Theoretical modeling of LAEs using cosmological simulations and semianalytic models of galaxy formation

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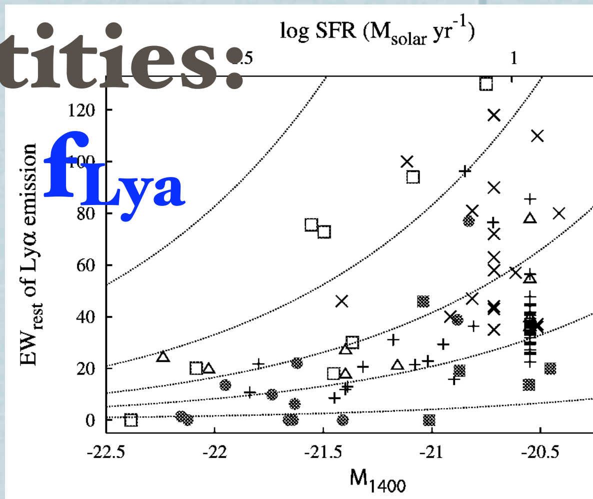
Outline

- **Motivation & Model Requirements**:
  - What do theorists need to reproduce in their models?
- **Results on LAE statistics**: past & recent works
  - **Correlations & scatters in various quantities:** e.g., M_{star}, M_{uv}, Z/Z_{sun}, E(B-V), EW, f_{ion}, $f_{Ly\alpha}$

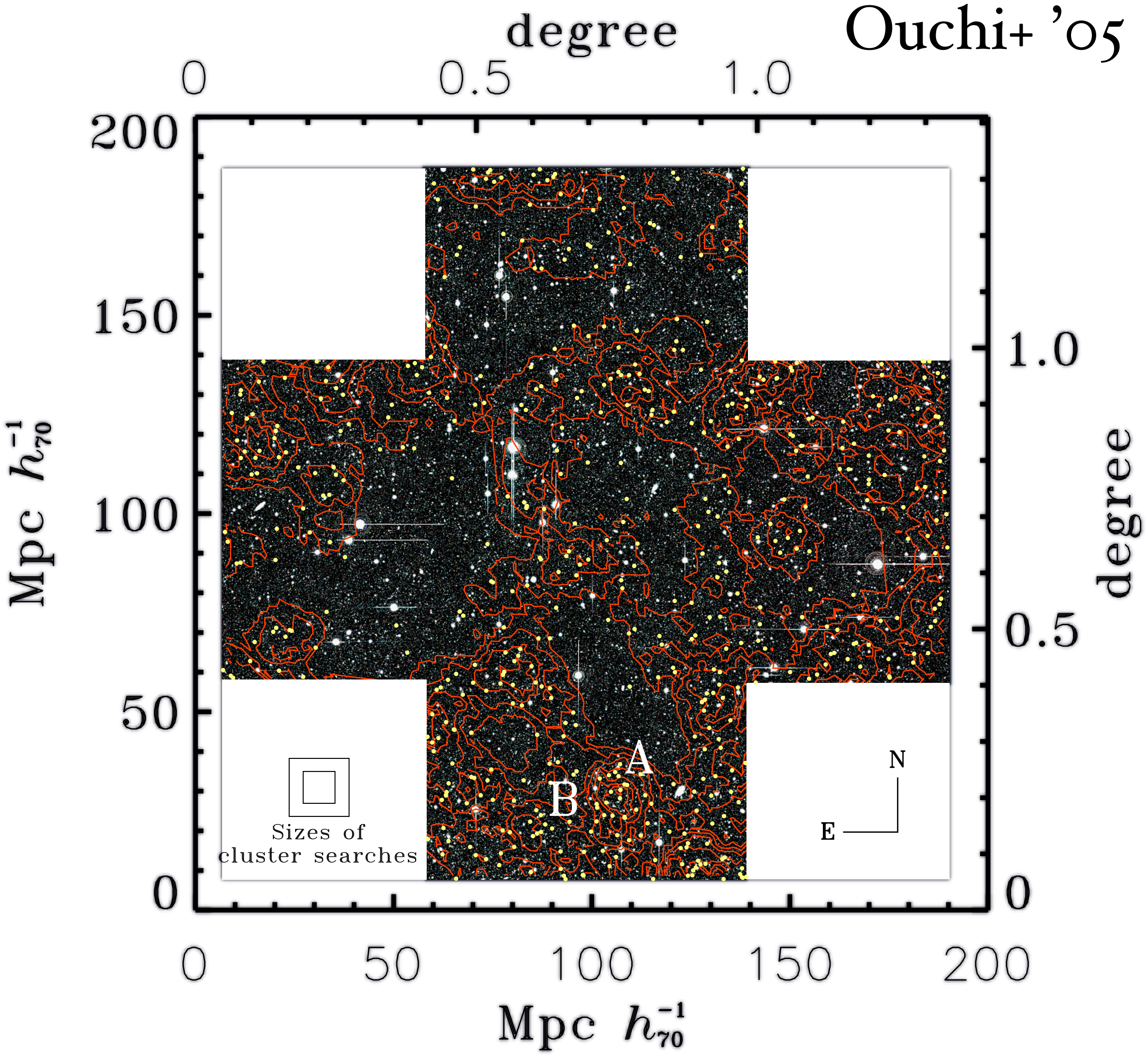


- **Scatter in $f_{esc,ion}$ -- effects on DLAs** (work w/ H. Yajima)
- **Conclusions**

Motivation

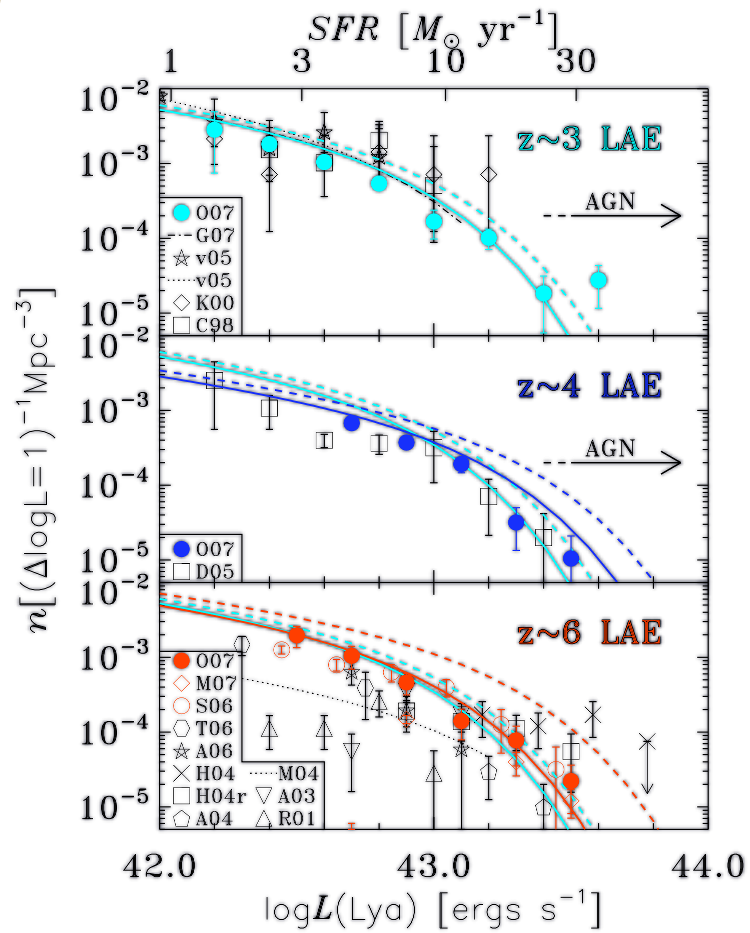
Large-scale structure traced by LAEs at z>3

Ouchi+ '05

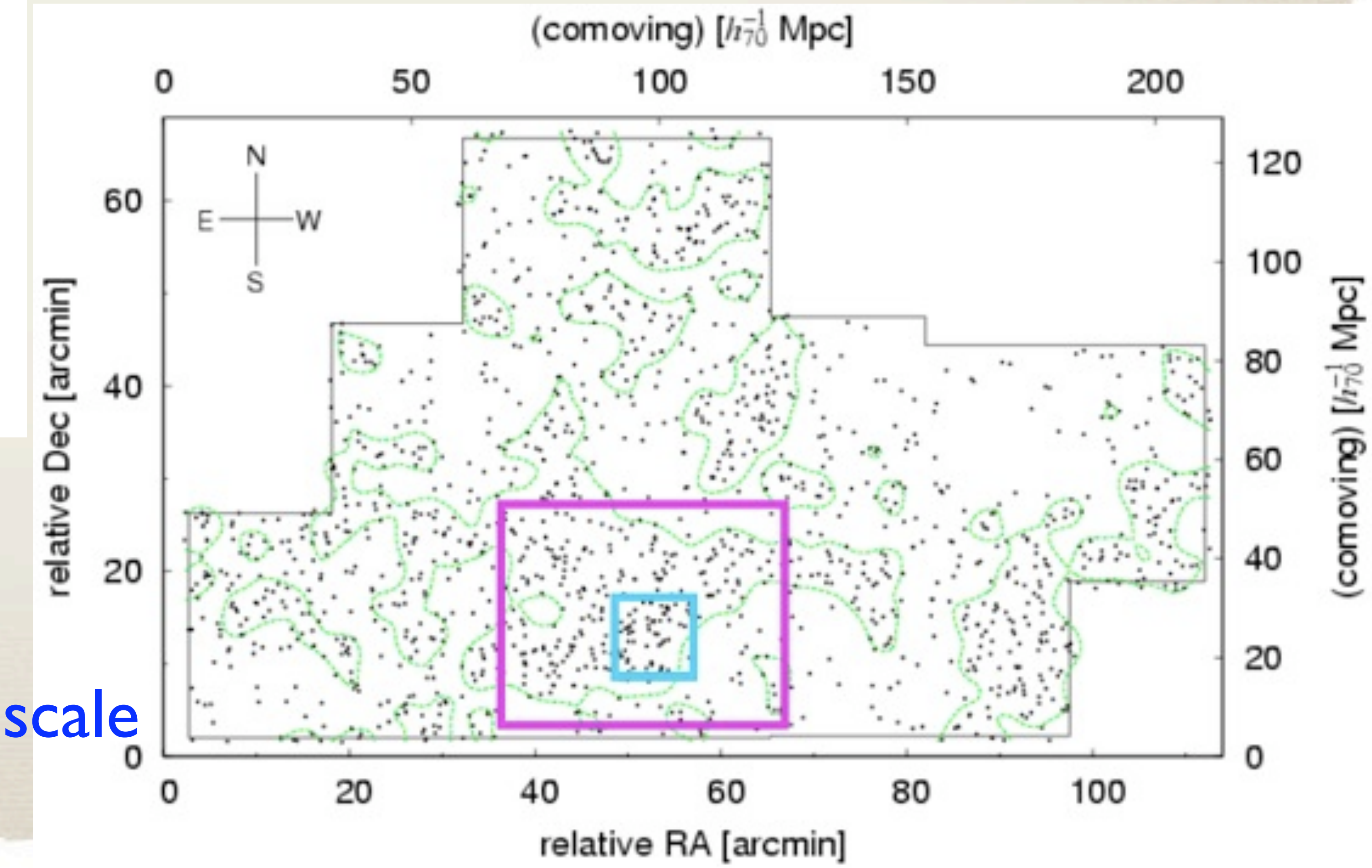


SXDS, 515 LAEs

Ouchi+ '08



Partridge & Peebles '67
Rhoads & Malhotra '01
Shapley+ '03
Malhotra & Rhoads '04
Ouchi+ '05
Hu & Cowie '06
Shimasaku+ '06
Kashikawa+ '06
Gronwall+ '07
Gawiser+ '07.....



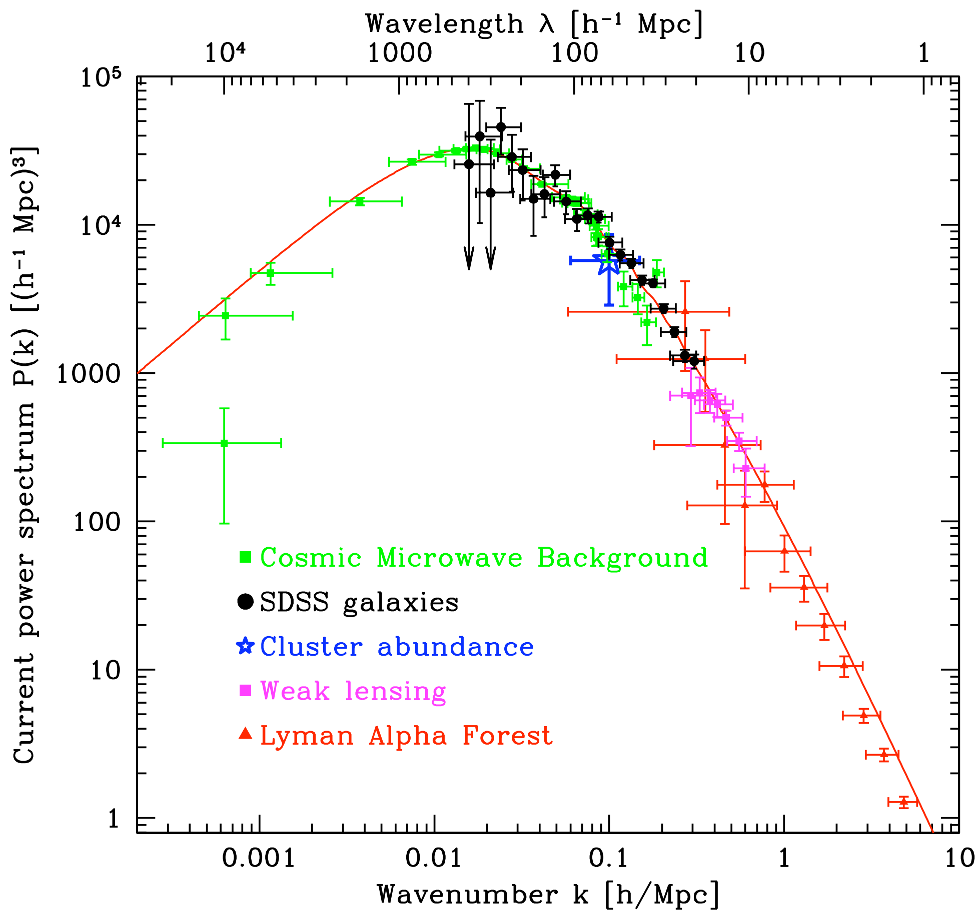
~1400 LAEs @ z=3.1 over 200 Mpc scale

Nakamura, Yamada+ '08

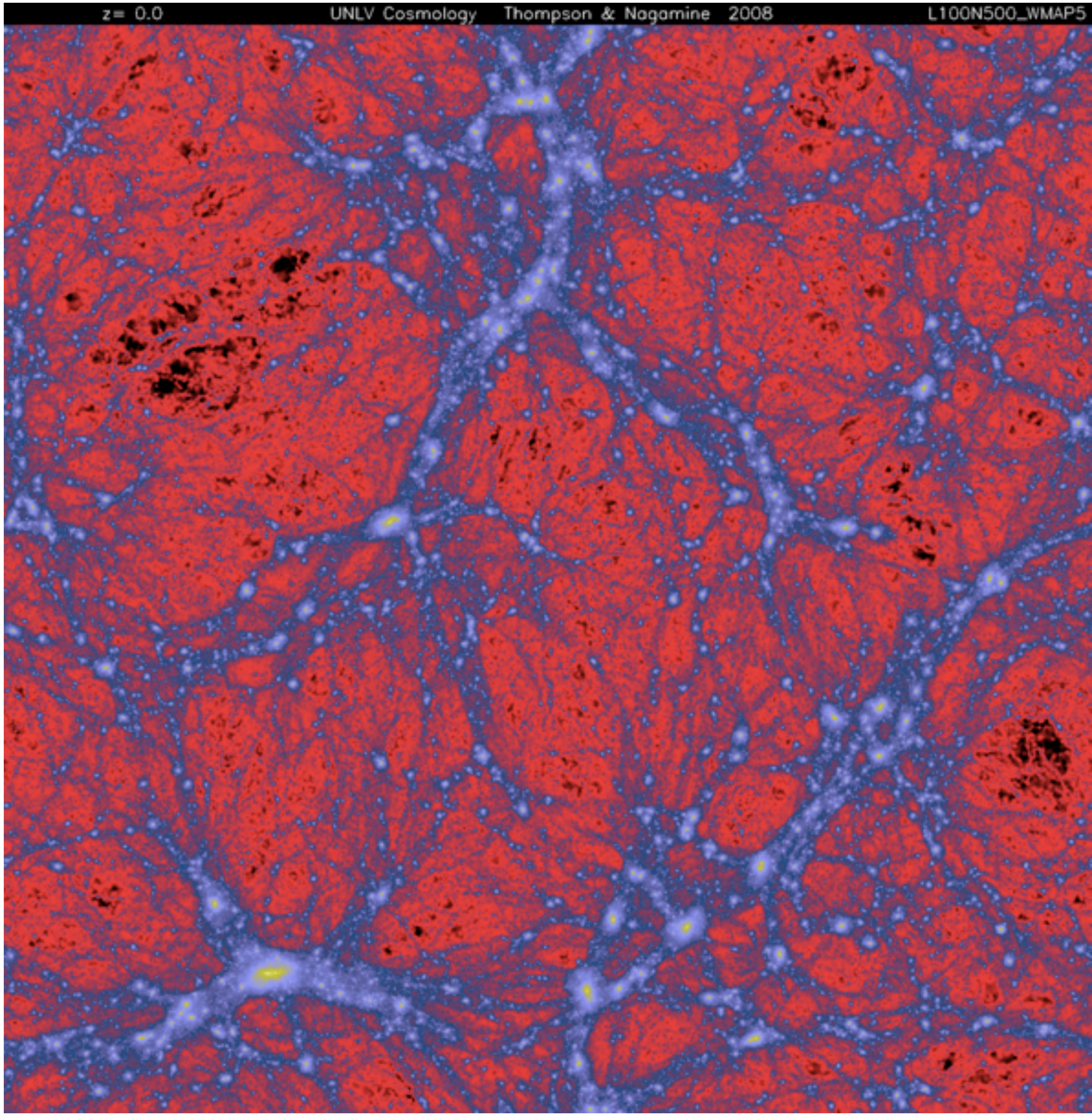
Concordance ΛCDM model

WMAP5 $(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.26, 0.74, 0.04, 0.7, 0.8, 0.96)$

- Successful on large-scales
- Interpret galaxy obs in the context of ΛCDM model



Tegmark et al. (2004)



Requirements

(for both theorists and observers...)

- Galaxy stellar mass function
- Luminosity functions (UV - K, IR, Lya,...)
- mass -- metallicity relationship (M_{star} vs. Z/Z_{sun})
- metal -- dust relationship (Z/Z_{sun} vs. E(B-V))
- effects of dust on Lya photons (f_{Lya} vs. E(B-V))
- escape fraction of ionizing photons f_{ion}
- gas kinematics around SF regions

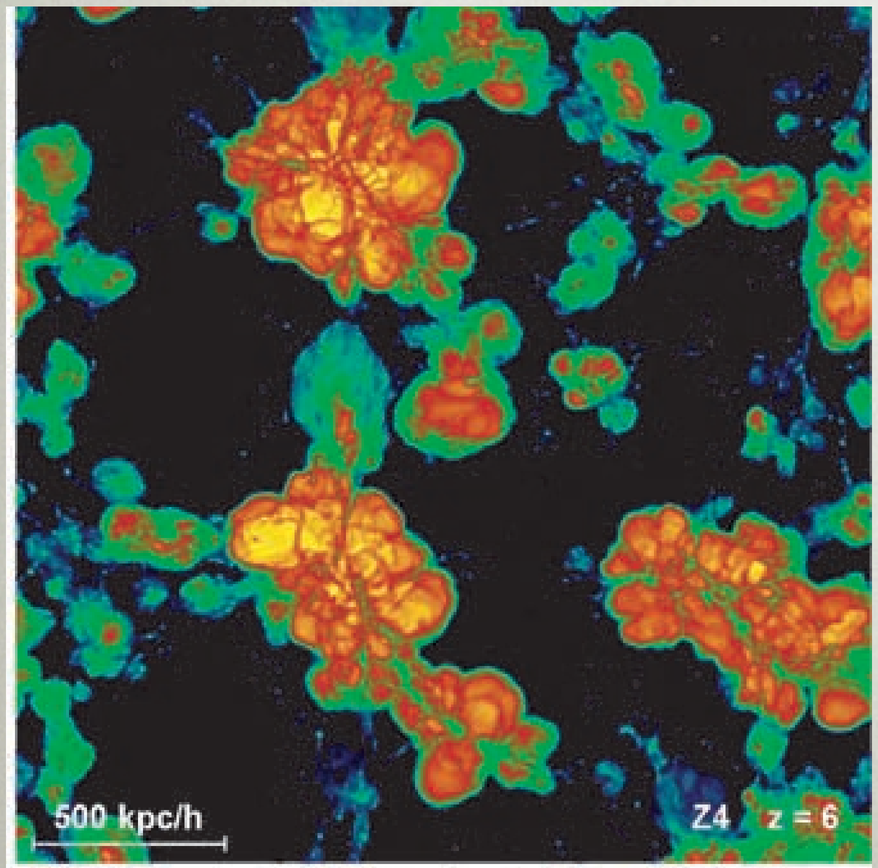
Cosmological Hydro Simulation + Multiphase ISM model

- model galaxy formation from first principles in a ΛCDM universe
- GADGET-2 Smoothed Particle Hydrodynamics code (Springel '05)

  radiative cooling/heating, star formation, SN & galactic wind feedback

  sub-particle multiphase ISM model
- LBG/LAEs @z=3-6, massive gals, DRGs/EROs, DLAs, ...

(KN+ 04ab, 05ab, 07, 08a,b)

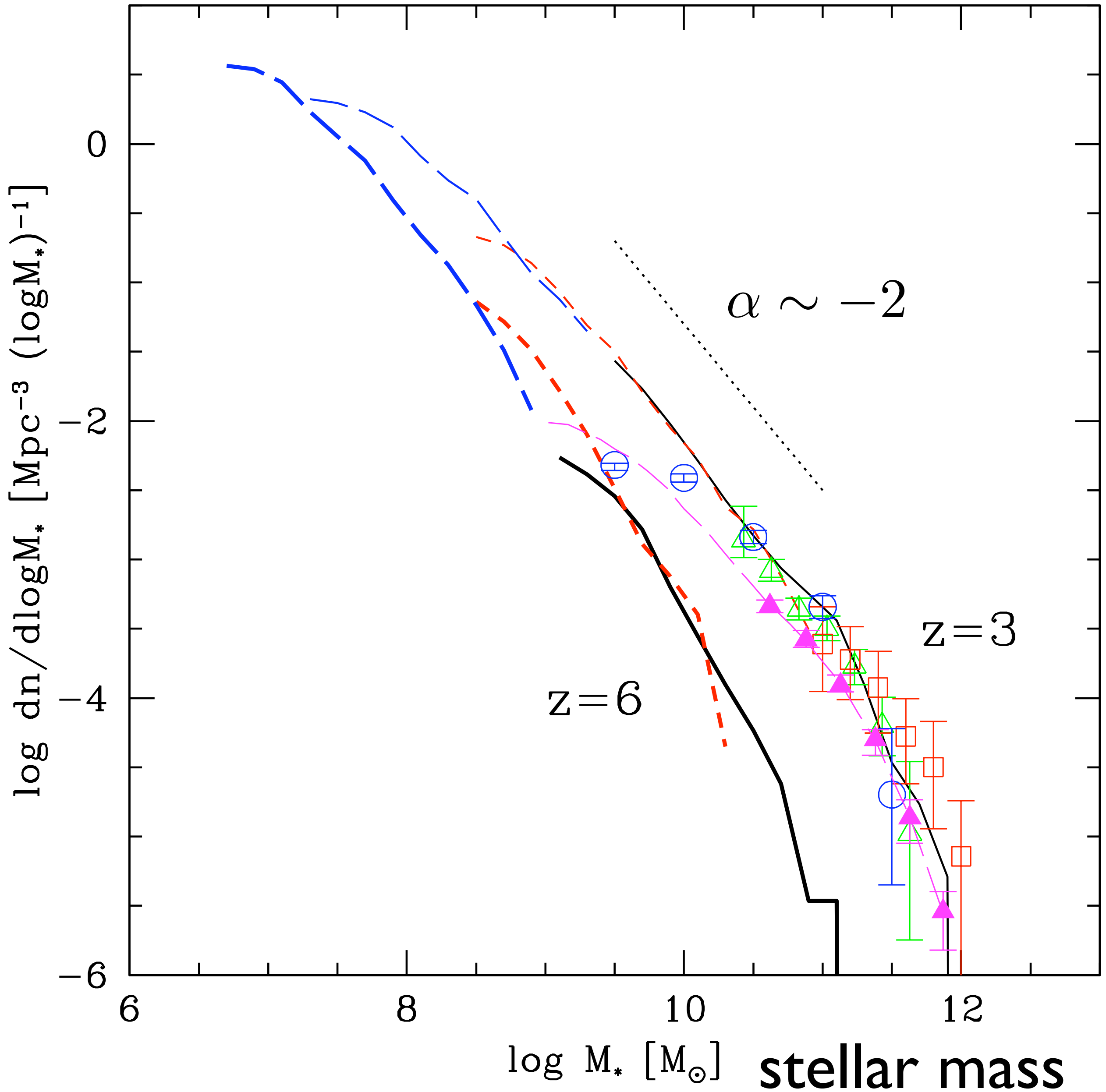


Box size $[h^{-1}\mathrm{Mpc}]$	N_p	m_{DM} $[h^{-1}M_\odot]$	m_{gas}	ϵ $[h^{-1}\mathrm{kpc}]$	z_{end}	Wind
10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	None
10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	Weak
10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	2.75	Strong
10.00	2×216^3	7.16×10^6	1.10×10^6	1.85	2.75	Strong
10.00	2×324^3	2.12×10^6	3.26×10^5	1.23	2.75	Strong
33.75	2×216^3	2.75×10^8	4.24×10^7	6.25	1.00	Strong
33.75	2×324^3	8.15×10^7	1.26×10^7	4.17	1.00	Strong
100.0	2×324^3	2.12×10^9	3.26×10^8	8.00	0.00	Strong
100.0	2×486^3	6.29×10^8	9.67×10^7	5.00	0.00	Strong

Galaxy Stellar Mass & UV Fcns

in cosmological SPH simulations

Galaxy Stellar Mass Function

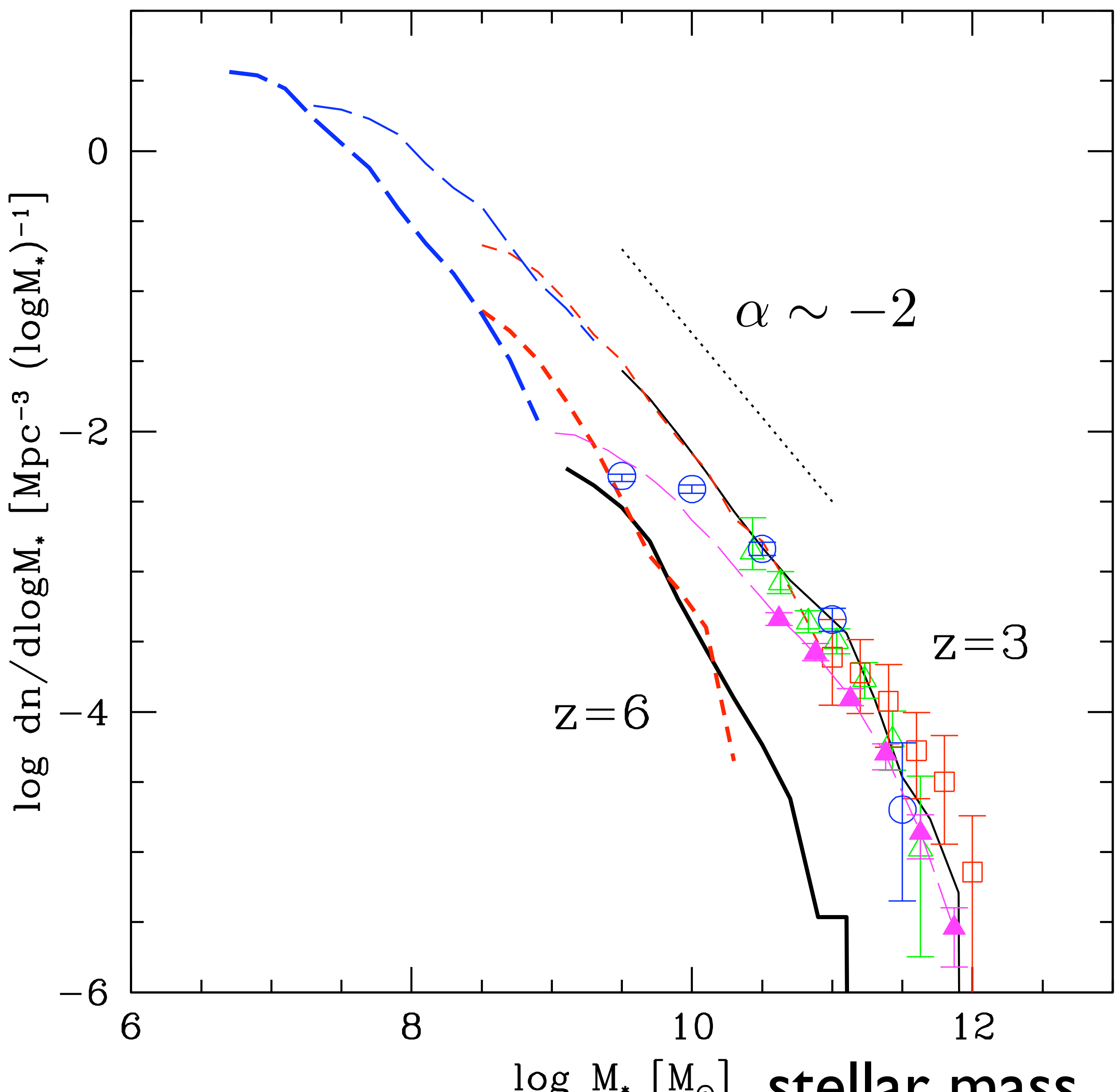


Data: Drory+ '05
Fontana+ '06
Perez-Gonzalez+ '07
Reddy+ '09

Galaxy Stellar Mass & UV Fcns

@ z=3 in cosmological SPH simulations

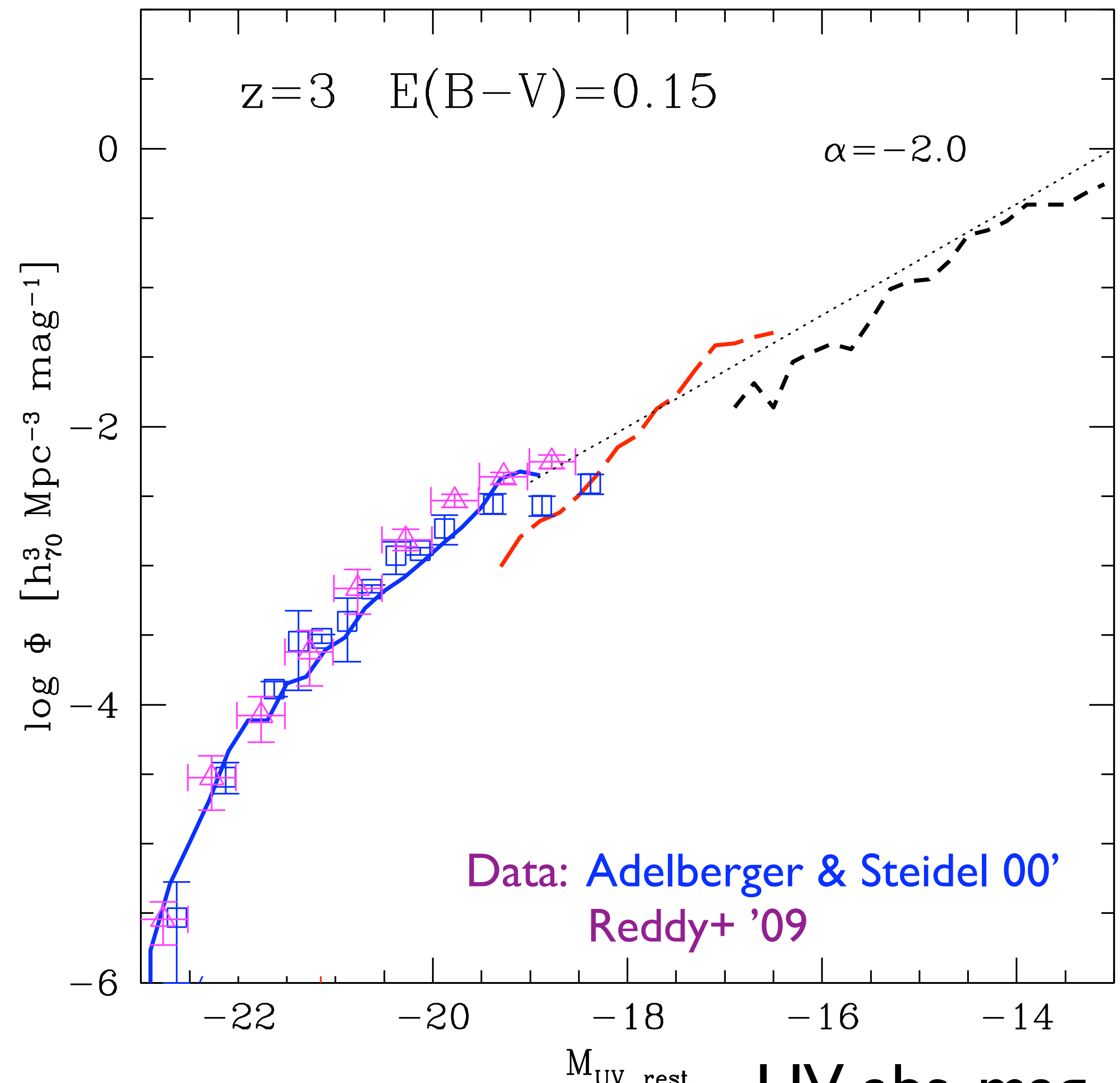
Galaxy Stellar Mass Function



stellar mass

Data: Drory+ '05
Fontana+ '06
Perez-Gonzalez+ '07
Reddy+ '09

Rest-frame UV LF



UV abs. mag

This means that our SFR func. is well behaved @ z=3

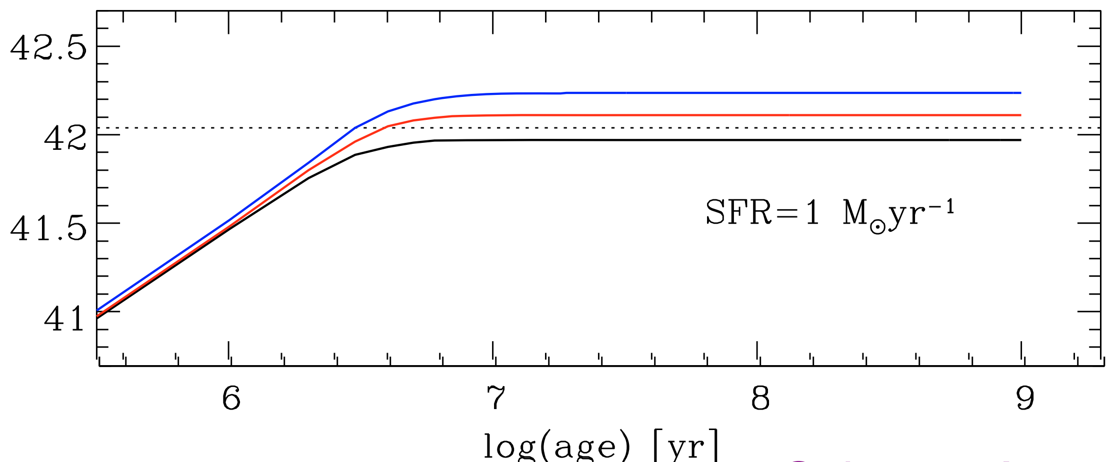
Lyα Luminosity Function

Assuming

$$\frac{L_{\mathrm{Ly}\alpha}}{10^{42}\mathrm{erg\,s^{-1}}} = \frac{\mathrm{SFR}}{1 M_\odot\,\mathrm{yr}^{-1}}$$

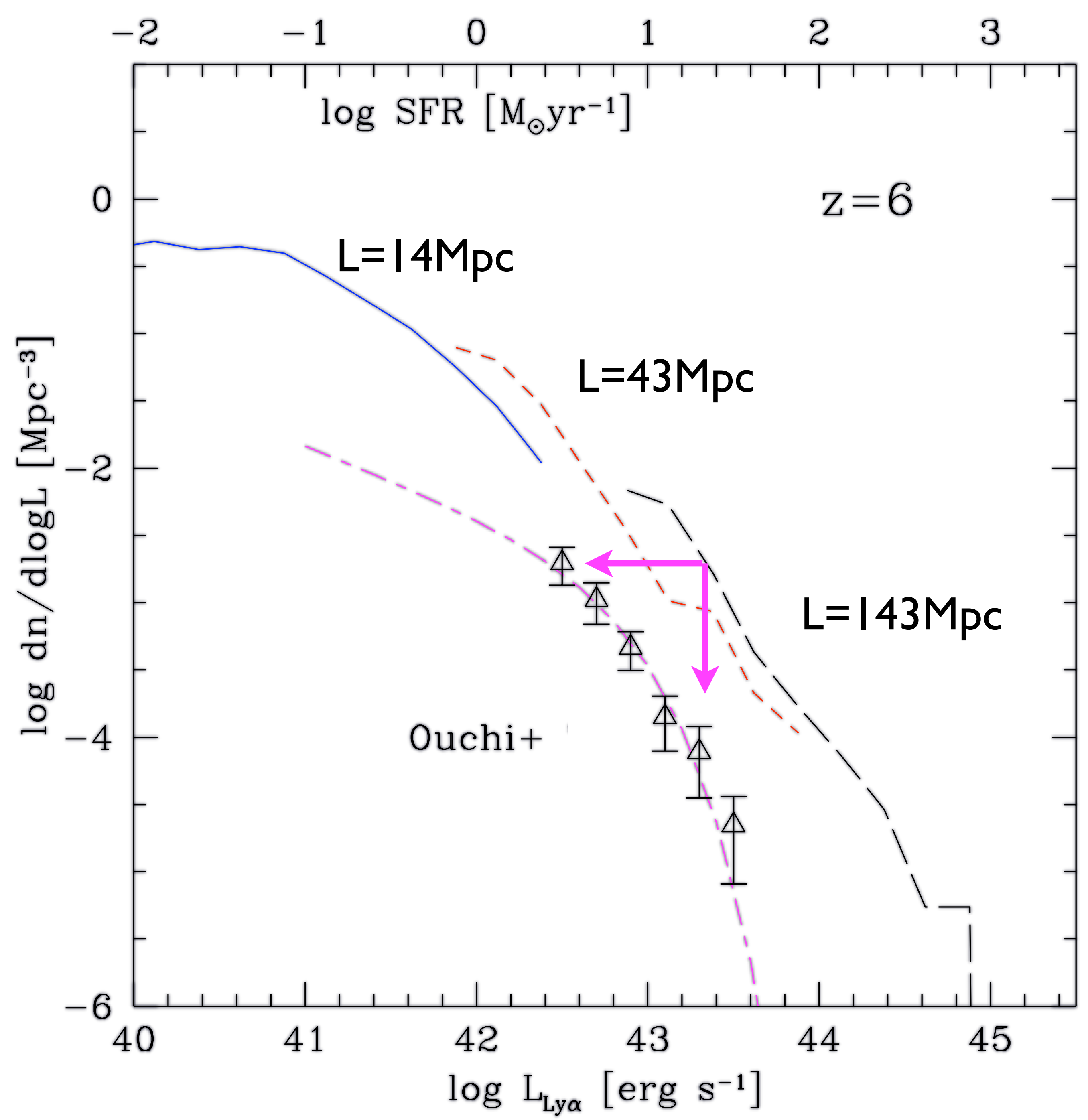
(Kennicutt '98; Leitherer+ '99)

Salpeter IMF, [0, 100]$M_\odot$, $0.05<Z/Z_\odot<2$



Schaerer '03

- Without any corrections, models based on CDM overpredict the Lyα LF by a factor of 5-10

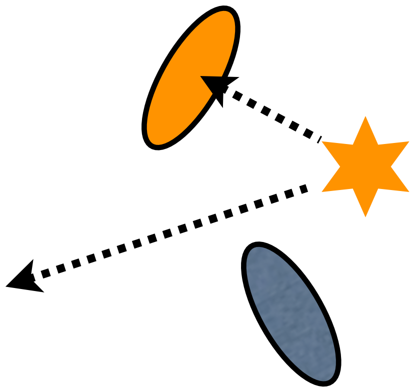


Two simple scenarios

- **"Escape fraction" scenario:**
  - all LBGs emit Lyα emission, but uniformly attenuated by a factor of **$f_{Ly\alpha}$**: $L_{Ly\alpha}^{observed} = f_{Ly\alpha} L_{Ly\alpha}^{sim}$

Effective escape fraction

$$f_{Ly\alpha} = f_{dust} \left(1 - f_{esc}^{ion}\right) f_{IGM},$$

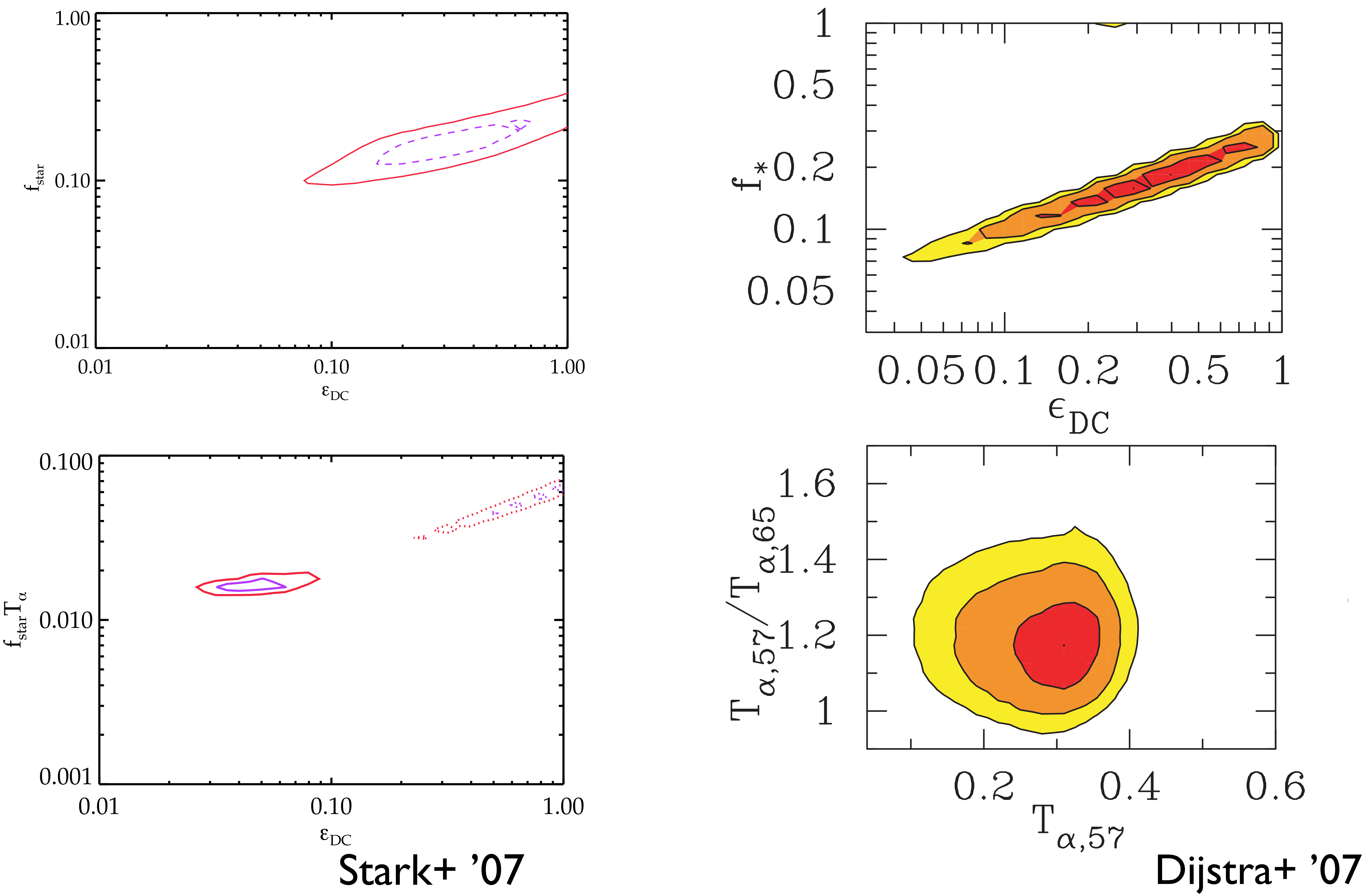


- **"Stochastic" scenario:** (or duty cycle)
  - only a fraction **C_{stoc}** of star-forming gals are active (or *can be observed*) as LAE

(due to "interstellar weather")

KN+ '08

Degeneracies btw f_*, ε_{duty}, $f_{esc,Ly\alpha}$



both based on semianalytic calculations using halo mass func.

Lya Effective Escape Fractions

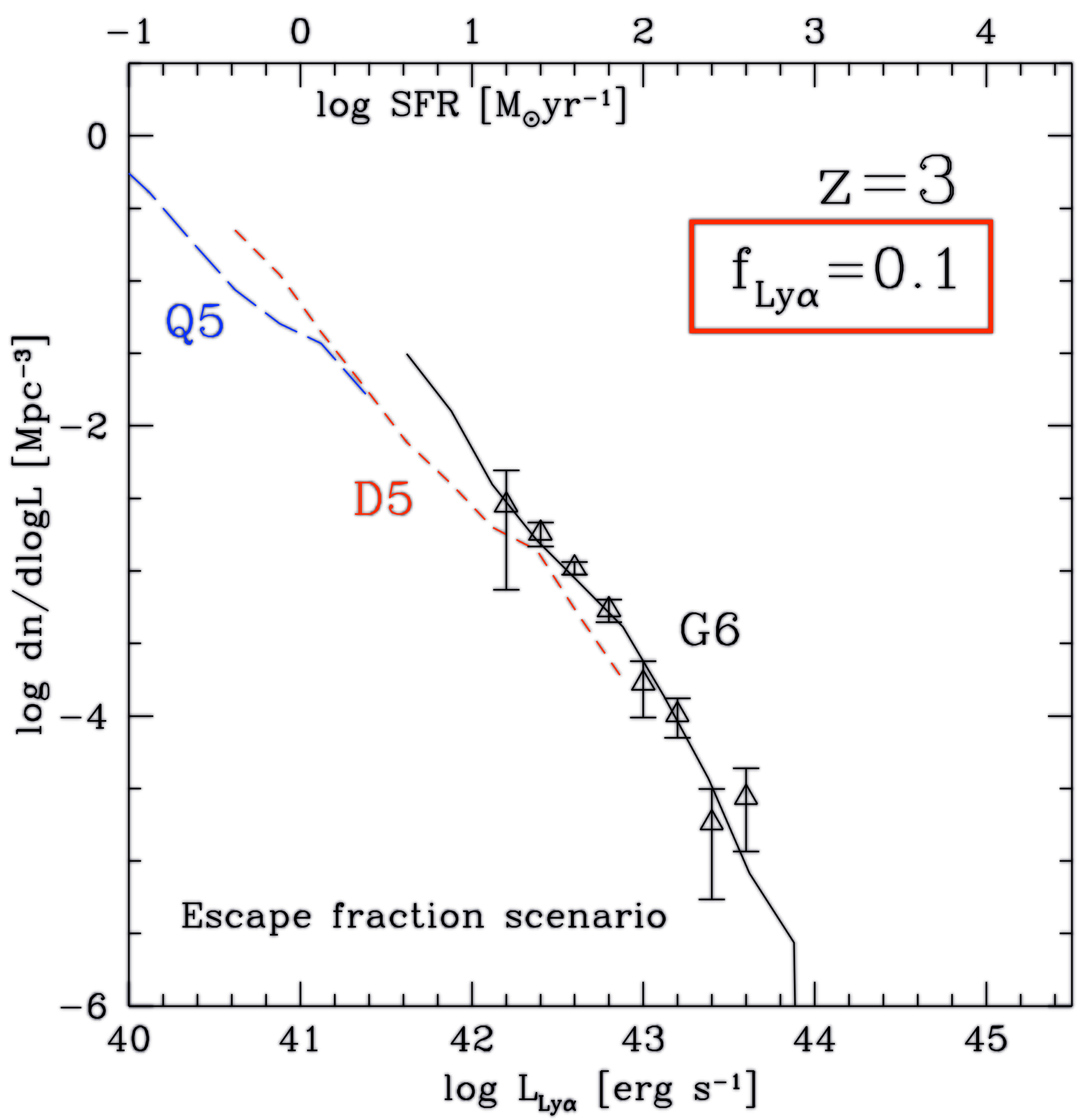
Authors	$f_{esc, Lya}$	Notes
Semianalytic models (uses halo mass fcn)		
Le Delliou+ '06	0.02	top-heavy IMF
Dijkstra+ '07	0.1 - 0.4	z~6
Stark+ '07	0.1 - 0.2	z~6
Kobayashi+ '09	~0.2	
Samui+ '09	0.1 - 0.3	
Dayal+ '09	0.3	z~6
Cosmological Hydro Simulations		
Barton+ '04	0.1 - 0.35	
Dave+ '06	0.02	adjusted to Santos+ '04
Nagamine+ '08	~0.1	

(also Mao+ '07; Fernandez & Komatsu '09)

Seems to converge on $f_{esc,Lya}$ ~ 0.1 - 0.3

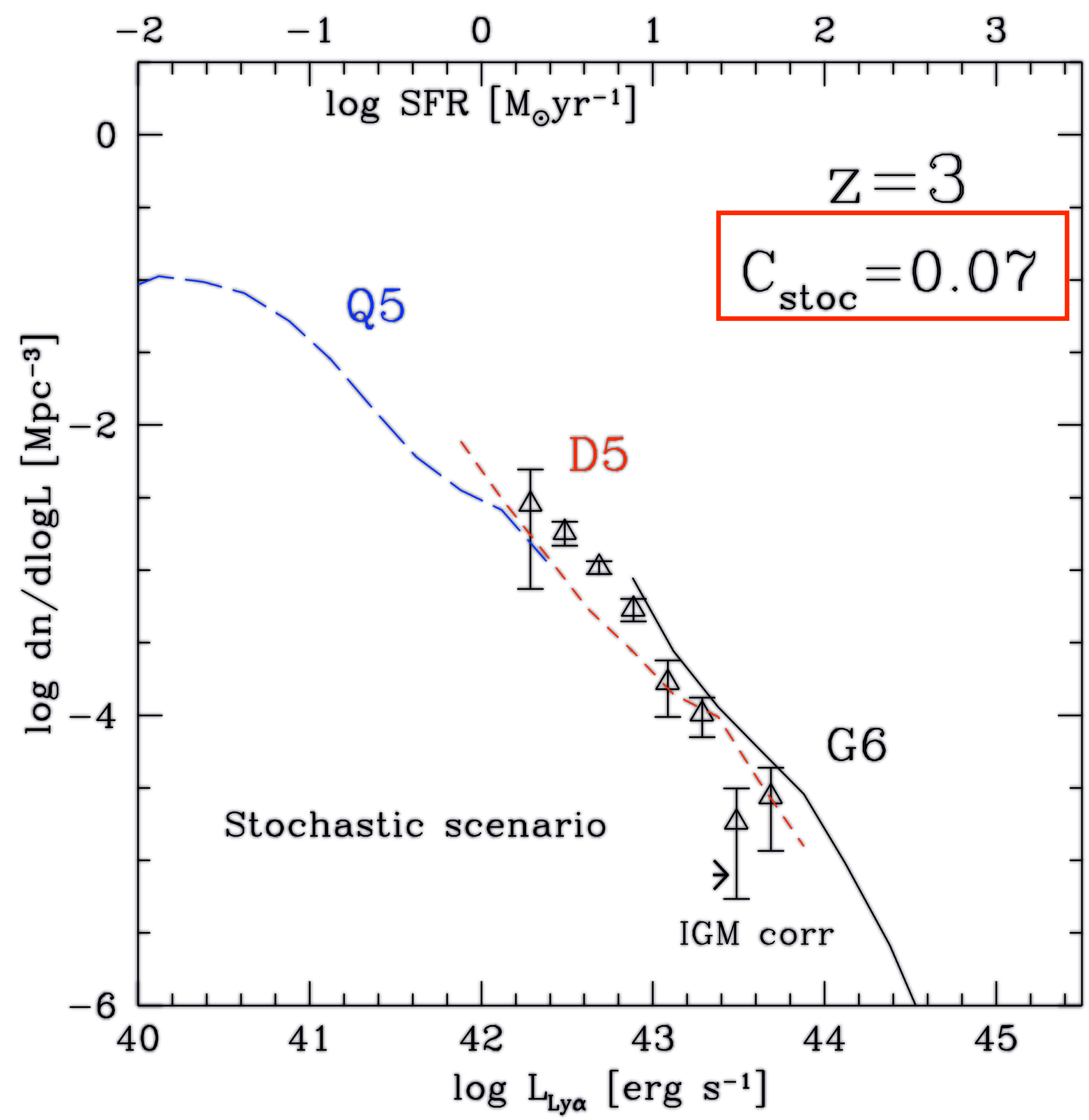
Lyα LF @ z=3

Escape fraction scenario



Data points: Ouchi+ '08

Stochastic scenario

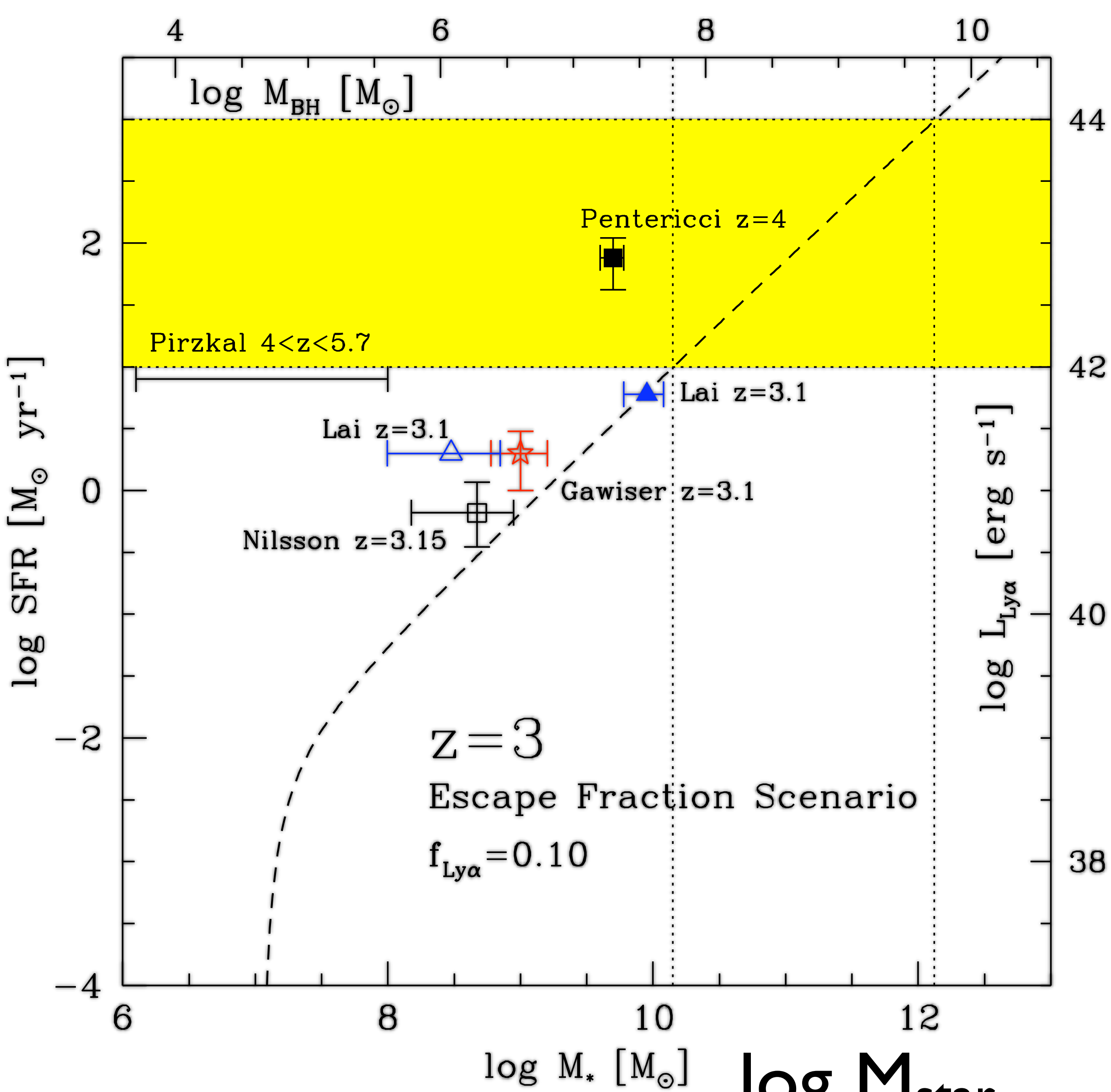


f_{IGM}=0.82 (Madau+ '95)

(cf. Samui+ '09; consistent result)

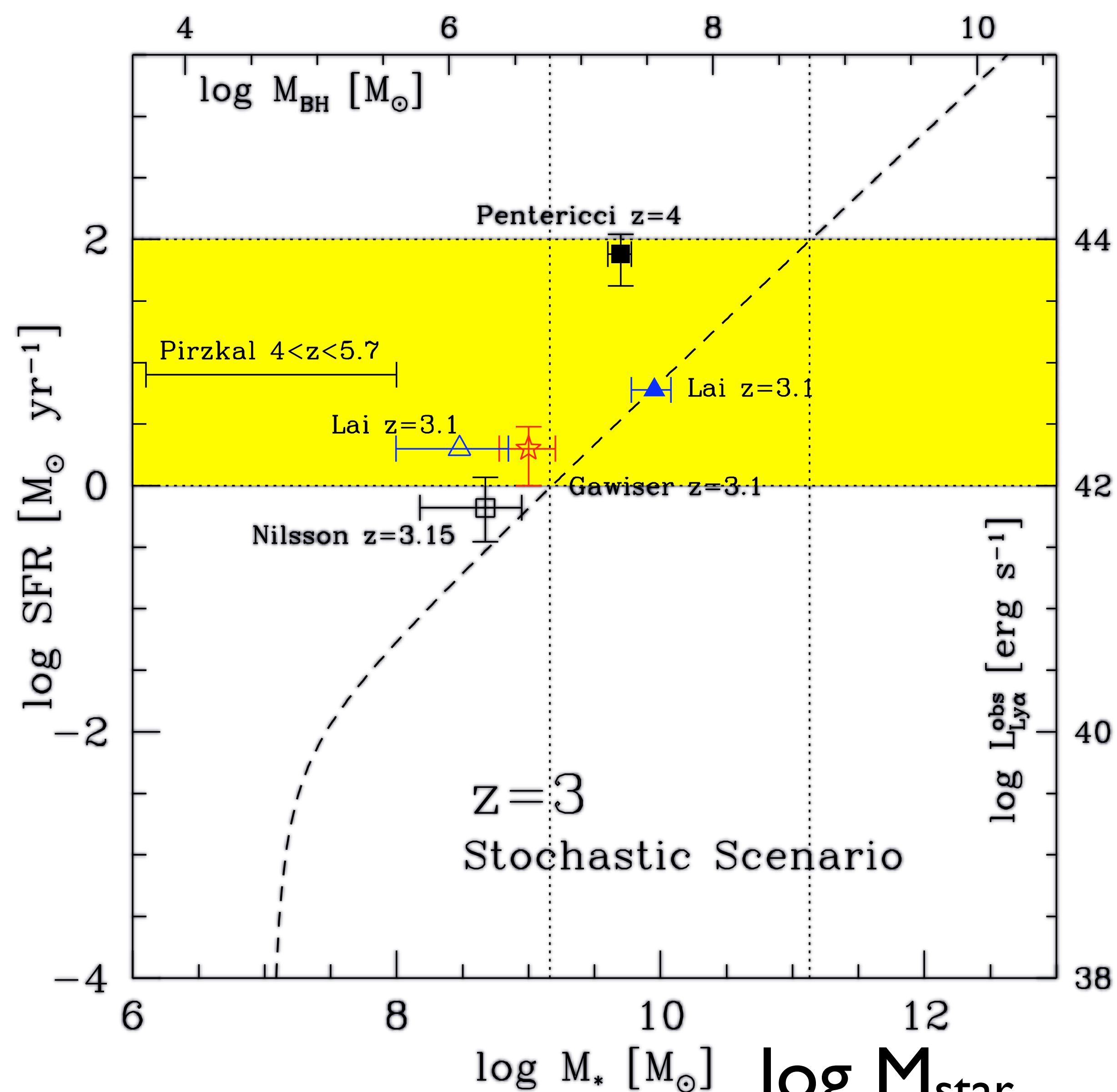
M* vs. SFR @z=3

Escape fraction scenario



log M_{star}

Stochastic scenario



log M_{star}

Favors the stochastic scenario.

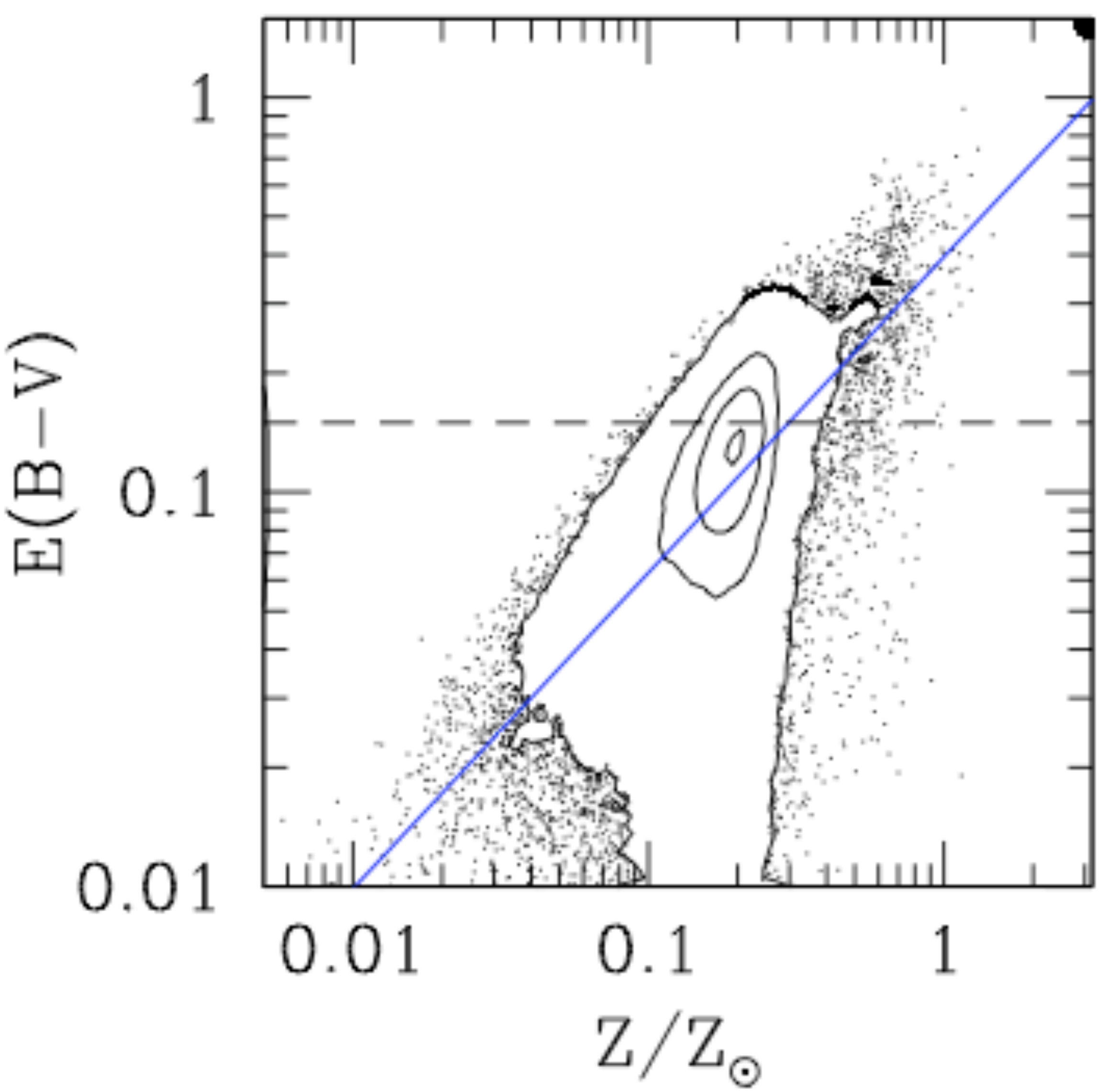
But this was with a fixed EW of 70Å for L_{Lya} & fixed E(B-V)

Scatter in E(B-V)

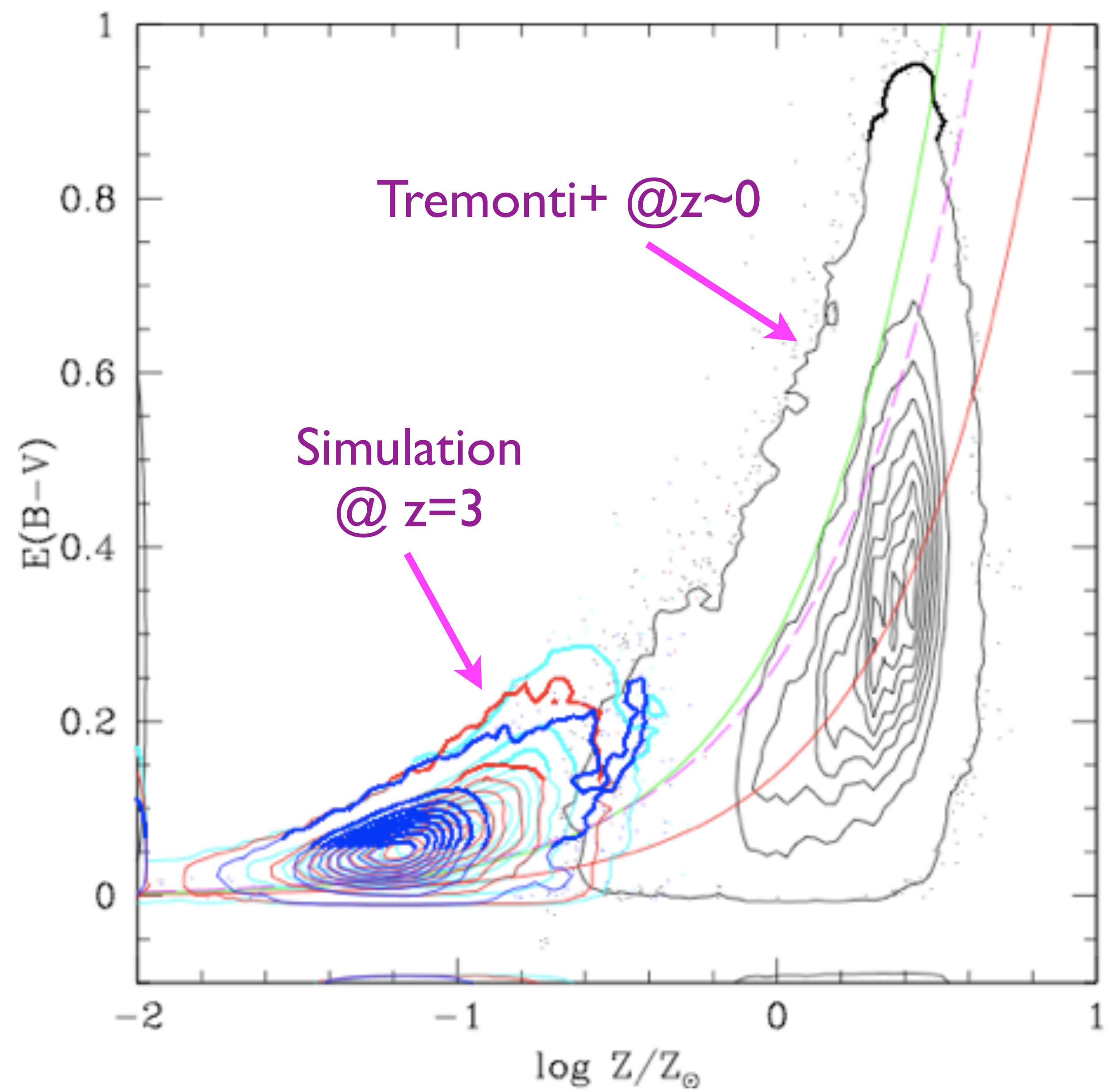
$$E(B-V) = 9.0Z^{0.8} + \Delta E$$

(cf. Finlator+ '06)

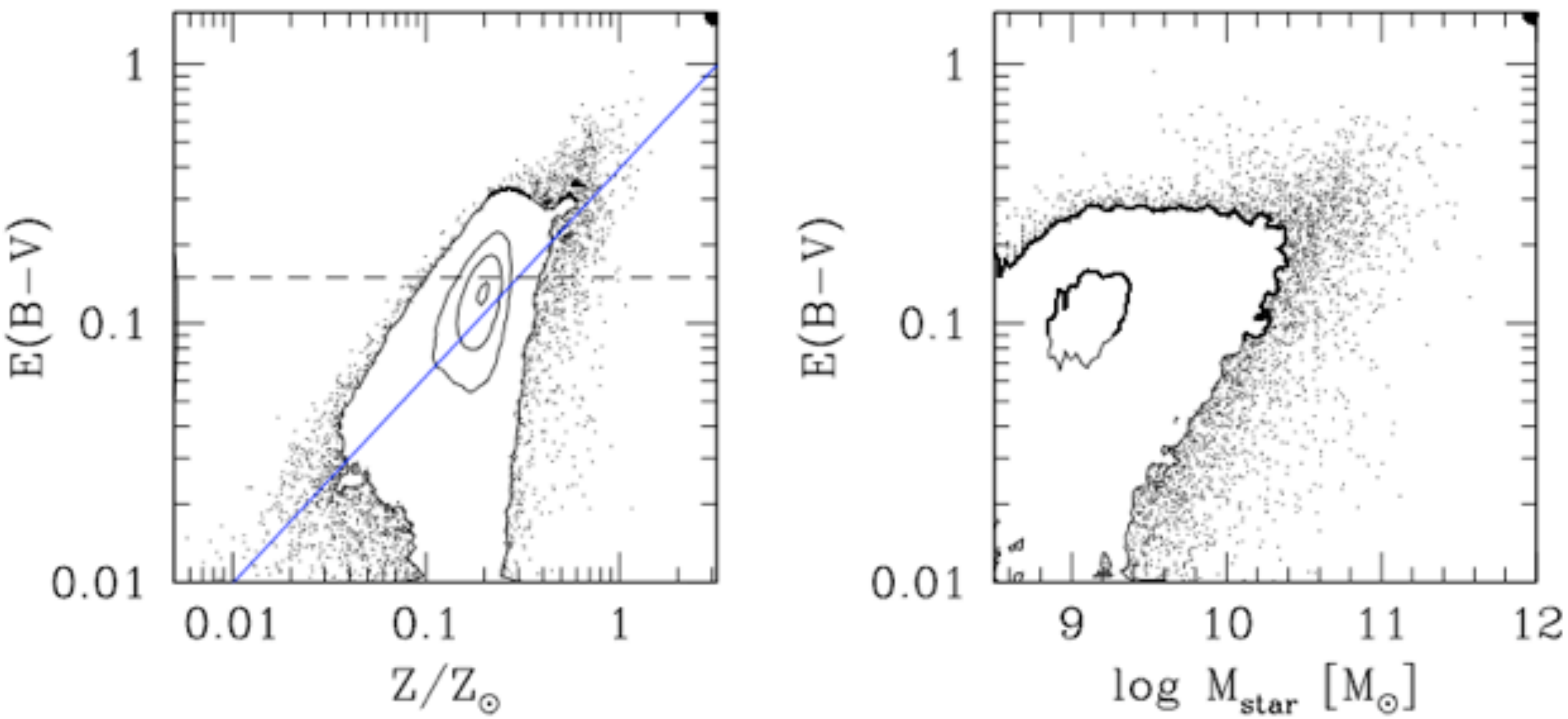
ΔE : random Gaussian scatter



smoothly connect to z=0 Tremonti result

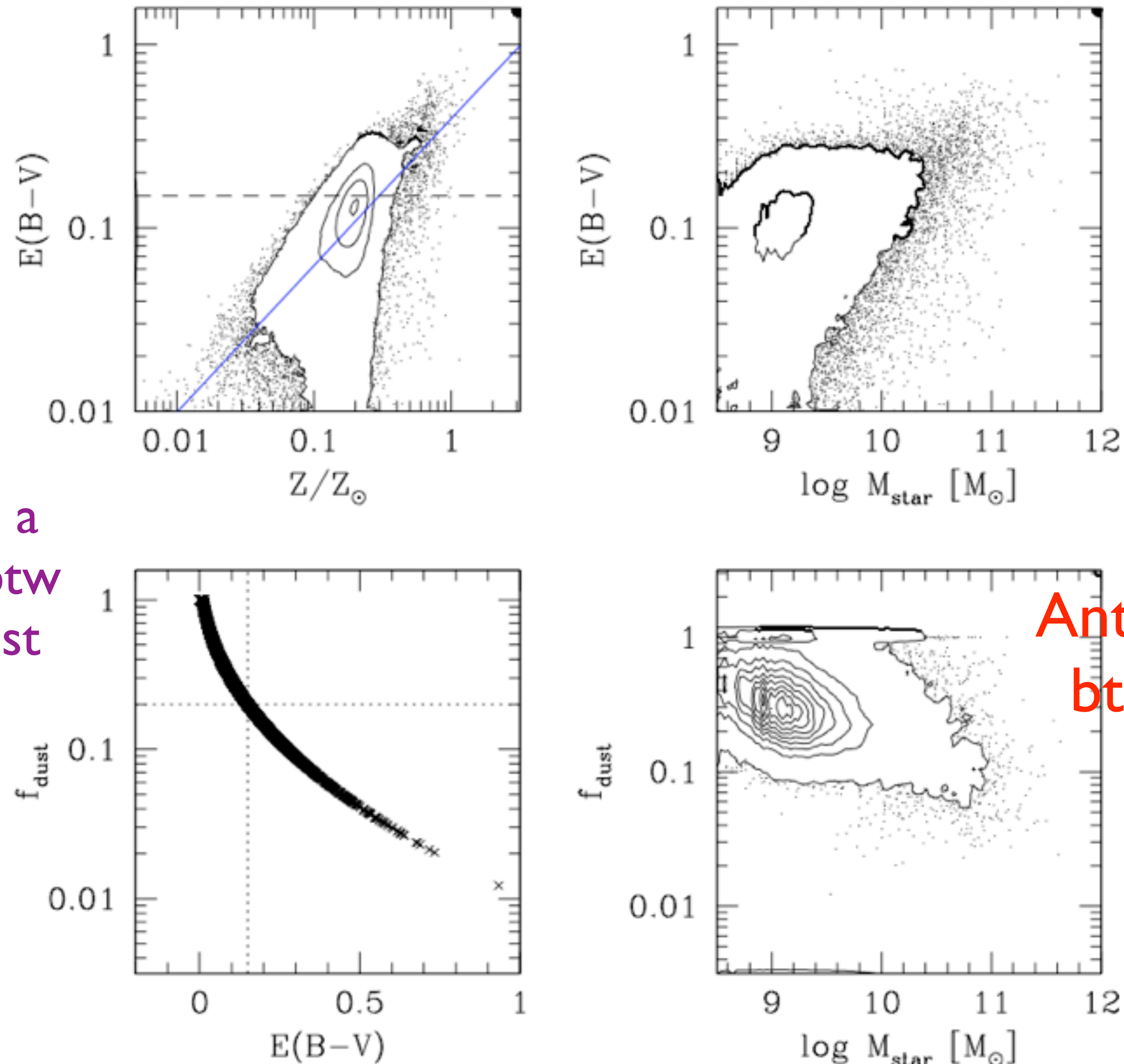


Considering the effect of dust on Lyα



based on the M* -- Z relationship in the simulation

Considering the effect of dust on Lyα



then assume a relationship btw E(B-V) & fdust

Lyα

UV

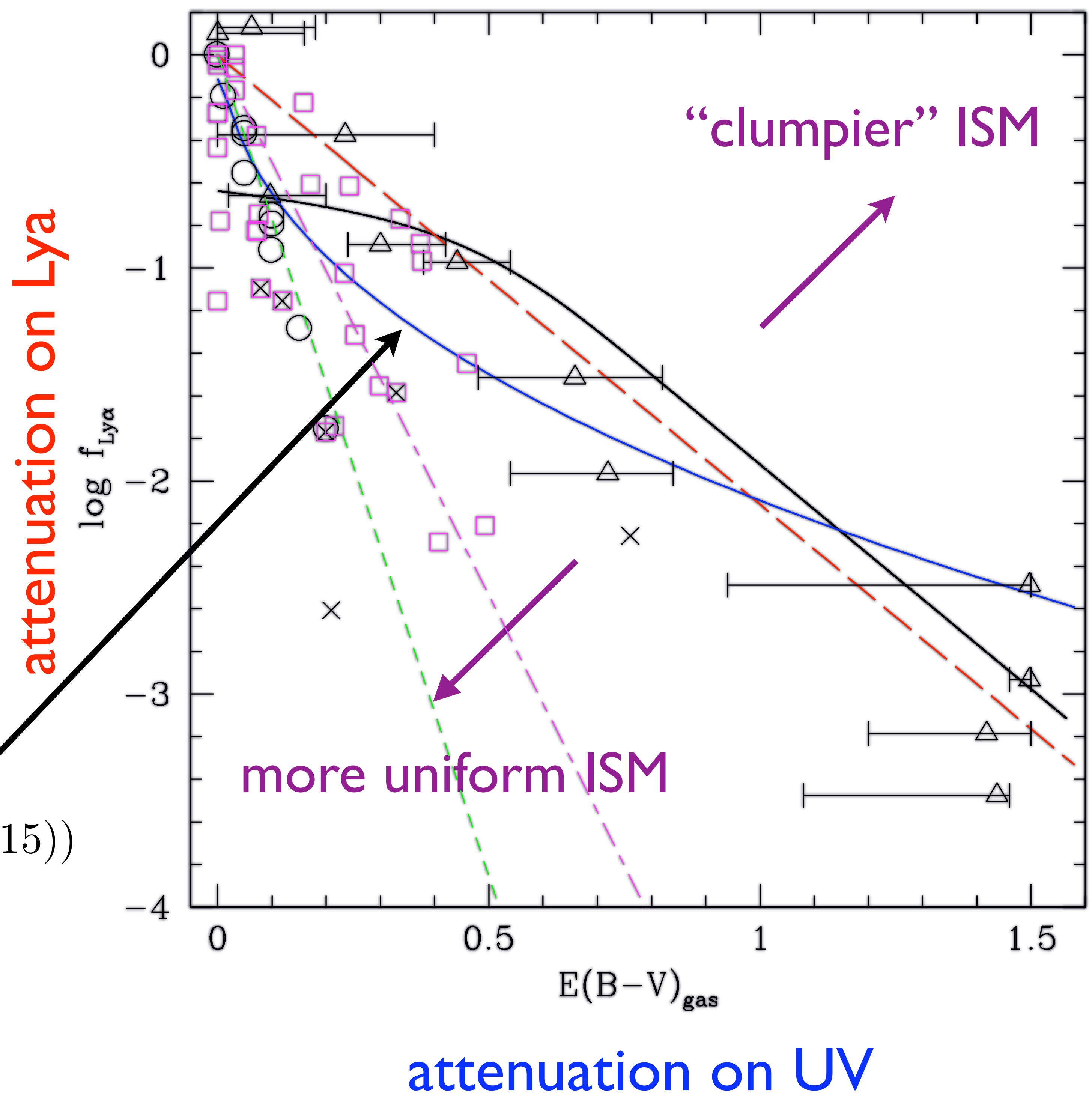
Anti-correlation btw f_{dust} & M_*

Effect of dust on Lya

- red-dashed: 1-to-1, fixed EW=70Å
- black curve: Kobayashi+'08
- blue curve: KN model with $\langle f_{dust} \rangle = 0.2$ @ Ebv=0.15
- data points: Verhamme+ '08, Ono+'09, Atek+ '09

Nagamine model:

$$\log f_{dust} = \log\langle f_d \rangle + 1. - \exp(\log(E_{bv}/0.15))$$



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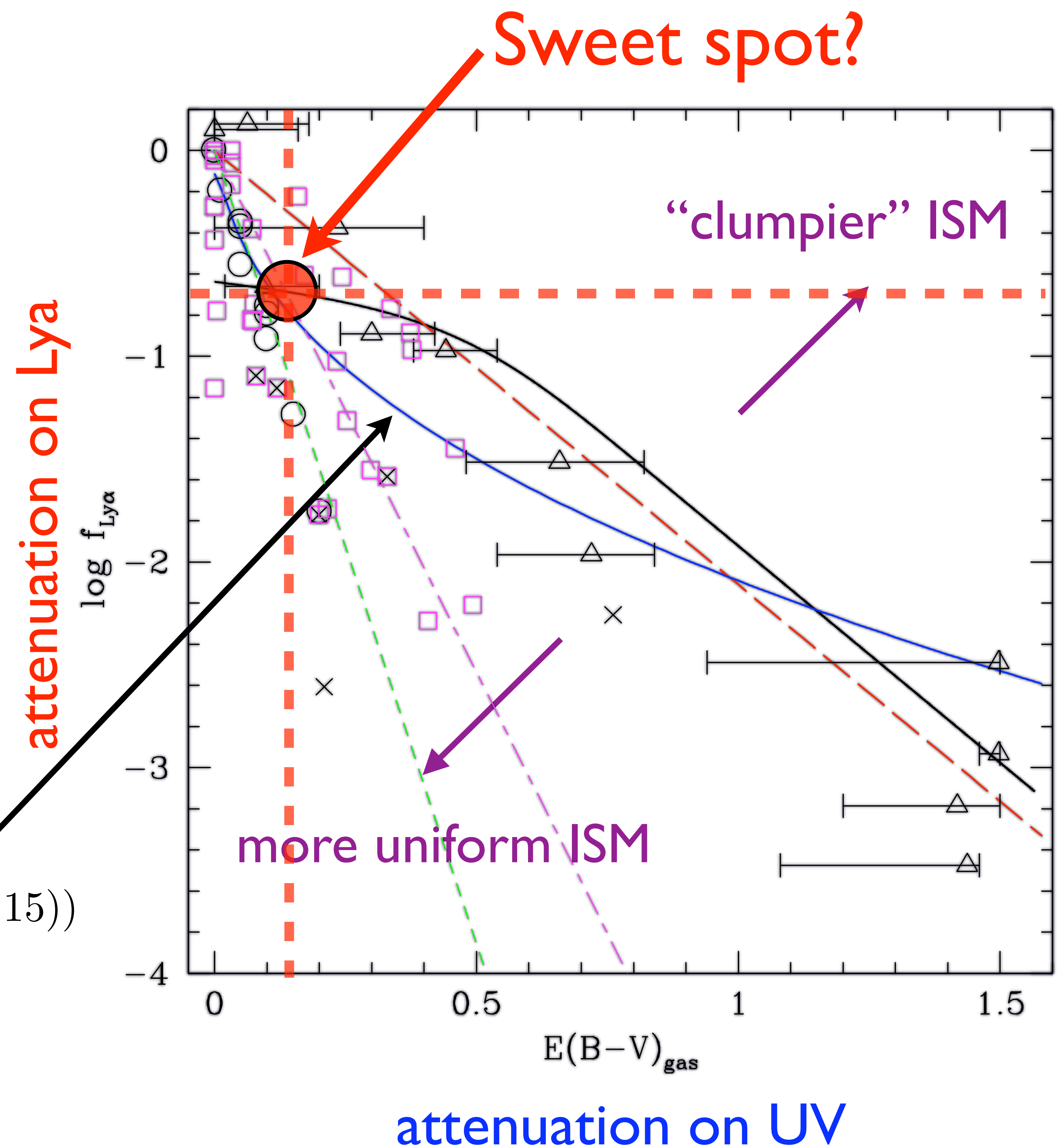
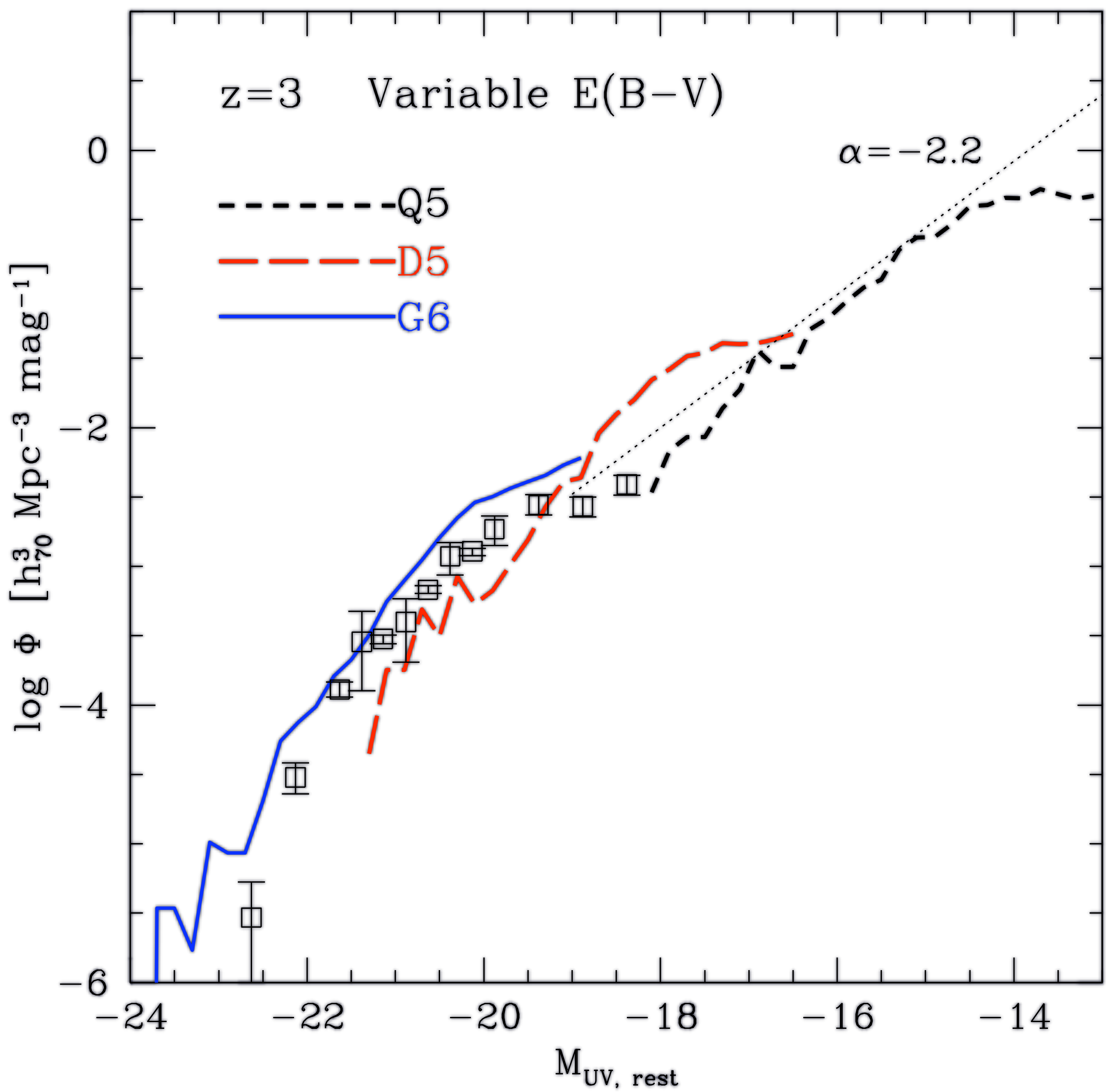
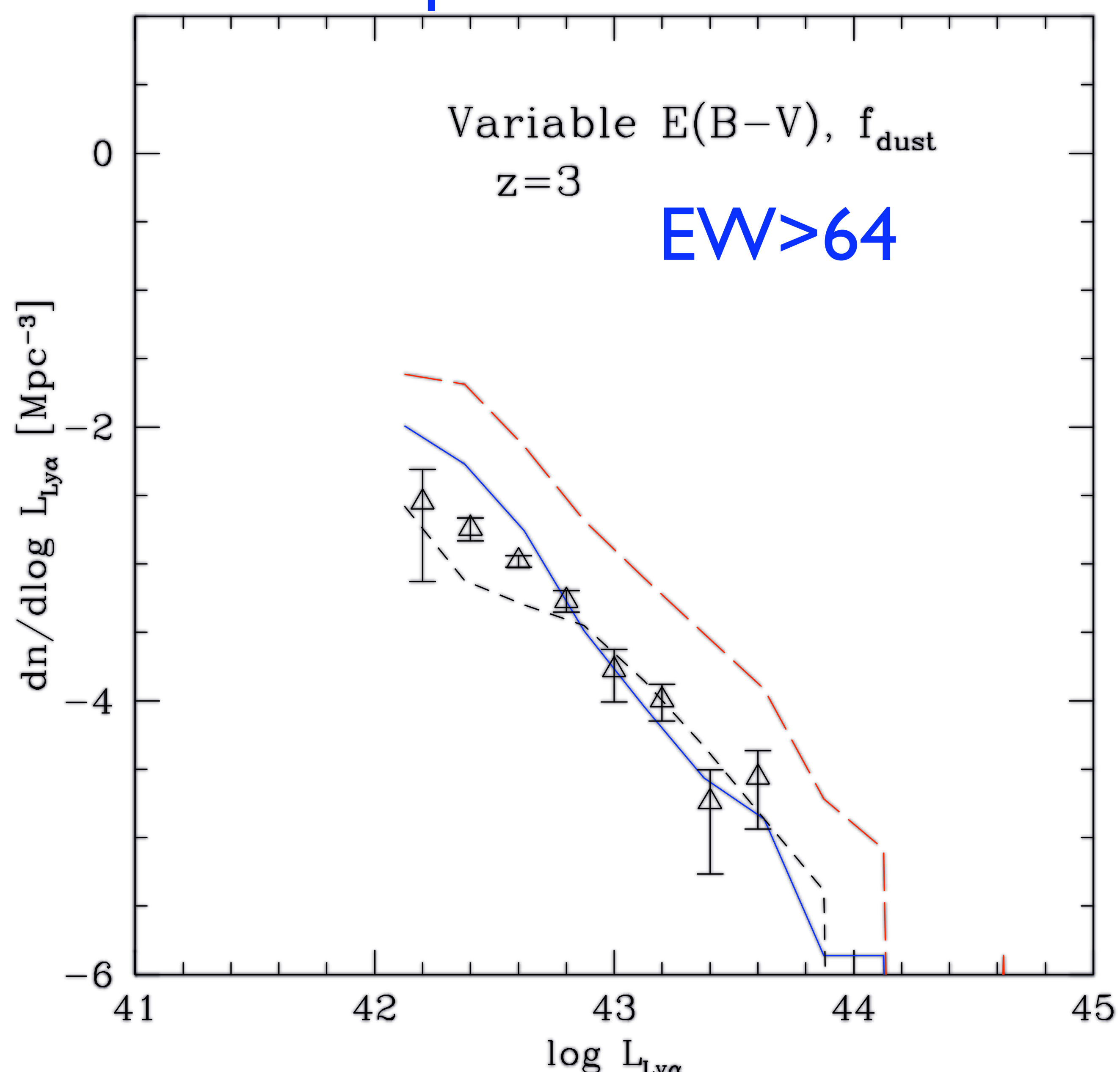


UV & Lyα LF w/ variable E(B-V) & EW cut

Rest UV LF of all LBGs



Lyα LF of LAEs in escape frac scenario

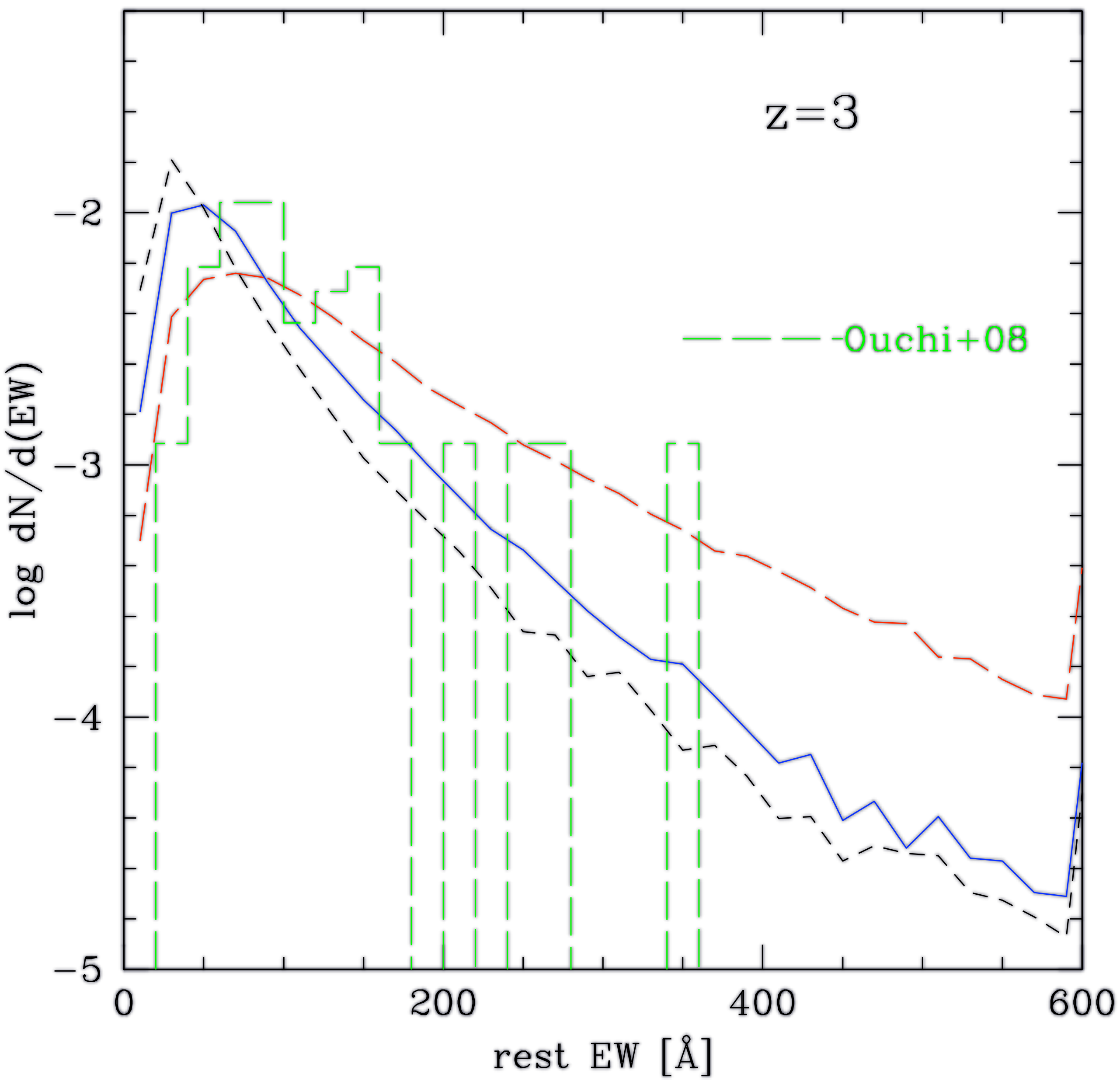


red dashed: linear 1-to-1, EW=70Å

black dashed: Kobayashi+ '09

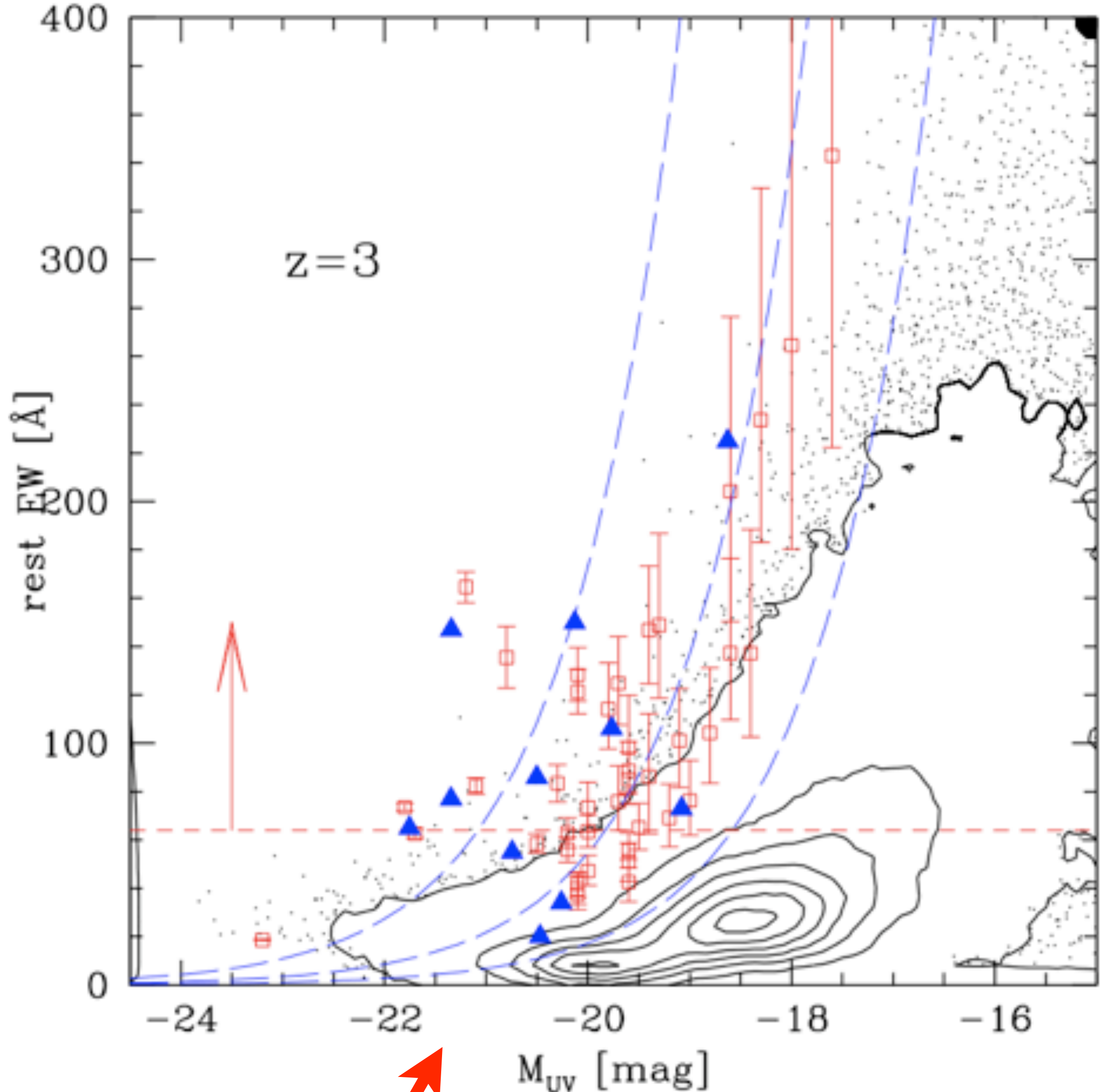
blue solid: Nag_fd020 model

Rest EW dist.



red dashed: linear 1-to-1, EW=70Å
black dashed: Kobayashi+ '09
blue solid: Nag_fd020 model

Rest EW vs. M_{uv} mag



Nag_fd020 model

This correlation is a natural outcome of M* -- Z relationship

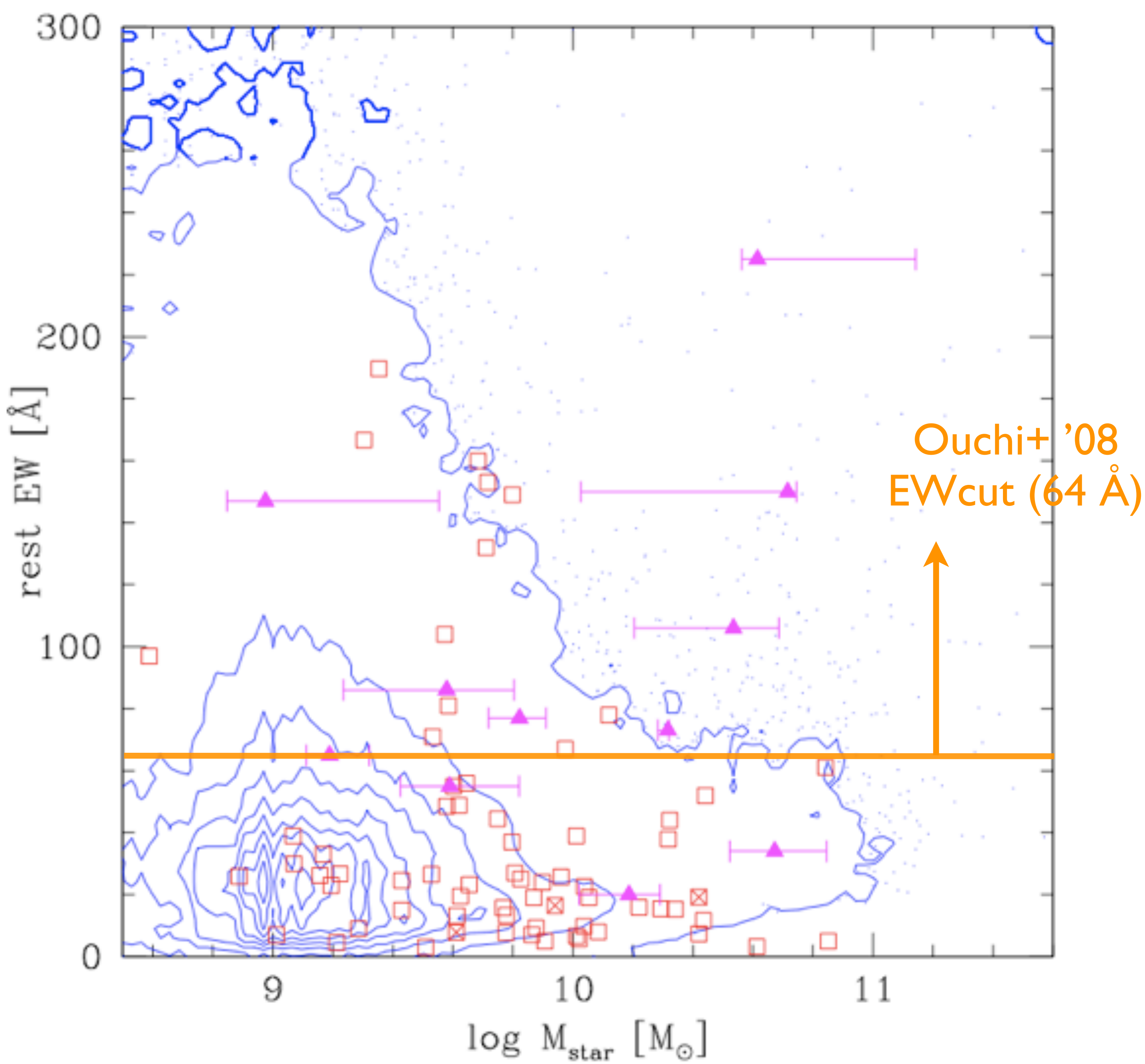
Rest EW vs. M_{star}

EW cut restricts the sample to lower mass population w/ mean $M_* \sim$ few x 10^9 M_{sun}

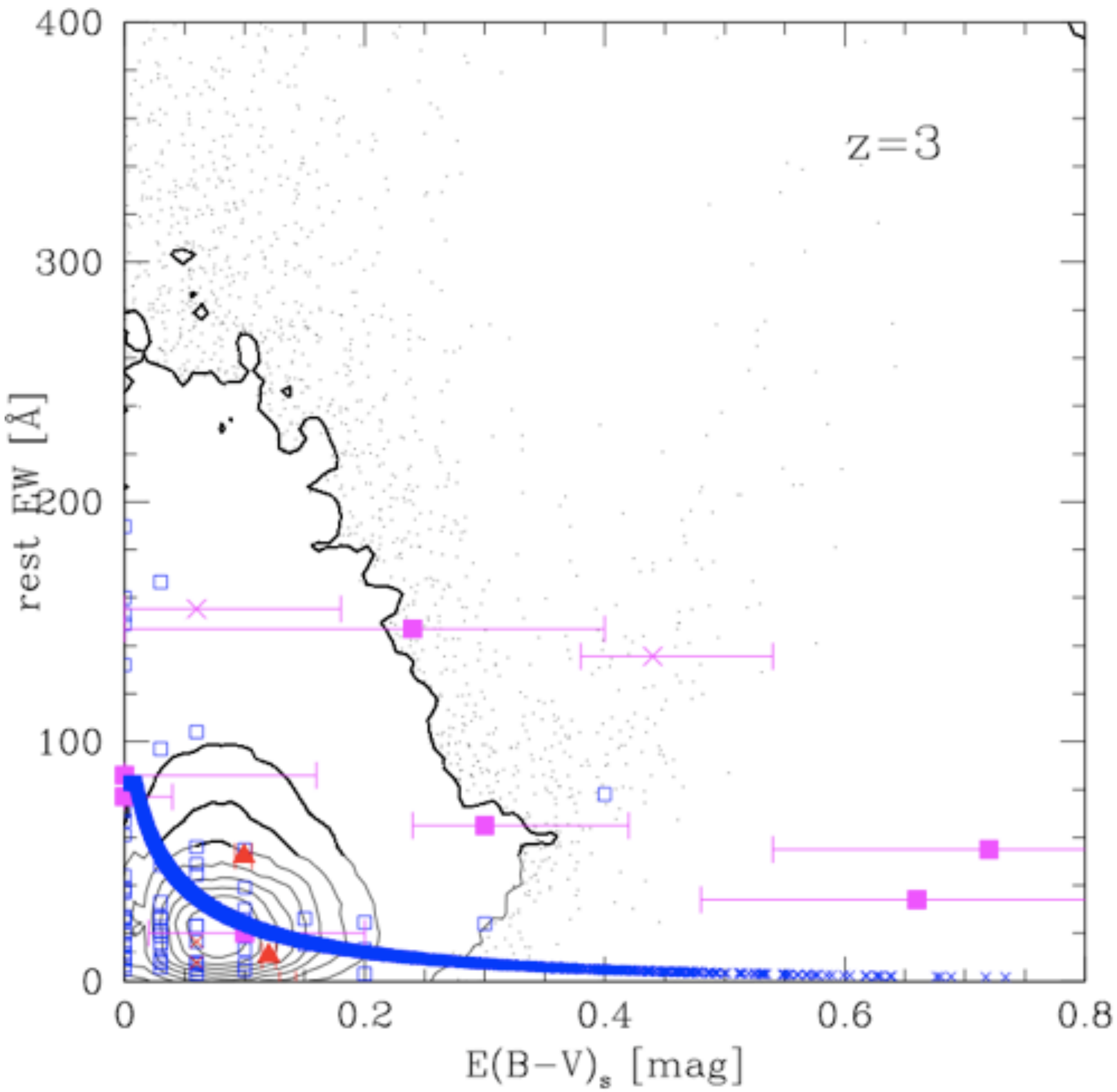
(thereby reviving the escape fraction scenario)

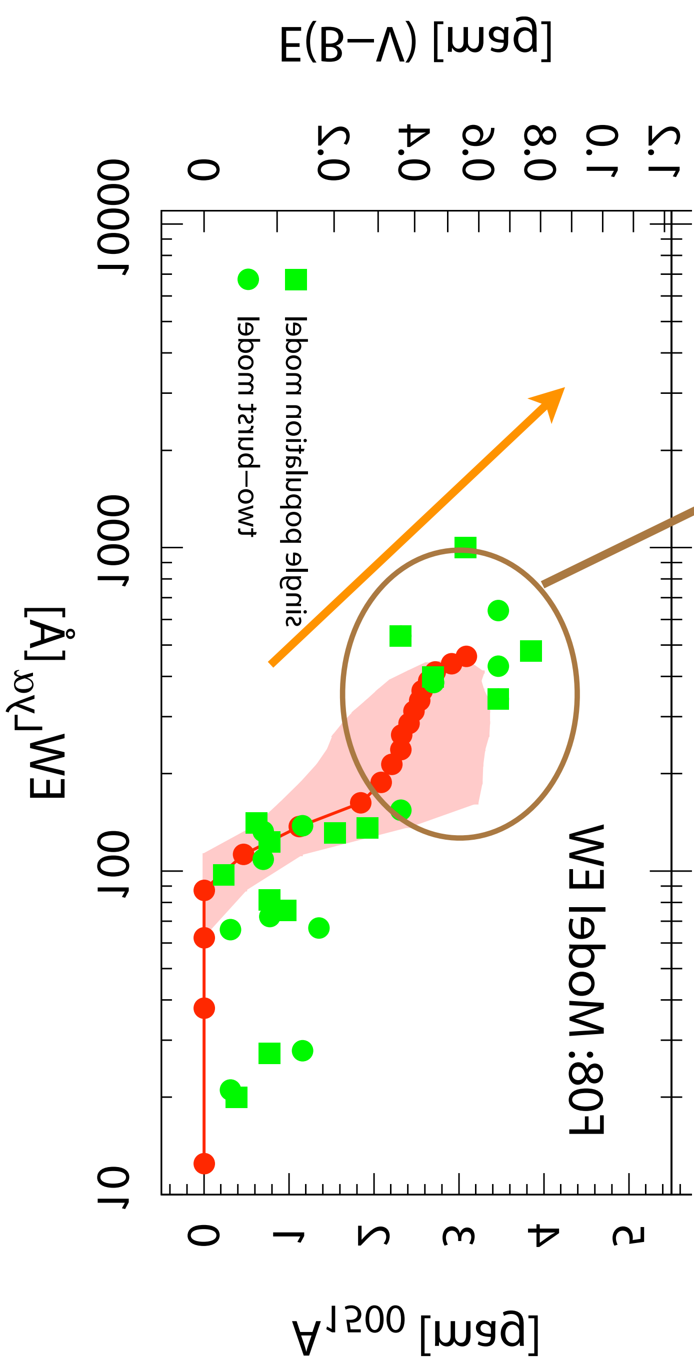
No significant population of large EW & large M_*

red open squares: Pentericci+ '09
magenta points: Ono+ '09



E(B-V) vs. Rest EW





highly extinct gals with clumpy ISM

Kobayashi+'09: completely opposite trend due to highly extinct gals with clumpy ISM

Variables involved in LAE study

M_* galaxy stellar mass

Variables involved in LAE study

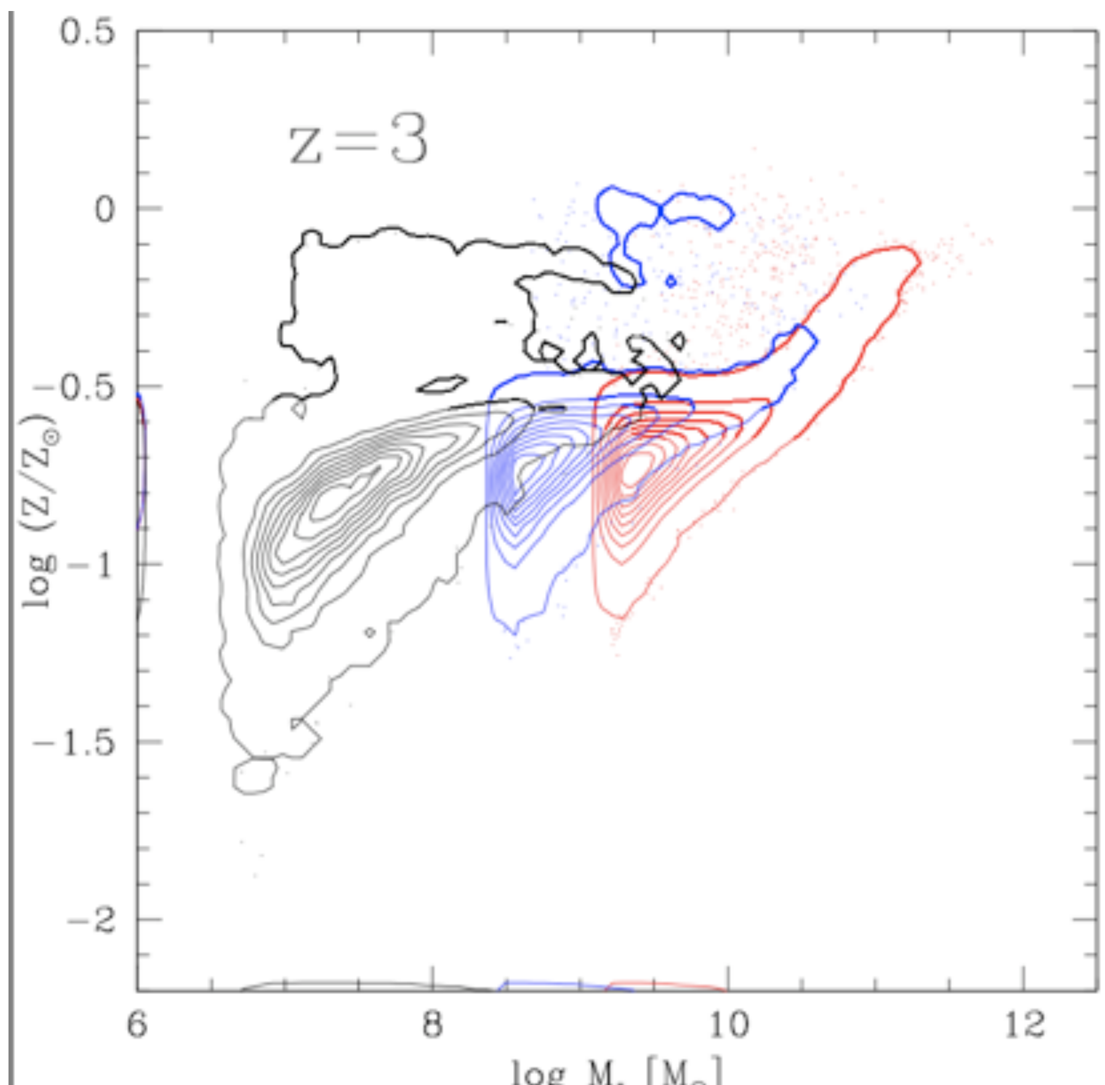
all followed dynamically in the simulation

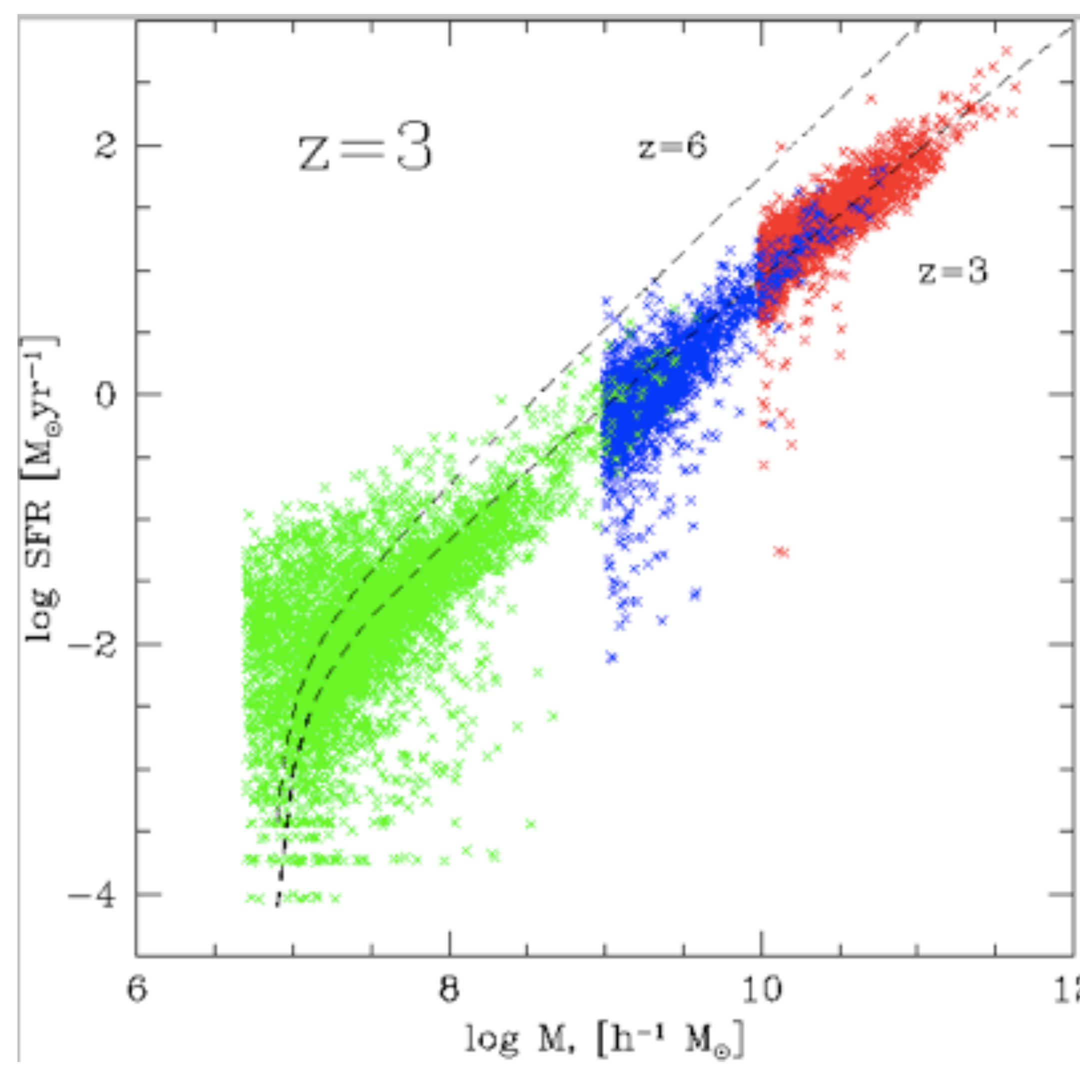
M_*

positive correlation

metallicity Z/Z_{sun}

SFR





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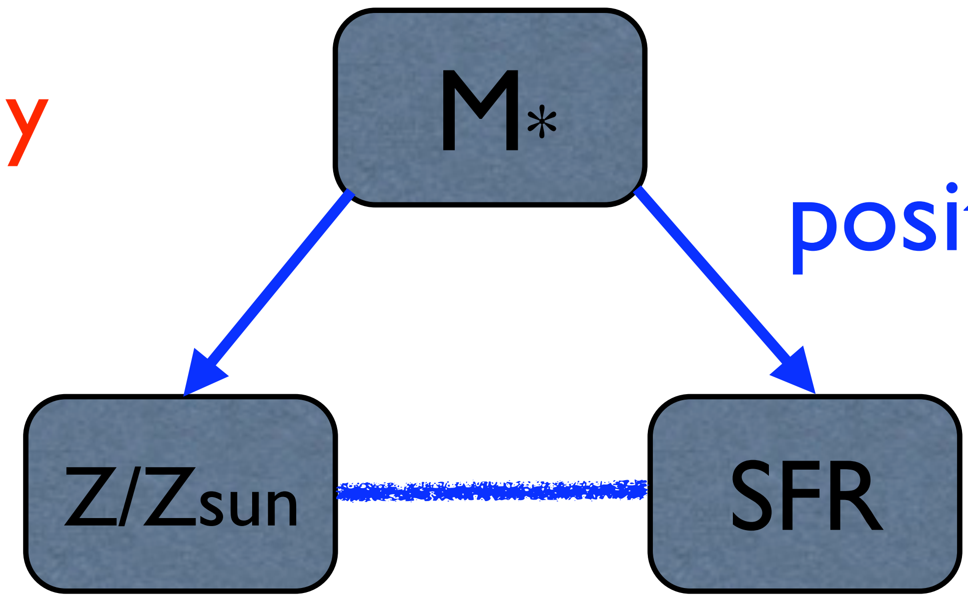
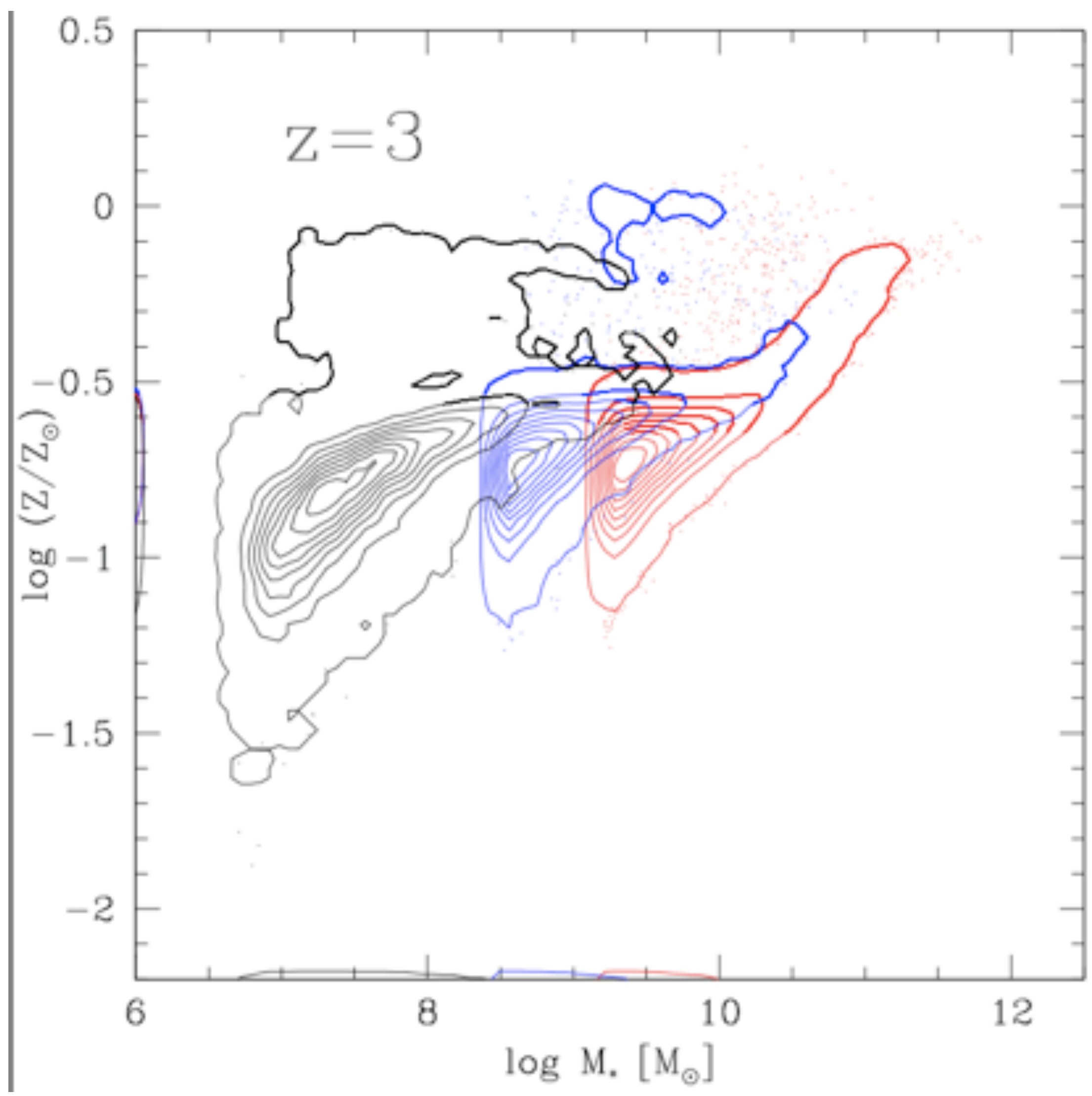
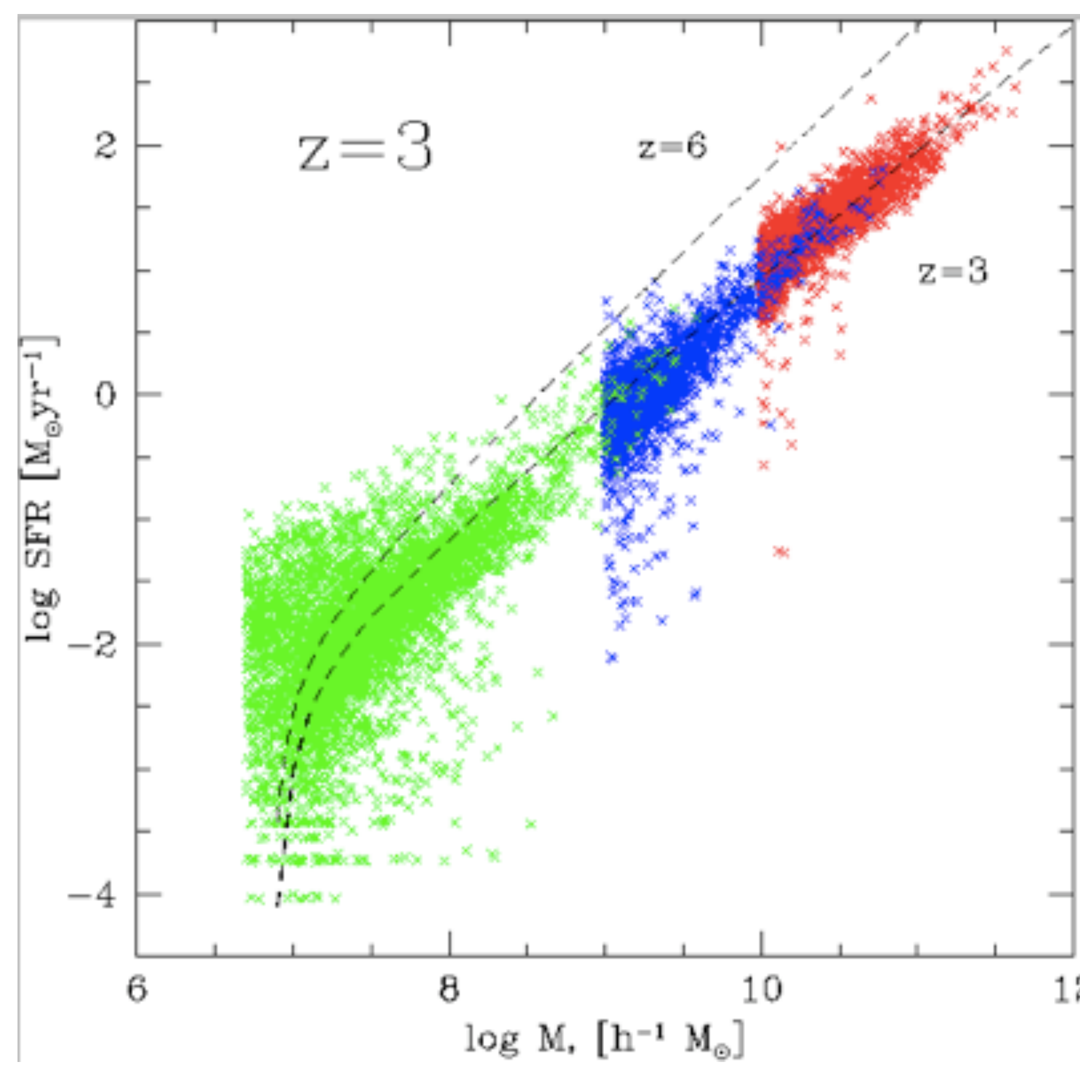
positive correlation

metallicity







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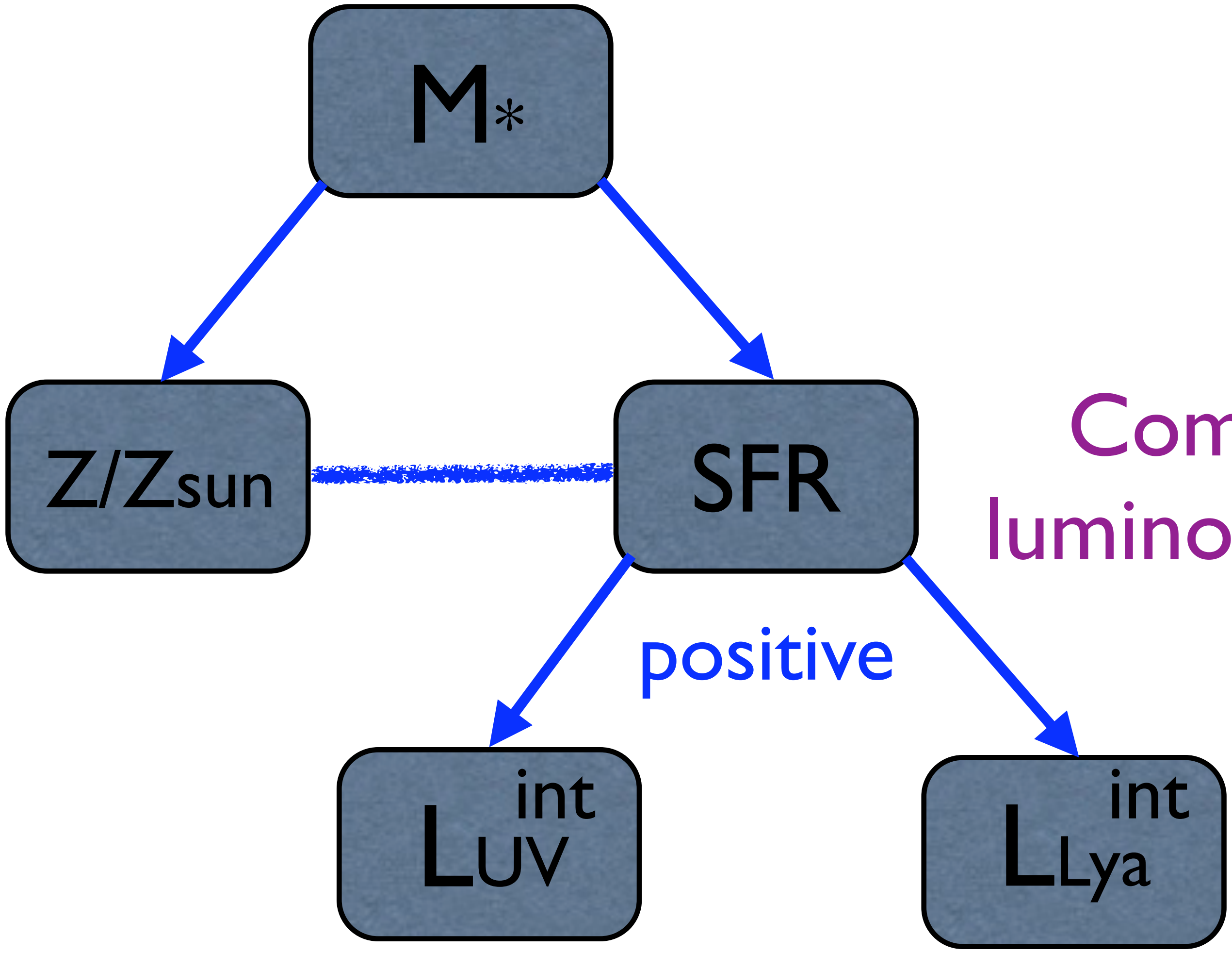
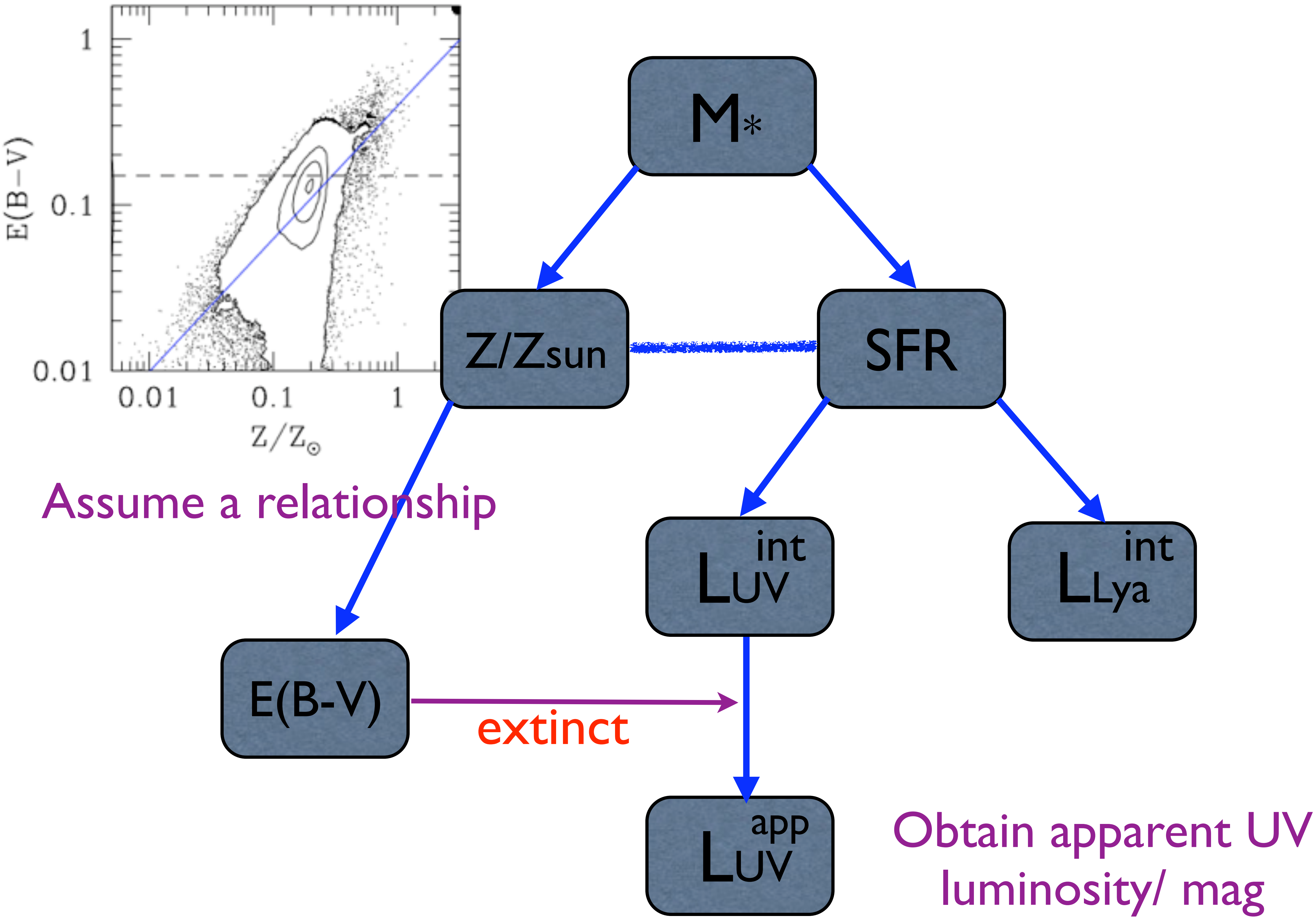
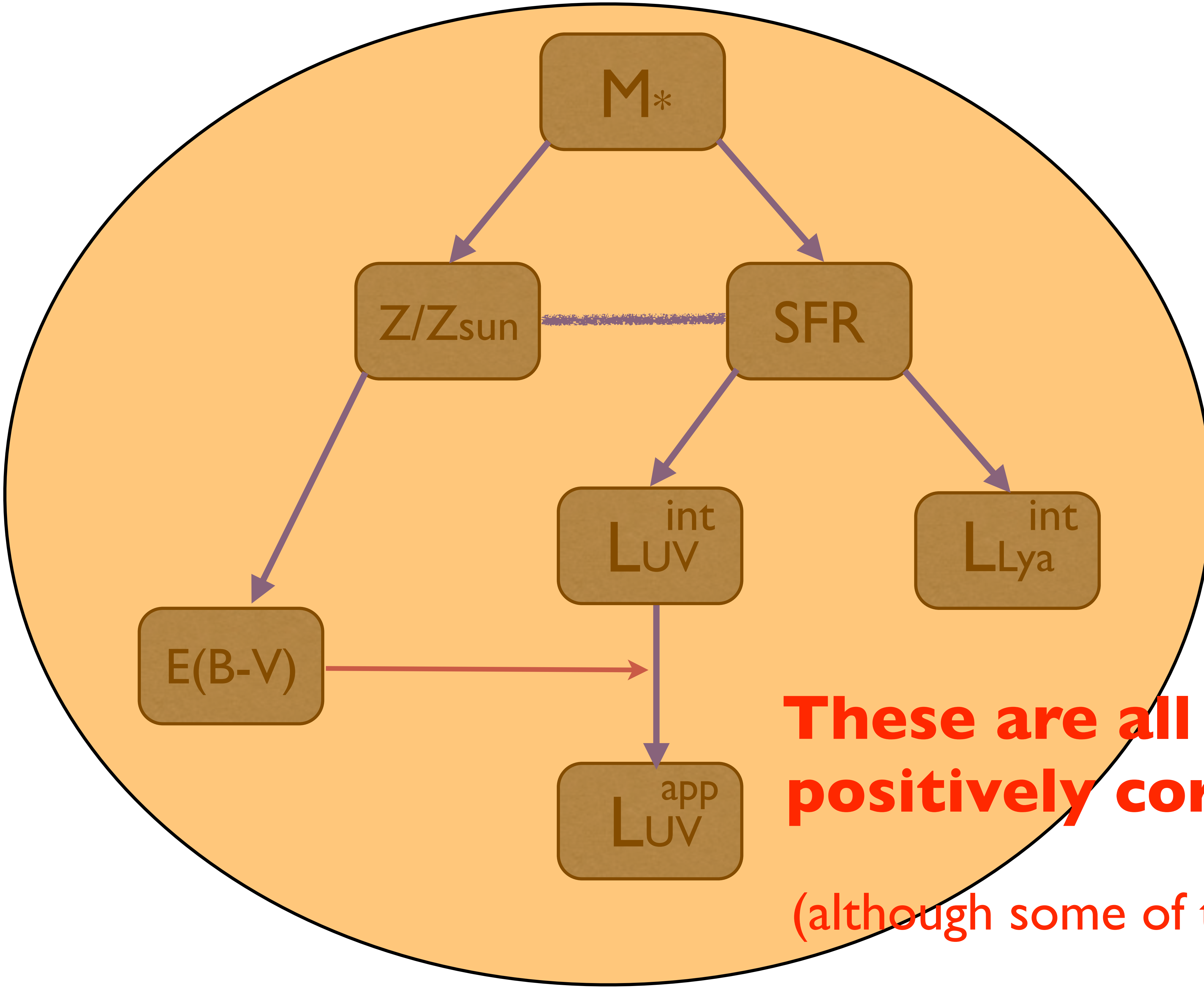


Compute *intrinsic* luminosities from SFR

Variables involved in LAE study



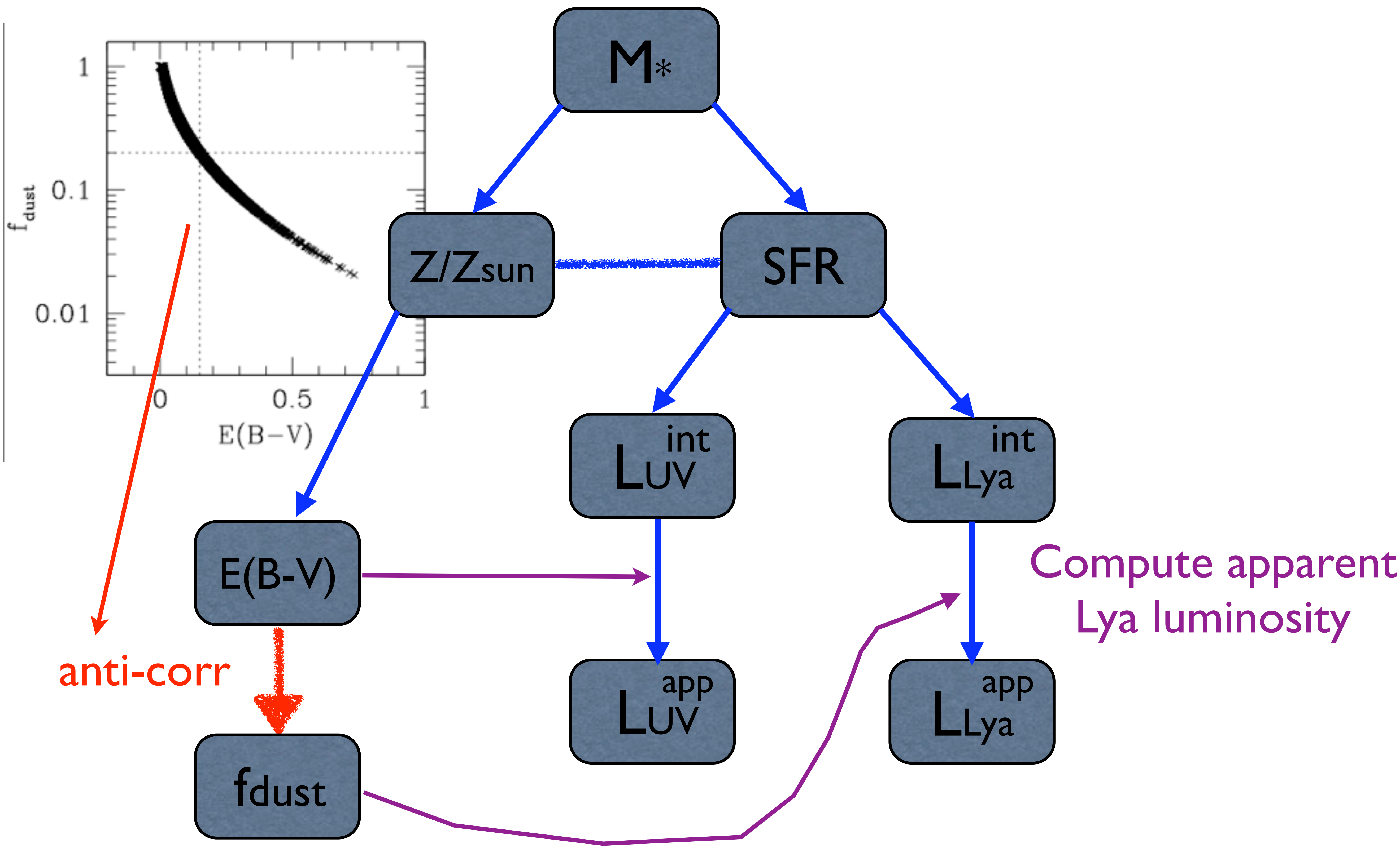
Variables involved in LAE study



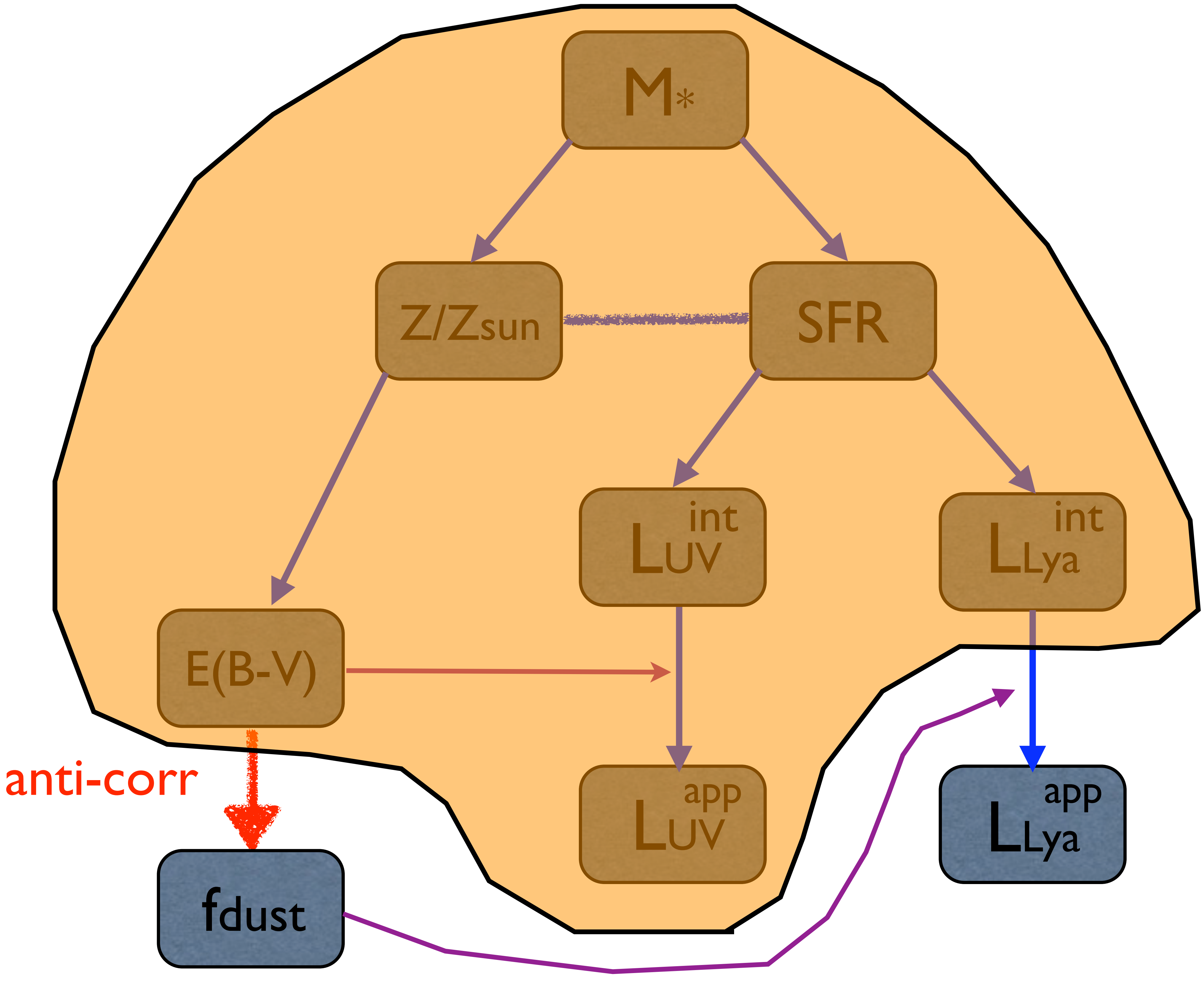
These are all roughly positively correlated

(although some of them weak)

Variables involved in LAE study



Variables involved in LAE study



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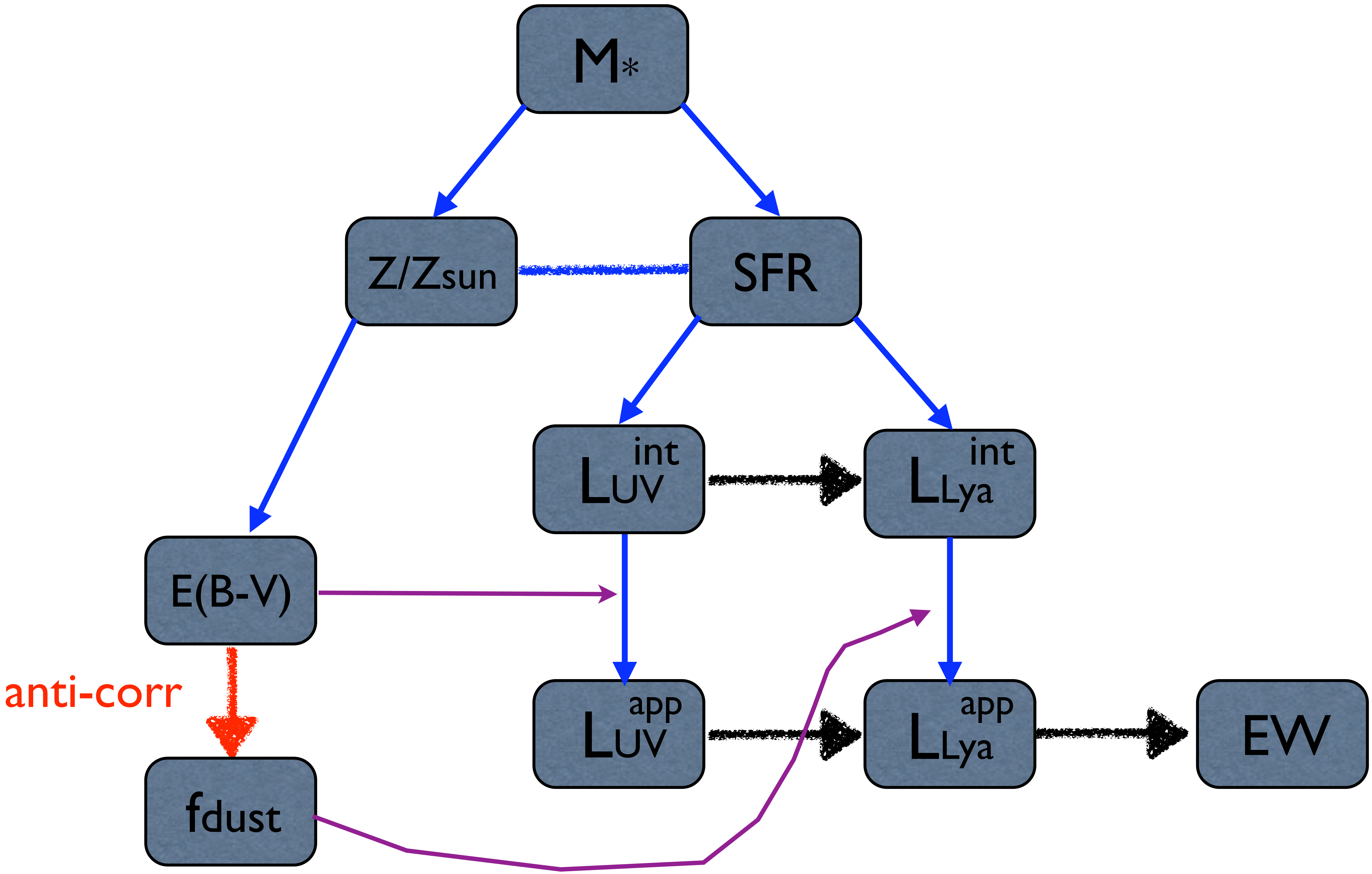


$$f_{Ly\alpha} = f_{\rm dust}(1 - f_{\rm esc}^{\rm ion}) f_{\rm IGM}$$

What about $f_{esc,ion}$?

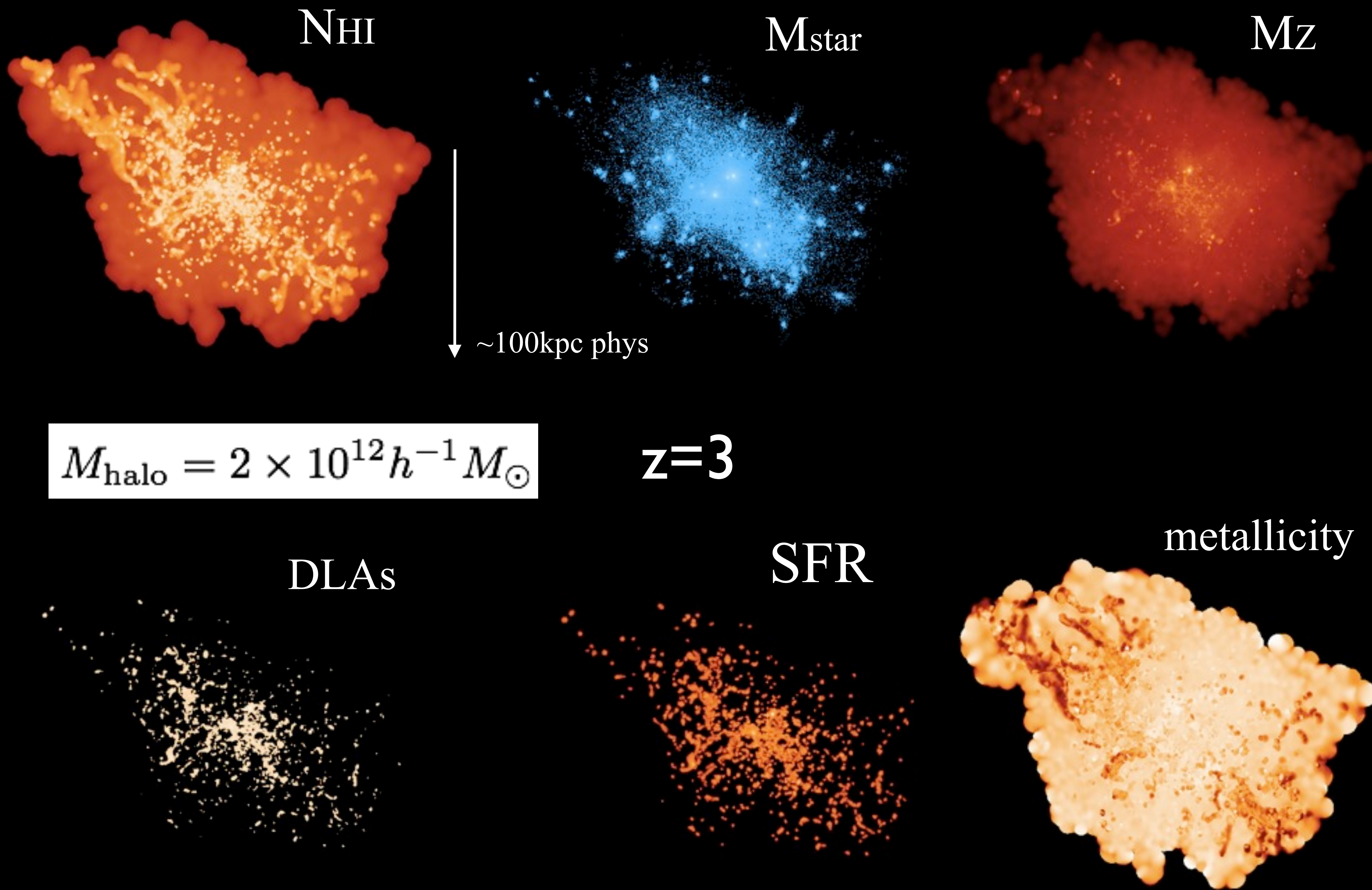
(Escape fraction of ionizing photons)

This requires a treatment of radiative transfer.

Also closely related to DLA study w/ numerical sims.

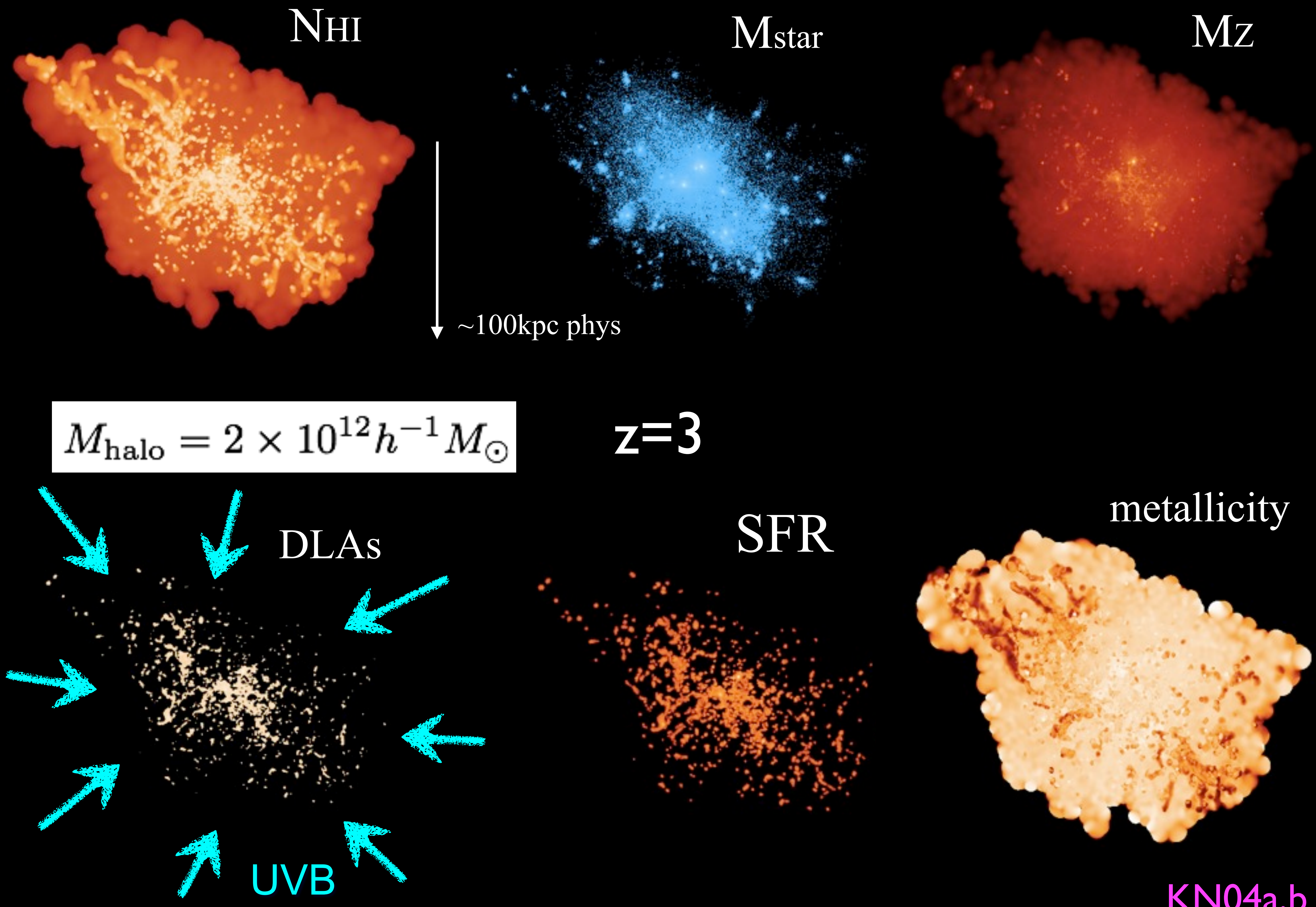
Collaborators: Hide Yajima (Tsukuba) (poster #41)
Junhwan Choi (UNLV)

Why is radiation important?



KN04a,b

Why is radiation important?



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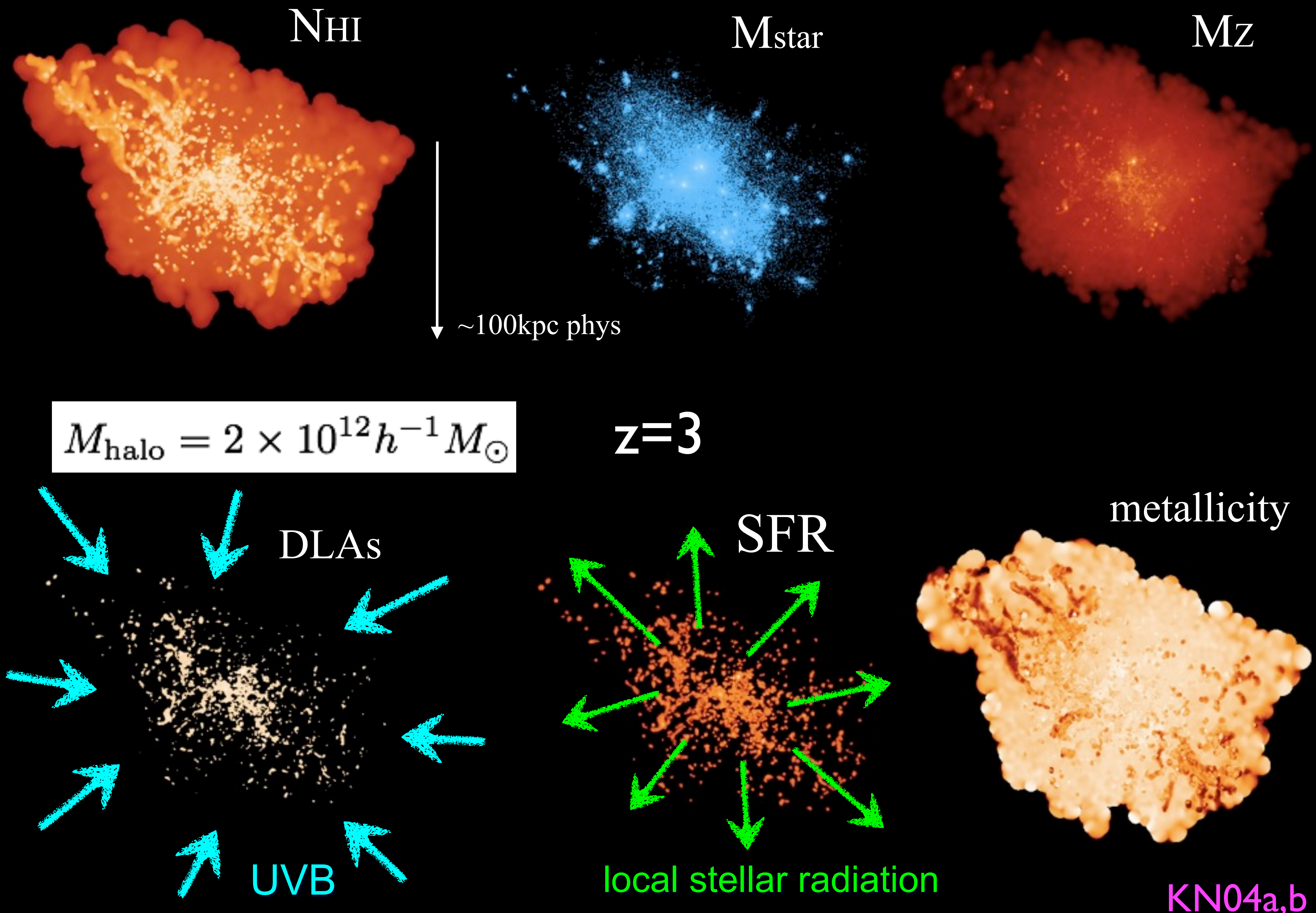
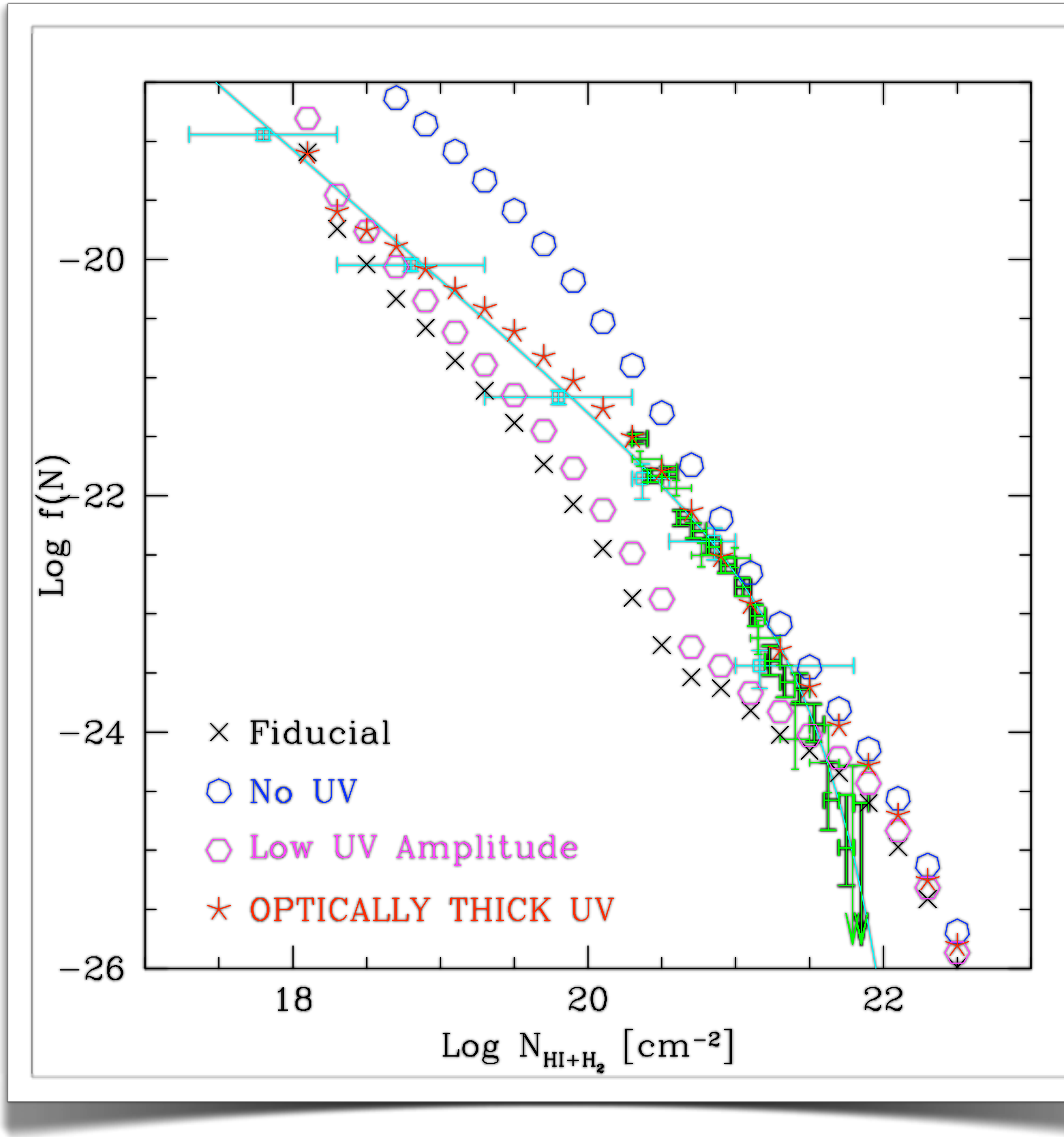


Effect of UVB

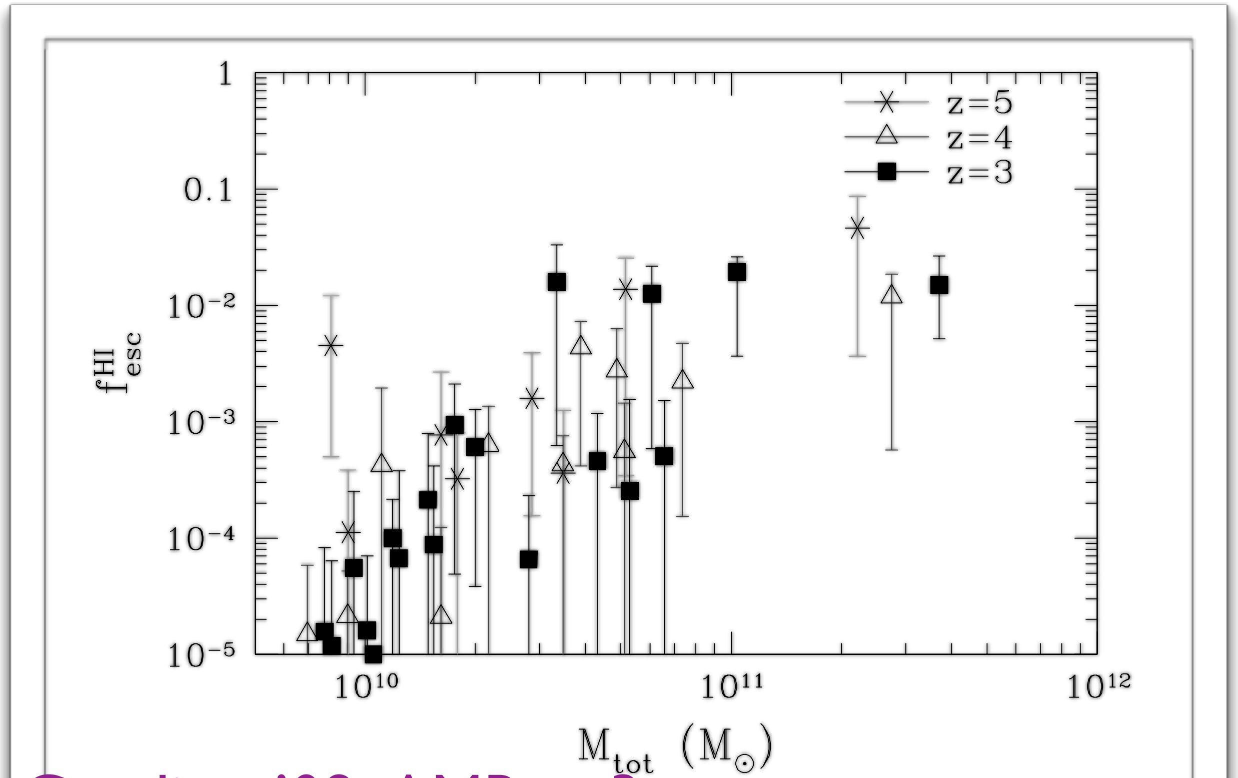
- Previous runs assumed optically thin approx.
- No-UVB run completely overpredicts.
- Weakening the UVB doesn't change the result compared to the orig run.
- Perhaps the UVB was sinking in too much into the halo.
- The run that limits UVB to $\rho<0.01\rho_{th}$ agrees well w/ data.

$\rho_{th}\sim 0.1$ cm^{-3}

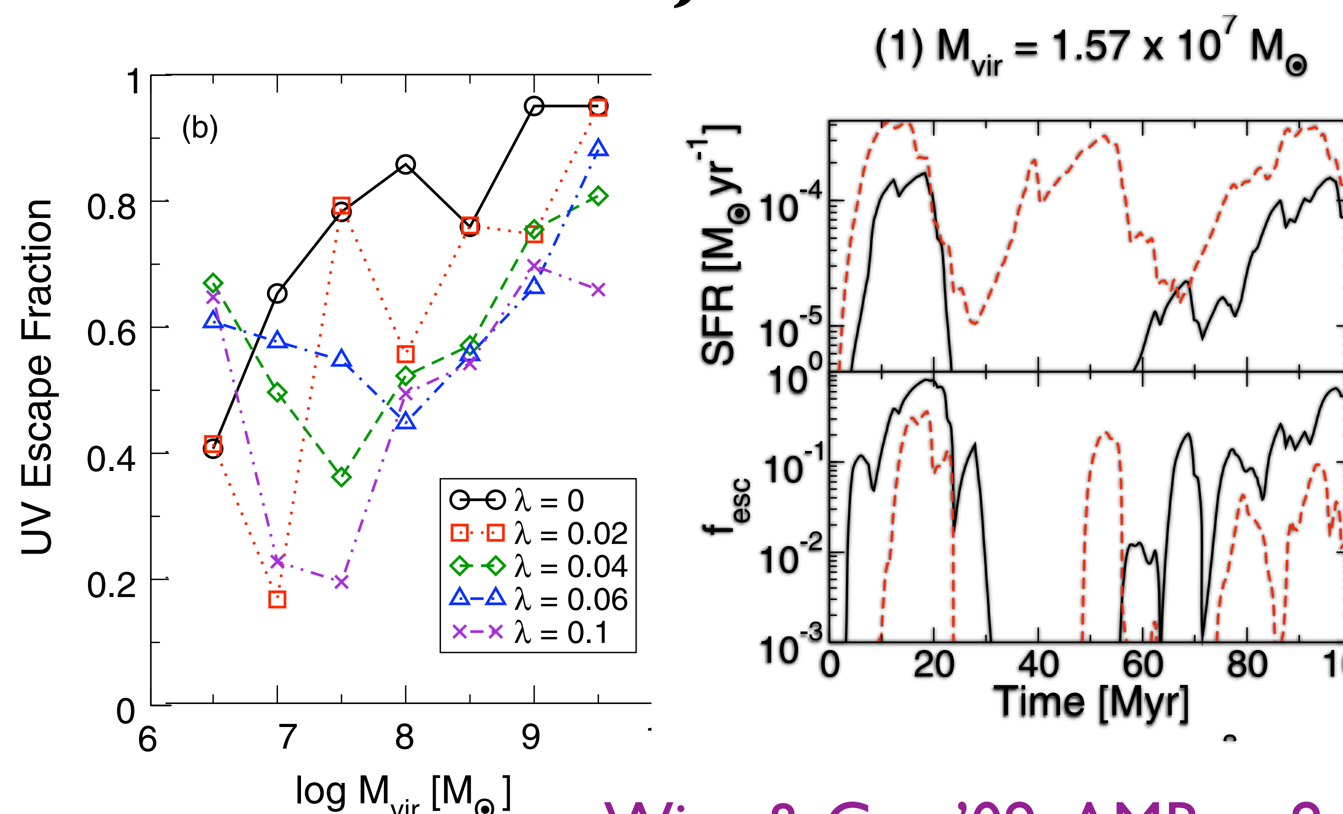


(cf. Kollmeier+ '09)

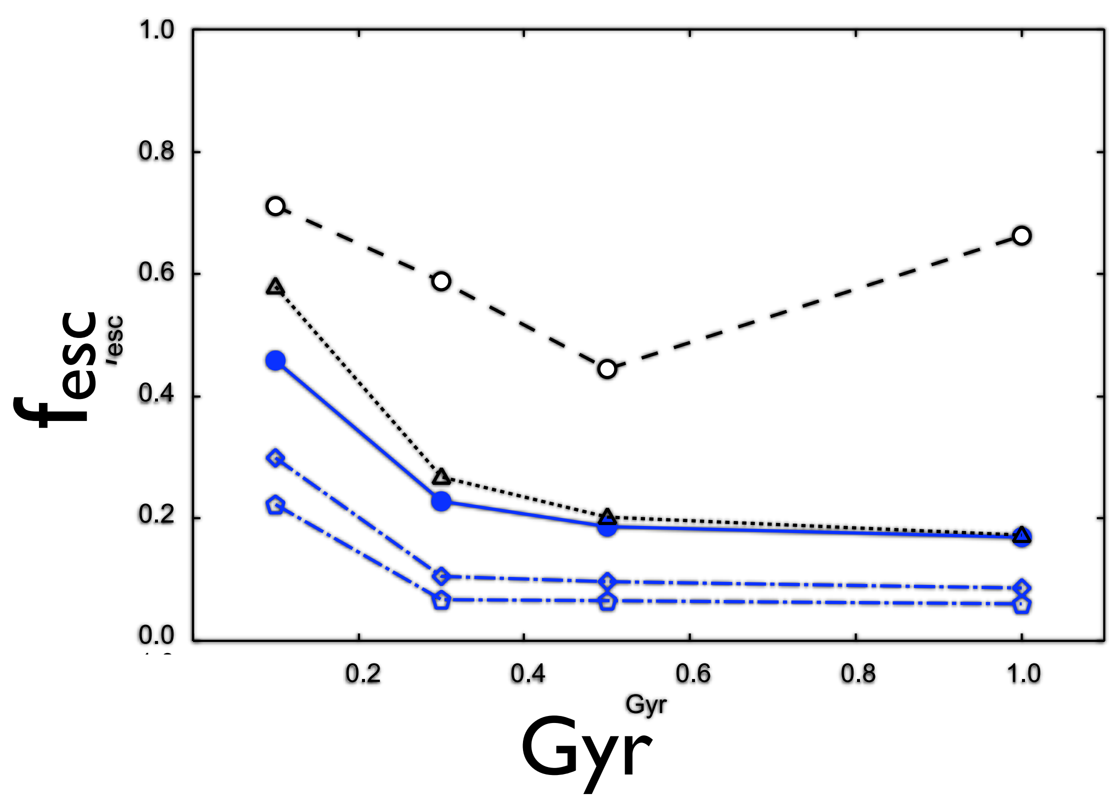
Varying results on $f_{esc,ion}$



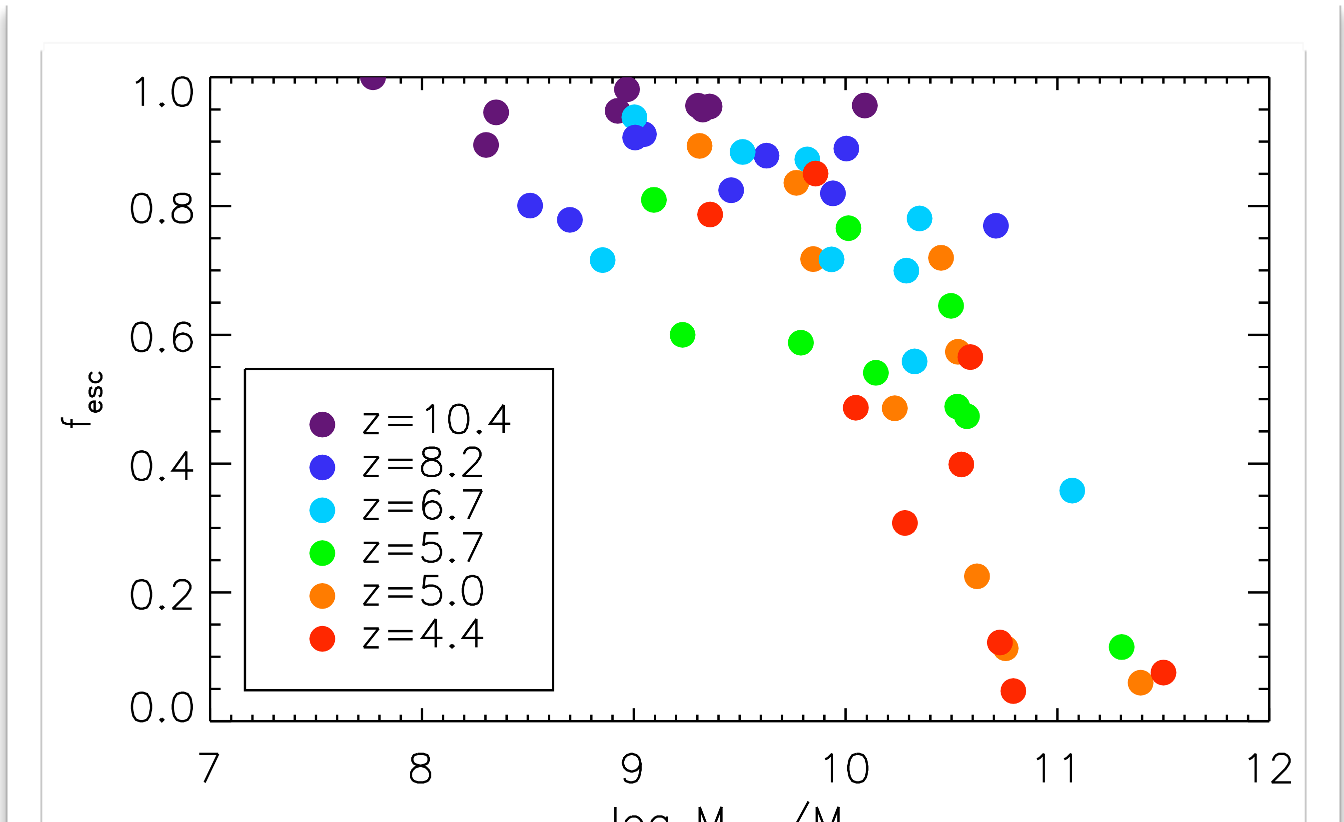
Gnedin+ '09 AMR z=3



Wise & Cen '09 AMR z=8

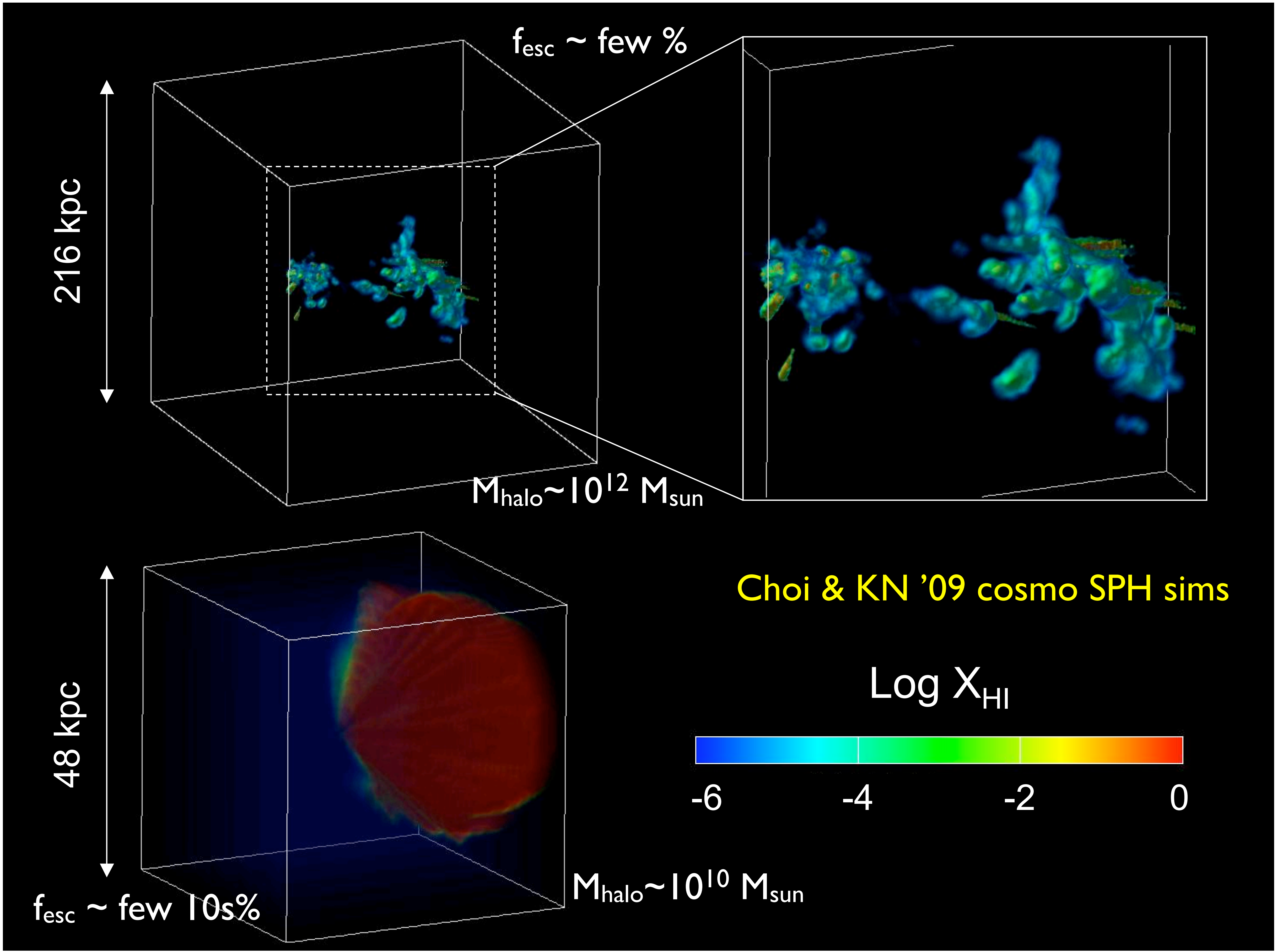


Yajima, Umemura, Mori+ '08 Eulerian

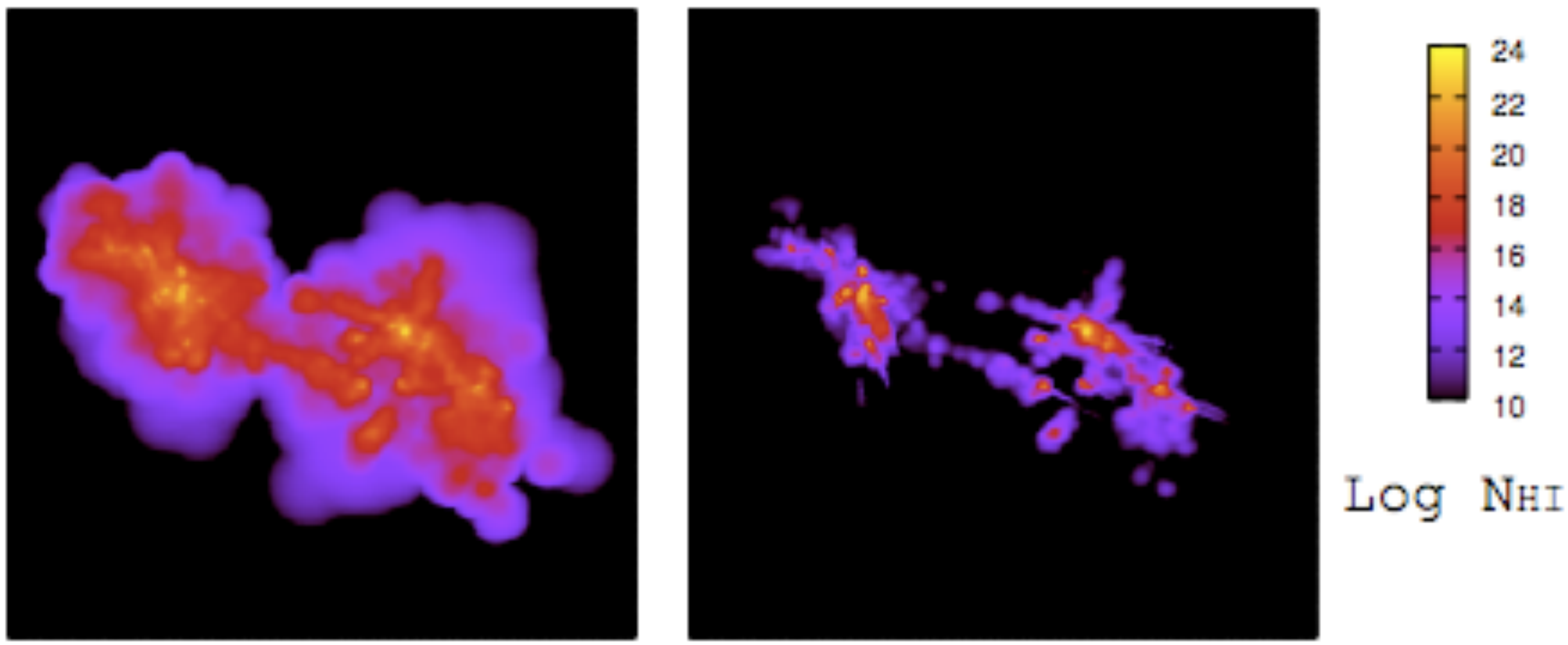


Razoumov+ '09 SPH

Yajima, Choi, KN '09 (in prep.)

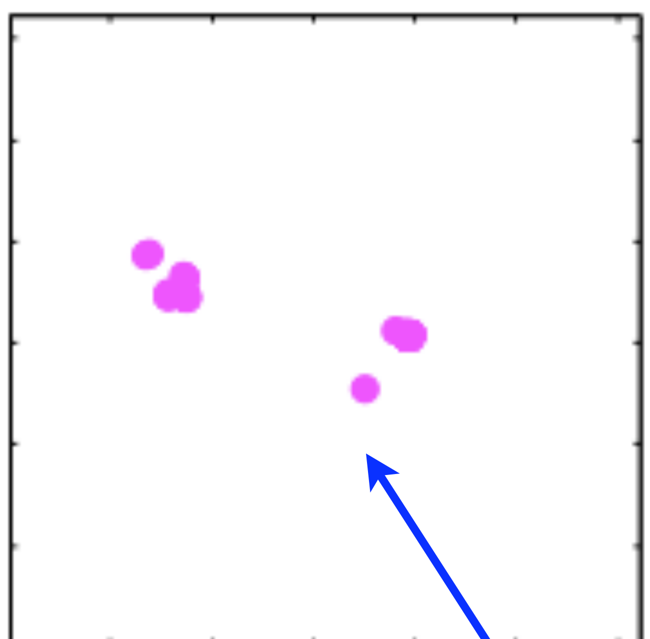


before RT after

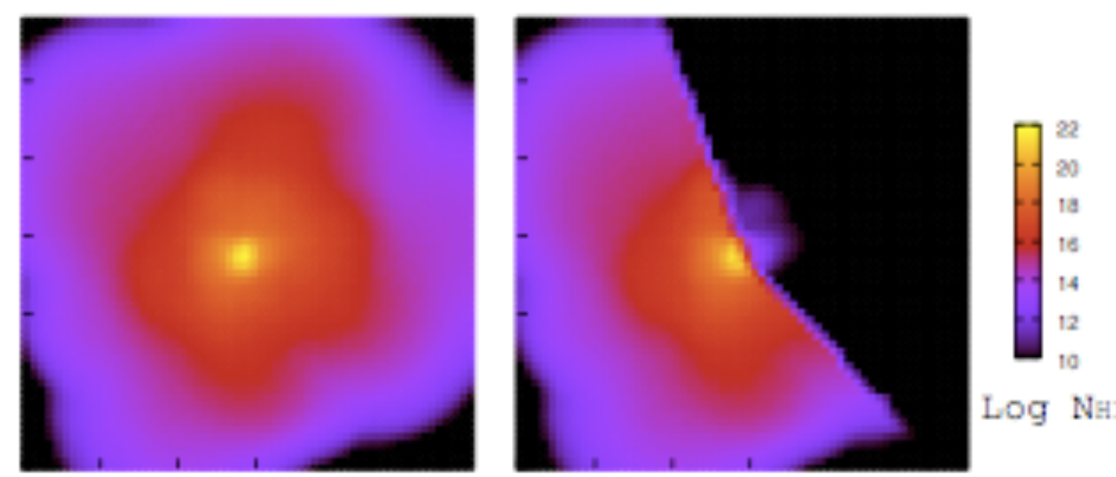


$M_{halo} \sim 10^{12}\ M_{sun}$

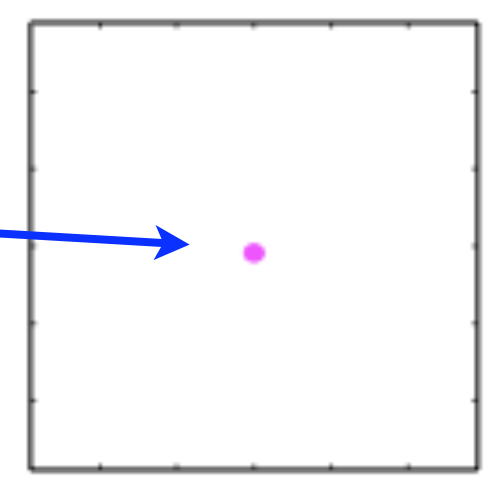
- Choi & KN ’09 cosmo SPH sims -- w/ wind feedback calibrated against galaxy obs.



before after



locations of
young star clusters

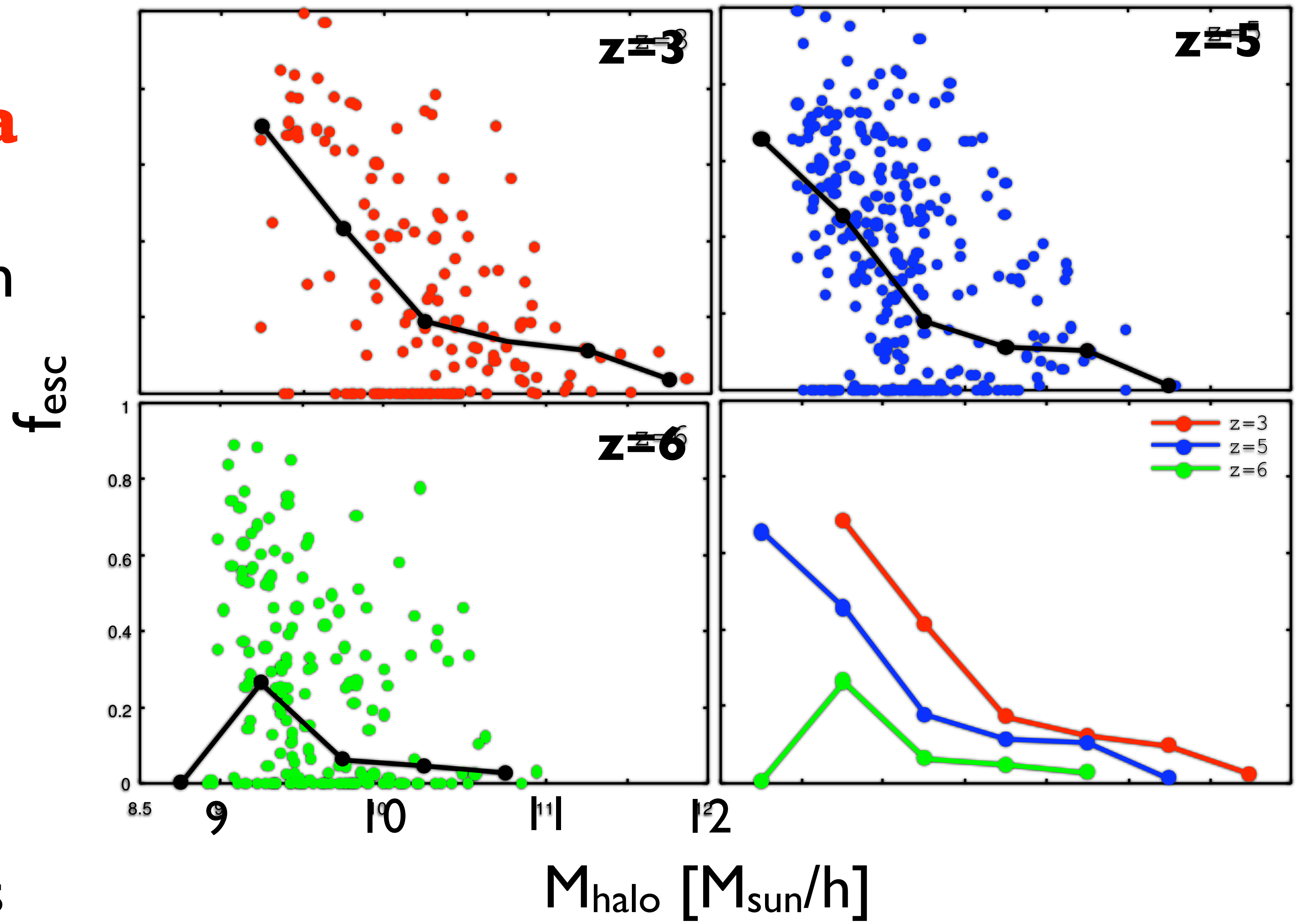


Yajima, Choi, KN ’09 (in prep)

$M_{halo} \sim 10^{10}\ M_{sun}$

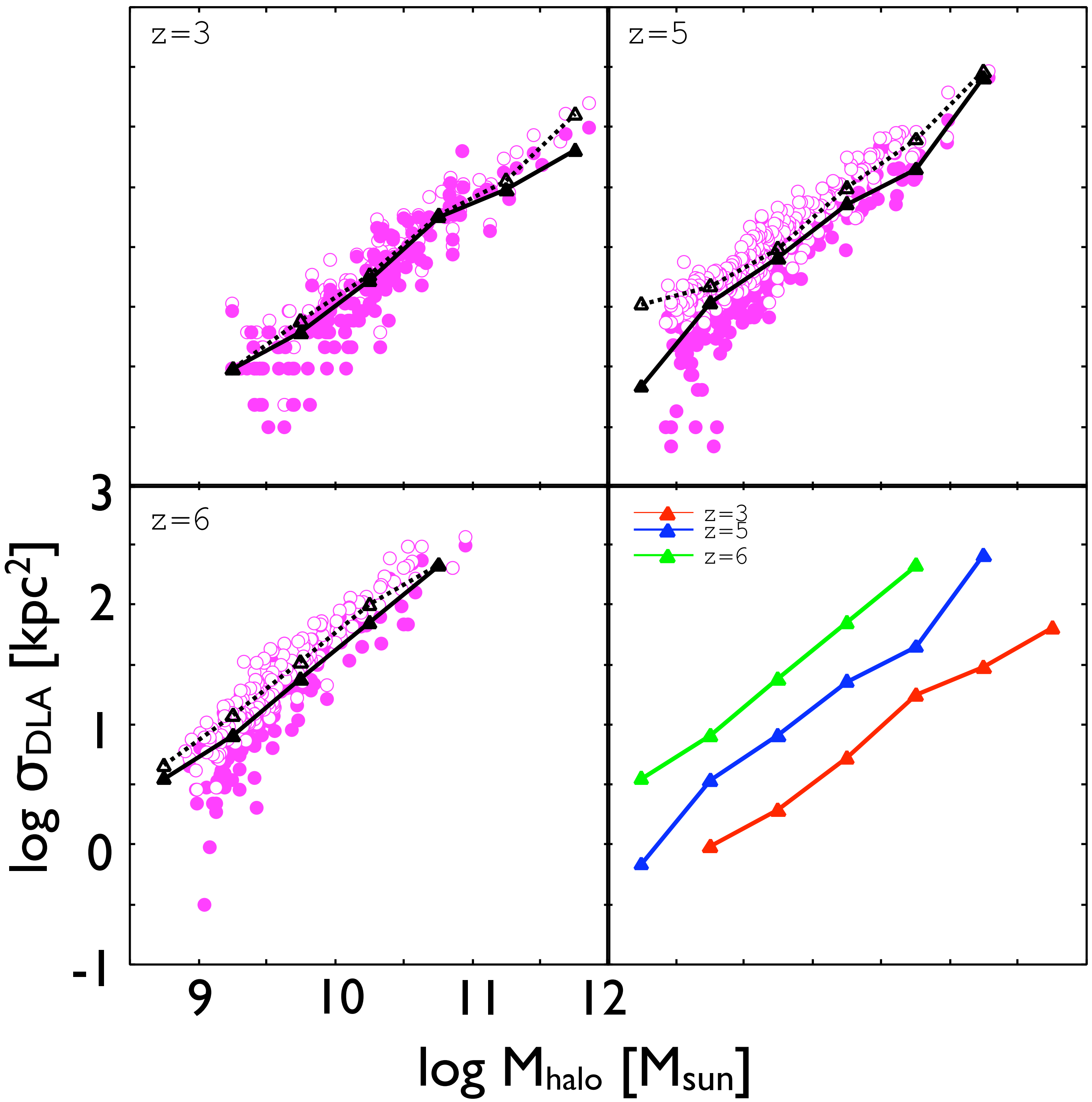
Yajima, Choi, KN '09 (in prep.)

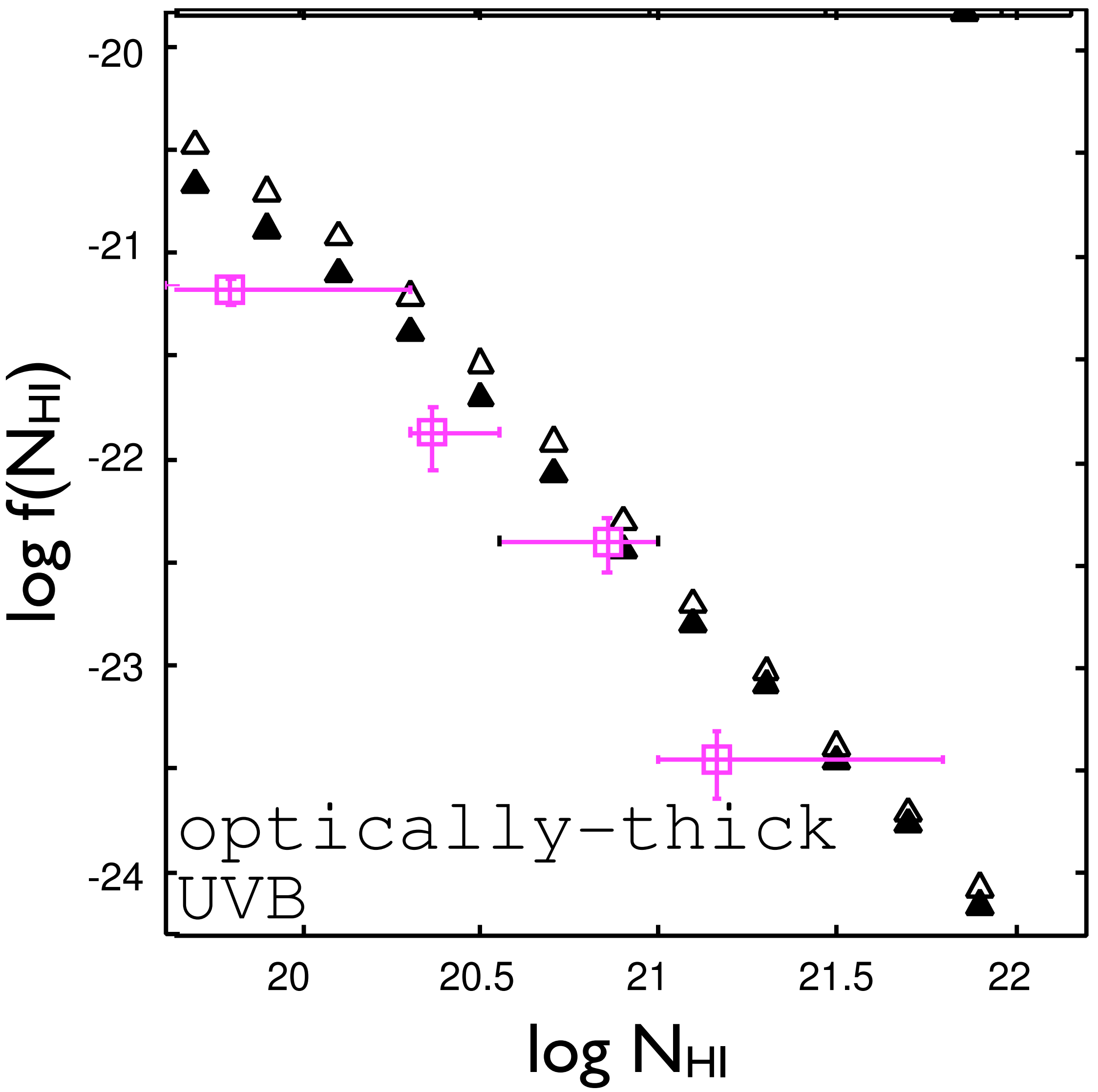
- **Decreasing f_{esc} as a func of M_{halo}** --- roughly consistent with Razoumov+'09; inconsistent with Gnedin+'09 & Wise & Cen '09
- **$f_{esc,ion}$** decreases with decreasing redshift
- Dwarf gals are perhaps important for reionization



This variation in **$f_{esc,ion}$** can be included in the LAE modeling

Effect of local stellar radiation on DLA cross section





Not so much effect on $f(N_{HI})$

Yajima, Choi, KN '09 (in prep)

Conclusions

- Properties of LBGs @z=3 (SFR, color, correlation, MF/LF) are well reproduced in current cosmo. sims.
- Stochastic scenario was favored over the escape fraction scenario from the comparisons of M_*-SFR relation, clustering & bias. But depending on the EW cut, the escape fraction scenario may survive.
- Simulation results are consistent w/ LAEs being lower M_*, lower metallicity, less clustered and less biased.
- Various correlations (e.g. EW vs. M_*, M_{uv}) can be understood as a reflection of M_* -- Z (~dust) relationship.
- **Dust is important for Lya:** LAE & reionization modeling need to take the scatter & mass dependence of $\mathbf{f_{esc,ion}}$, $\mathbf{f_{dust}}$ into account.
- Fully self-consistent pop. syn. calculation of L_{uv} & L_{Lya} is needed for more accurate results on EW.