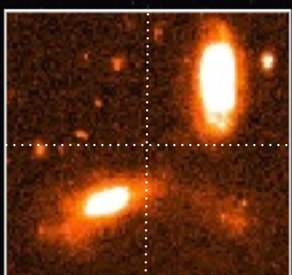
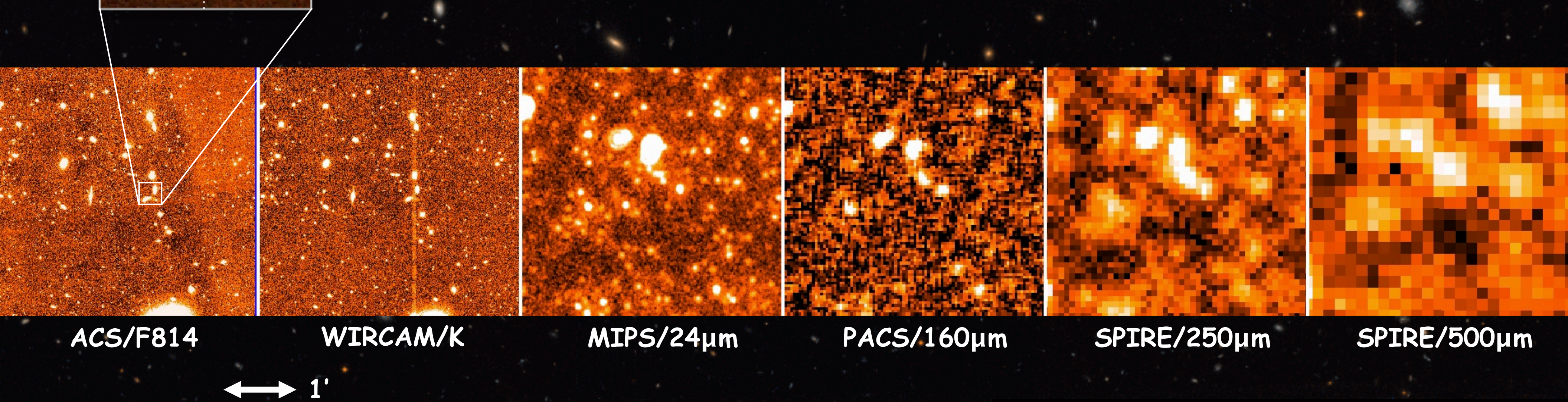
A Far-Infrared view on galaxy formation

E. Le Floc'h, CEA/AIM

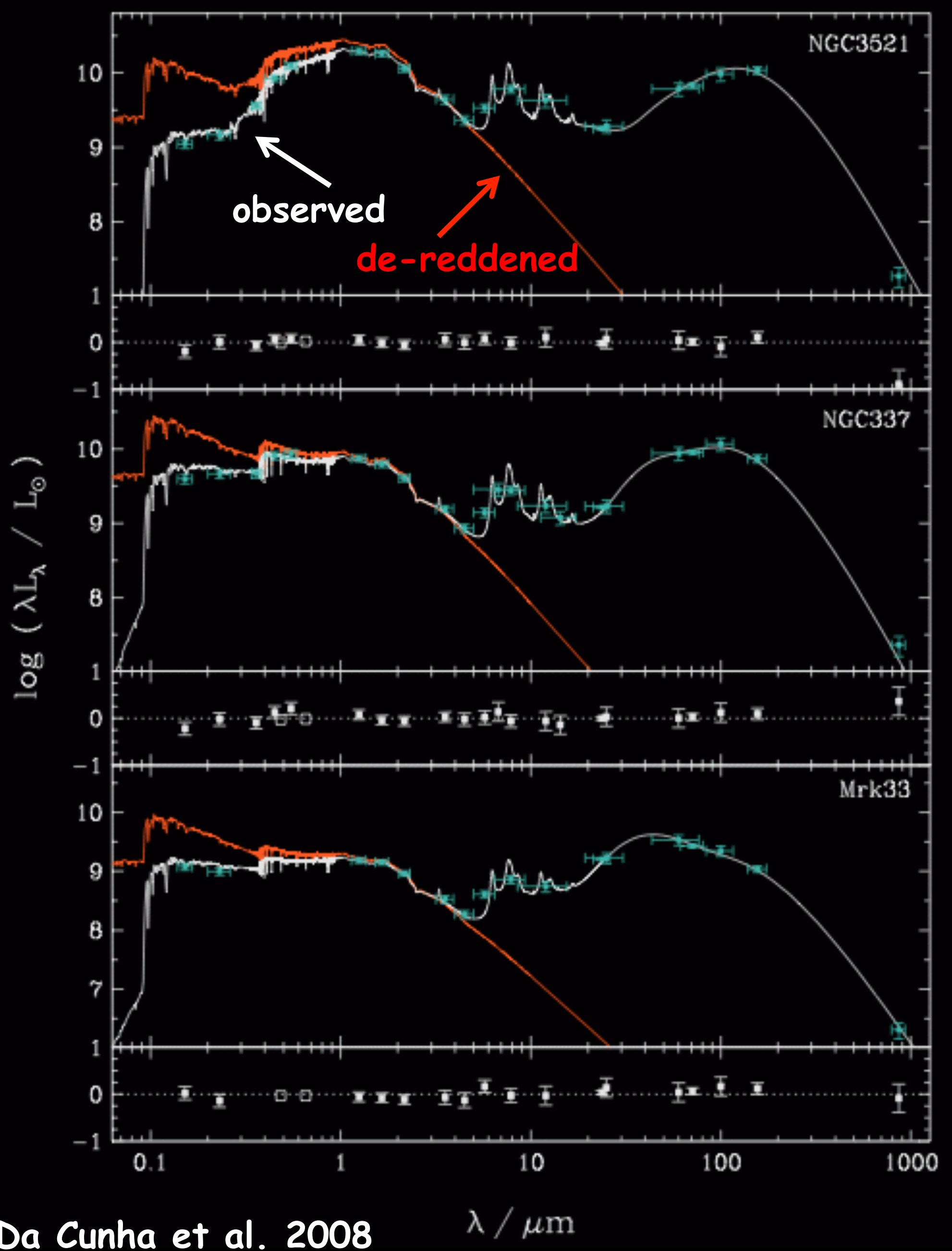
* Goals and basic principles, strengths and drawbacks, typical surveys undertaken so far…
* Major results: CIB build-up, SFR/Mass, (hidden) AGNs, …
* Which models to confront ?
* What next ?





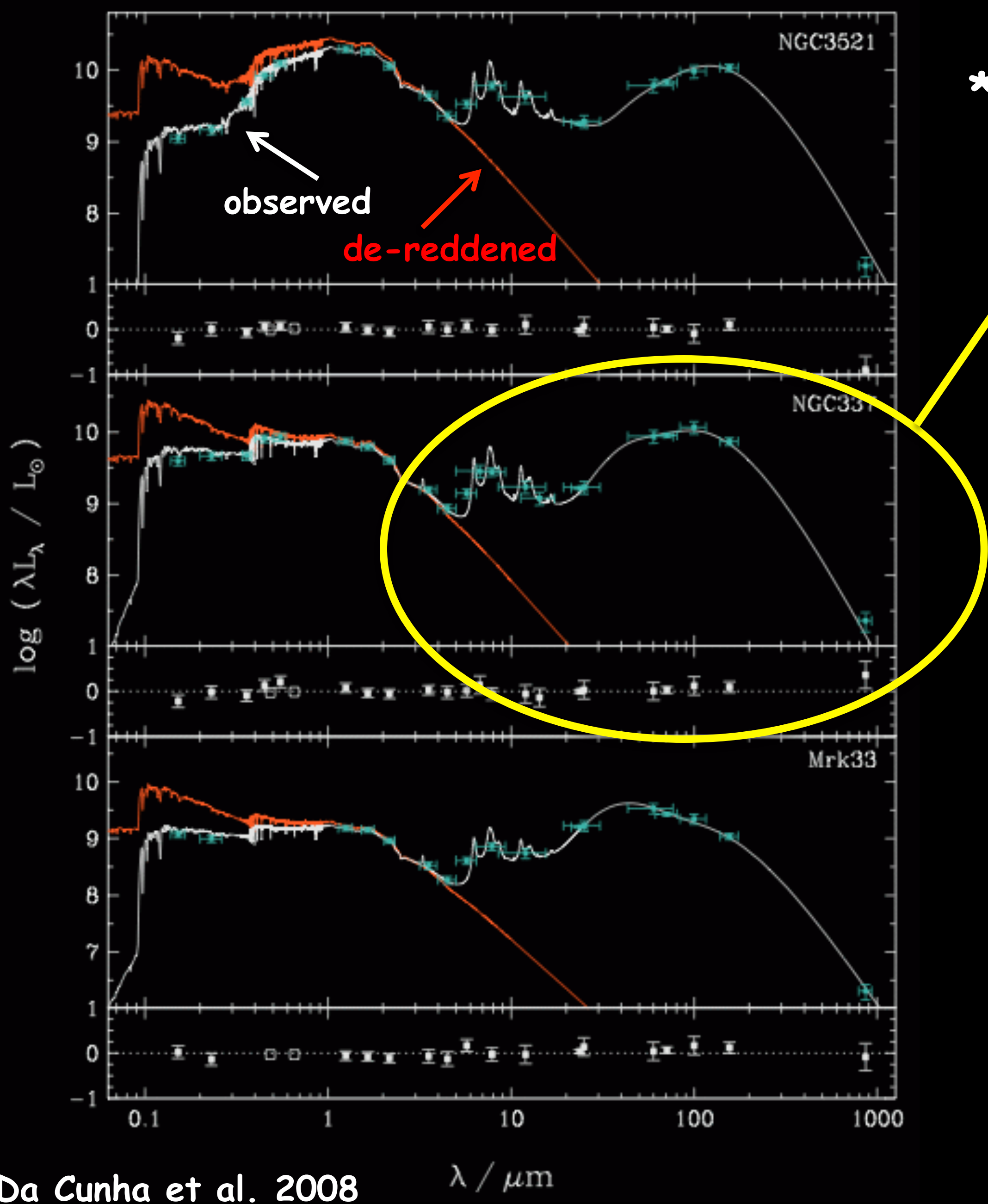
I - Surveying the sky in the FIR

A view on the hidden face of galaxies



Da Cunha et al. 2008

A view on the hidden face of galaxies

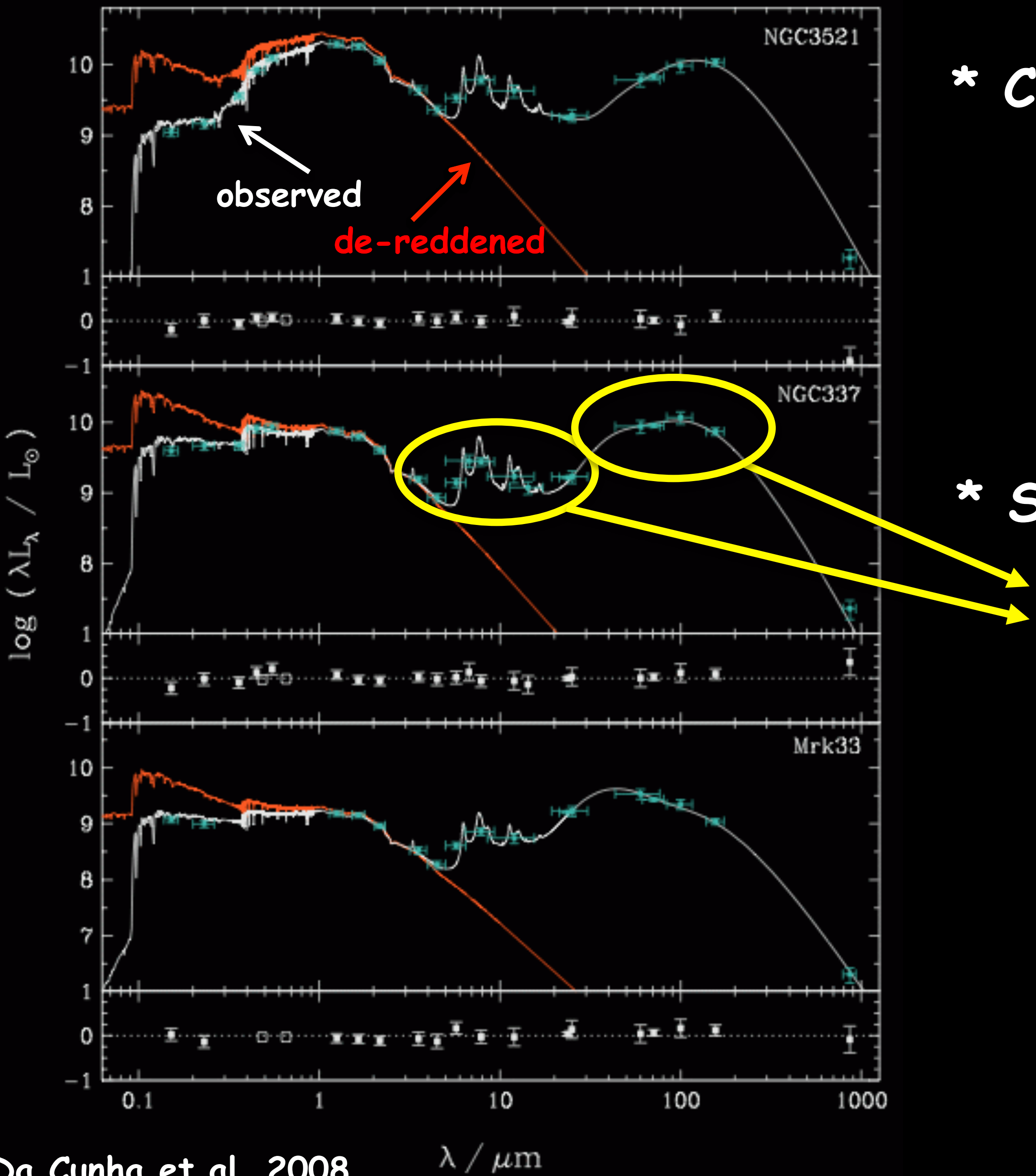


* Calorimetric function:
  measure the contribution of stellar light reprocessed by dust.

⇨ « extinction-free SFR »

Da Cunha et al. 2008

A view on the hidden face of galaxies



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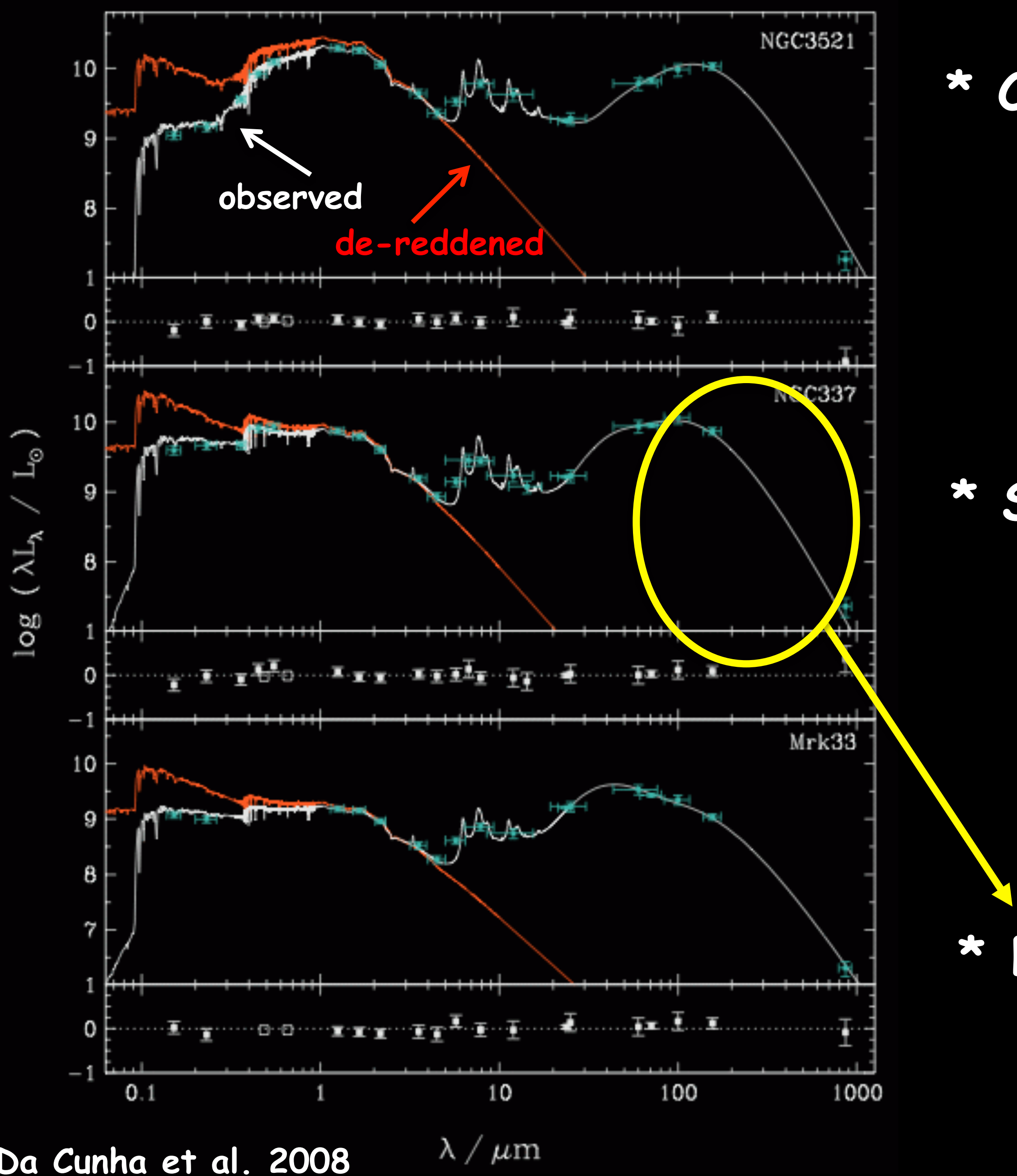
* Spectroscopy (PAHs, ionic lines, CO, …):
  reveal gas mass, excitation conditions, ISM ionizing properties, …

A view on the hidden face of galaxies



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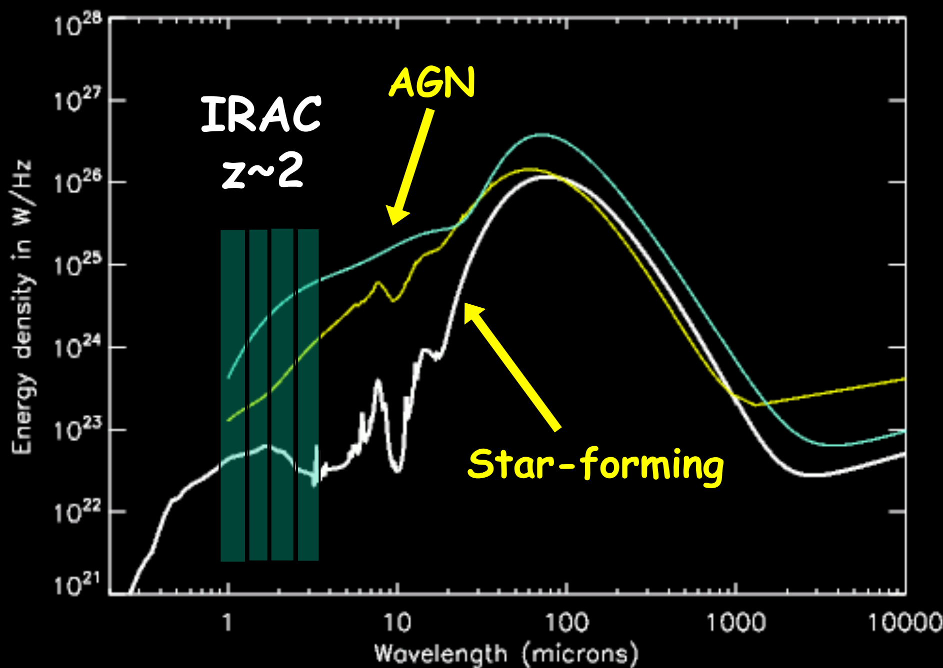
* Spectroscopy (PAHs, ionic lines, CO, …):
  reveal gas mass, excitation conditions, ISM ionizing properties, …

* Dust mass determination ("weighting" of the ISM, …), dust temperature, …

Obscured AGNs and elusive galaxies

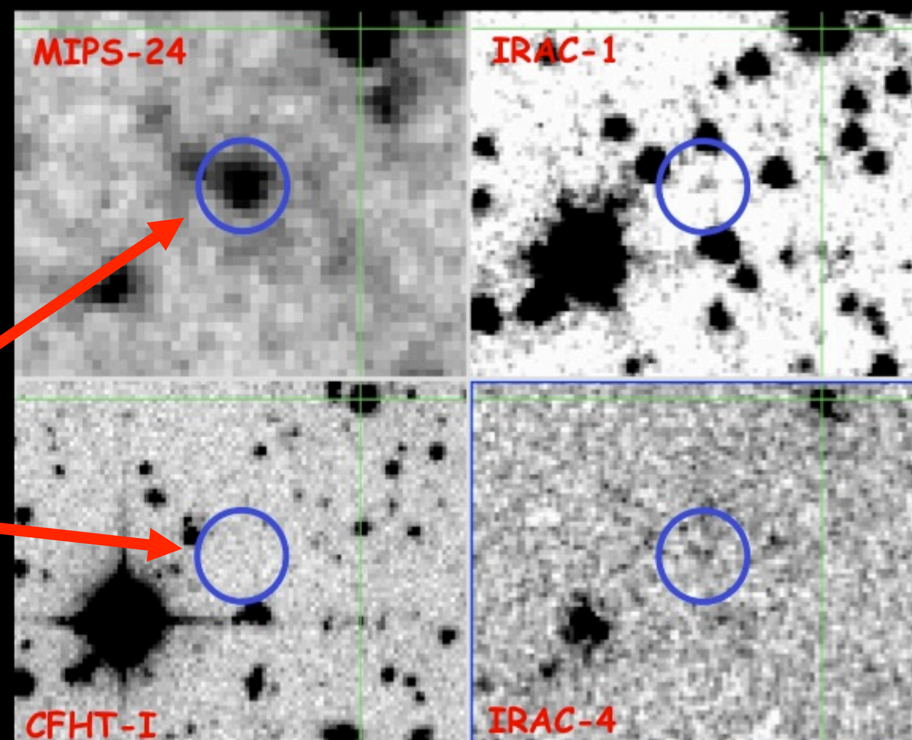


* Constraining nuclear accretion and SMBH growth

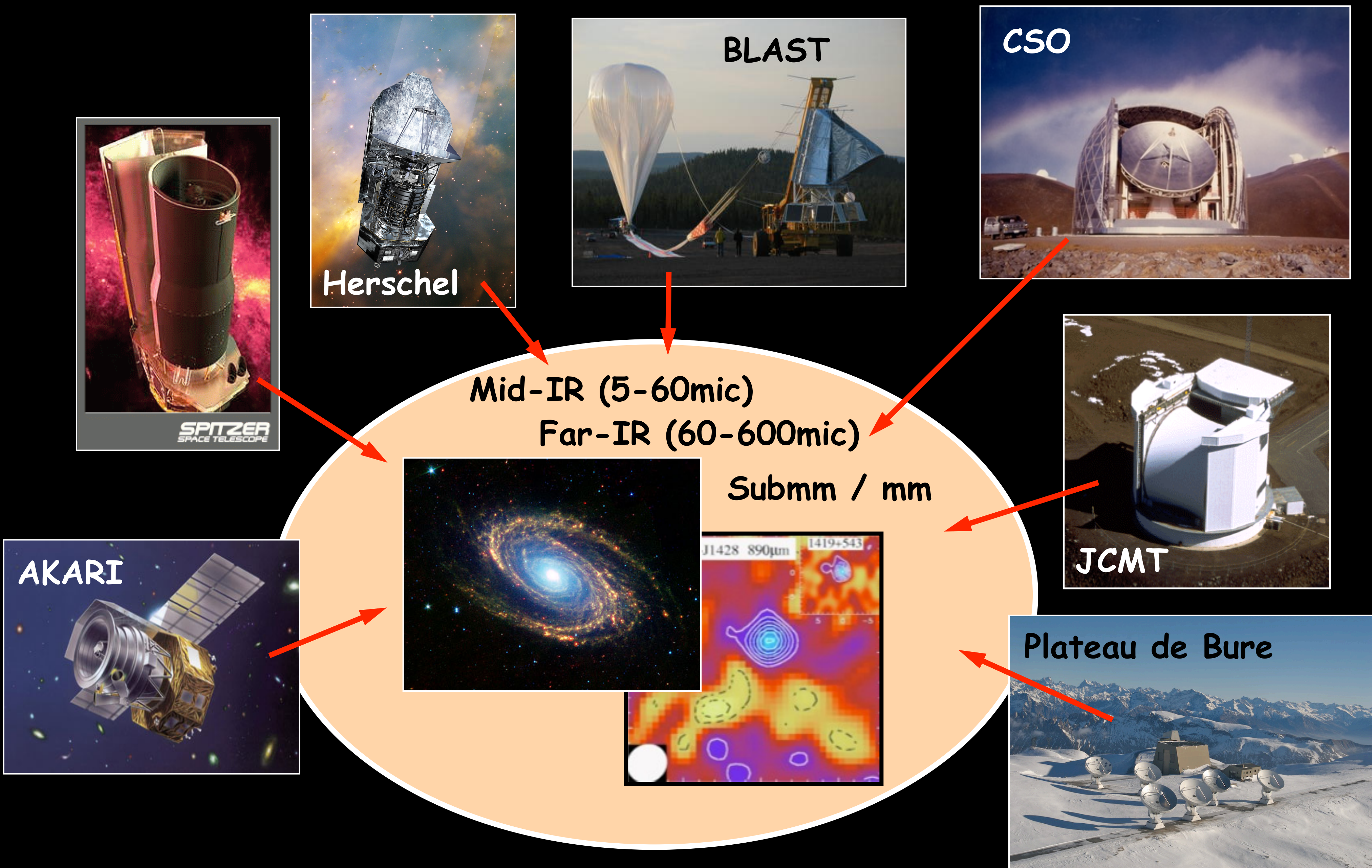
X-ray background synthesis models suggest a large population of obscured AGNs ($N_H > 10^{22}$ cm^{-2}) now revealed through their mid-IR signatures

* Probing the population of deeply-enshrouded SF galaxies missed at shorter wavelengths

- very high-z starburst candidates (e.g., SMGs w/o identification), proto-clusters ?
- moderate z but extremely dusty (e.g., “IRAC dropouts”, …)



A decade of far-IR experiments



Some drastic limitations…

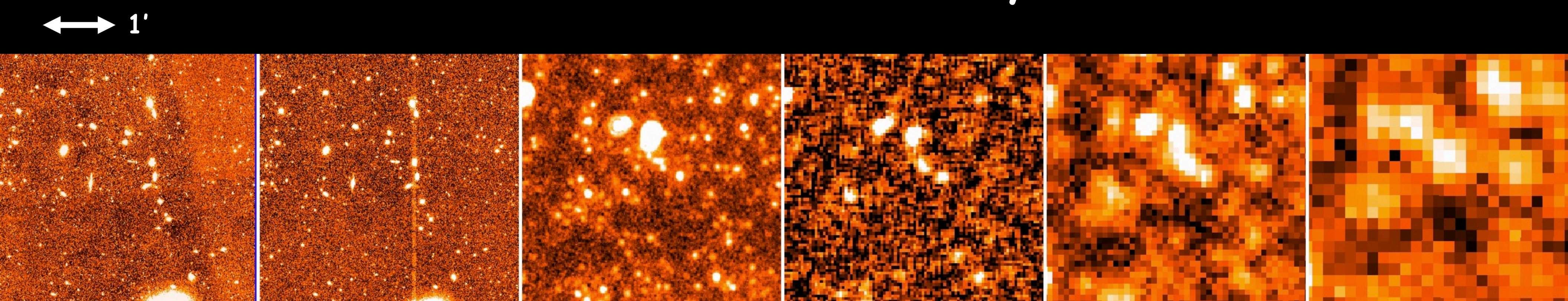
* Spitzer (80cm diameter): FWHM~6"/18"/38" at 24/70/160 μm

  5σ ~ 0.1mJy at 24μm for moderately-deep, 0.02mJy for ultra-deep (GOODS)

* Herschel (3.5m diam.): FWHM~8"/12"/18"/25"/37" at 100/160/250/350/500 μm

  * 5σ ~ 5mJy at 100μm for moderately-deep, 1.5mJy for ultra-deep (GOODS)
  * 5σ ~ 20mJy in the SPIRE bands (250/350/500μm). Confusion-limited surveys.

* Ground-based single dishes: 12-15m antennae (JCMT, APEX, ASTE, CSO): FWHM~18", λ~850μm-1.2mm, confusion-limited at ~2mJy



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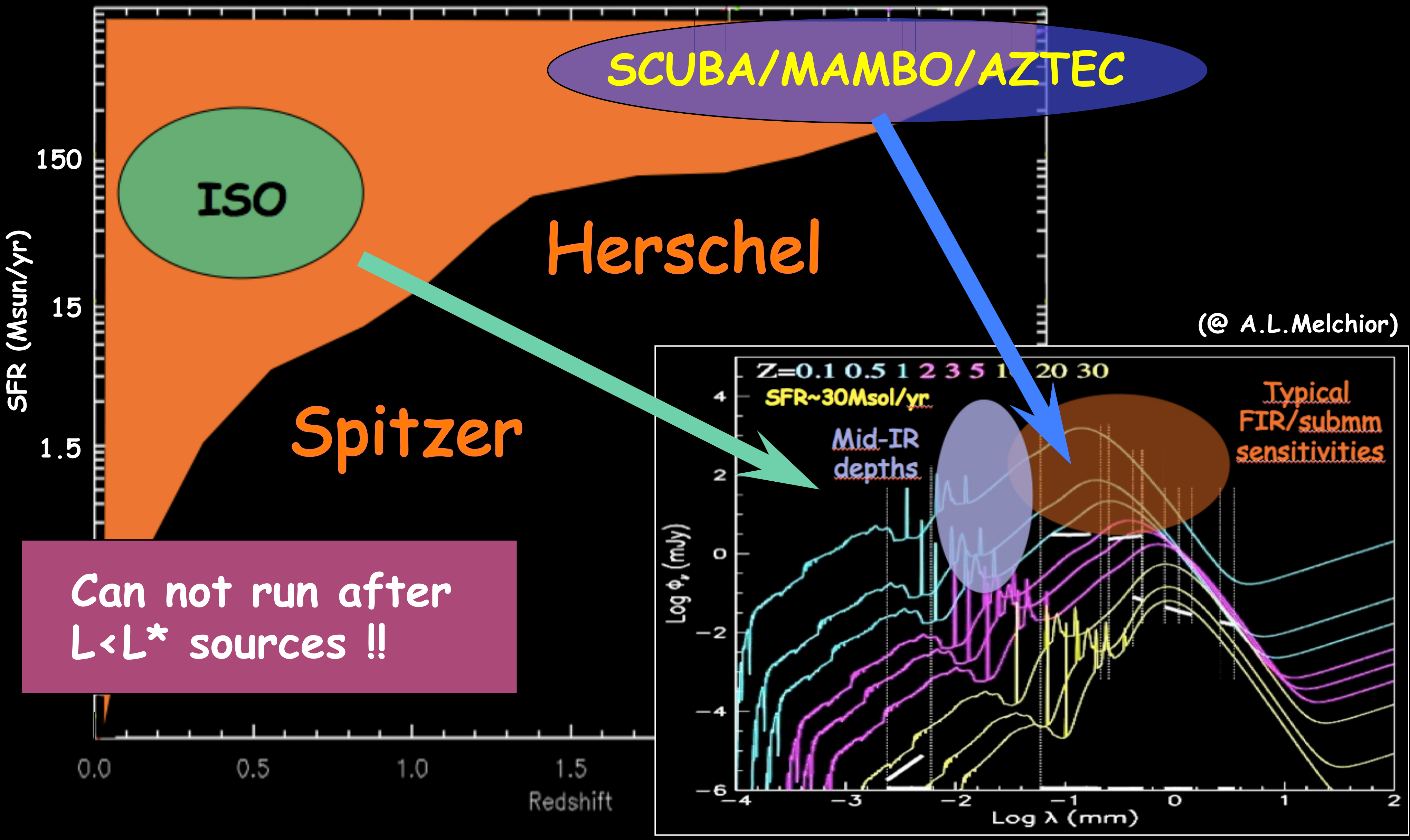
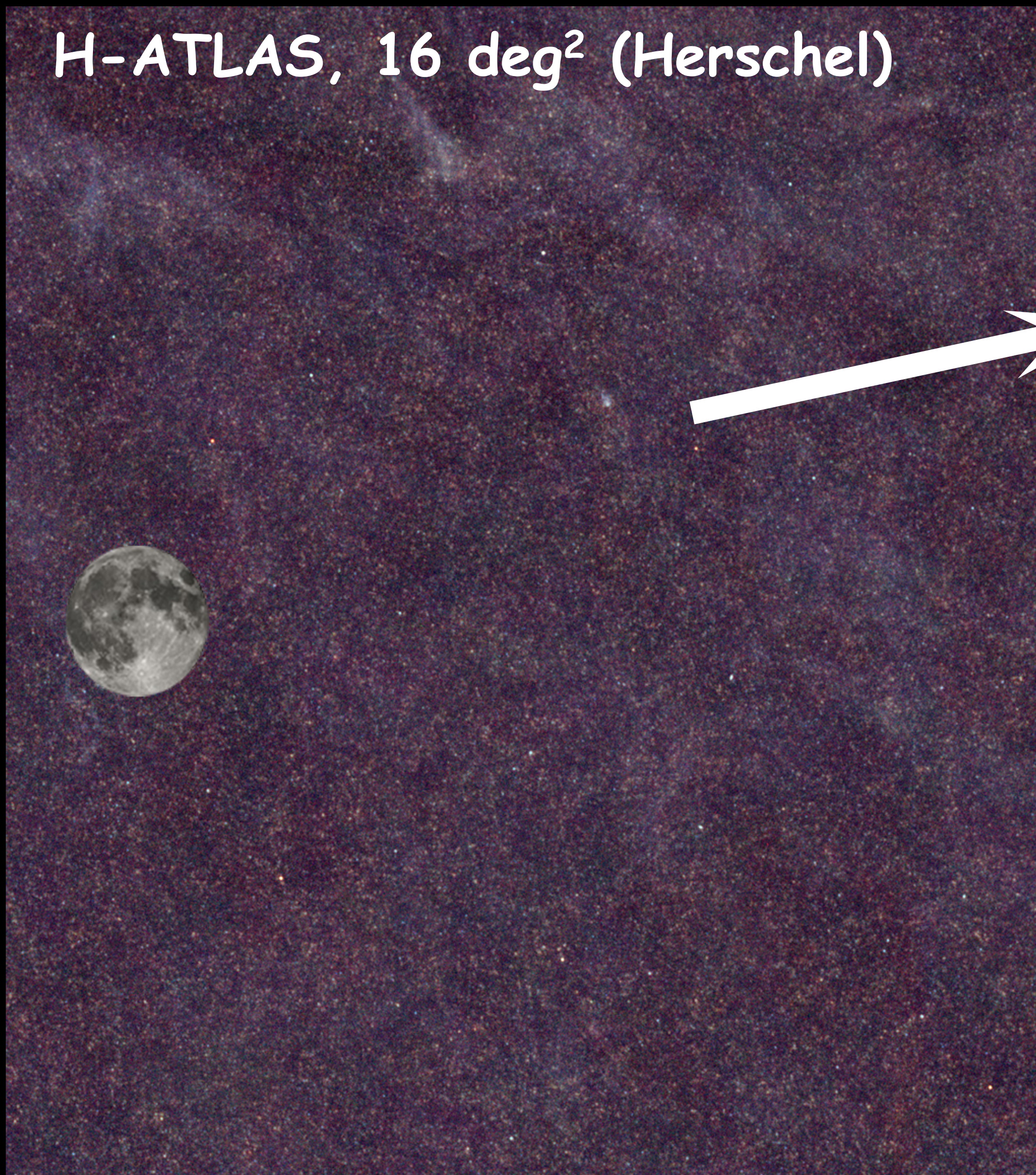


Far-IR surveys: fact sheet



Credits: H-ATLAS/PEP/GOODS-H

Follow the typical “wedding cake” strategy:

* Very large and shallow:
  e.g., H-ATLAS, 600hours, 5 bands, 550 deg^2

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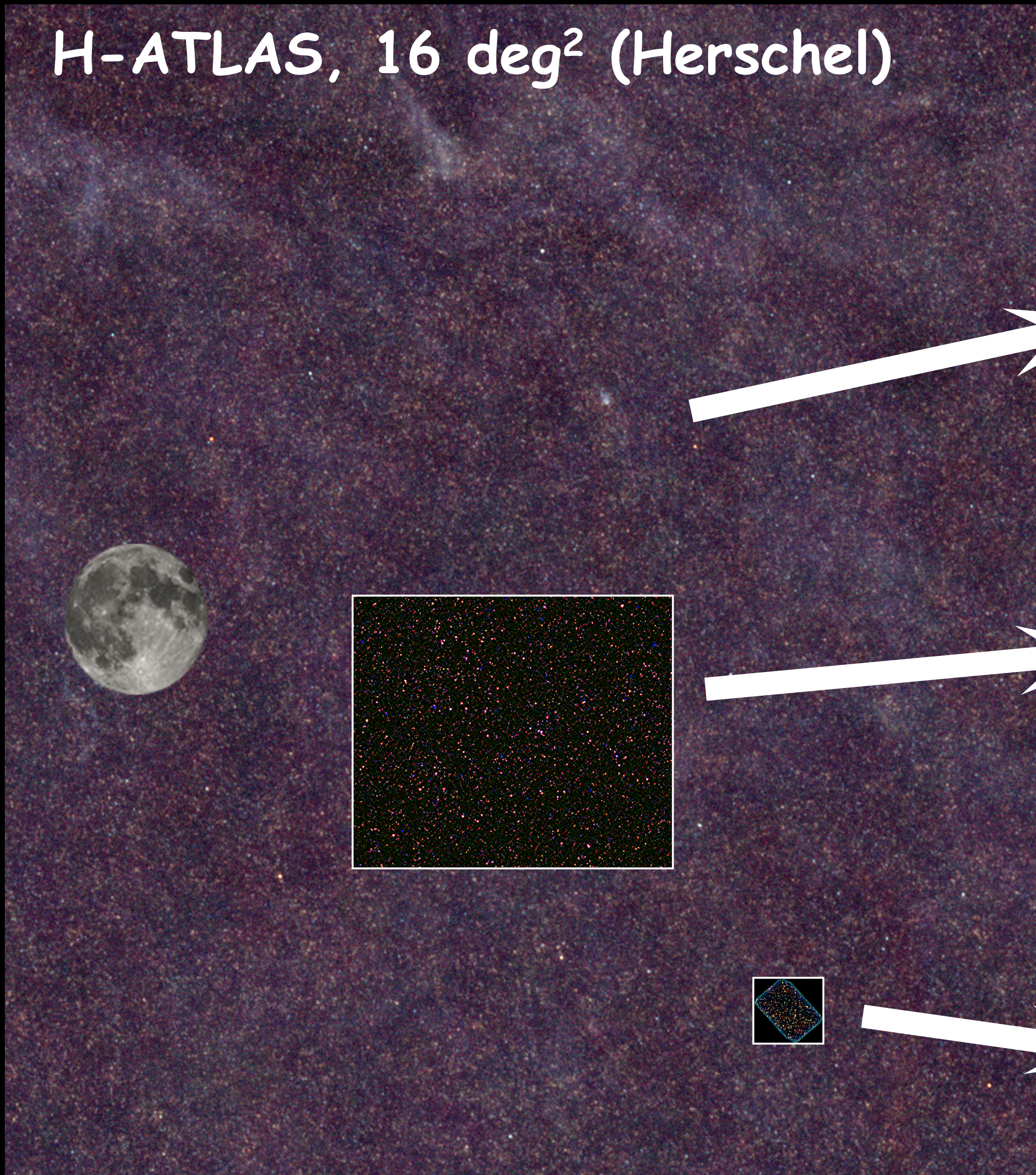

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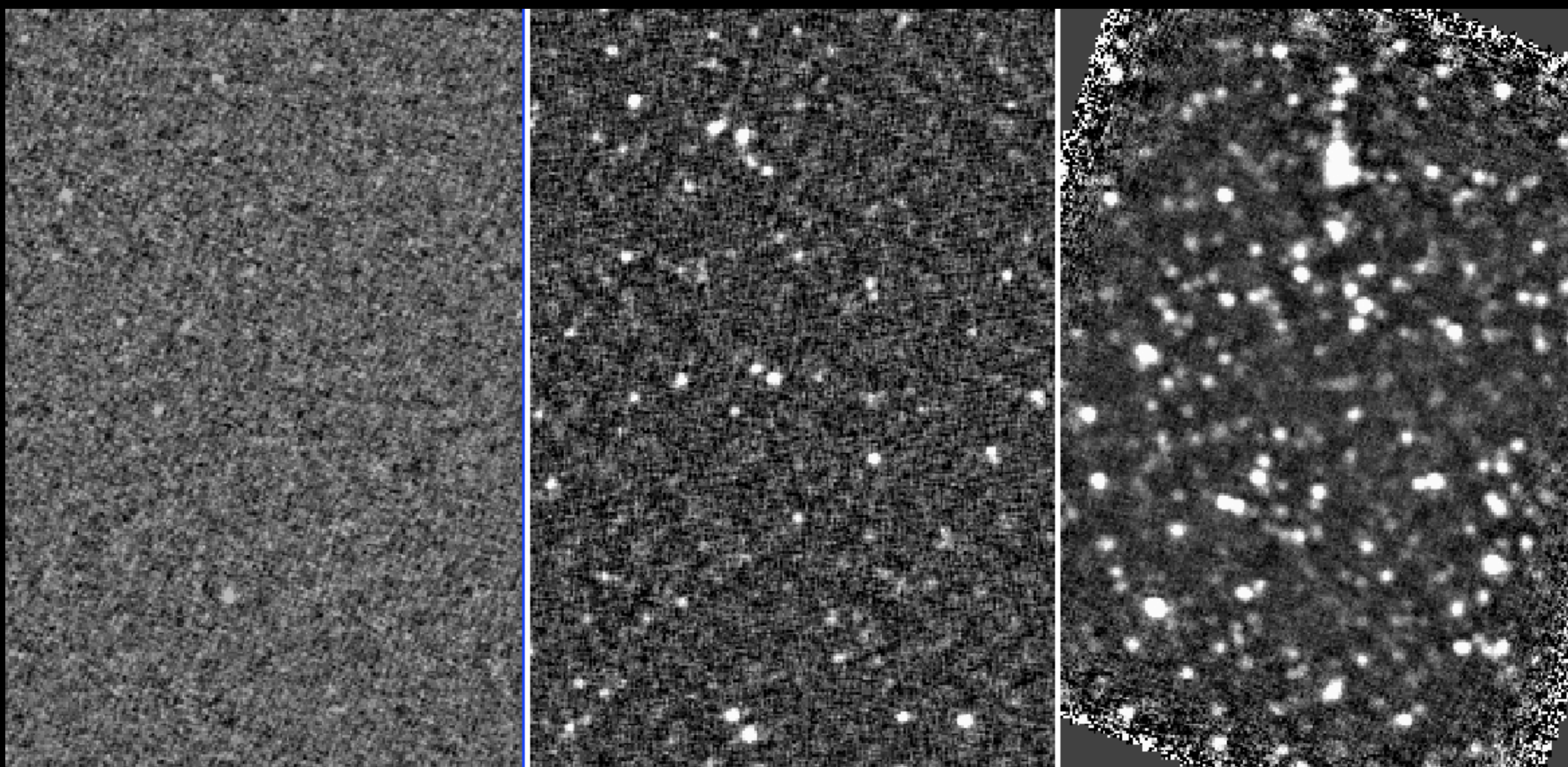
* "intermediate" (deep + wide):
  e.g., COSMOS, $2deg^2$, 400h at 24µm, 200h at 100/160µm

* Small and ultra-deep:
  e.g., GOODS-Herschel, 360h for 300 $arcmin^2$

Far-IR surveys: fact sheet

Comparison at 160μm: 5σ ~ 120mJy, 12mJy and 4mJy for H-ATLAS, COSMOS and GOODS, respect.

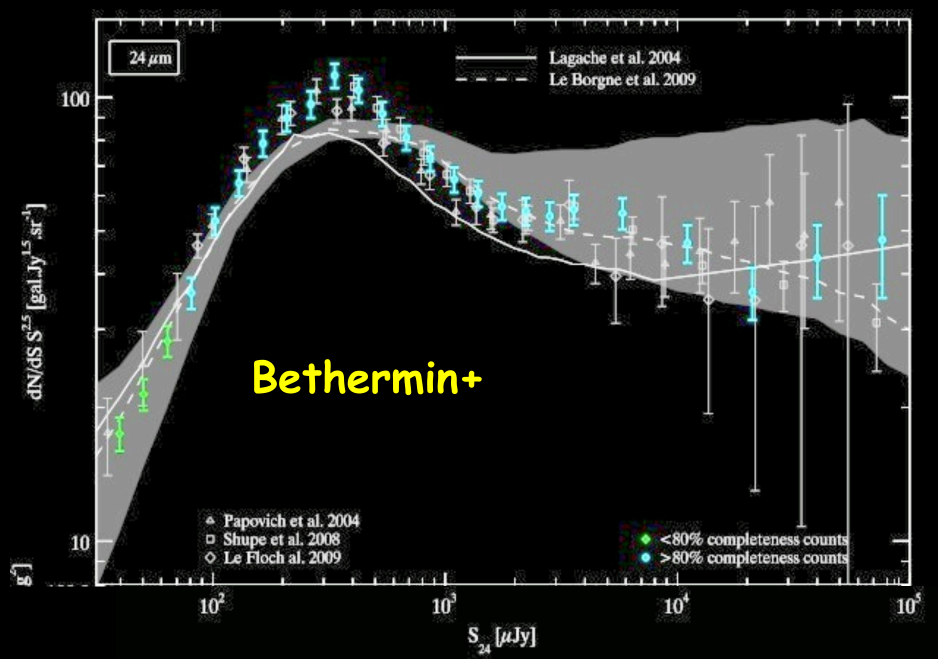


H-ATLAS | COSMOS | GOODS-South

Credits: H-ATLAS/PEP/GOODS-H

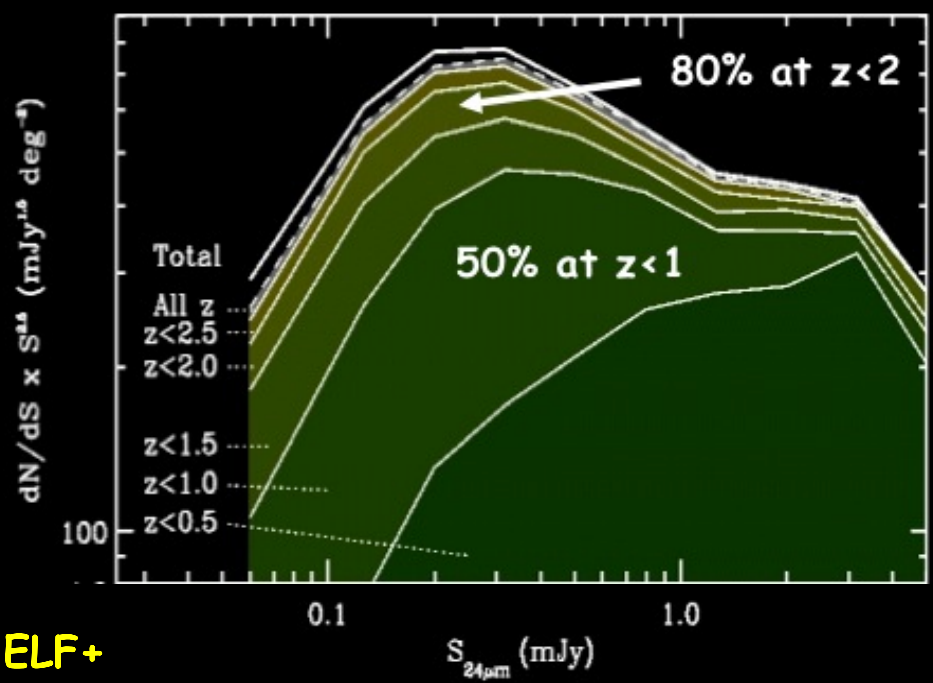
II - IR surveys: some key results

Source number counts

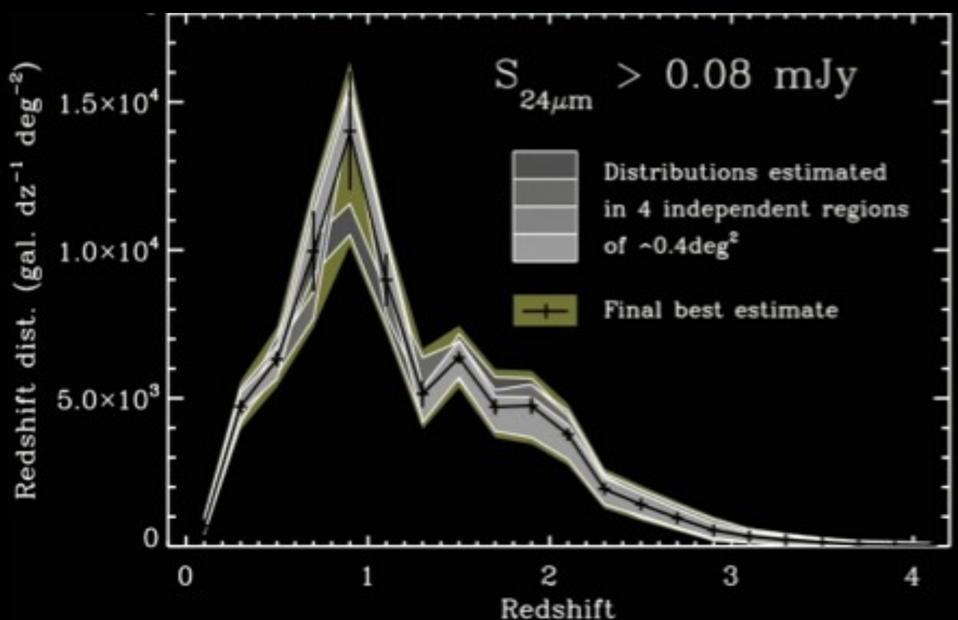


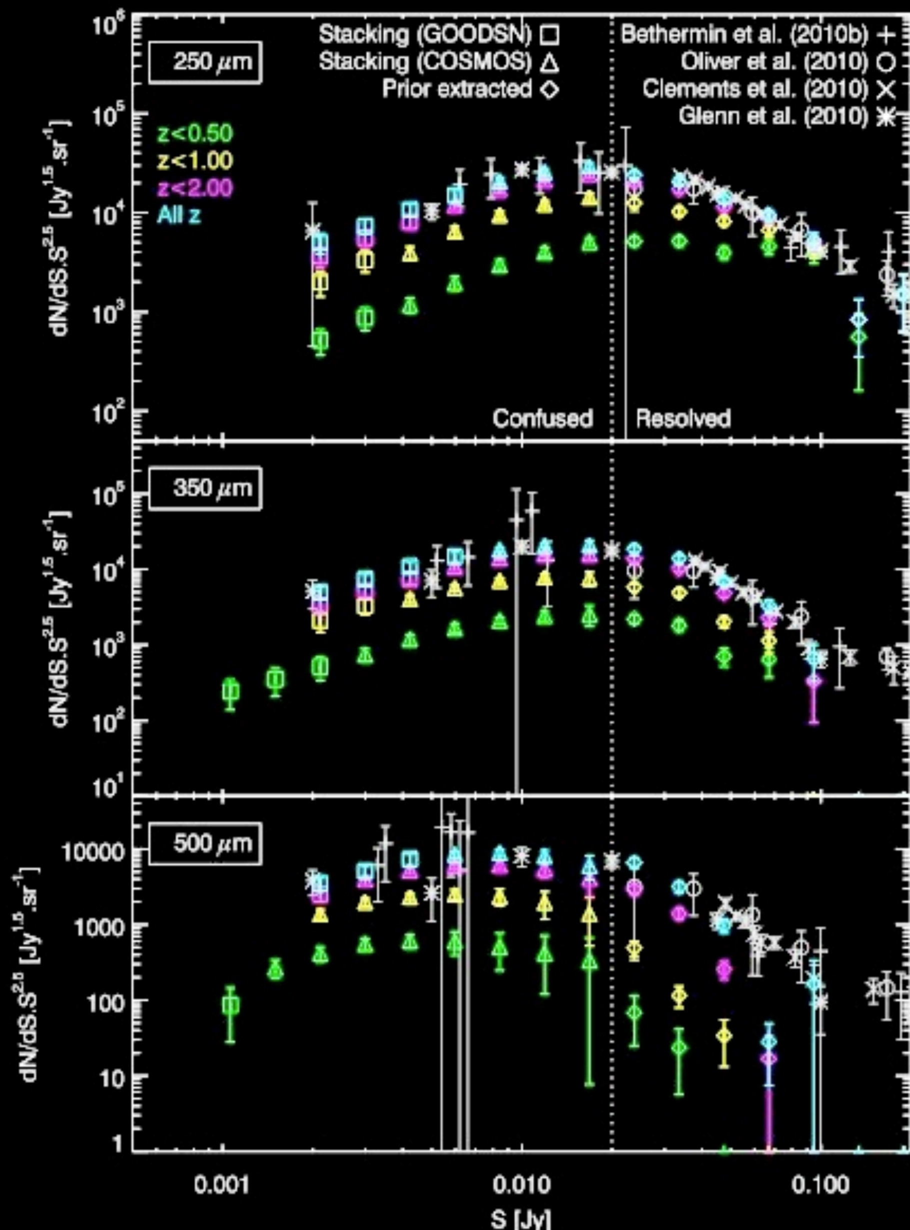
Berta+

Source counts and N(z)



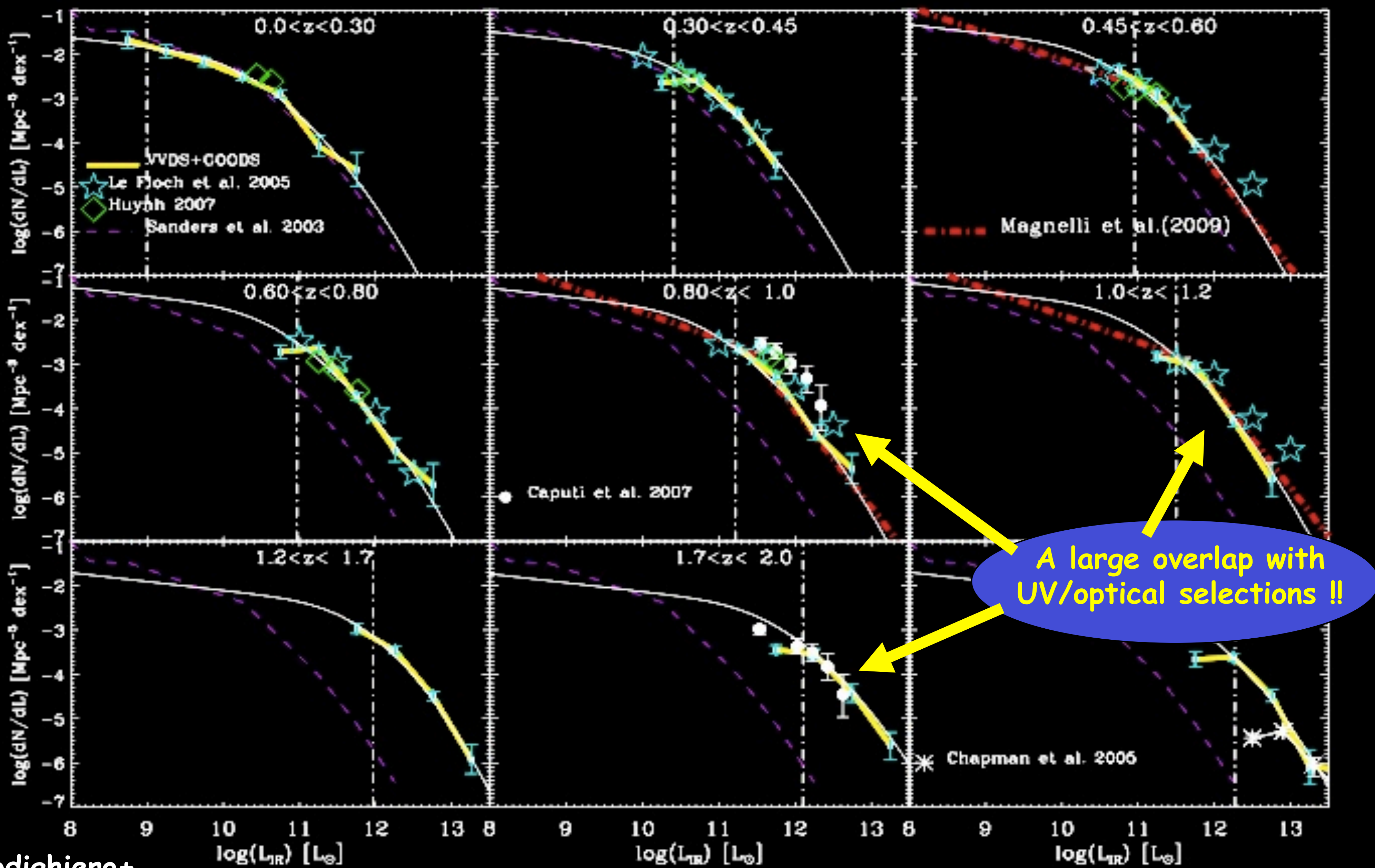
ELF+





Bethermin+

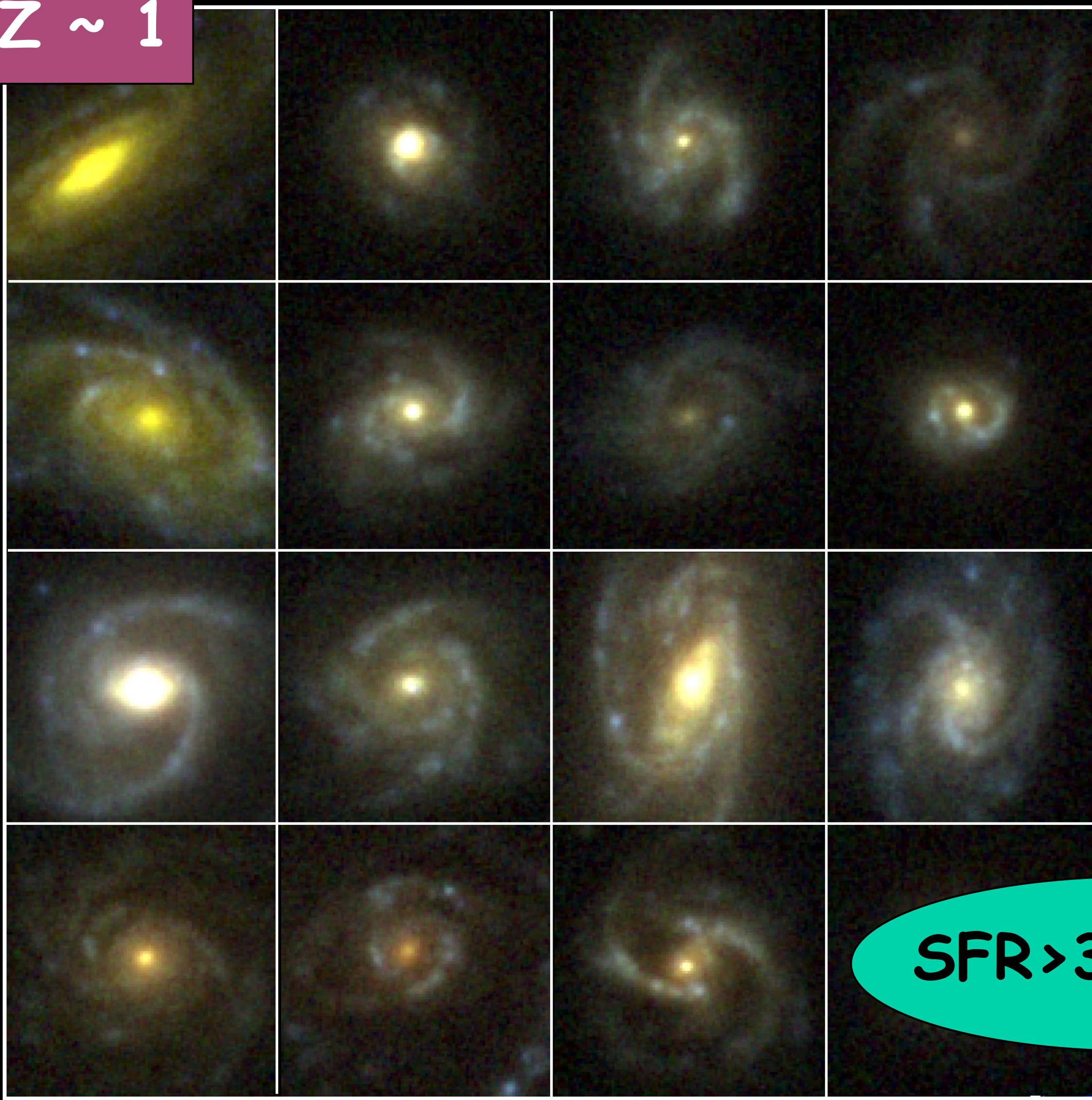
IR luminosity function at 0<z<3



Rodighiero+

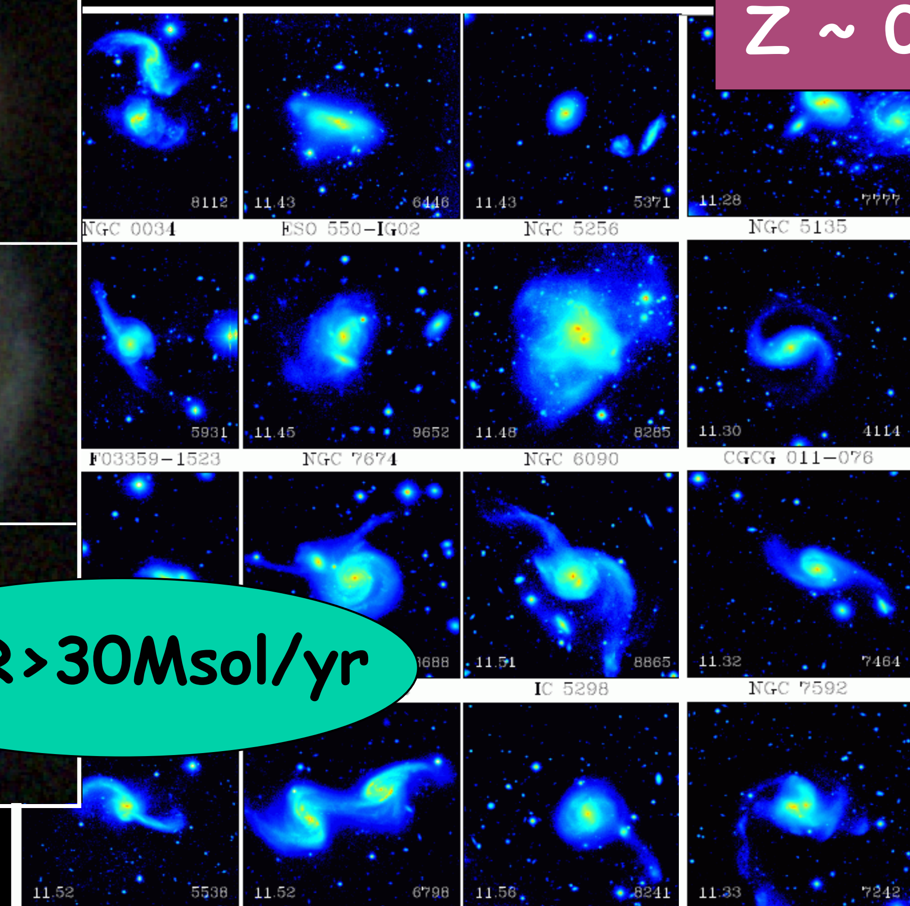
Morphology evolution

Z ~ 1



Much larger fraction of spirals/disks at high-z for a fixed cut in SFR (higher gas fraction)

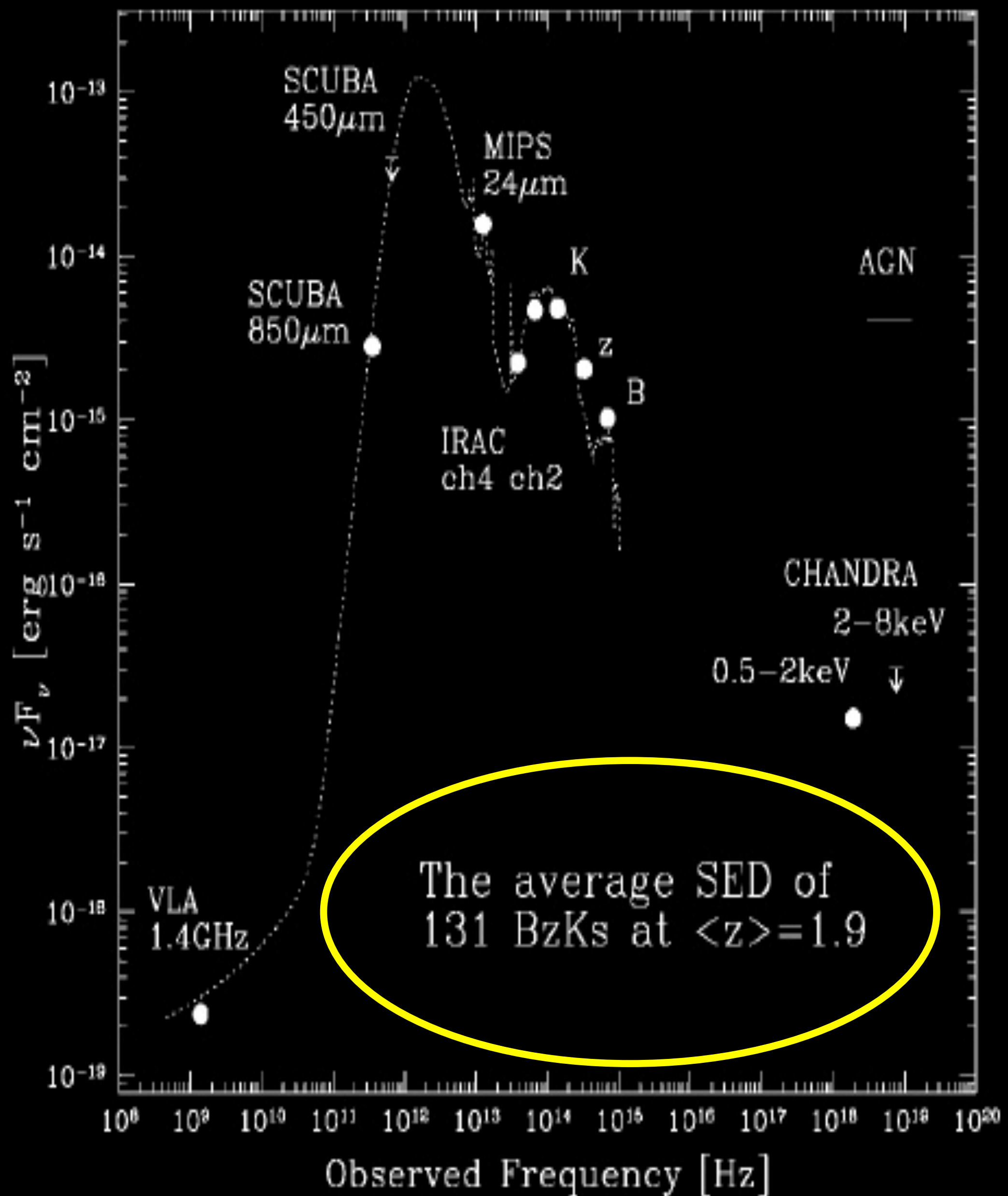
Z ~ 0

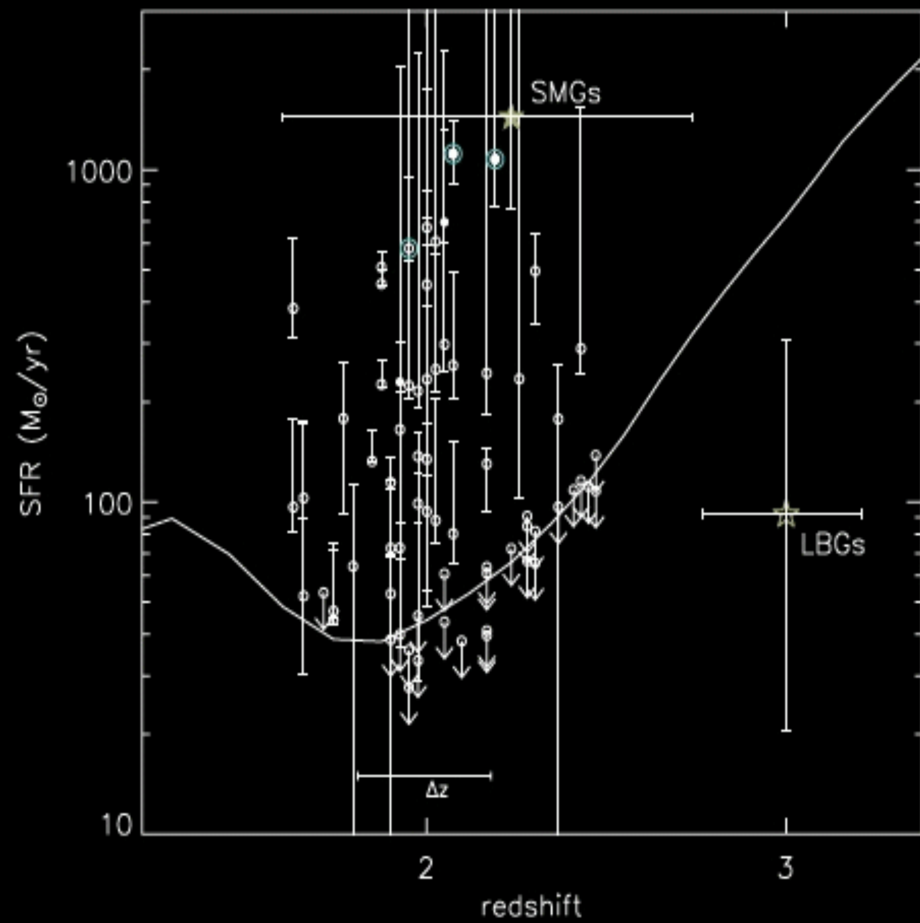


SFR>30Msol/yr

Bell+, Melbourne+, Jogee+, Lotz+, Sanders+

Star-forming BzKs and DRGs

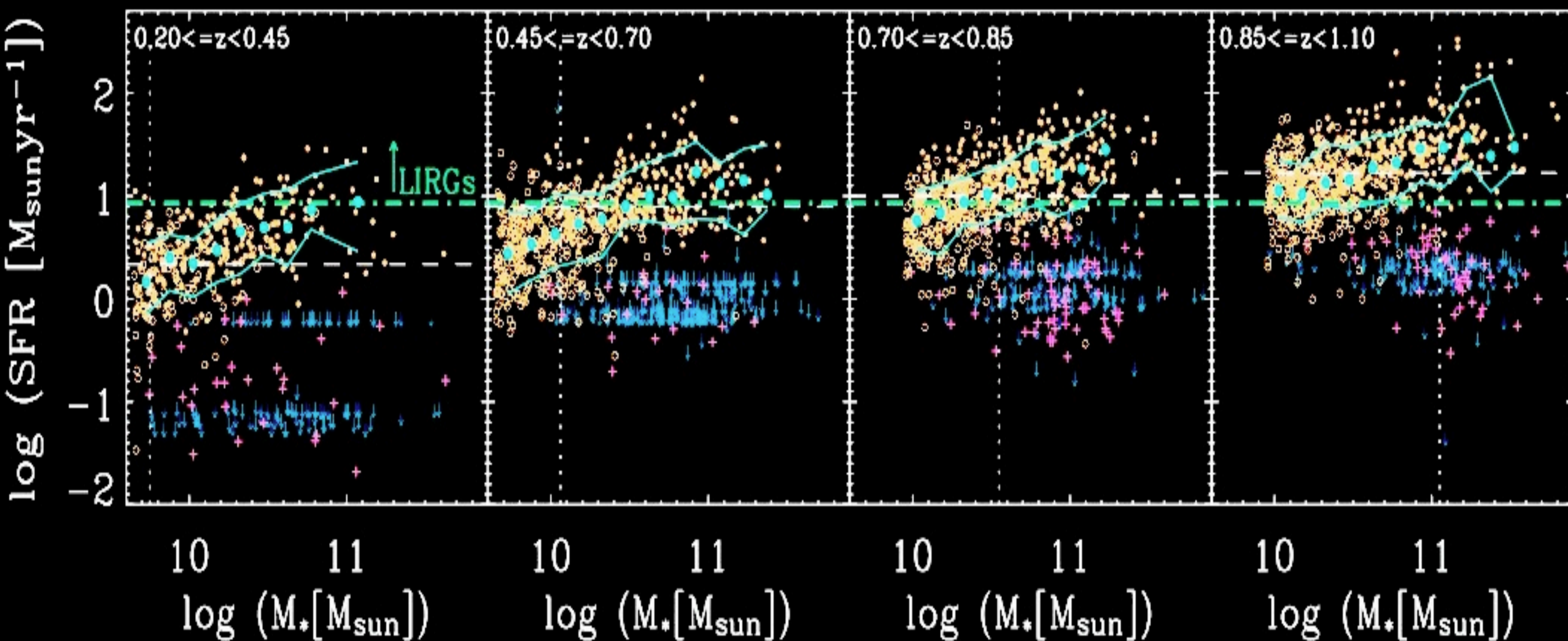




* High SFRs in (massive) BzKs DRGs, BM/BX, …

(Daddi+, Webb+, Papovich+, Reddy+,…)

The star-forming galaxy main sequence

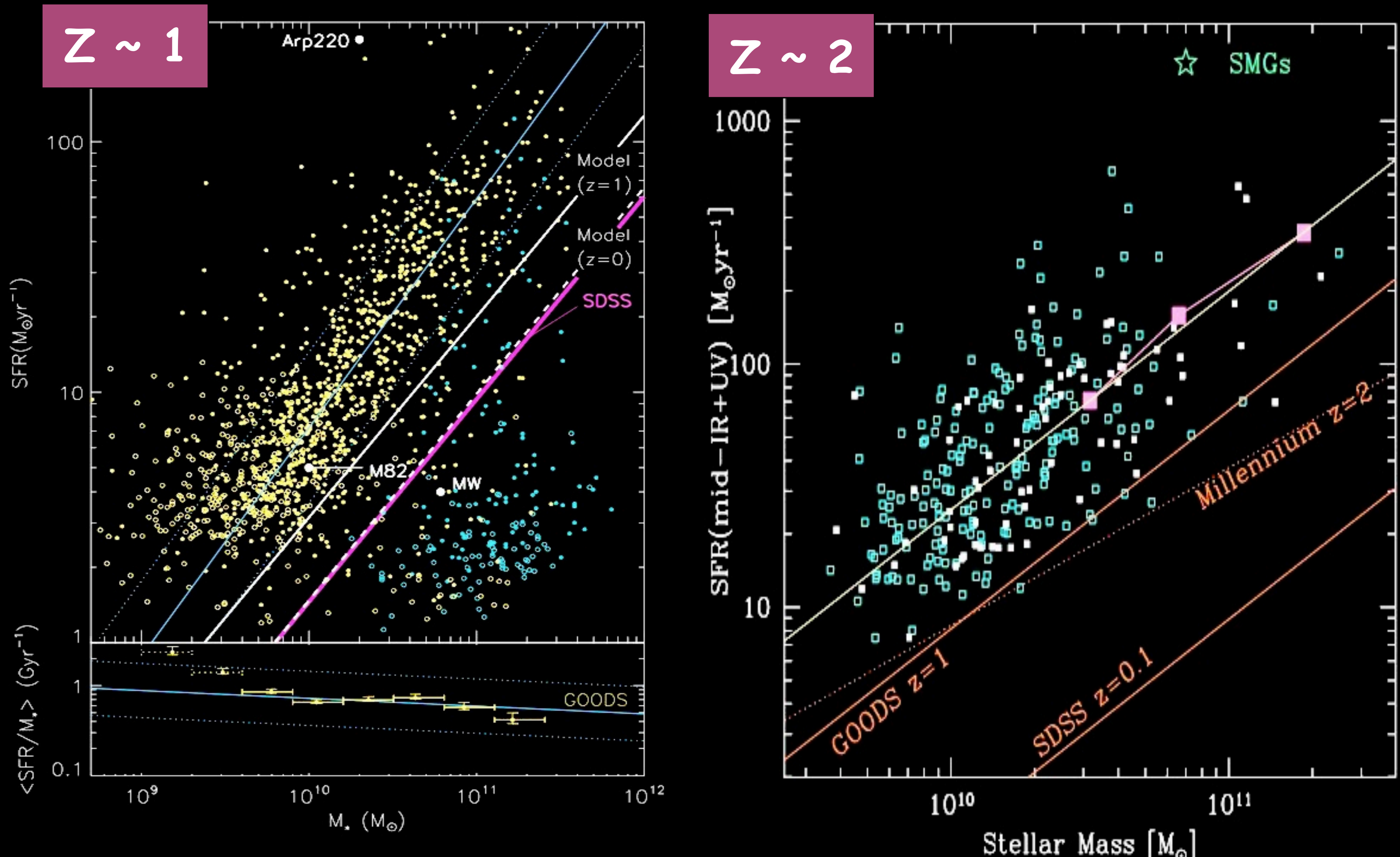


* A star-forming galaxy "main sequence" (Noeske et al. 2007).

Correlation between stellar mass and SFR

(sSFR almost mass-independent and increasing with z)

Mass / SFR relation

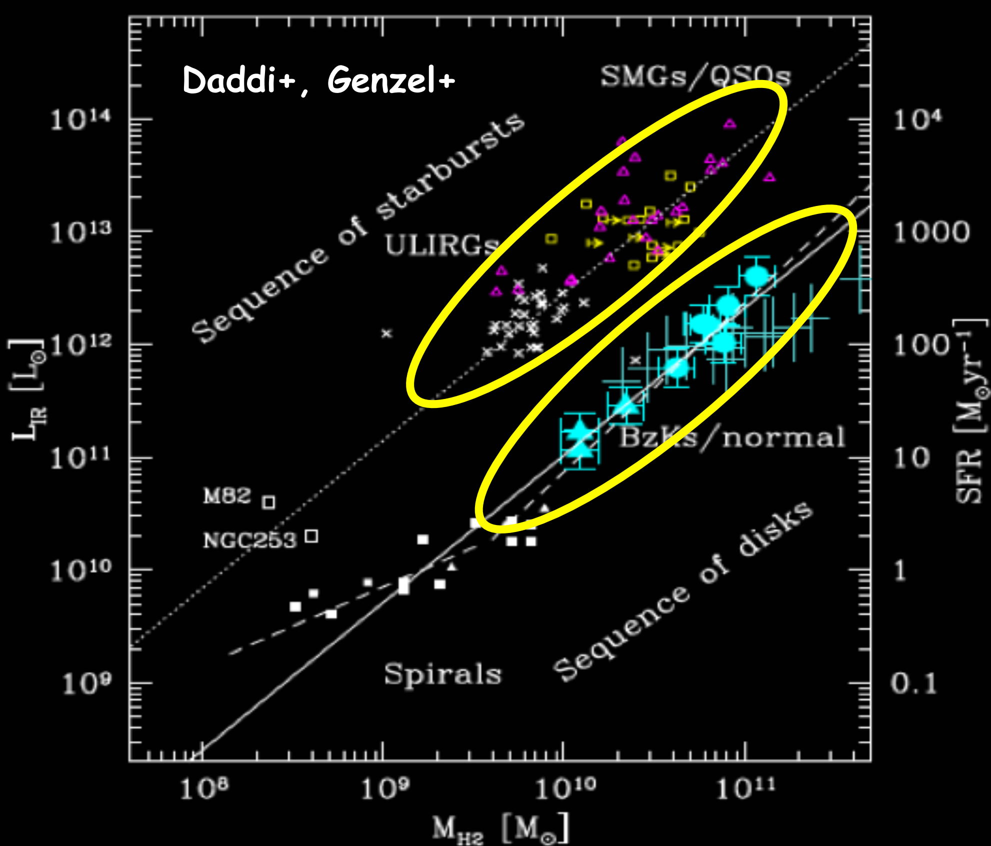


Elbaz+, Daddi+, Karim+, Pannella+, Peng+, Damen+, …

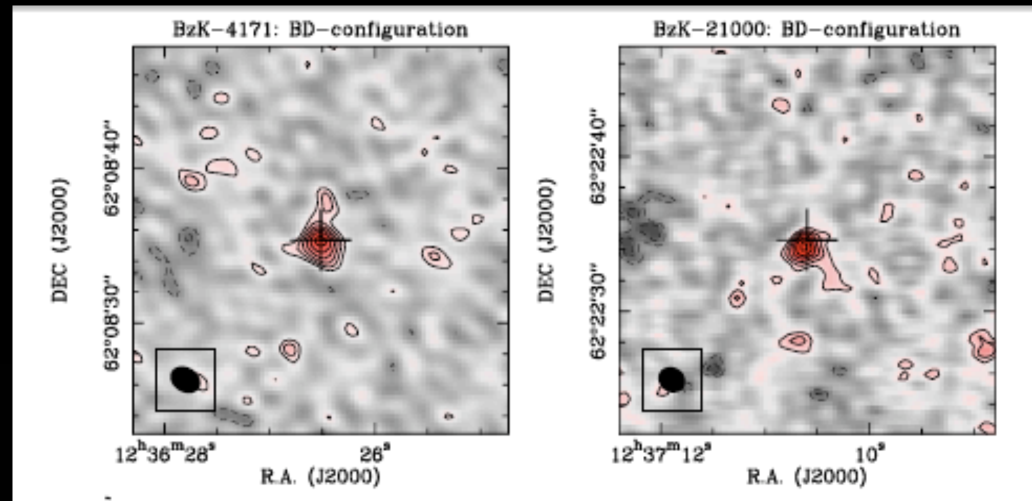
SFR / Mgas relation: 2 modes of SF ?

Follow-up of high star-forming galaxies in CO (Daddi+, Dannerbauer, Tacconi+)

Detection of luminous "starbursts" (e.g., SMGs) and "more typical" SF galaxies (galaxies following the SF main sequence)



Dannerbauer et al. 2009



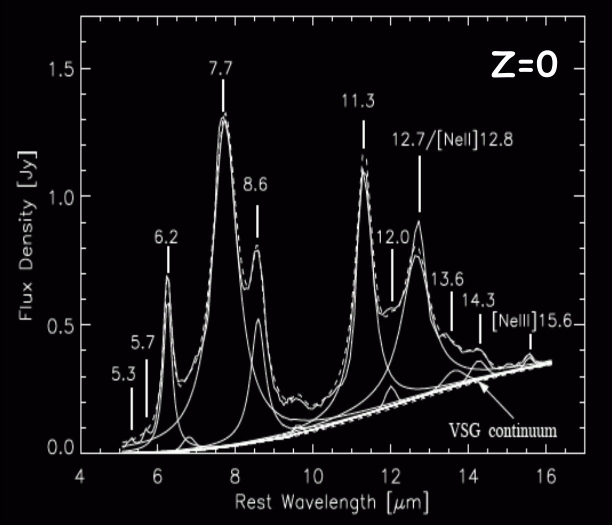
Schmidt-Kennicutt law at high-z:

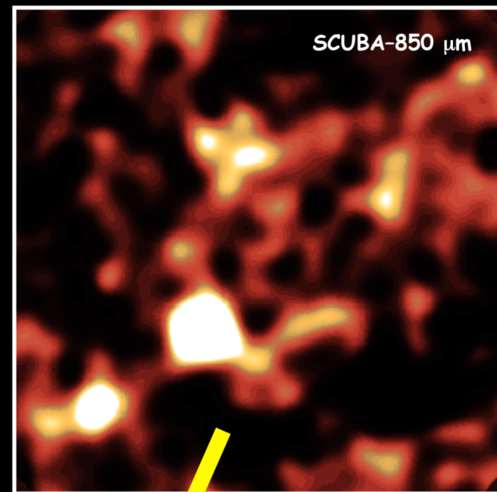
- "typical" SF galaxies follow the same relation as local disks
- Compact low-z ULIRGs and SMGs follow a separate correlation

* Reveals different modes of stellar mass assembly ?
 - compact / starbursts related to merging ?
 - extended SF and steady evolution ?

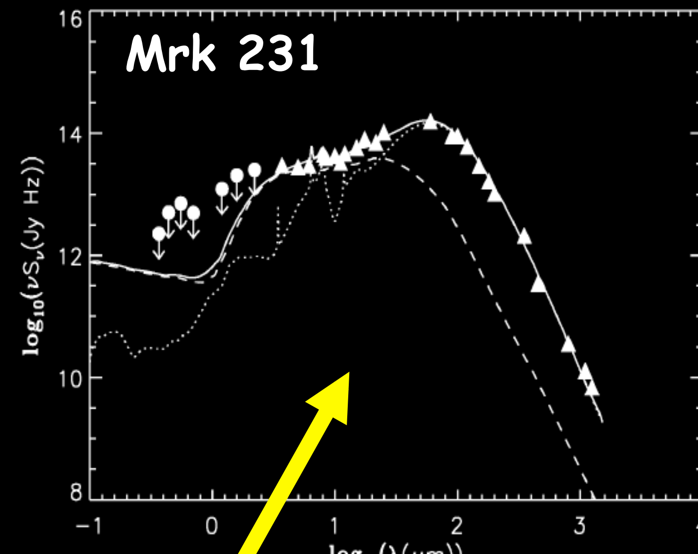
Submm/radio selection

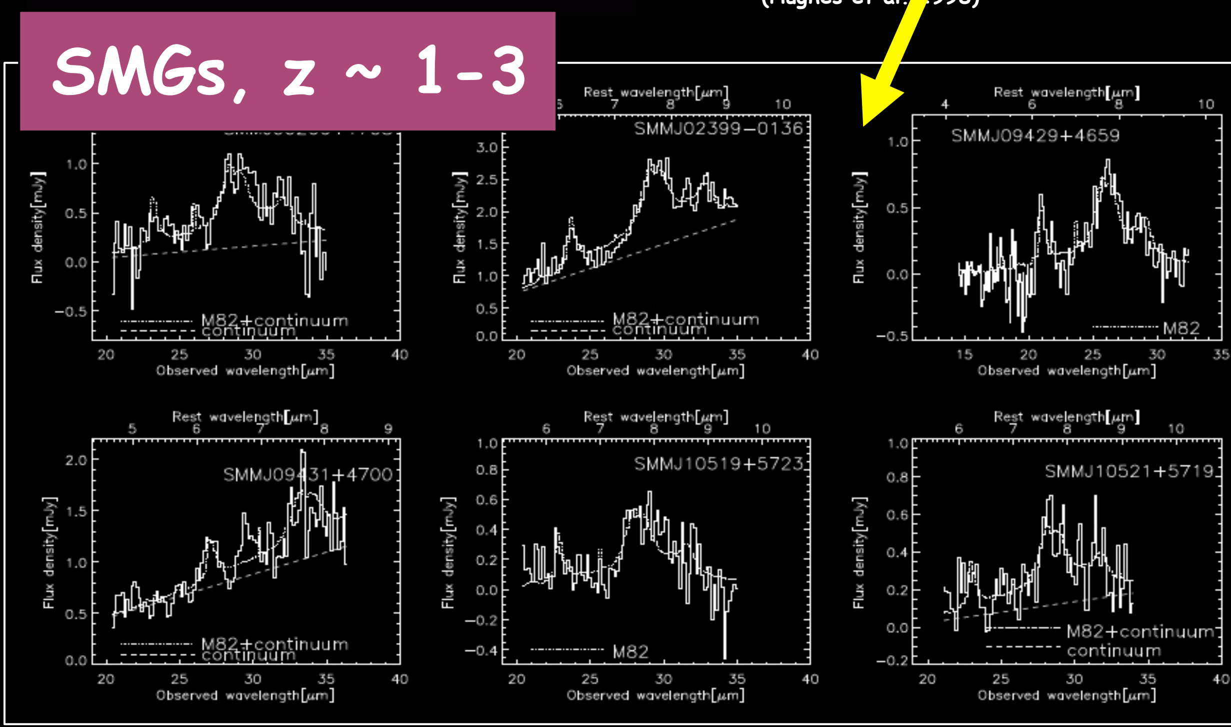
Egami et al. 2004, Pope et al. 2005/6, Lutz et al. 2005, Valiante et al. 2007, Farrah et al. 2003





(Hughes et al. 1998)





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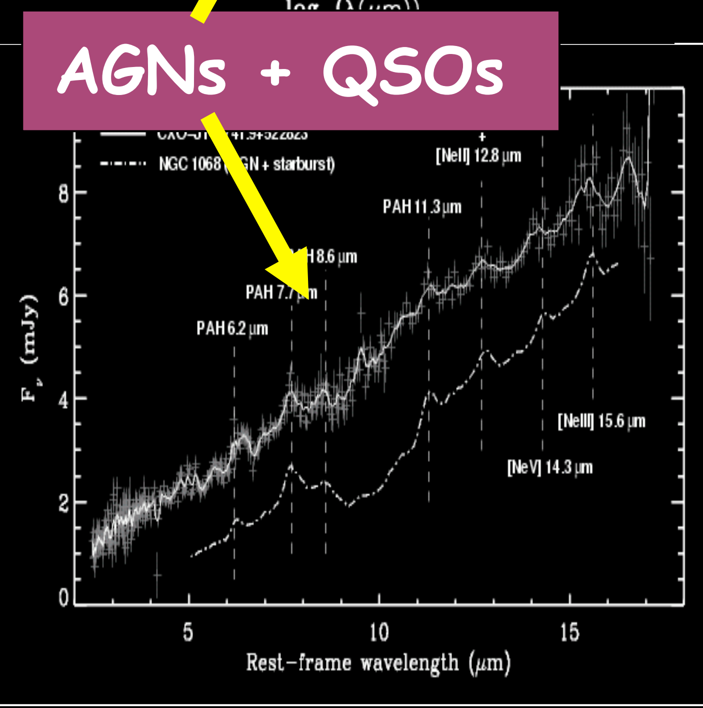
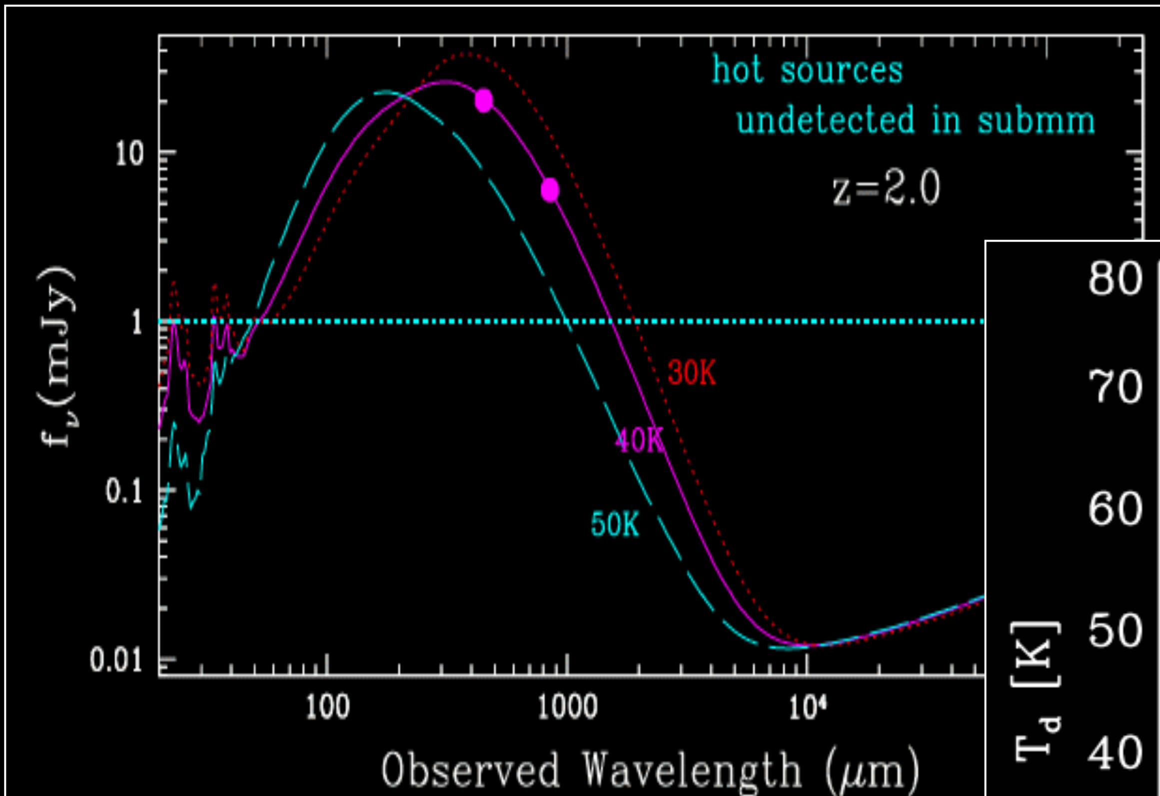
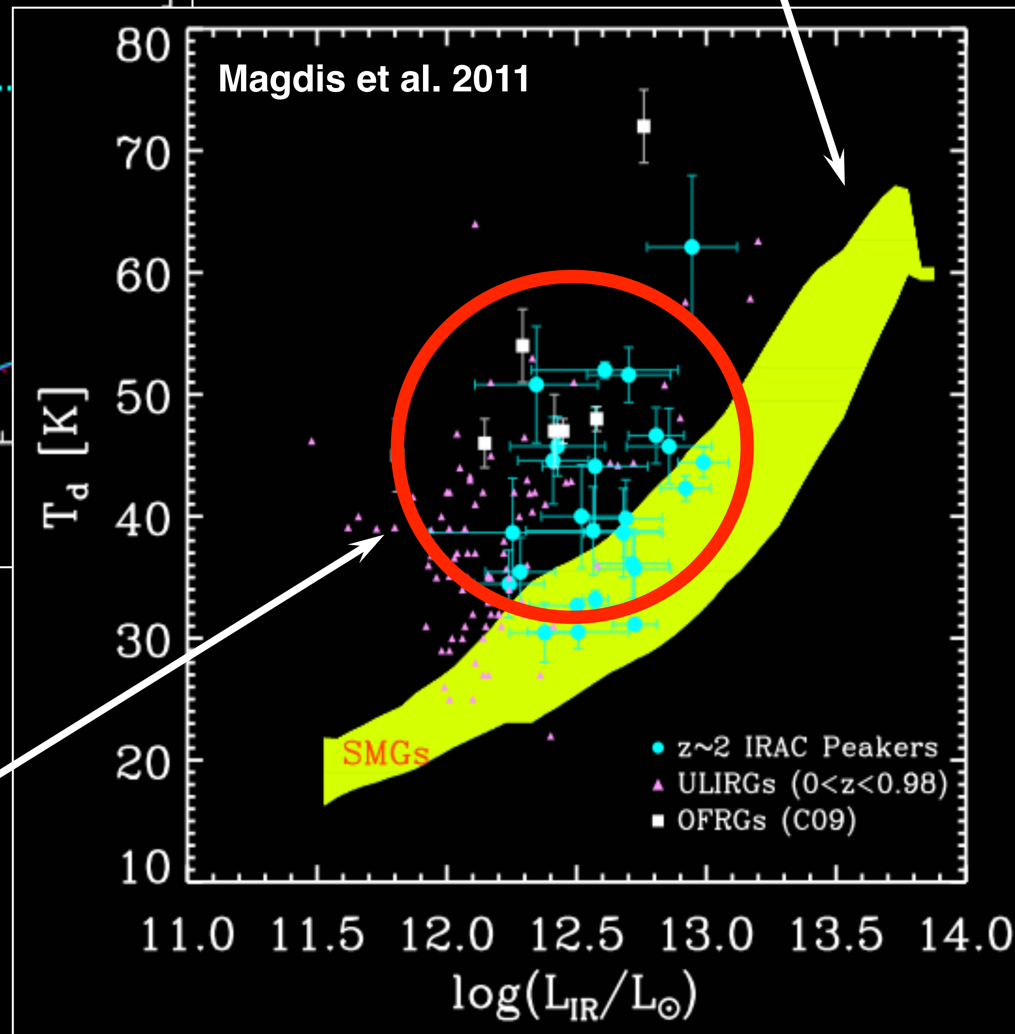


Dust temperature and selection effects



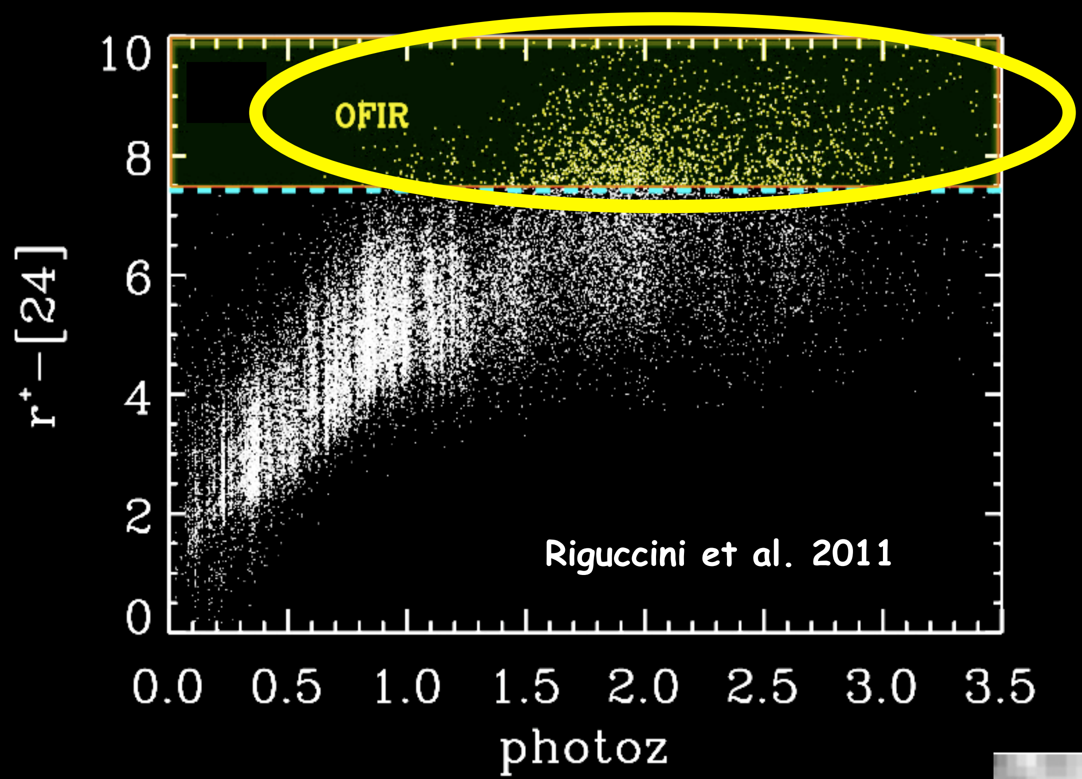
Chapman et al. 2005

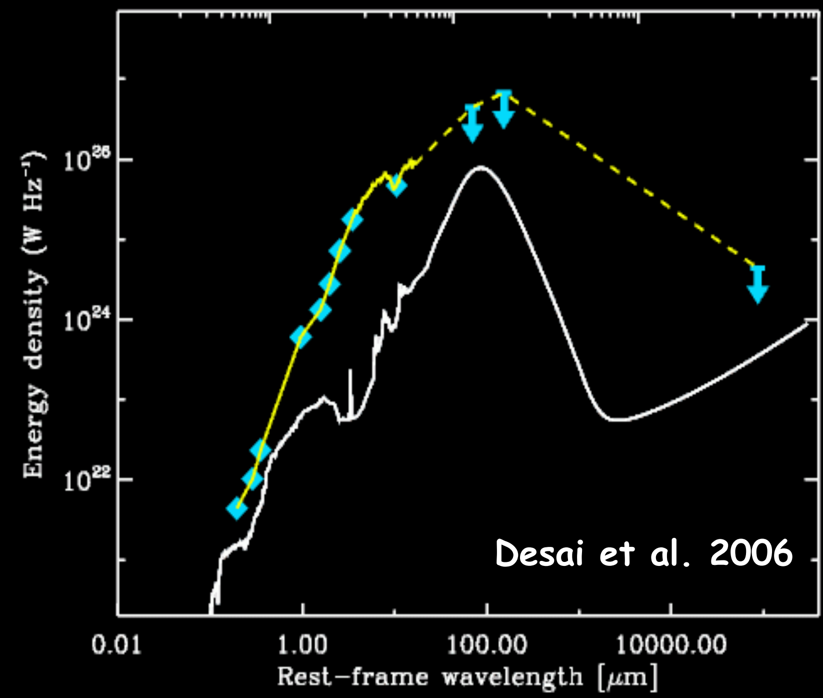
"T_{dust} - L_{ir}" relation for SCUBA sources



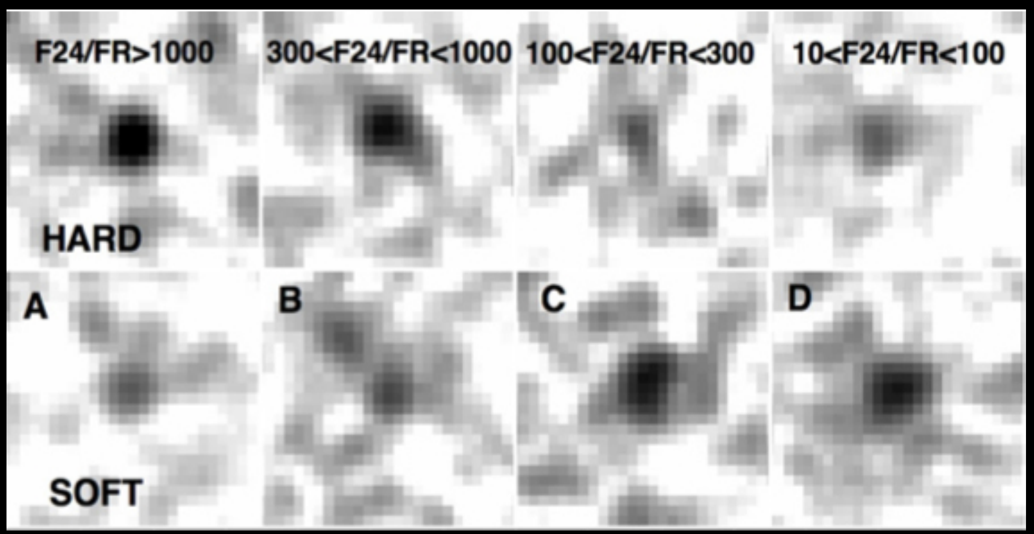
Herschel reveals a less biased view on dust temperatures in high-z galaxies

Obscured AGNs and optically-faint sources





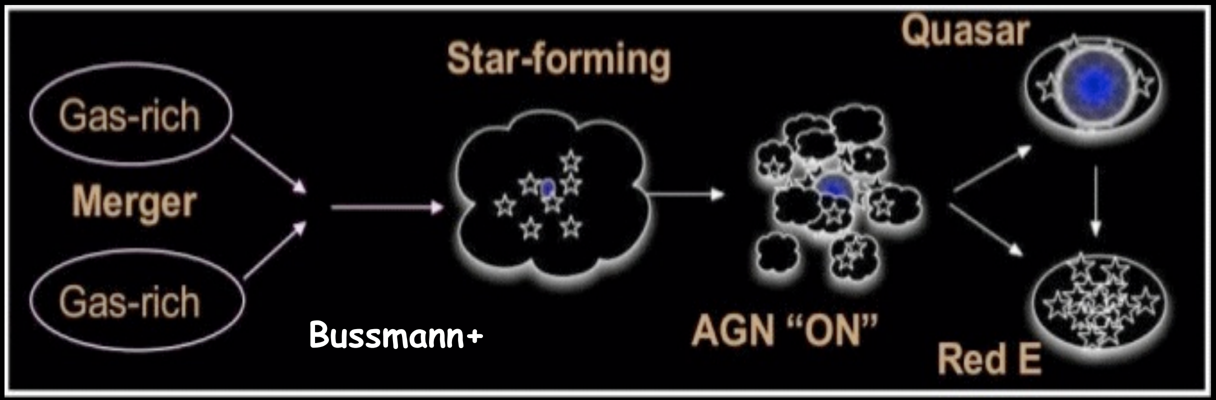
* DOGs/PIGs/OFIR/IRGs… :
  - large AGN fraction, rising with total luminosity
  - Obscured AGNs: confirmed with X-ray stacking
  - actively SF as well (FIR bright)

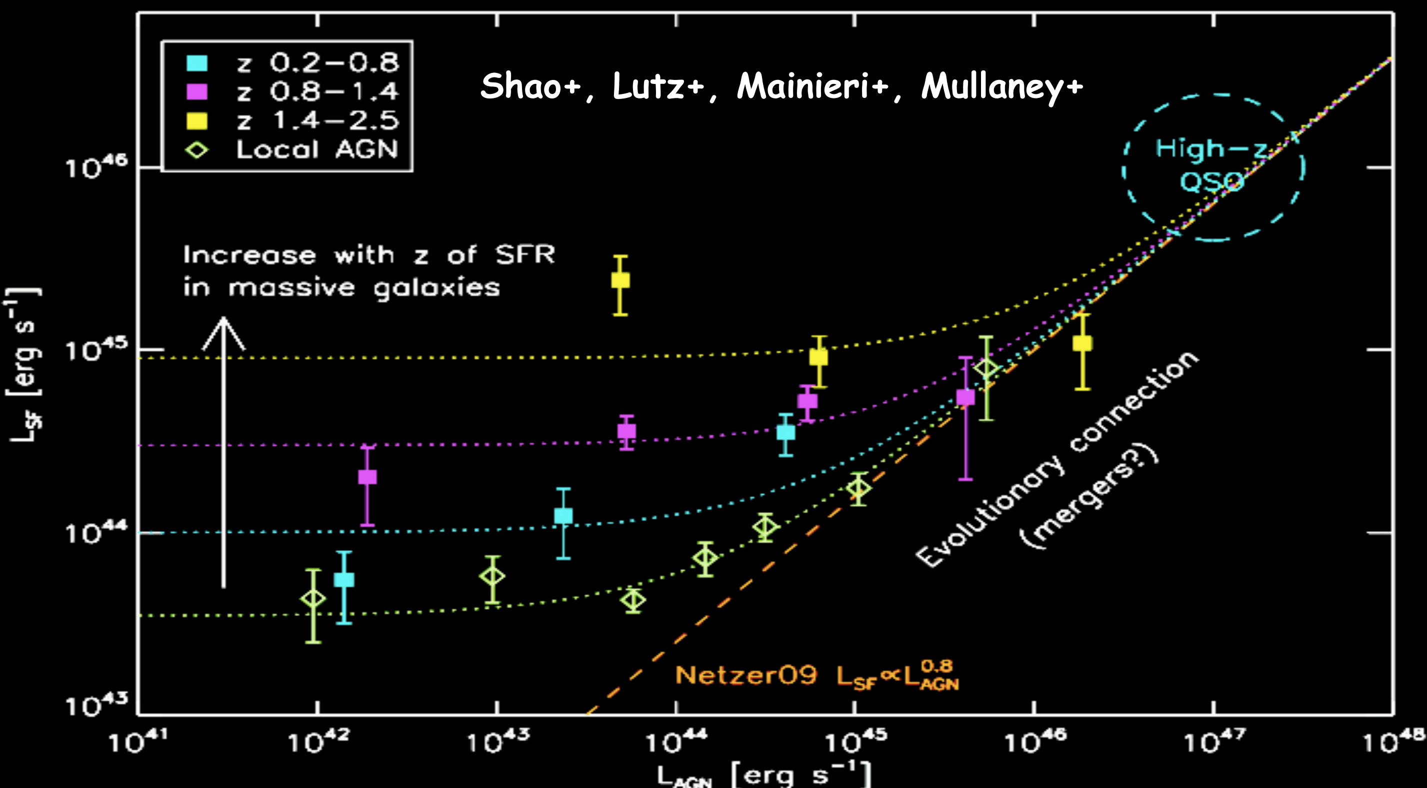


Fiore et al. 2009

AGN versus SFR: 2 modes of accretion ?

The merger of 2 gas-rich galaxies shows up as a cold starburst (SMG). After the trigger of the AGN, the system gets more compact and becomes warmer





(Highly reminiscent of Sanders et al. 1988.)

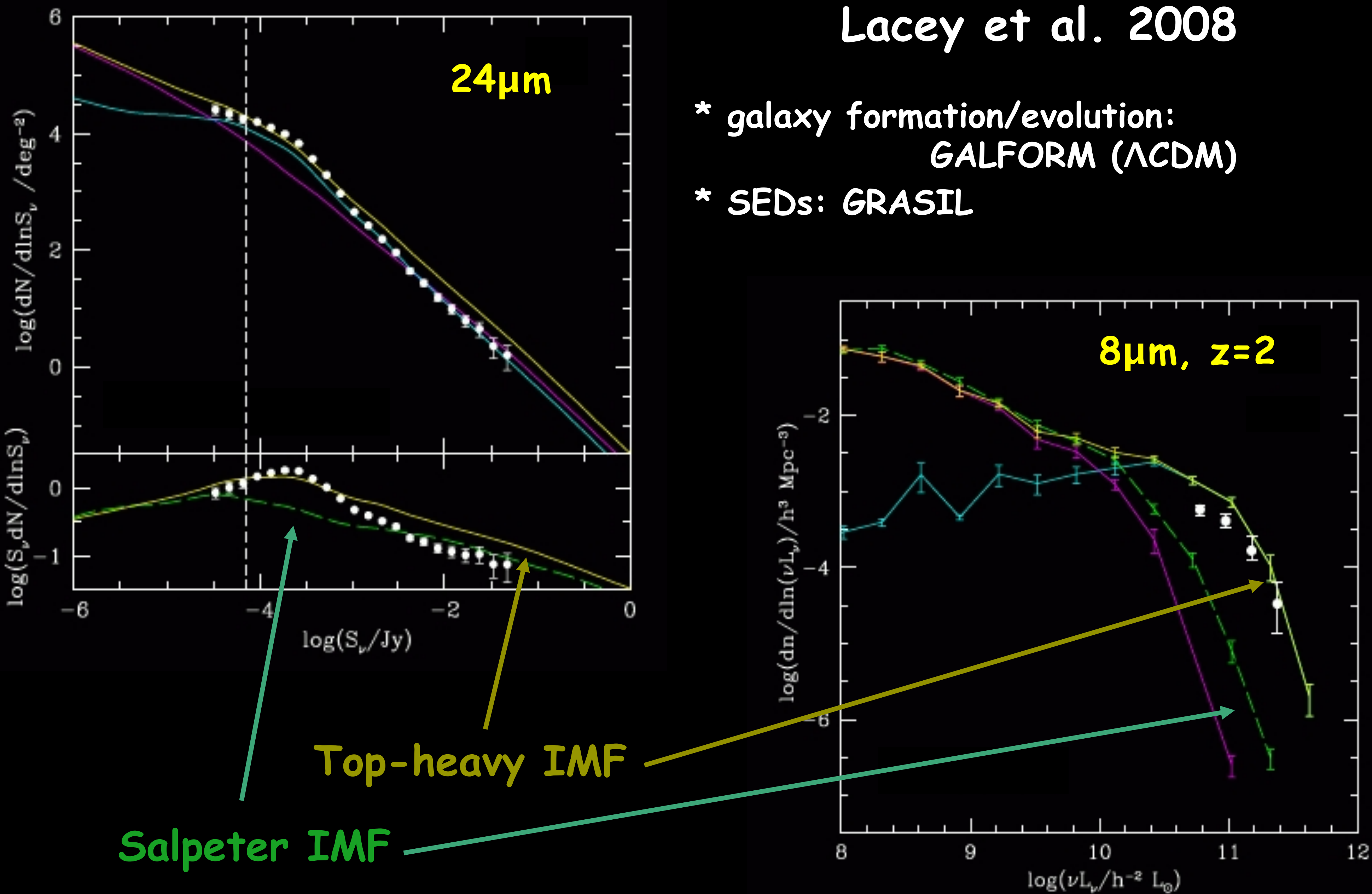
Competition between 2 modes (secular vs episodic), not only for stellar mass build-up but also for black hole growth ?

III - IR surveys: confronting the models

Semi-analytical models

Lacey et al. 2008

* galaxy formation/evolution: GALFORM (ΛCDM)
* SEDs: GRASIL



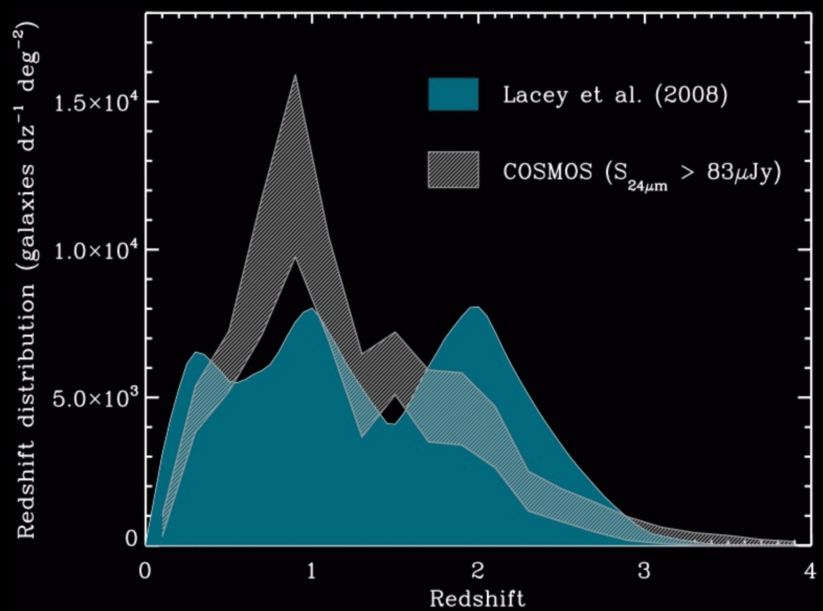
Semi-analytical predictions

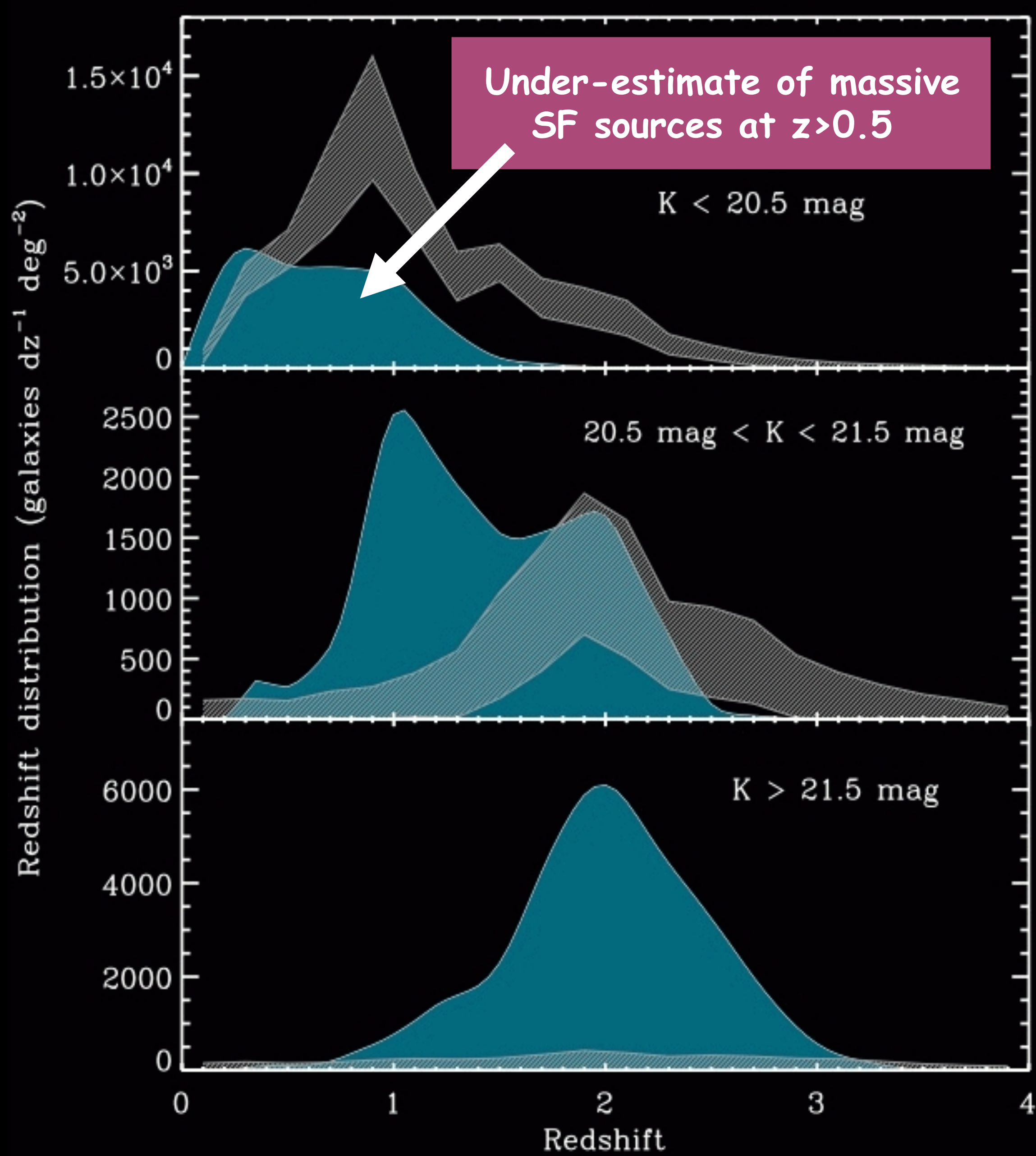
Lacey et al. 2008

* Top-heavy IMF
  (no AGN feedback, but AGNs dominate at the highest Lir)

⇨ excess of sources at z~2
⇨ too blue predicted colors

(LF+2009)





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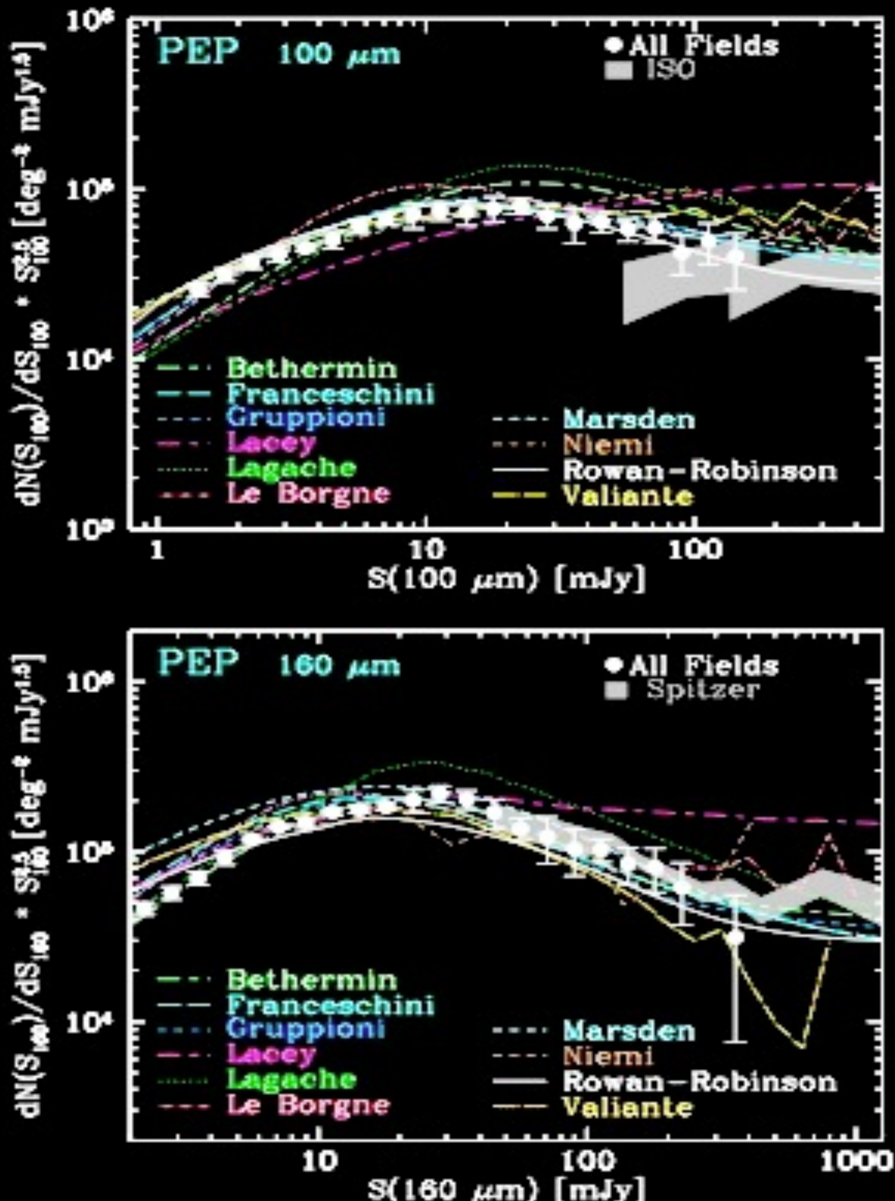

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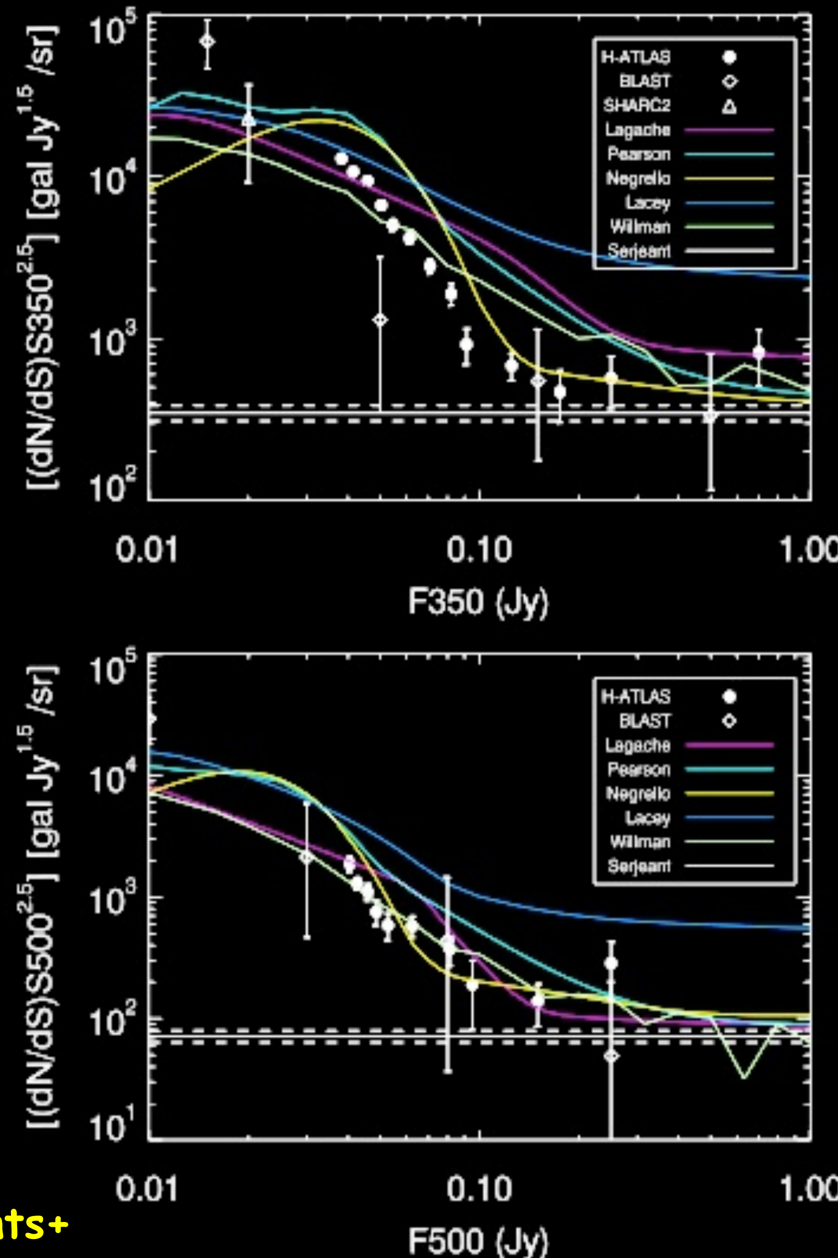

Clements+

Summary/Perspectives

* Counts, N(z), LFs, SFR/Mass: provide already tight constraints on galaxy formation models

* AGN population: must be considered seriously to understand the bright end (especially if feedback is key)

* Future studies: need a cleaner AGN/SF separation (maybe spatial resolution is the only way ?): ALMA, CCAT, METIS, … ? More constraints on the CO ladder (ALMA)…

* Many items I could not mention:
- very high-z proto-clusters (SMGs, Capak+)
- correlation lengths (still too much dispersed though…)
- environment effect: SFR/density flattening with z. Does it really reverse ???