Le fond diffus IR lève le voile

Unveiling the Cosmic Infrared Background

G. Lagache
Institut d'Astrophysique Spatiale

Mes compagnons de route à l’IAS:

Jean-Loup Puget

Hervé Dole

Post-doc:

Alexandre Beelen

Karina Caputi

En thèse:

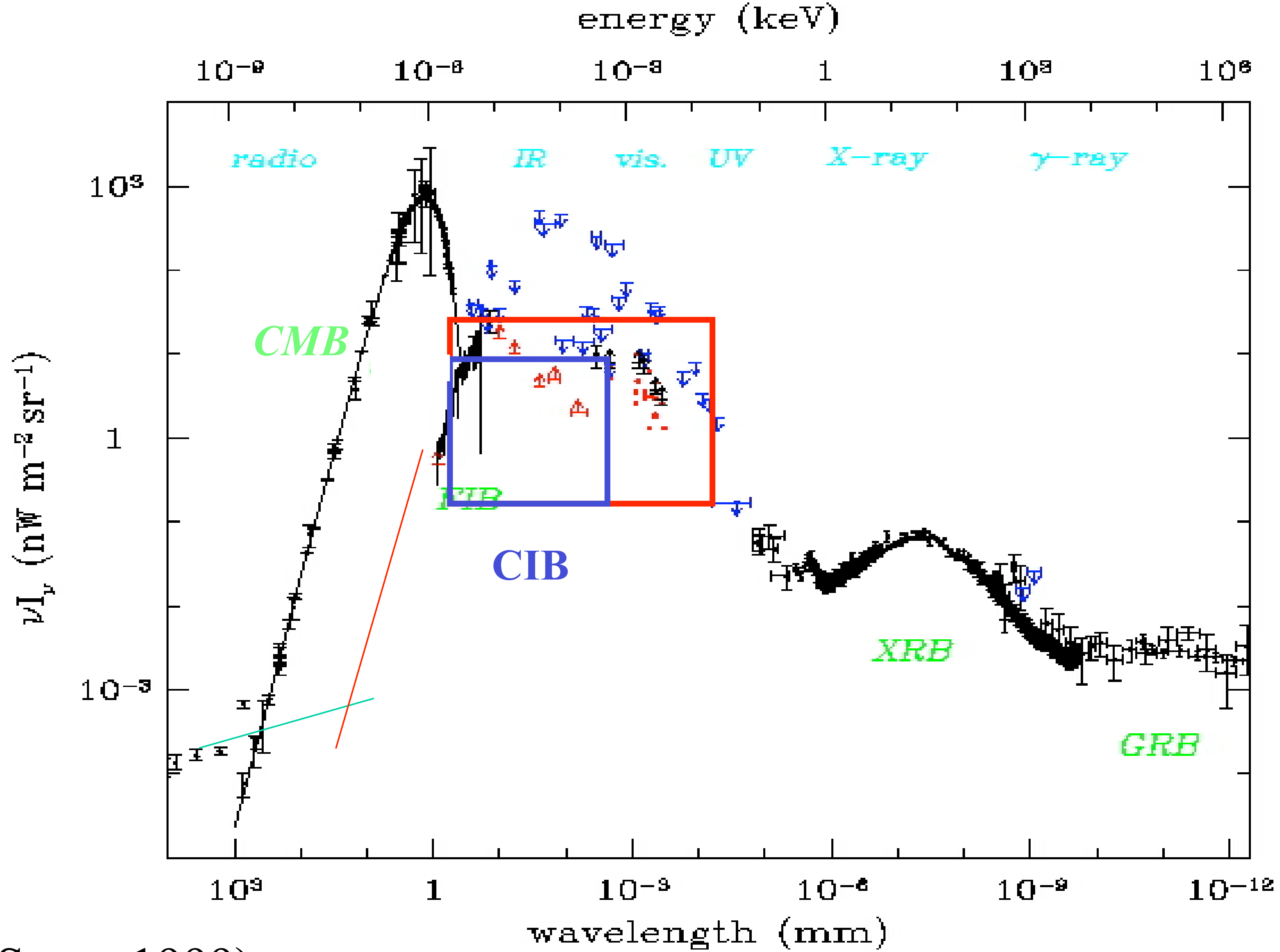
Nicolas Bavouzet

Benjamin Bertincourt

Nestor Fernandez-Conde

Lagache, Puget, Dole, ARAA 2005, vol43

Cosmic background from radio to gamma rays



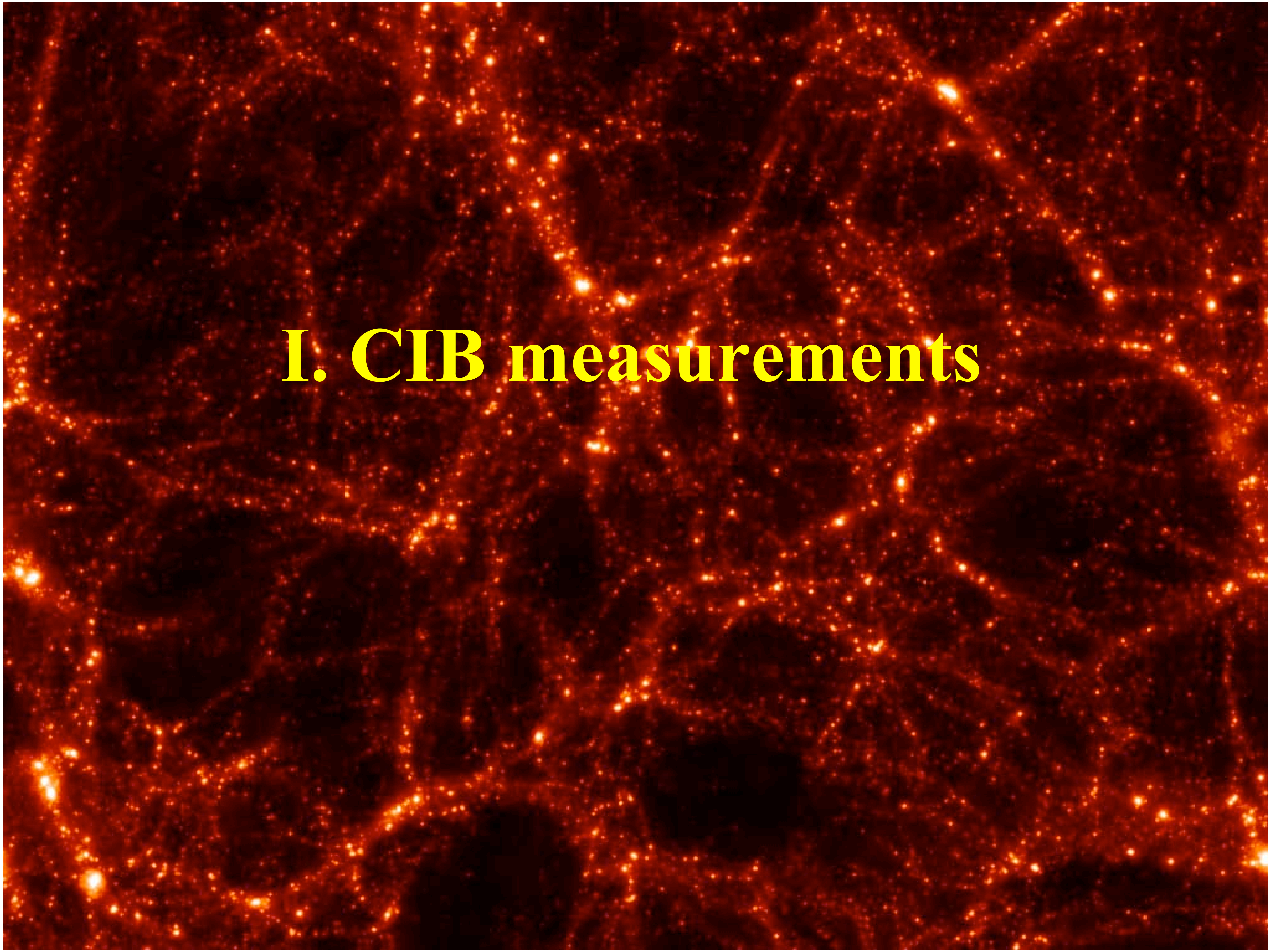
(D. Scott, 1999)

The Cosmic Infrared Background (CIB)

Definition: part of the radiation content of the Universe made of the long-λ (> 6 μm) output from all sources throughout the history of the Universe

1) CIB measurements
2) Direct cosmological implications
3) Deep surveys: detailed properties of the CIB galaxies
4) Cosmic evolution of IR galaxies
5) Conclusions and challenges

I. CIB measurements



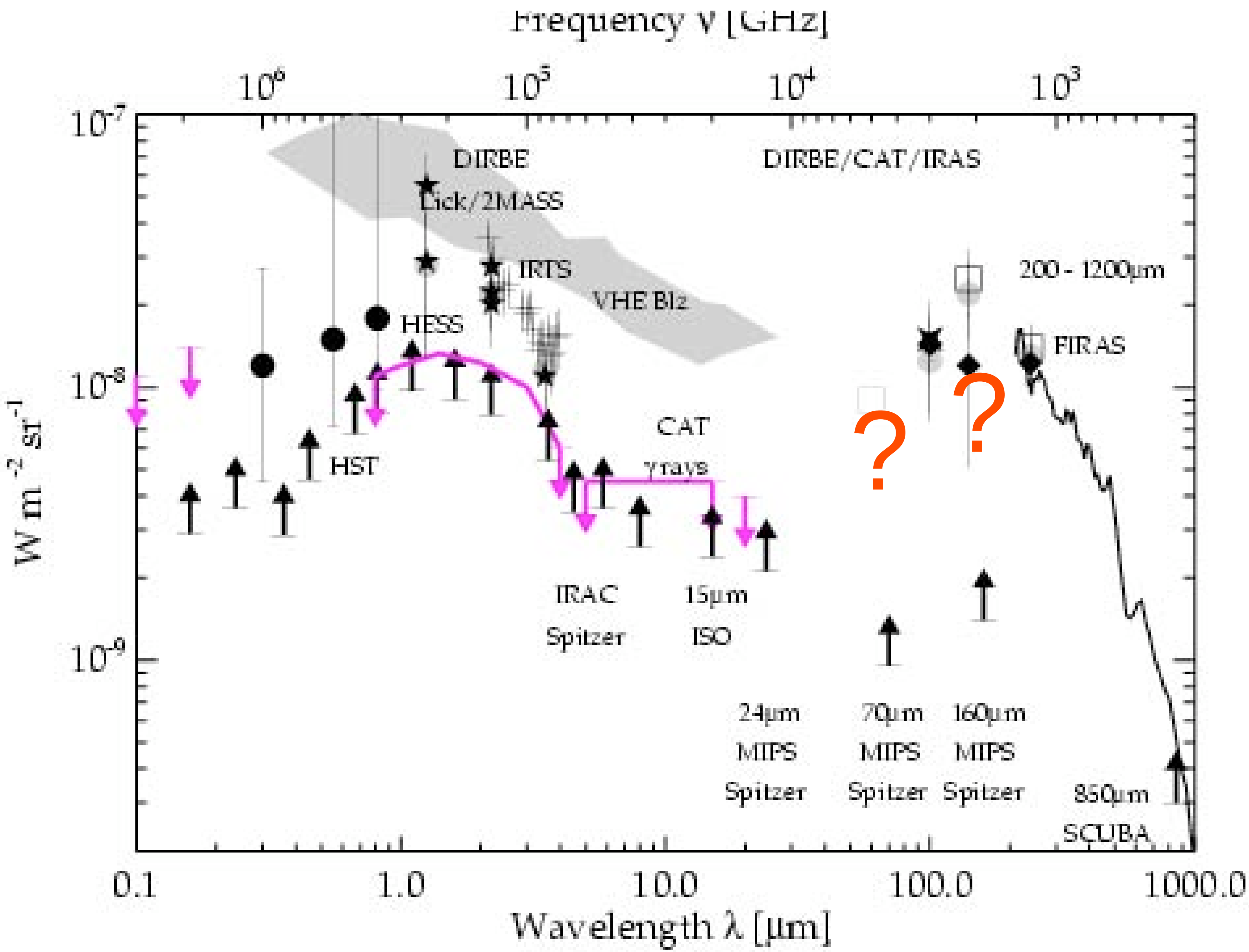
Measurements of the CIB

- Subtract from the diffuse emission the foreground components:
  => zodi, dust, CMB (λ~100-1000 μm)
- Lower limits: Integrate galaxy number counts
  mostly mid-IR, λ<100 μm
- Upper limits: Correct γ source spectra from the absorption
  (γ_{TEV} / γ_{CIB} interactions, λ~1-15 μm)

CIB: Before 1996: nothing

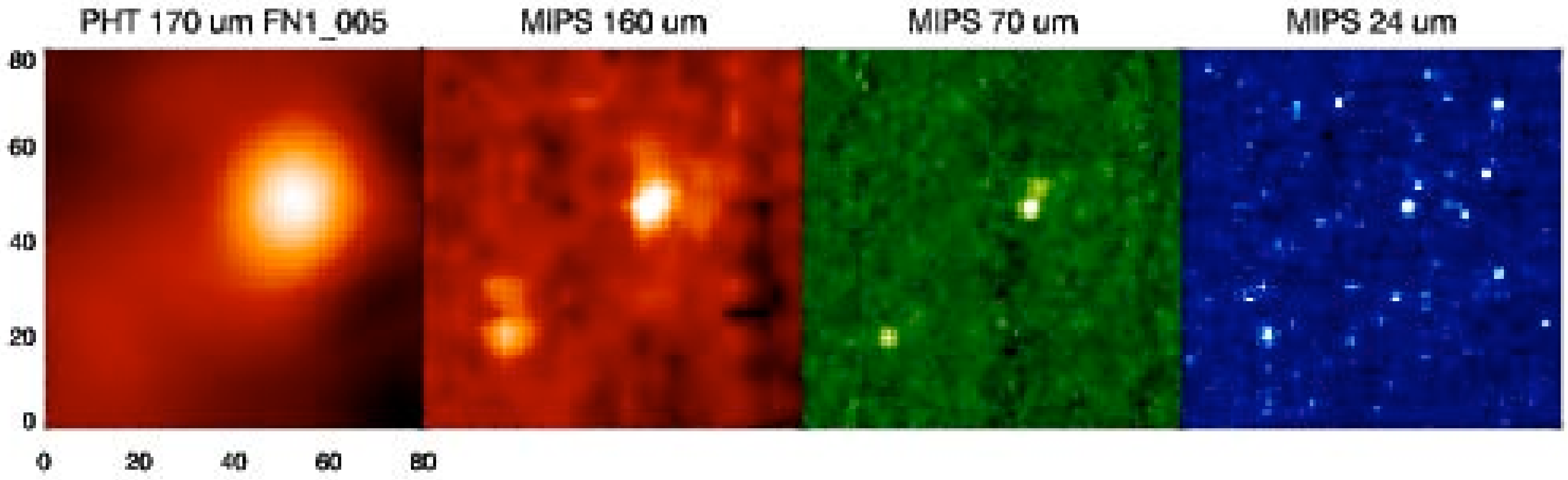
- FIRAS discovery 200-1000 μm (Puget et al. 1996).
- DIRBE points at 100,140 and 240 μm
- ISO, SPITZER, SCUBA: lower limits
- CAT, HESS : upper limits

The Cosmic Background

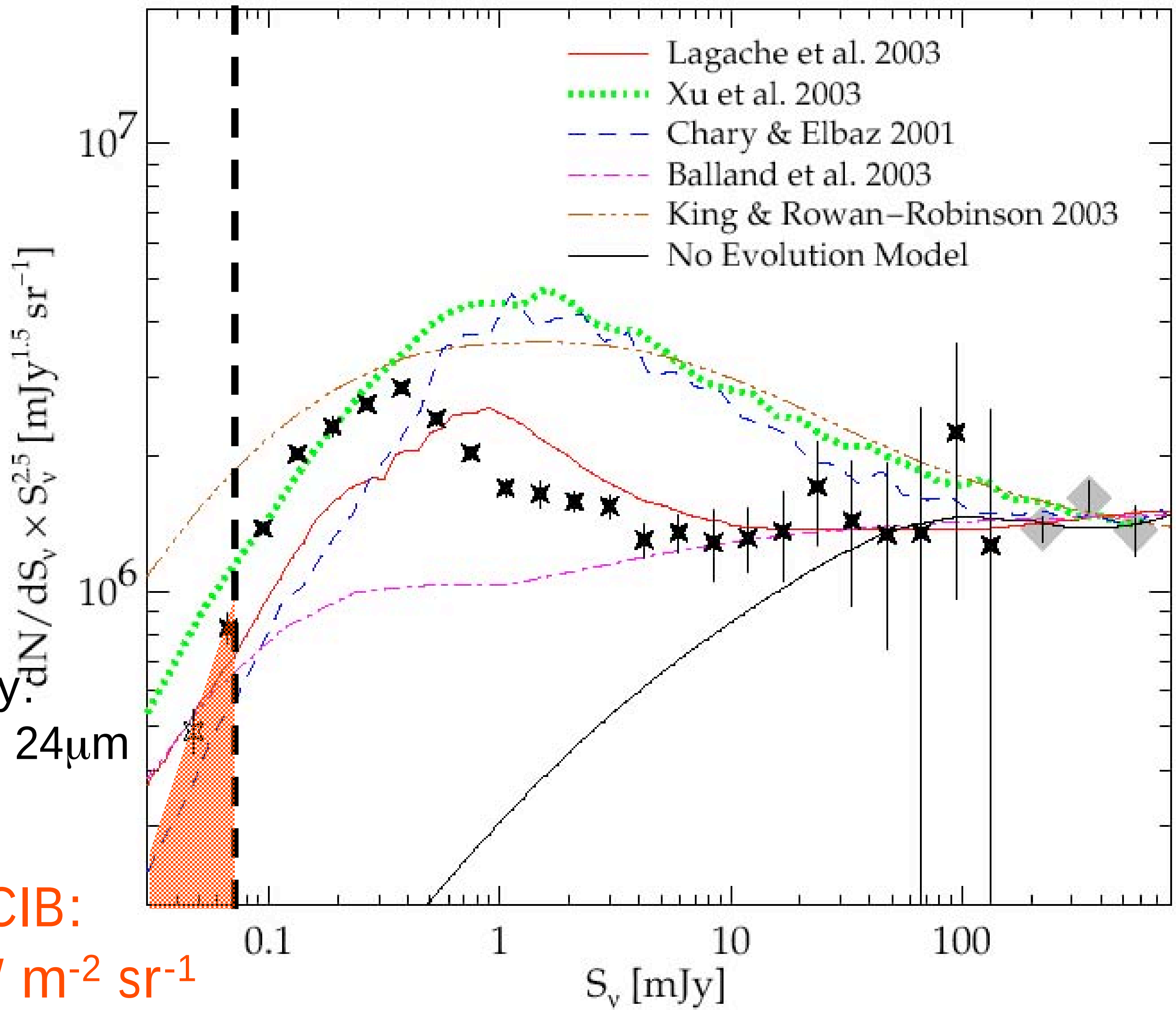


The CIB between 30 and 160 μm

- Zodical emission too bright
- Lower limits from galaxy number counts too low (confusion)



24 μm source counts & CIB

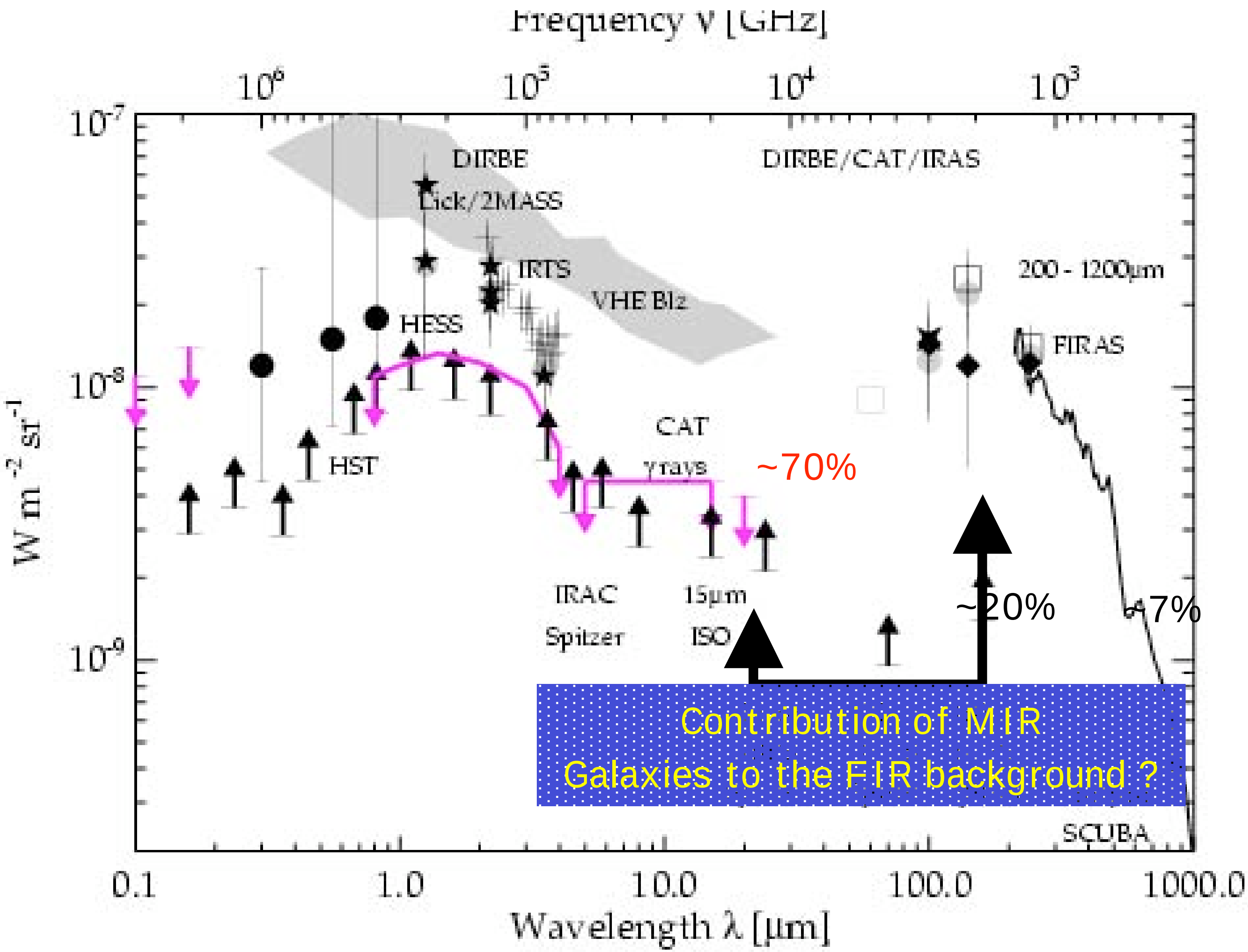


Below 60μJy:
<30% of the 24μm Background

24μm CIB:
2.7 nW m^{-2} sr^{-1}

Papovich et al., 2004

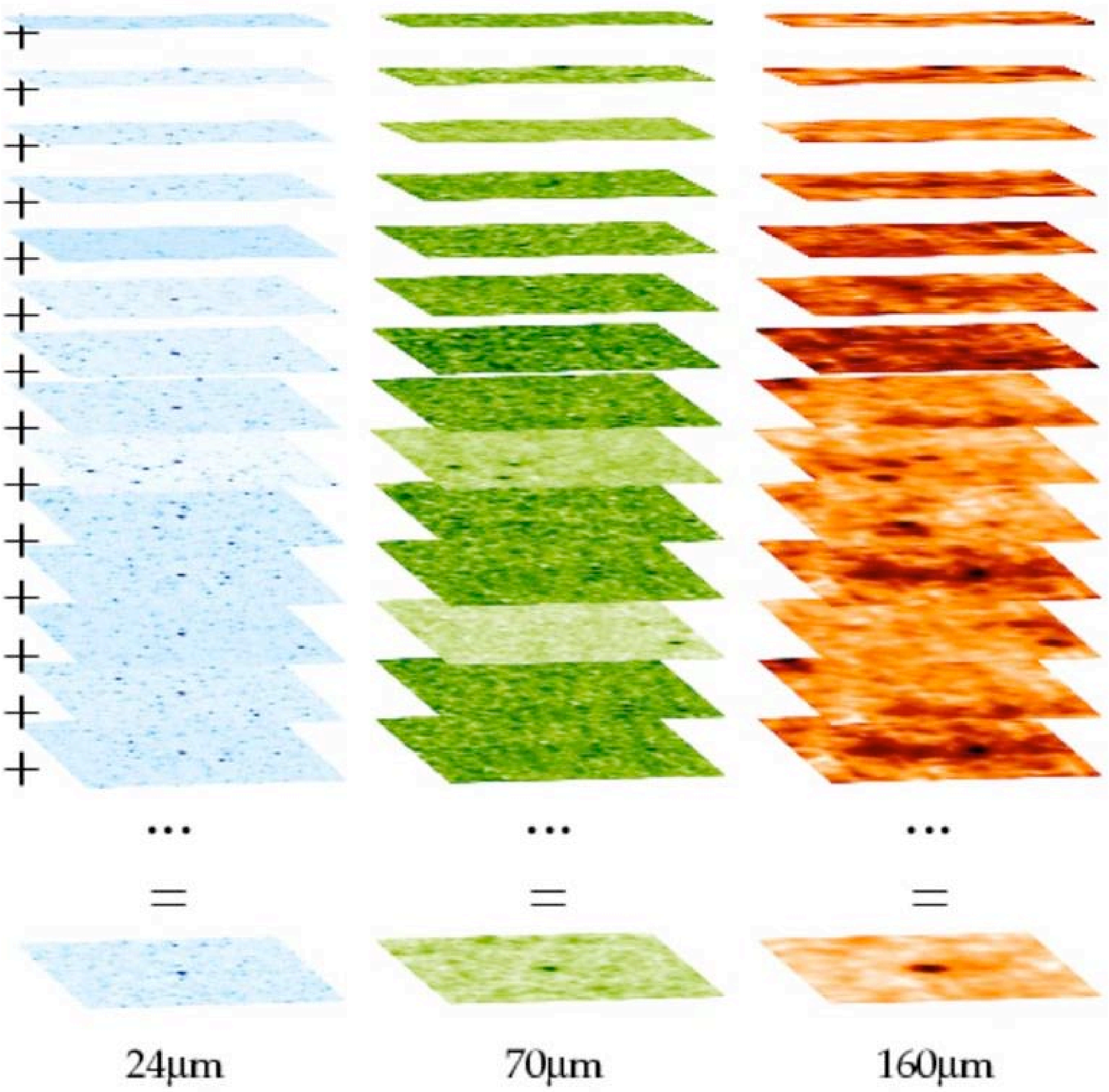
Cosmic Infrared Background



Dole et al., 2006

MIPS stacking analysis

Stack ~19000 Galaxies



Dole et al., 2006

MIPS stacking analysis

Dole et al. 2006

The Cosmic Infrared Background resolved by Spitzer

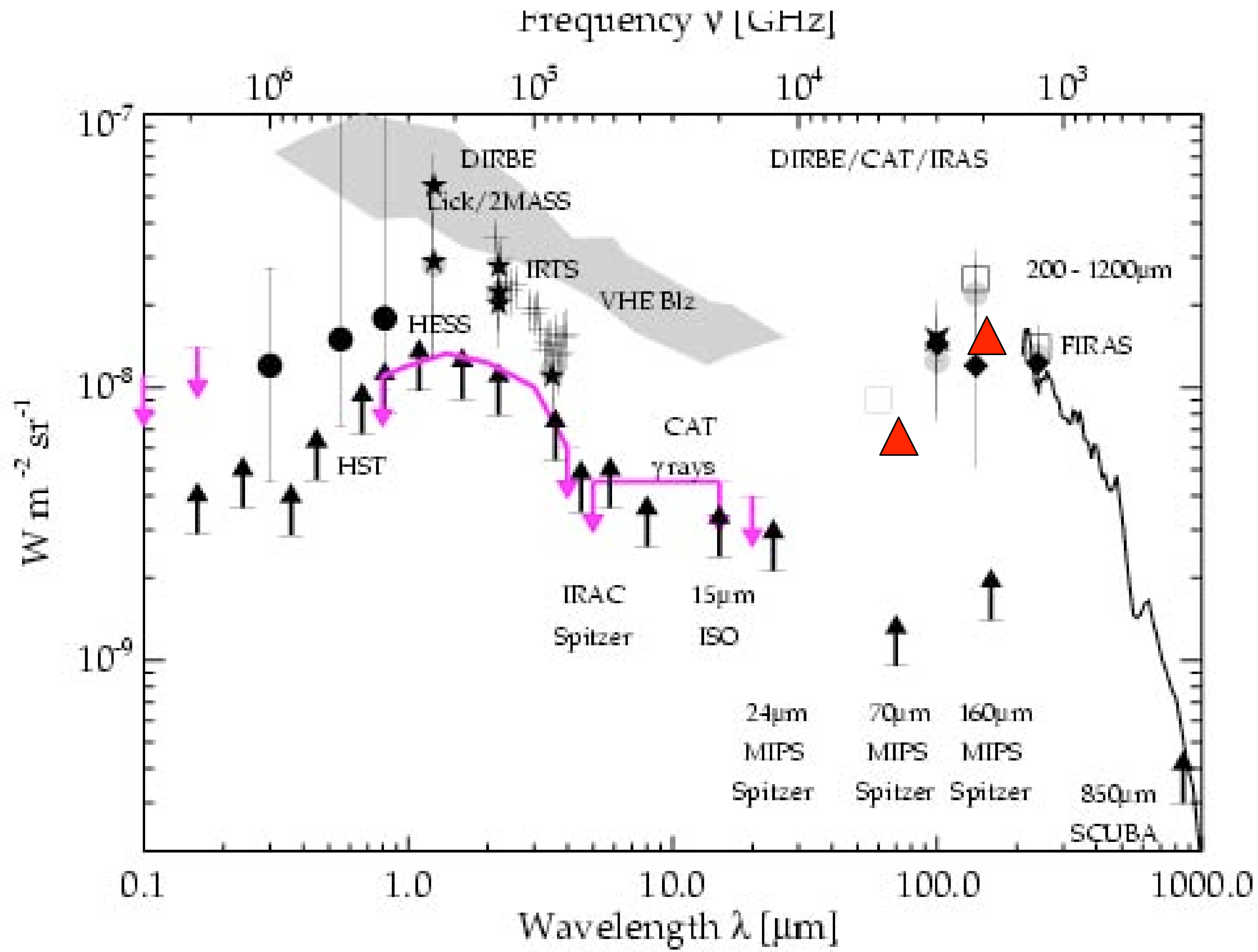
H. Dole et al. (2006)

Institut d'Astrophysique Spatiale, Universite Paris-Sud 11, CNRS

http://www.ias.u-psud.fr/irgalaxies

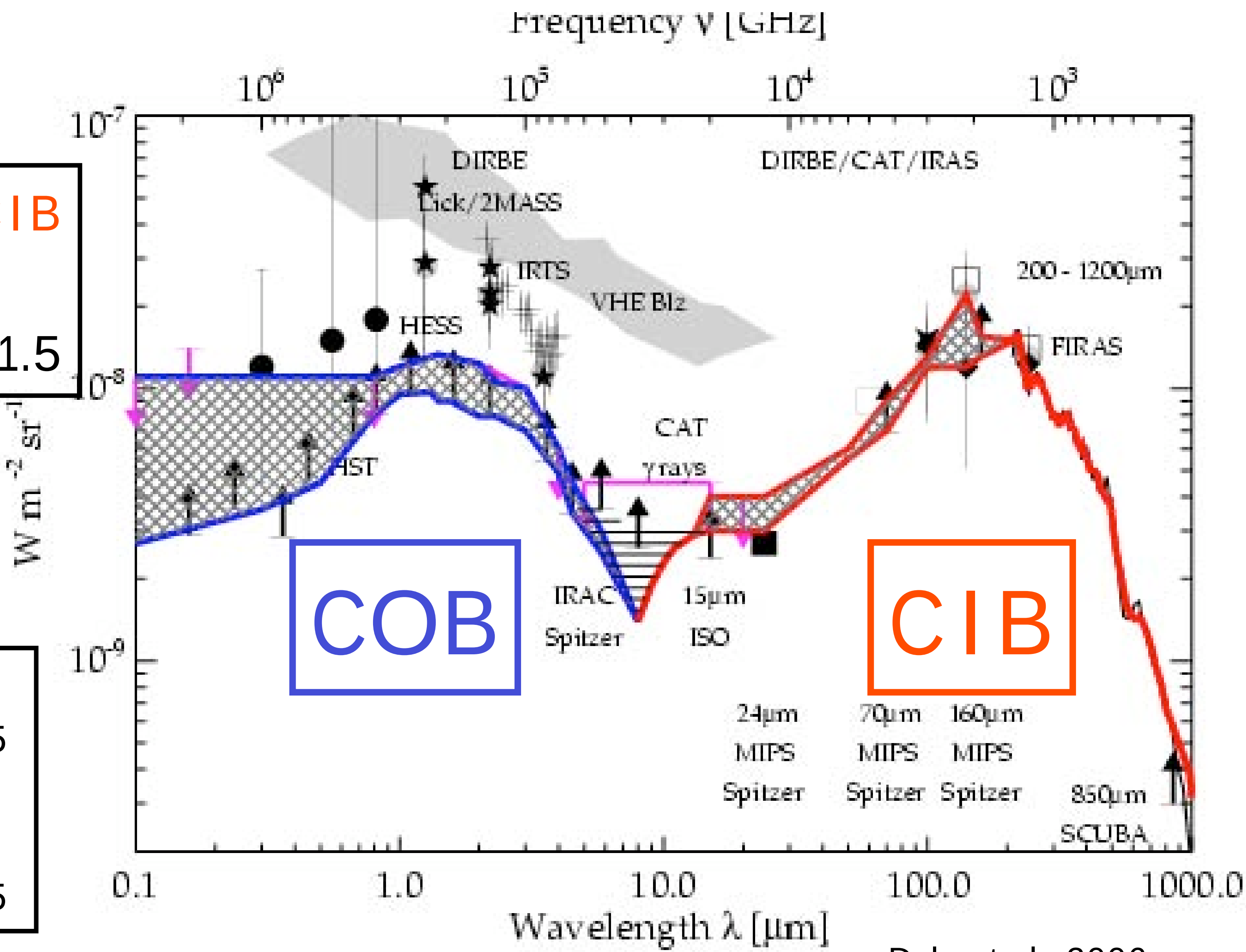
Credit: H. Dole/IAS/Arizona/NASA/JPL-Caltech

The Cosmic Background



The Cosmic Background

COB/CIB ~ 0.7 to 1.5

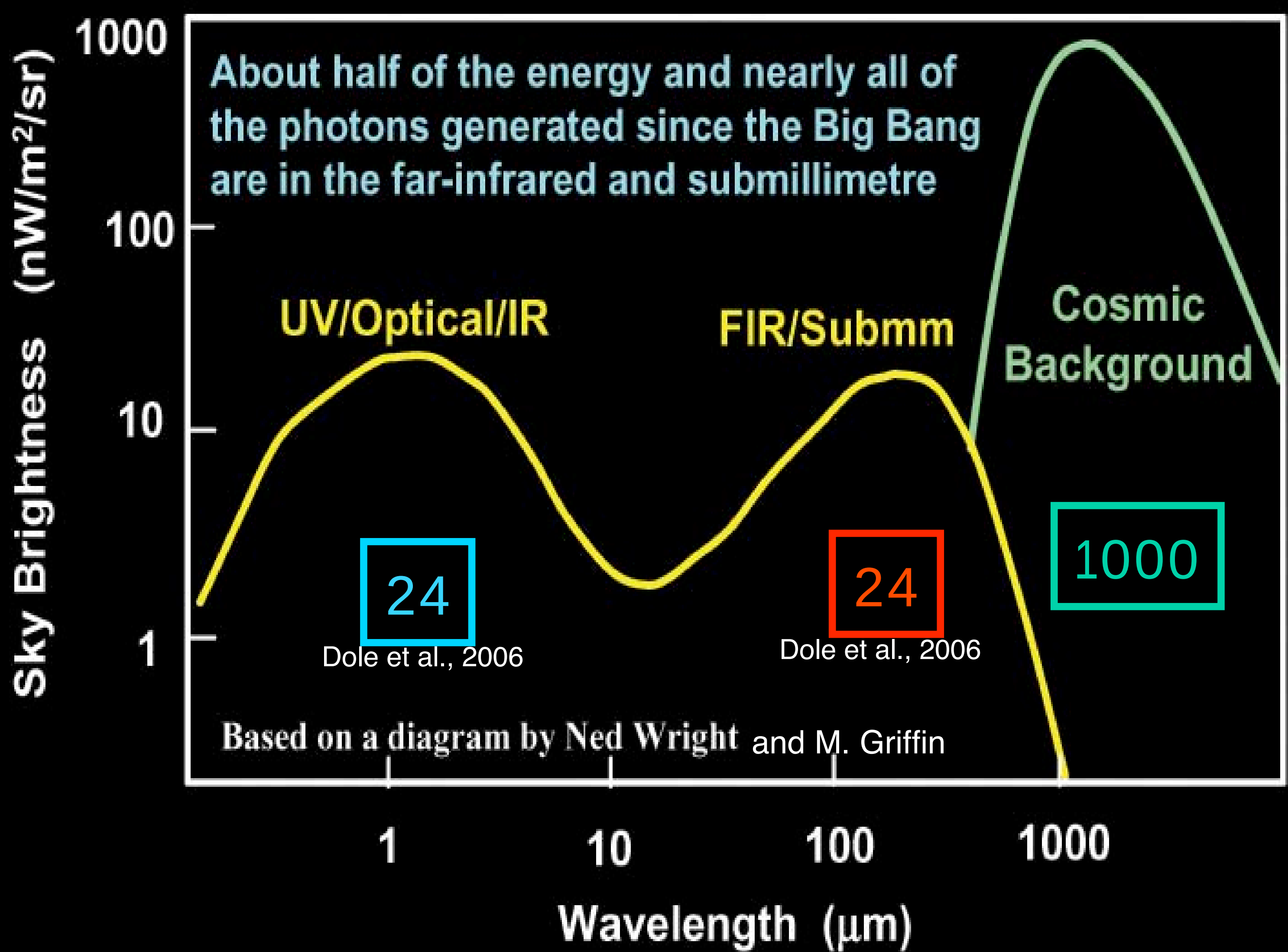


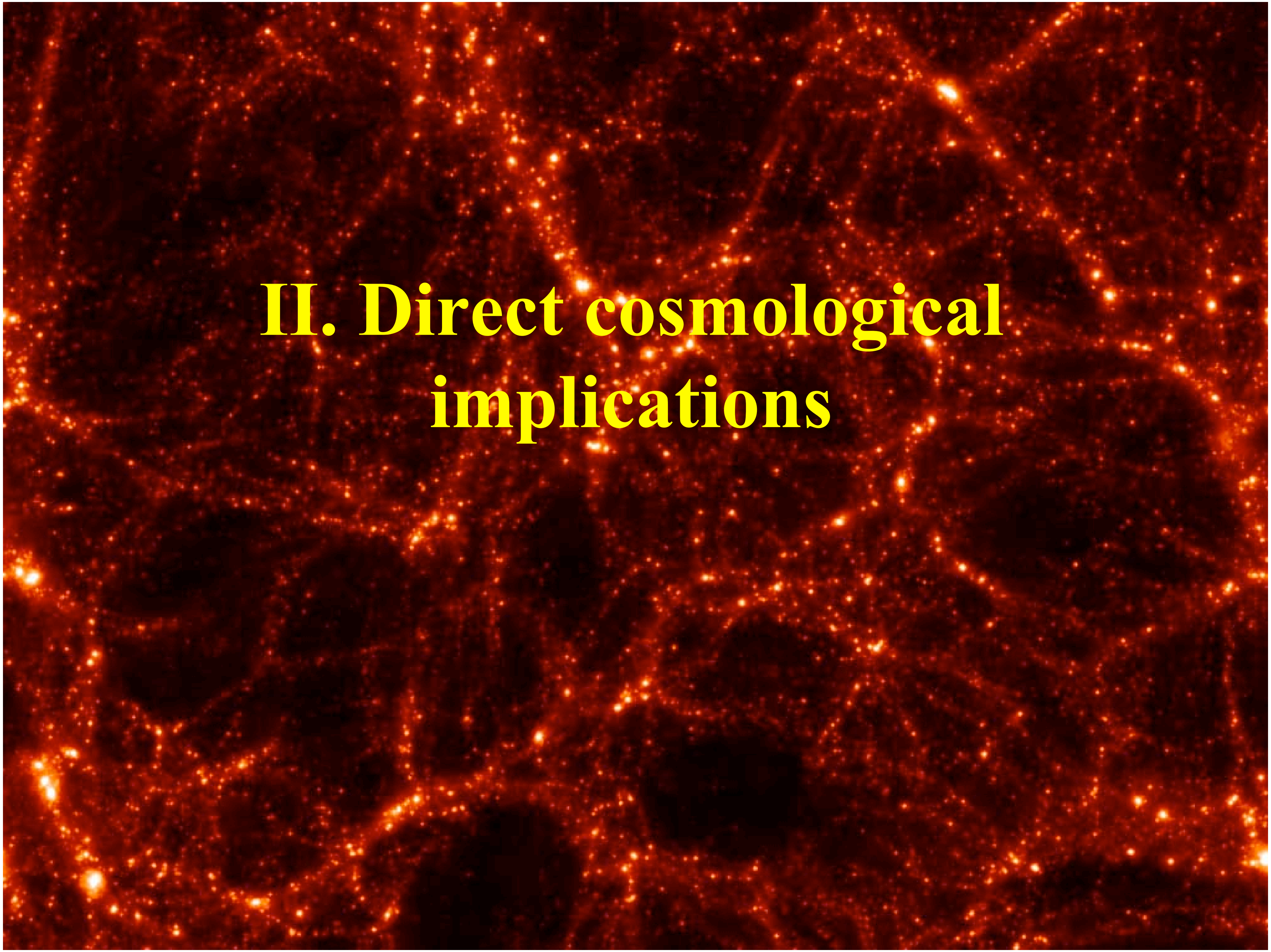
Dole et al., 2006

COB~ 25 to 35

CIB~ 23 to 25

Spectral Energy Distribution of the Universe

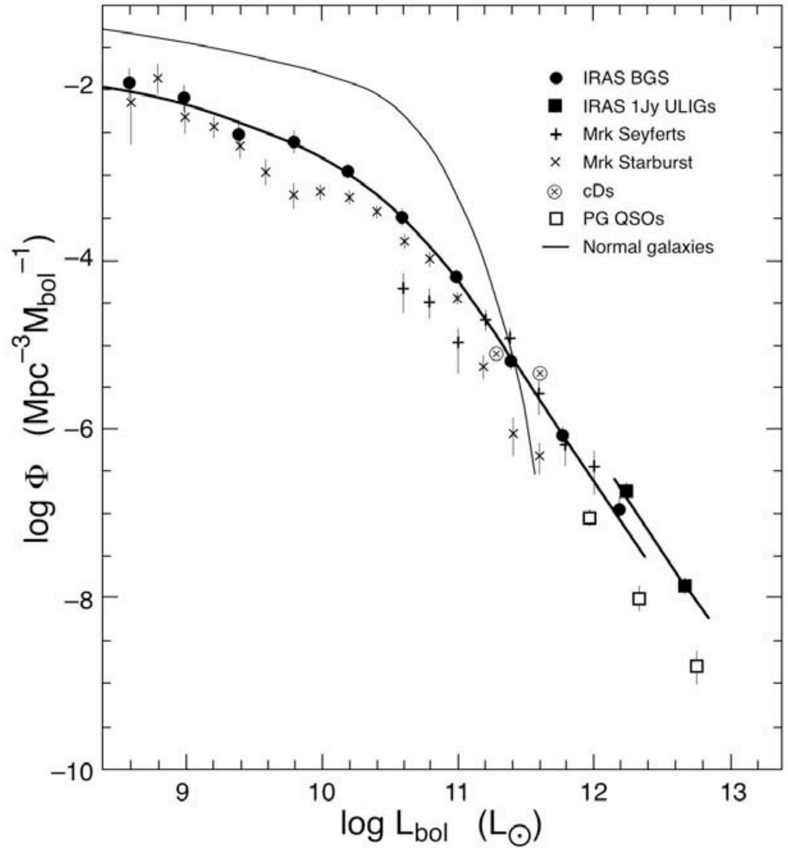



II. Direct cosmological
implications

Local IR galaxies

- IRAS: local LF at 60 and 100 μm dominated by L_* spiral galaxies. BUT: high-luminosity tail approximated by a power law $L_{IR}^{2.35}$
- LIRGs: $11<\mathrm{Log}(L_{IR})<12\ L_\odot$ and ULIRGs $\mathrm{Log}(L_{IR})>12\ L_\odot$
- Often associated with interacting or merging gas-rich disks, intense starburst activity (10-100 Mo/yr)

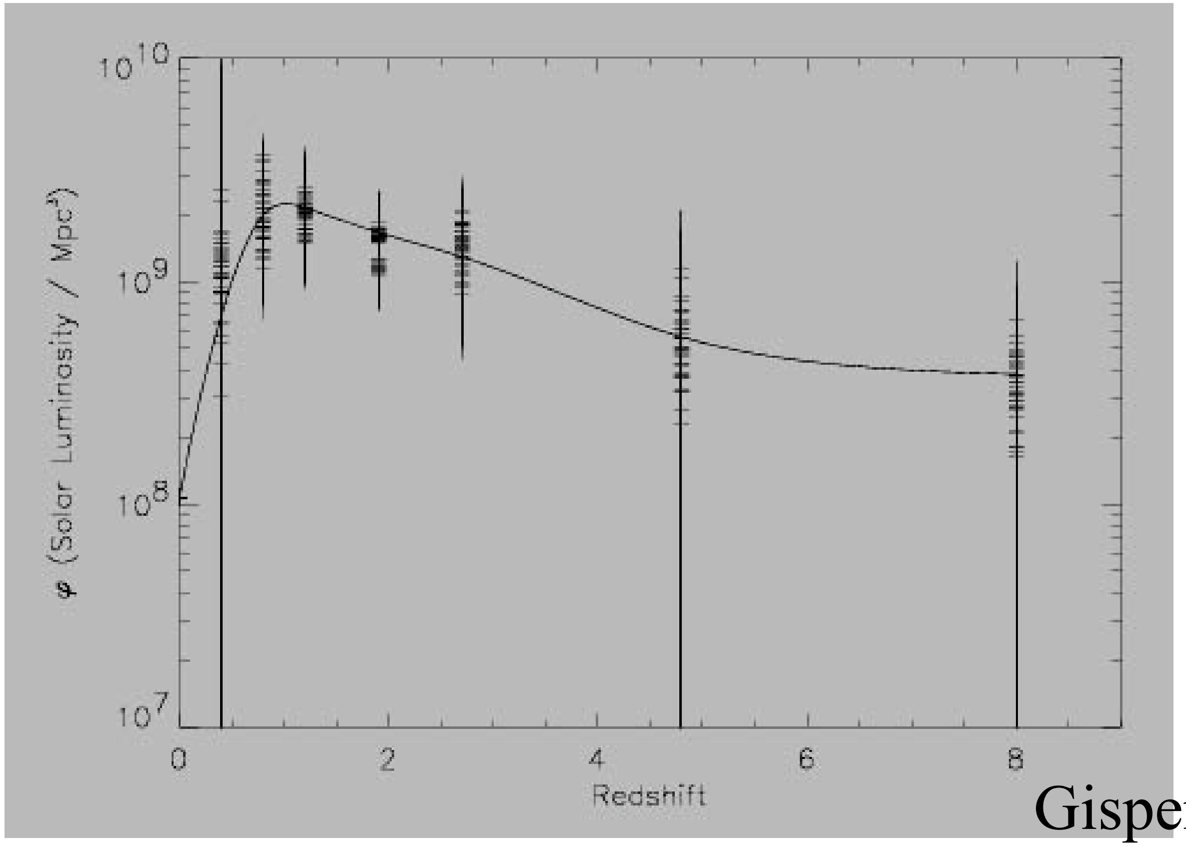
- **LIRGS and ULIRGs contribution to the IR energy production locally: 6%**
- **Locally: IR/Optical ~ 1/3**
- **This changes dramatically at high redshift**



Sanders & Mirabel, 1996

The CIB: First direct cosmological implication

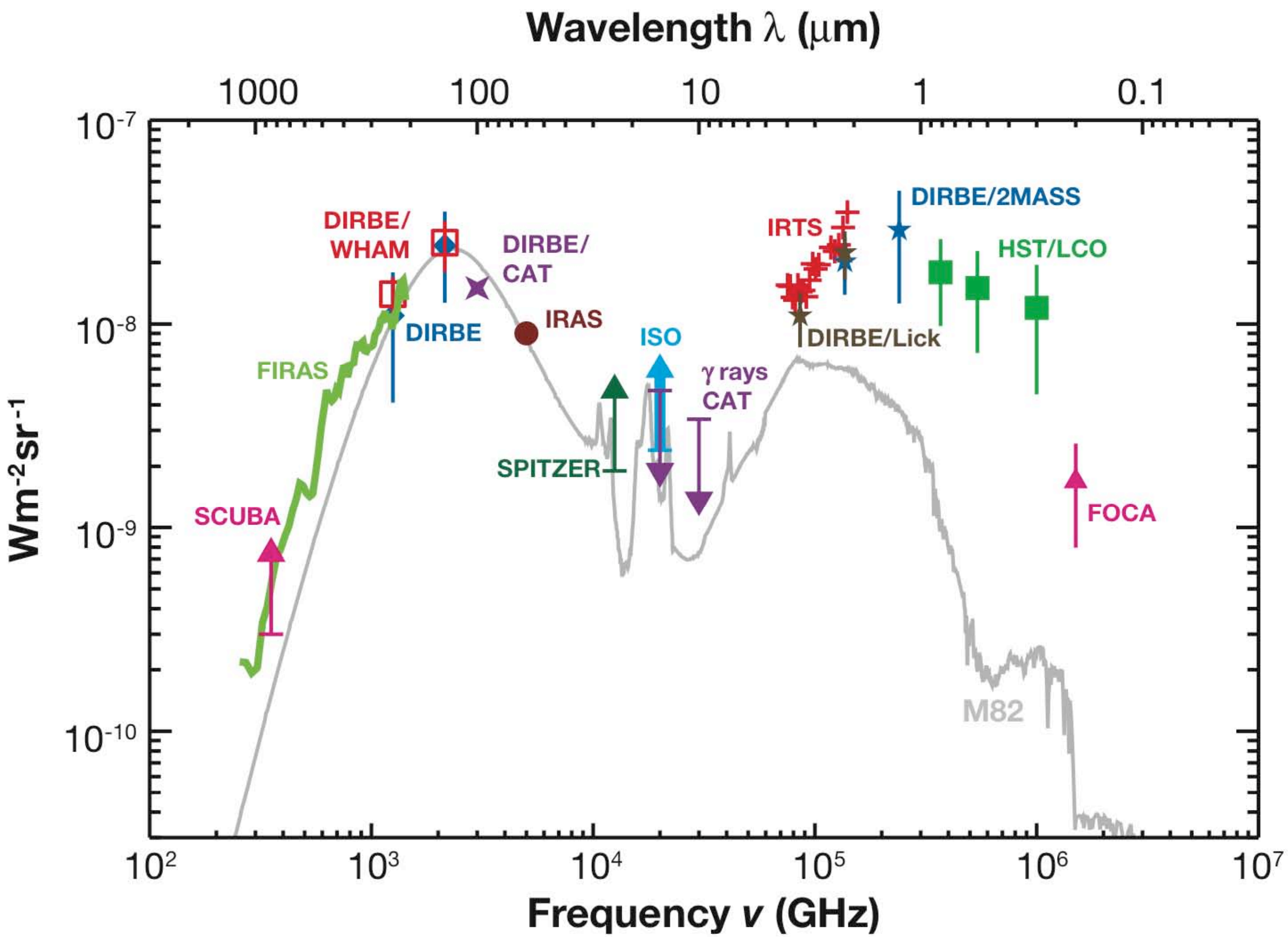
- Power in IR = power in optical (clearly different than locally)
  => IR galaxies grow more luminous with increasing redshift faster than do optical galaxies



Gispert et al. 2001

The CIB: Second direct cosmological implication

Millimeter CIB not due by mm emission of the galaxies that account for the peak of the CIB



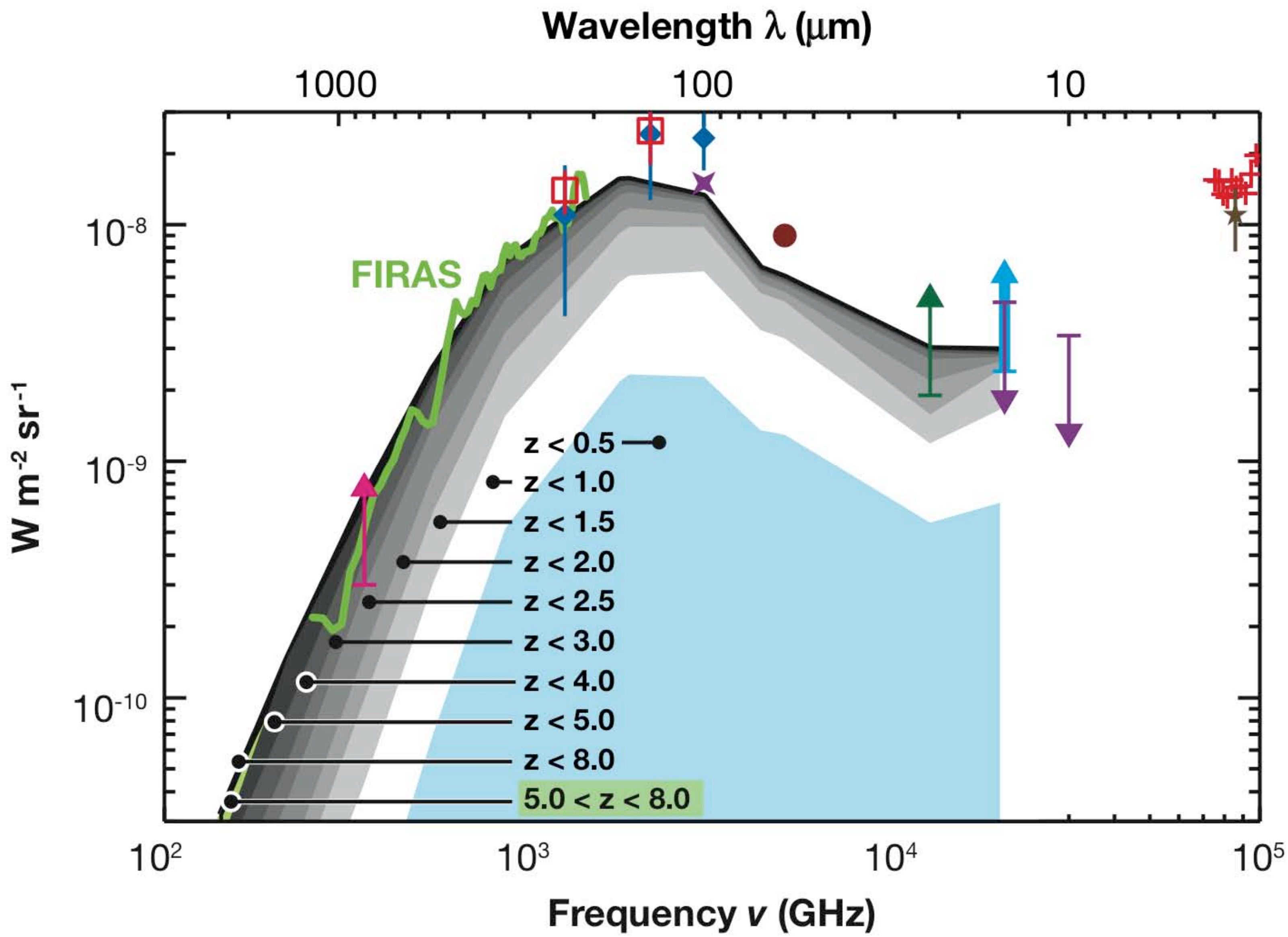
Redshift contribution to the CIB

- Contributions from galaxies at various redshifts are needed to fill the CIB SED shape

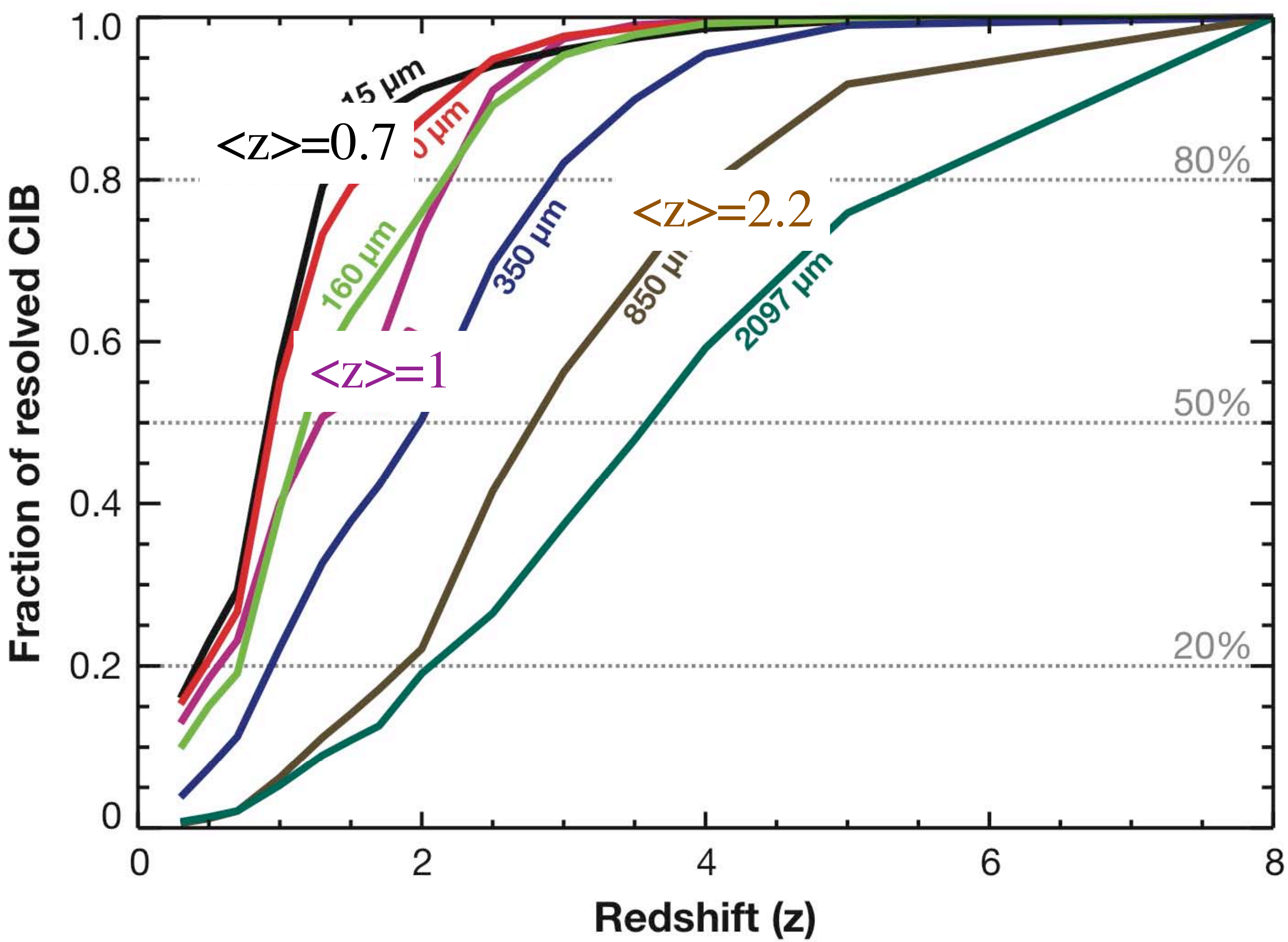
One example:

- Background at 140 μm: not resolved but the dominant contribution can be inferred from Spitzer deep surveys (24 μm population) - $<z>\sim 1$
- Submm and mm CIB: little contribution from Spitzer galaxies

Redshift contribution to the CIB

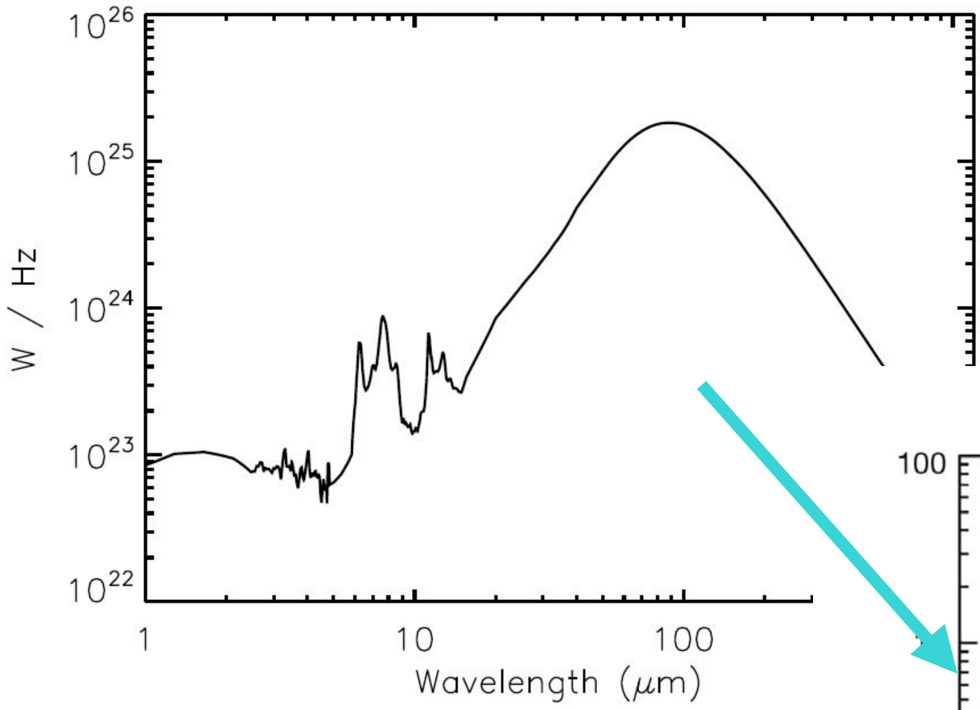


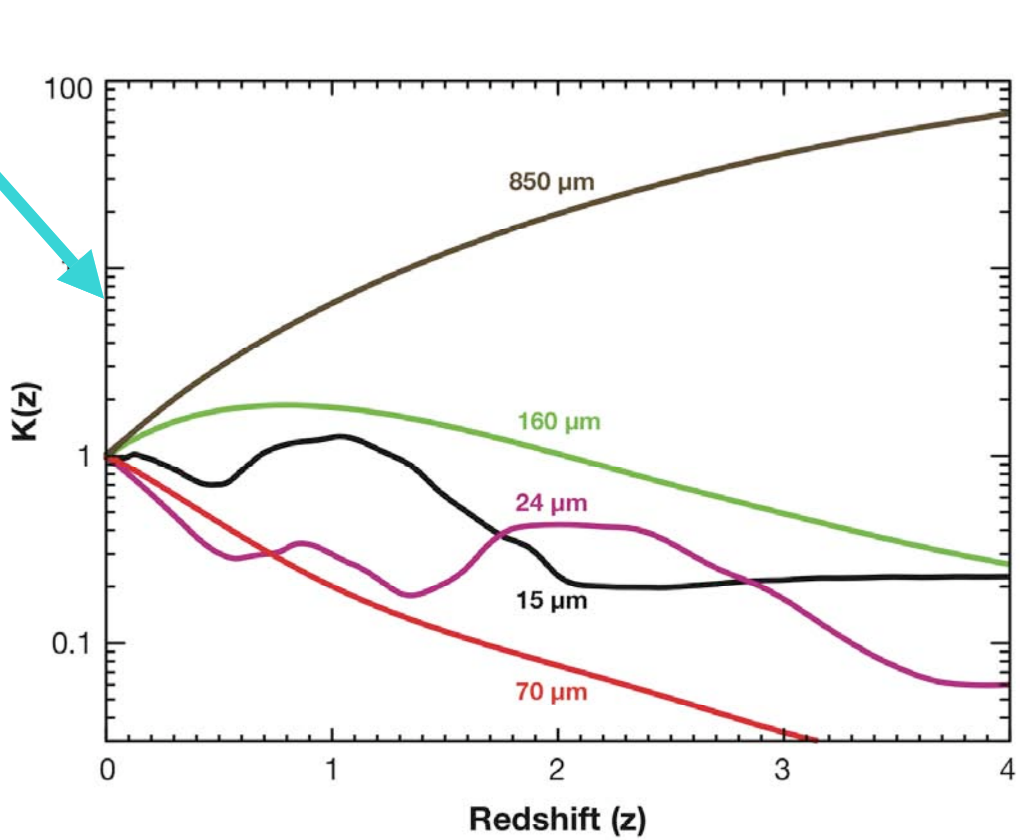
Redshift contribution to the CIB



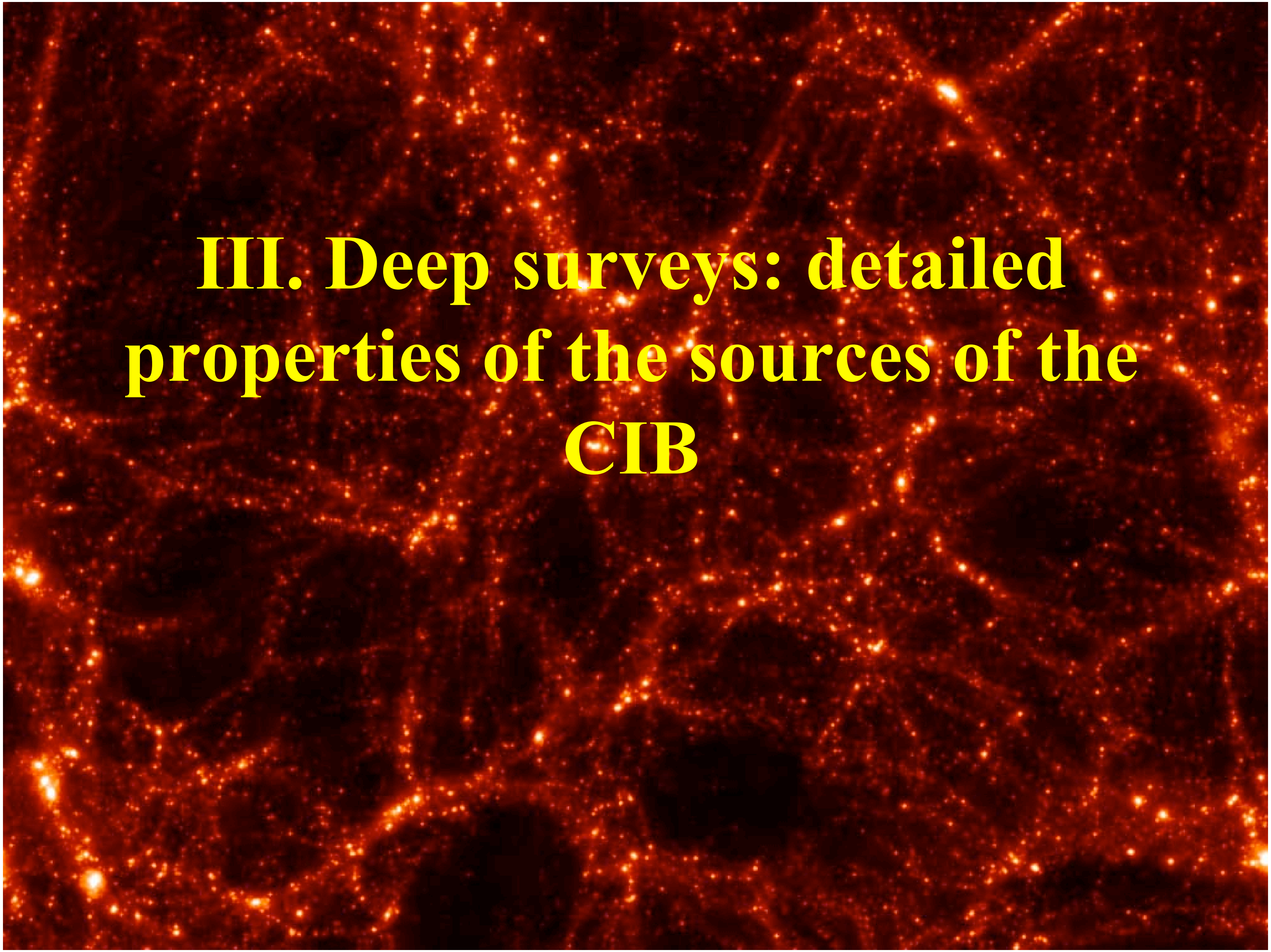
K-corrections

$K(L, z) = L\nu(1+z) / L\nu(z=0)$





III. Deep surveys: detailed properties of the sources of the CIB



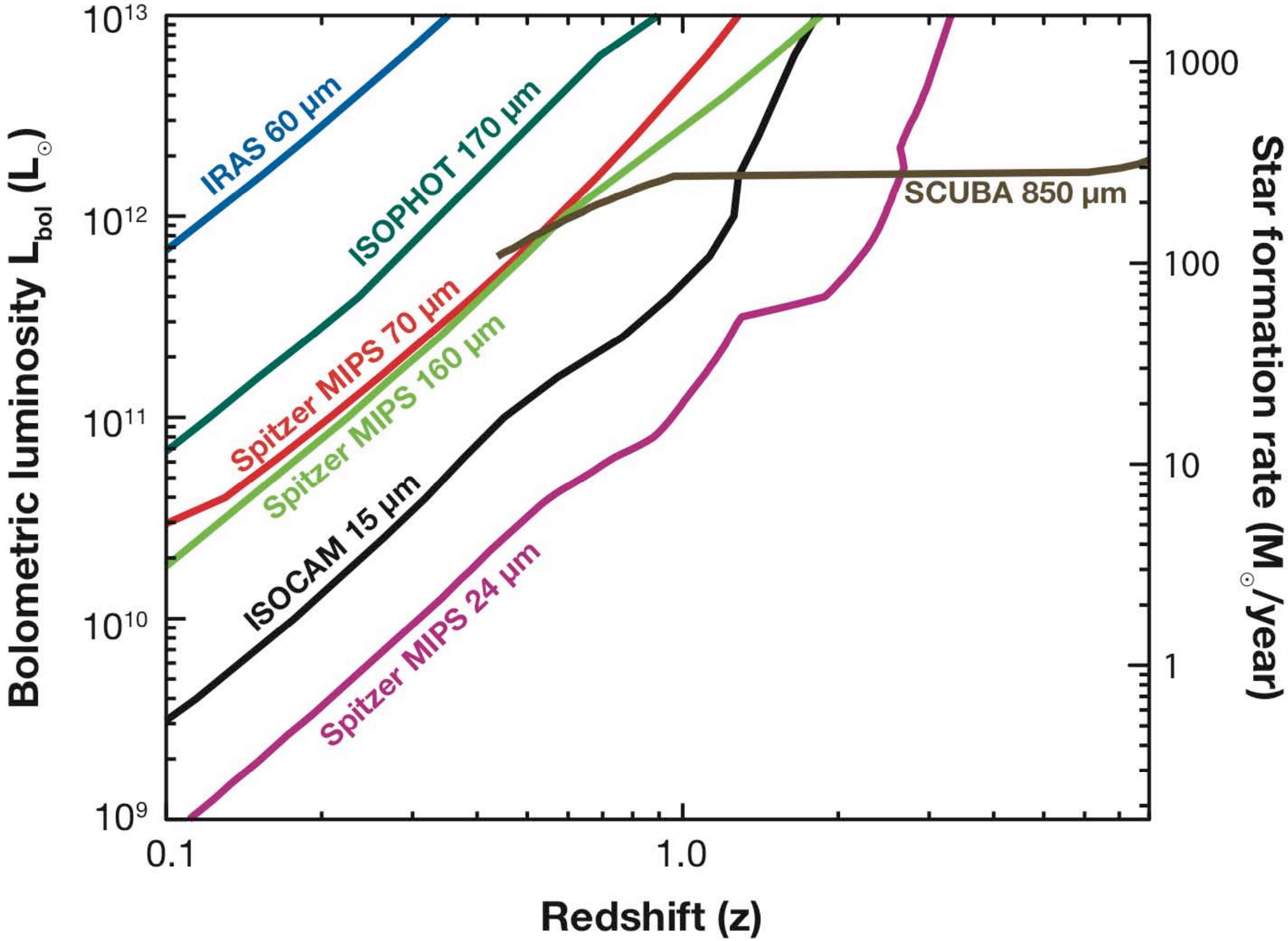
The resolved CIB: deep surveys

ISOCAM 15 μm	80%
SPITZER 24 μm	70%
SPITZER 70 μm	23%
ISOPHOT 90 μm	<5%
SPITZER 160 μm	7%
FIRBACK 170 μm	<5%
SCUBA 450 μm	15%
SCUBA 850 μm	60% (S>0.5 mJy) 30% (S>3 mJy)
MAMBO 1.2 mm	10%

The resolved CIB: deep surveys

ISOCAM 15 μm	80%
SPITZER 24 μm	70%
SPITZER 70 μm	23% (90%)
ISOPHOT 90 μm	<5%
SPITZER 160 μm	7% (70%)
FIRBACK 170 μm	<5%
SCUBA 450 μm	15%
SCUBA 850 μm	60% (S>0.5 mJy) 30% (S>3 mJy)
MAMBO 1.2 mm	10%

Basic capabilities of deep surveys



Detection of at least 10 sources: above the curves

Galaxies at redshift 0.5<z<1.5: detailed properties

- ISOCAM 15 μm + Spitzer 24 μm
- Followup observations. Counterparts easy to identify
- Median redshift: 0.52-0.8 (15 μm), ~1 (24 μm)
- ~85% are emission-line galaxies, consistent with HII regions, low ionisation level
- ~20% AGN
- Luminosity: 75% (dominated by SF) are LIRGs or ULIRGs, $\langle L_{IR} \rangle = 3\ 10^{11}\ L_{\odot}$

  => Star formation density at z<1 is dominated by the abundant population of LIRGs
- $\langle Av \rangle = 2.8$ @ z=0.7 (>>0.86 for local star forming galaxies)
- $\langle SFR \rangle = 50\ M_{\odot}/yr$ (>0.5-2 for faint-optically selected galaxies in the same z)
- Stellar masses: from 10^{10} to $3\ 10^{11}\ M_{\odot}$

Galaxies at redshift 0.5<z<1.5: detailed properties

- Time spent in the starburst phase: t[yrs]=M/SFR
  (if SFR=cst, t=time to double the stellar mass). Hammer et al. 2005
  => LIRGs z>0.4, t ranges from 0.1 to 1.1 Gyr
  => Newly formed stellar-mass in LIRGs from z=1 to z=0.4 corresponds to about 60% of the z=1 total mass of intermediate-mass gal.

- LIRGs are actively build up their metal content:
  => Z of LIRGs less than half of the z~0 disk with comparable brightness (Liang et al. 2004)

- Morphologies:
  - LIRGs: 36% disks, 25% LCGs, 22% irr, 17% major mergers
  - Local gal: 70% disks, <2% LCGs, 3% irr, <2% major mergers, 27% E/S0

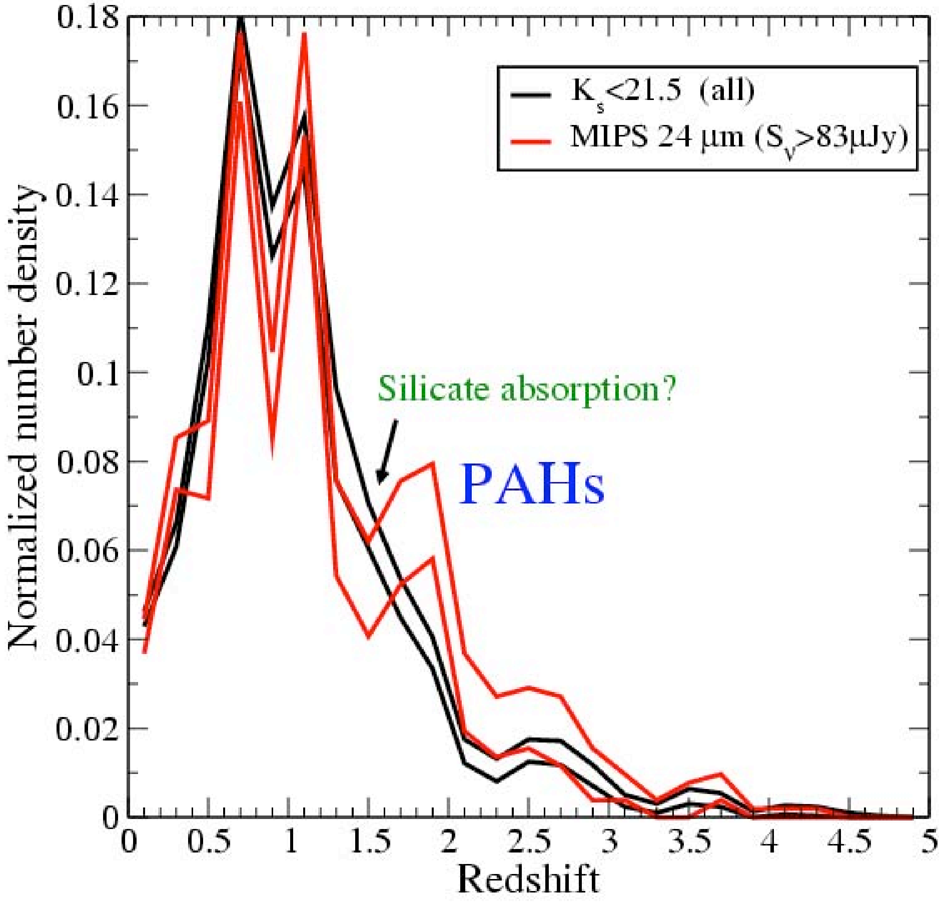
Galaxies at z>1 : SPITZER (24 μm)

– Detect LIRGs and ULIRGs up to z~3

⇒ PAH features passing through the filter

First results:

- SWIRE, Guaranteed time obs., FLS
- $L = 5\ 10^{11}$-$10^{14}\ L_{\odot}$ @ z=1-3
- $z_{med} \sim 1$ (~30% z>1.5)
- Starburst. At high z, $SFR > 500 M_{\odot}$ /yr



Caputi et al. 2005

(e.g. Lonsdale et al. 04, Le Floc'h et al. 04, Yan et al. 04, 05, Bell et al. 05)

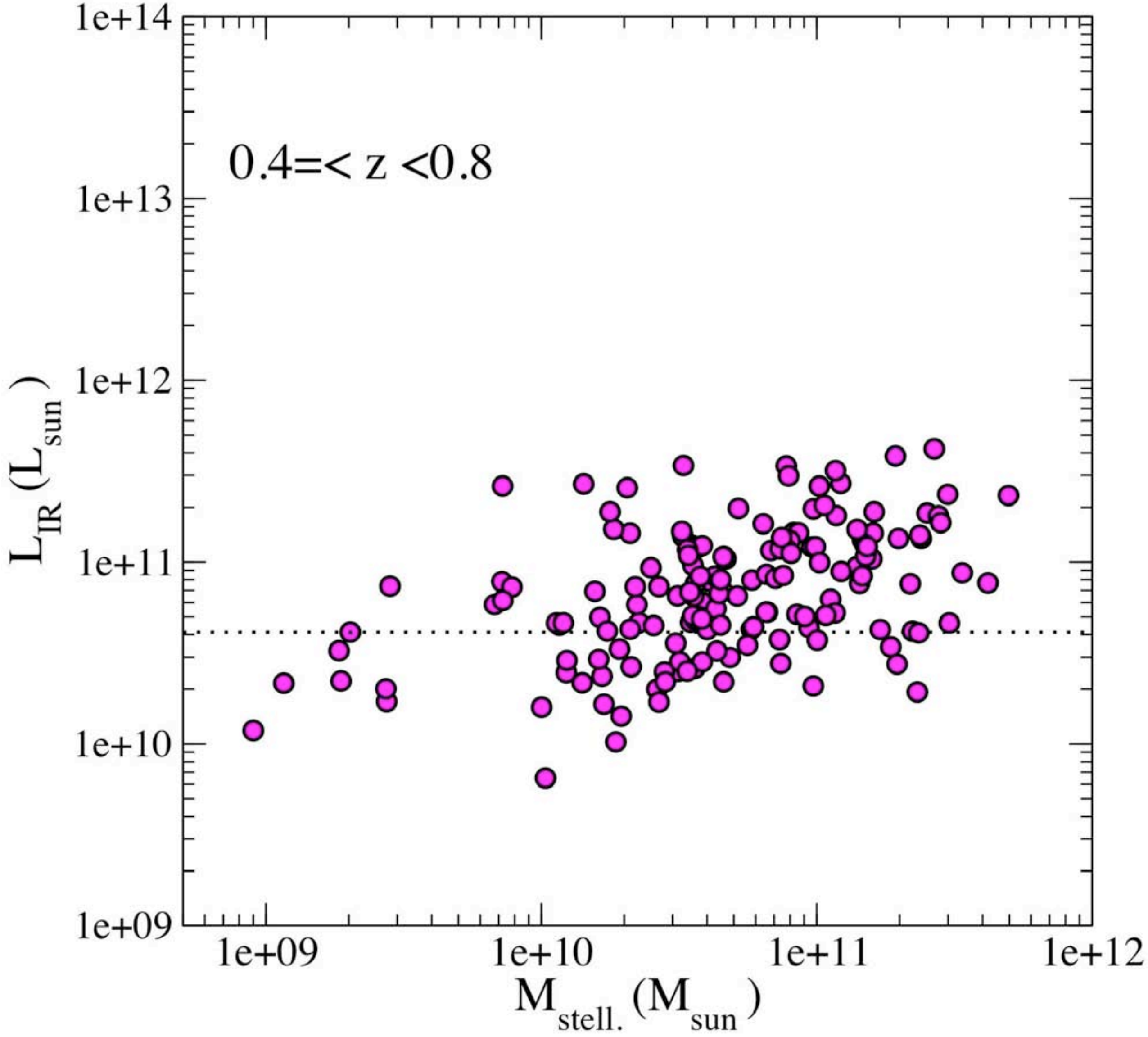
Stellar mass and star formation in Spitzer 24 μm galaxies

- CDFS, GTO observations
- 80% completeness at S(24 μm) = 83 μJy
- In 131 arcmin^2: identification of 747 24 μm sources including 94% of the sources with S(24 μm) > 83 μJy
- Redshift and stellar masses estimated from best fit SED (36% z spec)
- L_{IR} and SFR estimated from 24 μm fluxes

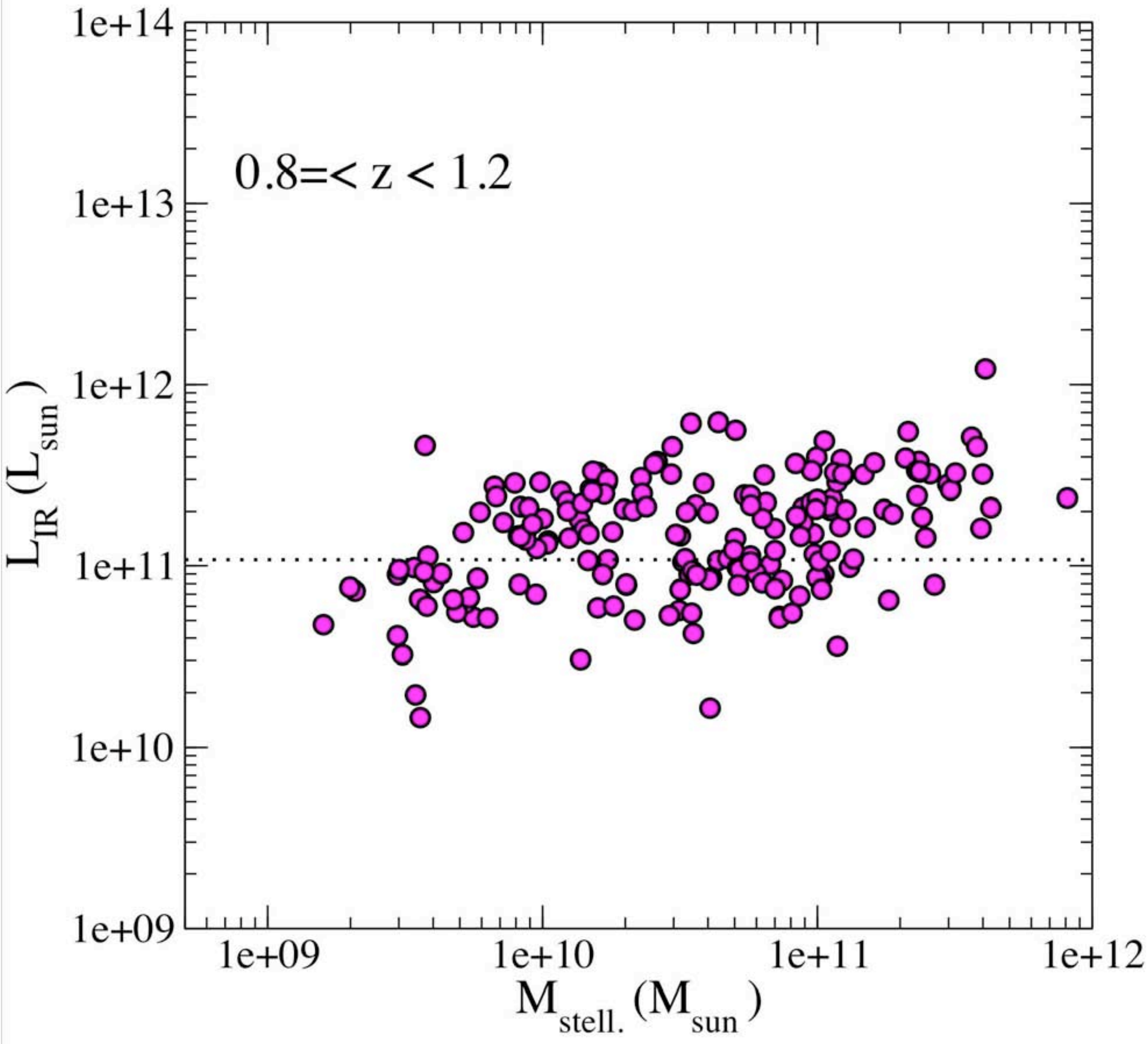
⇒ Evolution of L_{IR} versus $M_{stellar}$ (Caputi et al. 2006)

⇒ Role of ULIRGs in massive galaxy evolution (Caputi et al. 2006)

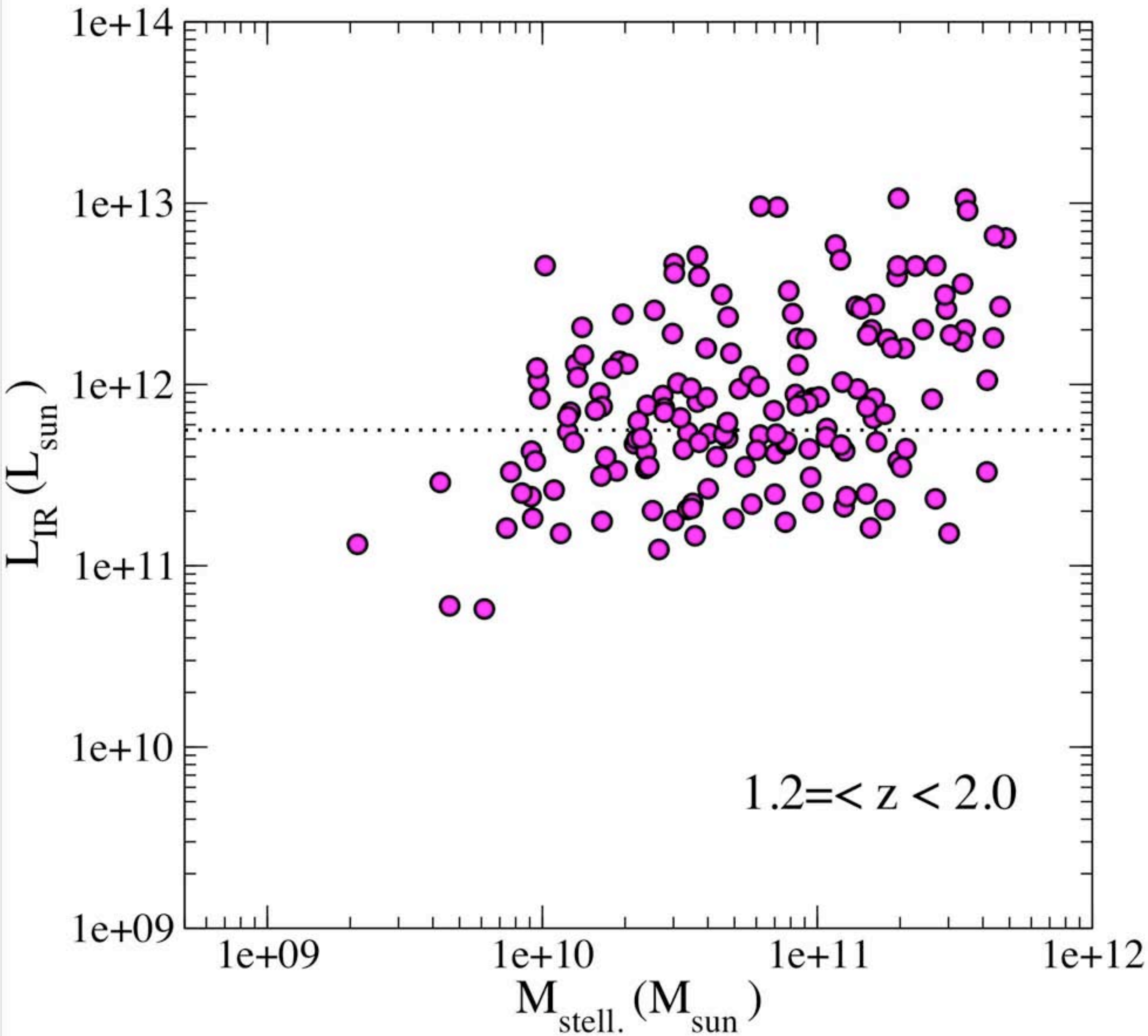
The evolution of L_{IR} versus $M_{stellar}$



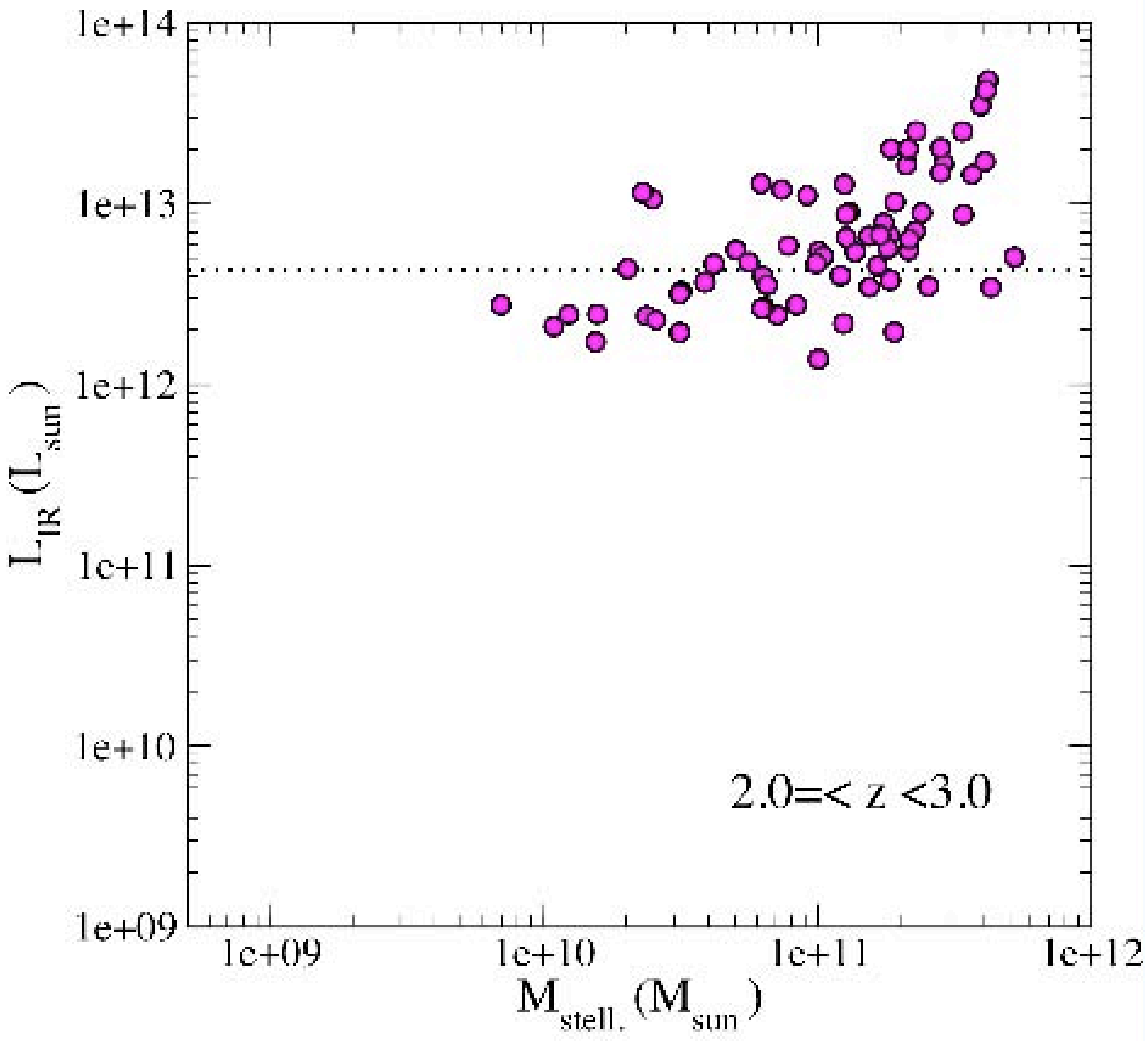
The evolution of L_{IR} versus $M_{stellar}$



The evolution of L_{IR} versus $M_{stellar}$



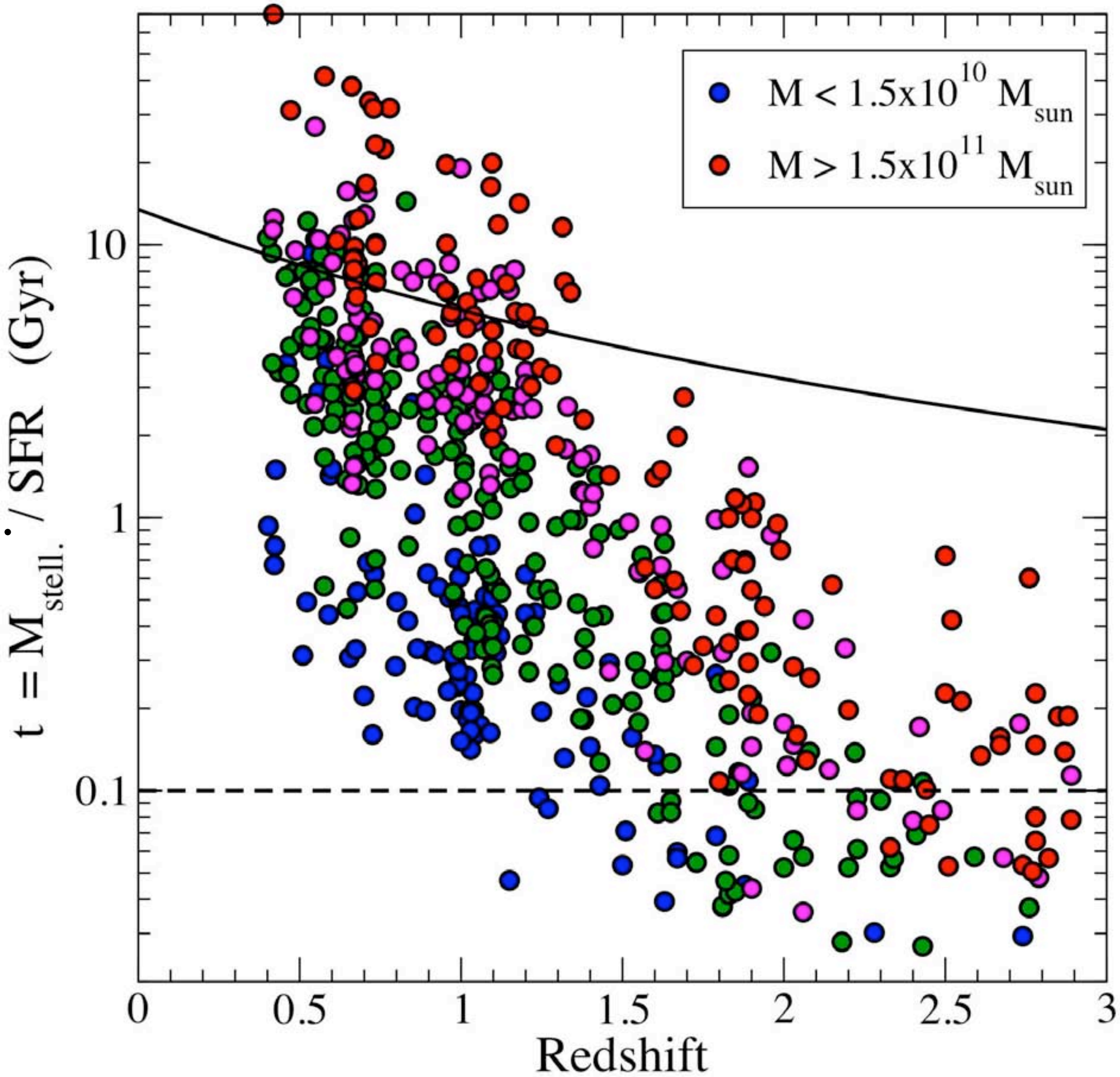
The evolution of L_{IR} versus $M_{stellar}$



The $M_{stellar}$/SFR ratio versus redshift

At z~~2-3, a starburst lifetime is sufficient to construct 10^{10}-10^{11} Mo

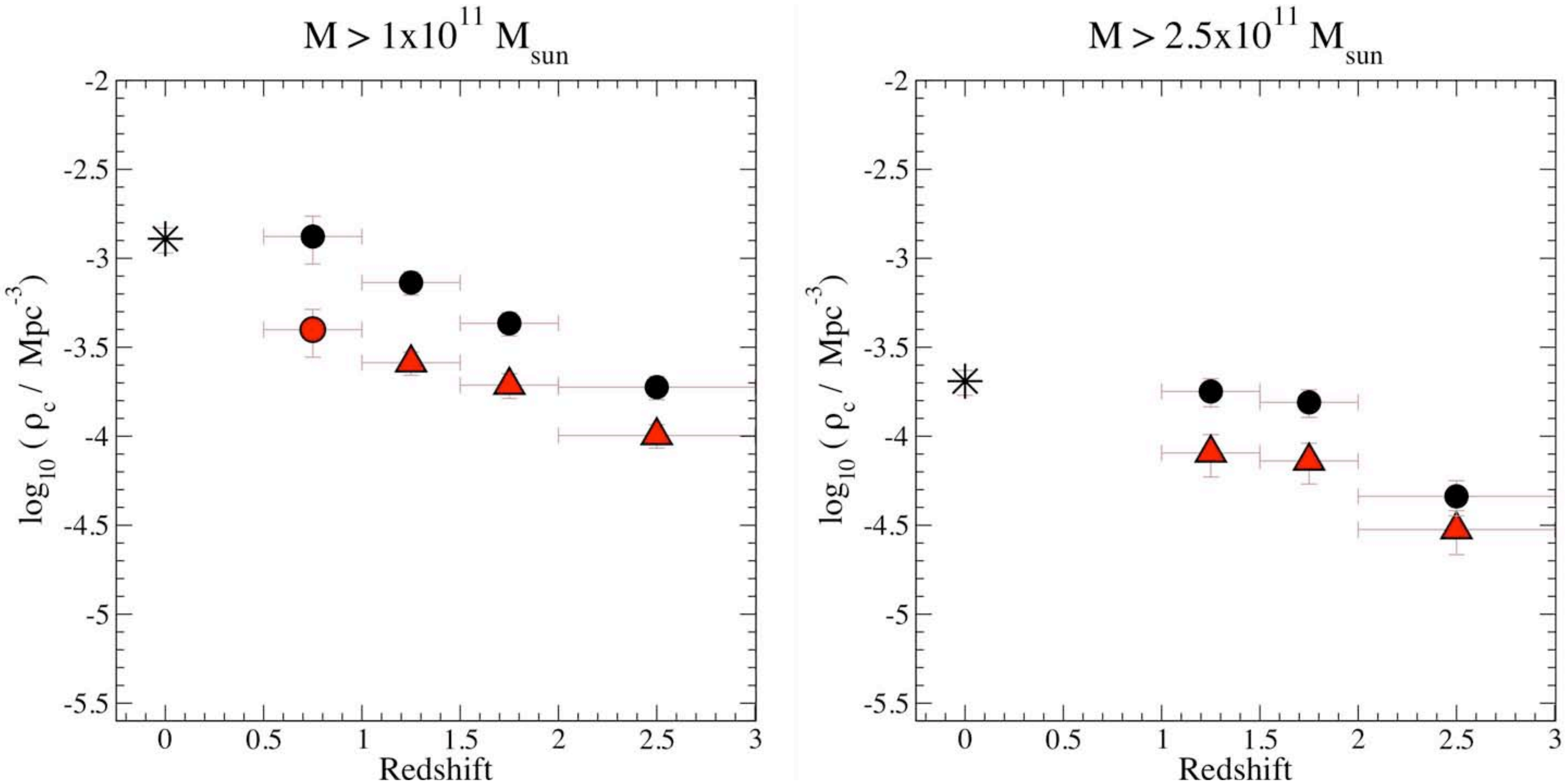
Burst-like mode is very efficient in constructing massive galaxies at high z. At low z, burst-like mode is only efficient in low-mass systems.



Caputi et al. 2006

The role of (U)LIRGs in massive galaxy evol.

$L > 10^{11}$ Lo

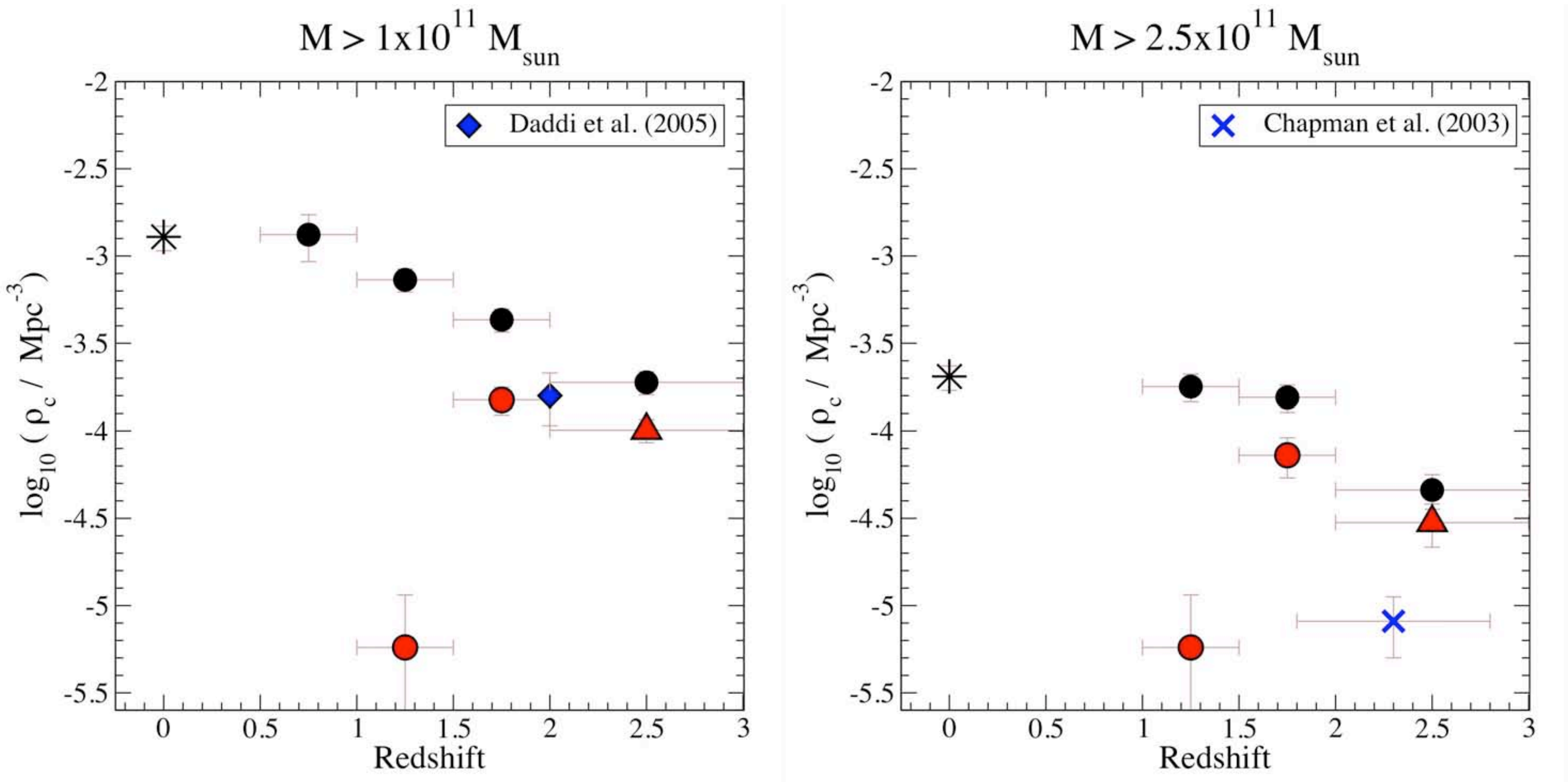


➢LIRGS and ULIRGs constitute a significant fraction of the assembled massive galaxies (the fraction increases with z)

➢Example: >65% of the most massive galaxies already present at z=2-3 are ultra-luminous in the IR

The role of ULIRGs in massive galaxy evol.

L > 10 [12] Lo



- **LIRGs dominated z<1.5 ; ULIRGs dominated z>1.5**
- **Radio-detected submm galaxies: smaller by a factor ~4**

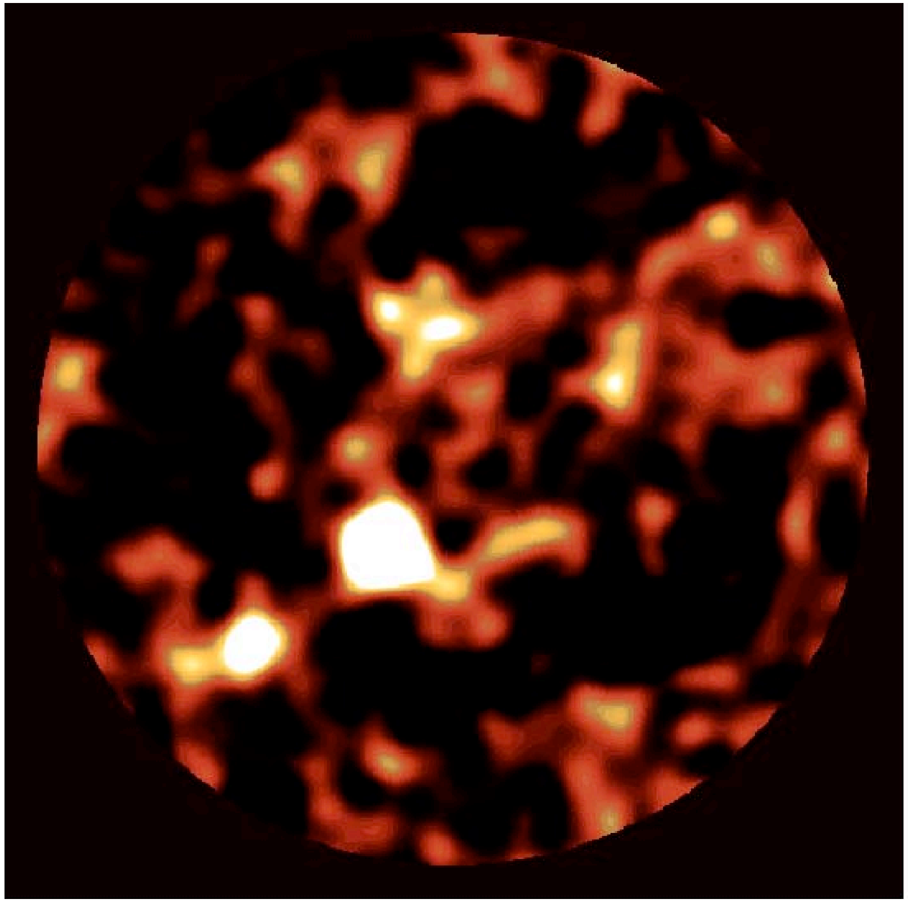
=> what kind of 24 μm selected ULIRGs are counterparts to radio-detected submm galaxies still to be investigated

SMGs (Submm Galaxies)

- Faint radio galaxies as an intermediate identification
- <z>=2.2 (S>3 mJy, 30% of the CIB)

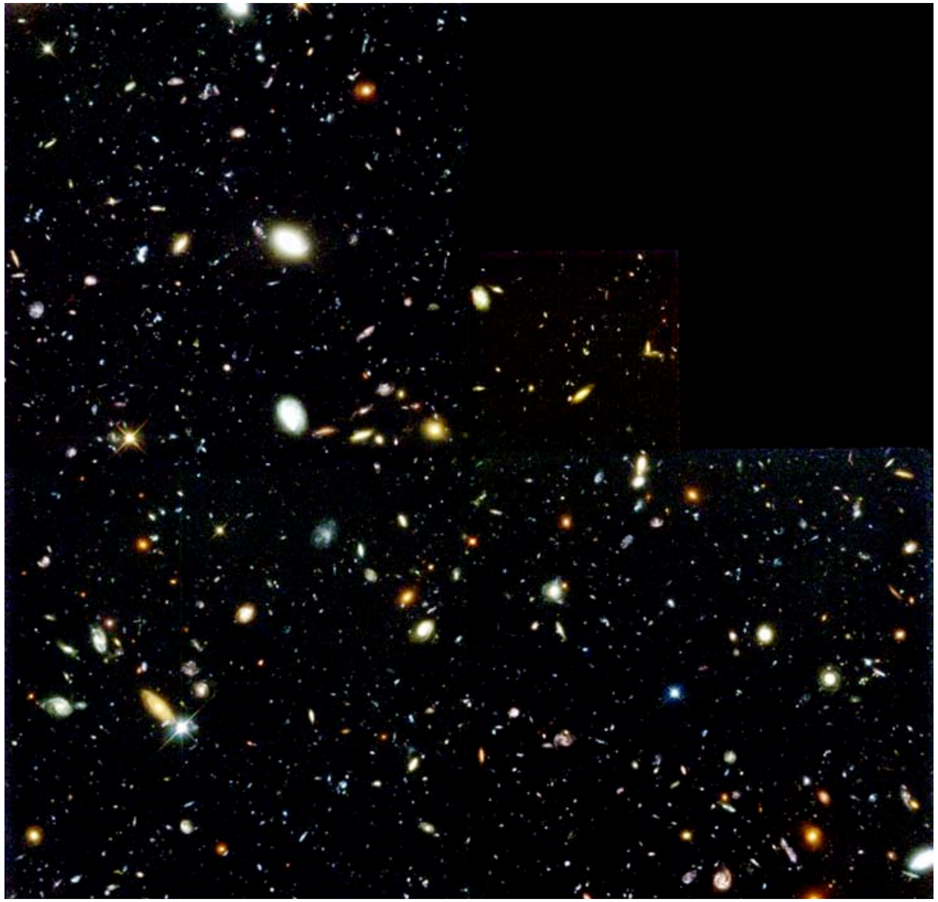
High angular resolution and identification

SCUBA

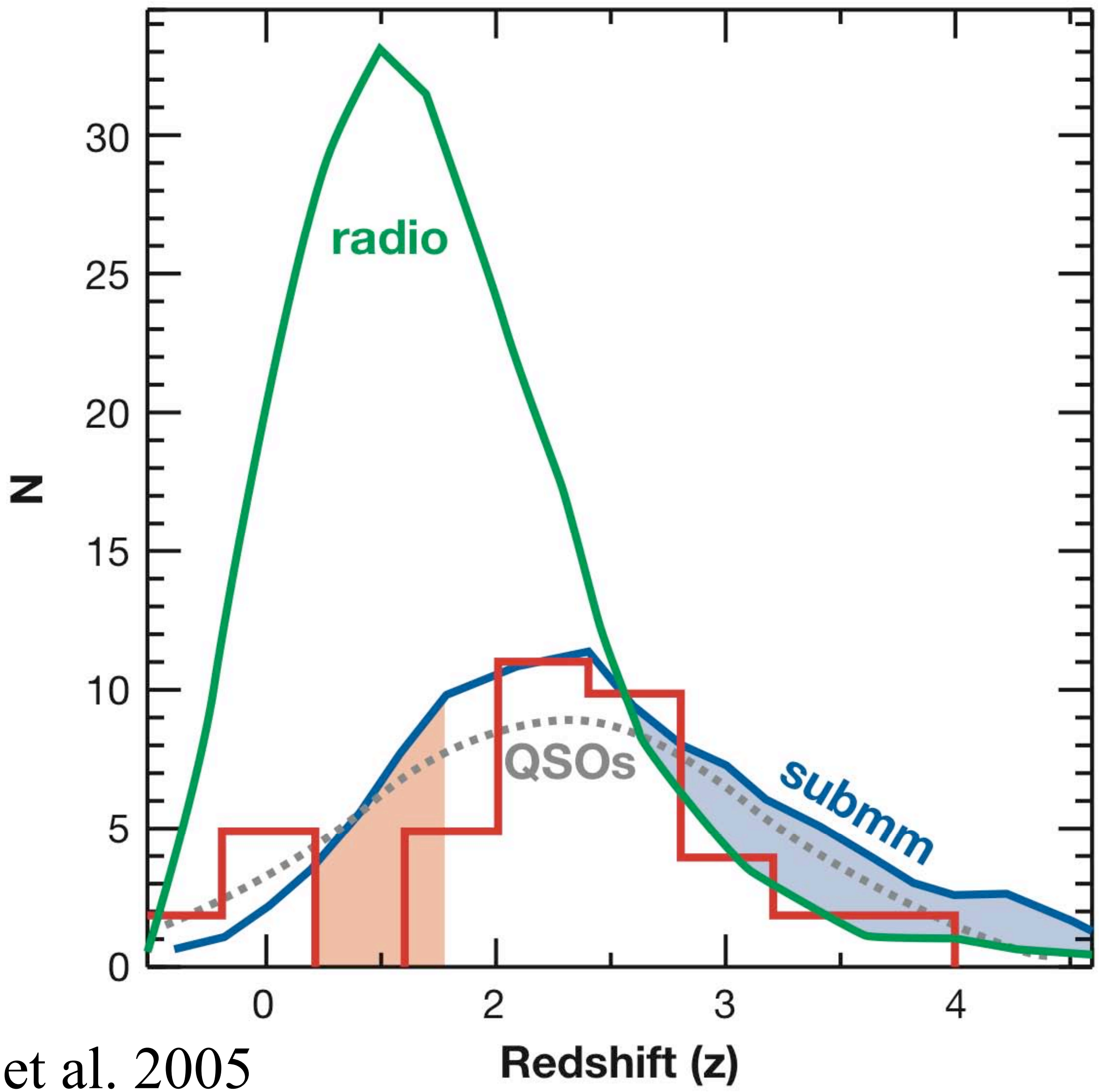


Hughes et al. (1998)

HST



SMGs: z-distrib



Chapman et al. 2005

SMGs (Submm Galaxies)

- Faint radio galaxies as an intermediate identification
- <z>=2.2 (S>3 mJy, 30% of the CIB)

- Multicomponent-distorted galaxy systems, irregular and highly complex morphologies
- Often red galaxies with bluer companions (as expected for interacting, star-forming galaxies)
- Extraordinarily large and elongated relative to the field population
- Large bolometric luminosity 10^{12}-10^{13} $L_{\odot}$ (ULIRGs)

  => Very high SFR (1000 $M_{\odot}$ /an)
- High mass (dynamical masses: 1-2 10^{11} $M_{\odot}$, 13xLBGs)

(e.g. Barger et al. 00, Chapman et al. 02-05, Greve et al. 05, Genzel et al. 05)

ULIRGs/AGNs

- SMGs and high-z Spitzer 24 μm galaxies: ULIRGs
- IR emission: star formation or AGN?
- Observations Opt/NIR + X

  => Star formation is dominant (sure?)
- Chapman et al. 2004: Original approach
  - Interferometry: radio high angular resolution
  - Extended emission in 70% of the objects
  - 30%: more compact emission (AGN or concentrated nuclear SB)

- Most consistent low-res spectral diagnostic for distinguishing an AGN-powered source from a SB: strength of PAH features (Genzel+98, Laurent+00, Weedman+05)
  - Strong PAHs => star formation
  - Strong continuum, deep SiO absorption => AGN

=> SPITZER spectroscopy

Summary of high-z IRS programs

Spitzer mid-IR selected:

- 24 µm selected, extremely red & 1mJy samples (58 sources, IRS GTO, Houck+05, Weedman+06 -- 52 sources, GO1, Yan+05)
- 24 µm + IRAC 1.6um bump (16 ULIRGS, 2<z<3, GO3, IRS GTO)
- 24 µm silicate dropout (15 sources, GO2, Borys; GO3: IRS GTO)
- 24 µm flux limited, >= 1 mJy sample (152 sources, GO2, Yan et al.)
- 24 µm flux limited sample, 0.15-0.4 mJy sample at z~1 and z~2 (48 sources, GO3, Yan, Lagache et al.)
- 16+24 µm selected -- very faint sources (DDT, Teplitz+06)
- 24 µm selected -- 0.1<z<0.6 (40 sources, GO2, Lagache et al.)
- 24 µm selected -- S>2 mJy -- z>0.6 (12 sources, GO1, Le Floc'h et al.)
- 24 µm selected + other criteria (32 obscured ULIRGs, 1<z<1.9, GO3, IRS GTO)
- 70 µm selected -- 0.02<z<0.55 (17 sources, GO2, Dole et al.)

GO1 and GO2 mid-IR samples: mostly «1 mJy» samples

Summary of high-z IRS programs

Submm, 20cm, UV+24um and AGN/QSOs samples:

• Submm/mm selected samples (12 sources, GO1, Lutz et al. -- 64 sources, GO2, Blain et al. -- ~few sources, GO2, Chary et al.)

• Bright ISO 15μm selected sample (70 sources, GO1, Perez-Fourmon et al.)

• Radio (20cm) + 24μm or submm selected samples (IRS GTO Weedman et al. 2005 -- 6 sources GO2, Chapman et al.)

• AGN/QSO selected samples (GO1 Sturm et al. 2006; GO2: Maiolino et al., Urry et al., Helfand et al., GO3:Lutz et al.)

• Lyman break galaxies (GO3: IRAC GTO, Siana et al.)

• Lensed z>1 ULIRGs (GO3: MIPS GTO)

Ultra Deep Spitzer Spectral Survey:

• 2 Sq. arcmin, HDFN, DDT, Helou et al.

High-z luminous IR galaxies: mid-IR spectroscopy

Tracing the mid-IR spectroscopic properties of distant IR galaxies: unique capability from IRS

1) AGN versus Starburst

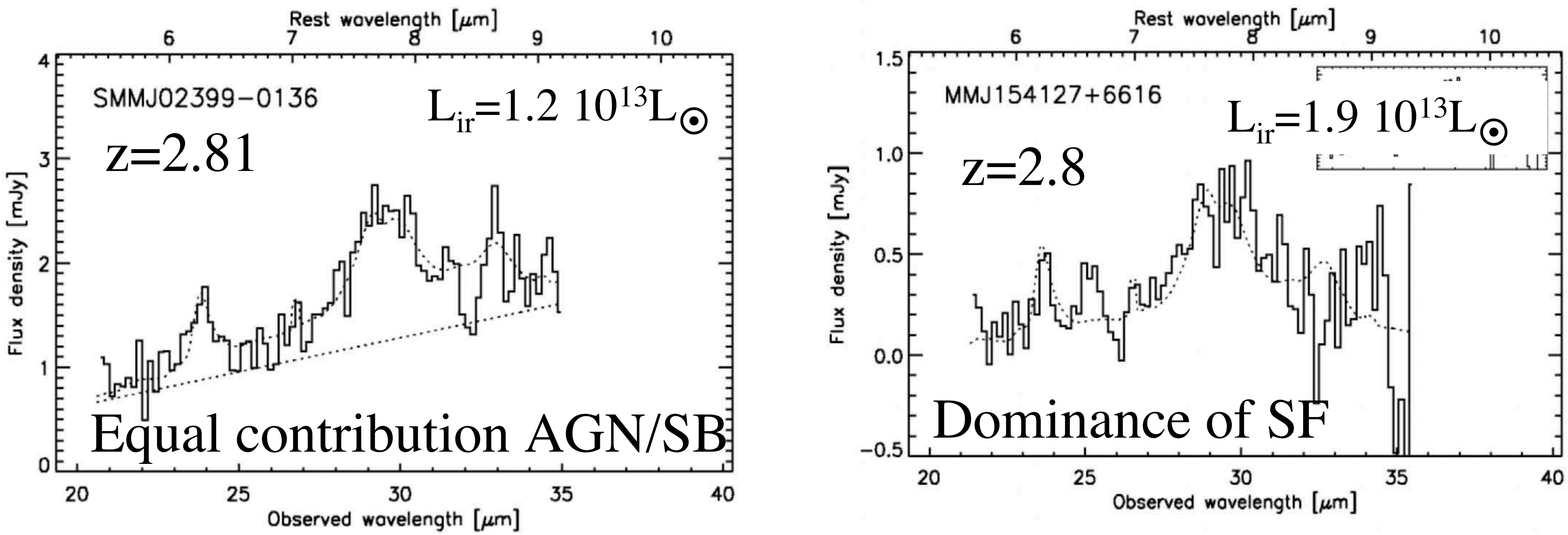
2) Overview of the prevailing ISM conditions

- Evolution of the mid-IR spectra as a function of Lir, z (=> proper modelling of the number counts and background)
- Understand the physical parameters that constrain Lir (ex: ISM pressure)
- Strength of PAHs versus metallicity
- etc….

3) Redshifts of the optically-faint IR galaxies (SiO absorption, PAHs)

AGN versus starburst: SMGs

- Rest-frame mid-IR spectroscopy:
  - **z** (currently z for the <~50% of the population accessible to optical spectro.)
  - **Constrain the energy sources** (AGN versus Starburst)



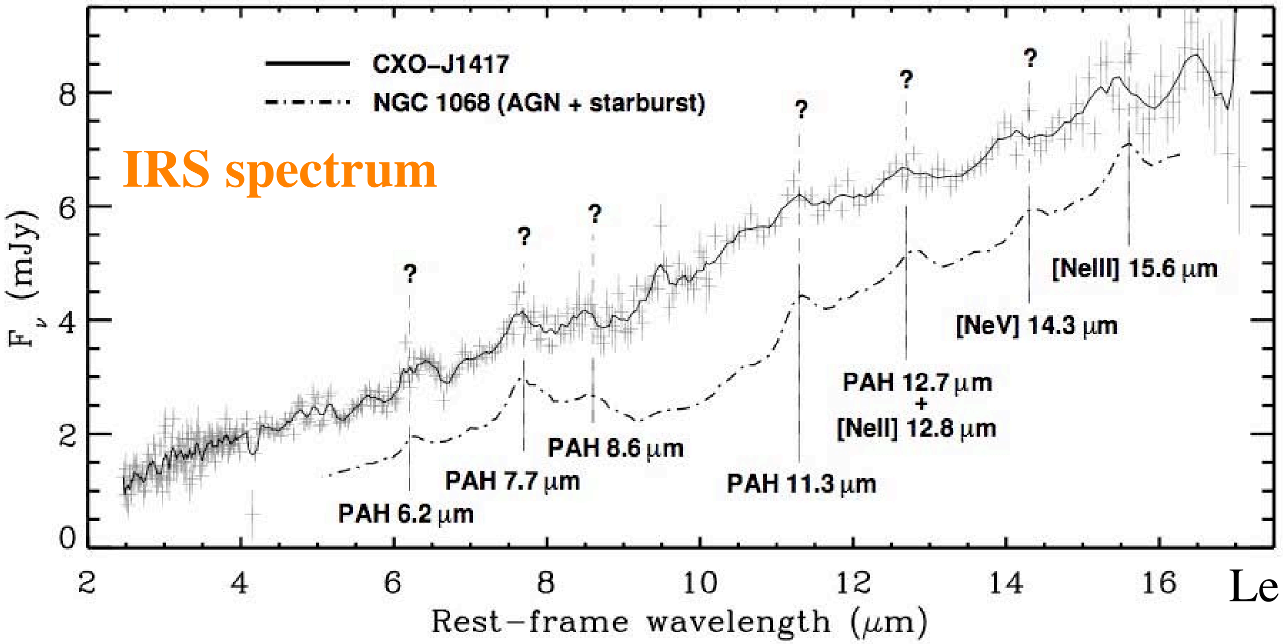
Mid-IR/Far-IR SEDs: SMGs are scaled-up versions of compact SF events in local ULIRGs ; support the scenario that SMGs are sites of extreme SF

Lutz+05

AGN versus starburst

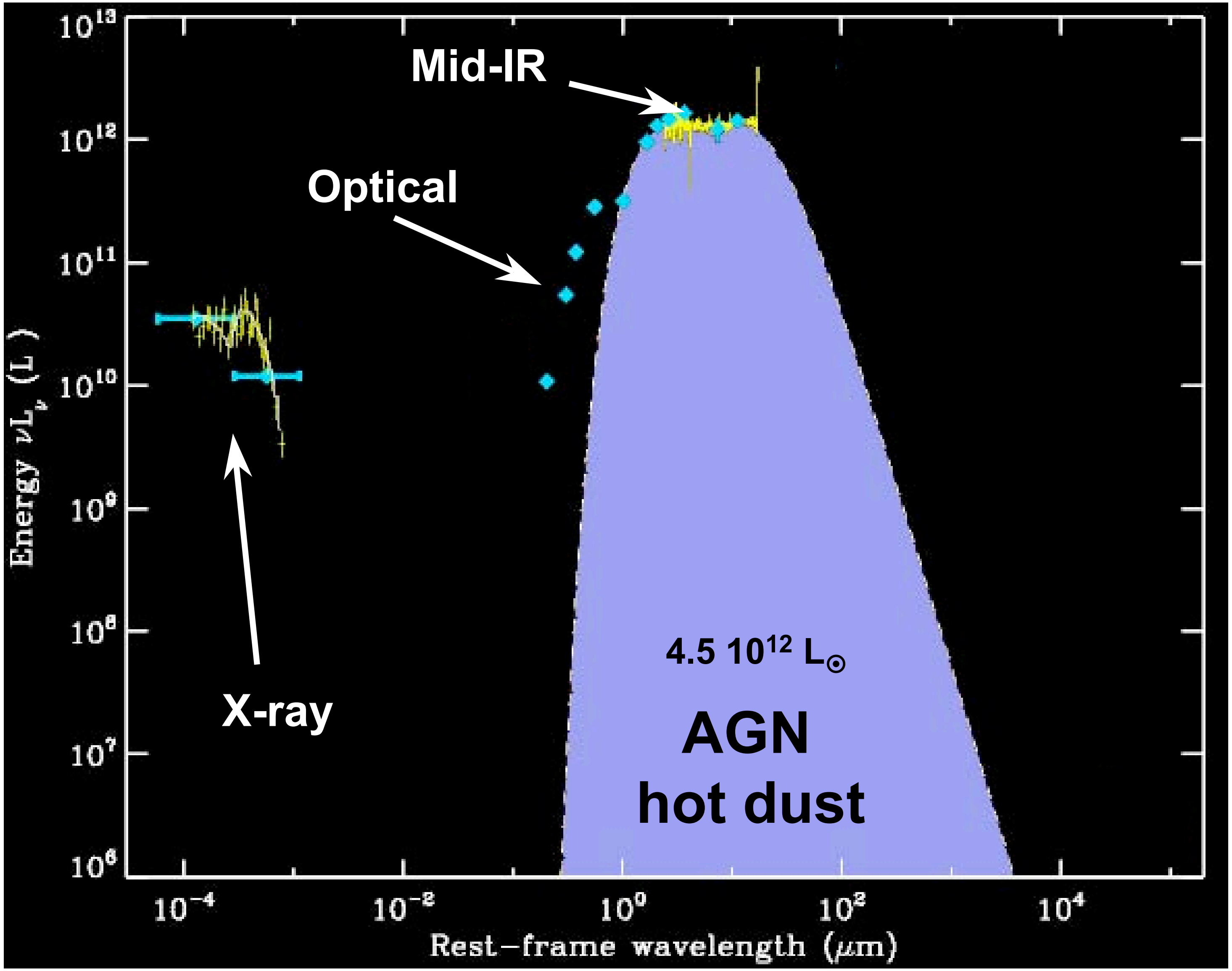
- Mid-IR spectroscopy:
    - Strong PAHs => star formation
    - Strong continuum => AGN?

  Not always: Exemple of CXOJ141741.9+522823 (AGN, z=1.15)



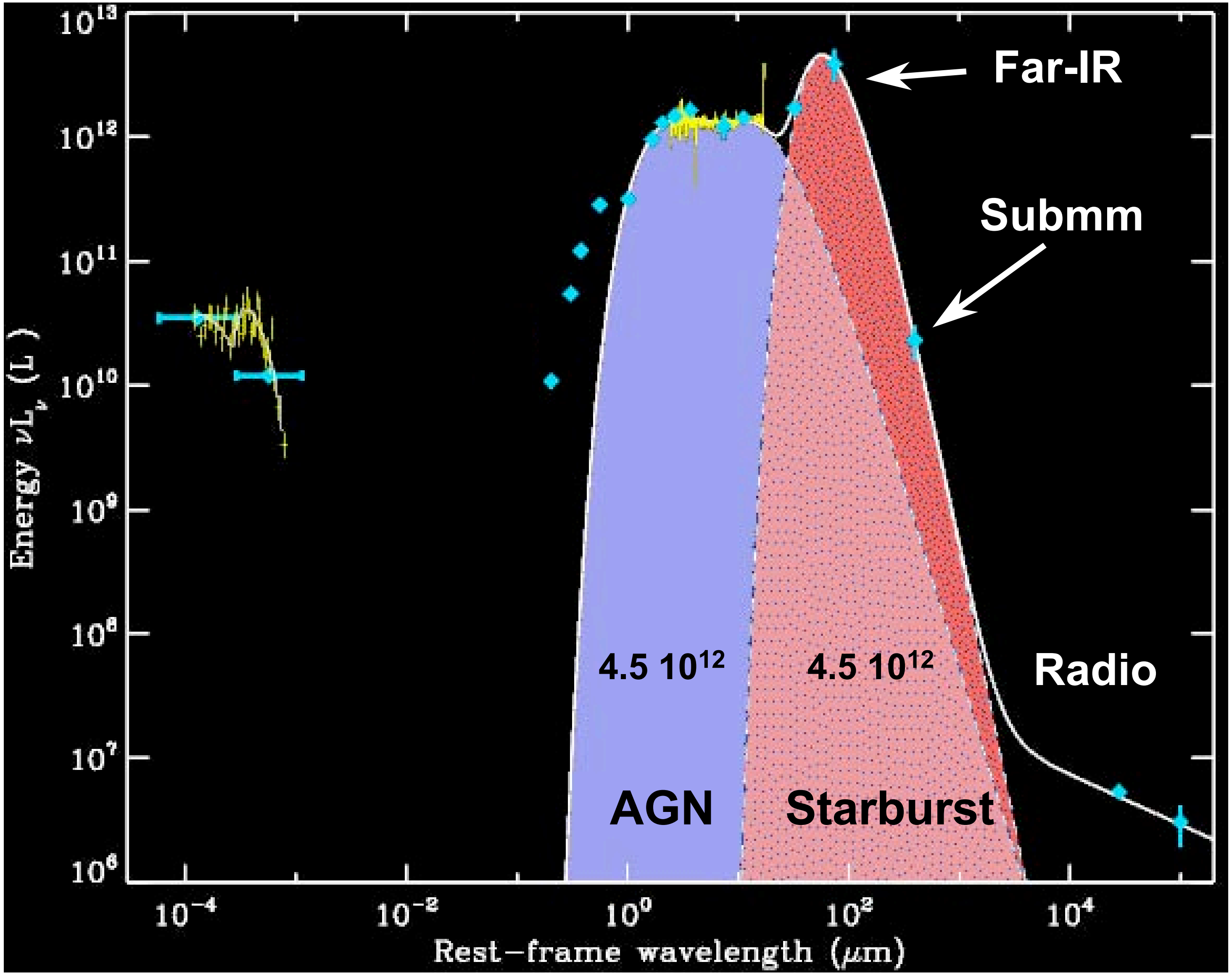
Le Floc'h+06

AGN versus starburst: CXOJ1417



Le Floc'h+06

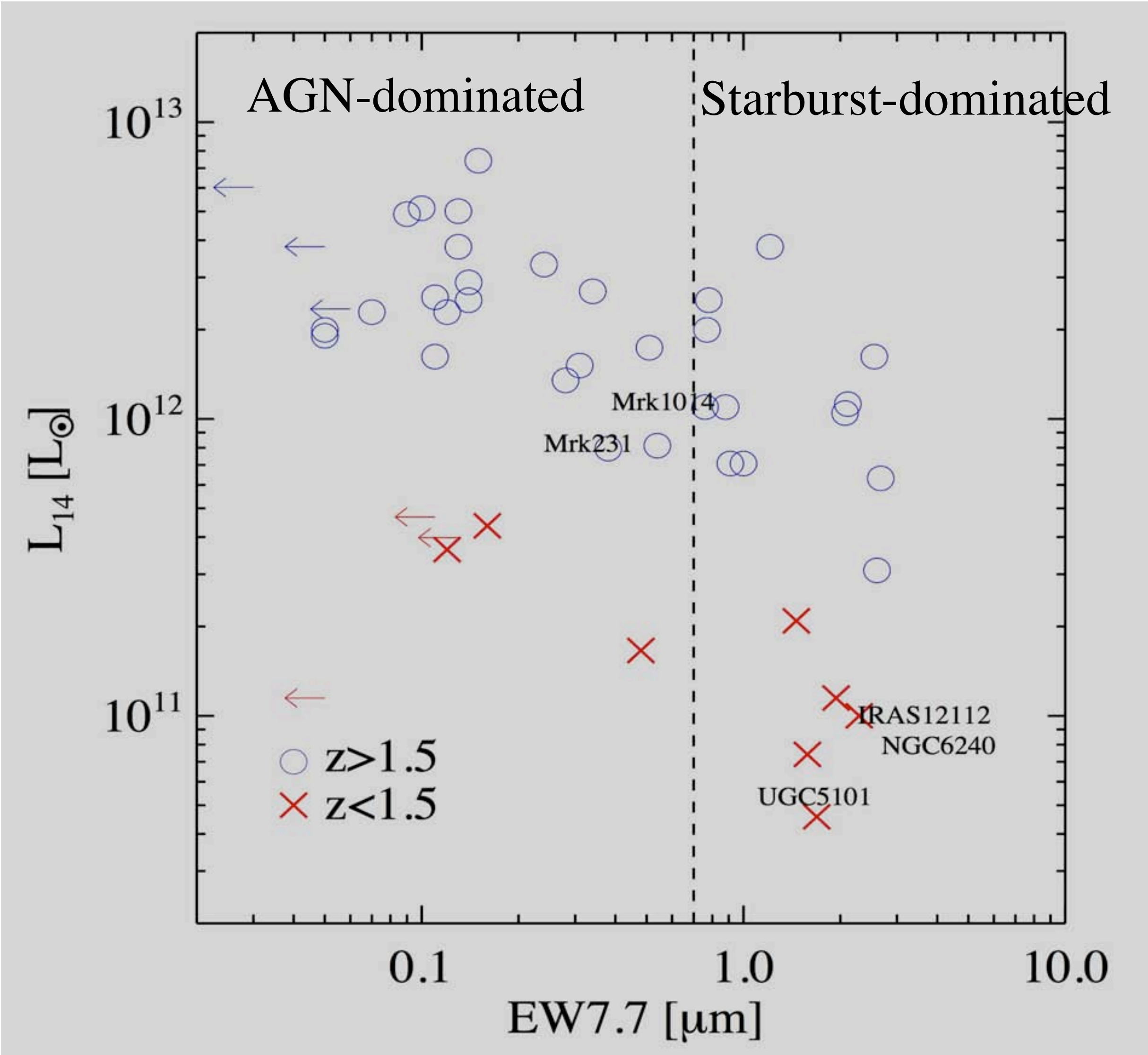
AGN versus starburst: CXOJ1417



Le Floc'h+06

Surveys of the mid-IR population: nature of the midIR sources

How strong is the PAH emission at z~2?



-Stronger PAH sources: lower mid-IR luminosity
⇒ AGN fraction grows with luminosity

- Few z~2 sources with PAH as strong as the local star formation-dominated ULIRGs BUT mid-IR luminosities already ~10^{12} (Lir~$10^{13}L_\odot$)

Sajina+06

ULIRGs and HLIRGs at high-z

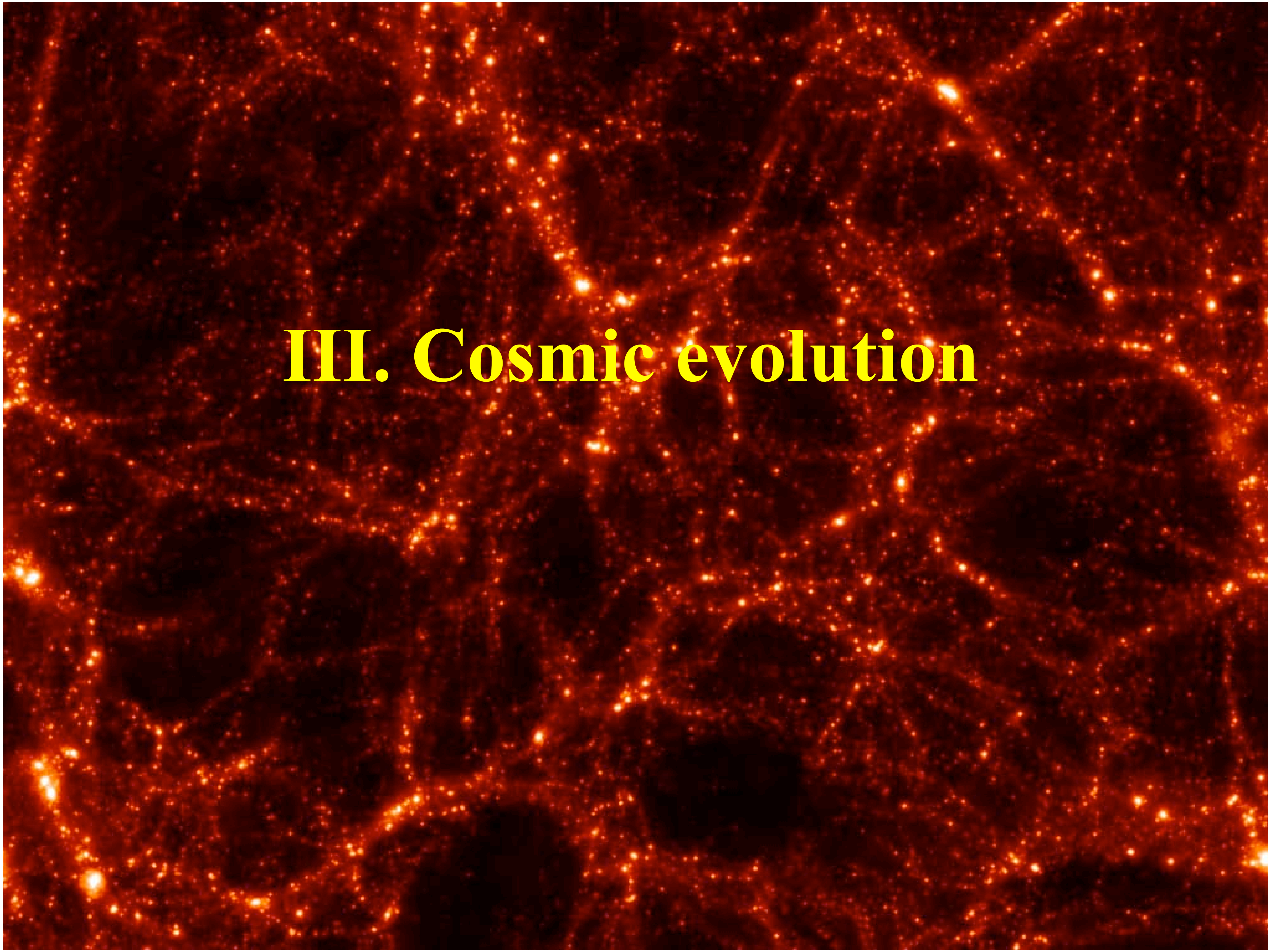
z~ 2-3 sources:

- GO1 samples -- 52 (Yan) + 58 (GTO) sources:
  Lir>= 10^{13} $L_\odot$, z~2-2.5, 15% strong PAHs
- The two SMGs of Lutz+05:
  Lir= 1-2 10^{13} $L_\odot$, z~2.8, one pure SB, one 50-50
- Large diversity of mid-IR spectra BUT
  The existence of SF-dominated systems at such high luminosities is unique of the high-z Universe (in the local Universe: SF-dominated systems only up to a luminosity of 4.5 10^{12} $L_\odot$)
  HLIRGs z~2-3: analogs of ULIRGs in the local Universe?

z~1-1.5 sources (GO1 Yan + Teplitz+06):

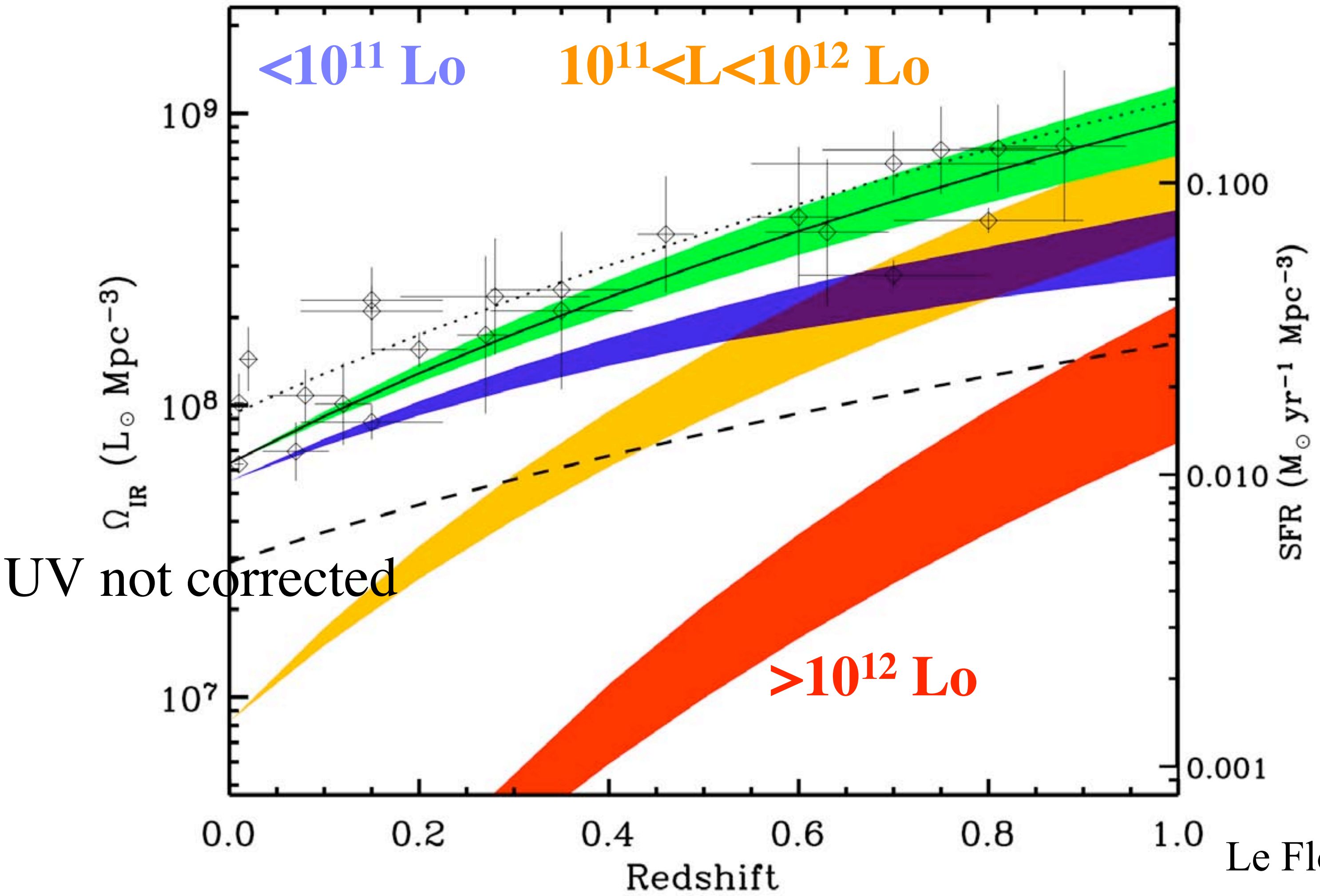
- Lir~1-6 10^{12} $L_\odot$, 80% strong PAHs
  ULIRGs z~1-1.5: analogs of LIRGs/SB in the local Universe?

III. Cosmic evolution



Cosmic evolution up to z=1

- Extremely high rate of evolution with redshift
- LIRGs and ULIRGs: 70% of the star-forming activity at z=1



Le Floc'h et al. 2005

Cosmic evolution up to z=1

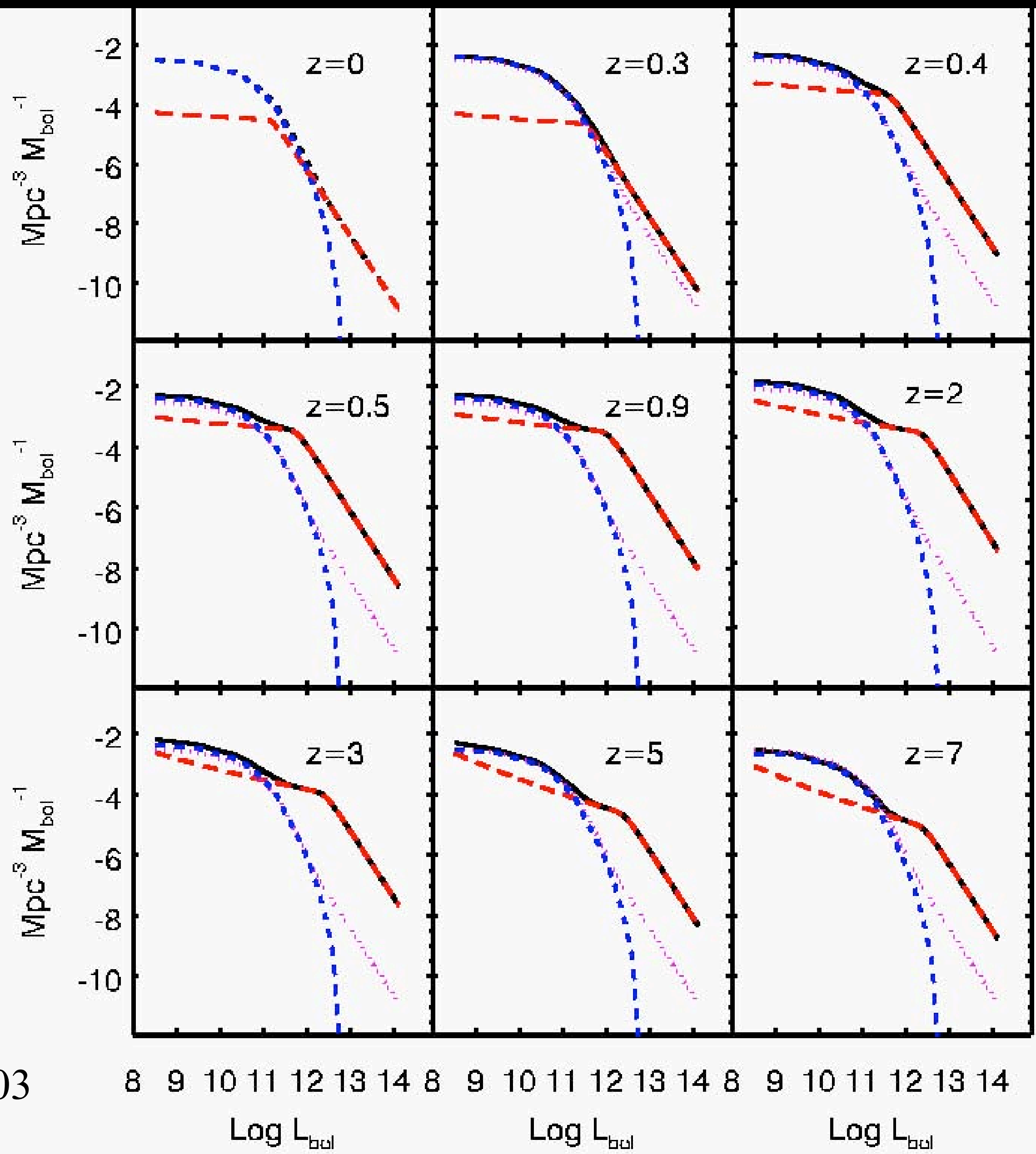
- UV(z=1)/UV(z=0) = 4
- IR(z=1)/IR(z=0)=15

- Strong SFR decrease between z~0.7 and z=0: strong decrease in SFR in morphologically undisturbed galaxies (e.g. Bell et al. 2005)

- Large number of LIRGs luminosity density: episodic and violent star-formation events (e.g. Hammer et al. 2005)

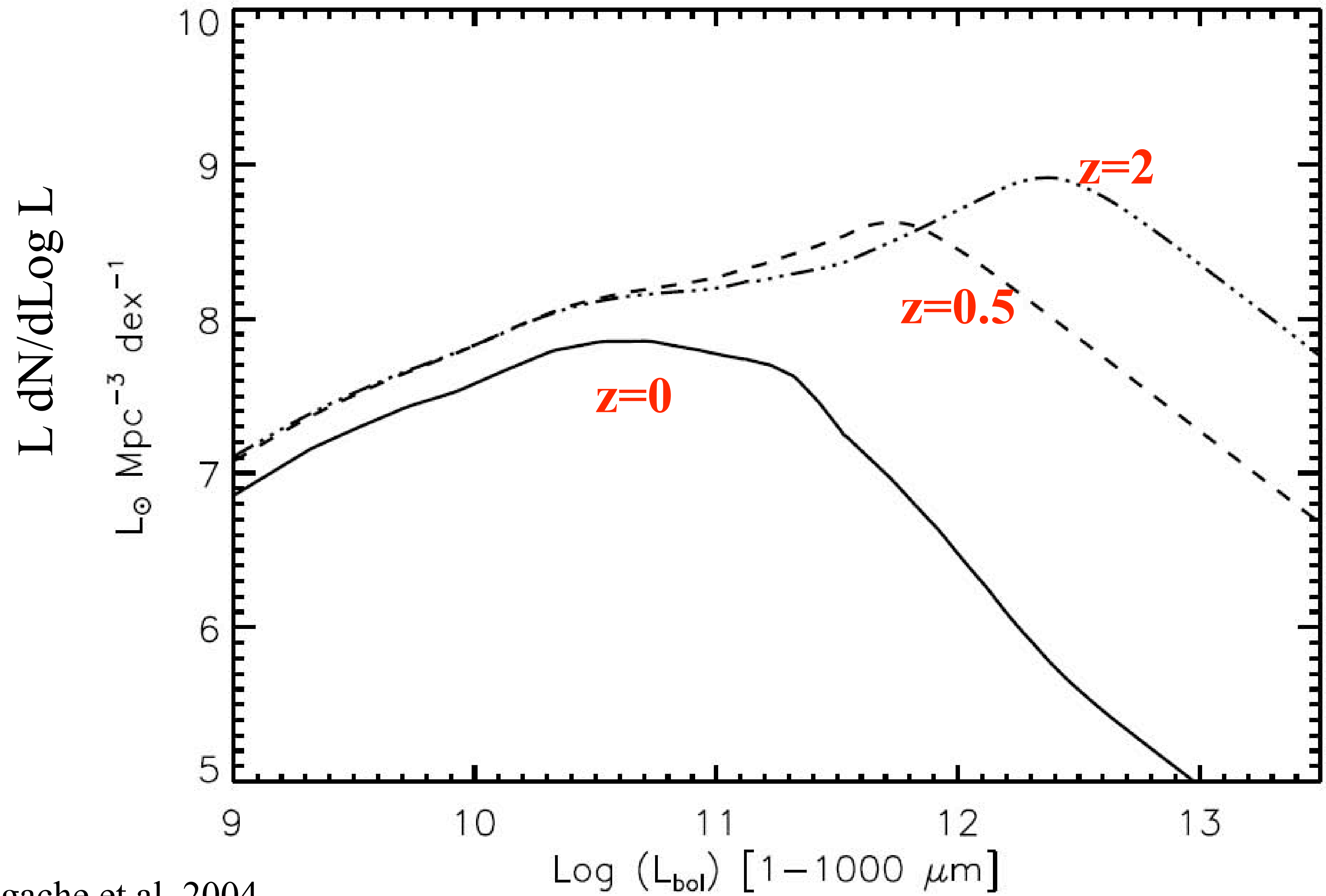
IR luminosity function evolution

Normal
Starburst
Total LF



Lagache et al. 2003

Co-moving evolution of the IR output



Lagache et al. 2004

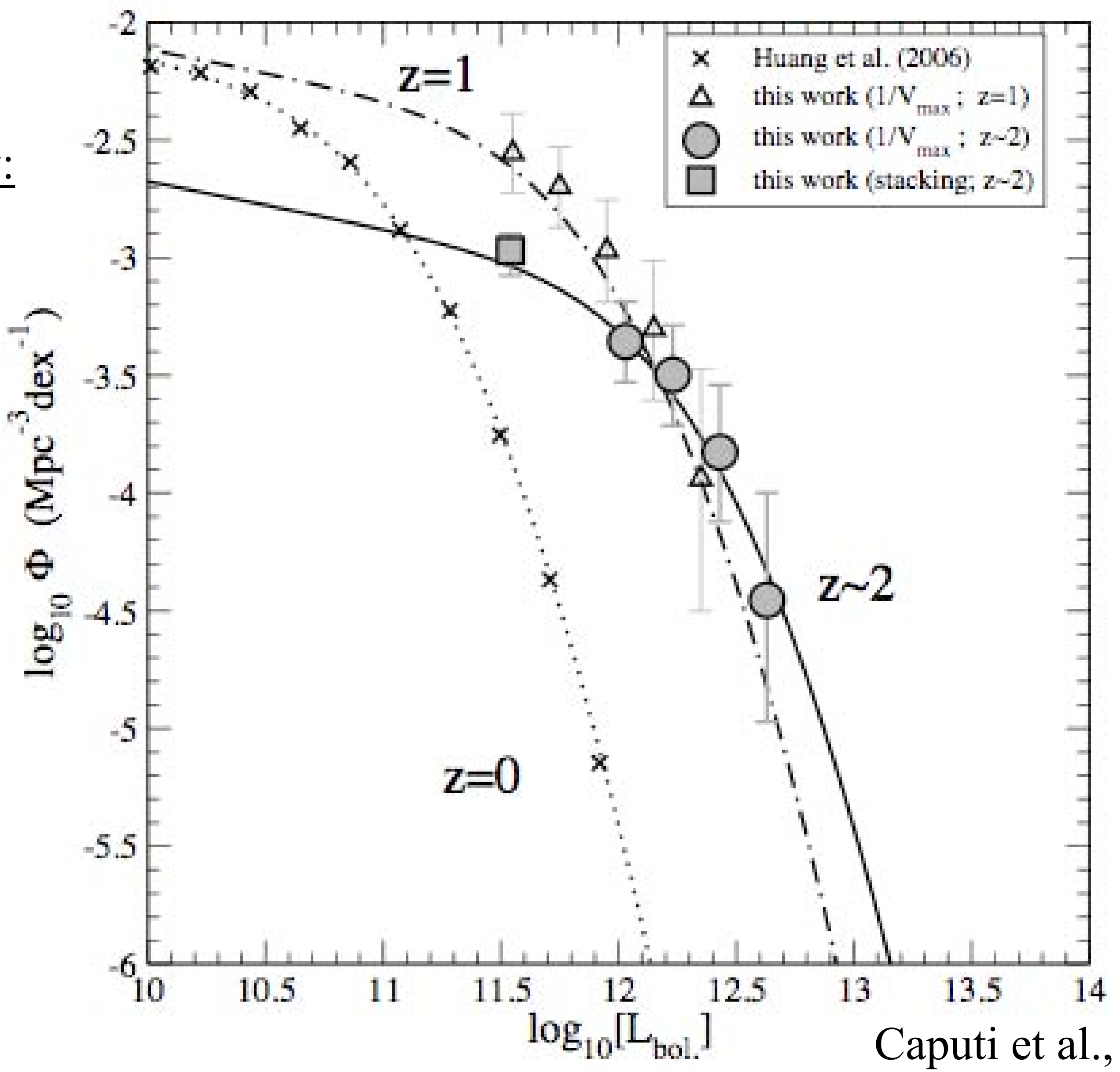
Bolometric LF from z~0 to z~2

Luminosity density:

- z=0:
LIRGs: 28%
ULIRGs: <1%

- z=1:
LIRGs: 60%
ULIRGs:17%

- z=2
LIRGs: 47%
ULIRGs: 42%



Caputi et al., in prep

Conclusions

- The comoving energy produced in the past that makes up the CIB at different λ is more uniform than suggested by its SED (factor 25 in integrated energy density between 150 μm and 850 μm = factor 10 in the Comoving energy production rate between z=0.7 and z=2.2)
- LIRGs and ULIRGs evolved much faster than optical galaxies
- LF evolution: power output is dominated by LIRGs at z=0.7-1.5 ULIRGs at z=2-3
- Energy output of the CIB: starburst activity
- AGN activity: very common in the most luminous but does not dominate the energy output
- Massive galaxies, high SFR
- LIRGs @ z=0.7 ≠ ULIRGs @ z=2.2

Challenges

- Making sure that no class of sources that contribute significantly to the CIB has been missed… (quite sure with Spitzer!)
- Identifying the SMGs not found through radio-selected sources and the question of the warm submm galaxies
- Clustering of these populations
- Mass assembly, hierarchical scenario
- SEDs of LIRGs and ULIRGs: not constrained in their ratio of far-IR to mid-IR or to submm λ at $z>0$
- IR galaxies at $z>4$?

- Herschel, Planck & ALMA is our future!