Astrophysical modeling of FAR-IR Sources

on behalf of the SISSA/PD/RM2 team

Special thanks to A. Lapi, J. Gonzalez-Nuevo , M. Negrello, Z. Cai

Overview

The observations of HERSCHEL and PLANCK confirmed and strengthened the evidence of a high-redshift $z>1$ galaxy population exhibiting:

-) SFR ~100 - 3000 M_sun/yr, in environment heavily obscured by dust (HERSCHEL)

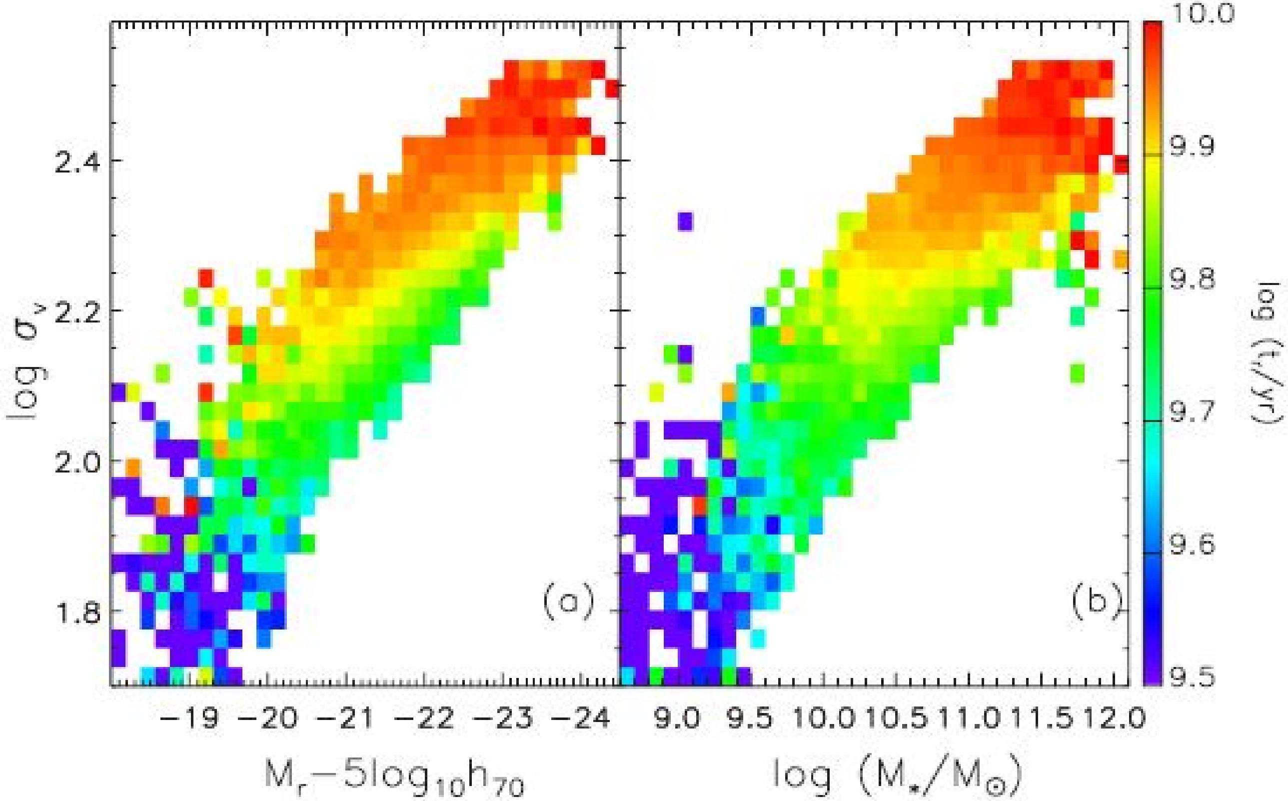
-) having a high chance 10^-3 to be strongly lensed by foreground galaxies (HERSCHEL)

-) strongly clustered (HERSCHEL+PLANCK)

STRONG LINK OF SUB-MM GALAXIES (progenitors) WITH LOCAL EARLY TYPE GALAXIES

- **Given the properties of local Early Type Galaxies, can we interpret the high-z bright submm sources as their progenitors?**
- **Which are the main physical processes ruling star formation in the progenitors of local massive ETGs?**
- **Why these progenitors extremely rich in gas and dust, forming stars at fantastic rates evolve into quiescent galaxies quite poor in cold gas and dust?**
- **Why after their splendid short lived QSO phase, they end up with practically inactive massive (up to 10^9÷10^10 M_sol) BH in their center?**

Hints from local ETGs…

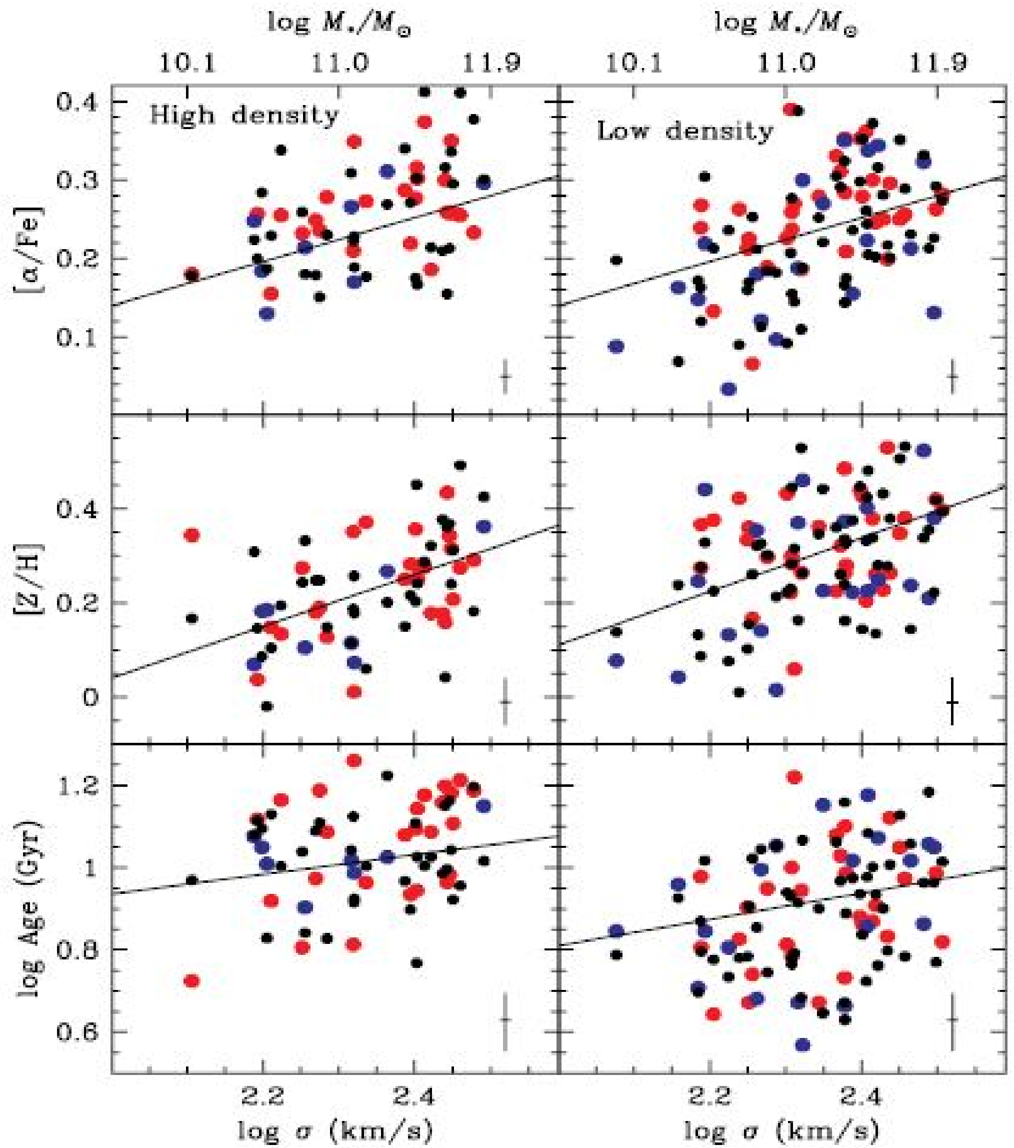


(Gallazzi+06)

ETGs with M$\geq 2-3\ 10^{10}$ M_sun are dominated by stars which now appear as old as $\geq$ 7-8 Gyr and formed at z≥1.

By contrast stars in thin discs of Late Type Galaxies are much younger and formed mostly at z<1.

Time available for star formation t≤ 1 Gyr for massive ETGs as probed by the $\alpha - enhancement$ (Fe depressed) of massive ETGs stars



SNIa not yet fully polluting the SNII yields with additional Fe

This implies that SF occurred within relatively short time-scale t≤ $1\ Gyr$, which corresponds to the time of onset of a significant rate of SNIa explosion

(Thomas+05)

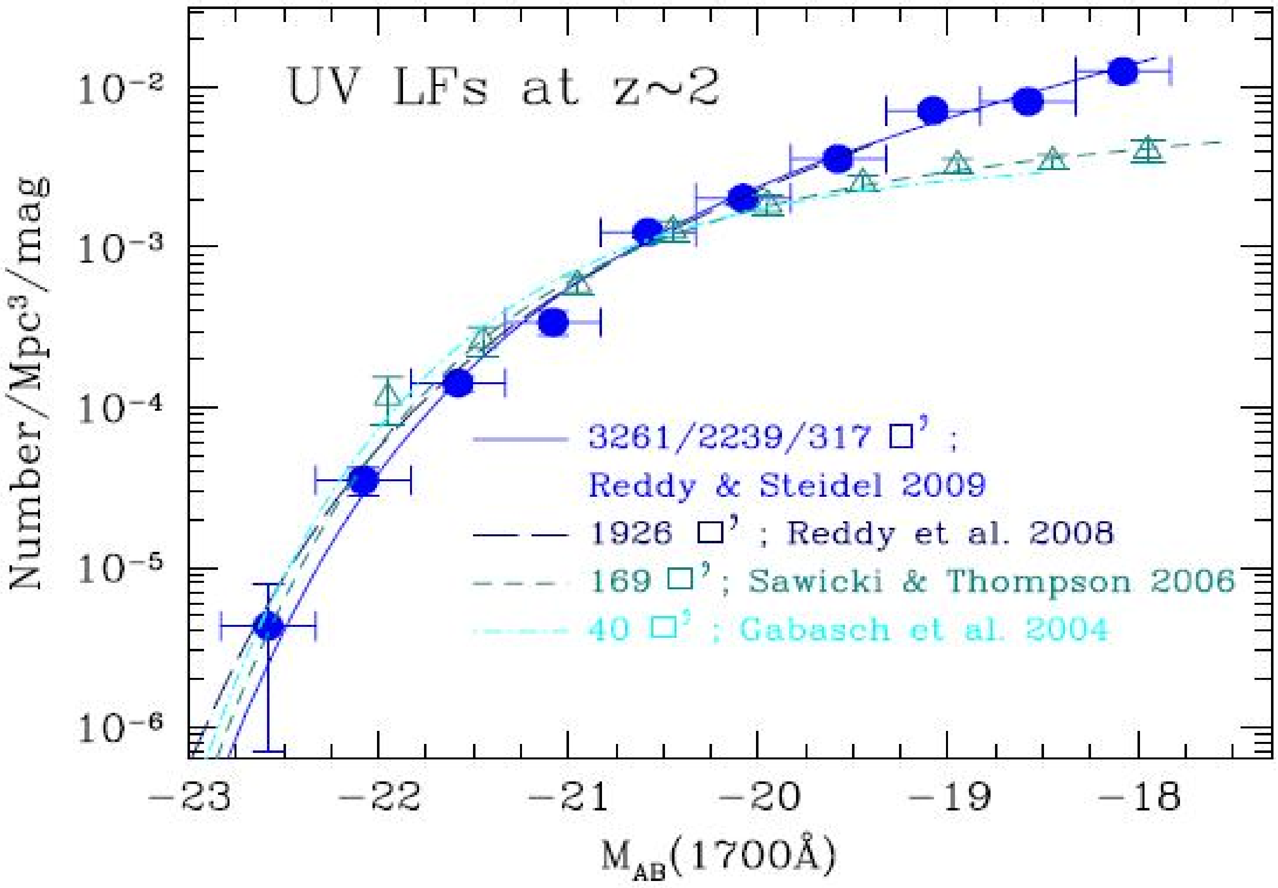
Consequence on average SFR for a present day ETG with M= 10^{11} M_sun

SFR =1.3-2 (IMF) x $10^{11}/10^{9} \approx 200-300$ M_sun/yr

Galaxies with such SFR would appear as strong UV emitters

SFR=200 M_sol/yr corresponds to $M_{AB}(1700\ A) \approx -24$

Partridge and Peebles 1967!

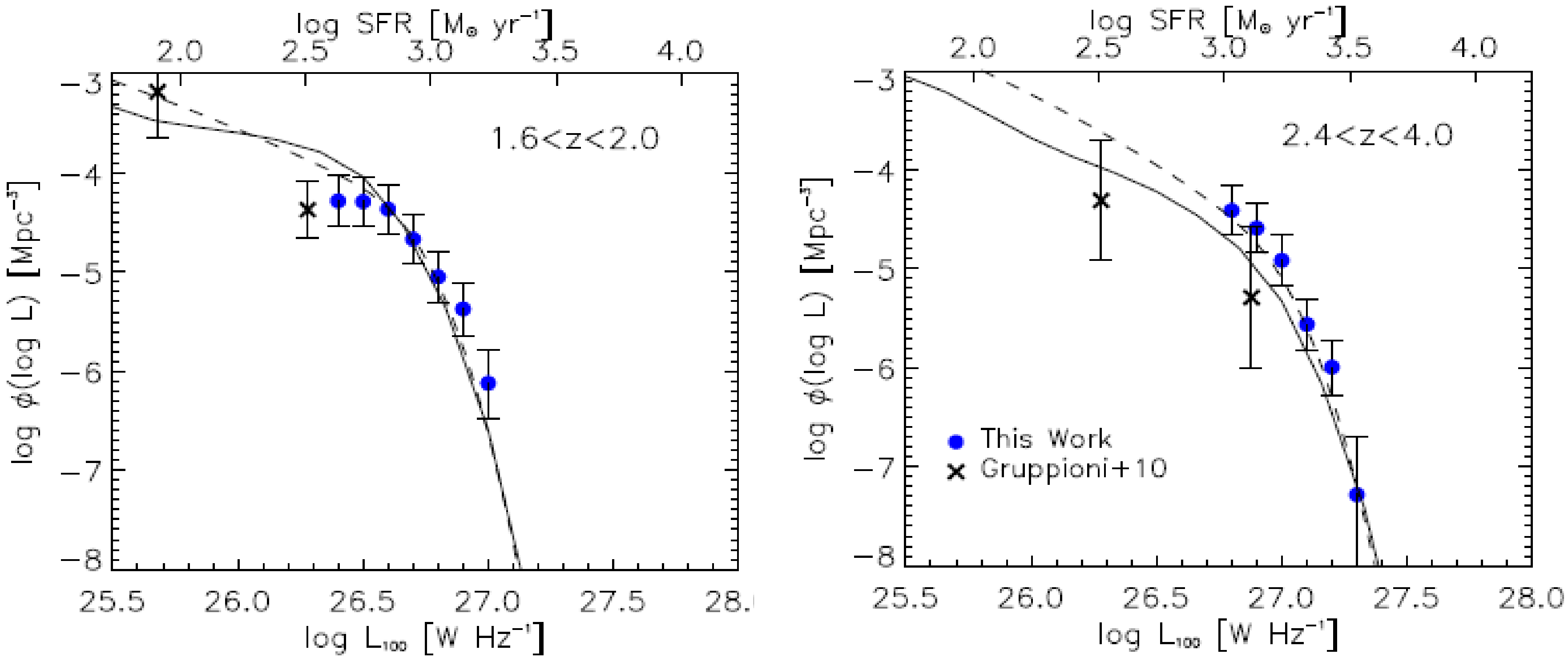


(Shapley, 2011)

Where are they? N<<$10^{-6}\ Mpc^{-3}$

Did ETGs form in small pieces gathering later on?

If dust absorbs ≈80-90% of the UV then SFR ~200-300 M_sun/yr corresponds $L_{FIR} \approx 2-3\ x10^{12}\ \ L_{sun}$



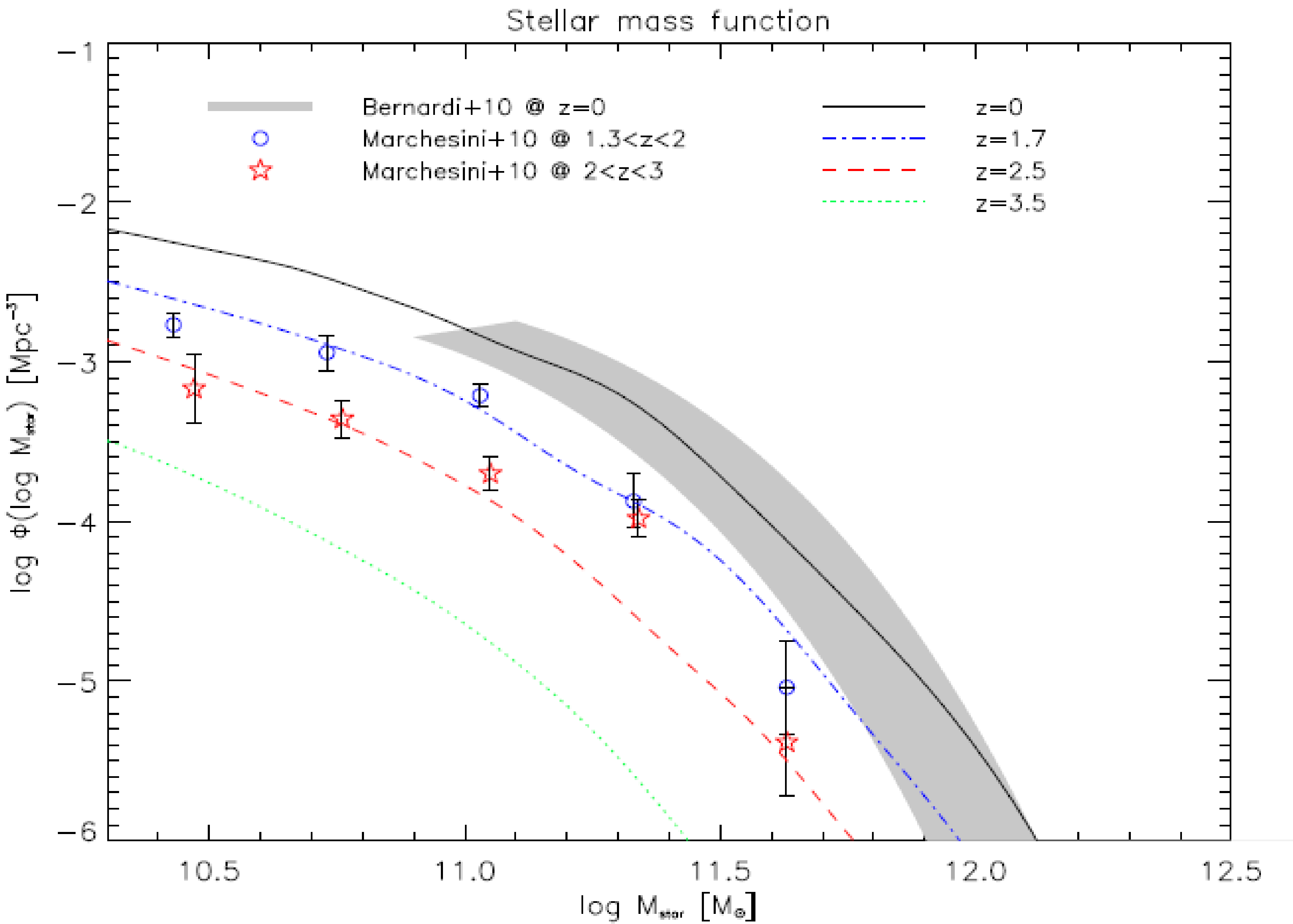
(Lapi+11)

Proto-ETGs appear with N ~ $10^{-3}\ - 10^{-4}\ \ Mpc^{-3}$ at z>1 (HERSCHEL ATLAS) !

DUST quite soon formed in order to get $\Delta t_{UV} \ll\ \Delta t_{FIR} \approx \Delta t_{SF} \sim 1\ \ Gyr$

SFR>200-300 M_sun/yr lasting ~ 1 Gyr → massive M_star > 10^11 M_sun

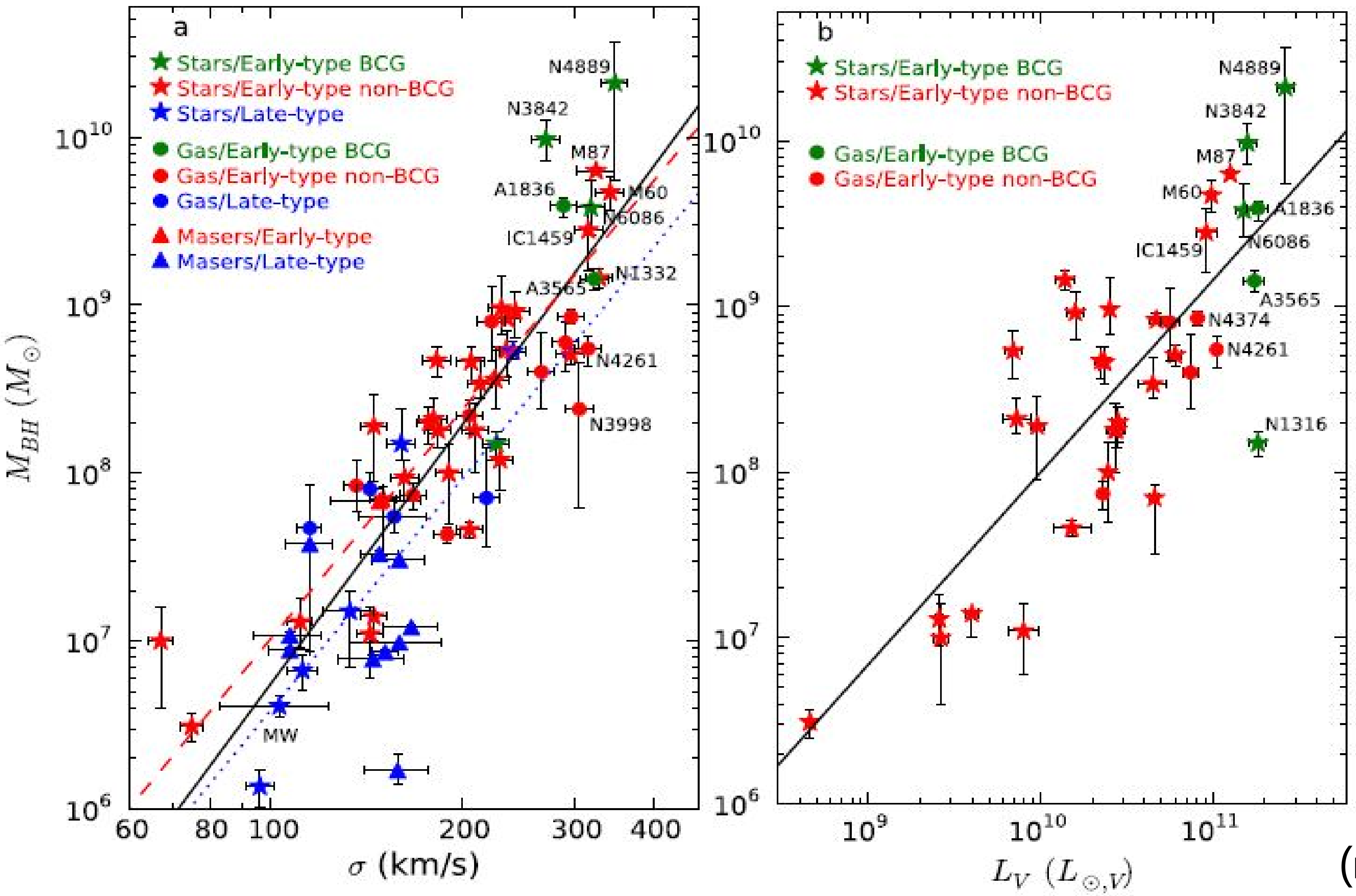
From LF of passively evolving galaxies (proto-ETGs), it is apparent that massive galaxies M_star > $10^{11}\ M_{sun}$ are in place at z>1 with N ~ $10^{-3} - 10^{-4}\ Mpc^{-3}$!



(Lapi+11)

The formation of stars in massive ETGs is apparent at FIR/submm wavelengths.

The formed stars detected at near-IR wavelengths



(McConnell+11)

Massive ETGs and Bulges host SMBH in their center $M_{BH} \sim 10^{-3}\ M_{old\,stars}$

The Mass Function of inactive BH mirrors the Mass Function of the gas accretion which fuelled the QSOs activity (Salucci+99; Marconi+04; Shankar+04)

FOR MASSIVE M> a few 10^10 M_star EARLY TYPE GALAXIES AND BULGES

- star formation starts at high z ≥ 1
- Short SF time-scale <1 Gyr
- Massive BH ($M_{BH} \sim 10^{-3}\ M_{old\ stars}$)

FOR less MASSIVE M<10^10 EARLY TYPE GALAXIES AND BULGES

- star formation starts at high z ≥ 1
- Long SF time-scale, SF lasting several Gyr
- Small Massive BH ($M_{BH} \lesssim 10^{-4}\ M_{old\ stars}$)

- Downsizing : in most massive ETGs SF has much shorter duty cycle than in less massive
- Local galaxy MFs show that star formation in DM halos globally is a rather inefficient process Ω_star/Ω_b ~ 0.003/0.046 ~ 7 %!

Can far-IR and sub-mm observations highlight which (and how) physical mechanisms are ruling the galaxy formation at high redshift ?

Two main possibilities :

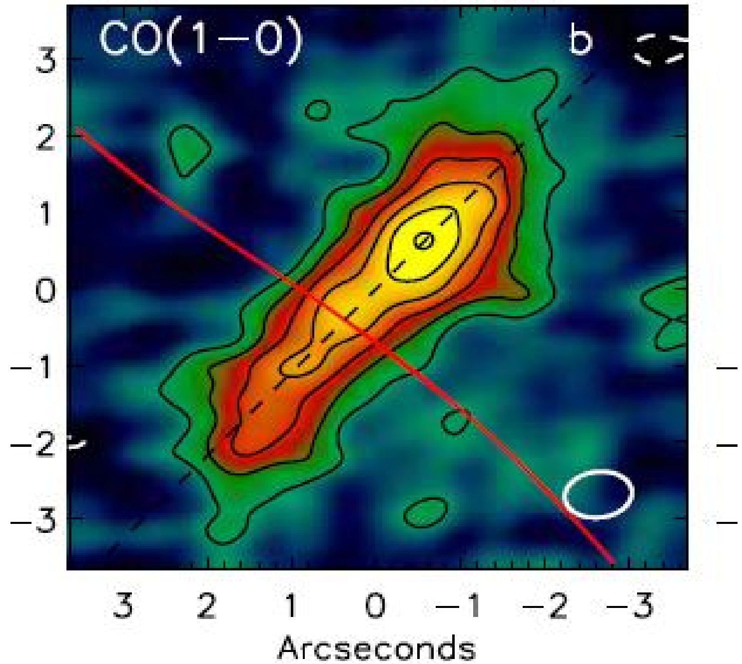
-) Secular (internal cooling + feedback SN and QSO) on short timescale (<1 Gyr)

-) Cosmological Merging (several cycles of SF spread over a longer timescale >> 1-2 Gyr)

→ We search for the dominant process (not exclusive)!

The fraction of stars formed in situ over a timescale <1 Gyr is the discriminating aspect!
Secular predicts f(situ) >> f(accreted by merging)!

By in situ we mean 1-10 kpc scale. This resolution has been achieved by follow up studies



SMM J2135-0102 (Swinbank+11)

M_dyn ~ 6 x 10^10 M_sun , within 2.5 kpc

M_gas/M_star ~ 60%

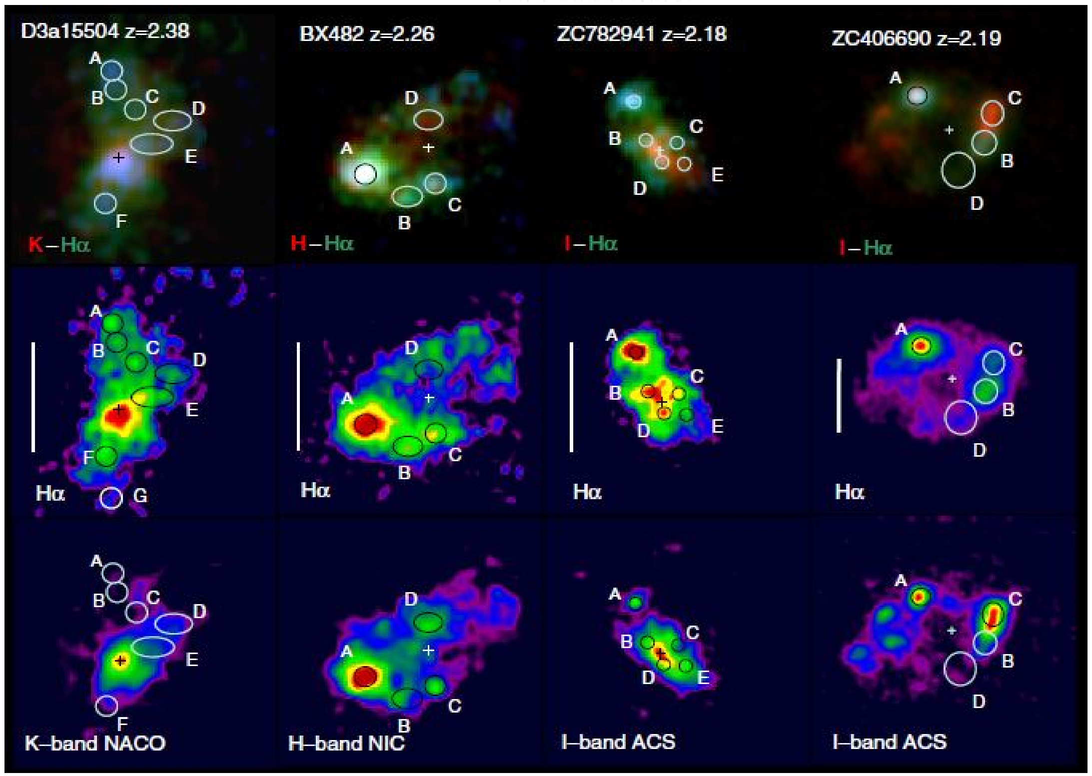
M_star + M_gas ~ M_dyn

V_rot ~ 320 km/s

V/sigma ~ 3.5

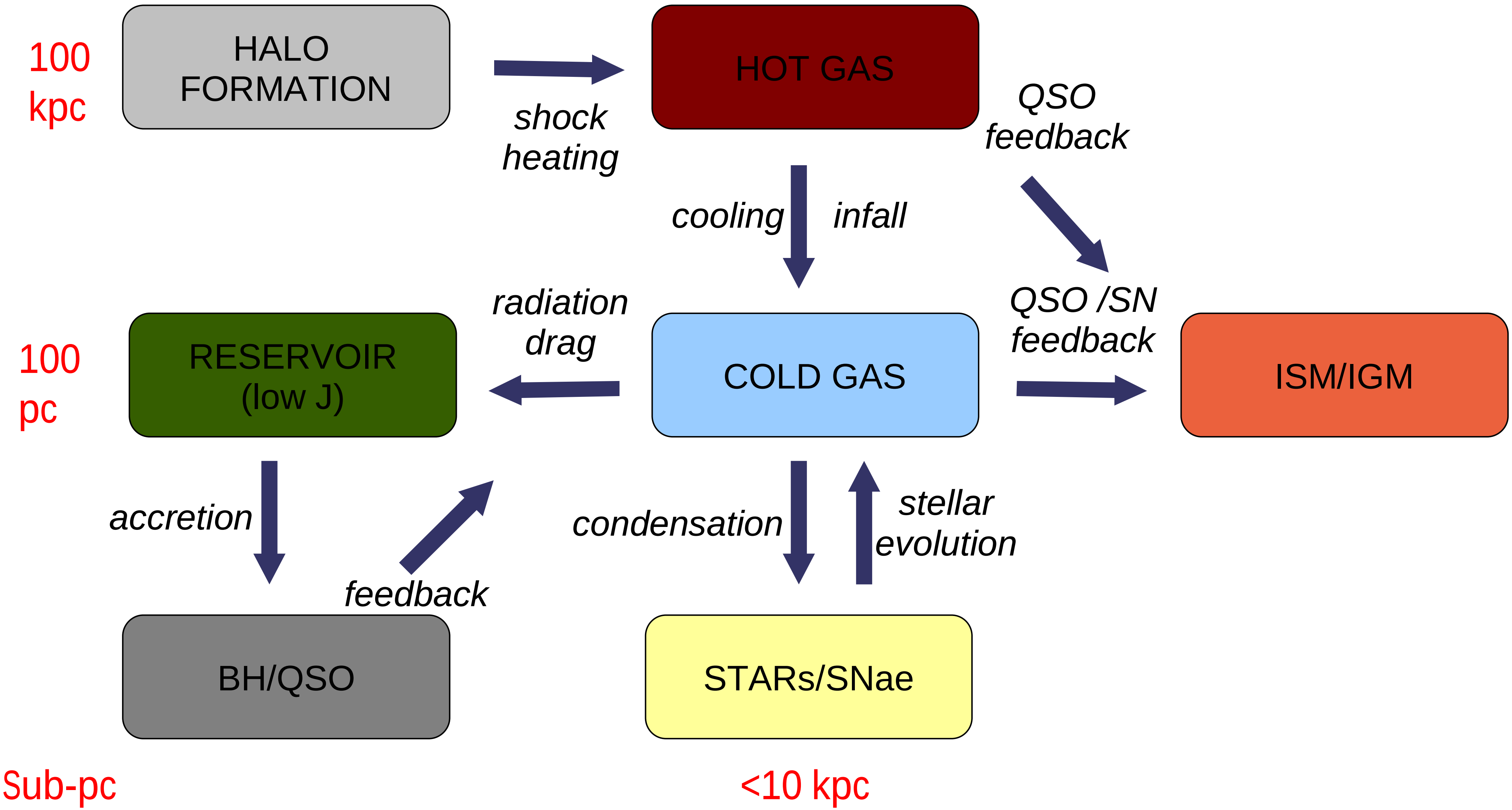
Q ~ 0.5 unstable disc

→ Similar results by e.g. Genzel+11



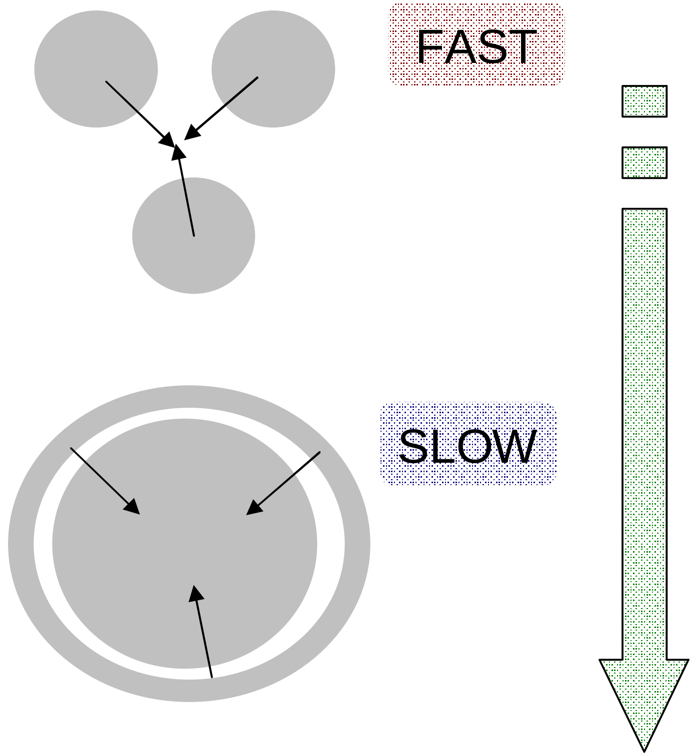
The Model from the Ground Up

- Schematic of main processes at work in secular hypothesis (Granato+01, 04; Lapi+06; Mao+07)



The Model from the Ground Up

- High-resolution simulations (Zhao et al. 2003a,b; Diemand et al. 2007) and numerical works based on Montecarlo schemes (e.g., Lin et al. 2007) show that the growth of a DM halo occur in two stages:
  - FAST accretion regime (high z): few massive clumps merge very rapidly and build up the halo potential well.
  - SLOW accretion regime (low z): smooth accretion of matter (max 20%) in the outskirts of the halo, without affecting central regions.



- Consequence for galactic (M_h<2-3 10^13 M_sol) halos:
  - at virialization baryons are likely to be clumpy, and thus prompt to cool and condense;
  - dynamical friction is efficient in removing angular momentum, so that baryons likely do not settle in a stable disk-like structure (see Mo & Mao 2003; Tonini et al. 2006, Lapi & Cavaliere 2009, 2011);
  - halos formed at z>1.5 are created and very rarely destroyed: formation rate is well approximated by positive term in the cosmic time derivative of the Sheth & Tormen (1999, 2002) mass function (see Haenhelt & Rees 1993, Sasaki 1996, Kitayama & Suto 1996).

The Model from the Ground Up

- Baryons in galactic DM halos multi-phase treatment

  - Basic equation from mass conservation (given halo mass and form. redshift)

$$\begin{aligned} \dot{M}_{\rm inf} &= -\dot{M}_{\rm cond} - \dot{M}_{\rm inf}^{QSO} \; ; \\ \dot{M}_{\rm cold} &= +\dot{M}_{\rm cond} - \dot{M}_\star + \mathcal{R}\,\dot{M}_\star - \dot{M}_{\rm cold}^{SN} - \dot{M}_{\rm cold}^{QSO} \; . \end{aligned}$$

$$M_{\rm inf}^0 = f_{\rm cosm}\, M_H$$

$$M_{\rm cold}^0 = M_\star^0 = 0.$$

  - Simple, standard parameterizations for infall rate, SFR and SN rate are assumed

$$\begin{aligned} \dot{M}_{\rm cond} &= M_{\rm inf}/t_{\rm cond} \; ; \\ \dot{M}_\star &= M_{\rm cold}/t_\star \; ; \\ \dot{M}_{\rm cold}^{SN} &= \beta \;\; \dot{M}_\star \; . \end{aligned}$$

$$t_{\rm cond} = \max[t_{\rm ff}, t_{\rm cool}, t_{DF}] \approx \; 4\times 10^8 \left(\frac{M_H}{10^{12}\, M_\odot}\right)^{0.2} \left(\frac{1+z}{7}\right)^{-3/2} \; {\rm yr} \; .$$

C

$$\dot{M}_{\rm cold,inf}^{QSO} = \frac{L_{\rm QSO}}{E_{\rm bind}}\,\frac{M_{\rm cold,inf}}{f_{\rm cosm}\, M_H}$$

$$\beta = \frac{\epsilon_{SN}\,\eta_{SN}\,E_{SN}}{E_{\rm bind}} \approx 0.35 \left(\frac{M_H}{10^{12}\, M_\odot}\right)^{-2/3} \left(\frac{1+z}{7}\right)^{-1}$$

ε_{SN}

IMF

Analytic solution can (remarkably) be found (impulsive QSO feedback)

$$M_{\rm inf} = M^0_{\rm inf}\, e^{-t/t_{\rm cond}} \; ;$$

$$M_{\rm cold} = \frac{M^0_{\rm inf}}{s\,\gamma - 1}\left[e^{-t/t_{\rm cond}} - e^{-s\,\gamma\,t/t_{\rm cond}}\right] \; ;$$

$$M_\star = \frac{M^0_{\rm inf}\, s}{s\,\gamma - 1}\left[1 - e^{-t/t_{\rm cond}} - \frac{1}{s\,\gamma}\,\left(1 - e^{-s\,\gamma\,t/t_{\rm cond}}\right)\right] \; ;$$

$$s \equiv t_{\rm cond}/t_\star \qquad \gamma \equiv 1 - \mathcal{R} + \beta$$

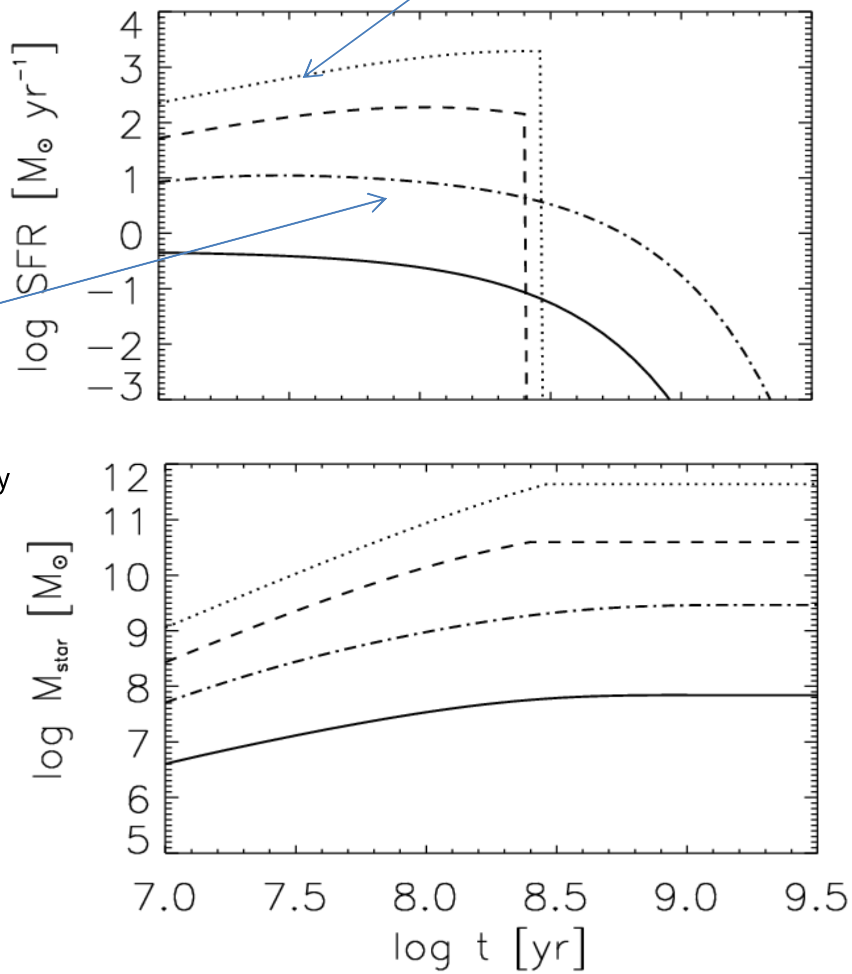
QSO stops SF (in massive halos) at

$$\Delta t_{\rm burst} \approx 2.5 \times 10^8 \left(\frac{1+z}{7}\right)^{-1.5} \mathcal{F}\left(\frac{M_H}{10^{12}\, M_\odot}\right)$$

Model @ z_{vir}=6
M_{DM}~$10^{10\text{-}11\text{-}12\text{-}13}$ M_{sun}

QSO feedback

SN feedback only



SFR

stellar mass

The Model from the Ground Up

- BH related quantities

- Matter funnelled through central regions by radiation drag, and stored in low-J reservoir around BH (Kawakatu & Umemura 2002).

$$M_{\rm inflow} = \alpha_{\rm RD} \times 10^{-3}\, M_\star \, \left(1 - e^{-\tau_{\rm RD}}\right)$$

α_{RD}

- BH accretes at (mildly super) Eddington rates from an initial small seed

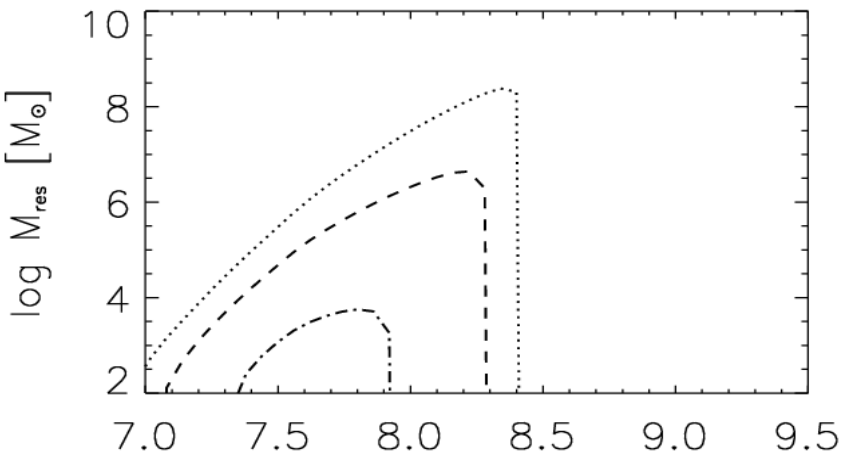
$$M_\bullet = M_\bullet^0 \, e^{t/\tau_{\rm ef}}$$

$M_\bullet^0$ λ

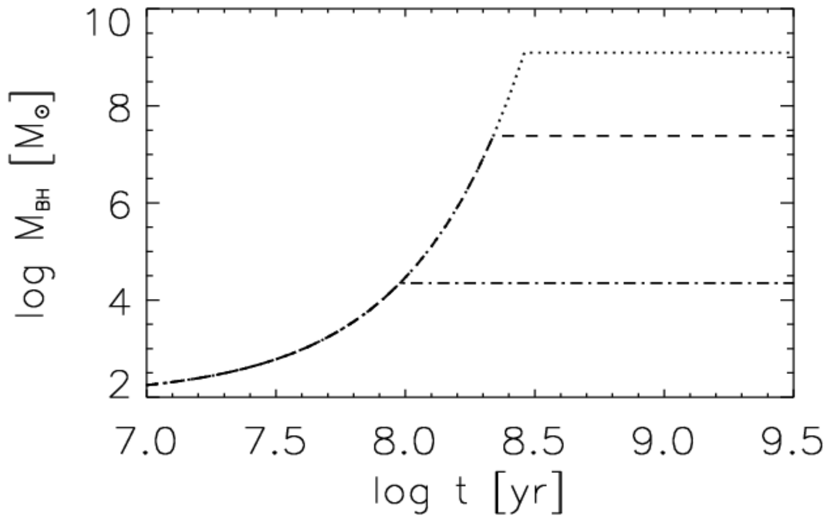
- BH stops growing when reservoir mass is exhausted

$$M_{\rm res} = M_{\rm inflow} - M_\bullet \, .$$

Model @ z_{vir}=6
M_{DM}~$10^{10\text{-}11\text{-}12\text{-}13}$ M_{sun}



reservoir mass



BH mass

The Model from the Ground Up

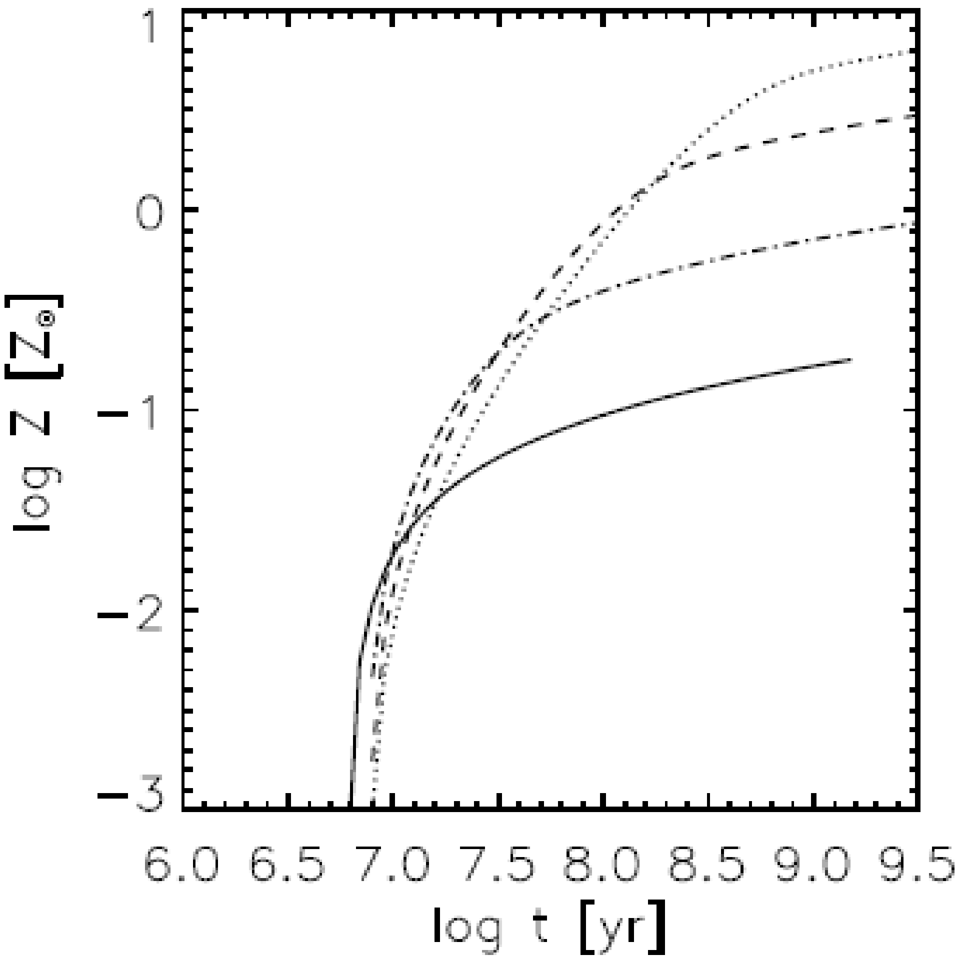
- Metals → rapid enrichment of the cold ISM (→ dust)
  For massive galaxies, Z~0.3 Z_sun over 3 x 10^7 yr

Model @ z_{vir}=4
M_{DM}~$10^{10\text{-}11\text{-}12\text{-}13}$ M_{sun}

$$\dot{Z}_{\rm cold} = \frac{Z_{\rm inf} - Z_{\rm cold}}{t_{\rm cond}}\,\frac{M_{\rm inf}(t)}{M_{\rm cold}(t)} + \frac{\mathcal{R}_Z(t)}{t_\star}$$

IMF

$$\mathcal{R}_Z(t) \approx \int_{m_{\star,t}}^{m_\star^{\rm sup}} {\rm d}m_\star\, m_\star\, q_Z(m_\star)\, \phi(m_\star)\, \frac{\dot{M}_\star(t-\tau_{m_\star})}{\dot{M}_\star(t)}$$



- Analytic solution is found, with limiting behavior

$$Z_{\rm cold} = Z_{\rm inf}^0 + \frac{s}{s\,\gamma - 1}\,\mathcal{R}_Z(t)$$

- The final metallicity increases with halo mass

The Model from the Ground Up

- Relevant model parameters

- Fiducial values

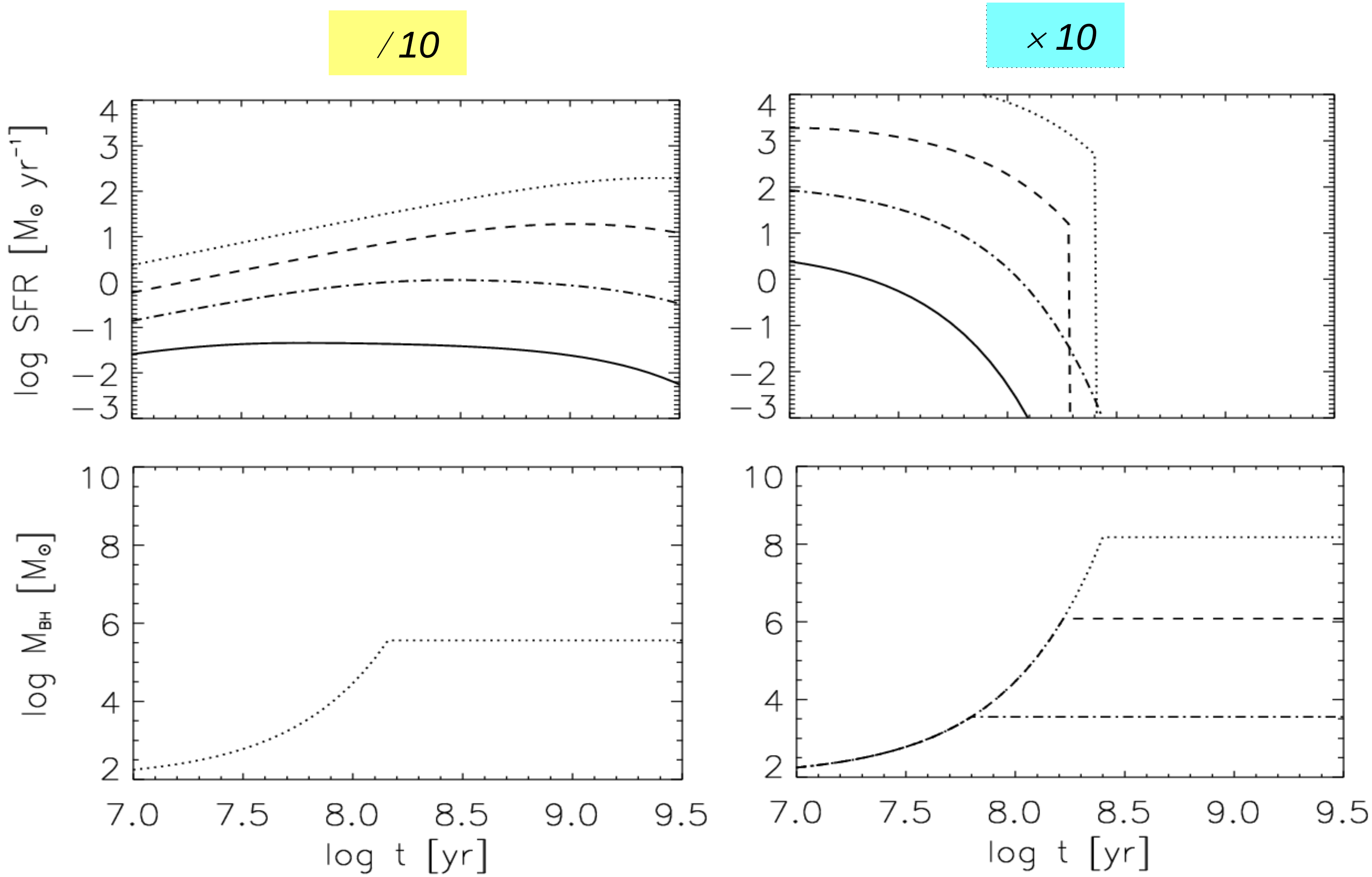
Symbol	*Description*	*Value*
C	*clumping factor*	*7*
ε_{SN}	*SN feedback efficiency*	*3%*
α_{RD}	*RD strength*	*1*
λ	*Eddington ratio*	*1*
$M_\bullet^0$	*BH seed mass*	$10^2\ M_{sun}$
ε_{QSO}	*QSO feedback efficency*	*5%*
τ^0	*optical depth IR γ (norm.)*	*1*

IMF

Chabrier IMF

The Model from the Ground Up

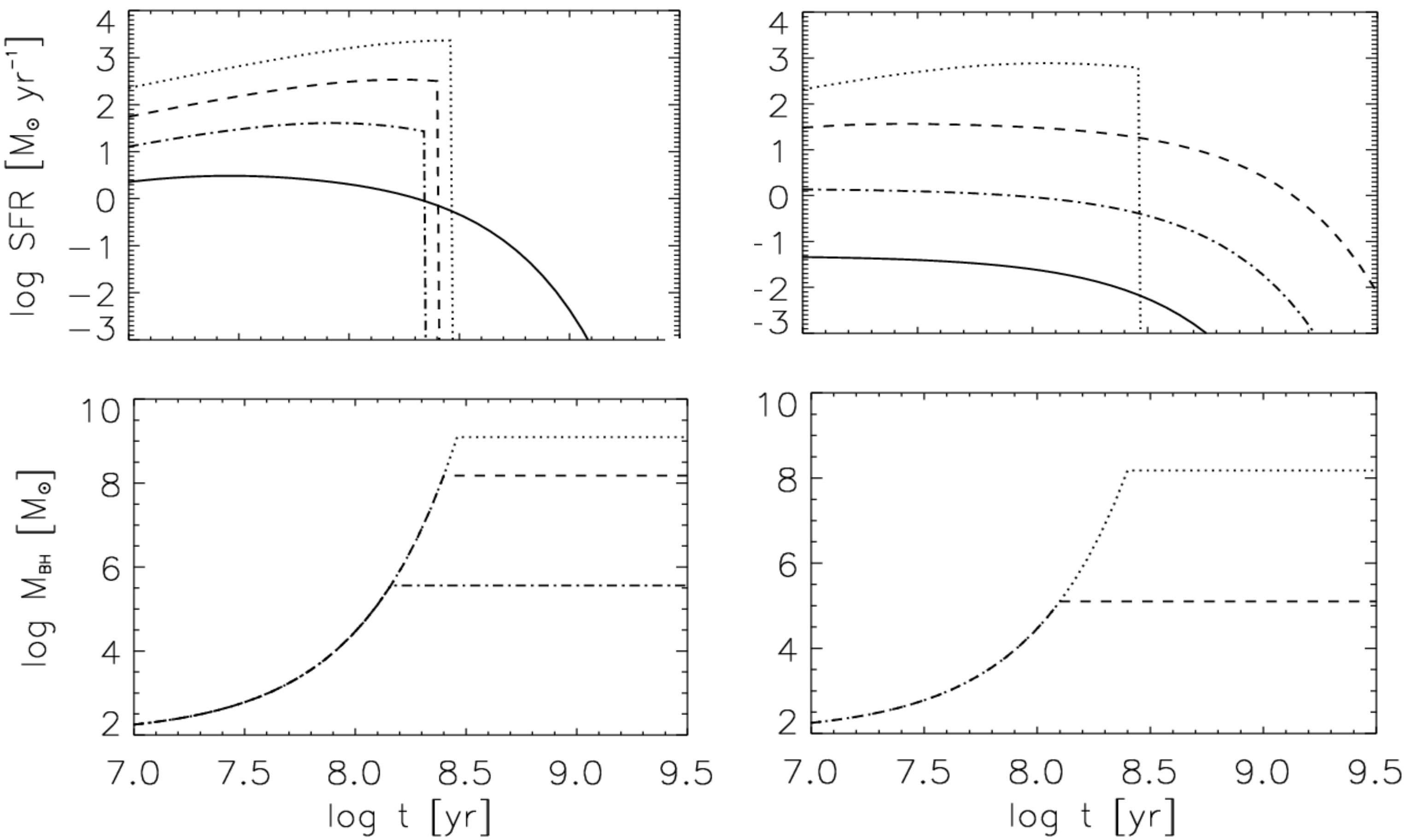
- Varying the clumping factor C



The Model from the Ground Up

- Varying the SN feedback efficiency ε_{SN}

$/10$ $\times 10$



Primeval Galaxies

PHASE I

Very clean and metal poor ISM, rising SFR
Primeval galaxies (LBGs, LAEs)

PHASE II

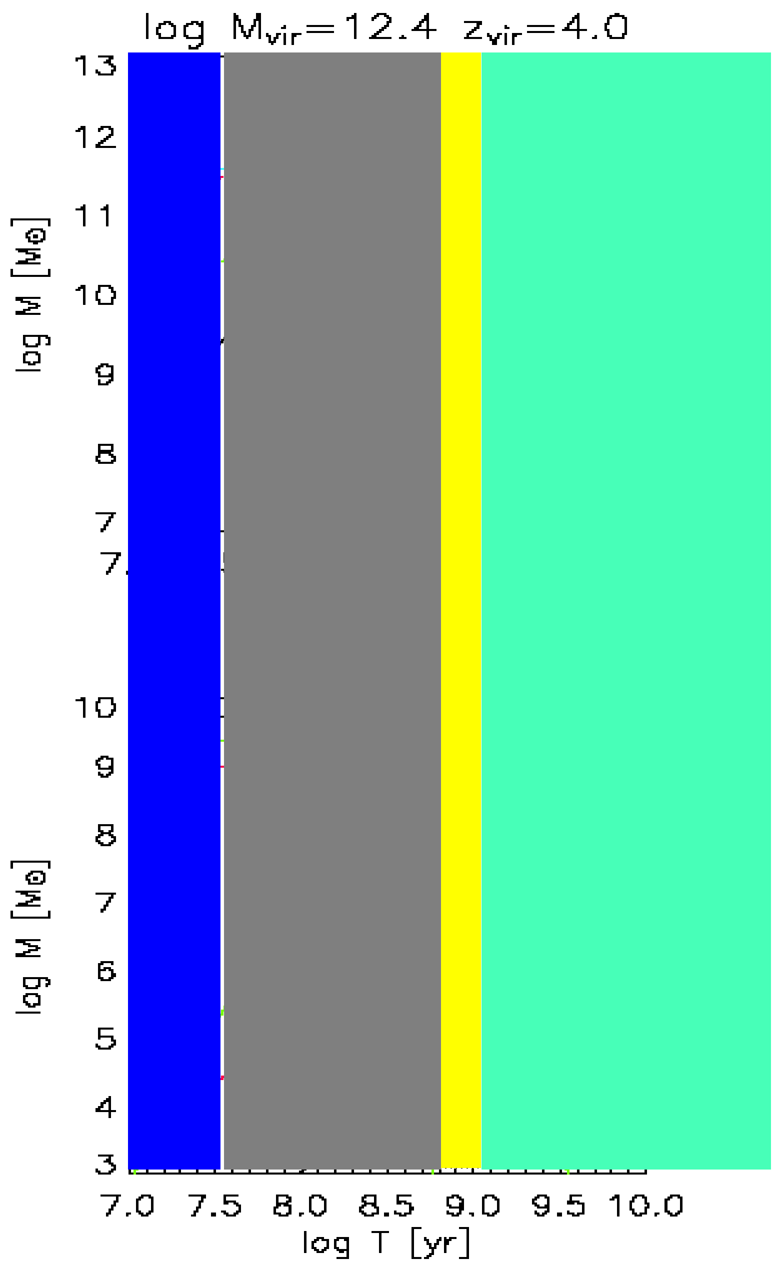
Very dusty ISM, huge SF, growing BH
Submm galaxies

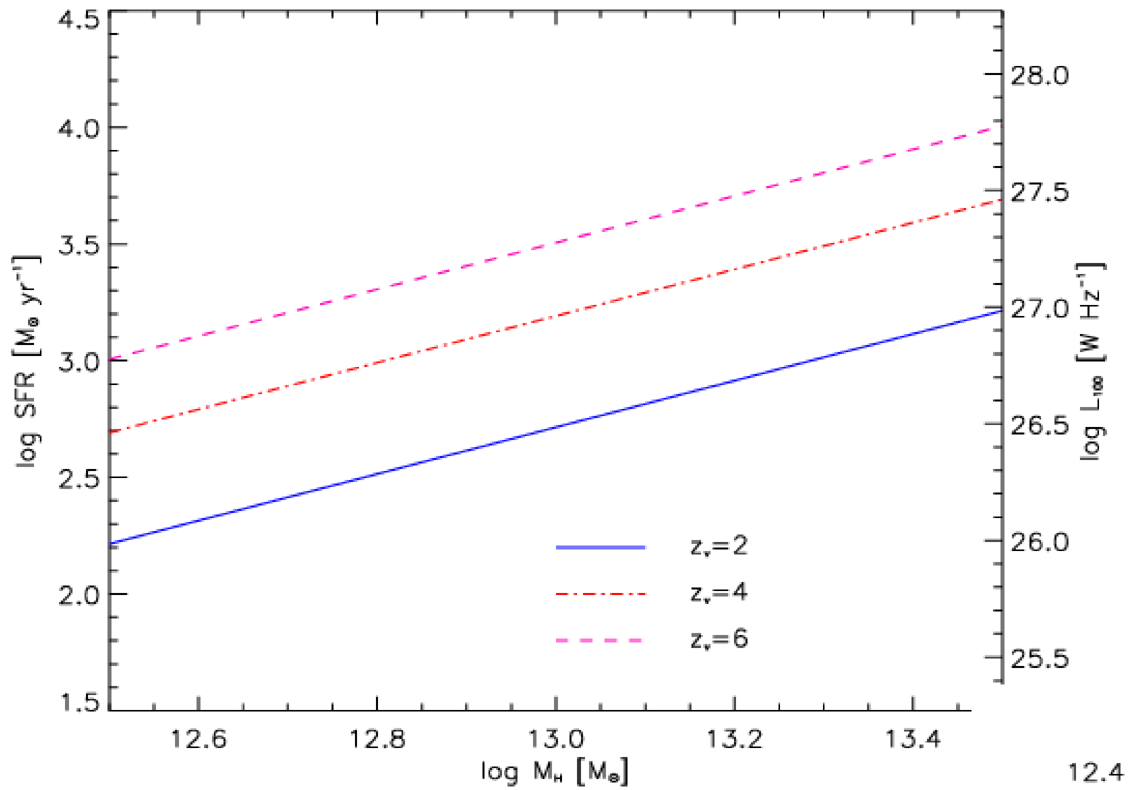
PHASE III

Strong BH activity, ISM ejected, SF ended
QSO phase

PHASE IV

ISM almost absent, passive evolution
EROs and local ellipticals





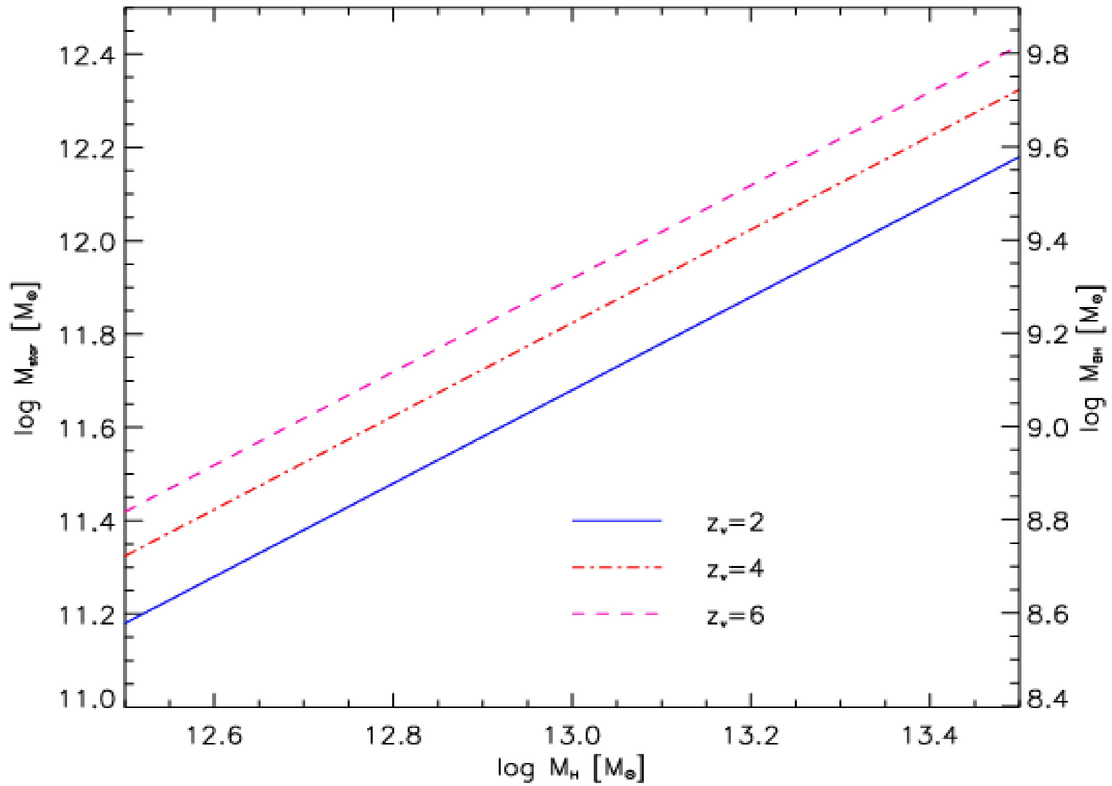
For each halo of mass M_H and redshift formation z we compute

$$SFR \approx 35 \left(\frac{M_H}{10^{12}\, M_\odot}\right) \left(\frac{1+z}{2.5}\right)^{2.1} \; M_\odot \; yr^{-1}$$

Typical SFR~100 M_sun/yr
M_H~ 3x10^12 M_sun

$$M_\star \approx 5 \times 10^{10}\, M_\odot \left(\frac{M_H}{10^{12}\, M_\odot}\right) \left(\frac{1+z}{2.5}\right)^{0.5}$$

$$M_{\rm BH} \approx 10^{8}\, M_\odot \left(\frac{M_H}{10^{12}\, M_\odot}\right) \left(\frac{1+z}{2.5}\right)^{0.5}$$



M_H>13.5 no more galactic halos , but groups and clusters...smaller clumping, longer t_df→ lower SFR!

Statistics at high z concerning
SFR, Bol Lum, L(λ), M_star (also with some work M_bh, L_QSO)

$$\Phi(\log L) \sim \frac{d^2 N}{\mathrm{d}M\,\mathrm{d}t} \times \frac{\mathrm{dM}}{\mathrm{d}\log L} \times \Delta t_{\mathrm{sf}}$$

Halo Formation Rates, standard Hierarchical paradigm

SF Timescale

$$\Delta t_{\mathrm{burst}} \approx 2.5 \times 10^8 \left(\frac{1+z}{7}\right)^{-1.5} \mathcal{F}\left(\frac{M_H}{10^{12} M_\odot}\right)$$

set in massive halos by strong AGN feedback

$$L_{FIR} \simeq 3 \times 10^{43} \frac{SFR}{M_\odot yr^{-1}}\ erg\ s^{-1}$$

$$\mathrm{SFR} = 35 \left(\frac{M_H}{10^{12} M_\odot}\right) \left(\frac{1+z}{2.5}\right)^{2.1} M_\odot\, \mathrm{yr}^{-1}$$

+ **SED**

LF(λ) Counts

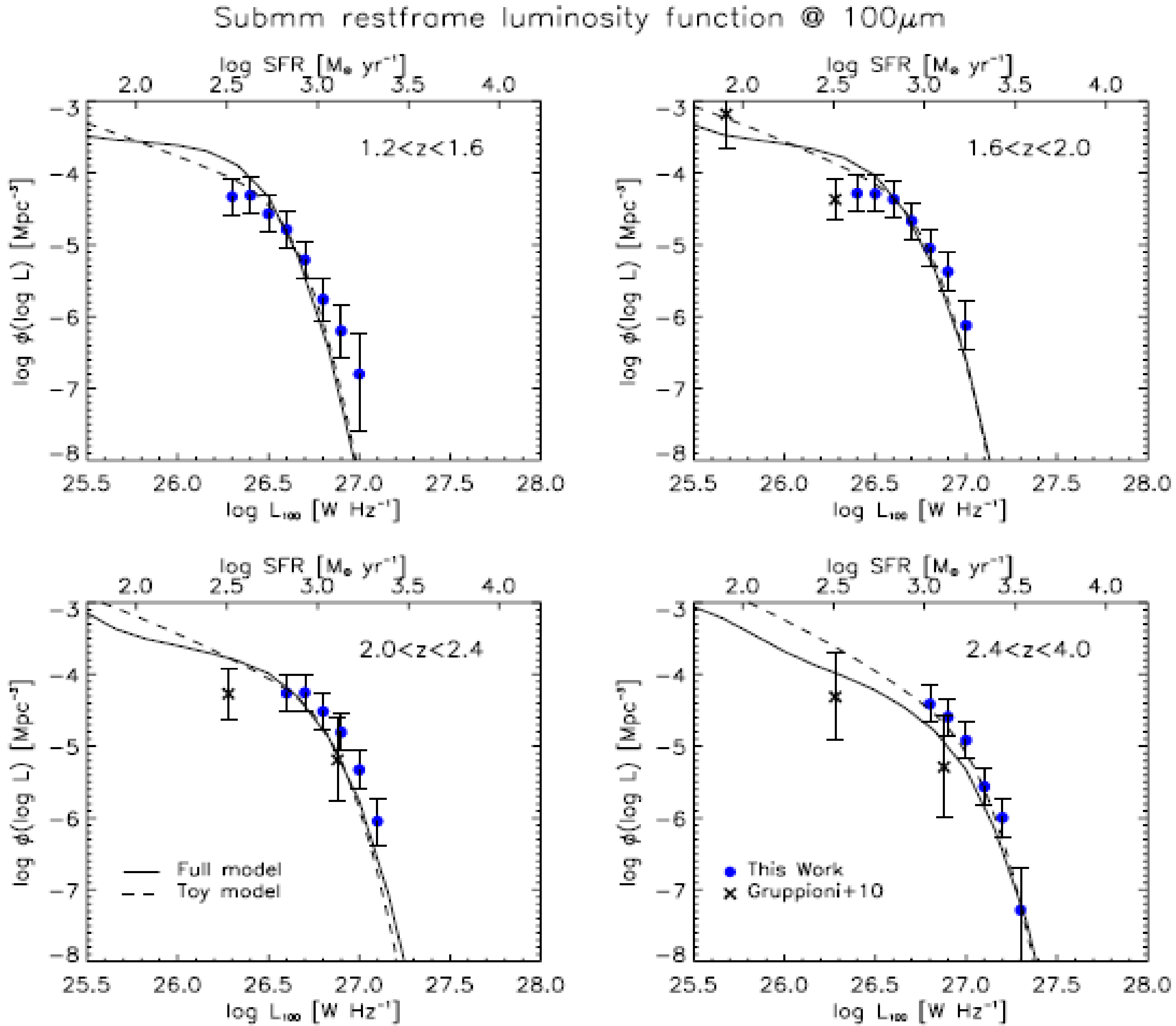
If we are locating the sub-mm galaxies into the 'right' DM halos, then we are going to get 'right' number densities, CIB, CIB power spectrum, clustering prop.

Parameters of our secular model fixed in Lapi et al **(2006)** by fitting relevant statistics

Overview of Model Results

Property or Statistics	External Inputs*
QSOs and BHs	
$M_\bullet - M_{\rm vir}$	no add
$\Delta t_{\rm peak} - M_{\rm vir}$	no add
Opt. LFs (z)	$\Delta t_{\rm vis} \approx 5 \times 10^7$ yr, $\Delta M_\bullet \approx 0.3$ dex
X-ray LFs (z)	$\Delta t_{\rm vis} \approx 3 \times 10^8$ yr
BH mass function	no add
QSO clustering	no add
$M_\bullet - \sigma$	no add
Spheroidal Galaxies	
VDF	$\sigma / V_{\rm vir}$
Faber-Jackson	$\sigma / V_{\rm vir}$
LF (z)	IMF, SEDs (GRASIL)
Metal abundances	IMF, chemical yields
K-band counts	IMF, dust modeling (GRASIL)
850 μm counts	IMF, dust modeling (GRASIL)
EROS	IMF, dust modeling (GRASIL)

Focus on millimeter and sub-millimeter selected galaxies (ATLAS)



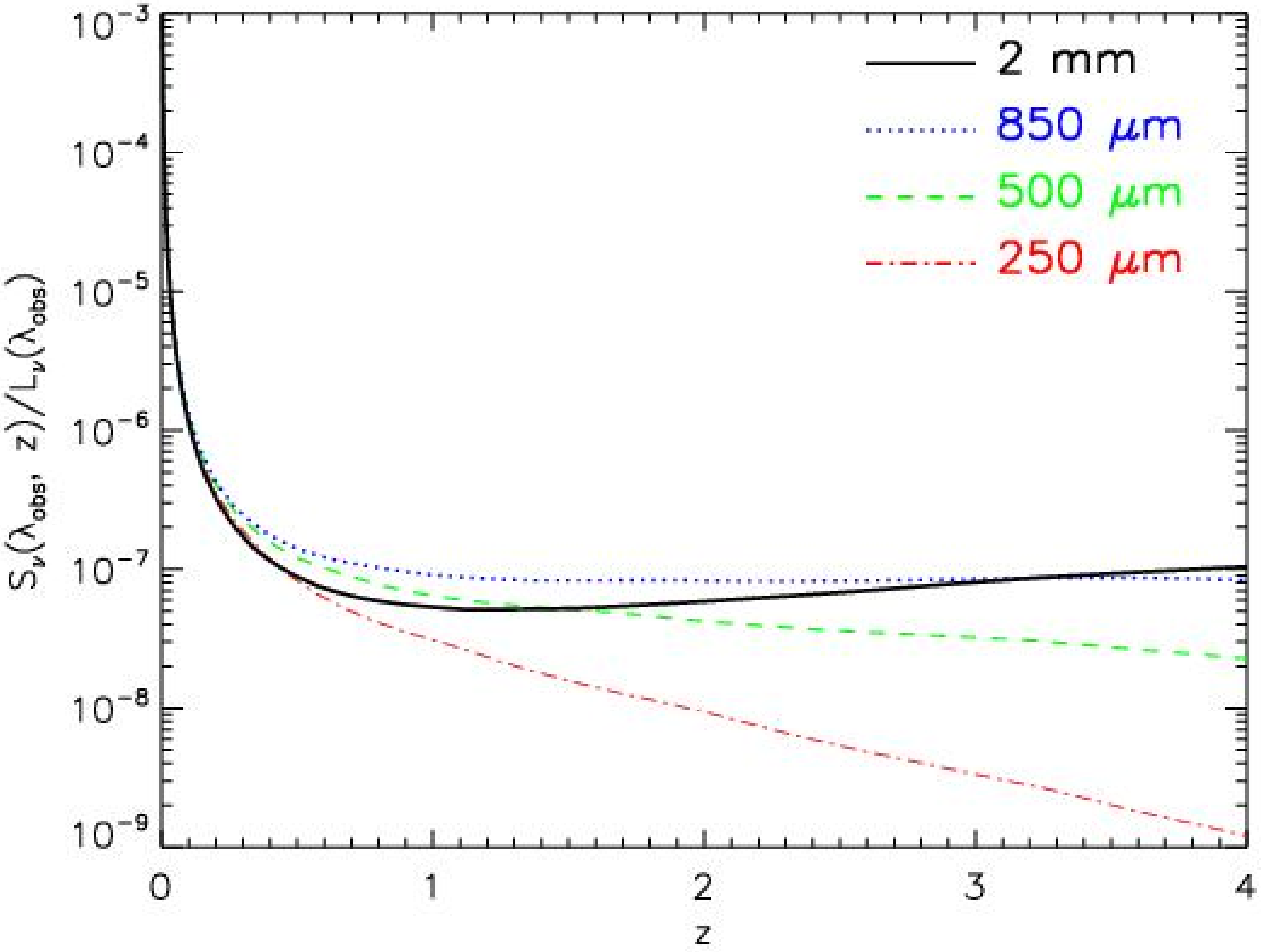
Steep LF!!!!!
Model agrees with data
it is not an ad hoc fit;
the parameters have
been set in Lapi +06!

$$n(L_{FIR}) \propto L^{-4.8 \div -5.0}$$

(Lapi+11)

SED SMM J2135..

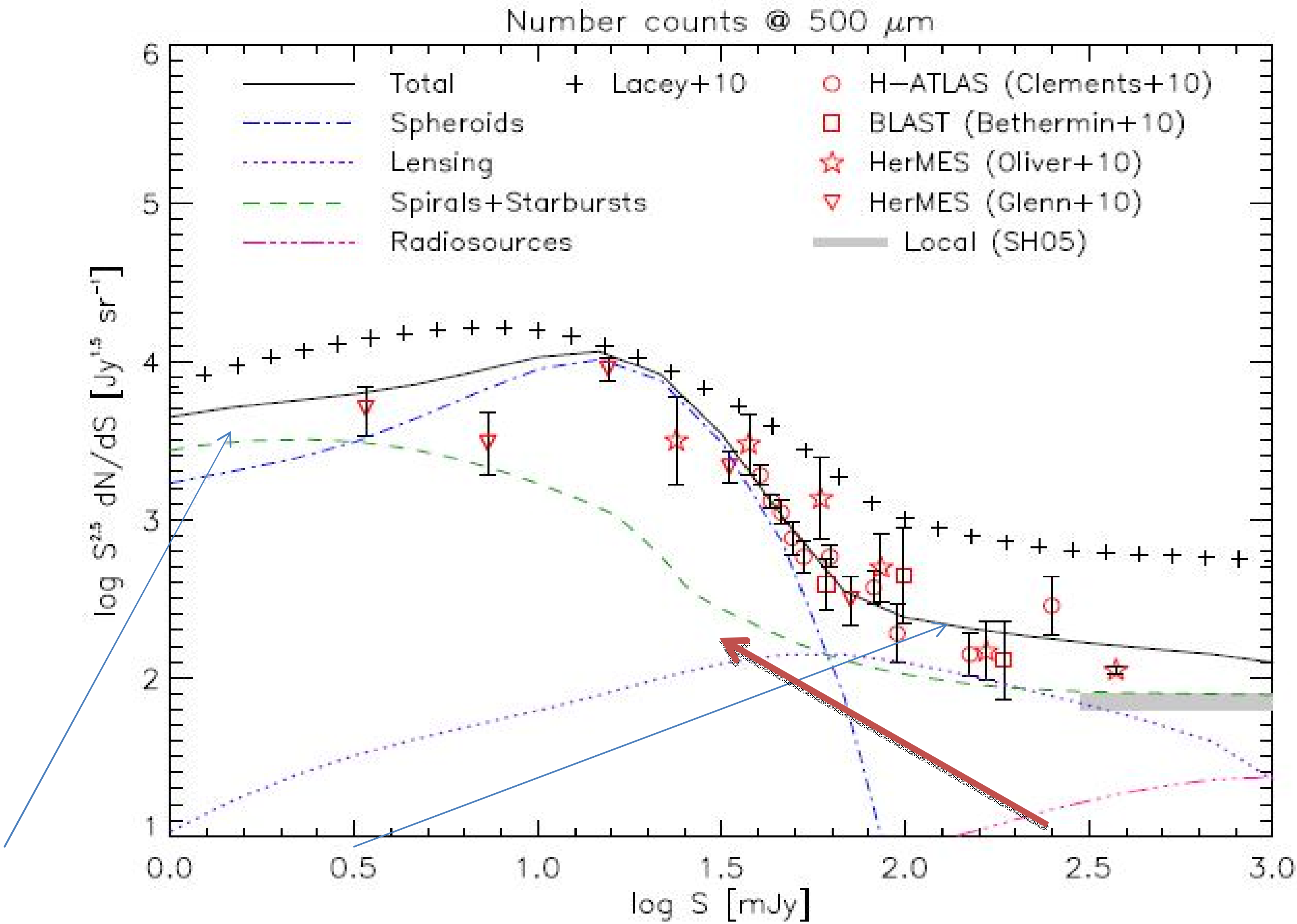
Flux / Luminosity ratio



Flux dimming compensated by K-correction!! The bright part of LF is ‘always’ visible!!

Same steepness of the LF in the counts!!!!!

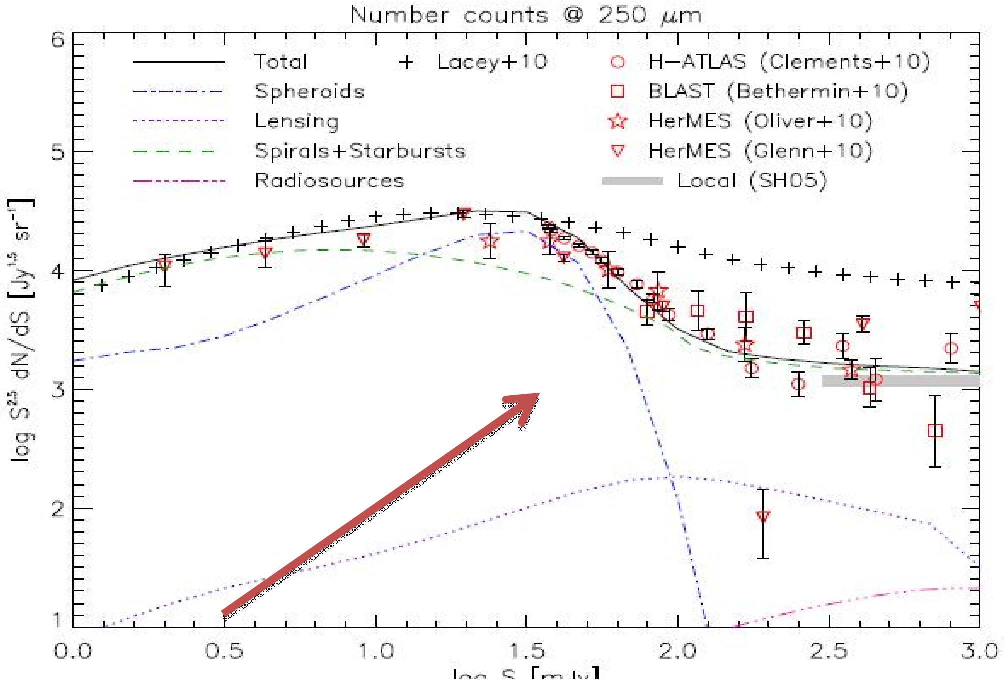
$$\frac{dn}{dS} \propto S^{-4.8 \div -5.0}$$

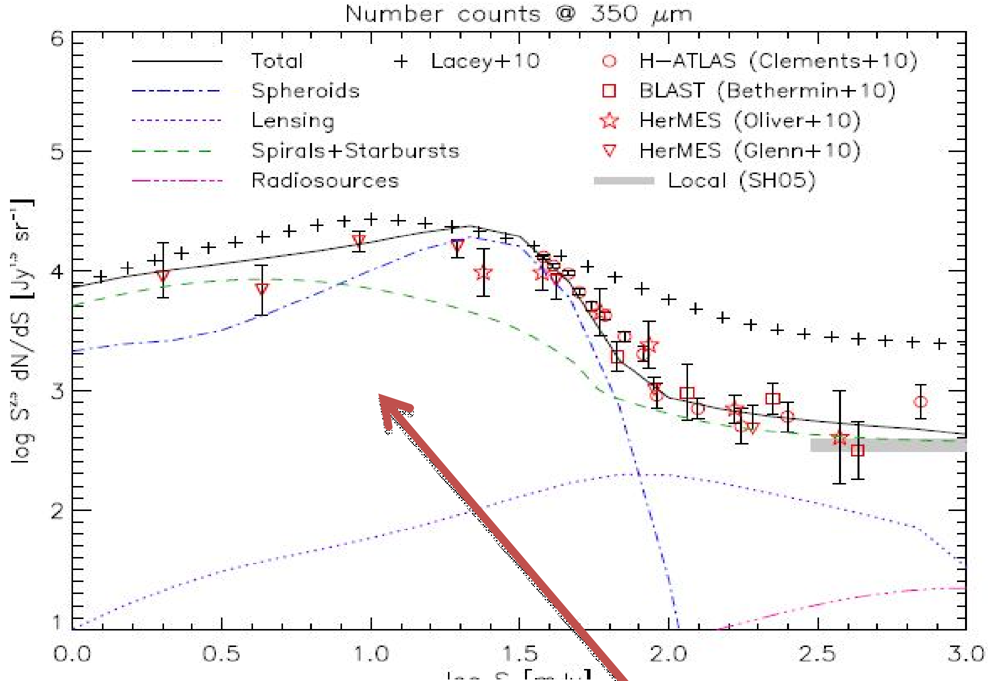


(Lapi+11)

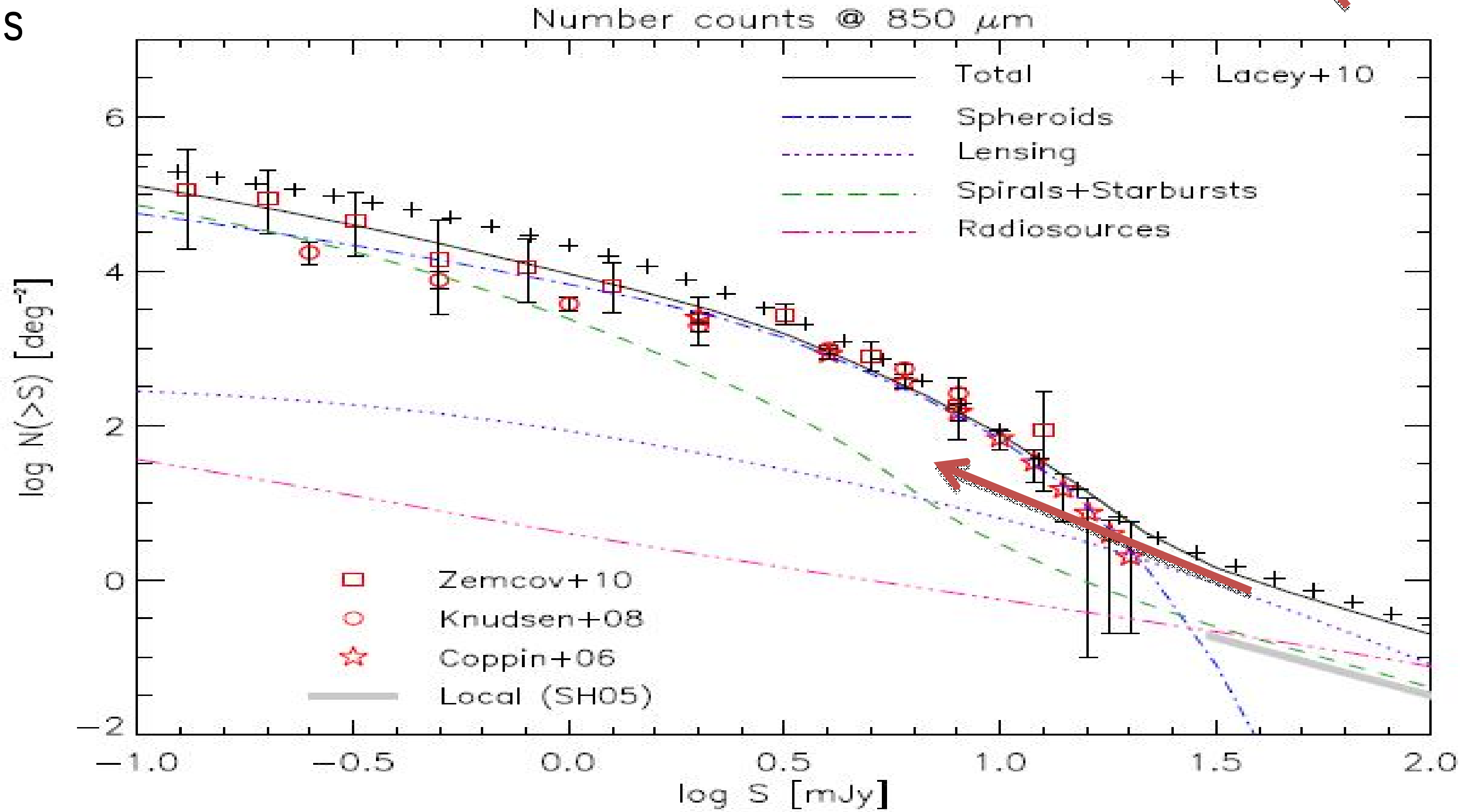
Proto-ETGs

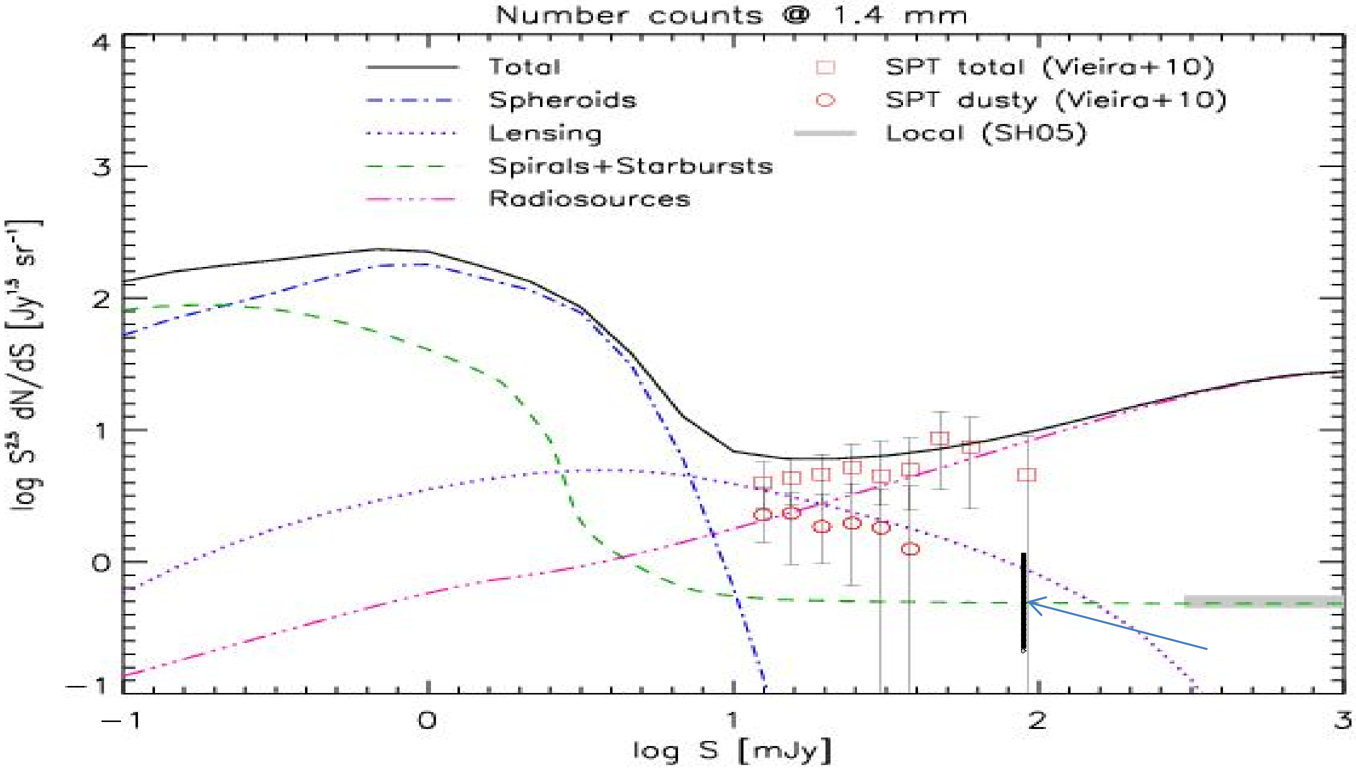
Note: local objects are overwhelmed in a large flux range!


Number counts @ 250 μm
Total
Spheroids
Lensing
Spirals+Starbursts
Radiosources
+ Lacey+10
H–ATLAS (Clements+10)
BLAST (Bethermin+10)
HerMES (Oliver+10)
HerMES (Glenn+10)
Local (SH05)
log S^2.5 dN/dS [Jy^1.5 sr^-1]

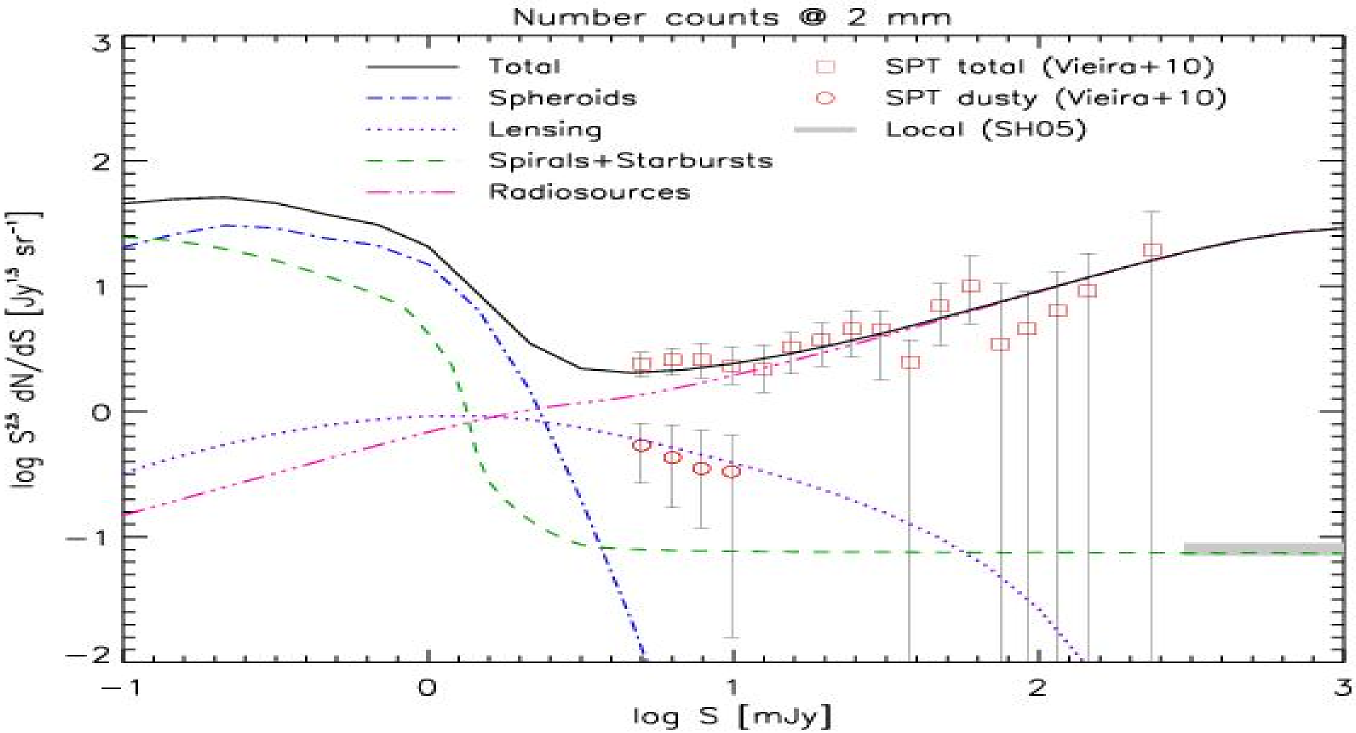

Number counts @ 350 μm
Total
Spheroids
Lensing
Spirals+Starbursts
Radiosources
+ Lacey+10
H–ATLAS (Clements+10)
BLAST (Bethermin+10)
HerMES (Oliver+10)
HerMES (Glenn+10)
Local (SH05)
log S^2.5 dN/dS [Jy^1.5 sr^-1]

Proto-ETGs


Number counts @ 850 μm
Total
+ Lacey+10
Spheroids
Lensing
Spirals+Starbursts
Radiosources
Zemcov+10
Knudsen+08
Coppin+06
Local (SH05)
log N(>S) [deg^-2]
log S [mJy]

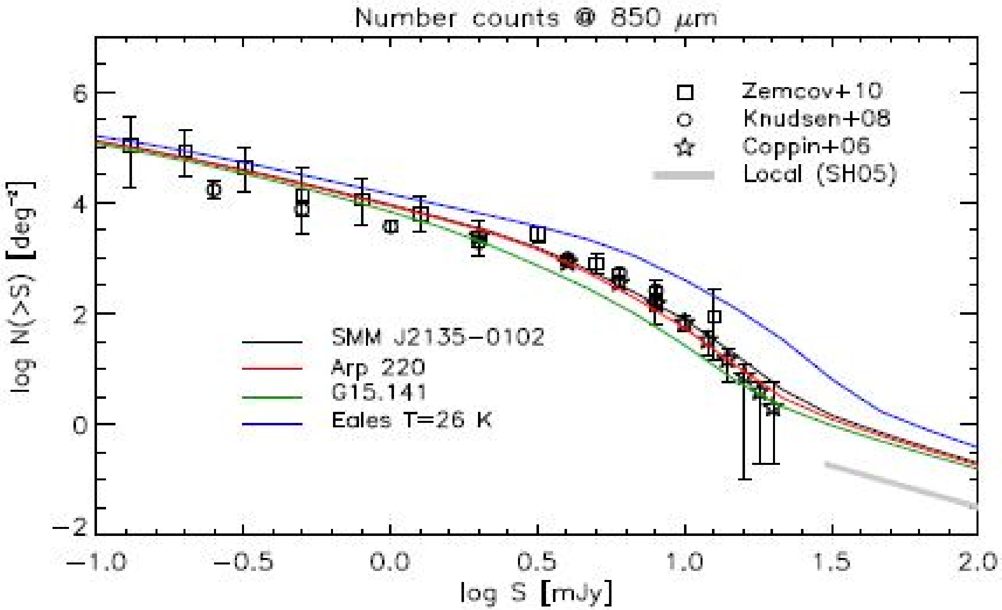


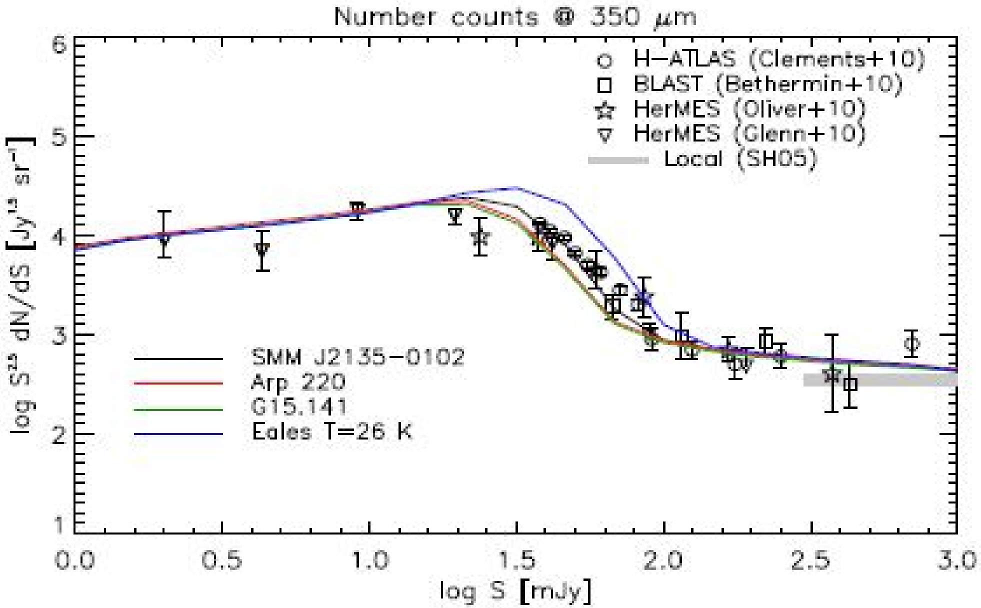
Number counts @ 1.4 mm
Total
Spheroids
Lensing
Spirals+Starbursts
Radiosources
SPT total (Vieira+10)
SPT dusty (Vieira+10)
Local (SH05)
log S[2.5] dN/dS [Jy[1.5] sr[-1]]
log S [mJy]

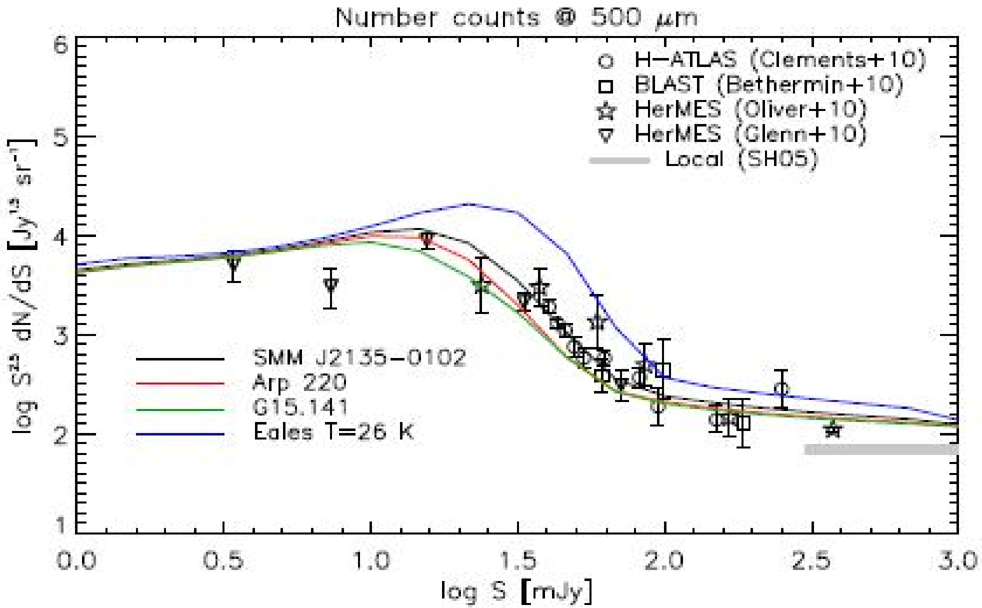


Number counts @ 2 mm
Total
Spheroids
Lensing
Spirals+Starbursts
Radiosources
SPT total (Vieira+10)
SPT dusty (Vieira+10)
Local (SH05)
log S[2.5] dN/dS [Jy[1.5] sr[-1]]
log S [mJy]

Dependence on SED: caution, but the main feature i.e. the steep rise is kept!

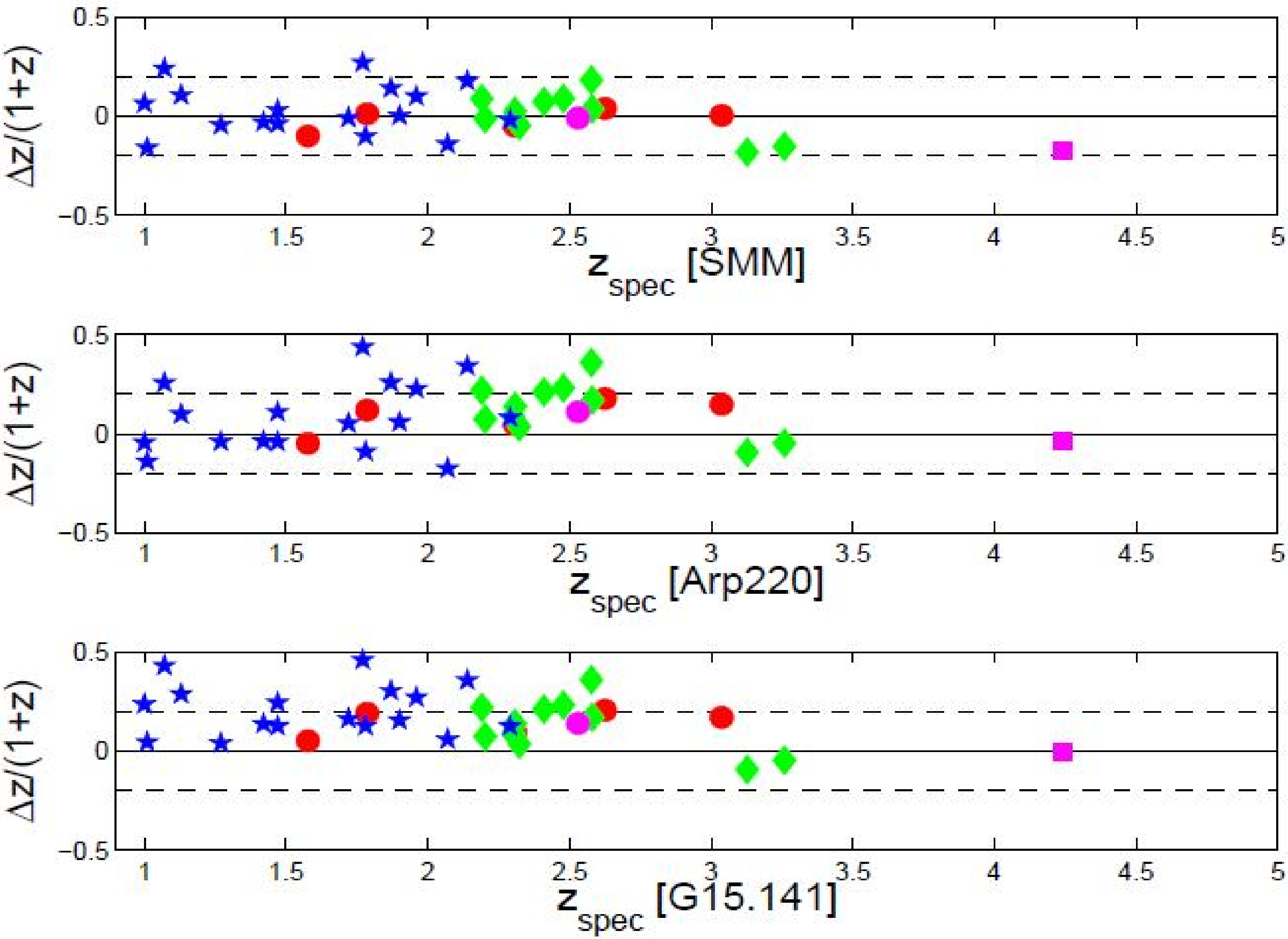




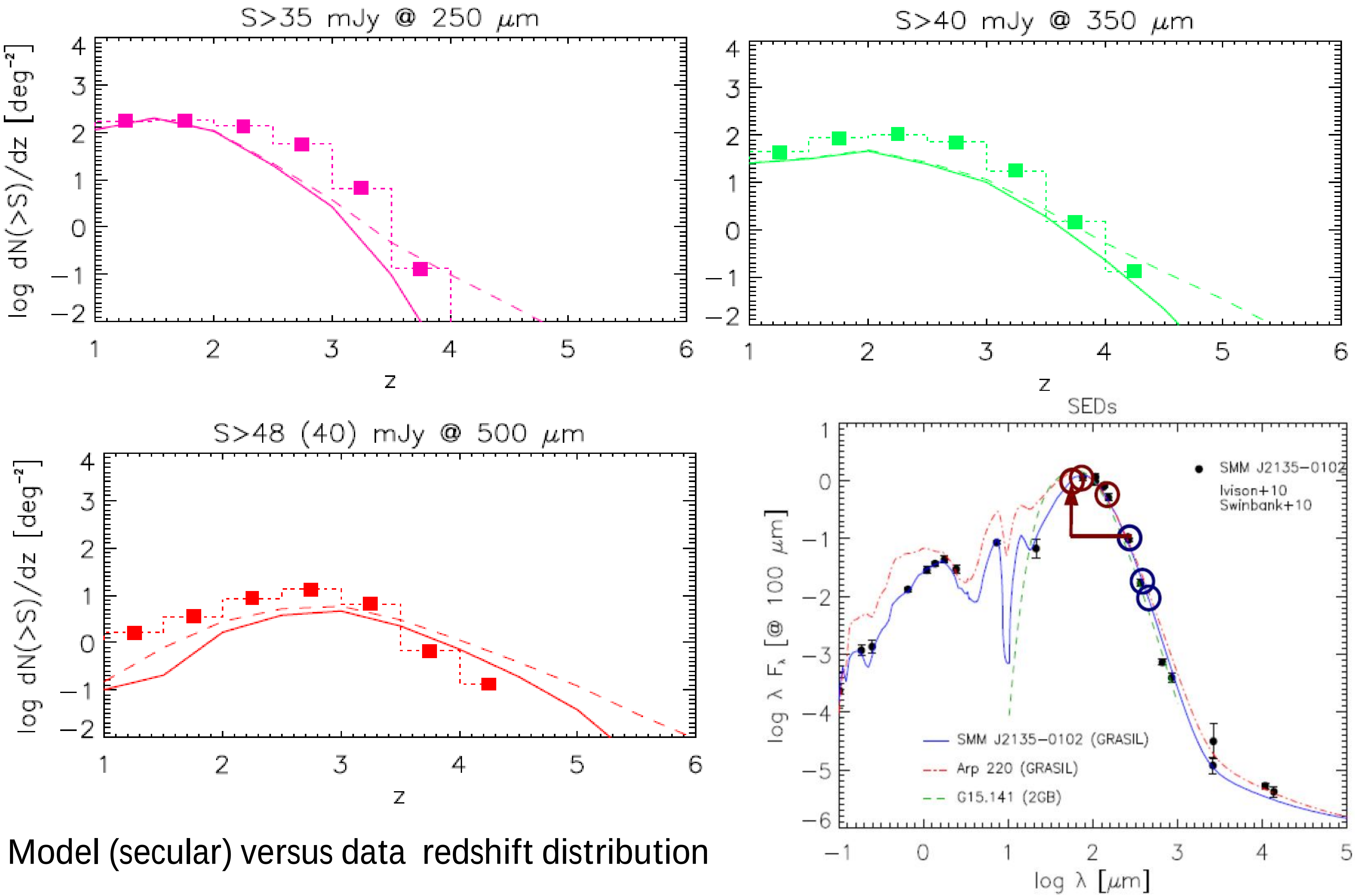


(Lapi+11)

Redshift with HERSCHEL far-IR photometry

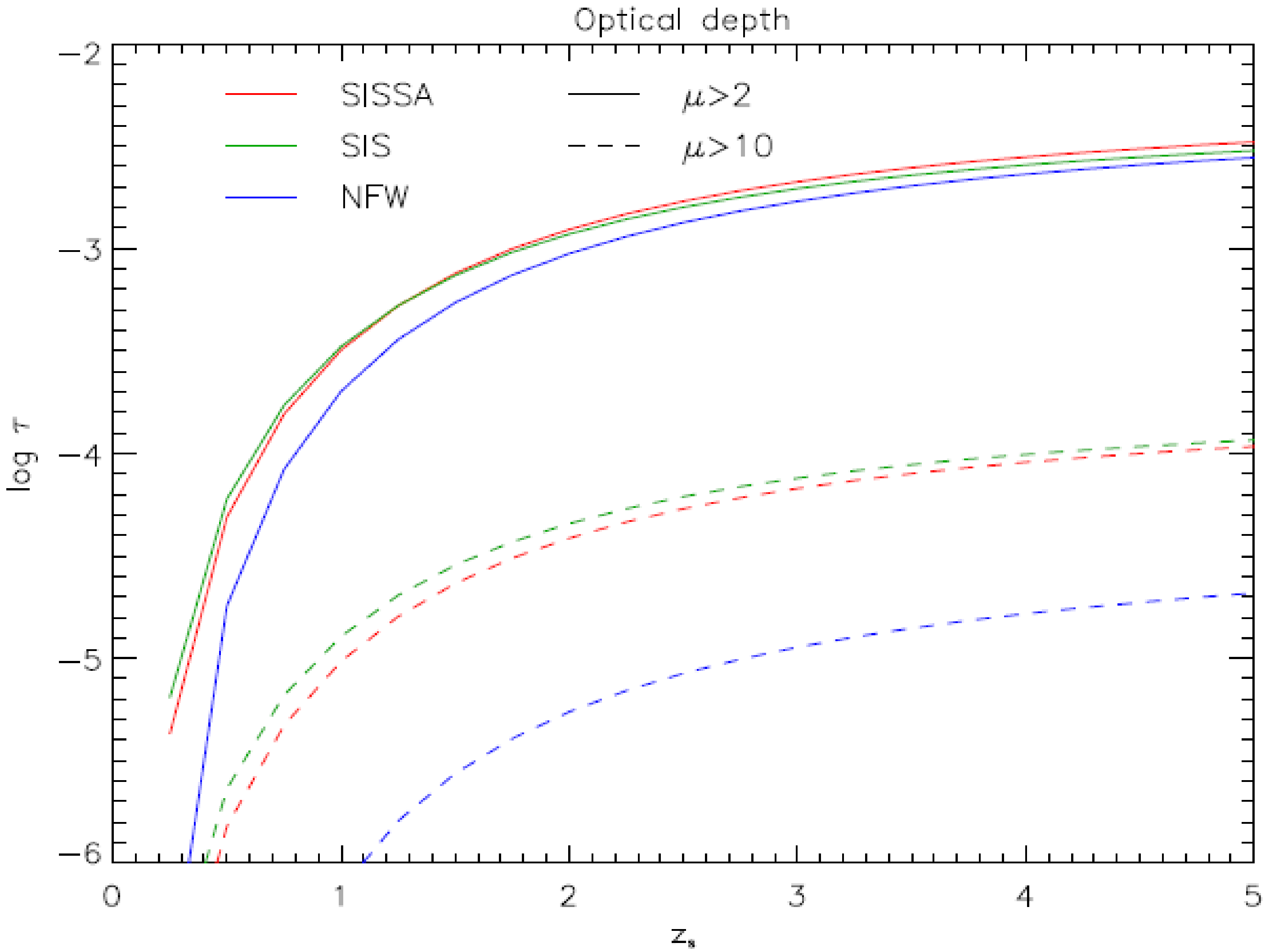


Gonzalez-Nuevo+12

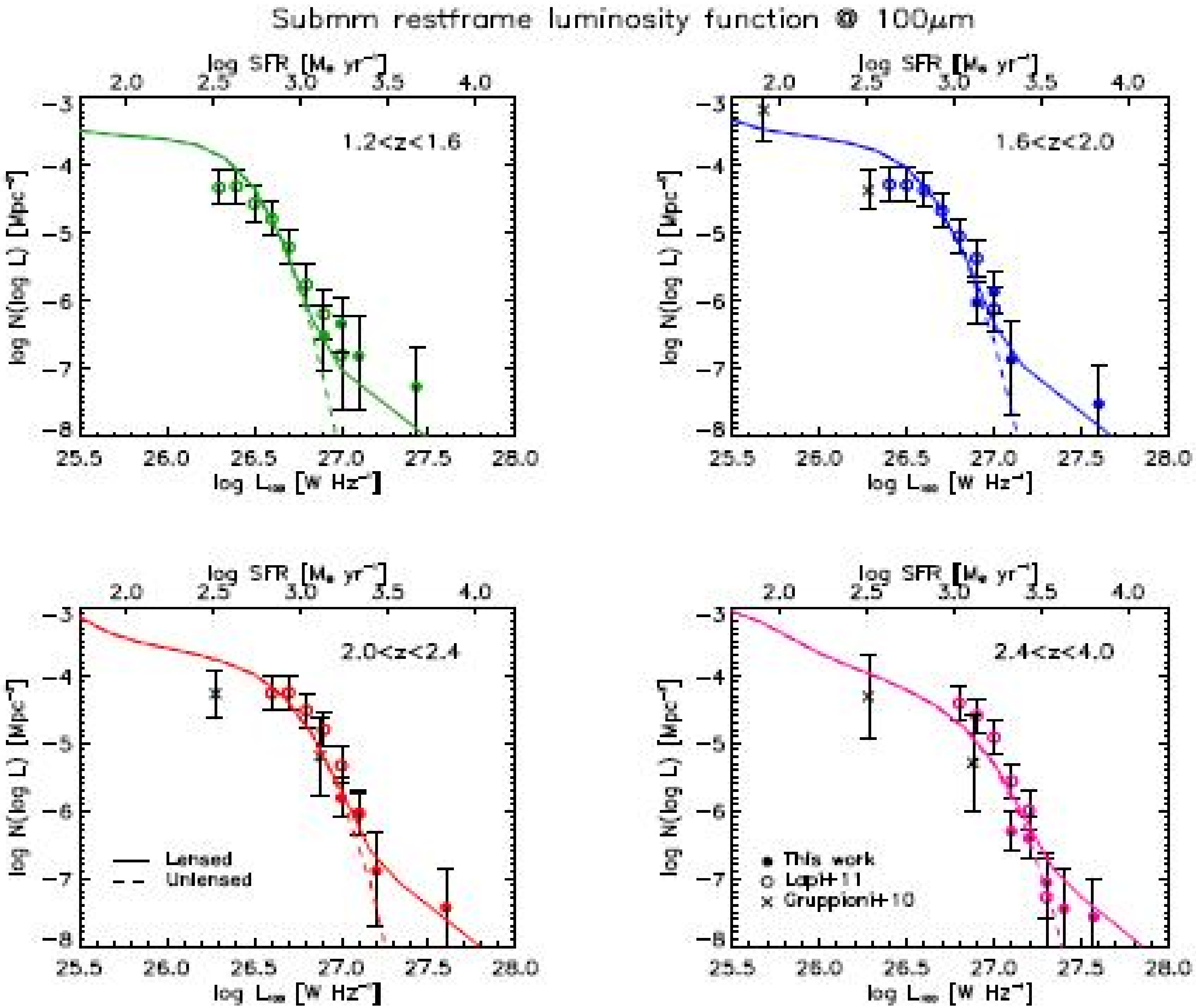


Model (secular) versus data redshift distribution

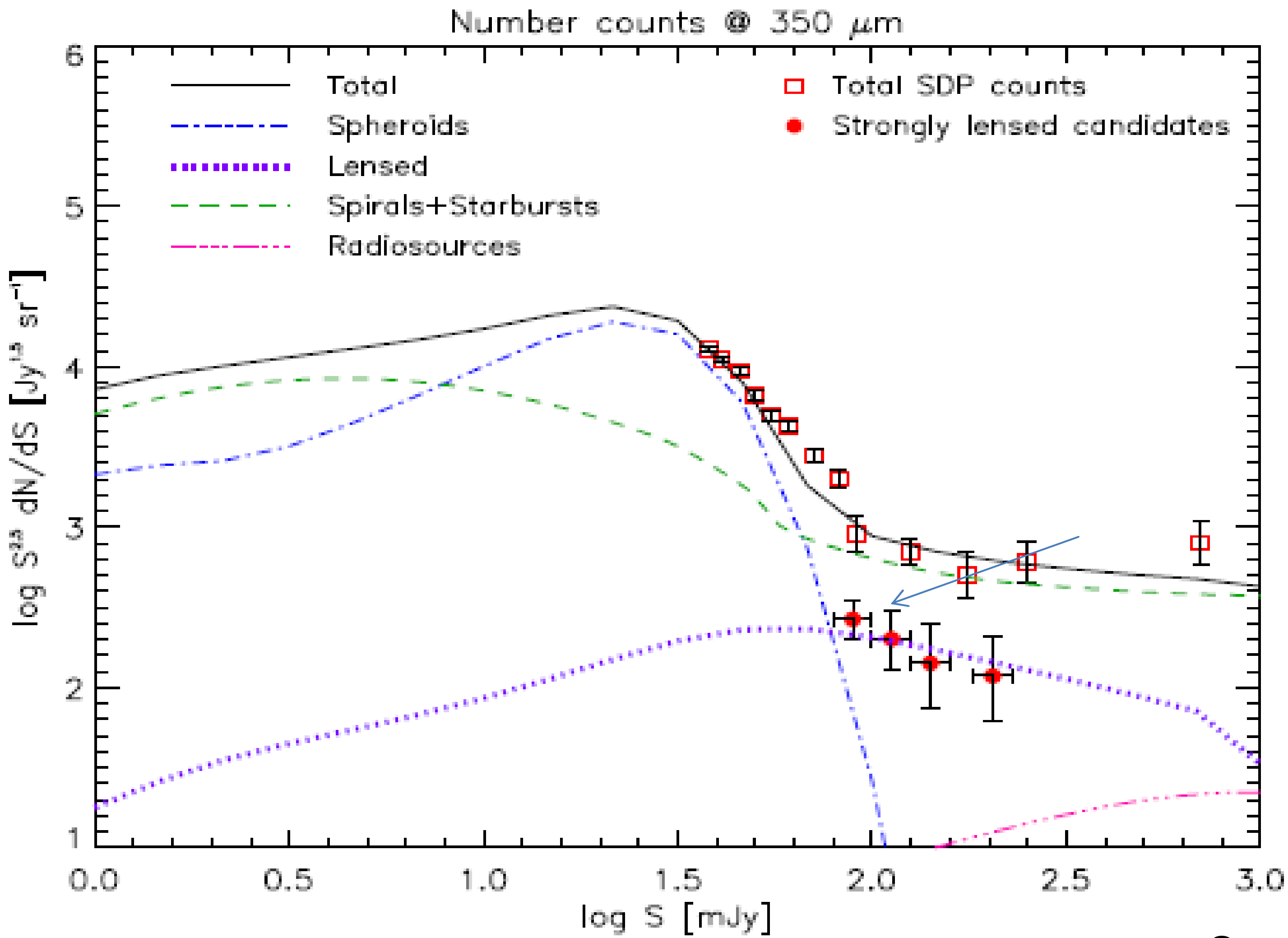
(Lapi+11)



IF LF (and hence counts) at z>1 are very steep significant number of lensed galaxies (gal-gal)!
Blain (96) Perrotta +02,03 Negrello +07



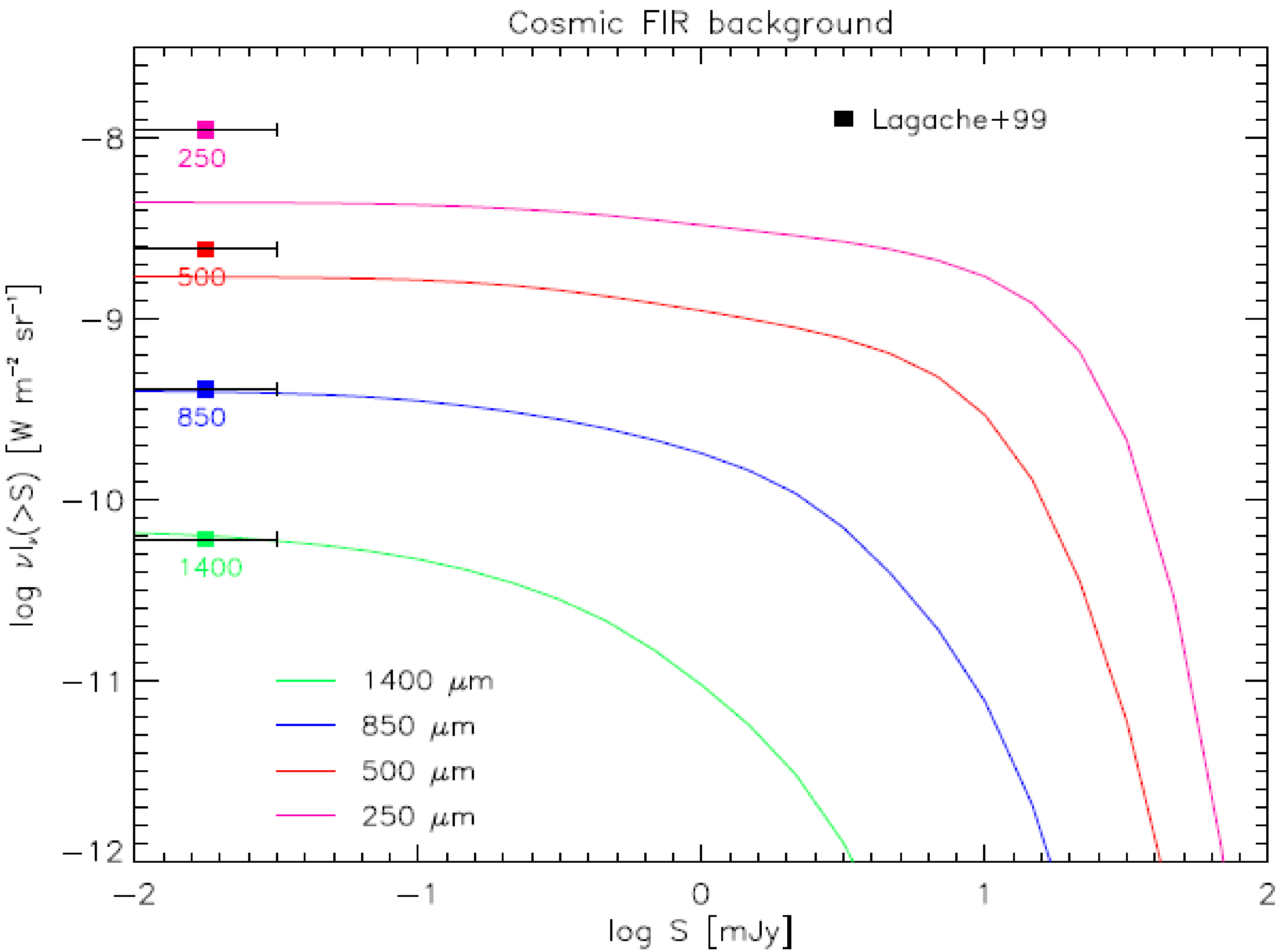
Negrello+10, Gonzalez-Nuevo + 11



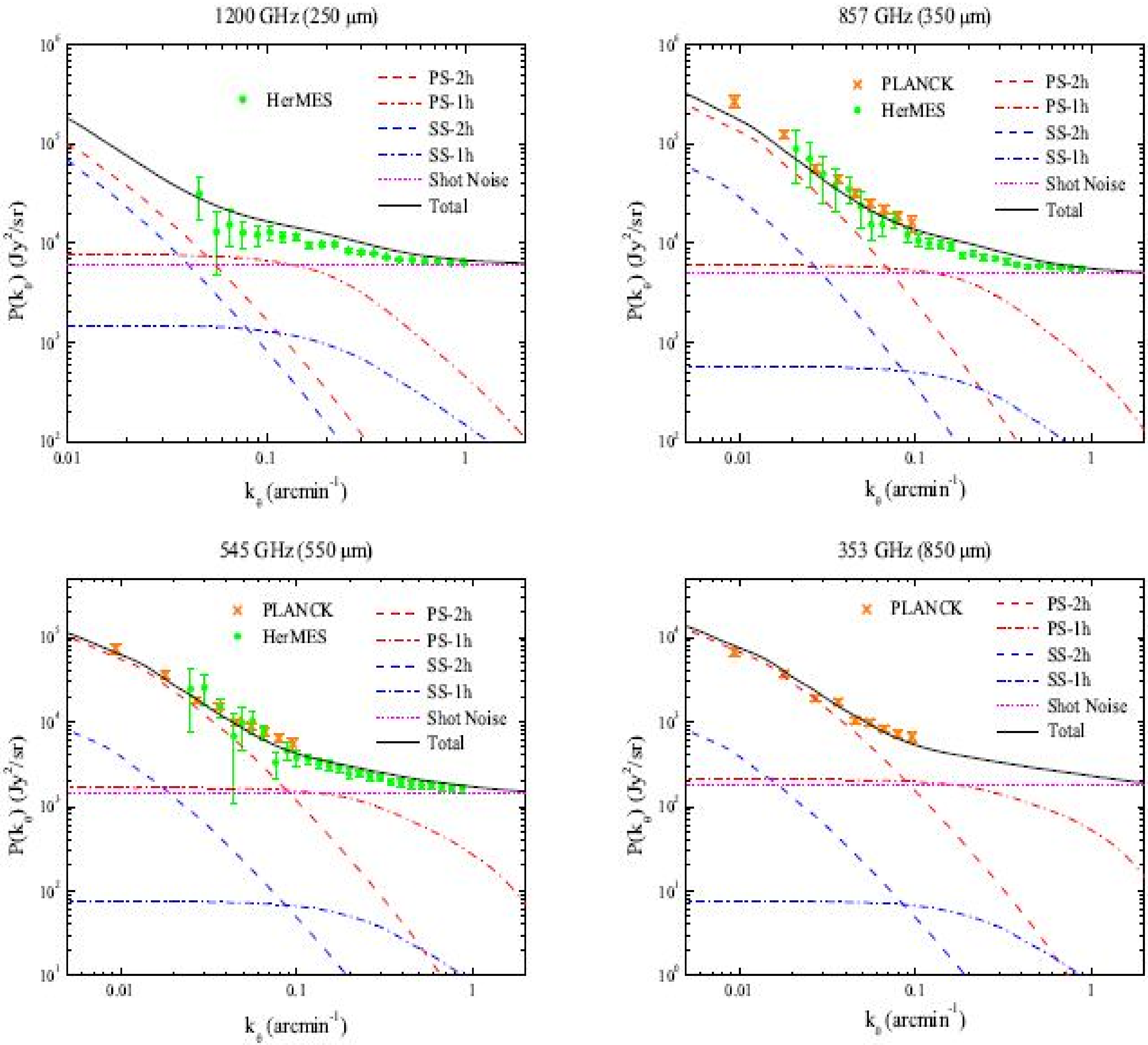
Lensed gal counts

Gonzalez-Nuevo + 11

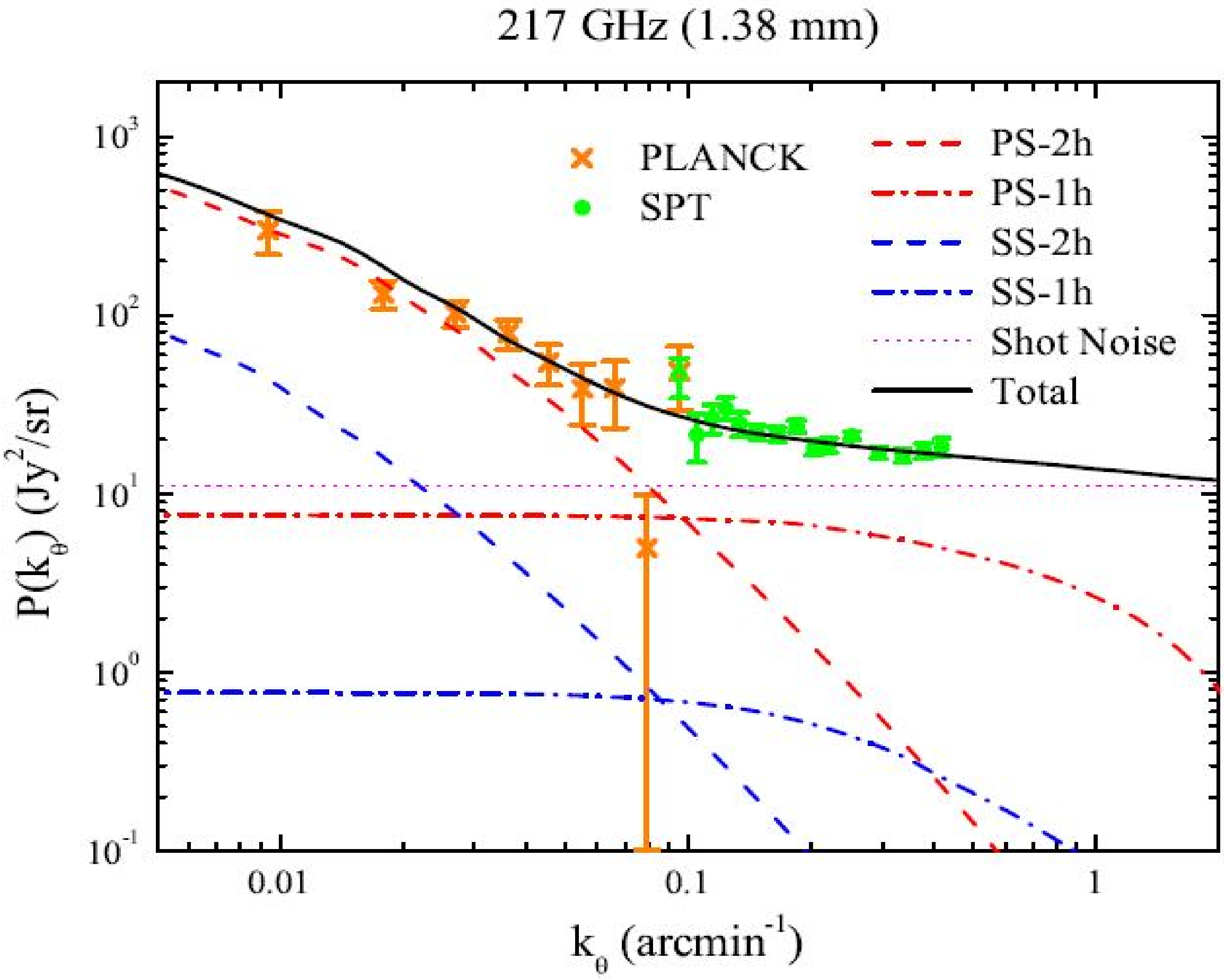
Lensed galaxies counts: toward 1000 lensed galaxies in ATLAS survey!


Cosmic FIR background
Lagache+99
250
500
850
1400
1400 μm
850 μm
500 μm
250 μm
log νI_ν(>S) [W m⁻² sr⁻¹]
log S [mJy]
−8
−9
−10
−11
−12
−2
−1
0
1
2

Lapi+11


1200 GHz (250 μm)
HerMES
PS-2h
PS-1h
SS-2h
SS-1h
Shot Noise
Total
857 GHz (350 μm)
PLANCK
HerMES
PS-2h
PS-1h
SS-2h
SS-1h
Shot Noise
Total
545 GHz (550 μm)
PLANCK
HerMES
PS-2h
PS-1h
SS-2h
SS-1h
Shot Noise
Total
353 GHz (850 μm)
PLANCK
PS-2h
PS-1h
SS-2h
SS-1h
Shot Noise
Total
P(k_θ) (Jy²/sr)
k_θ (arcmin⁻¹)
0.01
0.1
1

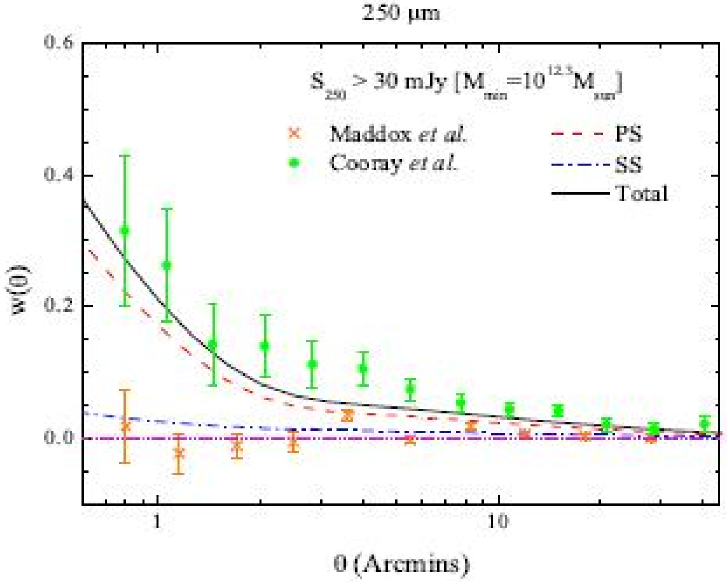
Xia+12

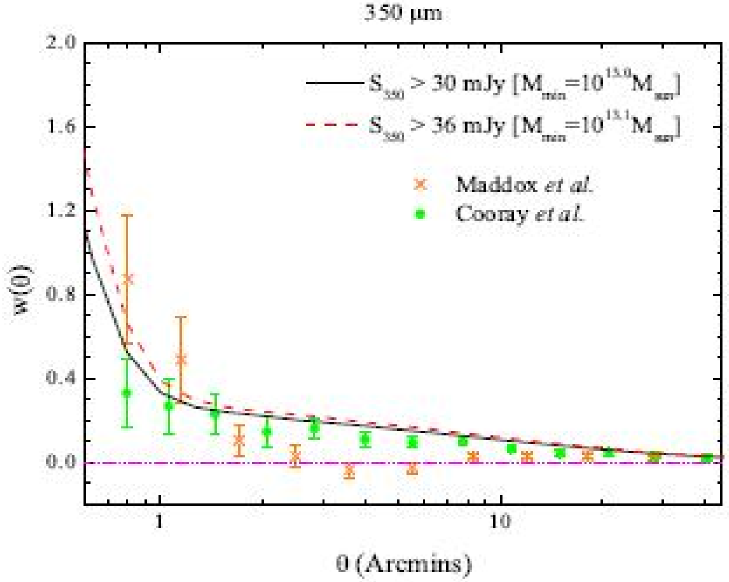


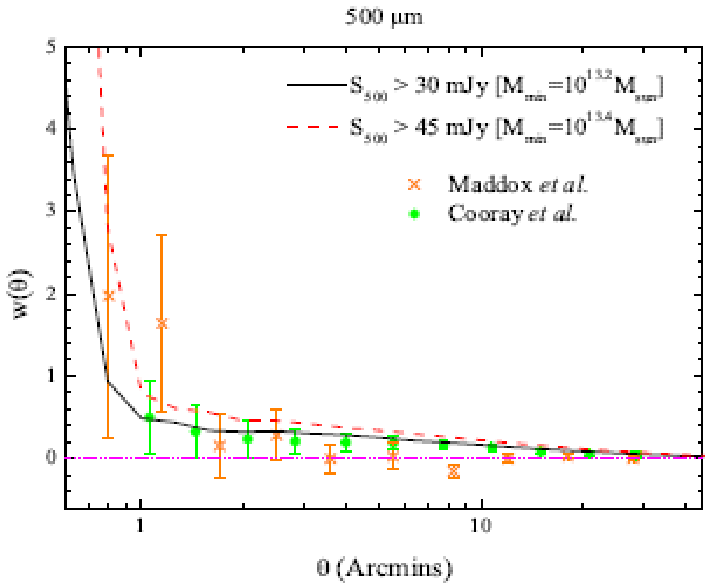
Xia+12

The large power implies that M_eff ~5 10^12 M_sun.
In the secular model this mass is predicted to have SFR ≈ 200-300 and number density $n \approx 10^{-4}\ Mpc^{-3}$. The secular model places the right SFR into the right massive halos!

CORRELATION FUNCTION







$z \simeq 2,\ r_0 \simeq 6.9\,h^{-1}\,\mathrm{Mpc} \quad b_{\mathrm{eff}} \simeq 3.$

Conclusion:

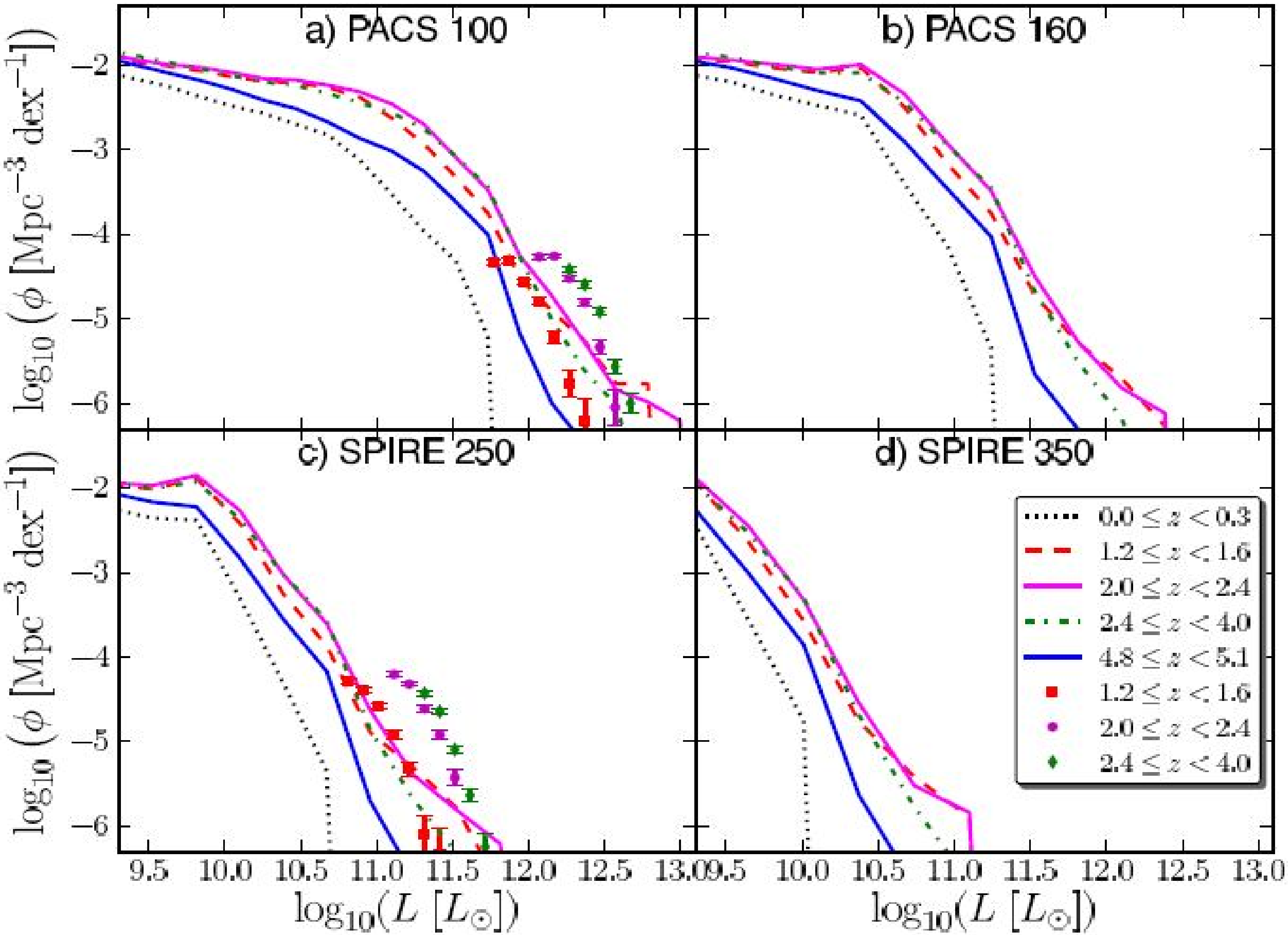
Granato+01,04;Lapi+06

Local, massive ETGs	**High-z submm galaxies (the progenitors)**	**Secular cooling + SN/QSO feedback**
Old stellar populations age > 7 Gyr, z_sf > 1	Redshift distribution z>1 + Strong lensing	✓
Alpha-enhancement Δ t_sf< 1 Gyr (but much longer in smaller galaxies)	Luminosity functions Δ t_sf < 1 Gyr	✓
High stellar metallicity Rapid enrichment of ISM	Dust soon in place (UV and submm LF)	✓
Steep local stellar mass function clustering properties →hosted in massive halos	Steepness of LF and counts + clustering + CIB fluct. → hosted in massive halos ~ 3-5 10^12	✓
BH-M_star relation	QSO luminosity function	✓

HERSCHEL AND PLANCK data strongly support the conclusion that

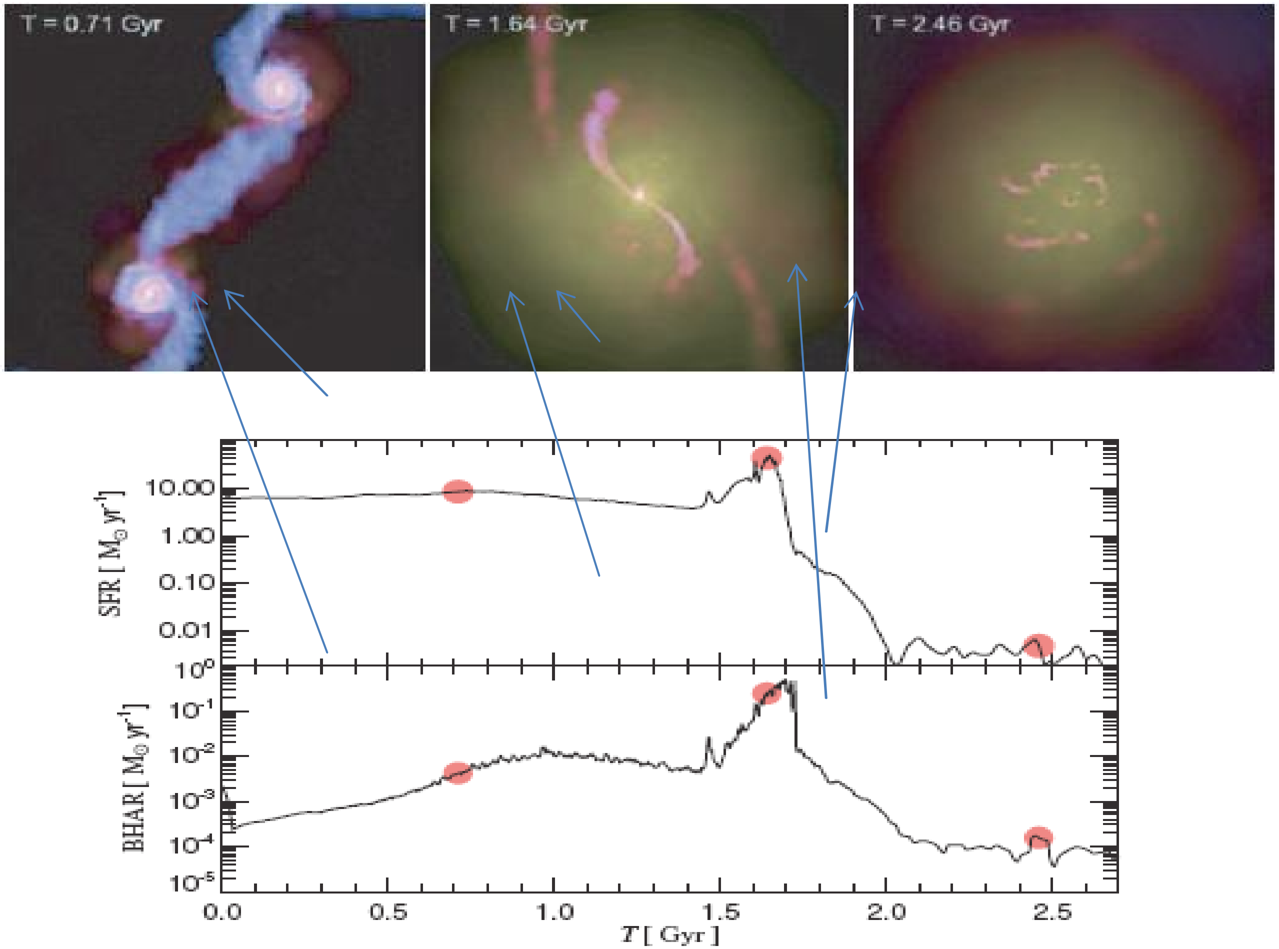
High z sub-mm gal are the progenitors of local massive ETGs!

SUB-mm and Far-IR data highlight the problems of physical models based on merging!

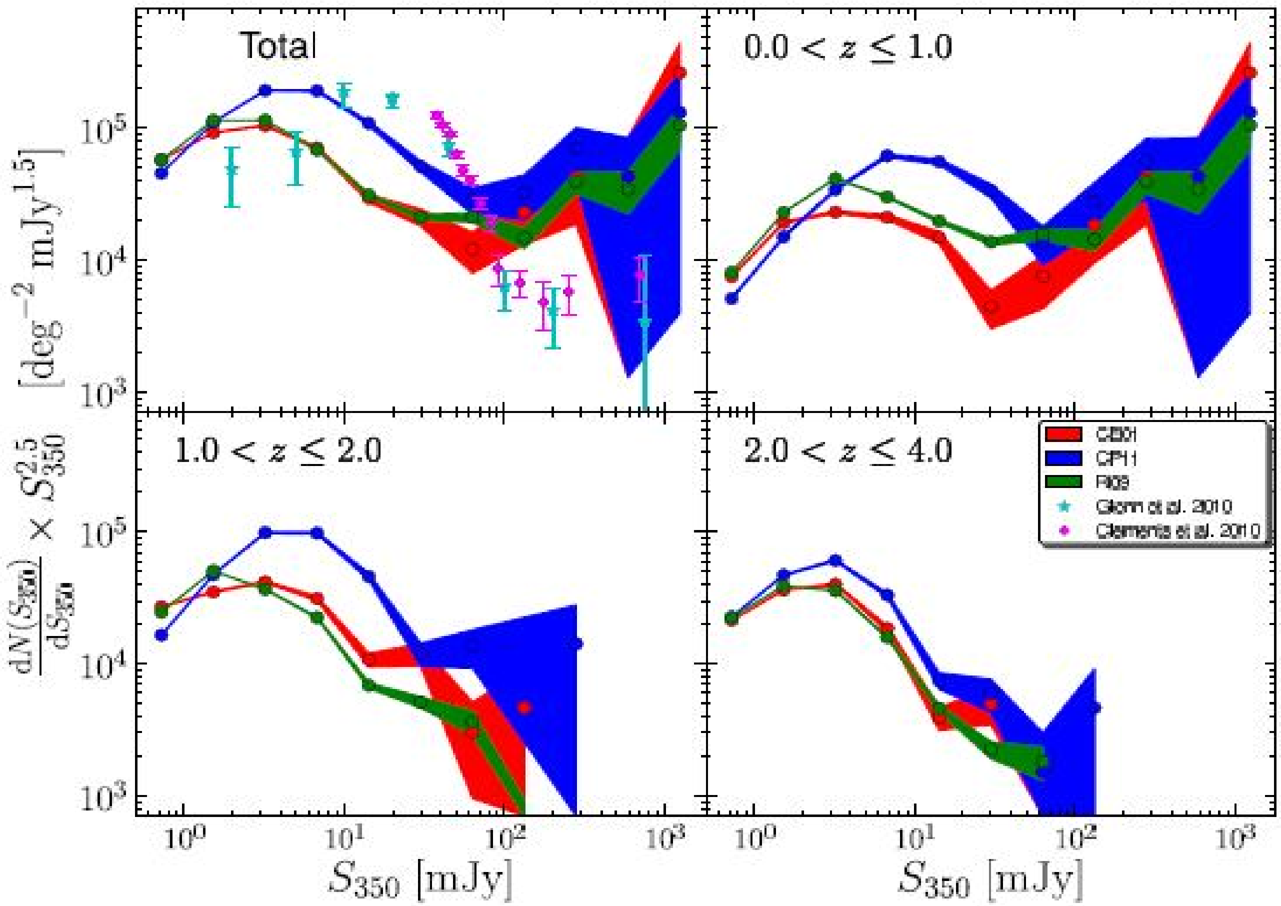


Niemi+12

Hopkins+ 07


T = 0.71 Gyr
T = 1.64 Gyr
T = 2.46 Gyr
SFR [M⊙ yr⁻¹]
10.00
1.00
0.10
0.01
BHAR [M⊙ yr⁻¹]
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.0
0.5
1.0
1.5
2.0
2.5
T [Gyr]

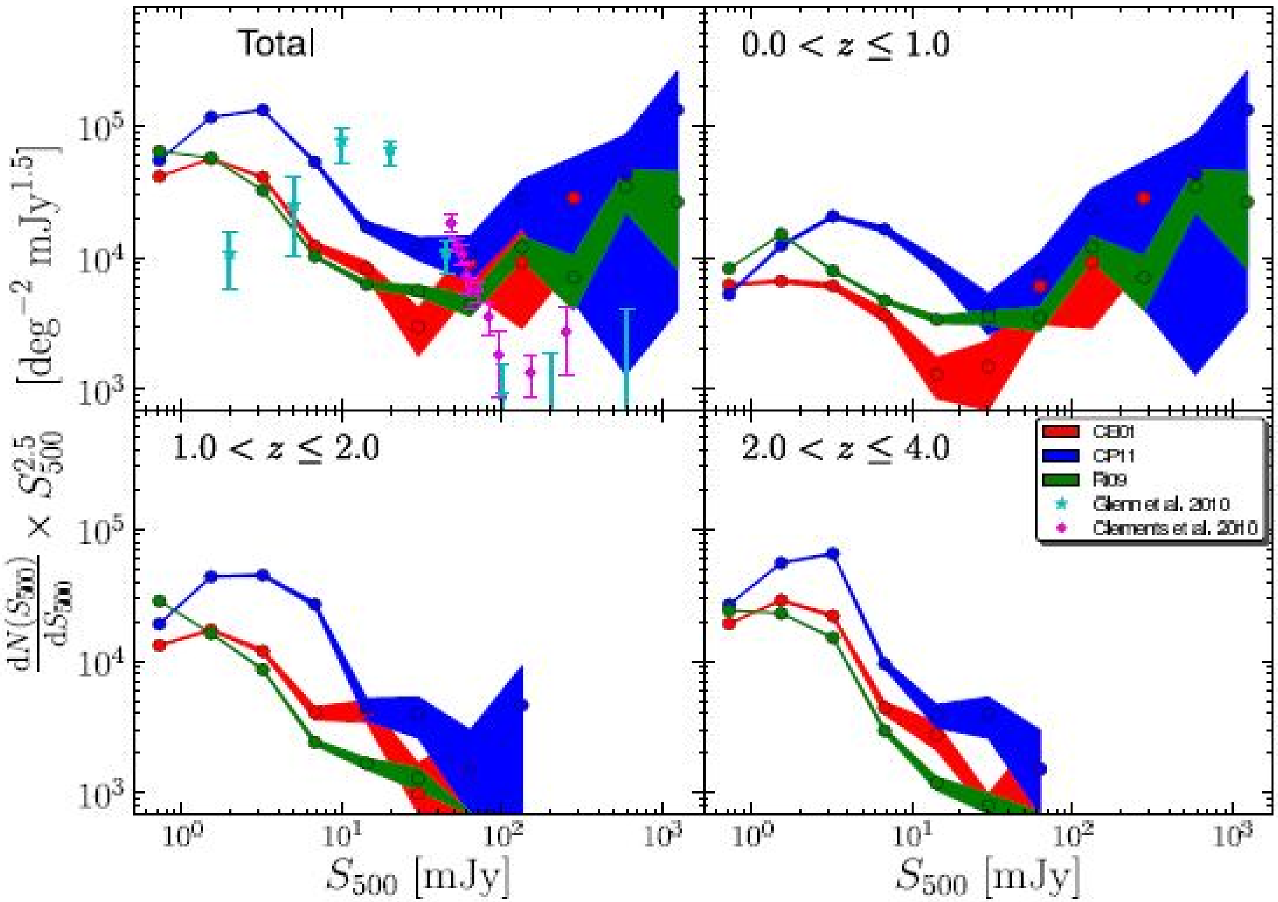
SUB-mm and Far-IR data highlight the problems of physical models based on merging!



(different colors different SED)

Niemi+12

SUB-mm and Far-IR data highlight the problems of physical models based on merging!



Niemi+12