

le fond diffus extragalactique infrarouge *(Cosmic Infrared Background – CIB)*

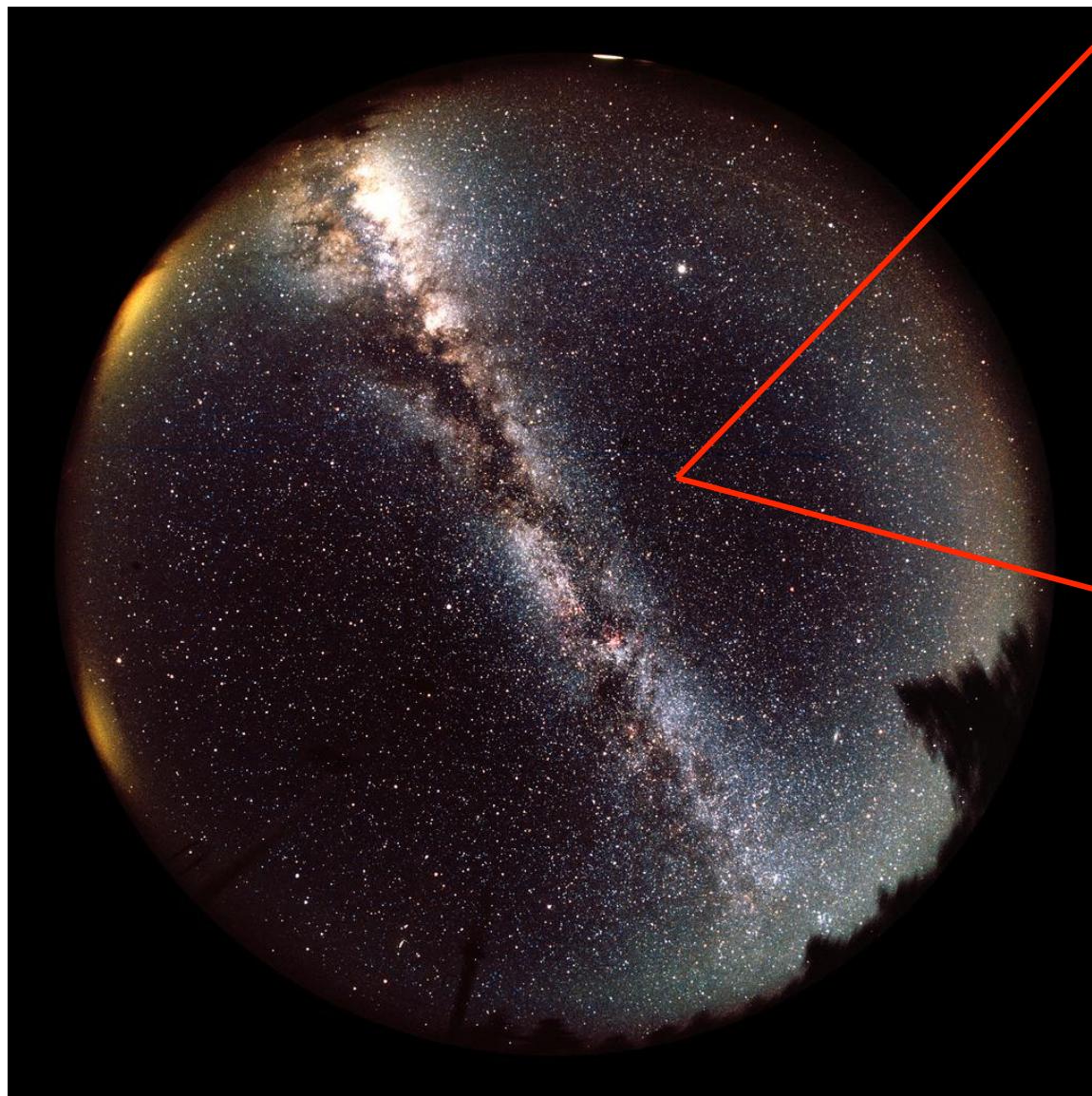
Hervé Dole

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Université Paris Sud & CNRS
Institut Universitaire de France
<http://www.ias.u-psud.fr/dole/>

Hervé Dole, IAS - CIB

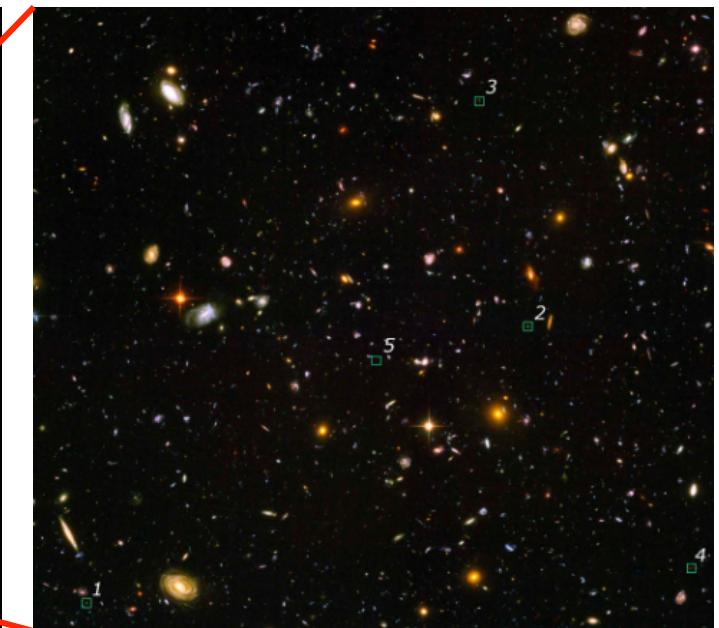


why is the night sky dark ?



Sept 9th 2014 - Ecole de Gif, APC

Hervé Dole, IAS - CIB

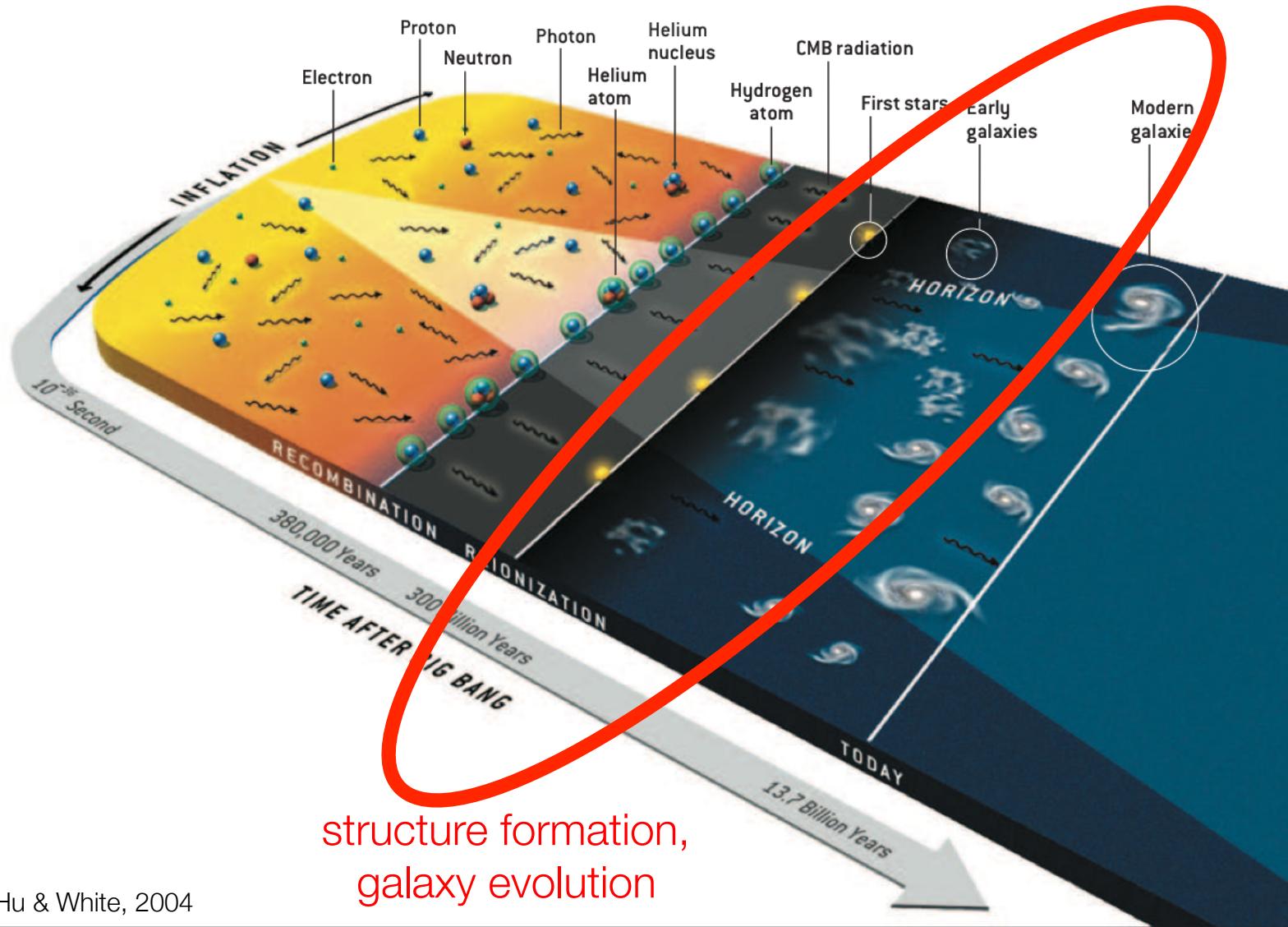


left: D. Officer, P. Welch, UofA
right: NASA, HST 2

pourquoi la nuit est-elle noire ?

- Digges (16^e), **Chézeaux** (17^e), Halley (18^e), **Olbers** (19^e)
 - Herschel, Kant, Proctor, Fournier d'Albe, Charlier
 - **Poe** (19^e), **Kelvin** (19^e)
 - Wesson (1987, 1991)
-
- finitude vitesse lumière c
 - âge fini des objets
 - expansion Univers
- **horizon cosmologique** → oui
-
- existence d'**émissions reliques**
 - recombinaison: **fond cosmologique**
 - formation et évolution des galaxies: **fond extragalactique**
 - expansion, et prise en compte de tout le **spectre e. m.**
- non

history of the universe



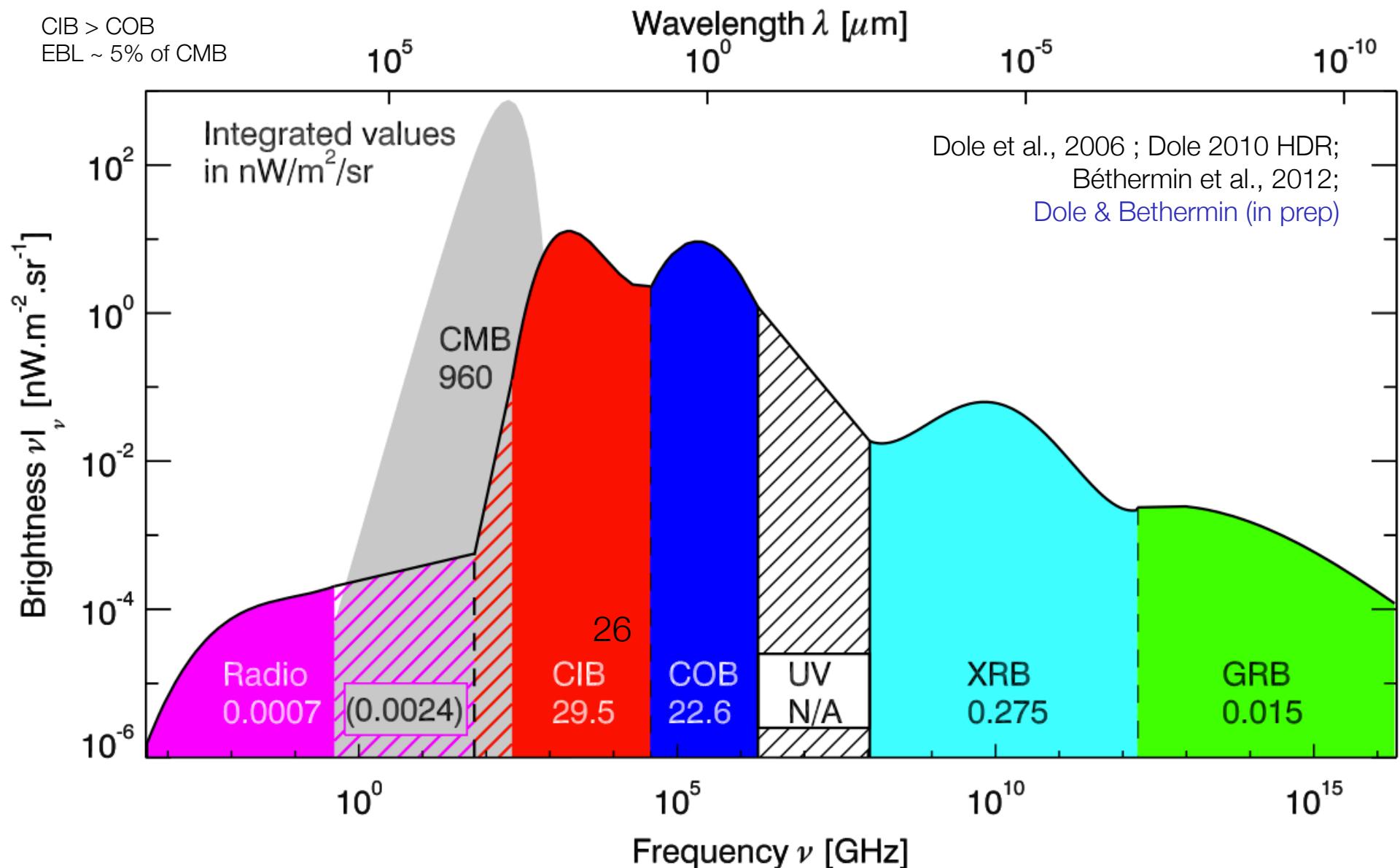
Hu & White, 2004

1. extragalactic background light

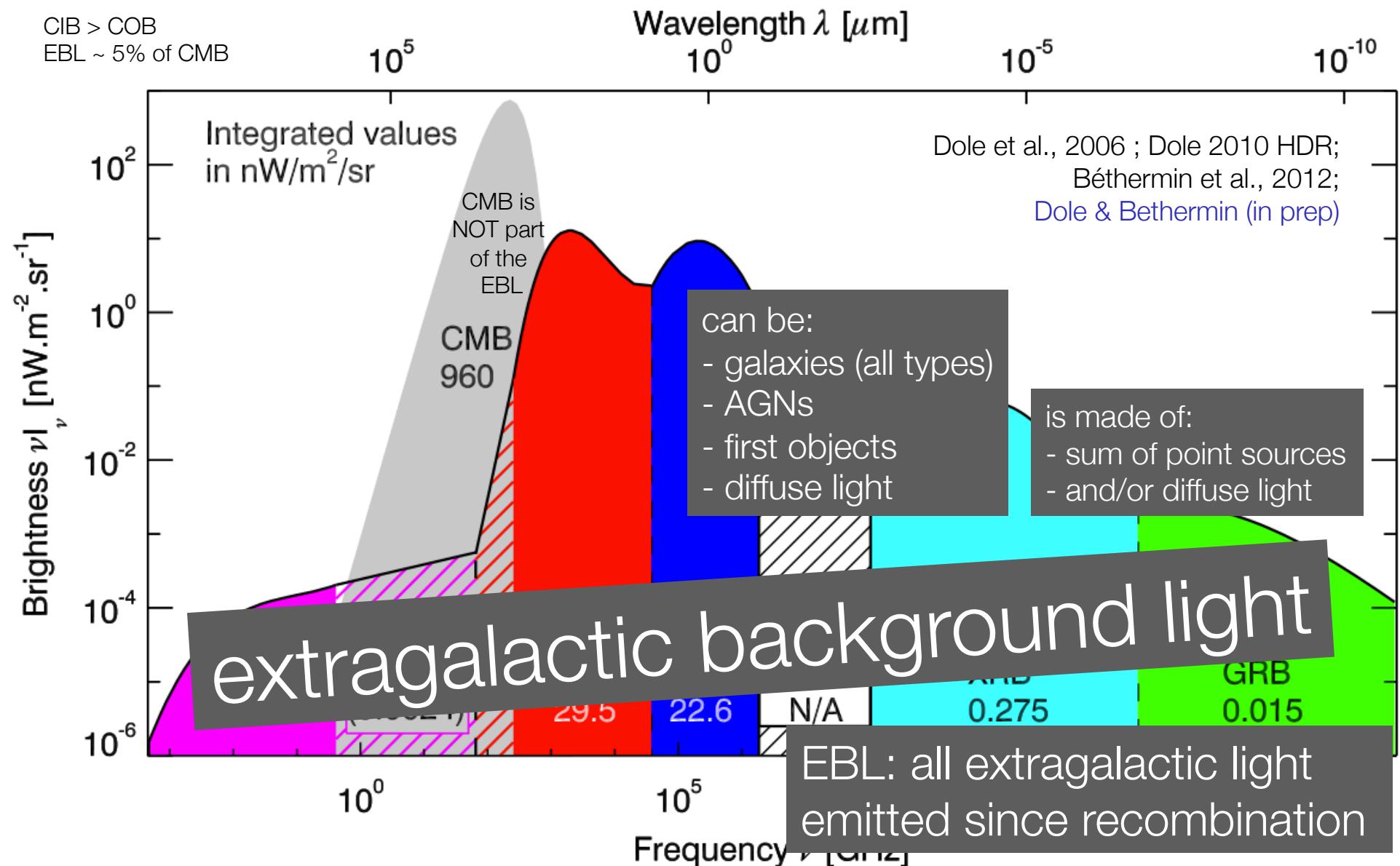
EBL (Extragalactic Background Light) tells us about the processes involved in galaxy formation & evolution (budget for radiation emission by nucleosynthesis & gravitation, presence of dust, ...)

CIB (Cosmic Infrared Background) level and structure depend on history of energy production in the post-recombination Universe [Kashlinsky, 2005]

a contemporary view of Universe's SED



a contemporary view of Universe's SED



Outline

1. what is the EBL/CIB ?
2. motivations to study the EBL/CIB

3. EBL / CIB SED measurements
4. EBL, galaxy populations and models
5. CIB fluctuations

6. Planck and the CIB

7. summary, conclusion and prospects

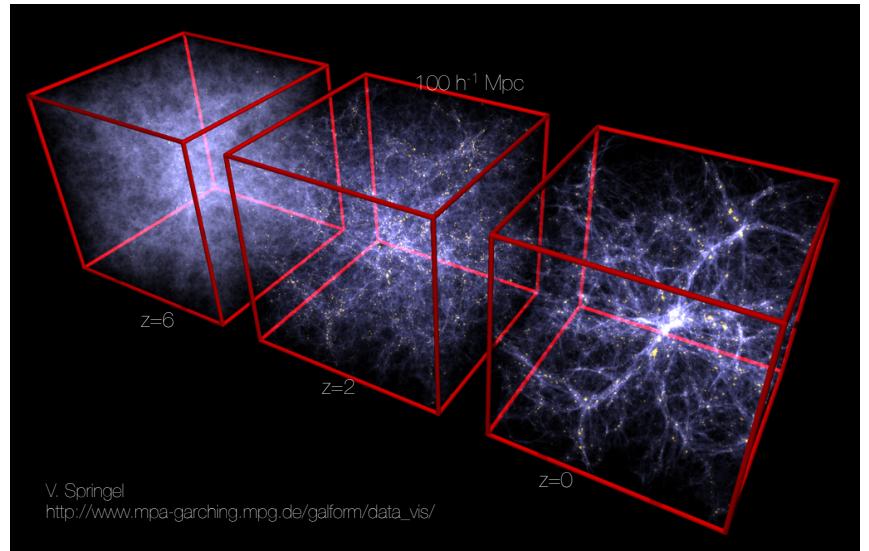
2. motivations to study the EBL / CIB

from EBL to galaxy populations

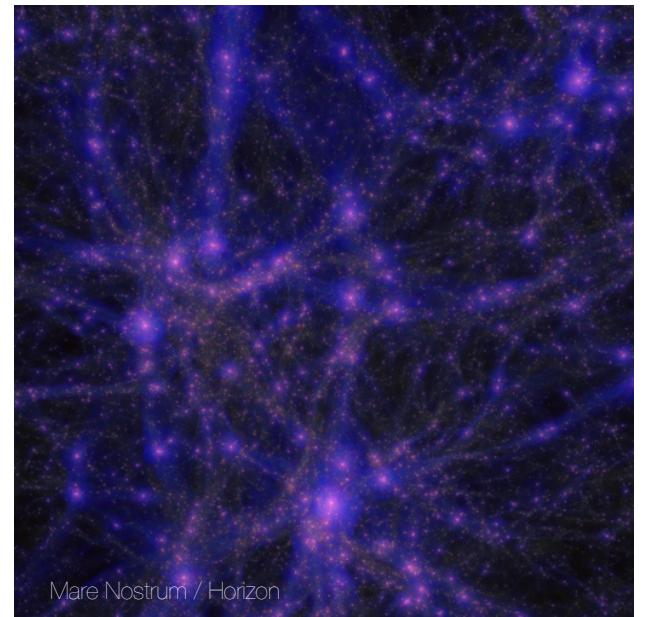
- galaxies
 - physical processes driving the evolution?
 - gravitation: black hole and AGN
 - strong, weak, electromagnetic: nucleosynthesis: star formation
 - relative importance ? redshift evolution ?
- TeV gamma emission of AGN
 - peak of photon-photon interaction
 - $\lambda_{\text{IR}}(\mu\text{m}) \sim E\gamma(\text{TeV})$
 - constraints on the intrinsic spectrum of blazars ?

structure formation

- Hierarchical structure formation ?
 - dark matter « well » described
 - what about « visible matter »?
 - in general, simulations reproduce well data in the visible (number counts, luminosity functions, redshift distributions, angular correlation functions)
 - in general, they **do not** reproduce well **infrared** data
 - After all, is it that important ?
 - poor understanding of the gas (baryons) physics cooling

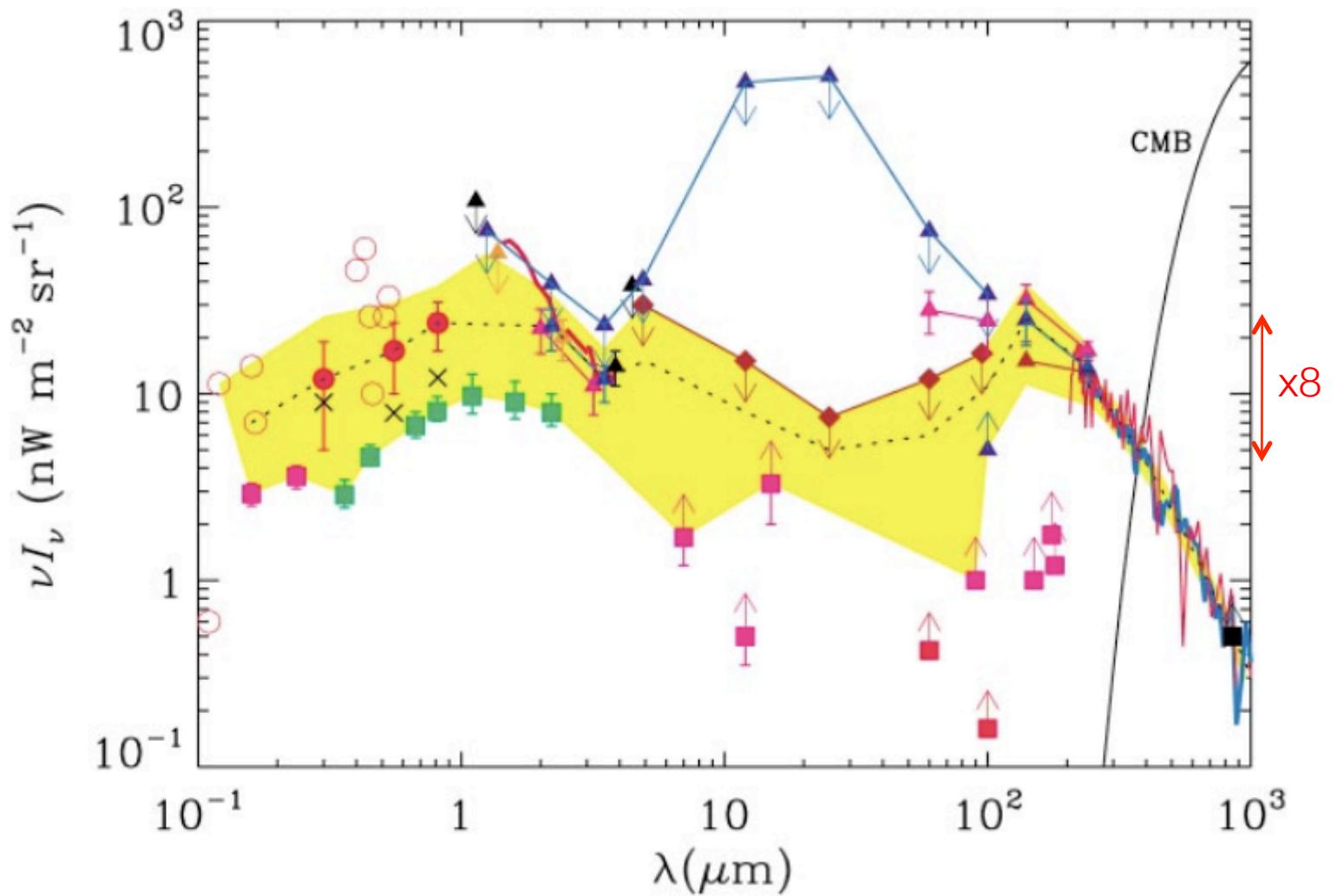


V. Springel
http://www.mpa-garching.mpg.de/galform/data_vis/



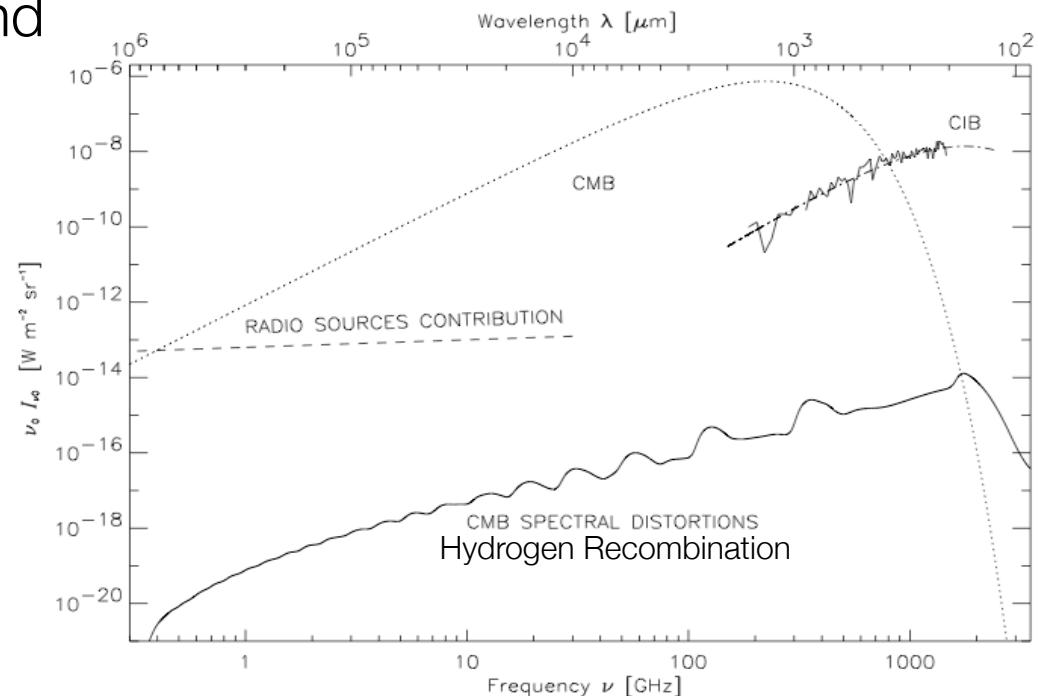
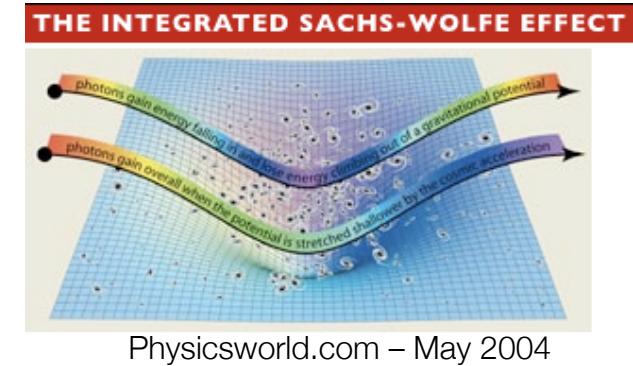
Mare Nostrum / Horizon

energy budget for galaxy formation



cosmology and early structures

- dark energy equation of state
 - ISW: correlations EBL - CMB ?
- reionization at $z > 6$?
 - structure of the background
- recombinations: H, He
 - CIB contaminates
- nasty foreground for CMB



Rubino-Martin et al., 2006
see also e.g. Chluba & Sunyaev, 2007

3. EBL / CIB measurements

3.1 historical status

3.2 measurements: tricky business

3.3 absolute

3.4 γ -rays absorption

3.5 galaxy counts

3.6 stacking

3.1 status in 1967

636

NOVIKOV & ZELDOVIĆ 1967, ARAA

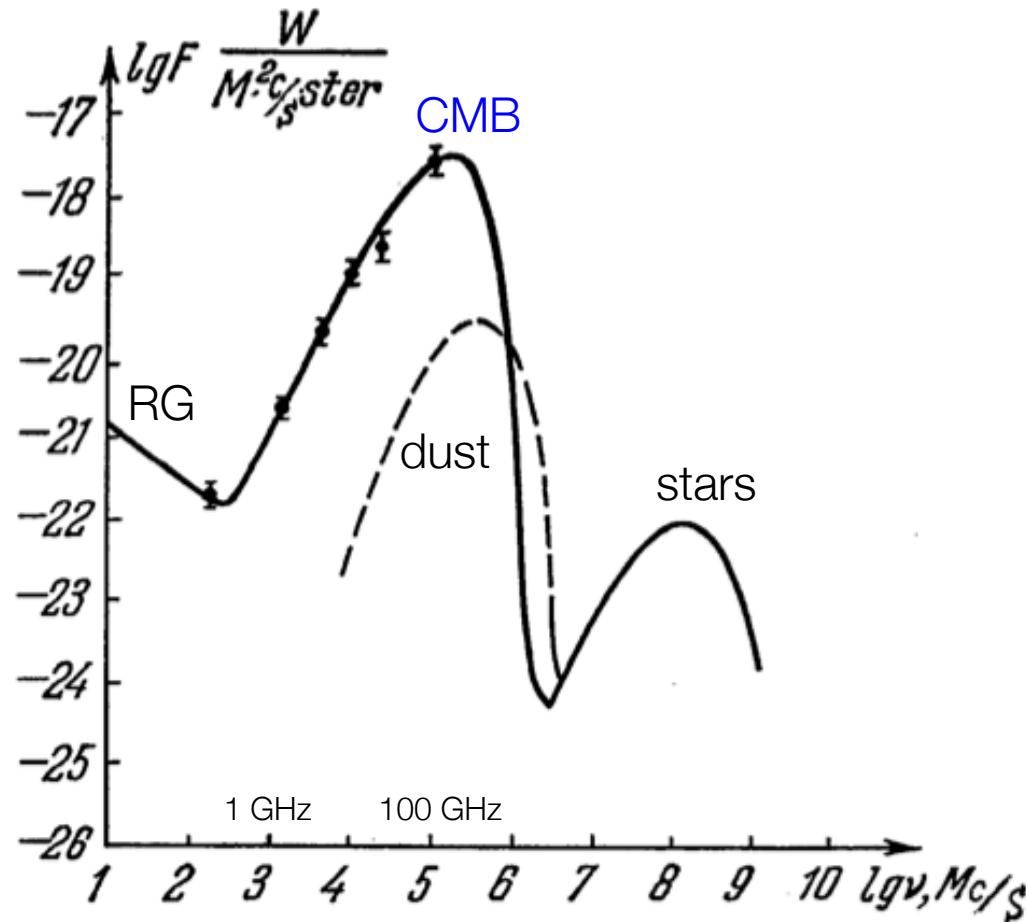


FIG. 1. Averaged spectrum of electromagnetic radiation in the universe. The maximum at $\lg \nu \approx 8$ is the radiation of stars; the straight line at $\lg \nu < 2.5$ is due to radio galaxies. The dotted line is the radiation of dust with $\bar{\rho} \approx 5 \cdot 10^{-34} \text{ g/cm}^3$ and $T = 10^\circ\text{K}$. The full line with maximum at $\lg \nu \approx 5.5$ is the black-body equilibrium radiation at 3°K —the relict radiation. The points give experimental results with their errors.

first predictions in 1967

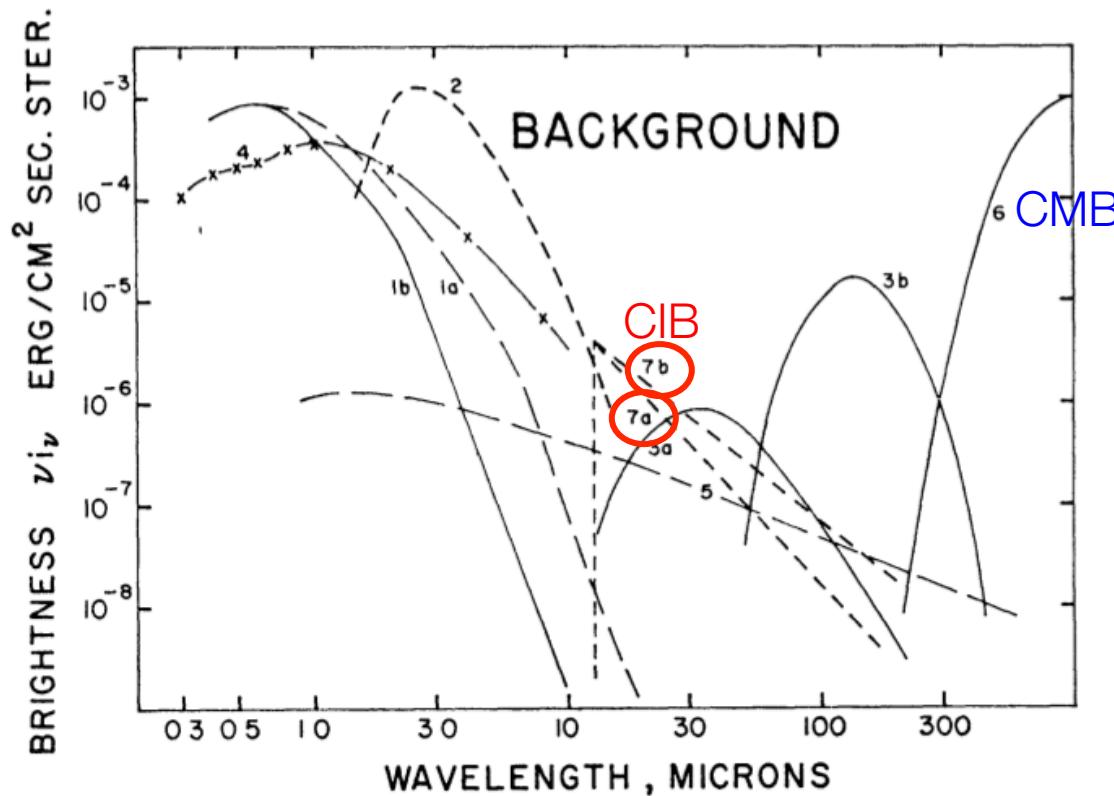
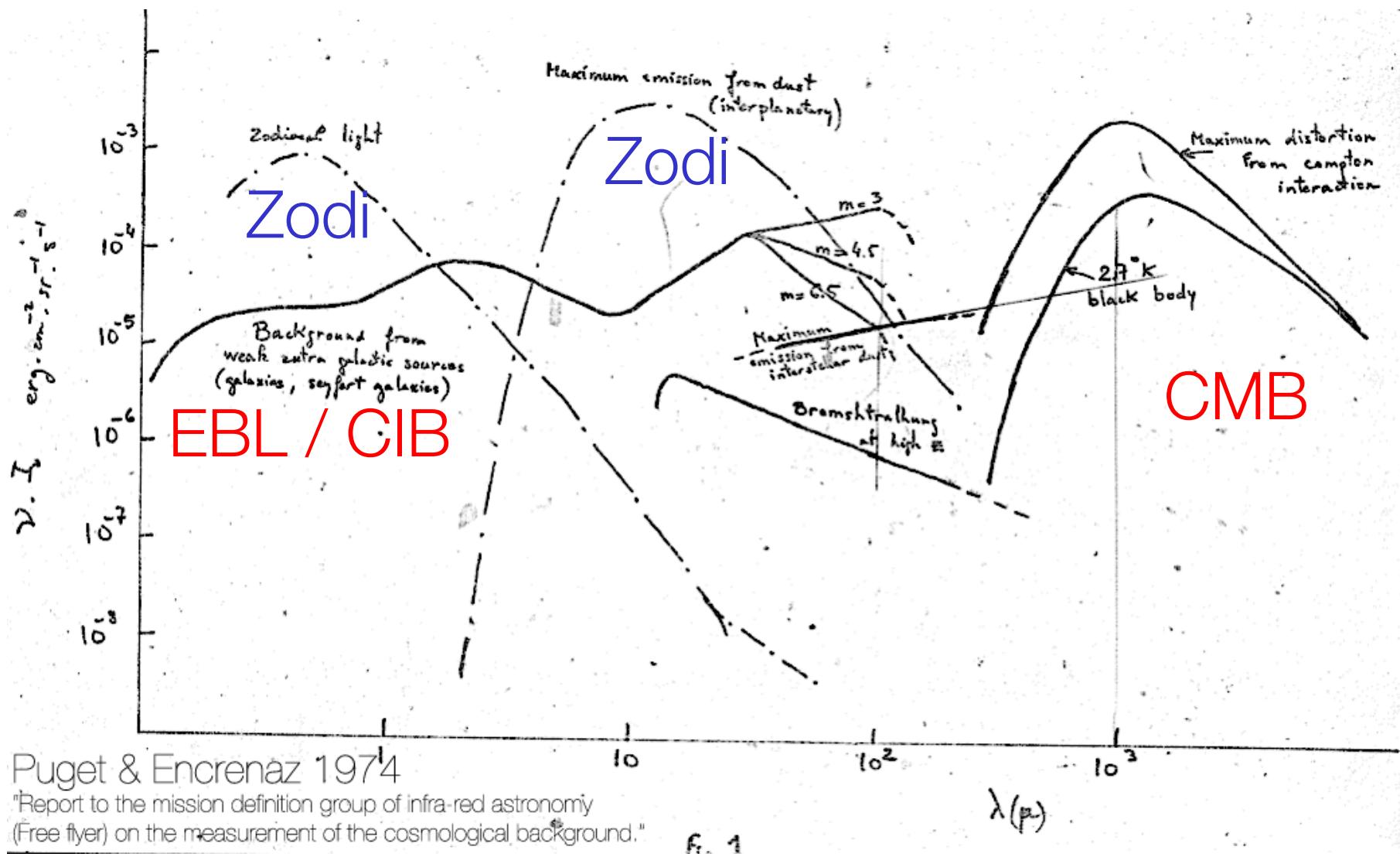


FIG. 8.—Other sources of background radiation. The contribution of local, galactic, and extragalactic sources is plotted as a function of wavelength. The various curves are defined as follows: 1a, zodiacal light perpendicular to the ecliptic with characteristic particle radius 1.8μ ; 1b, zodiacal light perpendicular to the ecliptic with characteristic particle radius 0.7μ ; 2, interplanetary dust (small particles); 3a, interstellar grains (metallic); 3b, interstellar grains (dielectric, or “dirty-ice”); 4, integrated starlight from the Galaxy, perpendicular to the galactic plane; 5, galactic free-free emission, perpendicular to the plane; 6, 3° K cosmic background radiation; 7a, 12.8μ Ne^+ emission from all galaxies (closed model); 7b, 12.8μ Ne^+ emission from all galaxies (open model).

Partridge & Peebles, 1967

un long chemin...



CIB discovery in 1996

Astron. Astrophys. 308, L5–L8 (1996)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Tentative detection of a cosmic far-infrared background with COBE

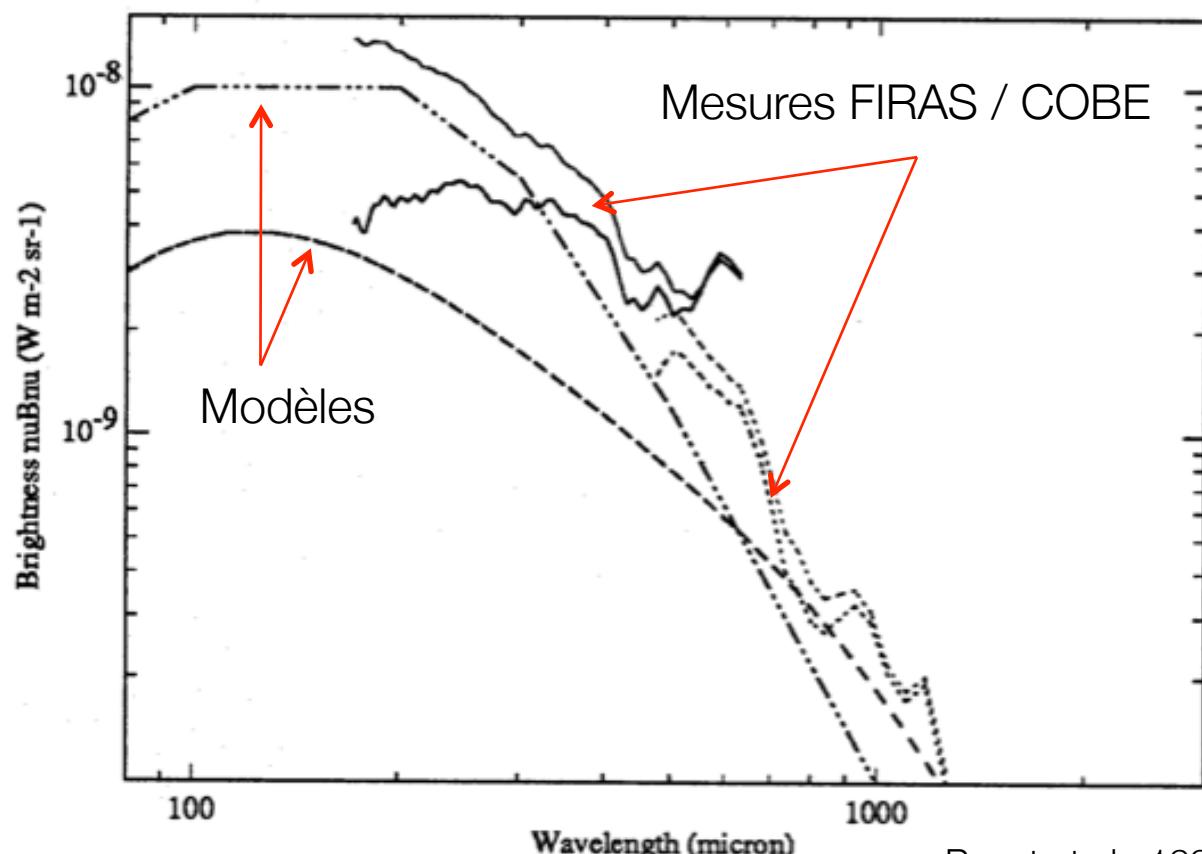
J.-L. Puget¹, A. Abergel¹, J.-P. Bernard¹, F. Boulanger¹, W.B. Burton², F.-X. Désert¹, and D. Hartmann^{2,3}

¹ Institut d'Astrophysique Spatiale, Bât. 121, Université Paris XI, F-91405 Orsay Cedex

² Sterrewacht Leiden, Postbox 9503, 2300 RA Leiden, The Netherlands

³ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

Received 4 August 1995 / Accepted 12 December 1995



Puget et al., 1996

Sept 9th 2014 - Ecole de Gif, APC

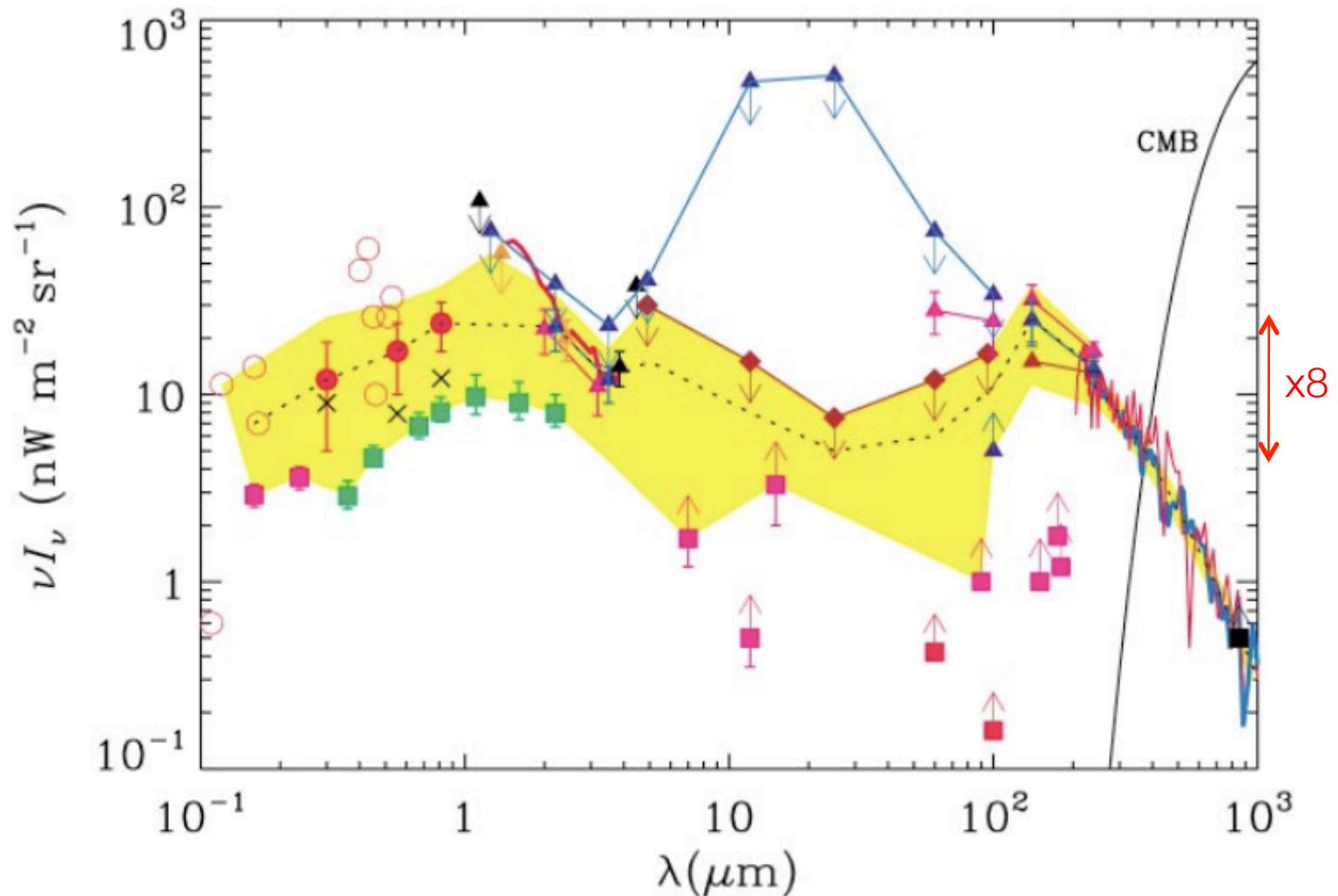
Fig. 1. Residual FIRAS spectrum after CMB, zodiacal and cir-

mesures à la fin des années 90 ...

la lumière zodiacale
est le principal
contaminant.

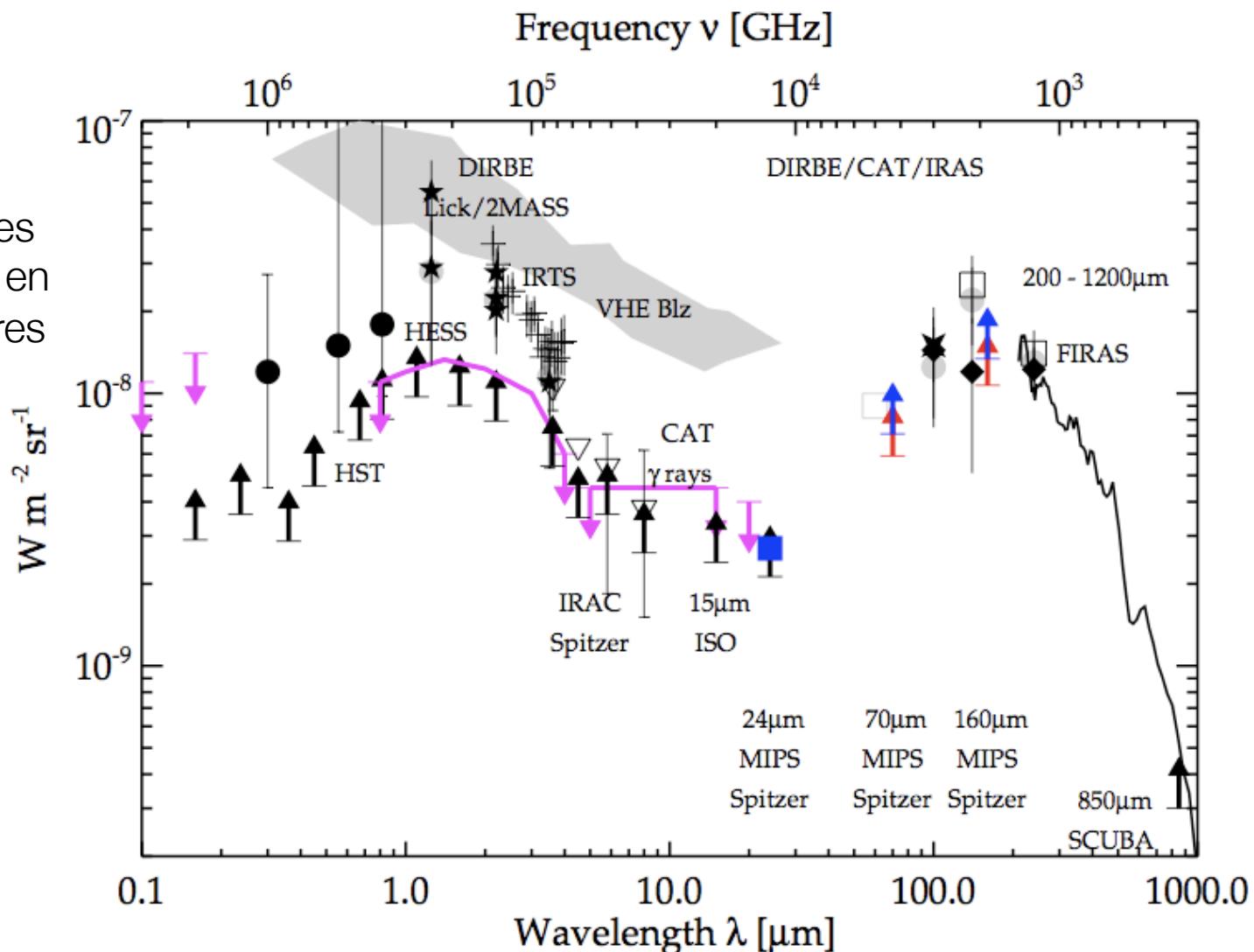
a 60um, zodi
 $\sim 50^{\circ}$ CIB

une erreur de 1%
sur la soustraction
du zodi peut faire
changer de moitié
la valeur du CIB



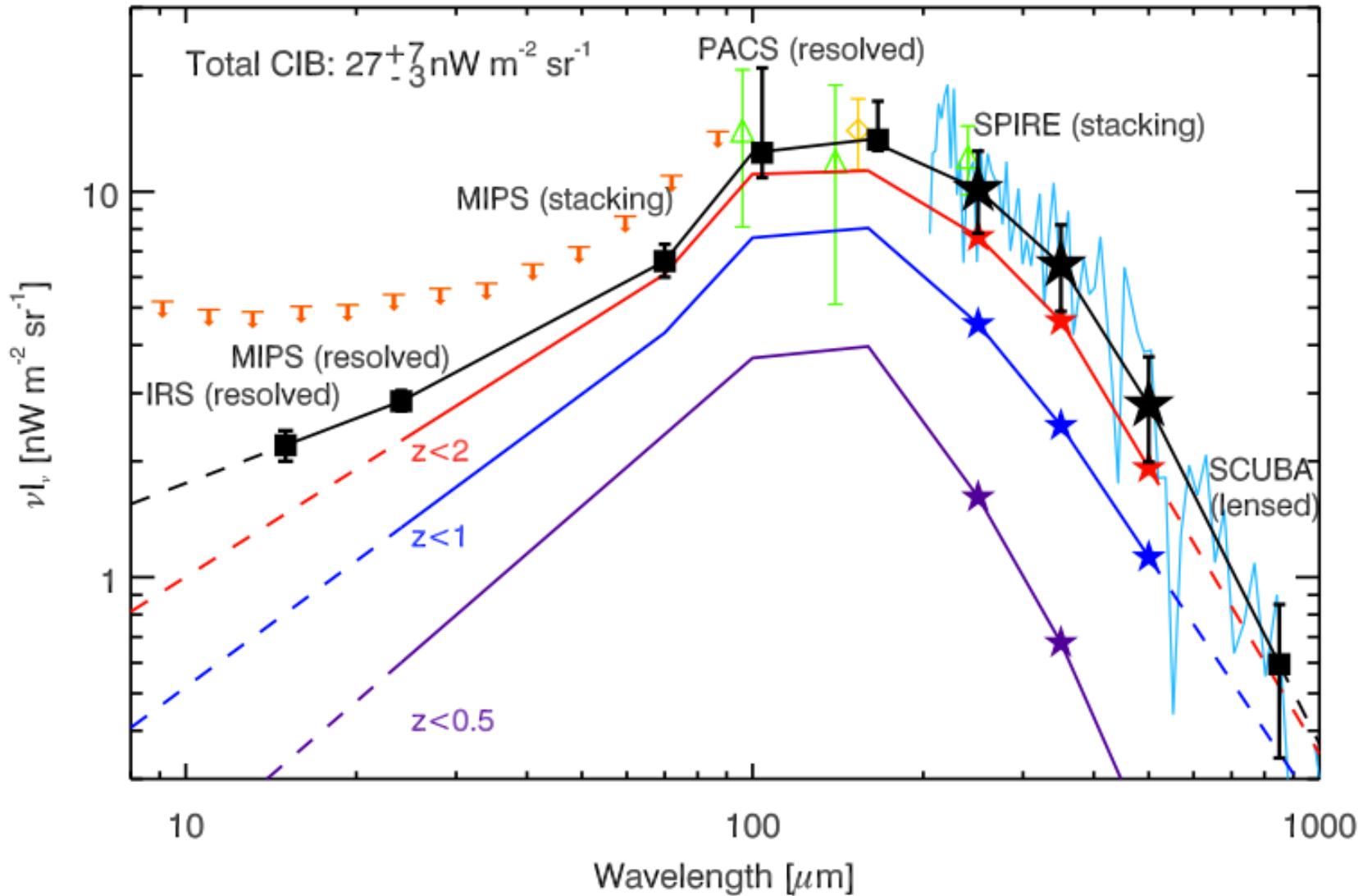
... il y a quelques années ...

apparition de limites inférieures et supérieures, en plus des mesures absolues



Dole et al., 2006; Béthermin, Dole et al., 2010

... et aujourd'hui (pour la partie CIB)



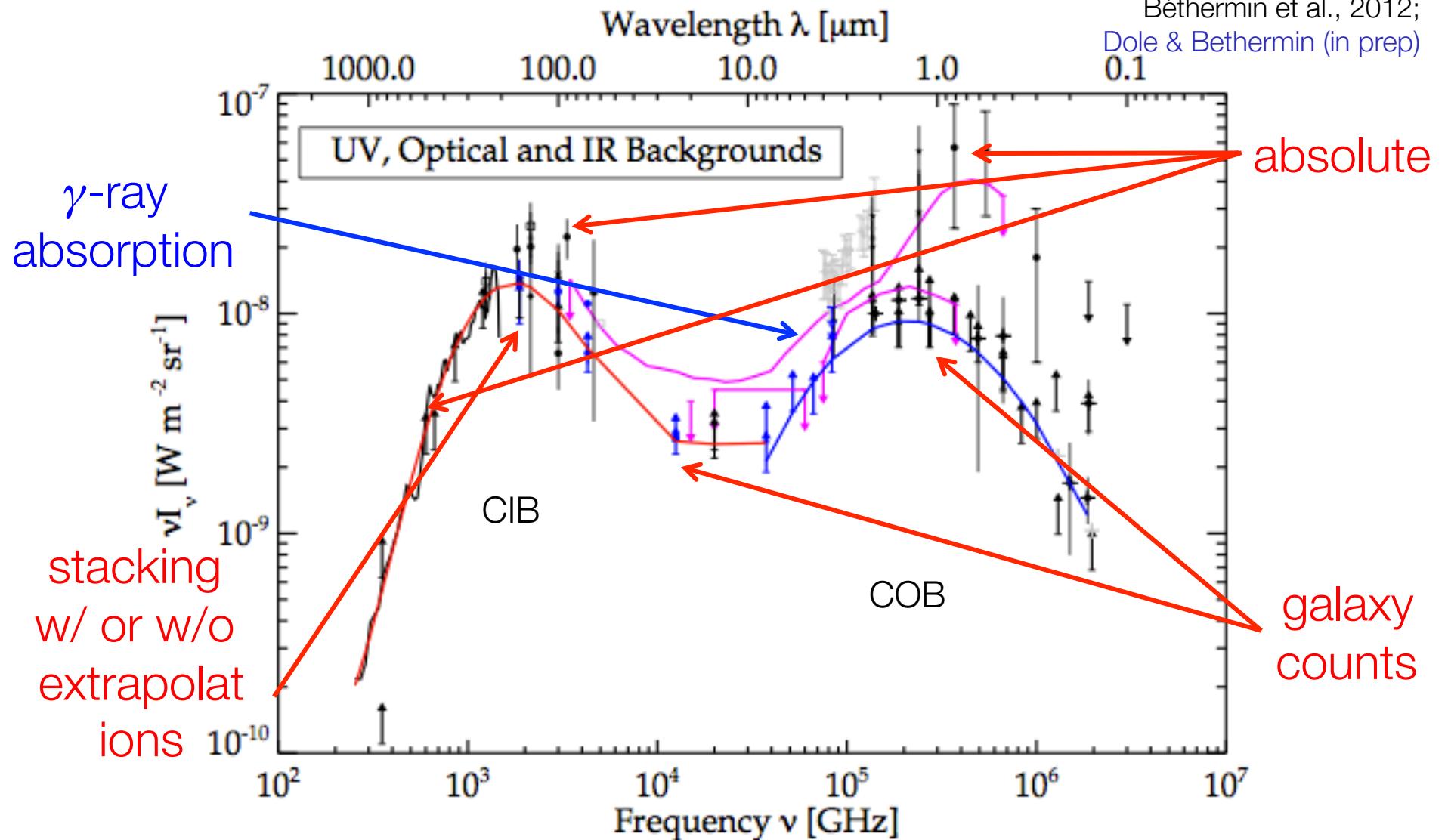
Béthermin et al., 2012, A&A

3.2 visible and infrared EBL – tricky business

Dole et al., 2006 ; Dole 2010 HDR;

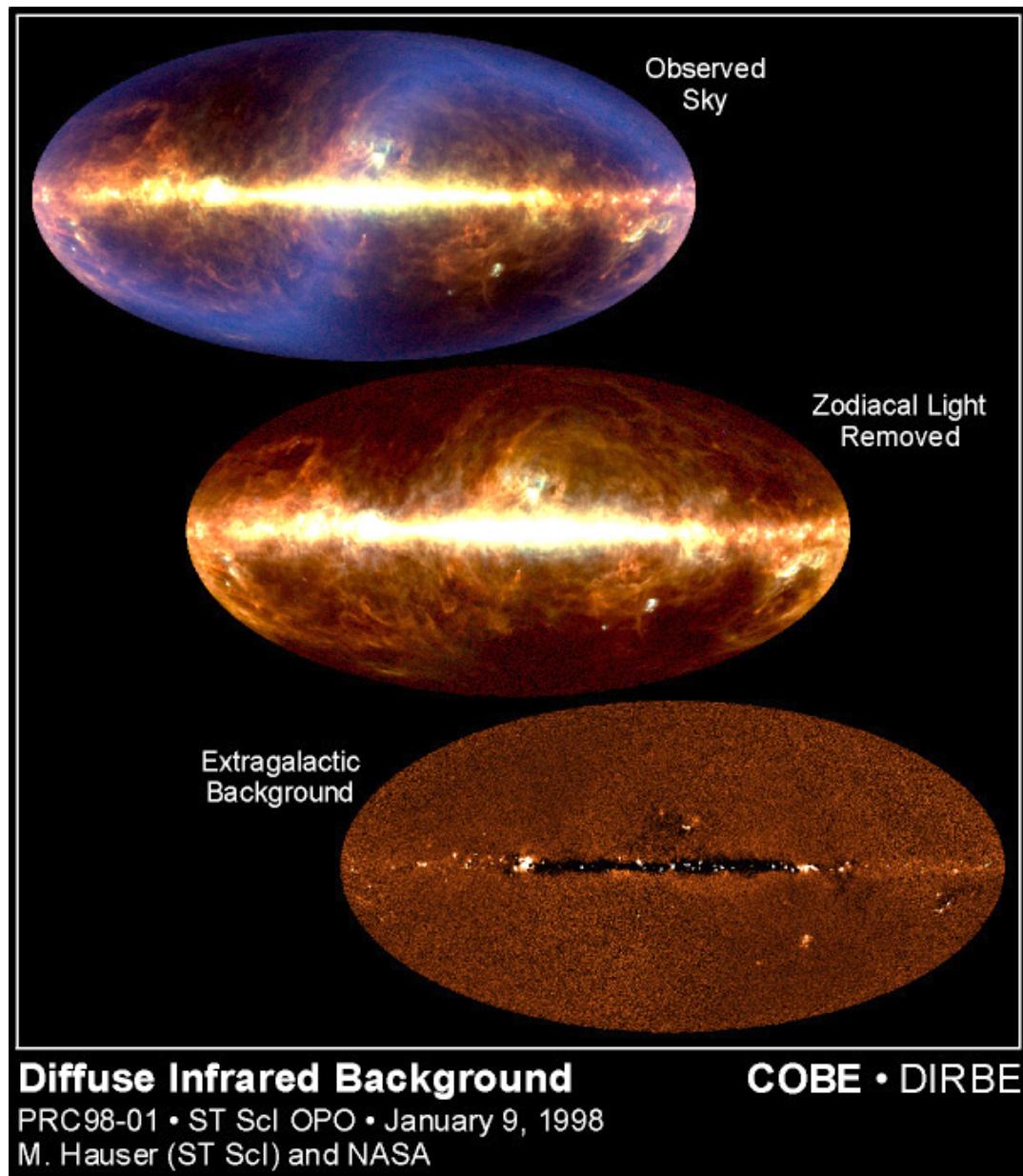
Béthermin et al., 2012;

Dole & Bethermin (in prep)

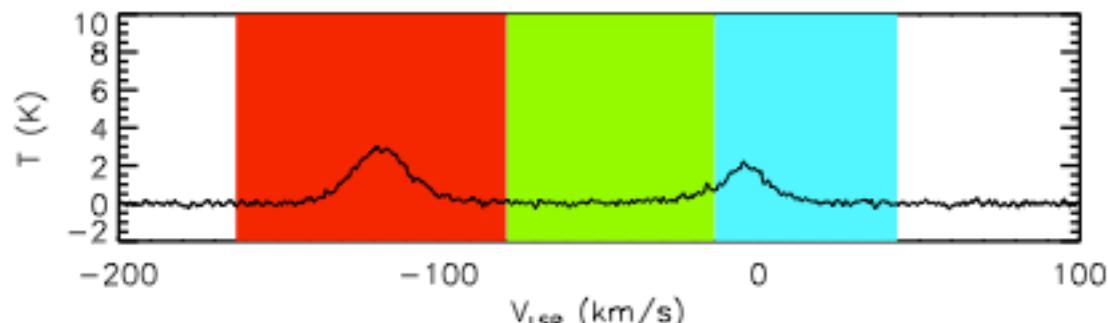
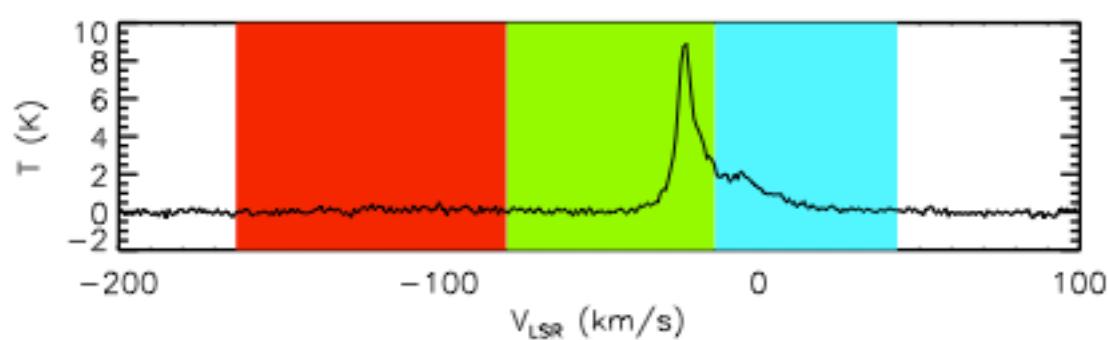
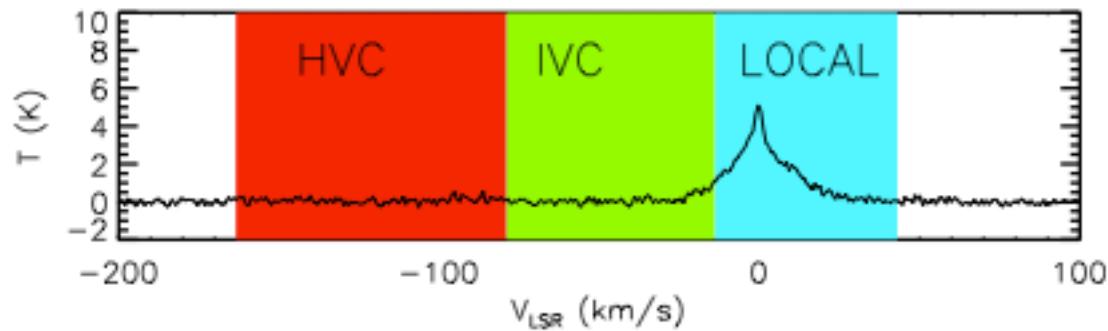


3.3 absolute measurements

- incredibly difficult
 - but very useful !
-
- systematic effects
 - quality of foreground model + removal
 - 1% of zodi error -> factor of 2 CIB in NIR



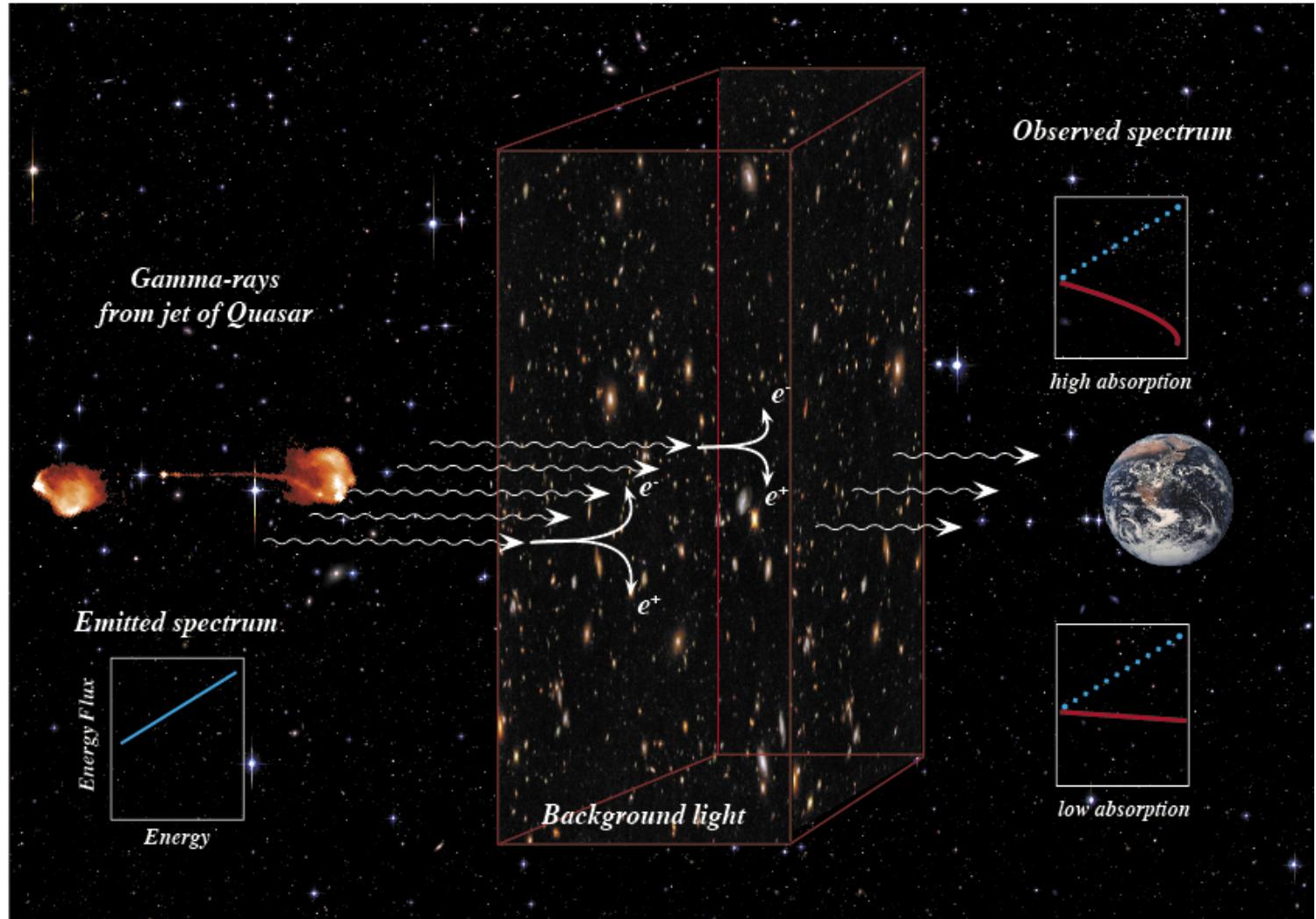
absolute measurements – cirrus removal



Decomposition of the HI emissivity into 3 components
(Penin+12b, see also Miville-Deschénes+05)

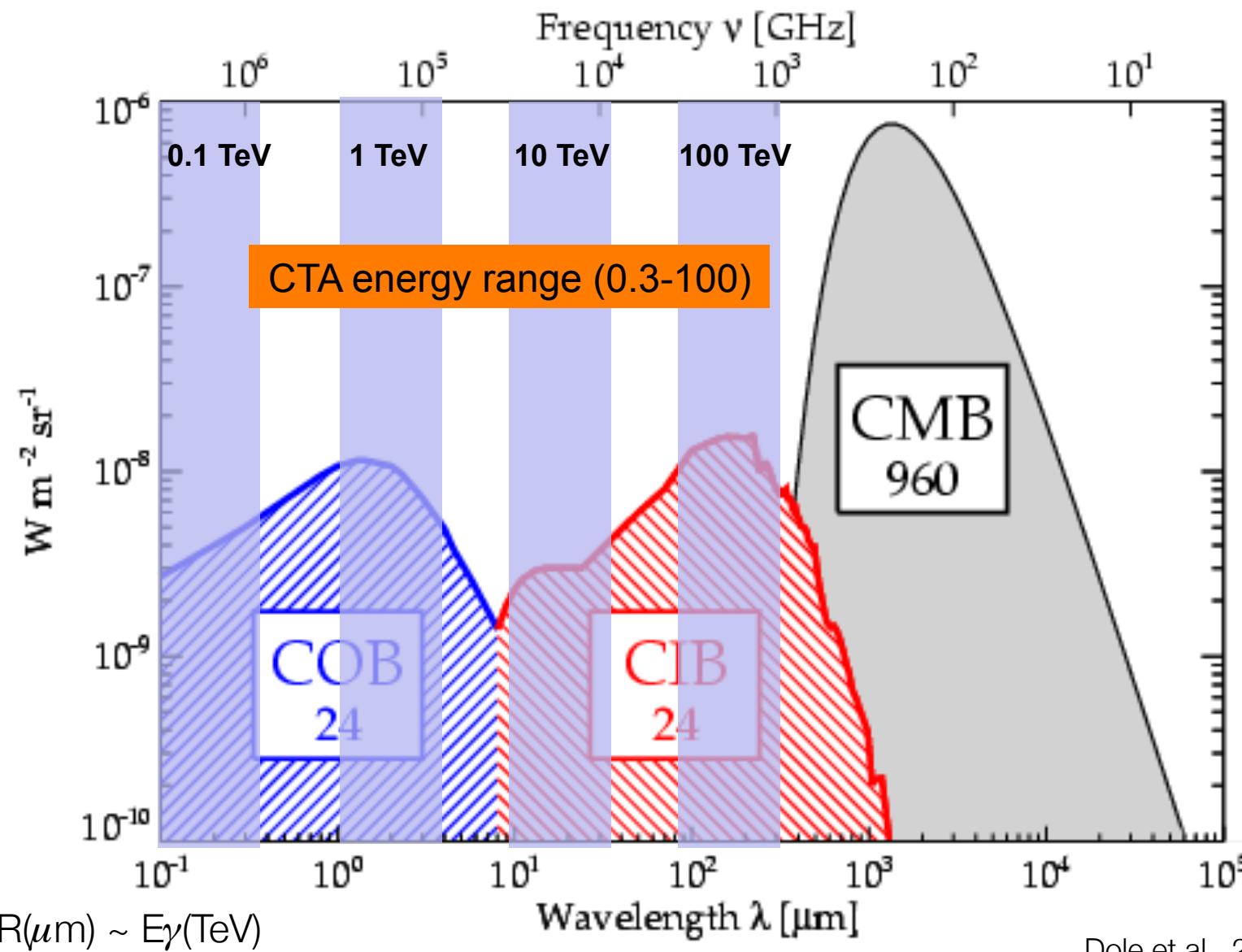
3.4 γ -rays absorption

gives usually
upper limits



H.E.S.S, Nature, 2006
Aharonian et al., 2006, Nature
Aharonian et al., 2007, A&A

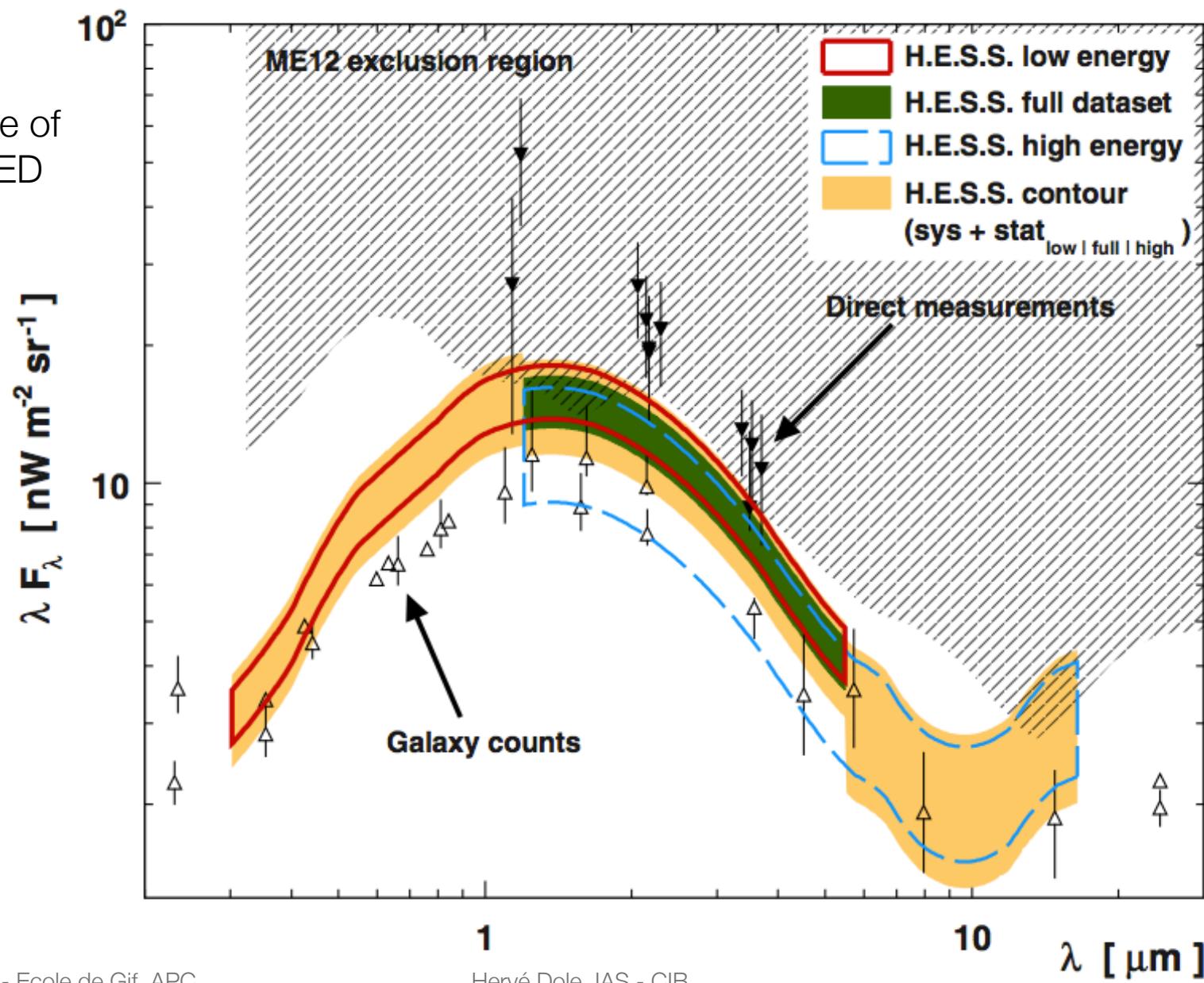
implications for TeV opacity



Dole et al., 2006

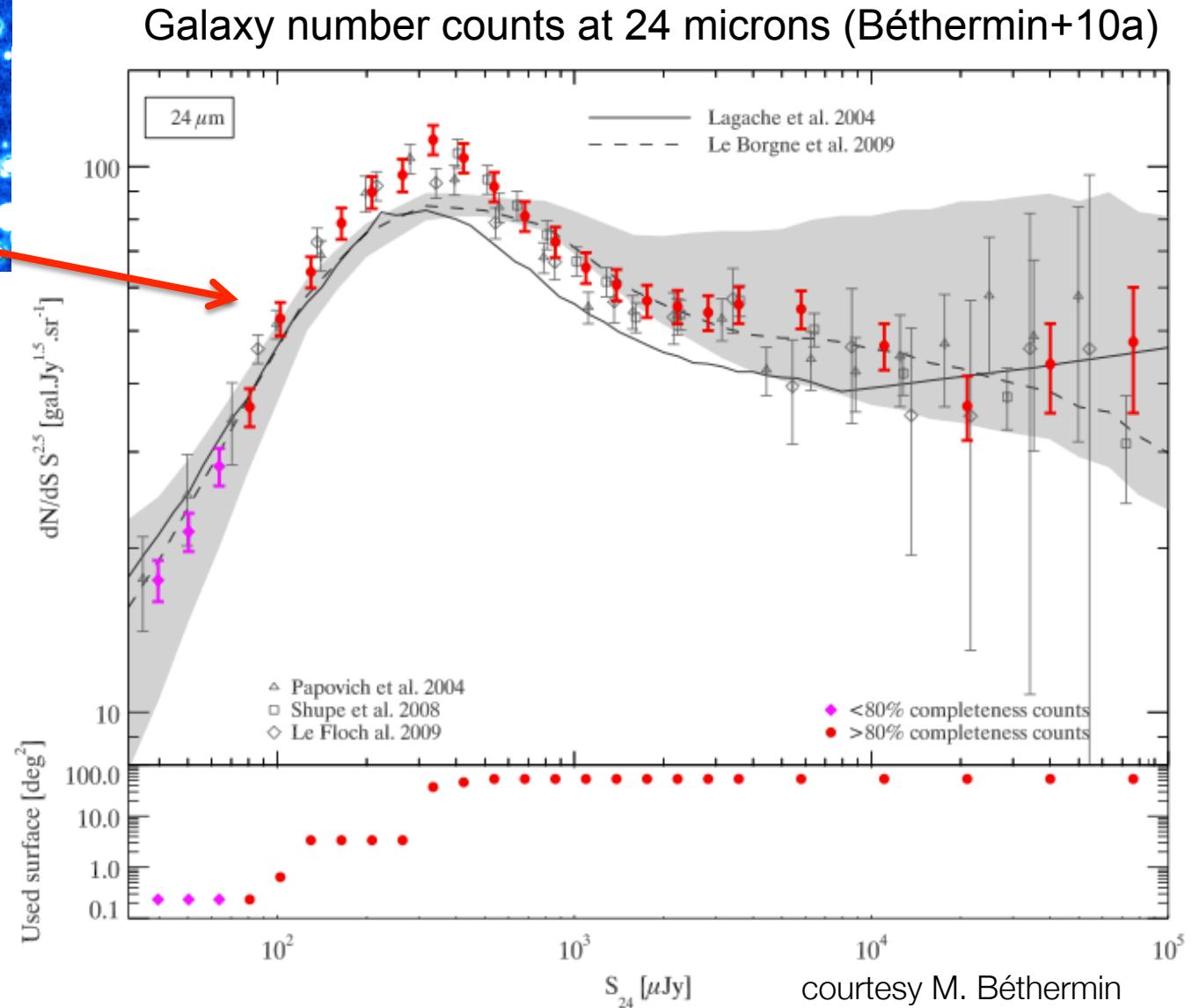
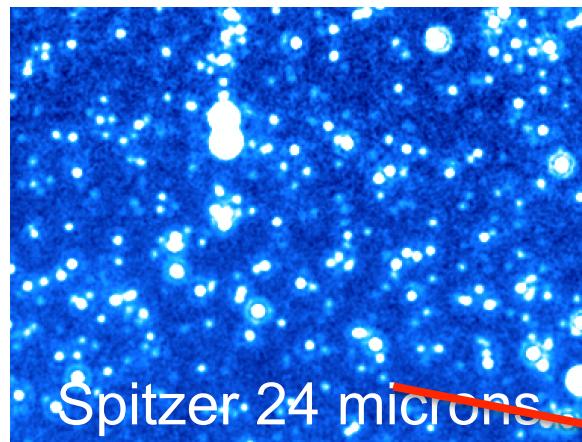
latest HESS results

estimate of
the SED

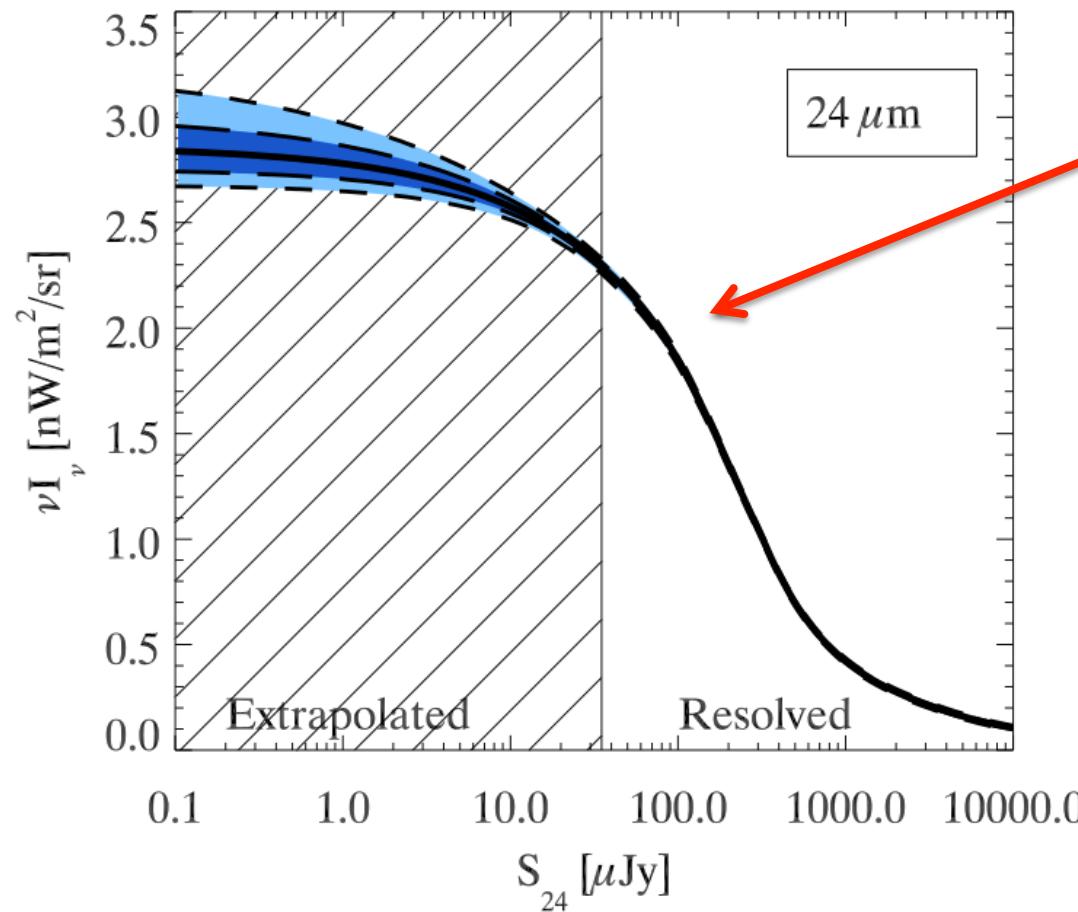
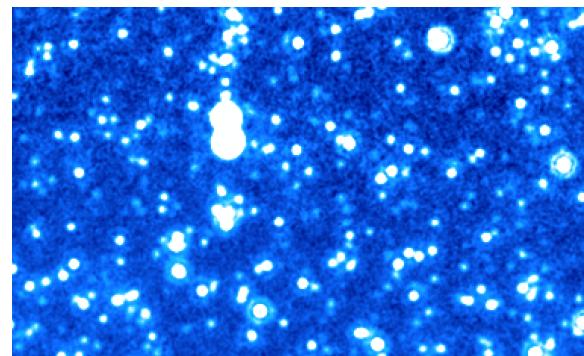


HESS Collab., 2013, A&A

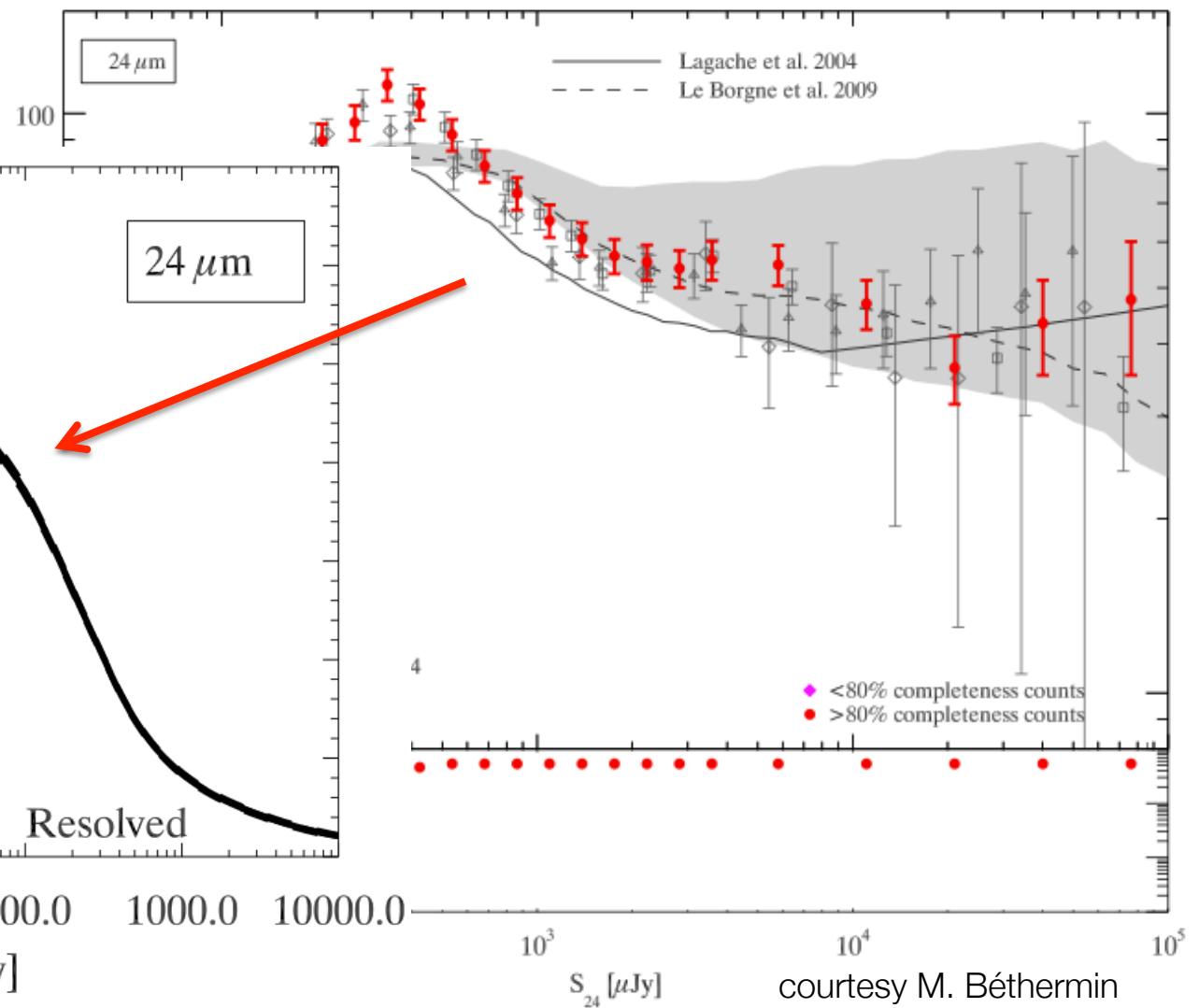
3.5 number counts – lower limits



3.5 number counts – lower limits



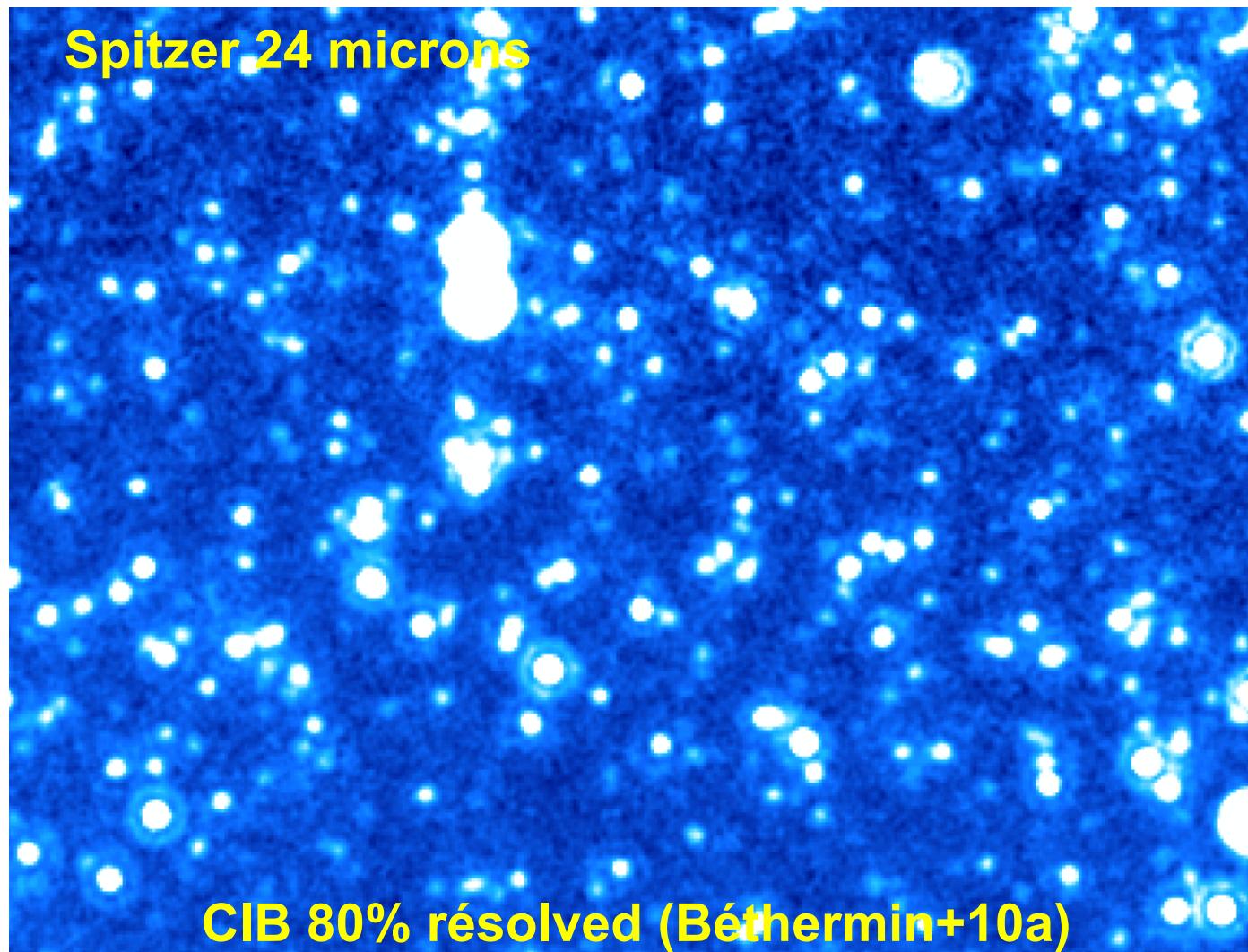
Galaxy number counts at 24 microns (Béthermin+10a)



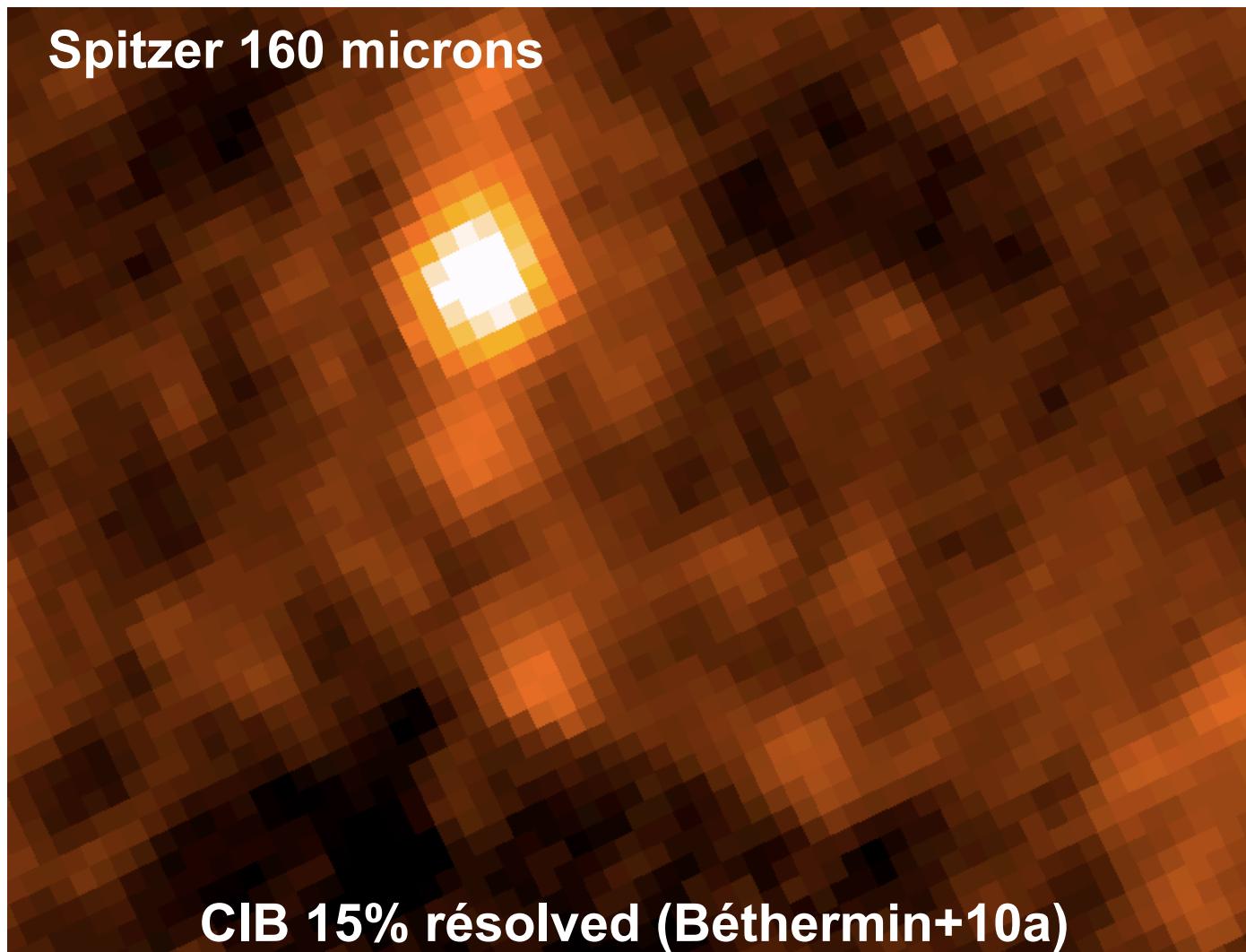
3.6 going deeper ! stacking

- or other statistical tool, like $P(D)$

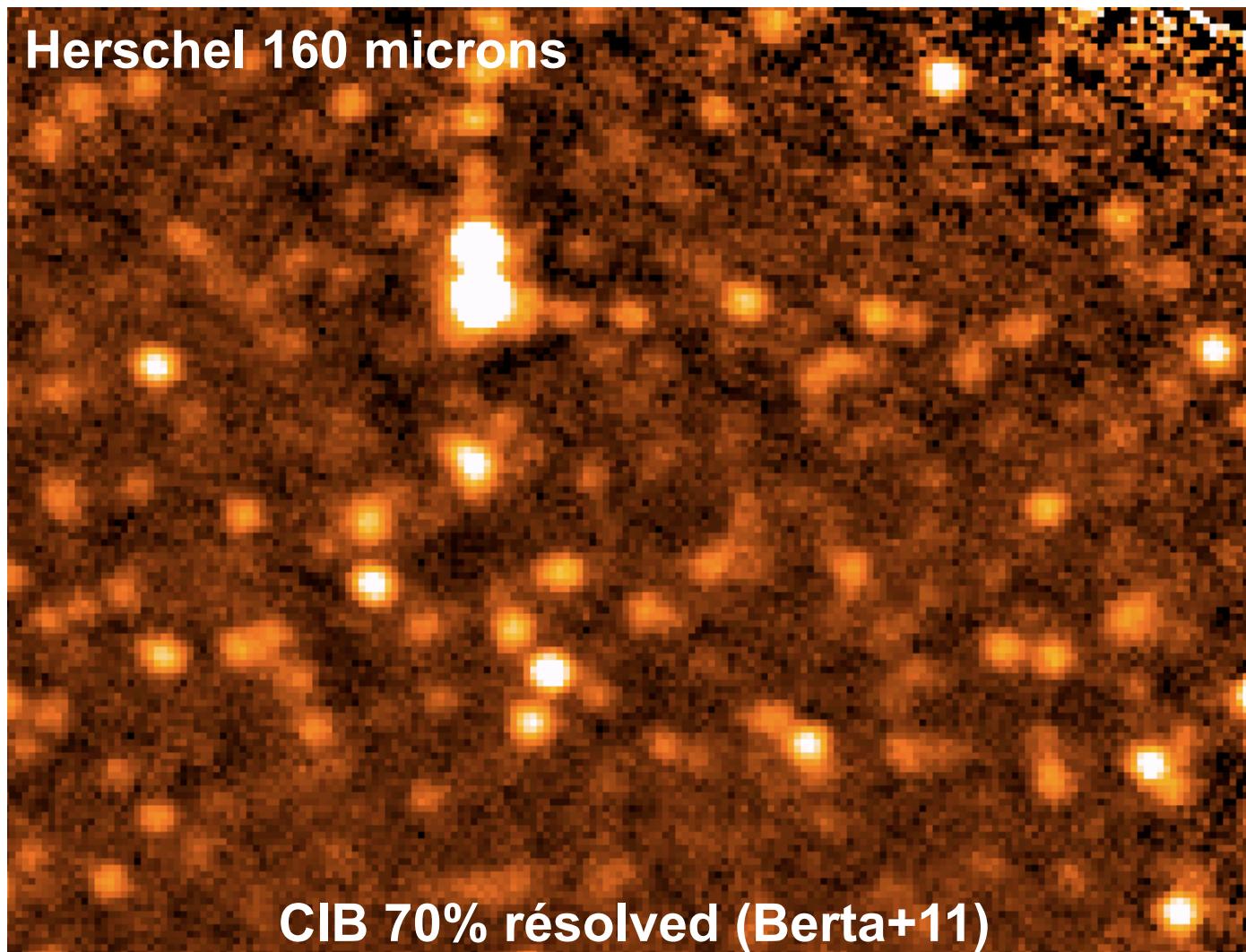
resolving the CIB: confusion



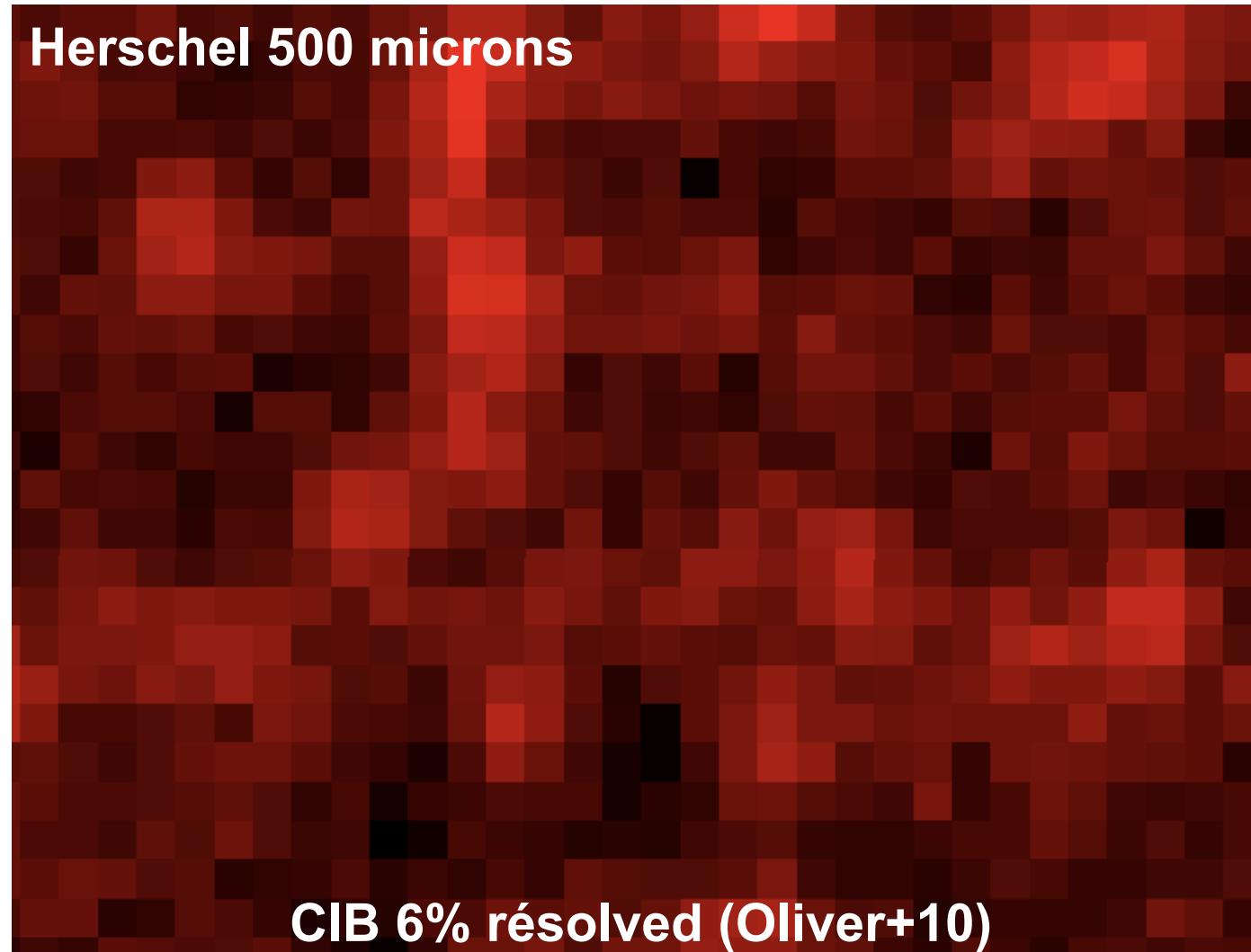
resolving the CIB: confusion



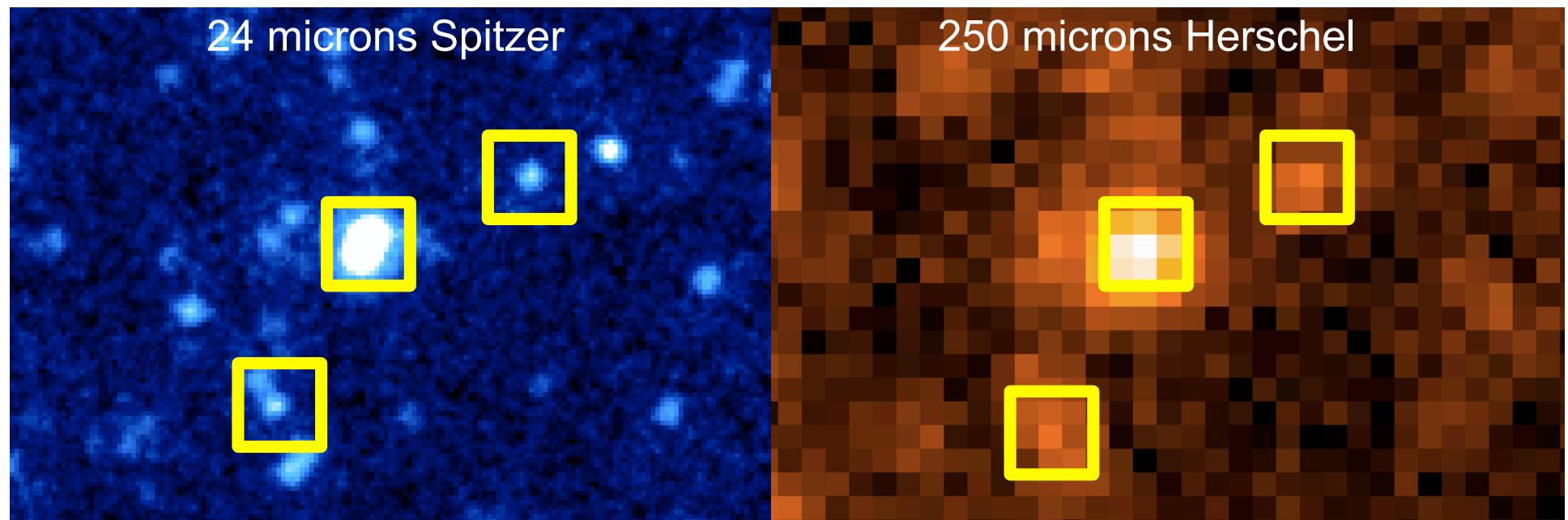
resolving the CIB: confusion



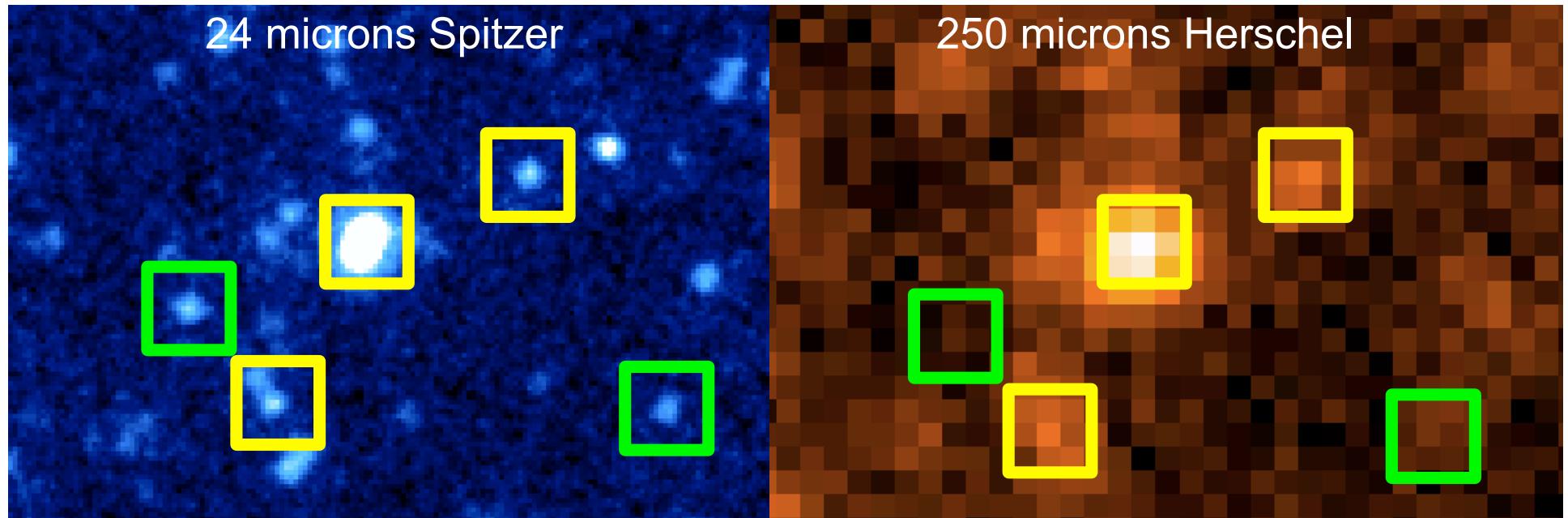
resolving the CIB: confusion



using the 24 micron observations as a prior



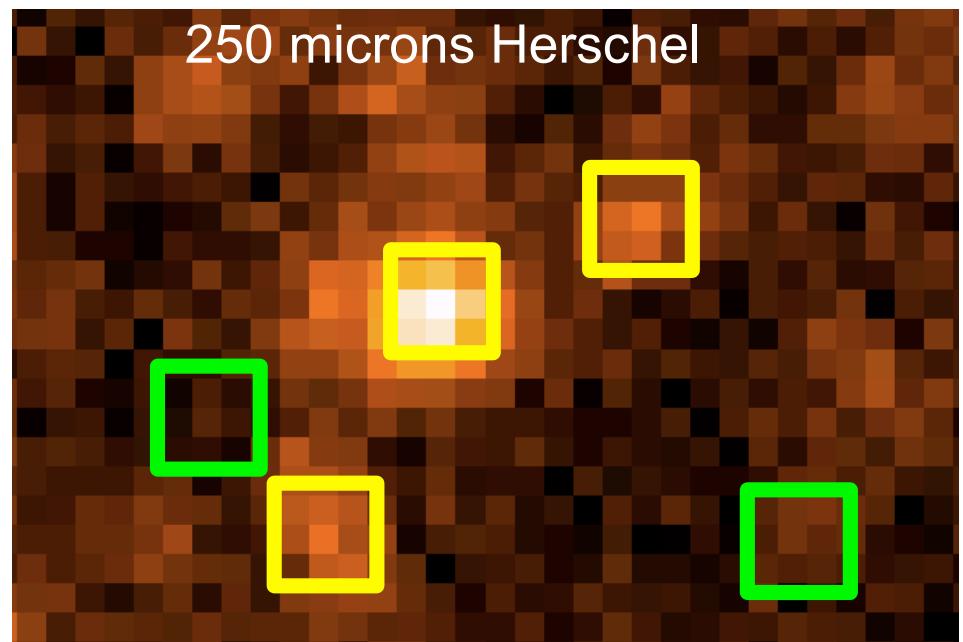
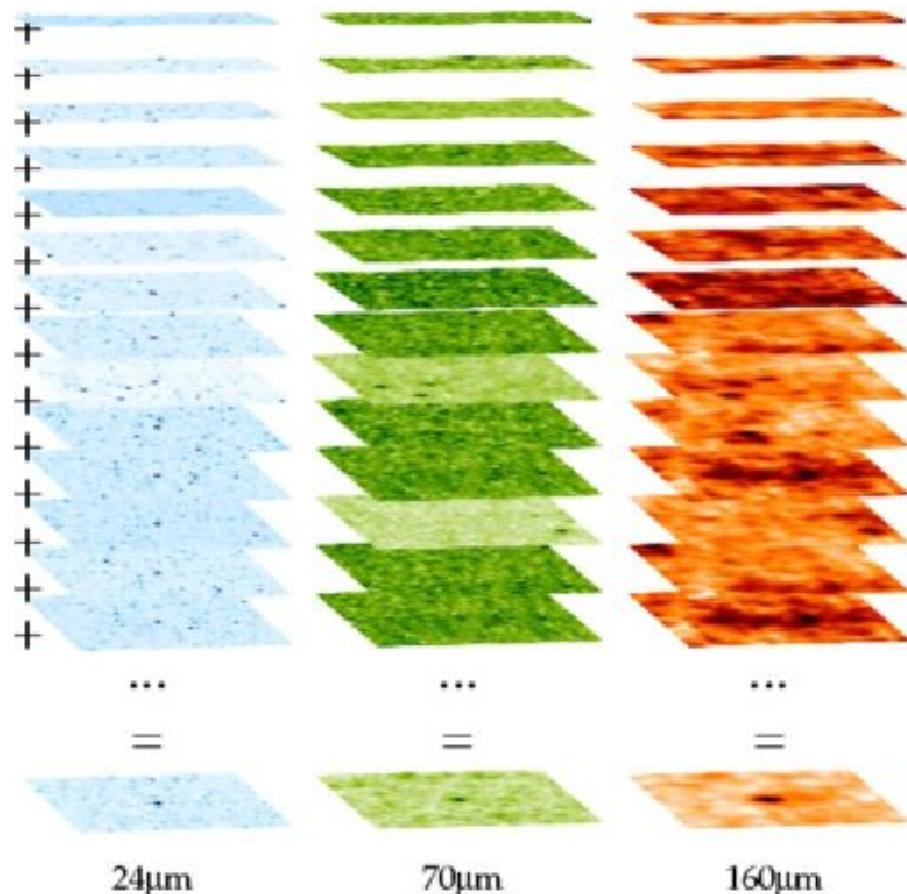
using the 24 micron observations as a prior



Using the 24 micron observations as a prior

MIPS Stacking Analysis

Dole et al., 2006



stacking: resolving the CIB at its peak

The Cosmic Infrared Background resolved by Spitzer

H. Dole et al. (2006)

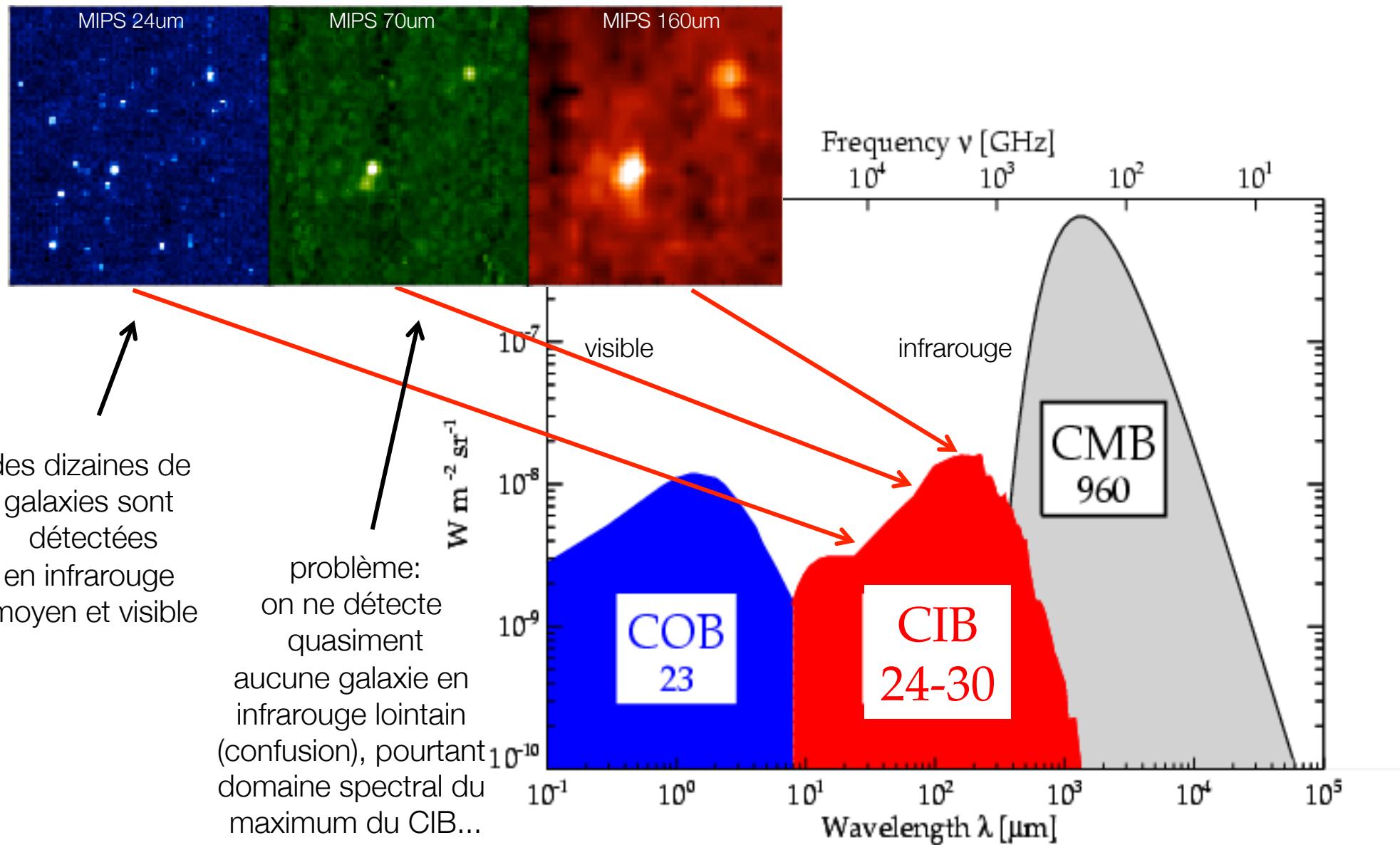
Institut d'Astrophysique Spatiale, Université Paris-Sud 11, CNRS

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

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

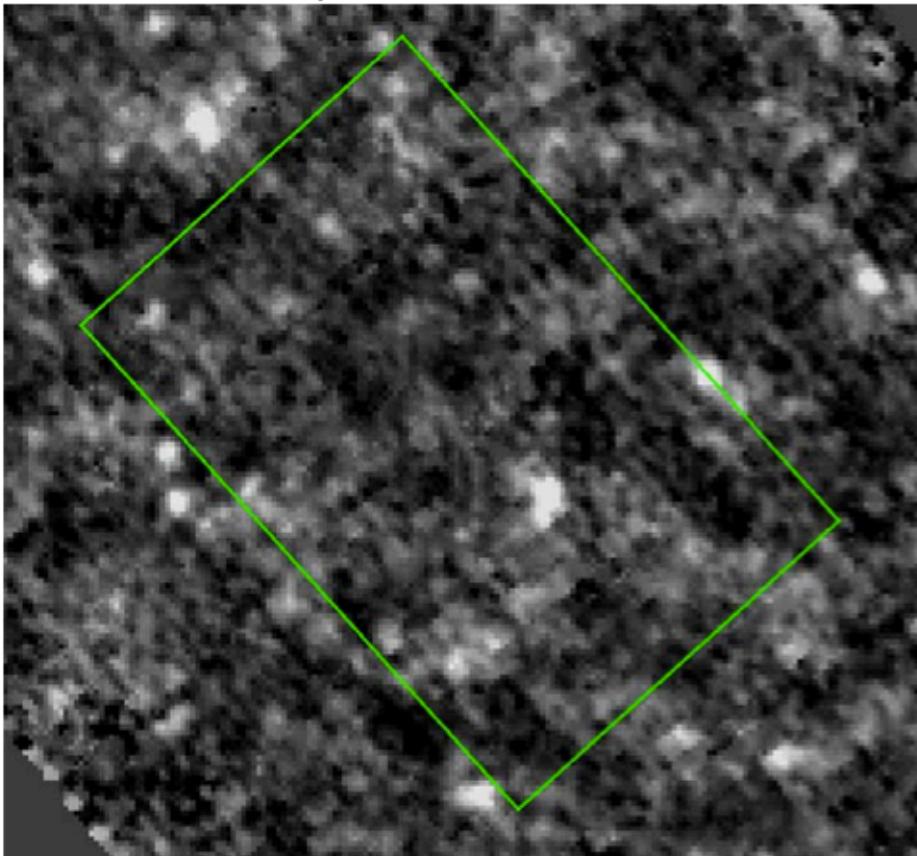
Dole et al., 2006

why is it interesting / needed ?

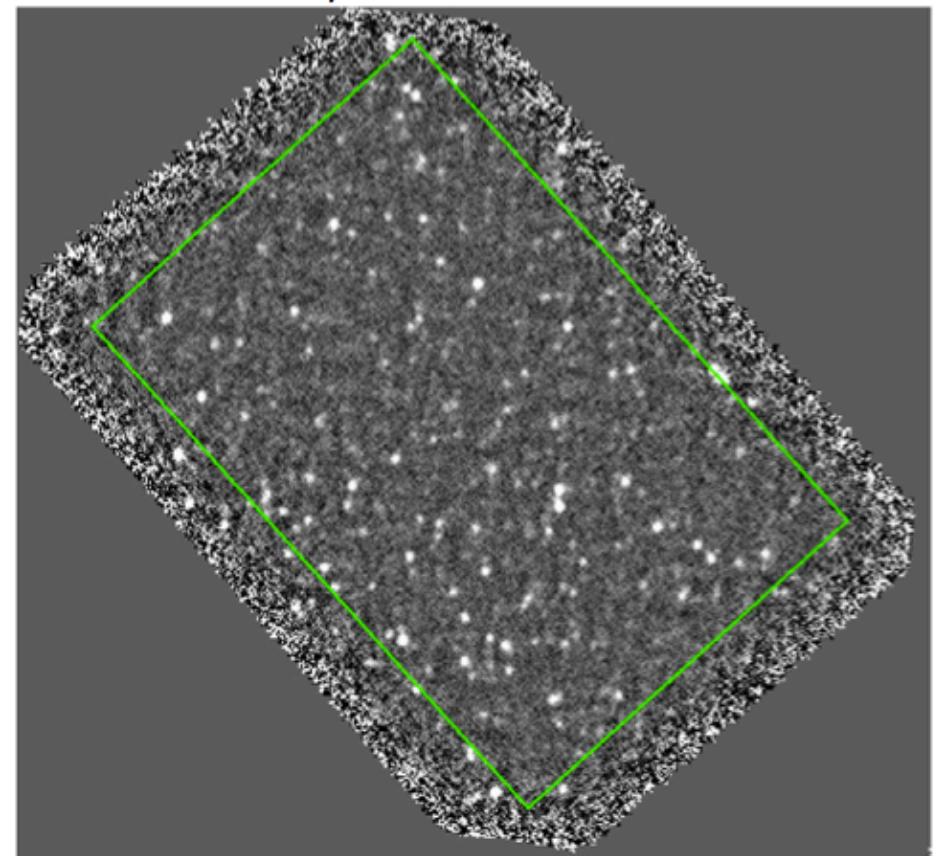


CIB almost resolved in galaxies

GOODS-N 160 μ m



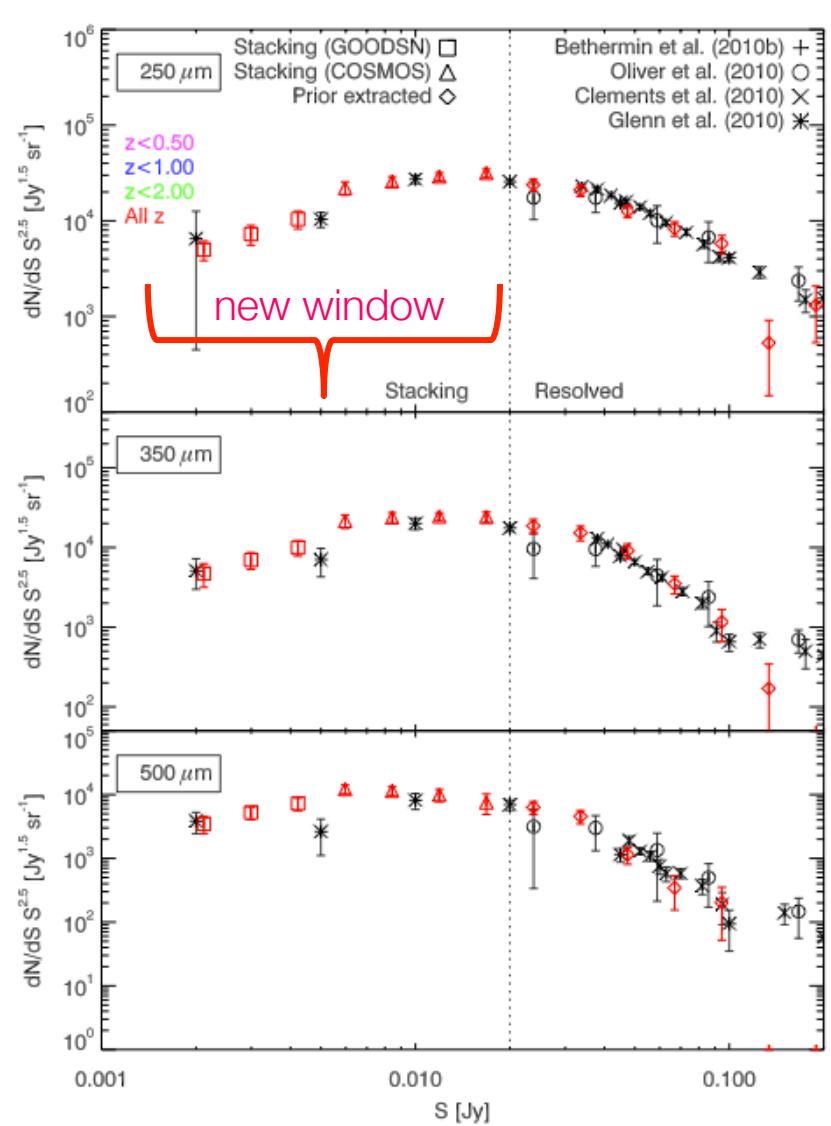
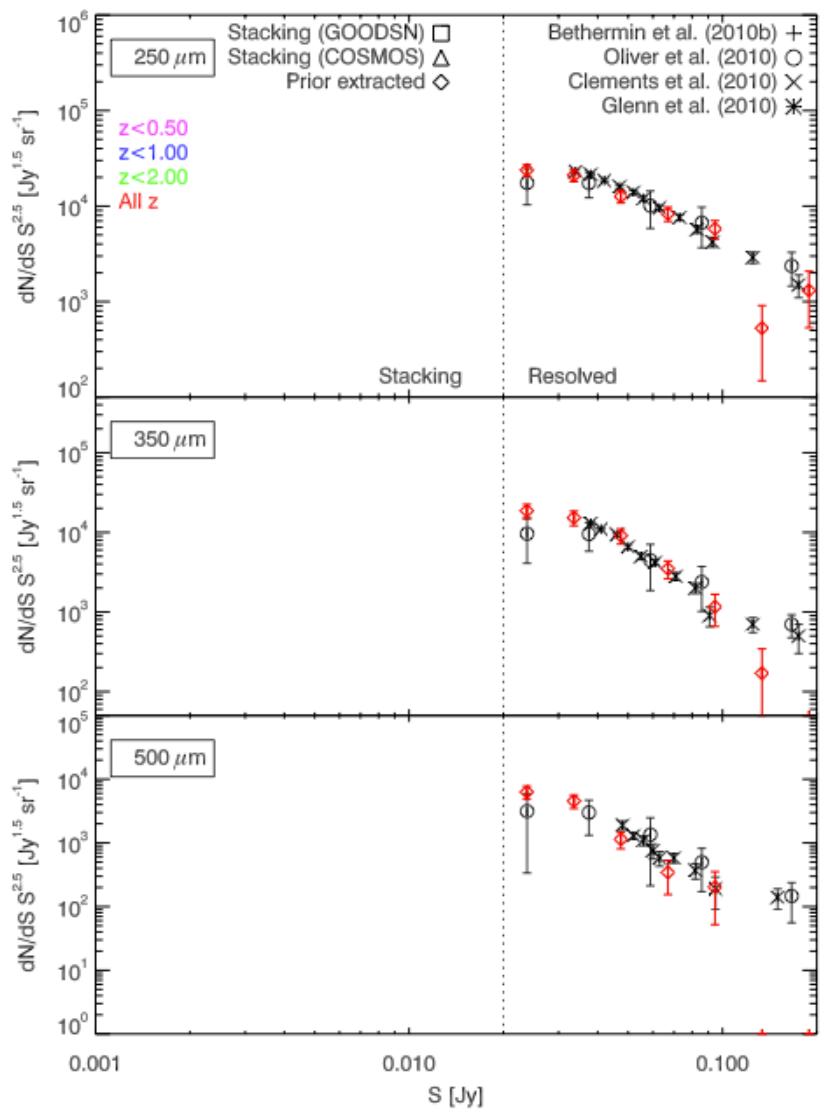
GOODS-N 160 μ m



Spitzer MIPS 160um
FIDEL
2005

Herschel PACS 160um
PEP
2010

stacking – statistical studies



recent works w/ Spitzer & Herschel

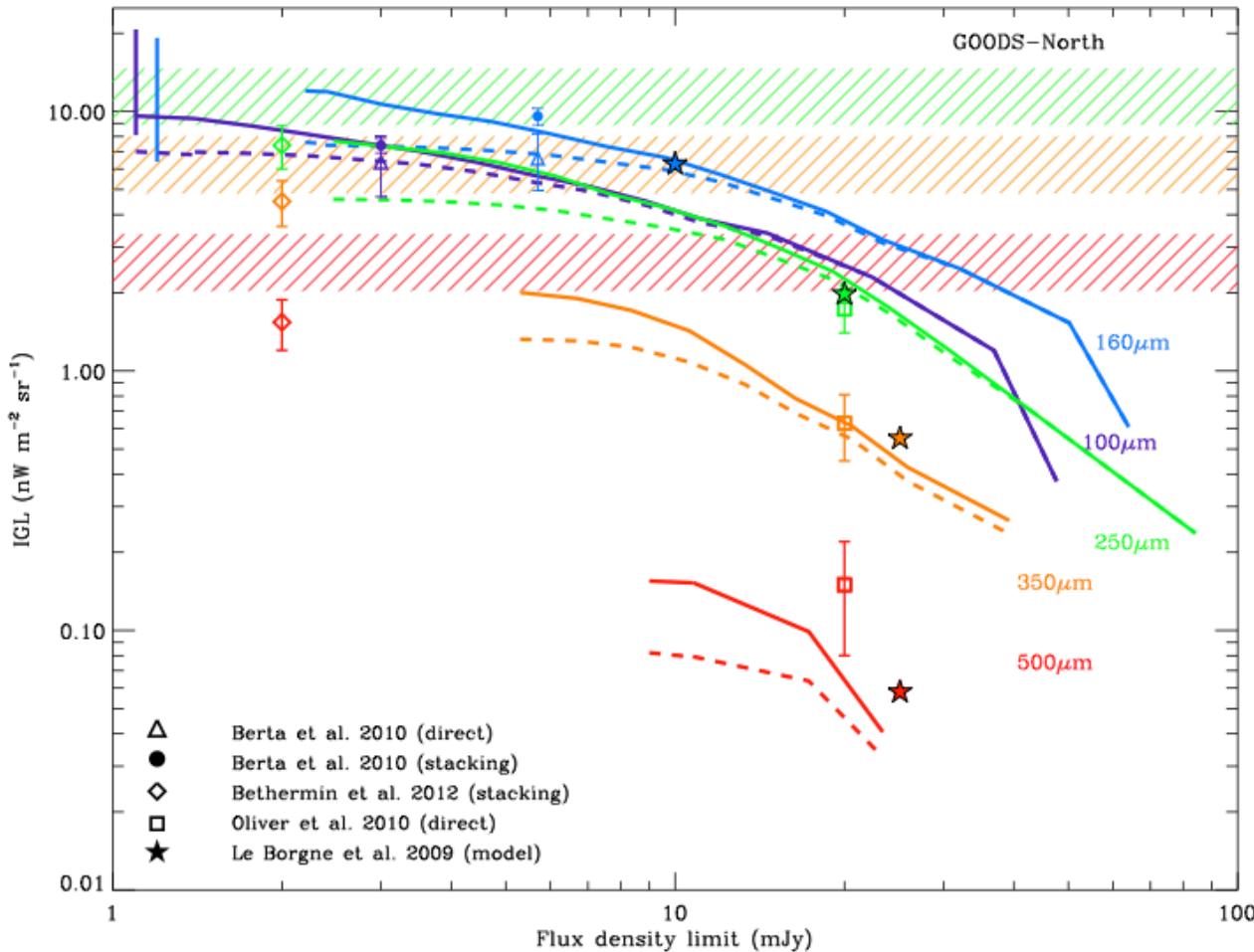


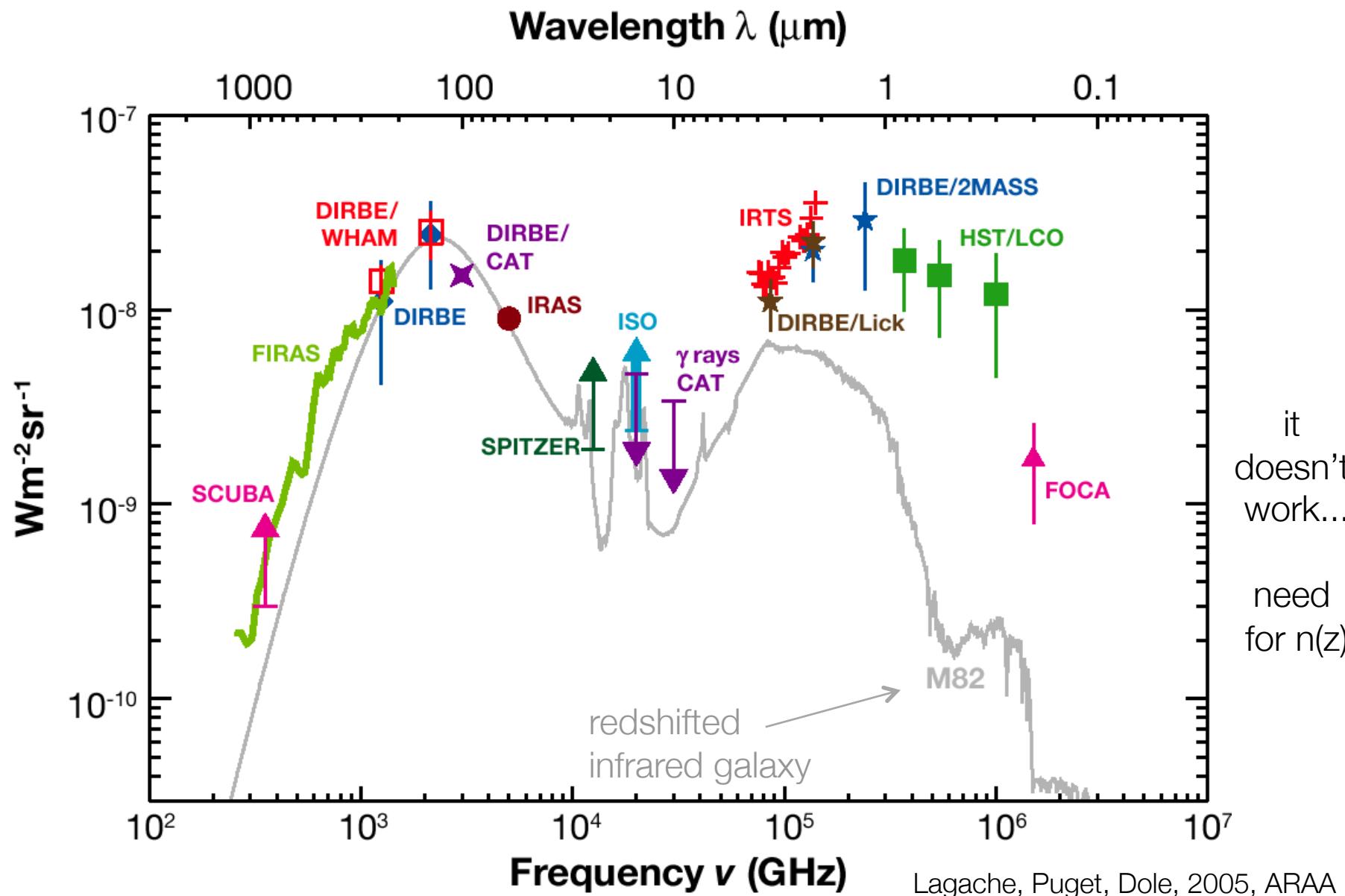
Fig. 11. Cumulative contribution to the CIRB of the IGL as function of the flux density limit in 100 μm (violet), 160 μm (blue), 250 μm (green), 350 μm (orange) and 500 μm (red) in the GOODS north field. *Dashed lines* show the cumulative flux density directly from the observed *GOODS-Herschel* sources and the *solid lines* are the same but corrected by completeness from the simulations in this work. Resolved and stacked results at different adopted S_{lim} are also shown for comparison (Berta et al. 2010; Oliver et al. 2010; Béthermin et al. 2012) as well as IGL predictions for *Herschel* based on a model of multi-wavelength galaxy counts (Le Borgne et al. 2009). Horizontal dashed bands show the total CIRB in the SPIRE bands adopted from Lagache et al. (2000) using the same colour coding than for the curves and their widths represent the limits of the errors. In the case of PACS absolute measurements, vertical bars mark the error in the estimations of Dole et al. (2006) for 100 μm and Berta et al. (2010) for the extrapolated 160 μm .

summary of measurements

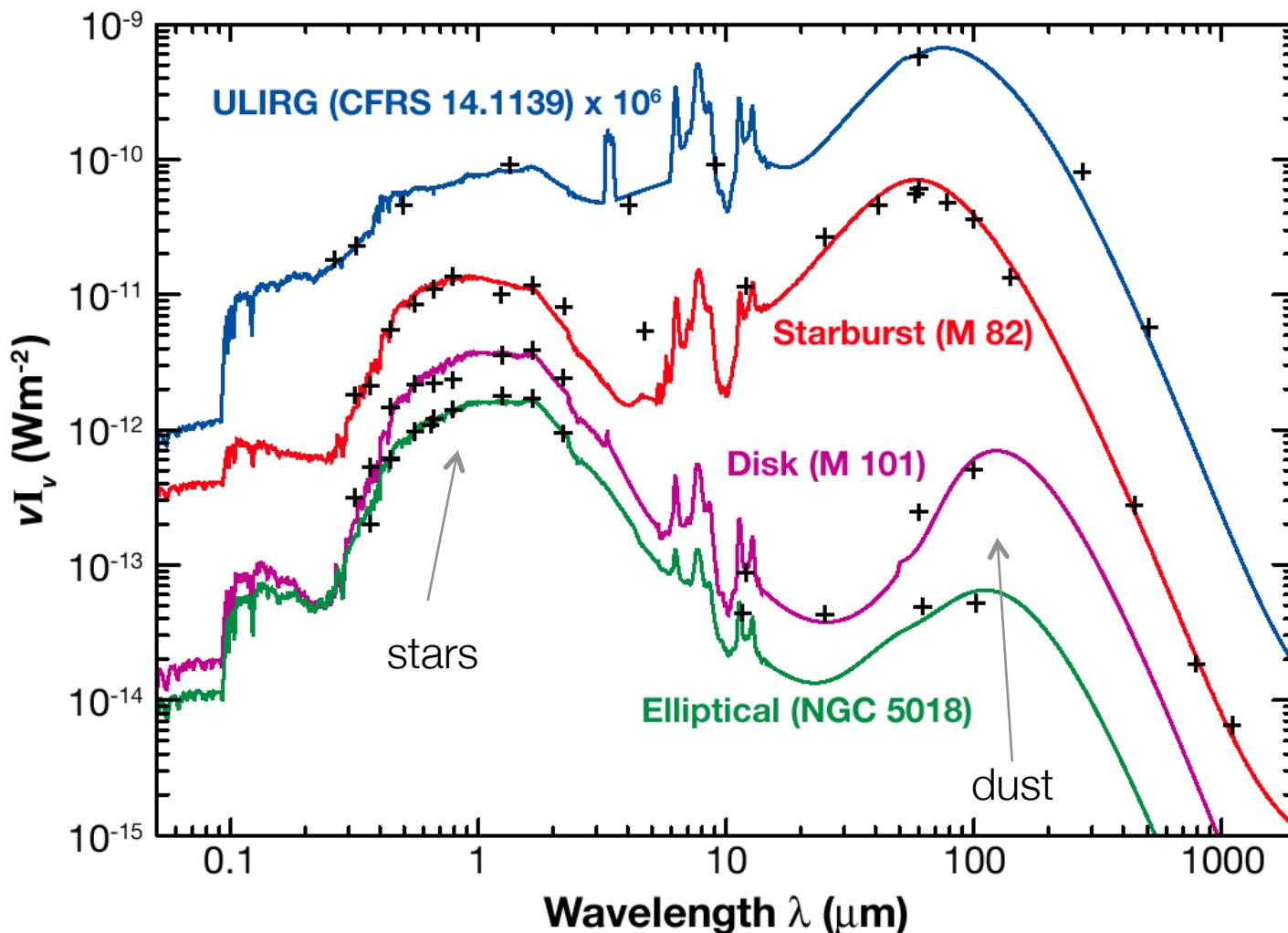
- very difficult
 - absolute (the most difficult ?)
 - γ -rays absorption (model dependant ?)
 - galaxy counts (easy but less constraining)
 - stacking / P(D) / extrapolations (model dependant ?)
-
- CIB SED fairly well constrained (better than 50%)
 - NIR still in debate
 - submm still at ~50% uncertainty
 - not resolved into individual galaxies e.g. at >300um

4. EBL, galaxy populations and models

4.1 trying to fill the CIB SED w/ galaxy SED...



different spectral types of galaxies



le rapport:

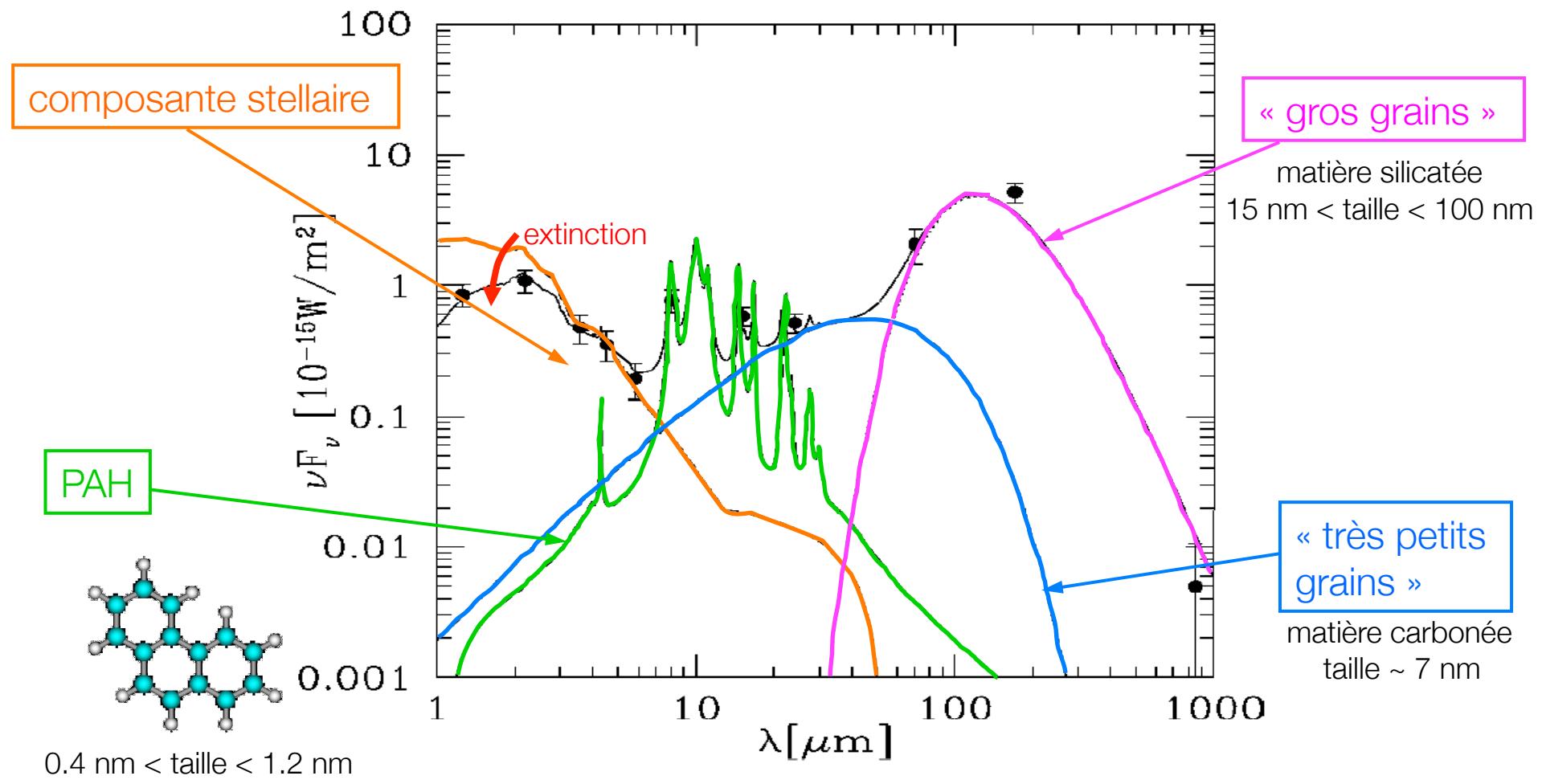
[UV+visible] /
infrarouge

varie selon le
type de galaxie

pourquoi de
telles
différences ?

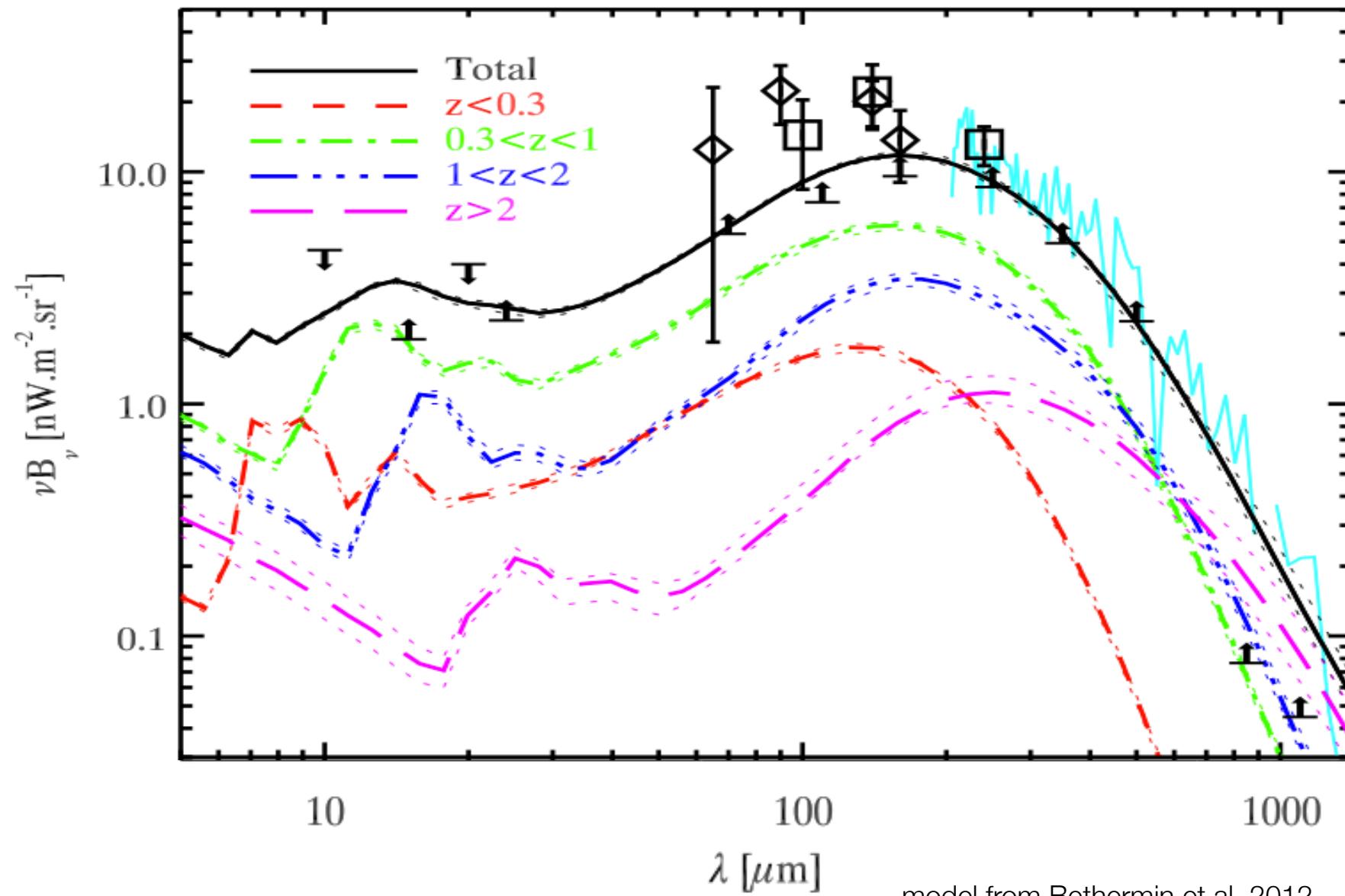
Galliano, dans Lagache, Puget, Dole, 2005, ARAA

galaxies: SED comes from stars and dust

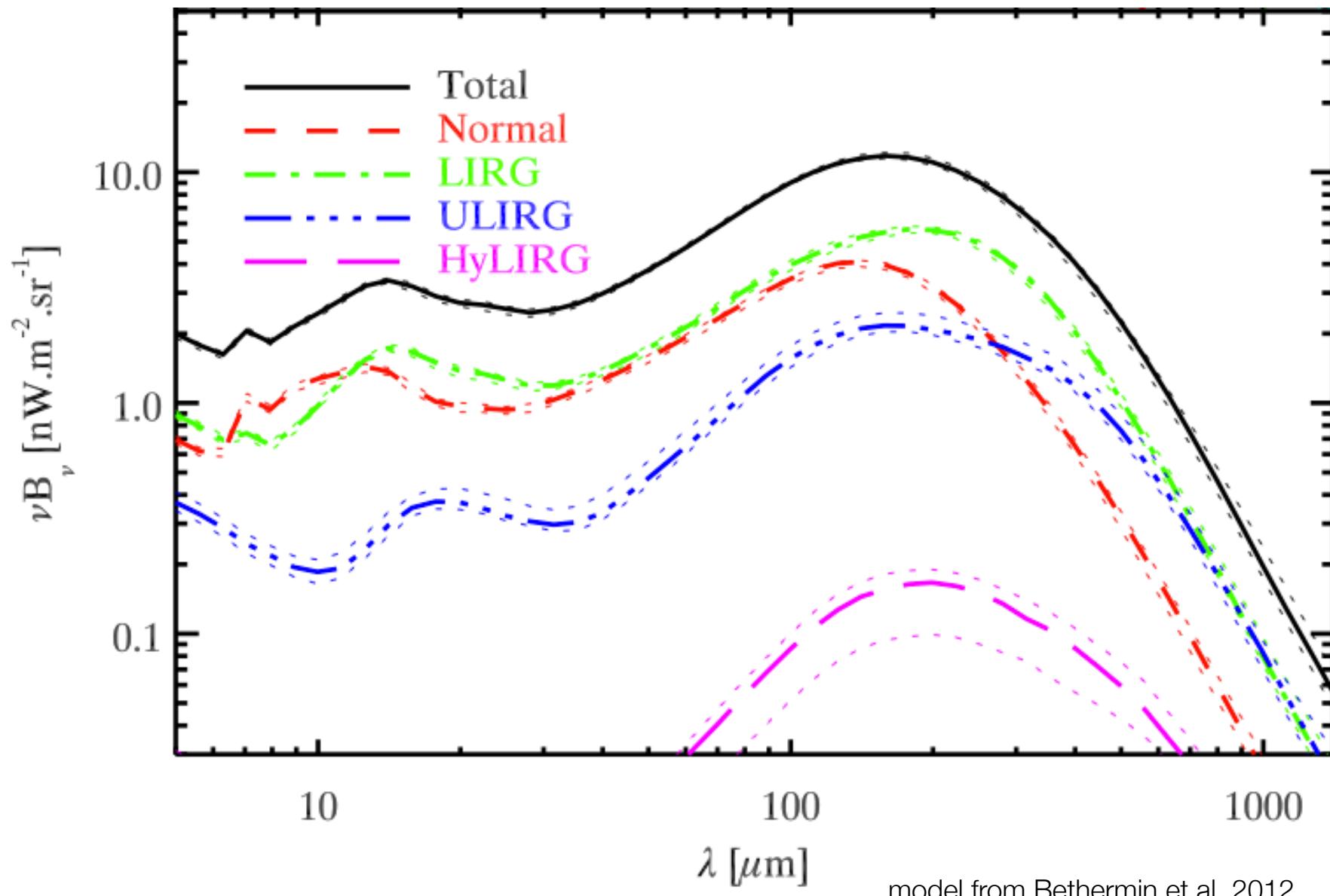


Sajina et al., 2006
Courtesy of N. Bavouzet

CIB SED and contributions: redshift



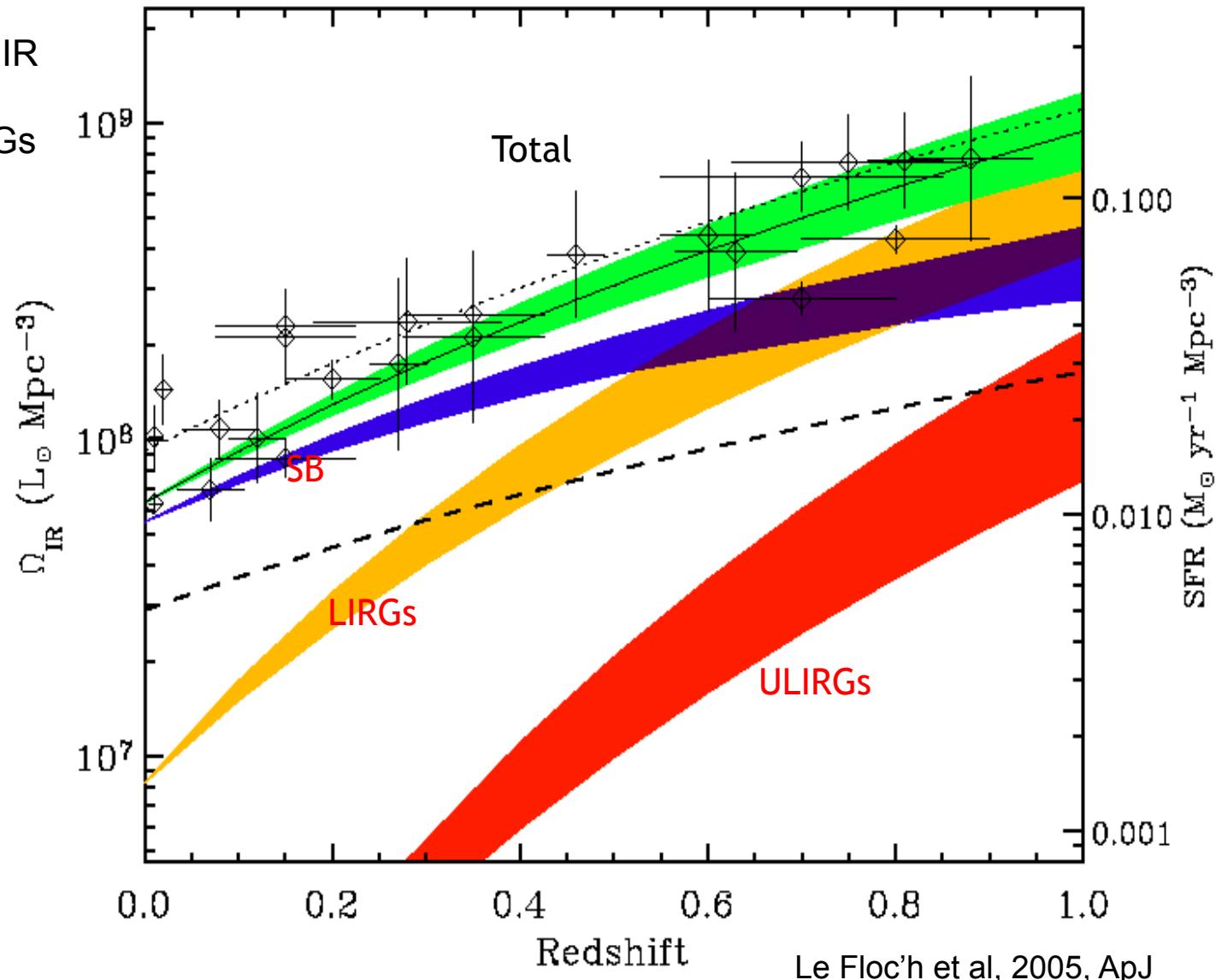
CIB SED and contributions: type



luminosity function evolution

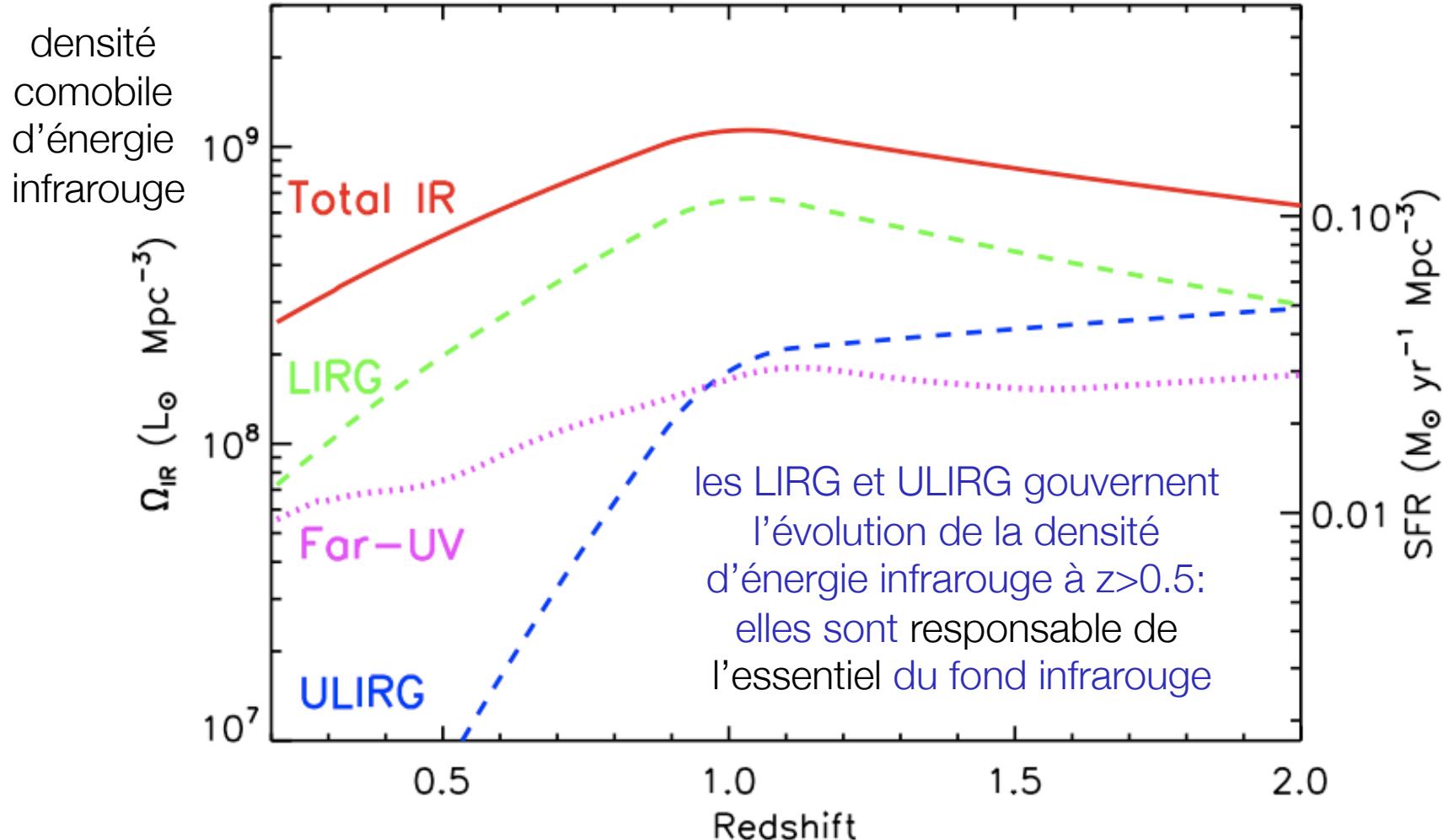


At $z \sim 1$, ~70% of IR energy density comes from LIRGs



Le Floc'h et al, 2005, ApJ

l'apport de Spitzer



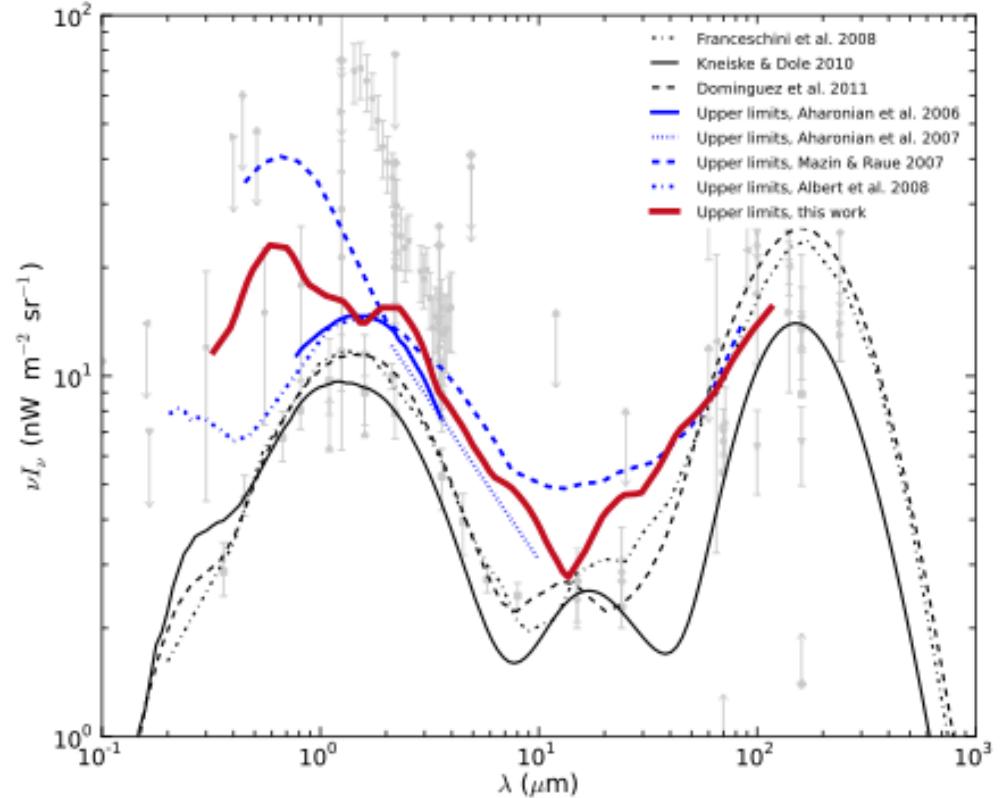
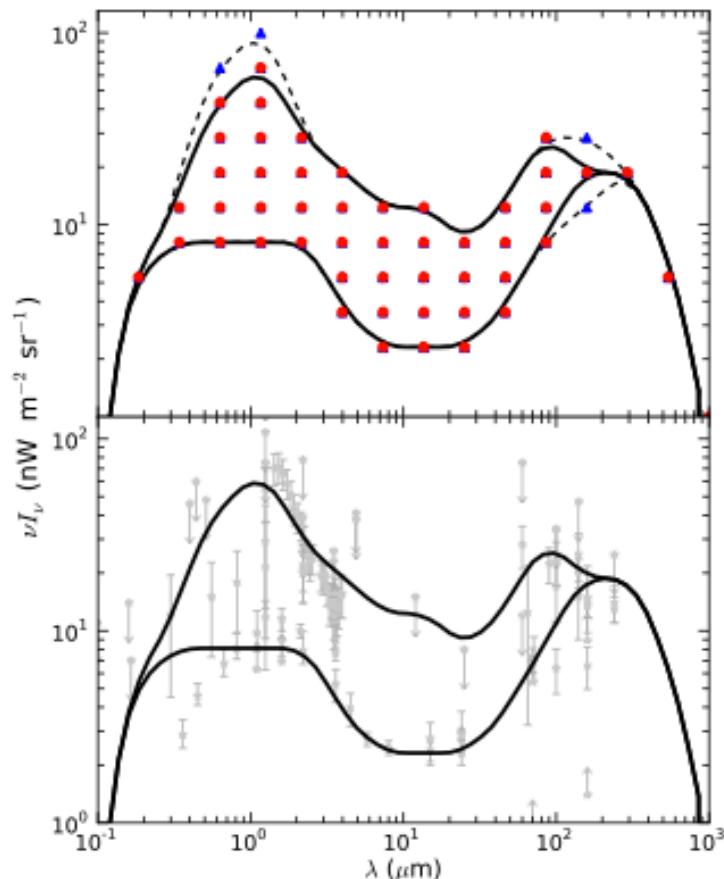
courtoisie de G. Lagache,
adapté de Caputi et al. (2007), Tresse et al. (2007), Le Floc'h (2005)

4.2 many models

2 ingredients:

-library of galaxies SED

-evolution with redshift of the luminosity function



Primack; Stecker; Franceschini; Kneiske & Dole; Raue; Mazin; Mayer;
Dominguez; Lagache; Béthermin; Chary & Elbaz; Cai; etc..

implications for TeV opacity

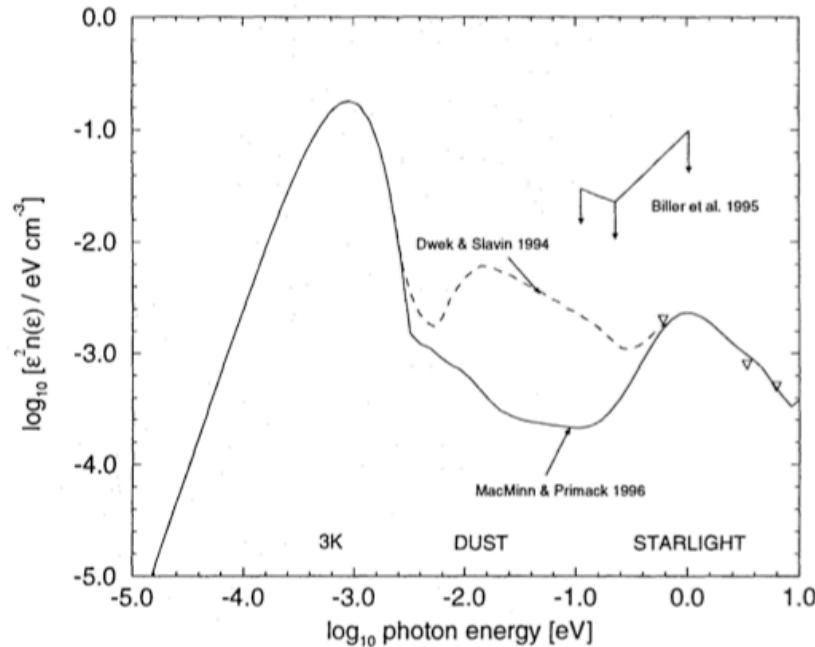


Fig. 2. Solid line: the infrared-to-ultraviolet diffuse background radiation field adopted in the present work. Dashed line: a diffuse background assuming that the γ -ray spectrum of Mrk421 cuts off at TeV due to cosmic absorption. Triangles denote estimates by Madau & Phinney (1996) of the optical-to-ultraviolet diffuse background based on deep galaxy surveys

Different EBL (level and history)
create different gamma-ray horizon

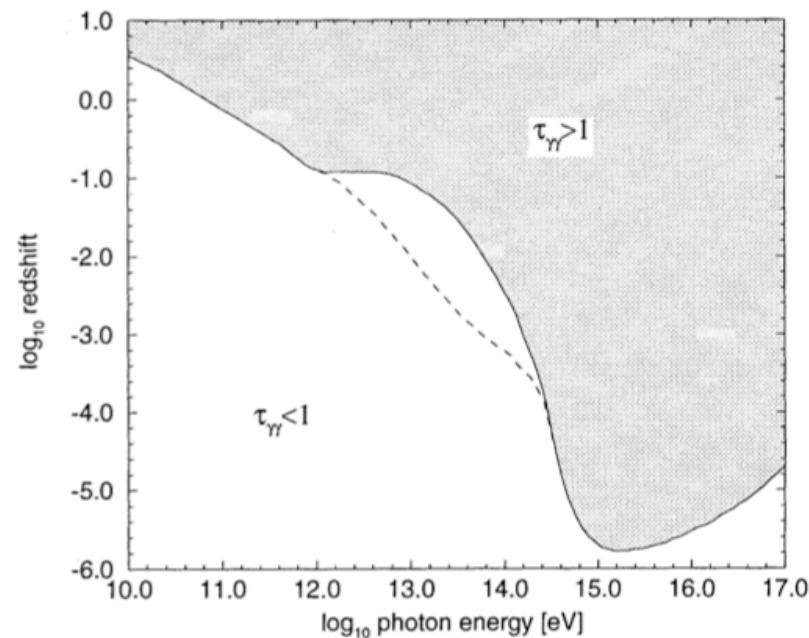


Fig. 1. The γ -ray horizons $\tau_{\gamma\gamma}(E, z) = 1$ corresponding to the two different diffuse background models shown in Fig. 2. The horizons were calculated assuming $\Omega = 1$, $q_0 = 0.5$, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a photon number density evolving with redshift as $n'de' = (1 + z)^3 nd\epsilon$ (conserved number of photons)

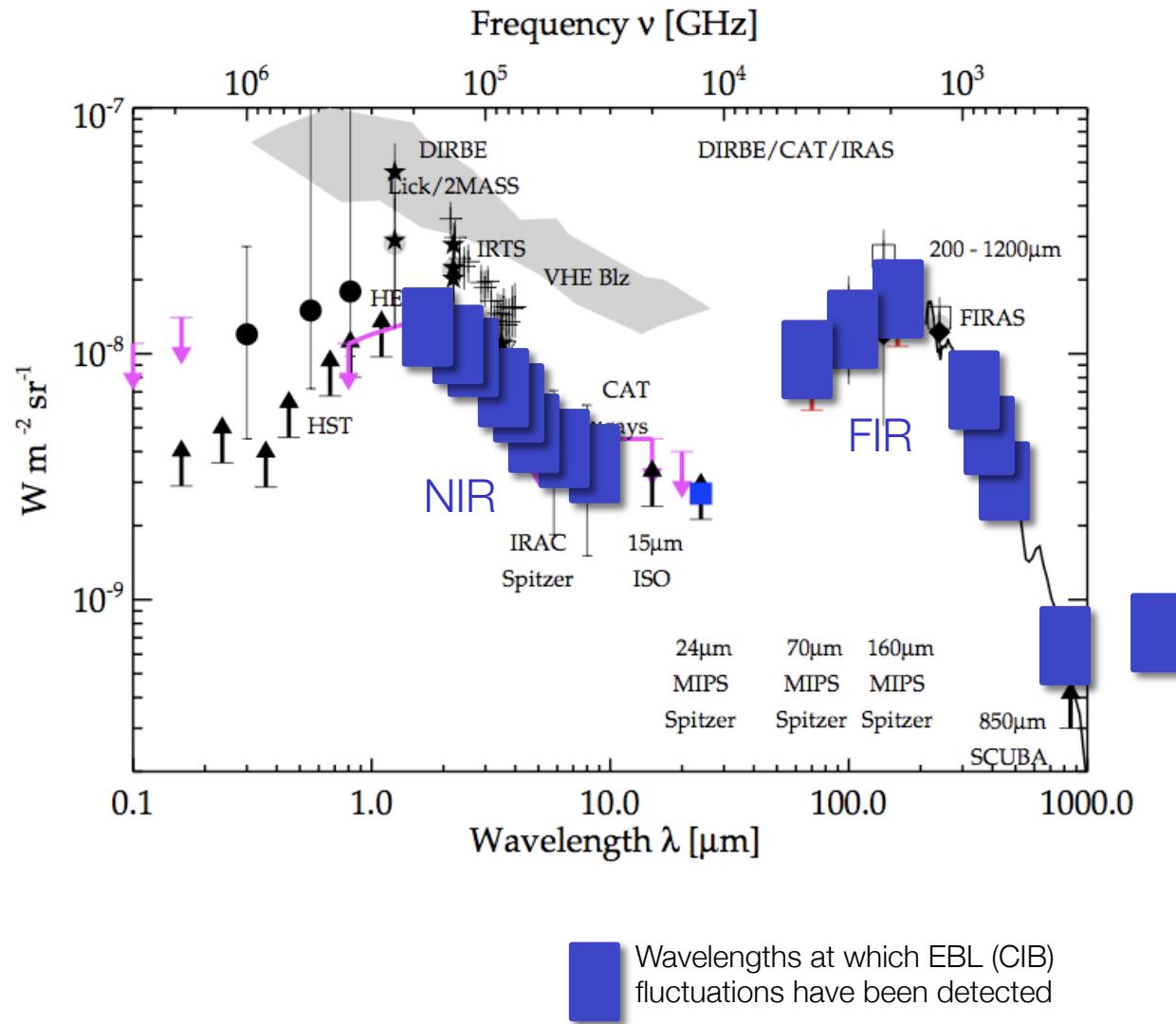
Mannheim et al., 1996

5. CIB fluctuations

infrared background fluctuations

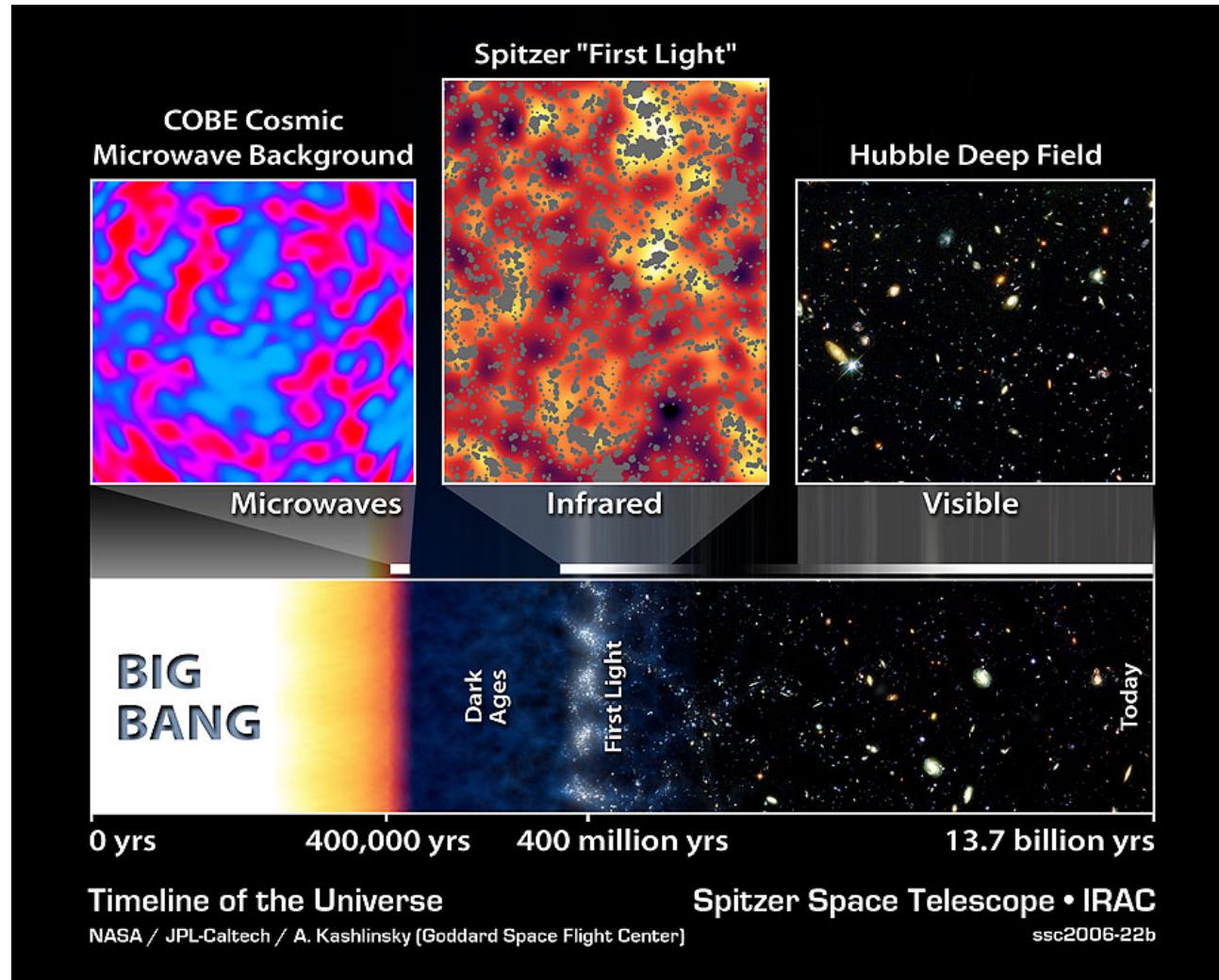
Detections:

- mm: Hall et al., 2010 SPT
- HFI: Planck collab, 2011,13
- 250, 350, 500um: Marsden; Viero; Amblard; BLAST; Herschel;
- 170um: Lagache & Puget, 2000, ISOPHOT
- 160um: Lagache et al., 2007, Spitzer
- 100um & 60um: Miville-Deschénes, Lagache, Puget, 2002, IRAS
- 3.6, 4.5, 5.8, 8.0um: IRAC Kashlinsky et al
- 1.25, 2.2, 3.5, 5um: Kashlinsky & Odenwald, 2000, DIRBE
- 1.6um: Thompson et al. 2007, NICMOS
- 1.4-2.4um: Matsumoto et al., 2004, IRTS
- J, H, K (1.25, 1.65, 2.17um): Kashlinsky et al. 2002 & Odenwald et al., 2003, 2MASS



NIRB fluctuations: $z < 2$ or $z > 6$ or popIII ?

Kashlinsky et al., 2007, ApJ

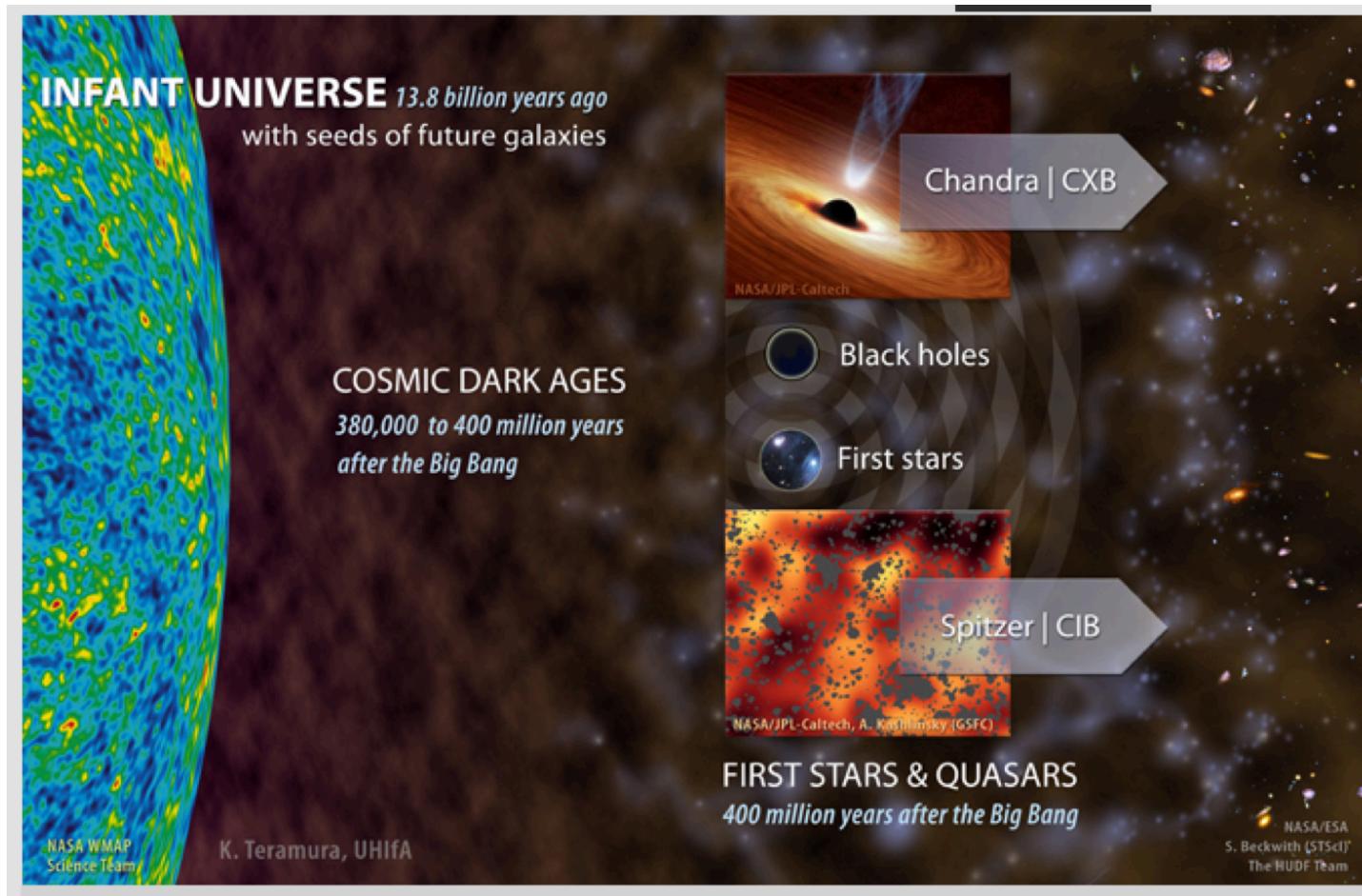


until recently there was controversy...

papers by Kashlinsky, or Thompson or Cooray etc

Other prospects for NIRB fluctuations ?

the NIR CIB (Spitzer) and X-ray EBL (Chandra) cross correlation is significant:
 $z > 5$: link btw first stars and first black holes ?



Cappelluti+2012

hierarchical formation

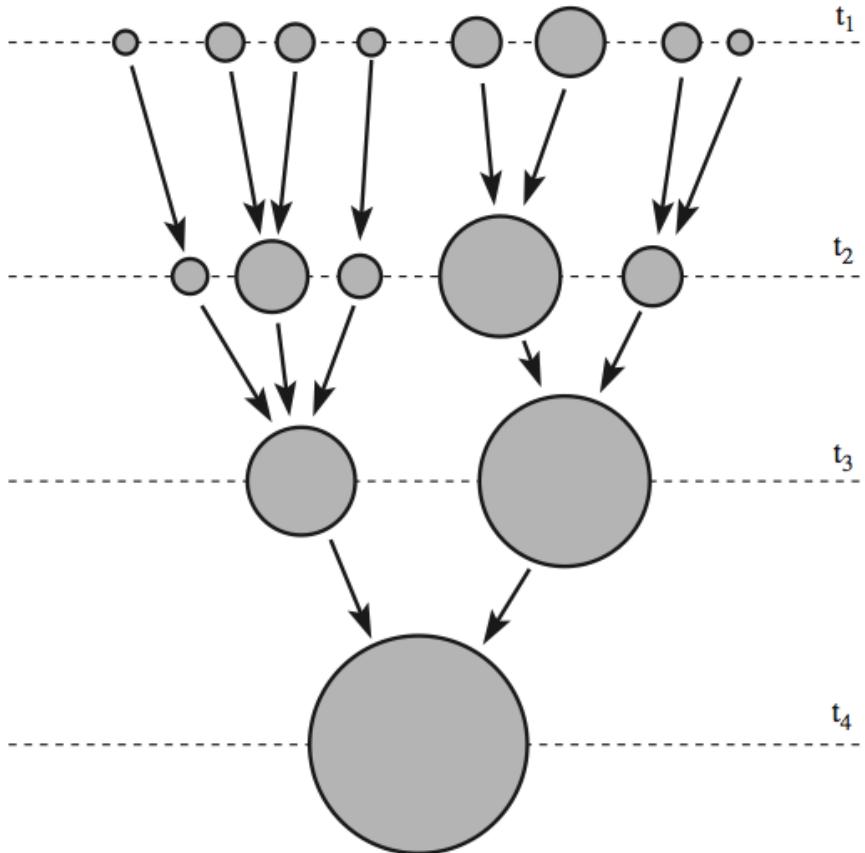


Fig. 1.3. A schematic merger tree, illustrating the merger history of a dark matter halo. It shows, at three different epochs, the progenitor halos that at time t_4 have merged to form a single halo. The size of each circle represents the mass of the halo. Merger histories of dark matter halos play an important role in hierarchical theories of galaxy formation.

Mo, van den Bosch, White fig 1.3

one and two-halo terms

1h term:
number of galaxies
within one halo of a
given mass

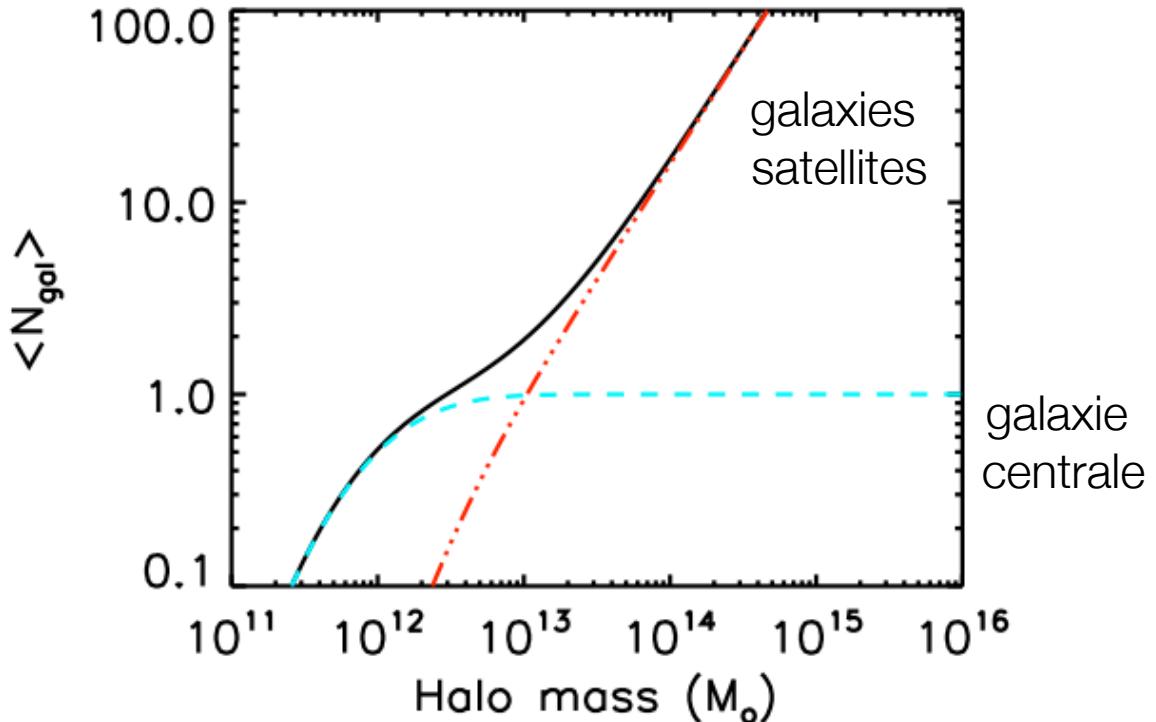
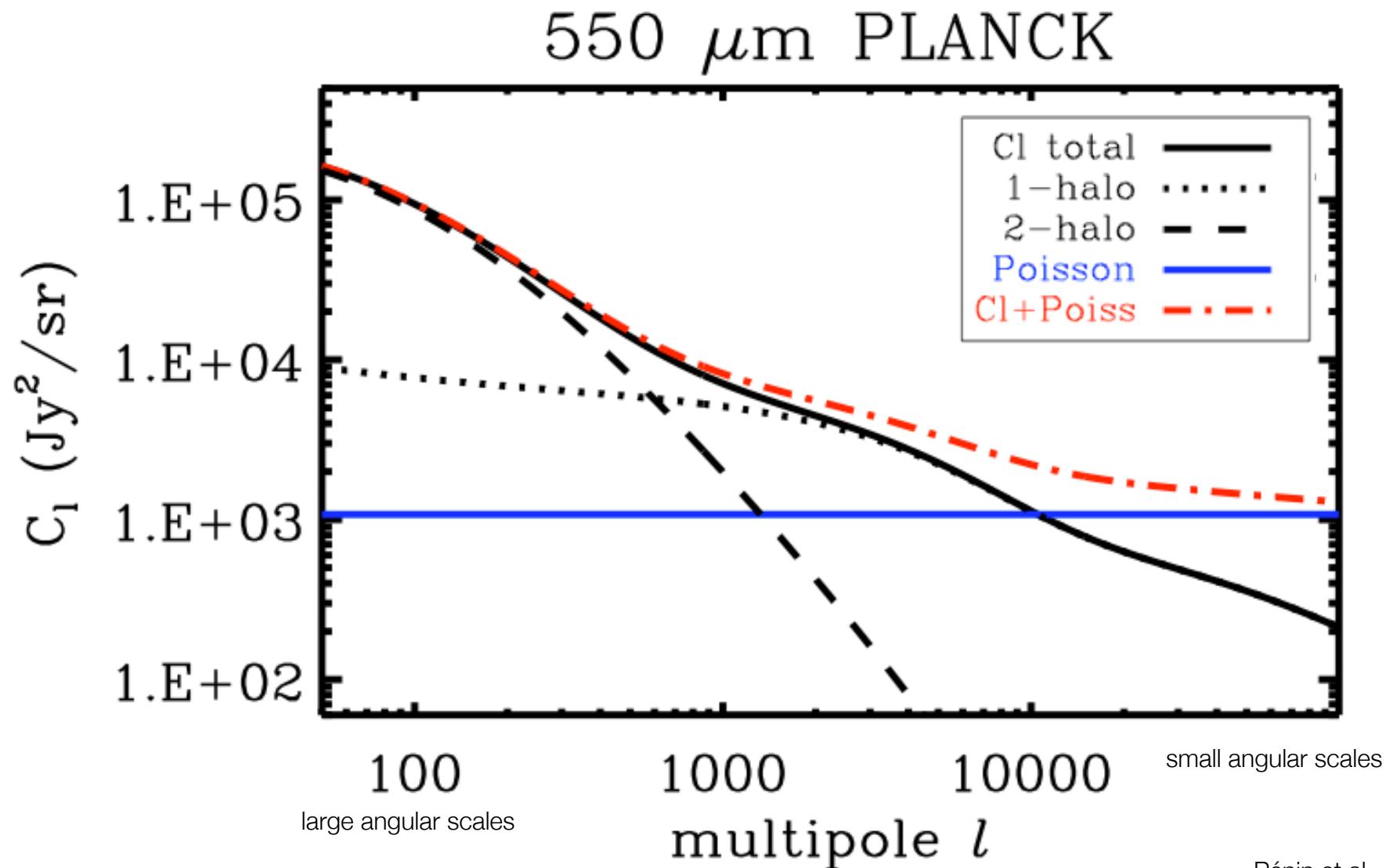


Fig. 3. Number of galaxies versus dark matter halo mass. The blue dashed line shows the central galaxies, the red dotted-dashed line shows satellite galaxies and the black continuous line shows the total. We use the parameters of our fiducial model (see Sect. 4), that is to say $\log M_{\min} = 11.5$, $M_{\text{sat}} = 10M_{\min}$ and $\alpha = 1.4$

Pénin et al., 2012

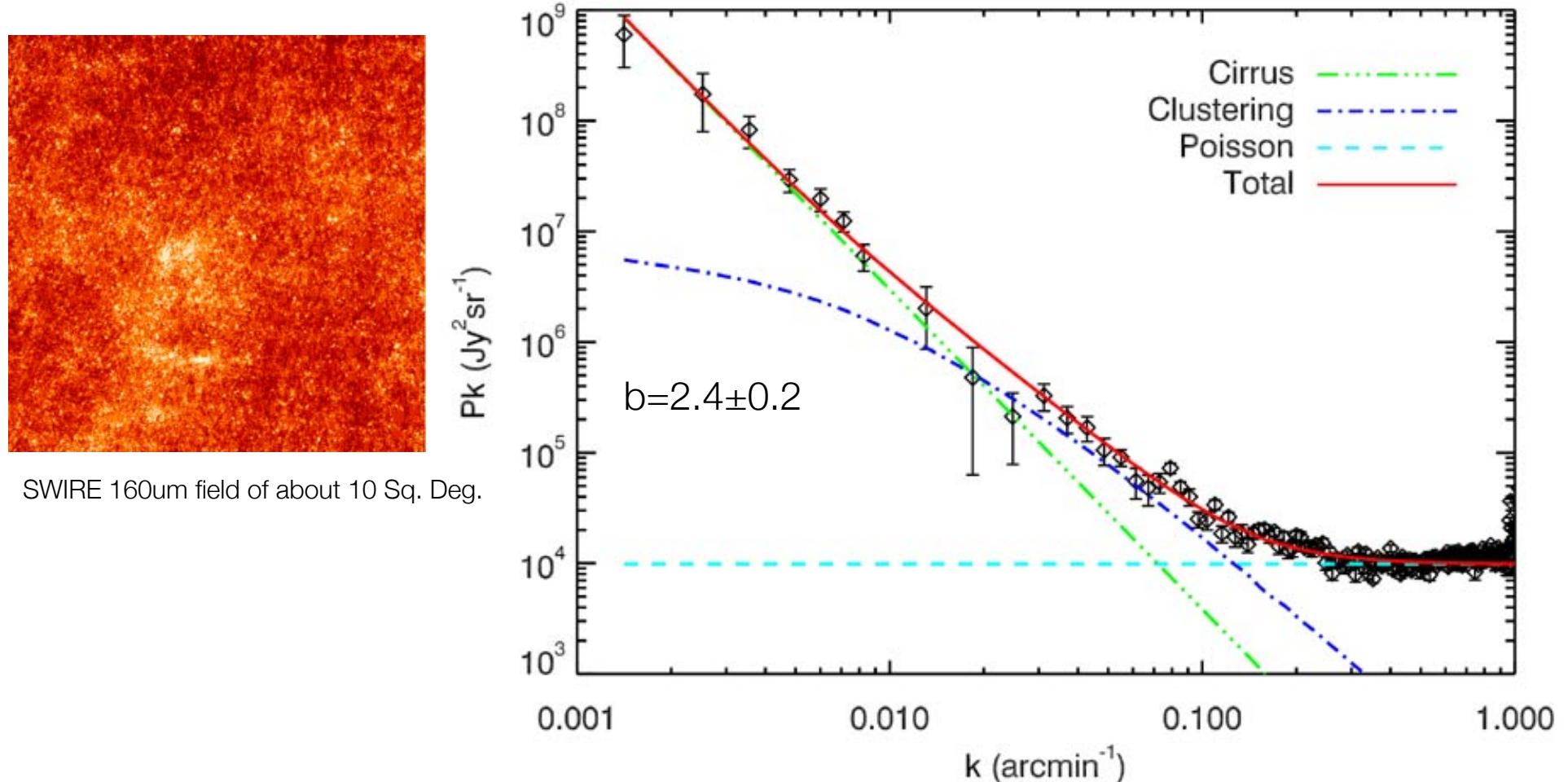
1h and 2h terms



fluctuations of CIB: 160um in 2007

Power Spectrum of CIB fluctuations at 160um.

Fluctuations are dominated by $z \sim 1$ sources



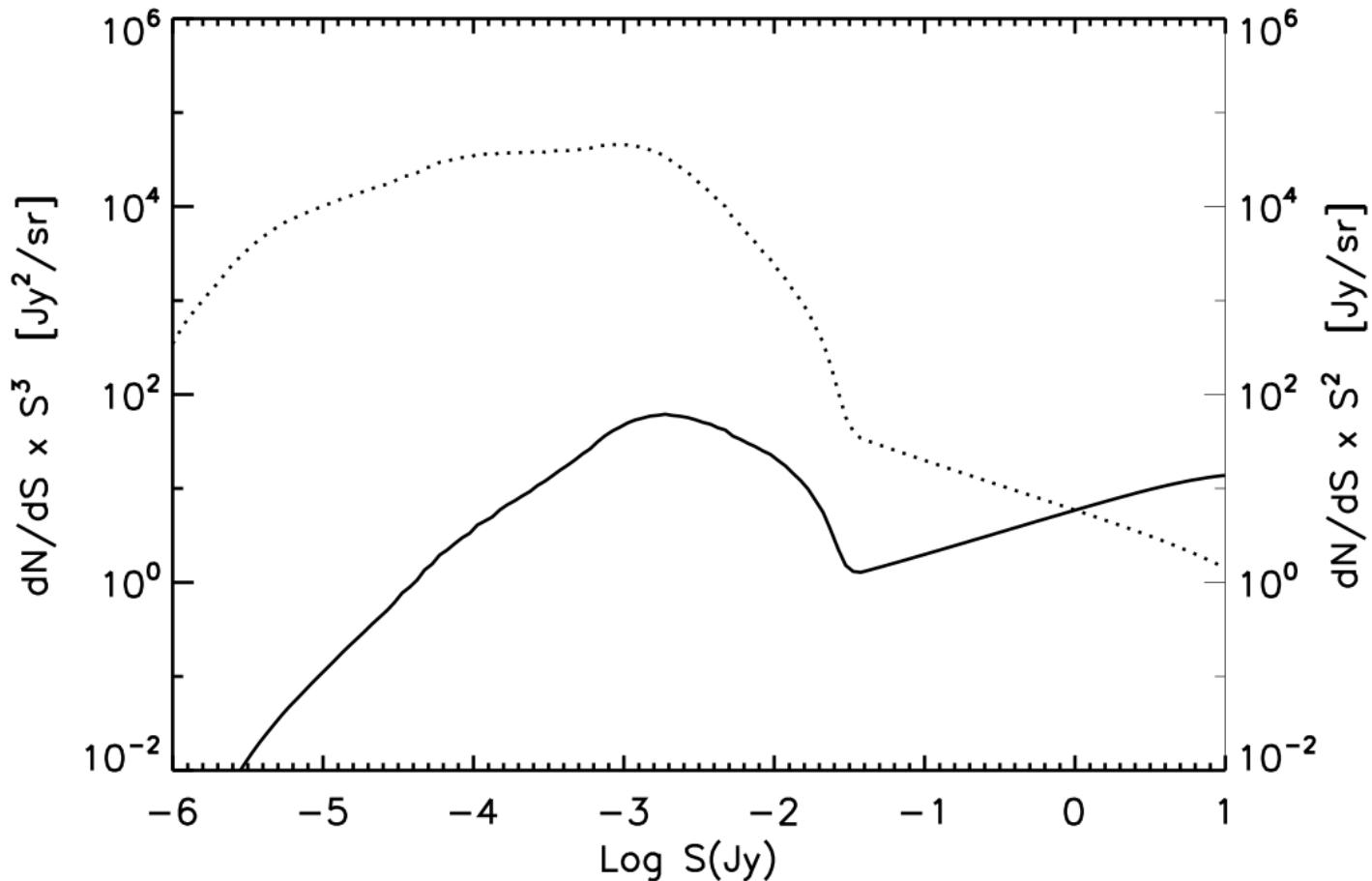
fluctuations of the Far Infrared Background

$$N(S > S_0) = N_0 \left(\frac{S}{S_0} \right)^{-\alpha}$$

$$I_{CIB} = \int_0^{S_{max}} S \frac{dN}{dS} dS$$

$$\sigma^2 = \int_0^{S_0} S^2 \frac{dN}{dS} dS$$

take-away message:
fluctuations are dominated by fainter galaxies,
so it's a natural probe of the bulk of the background



6. Planck and the CIB

6.1 CIB fluctuations

6.2 CIB as a nasty foreground

6.3 digging deeper into the CIB



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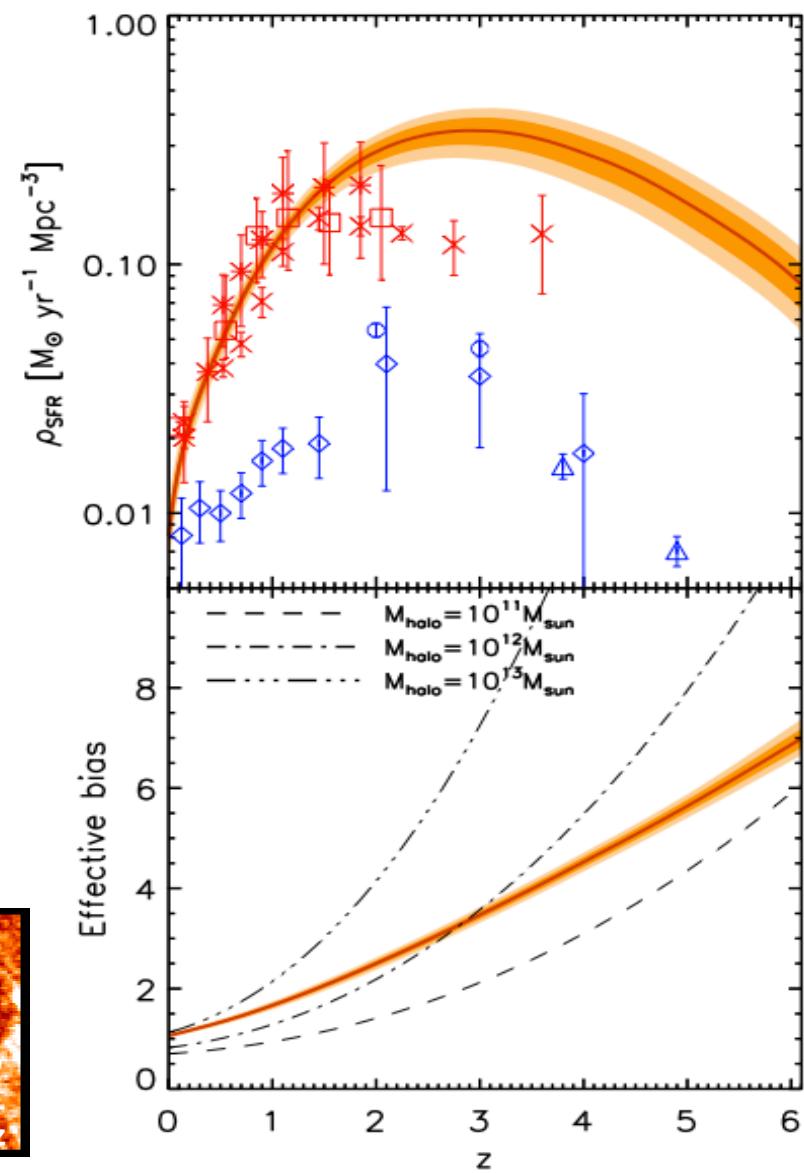
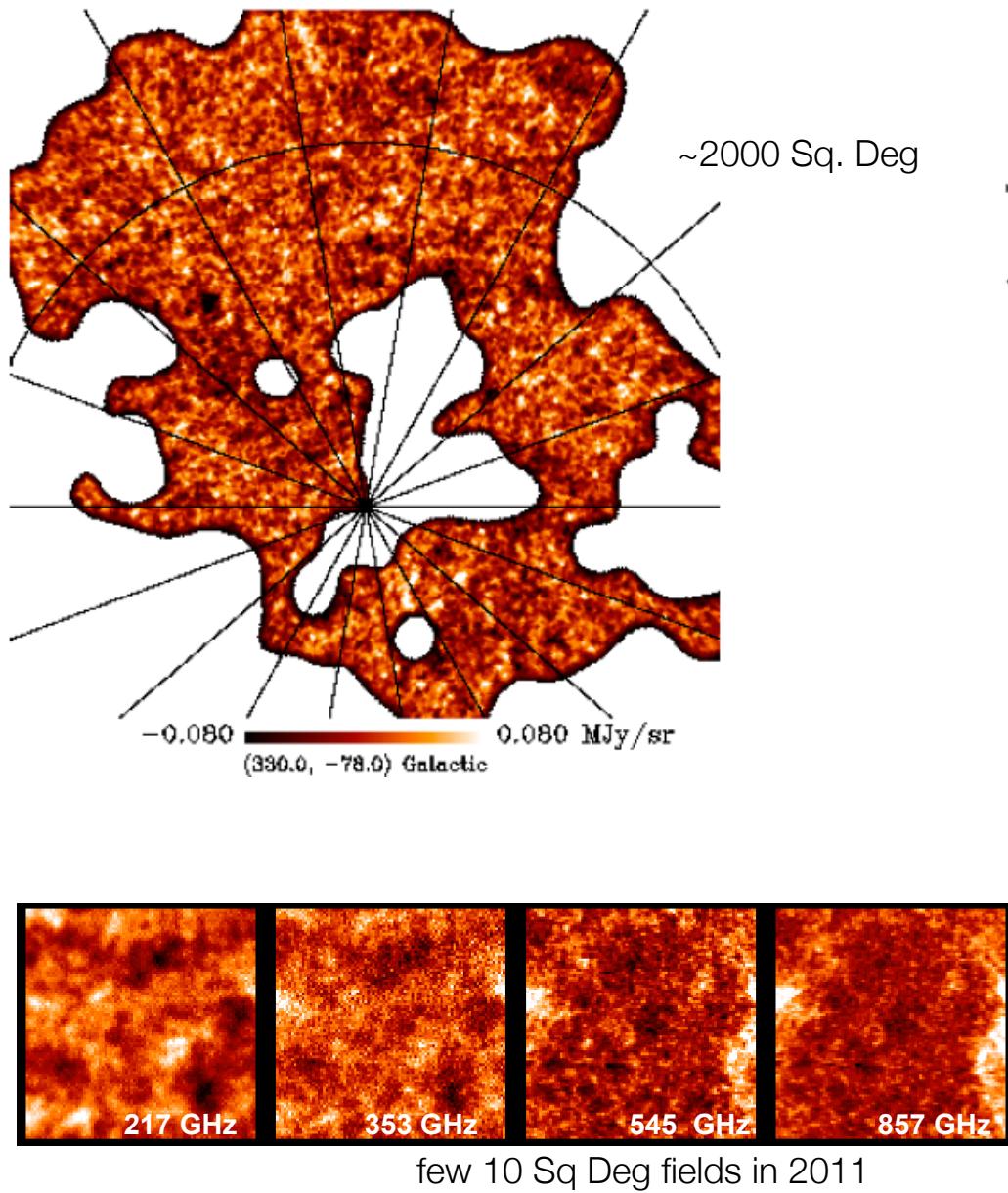


Hervé Dole, IAS - CIB



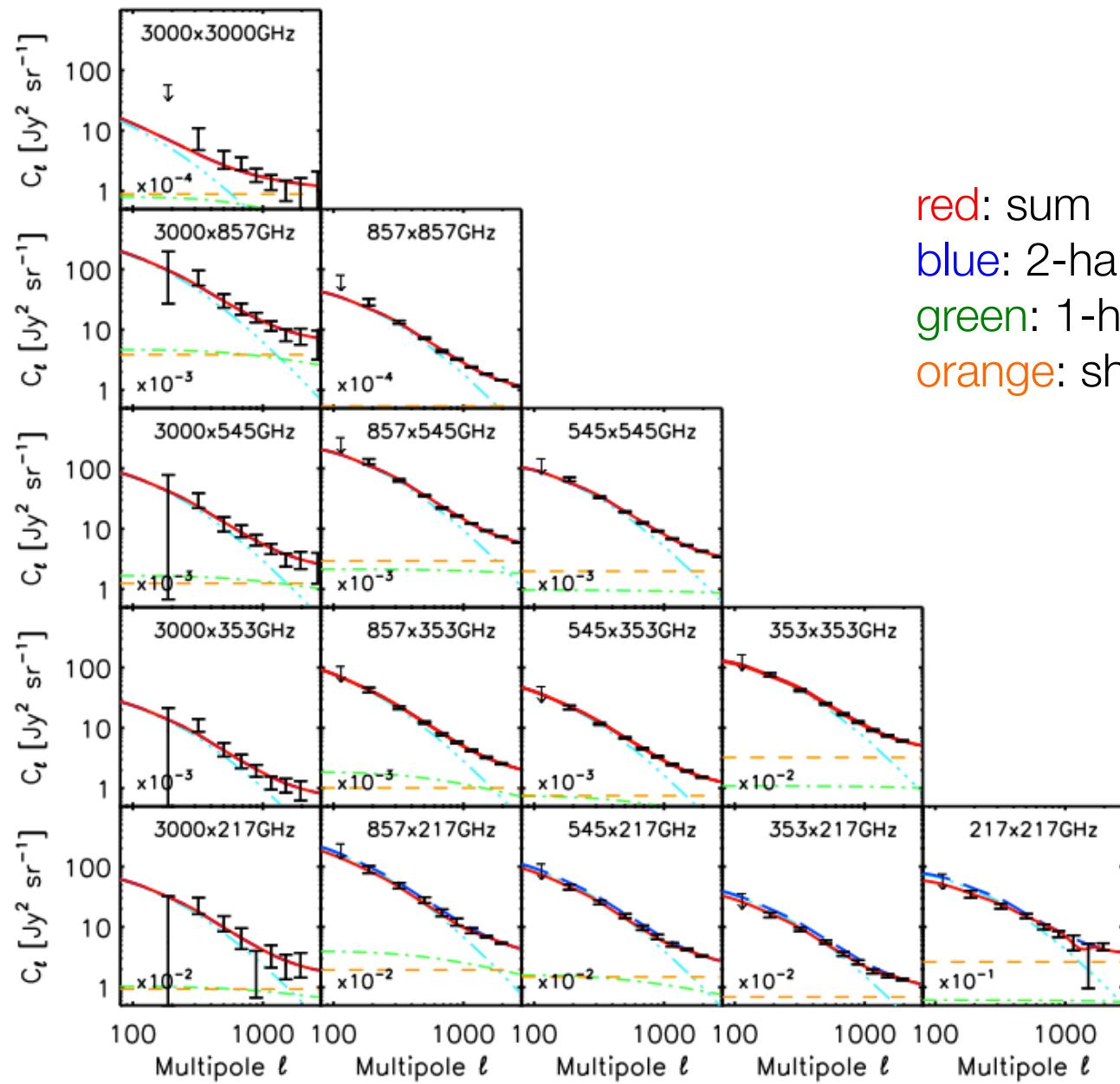
63

6.1 Planck submm CIB fluctuations

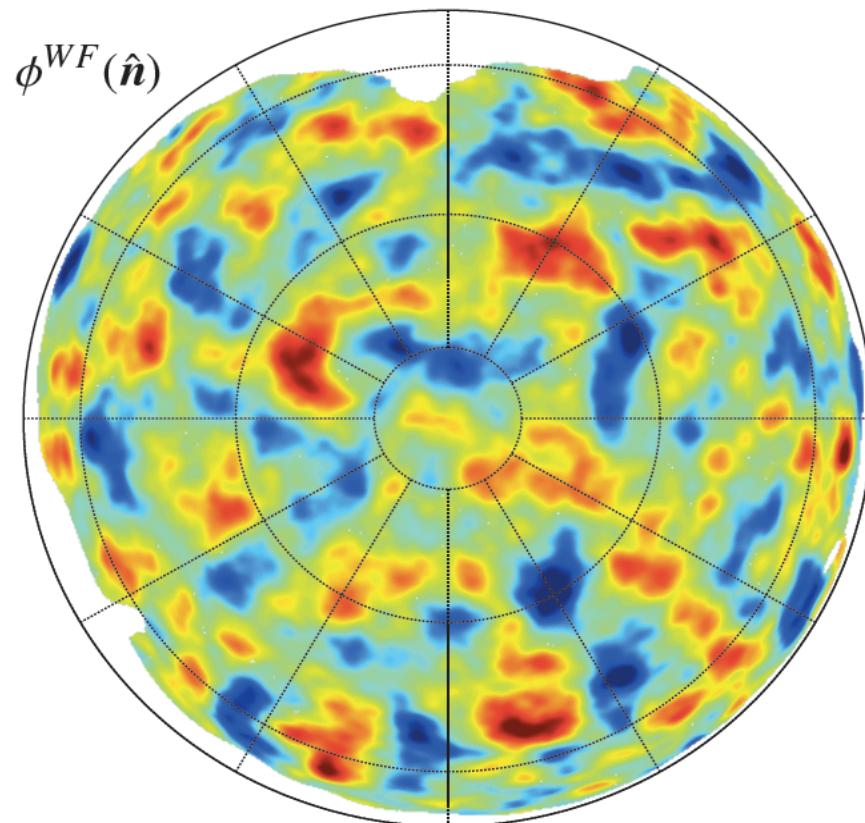


Planck submm CIB fluctuations

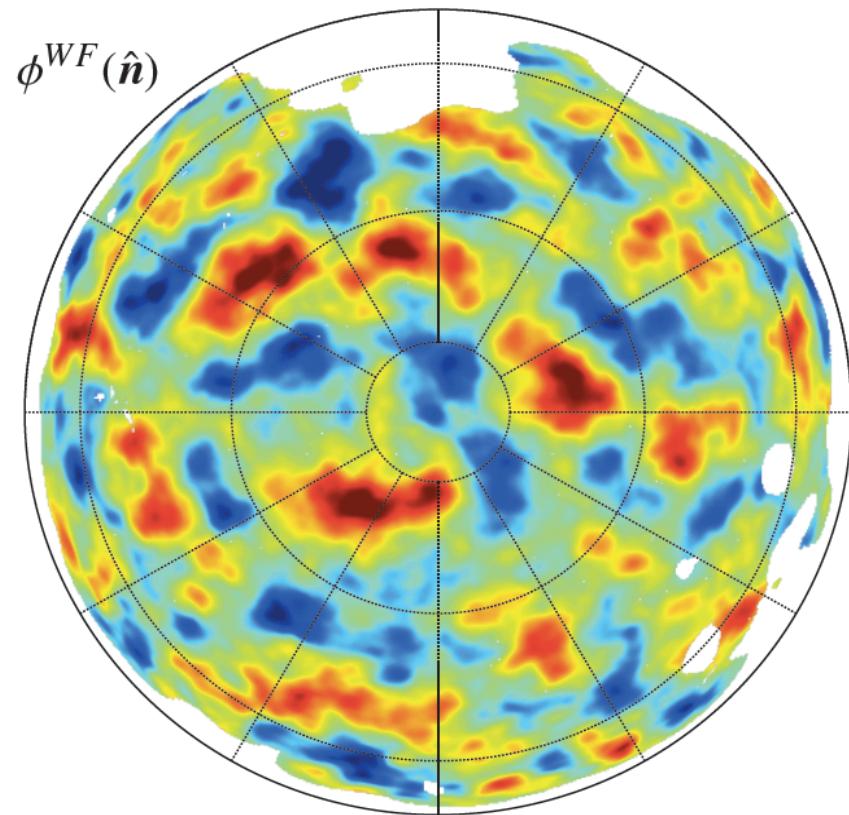
Planck Collab., 2013, XXX, in press



Planck all-sky map of the dark matter



Galactic North

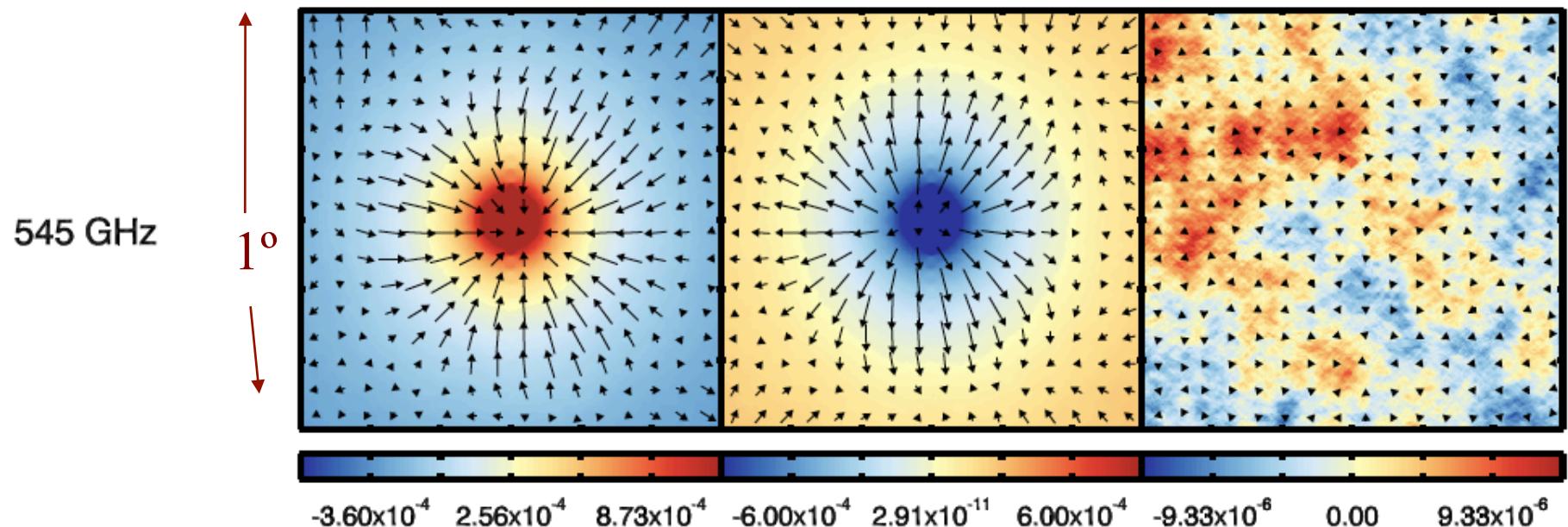


Galactic South

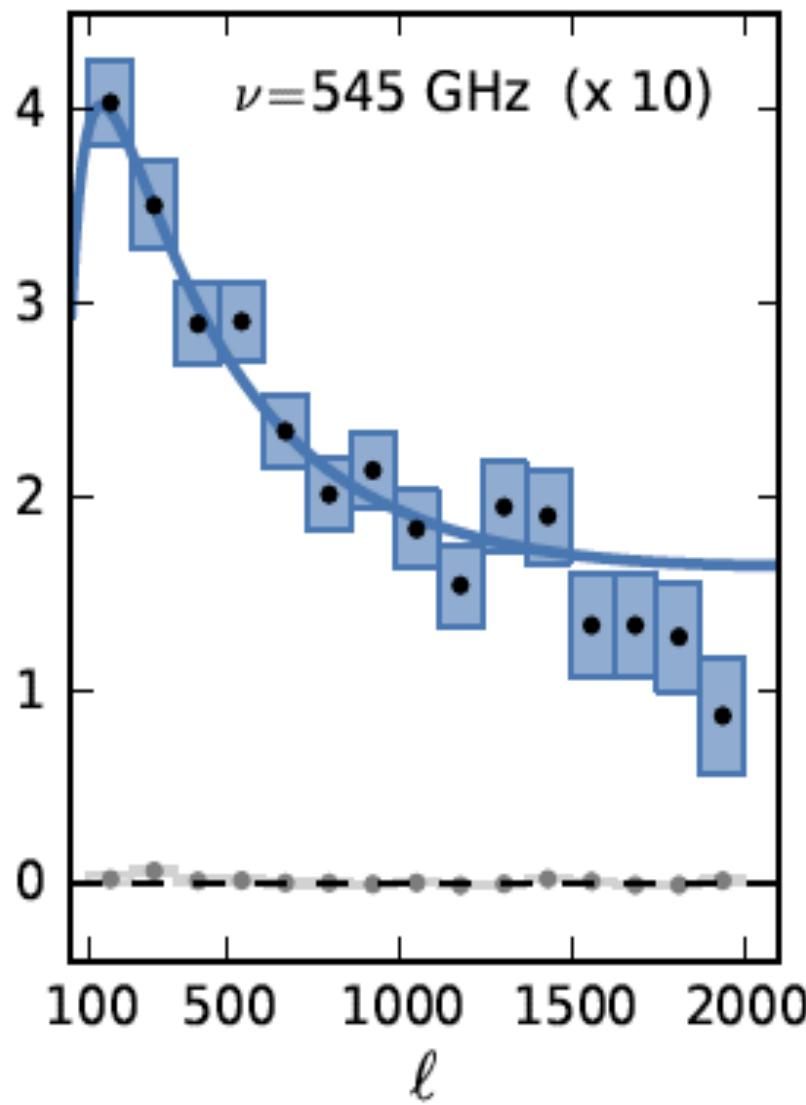
Planck 15 months
Planck Collaboration, 2013, 17

CIB peaks correspond to mass peaks

Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies. This is mostly Dark Matter.

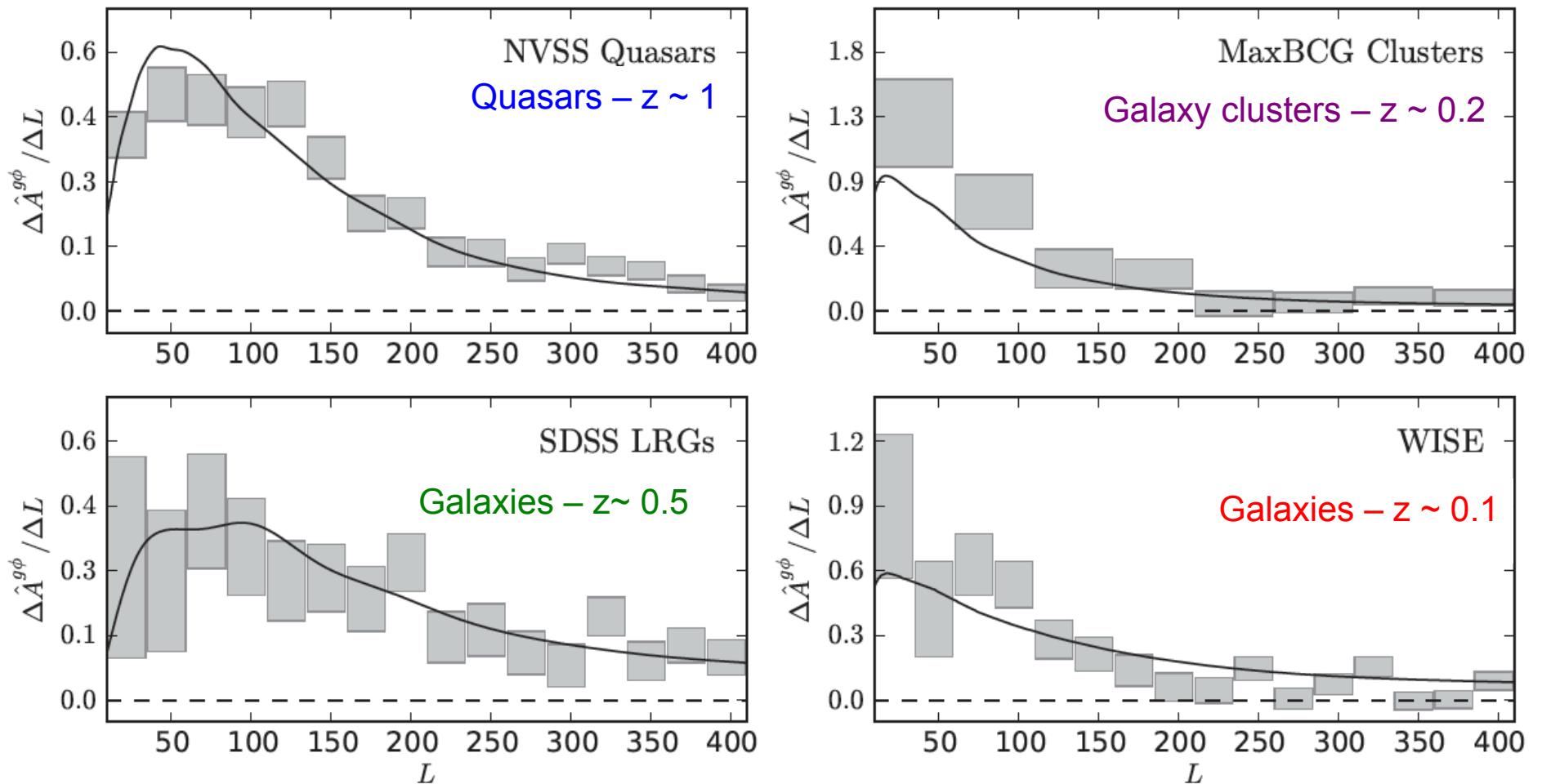


mass and CIB maps correspond closely



Planck 15 months
Planck Collaboration, 2013, 18

galaxies mirror the Planck mass map



SPT & Herschel do the same

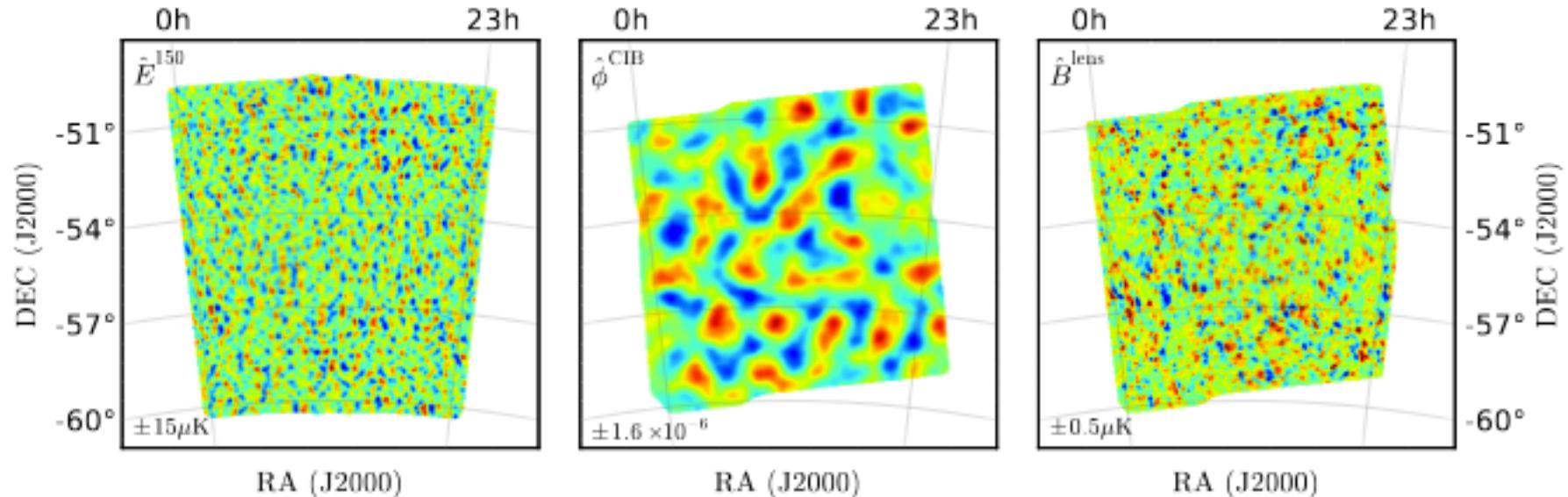


FIG. 1: (Left panel): Wiener-filtered E -mode polarization measured by SPTpol at 150 GHz. (Center panel): Wiener-filtered CMB lensing potential inferred from CIB fluctuations measured by *Herschel* at 500 μ m. (Right panel): Gravitational lensing B -mode estimate synthesized using Eq. (1). The lower left corner of each panel indicates the blue(-)/red(+) color scale.

Hanson et al., 2013 arXiv

6.2 CIB as a nasty foreground for cosmology

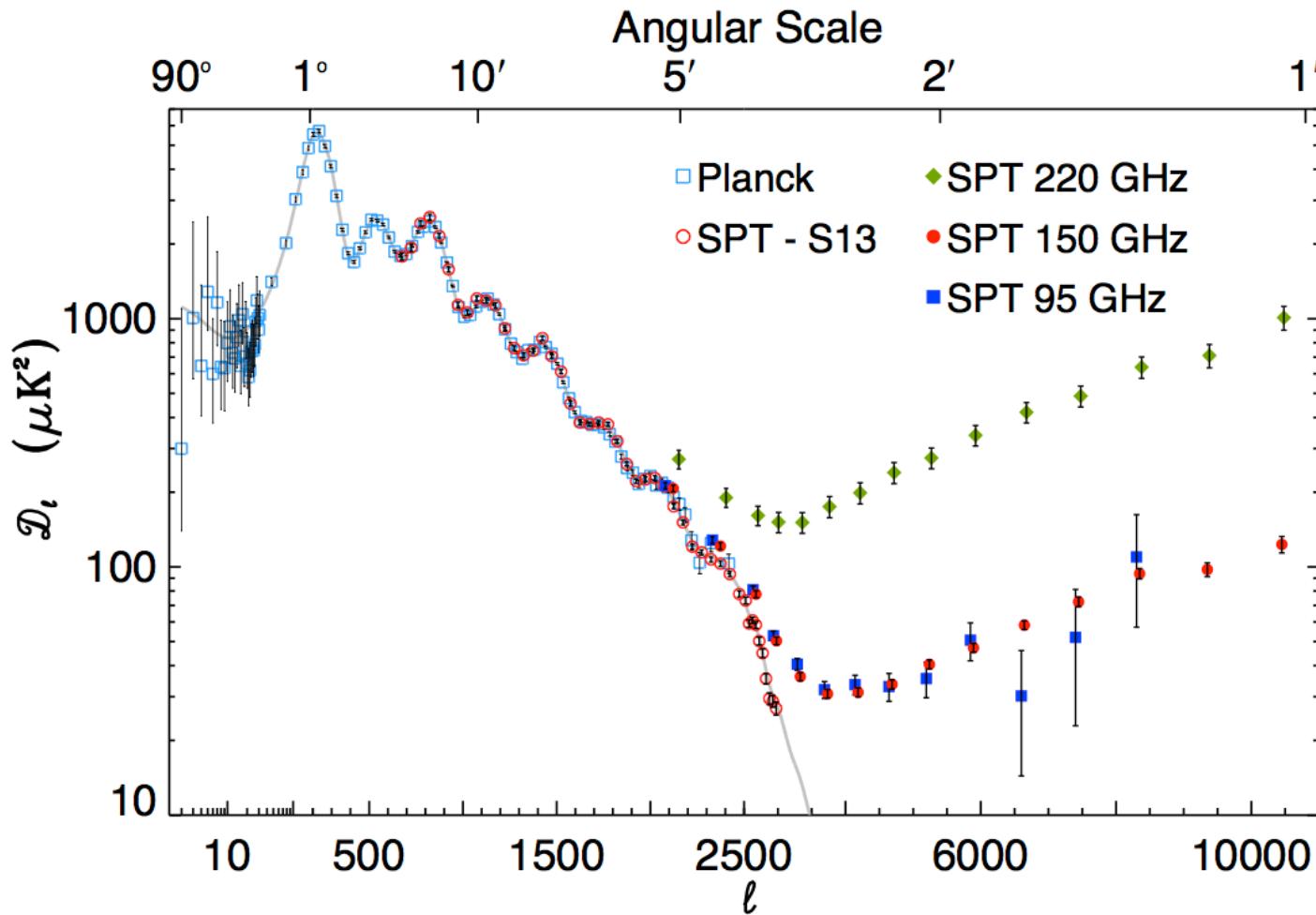


FIG. 2.— The SPT and *Planck* bandpowers. The *Planck* and S13 bandpowers (open squares and circles) are primary CMB only, and agree well on all angular scales. The grey line is the lensed Λ CDM CMB theory spectrum. We also show bandpowers at 95, 150, and 220 GHz (filled squares, circles and diamonds) measured with the SPT in this work. On large scales, the primary CMB anisotropy is dominant at all frequencies. On smaller scales, contributions from the CIB, radio sources, and secondary CMB anisotropies (tSZ and kSZ) dominate the observed power. The observed differences between frequency bands are due to these other sources of power. The CIB dominates the power spectrum at small scales at 150 and 220 GHz; radio galaxies are more important at 95 GHz.

George, Reichardt, et al., 2014, arXiv:1408.3161

CIB as a nasty foreground for cosmology

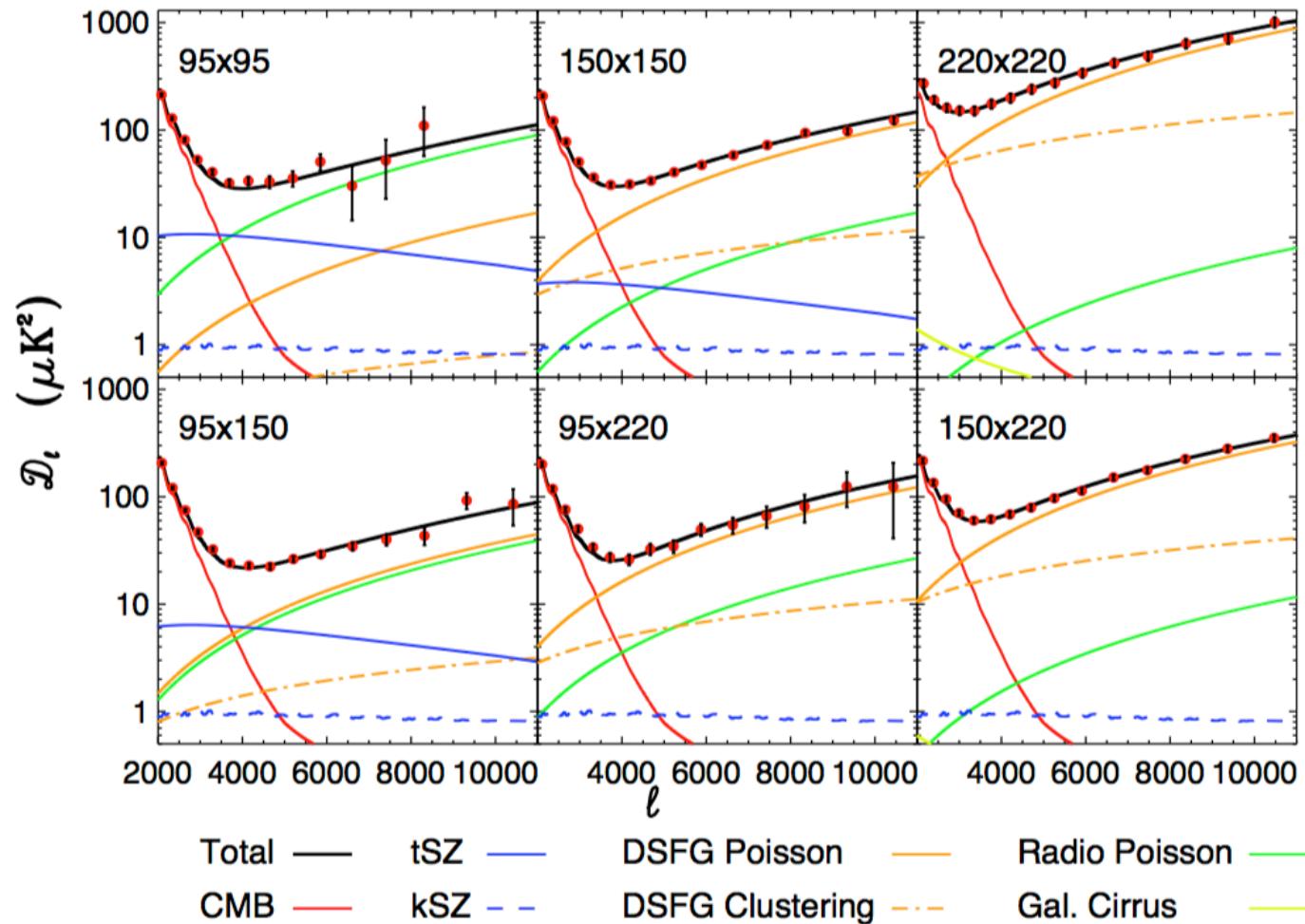


FIG. 3.— The six auto- and cross-spectra measured with the 95, 150, and 220 GHz SPT data. Overplotted on the bandpowers is the best-fit model for the fiducial set of model parameters. The bandpowers have not been corrected by the best-fit calibration or beam uncertainties.

George, Reichardt, et al., 2014, arXiv:1408.3161

CIB as a nasty foreground for cosmology

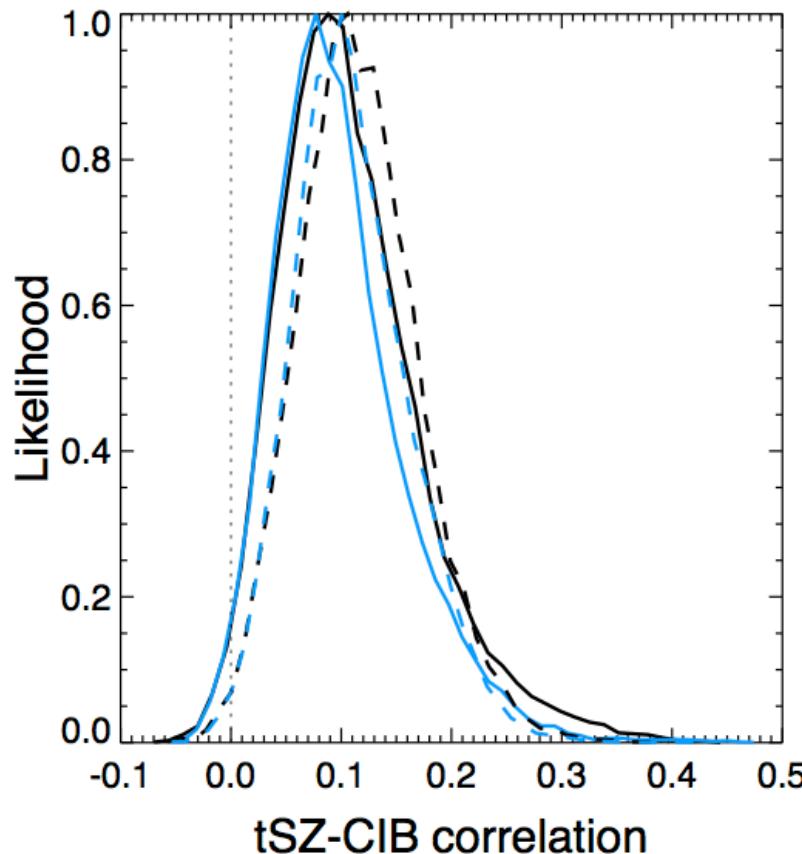


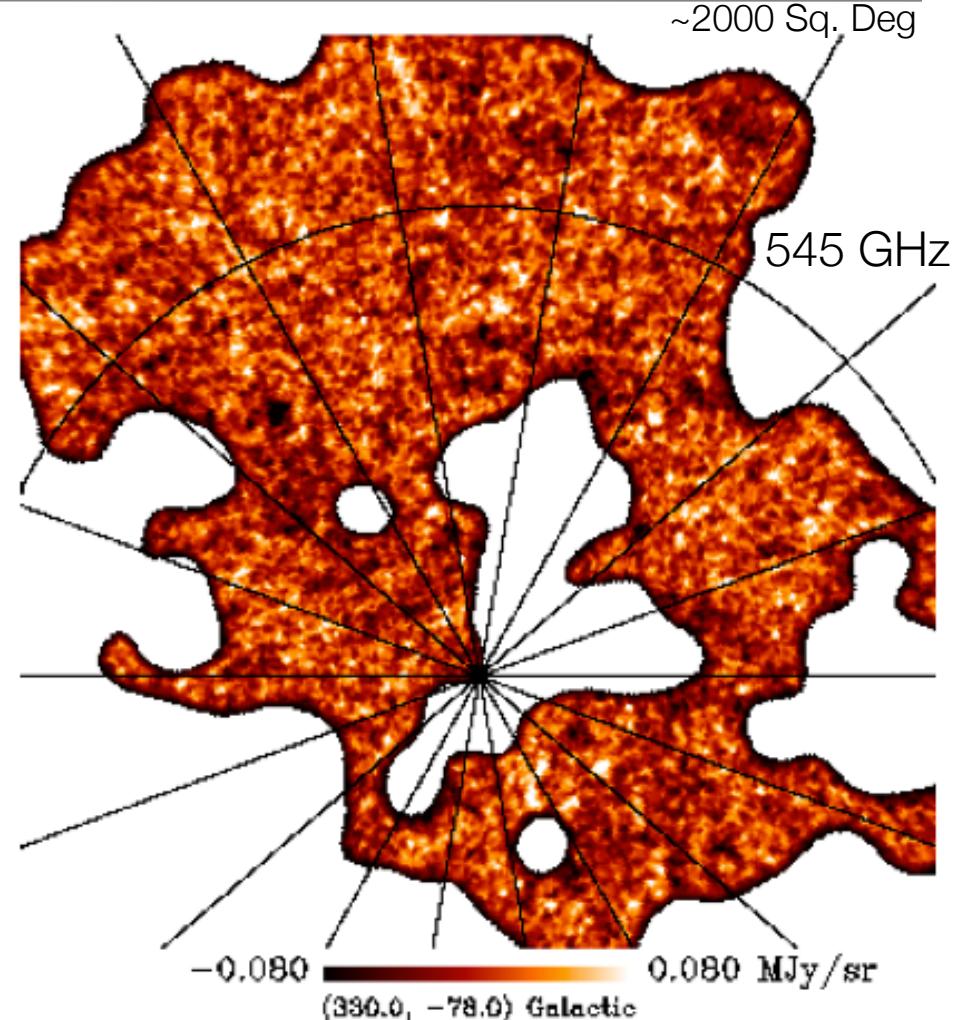
FIG. 11.— The **black solid line** shows the constraints on the tSZ-CIB correlation in our fiducial model. The **blue solid line** shows constraints on the tSZ-CIB correlation in a model where the angular slope of the correlation is a free parameter. The **dashed lines** are these same models including the prior on the tSZ power from the bispectrum measurement in C14.

George, Reichardt, et al., 2014, arXiv:1408.3161

6.3 digging into the Cosmic IR Background

our approach:
preferentially select
systems w/ *high SFR*.

With Planck: selection
of **extremely high SFR**
systems using CIB.



Planck Collab., 2013, 30

6.3 digging into the Cosmic IR Background

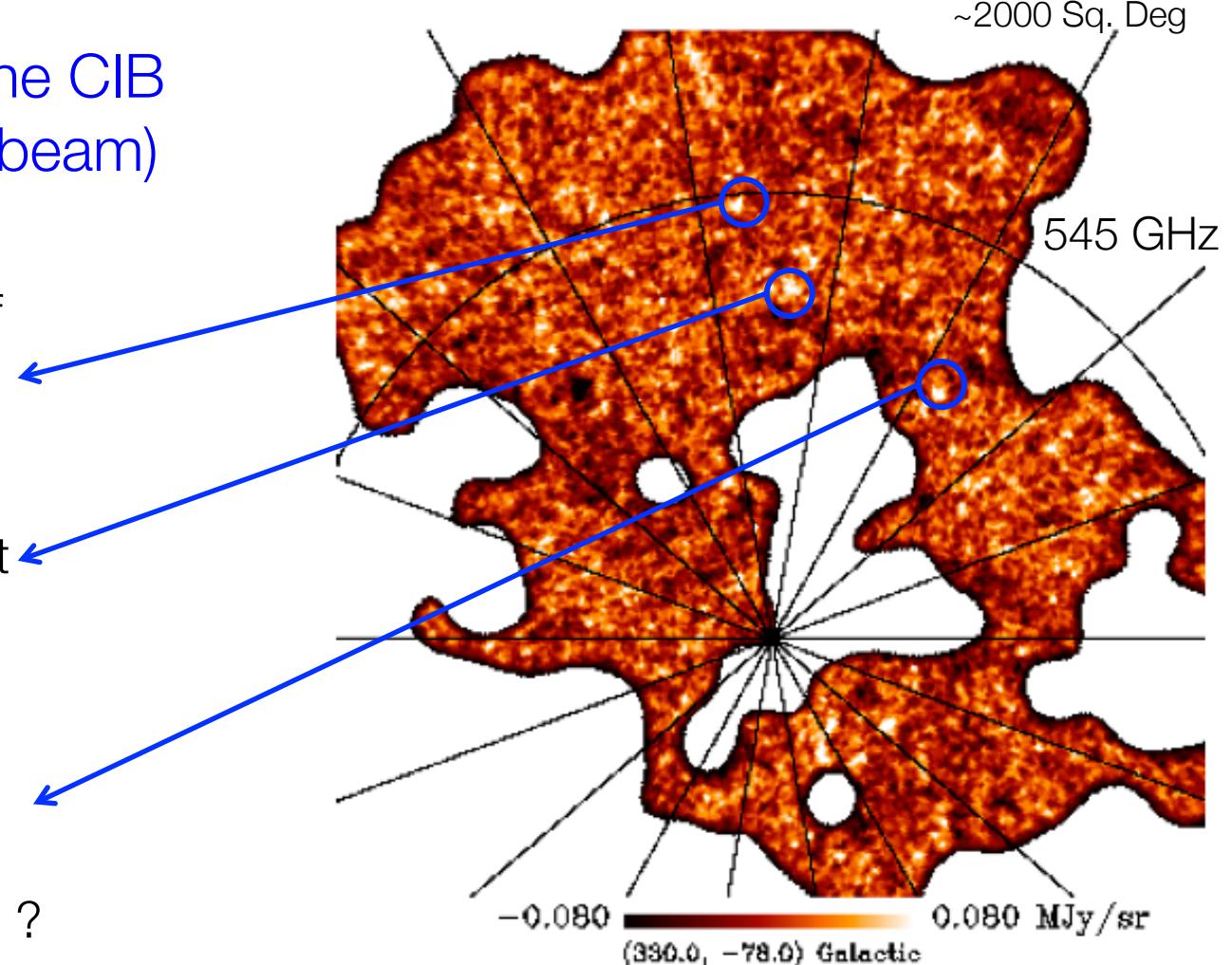
« cold sources » of the CIB
in Planck data (4.5' beam)

- $z > 1.5$ overdensities of intensely star forming galaxies ?

- $z > 1.5$ extremely bright lensed sources ?

- large scale structure alignments ?

- residual Galactic cirrus ?

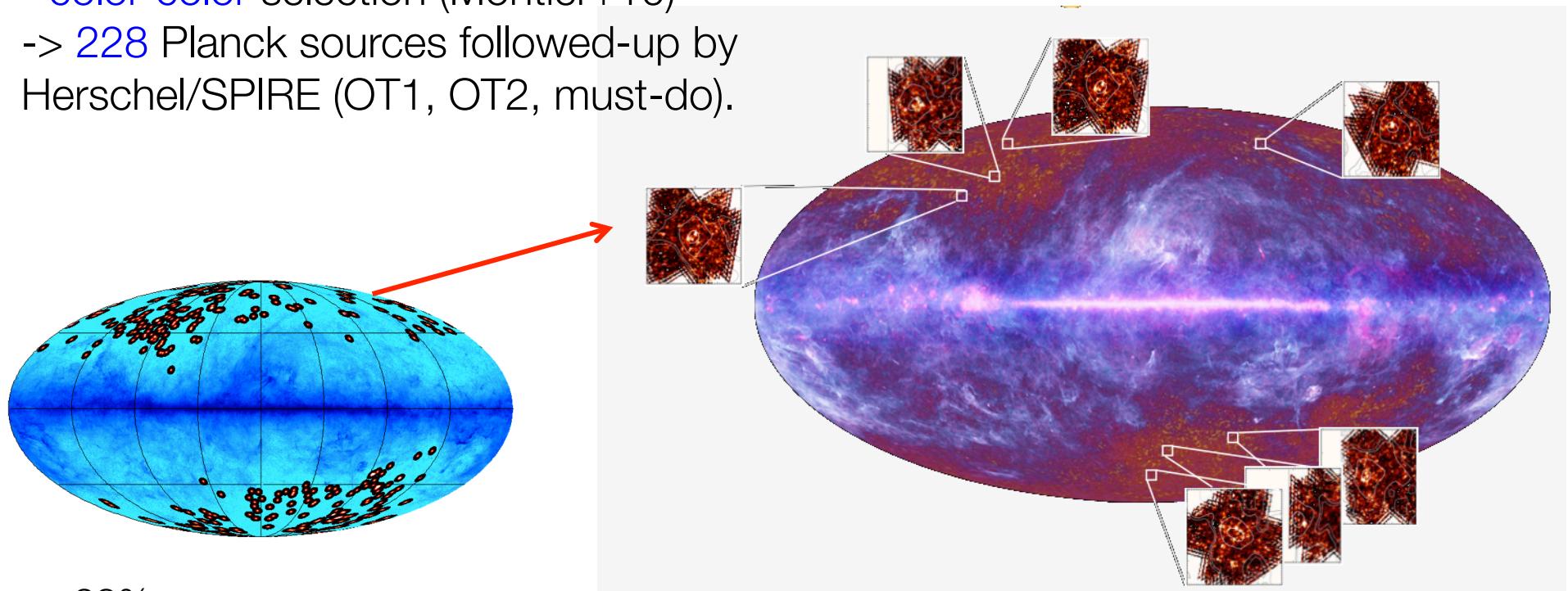


Planck Collab., 2013, 30

predicted number of extragalactic objects :
100 – 1000 (Negrello+2005)

several hundred Planck high-z candidates

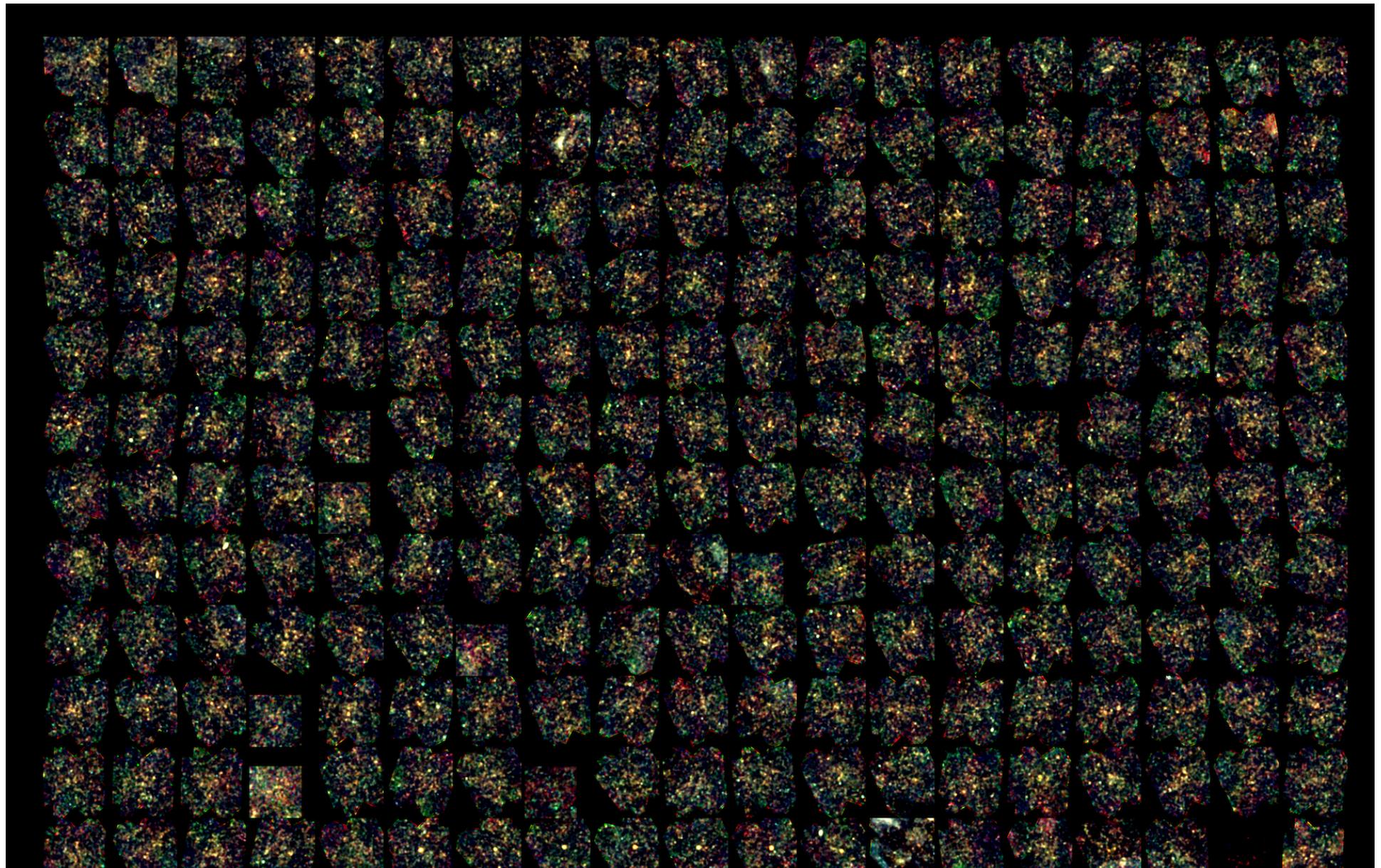
- best 35% of the sky
- **several hundred** Planck high-z candidates
- **color-color** selection (Montier+10)
-> **228** Planck sources followed-up by Herschel/SPIRE (OT1, OT2, must-do).



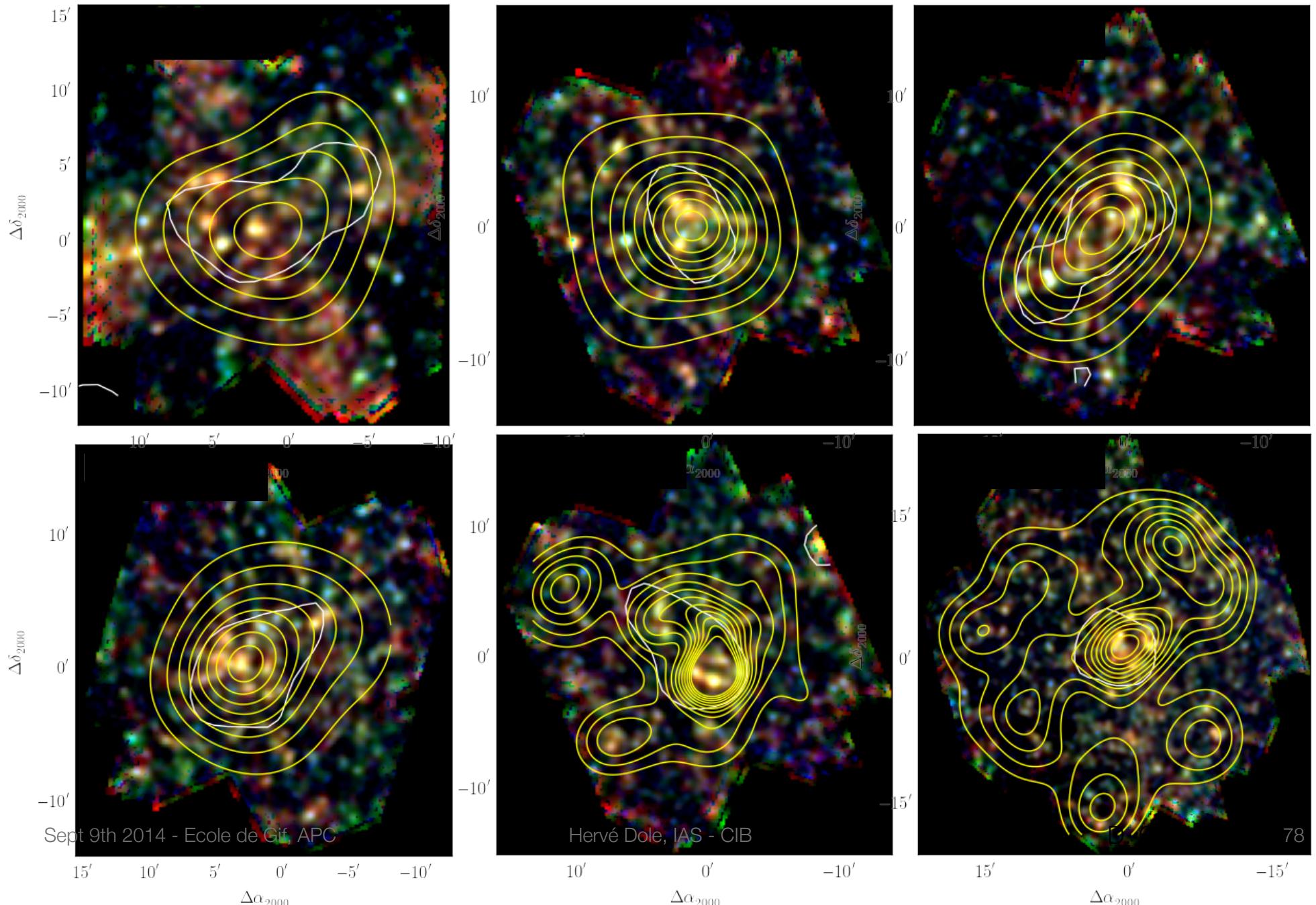
98% success

- few are bright lensed candidates
- most are overdensities of red galaxies
- 1.4% of the fields were Galactic cirrus

3. Herschel observations of Planck high-z candidates

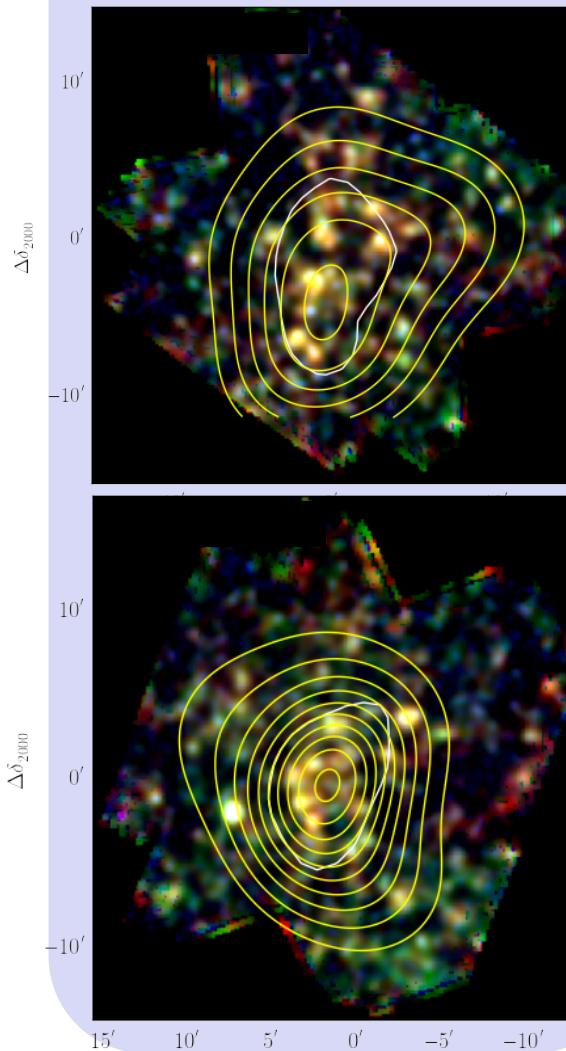


a remarkable dataset (30'x30' images)



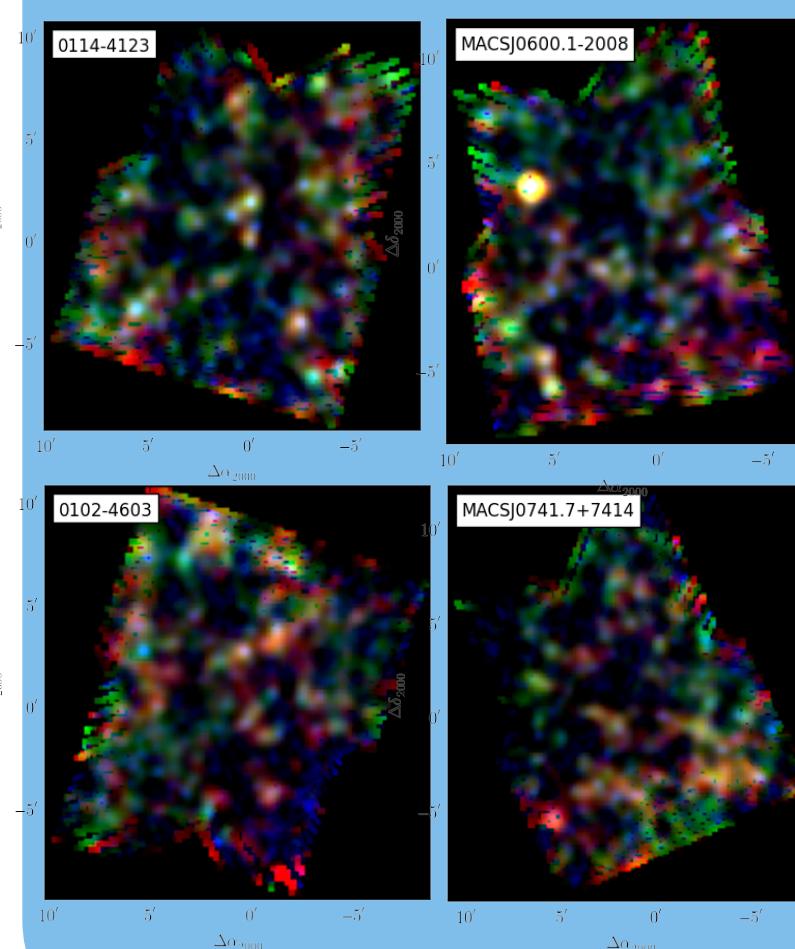
a remarkable dataset among others

Planck/Herschel HPASSS
30'x 30' (Dole+ in prep)



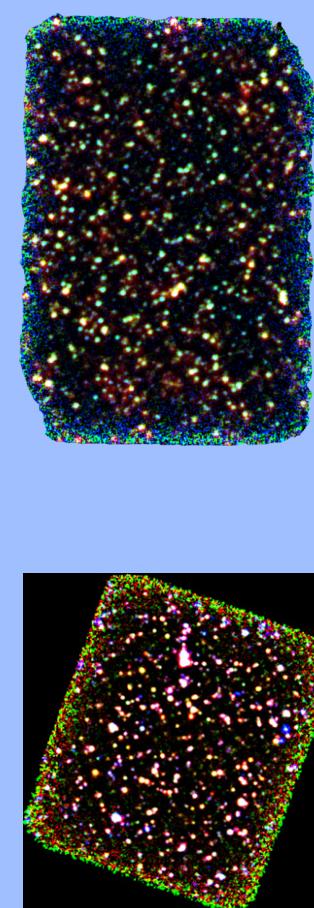
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HLS 20'x 20'
(Egami+2010)



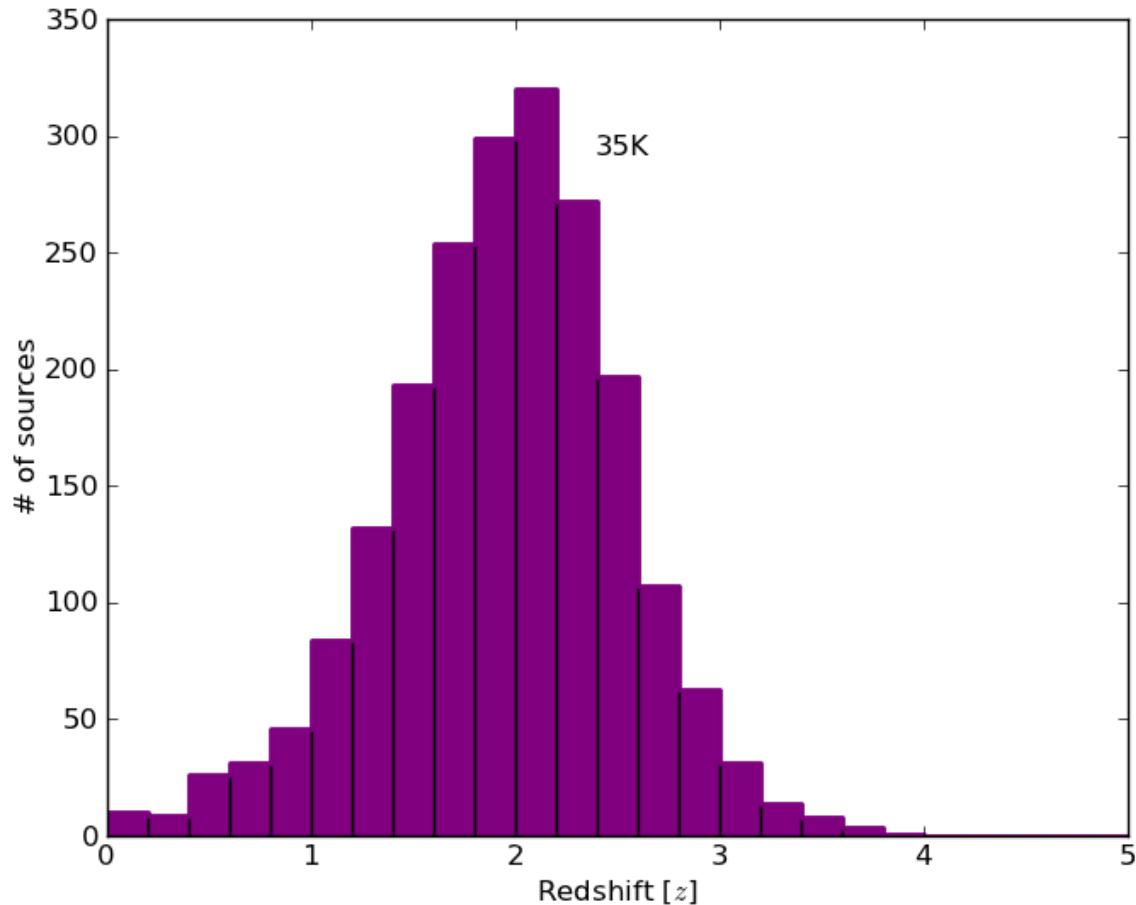
Hervé Dole, IAS - CIB

GOODS 16'x 10'
(Elbaz+2011)



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inferred sub-mm photometric redshifts



translates, for
cluster candidates, into:

total LIR $\sim 4.\text{e}13$ L_{sun}
total SFR $\sim 7.\text{e}3$ M_{sun}/yr

the case of one field: Spitzer and VLT

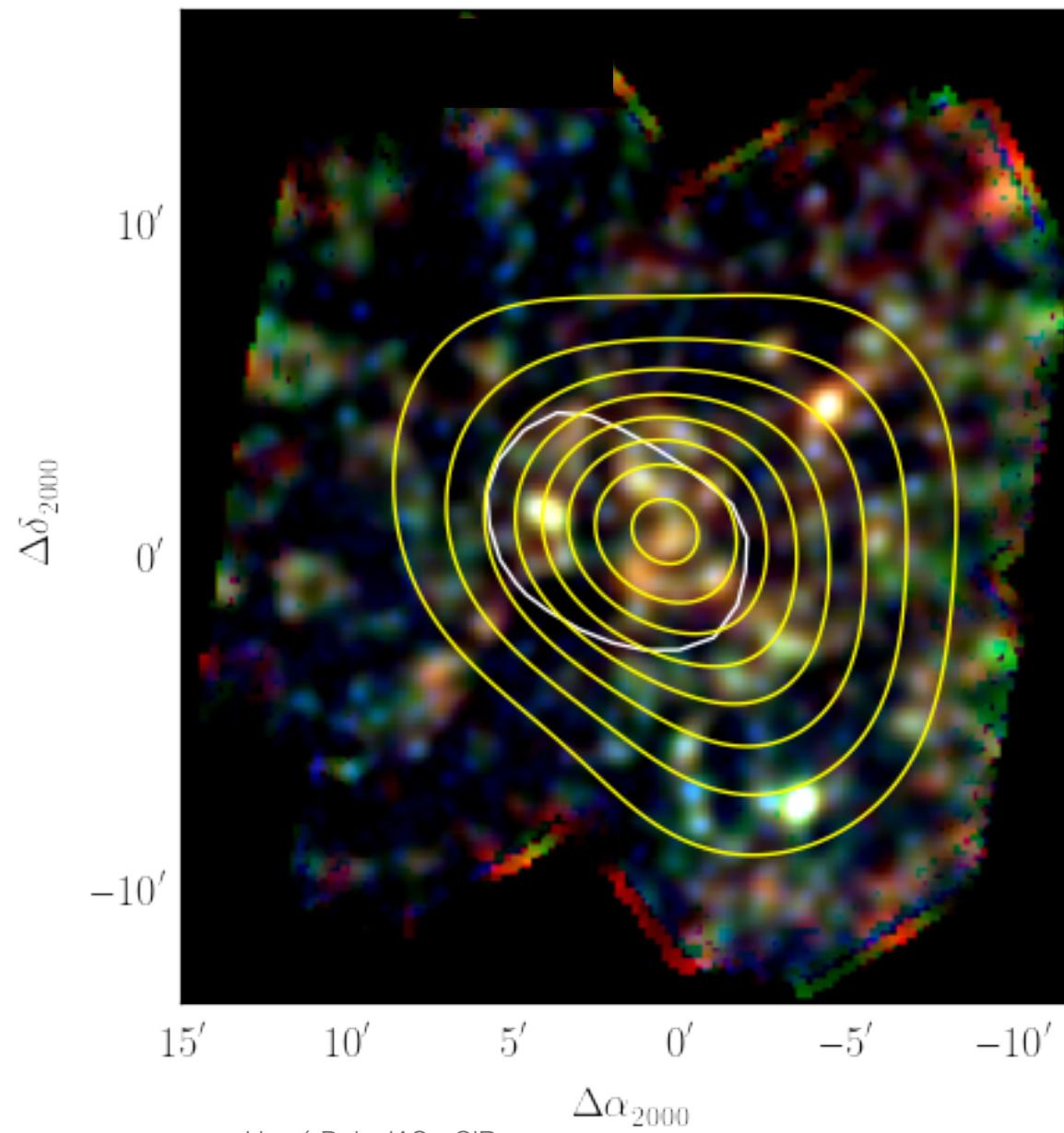
Herschel-SPIRE

3-color image:

blue = 250um

green = 350um

red = 500um



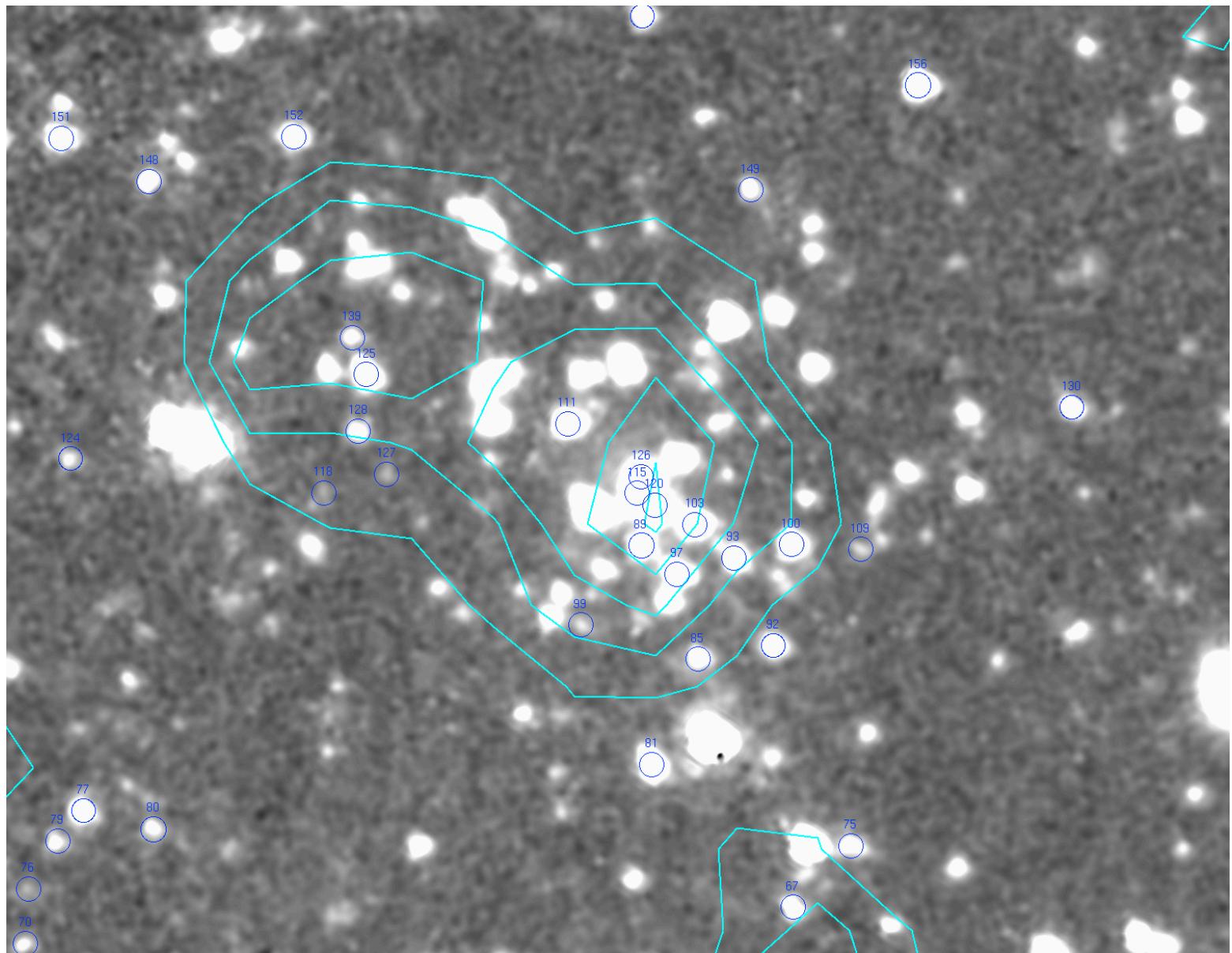
5. the case of one field: Spitzer and VLT

Spitzer 3.6um
image

Herschel 350
um contour
(cyan)

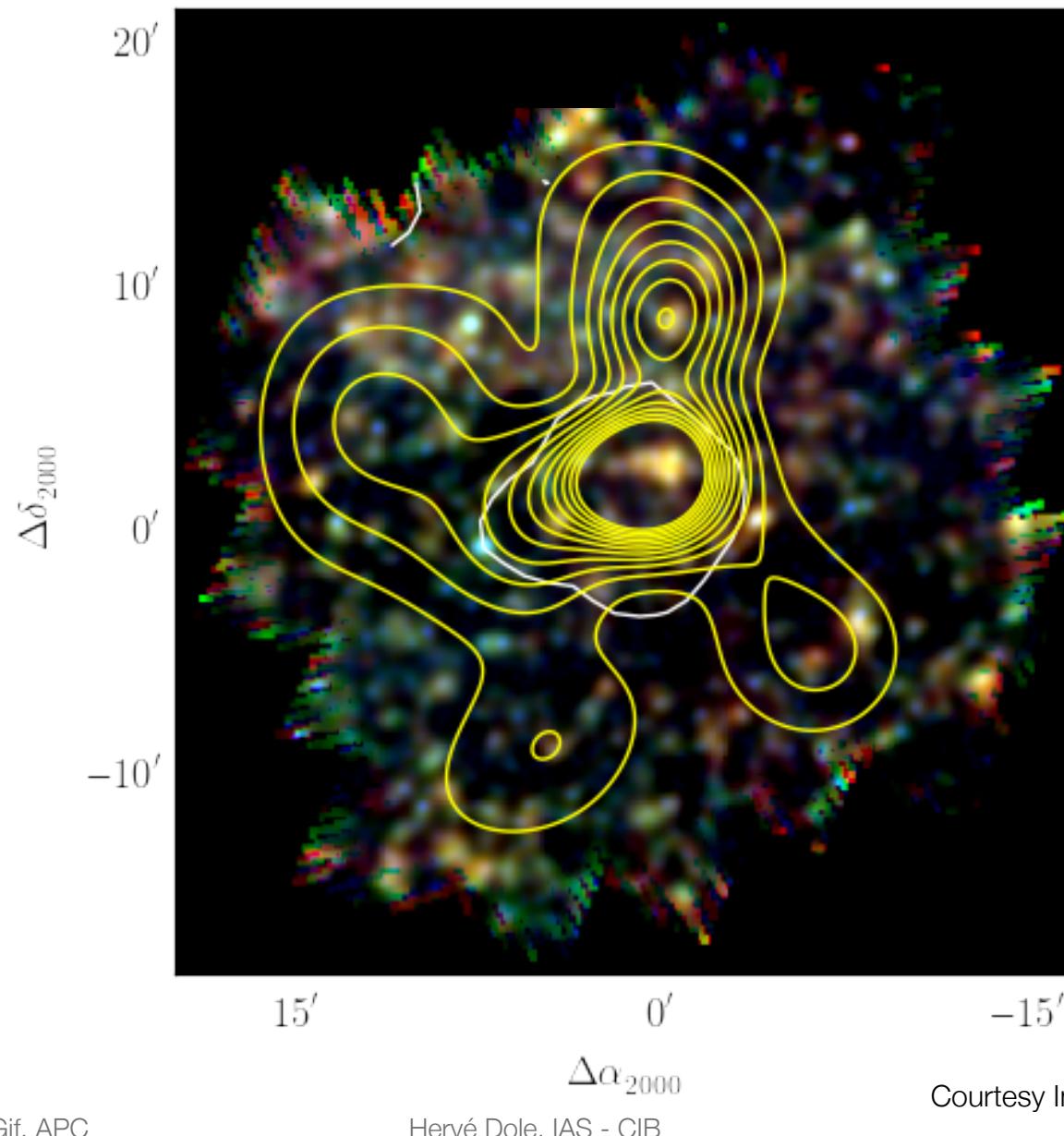
sources
 $J-K > 0.95$
(blue)

C. Martinache
thesis



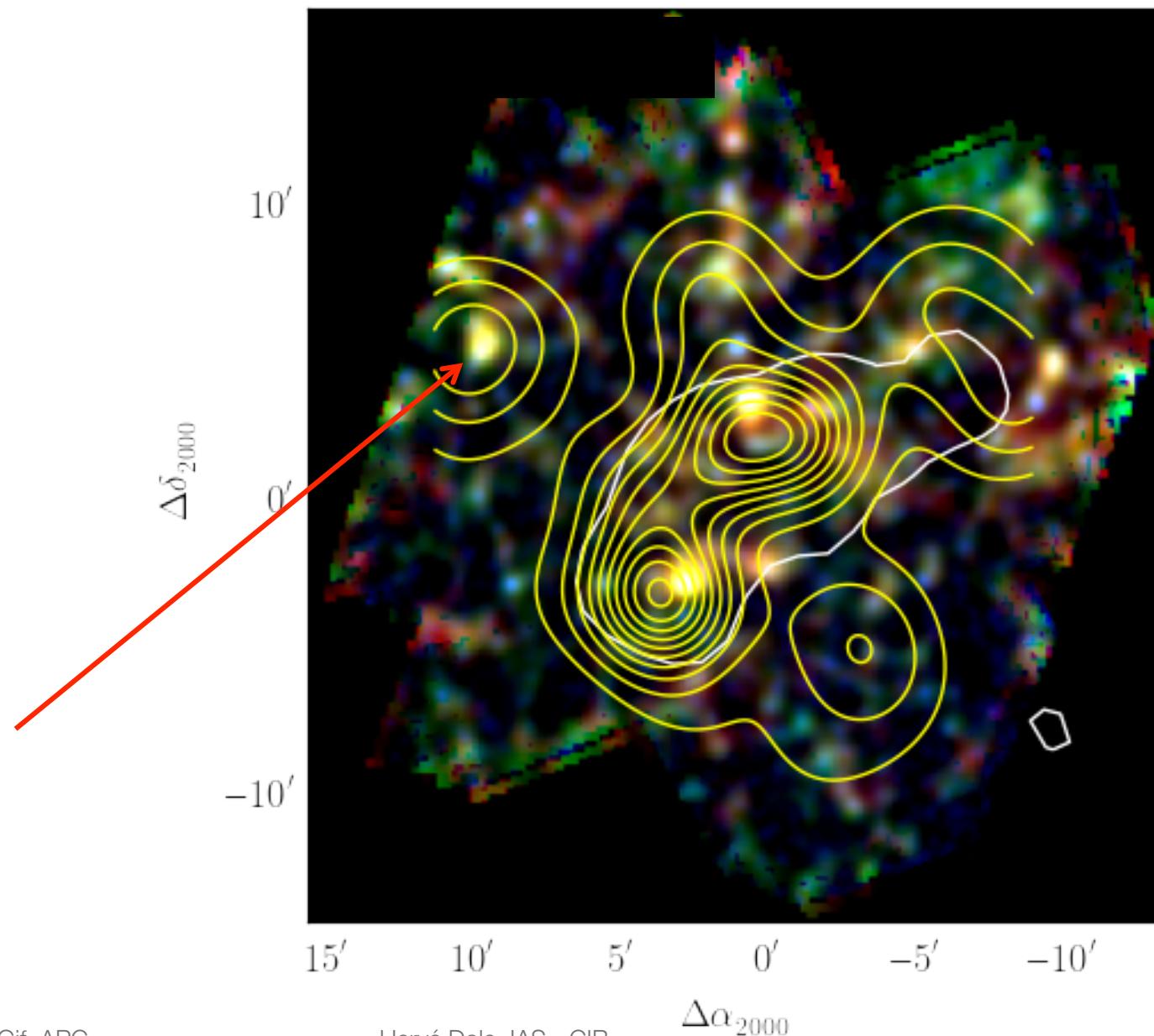
a double structure at z=1.7 and 2.0

Herschel-SPIRE
3-color image:
blue = 250um
green = 350um
red = 500um



Courtesy Ines Flores-Cacho

the case of XMMU J0044.0-2033 @z=1.58



8. summary, conclusion, prospects

conclusion: what tells us the EBL [1]

- encodes the **output of galaxy formation evolution**
 - is now well measured over >20 orders of magnitude
 - FIR/submm now well measured – Spitzer & Herschel
 - gives the **energy budget** (photons) for galaxy formation and evolution; useful to:
 - constrain the models
 - quantify the relative contributions of nucleosynthesis vs accretion
 - gives a degenerate information
-
- need for **more output energy in the infrared at higher z**
 - testimony of the central role of LIRG (Luminous IR galaxies)
 - tells us about the **opacity to TeV photons**

conclusion: what tells us the EBL [2]

- beyond the EBL intensity: its angular structure:
extragalactic background fluctuations
 - tell us about the emitting sources
- in the far-infrared ($> 70\text{um}$)
 - CIB not completely resolved in galaxies
 - fluctuations probe the galaxies populations making-up the bulk of the background
 - breakthrough w/ Planck & Herschel
- in the near- and mid-infrared ($<30\text{um}$)
 - CIB almost resolved into galaxies
 - fluctuations also probe the faintest populations:
 - popIII ? zodi ou cirrus ? very high-z galaxies ? faint low-z galaxies ?
 - sources at EoR ? early black holes ?

many prospects

- EBL as a tracer of large scale structure
 - incl e.g. the first clusters of galaxies ?
- physics of galaxies & blazars
- link between frequencies using cross-correlations
 - e.g. IR vs X or IR vs gamma
 - for galaxy population studies (e.g. SF vs AGN)

some references

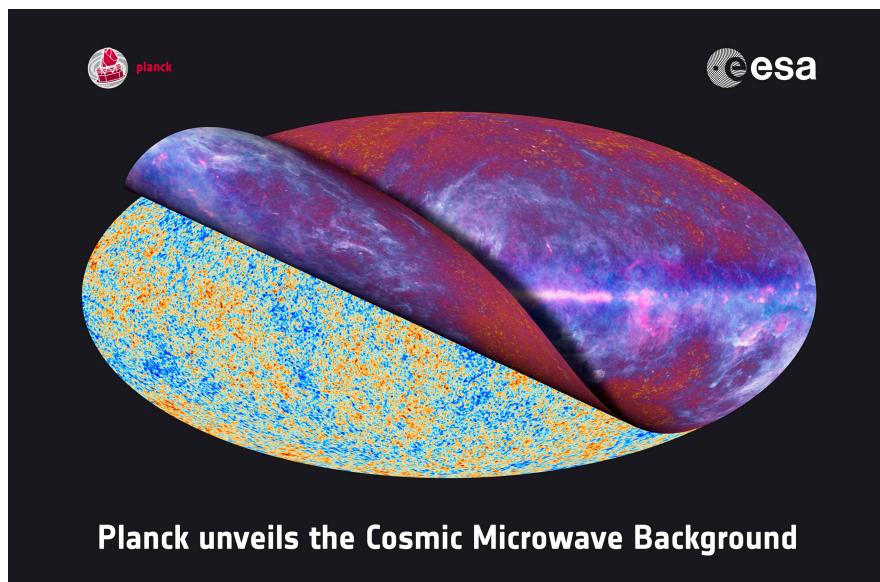
- Puget et al., 1996, A&A
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- Kashlinsky, 2005, Phys. Reports
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- books
- *Extragalactic Astrophysics and Cosmology: An Introduction*, P. Schneider, Springer
- *Galaxy Formation and Evolution*, H. Mo, F. van den Bosch, S. White, Cambridge
-
-

fin

<http://www.ias.u-psud.fr/dole/>

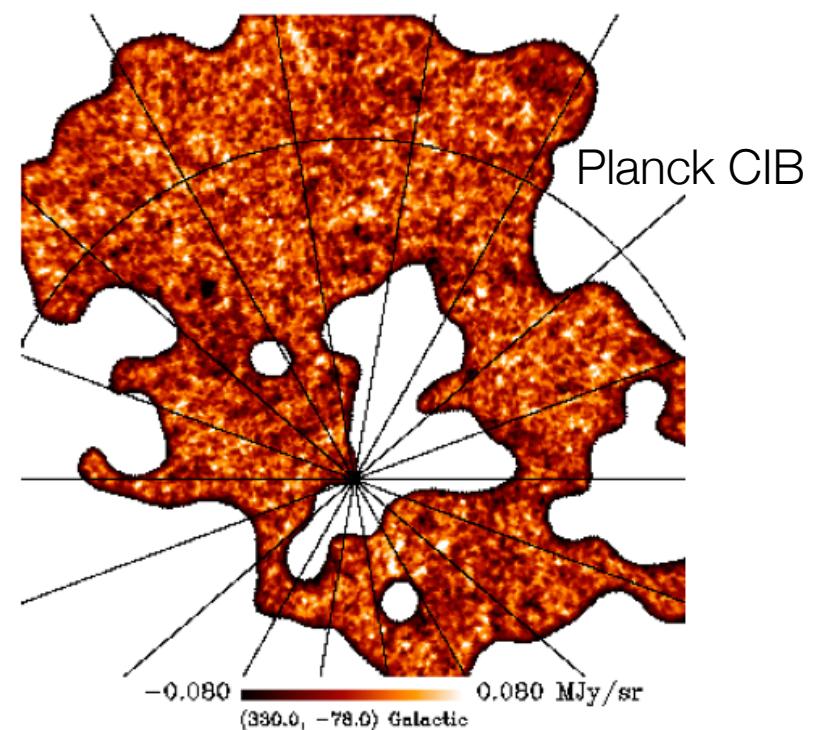
<http://www.planck.fr>



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Planck CMB

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