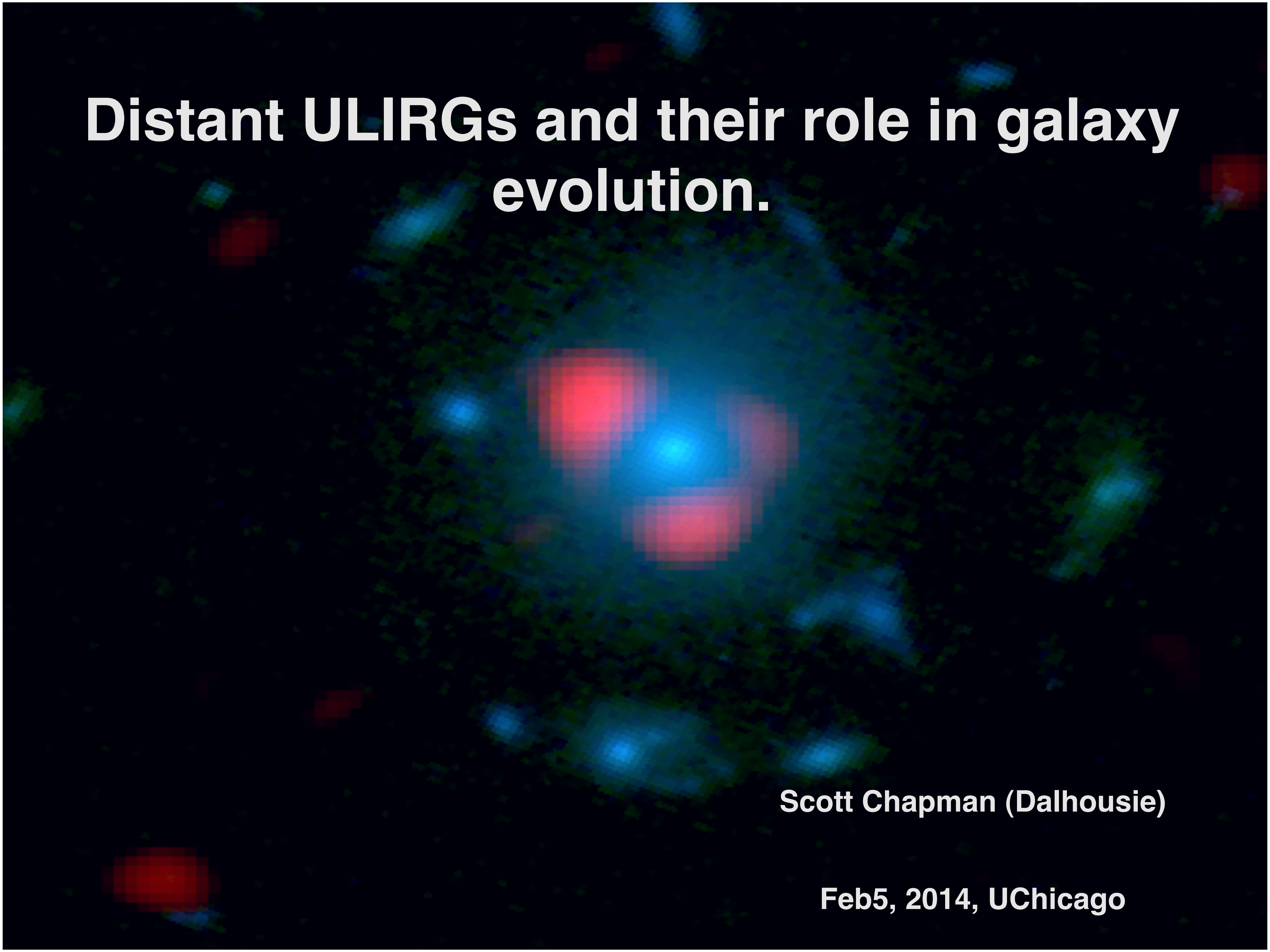


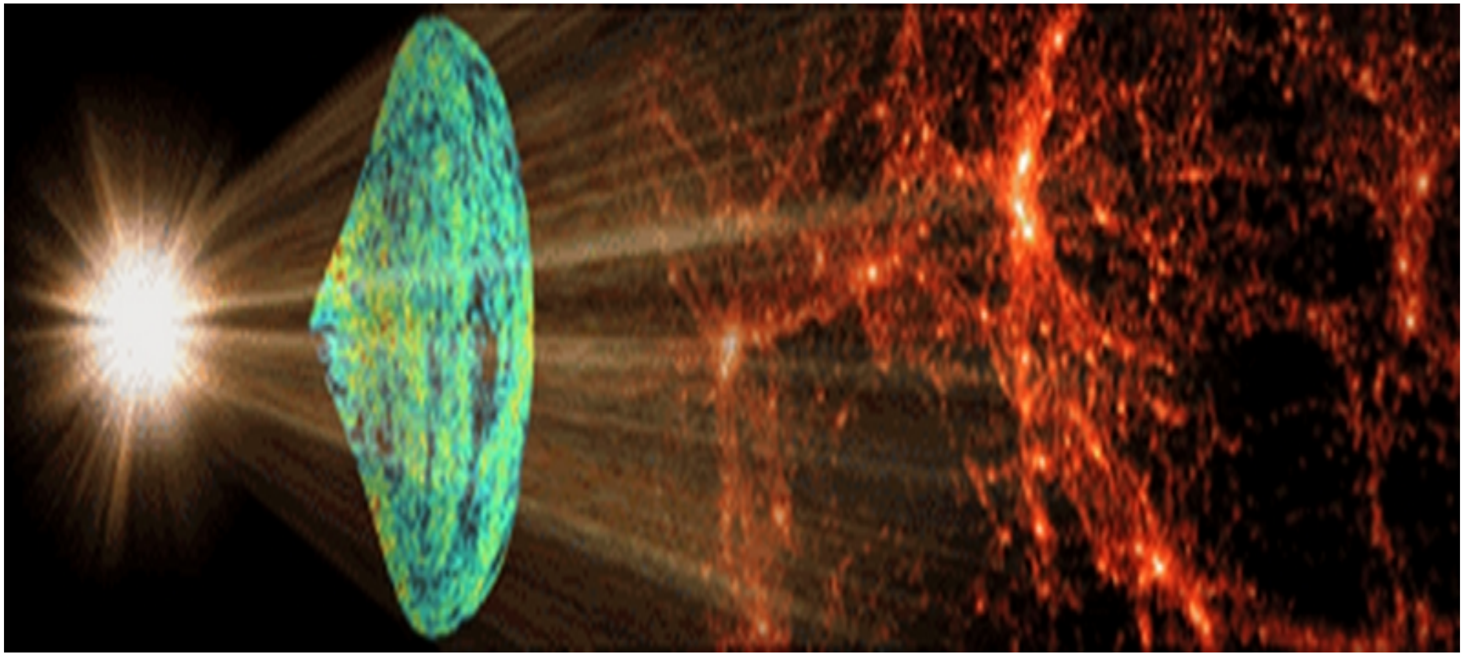
Distant ULIRGs and their role in galaxy evolution.

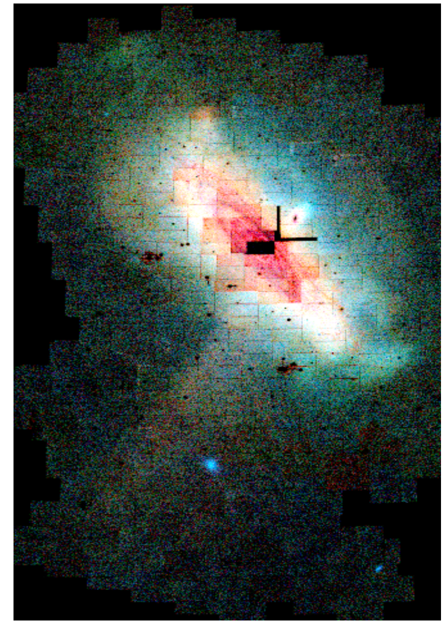
Scott Chapman (Dalhousie)

Feb5, 2014, UChicago

Context: *Hierarchical Galaxy Formation*

(How/when are the galaxy components assembled?)





Big Bang … Cosmic Microwave Background …
… Galaxy Formation and Evolution … Fossil Records today!

Submm/Far-IR is a superb probe of forming galaxies
Local Galaxies (like Andromeda) are ideal laboratory to study/ dissect components of typical 'large' galaxies

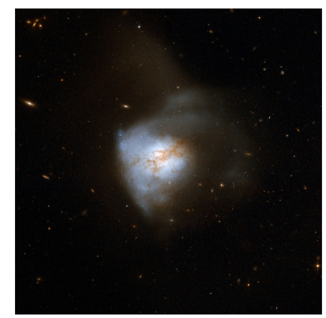
How do galaxies form?

- What is the total SF history of the Universe?
    - What is the role of starbursts in the SF history?
- How are galaxies built up?
    - What is the growth of halo mass?
    - What is the growth of their gas reservoirs?
- Is high-z star formation the same as in low-z galaxies?
    - Does the intense SF effect the ISM in high-z galaxies?
    - Is the IMF in high-z galaxies the same as at low z?
    - Is the SF law the same at high and low z?
    - What regulates SF in galaxies?
- How does AGN activity relate to the SF and influence it?

Galaxy Formation

Complex interplay between

- hierarchical merging of virialized dark matter halos,
- accretion and cooling of gas onto newly formed galaxies within the halos,
- formation of stars in self-gravitating dense gas clouds in these galaxies,
- metal-enriched gas outflows driven by massive stars, supernovae, and accreting supermassive black holes in nuclei

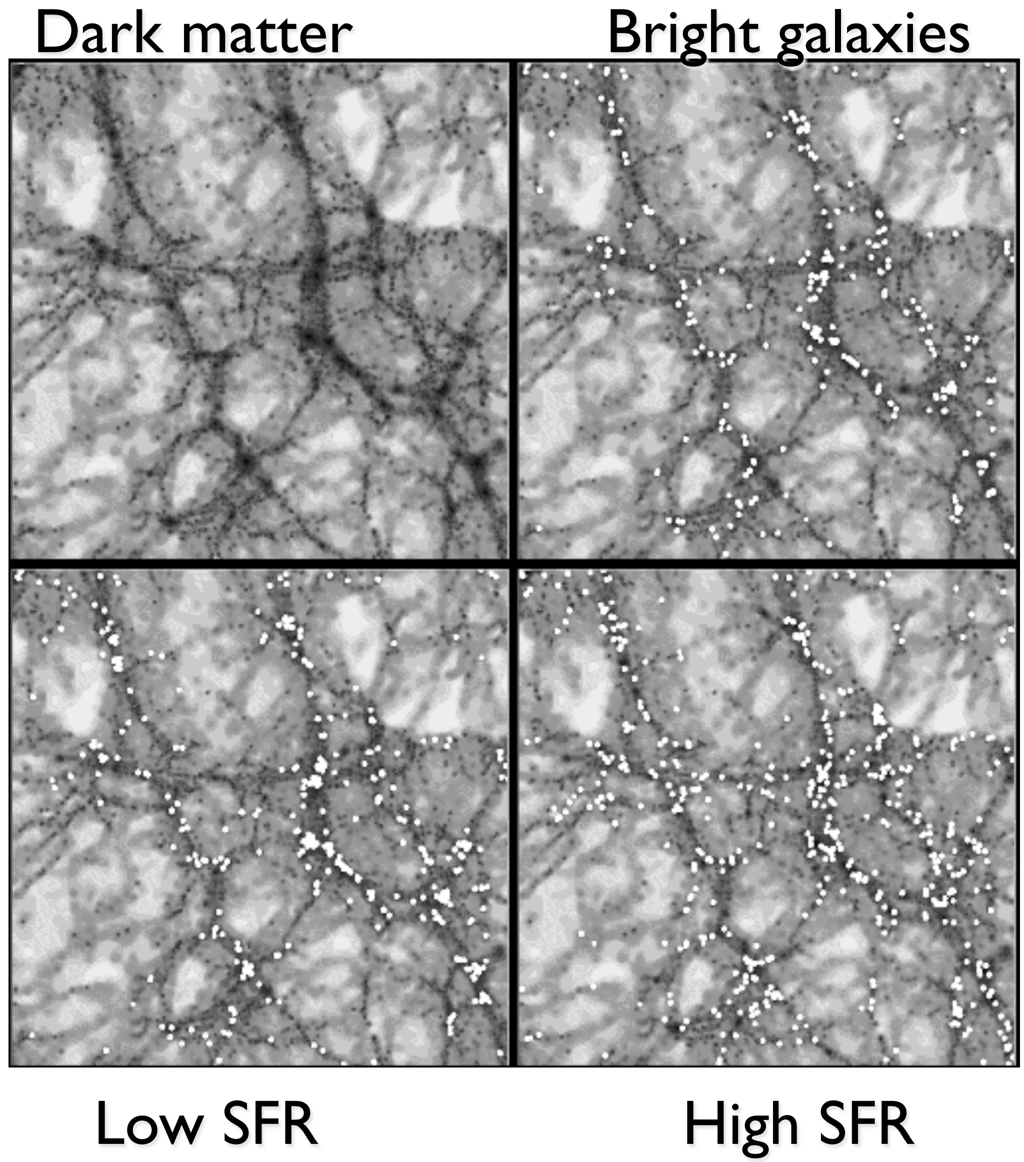


Galaxy Evolution - Dark Matter and Gravity

GALAXY FORMATION and EVOLUTION: ***with baryons becomes more difficult***

N-body + semi-analytic
-gas cooling
-star formation
-SNe feedback
-galaxy mergers
within halos

•Success reproducing observed parameters at z=0.
•High-z objects of various classes continue to be problematic -- SMGs, DRGs, (e.g., Sommerville et al. 2000; Baugh et al. 2005, Swinbank et al. 2010)

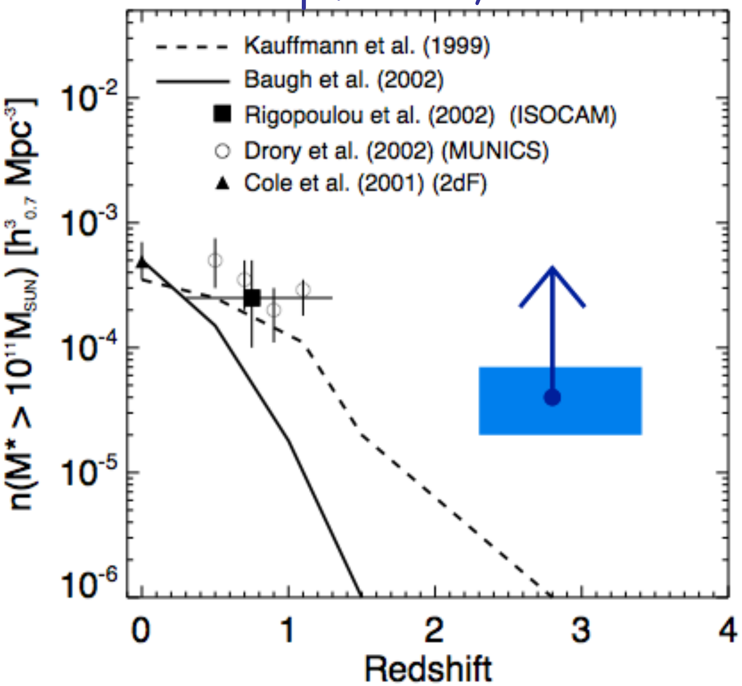


(Kauffmann et al. 1998)

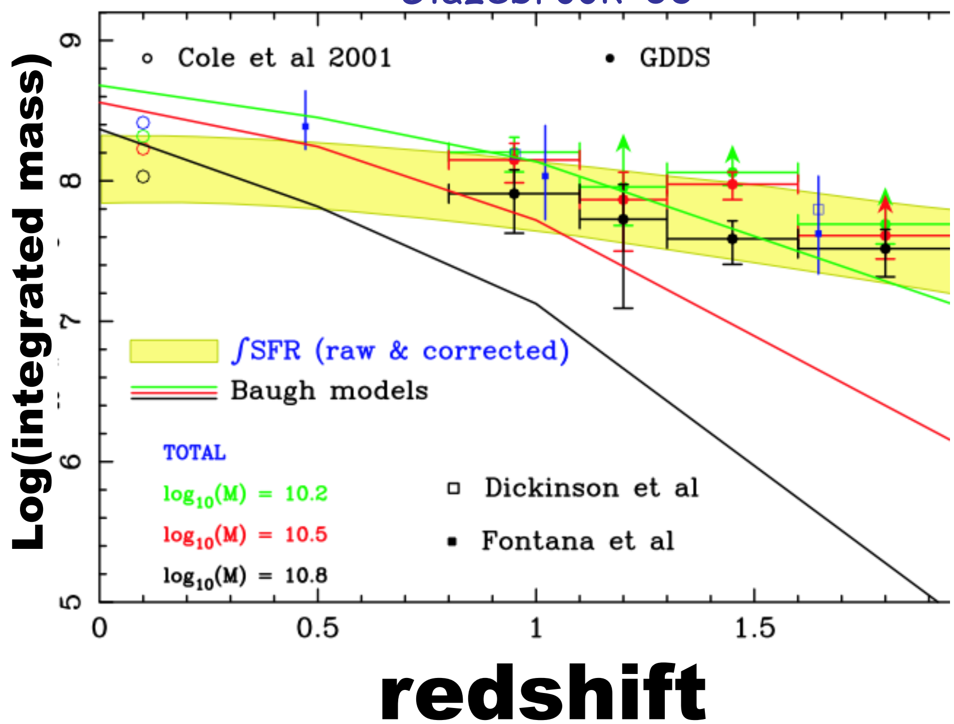
assembly tests

Semi-analytic models have struggled to account for a growing census of
luminous z>2 galaxies (truncated IMF?)
massive z>2 galaxies (solutions? cool gas accretion?)

Chapman+03, Neri+03

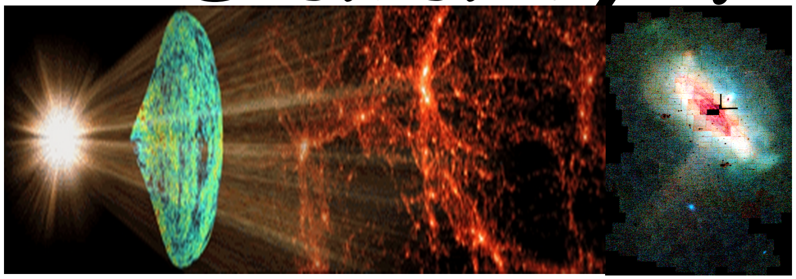


Glazebrook+03



How are these massive galaxies formed?

Galaxy Formation



HOW TO PROCEED?

1) **Full hydro-dynamical simulation** … compare to observations

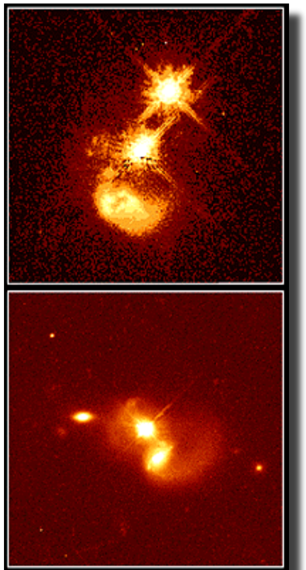
2) **Approximate some of the physics**: but difficult to produce a model consistent with all observations.
   - SUCCESS: Tune to particular problem at hand
   - **Durham: GALFORM (Baugh et al. 2005, Swinbank+2010) SMGs;**
   - **Abadi+2003; Bullock&Johnston 2005: stellar disks, halos, substructure**

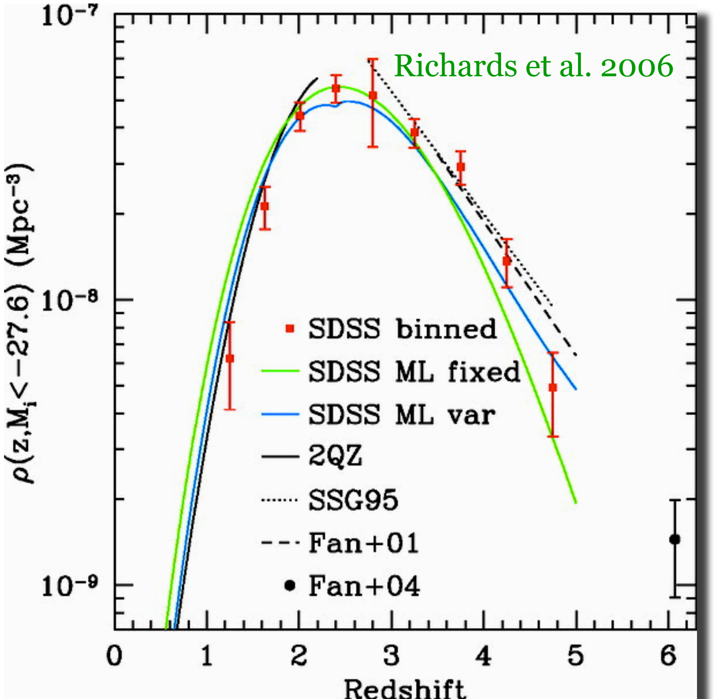
3) **Study "High-redshift" (z=1--6+) populations** in as many ways as possible
   - Try to connect populations in time.
   - Short timescale: Star Bursts/ Black Hole growth
   - Long timescale: Masses/Clustering; Volume densities (mergers); Chemical evolution (hard at high-z)

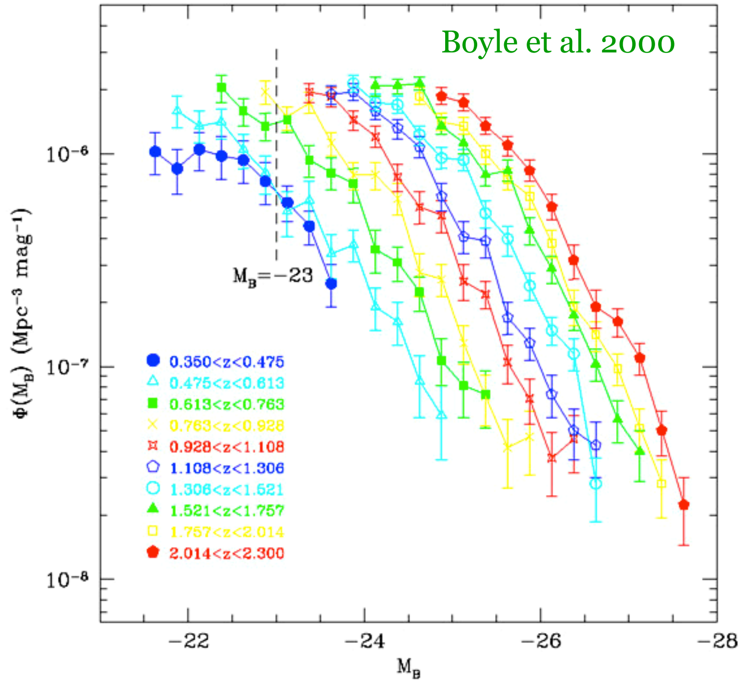
4) **Local Group** galaxies, ARCHEOLOGY -- FOSSIL RECORD

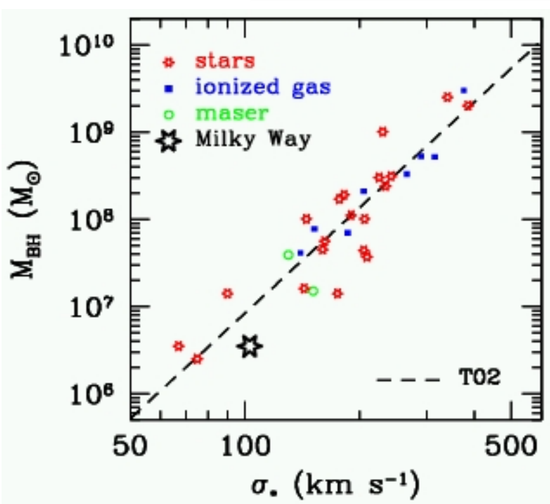
Dissect galactic components by kinematics and chemistry,

Things we know: QSOs: SMBH growth at high z





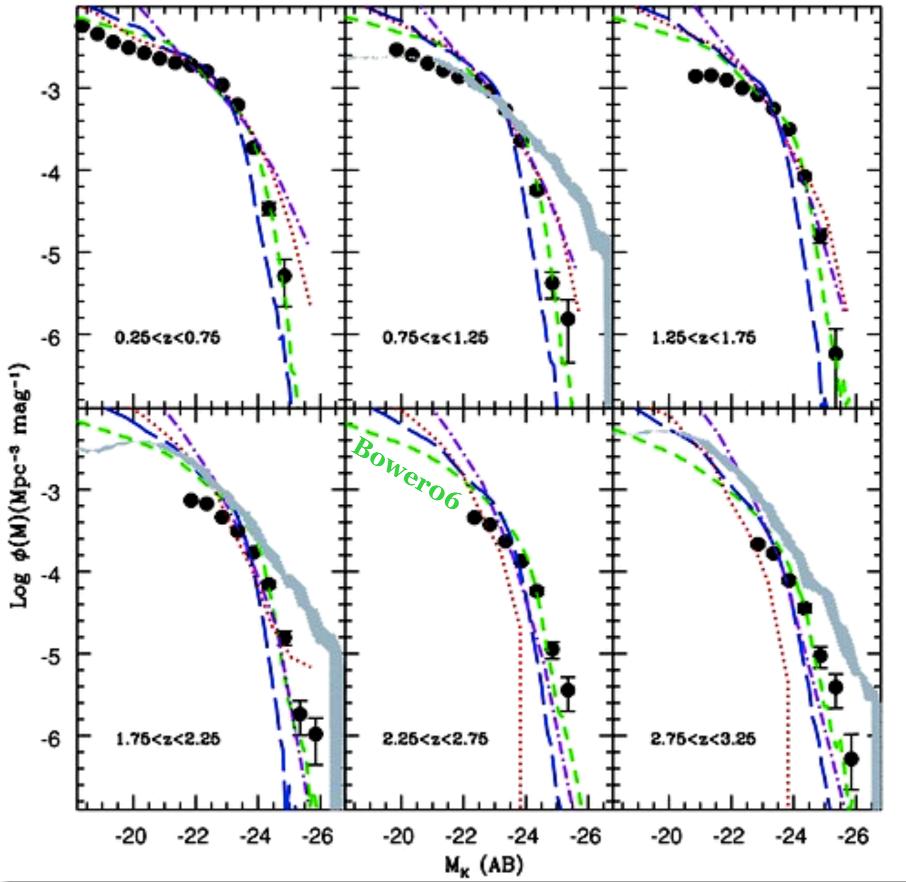




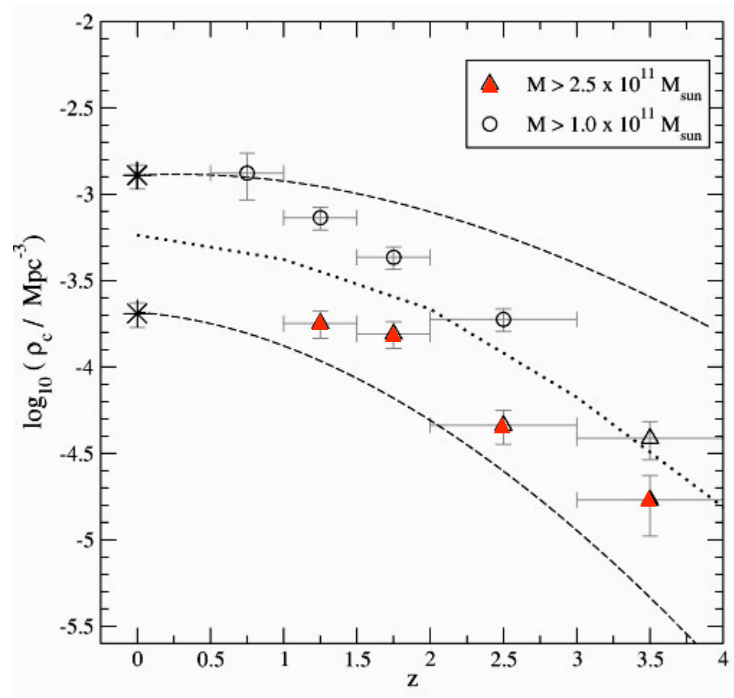
- Luminous, UV-selected QSOs show strong luminosity evolution out to z~2-3
- Indicate significant accretion onto supermassive black holes at this epoch
- *So how do we get M_{BH}-$M_{spheroid}$ relation?*

Things we know: Massive galaxies at high z

Cirasuolo et al. 2010

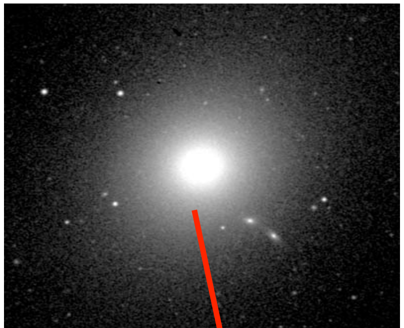


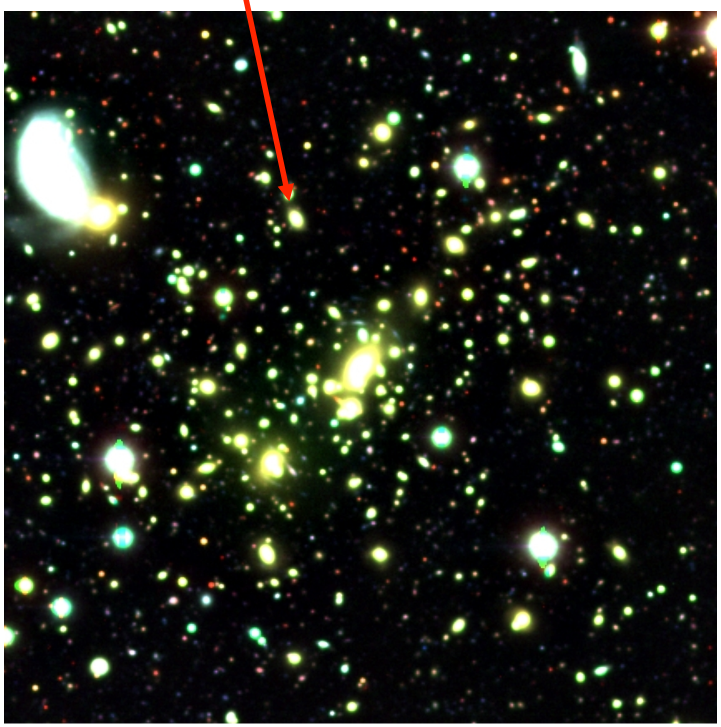
Caputi et al. 2006, 2011



- Evidence from near-/mid-IR surveys of large numbers of bright galaxies at high-z. Many of the most massive appear to be red (passive).
- Suggestion that this pop of massive galaxies builds up rapidly at z~1-3
- *What are the properties of these galaxies at the present-day?*

"Local" Luminous Elliptical Galaxies





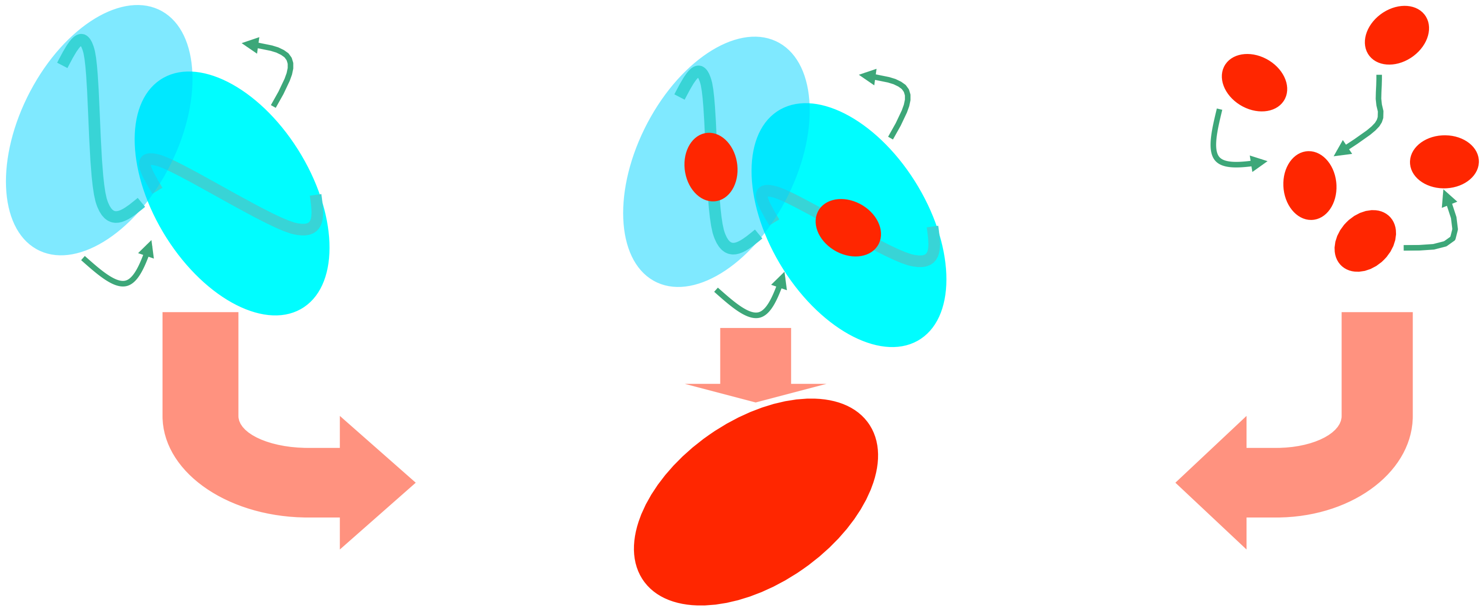
… the most massive galaxies in the local Universe

- Pressure-supported, metal-rich stellar systems.

"Simple" galactic-scale stellar systems

- Extremely homogeneous and old (implies **z>2** formation)
- Live in the highest density regions (clusters)
  - Largest stellar mass of any galaxies (up to 10 M*)
  - Host the most massive Black Holes in local Universe, >$10^9 M_o$

Formation Mechanisms

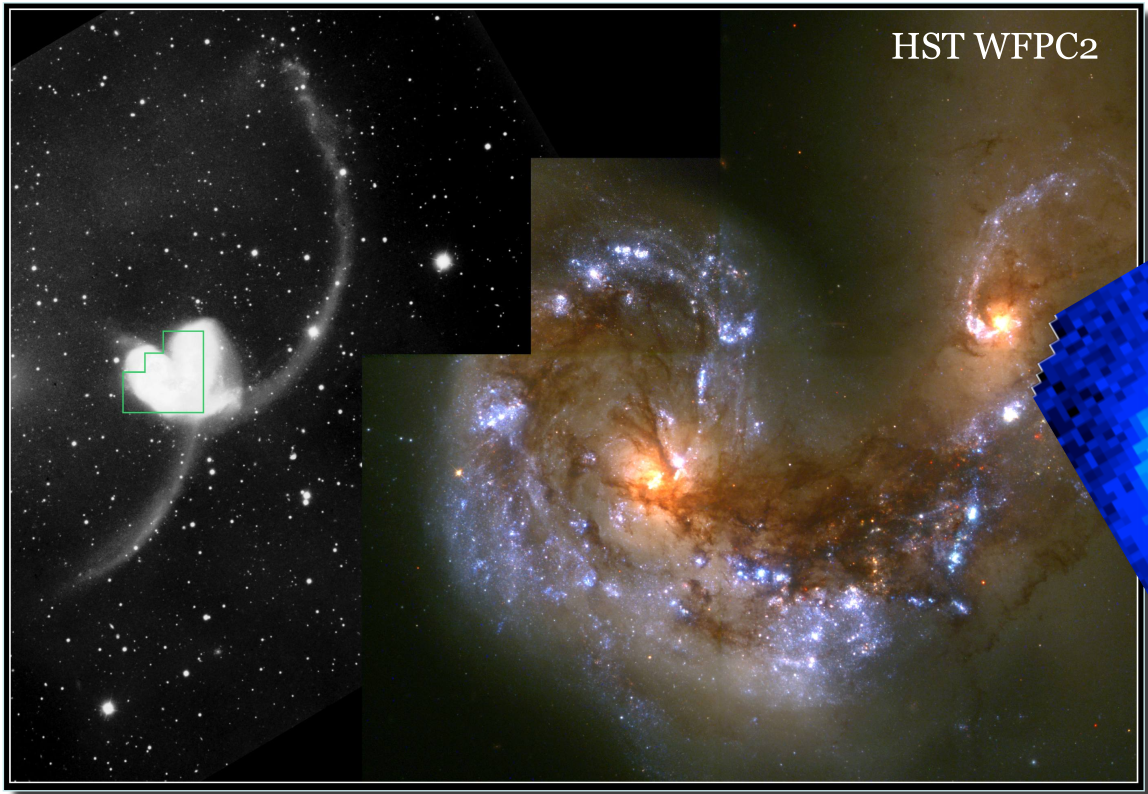


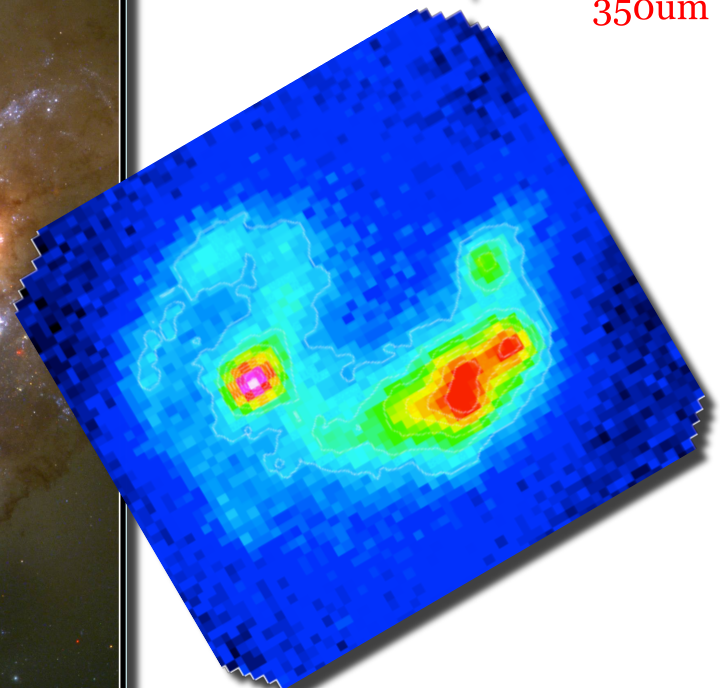
Wide range of proposed mechanisms for forming big galaxies:
(pseudo-)monolithic collapse ($T_{merge}<T_{SF}$)
major merger of two existing galaxies ($T_{merge}\sim T_{SF}$)
an extended series of minor mergers ($T_{merge}>T_{SF}$)

Add to this the 'cold flow accretion' and turbulent massive disks proposed for most star forming galaxies (e.g. Tacconi et al. 2013)

Can we observationally distinguish between these scenarios?

ULIRGs: An ***unimportant*** class of local galaxies

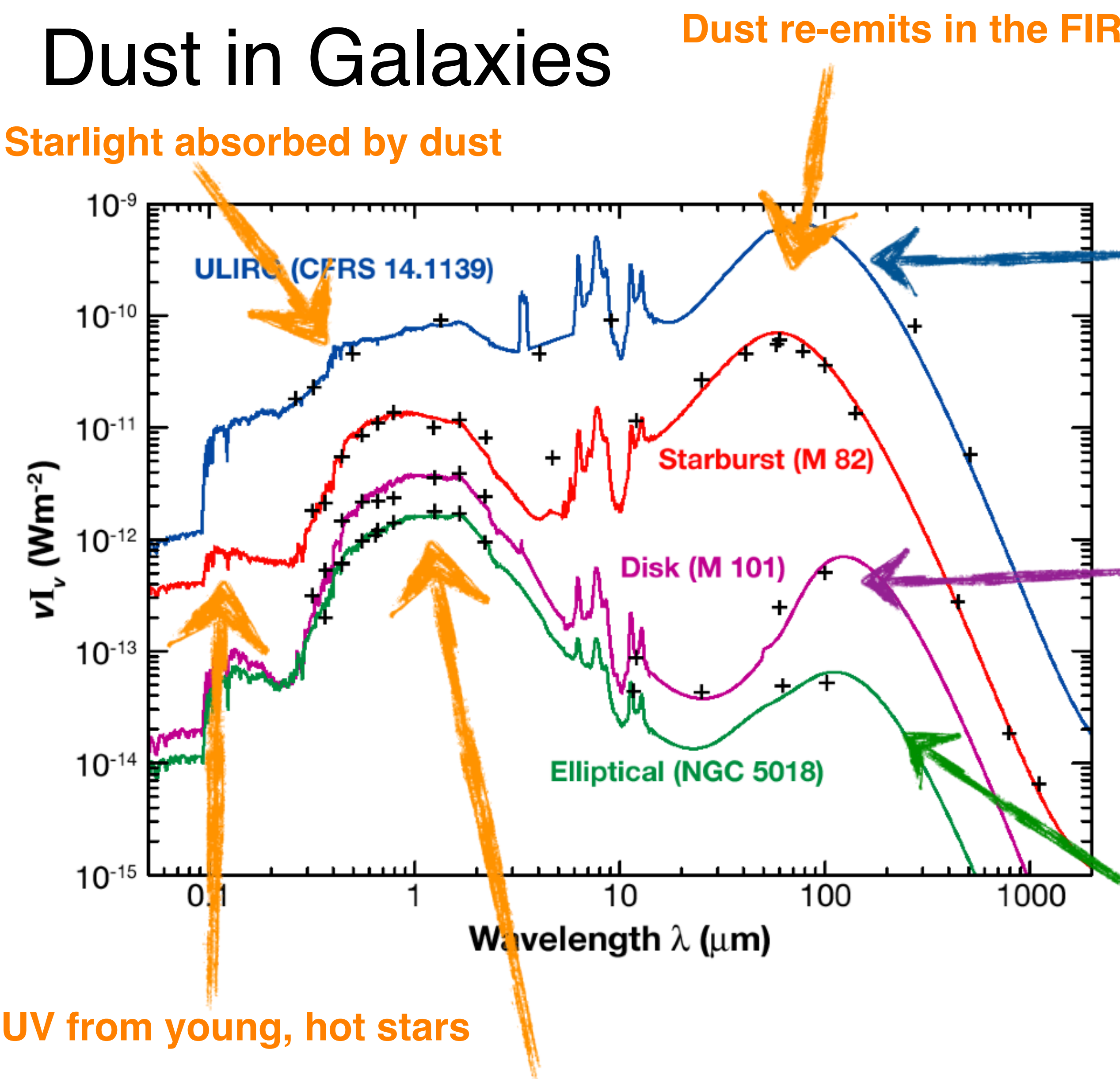


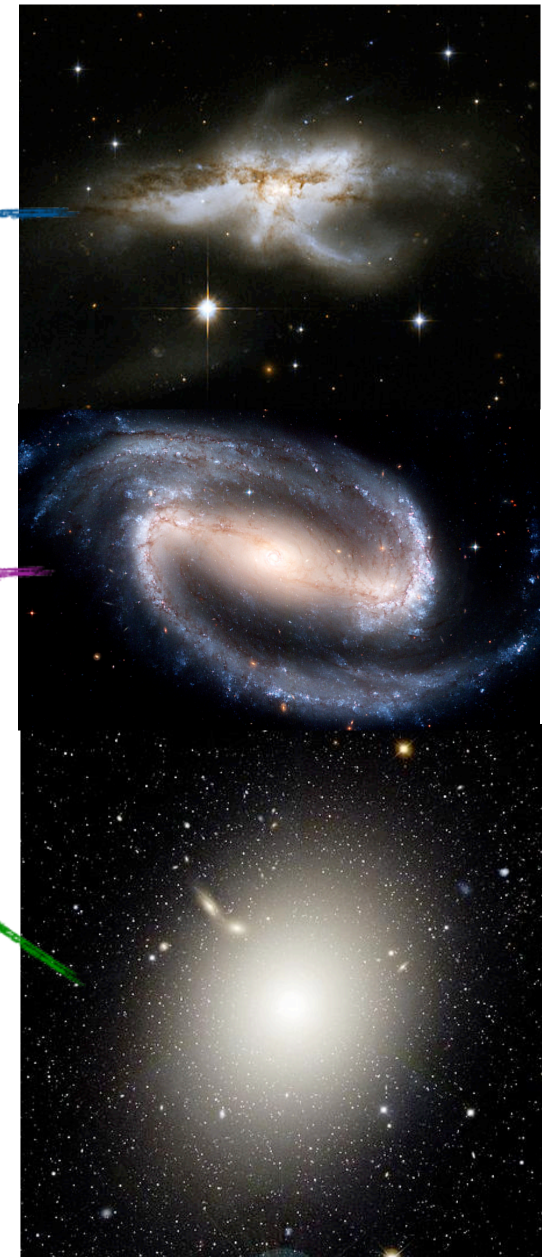


- Could the answer lie in luminous (but dusty) high-redshift starburst?
- The most luminous galaxies locally are ULIRGs (Ultra-Luminous InfraRed Galaxies). Bolometric luminosities > $10^{12}L_o$ (>100x MW), SFRs of 100's Mo/yr. 99% of L_{bol} emitted in the FIR/submm

- Unimportant population: only 0.3% of stars at z=0 formed in ULIRGs
- Have they always been unimportant?

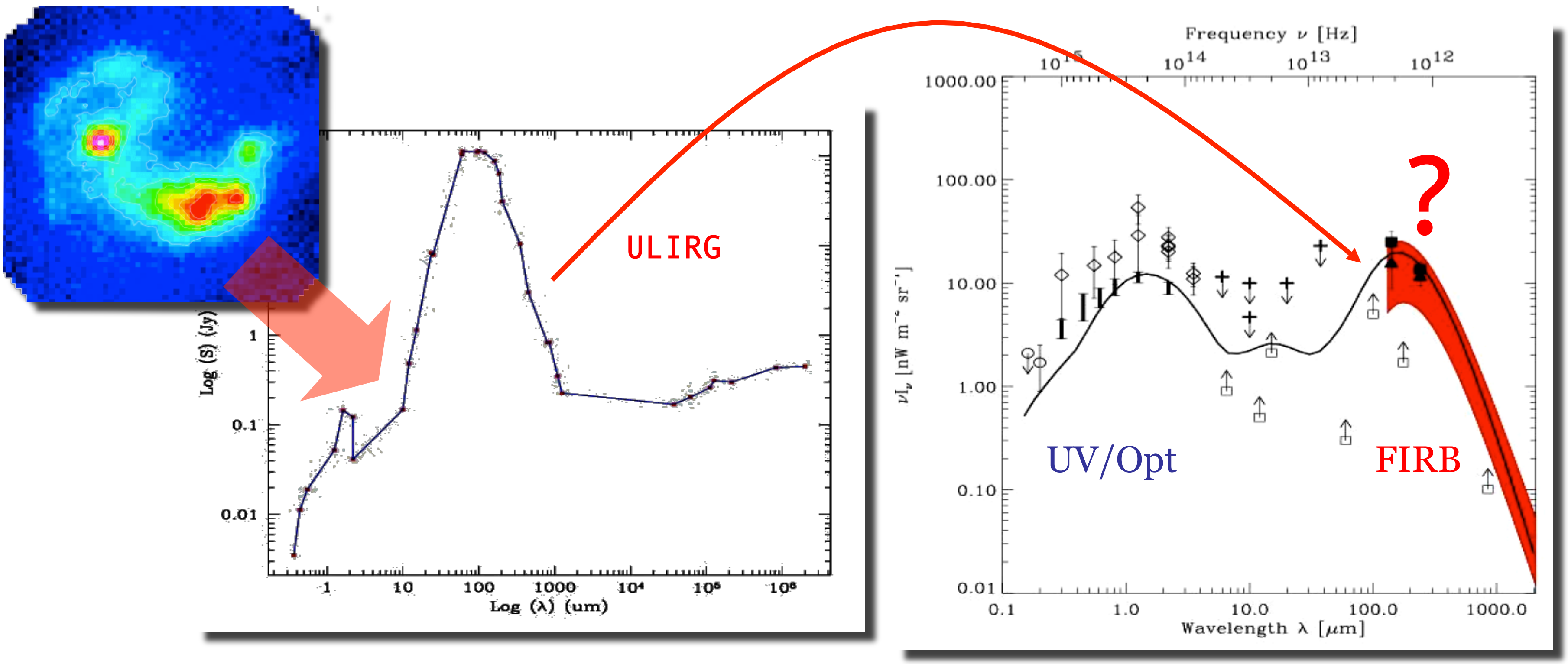
Dust in Galaxies





Lagache, Puget & Dole 2005 ARA&A

Why might high-z ULIRGs be important?

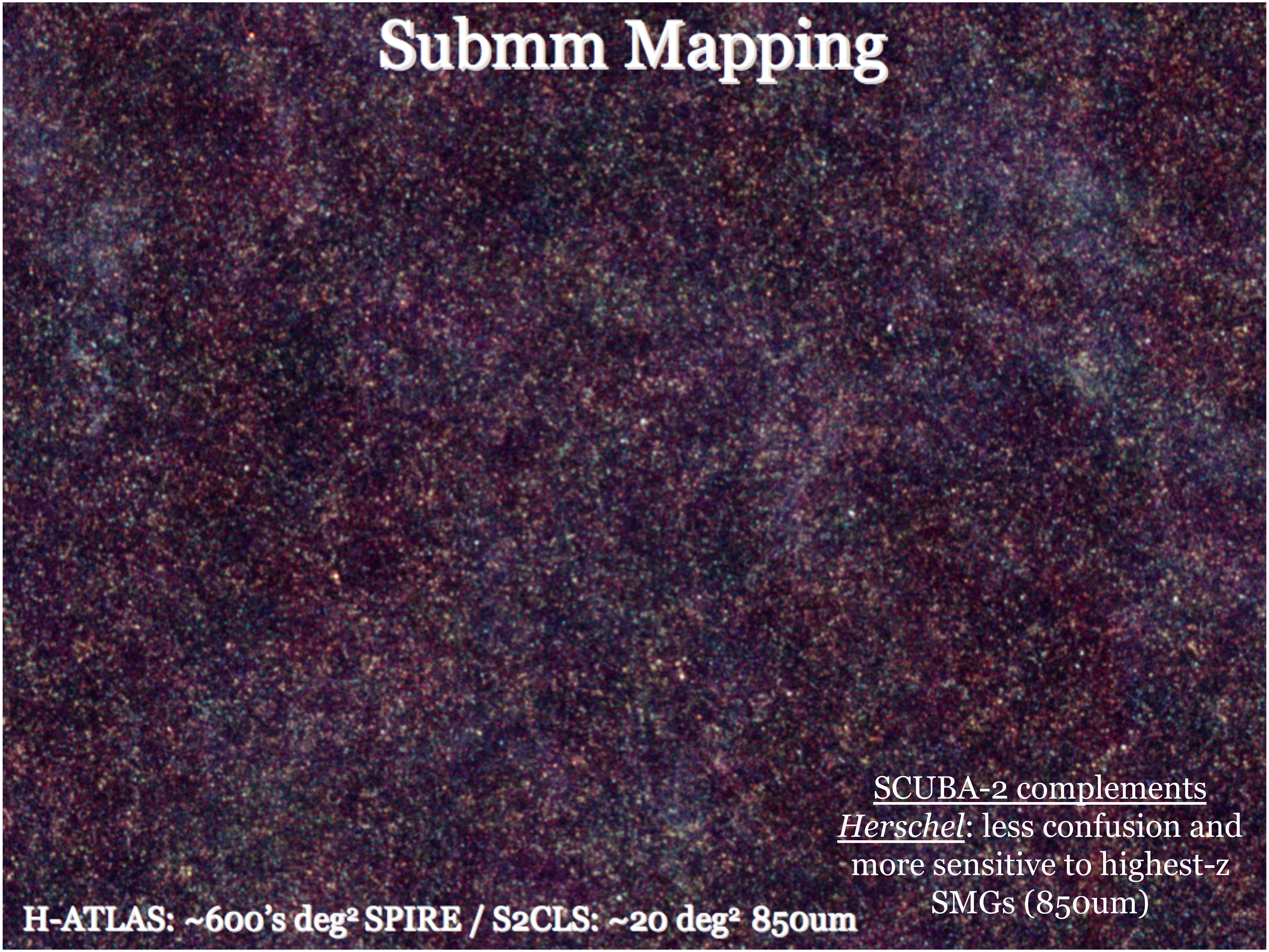


• FIR Background = opt/UV EBL -> half of the energy production (from star formation or AGN) over history of the Universe arises in obscured regions

• Is there a connection between the FIRB and high-z ULIRGs and the formation of massive high-redshift galaxies and QSOs?

<u>…to test this connection *need samples of high-z ULIRGs*</u>

Submmm Mapping



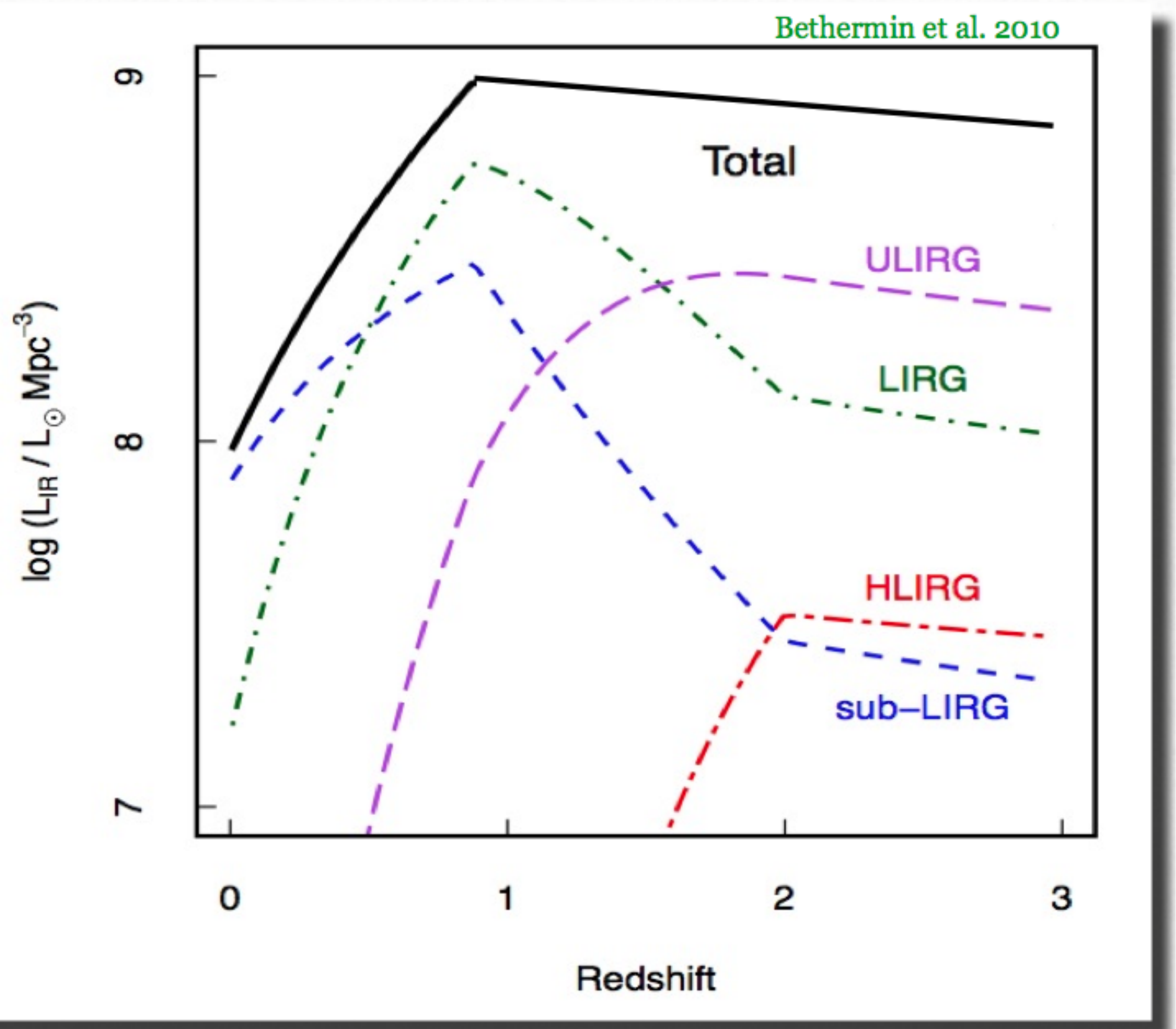
H-ATLAS: ~600's deg² SPIRE / S2CLS: ~20 deg² 850um

SCUBA-2 complements *Herschel*: less confusion and more sensitive to highest-z SMGs (850um)

Star Formation History

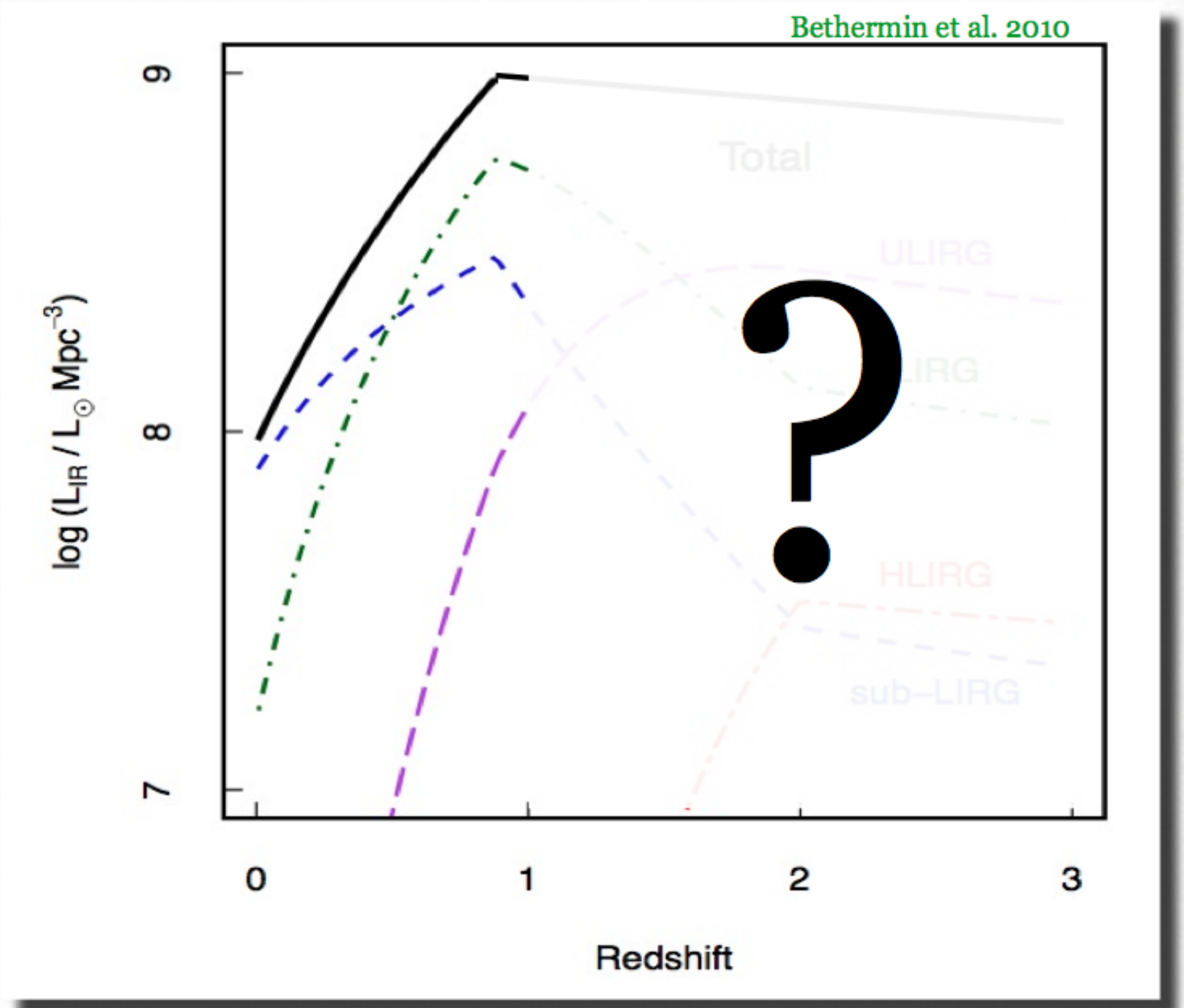
Herschel has helped paint an updated picture

...



- ULIRGs (dusty starbursts, SFR>100$M_\odot$/yr) produce ~50% stars @ z>1-2
- These are submm galaxies (SMGs) detected in FIR/submm

Star Formation History



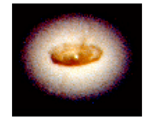
- ULIRGs (dusty starbursts, SFR>100M$_0$/yr) produce ~50% stars @ z>1-2
- These are submm galaxies (SMGs) detected in FIR/submm
- This is a cartoon because the data would be embarrassing to show…

Evolution of a luminous SMG:

dust from SN
+ debris disks

gas-rich
merger

dusty star
forming
galaxy

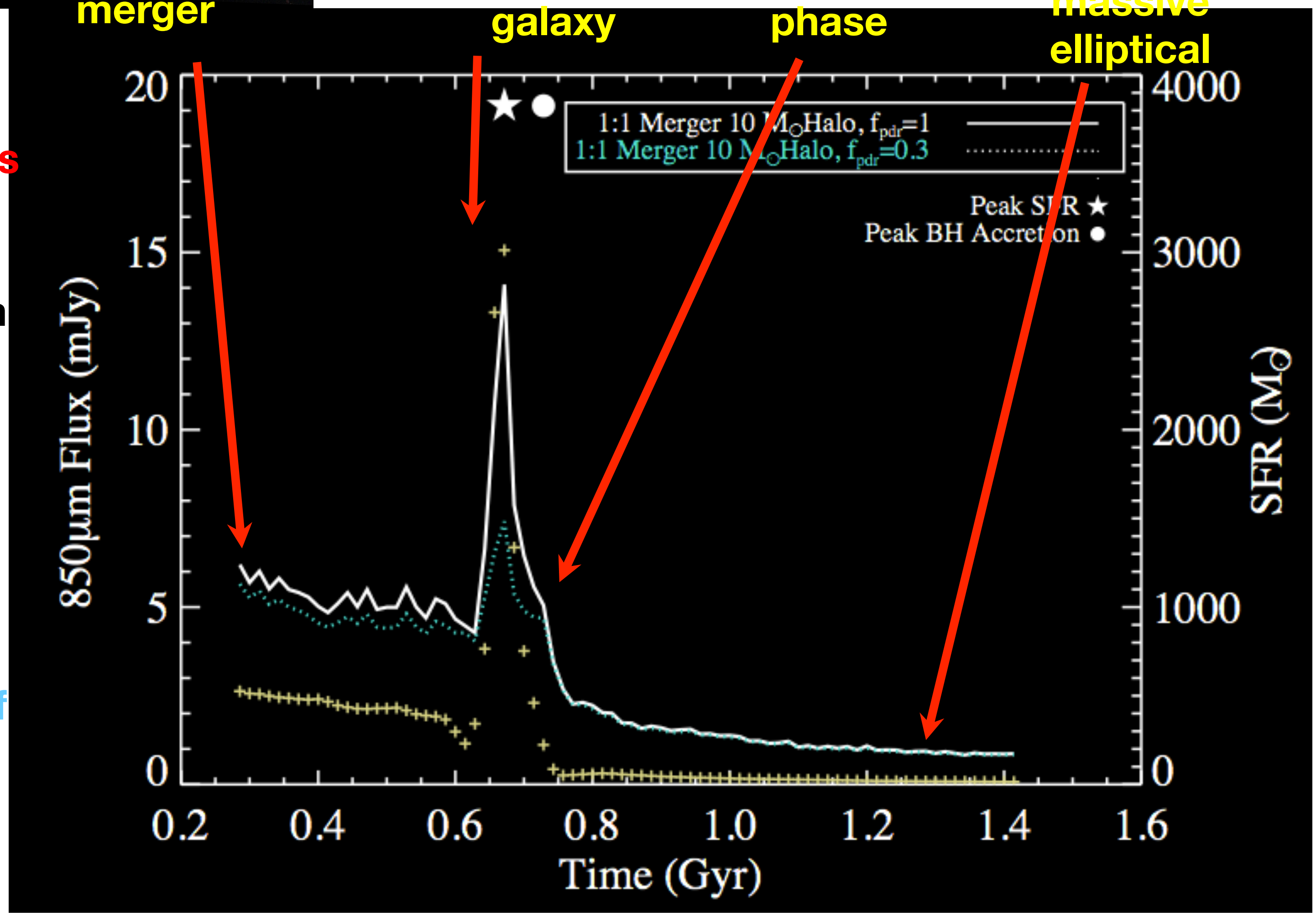


AGN
dominated
phase

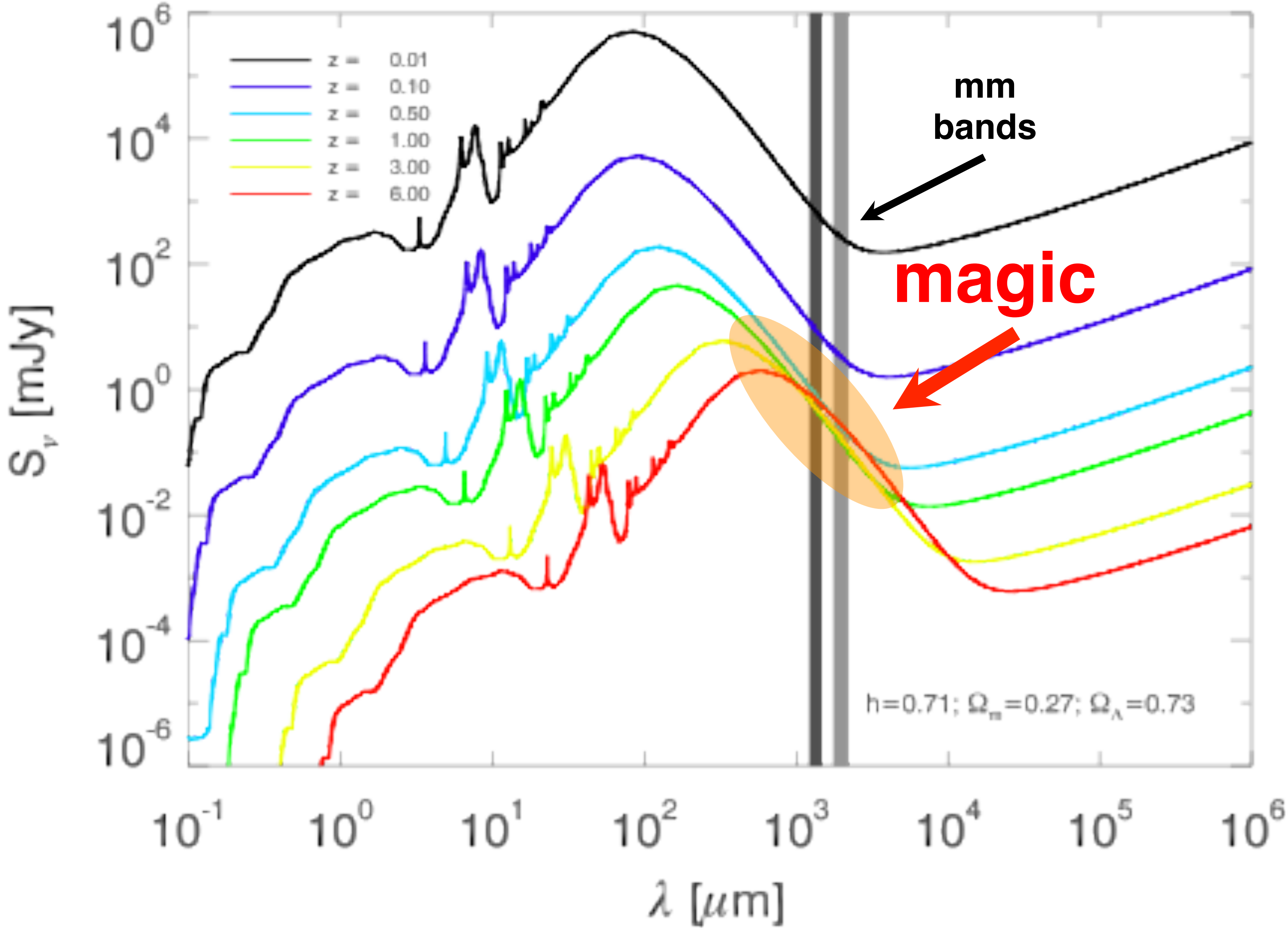
massive
elliptical

The brightest SMGs

Theoretical model
for the formation an
evolution of
submillimeter
galaxies

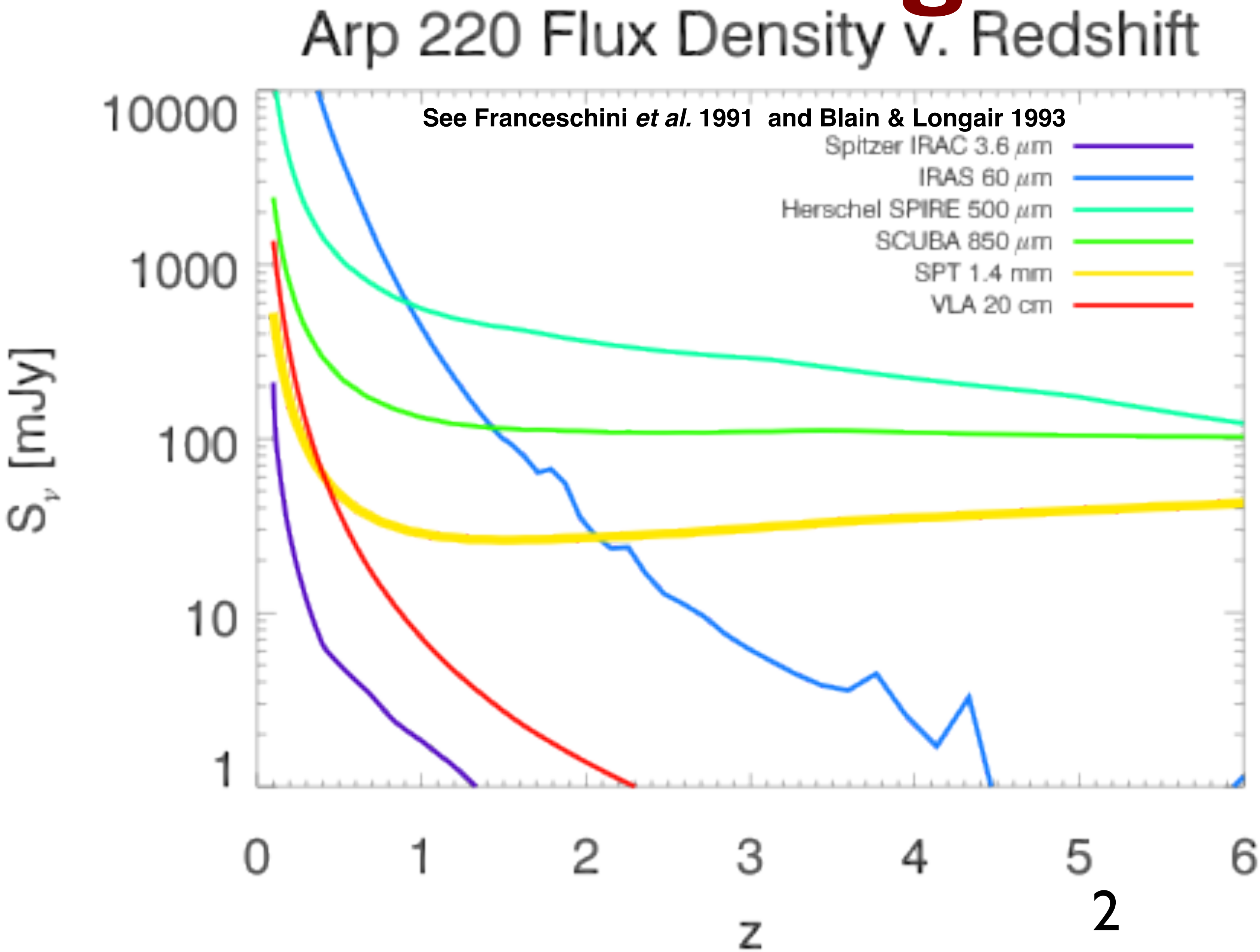


SMGs are biased
tracers of massive
halos and are an
evolutionary phase of
massive galaxy
formation.



z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
mm
bands
magic
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]

Sub-mm magic


Arp 220 Flux Density v. Redshift
See Franceschini et al. 1991 and Blain & Longair 1993
Spitzer IRAC 3.6 μm
IRAS 60 μm
Herschel SPIRE 500 μm
SCUBA 850 μm
SPT 1.4 mm
VLA 20 cm
10000
1000
100
10
1
S_ν [mJy]
0
1
2
3
4
5
6
z

We need Observational Tools

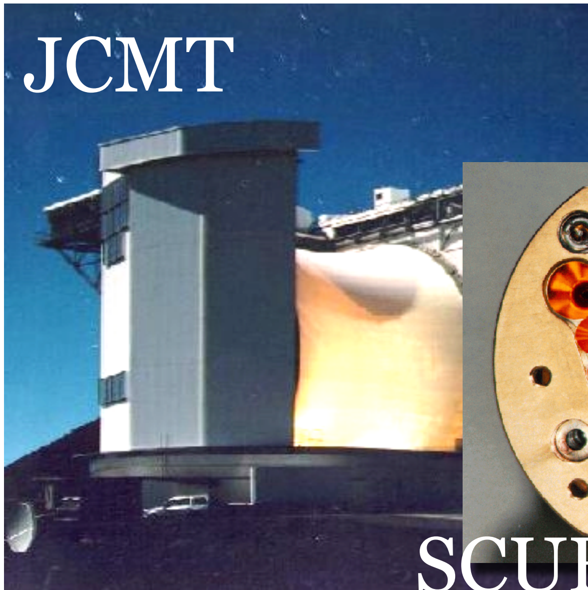
How do galaxies form?

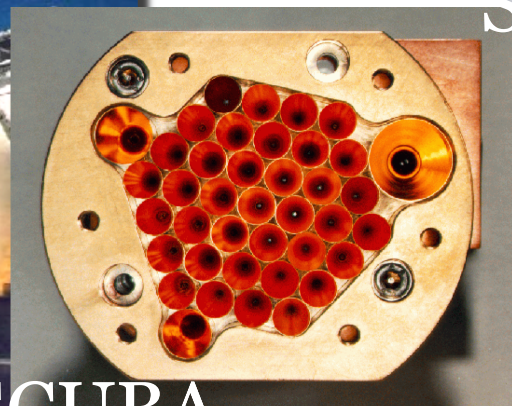
- As much SF/AGN activity at high-z may be obscured need sub/mm-FIR observations to tackle these questions:

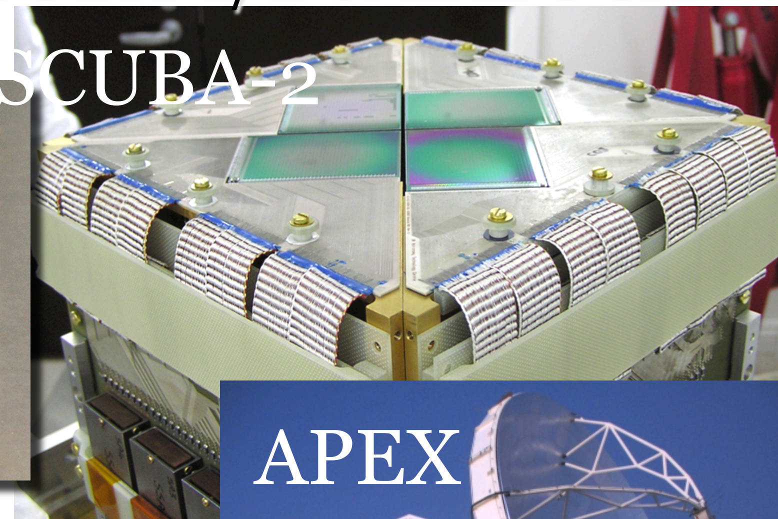
- Sub/mm continuum mapping
  - Sub/mm-FIR counts, source selection
  - 2-D clustering

- Sub/mm spectroscopy of molecular/atomic lines
  - Redshifts: N(z), LF evolution and SFRD
  - 3-D clustering: Halo masses, environment
  - Line luminosities: gas masses, abundances
  - Internal dynamics: galaxy masses, gas fractions
  - ISM physics: energetics, density, ionisation

850um SCUBA-1/2 & LABOCA





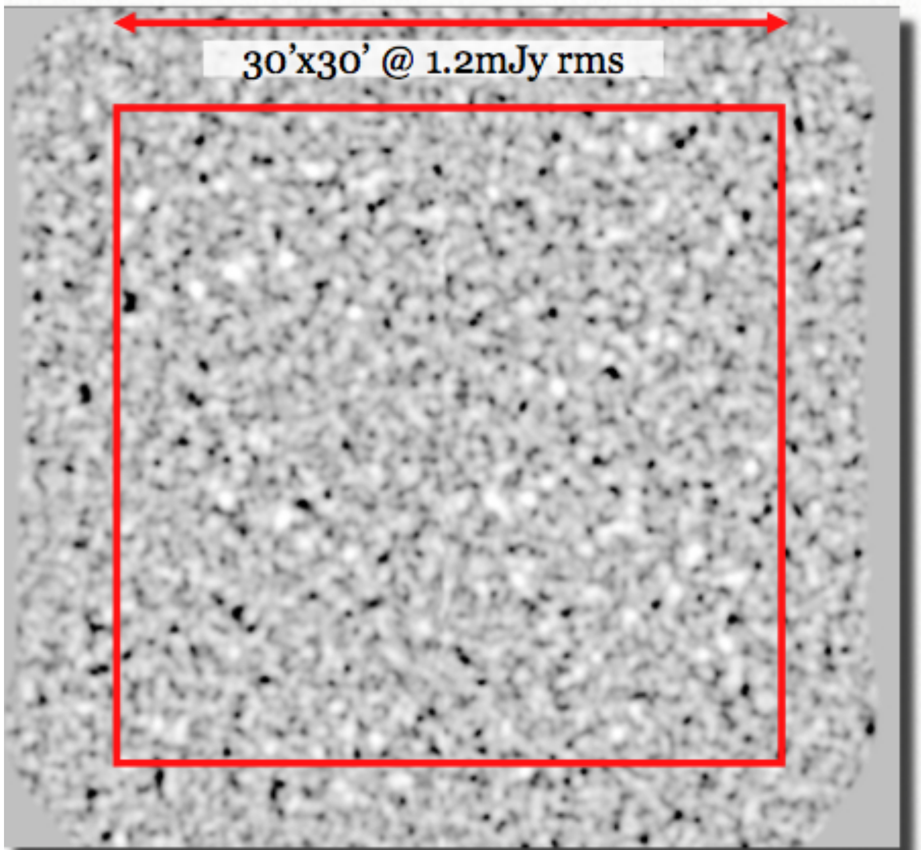


- SCUBA-1/2 450/850um cameras operating on the 15-m JCMT
- SCUBA first submm camera ('97-'05), almost as highly cited as HST
- 850um array: 37 bolometers, 2.5' FOV, 15" beam
- SCUBA2 is starting science operation at the moment: ~5120(x50%) pixels, 8' FOV

- LABOCA (on 12-m APEX): 295 bolometers @870um 11.4' FOV 19" beam
- So what's special about the submm waveband?

Resource intensive pursuit of SMGs' properties

Why we are ignorant: a "typical" submm survey…



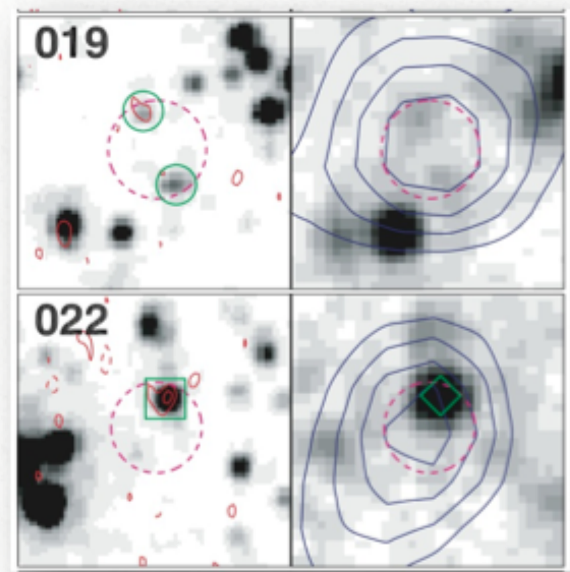
Weiss et al. (2009)

LABOCA survey of ECDFS: LESS

Joint ESO/MPI project: ~330hrs

126 submm sources above 3.7σ (S_{870um}=4.5mJy, 1σ=1.2mJy)

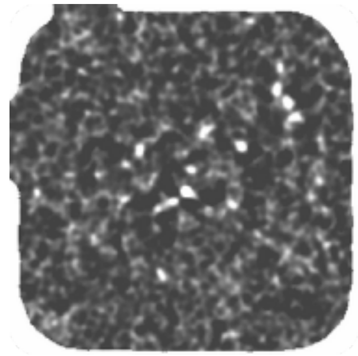
Challenge is to identify counterparts given modest S/N and low resolution: 18" FWHM



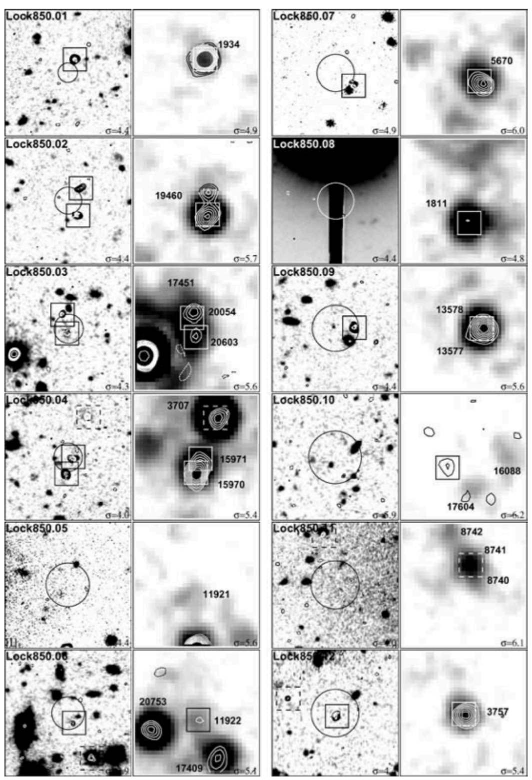
Biggs et al. (2011)

Redshifts: early days

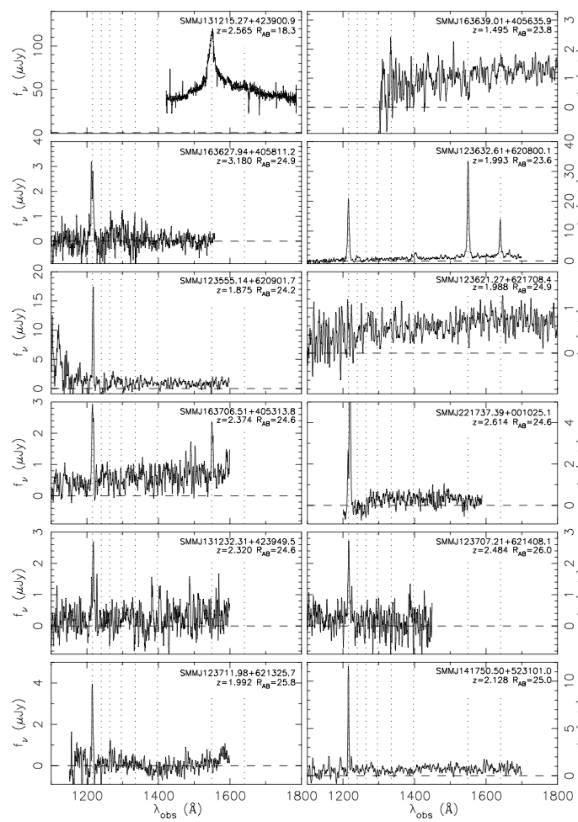
1) Blank field submm survey (e.g. Borys et al. 2002)



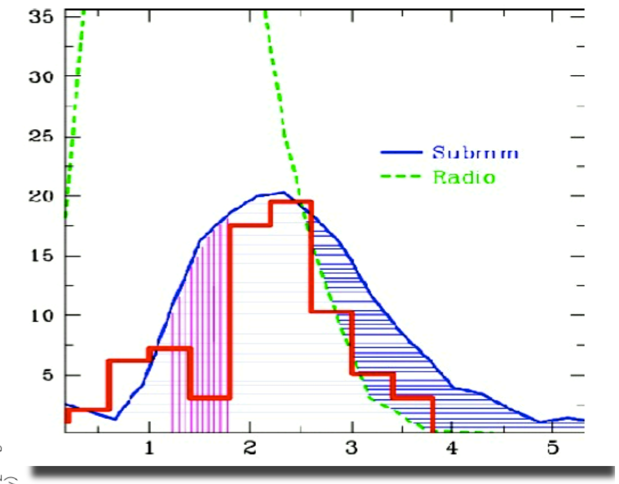
2) Find radio counterpart to SMG
Ivison *et al.* MNRAS 1998, 2002, 2007 ; Barger et al. 2000; Chapman et al. 01, 02



3) Obtain Keck spectroscopy
Chapman *et al.* Nature 2003, ApJ 2005



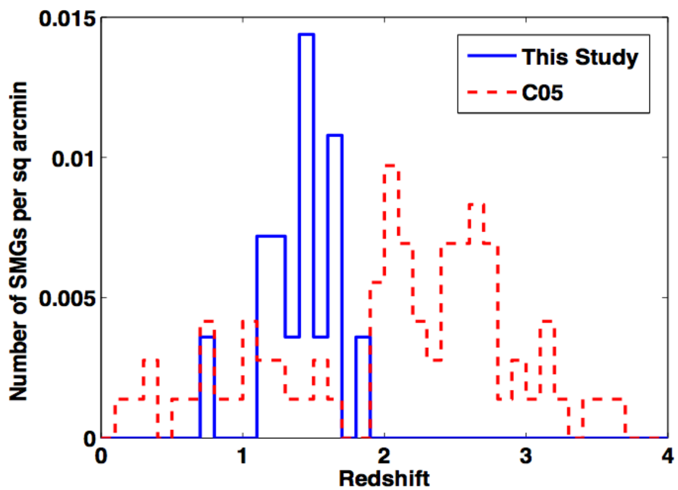
4) Estimate n(z)
Chapman et al Nature 2003; ApJ 2005

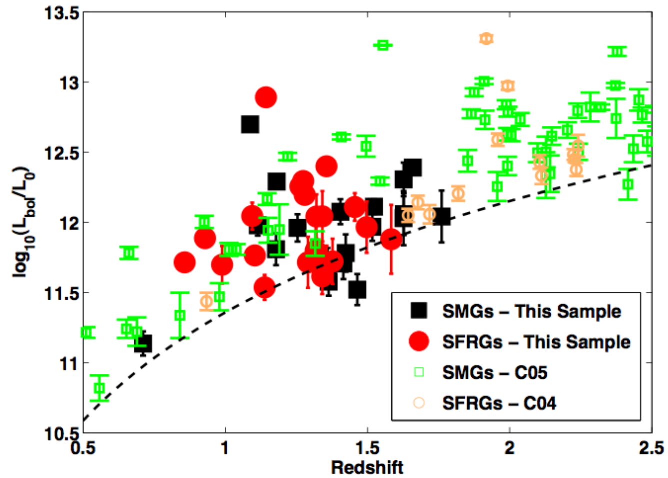


study indicates <z>=2.2, but potentially incomplete at z~1.5 and z>3 due to spectroscopic (and radio) selection

- To address this: more spec-z surveys, red sensitive Keck spectrographs; photo-z survey of LESS (and 200hr VLT spectroscopic zLESS)

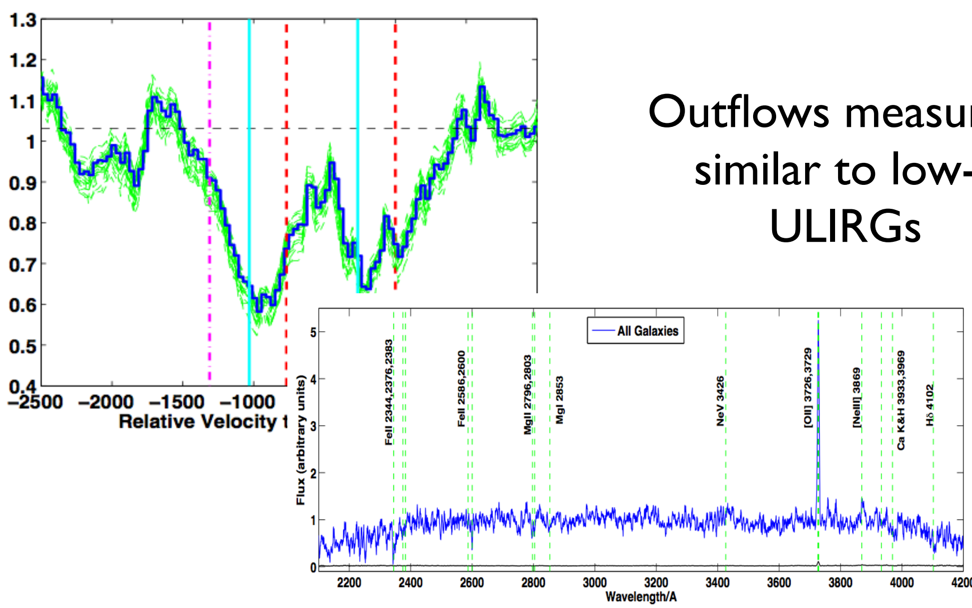
Spec-z desert (z~1.5) (Banerji, Chapman, etal. 2011)



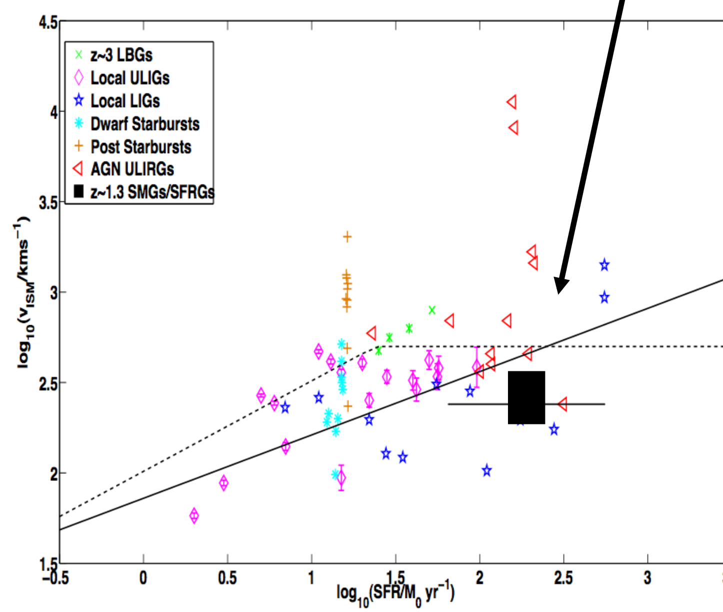


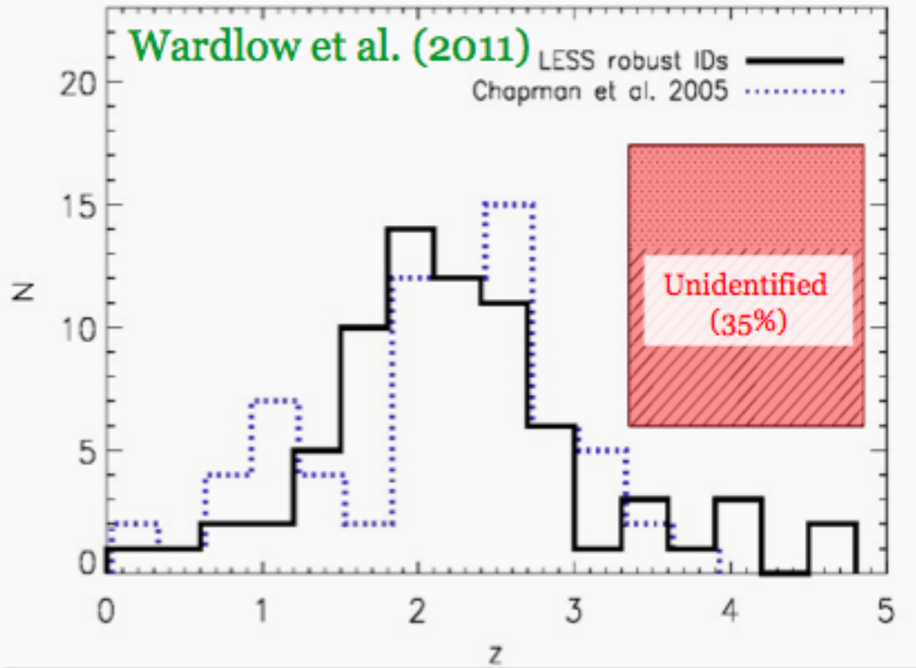
Highlights a lower-L, colder population that enters 850um survey detection limits

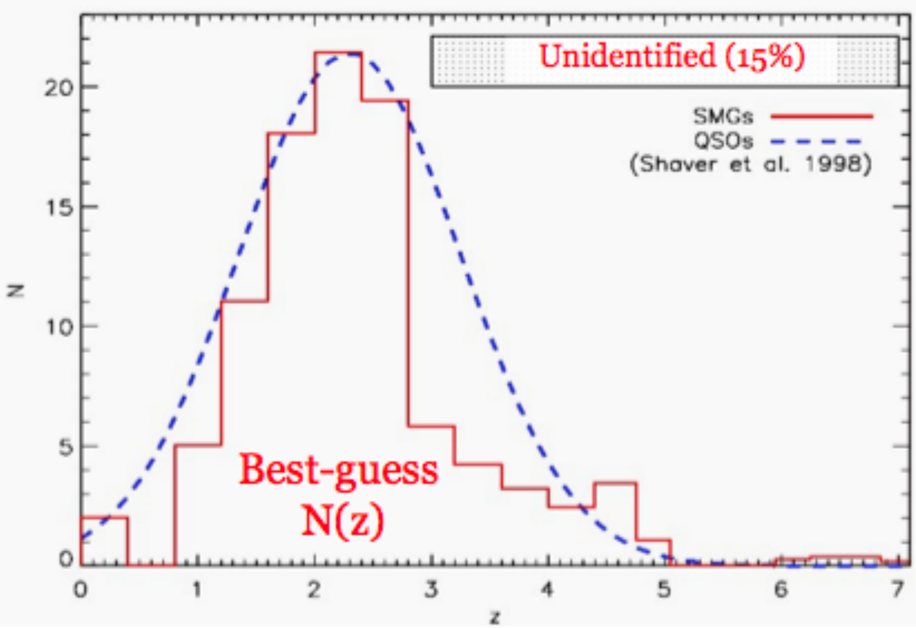
SMGs have wind velocities < Vescape suggests less of an impact on the evolution of the IGM than lower-L counterparts.



Outflows measured, similar to low-z ULIRGs







Stuff we thought we knew: "SMG" N(z)

- Median z for radio, MIPS & IRAC identified (65%) SMGs is:

  <z>=2.2

- Search blank submm error circles for "excess" IRAC galaxy population: find 20% peaking at z~2.5
- Remaining 15% un-ID likely at z>2.5 (below IRAC limit)
- Median z for **all** S_{850}>4mJy SMGs of <z>=2.5+/-0.6

  [= QSO N(z)]

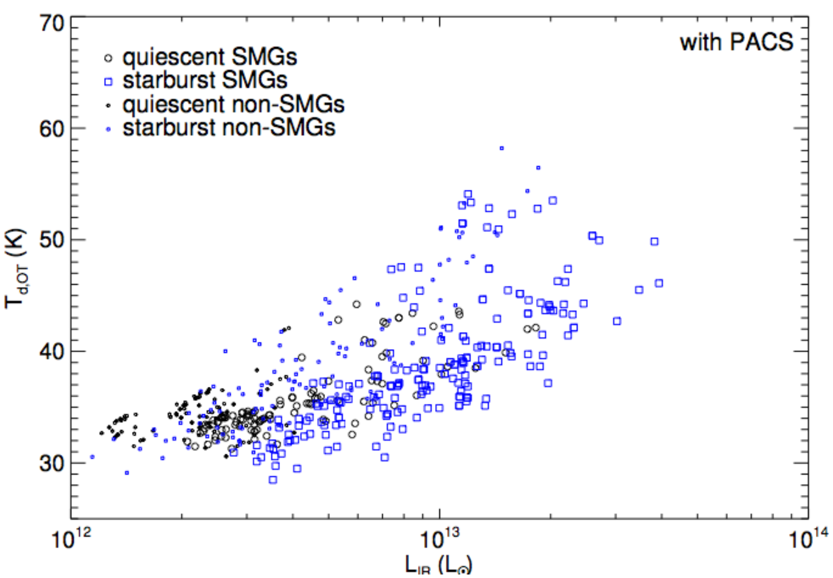
- Find SMGs out to z~5+, but decline at z>3-4 appears real (<30% at z>3) *if IDs correct*

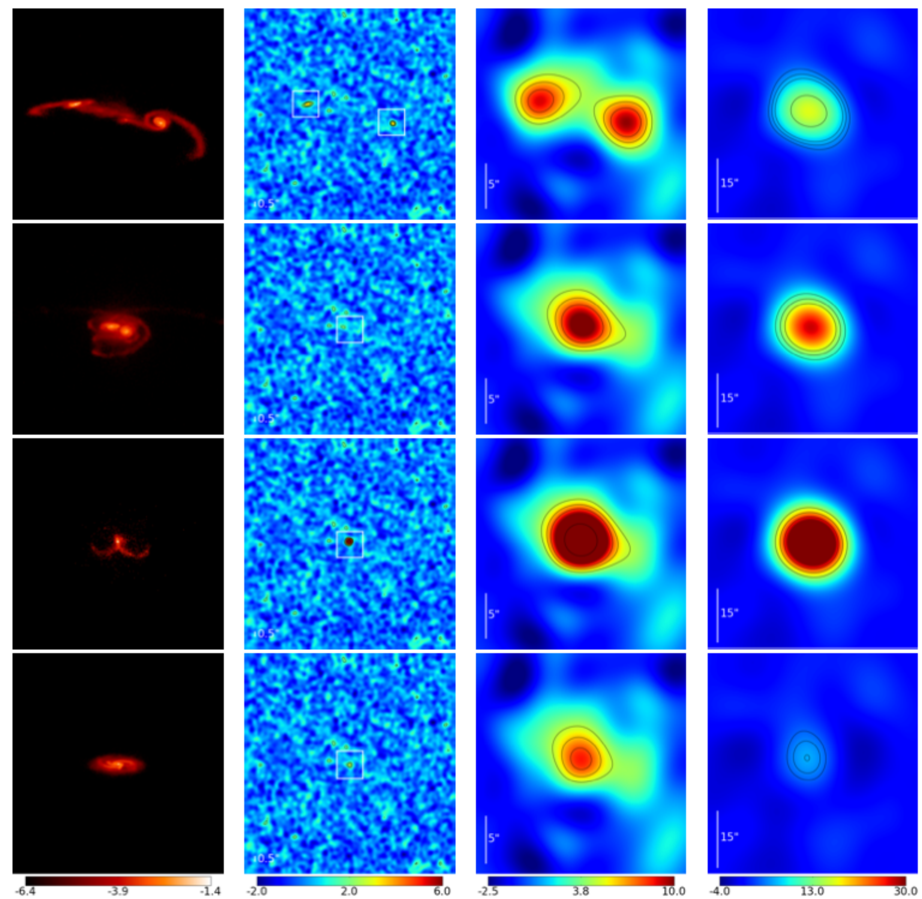
The “break-up” of SMGs

Hayward et al. (2011, 2012, 2013) hydro-simulations aimed at understanding the bright 850um population (SMGs)

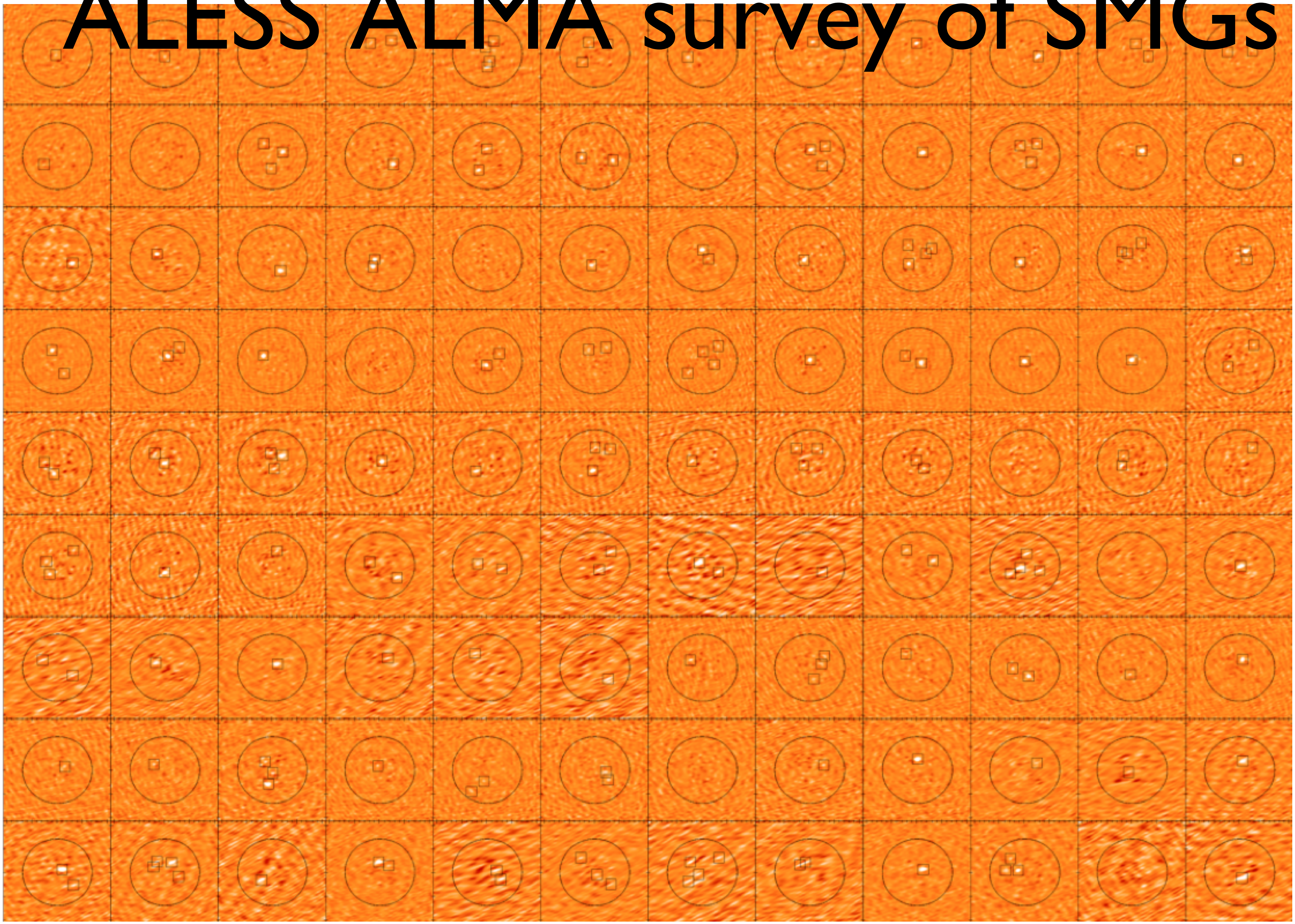
SMGs forming stars in both ***starburst*** and quiescent (disk) modes (as R.Dave 2010)

Importantly, often blended pairs of less luminous sources

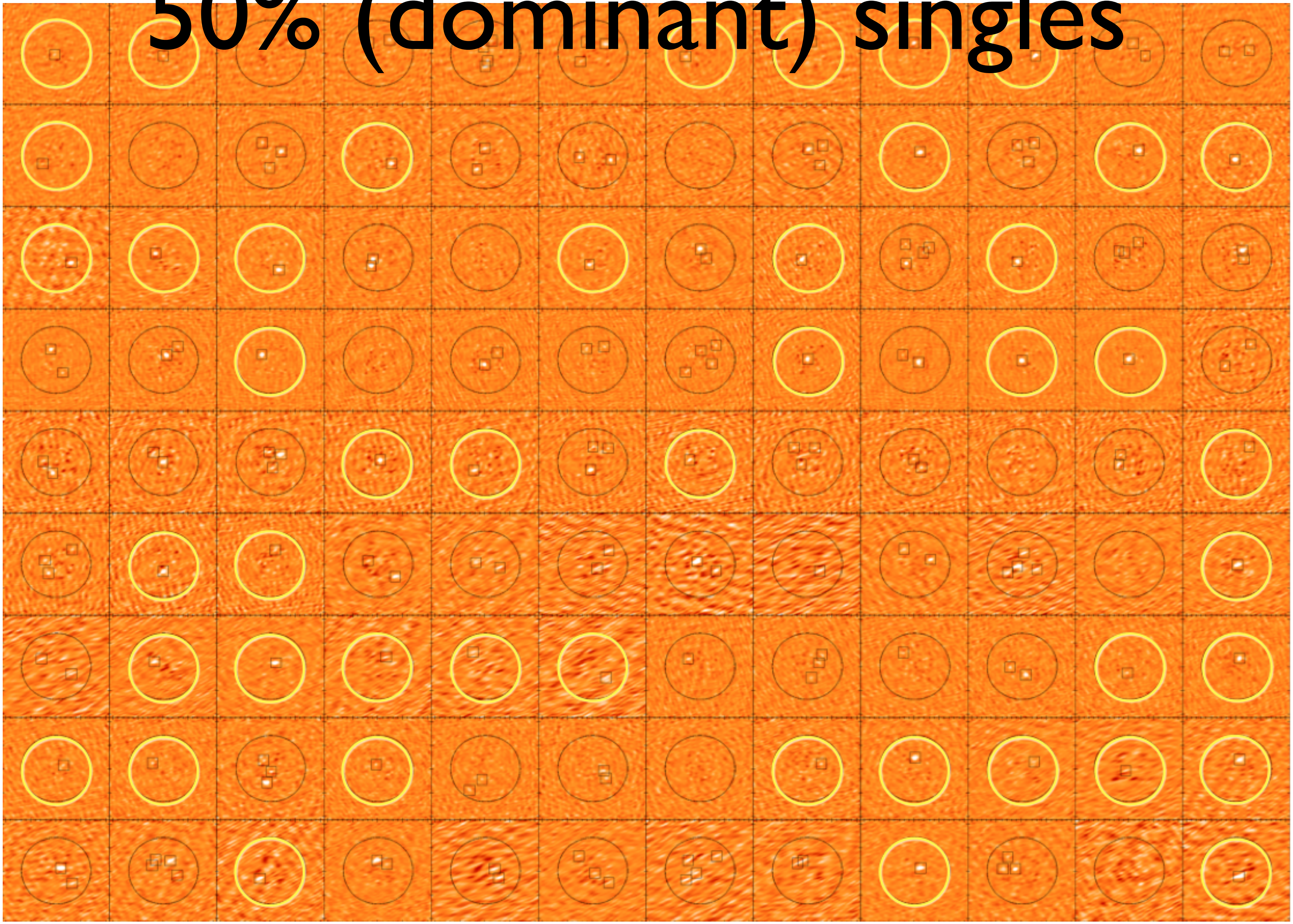




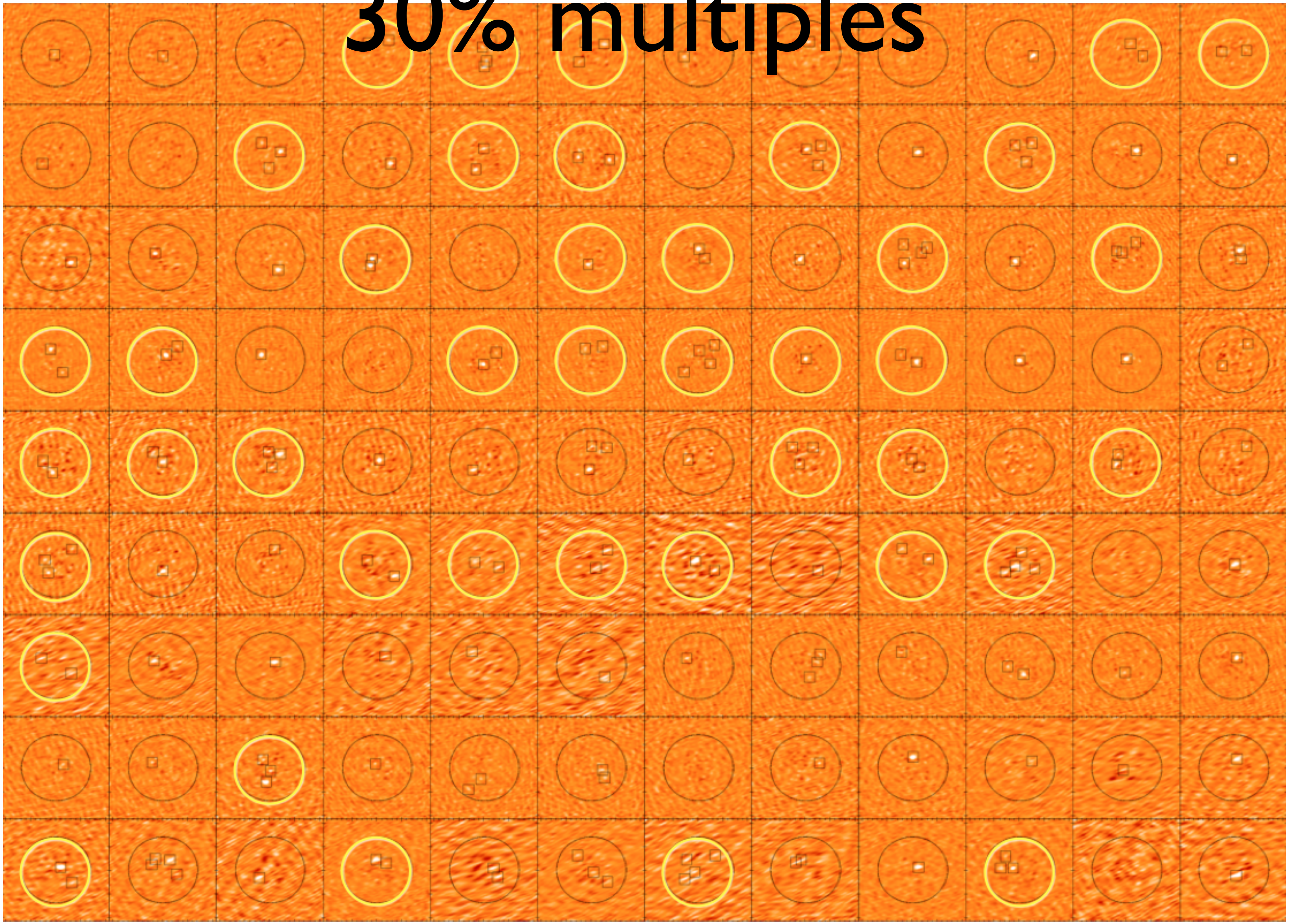
ALESS ALMA survey of SMGs



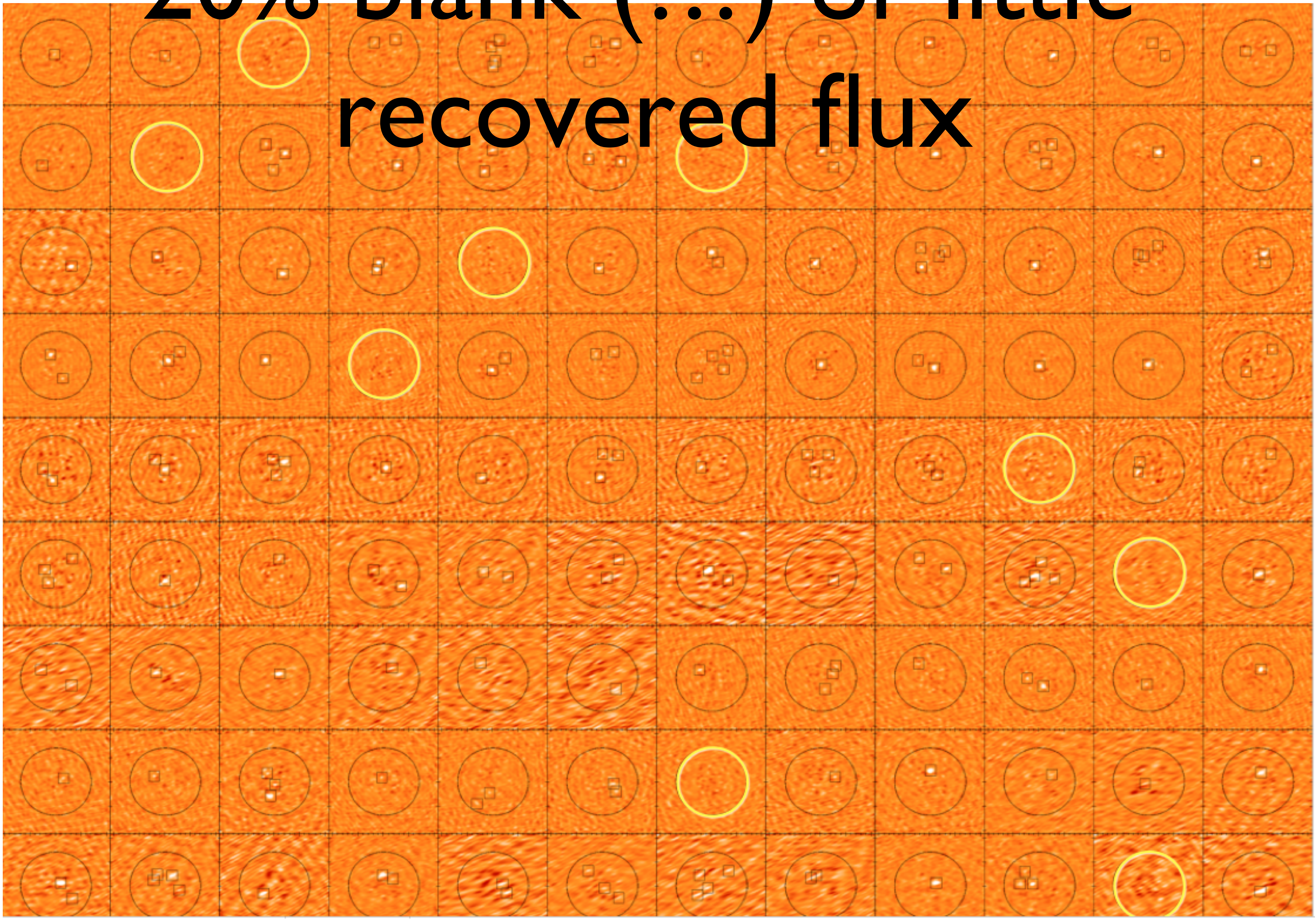
50% (dominant) singles



30% multiples

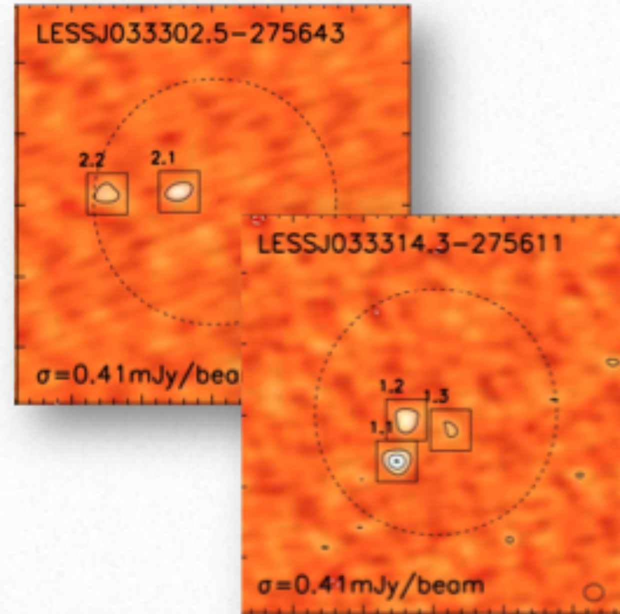


20% blank (?!?) or little recovered flux



SMG counts

Karim et al. (2013, MN, in press)



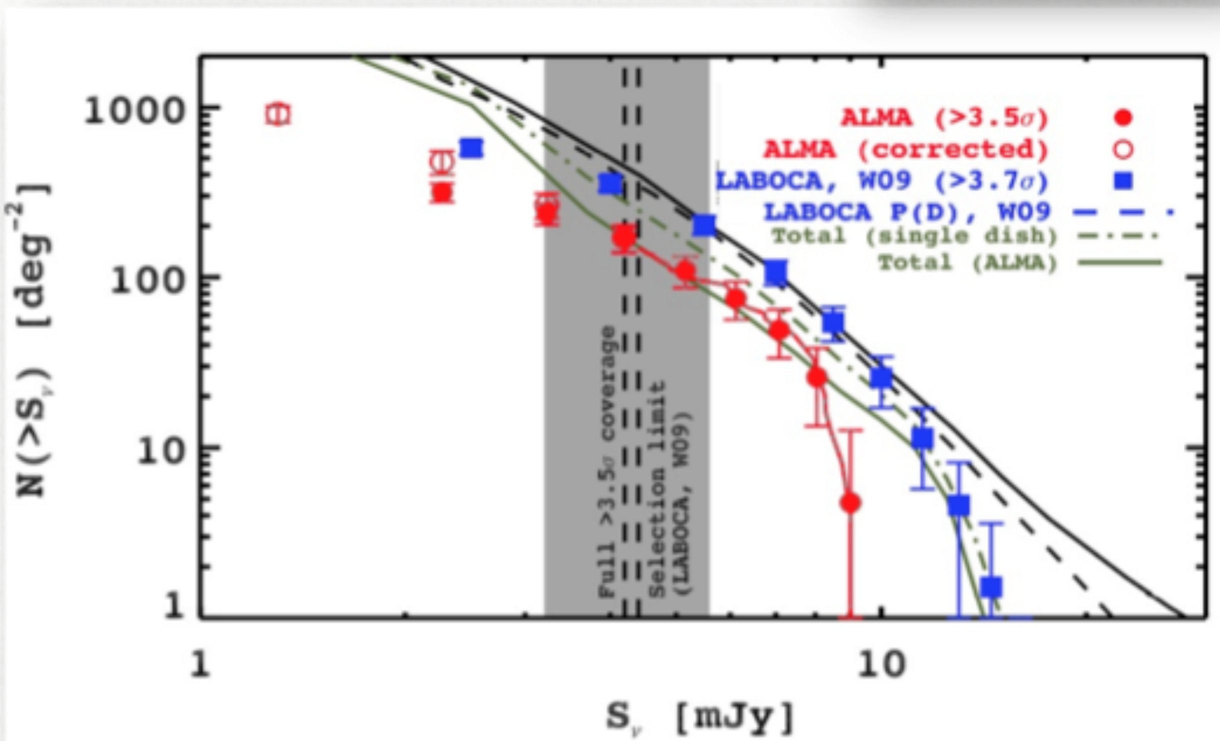
- All >12mJy submm sources are multiples:

  ***no** single SMG with S_{870um}>9mJy*

- Large fraction of undetected LESS sources may be multiple faint SMGs ($\Sigma>\pm3\sigma$: $S_{ALMA}/S_{LABOCA}=1$)

- Steepens count slope at bright end and lowers normalisation (but doesn't really improve agreement with theory models)

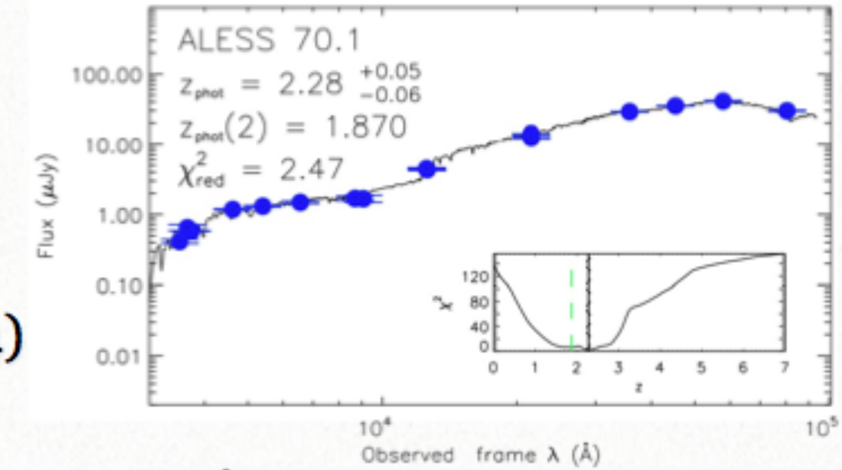
- Implies natural limit to SFR in a single source of $<10^3 M_o$/yr (few HyLIRGs?)

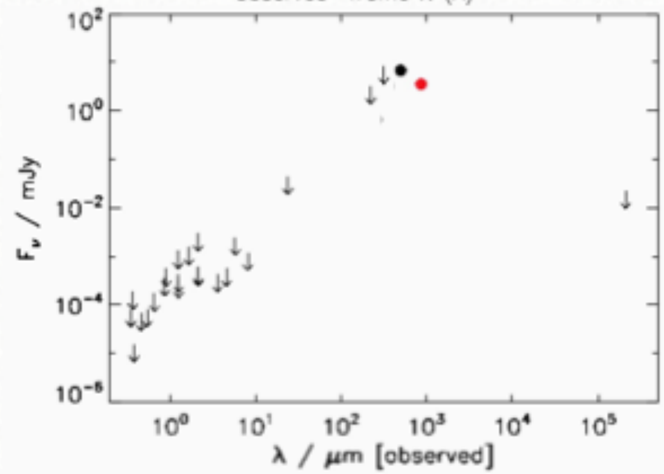


SMG N(z)

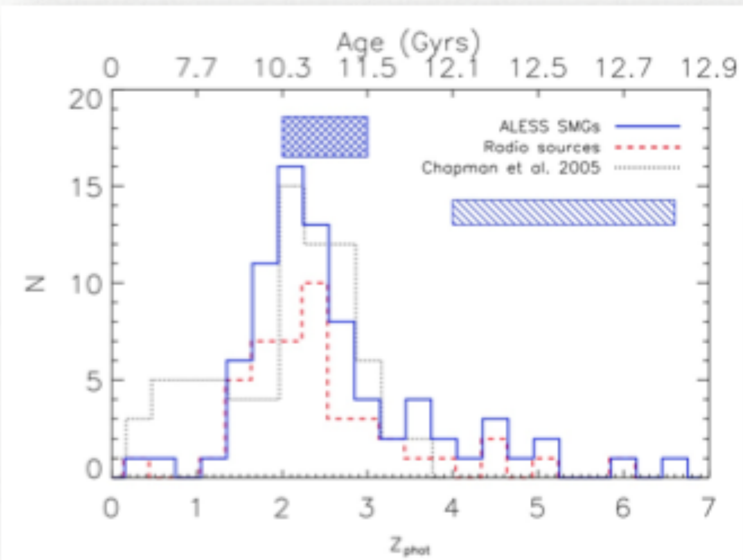
Simpson et al. MNRAS 2014

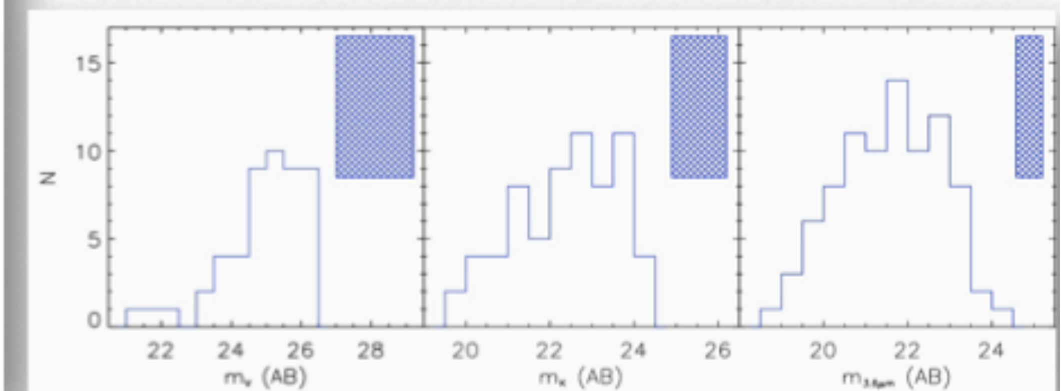
- Photo-z analysis of 99 MAIN SMGs
- 78/96 (80%) detected >4 filters (av. 14)
- 9 detected in 2-3 filters (stacked SED suggests z~2.5)
- 9 detected in 1/0 filters (but some in FIR)
- rms dz/(1+z)=0.06 for 23 spec-z
- Median <z>=2.4+/-0.1



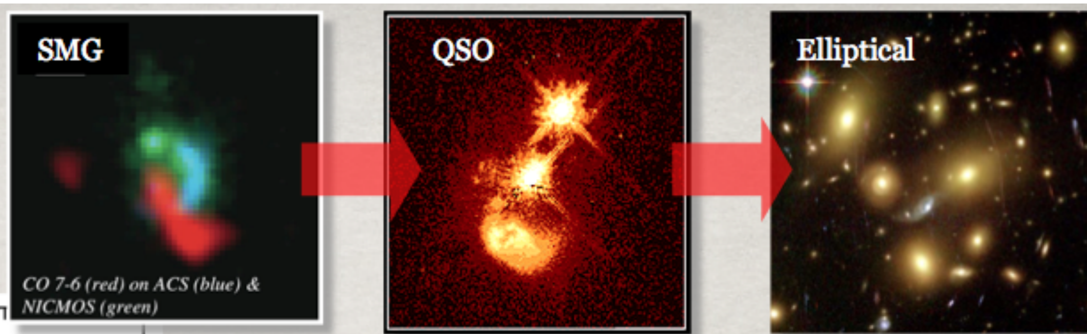


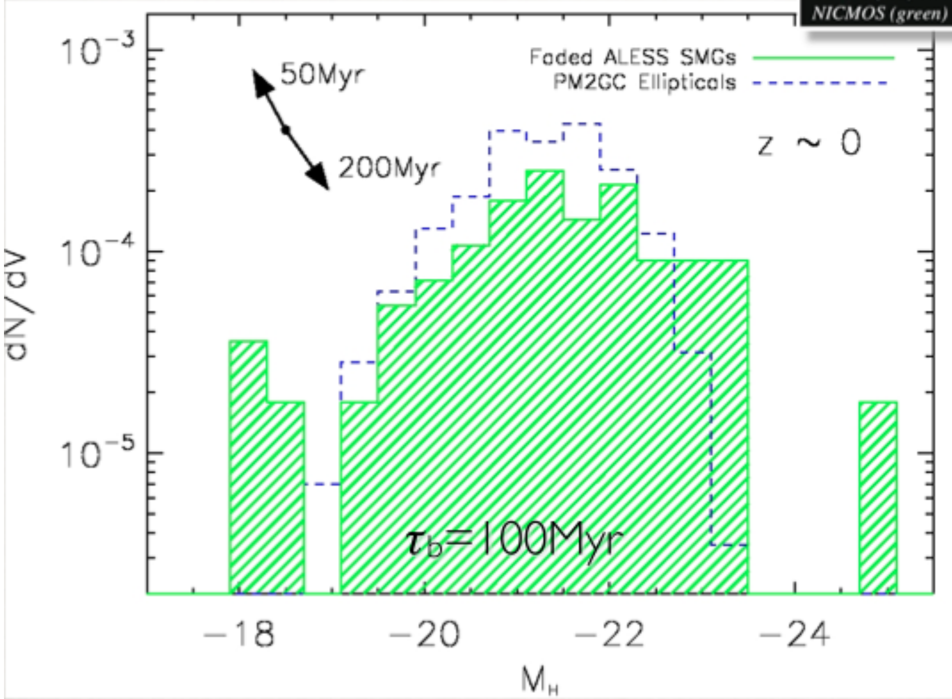
da Cunha et al. (2013)





SMG Evolution to z=0





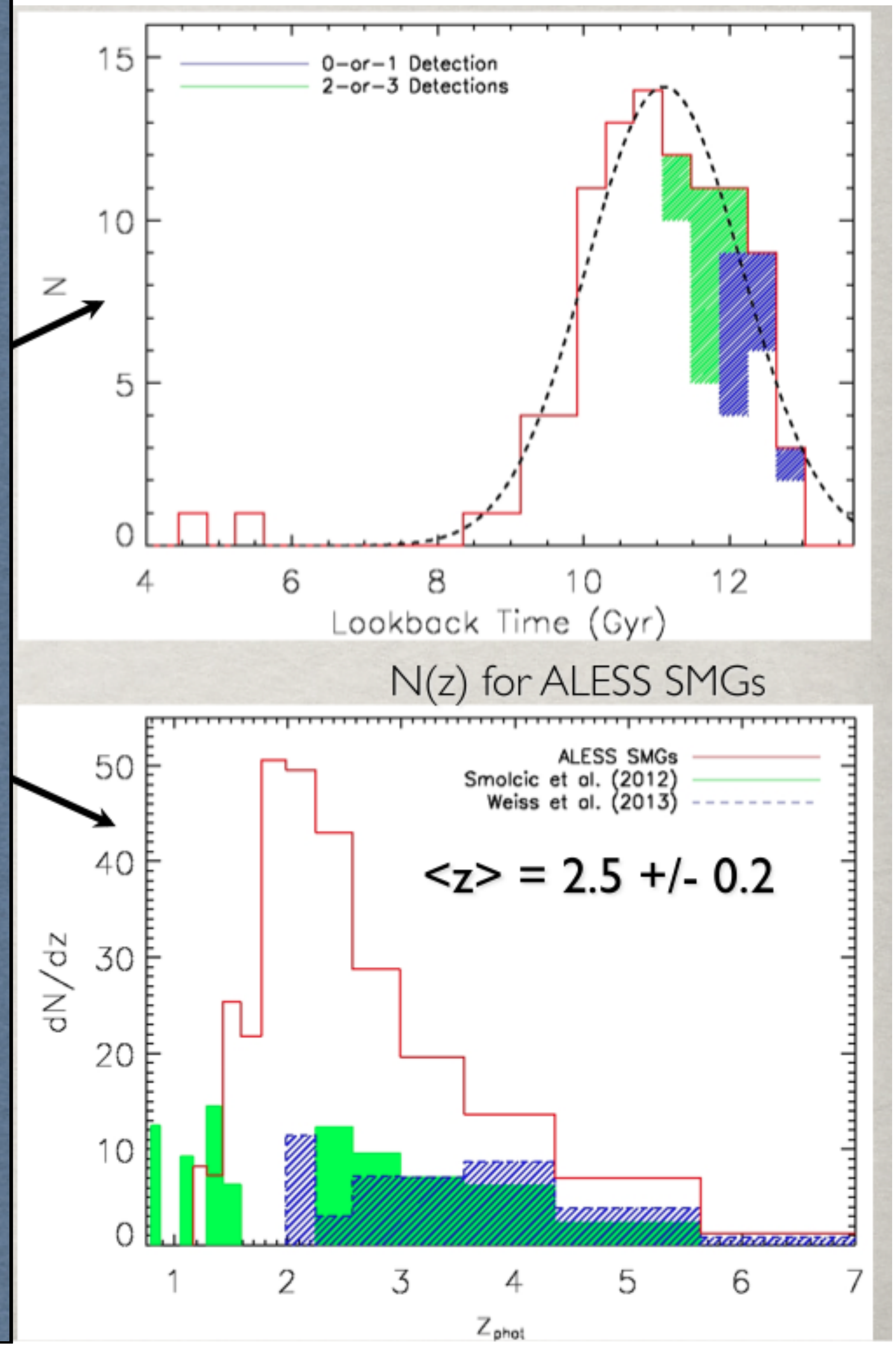
Take N(z); SFR; average lifetime and H-band fading (assume single burst) and calculate the space density of descendants at z=0

If the burst has a ~100Myr duration (compatible with the gas depletion timescales from M_{H2}/SFR ~ $4\times10^{10}M_o$/ $400M_o$/yr) and they only go through one burst then the space density and mass weighted ages of the faded SMG descendents are compatible with the majority of bright Elliptical galaxies at z=0.

ALESS SMGs have same N(z) as Chapman+2005
But seems like something strange going on!

1.2mm Smolcic+12 survey has no sources at z=2, and <z>=3 … all long wavelength bias?

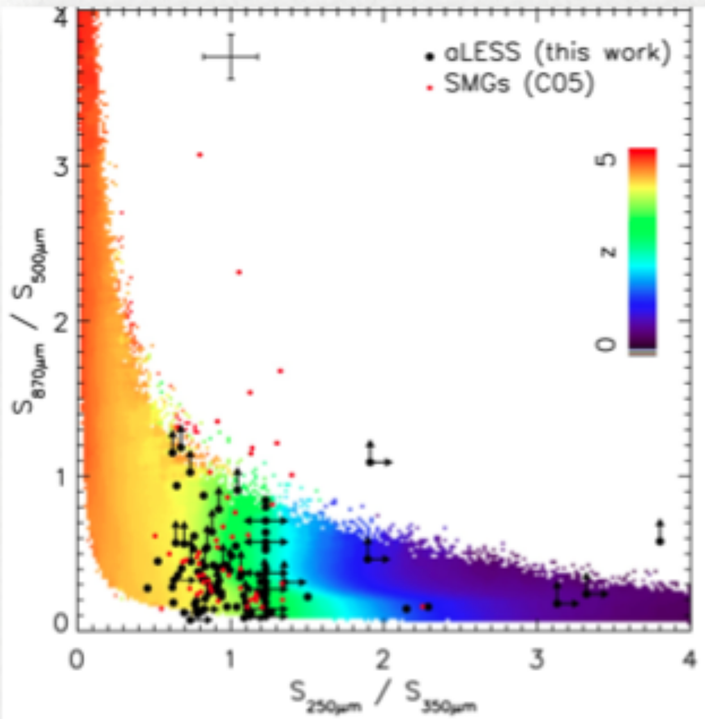
1.4mm Vieira+13 survey has <z>=3.5
… long wave bias + lens bias?



FIR properties of SMGs

Swinbank et al MNRAS 2014 --- builds on Chapman+2010 Herschel results – identical findings?

- Use ALMA positions and MIPS/radio priors for other sources in field to deblend SPIRE emission – fit C&E templates to FIR/radio SED
- Find SMGs comprise 23%/38%/29%/8% 250/350/500/870um peakers
- Median z from FIR SED fits (average Td=30+/-5K): <z>=2.4 with 350um peakers: <z>=2.1+/-0.2, 500um peakers: <z>=3.1+/-0.3
- 30% of SFRD at z=2-3 from SMGs with S_{870um}>1mJy



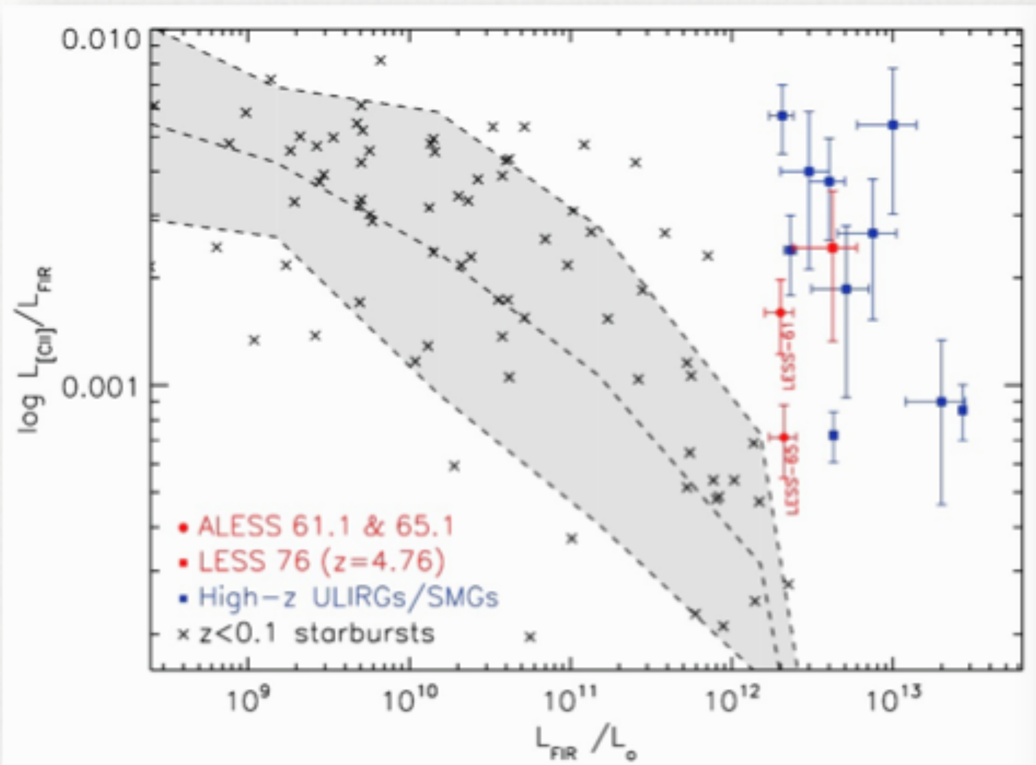
Suggests overestimated 850um flux in Chapman+05 sample?

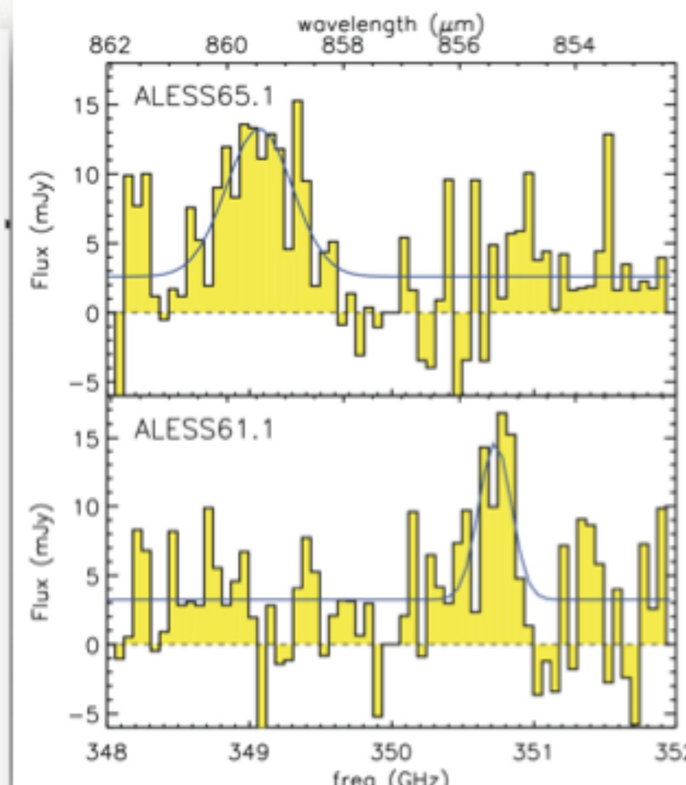
In process of reassessing C05 sample for multiplicity and better SED analysis (Beanlands in prep)

Serendipitous [CII] emitters

Swinbank et al. (2012, MN, 427, 1066,)

- ALMA data is 7.5-GHz cubes, search these for line emitters
- Find two z~4.4 SMGs with [CII] 157um (Simpson'13 N(z) predicts 1.5)
- One shows resolved velocity structure ~3kpc (M_{dyn}~$3.5 \times 10^{10} \sin^2 i \, M_o$)
- Suggests ~10% of SMGs z=4-5 (higher [CII]/L_{FIR} than similar local L_{FIR})





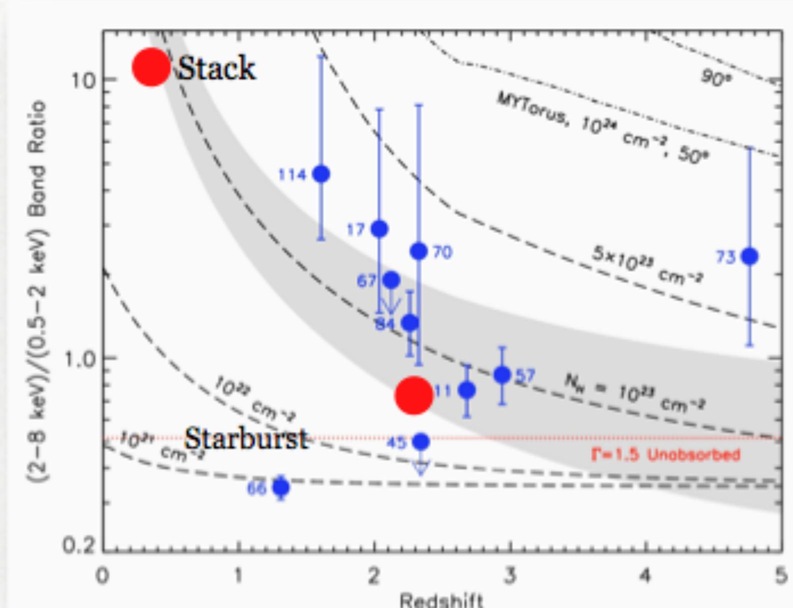
Xray

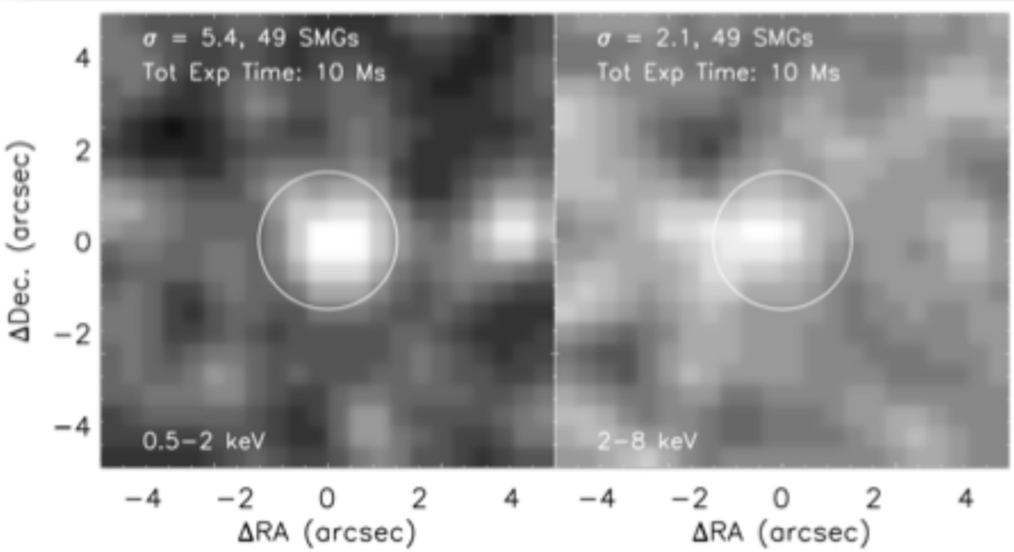
SMG: AGN?

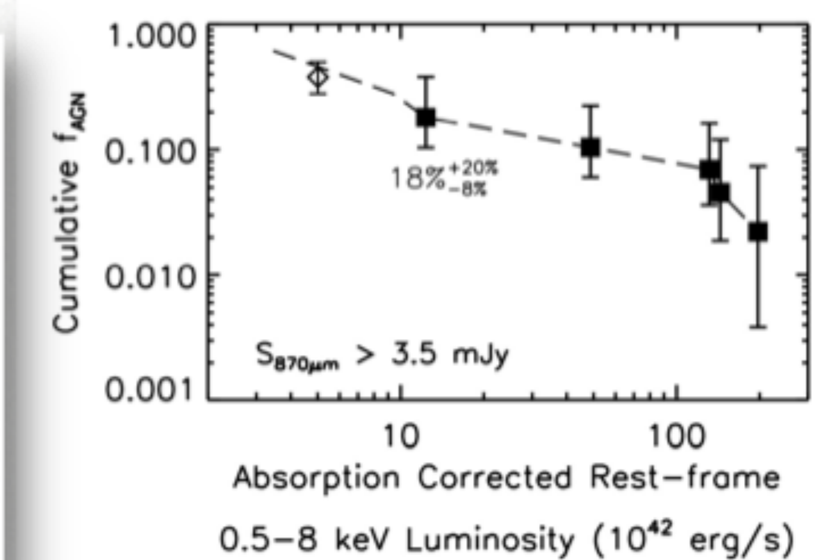
Wang et al.

ApJ 2014 – shows Alexander+05 work somewhat biased

- Compare ALESS to *Chandra* coverage of ECDFS (only ~2 fall in 4-Ms)
- 10/99 SMGs are X-ray detected (2 SF)
- ~10% host a luminous AGN, 15-20% have an AGN
- X-ray emission in stack of undetected SMGs consistent with star formation







Putting spec-ID'd SMGs in astrophysical context: Masses for SMGs

$$\boxed{M_{dyn} = C(\theta)\, R\, \sigma^2}$$

R = radius of tracer

$C(\theta)$ - Virial sphere or Disk model

$$\boxed{M_{gas} = I_{CO(J=x)}\, r_x\, \alpha_{\mathrm{CO}}}$$

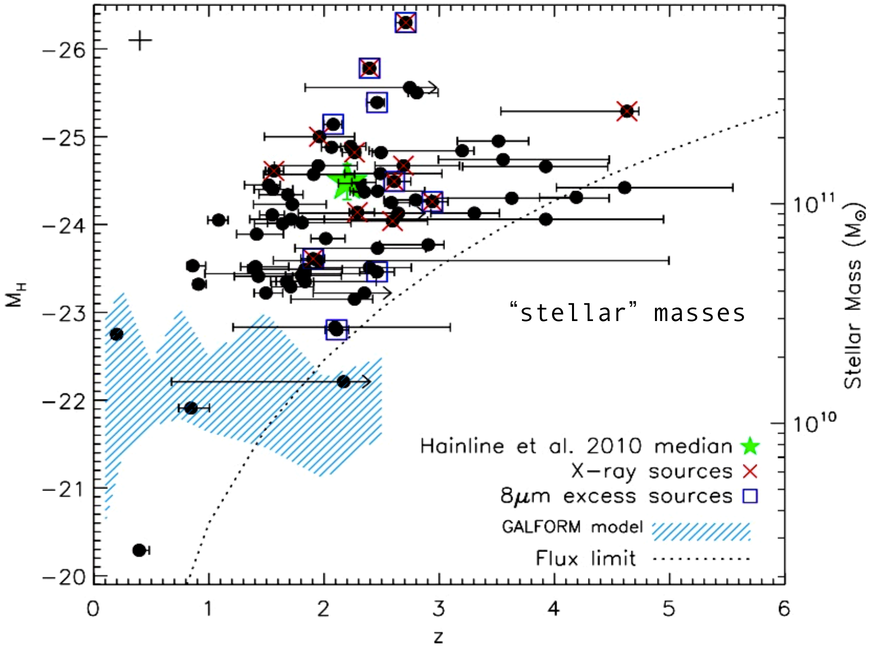
$r_x = I_{J=1}/I_{J=x}$

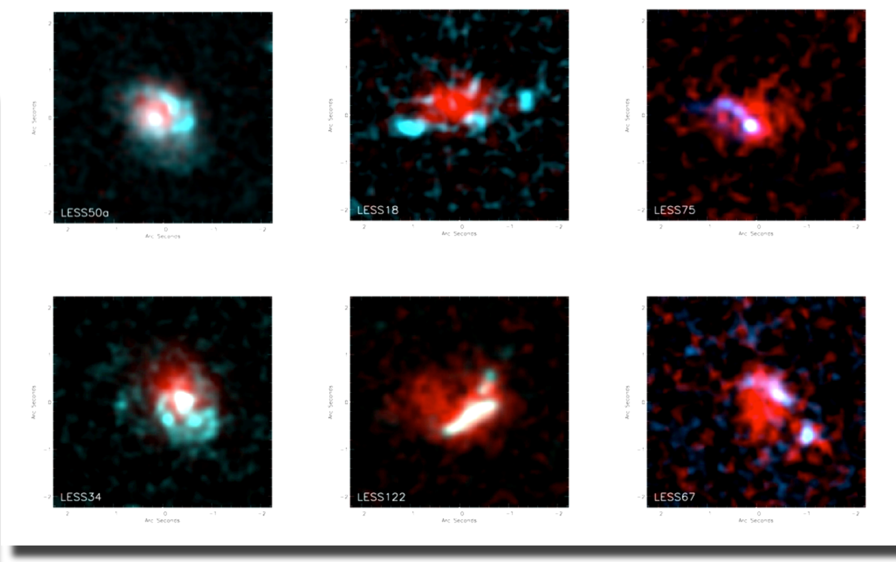
α_{CO}~5 in MW, α_{CO}~1 in local ULIRGs

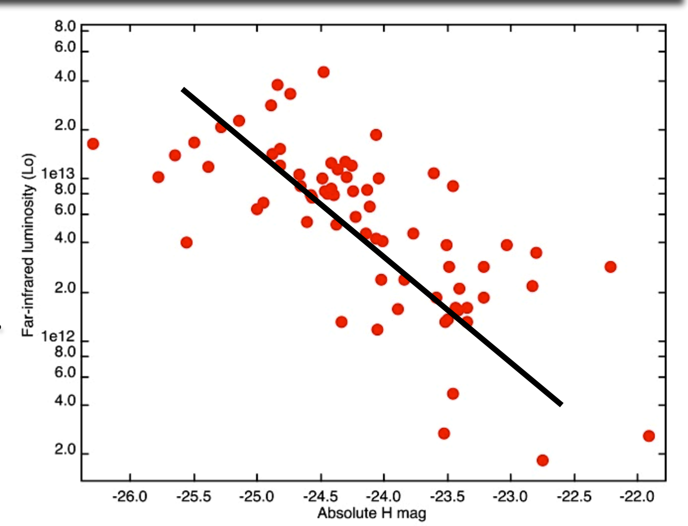
$$\boxed{M^* = Fn\left(\mathrm{T}, A_V(\mathrm{SFH}), \mathrm{SFH}, \mathrm{IMF}, Z\right)}$$

Stellar "masses"

Borys et al. 2006; Hainline et al. 2010; Wardlow et al. 2011







- SED fit -> stellar mass: ~$10^{11}M_o$ (L_H/M~3.8)
- But ***very*** uncertain - likely a *complex mix of emission (inc AGN?), age and extinction*
- 2/3rds of SMGs are equal well-fit by Burst or constant SFR models with L_H/M varying by >5x.

(Semi-analytic model predicts SMGs are 10x fainter in restframe NIR.)

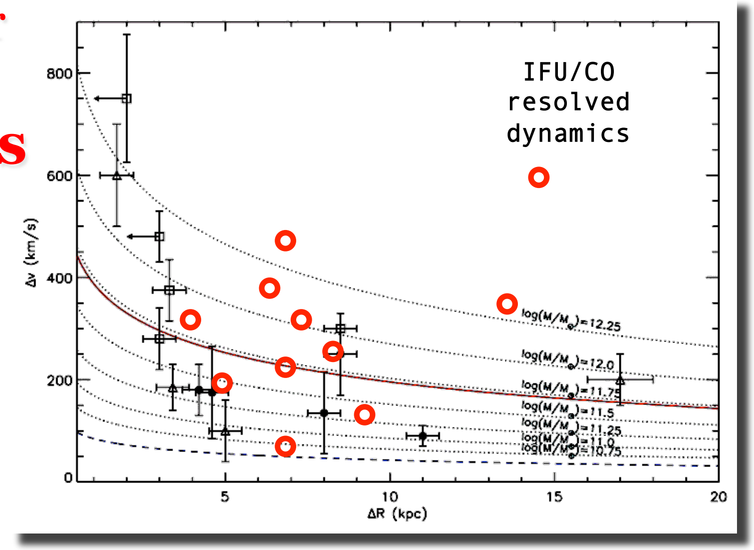
- ***What about the other baryonic component: gas?***

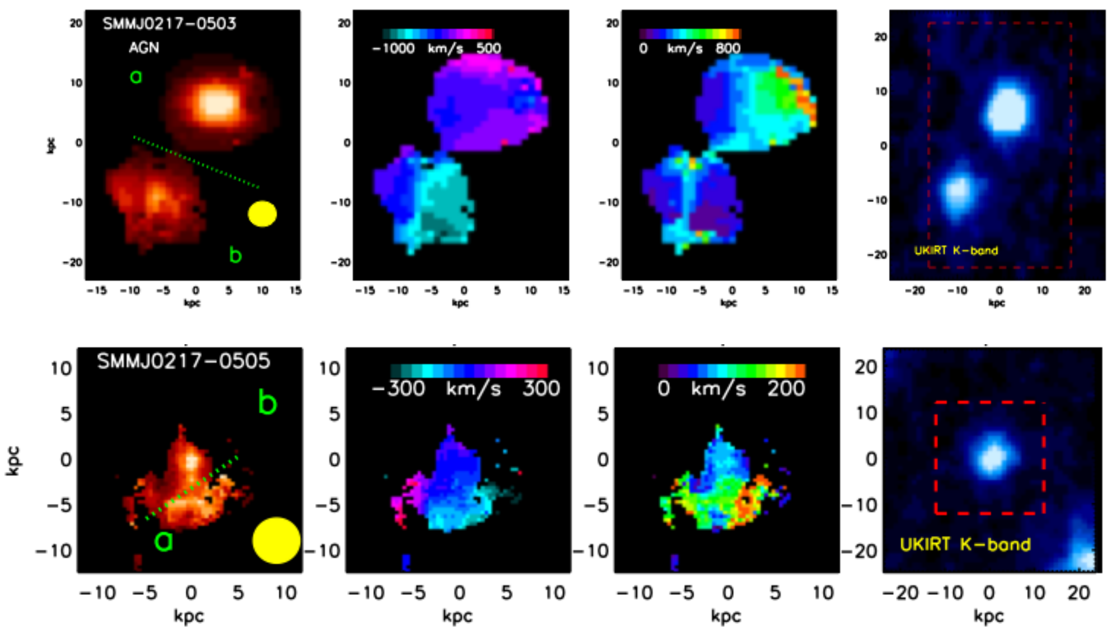
SMGs are mostly mergers from IFU/**Halpha** analysis.

Swinbank+2006; Alaghband-Zadeh+2012

Hα sensitive to a larger range (lower levels) of star forming enviroments (but dust extincted)

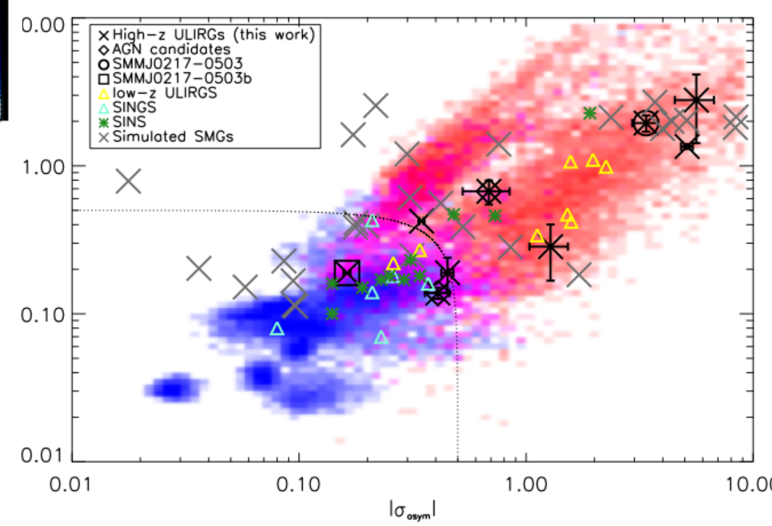
characterizing merger environments





Alaghband-Zadeh et al. 2012: **11** new NIFS/SINFONI maps of SMGs

“kinemetry”: study of field asymmetries



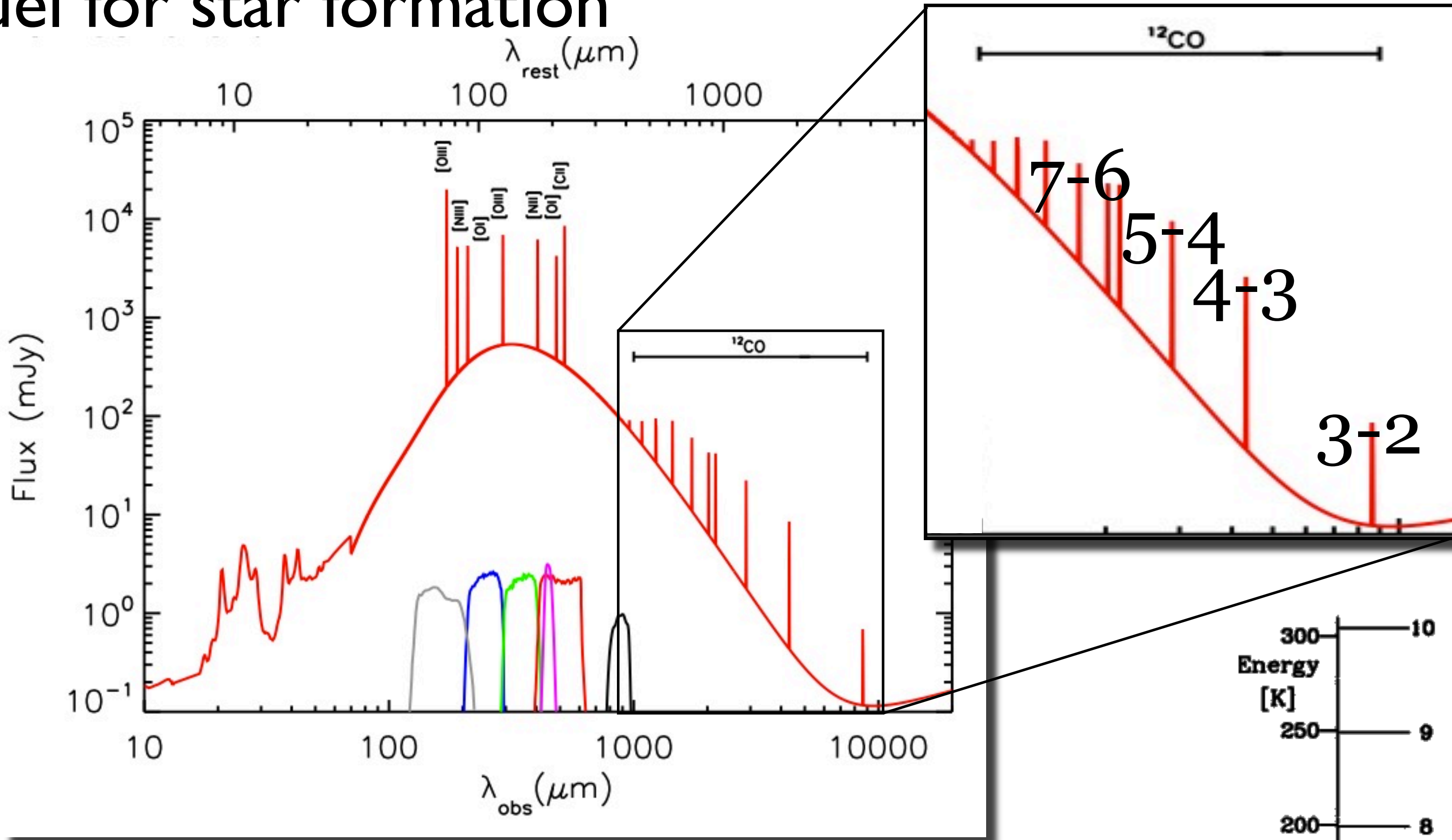
- Total masses within R_{vir} from resolved IFU

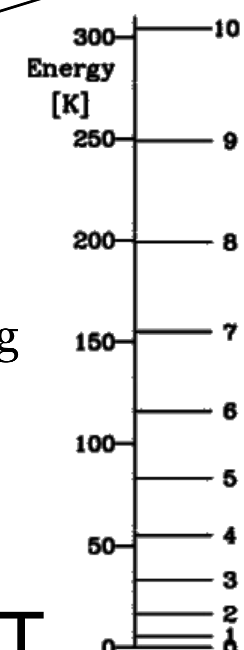
Ha kinematics: $<5 \times 10^{11} M_o$

(σ~200km/s)

The fuel for star formation

CO emission: H_2 Mass





$$\boxed{M(H_2) = I_{CO(J=x)}\ r_x\ \alpha}$$

α is an empirical factor relating CO(1-0) to H_2mass and is dependent on abundance, gas conditions and optical depth
α~5 in MW, α~1 in ULIRGs

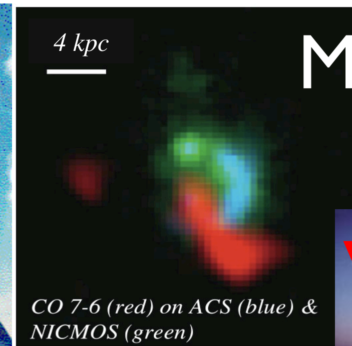
$r_x = I_{J=1}/I_{J=x}$ traces excitation.

~ geometry . (n_H2)$^{1/2}$ / T

Molecular Emission Lines

- ^{12}CO ladder is best studied - commonest tracer of H_2
  - Provides systemic redshift for gas reservoir
  - Line luminosity can be converted into M_{gas} (!)
  - Line kinematics can be used to estimate M_{dyn} (!)
  - Together these yield the gas fraction: M_{gas}/M_{dyn}
  - Line kinematics give hints about source structure
  - ^{12}CO SLED tells us about gas excitation

PdBI SMG CO survey

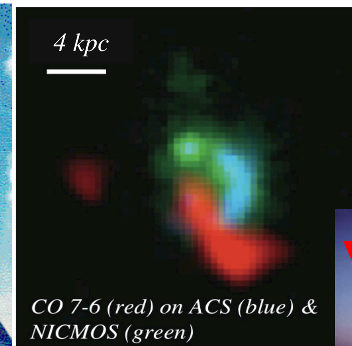


<u>Decade of CO followup of SMGs with PdBI since 2002:</u>

- Neri et al. 2003: First CO detection of unlensed SMGs
- Greve et al. 2005: Initial survey results
- Tacconi et al. 2006, 2008: 1st/2nd generation HIRES followup
- Bothwell+2010, Engel+2010:
  HIRES comparison with radio and final survey

- Bothwell+2013: Final summary paper, inc/ 40 SMGs surveyed

(Genzel, Ivison, Neri, Chapman, Smail, Blain, Greve, Bertoldi, Omont, Cox, Tacconi, Bothwell, Casey, Engel, Alaghband-Zadeh)



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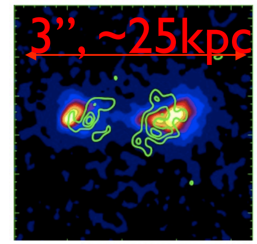
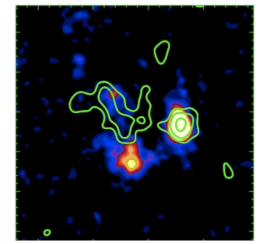
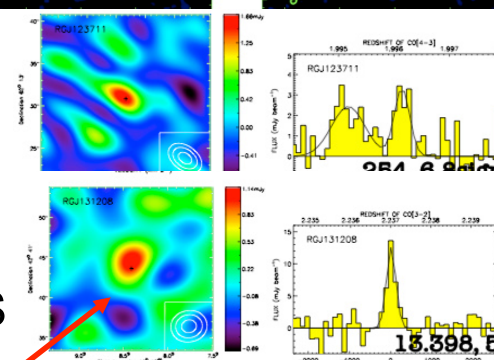
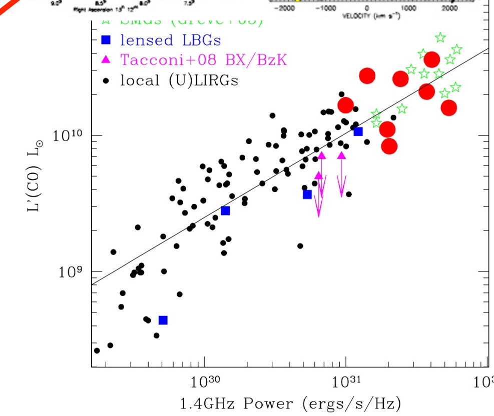
- Bothwell+2010, Engel+2010: HIRES comparison with radio and final survey
- Chapman+2008; Casey+2011: ***hot-dust ULIRGs*** that SCUBA missed (11/16 show CO(3-2) detections; similar SF efficiency to SMG)

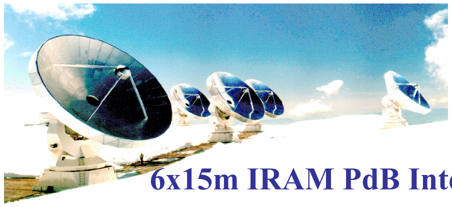
- Bothwell+2012: Final summary paper, inc/ 40 SMGs surveyed



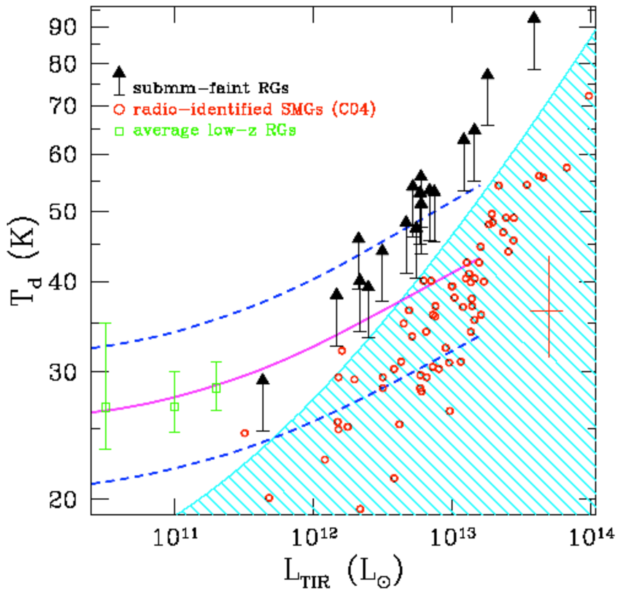


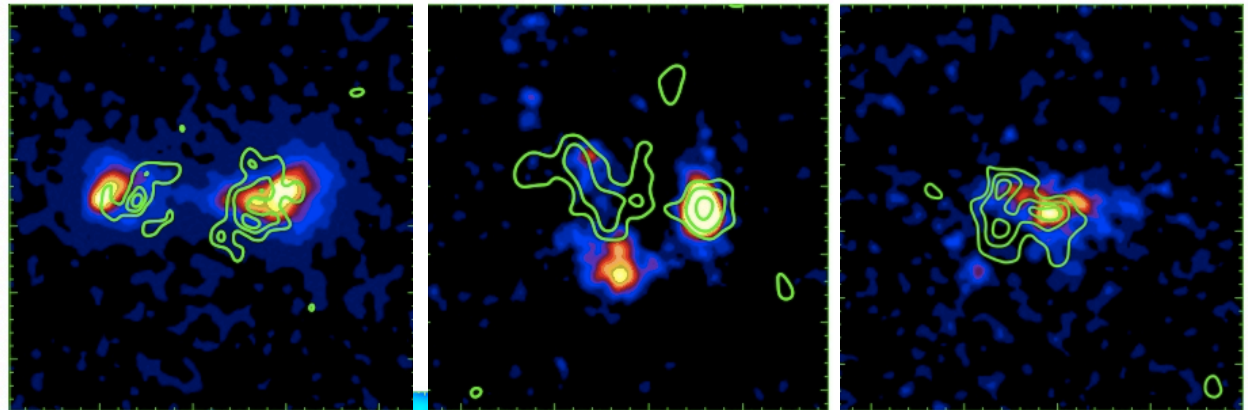


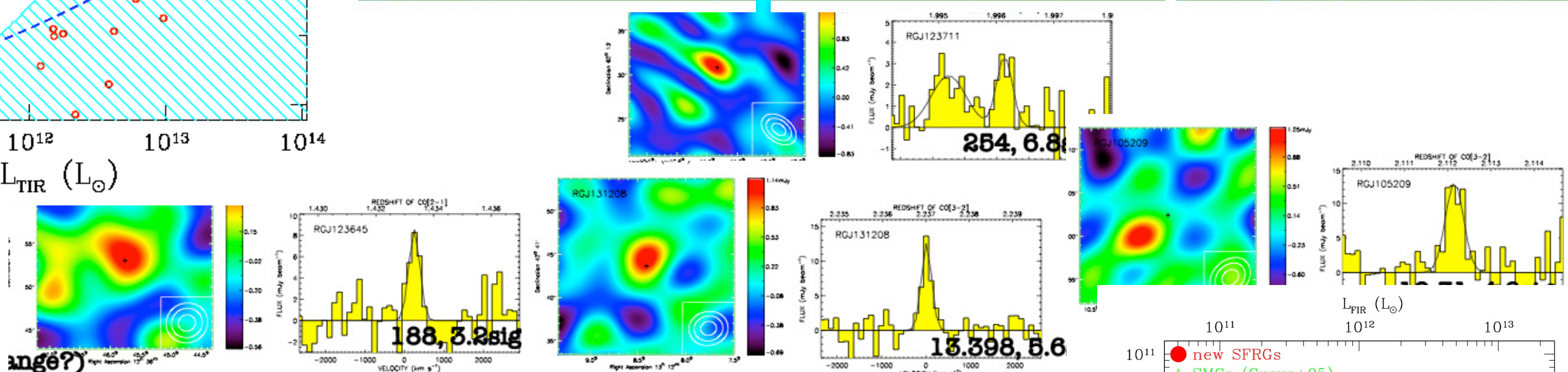


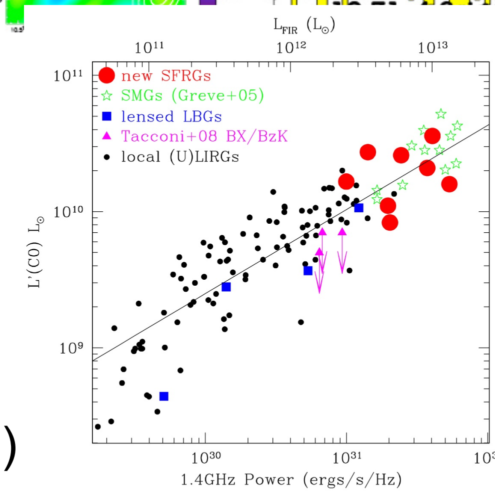


ULIRGs that SCUBA missed: higher T_{dust} SMGs?









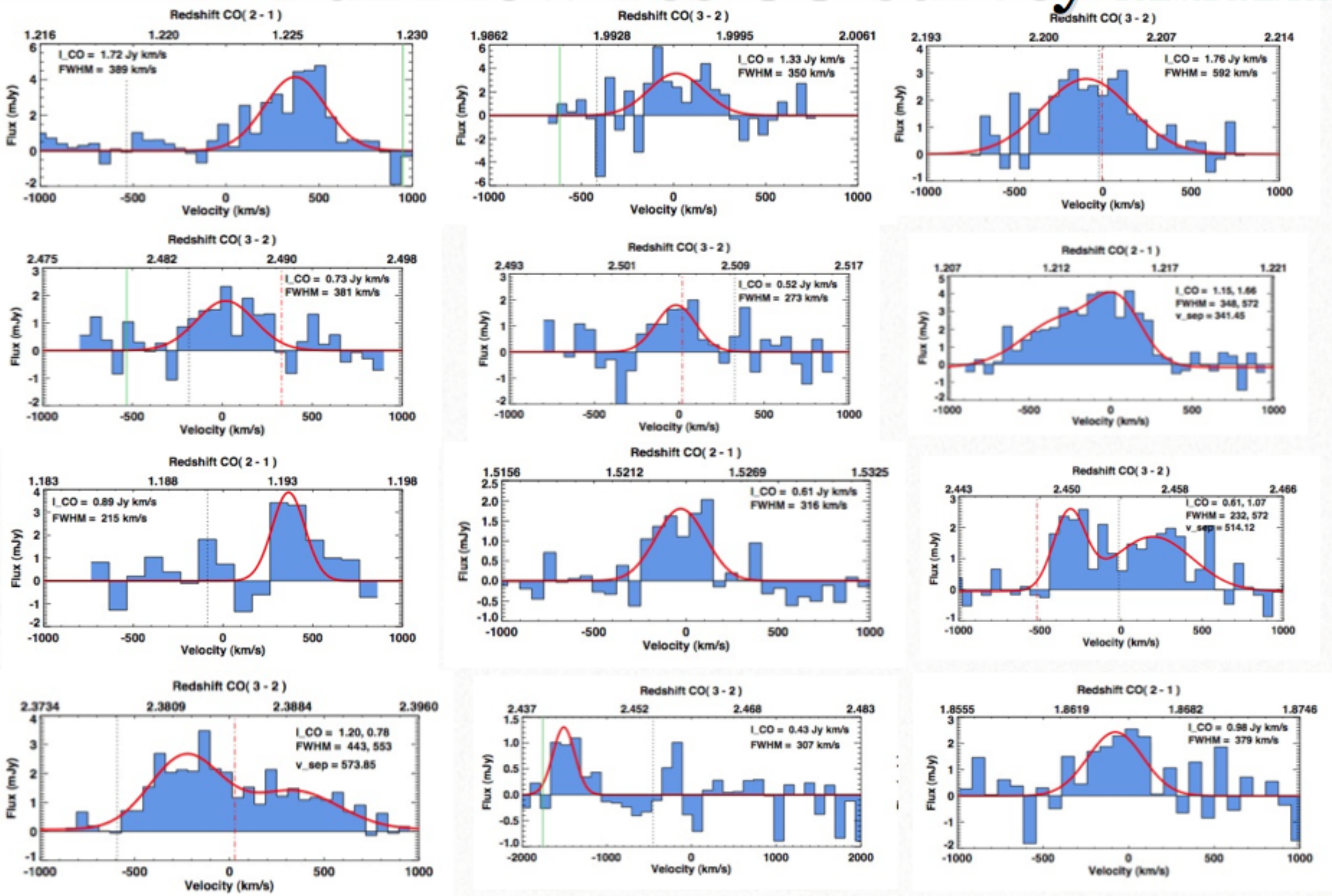
Chapman+2004,2008; Casey et al. 2009,2010,2011:

- 11/16 show CO(3-2) detections; similar SF efficiency to SMGs
  - But lower-SFR, lower mass systems.
- Narrower line widths => lower mass?

- Sample of 25, resolved MERLIN radio: >8kpc scales (mergers)

PdBI low-res CO survey

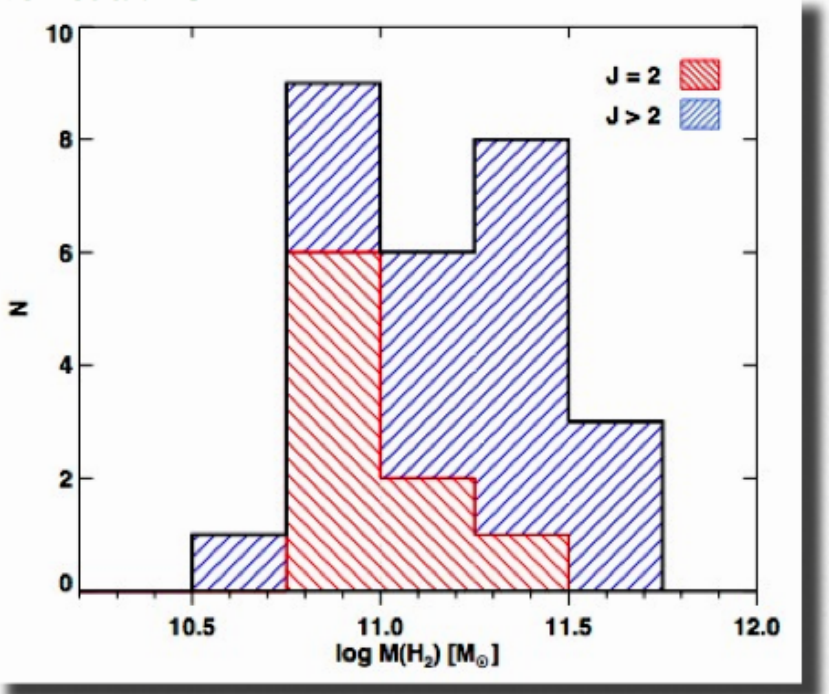
Bothwell et al. 2012

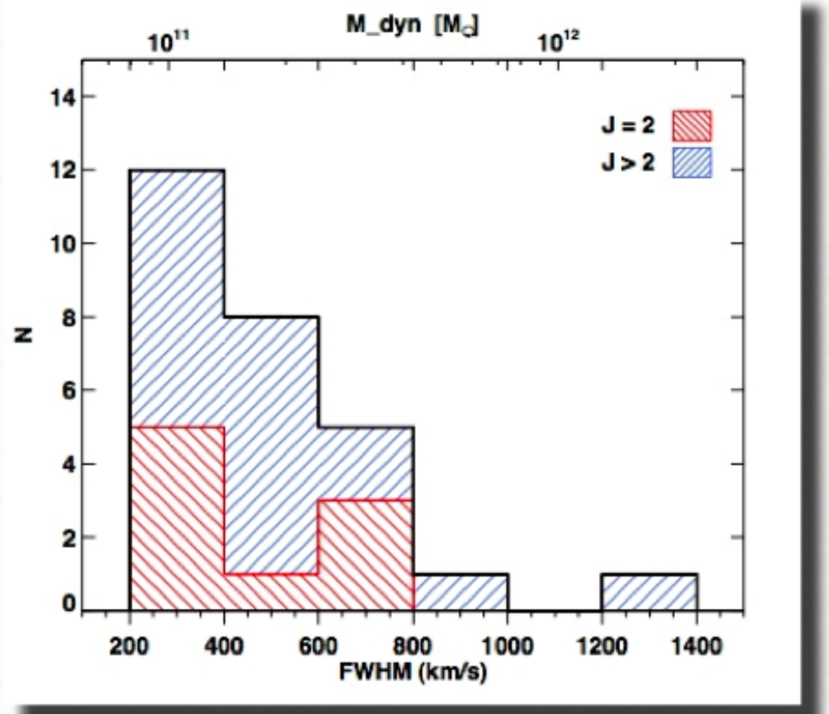


- 40 unlensed SMGs in CO(3-2)/CO(2-1): 32 detections, 8 non-detections
- +CO for ~50 lensed Herschel srcs (Riechers et al.) - differential magnification!

Gas & Dynamical Masses

Bothwell et al. 2012





$$\boxed{M_{gas} = I_{CO(J=x)}\ r_x\ \alpha_{CO}}$$

$r_x = I_{J=1}/I_{J=x}$ from SLED

α_{CO}~5 in MW, α_{CO}~1 in z=0 ULIRGs

$$\boxed{M_{dyn} = C(\theta)\ R\ \sigma^2}$$

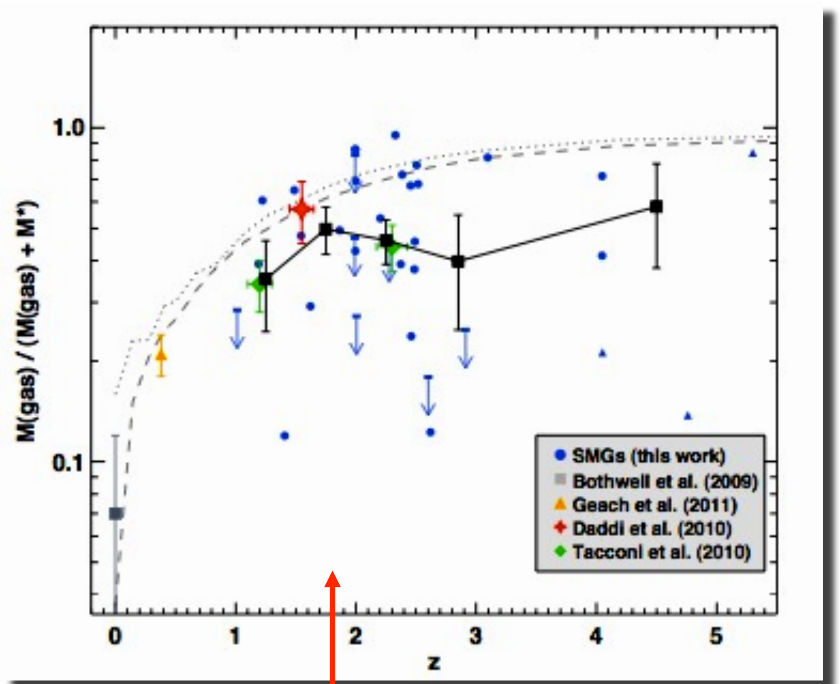
C(θ) - Virial sphere or Disk model

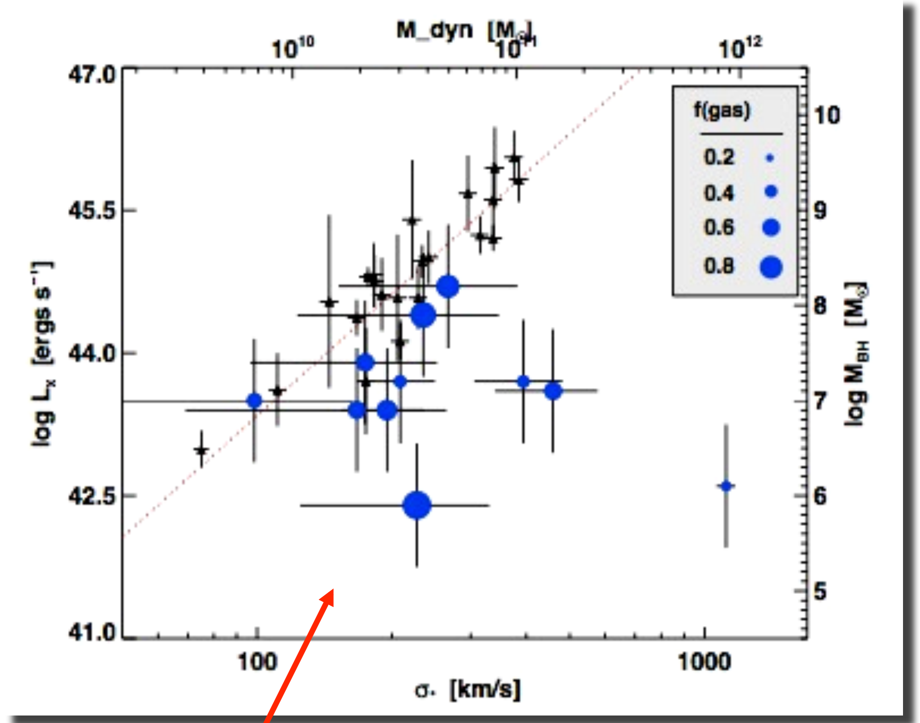
R = radius of gas reservoir

- Median gas mass (including limits): (1.0+/-0.2) x 10^{11}Mo (for α~2)
- FWHM of CO: 510+/-80km/s yields M_{dyn}(<7kpc) ~$3\times10^{11} M_o$ (disk model)
- Gas fraction ~30% vs 7% for z=0 LIRGs (Bothwell et al. 2009) - less evolved

Gas Baryon Fraction Evolution & SMBHs

Bothwell et al. 2012





- At most modest evolution in gas fraction in SMGs with redshift
- Use dynamics of CO to determine SMBH-M_{gal} relation for SMGs (adopting random sky orientations): ***confirms earlier claims*** that SMBHs in SMGs are less-massive than z=0 BH-spheroid relation predicts

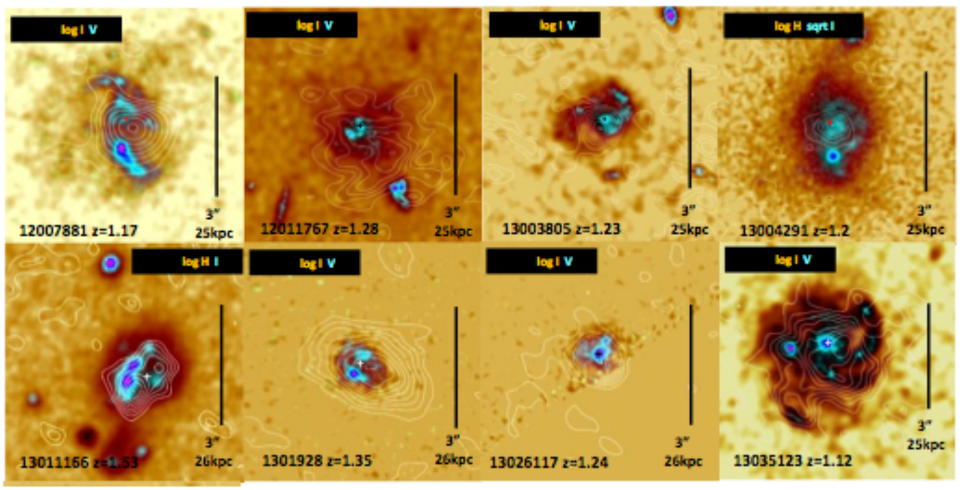
Normal star forming galaxies?

Note that L* is pretty luminous at z=2-3

SFR ~ 100 M/yr not unusual.

ULIRG no longer such an extreme object.

Tacconi et al. 2010, 2013 have pushed the field forward measuring CO gas in these 'normal' Star Formers.



SMGs L($CO_{3\text{-}2}$) … significant overlap with *normal star formers*

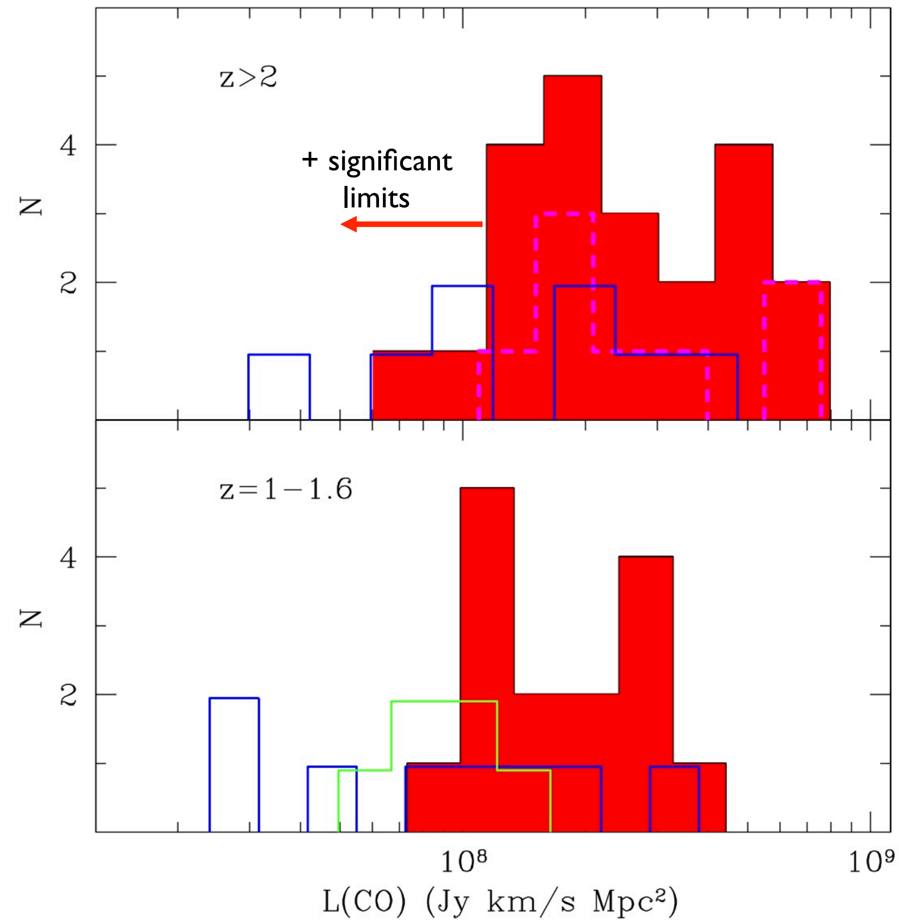
In L(CO), **SMGs (dashed z>3)** and **normal galaxies** not that different …
we were too cautious about normal star forming galaxies … eg. Daddi et al. (2008)

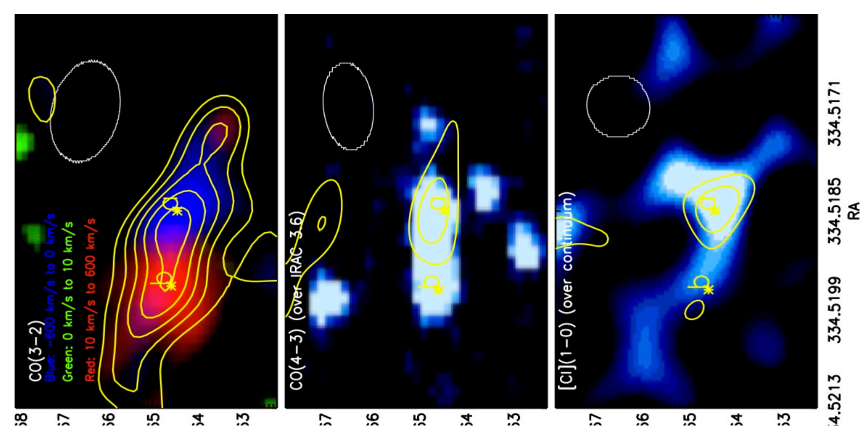
Line widths larger in SMGs … worse for detection

But …

1) X_CO magnifies the Mgas differences from SMGs (~1-2) to M-S star forming galaxies (~4-5), incl/ Helium contribution

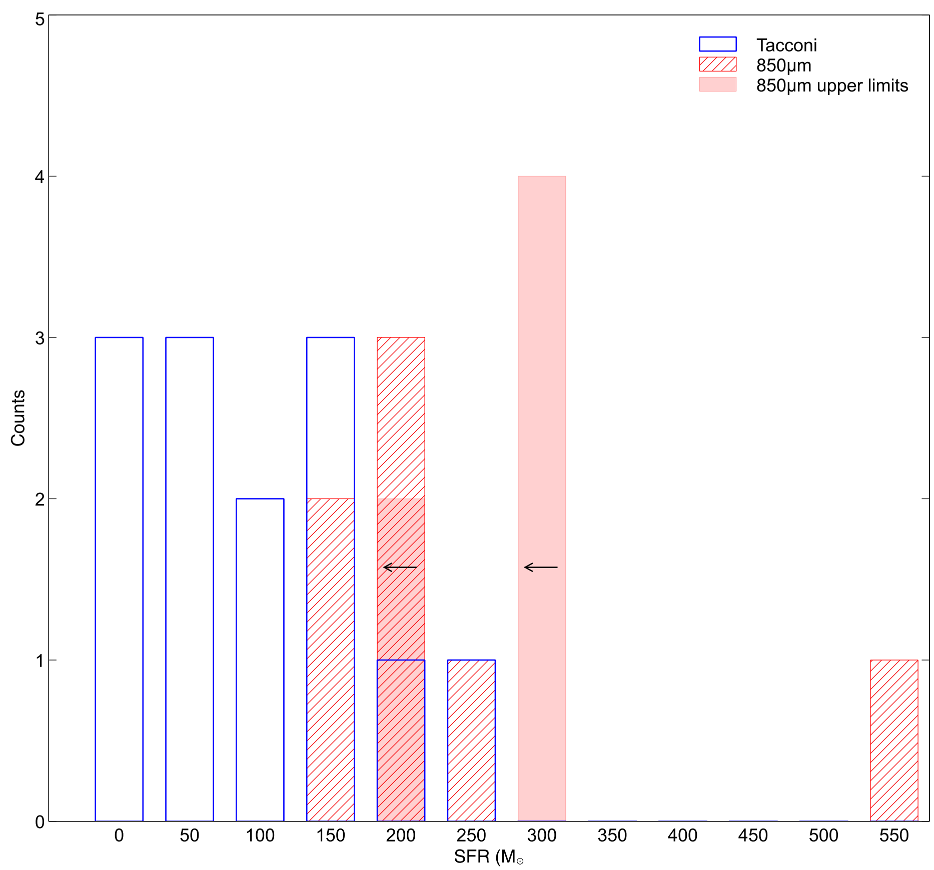
2) SFE: Mgas/L(FIR) further accentuates differences
SMGs ~5x larger L(FIR)

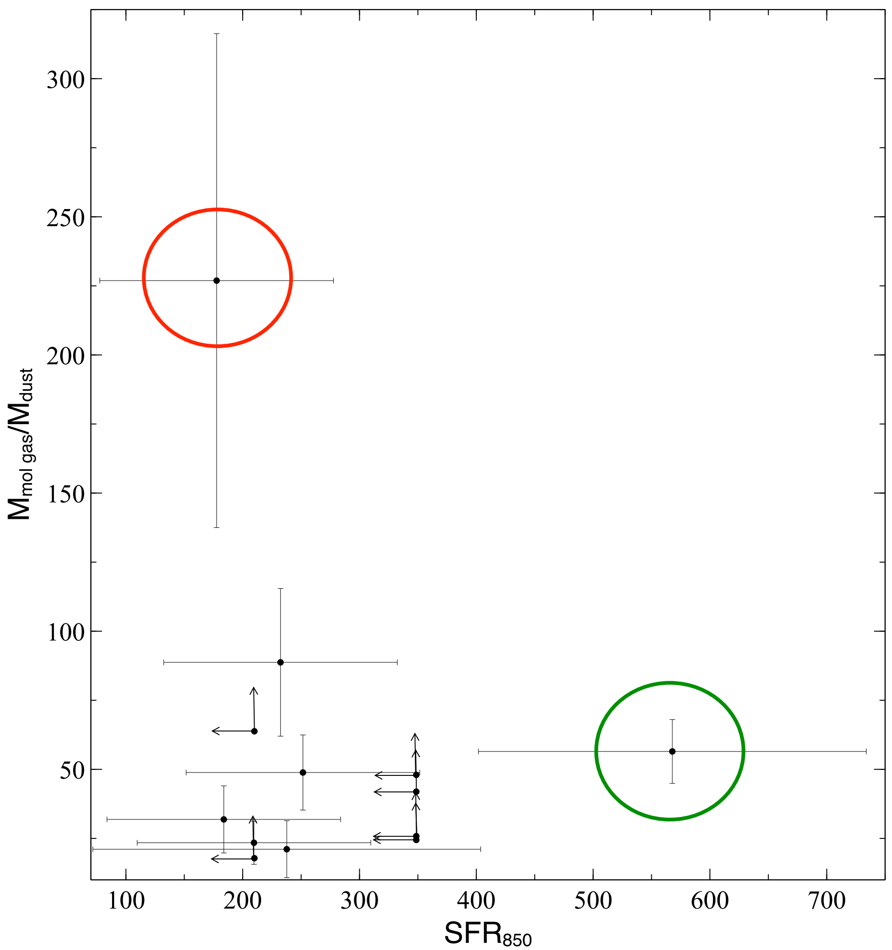




And how ‘normal’ is normal?

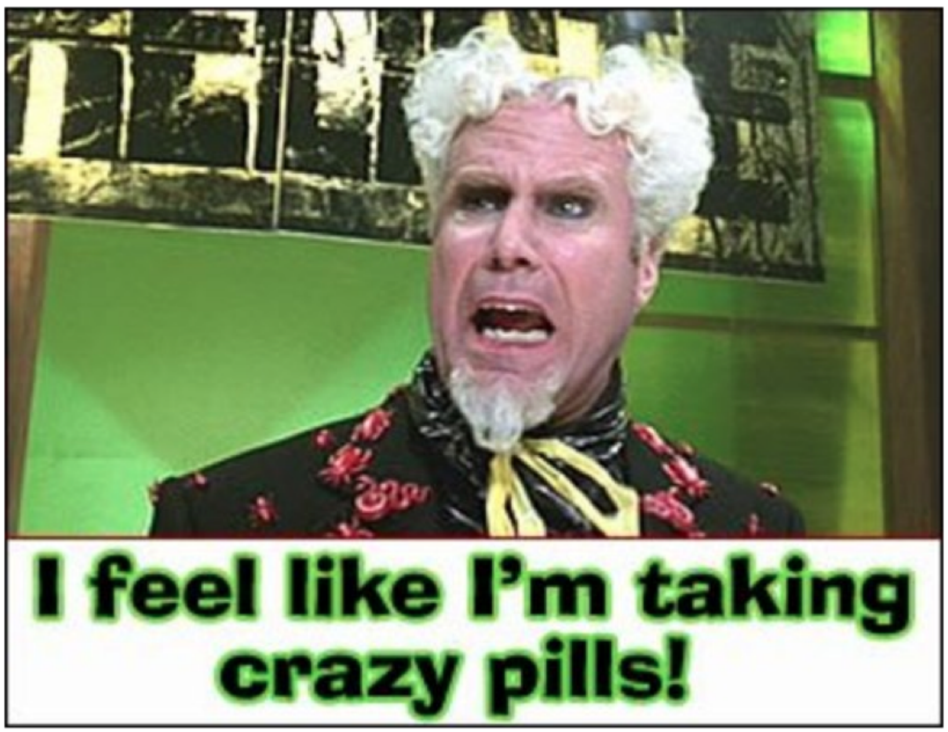
SCUBA2 survey of the Tacconi+10,13 CO(3-2) sample of SF’ers – (2/3 complete; Beanlands+2014). Mostly consistent S850 to Halpha SFRs, but one big outlier and one very weak for huge L(CO)





Aside: the SF main sequence

From Zoolander:
"vexation when the common consensus appears to go against common sense"



What physically do we learn from this *paradigm*?
"The physics which governs the SF in all galaxies *on the main sequence* is the same" ?!?

This links SF in the MW at z=0 to that in 1000Mo/yr sources with 10^{11}Mo masses at z~2

The physical conditions in the SF gas are clearly very very different!

Main sequence of SF

Distinct limits at high-SFR and high-mass as a function of z

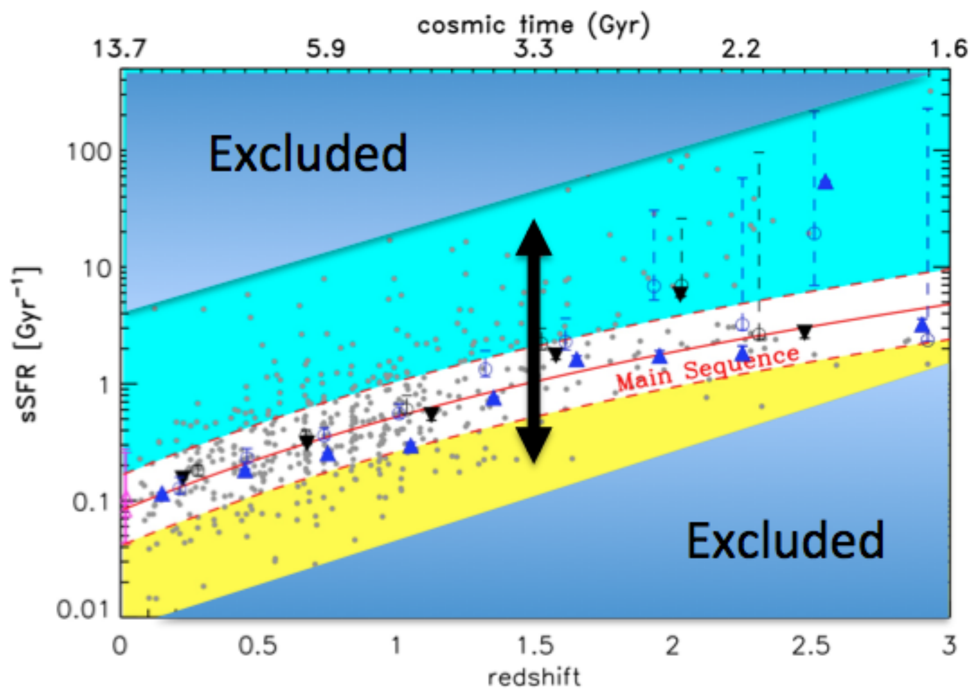
Areas of the sSFR-z plane can't be populated (the characteristic SFR increases with z and the maximum possible galaxy mass declines with redshift)

Hence don't find galaxies at very high masses - bottom/right part of the plot or extremely high SFR - upper/left part

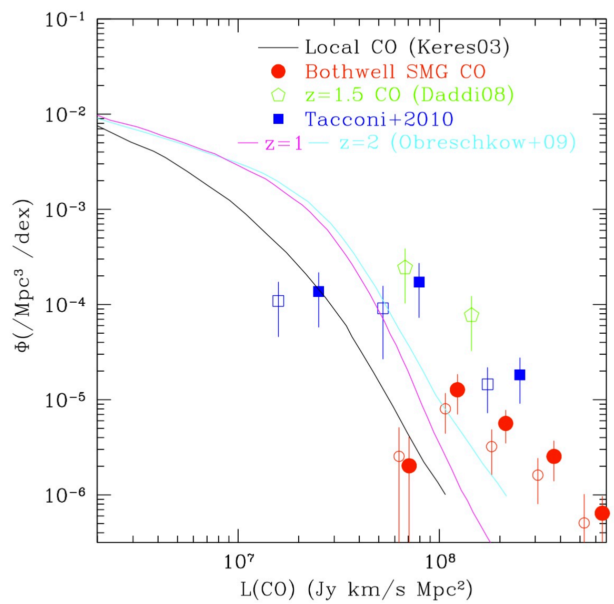
So always end up with a band where galaxies can be found.

AND THEN: observational constraints on the flux/mass limits of typical surveys - which cut off the distributions at the other ends

Elbaz et al. 2011



Empirial CO luminosity function?



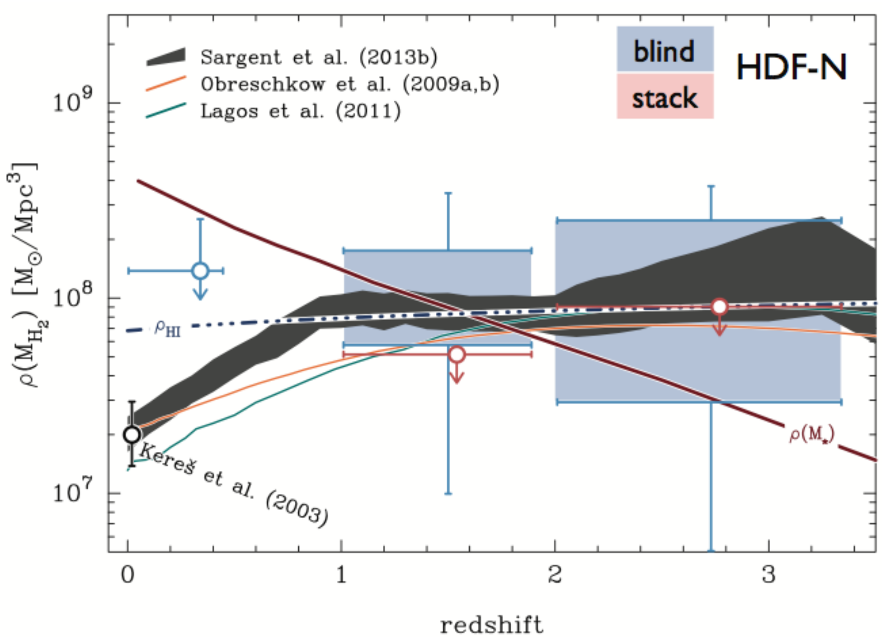
Difficult to accurately calibrate the
Source densities, Selection functions,
Completeness corrections …

Known galaxies preselected for CO followup
(UV/opt, submm)

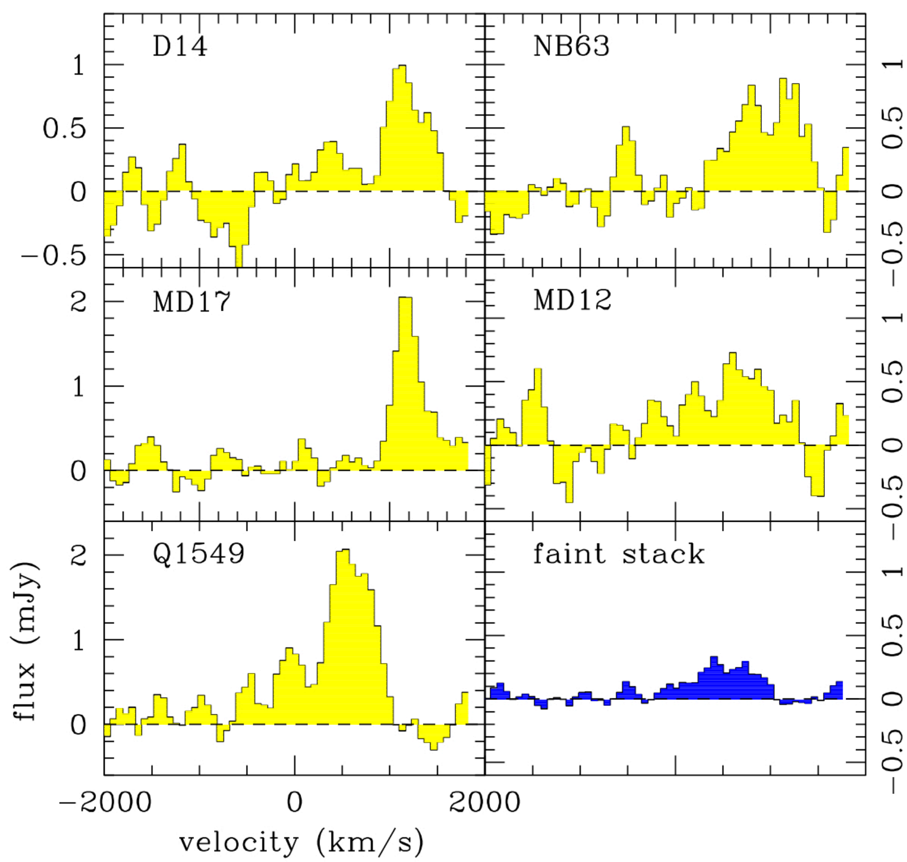
Blind CO surveys are crucial to understand the evolving fuel for star formation.

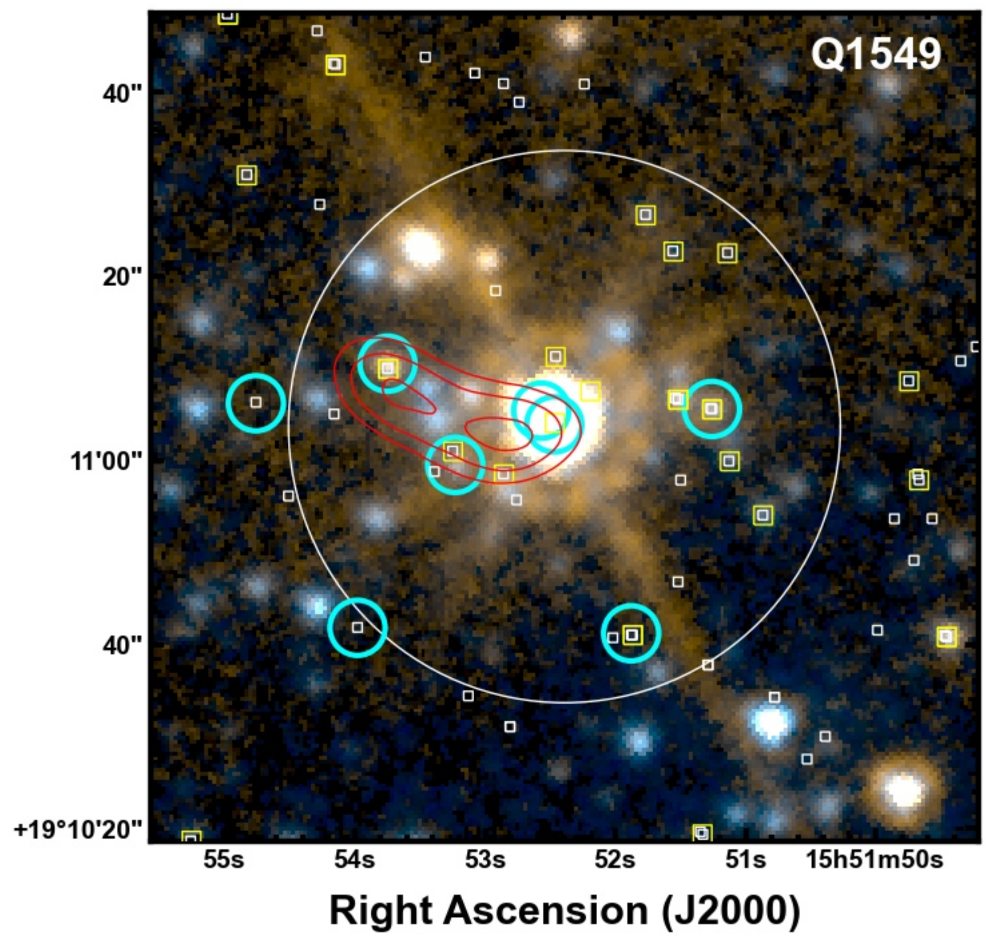
Walter+2014, deCarli+2014
Chapman+2014 have made
significant progress with
PdBI blind surveys

ALMA surveys coming up
(Dunlop et al.)



Blind CO in z=2.85 overdensity (Chapman+2014)





Wide field submm imaging:

QUEST for the Bright end of the counts …

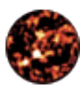
- we know there are lots of lensed SMGs (Vieira+2010,2013 …)
- are there *unlensed* hyper-luminous SMGs?

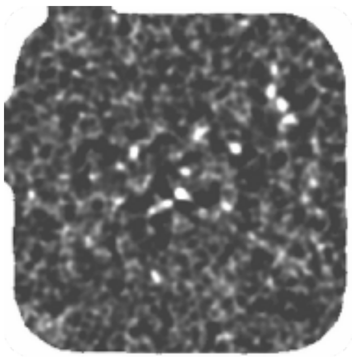
Blank field submm surveys

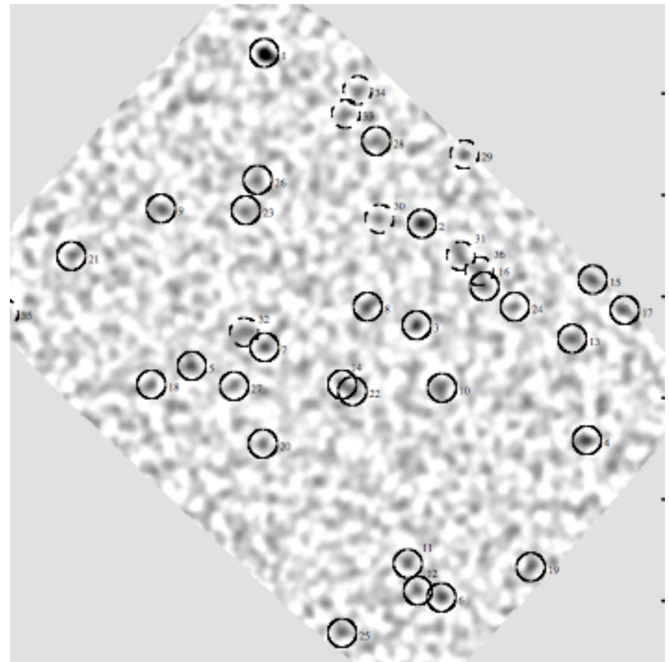
AzTEC
Perera *et al.* 2008

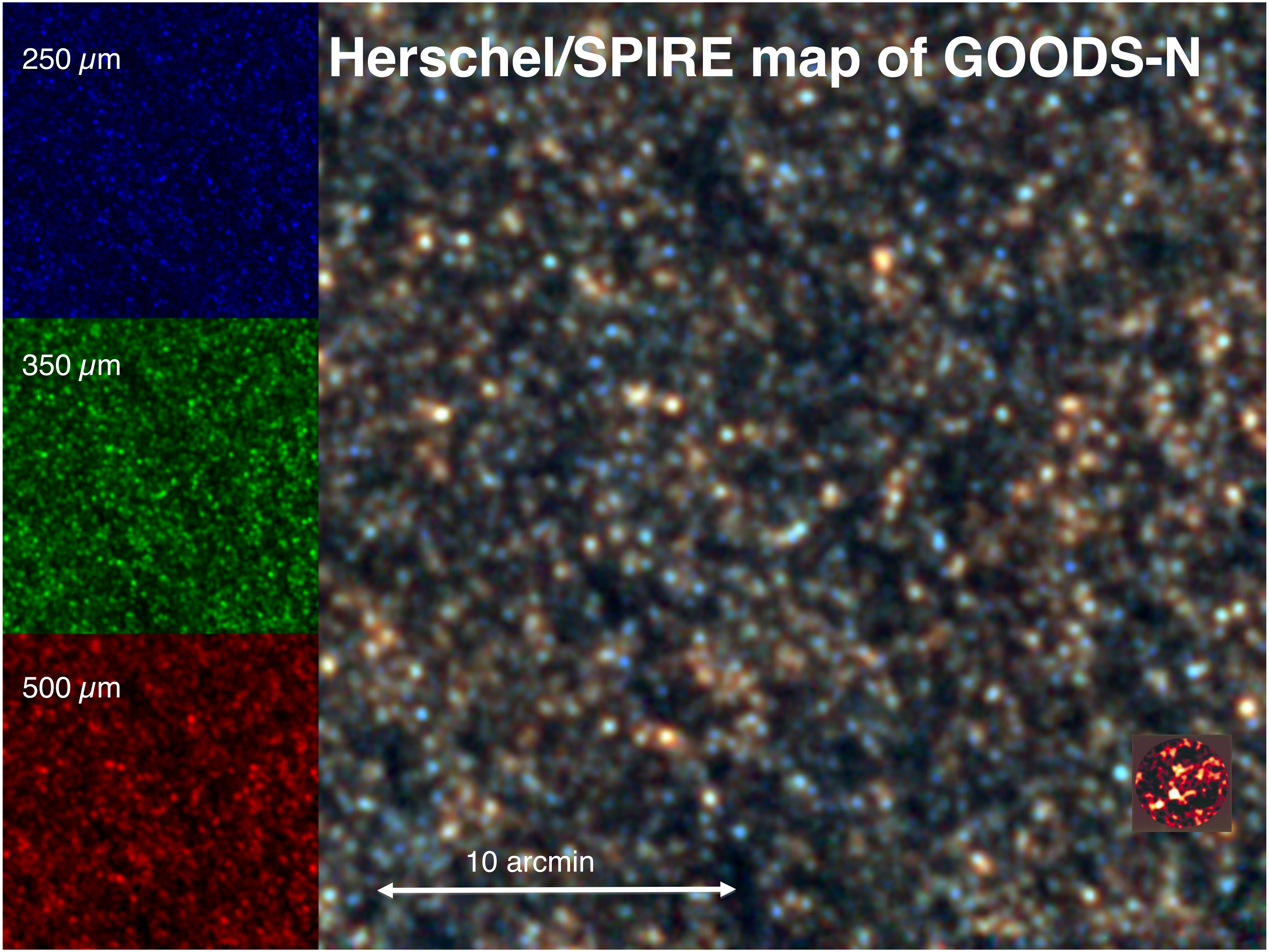
SCUBA "super map"
Borys *et al.* 2003

First SCUBA map
Hughes *et al.* 1998

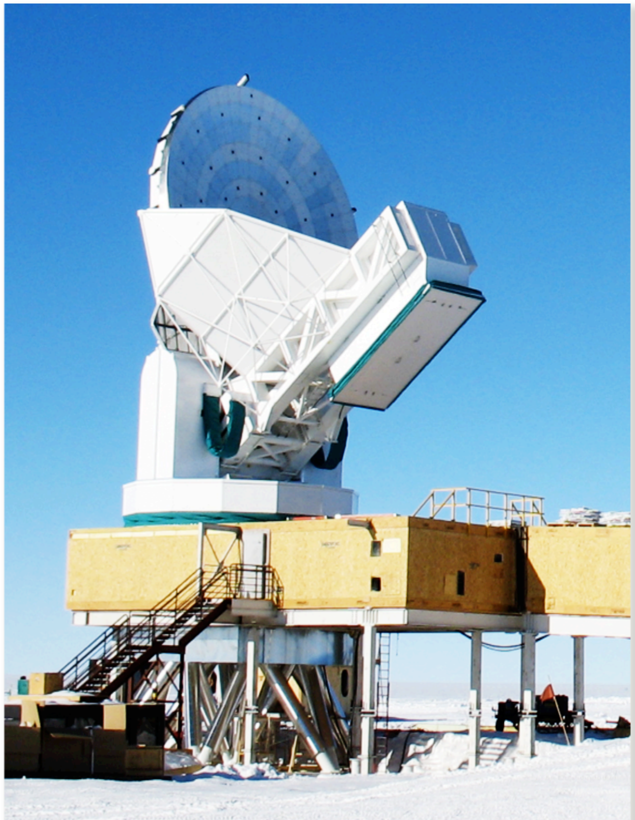







Herschel/SPIRE map of GOODS-N
250 μm
350 μm
500 μm
10 arcmin

The South Pole Telescope (SPT)



An experiment optimized for fine-scale anisotropy measurements of the CMB

- Dedicated 10-m telescope at the South Pole
- Background-limited 960-element mm camera

Science:

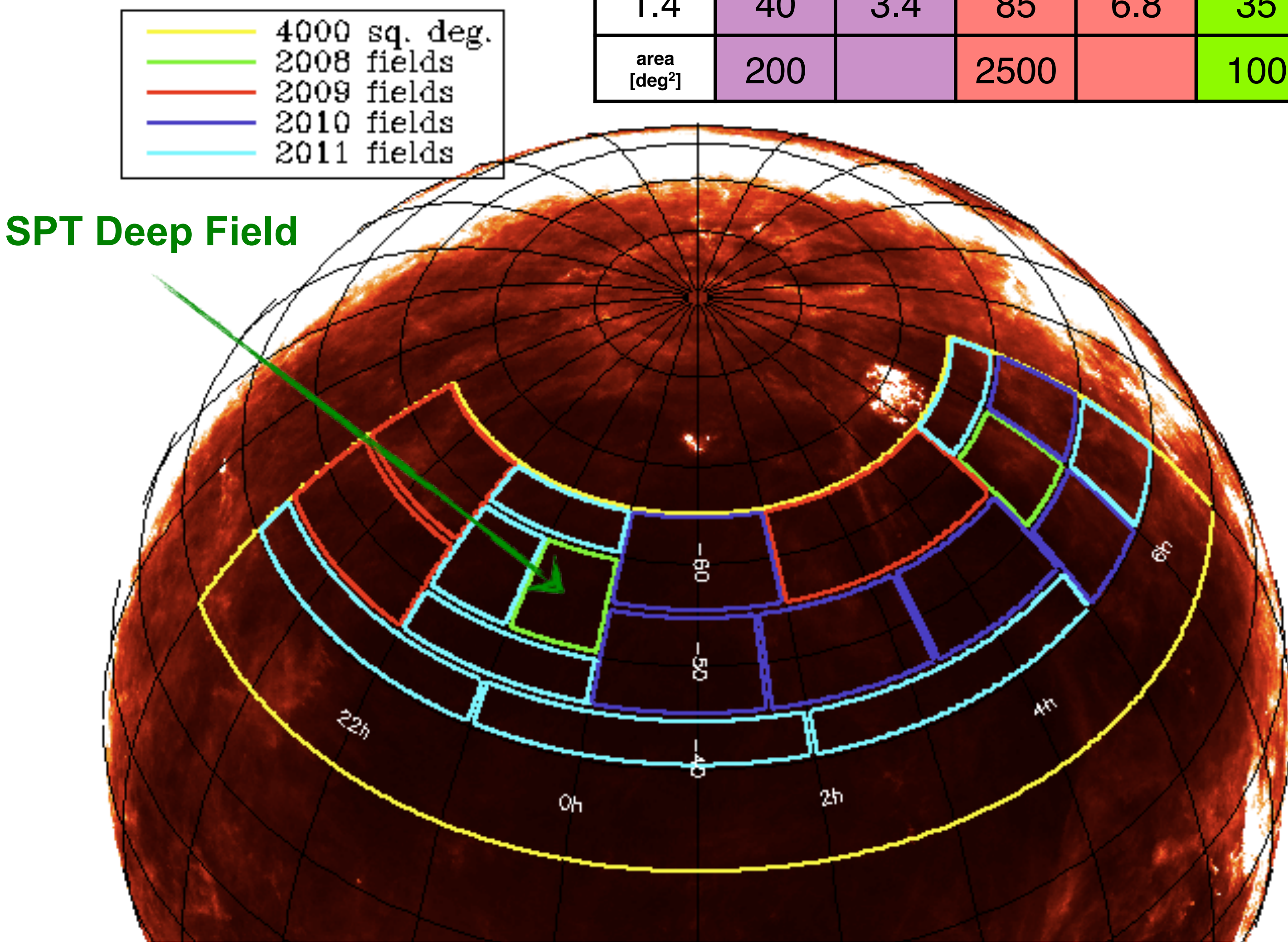
- Mass-limited SZ survey of galaxy clusters
  - study growth of structure, dark energy equation of state
- Fine-scale CMB temperature anisotropies
  - tSZ power spectrum to measure σ_8
- mm sources
  - high-redshift, strongly-lensed dusty star-forming galaxies
  - AGN
  - Other rare things

Funded by NSF

SPT-SZ survey now complete
SPTpol has deployed

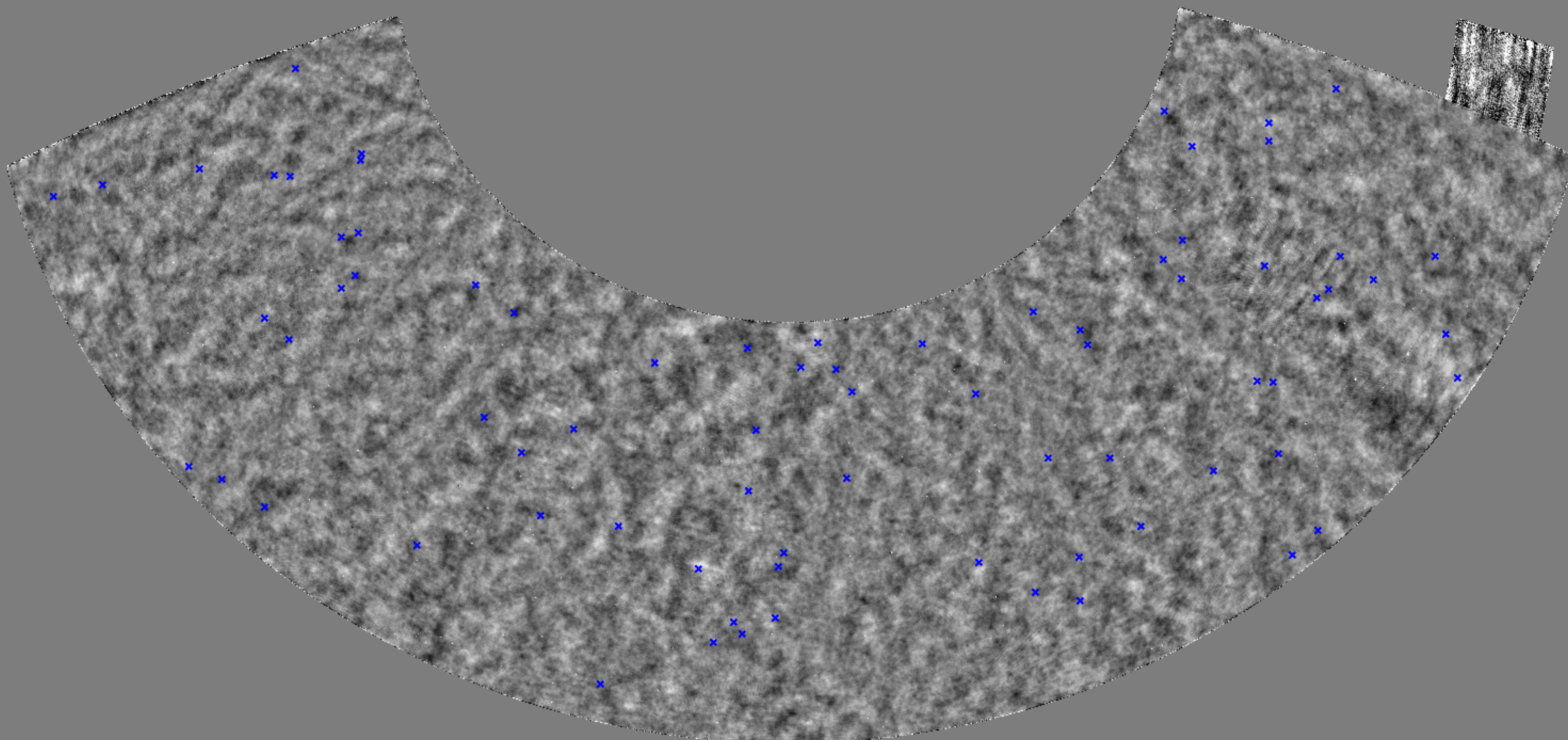
SPT SZ Survey

	2008		Main Survey	2009 -- 2011	Deep Field	2010	SPTpol	2012 -- 2014
band [mm]	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam
3.0	-	-	42	2.0	42	2.0	6.5	0.3
2.0	18	1.3	18	1.3	13	0.9	4.5	0.3
1.4	40	3.4	85	6.8	35	3.0	--	--
area [deg^2]	200		2500		100		~500	



2500 deg^2 SPT survey

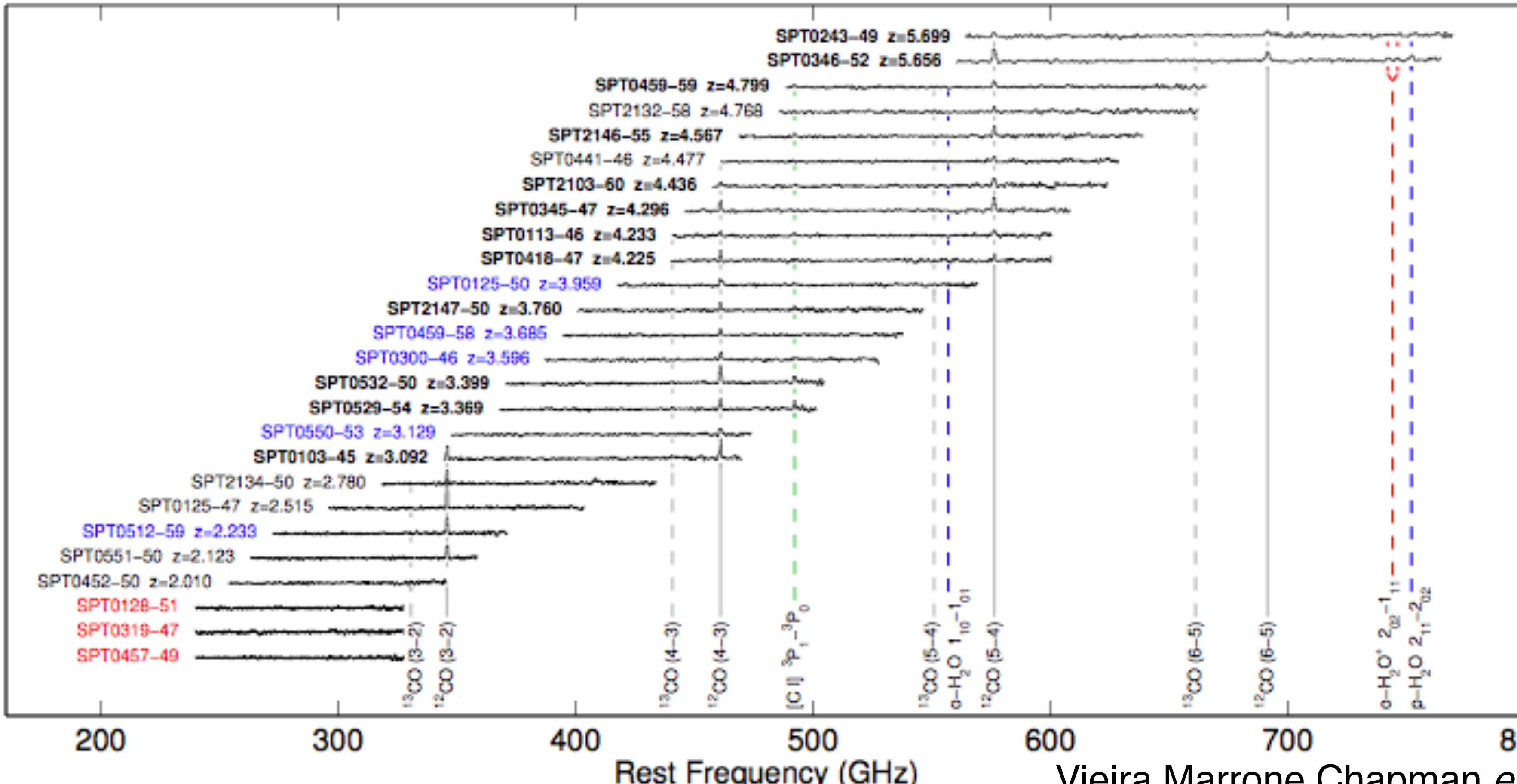
76 strongly lensed SMGs at $S_{1.4mm}$ > 20 mJy



~120 sources when we include radio loud and deep fields
Could go lower in S/N and get ~200 sources
Already limited by the amount of telescope time we can get

First blind spectroscopic redshift survey with ALMA

ALMA Cycle 0 Band 3
100 GHz compact configuration
26 sources
5 tunings in the 3 mm band
10 minutes per source



Vieira, Marrone, Chapman *et al.* 2013 Nature

Bold = unambiguous redshift from ALMA

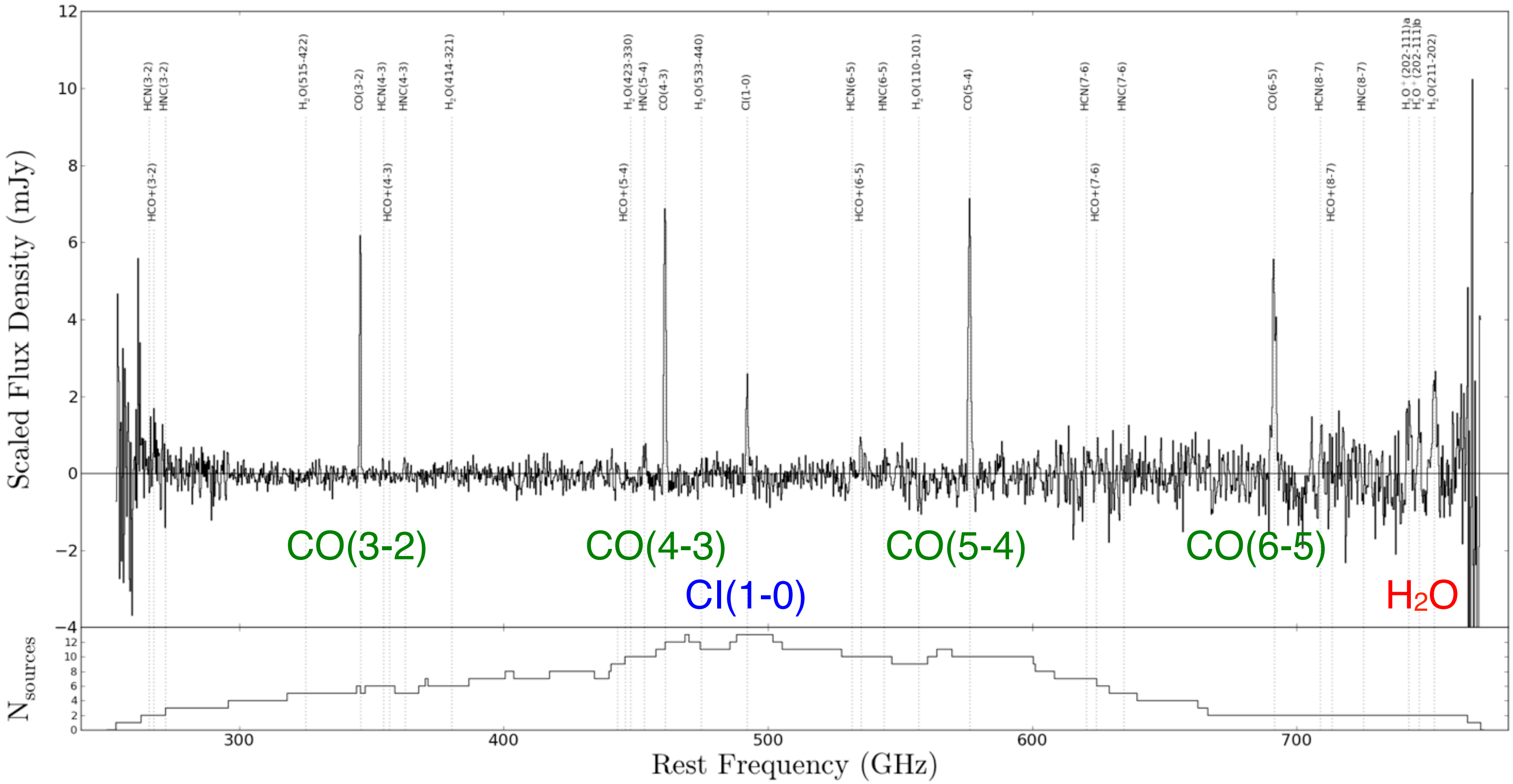
black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

blue = single line detected with redshift, most likely redshift from photo-z

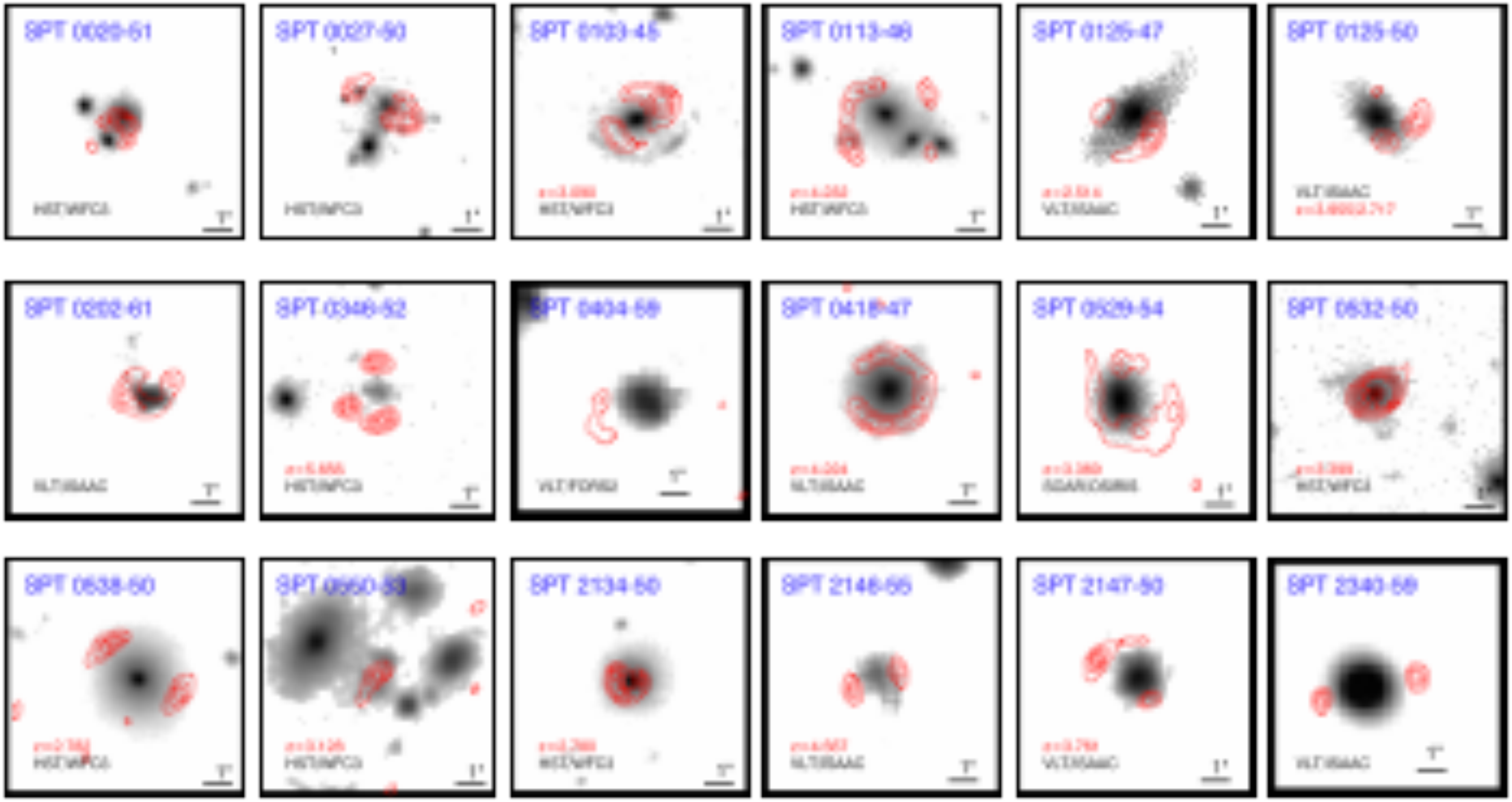
red = no line detected

Stacked spectra

Spilker *et al. 2014*



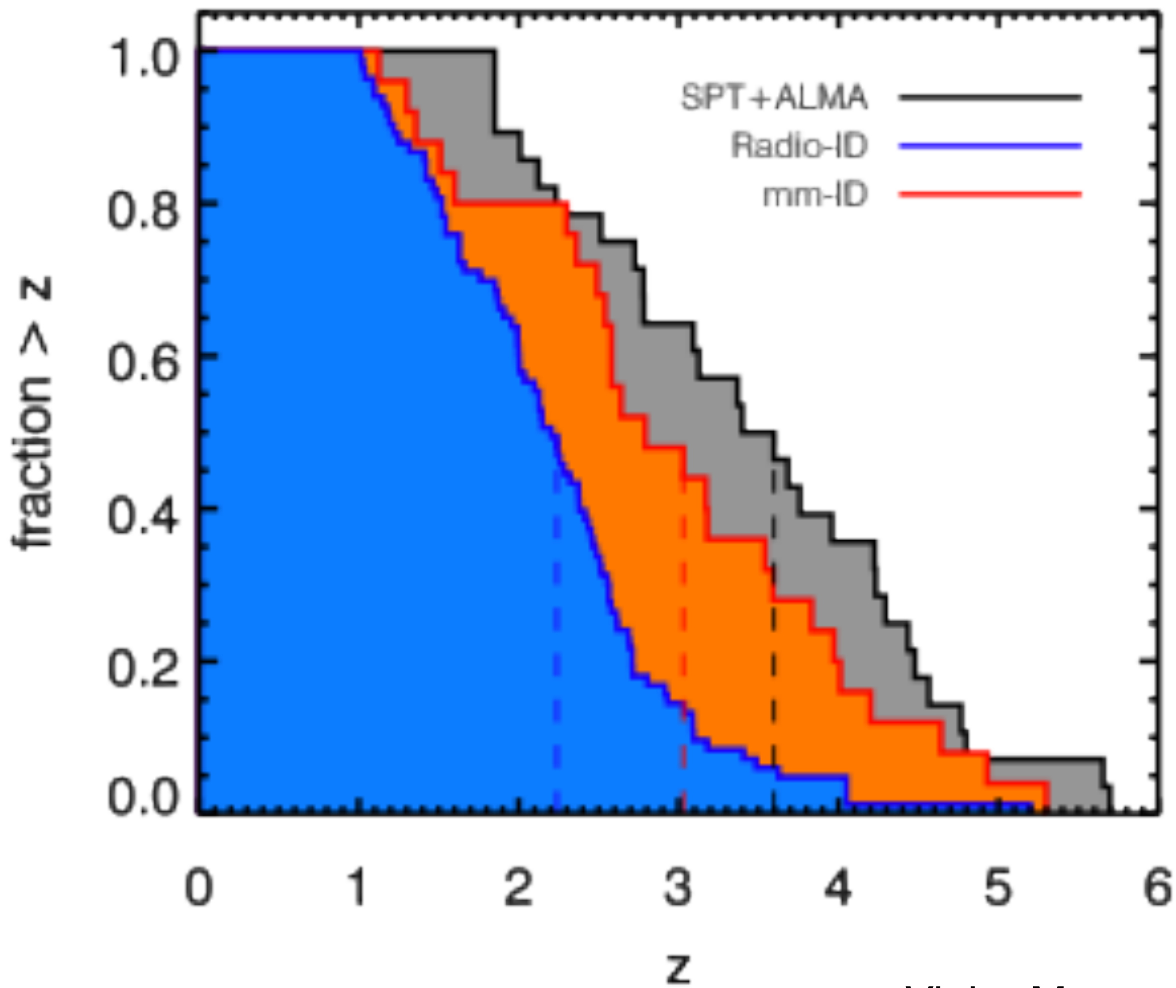
ALMA Cycle 0 Band 7 350 GHz
extended configuration 1 minute snapshots



Only through the combination of strong gravitational lensing, the SPT selection, and ALMA followup is this result possible

SPT + ALMA n(>z) more submillimeter galaxies in early Universe than previously thought

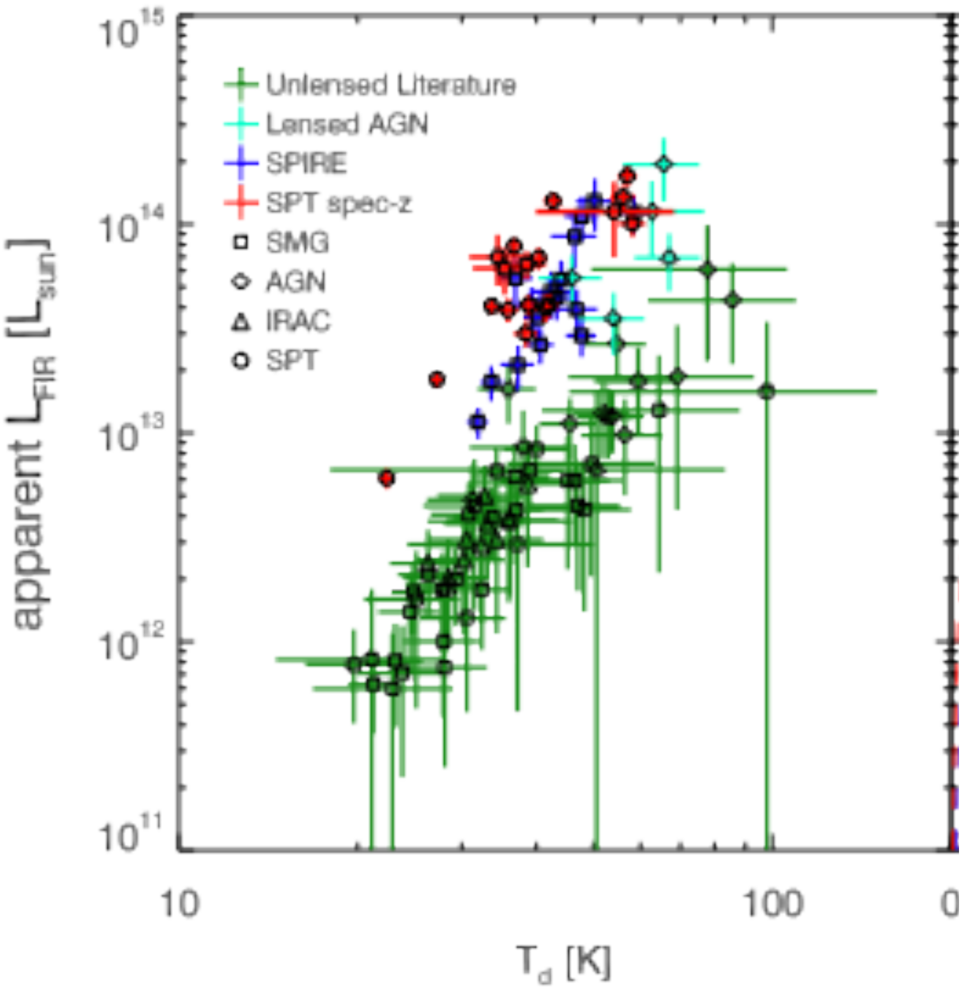
cumulative redshift distribution



Vieira,Marrone,Chapman *et al.*
2013 Nature

We appear to understand the population:
lensed versions of the blank-field "SCUBA source" SMG population

L_{IR} v. T_d



But are there unlensed hyperluminous sources hidden in the mix?

A natural limit to SFR in SMGs?

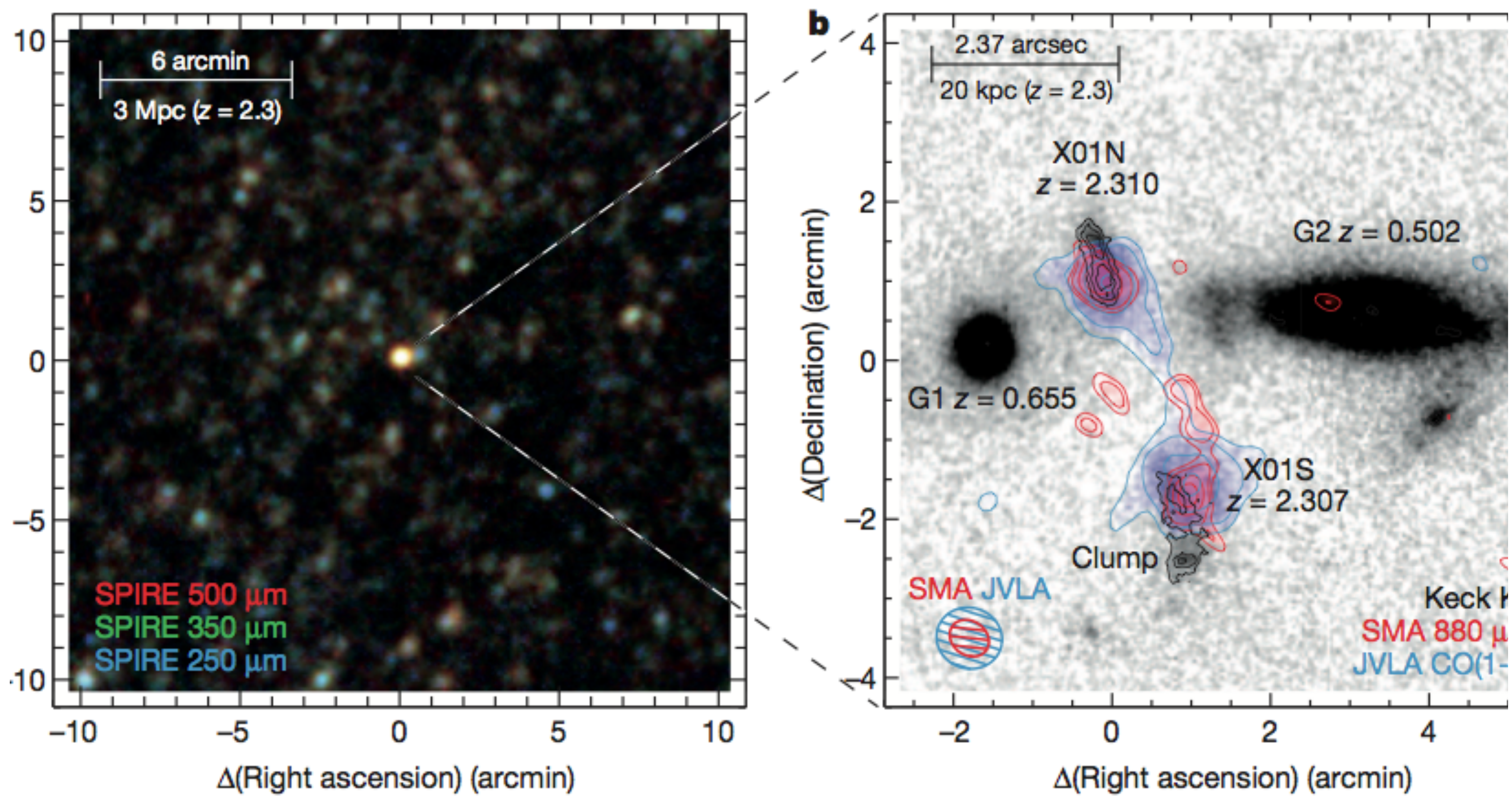
- Our ALMA survey suggested a maximal SFR in SMGs of ~1000M./yr (Karim et al. 2013).
  - in the first complete ALMA survey in ¼ deg^2 field
- Maximal SFR driven by
  - Mass of available gas reservoir
  - Free fall time (~50Myr in local starbursts – Kennicutt+)
- Implies cold gas mass limit of <$5x10^{10}$ M.

The most luminous galaxy in the Universe?

- Karim+2013 findings comparable to findings of largest gas mass from our PdBI CO survey (Bothwell+2013).
- Suggests space density of $<10^{-5}$ Mpc^{-3} for galaxies with greater gas masses.
- To find most luminous galaxies, go to wider surveys …

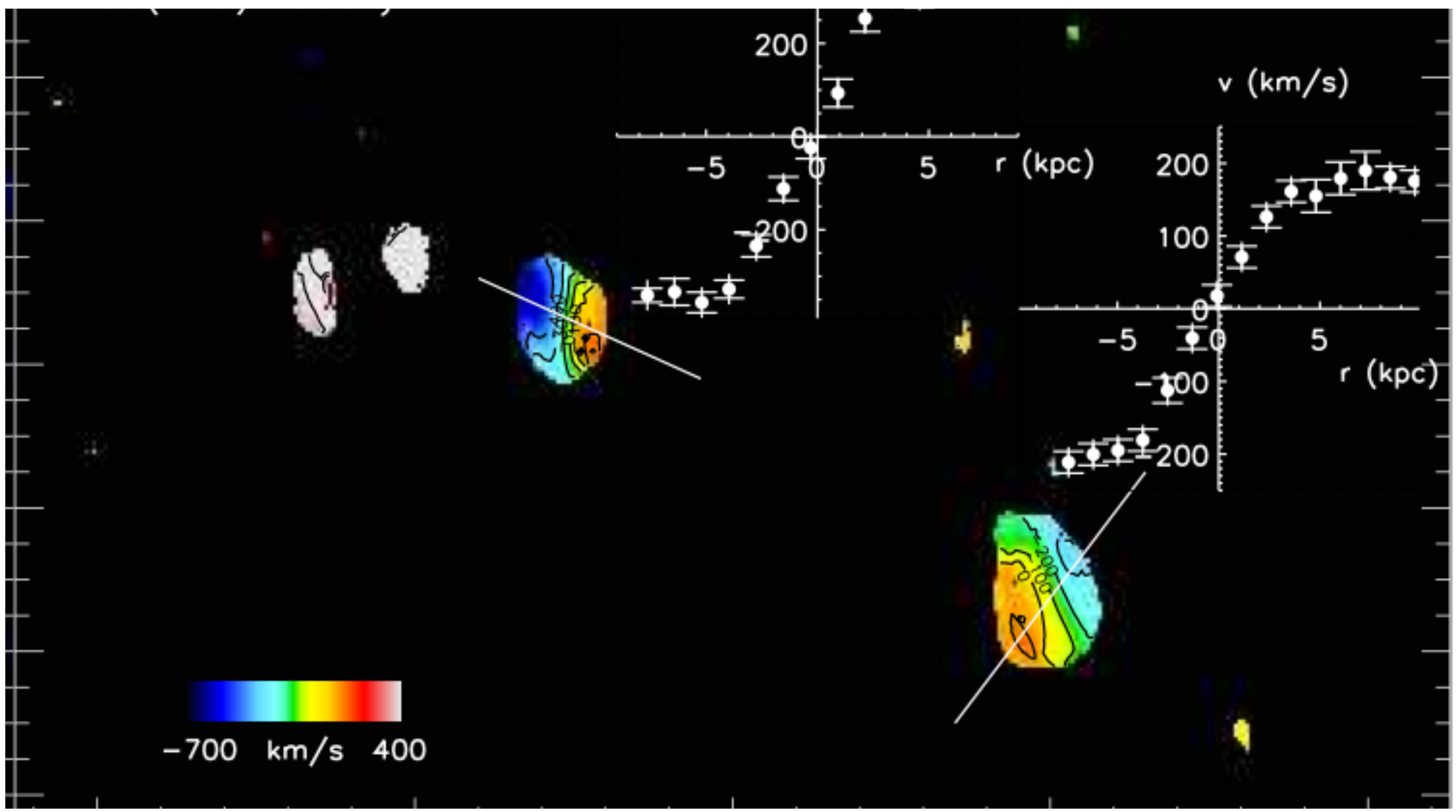
Herschel HerMES (from ~50deg^2)

(Fu+2013, Nature) z=2.30, S850=25mJy (after 2.0x delensing of components) L_IR~2x10^{13} Lsun



H-ATLAS (from ~200deg^2)

(Ivison+2013) z=2.38, S850=40mJy (after 2.5x delensing of one component) L_IR~3x10^{13} Lsun

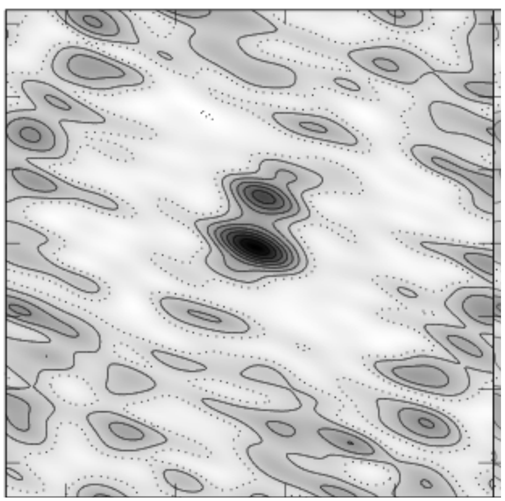


SPT0346-52 ***z=5.7***

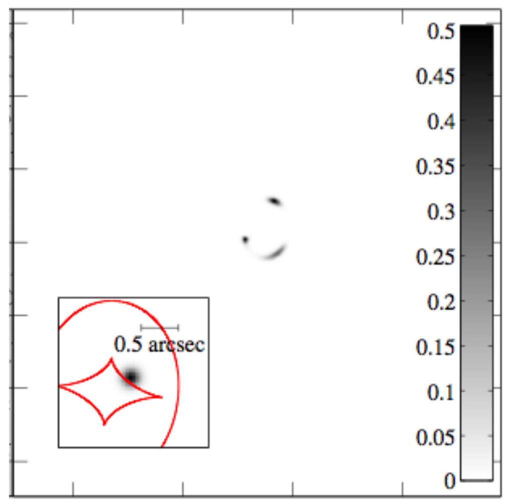
S850=150mJy / 5x lensing = 30 mJy;

Lens modeling : Hezaveh *et al.* 2012, ApJ

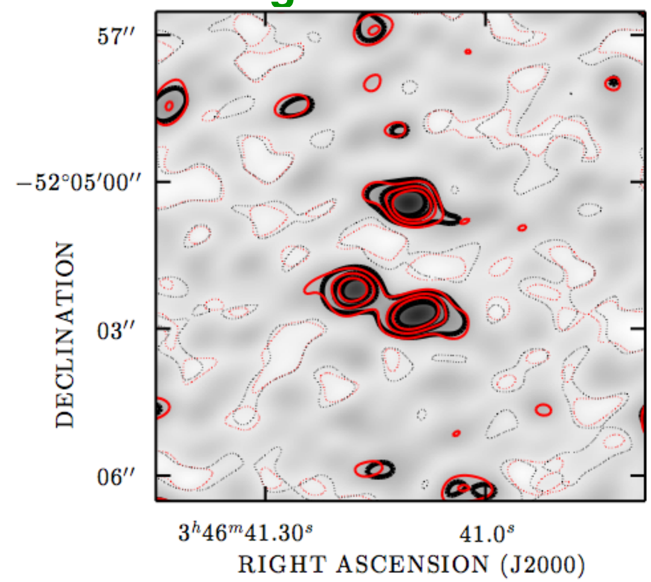
ALMA Band 7 compact configuration dirty image



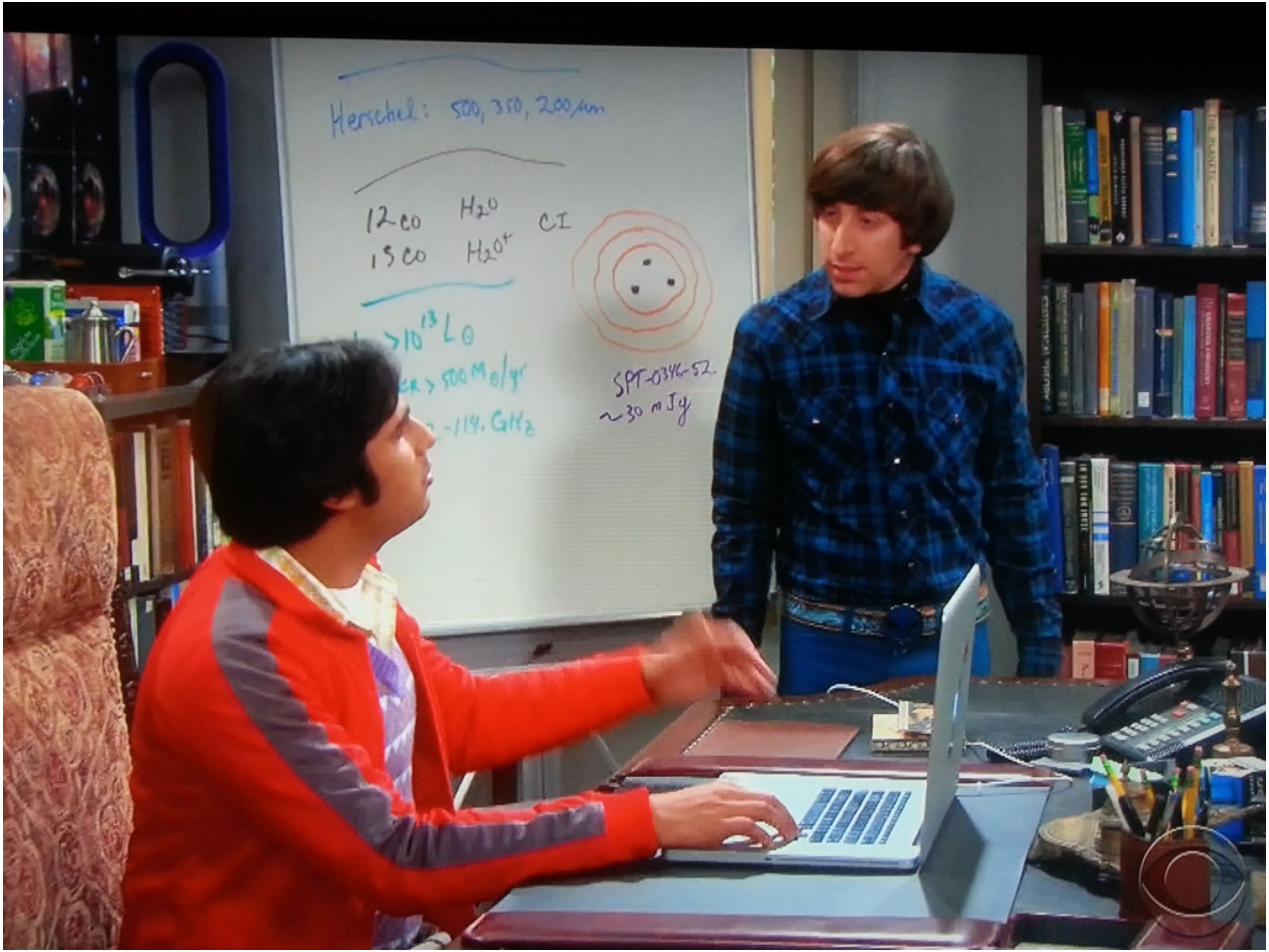
lens model



ALMA extended configuration



- **we model ALMA U-V plane data with a custom and statistically robust technique**
- **we know there are phase errors in the antennas, we incorporate the self-cal phases into the MCMC model fitting, we capture the additional model uncertainties**
- ***our models are working amazingly well***
- **we are working towards using this technique to set limits on dark matter substructure in cycle 1**

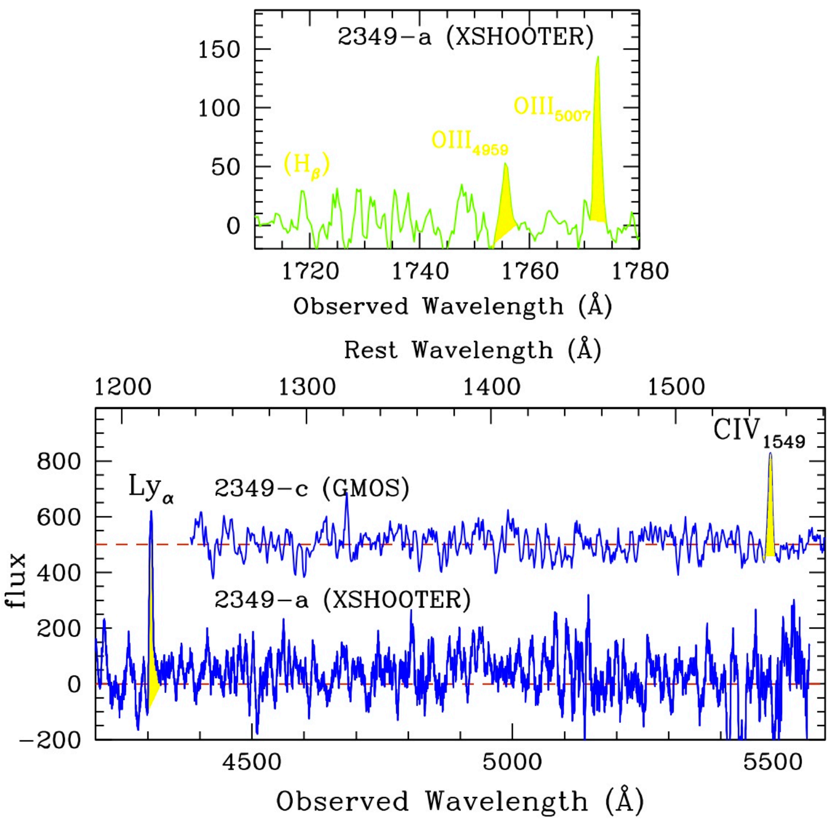


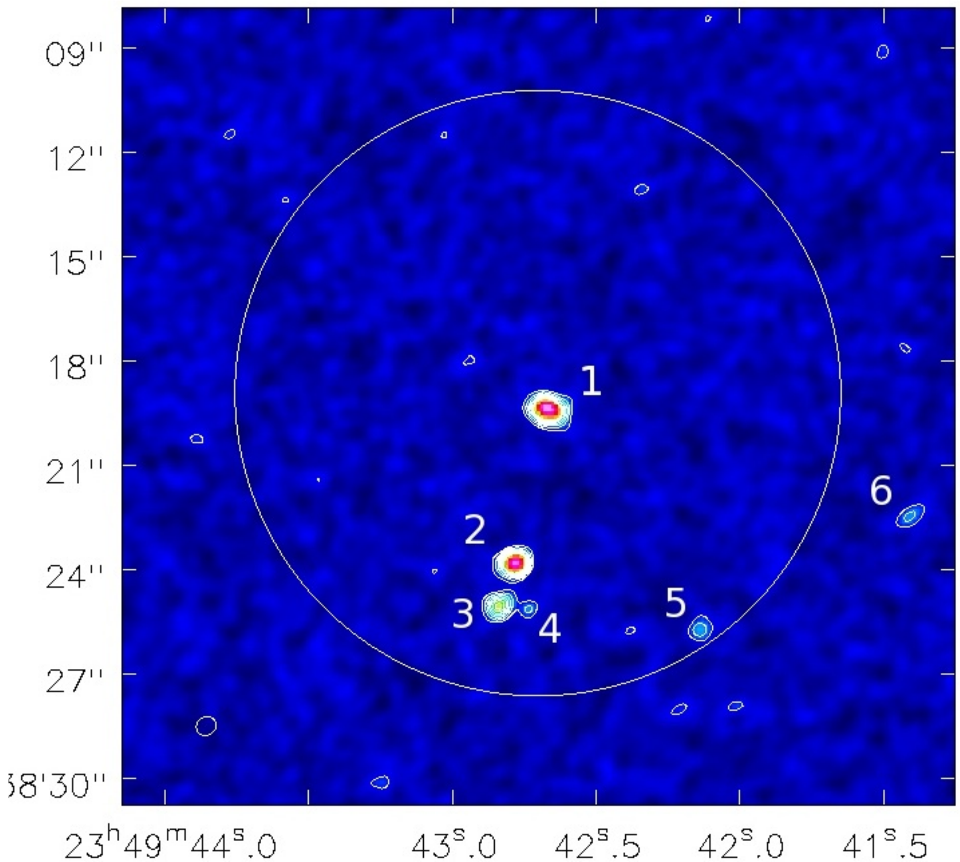
Herschel: 500, 350, 200 μm
12CO H2O CI
13CO H2O+
SPT-0346-52
~30 mJy

SPT2349-51 (*z*=2.54) … SPT's first clear unlensed source - S850=60mJy but truly the most luminous galaxy?

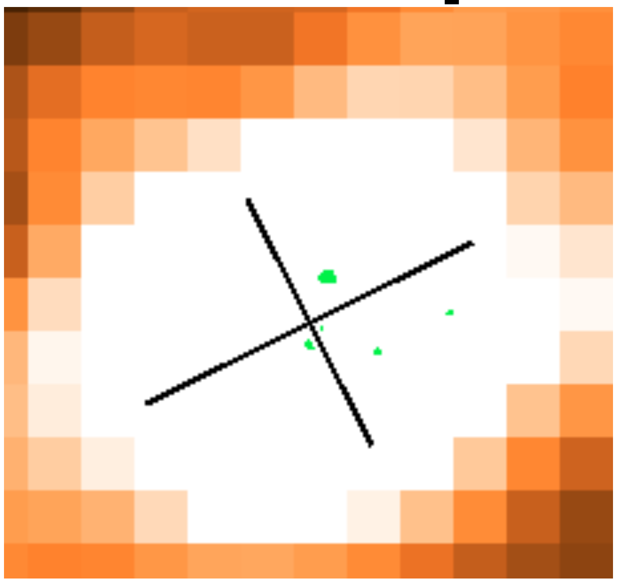
(Chapman et al. 2014)

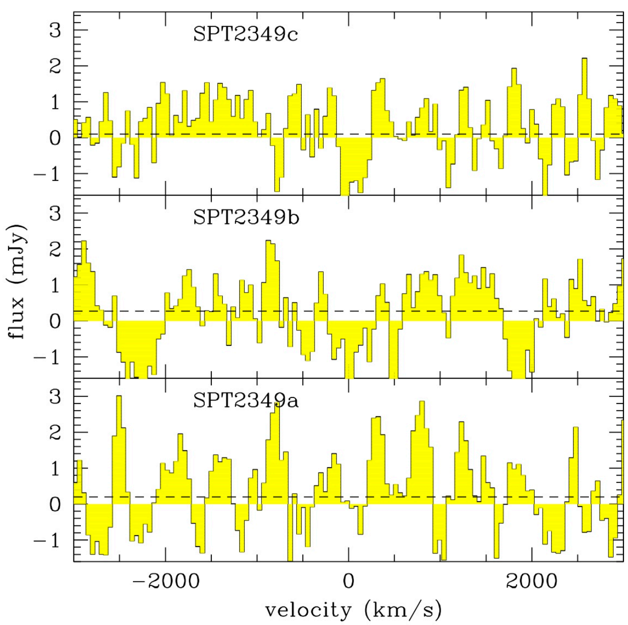
Note the 'peak epoch' when most of these hyper-luminous galaxies existed





A protocluster core?

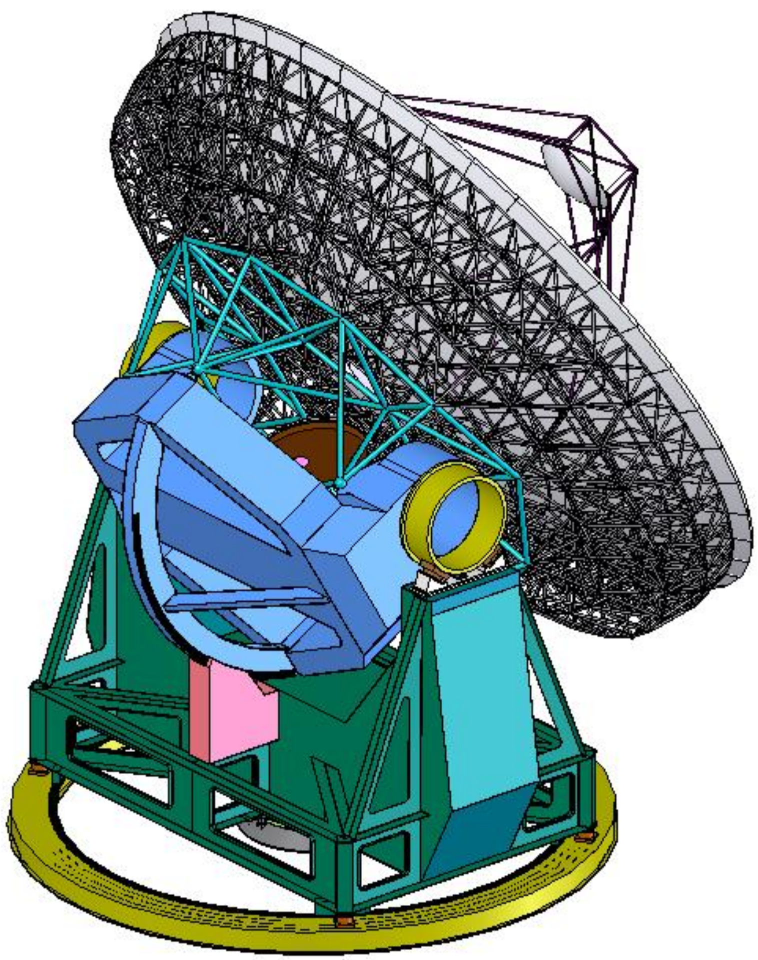


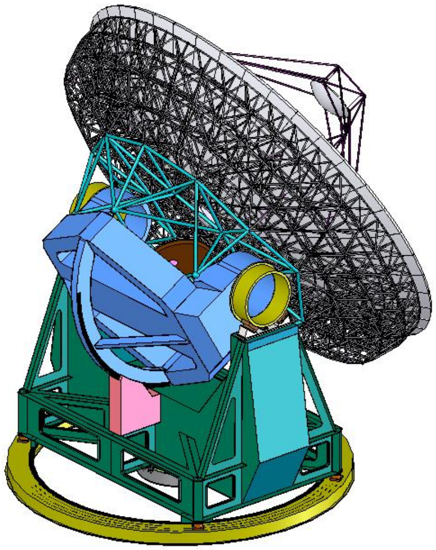


- 30” extended LABOCA source (19” beam) … ~250kpc ‘hyper-luminous structure’
- Must consist of >10 “ULIRGs” (ALMA imaging at 3mm and 850um)
- No individual sources >9mJy !!!! (>1000 Msun/yr)
- None detected in CO with ALMA (but limits are still above typical Bothwell+13 CO source).

New Directions:

- CCAT, an ideal complement to ALMA





CCAT

A submm telescope (~2018) aimed at massive spectroscopic surveys, and resolving the 350um background

- A 25 m submm telescope that will operate at wavelengths as short as 200 um – superb surface accuracy!
    - 25m to matches ALMA sensitivity in short submm
- Located in the Atacama desert in northern Chile at very high elevation - 5600 m ⇒ much of the time has PWV < 0.5 mm
- **Wide field-of-view (1 degree)**
- Takes advantage of rapid growth in submm detector technology to map large regions at high angular resolution
- A university-run facility with a high priority on graduate student training
- Galaxy Evolution; star formation and IMF; protoplanetary disks; Cosmology

CCAT Performance

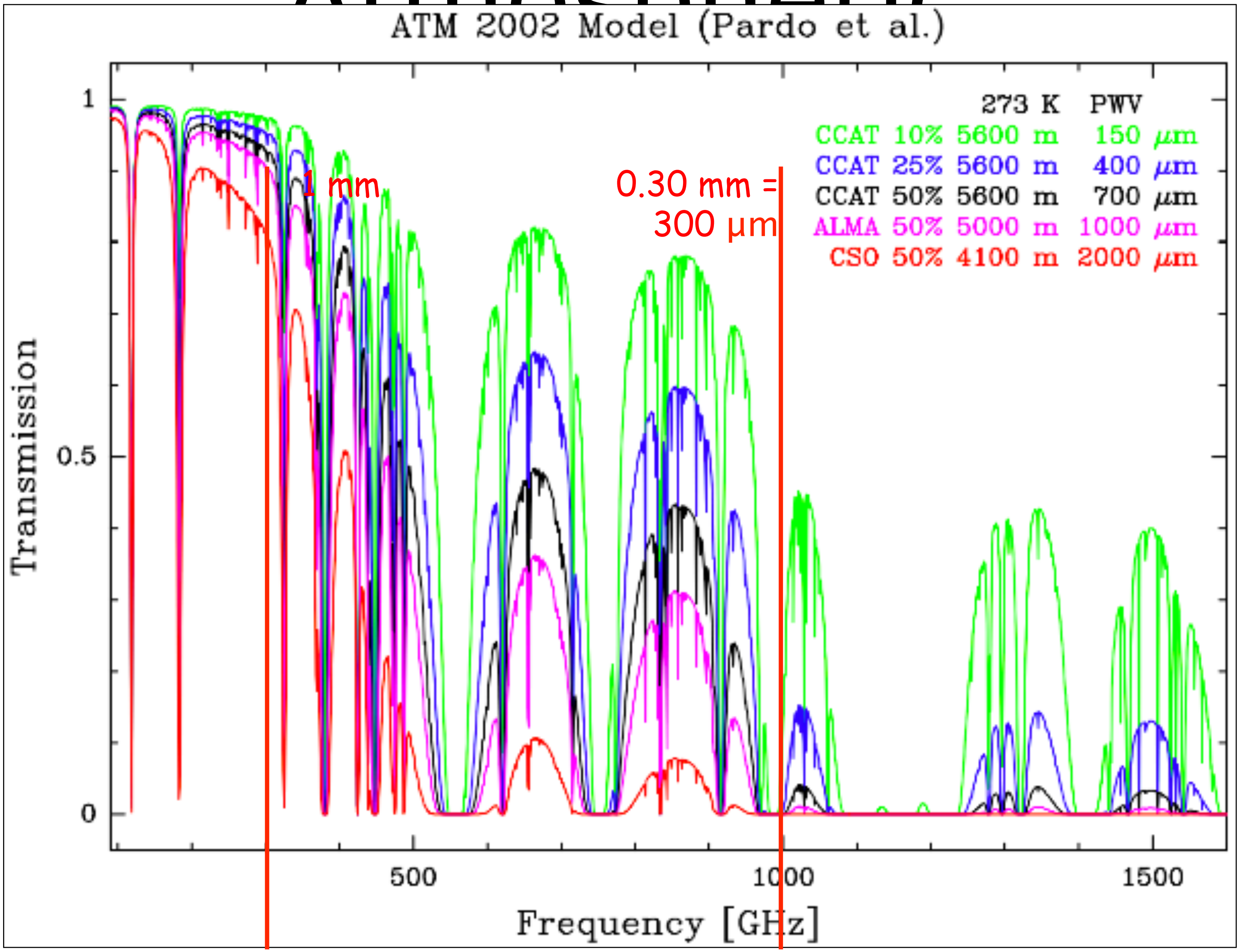
	JCMT	CCAT	
Wavelength	350 – 1400	200 – 2500	μm
Aperture	15 m	25 m	
Angular resoln.	6"	3.5"	@ 350 μm
Pointing	≈ 2"	< 0.4"	rms
Field of View	11'	60'	
Max Array Size	20 k	370 k	pix @ 350 μm
Surface Error	20 μm	< 12.5 μm	rms
Water Vapor	2 mm	< 0.7 mm	median

Cerro Chajnantor 5612 m

APEX QUIET ALMA (5050 m) ASTE & NANTEN2 (4800 m)
ex. CBI

Google Earth

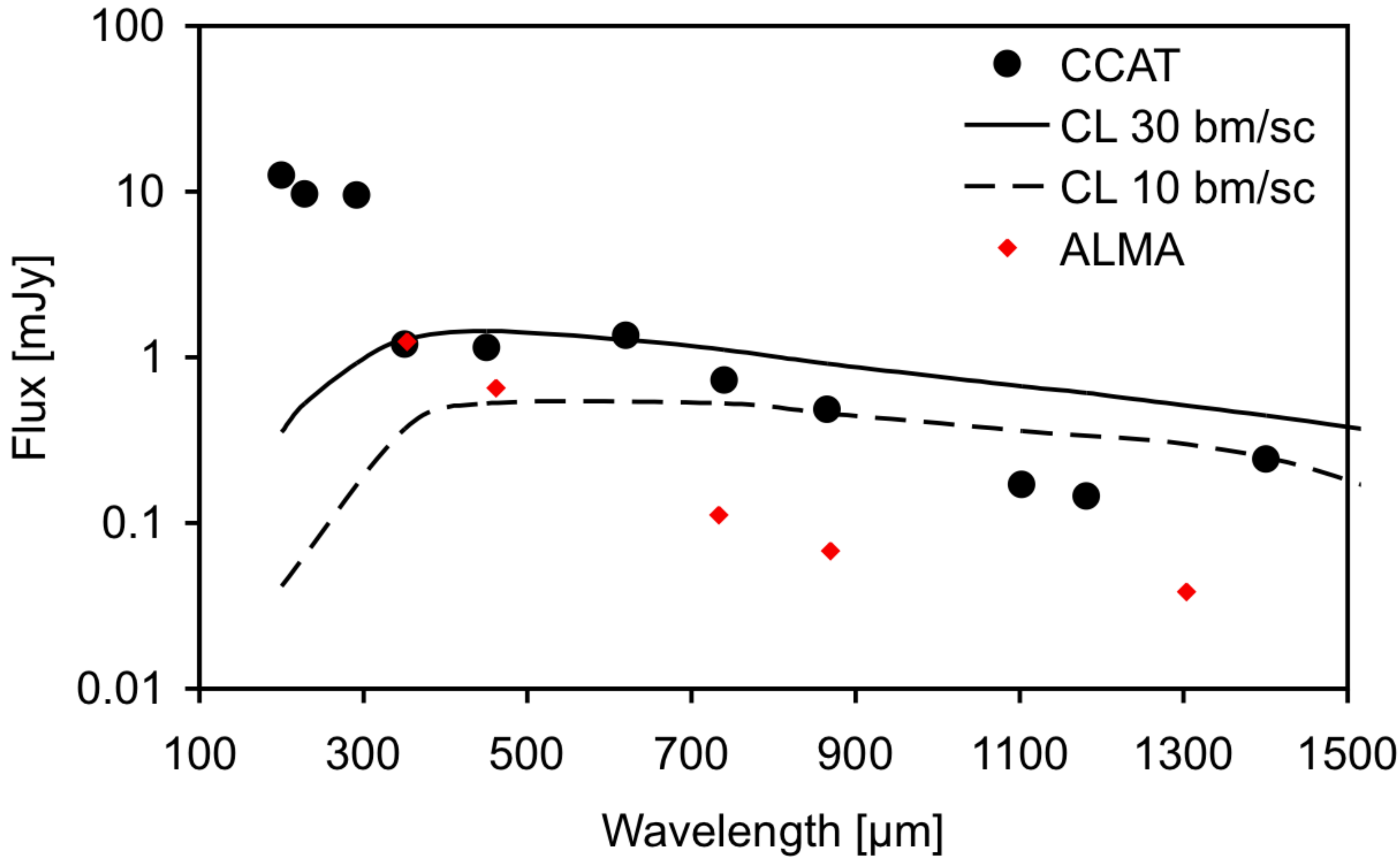
Atmospheric



600 µm

200 µm

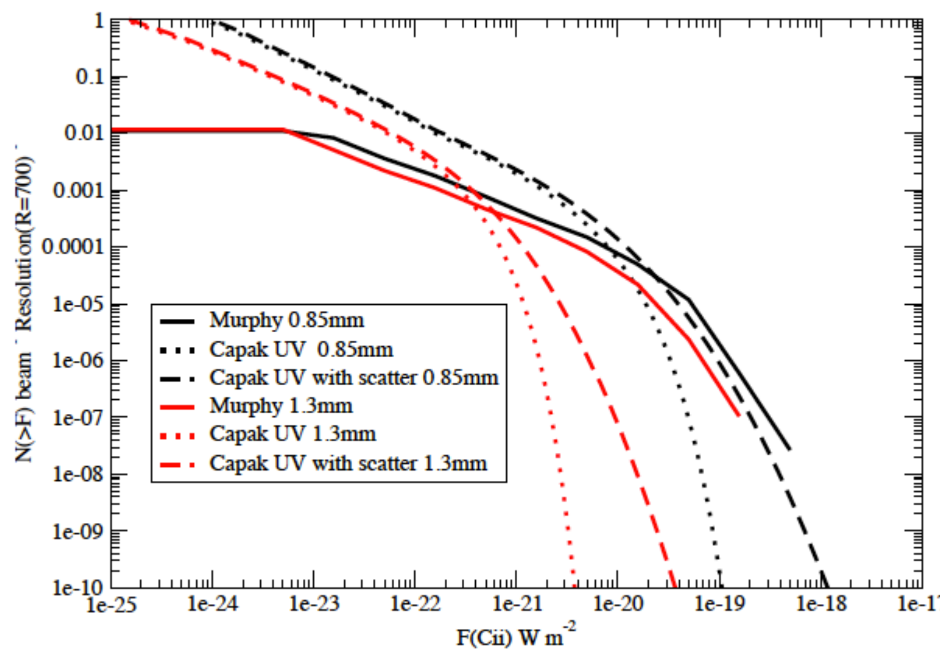
CCAT Sensitivity



Continuum sensitivities per pixel of *CCAT* and *ALMA* (5 σ in 1 hour) with confusion limits (30 and 10 beams source^{-1}). *CCAT* sensitivities computed for precipitable water vapor appropriate to that band.

C+ 158um cooling line and High-z Galaxy Formation

- Have two constraints
  - FIR background
    - Applies a weak integral constraint
  - UV Luminosity function
    - Apply dust correction as a function of z, L_{UV} along with scatter
    - Apply SFR->FIR relation
    - Apply FIR->CII relation with scatter
      - Conversion and scatter vary with luminosity



XSPEC: R~1000 submm MOS spectrograph

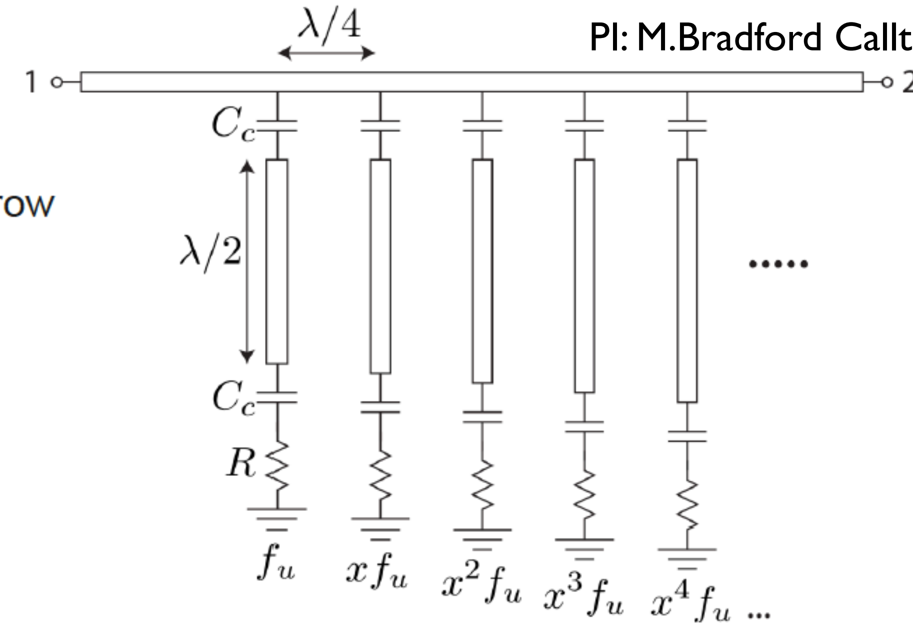
PI: M.Bradford Calltech/JPL

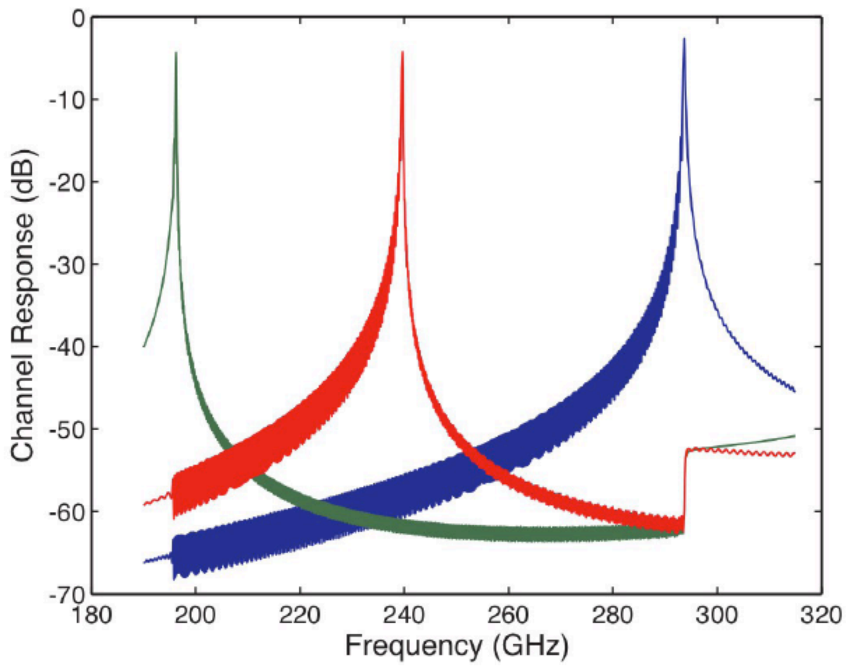
A general filter bank
(or cochlear) spectrometer:

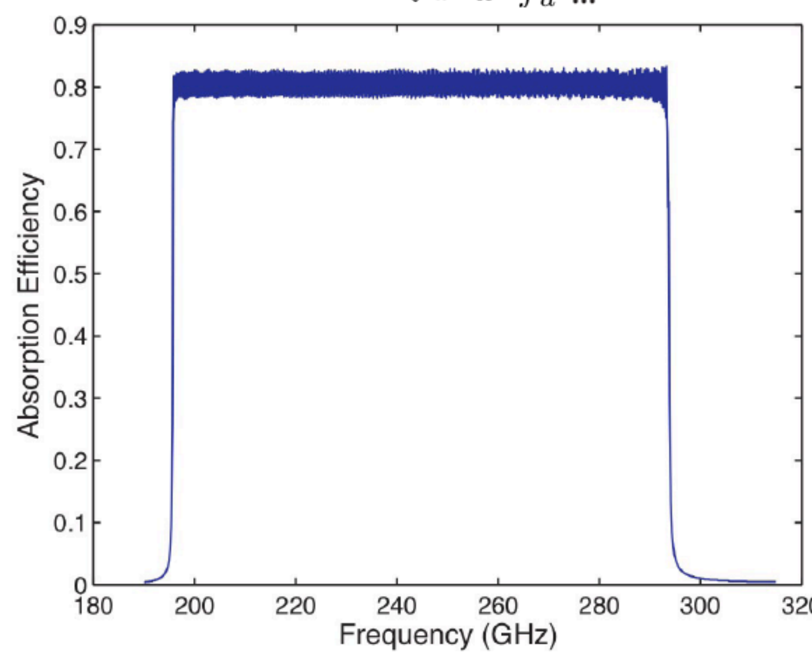
Incoming radiation is sorted by narrow band filters

Each channel couples to a power detector

Channel width and spacing are independently adjustable

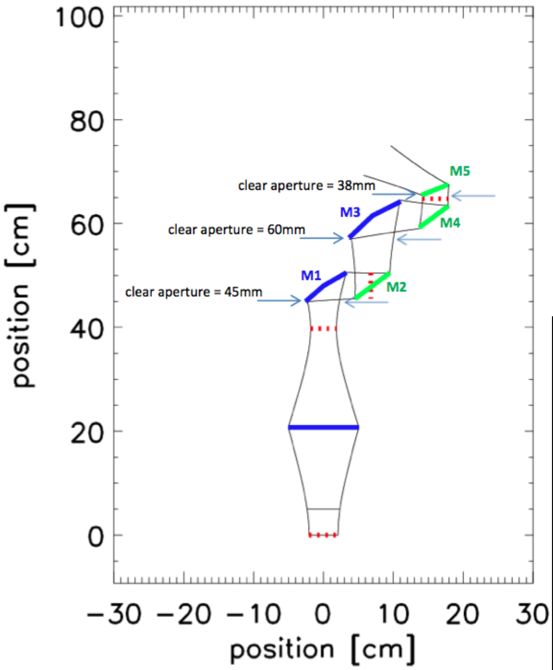


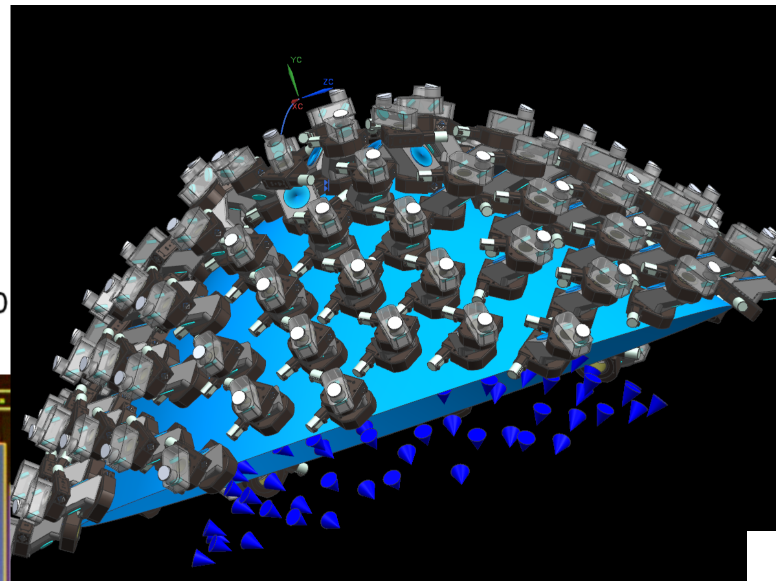


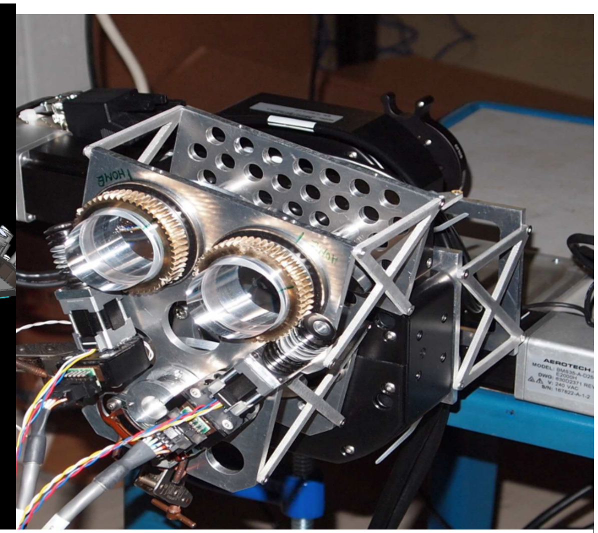


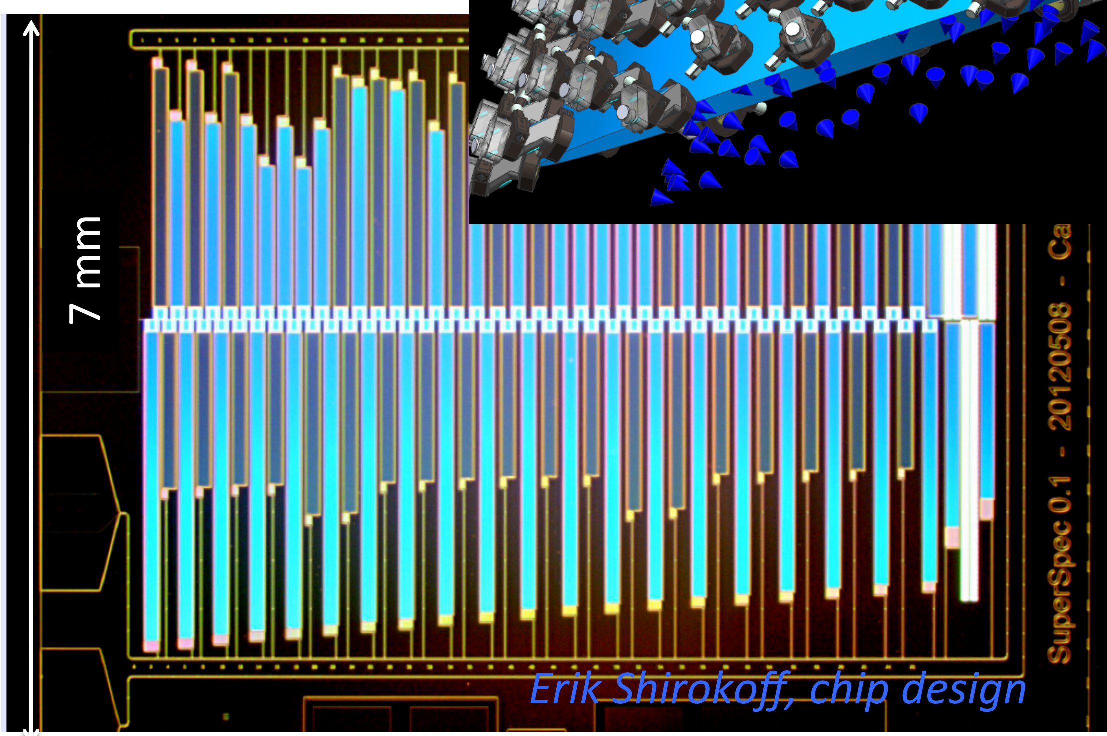
From Kovacs and Zmuidzinas, internal memo

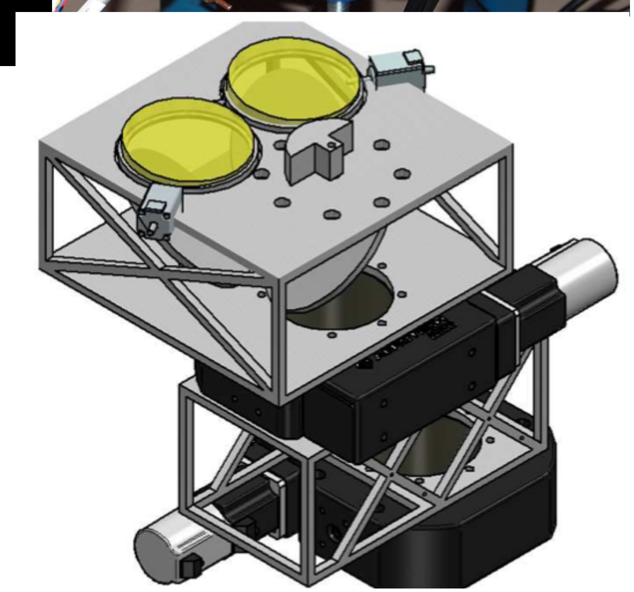
XSPEC: Enabling technologies are 3d MOS steering system (Dalhousie) and SuperSpec 80-channel test device (Caltech, JPL, Berkeley, Dalhousie)











Conclusions:

We are in the middle of a renaissance for su and mm instrumentation and observations.

Unlensed submm sources are important

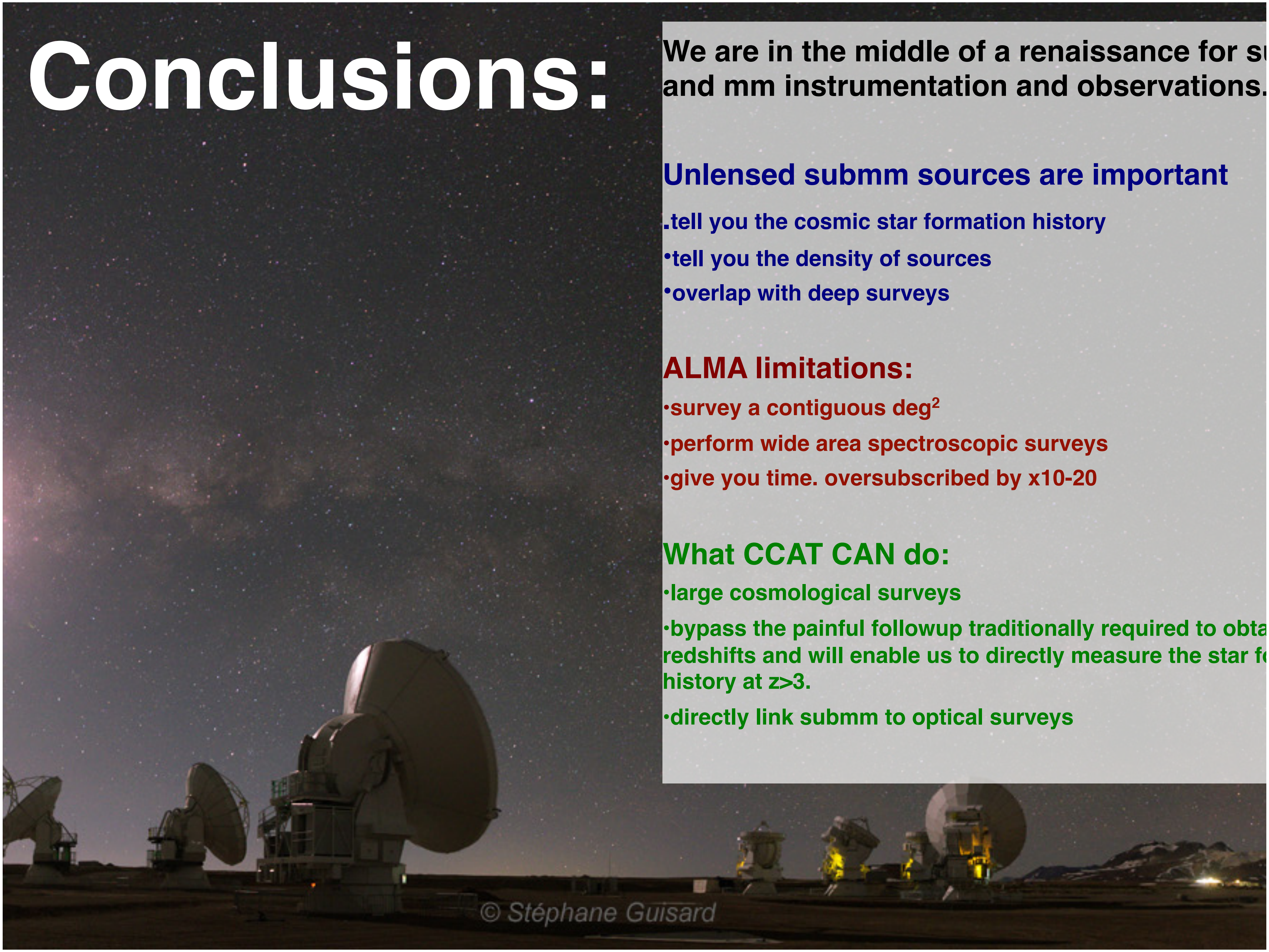
- tell you the cosmic star formation history
- tell you the density of sources
- overlap with deep surveys

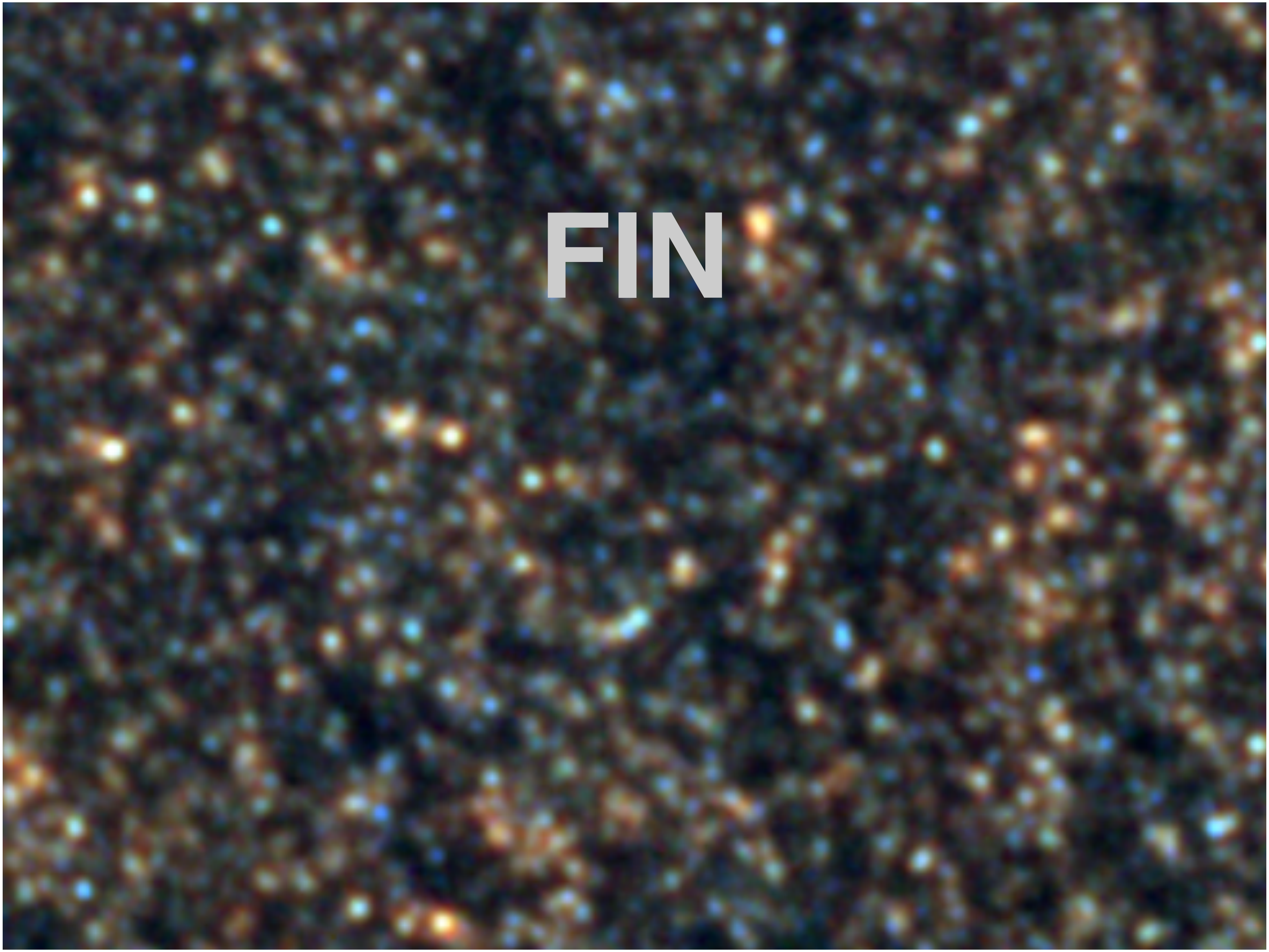
ALMA limitations:

- survey a contiguous deg^2
- perform wide area spectroscopic surveys
- give you time. oversubscribed by x10-20

What CCAT CAN do:

- large cosmological surveys
- bypass the painful followup traditionally required to obta redshifts and will enable us to directly measure the star fo history at z>3.
- directly link submm to optical surveys




FIN