Observational Cosmology

(C. Porciani / K. Basu)

Lecture 11

Starbursts and Sub-mm Galaxies

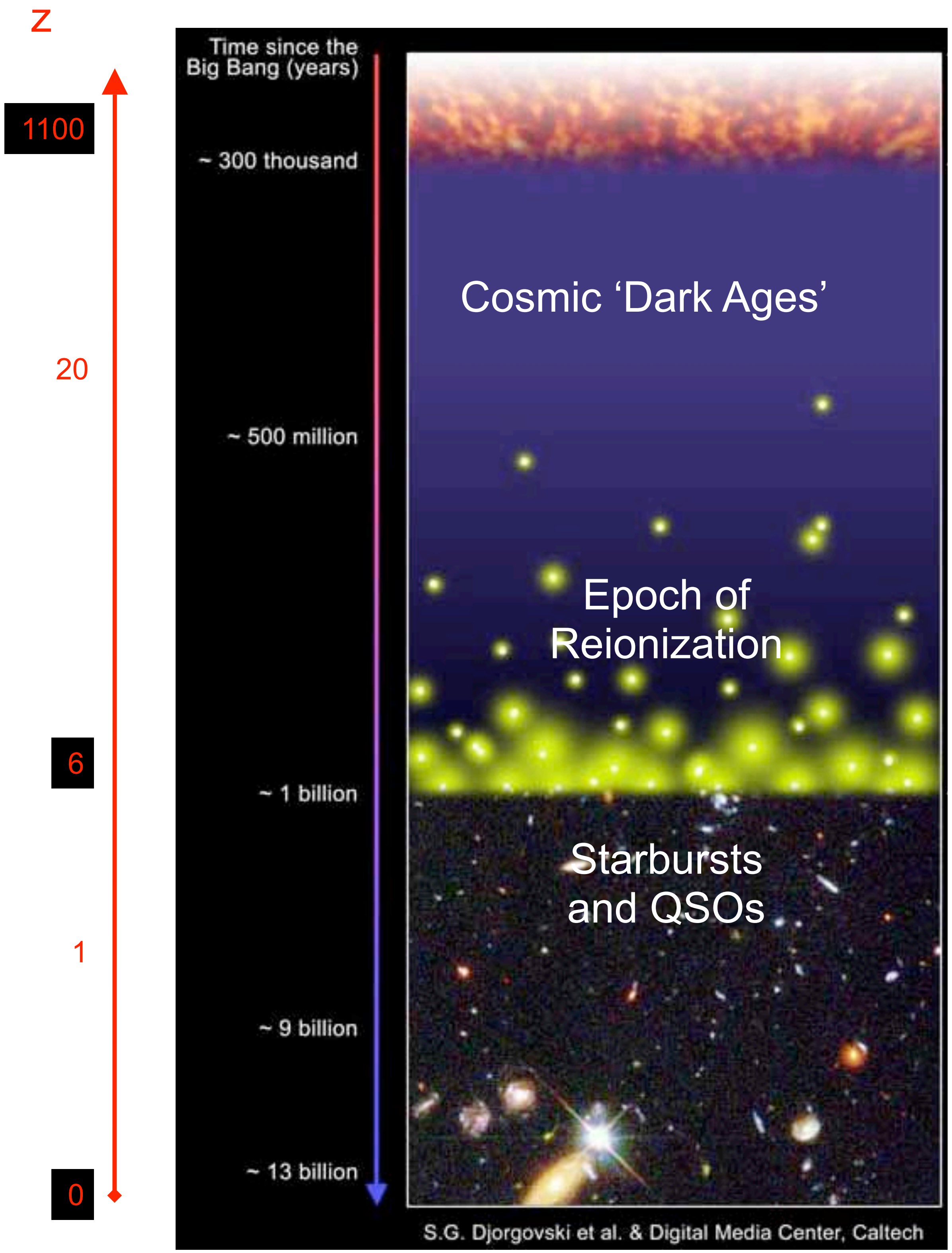
(high-z universe through dust)

Course website:
http://www.astro.uni-bonn.de/~kbasu/astro845.html

Outline of today's lecture

- ☑ **Structure formation and the first stars**
- ☑ **Distant starbursts, SED of sub-millimeter galaxies**
- ☑ **Global star formation and the stellar IMF**
- ☑ **Imaging blank sky at sub-mm wavelengths**
- ☑ **Sub-mm galaxies lensed by clusters**

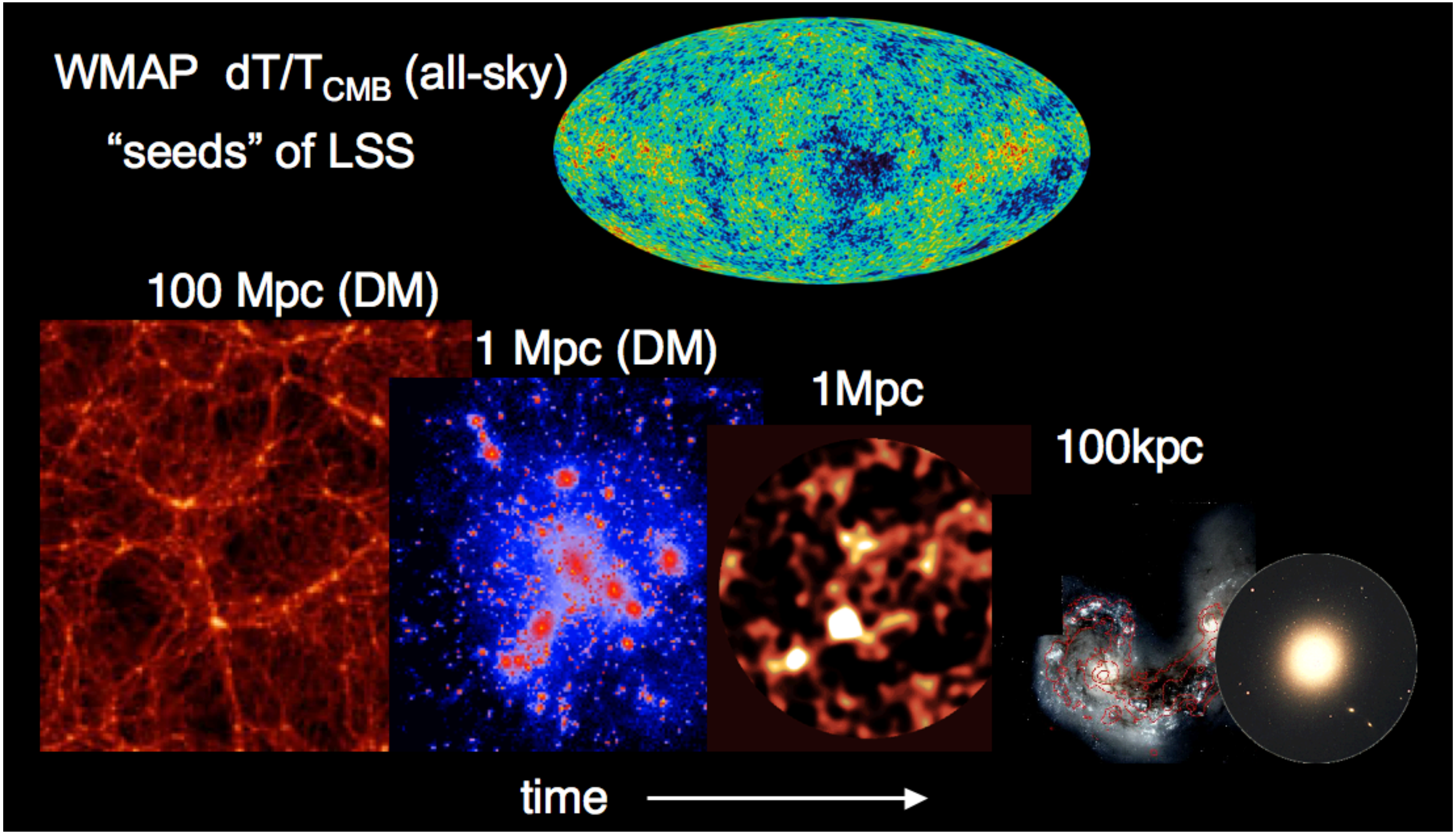
Starbursts and galaxy evolution



Major themes and questions regarding the formation and evolution of galaxies:

- First stars and AGN
- Mergers vs. cold streams driving galaxy formation
- Spatially resolved distributions of SF, gas, stellar populations, metallicities
- Rotation curves & connection to halo; angular momentum distribution
- Co-evolution of massive black holes and host galaxies
- Roles of mergers vs. secular evolution / environment
- Bulge vs disk formation
- Roles of stellar and AGN feedback

Evolutionary history of starbursts



Dust and star formation

Dust plays two crucial roles in star formation process

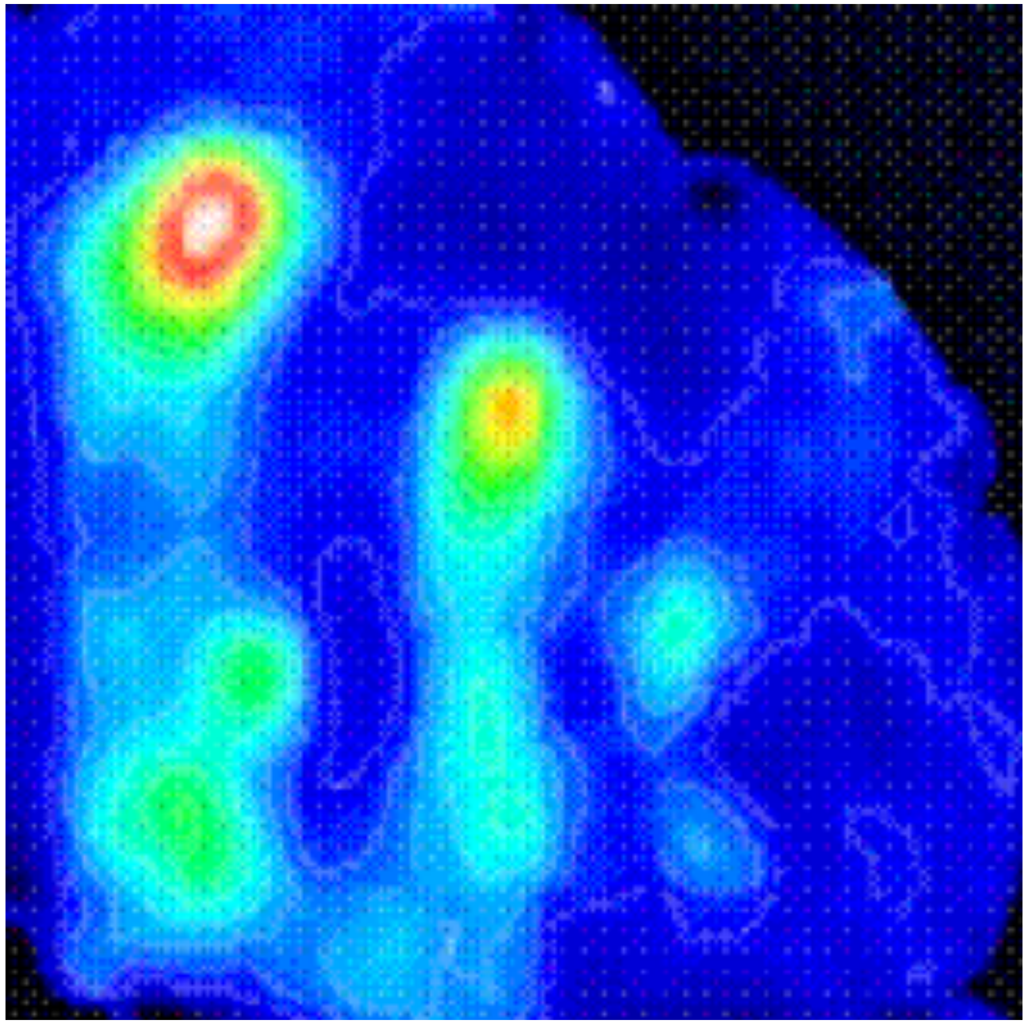
- protects fragile molecules from being dissociated by intense UV & optical interstellar radiation field & hence enables collapse of molecular gas to start

- the dust provides an efficient way for the protostar to radiate away energy associated with the gravitational collapse of the molecular envelope, allowing growth of protostar to continue

Although dust is important we still know very little about the composition and properties of the grains

Dust obscured star formation

Optical (HST)

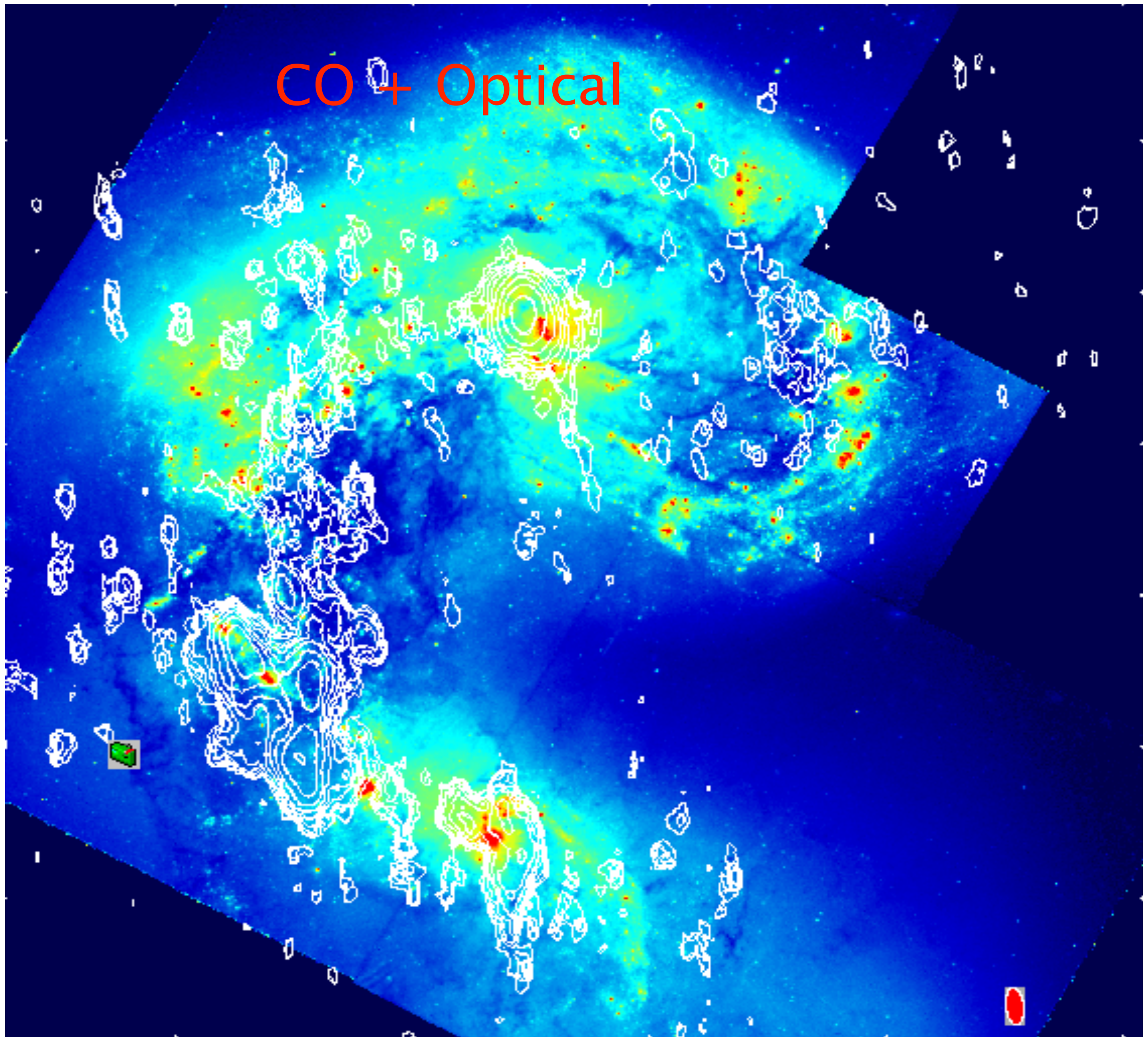


Sub-millimeter (450 μm)

Archetypical interacting galaxy

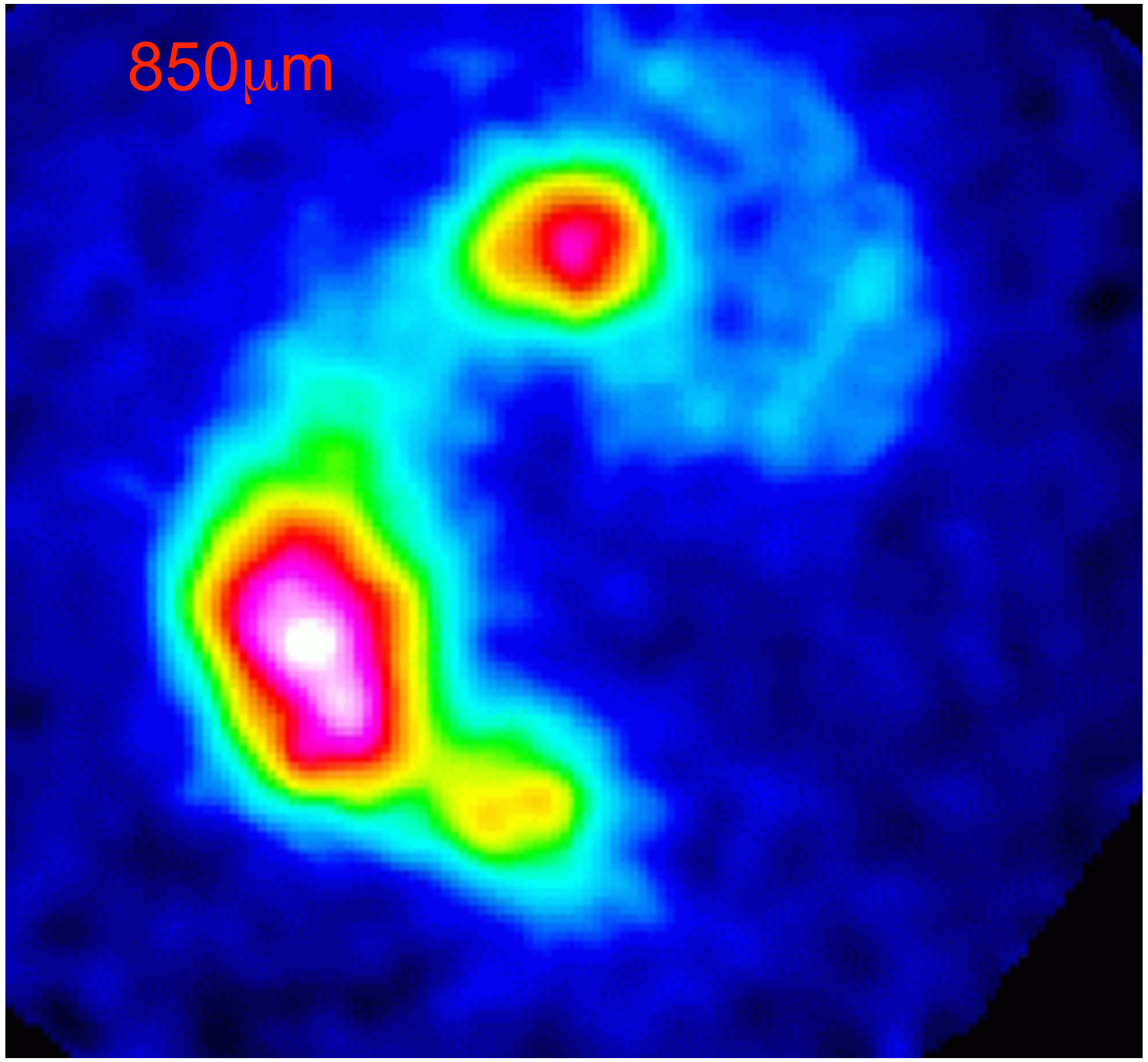
Arp 244 (“Antenna”)

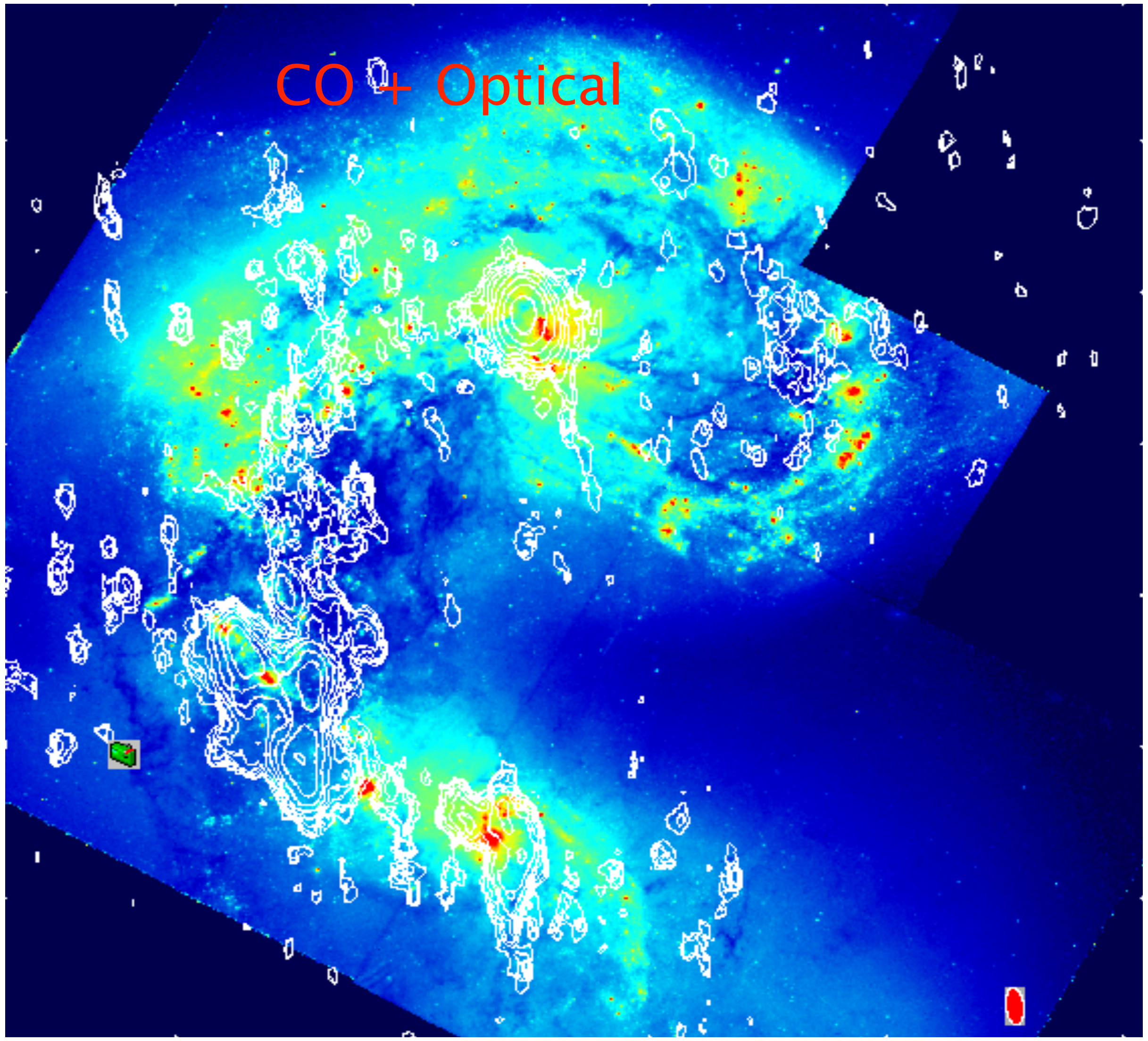
Location of starburst



The starburst is hidden behind dense dust clouds

Location of starburst

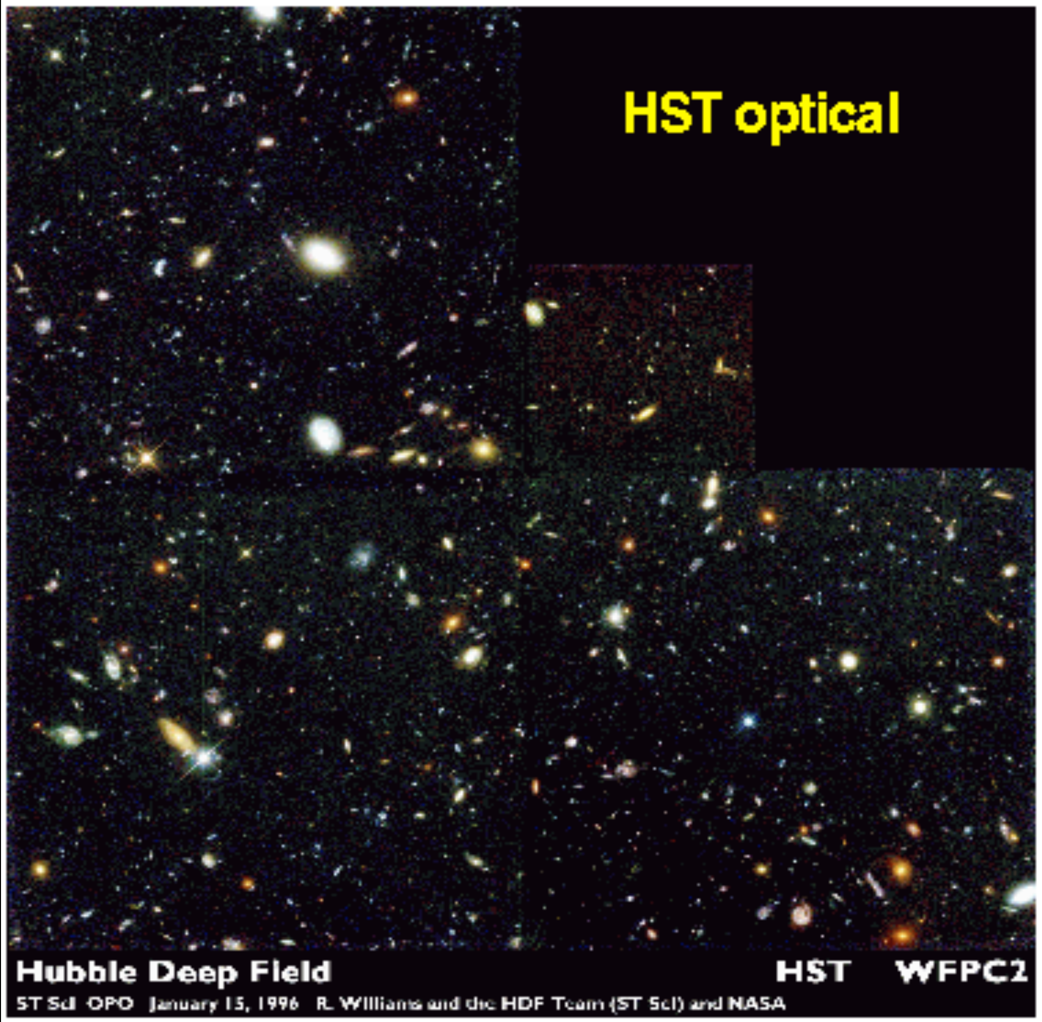


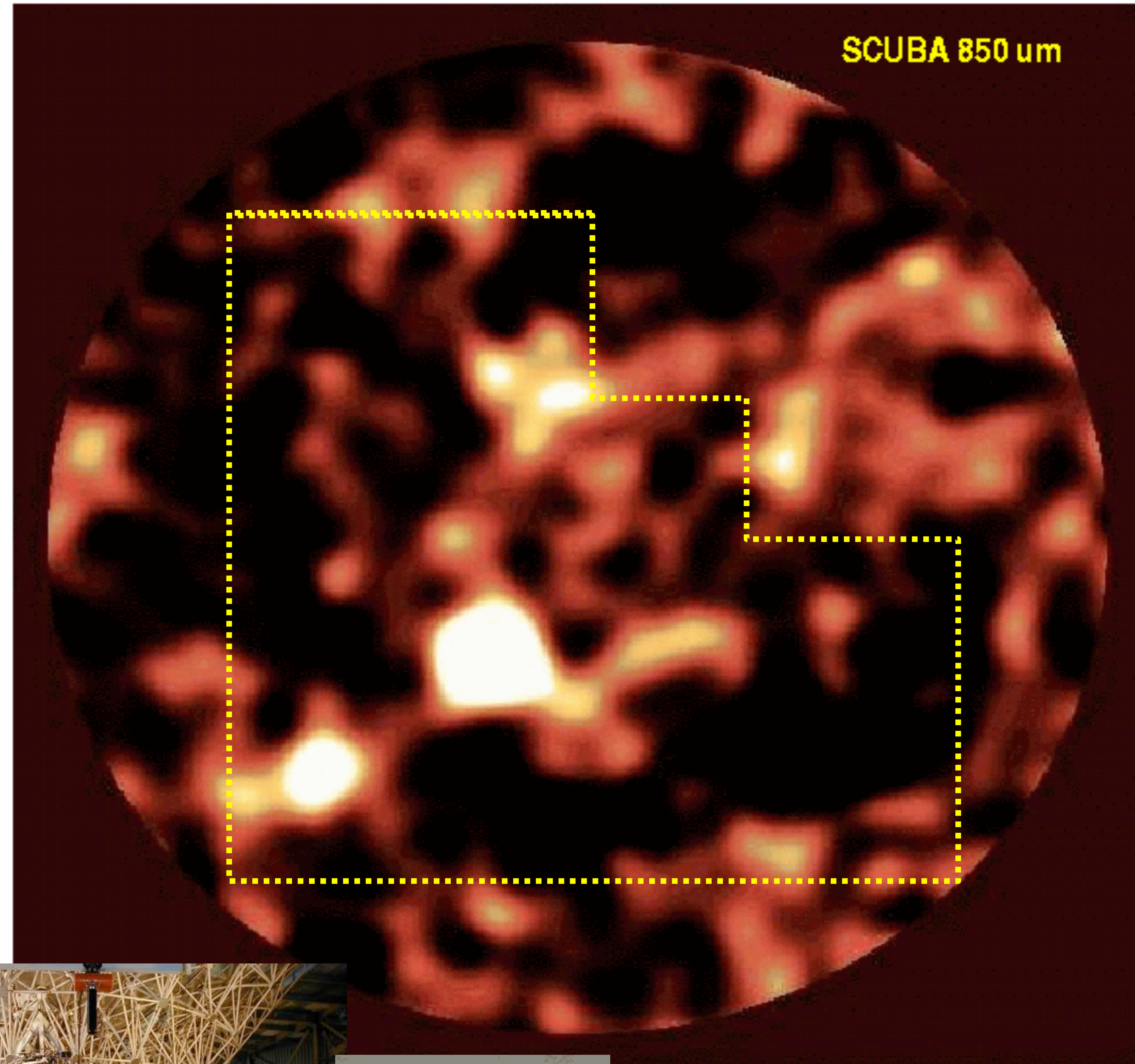


The starburst is hidden behind dense dust clouds

The submillimeter extragalactic Background

The Hubble Deep Field

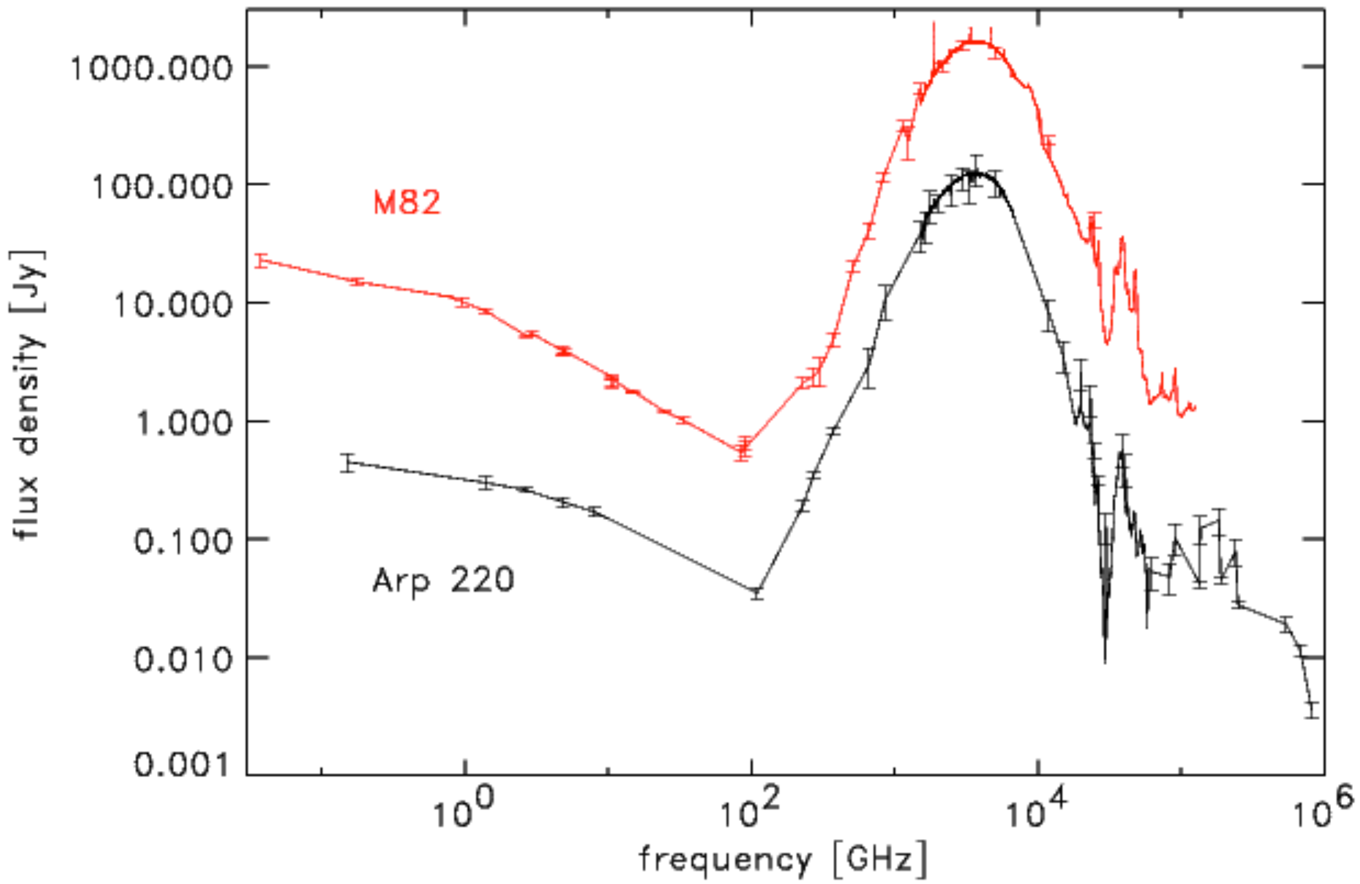


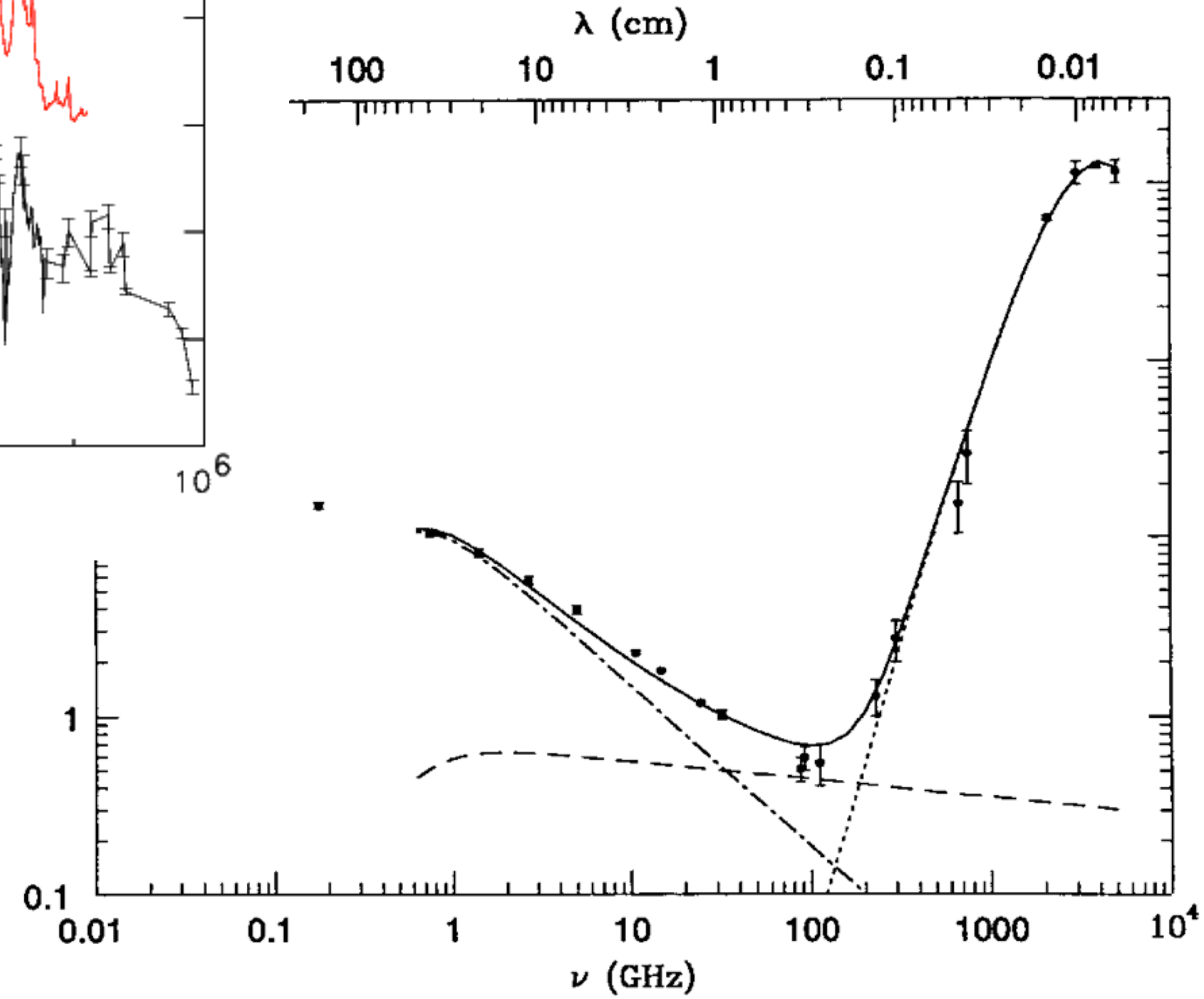


Hughes et al. 1998

SCUBA first resolved
the submm background

SED of starbursts





Distant starbursts

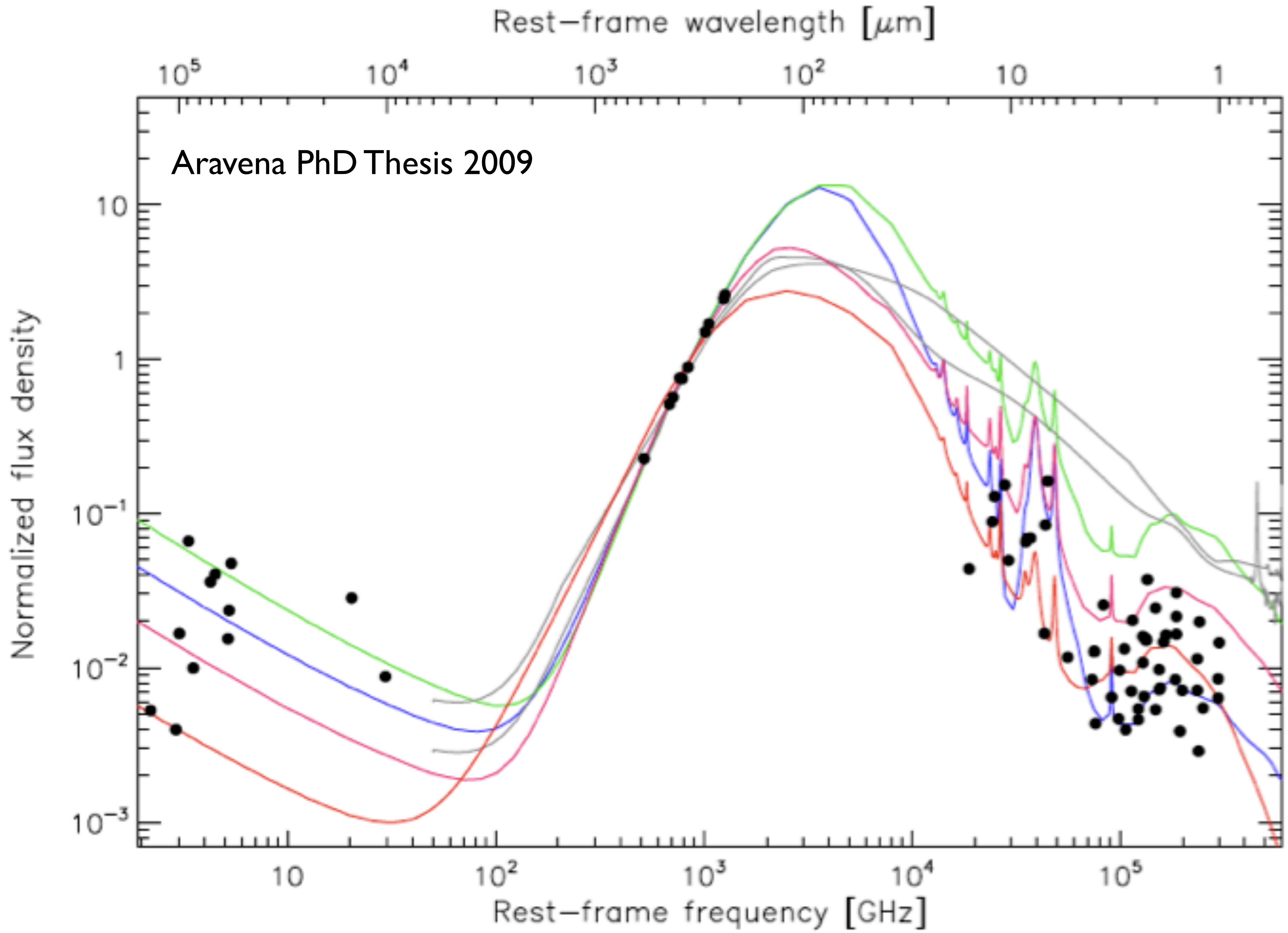
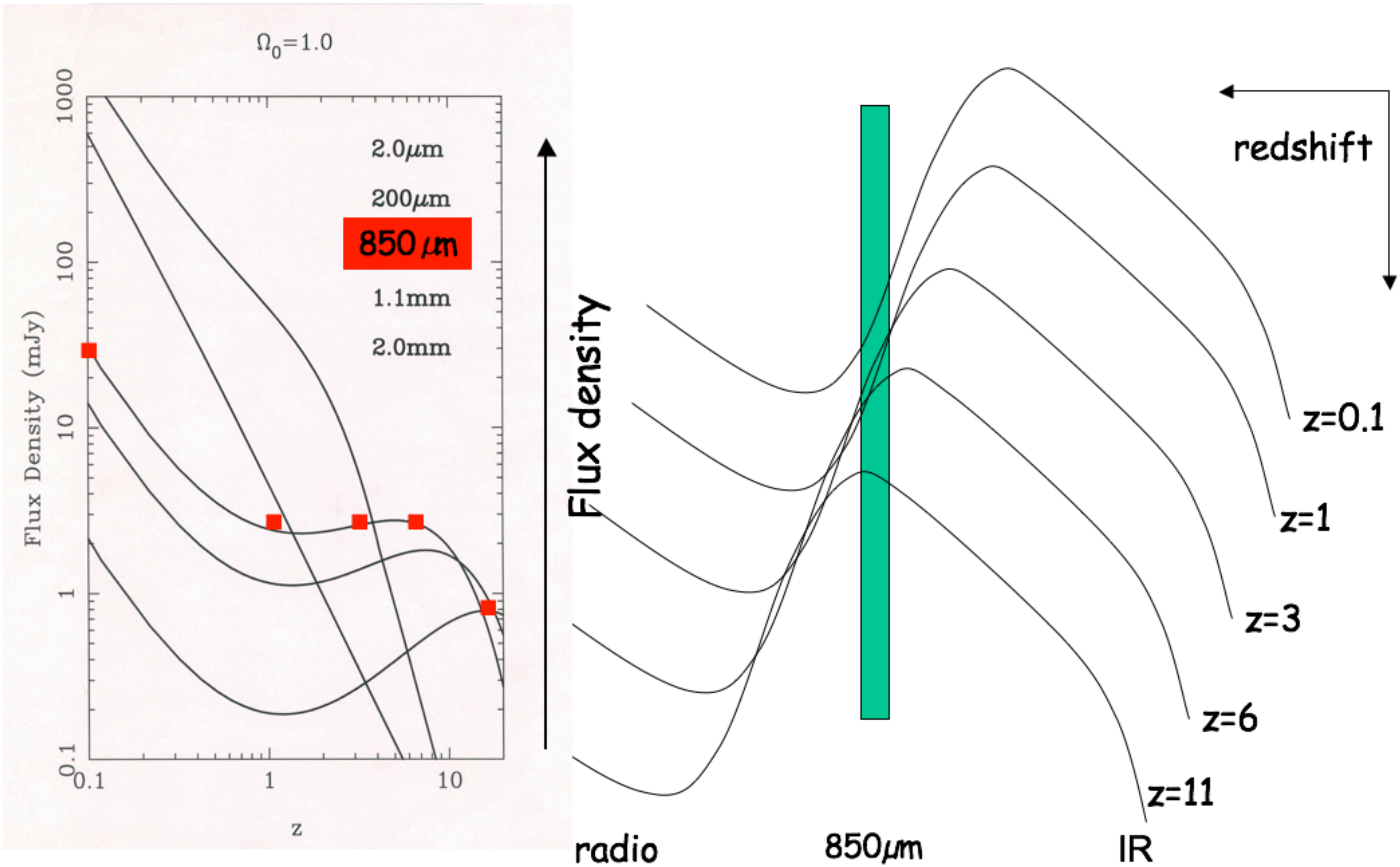
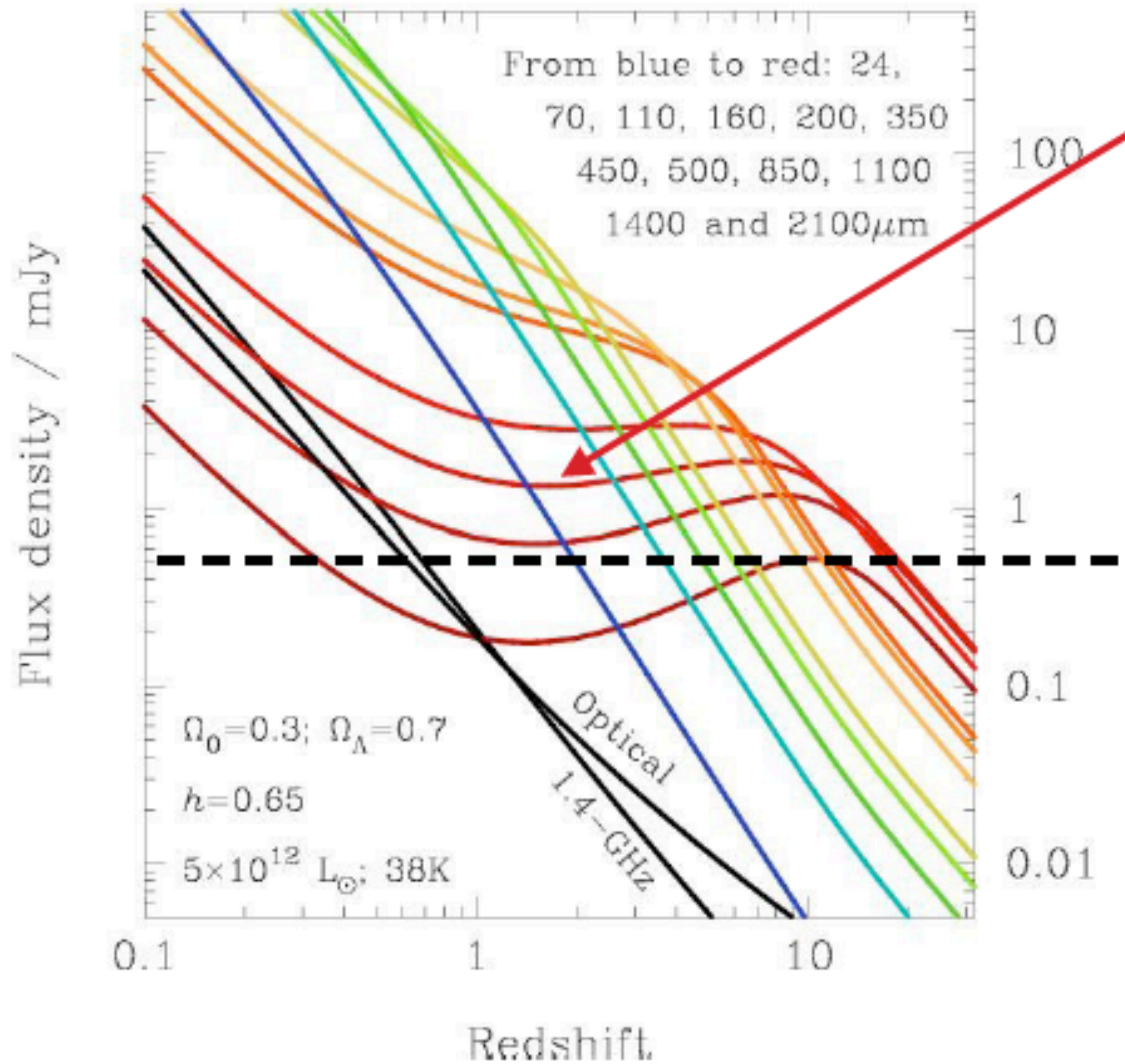


Figure 1.4: *Various observed restframe spectral energy distributions (SEDs) of starburst galaxies and QSOs from the radio to the optical wavebands normalized to unity at 350 μm. Solid curves represent model SEDs for three luminous low-redshift starburst galaxies Arp220 (blue), M82 (green) and NGC6090 (magenta), and for an extremely red object (ERO) at $z = 1.44$, HR10 (red), from Silva et al. (1998). The grey curves show the model SEDs for a QSO type-1 and type-2 from Polletta et al. (2007). Filled circles show the multi-frequency SED for SMGs detected in the Hubble Deep Field North (HDF-N), from Pope et al. (2006).*

Negative k-correction



Negative k-correction



At $\lambda \sim 1$ mm detecting a source at z=10 is as easy as at z=1

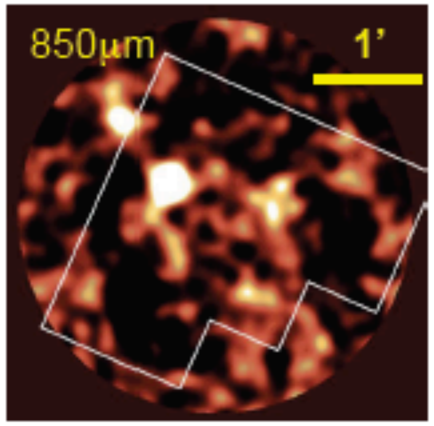
~ limit of current surveys

$\Rightarrow L>10^{12}\ L_\odot$ at 1<z<10

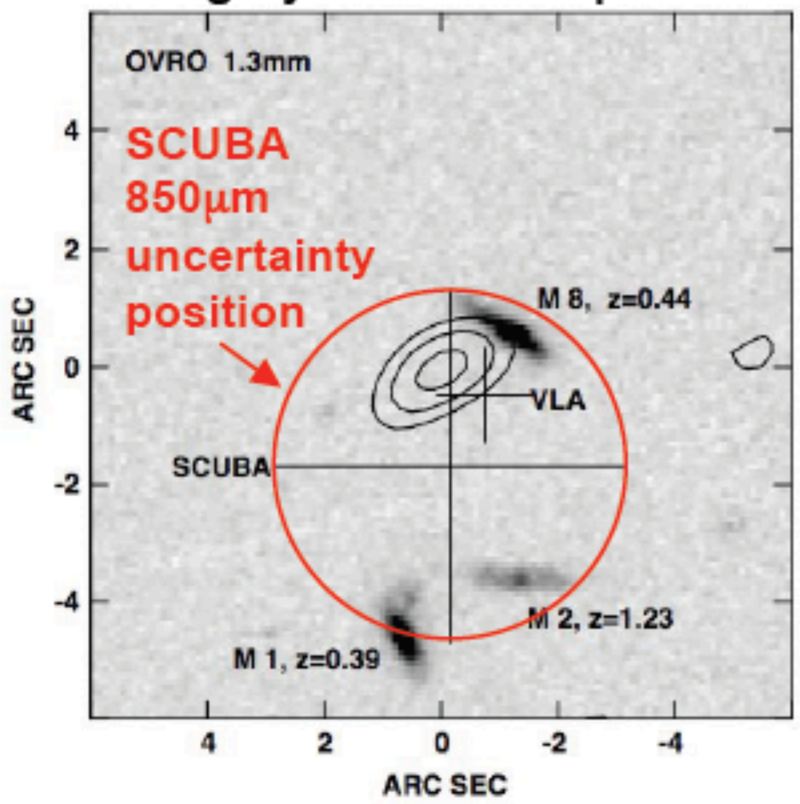
Finding counterparts for redshifts

The low angular resolution of past/current submm facilities has been a major problem for the optical and spectroscopic identification of high-z Submm Galaxies (**SMG**)

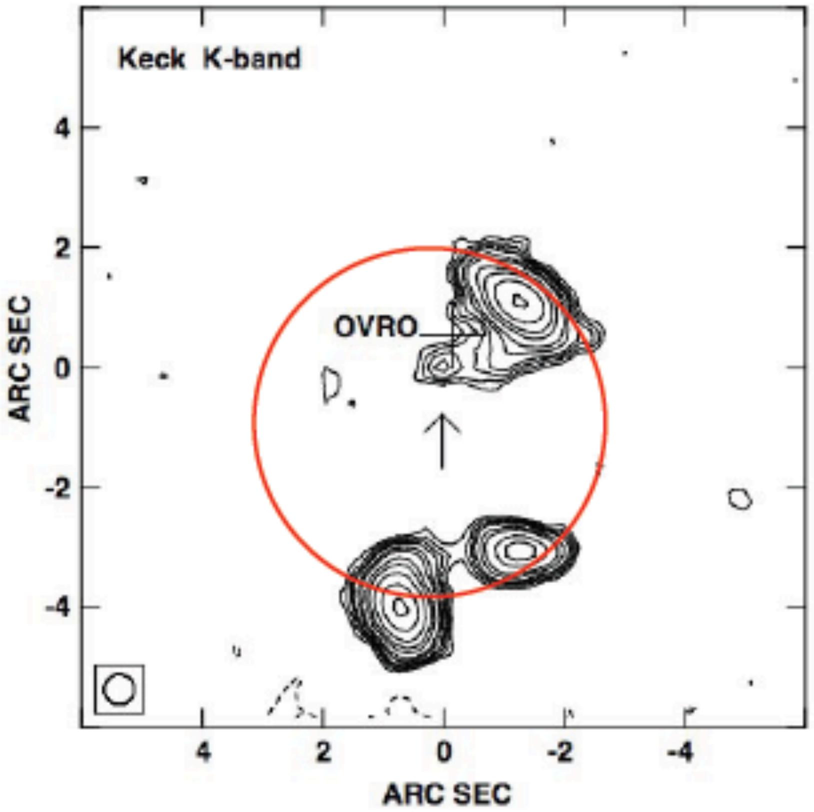
deep SCUBA map (HDF)



grayscale HST optical

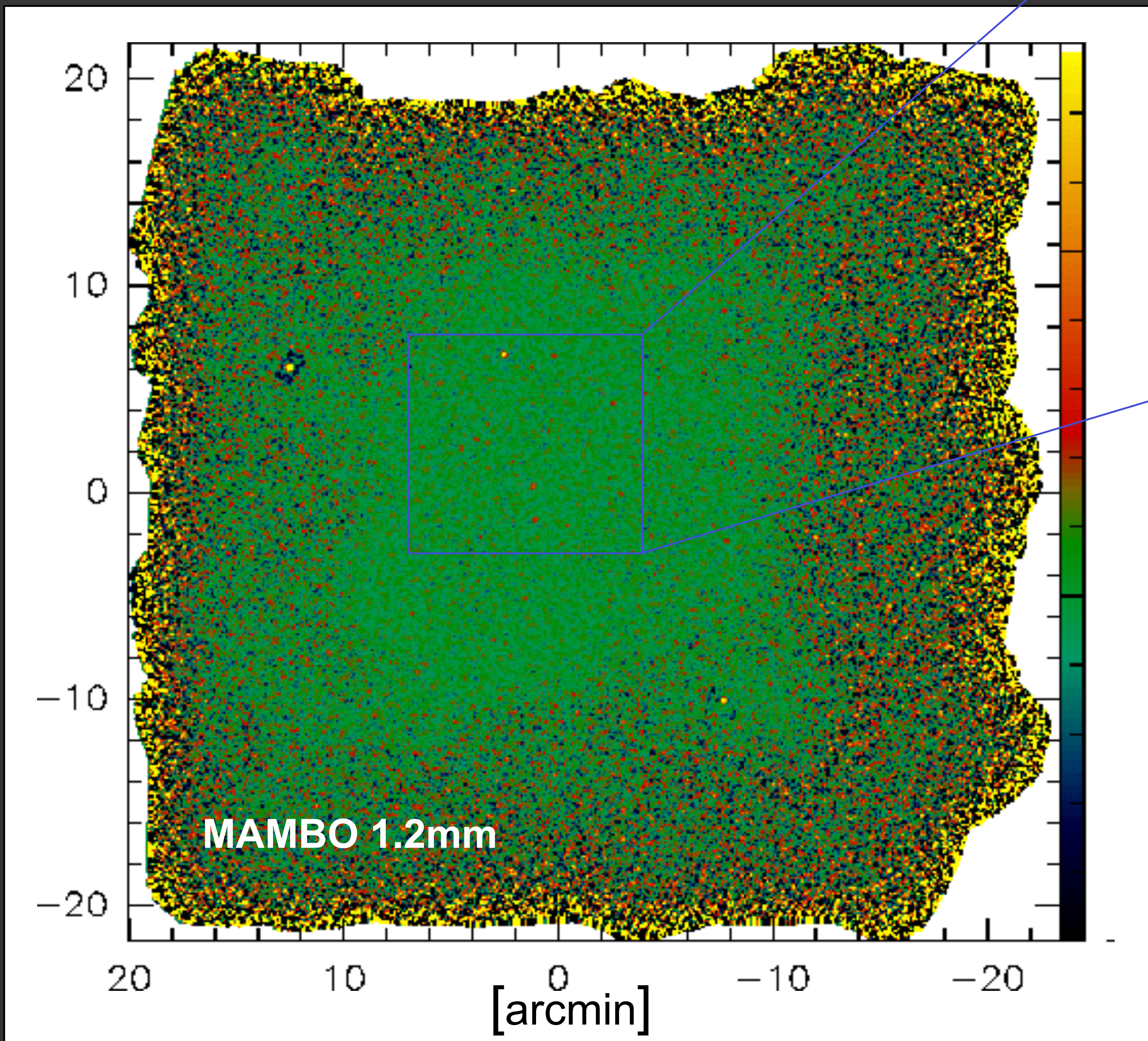


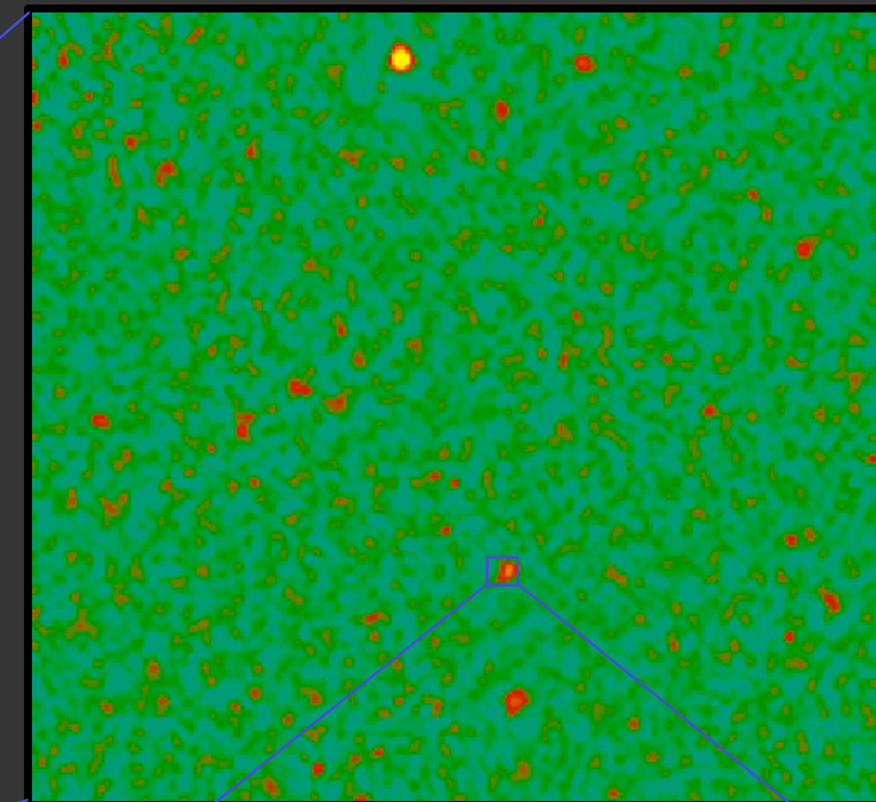
near-IR (2μm) image

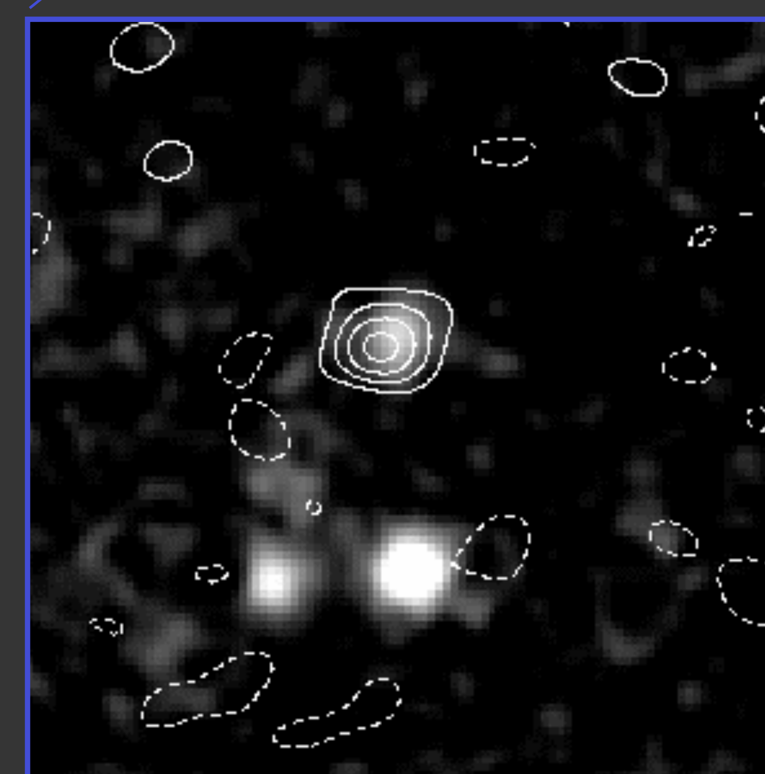


mm “Blank Field Surveys”

vigorous starbursts (HLIRGs) and QSOs



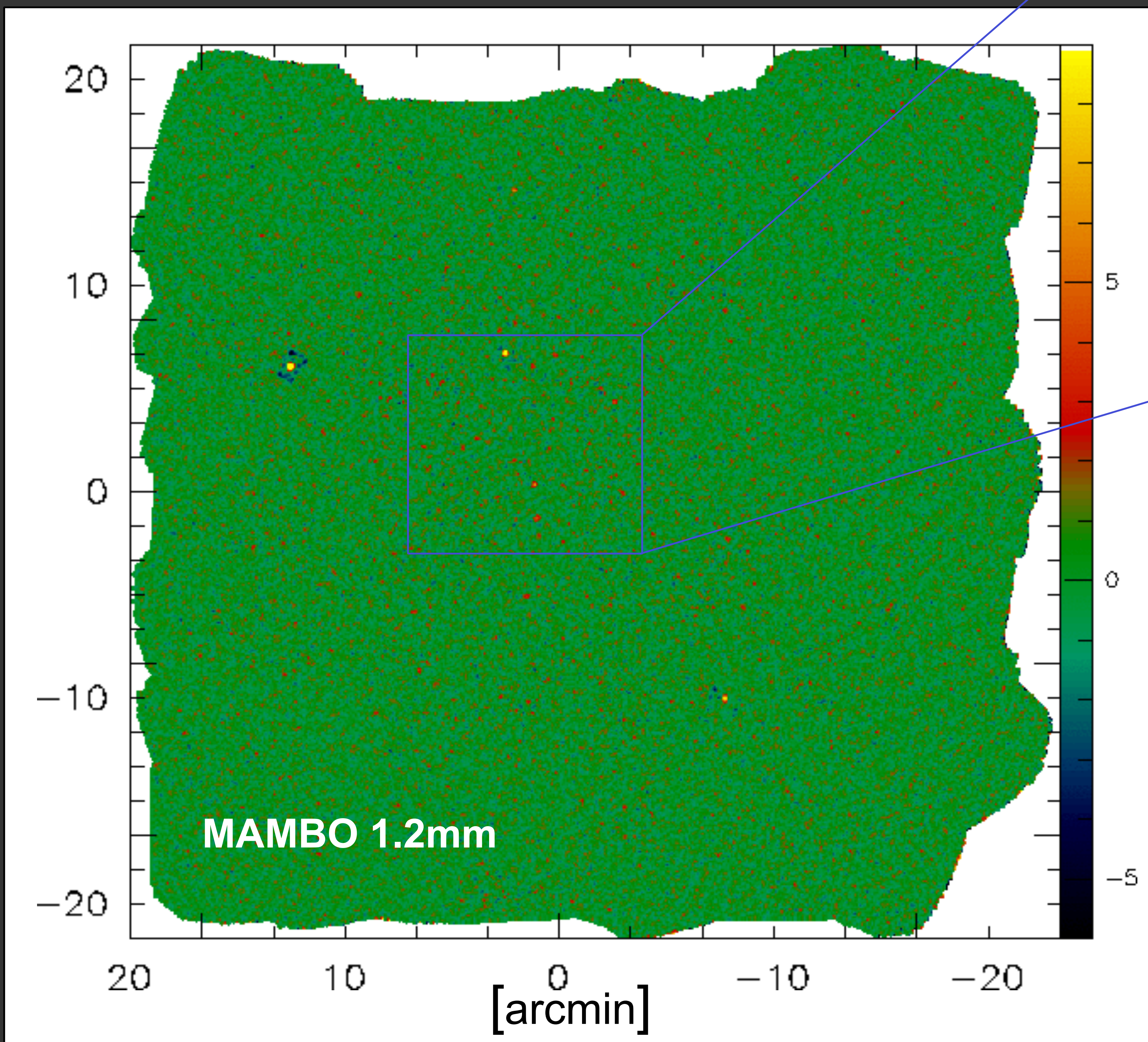


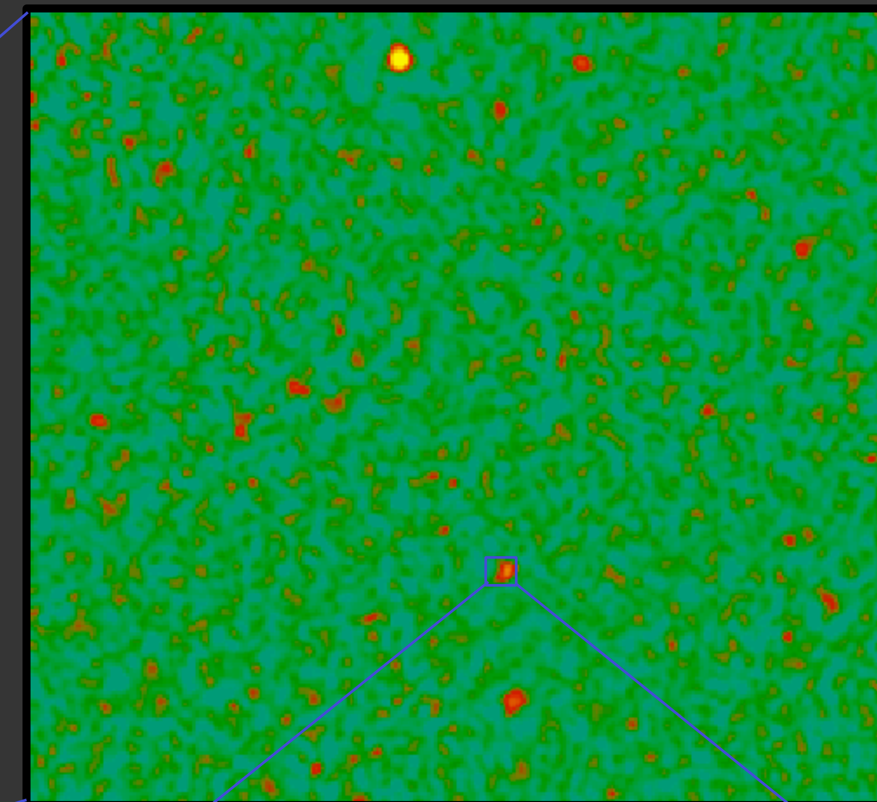


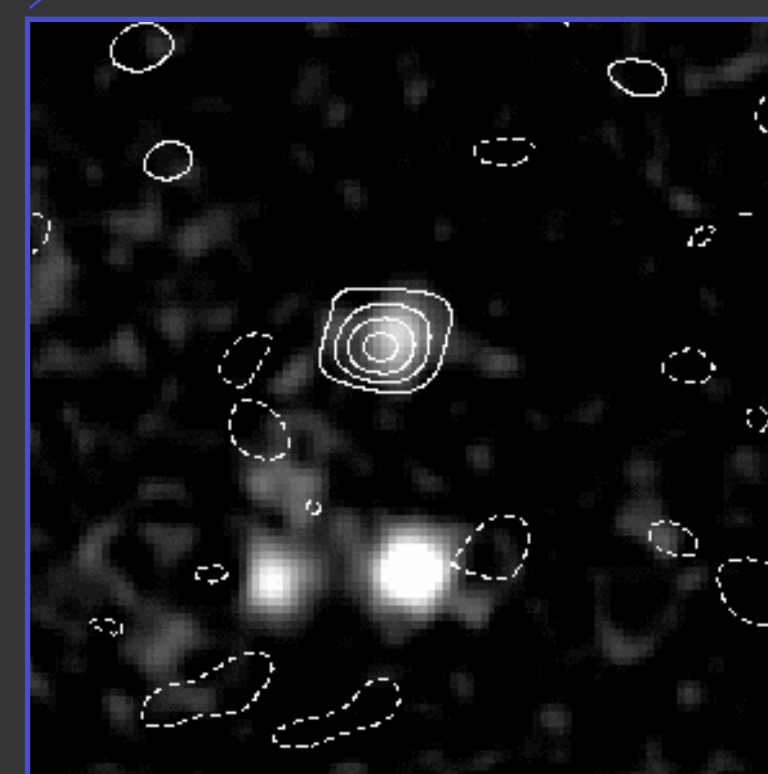
Near-IR (K band) plus
radio 1.4 GHz contours

mm "Blank Field Surveys"

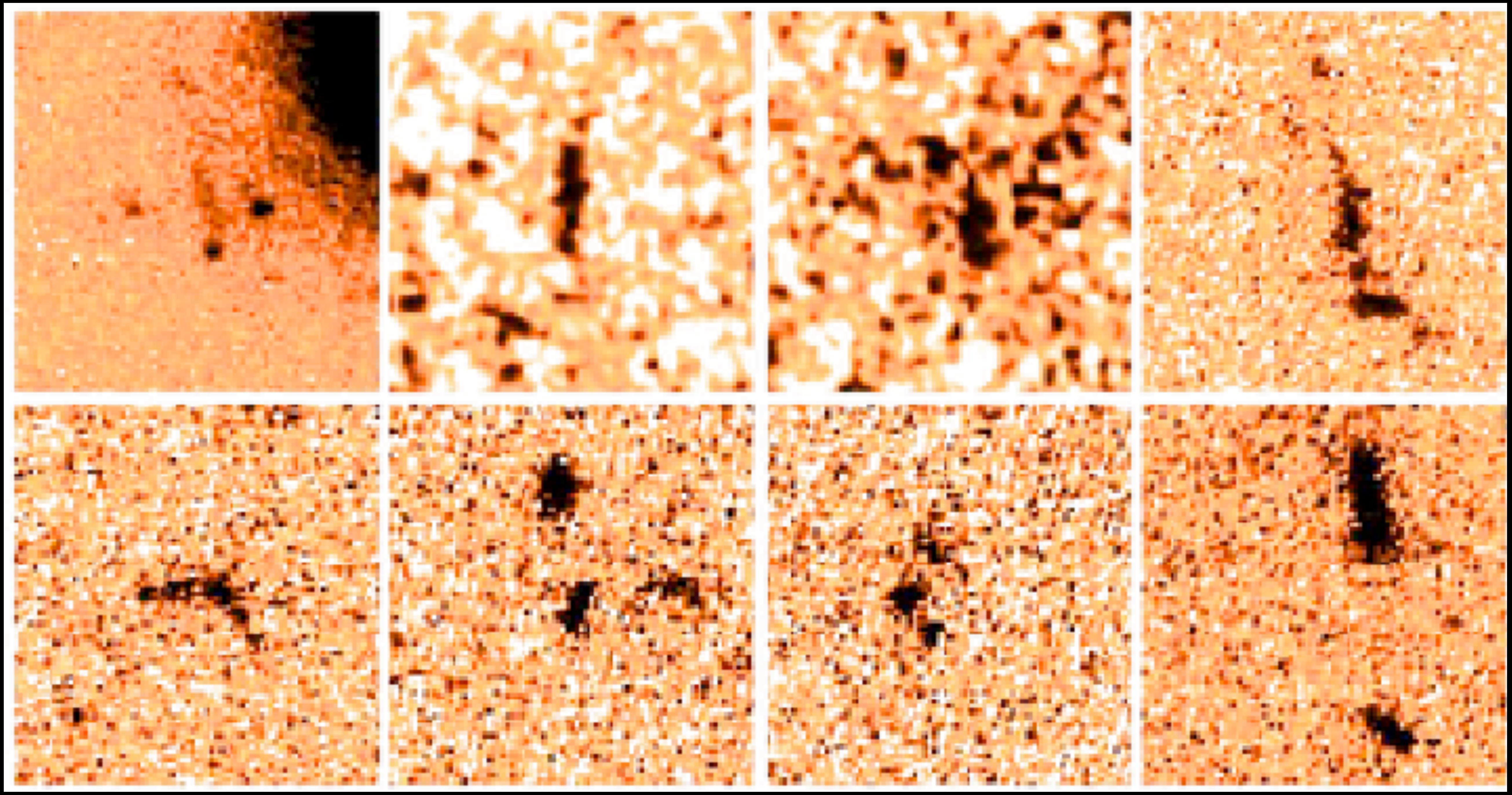
vigorous starbursts (HLIRGs) and QSOs





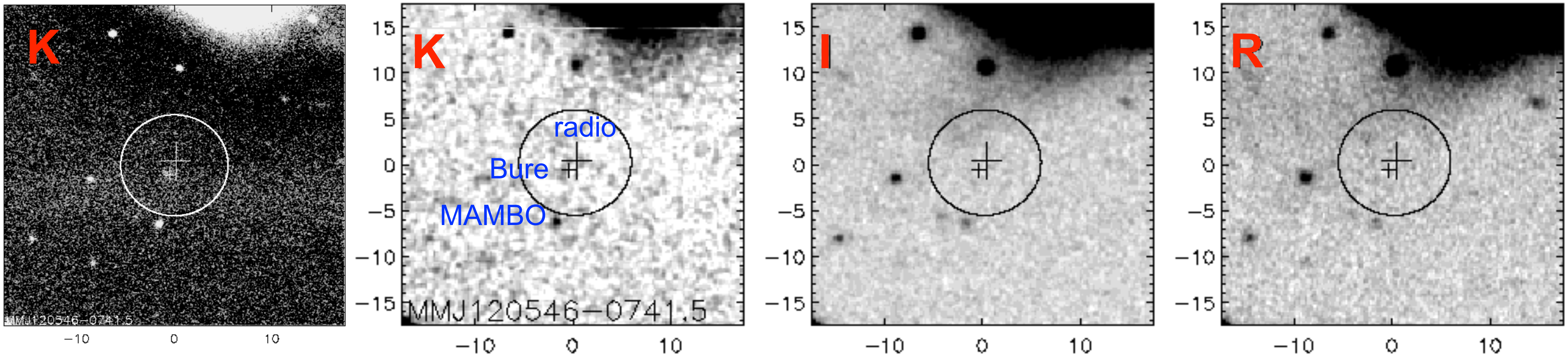


Near-IR (K band) plus radio 1.4 GHz contours

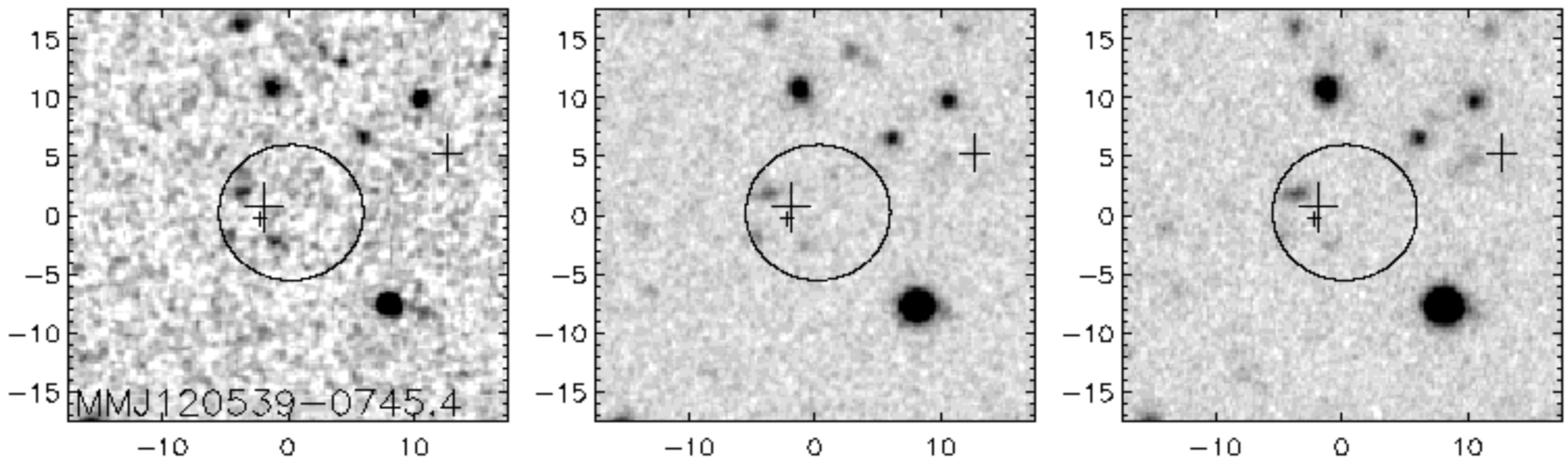


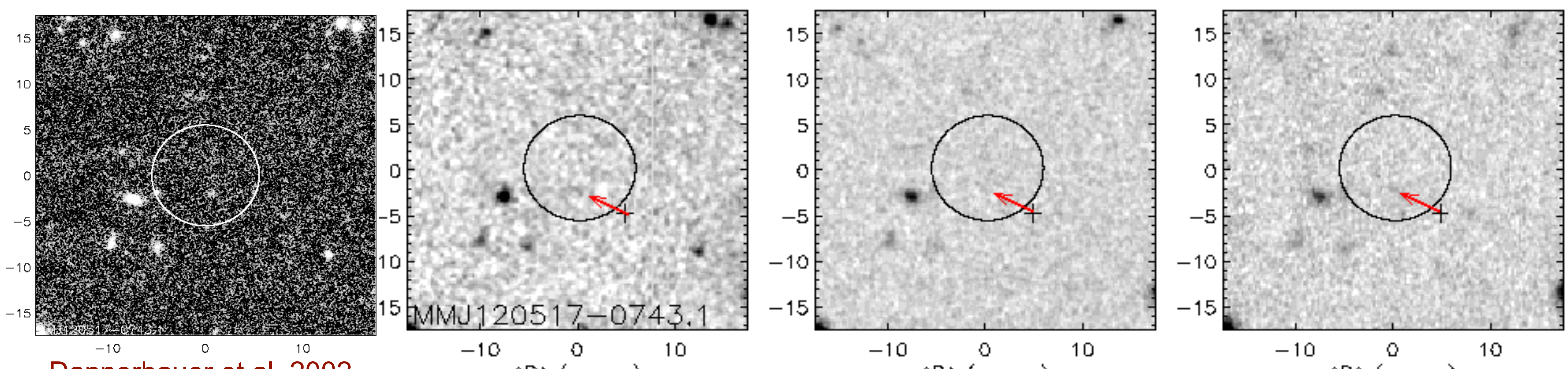
HST images of submm galaxies (Chapman et al.)

apparently these are interacting, irregular systems



Optical counterparts are very faint!

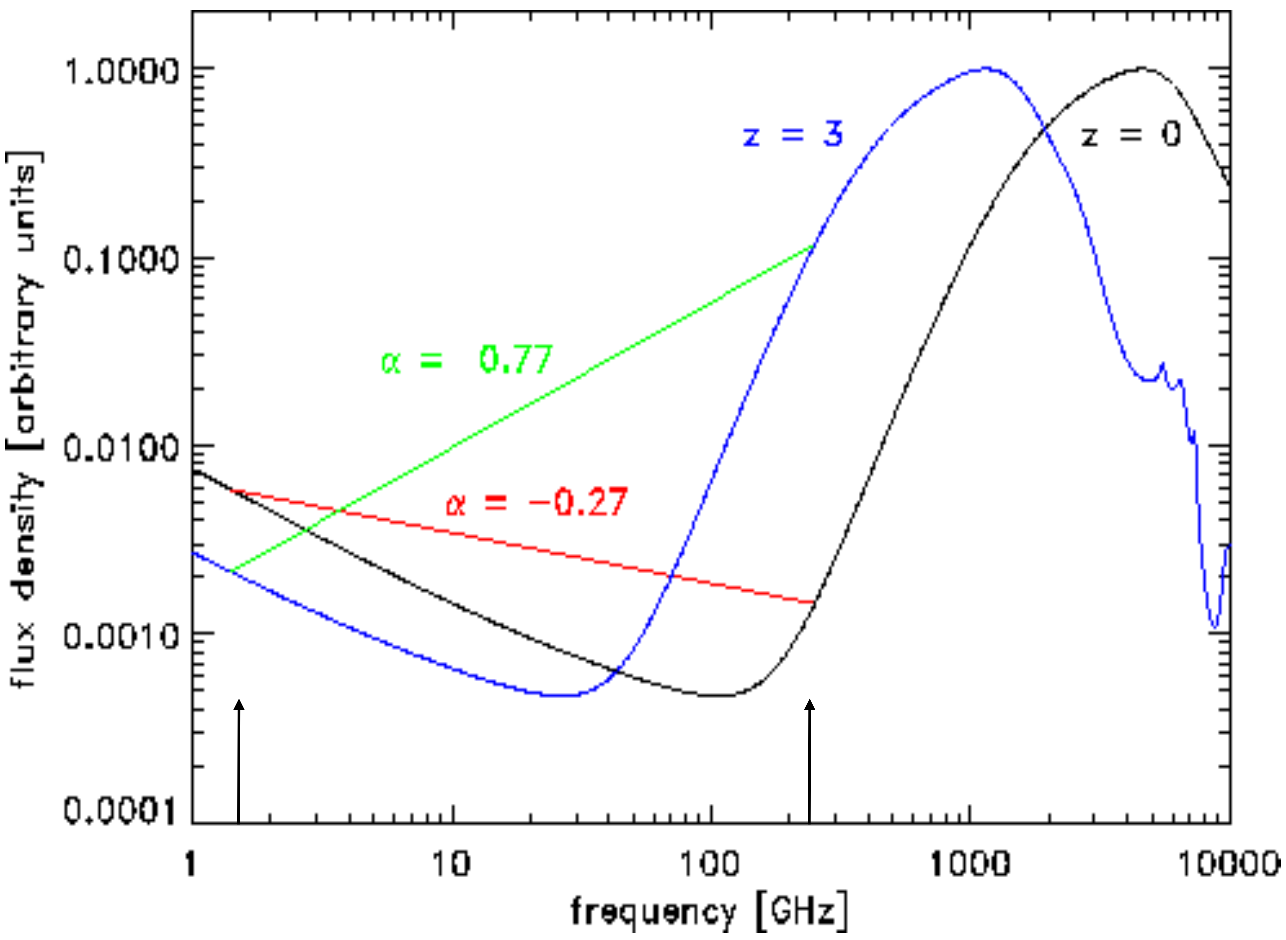


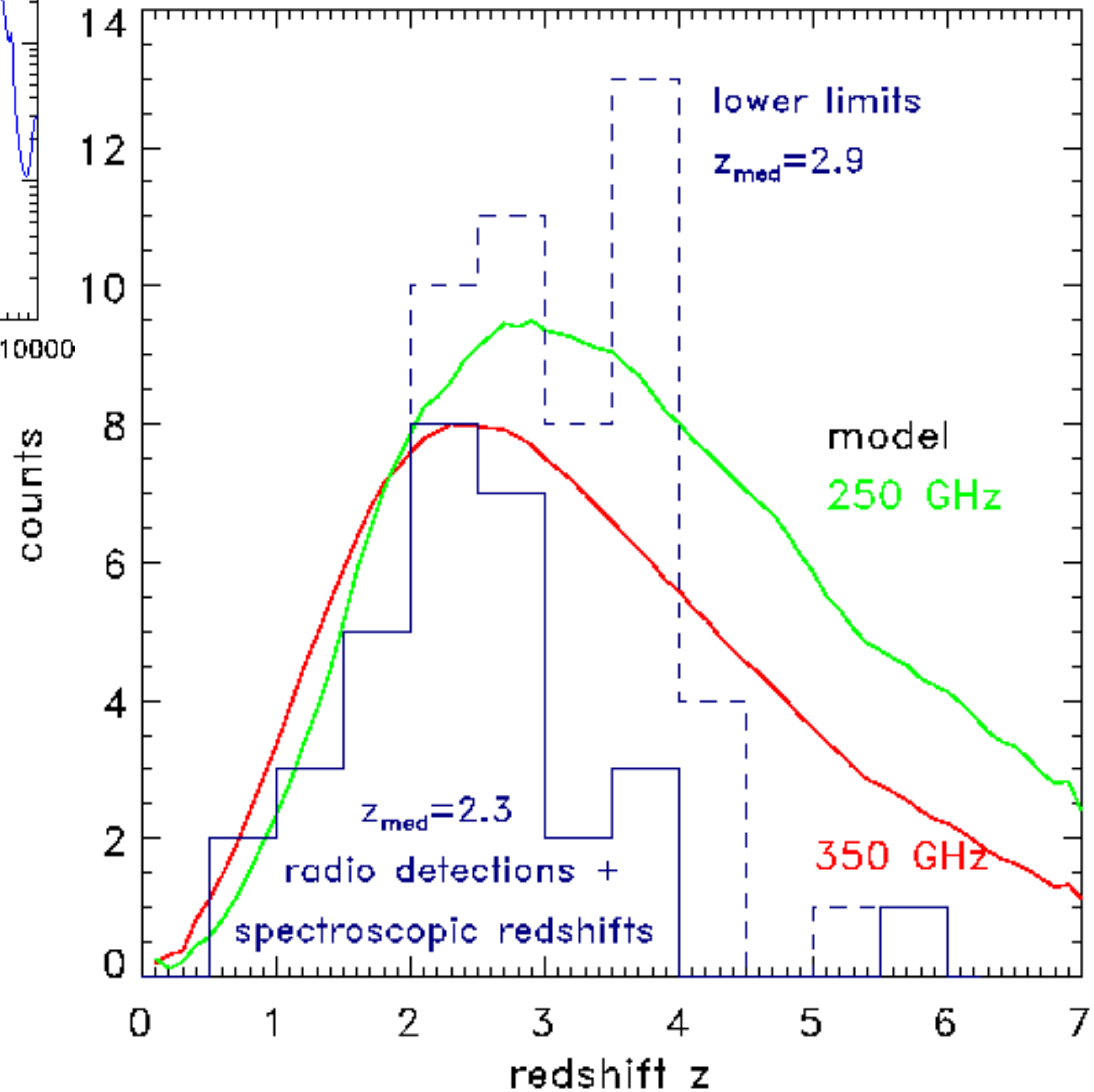


Dannerbauer et al. 2002

Redshift Distribution

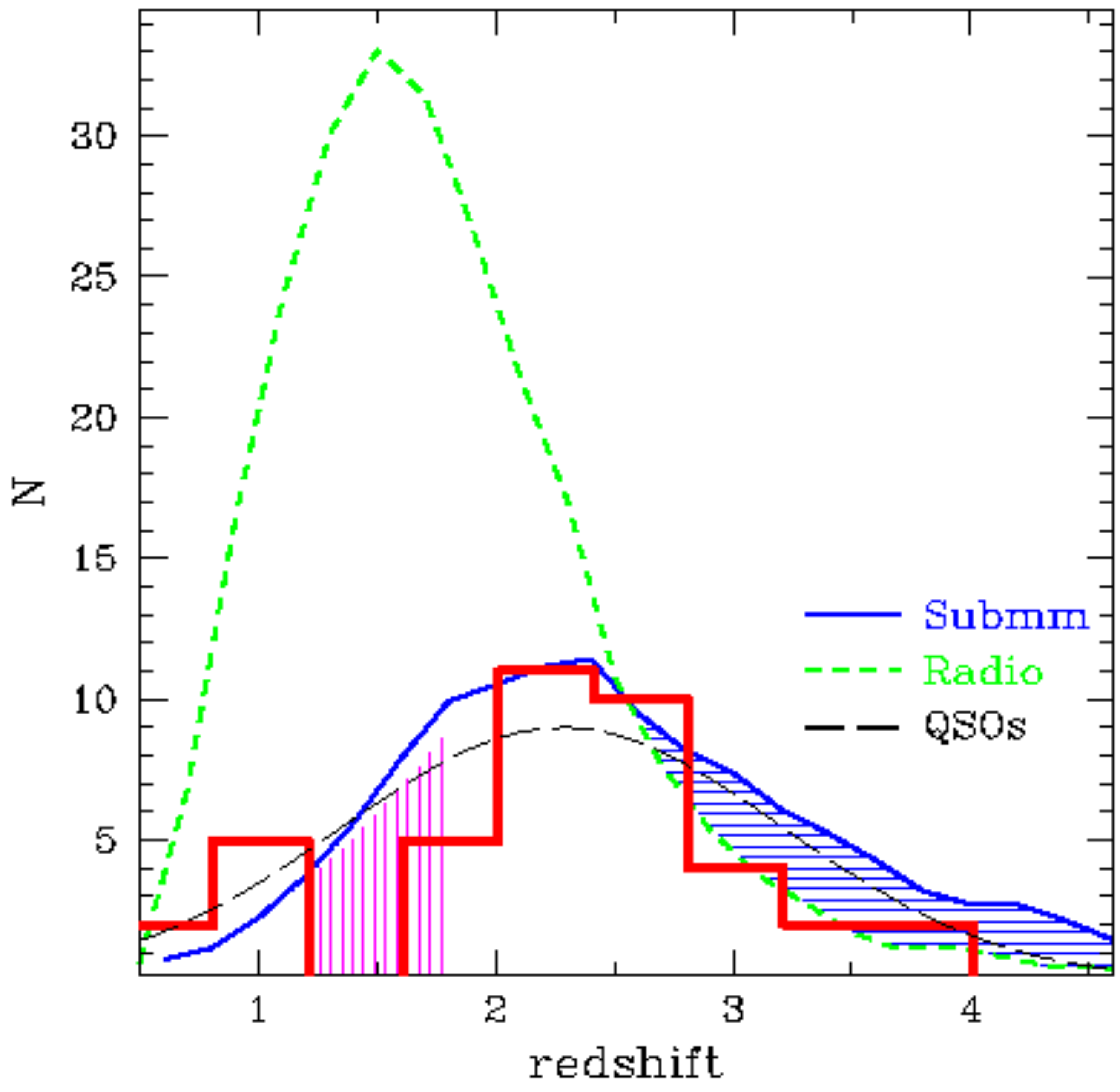
estimated from the mm/radio flux ratio, which steepens with increasing z.





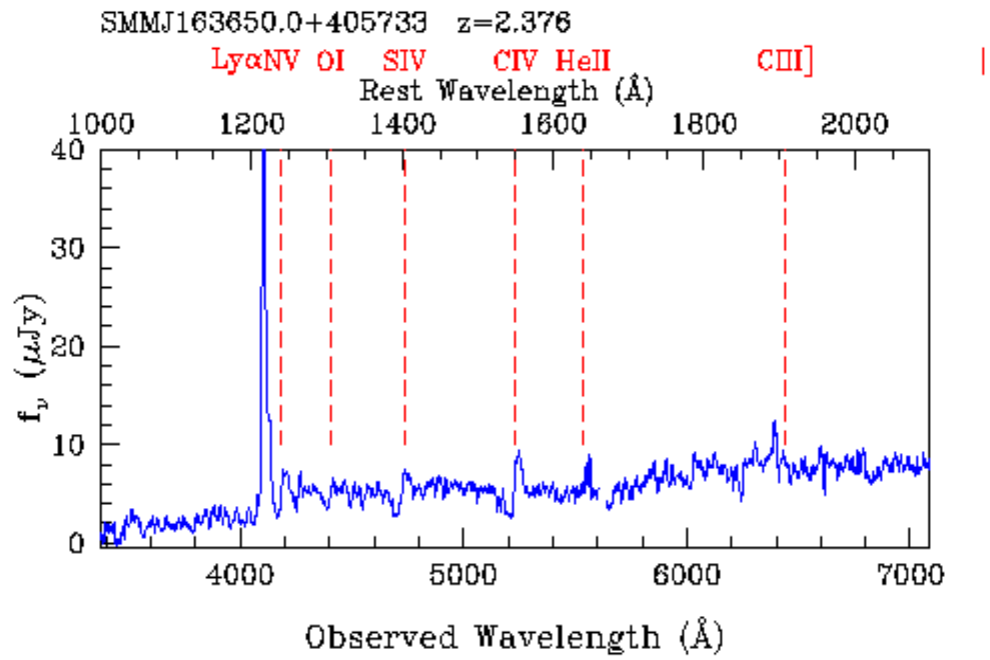
Aretxaga et al. 2007

Redshift distribution of SMGs



Chapman, Blain, Ivison & Smail 2003

KECK spectroscopy of SCUBA/MAMBO galaxies

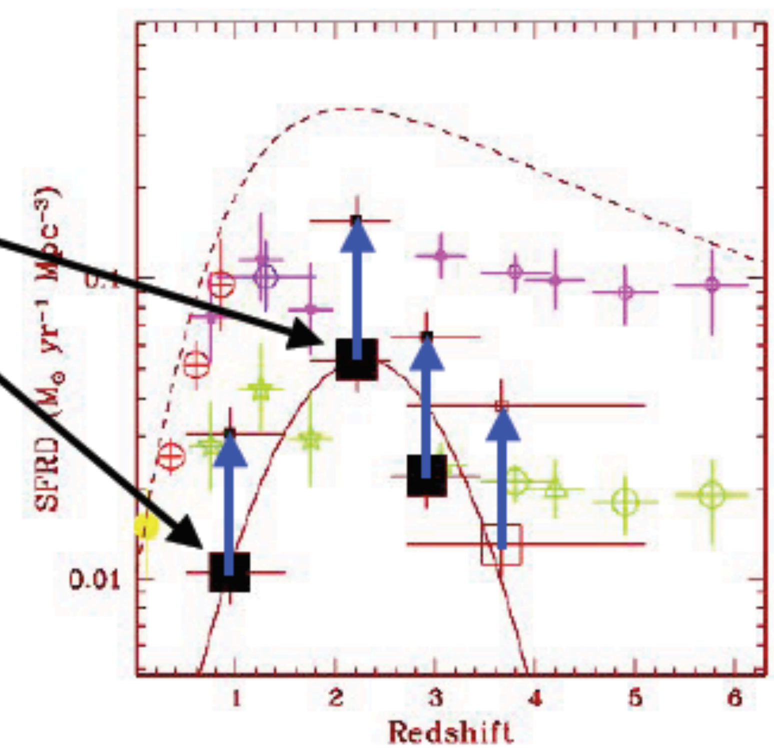


- SMGs are at high z.
- radio-submm photo-z agree on average with spectroscopic z
- radio selection introduces bias against z>3.

It has been very difficult to follow up SMGs without radio counterparts: potentially high-z or cold dust.

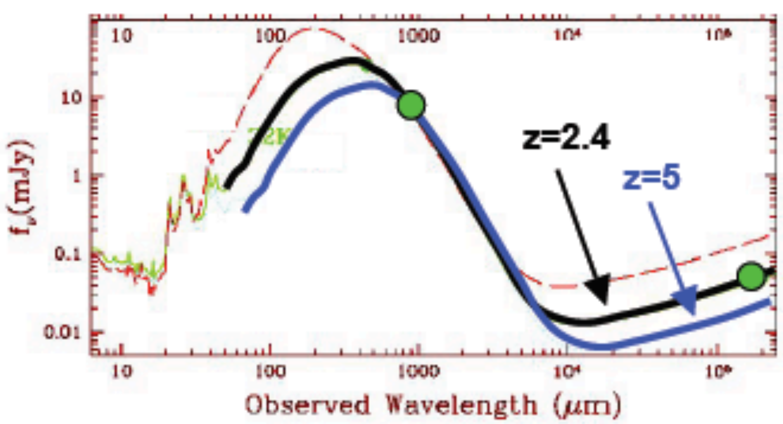
Problems with inferred SF

Inferred evolution of the cosmic star formation rate



Problems:

- Current submm surveys only sample extremely luminous objects (L_{IR}>10^{12} $L_\odot$, the tip of the iceberg) correct to “real” SFR with models



-Radio identification prevents the identification of high-z sources (radio K-correction goes other way)
- Also bias against cool SED

-The optical (=UV rest frame) spectroscopic identification has missed the most obscured objects

Cosmic star formation history

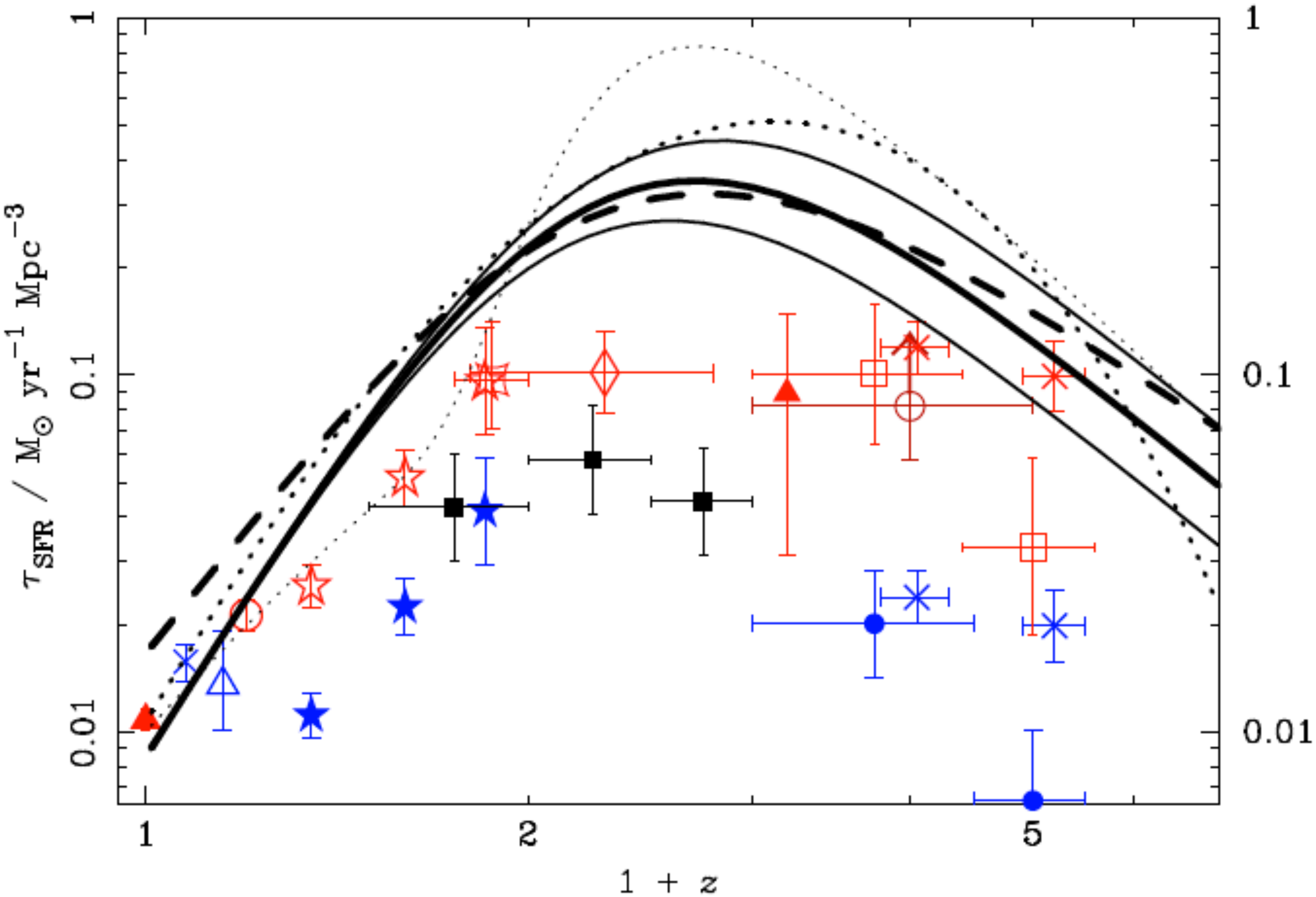
- **Studying the star formation history (temporal evolution of the star formation is key in understanding galaxy evolution in its broader context**

The star formation rate (SFR) is the key driver of structure evolution in the ISM, and strongly influences galaxy formation and evolution via energy, momentum, and chemical feedback from subsequent stellar winds and supernova explosions.

- UV emission from the first generation of massive stars is most likely responsible for the re-ionization of the Universe at $z > 6$, and the integrated light of evolving stellar populations generated a diffuse cosmic IR to X-ray backgrounds.

- IR-UV continuum emission and optical line emission can be used to determine the specific SFR in galaxies, and an extinction corrected rate density, SFR(z), can be estimated.

Energy generation in the universe



Field redshift surveys to z~1 (Lilly et al 1996, Ellis et al 1996)

Counts of LBGs at z>2 (Madau et al 1996)

Lilly-Madau plot: Observations (data points) and theoretical models based on hierarchical structure formation (lines). The normalization assumes Salpeter IMF. From review by A. Blain (2002).

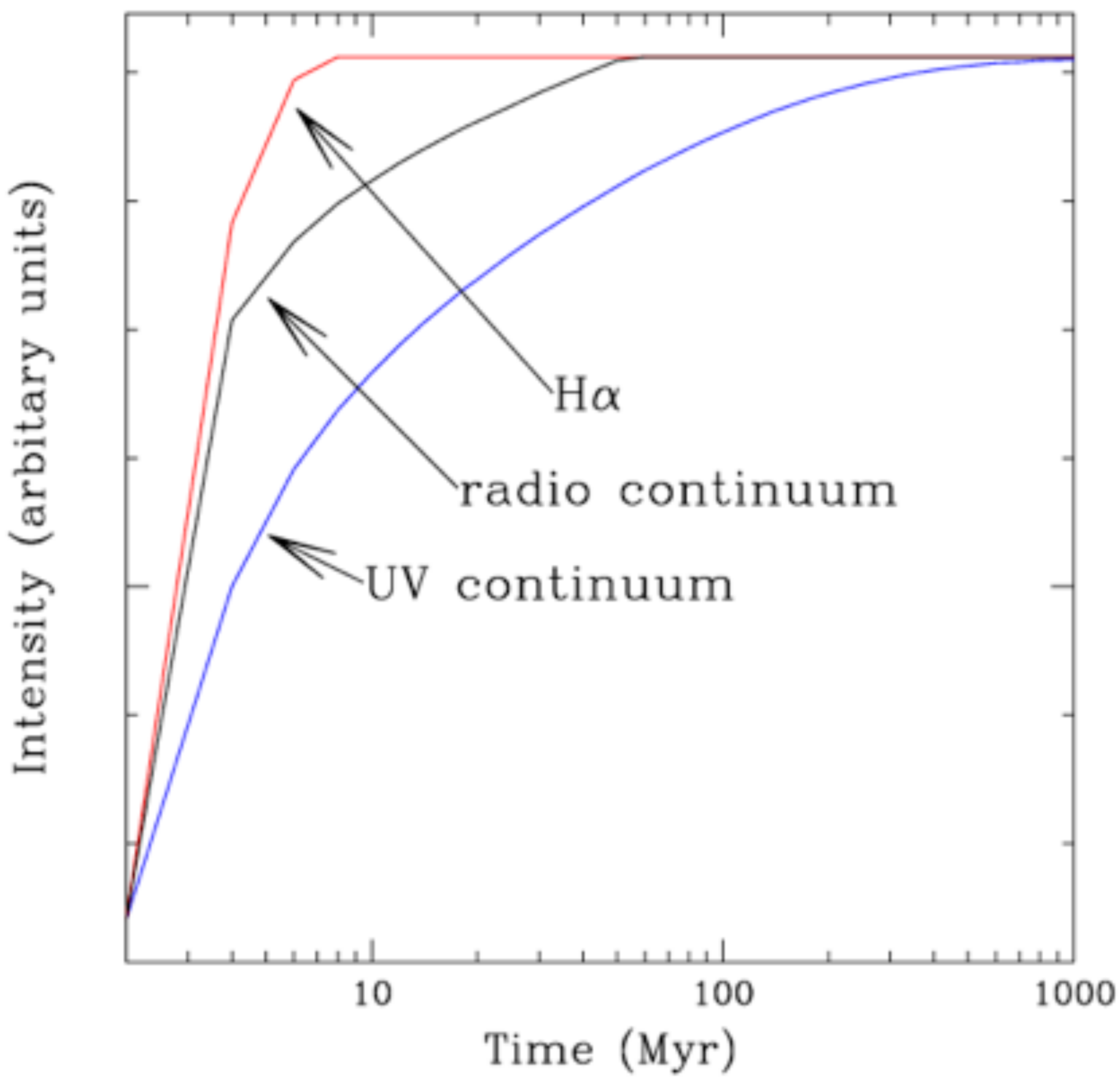
Star formation indicators

Various probes of the global SF rate:
$\rho_*(z)$ $M_\odot$ yr^{-1} comoving Mpc^{-3}

- UV continuum (GALEX, LBGs)
- H and [O II] emission in spectroscopic surveys
- mid-IR dust emission
- 1.4 GHz radio emission

No simple “best method”: each has pros and cons (dust extinction, sample depth, z range and physical calibration uncertainties)

Each has different time-sensitivity to main sequence activity so if SFR not uniform do not expect same answers for the same sources



Cosmic SF: Calibration

1. **UV continuum (1250-2500 Å) :**
   Pro: Extensive datasets over $0<z<6$: easily calibrated via MS models
   $M>5M_\odot$, timescales $>10^8$ yr, calibration largely independent of I
   Con: dust! (A < 3 mag); IMF-dependent

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 1.4 \times 10^{-28} L_\nu (\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

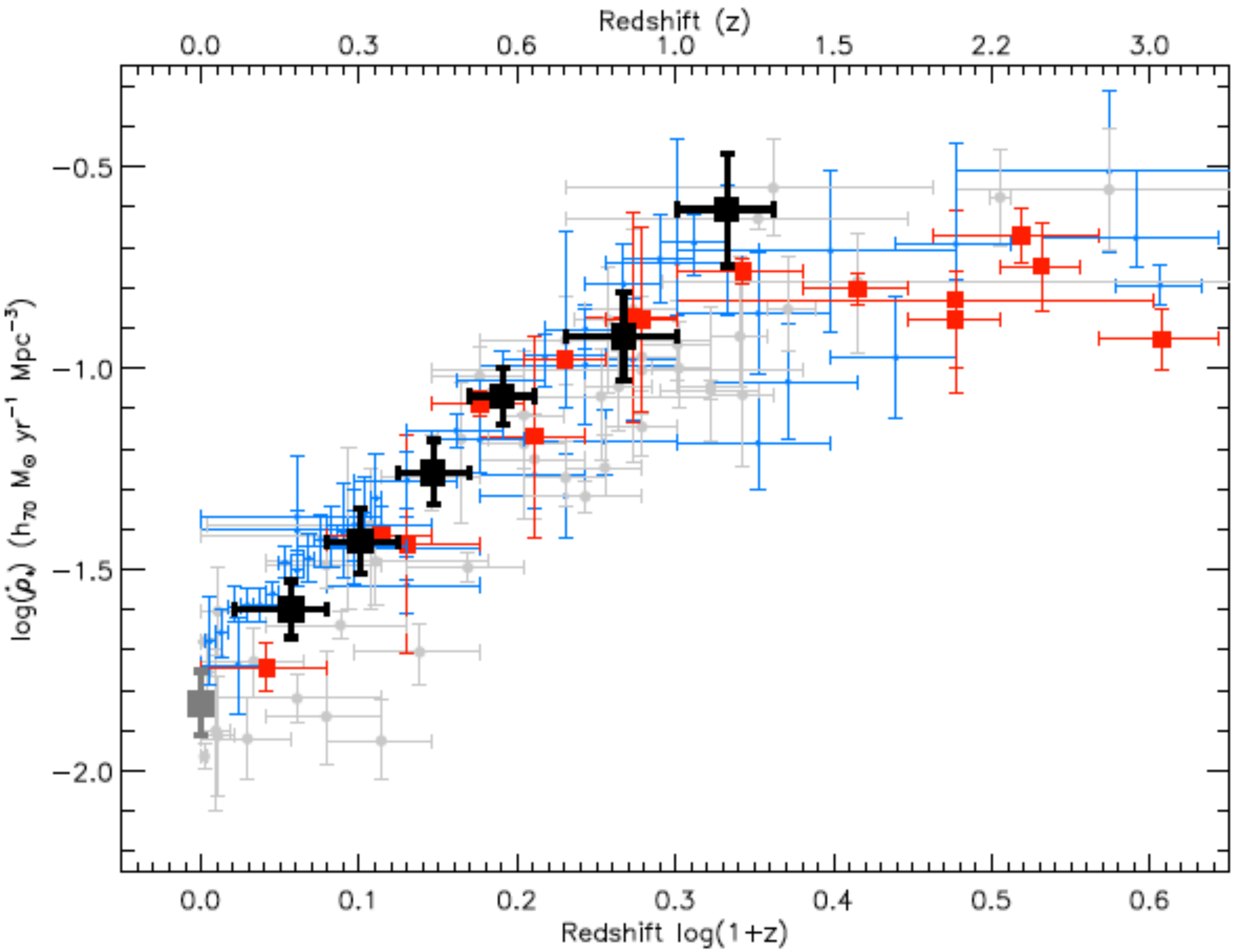
2. **Line emission (Hα, [O II] :**
   Pro: Very sensitive probe, available to z~2: $M>10M_\odot$ timescales $<10^6$ yr,
   Con: uncertain fesc of ionizing photons; strong IMF-dependence (×3),
   excitation uncertainties [OII]

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 7.9 \times 10^{-42}\ L(\mathrm{H}\alpha)\ (\mathrm{ergs\ s^{-1}})$$
$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[\mathrm{OII}]\ (\mathrm{ergs\ \ s^{-1}}),$$

3. **Far IR emission (10-300 μm) :**
   Pro: Independent method, available for obscured sources to high z:
   Con: uncertain source of dust heating (AGN/SF?); age of stellar popn,
   primarily applicable in starbursts, bolometric FIR flux required

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})\ (\mathrm{starbursts}),$$

Star-formation in the universe



State of the art: Mesurement of cosmic star formation history, taken from Rojopakarn et al. 2010 (black = 24μ rest frame luminosity, blue = extinction corrected UV, red = IR, grey = radio, X-ray, OII, Hα)

Initial Mass Function for stars

Definition: IMF

The stellar initial mass function (IMF) describes the number of newly formed stars per mass interval:

$$\xi(m) = \frac{dN_*}{dm} \, .$$

Why it is important?

- Link between stellar and galactic evolution
- Insight into theories of star formation

Salpeter IMF

The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He obtained:

$$\xi(M) = \xi_0 M^{-2.35}$$

Salpeter IMF

$\uparrow$ constant which sets the local stellar density

Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\xi(M)\Delta M$

To determine the total number of stars formed with masses between M_1 and M_2, integrate the IMF between these limits:

$$N = \int_{M_1}^{M_2} \xi(M)dM = \xi_0 \int_{M_1}^{M_2} M^{-2.35} dM$$

$$= \xi_0 \left[\frac{M^{-1.35}}{-1.35} \right]_{M_1}^{M_2} = \frac{\xi_0}{1.35} \left[M_1^{-1.35} - M_2^{-1.35} \right]$$

Salpeter IMF at low mass

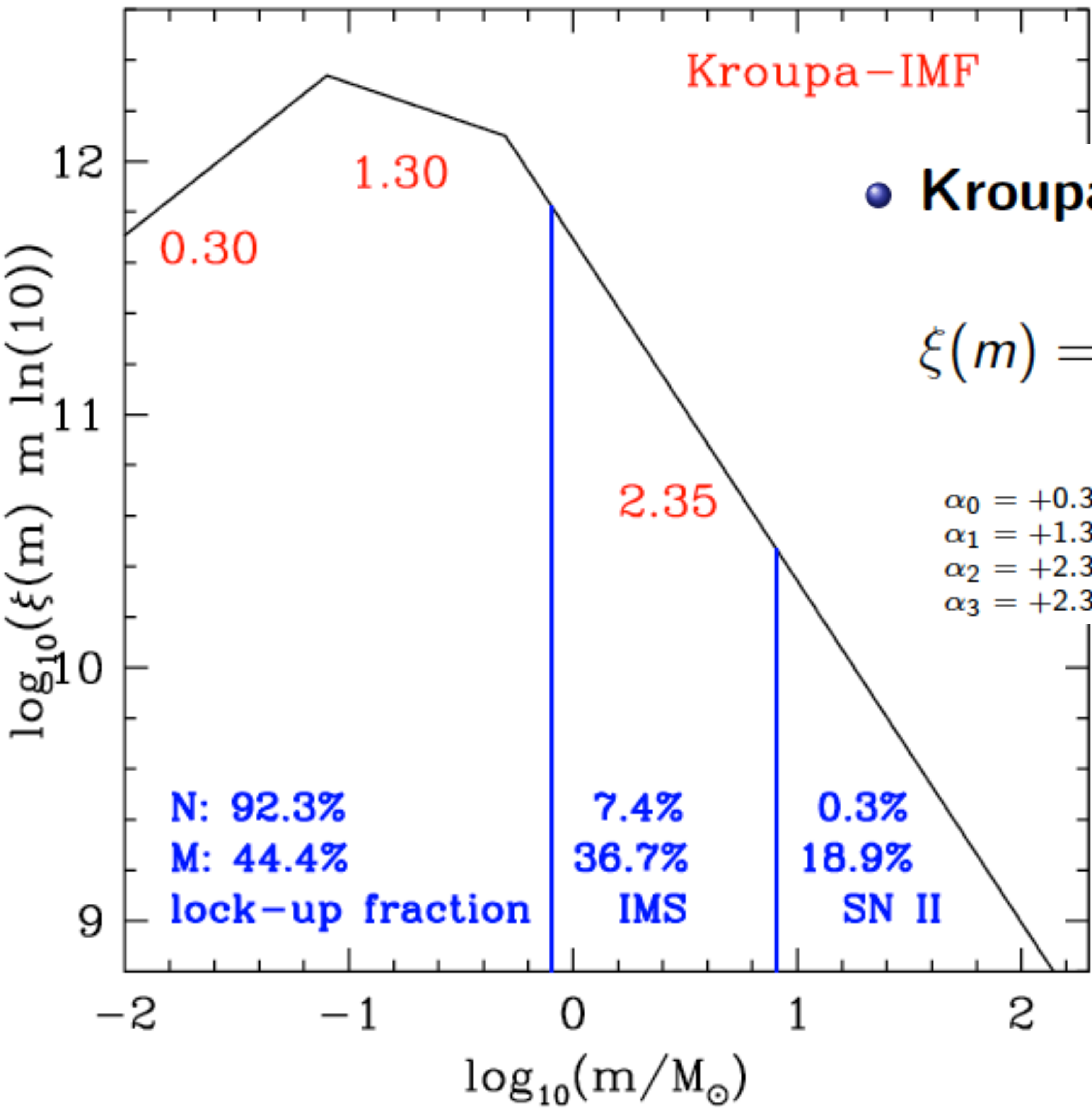
Properties of the Salpeter IMF:

- most of the stars (by number) are low mass stars
- most of the **mass** in stars resides in low mass stars
- following a burst of star formation, most of the **luminosity** comes from high mass stars

Salpeter IMF must fail at low masses, since if we extrapolate to arbitrarily low masses the total mass in stars tends to infinity!

Observations suggest that the Salpeter form is valid for roughly $M > 0.5\ M_{sun}$, and that the IMF `flattens' at lower masses. The exact form of the low mass IMF remains uncertain.

Modified stellar IMF



- **Kroupa-IMF** (multi power-law):

$$\xi(m) = k \begin{cases} \left(\frac{m}{m_H}\right)^{-\alpha_0} & , m_{low} \le m < m_H, \\ \left(\frac{m}{m_H}\right)^{-\alpha_1} & , m_H \le m < m_0, \\ \left(\frac{m_0}{m_H}\right)^{-\alpha_1} \left(\frac{m}{m_0}\right)^{-\alpha_2} & , m_0 \le m < m_1, \\ \left(\frac{m_0}{m_H}\right)^{-\alpha_1} \left(\frac{m_1}{m_0}\right)^{-\alpha_2} \left(\frac{m}{m_1}\right)^{-\alpha_3} & , m_1 \le m < m_{max}, \end{cases}$$

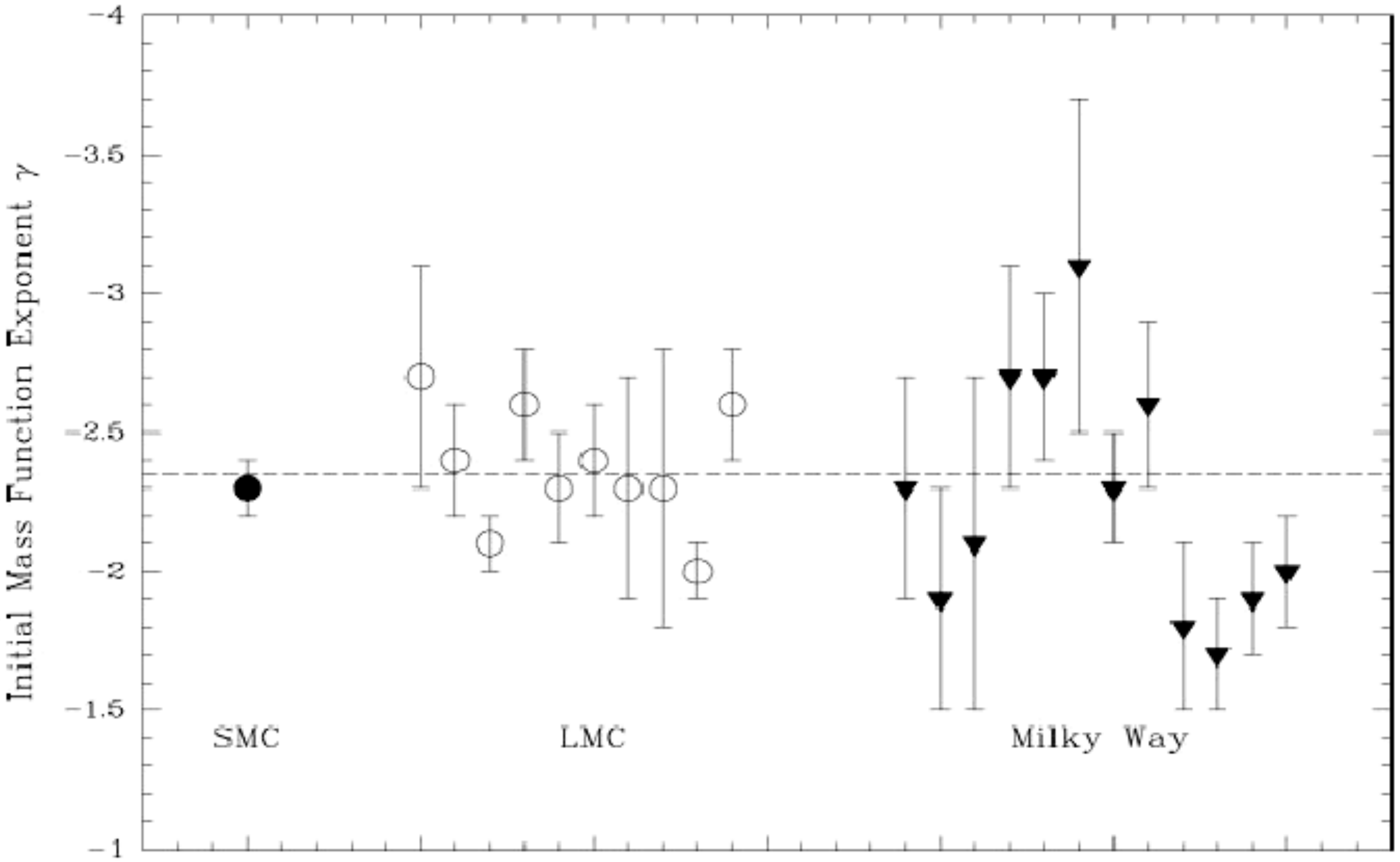
$$\begin{array}{ll} \alpha_0 = +0.30 & , \quad 0.01 \le m/M_\odot < 0.08, \\ \alpha_1 = +1.30 & , \quad 0.08 \le m/M_\odot < 0.50, \\ \alpha_2 = +2.35 & , \quad 0.50 \le m/M_\odot < 1.00, \\ \alpha_3 = +2.35 & , \quad 1.00 \le m/M_\odot . \end{array}$$

Uncertainties on the IMF

Is the IMF `universal'? i.e. is ξ(M) the **same function** everywhere?

Most theorists say no. Predict that fragmentation is easier if the gas can cool, so primordial gas without any metals should form more massive stars.

Observationally, little or no evidence for variations in the IMF in our galaxy or nearby galaxies.



Credit: H. Lux, University of Zurich

IMF and the SF history

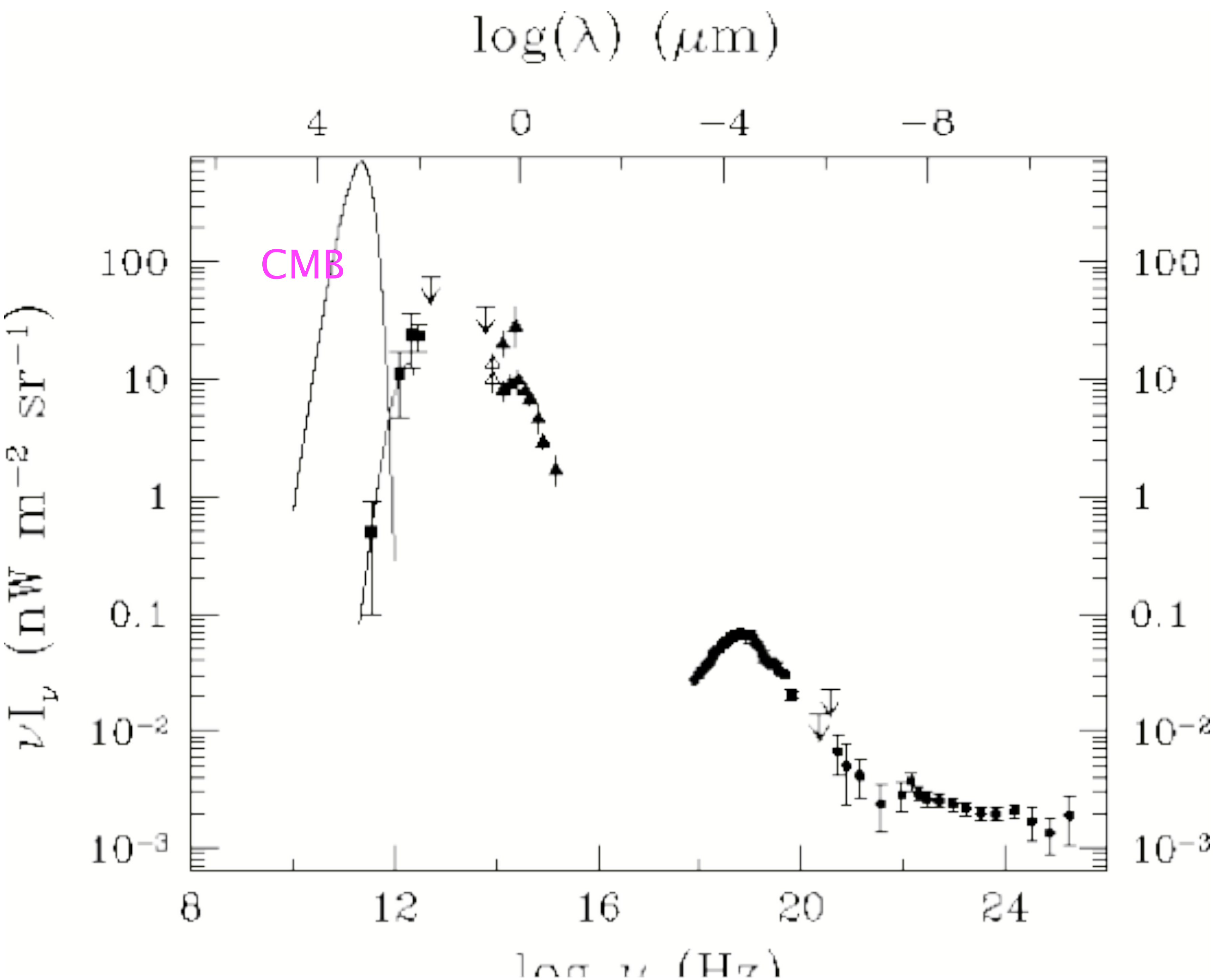
Simulations suggest a strong bias of the Initial Mass Function (IMF) to larger stellar masses with decreasing metallicity and thus, on average, higher redshift. In turn this affects the mass-loss of these early stars, and their subsequent explosions.

Low metallicity implies low mass loss, so that early stars will be more massive than present stars, even if the IMF were universal.

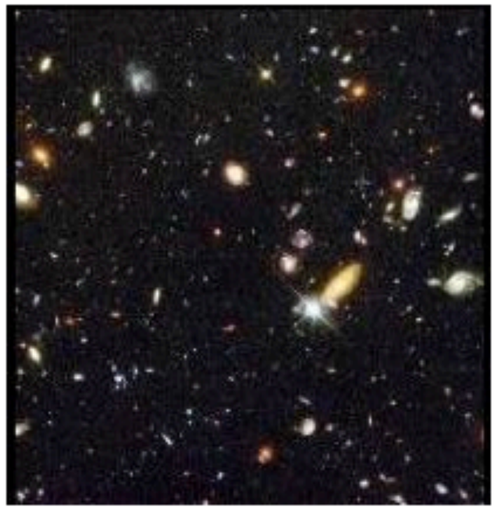
While most massive stars today explode as Type II core collapse supernovae (cc SNe or SNII), a near zero-metallicity star (Pop III) of $\sim 150\ M_\odot$ more likely dies by pair instability.

Feedback on the environment from the first generation of supernovae is different than in a present-day galaxy. Star formation today takes place in dense molecular clouds, while in the early Universe it was hampered by inefficient cooling in pristine H-He environments.

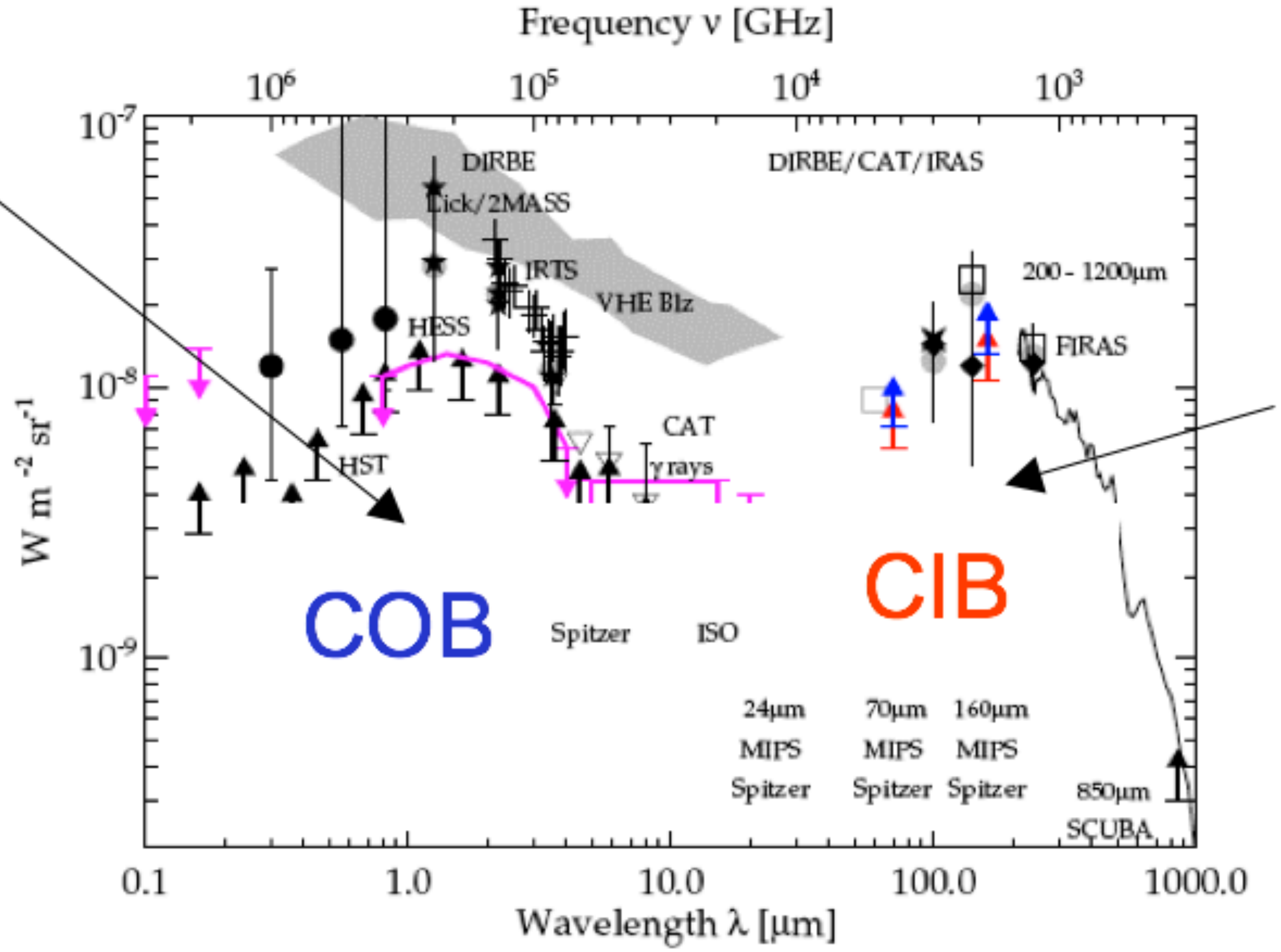
Optical to IR diffuse background

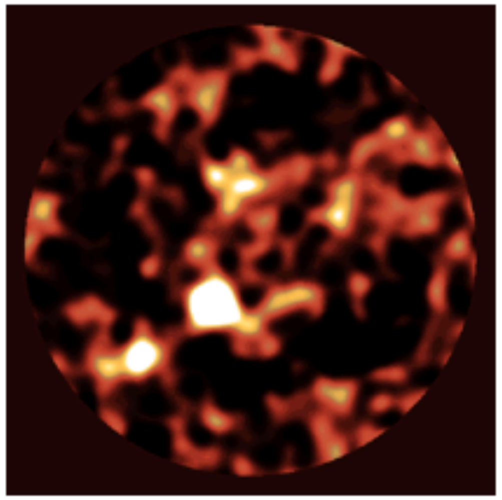


Optical to IR diffuse background



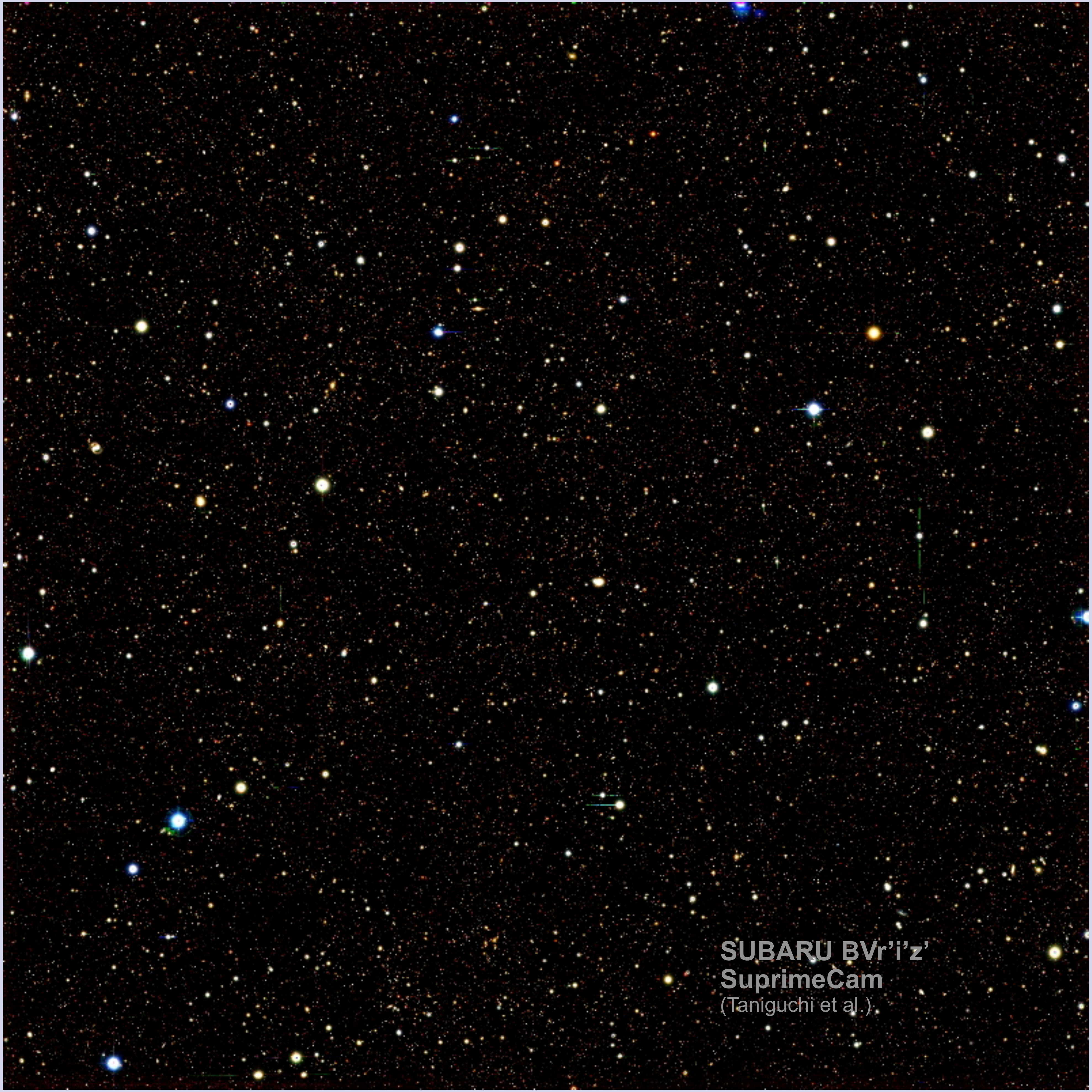
HST HDF
optical survey



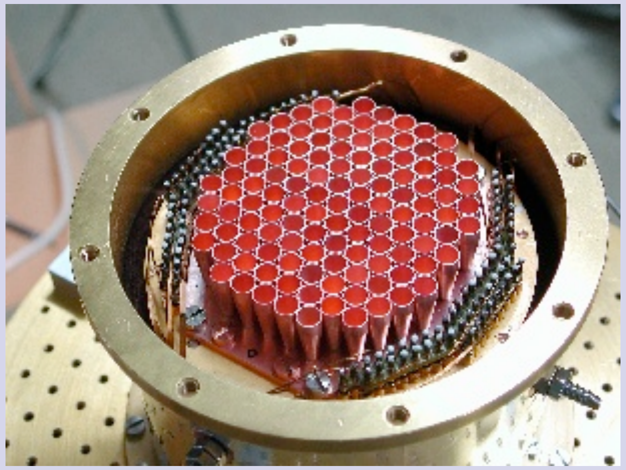


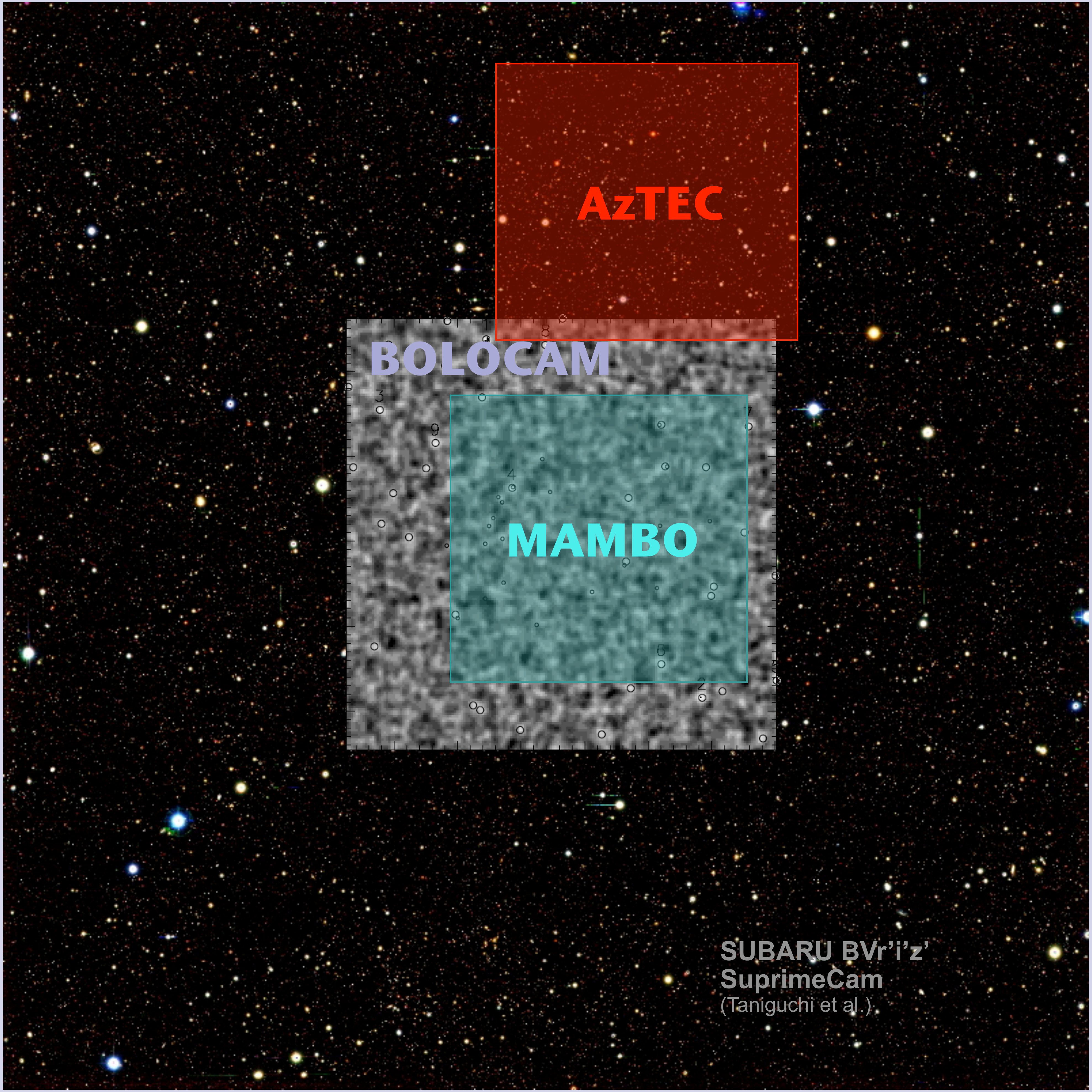
SCUBA HDF
850um survey

COSMOS
(2 sq. deg.)

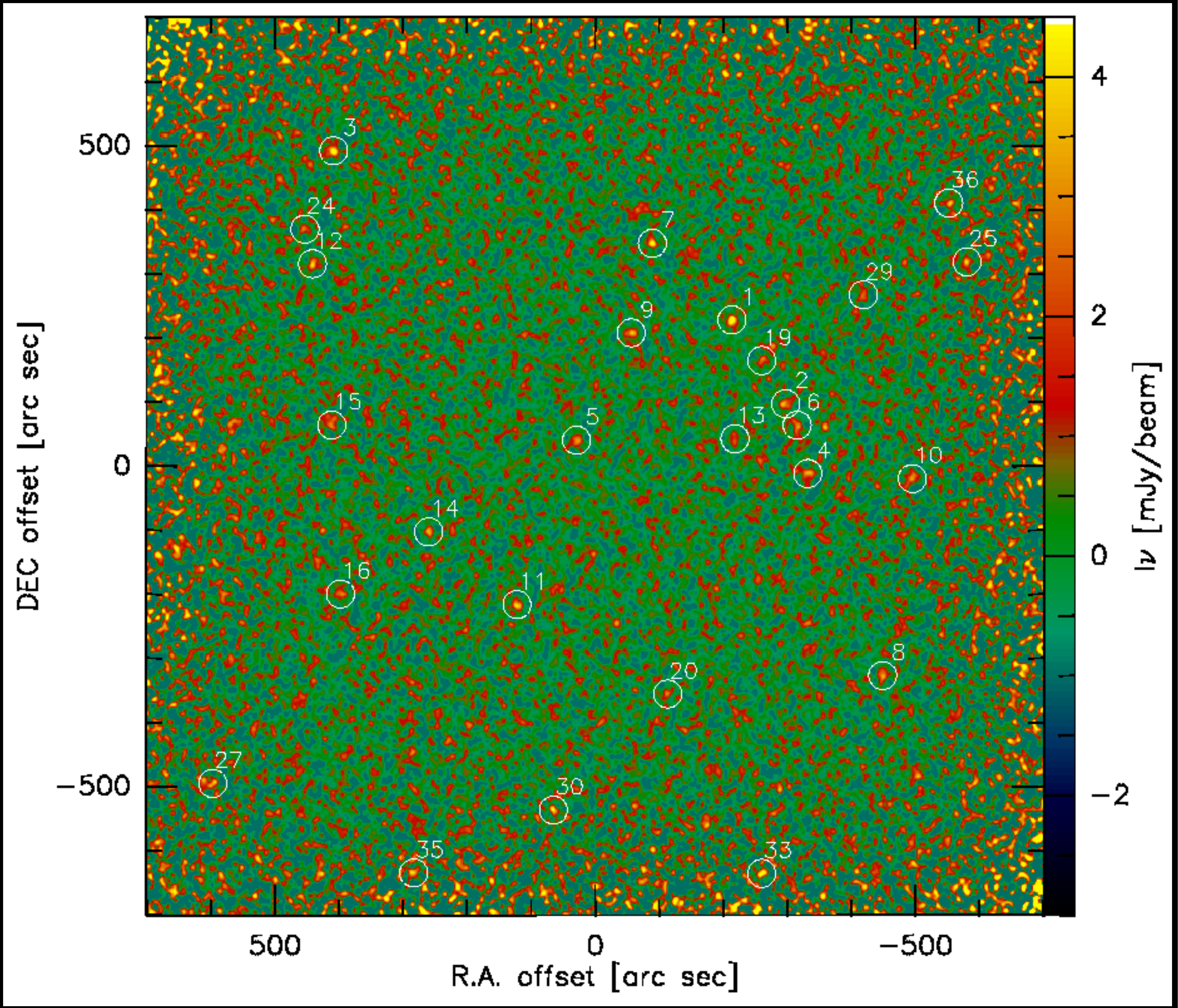


COSMOS
(2 sq. deg.)





COSMOS



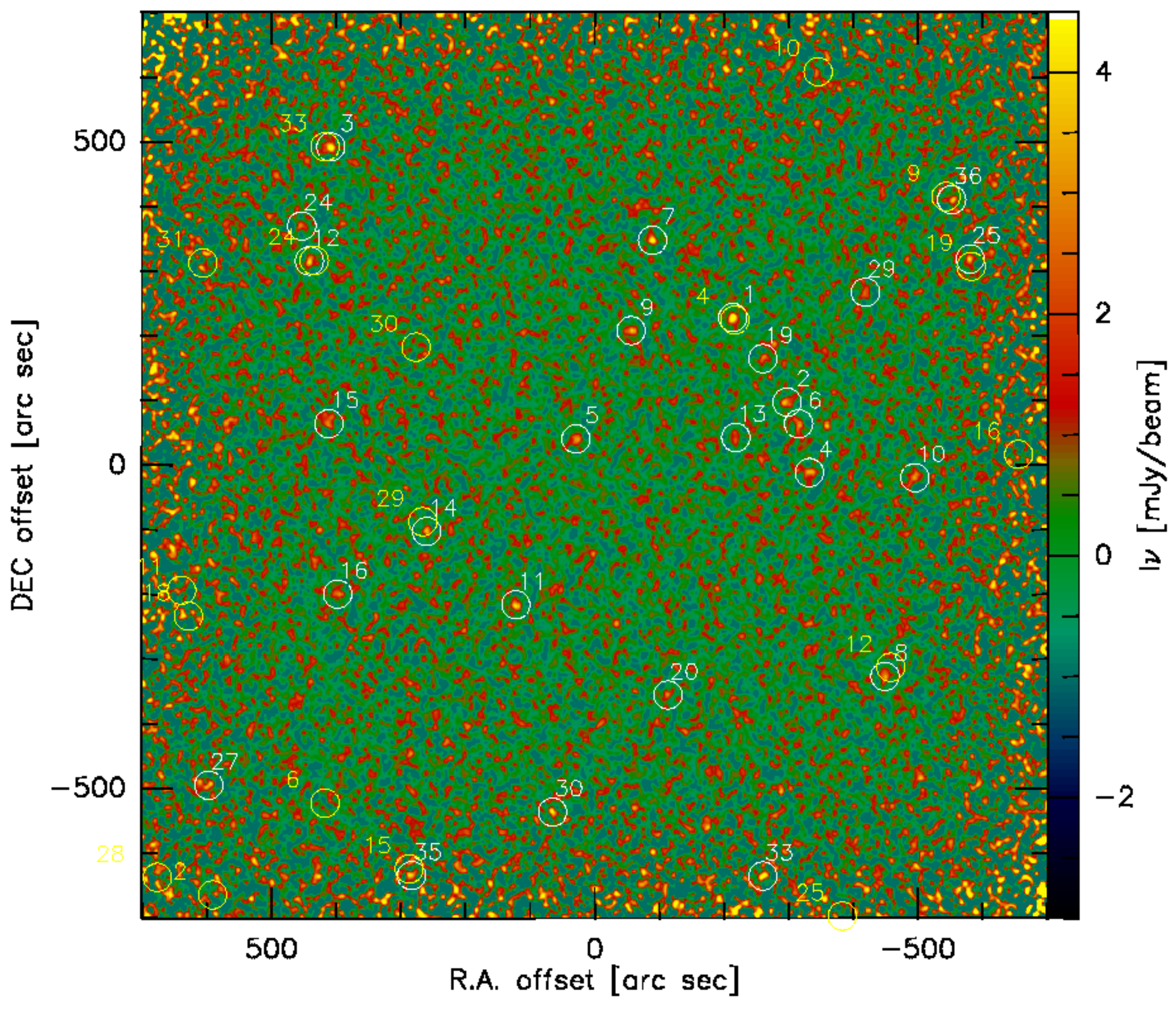
rms ~ 1 mJy

15 sources
S/N > 4

12 sources
S/N = 3.5-4
and radio

paper in ApJS

COSMOS



rms ~ 1 mJy

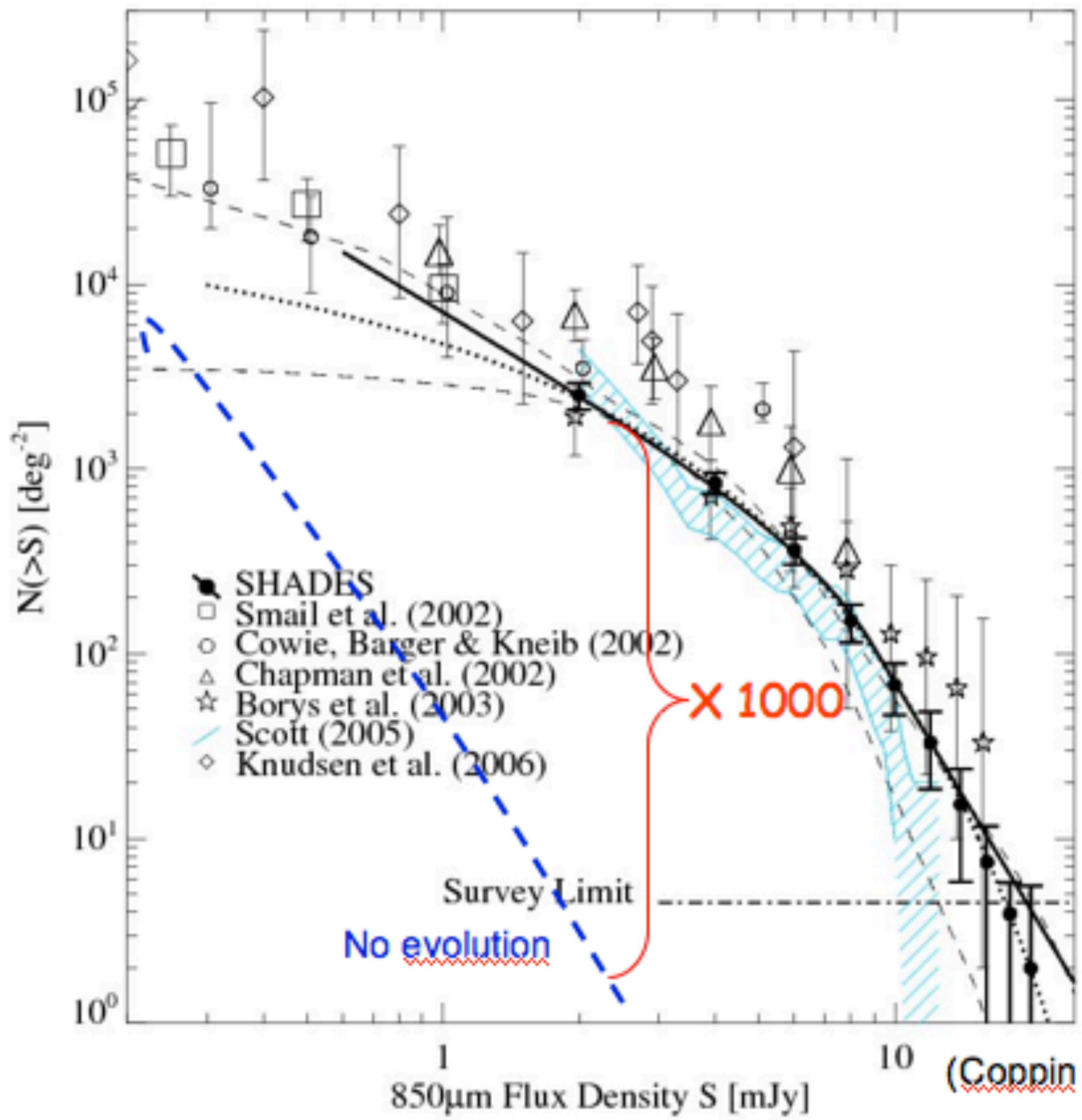
15 sources
S/N > 4

12 sources
S/N = 3.5-4
and radio

paper in ApJS

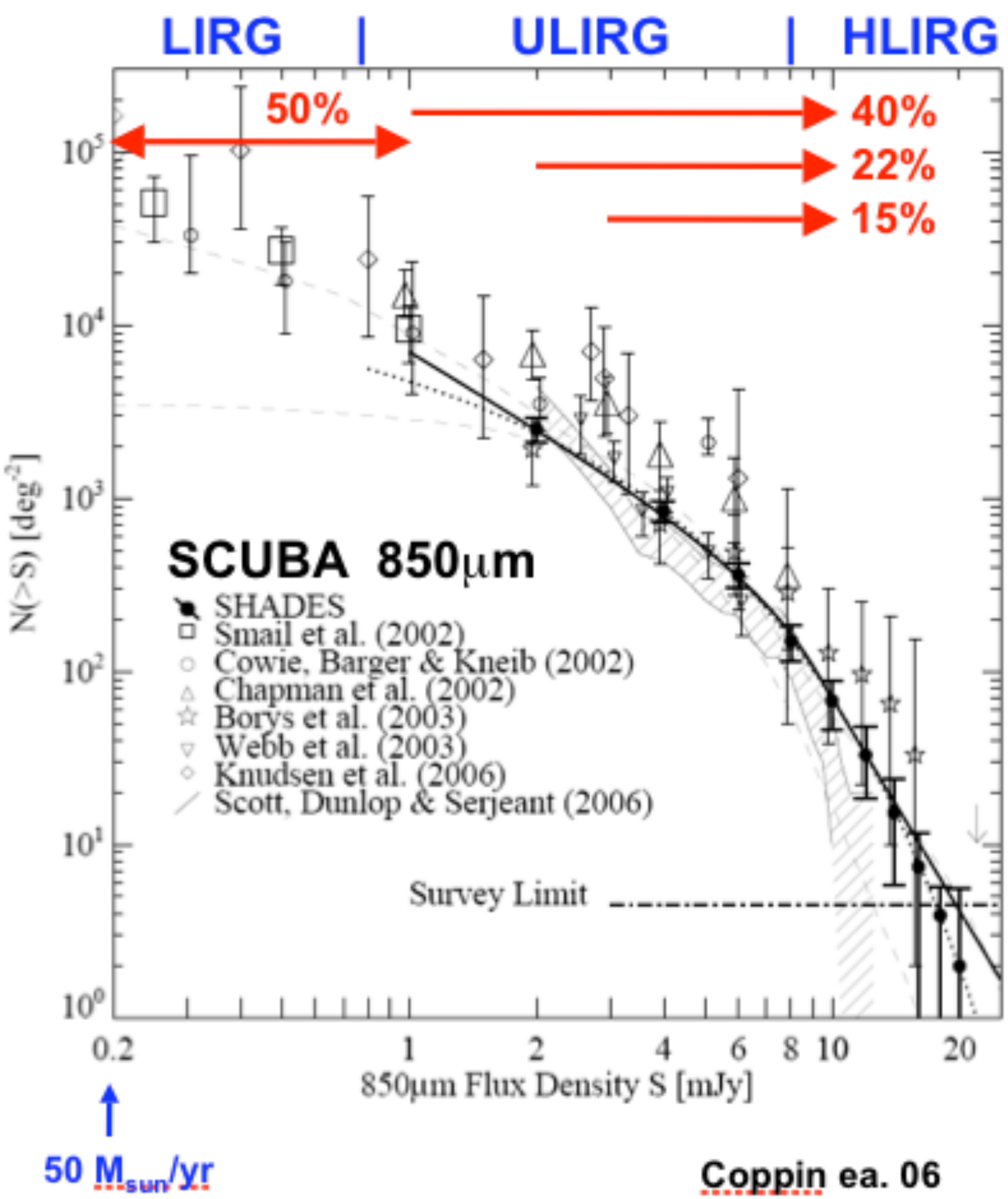
Sub-mm source counts

- Sub-mm surveys (source-counts) imply a strongly evolving, luminous ($L_{FIR} > 10^{12} L_\odot$), optically-obscured, galaxy population in the high-z Universe

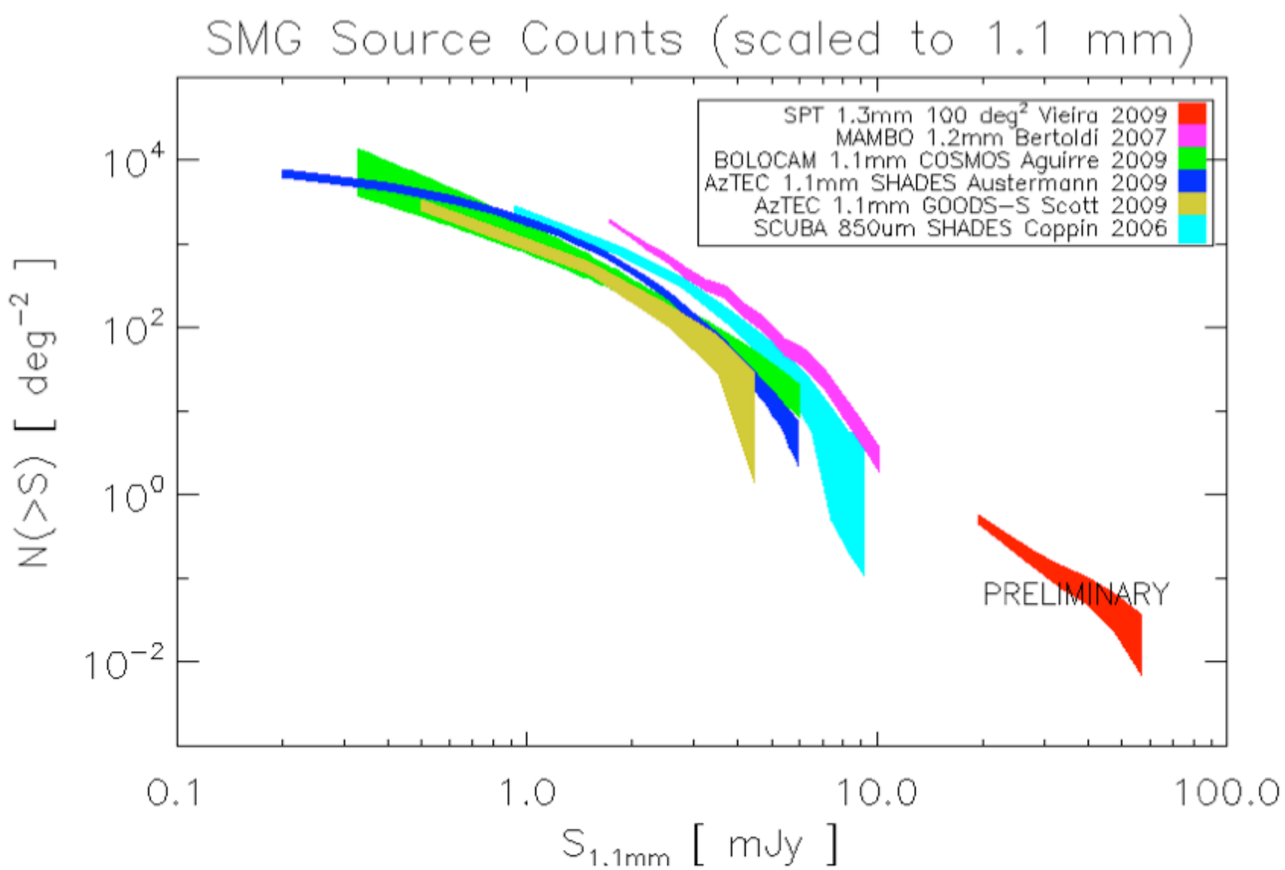


(Coppin et al. 2006)

Sub-mm source counts

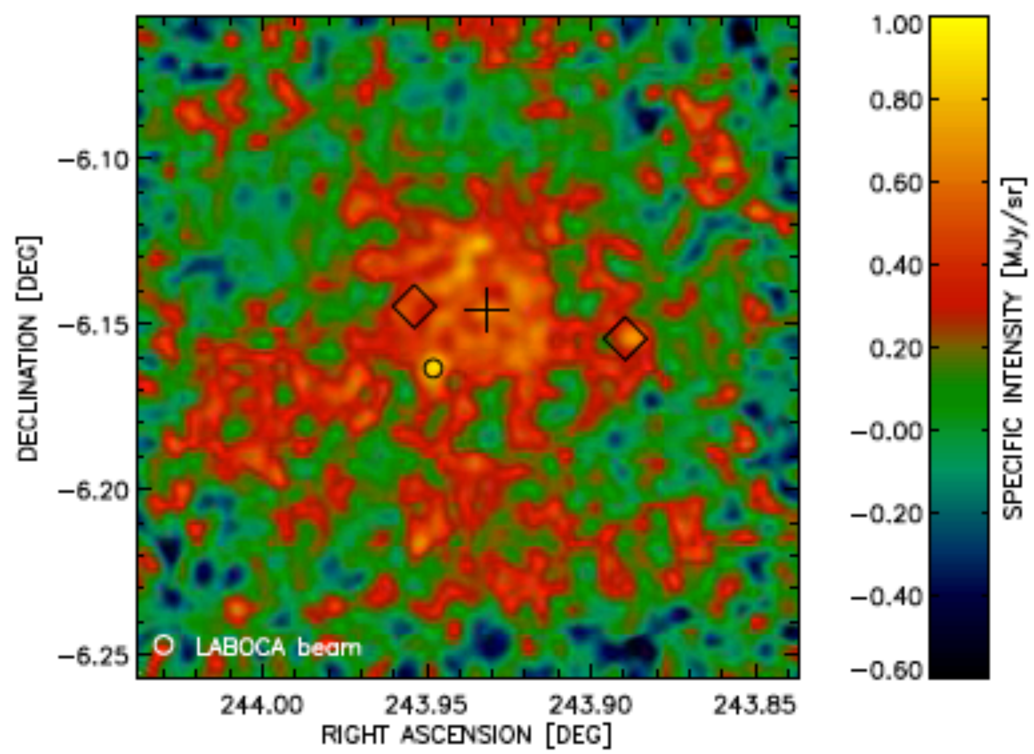


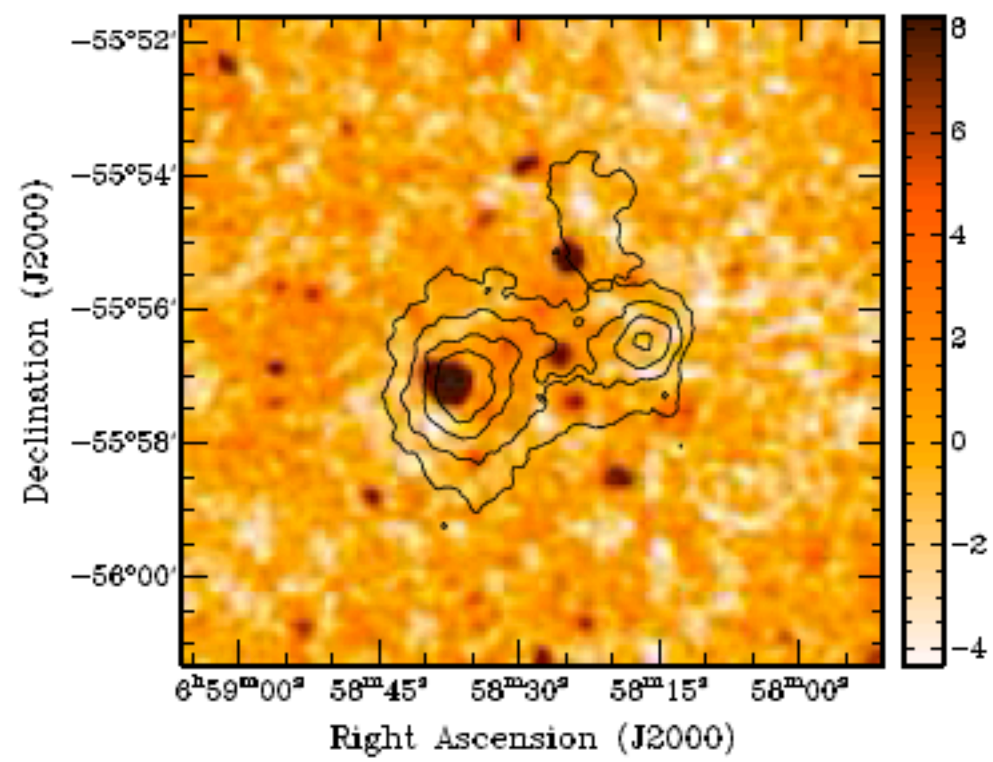
Only a small fraction of the CIB has been resolved



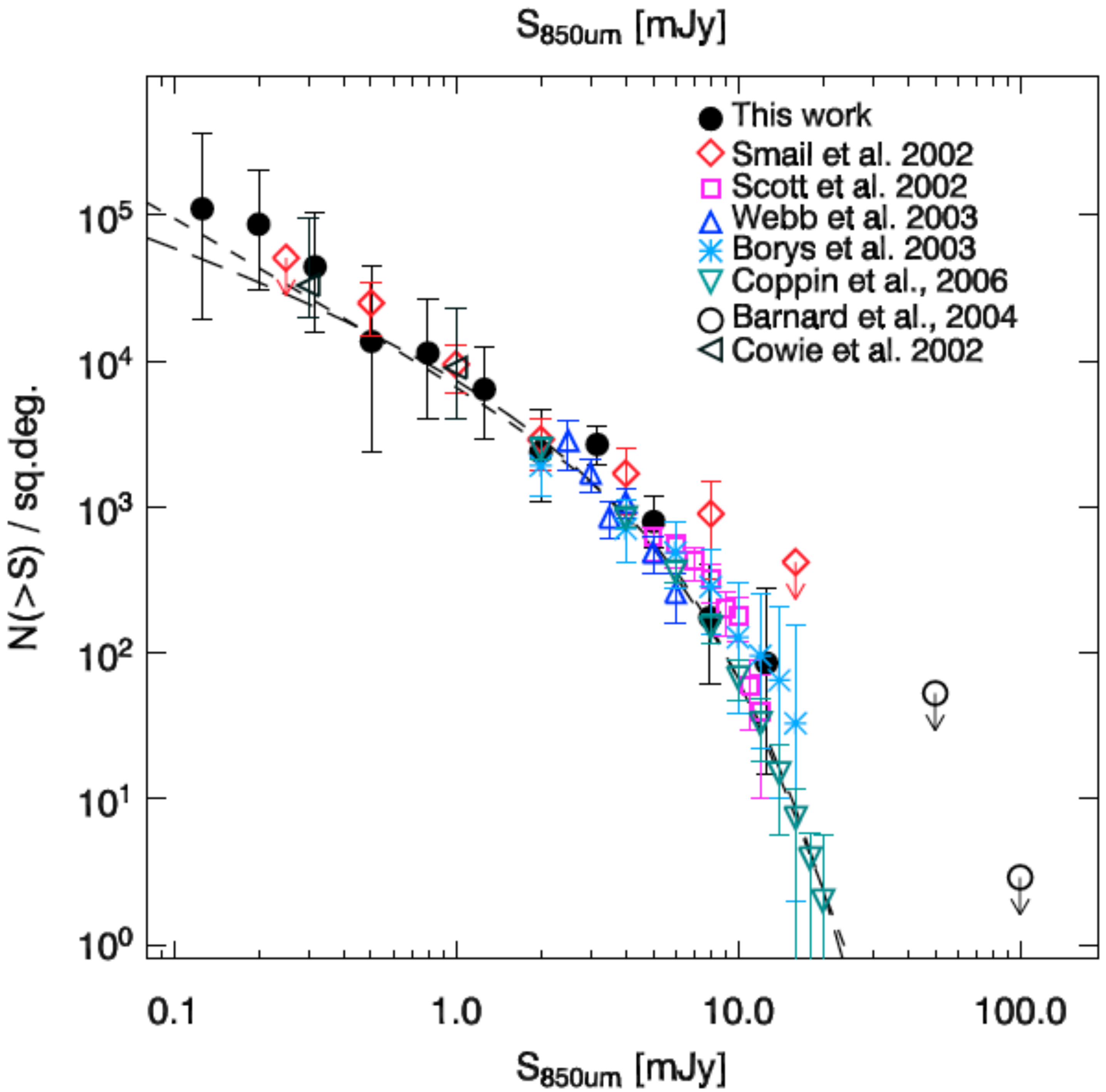
Sub-mm galaxies behind clusters

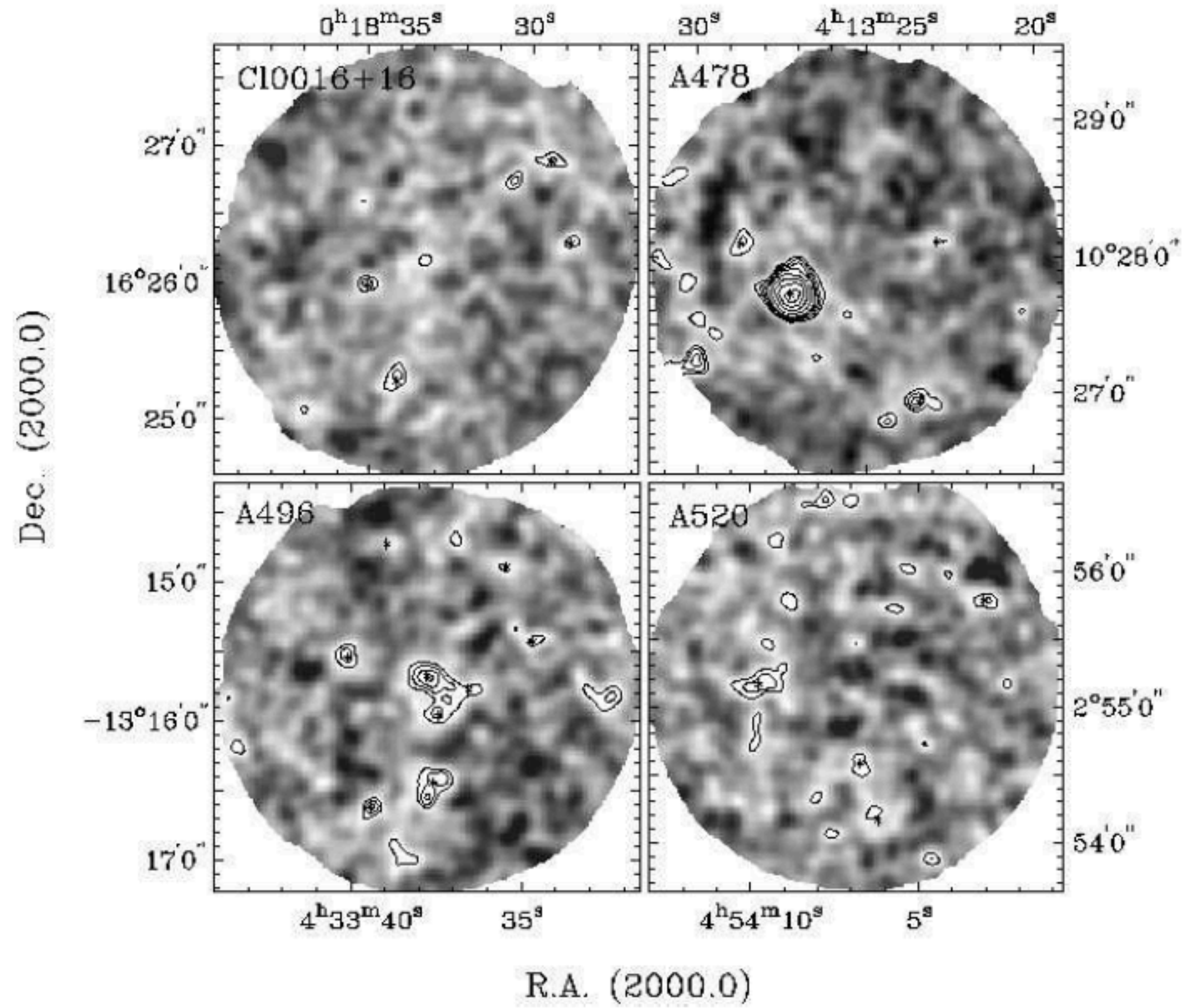
Observation of galaxy clusters at sub-mm wavelengths almost always reveal a host of sources coming out of the confusion. These are distant, faint sub-mm galaxies. Study of the faint end (< 2 mJy) of these sub-mm galaxy population is important to constrain the cosmic star formation history.





Lensed sub-mm galaxies





Knudsen et al. 2008

As seen behind the Bullet cluster

Source	α(J2000) (h:m:s)	δ(J2000) (° :′:″)	Flux density[a] (mJy)	Deboosted[b] flux density (mJy)	Demagnified[c] flux density (mJy)	$F/\Delta F$[d]
1	06:58:37.62	-55:57:04.8	48.6 ± 1.3[e]	48.0 ± 1.3	0.64	82.8
2	06:58:24.47	-55:55:12.5	15.1 ± 1.0	14.7 ± 1.0	8.8	29.9
3	06:58:25.45	-55:56:40.1	6.9 ± 0.9	6.4 ± 1.0	2.2	17.8
4	06:58:19.36	-55:58:30.3	8.2 ± 0.9	7.7 ± 0.9	4.7	16.2
5	06:58:27.27	-56:01:16.3	9.0 ± 1.3	8.0 ± 1.3	6.3	15.9
6	06:58:28.94	-55:53:48.4	9.3 ± 1.2	8.6 ± 1.2	6.3	15.4
7	06:59:01.39	-55:52:18.1	11.9 ± 2.1	9.7 ± 2.1	8.4	14.2
8	06:58:24.05	-55:57:23.0	5.3 ± 0.9	4.7 ± 1.0	1.8	13.1
9	06:58:55.98	-55:56:51.7	5.4 ± 1.2	4.4 ± 1.3	3.3	12.8
10	06:58:45.60	-55:58:48.0	6.2 ± 1.1	5.5 ± 1.1	3.6	12.0
11	06:58:53.22	-56:00:45.0	7.8 ± 1.5	6.4 ± 1.6	5.2	11.9
12	06:58:52.22	-55:55:45.7	5.5 ± 1.2	4.5 ± 1.2	3.4	11.2
13	06:58:22.88	-56:00:40.7	4.8 ± 1.2	3.8 ± 1.3	2.9	11.0
14	06:58:46.68	-56:02:11.8	7.2 ± 1.9	4.6 ± 2.5	3.8	10.8

Johansson et al. 2010

z = 3.9