Stellar mass assembly since z=4 in COSMOS

Olivier Ilbert

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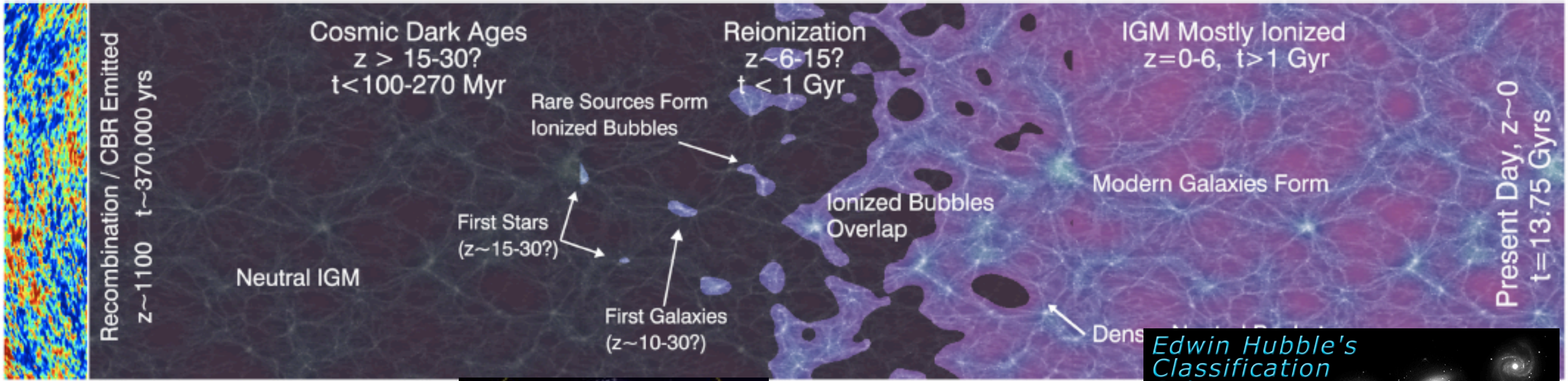
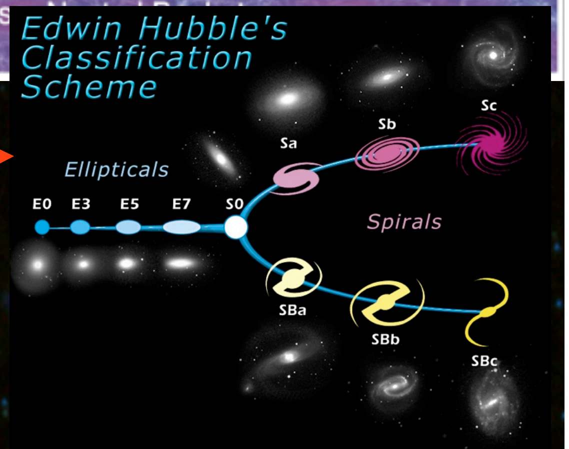
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

cosmological context

Robertson et al. 2010



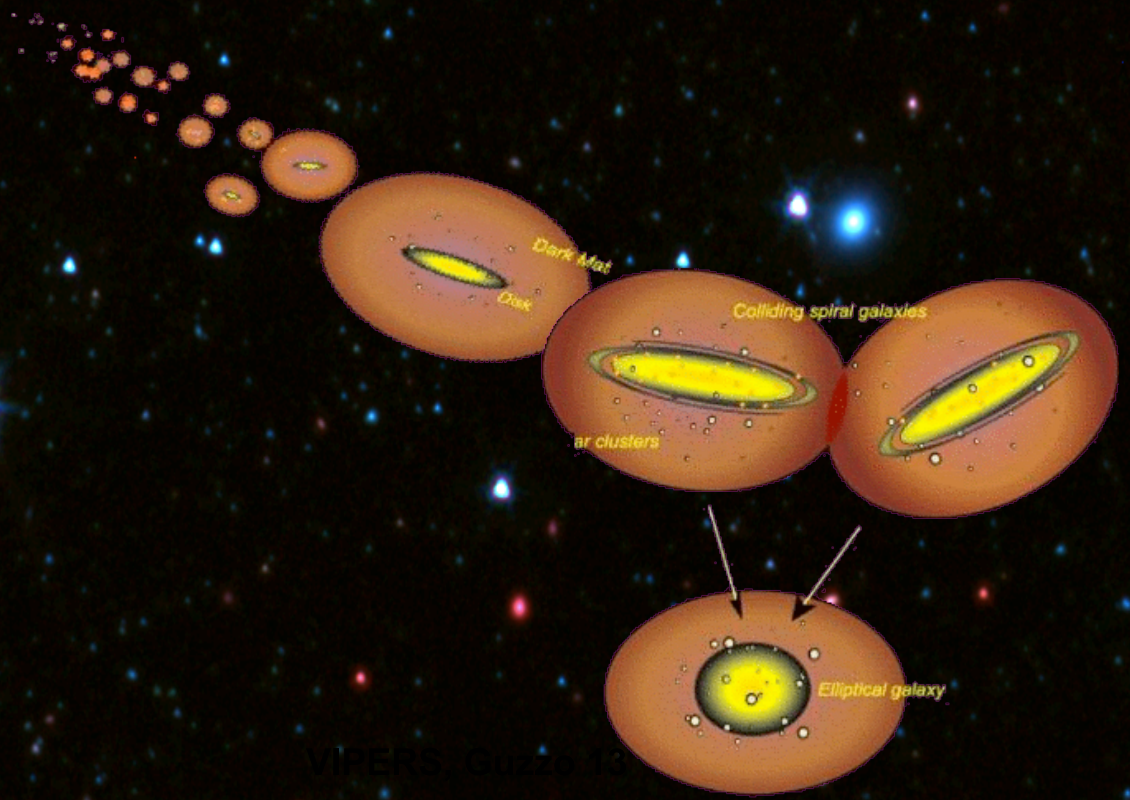


How galaxies assemble $10^{12}M_{\odot}$ in 13-14 Gyr ?

Galaxy formation in the ΛCDM

Hierarchical growth of dark matter halos

➢ continuous increase of the baryons available for the galaxy stellar mass assembly

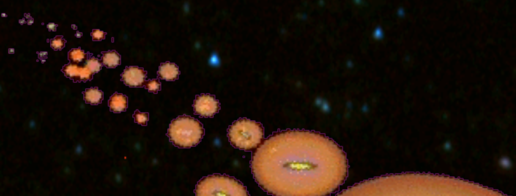


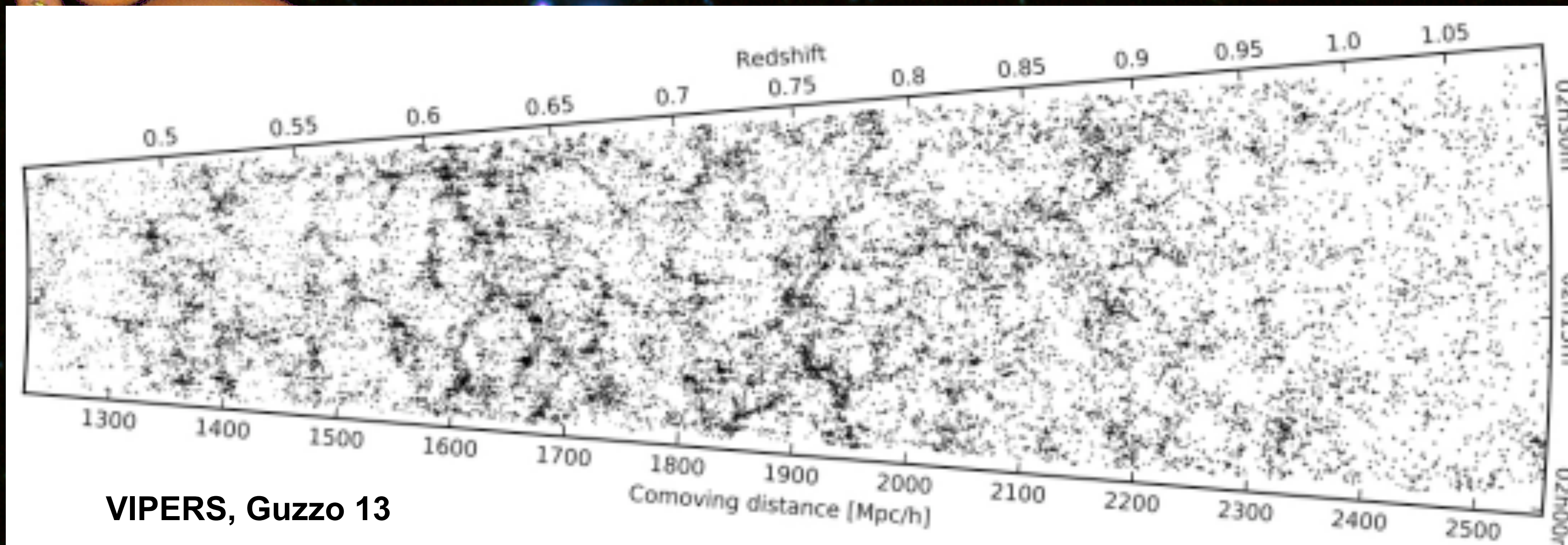
Galaxy formation in the ΛCDM

Hierarchical growth of dark matter halos

➢ continuous increase of the baryons available for the galaxy stellar mass assembly

➢ best context to explain the galaxy large-scale structures

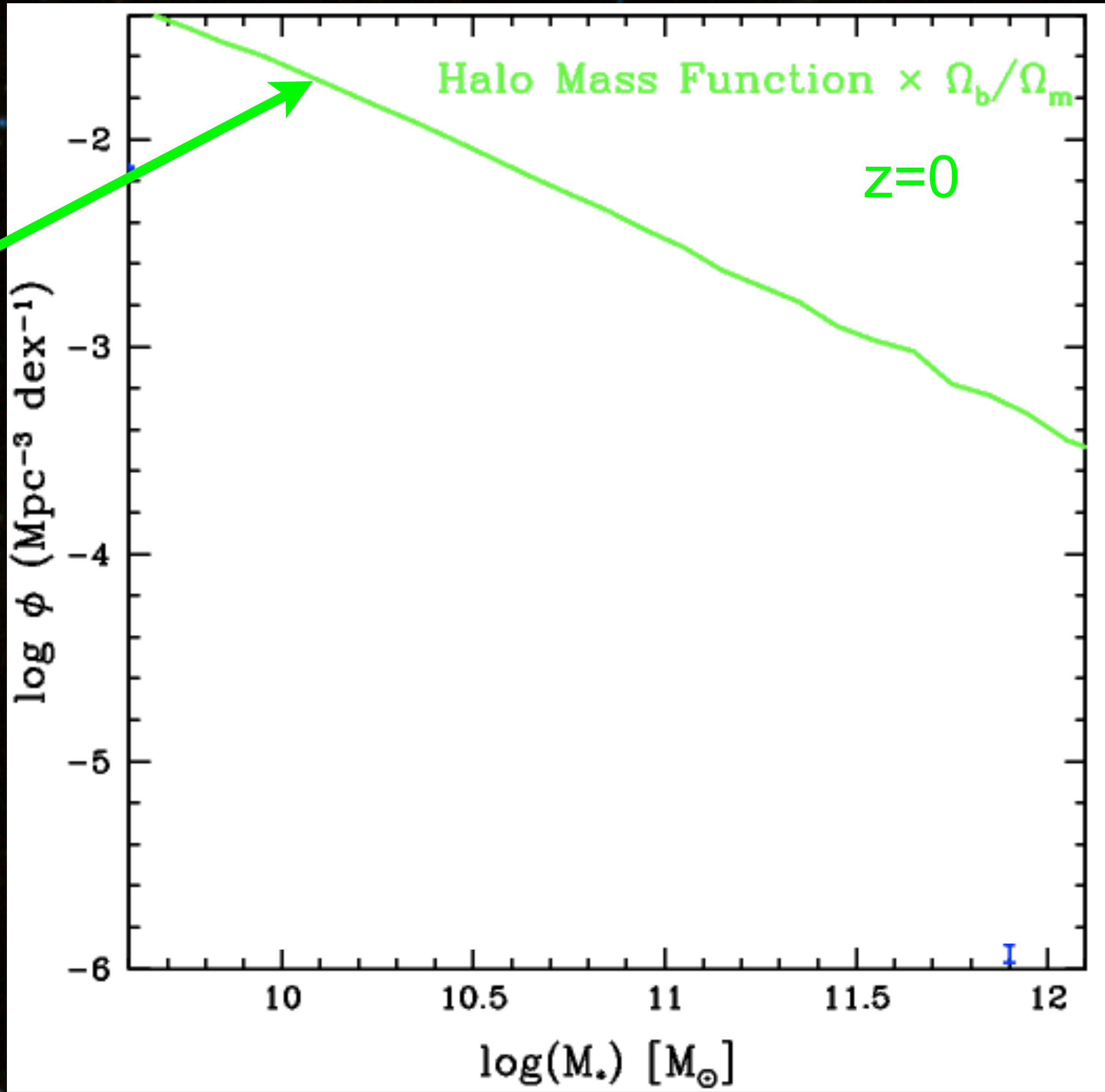




VIPERS, Guzzo 13

From dark matter halos to stars

If all the baryons present in one halo were converted into stars

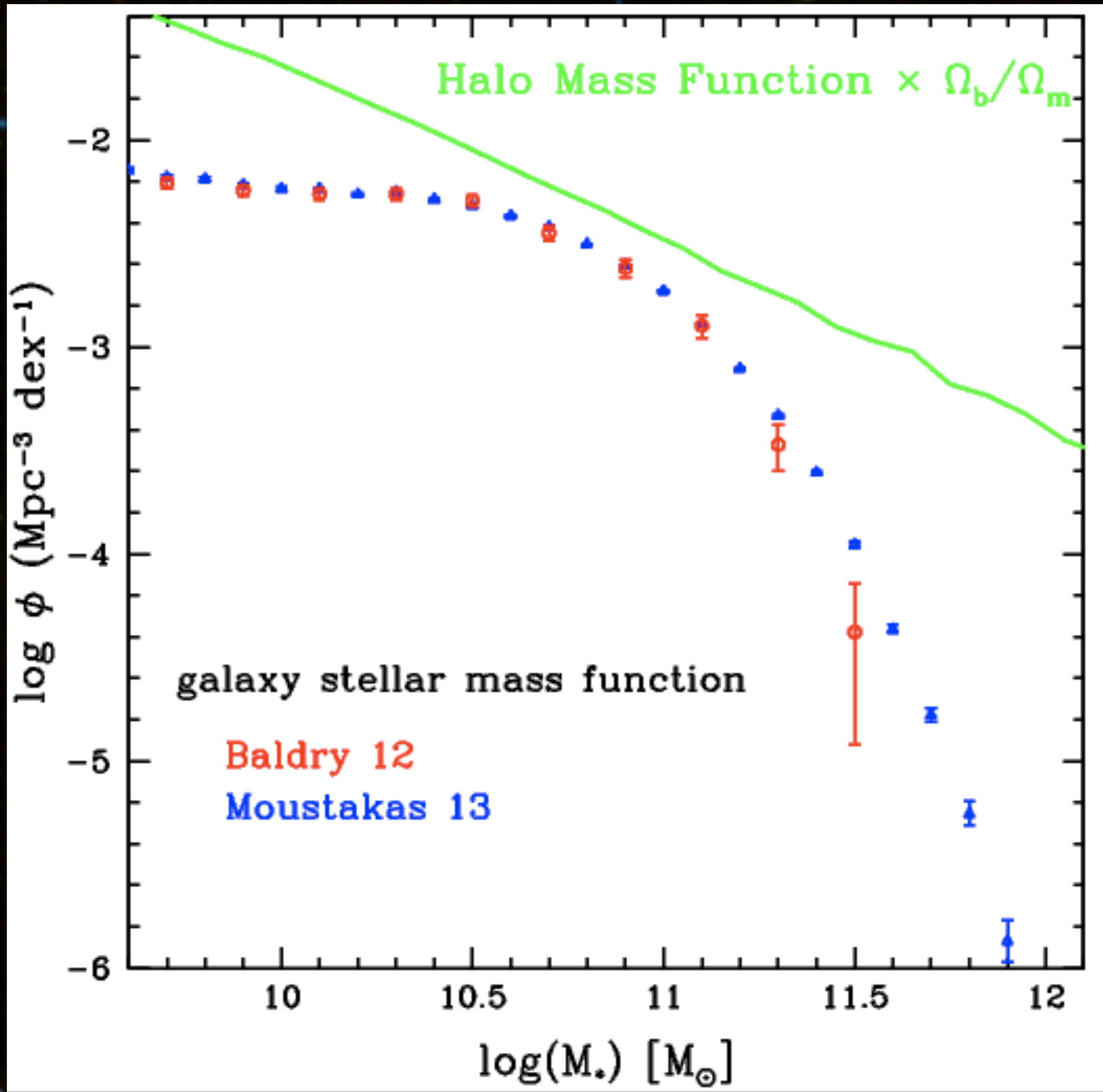


From dark matter halos to stars

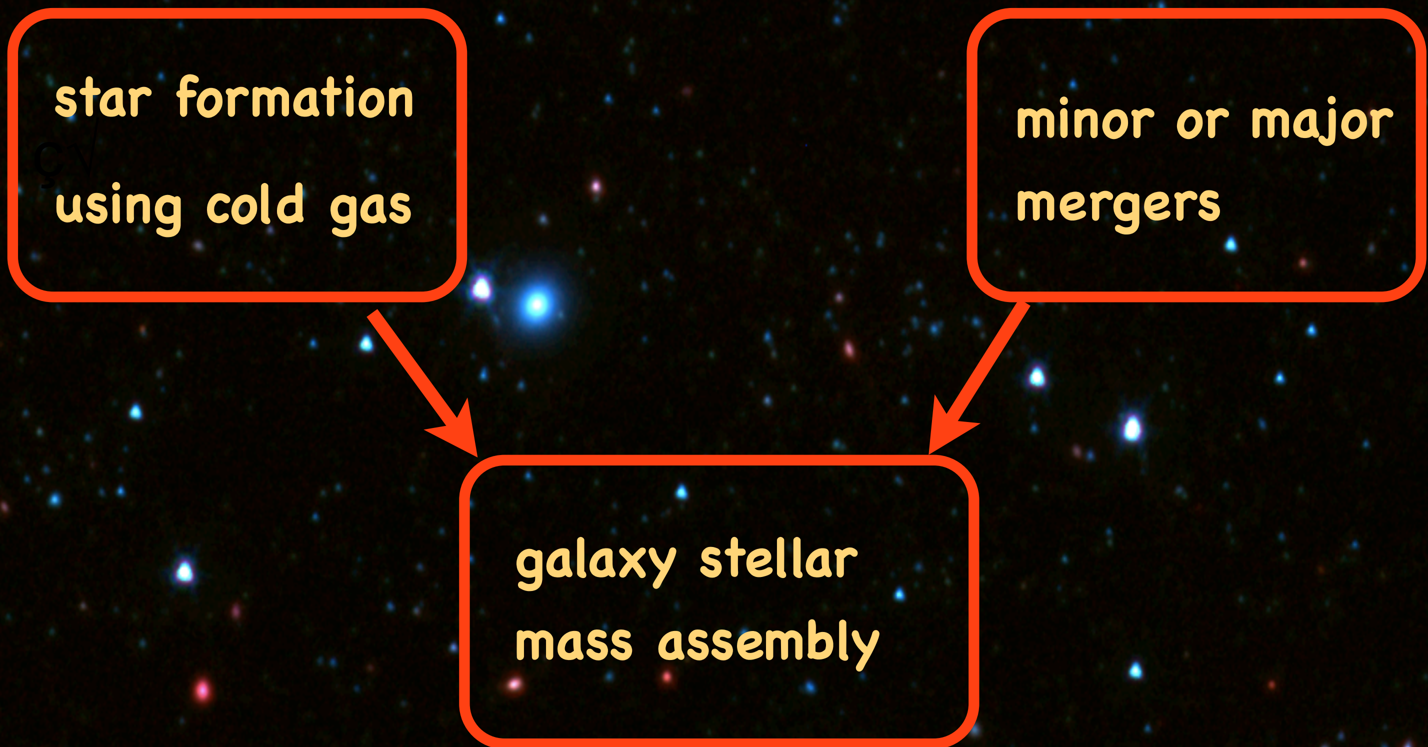
Only a fraction of the baryons are converted into stars

Depends on the mass

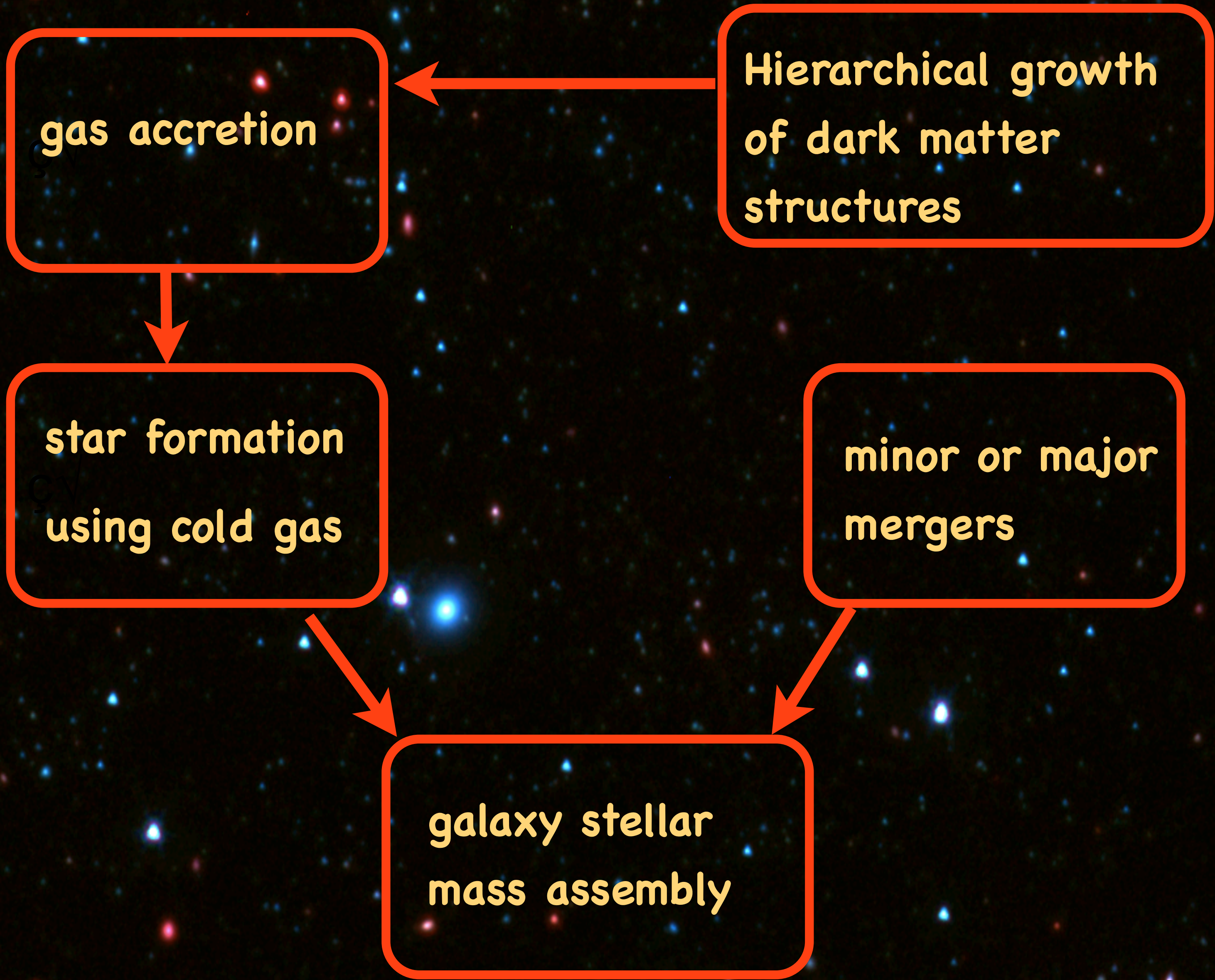
➢ complex baryonic physics



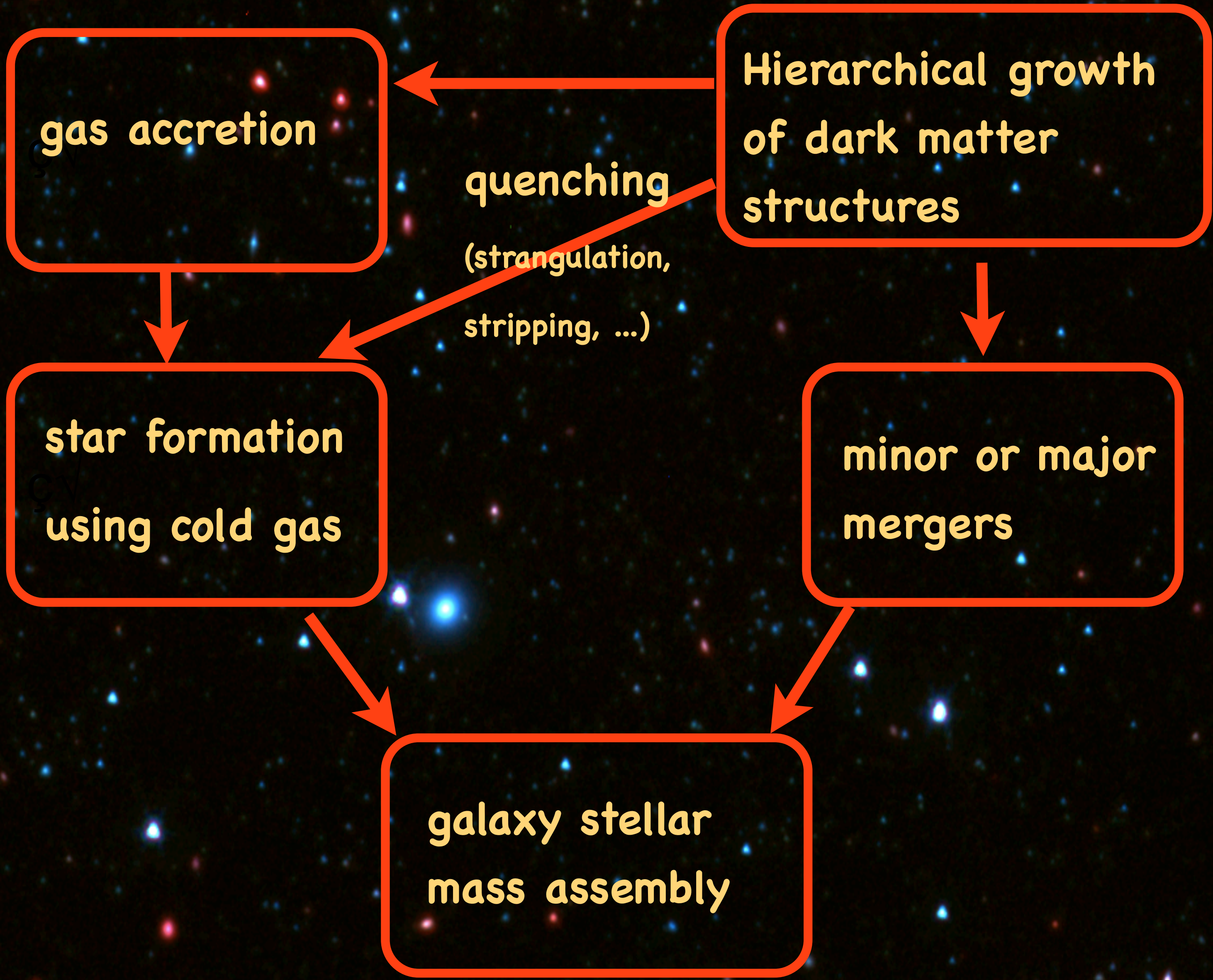
Possible physical processes



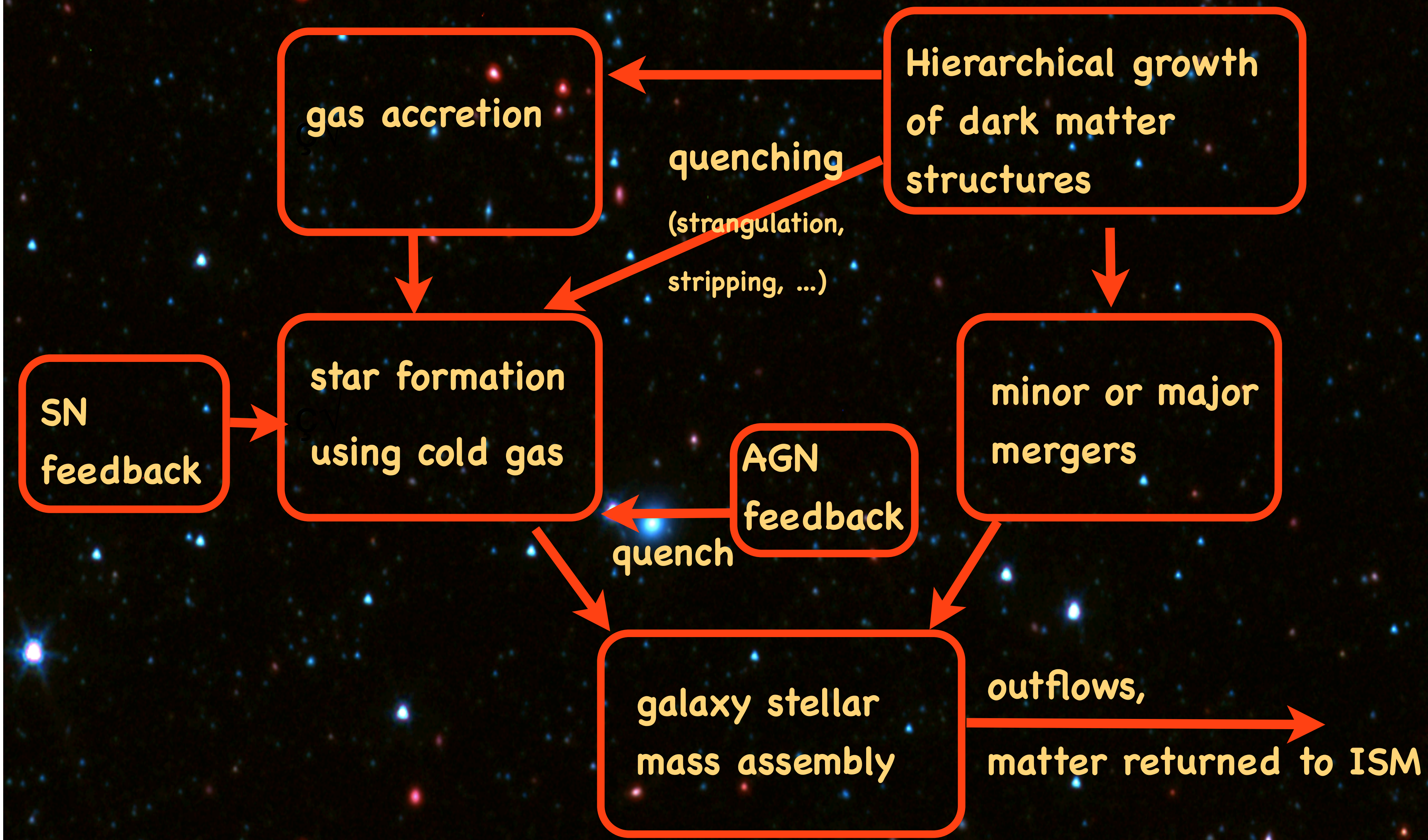
Possible physical processes



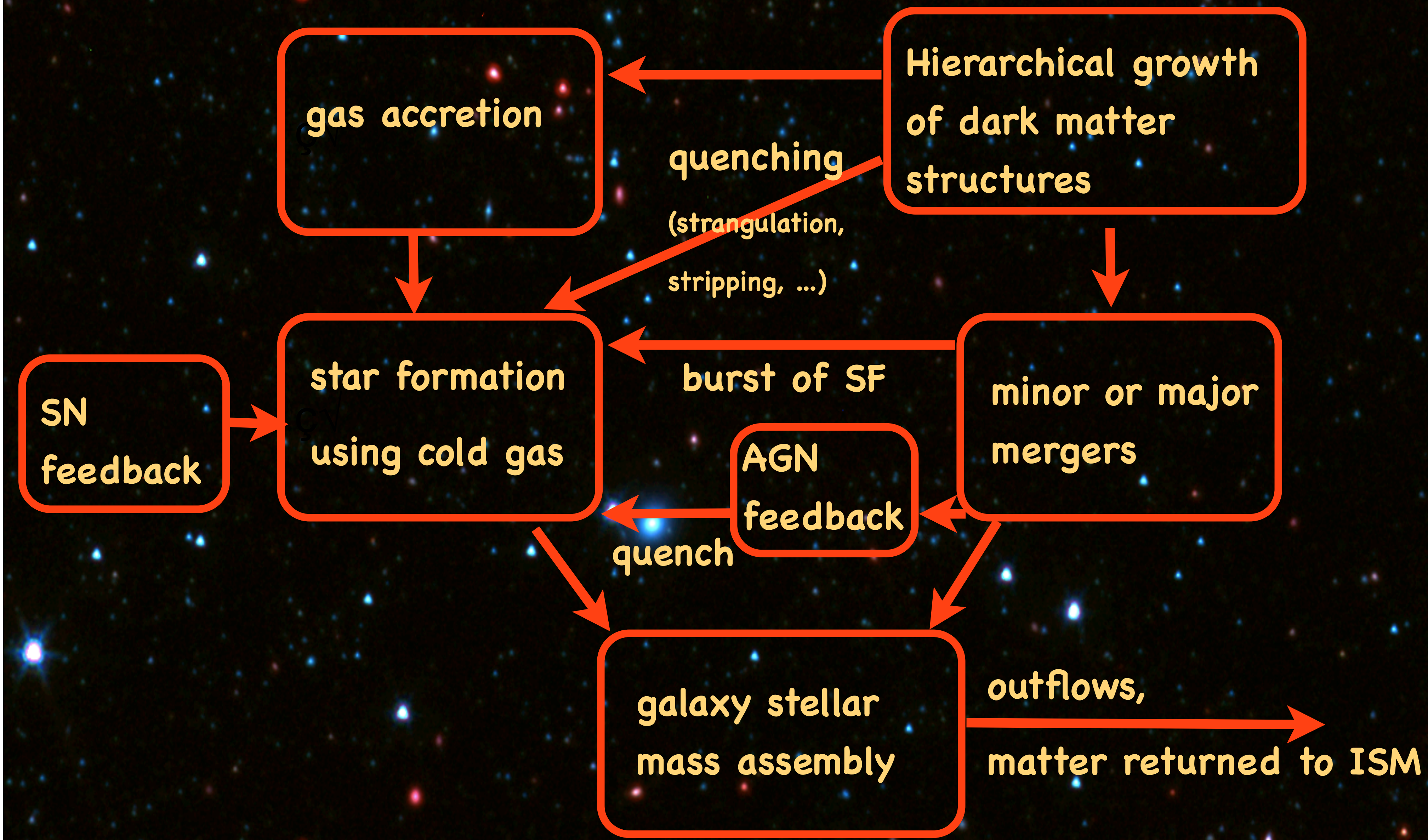
Possible physical processes



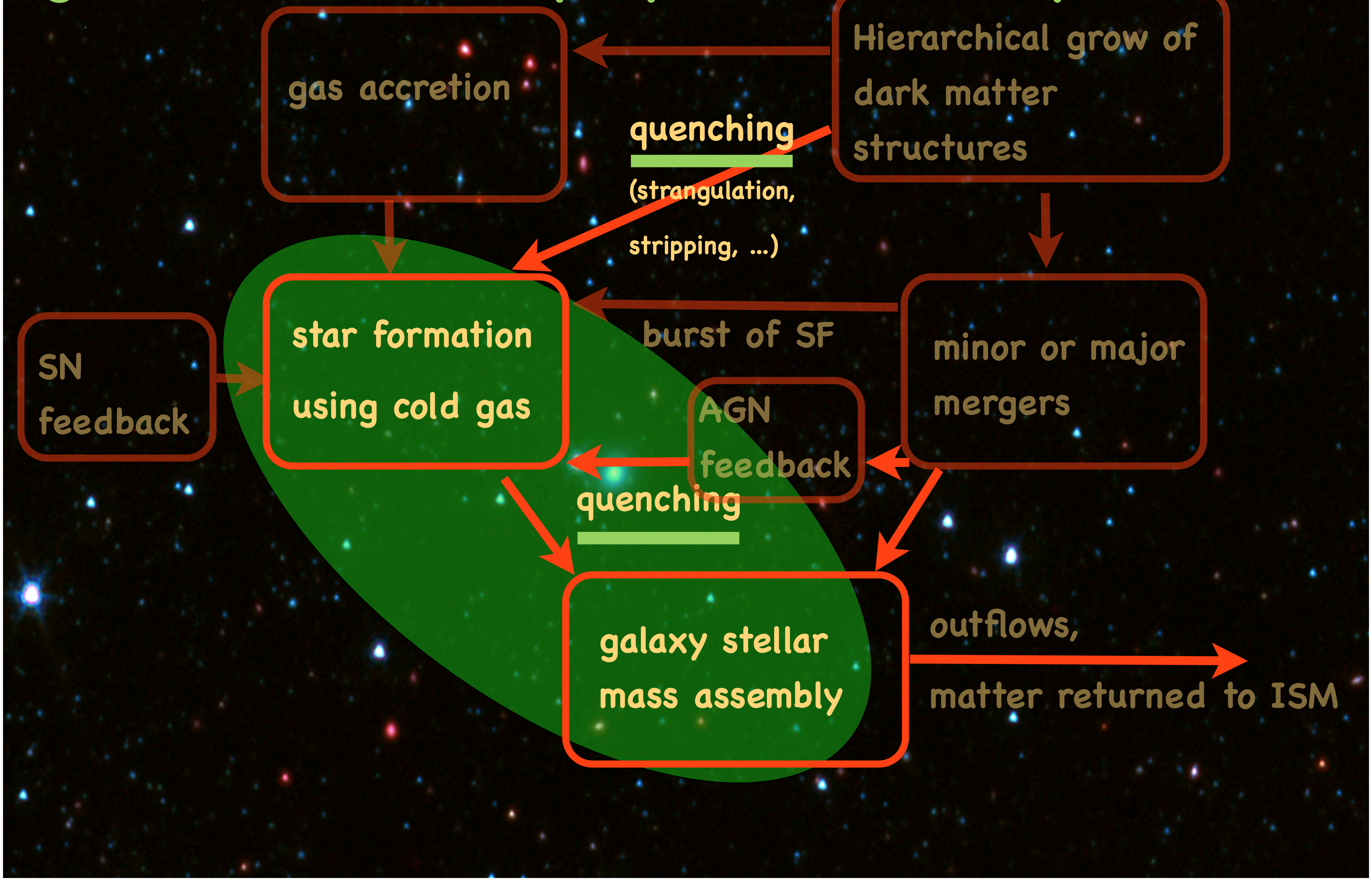
Possible physical processes



Possible physical processes



Observational constraints using galaxy statistical properties in deep surveys



Open questions

Relative efficiency of these processes across cosmic time

- Accretion mode of the cold gas: radiative cooling, cold accretion ?
  - ➢ Evolution the star formation rate
- Action mode of AGN and SN feedback
  - ➢ shape of the mass function, quenched galaxies
- importance of major mergers versus secular evolution, bursty versus passive star formation
  - ➢ evolution of the relation between mass and SFR

Outlines

I. The COSMOS Ultra/VISTA data

II. The star formation history from a MF perspective

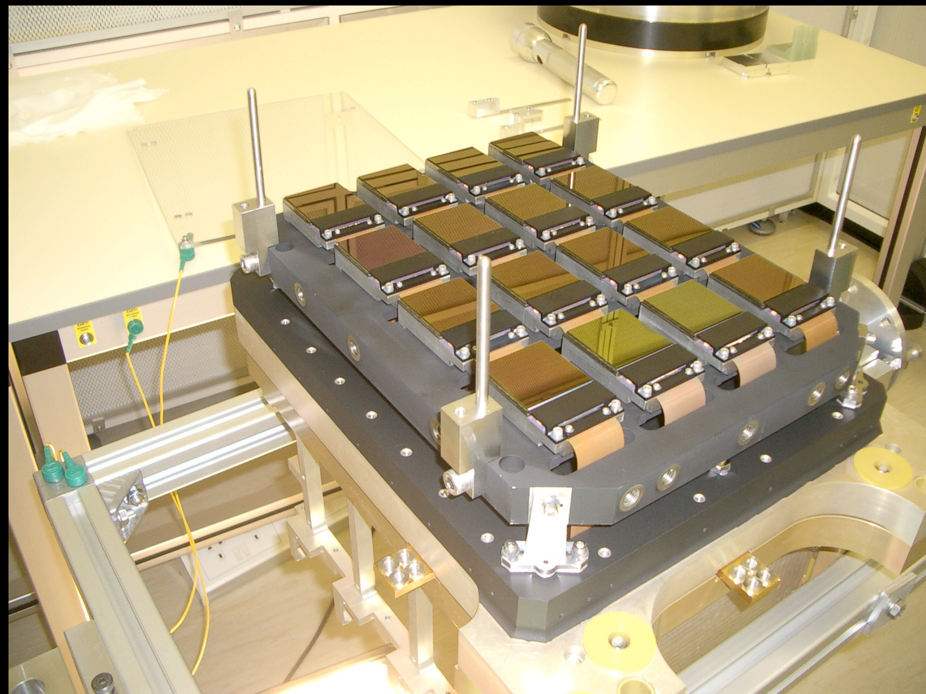
III. Quenching

IV. Evolution of the specific SFR

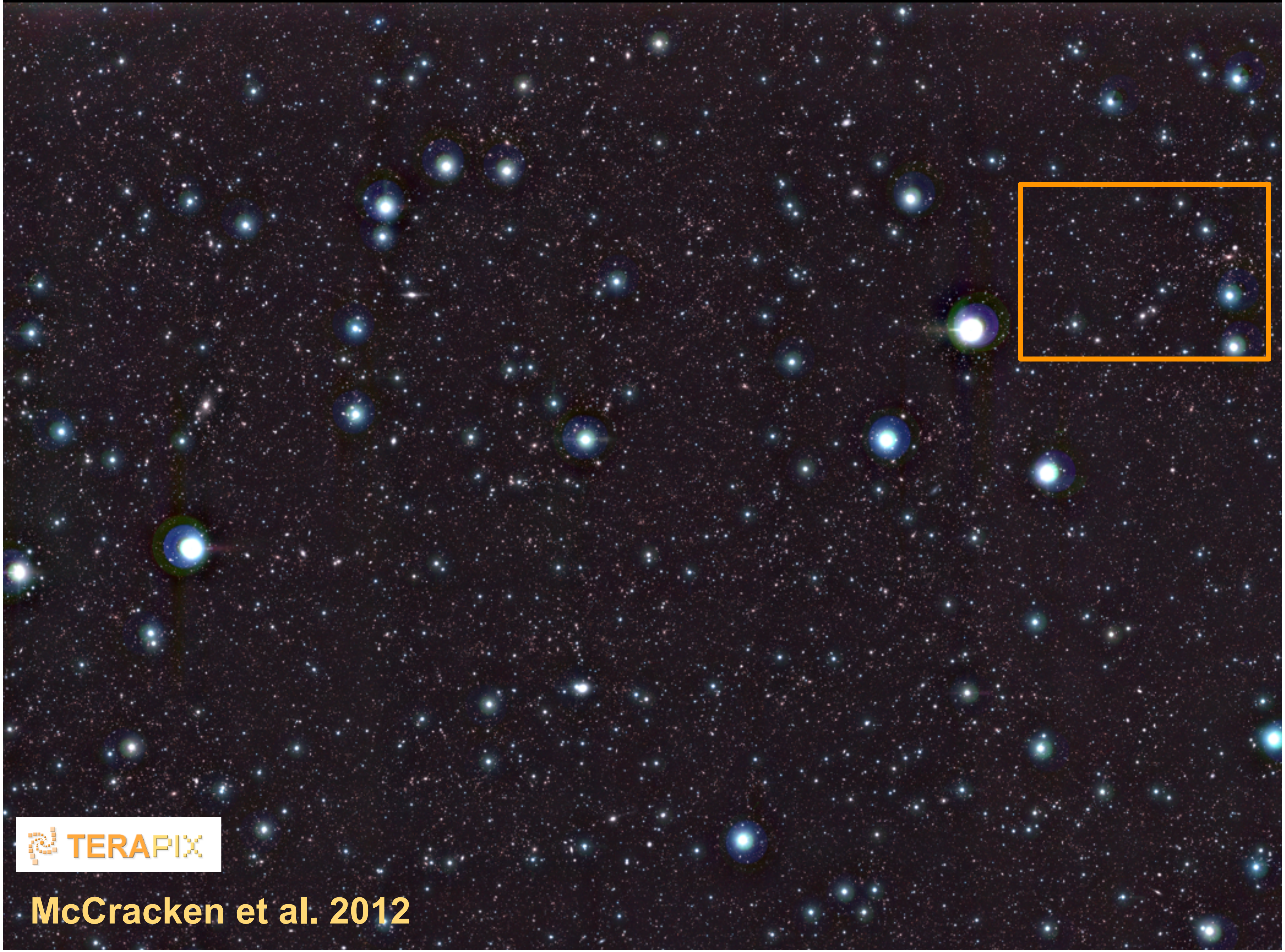
UltraVISTA – deepest public survey with Vista telescope

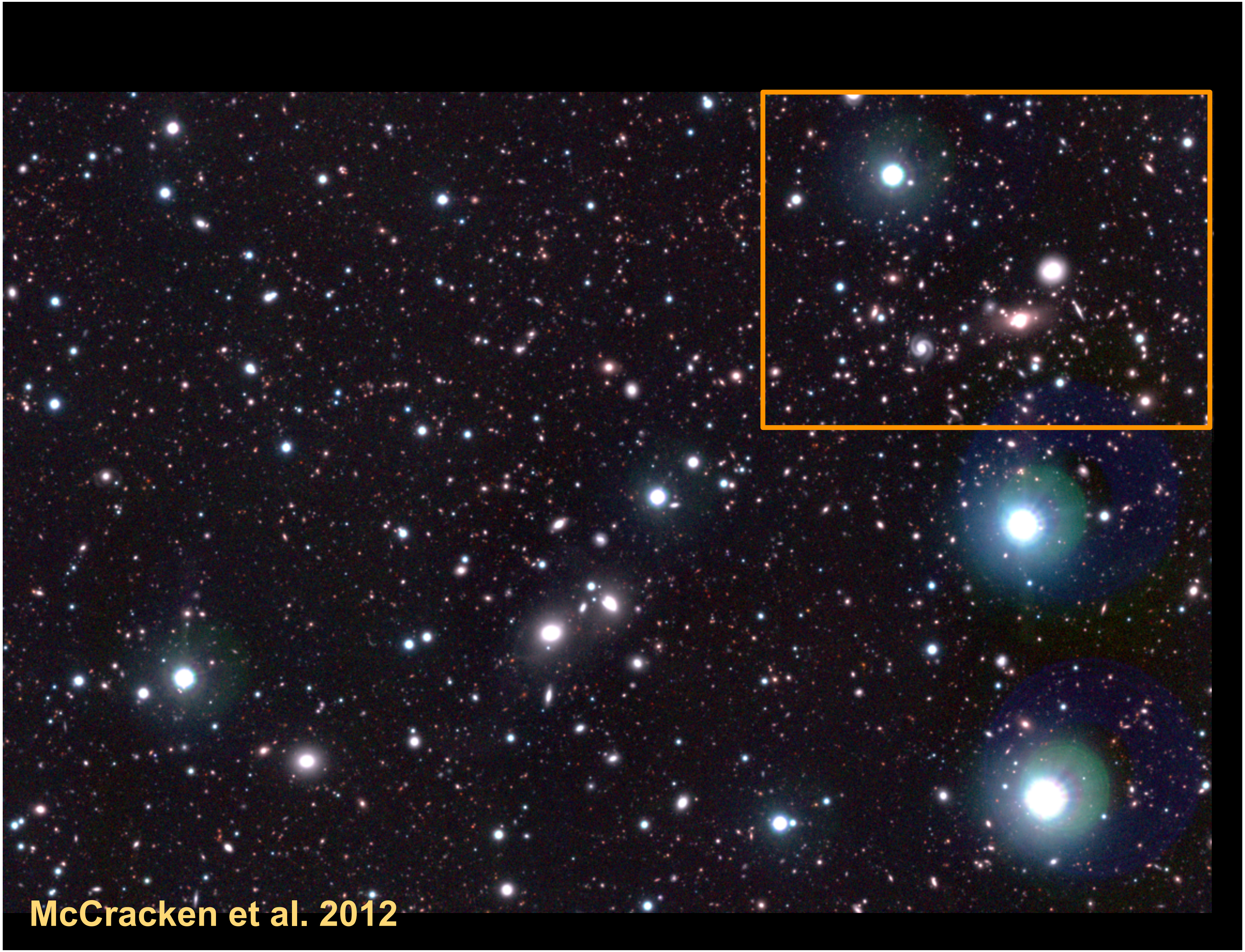
- PIs Dunlop, Franx, Le Fevre, Fynbo
- DEEP - 0.73 sq. deg., Y=26.7, J=26.6, H=26.1, K=25.6 (1408 hr)
- WIDE – 1.50 sq. deg., Y=25.3, J=25.2, H=24.7, K=24.2 (212 hr)
- Narrow-band survey, at 1.185 microns (z = 8.8 for Lyman-alpha) (180 hr)
- 1800 hours over 5 years – started Jan 2010

VISTA: Paranal, Chile

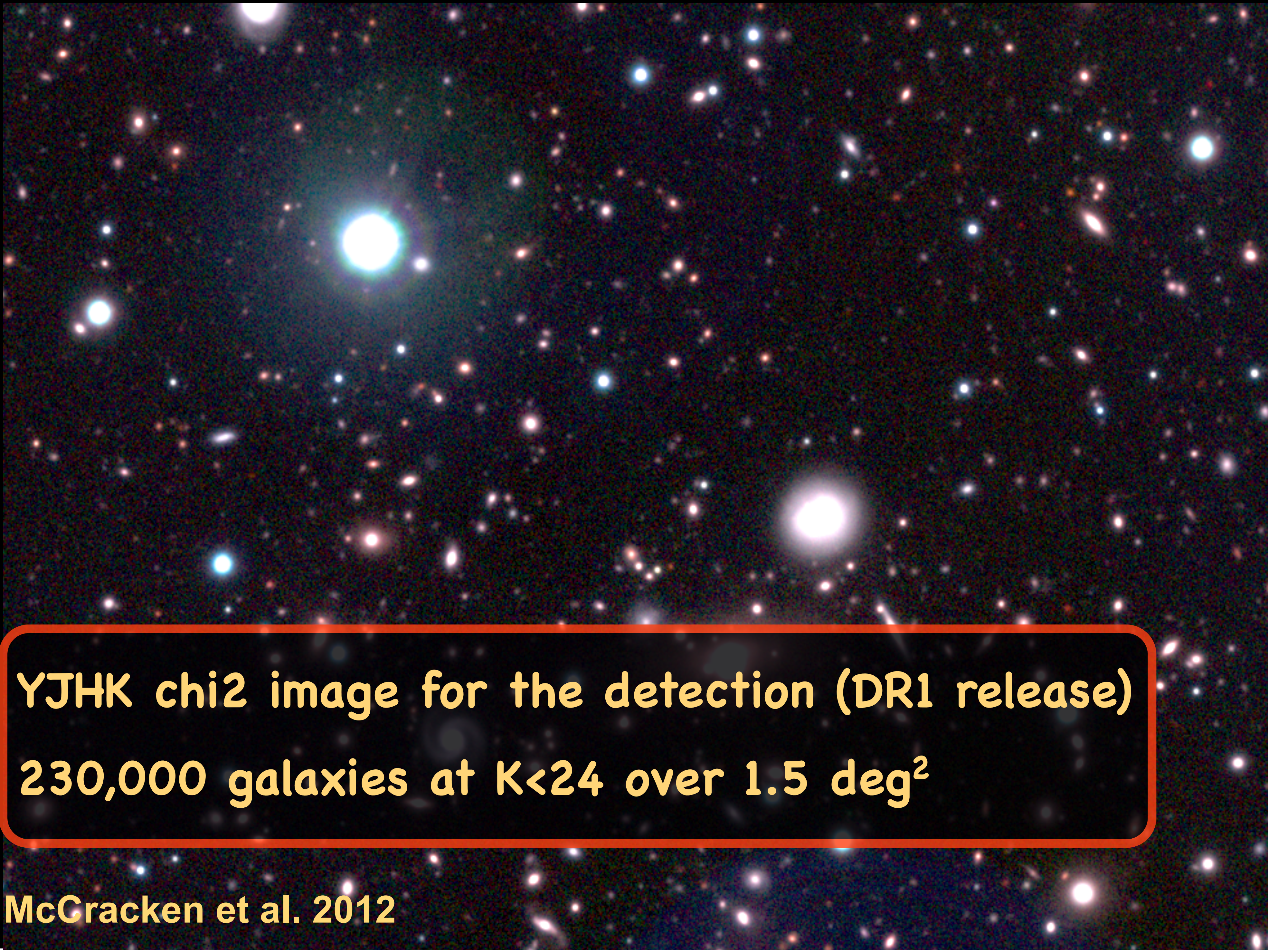


VIRCAM: 67 mega-pixel camera (1.5 sq. deg)


TERAPIX
McCracken et al. 2012


McCracken et al. 2012


McCracken et al. 2012



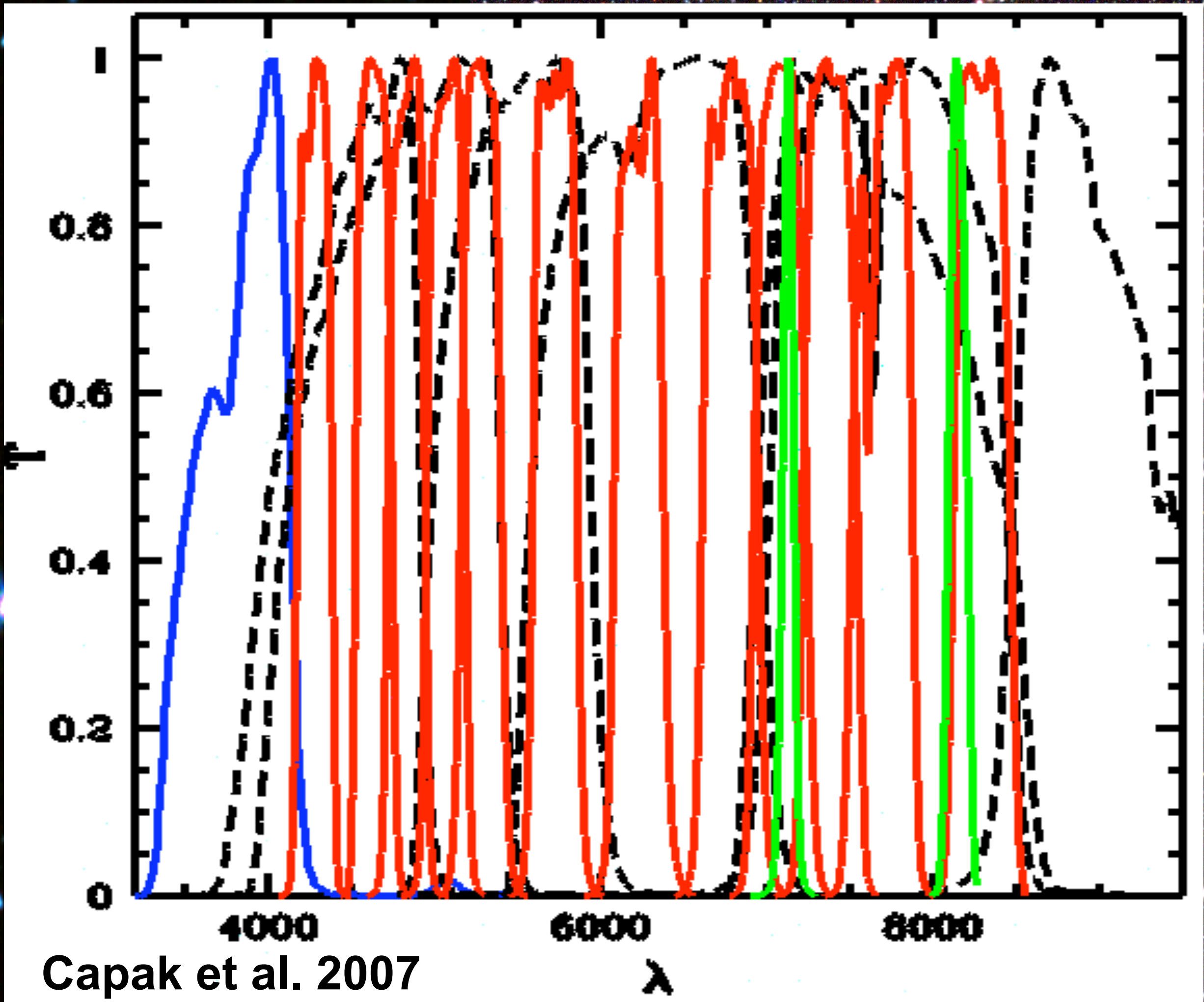
YJHK chi2 image for the detection (DR1 release)

230,000 galaxies at $K<24$ over 1.5 deg^2

McCracken et al. 2012

The COSMOS multi-color data

30 bands over 2 deg^2



Capak et al. 2007

x6 Subaru

The COSMOS multi-color data

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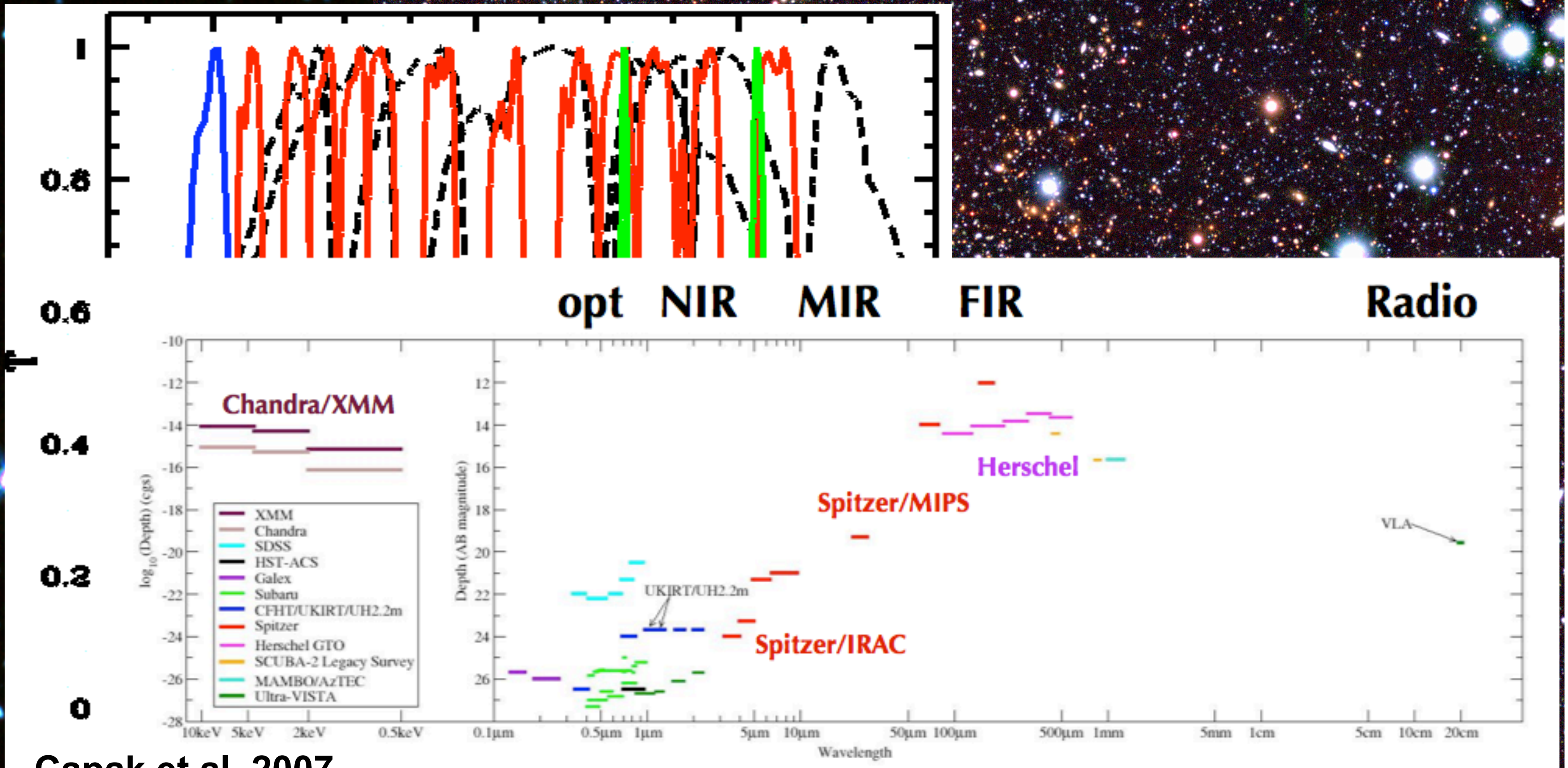
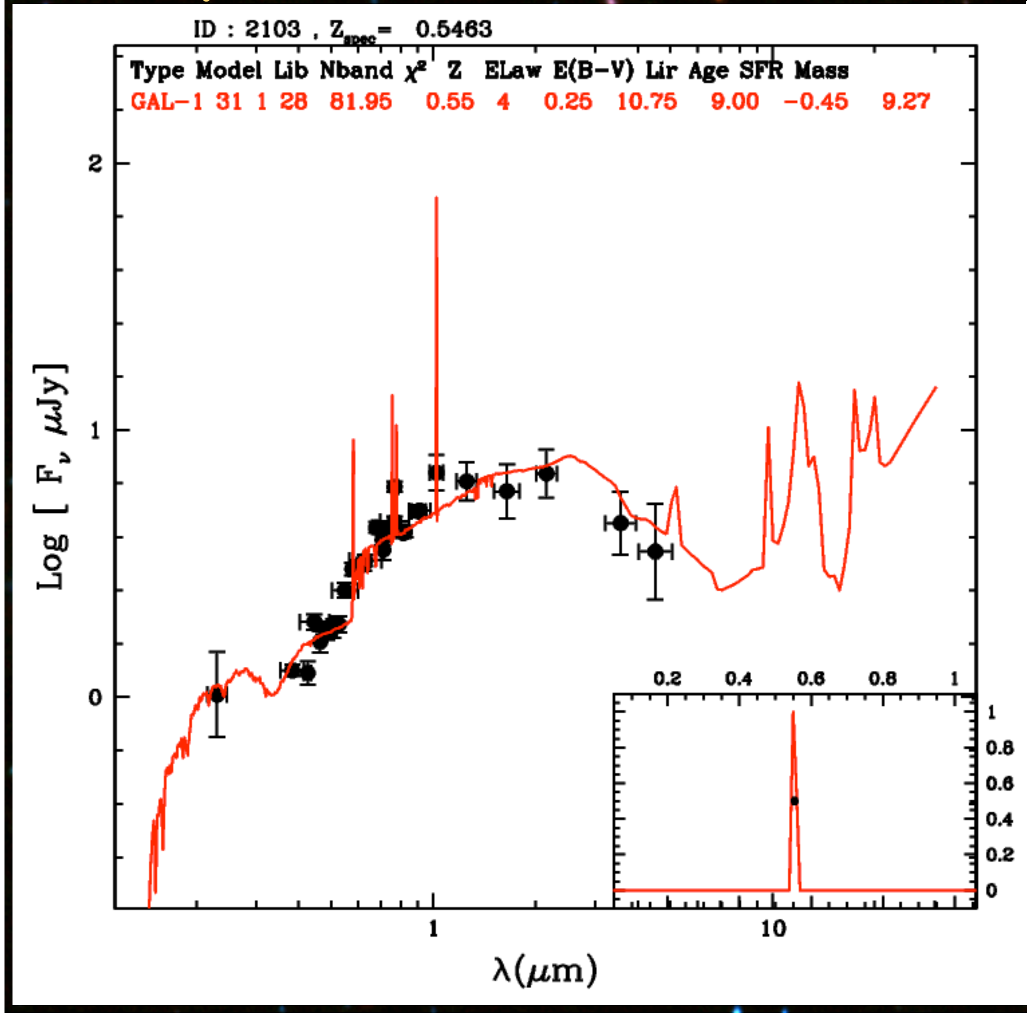
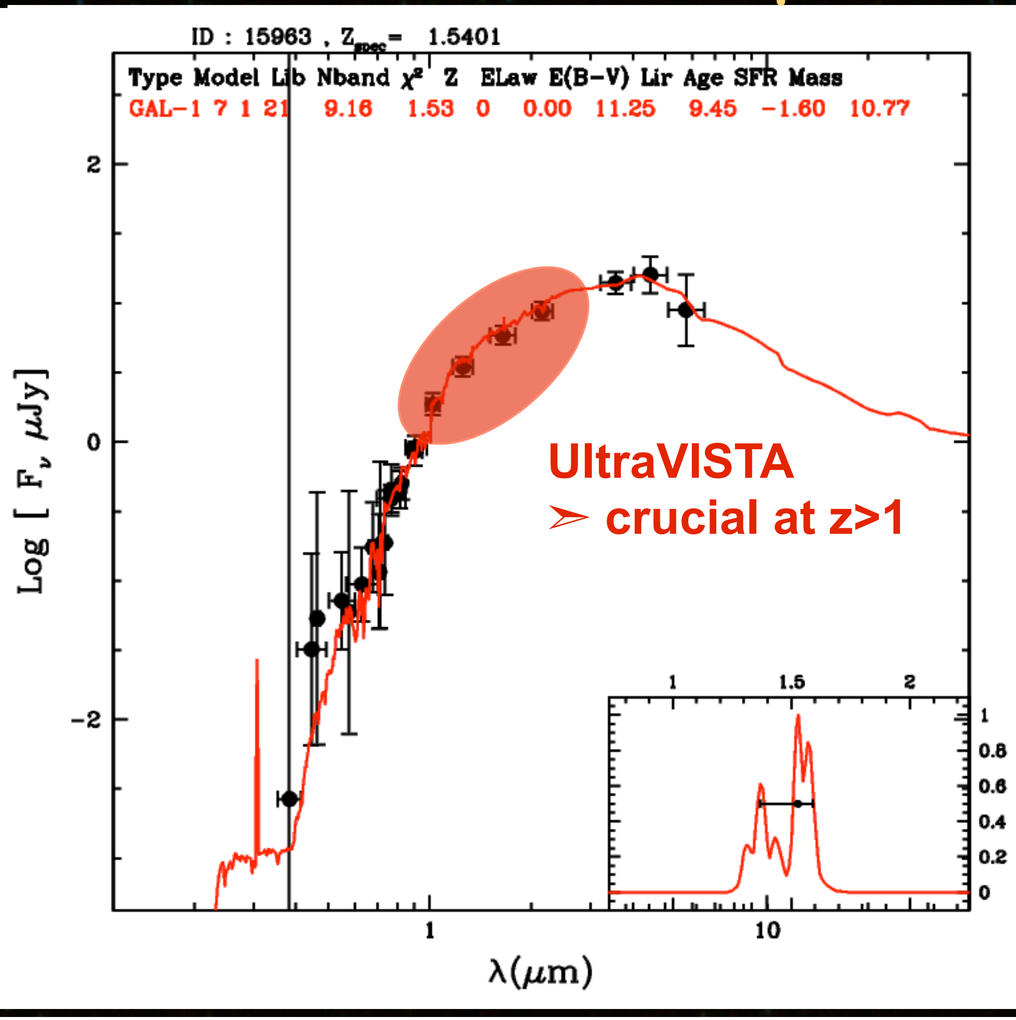


Capak et al. 2007

http://www.cfht.hawaii.edu/~arnouts/LEPHARE/cfht_lephare

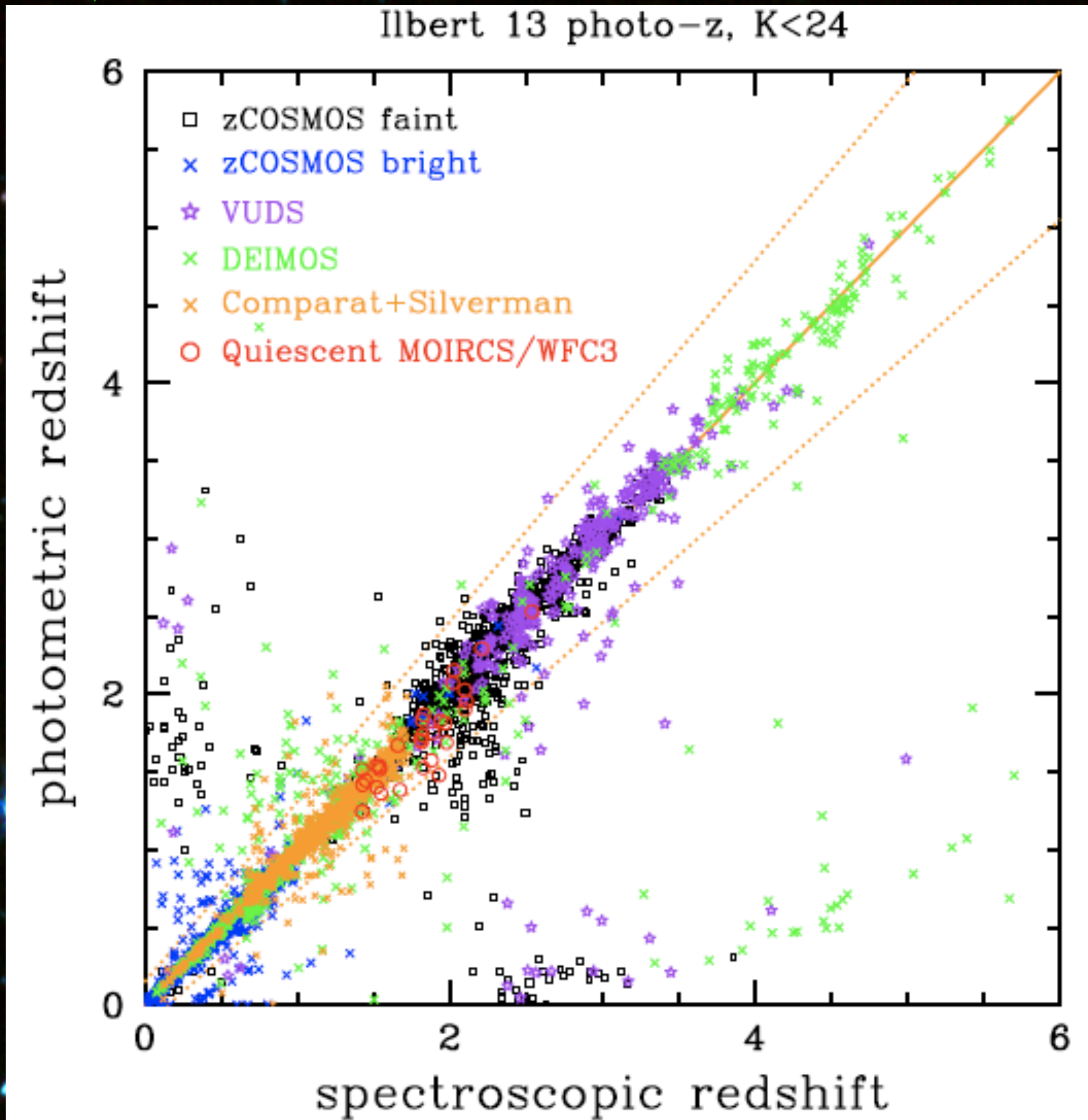




comparison with spectroscopic redshifts

spectroscopic survey	Nb spec-z $K_s < 24$	z_{med}	I_{med}
zCOSMOS bright	9389	0.50	21.4
Kartaltepe 2013	548	0.73	22.0
Comparat 2013	1105	1.14	22.7
Capak 2013	631	1.15	23.5
Onodera 2012	17	1.55	23.9
Silverman 2013	97	1.58	23.2
Krogager 2013	13	2.02	24.8
zCOSMOS faint	1392	2.15	23.6
VUDS	327	2.75	24.3

comparison with spectroscopic redshifts



1-3% accurate well tested photo-z

spectroscopic survey	Nb spec-z $K_s < 24$	z_{med}	I_{med}	$\sigma_{\Delta z/(1+z)}$	$\eta(\%)$
zCOSMOS bright	9389	0.50	21.4	0.0080	0.5
Kartaltepe 2013	548	0.73	22.0	0.0105	3.3
Comparat 2013	1105	1.14	22.7	0.0133	2.9
Capak 2013	631	1.15	23.5	0.0213	9.5
Onodera 2012	17	1.55	23.9	0.0446	0.0
Silverman 2013	97	1.58	23.2	0.0265	2.1
Krogager 2013	13	2.02	24.8	0.0708	7.7
zCOSMOS faint	1392	2.15	23.6	0.0297	7.6
VUDS	327	2.75	24.3	0.0360	9.8

Ilbert et al. 2009

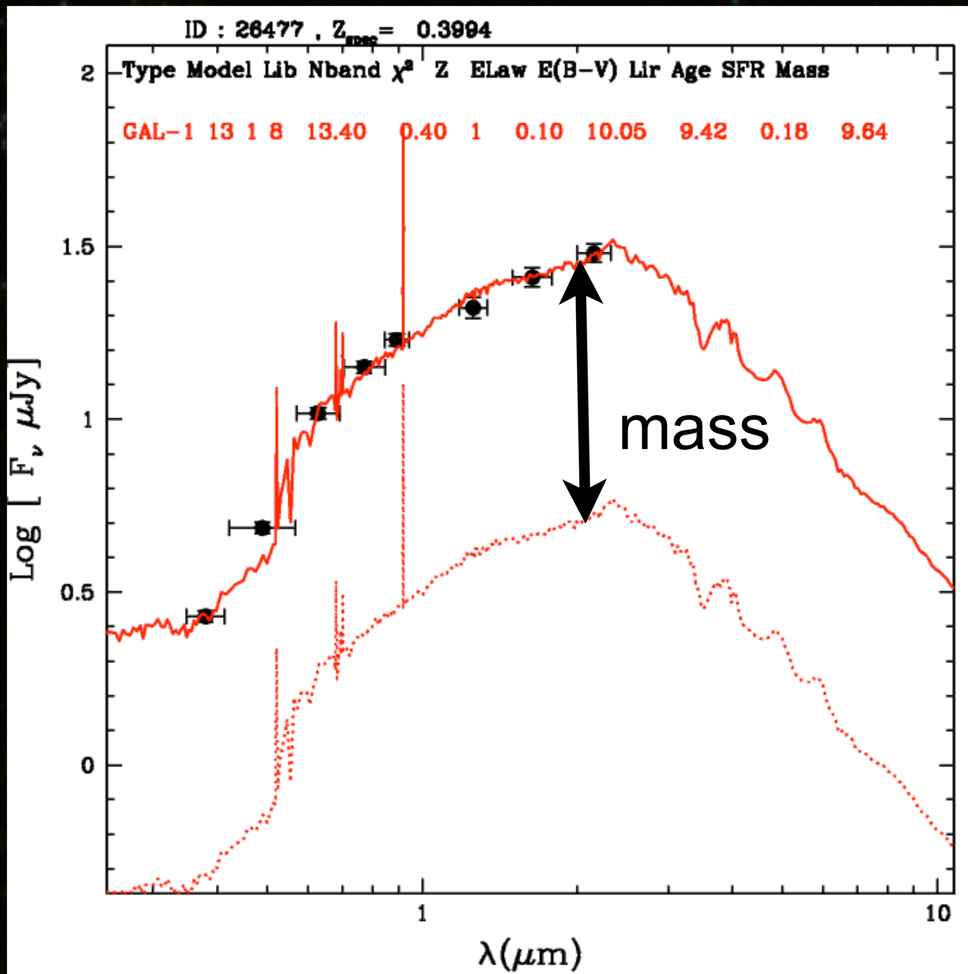
Characterize the stellar mass

Simulated galaxy spectra with Stellar Population Synthesis codes at different ages, various star formation histories, metallicities, ...

Fit to the data points

model dependent !

- possible 0.2 dex systematic uncertainties



Global stellar mass function

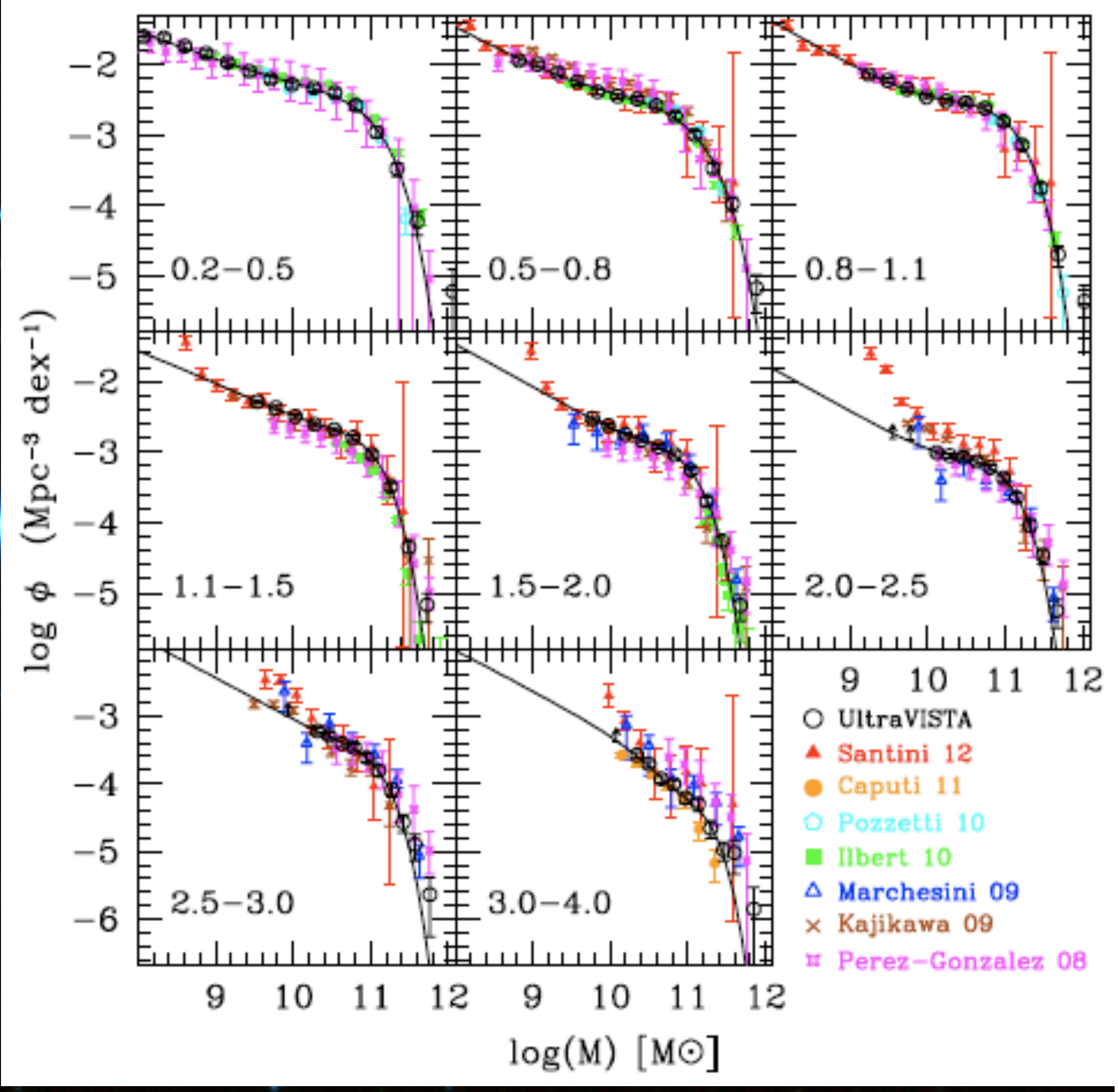
MF computed with ALF (Ilbert 05)

➢ several estimators

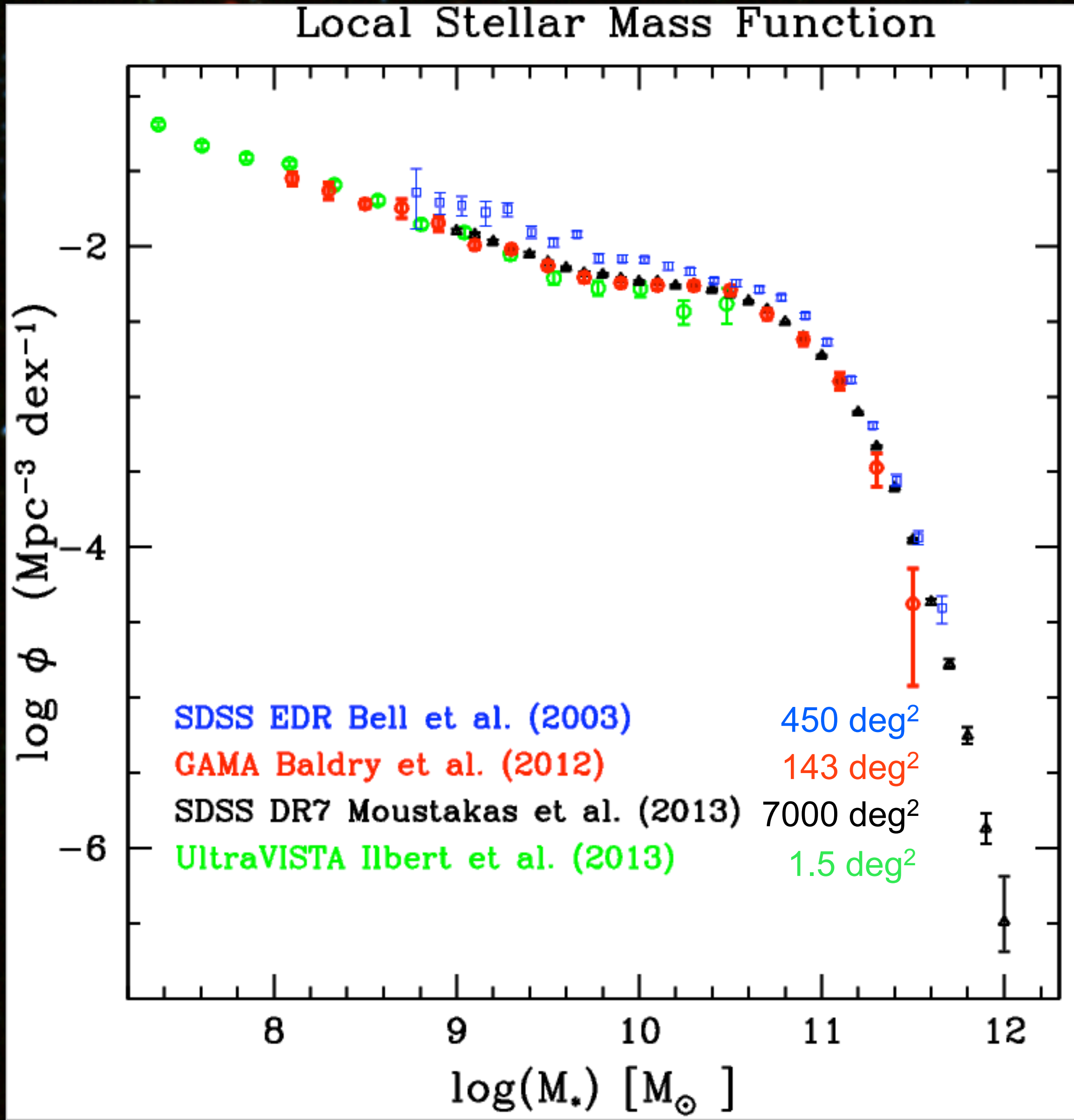
Fit the V_{max} with a double-Schechter function

$$\phi(\mathcal{M})\,\mathrm{d}\mathcal{M} = \mathrm{e}^{-\mathcal{M}/\mathcal{M}^*}\left[\phi_1^*\left(\frac{\mathcal{M}}{\mathcal{M}^*}\right)^{\alpha_1} + \phi_2^*\left(\frac{\mathcal{M}}{\mathcal{M}^*}\right)^{\alpha_2}\right]\frac{\mathrm{d}\mathcal{M}}{\mathcal{M}^*}$$

Take into account the Eddington bias

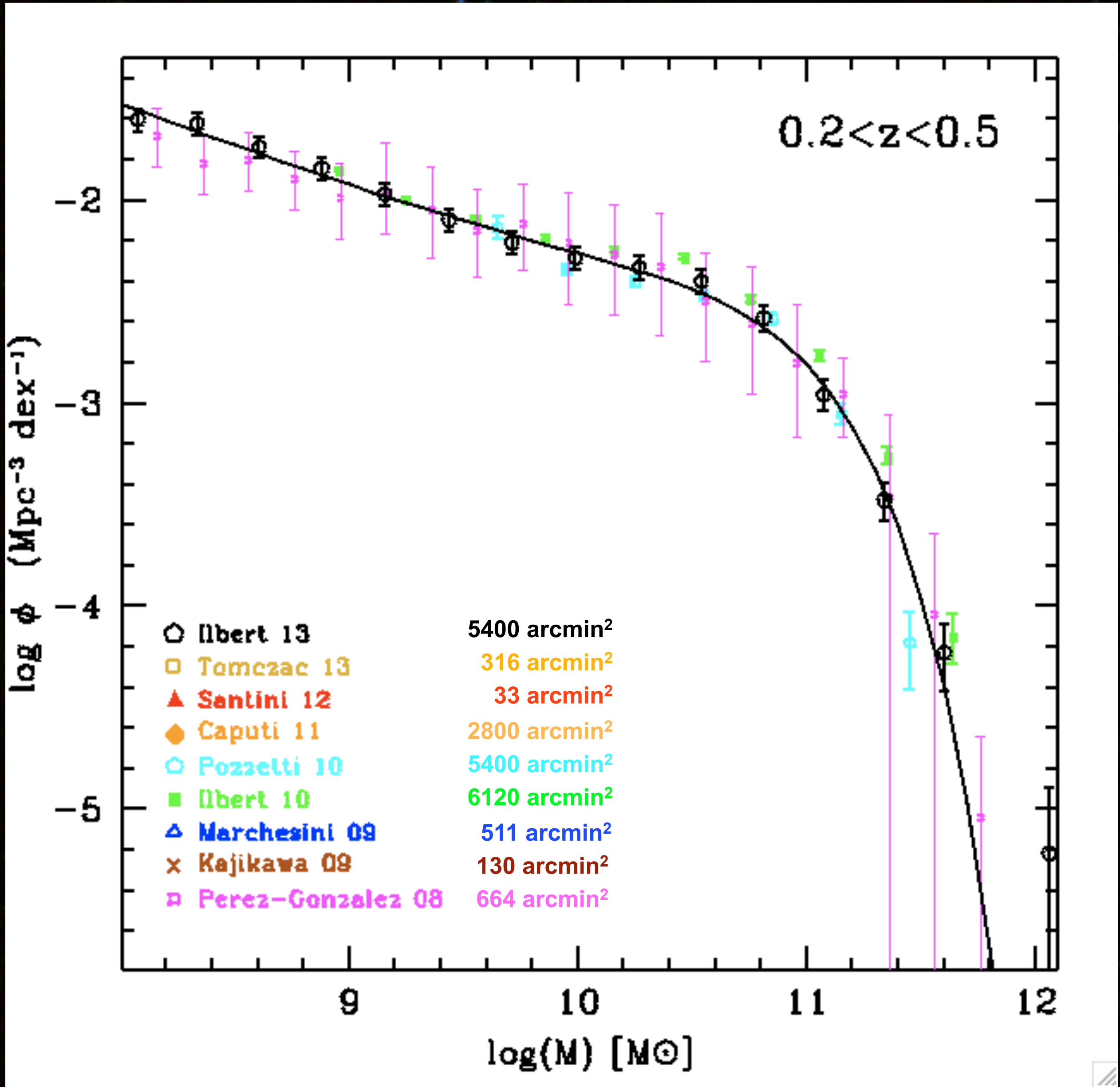


Local stellar mass function



Stellar mass function at 0.2<z<4

dispersion below 0.2 dex between various MFs from in the last 5 years



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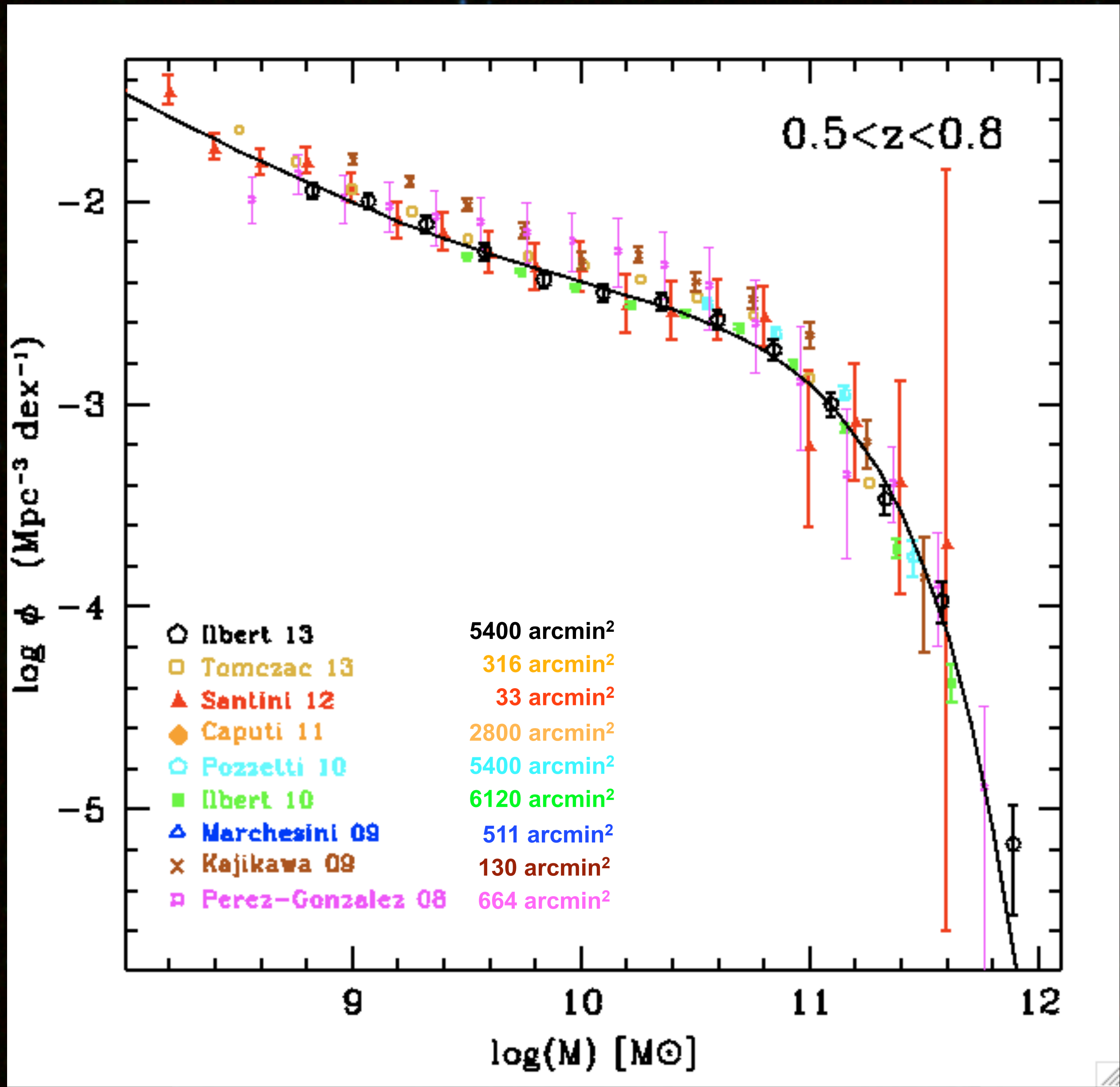

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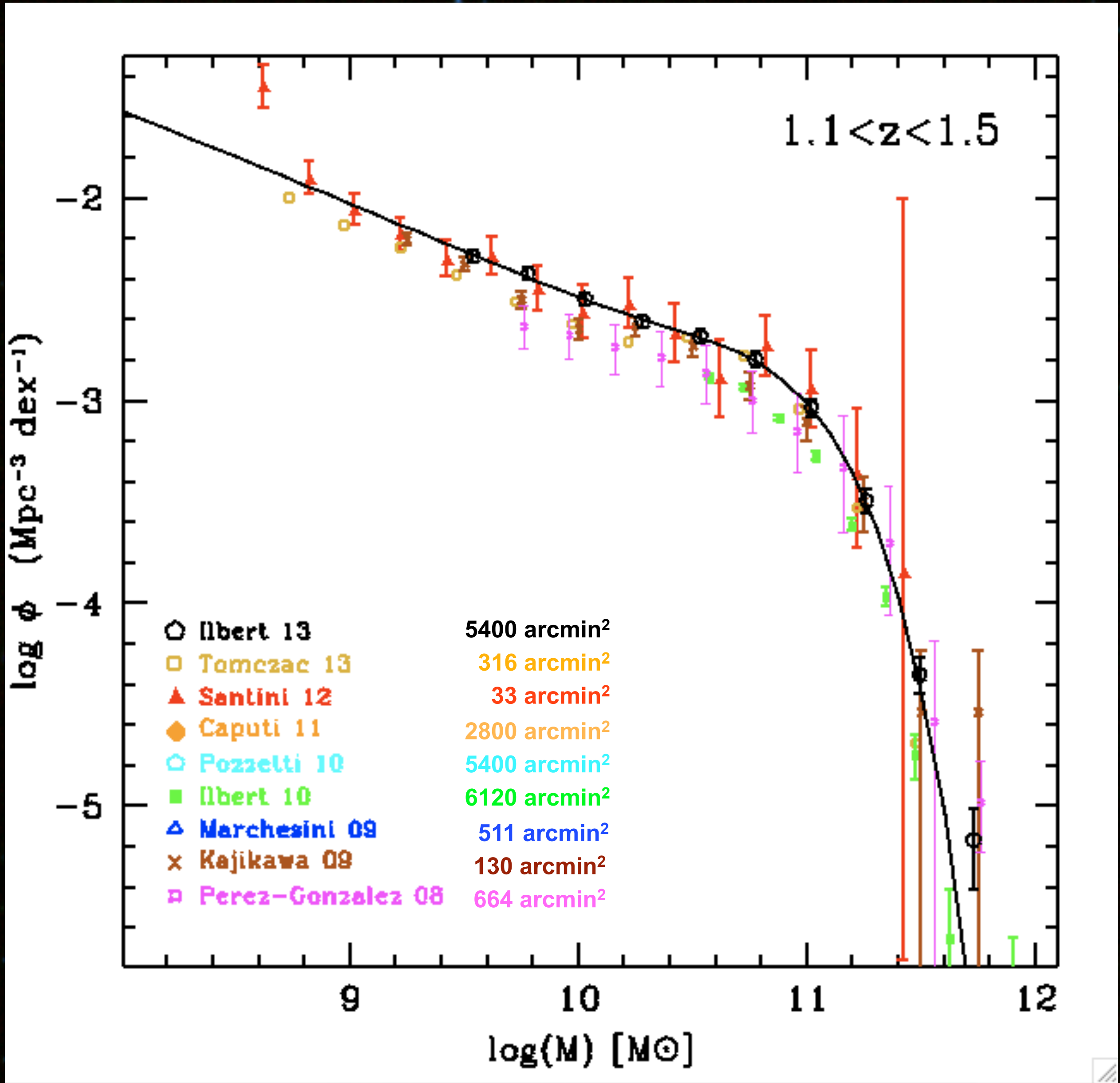
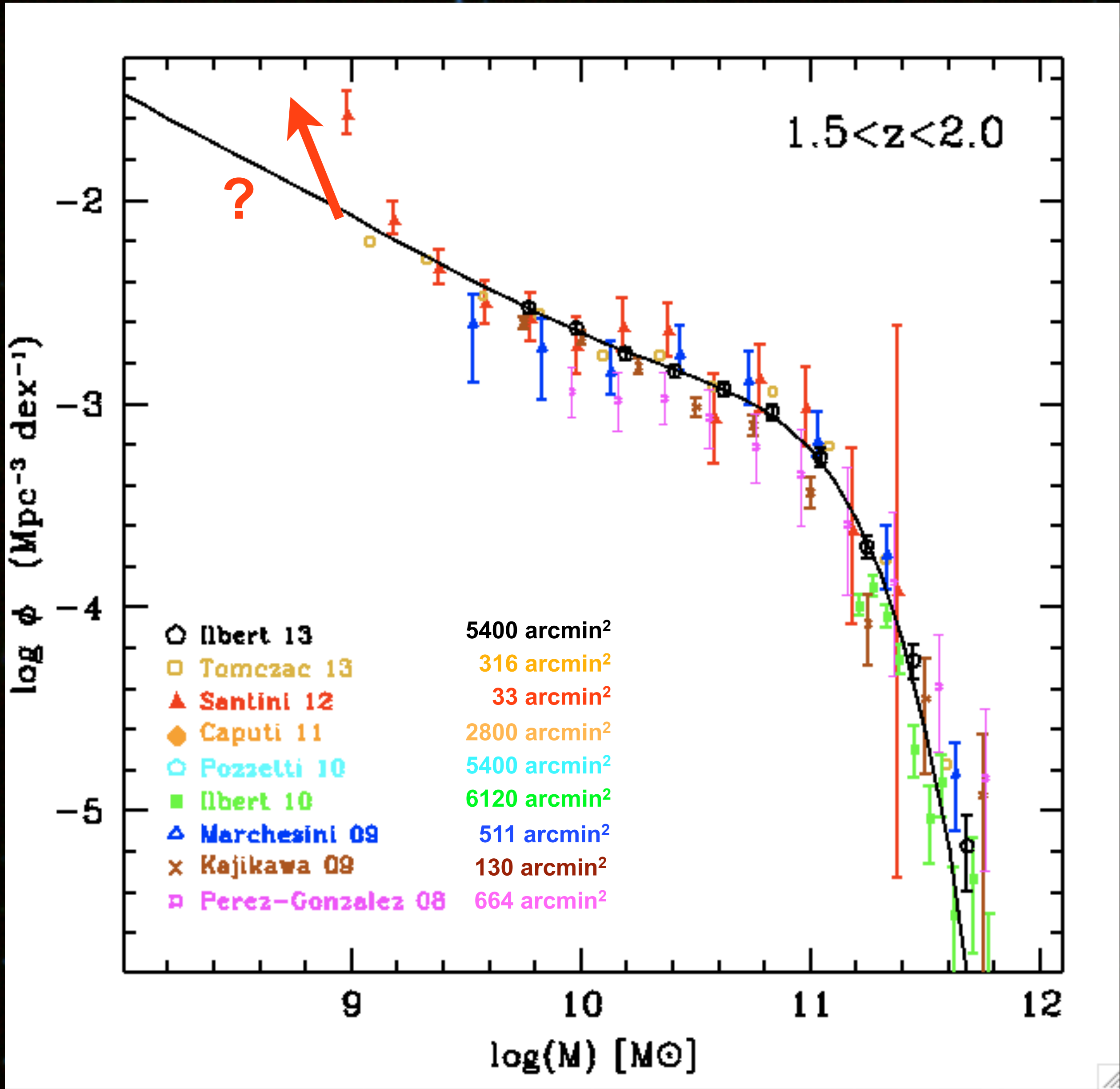


Stellar mass function at 0.2<z<4

dispersion below 0.2 dex between various MFs from in the last 5 years

Still some uncertainties on the low-mass end slope



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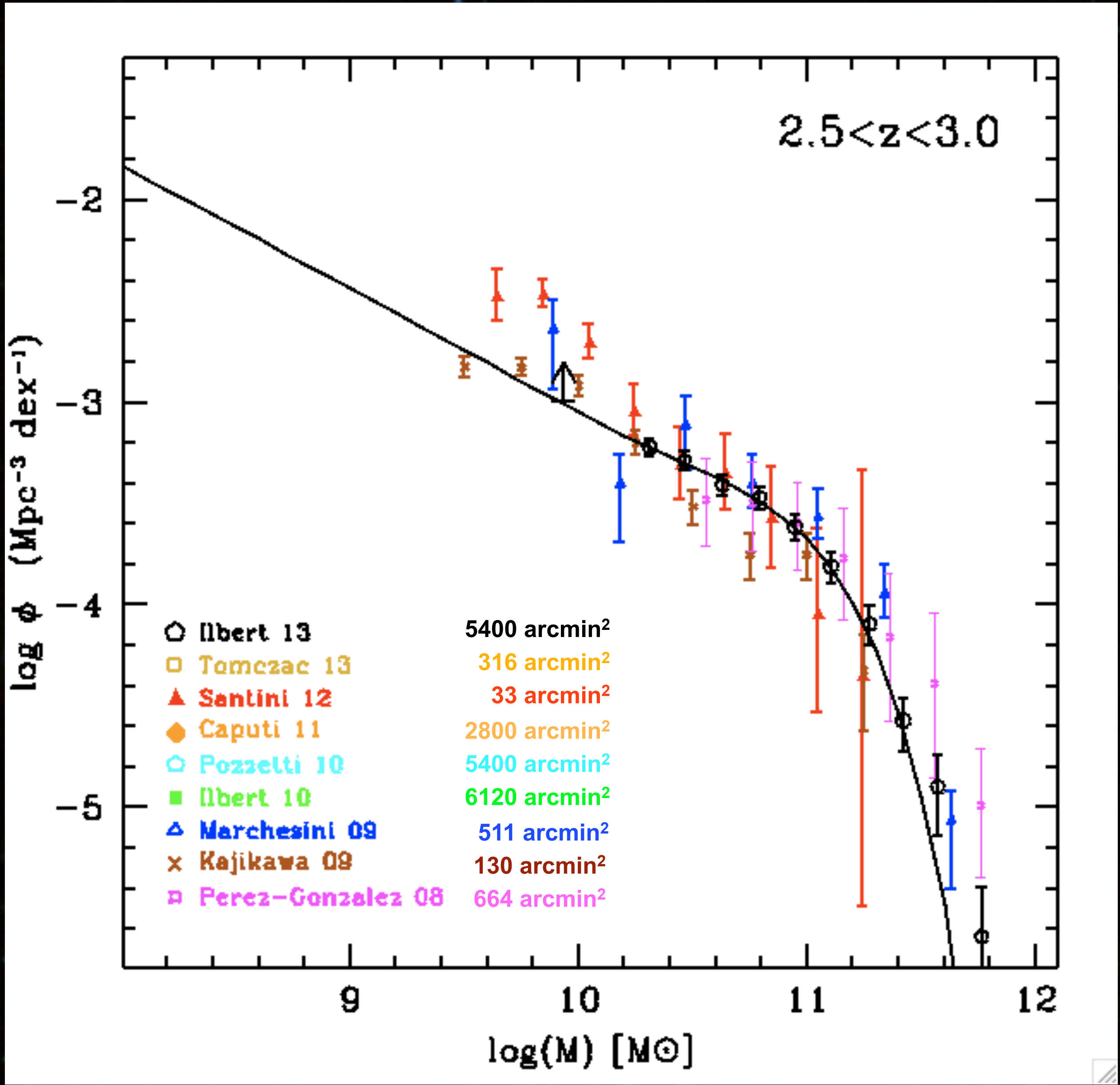

Stellar mass function at 0.2<z<4

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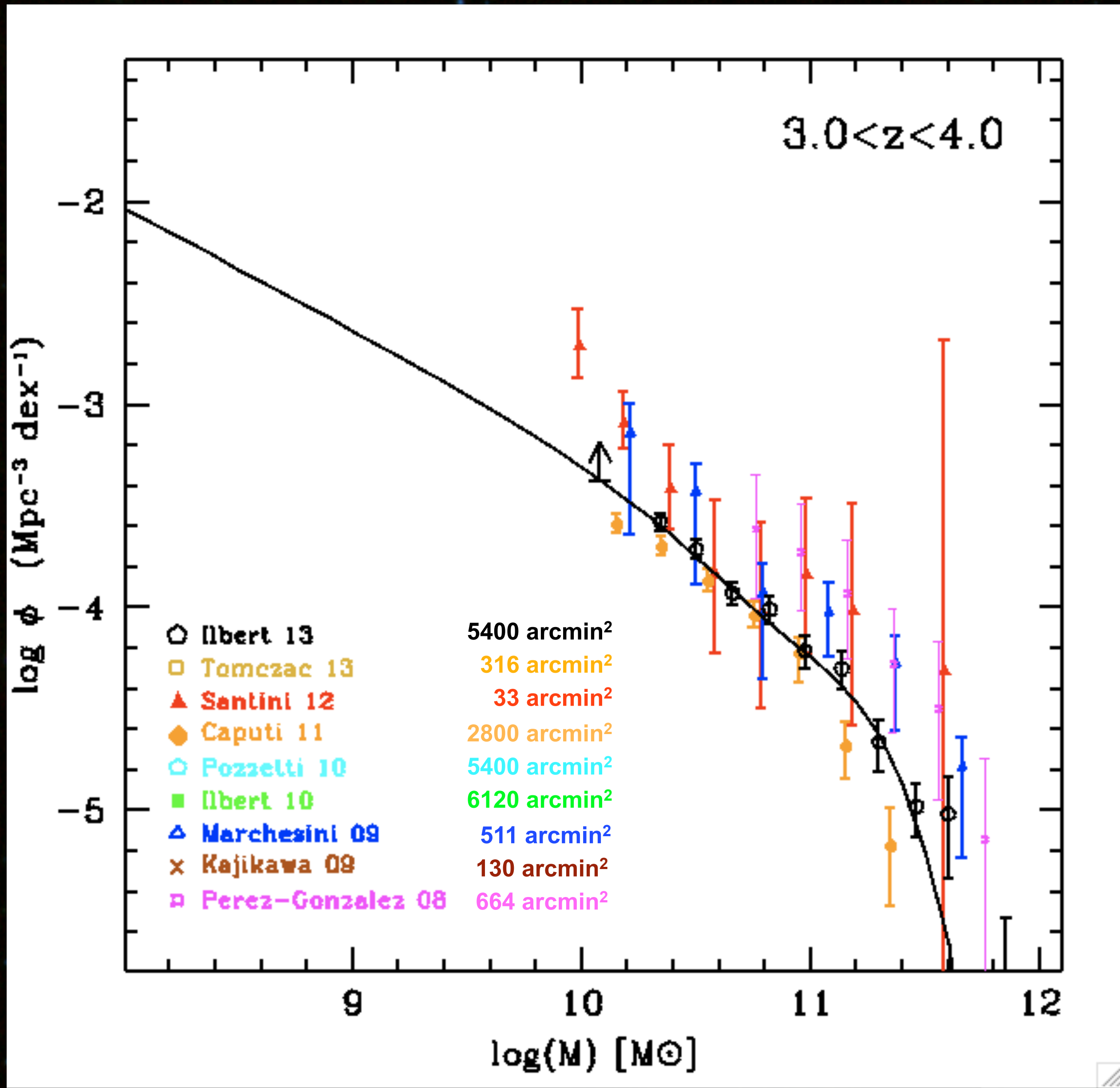

Outlines

I. The COSMOS Ultra/VISTA data

II. The star formation history from a MF perspective

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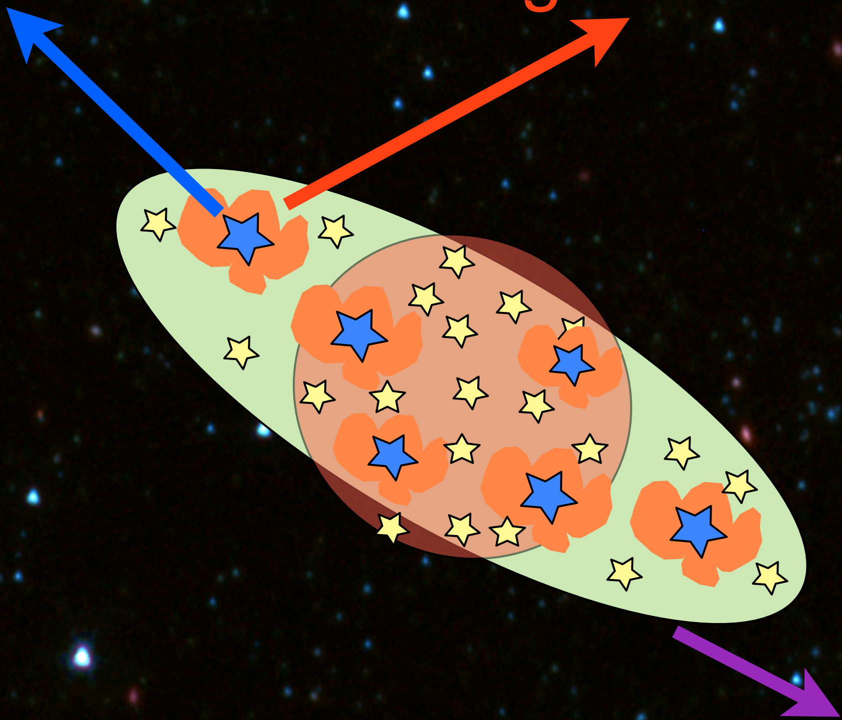
direct Star Formation Rate tracers

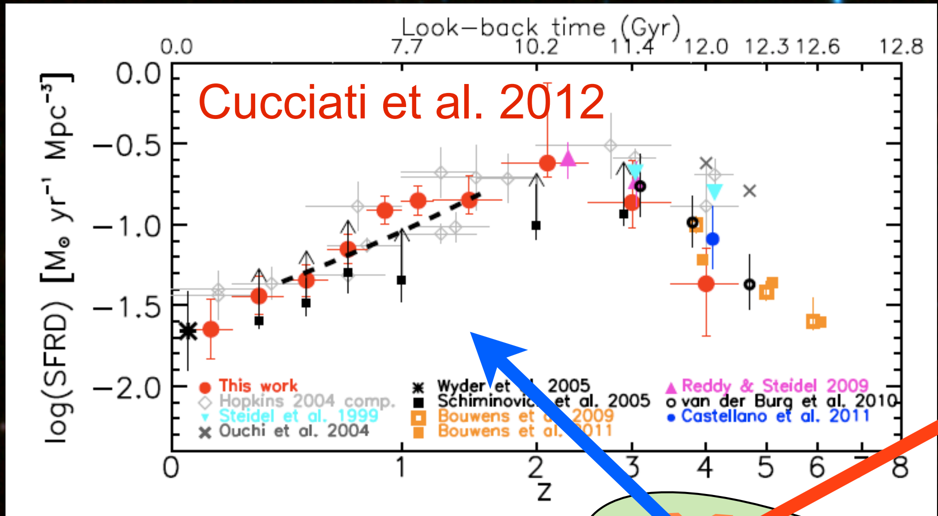
UV light
light from young stars
need dust-correction

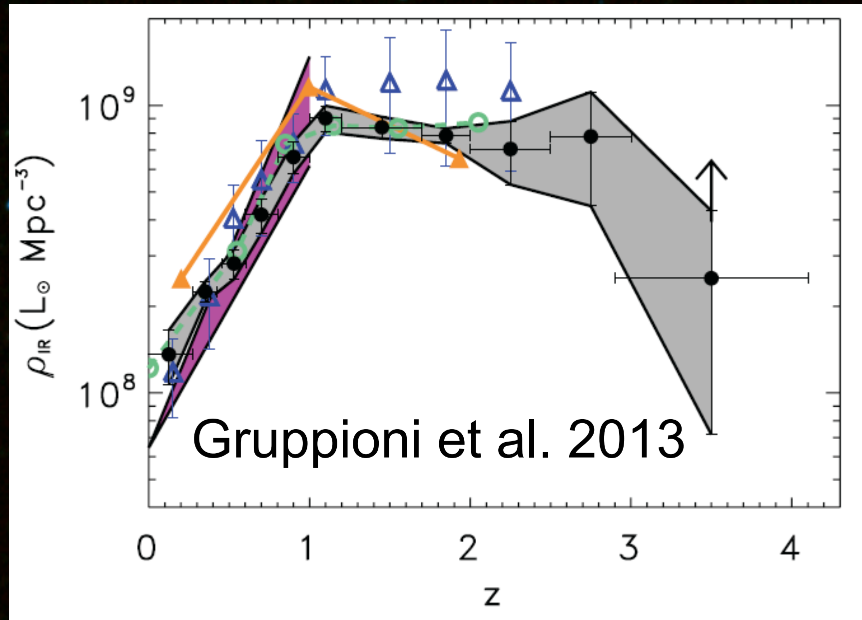
IR light reemitted by dust
but only the most star-forming
galaxies at z>1

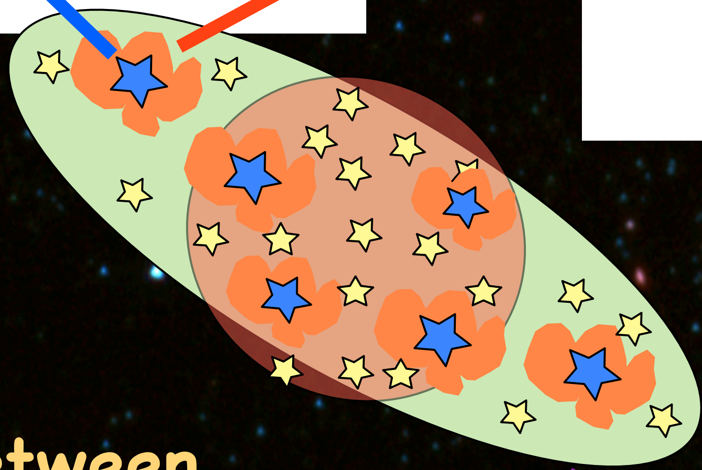


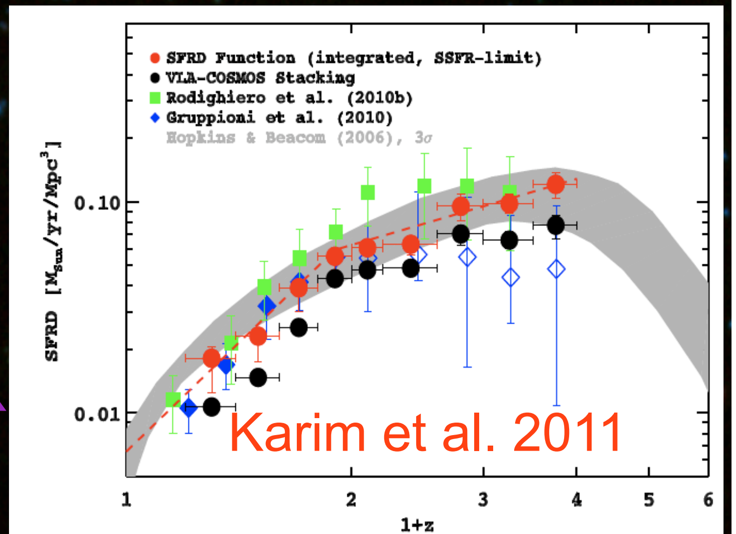
radio from SN
but requires stacking

direct Star Formation Rate tracers









x10 increase between

z=0 and z~1.5,

much more confused at z>1.5

Link Star Formation Rate Density and stellar mass density

Star formation rate density: amount of new stars created instantaneously in a given comoving volume

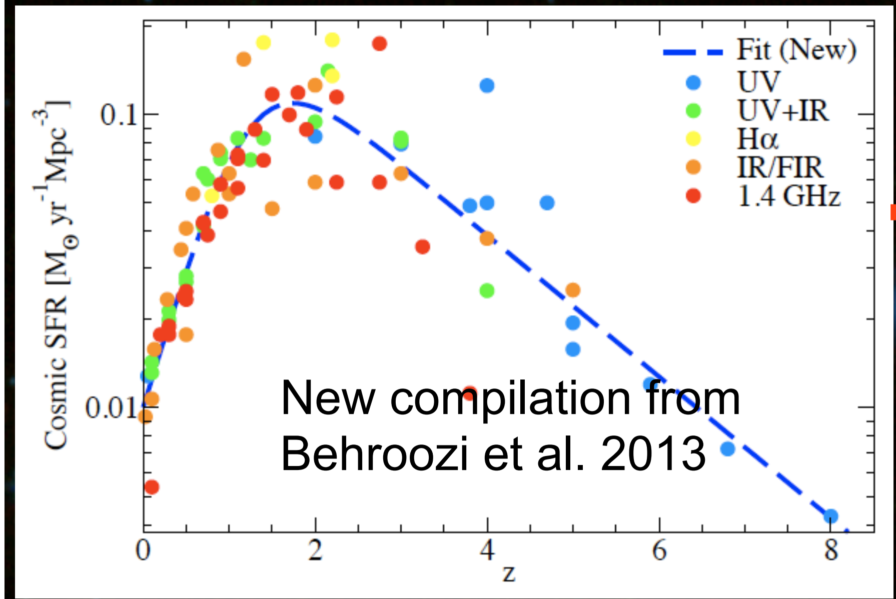
➢ increase of the stellar mass present in a given volume, i.e. the stellar mass density

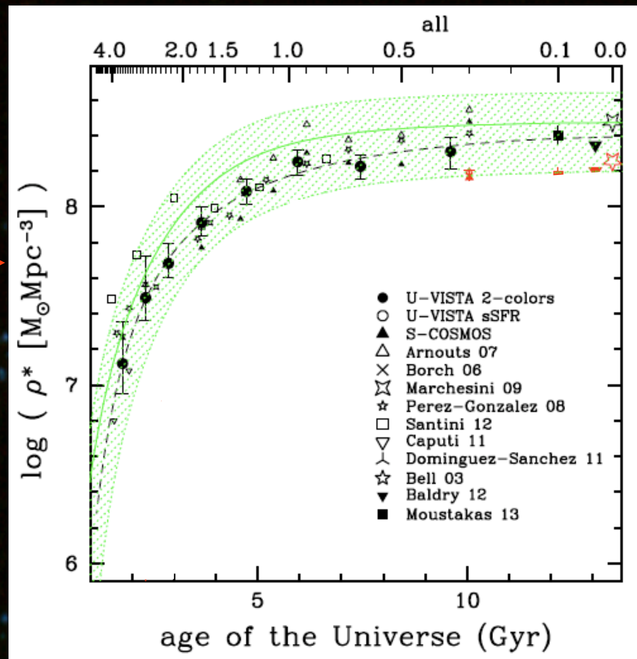
Stellar mass density obtained by integrating the mass function $\int M \, \phi(M) \, dM$

Link Star Formation Rate Density and stellar mass density

cosmic SFRD

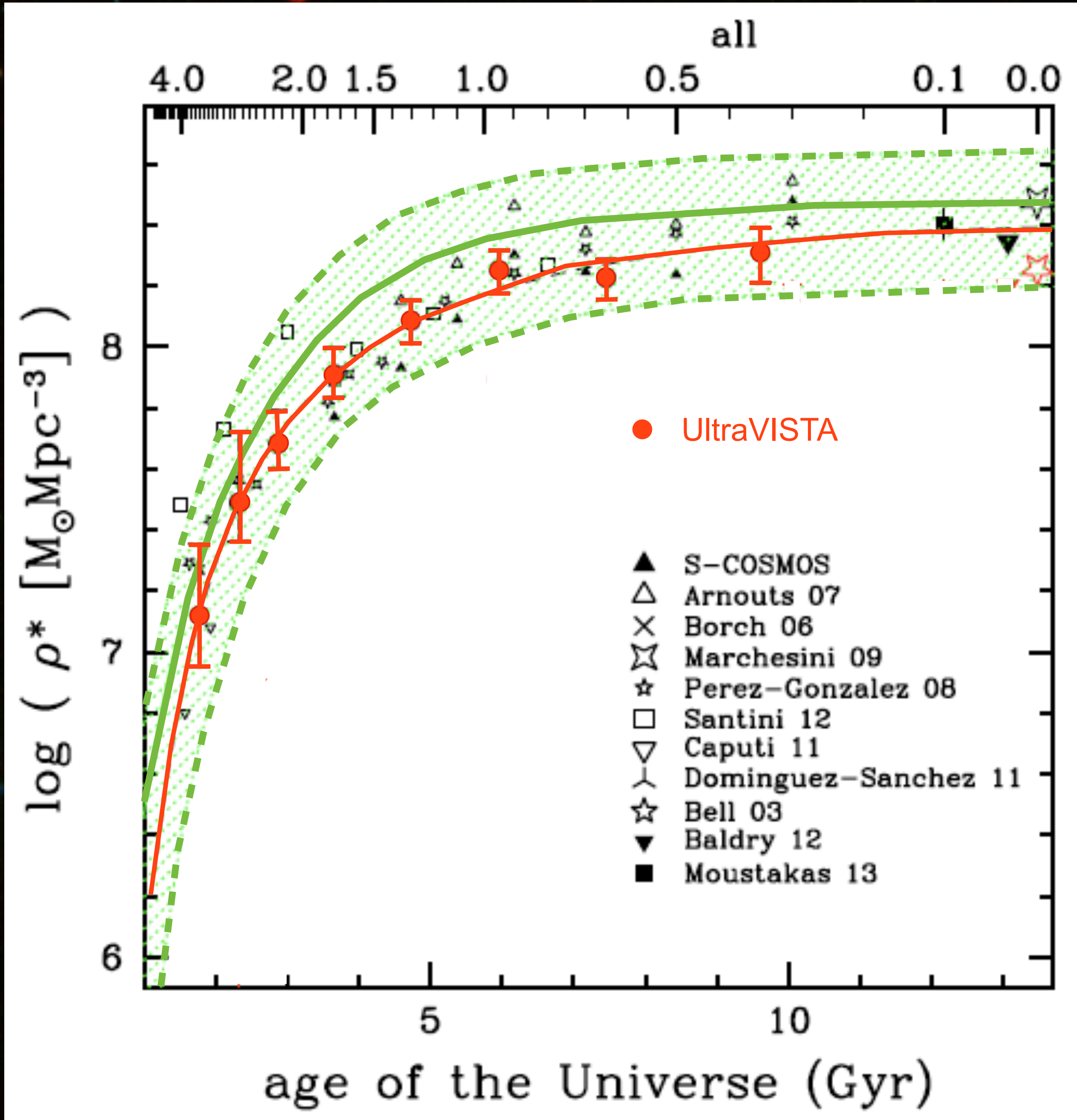
stellar mass density





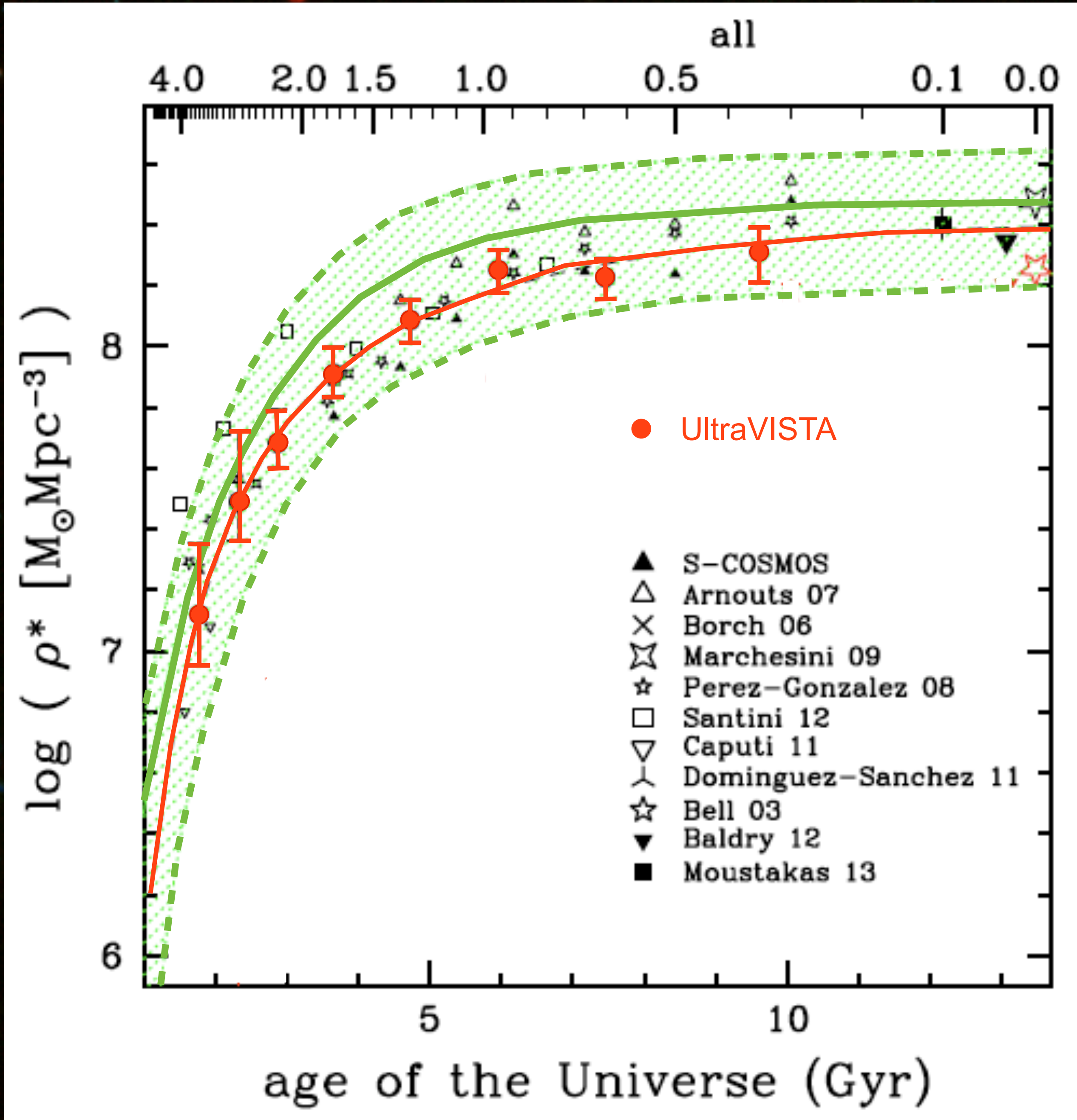
$$\rho_*(t) = \int_0^t SFRD(t')(1 - f_r[t - t'])dt'$$

1. Integrate SFH from the literature

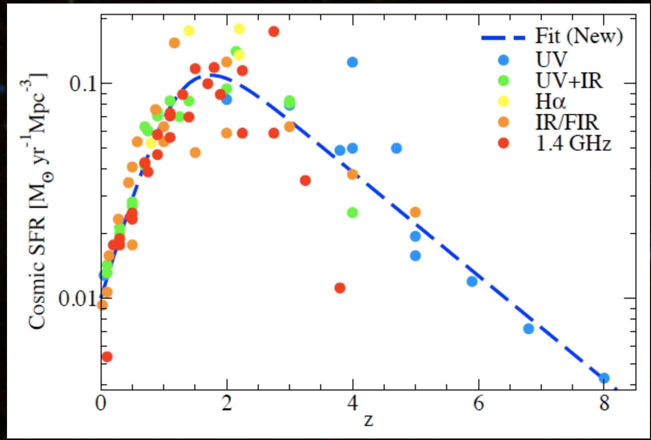


Integrate the stellar mass function of UlraVISTA to get the mass density ρ* evolution

1. Integrate SFH from the literature



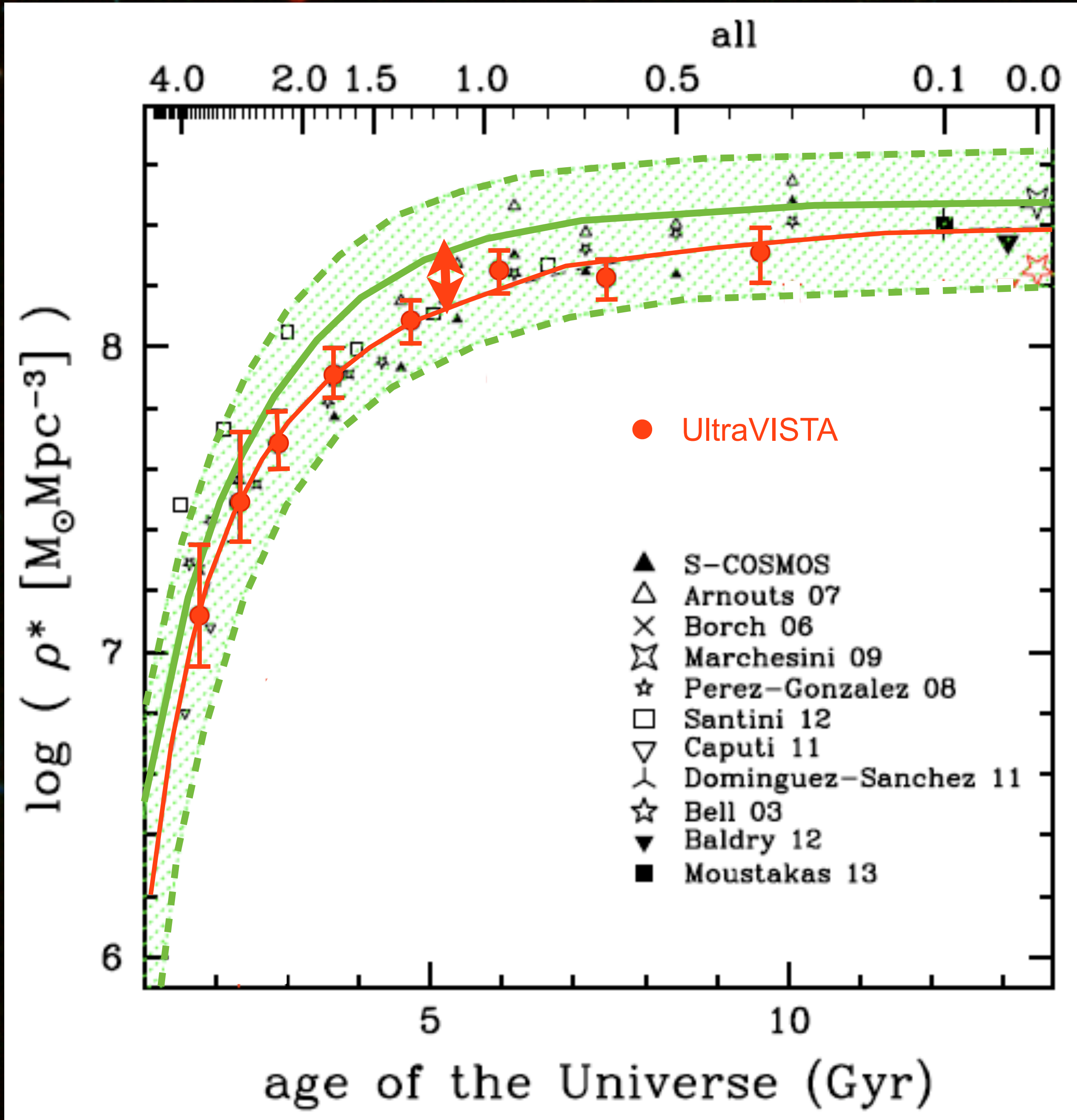
Integrate along cosmic time the new compilation of SFRD from Behroozi 2013



$$\rho_*(t) = \int_0^t SFRD(t')(1 - f_r[t - t'])dt'$$

➢ shaded area

1. Integrate SFH from the literature



mass density ρ*
UltraVISTA

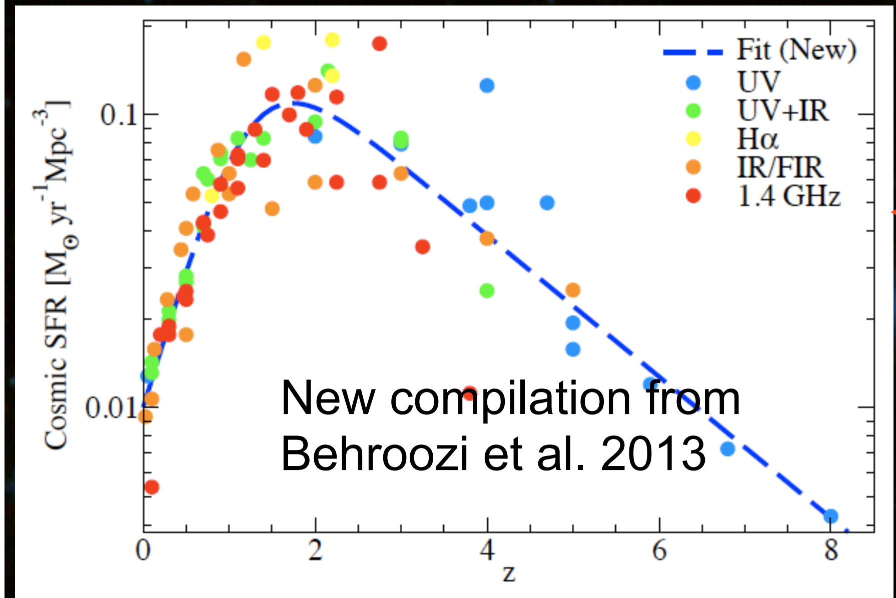
consistent with the integrated SFH

within the uncertainties

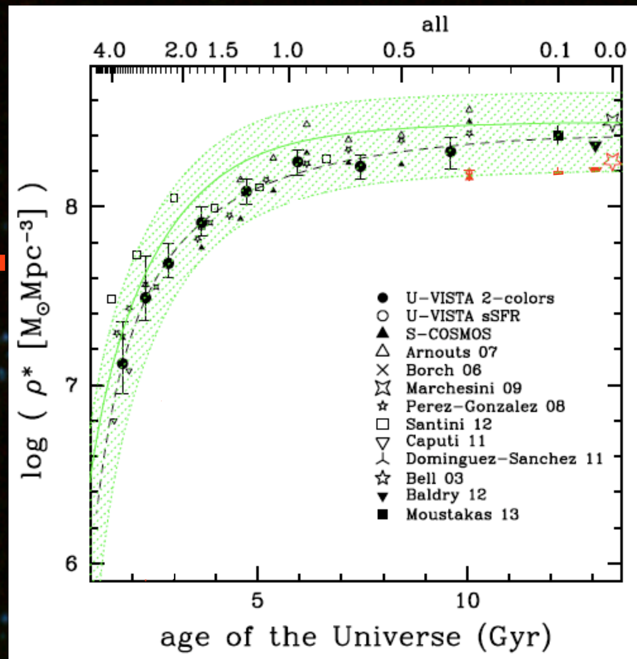
➢ tell the same story

2. Reconstruct the SFH from the observed mass density

cosmic SFRD

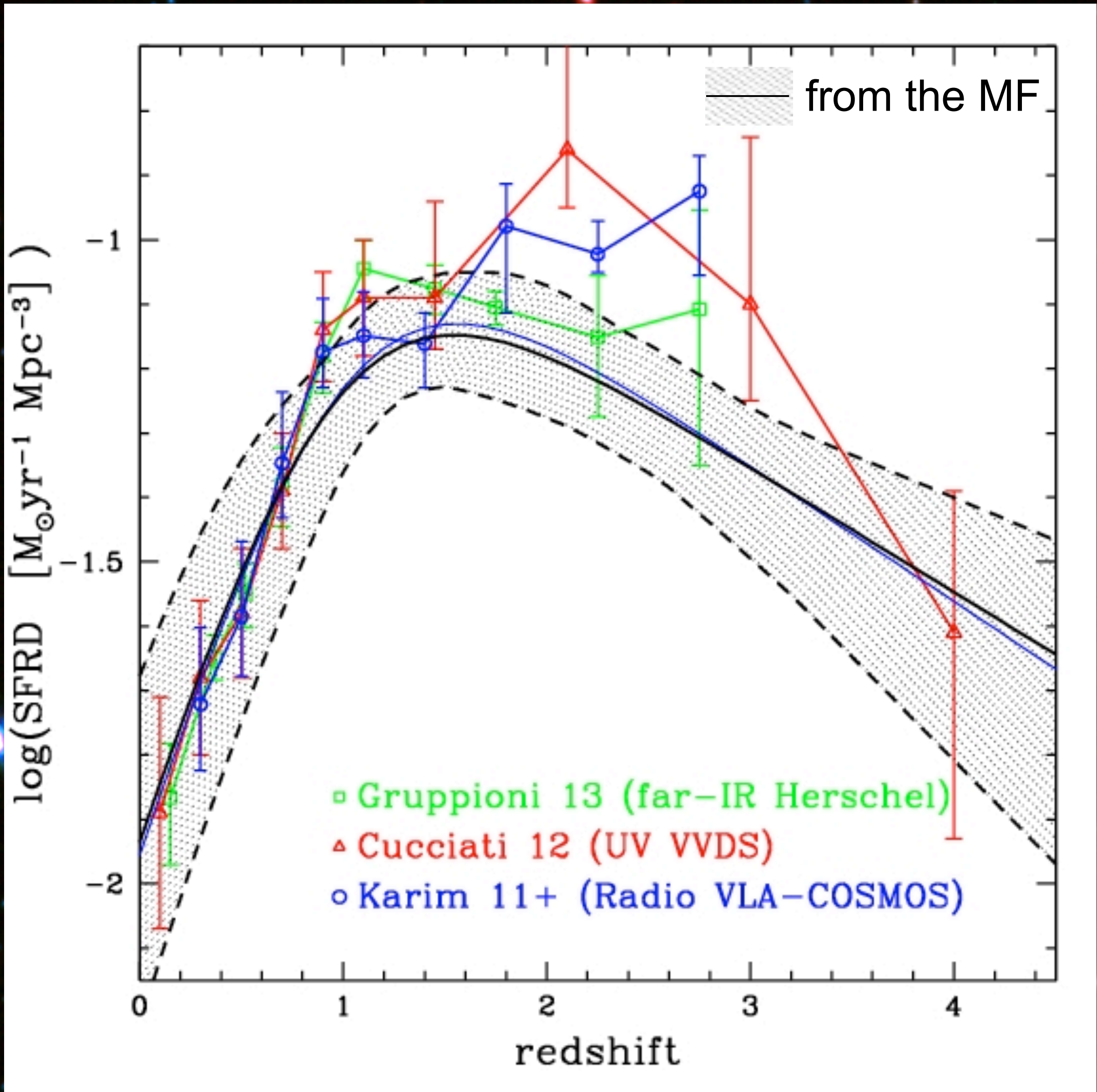


stellar mass density



$$\rho_*(t) = \int_0^t SFRD(t')(1 - f_r[t - t'])dt'$$

2. Reconstruct the SFH from the observed mass density

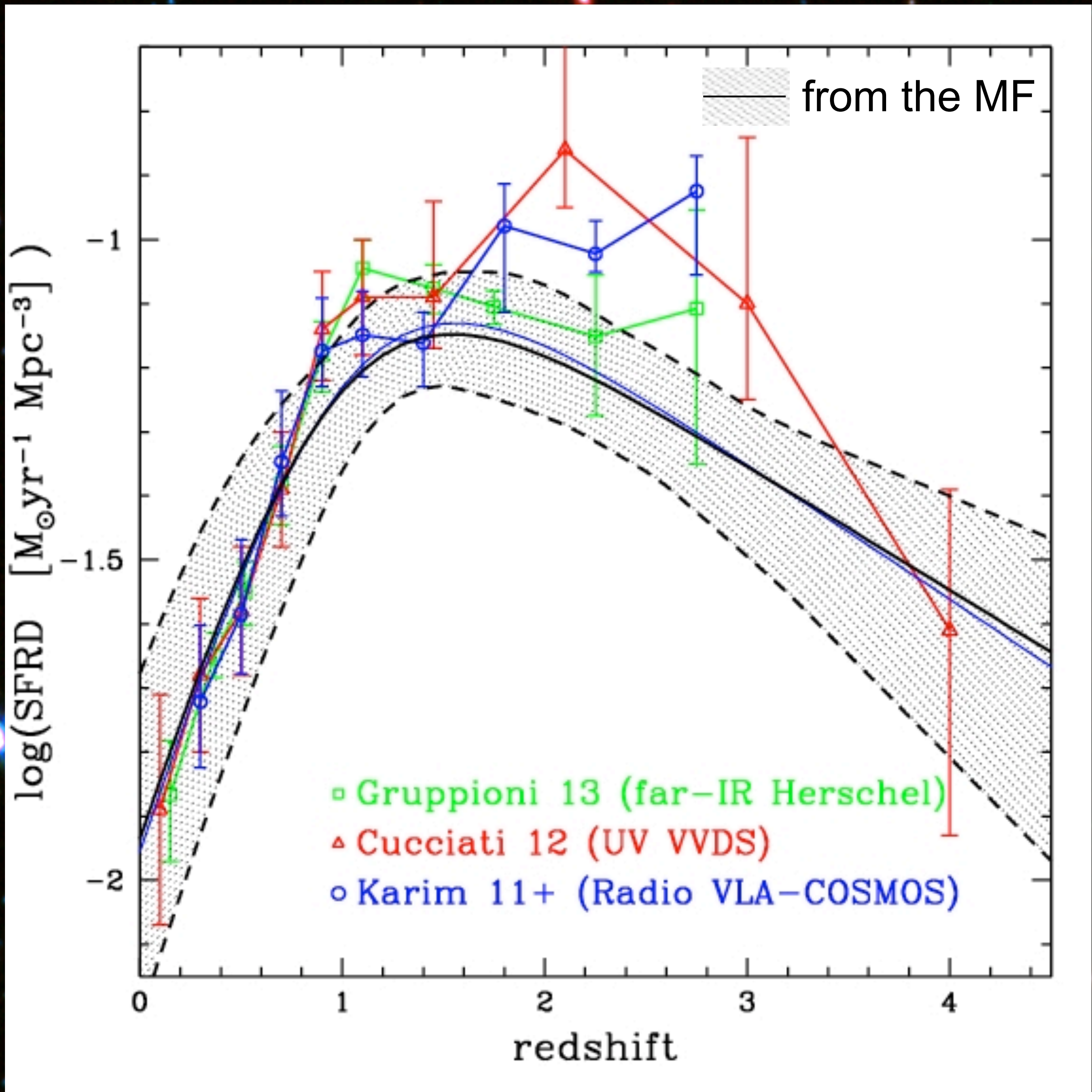


Find the SFHs able to reproduce the UltraVISTA mass density evolution

(same method as Wilkins et al. 2008)

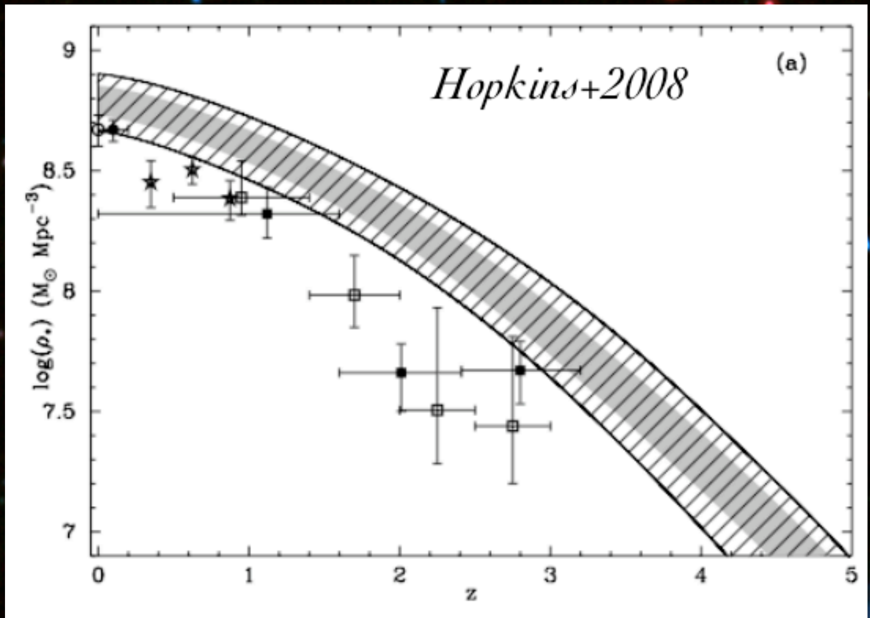
SFRD peaks at z~1.5

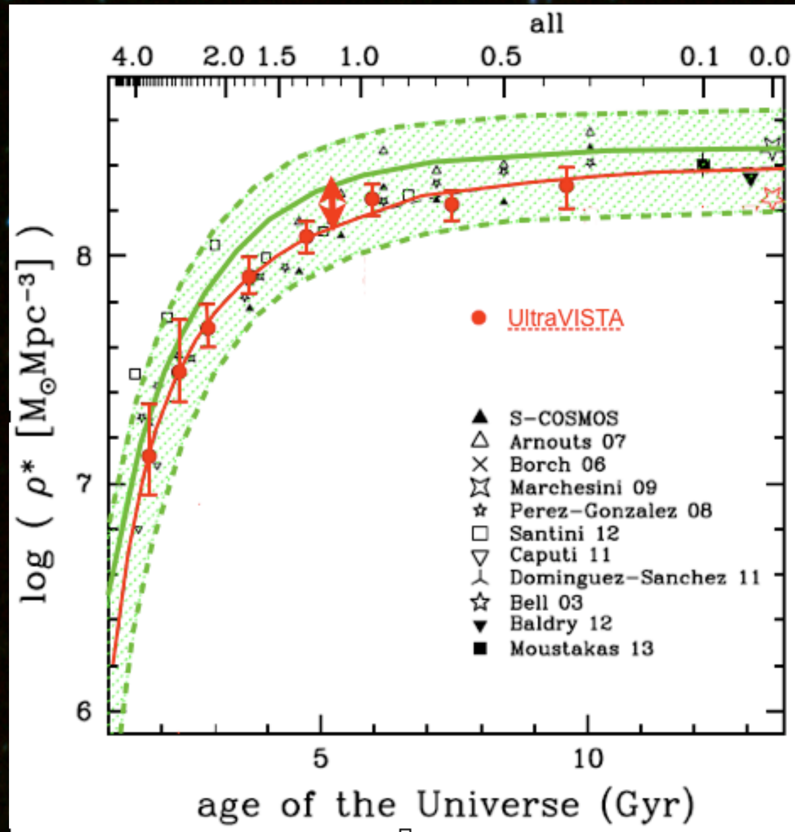
2. Reconstruct the SFH from the observed mass density



- ➢ excellent agreement @z<1.5 with any SFR tracer
- ➢ differ @z>1.5 large uncertainties even between direct SFR tracers

Converge toward a consistent picture





possible need for an evolving IMF → uncertainties in SFRD estimates at $z>2$ are still large

Outlines

I. The COSMOS Ultra/VISTA data

II. The star formation history from a MF perspective

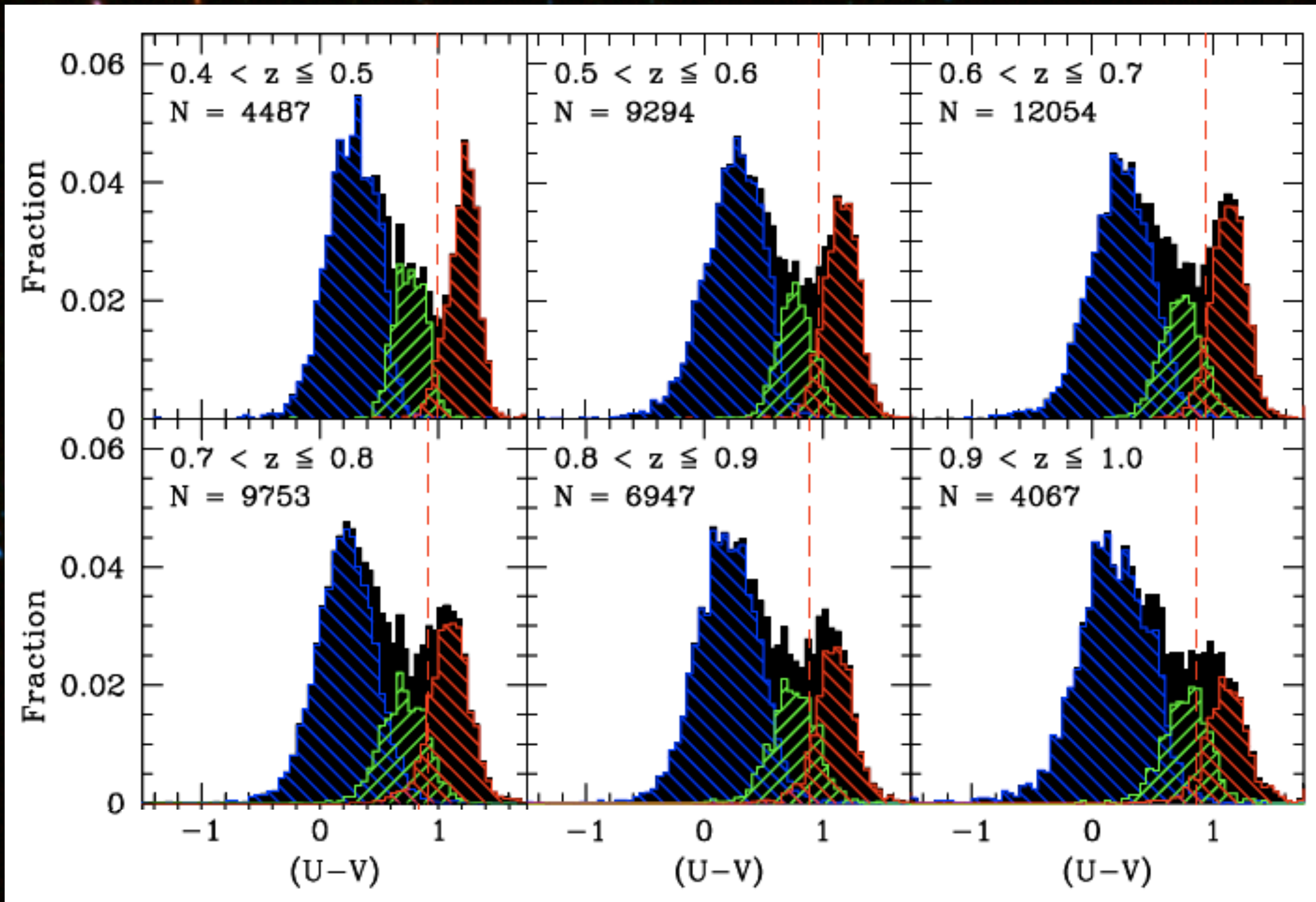
III. Quenching

IV. Evolution of the specific SFR

Color bimodality

Sharp transition between star-forming and quiescent galaxies

Fritz et al. 2014, with VIPERS data

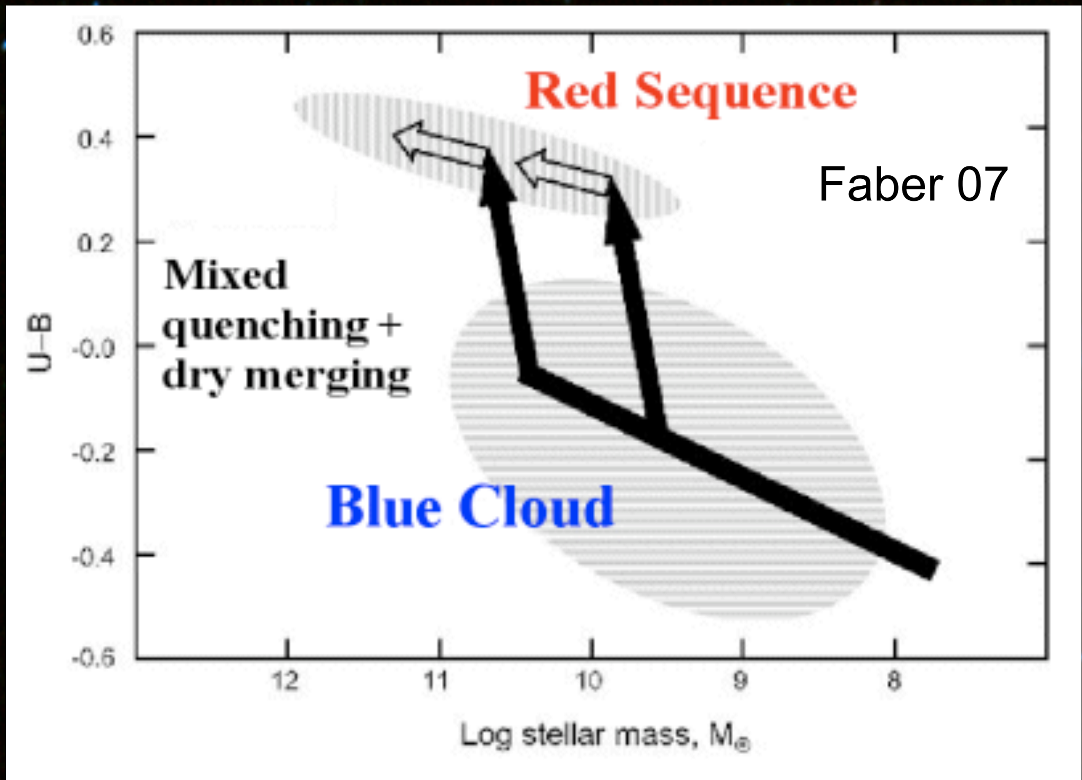


Quenching

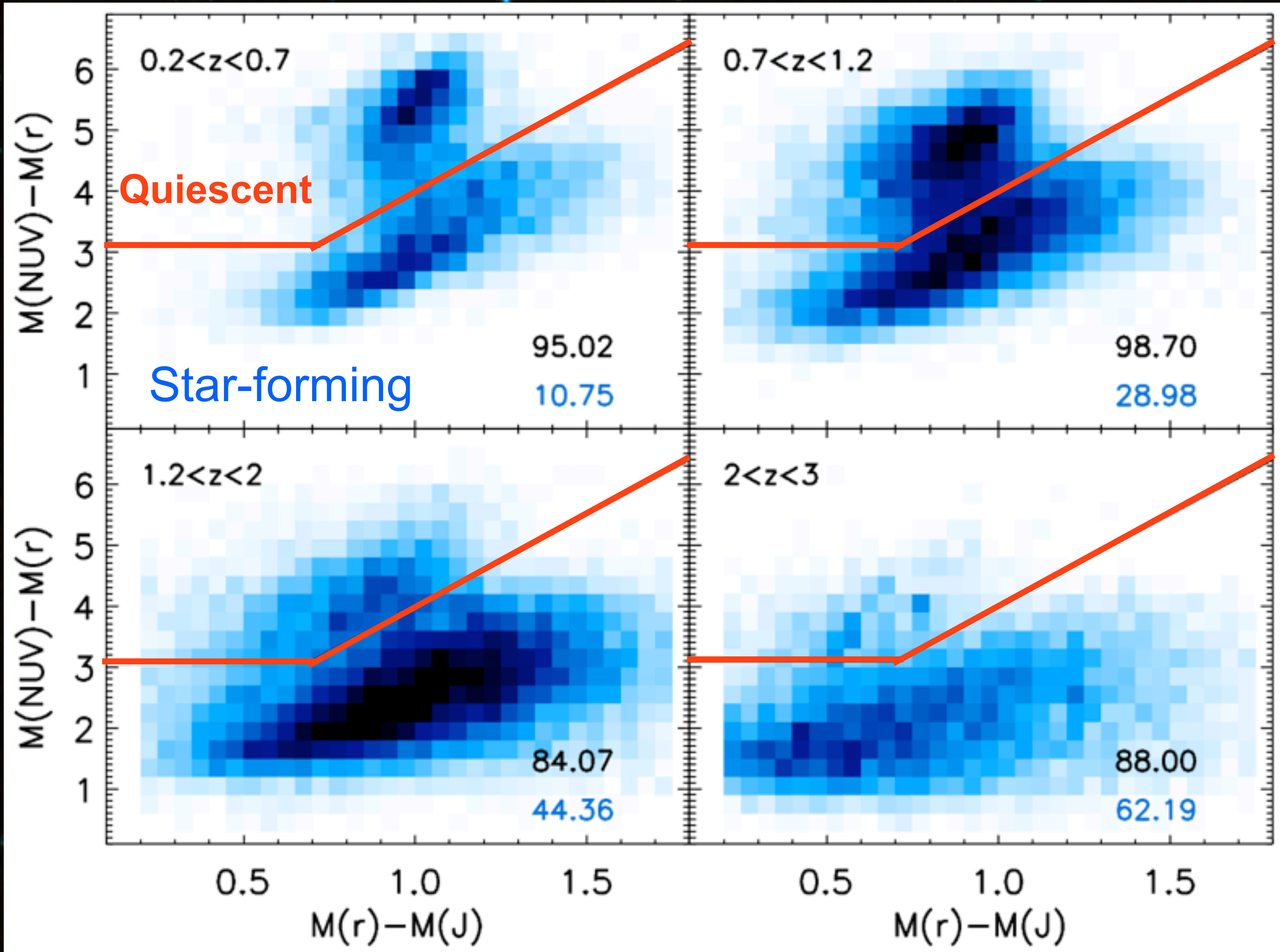
Cessation of the star formation activity

At which rate, which mass, which environment ?

➢ Physical processes involved ? AGN feedback, mergers, ...



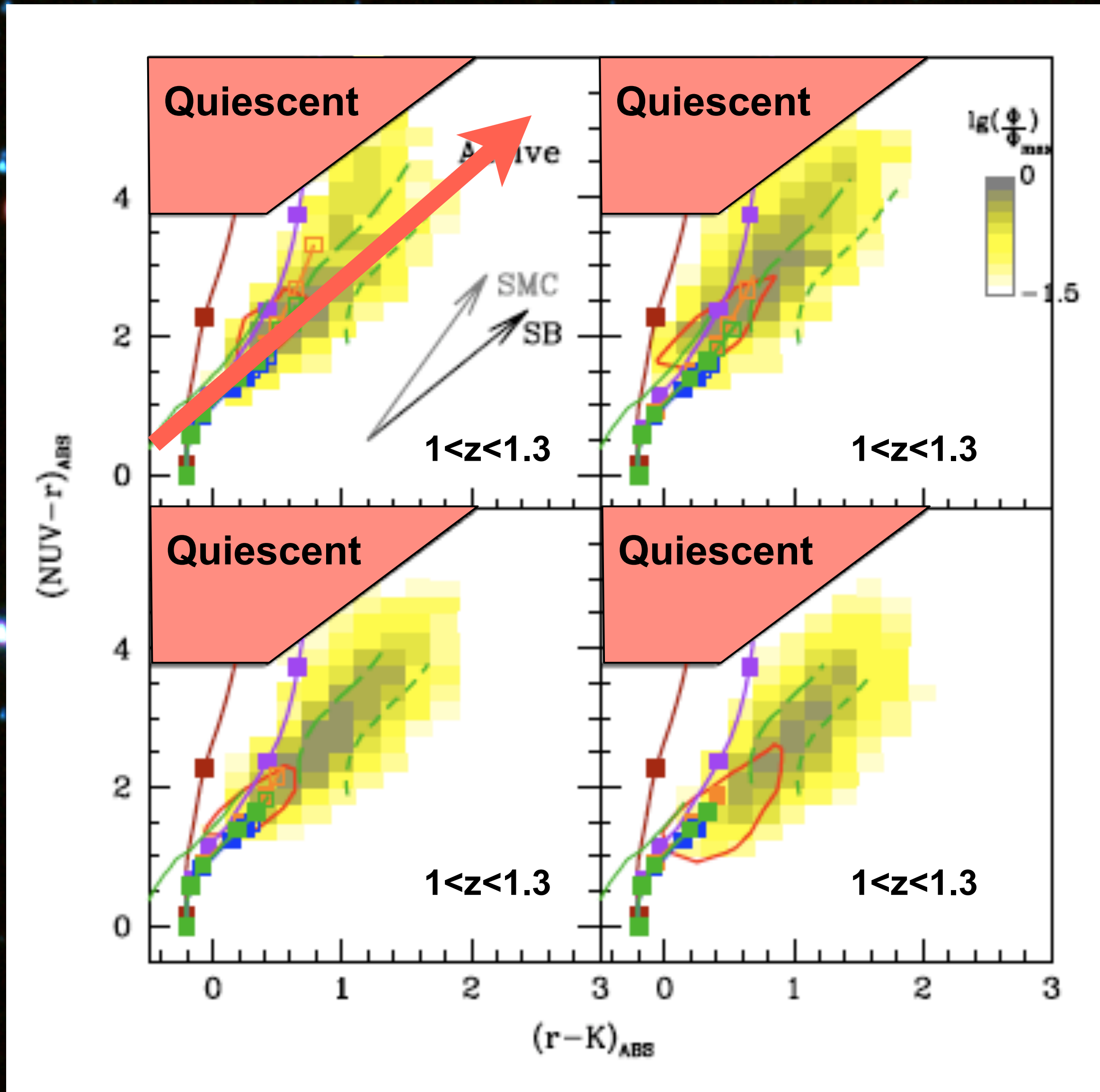
Select the quiescent population



Select the quiescent population

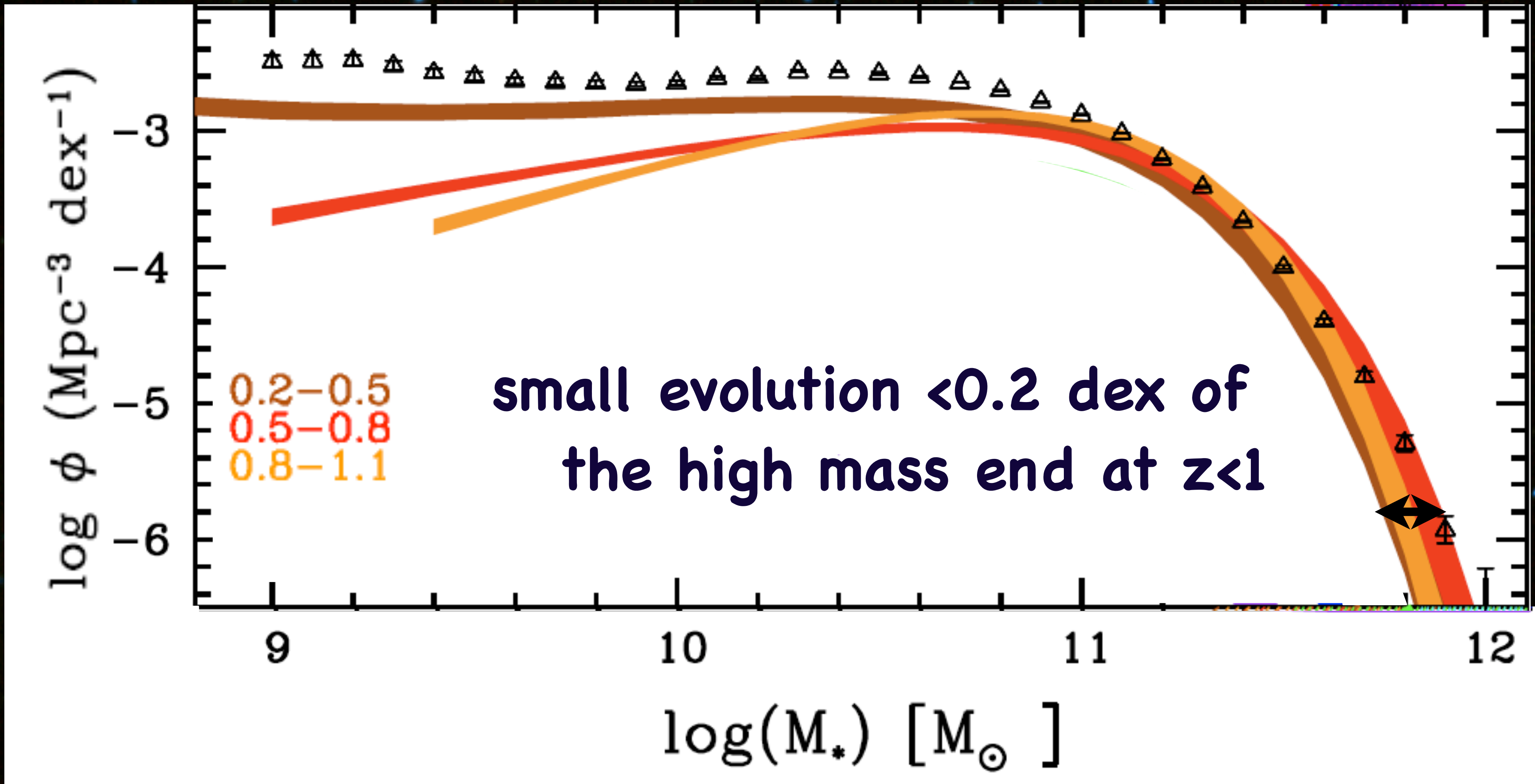
Extinction is moving galaxies along a diagonal axis

Star forming galaxies with extinction fall in a different locus than galaxies with a quenched SFR



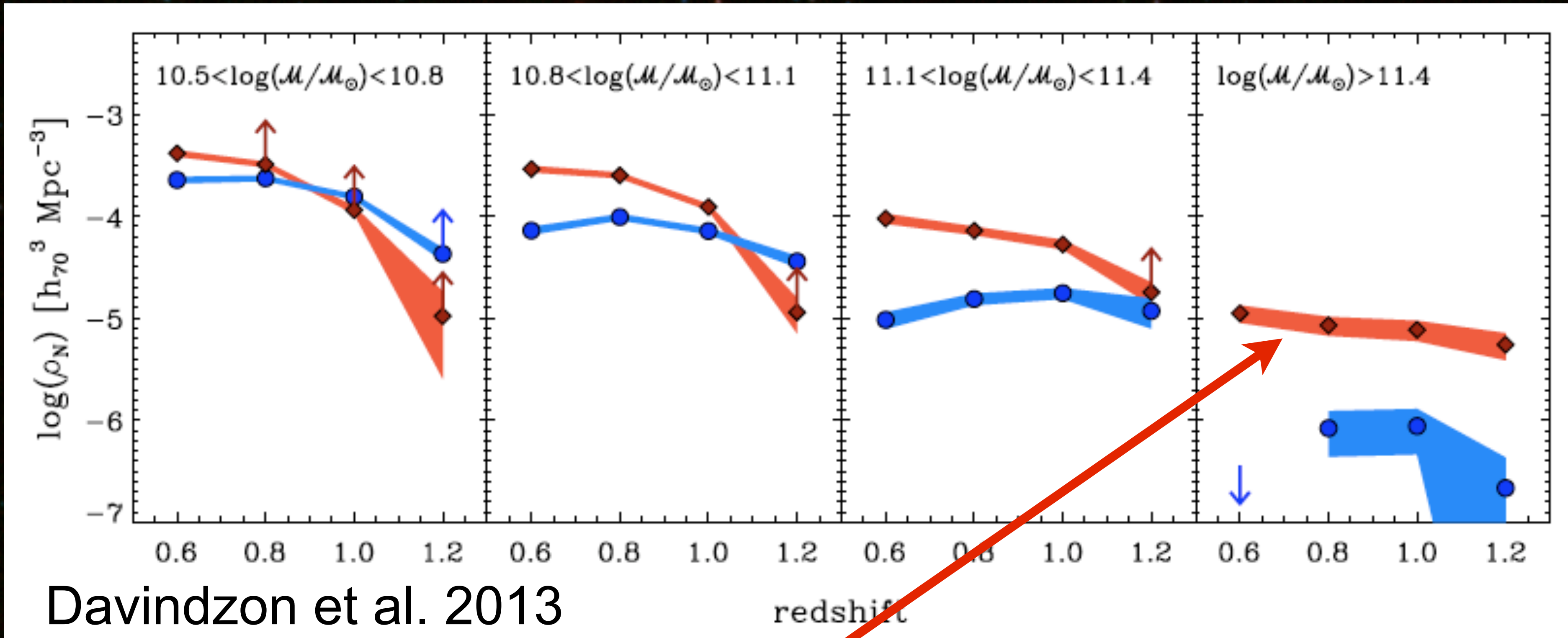
Arnouts et al. 2013 with COSMOS MIPS

Stellar mass function of the quiescent



Confirmation on larger area

Two fields of $2x5$ deg^2 in the VIPERS survey

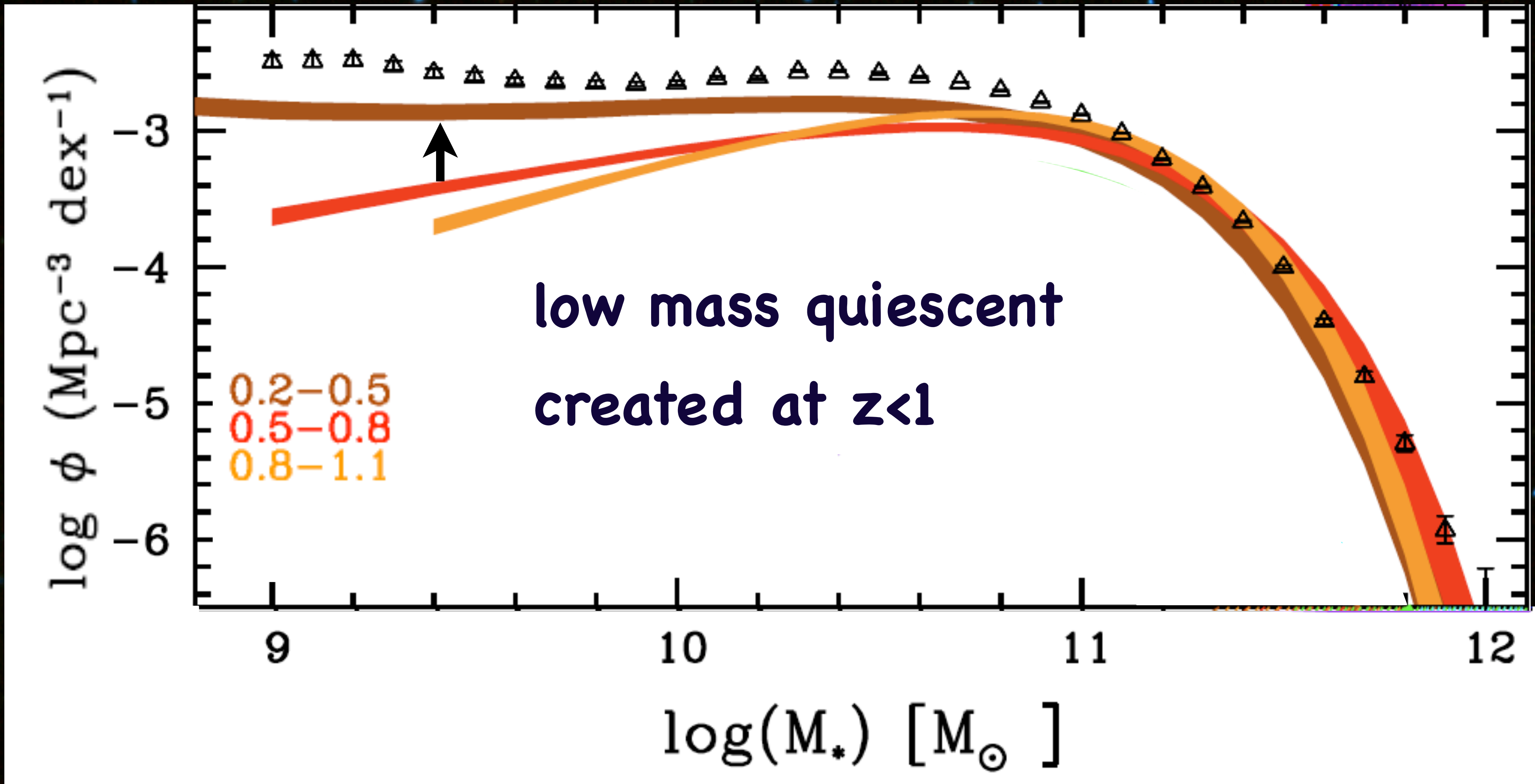


Davindzon et al. 2013

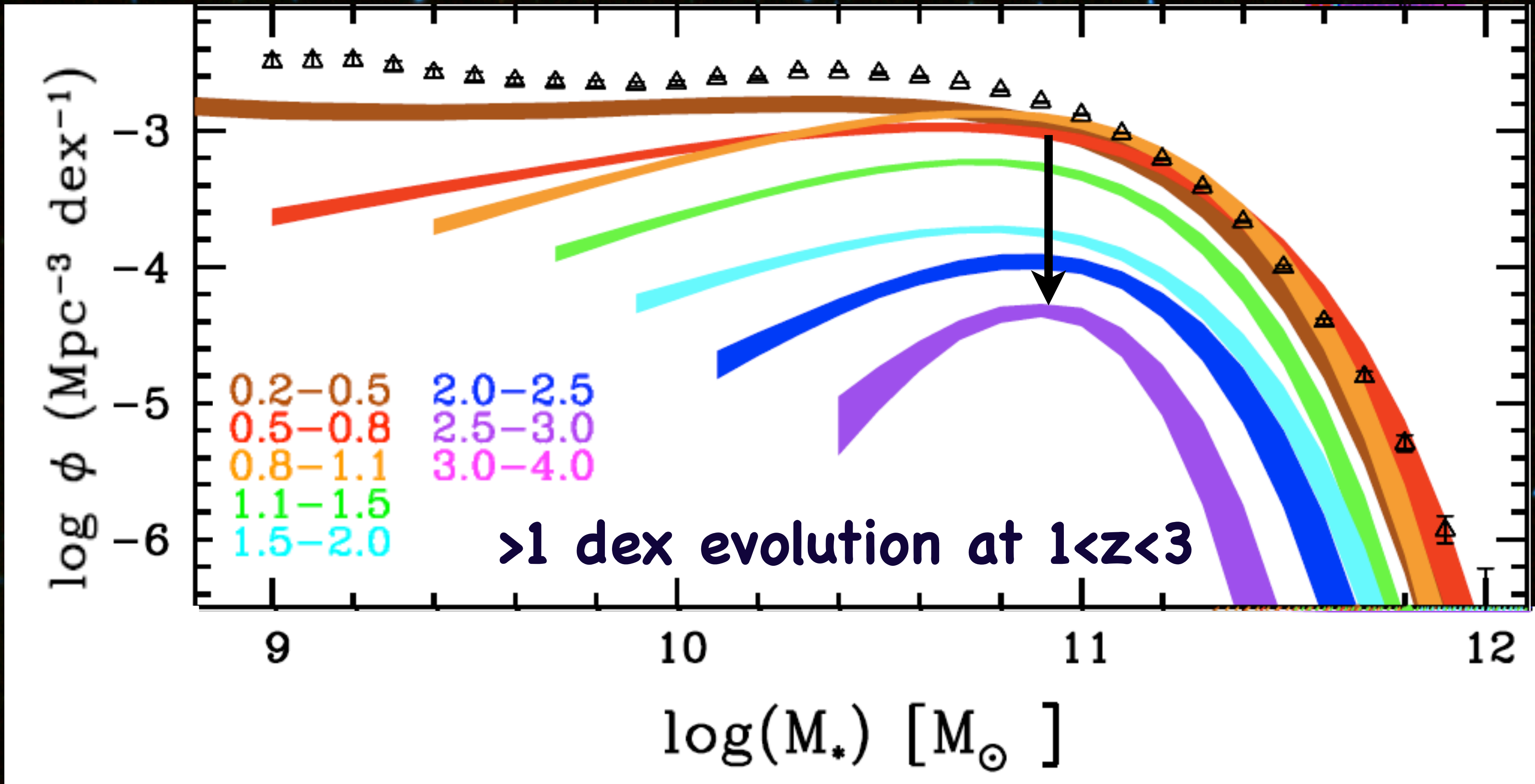
Evolution of less than 0.2 dex for the most massive (45%)

➢ low efficiency of dry mergers in massive quiescent

Stellar mass function of the quiescent



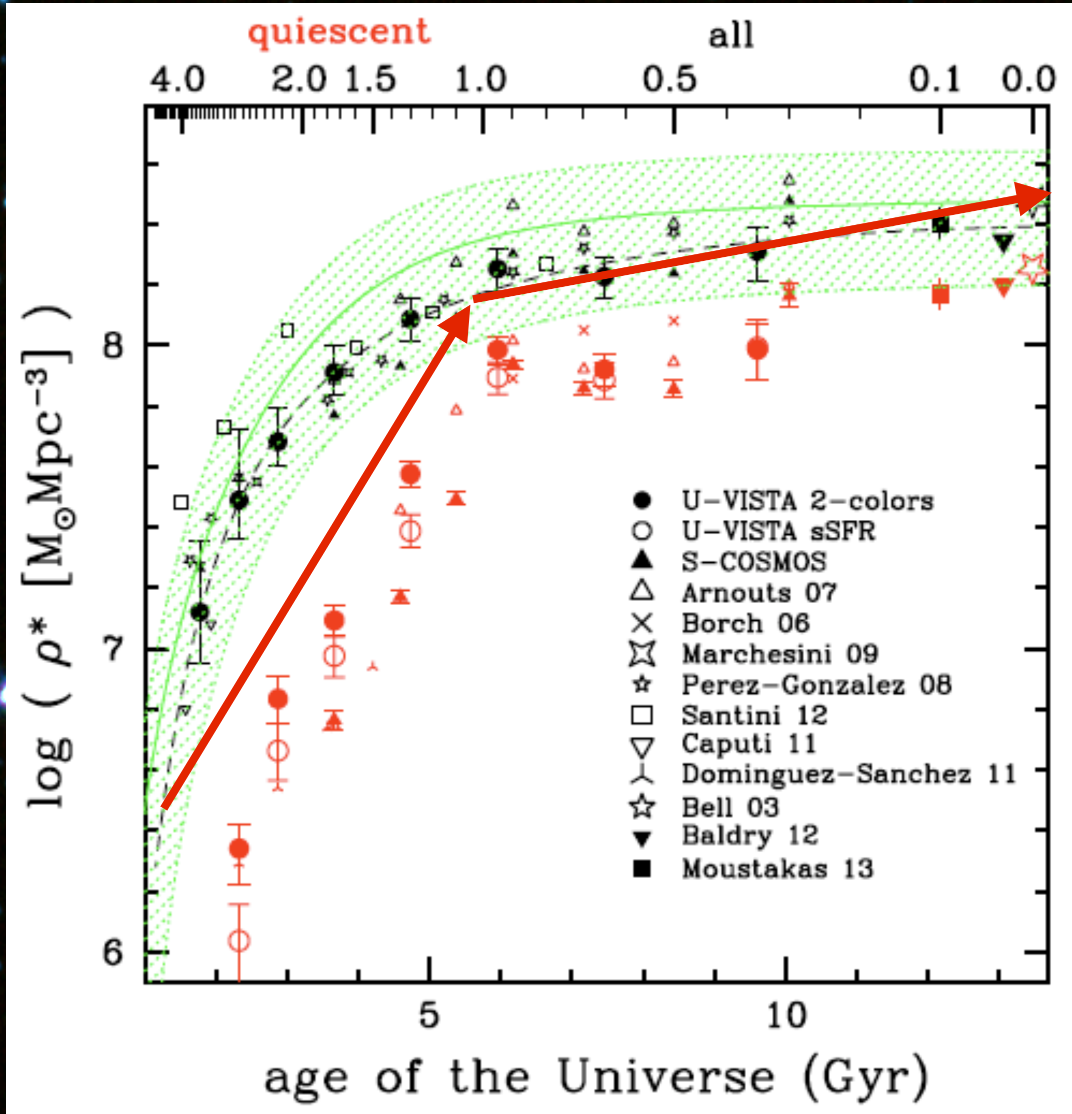
Stellar mass function of the quiescent



Stellar mass density of quiescent galaxies

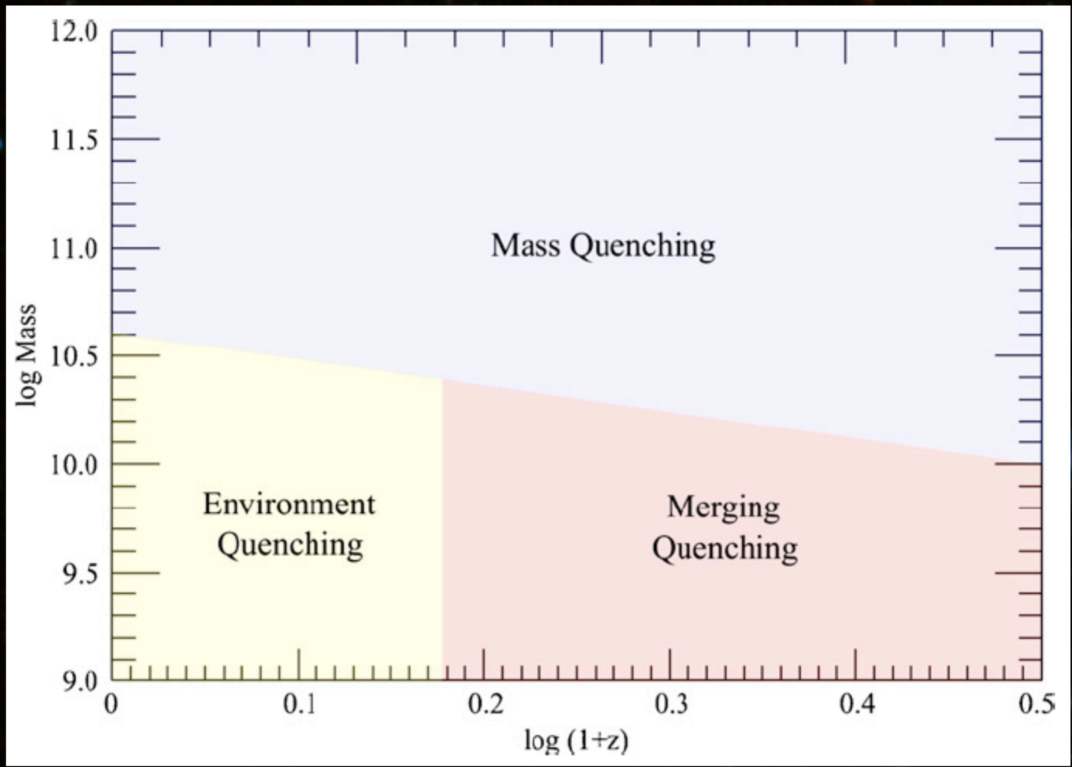
confirm the steep increase at $1<z<3$

➢ quiescent galaxies assemble most of their mass at $z>1$

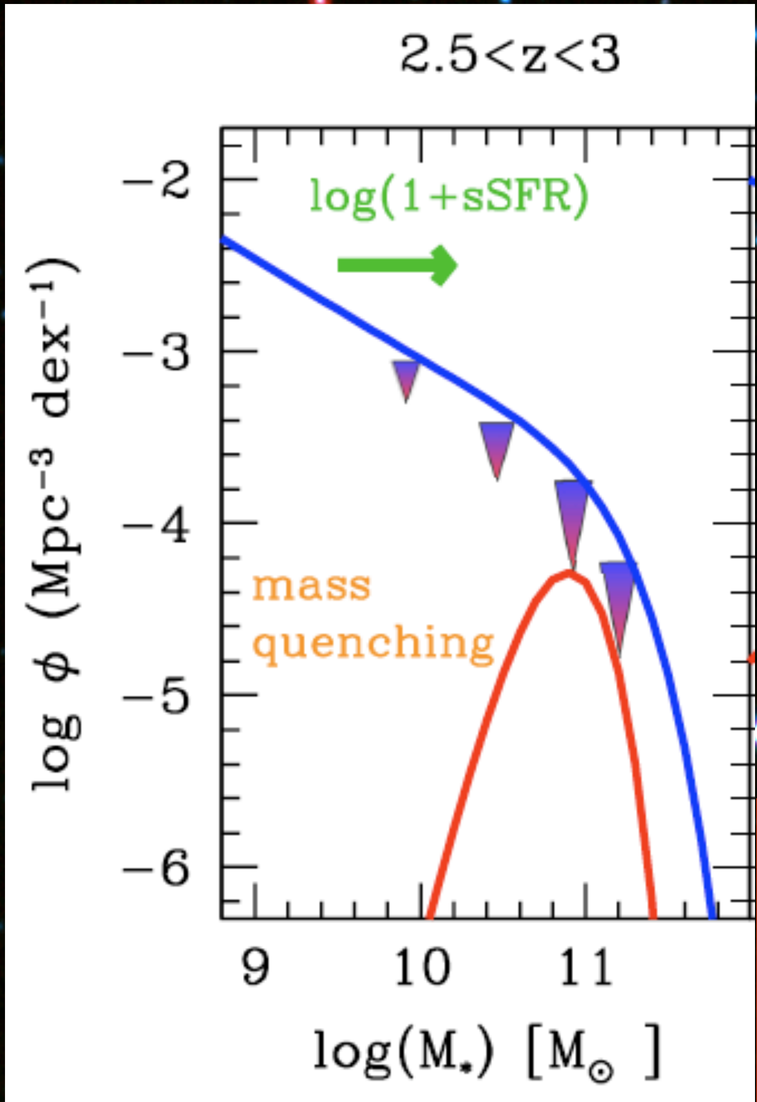


Peng 2010 model

- Mass quenching dominate at $M>10^{10.5}$ $M_\odot$
- Environment quenching at $z<0.5$ for $M<10^{10.5}$ $M_\odot$



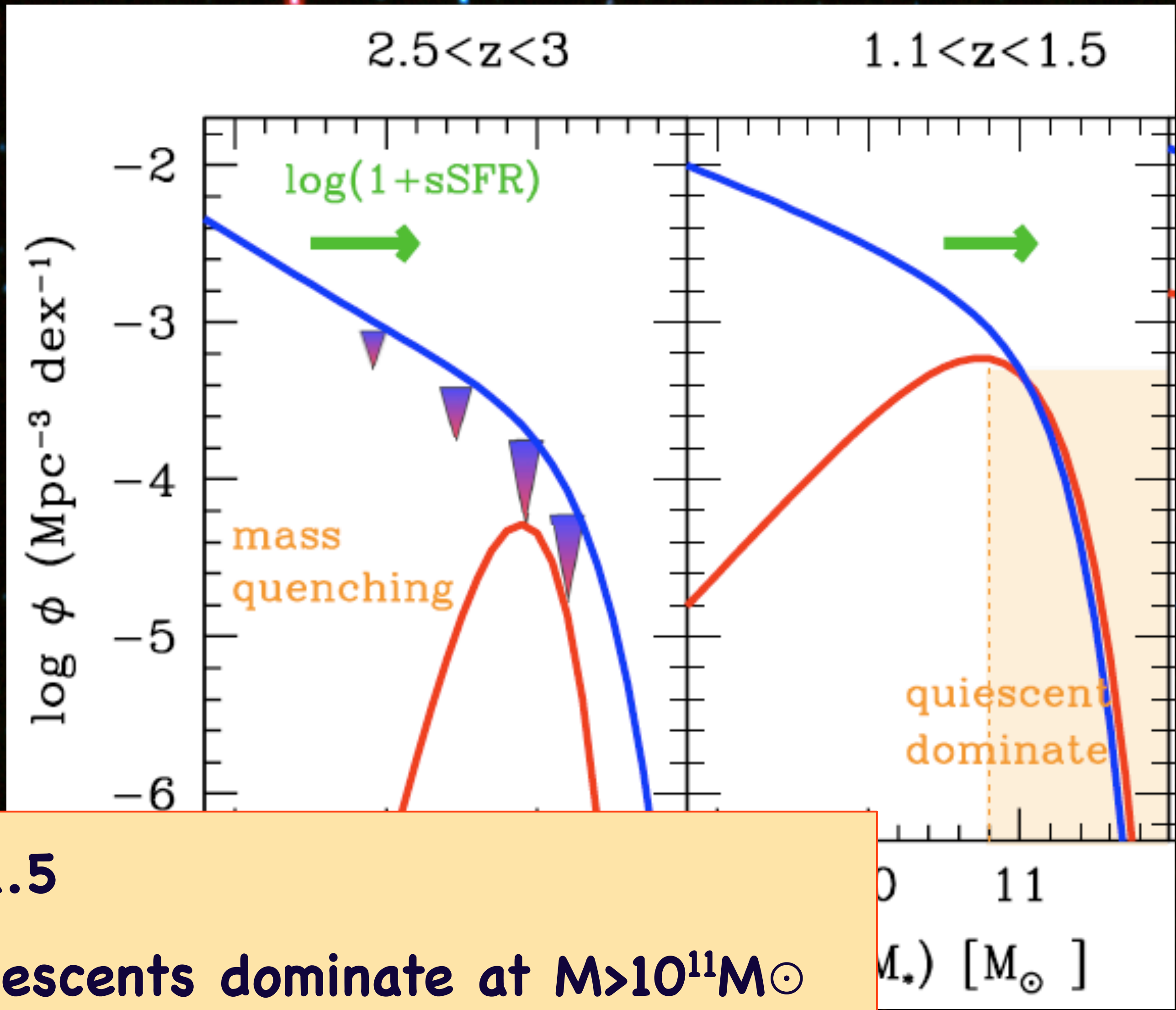
Proposed global picture



z>1.5

Star-forming dominate ➢ mass quenching transfers rapidly SF to quiescent

Proposed global picture

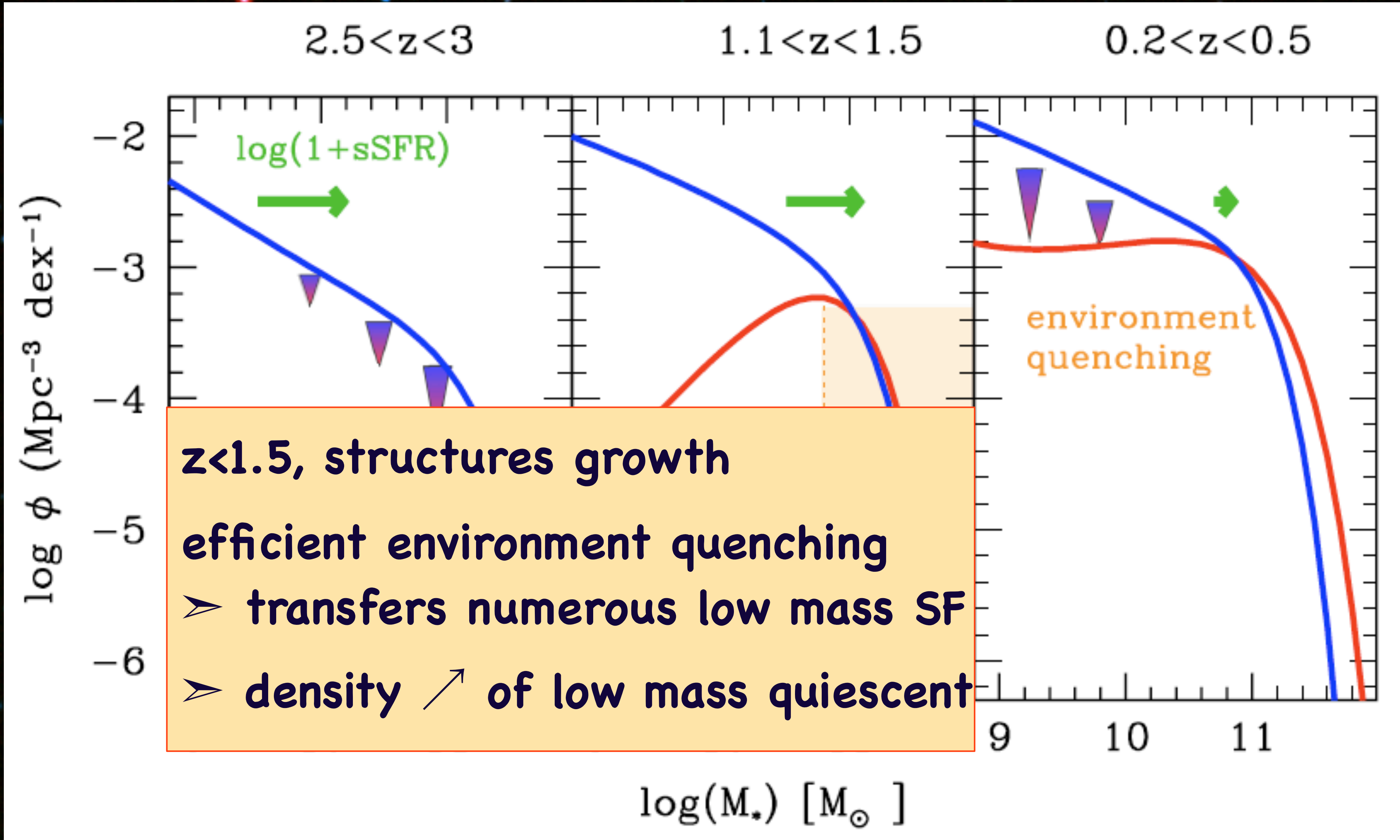


z<1.5

quiescents dominate at M>10^{11}M⊙

➢reduces the reservoir of massive SF which could be quenched

Proposed global picture



z<1.5, structures growth

efficient environment quenching

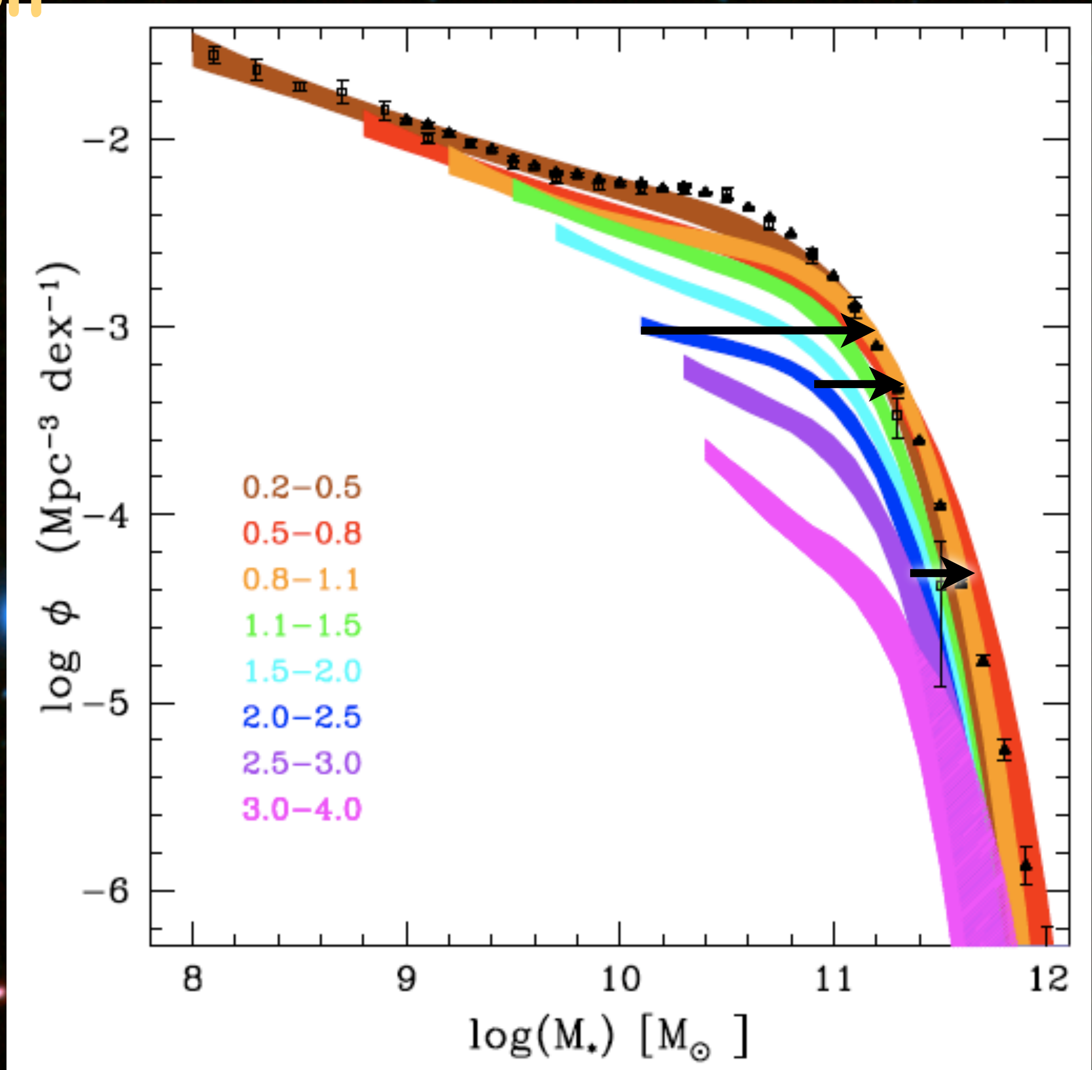
➢ transfers numerous low mass SF

➢ density ↗ of low mass quiescent

Global stellar mass function

Mass dependent evolution

➢ Stronger evolution of the low mass end



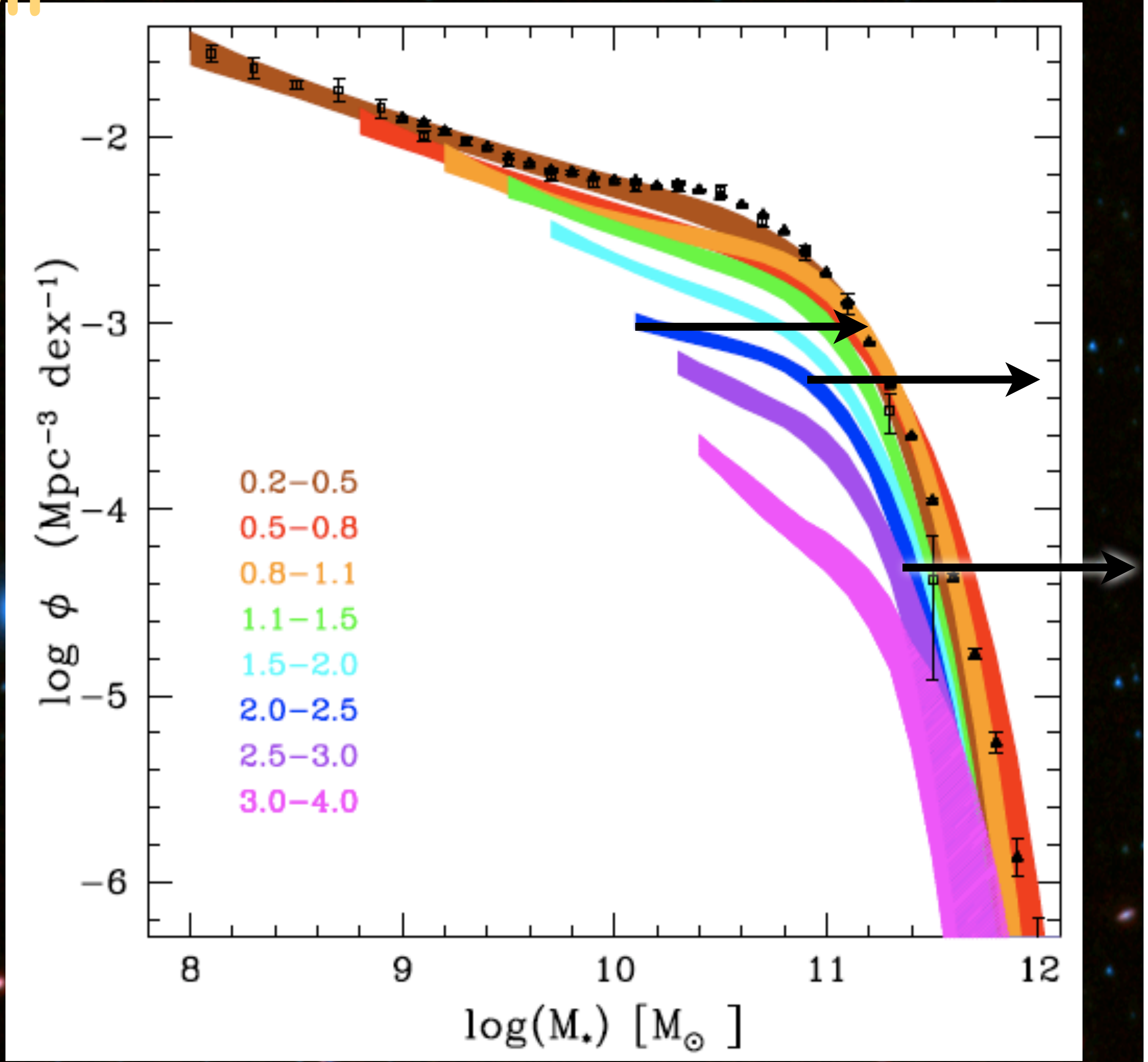
Global stellar mass function

Mass dependent evolution

➢ Stronger evolution of the low mass end

For a constant sSFR

➢ same horizontal shift at all masses



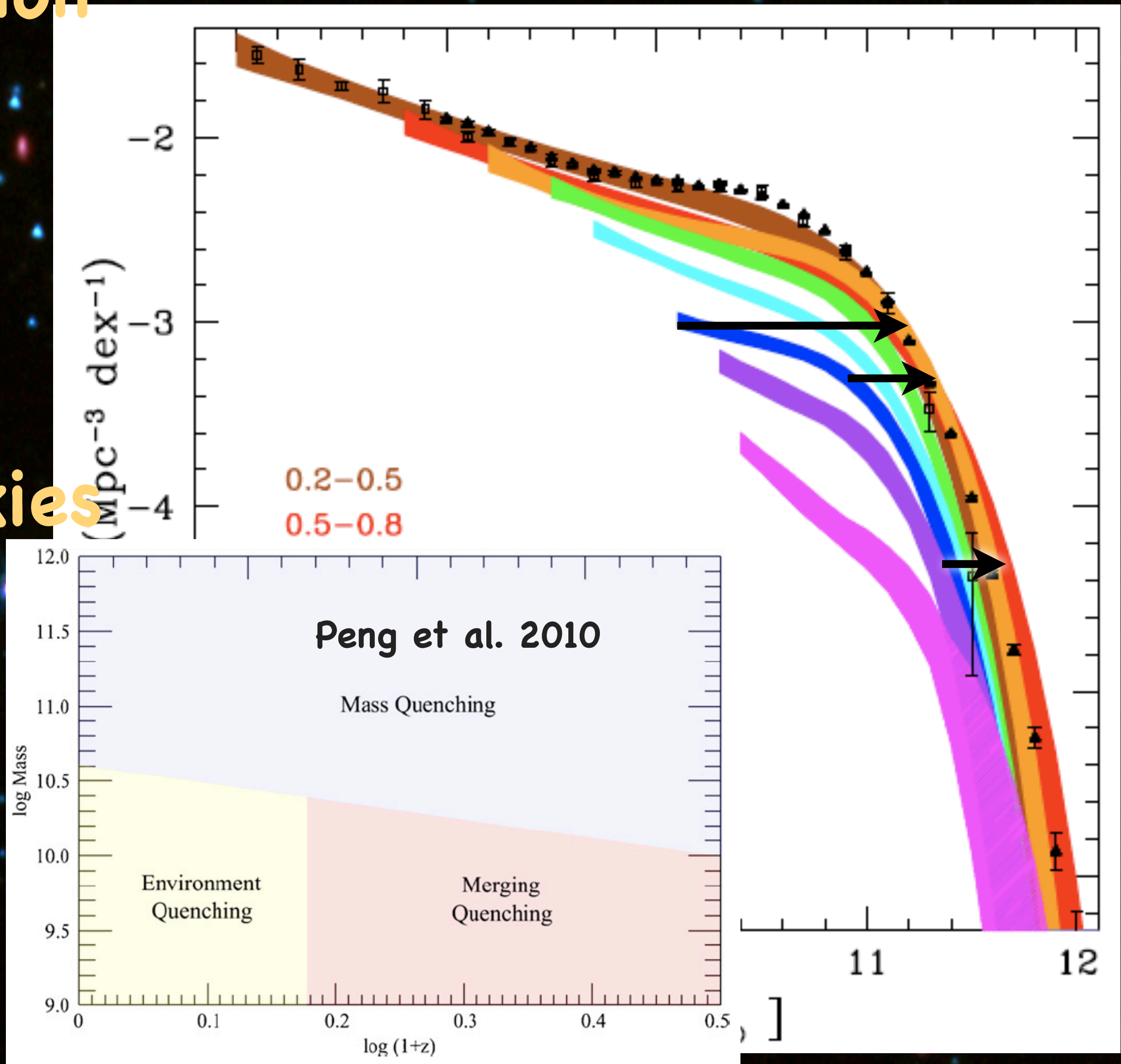
Global stellar mass function

Mass dependent evolution

➢ Stronger evolution of the low mass end

The most massive galaxies are quenched

AGN feedback ?



Outlines

I. The COSMOS Ultra/VISTA data

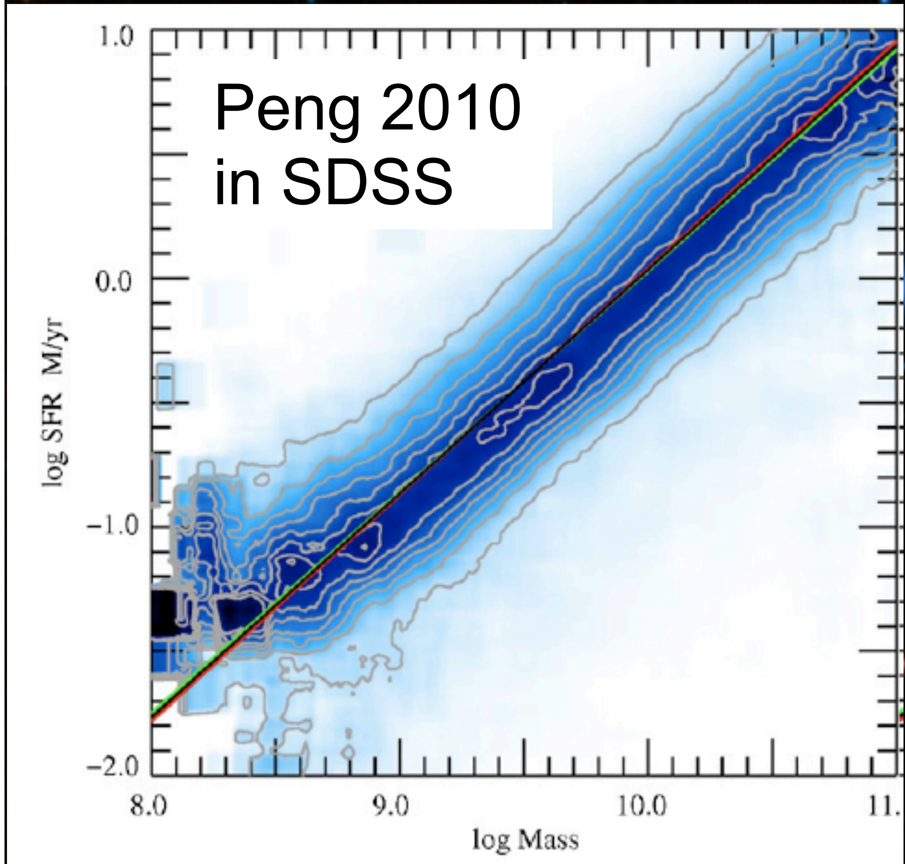
II. The star formation history from a MF perspective

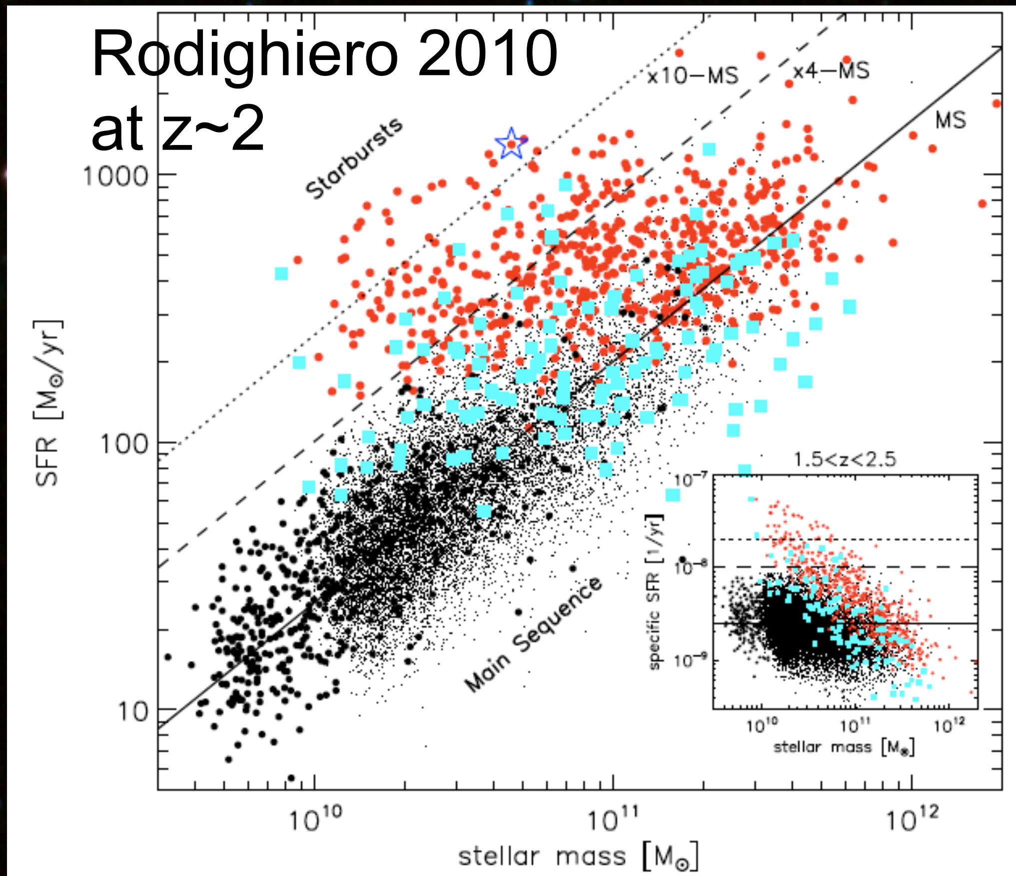
III. Quenching

IV. Evolution of the specific SFR

Mass-SFR relation

Tight relation seen in the local Universe for star-forming galaxies, established out to z~2

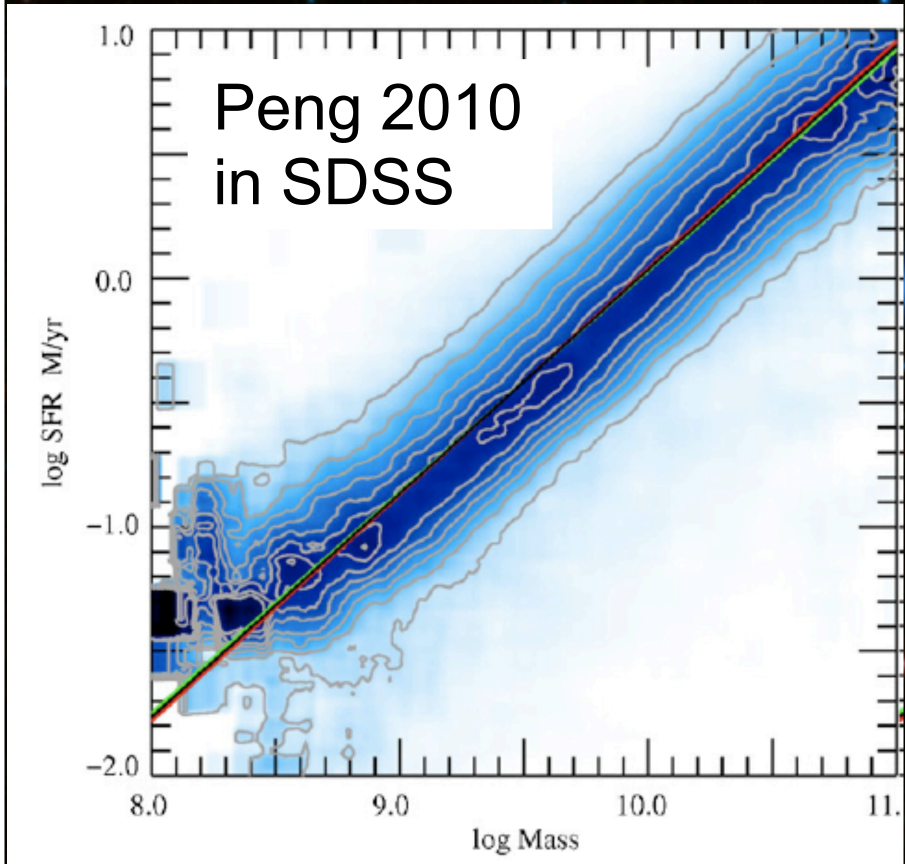


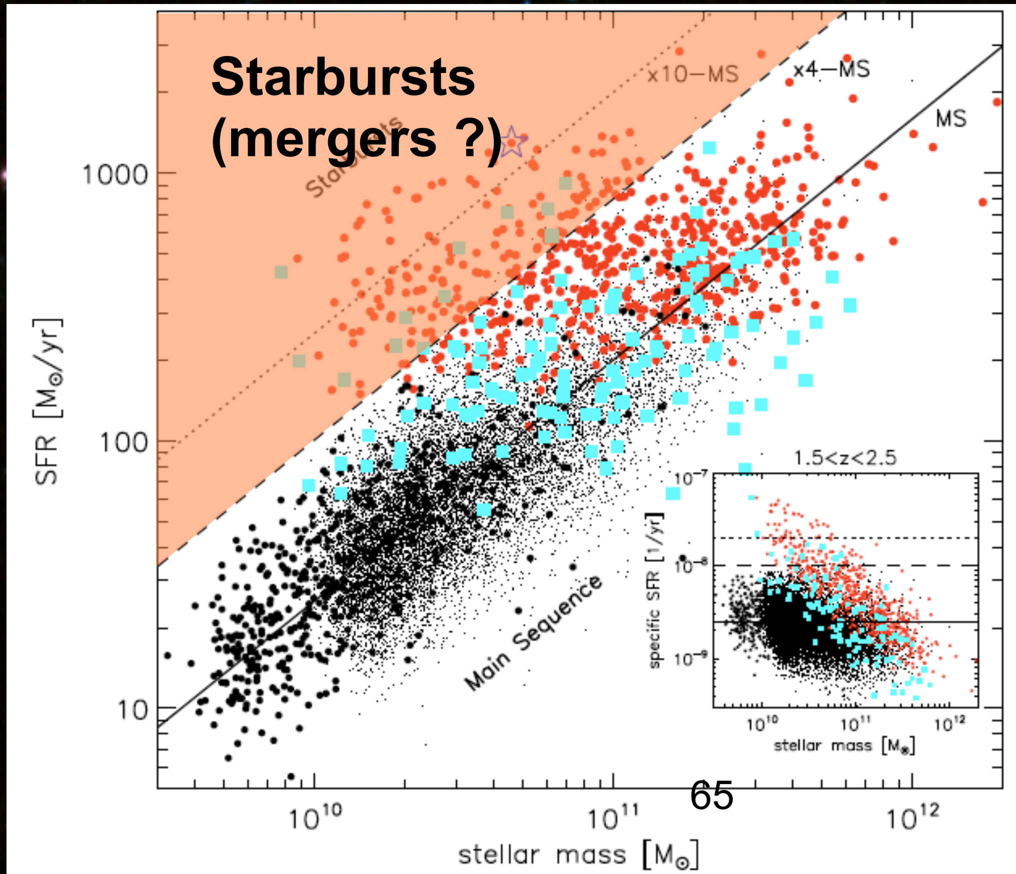


Mass-SFR relation

Tight relation seen in the local Universe for star-forming galaxies, established out to z~2

➢ smooth star formation history versus episodic

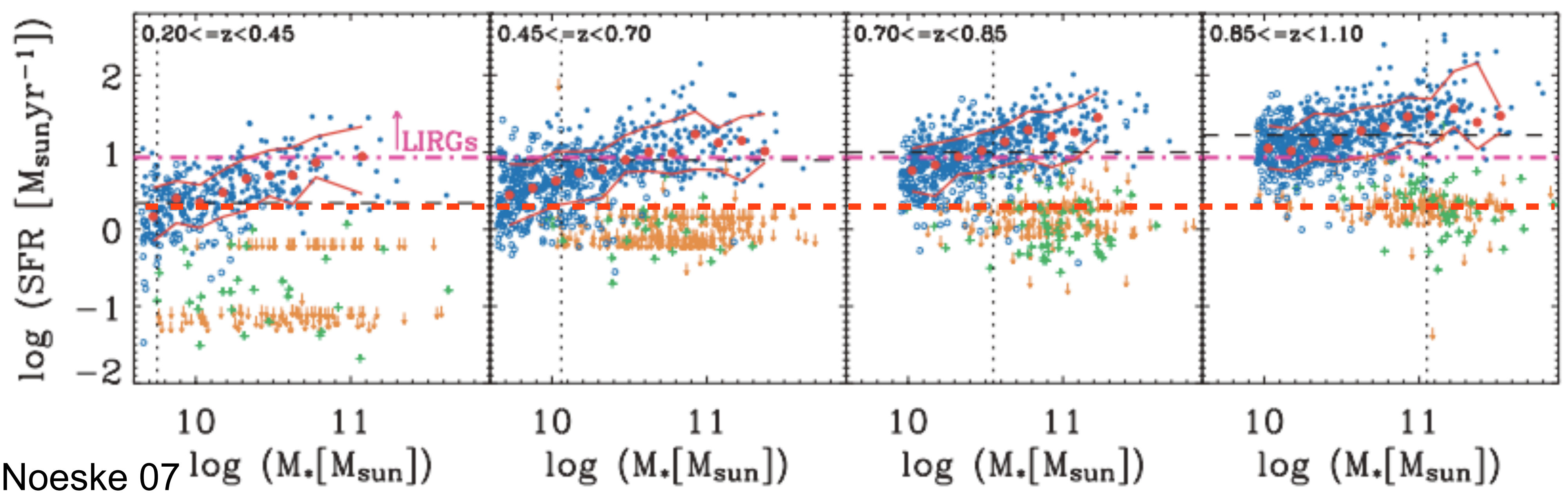




Evolution of the mass-SFR relation

SFR increases with redshift at a given mass

➢ star formation more efficient at high redshift



Noeske 07

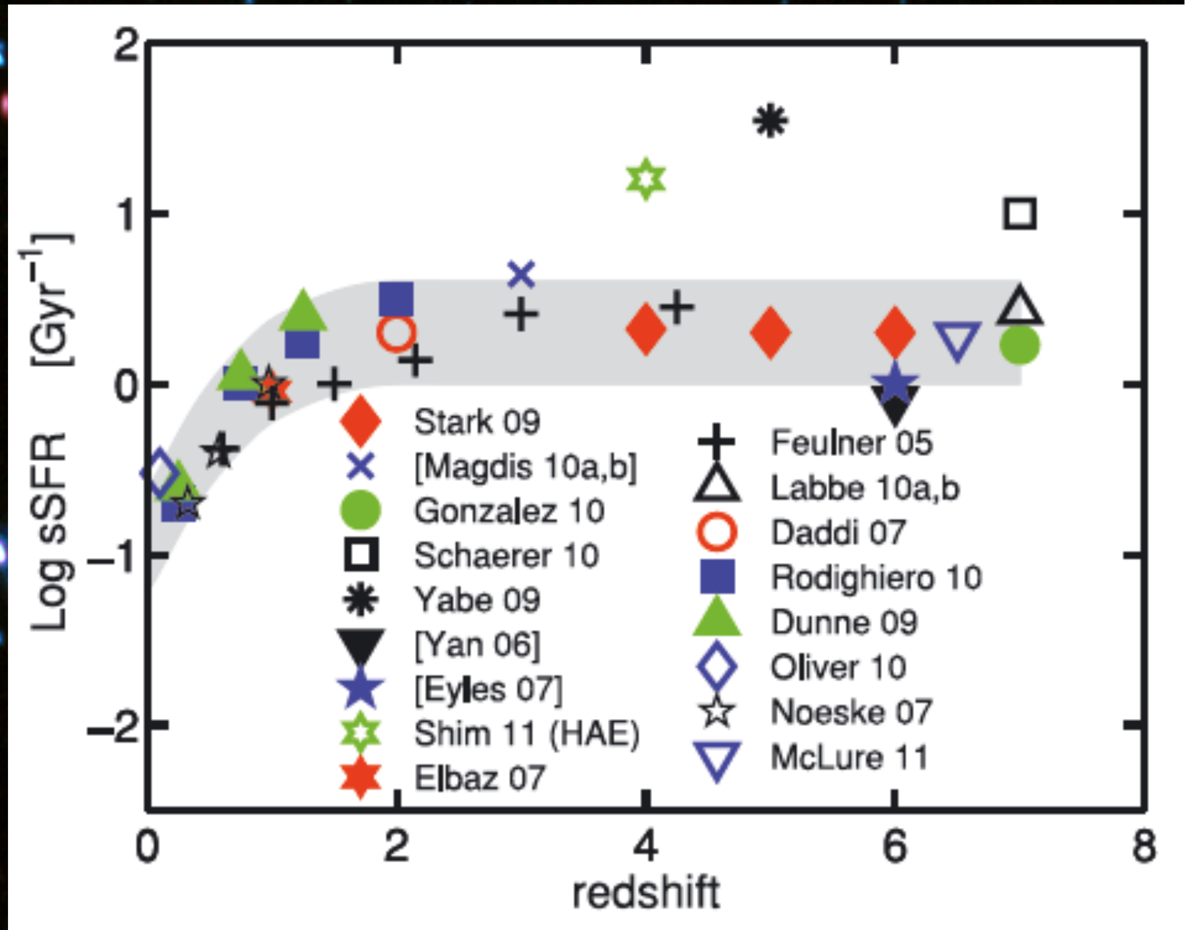
specific SFR (SFR/Mass) increases with redshift

Evolution of the specific SFR at z>2

Weinmann et al. 2011

sSFR (SFR/Mass)

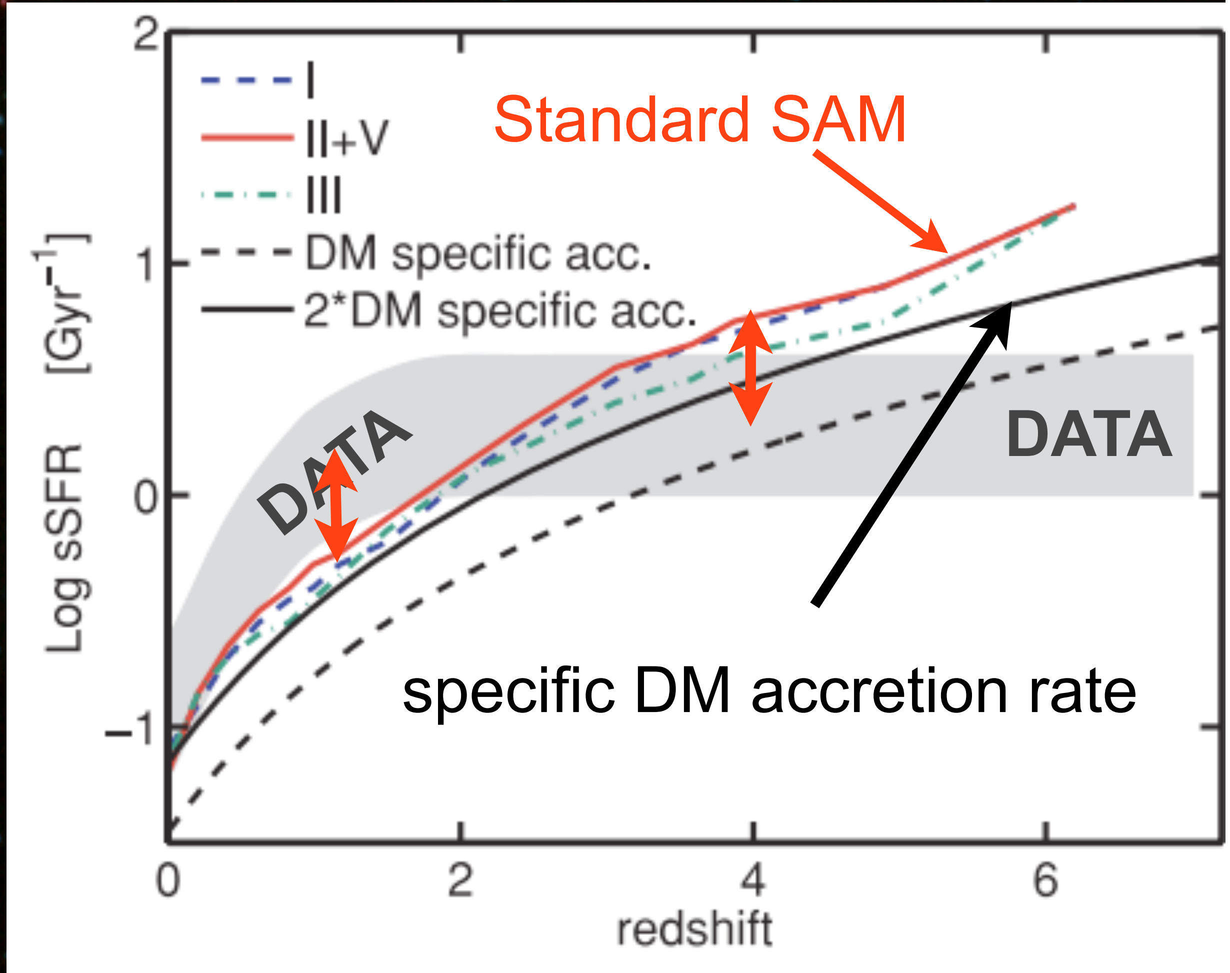
Plateau at z>2 ?



"On the puzzling plateau of the sSFR at z=2-7" Weinmann 2011

Tension between theory and sSFR data

sSFR follows closely DM specific accretion rate in standard SAM



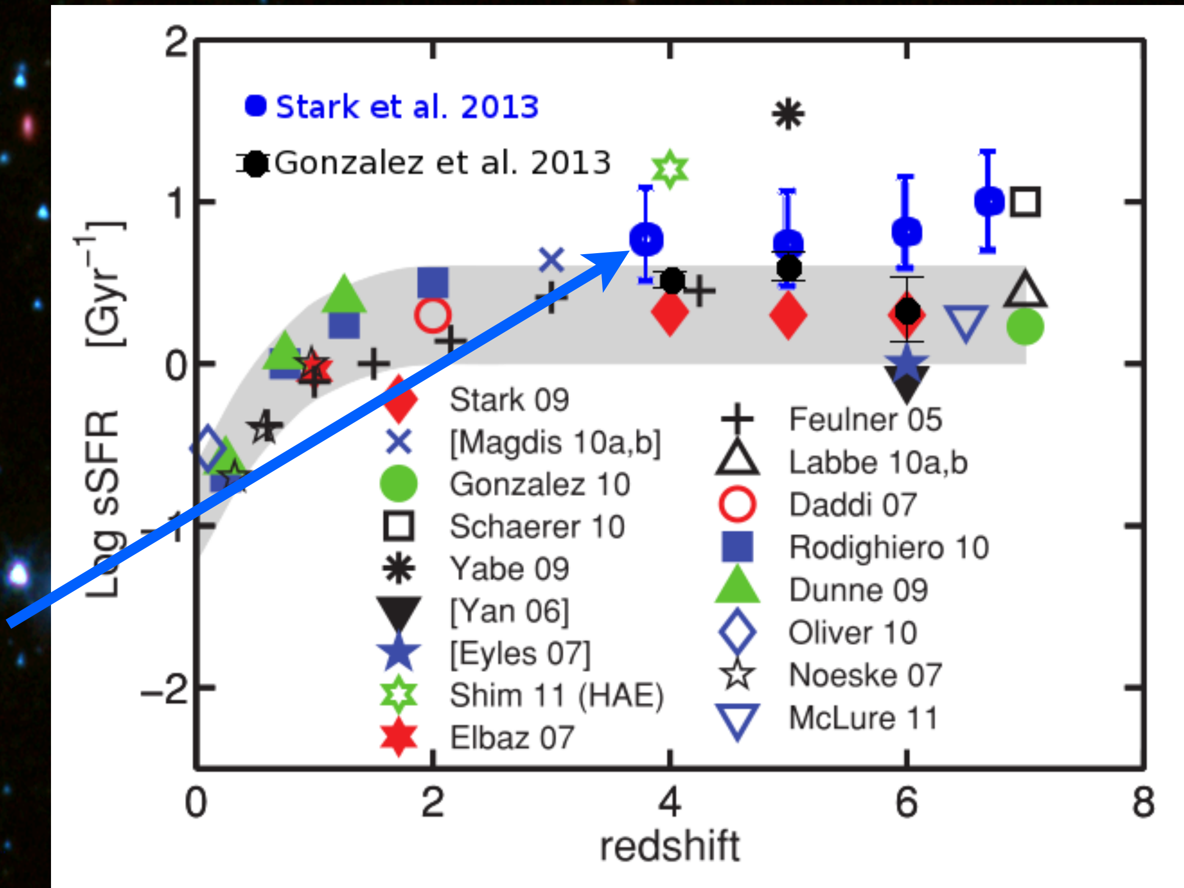
$M'_{DM}/M_{DM} = M'_{baryons}/M_{baryons}$ evolve in $(1+z)^{2.5}$

Evolution of the specific SFR at z>2

Weinmann et al. 2011

Measurement of the SFR extremely challenging, specially at z>2-3

e.g. recent changes by including emission lines in template fitting



➢ Evolution of the MF as an alternative to infer the sSFR evolution

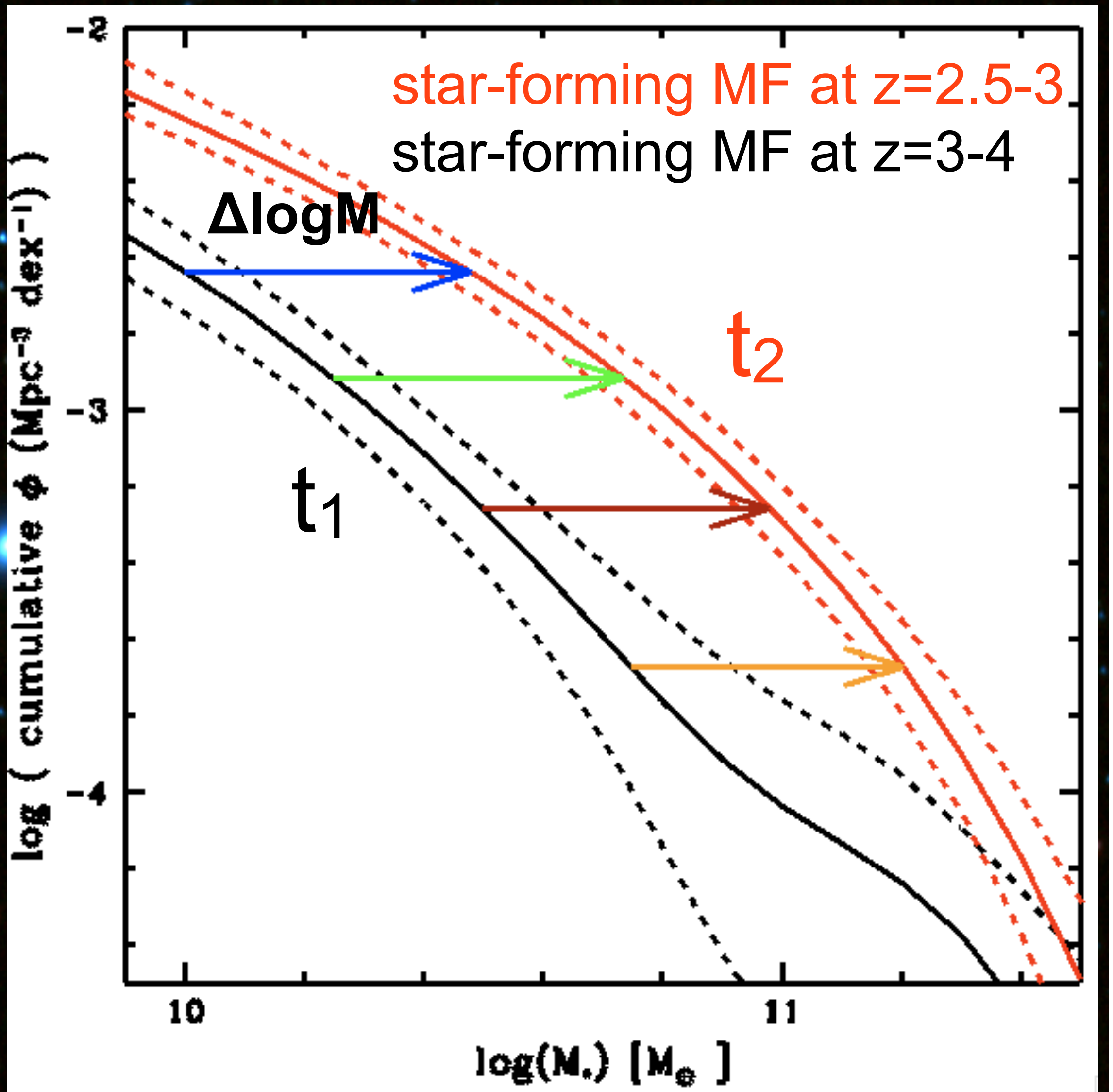
Infer the specific SFR from the star-forming MF evolution

Evolution of the star-forming MF

ΔlogM α log(1+sSFR*δt)

$$\mathrm{sSFR}(t_1) = \frac{10^{\Delta\log M} - 1}{(t_2 - t_1 - \int_{t_1}^{t_2} f_r(t_2 - t')dt')}$$

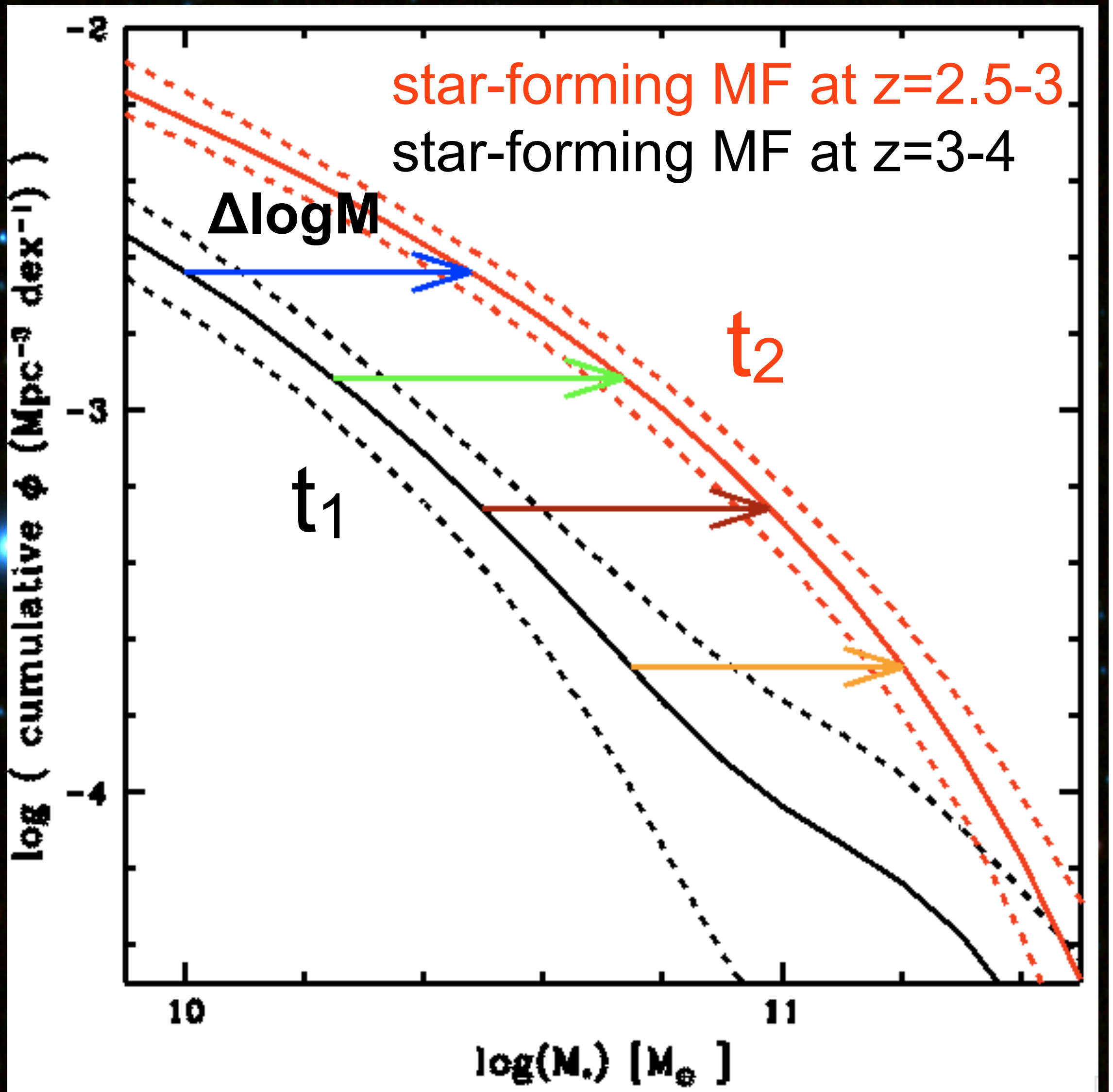
⚠ Need to remove the contribution of galaxies quenched during δt



Infer the specific SFR from the star-forming MF evolution

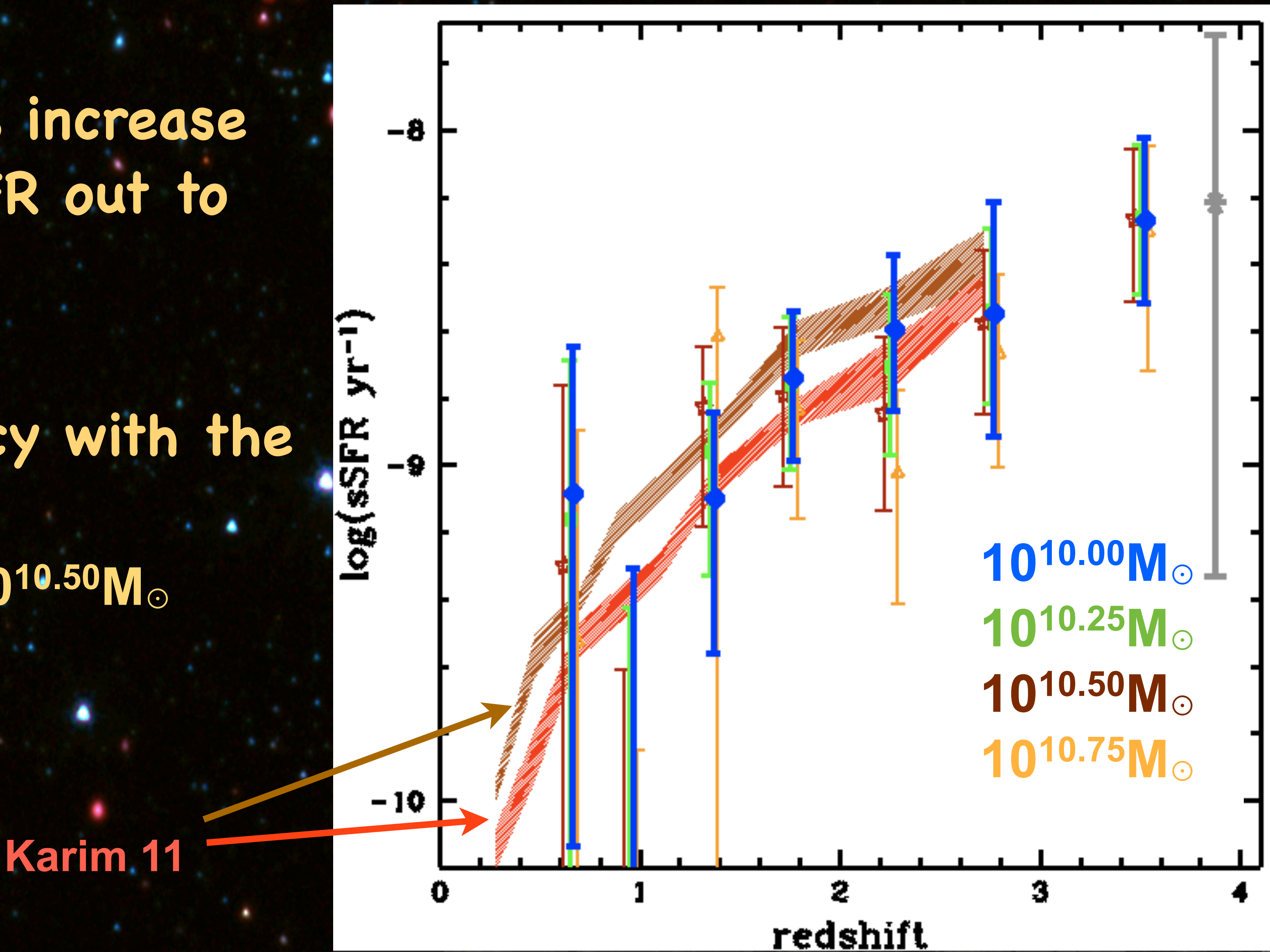
Measure ΔlogM at different redshifts and different masses

➢ evolution of the sSFR estimated at various masses



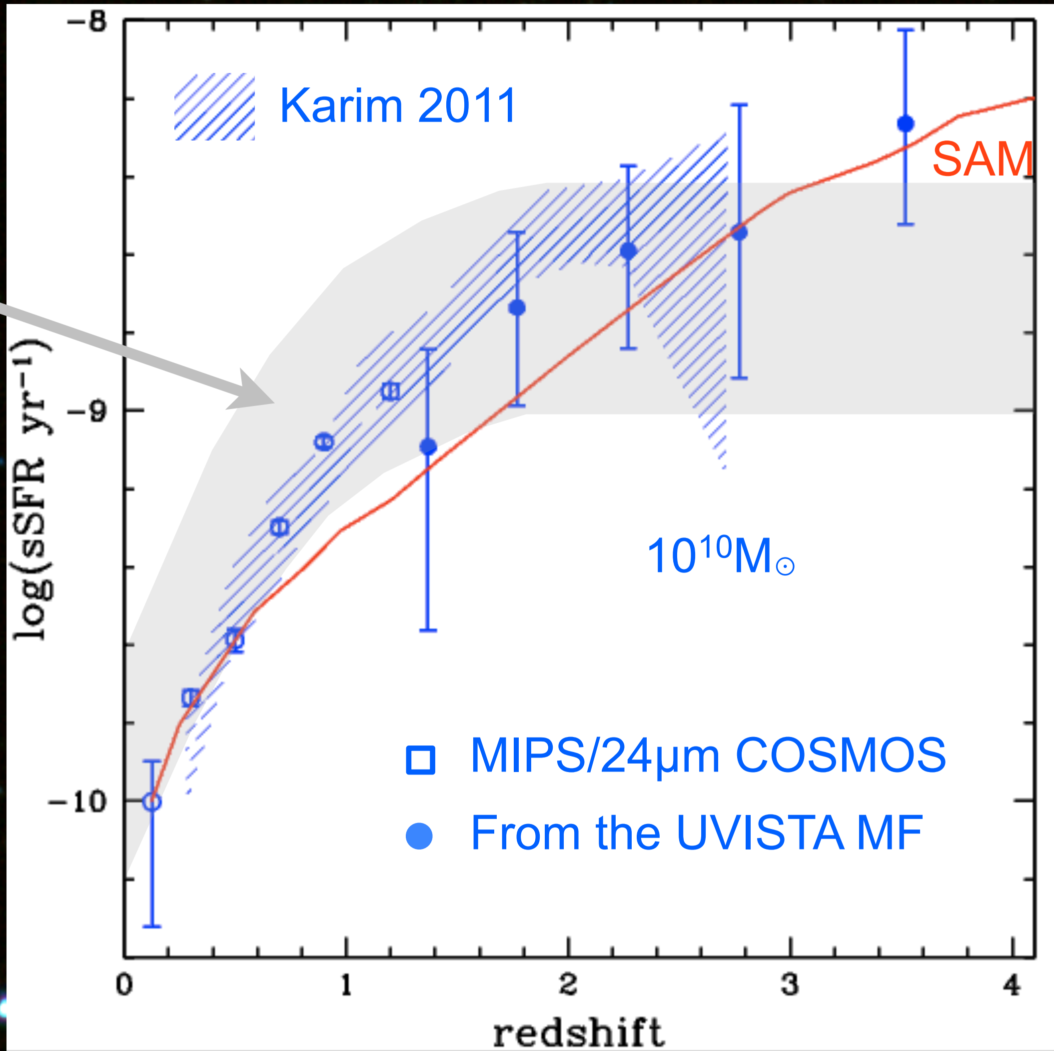
Evolution of the specific SFR from the MF perspective

- continuous increase of the sSFR out to z~4
- no obvious dependency with the masses $10^{10.00}M_\odot$-$10^{10.50}M_\odot$



Comparison with SAM predictions

Data compilation
Weinmann 11



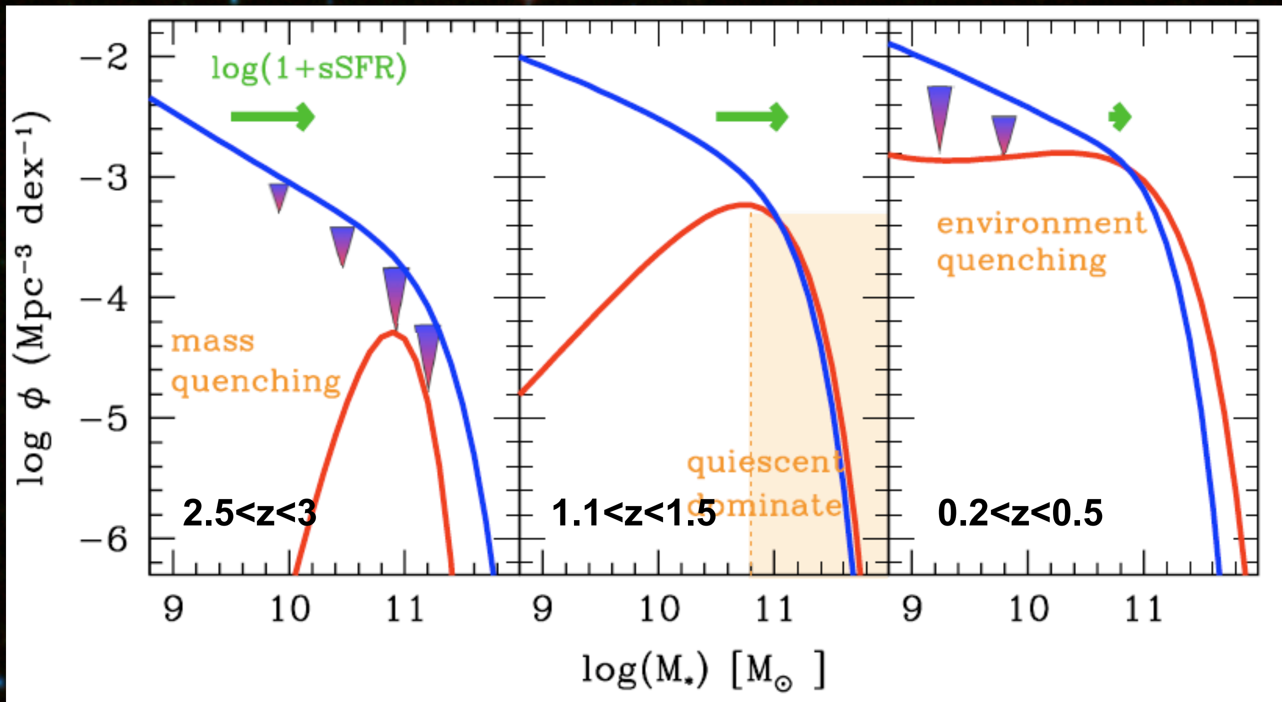
Prediction
by Weinmann

Less tension with specific DM accretion rate

still a difference of 0.3 dex at z~1

conclusions

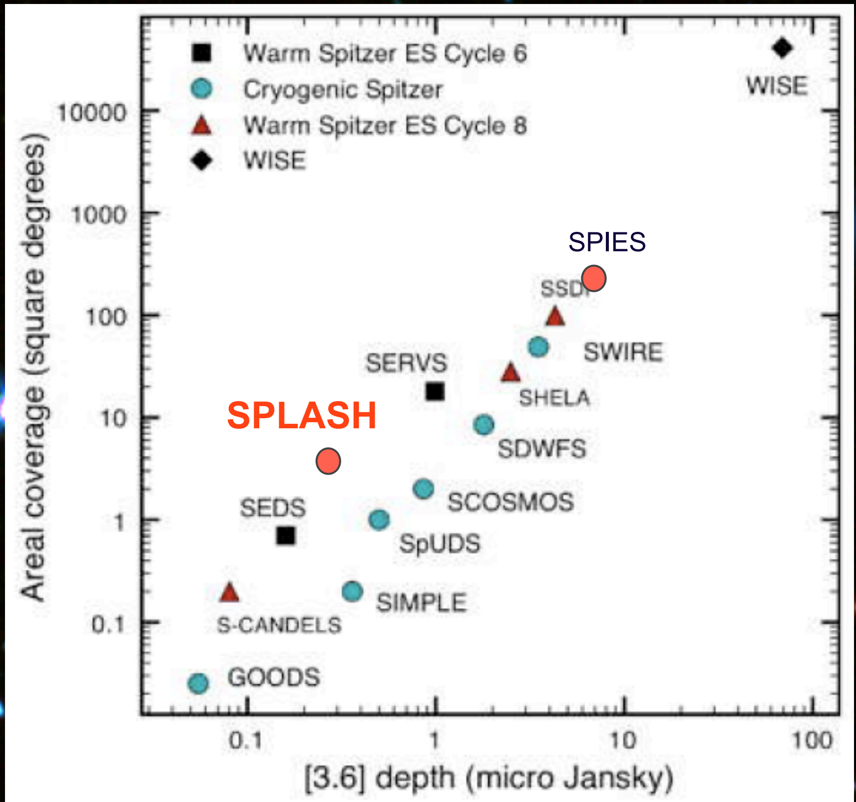
- consistent picture between recent SFRD compilation and mass density evolution out to z~4
  - ➢ still large uncertainties on the SFRD at z>1.5 ?
- quiescent MF and high mass end of the global MF
  - ➢ nicely described by the Peng et al. 2010 formalism

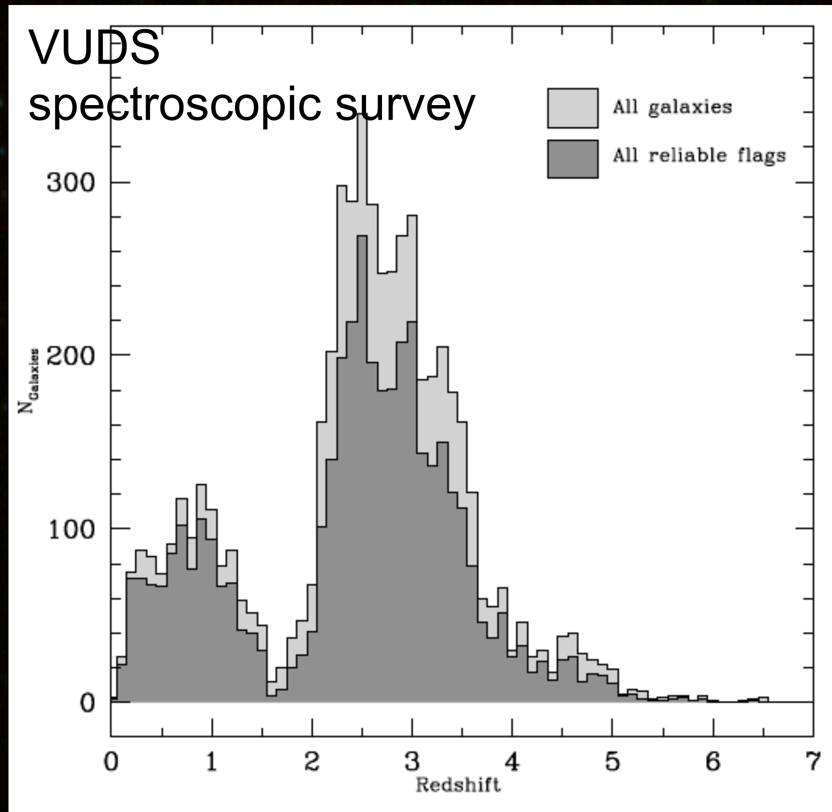


conclusions

- complementary view of the sSFR evolution at z>1 using the Mass Function ➢ continuous increase out to z<4
- SPLASH/IRAC survey at $m_{3.6\mu m}$~25.5 + VUDS

  ➢ extend at 4<z<6-7





conclusions

Public catalogue

230 000 galaxies selected at K<24 in UltraVISTA with 1-3% precise photo-z, associated with stellar masses

http://terapix.iap.fr/article.php?id_article=844

Cassata et al. 2011

Outlines

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V. Mass-SFR COSMOS

Mass-SFR relation

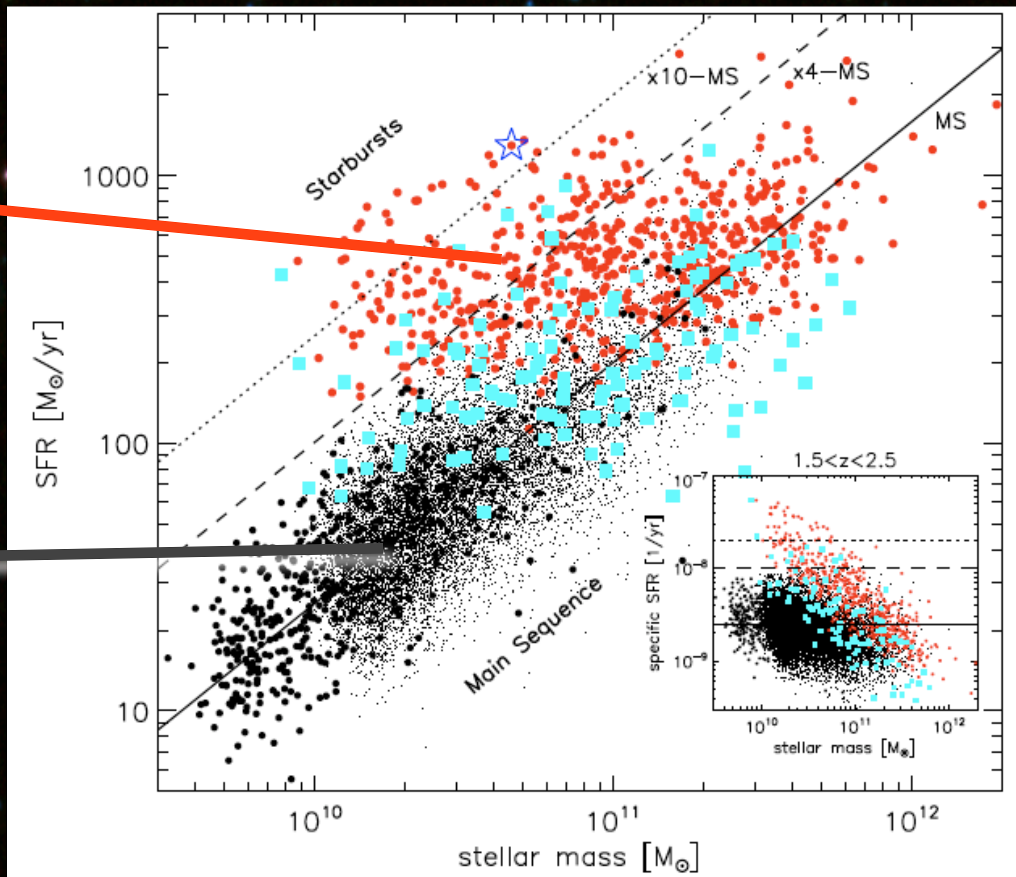
Tight relation seen in the local Universe for star-forming galaxies, established out to z~2

➢ smooth star formation history versus episodic

COSMOS, Herschel

GOODS, UV

Rodighiero 2010
at z~2

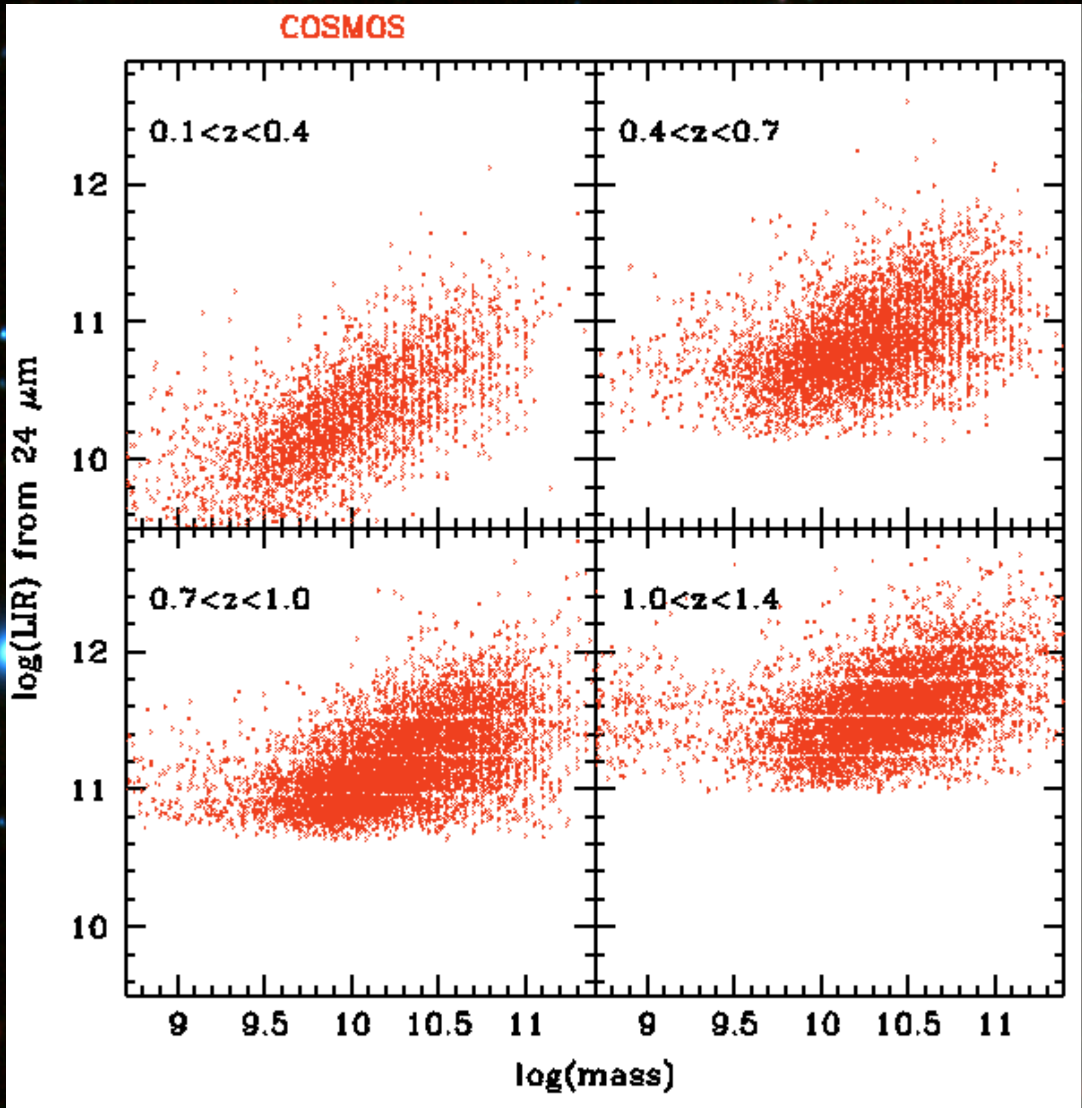


visible in the COSMOS field ?

SFR computed with the MIPS/24μm data

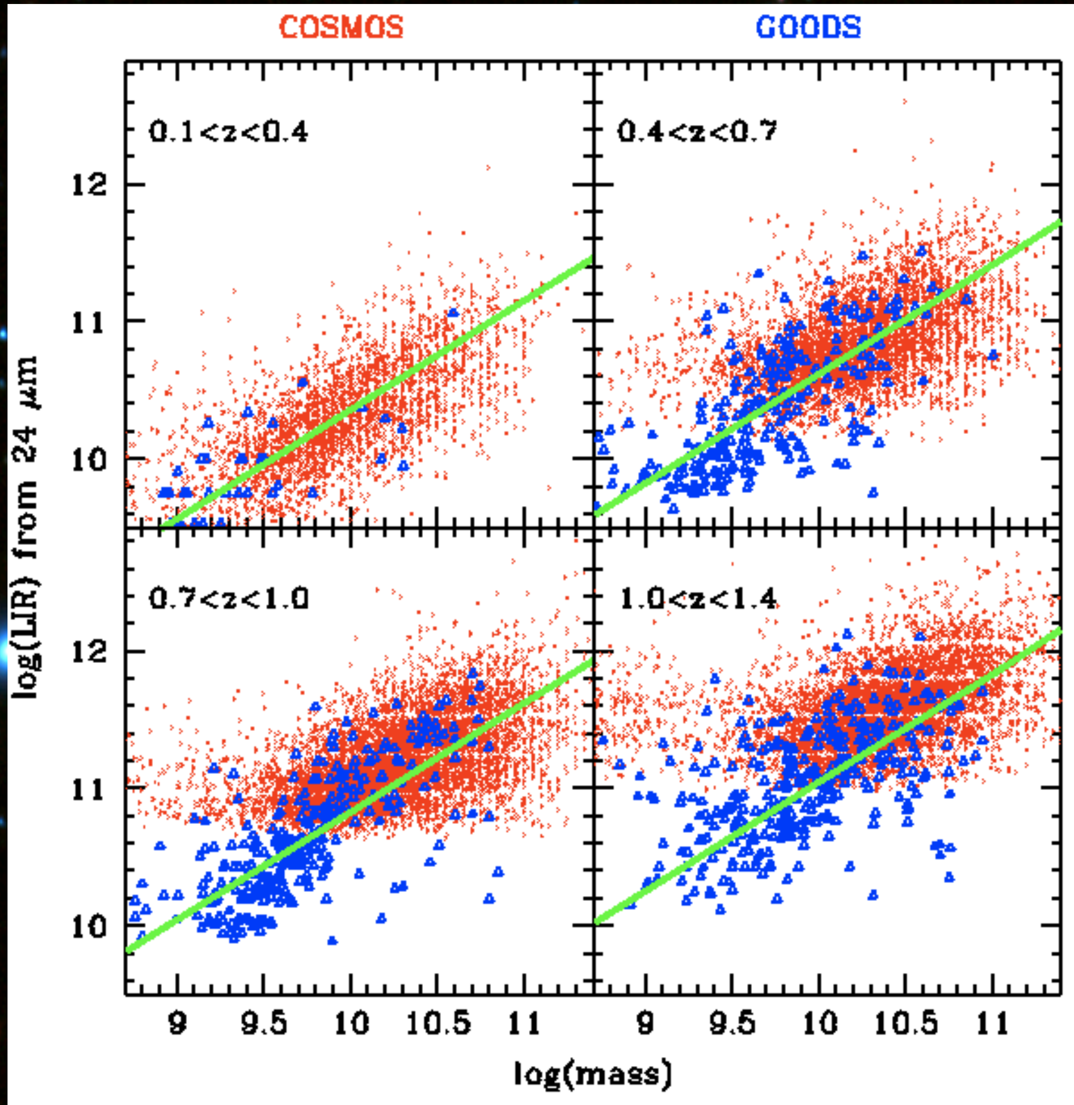
Advantage over Herschel
➢ reach lower SFR values

Not a clear mass-SFR relation



visible in the COSMOS field ?

Mass-SFR relation clearly visible in the GOODS field

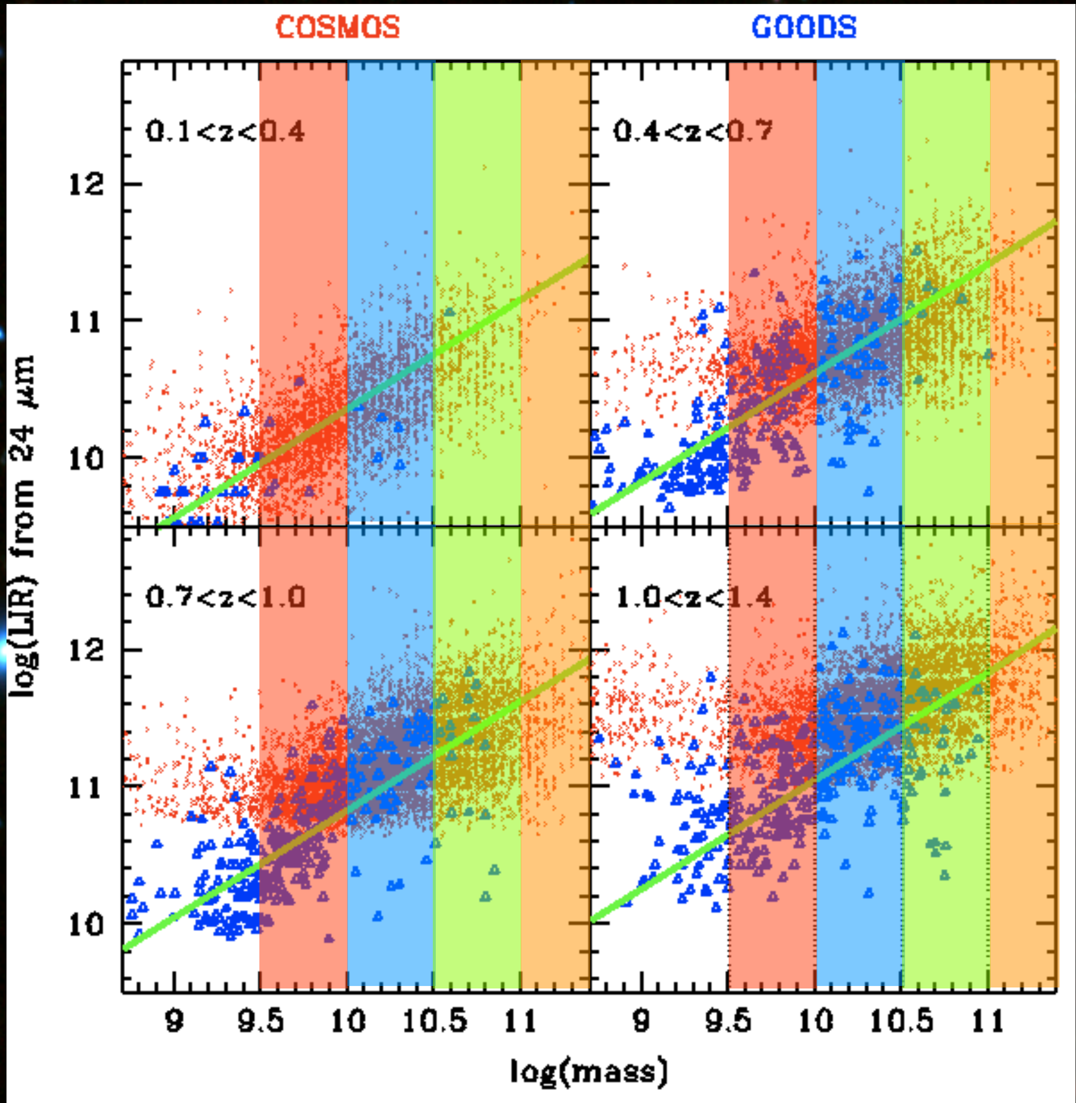


visible in the COSMOS field ?

Mass-SFR relation clearly visible in the GOODS field

Selection effect

➢ compute the density of sources per stellar mass bin, combining both fields



SFR distribution per stellar mass bin

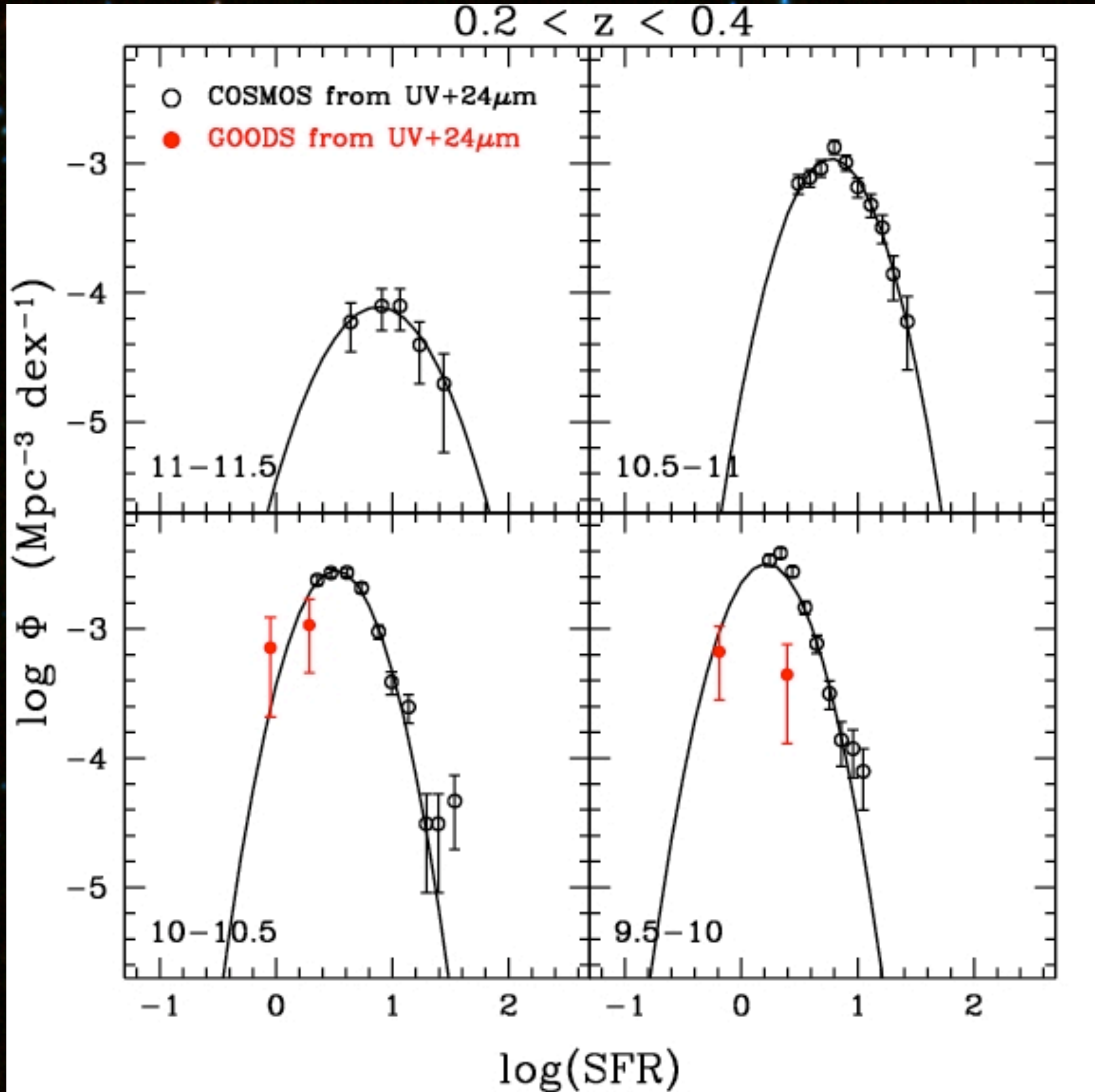
Peak changes with the stellar mass, as expected from the mass-SFR relation

Fit with a gaussian

➢ σ~0.3-0.35 dex

Could be fitted with a Schechter

➢ little constraint on the low SFR slope



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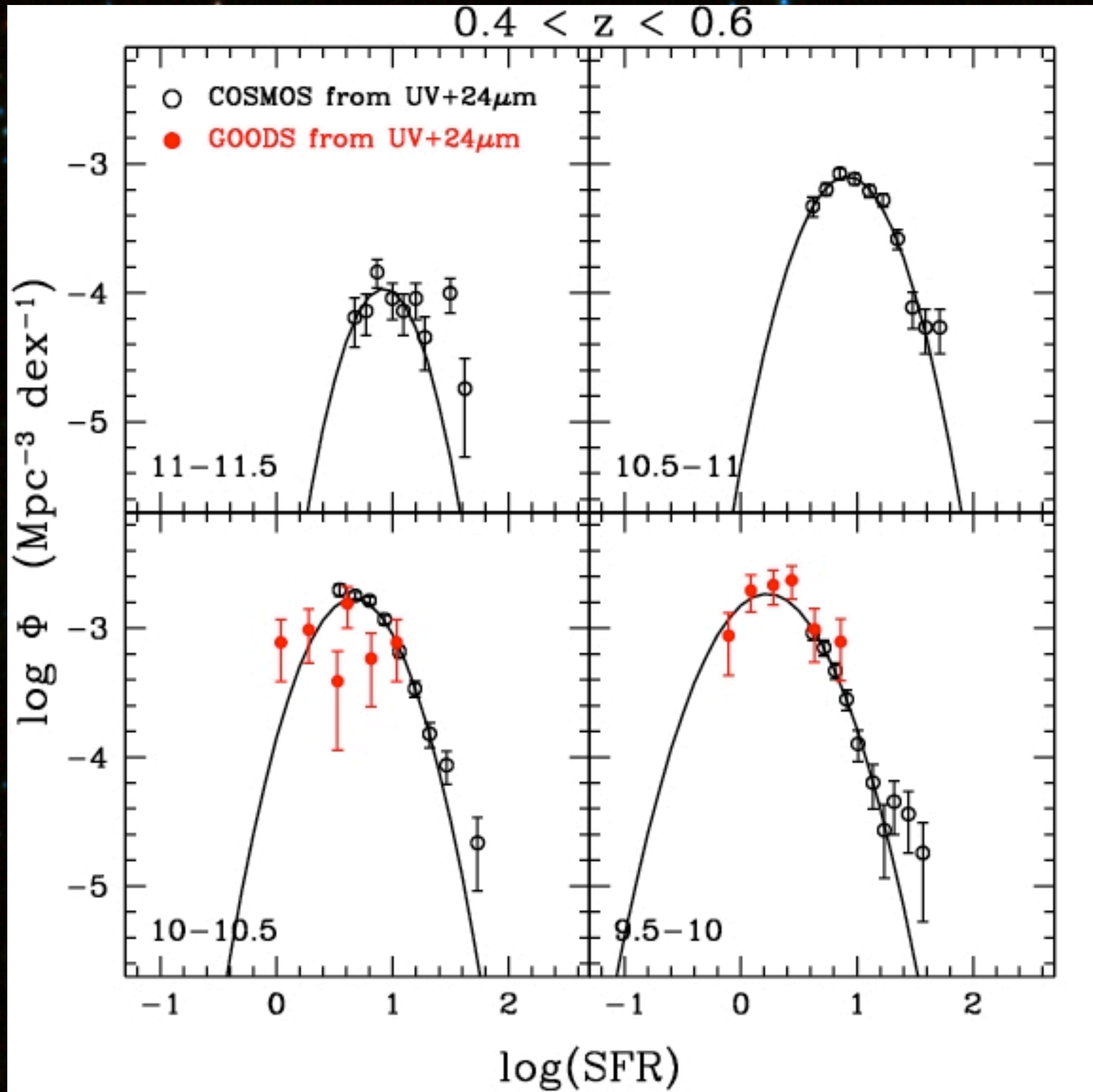

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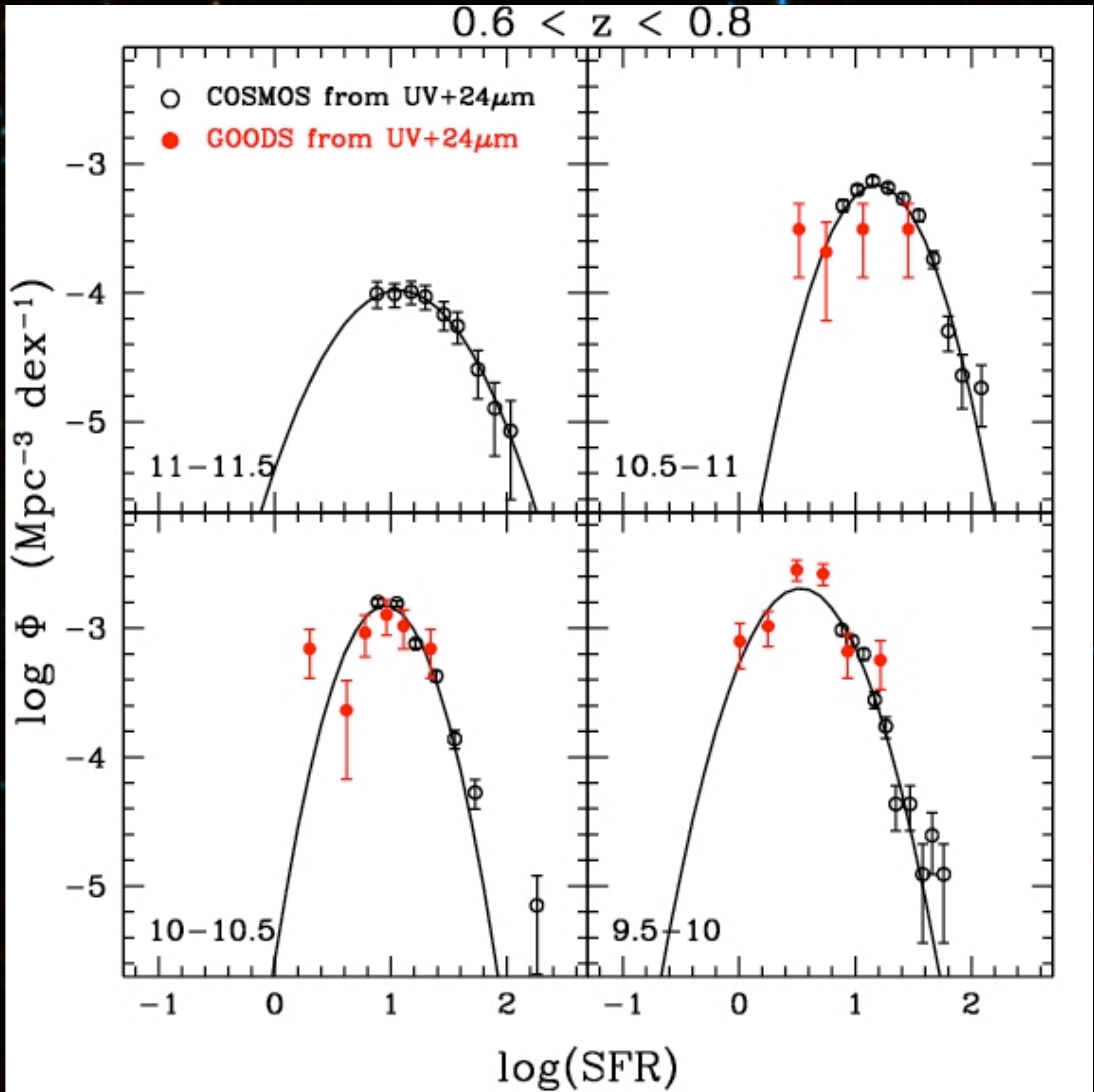

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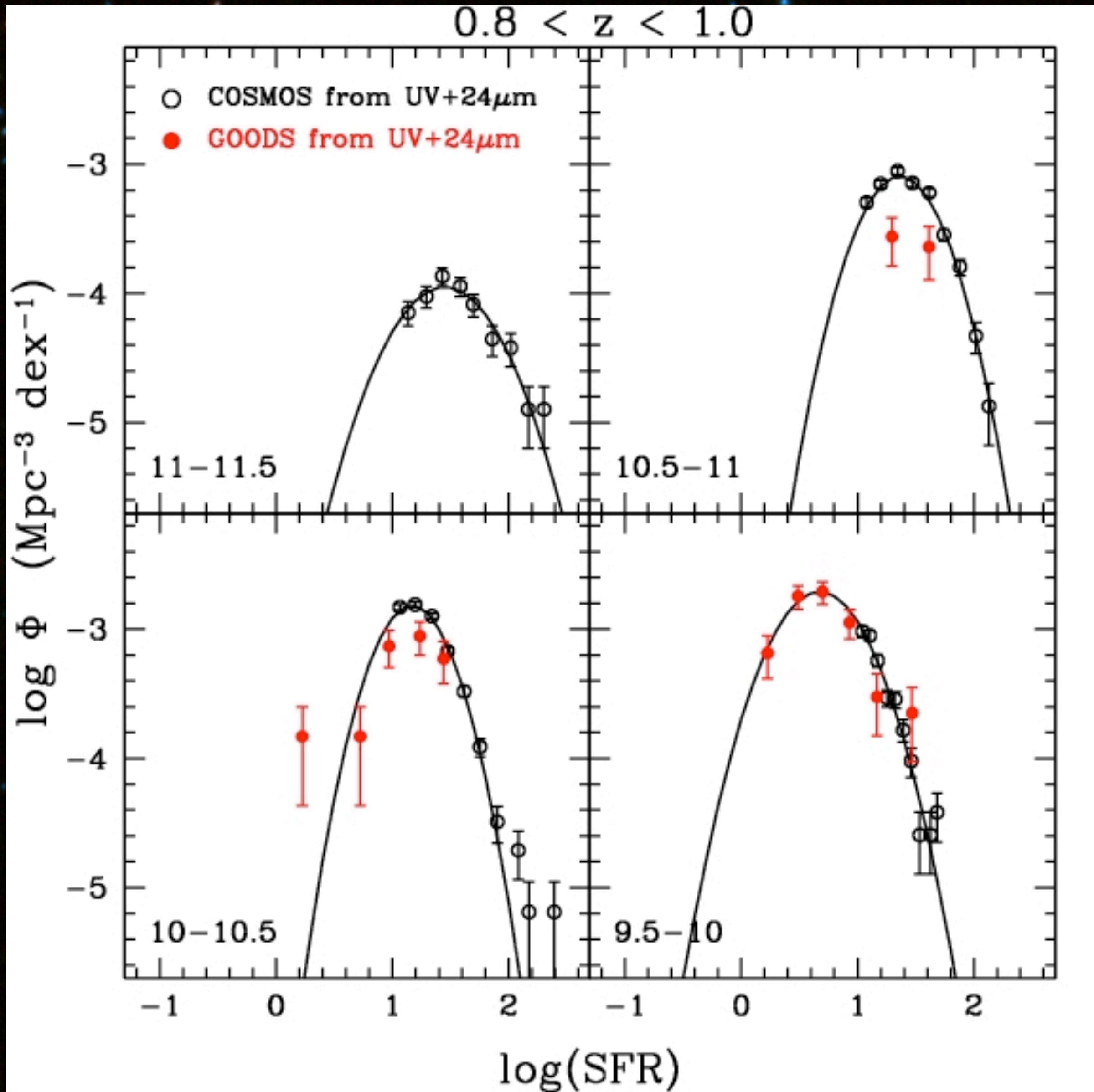

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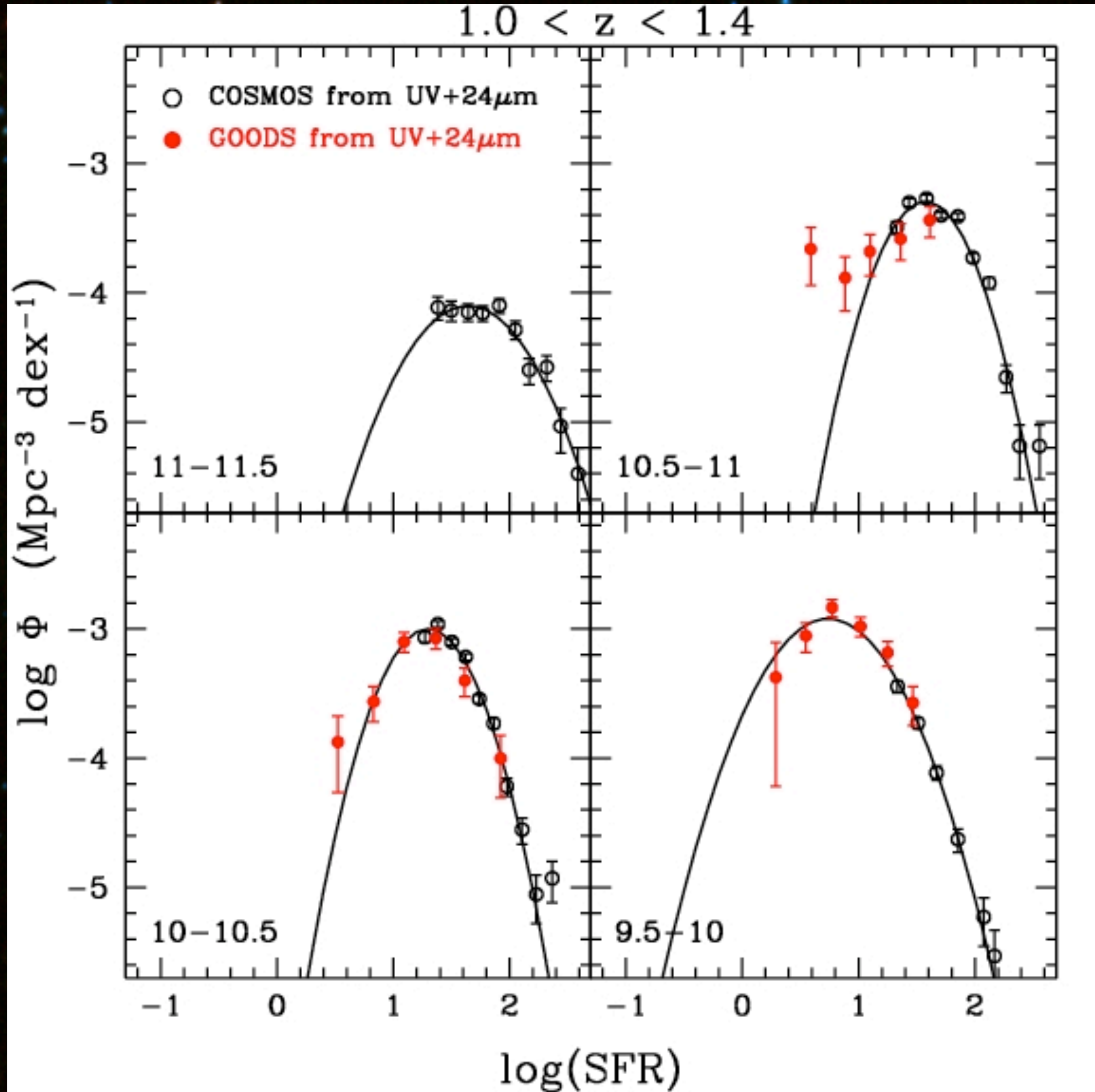
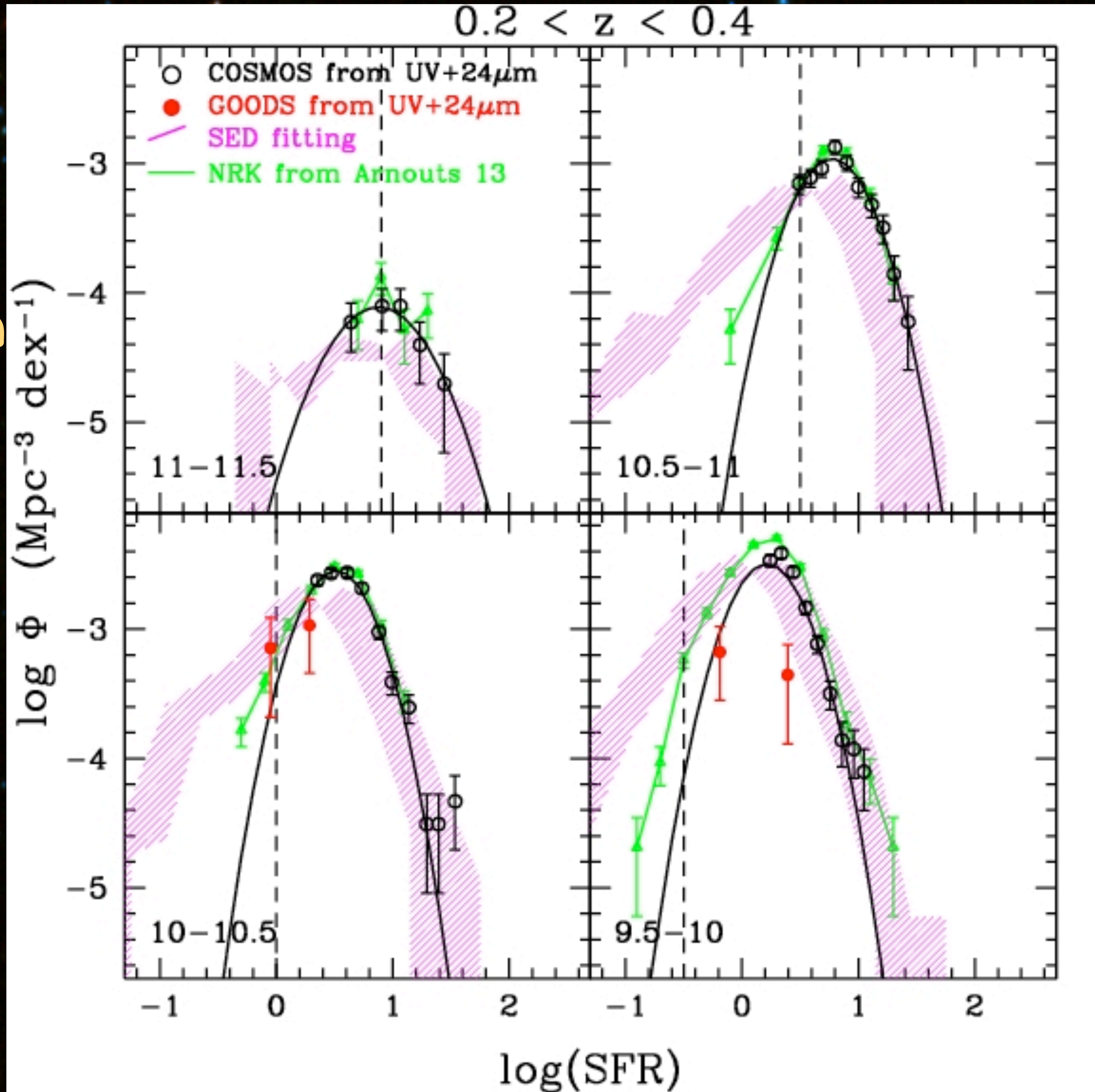


SFR distribution per stellar mass bin

Combine several probes of the SFR

Excellent agreement with the new NRK SFR estimator by Arnouts 13

SFR estimate based only on M(NUV), M(R), M(K)



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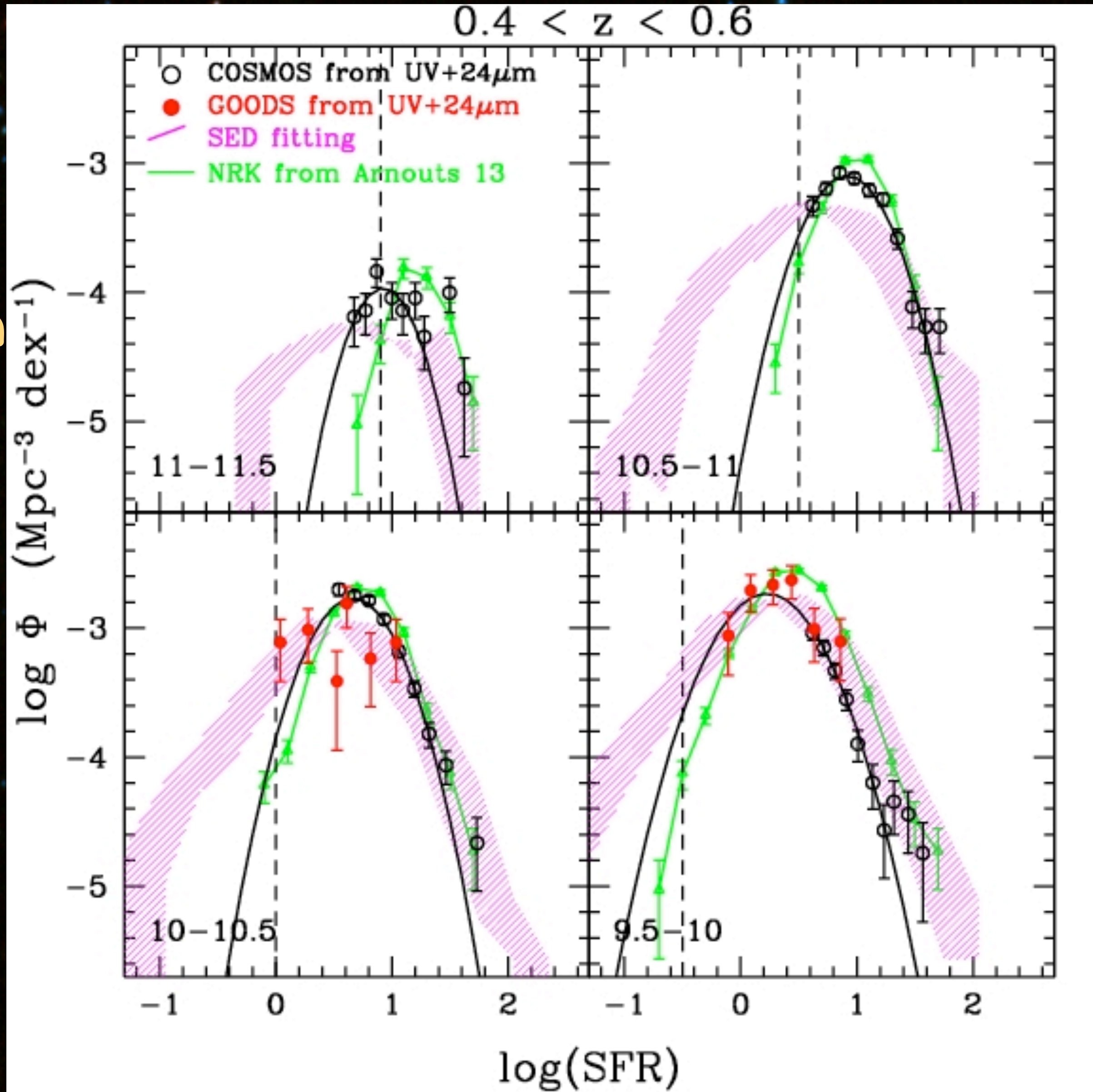

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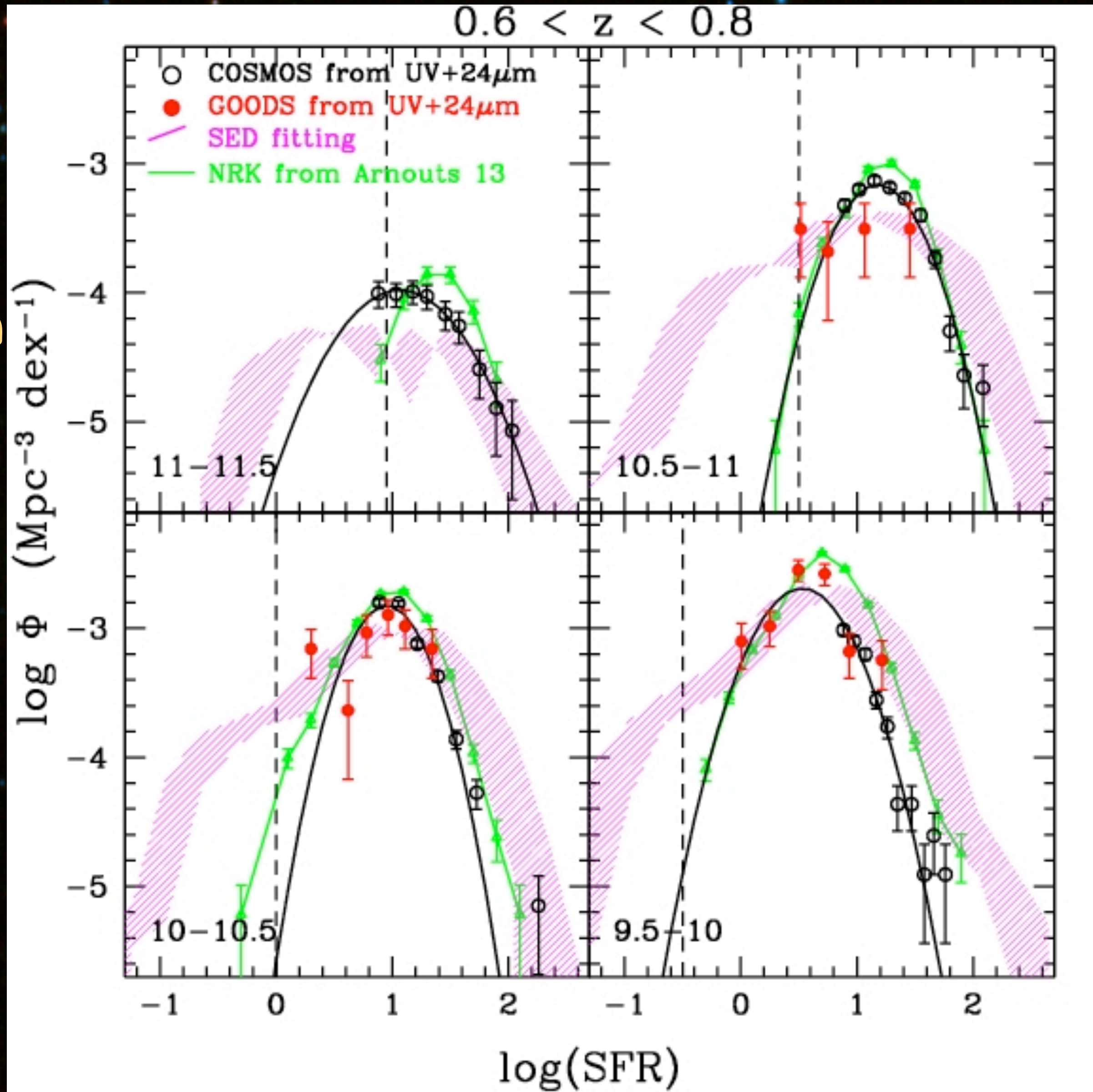

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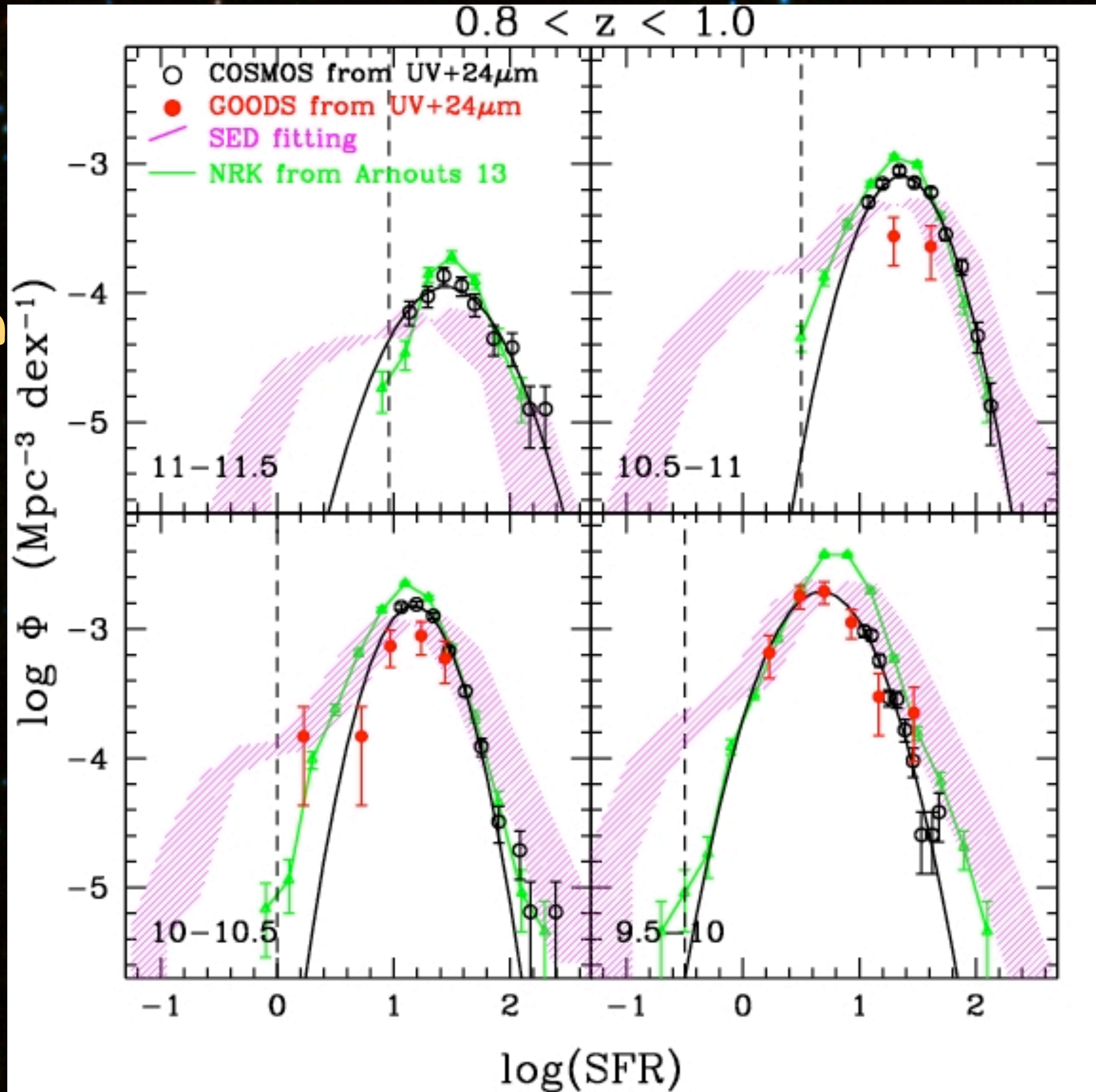

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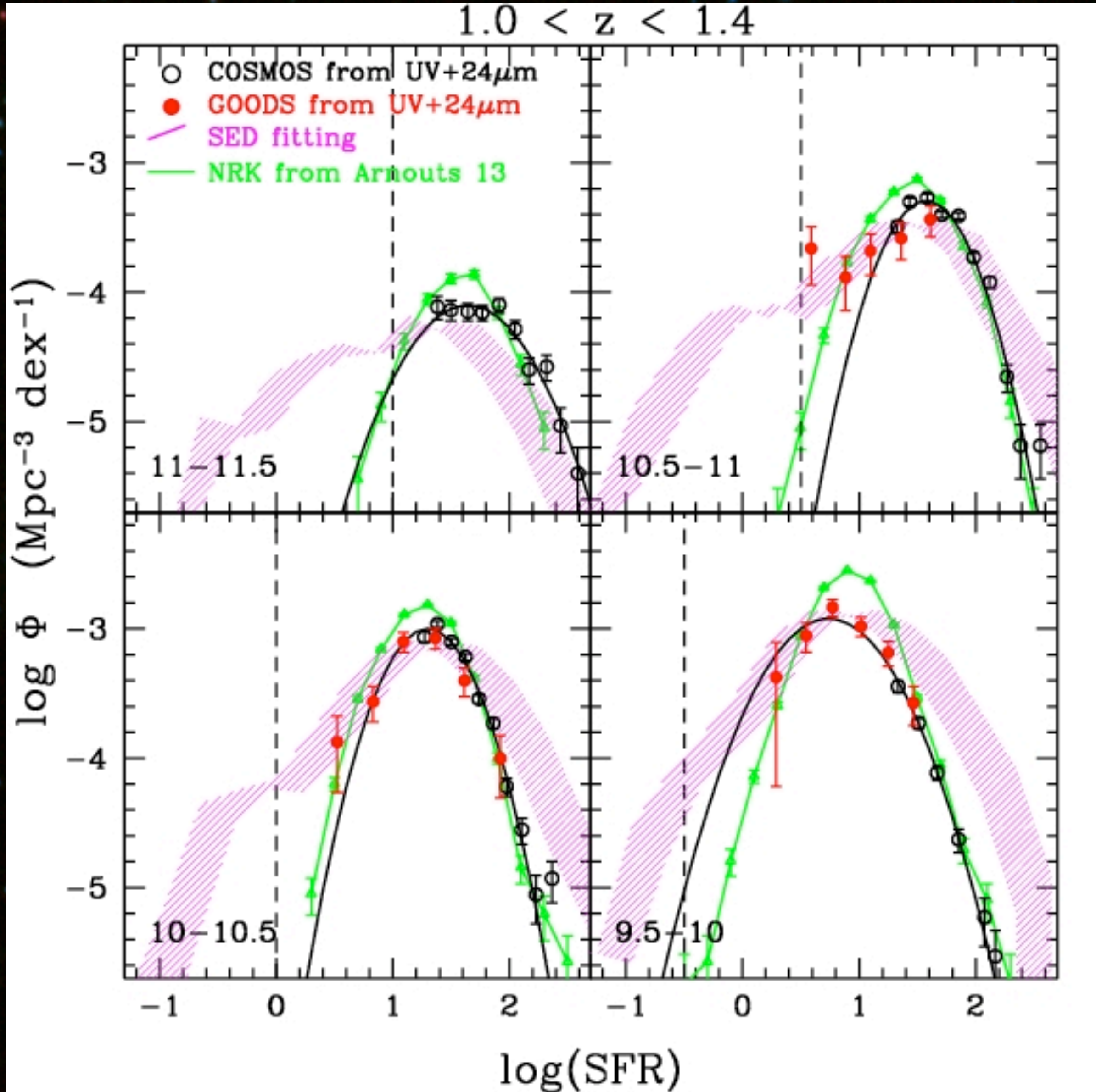


Evolution of the specific SFR

SFR/Mass ➢ specific SFR

- increases with redshift
- decreases with mass

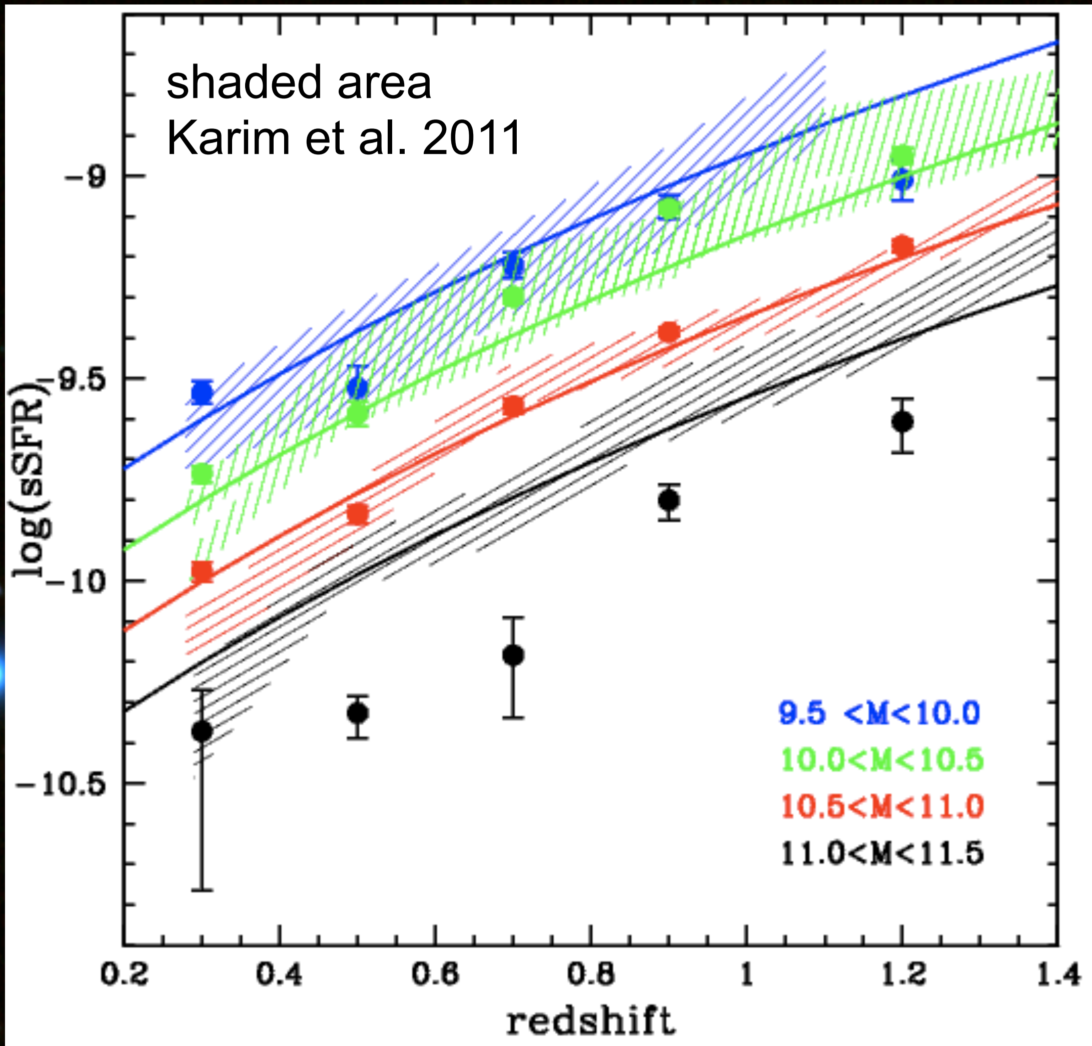
Parametrisation by

Karim et al. 2011,

using COSMOS radio data

$$\mathrm{SSFR}(\mathrm{M}_*, \mathrm{z}) \propto \mathrm{f}(\mathrm{M}_*) \times \mathrm{g}(\mathrm{z}) = \mathrm{M}_*^{\beta} \times (1+\mathrm{z})^{\mathrm{n}}$$

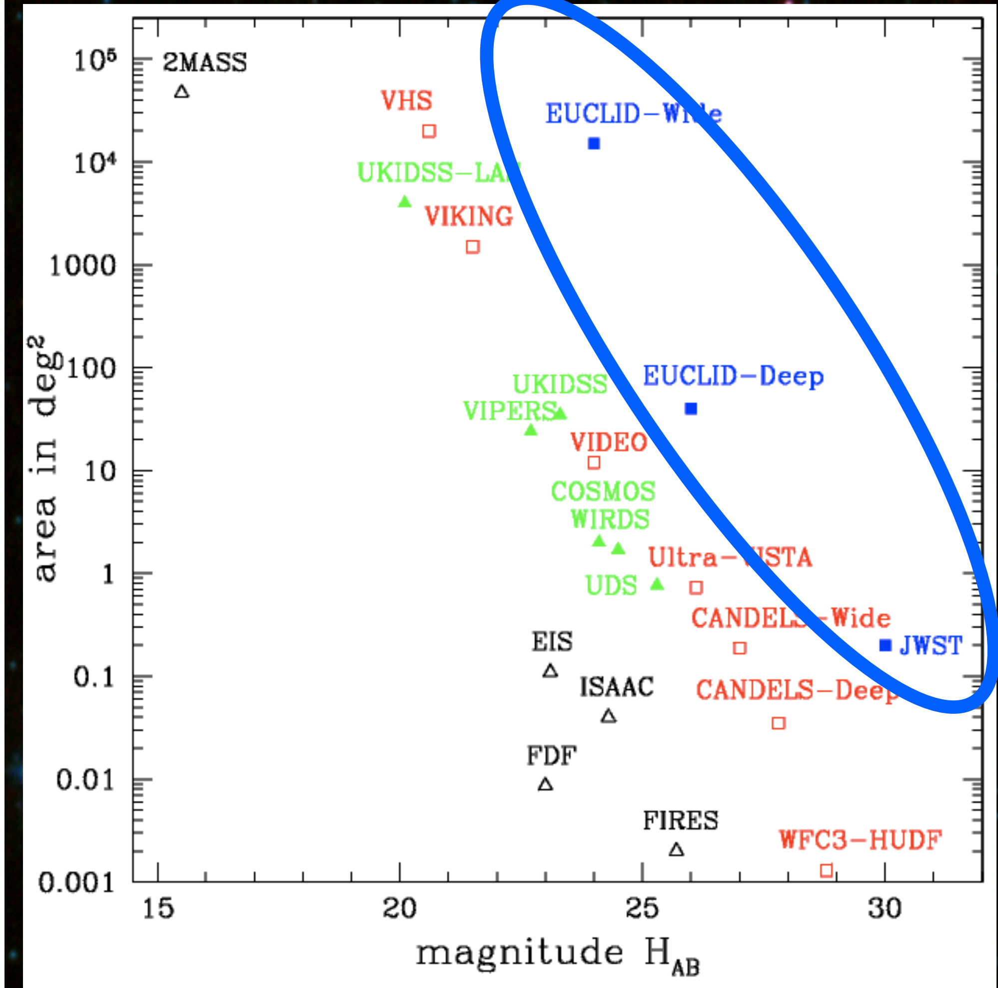
$$\beta_{\mathrm{SFG}} \approx -0.4 \text{ and } n_{\mathrm{SFG}} \approx 3.5$$



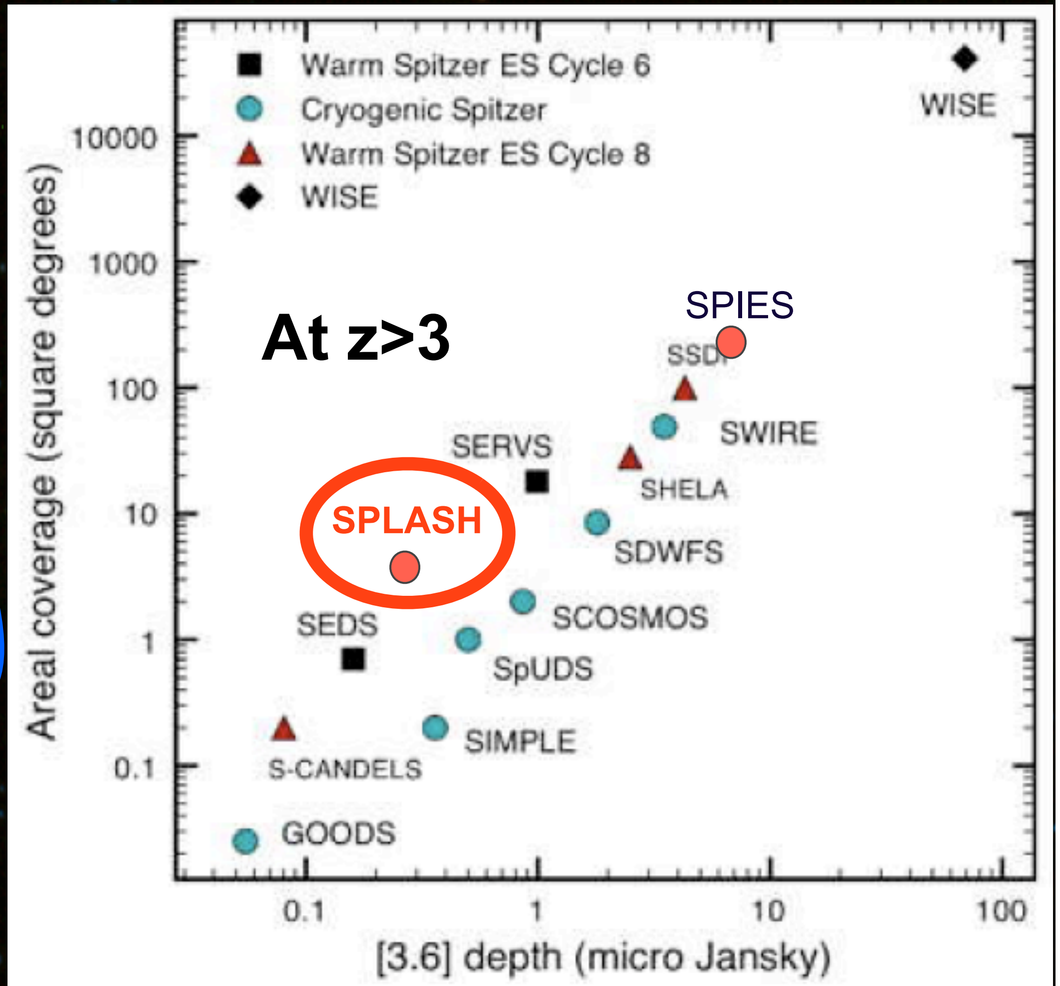
Excellent agreement

except for the most massive galaxies $>10^{11}M_{\odot}$

Next

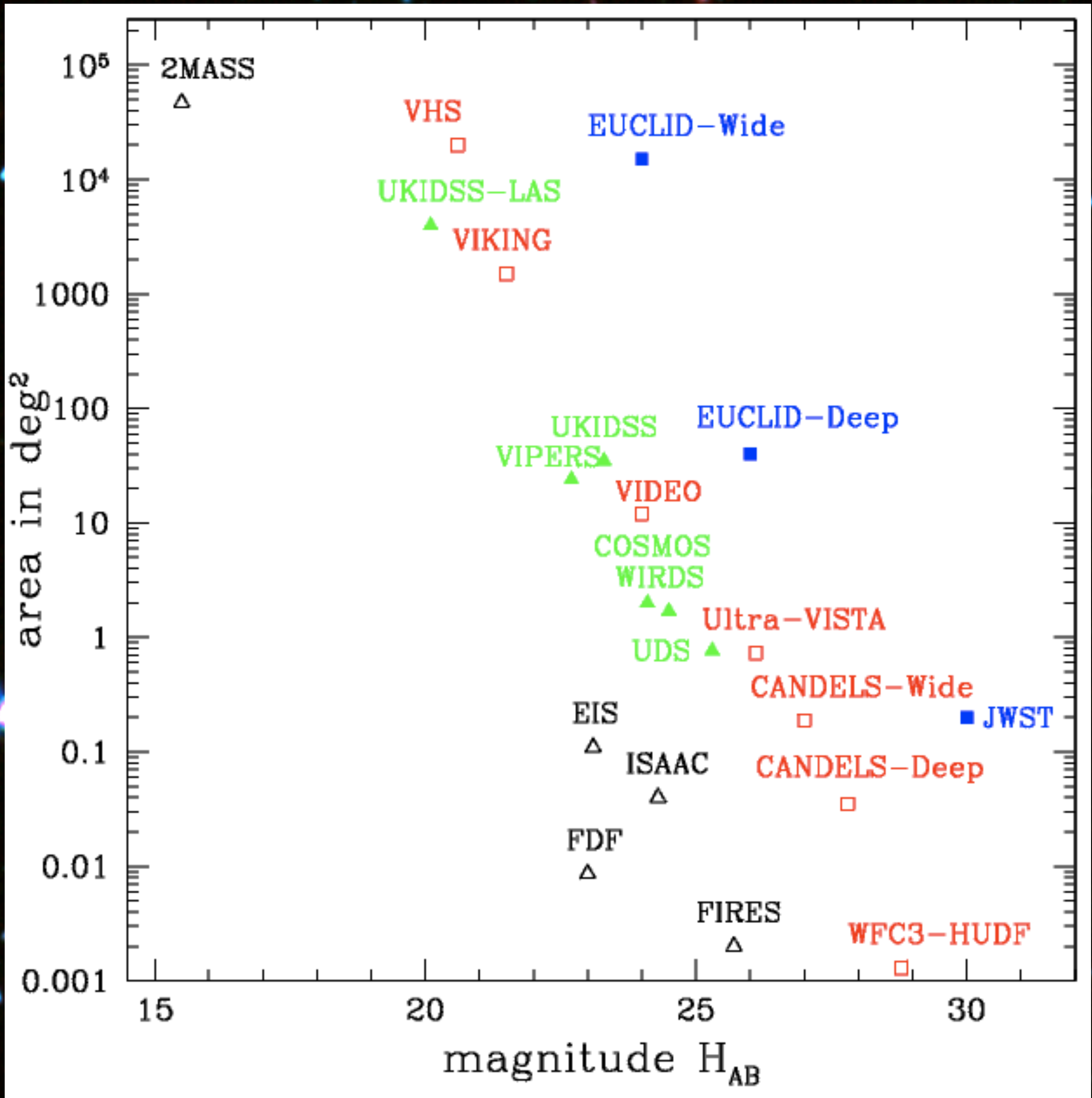


2MASS
VHS
EUCLID−Wide
UKIDSS−LAS
VIKING
UKIDSS
VIPERS
EUCLID−Deep
VIDEO
COSMOS
WIRDS
Ultra−VISTA
UDS
CANDELS−Wide
JWST
EIS
ISAAC
CANDELS−Deep
FDF
FIRES
WFC3−HUDF
area in deg²
magnitude H_AB



Warm Spitzer ES Cycle 6
Cryogenic Spitzer
Warm Spitzer ES Cycle 8
WISE
At z>3
SPIES
SSDF
SWIRE
SERVS
SHELA
SPLASH
SDWFS
SCOSMOS
SEDS
SpUDS
S-CANDELS
SIMPLE
GOODS
Areal coverage (square degrees)
[3.6] depth (micro Jansky)

Near-infrared surveys for robust stellar masses at z<3



WIRCAM, WFCAM

done in the last 5 years, almost done

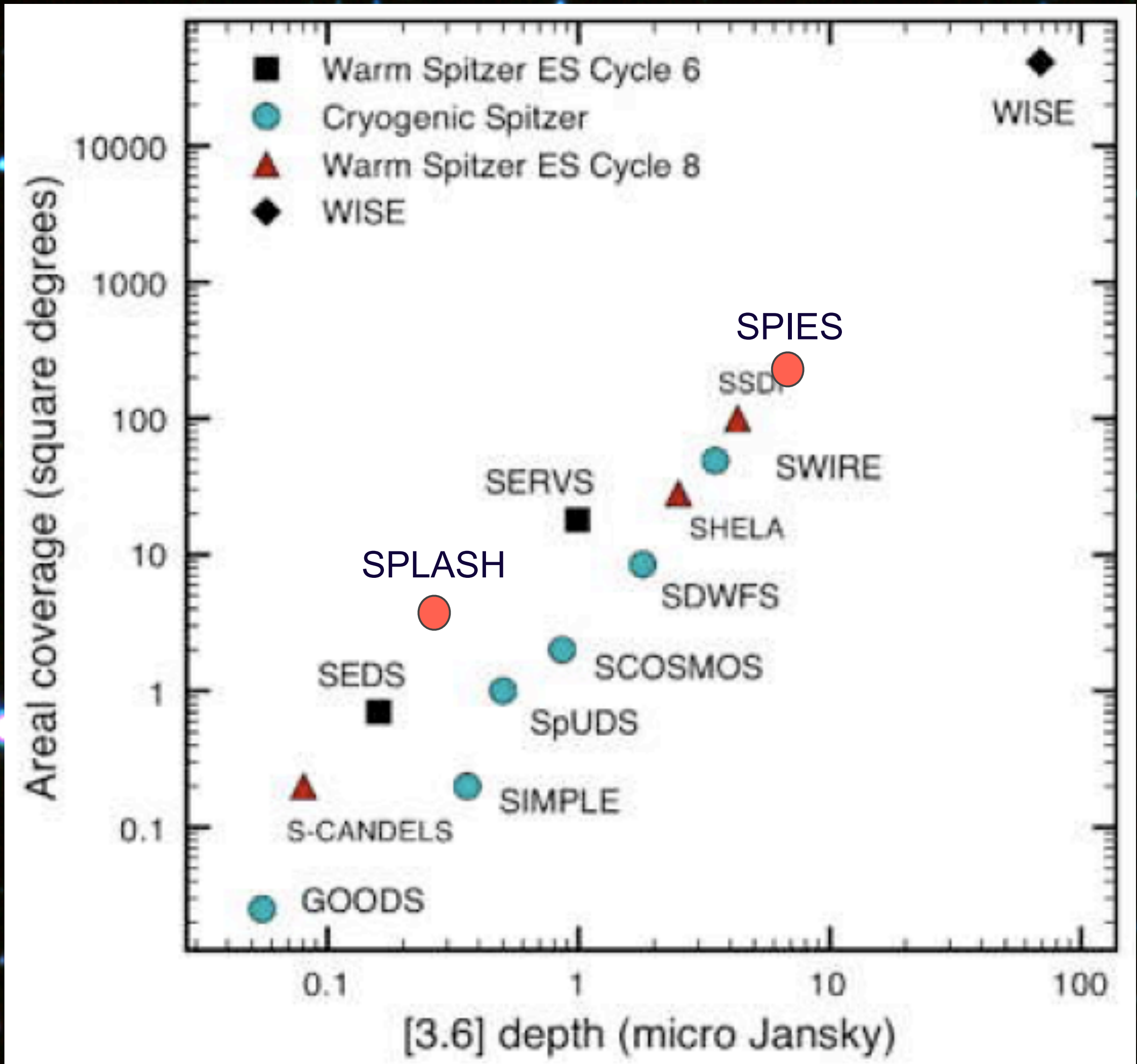
VISTA, WFC3

on-going, next 5 years

EUCLID, JWST

in 10 years

IRAC/Spitzer surveys for robust stellar masses at z>3



IRAC is the only instrument to probe the rest-frame optical at z>3

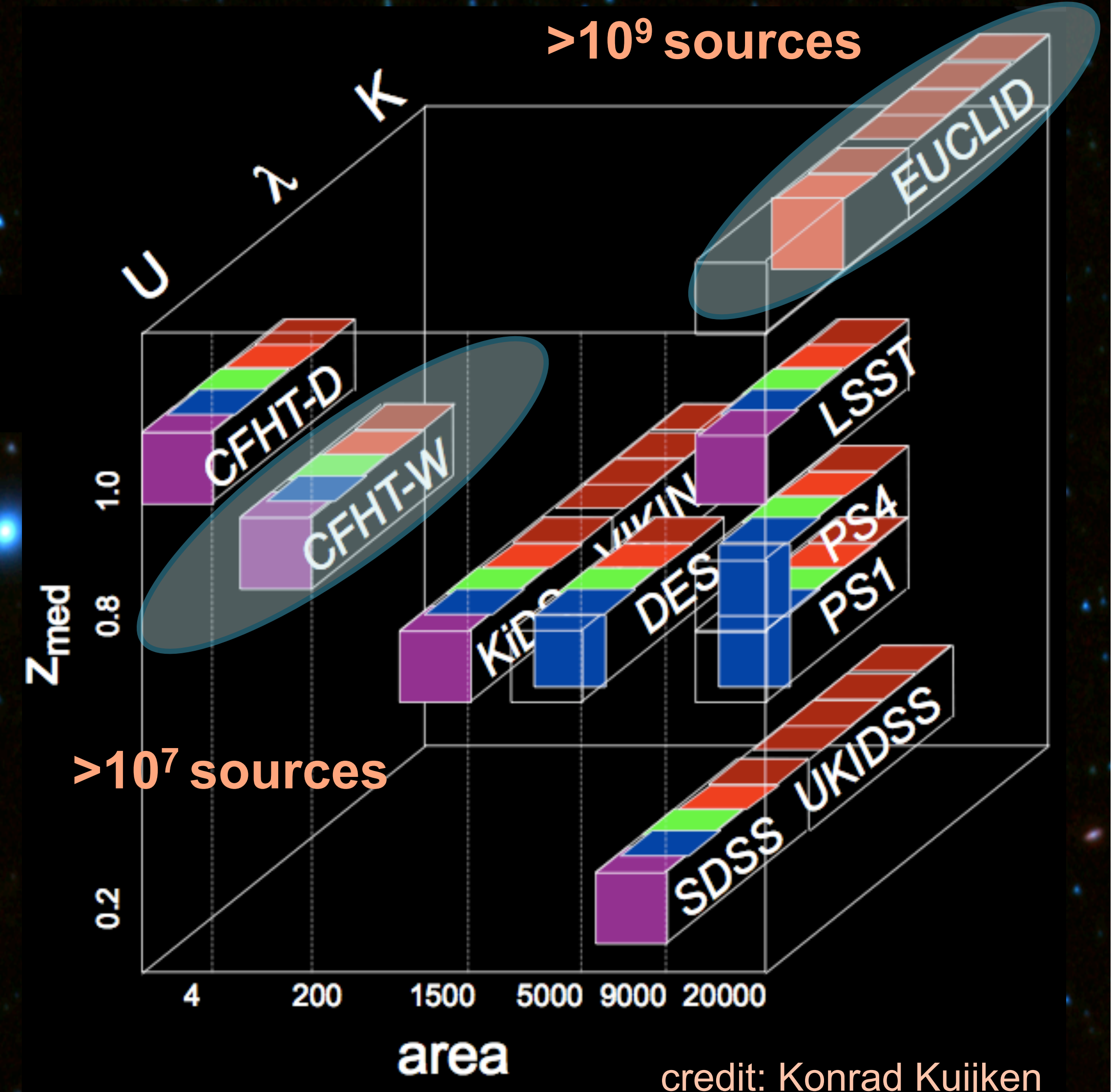
done in the last 5 years, almost done

on-going, next 5 years

conclusions

Numerous deep optical/NIR surveys in the next decade for weak lensing

➢ rely on photo-z



credit: Konrad Kuijken

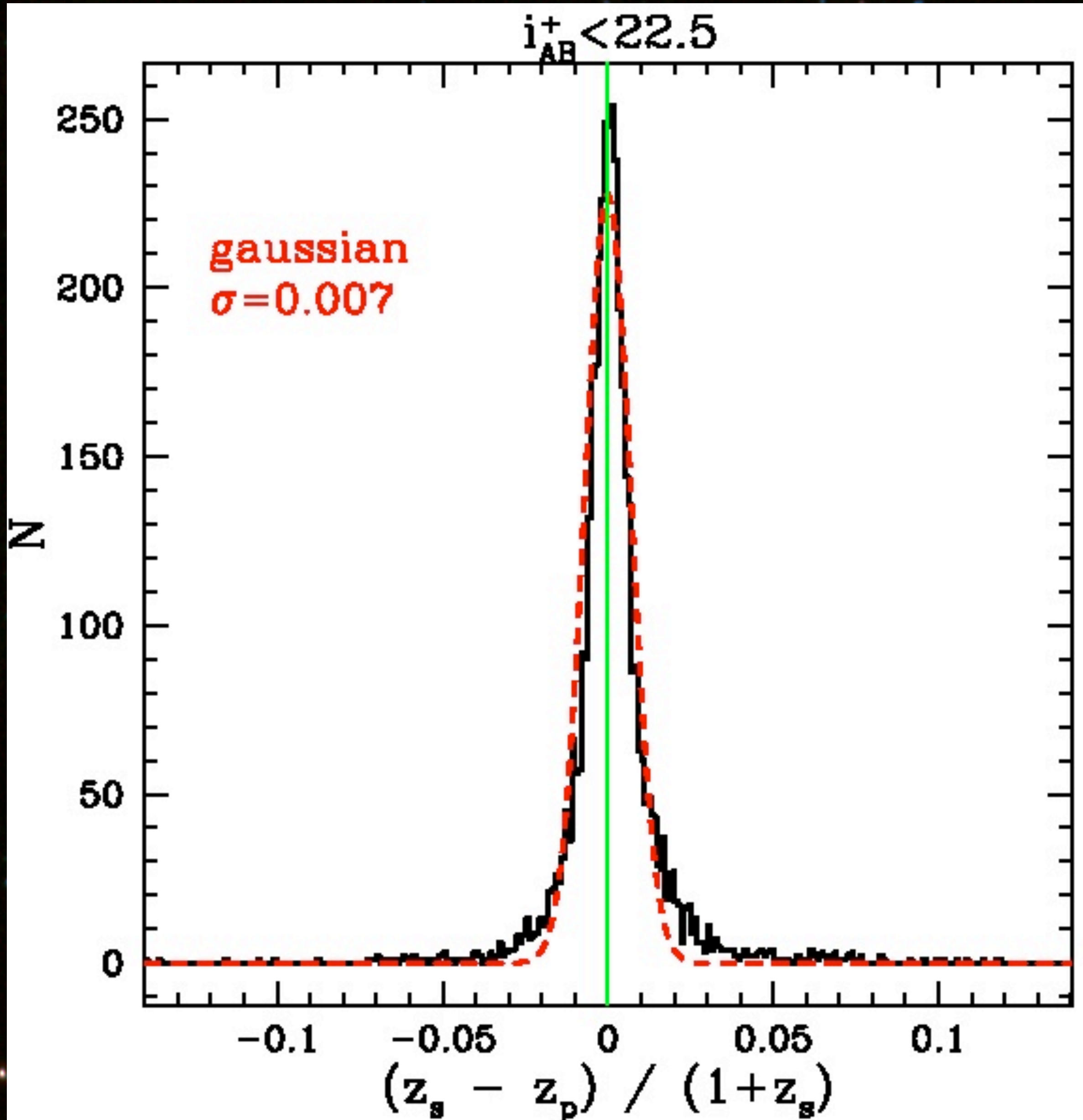
Importance of the medium bands

With

medium bands

$\sigma_{dz/(1+z)} < 1\%$

at i'<22.5



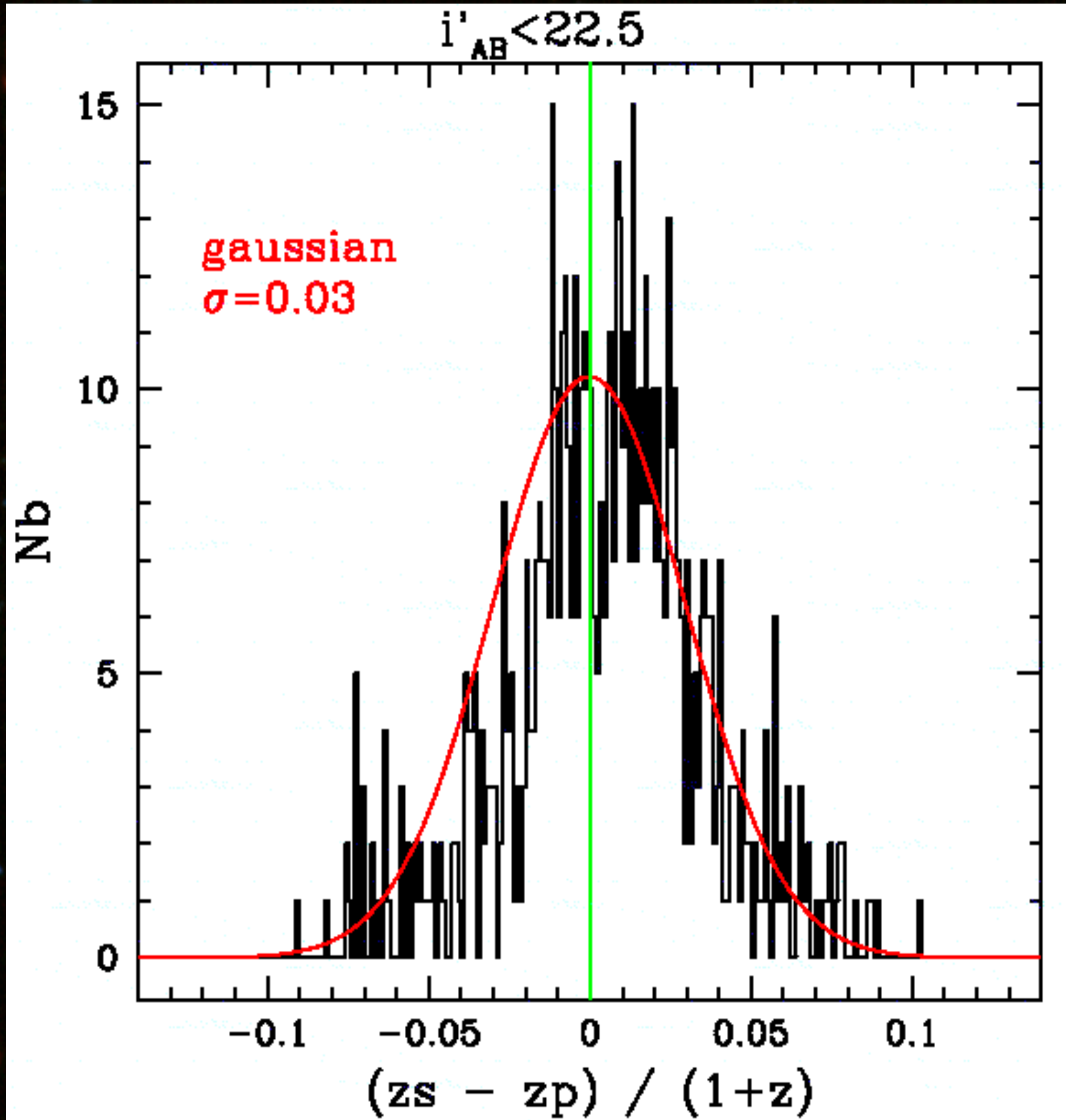
Importance of the medium bands

Without

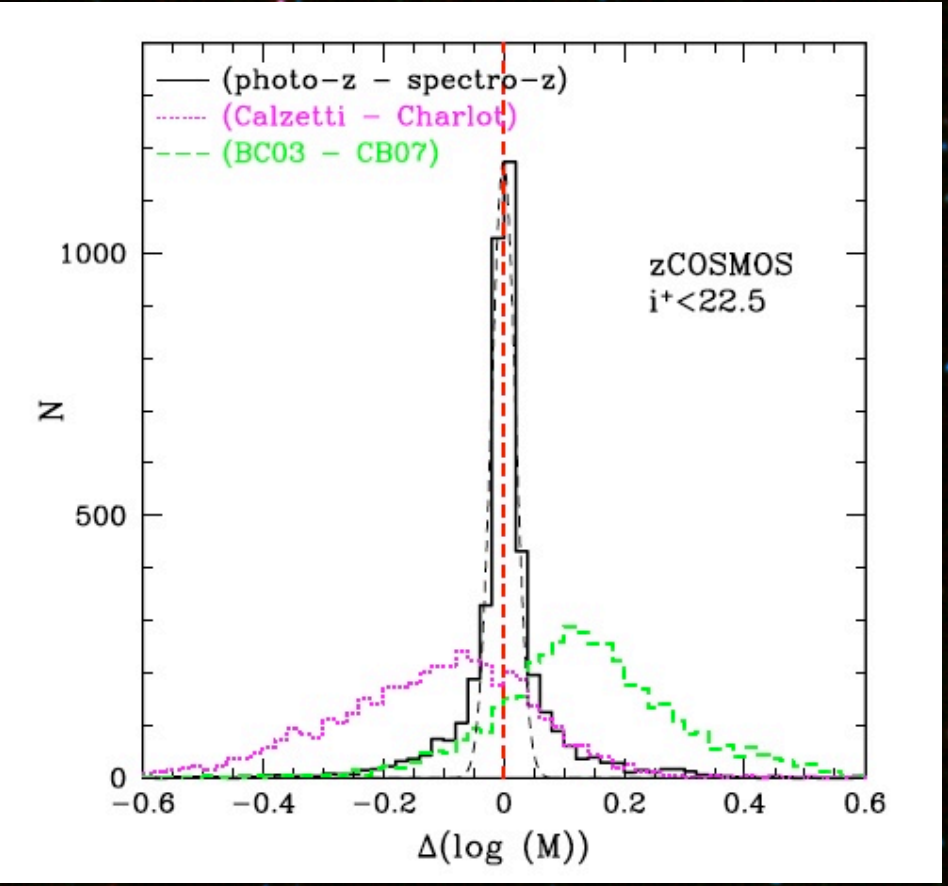
medium bands

$\sigma_{dz/(1+z)}$ ~ 3%

at i'<22.5



impact of the model in the stellar mass estimate

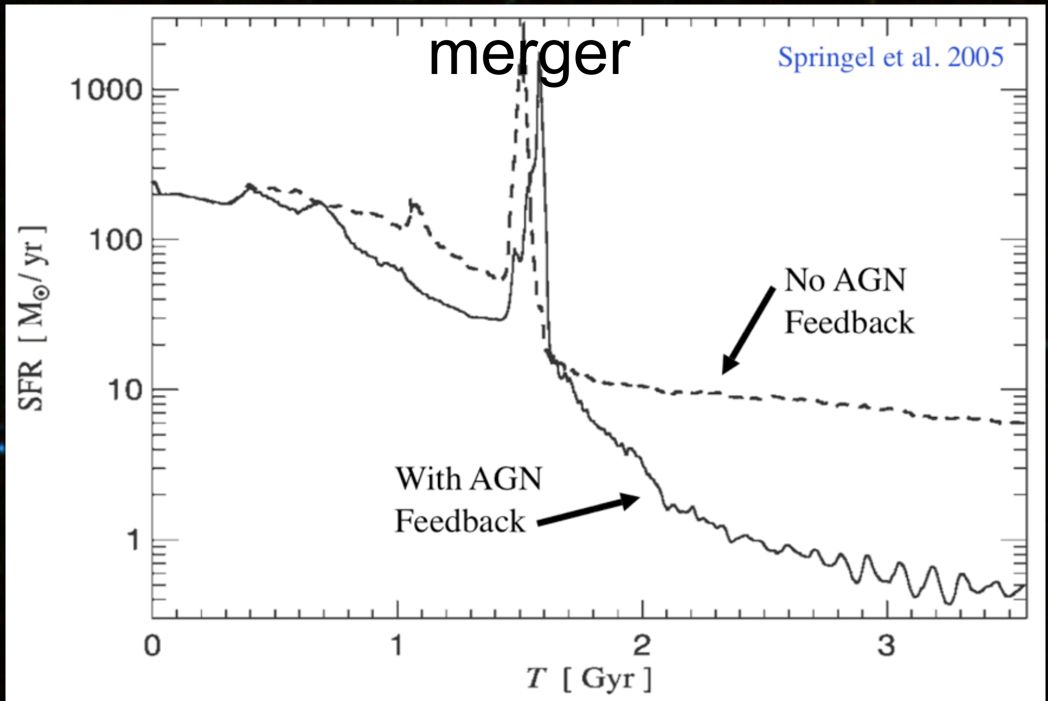


Systematic uncertainties dominated by the SED library with 1% accurate photo-z and deep NIR

AGN feedback

AGN power can switch off star-formation into the most massive galaxies

➢ Introduced in semi-analytical models to limit the growth of the most massive galaxies

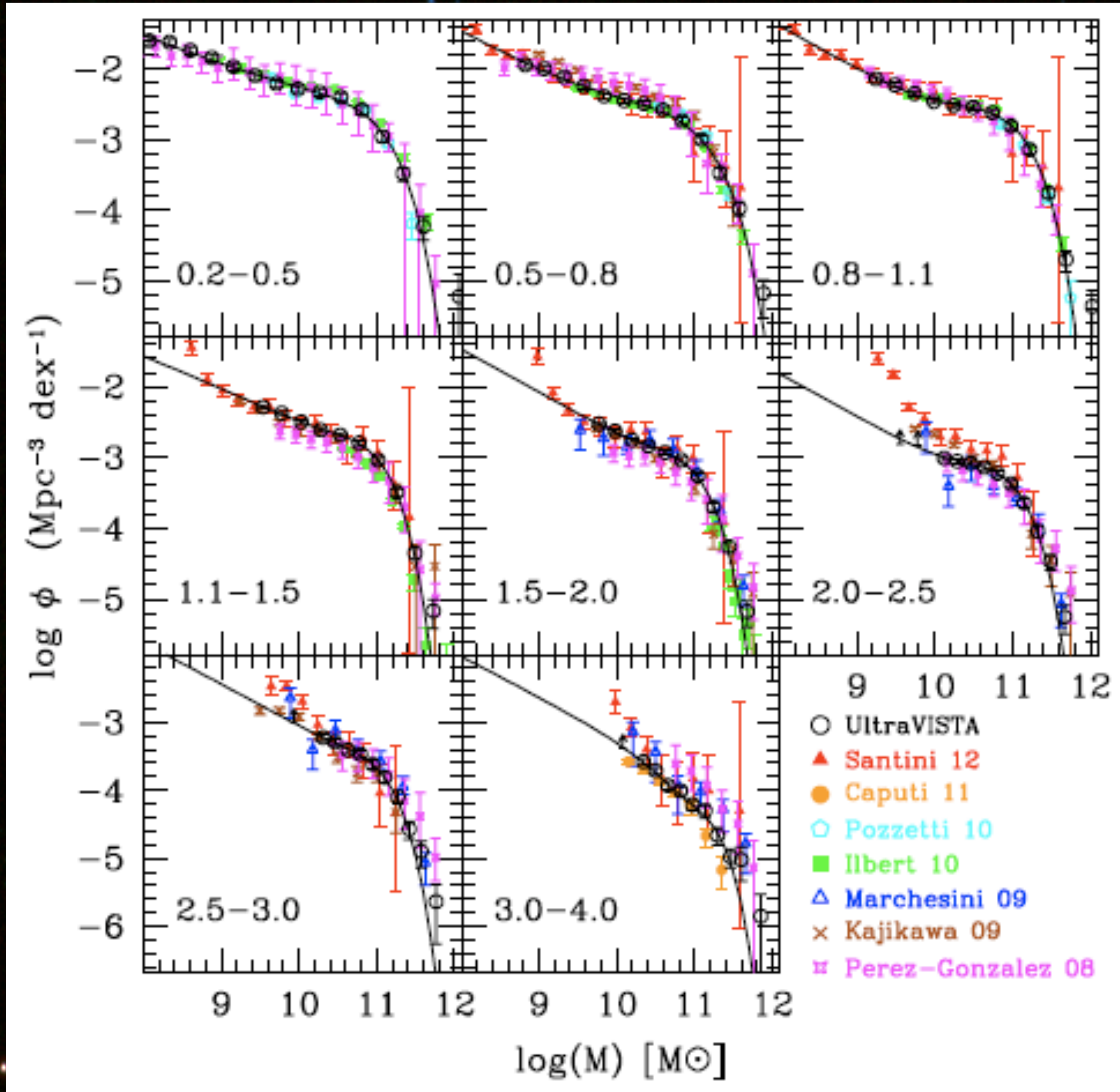


Global stellar mass function

Stellar masses from template-fitting

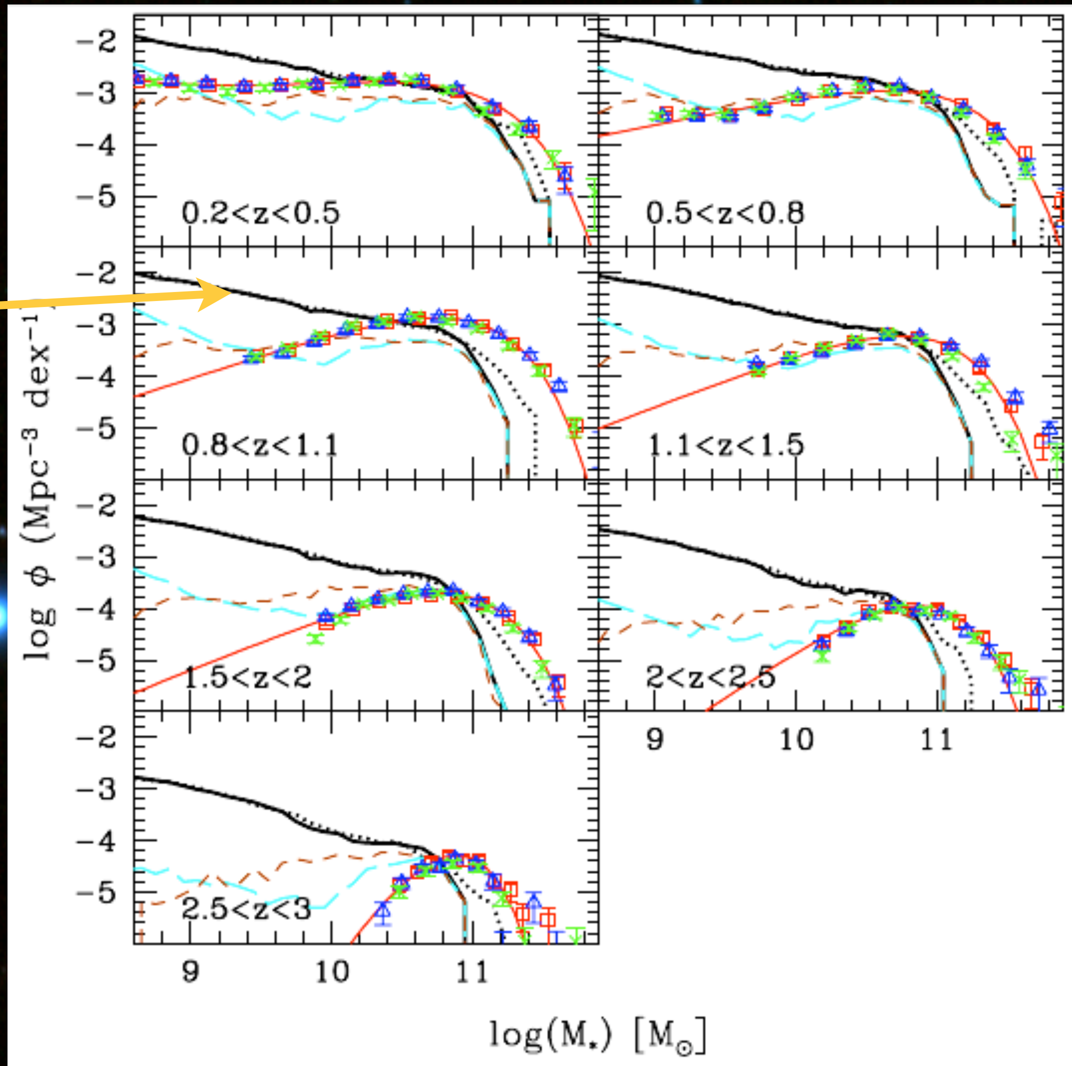
Fit the Vmax with a double-Schechter function

Take into account the Eddington bias



comparison with semi-analytical models for quiescent galaxies

x10-100 too many low mass quiescent galaxies in the model



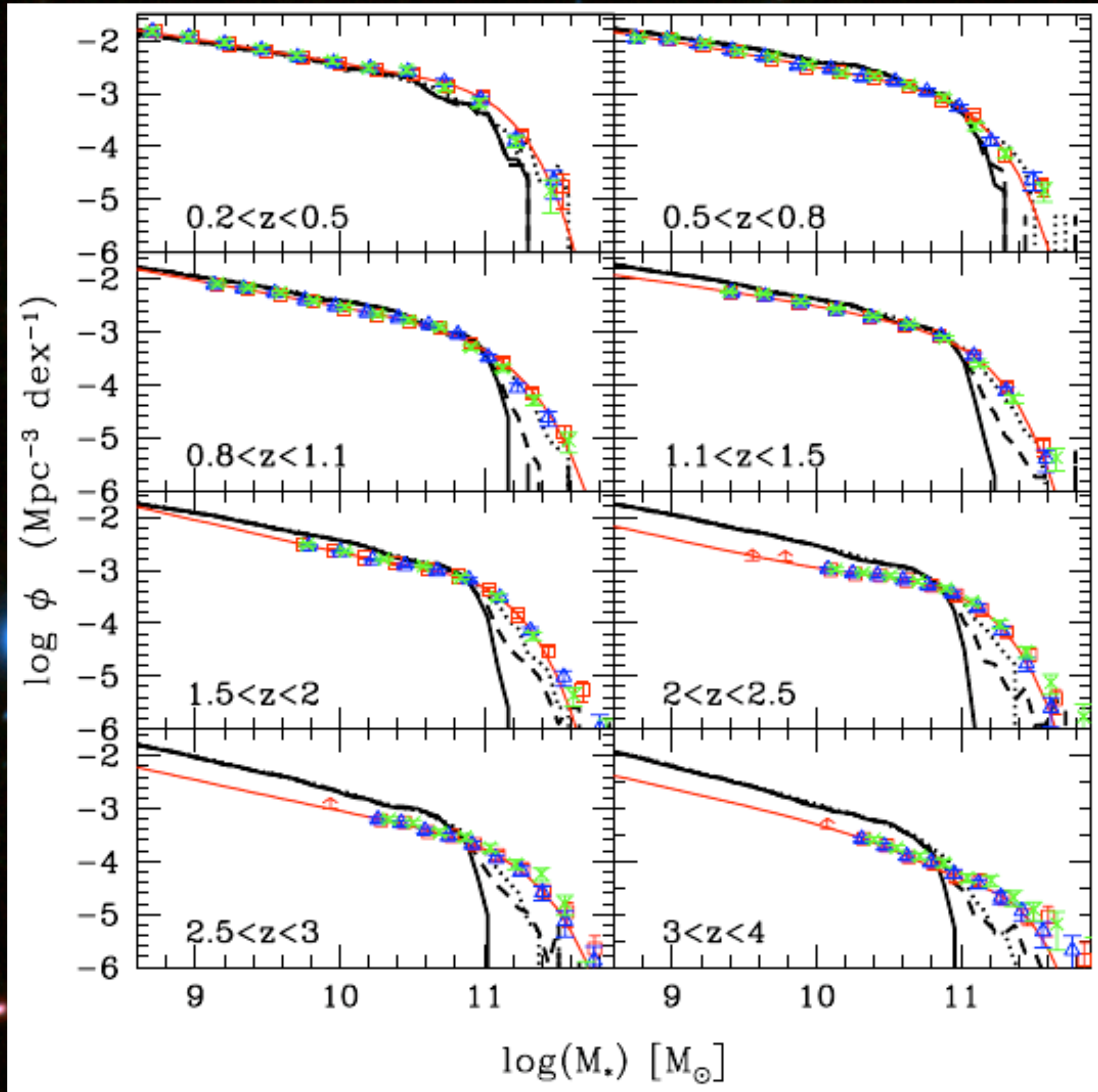
quenching too efficient for satellites in SAM ?

comparison with semi-analytical models
1. Star-forming galaxies

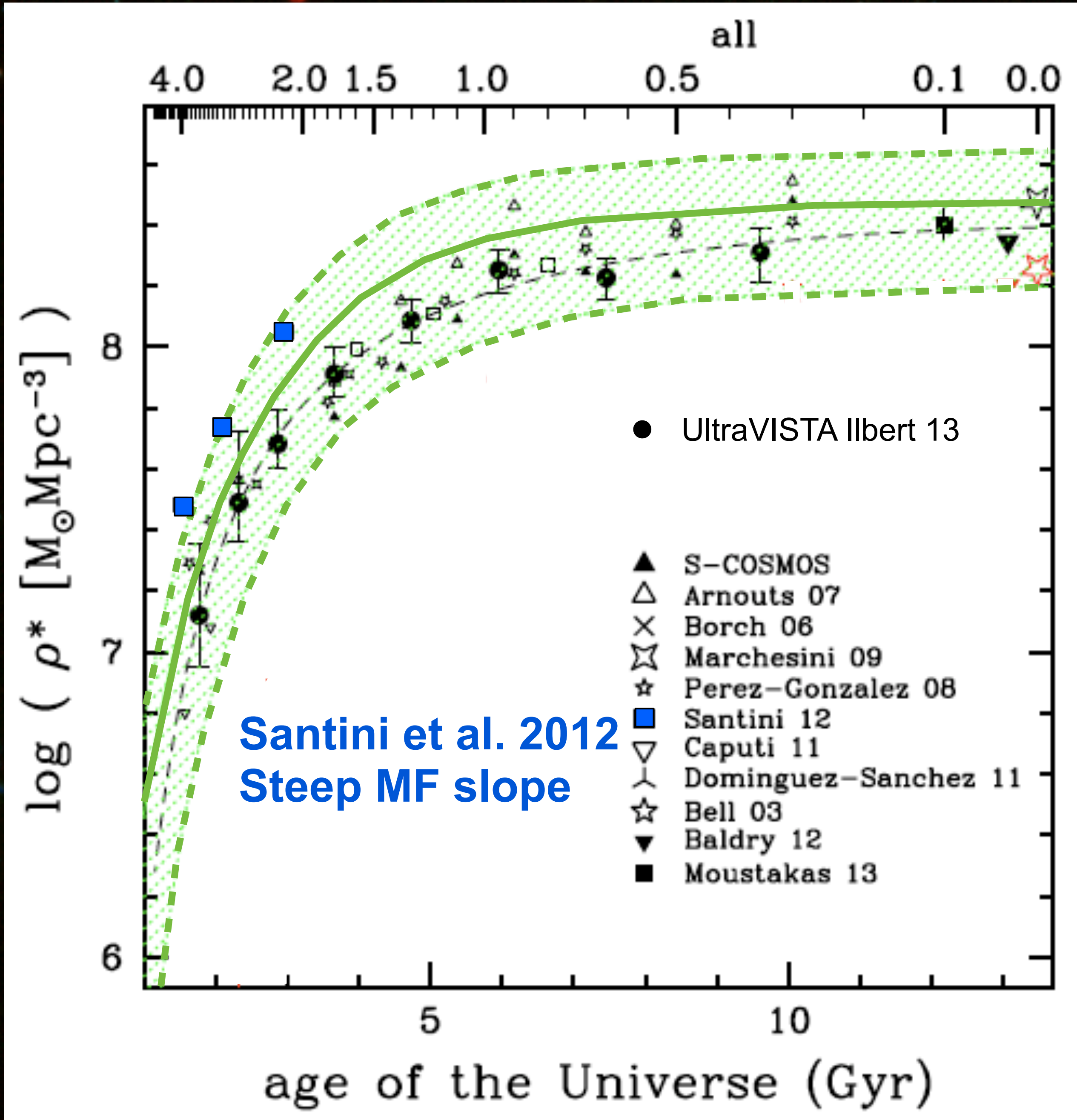
Millenium simulation

Wang et al. 2008

- Right slope
- Under-estimate the high mass end



Stellar mass density



$\rho=\int\phi(M)dM$ with ϕ in $M_\odot Mpc^{-3}dex^{-1}$

SFRD compilation Behroozi 2013

$$\rho_*(t) = \int_0^t SFRD(t')(1 - f_r[t - t'])dt'$$

➢ shaded area

2. Reconstruct the SFH from the observed mass density

Follow the method of Wilkins et al. 2008

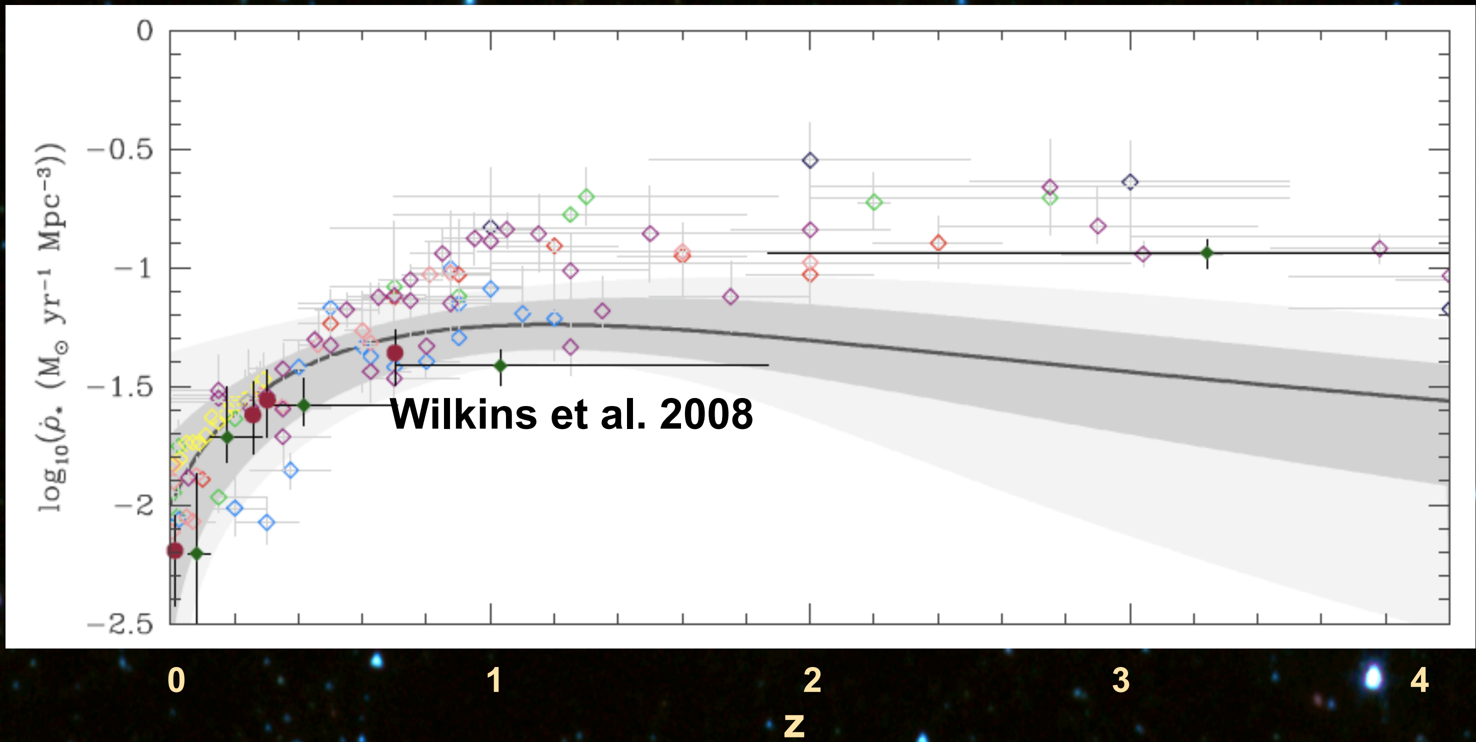
➢ find the SFHs which could explain the measured mass density evolution

* Parametrization of the SFH

$$\frac{C}{10^{A(z-z_0)} + 10^{B(z-z_0)}}$$

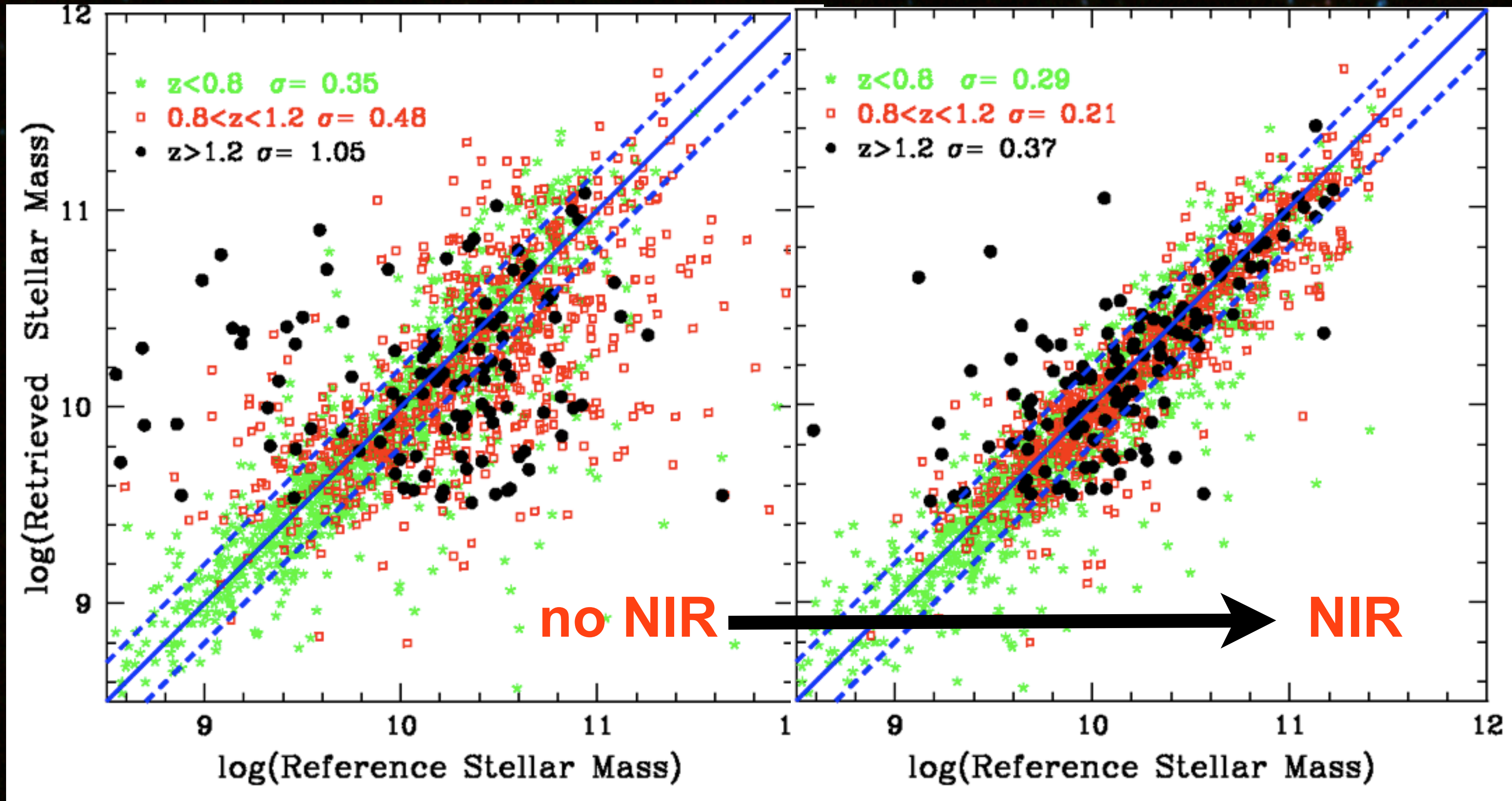
* Adjust A, B, C, z_0 to match the observed stellar mass density

2. Reconstruct the SFH from the observed mass density

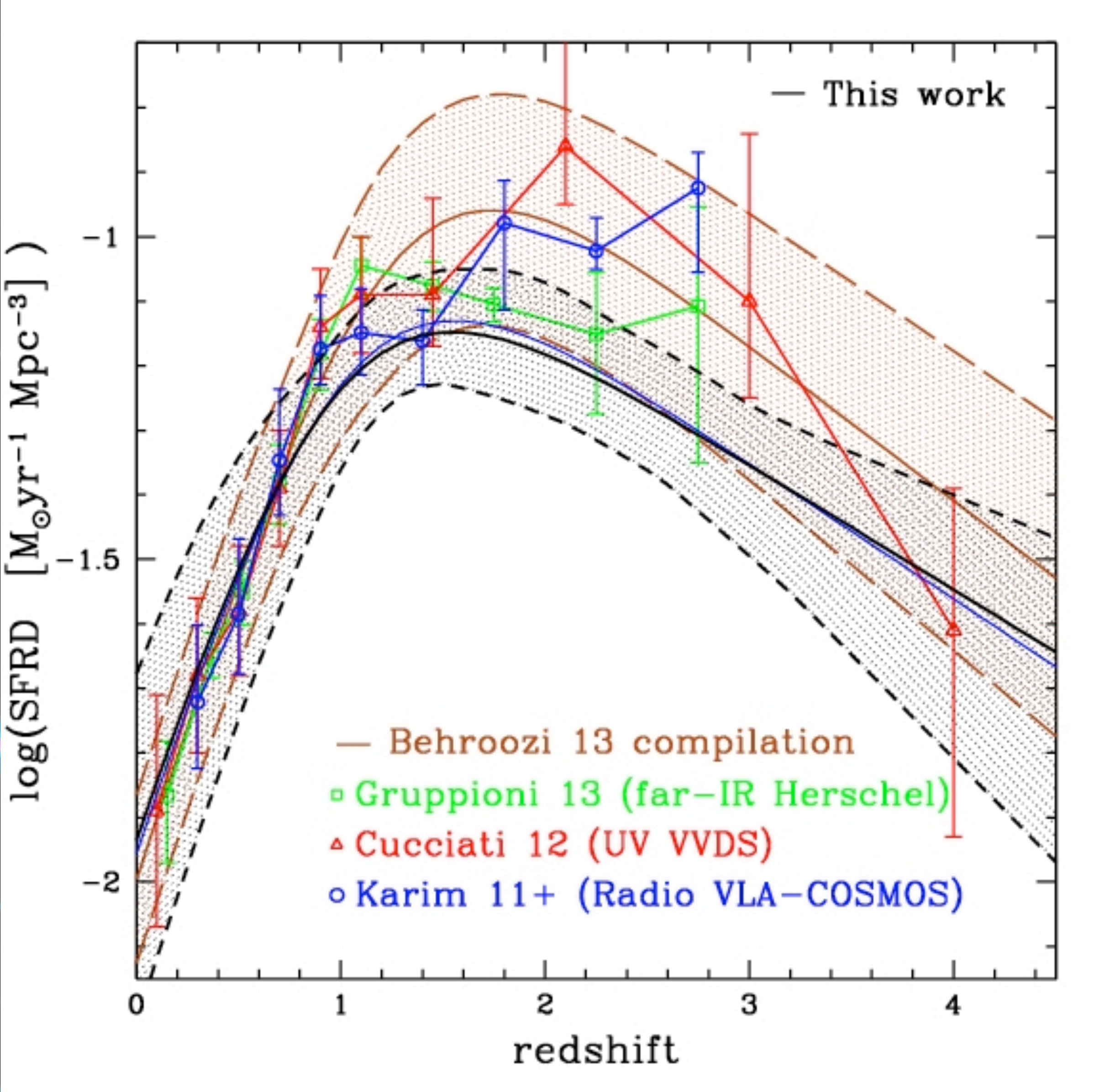


➢ several previous results point out an inconsistency at z>1.5, possibly explained by a change of IMF with time

NIR for accurate stellar masses



2. Reconstruct the SFH from the observed mass density

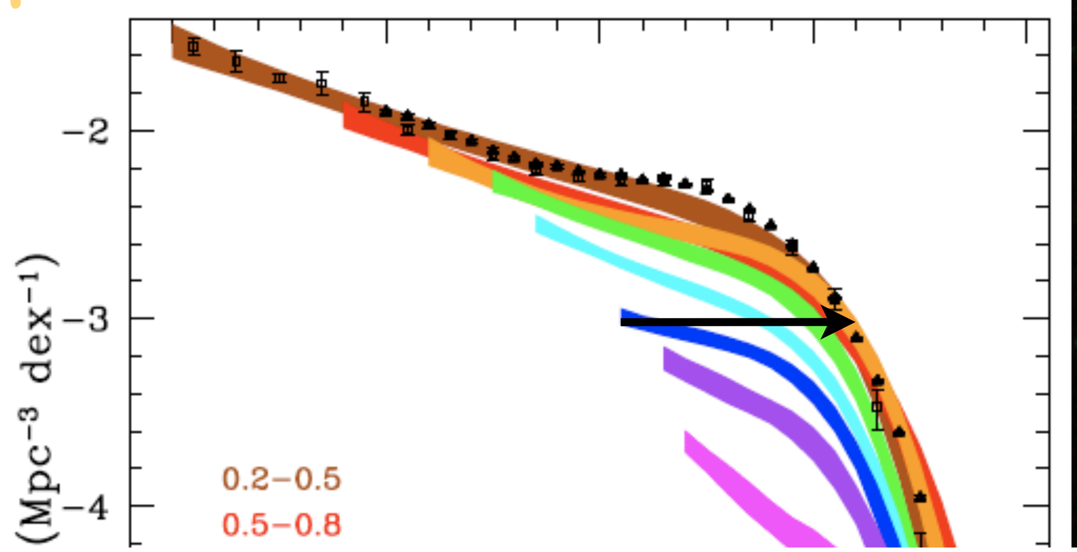


- ➢ excellent agreement @z<1.5 with any SFR tracer
- ➢ differ @z>1.5 large uncertainties even between direct SFR tracers

Global stellar mass function

Mass dependent evolution

➢ Stronger evolution of the low mass end



The star formation is quenched efficiently at high mass

Peng et al. 2010

$$\frac{dP}{dt} = -\eta P = -\mu \frac{dm}{dt} P$$

$$\eta = \mu \bullet \mathrm{SFR} \Longleftrightarrow \frac{dP}{P} = -\mu dm$$

$$P \propto \exp(-\mu m) = \exp(-m / M^*)$$

Survival probability is simple f (m), not of the detailed SFR history.

Quenching rate

Purely empirical analytic model of (Peng et al. 2010)

- ➢ Variation of the quenching efficiency with mass is independent of the environment
- ➢ Variation of the quenching efficiency with environment is independent of the mass

$$\text{Quenching rate } \eta = \mu \mathrm{SFR} + \left(\frac{1}{1-\varepsilon_\rho} \frac{\partial \varepsilon_\rho}{\partial \log \rho} \frac{\partial \log \rho}{\partial t} + \kappa_- \right)$$

Mass quenching

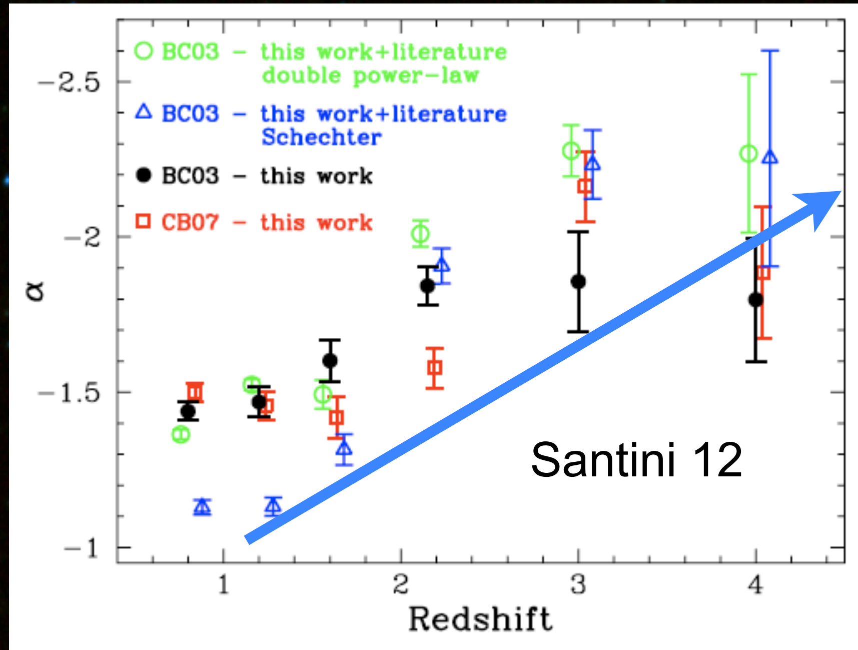
Environment + merger quenching

Differential effect of mass and environment in the quenching of galaxies are completely separable (at $z<1$)

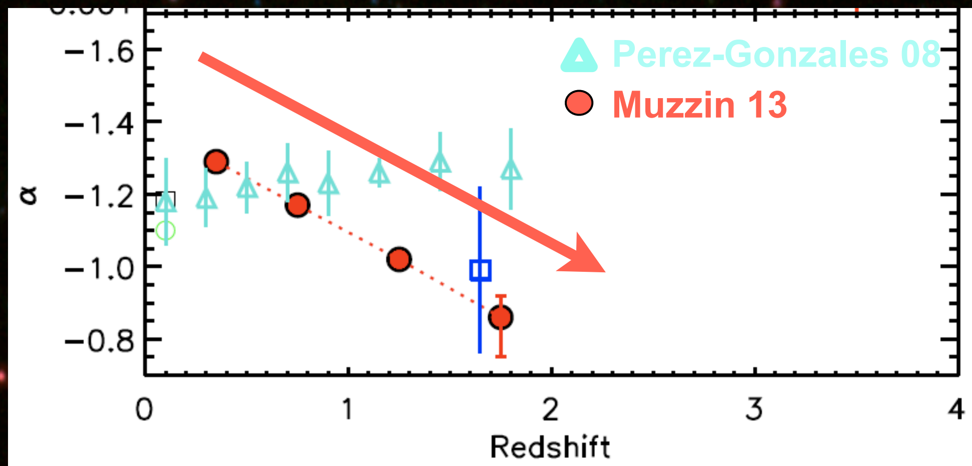
Slope evolution

Numerous studies use a single Schechter function

$$\phi(\mathcal{M})\,\mathrm{d}\mathcal{M} = \mathrm{e}^{-\mathcal{M}/\mathcal{M}^*}\left[\phi_1^*\left(\frac{\mathcal{M}}{\mathcal{M}^*}\right)^{\alpha_1} + \phi_2^*\left(\frac{\mathcal{M}}{\mathcal{M}^*}\right)^{\alpha_2}\right]\frac{\mathrm{d}\mathcal{M}}{\mathcal{M}^*}$$

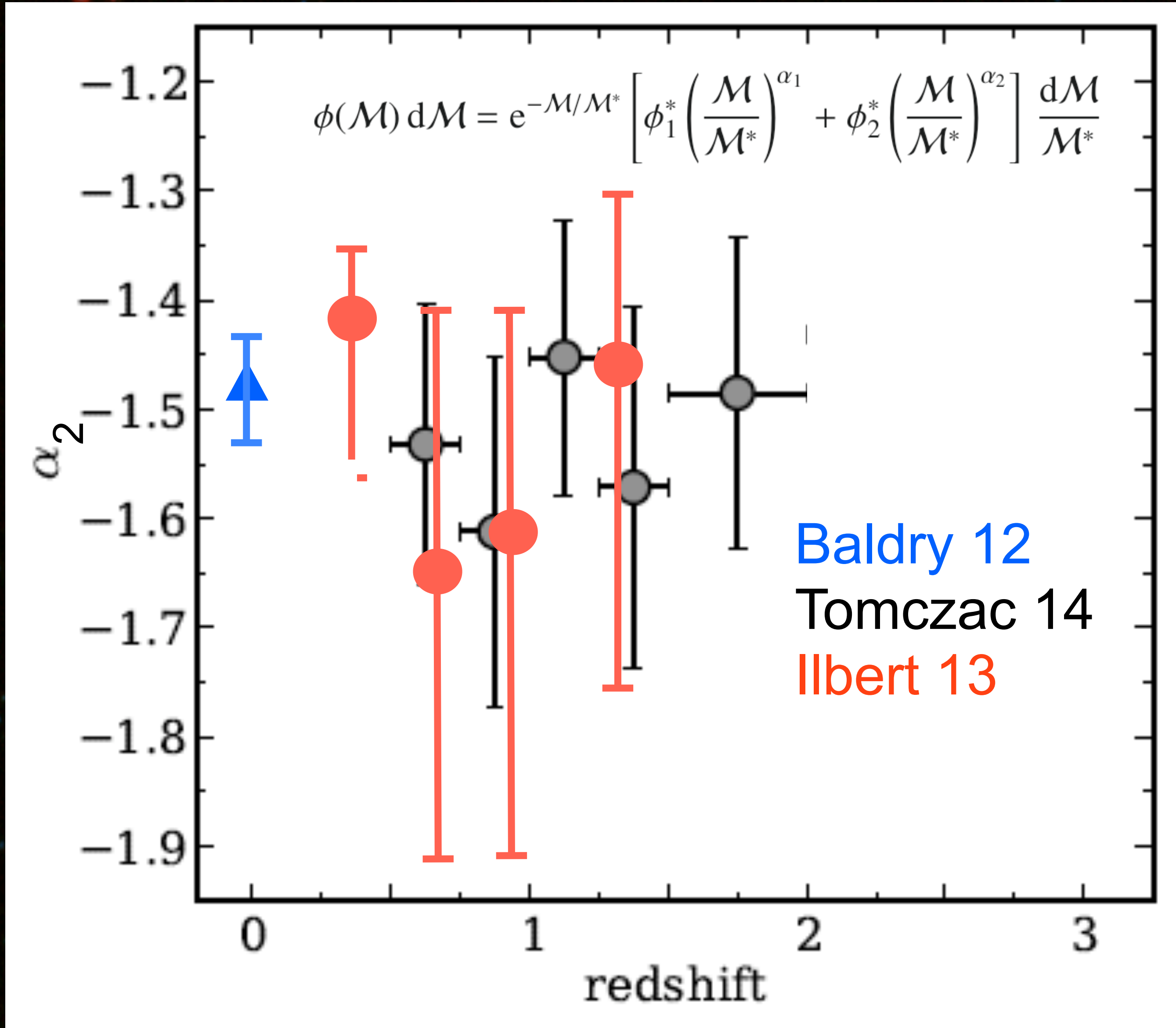


inconsistent results ➢ double

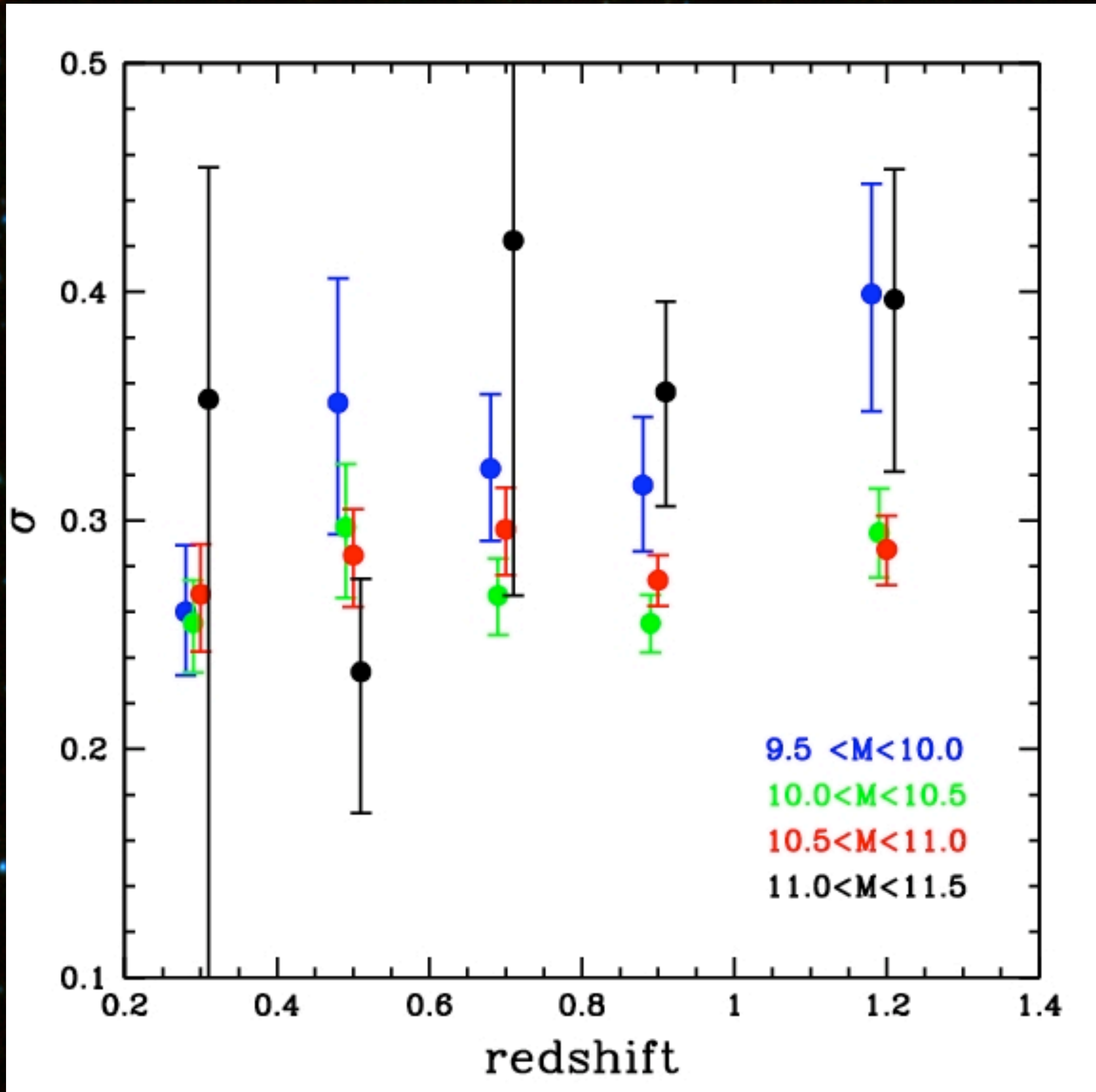


Slope evolution

No clear evolution of the slope using a double Schechter function



Width of the mass-SFR relation

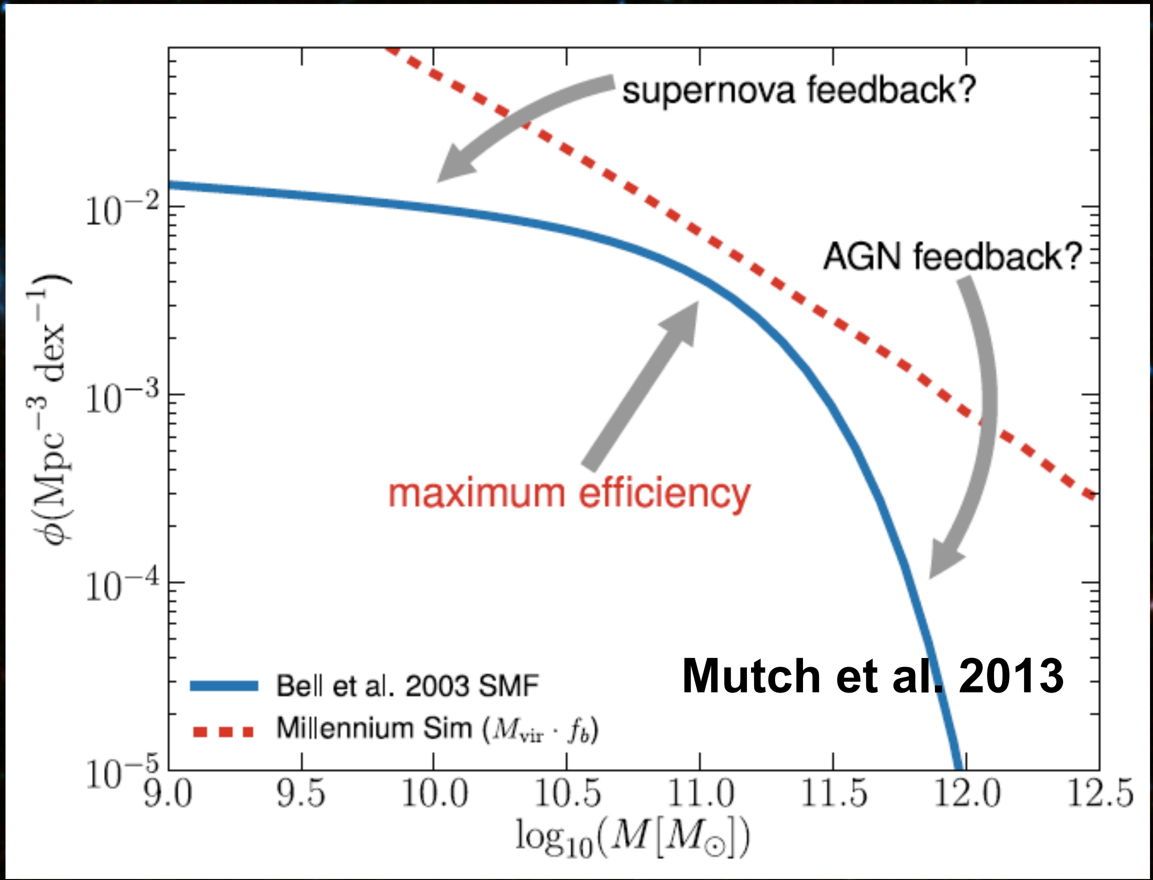


Open questions

Relative efficiency of these processes across cosmic time

- Action mode of AGN and SN feedback (mechanical or radiative) ➢ regulate/quench the star formation

Observational constrains from the galaxy stellar mass functions



Stellar mass function at 0.2<z<4

Ilbert 10, 13

➢ 230000 - 1.7 deg^2

Pozzetti 10

➢10000 - 1.5 deg^2

Perez-Gonzalez 08

➢28000 - 664 $arcmin^2$

Marchesini 09

➢3000 - 511 $arcmin^2$

Tomczac 13

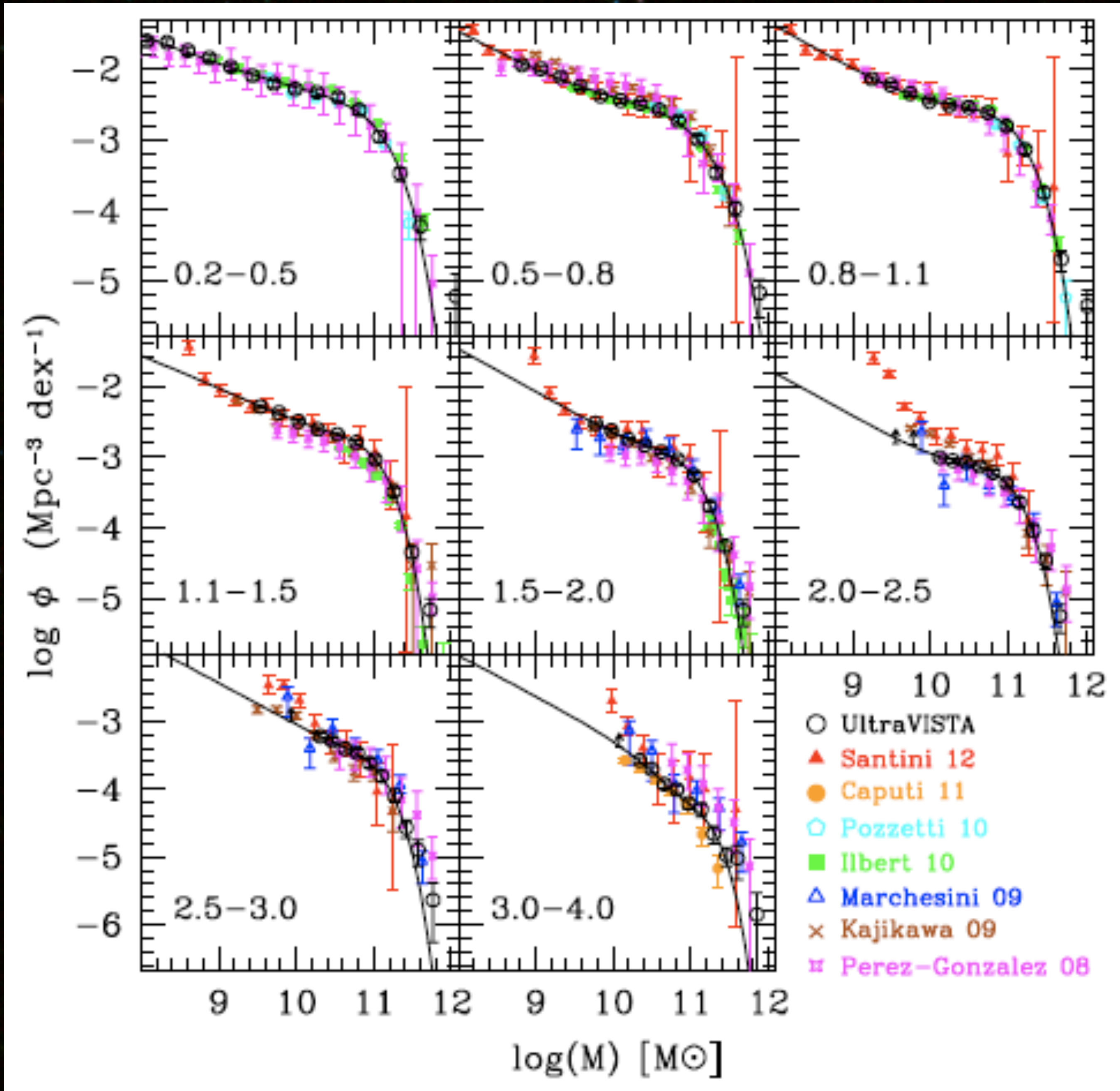
➢15000 -316 $arcmin^2$

Kajikawa 09,

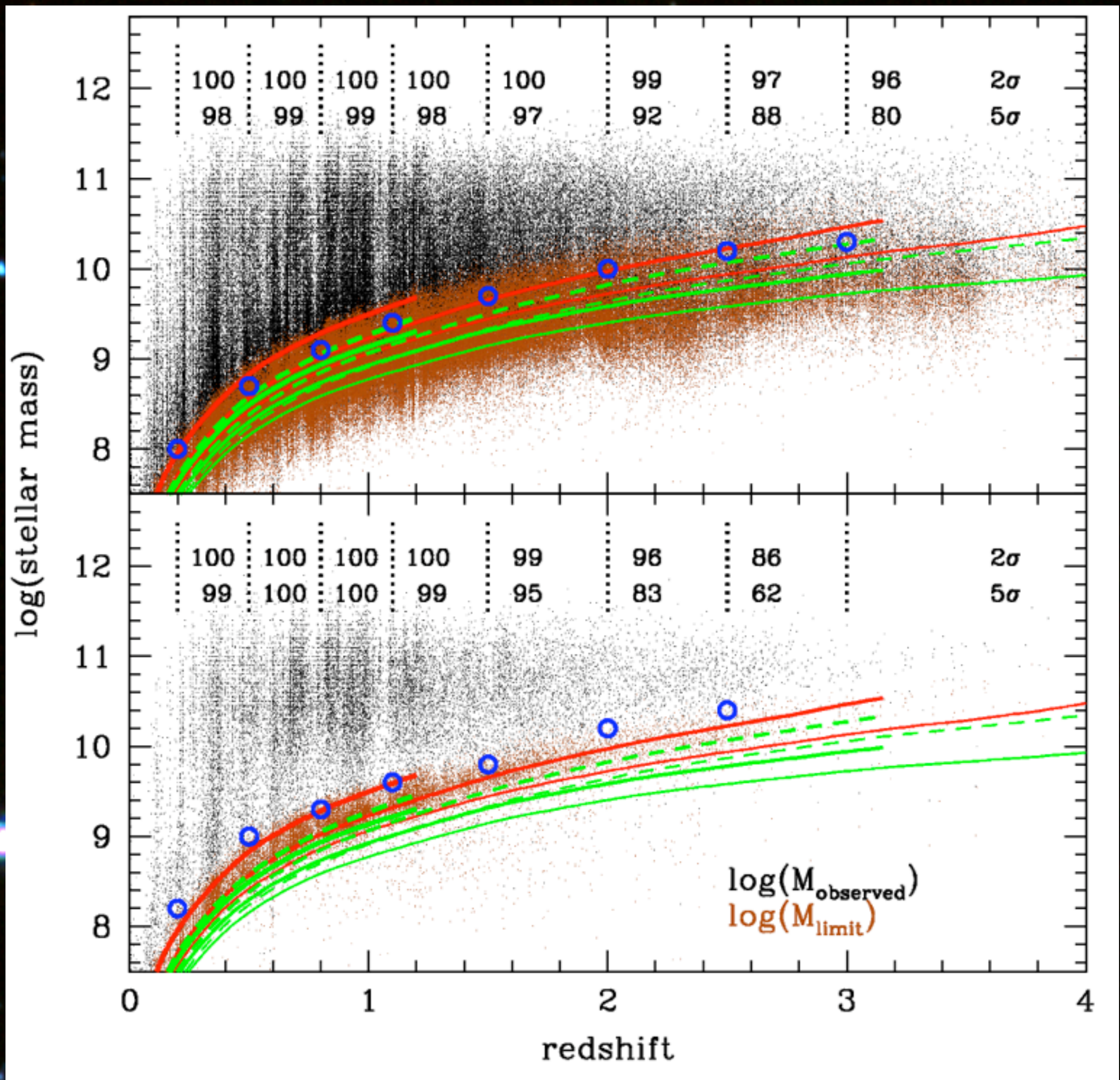
➢10000 - 130 $arcmin^2$

Santini 12

➢3200 - 33 deg^2



Stellar mass sample



230000 galaxies at K<24 with 1-3% accurate and well tested photo-z

Ilbert et al. 2010

http://www.cfht.hawaii.edu/~arnouts/LEPHARE/cfht_lephare

Template-fitting

- Polletta et al. (2007) + blue BC03 templates
- Iterative calibration of the zero-points using spec-z
  - ➢ Remove systematic shift
- Take into account the emission line contribution
  - ➢ Improve the accuracy by 2
- Calzetti and Prevot attenuation curves