Building Late-Type Spirals by In-Situ and Ex-Situ Star Formation: Eris' Stellar Halo

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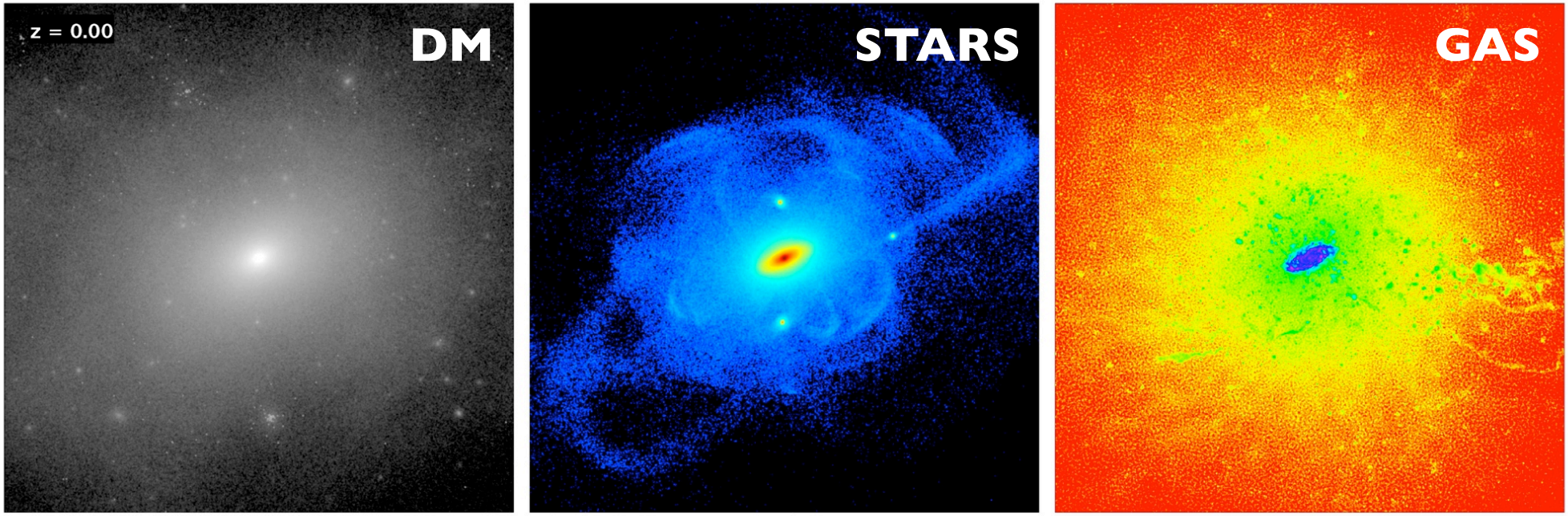
with Piero Madau, Javiera Guedes, Mike Kuhlen, Lucio Mayer, Valery Rashkov, Sijing Shen, Alis Deason, Connie Rockosi,
and all the Gasoline Team.

The Simulation

See Rashkov, Pillepich, et al. 2013 and later in this talk

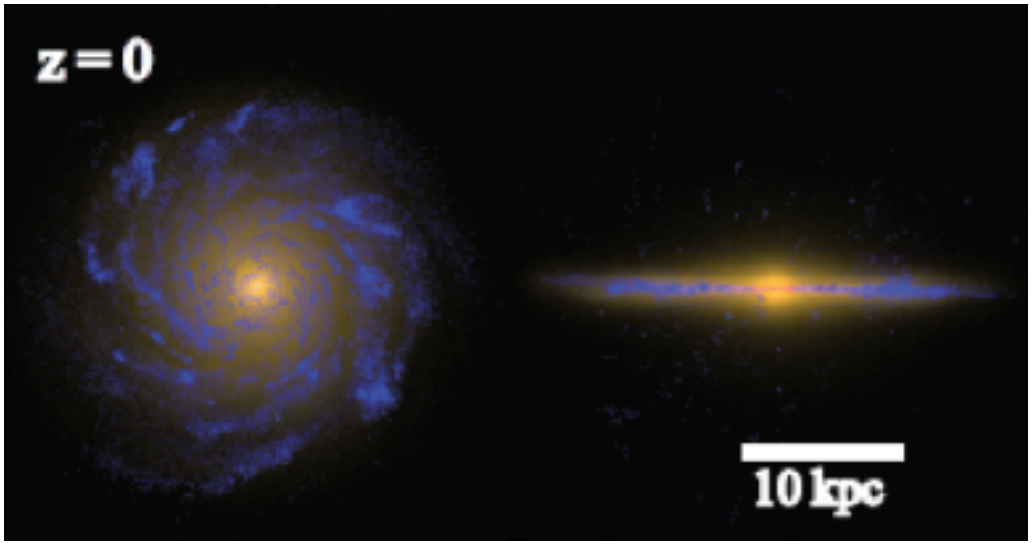
Eris is a simulation of a “slightly light” Milky Way galaxy.



Method: **zoom-in simulation**
Code: **GASOLINE (SPH): DM+GAS+STARS**
Resolution: 7.0+2.8+8.6 million particles with Rvir⊙
Mass Resolution: DM = 9.8×10^4 $M_\odot$, GAS= 2×10^4 $M_\odot$, STARS= 6×10^3 $M_\odot$
Force Softening: 124 pc

The Simulation

Eris is a good analog of our Milky Way...



Guedes et al. 2011, 2012

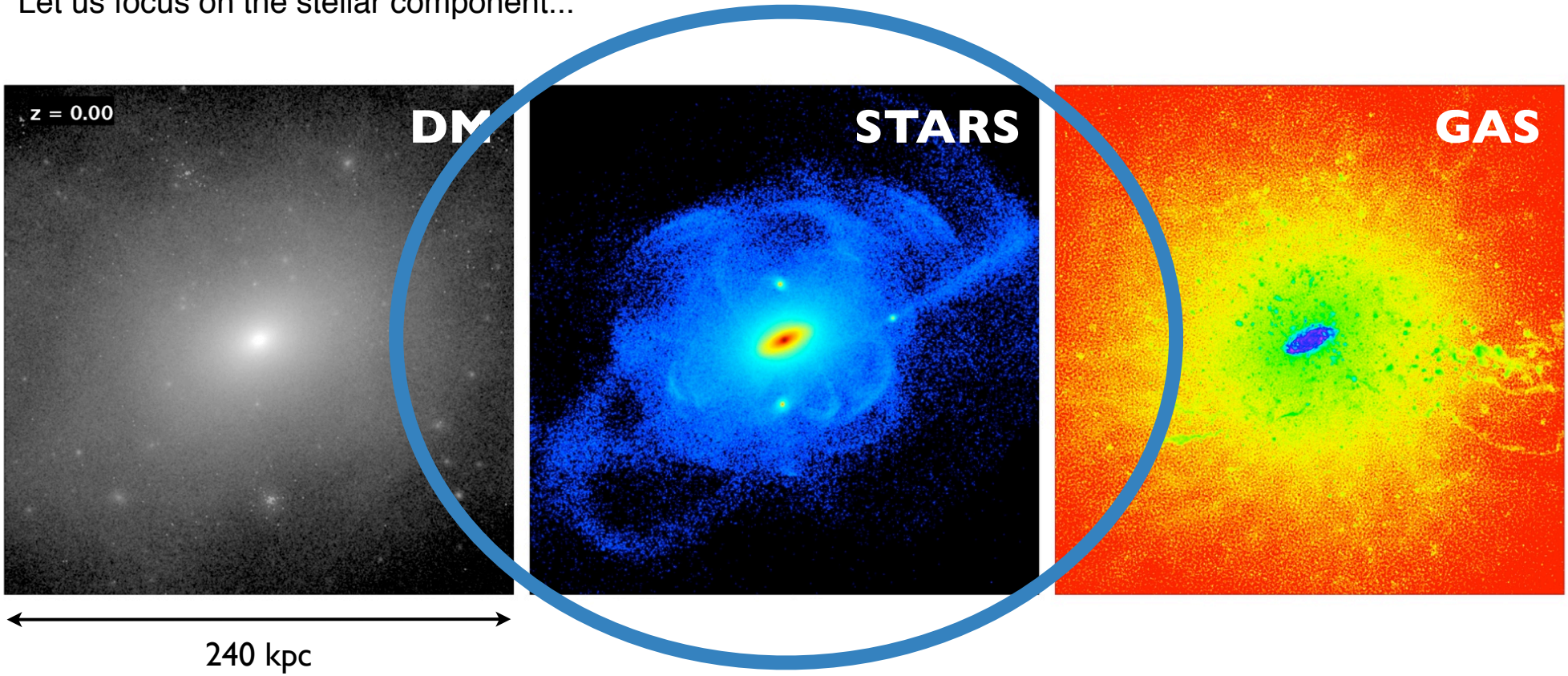
CAVEATS:
one only MW realization
specific subgrid choices

The Prescriptions:

- radiative cooling of the gas
  (Compton, atomic, low T metallicity-dependent)
- heating from cosmic UV Background
- Supernova feedback, a' la Stinson:2006
  i.e. thermal feedback from SN Type Ia and Type II
  (ε_{SN} = 0.8)
- Star Formation a' la Governato 2010:
  - threshold n_{SF} = 5 atoms/cm3
  - efficiency ε_{SF} = 0.1
  - IMF: Kroupa et al. 1993
- NO AGN feedback

Eris Evolution

Let us focus on the stellar component...



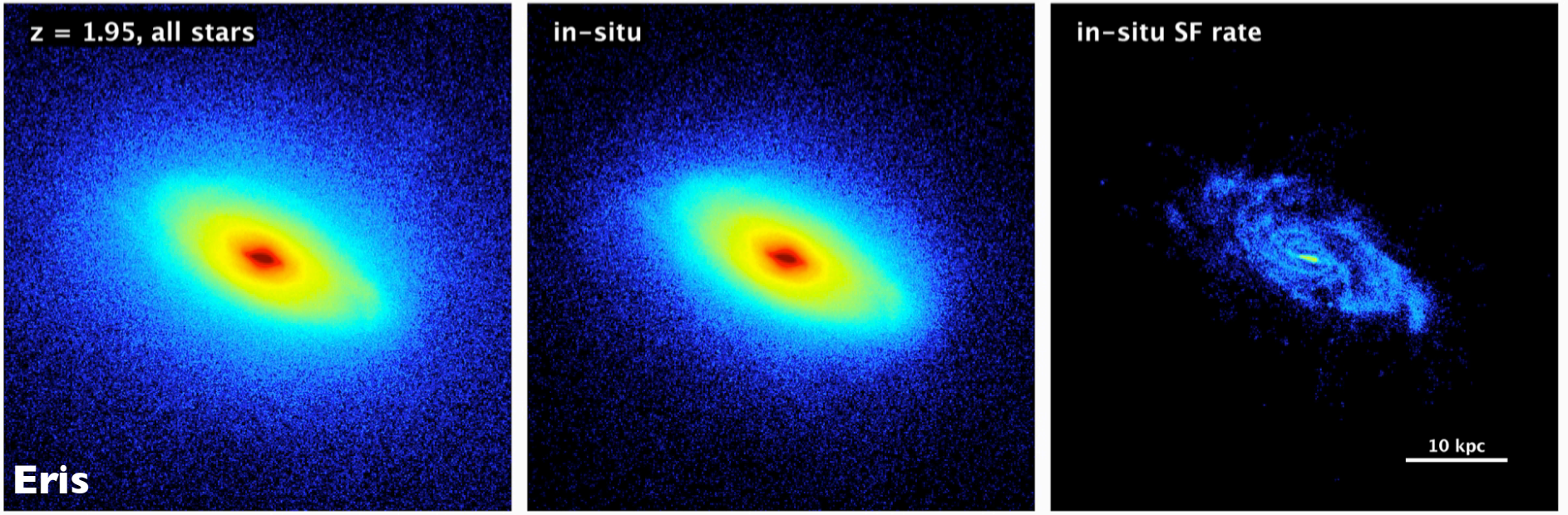
TWO CHANNELS TO BUILD UP GALAXIES STELLAR COMPONENT:

- STARS FORMED WITHIN THE MAIN HOST → **in-situ stars!**
- STARS ACCRETED FROM SATELLITE GALAXIES → **ex-situ stars!**

In-Situ Stars, broadly speaking

STAR FORMATION HISTORY OF THE MAIN/HOST GALAXY..

- In-Situ stars form within the **bulge** and the **disk**...
- They *tend* to be found at z=0 *not far* from their birth sites.
- They can be both young and old, metal poor or metal rich...

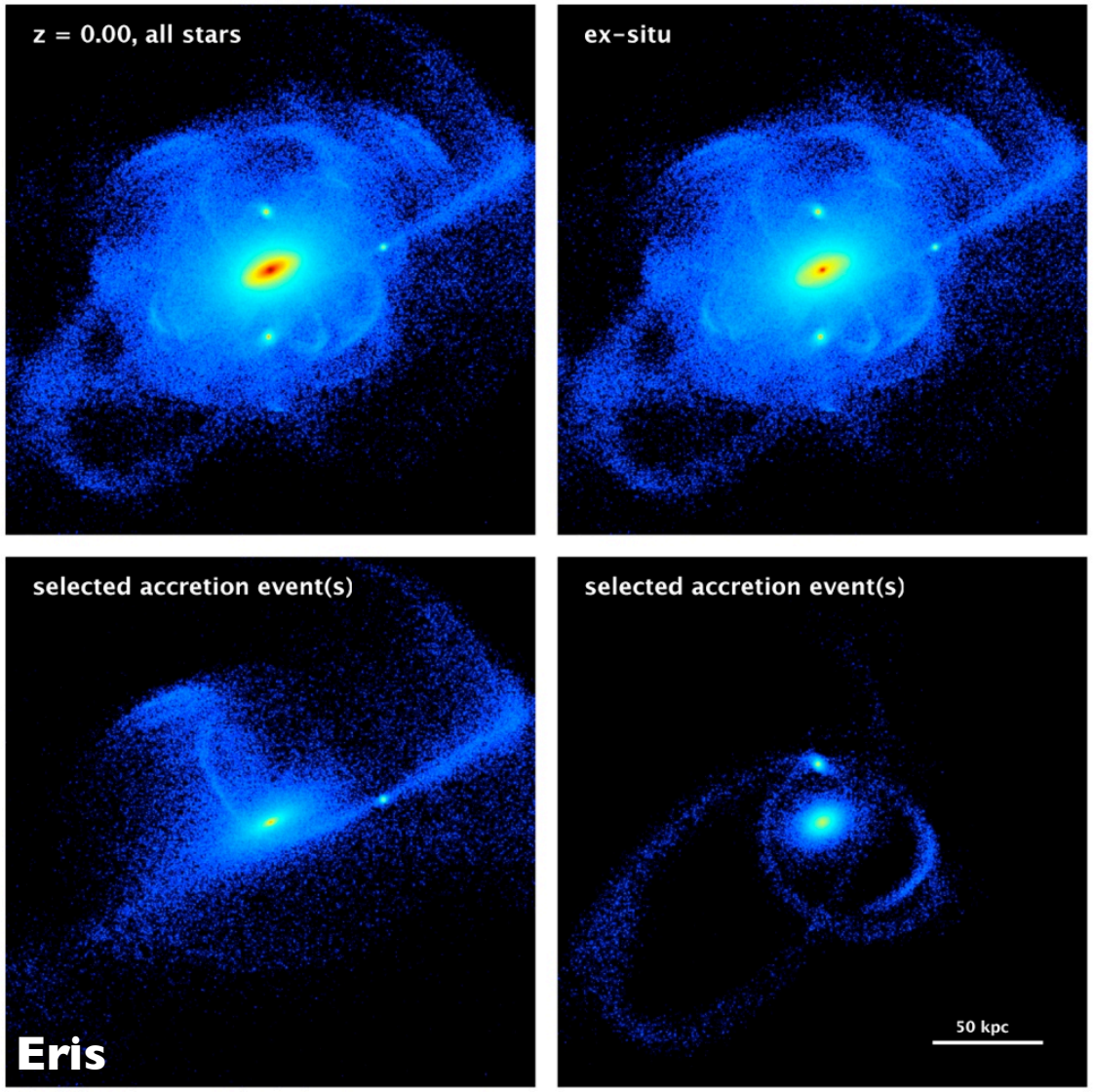


Ex-Situ Stars, broadly speaking

ACCRETION HISTORY OF THE HOST

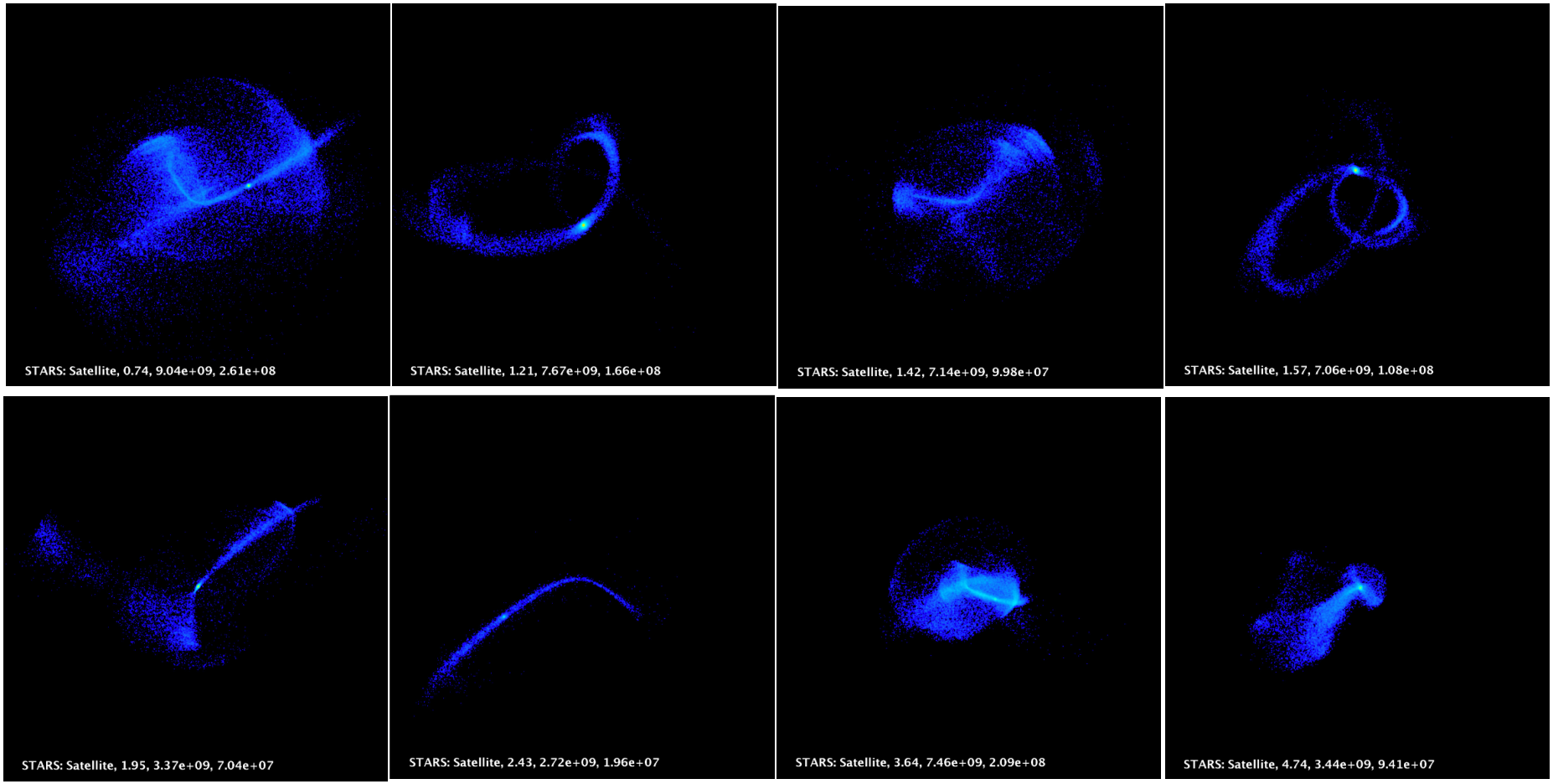
- Ex-Situ stars form in outer (dwarf) galaxies, subsequently accreted...
- After accretion, **satellite** stars get **stripped**, **mixed**, and end up populating the host galaxy
- Their properties reflect the SF histories of the satellites, but people tend to think they are mostly *old stars* and *metal poor*...

SF HISTORY OF THE DWARFS!



Ex-Situ Stars, broadly speaking

Ex-Situ stars are the main responsible for the existence of the **stellar halo**...
They appear in streams, shells, plumes, debris, and umbrellas :-)



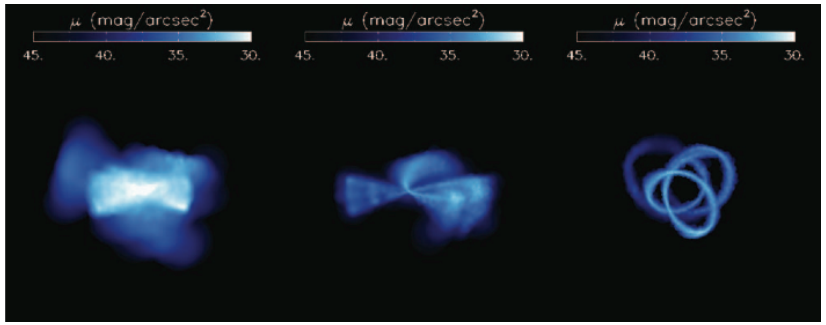
Not a new story, of course...

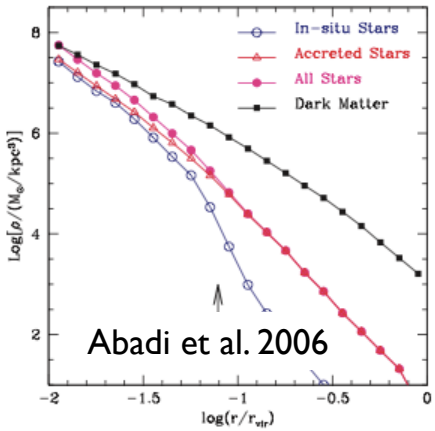
Abadi et al. 2006
Zolotov et al. 2009
Cooper et al. 2010
Tissera et al 2013
...

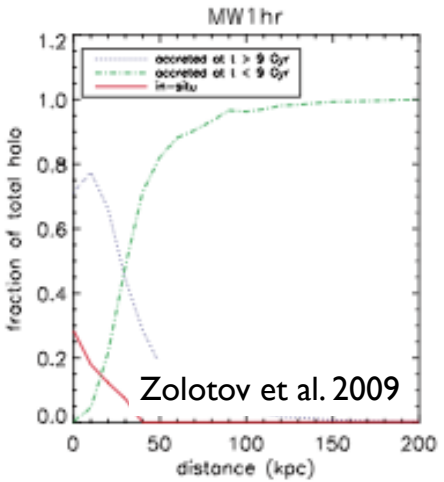
Oser et al. 2010
Font et al. 2011
McCarthy et al. 2012
...

Theory/Simulations:s

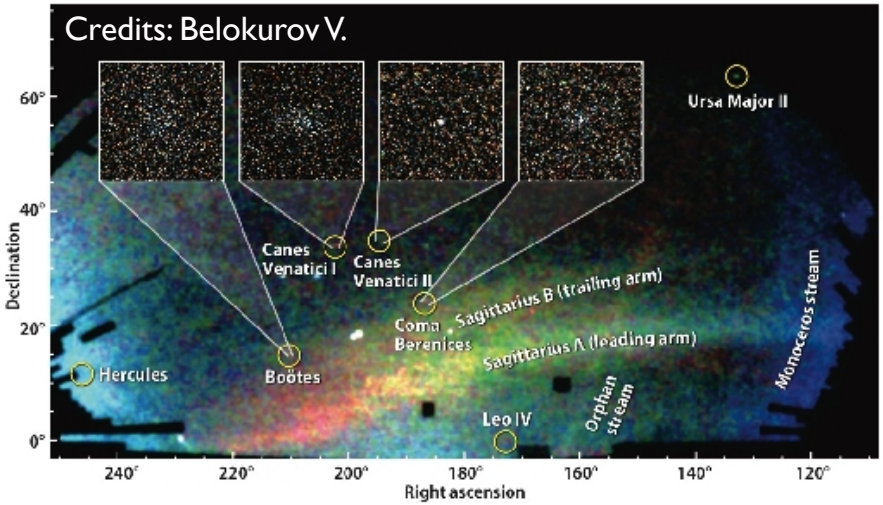
Helmi & White 1999, Johnston et al. 2008, ...

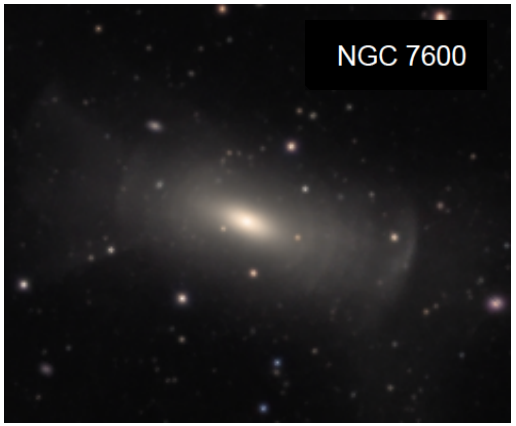


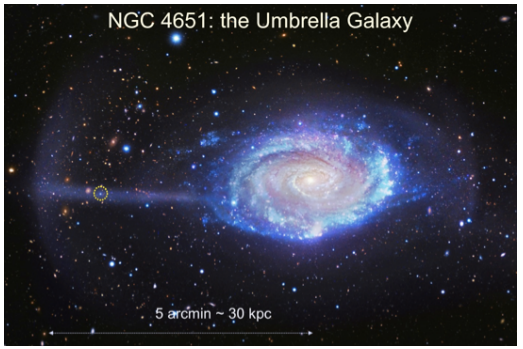




Observations:







See A. Romanovsky's Talk

... But outstanding questions remain

1. What is the relative importance of accreted, in-situ and satellite stars as a function of distance?
2. How does this balance depend on halo mass?

NO CONSENSUS AMONG SIMS...

3. For MWs, how many satellites contributed to the stellar halo?

NOT THE RIGHT QUESTION...

4. Are there differences between stars of surviving satellite and debris stars of disrupted accretion events?
5. Where shall we find the oldest stars?
6. Are the oldest stars the most metal poor?
7. How all these fact depends on the specific merger and star-formation histories?
8. Can we predict the properties of the stellar halo i.e. interpret observations? How smooth and lumpy? Gradients in ages, metallicities, density profiles?

INTENSE OBSERVATIONAL ACTIVITY
(SEGUE:1, SEGUE:2, GAIA,...)

The in-situ vs ex-situ balance for Galactic Archeology

HOST SF HISTORY

+

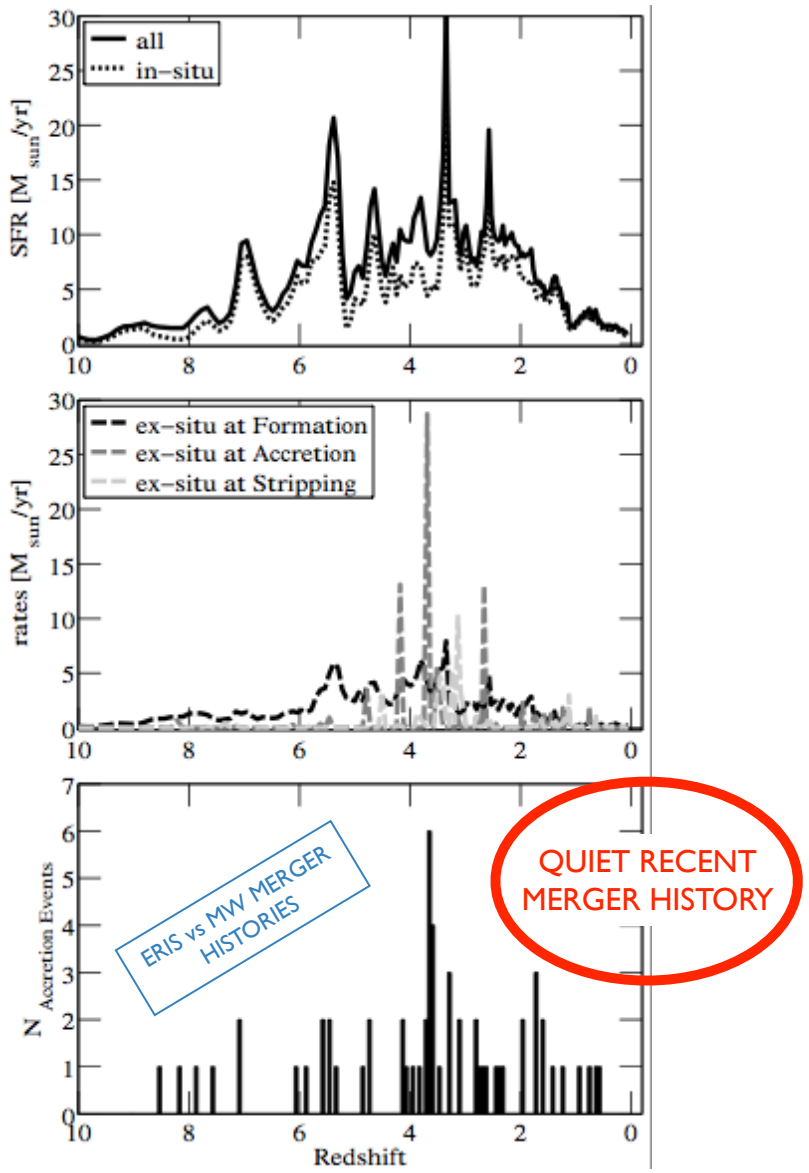
GLOBAL SF HISTORY

+

HOST ACCRETION HISTORY

=

IN-SITU vs EX-SITU BALANCE



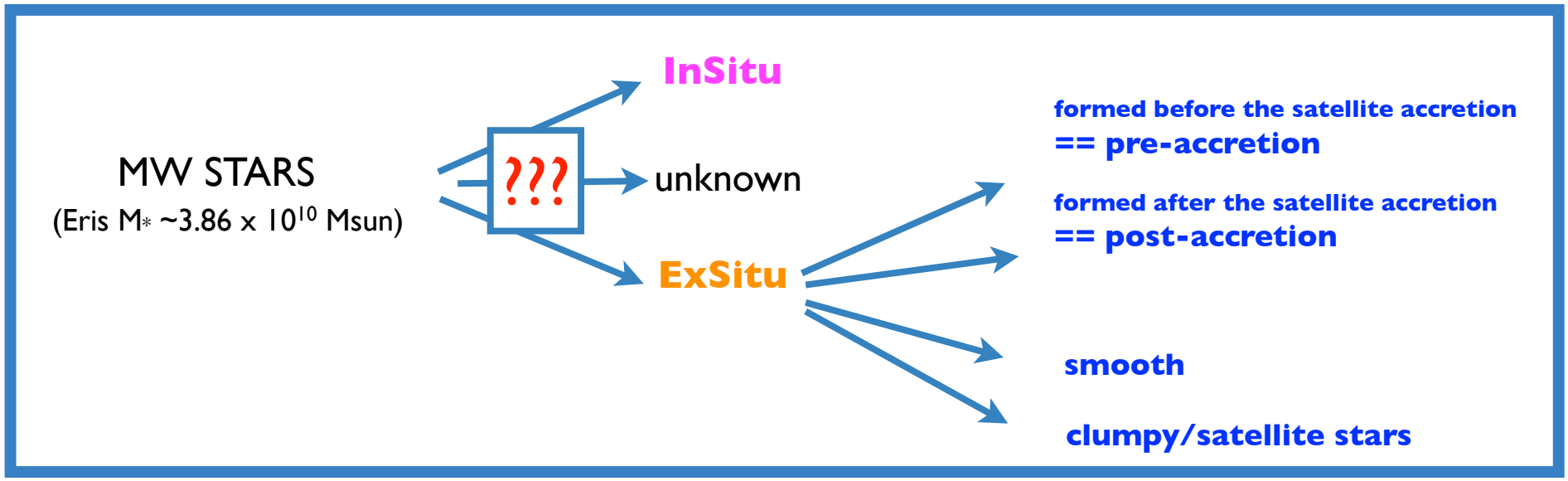
In-Situ vs Ex-Situ Stars: our operational definitions

Steps:

1. Halo Finder output at *every* available snapshot
2. Identification of Stars belonging to the MW at z=0
3. Question: to which halo/subhalo did every MW star belong to at its *formation time?*

Answers:

MW, no bound structure, a halo external to the MW, a subhalo within the MW radius

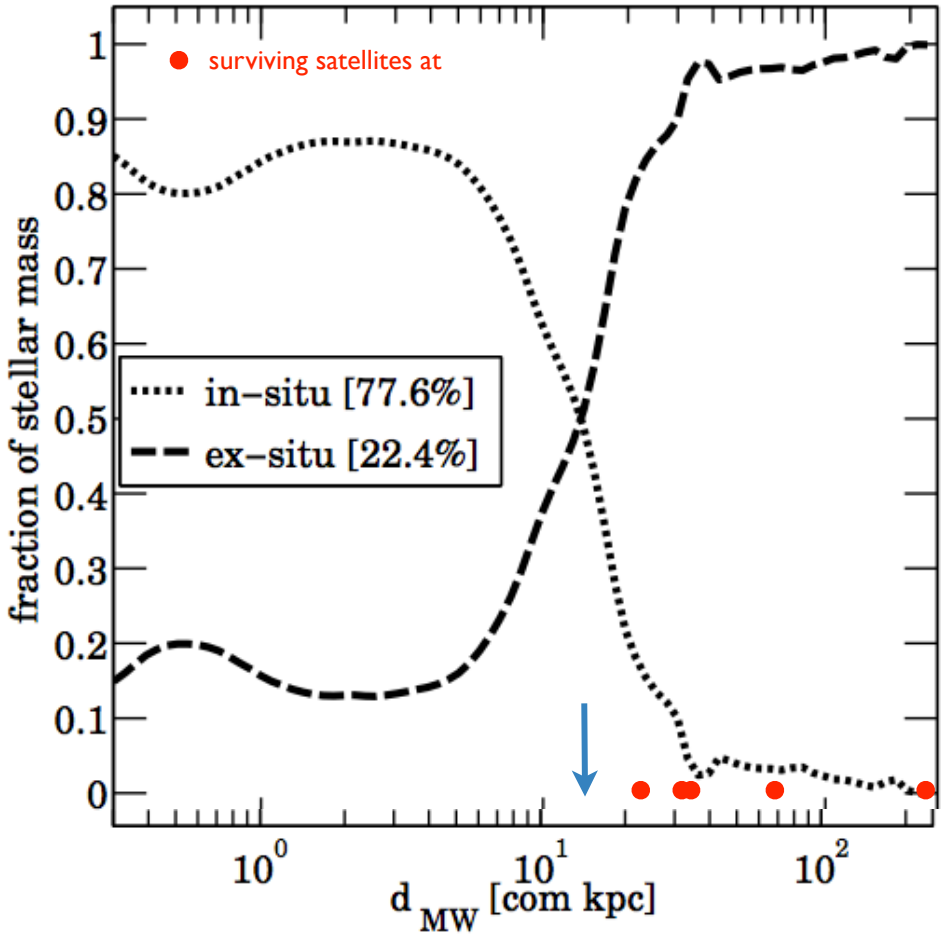


Careful: Different simulators use different definitions, they cut away pieces of stellar populations, ... Comparisons are tricky!

Eris at z=0

SPHERICALLY AVERAGING...

	Stellar Mass [$M_\odot$]	Fraction to Total [%]
All	3.9×10^{10}	100
In-Situ	3.0×10^{10}	77.6
Ex-Situ	8.6×10^{9}	22.3
Ex-Situ:preAccretion	2.9×10^{9}	7.4
Ex-Situ:postAccretion	5.7×10^{9}	14.9
Ex-Situ:smooth	8.1×10^{9}	21.0
Ex-Situ:satellites	5.1×10^{8}	1.3

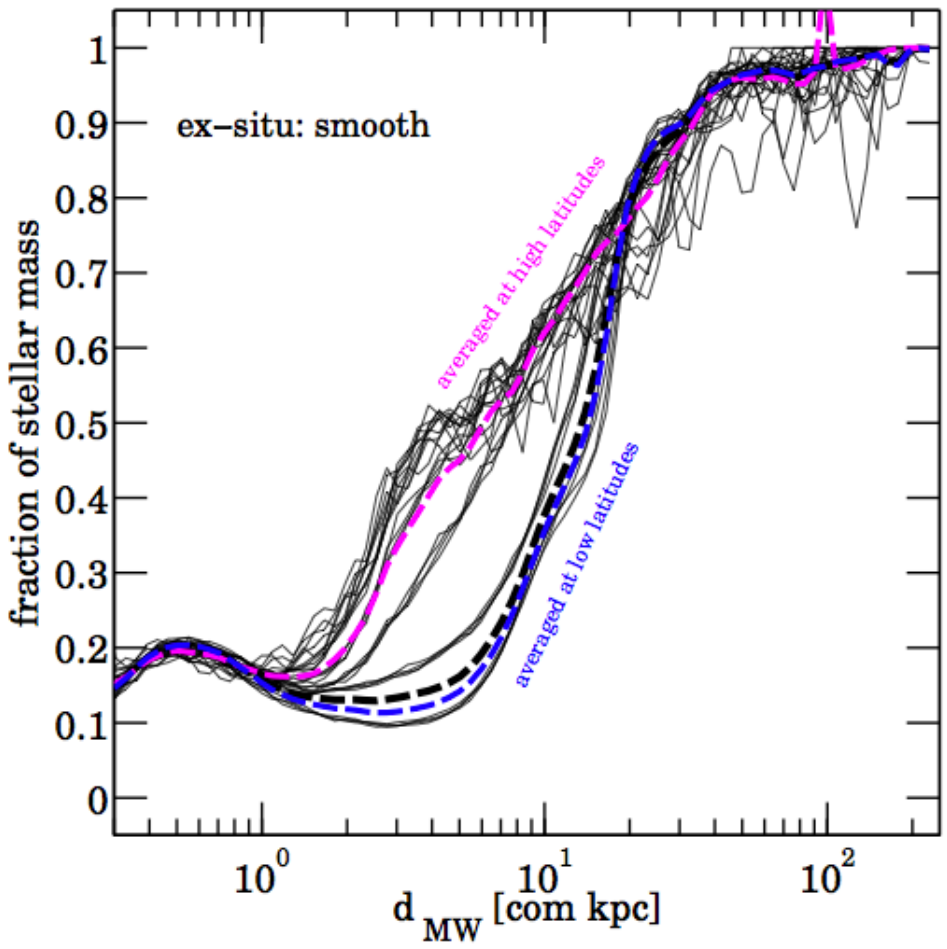


- GLOBALLY, 22% OF ERIS STELLAR MASS HAS BEEN ACCRETED VIA SATELLITES
- EX-SITU STARS DOMINATE THE STELLAR DENSITY ONLY AT LARGE RADII (> 20 kpc)

Eris at z=0

ALONG DIFFERENT LINES OF SIGHT:

SDSS MOCK OBSERVATIONS



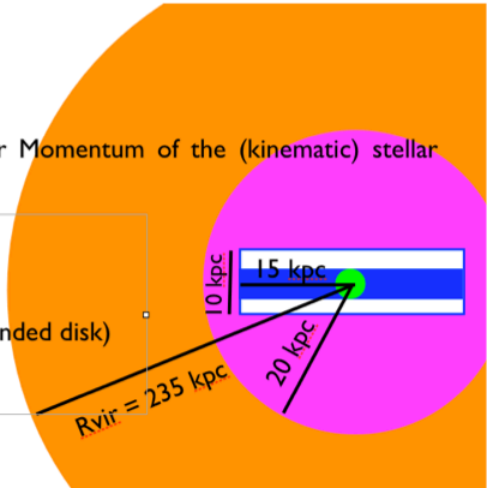
- IN-SITU CONTRIBUTION DROPS FASTER AT HIGH LATITUDES THAN AT LOW LATITUDES
- THE STELLAR HALO (>15 kpc) IS NOT SPHERICALLY SYMMETRIC AT ALL

Eris at z=0, component by component

POSITION-BASED MORPHOLOGICAL DECOMPOSITION

The only kinematically derived quantity is the Angular Momentum of the (kinematic) stellar disk, to fix the axes.

Bulge: sphere of 1.5 kpc
Disk: cylinder of height +-1.5 kpc and radius 15kpc (excluding the bulge)
Inner Halo: shell within 5 and 20 kpc (excluding extended disk)
Outer Halo: shell beyond 20 kpc



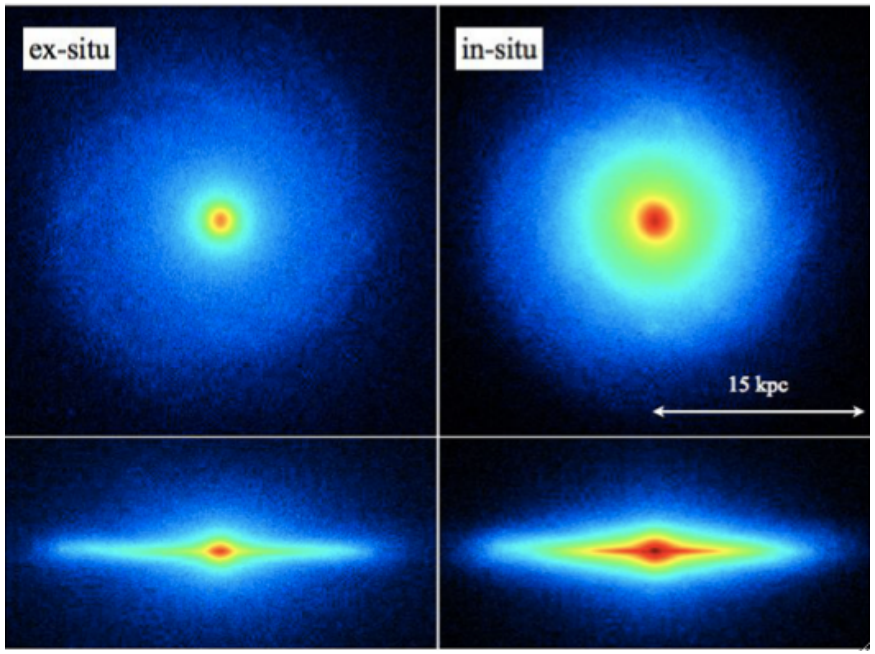
	Milky Way	Disk	Bulge	Inner Halo	Outer Halo
Total Stellar Mass	3.9×10^{10} M$_\odot$	1.9×10^{10} M$_\odot$	1.5×10^{10} M$_\odot$	7.8×10^{8} M$_\odot$	1.7×10^{9} M$_\odot$
In-Situ Fraction	78 %	83 %	84 %	30 %	5%
Ex-Situ Fraction	22 %	17 %	16 %	70 %	95%
Ex-Situ Fraction In Satellites	1.3 %	-	-	-	21%

- SATELLITE GALAXIES DEPOSIT STARS IN ALL THE MW COMPONENTS
- THE STELLAR HALO IS MAINLY COMPOSED OF EX-SITU STARS
- Interestingly, there are more ex-situ stars in the disk than in the whole halo!

Cool Point #1: ex-situ stars at small distances

1. THERE ARE LOCAL ENHANCEMENTS OF EX-SITU STARS AT SMALL DISTANCES: EX-SITU DISK
2. MORE THAN 2/3 OF THE EX-SITU STARS ARE POST-ACCRETION!

1.



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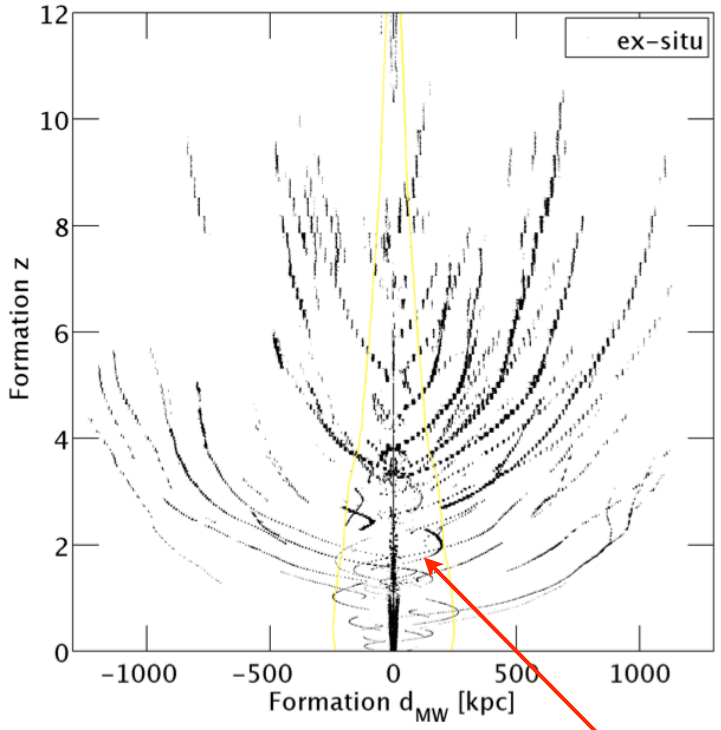
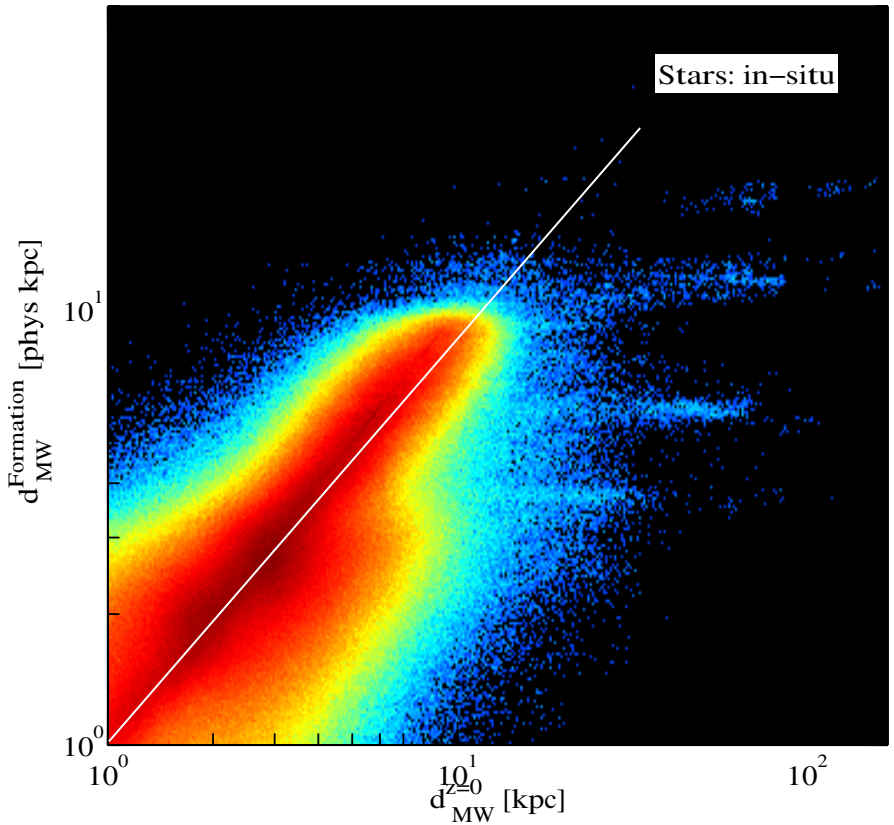


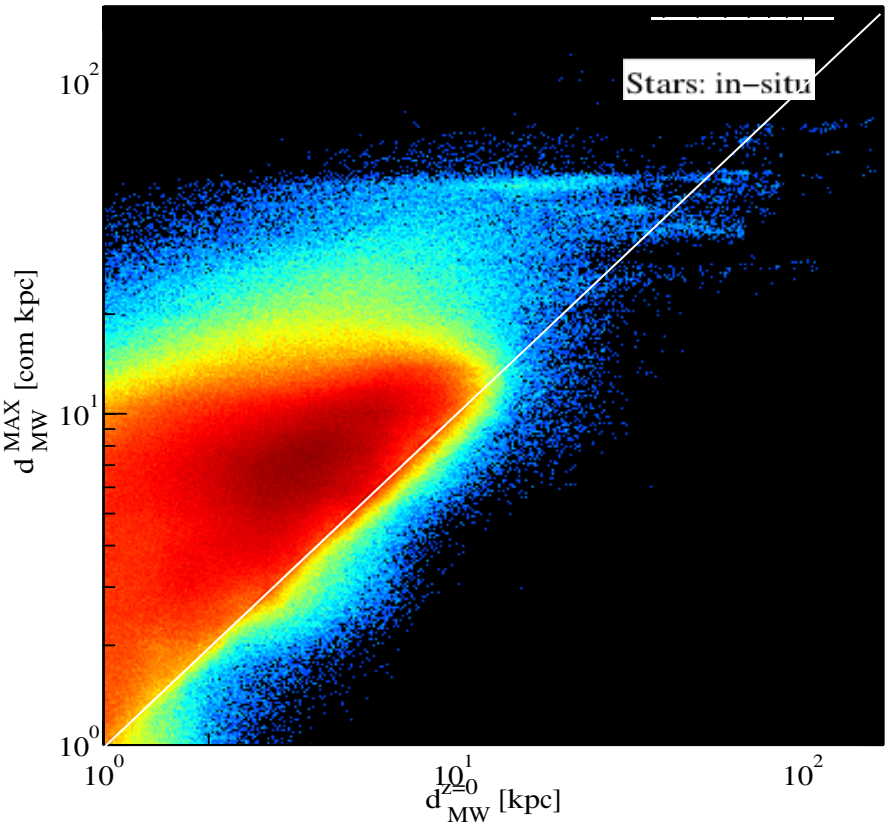
SF keeps occurring in orbiting satellites: these are ex-situ!

Cool Point #2: in-situ stars at large distances

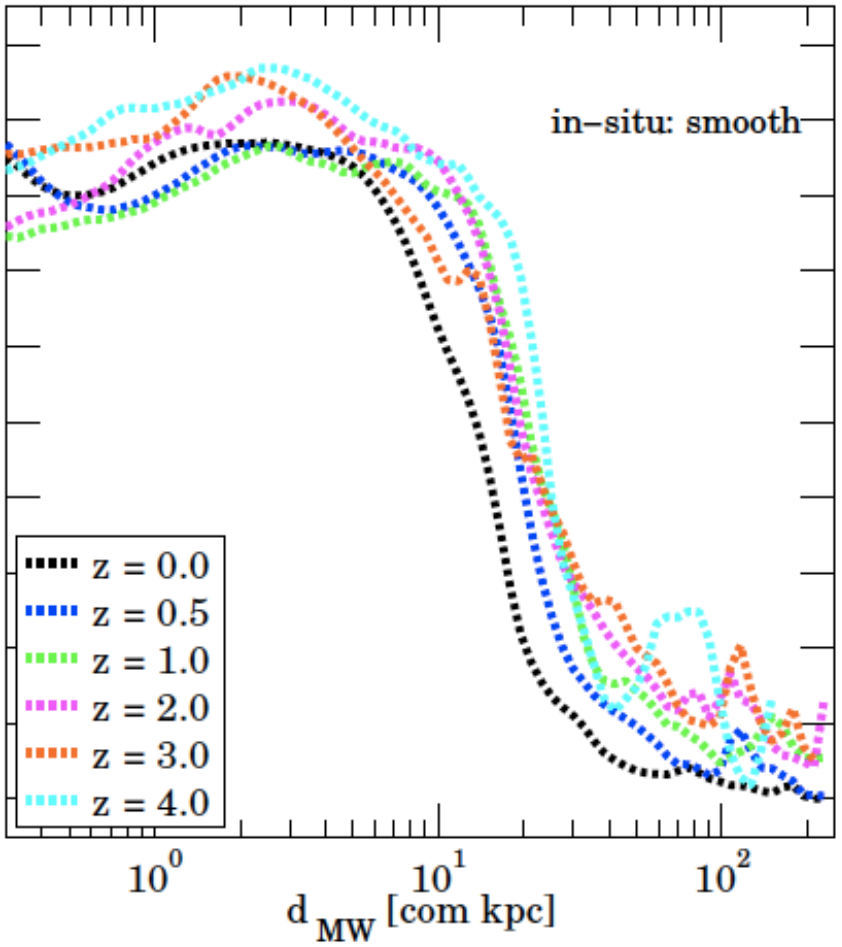
DISK HEATED STARS
IN-SITU HALO STARS

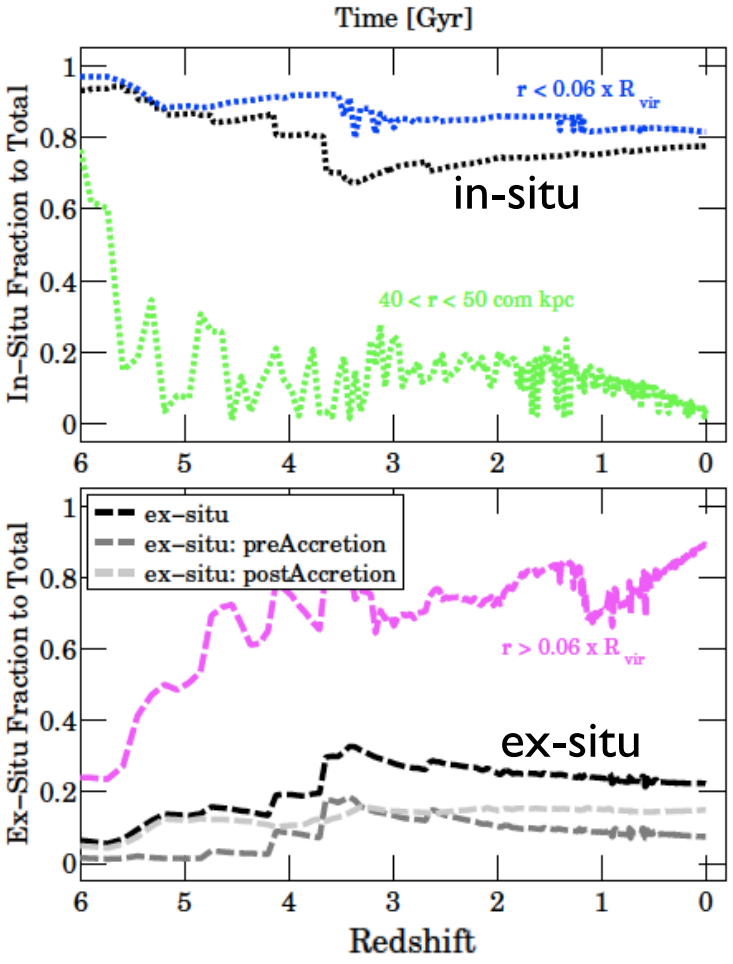
1. THERE ARE LOCAL ENHANCEMENTS OF IN-SITU STARS AT LARGE DISTANCES
2. IN-SITU STARS HAVE TRAVELED DURING THEIR LIFE AT EVEN LARGER DISTANCES THAN WHERE WE FIND THEM TODAY





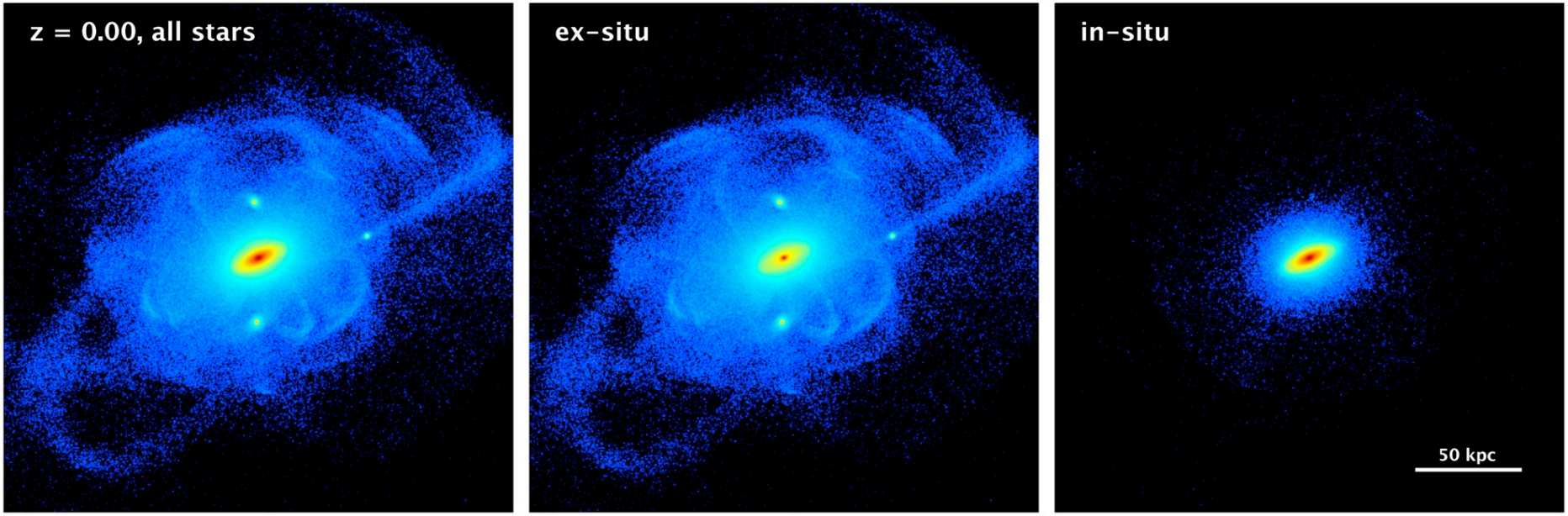
In-situ vs Ex-situ Stars as a function of time





- SMALLER GLOBAL IN-SITU FRACTIONS AT THE PEAK OF THE ACCRETION HISTORY
- BUT ALSO IN-SITU STARS UP TO FARTHEST DISTANCES

Concluding



In-situ vs Ex-situ Contributions
Geometry of the stellar halo
Property distributions of the two populations

are the results of the
balance among different time-scales

(cadence and duration of SF history and accretion history, stellar mixing time scales, time of last luminous accretion event)