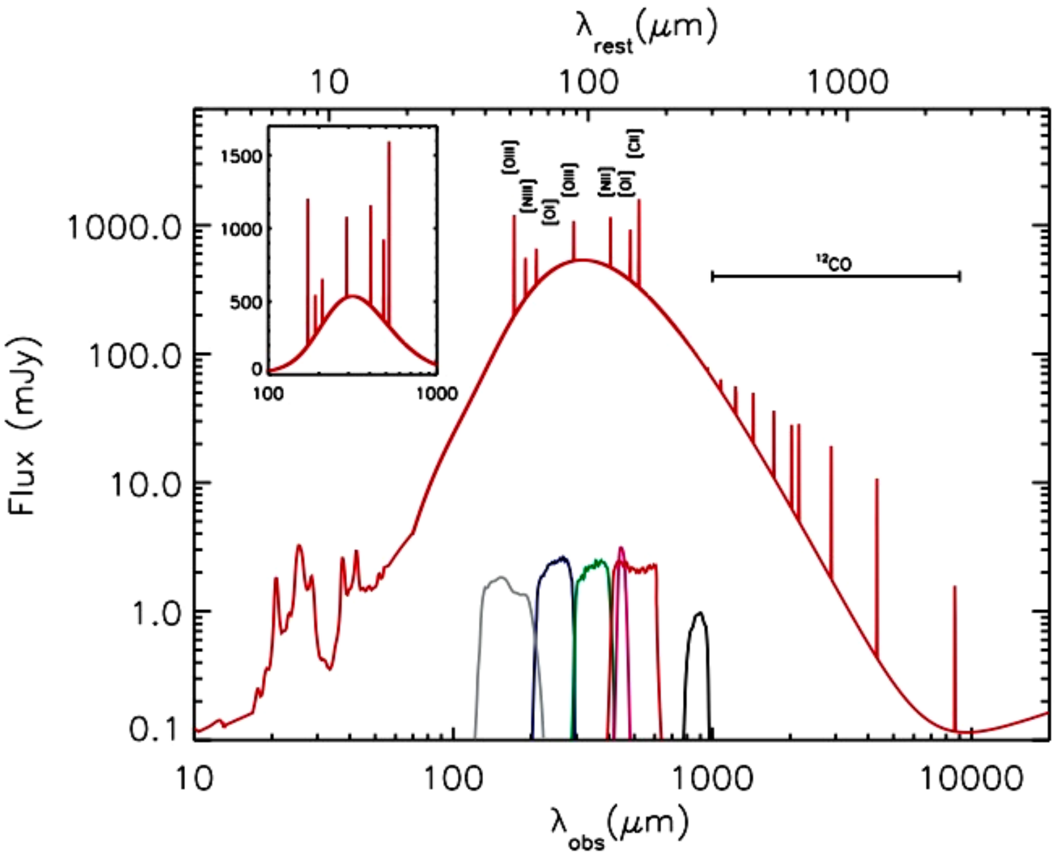
The Future of UK Submillimetre Astronomy Workshop



Galaxy Evolution 2

Ian Smail

Durham University

UK-ATC 12/11

Danielson et al. 2011; Ivison et al. 2010

Overview

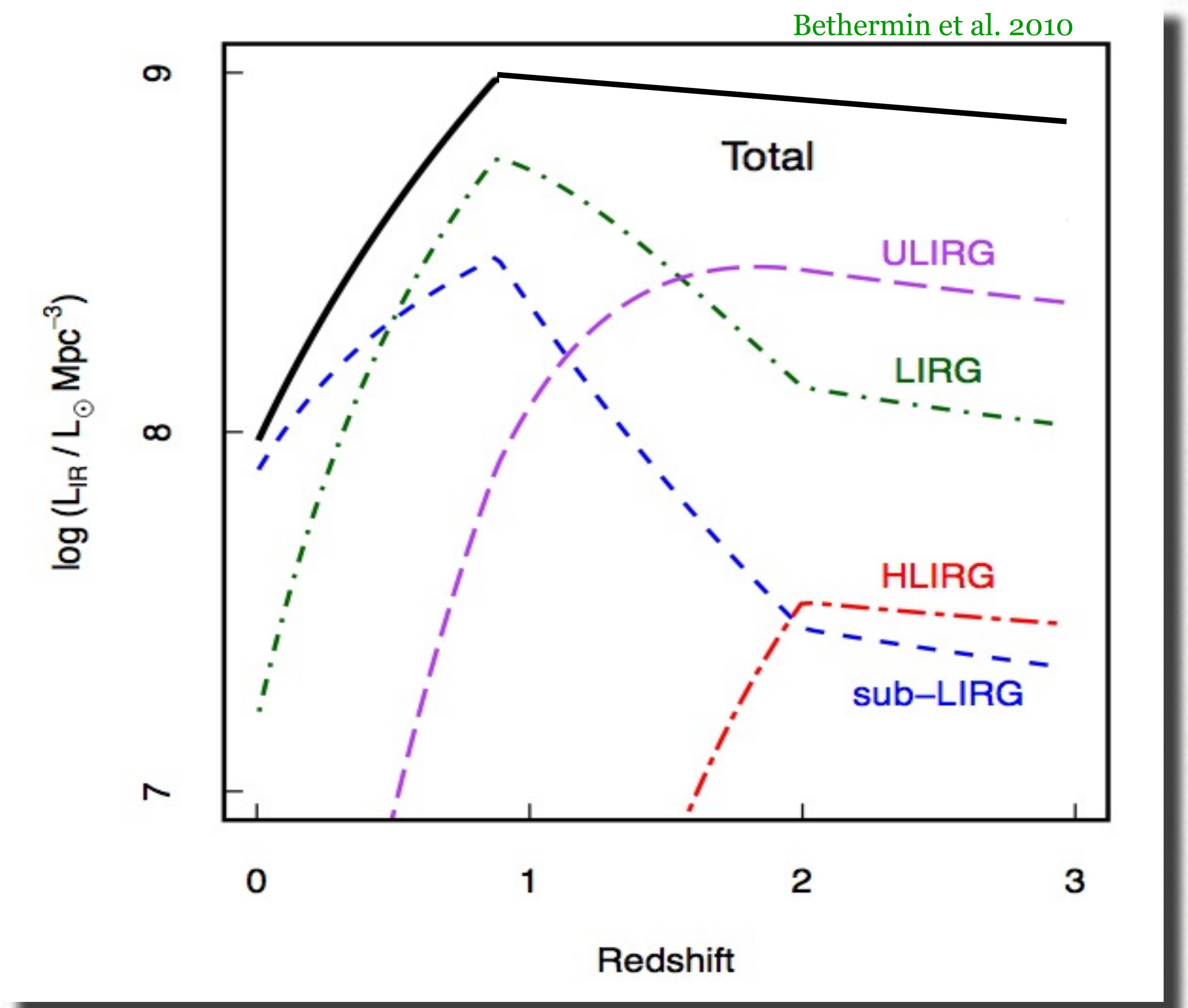
- Introduction: Questions in Galaxy Formation
    - Submm galaxies (SMGs)
- Molecular emission lines in the sub/mm
    - ^{12}CO surveys
- Atomic emission lines in the sub/mm
    - [CII] surveys
- Parameter space for a submm dish
- Conclusions

Questions

How do galaxies form?

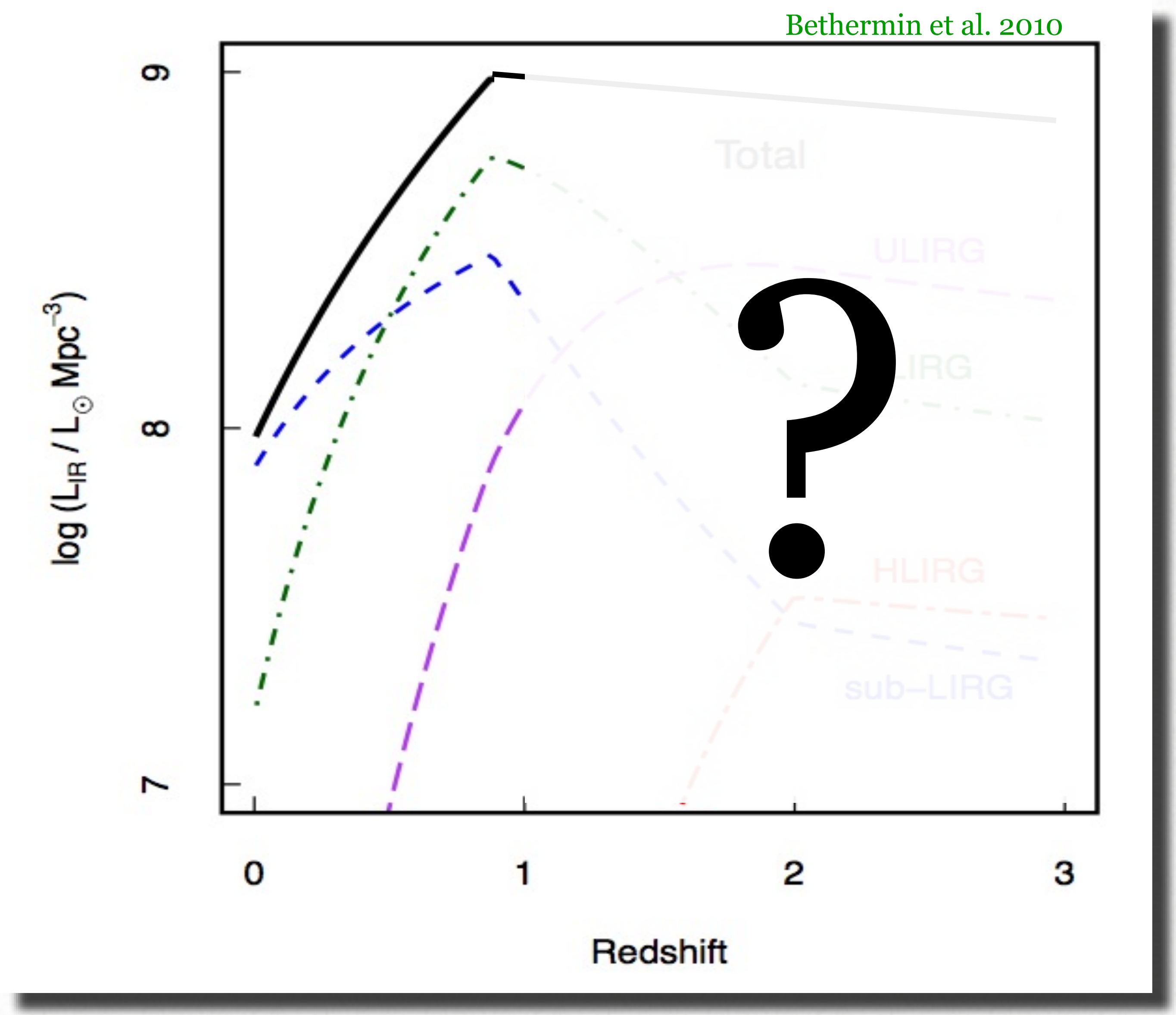
- What is the total SF history of the Universe?
    - What is the role of starbursts in the SF history?
- How are galaxies built up?
    - What is the growth of halo mass?
    - What is the growth of their gas reservoirs?
- Is high-z star formation the same as in low-z galaxies?
    - Does the intense 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?

Star Formation History



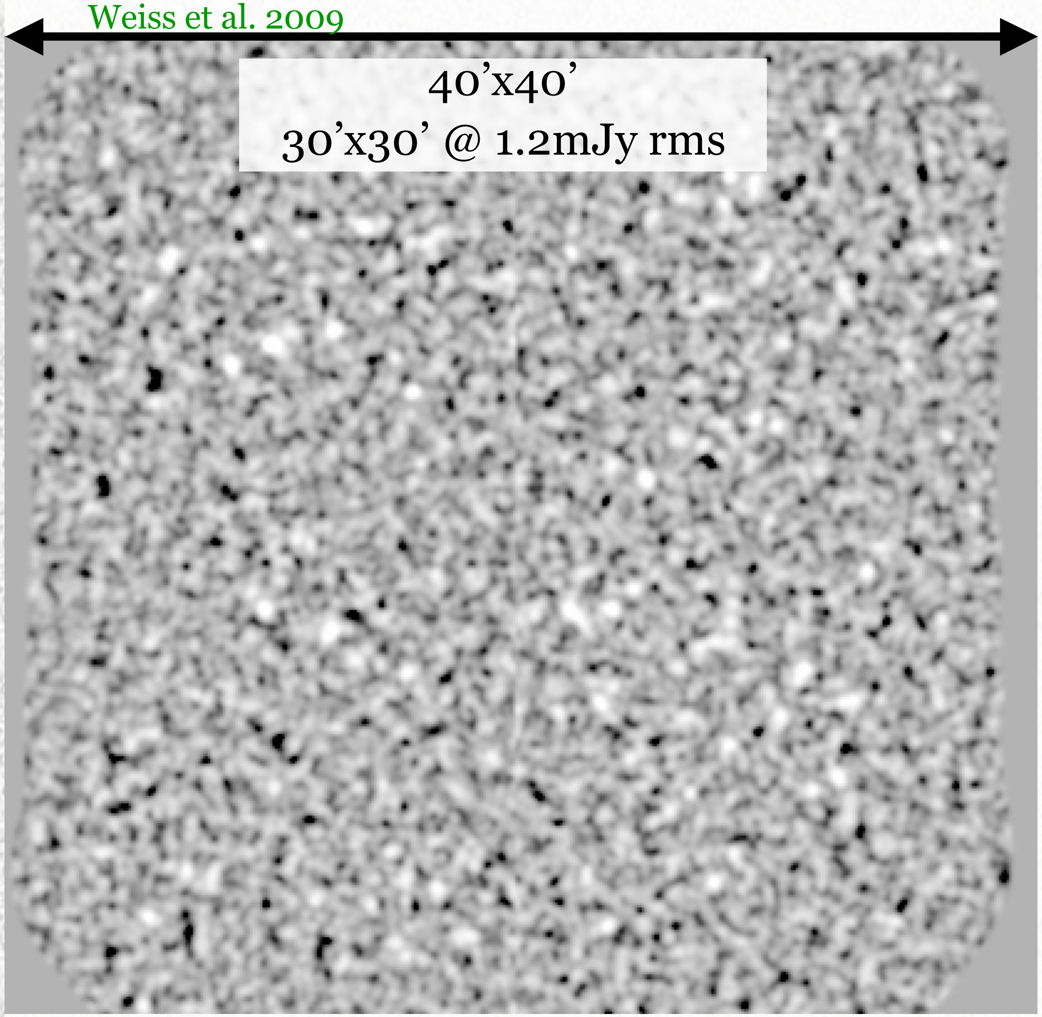
- ULIRGs (dusty starbursts, SFR>100M_0/yr) produce ~50% stars @ z>1-2
- These are submm galaxies (SMGs) detected in FIR/submm

Star Formation History



- ULIRGs (dusty starbursts, SFR>100M_o/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…

Why are we ignorant: a “typical” submm survey…



LABOCA survey of ECDFS: LESS

Joint ESO/MPI project: ~330hrs

126 SMGs above 3.7σ (4.5mJy)

79 (63%) have radio/MIR IDs

Biggs et al. 2011

On-going ALMA Cycle 0 study to map all 126 sources.

Simpson et al. 2012

72 (57%) have photo-z

Wardlow et al. 2011

On-going VLT LP (200hrs with VIMOS & FORS2) spectra of SMGs

Danielson et al. 2012

Those without IDs or redshifts are likely to include the highest-z SMGs.

Challenge is to measure precise redshifts for complete samples of SMGs…

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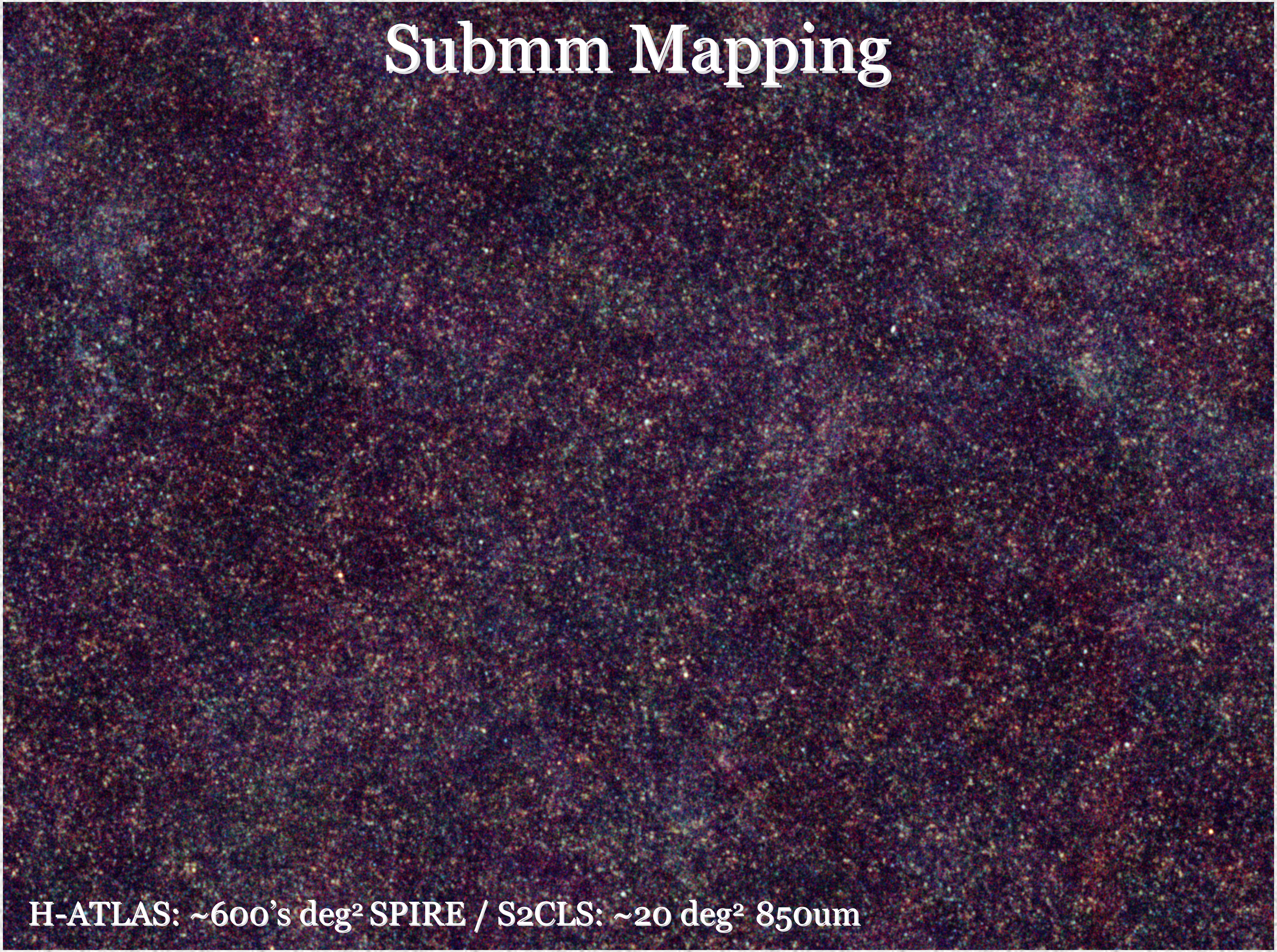
Observational Tools

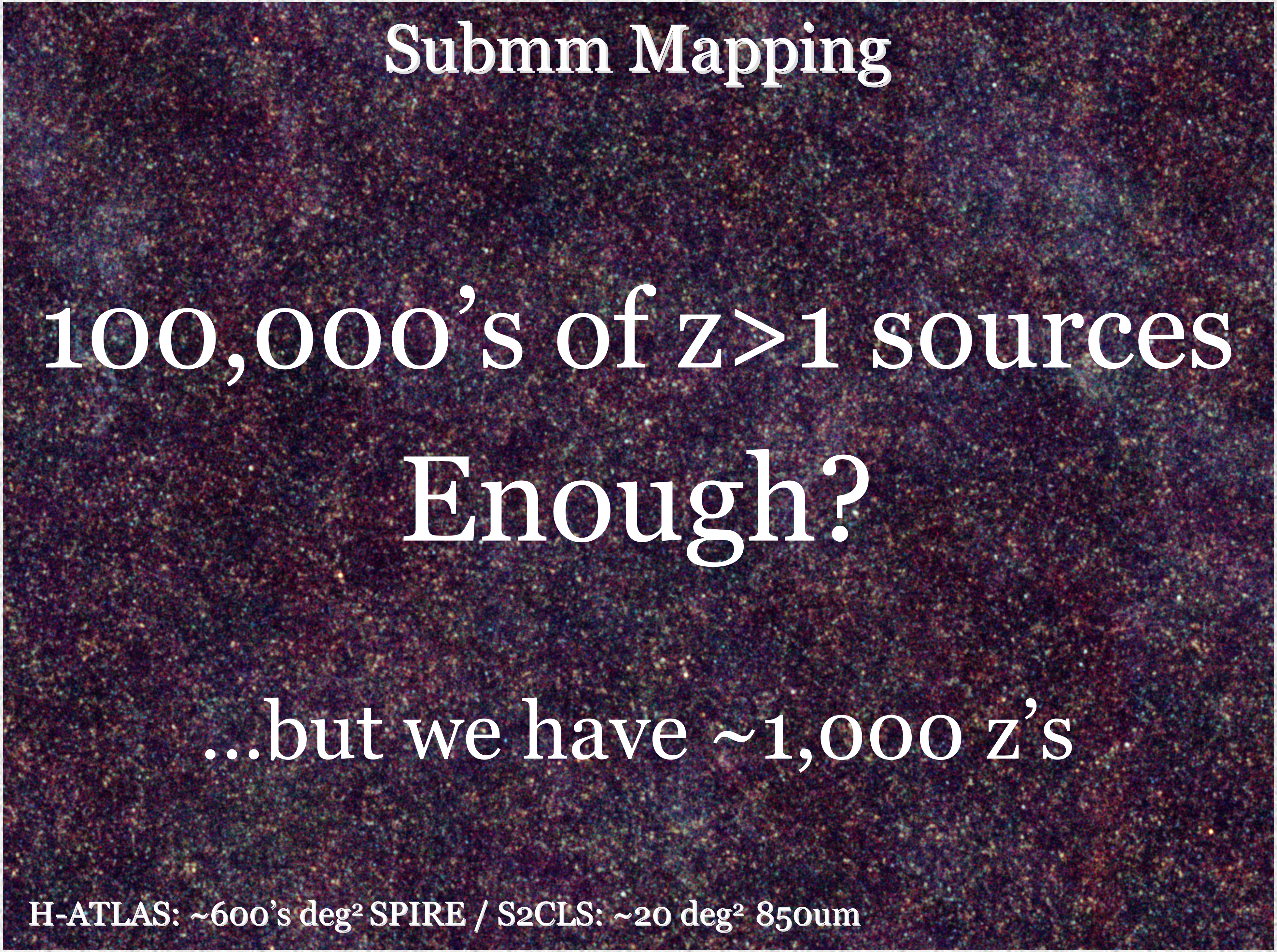
How do galaxies form?

- 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
  - ISM chemistry: chemical clocks

Submm Mapping



H-ATLAS: ~600's deg^2 SPIRE / S2CLS: ~20 deg^2 850um


Submm Mapping
100,000's of z>1 sources
Enough?
...but we have ~1,000 z's
H-ATLAS: ~600's deg^2 SPIRE / S2CLS: ~20 deg^2 850um

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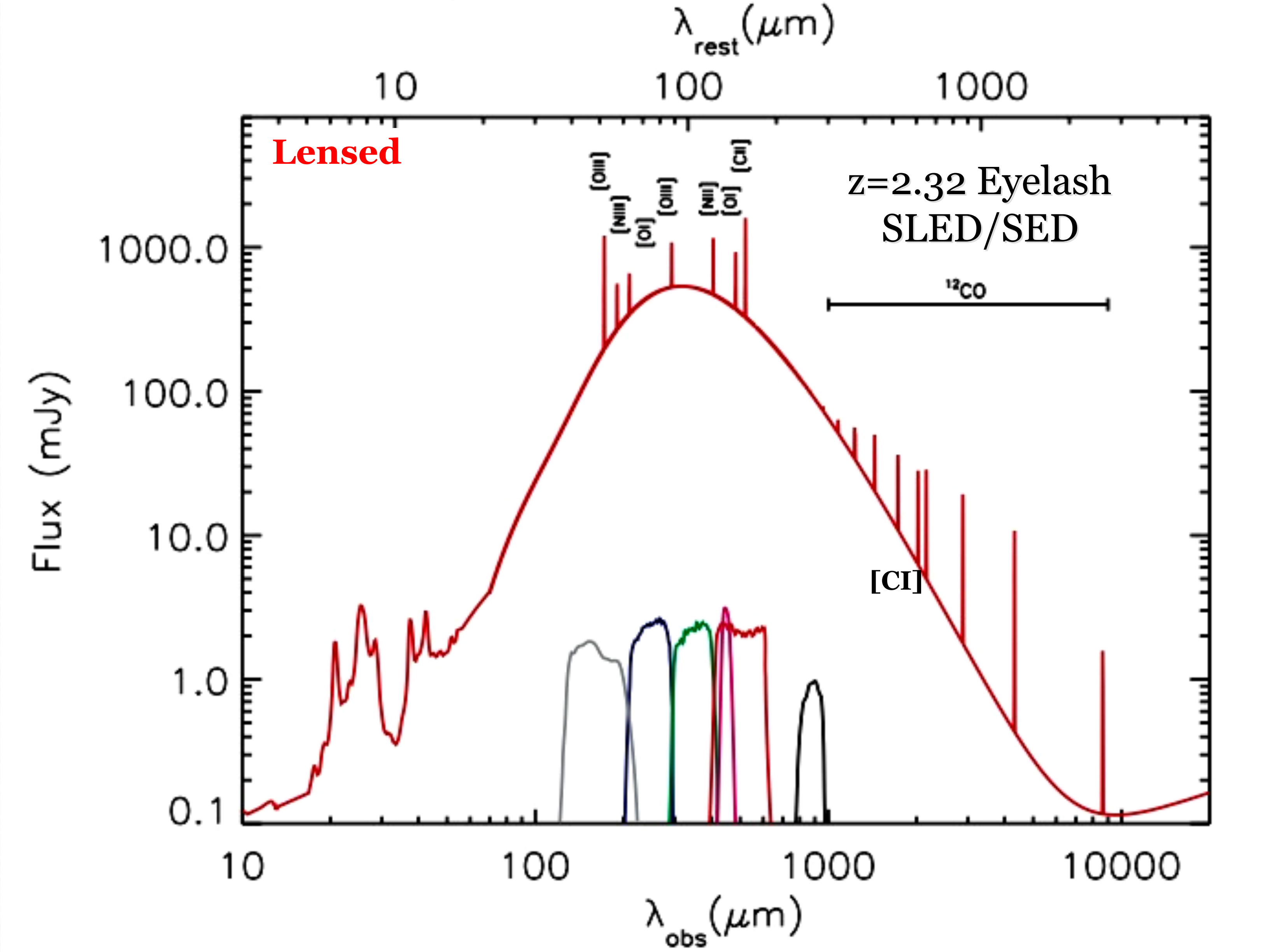
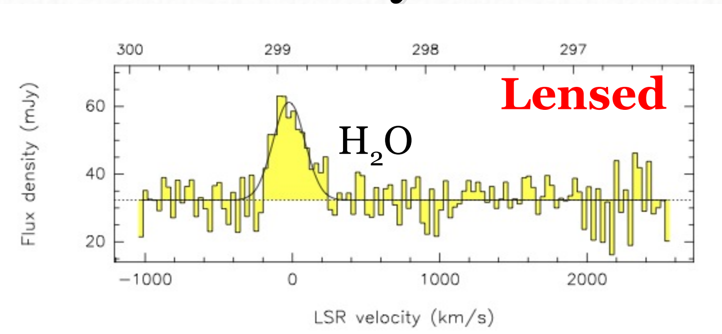
Molecular & Atomic Emission Lines



Swinbank et al. 2010; Ivison et al. 2010; Danielson et al. 2011

Molecular Emission Lines

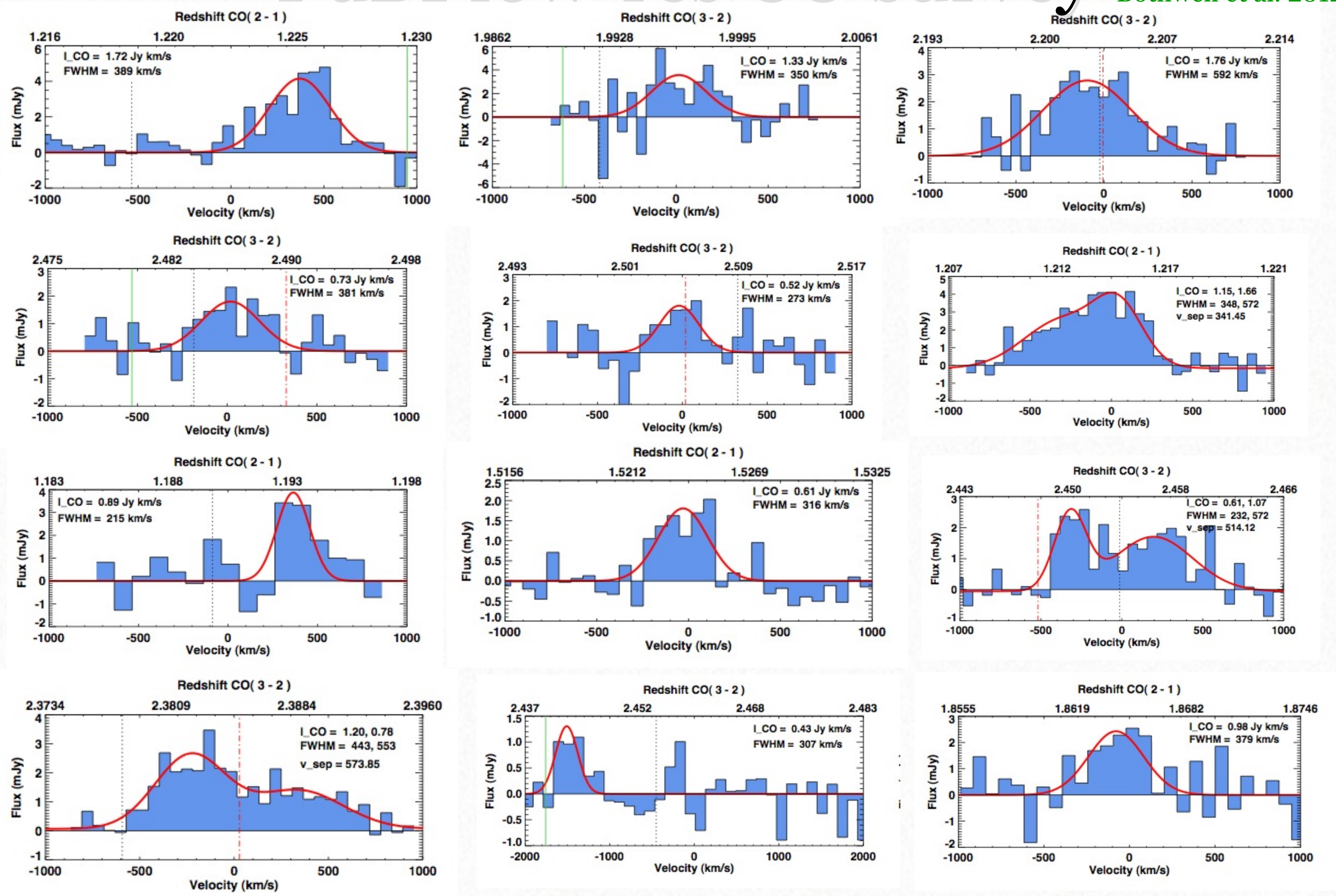
- ^{12}CO ladder is best studied - commonest tracer of H_2
    - Provides systemic redshift for gas reservoir
    - Line luminosity can be converted into M_{gas}
    - Line kinematics can be used to estimate M_{dyn}
    - Together these yield the gas fraction: M_{gas}/M_{dyn}
    - Line kinematics give hints about source structure
    - ^{12}CO SLED tells us about gas excitation
- Also dense molecular gas tracers: ^{13}CO, HCN, H_2O
    - Only seen in rare lensed/AGN sources…



Omont et al. 2011
PdBI SDP17b
z=2.30

PdBI low-res CO survey

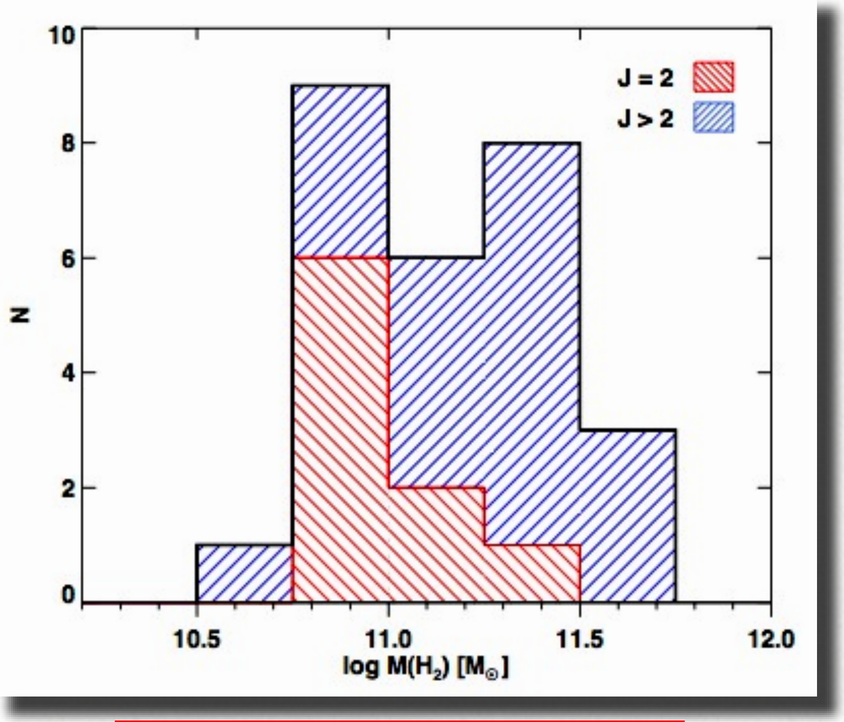
Bothwell et al. 2012

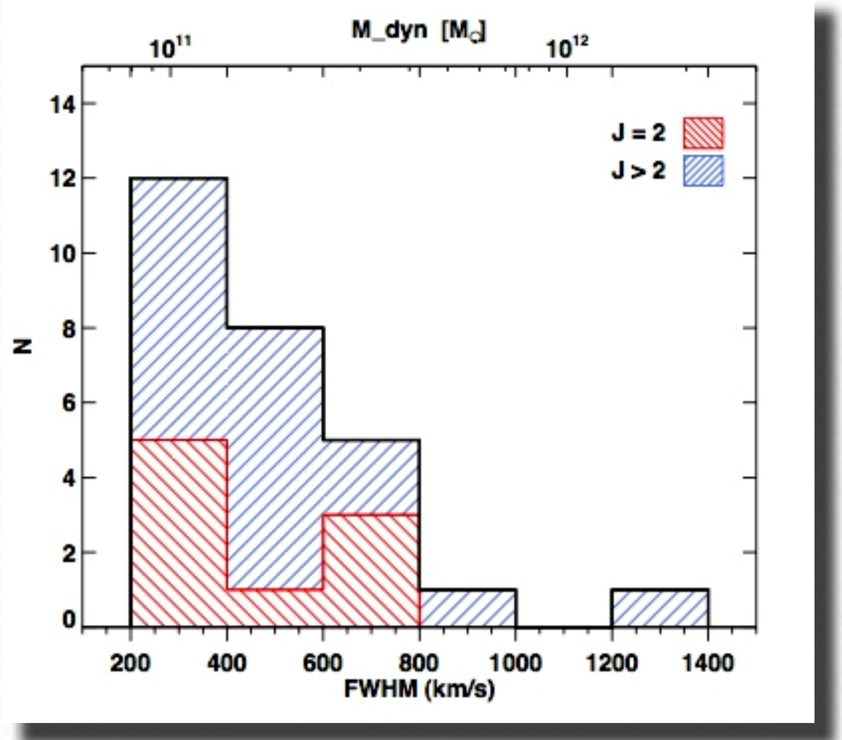


- 36 unlensed SMGs in CO(3-2)/CO(2-1): 28 detections, 8 non-detections
- +CO for ~50 lensed Herschel srcs (Riechers et al.) - differential magnification!

Gas & Dynamical Masses

Bothwell et al. 2012





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

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

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

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

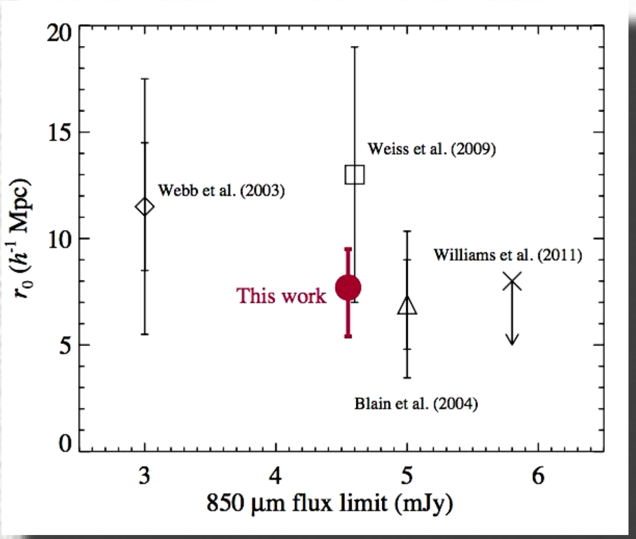
C(θ) - Virial sphere or Disk model

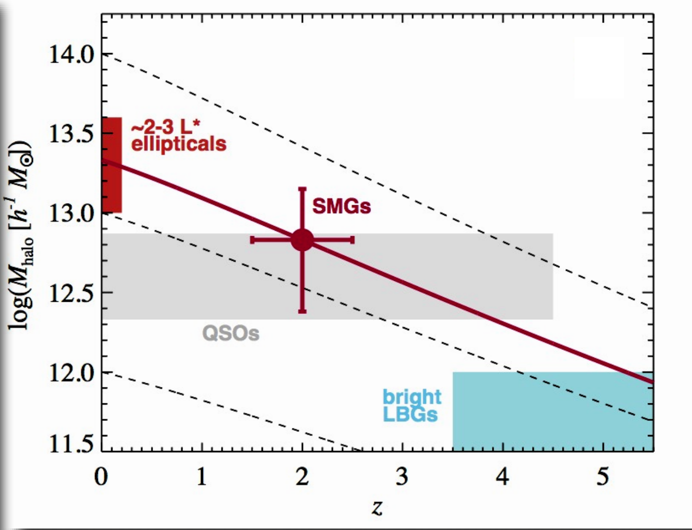
R = radius of gas reservoir

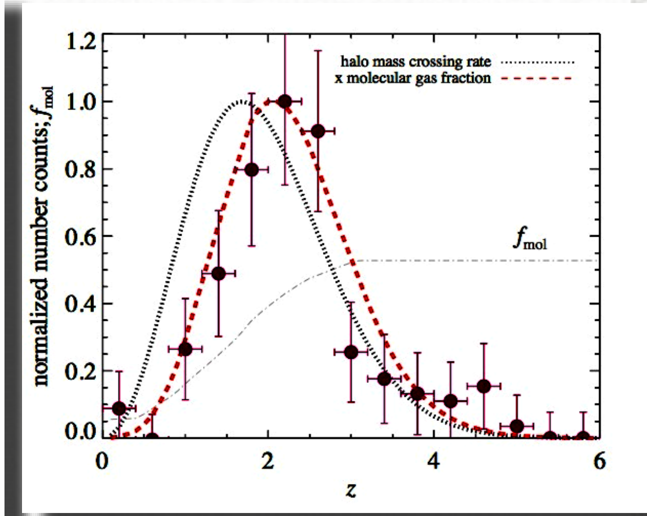
- Median gas mass (including limits): (1.0+/-0.2) x 10^{11}Mo (for α~2)
- FWHM of CO: 510+/-80km/s yields M_{dyn}(<7kpc) ~3x$10^{11}M_o$ (disk model)
- Gas fraction ~30% vs 7% for z=0 LIRGs (Bothwell et al. 2009) - less evolved

Halo masses for SMGs

Hickox et al. 2011



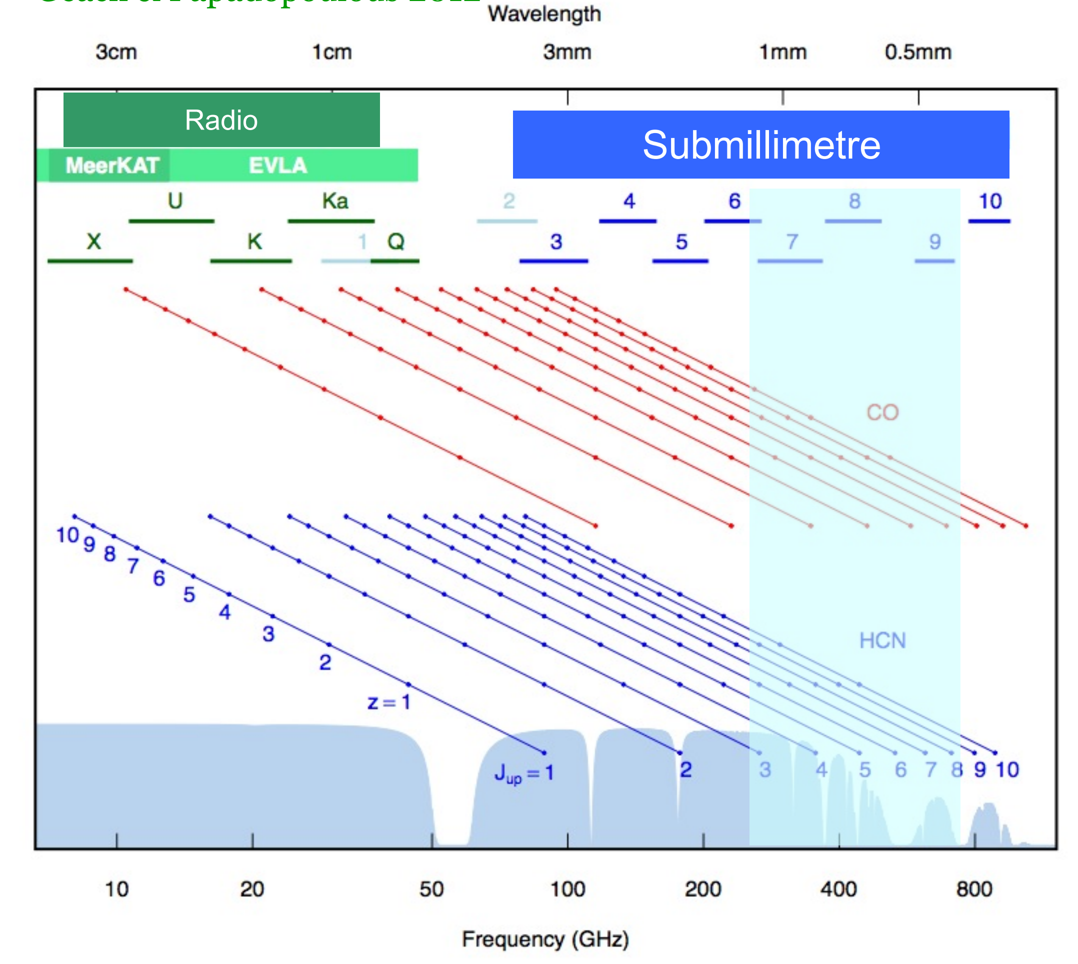




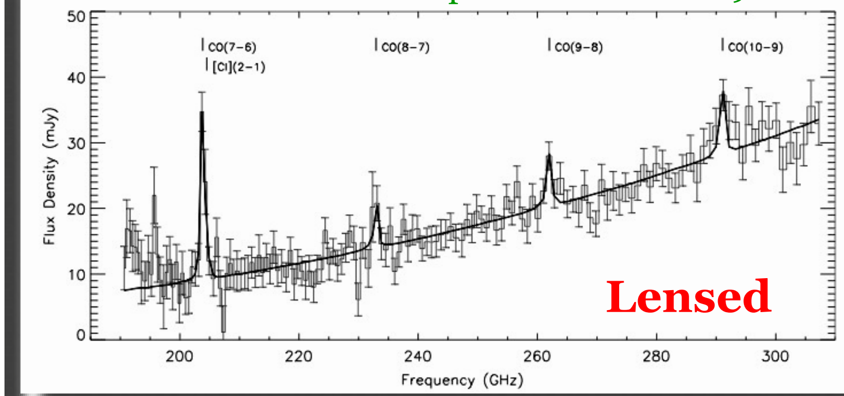
- 2-D clustering of SMGs (here only at 850um) - huge depth of survey and small areas mean measurements are weak.
- But with precise redshifts for SMGs can start to measure their 3-D clustering - Hickox et al. used cross-correlation of spectroscopic SMG sample with photo-z sample of IRAC srcs
- Derive halo mass for SMGs of $6\times10^{12}M_o$ - evolve into ~2-3L^* ellipticals with duty-cycle for burst of ~100Myrs (consistent with gas/stellar masses)
- Simple evolution model: goes "bang" when crosses threshold mass (with observed evolution of gas fraction) provides a good fit to the SMG N(z)

Submm science from CO

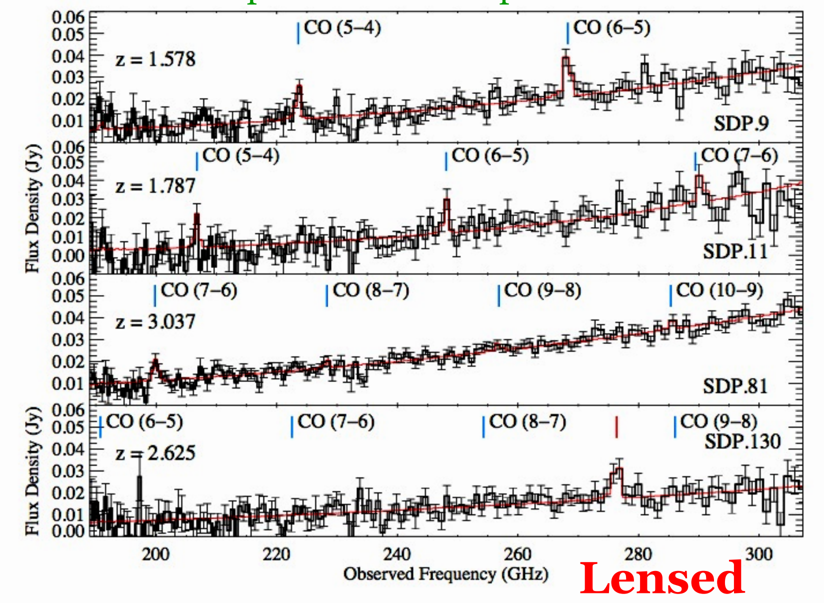
Geach & Papadopoulous 2012



Scott et al. 2011 Z-spec HLSW-01 z=2.96



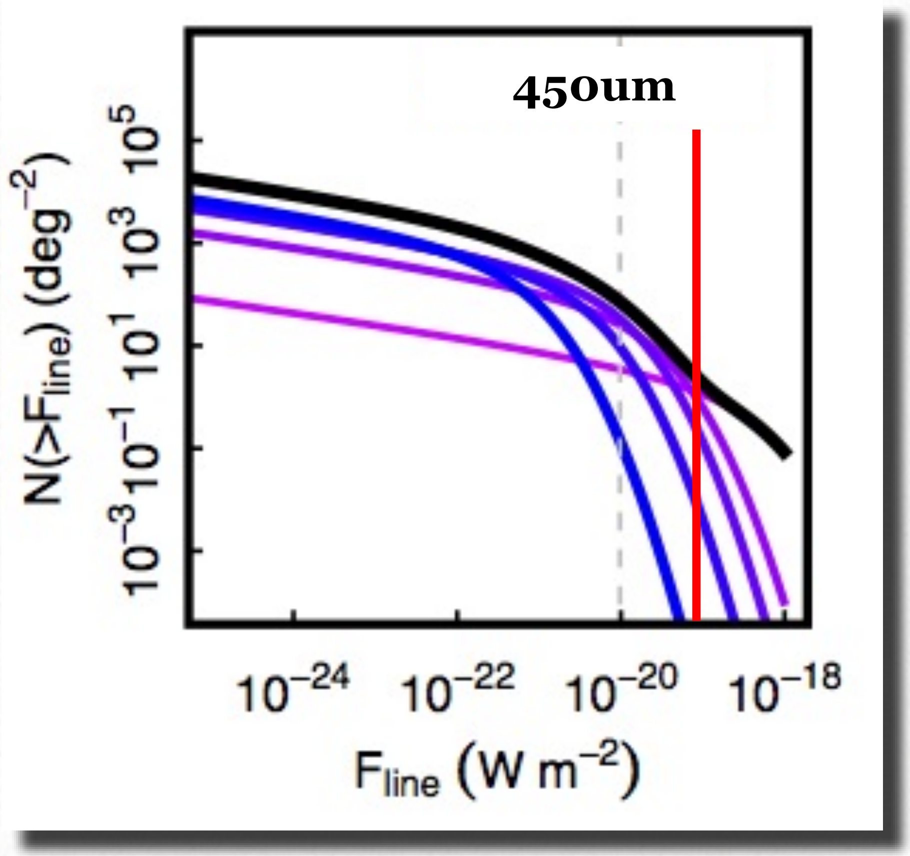
Lupu et al. 2011 Z-spec SDP1 srcs

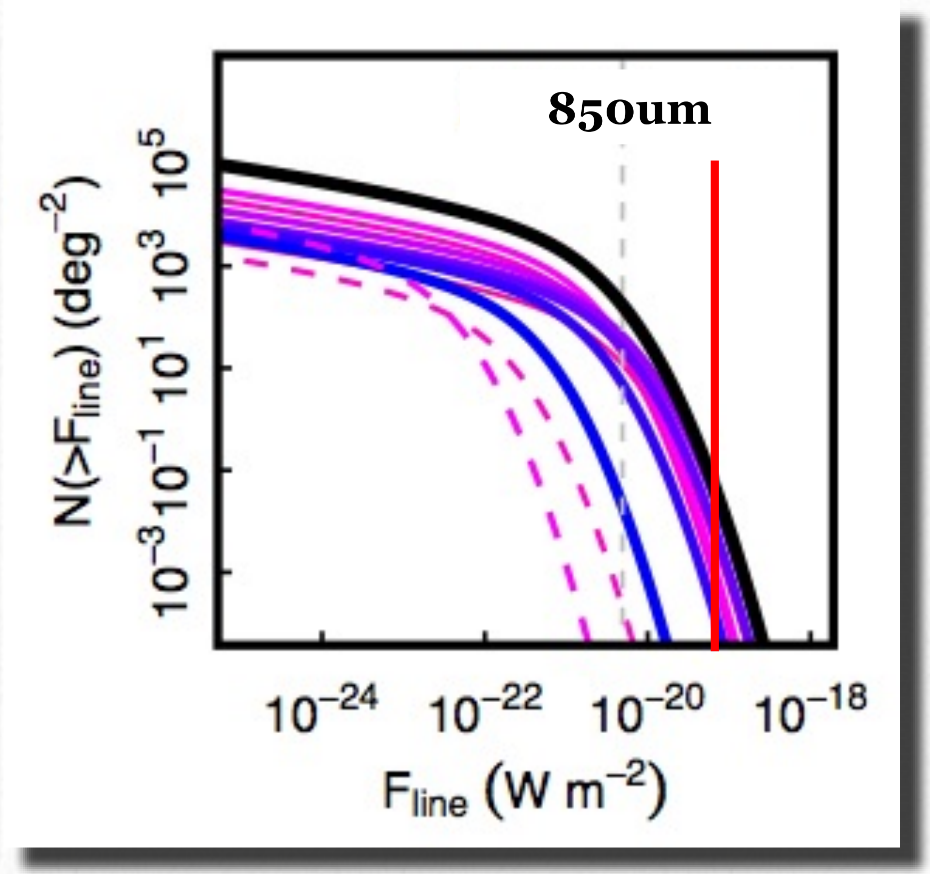


- Draw back of CO in submm is all J_{up}<6 transitions at >1mm for z>1.3
- High-J lines are weak and poor indicators of M_{gas} (can test PDR-vs-XDR)

^{12}CO count predictions

Geach & Papadopoulous 2012





- Predicted blank-field ^{12}CO number counts in 8-GHz bandwidth
- ~10^-19 W/m^2 is the limit for few-hour integration on JCMT
- Predicted CO source surface densities are ~0.1-10 degree^{-2}
- CO redshift surveys of SMGs are better done in mm/radio...

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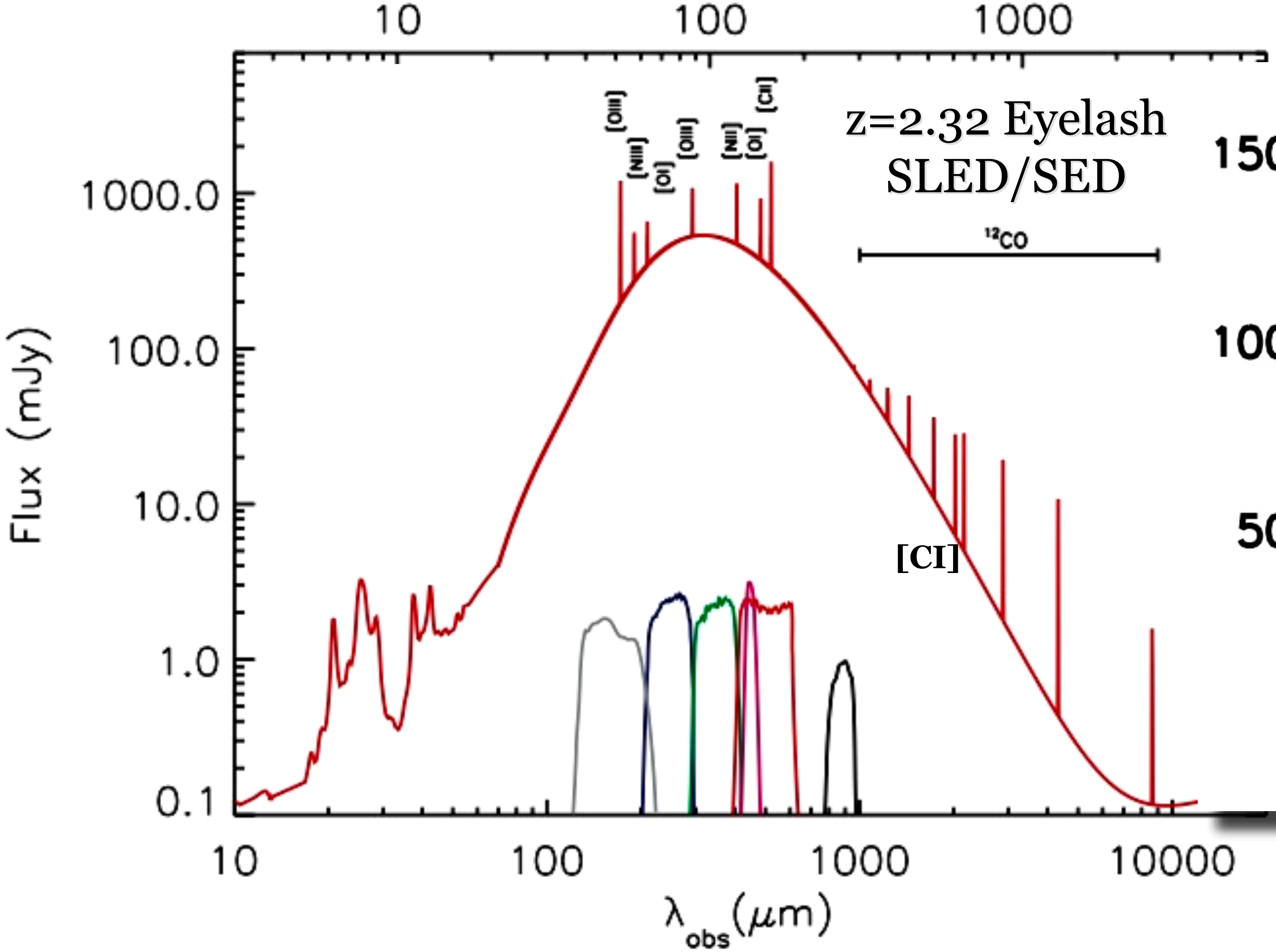
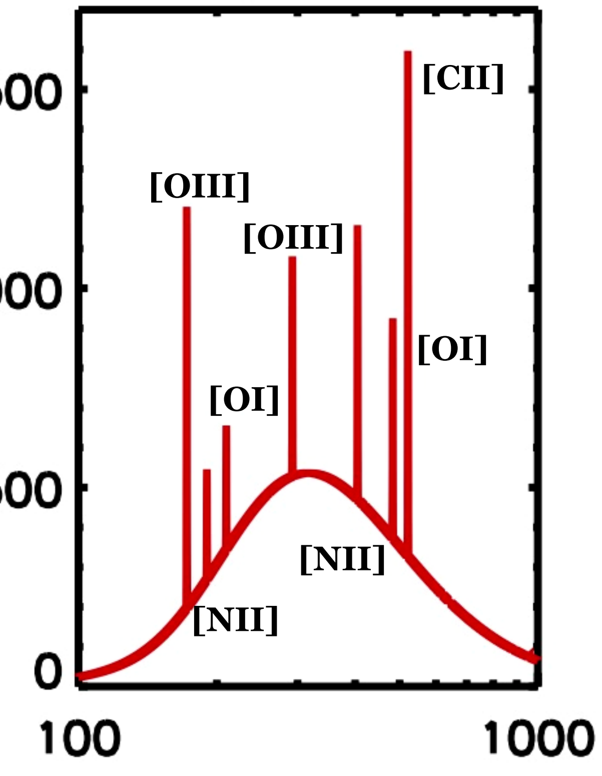
Molecular & Atomic Emission Lines

Swinbank et al. 2010; Ivison et al. 2010; Danielson et al. 2011



Smail et al. 2011



- Atomic lines at 50-200um are far brighter than ^{12}CO:

All ^{12}CO lines: 0.09% L_{FIR} [CII] 158um: 0.24% L_{FIR}

Stacey PPT

Atomic Emission Lines

- Atomic lines are bright and yield critical information:

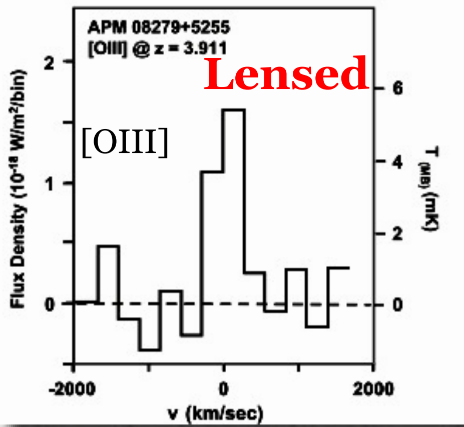
[CII] 158 1
[NII] 205 0.1
[NII] 122 0.15
[NIII] 57 0.1
[OIII] 88 1
[OIII] 52 0.5
[OI] 63 0.5
[OI] 146 0.1

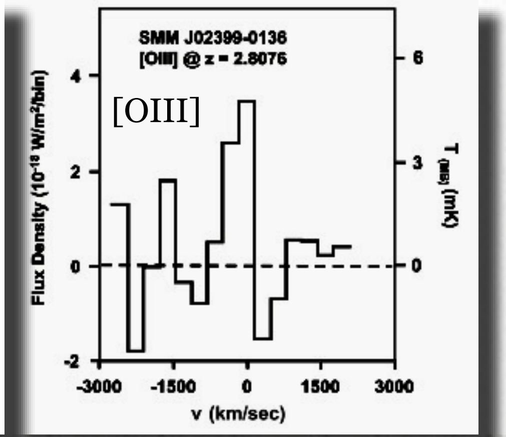
UV field hardness and HII region density

N/O abundance ratio: "Age of the ISM"

PDR parameters: density

- Together can test PDR vs XDR/CRDR (SF vs AGN) and derive physical properties of the ISM: G_o, n, etc

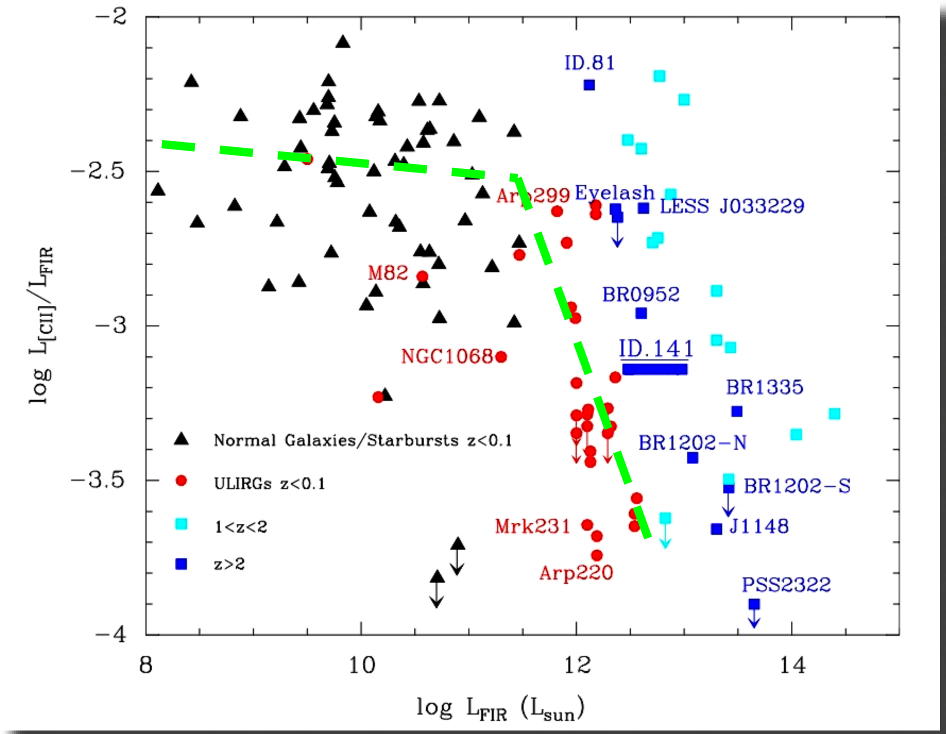




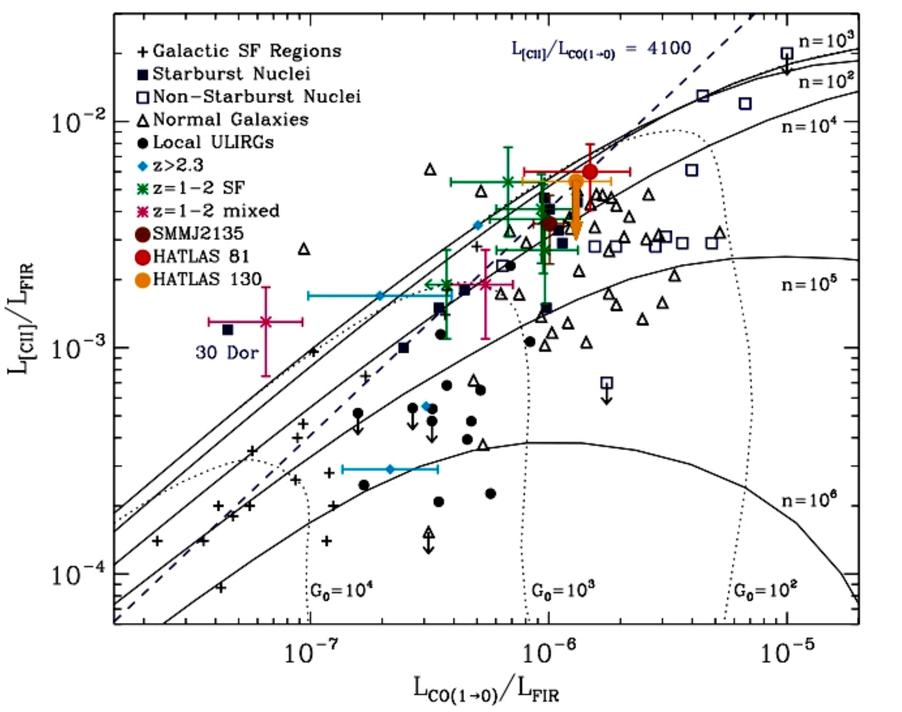
Ferkinhoff et al. 2011 ZEUS

[CII]

Cox et al. 2011 PdBI SDP141 z=4.24



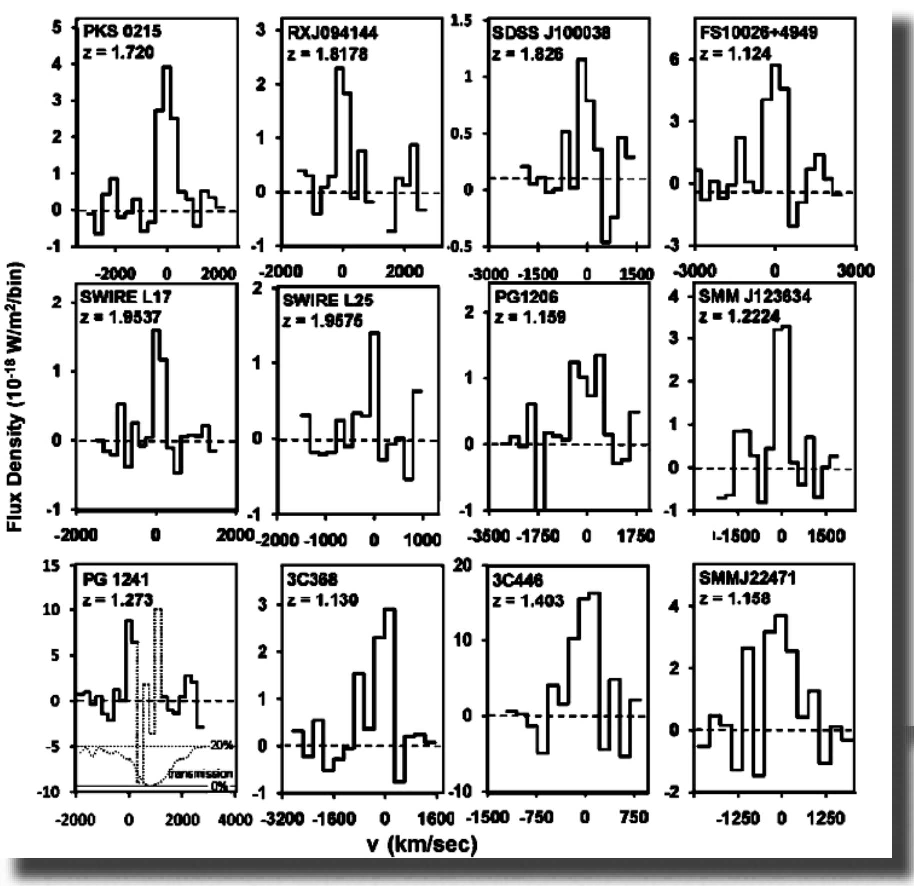
Valtchanov et al. 2011 SPIRE FTS SDP81/130 z=3.04, 2.62

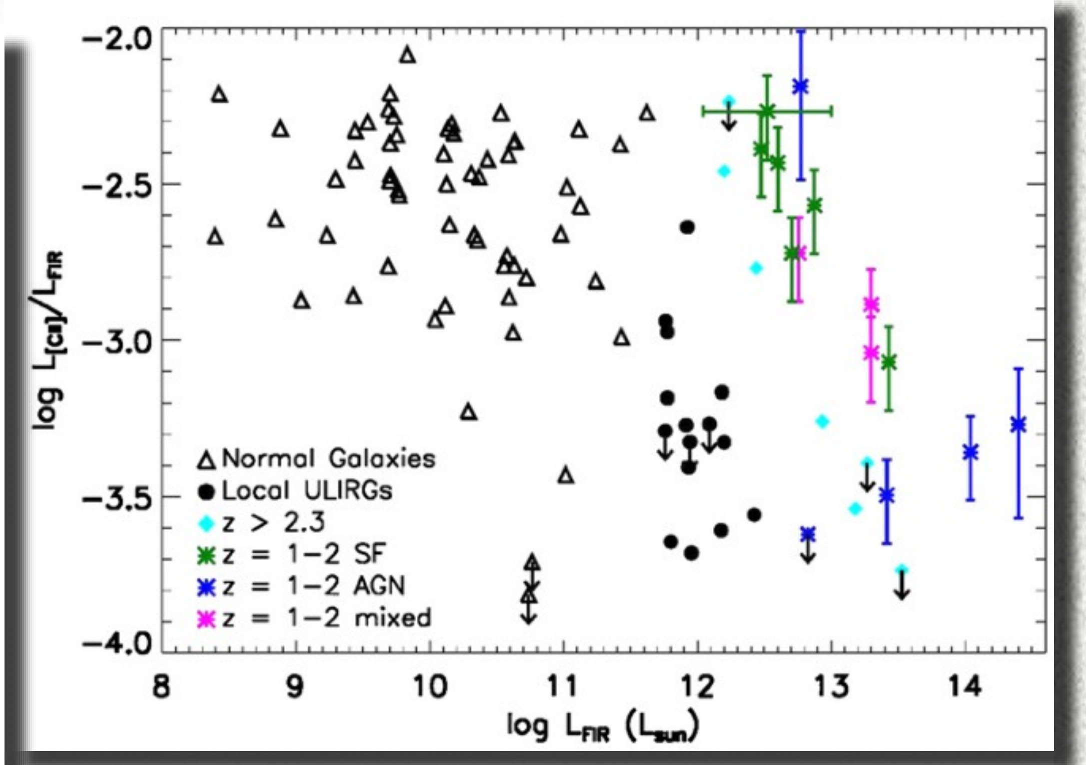


- [CII] (and [OI] in denser regions) are major cooling line: from PDRs, diffuse ionised and warm neutral ISM - tell you about heating
- Luminosity ~0.1-1% L_{FIR} in a *single* line (up to ~3%)!
- z~0 ULIRGs have low [CII]/L_{FIR} due to higher ionisation of grains by UV field from intense starburst, reducing photo-electron heating.
- SMGs don't show this [CII] deficit - more extended starburst?
- Can use [CII]/L_{FIR} to estimate G_o,n in the ISM

ZEUS/CSO [CII] survey

Stacey et al. 2010



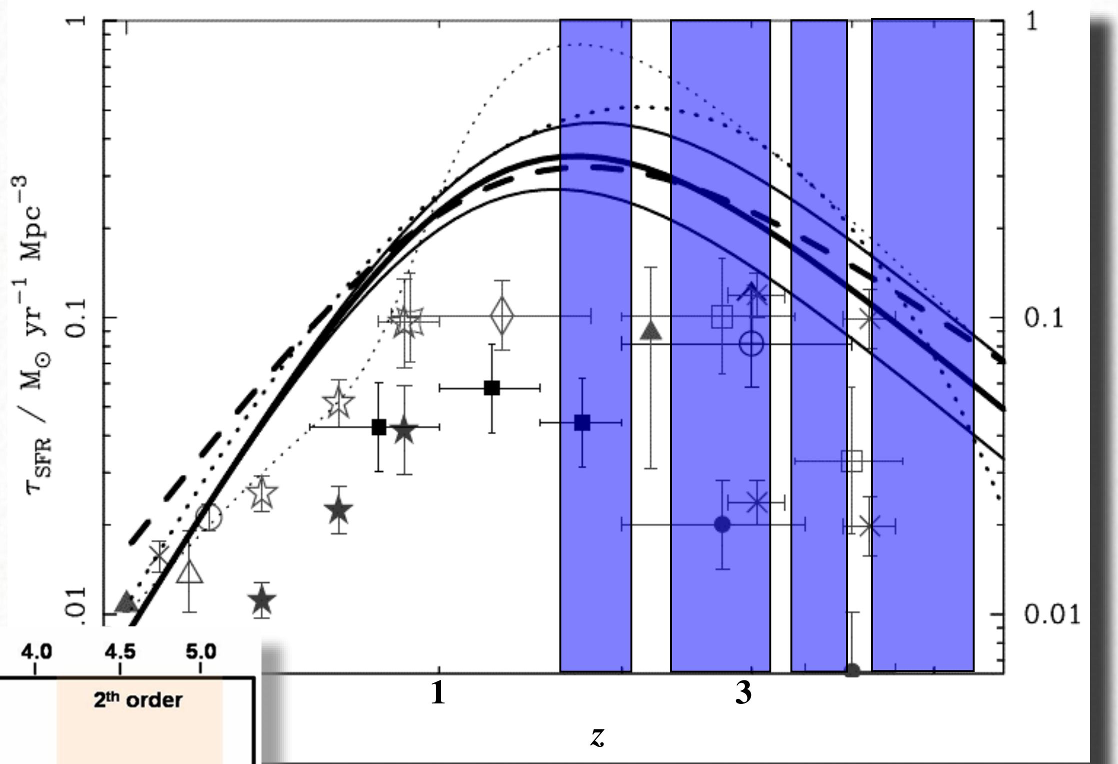


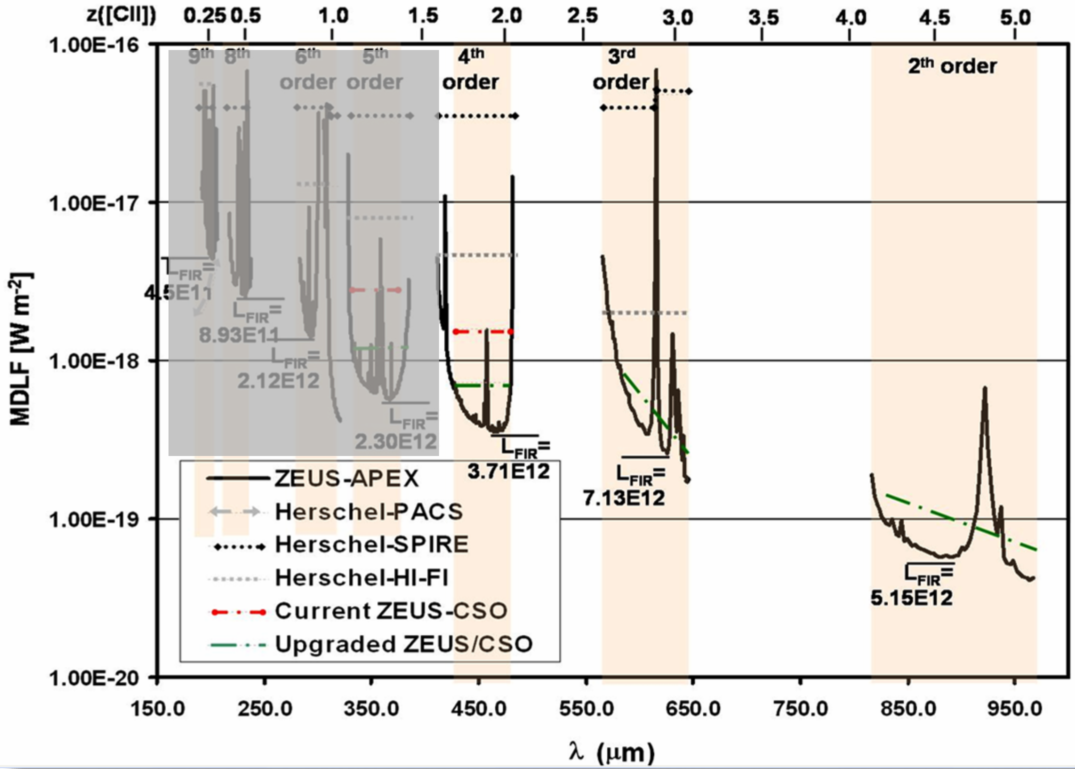
- ~1hr integrations with ZEUS on CSO of mix-bag of ULIRGs/AGN at z~1-2 [ZEUS 3 band spectrograph ~500-900 GHz simultaneous coverage]
- [CII] detections - these are *unlensed!*
- Determine: redshifts, FWHM, line fluxes & [CII]/L_{FIR}

[CII] coverage

Stacey PPT

- >450um covers [CII] from z=1.7 to z~5+
- Peak of the SFH of galaxies
- Windows at <450um only cover below SFH peak





- JCMT limit for [CII]/L_{FIR}~0.3% is L_{FIR}> 3 x $10^{12}L_o$ in few hrs
- Surface density of srcs at z>1.7 is ~10^3 degree^{-2}
- Can measure redshifts, clustering and dynamics of these galaxies.
- Obviously need >>10^3 z's

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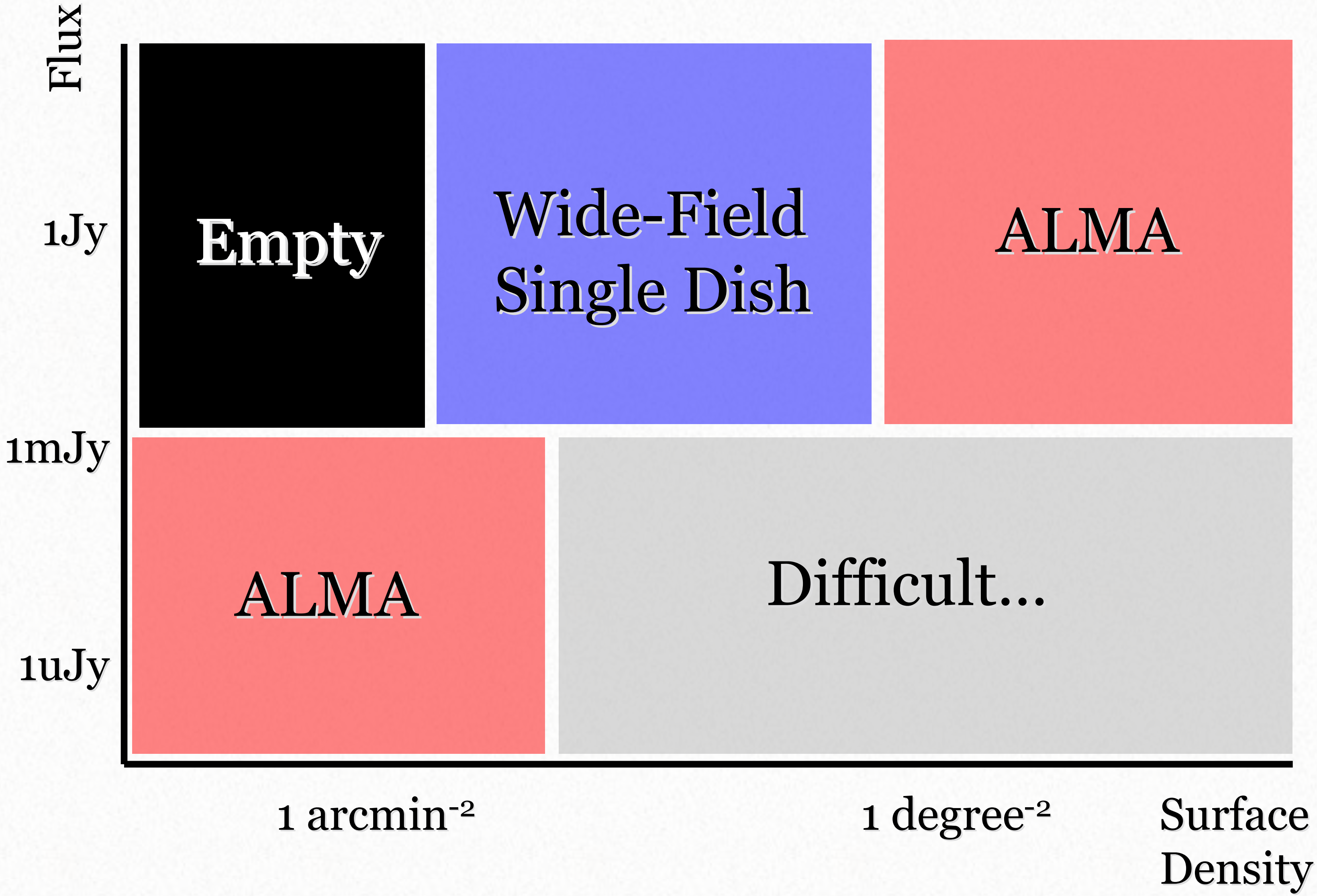
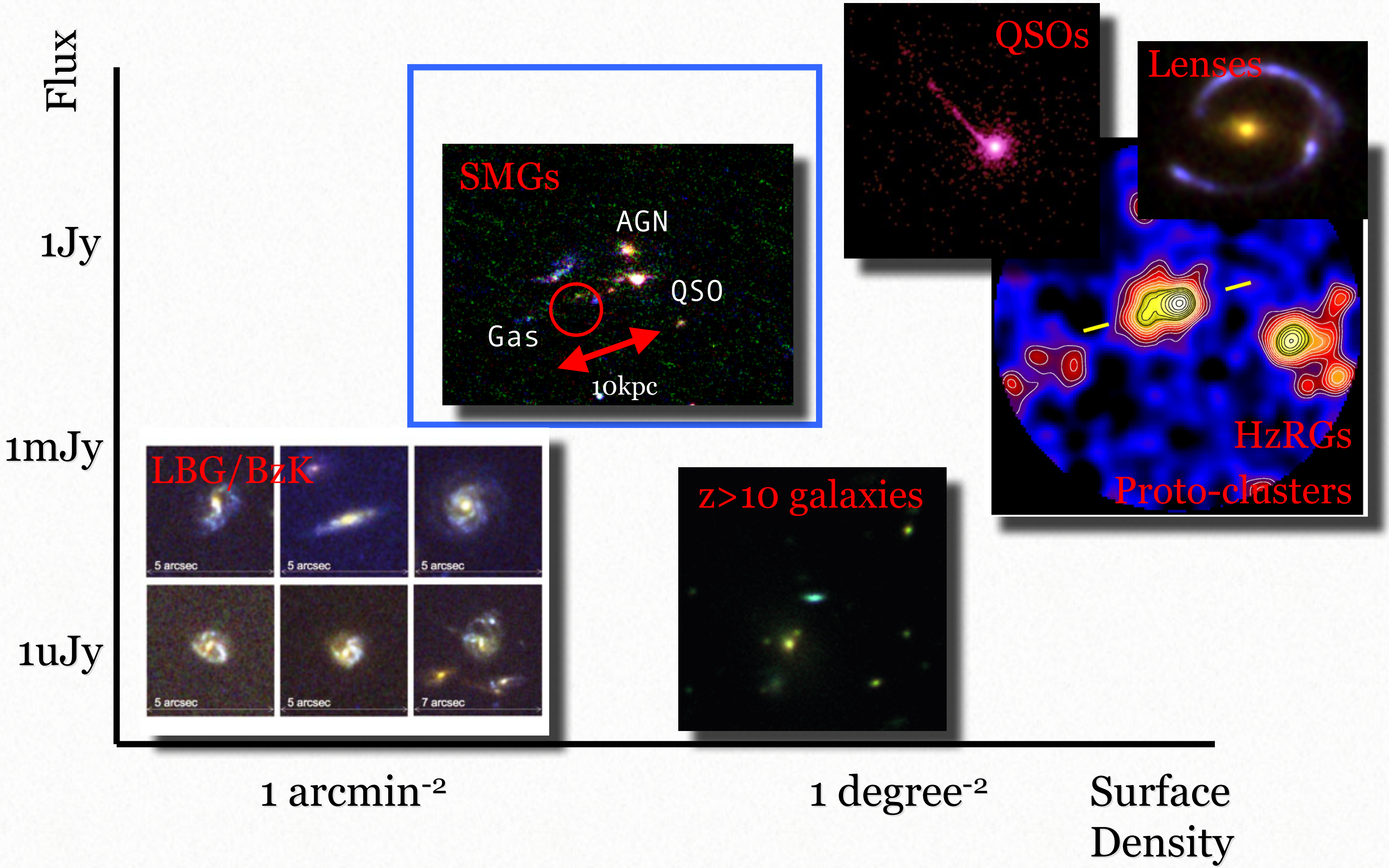
Extragalactic Parameter Space



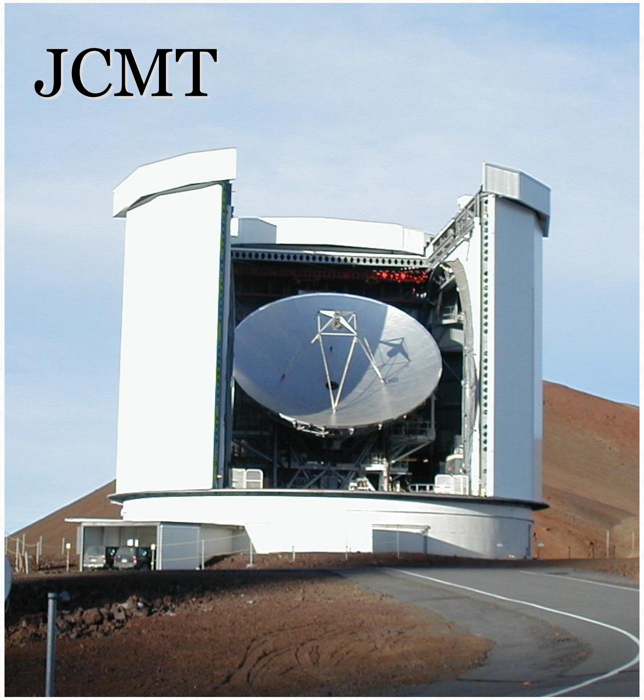
- Surface densities of between ~1 arcmin^{-2} and ~1 degree^{-2} and fluxes > confusion (~1mJy)

Extragalactic Parameter Space



- As we've seen - high-z ULIRGs are an important population for understanding high-z SF
- Well-matched to capabilities of a wide-field, large submm dish

ALMA-vs-JCMT/CCAT



- For sources with N(FoV)<1: FoM = Collecting area x T_{Frac}
- For sources with N(FoV)>>1: FoM = Collecting area x T_{frac} x Multiplex
- ALMA - 50x12m = 5650 m^2
- UK gets ~20% of 33% = 1/15 -> 377 m^2
- Only ~2 x JCMT (177 m^2) [or 30% less than a 25-m dish]
- So a multiplex instrument on JCMT can compete (like 2dF vs Gemini)
- JCMT exists and works now….

Conclusions

- FIR/submm studies are important probes of galaxy formation
- But most of the astrophysics from FIR/submm surveys require spectroscopy (z, M_{dyn}, clustering, etc) of *complete* samples
- The wavelengths of the main CO lines (J_{up}<6) are redshifted into the mm for z>>1. So these aren't natural targets for JCMT/CCAT.
- The brightest submm cooling line is [CII]158um - accessible longward of 450um at z~1.7-5 and >5x brighter than CO lines
- [CII] luminosity can approach 1% L_{FIR}
- Galaxies with L_{FIR}~3x$10^{12}L_o$ should be detectable in a few hrs
- Surface density of z>1.7 L_{FIR}>3x$10^{12}L_o$ sources is ~10^3 degree^{-2}
- A multiplexed 400-1200um spectrograph on JCMT/CCAT is competitive with ALMA for redshift-identification of SMGs