The Cosmic Infrared Background

A New View on High-Redshift Galaxy Formation

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Observation of IR/submm Galaxies and Cosmology ?

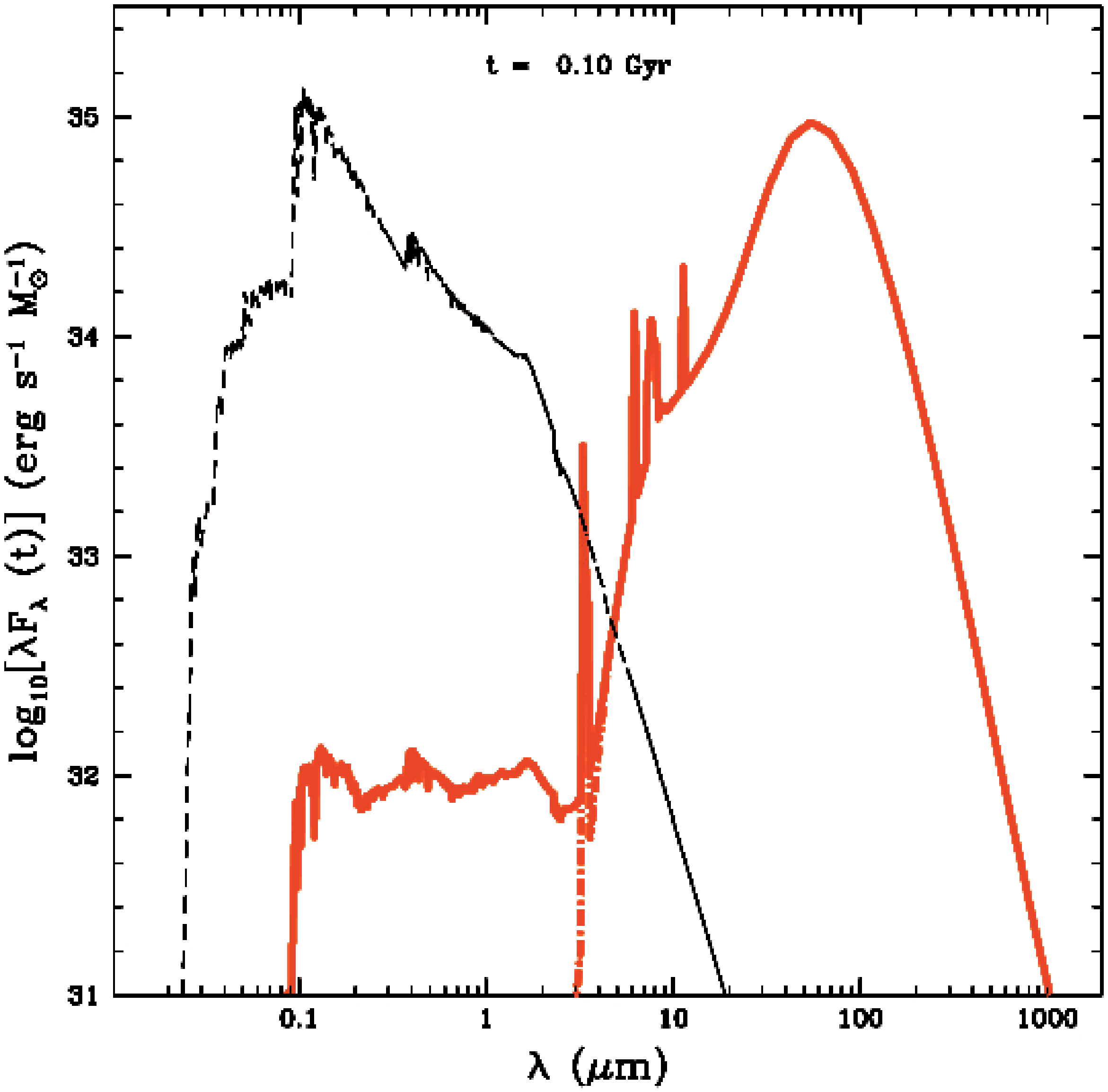
- The observation of the Cosmic IR Background is necessary for the complete test of Olbers’ paradox.
- The objects that contribute to the CIRB could be the progenitors of local giant galaxies (test HGF).
- The *background* due to dusty galaxies is a *foreground* for the observation of CMB anisotropies.
- Early phenomena (e.g. the formation of Pop III stars) are observed in the IR (redshifts z=10-30).

The Infrared View on Galaxy Formation

Outline of the talk

- IR Starbursts
- The CIRB and dust heating : starbursts vs. AGNs
- Breaking the CIRB into sources : ISOPHOT (ISO), SCUBA (JCMT), MAMBO (IRAM)
- Forthcoming observational landscape : SIRTF, PLANCK, HERSCHEL, ALMA

How dusty are forming galaxies ?



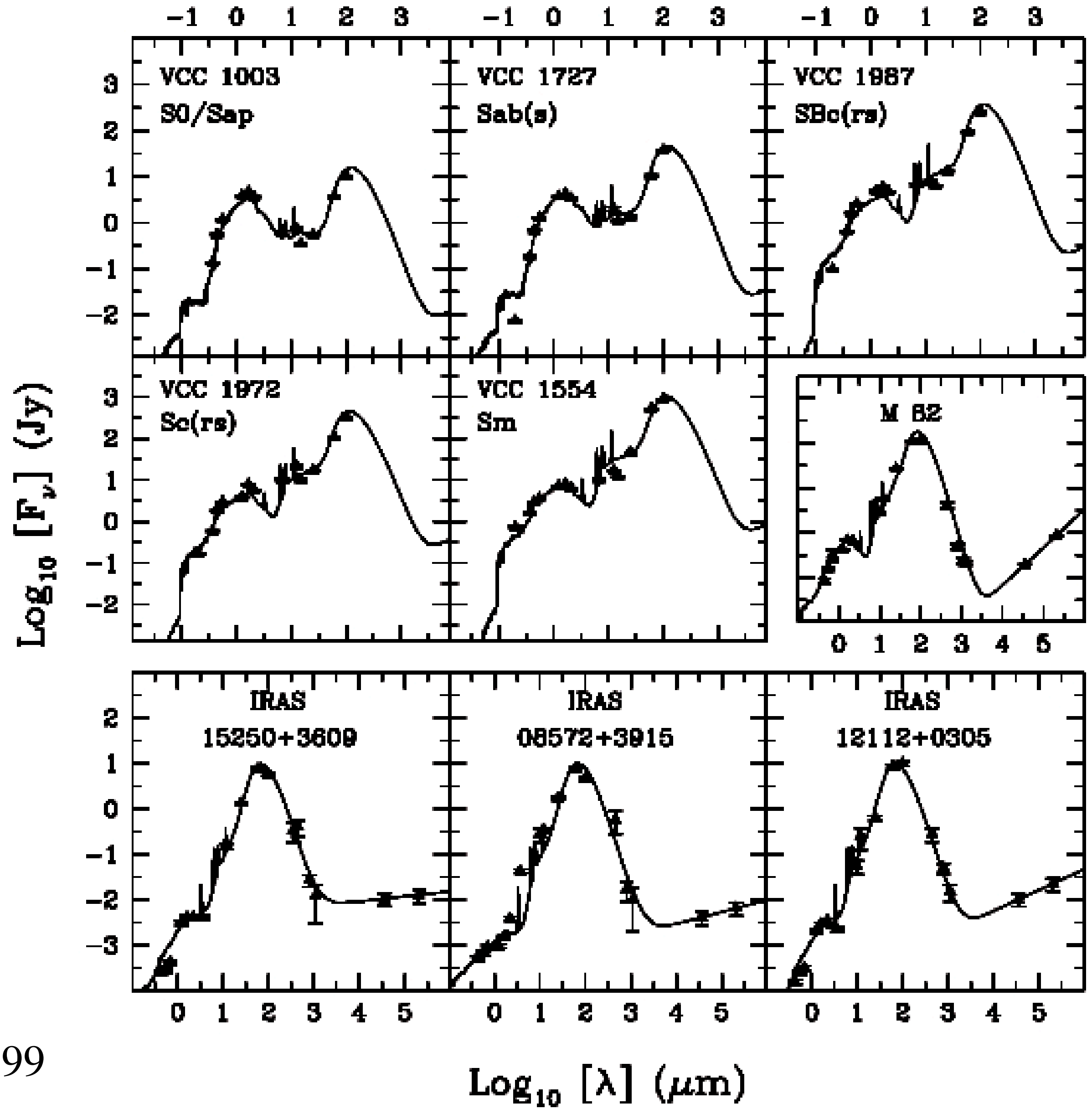
Young
stellar
population

WITHOUT
DUST

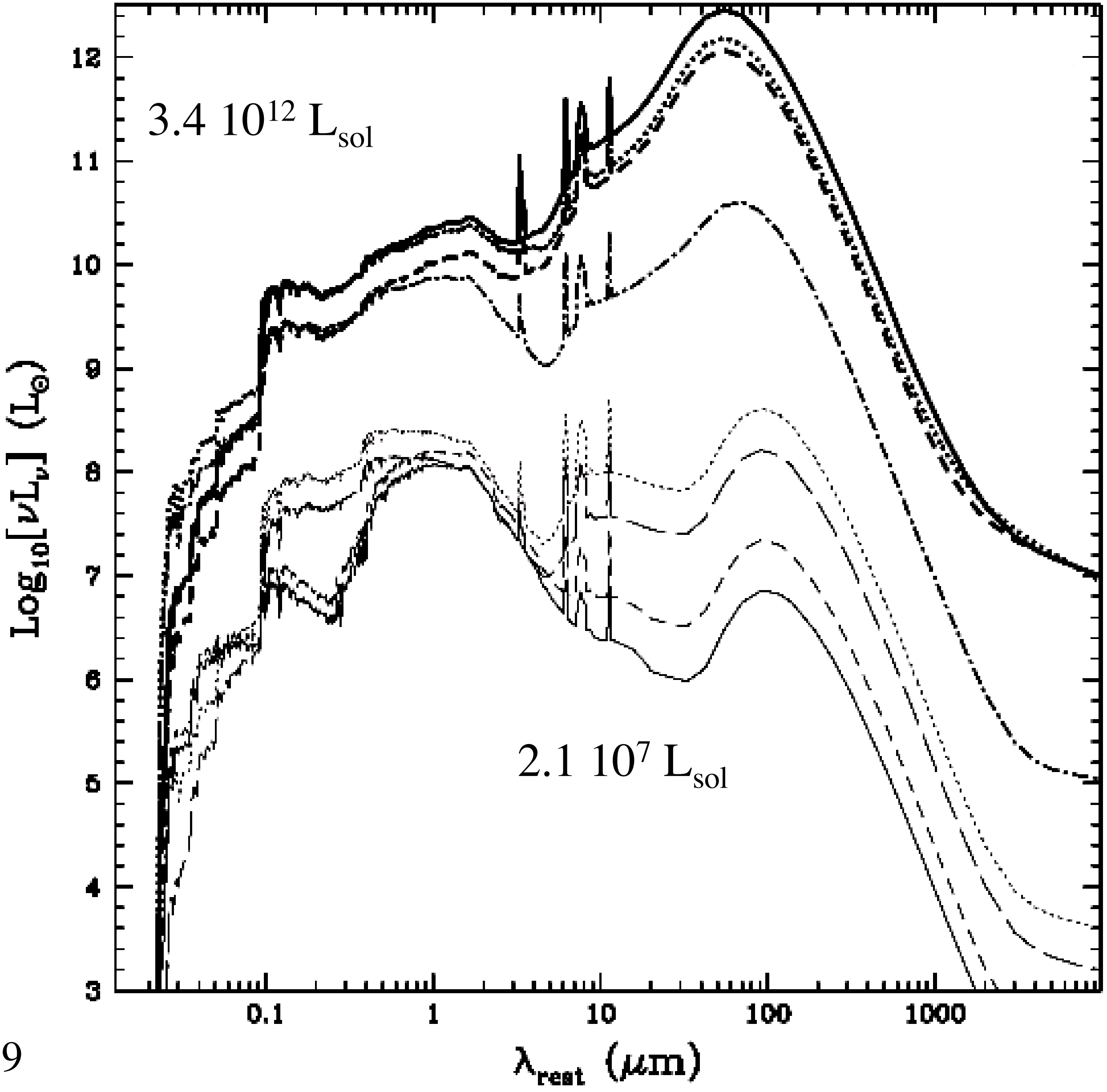
WITH DUST

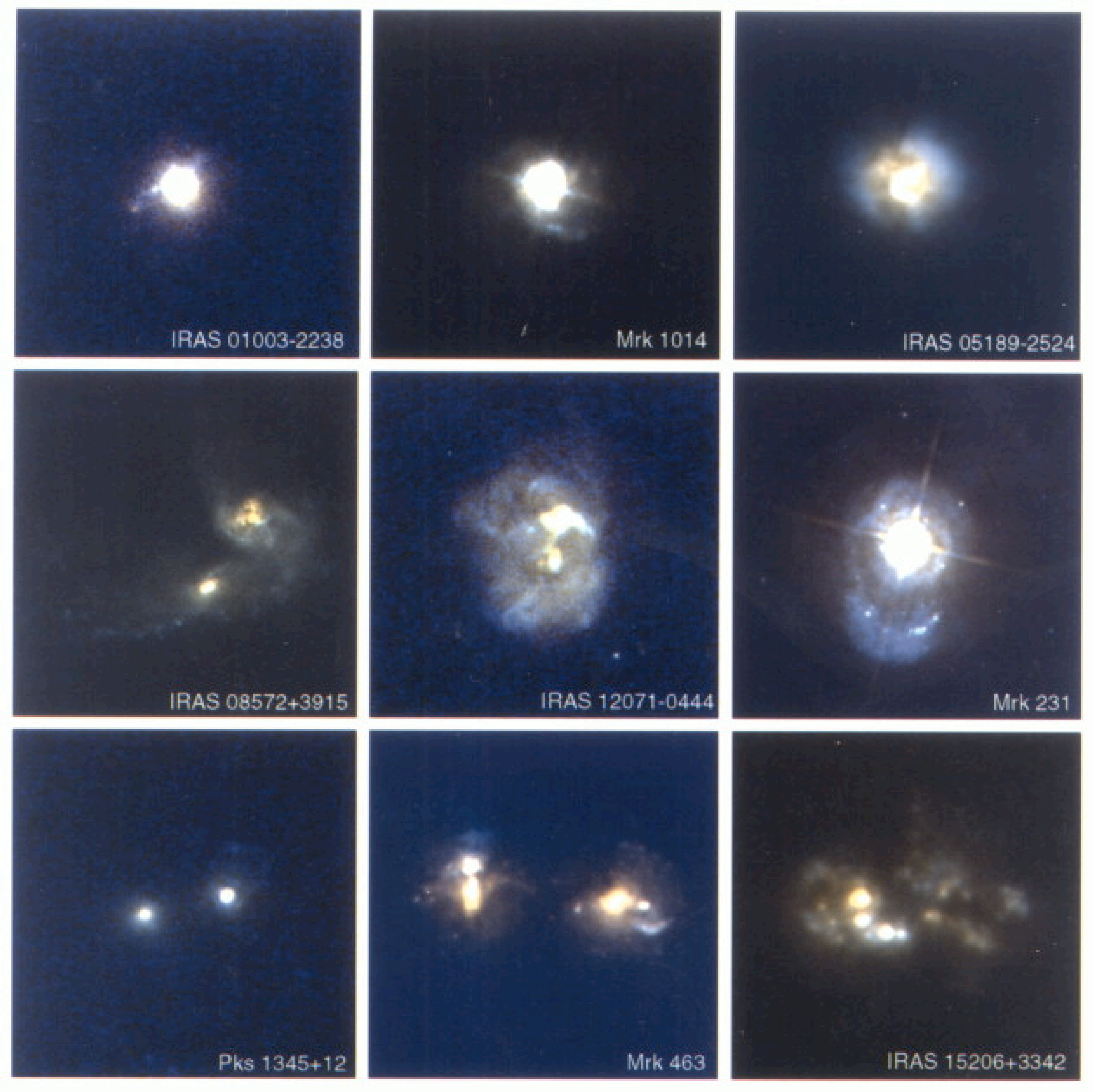
From the STARDUST model (Devriendt, Guiderdoni, & Sadat, 1999)

Spectra of nearby galaxies : spirals and ULIRGs

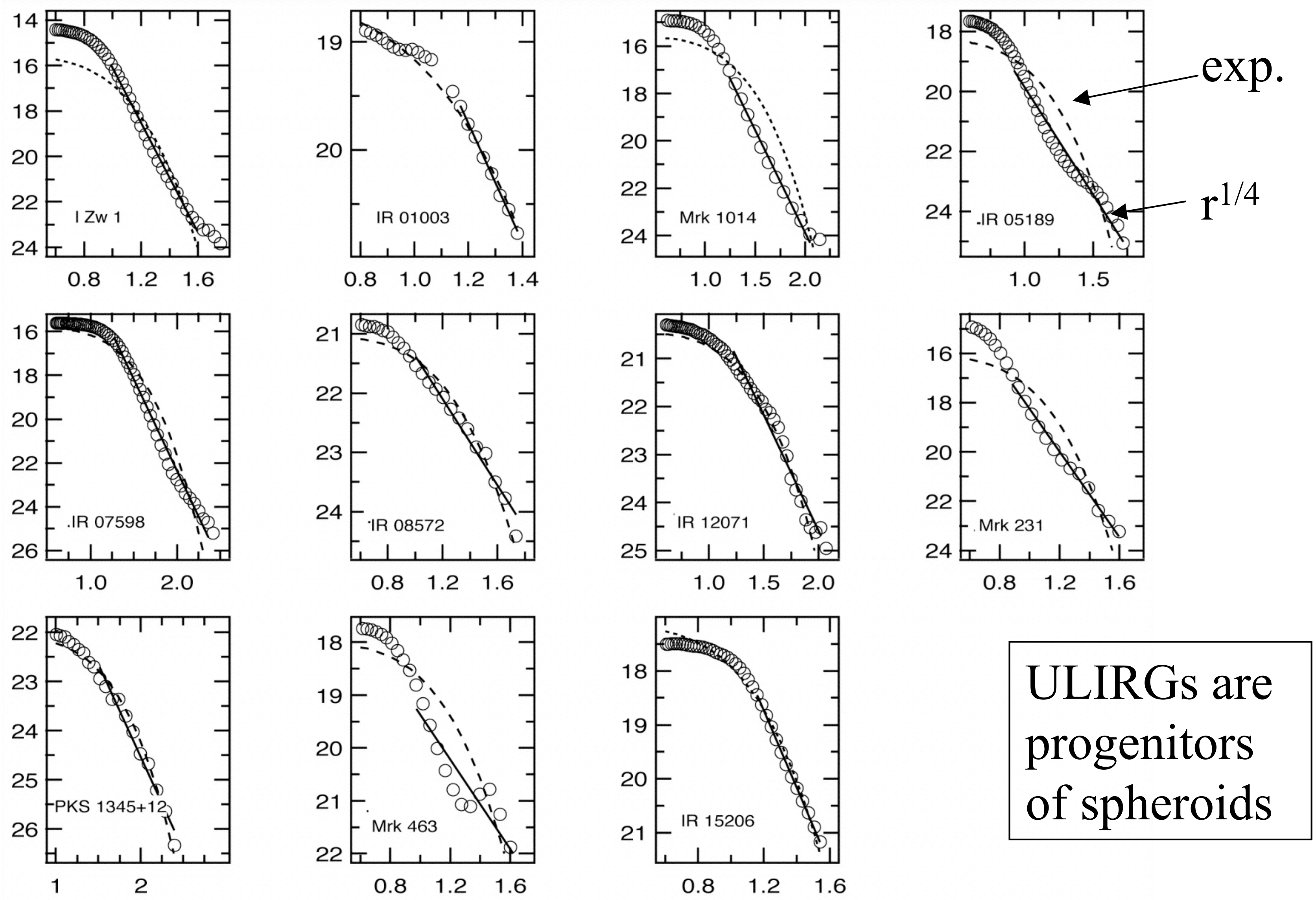


The IR luminosity sequence from spirals to ULIRGs





Morphologies of ULIRGs (Surace et al. 1998)

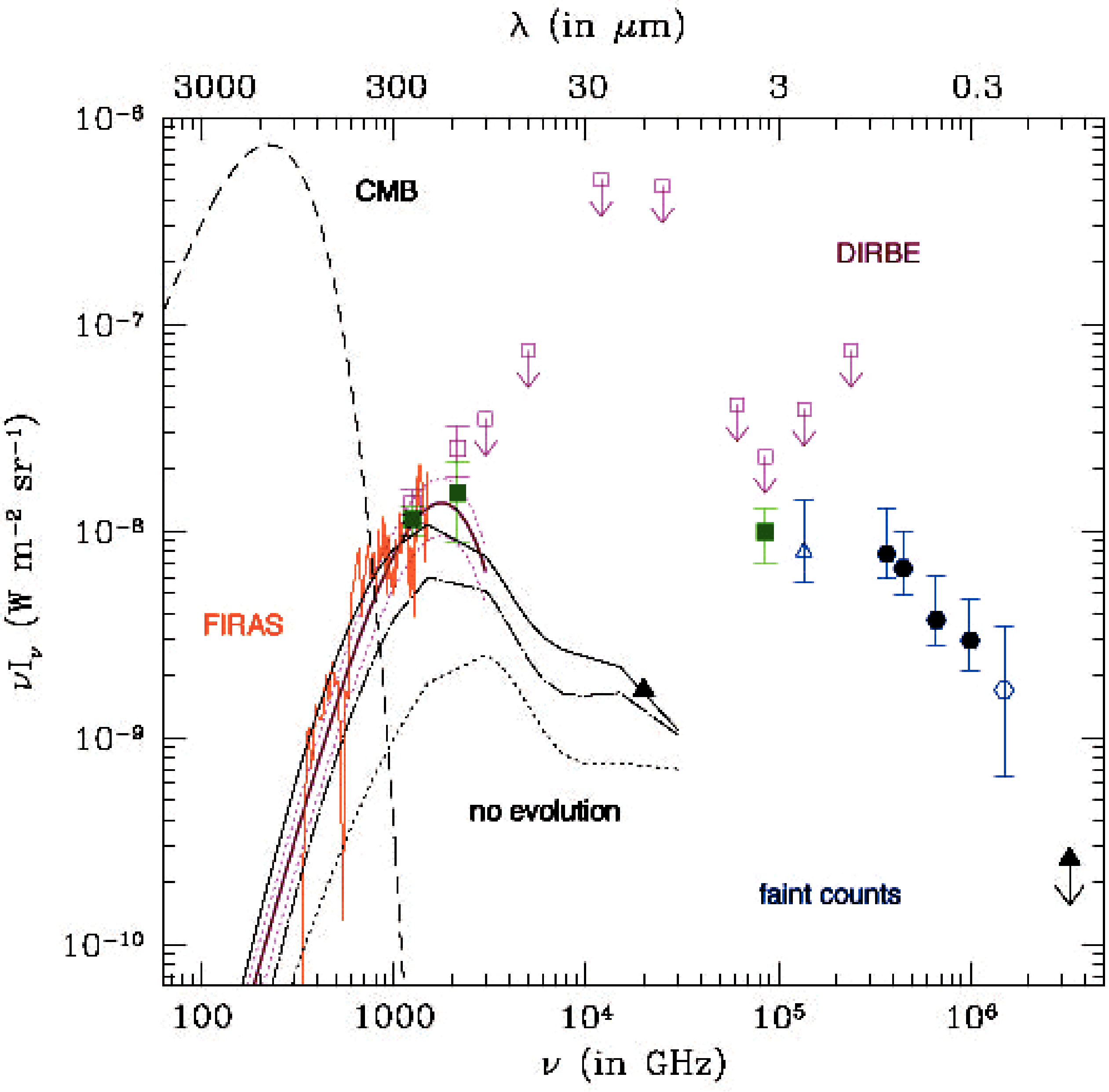


ULIRGs are
progenitors
of spheroids

Surace &
Sanders 2000

U Surface Brightness versus $r^{1/4}$ (in kpc)

The Cosmic Infrared and Optical Background



The Origin of the Cosmic IR/optical Background

- 1996-1998 : discovery of the CIRB in FIRAS data (Puget et al. 1996, Guiderdoni et al. 1997, Fixsen et al. 1998, Lagache et al. 1998) and DIRBE data (Schlegel et al. 1998, Hauser et al. 1998). Strong evolution :10 x the no evolution prediction (IRAS lum. funct.), twice the COB. Interpolating/extrapolating gives
- (λ>6 μm) $I_{bol}^{CIRB} = 40 \times 10^{-9}\,W m^{-2} sr^{-1}$ $I_{bol}^{COB} = 20 \times 10^{-9}\,W m^{-2} sr^{-1}$
- Thermal emission from dust : extinction is crucial in the luminosity budget at high z, even if $Z < Z_{sun}$
- Heating engine I: AGN should contribute 10—20 % (Almaini et al. 1999)
- Heating engine II: starbursts should contribute 80—90%

Le fond diffus dépend de l'émissivité lumineuse de l'univers $\square_{bol}$ (W/m^3) intégrée sur la ligne de visée

$$I_{bol} = \square \frac{\square_{bol}}{4\square} \frac{c\ dt}{(1+z)^4}$$

L'intégrale est effectuée sur une durée de temps finie: l'âge de l'univers

Effet cosmologique dû à l'expansion de l'univers

Black Hole Growth and the Cosmic Background

$$\boxed{I_{bol} = \frac{c}{4\pi}\varepsilon_{BH}\int\frac{\dot{\rho}_{BH}c^2}{1+z}dt = \frac{c}{4\pi}\frac{0.1\rho_{BH}(0)c^2}{1+z_{eff}}}$$

Census of BH mass density from the local luminosity density :

$$\rho_B(0) = (9.0 \pm 1.4)10^7\, L_{Bsun}Mpc^{-3}$$

1/3 from E ; $\frac{M}{L_B} = 6\frac{M_{sun}}{L_{Bsun}}$ and $M_{BH} = 0.005M$ Magorrian et al. 1998

→ $\rho_{BH}(0) = 9\times 10^5\, M_{sun}Mpc^{-3}$

→ $I_{bol} = \frac{14}{1+z_{eff}}10^{-9}Wm^{-2}sr^{-1}$

$z_{eff} \approx 2.5$ → $I_{bol} = 4\times 10^{-9}\,Wm^{-2}sr^{-1}$

Stellar Nucleosynthesis and the Cosmic Background

$$\boxed{I_{bol} = \frac{c}{4\pi}\int\left(\frac{\Delta Y}{\Delta Z}\varepsilon_Y + \varepsilon_Z\right)\frac{\dot{\rho}_Z c^2}{1+z}dt = \frac{c}{4\pi}\frac{0.03\rho_Z(0)c^2}{1+z_{eff}}}$$

Census of local metal density from the local luminosity density :

$$\rho_B(0) = (9.0 \pm 1.4)10^7\, L_{Bsun} Mpc^{-3}$$

2/3 from Sp ; $\frac{M}{L_B} = 2\frac{M_{sun}}{L_{Bsun}}$ and $Z \approx 0.02$

1/3 from E ; $\frac{M}{L_B} = 6\frac{M_{sun}}{L_{Bsun}}$ and $Z \approx 0.03$ +0.02 for metals in IGM

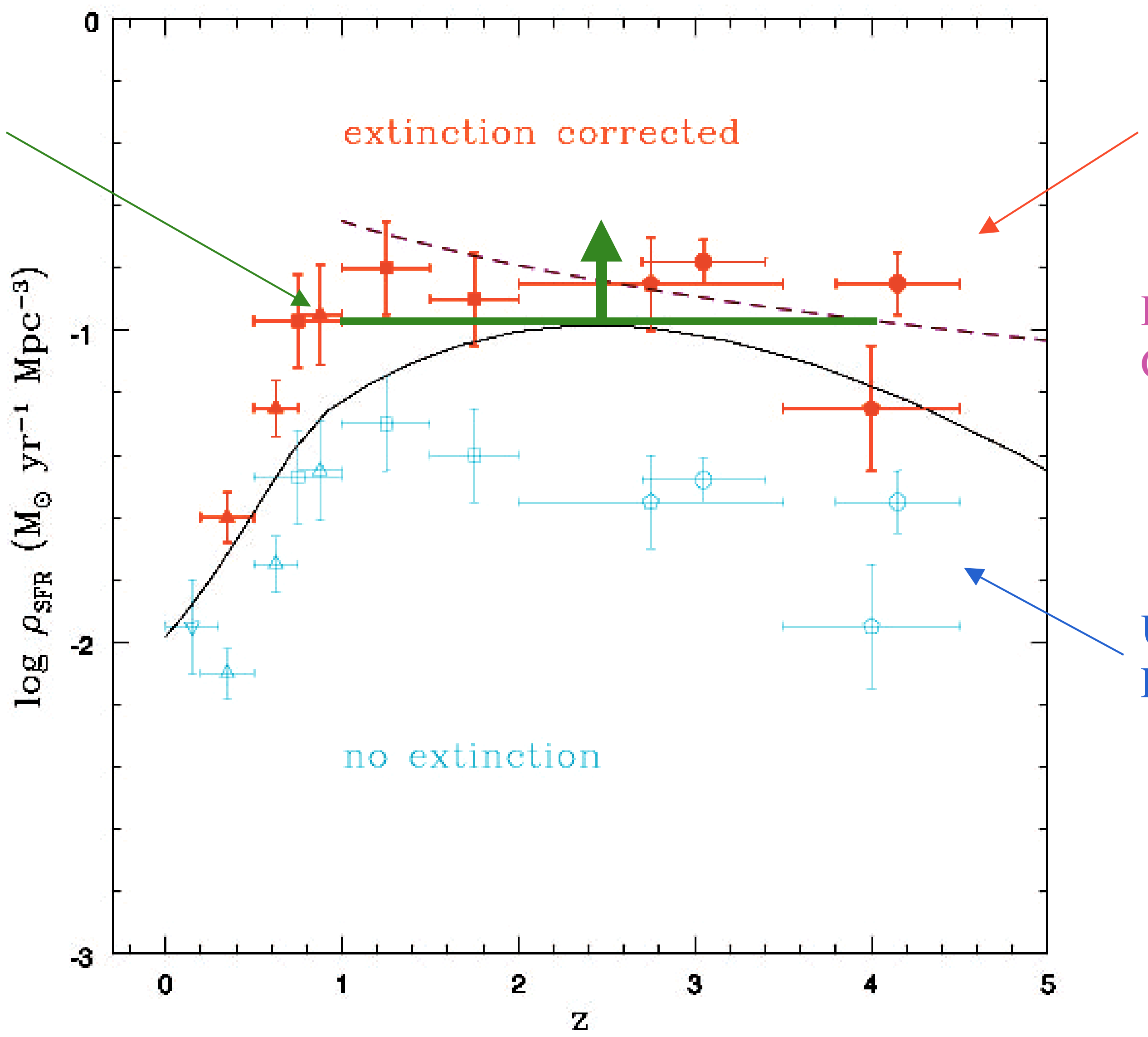
$\frac{M_Z}{L_B} = 0.3\frac{M_{sun}}{L_{Bsun}}$ (Mushotzky & Loewenstein 1997)

→ $\rho_Z(0) = 1.1 \times 10^7\, M_{sun} Mpc^{-3}$

→ $I_{bol} = \frac{50}{1+z_{eff}} 10^{-9} W m^{-2} sr^{-1}$

$z_{eff} \approx 1.5$ → $I_{bol} = 20 \times 10^{-9}\, W m^{-2} sr^{-1}$

The Cosmic Star Formation History



SCUBA sources

LBGs corrected for dust

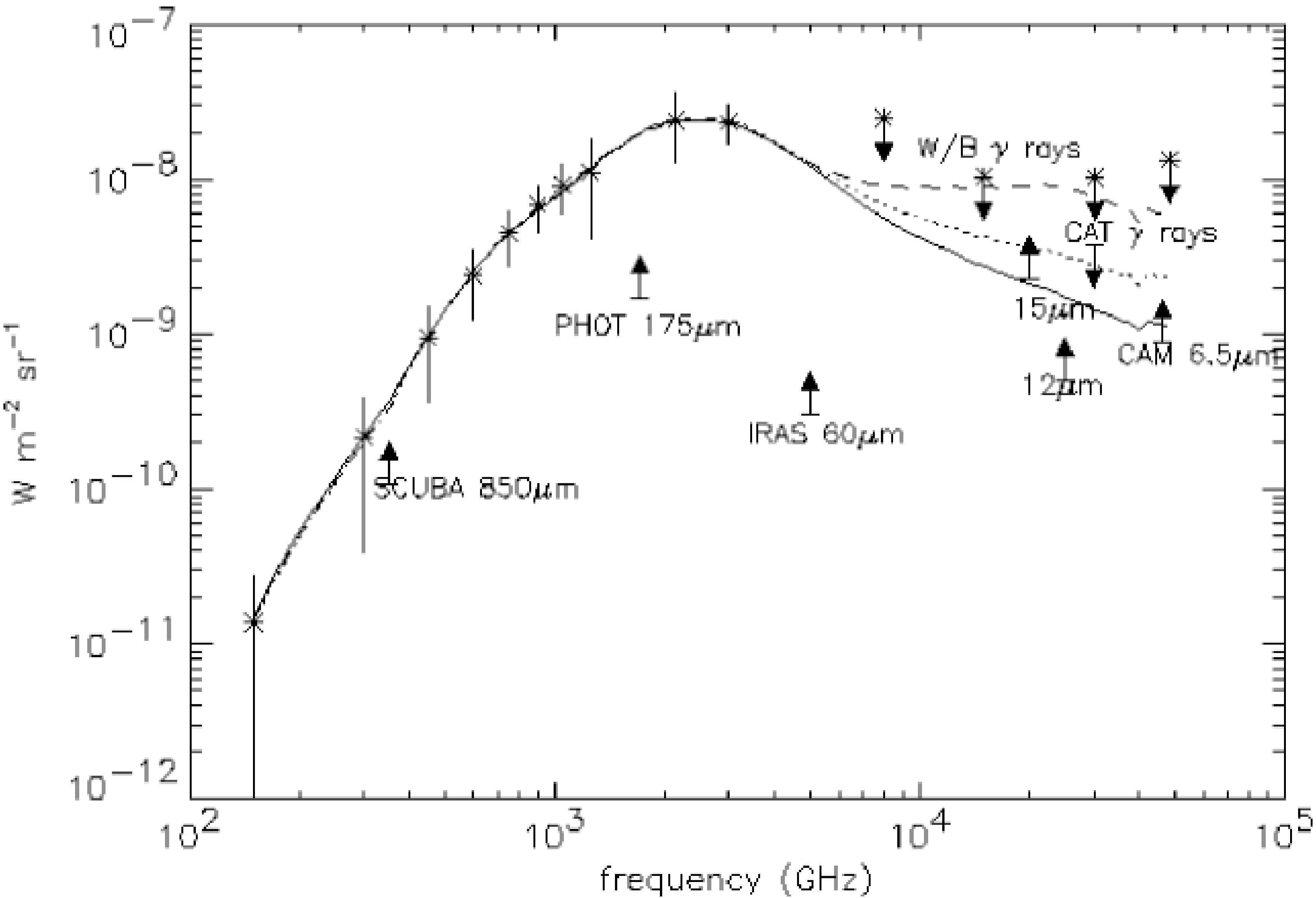
Deconvolved CIRB

SAM

Uncorrected LBGs

Resolution of the CIRB into point sources

- ISO/ISOCAM (15 μm) : 70 % @ S_ν>30 μJy
- ISO/ISOPHOT (175 μm) : 5 % @ S_ν>200 mJy
  - About 200 sources (Puget et al. 1999, Dole et al. 2000)
- JCMT/SCUBA (850 μm) : 40 % @ S_ν>2 mJy
  - About 100 sources (Smail et al. 1997, Hughes et al. 1998, Eales et al. 1998, etc.)
- IRAM/MAMBO (1300 μm) : 30 % @ S_ν>2 mJy
  - 36 sources (Carilli et al. 2000, Bertoldi et al. 2000)



Gispert et al. 2000

From Faint Counts to the Diffuse Background

Diffuse background

$$I_\nu = \int_0^\infty S_\nu \frac{dN}{dS_\nu} dS_\nu$$

In Jy sr^{-1} or W m^{-2} Hz^{-1} sr^{-1}

Fluctuations in solid angle Ω

$$\sigma_\nu = \left(\int_0^\infty S_\nu^{\ 2} \frac{dN}{dS_\nu} \frac{dS_\nu}{\Omega} \right)^{1/2}$$

In Jy sr^{-1} or W m^{-2} Hz^{-1} sr^{-1}

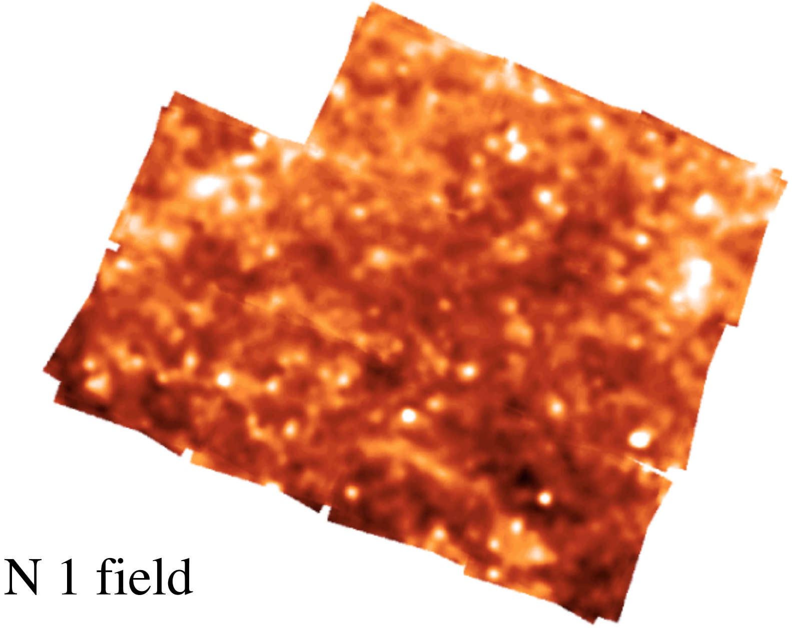
Confusion limit in solid angle Ω

$$S_{conf} = \sigma_\nu \equiv \left(\int_0^{3S_{conf}} S_\nu^{\ 2} \frac{dN}{dS_\nu} dS_\nu \Omega \right)^{1/2}$$

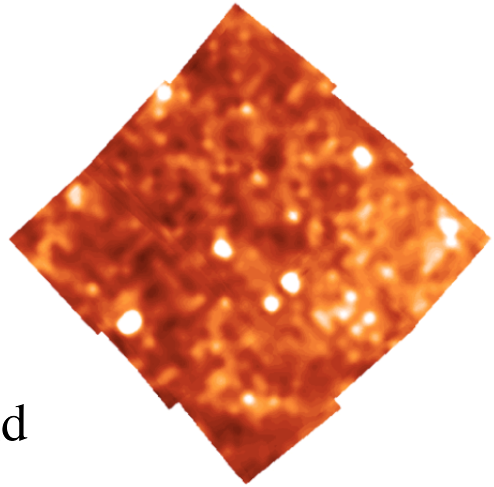
In Jy or W m^{-2} Hz^{-1}

The FIRBACK ISOPHOT Deep Survey at 175 □m

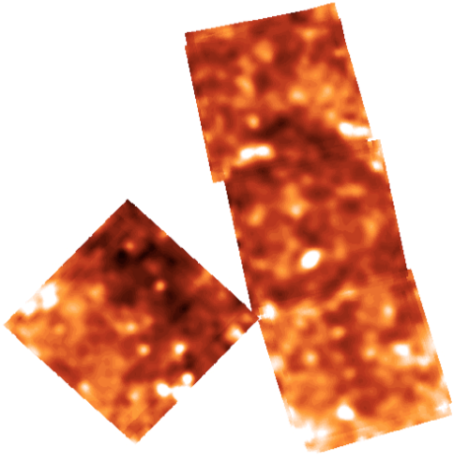
3.89 deg^2 in 3 fields (2 North, 1 South); 196 galaxies with $S_{\square}$>135 mJy ; counts show strong evolution



N 1 field

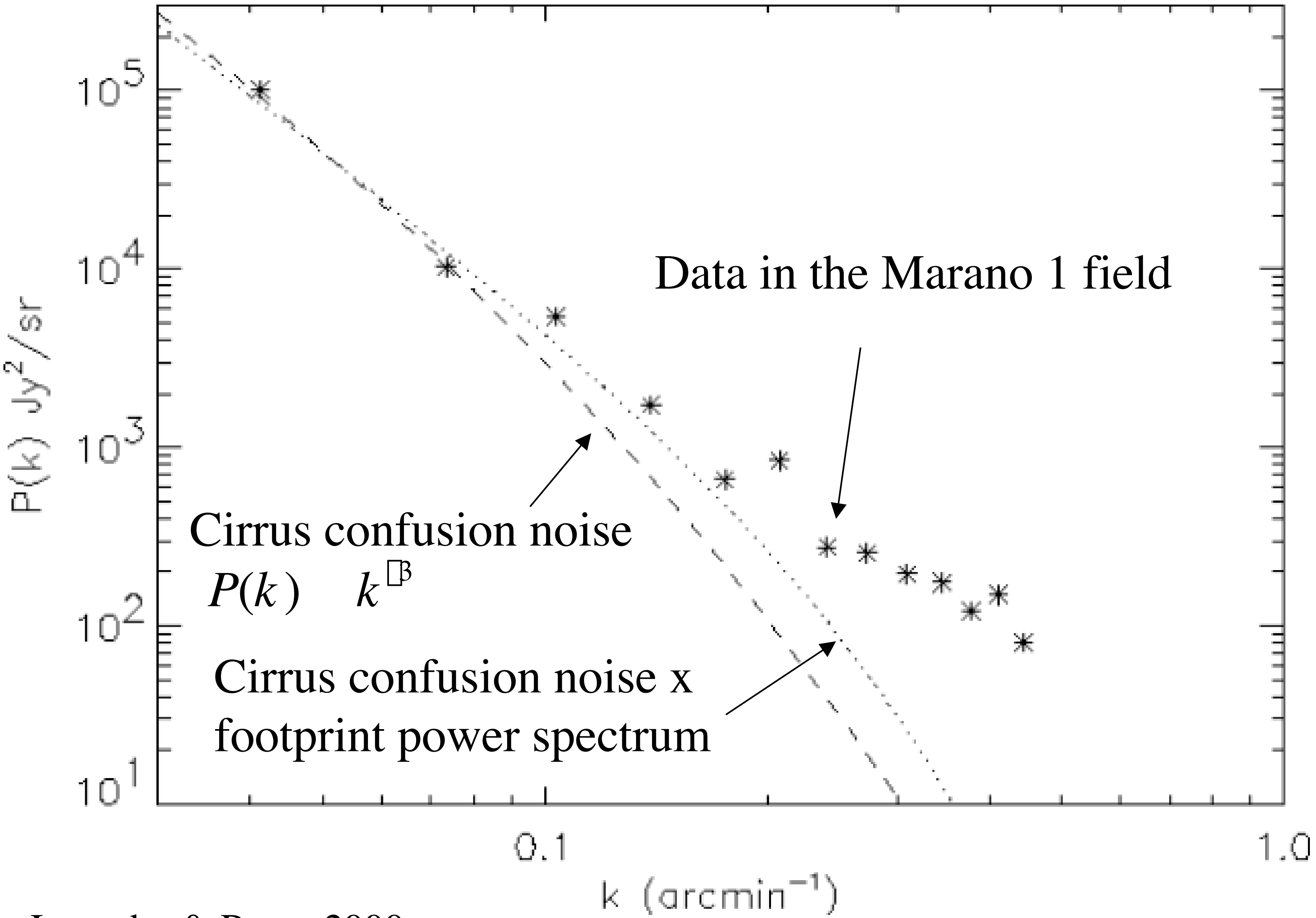


N 2 field



Marano S field

Detection of CIRB fluctuations in the FIRBACK survey



Data in the Marano 1 field

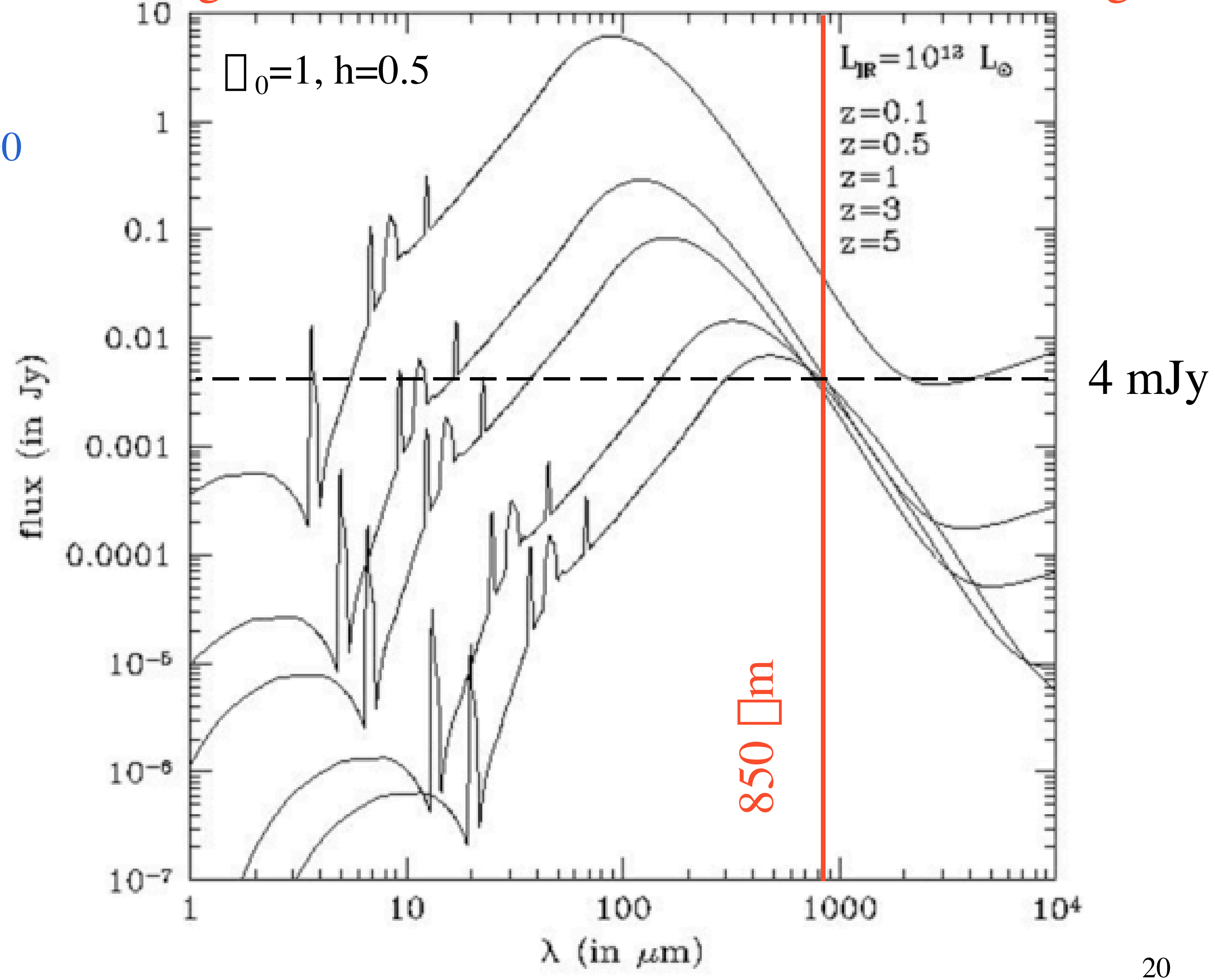
Cirrus confusion noise
$P(k) \propto k^{-\beta}$

Cirrus confusion noise x
footprint power spectrum

Lagache & Puget 2000

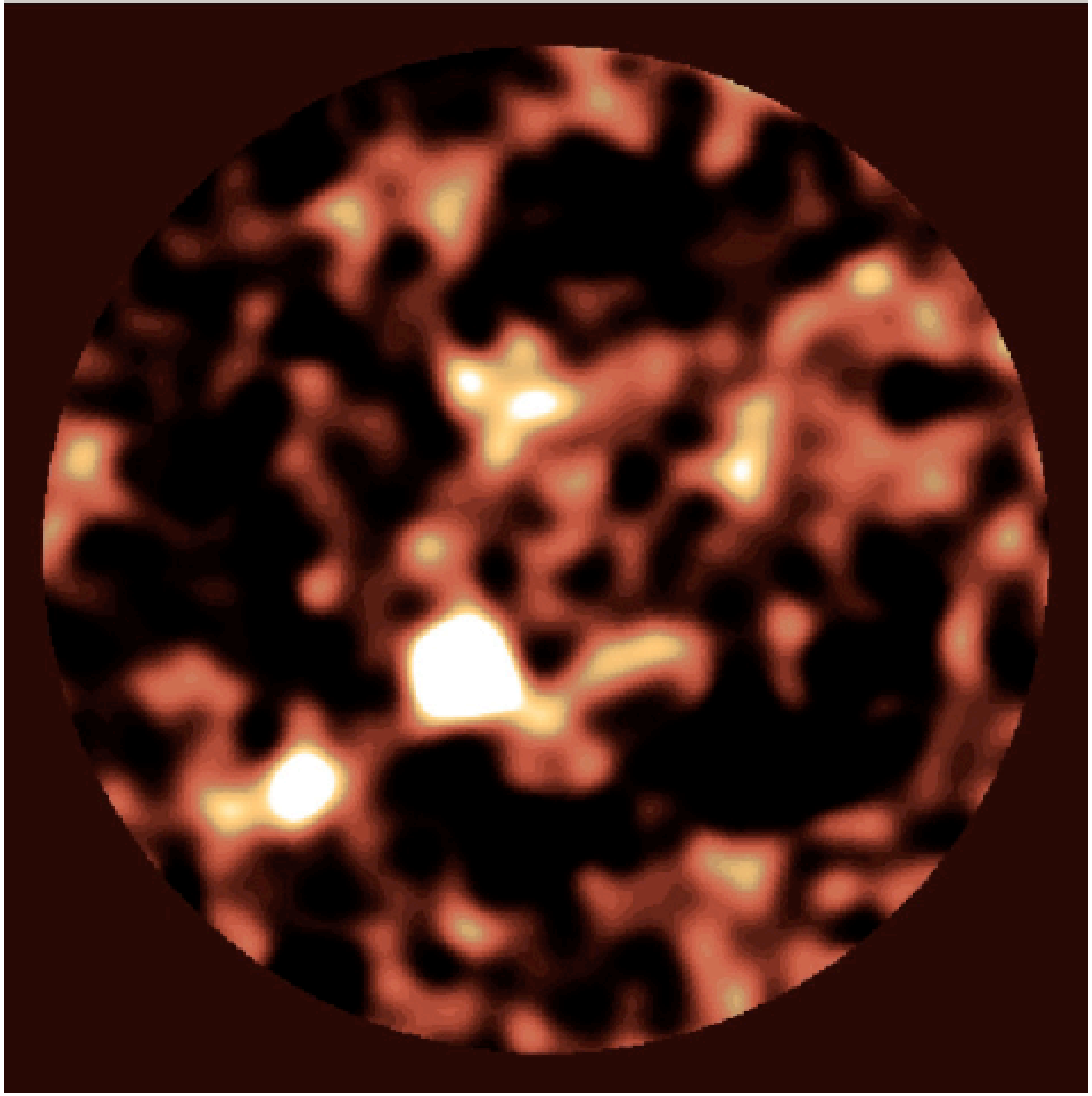
The «negative K-correction» at submm/mm wavelengths

The 600—2000 μm flux directly measures L_{IR} provided z>0.5



Guiderdoni et al. 1998

The Hubble Deep Field observed by SCUBA at 850 μm

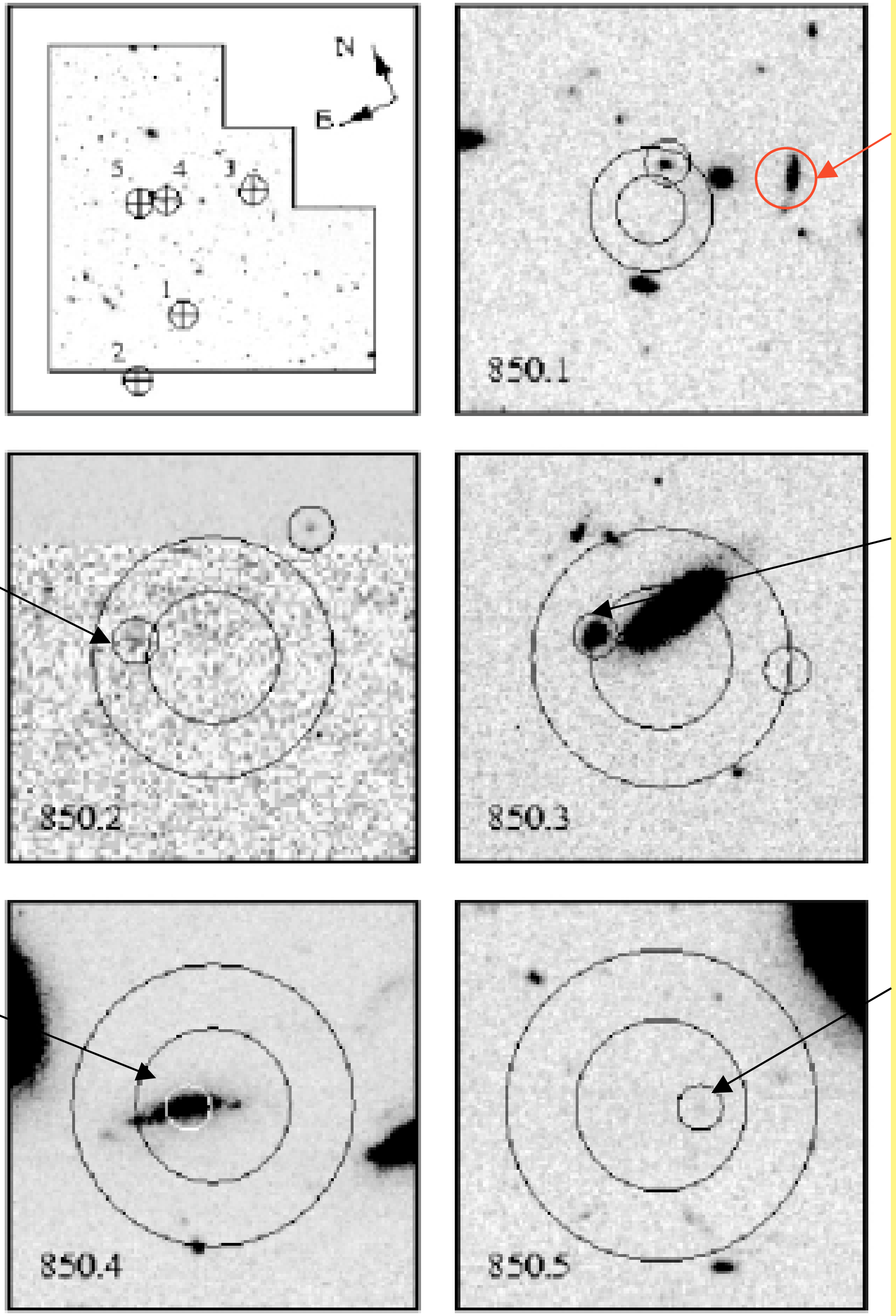


8.7 arcmin^2

σ=0.45 mJy

FWHM=14.7 arcsec

ID of SCUBA sources: optical



This is the actual optical ID (lensed)

~~z=3.4~~

z=3.8

$\log L_{IR}=11.9$

z=2.0

$\log L_{IR}=11.8$

z=0.9

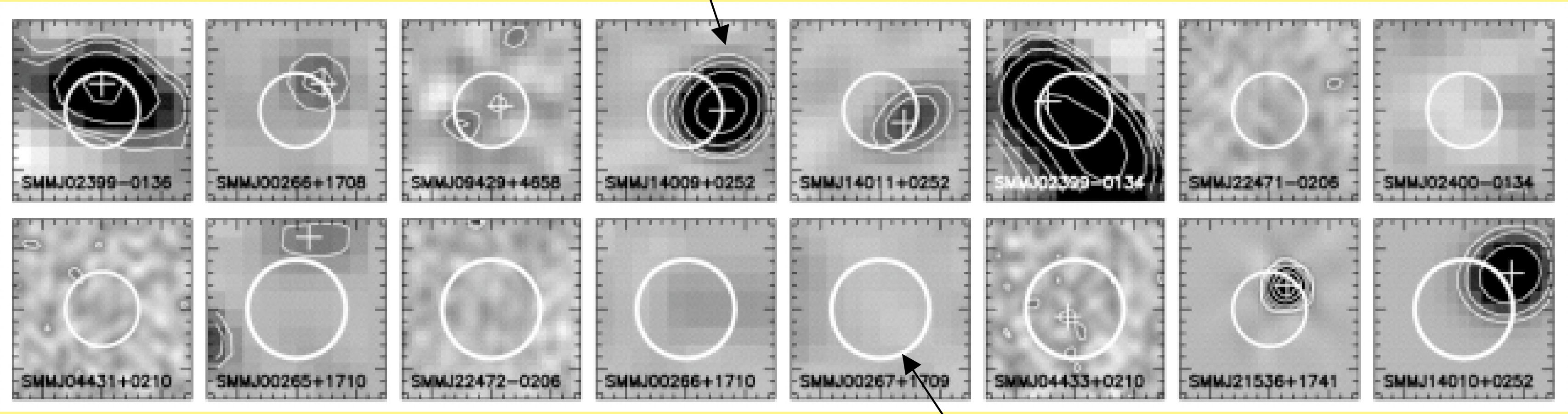
$\log L_{IR}=11.8$

z=3.2 ?

$\log L_{IR}=11.6$

ID of SCUBA sources : radio continuum

VLA 1.4 GHz contours



SCUBA error box

Radio/submm «photometric»
redshifts (Carilli & Yun 1999)
give <z> > 2

Smail et al. 2000

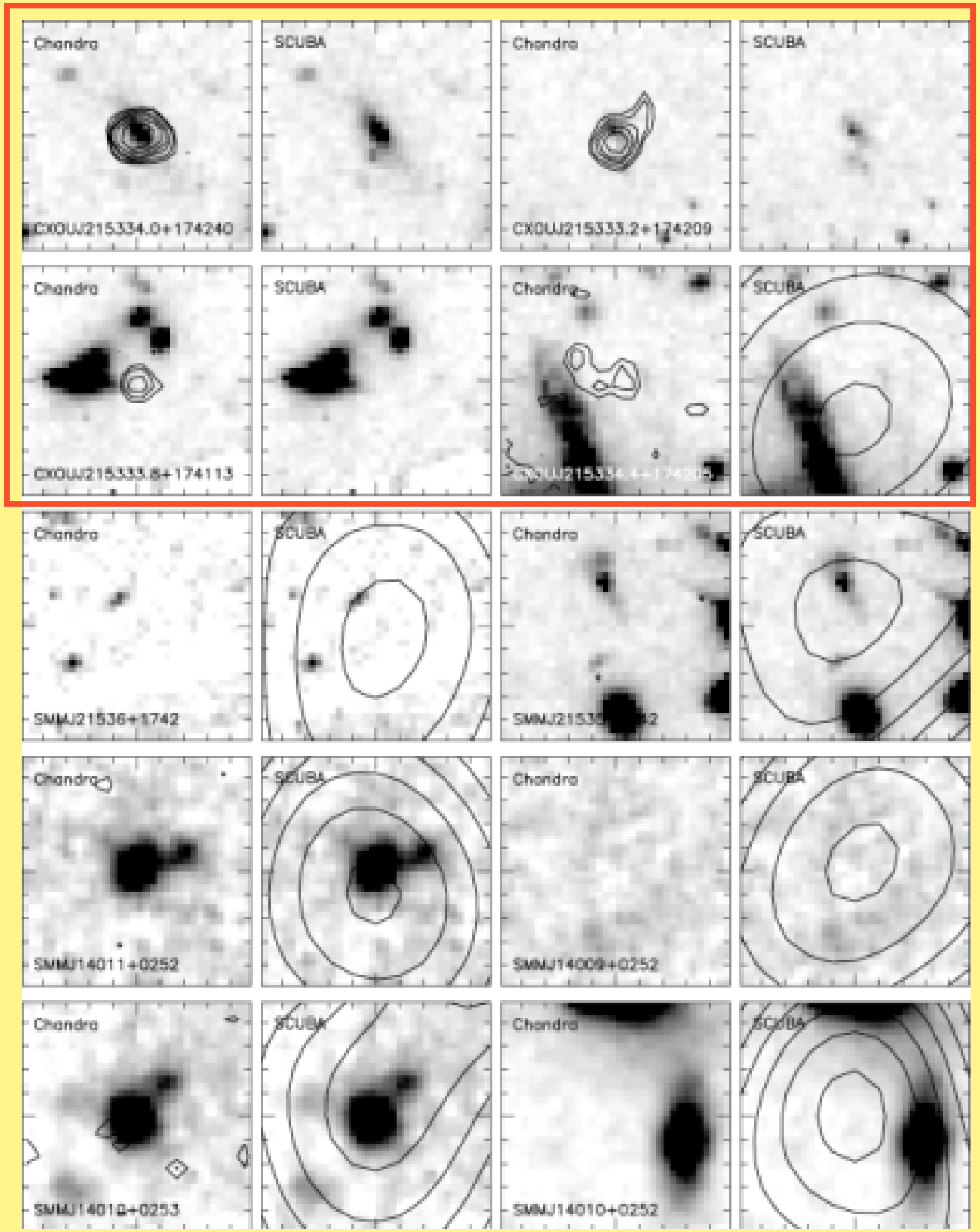
ID of IR/submm sources

- ISOCAM @ 15 μm, S_ν>30 μJy : ID z = 0.5-1 (~ dusty, luminous galaxies of the CFRS)
- ISOPHOT @ 175 μm, S_ν>200 mJy : ID z < 0.5, + some sources à z ~1 ? (FIRBACK)
- SCUBA @ 850 μm, S_ν>2 mJy : 1 source arcmin^{-2}, IDs are diffficult; many «blank fields»; majority of source IDs at 1<z<4
  - some AGNs (10 % of CIRB ?)
  - some EROs (10 % du CIRB ?)
  - L_{IR} luminosities : a few 10^{11} to a few 10^{12} $L_\odot$ **provided z>1**
  - $\rho_{SFR}(z>1) = 10^{-1}$ $M_\odot yr^{-1} Mpc^{-3}$ (Hughes et al. 1998)

No connection between the SCUBA and Chandra sources at $S_{850mm} > 2$ mJy & $F_{0.5-2keV} > 1-3\ 10^{-15}$ erg $cm^{-2}\ s^{-1}$

Most natural interpretation : SCUBA sources are powered by starbursts

Fabian et al. 2000,
Severgnini et al. 2000

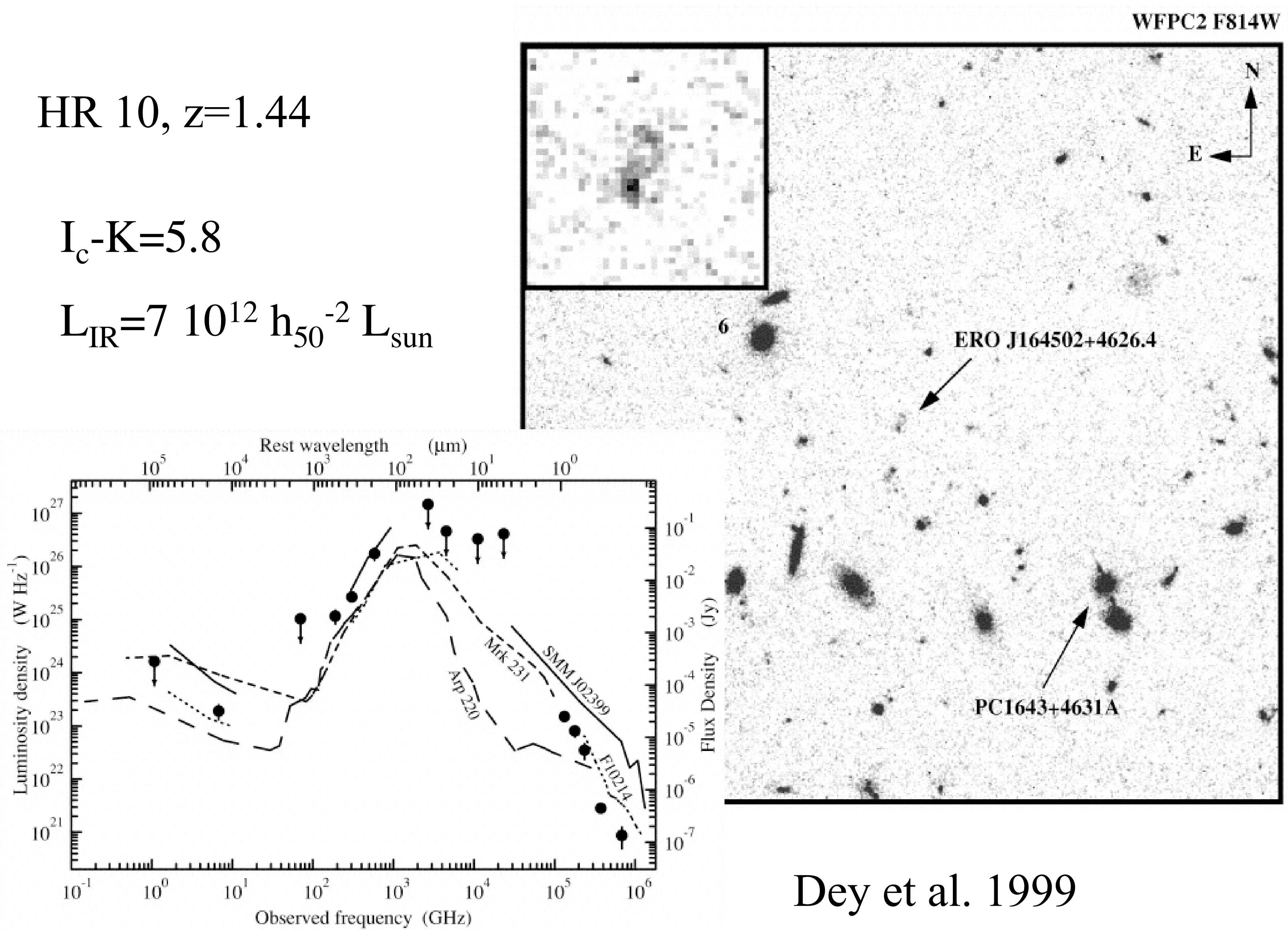


Chandra sources

HR 10, z=1.44

I_c-K=5.8

L_{IR}=7 10^{12} h_{50}^{-2} L_{sun}

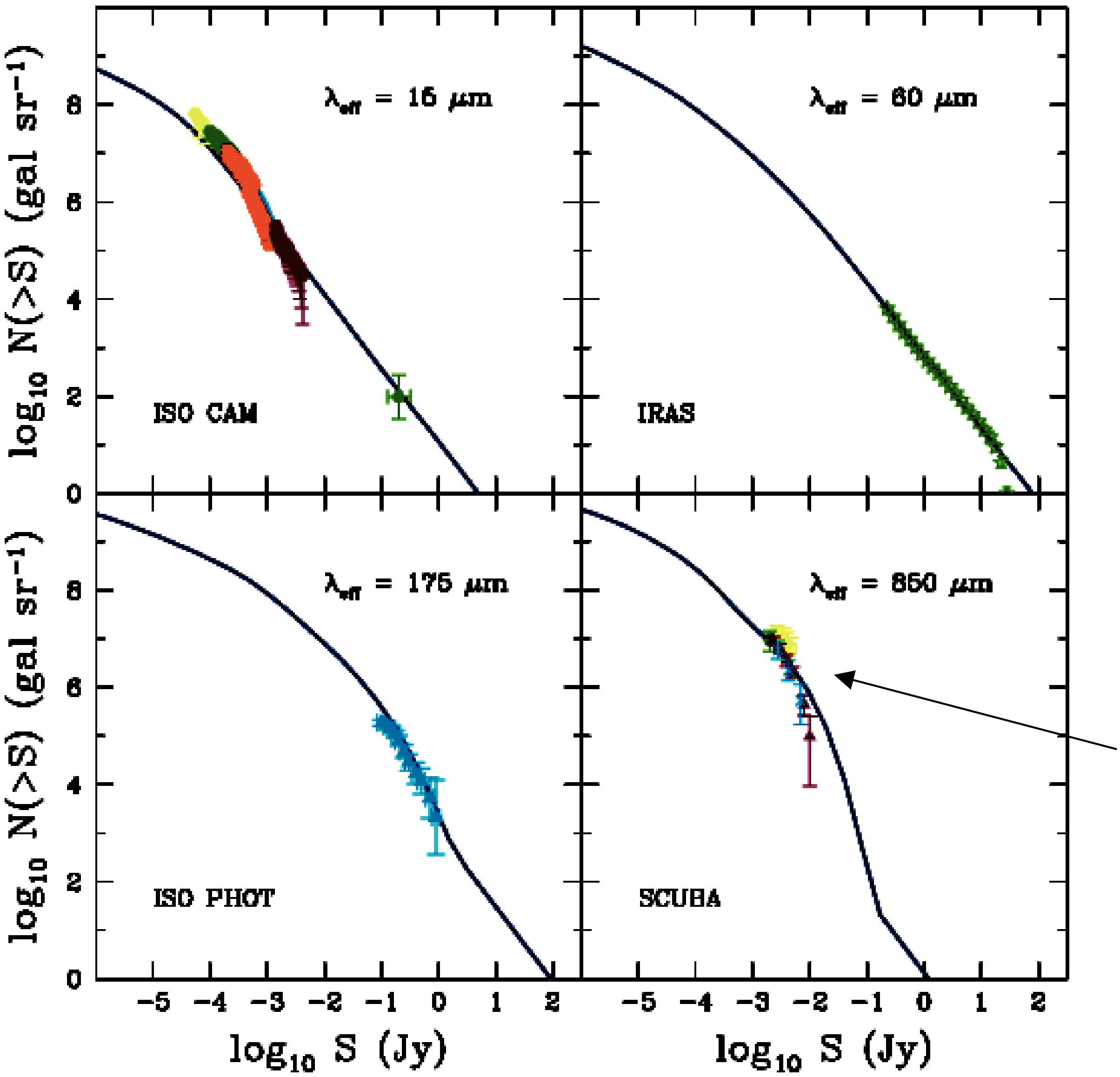


Dey et al. 1999

The Cosmological Interest of SCUBA sources

- *Local LIRGs and ULIRGs* are powered by starbursts (and AGNs for the most luminous objects, Lutz et al. 1998) triggered by interaction and merging. They are thought to be the progenitors of E galaxies.
- *If SCUBA high z LIRGs and ULIRGs are mergers* (very little direct observational evidence so far), we are seeing the crucial step of hierarchical galaxy formation

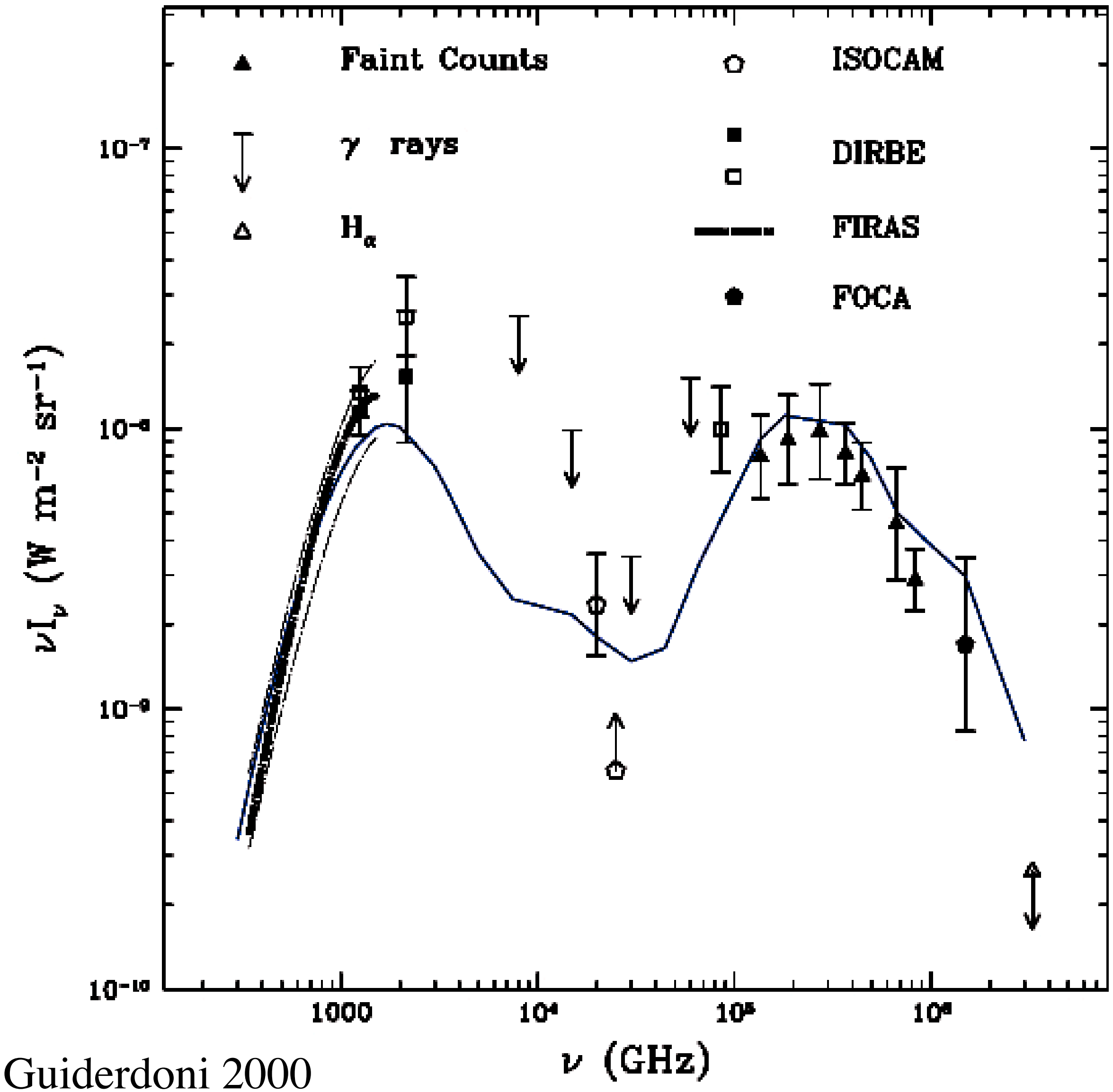
Predicted IR/submm counts with simple SAM



Fit submm
counts with
ad hoc
extinguished
starbursts

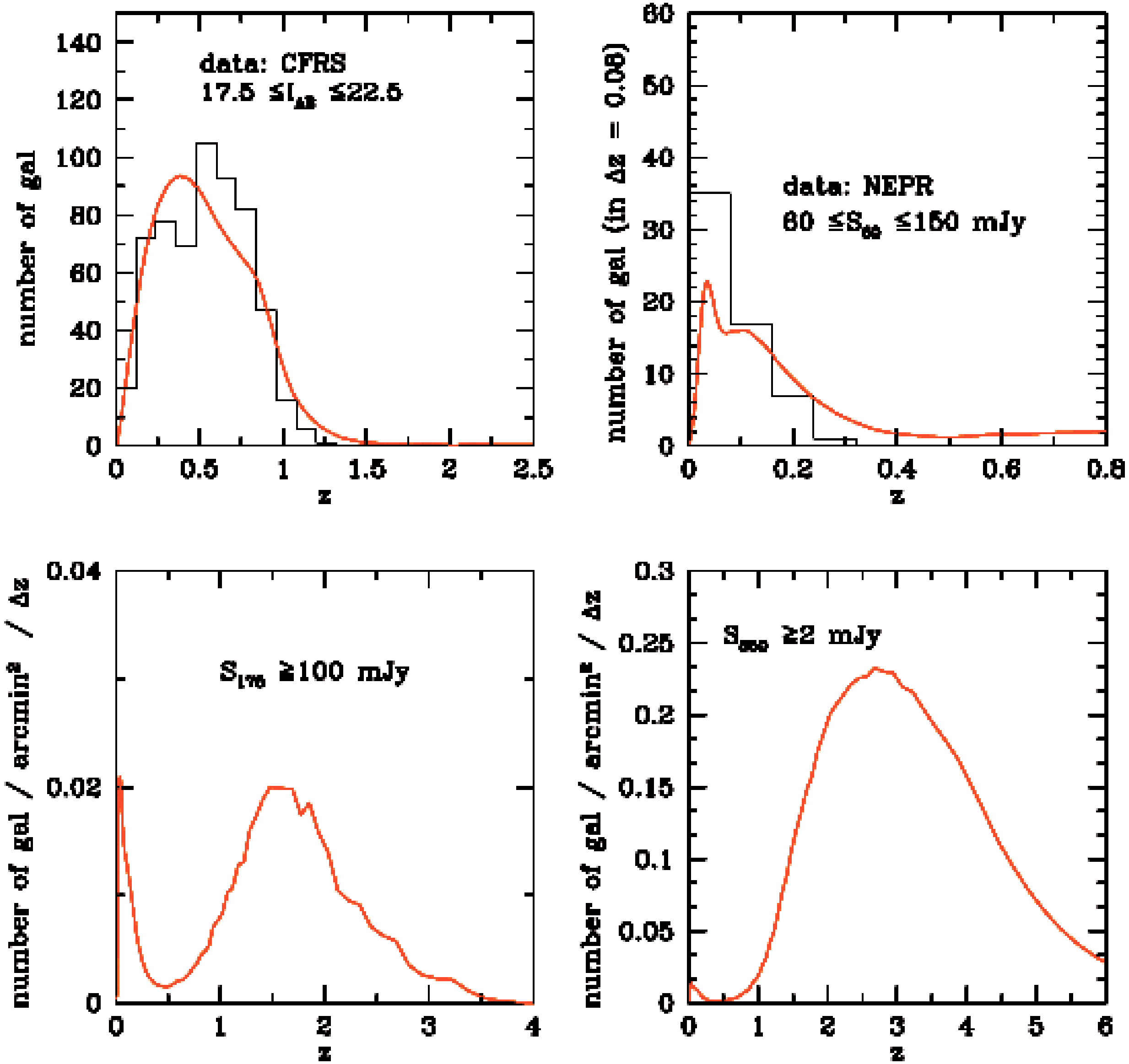
Devriendt & Guiderdoni 2000

Predicted COB+CIRB with simple SAM

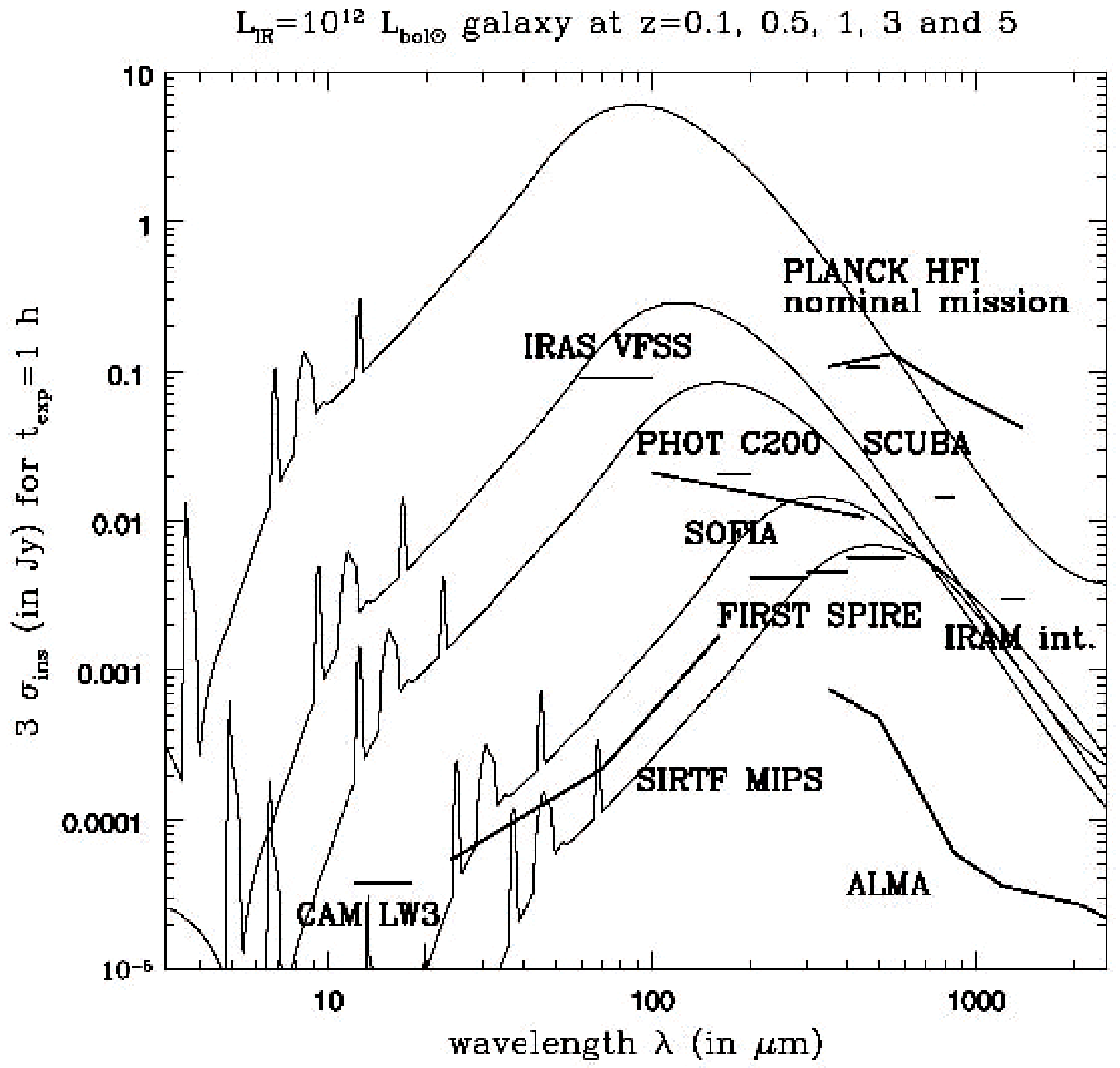


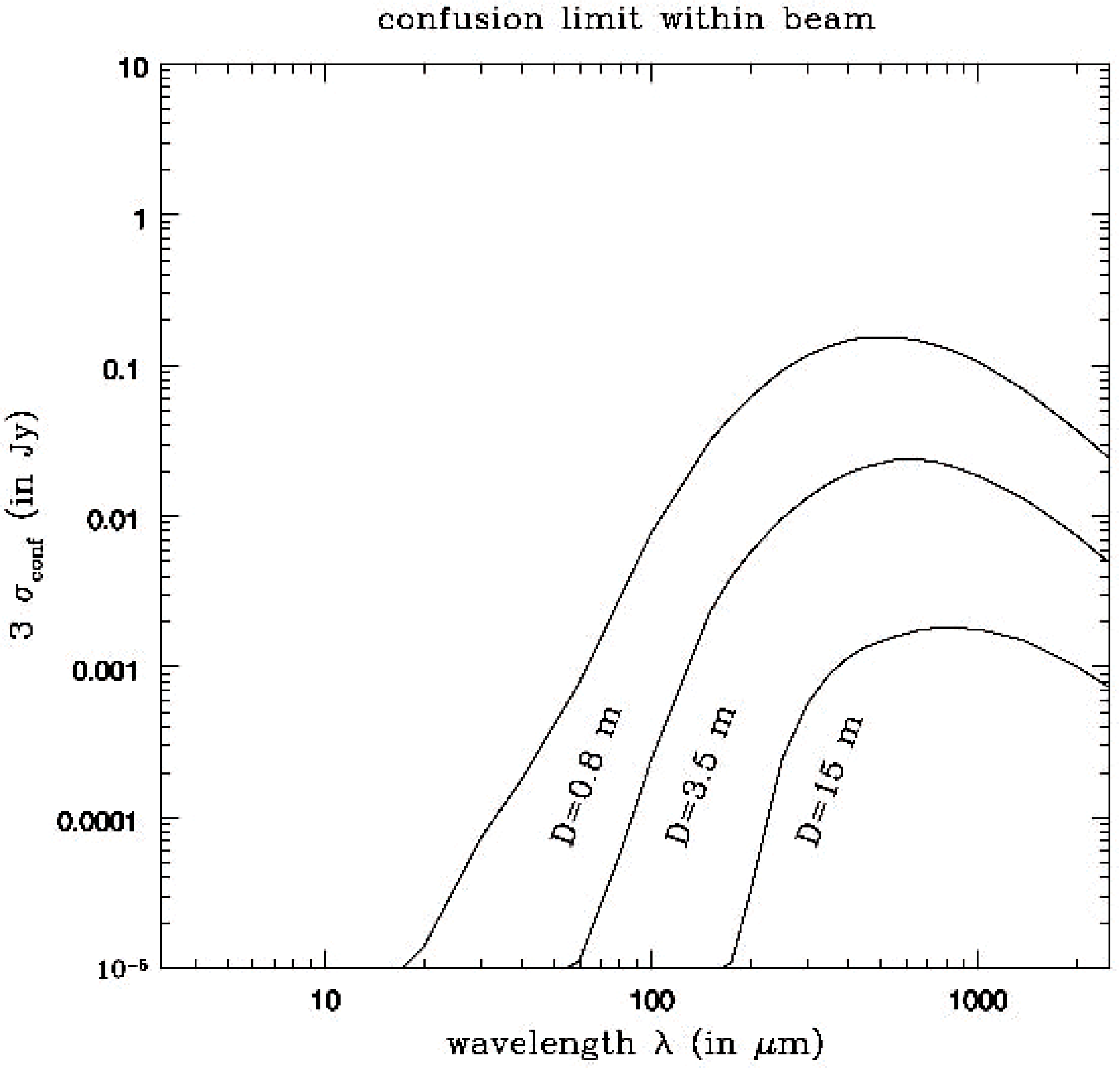
Devriendt & Guiderdoni 2000

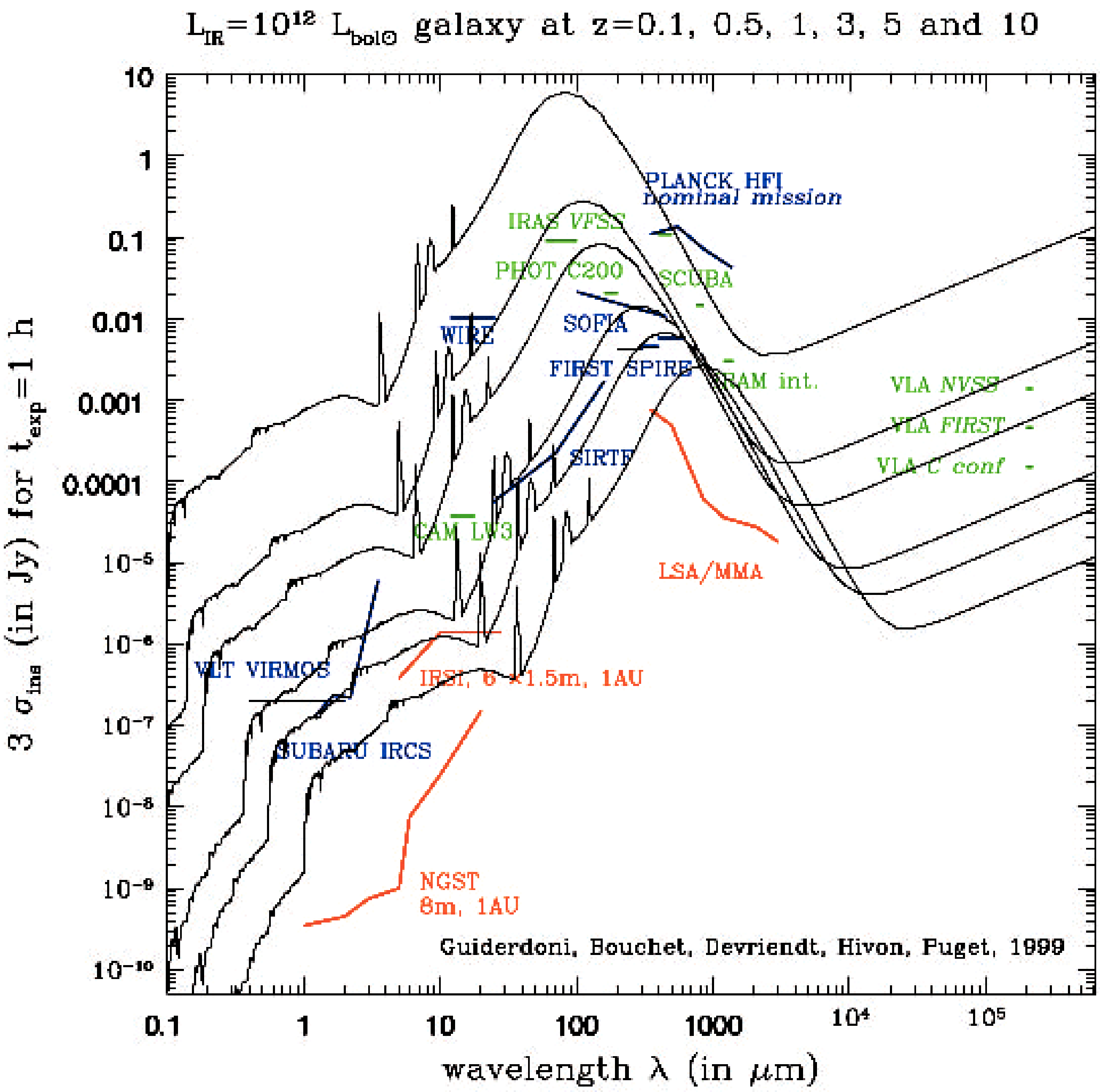
Predicted z distribution with simple SAM



Devriendt & Guiderdoni 2000


$L_{IR}=10^{12}\ L_{bol\odot}$ galaxy at z=0.1, 0.5, 1, 3 and 5
3 σ_{ins} (in Jy) for t_{exp}=1 h
10
1
0.1
0.01
0.001
0.0001
10^{-5}
10
100
1000
wavelength λ (in μm)
PLANCK HFI
nominal mission
IRAS VFSS
PHOT C200
SCUBA
SOFIA
FIRST SPIRE
IRAM int.
SIRTF MIPS
ALMA
CAM LW3


confusion limit within beam
$3\ \sigma_{\rm conf}$ (in Jy)
10
1
0.1
0.01
0.001
0.0001
10^{-5}
10
100
1000
wavelength λ (in μm)
D=0.8 m
D=3.5 m
D=15 m


$L_{IR}=10^{12}\ L_{bol\odot}$ galaxy at z=0.1, 0.5, 1, 3, 5 and 10
3 σ_{ins} (in Jy) for t_{exp}=1 h
10
1
0.1
0.01
0.001
0.0001
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100
1000
10^4
10^5
wavelength λ (in μm)
PLANCK HFI
nominal mission
IRAS VFSS
PHOT C200
SCUBA
WIRE
SOFIA
FIRST SPIRE
IRAM int.
VLA NVSS
VLA FIRST
VLA C conf
SIRTF
CAM LW3
LSA/MMA
VLT VIRMOS
IRSI, 6 × 1.5m, 1AU
SUBARU IRCS
NGST
8m, 1AU
Guiderdoni, Bouchet, Devriendt, Hivon, Puget, 1999

Forthcoming IR/submm Observations

A golden era for high-z submm sources

- **SIRTF** (launch in 2003) : MIPS (24, 70, 170 μm) : rest-frame MIR for z<3.
- **HERSCHEL** (launch in 2007) : PACS (60-90, 90-130, 130-210 μm) and SPIRE (200-350, 350-450, 450-670 μm)
  - Deep fields (S_{lim}=15 mJy @ 350 μm) : a few 10^4 sources. Expected 1<z<3. Confusion limited
  - *Will study the SEDs of a large sample of high-z ULIRGs*
- **PLANCK** (launch in 2007) : HFI (350, 550, 850 μm, 1.3, 2 mm)
  - All-sky Compact Source Catalogue (S_{lim}=260 mJy @ 350 μm) : a few 10^4 to 10^5 sources. Expected <z>=0.2.Confusion limited
  - *Will study the rarest/most luminous ULIRGs*
- **ALMA** (full operation 2010) : (850 μm, 1.3, 2 mm)
  - 5σ = 30 μJy/beam in t_{exp}=1h. With 0.1 arcsec resolution : ID, morphology
  - Spectroscopic measures of z with CO lines
  - *Will follow-up blank fields and optically selected high-z sources (LBGs)*