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The origin of metallicity & color gradients in massive galaxies at large radii

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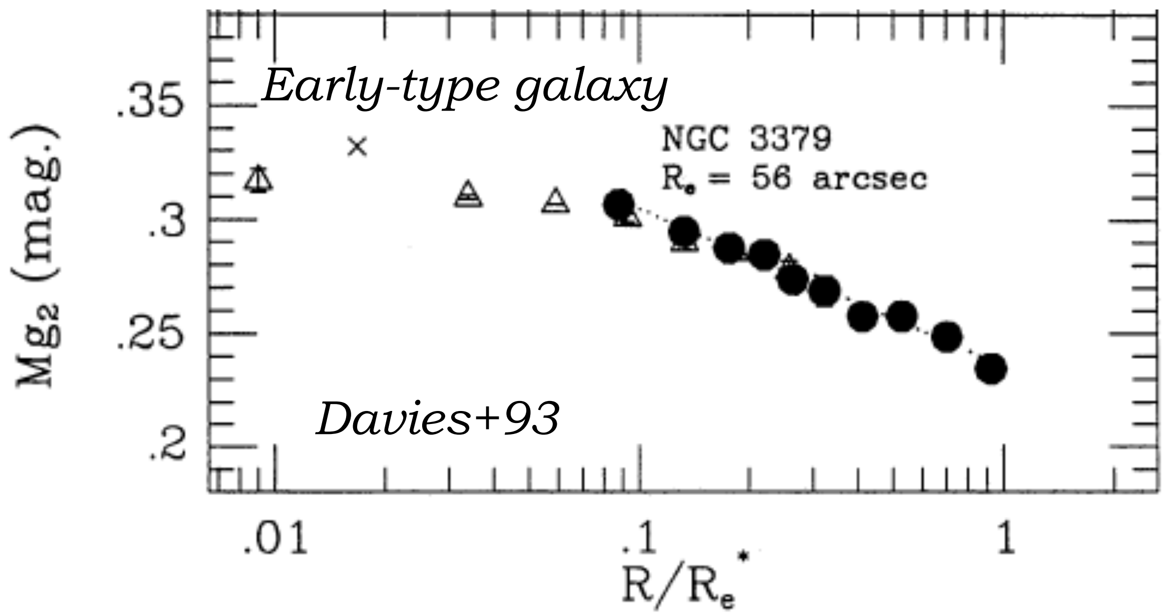
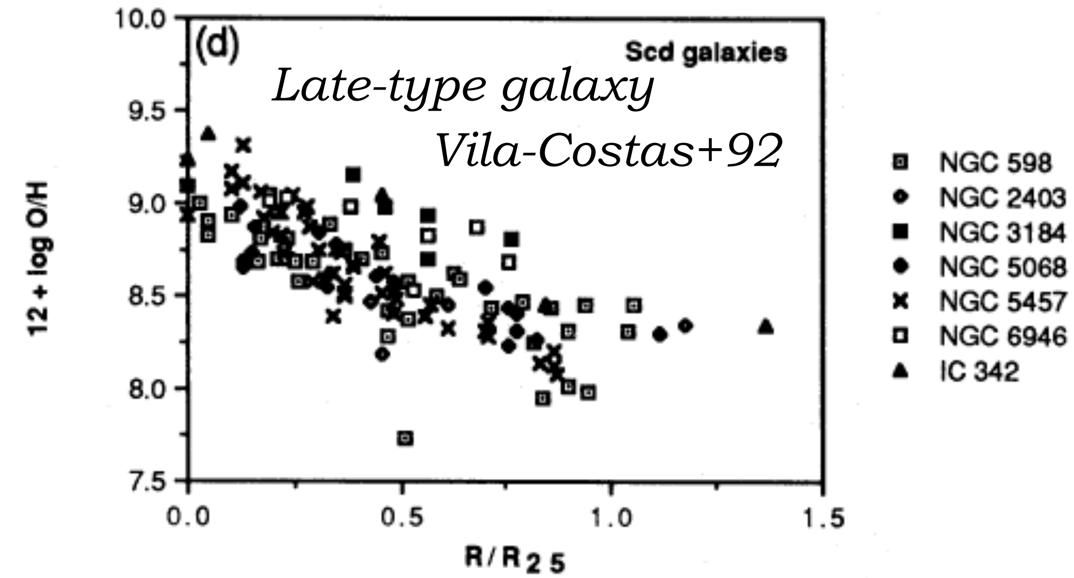
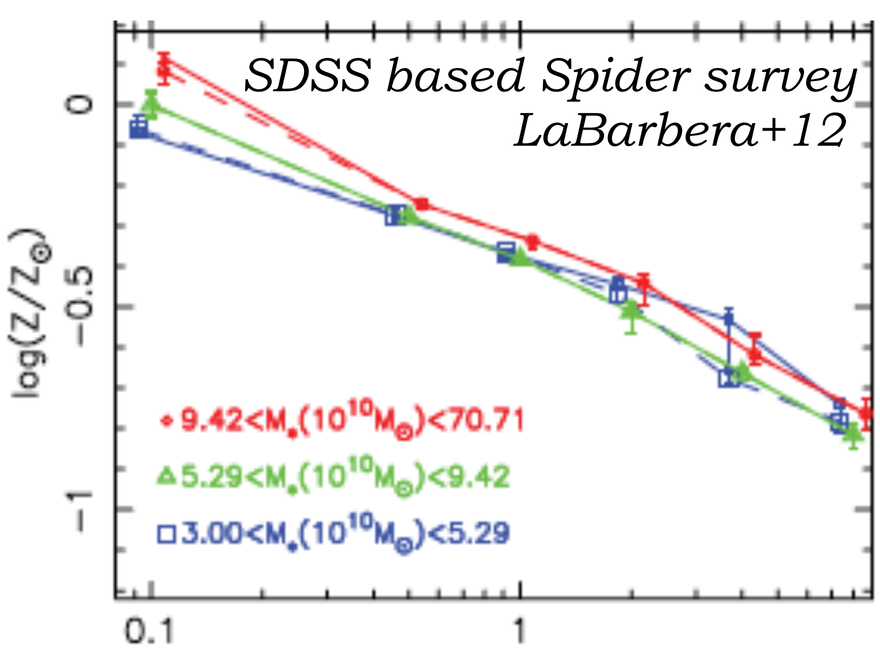
Observational evidence…

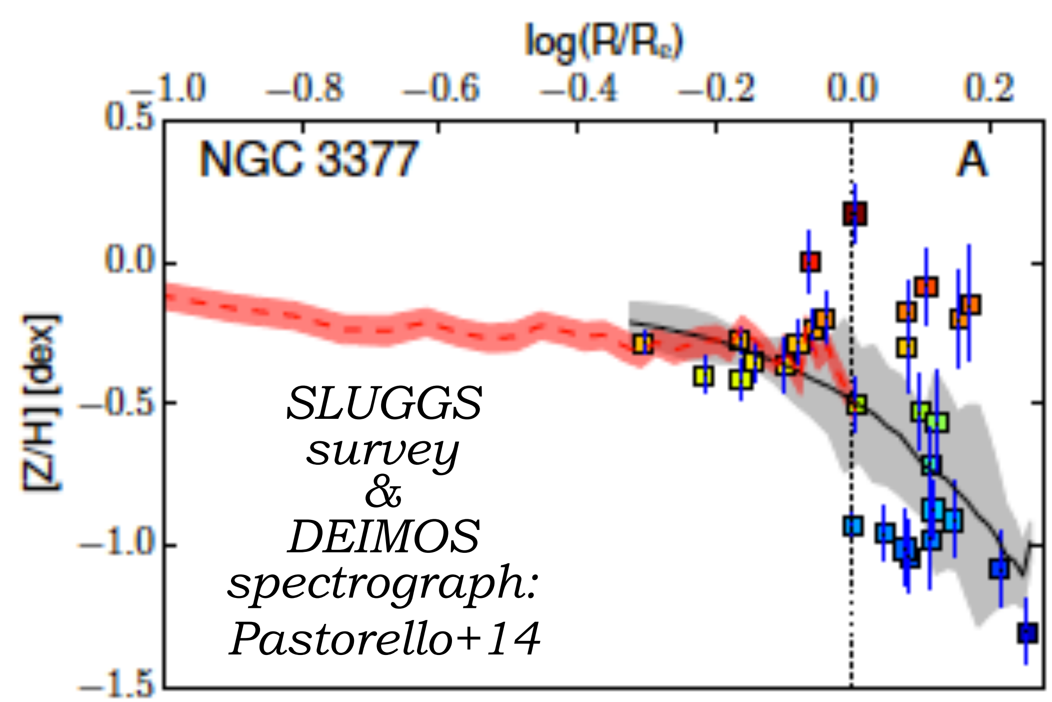
20 years ago, metallicity gradients were discovered in both early- & late-type galaxies (e.g. Davies+93, Carollo+93, Wyse&Silk89, Vila-Costas+92)





Nowadays, thanks to multi-waveband surveys, metallicity gradients at large radii, > 1 R$_{eff}$, can be measured (e.g. LaBarbera+12, Greene+13, Pastorello+14)





Theoretical work…

Metallicity gradients can emerge from

- *Insitu star formation* due to continuous infall of metal-poor gas onto the disk which can be turned into metal-poor stars, inside-out growth *(e.g. Steinmetz&Mueller+94, Chiappini+01, Pilkington+12)*

- *Late-time accretion* of low-mass & metal-poor systems in already formed early-type galaxies, *to be tested!*
  - Bimodal mass assembly of massive ETs: at late times, *addition of stellar material at large radii in collisionless minor mergers* is dominating (not the in-situ formation of stars)(e.g. Villumsen+83, HOD: *Moster+13, Behroozi+12*, SAMs: *DeLucia+07*, Guo&White08, *Hirschmann+12,* Sims: *Oser+10, Lackner+12, Gabor+12, Hirschmann+13*)
  - "Minor merger picture" successful in predicting a strong size evolution, increasing Sersic index and higher DM fractions (e.g. Naab+09, Oser+12, Hilz+12, Hilz+13)

- Can we see an effect of the stellar accretion in minor mergers on the metallicity gradients at large radii?
- Can a comparison with observations help to constrain uncertain feedback processes in the models?

Cosmological zoom simulations

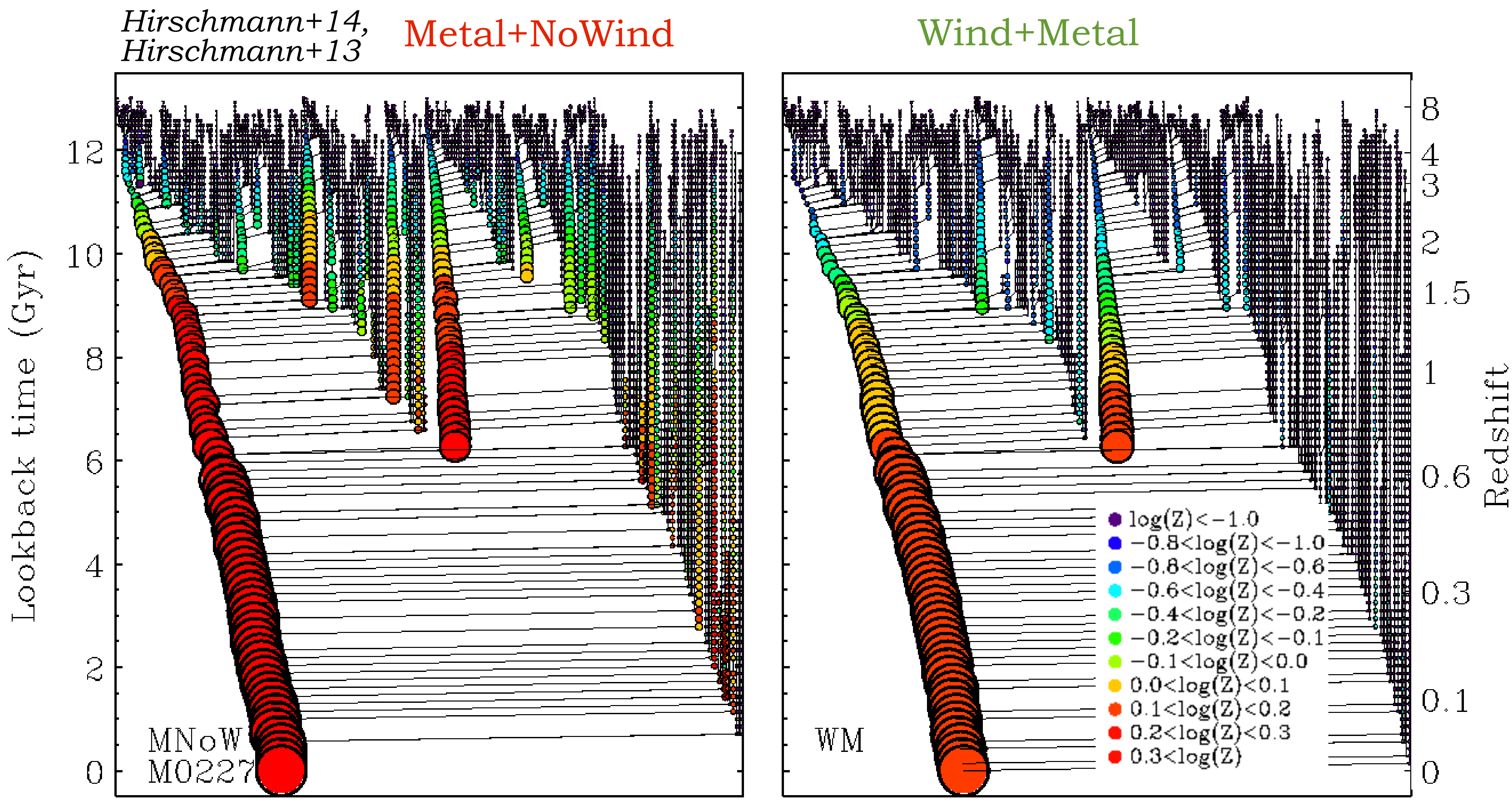
- *10 massive individual halos* selected from the cosmological zoom simulation sets presented in *Hirschmann+13*
  - with a mass range of $5*10^{12}$-$10^{13}M_\odot$
  - with spatial resolution of 400pc,
  - $m_{dm} = 2.5*10^7 M_\odot$ & $m_{gas} = 4.2*10^6 M_\odot$,
  - WMAP3 cosmology

- *Gadget-2 version of Oppenheimer/Dave* including models for *chemical enrichment* and *momentum-driven galactic winds*

- *Test the effect of galactic stellar winds*: Comparison of two simulation sets with and without winds (MNoW, WM)

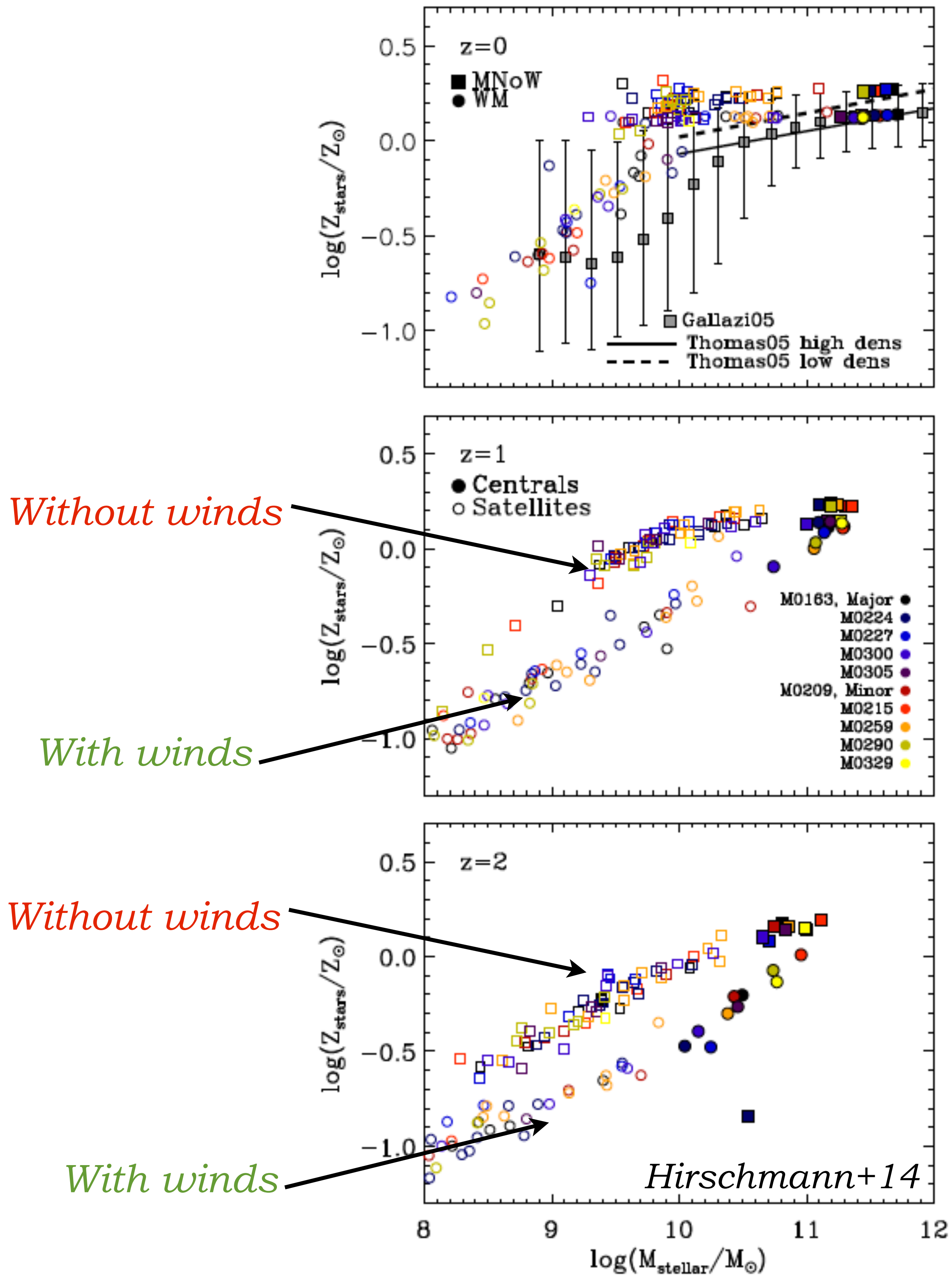
- WM model is *successful in predicting* many galaxy properties *(see papers by Oppenheimer/Dave/Finlator/Genel since 2006 and Hirschmann+13)*
  - cold gas fractions
  - star formation rates
  - insitu/accreted fractions
  - global metallicity content

The complex merger history



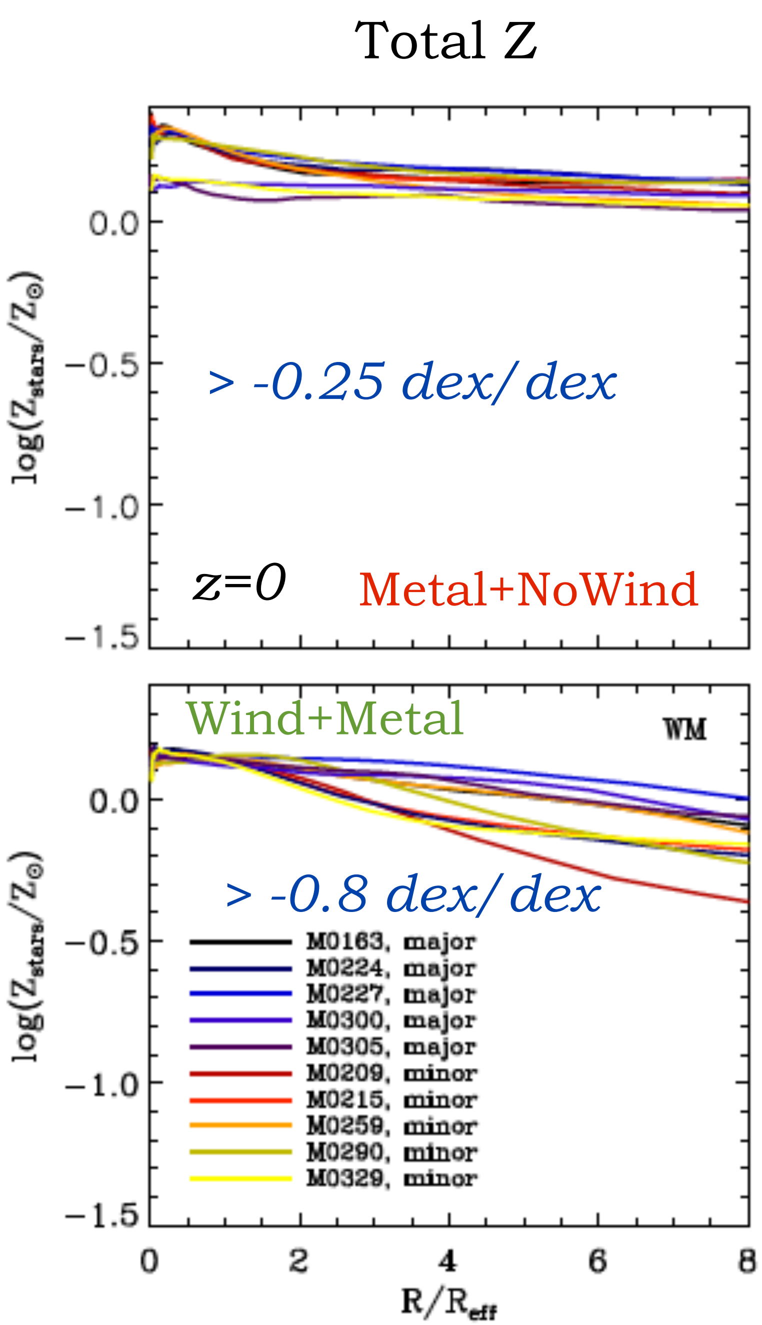
- Merger trees constructed based on the dark matter component using halo finder FOF & Subfind, galaxy proper-ties within 1/10 R_{vir} *(Hirschmann+10, Hirschmann+12)*
- Symbol size scales with the galaxy stellar mass & color coded with the stellar metallicity

Stellar mass-metallicity relation



- Feedback delays metal enrichment in all galaxies
- Low mass galaxies in feedback models have lower stellar metallicities
- *Good agreement with observations*

Accretion origin of metallicity gradients



- Galaxies in the Wind model typically have *steeper gradients*
- The steeper gradients are supported by the *accreted systems*
- Gradients in the Wind model more *consistent with observed diversity* (Pastorello+14: *-0.3 - -1.15 dex/dex*, La Barbera+12: *-0.29 - -0.74 dex/dex*)

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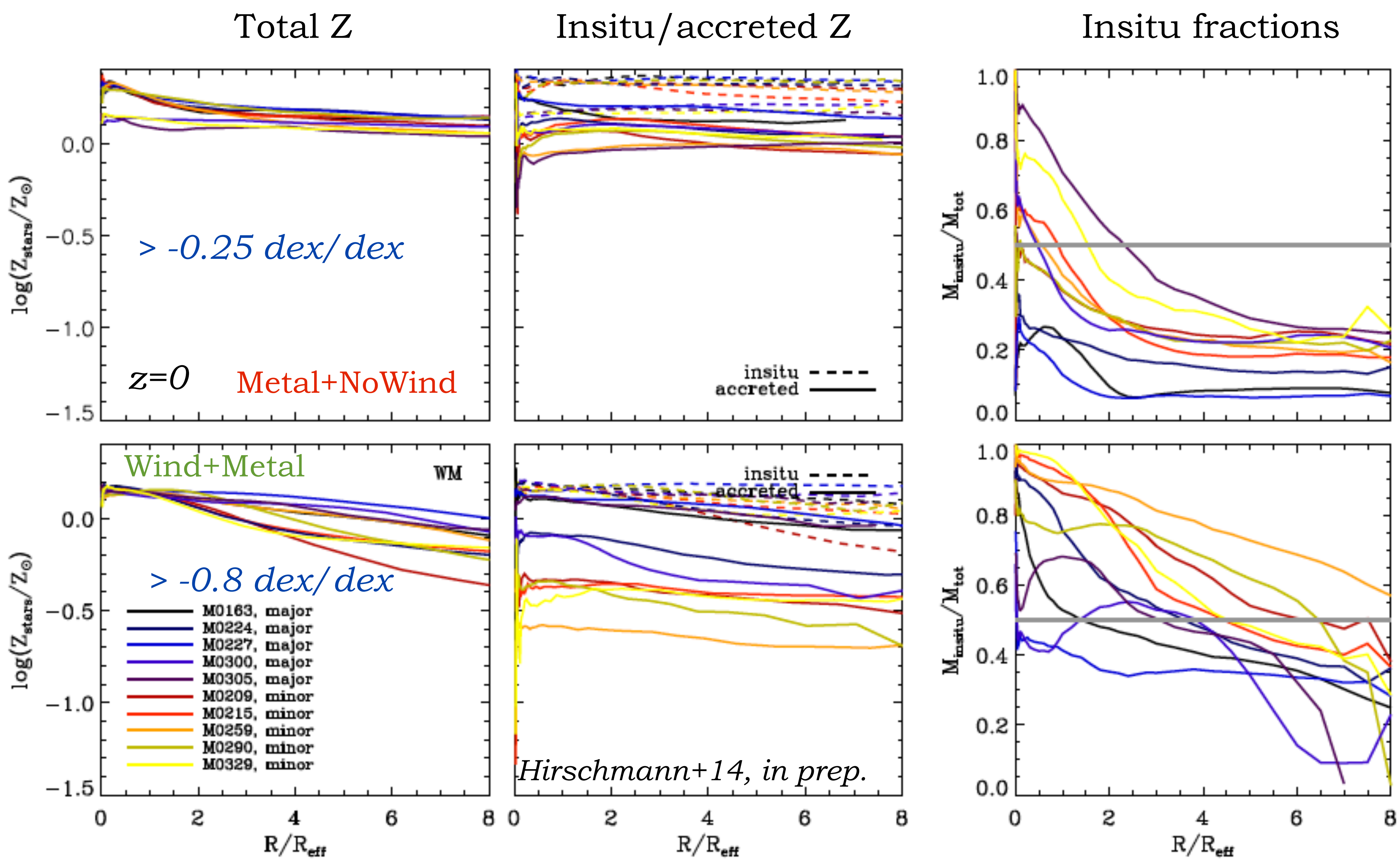

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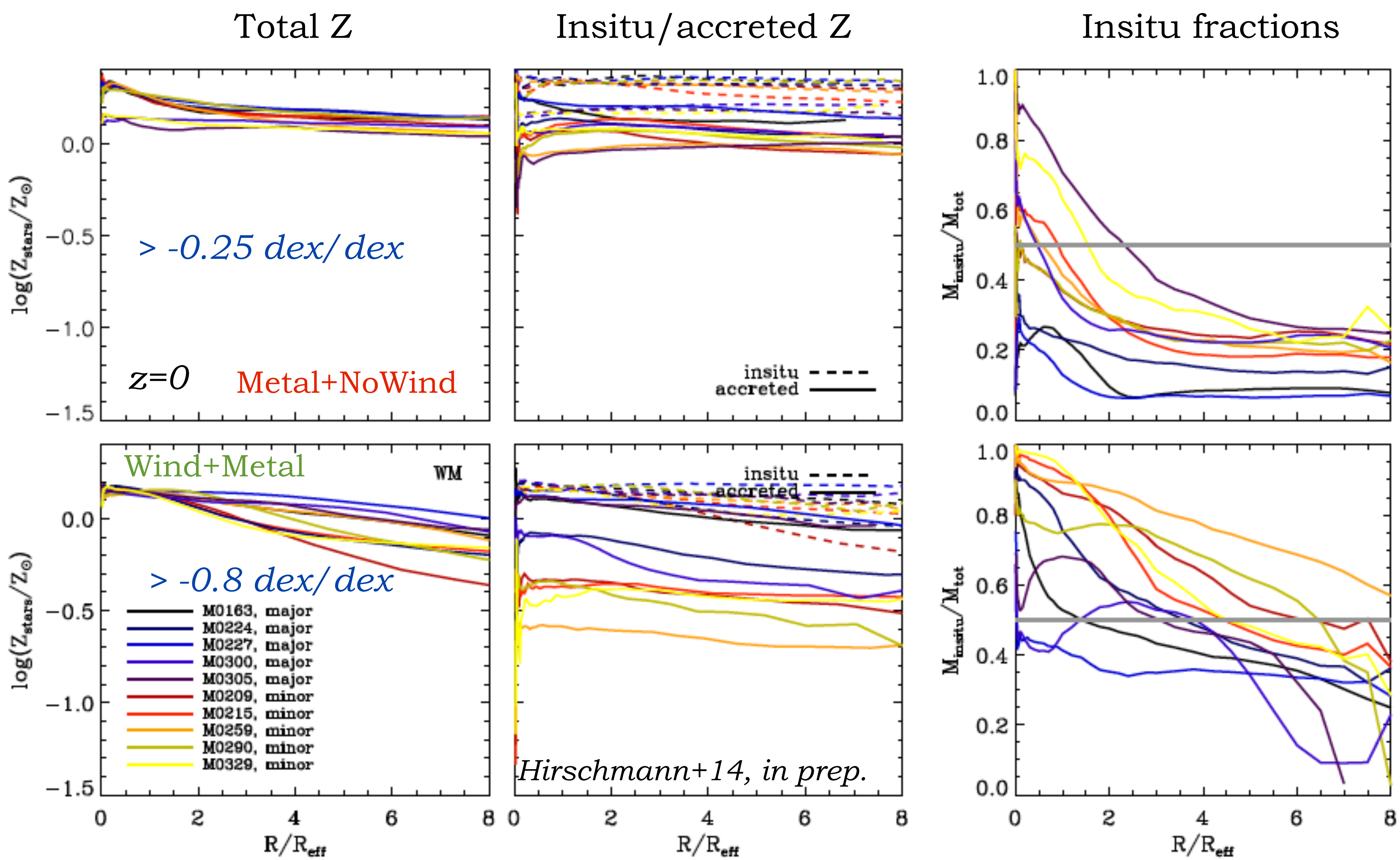

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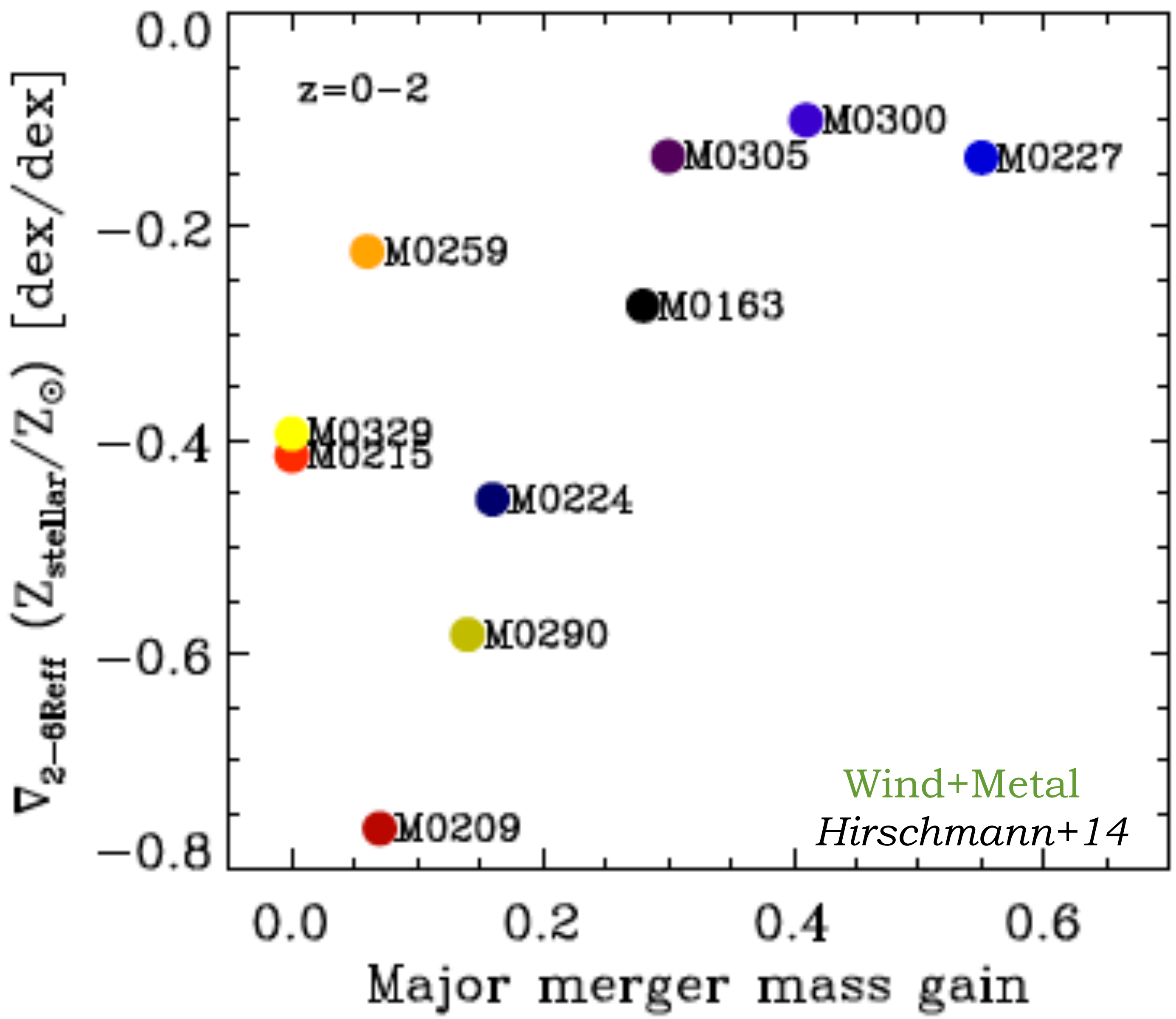
Strong stellar feedback is a key mechanism!

Effect of the merger mass ratio



- The larger the mass gain by major mergers the flatter the slope *(see also Kobayashi04, Rupke+10, Navarro-Gonzalez+13)*
- M0259 is an exception, this halo had no minor merger mergers since z=1

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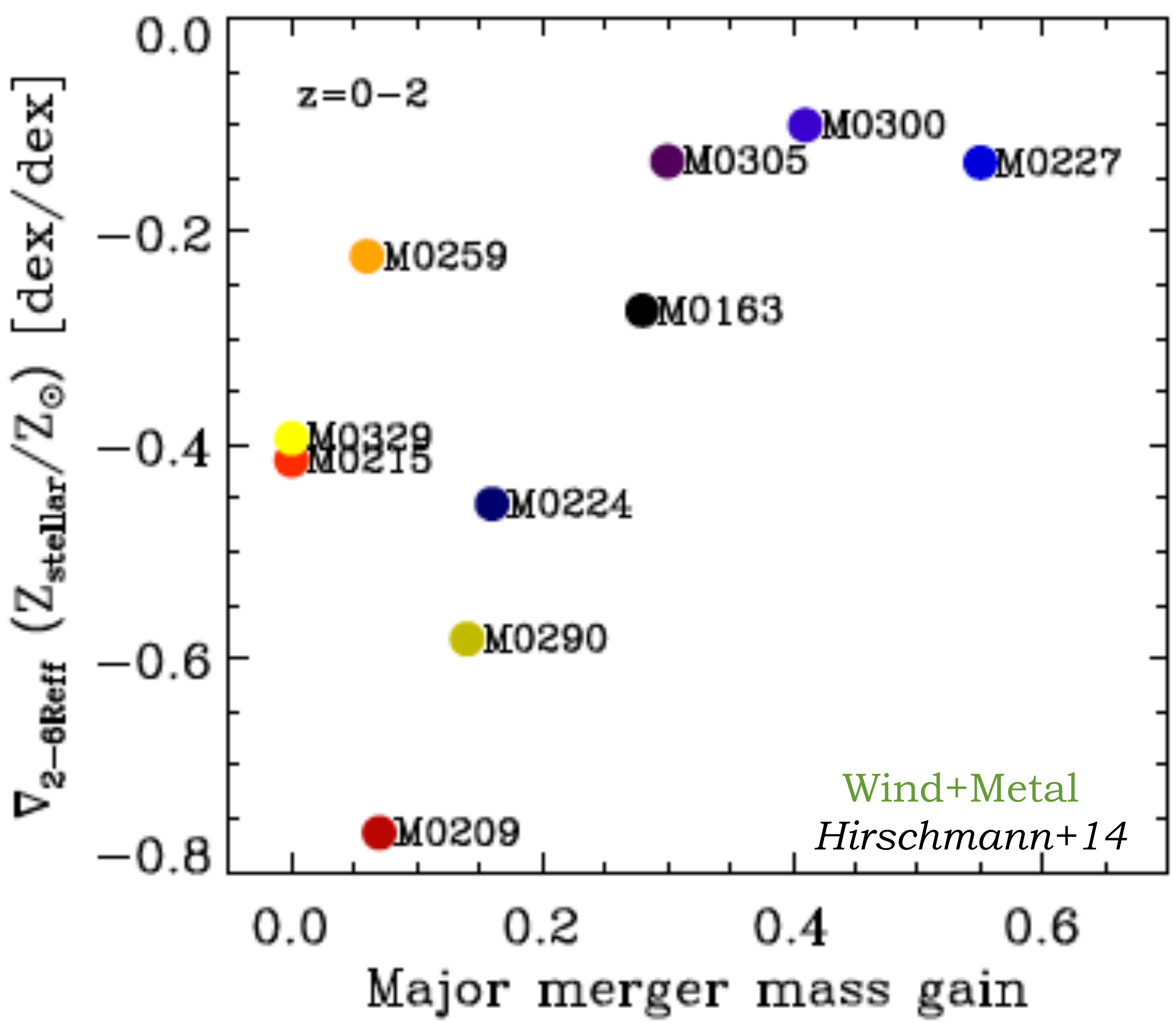

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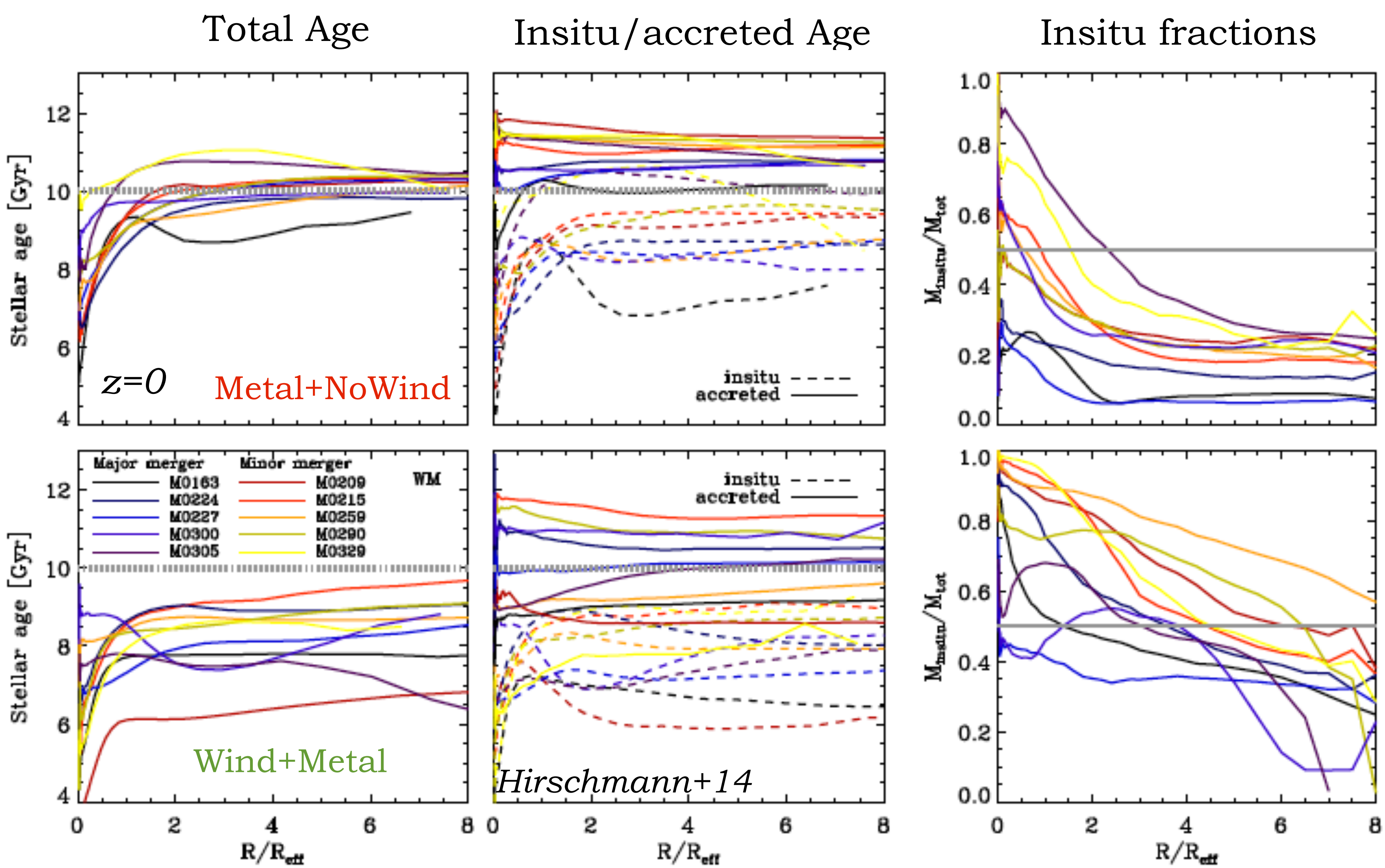
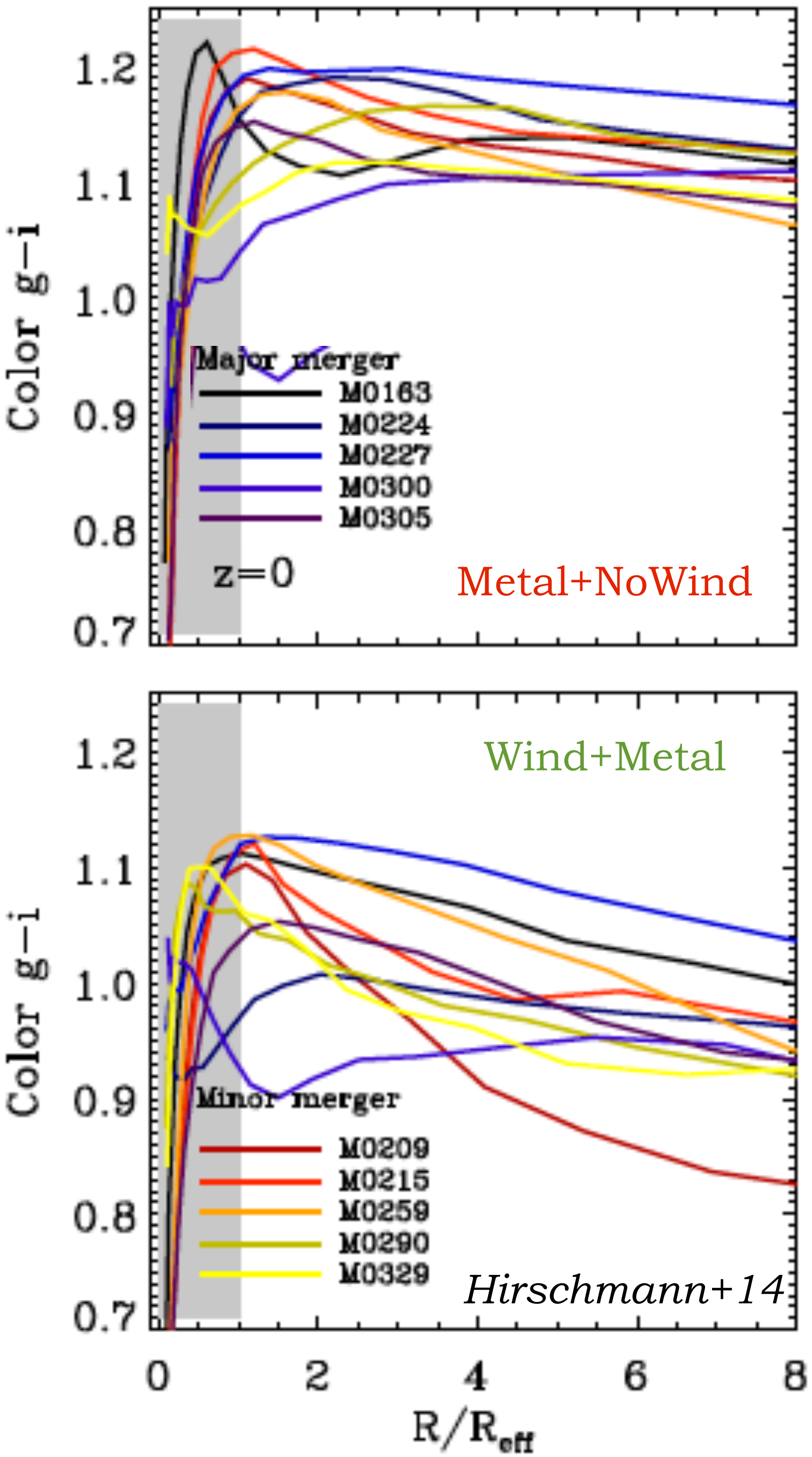
Besides *strong feedback, minor mergers* are necessary for steepening the outer metallicity gradients

Stellar age gradients



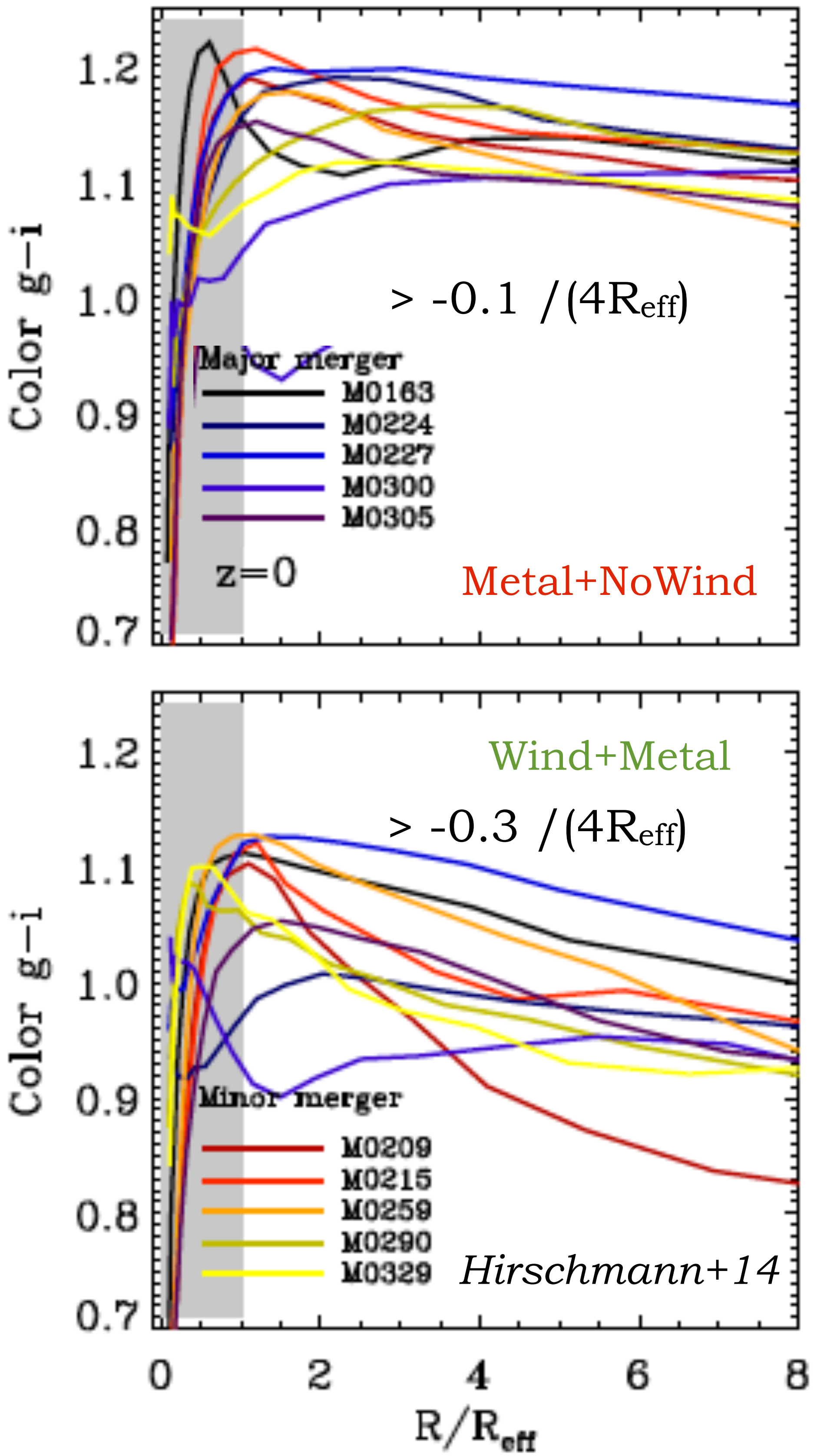
- Galaxies in the Wind model *slightly too young* in tension with observations: at r~2R_{eff} stars have a stellar age of 10 Gyr *(Greene+13)*
- Inner drop (<1R_{eff}), maybe too strong due to missing AGN fb
- r>2R_{eff}: *Very shallow positive gradients* due to accretion of older stars, observational situation unclear *(LaBarbera+12 <-> Greene+13, Raskutti+14)*

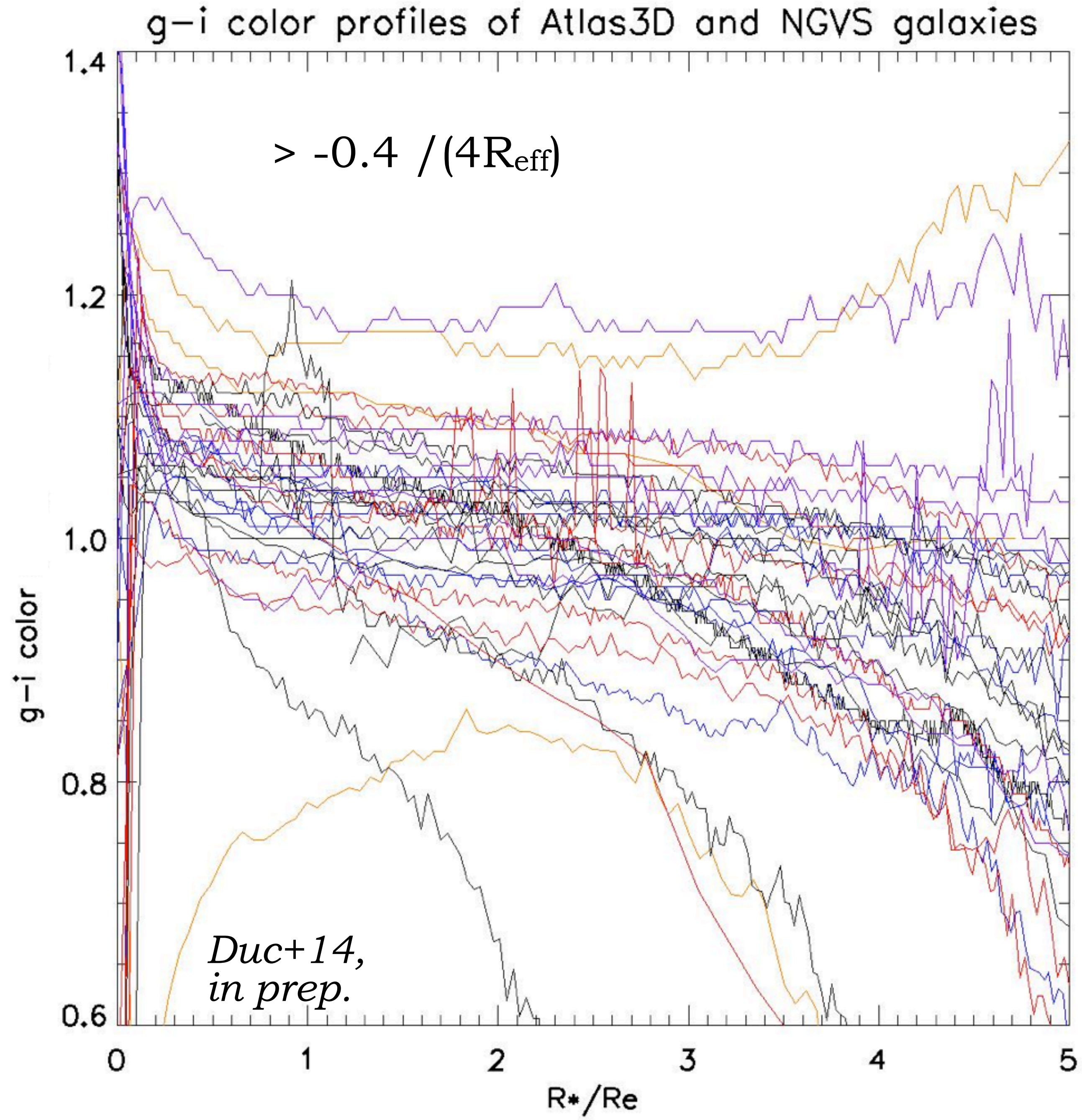
Accretion origin of color gradients



- Colors are degenerately dependent on metallicity and ages of the stellar populations of a galaxy
- Metal- and age-dependent *models for stellar evolution* *(Bruzual&Charlot03)* to estimate the color (treating every star particle as a single stellar population)
- Steeper color gradients in Wind model driven by steeper metal gradients
- Connection with the merger mass ratio: Flattening due to major mergers

Comparison to obs. color gradients





Wind model: *Reasonable agreement with the observed diversity* of color gradients, maybe slightly too shallow…

Conclusion

Cosmological zoom simulations including a momentum-driven wind model…

…predict realistic galaxies in several aspects (SFR, cold gas fractions, insitu/accreted fractions etc) (Hirschmann+13)

…confirm the "minor merger picture": observed steep negative color & metallicity gradients of massive galaxies at large radii can be explained by the accretion of metal-poor stellar systems (Hirschmann+14)

- *Strong stellar feedback is essential* in delaying metal enrichment in low-mass, later on accreted (and metal-poor) galaxies
- *Individual merger history responsible for the diversity in the gradients*: flattening by major mergers (in agreement with Kobayashi+04), but steepening by minor mergers
- *Negative color gradients* are driven by the negative metallicity gradients