The impact of mergers & energetic phenomena on stellar metallicity gradients in massive galaxies

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

Nowadays, thanks to more elaborated techniques, metallicity gradients in early-type galaxies can be measured out to large radii, > 1 $R_{\text{eff}}$, (e.g. LaBarbera +12, Greene+13, Pastorello+14)
Theoretical work

**Metallicity gradients can emerge from**

**Late-type, disk galaxies:**
- *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)*

**Massive, early-type galaxies:**
- *Insitu star formation* dominant at higher z
- *Late-time accretion* of stellar material at large radii in collisionless minor mergers *(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)*
  - Stellar systems accreted onto already formed early-type galaxies may affect metallicity gradient? *To be tested!*
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Use high-resolution cosmological zoom simulations to understand the origin of observed gradients of massive gal’s:

*Can we see an effect of the stellar accretion in minor mergers?*

*What is the differential impact of environment and feedback?*

*Can a comparison with observations help to constrain uncertain models for feedback processes?*
Model for stellar-driven winds

Impact of stellar-driven galactic outflows on massive
galaxies (>2e11 $M_\odot$)
in cosmological zoom simulations of massive galaxies
with $x_{\text{spatial}} = 400\text{pc}$, $m_{\text{dm}} = 2.5*10^7M_\odot$ & $m_{\text{gas}} = 4.2*10^6M_\odot$

Empirically motivated model for momentum
 driven winds
(Oppenheimer & Dave, 2006/08, Murray+05, Martin’05)

\begin{align*}
    v_{\text{wind}} & \propto \sigma \\
    \dot{M}_{\text{wind}} \times v_{\text{wind}} & \propto \dot{M}_{\text{stellar}} \\
    \eta & \propto \frac{M_{\text{wind}}}{M_{\text{stellar}}} \\
    & \propto \frac{1}{v_{\text{wind}}} \propto \frac{1}{\sigma}
\end{align*}

Gas density of a $3*10^{11} M_\odot$
galaxy

$x_{\text{spatial}} = 200\text{pc}$,
$m_{\text{gas}} = 5.2*10^5M_\odot$

Hirschmann+13/15
Stellar accretion history

of massive galaxies (>2e11 M⊙)

They assemble **through (minor) mergers with smaller galaxies** which are **strongly affected by stellar feedback**

- delayed star formation
- smaller stellar masses
- lower metallicity
- smaller amount of accreted stellar mass

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**No galactic, stellar-driven winds**

**With galactic outflows**

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**Stellar accretion history**

**Note that all simulations include thermal supernova feedback as described in detail in Springel & Hernquist (2003).** For more details on the simulation set-up, we refer the reader to Hirschmann et al. (2013). As in this study, the simulations including winds were shown to predict more realistic galaxies in several aspects (even if some drawbacks remain as e.g. too much late star formation as a consequence of missing AGN feedback), we **a priori** expect the metallicity and colour gradients of the WM galaxies to be closer to reality.

Note that tables 1 and 2 summarise different galaxy properties such as halo mass, total and in-situ formed stellar mass, number of stellar minor and major mergers (also the fitted metallicity and age gradients at z=0, which will be discussed in the course of this study) of the 10 selected halos in the MNoW and the WM re-simulations, respectively.
Stellar mass-metallicity relation

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

Hirschmann+15
Stellar metallicity profiles of massive galaxies (>2e11 M☉)

- Steeper metal gradients in the wind model (-0.3 dex/dex) due to accretion of more metal-poor stars
- Good agreement with observations for wind model (e.g. LaBarbera+12, Pastorello +14 etc)
- Strong outflows necessary for steepening outer metallicity grads
- Different behaviour for major/minor mergers (see e.g. Villumsen+83, Kobayashi+04)
- Minor mergers steepen the gradients
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Graphs showing total gradients and insitu/accreted gradients for NoWinds and Winds conditions, with different subplots for major and minor mergers.
The role of stellar accretion

...for steepening stellar metallicity profiles in the stellar-driven feedback model

- Existing insitu gradients are steepened by -0.2 dex/dex at z < 1 through accretion of metal-poor stars
- The same applies to present-day color gradients which are mostly influenced by metallicity
- Towards higher redshifts, stellar accretion less significant due to stronger gas-dissipative processes
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Superposition of internal and environmental effects are shaping the stellar population (metallicity & color) gradients at large radii
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Inner gradients realistic?
Additional effect of AGN-driven winds?

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Superposition of internal and environmental effects are shaping the stellar population (metallicity & color) gradients at large radii
Mass, momentum and energy input (conservation) into the surrounding gas motivated by observations of broad absorption line winds, $v_w = 10,000 \text{km/s}$, $\epsilon_f = 0.005$

*Ostriker+10, Choi+13/14*

So far, two zooms of massive halos with $M_{\text{halo}} \sim 1 \times 10^{13} \ M_\odot$ ($x_{\text{spatial}} = 100 \text{pc}$, $m_{\text{gas}} = 6.6 \times 10^4 \ M_\odot$)
By up to one order of magnitude reduced SFRs

AGN winds can affect stellar, stellar metallicities and ages out to $8 \text{ R}_{\text{eff}}$

Older stellar populations

Steeper inner gradients (-0.1 -0.2 dex/dex at $<1\text{ R}_{\text{eff}}$) due to inside-out growth & AGN fb

Stellar accretion still steepens the outer metallicity gradients
By up to one order of magnitude reduced SFRs

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Stellar accretion still steepens the outer metallicity gradients

Hirschmann, Naab+ in prep.
Stellar feedback can strongly influence massive galaxies with respect to integrated and spatially resolved stellar populations at large radii (> 2 \( R_{\text{eff}} \)).

AGN feedback affects stellar populations in massive galaxies, particularly strongly in the central region within 2 \( R_{\text{eff}} \).

Superimposed effect of environment, in the form of mergers, at large radii, “minor merger picture” confirmed.

Individual merger history responsible for the diversity in the gradients: flattening by major mergers (in agreement with Kobayashi+04), but steepening by minor mergers.

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Future:
- Construction of a statistically complete sample of cosmological zoom simulations of massive galaxies (>3e11 M$_\odot$) with unprecedented high resolution
- Including further AGN feedback mechanisms (radiative-X-ray)
- Gas metallicity gradients, creating synthetic emission line maps by coupling zooms to new-generation stellar evolution models (w. S. Charlot)