Formation of cluster compact ellipticals through the pre-processing in groups

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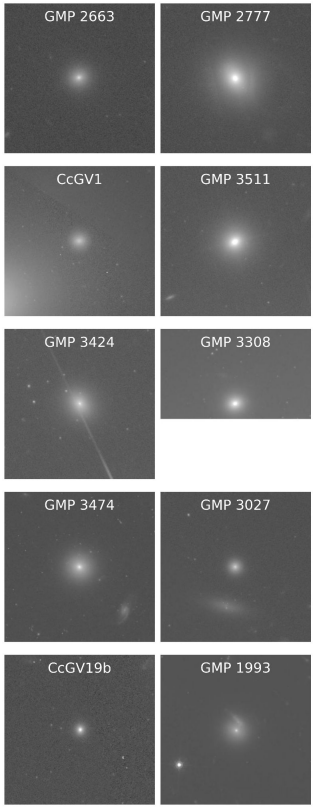
Compact ellipticals - definition

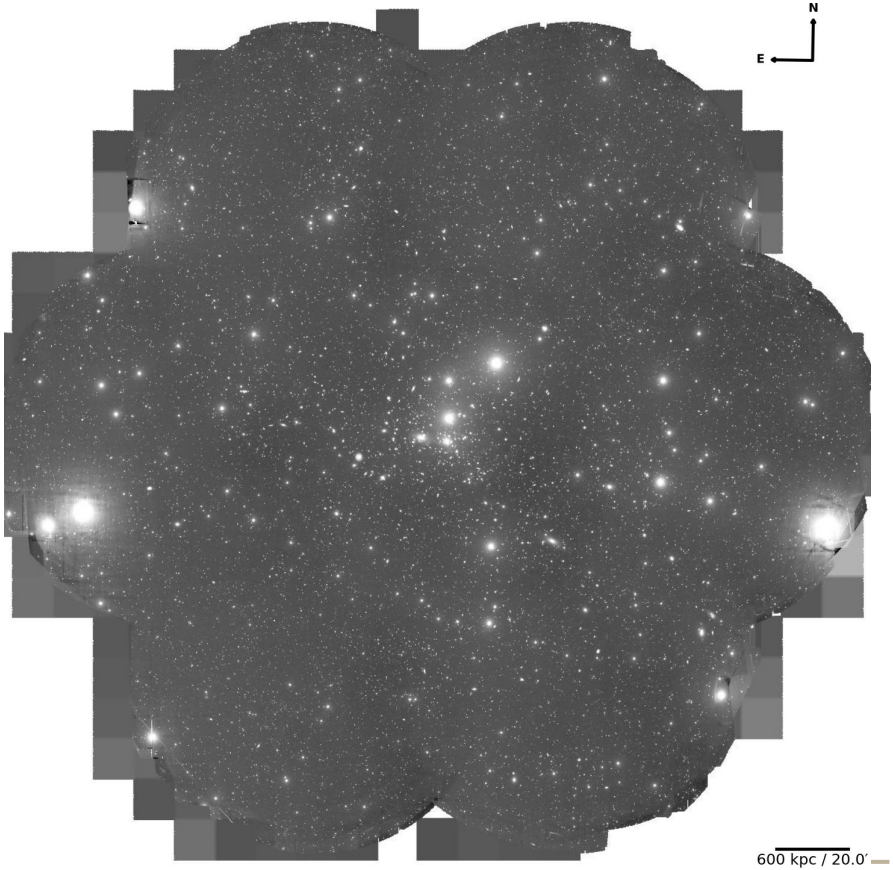
- cEs definition:
  - $10^8 \leq M_*/M_\odot \leq 10^{10}$
  - $R_e < 0.6$ kpc
- Biggest sample - 195 galaxies (Chilingarian & Zolotukhin 2015)
- Evolutionary pathways
  - Tidal stripping channel (Faber 1973; Bekki et al. 2001; Graham 2002; Drinkwater et al. 2003)
  - Intrinsic formation (Wirth & Gallagher 1984; Kormendy et al. 2009; Martinović & Micic 2017)
- ~50% of cluster members are accreted as part of galaxy groups (McGee et al. 2009; Dressler et al. 2013, Han et al. 2018)



HST F814W images of Coma Cluster cEs

Hyper Suprime-Cam dataset

- 175 frames with 240s exposures + 198 frames with 60s exposure (2016,2017)
- Extends to 1.7 deg or 1.23 R_{vir}
- Cover 13.4 deg^2 with 3σ limit of 25.6
- PSF: 0″.59 to 1″.27 FWMH (mean 0″.80)



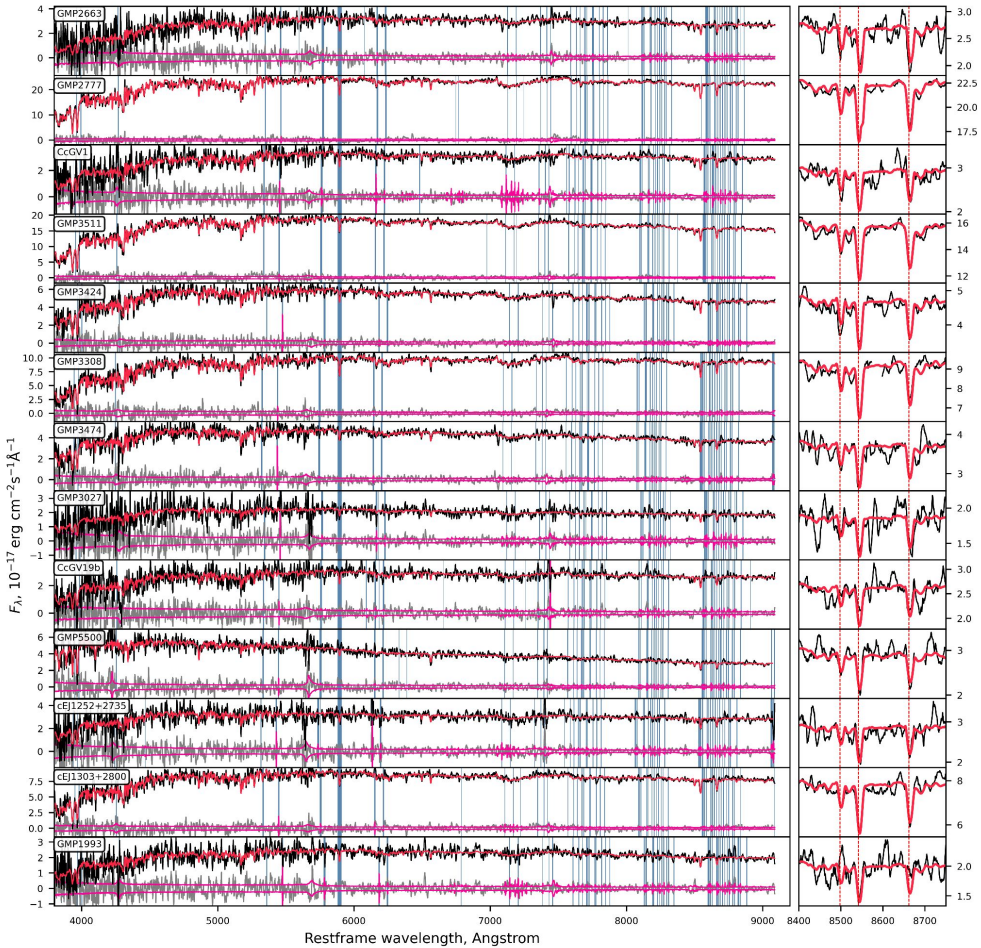
HSC-g data of the Coma Cluster

DESI EDR spectra

BGS spectra (Hahn et al. 2023):

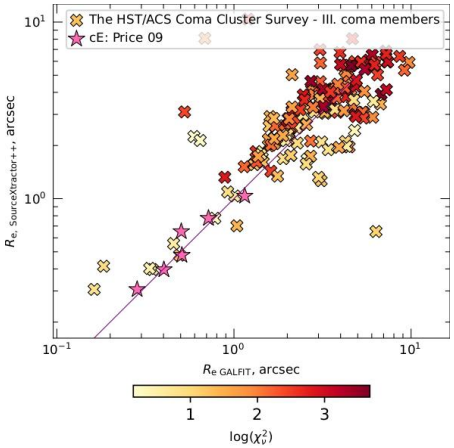
- Bright sample complete to M_r<-15.5 mag
- Faint sample 75-85% completeness for -15.5 < M_r<-14.8 mag

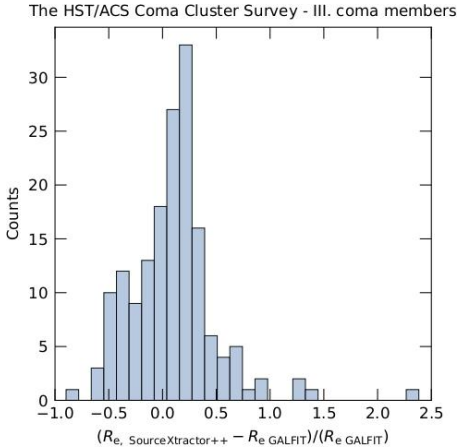
3292 spectra within the range 0.01<z<0.037 (≥4σ, σ ∼ 1000 km s^{-1} (Sohn et al. 2017))



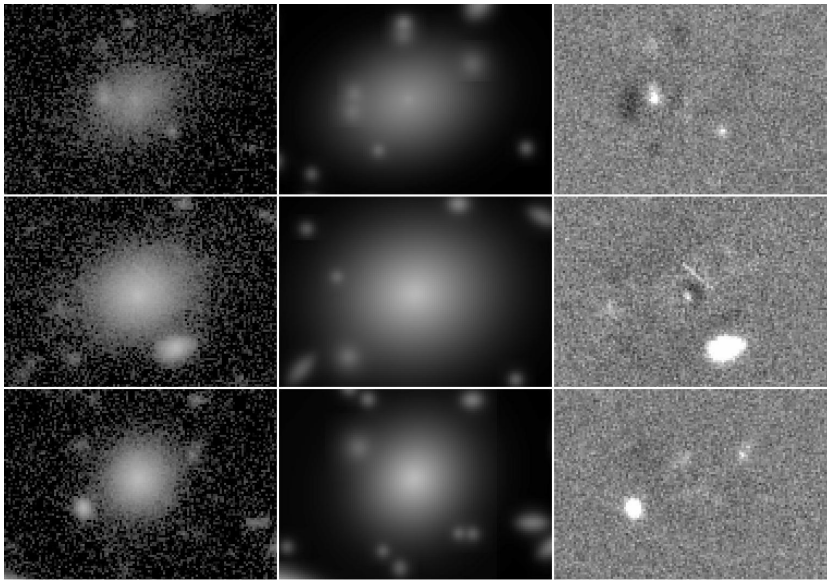
Model fitting tool - SourceXtractor++

Combination of Sérsic + PSF models





Measurements of R_e with SourceXtractor++ applied to HSC-g images compared to the literature GALFIT measurements on HST data from **Hoyos et al. 2011** and **Price et al. 2009**, along with a histogram of the relative differences between measurements



Original image (left), best fit Sérsic + PSF (center),residuals (right)

Can we select cEs using photometry alone?

Initial set of criteria:

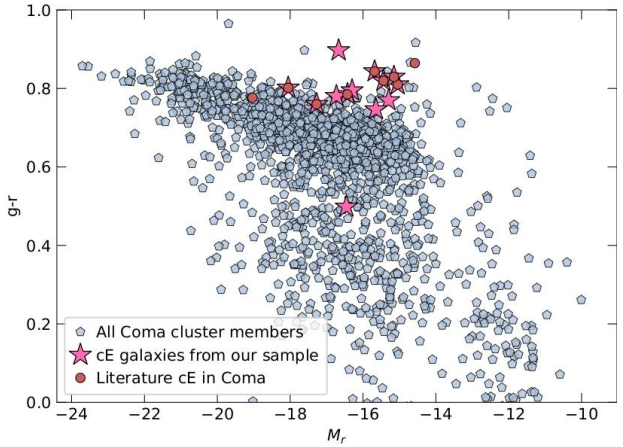
- $R_e < 0.6$ kpc
- $M_r > -19.5$
- $0.75 < g-r < 0.9$
- $(1-b/a) < 0.25$

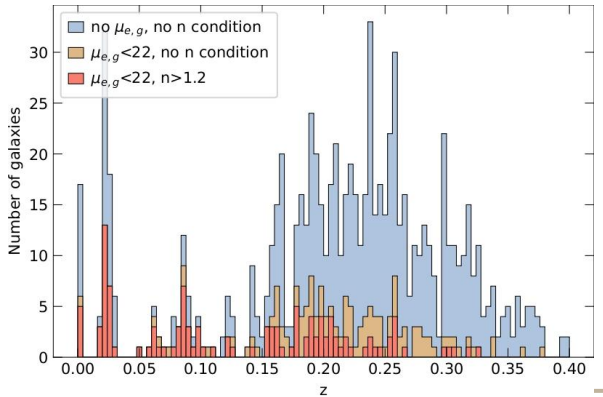
Purity: 2%

Additional cuts:

- $\langle \mu_{e,G} \rangle < 22$
- $n < 1.2$

Purity: 10%



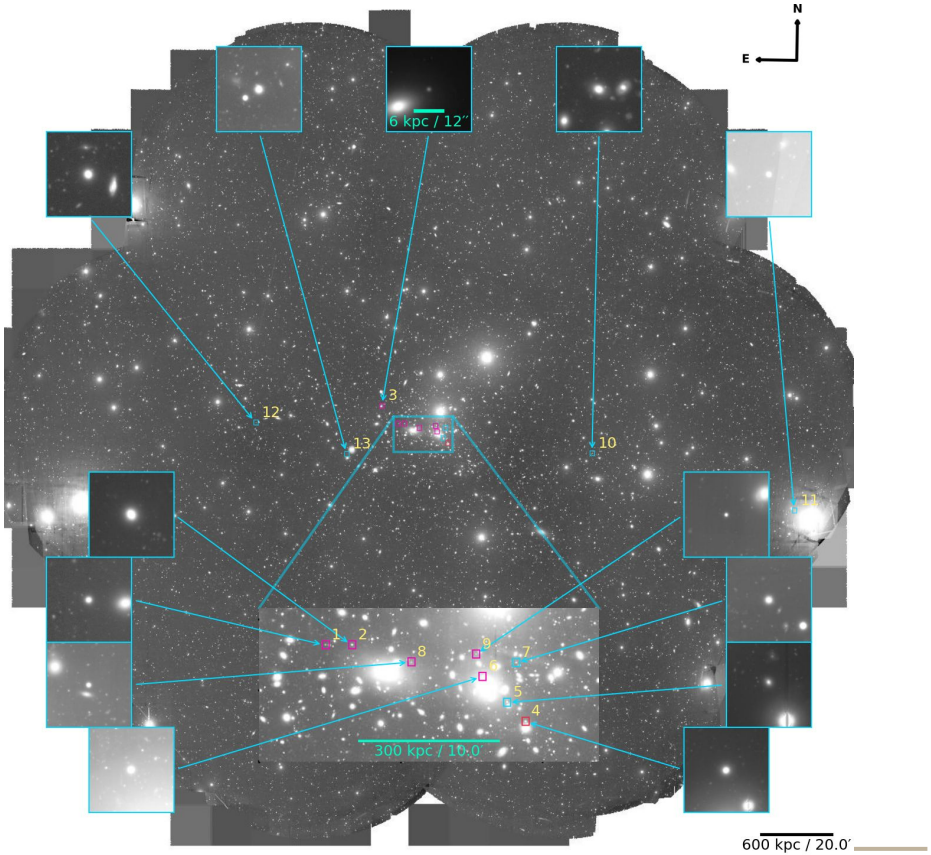


No, we need spectroscopy for the cluster membership

Final cE sample

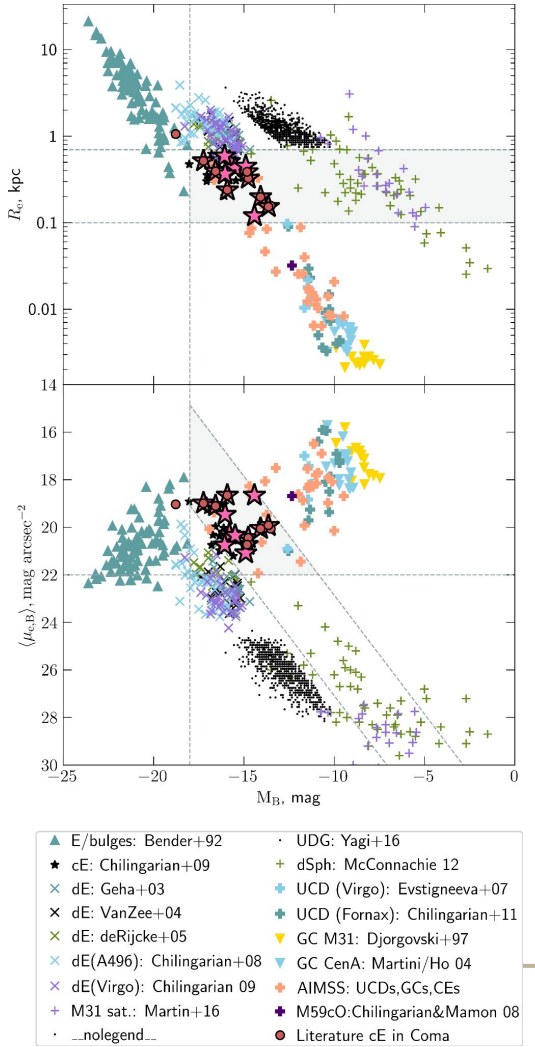
Search criteria:

- Effective radius: R_e < 1.2" (0.6 kpc)
- Mean surface brightness: $\langle \mu_e \rangle$ < 22 mag/arcsec²
- Redshift: 0.01 < z < 0.037 (Coma membership)
- Hα: non-detection ($F_{H\alpha} < 5\,\Delta F_{H\alpha}$)
- Spectra (DESI) S/N: > 2



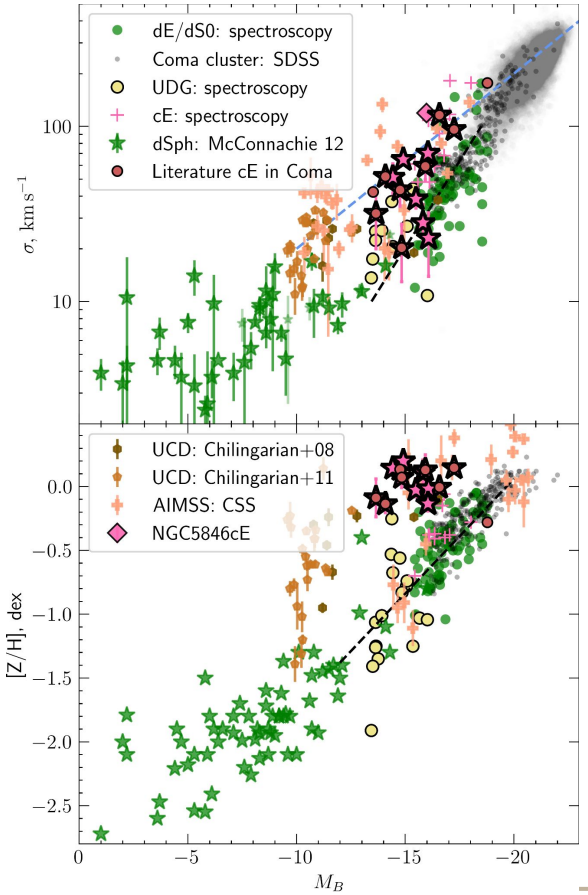
Photometric properties of the cE sample

#	cE Name	RA	Dec	M_g	$\langle\mu_g\rangle_e$	R_e
		J2000	J2000	mag	mag arcsec^{-2}	kpc
1	GMP2663	195.11394	28.00929	-14.833 ± 0.004	21.633 ± 0.012	0.388 ± 0.002
2	GMP2777	195.07869	28.00932	-17.241 ± 0.001	19.854 ± 0.004	0.518 ± 0.001
3	CcGV1	195.19862	28.09277	-14.763 ± 0.010	21.326 ± 0.041	0.326 ± 0.006
4	GMP3511	194.84753	27.91959	-16.572 ± 0.012	19.926 ± 0.040	0.393 ± 0.007
5	GMP3424[a]	194.87220	27.94189	-15.807 ± 0.006	21.247 ± 0.029	0.508 ± 0.007
6	GMP3308	194.90498	27.97221	-15.920 ± 0.008	19.499 ± 0.035	0.239 ± 0.004
7	GMP3474	194.85990	27.98843	-15.488 ± 0.018	21.204 ± 0.065	0.430 ± 0.012
8	GMP3027	194.99960	27.98940	-14.084 ± 0.008	20.927 ± 0.018	0.198 ± 0.001
9	CcGV19b	194.91344	27.99852	-13.650 ± 0.075	20.800 ± 0.196	0.153 ± 0.013
10	GMP5500	194.07849	27.86737	-16.069 ± 0.038	21.311 ± 0.118	0.591 ± 0.030
11	cEJ1252+2735	193.00710	27.58707	-14.426 ± 0.026	19.489 ± 0.074	0.120 ± 0.004
12	cEJ1303+2800[b]	195.87065	28.01165	-16.044 ± 0.002	20.296 ± 0.010	0.366 ± 0.002
13	GMP1993	195.38512	27.86547	-14.902 ± 0.012	21.886 ± 0.040	0.450 ± 0.008



Stellar population properties

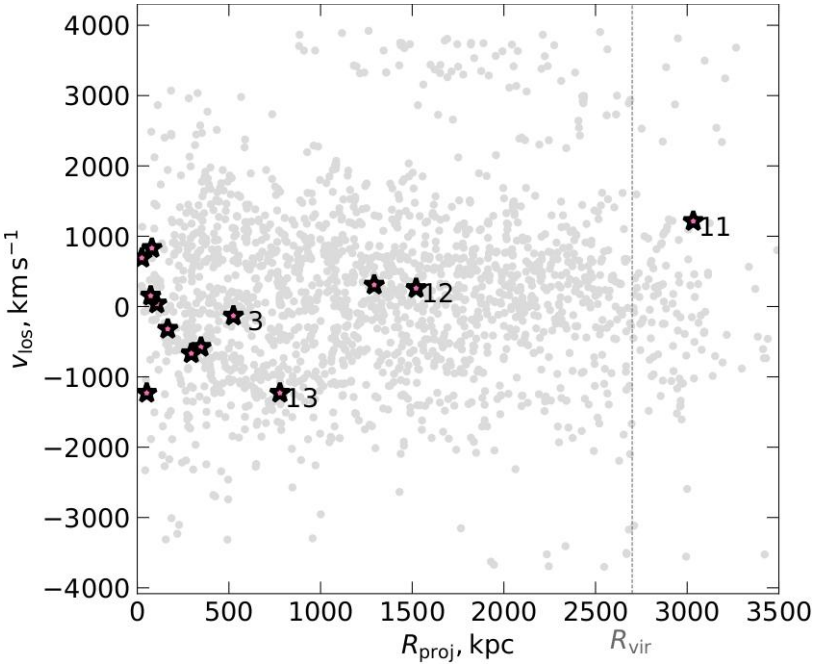
#	V (km s^{-1})	σ (km s^{-1})	t_{SSP} (Gyr)	[Z/H] (dex)
1	6380.4 ± 4.9	28.2 ± 7.4	13.09 ± 0.88	0.11 ± 0.10
2	6217.3 ± 2.6	95.9 ± 2.5	5.30 ± 0.16	0.15 ± 0.00
3	6765.5 ± 3.8	20.3 ± 7.3	10.46 ± 0.61	0.07 ± 0.08
4	6945.7 ± 3.9	116.0 ± 3.9	7.20 ± 0.11	−0.01 ± 0.03
5	5650.1 ± 3.2	38.5 ± 4.2	4.21 ± 0.19	−0.03 ± 0.05
6	7621.5 ± 3.4	64.7 ± 3.7	8.07 ± 0.06	0.20 ± 0.00
7	7746.0 ± 5.0	51.7 ± 5.9	4.45 ± 0.21	−0.14 ± 0.07
8	6585.1 ± 8.3	31.8 ± 11.8	4.97 ± 0.70	−0.09 ± 0.15
9	7059.5 ± 8.6	59.3 ± 9.6	7.50 ± 0.50	0.13 ± 0.12
10	7233.0 ± 6.1	43.4 ± 8.3	1.32 ± 0.01	0.13 ± 0.05
11	8141.3 ± 5.3	23.0 ± 9.1	4.23 ± 0.37	−0.02 ± 0.11
12	7180.9 ± 4.3	70.3 ± 4.6	9.34 ± 0.40	−0.13 ± 0.06
13	5651.2 ± 8.6	51.2 ± 9.9	5.31 ± 0.95	0.14 ± 0.03



cEs that are likely preprocessed in galaxy groups

- 4 cEs have non-central hosts.
- No visible tidal features in HSC-g down to $\mu_g \sim 29$ mag arcsec^{-2} → stripping must have occured 2Gyr ago (Mancillas et al. 2019).
- Most of infalling groups become unbound within 0.5 - 1Gyr after cluster entry (Haggar et al. 2023).

#	Galaxy Name	Host	$d_{\rm proj}$ (kpc)	Δv (km s^{-1})
3	CcGV1	IC4045	7.30	193.63
11	cEJ1252+2735	PGC43618	34.36	119.90
12	cEJ1303+2800	PGC093700	26	776
13	GMP1993	NGC4921	44.23	163.01



Contribution of pre-processing - free-fall time estimation

Assumption:

- galaxies are infalling with zero orbital energy and negligible angular momentum

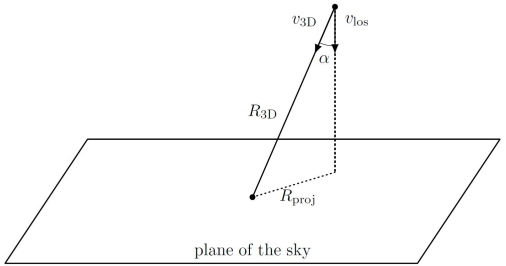
The free-fall velocity profile:

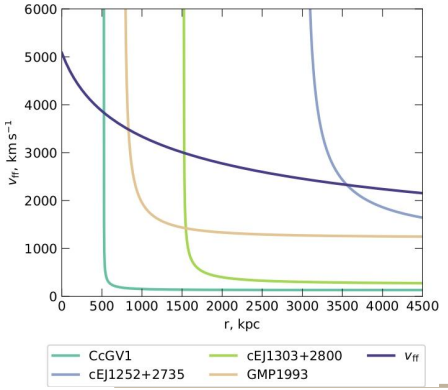
- $v_{\rm ff}(r) = \sqrt{-2\Phi(r)}$, where Φ(r) is NFW profile. Total mass profile of the Coma is close to the dark matter mass profile (Łokas & Mamon 2003).

Recovering 3D values from geometry:

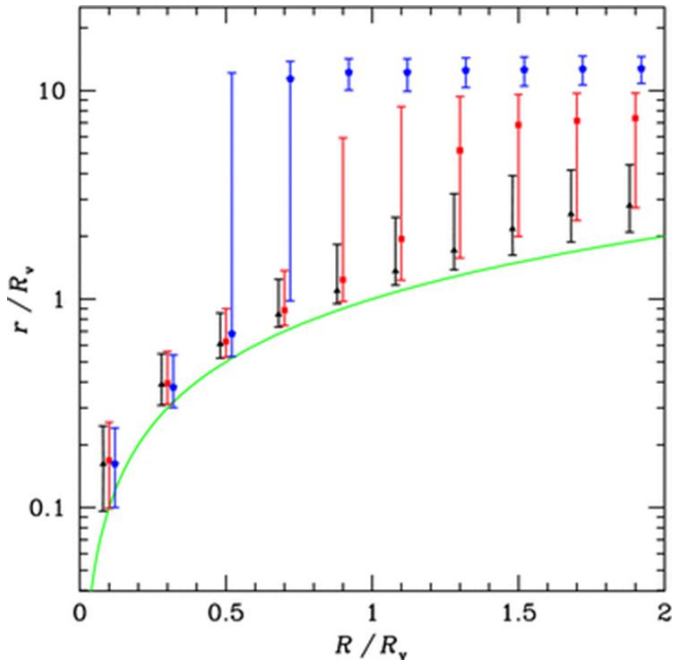
- $v_{\rm 3D} = \dfrac{v_{\rm los}}{\cos\alpha}, \quad r_{\rm 3D} = \dfrac{r_{\rm proj}}{\sin\alpha}$
- α - is determined by 3D phase space values at the intersection point

$$t_{\rm ff} = \int_0^{r_0} \frac{dr}{\sqrt{v_0^2 + 2\left[\Phi(r_0) - \Phi(r)\right]}}$$





Comparing measurements with simulations: Distances



Mahajan et al. 2011 Physical radius (r) versus projected radius (R) for particles of stacked mock cluster (medians with error bars for quartiles) in bins of absolute LOS velocity: 0–1 σ_v (black triangles), 1–2 σ_v (red squares) and 2–3 σ_v (blue pentagons). The green curve shows $r=R$.

#	Name	$v_{\rm LOS}$ (km s^{-1})	$R_{\rm proj}$ (kpc)	$v_{\rm 3D}$ (km s^{-1})	$R_{\rm 3D}$ (kpc)
3	CcGV1	-131	525	3817	525
11	cEJ1252+2735	1213	3033	2327	3555
12	cEJ1303+2800	260	1521	2992	1527
13	GMP1993	-1228	778	3482	832

- cEs 3 and 12: $v_{los} < \sigma_{vir}$, $R_{proj} < R_{vir}$ → $R_{proj} \sim R$
- cE 13: $v_{los} \sim$ 1-2 σ_{vir}, $R_{proj} \sim 0.2\, R_{vir}$ → $R_{proj} \sim R$
- cE 11: $v_{los} \sim$ 1-2 σ_{vir}, $R_{proj} \sim R_{vir}$ → $R_{proj} < R$

Comparing measurements with simulations: free-fall timescales

#	Name	$R_{\rm proj}$ (kpc)	$R_{\rm 3D}$ (kpc)	$t_{\rm ff}$ (Myr)
3	CcGV1	525	525	122
11	cEJ1252+2735	3033	3555	1204
12	cEJ1303+2800	1521	1527	423
13	GMP1993	778	832	206

- Haines et al. 2015: timescales to reach first pericenter after being accreted ~ 0.5-0.8 Gyr (galaxy accreted around r_{200})
- Oman & Hudson et al. 2016: start of infall around 2.5 R_{vir}:
  - 2.5 - 3.0 Gyr to reach R_{vir}
  - 1.0-1.5 Gyr to reach pericenter
- Tollet et al. 2017: cosmological simulation with cluster mass growth through filament accretion With $R_{apo} \gg R_{vir}$ timescales less than 0.5 Gyr

- Haines et al. 2015 - Millennium Simulation
- Oman & Hudson et al. 2016 - Multidark Run 1 (MDR1)
- Tollet et al. 2017 - 1024^3-particle N-body simulation

What if angular momentum is not negligible?

- Estimated the effect by solving the equation of motion:

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM(r)}{r^3}\mathbf{r}$$

- The physical distances can't be constrained. We know: x and y - coordinates in the plane of the sky, v_{los}.

  z varies between -10 Mpc and +10Mpc

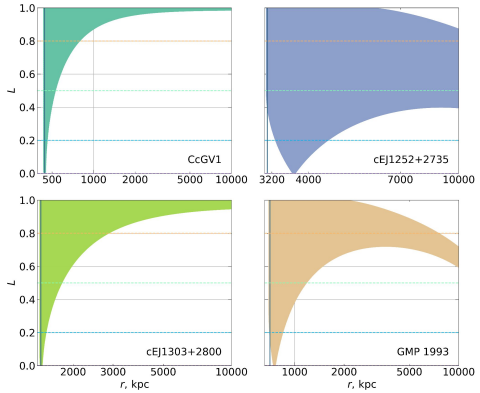
- Galaxies are infalling: $v_{3D} = \sqrt{-2\Phi(r)}$

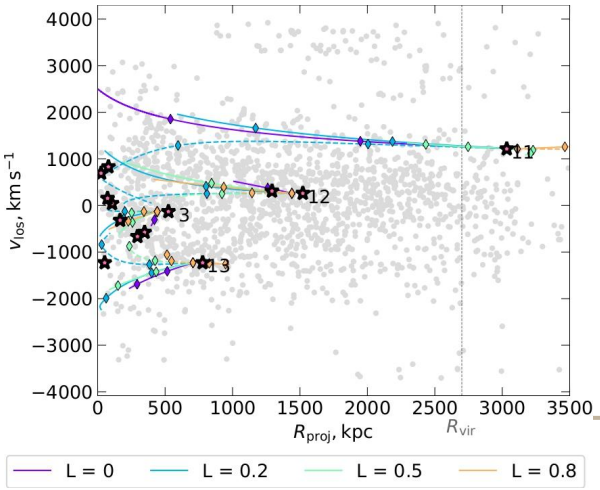
$$v_x^2 + v_y^2 = v_{3D}^2 - v_z^2$$

- Measured dimensionless angular momentum:

$$L = |\mathbf{v}_{3D} \times \mathbf{r}_{3D}|/(v_{3D}\, r_{3D})$$

- Estimated r_{min} and r_{max} for L = 0; 0.2; 0.5; 0.8 - used as initial condition for equation of motion.





Results/Summary

- The current cE population of the Coma Cluster is bimodal:
  - A dominant population of the central galaxies.
  - A subpopulation in the cluster outskirts .
- Nearly all outer cEs are associated with massive hosts, supporting a pre-processing scenario in infalling groups, predominantly tidal stripping.
- HST images of galaxies do not reveal prominent host globular cluster systems (no overdensities around them)
- Based on our estimates the preprocessing in groups will contribute by up to 30% to the growth of central cE population in the next 0.4 Gyr.

For more details see: Aleksandra V. Sharonova et al 2025 ApJ 993 229

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