A Gradual Decline of Star Formation since Cluster In-fall:

New Kinematic Insights into Environmental Quenching at 0.3 < z < 1.1

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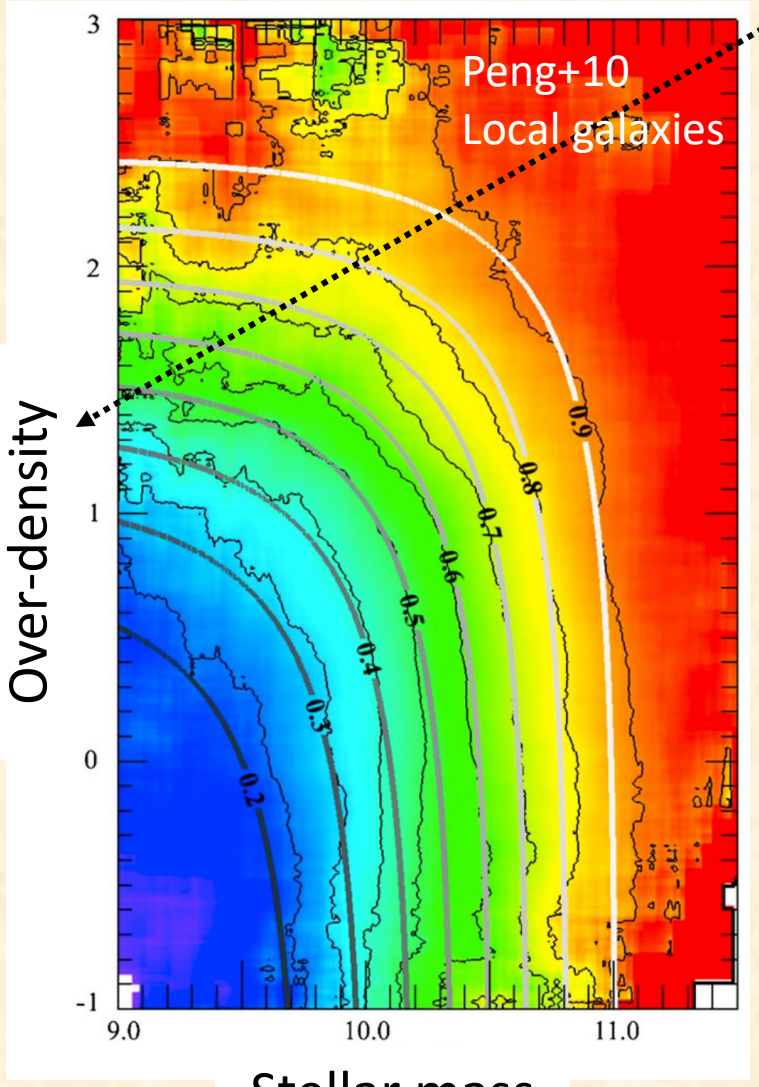
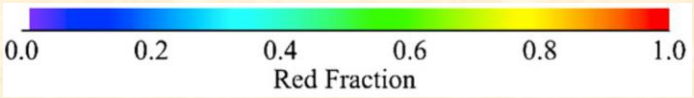
Veronica Strazzullo (INAF, Trieste) South Pole Telescope-clusters collaboration

Background: Where galaxies live (Environment) matters for their lives and deaths (Quenching)



* **Environment** is one of the two main factors known for **quenching star formation in galaxies**

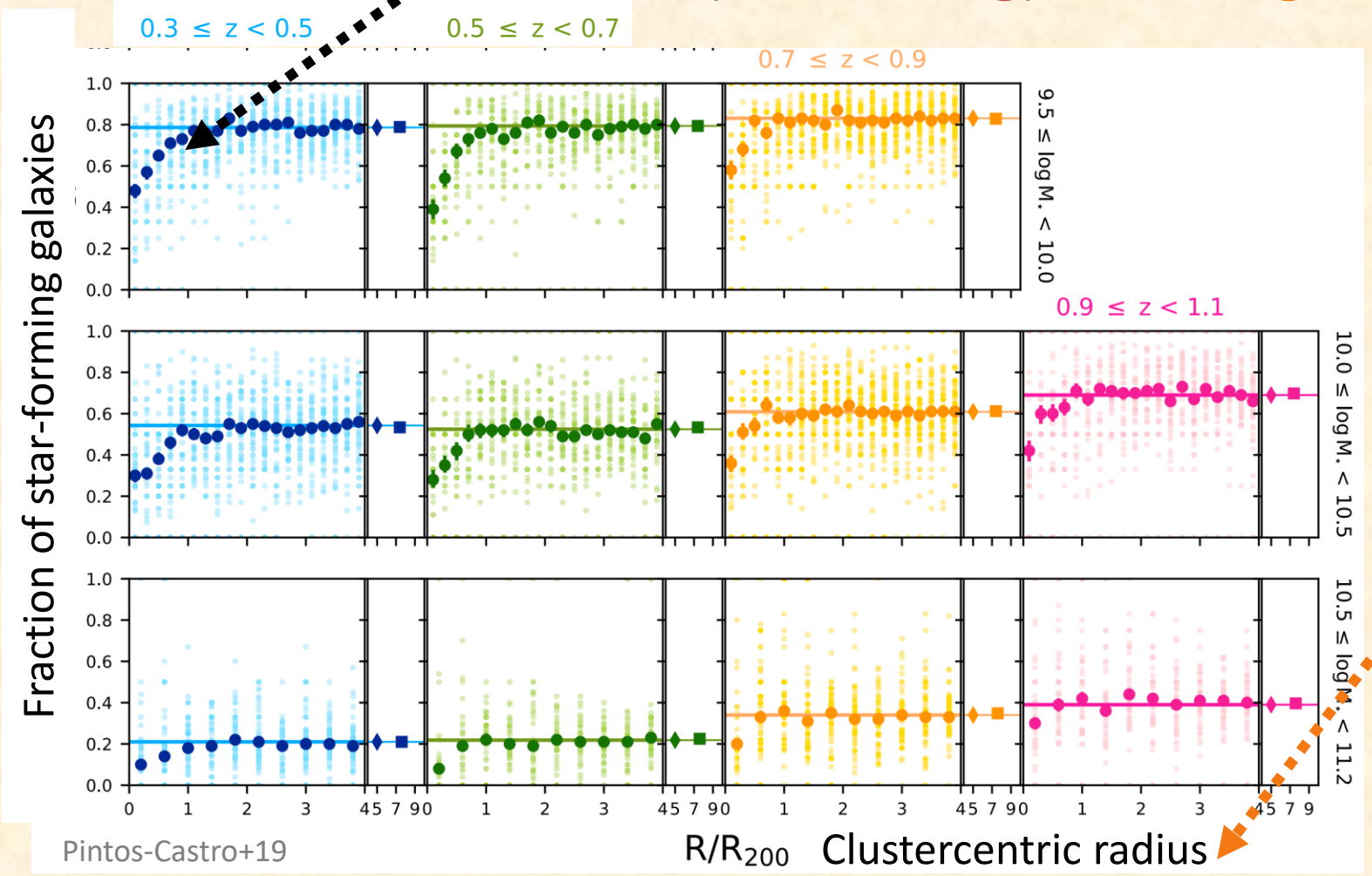
* Star formation **is suppressed in denser** regions compared to isolated/field galaxies

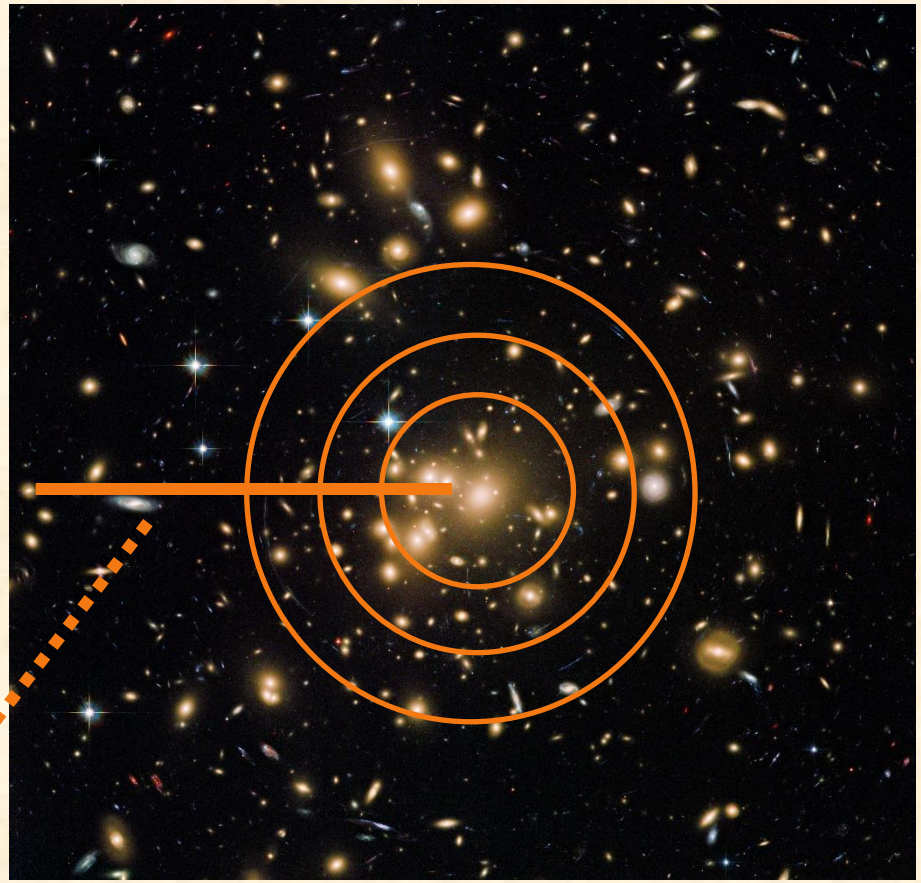


Blue to Red color:
fraction of quiescent galaxies

e.g., Peng+10; Noble+13,15; Kim+18; Pasquali+19; Pintos-Castro+19; Sobral+21

Background: Where galaxies live (Environment) matters for their lives and deaths (Quenching) even in **galaxy clusters**





Abell 1689, credit: NASA/ESA

e.g., Peng+10; Muzzin+12; Noble+13,15; Kim+18; Pasquali+19; Pintos-Castro+19

Kinematic measure for environmental effects using the projected Phase-Space:

Cluster in-fall time

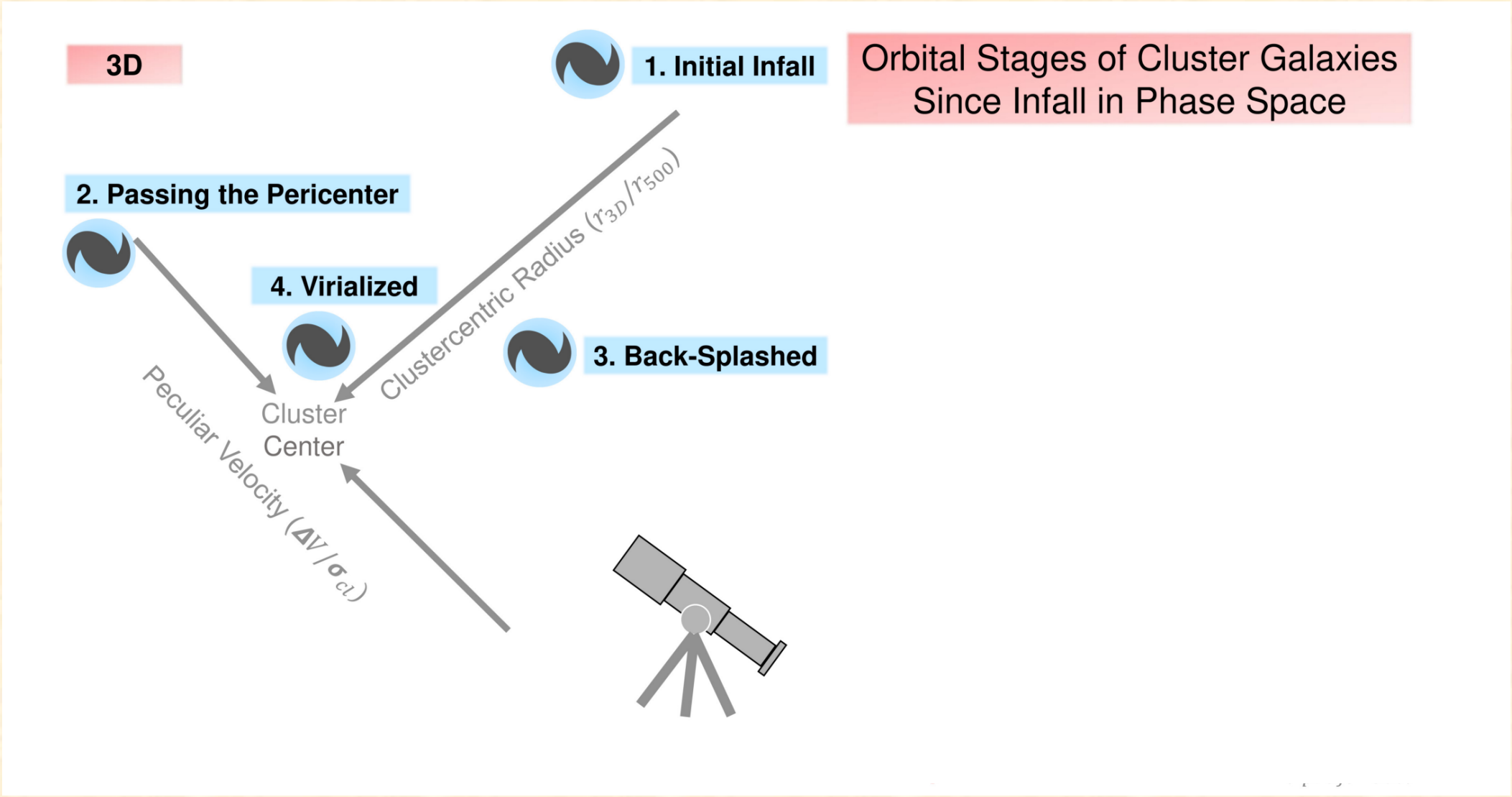


Figure: Kim, J. K. et al. arXiv: 2207.12491

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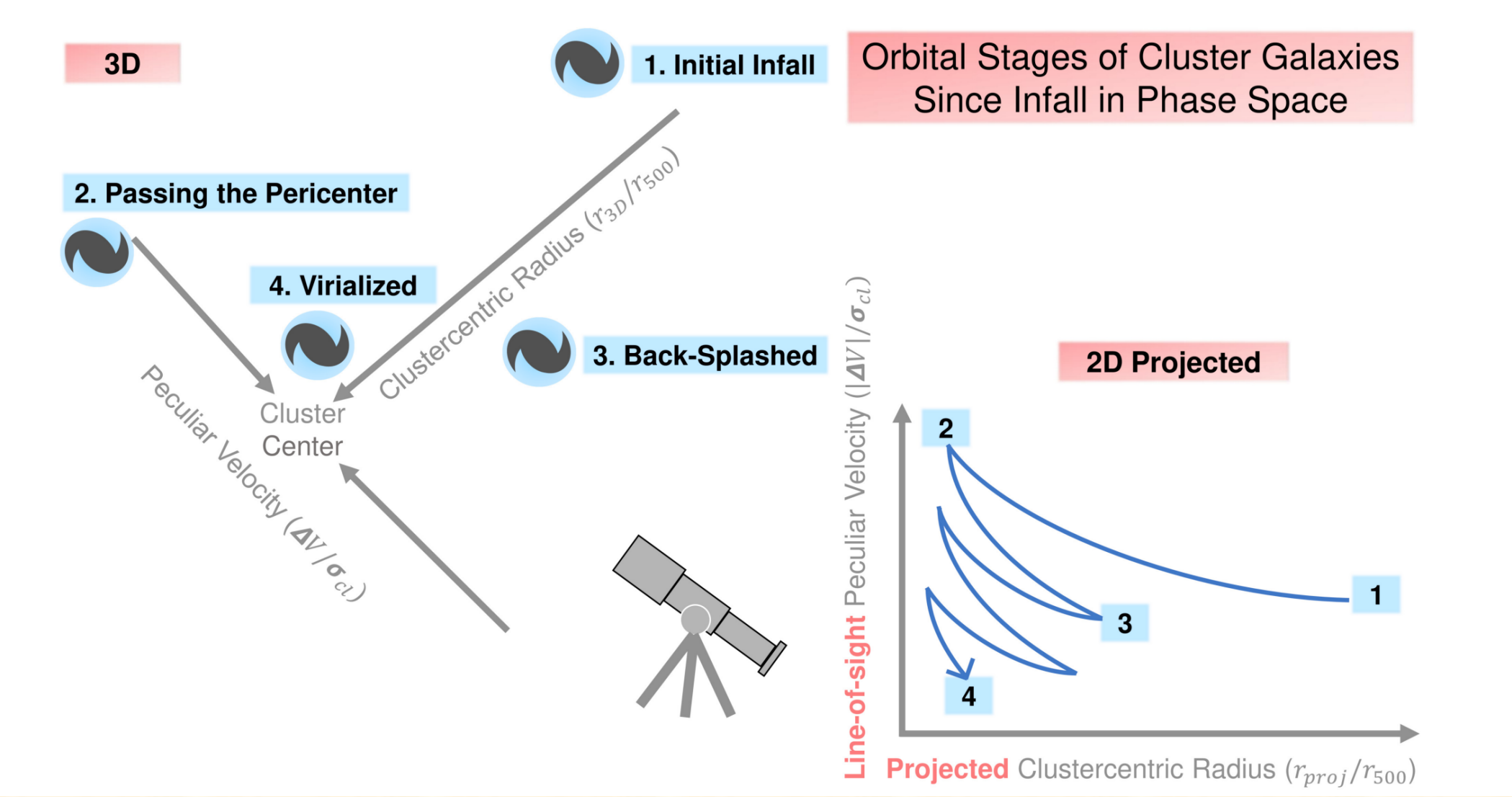

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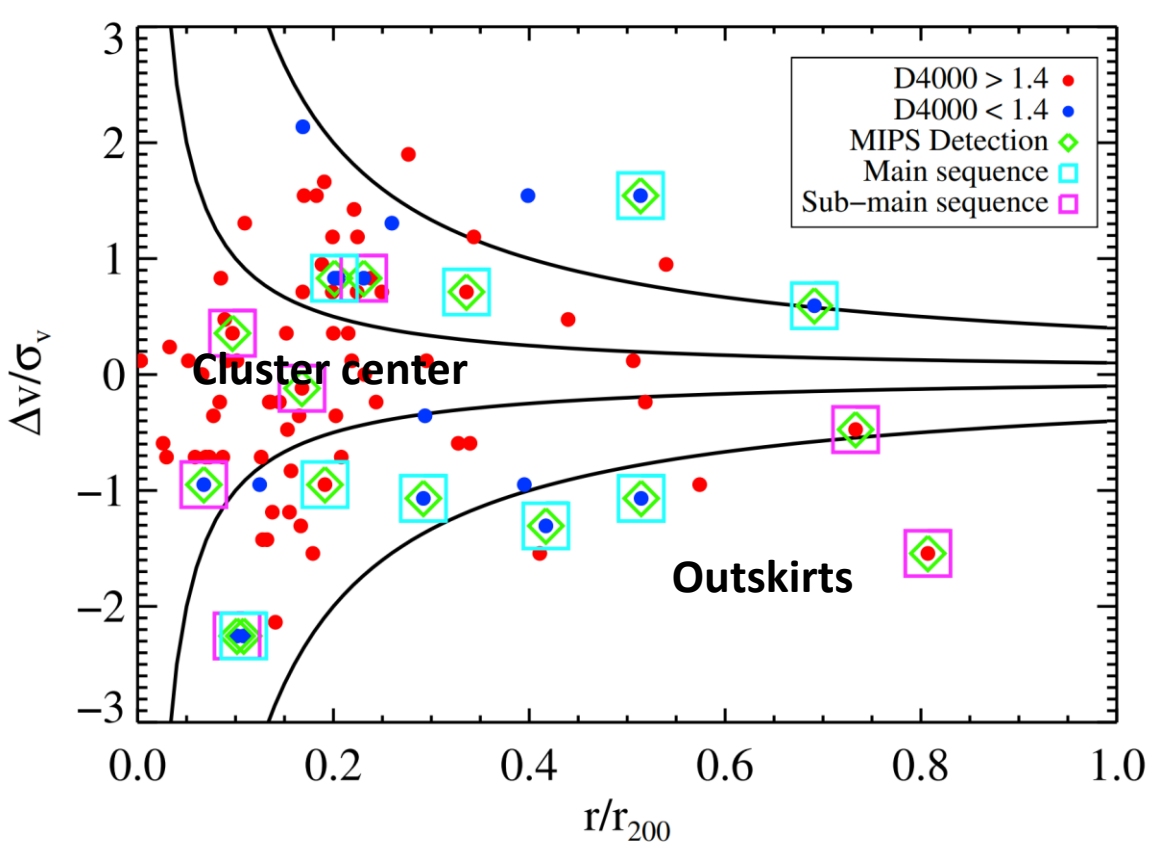
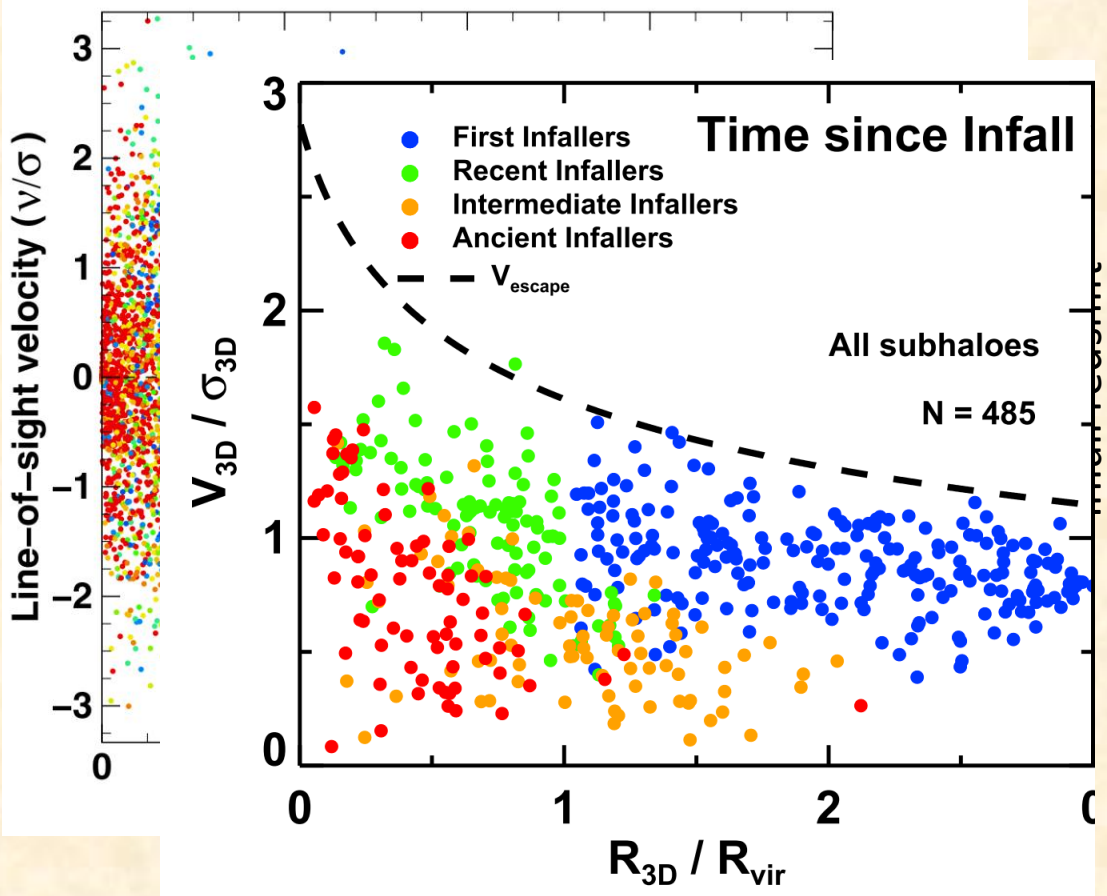
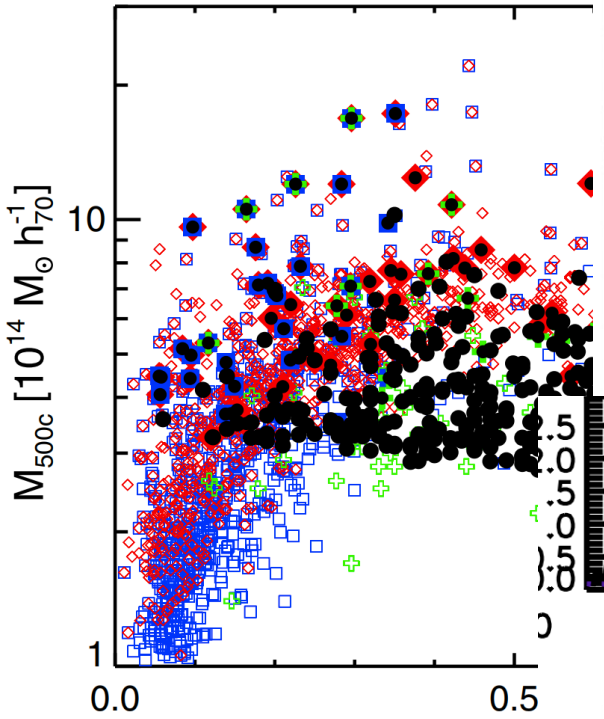
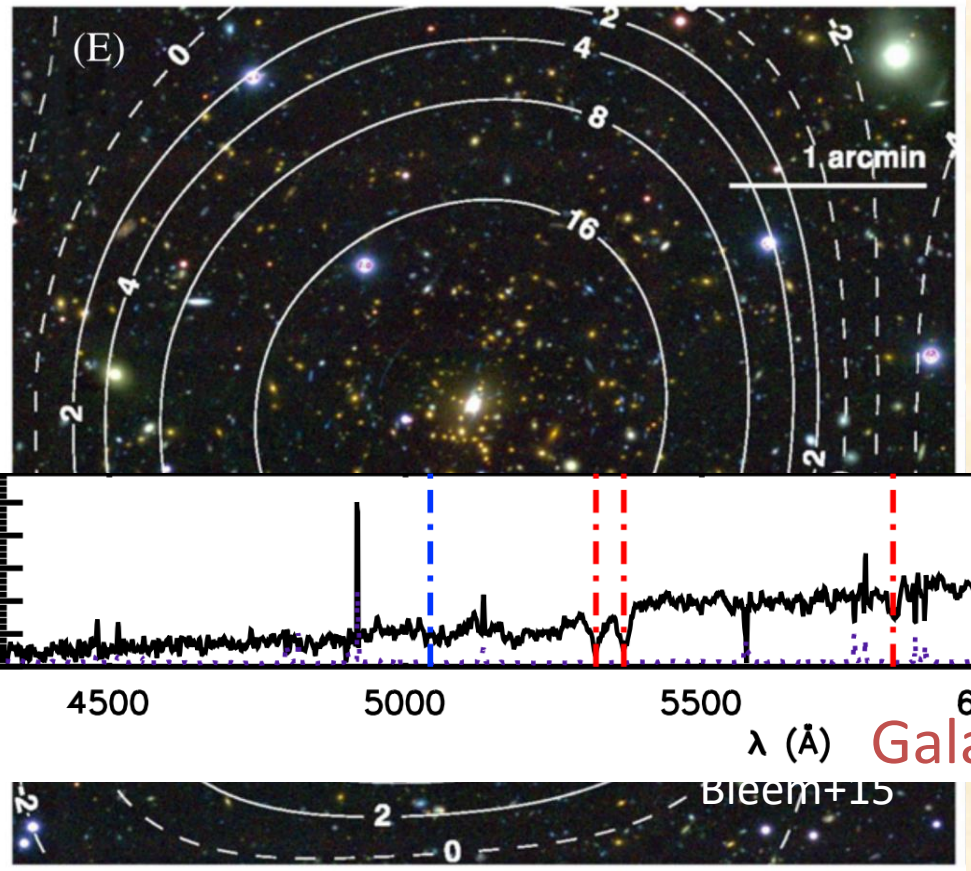




Mahajan+11; Hanes+12;
Noble+13; Rhee+17; Pasquali+19

Sample: Galaxies in Sunyaev-Zeldovich-selected clusters from SPT and ACT with Luminosity and the 4000 Å break measurements



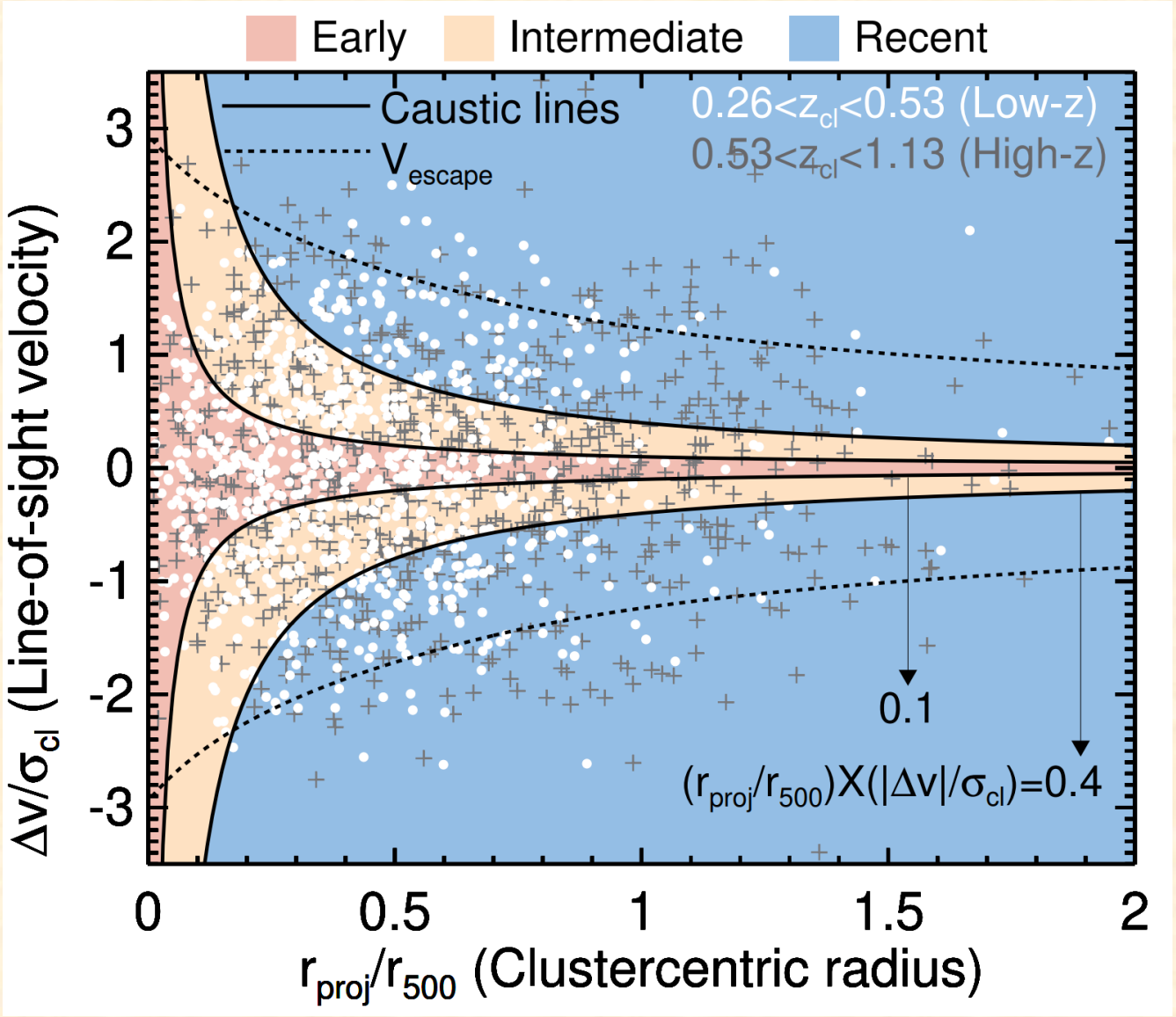


Galaxy spectrum taken from GMOS

Uniformly selected over
Wide redshift: 0.26 < z < 1.13
Large sample: 105 clusters and 1626 spectroscopically-confirmed member galaxies
(with i-band luminosity $L_i/L^* > 0.35$)

Hasselfield+13; Sifon+13;Ruel+14;Bleem+15; Bayliss+16,17

Mapping the galaxy's location in phase space to its mean infall time



* Based on the caustic lines by Noble+13, defined infall regions:
Early in-fall, Intermediate in-fall, and Recent in-fall.

(i) Early in-fall: $(r_{\rm proj}/r_{500}) \times (|\Delta v|/\sigma_{\rm cl}) < 0.1$

(ii) Intermediate in-fall: $0.1 < (r_{\rm proj}/r_{500}) \times (|\Delta v|/\sigma_{\rm cl}) < 0.4$

(iii) Recent in-fall: $(r_{\rm proj}/r_{500}) \times (|\Delta v|/\sigma_{\rm cl}) > 0.4$

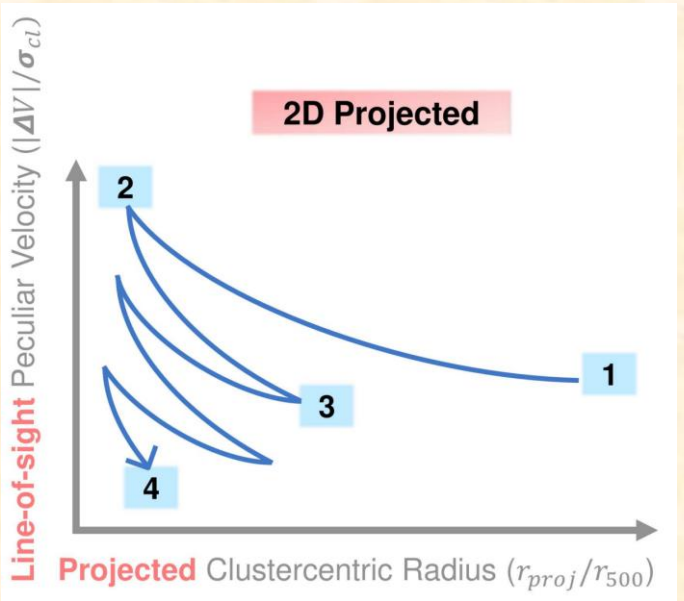
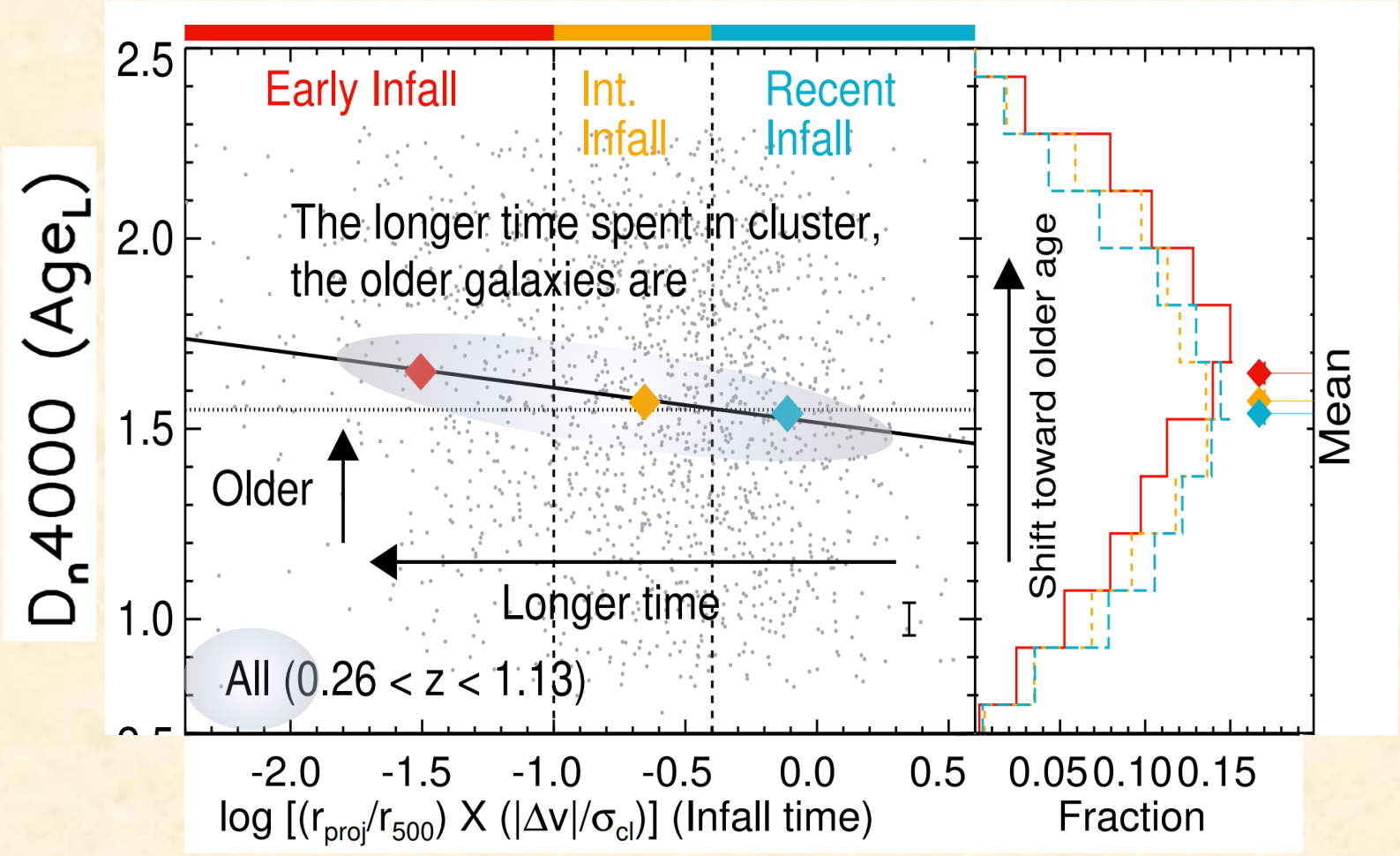


Figure: Kim, J. K. et al. arXiv: 2207.12491

Results: Galaxies have become quenched since in-fall, showing **a gradual age increase from Recent to Early infall** galaxies at 0.3 < z < 1.1



Infall time: $\log[(r_{proj}/r_{500})\mathrm{X}\,(\boldsymbol{\Delta V}/\boldsymbol{\sigma}_{cl})]$

* **0.71 ± 0.4 Gyr older mean age** of Early infallers compared to Field galaxies (c.f., Kauffmann+2003; Hernan-Caballero+13)

Figure: Kim, J. K. et al. arXiv: 2207.12491

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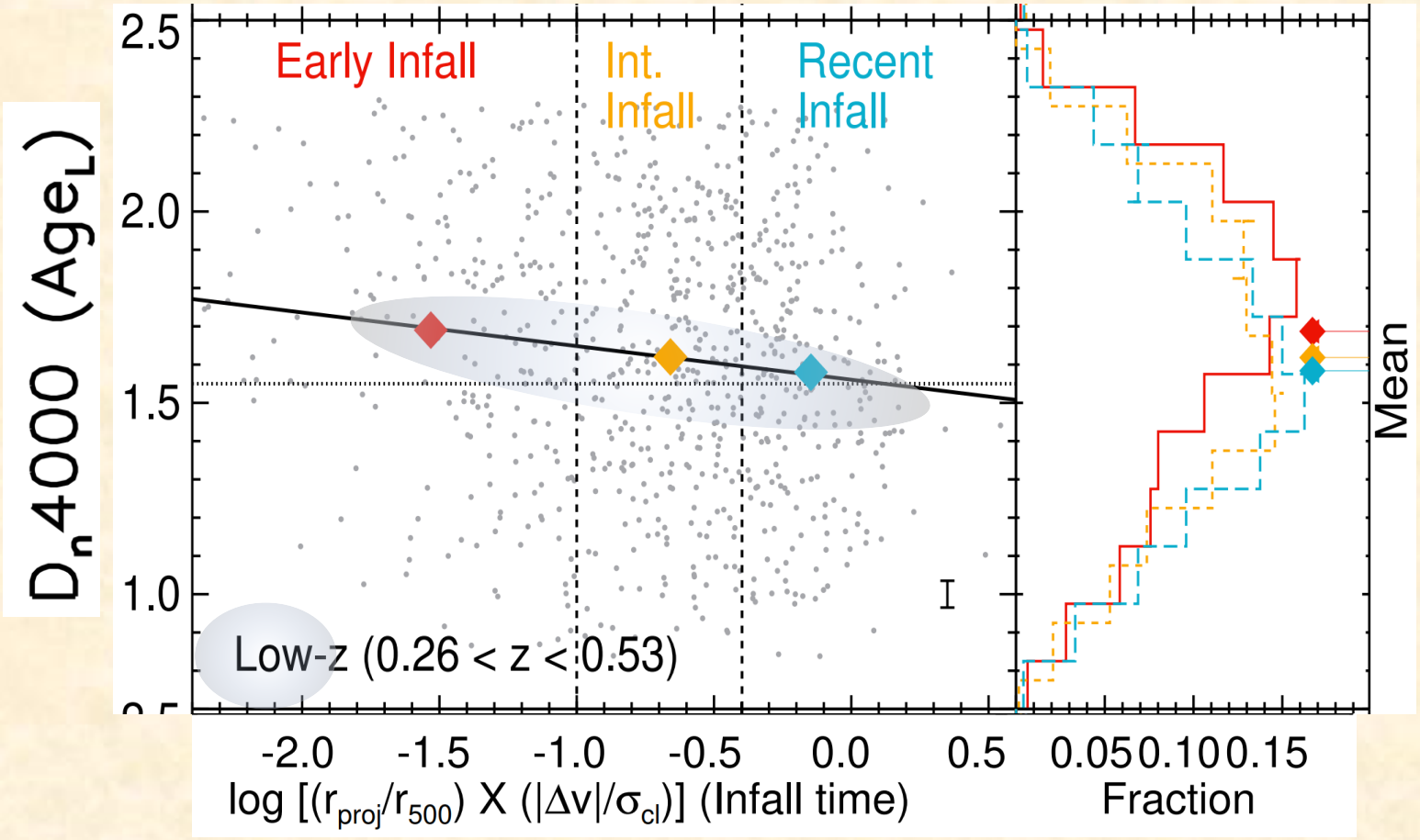

Infall time: $\log[(r_{proj}/r_{500})\mathrm{X}\ (\boldsymbol{\Delta V}/\boldsymbol{\sigma}_{cl})]$

* **0.84 ± 0.6 Gyr older mean age** of Early infallers compared to Field galaxies (c.f., Kauffmann+2003; Hernan-Caballero+13)

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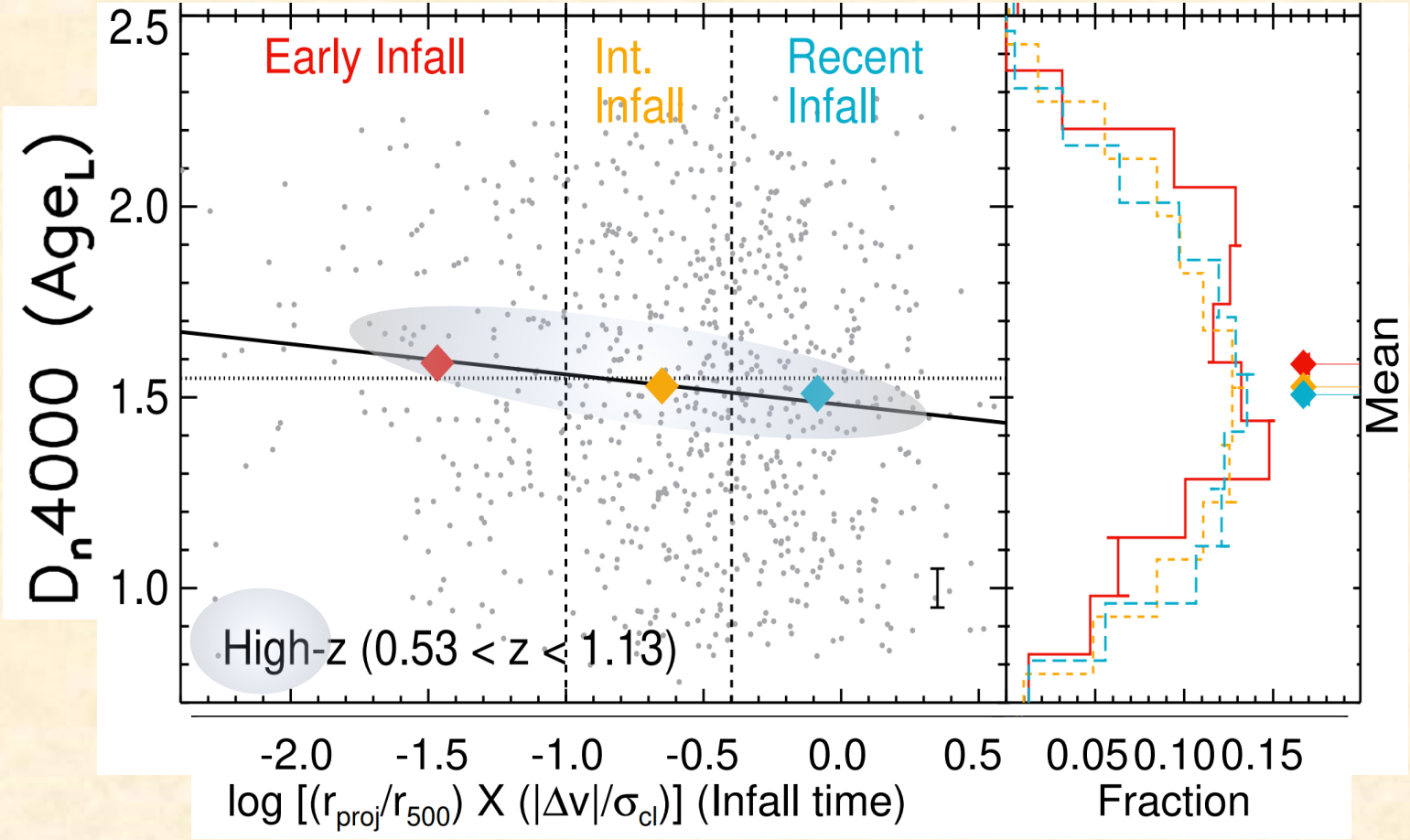

Infall time: $\log[(r_{proj}/r_{500})\mathrm{X}\ (\boldsymbol{\Delta V}/\boldsymbol{\sigma}_{cl})]$

* **0.63 ± 0.4 Gyr older mean age** of Early infallers compared to Field galaxies (c.f., Kauffmann+2003; Hernan-Caballero+13)

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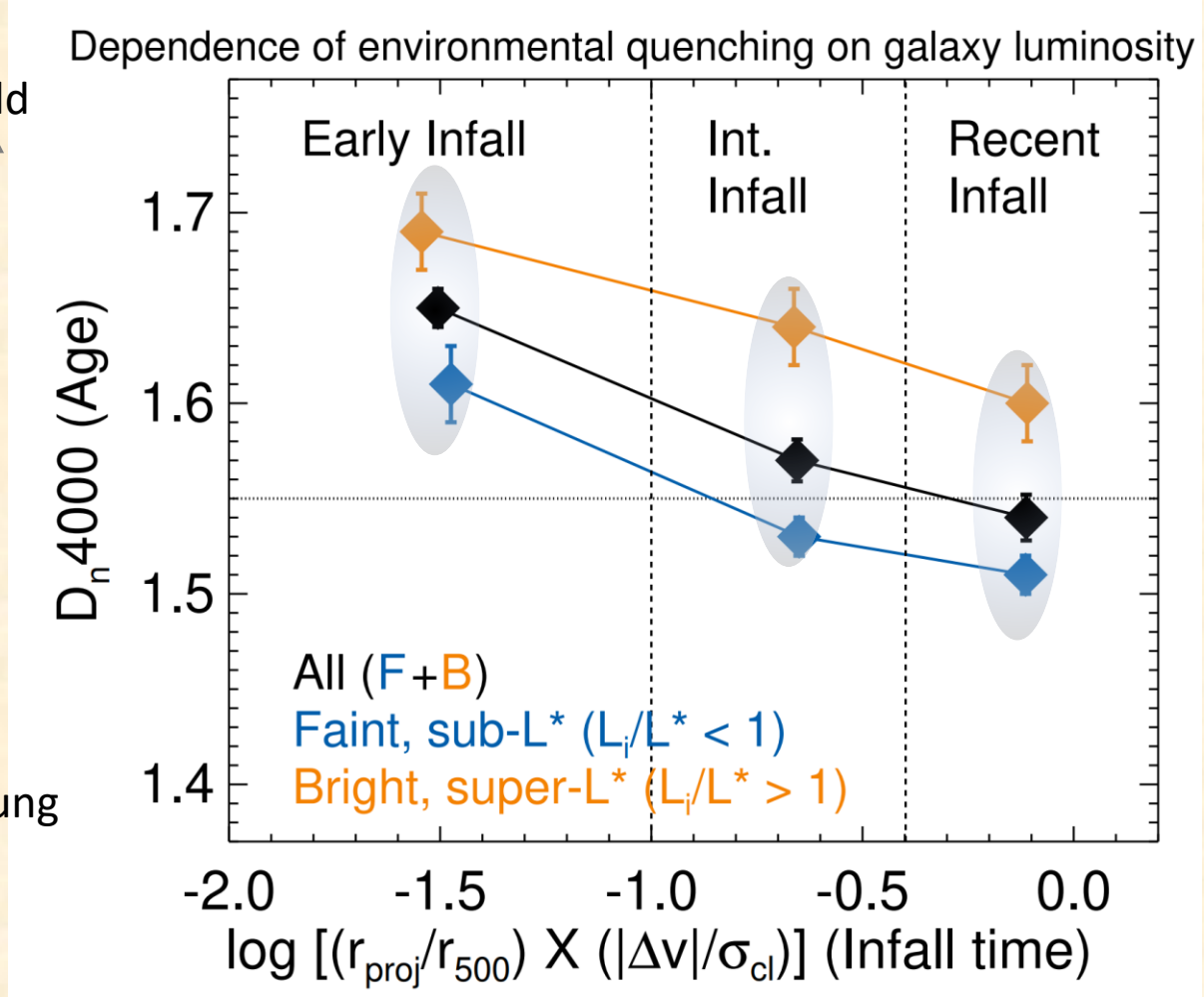
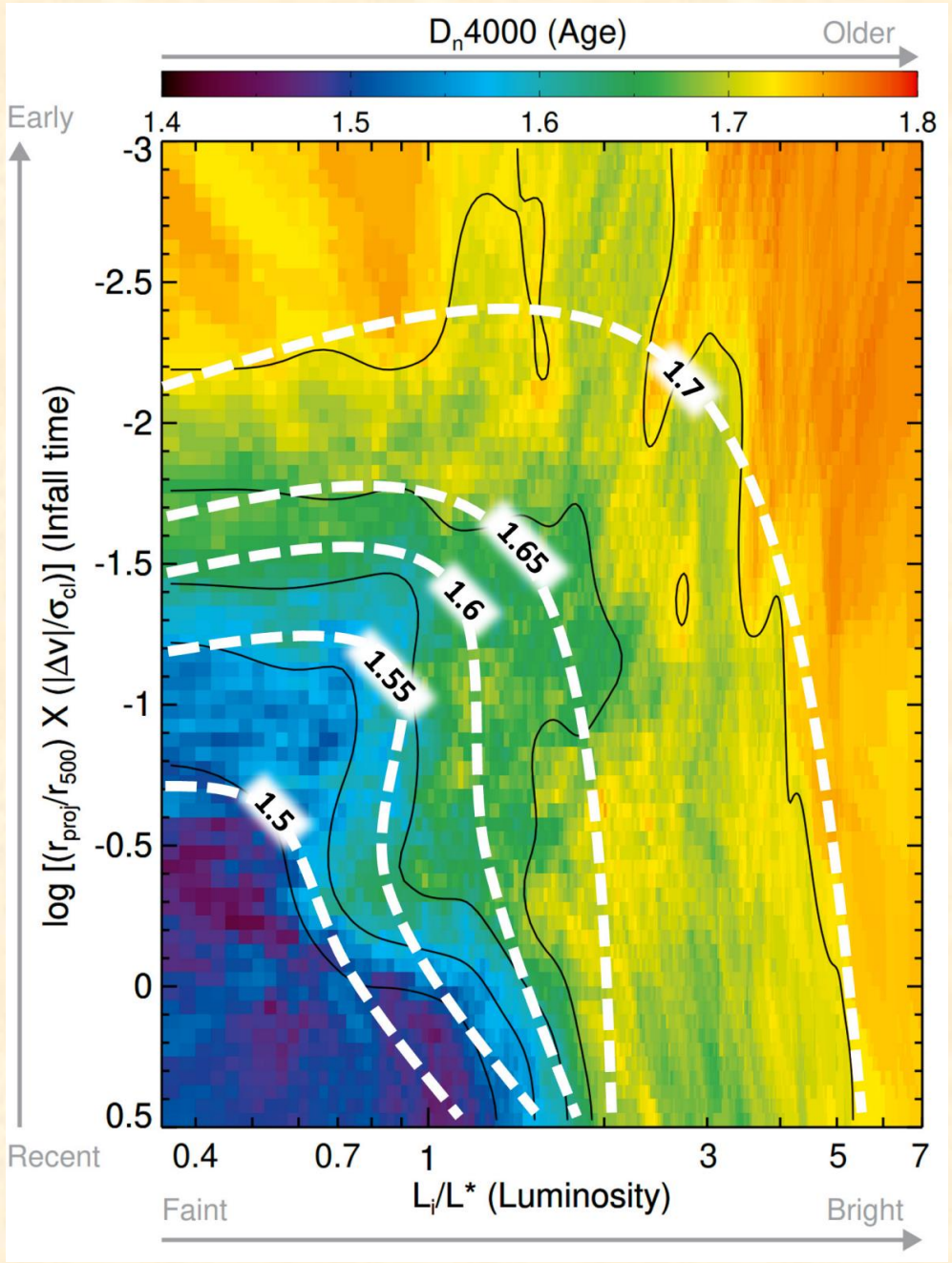
Results: Dependence of envrionmental quenching on galaxy luminosity (stellar mass)



→ Suggesting that cluster member galaxies experience the **environmental quenching effect since in-fall, regardless of their mass.**

Figure: Kim, J. K. et al. arXiv: 2207.12491



Results: Disentangling the effects of

Environment (y-axis)

Luminosity (stellar mass) (x-axis)

* The environmental effect is **kinematically** measured from the phase-space of cluster galaxies

e.g., Peng+10; Noble+13,15; Kim+18; Pasquali+19; Pintos-Castro+19; Sobral+21

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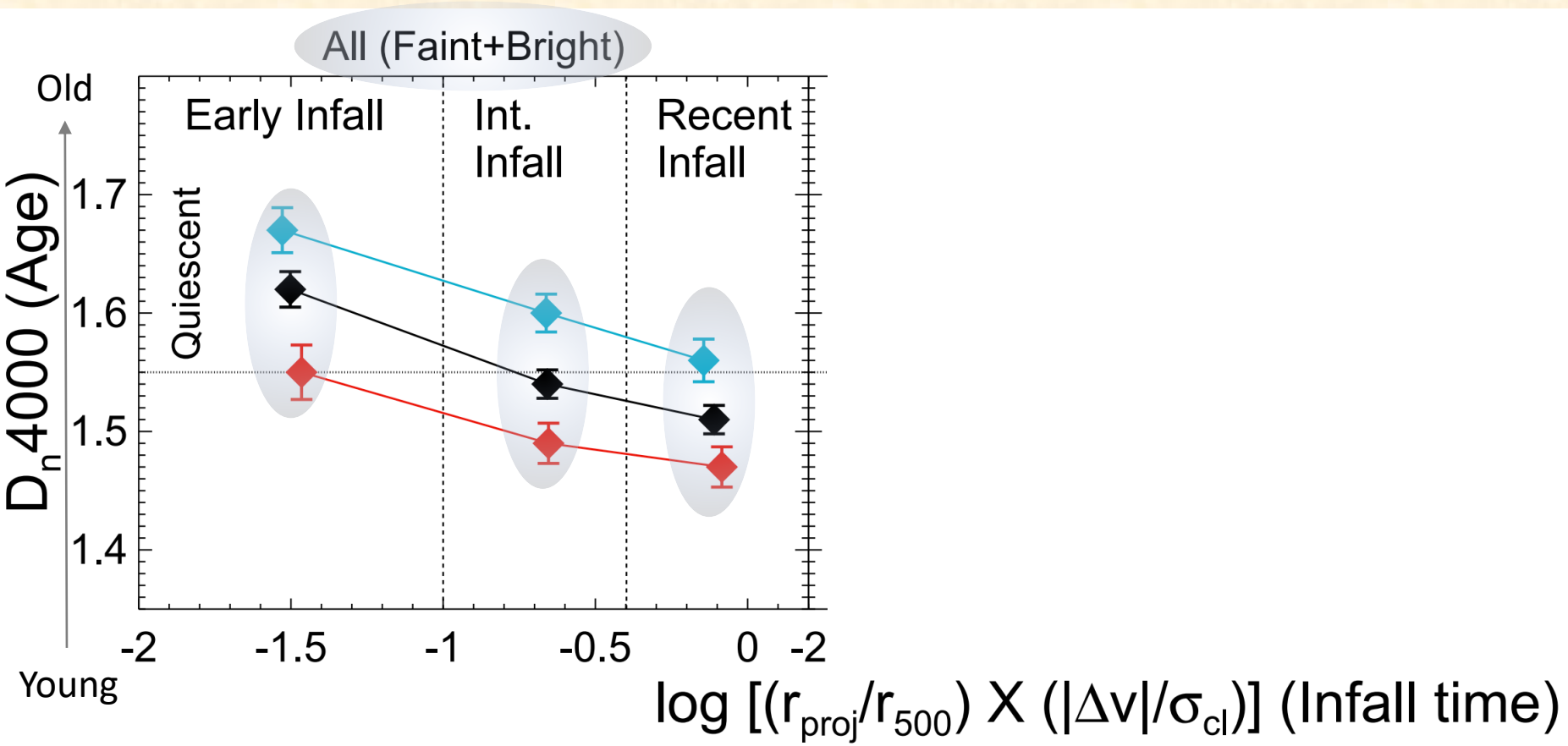
Results: The environmental quenching since in-fall is also seen at any redshifts up to z ~ 1.13 both low-redshift and high-redshift



Low-z: 0.26 < z < 0.53

High-z: 0.53 < z < 1.13

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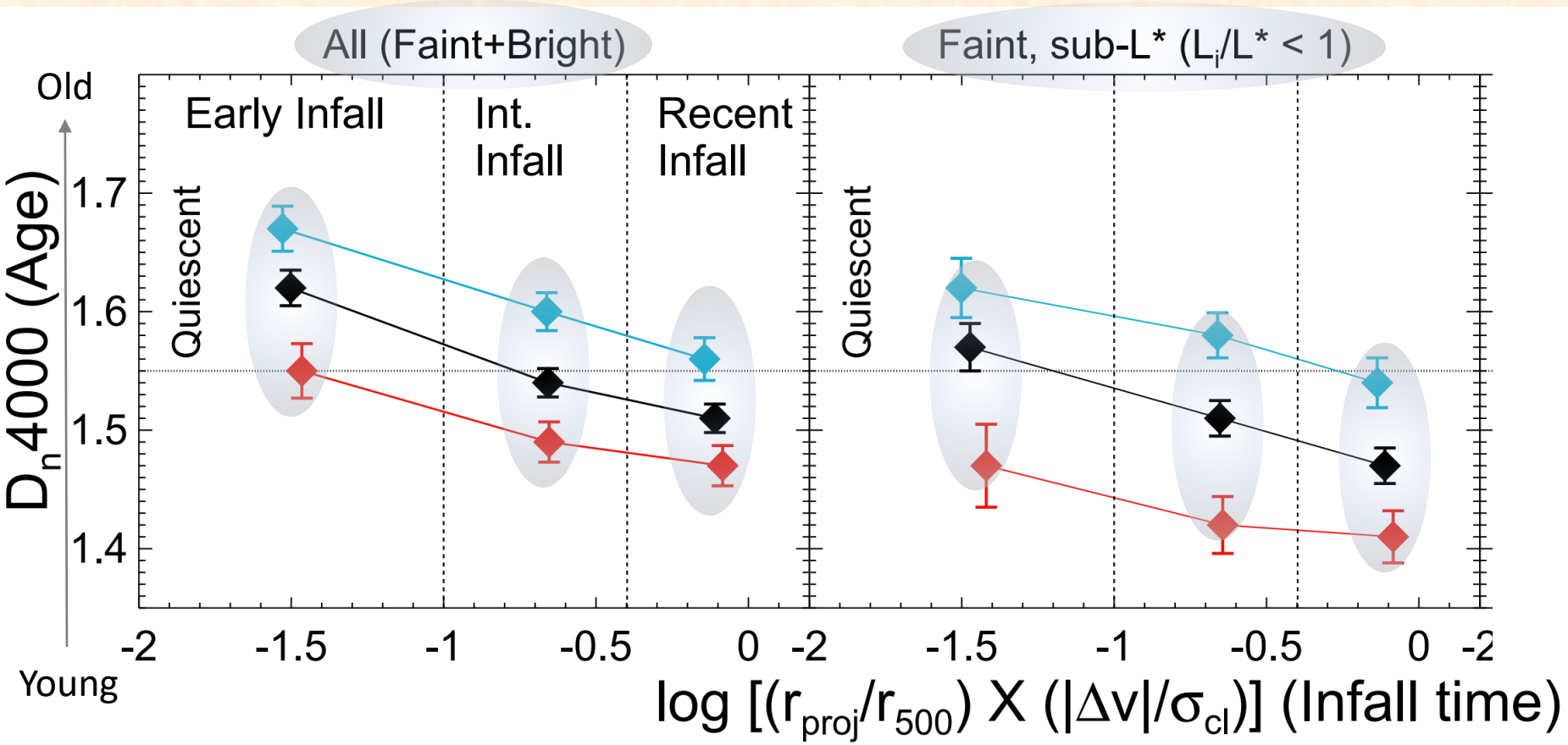

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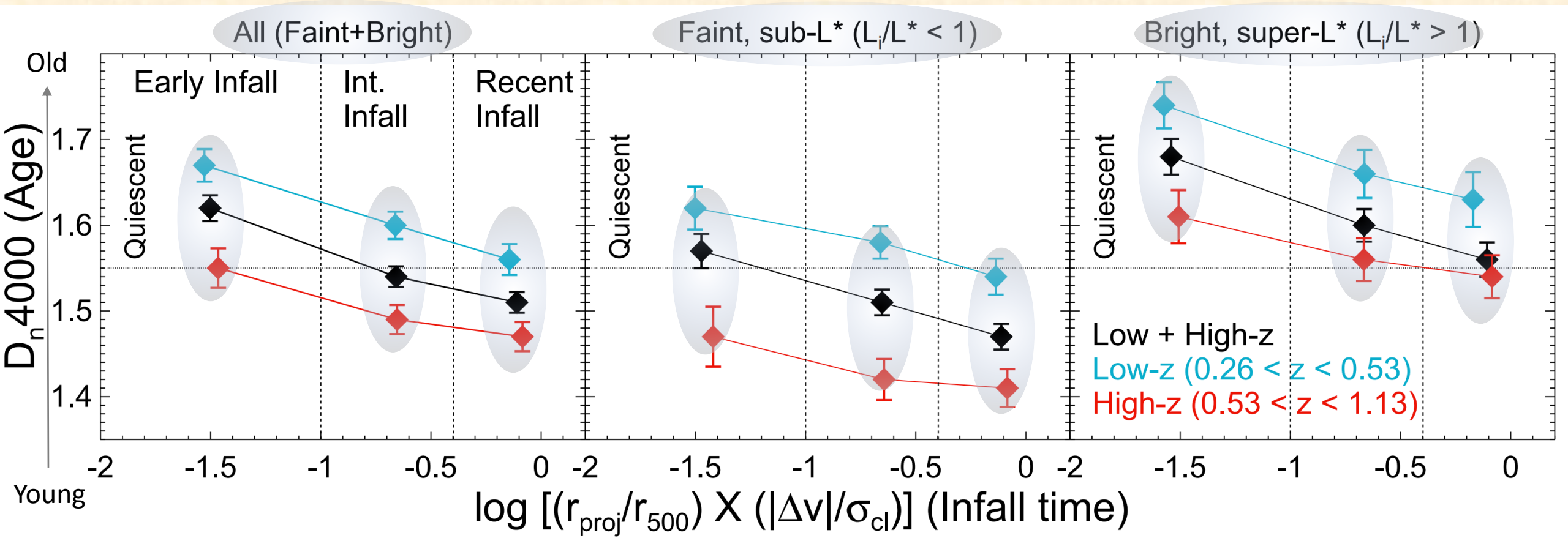

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Summary and Conclusions

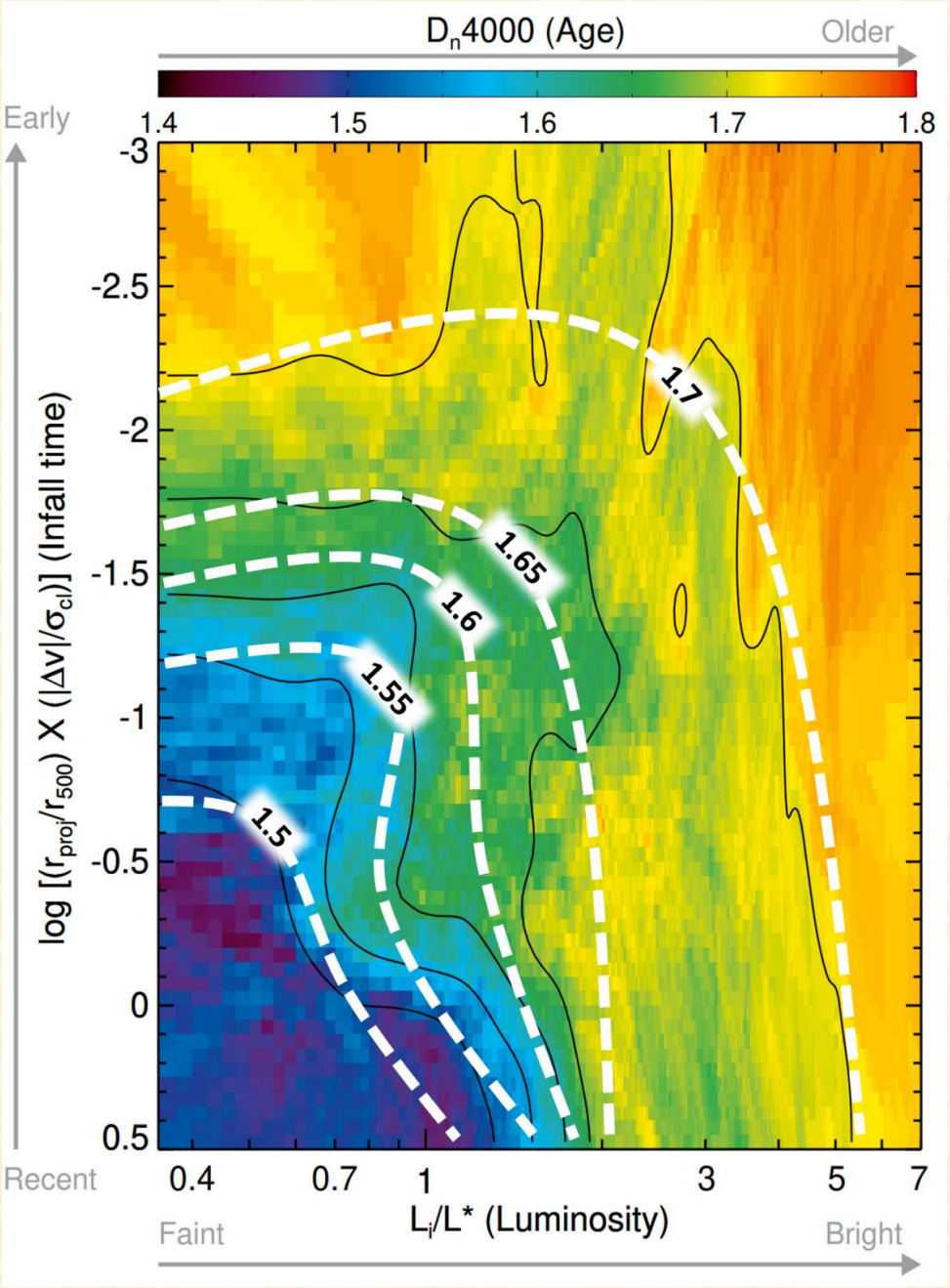
* Updated the environmental process by adopting **kinematically**-derived cluster mean in-fall time over a wide redshift range **(0.26 < z < 1.13, ~5 Gyr span)** using cluster phase-space

* **A gradual age increase (~ 0.71 Gyr) from Recent to Early in-fall galaxies,** suggesting that galaxies become quiescent since in-fall (c.f., Noble+13,15; Pasquali+19)

* The environmental quenching since in-fall is shown for galaxies of any luminosity/mass (faint or bright) and at any redshifts up to z ~ 1.13

* **Longer exposure since in-fall to environmental effects** such as ram pressure stripping and strangulation

Thus, galaxies experience a gradual decline of star formation after they fall into cluster environments up to z ~1



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