Galactic Archaeology for Near-Field Cosmology

Introduction: Local Answers to Difficult Galaxy Questions

Vasily Belokurov
IoA, Hoyle 20, vasily@ast.cam.ac.uk

Data Intensive Science **MPhil** Minor Module

Galactic Archaeology for Near-Field Cosmology

- **Introduction and big picture Part 2** (you are here)
  Vasily Belokurov

- **Stars as probes of Galactic Archaeology**
  Anke Ardern-Arentsen

- **The Milky Way and Galactic Dynamics**
  GyuChul Myeong

- **Galaxy evolution in the local Universe**
  Elisabeth Sola

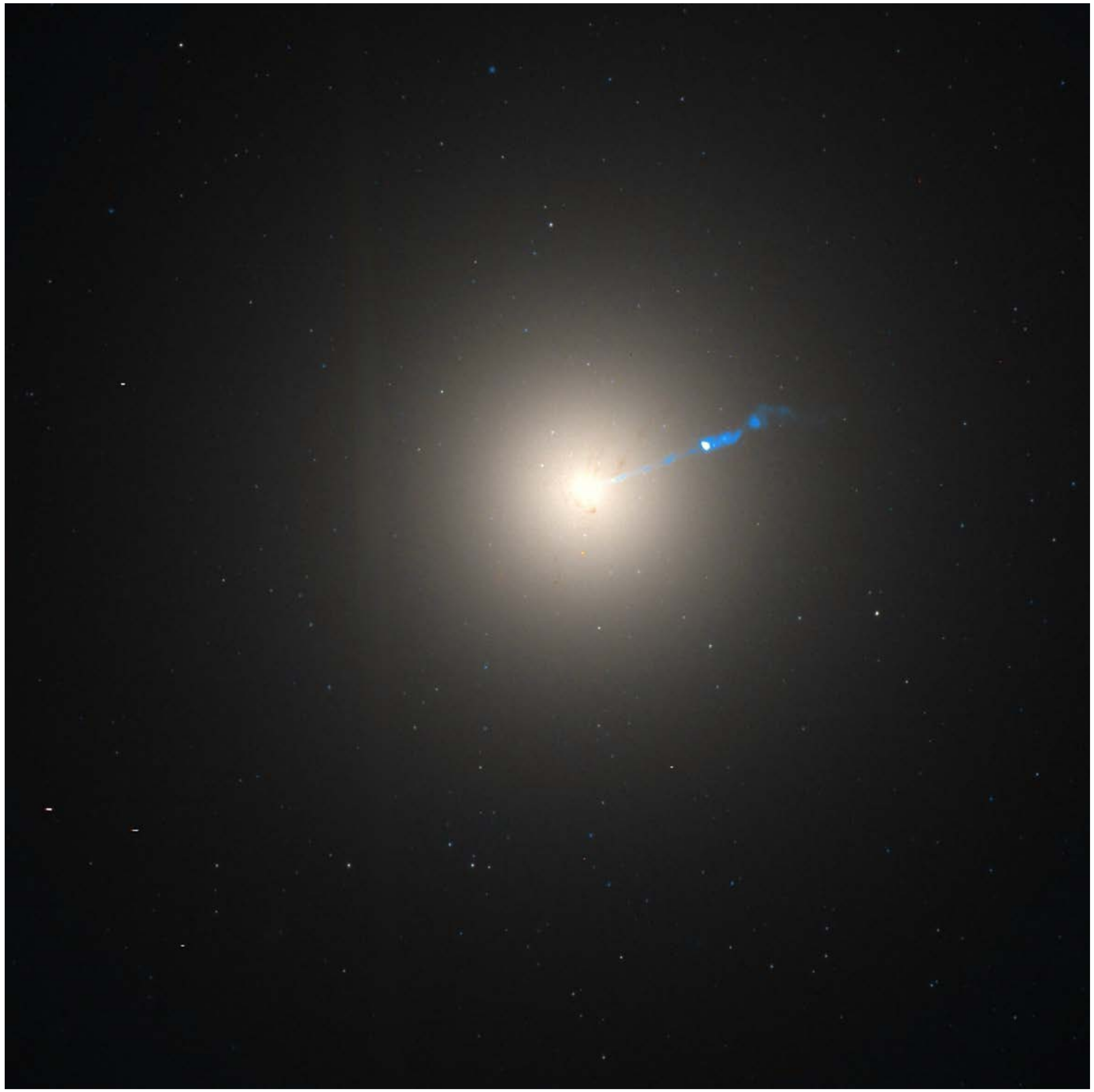
- **Wrap-up**
  Vasily Belokurov

Questions from the last lecture

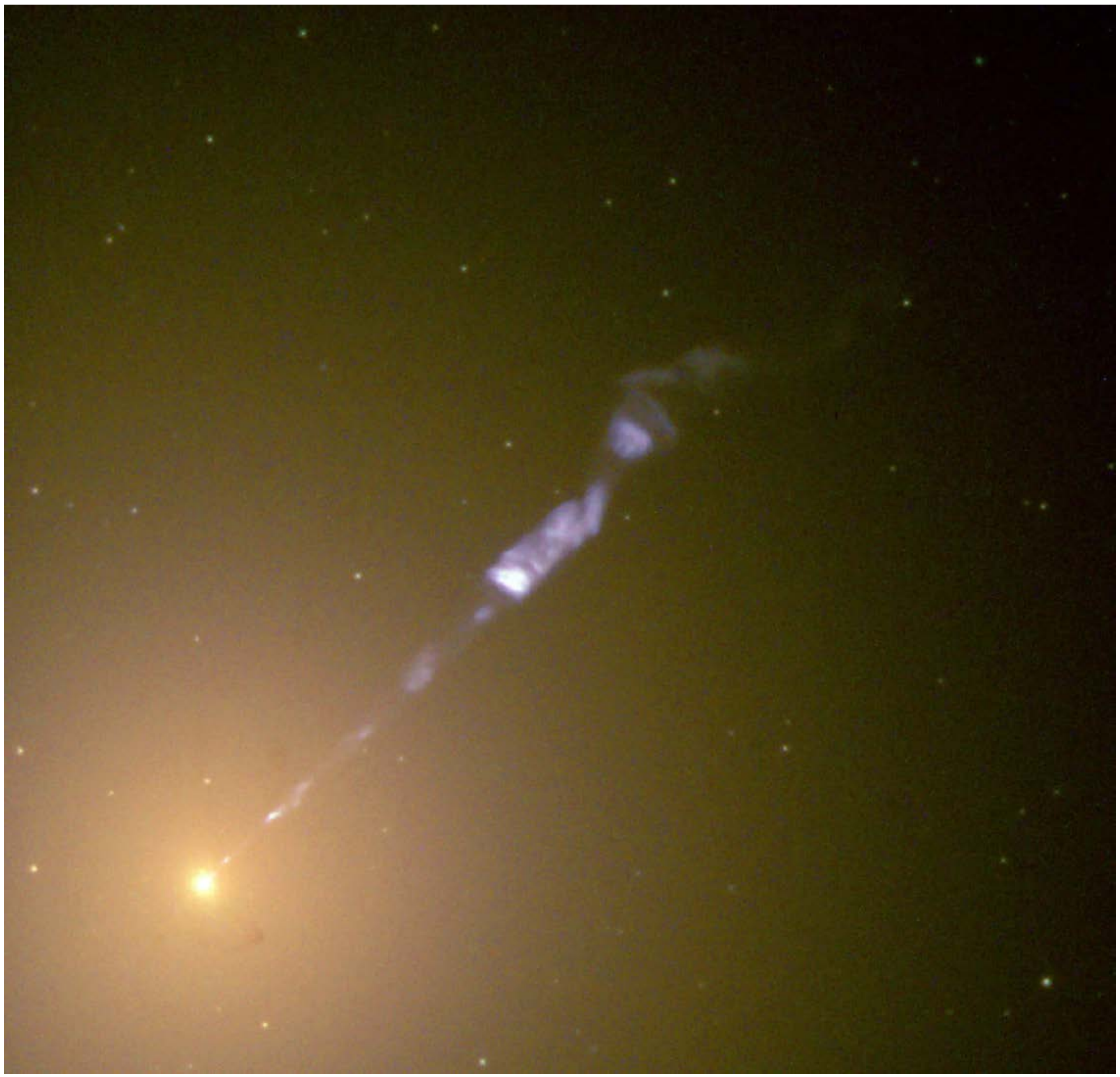
- What’s the blue streak sticking out of the M87’s centre?
- What is “phase-mixing”?
- How does SDSS “know” what is a star and what is not?
- Is binning stars in “boxes” of RA, Dec sensible/correct?
- Why Gaia’s all-sky view of the Galaxy is not a photograph?
- Why does the S02 star’s orbit around the Galactic (super-massive) Black Hole close and the stream progenitor’s does not?

Answers

M87's blue streak



M87's blue streak

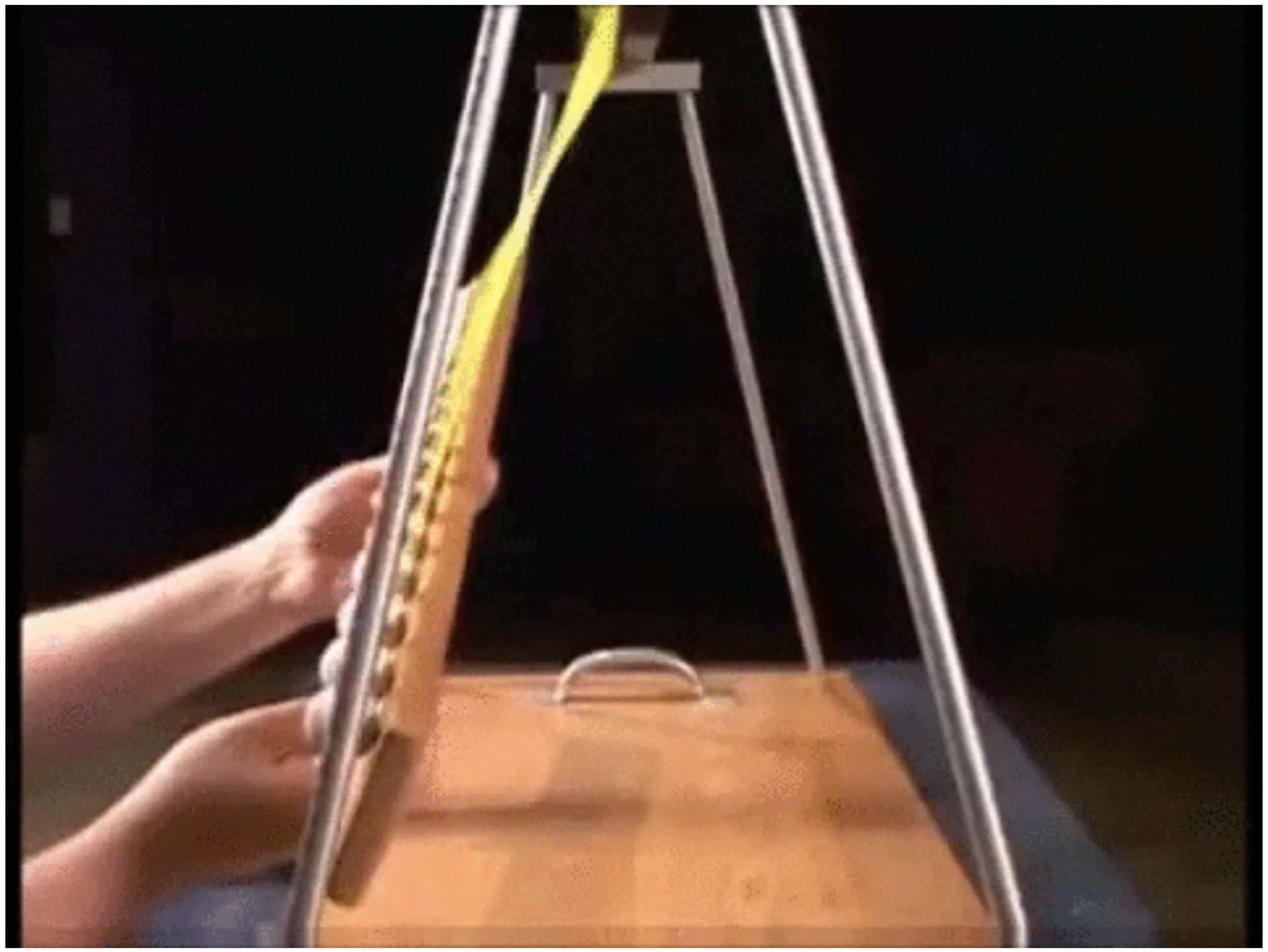


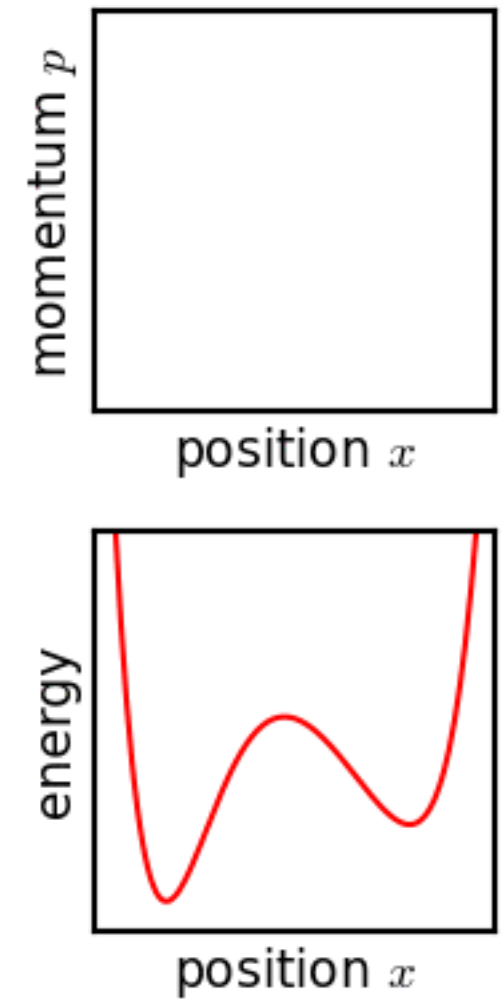
- Jet of charged particles accelerated to near-light speeds
- Originates from the supermassive black hole at the core of M87
- M87's SMBH is $\approx 6 \times 10^9 M_\odot$
- For comparison, our Galaxy's SMBH is $\approx 5 \times 10^6 M_\odot$
- Strong magnetic fields keep the jet narrow
- Charged particles spiralling around magnetic field emit synchrotron radiation in a broad range of wavelengths

How many galaxies have an active **SMBH**?

How many galaxies have a **SMBH**?

Phase-mixing





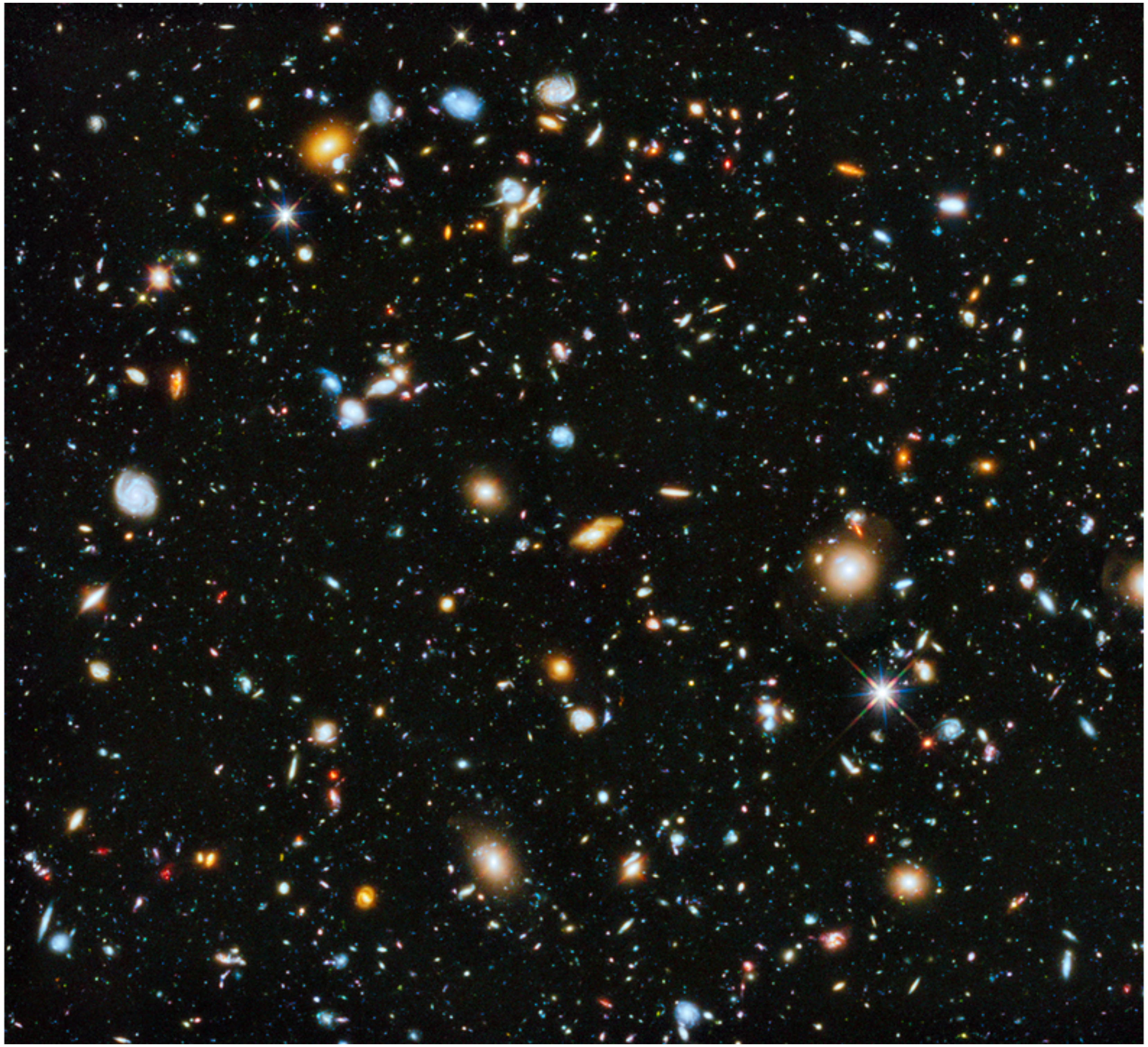
phase mixing scales linearly with time

$$\Delta\theta = \delta\omega \times t$$

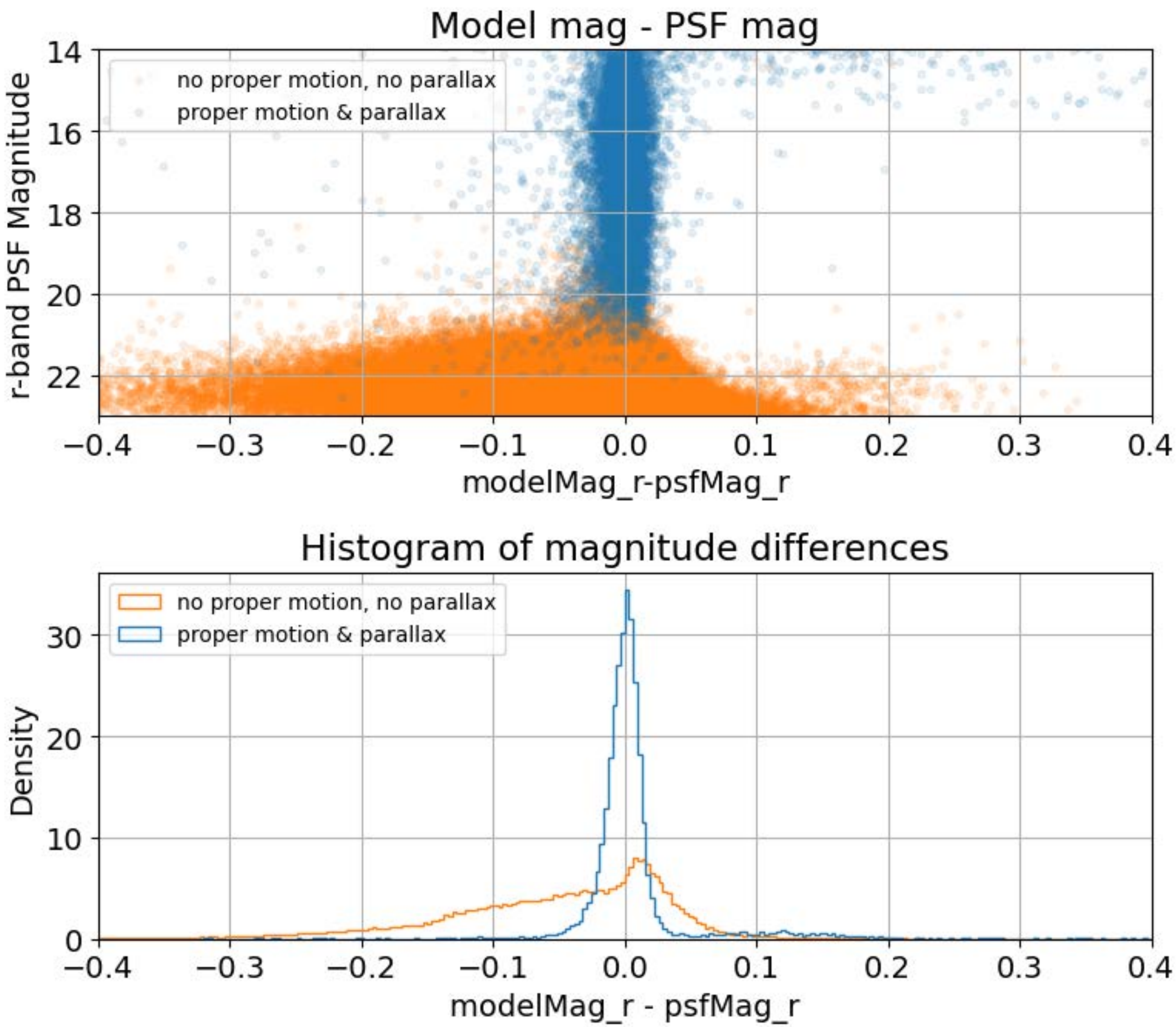
phase offset

frequency difference

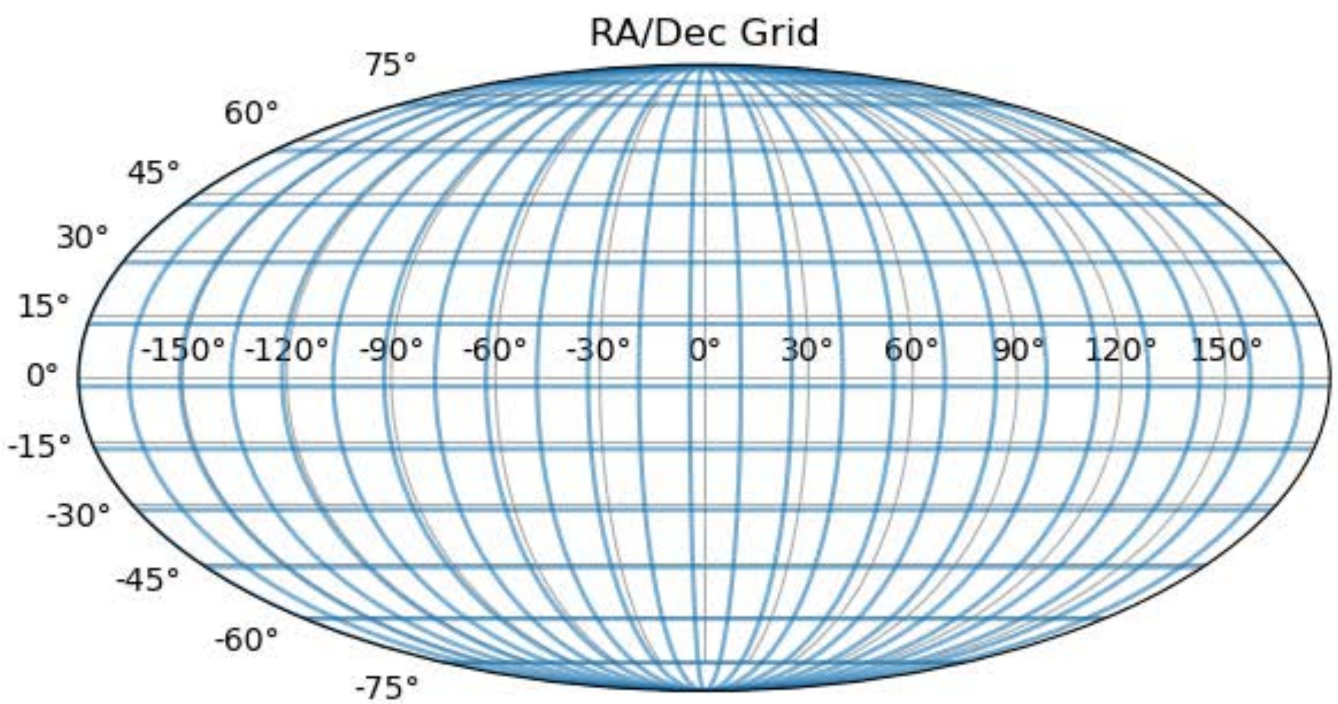
Star or galaxy?

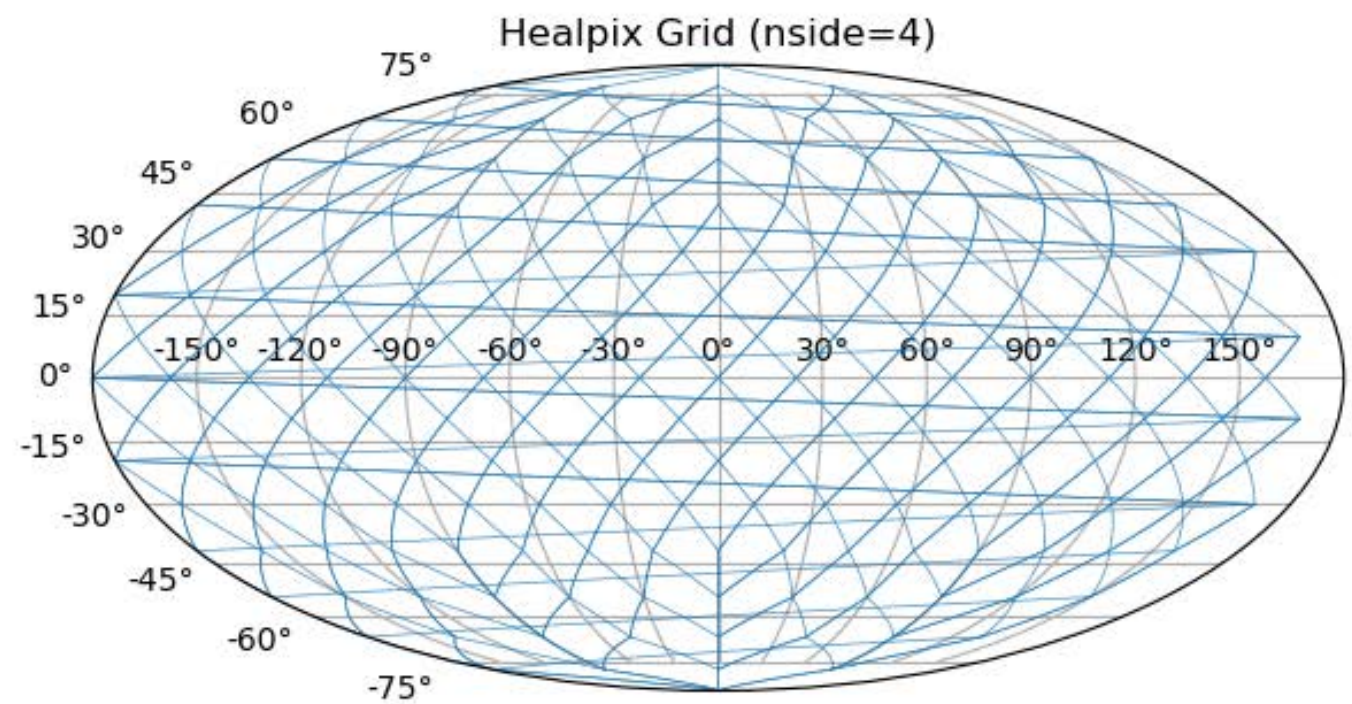


Star or galaxy?

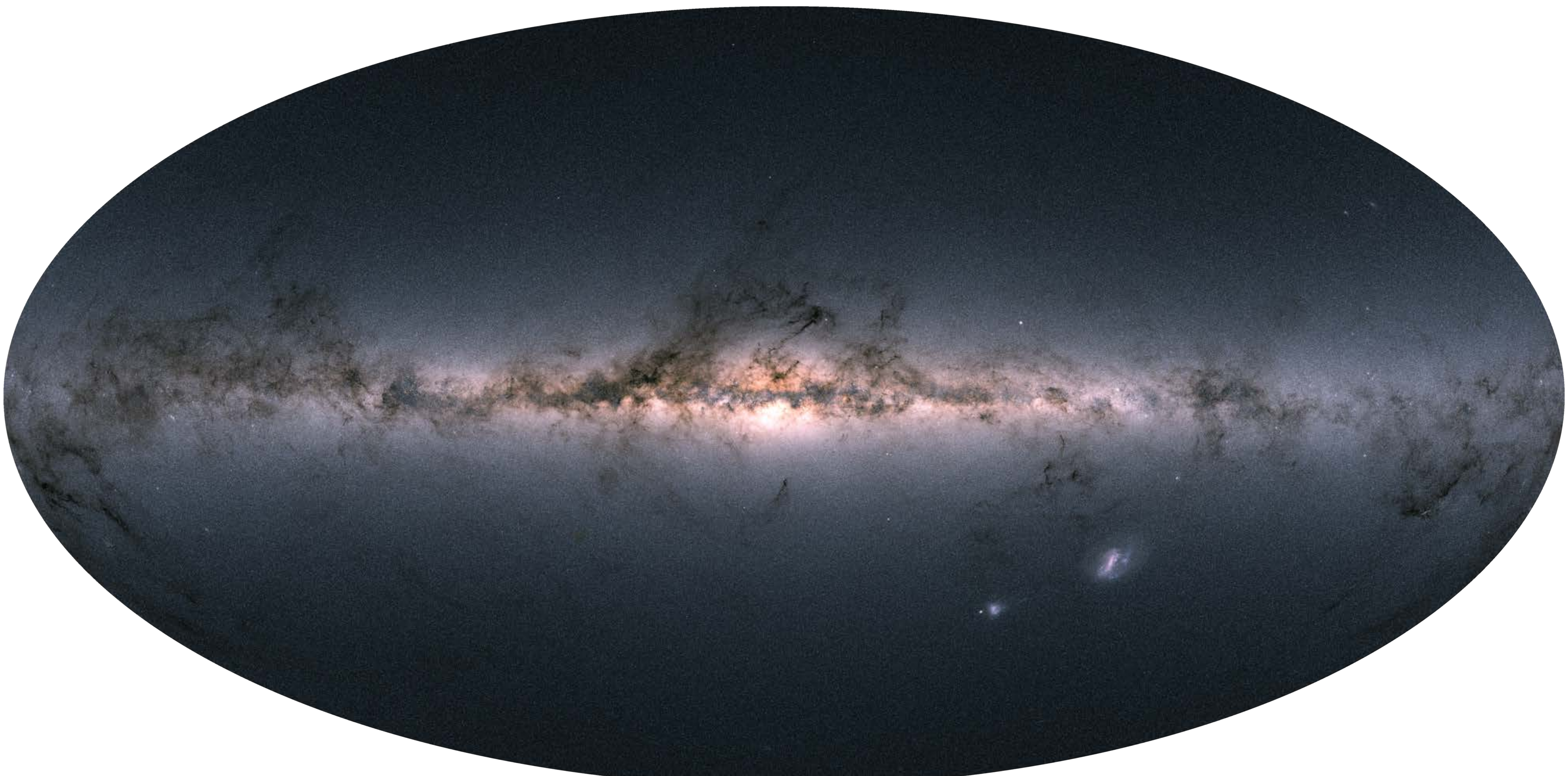


Are same **range** RA, Dec bins really same **area**?

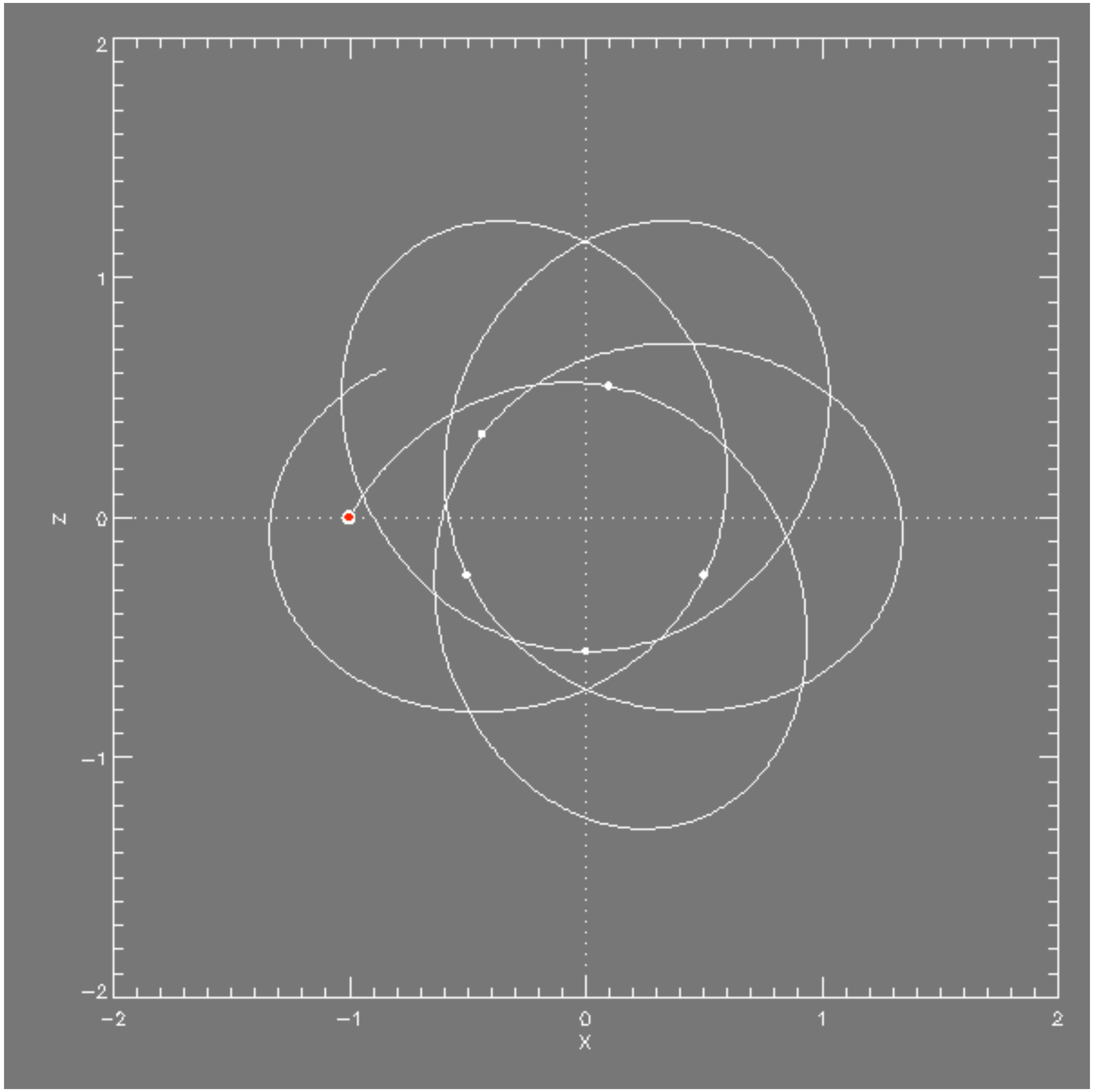




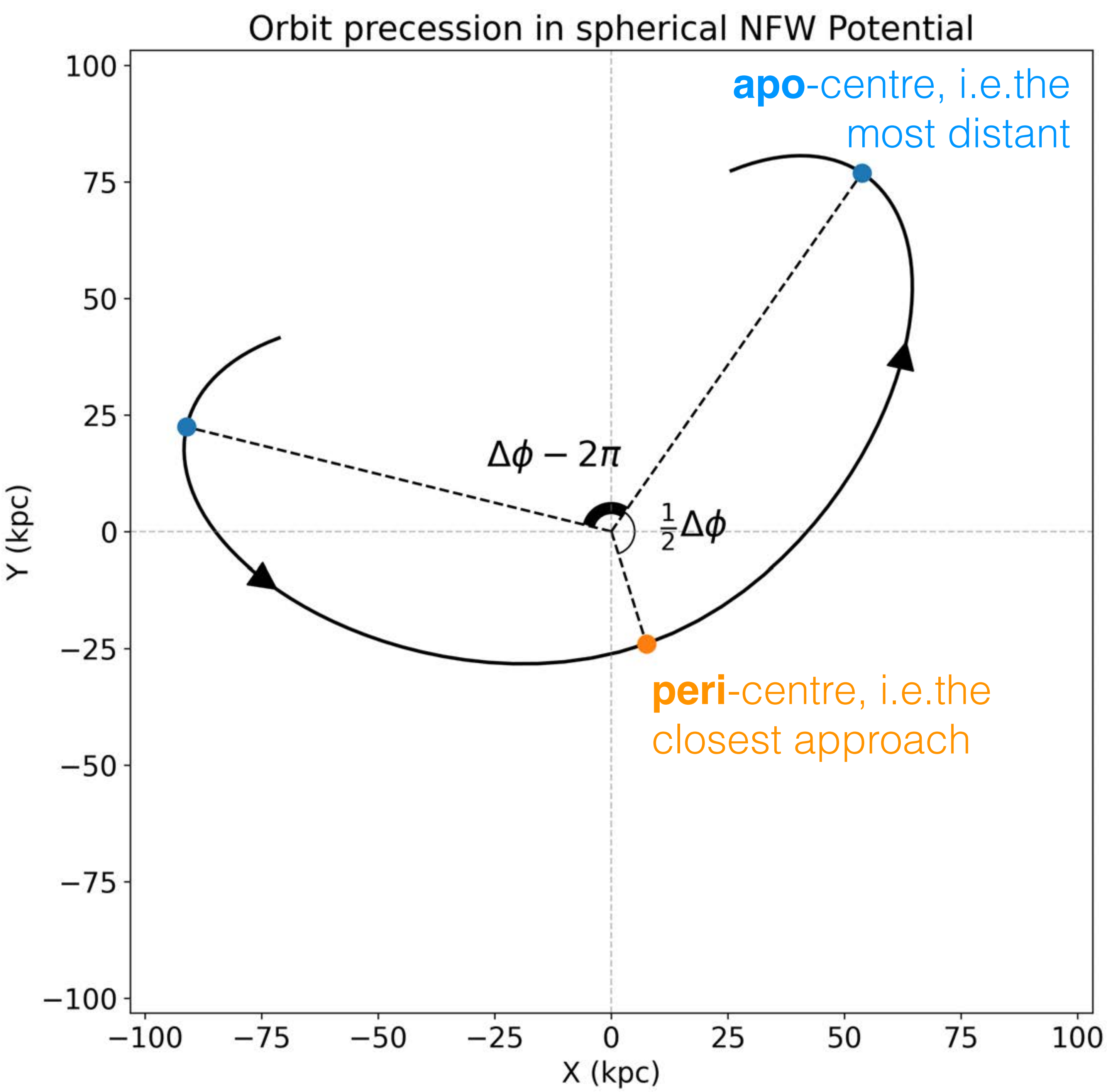
If not a photograph, then what is it?



Why do orbits not close sometimes?

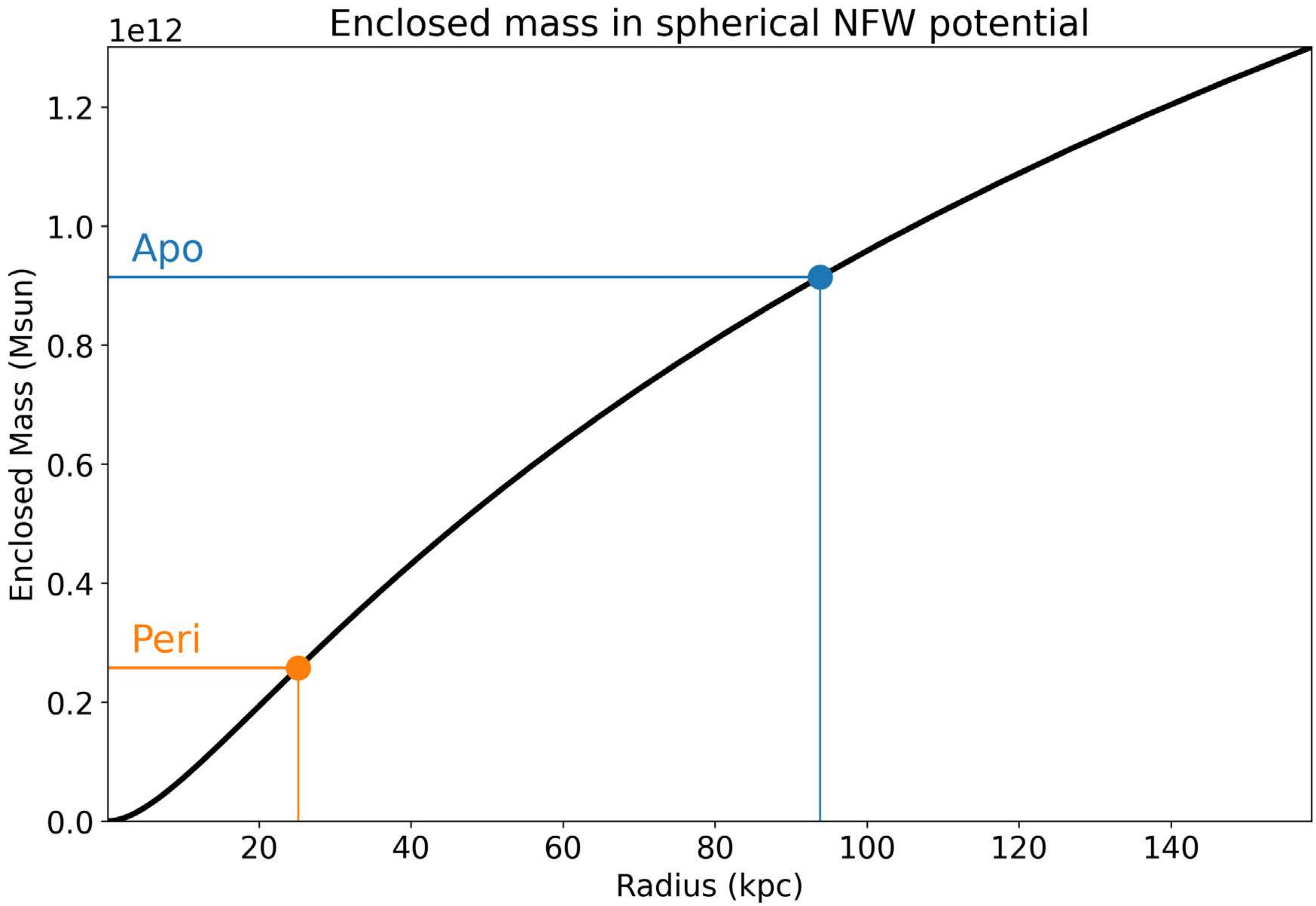


Why do orbits not close sometimes?



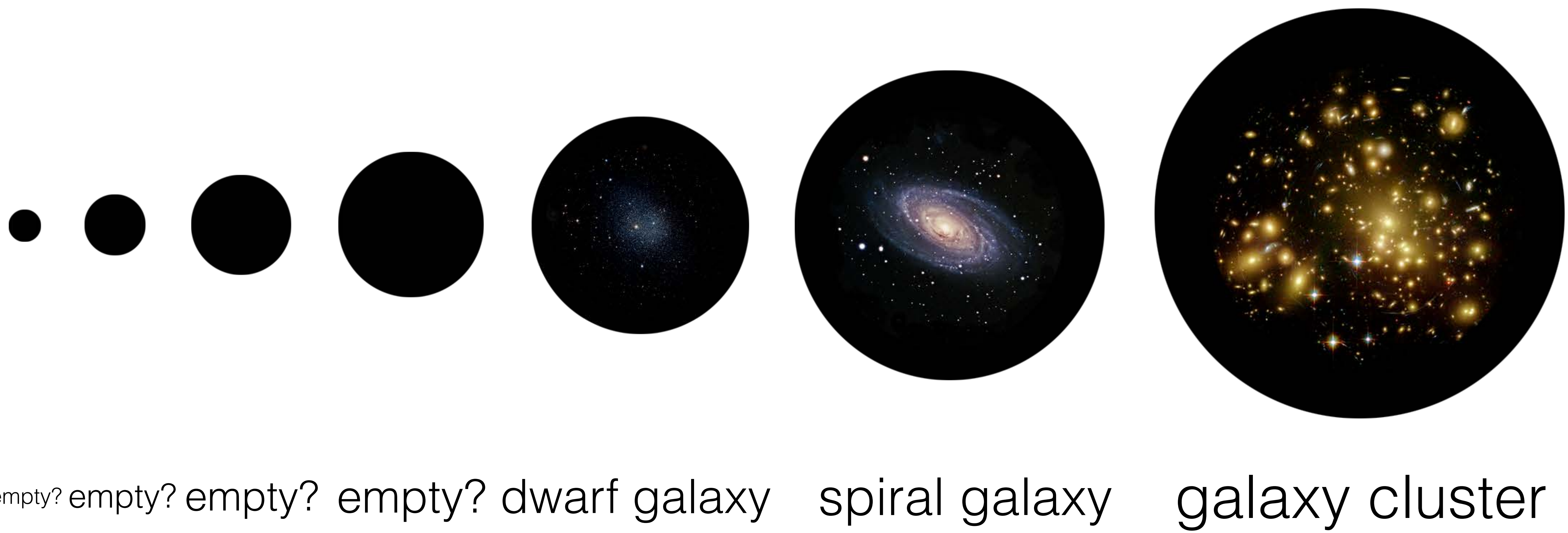
- At its apo and at its peri, the star ``sees'' different mass, i.e. there is different amount of mass inside the star's distance from the Galaxy's centre.
- The star is accelerated by much larger mass than the one it encounters when it arrives to the peri-centre.
- The mass it encounters at peri is much smaller that that required to turn the star around on its orbit completely. With lower mass pulling it, the star's velocity is too high and it overshoots.
- Think back to the Keplerian orbit case. There the star ``sees'' the same mass at apo and at peri.
- How much mass is missing by the time this star gets to the peri-centre?

Why do orbits not close sometimes?

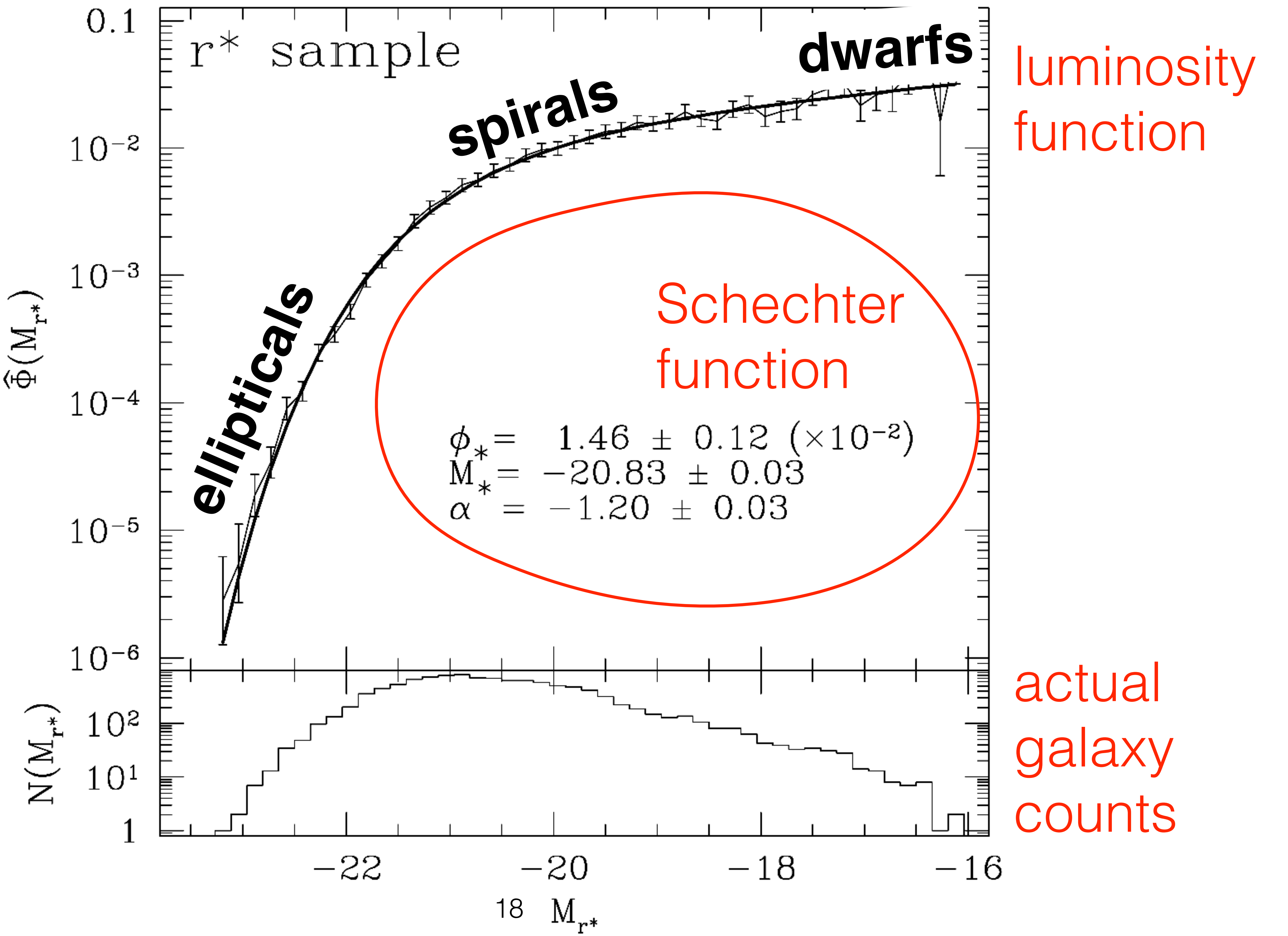


Connection between **galaxies** and their **dark matter halos**

Dark Matter (sub)-halo mass function



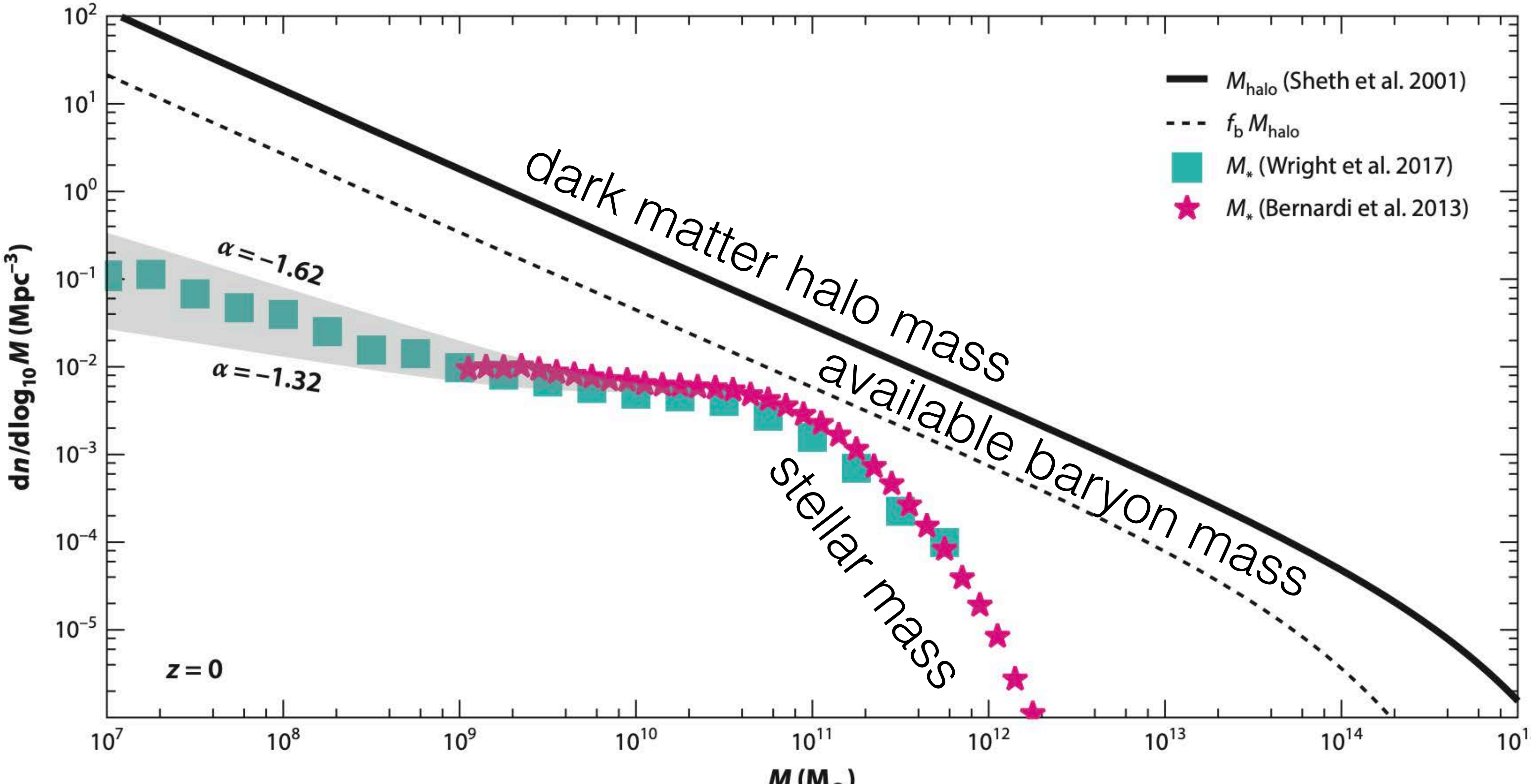
Galaxy luminosity function



Blanton et al 2001

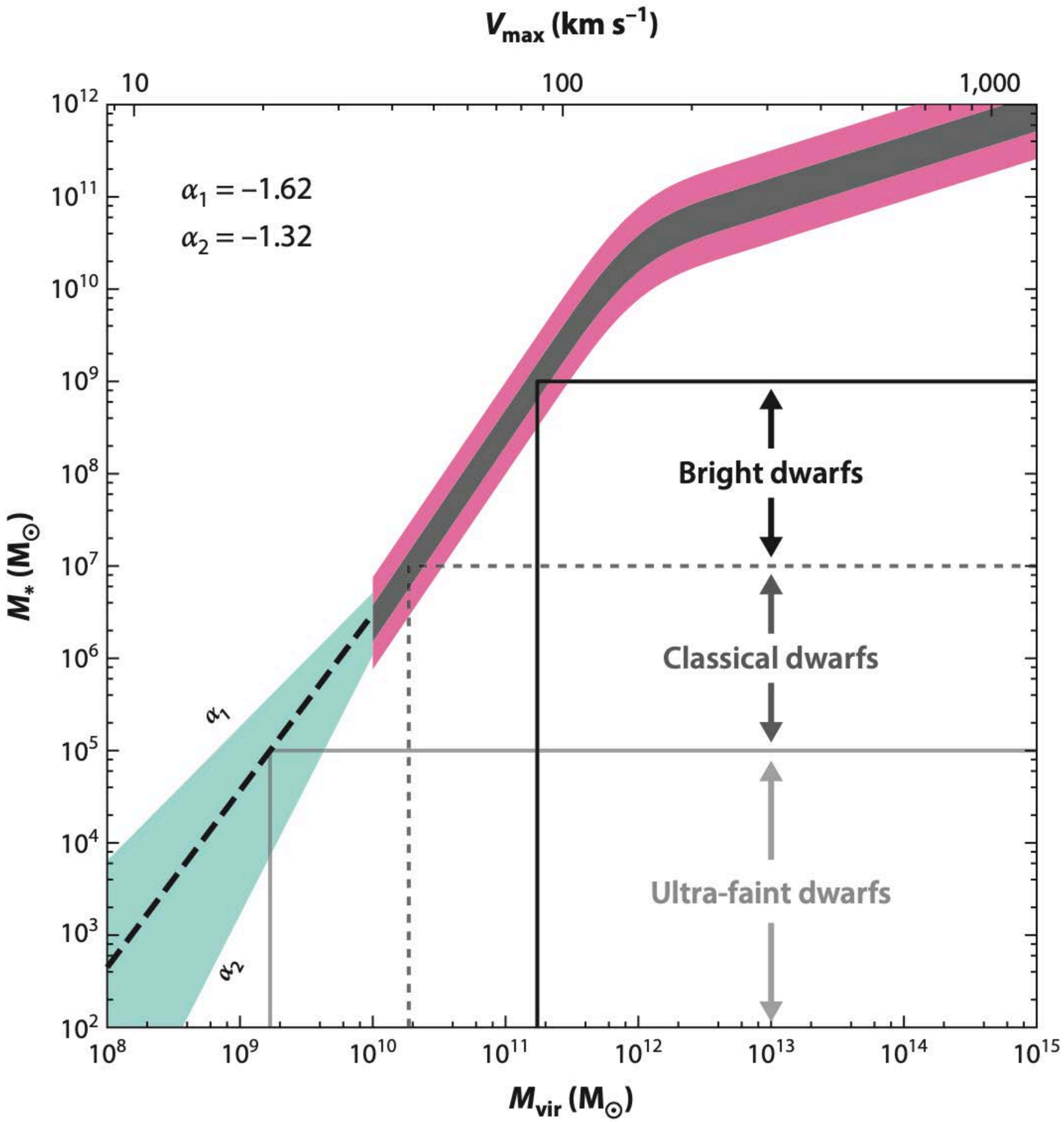
DM halo mass function vs galaxy stellar mass function

- Dark Matter halo mass function keeps growing as $\propto M^{-1.9}$ this is likely a fundamental property of the DM particle
- Baryons are not converted into stars with constant efficiency due to different aspects of baryon physics



Bullock & Boylan-Kolchin 2017

Stellar mass - DM halo mass



Bullock & Boylan-Kolchin 2017

Extension of the stellar mass - halo mass relation into the **ultra-faint** regime

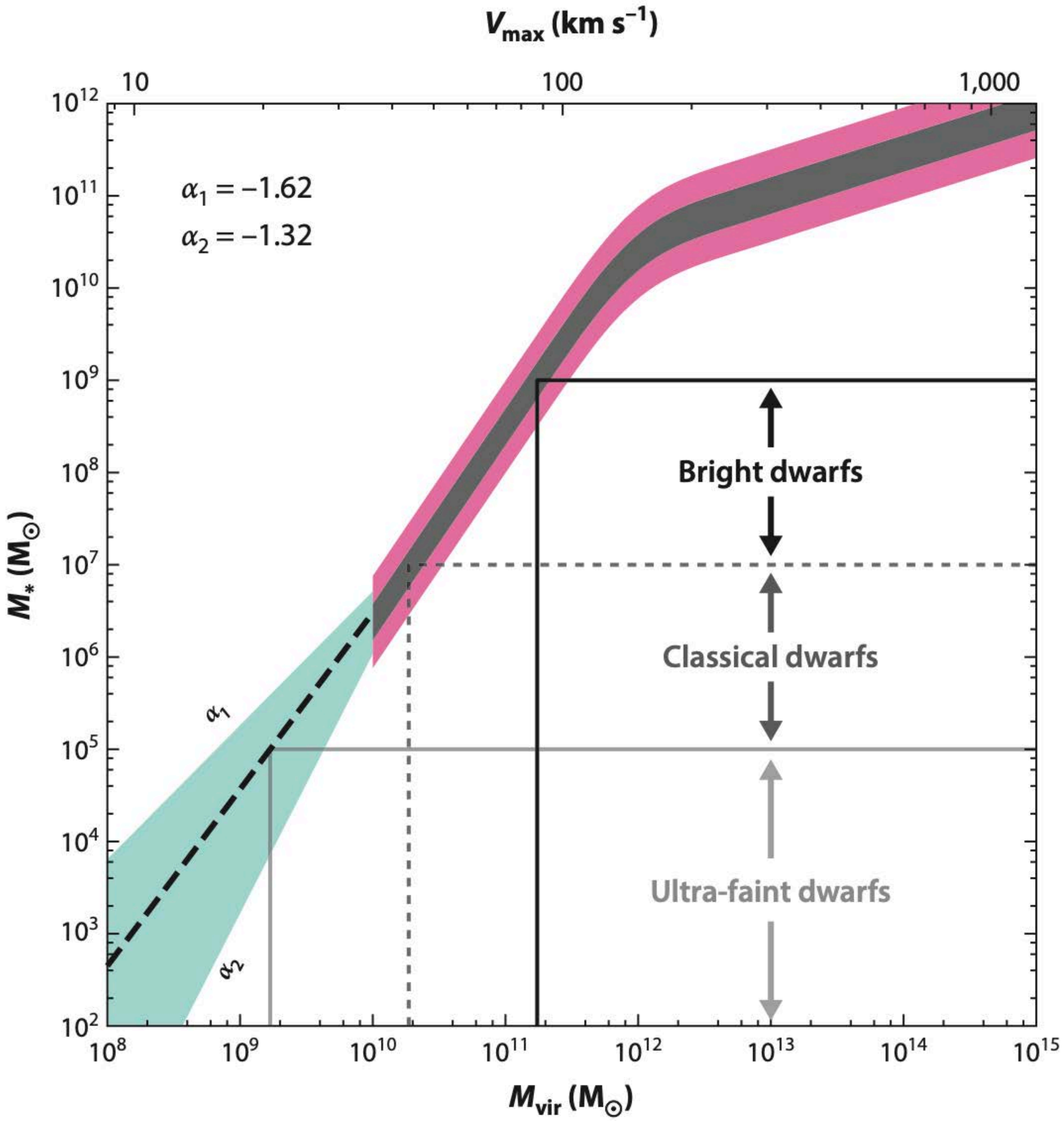
There is a break just below $10^{12} M_\odot$

Goes down to luminosities of a single supergiant star

8 orders of magnitude in stellar mass but only 4 orders of magnitude in DM mass

Appearance of the stellar halo

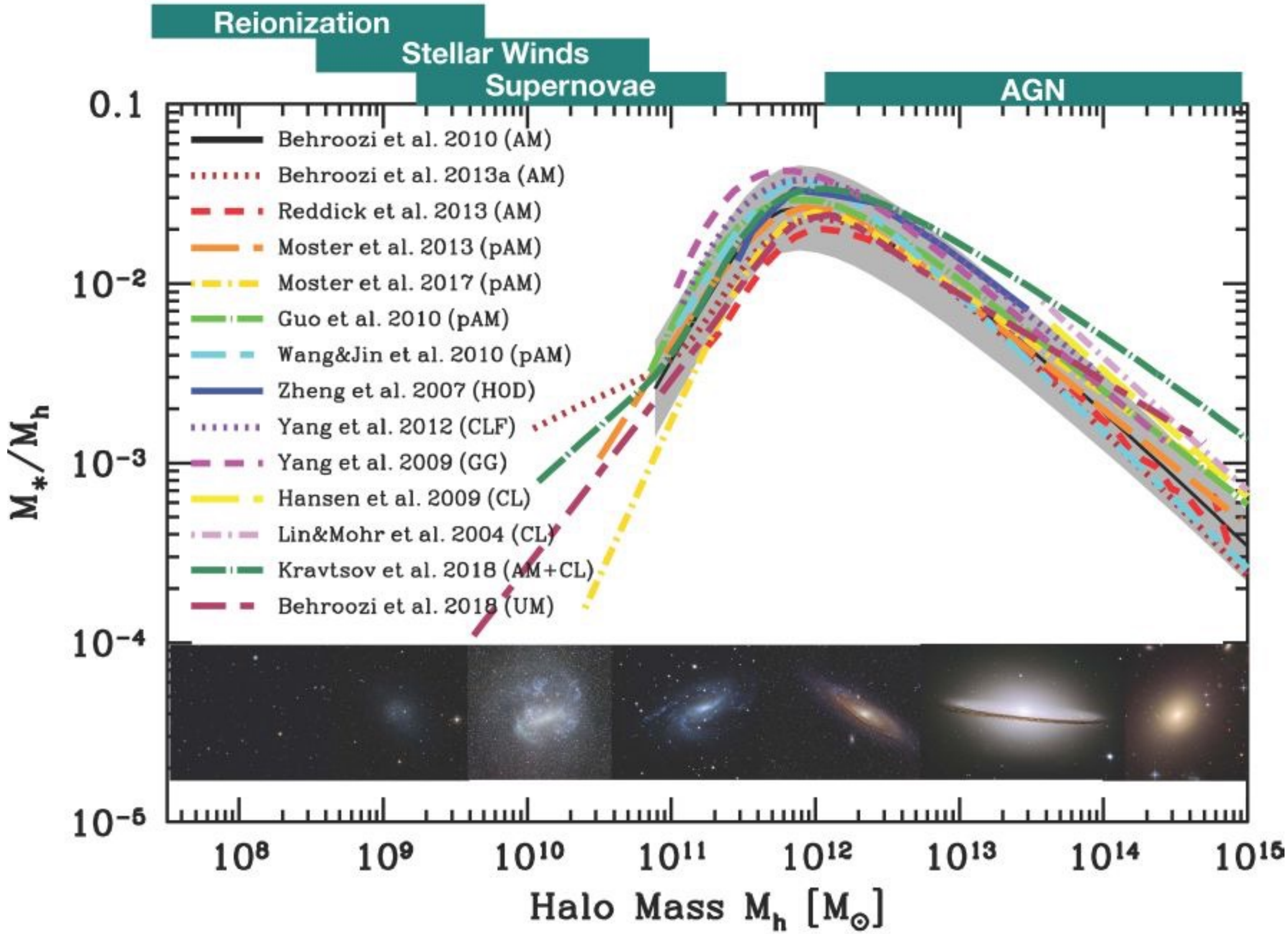
Stochasticity



Bullock & Boylan-Kolchin 2017

- Is due to a turn-over in stellar mass - halo mass relation
- Dark Matter halo is a hotchpotch of myriads of accretion events - appears smooth and well mixed on large scales
- Stellar halo is dominated by a small number of massive satellites
- All sub-galactic fragments bring in Dark Matter
- But only few most massive ones bring (appreciate number of) stars

Galaxy formation efficiency



Wechsler & Tinker 2018

A different way to show the same relation is by plotting the ratio of stellar mass to halo mass as a function of DM halo mass.

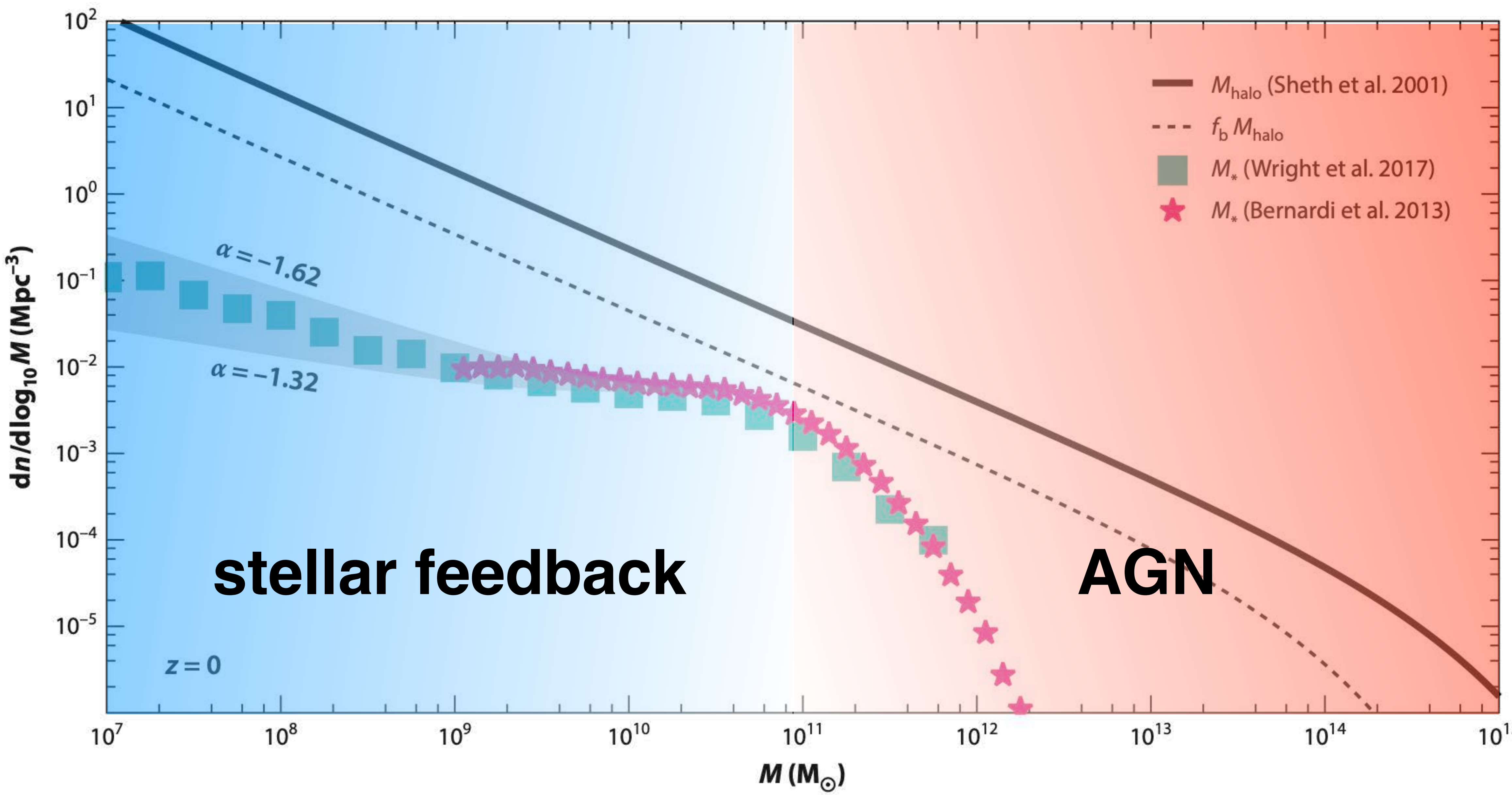
This gives us an efficiency of galaxy formation.

Corresponding representative galaxies are shown at the bottom, from giant ellipticals on the right to dwarf galaxies on the left

What makes galaxy formation **inefficient** at the faint and bright ends?

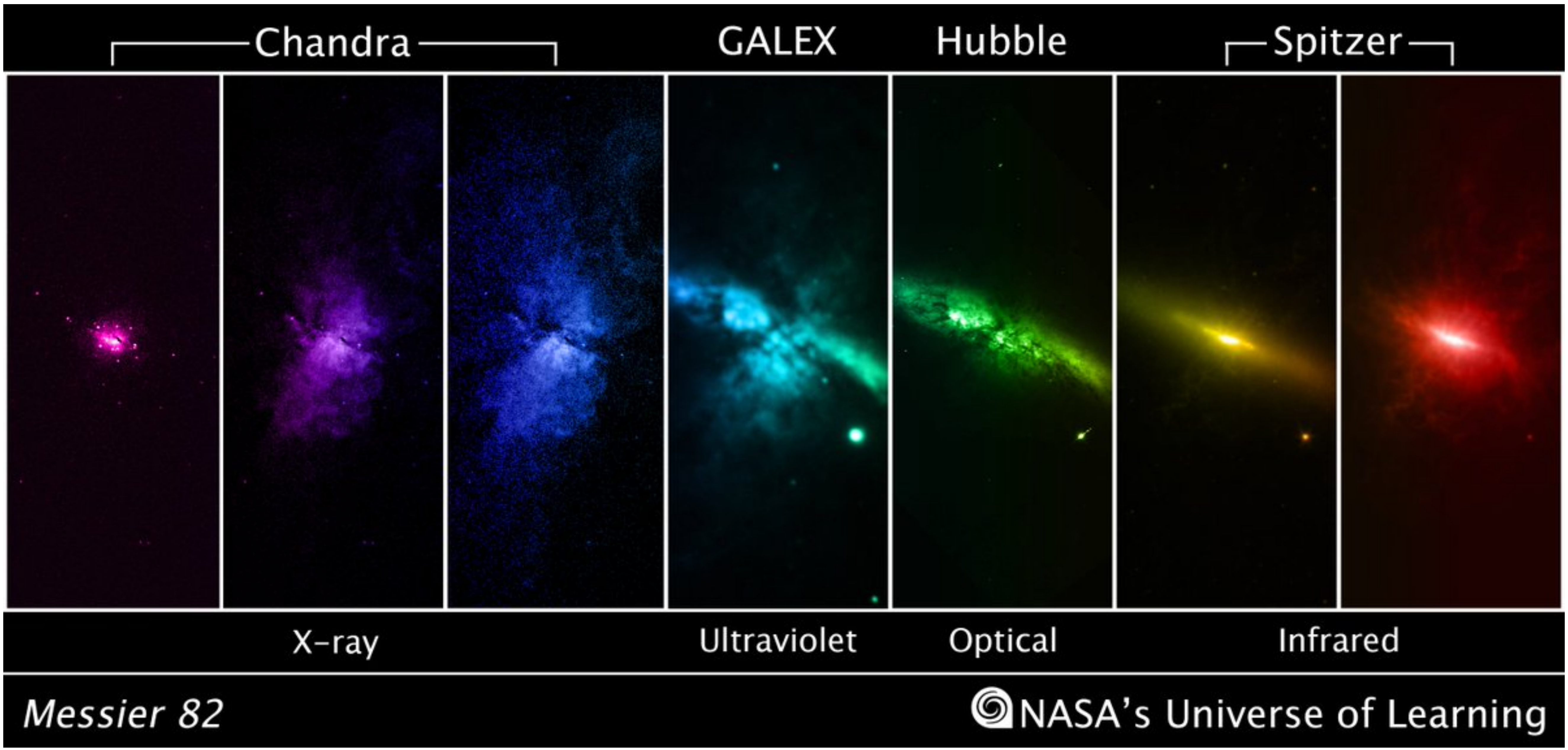
Need for feedback

galaxy luminosity function vs halo mass function



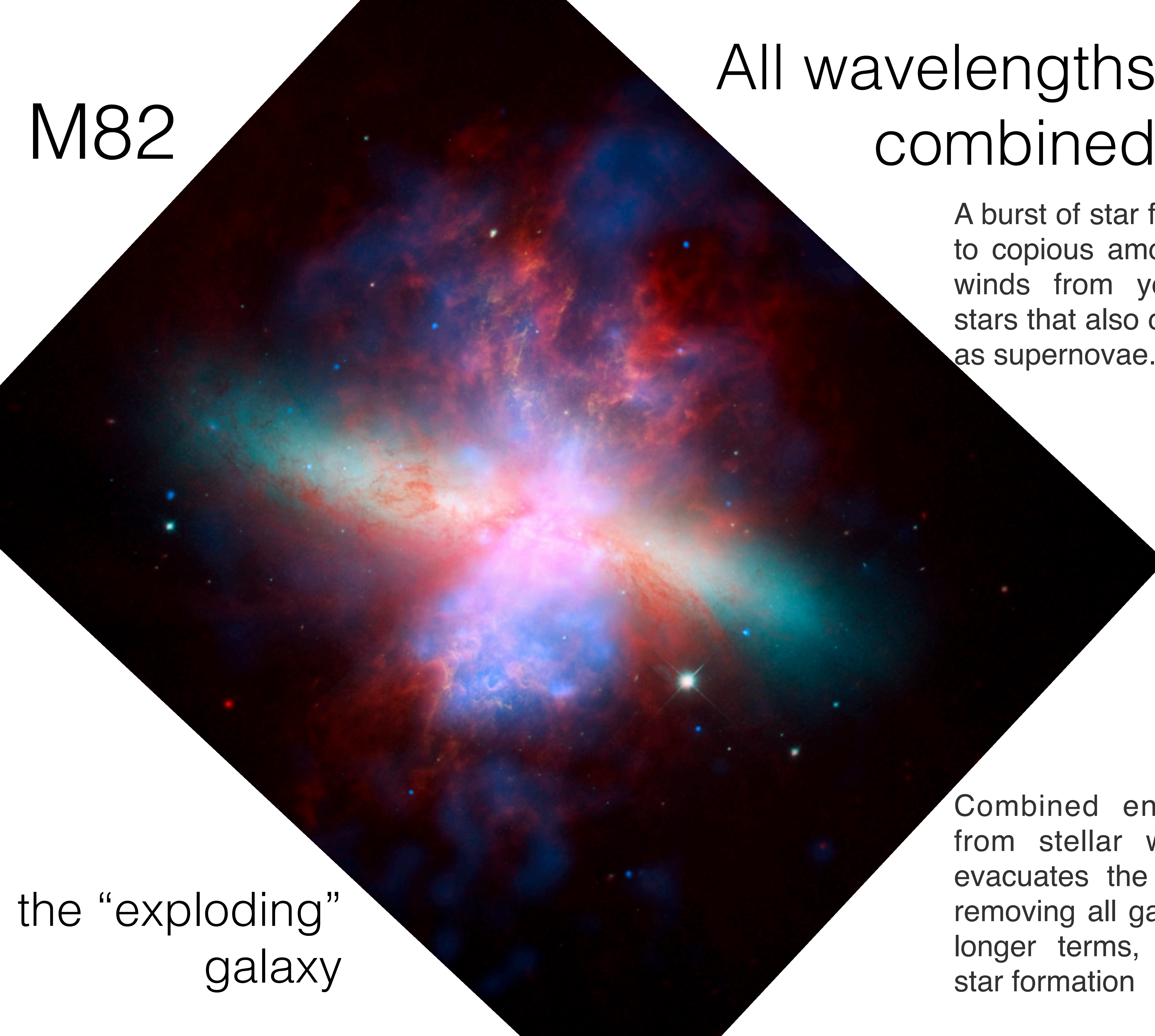
Bullock & Boylan-Kolchin 2017

Stellar feedback
multi-wavelength view of M82



M82

All wavelengths combined

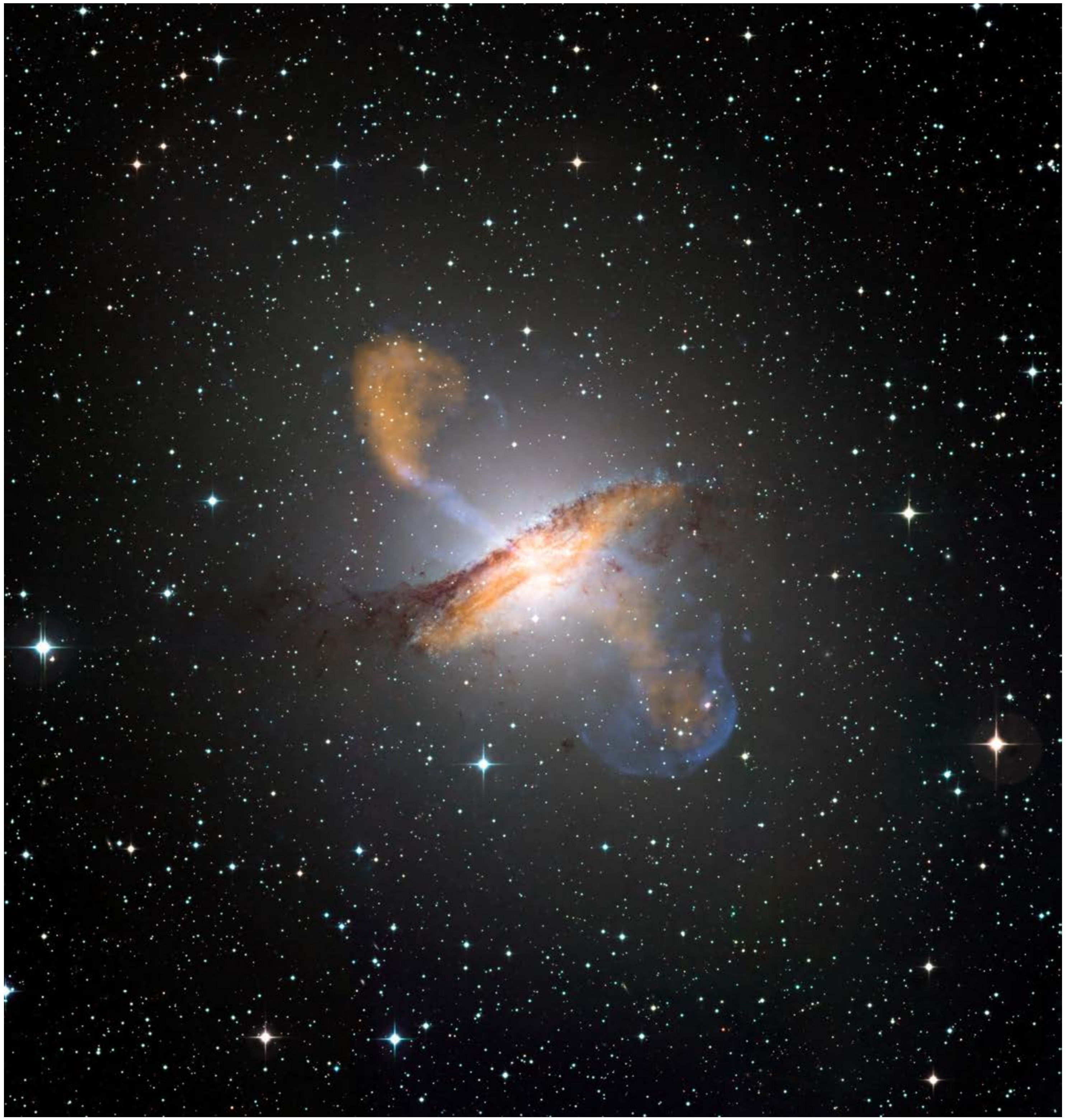


A burst of star formation leads to copious amounts of stellar winds from young massive stars that also quickly explode as supernovae.

Combined energy injection from stellar winds an SNe evacuates the central galaxy, removing all gas, and, thus, in longer terms, suppresses all star formation

the “exploding” galaxy

AGNs=Active Galactic Nuclei



Cold (molecular) gas us needed for star formation

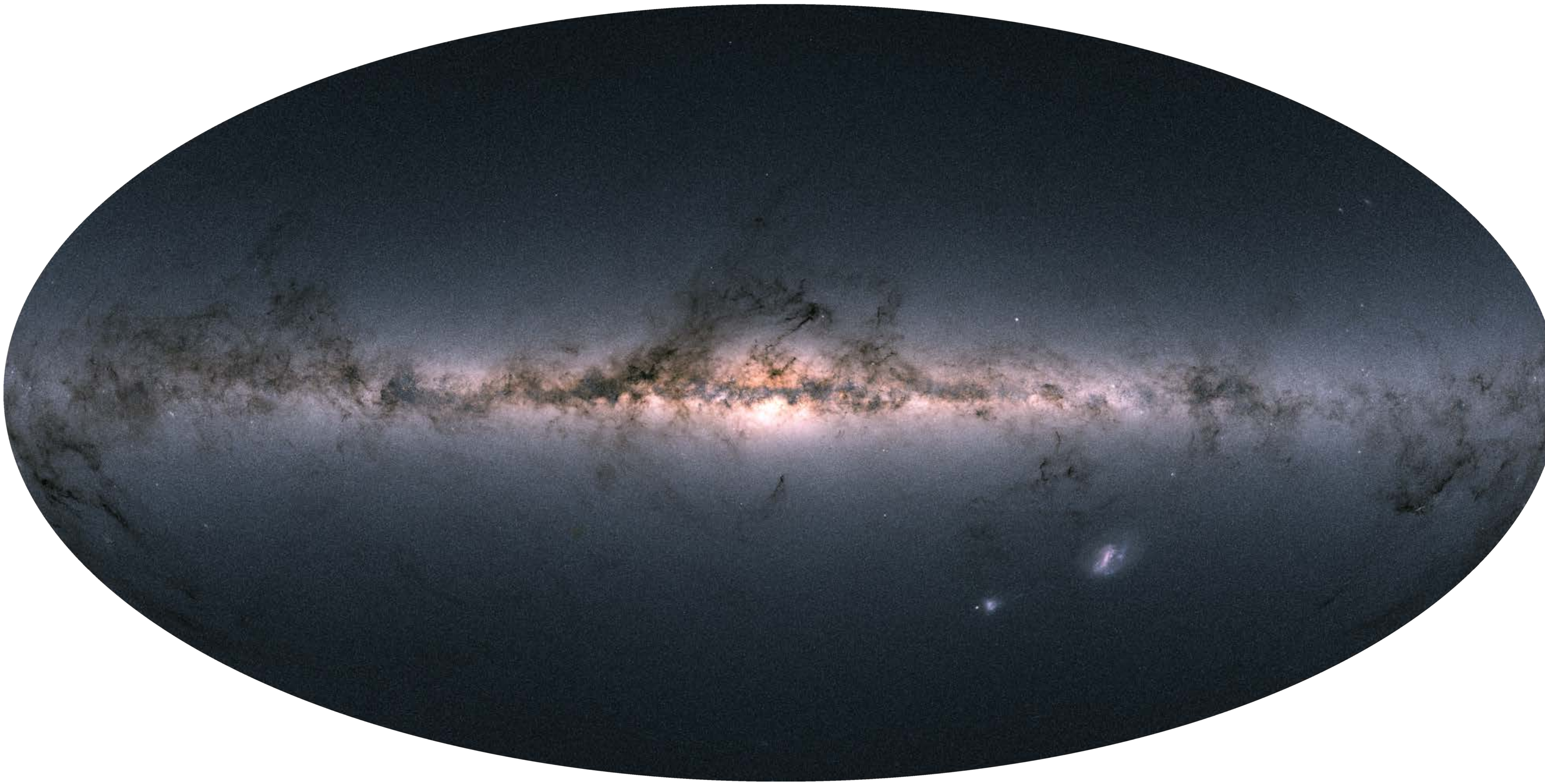
Emission from the region around the SMBH heats the gas in the rest of the galaxy

Galaxy is filled with hot, ionised gas

Star formation is paused or completely suppressed

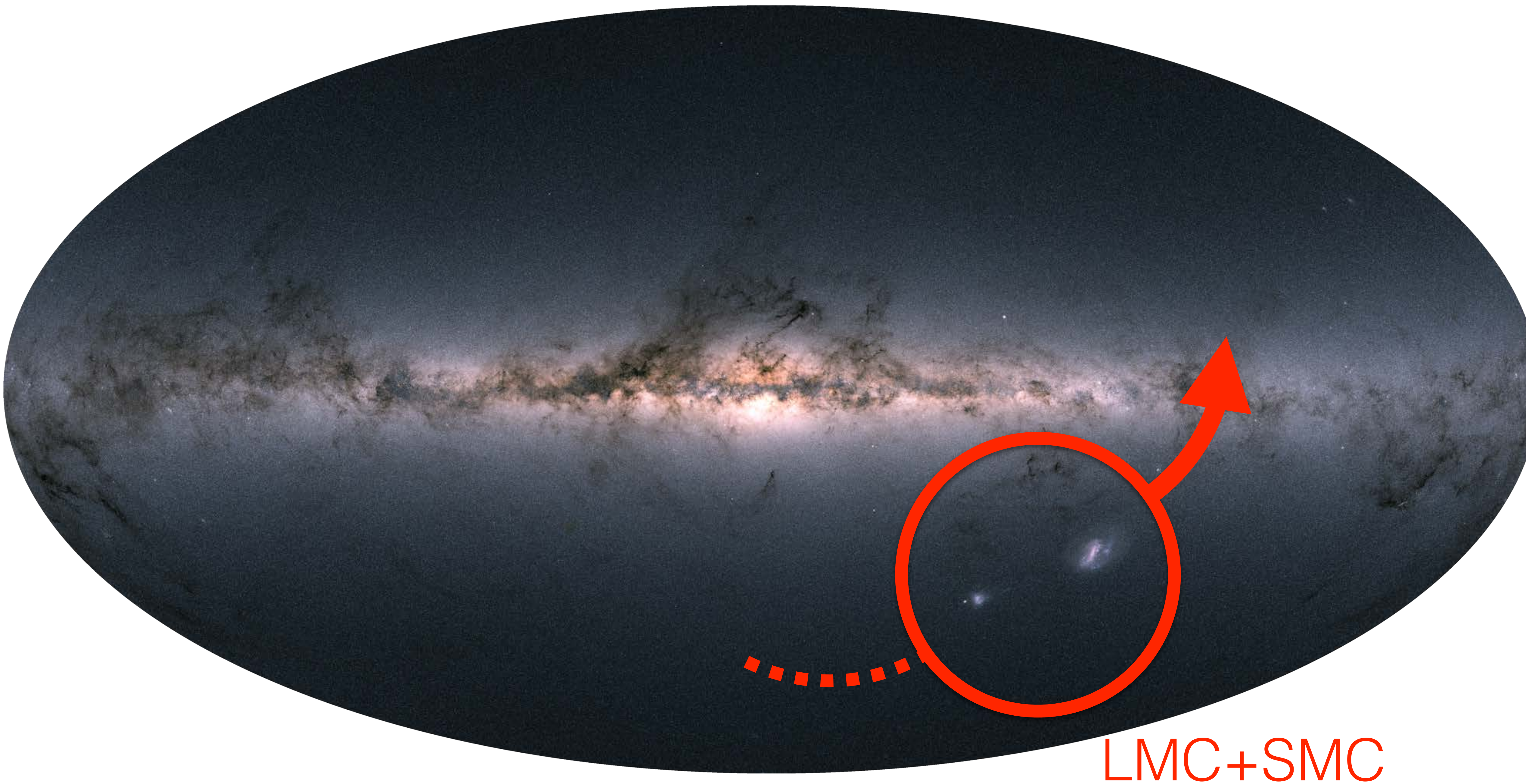
Are AGN and stellar feedback the only two ways to damage a galaxy?

All-sky view of the Milky Way



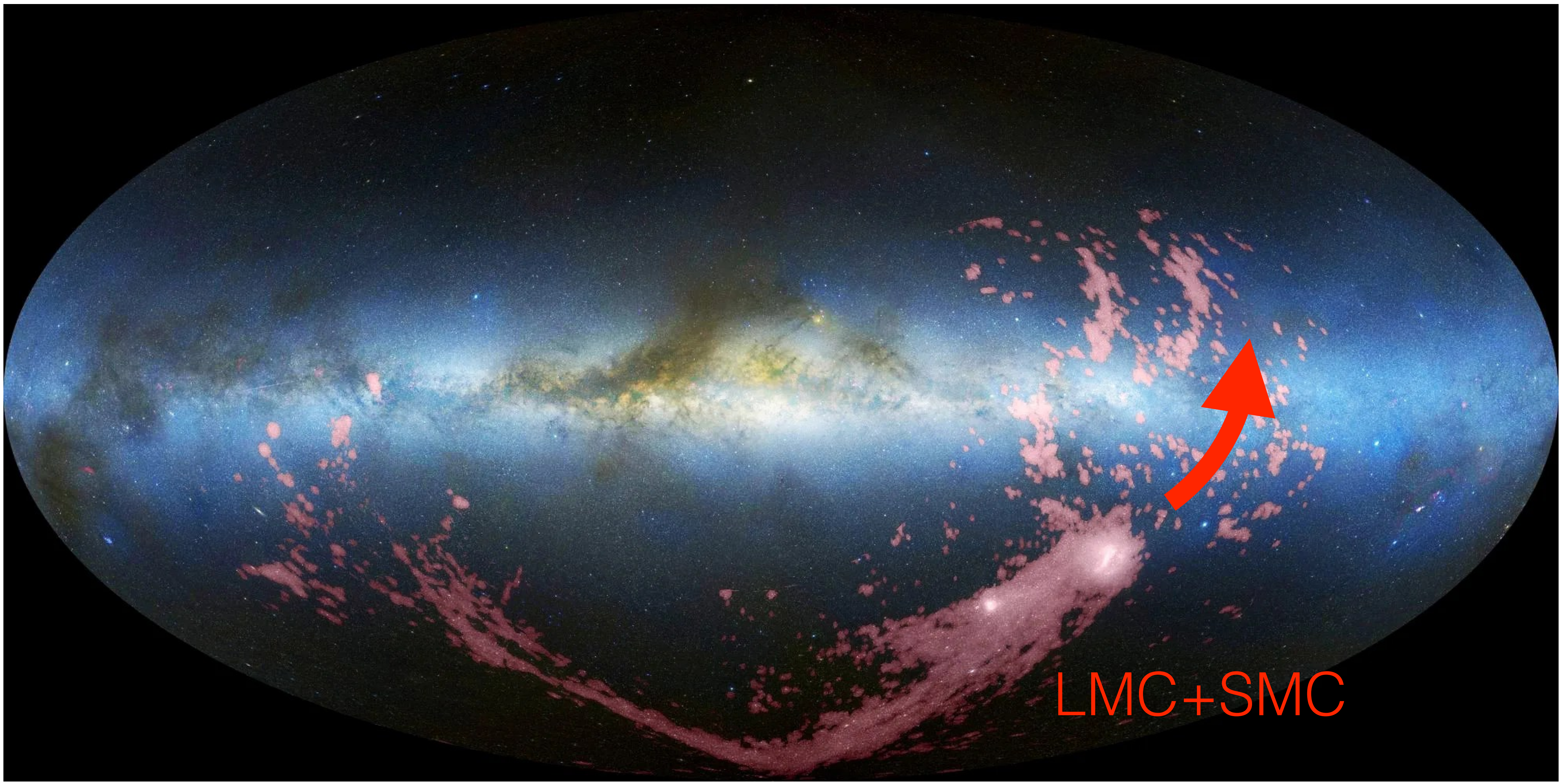
Suspicious guests

Two largest satellite galaxies around the Milky Way



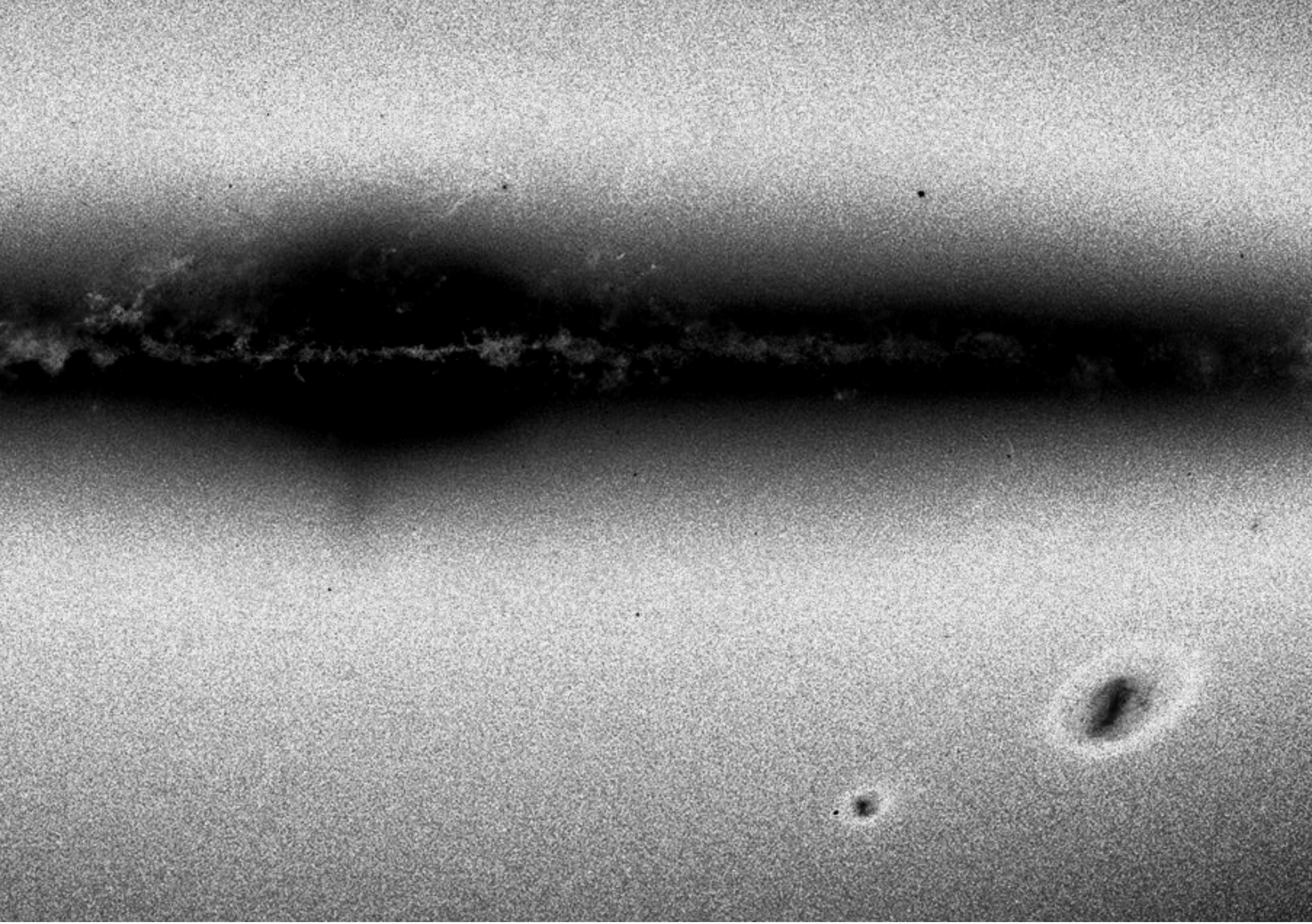
The satellite galaxies are losing gas (and stars)

optical image with radio detections of fast moving HI gas overlaid



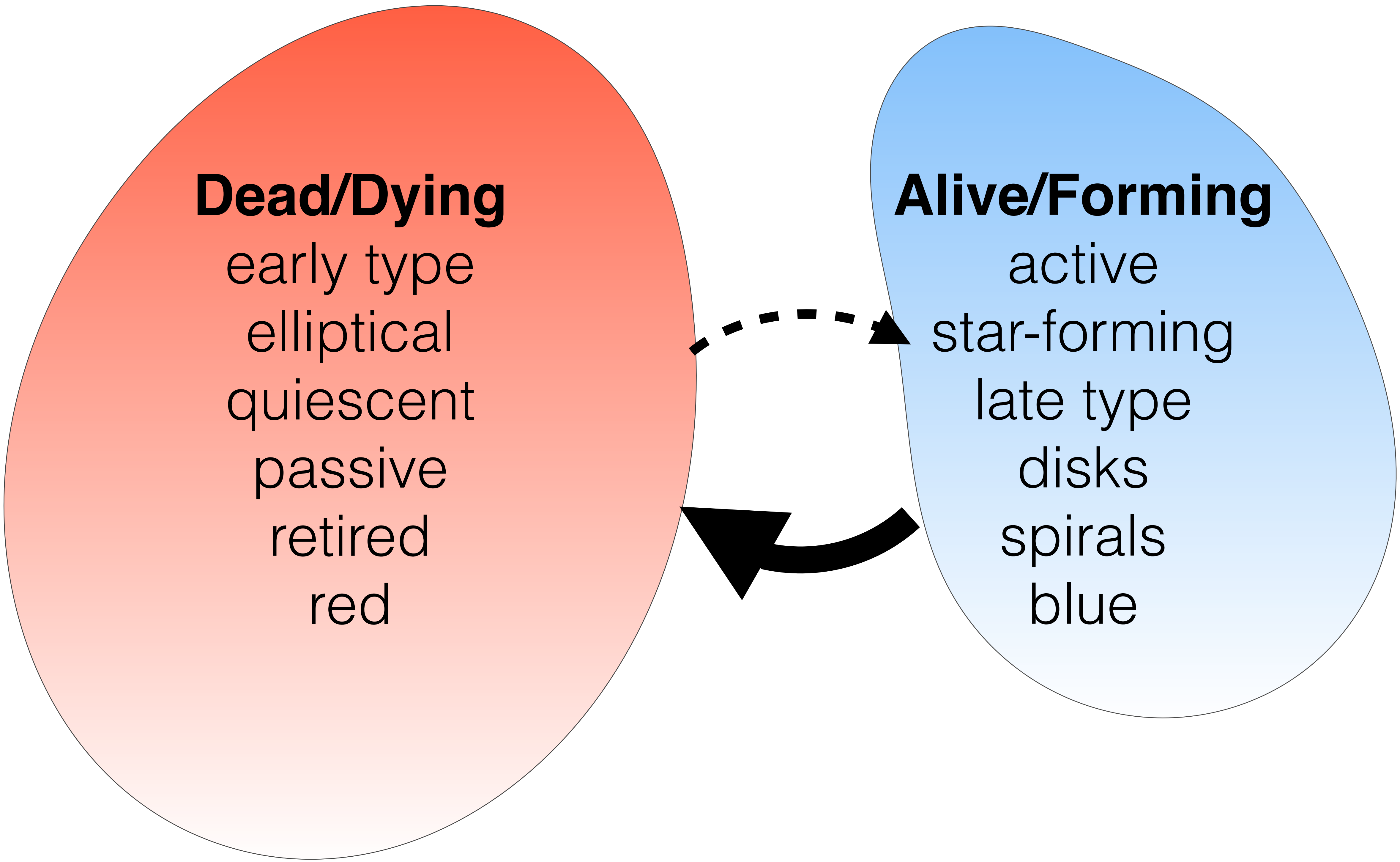
NASA

Tail of hydrogen gas stripped from the Clouds by the Milky Way

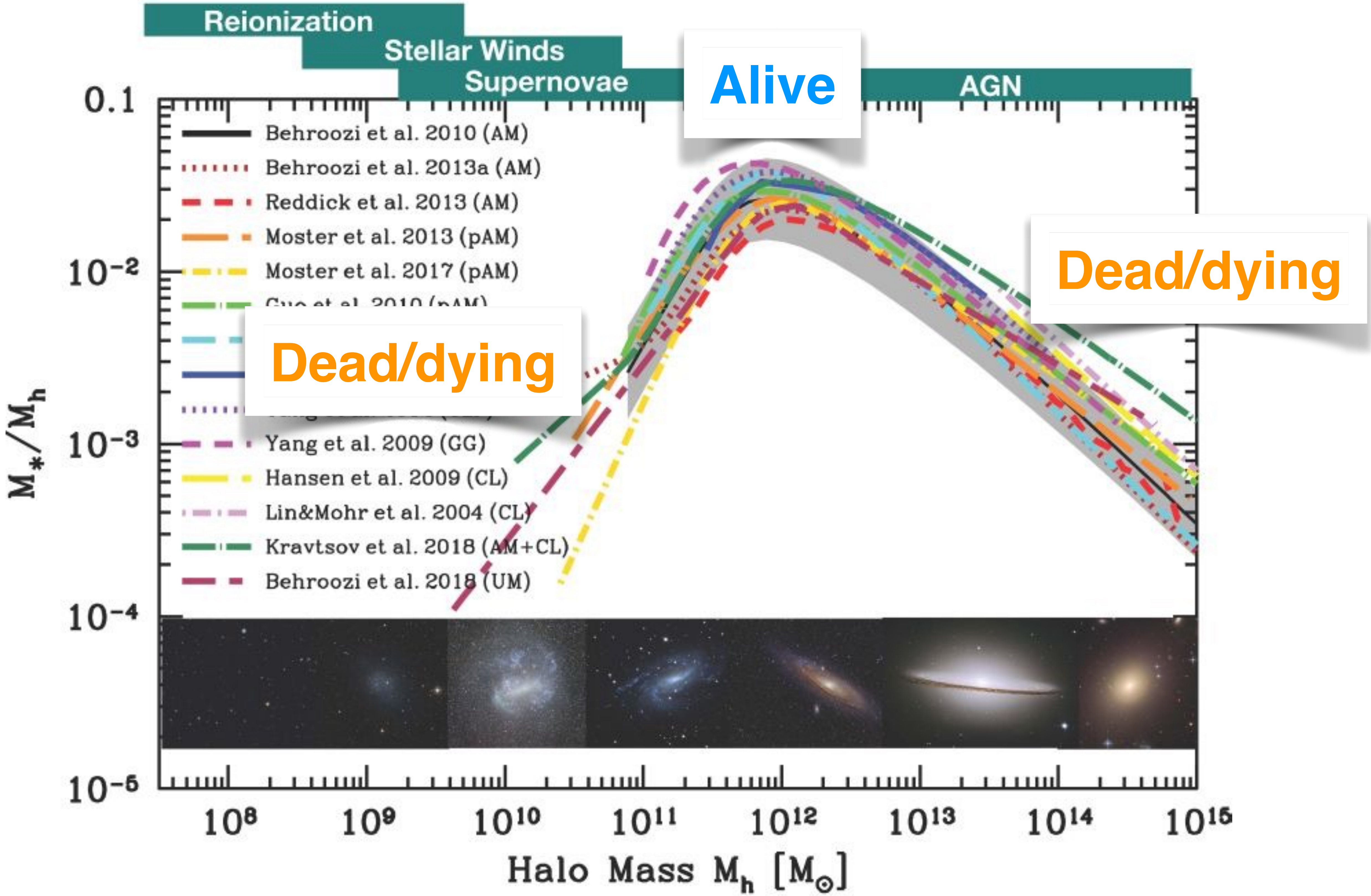


Ram pressure stripping (of gas) and **tidal disruption** are important drivers for <u>dwarf</u> galaxy transformations

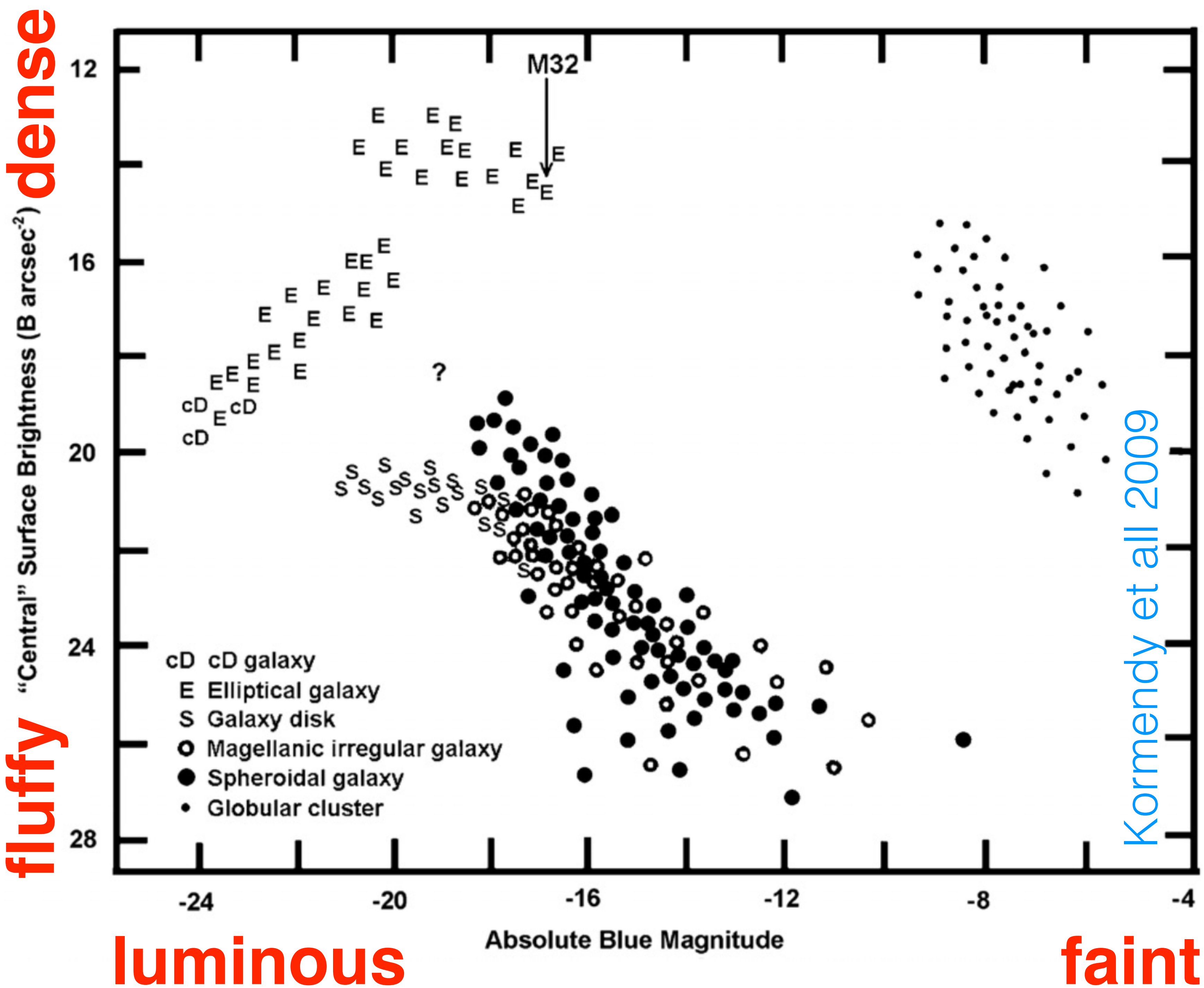
Two types of galaxies



Galaxy formation efficiency



Absolute magnitude vs surface brightness or luminosity vs concentration

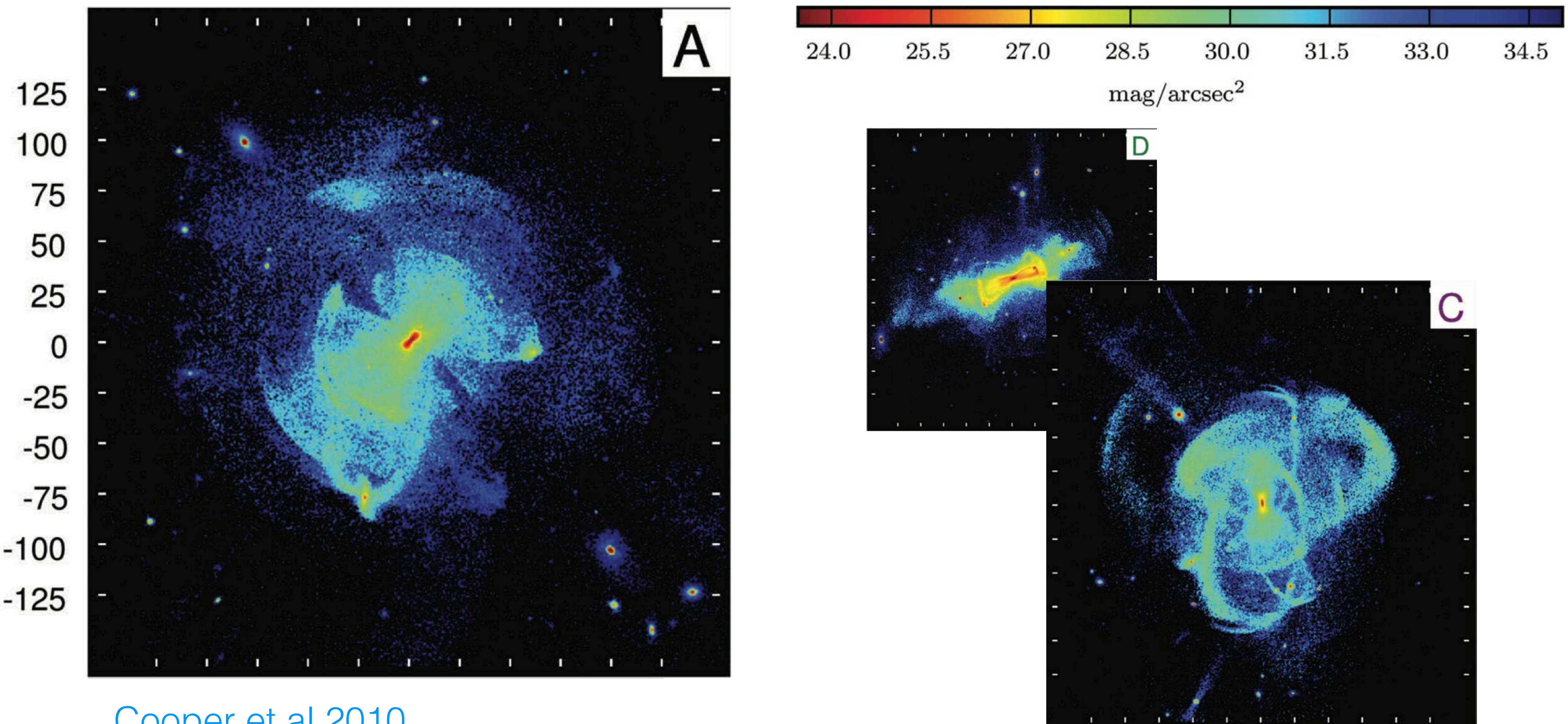


Distribution of galaxies in the plane of surface brightness (on the Y axis) and absolute magnitude on the X.

Or in other words the concentration of the stellar distribution (the smaller this number is the higher the concentration) vs its total luminosity (again the smaller the number the higher the luminosity)

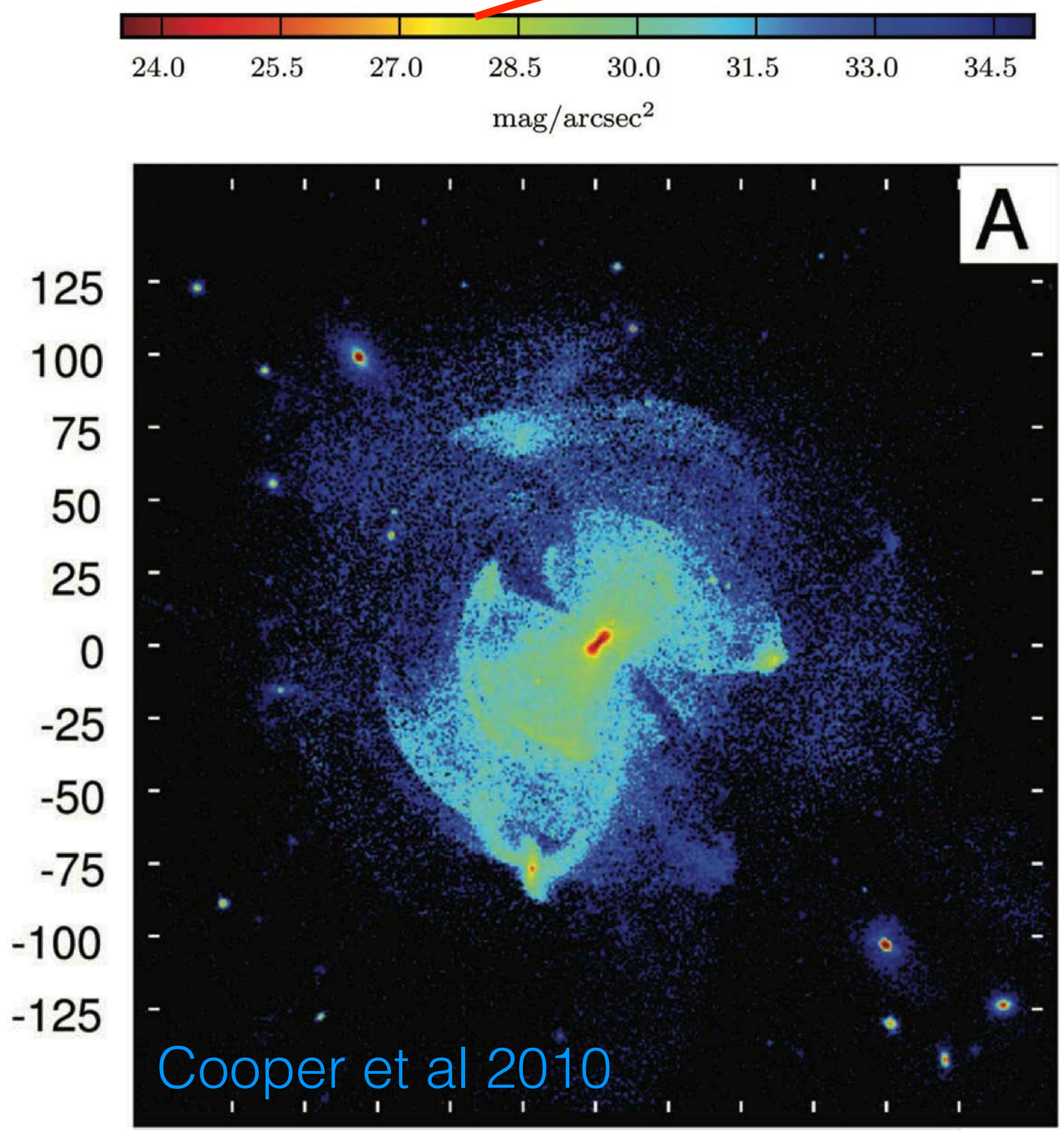
Stellar halo surface brightness

Stellar density of simulated stellar halos is converted into surface brightness

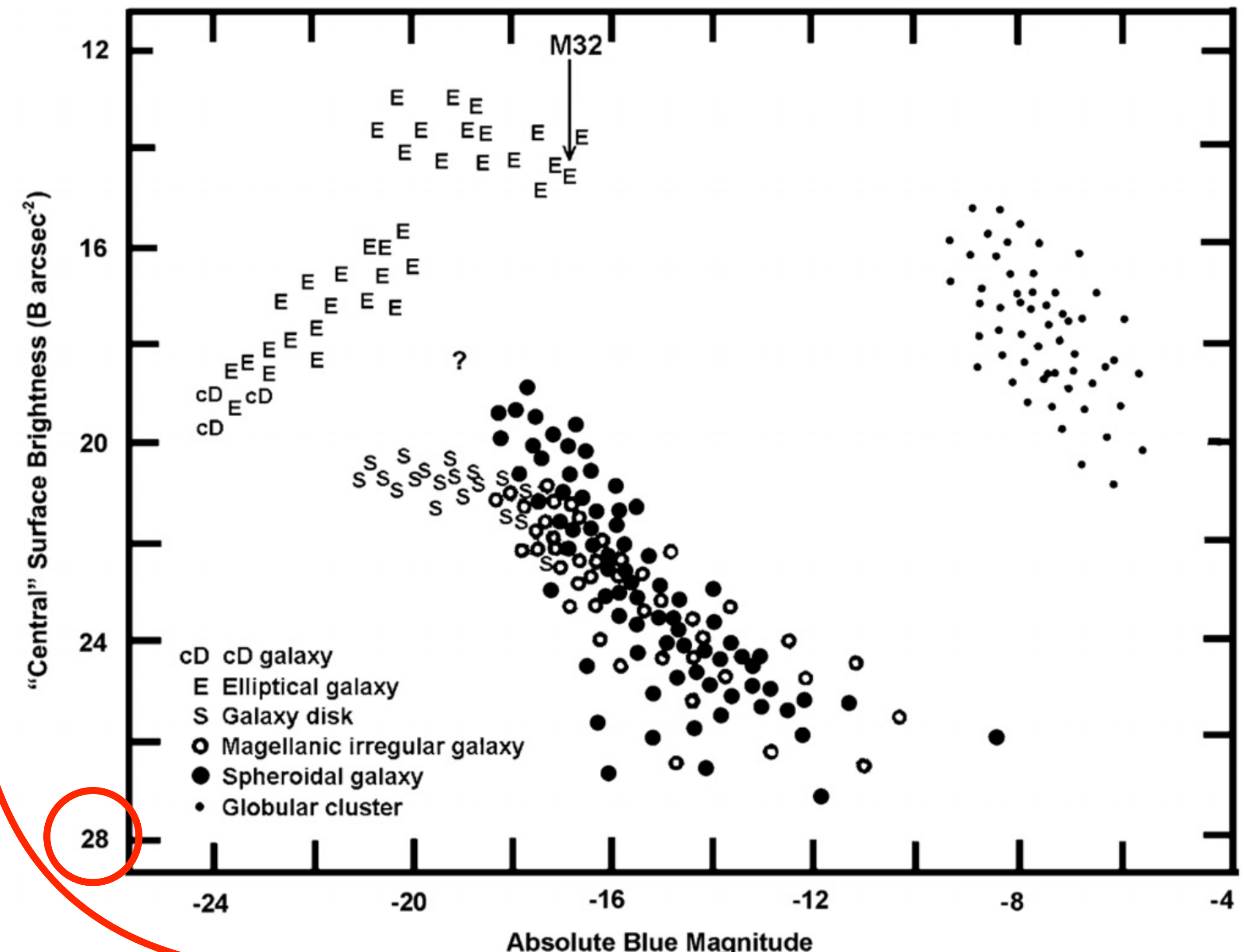


Cooper et al 2010

Stellar halo surface brightness



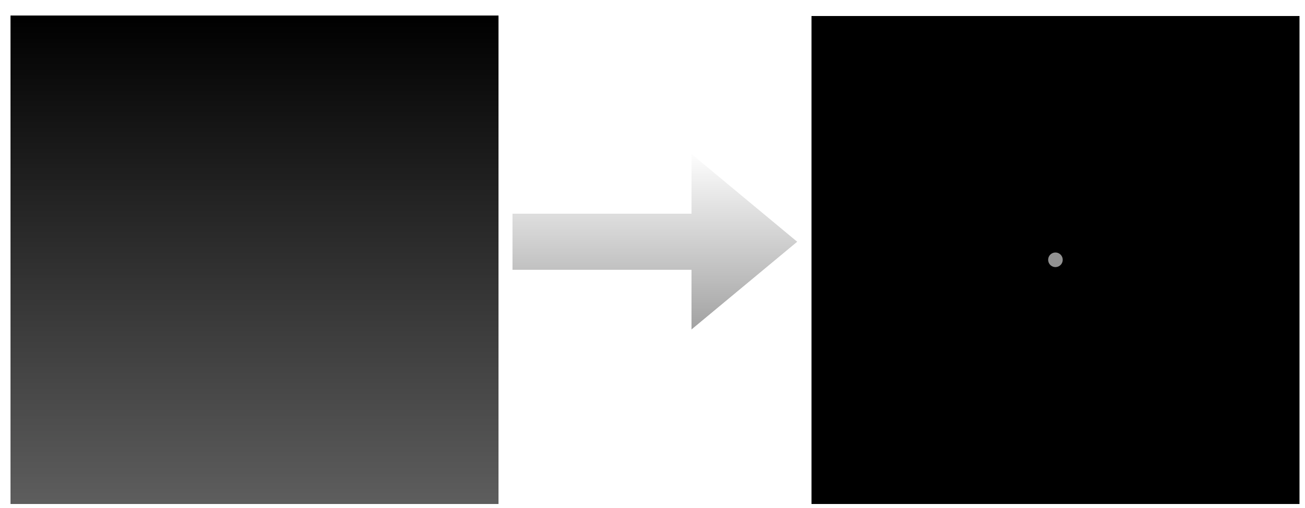
stellar halos start where the rest of the galaxy stops



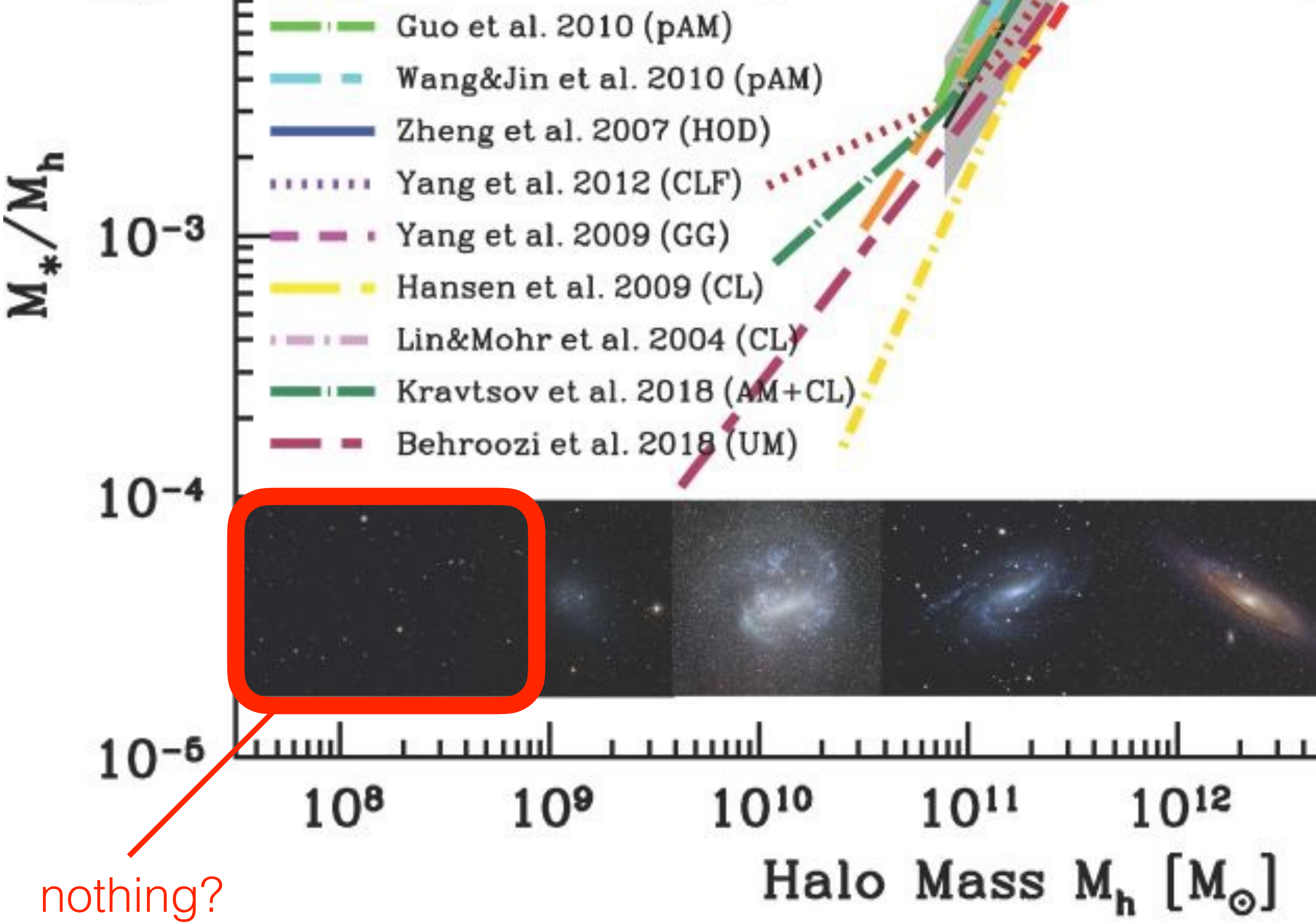
Stellar halos easily reach **ridiculous levels of surface brightness** of 28-36 mag/arcsec^2
The outskirts of the stellar halos are above 30-32 mag/arcsec^2
And yet these are **detectable** and can be measured/studied i**n the Milky Way**. How?
Because the **individual stars** are seen you are essentially not smearing the flux but detecting faint objects with small angular sizes

Reaching extreme surface brightness levels

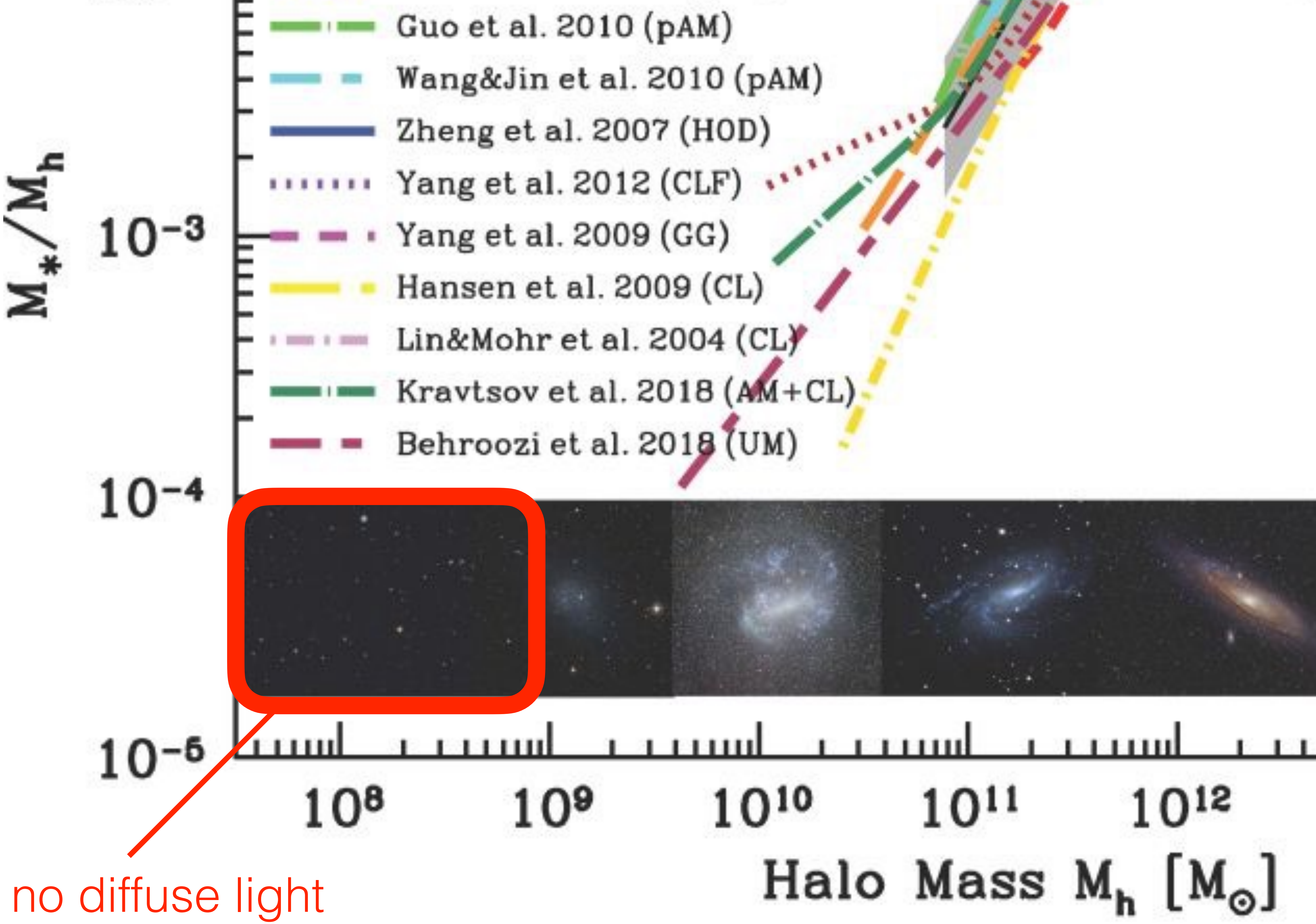
- Darkest night sky has surface brightness of $\mu = 22$ mag/arcsec^2
- 100 stars with magnitude 22 over 1 square degree have $\mu = 28$
- 1 star with magnitude 22 per 1 square degree has $\mu = 33$



If you are observing the unresolved light you need to spread photons over a large area and the number of photons per pixel will be lower than the sensitivity of the camera and lower than the dark sky



Guo et al. 2010 (pAM)
Wang&Jin et al. 2010 (pAM)
Zheng et al. 2007 (HOD)
Yang et al. 2012 (CLF)
Yang et al. 2009 (GG)
Hansen et al. 2009 (CL)
Lin&Mohr et al. 2004 (CL)
Kravtsov et al. 2018 (AM+CL)
Behroozi et al. 2018 (UM)
M_*/M_h
10^{-3}
10^{-4}
10^{-5}
10^8
10^9
10^{10}
10^{11}
10^{12}
Halo Mass M_h [$M_\odot$]
nothing?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M_*/M_h
10^{-3}
10^{-4}
10^{-5}
10^8
10^9
10^{10}
10^{11}
10^{12}
Halo Mass M_h [$M_\odot$]
no diffuse light

Nearby dwarf galaxies

these galaxies are invisible

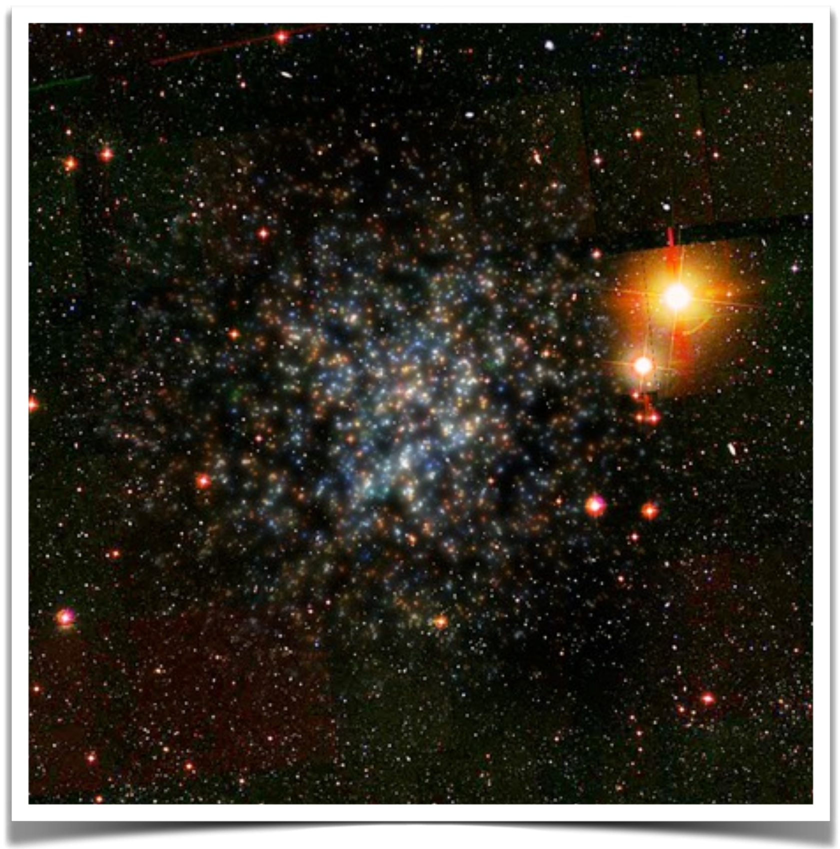
Classical

Leo I

8,000 times fainter
then the Milky Way

Ultra-faint

Bootes I



2,000,000 times fainter
then the Milky Way
discovered with SDSS

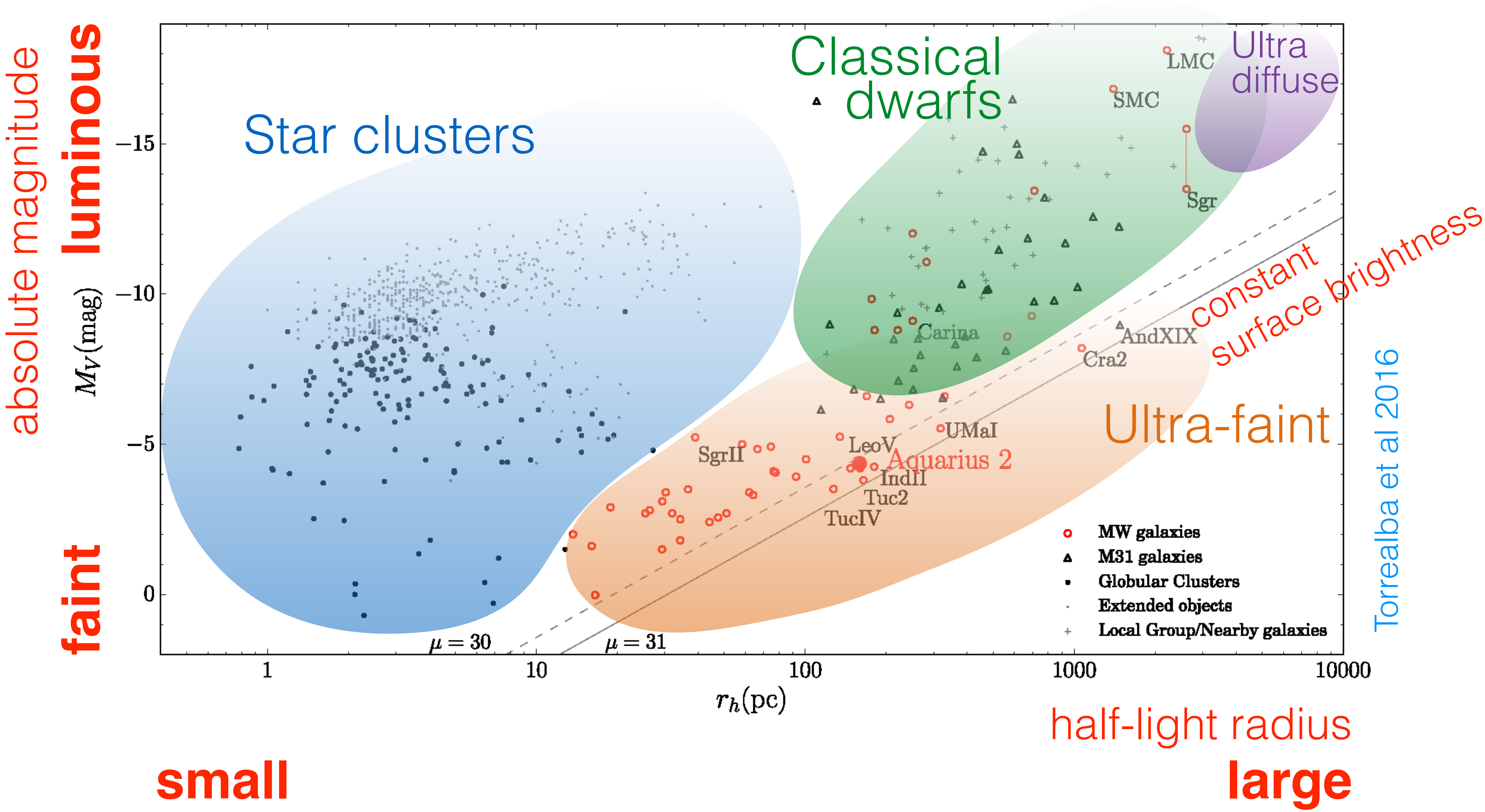
Super-mega-ultra-faint

Horologium I

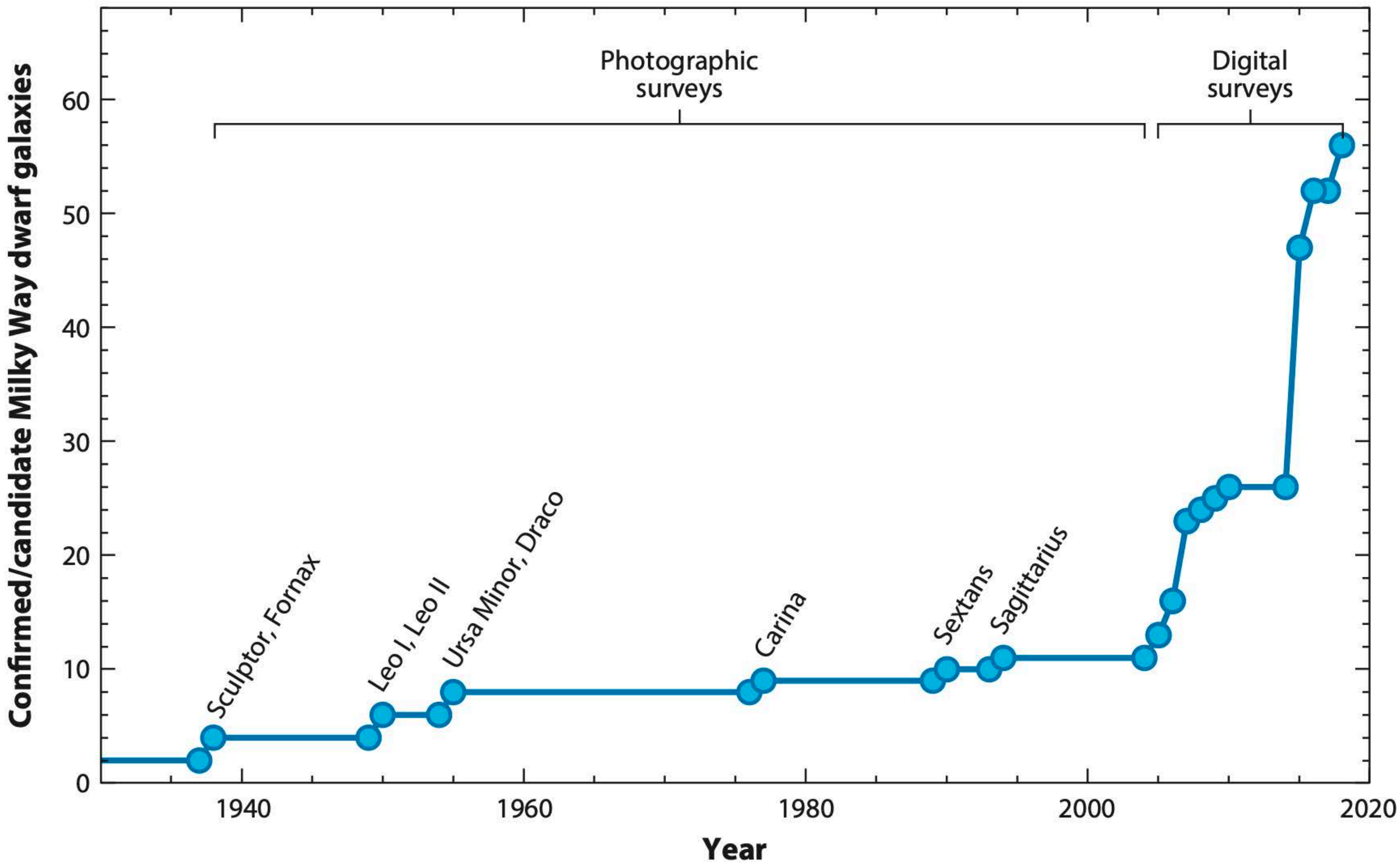
100,000,000 times fainter
then the Milky Way
discovered with DES

these can be revealed by artificially increasing brightness of member stars

The zoo of low-luminosity stellar systems



Discovery of faint dwarfs



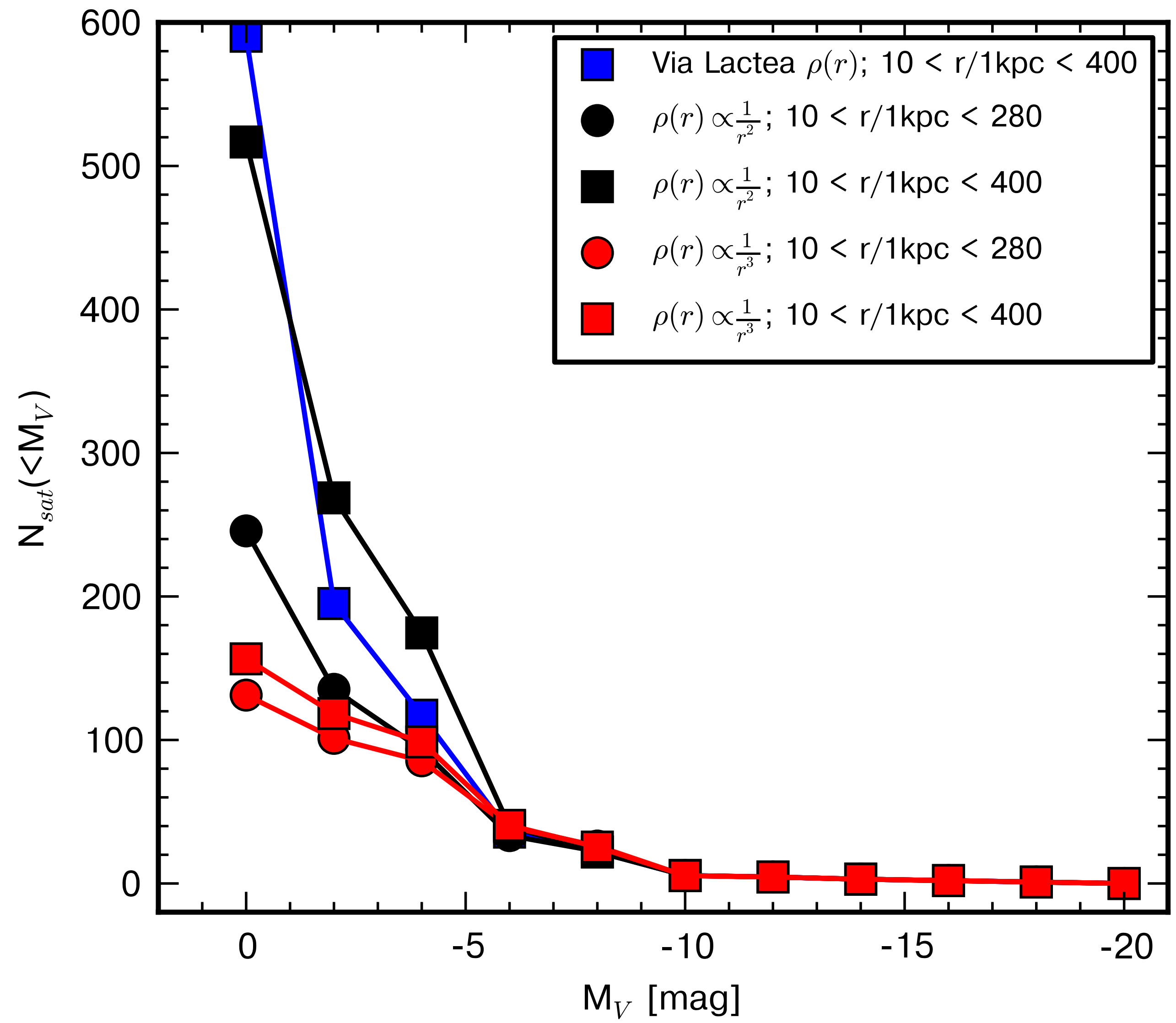
Simon et al 2019

Once digital surveys started to operate, automated dwarf galaxy searches became possible
Believe it or not, before 2005, searches for faint dwarf galaxies were carried out using visual inspection

Faintest (and fluffiest) dwarfs - ultimate test of the LCDM theory

Dwarf detections so far are only a tip of the iceberg

Predicted dwarf luminosity functions



The total number of dwarfs depends on the assumptions as to their radial distribution in the Milky Way

Faintest (and fluffiest) dwarfs - ultimate test of the LCDM theory

Dark Matter to **ordinary matter** density ratio

Universe average
$\approx 5/1$

Cambridge Westhub
$\approx 0/1$

Faint dwarf galaxy
$\approx 1000/1$

Play with the data

- **Write your own, different (better) star/galaxy classifier.** Do not (only) use image morphology
- Find other jets like the one in M87
- Find non-stellar and/or extragalactic objects with proper motion
- Find ultra-faint dwarfs in the Milky Way
- Find star clusters in the Milky Way
- Find star clusters around M87, other galaxies