The baryon cycle and its (lack of) environmental dependencies

or

Environmental dependencies of gas-fuelling

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with

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Baryon Cycle: Expectations

$$\dot{M}_{\rm ISM} = \dot{M}_{\rm in} - \lambda\Phi_* - (1-\alpha)\Phi_*$$

$$= \overbrace{\dot{M}_{\rm in} - \frac{M_{\rm ISM}}{\tau_{\rm res}}}^{\dot{M}_{\rm in,eff}} - (1-\alpha)\kappa M_{\rm ISM}$$

Gas-fuelling/ Accretion

Ext. Pres.

Feedback

SFE

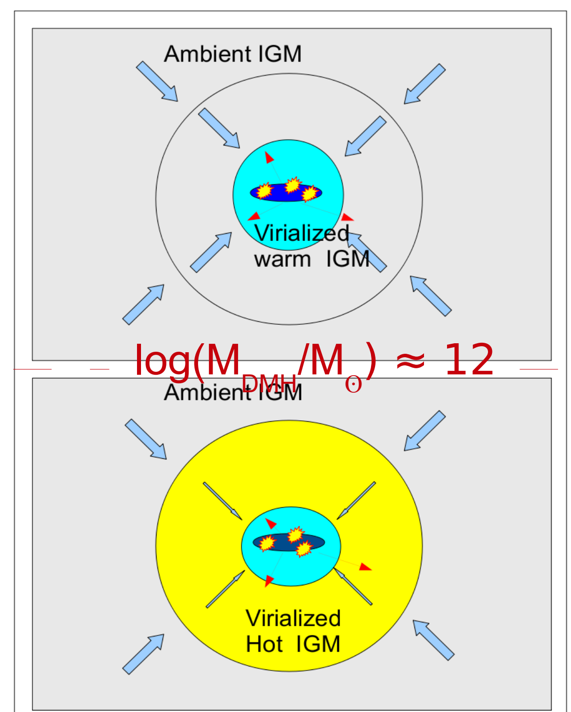
Set by environment, halo mass

Set by galaxy properties, e.g. stellar mass

Effective Inflow / Gas-fuelling depends on environment and galaxy specific properties

Expect self-regulated balance if timescale on which inflow changes is large compared to timescales given by $\tau_{\rm res}$ and κ

→ MS evolution with halo accretion rate



(e.g. Davé+11,Lilly+13,Saintonge+13)

Baryon Cycle: Expectations

≳40 % of galaxies reside in groups
(Eke+2004,Robotham+2011)

Central & Satellite Galaxies

Satellite galaxies:

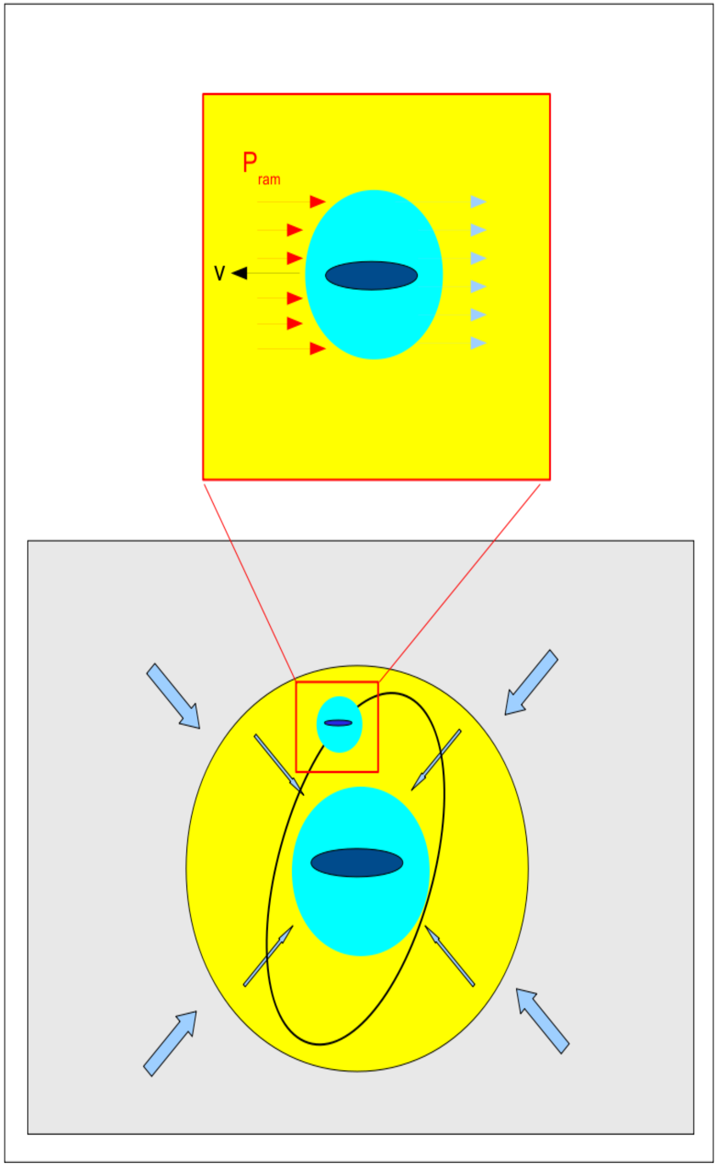
Ram-pressure stripping
(Gunn&Gott1978)

'Strangulation'
(Larson+1980,Kimm+2008)

⬇

No gas-fuelling

Quenching of SF



Baryon Cycle: Expectations

- Effective inflow dependent on galaxy and environmental properties (stellar mass & halo mass)
- Gradually evolving self-regulated equilibrium effective inflow / SFR for MS galaxies/central galaxies; evolution traces halo accretion rate
- Zero or negative (over-consumption McGee+2014) effective inflow for satellite galaxies
- Systematically lower/quenched SFR for satellite galaxies

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We lack an (incisive) empirical reference for these expectations

What's the problem?

Gas content is hard to measure for large complete samples (spanning redshift and environment); Use proxy – invert KS

MS / Centrals	Satellites
Disentangle SFE and accretion	As for centrals but in addition:
Probe halo mass	Morphology -density relation (SFE)
Dominance of stellar mass dependency	Galaxy-Galaxy interactions (SFE and addition/removal of gas)
SFE and galaxy dichotomy	Sensitivity on timescales short w.r.t dynamical timescale

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BUILD SAMPLES FROM GAMA*

* In a smart way

The GAMA survey

Driver+2011, Liske+2015

300 k redshifts

r < 19.8 $_{AB}$mag

Quantitative spectroscopy

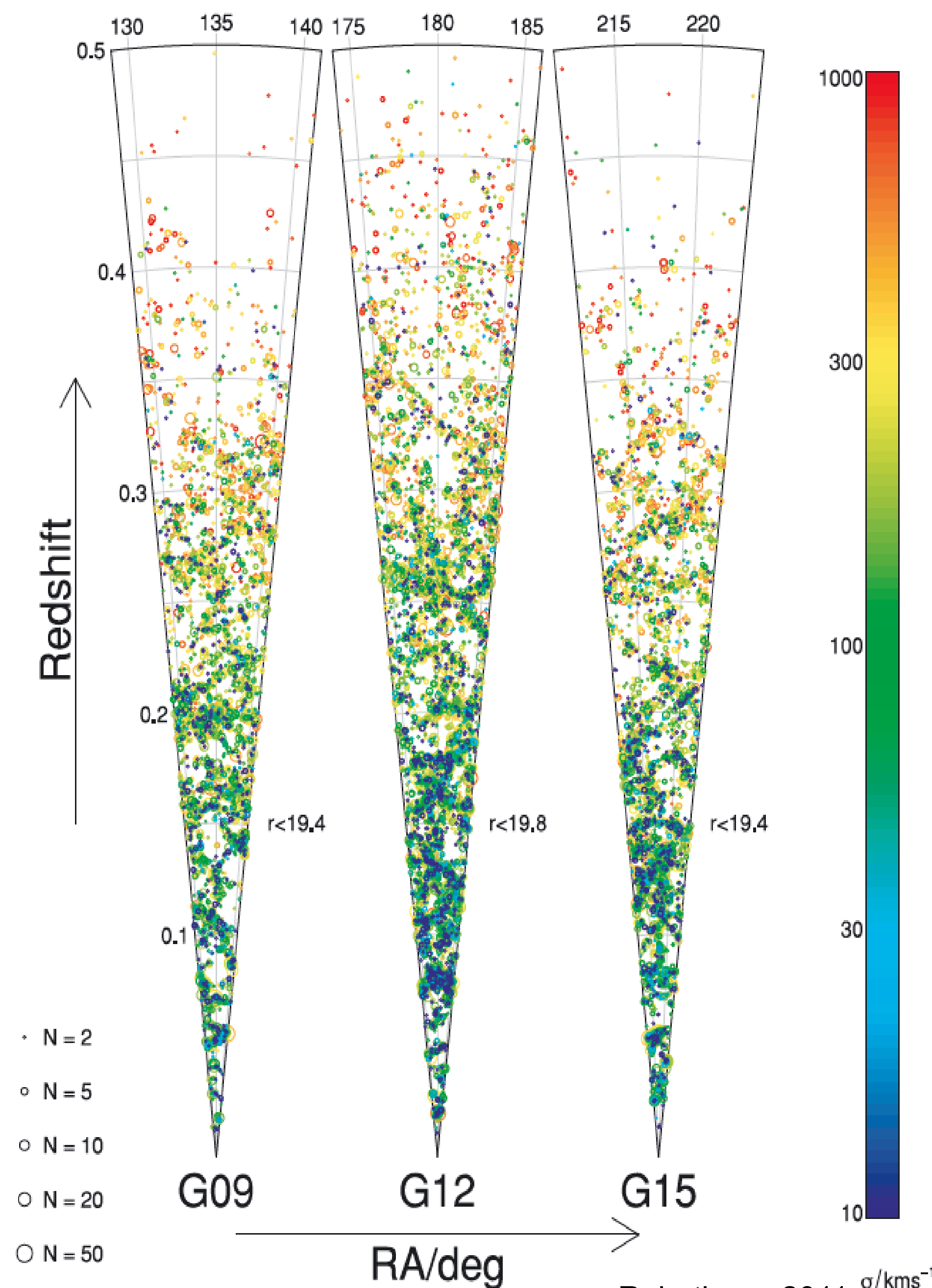
>98% target completeness,
even in crowded regions

HMF to $\lesssim 10^{12}$ $M_\odot$

Unprecedented characterization
Of cosmic web and galaxy groups
Over z=0-0.5

Complementary coverage of full
UV – FIR/submm SED with uniform
broad-band photometry

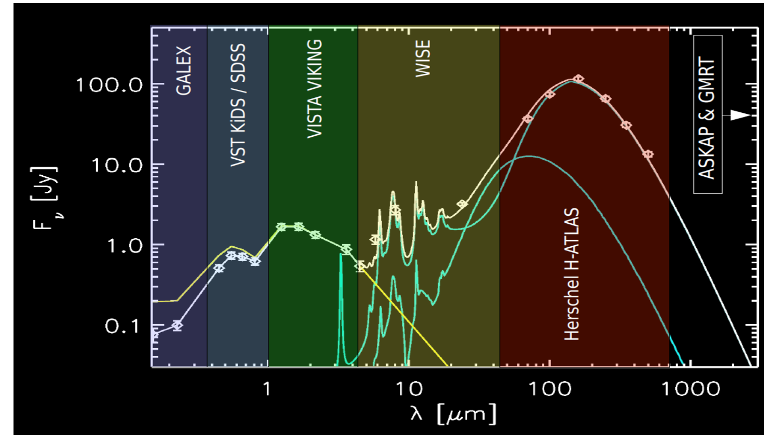
DR2 availabale (www.gama-survey.org)
DR3 (full release) end of the year

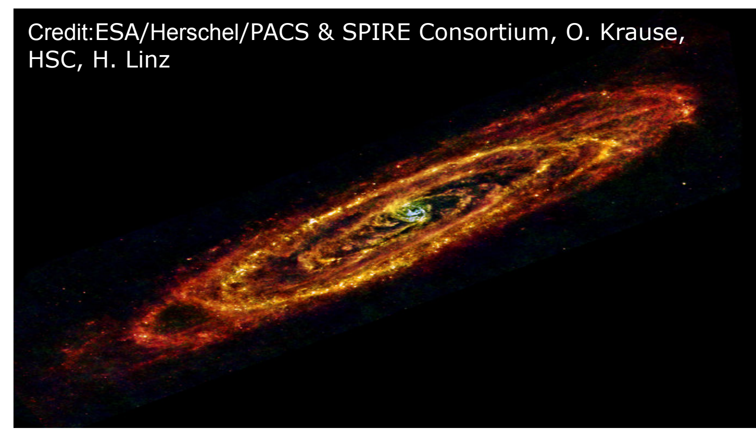


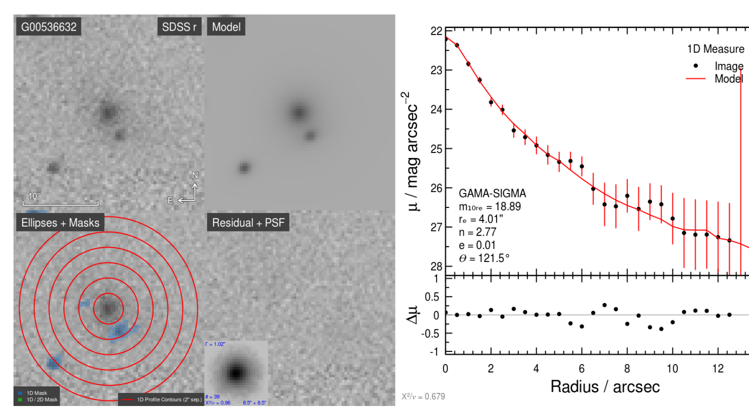
Robotham+2011

Building Samples

- Construct a pure and complete morphologically selected volume limited ($z < 0.14$, $\log(M^*) > 9.5$) sample of central and satellite disk/spiral galaxies using a new purpose built method (Grootes+2014)
- Apply a 'relative' isolation criterion for group galaxies (no neighbour within 50 kpc/h projected and 1000 km/s)
- Deselect AGN host galaxies using BPT emission line diagnostics
- Determine highly accurate NUV-based star formation rates using radiative transfer modelling techniques applied to large samples (Popescu+2011, Grootes+2013)




Credit:ESA/Herschel/PACS & SPIRE Consortium, O. Krause, HSC, H. Linz



Kelvin+2012

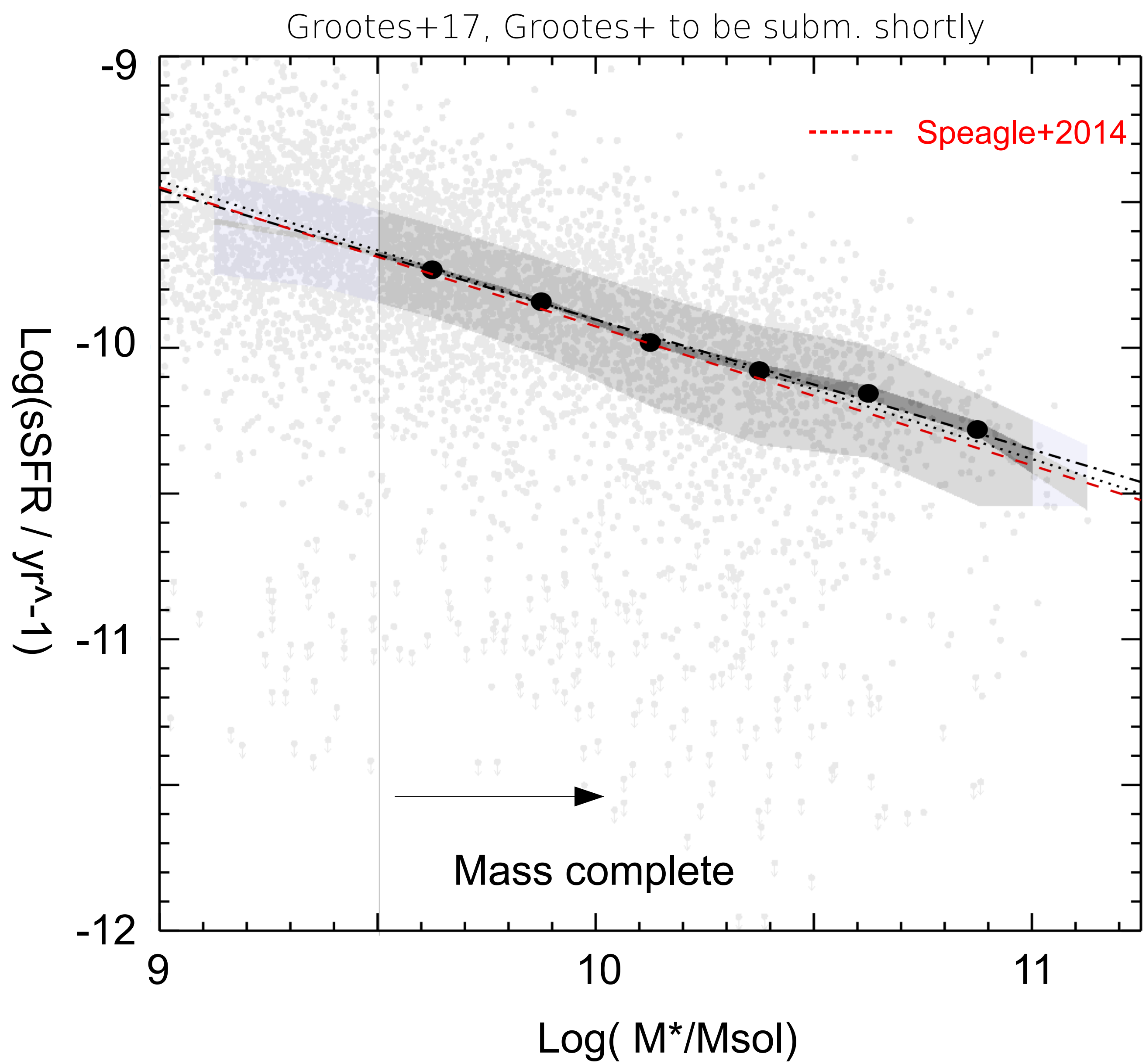
MS of Field disk galaxies

z < 0.13, 3500 (5300) galaxies

<z> = 0.1

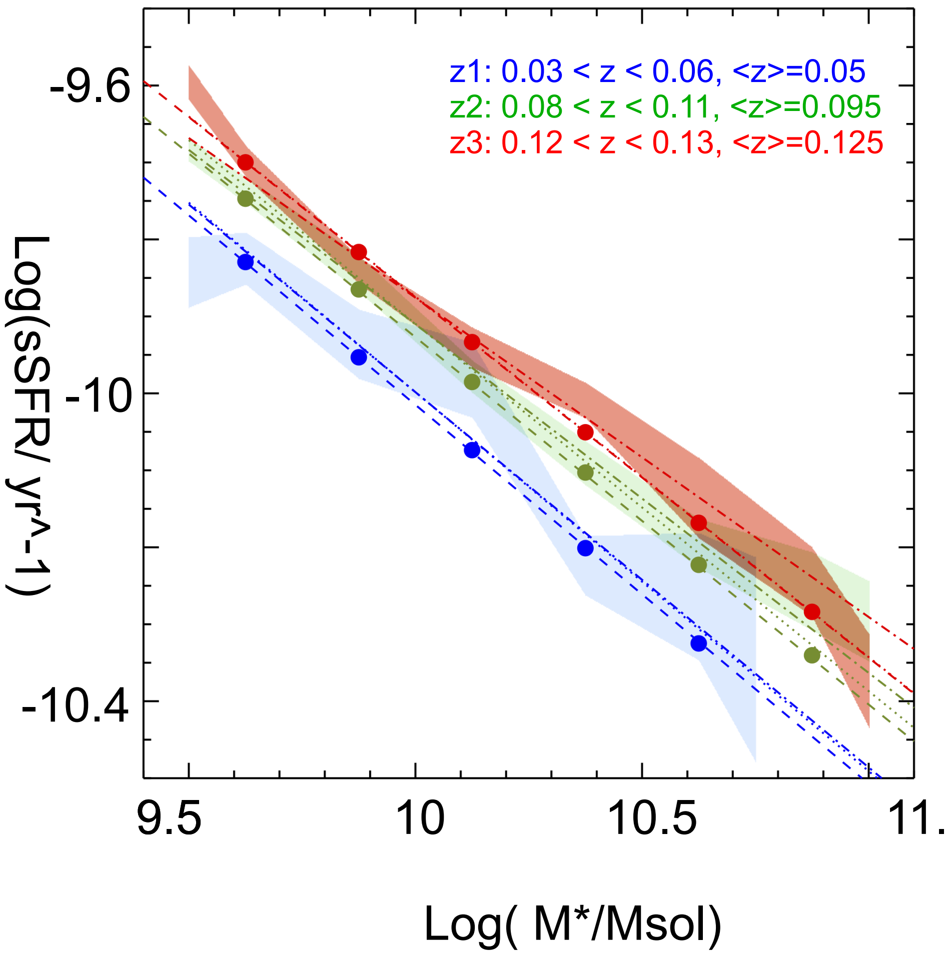
γ = -0.45 +/- 0.01

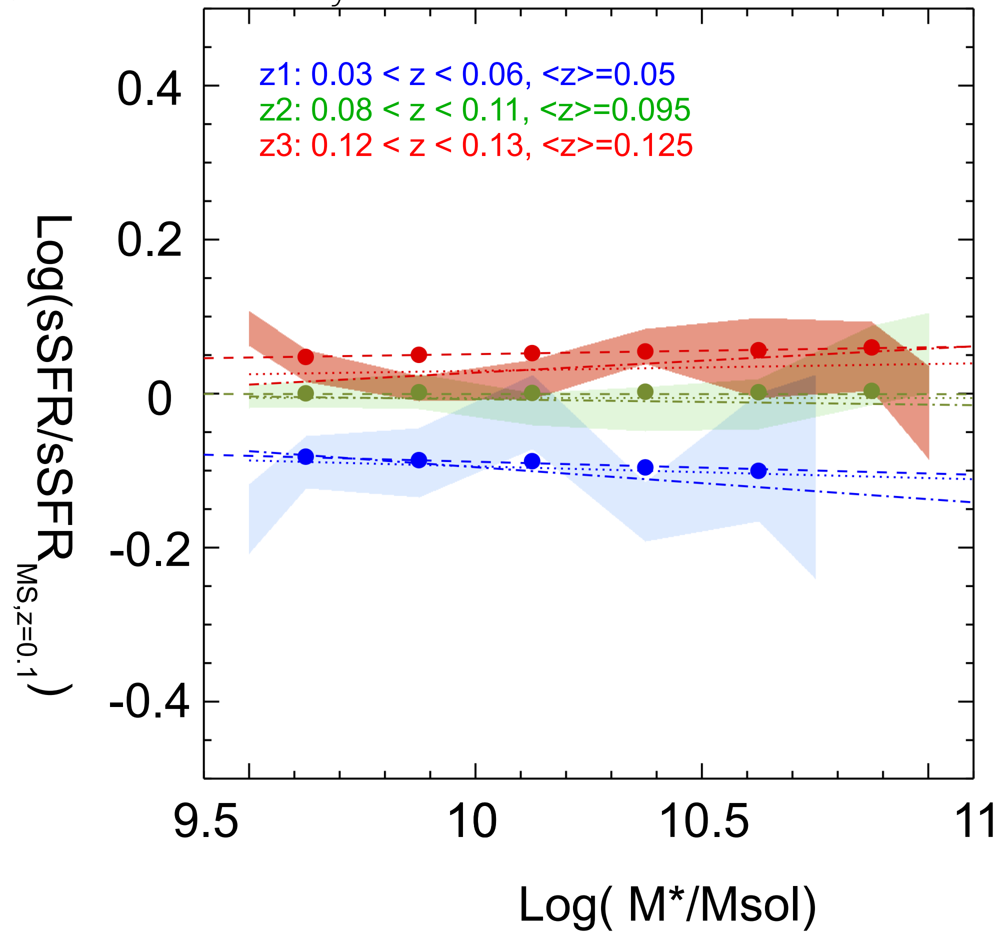
Consistent with full main sequence (Speagle+2014)



Redshift evolution of the 'MS'

Grootes+ to be subm. shortly

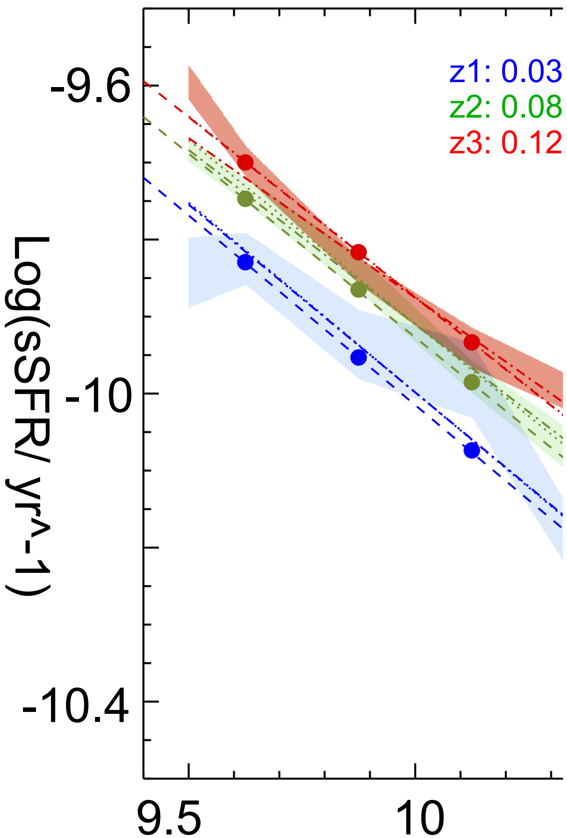


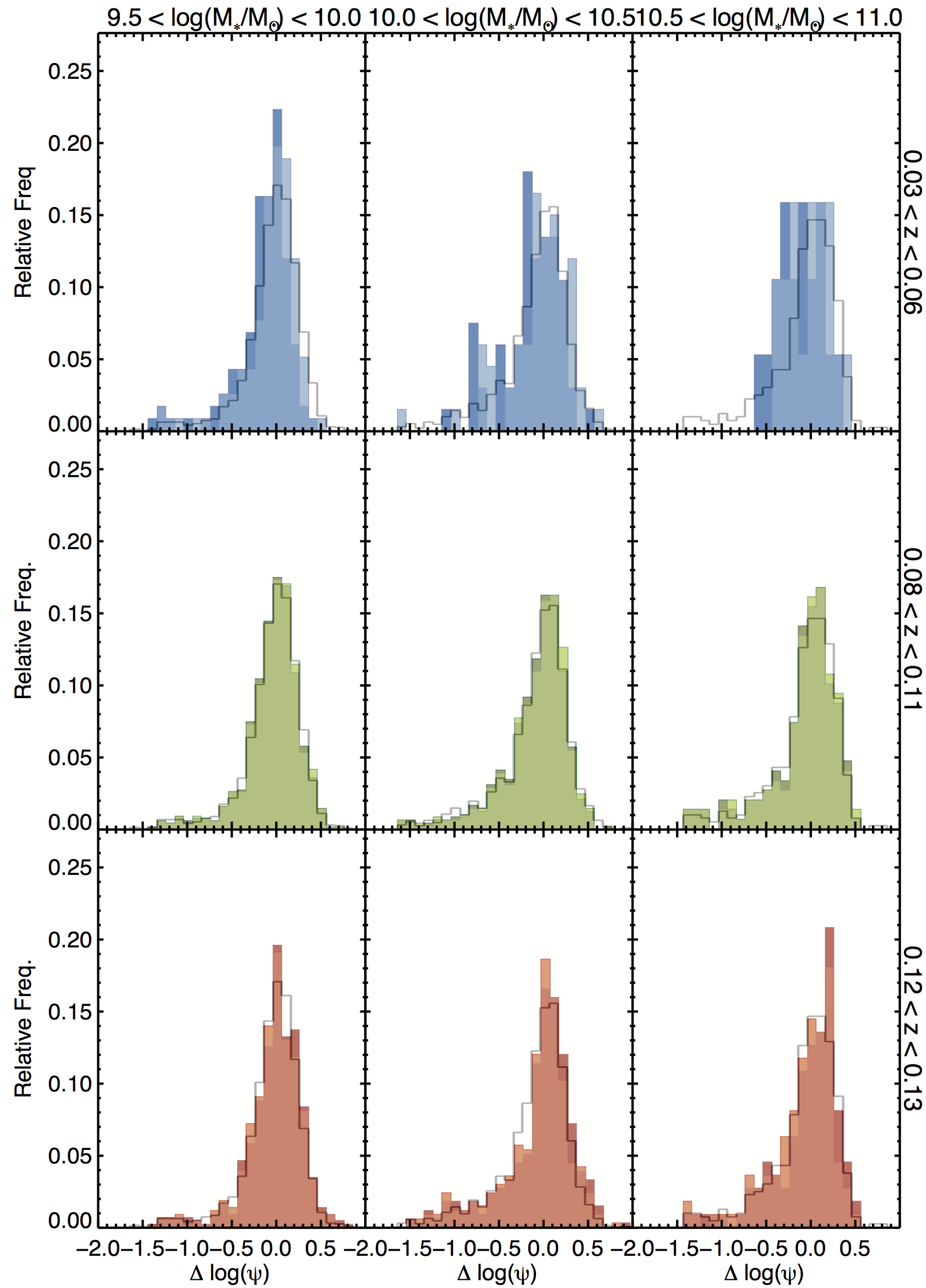


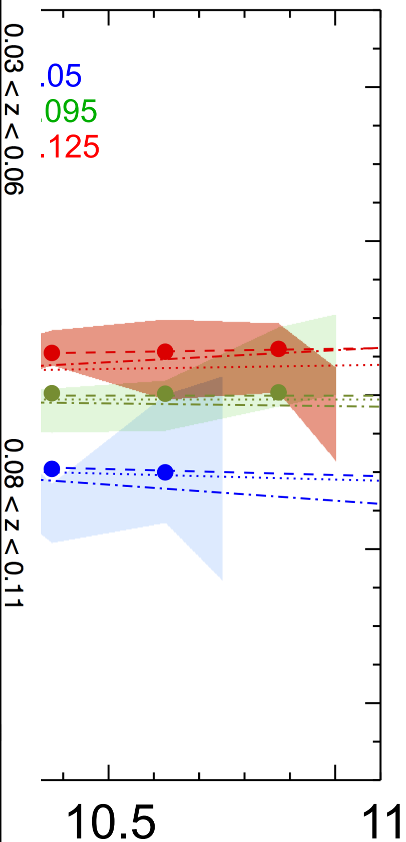
Normalization and slope consistent with MS (Speagle+2014) for each redshift subsample

Evolution of normalization consistent within uncertainties

Redshift evolut







Normalization a
(Speagle+2014)

Evolution of nor

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Redshift evolution of the 'MS'

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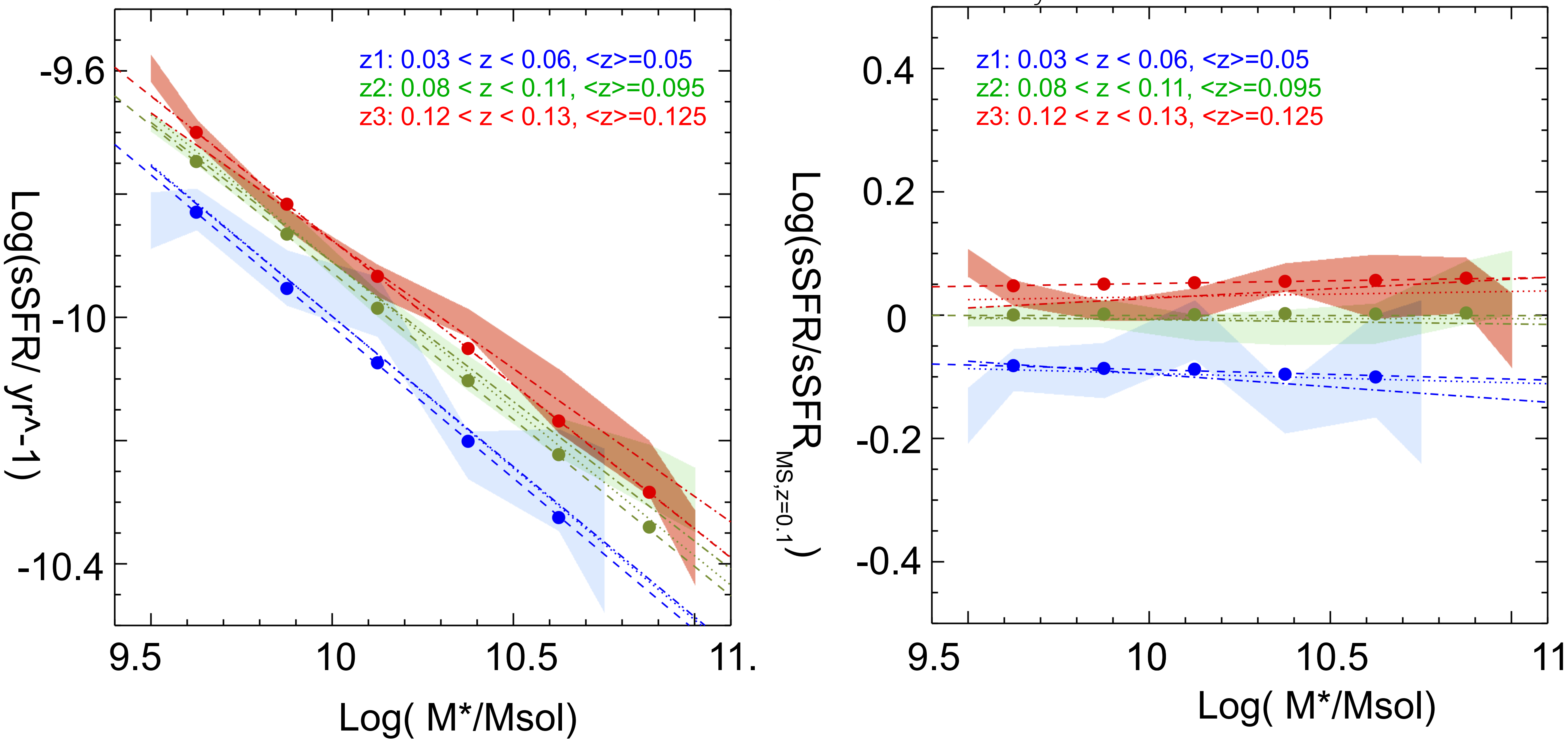
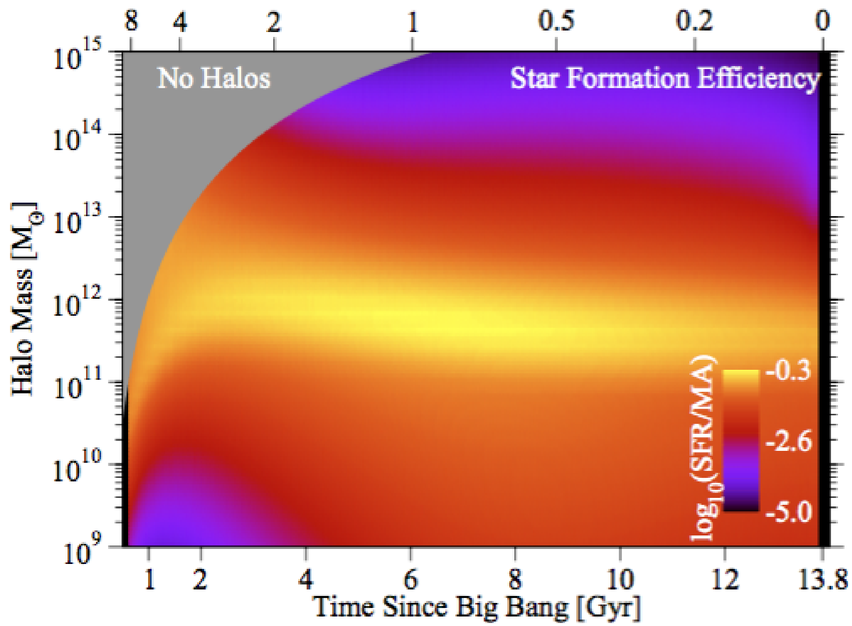


Normalization and slope consistent with MS (Speagle+2014) for each redshift subsample

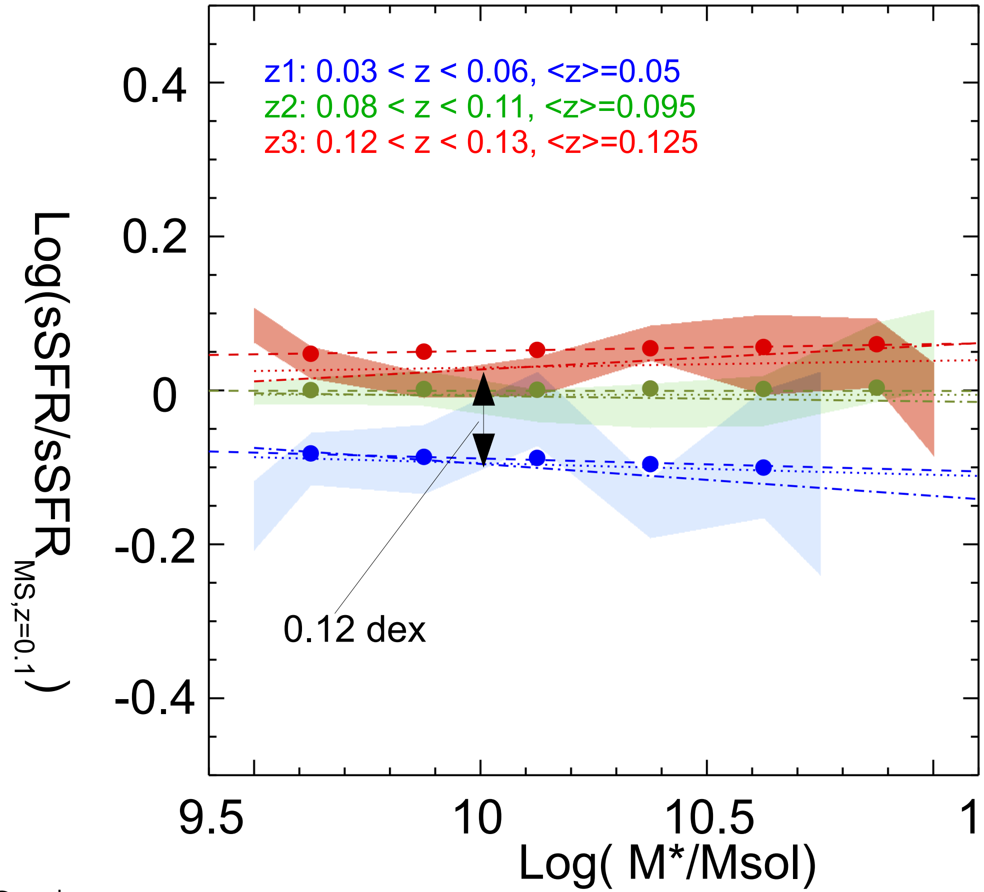
Evolution of normalization consistent within uncertainties

Offset distributions statistically indistinguishable, true evolution of normalization; SFE likely constant

Redshift evolution of the 'MS'



Behroozi+2013



Grootes+ to be subm. shortly

Evolution z3 → z1: decrease by ~ 0.12 dex

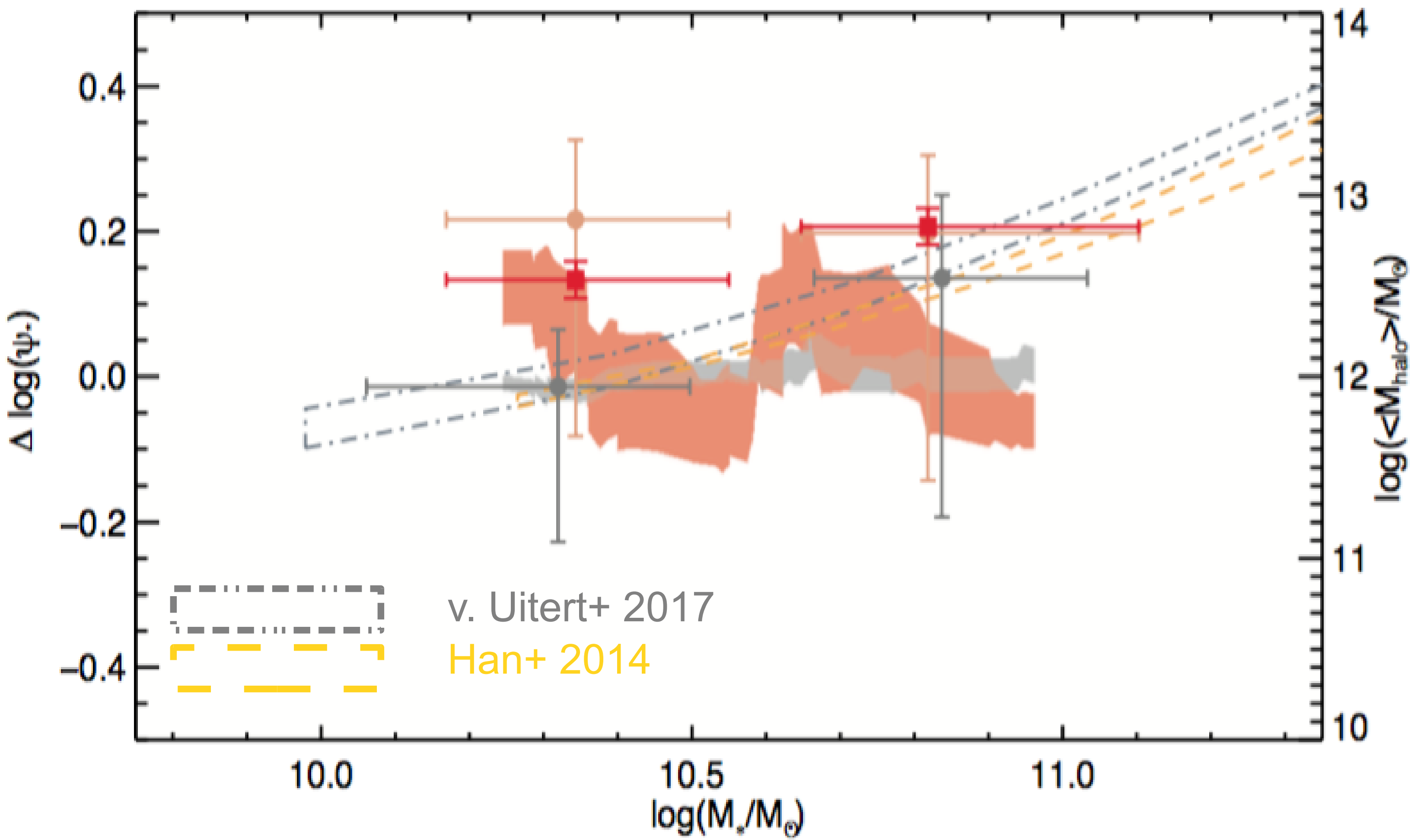
Expected decrease in halo mass accretion rate (HMR) only ~0.06 dex

Decrease in SFR/HMR (Behroozi+2013) ~0.06 dex; Interpret as decrease in accretion at const. SFE.

MS evolution even in local Universe and over short Δz consistent with self-regulated SF with inflow tracing halo accretion, but require evolving accretion efficiency

Halo mass dependence

Grootes+ to be subm. shortly



Group and field central disk galaxies have statistically indistinguishable sSFR-M* relations

Halo mass dependence

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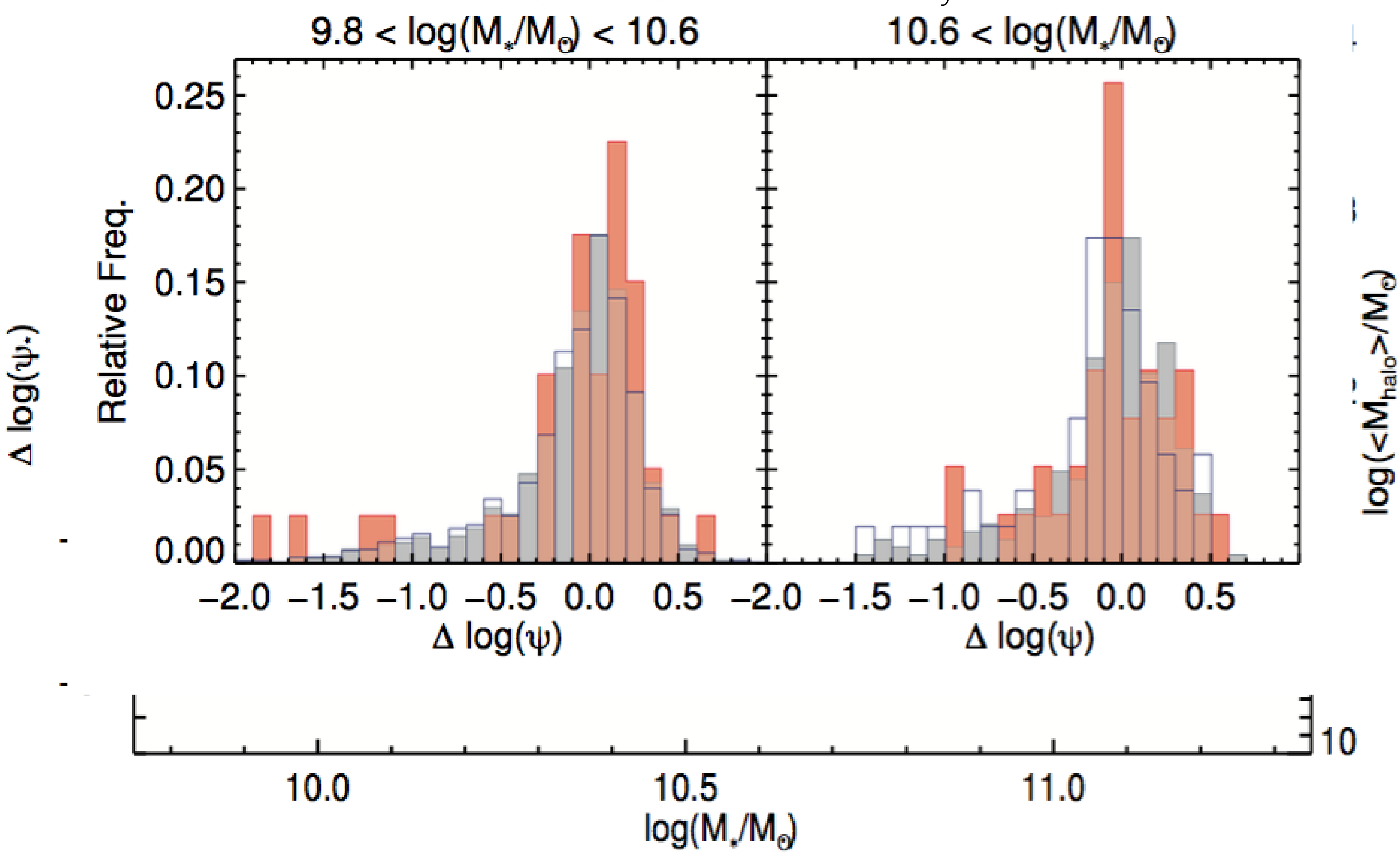

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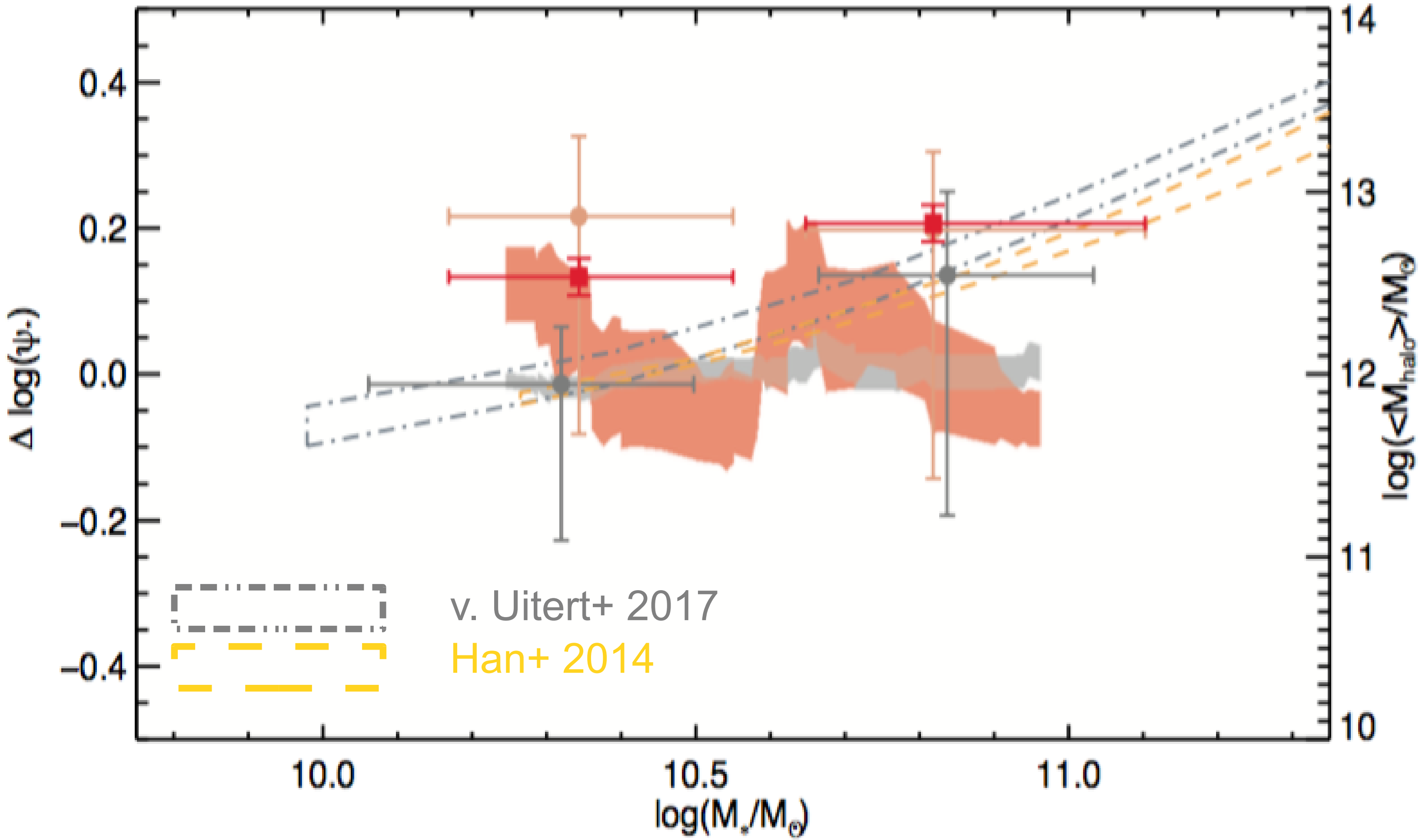
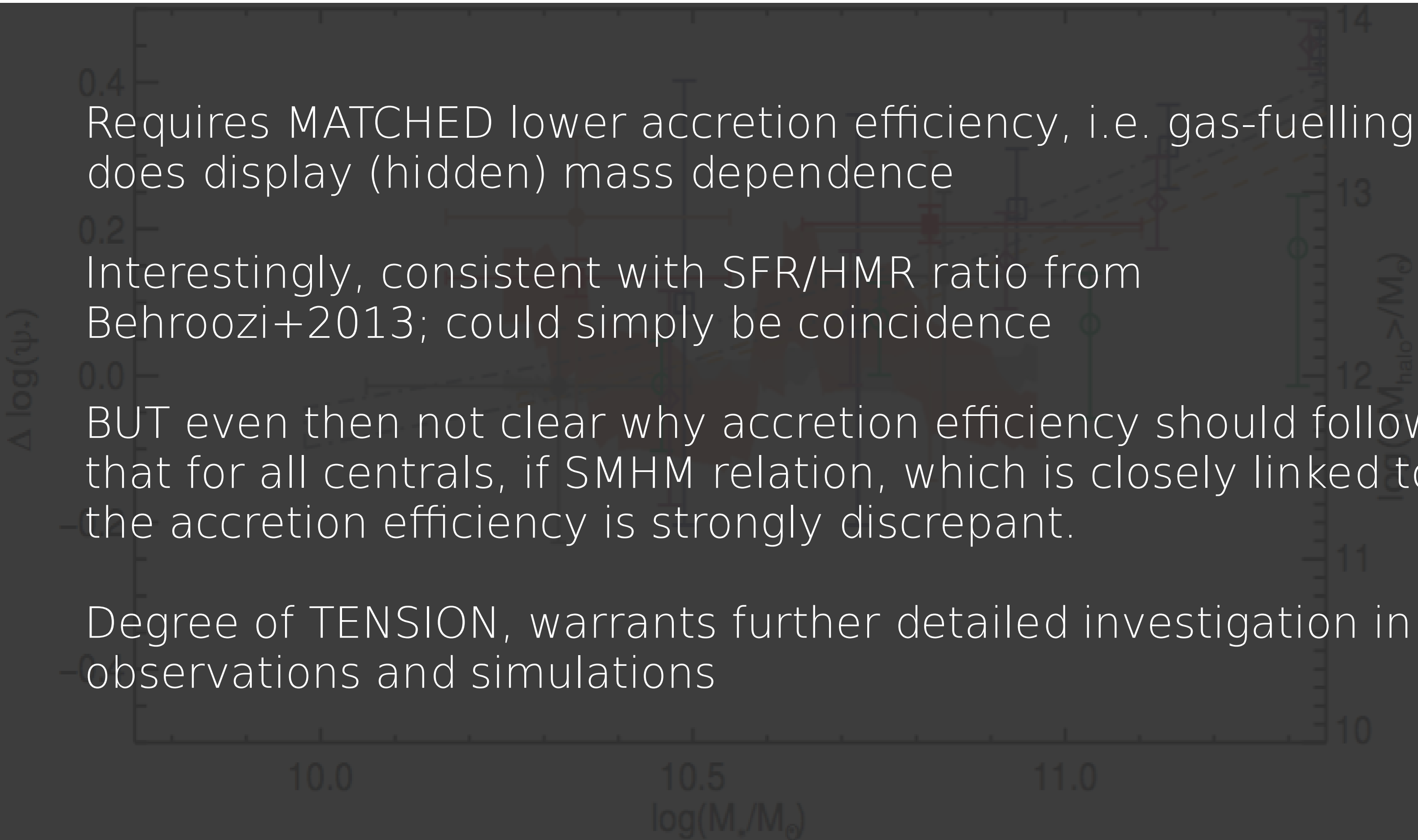


Group and field central disk galaxies have statistically indistinguishable sSFR-M* relations

For lower M* range WL masses from KiDS data suggest 4-8 times more massive DMH for group central disks at fixed M* ; implies a 4.5-9.5 times higher HMR

Halo mass dependence



Requires MATCHED lower accretion efficiency, i.e. gas-fuelling does display (hidden) mass dependence

Interestingly, consistent with SFR/HMR ratio from Behroozi+2013; could simply be coincidence

BUT even then not clear why accretion efficiency should follow that for all centrals, if SMHM relation, which is closely linked to the accretion efficiency is strongly discrepant.

Degree of TENSION, warrants further detailed investigation in observations and simulations

Group and field central disk galaxies have statistically indistinguishable sSFR-M* relations

For lower M* range WL masses from KiDS data suggest 4-8 times more massive DMH for group central disks at fixed M* ; implies a 6-9 times higher HMR

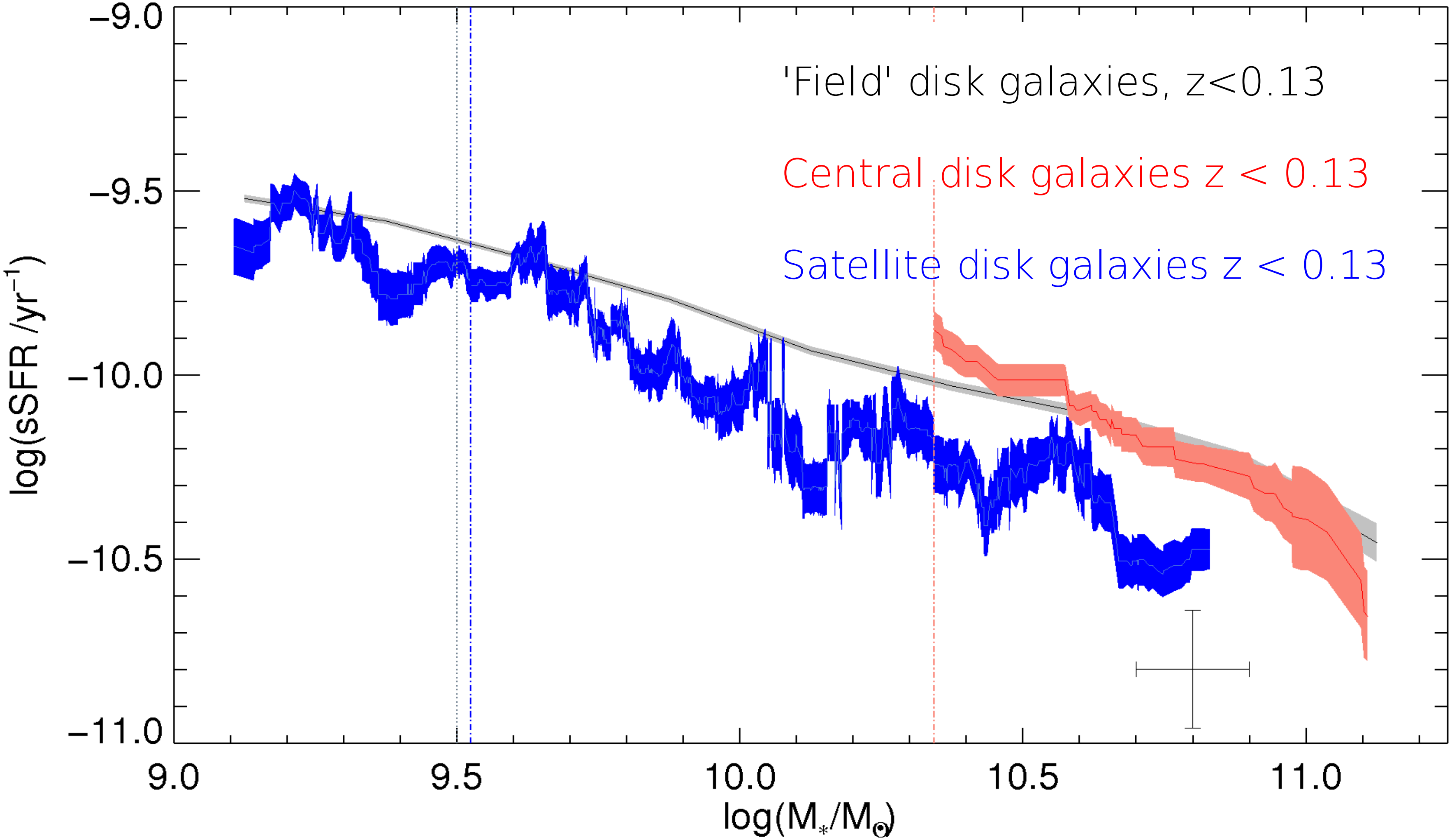
Intermediate Conclusions

Central disks

- Local Universe field MS (of disks) consistent with self-regulated evolution tracing HMR with varying efficiency

- No impact of halo mass on sSFR-M* relation of centrals; possibly consistent with co-incidental counterbalancing inflow rate and accretion efficiency (a hidden halo mass dependence on inflow), but even then tension with SMHM relation

Satellites and Centrals

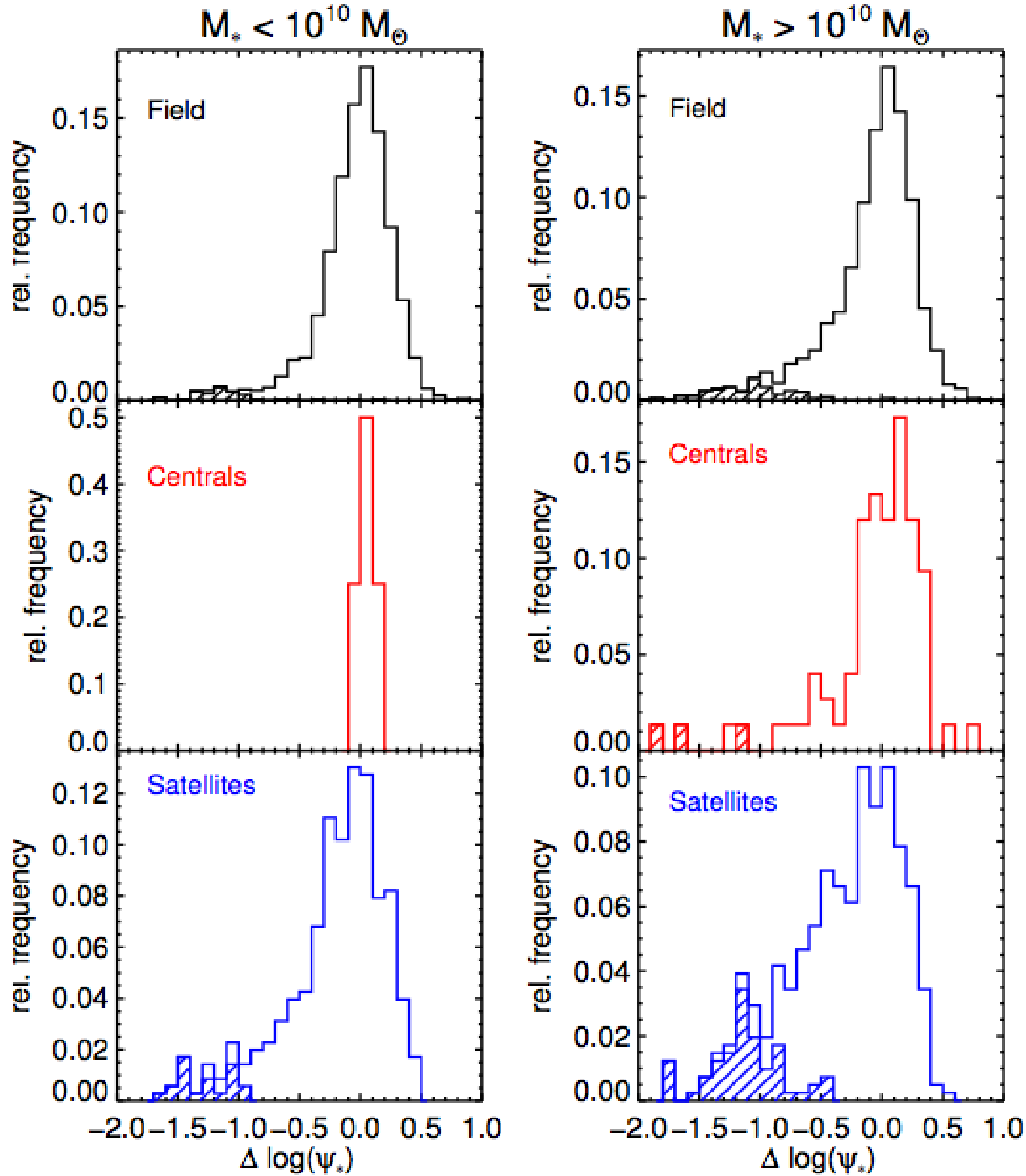


Grootes+2017

Satellites and Centrals

disk fraction only decreases by 40% w.r.t field

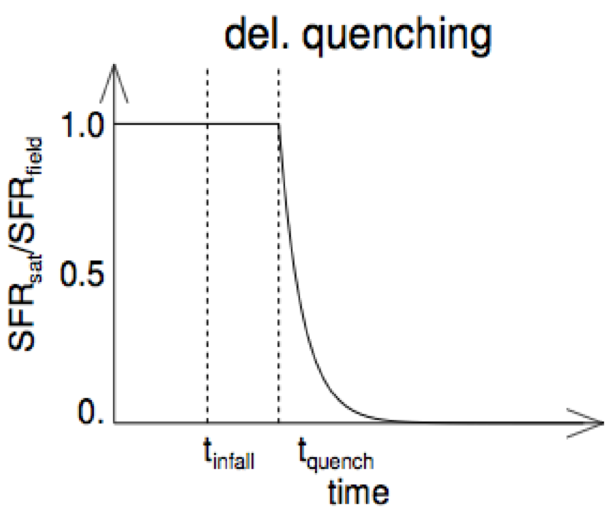
Large fraction of galaxies have spent Gyrs as satellites



Modelling Disk Satellites

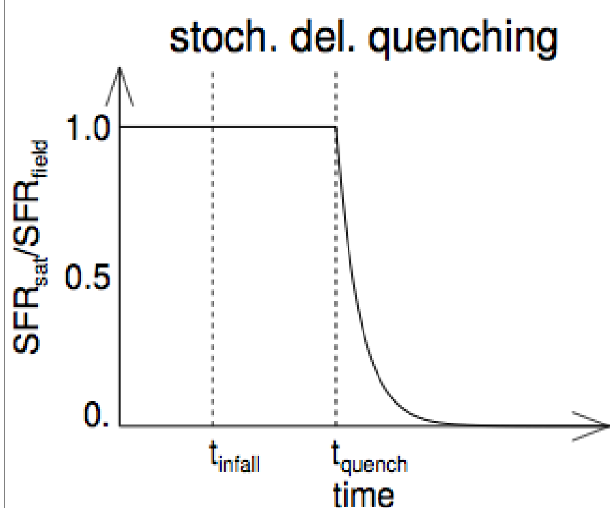
Parametrized SFH

Identify key characteristic elements of underlying SFH



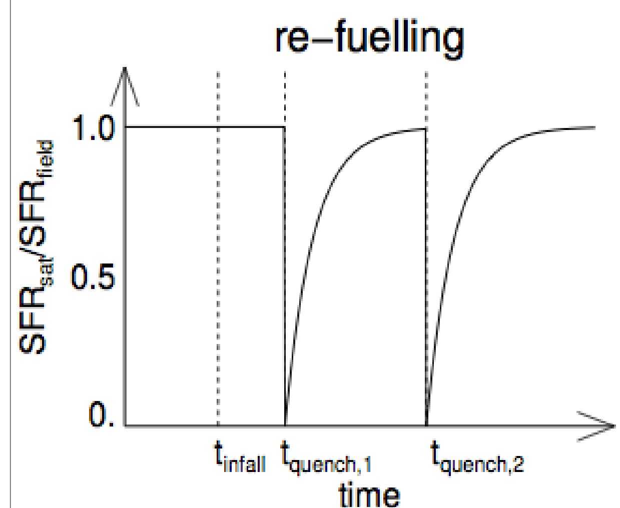
Fixed delay time

Exponential decay



Stochastic delay time

Exponential decay



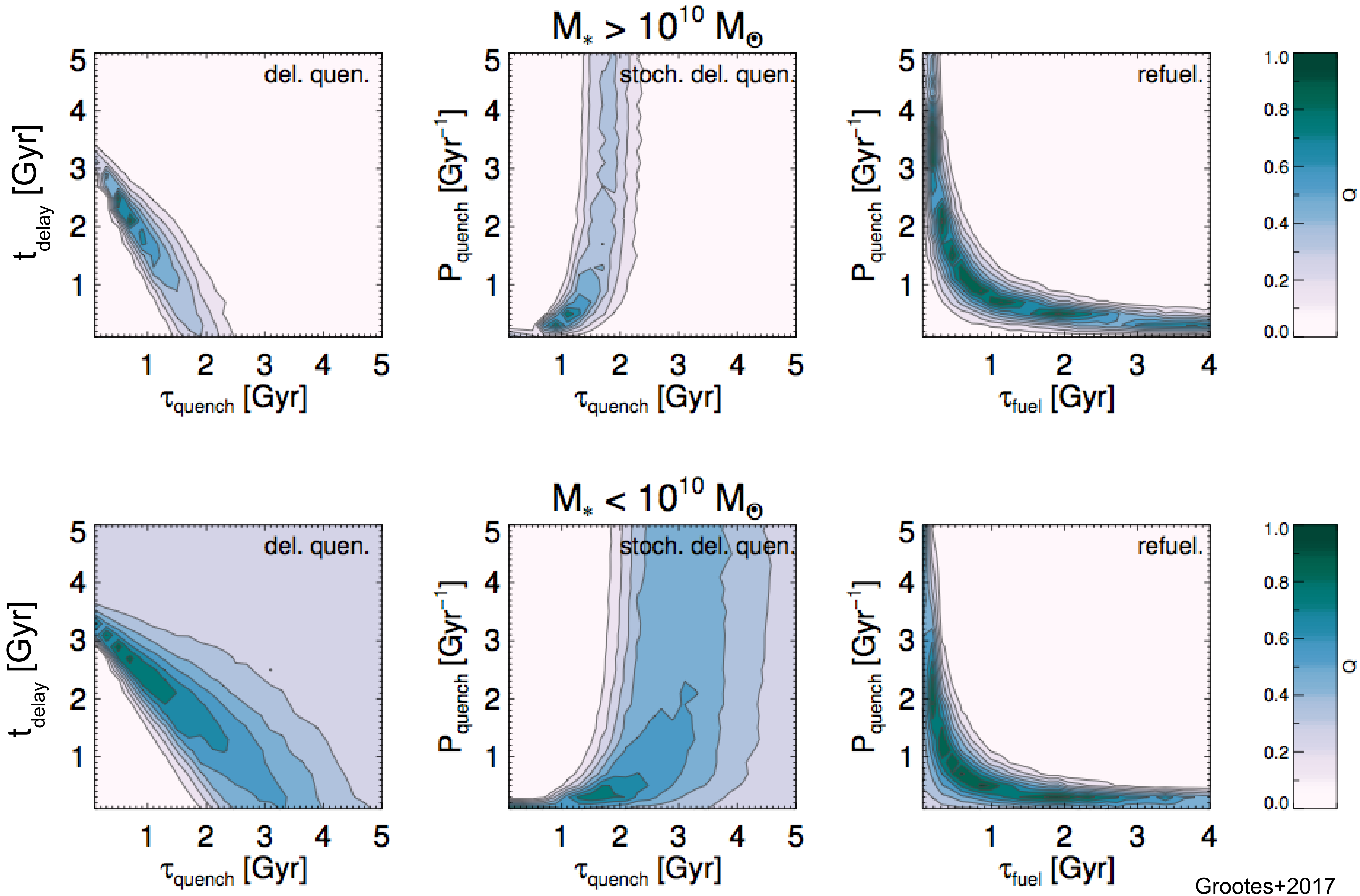
Stochastic instantaneous quenching

Exponential resurrection

Repeated quenching

Grootes+2017

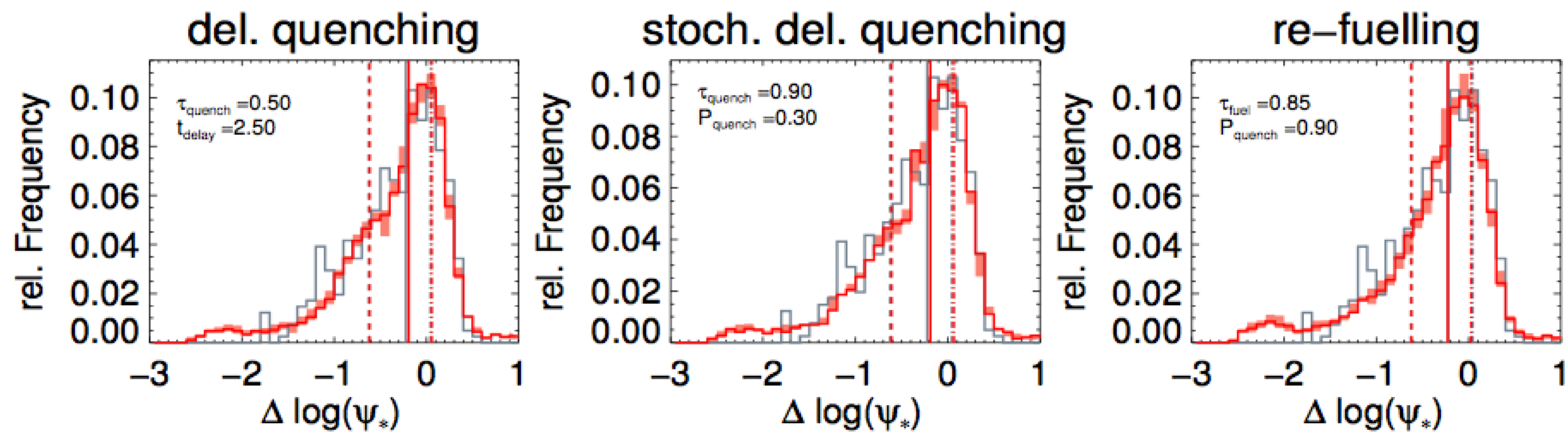
Comparison with data



Grootes+2017

Comparison with data

$M_* > 10^{10}\ M_\odot$



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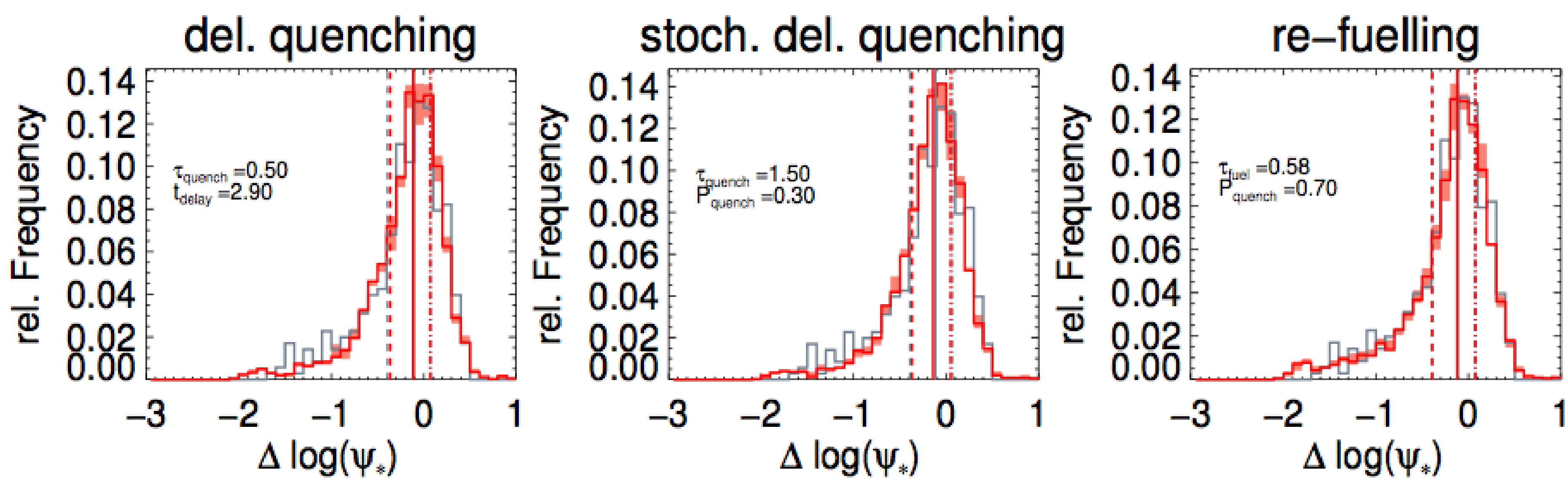

Grootes+2017

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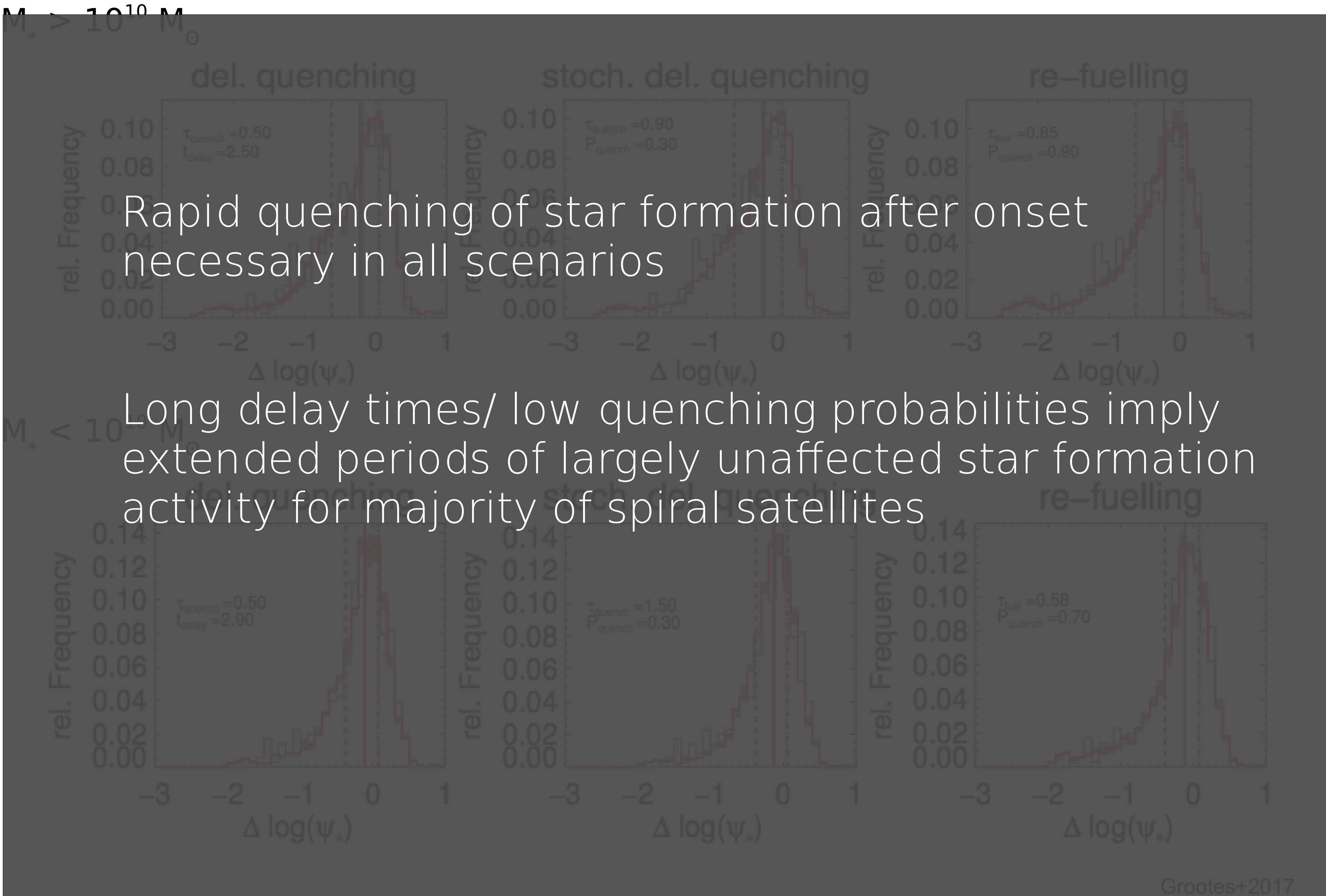


Rapid quenching of star formation after onset necessary in all scenarios

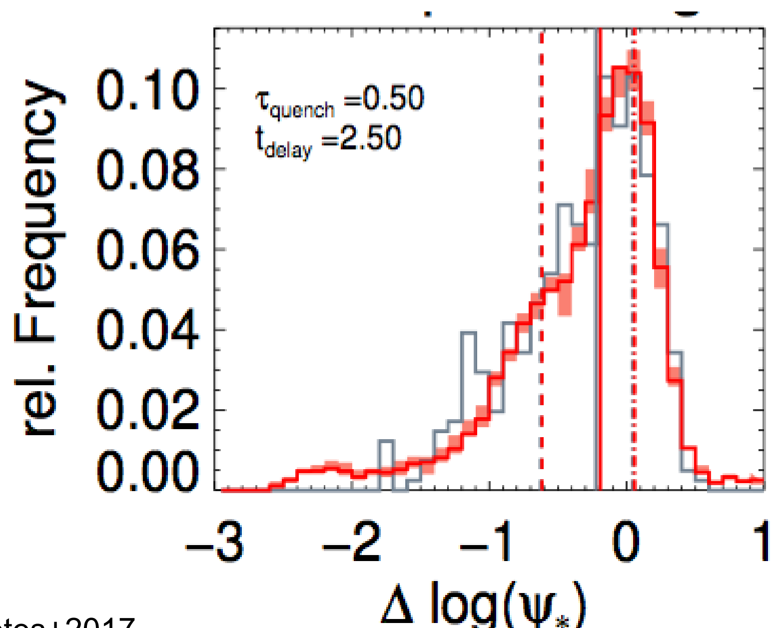
Long delay times/ low quenching probabilities imply extended periods of largely unaffected star formation activity for majority of spiral satellites

Connecting to the gas-cycle

Rapid cycle of gas into/out of ISM ~ several times SFR

For all models gas associated with galaxy upon infall (ISM & CGM) insufficient to support sustained SF activity

Require (additional) fuelling of ISM from IGM of group at rate comparable to SFR (depends on retention of ISM & CGM)



Grootes+2017

steady-state

$$\dot{M}_{\rm in} = (\frac{1}{\tau_{\rm res}} + \kappa) M_{\rm ISM}$$

Identify SFH with solutions

$$\frac{1}{\tau_{\rm quench}} = \frac{1}{\tau_{\rm res}} + \kappa$$

$$\frac{1}{\tau_{\rm fuel}} = \frac{1}{\tau_{\rm res}} + \kappa$$

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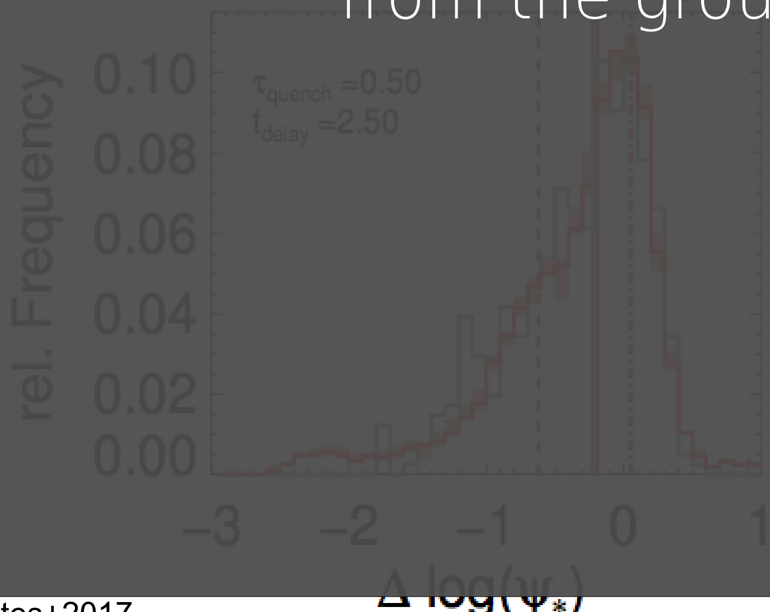
Contrary to expectations the preferred SFH elements imply on-going gas-fuelling of satellite spiral galaxies over extended periods via accretion of gas from the group halo (IGM) into the ISM

steady state $$\dot{M}_{\rm in} = \left(\frac{1}{\tau_{\rm res}} + \kappa\right) M_{\rm ISM}$$



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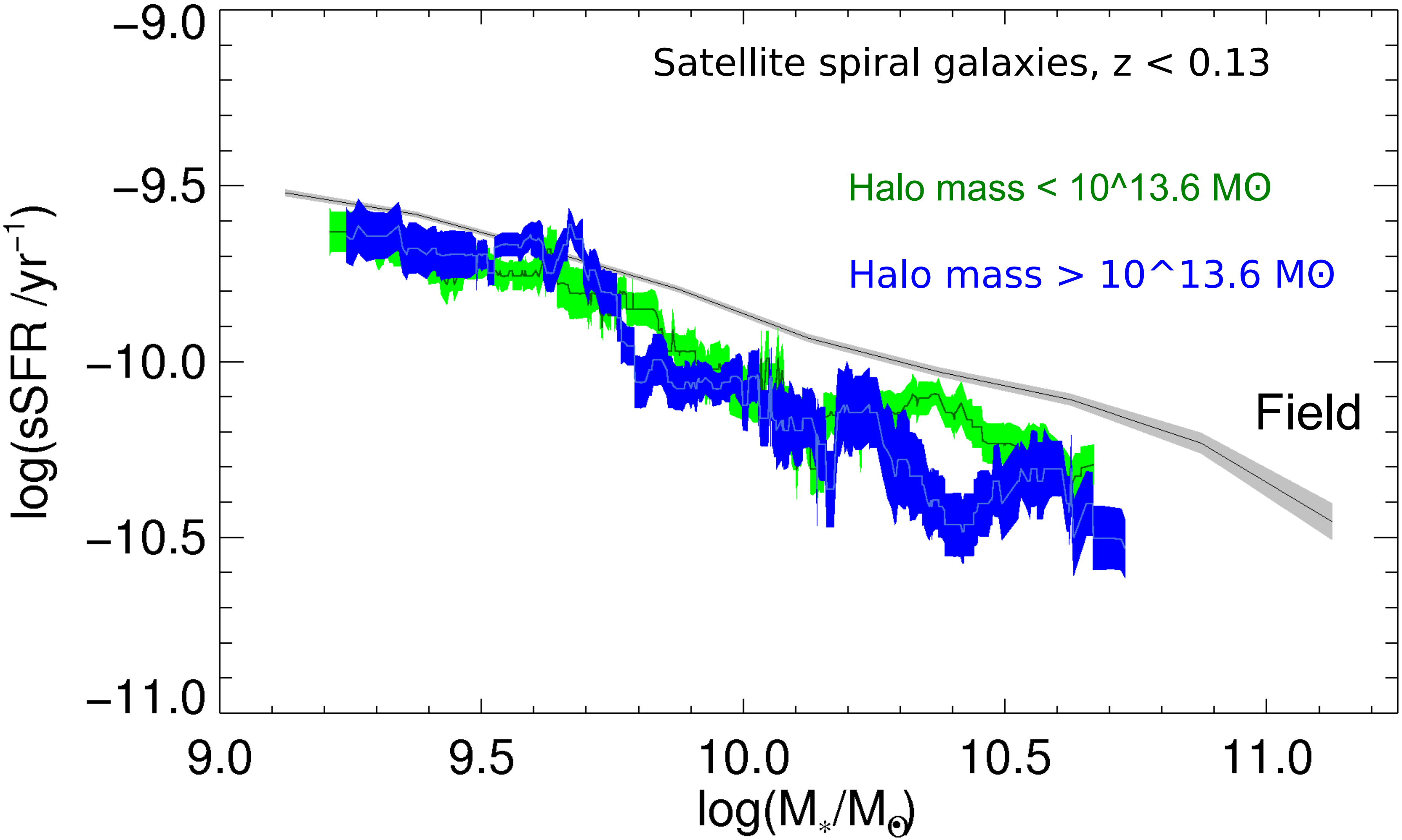
Grootes+2017

Environment in detail: DMH



Grootes+, in prep

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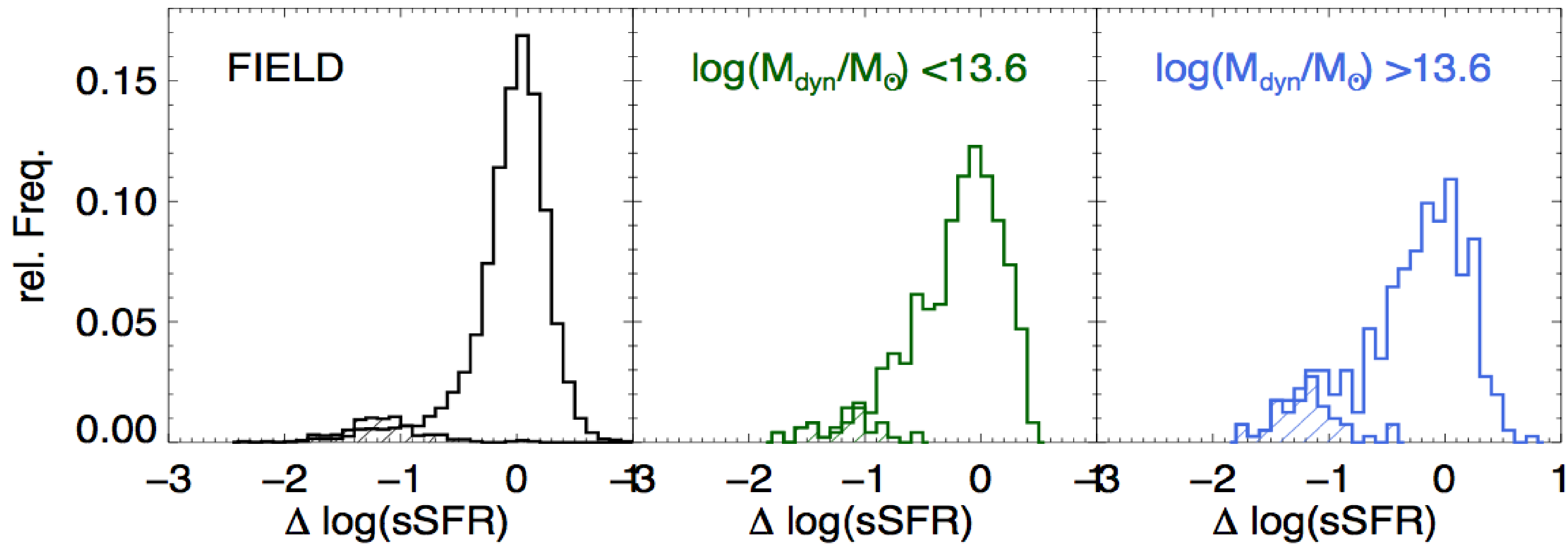
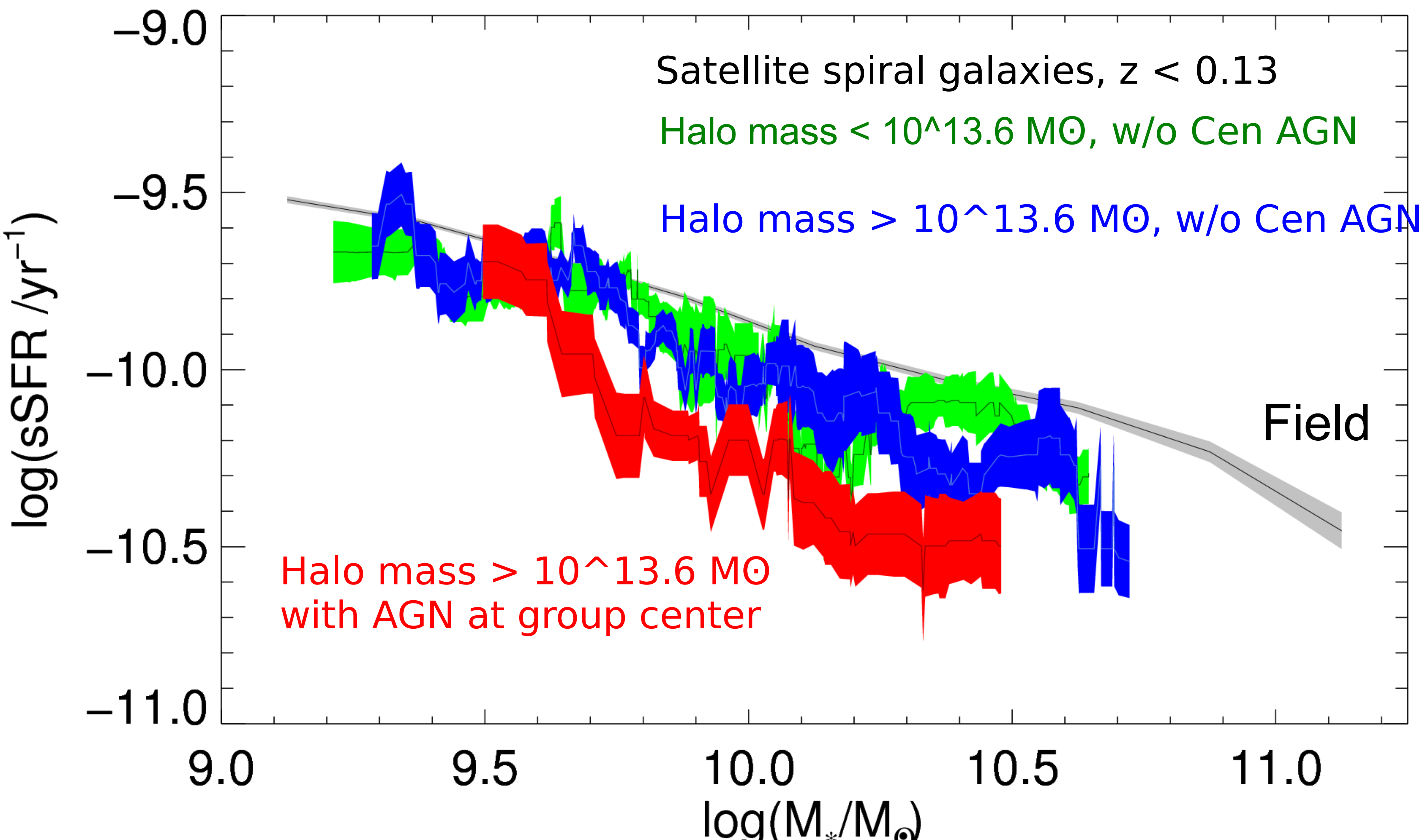


Grootes+, in prep

Satellite spiral galaxies, $z < 0.13$

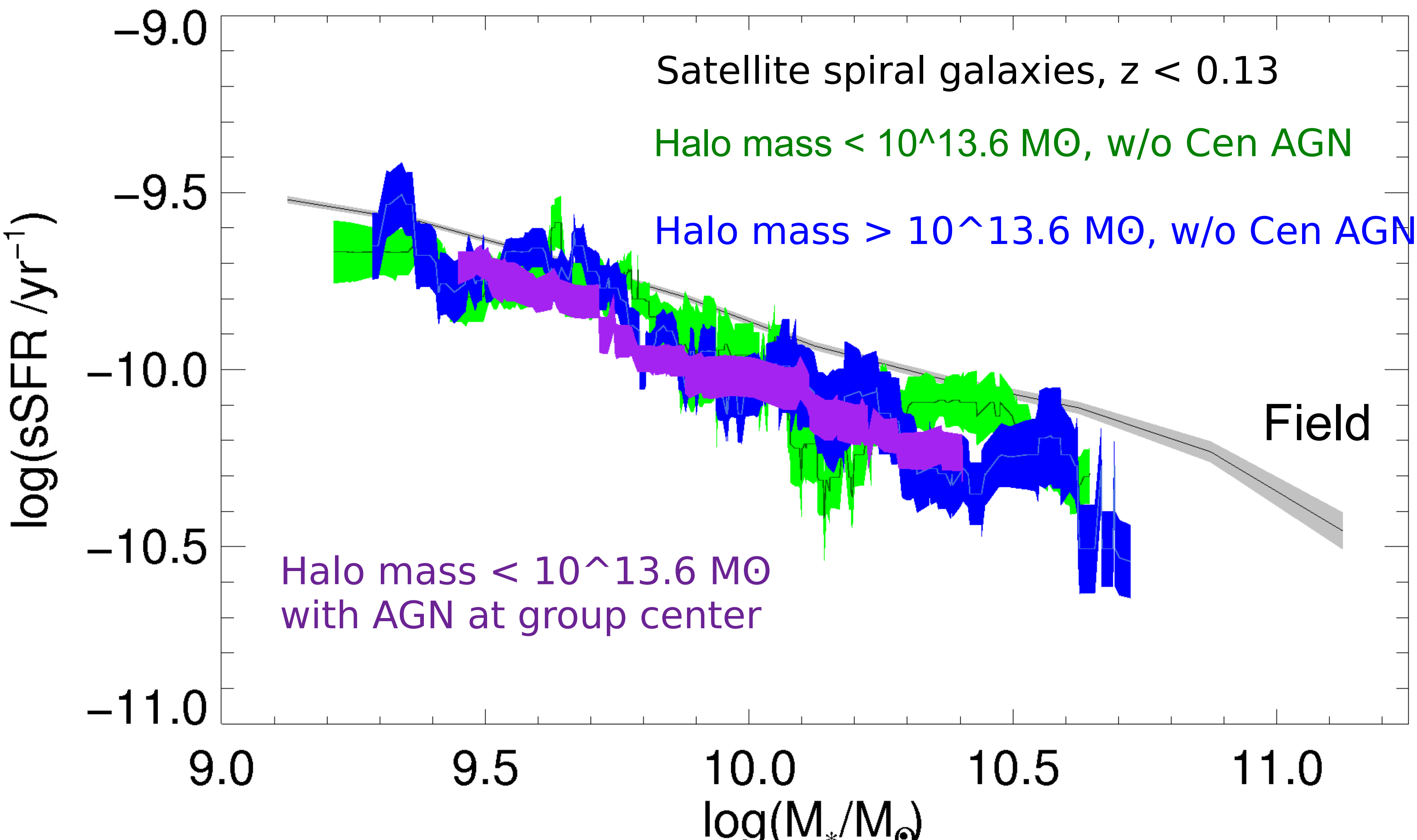
Split at median dynamical halo mass

Group Central AGN



Grootes+, in prep

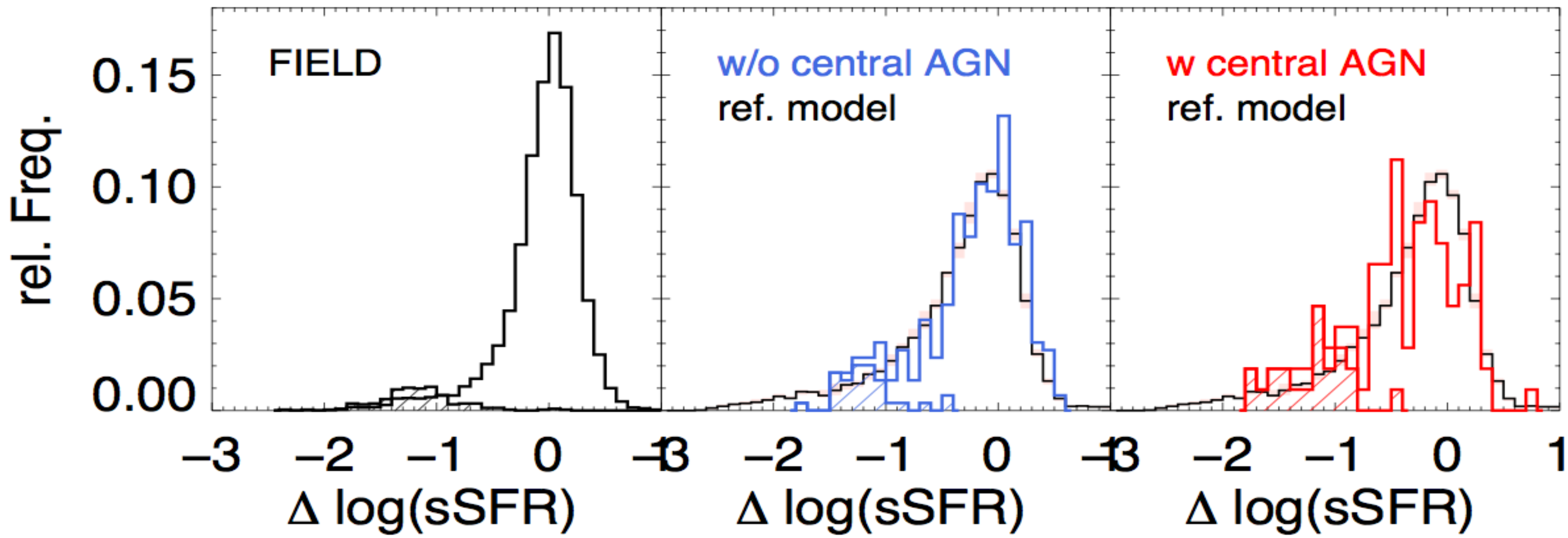
Group Central AGN



Grootes+, in prep

Group Central AGN

Satellite spiral galaxies; Halo Mass > 10^13.6 Mo



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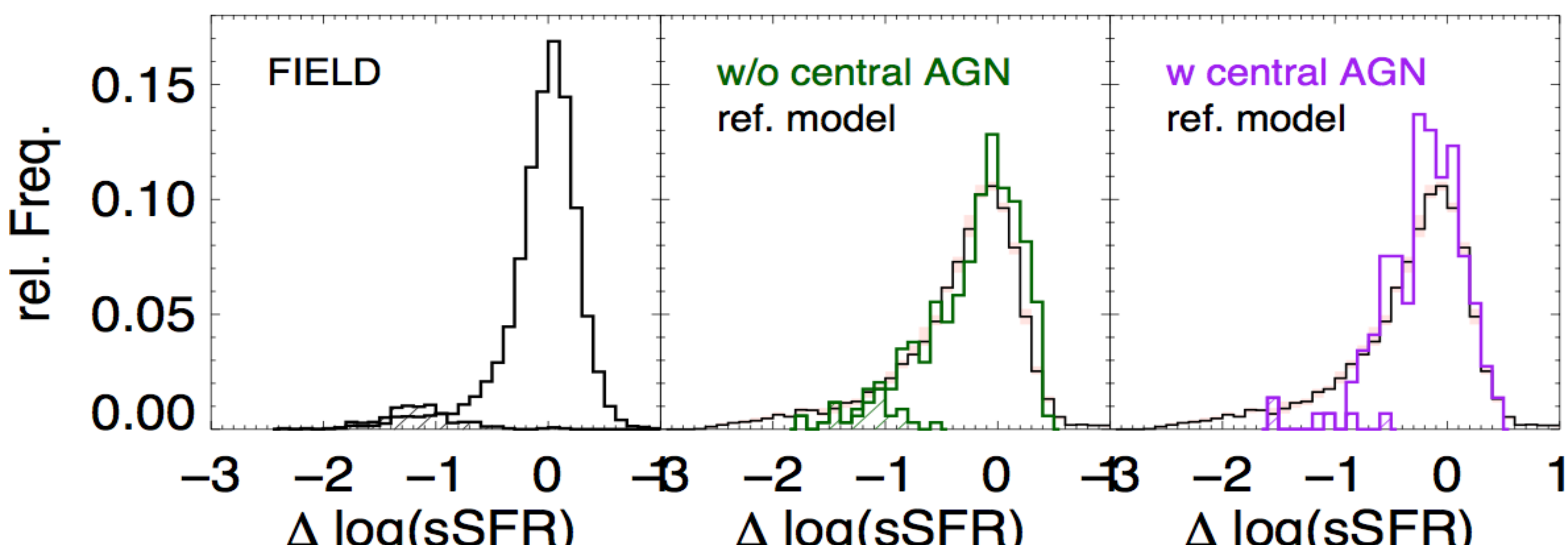


Grootes+, in prep

Conclusions

Central disks

- Local Universe field MS (of disks) consistent with self-regulated evolution tracing HMR with varying efficiency
- No impact of halo mass on sSFR-M* relation of centrals; possibly consistent with co-incidental counterbalancing inflow rate and accretion efficiency (a hidden halo mass dependence on inflow), but even then tension with SMHM relation

Satellite disks

- Gas-fuelling is on-going in satellite disk galaxies. Accretion from gas in group
- halo(IGM).
- Gas-fuelling largely independent of environment (halo mass)
- Independence only broken for massive groups with a central AGN.

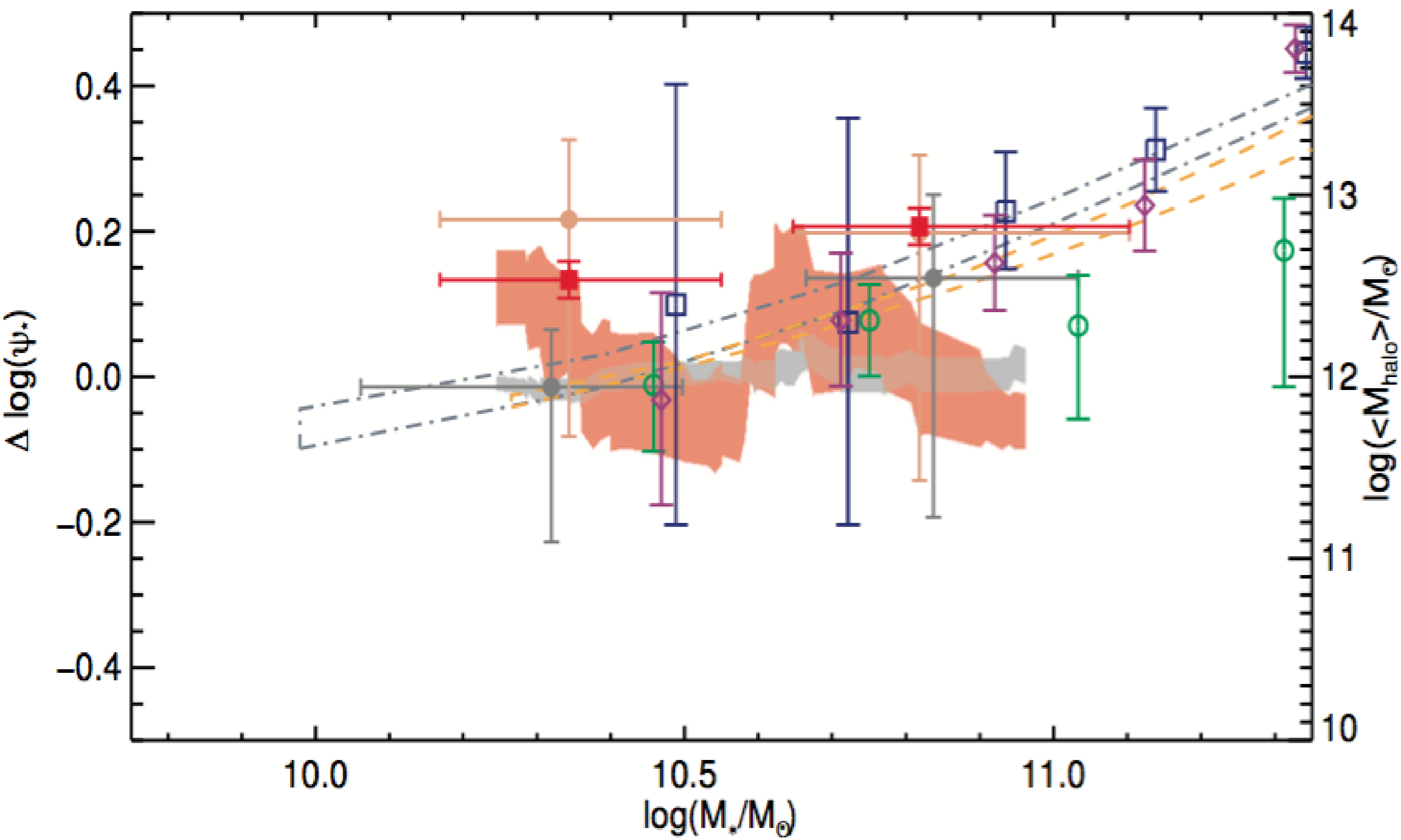
How complete is our picture of gas-fuelling and the baryon-cycle really?

THANK YOU

Title Box

Title Box

Halo mass dependence



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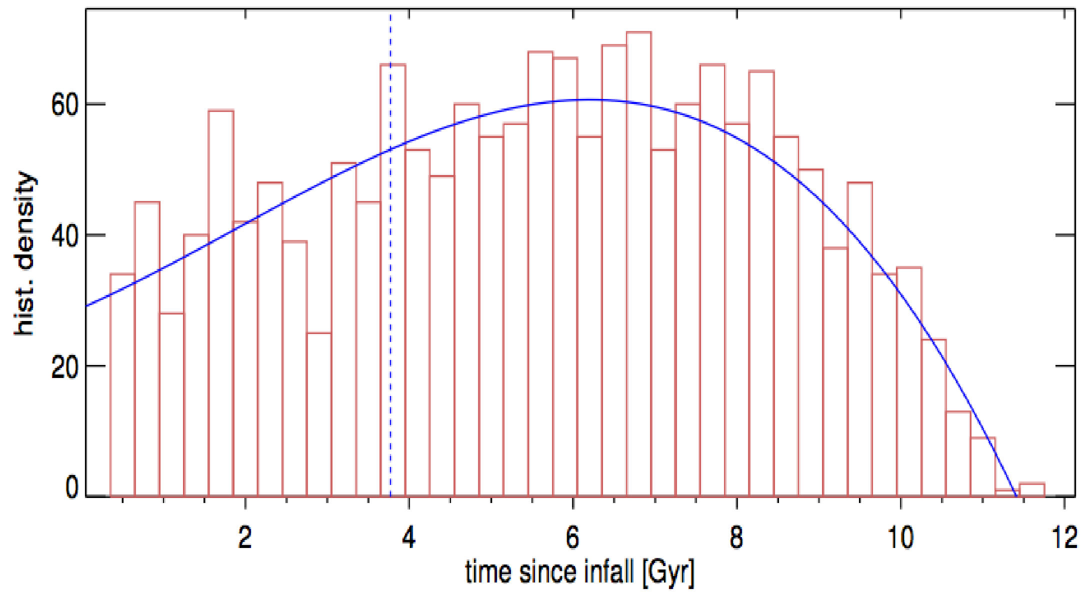
Modelling Spiral Satellites: Galaxy Populations at Infall

MC sample mass and appropriate SFR distribution of field sample at present

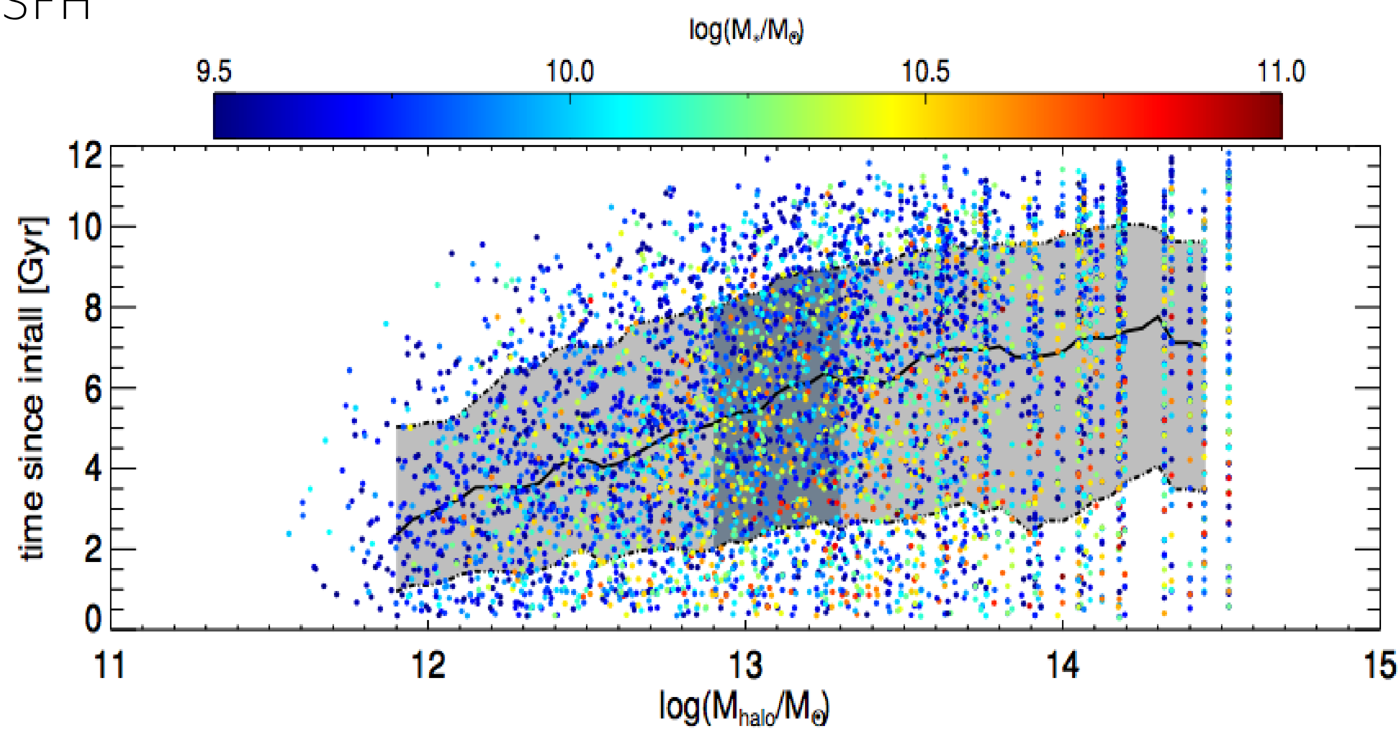
MC sample infall time (based on mocks) accounting for spiral fraction

Evolve backwards according to MS relation
of Speagle+2014

Evolve galaxies forward following parameterized SFH

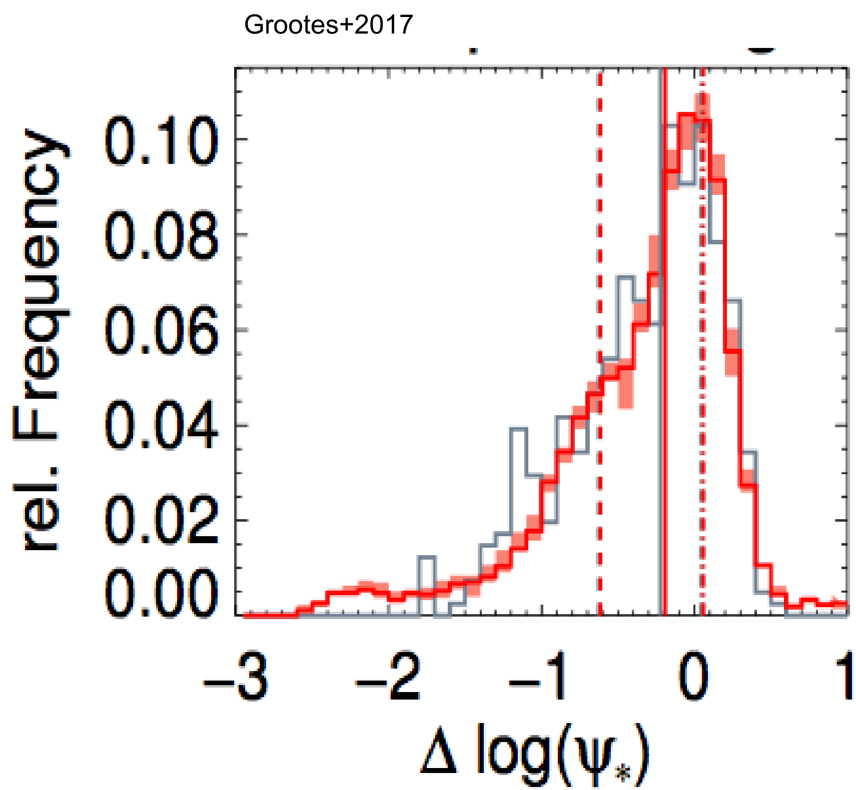


Grootes+2017



Grootes+2017

Comparison with Data



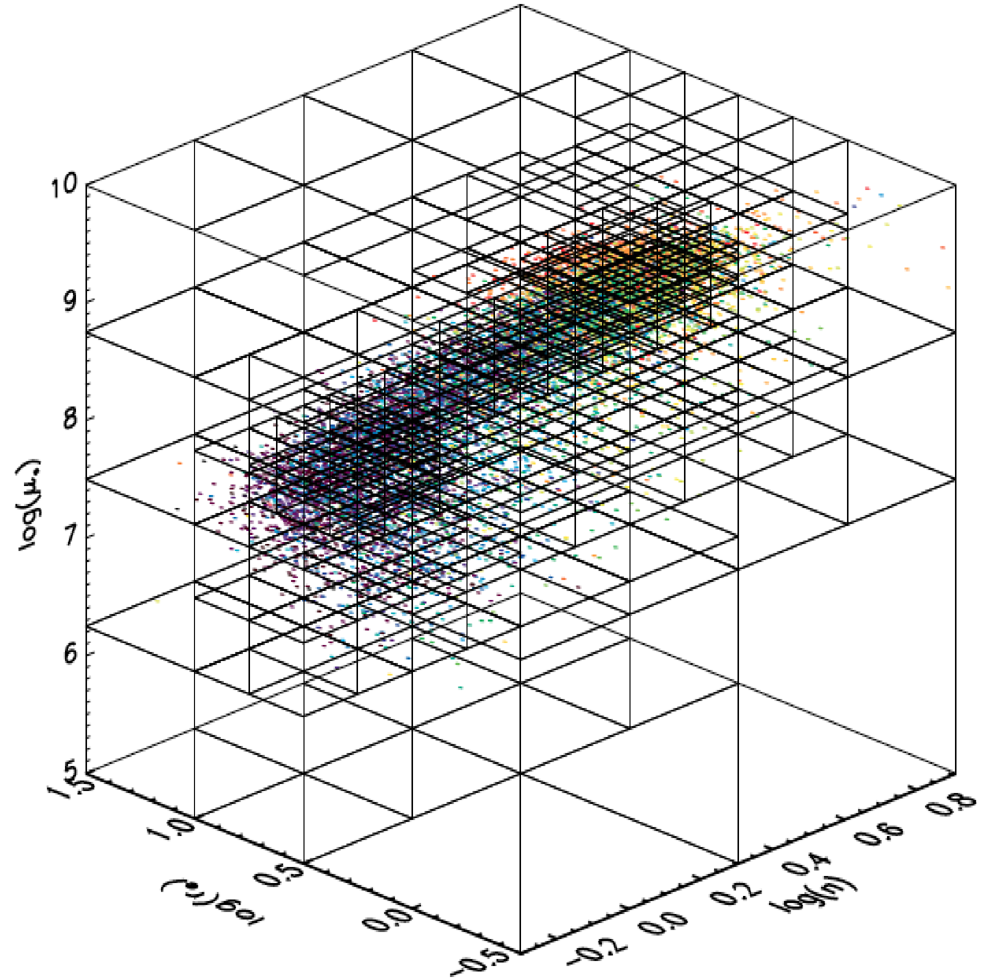
Compare 2 noisy distributions

FoM: recovery of characteristics (quartiles) of distribution

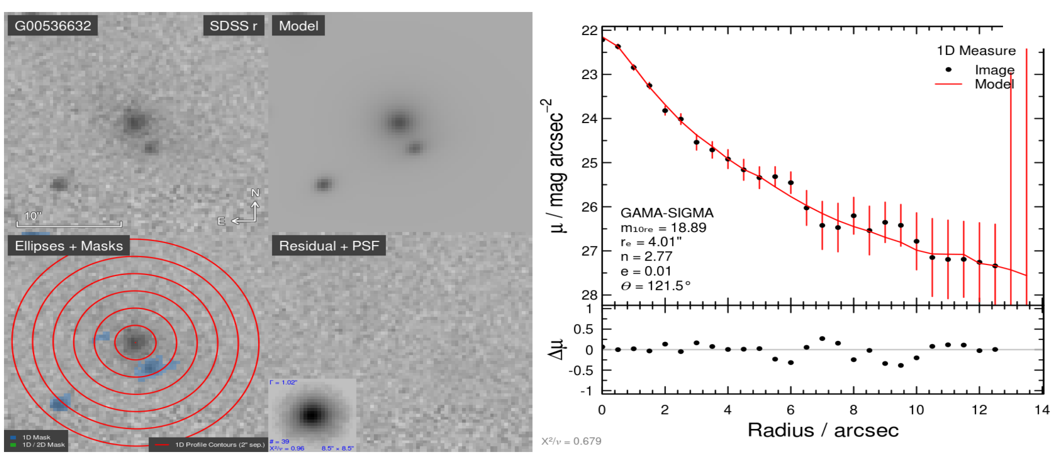
$$Q_i(p_1,p_2) = \begin{cases} [1-\Delta q_i(p_1,p_2)]\cdot 0.3^{-3} & \text{for } \Delta q_i(p_1,p_2) \le 0.3 \\ 0 & \text{otherwise} \end{cases}$$

$$Q(p_1,p_2) = \prod_i Q_i(p_1,p_2)$$

Controlling for Galaxy Morphology



Grootes+2014



Kelvin+2012

Controlling for Galaxy Morphology

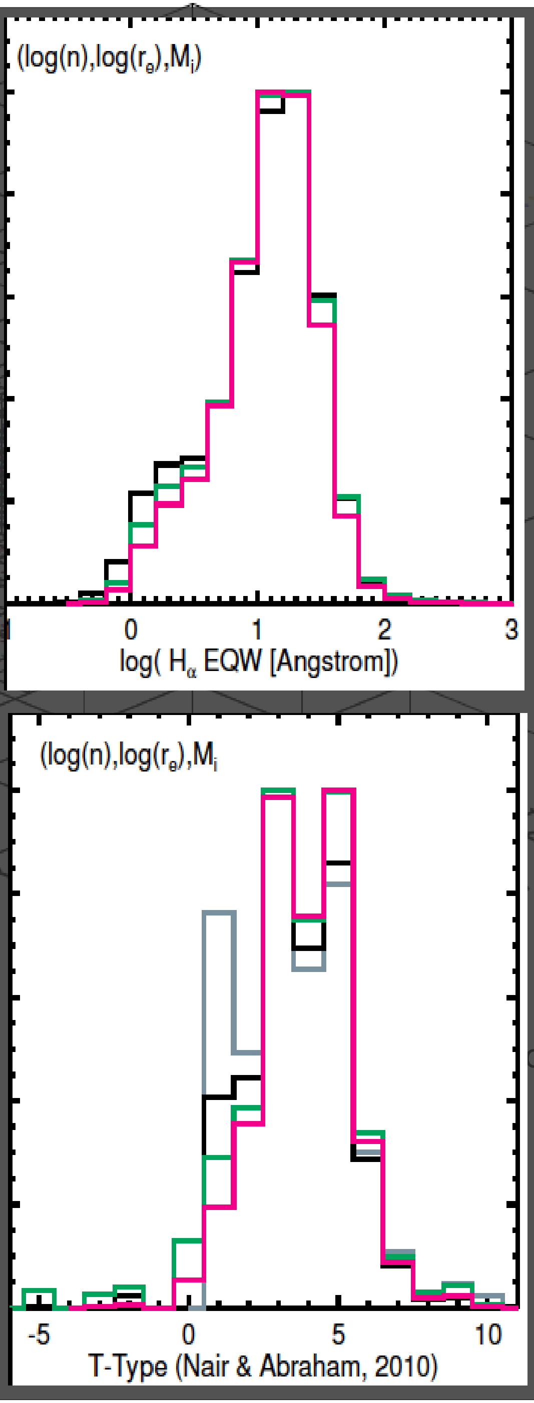
Parameters $(\log(n), \log(r_e), M_i)$

< 2 % contamination by Elliptical galaxies

≳ 80 % completeness of late-type galaxies

Unbiased in distribution of HAEW (SF) and morphological type

Pure complete sample with robust morphologies including quiescent sources.



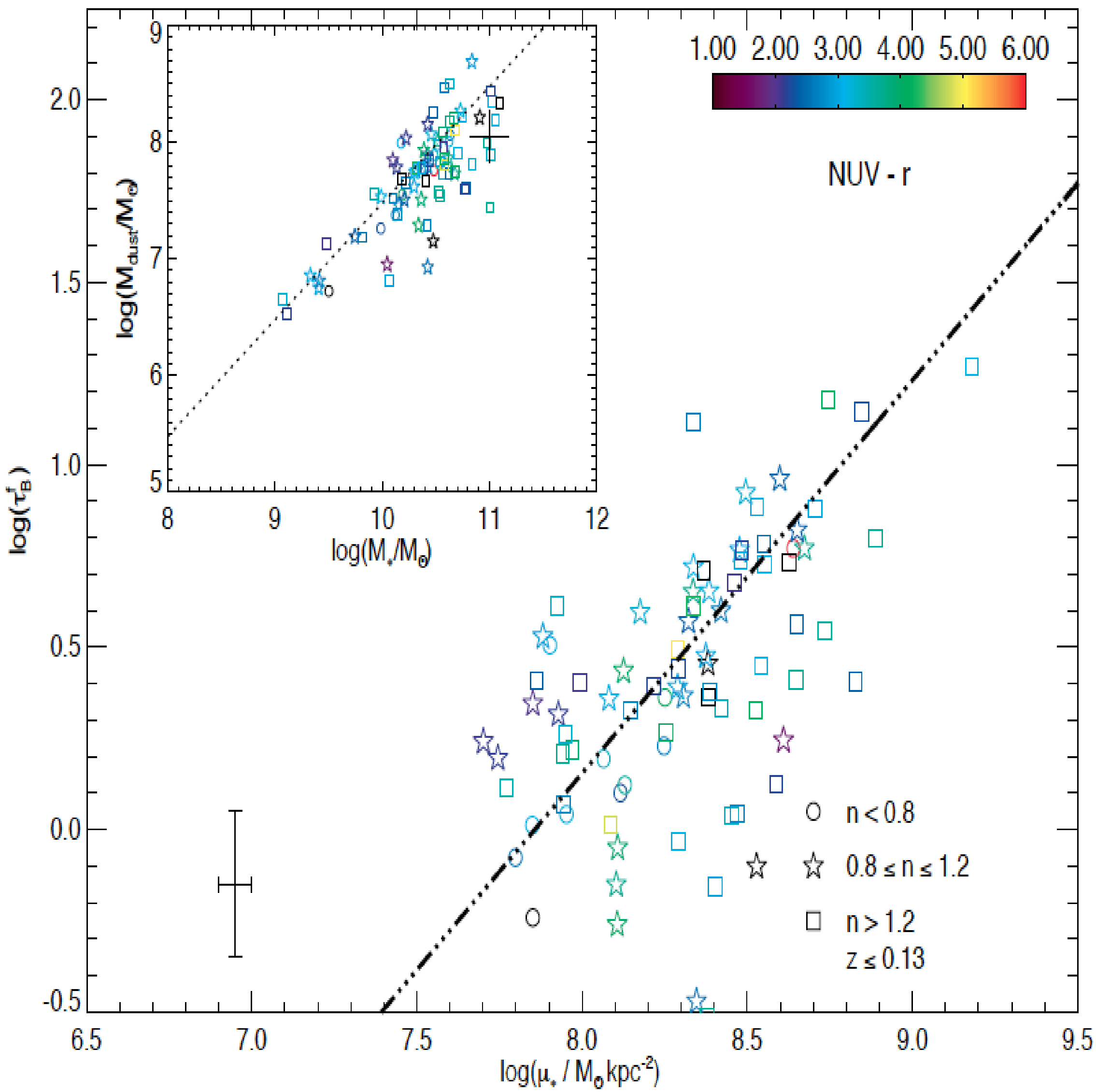
Grootes+2014

Kelvin+2012

Radiation transfer attenuation corrections for ALL spirals!

Stellar mass surface density traces opacity due to dust (Grootes+2013)

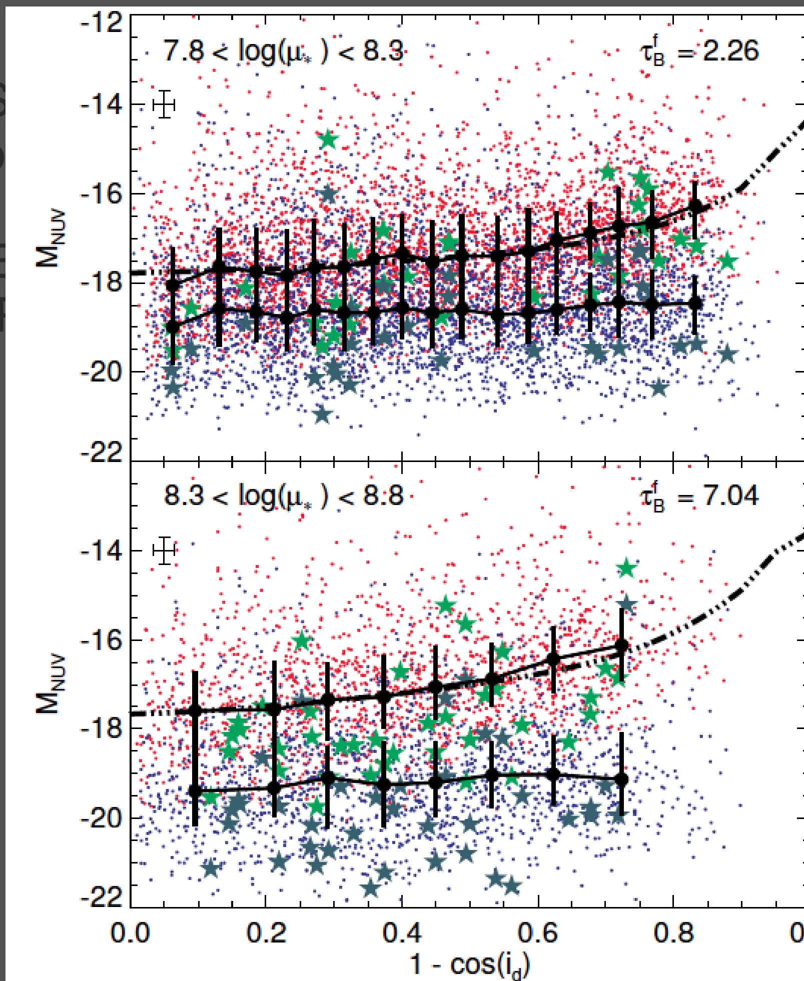
Enables use of RT model (Popescu+2011) without FIR data



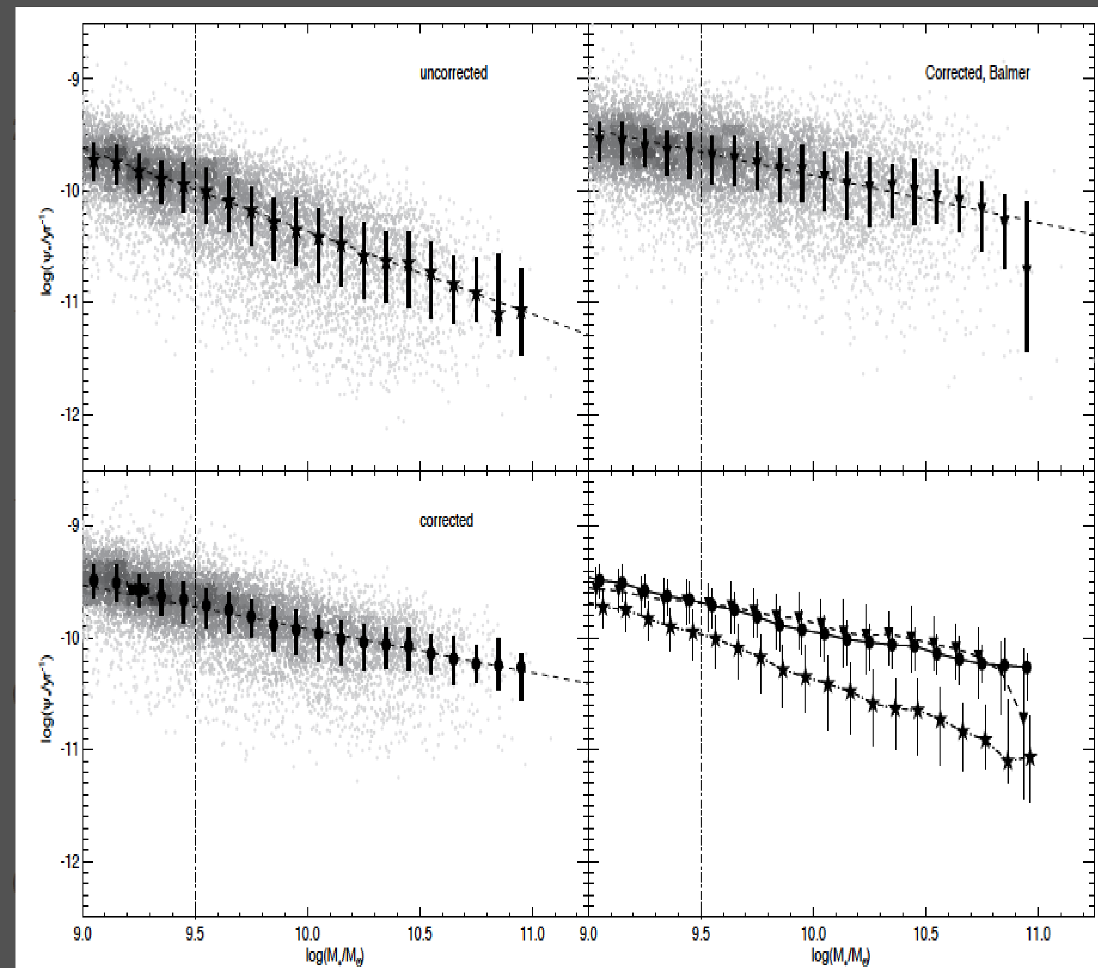
Grootes+2013

Radiation transfer attenuation corrections for ALL spirals!

Grootes+2013,2014

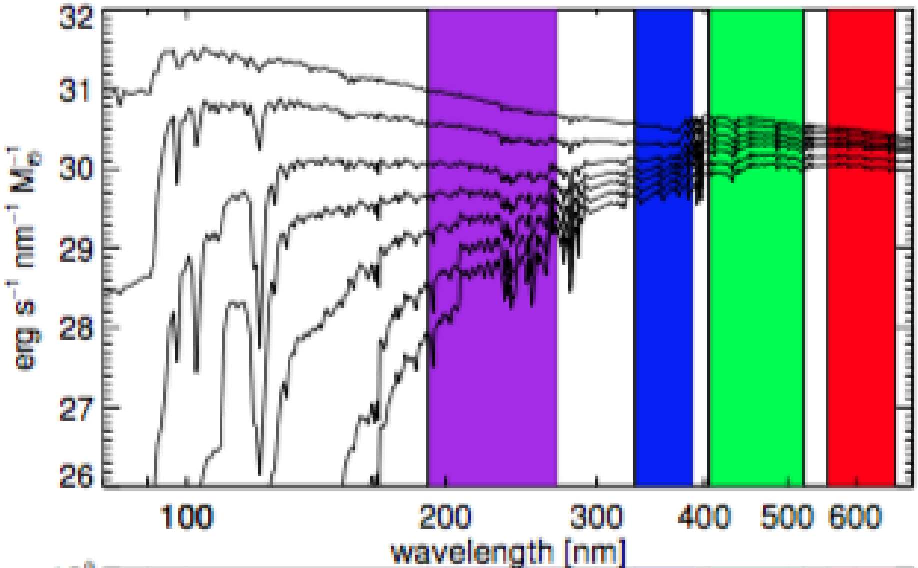


Correct inclination dependence

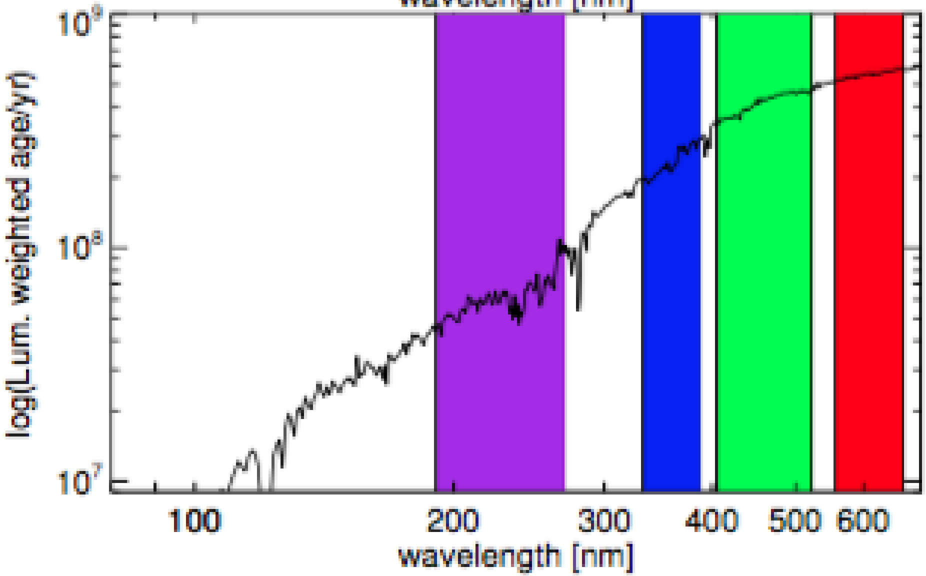


unparalleled reduction in scatter

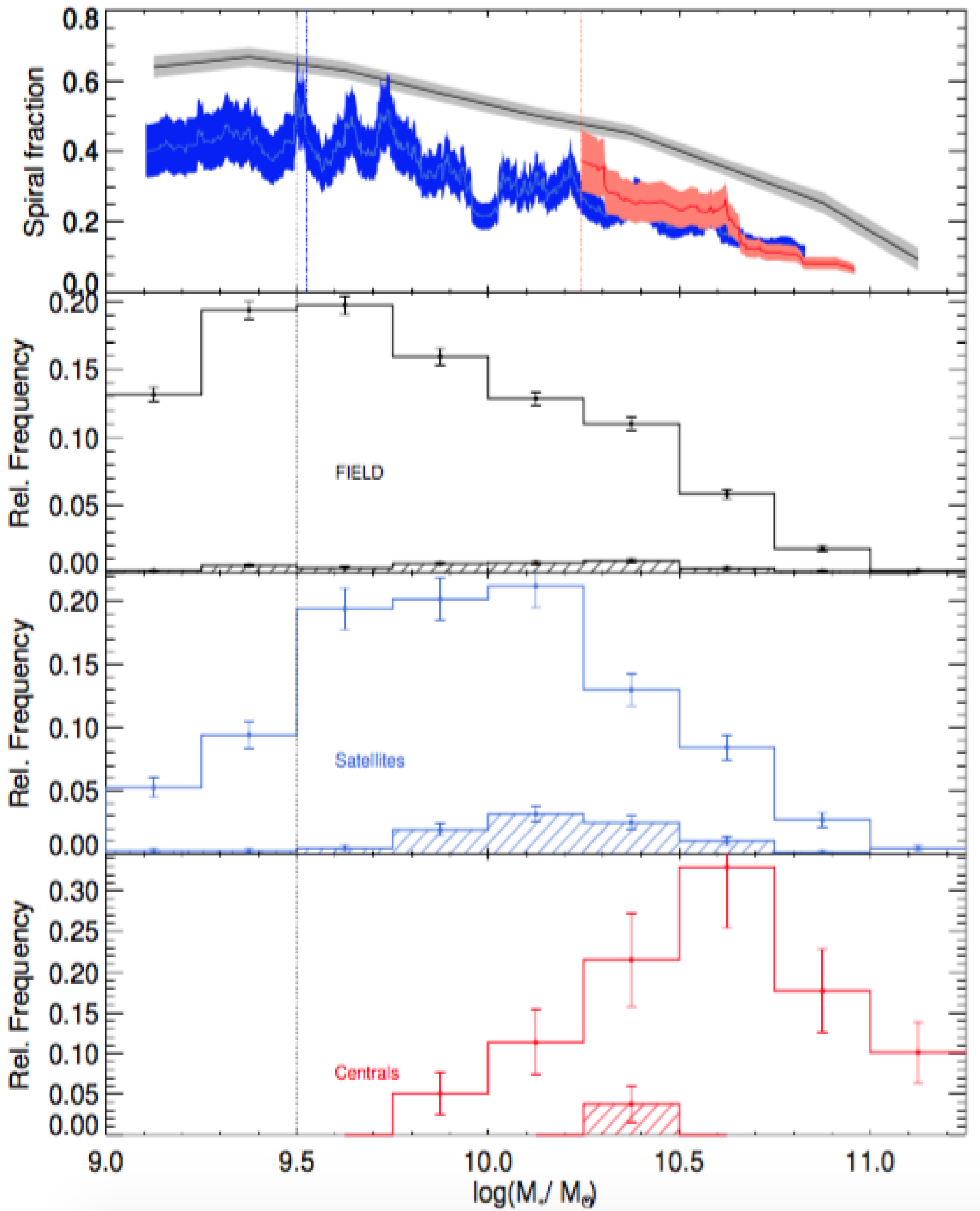
Grootes+2013



32
31
30
29
28
27
26
erg s^{-1} nm^{-1} M$_\odot^{-1}$
100
200
300
400
500
600
wavelength [nm]



10^9
10^8
10^7
log(Lum. weighted age/yr)
100
200
300
400
500
600
wavelength [nm]



0.8
0.6
0.4
0.2
0.0
Spiral fraction
0.20
0.15
0.10
0.05
0.00
Rel. Frequency
FIELD
0.20
0.15
0.10
0.05
0.00
Rel. Frequency
Satellites
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Rel. Frequency
Centrals
9.0
9.5
10.0
10.5
11.0
log(M*/ M⊙)