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

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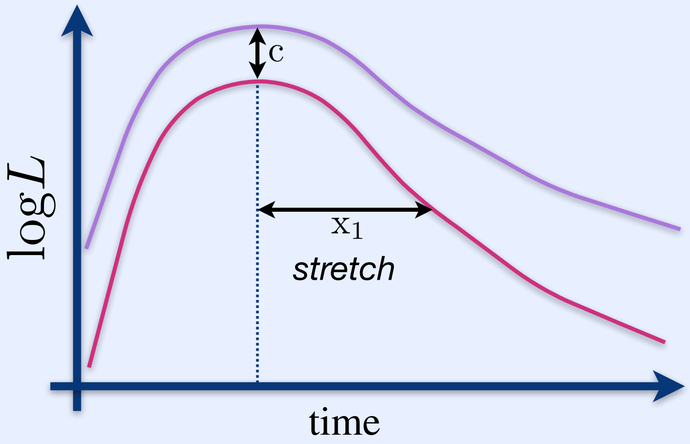
In collaboration with: the ZTF collaboration

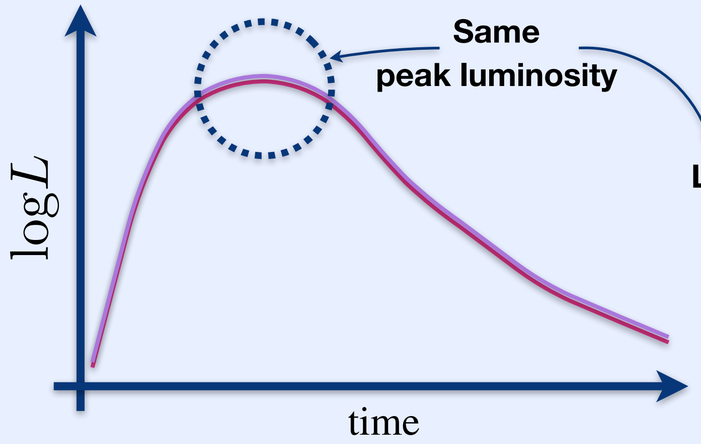
Rubin LSST-France, CC-IN2P3 Lyon, 13-15/12/2023

Cosmology with type Ia supernovae

Measure SN Ia light curve



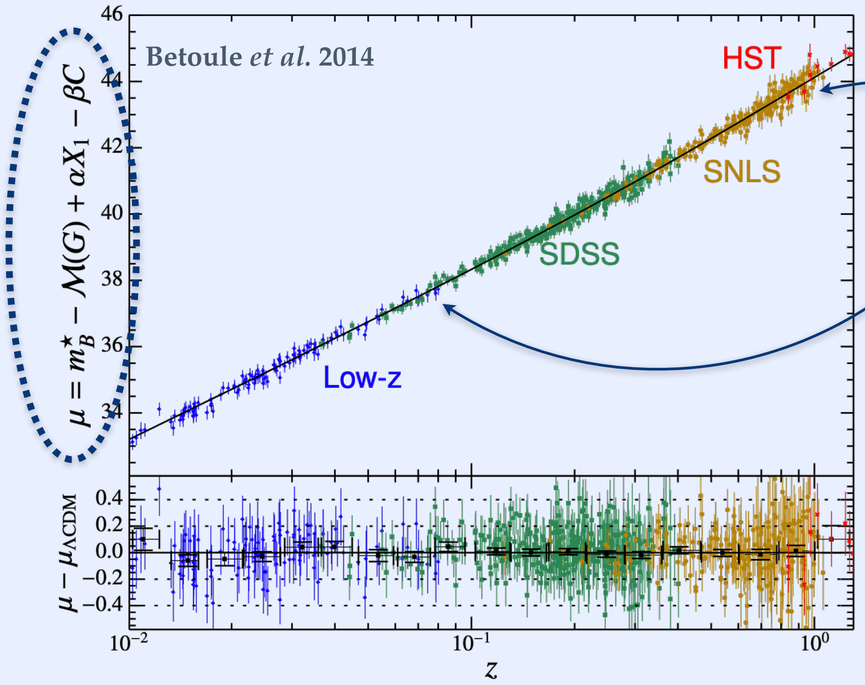
Standardization



Same peak luminosity

Luminosity distance $F = \frac{L}{4\pi D_L^2}$

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

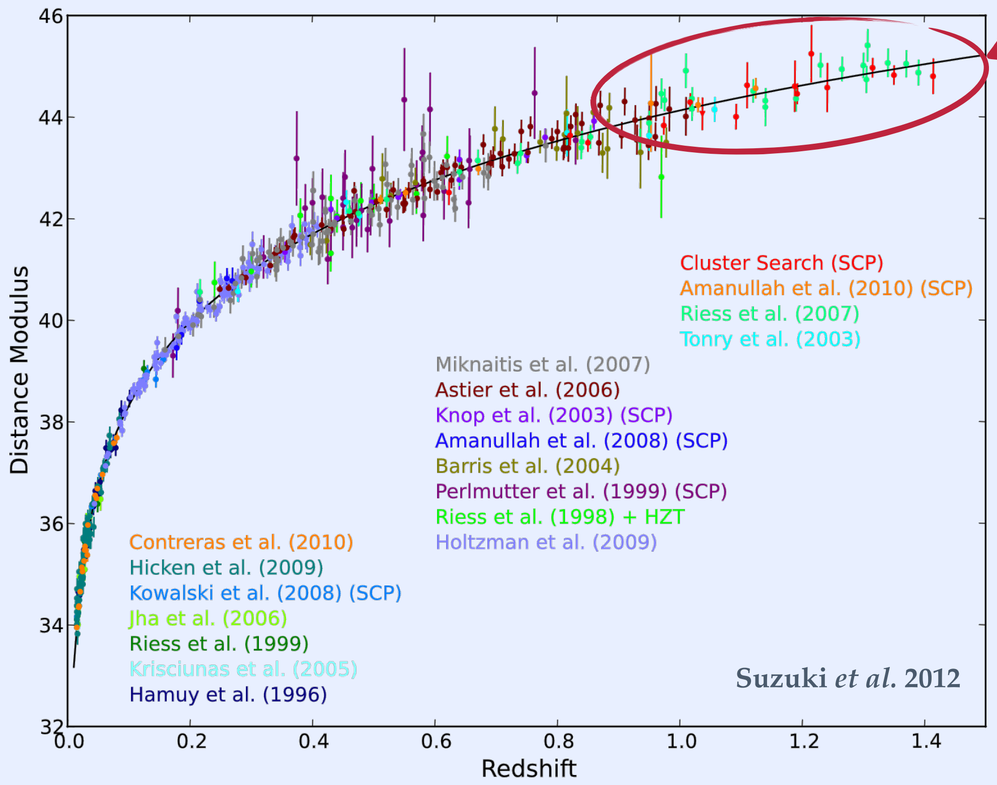


Most leverage on cosmological parameters from high-z SNe Ia

Cosmological model

Starting point of the analysis

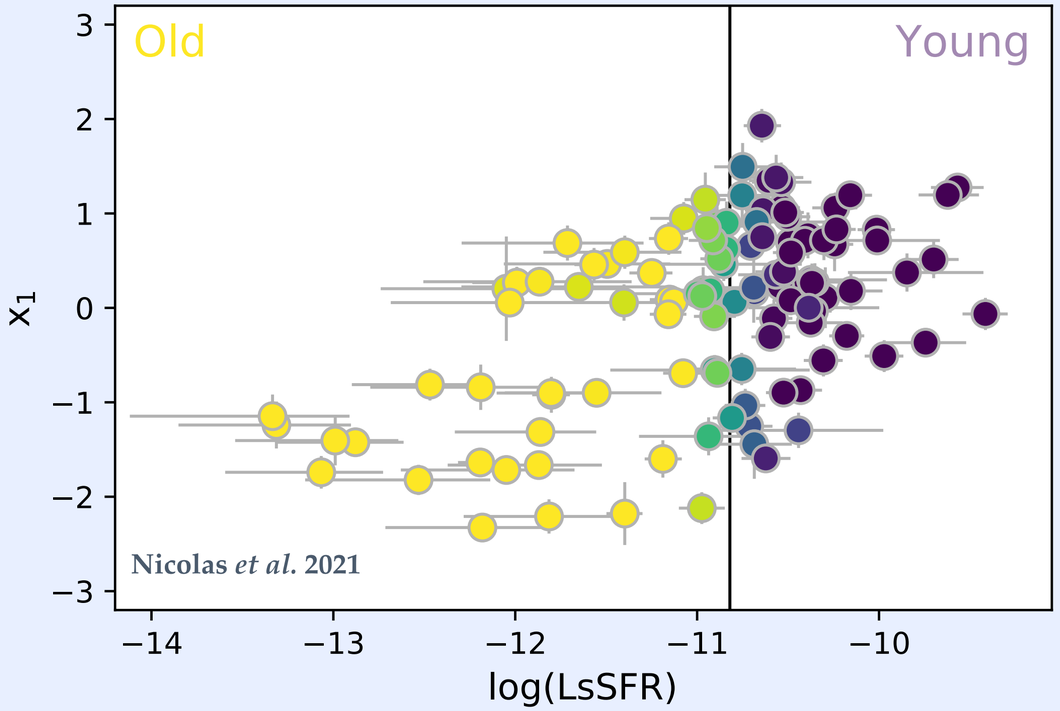
- HST Cluster Supernova Survey: search for SNe Ia in 25 distant galaxy clusters to maximize detection probability

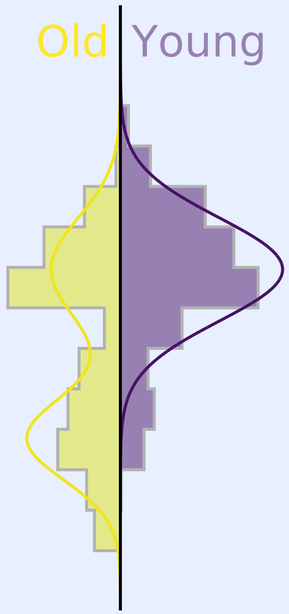


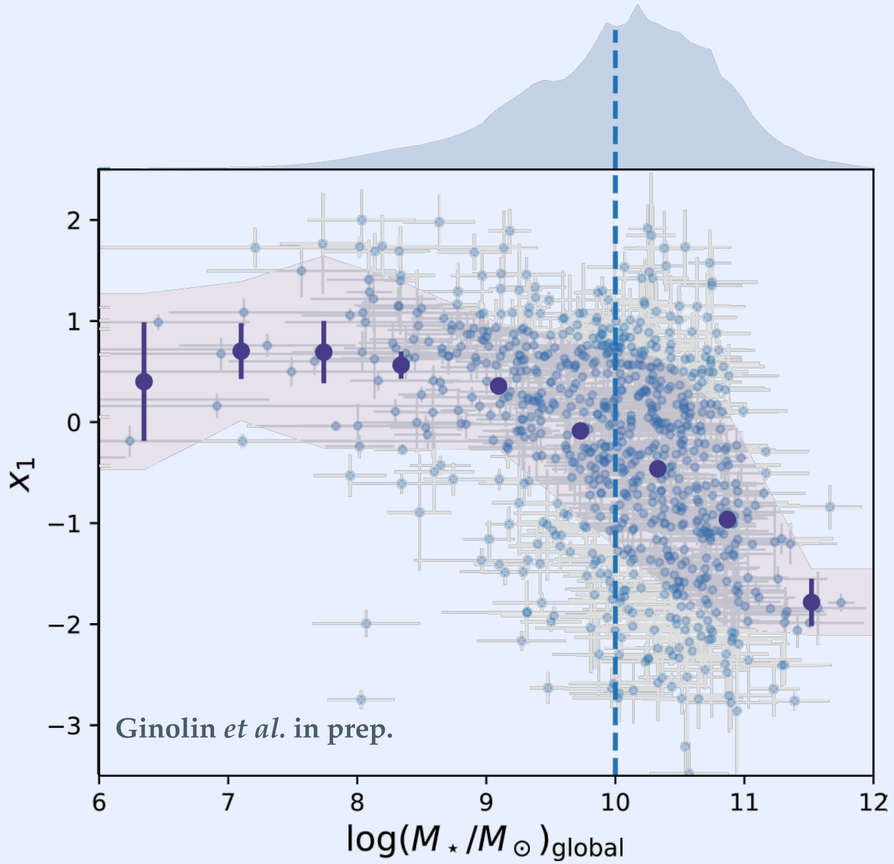
SNe Ia found in clusters
⟶ Better constraints on $w(z)$

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



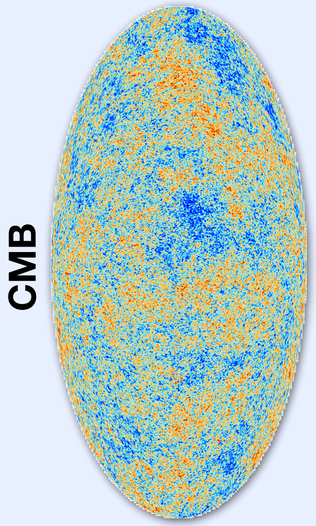




- Stretch distribution depends on star formation rate
- Stretch distribution depends on host mass

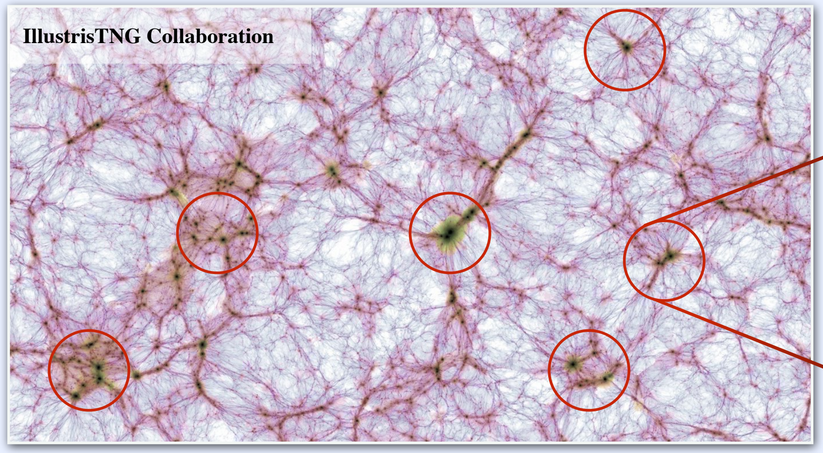
Direct impact on standardisation procedure *(cosmology)*

Galaxy cluster environment

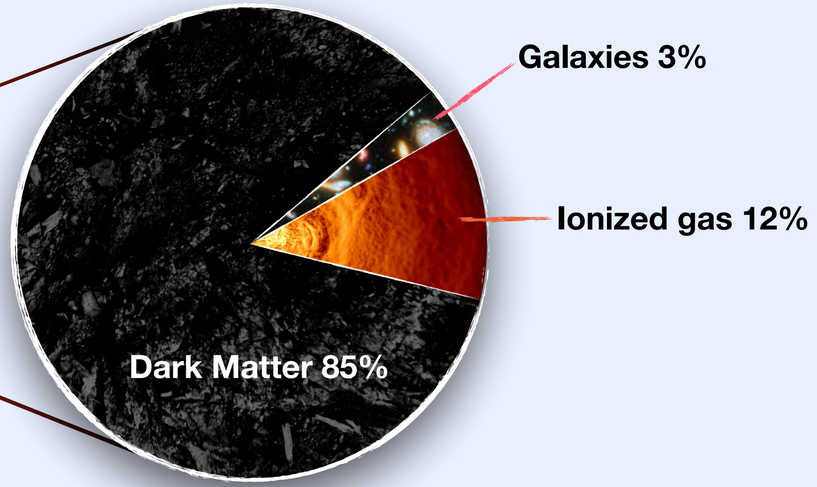


Structure growth

Large scale structures



Galaxy cluster



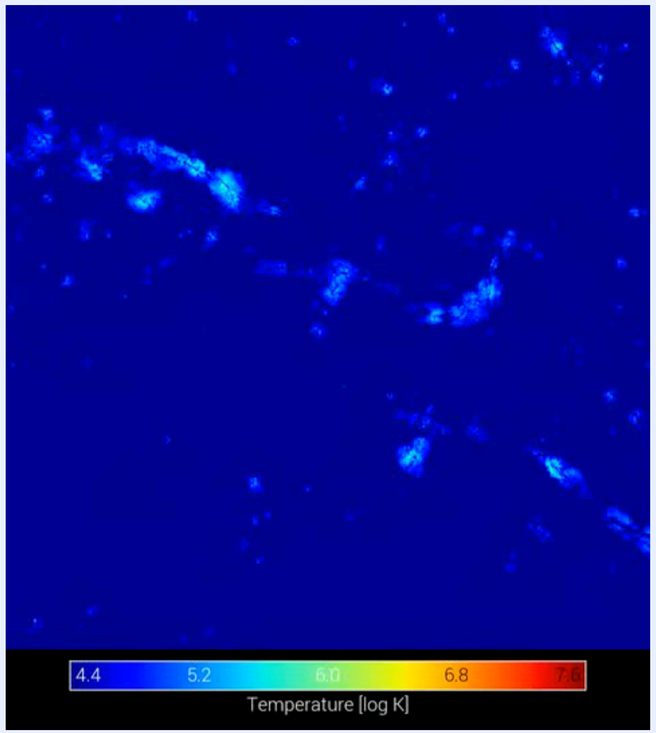
- Culmination of the large scale structure formation process
- Largest gravitationally bound structures in the Universe
- Formed through slow accretion of surrounding material (linear) and merger events / virialization / feedback processes (non-linear)

Galaxy cluster environment

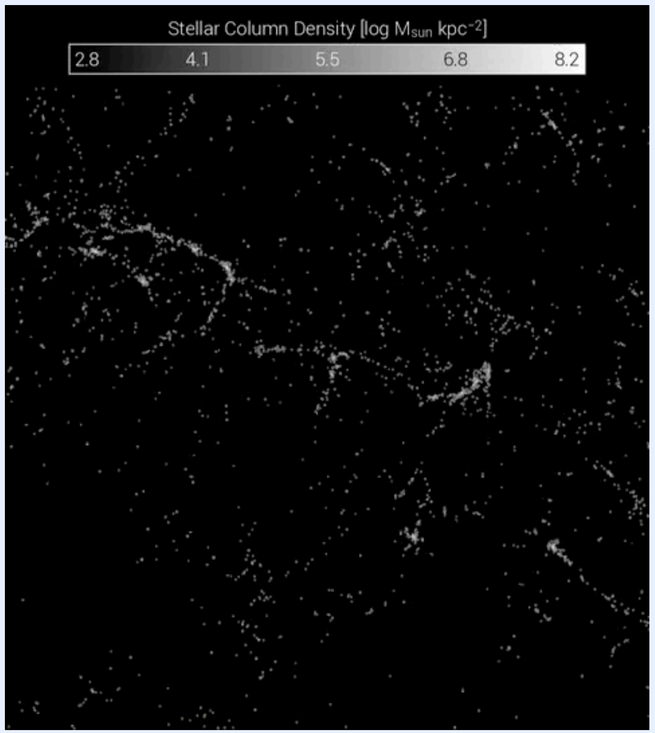
Hierarchical formation process

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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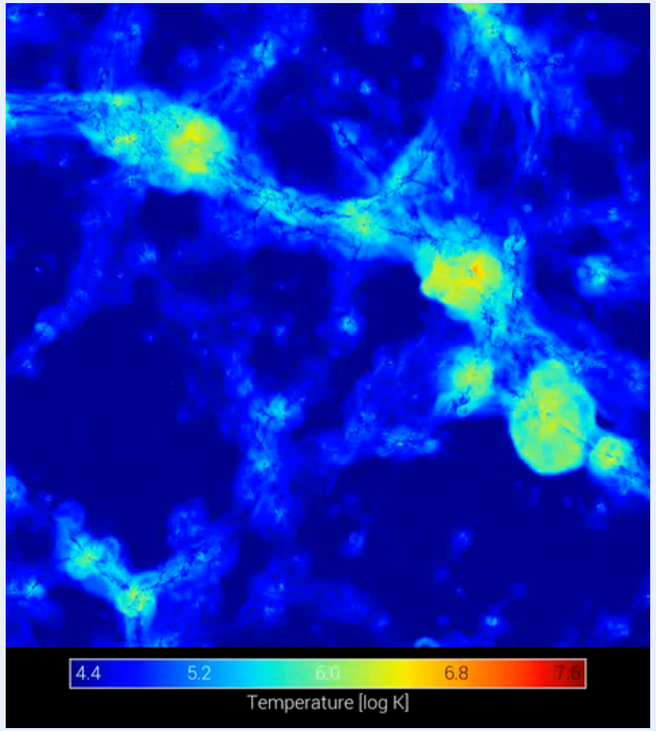

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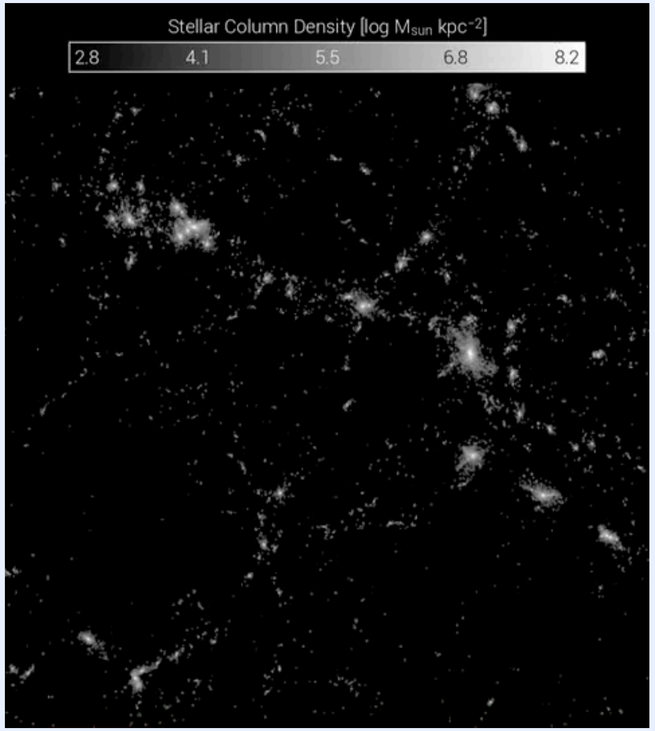

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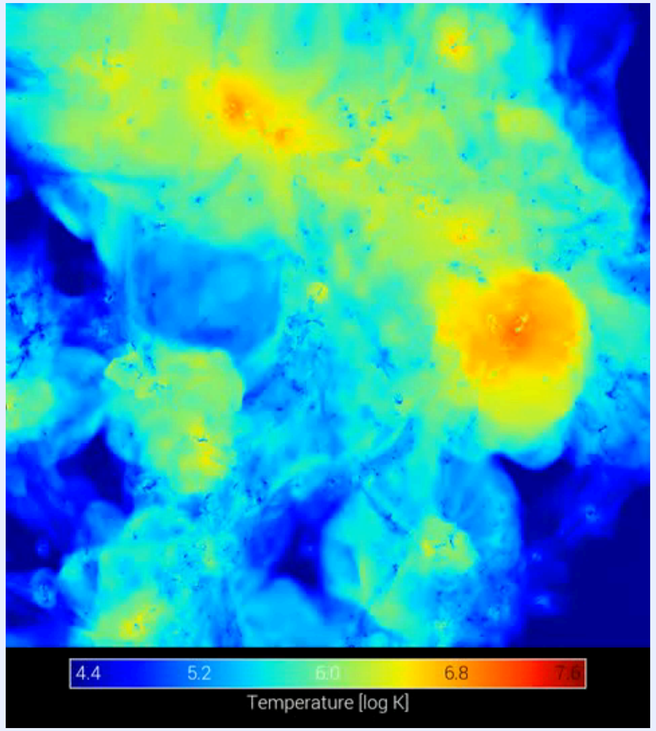
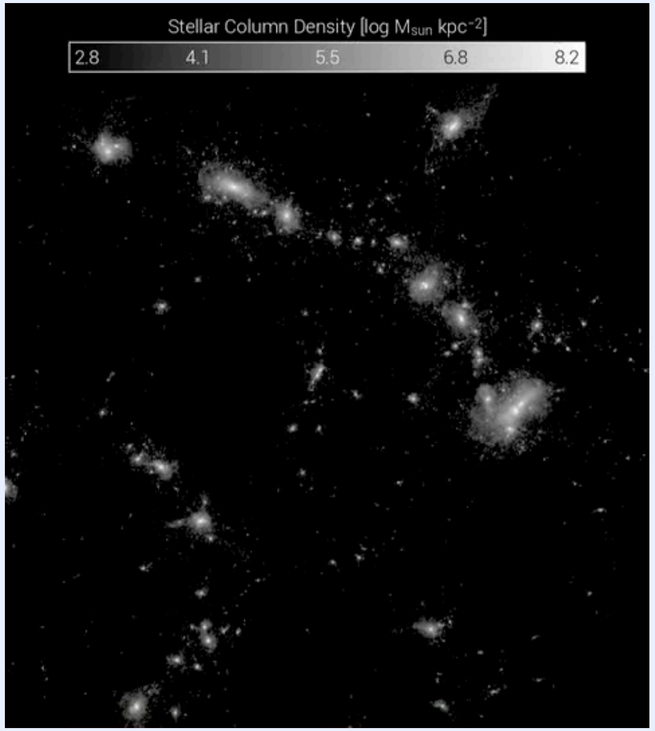


Galaxies



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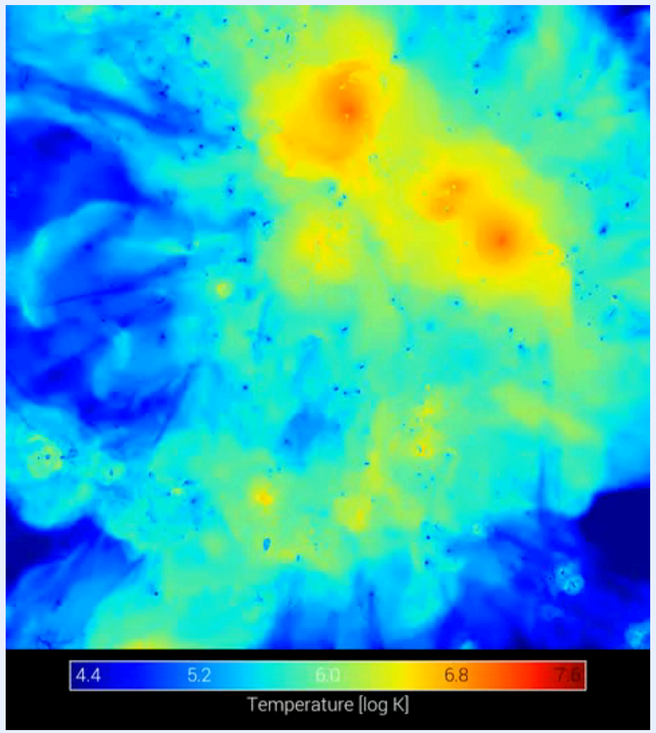

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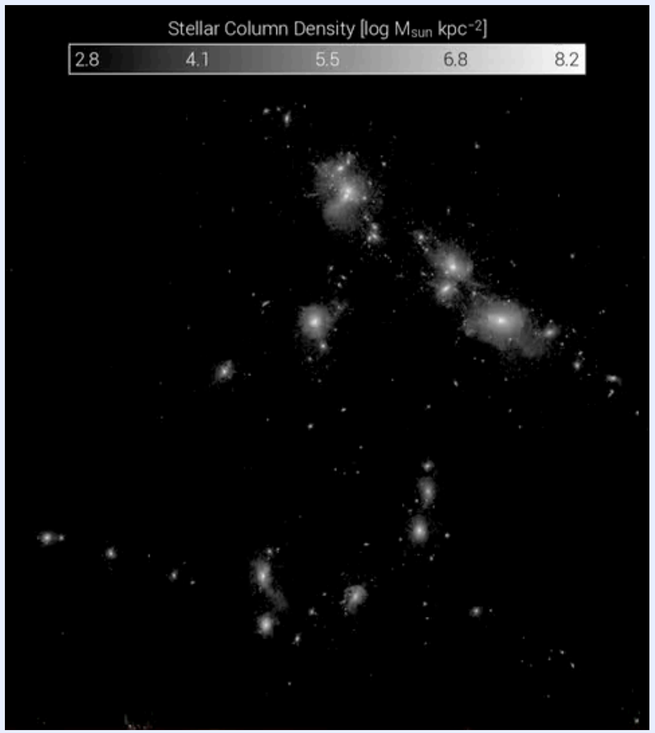

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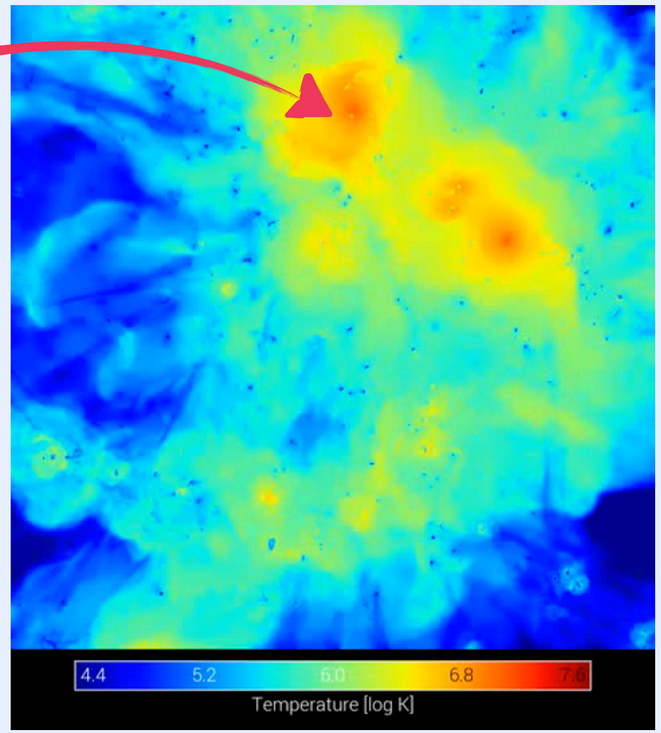
Gas temperature

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



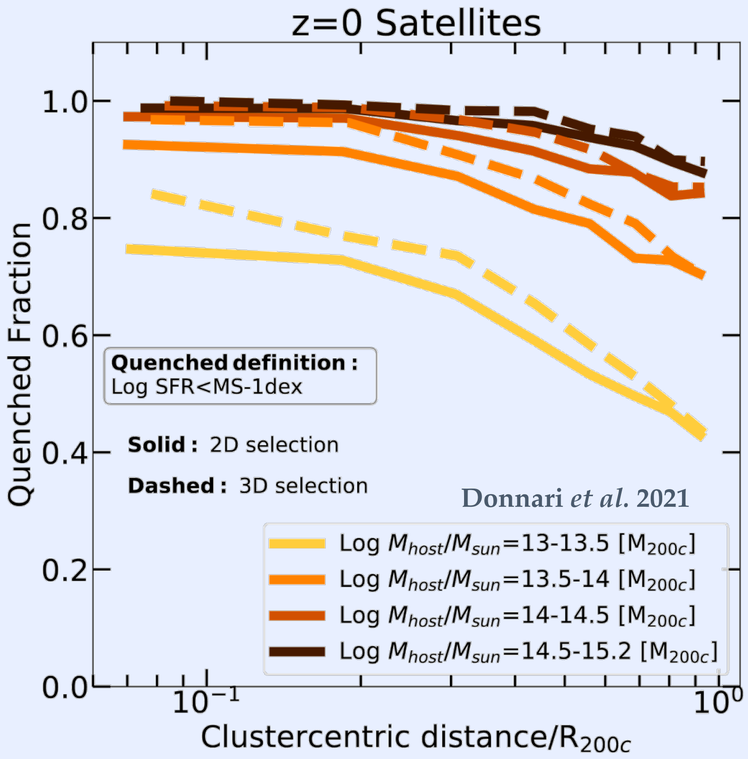
Galaxies

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

→ Old and massive galaxies in a high-temperature environment

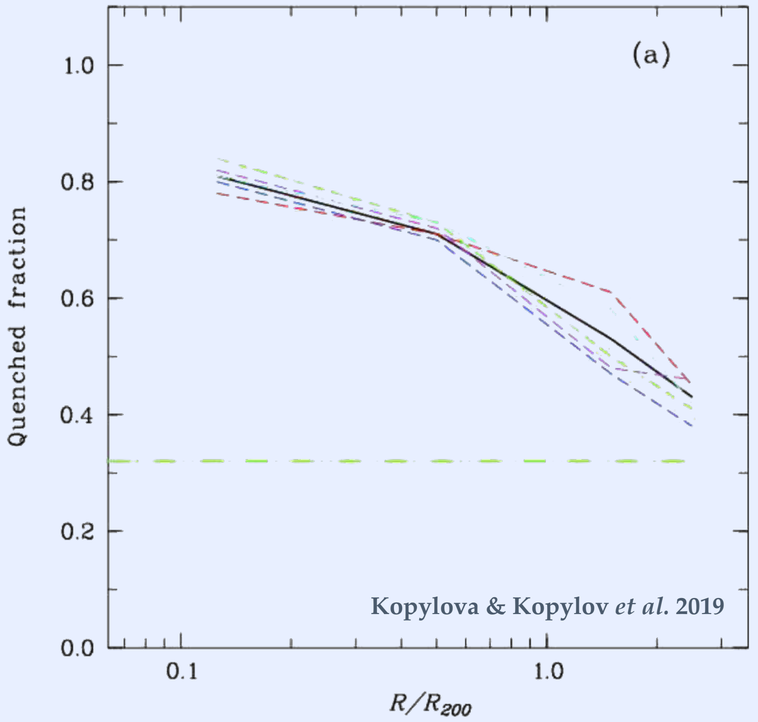
Cluster galaxies: age and star formation rate

Simulation



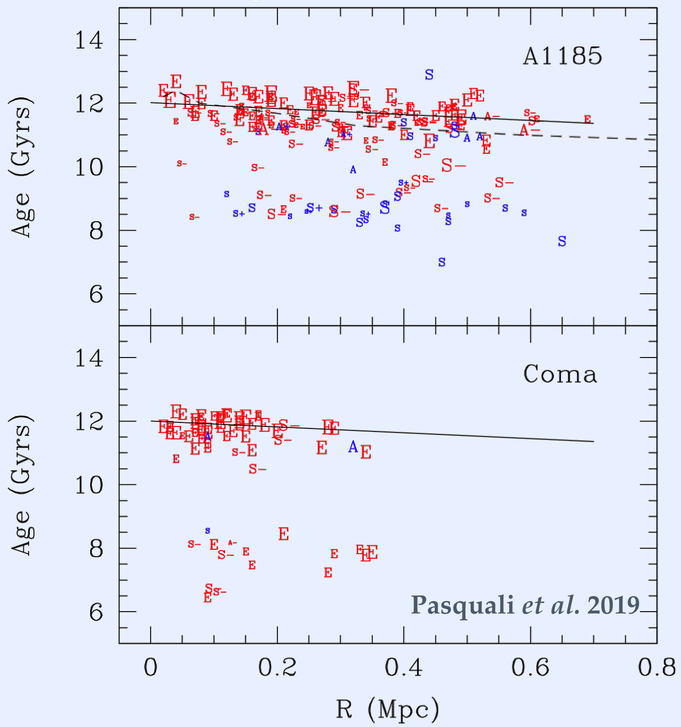
Data (SFR)

Based on SDSS data



Data (age)

Targeted observations

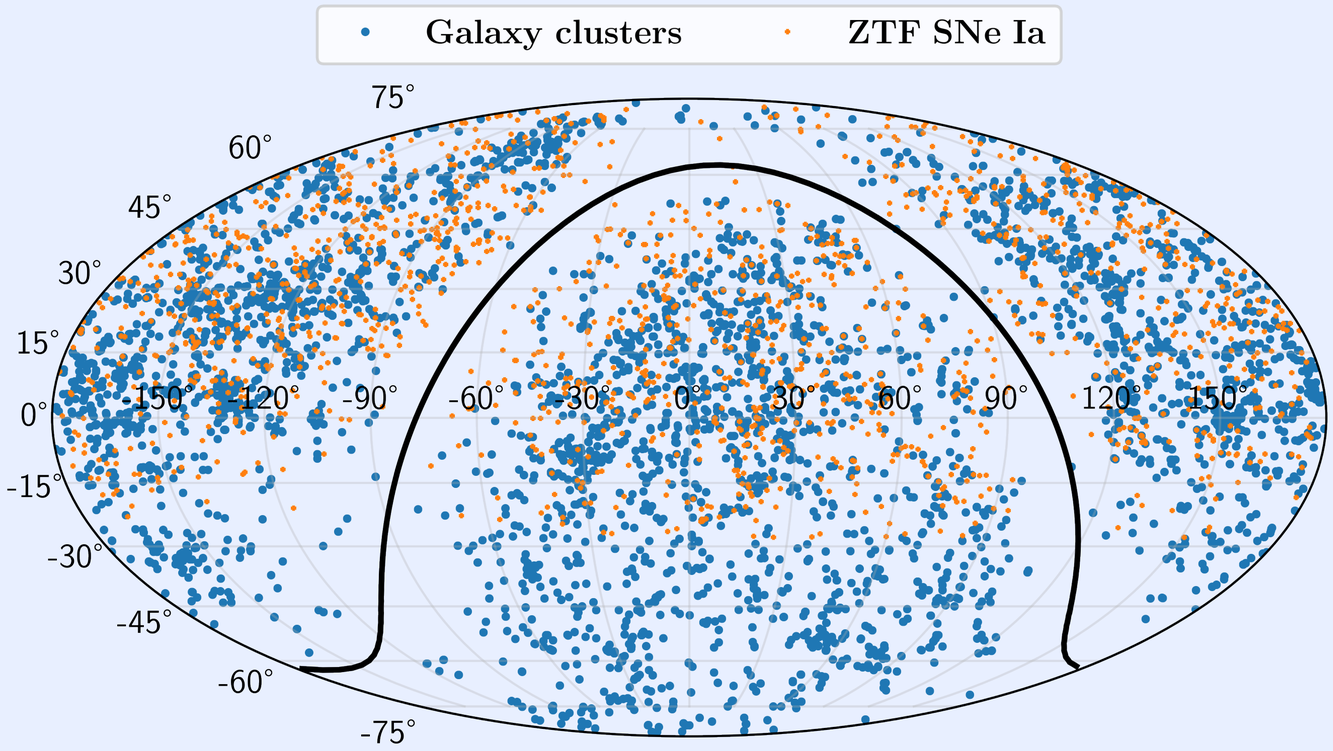


→ Low star formation rate and old/massive galaxies in clusters w.r.t. field galaxies

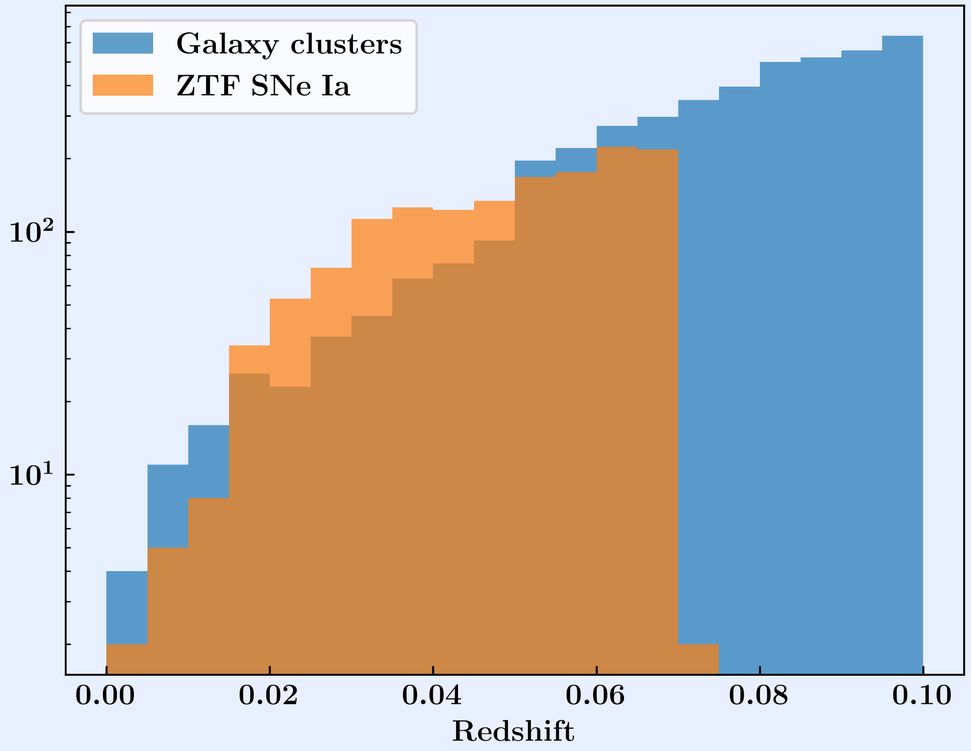
Selection of SNe Ia and clusters for our samples

Sne Ia: ZTF catalog -- 1403 SNe Ia at $0 < z < 0.07$, $-3 < x_1 < 3$, and $-0.3 < c < 0.3$

Clusters: MCXC -- detected in X-ray from the ROSAT All Sky Survey
Planck, SPT, ACT — detected in SZ from space and ground
WHL15 -- detected in optical/IR from 2MASS, WISE, and SuperCOSMOS
} 7913 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 :

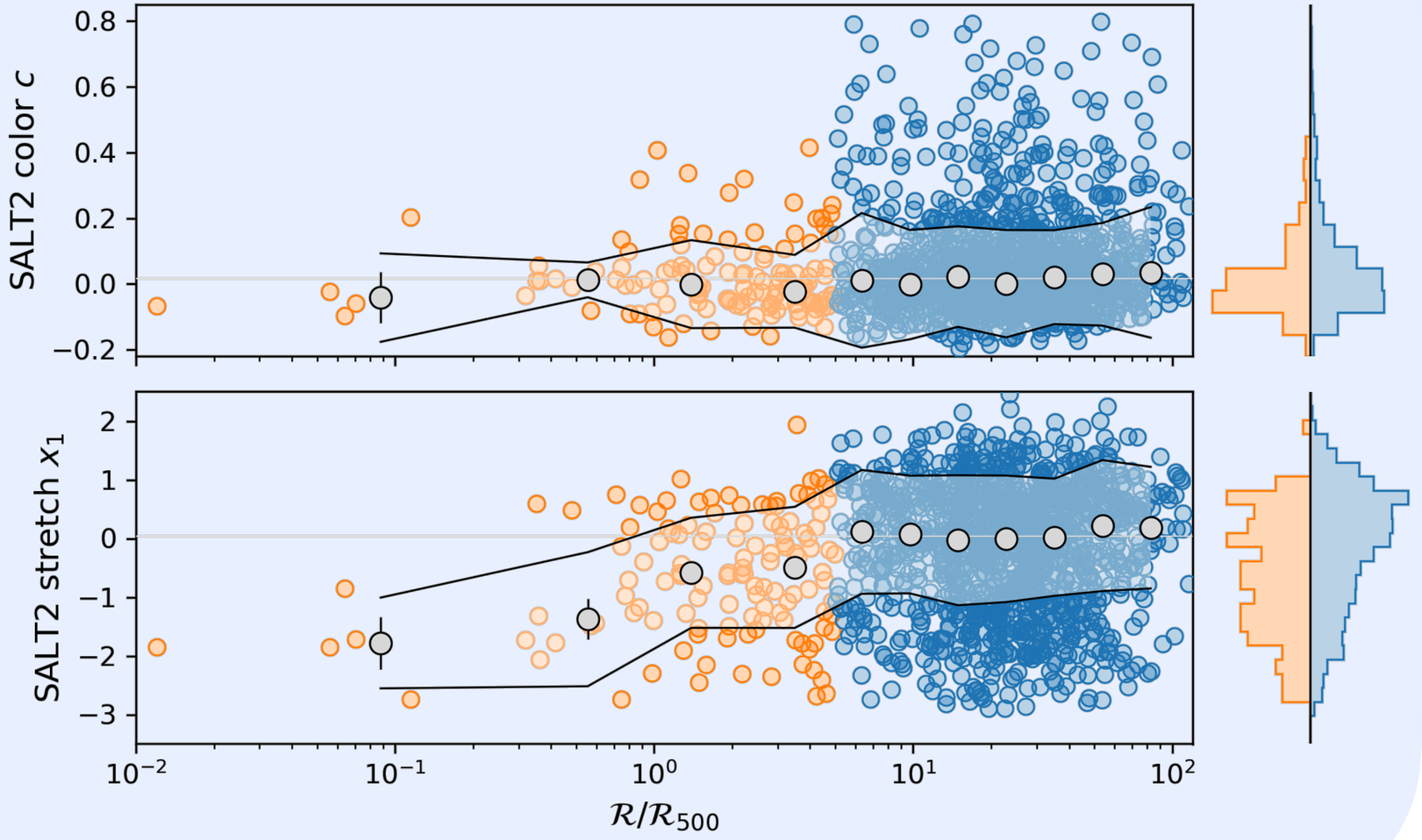
$$p = \frac{1}{\sqrt{2\pi\,(\sigma_{SN}^2 + \sigma_{Cl}^2)}} \int_{-z_d}^{+z_d} \exp\left[-\frac{(z - [z_{SN} - z_{Cl}])^2}{2(\sigma_{SN}^2 + \sigma_{Cl}^2)}\right] dz$$

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 found at $R/R_{500} < 5$ are inside clusters



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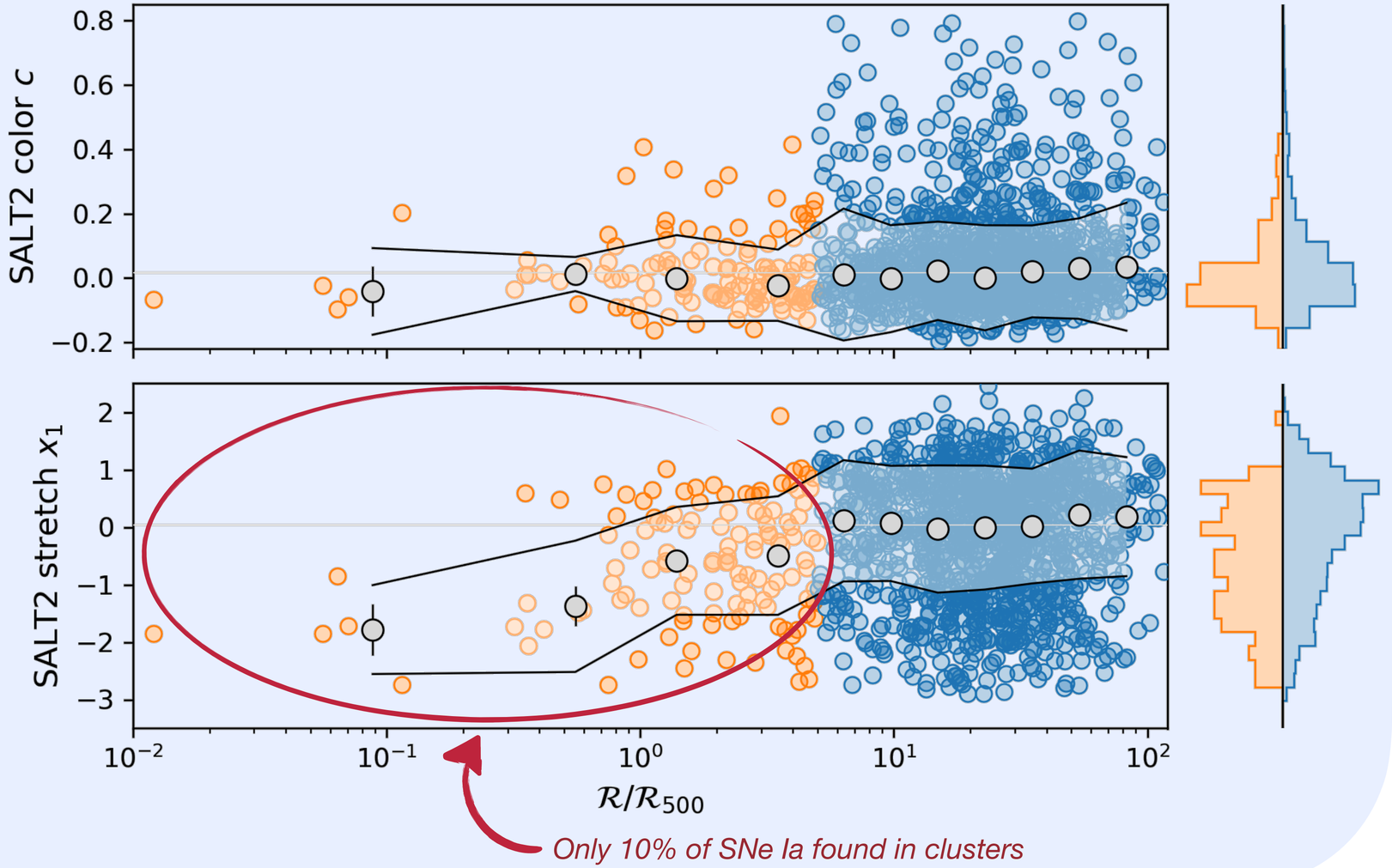

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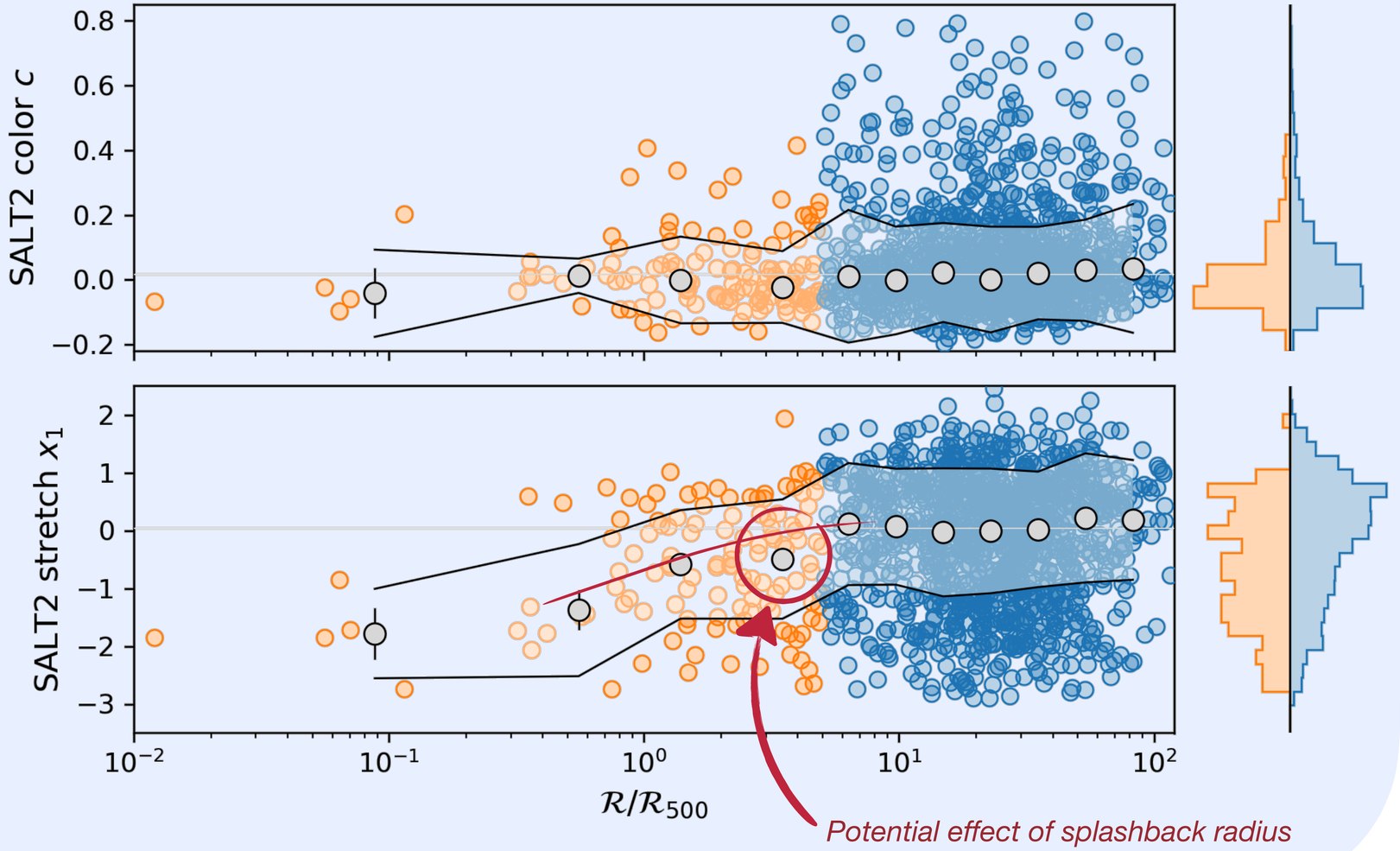


Stretch distribution model

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

$$X_1(z\,|\,\frac{R}{R_{500}}, M_*) = \underbrace{\xi(z, \frac{R}{R_{500}}) \times \mathcal{N}(\mu_1(M_*), \sigma_1^2)}_{\text{young}} + \underbrace{(1 - \xi(z, \frac{R}{R_{500}})) \times [a \times \mathcal{N}(\mu_1(M_*), \sigma_1^2) + (1-a) \times \mathcal{N}(\mu_2(M_*), \sigma_2^2)]}_{\text{old}}$$

with $\xi(z, \frac{R}{R_{500}}) = (1 - B \times (1 + \frac{R}{R_{500}})^{-\gamma}) \times \delta(z)$ using same $\delta(z)$ as in previous works *(Rigault+20, Nicolas+21)*

and $\mu_1(M_*)$ and $\mu_2(M_*)$ are linear relations depending on host mass *(Ginolin+24 in prep.)*

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

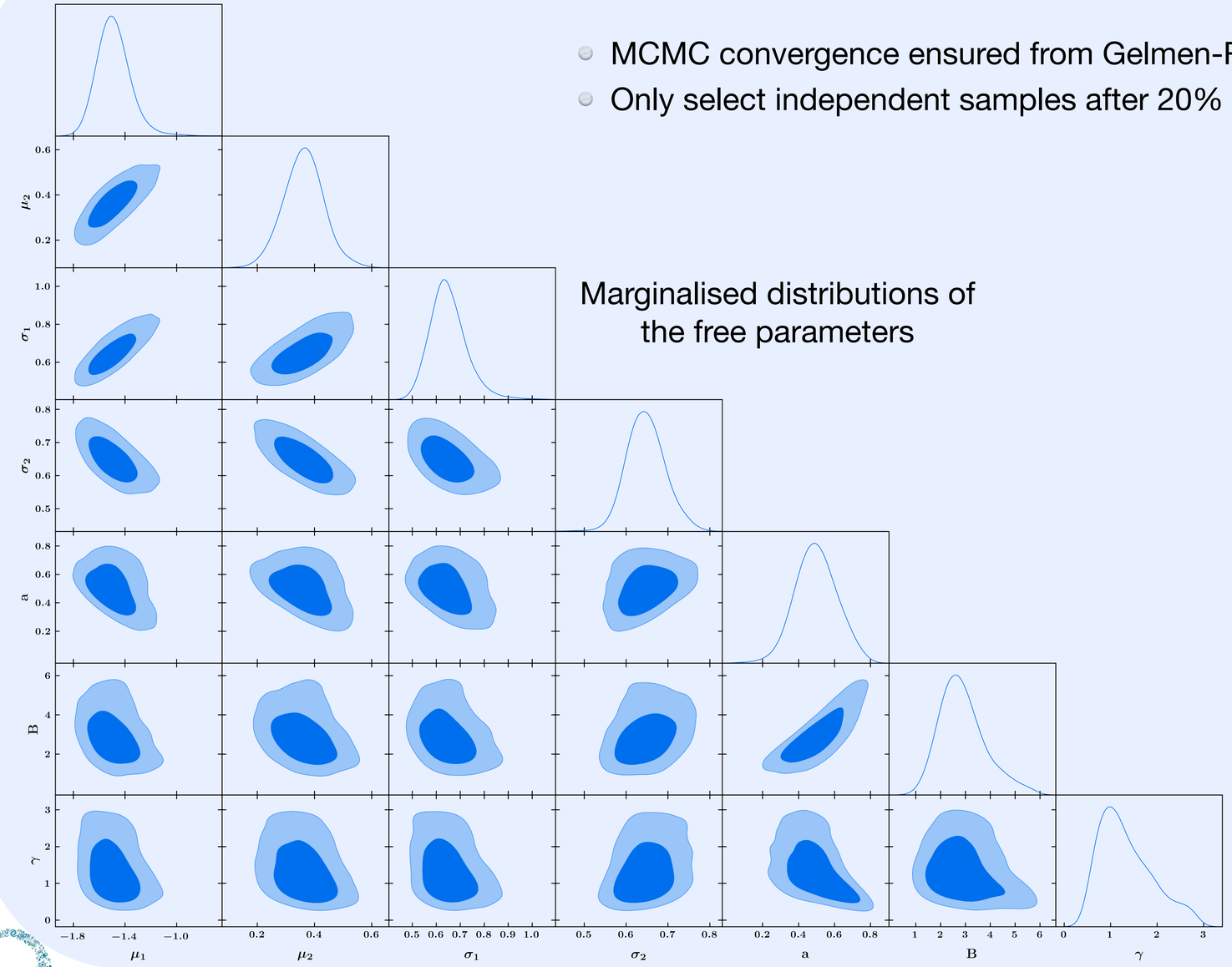
(In practice, maximise $\sum_i \log[x_1^i(z^i\,|\,\frac{R^i}{R_{500}^i}, M_*^i)]$)

use MCMC analysis to find best-fit values and uncertainties of the 7 free parameters $(\mu_1, \sigma_1, \mu_2, \sigma_2, a, B, \gamma)$

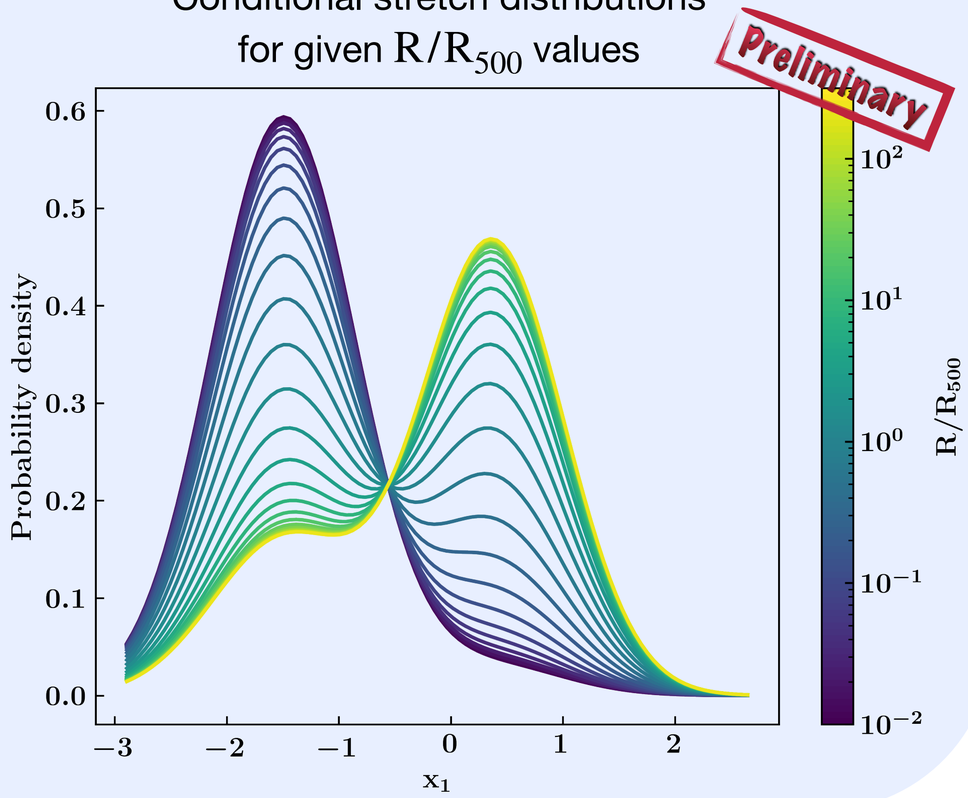
Results of the fitting procedure

- MCMC convergence ensured from Gelmen-Rubin test + autocorrelation time
- Only select independent samples after 20% burn-in cut-off

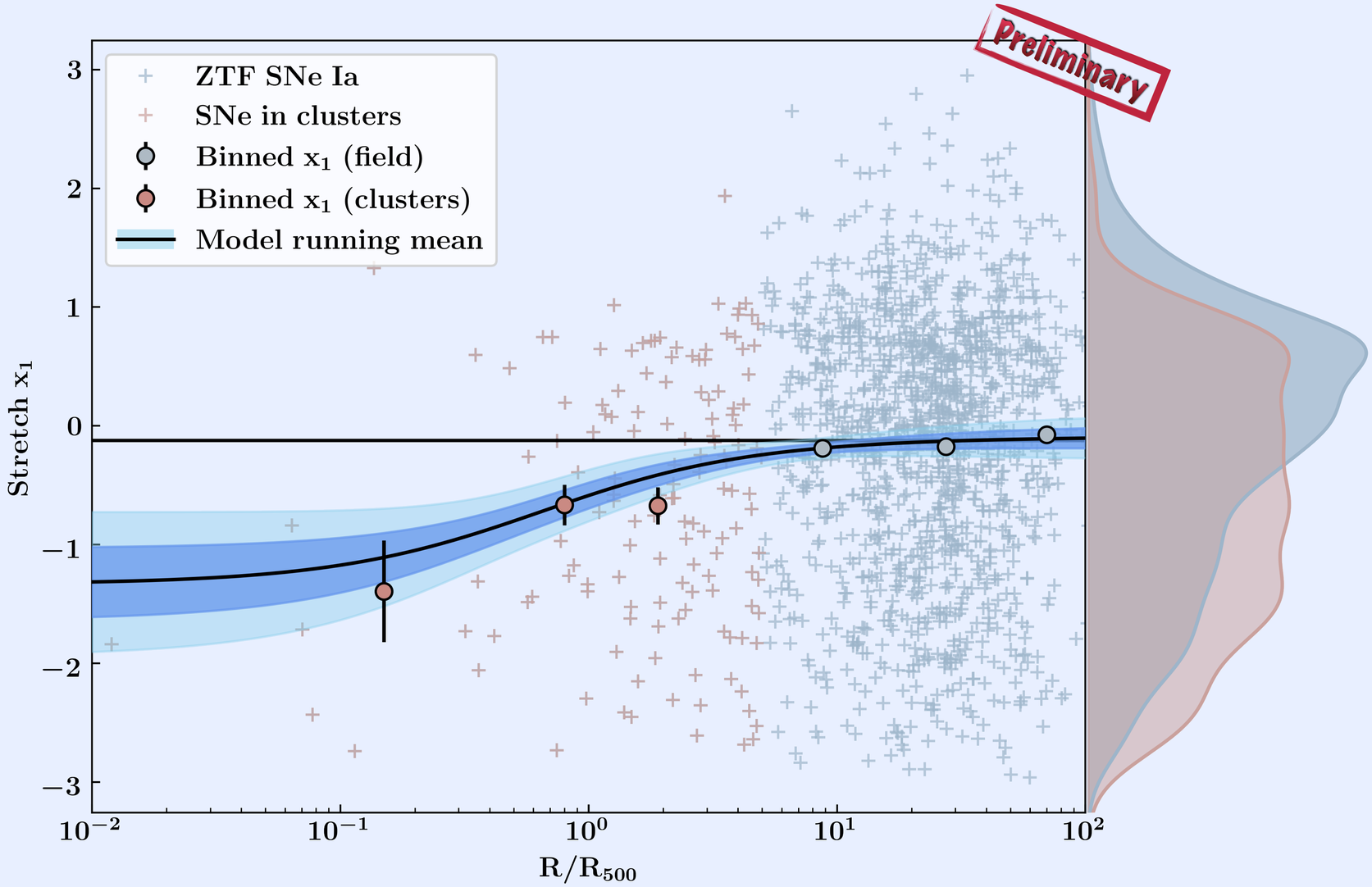
Marginalised distributions of the free parameters



Conditional stretch distributions for given R/R_{500} values



Running mean of the stretch distribution

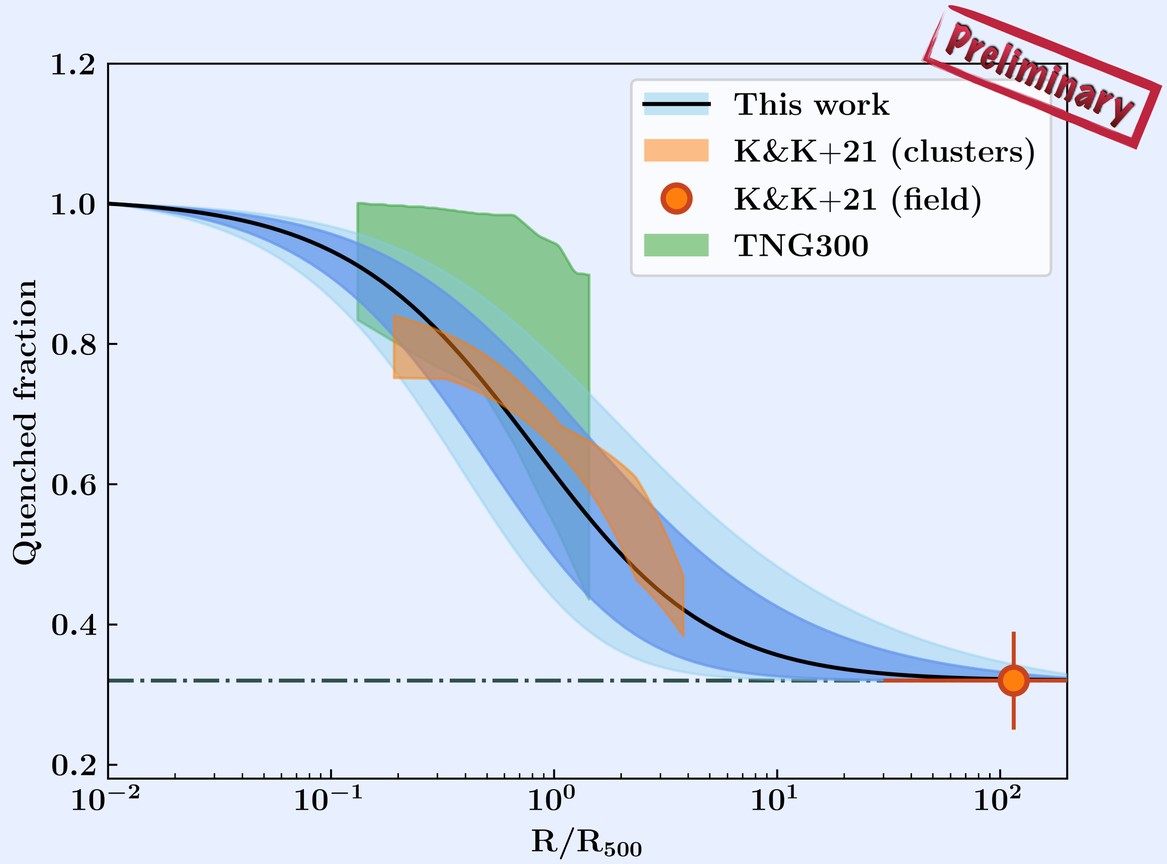


→ Significant evolution of the stretch distribution of SNe Ia w.r.t to distance from the nearest cluster

Variation of the fraction of quenched galaxies

Method: - assume that the stretch distribution in the core of clusters corresponds to $q = 1$ *(BCGs are all red and dead)* and that it corresponds to $q_{\rm field}$ far from clusters

- compute $q(R/R_{500})$ from amplitude ratios of the two Gaussian components at each $\dfrac{R}{R_{500}}$



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

- First analysis of the continuous evolution of SN Ia stretch distribution with cluster-centric radius
- Significant evolution of the amplitude ratio of the two modes in the stretch distribution with R/R_{500}
- Yet another analysis showing that the age of the host galaxy is the main parameter defining the stretch distribution
- Almost all SNe Ia found at $R < 0.1\,R_{500}$ are a realization of the low-stretch mode
- New estimator of the evolution of the fraction of quenched galaxies with cluster-centric radius
- May affect cosmology if SNe Ia detected through targeted observations of clusters are included in the Hubble diagram