Dusty Universe

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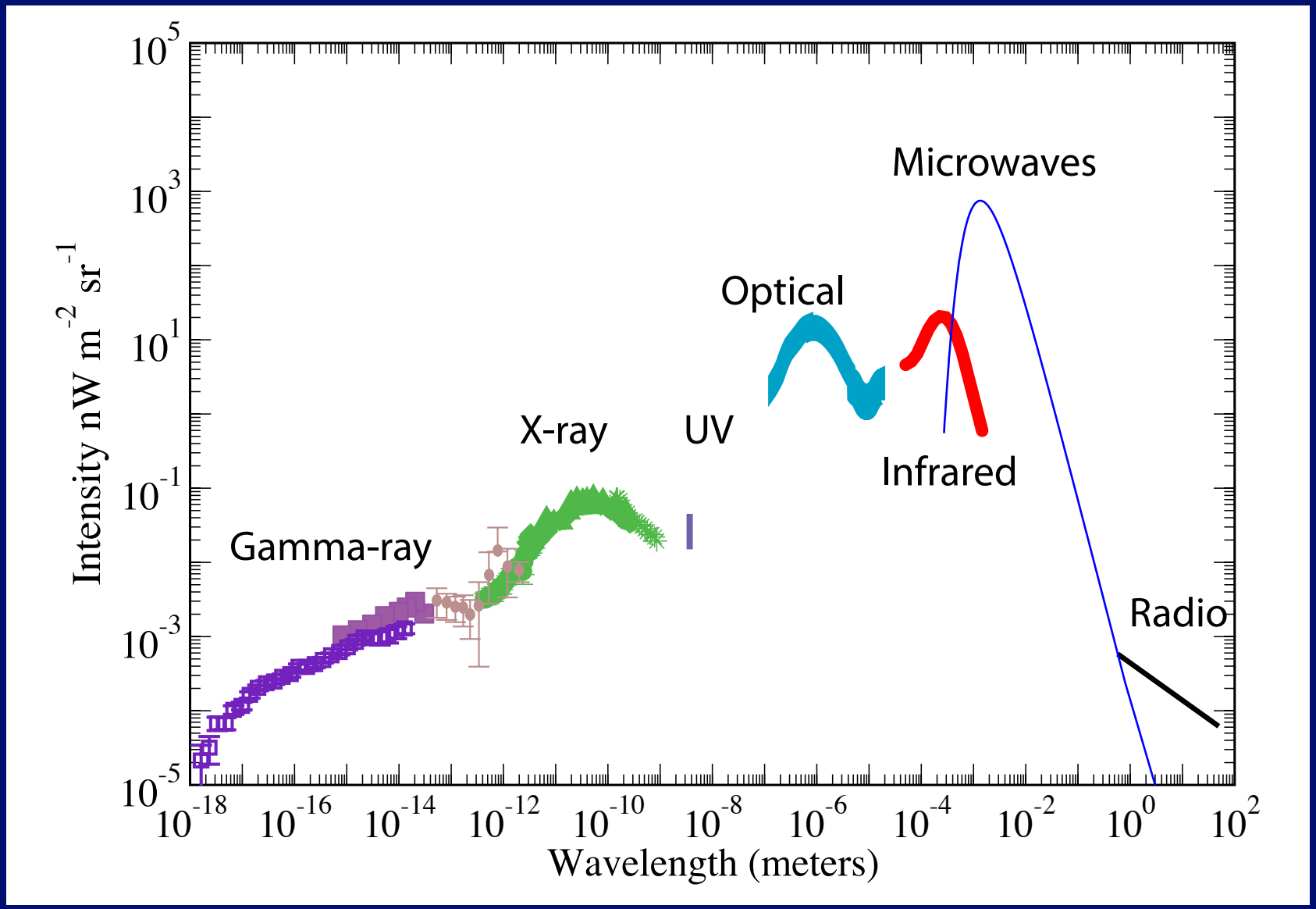
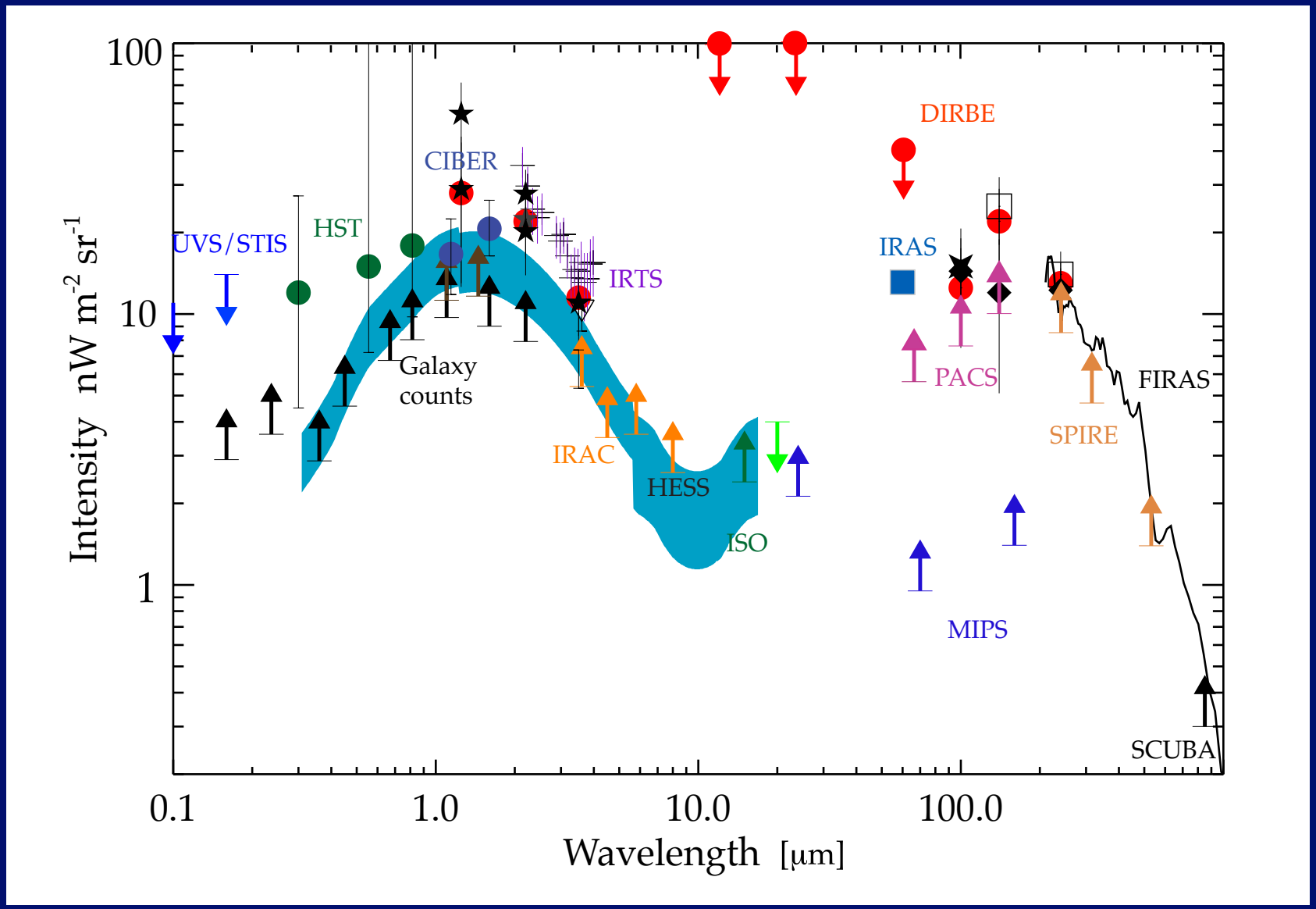
- Far-Infrared Background
- Dusty galaxies and their role in galaxy formation and evolution
- Far-IR spectroscopy as a probe of interstellar medium and AGN activity
- Review of results from Herschel Space Observatory and ALMA

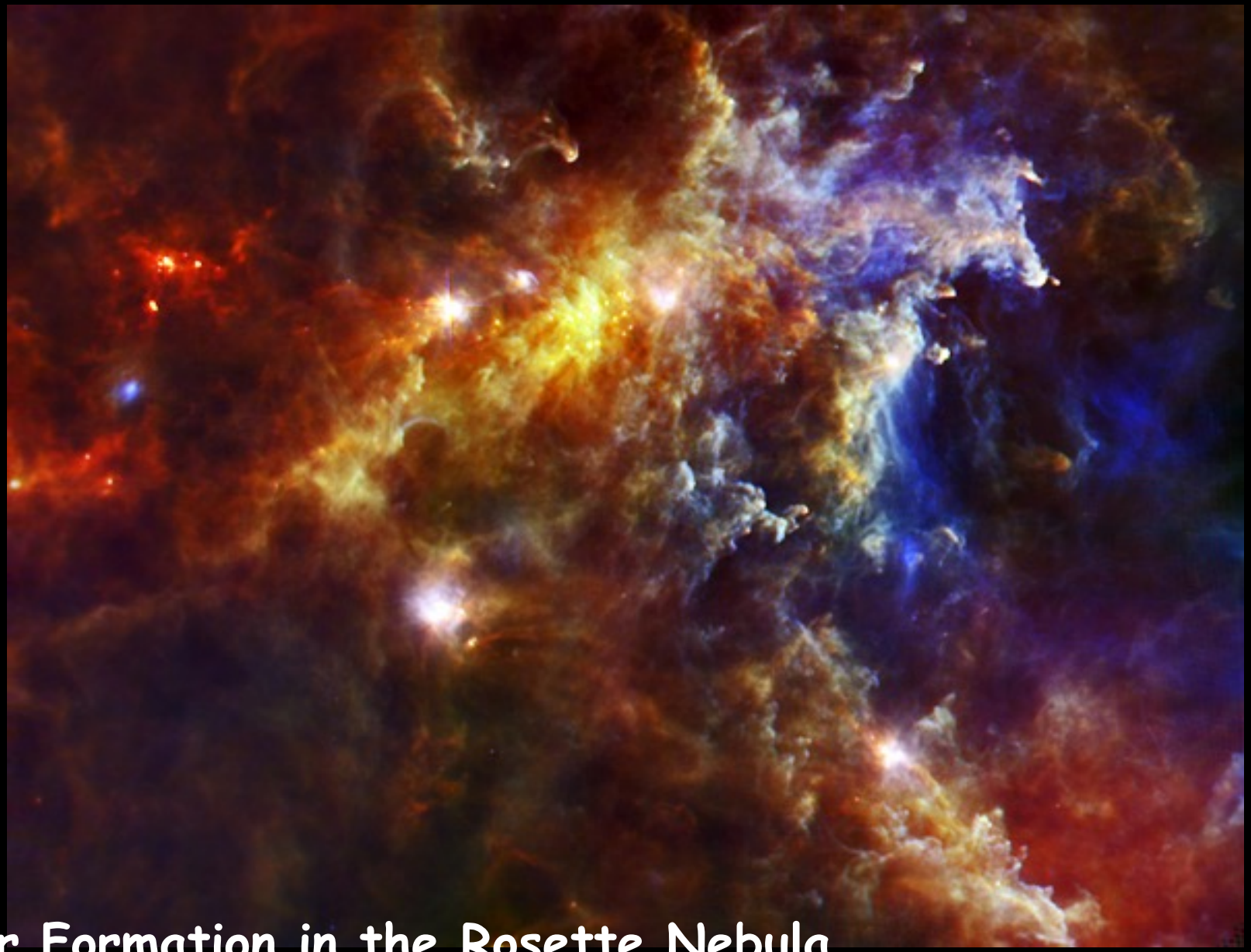
Outline



Cosmic Background Light

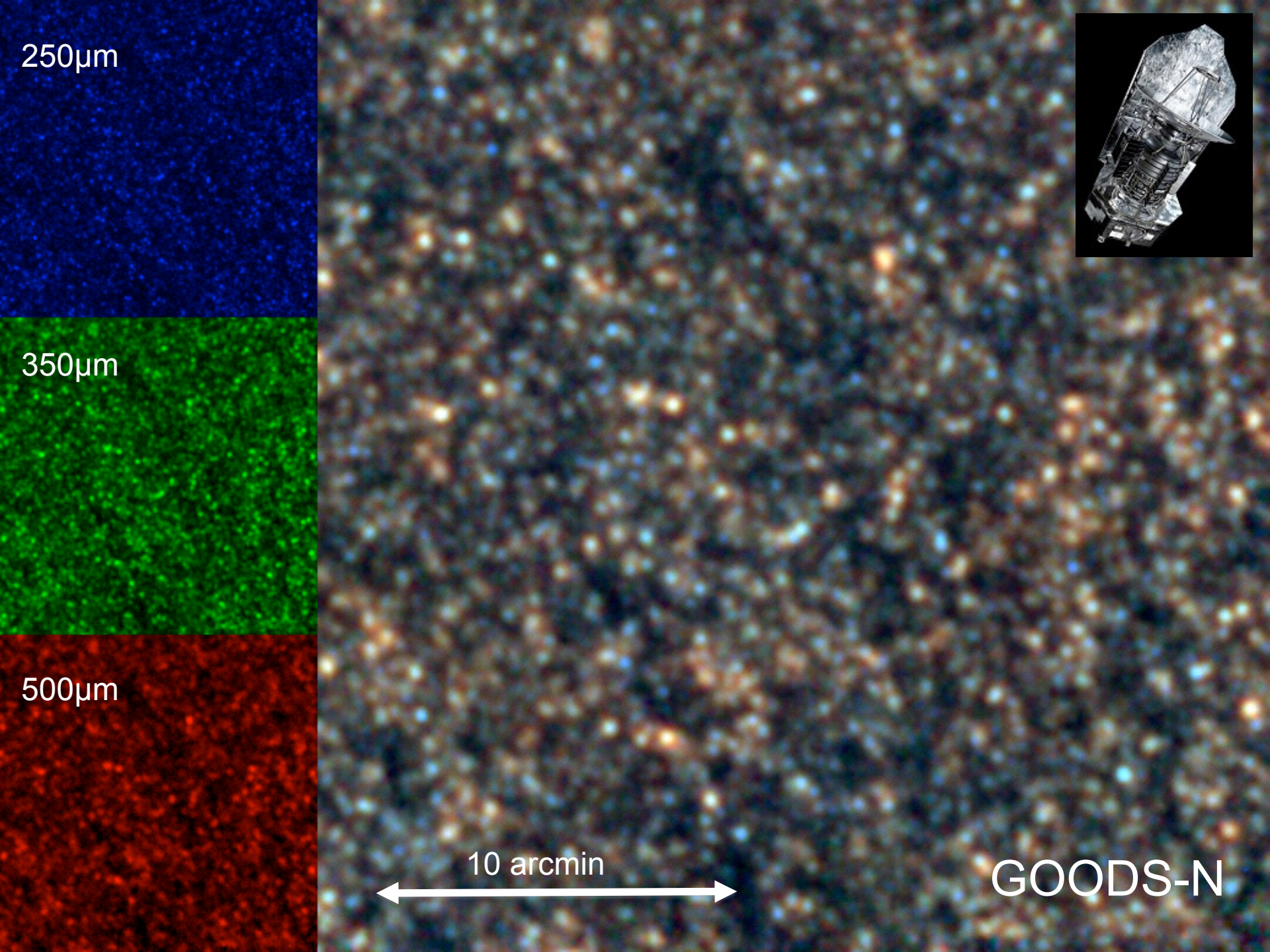


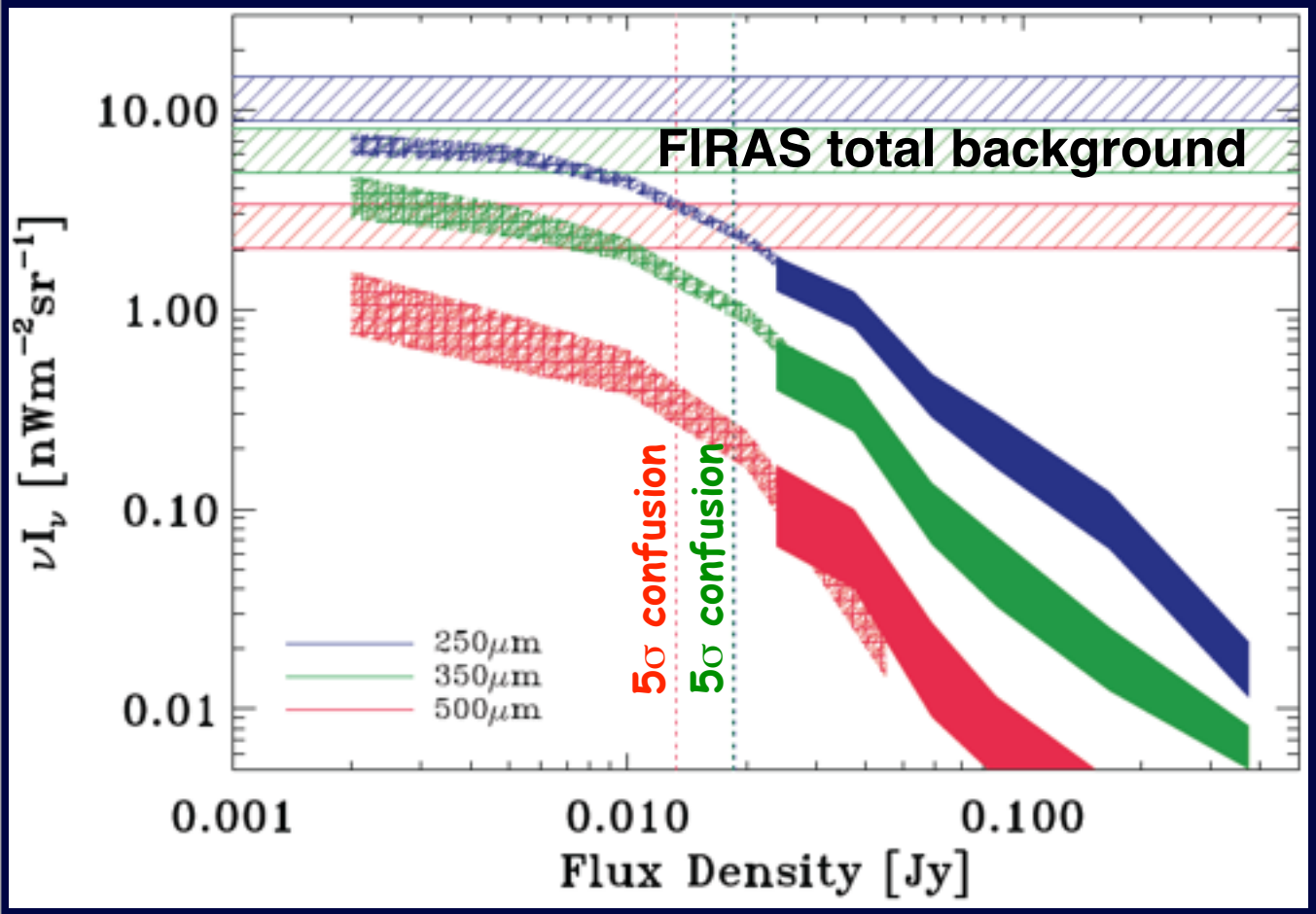
Cosmic Background Light



Star Formation in the Rosette Nebula

PACS 70 & 160 um + SPIRE 250 um


250μm
350μm
500μm
10 arcmin
GOODS-N



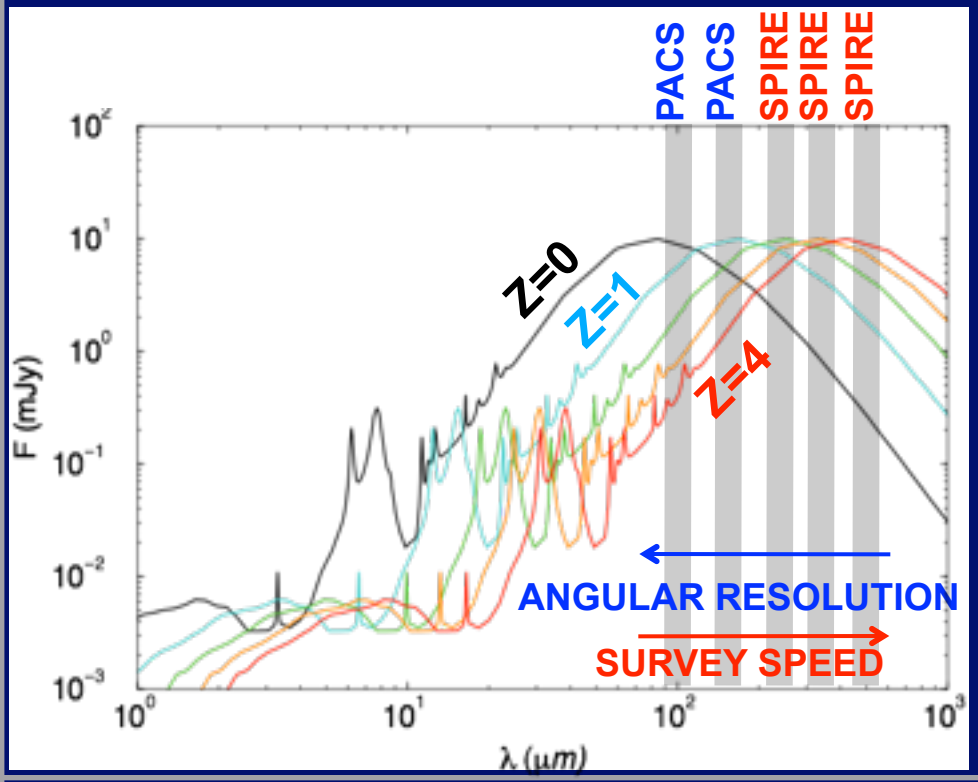
- Source Counts
  250, 350, 500 μm
  15%, 10%, 6%
- P(D)
  250, 350, 500 μm
  65%, 60%, 45%
- Stacking:
  250, 350, 500 μm
  80%, 80%, 85%

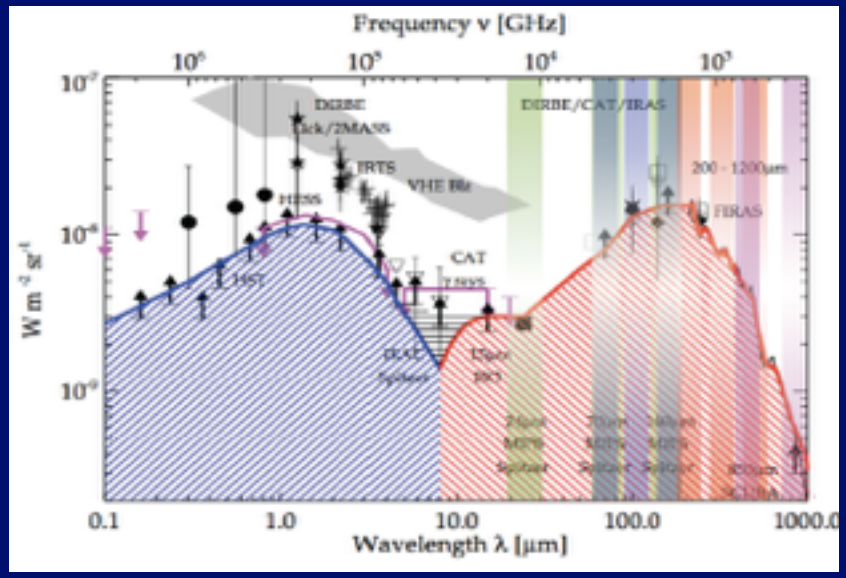
<u>Of course</u>: The remainder are the most interesting sources!
E.g. z > 3 galaxy populations

Resolving the extragalactic background spectrum

Unsolved problems in far-infrared astronomy?

- How do dusty, starburst galaxies assemble?
- Where are luminous infrared galaxies today?
- How do starbursts relate to dark matter?
- What is the role of dust in star formation?
- What is the connection between dusty star formation and AGNs?

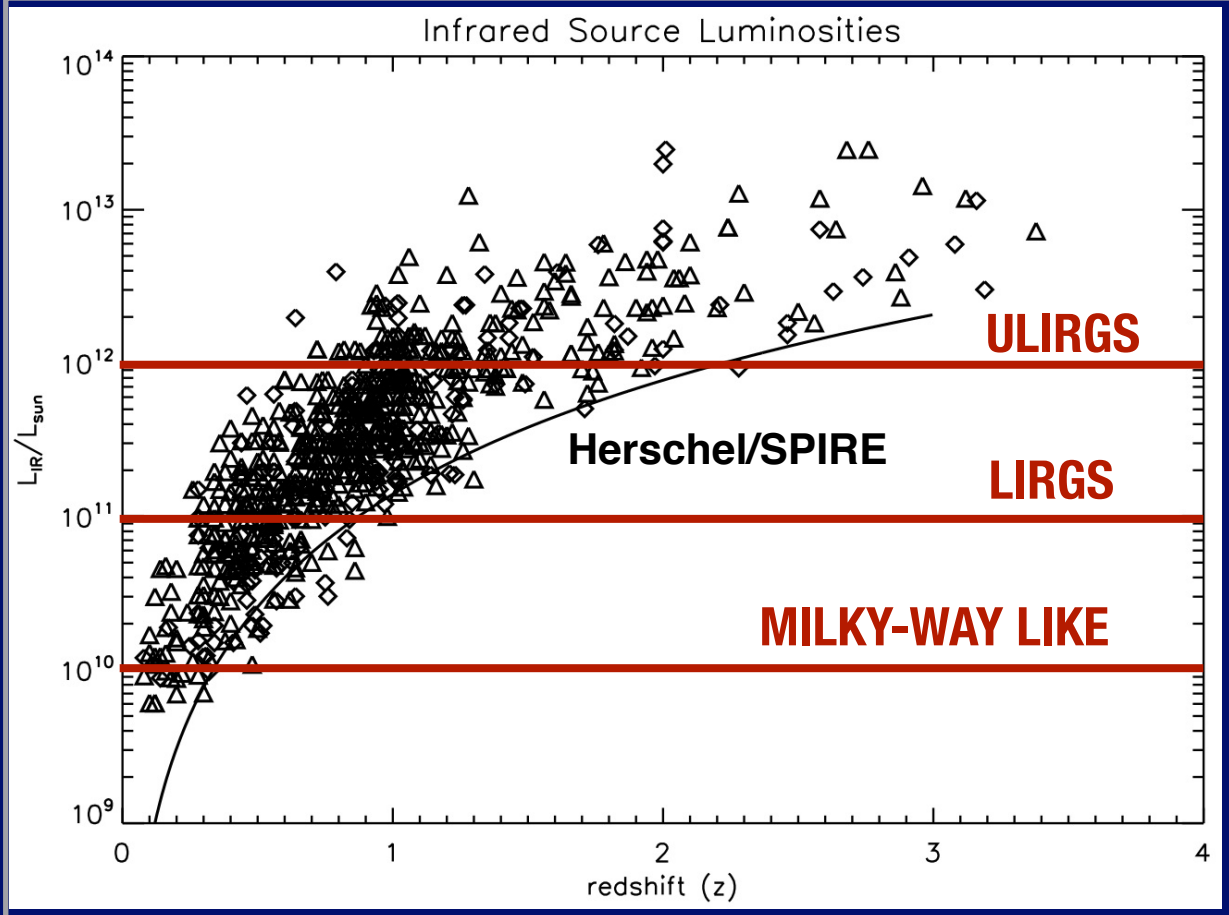




Herschel Extragalactic Surveys
- Observe at SED peak
- Bolometric far-IR luminosities
- Large and uniform samples

Herschel Science Motivation

HERMES INFORMATION ON THE WEB: HERMES.SUSSEX.AC.UK AND HERSCHEL.UCI.EDU



2000

200

20

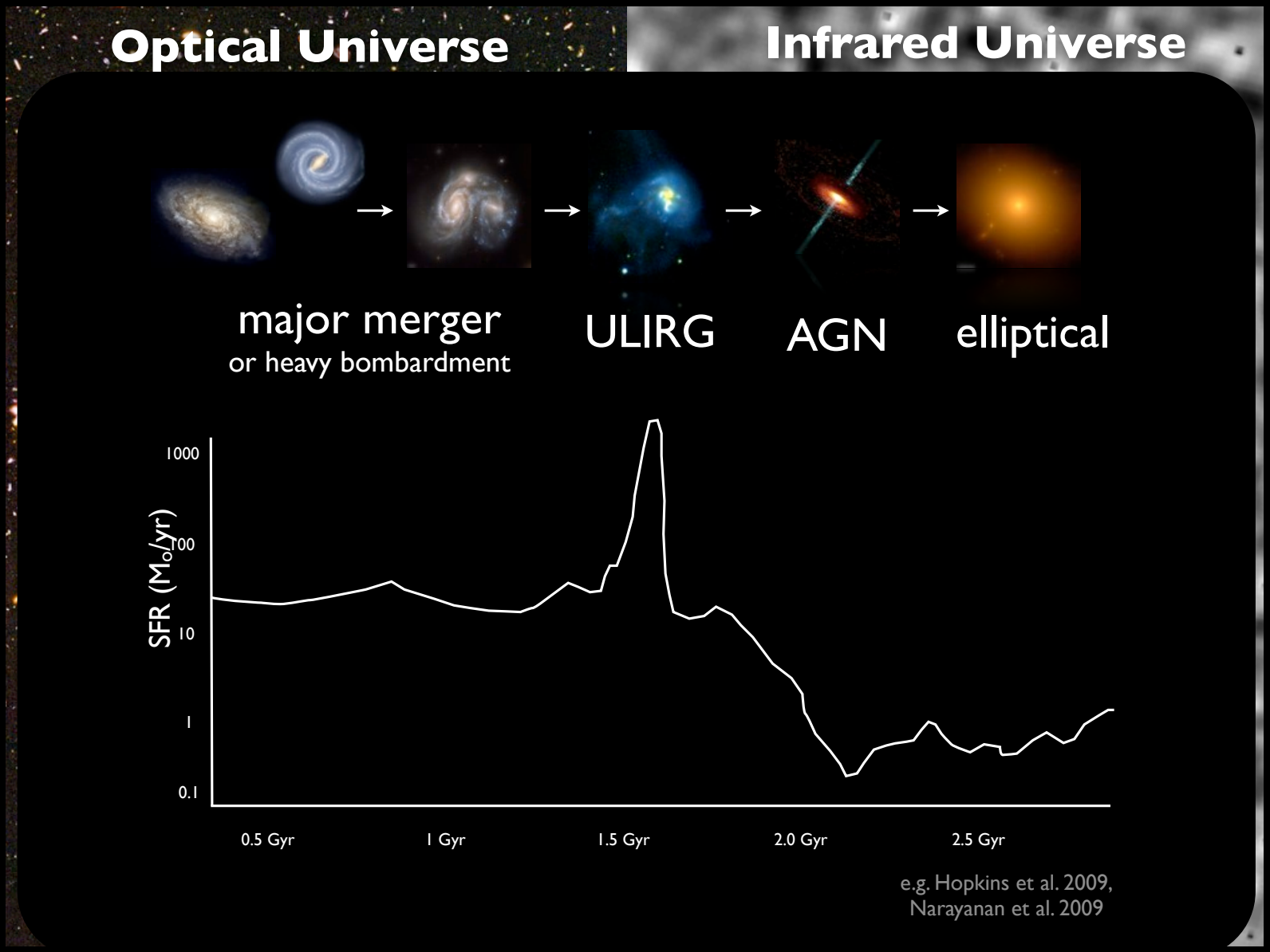
2 (~Milky-way SFR)

Star-Formation Rate in solar masses per year

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

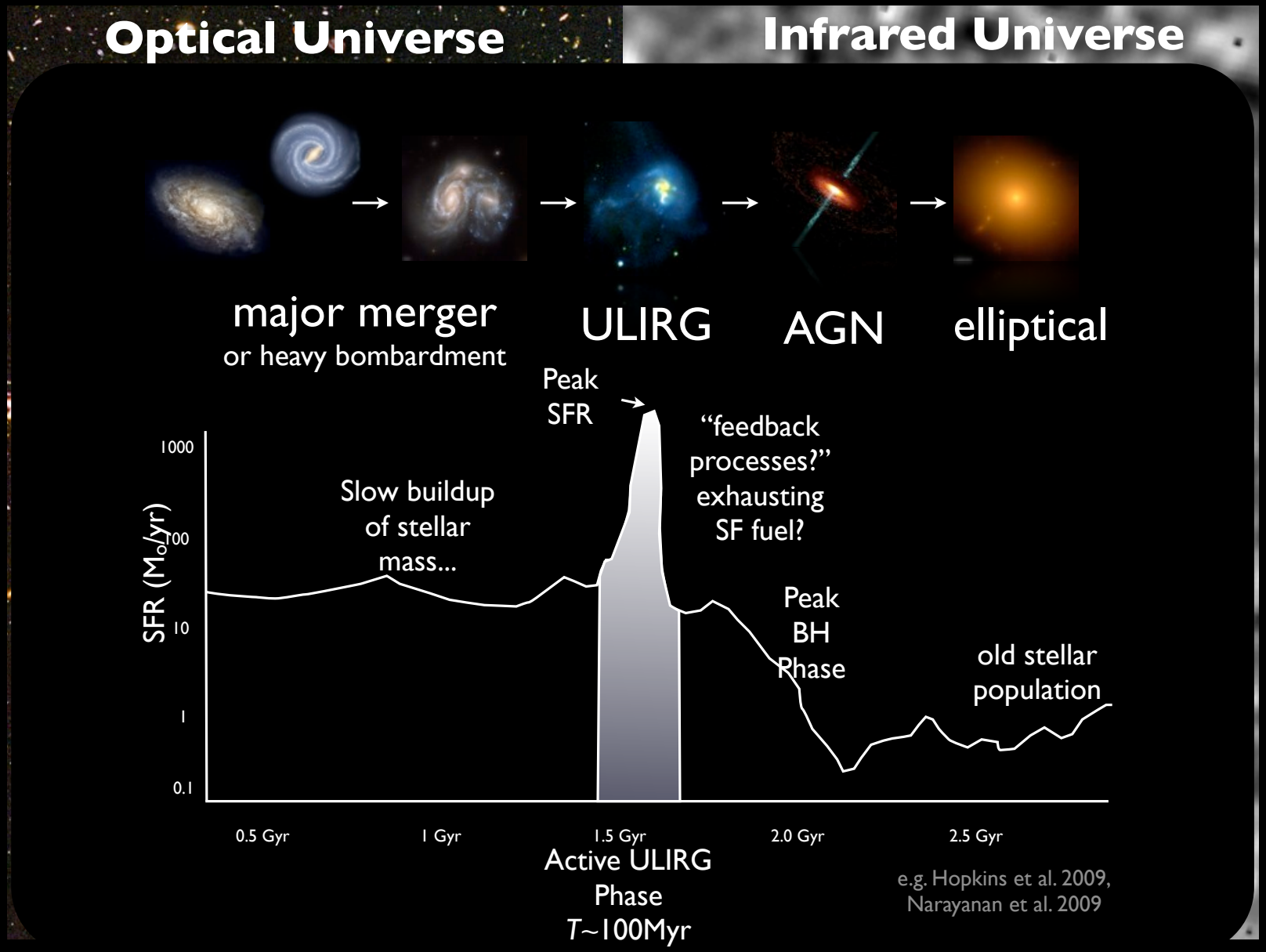
(ii) So the time scale for star-formation is $[M_*/(dM_*/dt)]$ ~ 100 Million years

What kind of galaxies did we detect with Herschel?



What are Dusty Star Forming Galaxies?

Illustration from Caitlin Casey

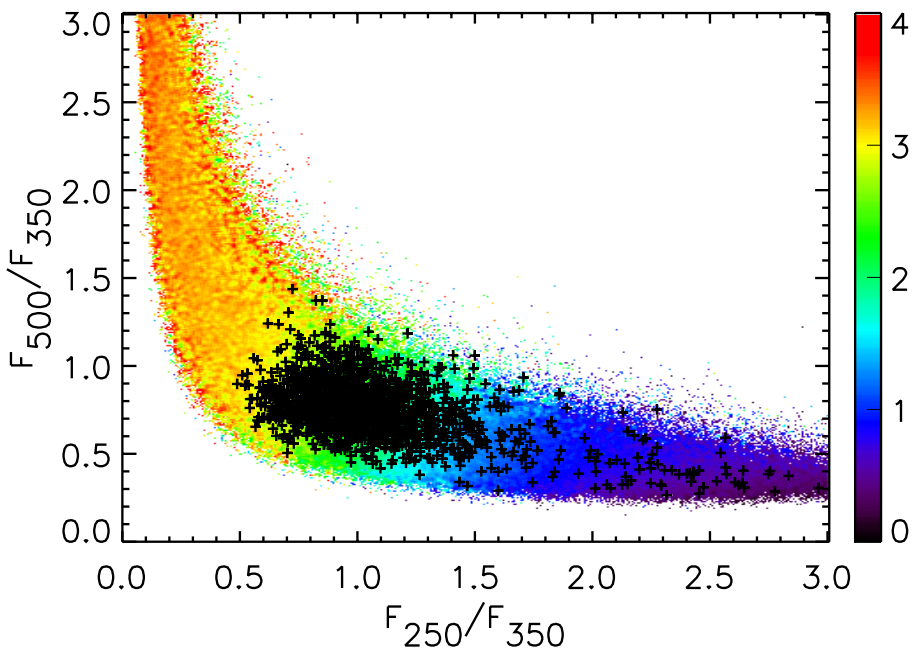


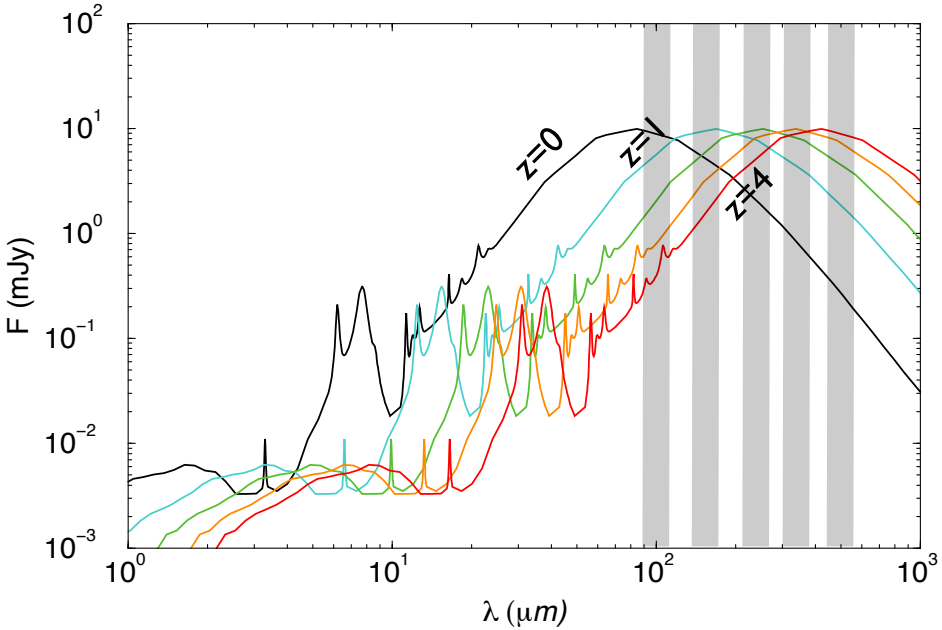
What are Dusty Star Forming Galaxies?

Illustration from Caitlin Casey

Redshift distribution of SPIRE Sources?

Alex Amblard et al. 2010
(ex-UCI postdoc; now NASA Ames)





The surface density of 350 μm selected sources (z~1.8 to 3) $S_{350} > 20$ mJy is ~800/deg^2

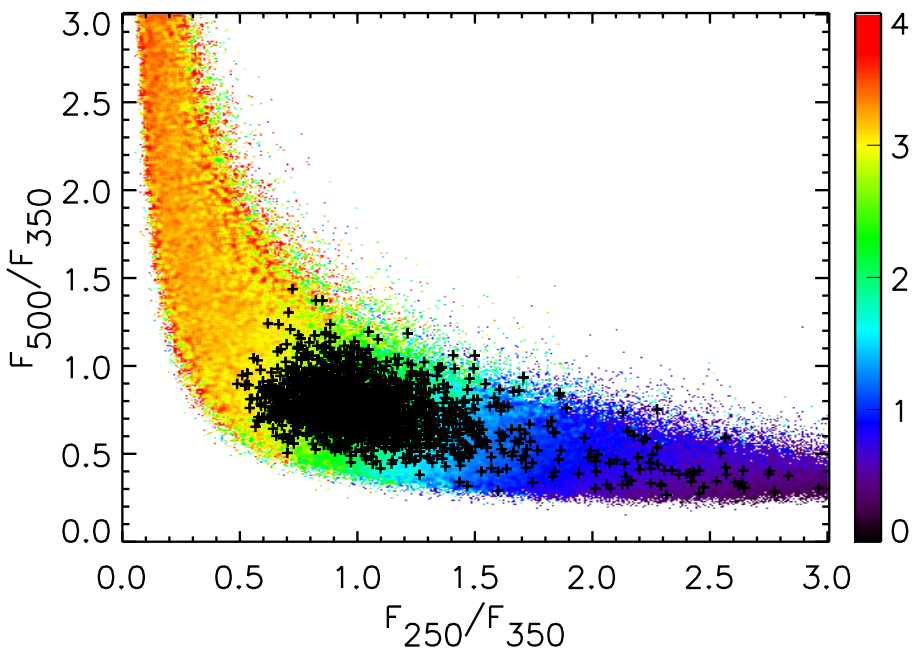
Naive expectation based on the SED:
$S_{250} > S_{350} > S_{500}$: z < 2
$S_{250} <\sim S_{350} > S_{500}$: z ~ 2 to 3
$S_{250} < S_{350} < S_{500}$: z > 4

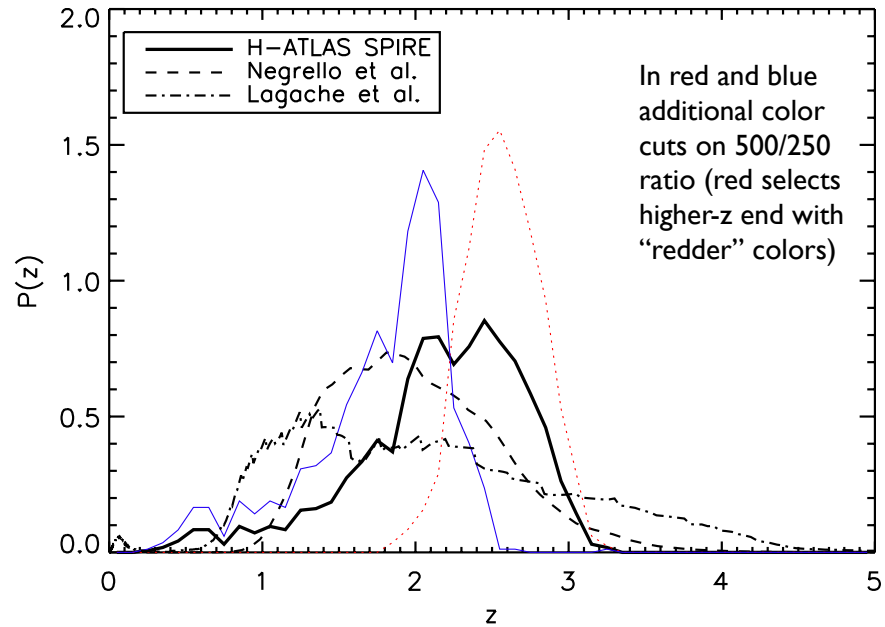
Amblard et al. 2010

sub-mm colors as a mechanism to select z > 2 galaxies

Redshift distribution of SPIRE Sources?

350μm selected galaxies > 5σ are at mostly at z = 2.2 ± 0.6





The "statistical" redshift distribution implied by SPIRE colors for the 1686 sources

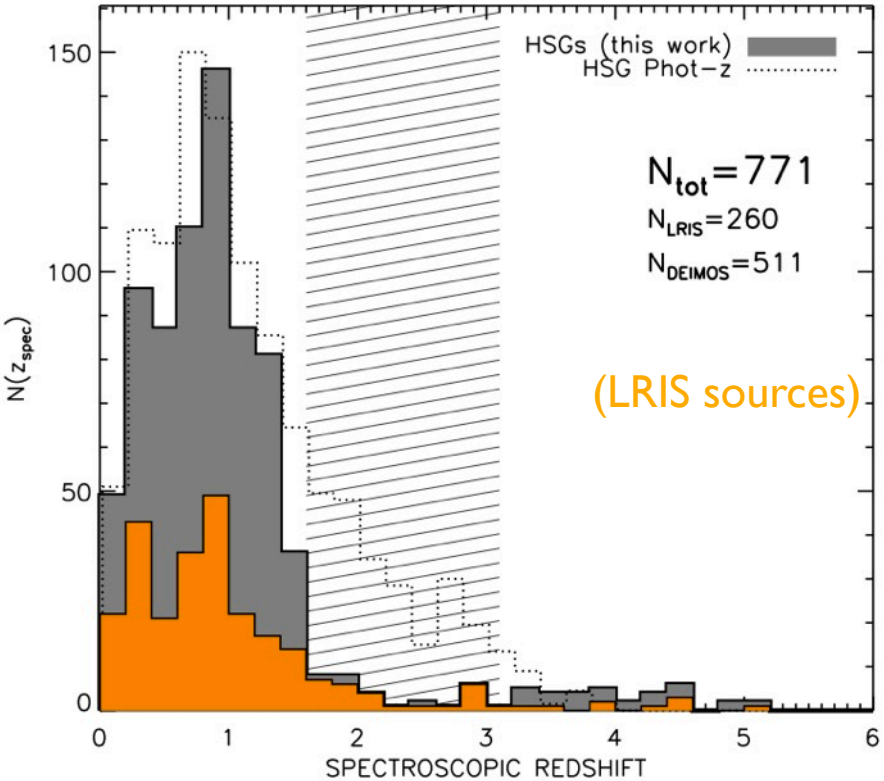
[equivalent to fitting each SED with a single-temp model and marginalizing over T,β] *(Hughes et al 2002; Aretxaga et al. 2007)*

The surface density of 350 μm selected sources (z~1.8 to 3) S_{350} > 20 mJy is ~800/deg^2

Amblard et al. 2010

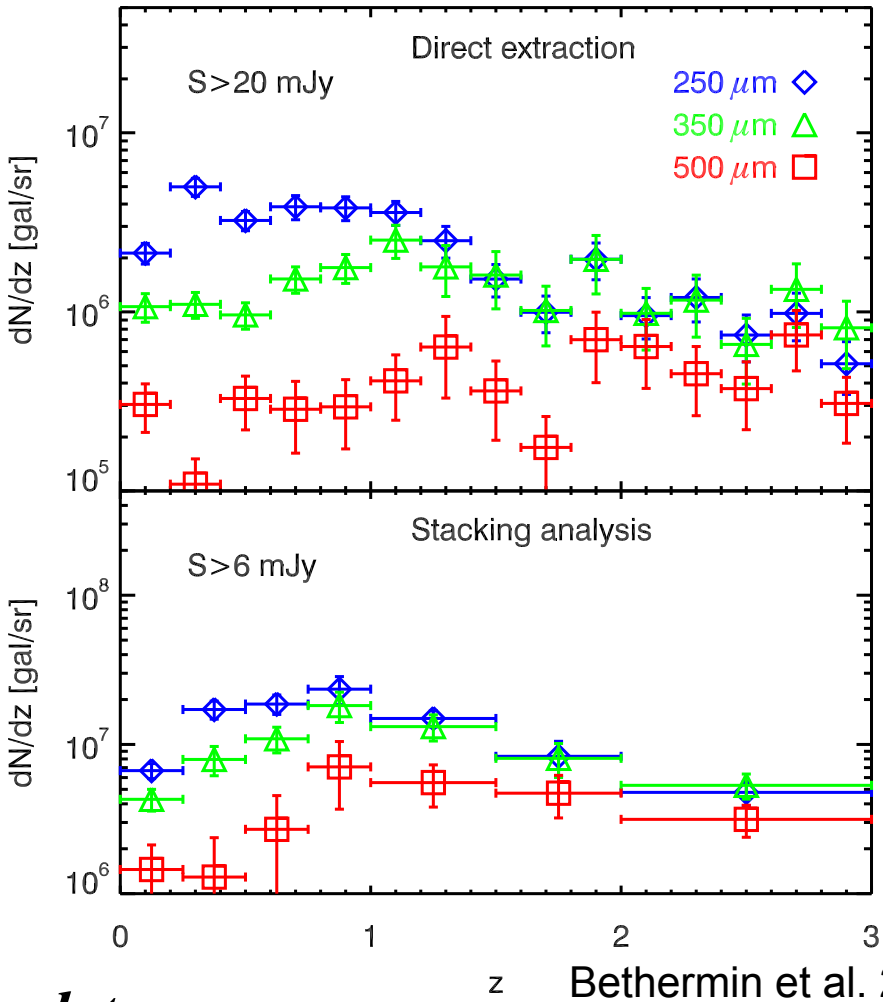
Redshift distribution of SPIRE Sources?

Caitlin Casey et al. 2012 (ex-UCI postdoc; UT Austin faculty)



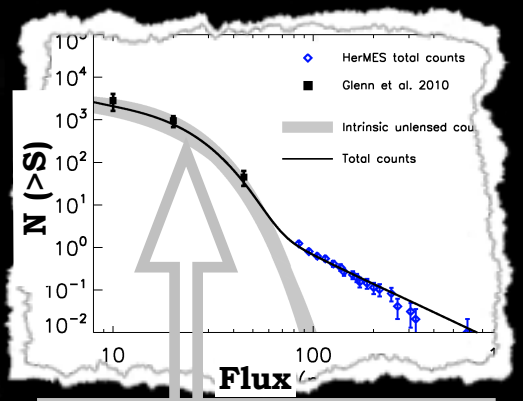
Keck LRIS/DEIMOS followup.
z peak is around z~1 (250 micron dominated)

~1000 redshifts in the optical



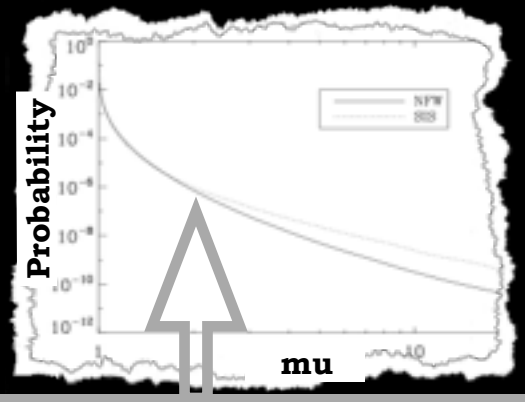
Bethermin et al. 2012

Redshift gap; z > 1.5 highly incomplete.



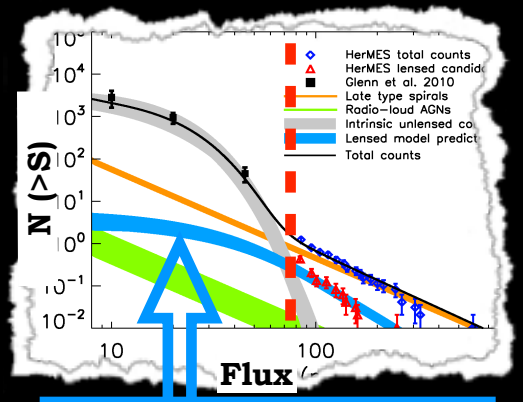
Intrinsic Source Count

⊗



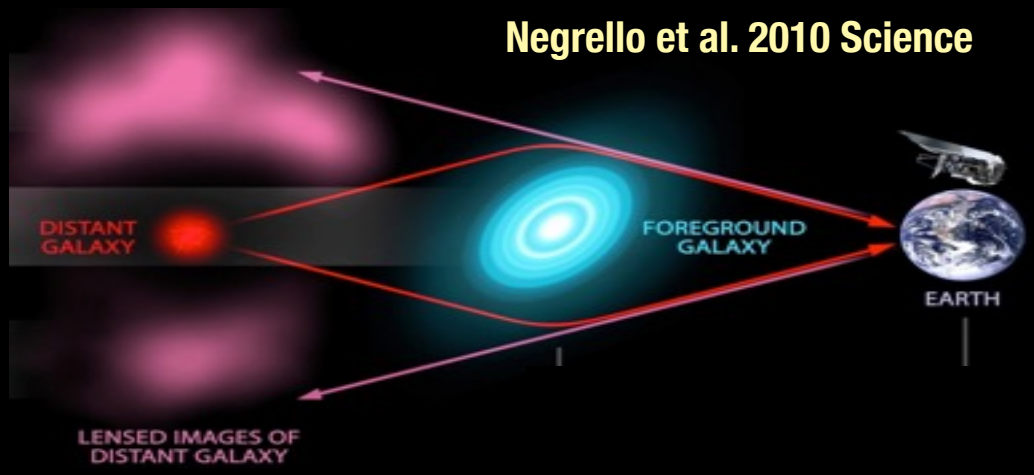
Magnification Cross Section

=



Lensed Source Count

Negrello et al. 2010 Science

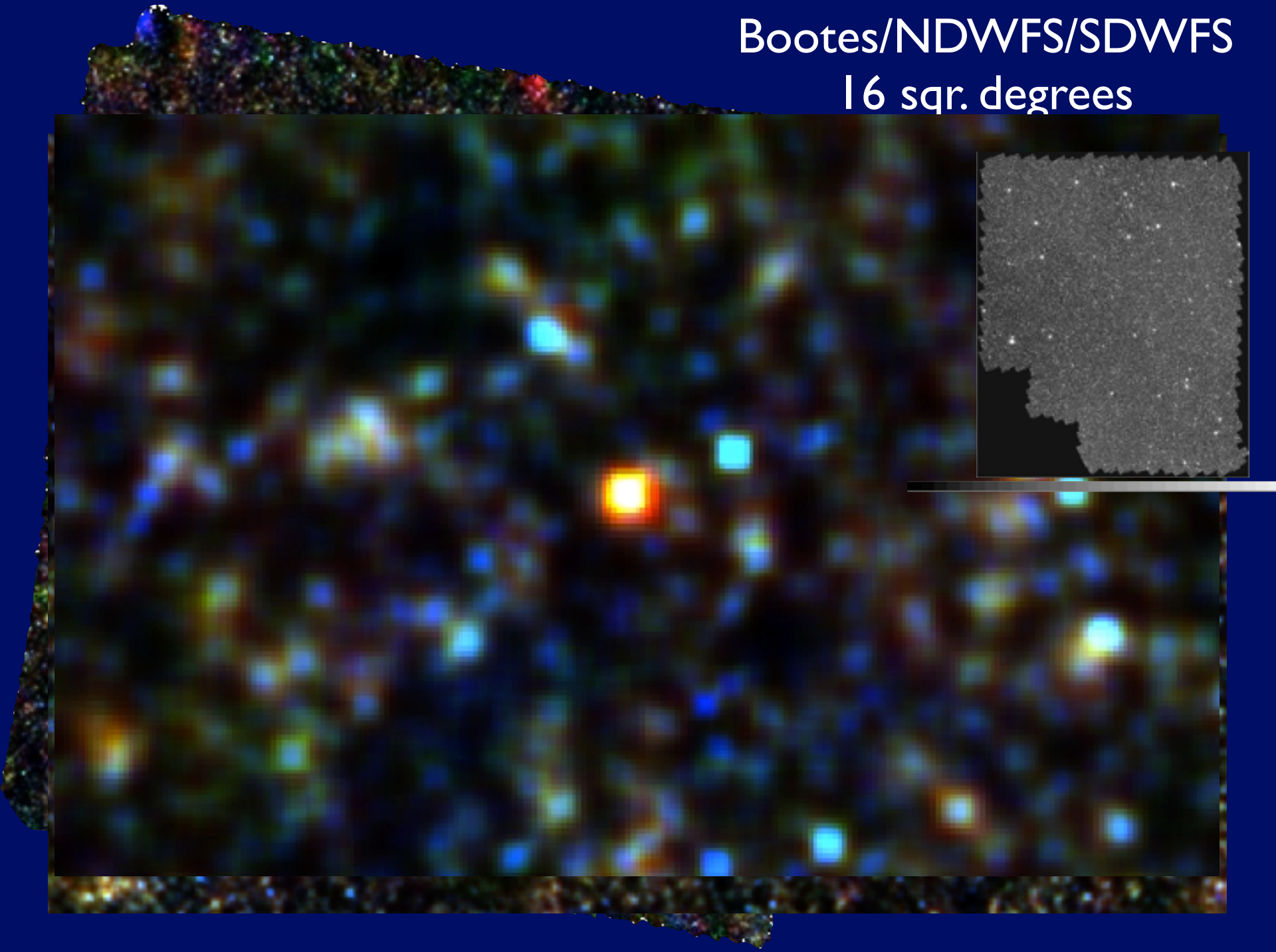


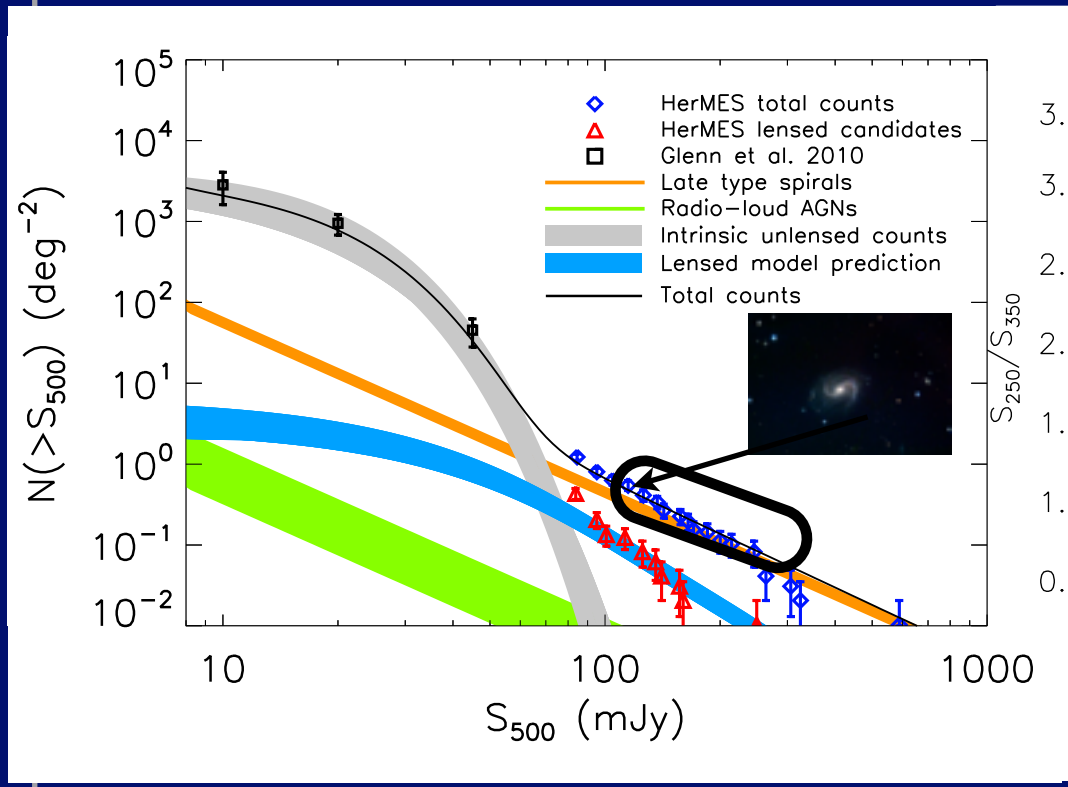
Julie Wardlow et al. 2013, ApJ
(UCI ex-postdoc; Durham lecturer)

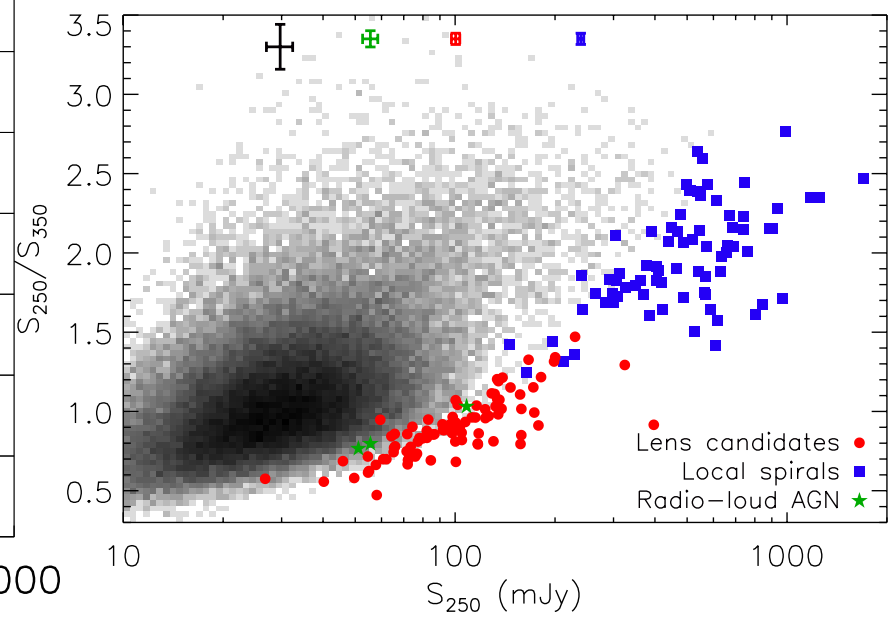
Lensing galaxy selection at sub-mm wavelengths > 95% efficient

The Nature of Brightest high-z Herschel Galaxies

Bootes/NDWFS/SDWFS
16 sqr. degrees





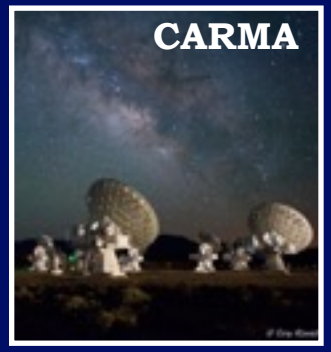


- Lensing: Flux boosted (magnified)
- Can study fainter objects than usually available.
- Can study spatial distribution of gas, dust, stars at higher resolution than with normal galaxies at the same distances.

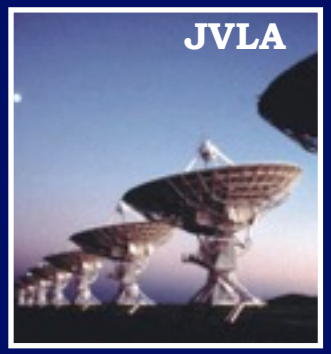
The Nature of Brightest high-z Herschel Galaxies

Negrello et al. 2010 Science; Wardlow et al. 2012, ApJ; Bussman et al. 2012 ApJ

Source CO Redshift



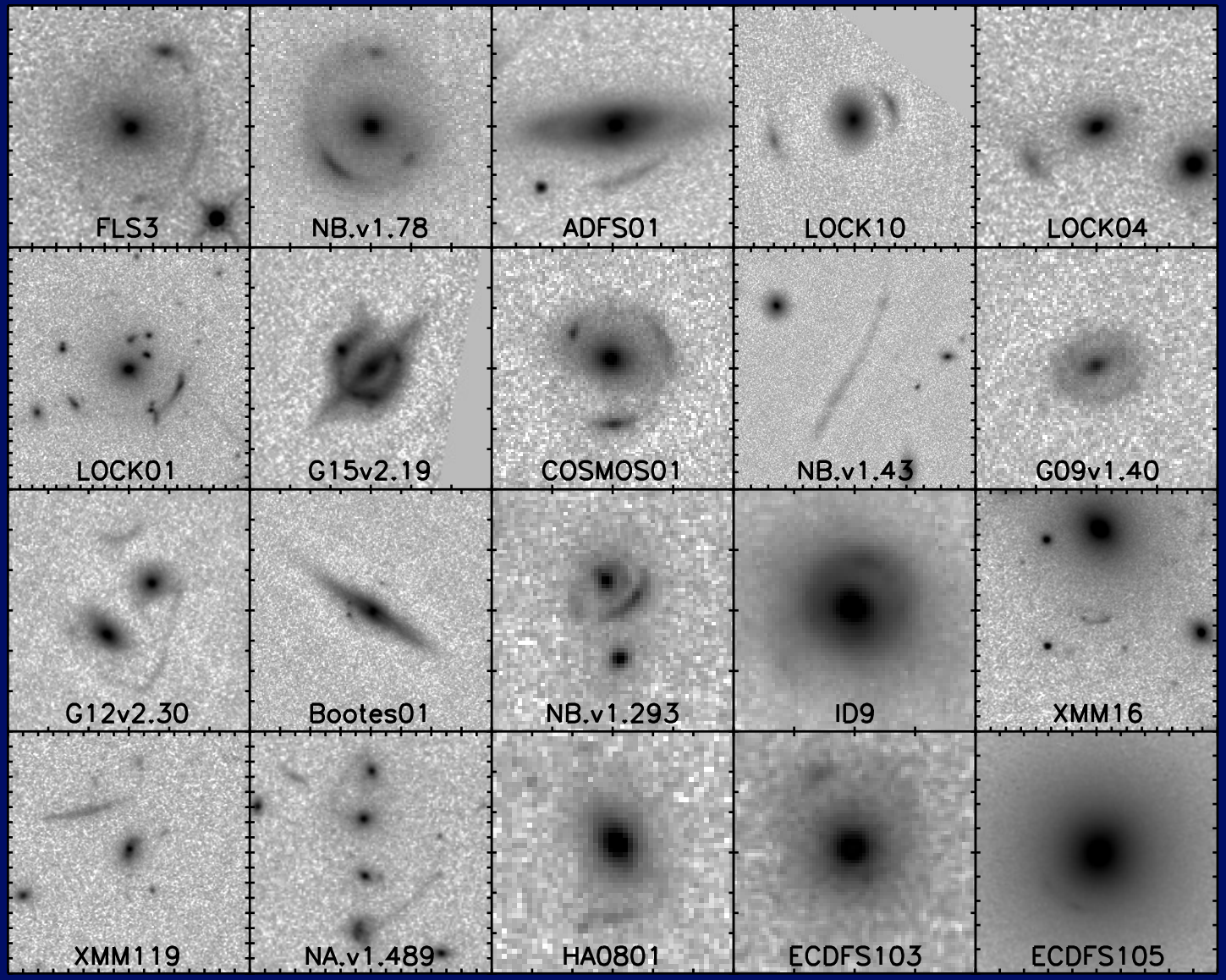
High-Resolution Imaging



Extensive Ground-based Follow-up Observations

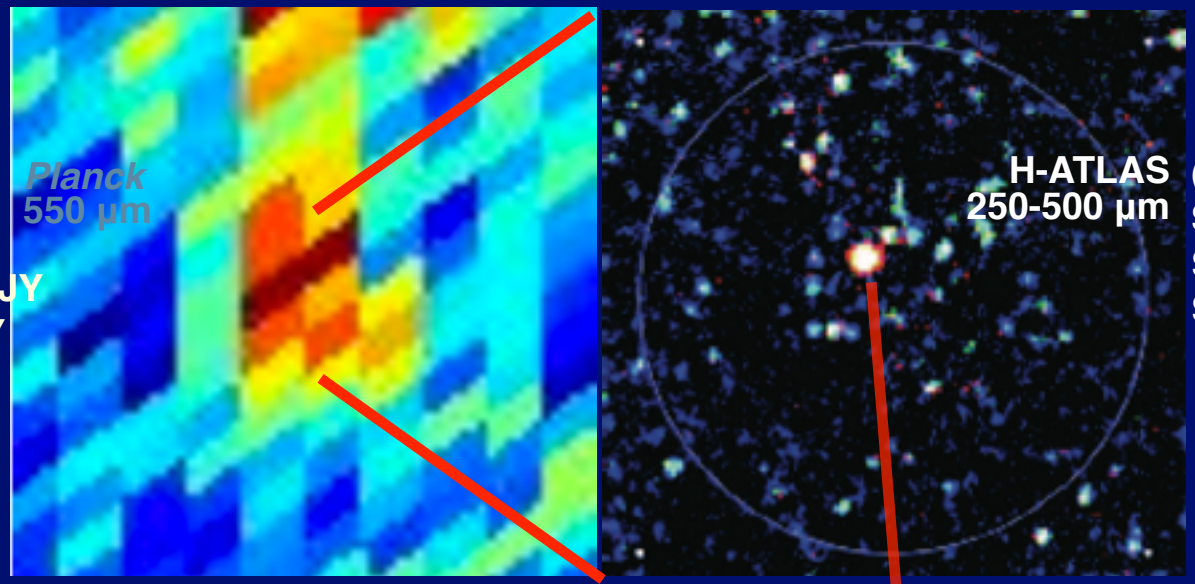
Jae Calanog
UCI PhD 2014

We now have 100 images like these in total with Keck/LGS AO/HST



Keck LGS-AO Imaging

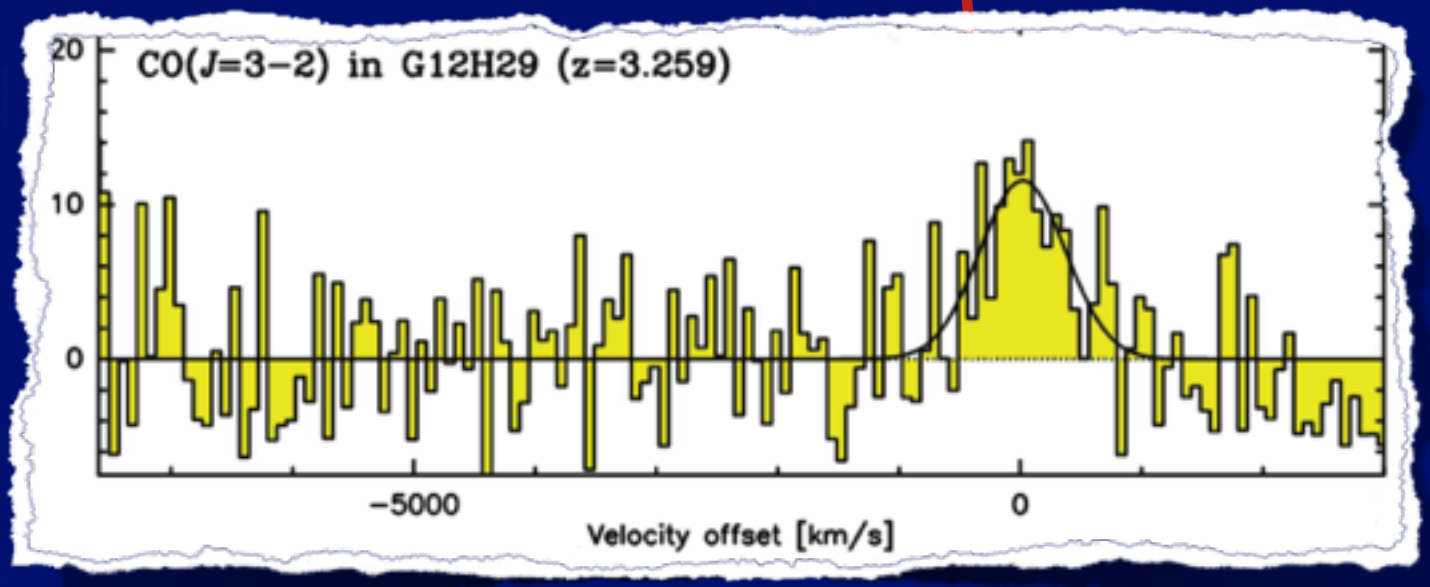
Fu et al. 2012; Bussmann et al. 2012; Fu et al. 2013; Calanog et al. 2014; Timmons et al. 2015



S_{550} = 1.07 ± 0.12 JY
S_{350} = 1.1 ± 0.2 JY

(brightest source)
S_{250} = 320 ± 20 mJy
S_{350} = 380 ± 60 mJy
S_{500} = 300 ± 20 mJy

Z_{CO} = 3.26



A lensed Planck source resolved by Herschel (in ATLAS)

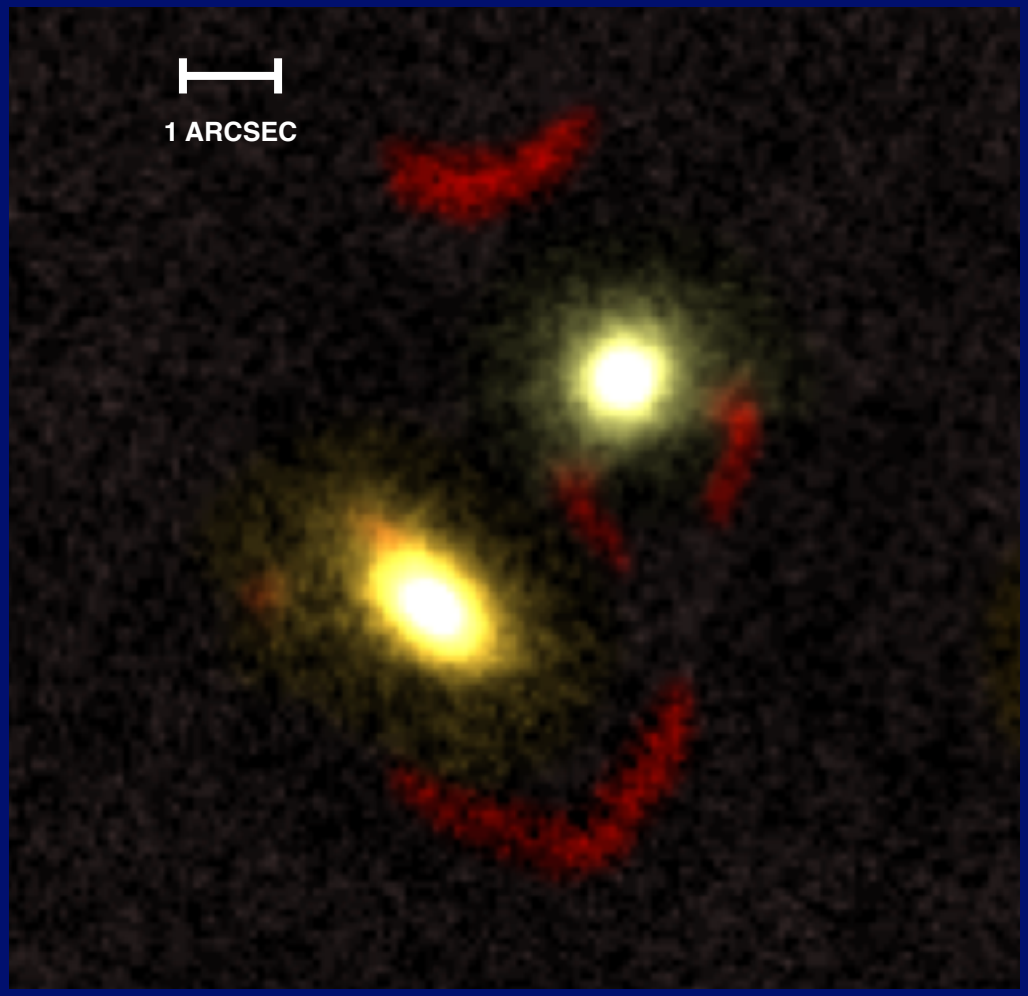
Fu, Hai et al. 2012, ApJ

$L_{FIR} = 1.6 \times 10^{13}\ L_\odot$
SFR ~ 1900 $M_\odot$/yr
$T_{DUST} = 62 \pm 3$ K

No evidence for AGN

$M_{DUST} = 6 \times 10^{8}\ M_\odot$
$M_{STARS} = 3 \times 10^{10}\ M_\odot$
$M_{GAS} = 7 \times 10^{10}\ M_\odot$
$M_{DYNAMICAL} = 3 \times 10^{11}\ M_\odot$

Gas-rich (70% of baryons in gas)
Young (M_{STARS}/SFR~20 Myr)
Short Star-burst (M_{GAS}/SFR~40 Myr)



Hai Fu et al. 2012, ApJ (ex-UCI postdoc; Iowa faculty)

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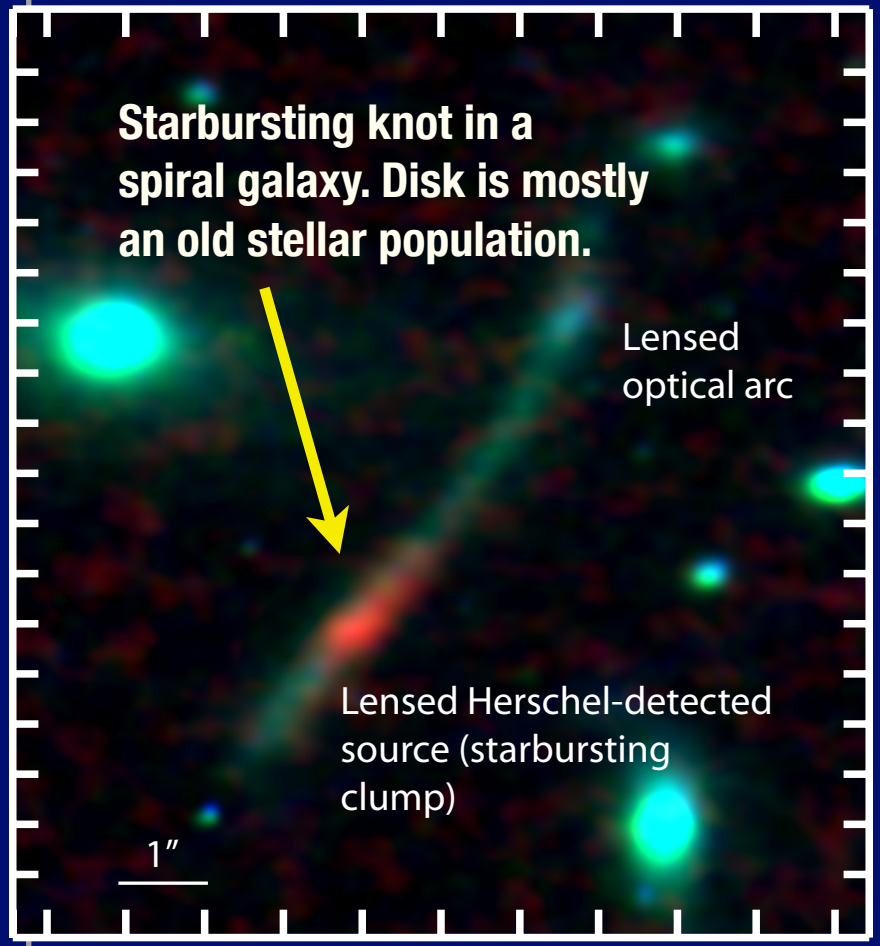
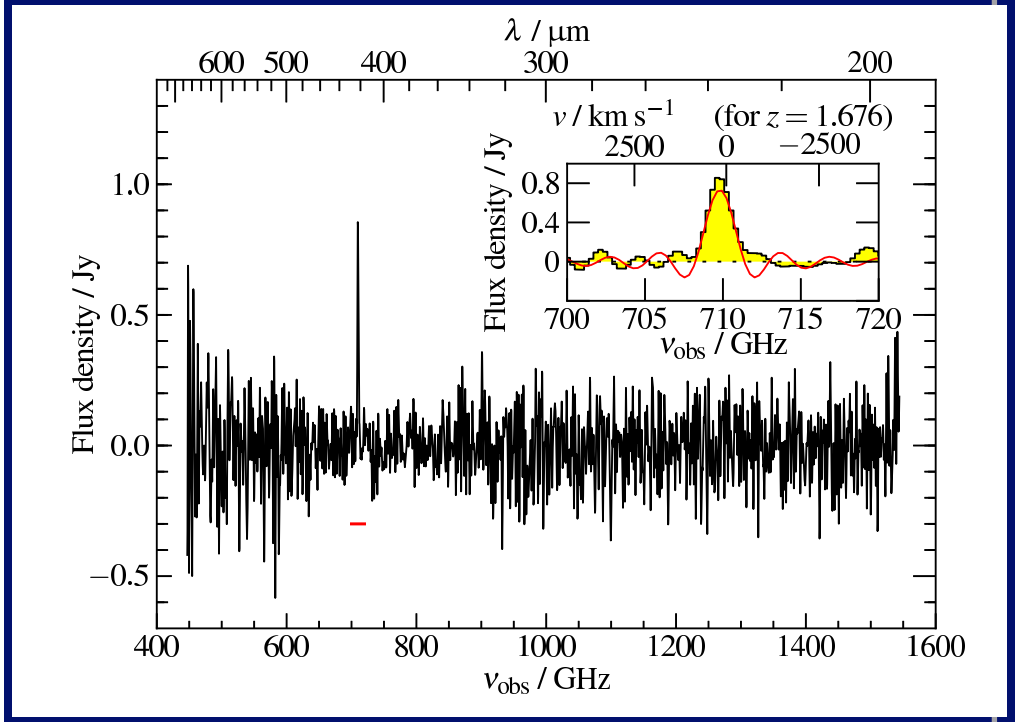
Fu, Hai et al. 2012, ApJ



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

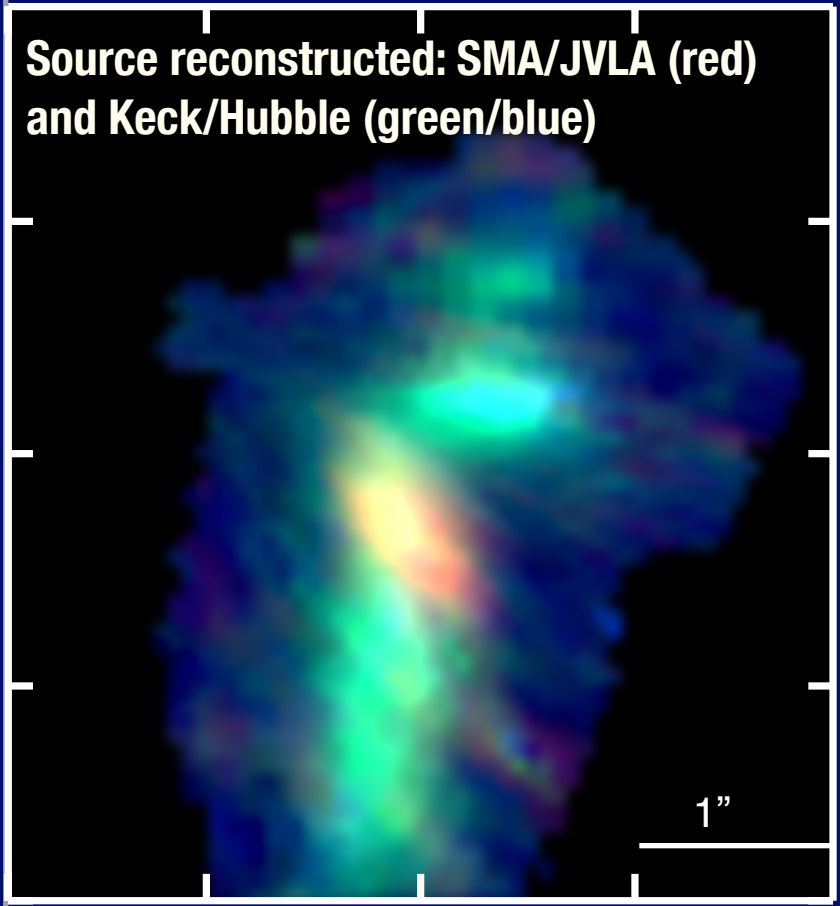


z=1.68, z determined from the Herschel-SPIRE/FTS spectrum with the 158 micron CII line

George et al. 2014; Timmons et al. 2015

Nick Timmons
UCI PhD 2017

Herschel Lensed Sources



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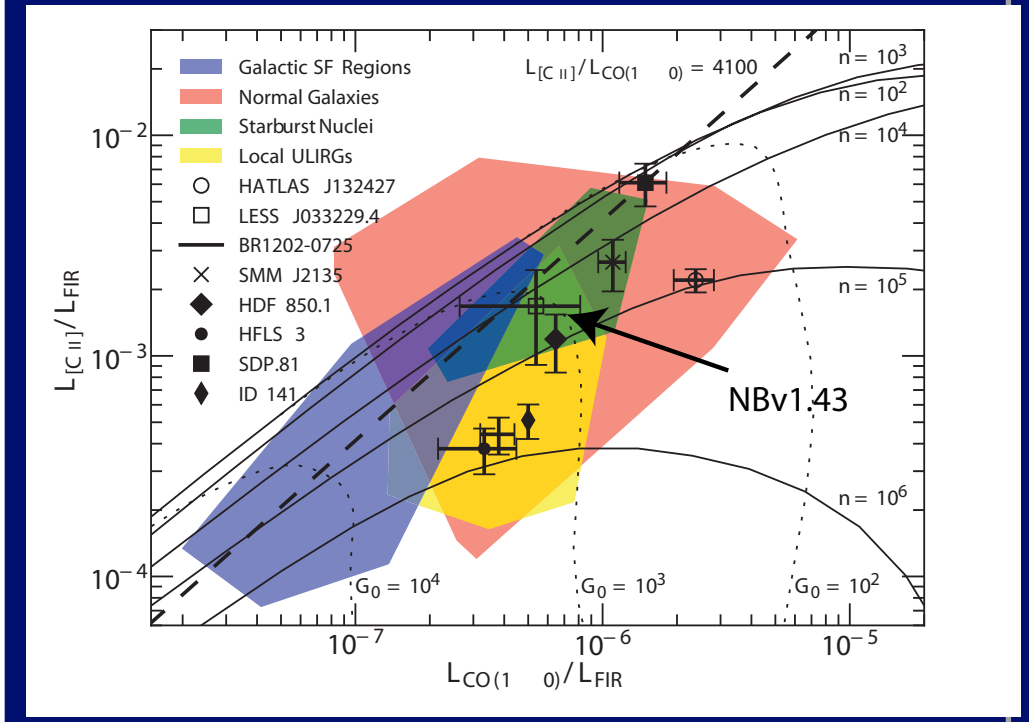

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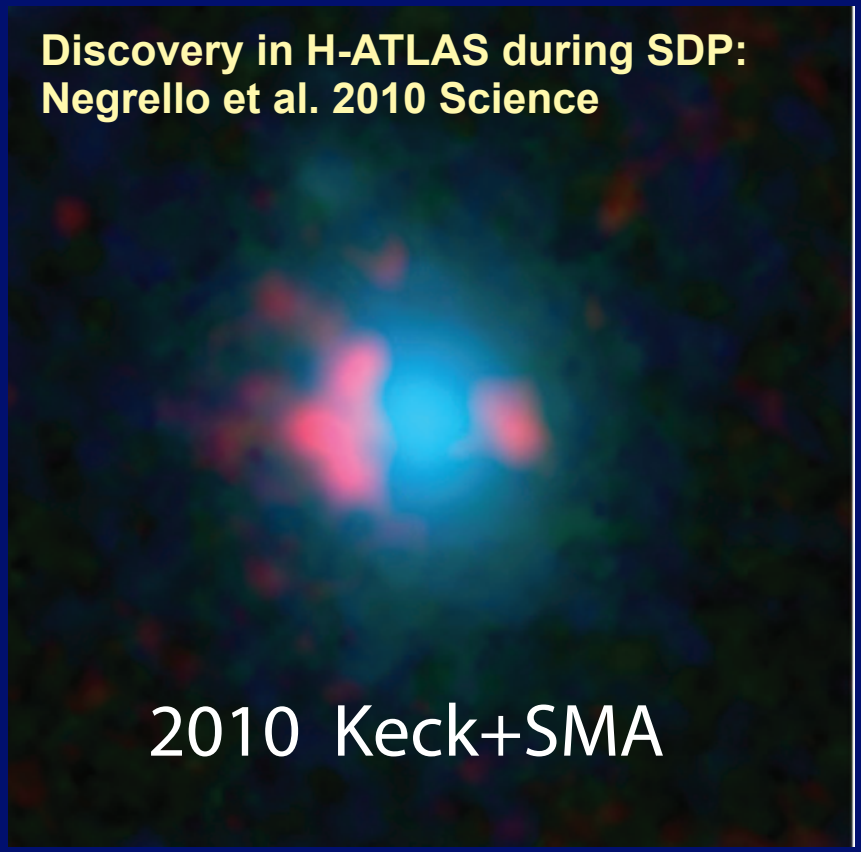
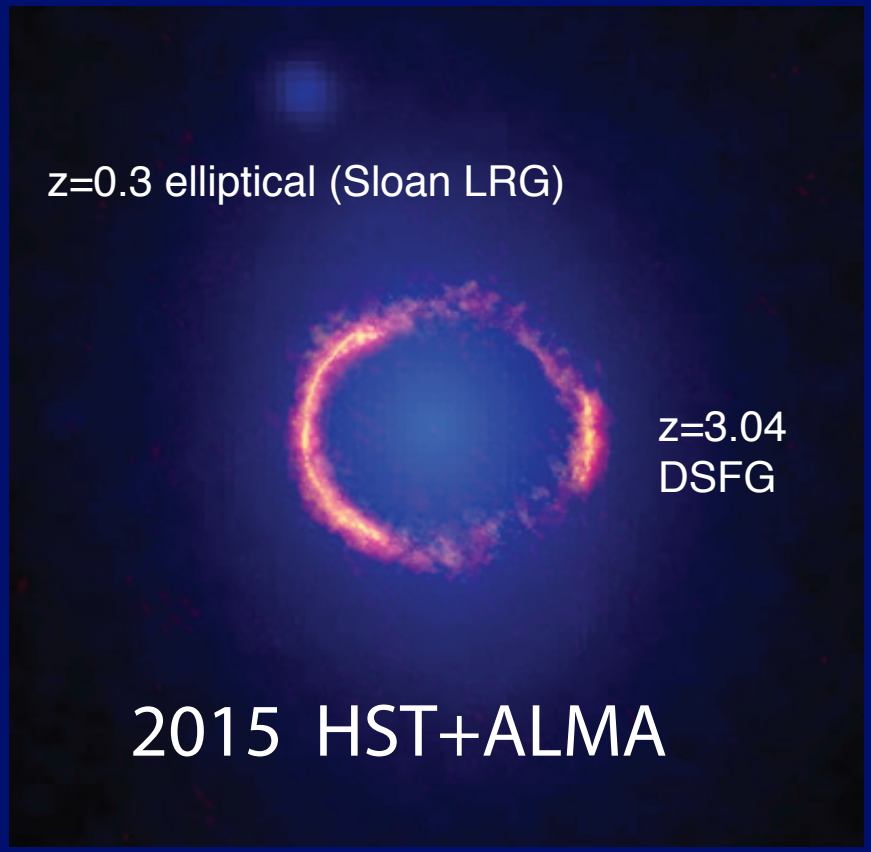
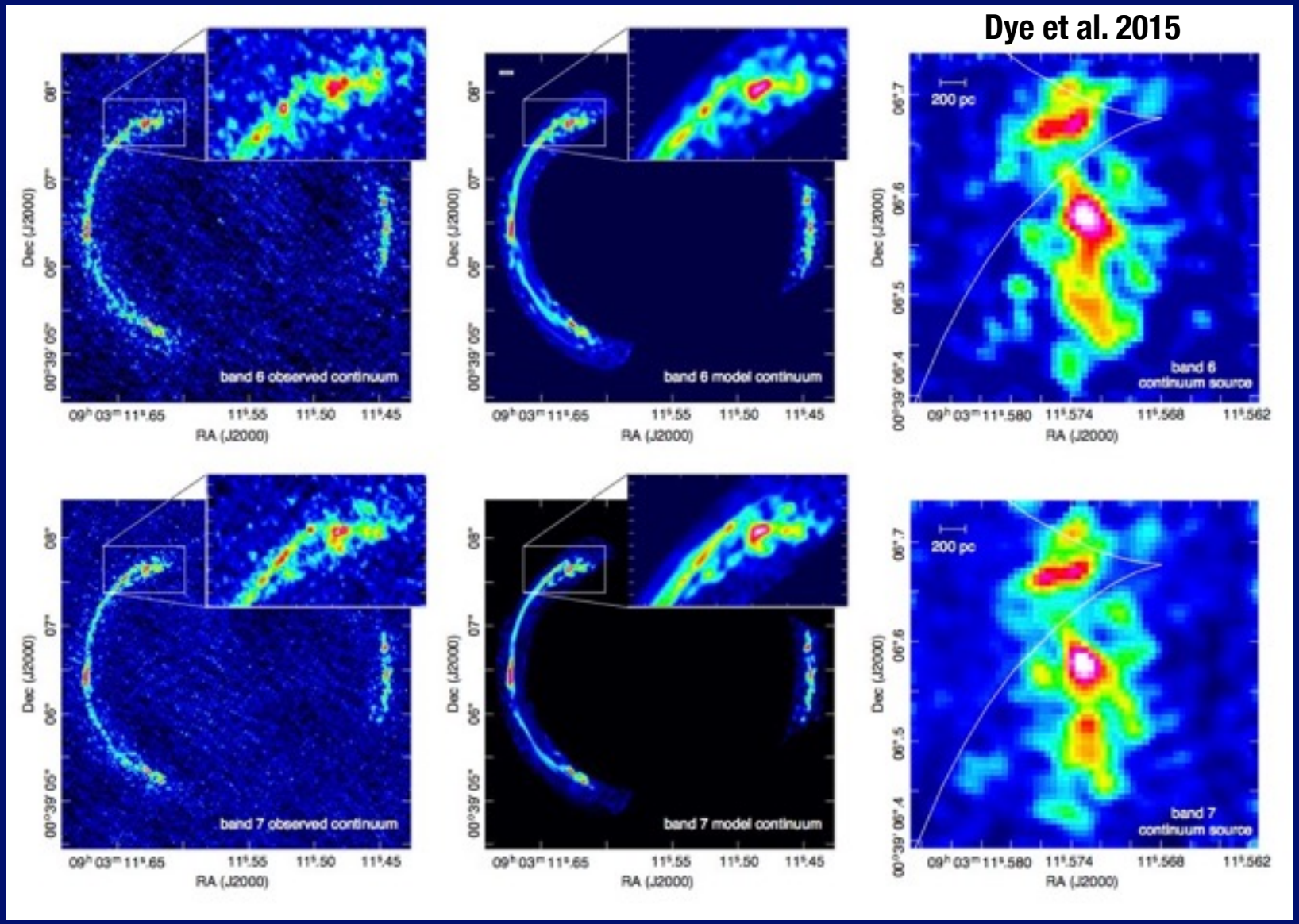
Herschel Lensed Sources


Discovery in H-ATLAS during SDP:
Negrello et al. 2010 Science
2010 Keck+SMA

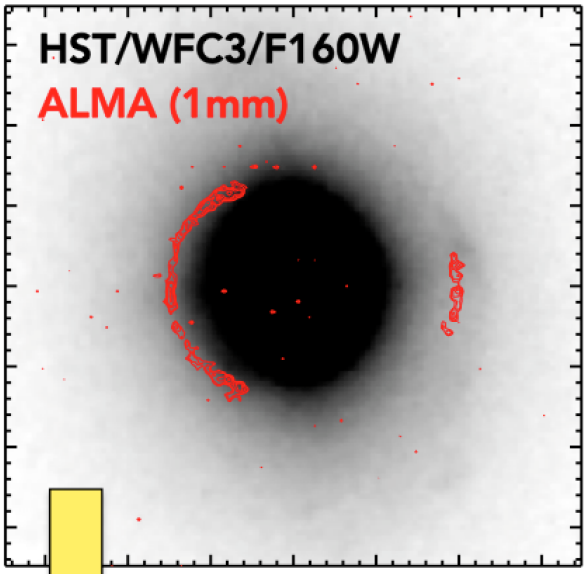

z=0.3 elliptical (Sloan LRG)
z=3.04
DSFG
2015 HST+ALMA

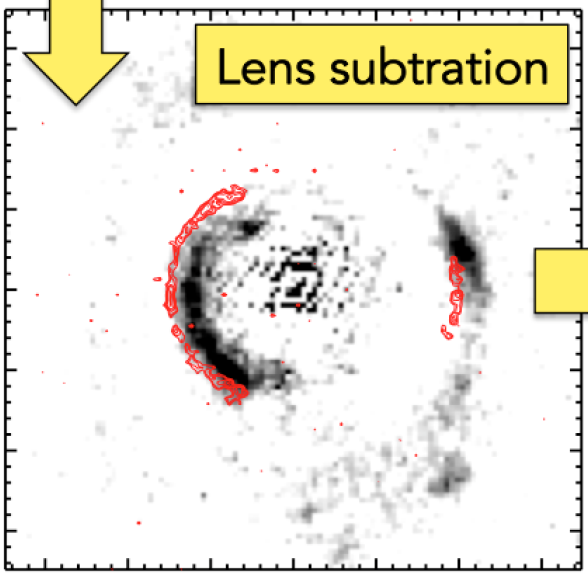
SDP.81

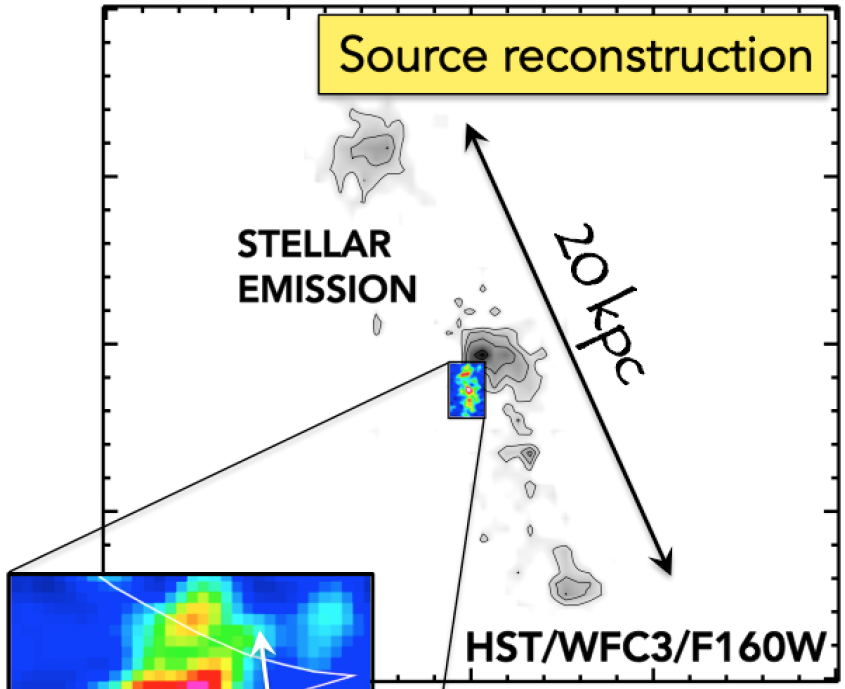


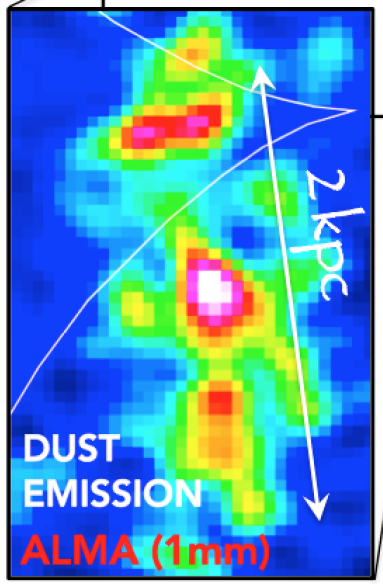
SDP.81

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









50 pc resolution in a z of 3 galaxy thanks to lensing + ALMA

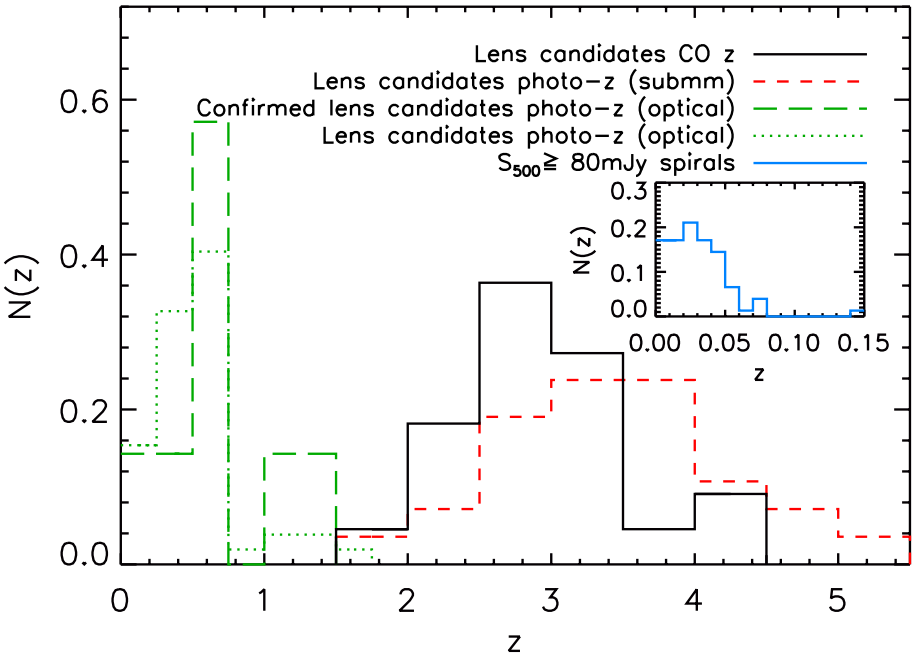
Negrello et al. 2014, MNRAS, 440, 1999
Dye et al. 2015, MNRAS, 452, 2258

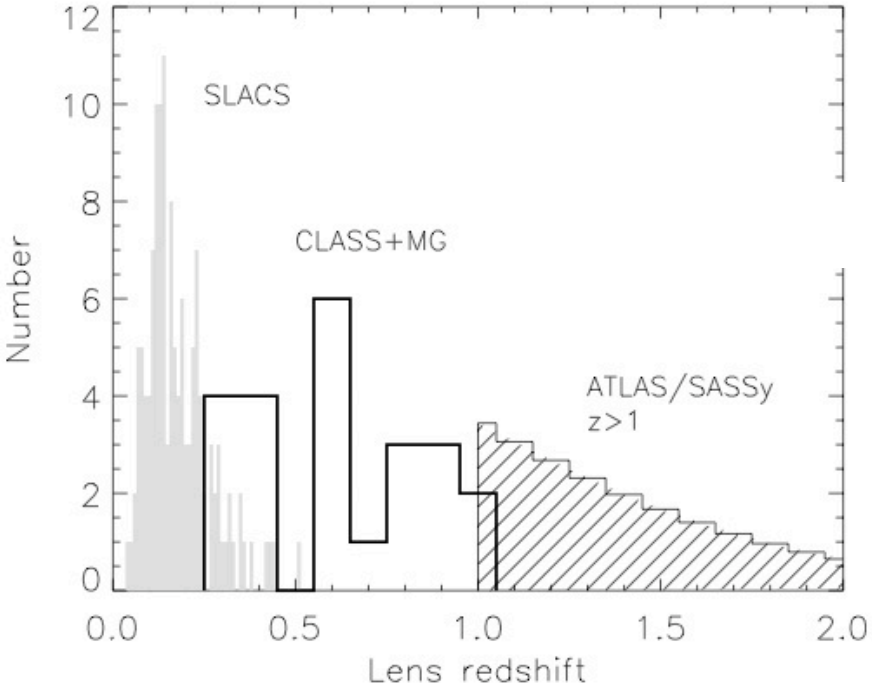
SDP.81

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

Promise of Herschel in Lensing Studies

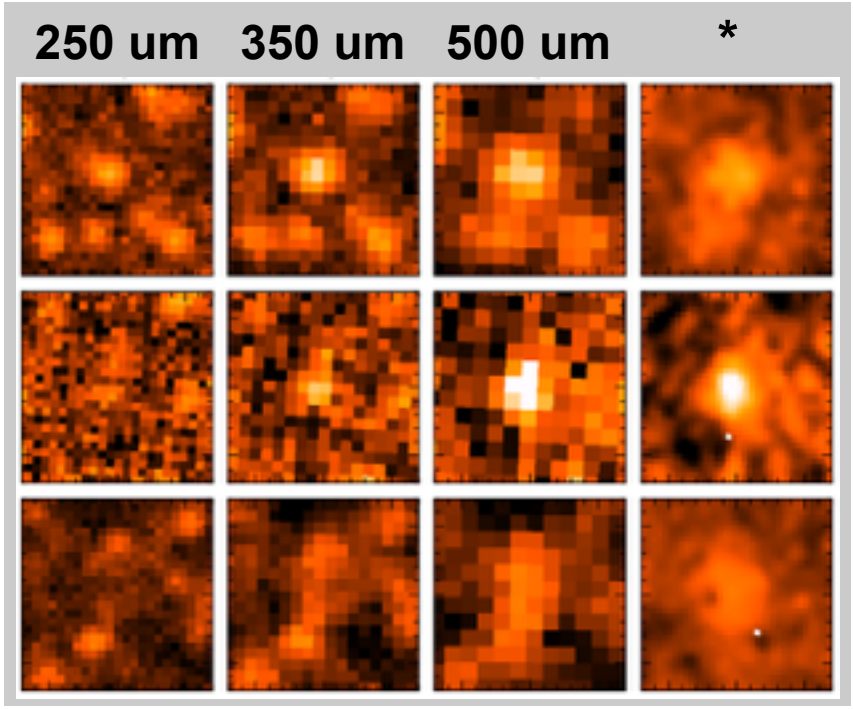
- ~0.2/sq. deg (S_{500}>100 mJy) lensed source - ***identified ~90% efficiency.***
- Herschel extragalactic surveys: ~1200 sq. degrees, so ~250 lensed galaxies.
- Compared to ~200 lensed galaxies now known in optical and radio



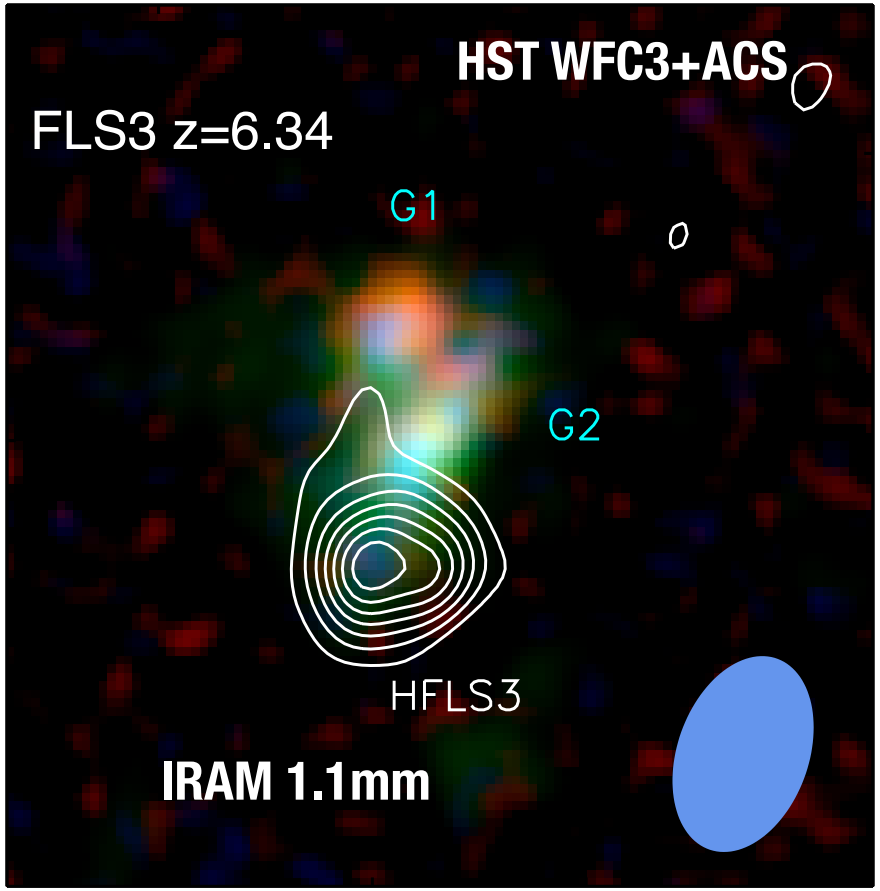


500 um peaked sources $S_{250} < S_{350} < S_{500}$: $z > 4$?

*Confusion reduced S(500) – fS(250)

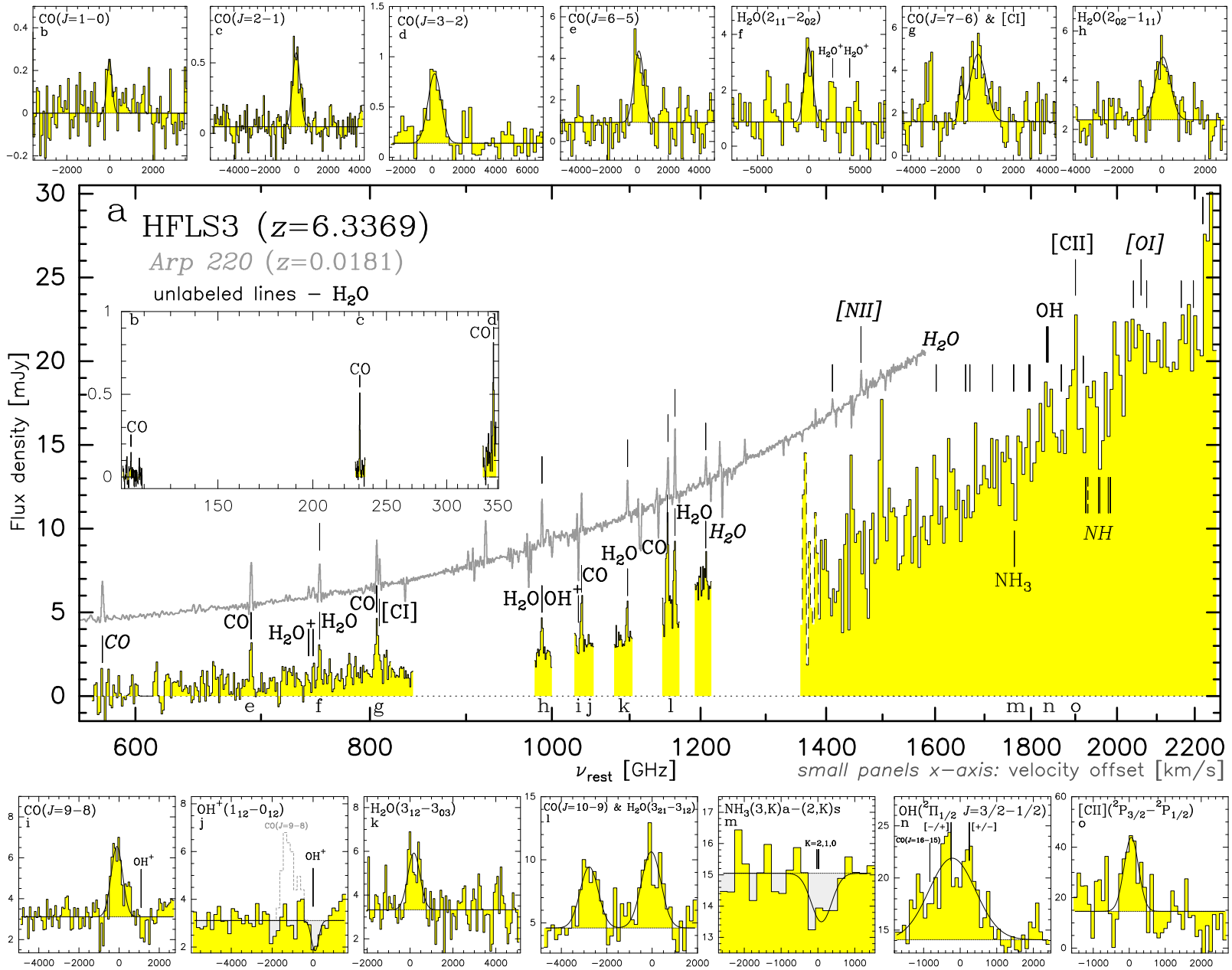


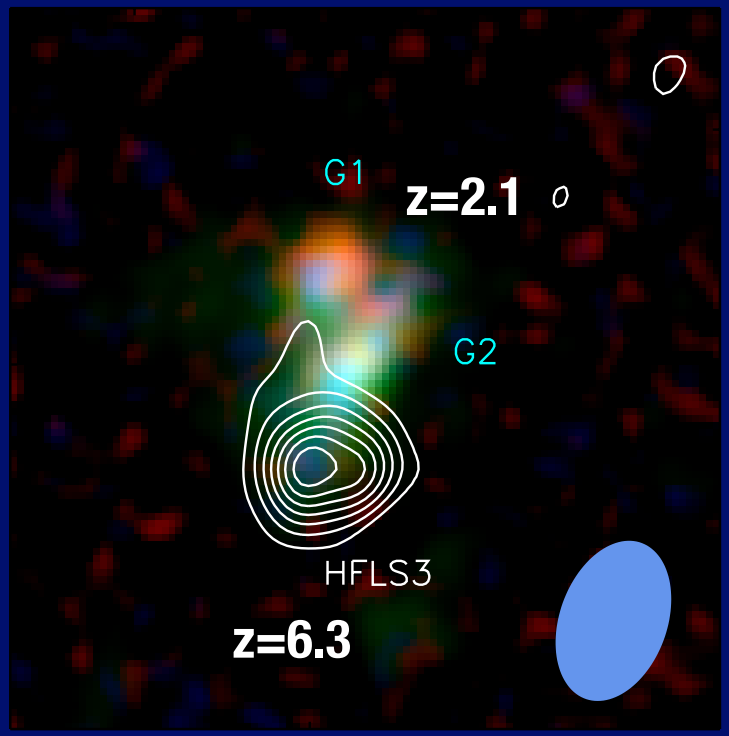
Dowell et al. 2014 ApJ technique

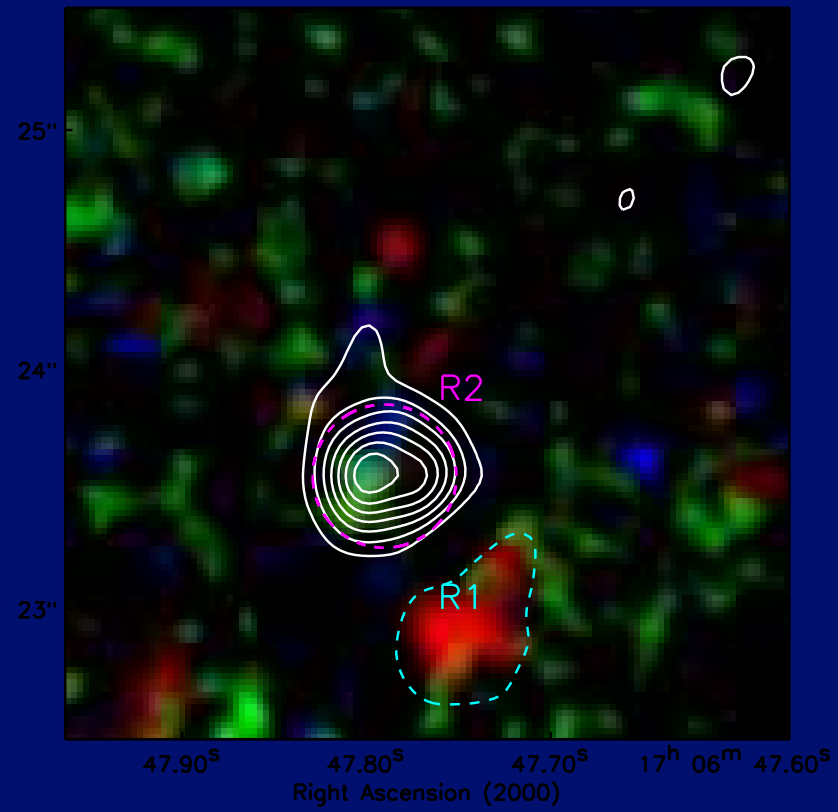


z = 6.34 Dusty Starburst Galaxy in HerMES

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]
νrest [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
NH
NH3
[CI]





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]

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

SFR ~ 1300 $M_\odot$/yr

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

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

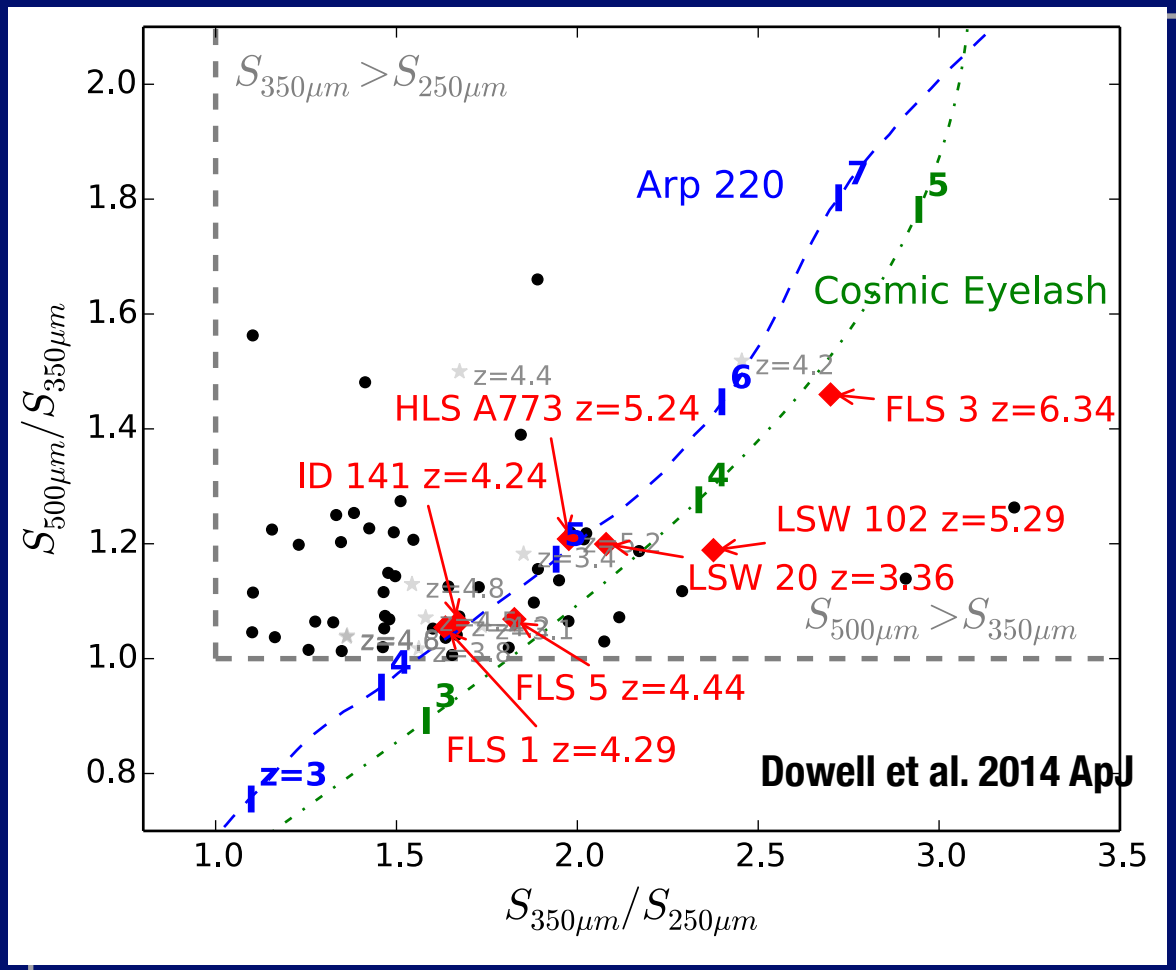
$M_{STARS} \sim 5X10^{10}\ M_\odot$

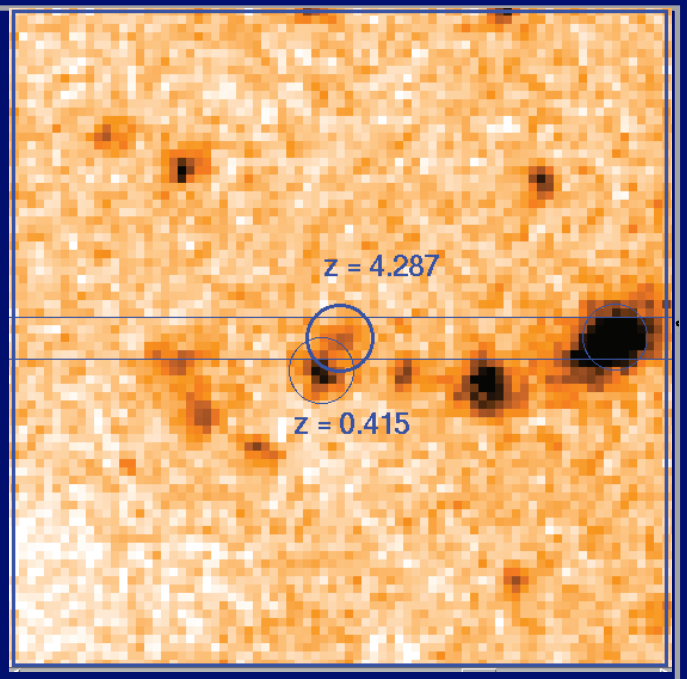
$M_{GAS} \sim 10^{11}\ M_\odot$

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





Are all Herschel-detected z >4 galaxies weakly lensed?

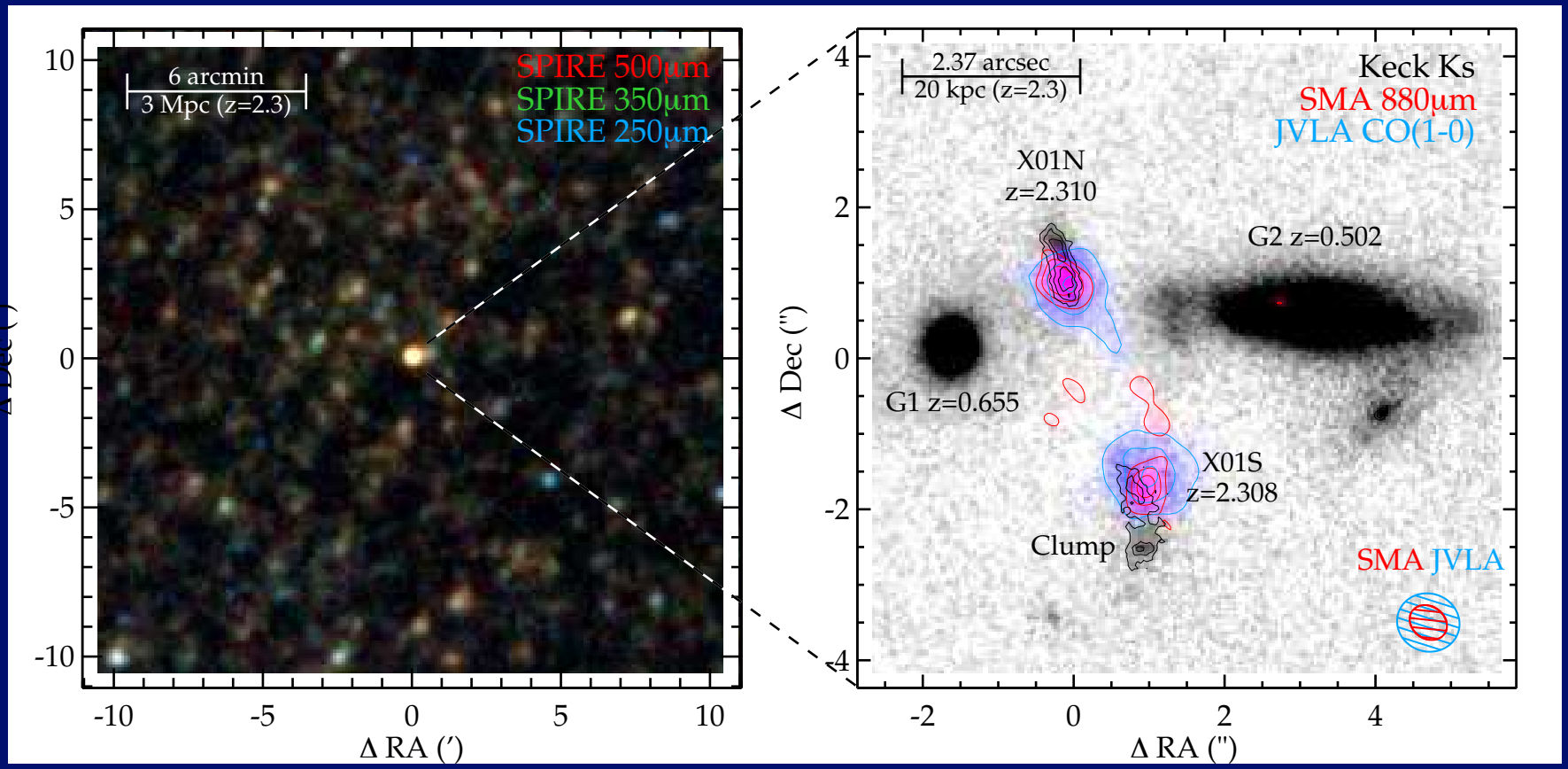
[SPT at 1.4mm Vieira+ 2013]

How many z > 5 in Herschel surveys? unclear right now! Lots of area still to be searched.

<u>800 deg2 of Herschel still to be searched for next z>6 SMG.</u>

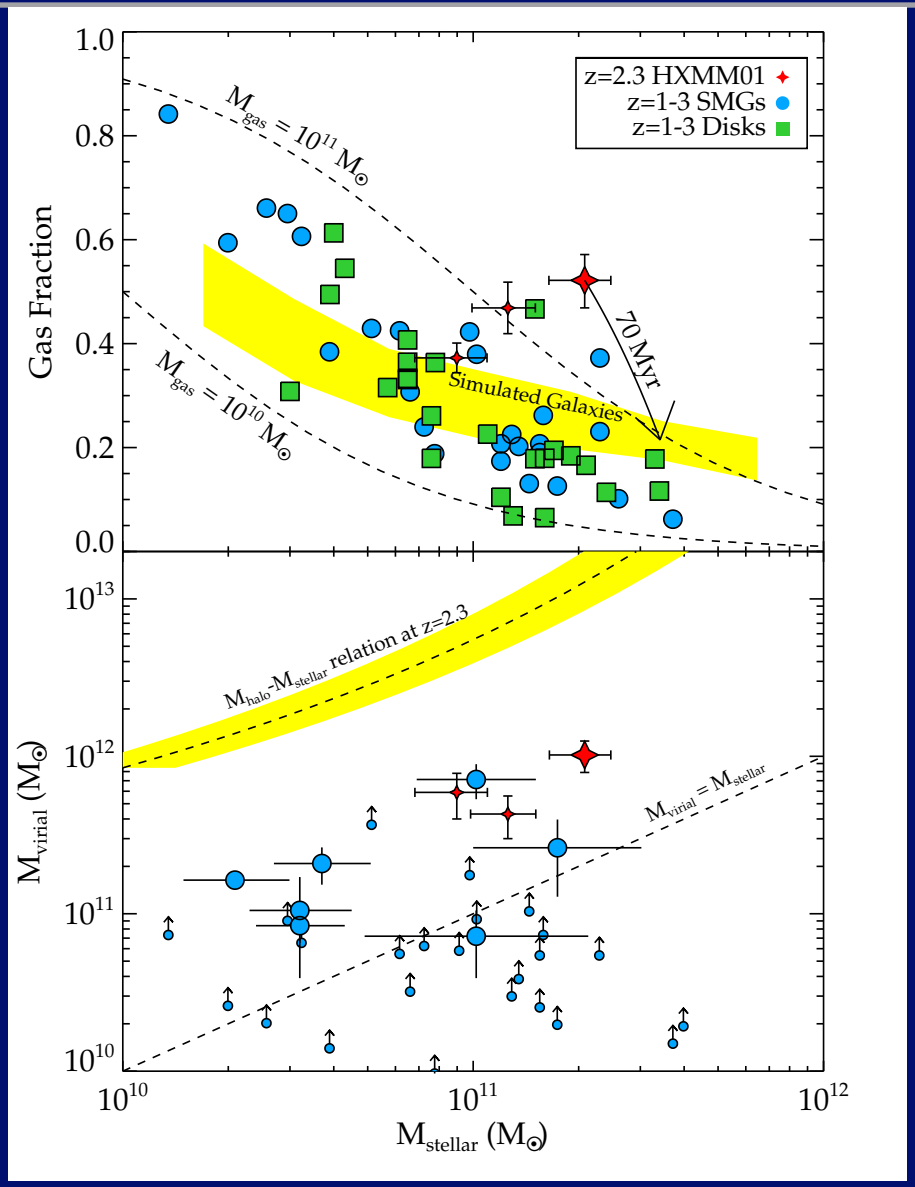
"red" galaxies in Herschel

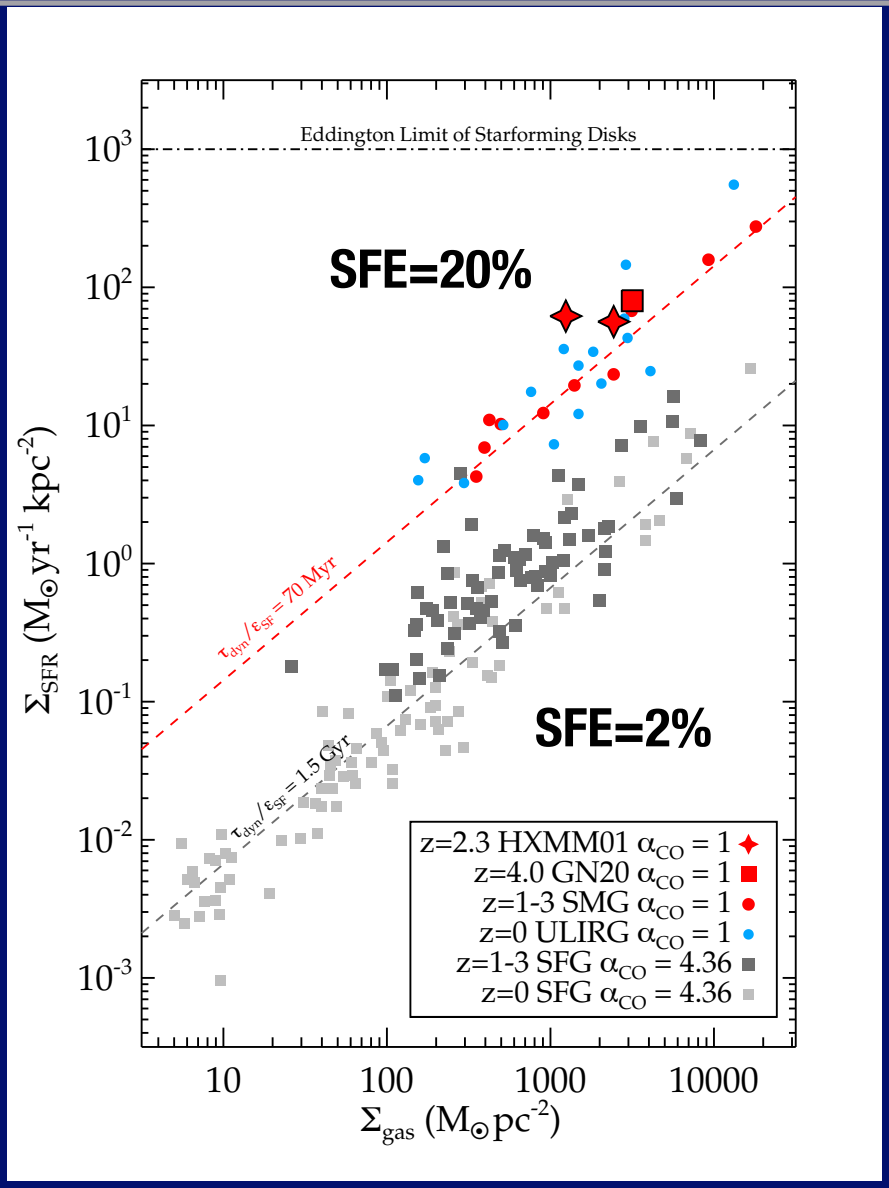
Why sub-mm lensing selection ~90% efficient?



Fu, Cooray et al. 2013 Nature

SMG-SMG mergers!

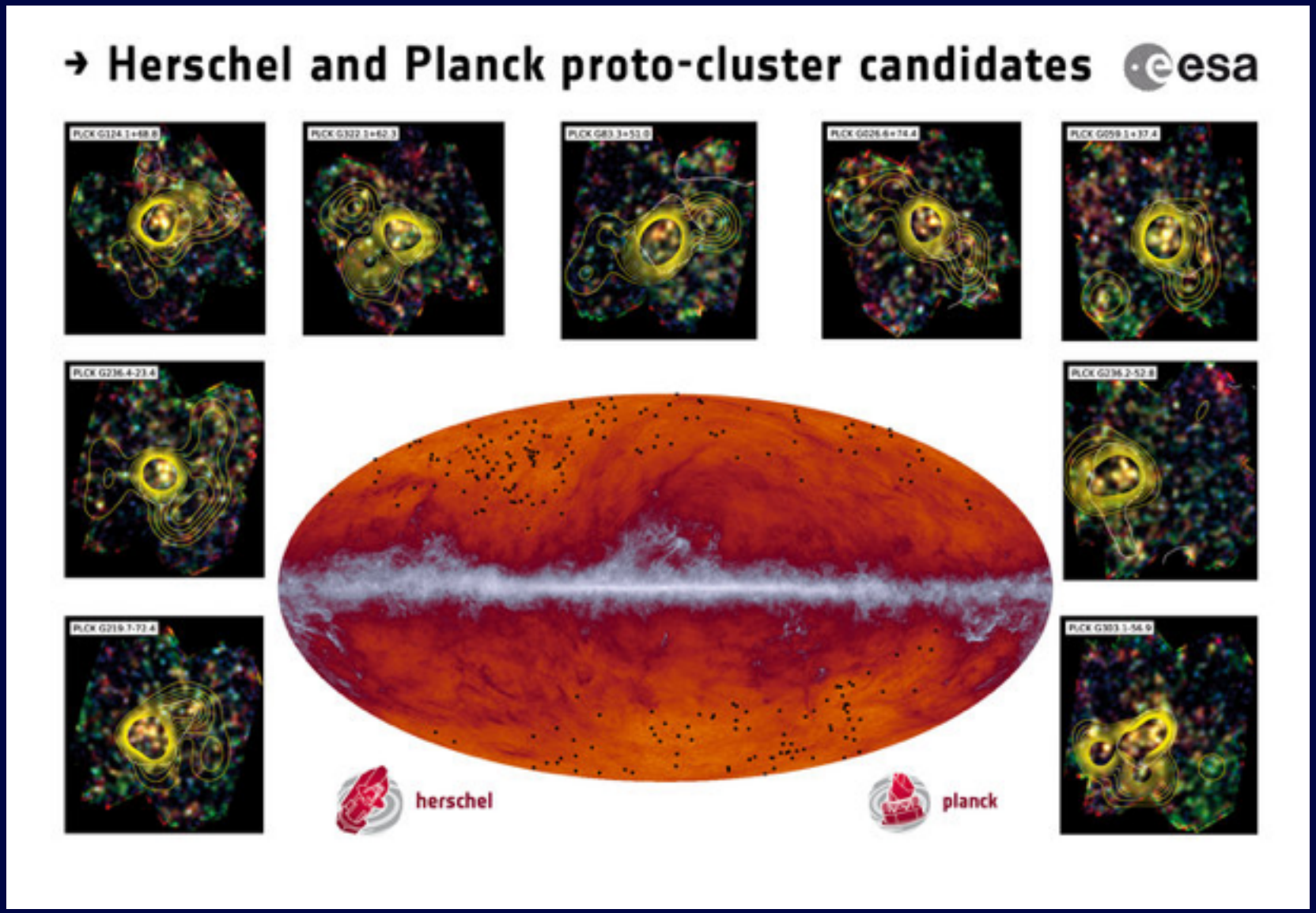




SMG-SMG mergers are rare (one per 100 sq. degrees)!

About ~10 of these in total in Herschel archive (we know 2: XMM01 and G09.124 Ivison et al. 2013)

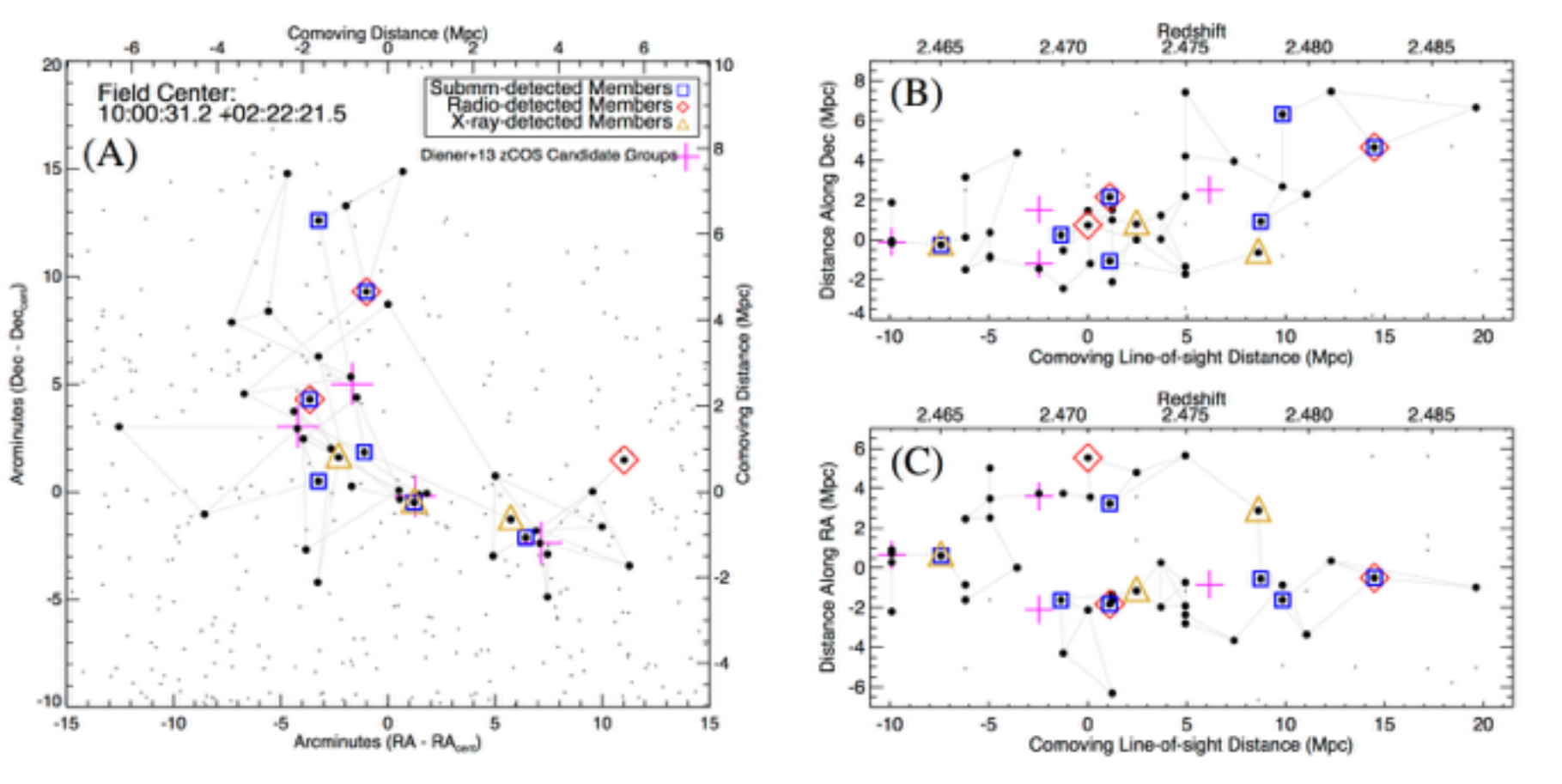
Galaxy proto-clusters at z >2
(before clusters "virialized" and bright in X-rays and SZ)



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



Connect galaxy clusters today with their progenitors during rapid star-formation.

Spectral probes from 10 – 500 μm

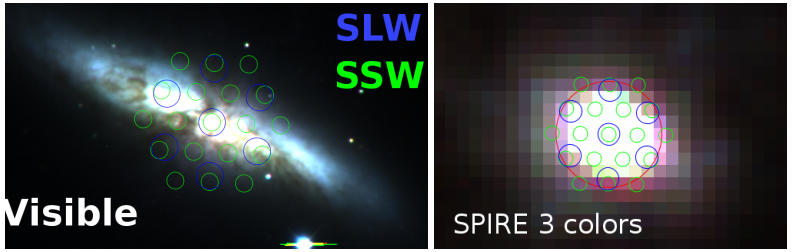
Species	Wavelength [μm]	f (M82)	f (Arp220)	Diagnostic Utility
		Ionized Gas Fine Structure Lines		
Ne V	24.3			Unambiguously AGN
O IV	25.9, 54.9			Primarily AGN
S IV	10.5	2.1 (-5)		
Ne II	12.3	1.2 (-3)	7.5 (-5)	Probes gas density and
Ne III	15.6, 36.0	2.05 (-4)		UV field hardness in
S III	18.7, 33.5	1.0 (-3)	7.3 (-5)	star formation HII
Ar III	21.83	9.1 (-6)		regions.
O III	51.8, 88.4	1.3 (-3)		
N III	57.3	4.2 (-4)		
N II	122, 205	2.1 (-4)		Diffuse HII regions
		Neutral Gas Fine Structure Lines		
Fe II	26.0			Density and temperature probes
Si II	34.8	1.1 (-3)	7.7 (-5)	of photodissociated-neutral
O I	63.1, 145	2.2 (-3)	6.8 (-5) (abs)	gas interface between HII
C II	158	1.6 (-3)	1.3 (-4)	regions and molecular clouds.
		Molecular Lines		
H_2	9.66, 12.3, 17.0, 28.2	2 (-5)	3 (-5)	Coolants of first collapse
CH	149		4 (-5)	Ground state absorbtion:
OH	34.6, 53.3, 79.1, 119	2 (-6)	2 (-4) (abs)	gives column and abundance.
OH	98.7, 163		5 (-5)	Emission: gas coolants, constrain
H_2O	73.5, 90, 101, 107, 180		5 (-5)	temperature, density of warm
CO	325, 372, 434, 520	3 (-6)	1 (-5)	(50K < T < 500 K) mol. gas

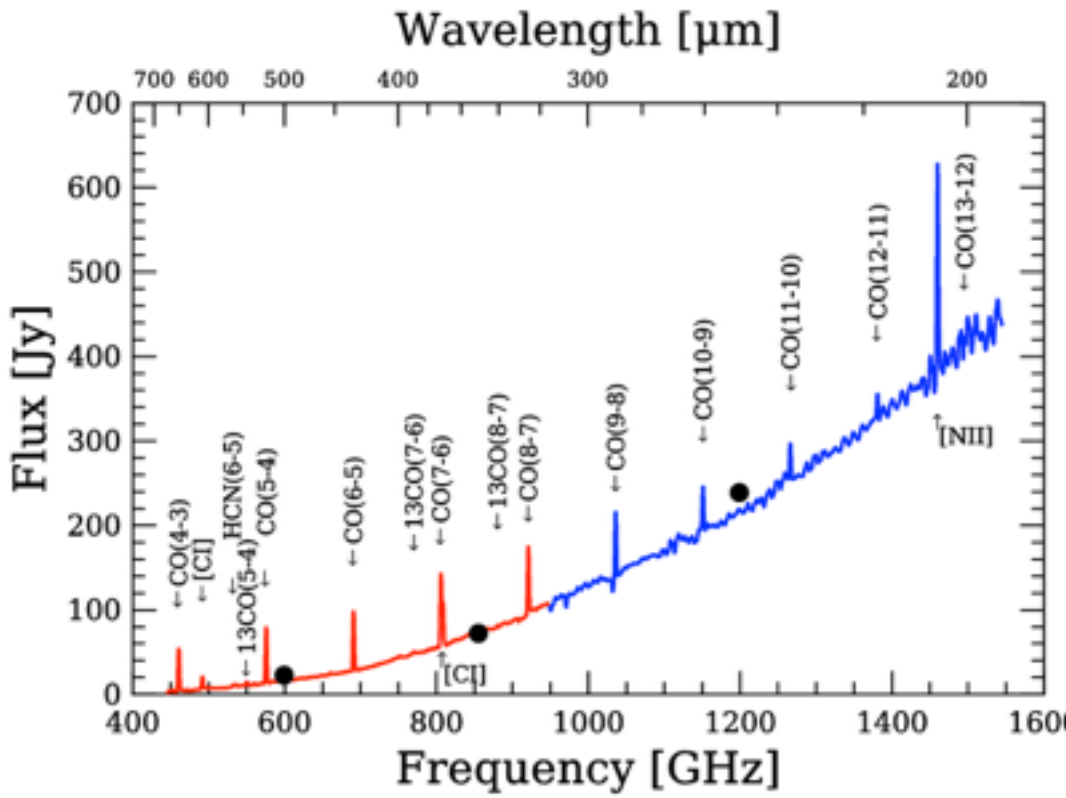
Far-IR rich in spectral lines

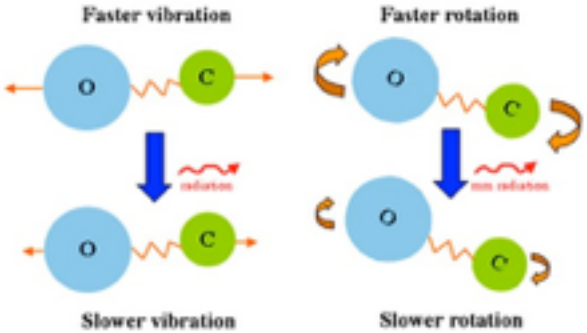
Probing the interstellar medium of M82

M82 SPIRE FTS observations

- M82 is the nearest (3.9Mpc) starburst (~10Msun/yr)
  - Brightest IRAS extragalactic source (1390Jy at 100μm)
  - Widely used in cosmology as starburst prototype
- Target of the *Very Nearby Galaxies Survey* (SAG2)
- M82 was observed as Performance Verification target
  - High resolution (FWHM=0.048 cm^{-1} R~1000)
  - 1332 seconds (10 repetitions)
  - Point source mode (single staring pointing)



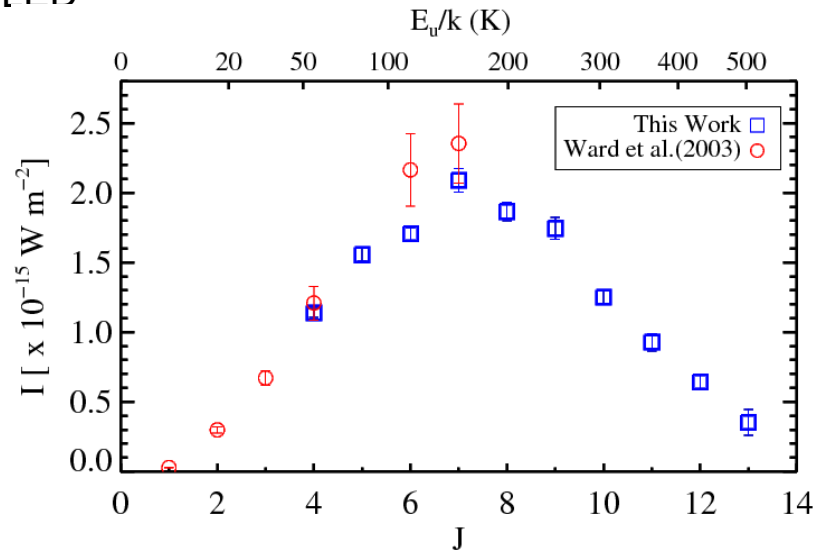


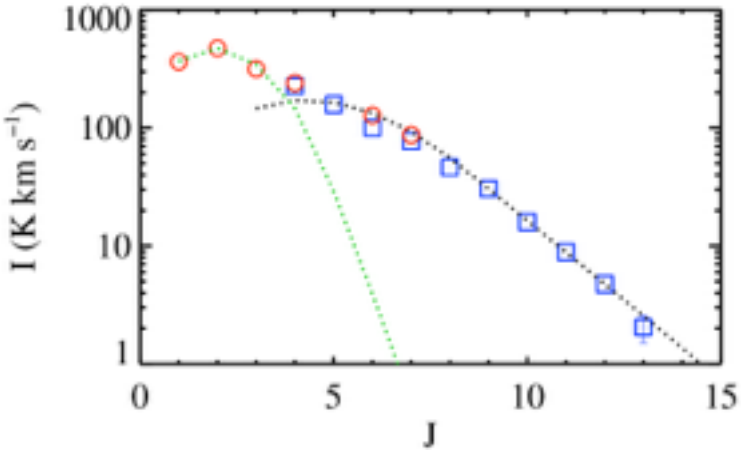


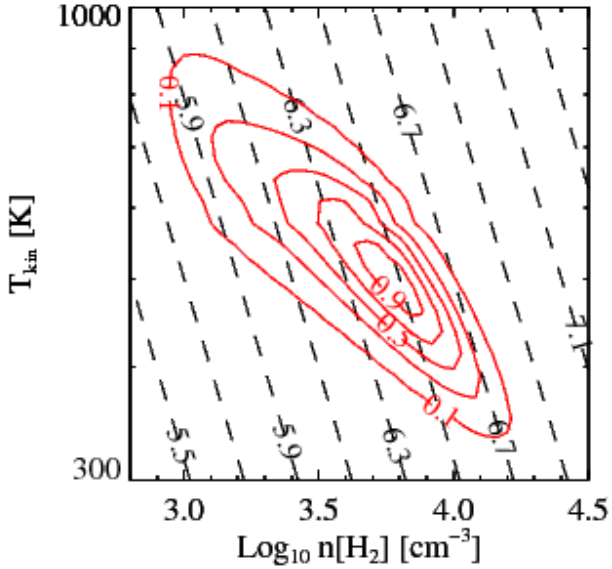
Probing the interstellar medium of M82

M82 ^{12}CO SLED

- The Spectral Line Emission Distribution (SLED) of ^{12}CO peaks at J=7-6
- Low J lines taken from Ward et al (2003) in a similar area
- Only with Herschel we can determine the peak of the SLED





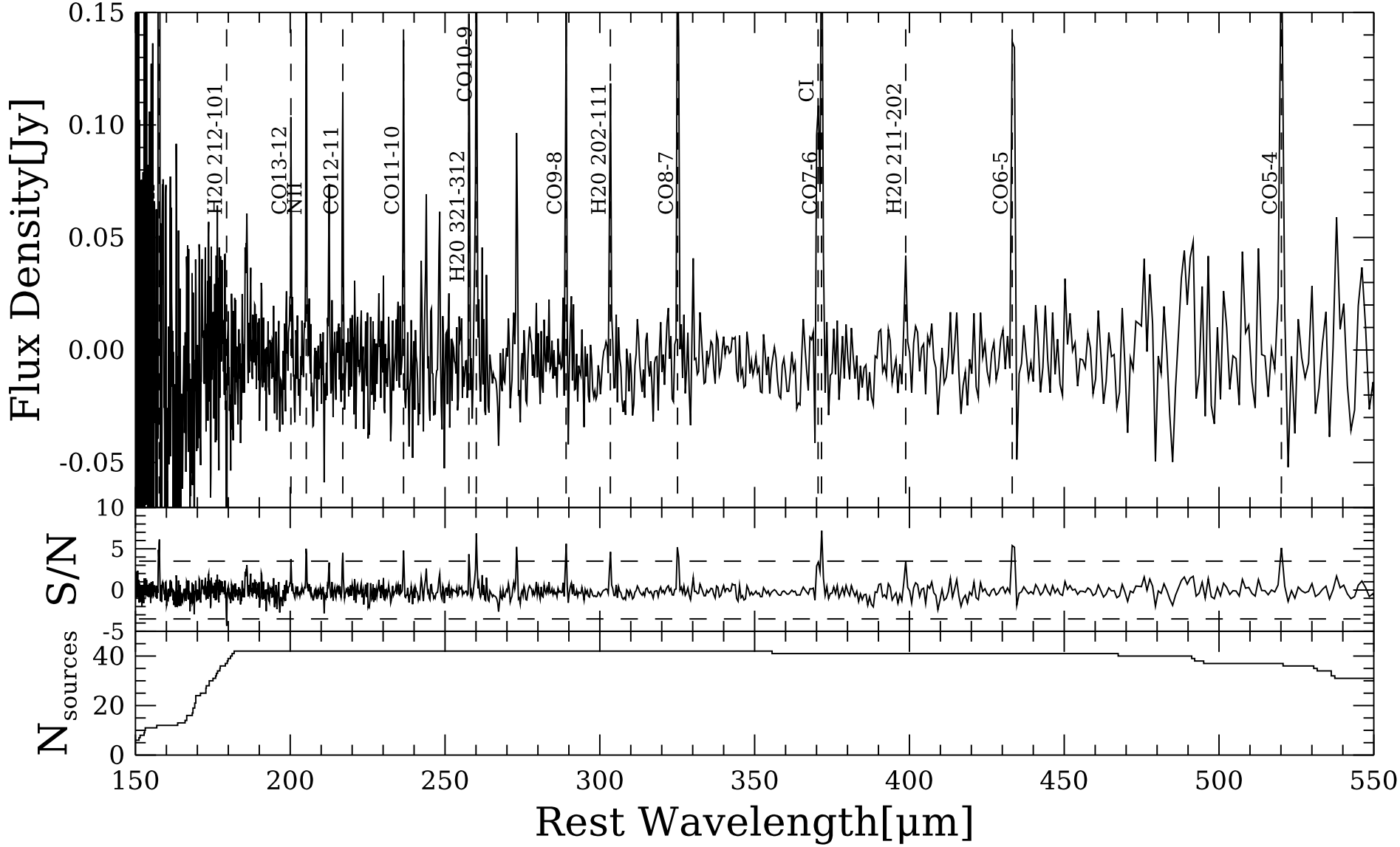


Best-fit model has T=545 K and 1.2x10^7 M_o of warm gas

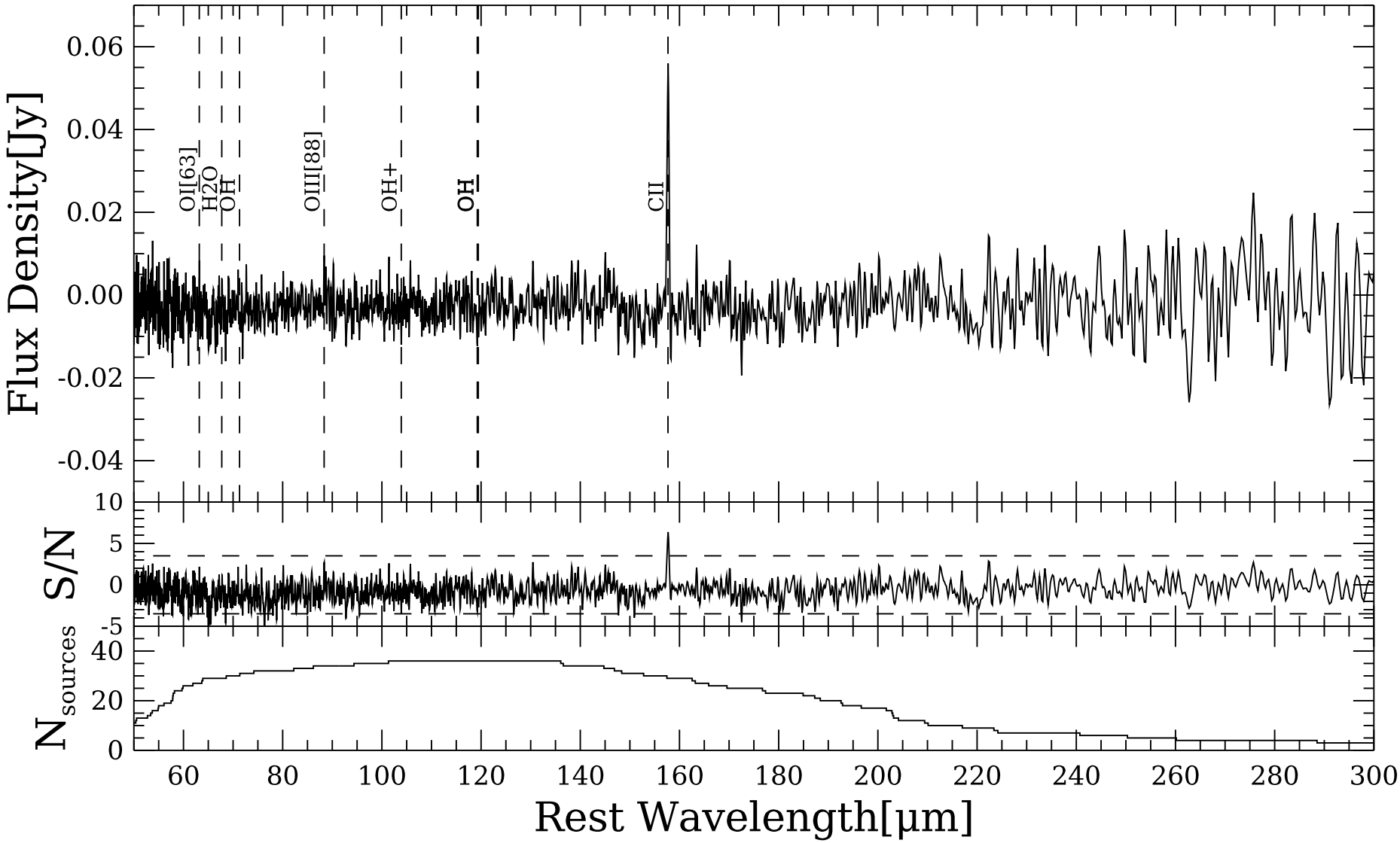
- **What heats gas to 545 K? turbulence, cosmic ra**

no evidence for an AGN in M82.

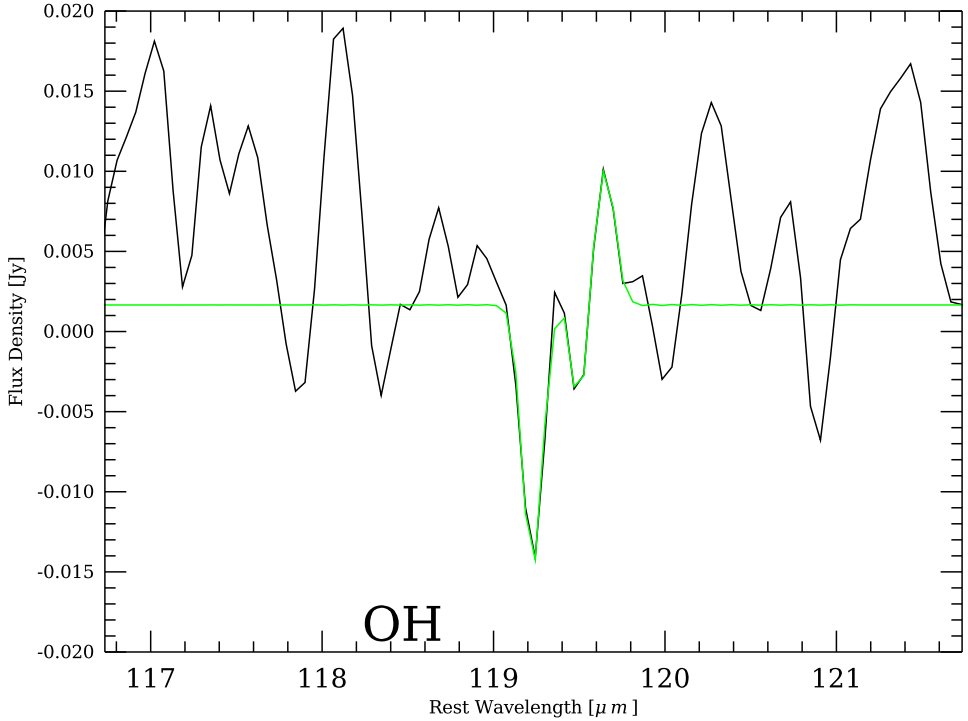
SPIRE FTS stacks: 0.1 < z < 1.0 (Wilson+ in prep)

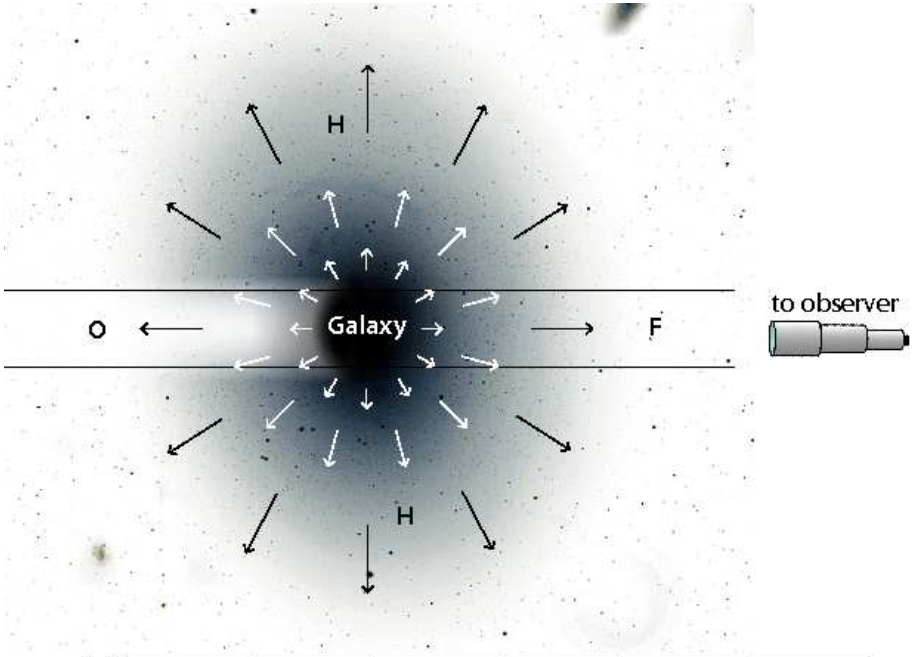


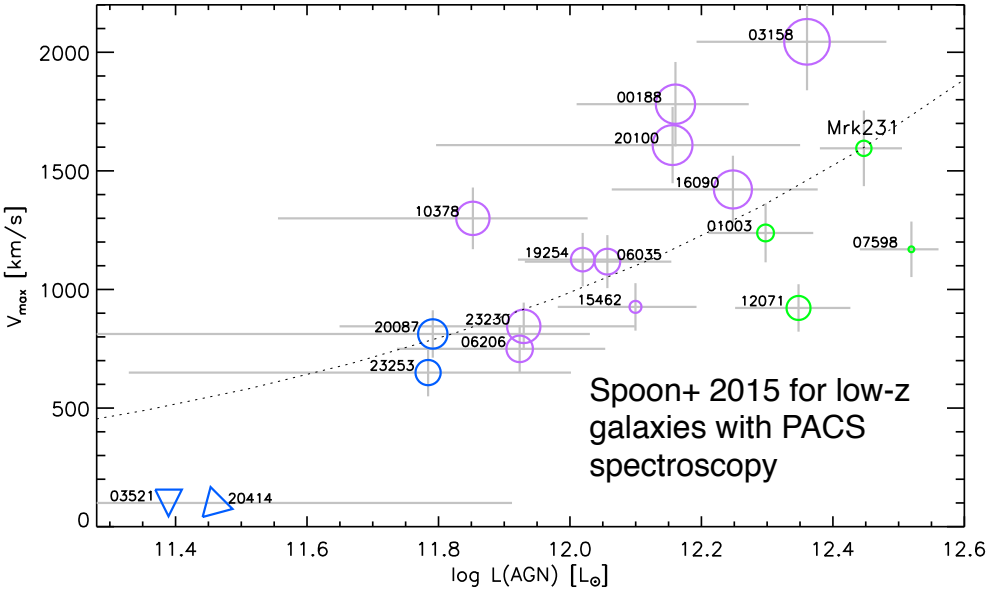
SPIRE FTS stacks: 1.0 < z < 3.8 (Wilson+ in prep)

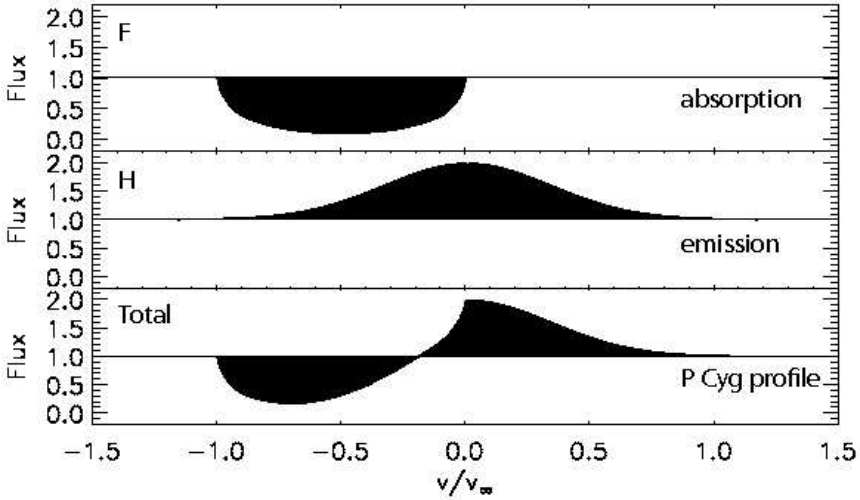


119 micron OH absorption at z=1-3!



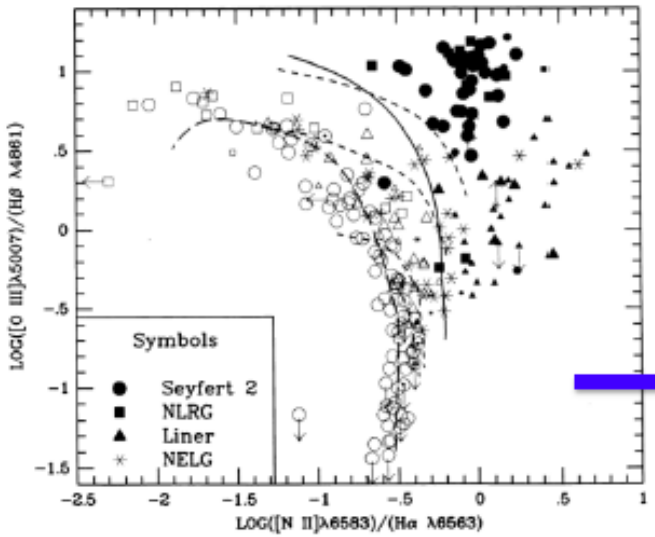




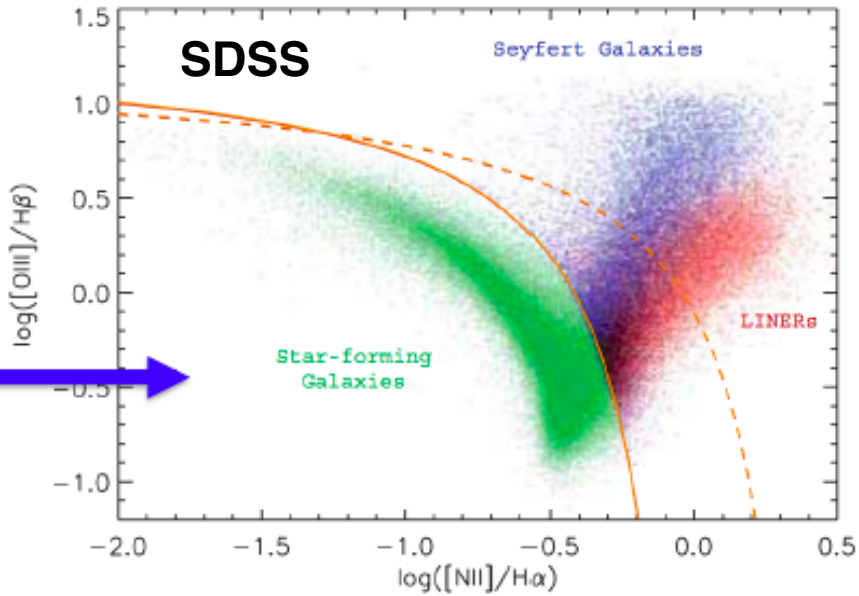


OPTICAL SPECTROSCOPY

Veilleux & Osterbrock **1987** (~100 galaxies)

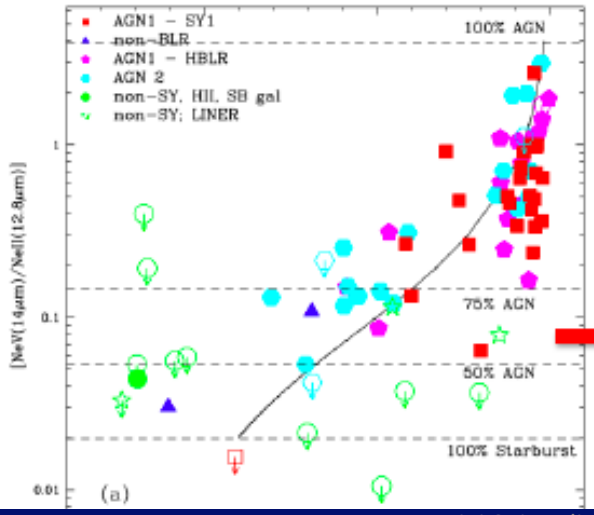


Groves+ **2006** (>10^5 galaxies)



MIR-FIR SPECTROSCOPY

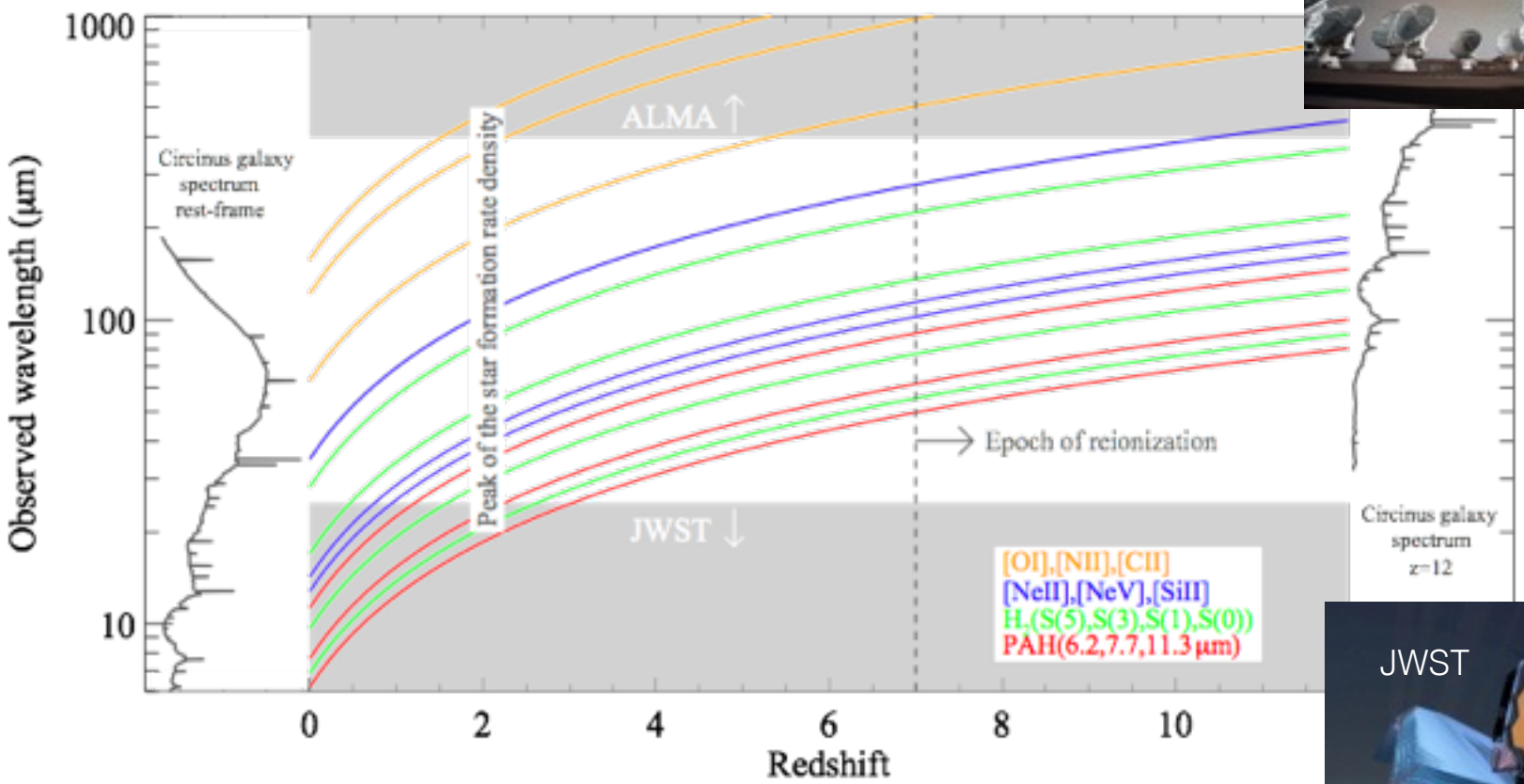
Tommasin+ **2010** (~60 galaxies)



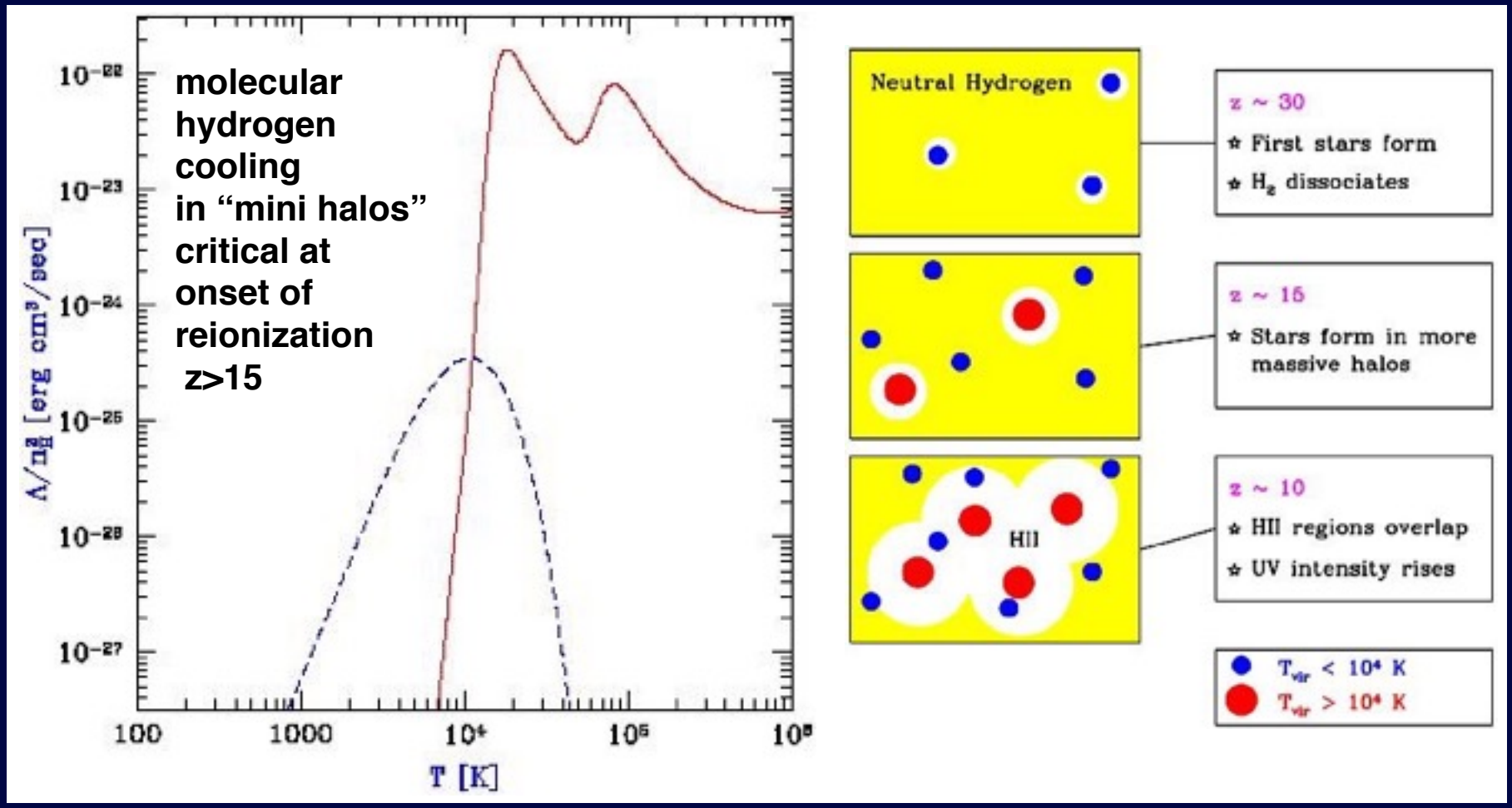
Still a long way to go to get million spectra in mid/far-IR!

Far-IR rich in spectral lines

Far-IR provides the crucial link between JWST and ALMA to complete our view of the evolution of the universe.



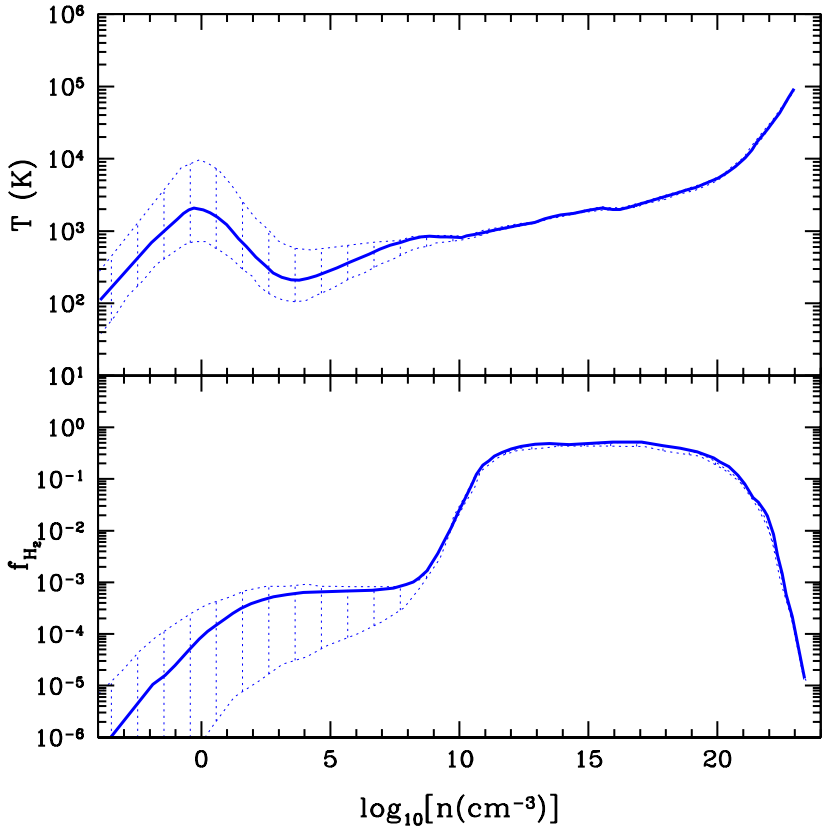
Molecular Hydrogen tracing primordial cooling sites/halos

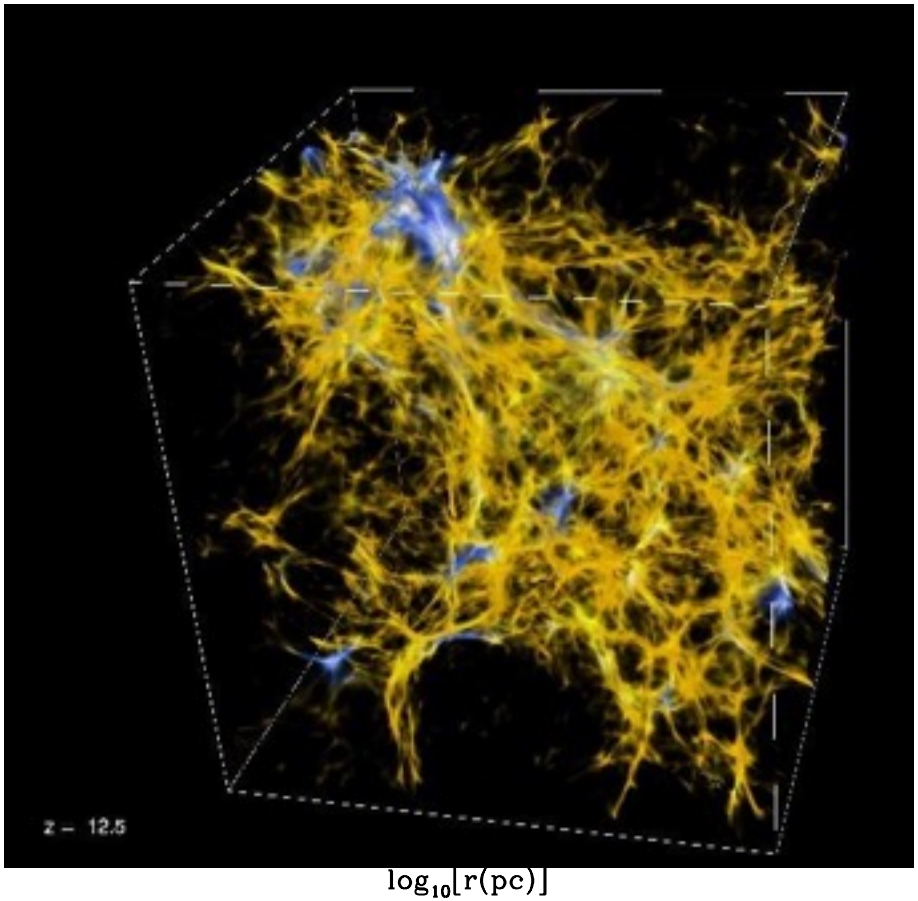


Outstanding problems at z > 6: billion to ten billion solar mass black-holes in SDSS quasars, Universe at < 600 Myr.
One solution is massive PopIII clusters collapsing - seed blackholes.
Need formation in minihalos at z > 15.

Molecular Hydrogen tracing primordial cooling sites/halos

Gong et al. 2012





To detect primordial H_2 line cooling at formation sites of first stars and galaxies at z ~10-15 next-gen far-infrared sensitivities down to 10^{-23} Wm^{-2} (for rest-frame H2 lines at 12.3,17, 28 microns etc)

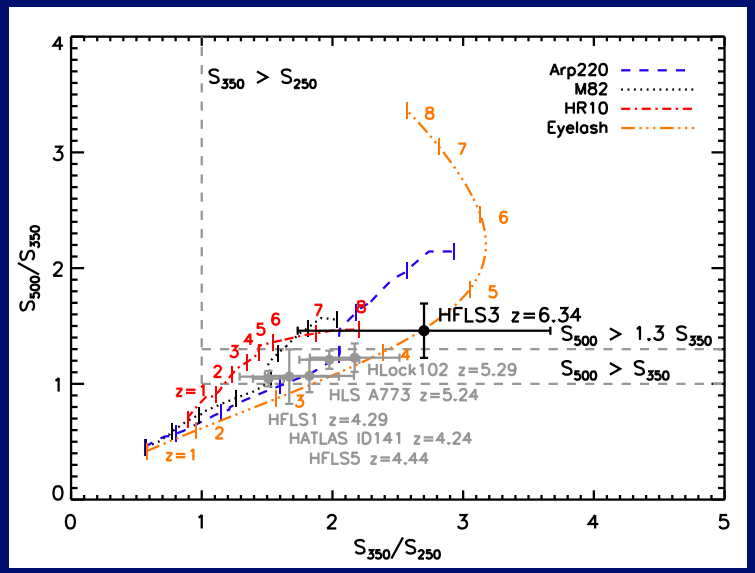
~2100 peer-reviewed papers with Herschel Space Observatory or an instrument (in abstract), 2010-2016.

with 55,000 citations, 600K total downloads according to ADS

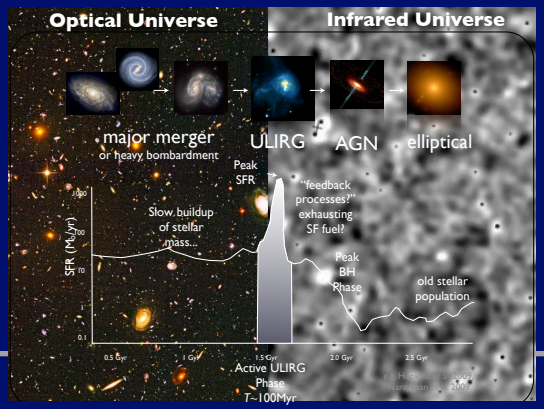
~6000 papers with some appearance/mention of Herschel Space Observatory since 2007.

Herschel summary

Dusty, starbursts are not limited to z~2 (Riechers et al 13 Nature)



Role of starbursts vs. cold accretion still unclear. SMGs are likely all mergers!



Extensive followup programs, currently on bright lensed and rare SMGs, are providing a detailed view of high-z star-formation, the relative distribution of gas, dust, and stars.

For an extensive review of dusty, star forming galaxies see
Casey, Narayanan & Cooray (2014) *Physics Reports*

Summary

THIS TALK AVAILABLE AT HERSCHEL.UCI.EDU