Impact of the galaxy cluster environment on the stretch distribution of type-Ia supernovae with ZTF

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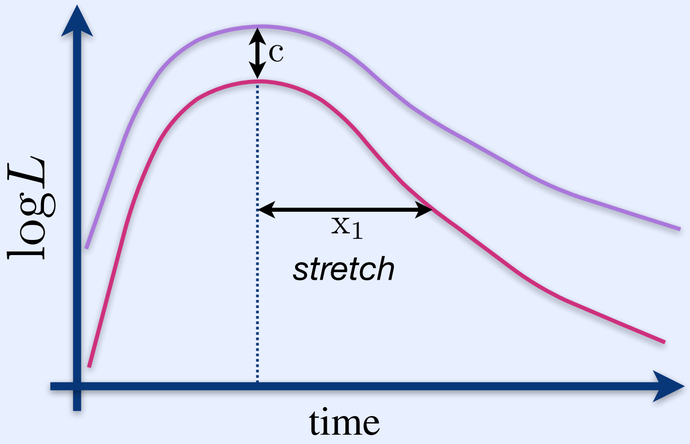
In collaboration with: the ZTF collaboration

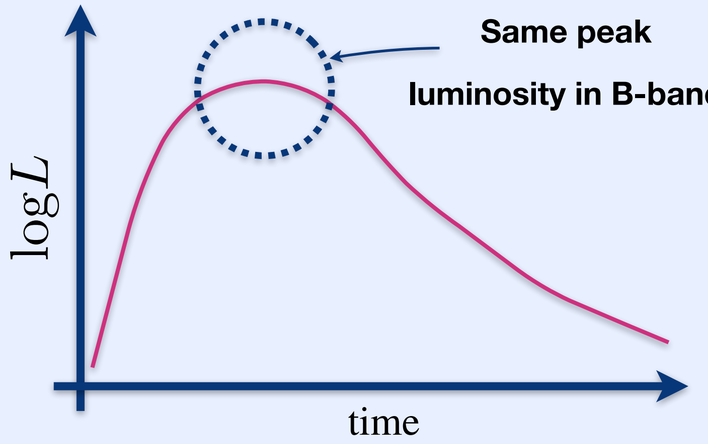
Action Dark Energy, Institut Henri Poincaré, 28-30/10/2024

Cosmology with type Ia supernovae

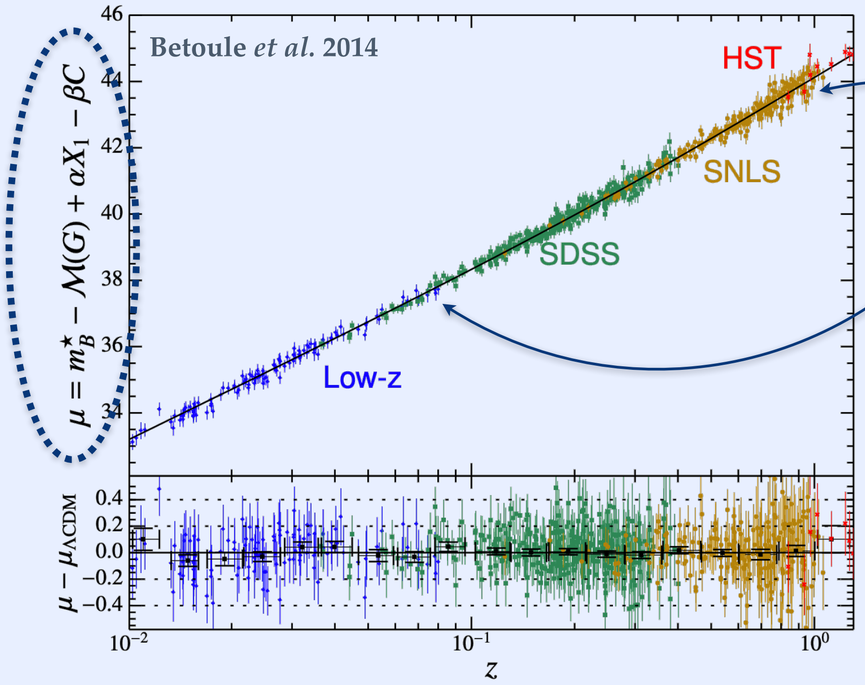
Measure SN Ia light curve



Standardization



Standardized magnitude



Most leverage on cosmological parameters from high-z SNe Ia

Cosmological model

Cosmology with type Ia supernovae

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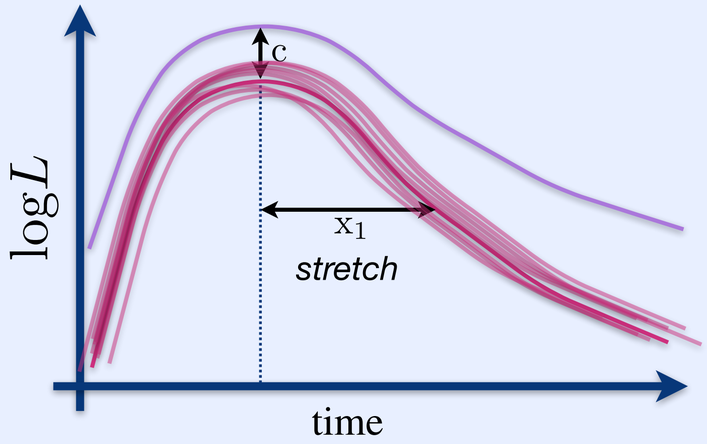

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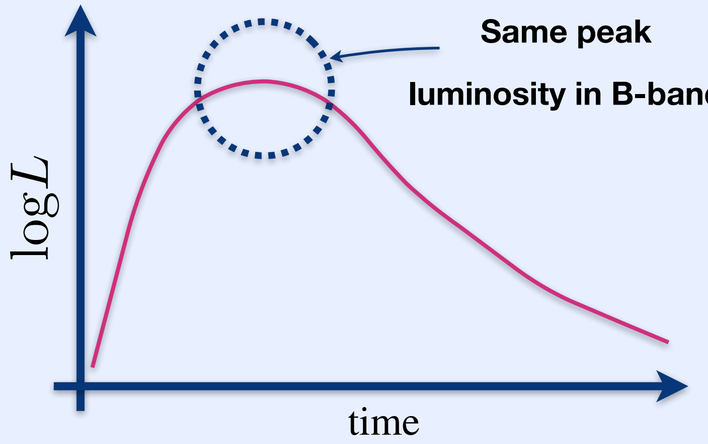
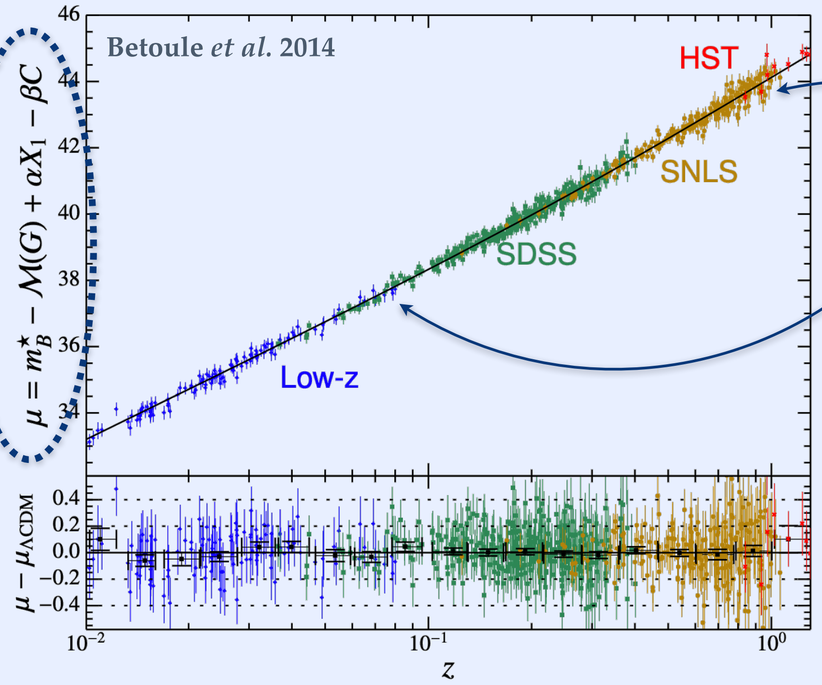


Standardized magnitude

$\mu = m_B^\star - \mathcal{M}(G) + \alpha X_1 - \beta C$

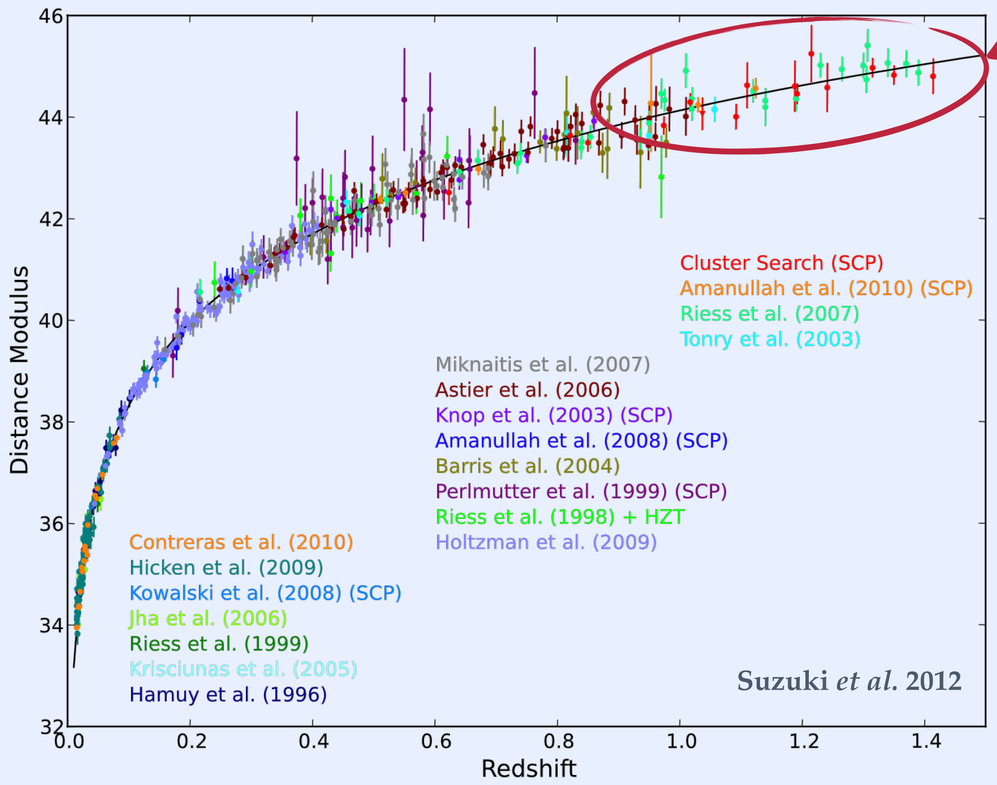


Most leverage on cosmological parameters from high-z SNe Ia

Cosmological model

Starting point of the analysis

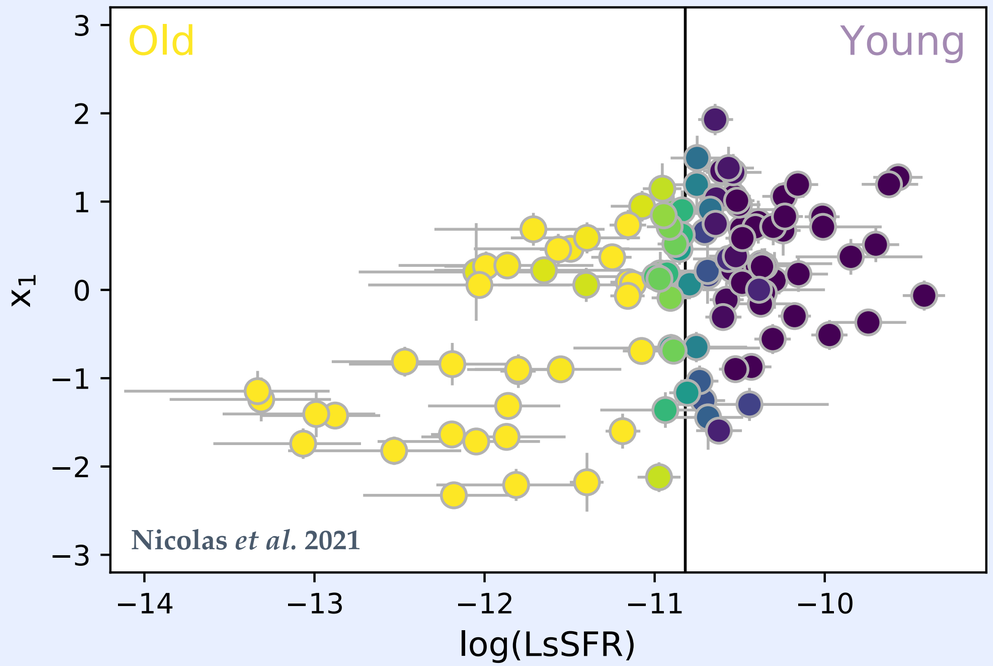
- HST Cluster Supernova Survey: search for SNe Ia in 25 distant galaxy clusters to maximize detection probability

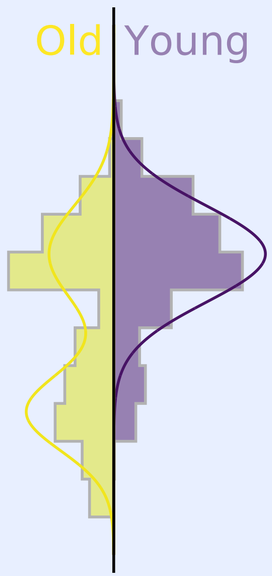


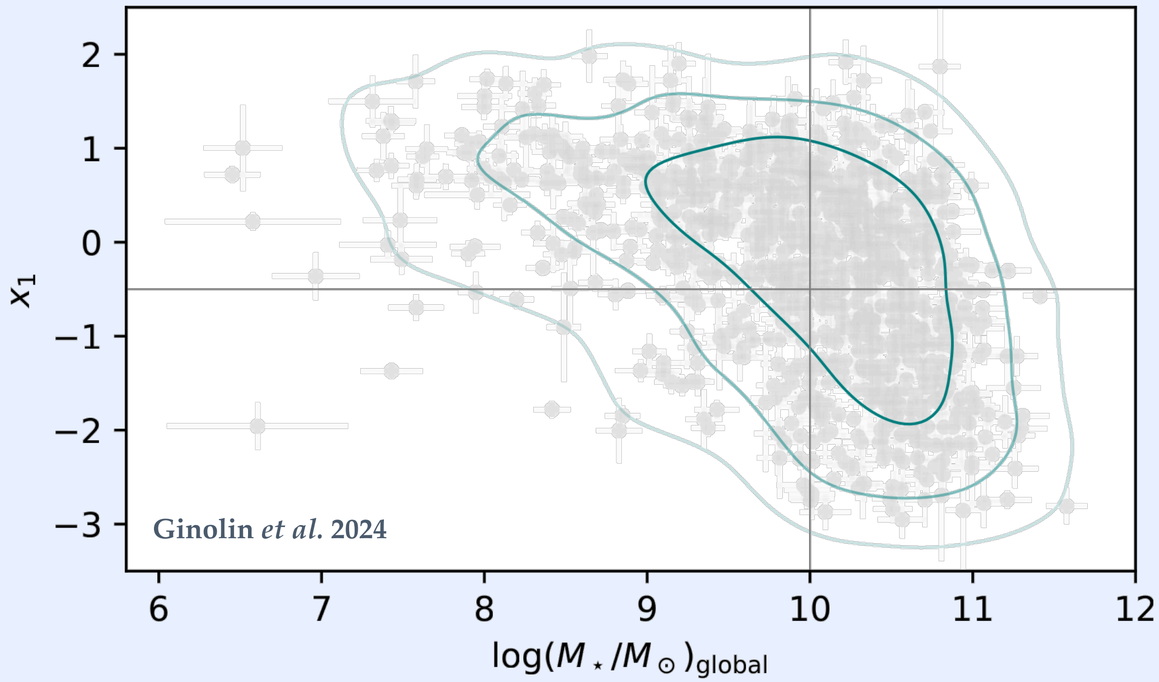
SNe Ia found in clusters
⟶ Better constraints on $w(z)$

Question: Is there an impact of galaxy cluster environment on the light-curve parameters of SNe Ia found in clusters?

Stretch distribution depends on environment



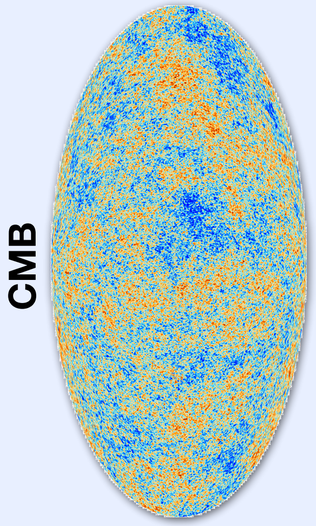




- Stretch distribution depends on star formation rate *(redshift evolution)*
- Stretch distribution depends on host mass

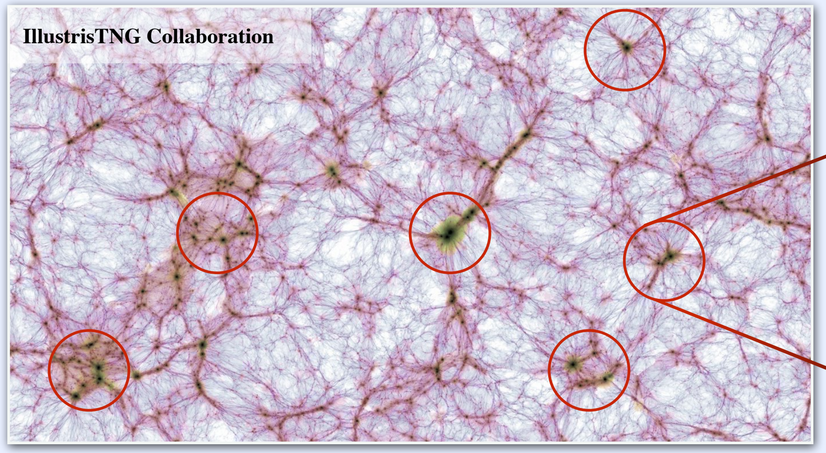
Direct impact on standardisation procedure *(cosmology if the WLR depends on stretch)*

Galaxy cluster environment

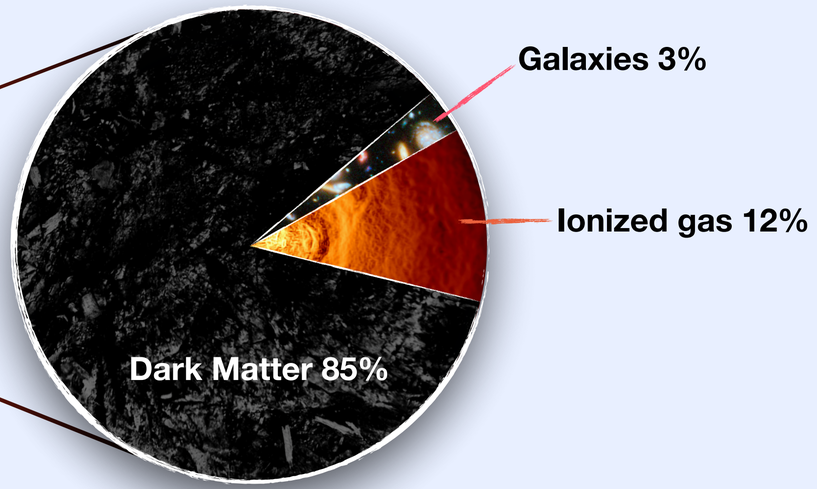


Structure growth

Large scale structures



Galaxy cluster



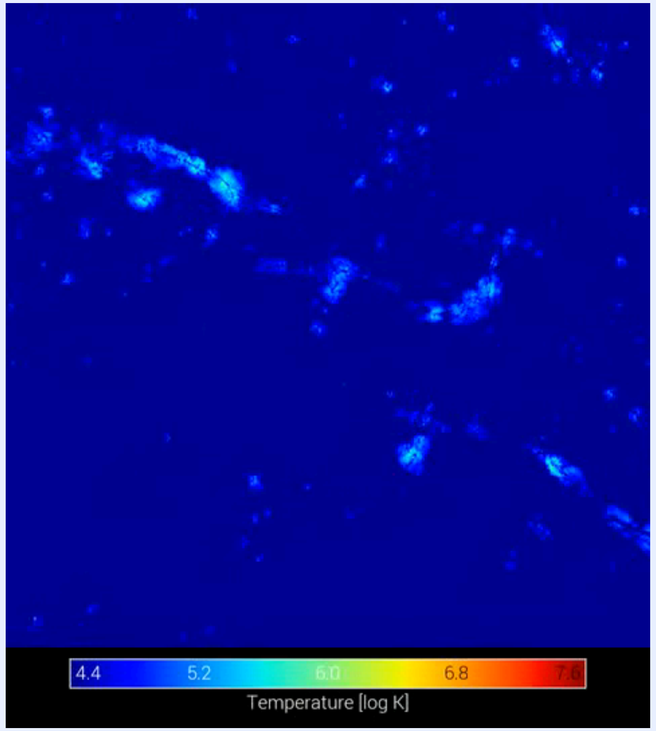
- Formed through slow accretion of surrounding material (linear) and merger events / virialization / feedback processes (non-linear)
- Culmination of the large scale structure formation process
- Representative of the average matter repartition in the Universe

Galaxy cluster environment

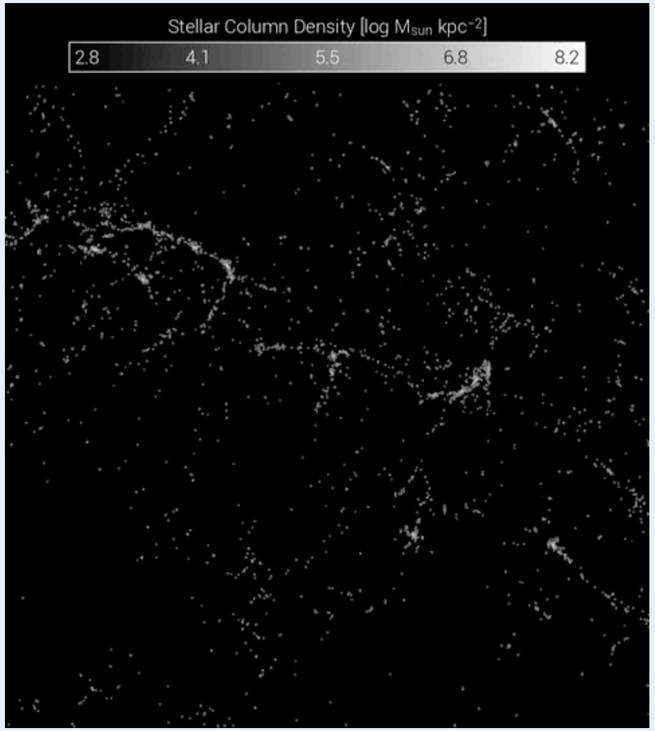
Hierarchical formation process

Cluster formation in IllustrisTNG simulation

Gas temperature



Galaxies



→ Old and massive galaxies in a high-temperature environment

Galaxy cluster environment

Hierarchical formation process

Cluster formation in IllustrisTNG simulation

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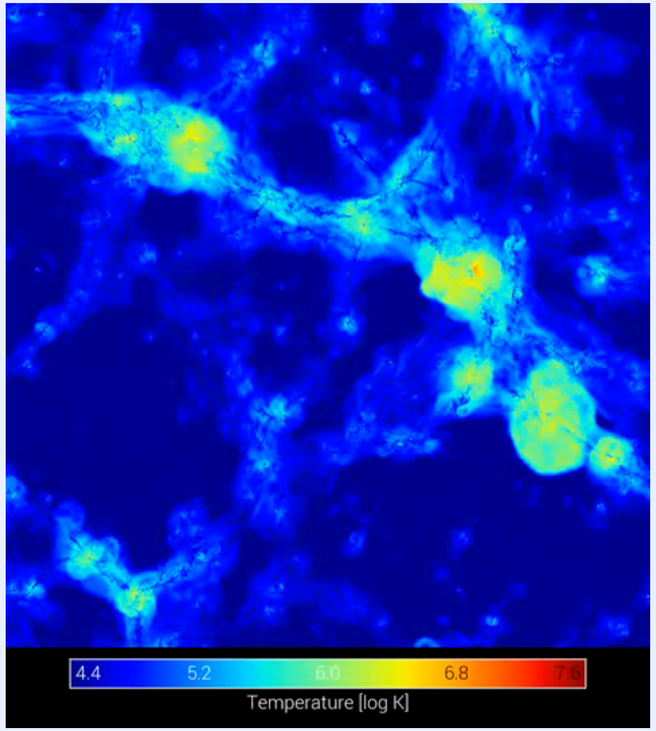
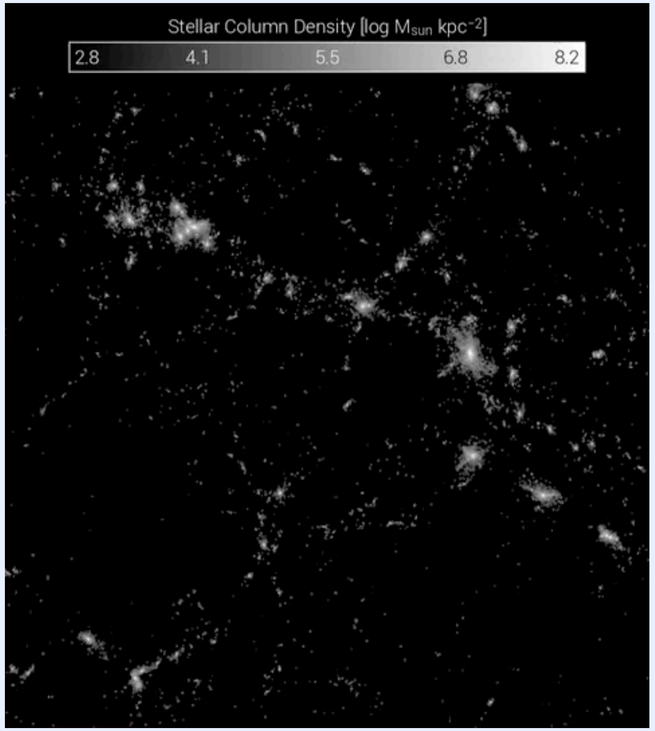


Galaxies



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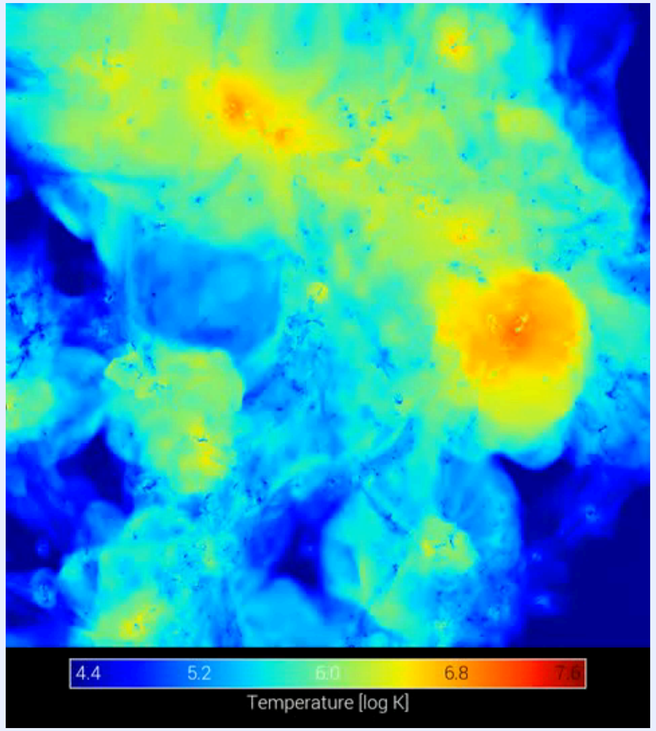
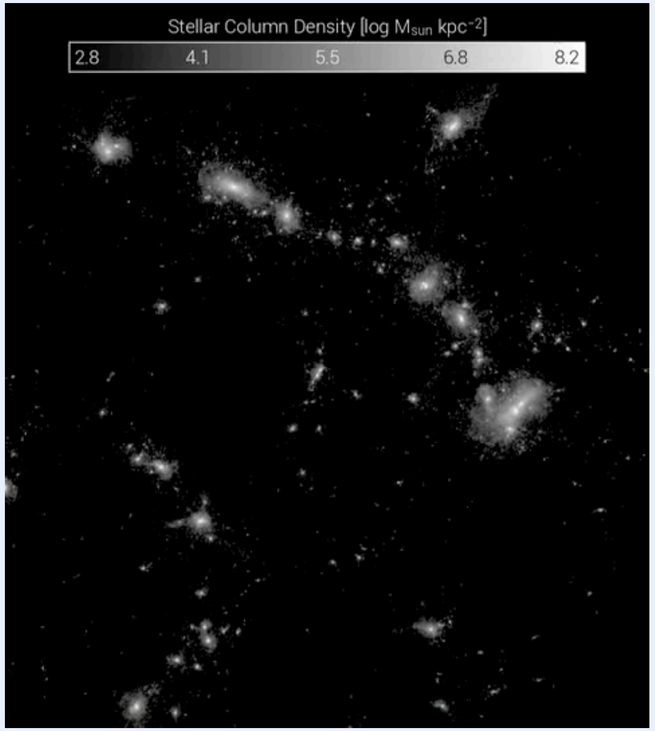


Galaxies



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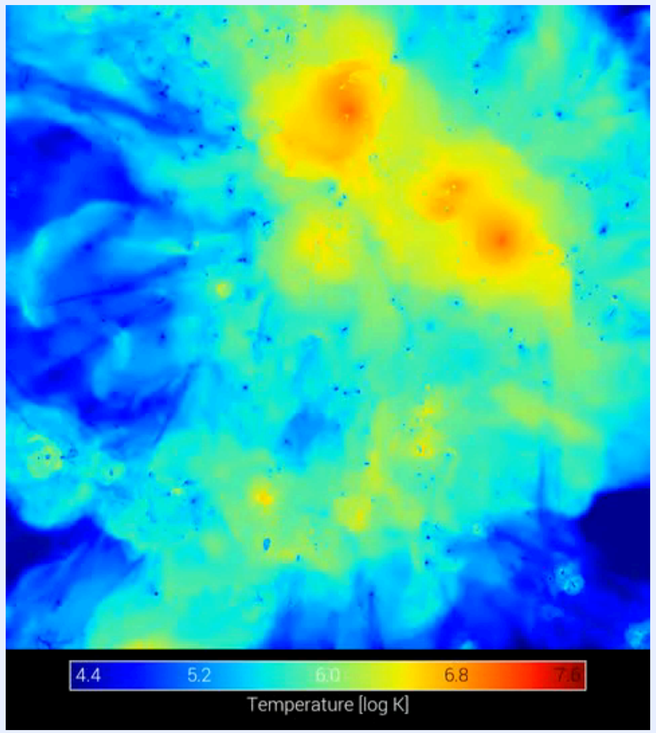
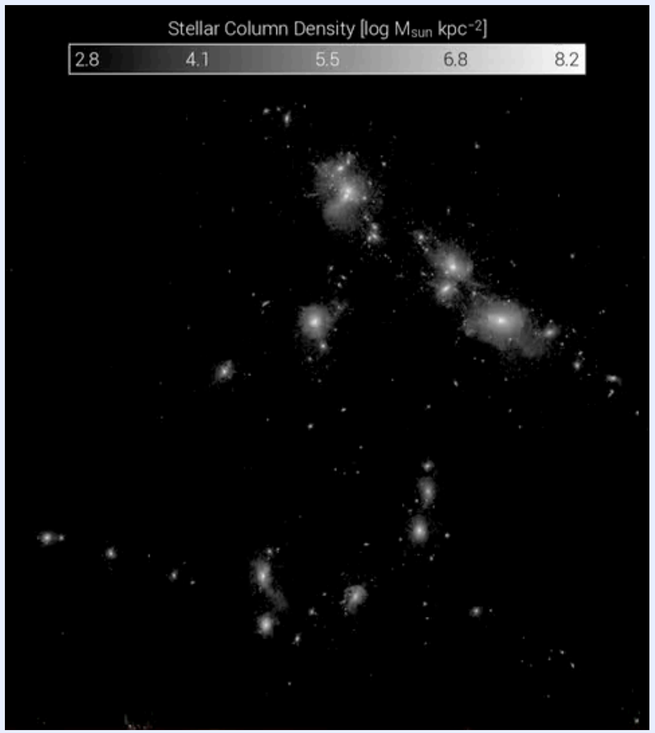


Galaxies



→ Old and massive galaxies in a high-temperature environment

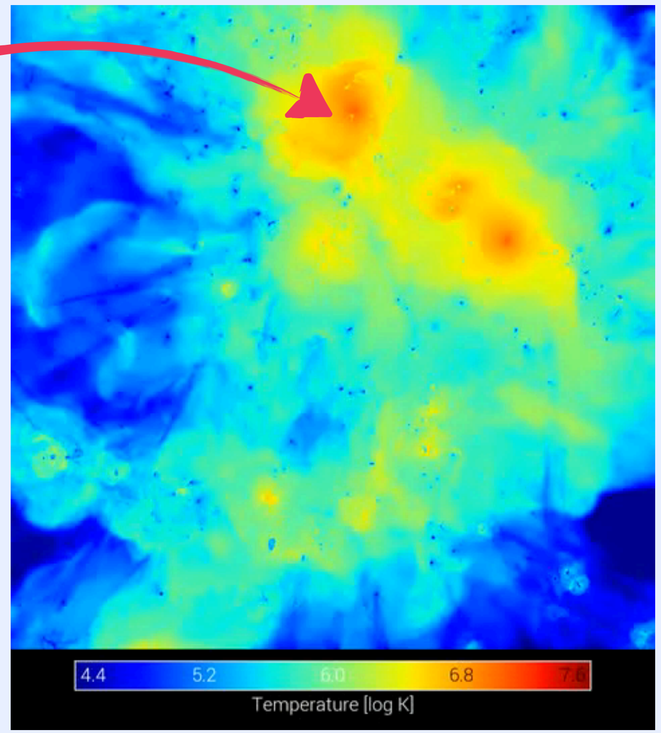
Galaxy cluster environment

Hierarchical formation process

Cluster formation in IllustrisTNG simulation

Gas temperature

Hot intracluster medium
$\mathcal{O}(10^5)$ K



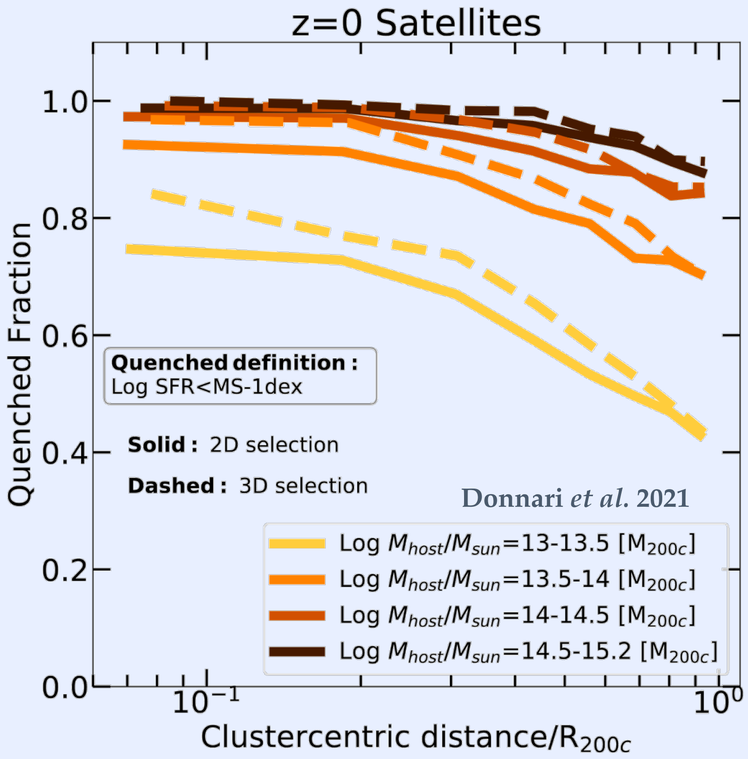
Galaxies

Massive galaxies
$M_* = 10^{11} - 10^{12}$ $M_\odot$

→ Old and massive galaxies in a high-temperature environment

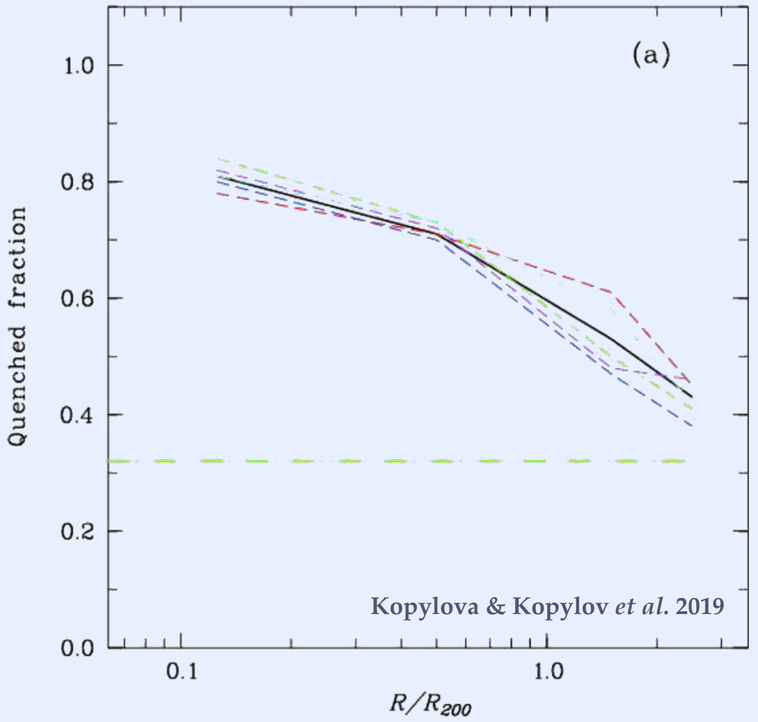
Cluster galaxies: age and star formation rate

Simulation



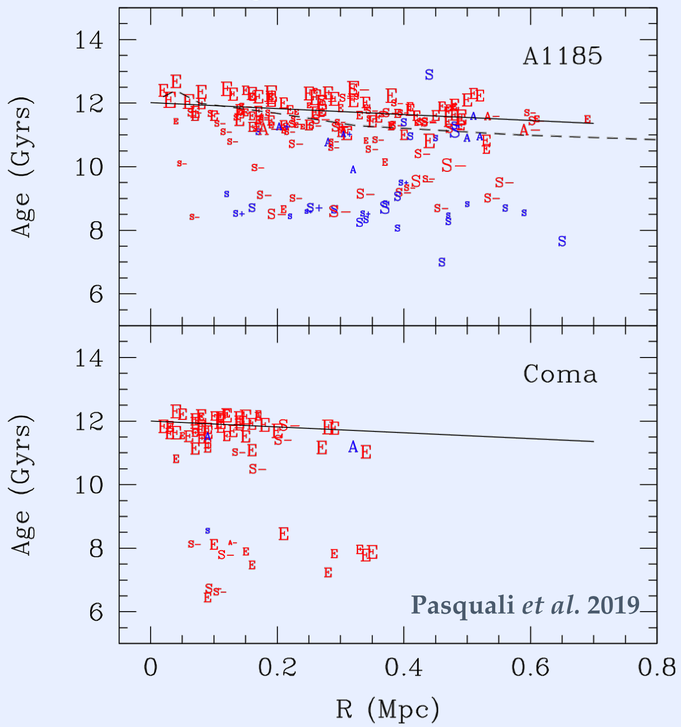
Data (SFR)

Based on SDSS data



Data (age)

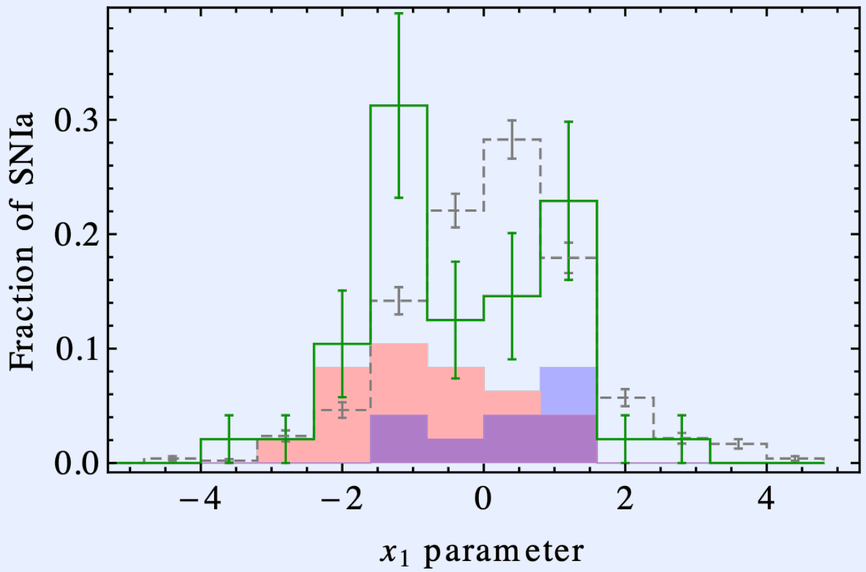
Targeted observations



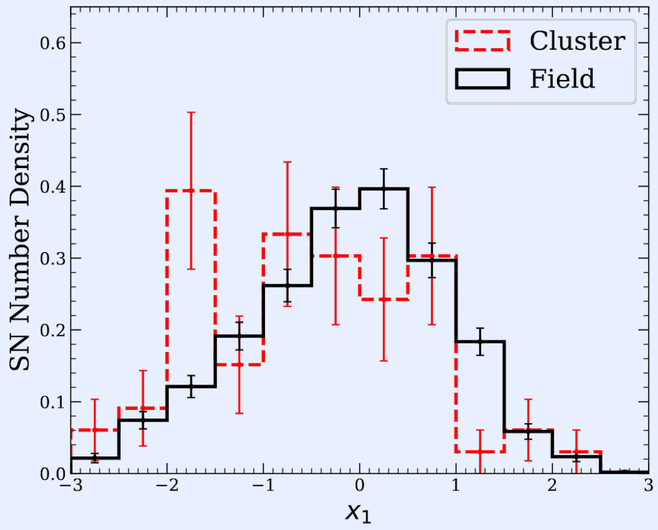
→ Low star formation rate and old/massive galaxies in clusters w.r.t. field galaxies

Impact of cluster environment on SNe Ia: previous works

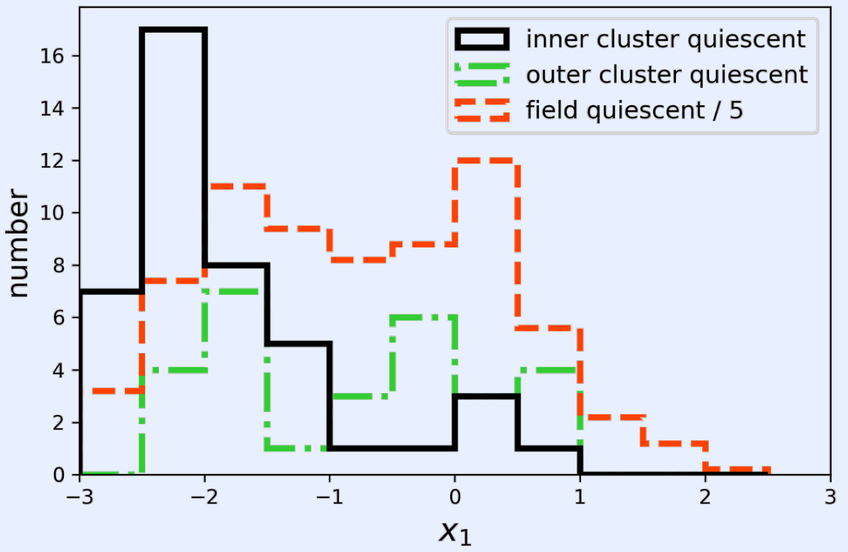
Xavier et al. 2013



Toy et al. 2023



Larison et al. 2024



- 48 SNe Ia in clusters in 2013 (SDSS-II), 66 in 2023 (DES), and 102 in 2024 (ZTF and ATLAS)
- Significant difference between the stretch distributions of SNe Ia inside clusters and in the field
- No difference observed between the color distributions in all previous studies

ZTF SN Ia DR2

3 filters (g, r, i)

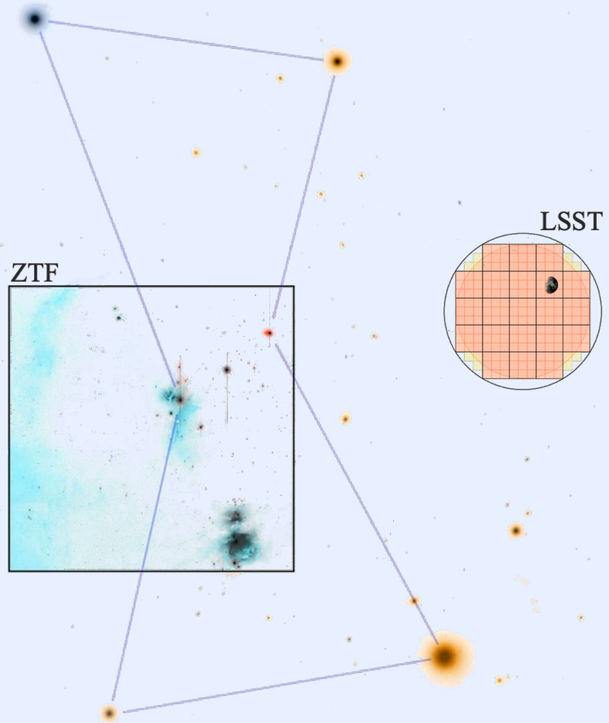
FoV **47** deg²

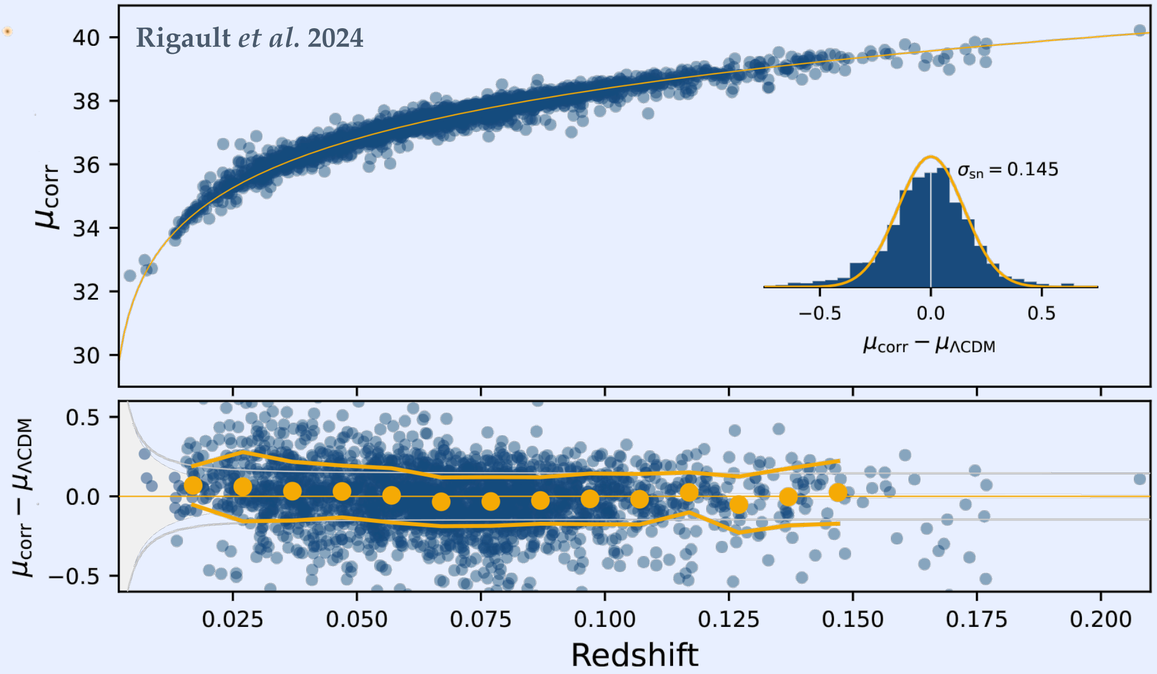
surveys **3750** deg²/h

20.5 mag 5 σ depth

1 arcsec/pixel

dedicated spectroscopy



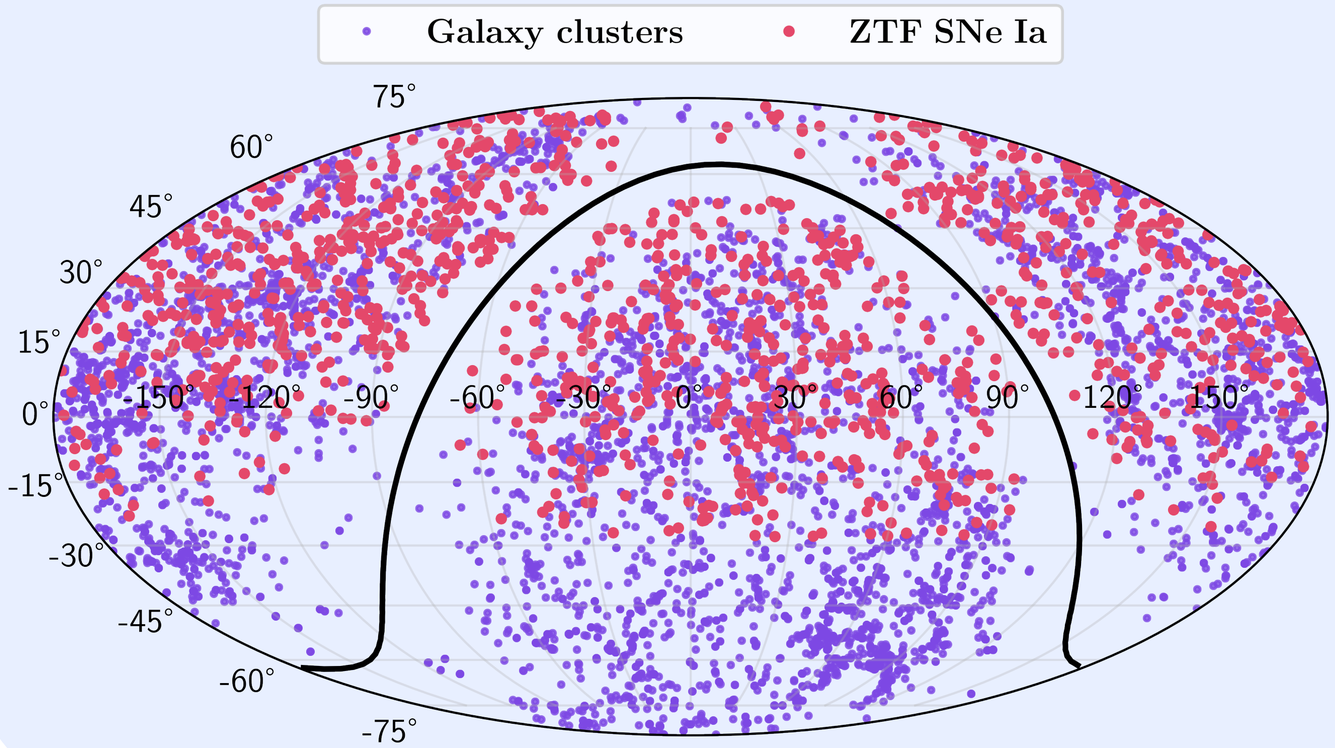


- Observation of the transient northern sky for 2.5 years
- 3628 SNe Ia - 72% with cosmological quality - 21 papers in an A&A special issue
- See talks from Mahmoud, Dylan, Chloé, Constance, Marie

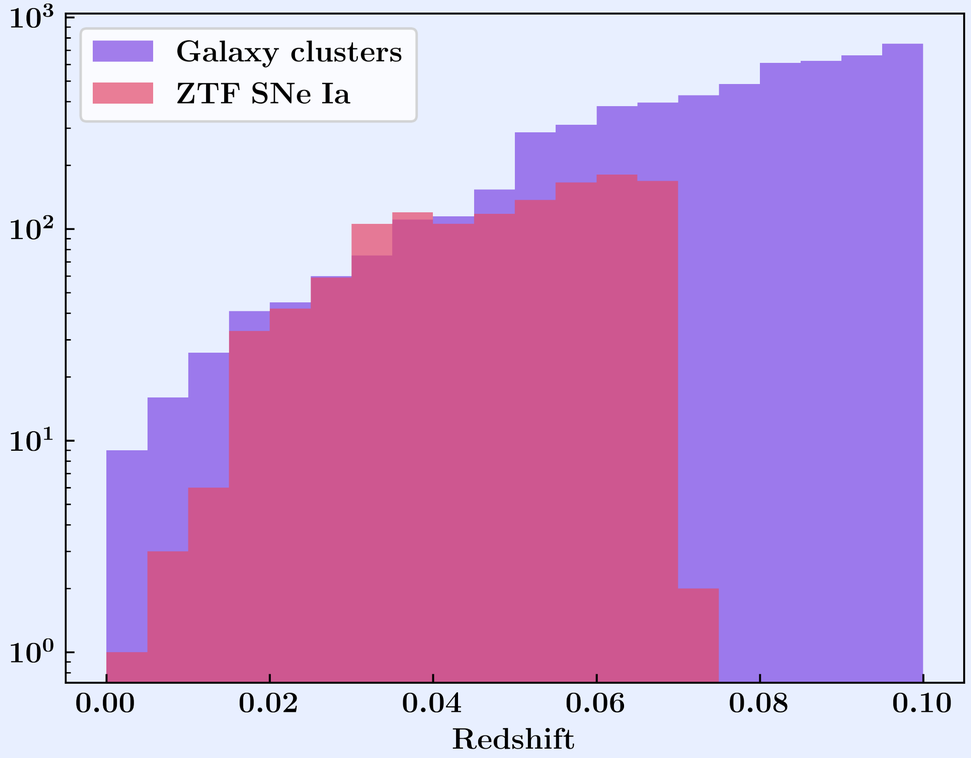
Selection of SNe Ia and clusters for our samples

Sne Ia: ZTF catalog -- 1249 SNe Ia at $0 < z < 0.07$, $-3 < x_1 < 3$, and $-0.3 < c < 0.3$

Clusters: MCXC, eRASS -- detected in X-ray with ROSAT and SRG/eROSITA
Planck, SPT, ACT — detected in SZ from space and ground
WHL15 -- detected in optical/IR from 2MASS, WISE, and SuperCOSMOS
} 5586 clusters at $z < 0.1$



Redshift distributions



Stretch VS relative distance to nearest cluster

Matching procedure:

- Find the nearest cluster for each ZTF SN
  2D distance + member probability based on z :

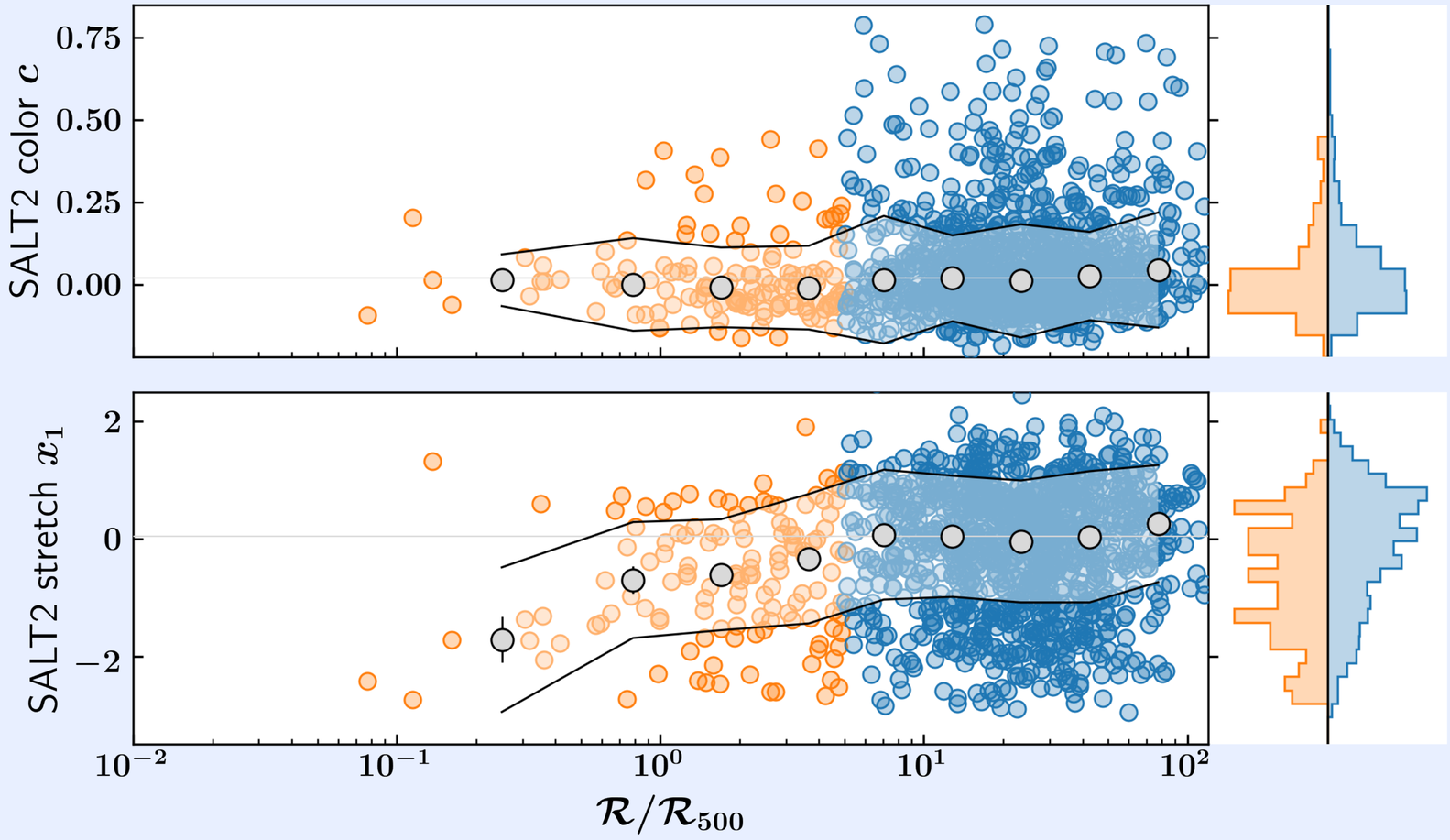
$$p = \frac{1}{\sqrt{2\pi\,(\sigma_{SN}^2 + \sigma_{Cl}^2)}} \int_{-z_d}^{+z_d} \exp\left[-\frac{(z - [z_{SN} - z_{Cl}])^2}{2(\sigma_{SN}^2 + \sigma_{Cl}^2)}\right] dz$$

with $z_d = 3 \times \sigma_{R_{500}}$ *(velocity dispersion at R_{500})*

Keep matches with $p > 90\,\%$

- Normalize 2D distance by the characteristic radius of the nearest cluster

- SNe Ia at $R/R_{500} < 5$ are inside clusters
  (129 SNe Ia)



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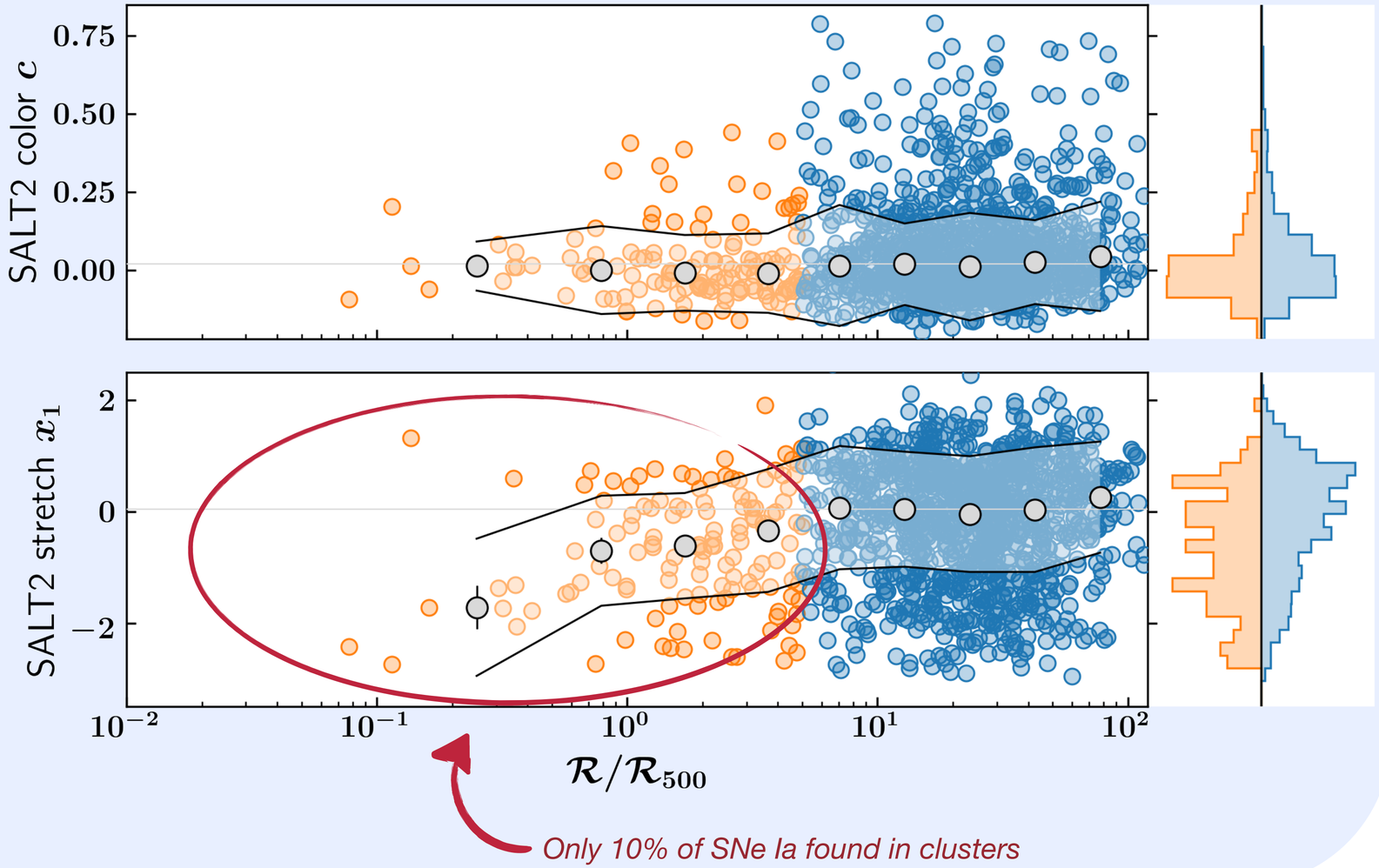

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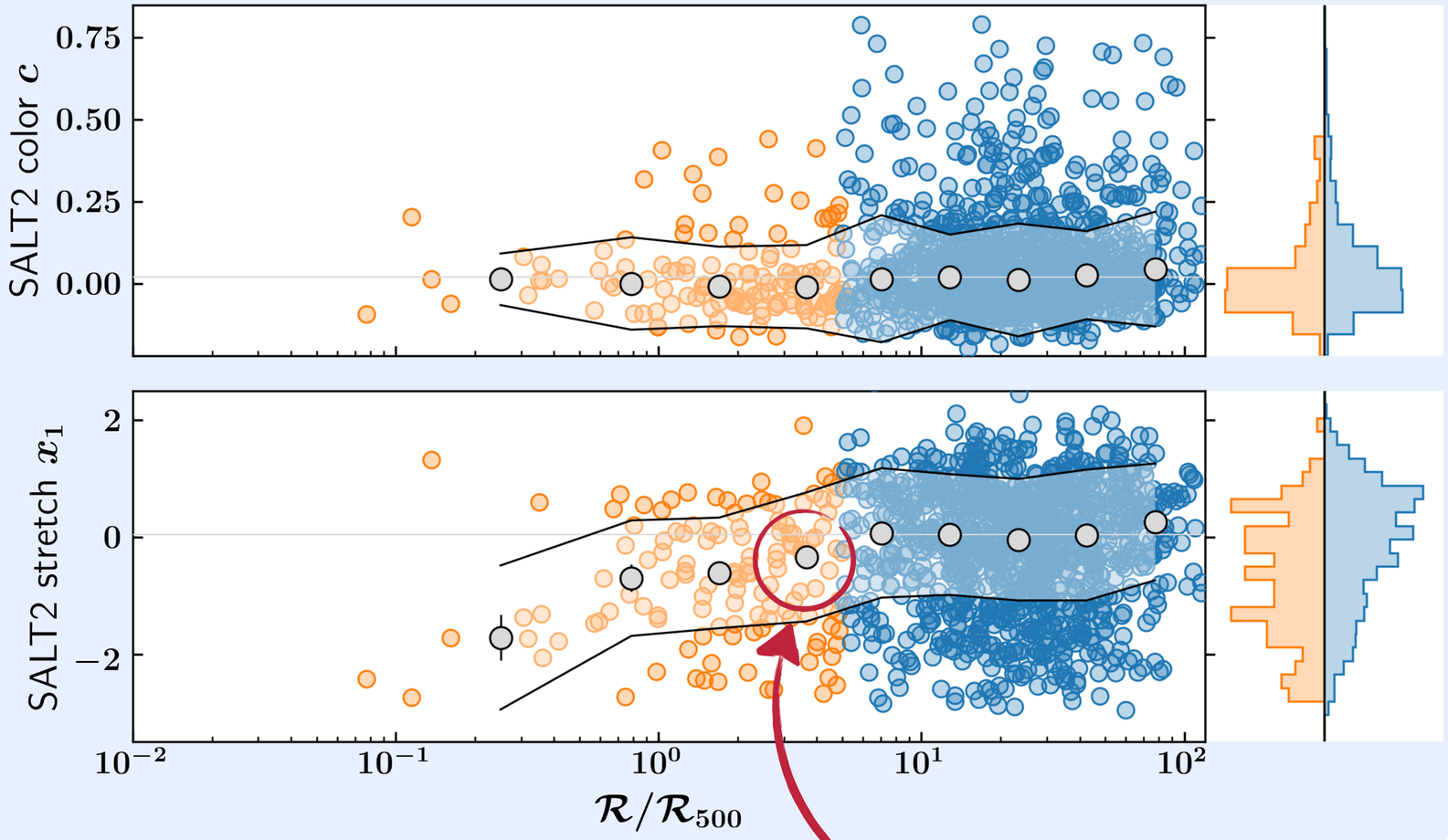

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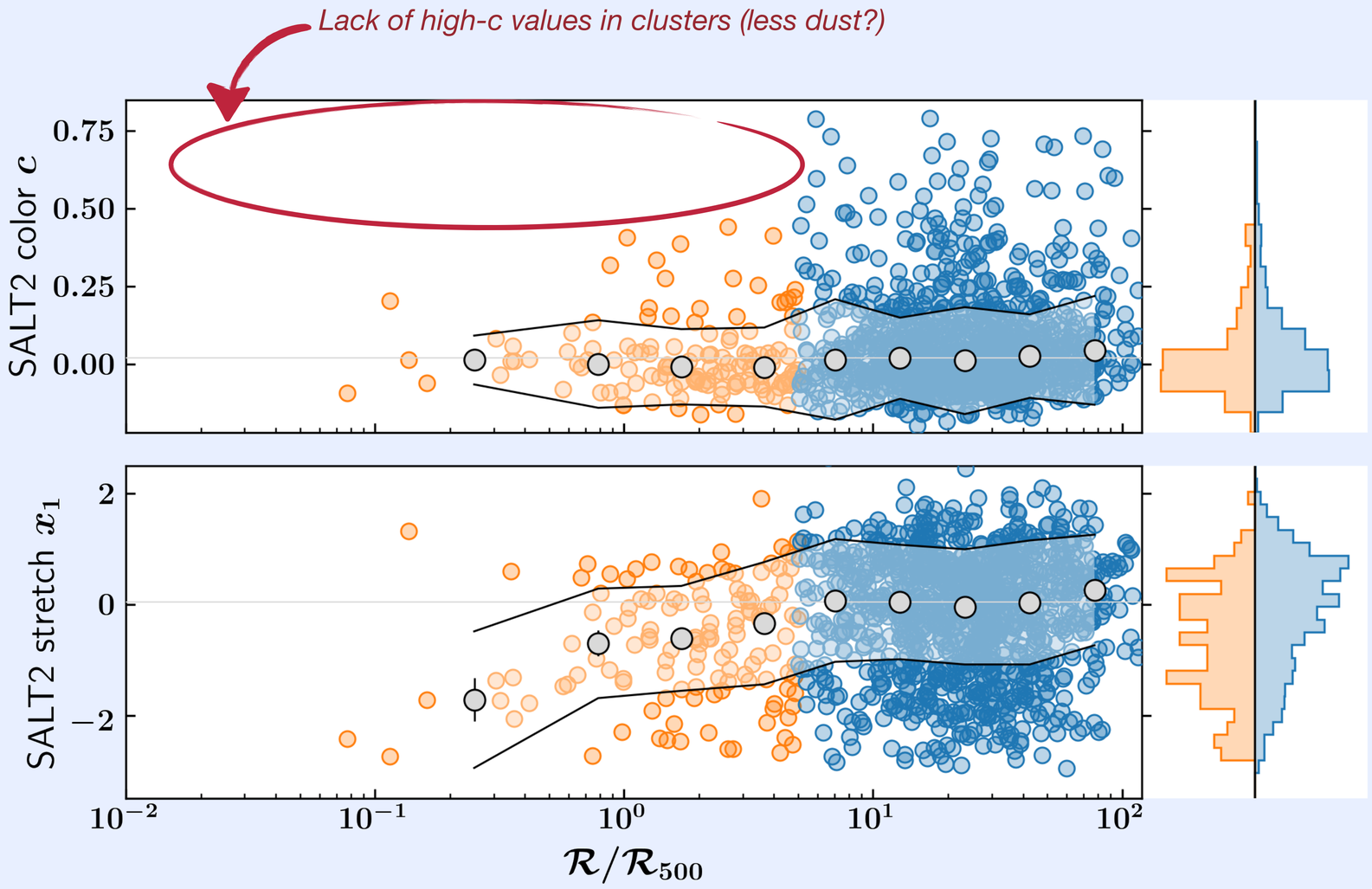


Stretch distribution model

Model: double Gaussian distribution with amplitude ratio varying with distance to nearest detected cluster

$$X_1(z\,|\,\frac{\mathscr{R}}{\mathscr{R}_{500}}, M_*) = \underbrace{\xi(z, \frac{\mathscr{R}}{\mathscr{R}_{500}}) \times \mathcal{N}(\mu_h(M_*), \sigma_h^2)}_{\textbf{young}} + \underbrace{(1 - \xi(z, \frac{\mathscr{R}}{\mathscr{R}_{500}})) \times [a \times \mathcal{N}(\mu_h(M_*), \sigma_h^2) + (1-a) \times \mathcal{N}(\mu_l(M_*), \sigma_l^2)]}_{\textbf{old}}$$

with $\xi(z, \frac{\mathscr{R}}{\mathscr{R}_{500}}) = \left[1 - \left(1 + \frac{\mathscr{R}/\mathscr{R}_{500}}{R_{cut}}\right)^{-\gamma}\right] \times \delta(z)$ using same $\delta(z)$ as in previous works *(Rigault+20, Nicolas+21)*

and $\mu_{h,l}(M_*) = \mu_{h,l}^0 + s \times (M_* - 10)$ are linear relations depending on host mass *(Ginolin+24)*

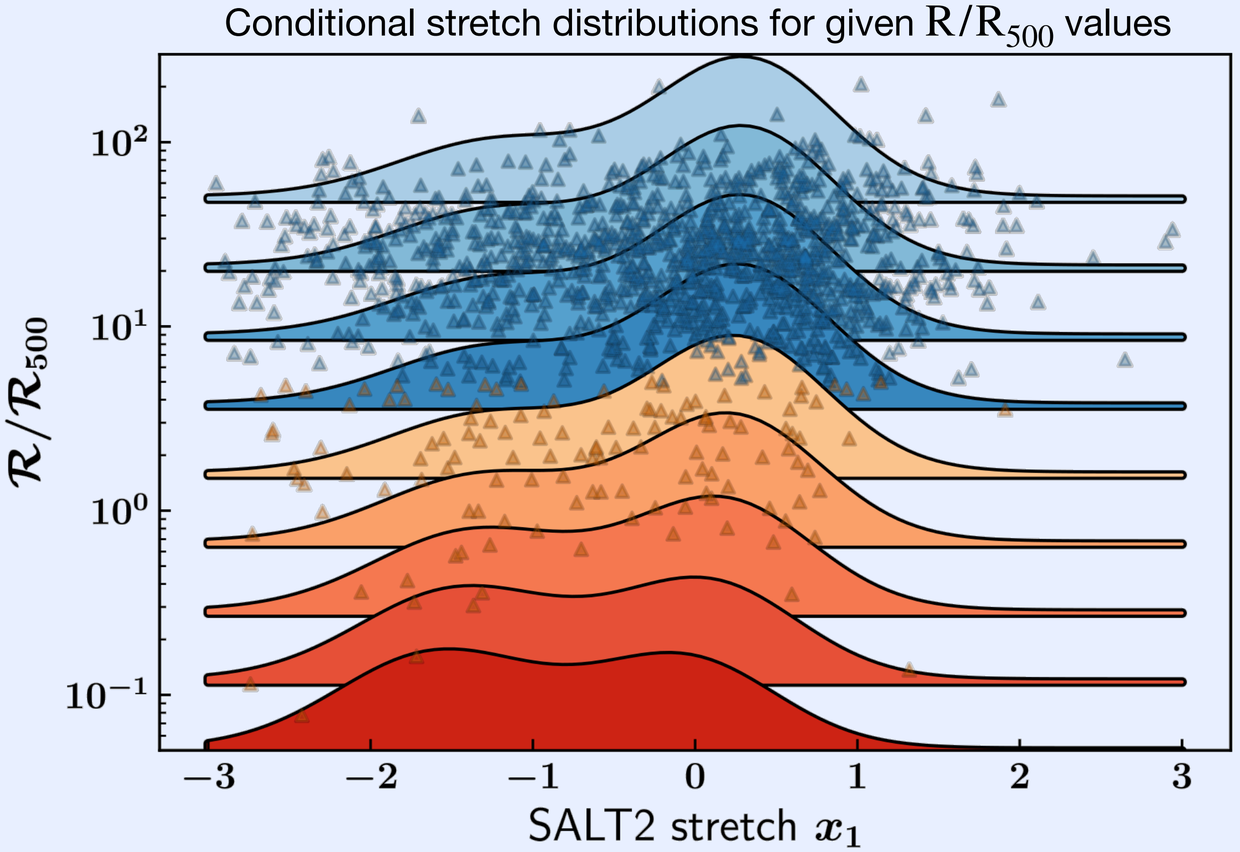
Method: maximise $\prod_i x_1^i(z^i\,|\,\frac{R^i}{R_{500}^i}, M_*^i)$ taking into account measurement uncertainties on each data point Δx_1^i

(In practice, maximise $\sum_i \log[x_1^i(z^i\,|\,\frac{R^i}{R_{500}^i}, M_*^i)]$)

use MCMC analysis to find best-fit values and uncertainties of the 8 free parameters $(\mu_h^0, \sigma_h, \mu_l^0, \sigma_l, s, a, R_{cut}, \gamma)$

Results of the fitting procedure

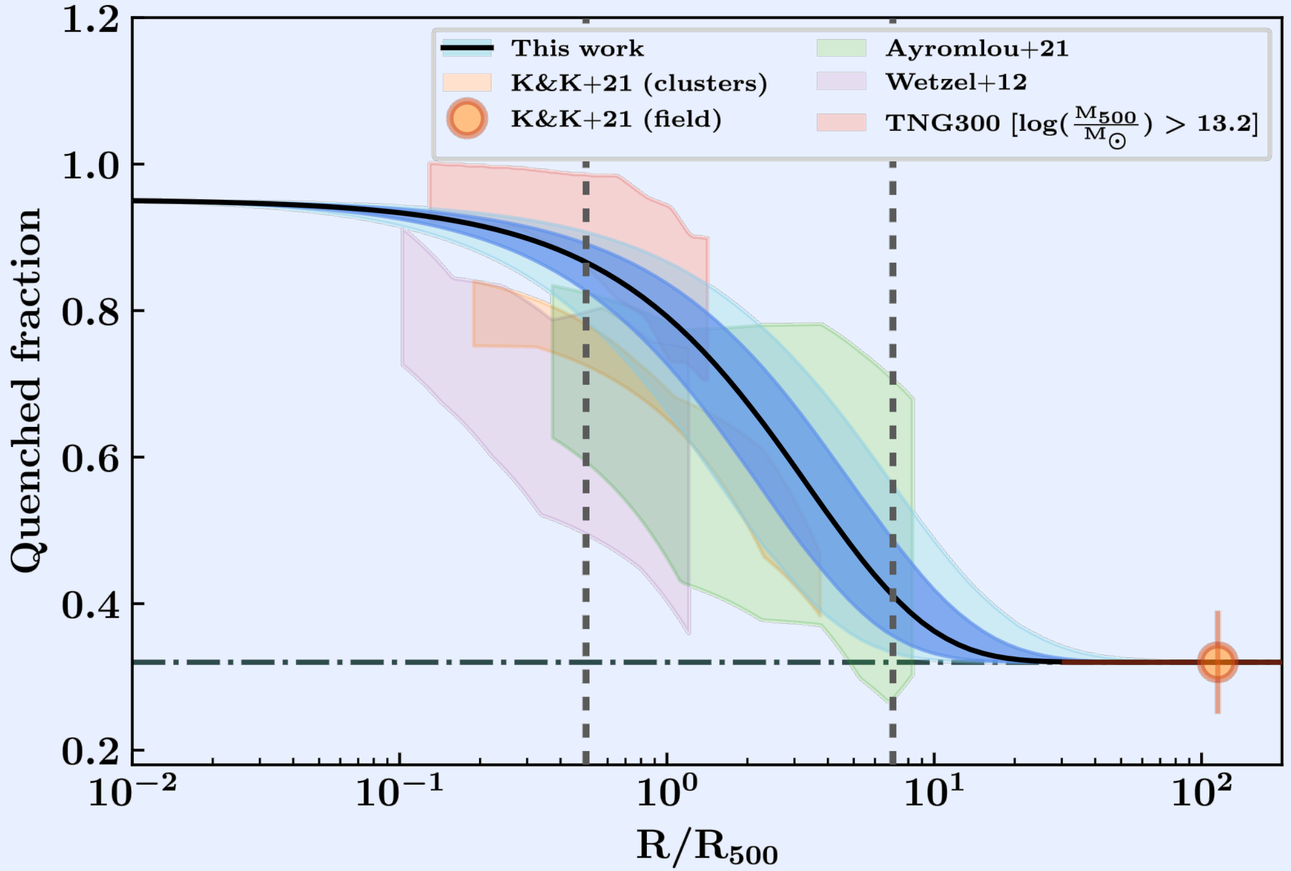
- MCMC convergence: Gelmen-Rubin test + autocorrelation time
- Only select independent samples after 20% burn-in cut-off
- Significant evolution of the amplitude of the low-stretch mode with cluster radius
- Null-test: no radial dependence. Is it only a host-mass effect?
  $\Delta\mathrm{AIC} = -10.2$ → strongly disfavored



Variation of the fraction of quenched galaxies

Method: - assume that the stretch distribution in the core of clusters corresponds to $q = 0.95$ *(BCGs are all red and dead)* and that it corresponds to $q_{\rm field}$ far from clusters

- compute $q(R/R_{500})$ from modeled fraction of old SNe Ia



Galaxy is quenched if $\log(sSFR[\mathrm{yr}^{-1}]) < -10.75$

→ We find results that are fully compatible with independent measurements of $q(R/R_{500})$ based on Hα line or 4000 $\mathring{A}$ break fits

Conclusions

Summary:

- ZTF DR2 data: a new sample of more than 3500 SNe Ia to understand systematics and perform cosmological analyses
- First analysis of the continuous evolution of SN Ia stretch distribution with cluster-centric radius

Conclusions:

- Significant evolution of the amplitude ratio of the two modes in the stretch distribution with R/R_{500}
- Age of the host galaxy plays a fundamental role *(in addition to host mass)*

SN Ia Cosmology

New systematic effect to take into account if SNe Ia from targeted searches are included in the Hubble diagram

Cluster evolution

New estimator of the evolution of the fraction of quenched galaxies with cluster-centric radius

Broken alpha