Connections Between Nuclear Star Clusters, Globular Clusters, and Intermediate Mass Black Holes

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Drawn from review by
Neumayer, Seth, Böker 2020
https://arxiv.org/abs/2001.03626

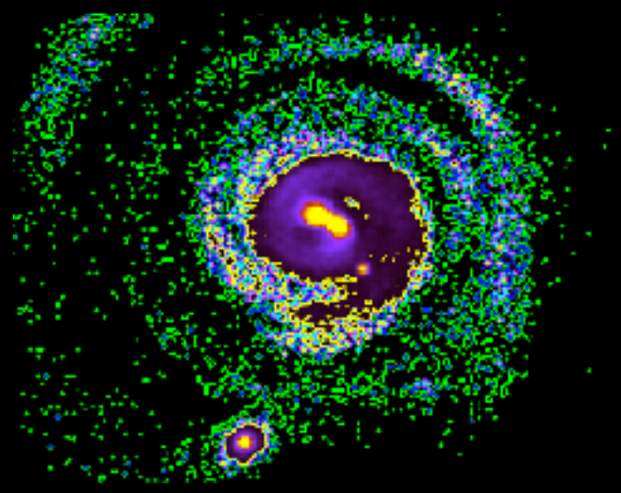
SDSS Image

NGC 4244

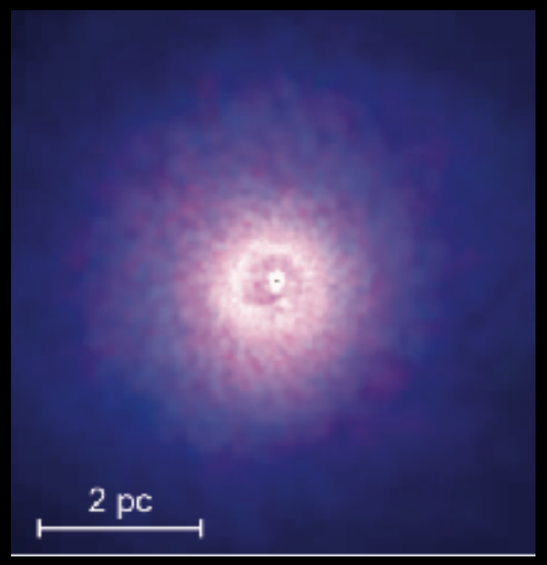
Why Nuclear Star Clusters are Interesting

- Densest Stellar Systems
- Record galaxies nuclear mass accretion
- Connection to *and* interaction with massive BHs
- Formation from (and returning to) globular clusters.
- Present in majority of massive ($>10^8$ $M_\odot$) galaxies
  NSCs are special, but not unusual

NSC formation



Arca-Sedda+ 2015



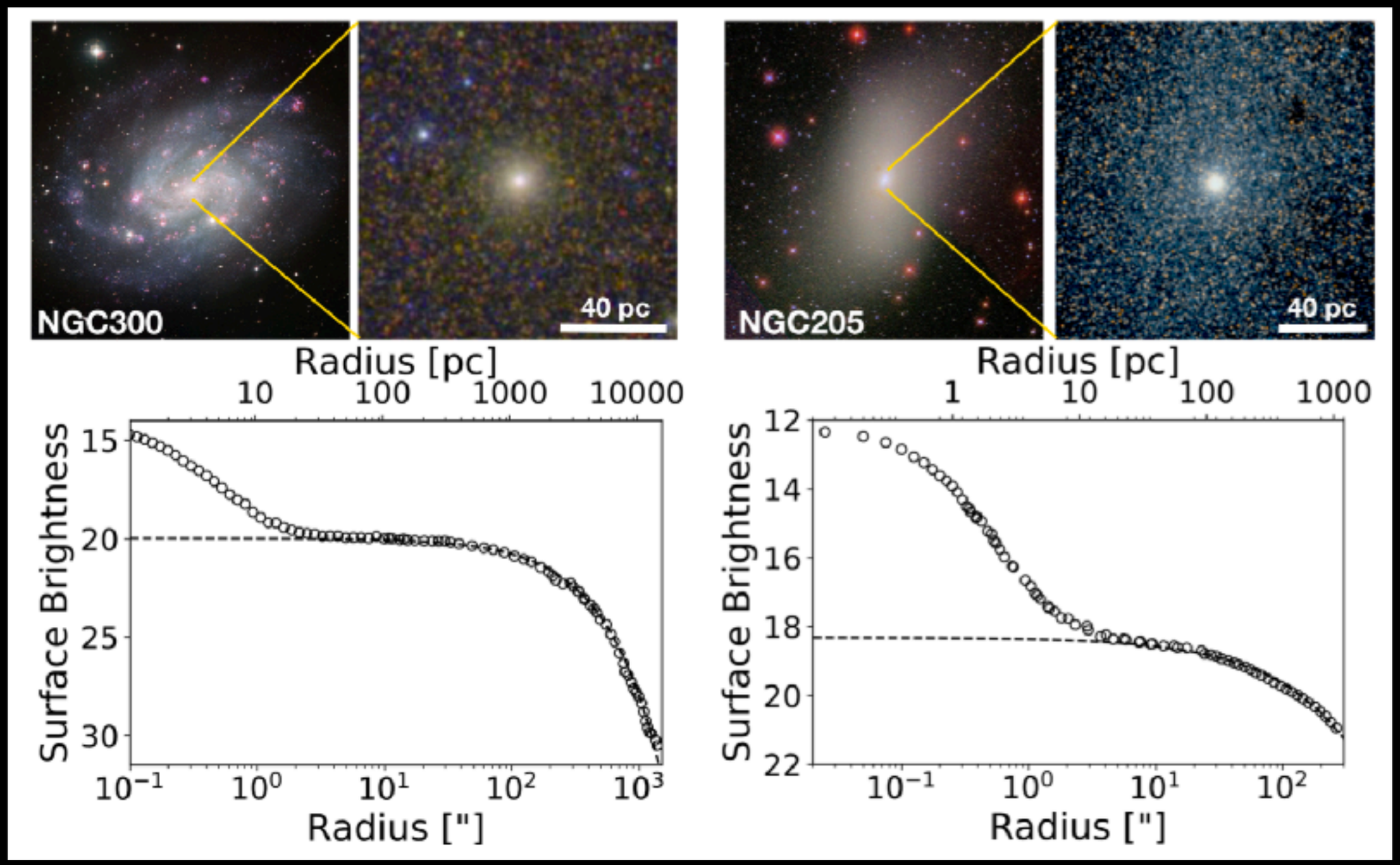
Hopkins & Quataert 2010

- Formation from dynamical friction of massive globular clusters e.g. Tremaine 1975, Lotz+ 2001, Antonini+ 2013, Gnedin+ 2014
- Formation from gas accretion into the nucleus e.g. McLaughlin+ 2006, Hopkins+ 2010, Brown+ 2018
- Some mix: Antonini+ 2015, Guillard+ 2016
- **Clear evidence for both processes in different environments**

Outline

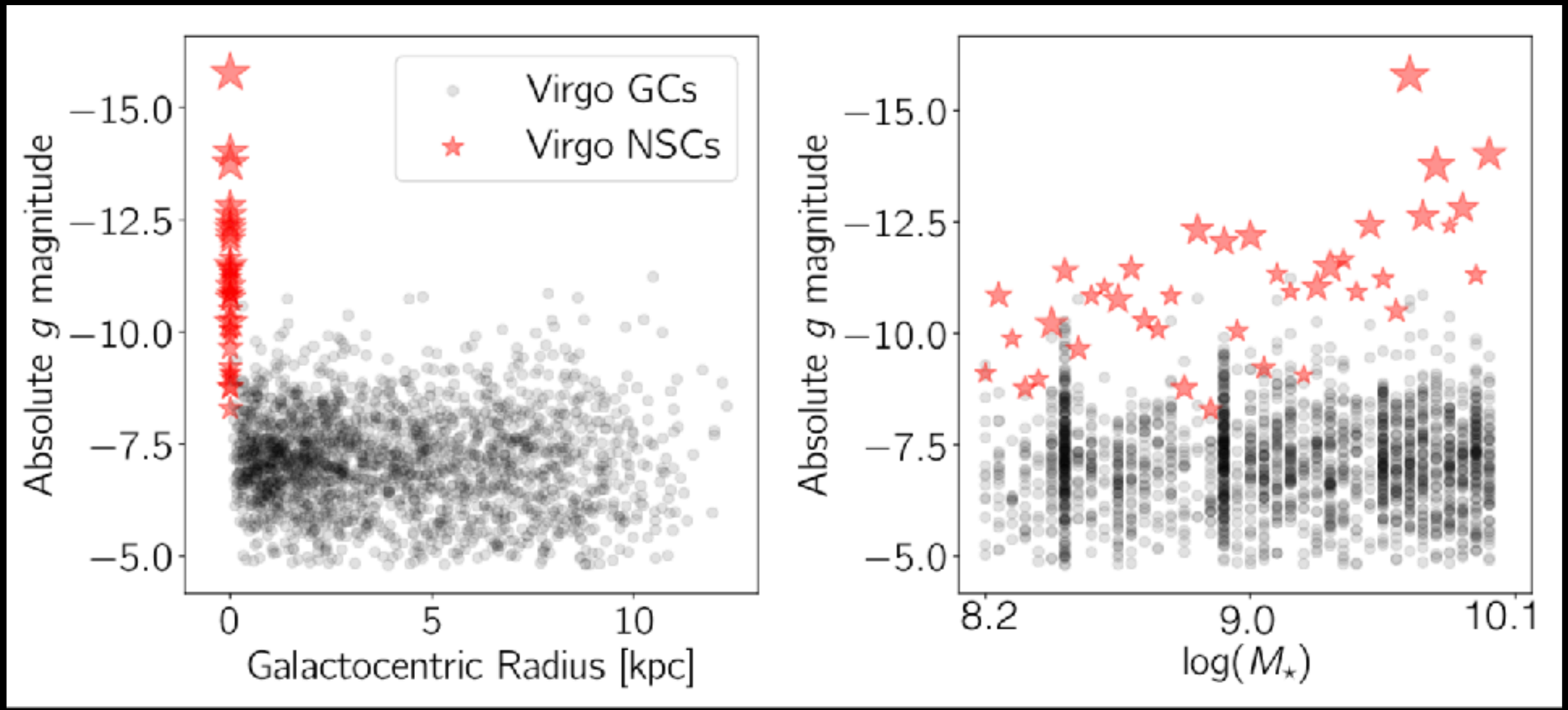
- NSCs: what are they, where do we find them, what do we know about their properties?
- What do we know about low mass BHs in NSCs?
- Stripped NSCs
- Open Questions

NSCs are distinct galactic components



- Resolvable by HST out to ~30 Mpc
- Broad definition: overdensities relative to underlying galaxy on <50 pc scales

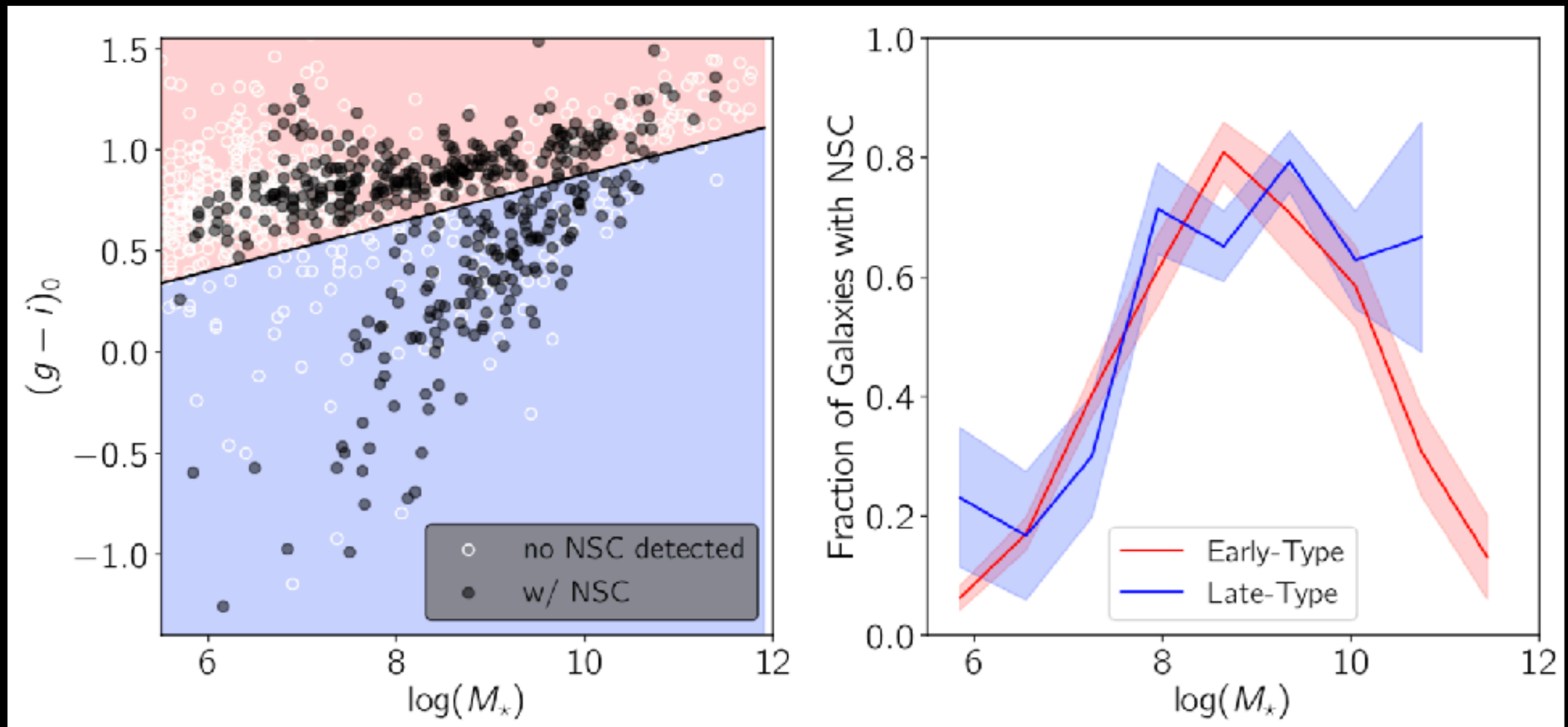
NSCs: the most luminous clusters



Data of 39 early type galaxies in Virgo
from Côté et al. 2006 and Jordán et al. 2009

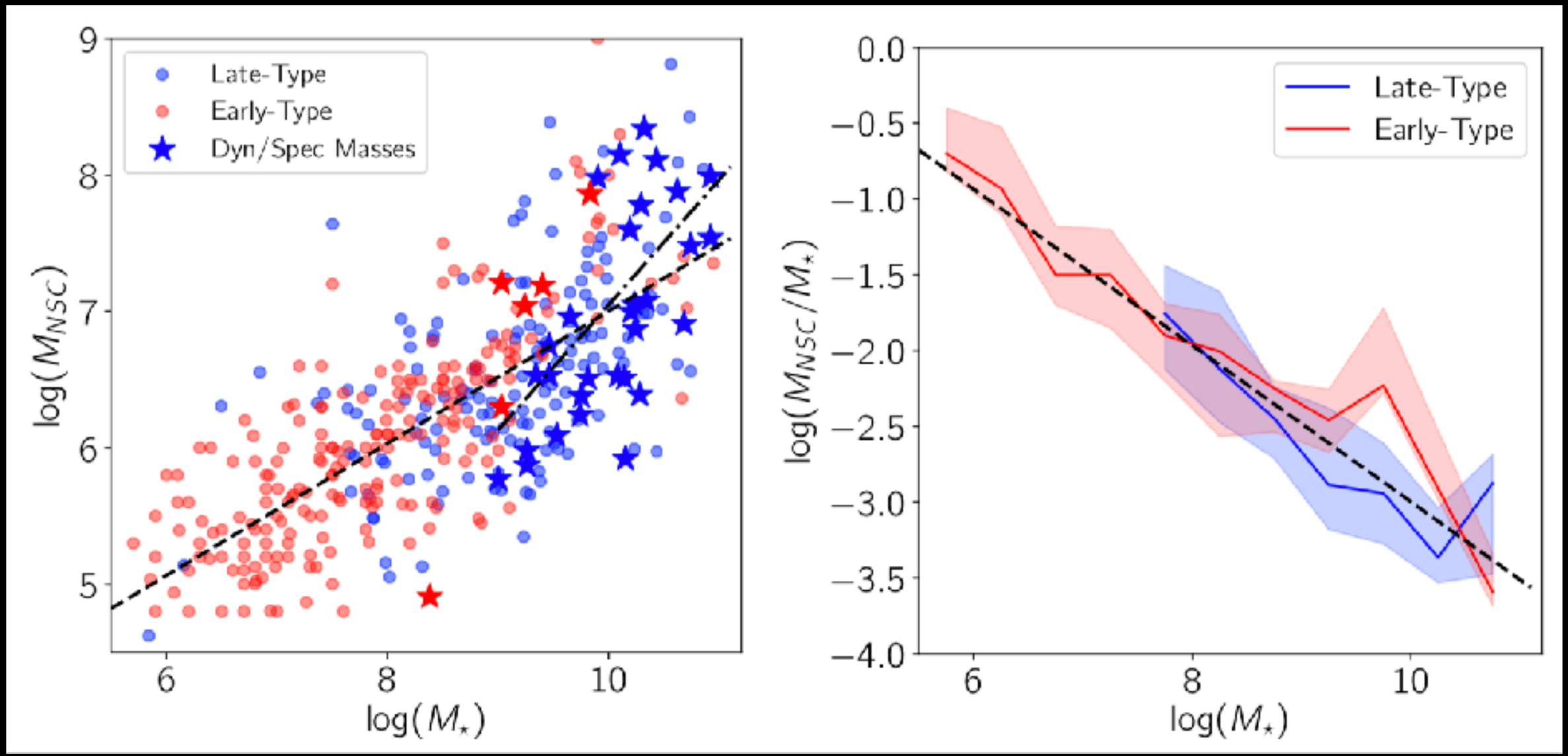
Note: figure data/code available here: https://github.com/anilseth/nsc_review

NSC Demographics



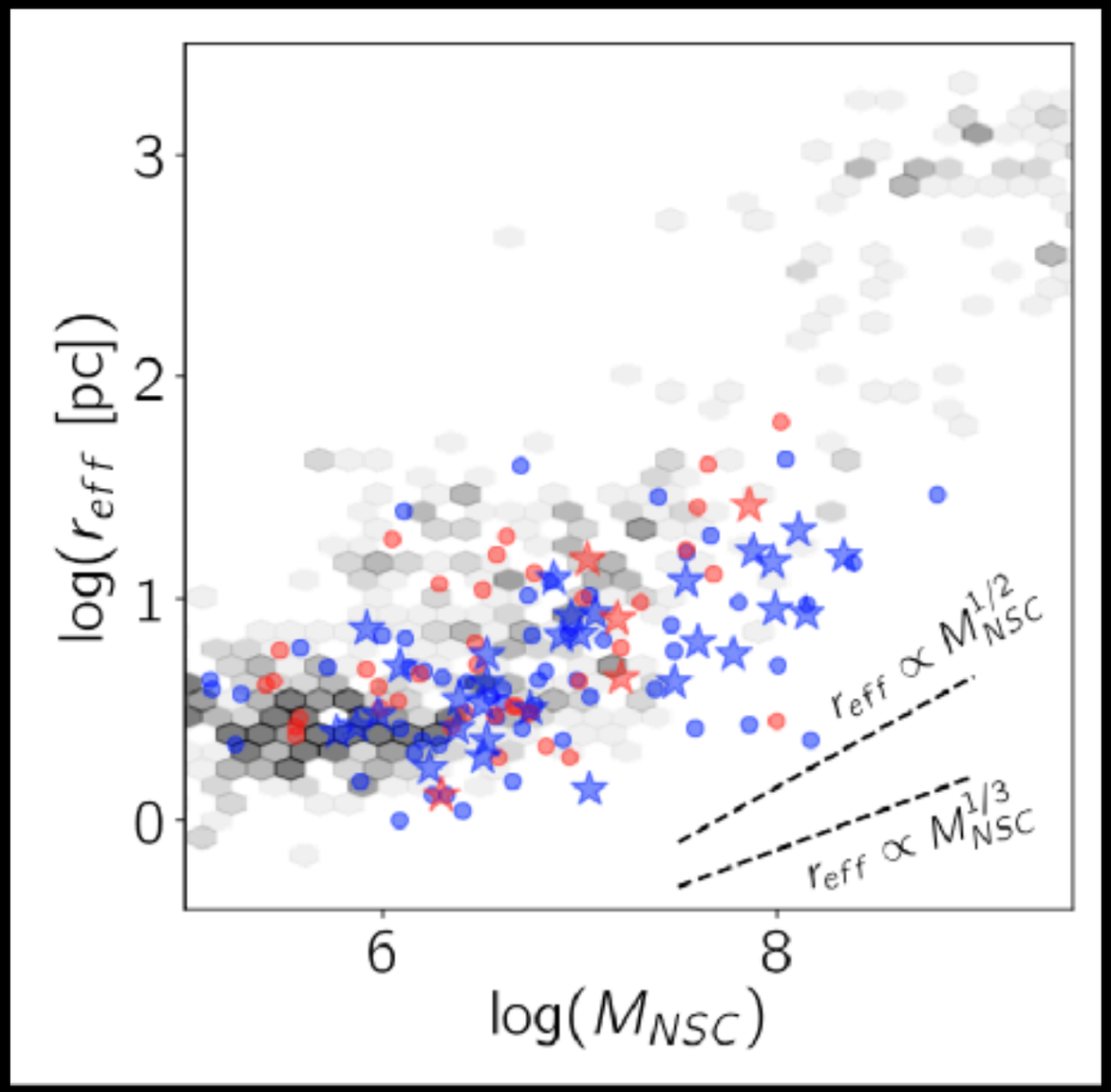
See also Sanchez-Janssen+ 2019; environmental dependence

Massive NSCs live in massive galaxies

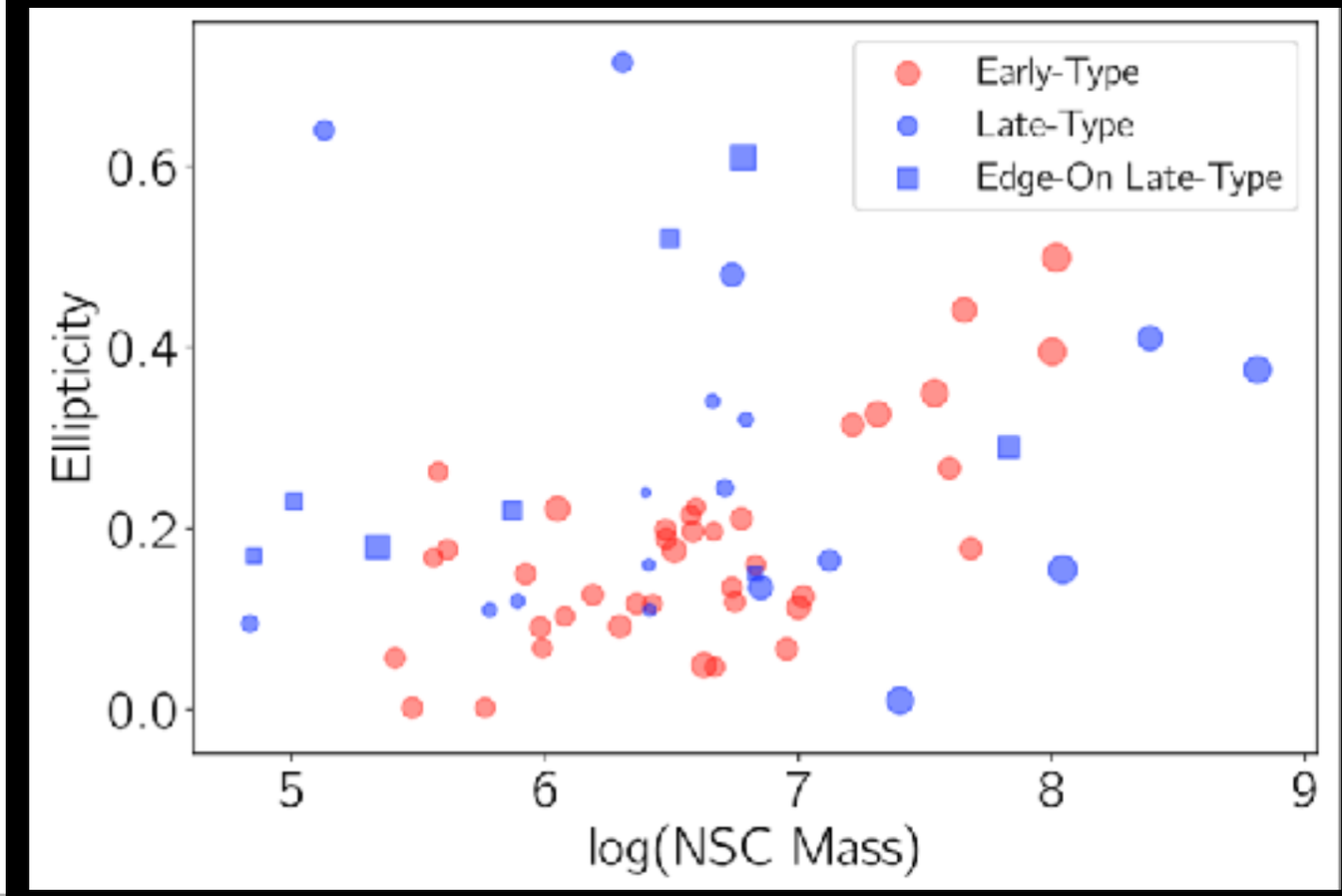


- Overall trend suggests $M_{NSC} \propto M_{\star}^{0.5}$
- Steeper relation at higher mass?

Mass, Size & Shape

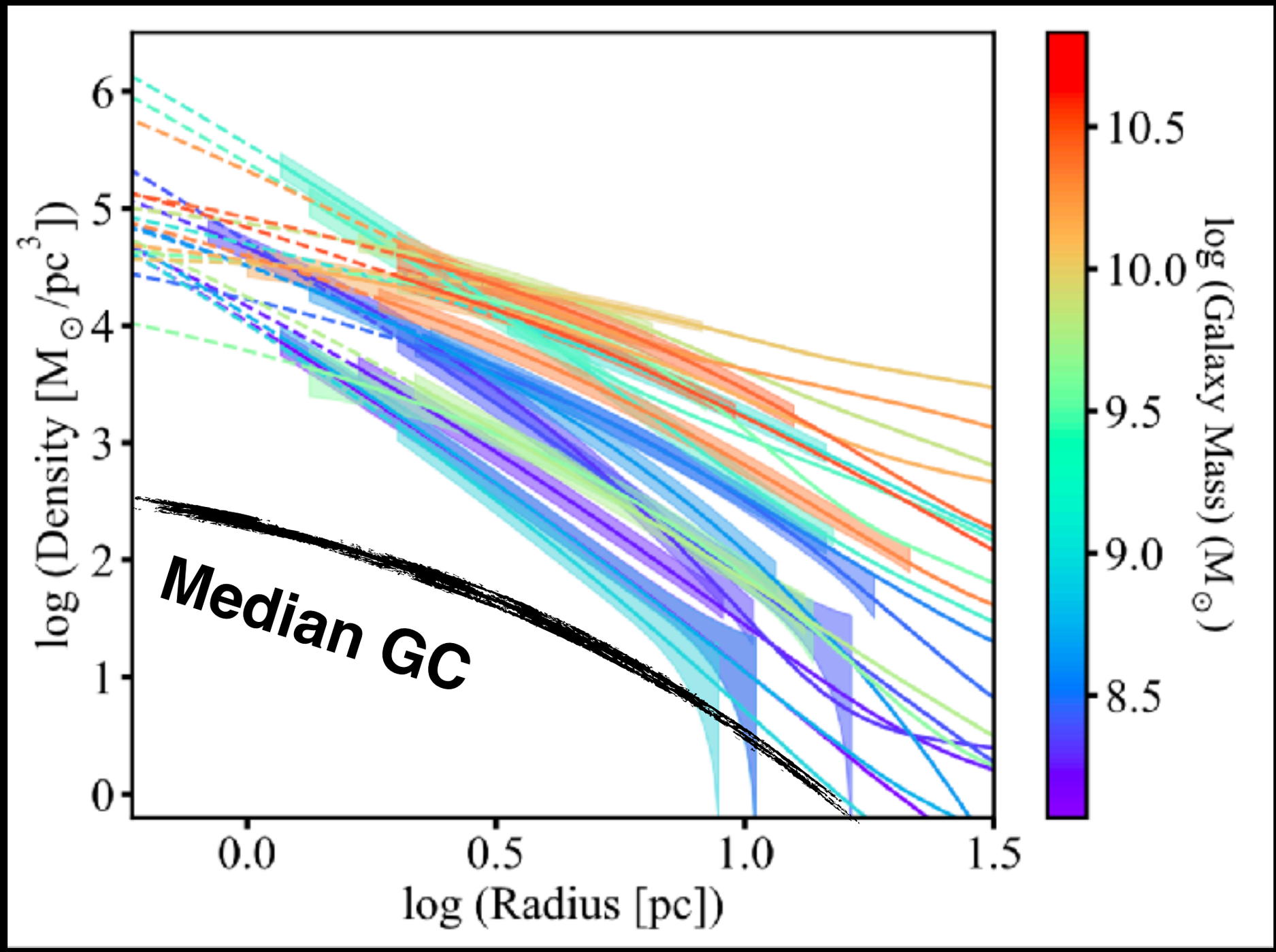


NSCs can be disky



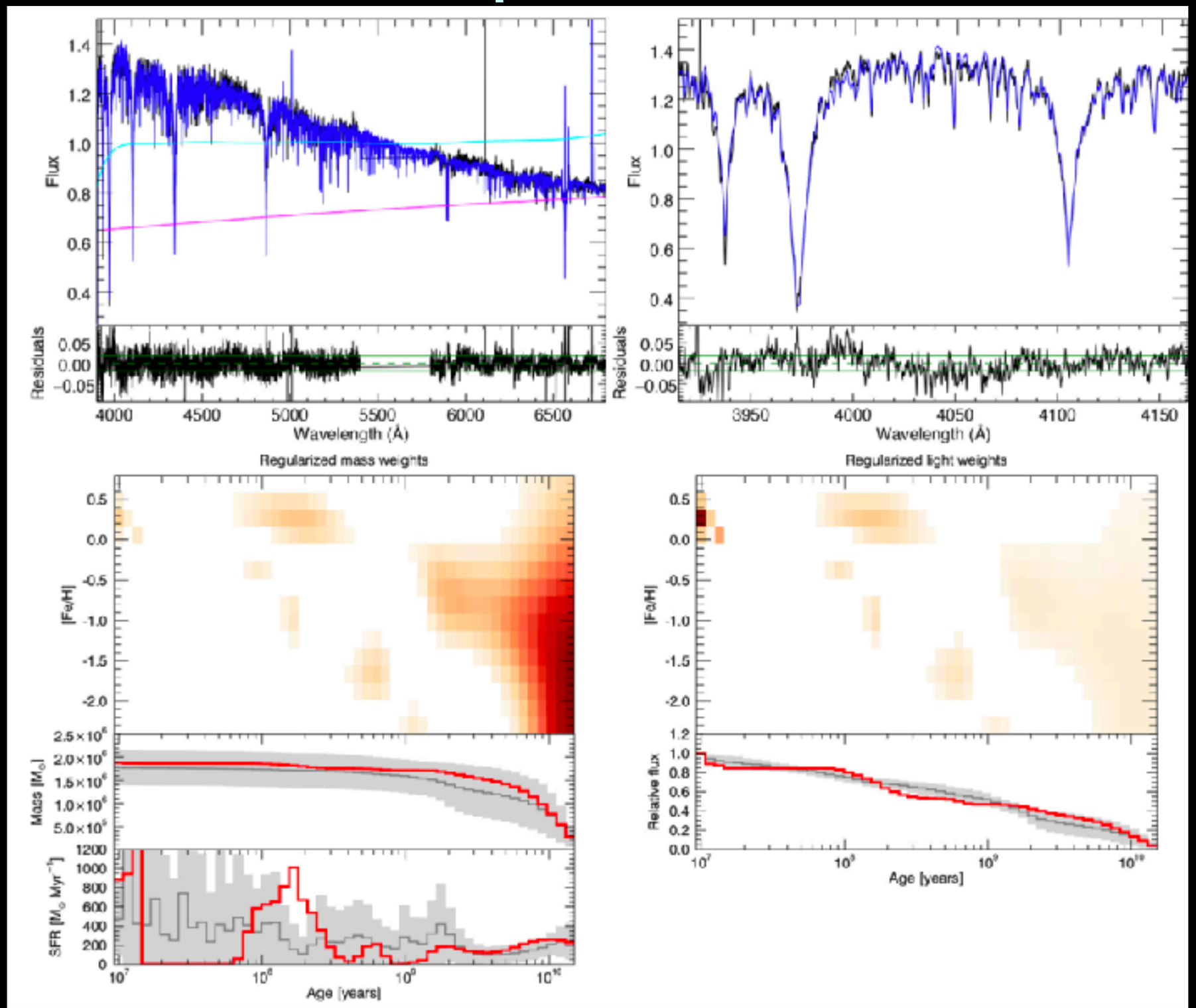
Background data includes GCs/ UCDs from Norris+ 2014

Density relative to GCs



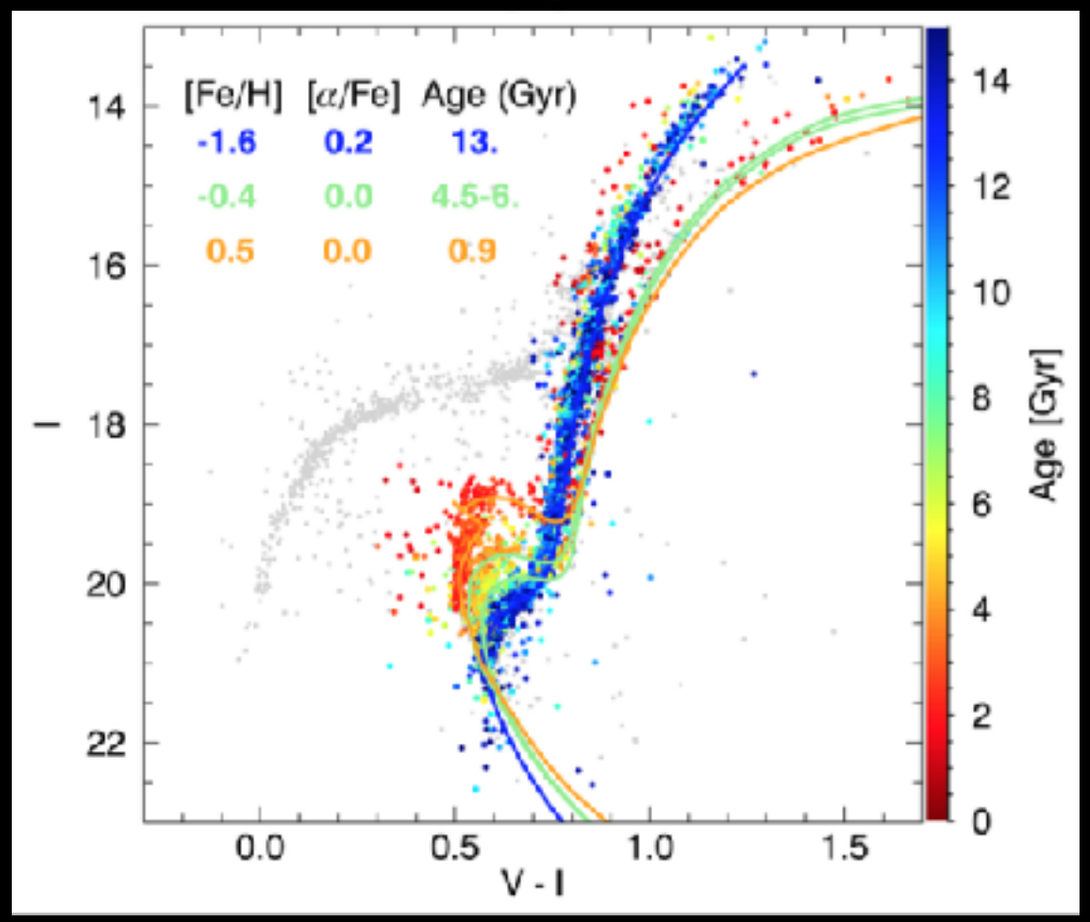
Pechetti et al. 2020, https://arxiv.org/abs/1911.09686

Extended star formation histories are the norm (especially at high mass)



NGC247
Star Formation History
Kacharov+ 2018

M31, Lauer+ 2012

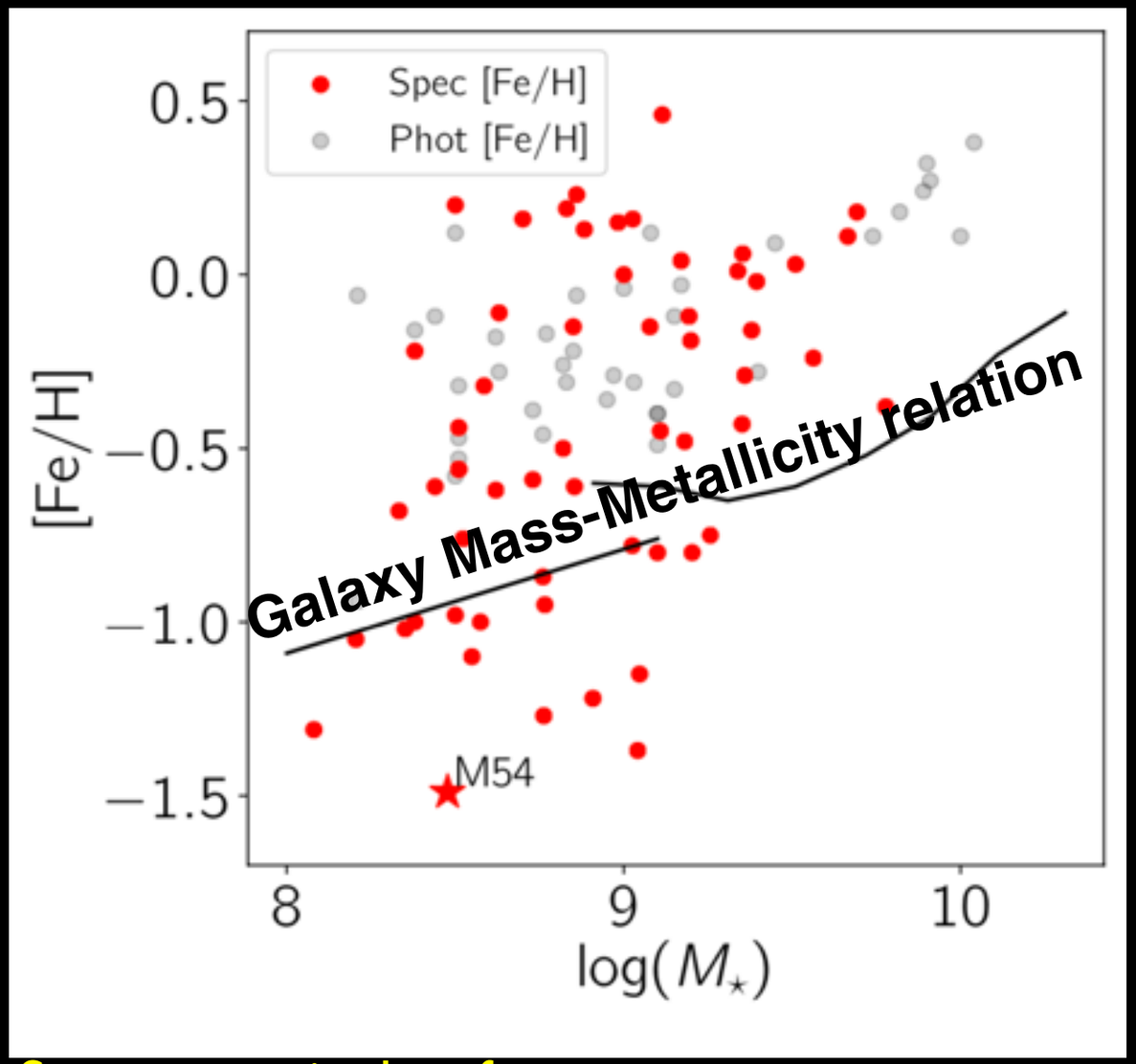


M54; Alfaro-Cuello+ 2019

Young populations common

- MW has >10^4 $M_\odot$ of young (<10 Myr) stars within 0.5 pc (Feldmeier-Krause+ 2015), while M31 has 100-200 Myr stars surrounding BH at center of NSC (Lauer+ 2012)
- Late type spirals >10^9 $M_\odot$: typically ~solar metallicity, more than half have emission lines, youngest pops <100 Myr (Seth+ 2006, Walcher+ 2006, Kacharov+ 2018)
- Younger populations also present in nearby early-type galaxies

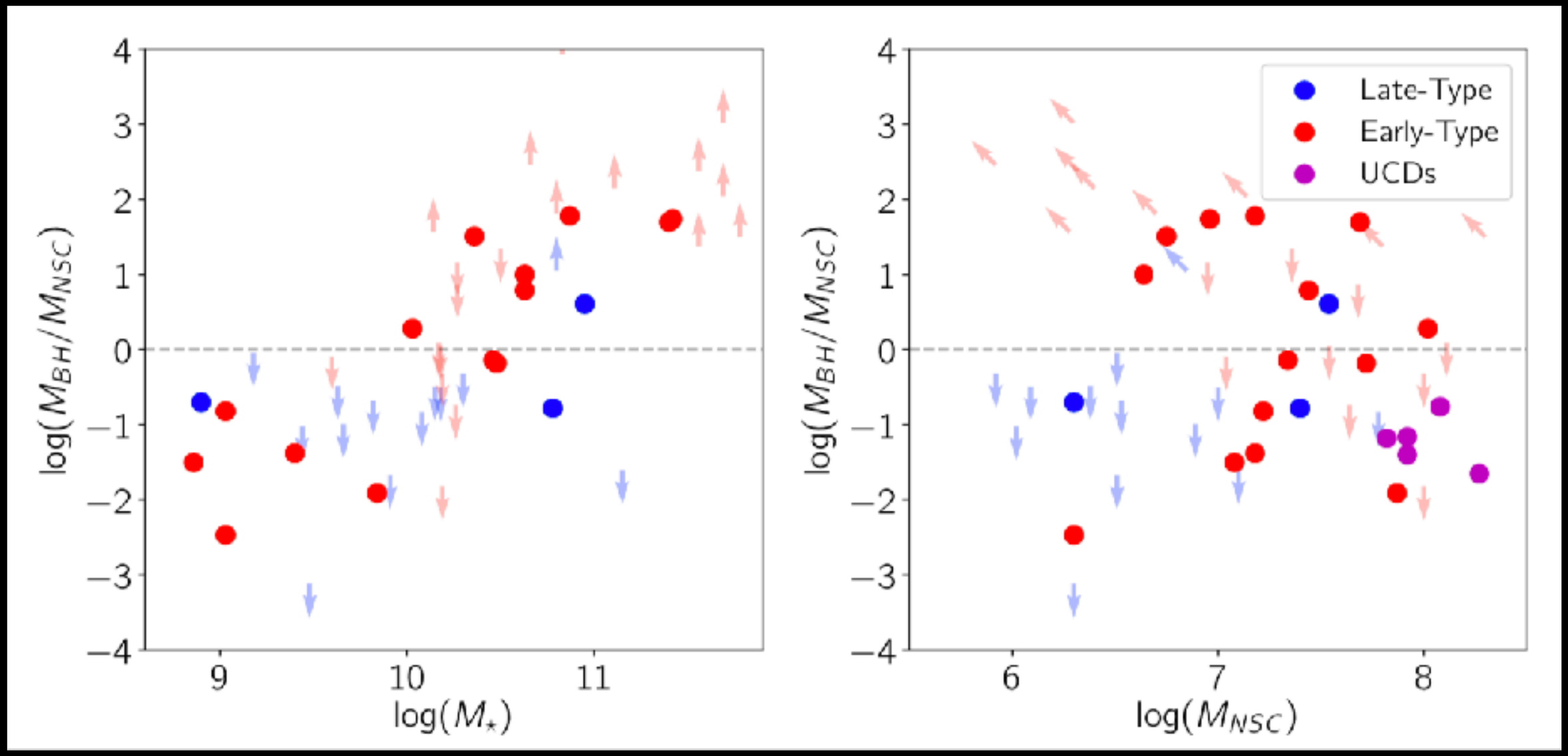
A trend of NSC metallicity with galaxy mass

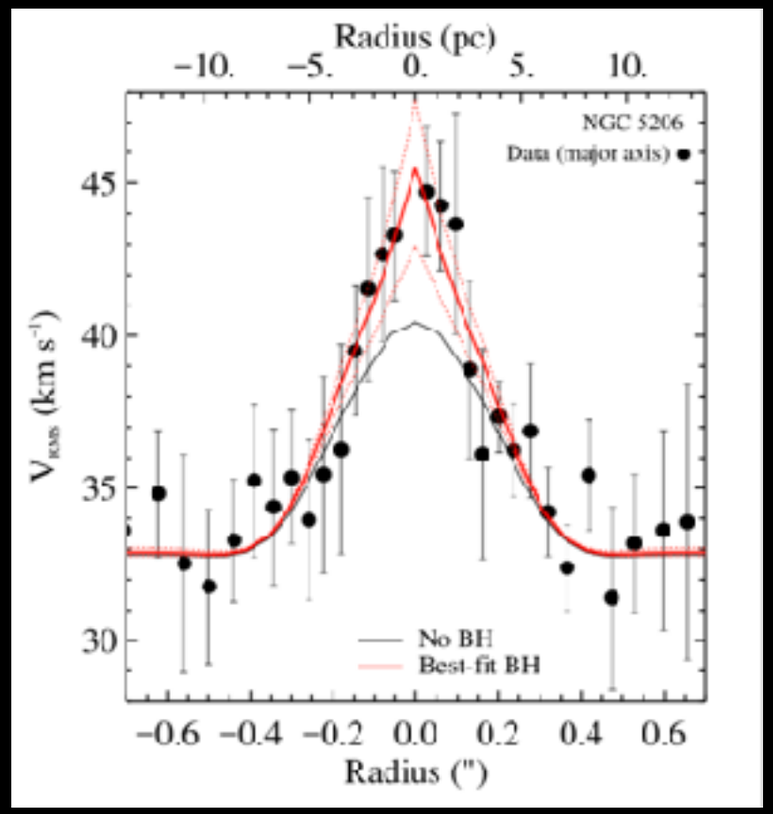


Spectroscopic data from
Koleva+ 2009, Paudel+ 2009, Kacharov+ 2018
see also Johnston+ 2020, Fahrion+ 2020

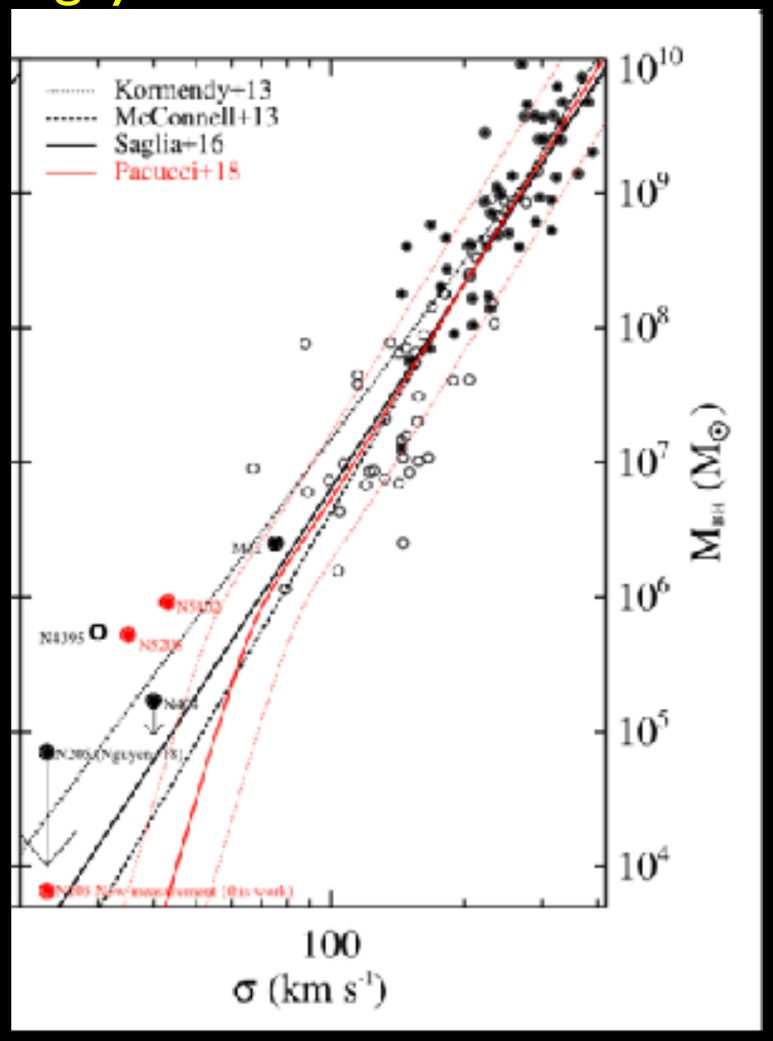
- A systematic change in stellar populations with mass
  - High metallicity (and young pops) suggest gas accretion common in high mass galaxies
  - Dominant old metal poor population in (some) lower mass NSCs.

Black holes found in many NSCs; some trend with galaxy mass, large scatter!





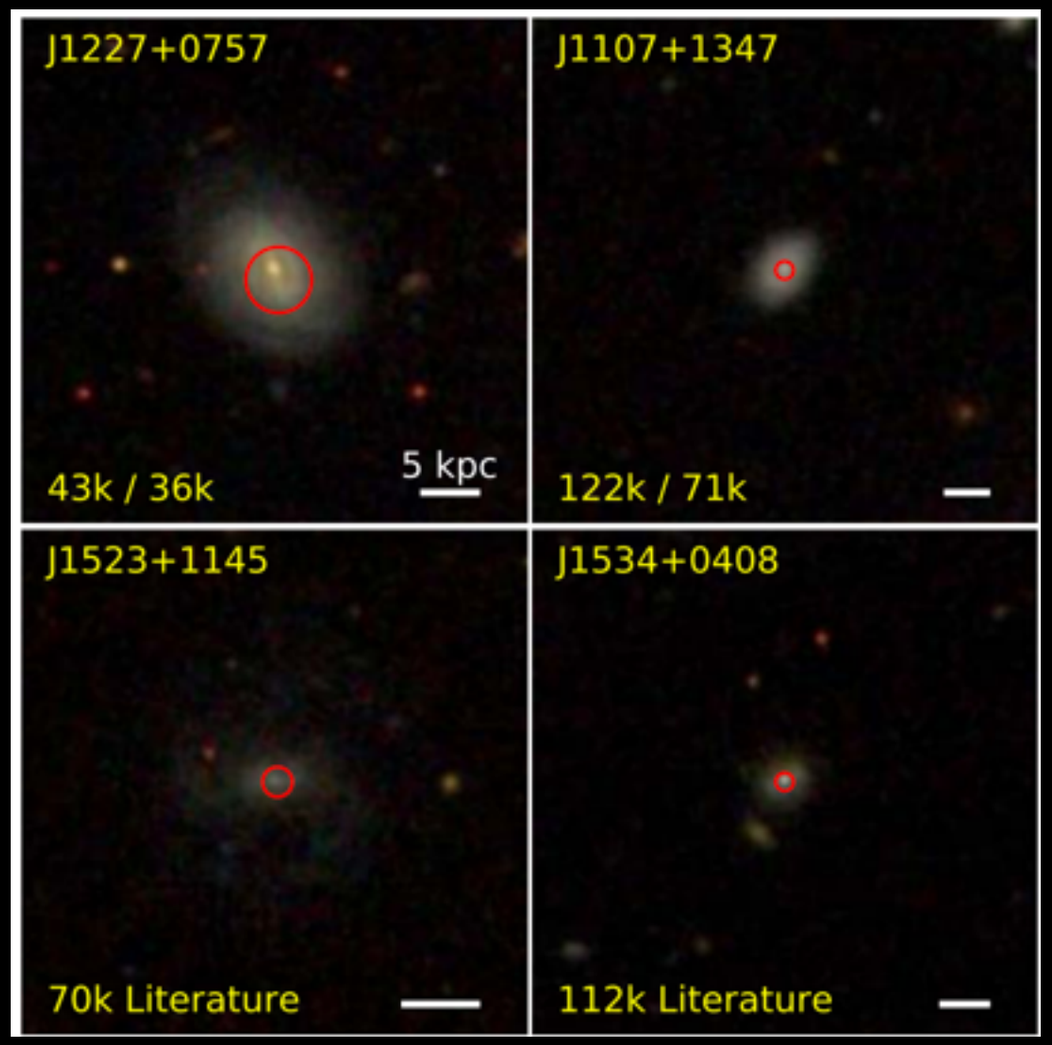
Nguyen+ 2019



Black Holes in lower-mass NSCs

- First dynamical detections of $10^{5\text{-}6}$ M⊙ BHs
  (den Brok+ 2015, Nguyen+ 2017, 2018, 2019, Davis+ 2020)
- In 5 nearest 1-7x10^9 M⊙ early-types: evidence for BHs in all 5; strong evidence in 4.
- High occupation favors common BH seeds.

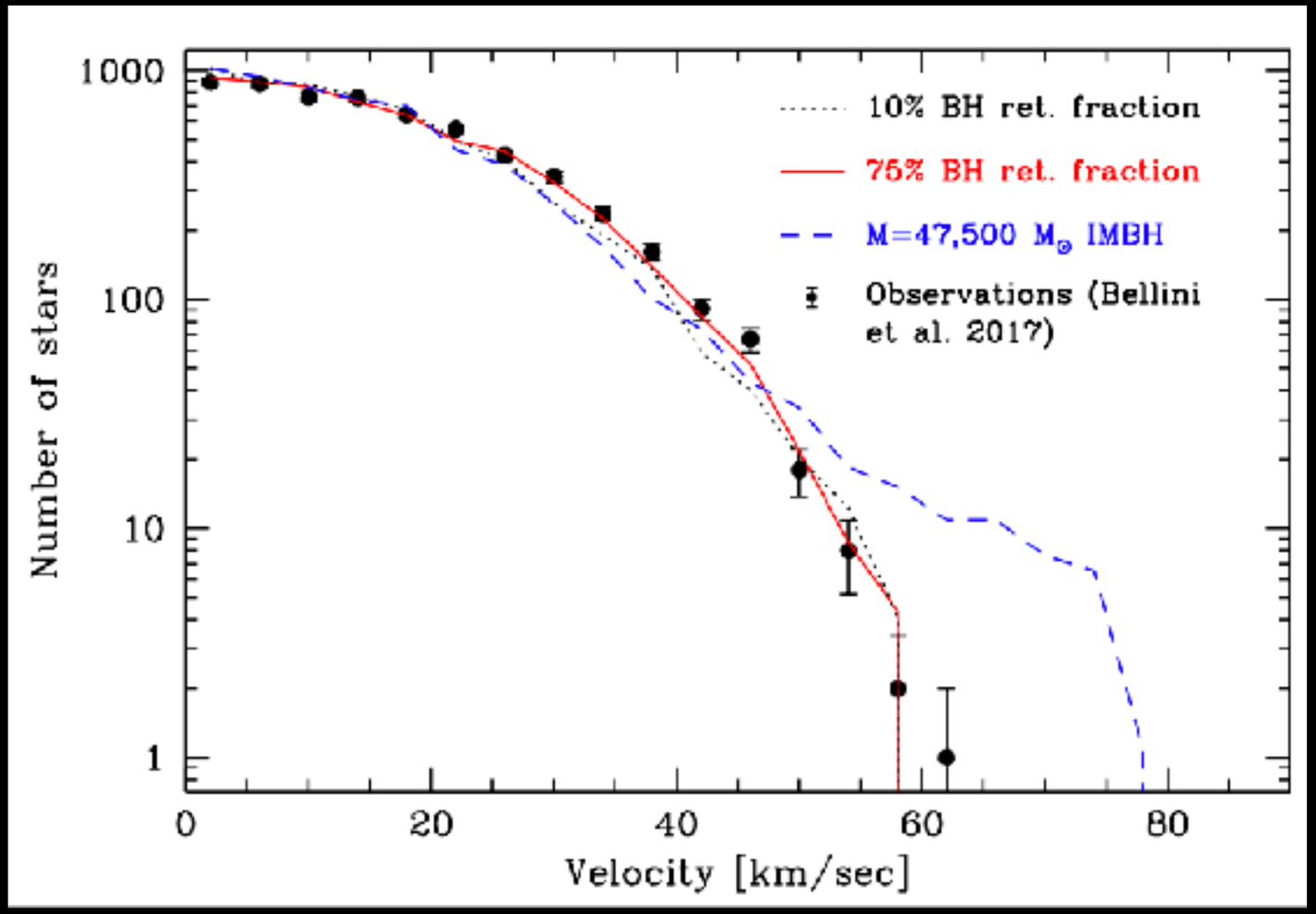
Accretion Evidence for/against IMBHs

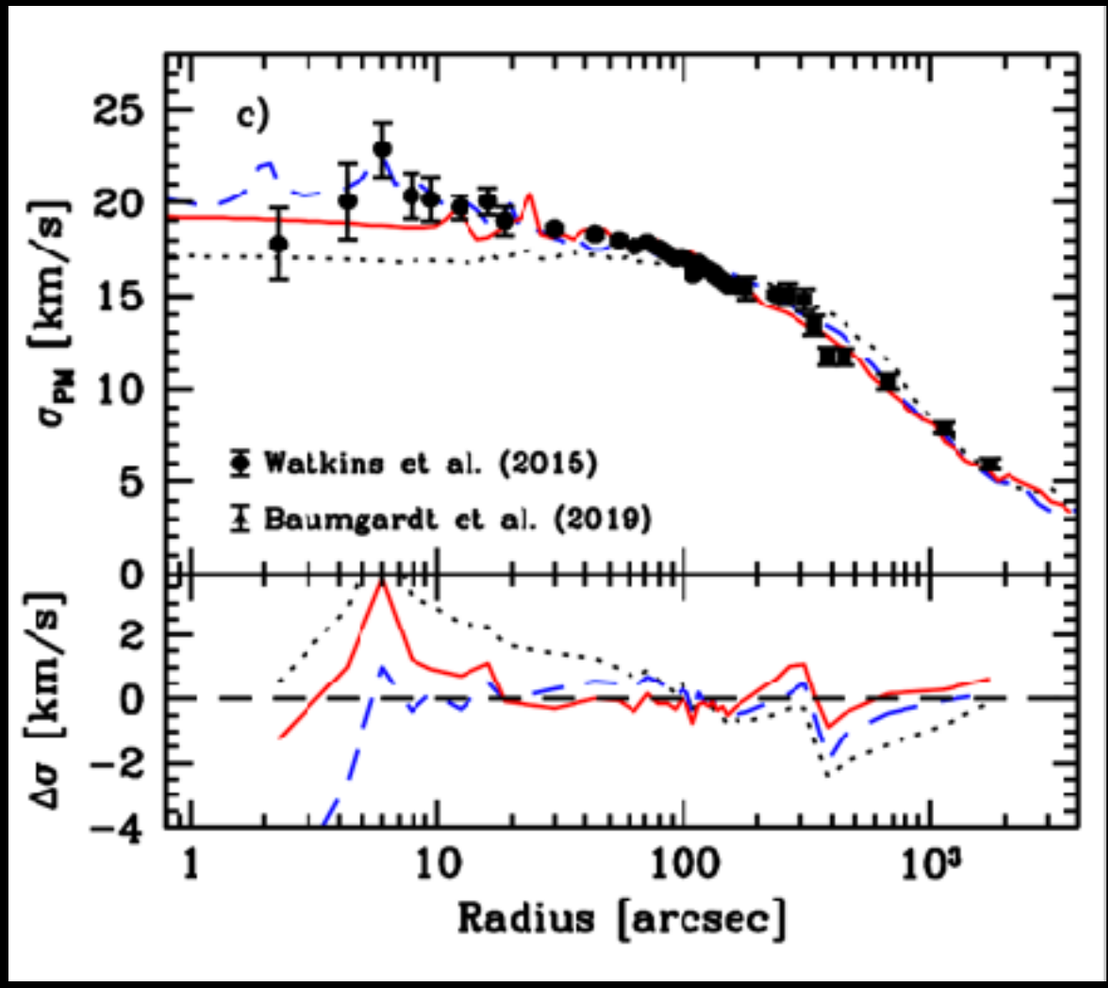


Chilingarian+ 2018

- Accretion evidence (broad line emission) of even lower mass nuclear $10^{4\text{-}5}$ M⊙ BHs (Baldassare+ 2015, Chilingarian+ 2018)
- Best candidate $<10^5$ M⊙ HLX-1, non-nuclear! (e.g. Webb+ 2012)
- Lack of radio/X-ray detections in Milky Way GCs (Haggard+ 2013, Tremou+ 2018)

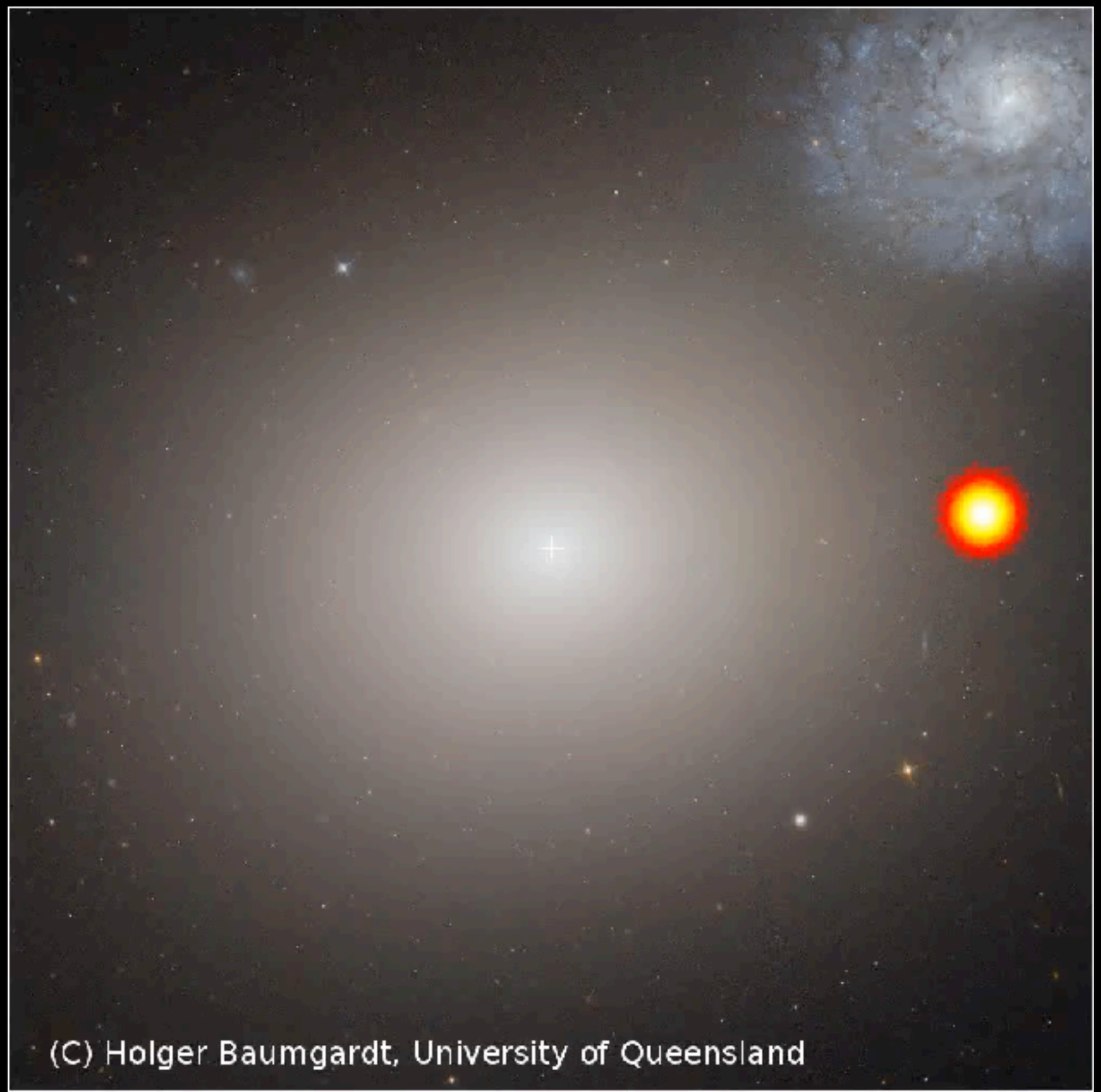
Challenge of IMBH searches: Stellar mass black holes



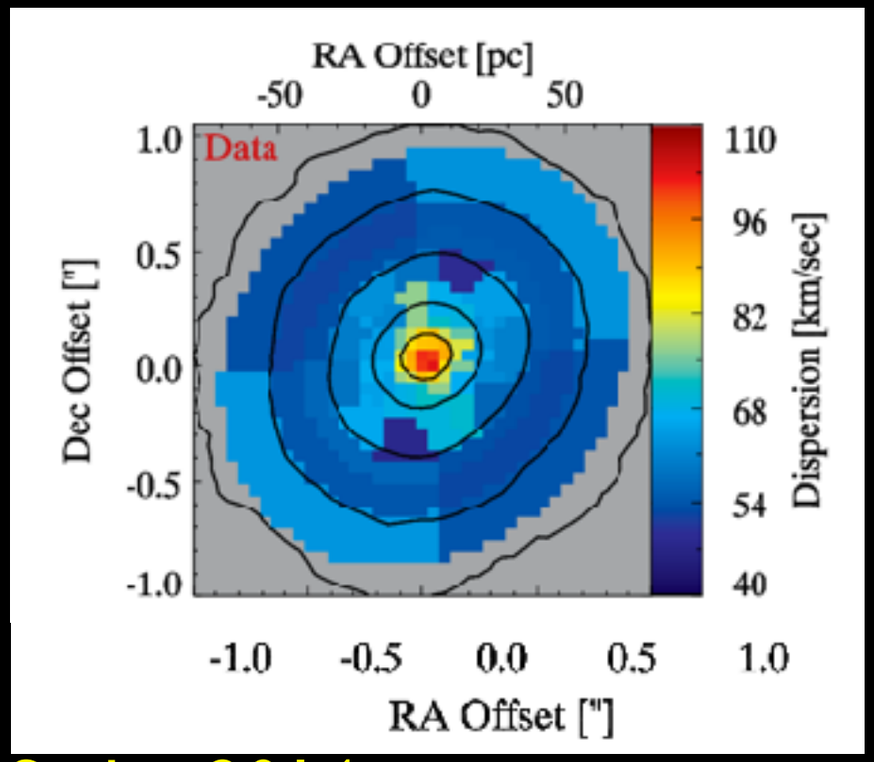


Baumgardt+ 2019;
Constraining BH retention: Weatherford+ 2019

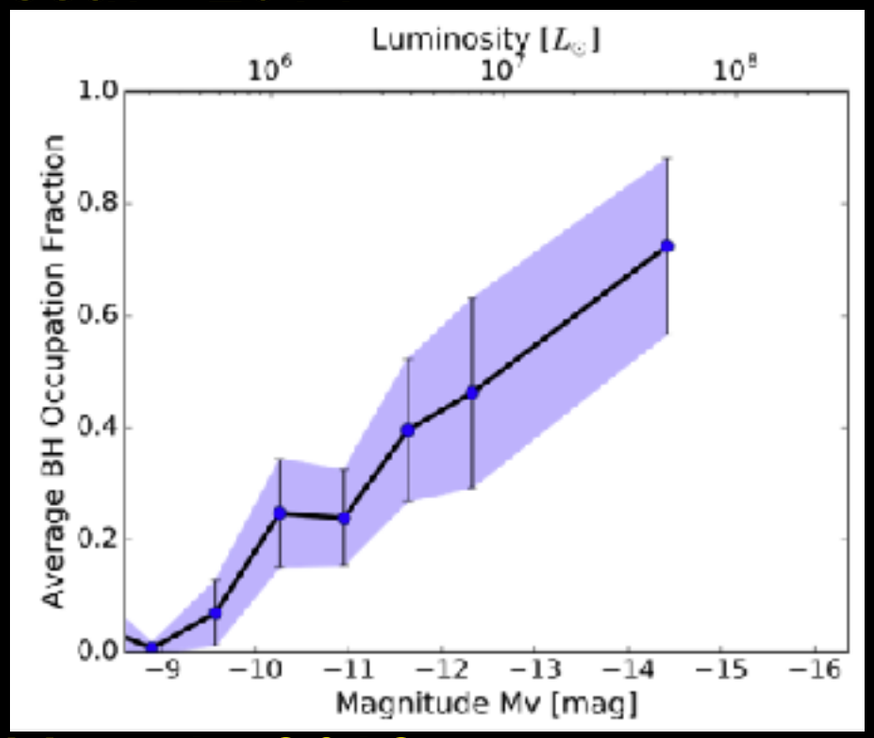
When NSCs go rogue — UCDs



How do we know they're nuclei?



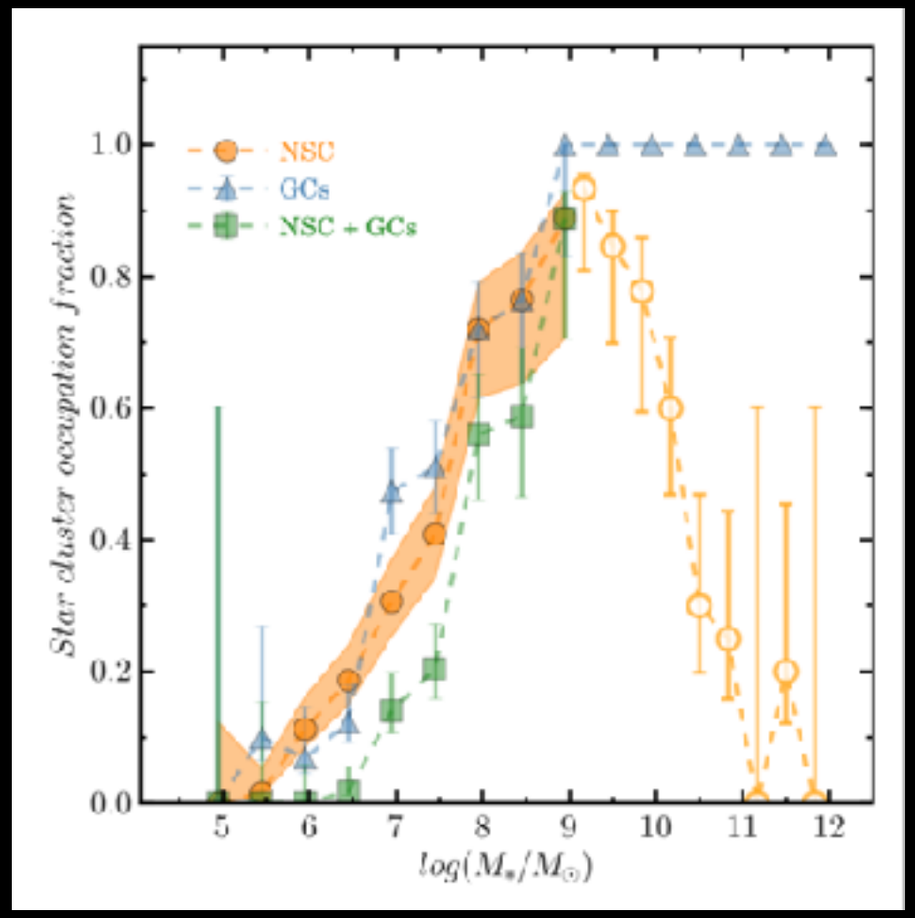
Seth+ 2014



Voggel+ 2019

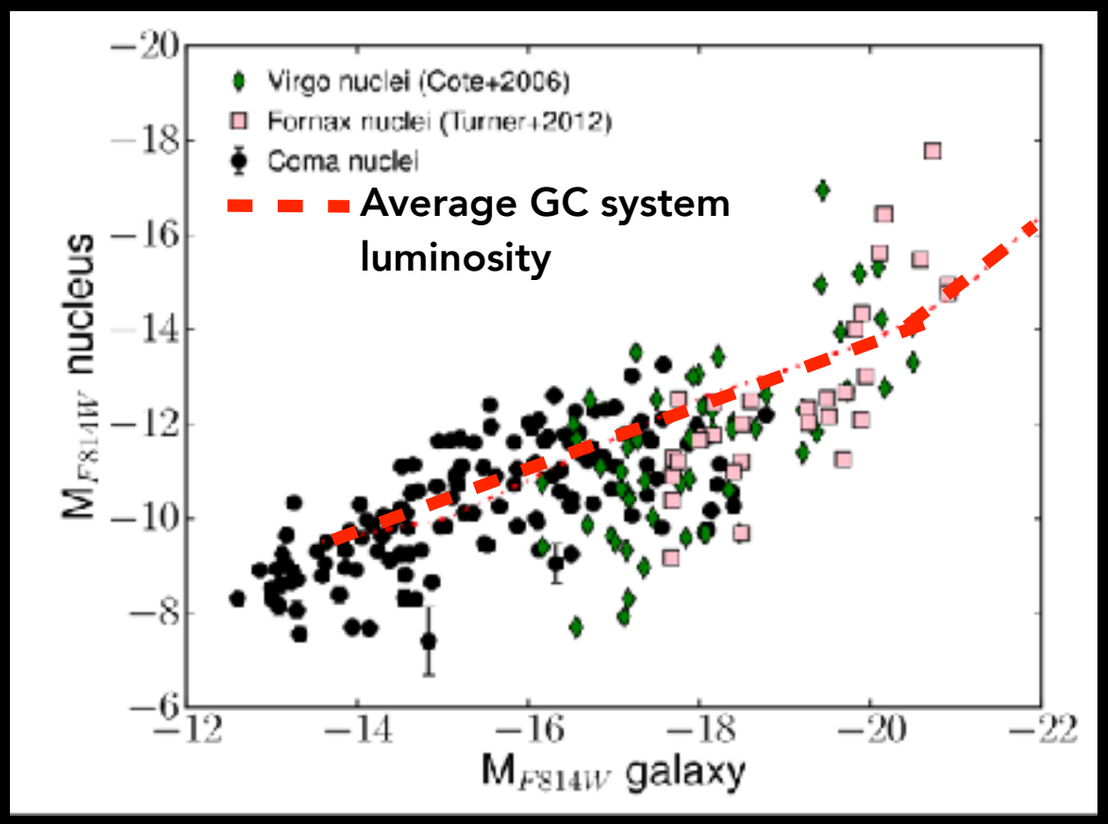
- High mass fraction black holes detected in all five UCDs above 10^7 $M_\odot$, but so far not in lower mass UCDs (Seth+ 2014, Ahn+ 2017, 2018, Afanasiev+ 2018, Voggel+ 2018)
- Indirect evidence that most massive UCDs have BHs (Mieske+ 2013, Voggel+ 2019)
- Extended star formation histories (Norris+ 2015)

The **GC-NSC** Connection



Sanchez-Janssen+ 2019

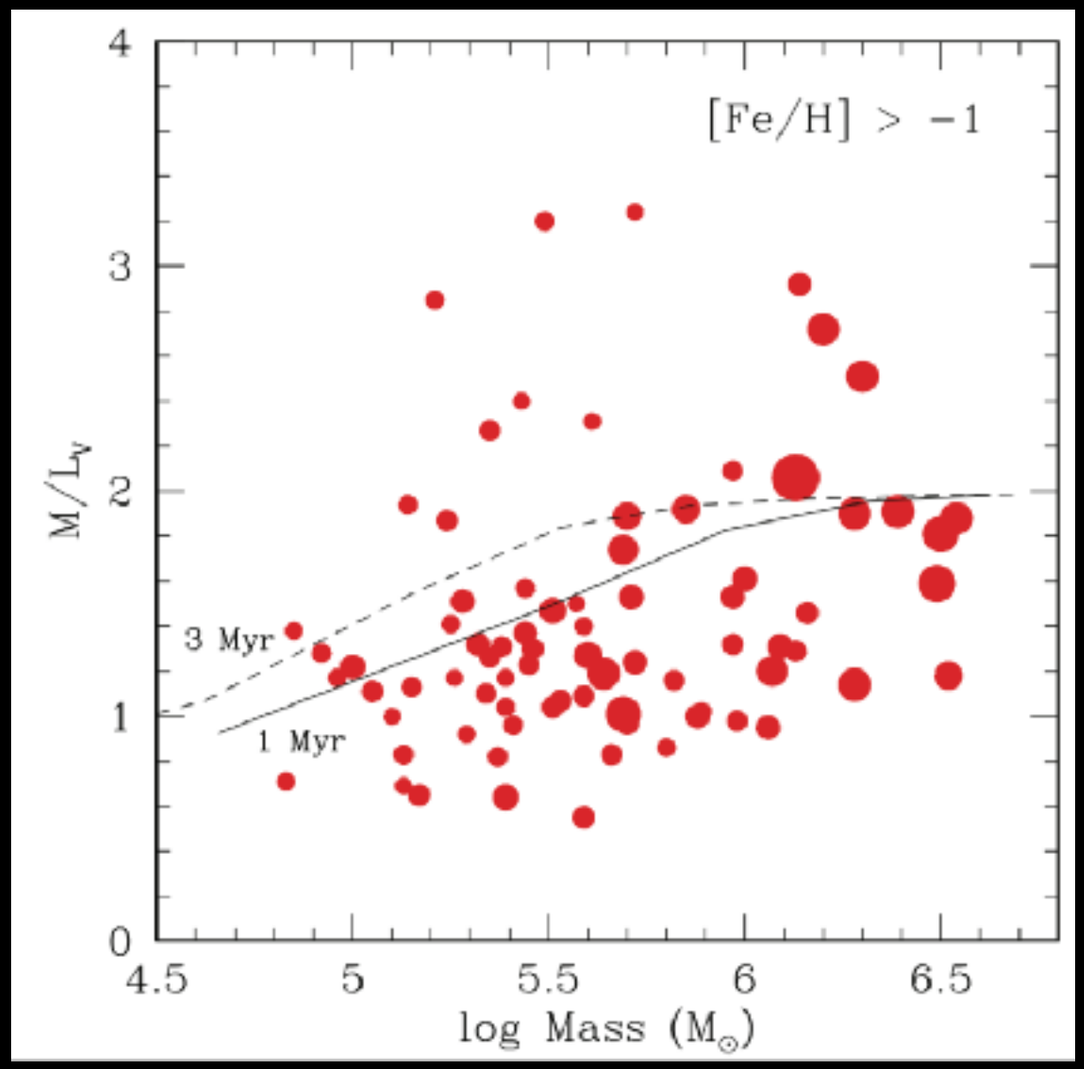
- Low mass galaxy NSCs seem to be made from inspiraled GCs
- NGVS results suggest similar fraciton of galaxies have NSCs and GCs at masses (Sanchez-Janssen 2019)



den Brok+ 2014

- Similar mass in NSCs and GCs !?!?(Cote+ 2006, den Brok+ 2014)
- Return back into the GC population as stripped nuclei. (Pfeffer+ 2013, 2014, 2016)
  ~6 expected in the Milky Way;
  the hunt is on
  (Kruijssen+ 2019; Massari+ 2019, Myeong+ 2019, Forbes+ 2020, Pfeffer+ 2020)

Stripped nuclei likely the easiest place to find IMBHs



Strader+ 2011

- In the local group (and beyond) stripped NSCs likely outnumber present day NSCs, especially for $<10^9$ $M_\odot$ galaxies (e.g. Voggel+ 2019)
- Proximity and lack of surrounding galaxy could make these IMBHs easier to find (Pechetti+ 2017)
- Dynamical detection very hard to differentiate from black holes at low mass fractions (Baumgardt+ 2019)

Open Questions

- How many stripped NSCs are hiding amongst GCs? Can simulations on this be improved (Pfeffer+ 2014/2016)?
- Can we use stripped NSCs to usefully recover formation histories of nearby galaxies like we are starting to do in the MW?
- What can we learn about NSCs from the nearby stripped examples? Can we resolve their formation?
- Can we gain additional proof of the presence of stripped NSCs in the Milky Way or M31?
  - Can we overcome the uncertainties of abundance variations to derive robust MWGC age spreads, especially in ω Cen? (Marino+ 2012, Joo & Lee 2013, Villanova+ 2014)
  - Can we make a secure IMBH detection in any local group globular clusters/ stripped nuclei? (Pechetti+ *in prep*)
  - Are metallicity spreads a robust indicator of NSCs? (Da Costa 2016, Pfeffer et al. 2020)