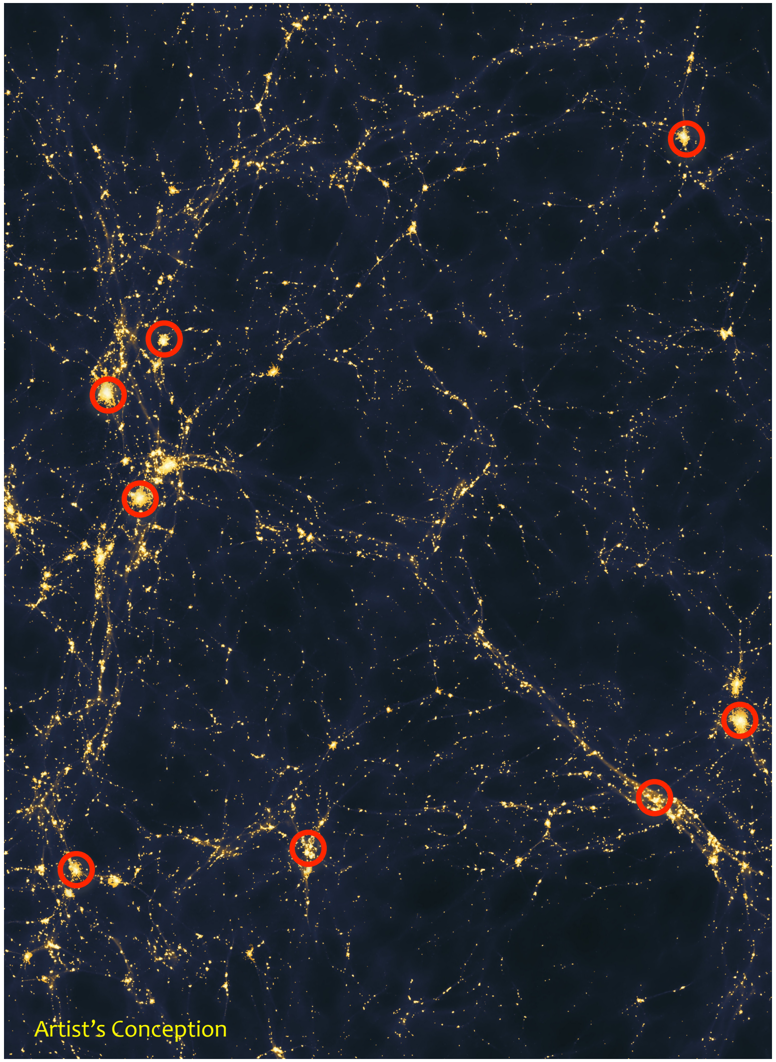






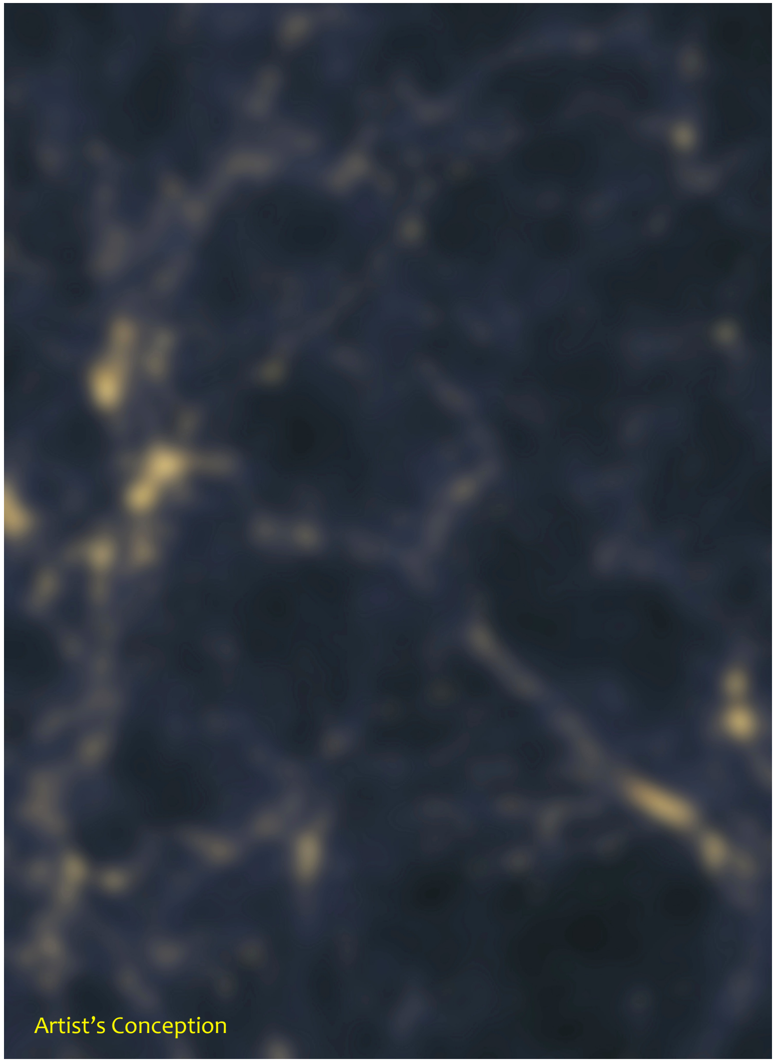
To-do: calculate al of these, parameters expected at z=1 to 3 with realistic survey
[But in 2030 1% cosmology distances to z of 2 could be old news]

An Introduction to Fluctuations



- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.

An Introduction to Fluctuations



- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.
- Alternatively, we could sum all the emission in large areas and measure fluctuations.
- This is called "Intensity Mapping".

Why Intensity Mapping?

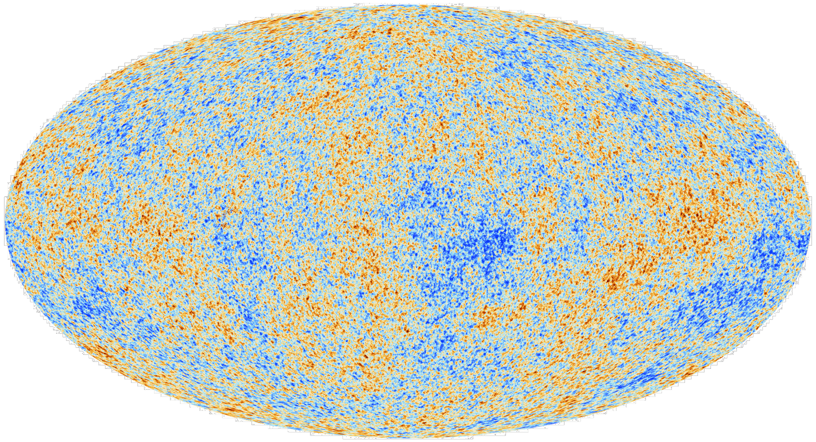
1. Individual sources are difficult to detect (sources are intrinsically faint, large instrument beam, etc),

2. We are interested in the total power from all sources, or

3. There is truly diffuse emission,

Science Applications:

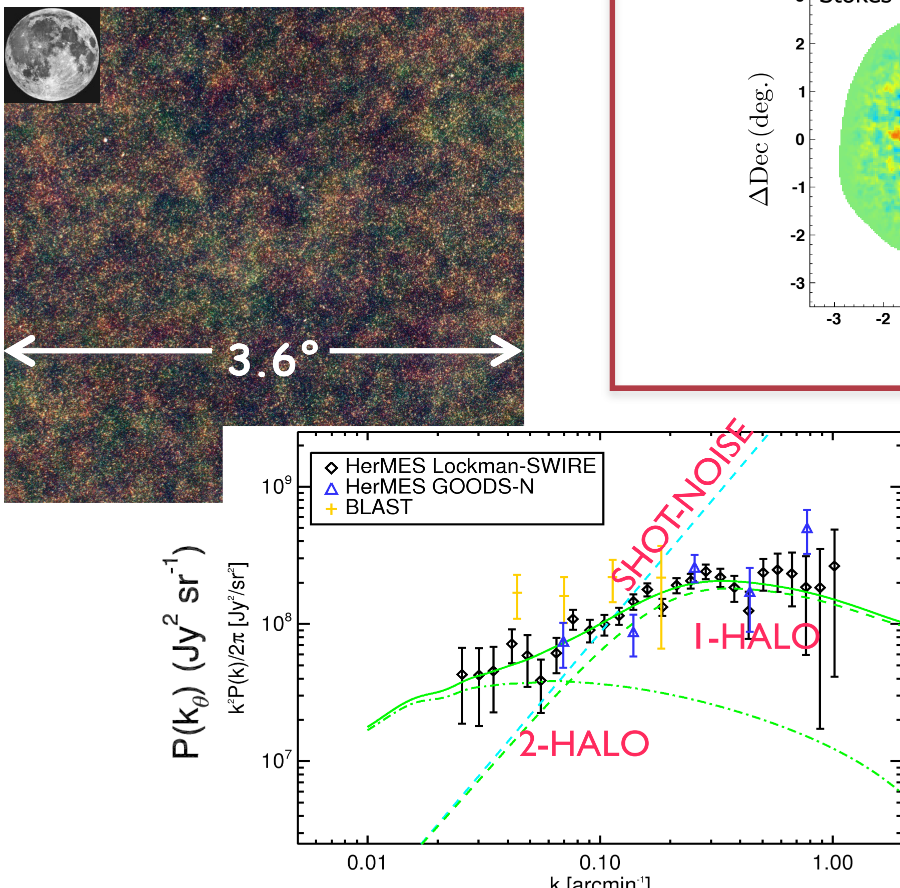
- Galaxy Evolution
- Dark Matter and Galaxy Formation
- Epoch of Reionization
- Baryon Acoustic Oscillations.



CMB is the canonical example of IM
(Planck Collaboration 2013).

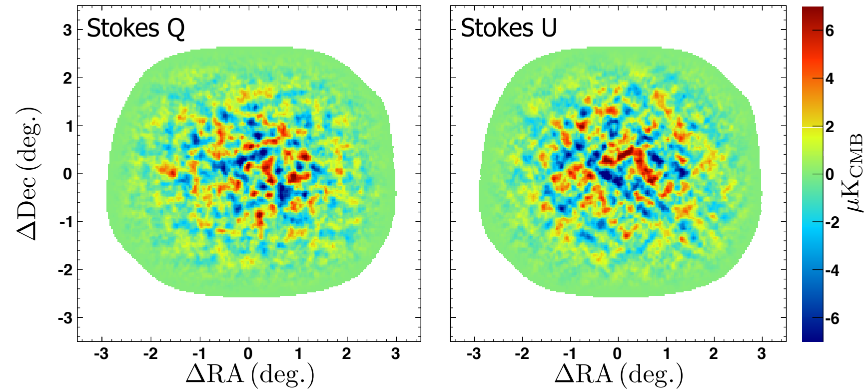
Recent Intensity Mapping Results

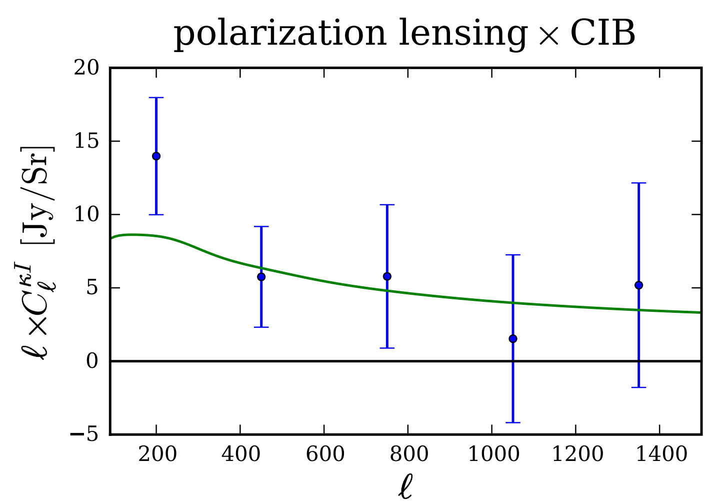
Herschel-SPIRE:



Amblard, Cooray *et al.* 2011, Nature

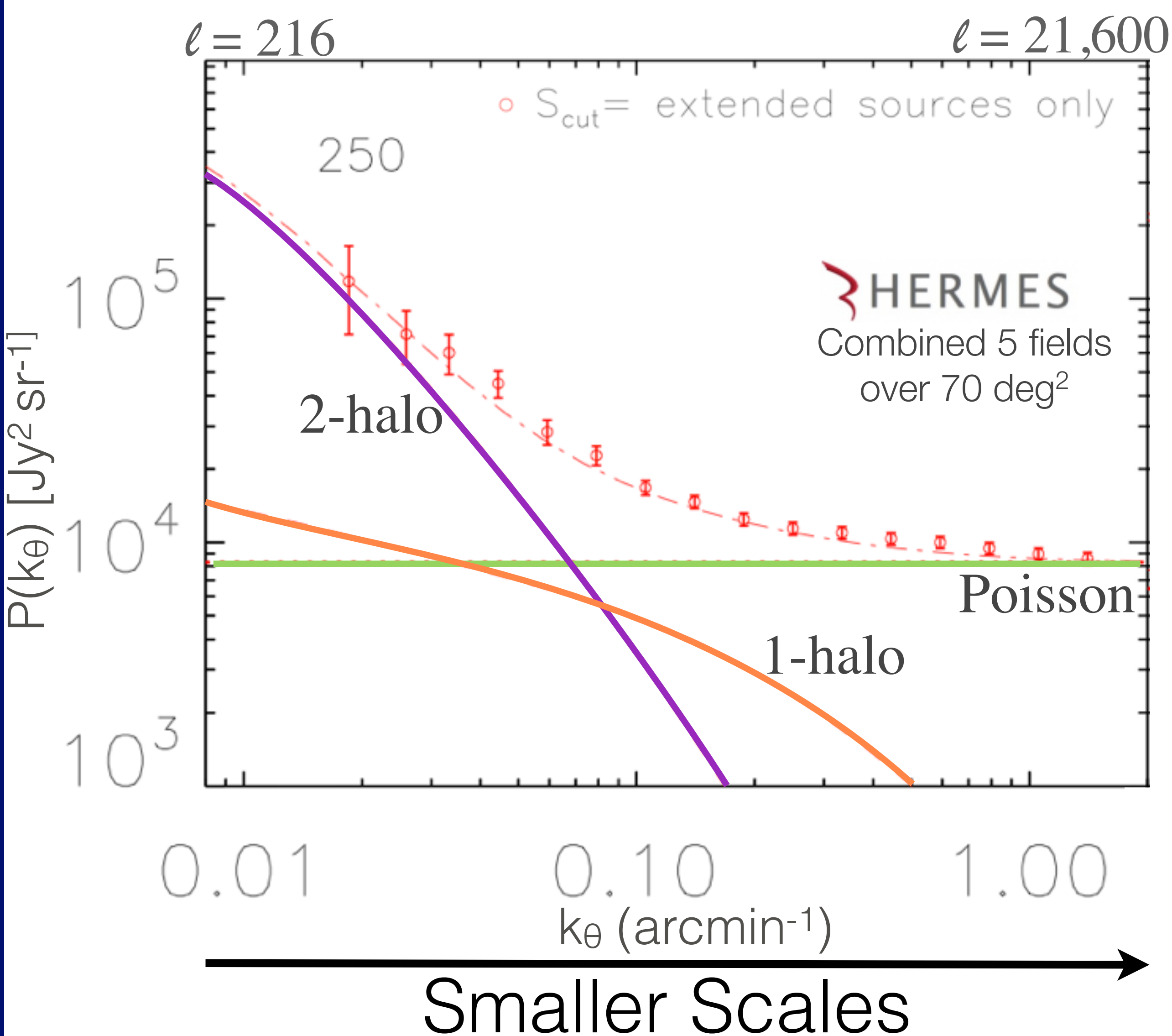
SPIRExPOLARBEAR B-modes:

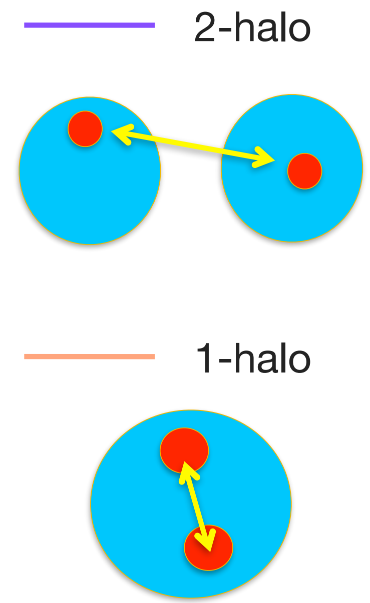




POLARBEAR *et al.* 2014, PRL

Viero et al. 2012



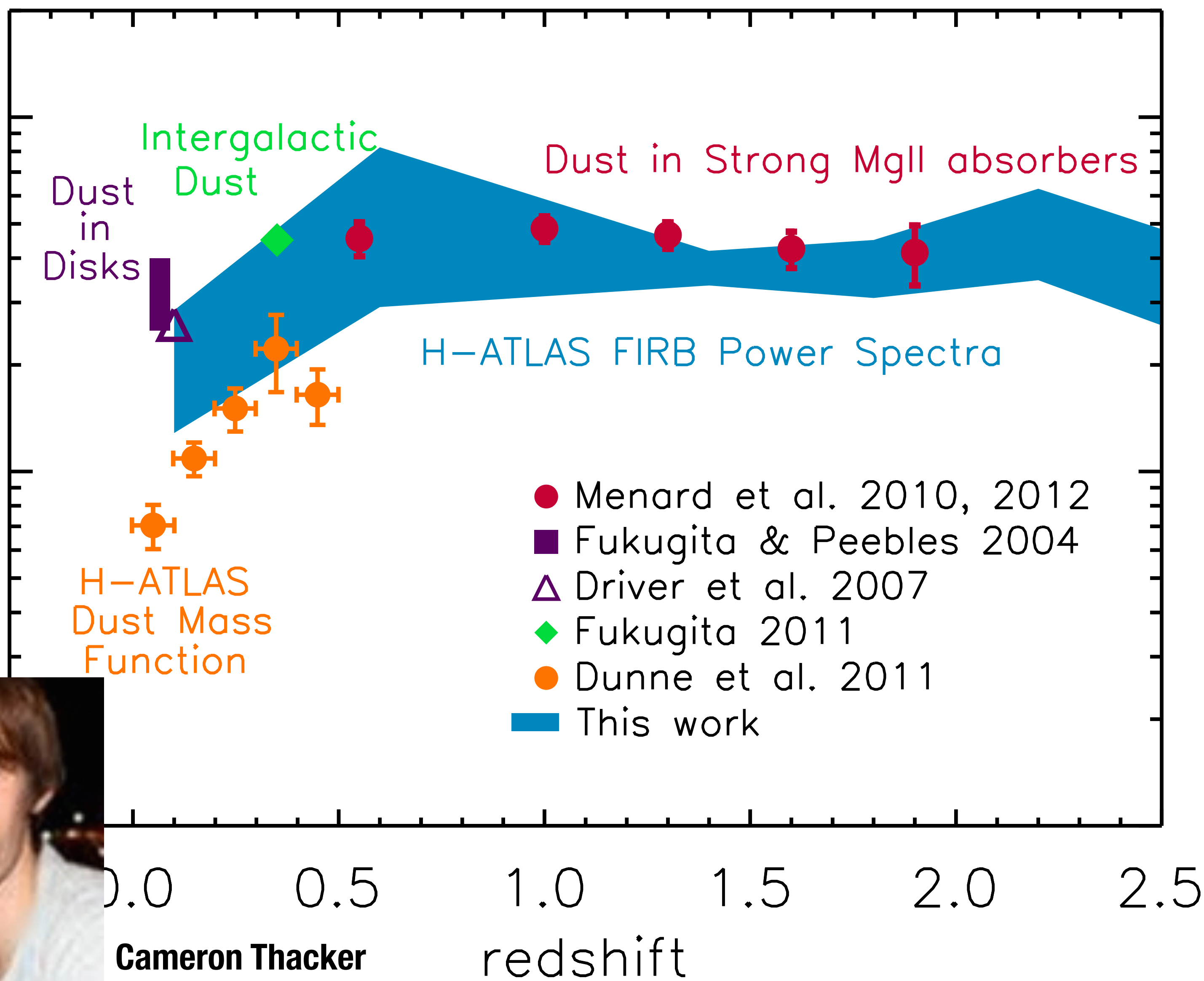


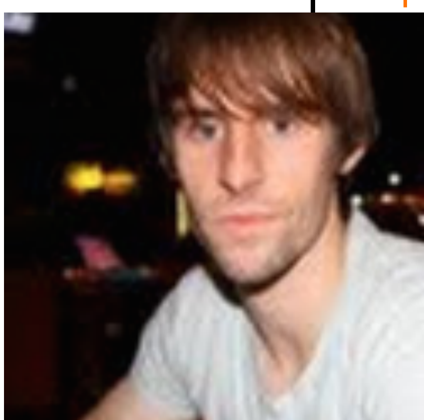
Halo Model: see e.g., Cooray & Sheth (2000), Zehavi et al. (2005, 2008)

Cosmic Infrared Background Fluctuations with SPIRE

Viero et al. 2012; Thacker et al. 2013

Cosmic Infrared Background Fluctuations = Dust Content



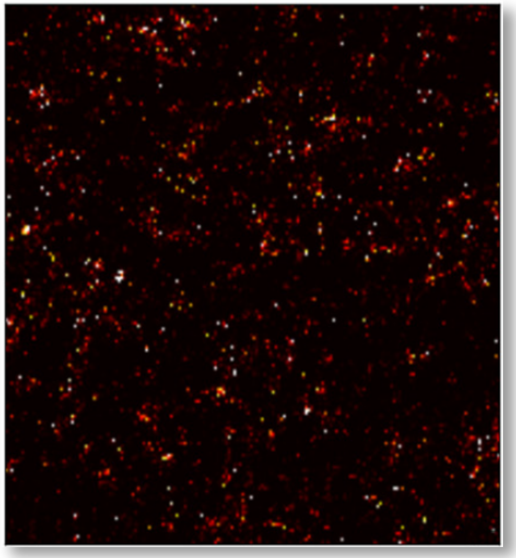


Cameron Thacker
UCI PhD 2015

3-D Intensity Mapping

Sky map at z

Intensity map at z



- No need to resolve individual source
- Measure the collective emission from many sources
- Map large volume and faint sources at high z economically

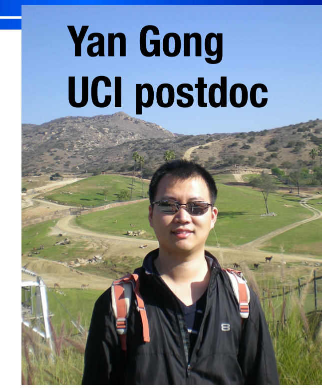
For CALISTO:

[CII] at z = 0 and 3

[OI] at z = 1 and 7 - extend to reionization

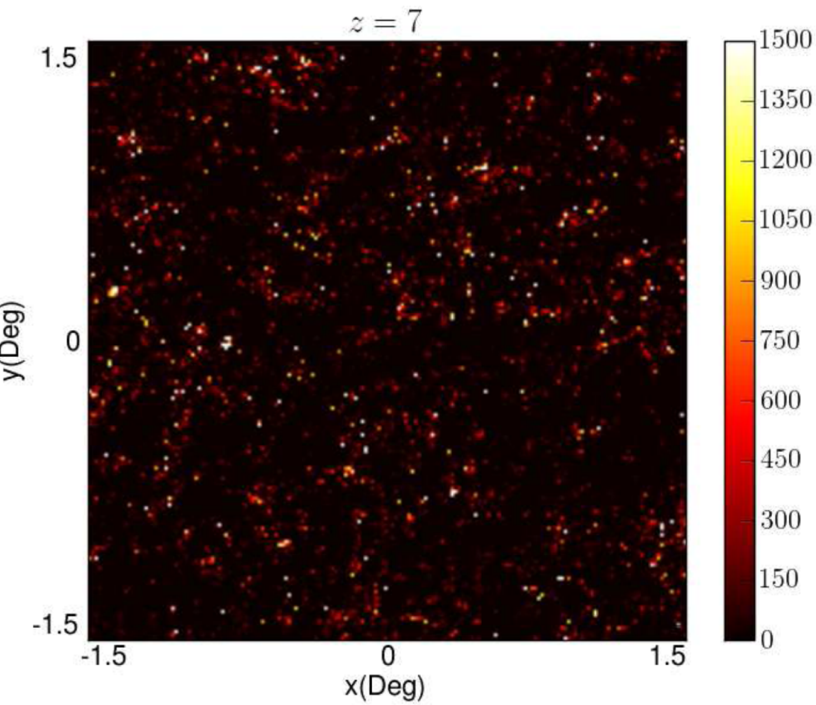
[OIII] … etc

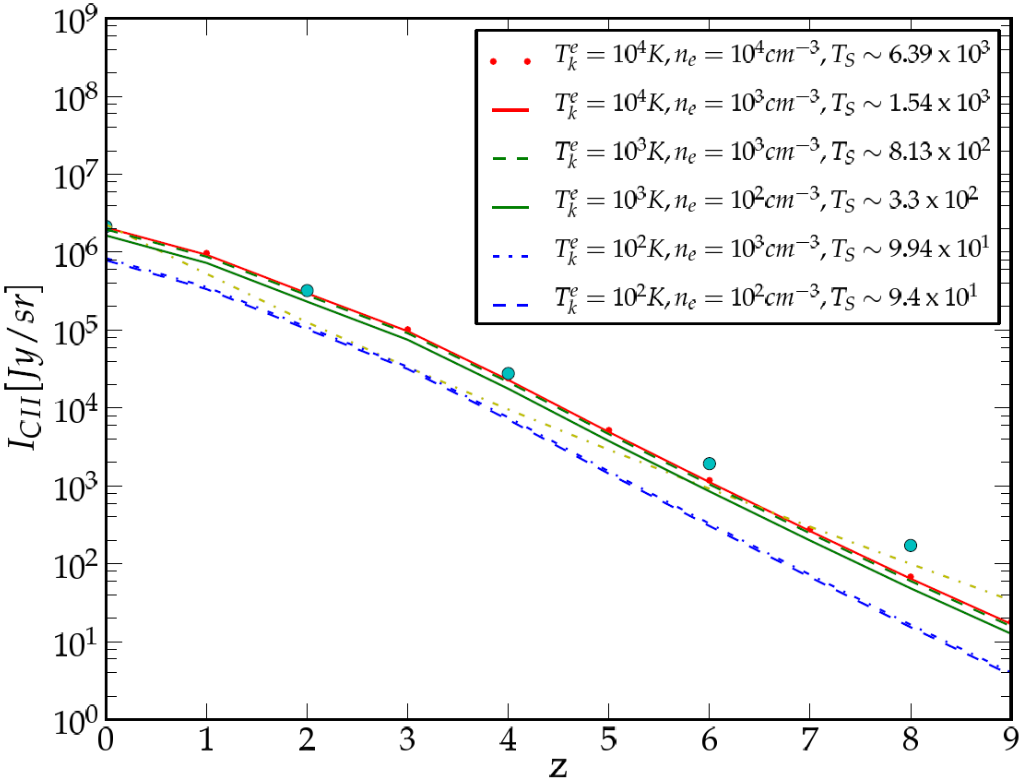
[CII] ([OI] is more interesting for CALISTO)



- [CII] serves as a tracer of star formation
- The clustering signal traces total luminosity
  - -> unlike a flux-limited galaxy survey
- Use [CII] to spatially trace SF during the reionization epoch

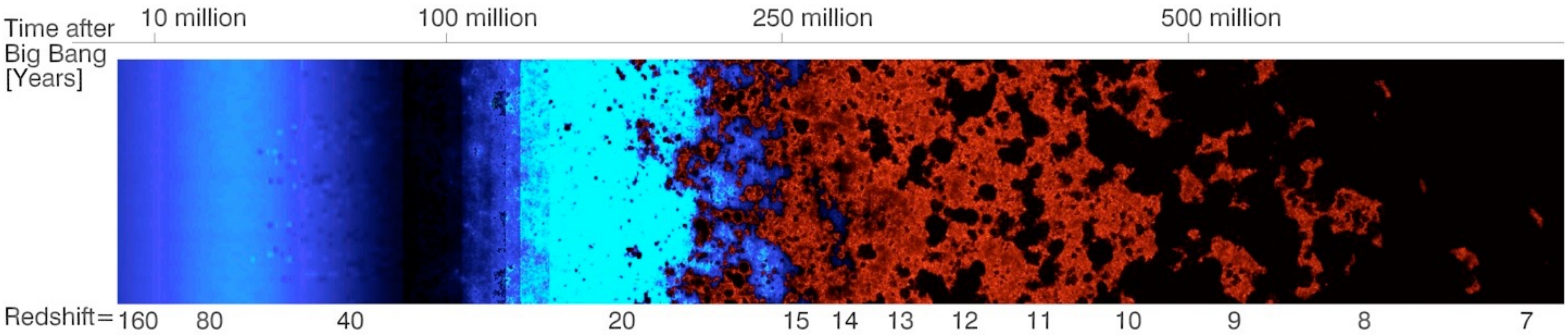
Simulated Sky in [CII]



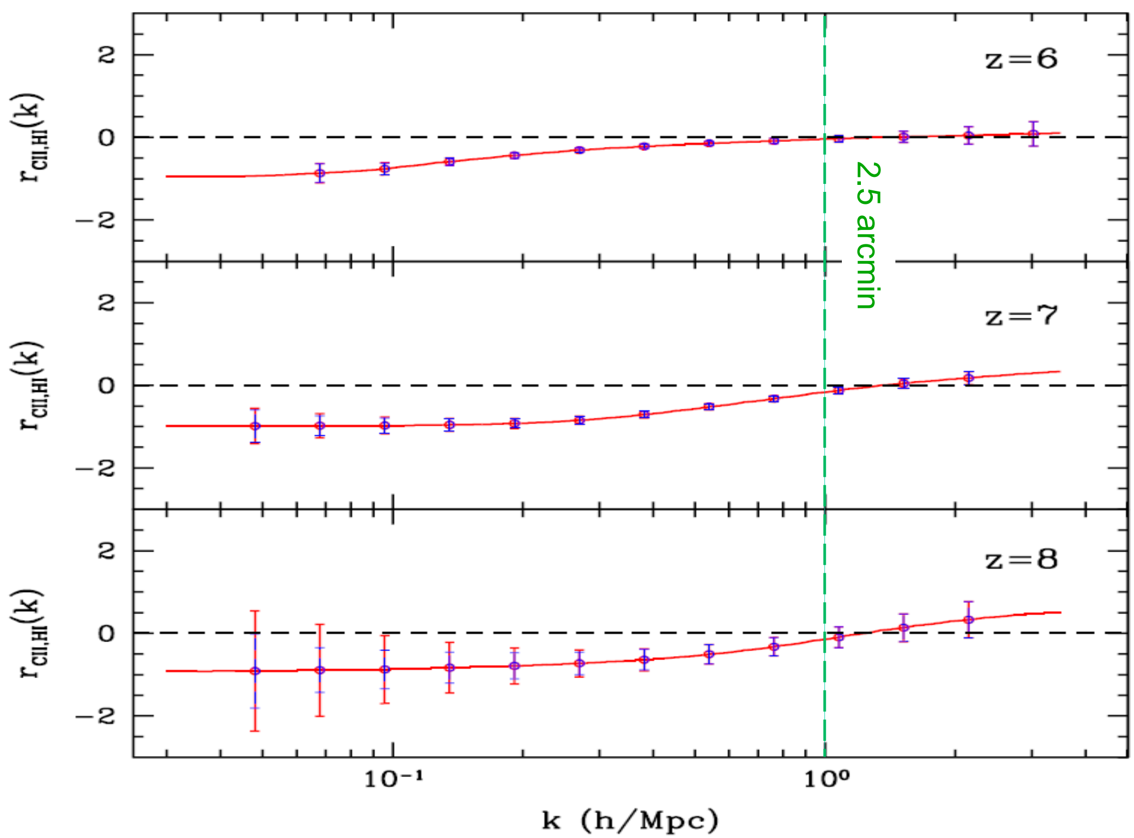


Gong, Cooray et al. 2012, ApJ 745, 49G

Using 21 cm & [CII] Together



[CII] and 21 cm Cross-Correlation



- Star formation rate vs. z
- Ionization state vs. z
- Bubble size

Gong et al. 2012, ApJ 745, 49G

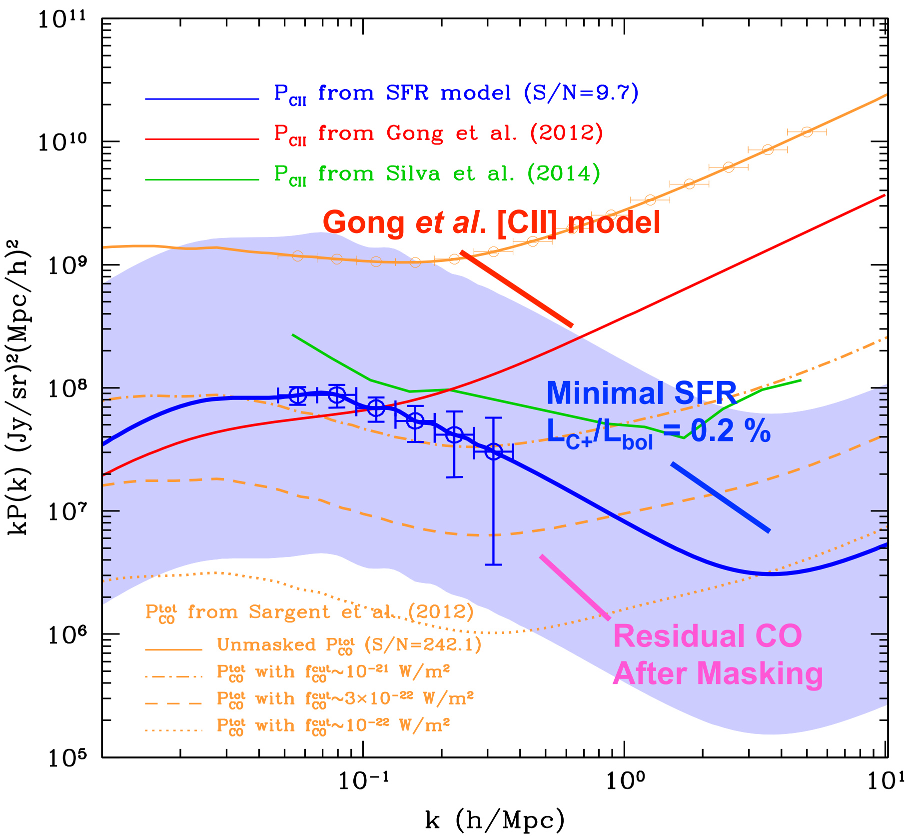
First Detections with TIME-*Pilot*

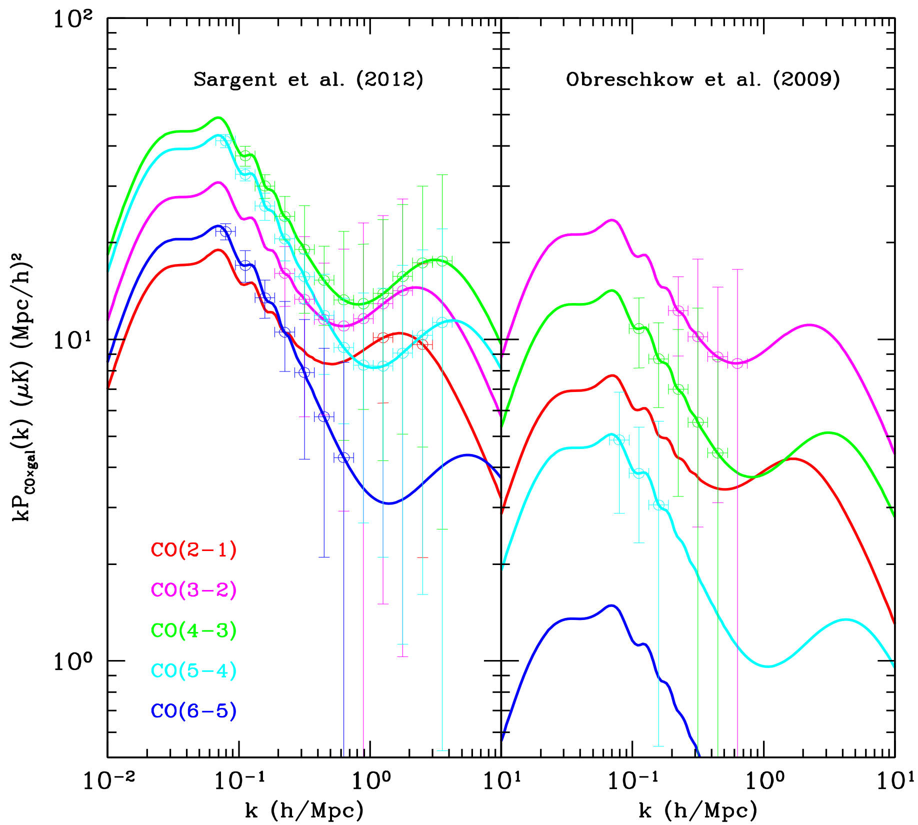
Epoch of Reionization Science

- Detect [CII] clustering
- Detect [CII] Poisson fluctuations
- Discriminate between models

Ancillary Science

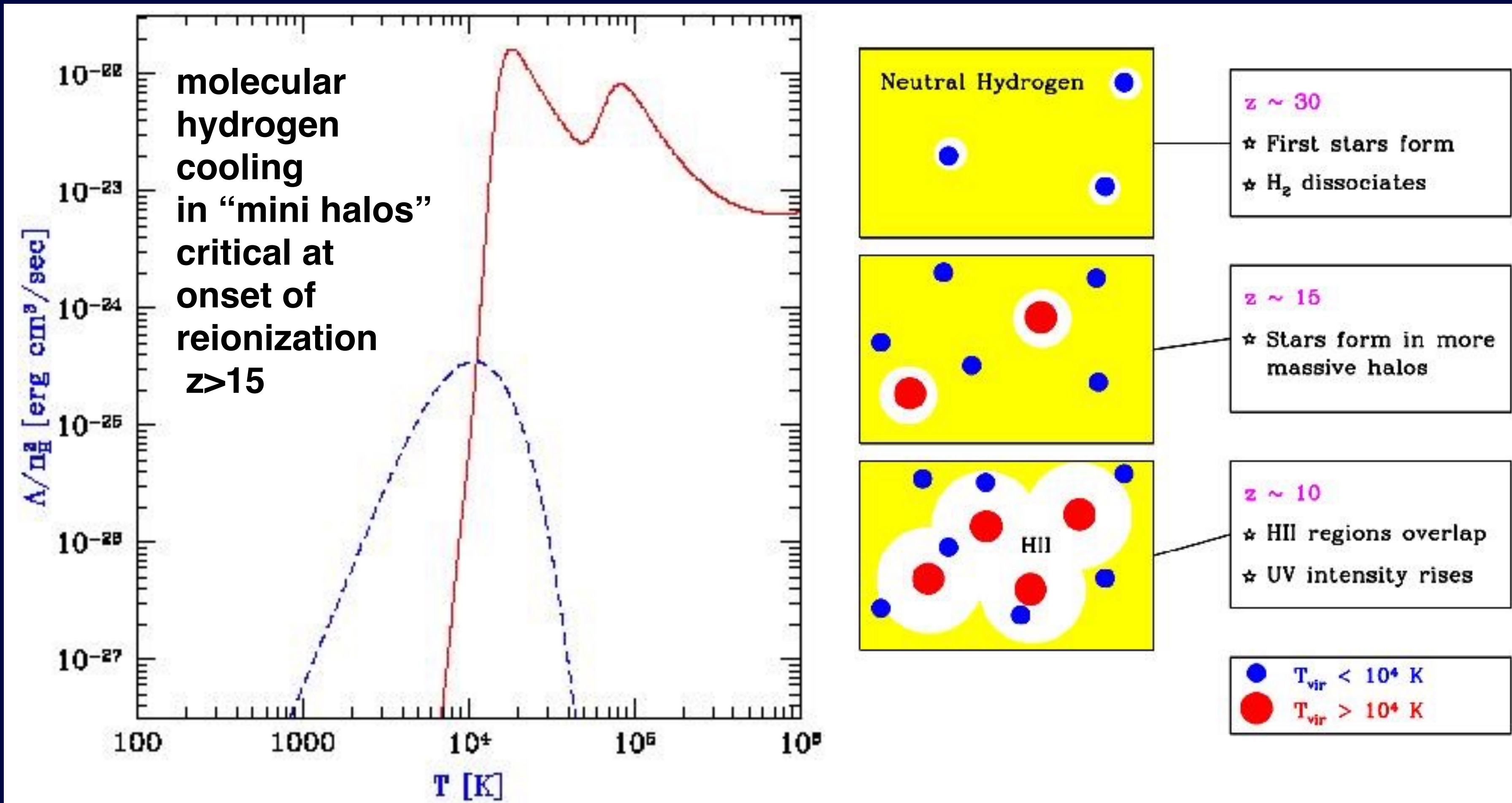
- CO clustering fluctuations
- Assess residual CO foreground
- Powerful kSZ instrument





For CALISTO, similar sciences at z = 6-8 with OI 63 microns.

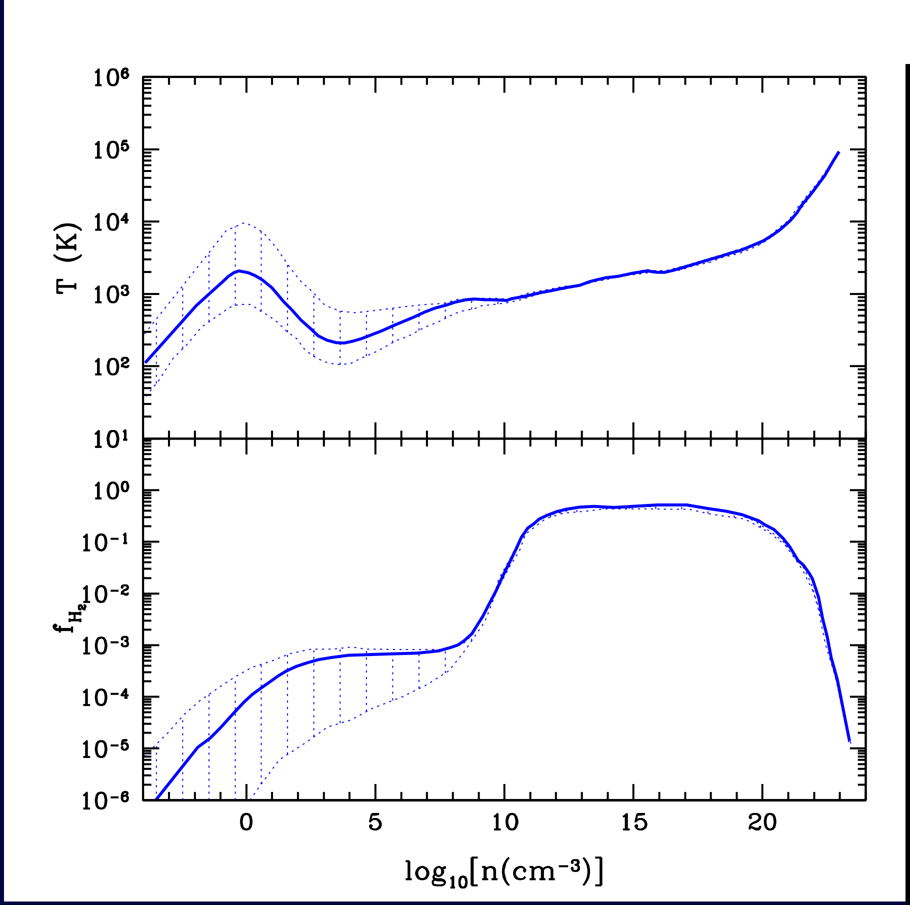
Molecular Hydrogen tracing primordial cooling sites/halos

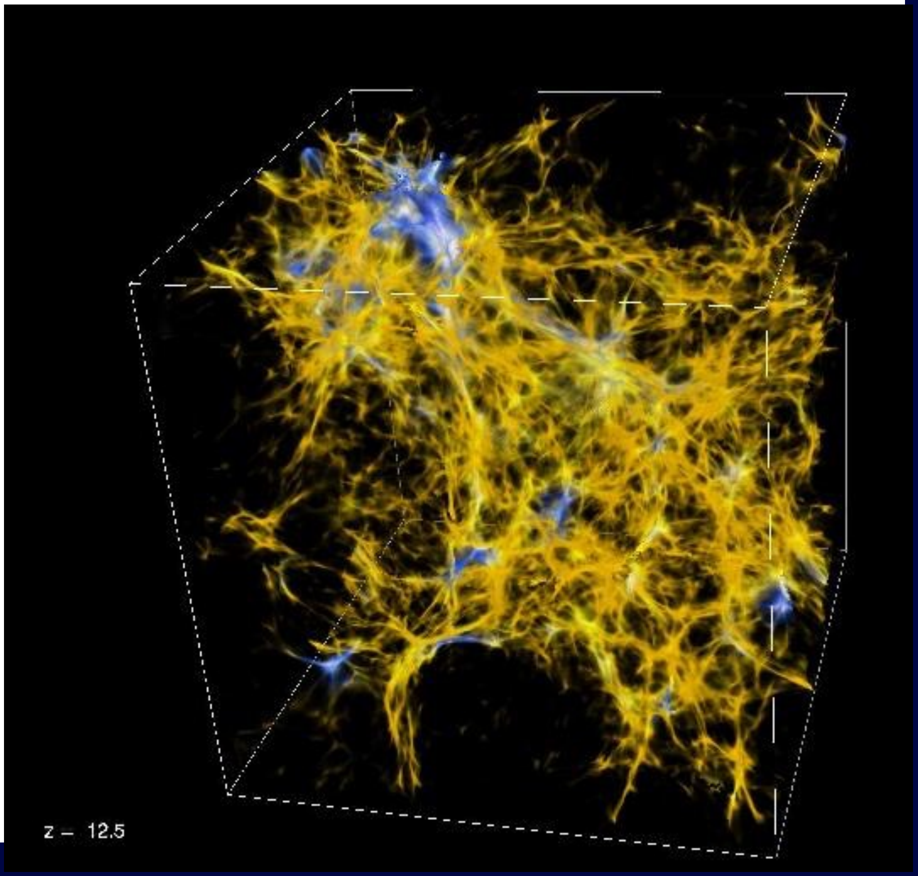


Outstanding problems at z > 6: billion to ten billion solar mass black-holes in SDSS quasars, Universe at < 600 Myr.
One solution is massive PopIII clusters collapsing - seed blackholes.
Need formation in minihalos at z > 15.

Molecular Hydrogen tracing primordial cooling sites/halos

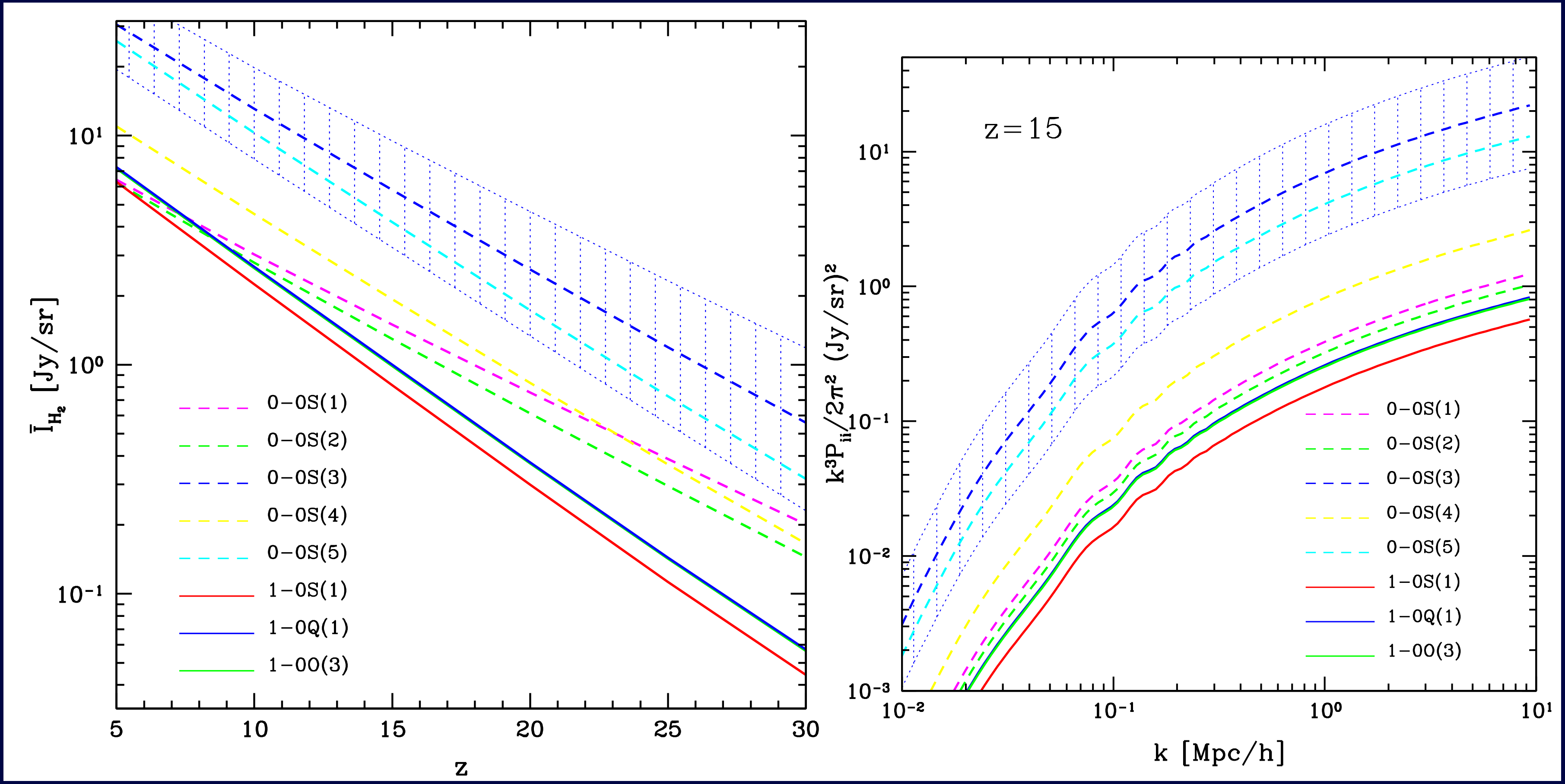
Gong et al. 2012, ApJ
arXiv:1212.2964



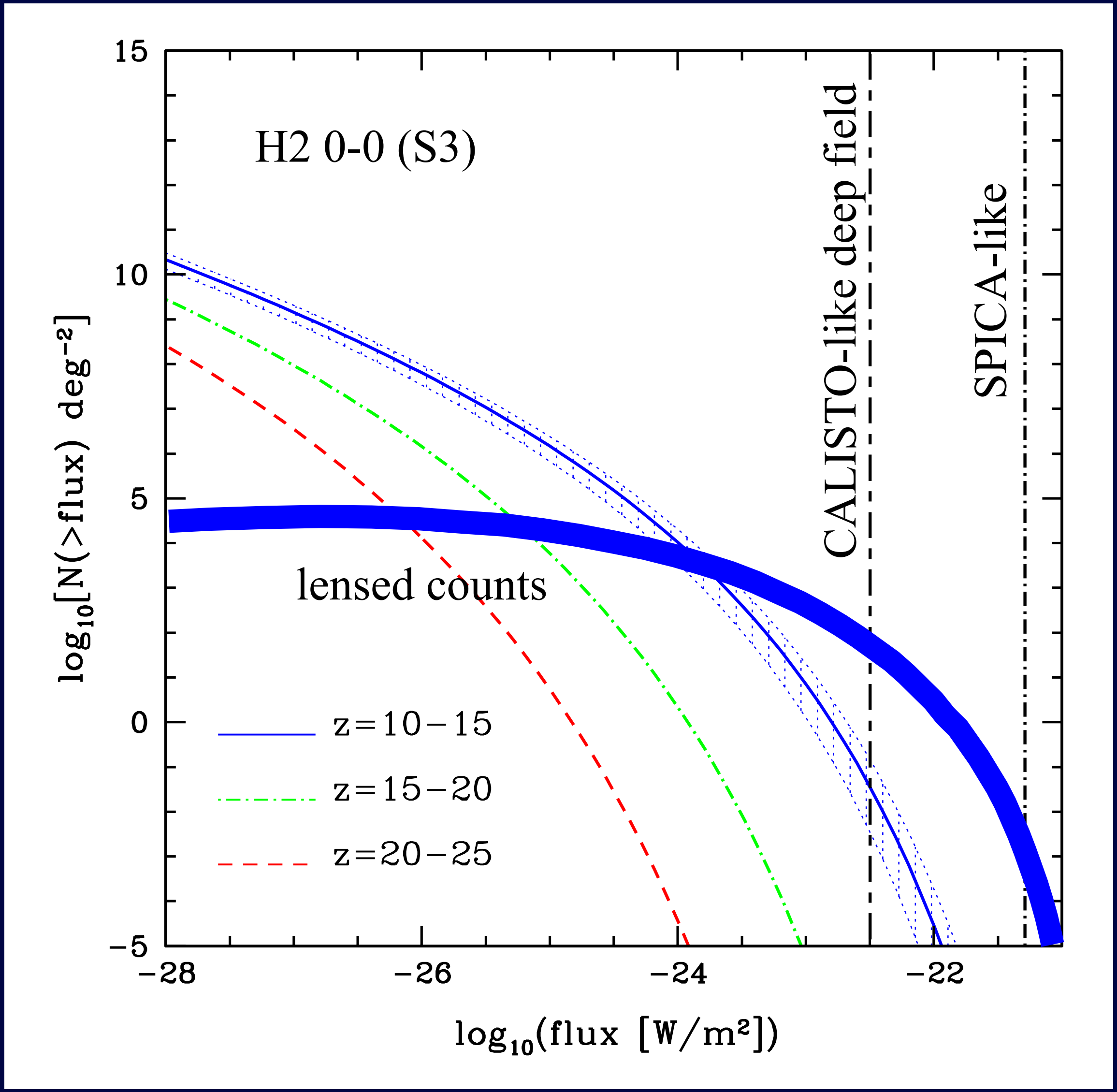


Molecular Hydrogen tracing primordial cooling sites/halos

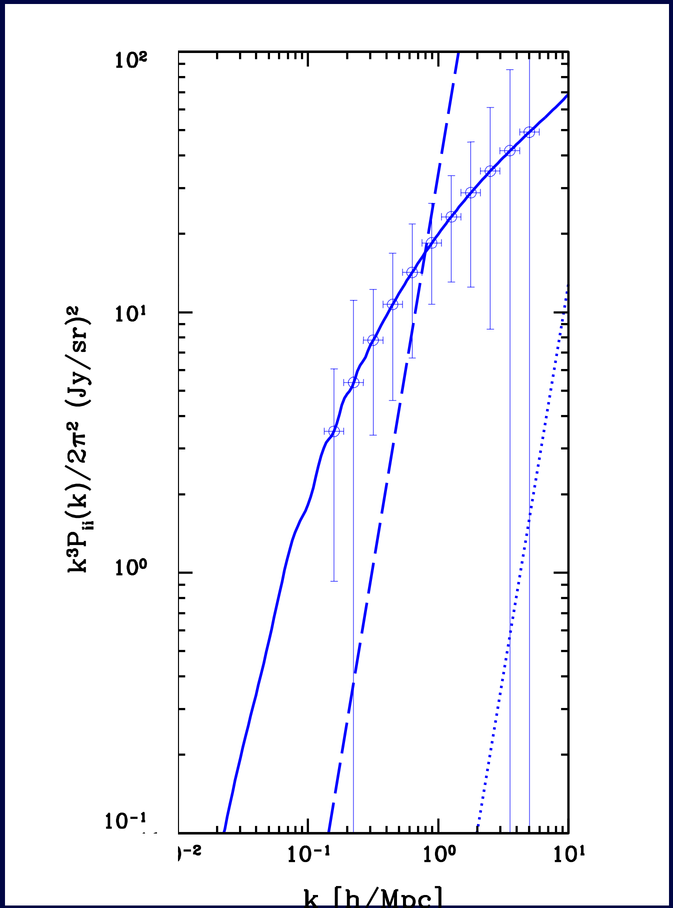
Gong et al. 2012, ApJ
arXiv:1212.2964



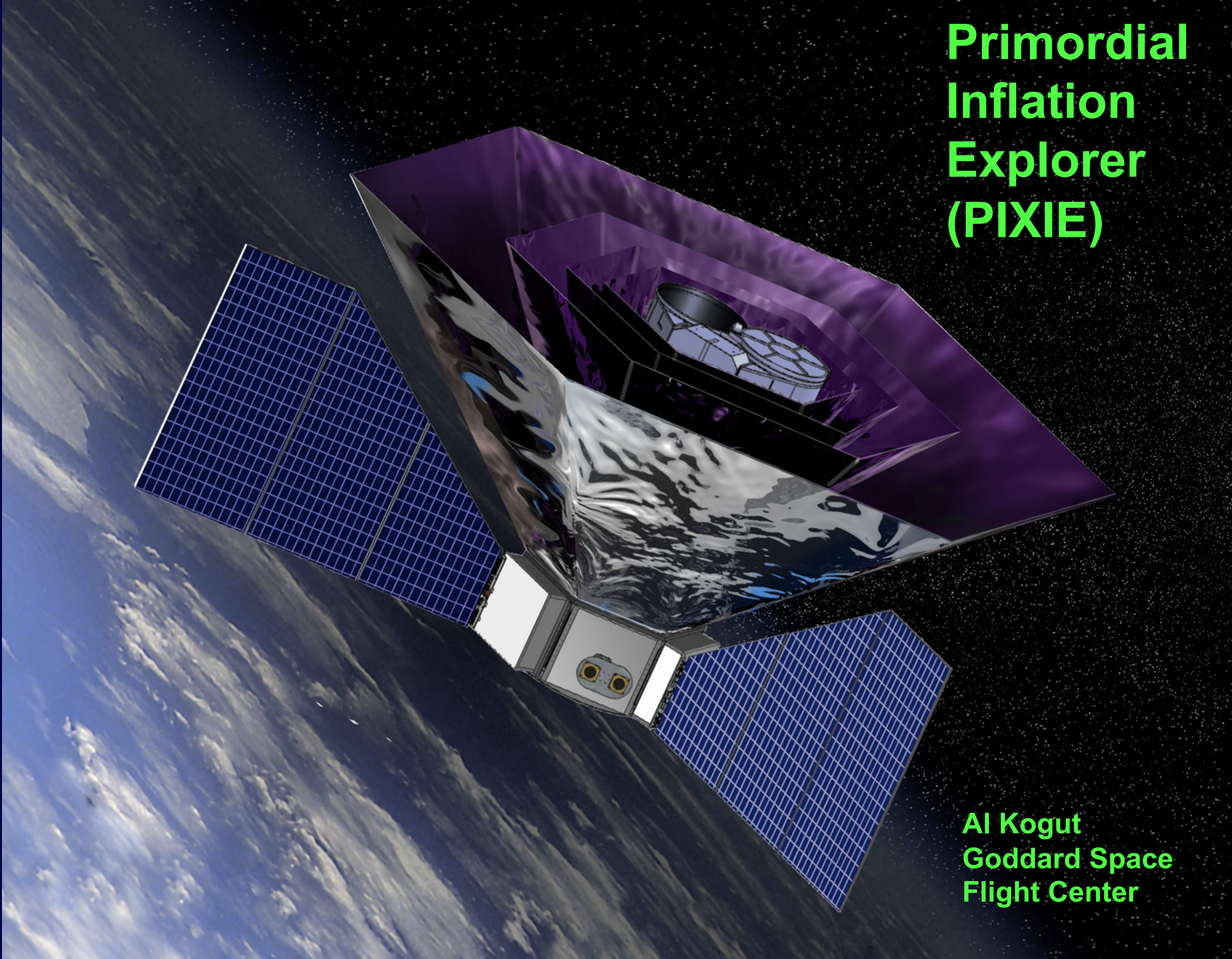
Molecular Hydrogen tracing primordial cooling sites/halos



Gong et al. 2012, ApJ
arXiv:1212.2964

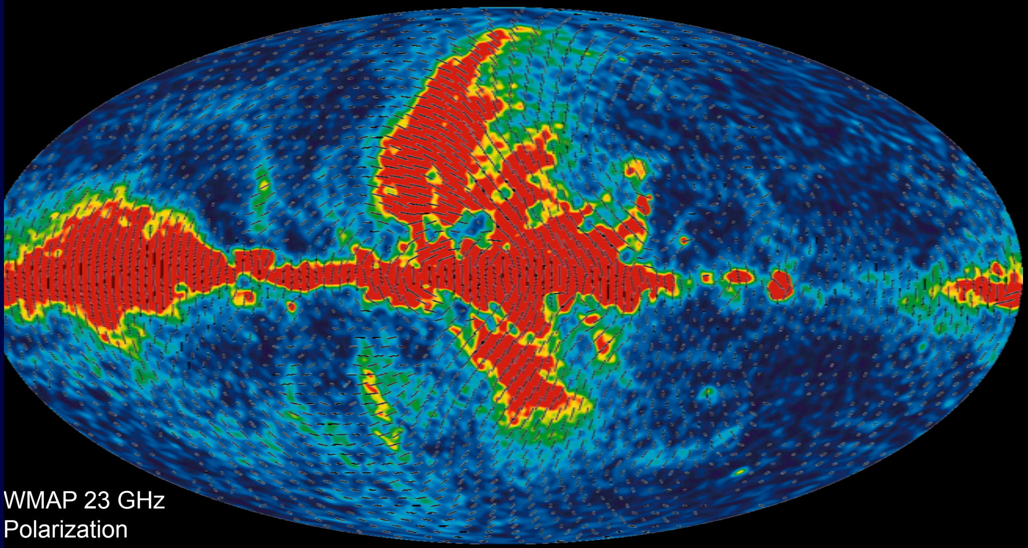


Primordial Inflation Explorer (PIXIE)



Al Kogut
Goddard Space Flight Center

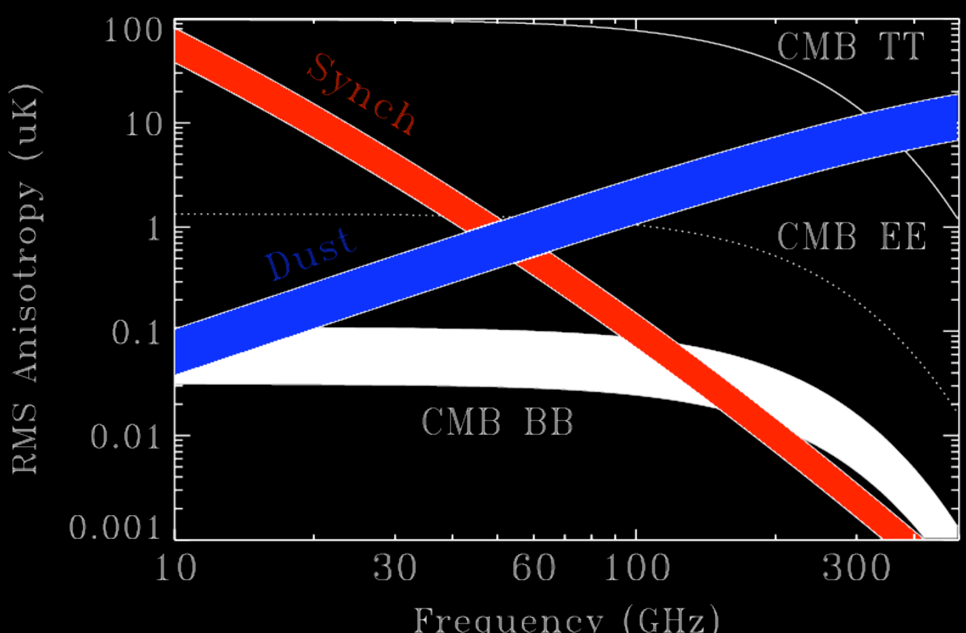
B-Mode Fundamentals


WMAP 23 GHz
Polarization

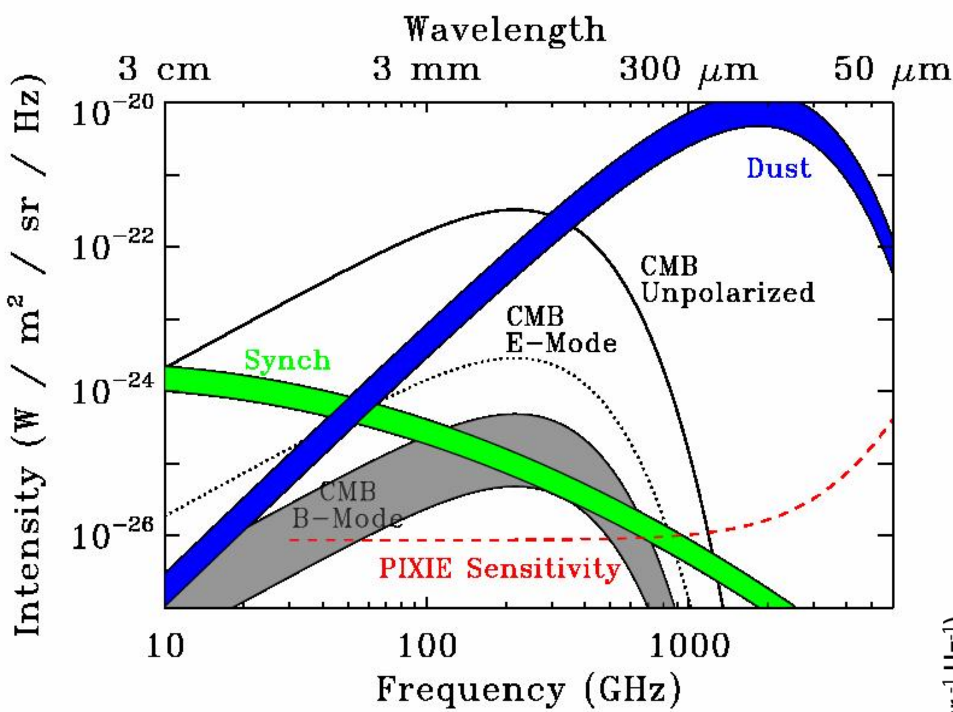
Signal is faint
Foregrounds are bright
Everything is confusing

Requirements for B-Mode Detection

- Sensitivity
- Foreground Subtraction
- Systematic Error Control



Foreground Subtraction



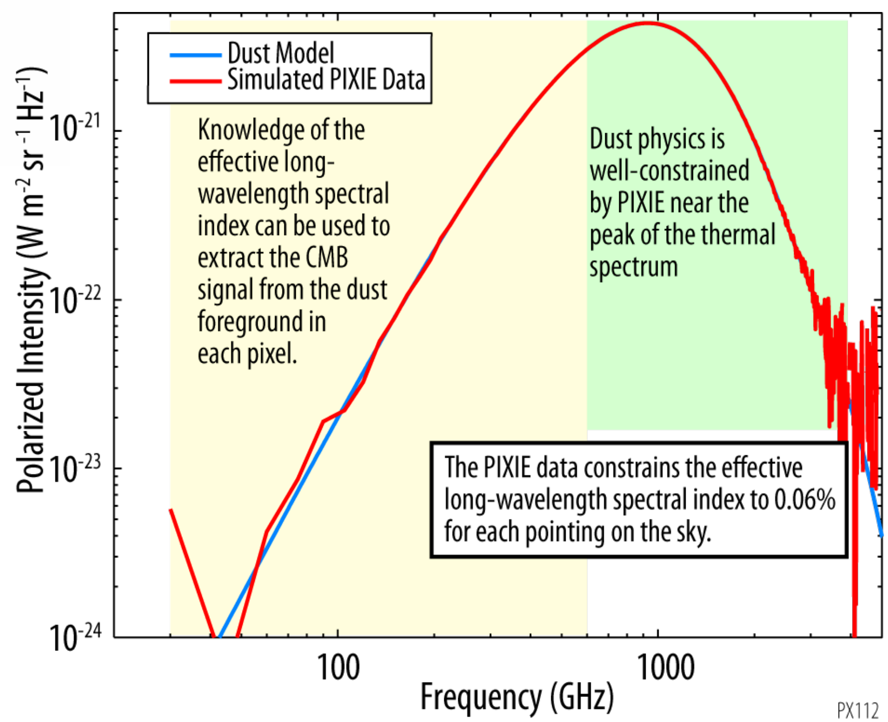
Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz
400 channels to fit 15 free parameters
Foreground noise penalty only 2%

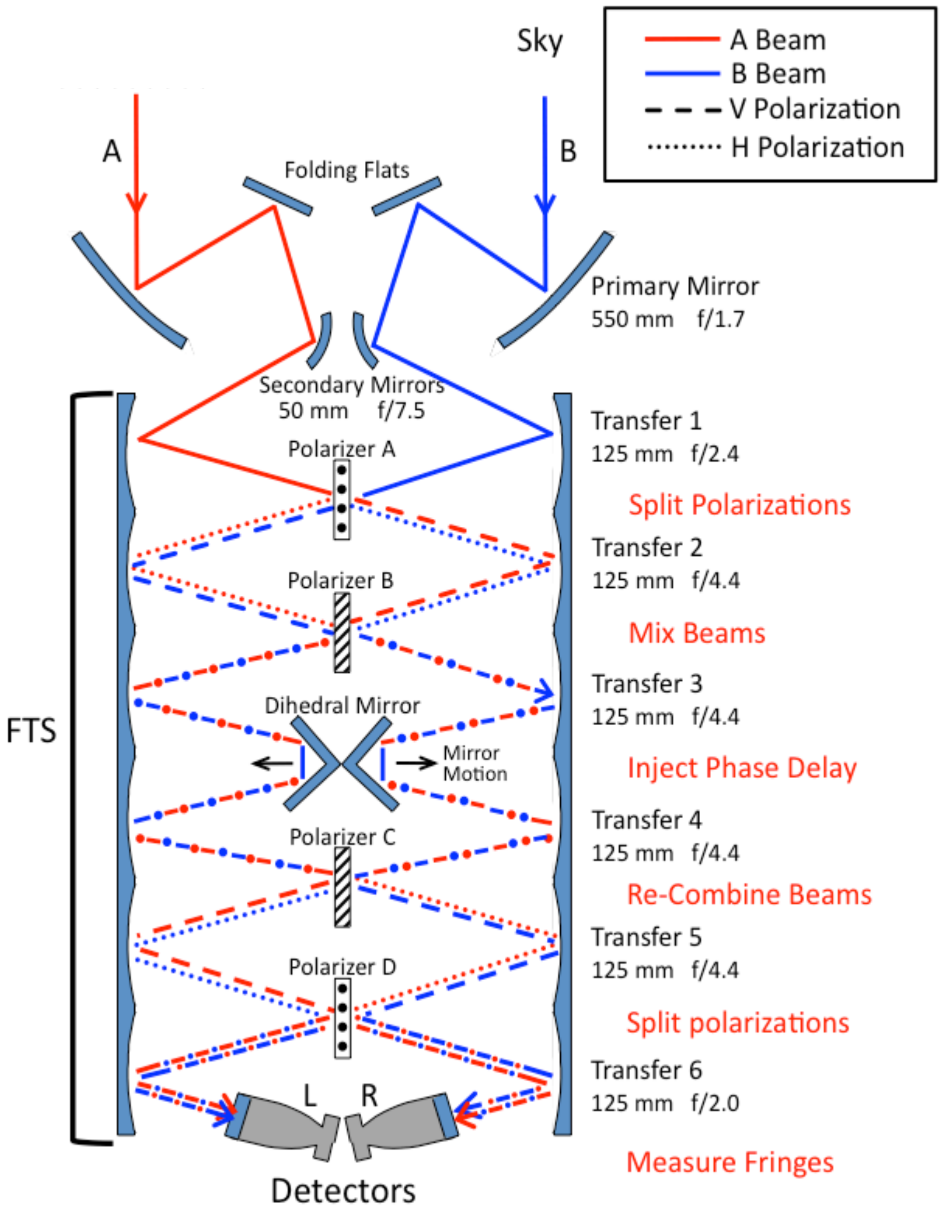
15 GHz spectral resolution;
1-3 degree beam on the sky
all-sky

Sensitivity plus broad frequency coverage

Foreground S/N > 100 in each pixel and freq bin
Spectral index uncertainty ±0.001 in each pixel
Dust physics to inform foreground subtraction



PIXIE Nulling Polarimeter



Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

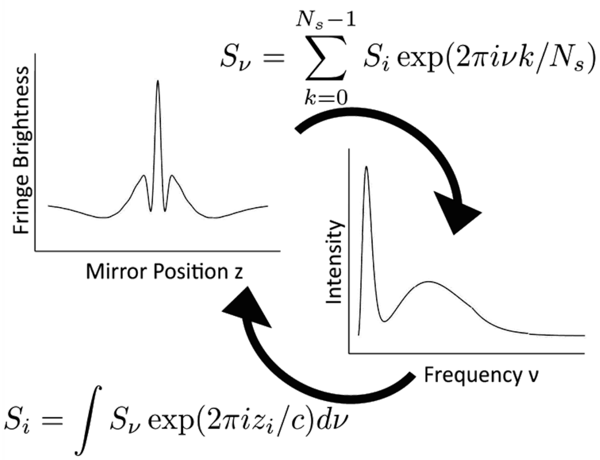
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\; d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \underbrace{\left(E_{By}^2 - E_{Ax}^2\right)}_{\text{Stokes Q}}\cos(z\omega/c)\; d\omega$$

Nulling Polarimeter: Zero = Zero

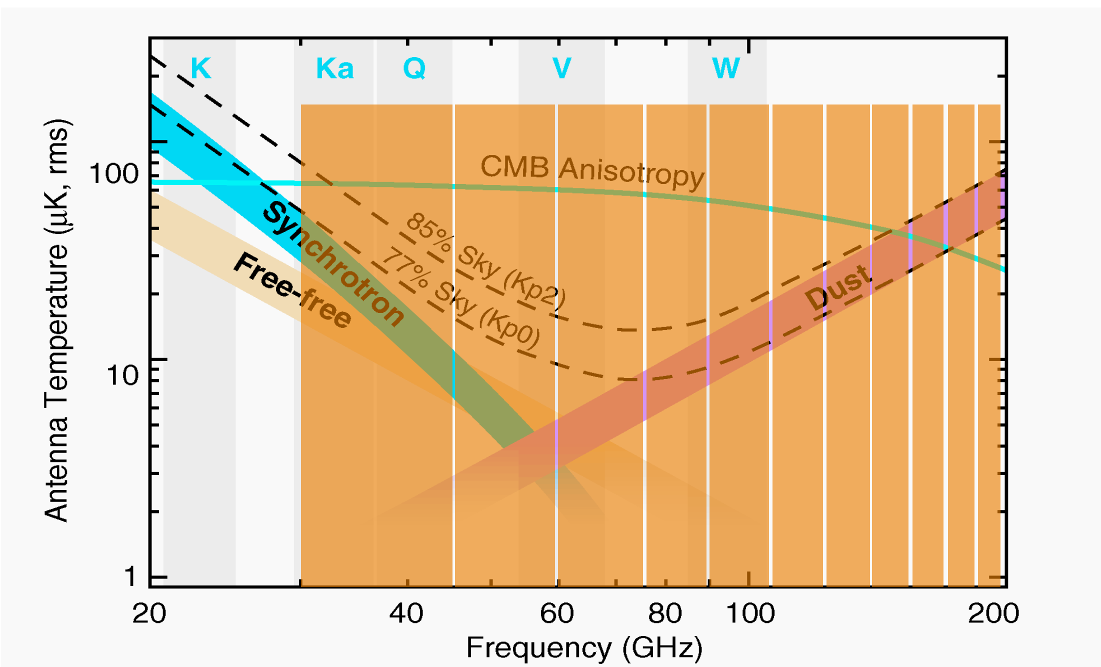
Kogut et al. 2011, JCAP, 7, 025
Kogut et al. 2011, SPIE, 7731, 77311S

Solving the Foreground Puzzle



Phase delay L sets channel width
$\Delta\nu = c/L = 15$ GHz

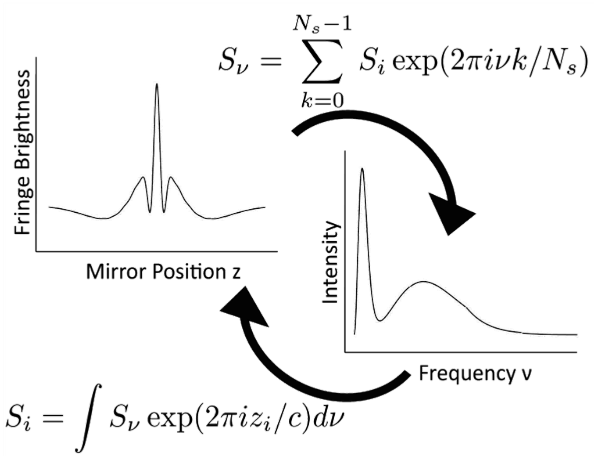
Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)^*\Delta\nu$



Example:
24 samples during fringe sweep
12 channels 15 GHz to 180 GHz

But why stop there?

Solving the Foreground Puzzle



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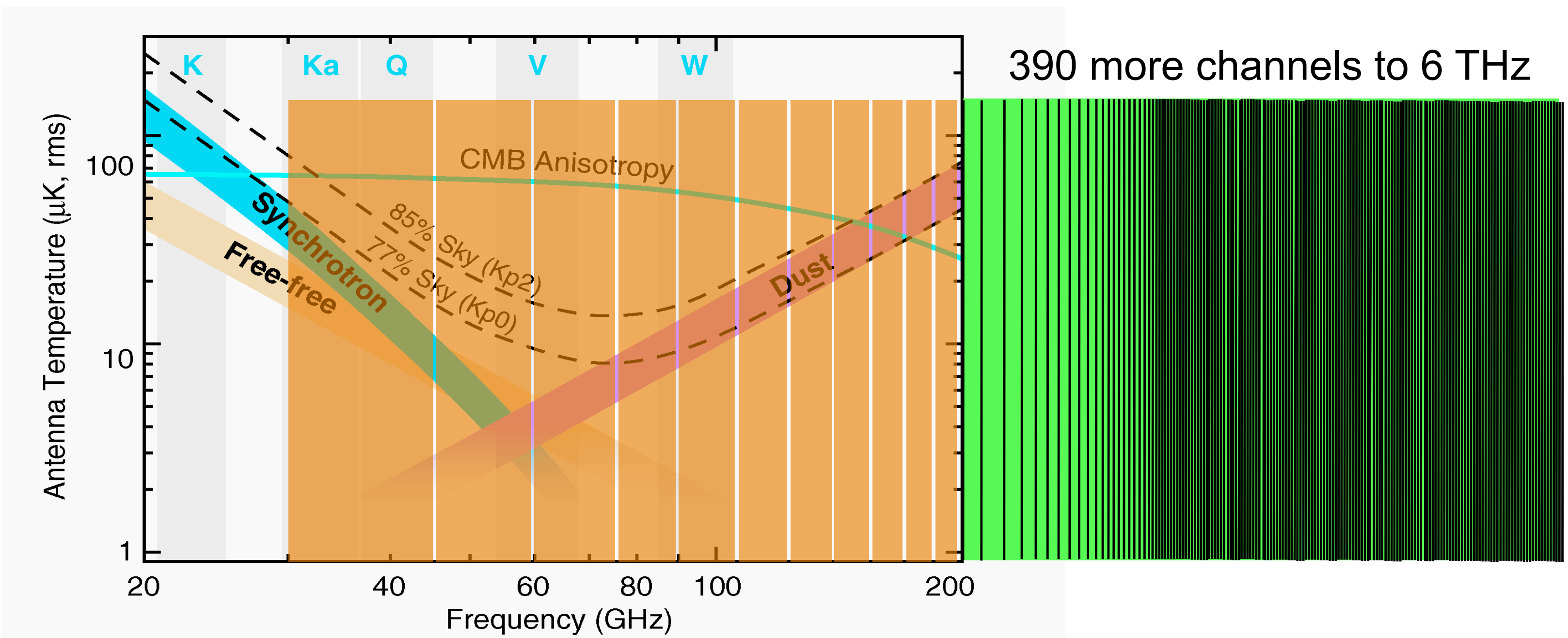
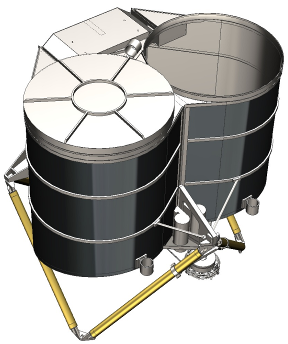


Sample more often: Get more frequency channels!

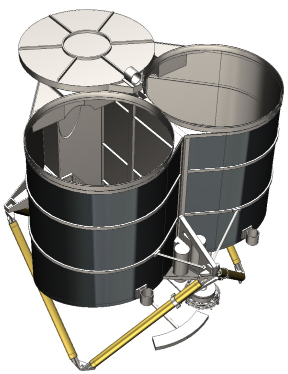
Blackbody Calibrator Adds Spectrum Science



Calibrator blocks "A" beam: Fringes measure ΔI + [Q,U]

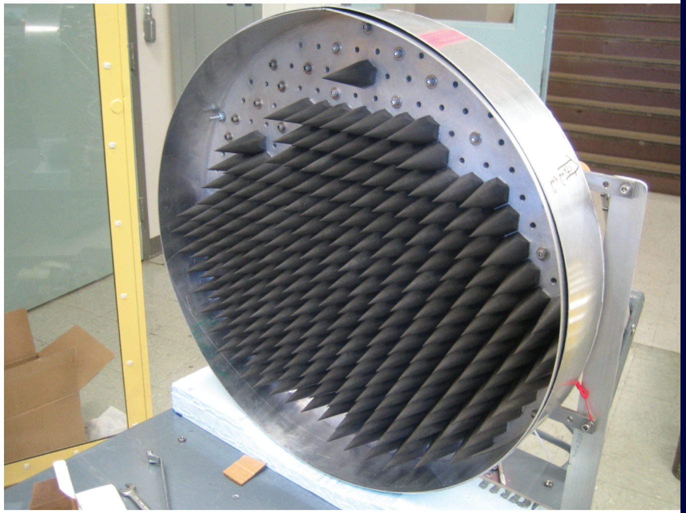
$$
\begin{aligned}
S(\nu)_{Lx} &= 1/4\,[\, I(\nu)_{\rm sky} - I(\nu)_{\rm cal} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/4\,[\, I(\nu)_{\rm sky} - I(\nu)_{\rm cal} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Rx} &= 1/4\,[\, I(\nu)_{\rm cal} - I(\nu)_{\rm sky} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/4\,[\, I(\nu)_{\rm cal} - I(\nu)_{\rm sky} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,]
\end{aligned}
$$

Flip sign:
Hot vs cold calibrator

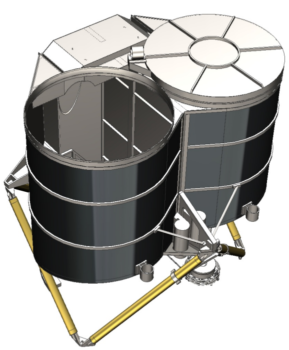


Calibrator stowed: Fringes measure [Q,U] only

$$
\begin{aligned}
S(\nu)_{Lx} &= 1/2\,[+Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/2\,[-Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Rx} &= 1/2\,[+Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/2\,[-Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,]
\end{aligned}
$$



Partially-assembled
blackbody calibrator



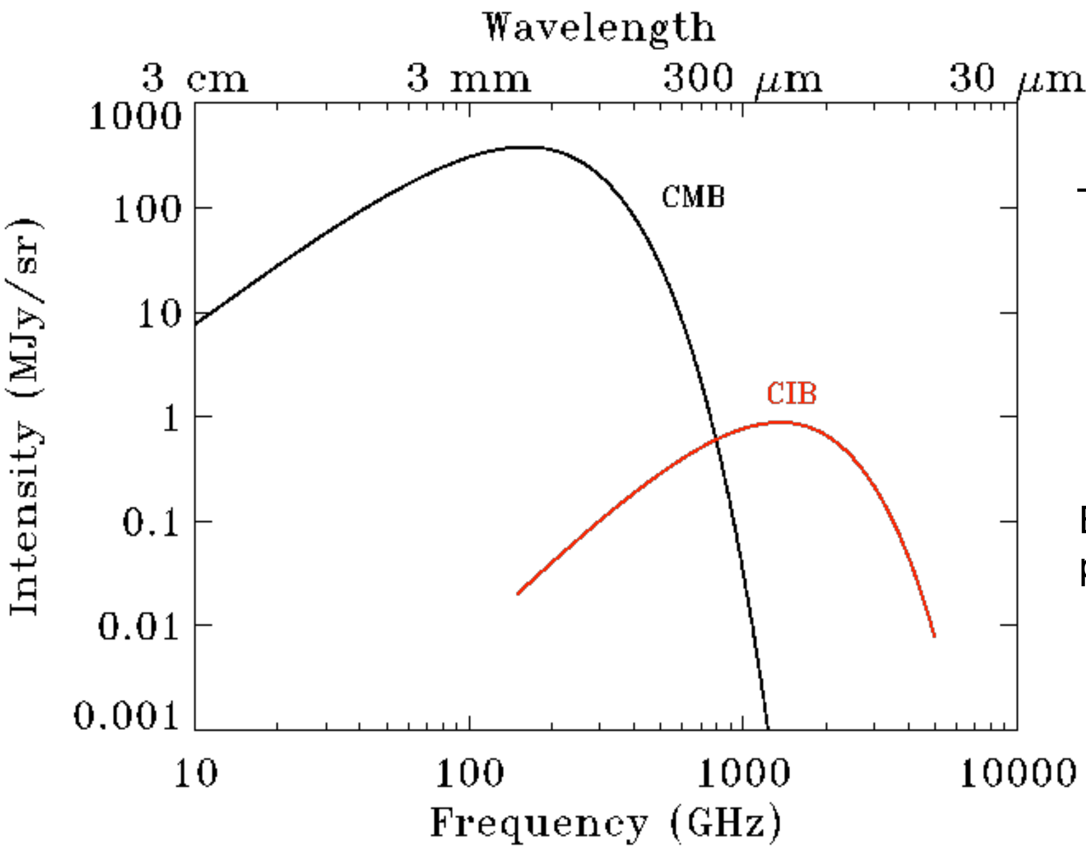
Calibrator blocks "B" beam: Fringes measure -ΔI - [Q,U]

$$
\begin{aligned}
S(\nu)_{Lx} &= 1/4\,[\, I(\nu)_{\rm cal} - I(\nu)_{\rm sky} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/4\,[\, I(\nu)_{\rm cal} - I(\nu)_{\rm sky} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Rx} &= 1/4\,[\, I(\nu)_{\rm sky} - I(\nu)_{\rm cal} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma \,] \\
S(\nu)_{Ly} &= 1/4\,[\, I(\nu)_{\rm sky} - I(\nu)_{\rm cal} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma \,]
\end{aligned}
$$

Flip sign:
A vs B beam

Blackbody Spectral Distortion!
1000 Times More Sensitive Than COBE/FIRAS

Secondary Science: Cosmic Infrared Background



Thermal Dust Emission from z ~ 1--3

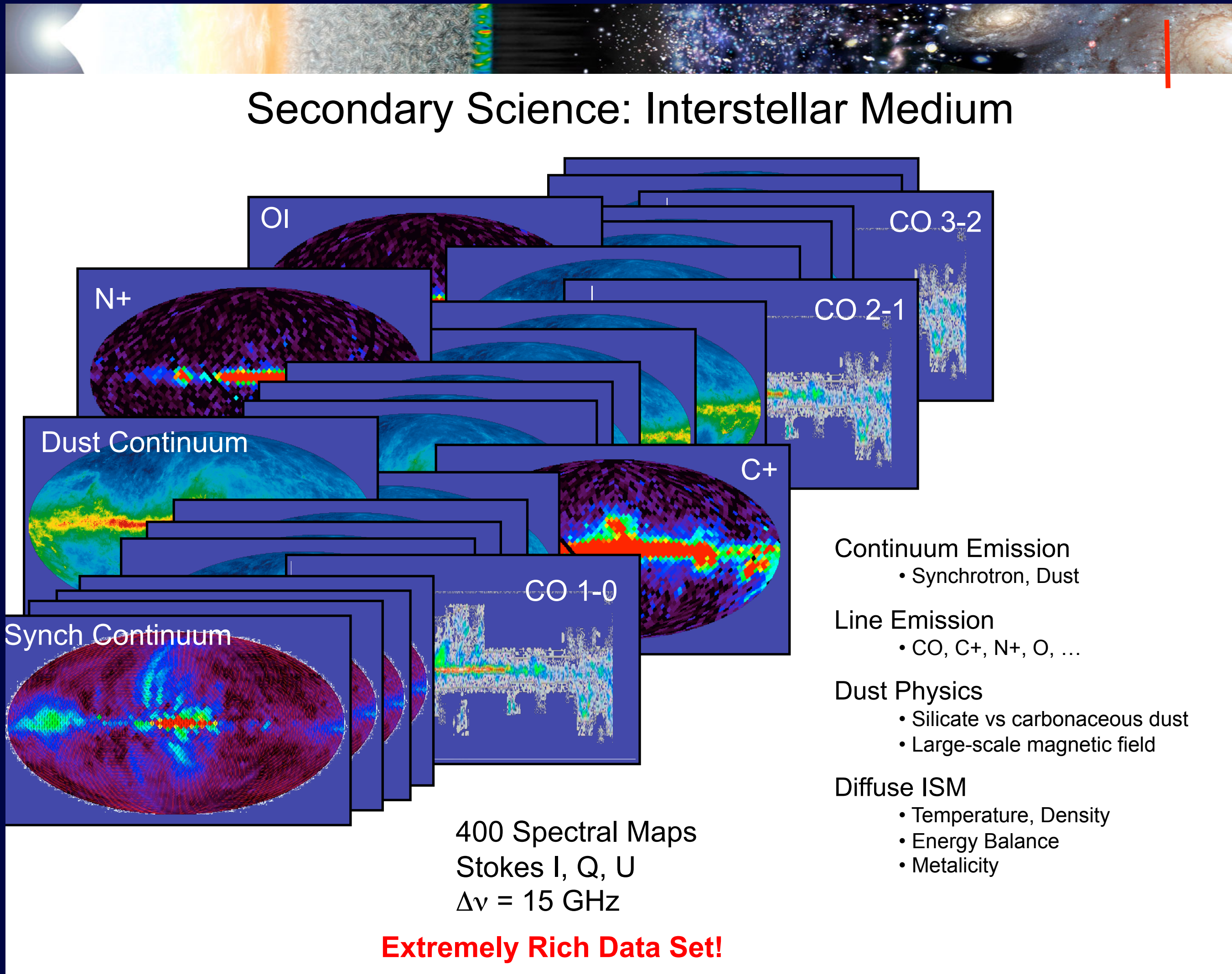
- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

Broad frequency coverage over CIB peak

- Complement Herschel, Planck

PIXIE noise is down here!

Knox et al. 2001
Fixsen & Kashlinsky 2011



PIXIE is a great instrument for CMB sciences, cm and mm-wave polarization, all-sky -> Galactic sciences. Improve EBL spectrum over FIRAS.

For extragalactic sciences lacks spatial and spectral resolution. Even impossible to do “intensity mapping”.

Things to do and some science list

Wish list: 1000 deg2, 60-600 microns, 12 arcsec resolution at 250 um

Some interesting sciences:

(a) Molecular Hydrogen pre-reionization at z ~15 (especially in a deep survey of galaxy clusters for example - Appleton talk tomorrow). Or as intensity mapping.

(b) OI at z > 6 to combine with mm-wave CII etc

(c) Galaxy clustering, 3D spectral line intensity fluctuations centered around z of 2-3

(d) rare sources (lensed galaxies) with automatic redshifts

(e) galaxy proto-clusters at z > 2

Summary