Scaling relations and feedback at low mass and high redshift

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The Physics of Galaxy Scaling Relations and the Nature of Dark Matter
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With Jessie Hirtenstein, Tommaso Treu, Xin Wang, Richard Ellis, Dan Stark, & the GLASS team
Scaling relations over cosmic time: plenty of room at the bottom!

Mass-metallicity relation (Zahid et al. 2014)

Low-mass galaxies at early cosmic times (z>1):
- Extend the dynamic range of scaling relations to lower mass
- Emergence of the Hubble Sequence: transition from irregular to disk+spheroid morphology occurs later for lower galaxy mass
- High dark matter fractions, and greatest challenges to cold dark matter

Rotational support (Simons et al. 2016)
The galaxy population at $z=2$

- **Stellar mass**
- **Radius**
  - $\log(r_e)$ [kpc]
- **Star formation rate**
  - $\log(SFR)$ [$M_\odot$/yr]

CANDELS: Wuyts et al. 2012
The galaxy population at $z=2$

**Diagram:**

- **X-axis:** Logarithm of Stellar Mass ($\log(M) [M_{\odot}]$)
- **Y-axis:**
  - Upper panel: Logarithm of Radius ($\log(r_e) [\text{kpc}]$)
  - Lower panel: Logarithm of Star Formation Rate ($\log(\text{SFR}) [M_{\odot}/\text{yr}]$)

- The diagram shows the distribution of galaxies in the redshift range $1.5 < z < 2.5$.

**Source:** CANDELS: Wuyts et al. 2012
The galaxy population at $z=2$

**Graph:**
- **X-axis:** Stellar mass [$M_\odot$]
- **Y-axis:** Star formation rate [$M_\odot$/yr]
- **Additional lines:**
  - Green dashed line: HST diffraction limit (~1 kpc)
  - Red dashed line: Gravitational lensing + adaptive optics (or HST)

**Notes:**
- CANDELS: Wuyts et al. 2012
2-D Hubble grism spectroscopy of 10 strong-lensing galaxy clusters
PI: Tommaso Treu

Treu et al. 2015 (survey overview)
Jones et al. 2015 (first results at z~2)
Wang et al. 2017 (metallicity gradients)
Mason et al. 2017 (KMOS kinematics)

Note: consider what JWST’s grisms will be capable of...
The mass-metallicity relation at z~2: low $M_*$

Slope: $\frac{d(\log O/H)}{d(\log M_*)} = 0.40 \pm 0.07$, similar to simulations with strong feedback

Suggests energy-driven outflow scaling at low $M_* < 10^{10} M_\odot$

Inconsistent (~3σ) with momentum-driven outflows at low mass

Wang, TJ, Treu, et al. 2017
Galaxies at $z \approx 2$ typically have shallow negative metallicity gradients. Gas mixing suggests strong feedback.

Wang, TJ, Treu, et al. 2017
Bright lensed galaxies: outflow kinematics and composition from near-UV absorption spectroscopy

Jones et al. 2018
Direct measurements of outflows

Bright lensed galaxies: outflow kinematics and composition from near-UV absorption spectroscopy

- Metal column density is mostly associated with outflow
- Velocities reach several hundred km/s, average $\approx -150$ km/s
- Alpha-enhanced abundance pattern ($[\text{Si/Fe}] \approx +0.2$), with substantial dust depletion
- $\sim 1/2$ or more of the metals are ejected in outflows

Jones et al. 2018
Direct measurements of outflows

Outflow profiles N(v) → mass loss rates

Muratov et al. 2015

Jones et al. 2018
Dynamical effects of outflows

Stellar feedback may transform cusps into cores
Most effective at stellar mass range $M^* \approx 10^{7-9} M_\odot$

→ Prediction: this should induce a correlation between SFR and $\sigma$ in dwarf galaxies
Low-mass galaxy kinematics at z~2

$\log(M_*/M_\odot) = 9.26$
$\Delta v = 163.0 \text{ km/s}$

$\log(M_*/M_\odot) = 9.33$
$\Delta v = 193.2 \text{ km/s}$

$\log(M_*/M_\odot) = 9.34$
$\Delta v = 182.3 \text{ km/s}$

$\log(M_*/M_\odot) = 9.67$
$\Delta v = 182.9 \text{ km/s}$

$\log(M_*/M_\odot) = 9.76$
$\Delta v = 109.8 \text{ km/s}$

Hirtenstein et al. in prep
Low-mass galaxy kinematics at z~2

Hirtenstein et al. in prep

log($M_\ast/M_\odot$) = \textcolor{red}{9.26} \quad \Delta v = 163.0 \ km/s

log($M_\ast/M_\odot$) = \textcolor{blue}{9.33} \quad \Delta v = 193.2 \ km/s

log($M_\ast/M_\odot$) = \textcolor{orange}{9.34} \quad \Delta v = 182.3 \ km/s

log($M_\ast/M_\odot$) = \textcolor{green}{9.67} \quad \Delta v = 182.9 \ km/s

log($M_\ast/M_\odot$) = \textcolor{cyan}{9.76} \quad \Delta v = 109.8 \ km/s

log($M_\ast/M_\odot$) = \textcolor{red}{8.59} \quad \Delta v = 40.1 \ km/s

log($M_\ast/M_\odot$) = \textcolor{blue}{8.77} \quad \Delta v = 104.7 \ km/s

log($M_\ast/M_\odot$) = \textcolor{orange}{8.81} \quad \Delta v = 36.2 \ km/s

log($M_\ast/M_\odot$) = \textcolor{green}{8.88} \quad \Delta v = 50.1 \ km/s
Dynamical effects of outflows

Simulations (in which cusp-core problem is resolved by stellar feedback)

Observed (Keck AO + lensing)

Hirtenstein et al. in prep
Low-mass galaxy kinematics at $z \sim 2$

Keck AO + lensing

Still plenty of room at the low-mass end...
Summary: feedback-driven scaling relations at $z \sim 2$

Scaling relations extended to lower masses and higher redshifts with gravitationally lensed galaxies

➢ Scaling relations spanning 3 orders of magnitude in stellar mass
  ➢ Growing sample of lensed galaxies reaching $M_* \sim 10^8 M_\odot$ at $z = 2$

➢ Strong feedback: evident in mass-metallicity relation, metallicity gradients, and direct measurements of outflows
  ➢ Feedback may be sufficient to resolve dwarf galaxy cusp-core problem