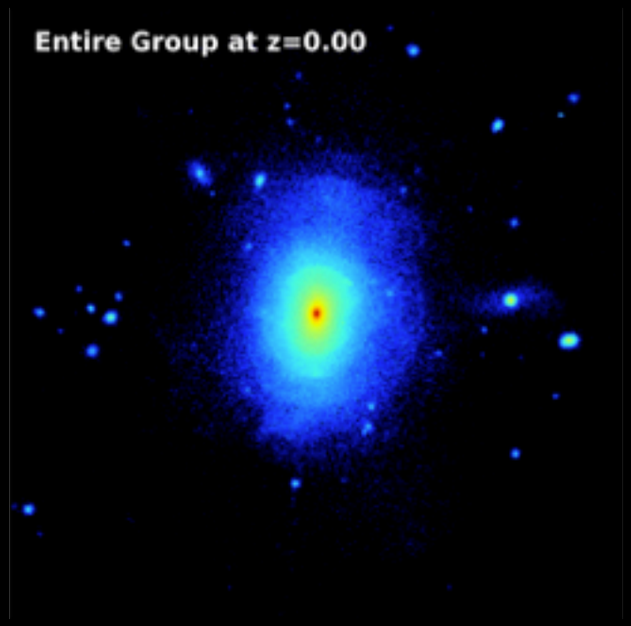
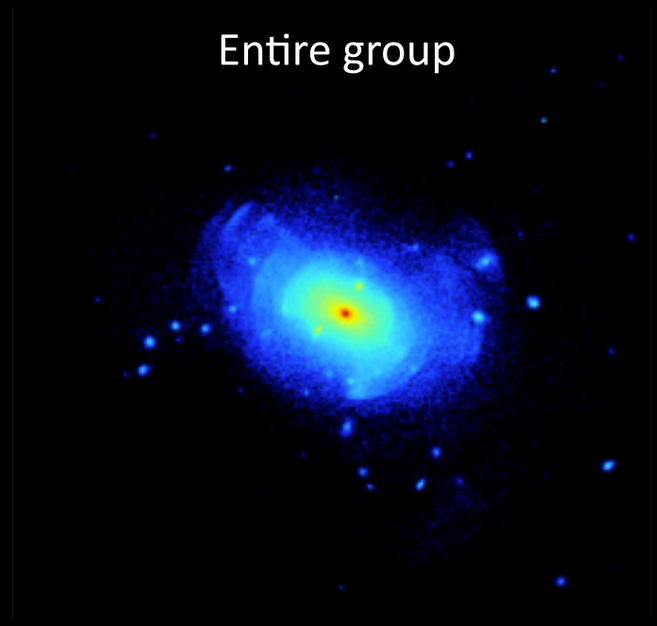
STELLAR SHELLS IN THE ILLUSTRIS SIMULATION

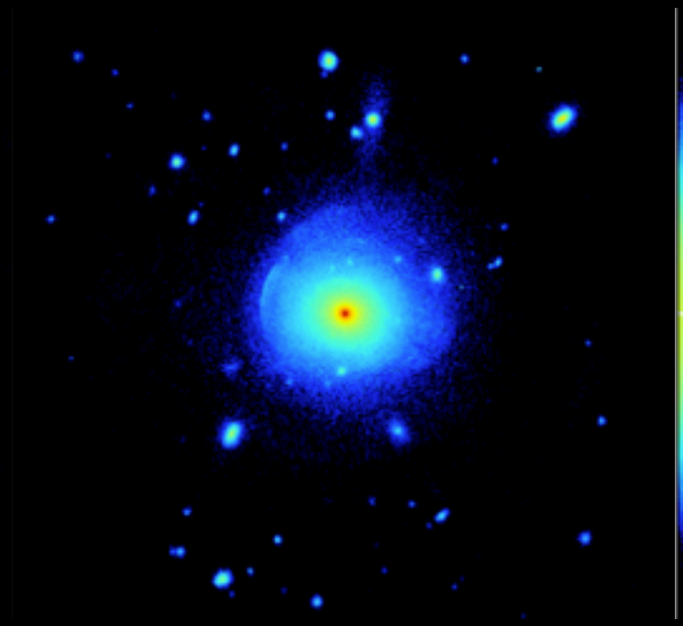
Ana-Roxana Pop

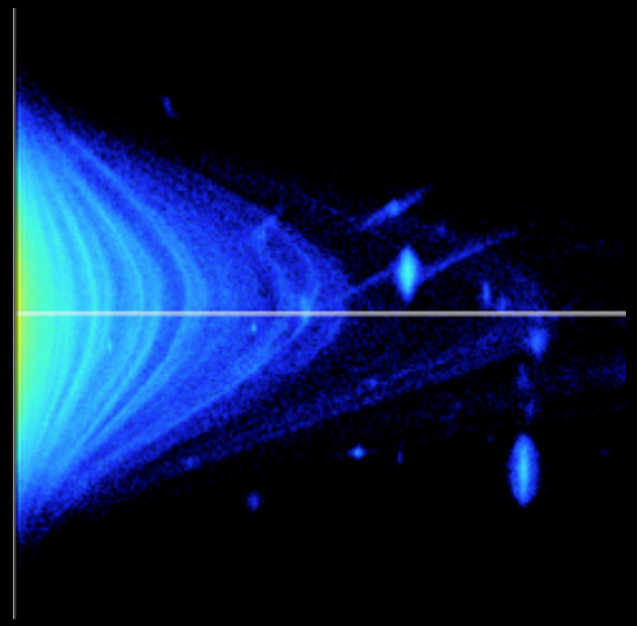
in collaboration with Lars Hernquist, Annalisa Pillepich, Nicola Amorisco

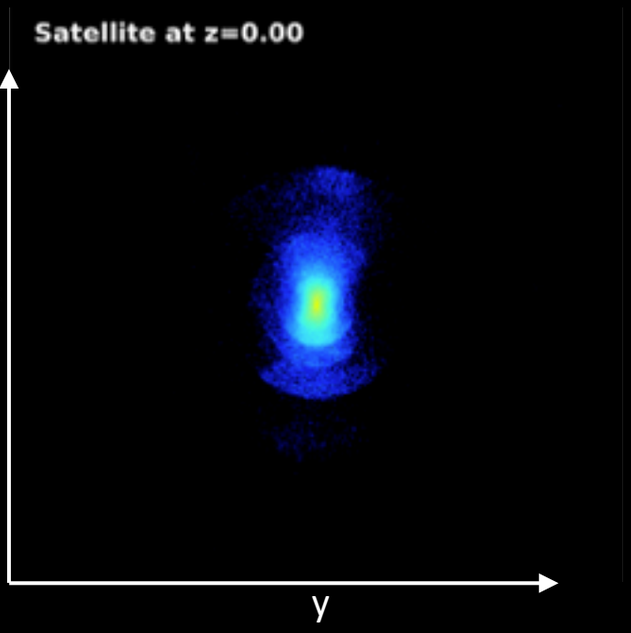


Entire group

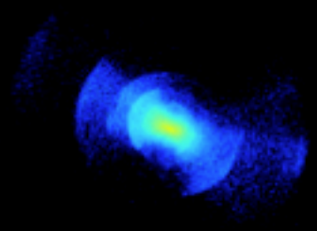


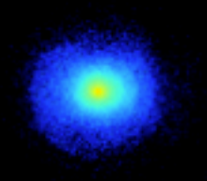


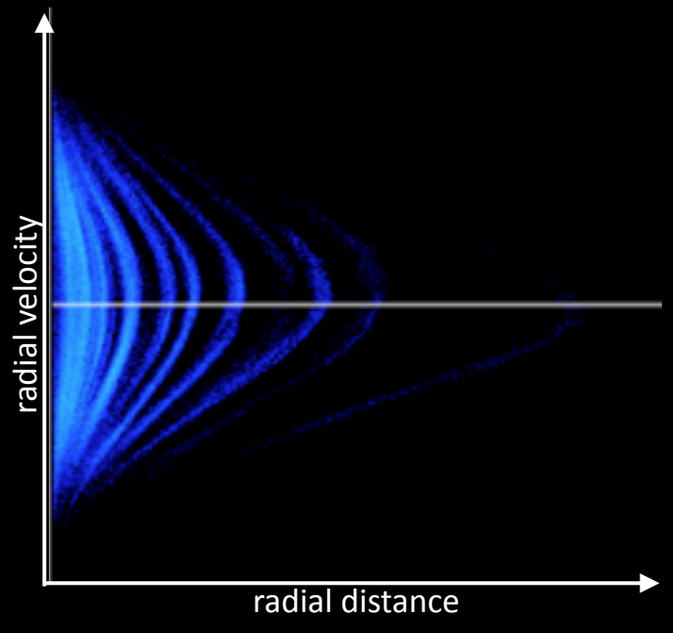




Satellite forming shells





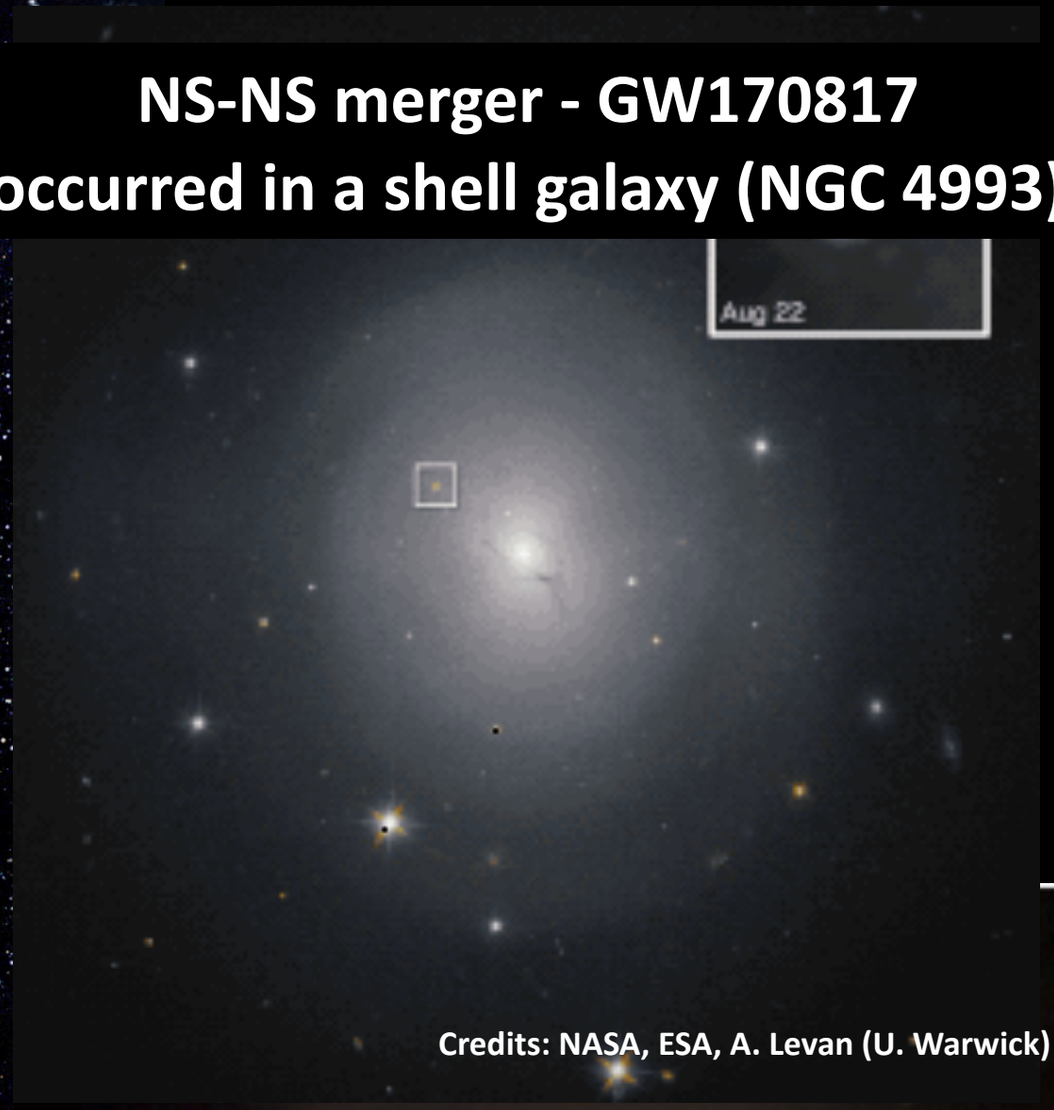


A few famous shells

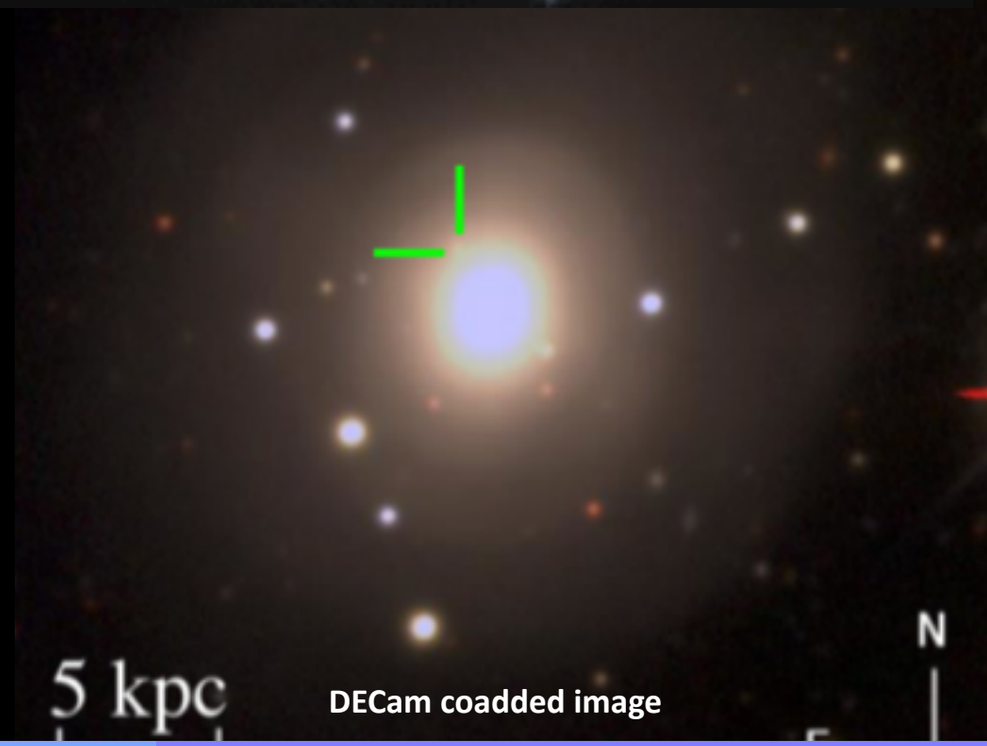
NGC 474
CFHT/Coelum/MegaCam J.-C. Cullandre & G.A. Anselmi

ESO 381-12
NASA, ESA, P. Goudfrooij (STScI)

NS-NS merger - GW170817 occurred in a shell galaxy (NGC 4993)

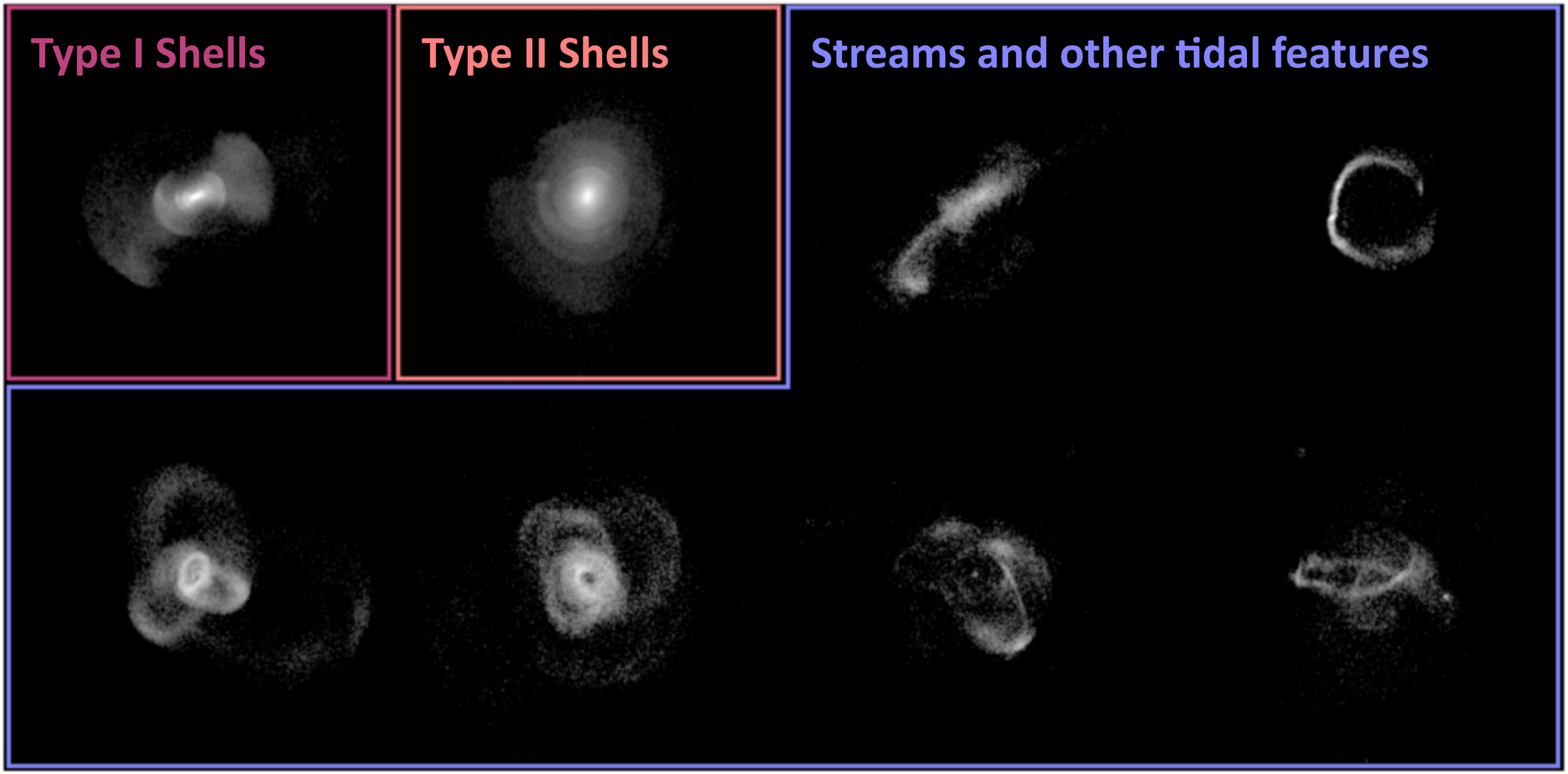


Credits: NASA, ESA, A. Levan (U. Warwick)



DECam coadded image

Tidal Features in Illustris



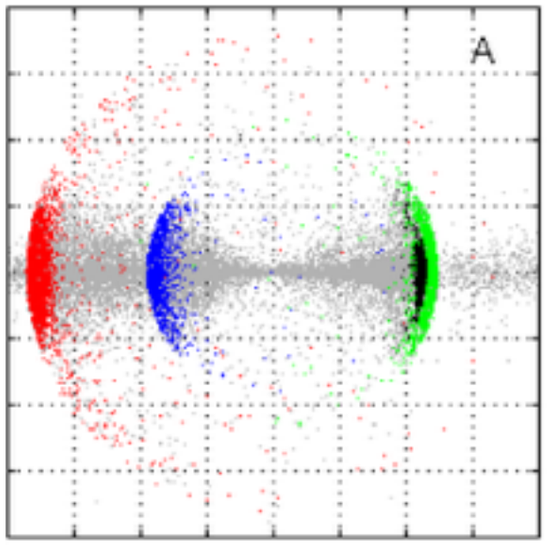
Pop+2017a, arXiv:1706.06102

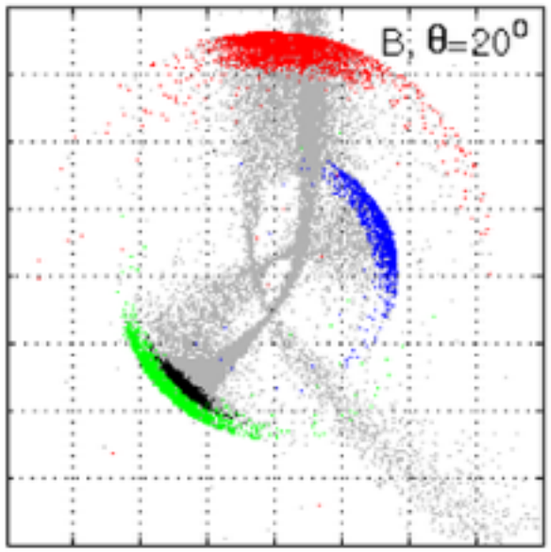
From Shells to Streams

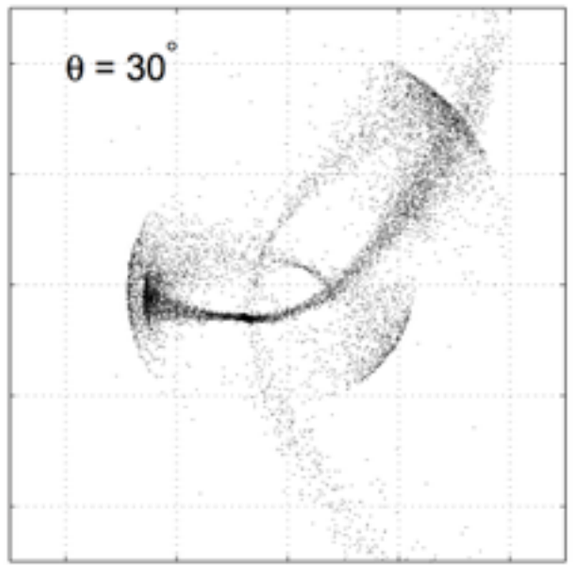
increasing angular momentum

of the accreted satellite

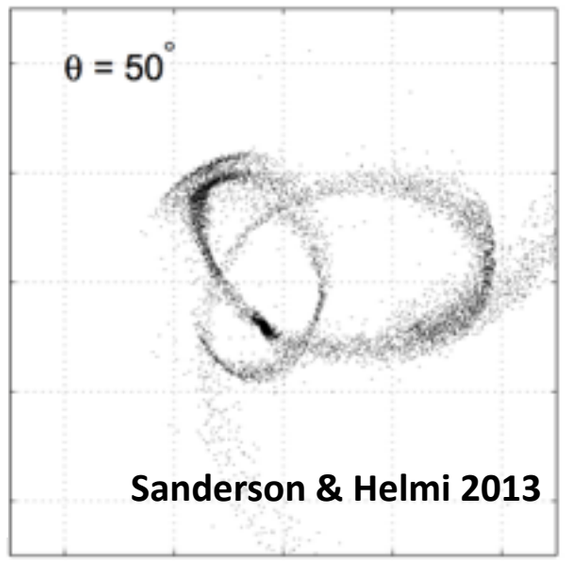
radial orbit







more circular orbit

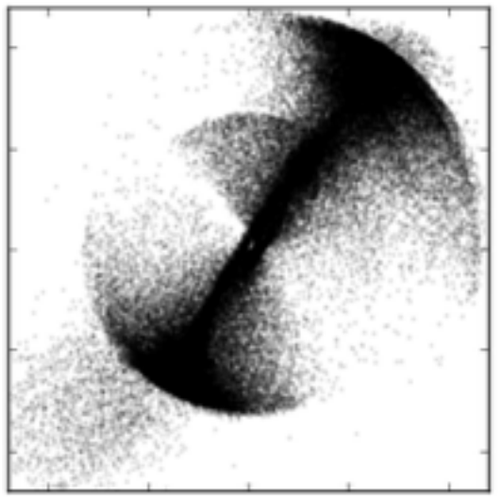


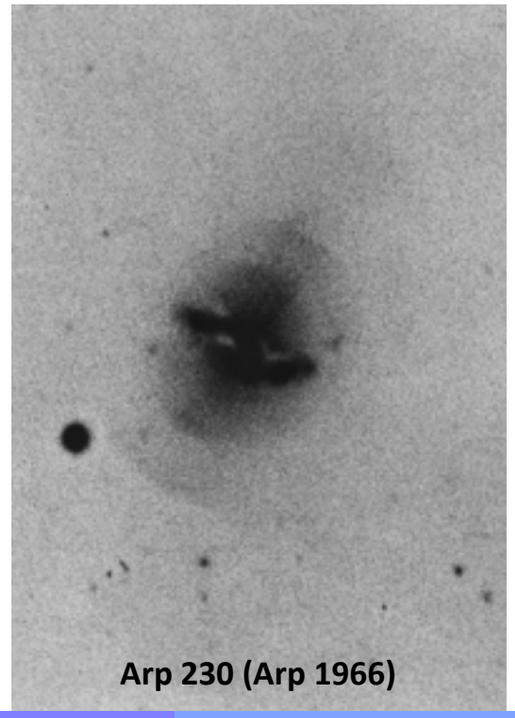
Sanderson & Helmi 2013

SHELLS

“wrappings”

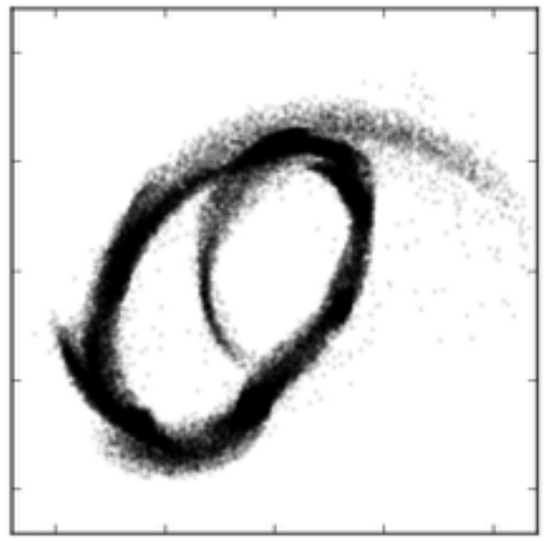
STREAMS





Arp 230 (Arp 1966)

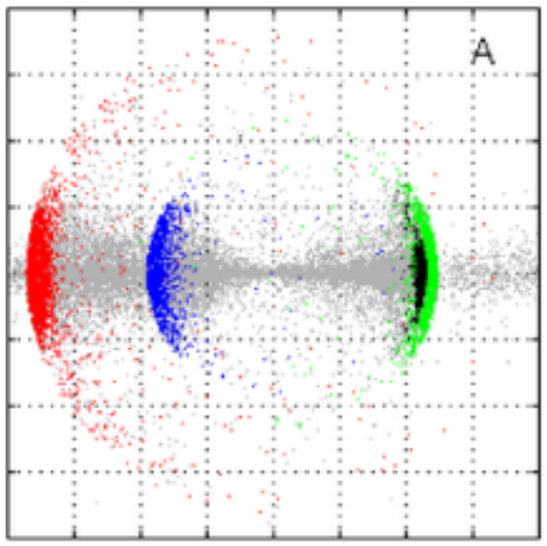
Martinez-Delgado+2008



Hendel & Johnston 2015

Different Types of Shells

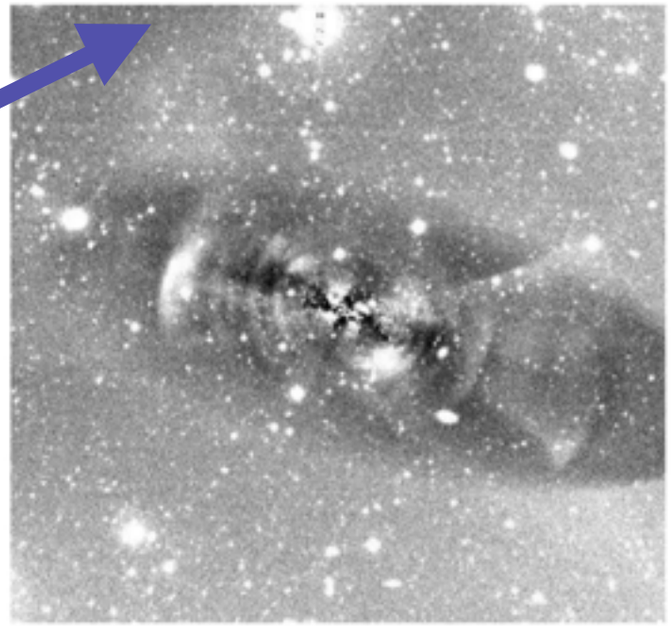
radial orbit



SHELLS

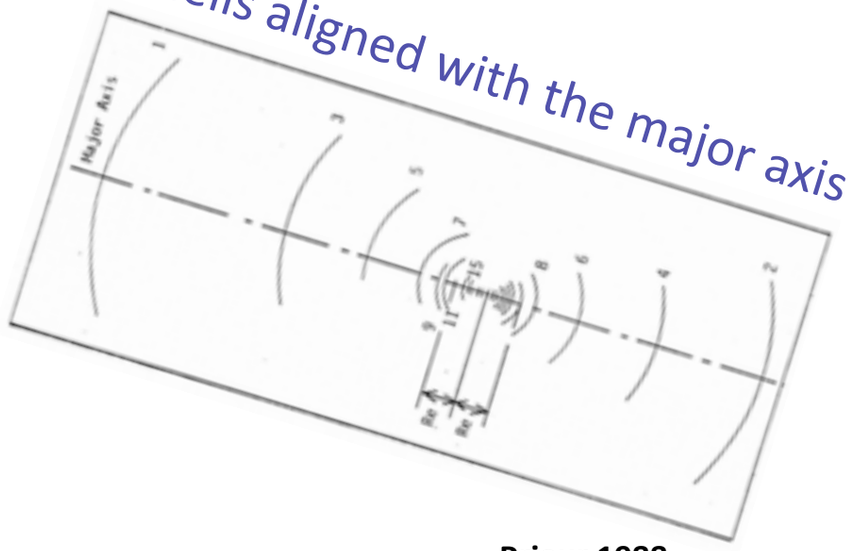
Prieur (1989) and Wilkinson et al. (1987) introduced a system of classifying shells based on their morphology

Type I shells



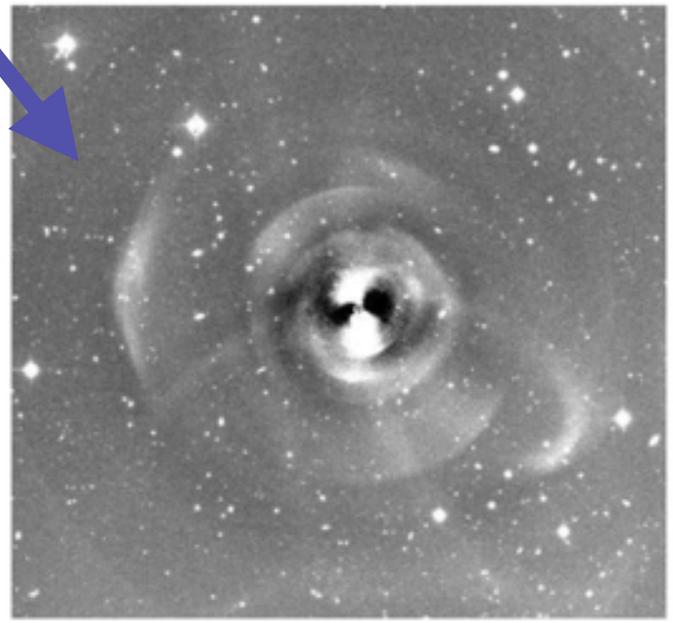
NGC 7600 - Turnbull et al., 1999

shells aligned with the major axis

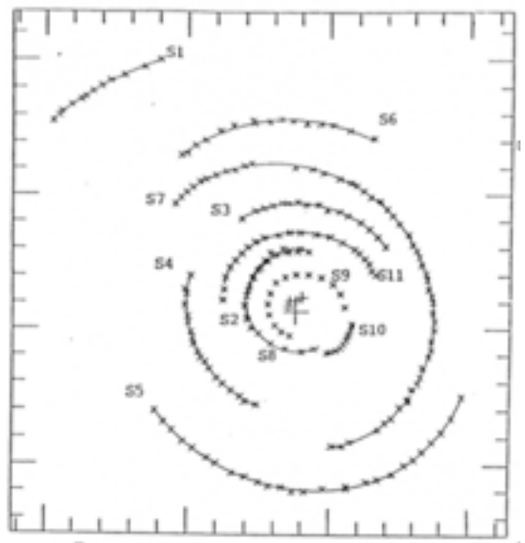


Prieur 1988

Type II shells



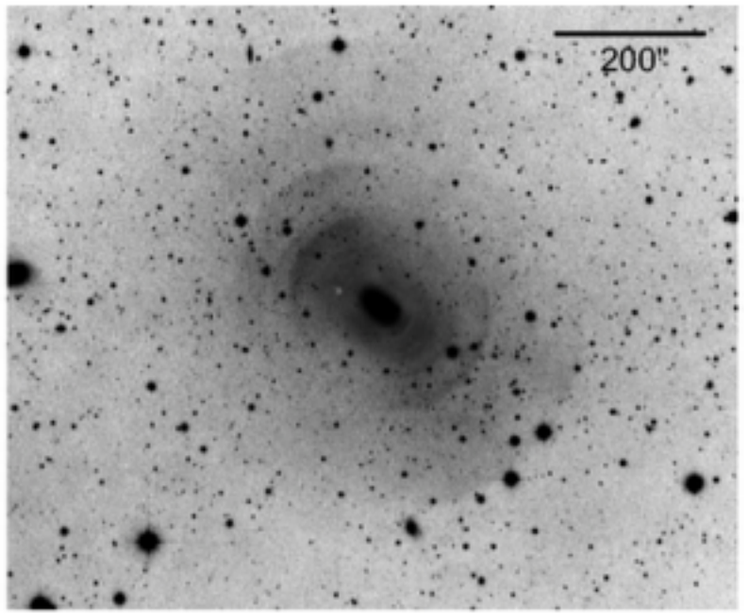
NGC 474 - Turnbull et al., 1999



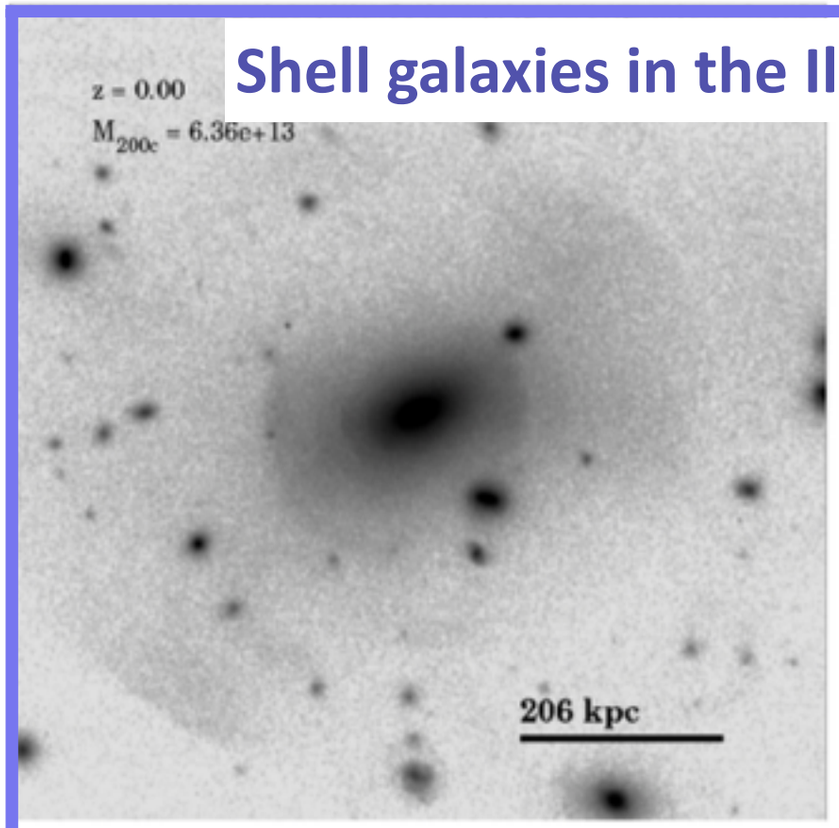
shells more randomly distributed

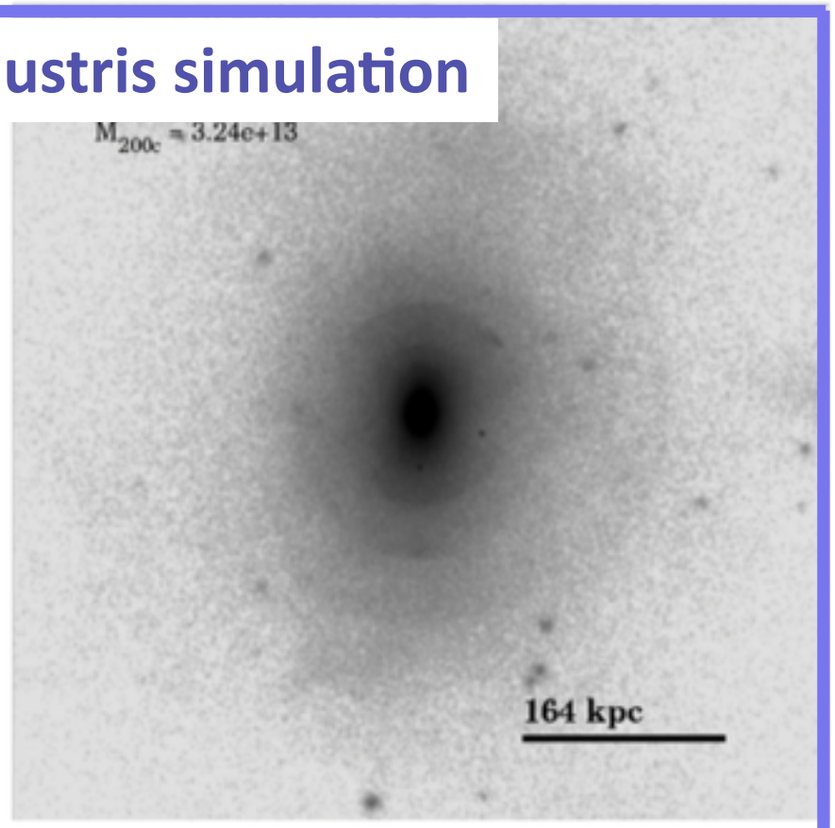
Prieur 1988

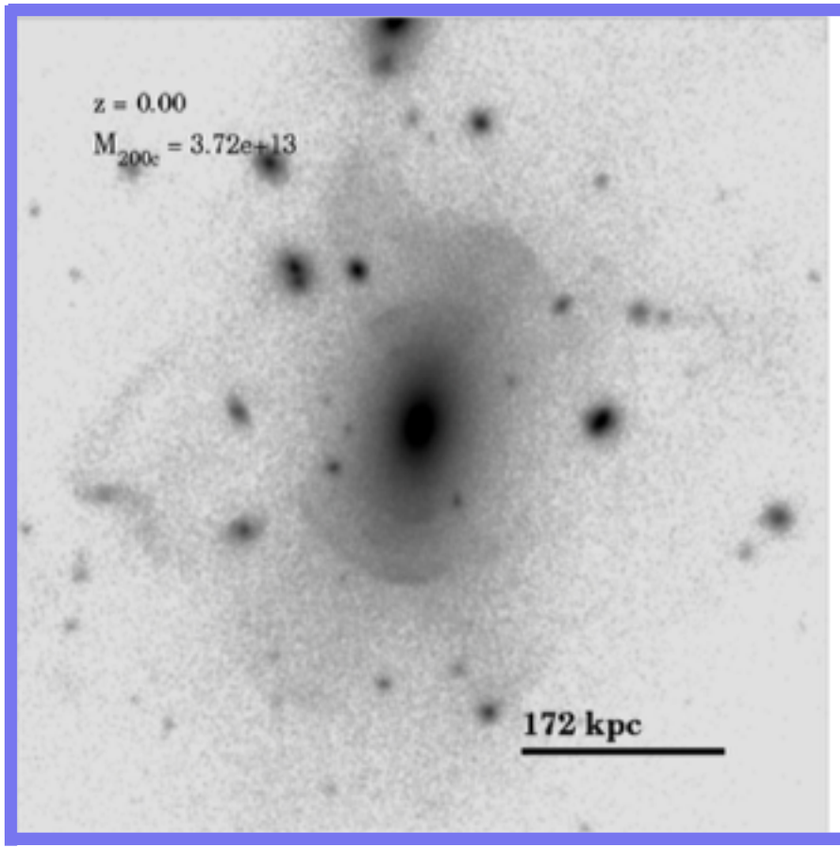
Observed shell galaxy
NGC 3923

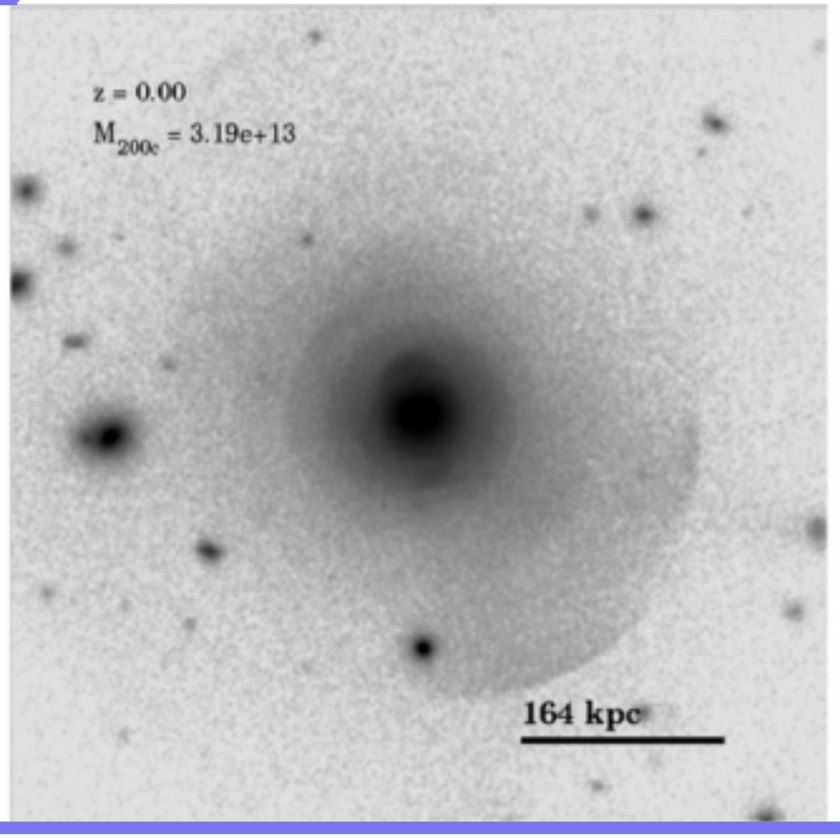


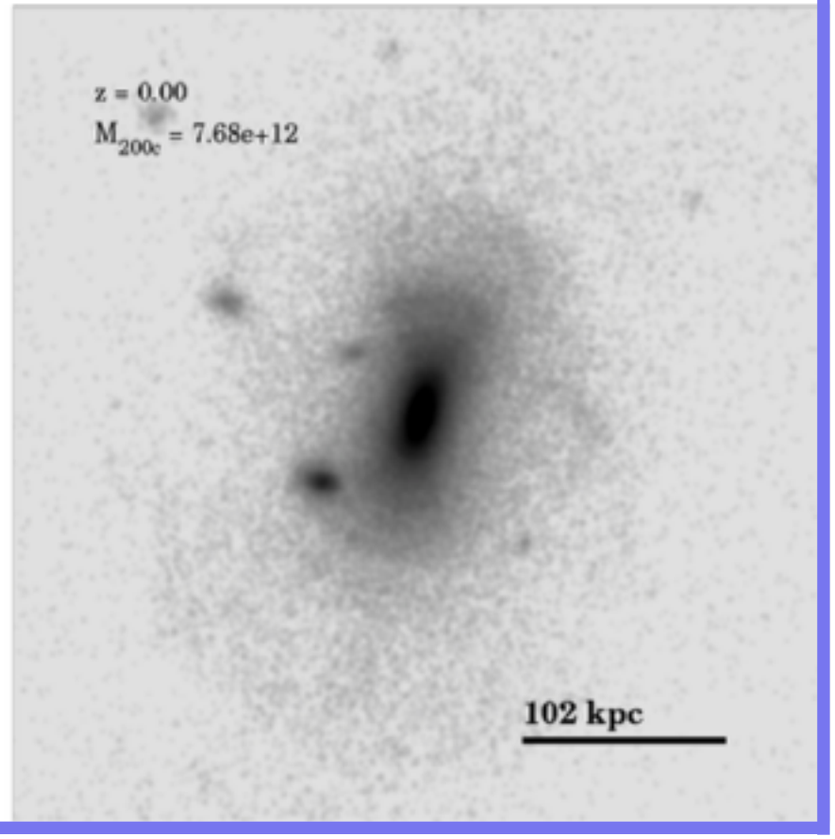
Shell galaxies in the Illustris simulation











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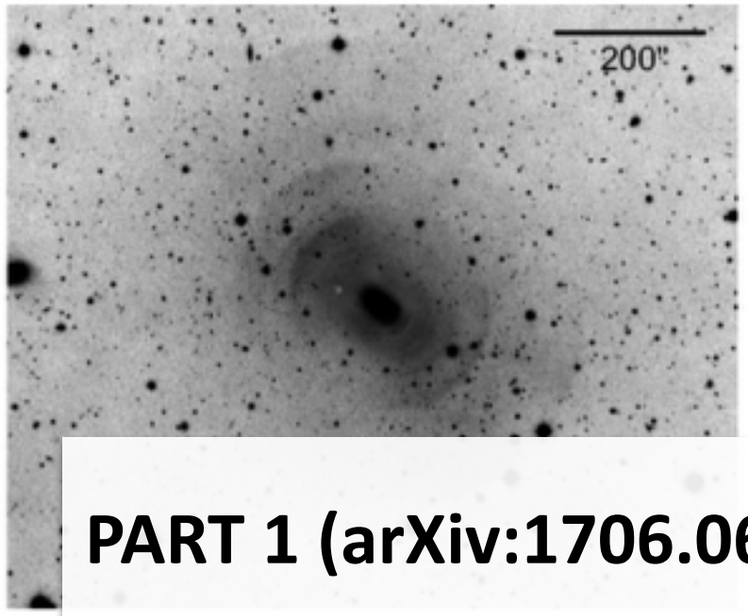

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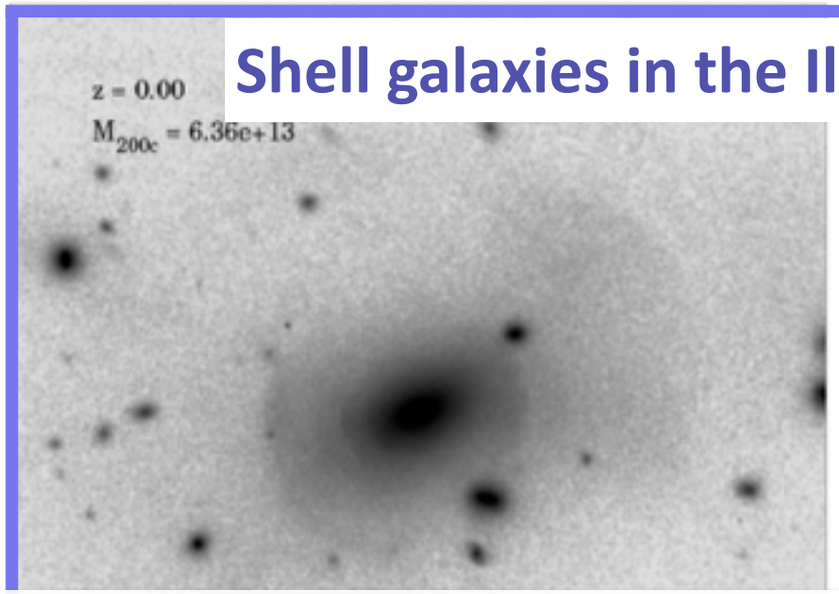
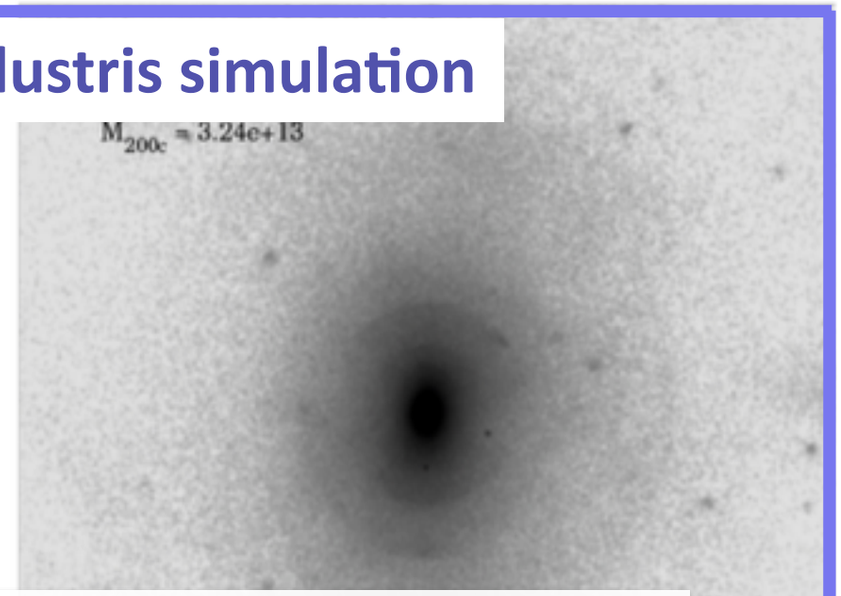


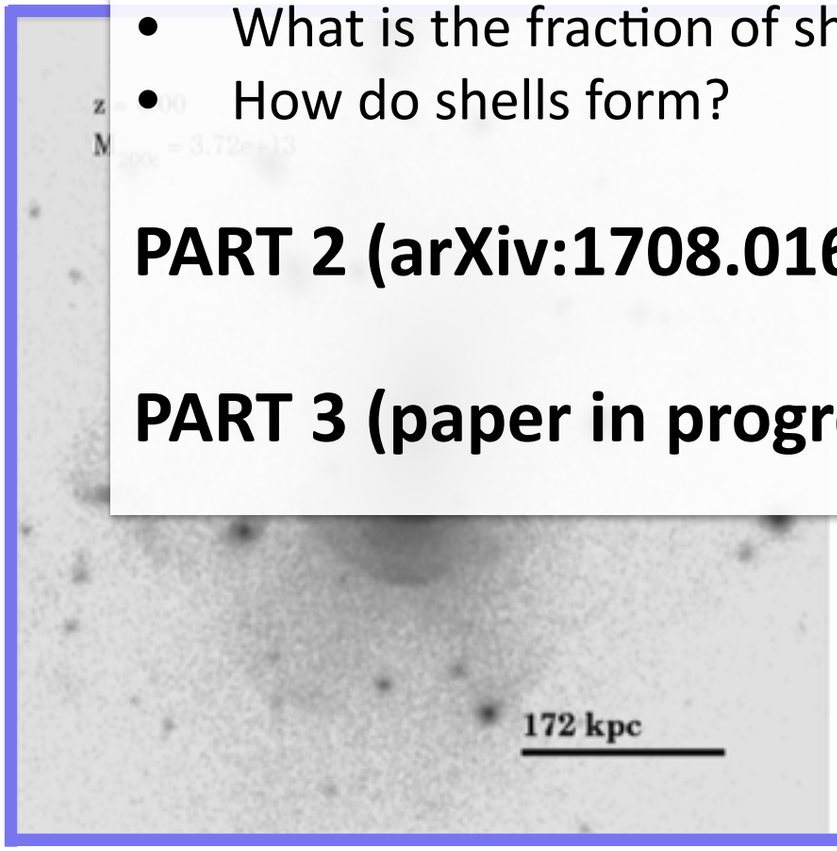


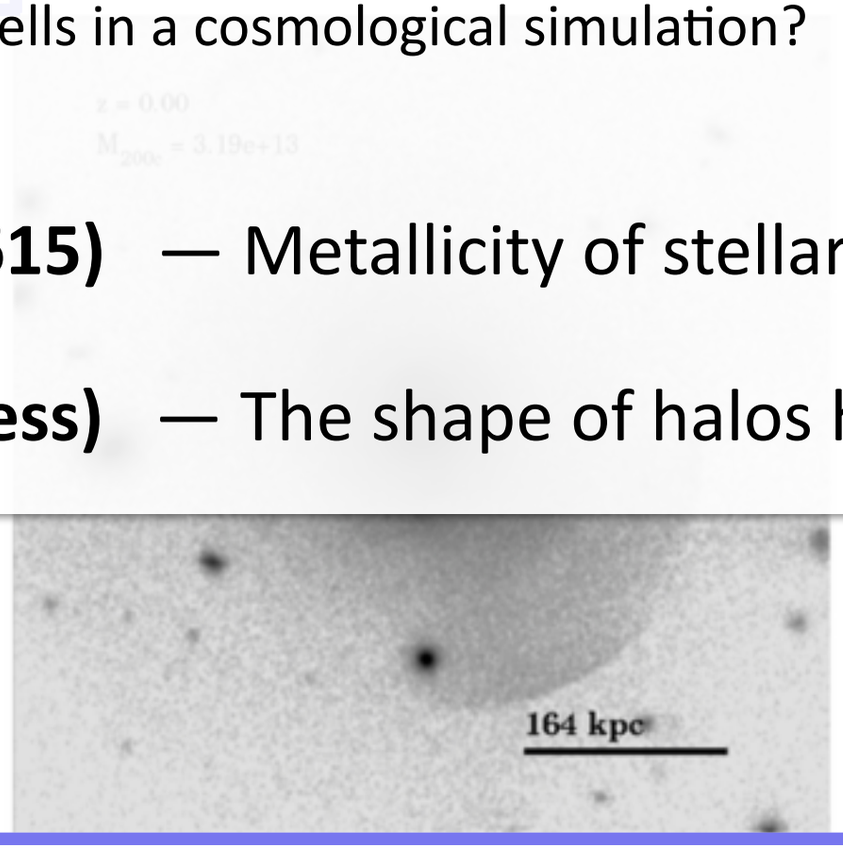
PART 1 (arXiv:1706.06102) — First study of shell galaxies in a cosmological setting (Illustris)

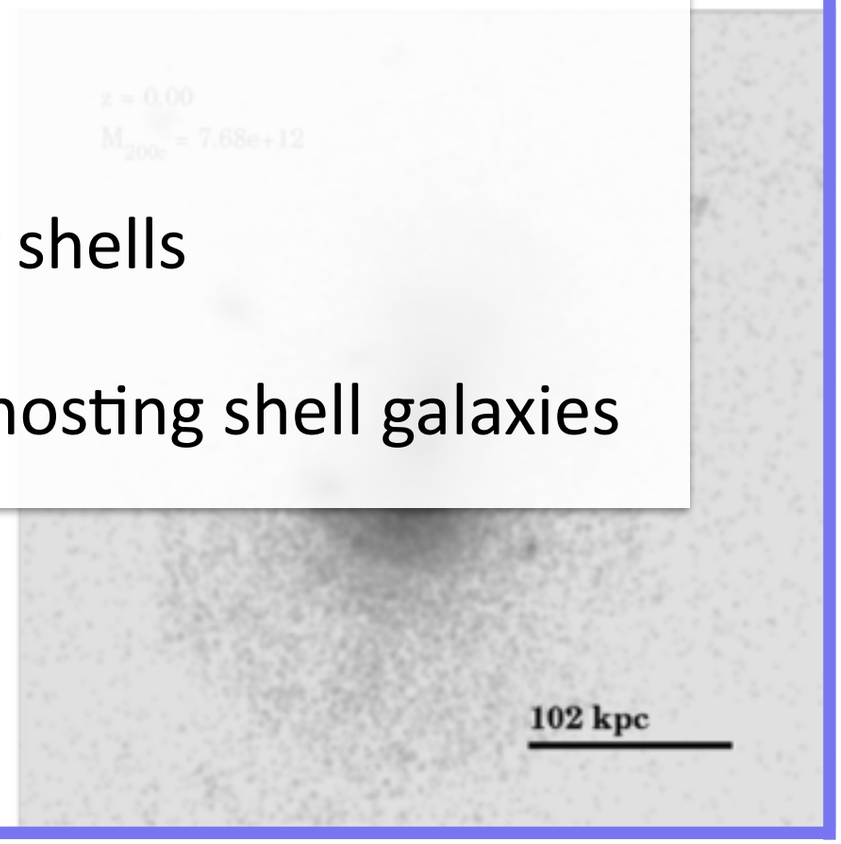
- What is the fraction of shells in a cosmological simulation?
- How do shells form?

PART 2 (arXiv:1708.01615) — Metallicity of stellar shells

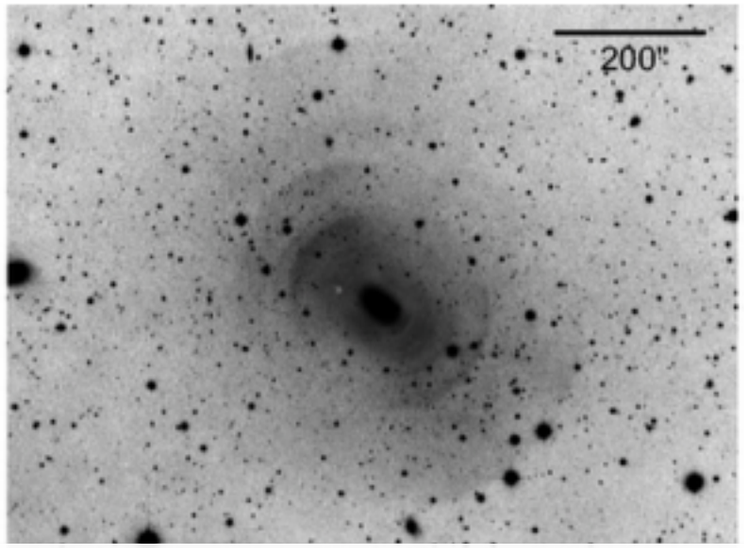
PART 3 (paper in progress) — The shape of halos hosting shell galaxies



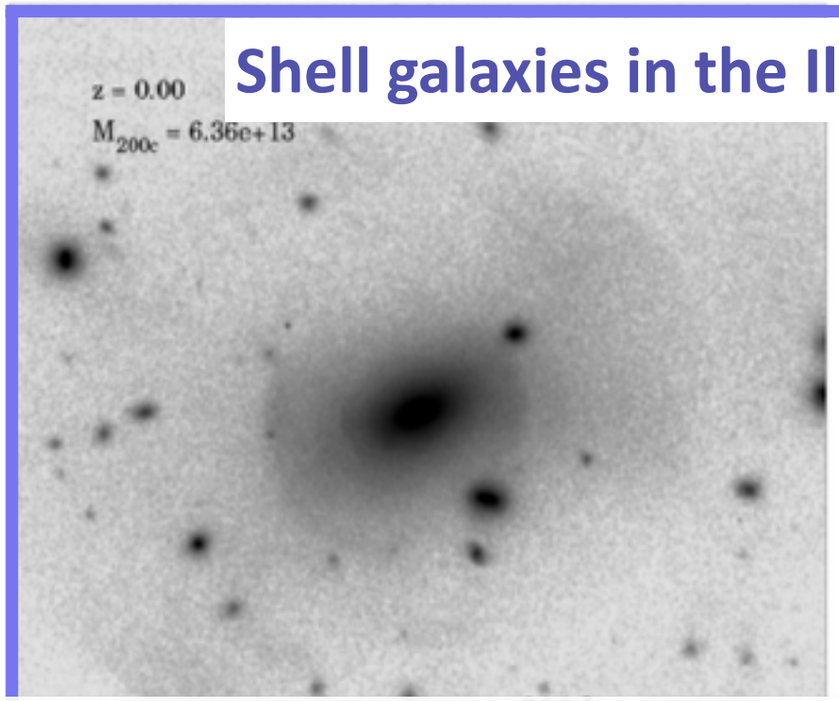


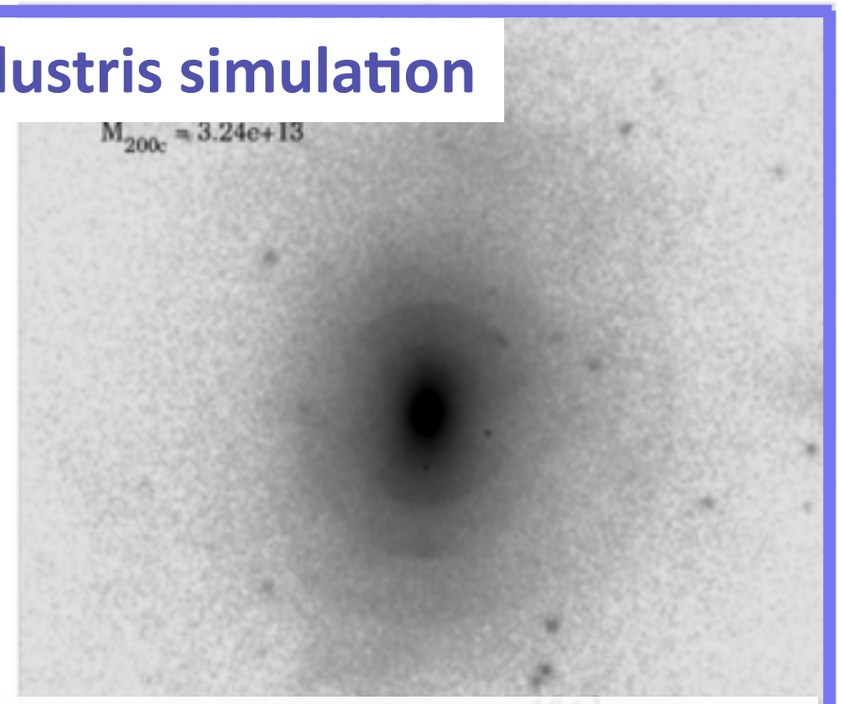


Observed shell galaxy
NGC 3923



Shell galaxies in the Illustris simulation



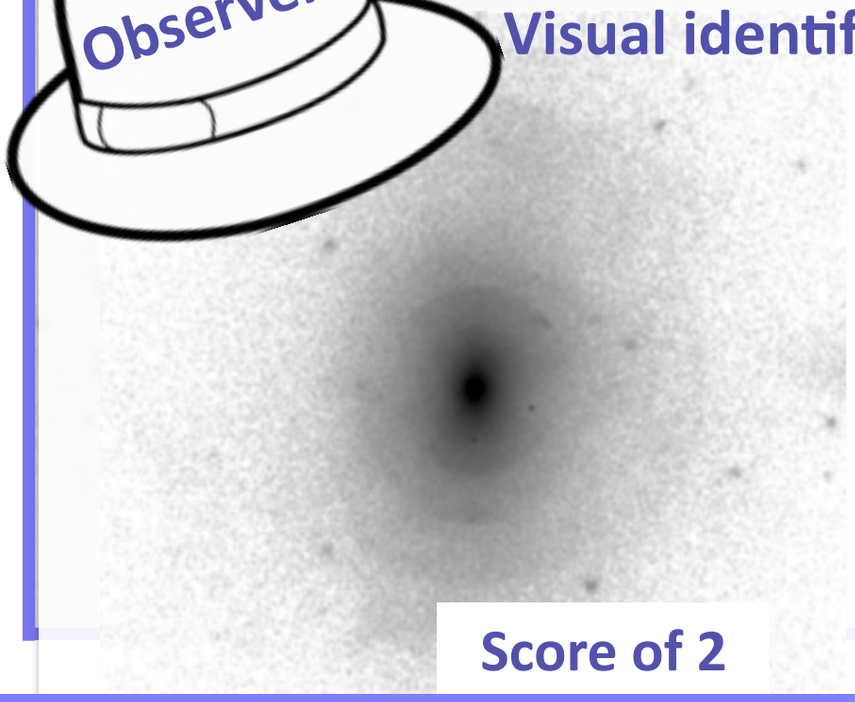


Galaxy sample: 220 most massive galaxies in Illustris at z=0, $\mathrm{M_{200crit}} > 6 \times 10^{12}\,\mathrm{M_\odot}$

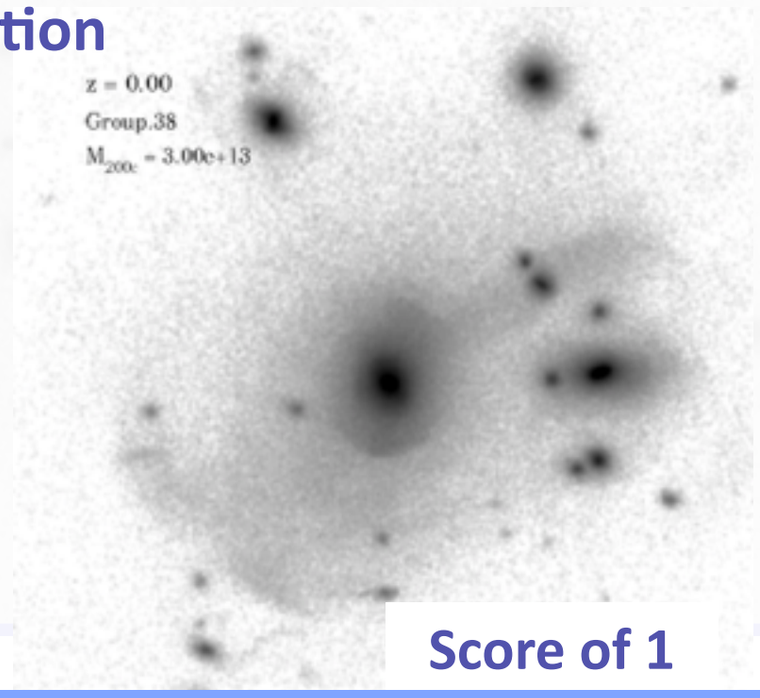
Two selection steps:

Step 1

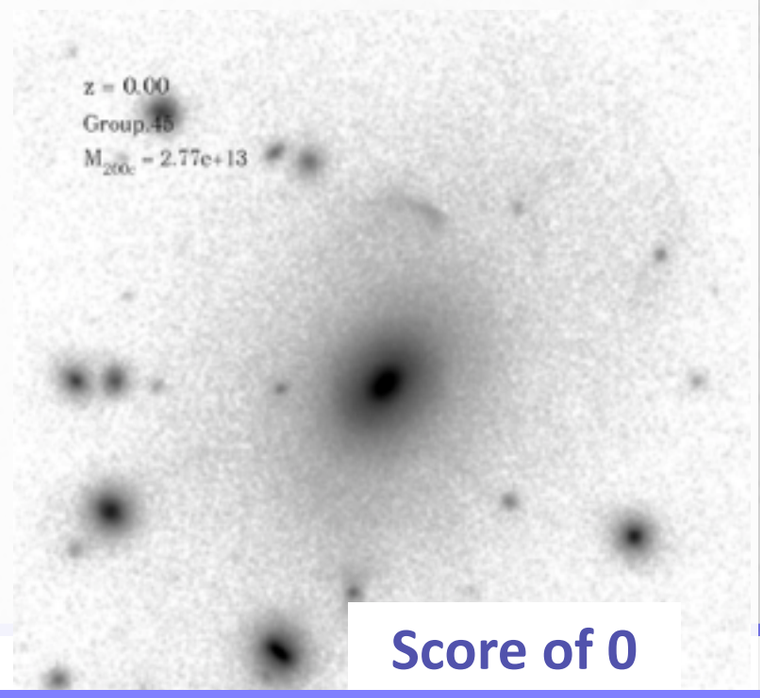
Visual identification



Score of 2

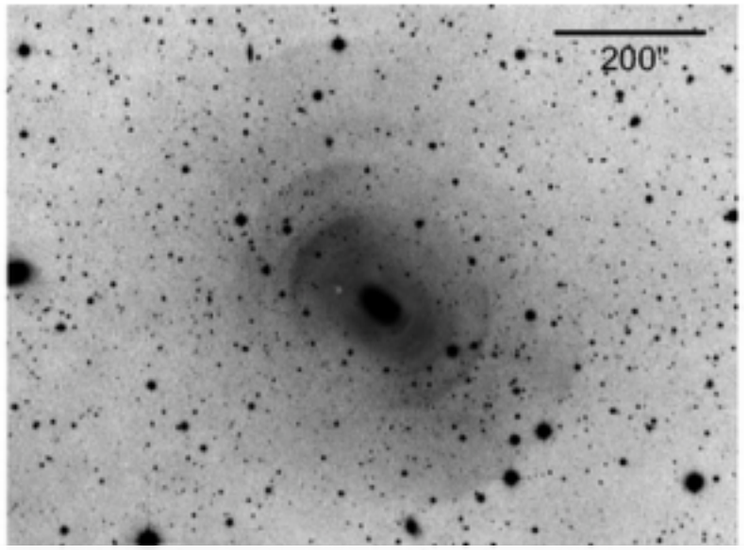


Score of 1

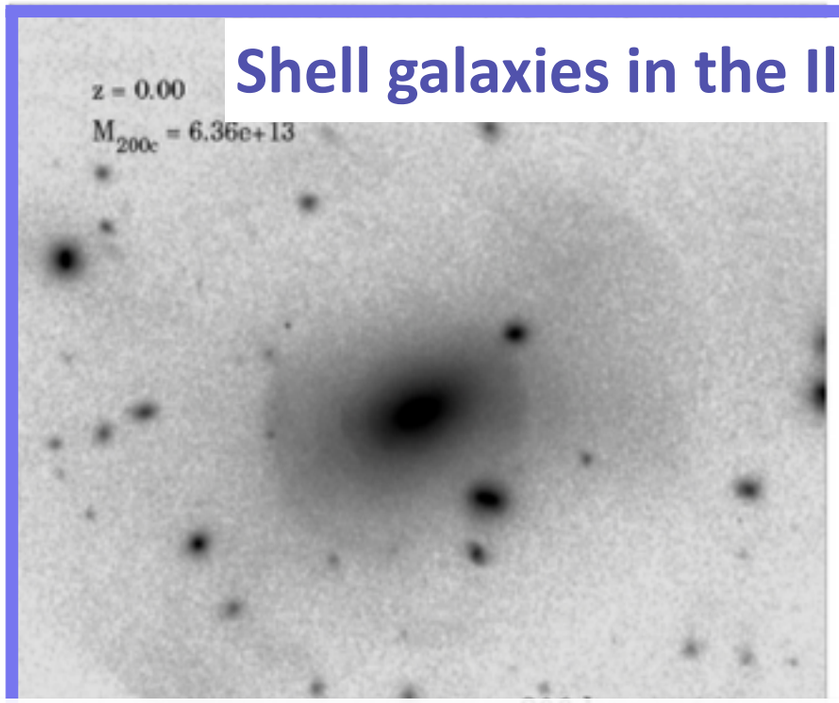


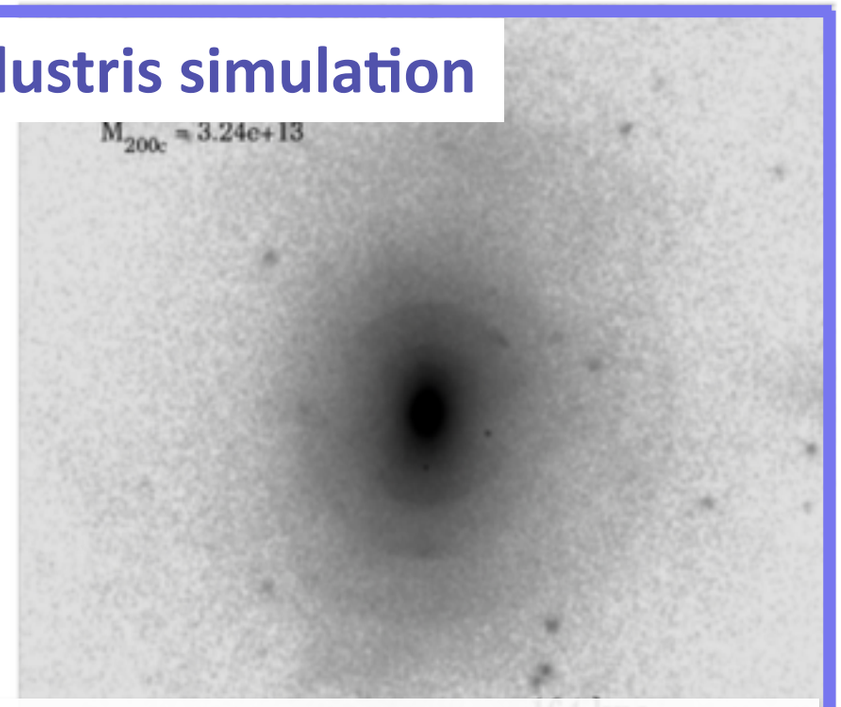
Score of 0

Observed shell galaxy
NGC 3923



Shell galaxies in the Illustris simulation





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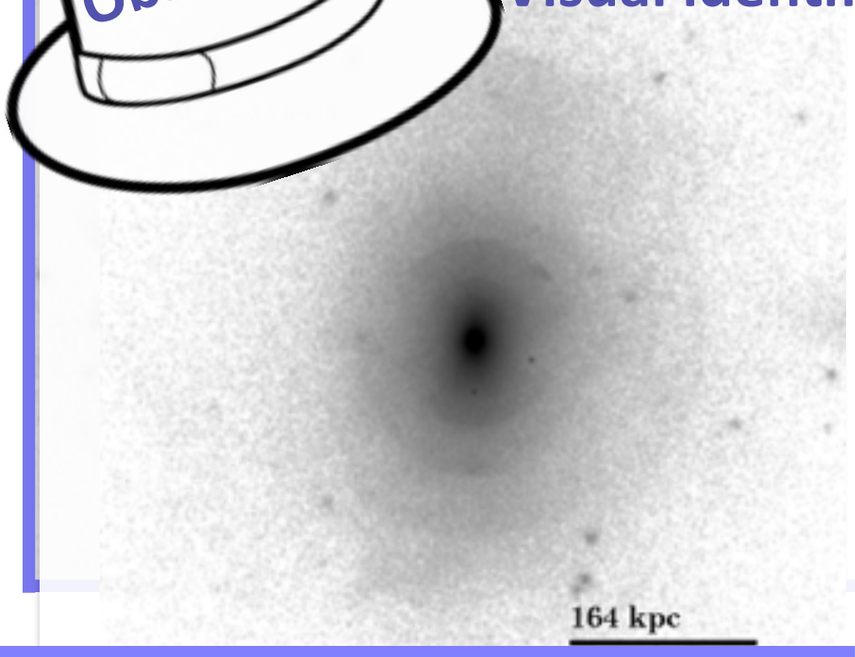
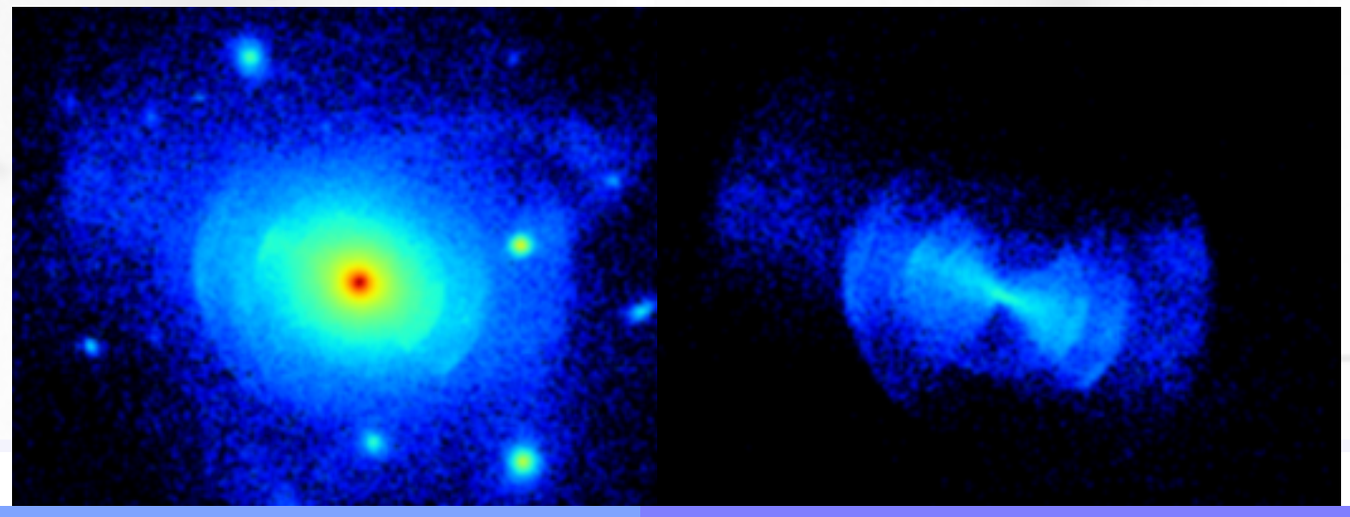
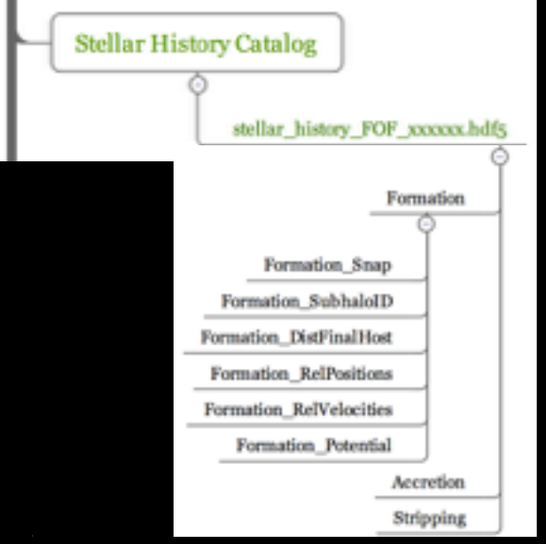


Step 2

Stellar History Catalogs &
tracing the individual satellites forming shells

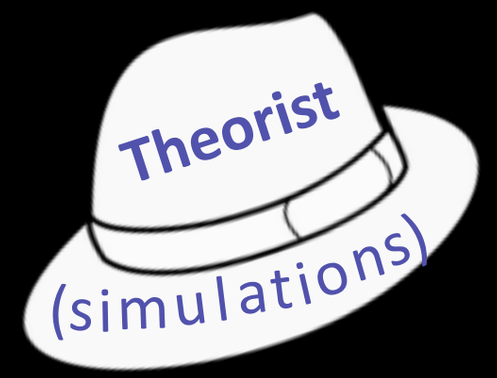


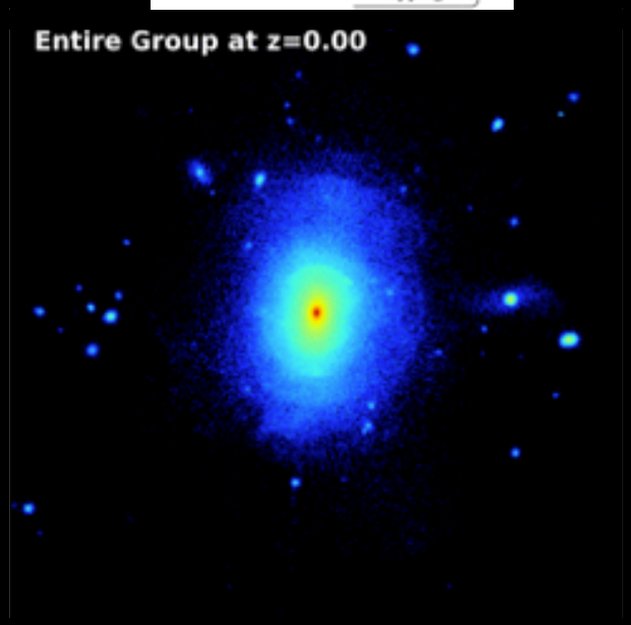


At each important time in the lifetime of a star **(formation, accretion, stripping)** we save information about the star and its progenitor galaxy.

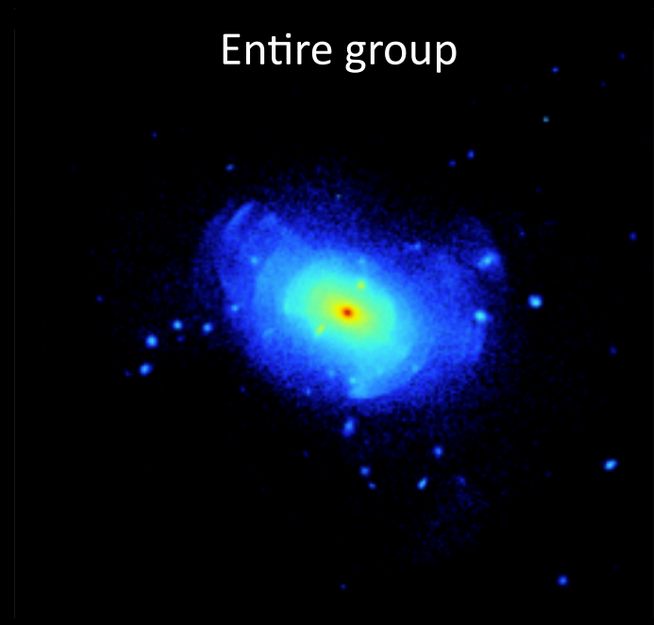
Step 2

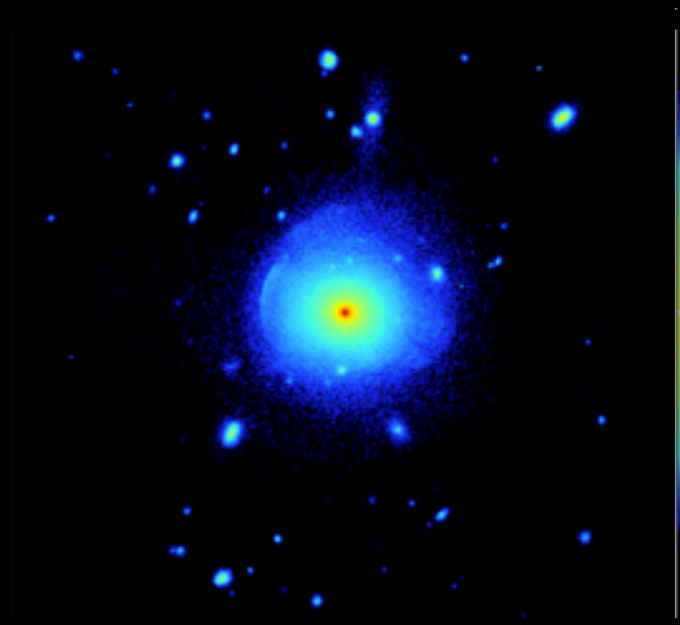
Stellar History Catalogs & tracing the individual satellites forming shells

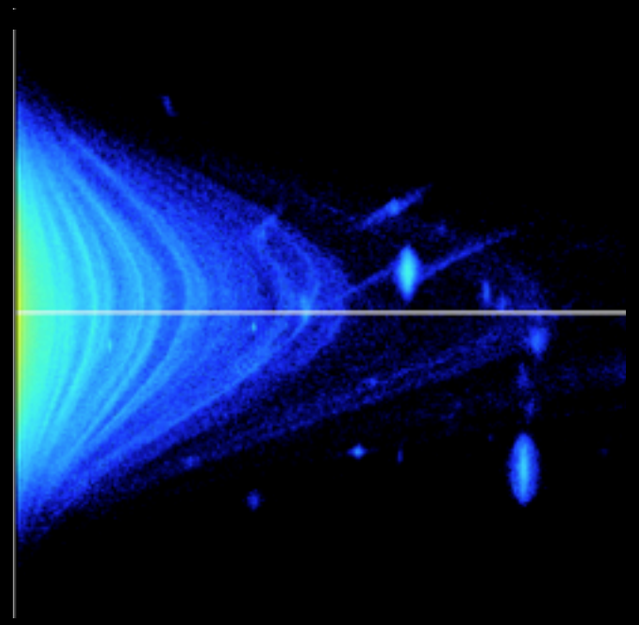


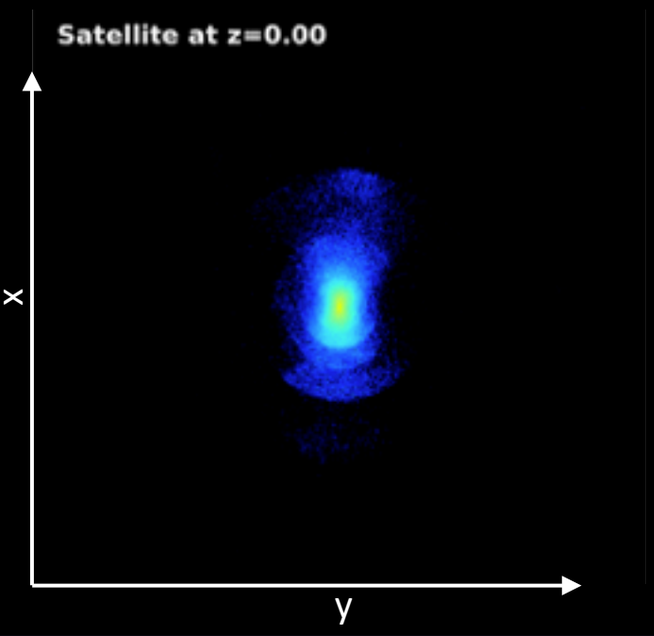


Entire group

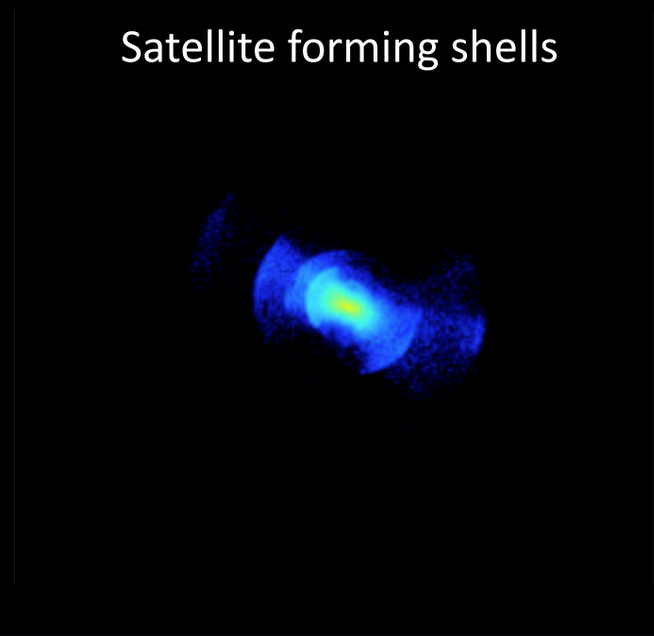


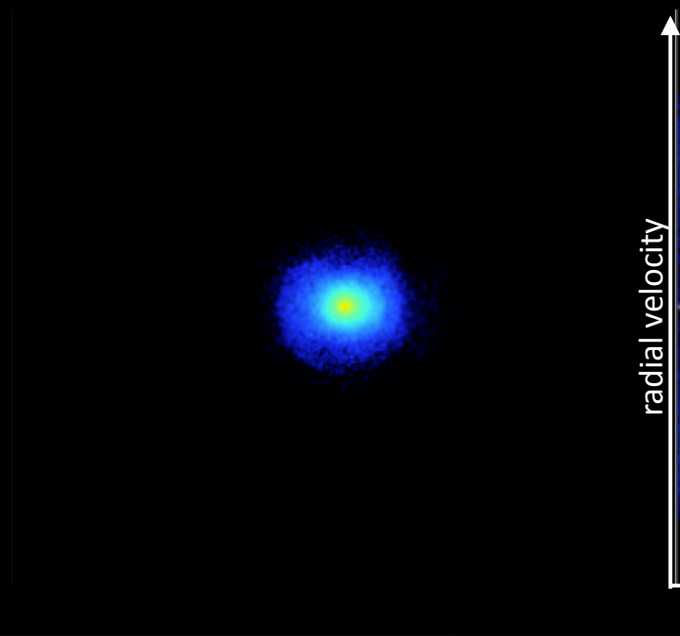


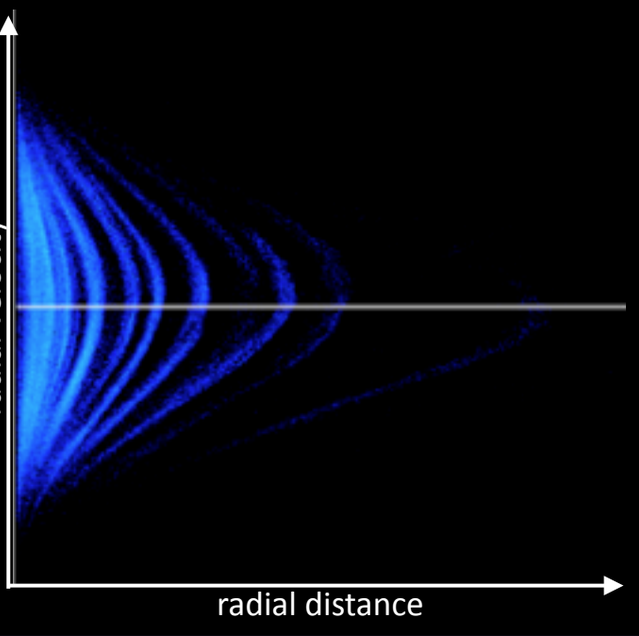




Satellite forming shells

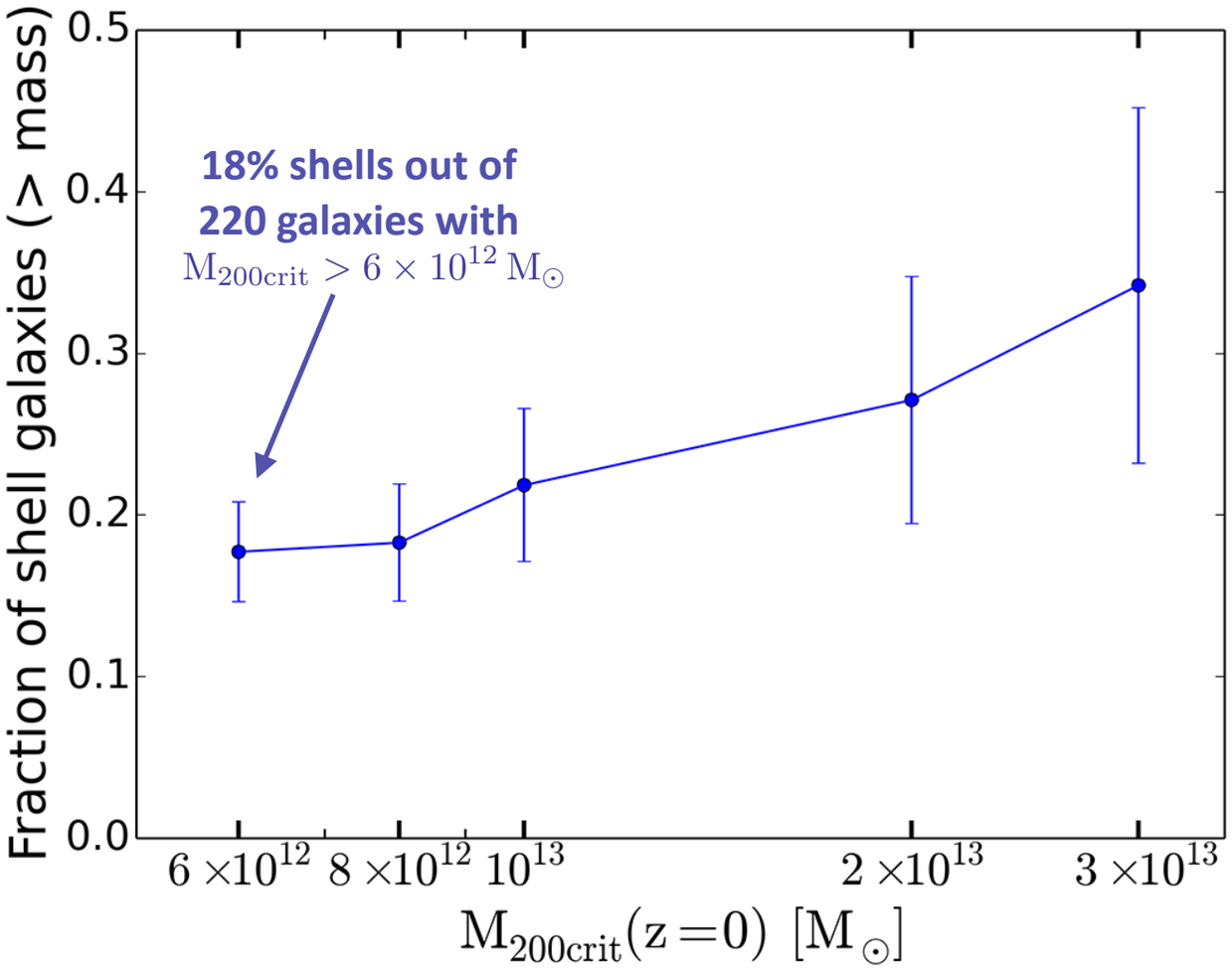


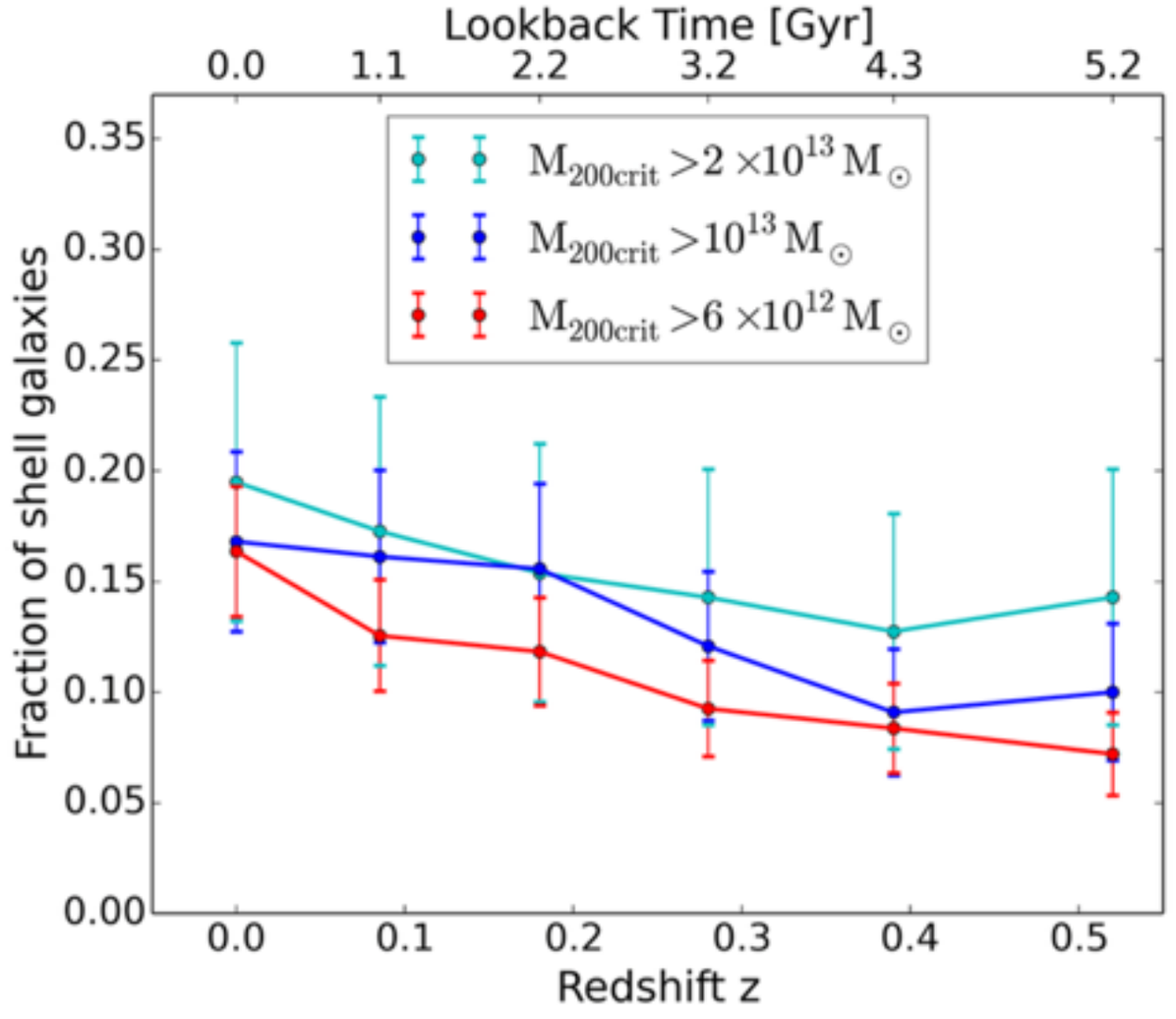




Shell Galaxies in Illustris

We find that the fraction of shell galaxies increases with stellar and virial mass.
In our total sample of 220 galaxies, we find 18% +/- 3% of the galaxies have shells.
This estimate is in overall agreement with the latest observations.





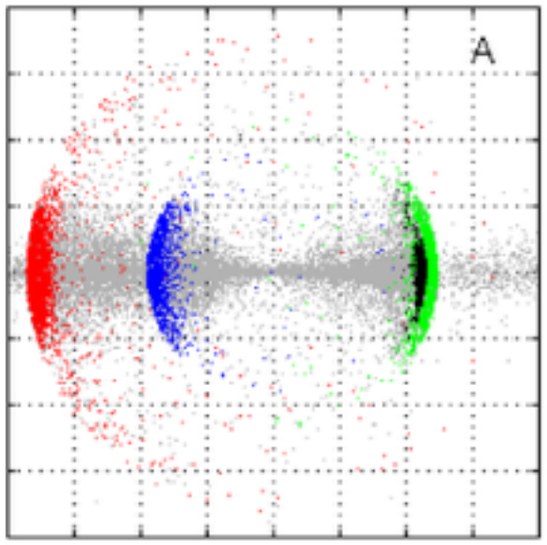
Pop+2017a, arXiv:1706.06102

The Progenitors of Shell Galaxies

increasing angular momentum

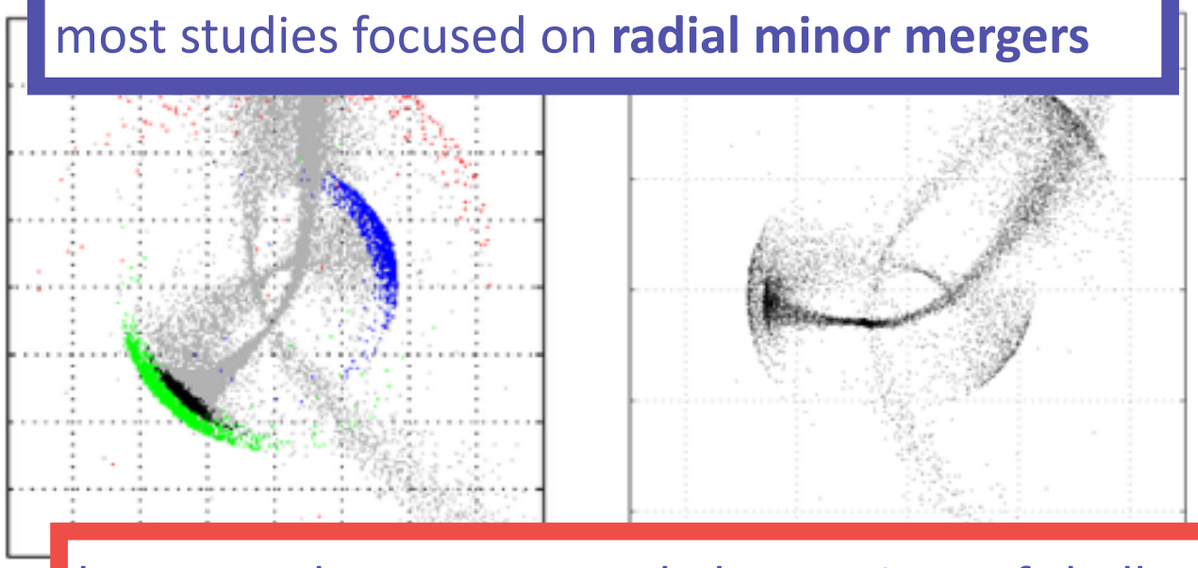
of the accreted satellite

radial orbit



SHELLS

most studies focused on **radial minor mergers**

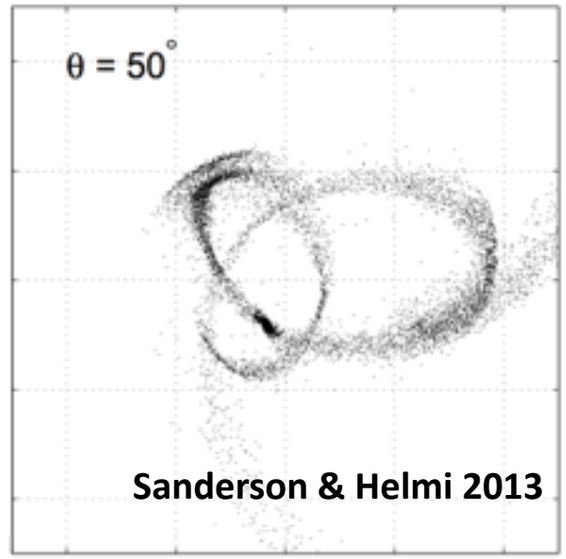


however, there are several observations of shells that seem to be the result of **major mergers**:

Schiminovich et al. 1995, Balcells et al. 2001

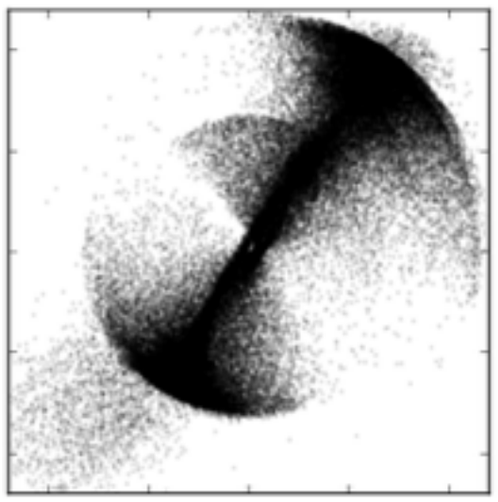
Goudfrooij et al. 2001, Serra et al. 2006

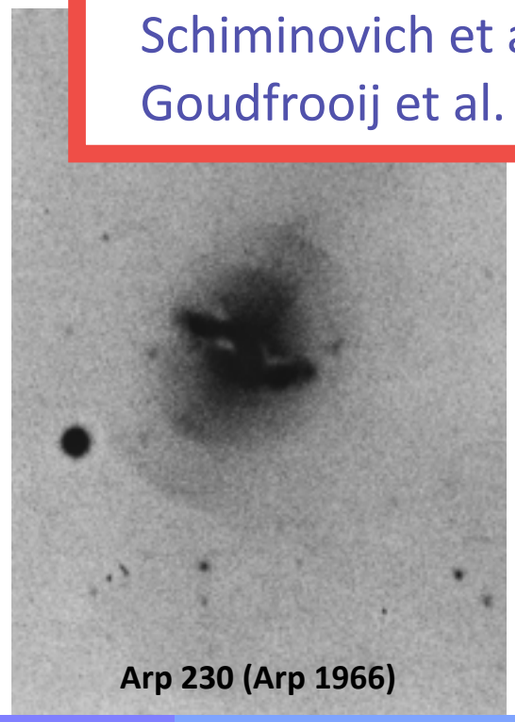
more circular orbit



Sanderson & Helmi 2013

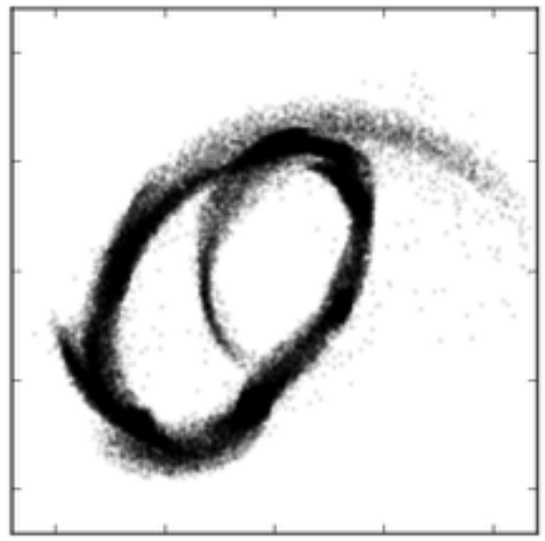
STREAMS





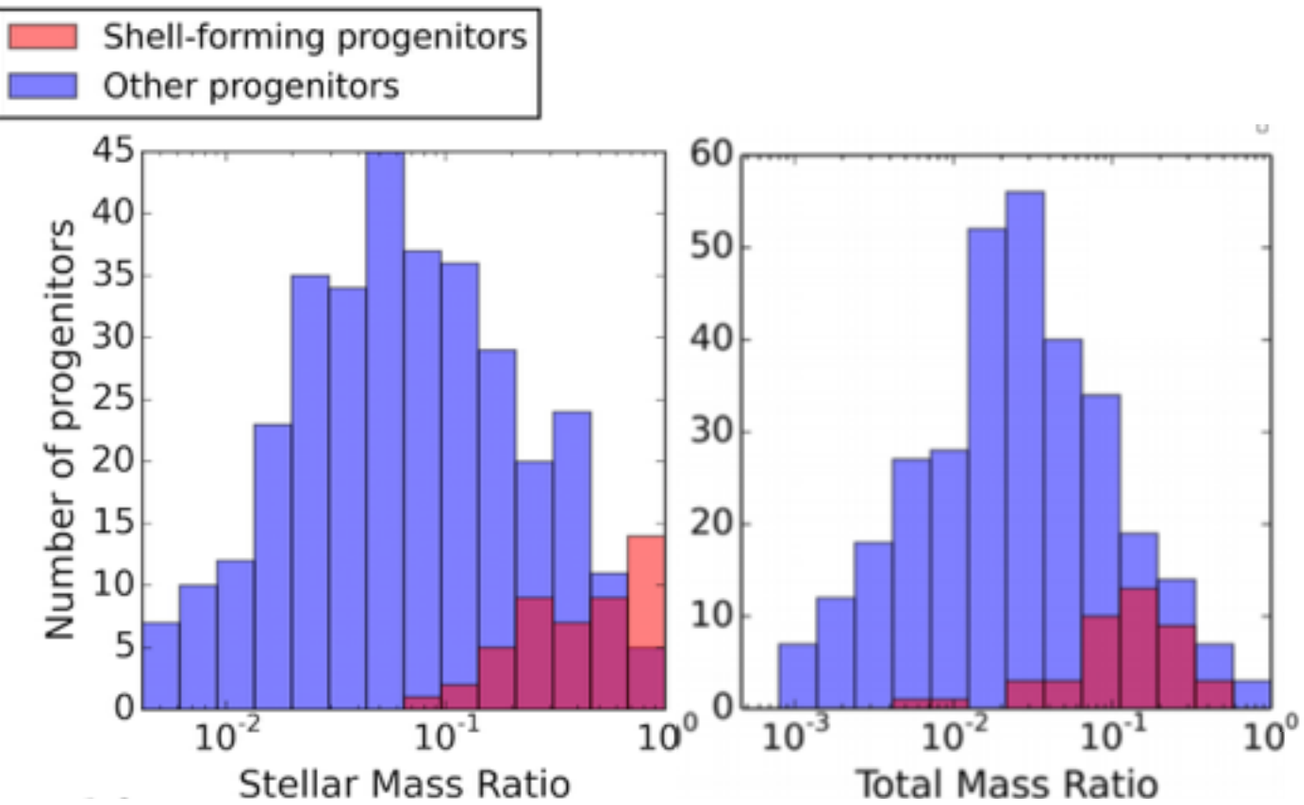
Arp 230 (Arp 1966)

Martinez-Delgado+2008



Hendel & Johnston 2015

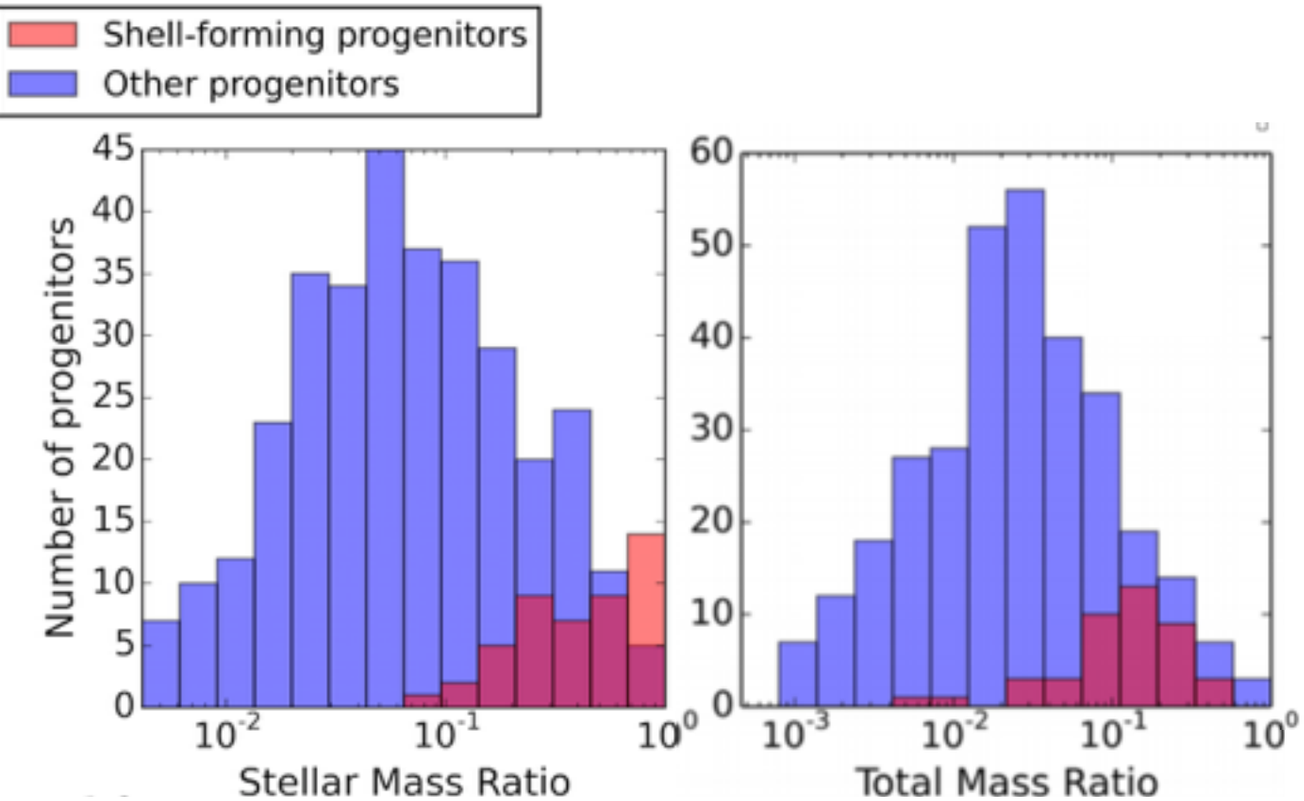
The Progenitors of Shell Galaxies



We aim to identify the key parameters that make a satellite likely to form shells in a **cosmological setting.**

the satellites forming shells are relatively massive compared to the host galaxy!

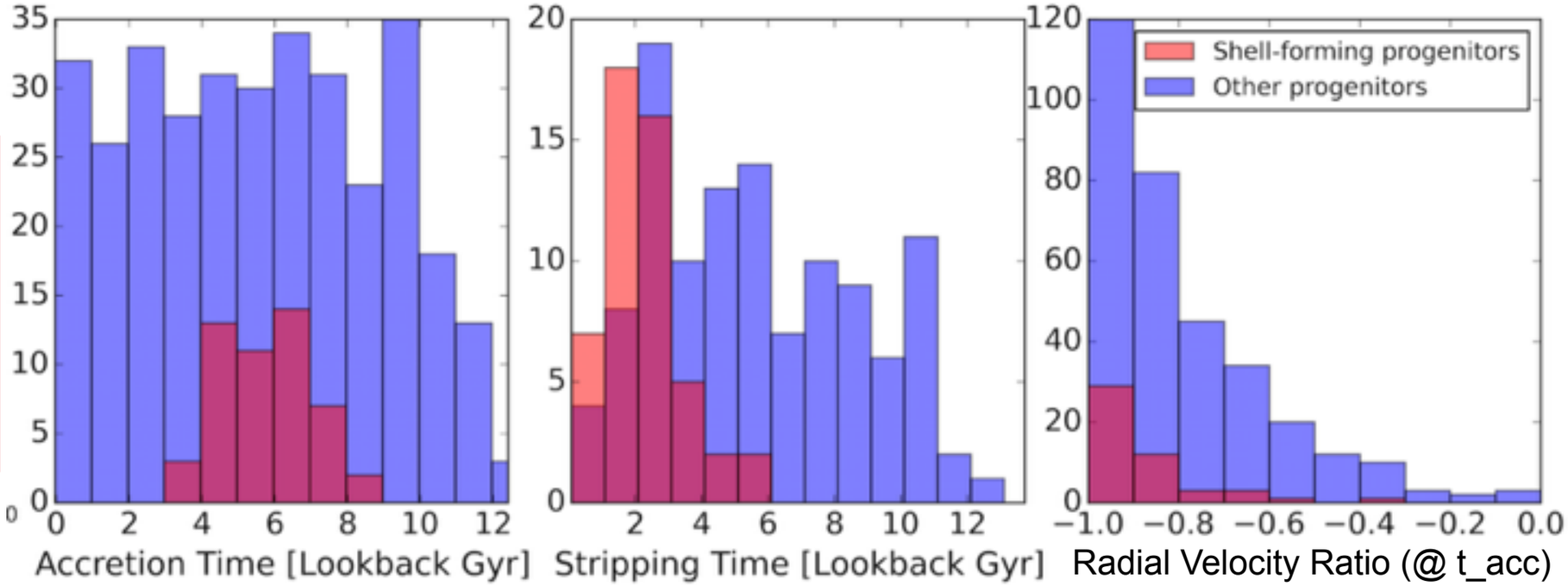
The Progenitors of Shell Galaxies



We aim to identify the key parameters that make a satellite likely to form shells in a **cosmological setting.**

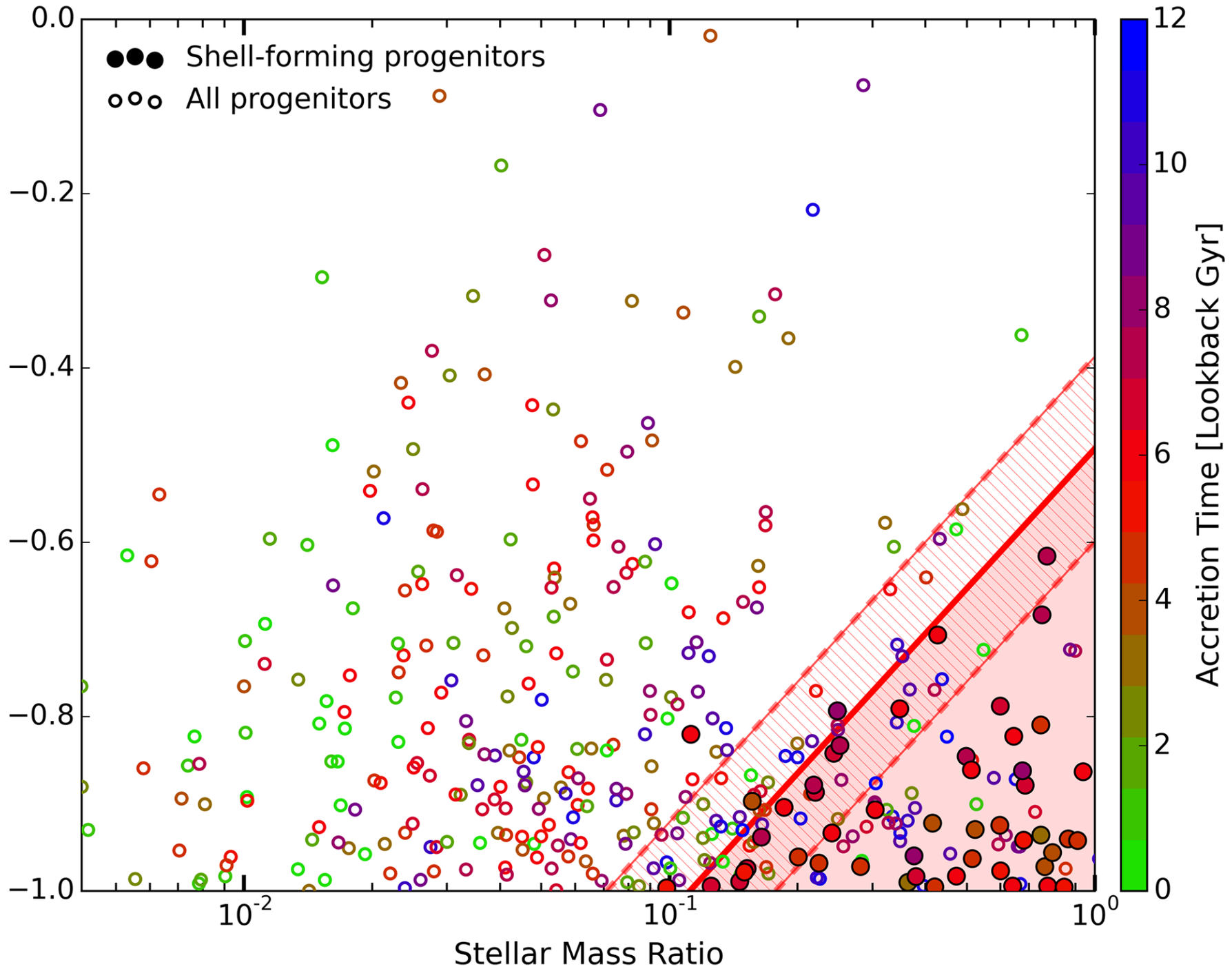
Order-zero recipe:

1. radial infall orbit
2. massive satellite
3. accretion time 4-8 Gyr ago



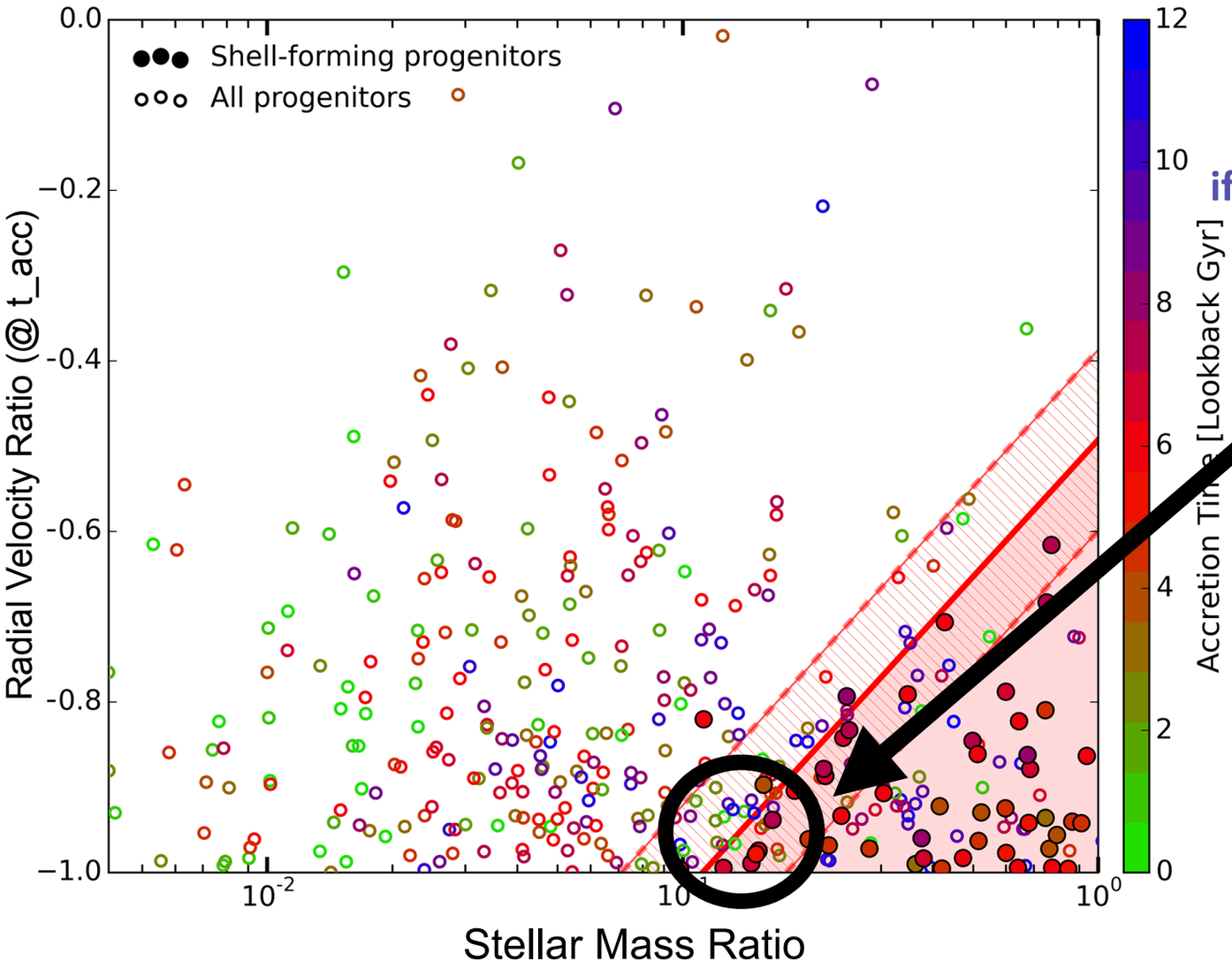
What type of mergers produce shell galaxies?

Radial Velocity Ratio at **Accretion Time**

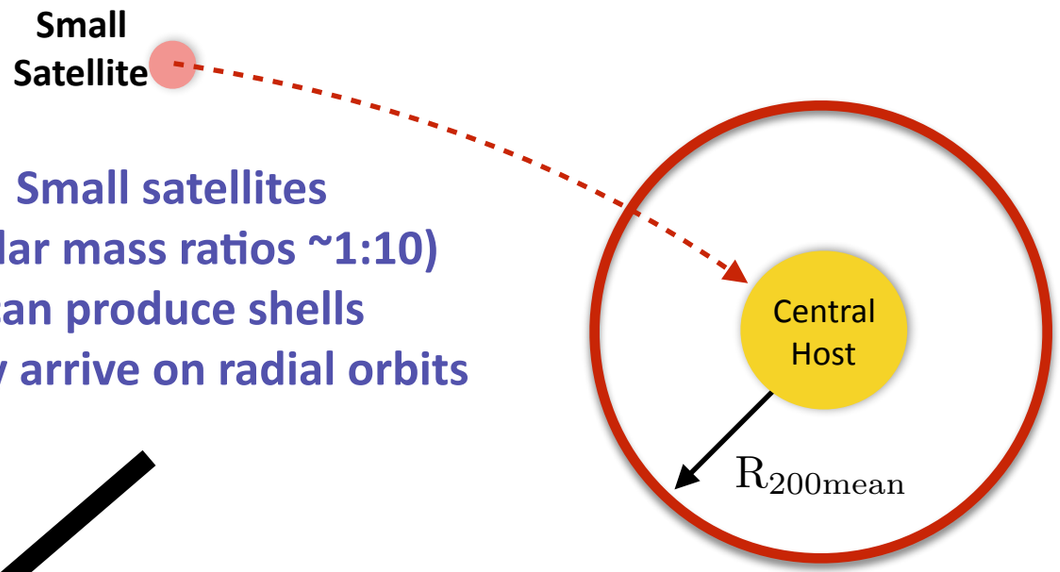


Pop+2017a, arXiv:1706.06102

What type of mergers produce shell galaxies?

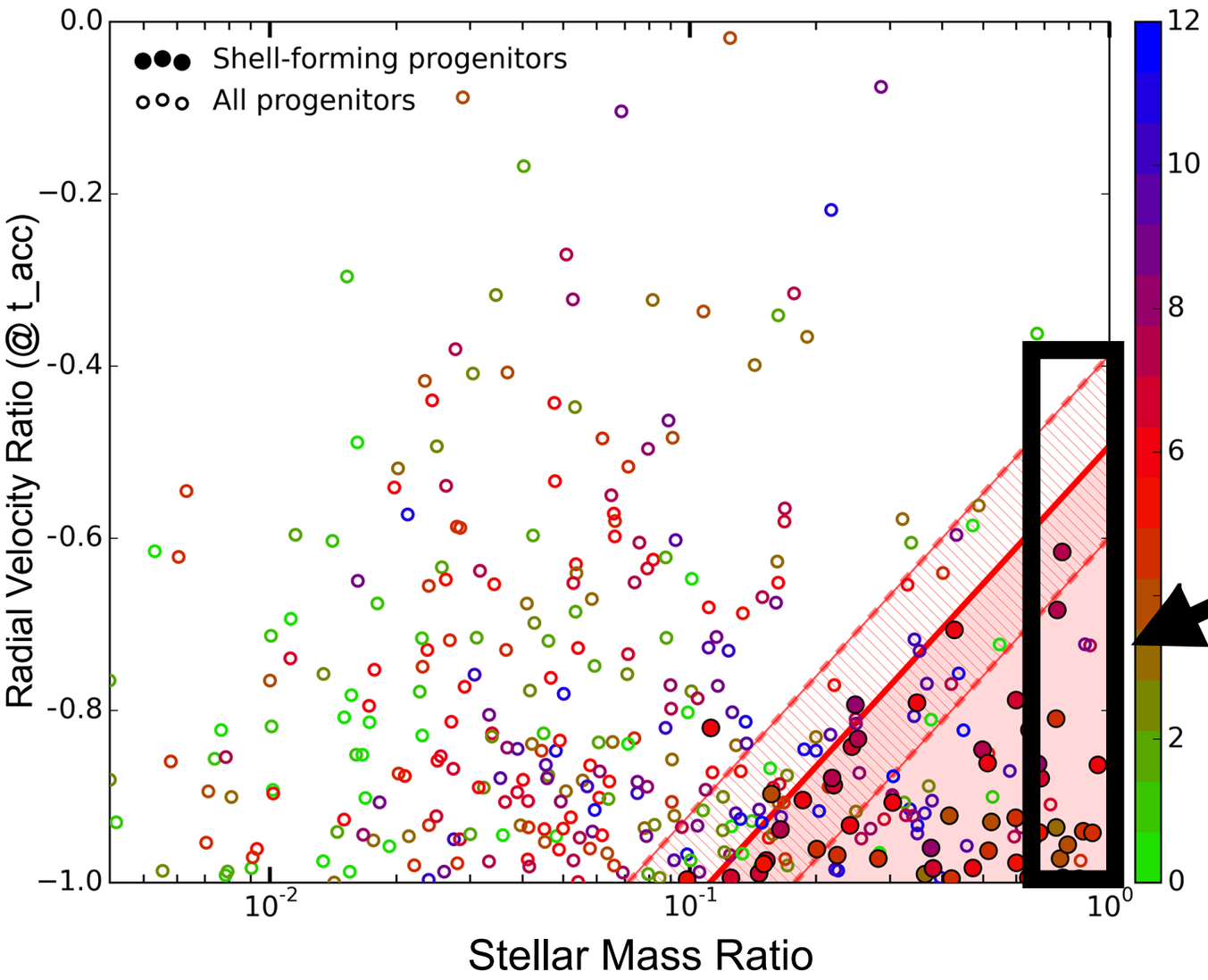


Small satellites (stellar mass ratios ~1:10) can produce shells if they arrive on radial orbits



Pop+2017a, arXiv:1706.06102

What type of mergers produce shell galaxies?



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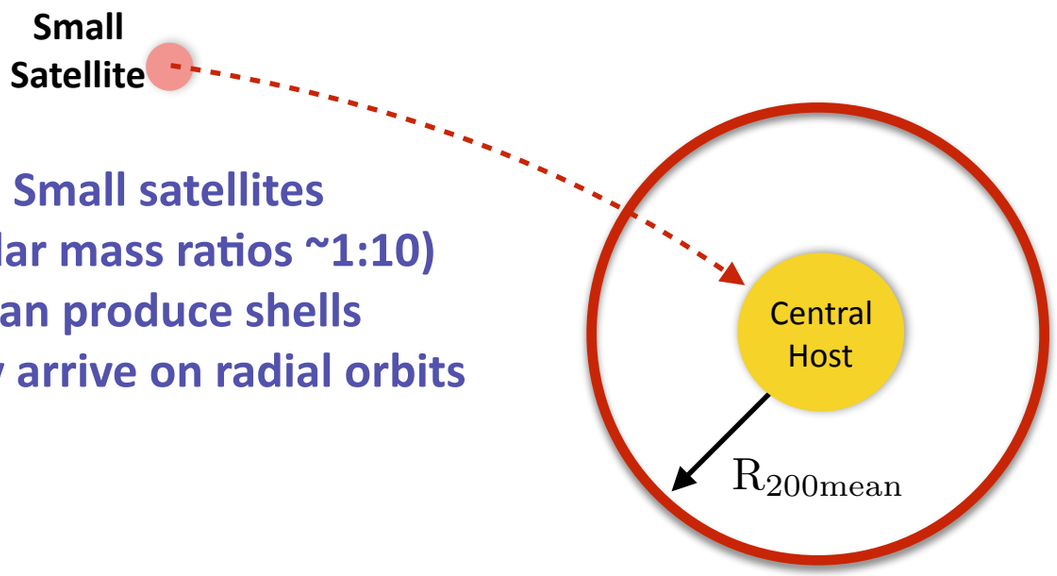
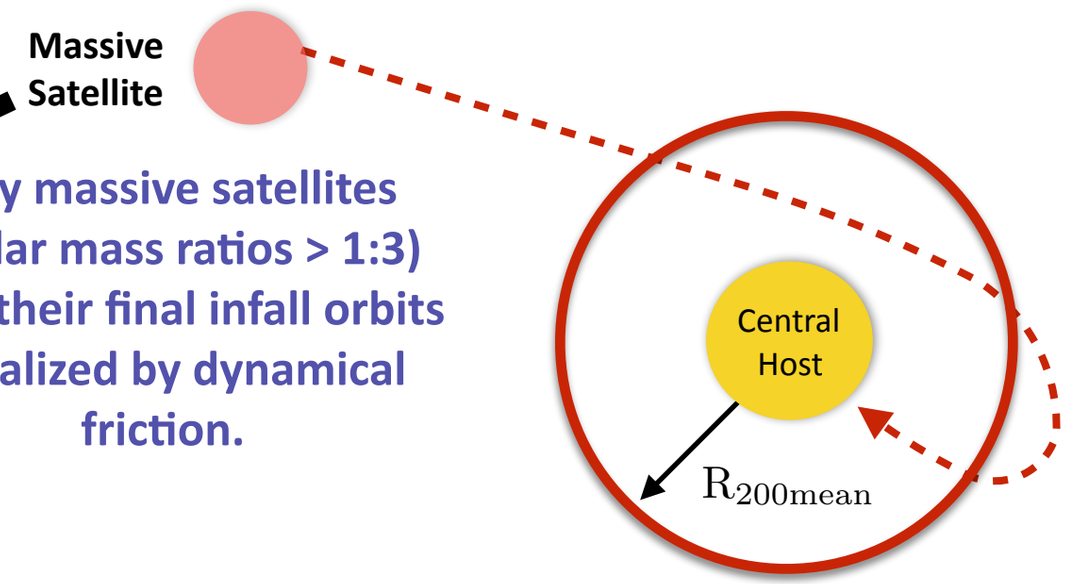


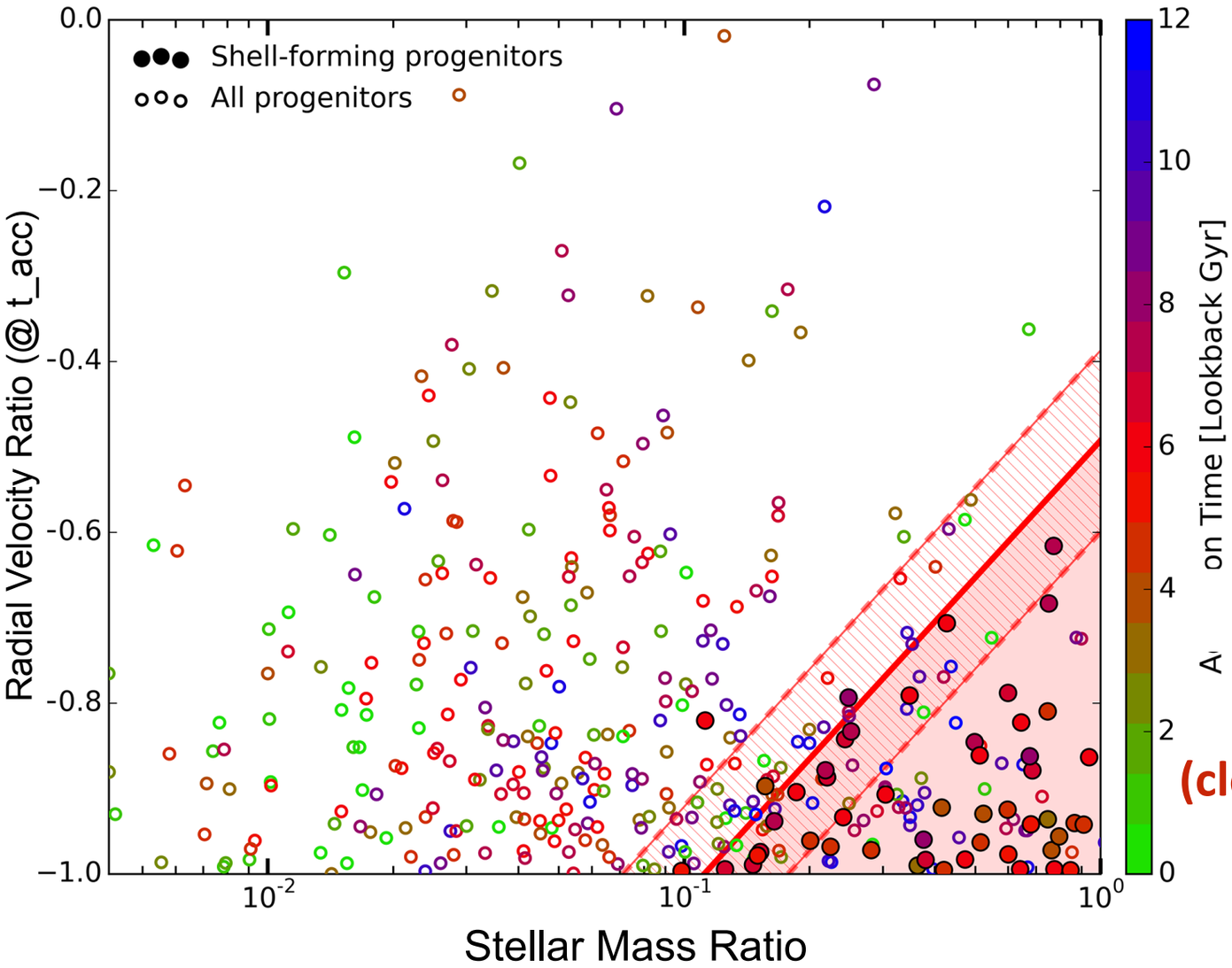
Very massive satellites (stellar mass ratios > 1:3) have their final infall orbits radialized by dynamical friction.

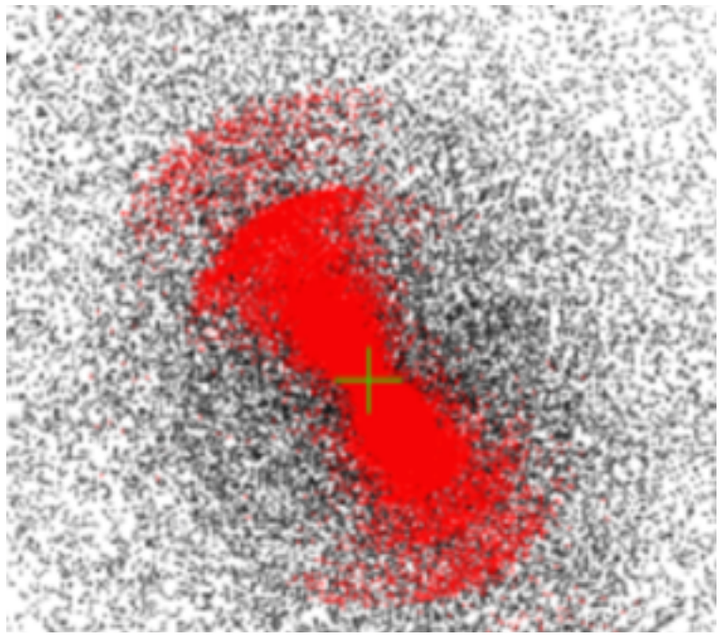


Pop+2017a, arXiv:1706.06102

What type of mergers produce shell galaxies?

Remember
Nicola “the younger”
talk on Monday!



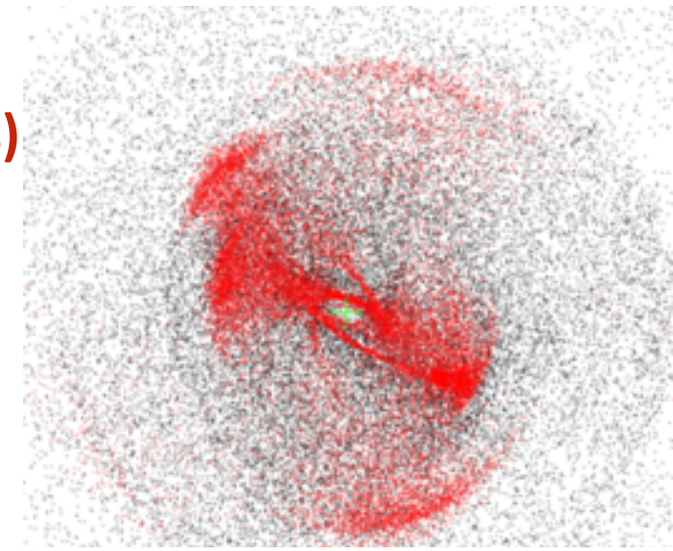


Msat/Mhost - 1/6

Amorisco 2017a

higher mass ratio
(close to major mergers)

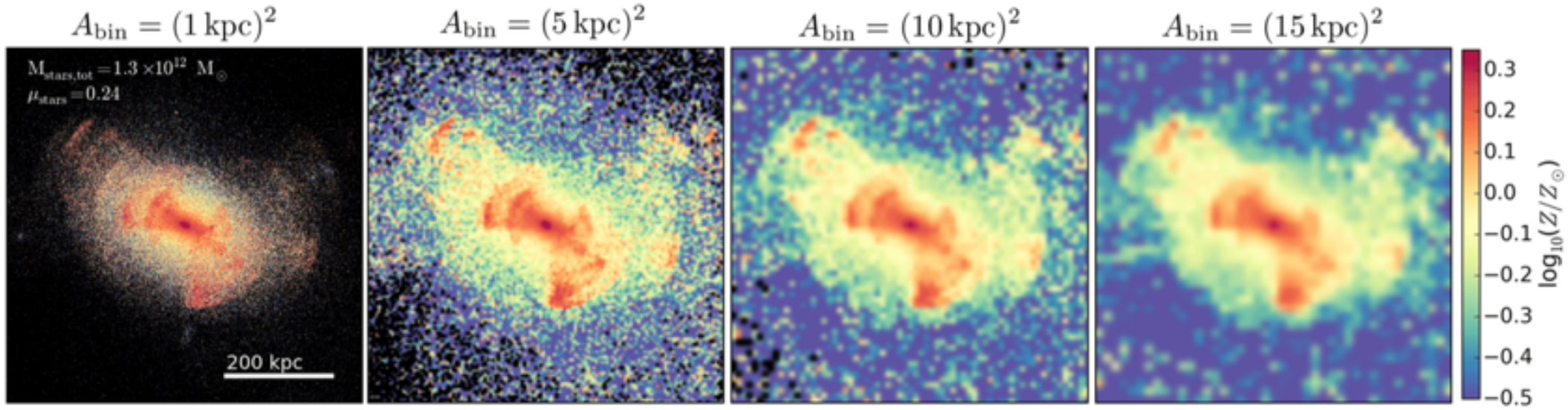
more efficient
orbit radialization

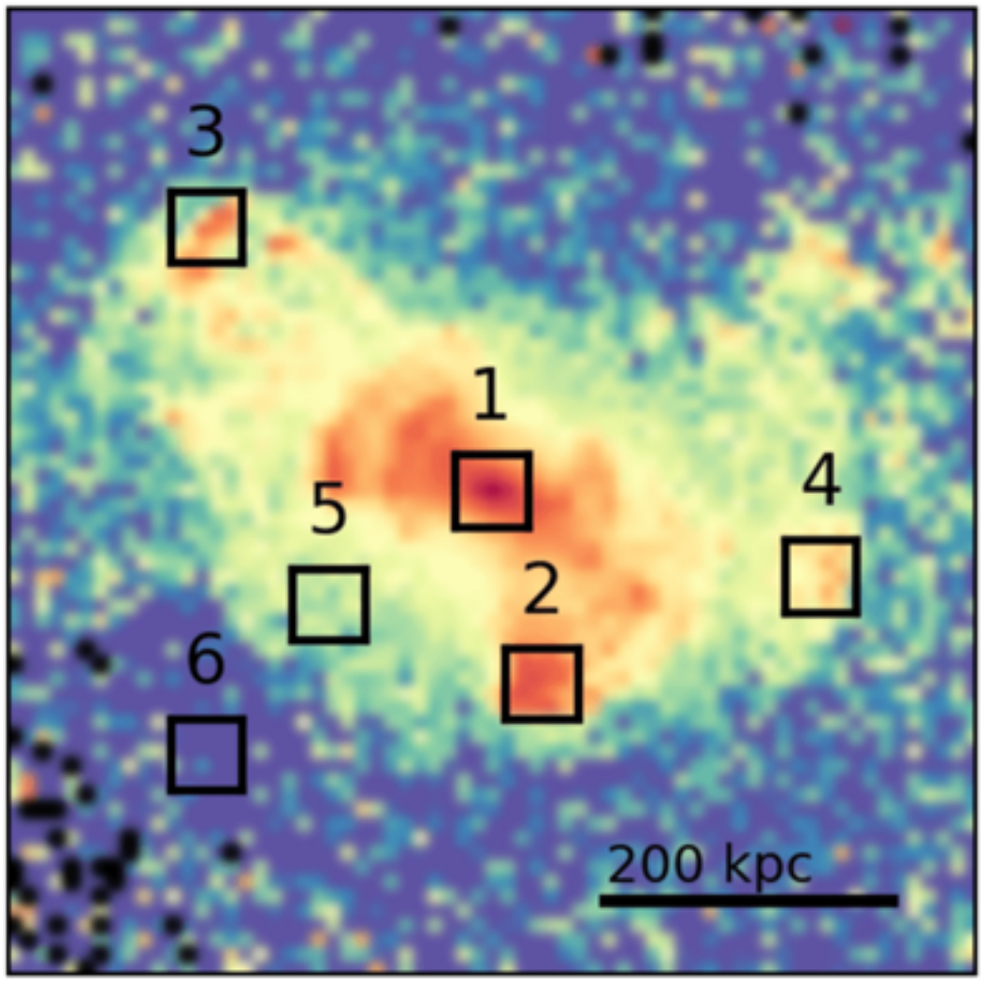


Msat/Mhost - 1/40

Pop+2017a, arXiv:1706.06102

Metallicities of Stellar Shells

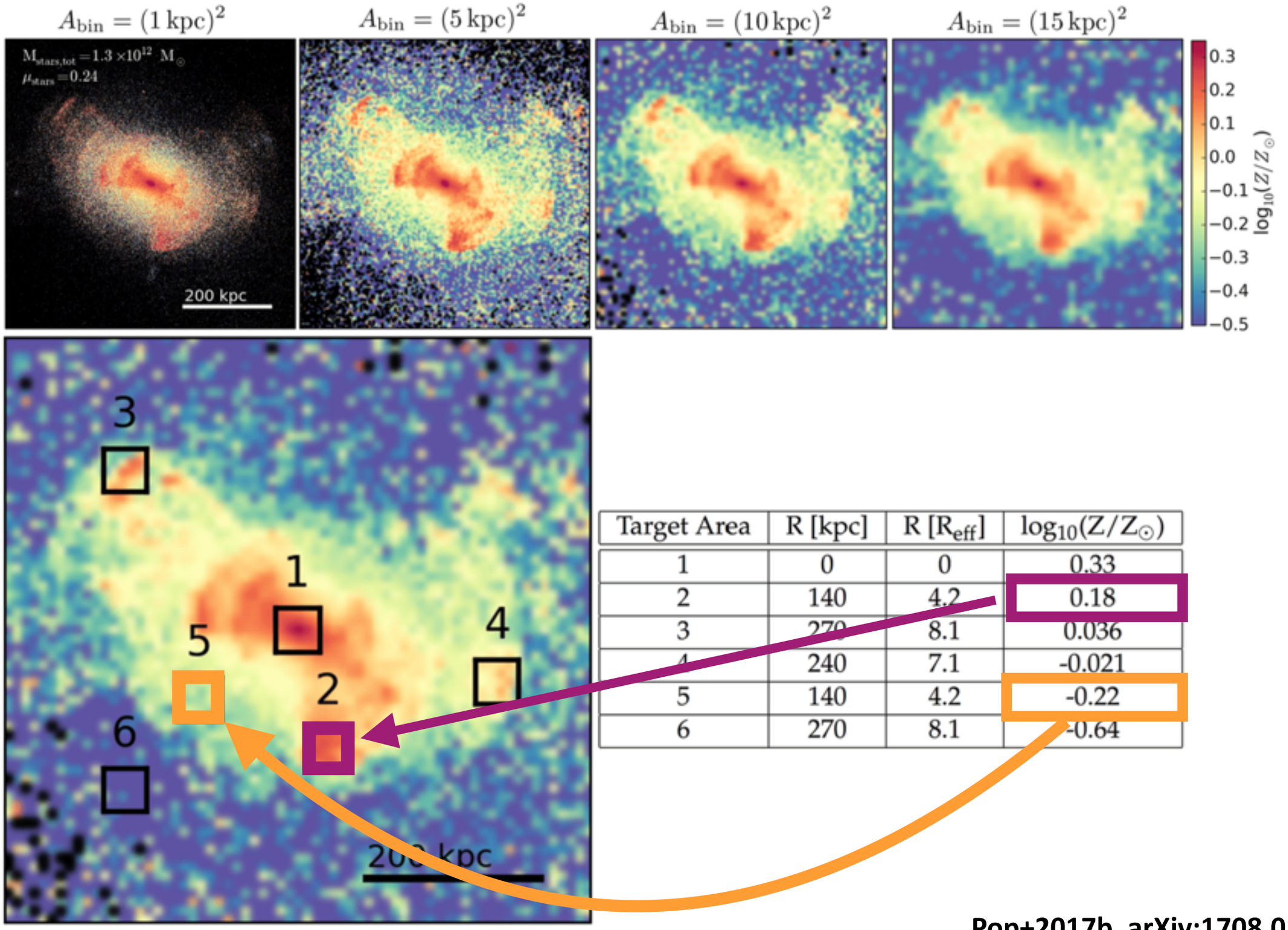




Stellar shells formed due to
relatively major mergers
can be more metal rich than host stars
at **similar radii**.

Pop+2017b, arXiv:1708.01615

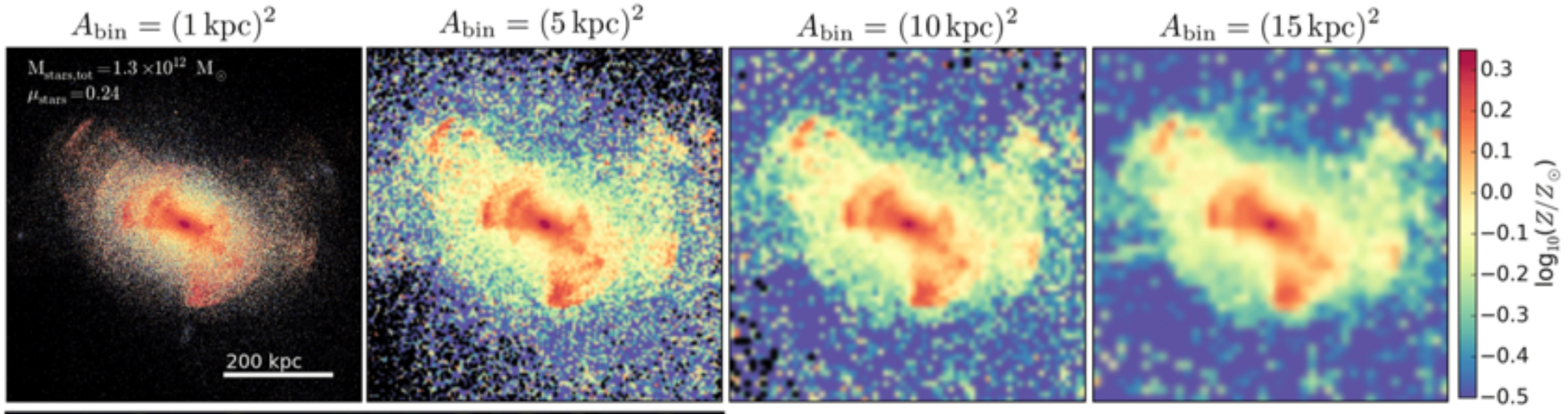
Metallicities of Stellar Shells

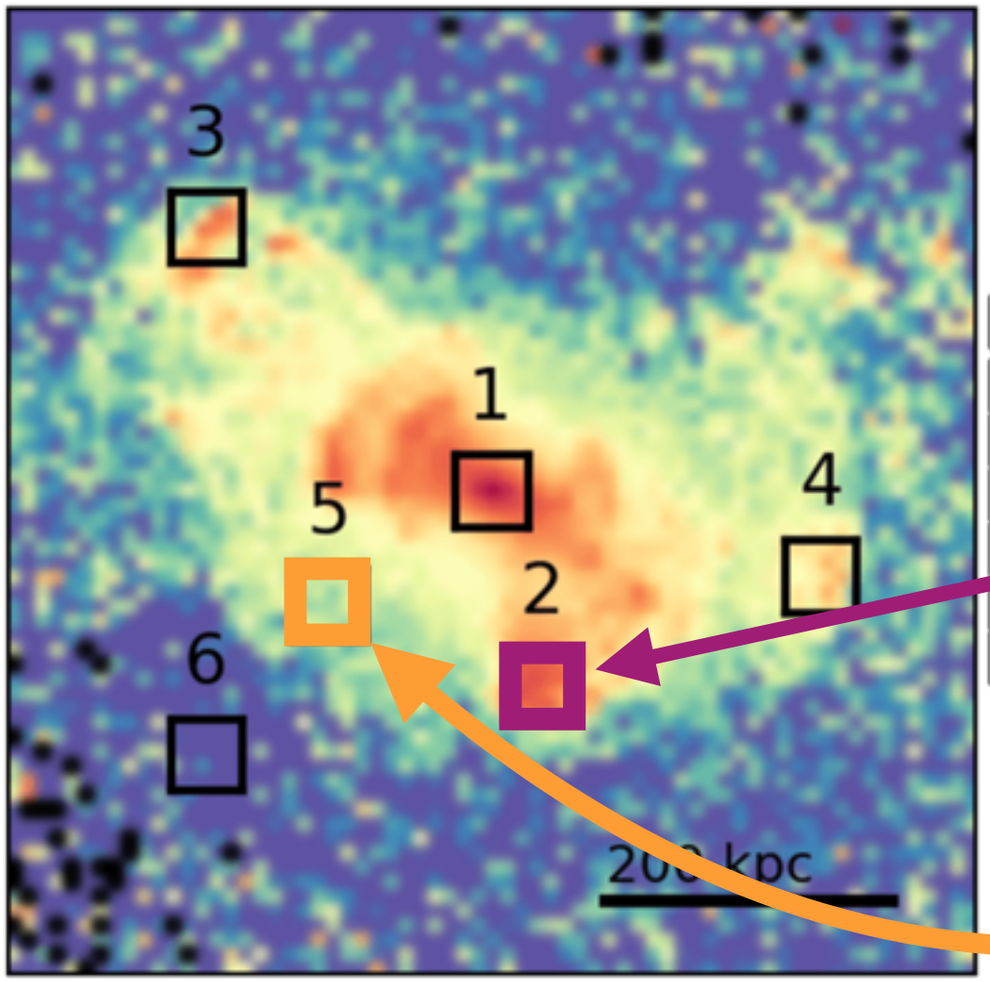


Target Area	R [kpc]	R [$R_{\rm eff}$]	$\log_{10}(Z/Z_\odot)$
1	0	0	0.33
2	140	4.2	0.18
3	270	8.1	0.036
4	240	7.1	-0.021
5	140	4.2	-0.22
6	270	8.1	-0.64

Pop+2017b, arXiv:1708.01615

Metallicities of Stellar Shells





See Erin's talk on observed HSC shells
arXiv:1805.05970

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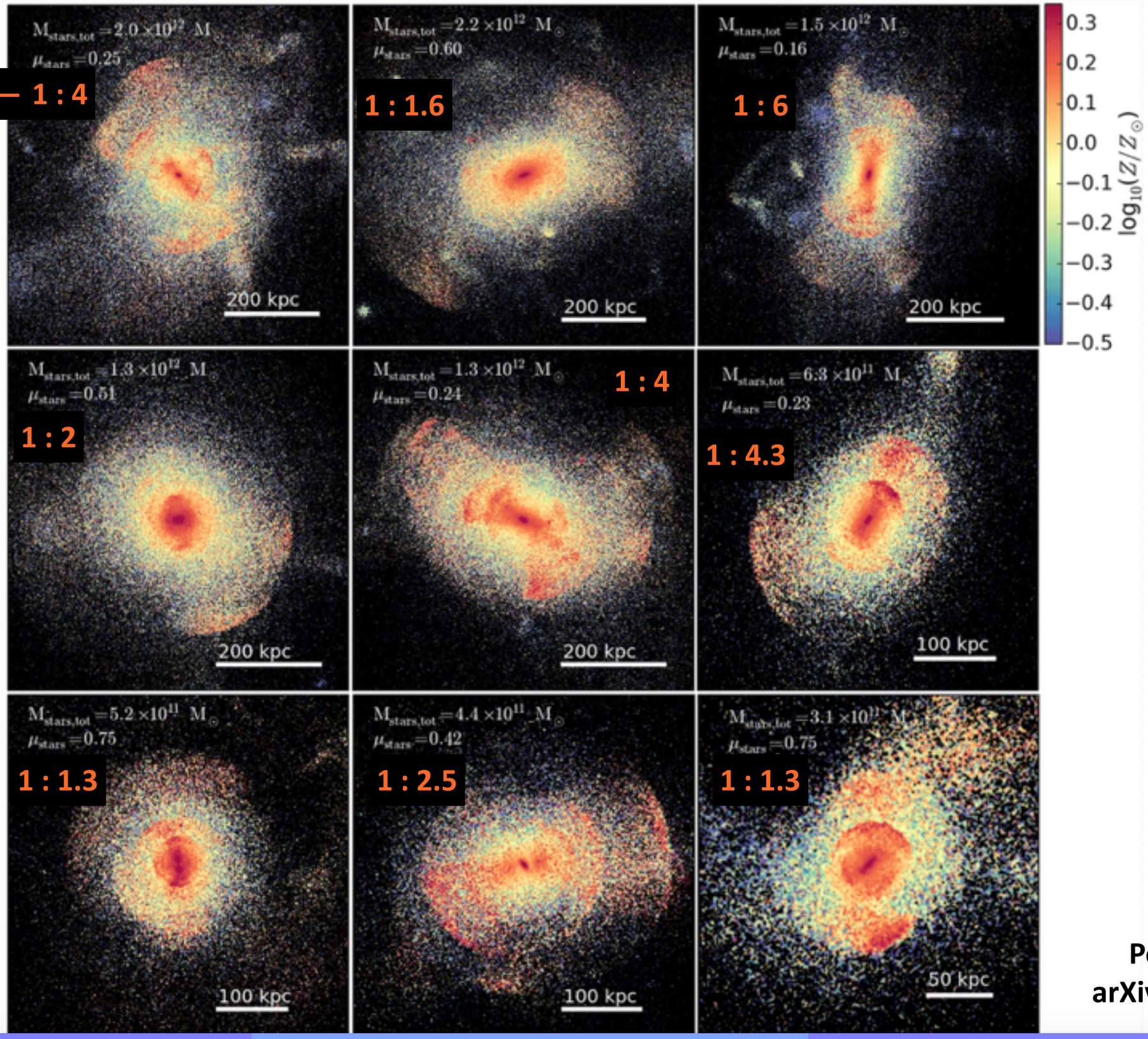
Pop+2017b, arXiv:1708.01615

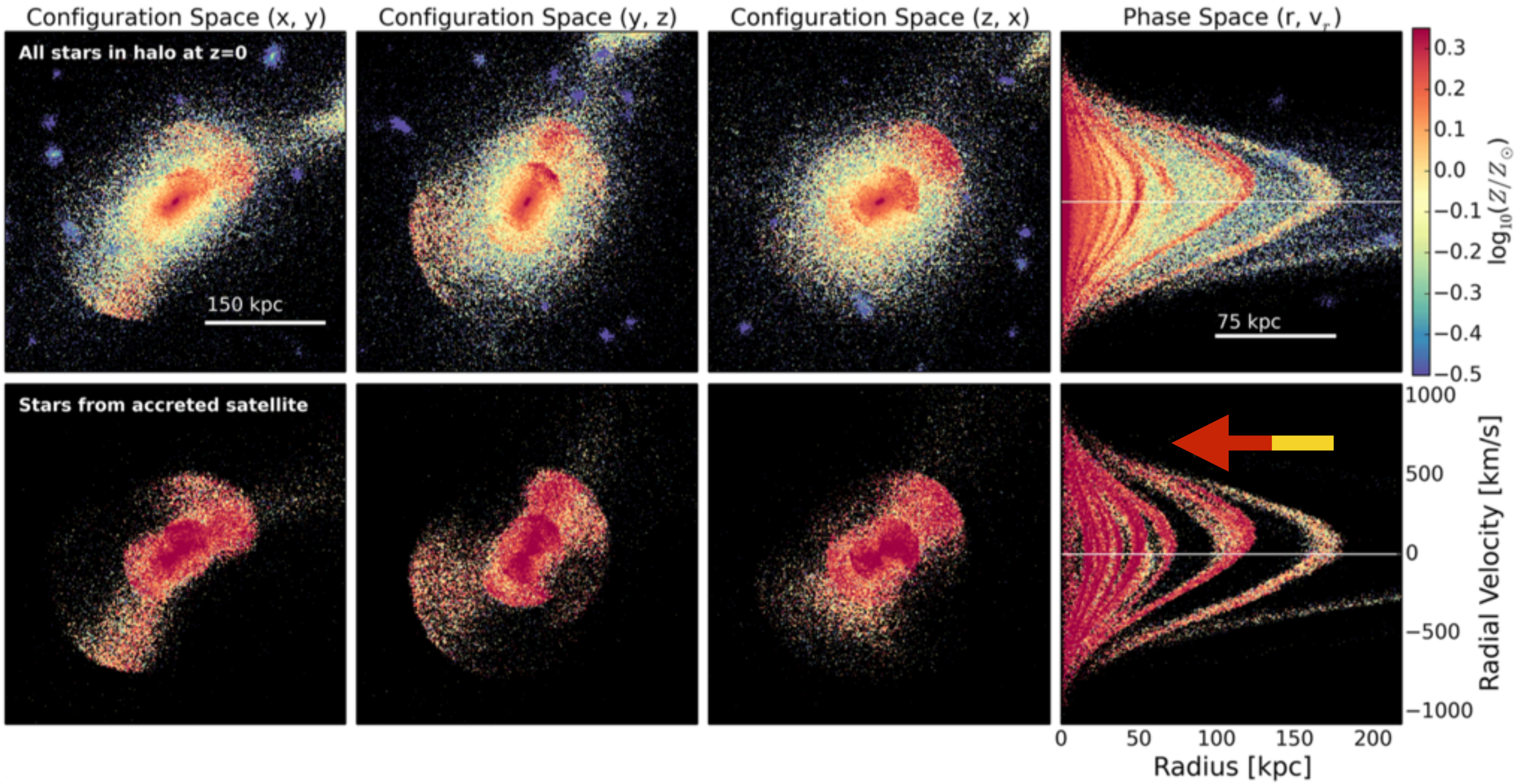
Metallicities of Stellar Shells



Pop+2017b, arXiv:1708.01615

Metallicities of Stellar Shells

Competing effects: outer shells correspond to the first stars stripped -> metal-poor stars
BUT for ~major mergers, outer shells contain metal-rich stars
which are deposited at large effective radii, where the host galaxy is metal-poor.



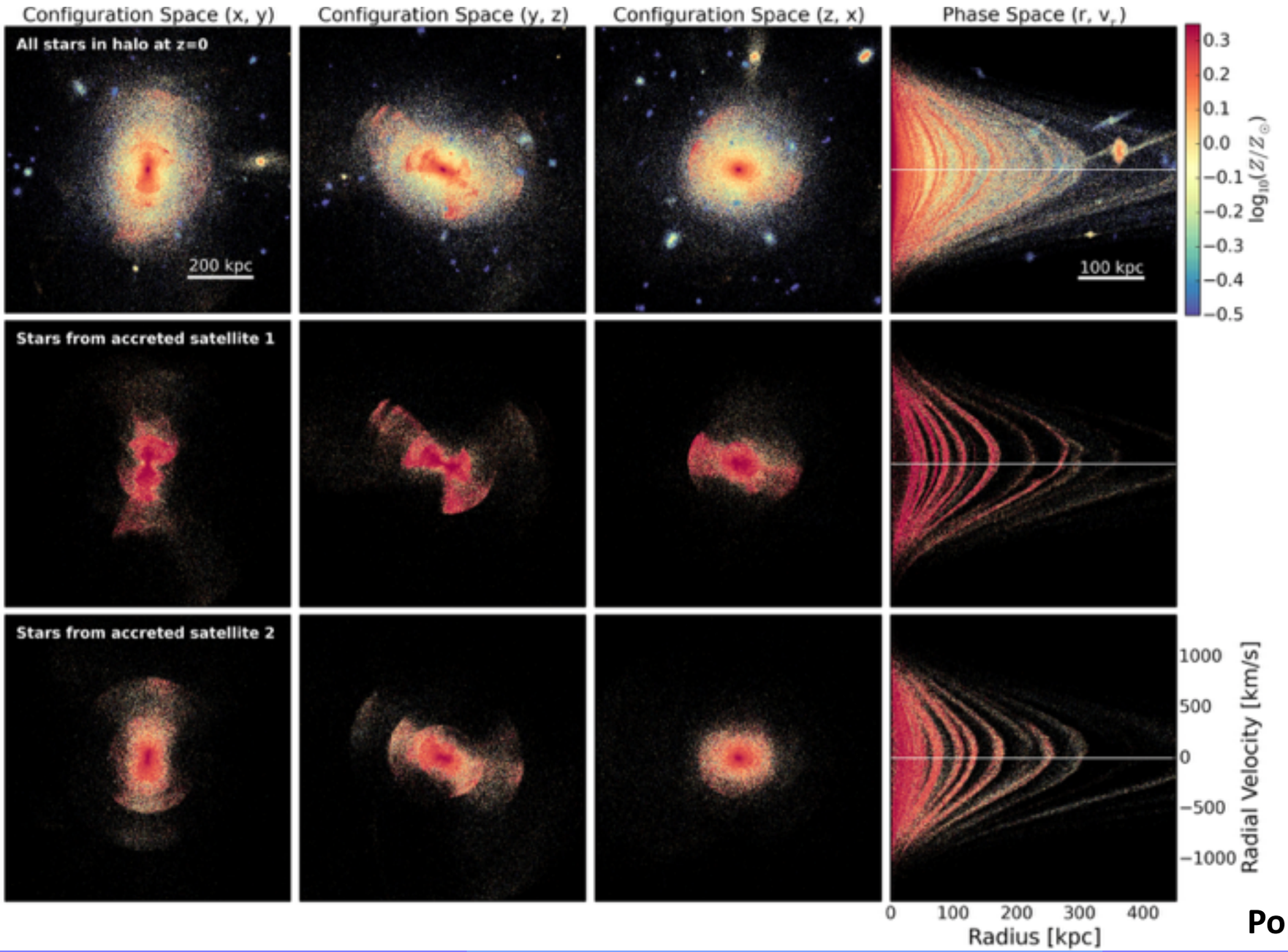
Pop+2017b, arXiv:1708.01615

Metallicities of Stellar Shells

10 out of 39 shell galaxies in our sample have multiple shell-forming progenitors.

In some cases, there is a significant difference in the metallicity of shells formed from the two different progenitors

-> metallicity measurements can be used to identify systems with multiple progenitors.



Pop+2017b, arXiv:1708.01615

Halo Shapes of Shell Galaxies

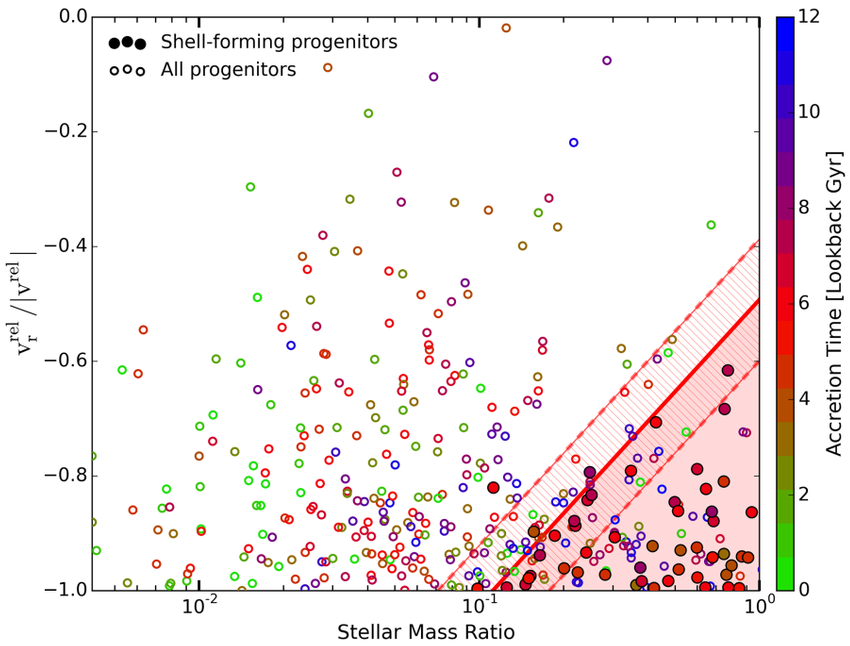
Preliminary results

Email me at ana-roxana.pop@cfa.harvard.edu to discuss results presented in the talk about the stellar and dark matter halo shapes of shell galaxies.

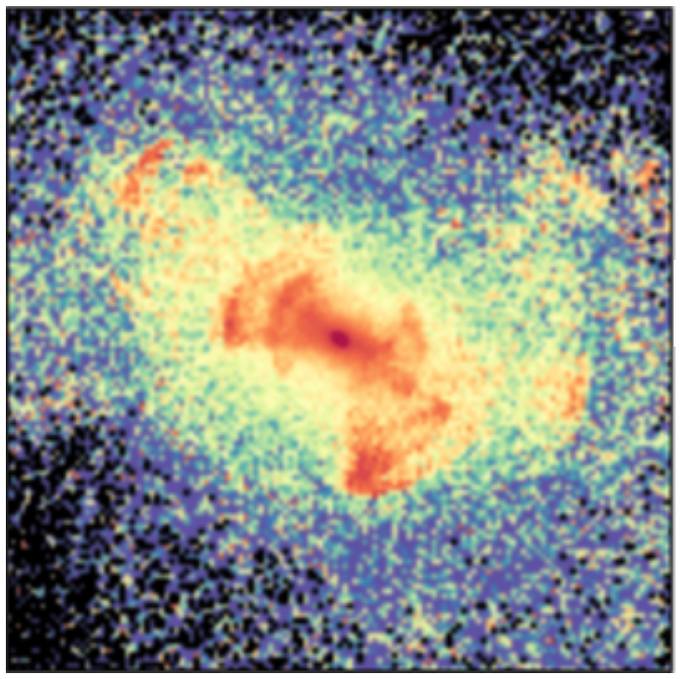
Pop+2018, in preparation

Conclusions

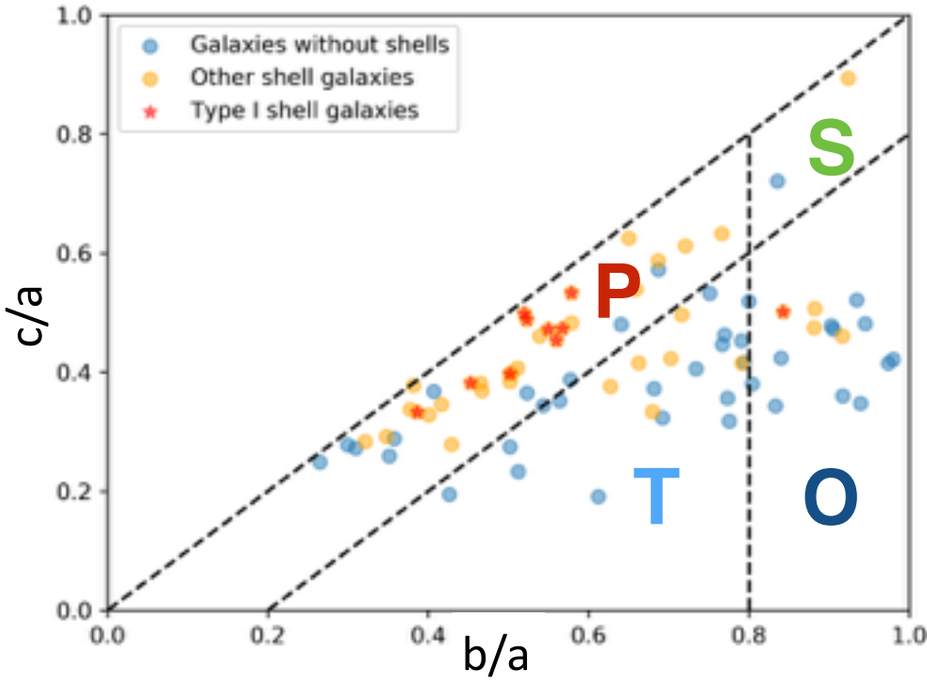
- In Illustris, at redshift z = 0, 18% +/- 3% of galaxies with $\mathrm{M}_{200\mathrm{crit}} > 6 \times 10^{12}\,\mathrm{M}_{\odot}$ have shells. The fraction of shells is higher for more massive galaxies.
- Shells in massive hosts form through **mergers between about 1:10 - 1:1 in stellar mass ratio**, with the progenitors being accreted on **radial orbits between 4-8 Gyrs ago**.
- **Dynamical friction** is more effective at radializing the orbits of massive satellites, while smaller ones need to be accreted on very radial orbits.
- Outer shells are often times more **metal-rich** than the surrounding stellar material in the host halo at similar radii. Can potentially use metallicity measurements to distinguish between different shell-forming progenitors in the same system.
- **Type I shells** are predominantly found in **prolate halos**.



shells in massive galaxies form through mergers 1:10 - 1:1 in stellar mass ratio on radial orbits, 4 - 8 Gyrs ago



Outer shells are often metal-rich (compared to host stars at same radius)



Most shell galaxies are prolate. Especially Type I shells!