Star Formation Histories and Stellar Mass Growth out to z~1

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and the AEGIS collaboration

Galaxy Evolution: Emerging Insights and Future Challenges
Austin, TX, Nov 15, 2008

AEGIS
All-wavelength Extended Groth strip International Survey

CfA

Overview

I. Deep multi-wavelength surveys: A census of SF in field galaxies to z>2

- Main Sequence of star-forming galaxies to z=1 (>2)
- gradual decline of star formation in galaxies dominant since z~1 (>2);
- limited role of starbursts
- new prospects to quantify and understand processes that regulate SF

II. Using the SFR-M* relation to quantify star formation histories as a function of galaxy mass

III. Delayed SF in less massive galaxies

- unknown baryon physics?

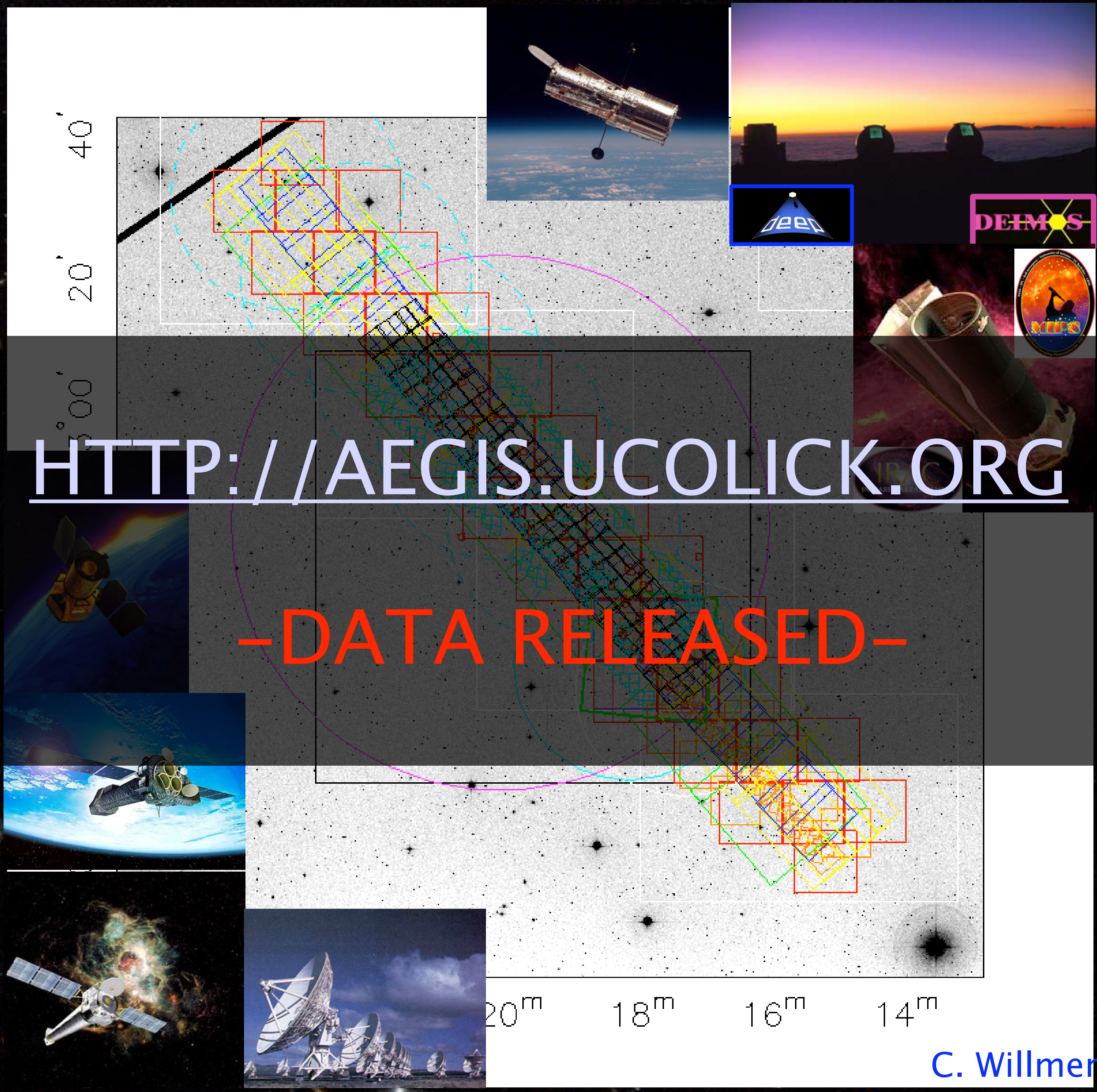
IV. Measuring SFR: Uncertainties and hope from adding new methods

V. Summary

AEGIS

All-wavelength Extended Groth strip International Survey

The All-Wavelength Extended Groth Strip International Survey

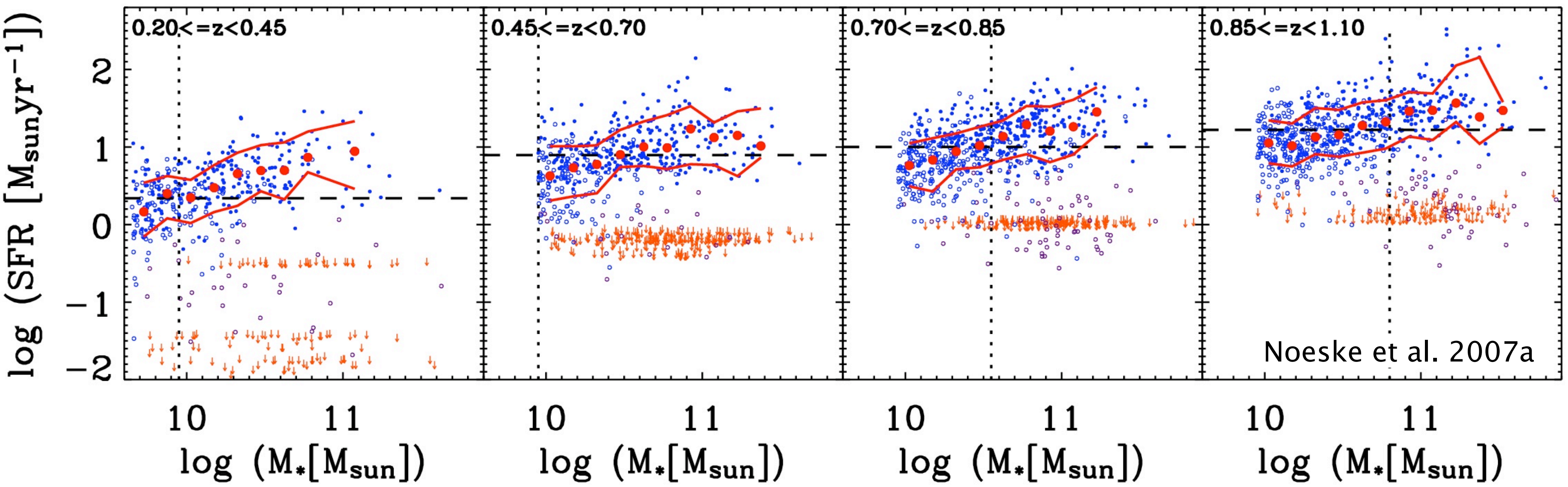


HTTP://AEGIS.UCOLICK.ORG

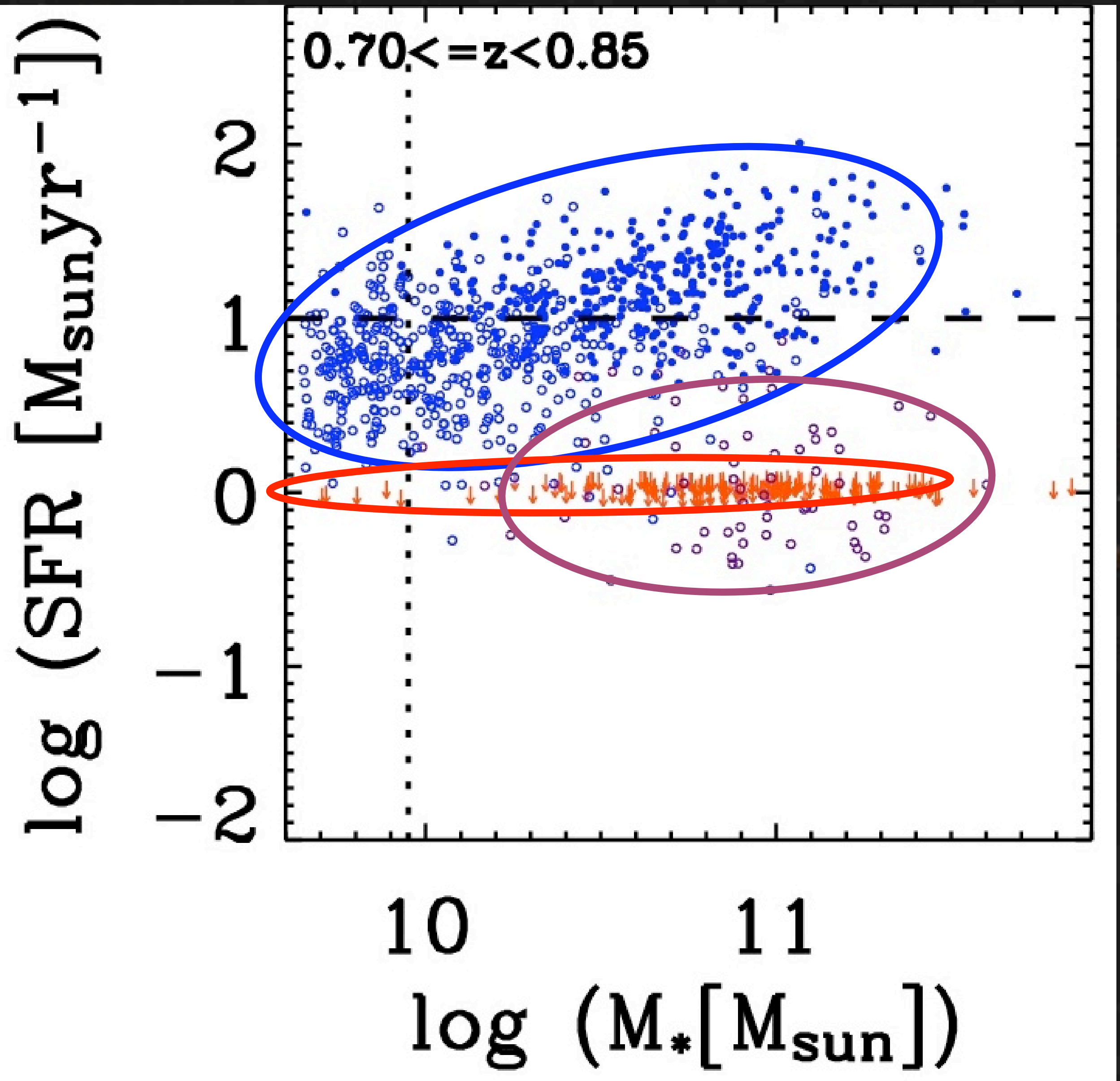
-DATA RELEASED-

- DEEP2:Keck /DEIMOS spectra: ~10,000 precision redshifts, galaxy kinematics
- HST V,I (700 sq arcmin-2xGOODS)
- Very deep:
  - Spitzer (IRAC, MIPS)
  - GALEX (NUV, FUV)
  - Chandra ACIS
  - VLA 6/20cm
- Herschel FIR
- submm
- Ground-based deep U- to K-imaging

The Star Formation Rate-Stellar Mass Relation(“Main Sequence”)



A more detailed view of star formation properties



1) Fiducial star-forming galaxies:

24μm sources, or blue emission line galaxies

(~2/3 of sample)

2) Galaxies not detected in 24μm or emission lines:

early-type HST morphologies, red sequence:

likely not significantly star-forming

(~1/3 of sample)

3) Galaxies with no detection in 24μm, but weak emission lines:
red sequence, 2/3 early-type HST morphologies,

large fraction LINERs/AGN

(<20% of sample)

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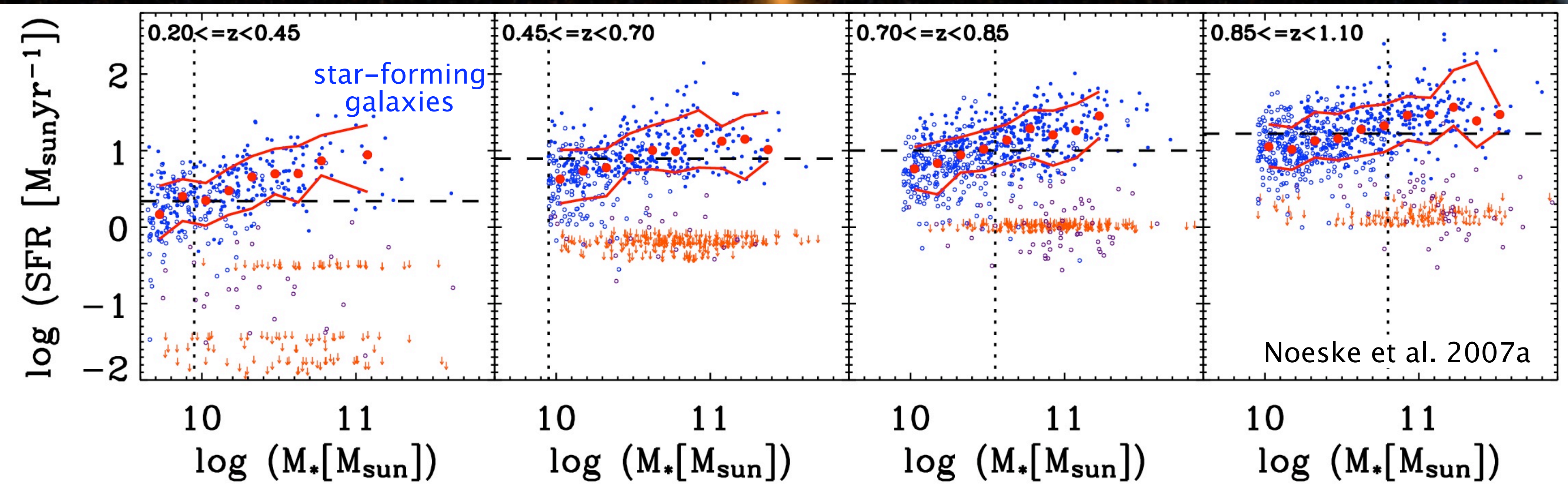
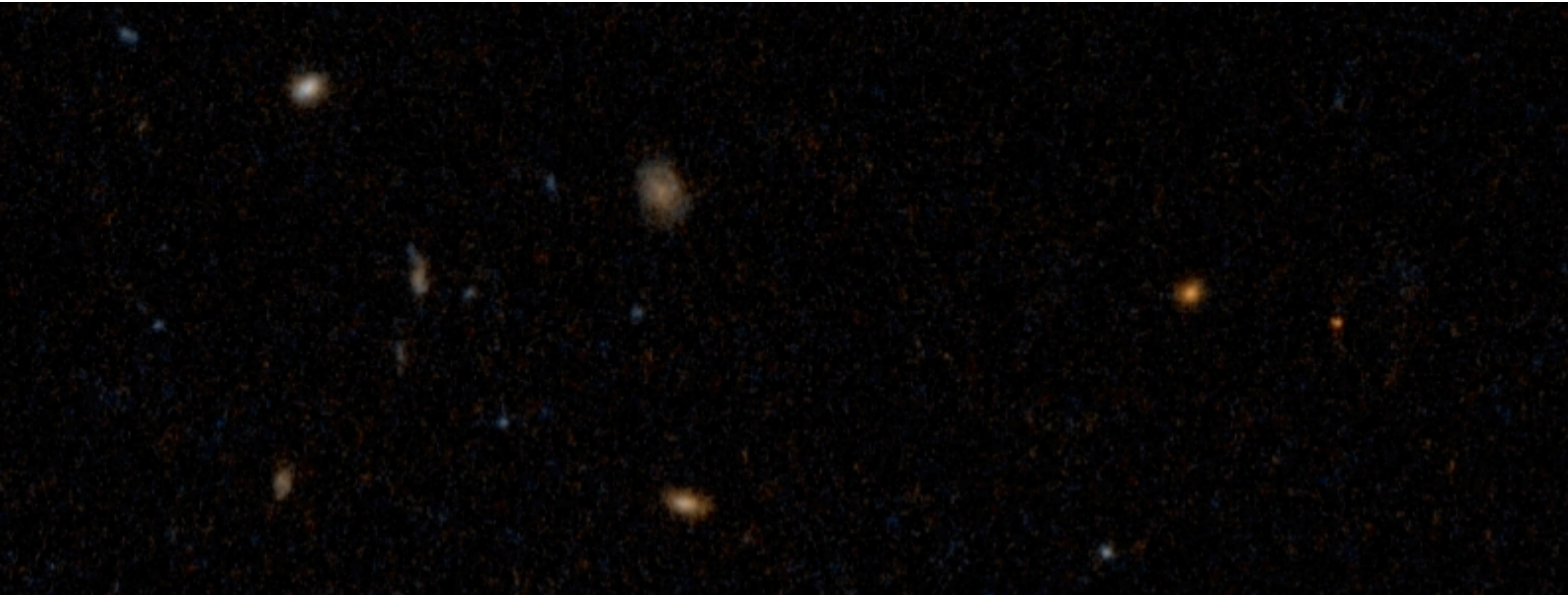
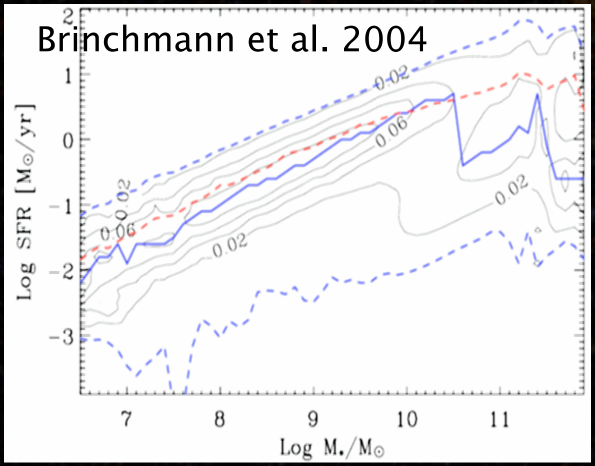
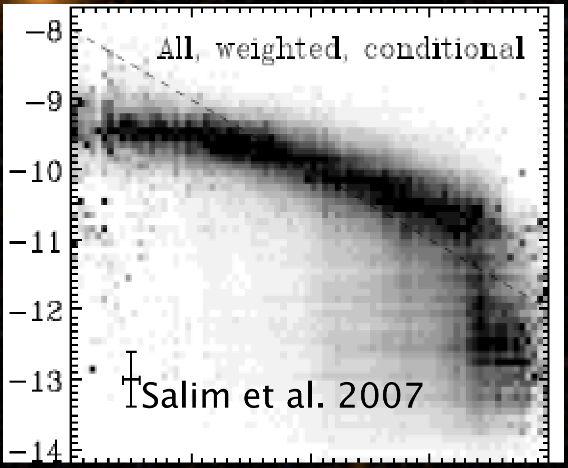


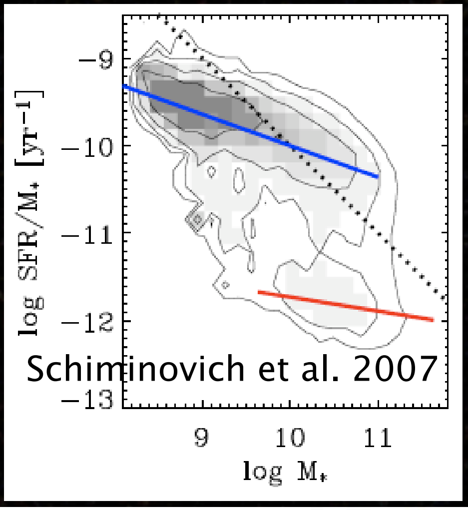


The Star Formation Rate–Stellar Mass Relation(“Main Sequence”)

z~0.1



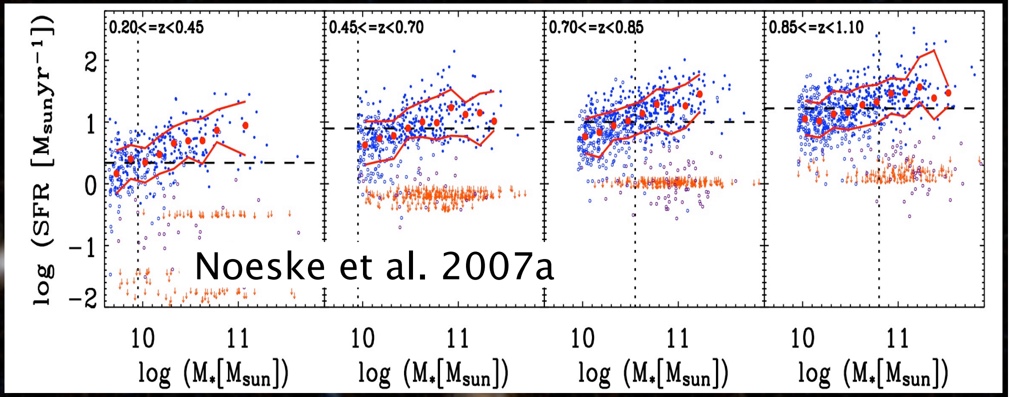


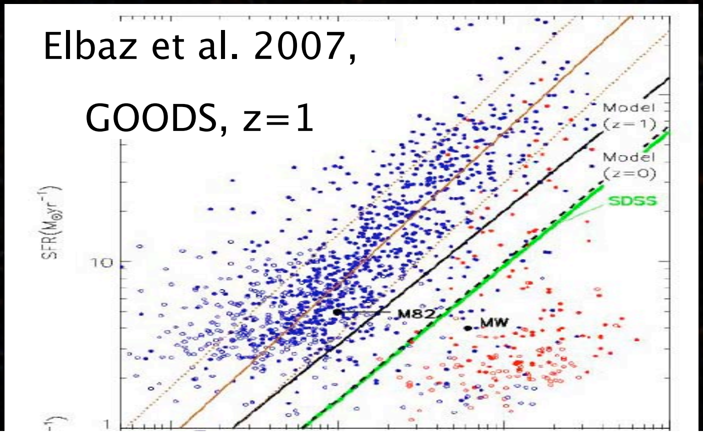


z<~1

also Zamojski et al. 2007

Zheng et al . 2007

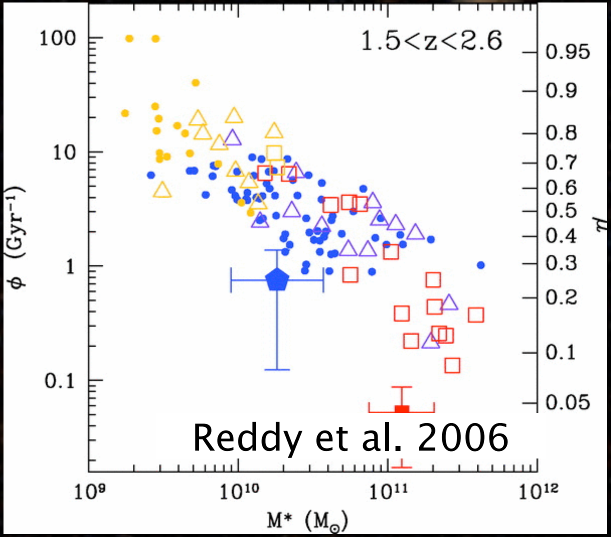


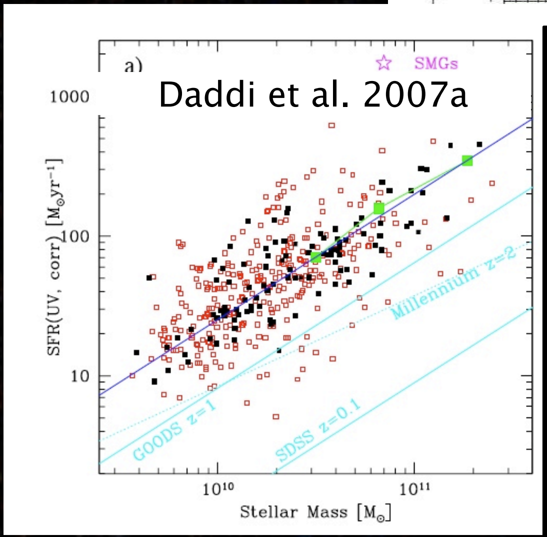


z~2

also Erb et al. 2006,

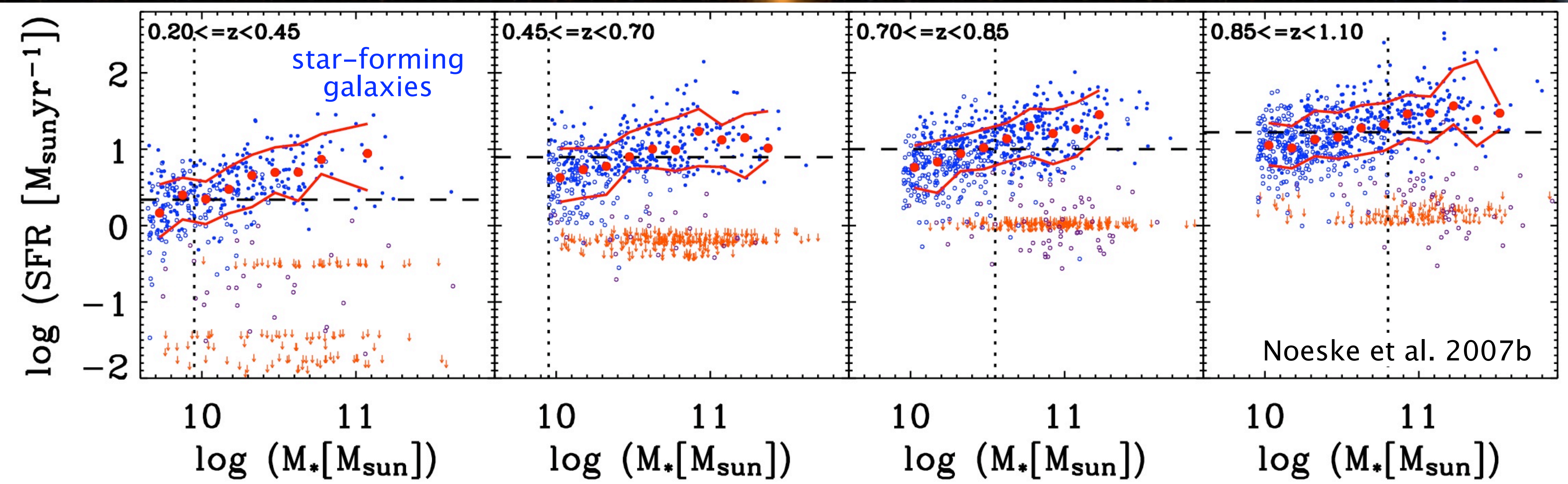
Genel et al. 2008, Foerster-Schreiber et al. 2008





Existence to z~2

The Star Formation Rate-Stellar Mass Relation(“Main Sequence”)



1) Star-forming galaxies form a defined relation:
SFR – stellar mass out to z>2.
(Generic mode of star formation in galaxies, prior to quenching of SF?)

2) Range of log(SFR) ~±0.3 dex (1σ) at all z:

starbursts had only a modest, barely evolving role out to z~2
(constraint on merger-driven starbursts, feedback)

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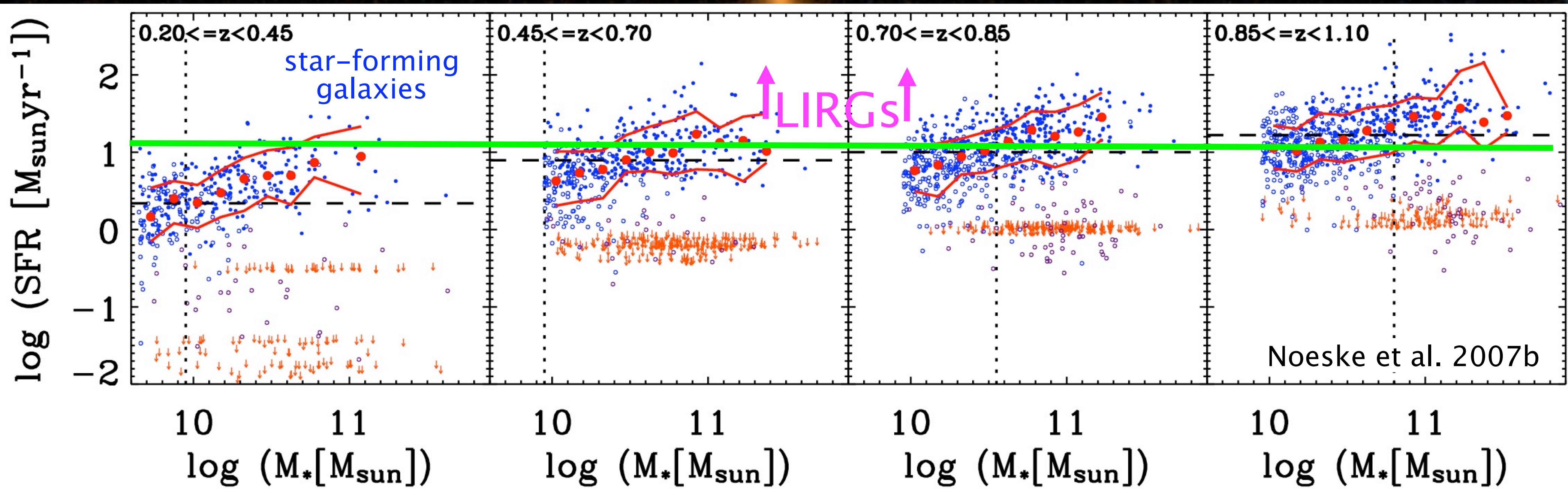

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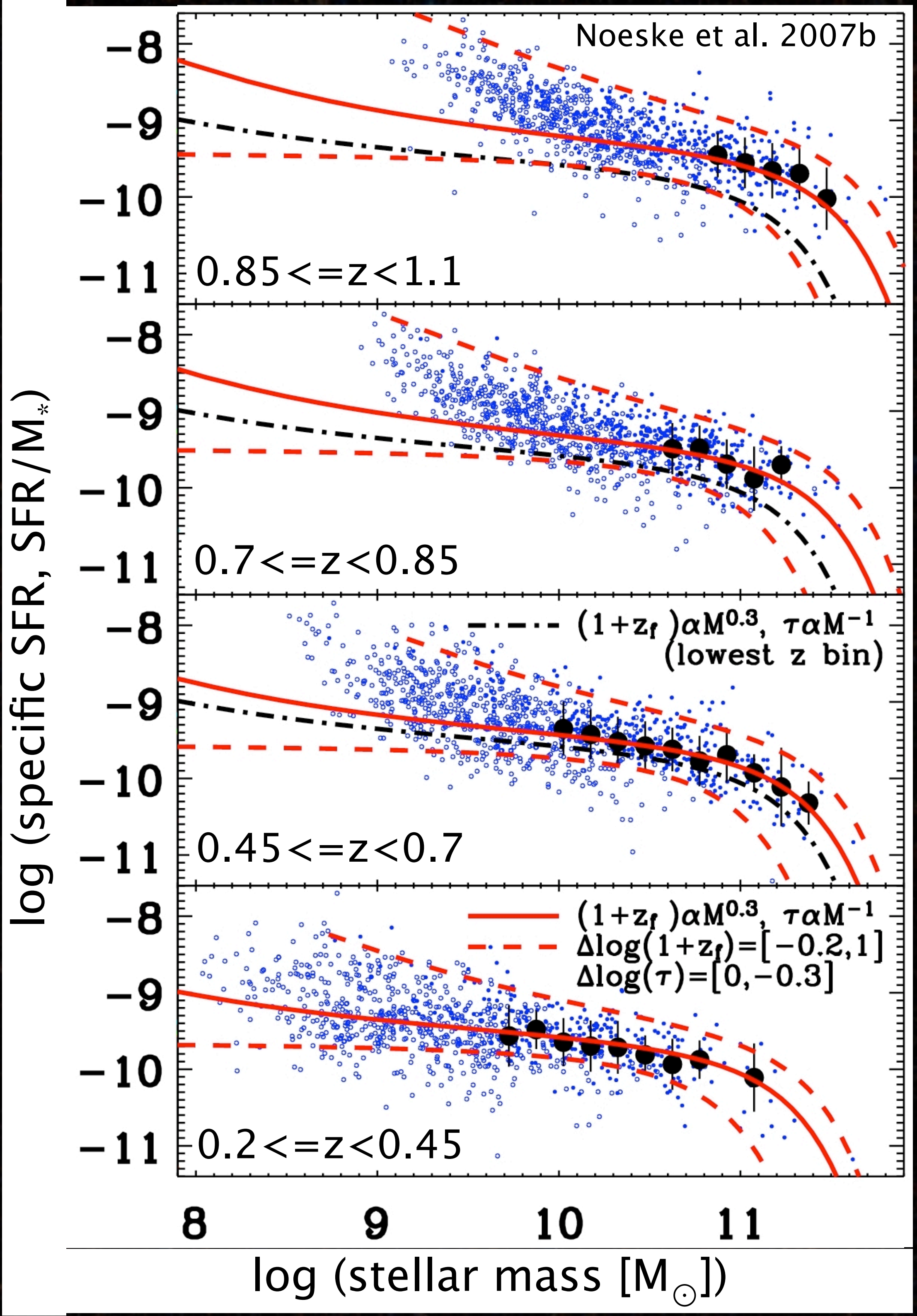
(constraint on merger-driven starbursts, feedback; cf effect of mergers, this conf.)

3) Normalization evolves strongly with z:
evolution of SF since z~2 dominated by a gradual decrease of SFR

<u>LIRGs</u> at z~1 are normal massive galaxies, <u>NOT</u> brief stochastic starbursts (ALL have equally high SFR at the SAME TIME!
Early, gas-rich phase of smoothly declining SF history of >~L* galaxies

The Star-Forming sequence encodes mass-dependent SF histories:

HRD of galaxies



Main Sequence encodes mass-dependence of SF history timescales :

Exponential SF histories

τ and z_f mass-dependent (power laws)

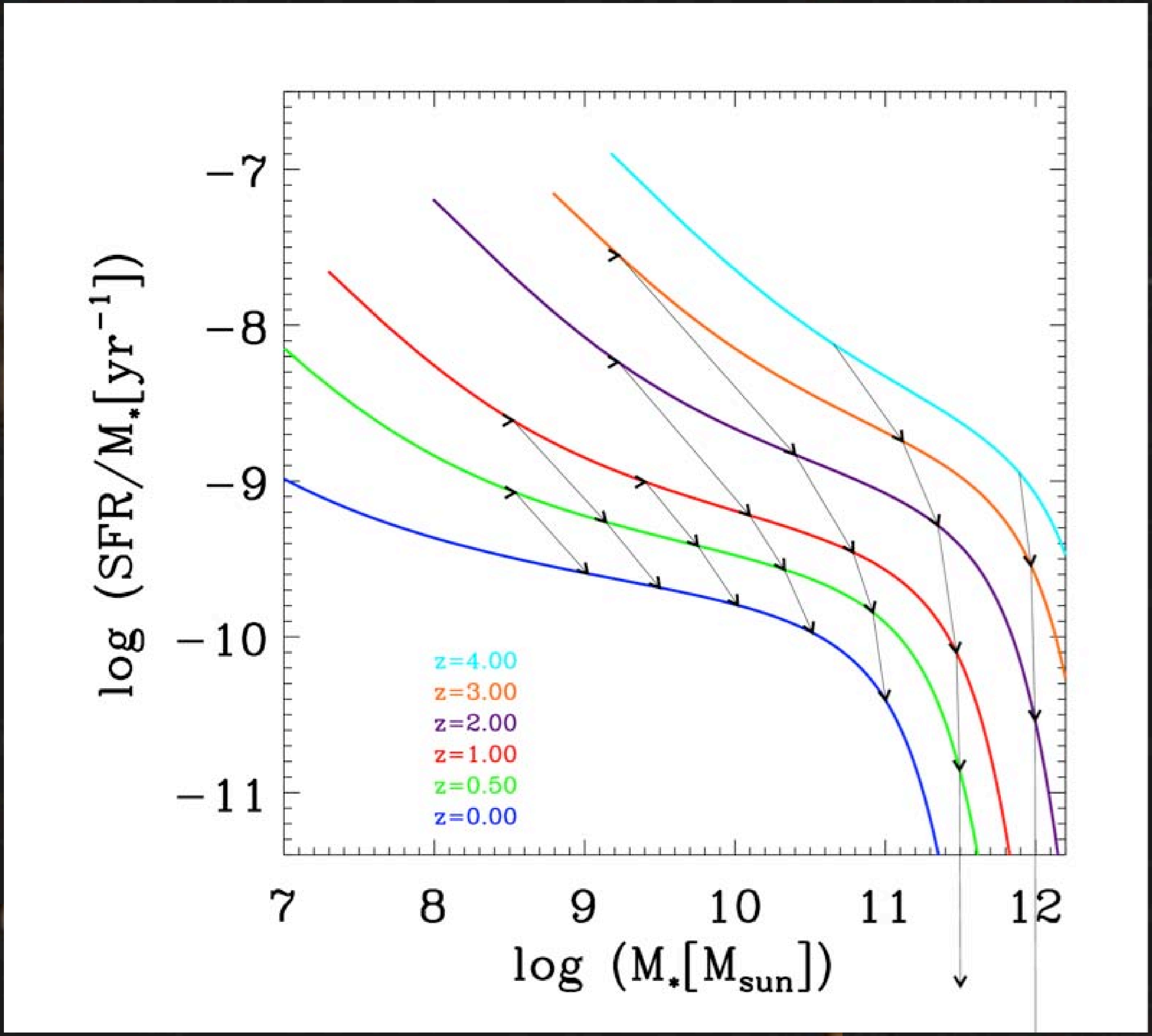
low mass galaxies form stars slower and start later

("Downsizing" needs 2 components!)

Parametrization tool, provides an average mass-dependent reference SF history

(phenomenological!)

Resulting evolutionary tracks: significant mass growth, requires mass corrections to measure evolution of galaxy properties



A promising perspective to further our understanding of star formation:

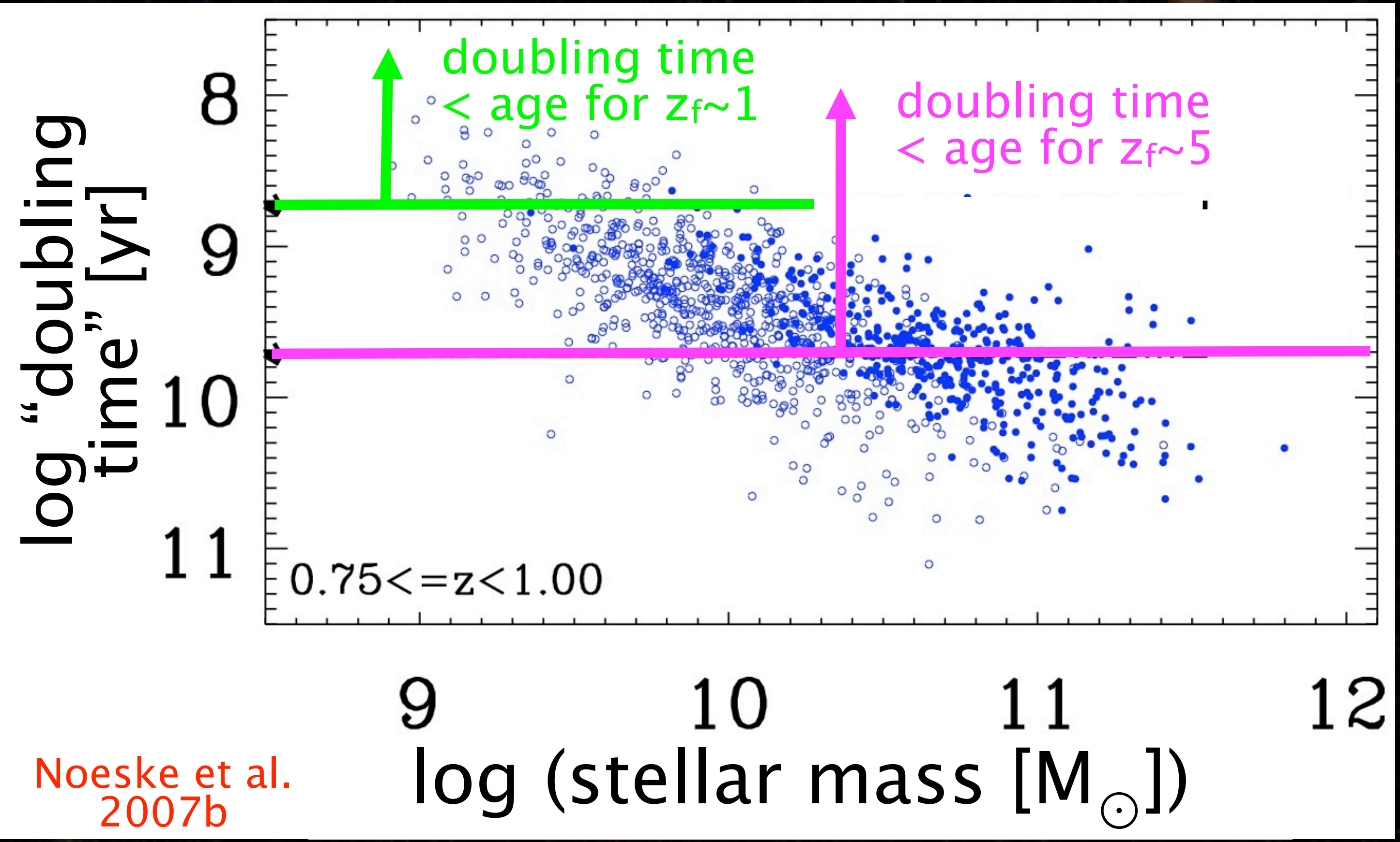
1) SF histories to z~2: regular, mass-dependent, rather uneventful (pre-quenching)
-> same physical processes dominant?

2) The MS as the HRD of galaxies:
encodes mass-dependence of SF history timescales

3) Reference data for observational and theoretical work

4) Baseline to quantify influence of AGN, mergers/environment, morphology, etc. on SF, and measure quenching processes

A delayed onset of star formation in low mass galaxies

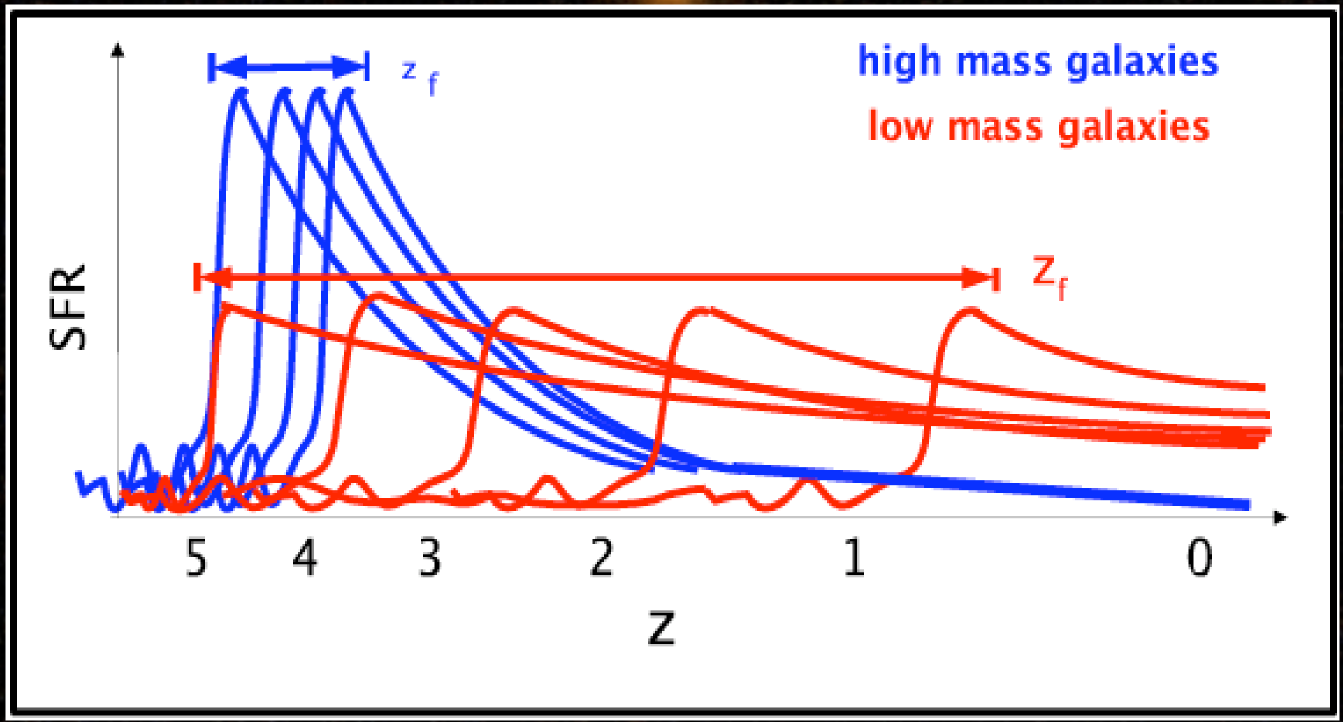


"Doubling Time Problem":

Given their SFR, low mass galaxies would produce their stellar mass in $t_d < t_H$:high SFR are not sustainable for $\sim t_H$.

Simultaneous starbursts?
Not plausible, and inconsistent with gradual decline of SFR.

Only alternative: delayed onset of major star formation in many less massive galaxies



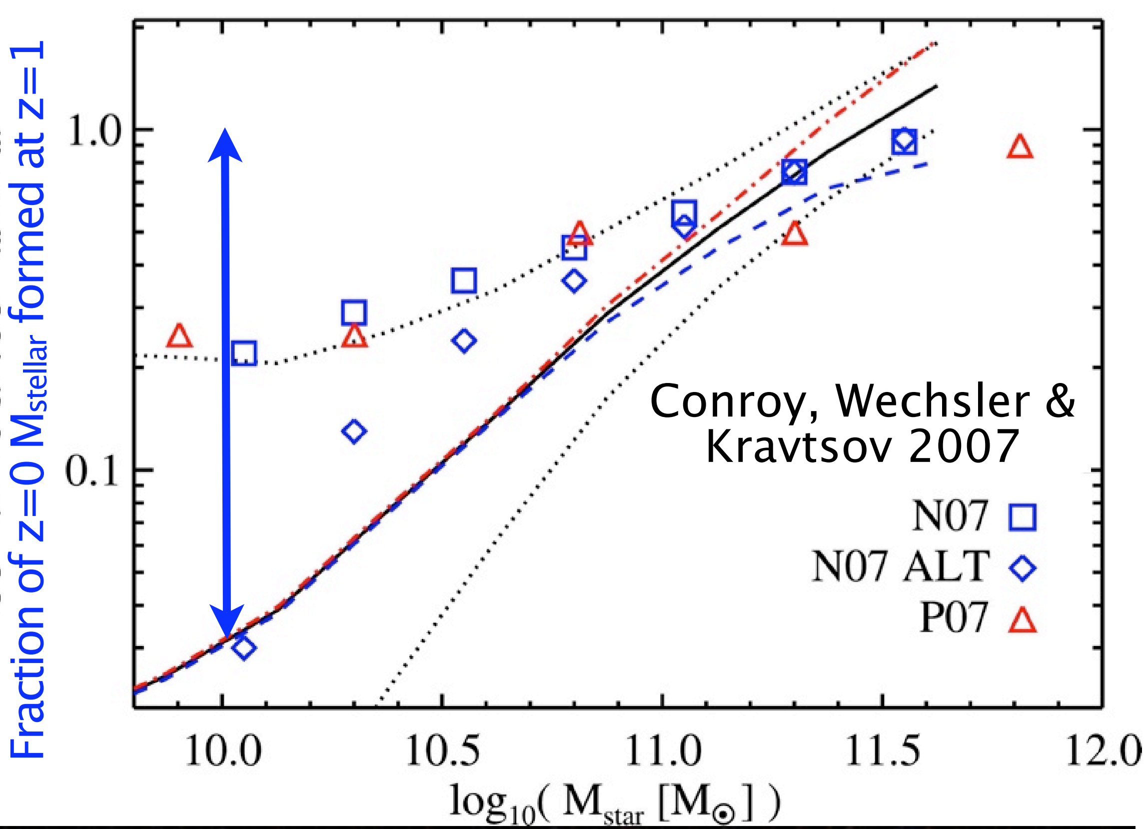
From SF sequence:
Less massive galaxies start major SF on average later:
Onset of SF (z_f) more broadly distributed from high to low z

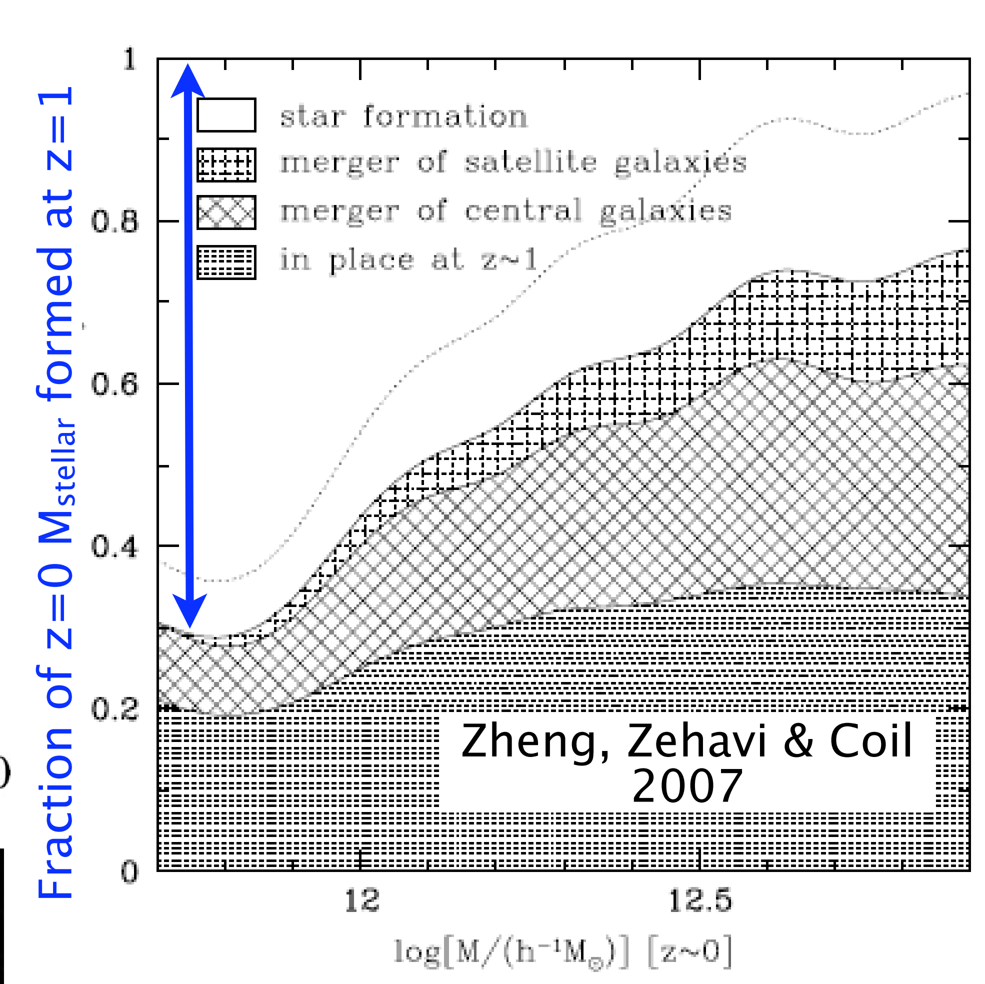
("Staged galaxy formation" Noeske et al. 2007b)

– Supported by various independent evidence –

Independent evidence: combining cosmological simulations with stellar mass functions at z=0 and 1

isolate mass growth due to merging and star formation



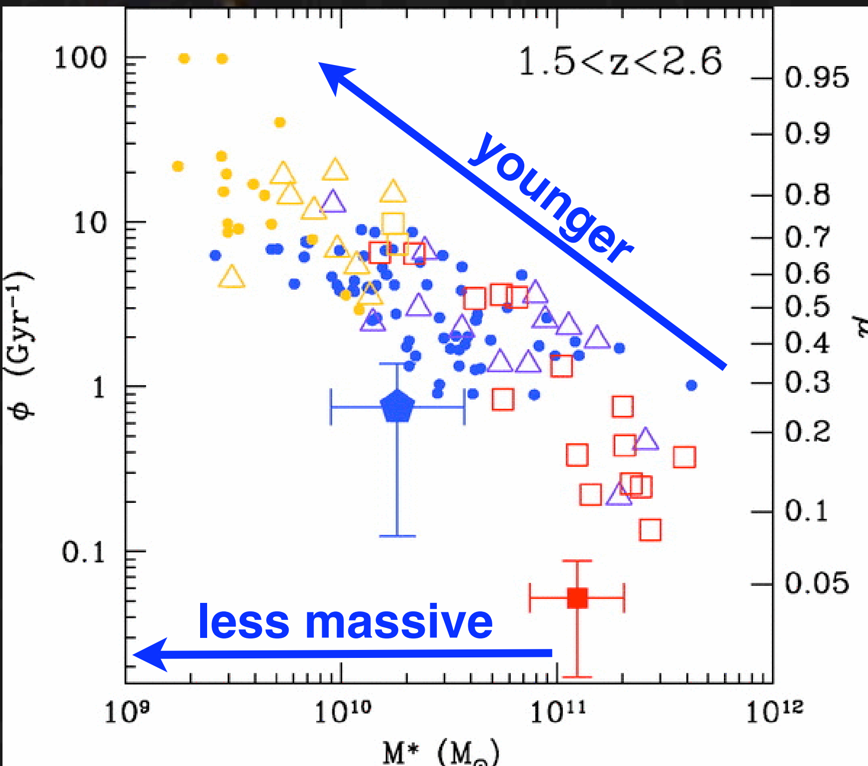


Today's low-mass galaxies (<10^{10} M_{sun})

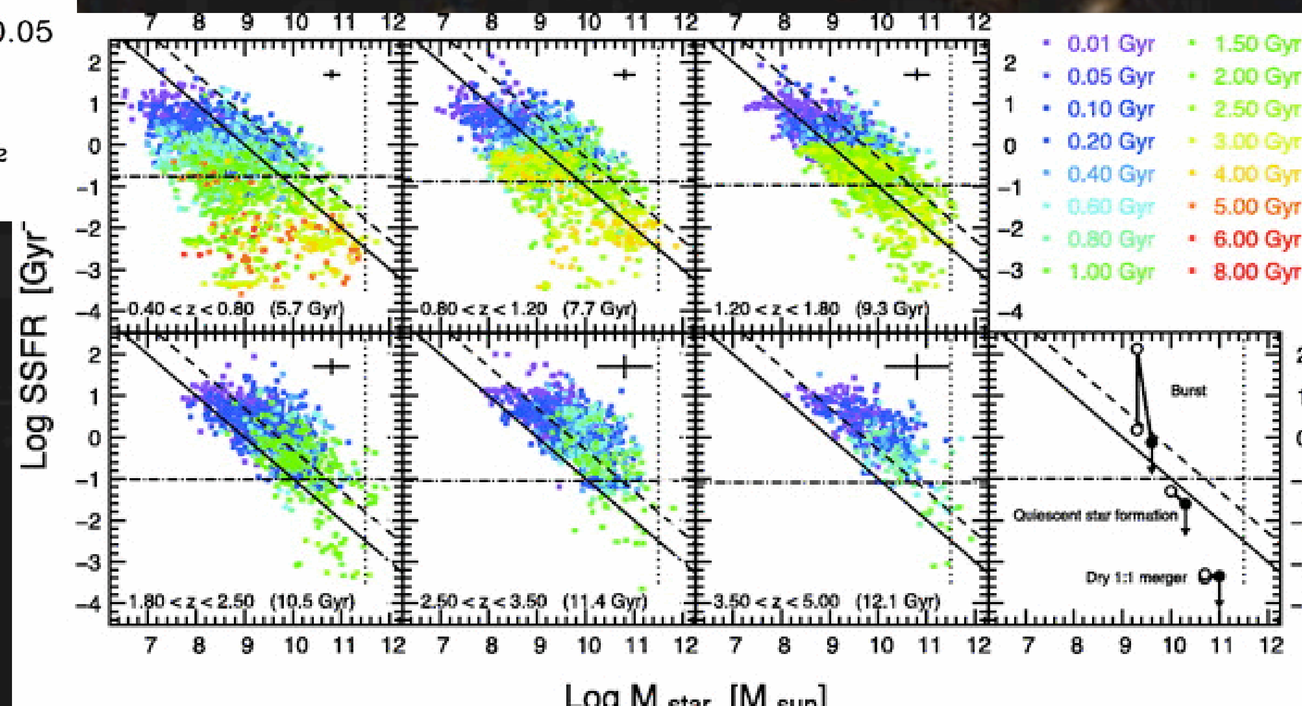
formed more than 70-80% of their stellar mass since z~1

-> inefficient star formation at z>1

Stellar populations of high z galaxies: more recent onset of SF in less massive galaxies



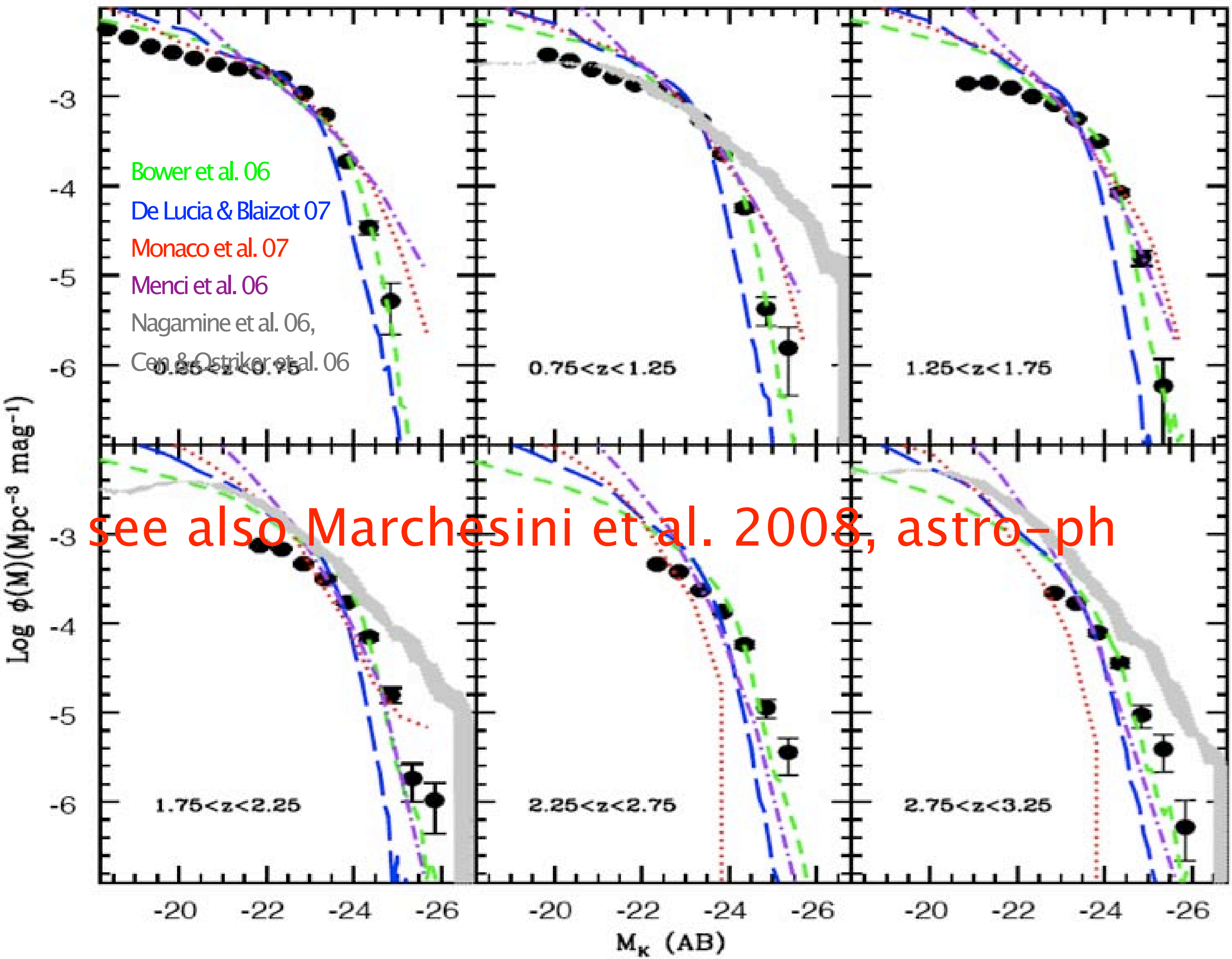
Reddy et al. 2006



Feulner et al. 2005

Evolution of the stellar mass function

Cirasuolo et al. 2008, UKIDSS UDS



see also Marchesini et al. 2008, astro-ph

Do most current models form sub-L* galaxies too early?
Better agreement for hydrodynamical simulations (at low z) ?

Possible Origin of mass-dependent delays?

1) Cosmological (DM assembly history) ?

Observed Downsizing of SF with time requires baryonic processes that decouple the histories of star formation from those of halo assembly (Neistein et al. 2006)

(Example: threshold halo mass for SF; needs to increase with z, and be >> M_{min} for HI cooling)

2) Current understanding of baryon physics?

Current simulations do not reproduce the observed evolution of SFR: Model SFR are too low at z~1 and z~2

(Elbaz et al. 2007, Daddi et al. 2007, Dave 2007)

A delay in SF would help, but is hard to reconcile with physical understanding of gas accretion and star formation.

Tentative Conclusion:

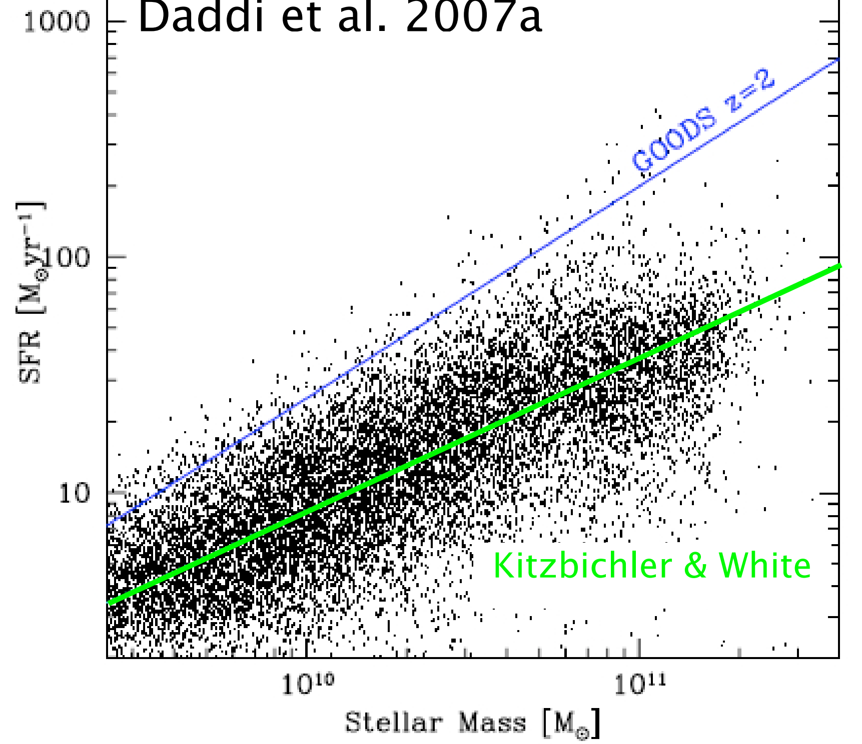
Either our understanding of high z SFR is fundamentally flawed,
(e.g. evolving IMF, Dave/van Dokkum 2007, but results from stellar mass functions are less affected by IMF evolution),

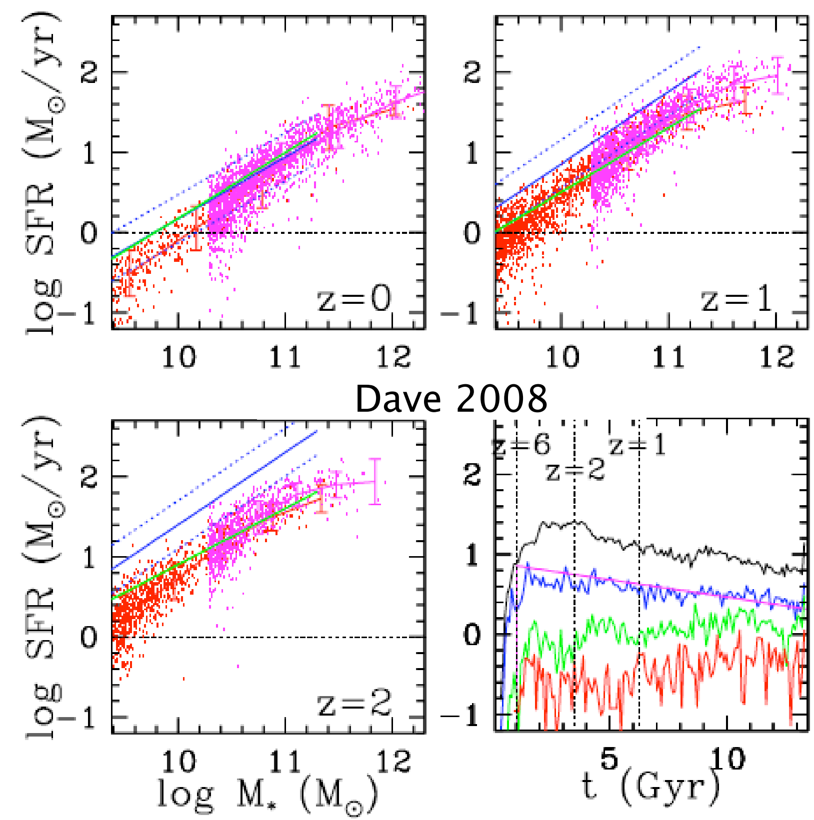
Or we do not understand/correctly treat processes
(if LCDM correct, likely baryonic)
that delay or partially suppress SF
in a mass-dependent way

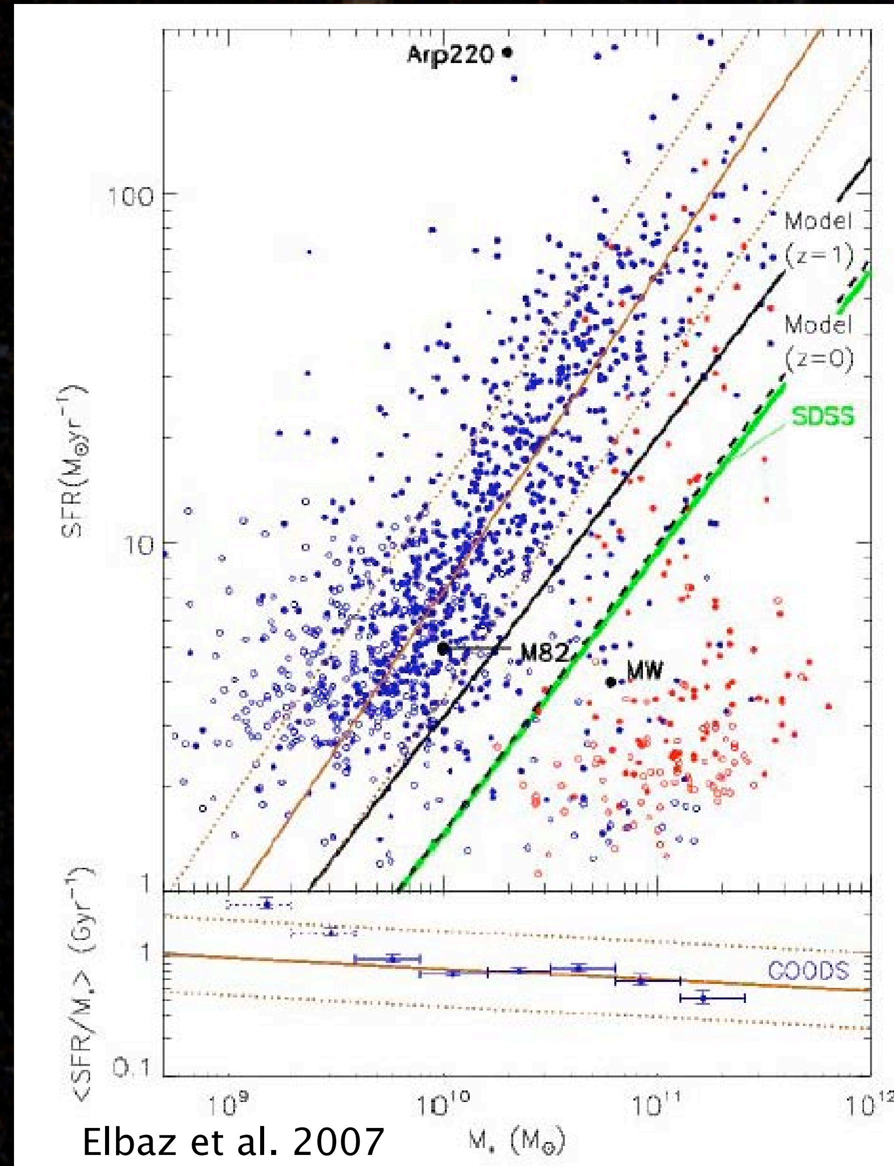
- Current treatments of SN feedback: generally not sufficient
- Suppression of gas cooling by the UV background? only efficient for very low mass halos (but see astro-ph, Susa 2008).
- Additional processes? E.g. H_2 formation/destruction (Robertson+ 2007, Gnedin+ 2008)?

Whatever process, it will lead to higher gas fractions -> higher disk survivability, lower B/T in mergers; bulgeless galaxies

Star Formation in Models vs Data: A mismatch in redshift evolution?







MODELS (SAMs and hydro-sims) reproduce SFR–M* relation,

but predict less z evolution of SFR at a given stellar mass than observations

BUT:

Measuring SFR diagnostics is not trivial.
Various systematics remain poorly understood.

The SFR–M_* relation vs z is fundamental to understand SF and baryon physics of galaxies – improved accuracy of SFR measurements will be important near-future work.

SFR tracers available for large numbers of galaxies to z~2:

1) Thermal IR (usually 24mum + UV continuum) :

Advantage: In principle, self-correcting for extinction (L_{Bol} of young *s)

Problems: AGN - SF separation (Daddi et al. 2007; Rieke et al. 2008)

Are local IR SED templates correct at z>~1?

Hope: longer λ (FIDEL,Herschel,LMT/ALMA); improved diagnostics

2) UV continuum

Advantage: widely available from broad-band imaging to high z

Problems: extinction correction (UV slope, ...) uncertain (Seibert+ 05)

Hope: SED fits (Salim et al.), calib from other tracers

3) Emission lines (Balmer, OII, OIII)

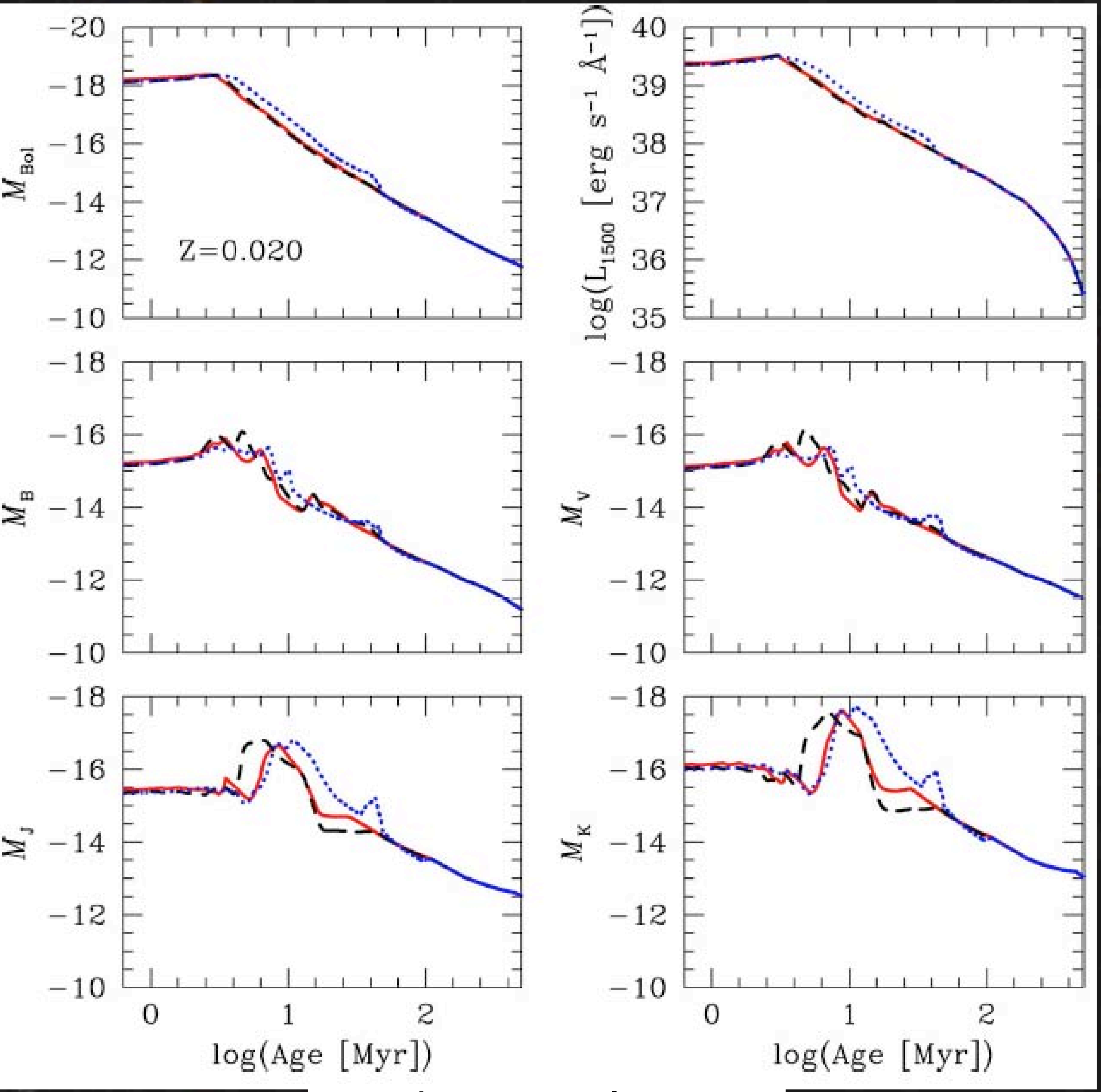
Advantage: Robust extinction correction from Balmer decrement

Problems: Balmer lines need NIR spectroscopy at z~1

OII, OIII depend on T,O/H, calibration problematic

Hope: NIR, massively Multi-Object spectrographs

Common Systematic Uncertainties of SFR measures:



Leitherer et al. 2008

1) IMF:

Evolution with z?

van Dokkum 2008, Dave 2008, Wilkins et al. 2008 (arXiv:0809.2518)

Evolution with Galaxy properties? Meurer et al. 2008

2) Different SFR diagnostics probe different timescales:

problem for young bursts, not for ~continuous SFH

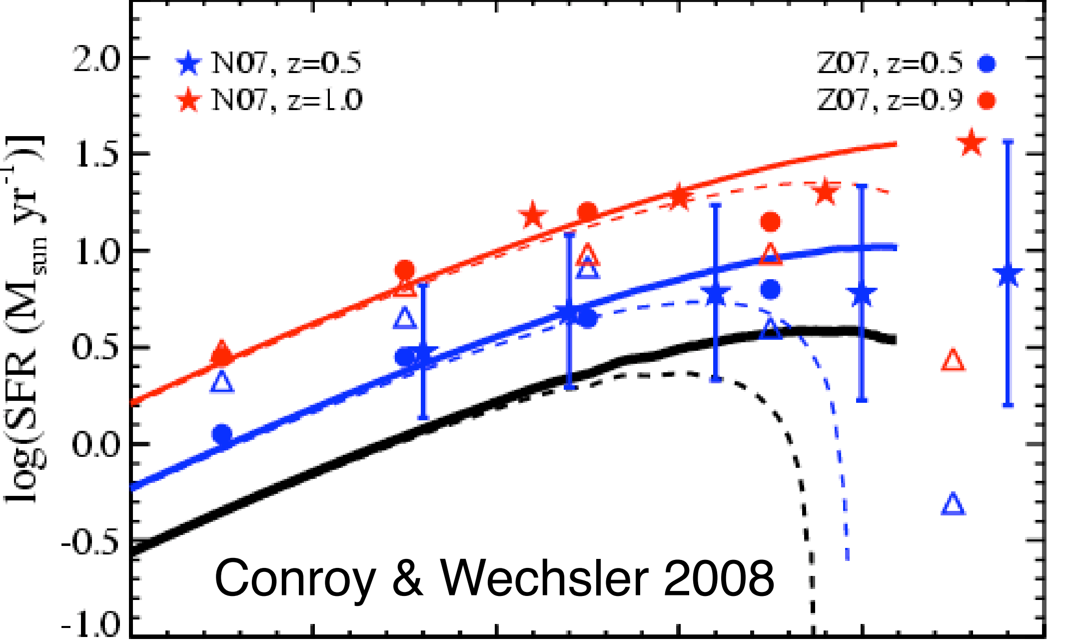
3) Stellar input physics correct (Leiterer 2008, astro-ph)?

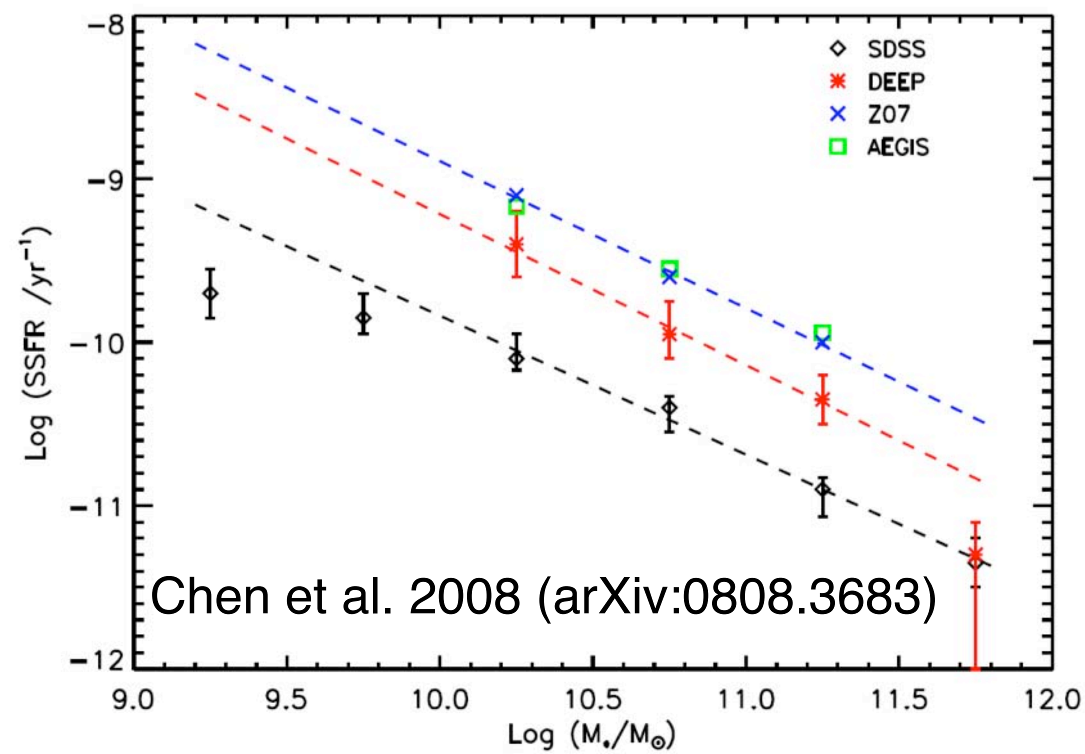
Massive stars with rotation:

SFR(Ha) overest. by 25(50)%

for Z_{solar}(Z_{solar}/5)

Independent Measures of SFR (M,z)





Mass-dependent evolution of stellar mass functions

+probes less massive stars (evolved * pop)

-requires merger mass assembly from LCDM

SSFR (~1Gyr averaged) from PCA of spectral stacks, young stars from Balmer absorption

largely dust-independent

Radio continuum

Dunne et al. 2008, arXiv: 0808.3193

Encouraging:

Even out to z~2, SFR measures agree within <~x2

(on average!)

Summary (1):

(NOTE: star-forming field galaxies)

1) Star formation in multi-wavelength surveys:

Main Sequence of SF galaxies, limited range of SFR at a given M,z.

2) Limits amplitude of starbursts, merger effects on SFR.

3) Gradual decline of SF, not starbursts, dominant since z<2+;

- most stellar mass formed in continuous mode of SF
- starbursts (merger-driven, others) play modest, non-evolving role
- LIRGs at z>>0 are not brief, stochastic starbursts, but the early, gas-rich phase of the smoothly declining SF history of >~L* galaxies

4) New scenario: less massive galaxies have longer SF timescales, and a delayed onset of major star formation

→ 2 effects contributing to "downsizing": $\tau(M)$, $z_f(M)$

5) Mass-dependent τ models: model of SFR vs M, z over 2/3 t_H

Summary (2):

6) "Observed" SFR include many simple assumptions, like models

7) Different SFR measures differ by <~x2 (rms!) at z<1.

At z>~2 mostly <~x2, expect worse for extreme objects (high SFR, obscured AGN, ...).

8) Additional systematic uncertainties:

IMF, physics of massive stars -> together another factor ~x2

9) Hope from comparing SFR tracers:

- Add multi-lambda, FIR, mm, radio
- probe stars of different masses
- less dust-affected techniques

Systematic SFR offsets between models and data at a factor of ~2 do not imply incorrect model physics