STUDYING THE POST-MERGER EVOLUTION OF EARLY-TYPE GALAXIES THROUGH THE EYES OF VEGAS

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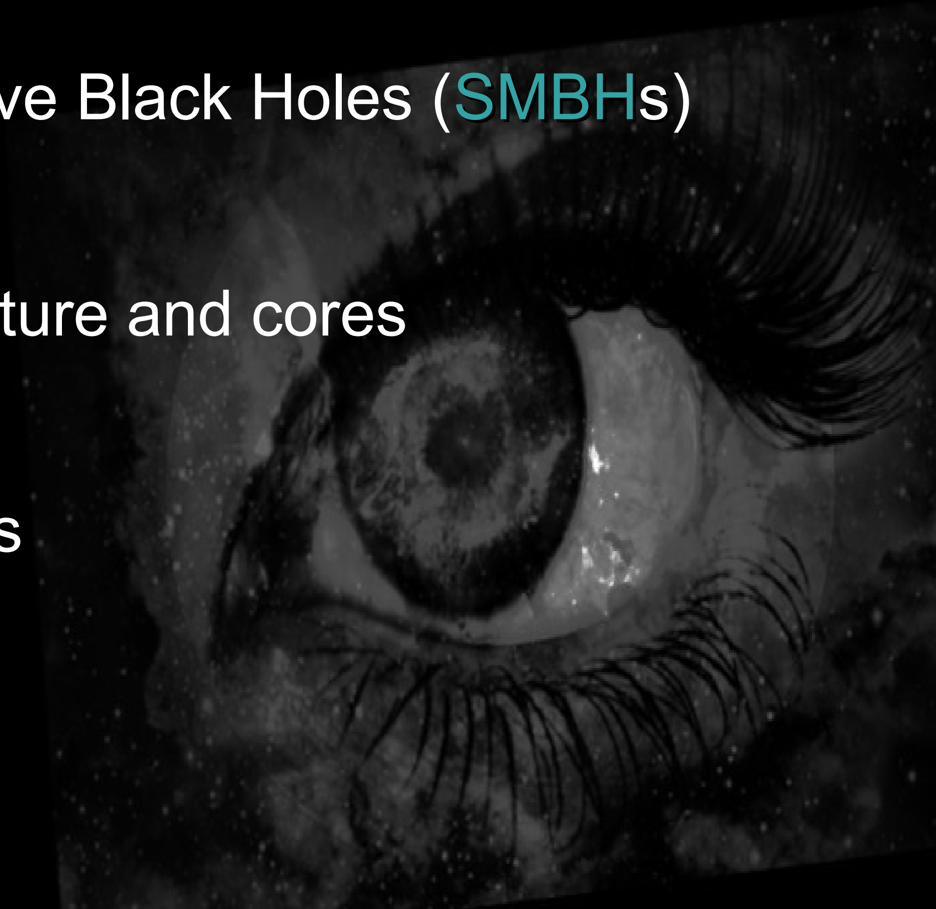
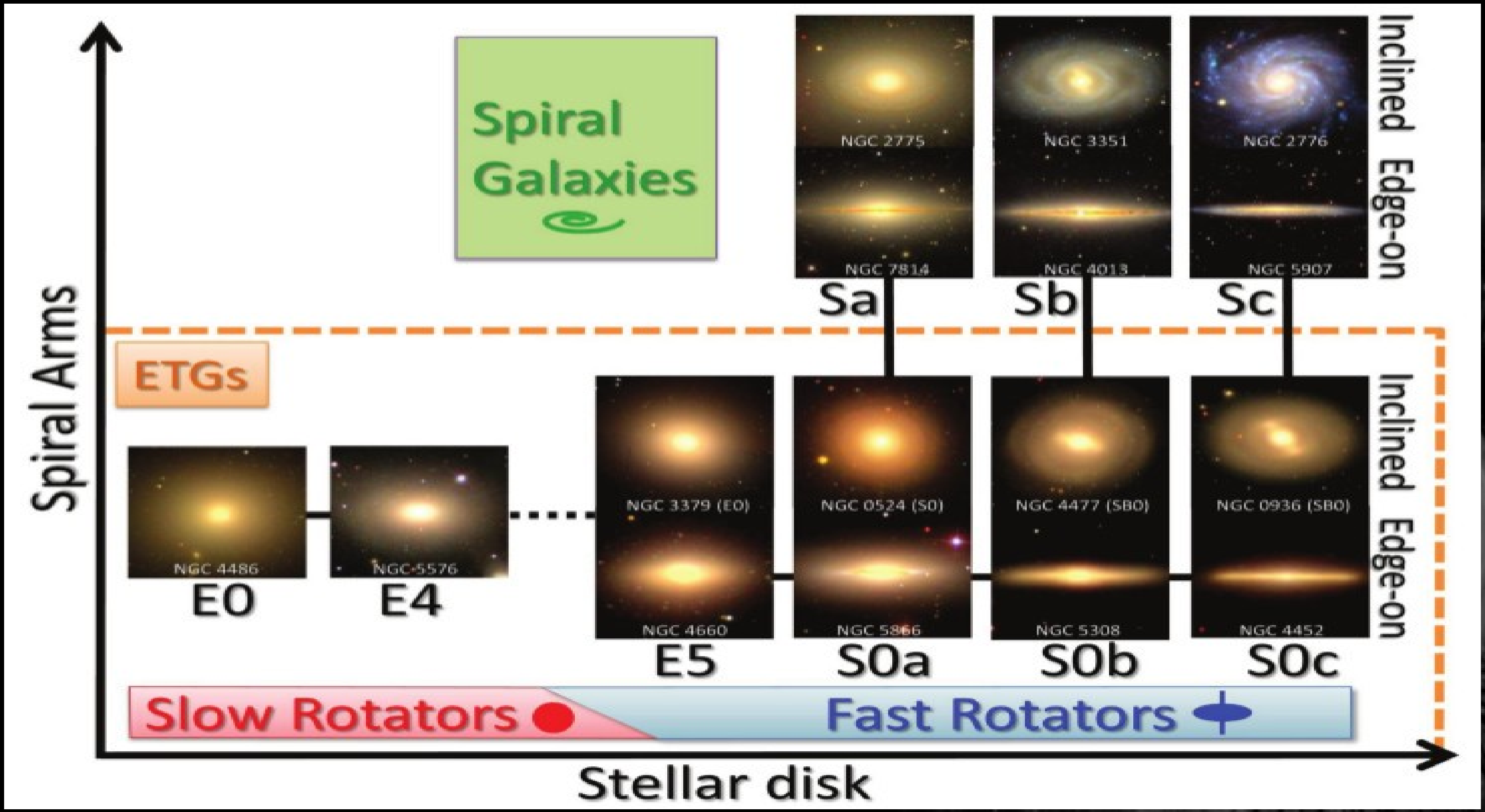
- ✪ Post-merger features in Early-Type Galaxies (ETGs): fine structures
- ✪ Stellar depleted cores & Super-Massive Black Holes (SMBHs)
- ✪ Post-merger co-evolution of fine structure and cores
- ✪ Post-merger features in VEGAS ETGs



THE FAMILY OF ETGs

- Early-Type Galaxies (ETGs) are bulge-dominated objects which can hower host rotational components varius significance



[ATLAS3D view: Cappellari 2011]

THE FAMILY OF ETGs

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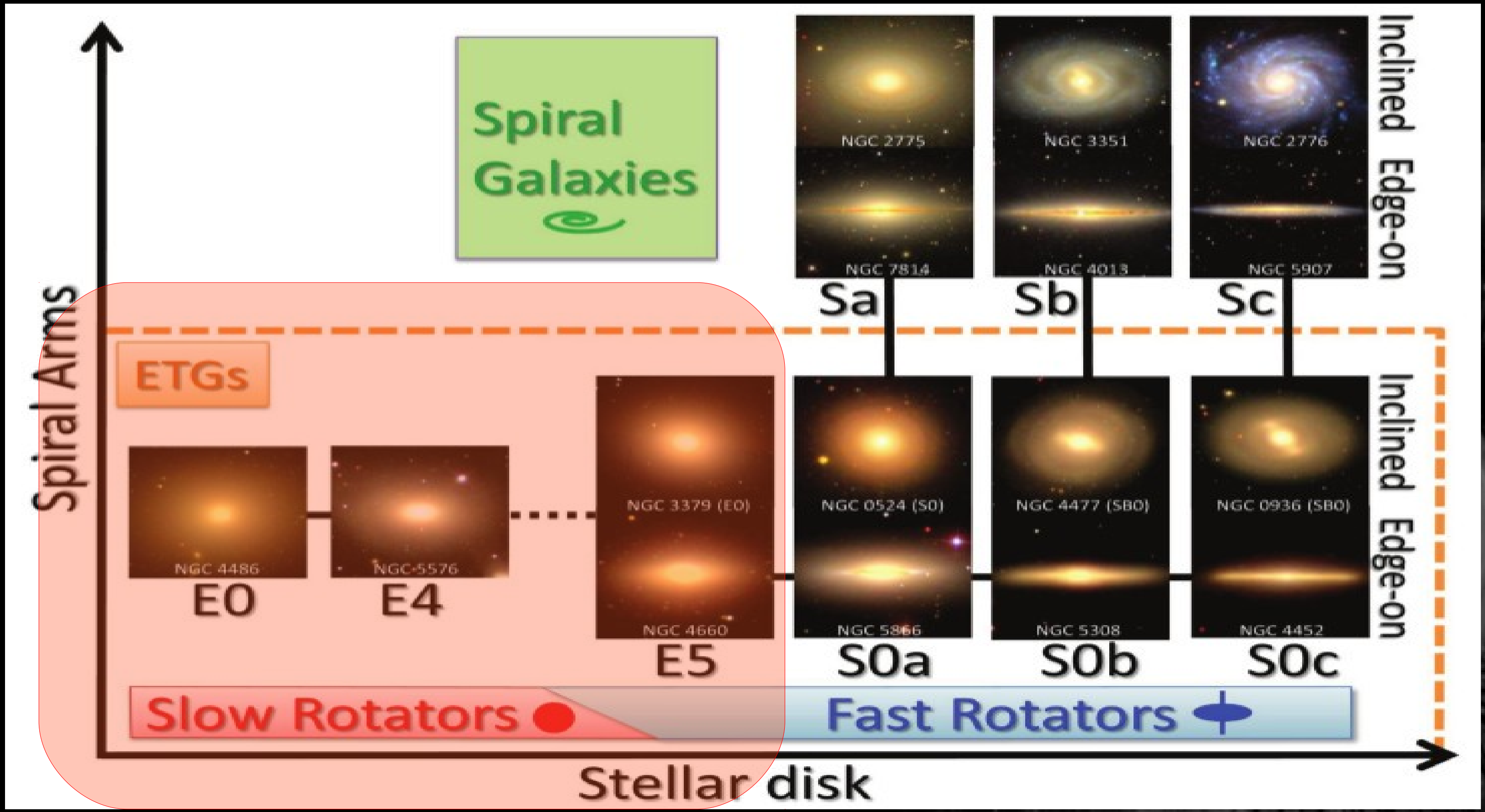
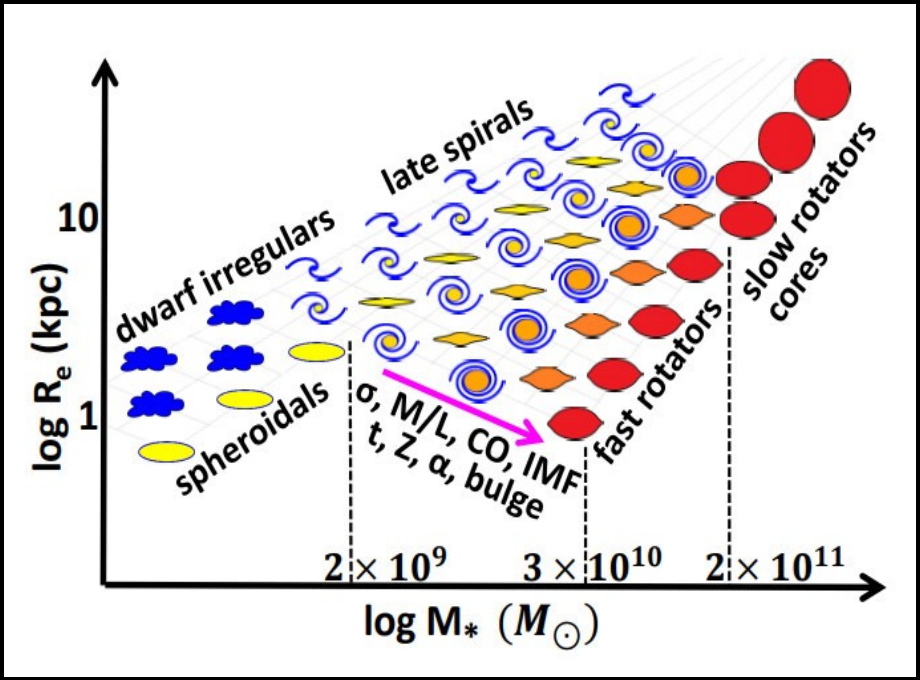


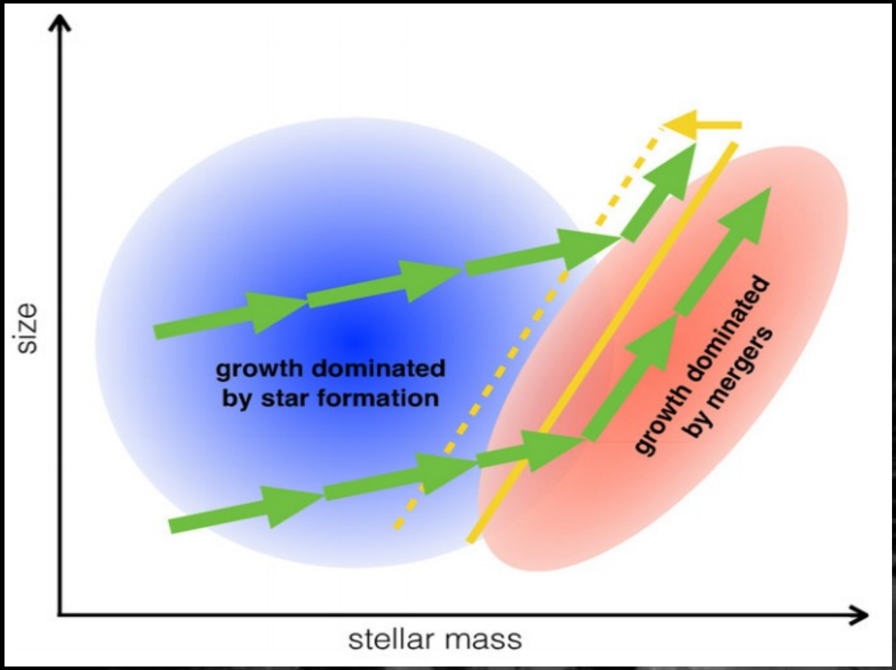
[ATLAS3D view: Cappellari 2011]

ETGs IN THE HIERARCHICAL FORMATION SCENARIO

✪ Hierarchical formation scenario → mass of ETGs assembled through mergers
(e.g. White & Rees 1978; Springel et al. 2005; Hopkins et al. 2006, 2010)



[Cappellari 2016]



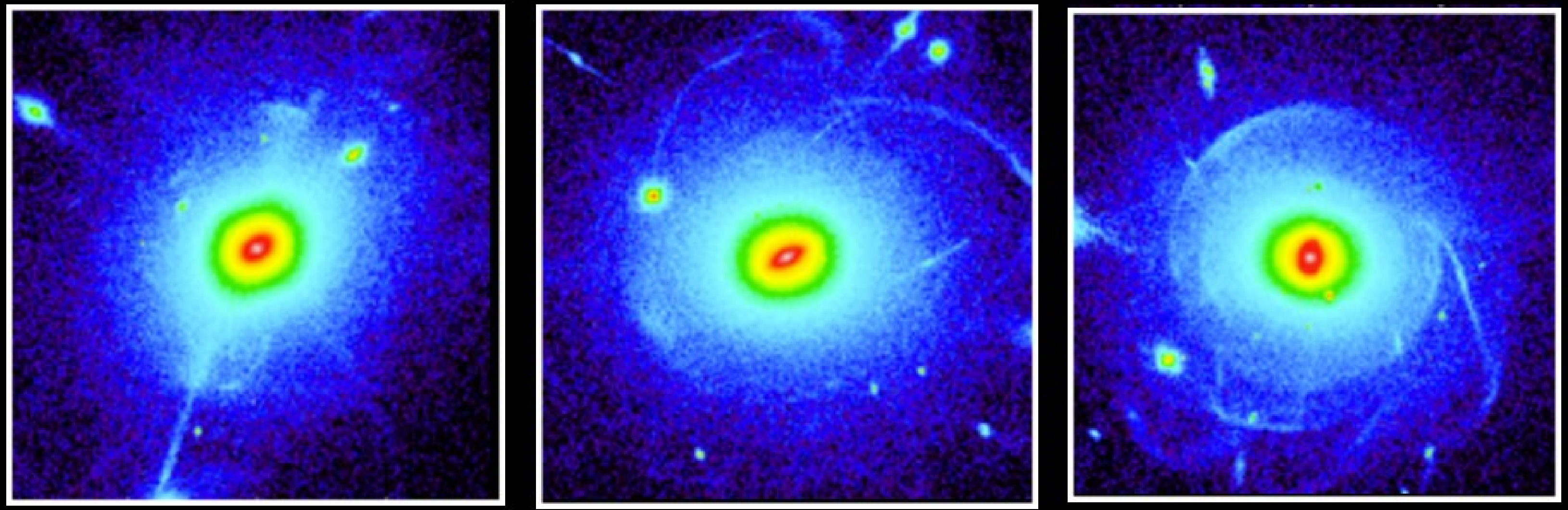
[van Dokkum 2015]

▸ Small ETGs / fast rotators → star-formation / wet mergers
▸ Massive ETGs / slow rotators→ dry mergers

FINE STRUCTURES IN ETGs

- Mergers leave an imprint: fine structures

TAILS **STREAMS** **SHELLS**



[Credit: MATLAS collaboration]

- Different features are associated with different interaction events (major/minor, gas-rich/gas-poor, etc.)

- Future surveys (by EUCLID, LSST, ELT) will detect fine structure routinely

Fine Structures - Shells

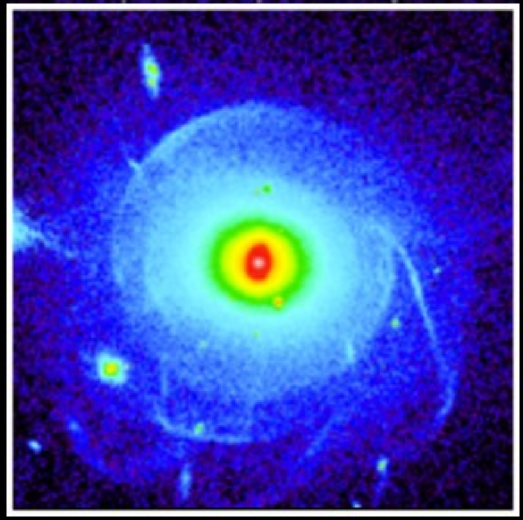
- Shells are the features most related to dry mergers
  (but see Peirani et al. 2010 for wet mergers)

- Features:
  - ▶ concentric arcs
  - ▶ red colors (no star-formation)
  - ▶ relatively bright ($\mu < 23$ mag/arcsec^2)
  - ▶ symmetric if “head-on”

  (Prieur 1990)

[Credit: P.A. Duc]

SHELLS



SHELLS IN COSMOLOGICAL SIMULATIONS

✪ Shells have been re-produced in both:

▸ idealized simulations *(e.g. Bullock 2005; Iodice 2017)*

▸ cosmological simulations *(e.g. Vogelsberger 2014; Pop 2017)*

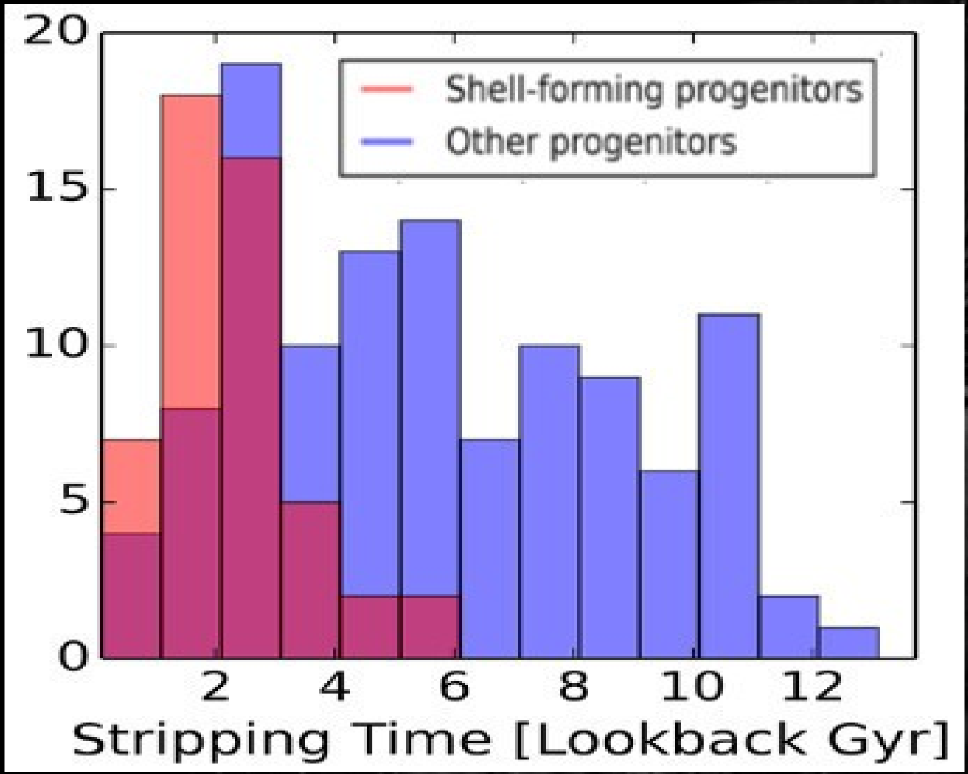
✪ ILLUSTRIS results:
(Pop 2017)

▸ Shell progenitors:

- Mass ratio 1:10 or above
  (major mergers)

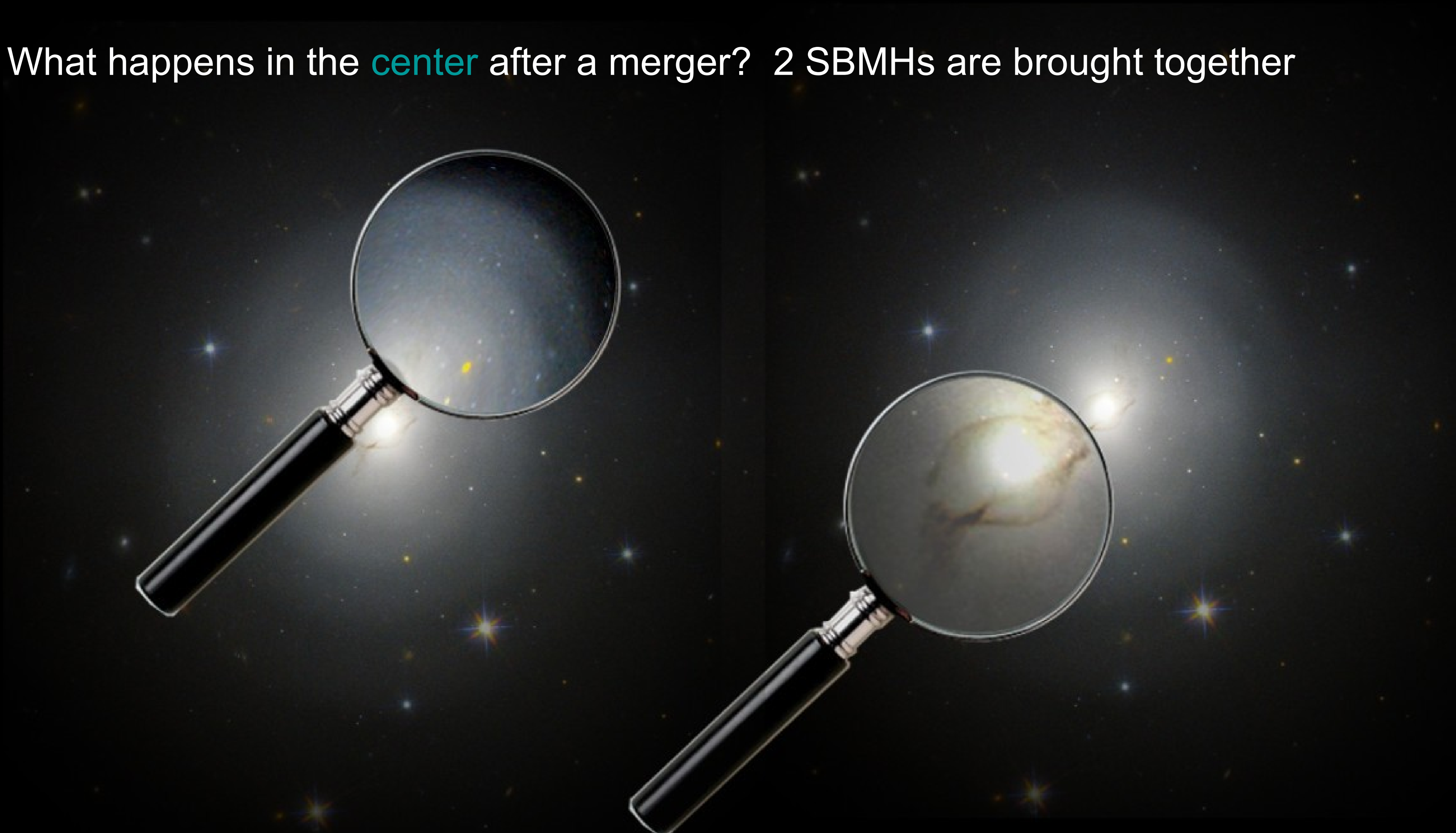
- Predominantly radial encounters

▸ Shells lifetime: ~2 Gyr

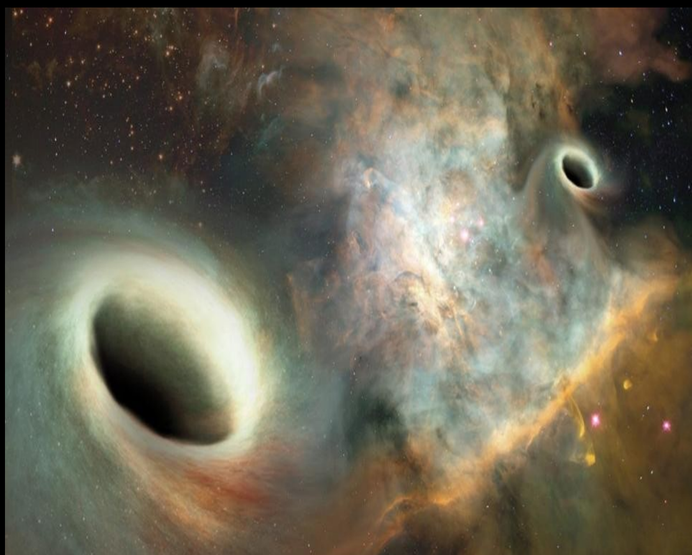


POT-MERGER SGNATURES: INSIDE & OUTSIDE

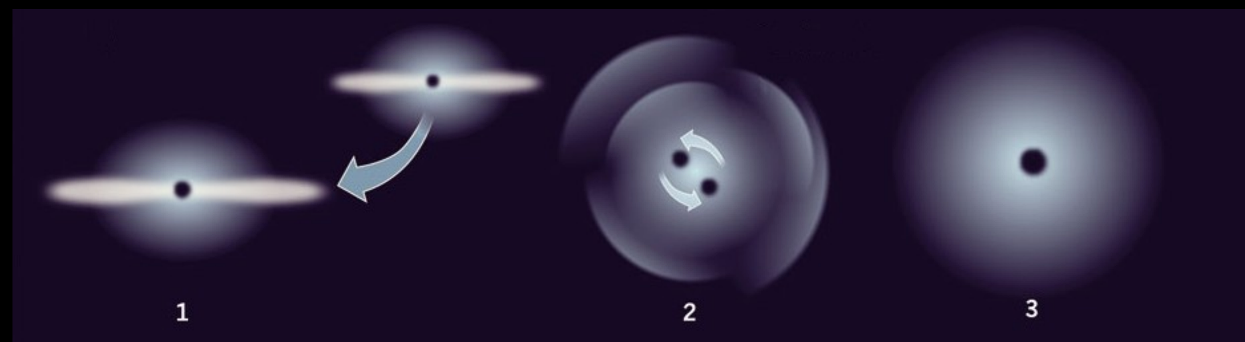
- ✪ Fine structures trace merger events
- ✪ What happens in the center after a merger? 2 SBMHs are brought together



BINARY SMBH SCOURING SCENARIO



- Stars ejected via 3-body interaction by binary SMBH (SMBH binary system created in “dry” mergers) *(Begelman et al. 1980)*

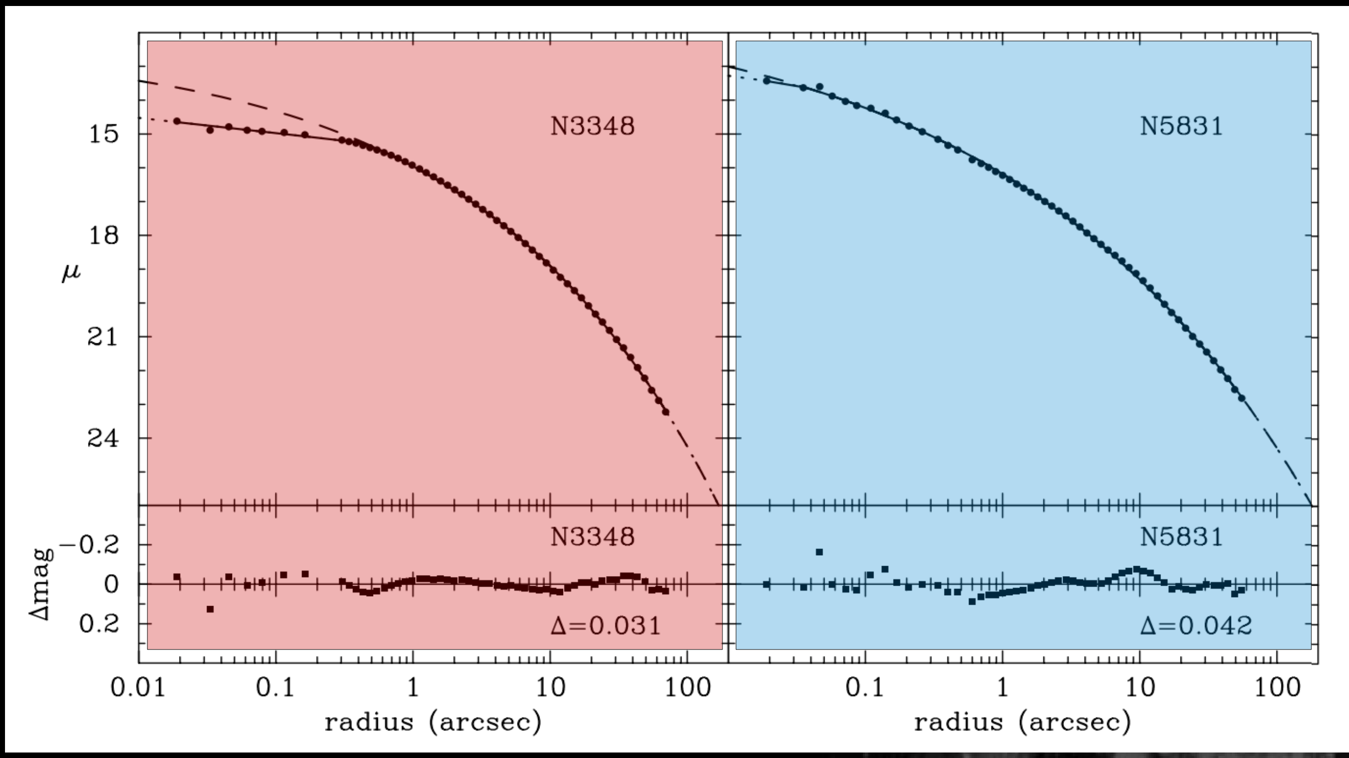


[Adapted from Cappellari 2011]

- SMBH binaries (~1 kpc) observed in X-ray / radio *(e.g., NGC 6240, Komossa et al. 2003; Arp 299, Ballo et al. 2004; 0402+379, Rodriguez et al. 2006; Mrk 463, Bianchi et al. 2008)*
  - ► Last year's: first “visual” (VLBI) SMBH binary with separation ~7 pc! *(0402+379, Bansal et al. 2017)*
- SMBH scouring creates a core in the stellar light distribution of ETGs

CORE GALAXIES

- ✪ core = central flattening of profile w/r to outer Sersic profile



[Graham et al. 2003]

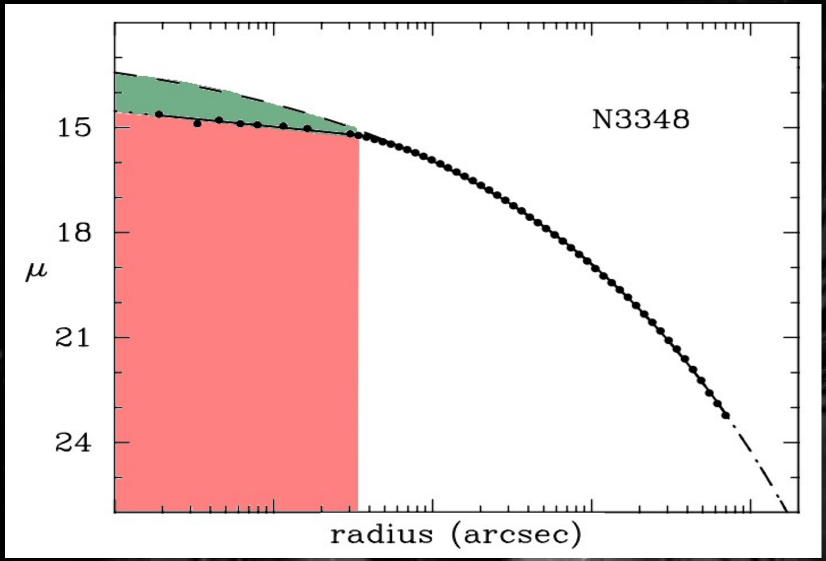
- ✪ All luminous ($M_B \lesssim$ -20.5) ETGs host cores → massive ETG = core galaxy

  (e.g. King & Minkowski 1966, 1972; King 1978; Young et al. 1978; Duncan & Wheeler 1980; Begelman et al. 1980; Kormendy 1985; Lauer 1985)

  (Bonfini 2014, PASP, 126, 935 - Bonfini & Graham 2016, ApJ, 829, 81)

CORE ↔ SMBH SCALING RELATIONS

- Several scaling relations connect cores with the central SMBH:
  - $M_{BH} \longleftrightarrow$ core radius
    (Lauer 2007a; Rusli 2013; Dullo & Graham 2014)
  - $M_{BH} \longleftrightarrow$ mass within the core (M_{core})
    (Lauer et al. 2007A)
  - $M_{BH} \longleftrightarrow$ mass deficit (M_{def})
    (Hyde et al. 2008)



- *NOTE:*
  core mass (M_{core}) $= M(r < r_{core})$
  mass deficit (M_{def}) $= M_{core\text{-}Sersic} - M_{sersic}$

→ PROOF THAT CORES ARE GENERATED BY SMBH SCOURING

(but see Bonfini & Graham 2016, ApJ, 829, 81B for alternative scenarios)

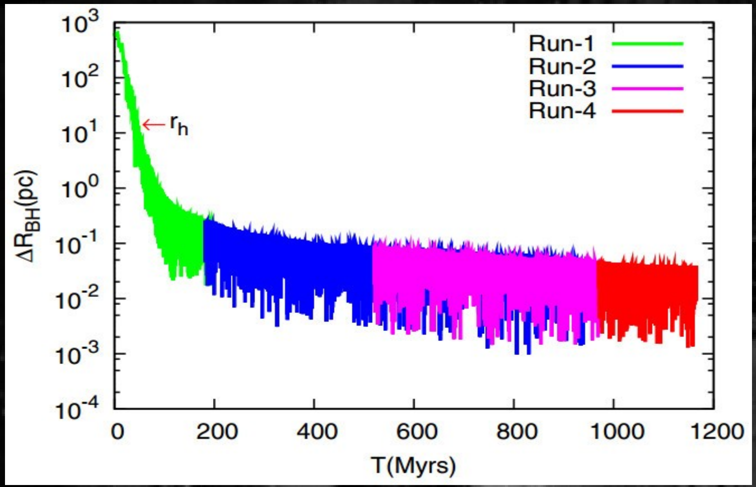
CORE EXCAVATION TIMESCALE

- The coalescence of a SMBH binary happens in 3 steps:
  (Khan et al. 2012a, Bortolas et al. 2018)

  1 ▸ SMBHs infall by dynamical friction
  ~100 Myr

  2 ▸ SMBH binary scouring (core excavation)
  ~1 Gyr

  3 ▸ Shrinking by gravitational wave
  ~100 Myr



[Khan et al. 2012a]

NOTE: For 10^9 $M_\odot$ SMBH with low eccentricity → core phase can last up to 2 Gyr
(Khan et al. 2012B, Bortolas et al. 2017)

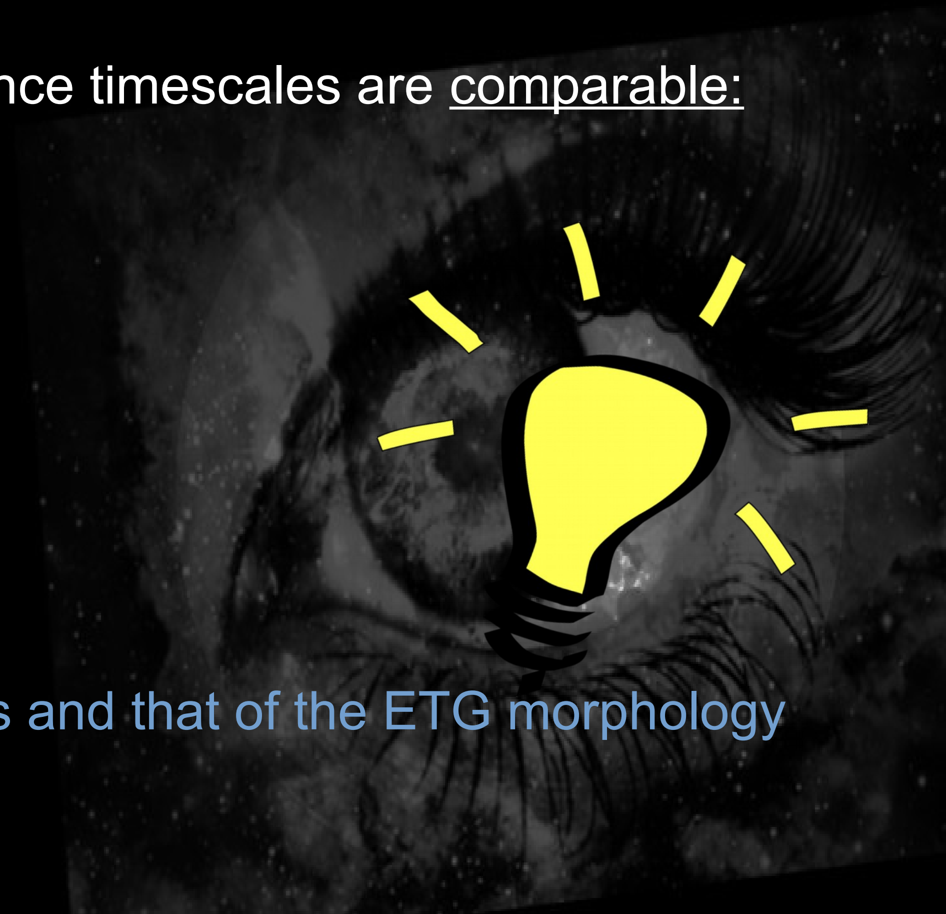
TIMESCALE COMPARISON

✪ Following the merger which created the ETG:

- ▸ core progressively excavated by SMBH binary
- ▸ galaxy potential relaxes and interaction features fade away

✪ core escavation and fine structure disapperance timescales are comparable:

- ▸ core formation → ~1 Gyr
- ▸ fine structures → ~1-2 Gyr



→ We can connect the evolution of cores and that of the ETG morphology

FINE STRUCTURE AND CORE EVOLUTION

- ✪ We related the evolution of cores and fine structures in a sample of core ETGs

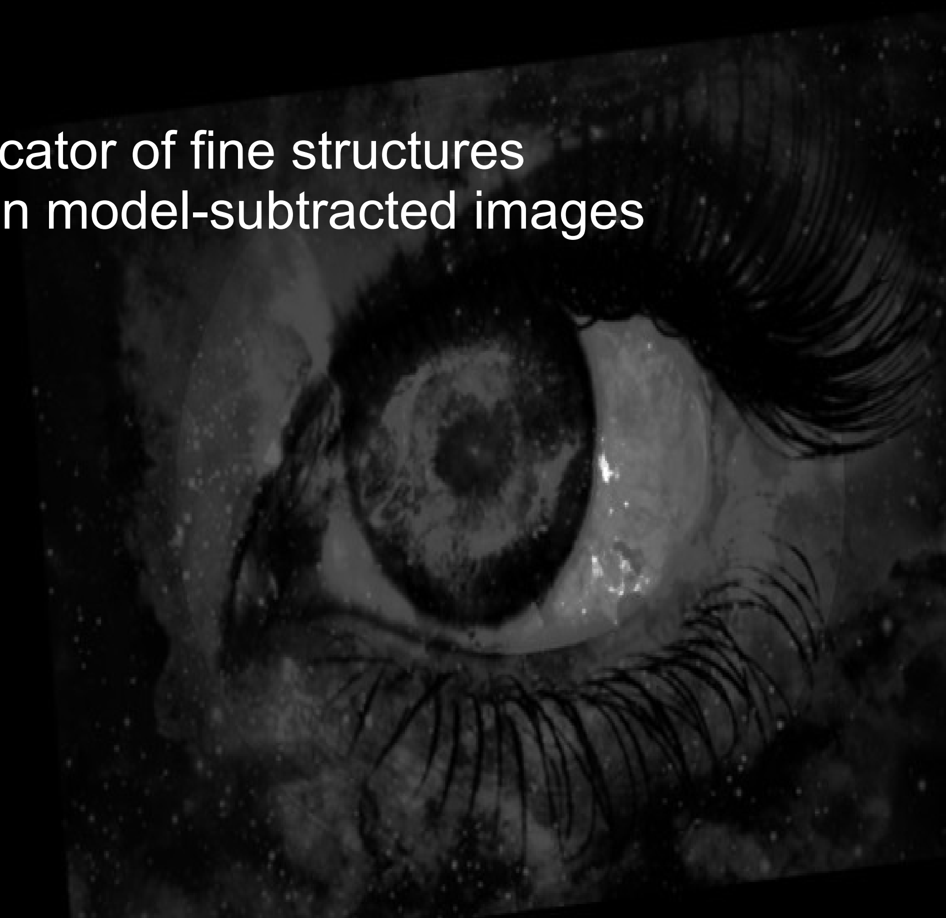
- ✪ To perform the comparison, we used archival measurements of:

  - ▸ significance of fine structure

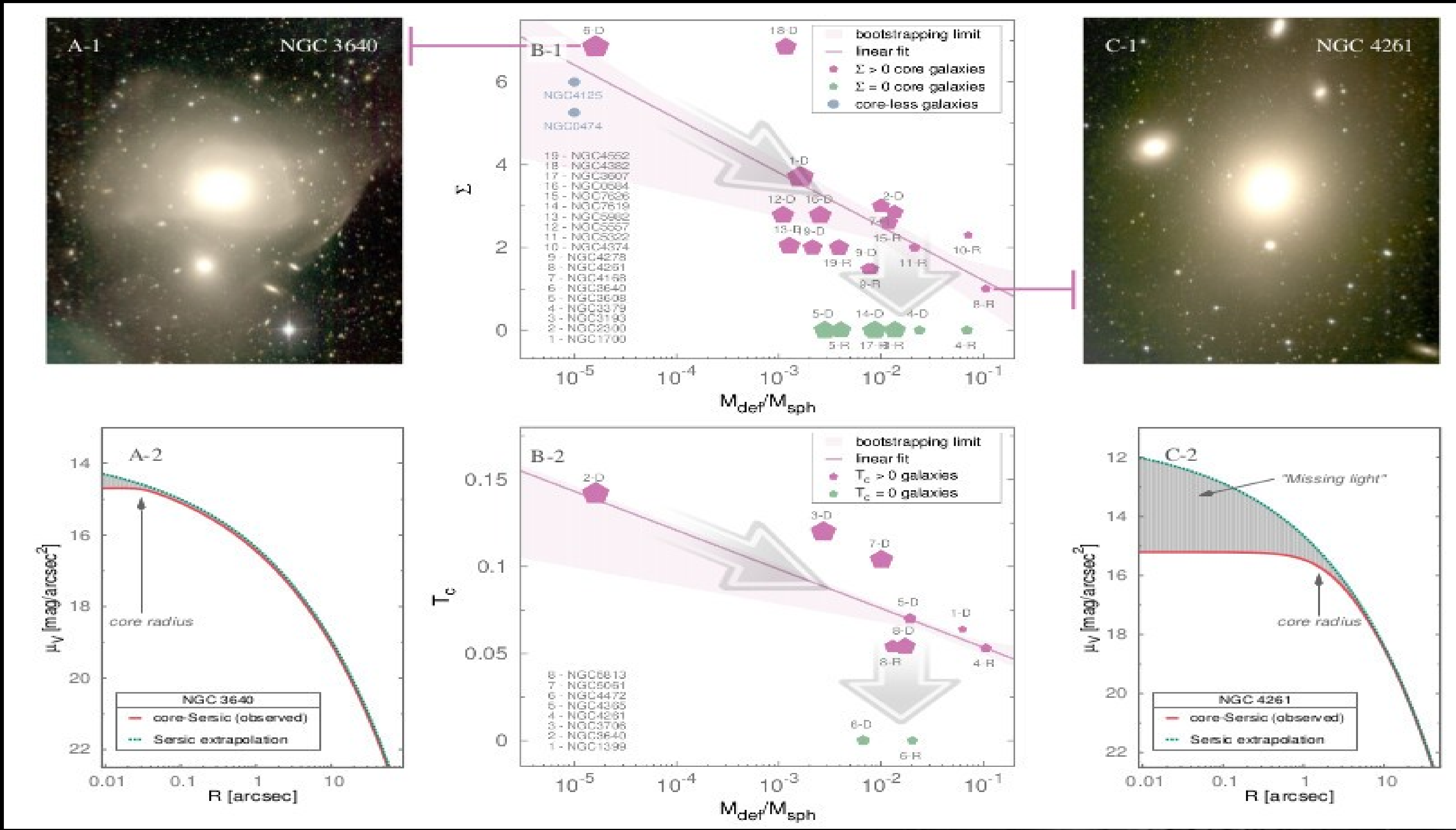
    - Schweizer et al. (1990): Σ → visual indicator of fine structures
    - Tal et al. (2009): T_C → distortion in model-subtracted images

  - ▸ depleted mass

    - Richings et al. (2011)
    - Dullo & Graham (2014)



RESULTS



Bonfini et al. 2018, MNRAS, 473, 94

FINE STRUCTURES AS AGE PROXY

→ CLEAR INDICATION FOR EVOLUTIONARY TRACK !

✪ How to improve on this result?

▸ Additional data: **VEGAS** + MATLAS
E. Iodice & VEGAS collaboration – Osservatorio Astronomico Capodimonte
P. Duc & MATLAS collaboration – Observatoire Astronomique de Strasbourg

▸ Define a more robust estimator for fine structure:
- automated
- independent of image depth
- able to distinguish between dry/wet mergers

A. Zezas, J. Andrews – University of Crete
T. Bitsakis – IRyA (UNAM)

▸ Calibrate fine structure *vs.* age from merger via cosmological simulations
C.C. Hayward – Center for Computational Astrophysics (New York)

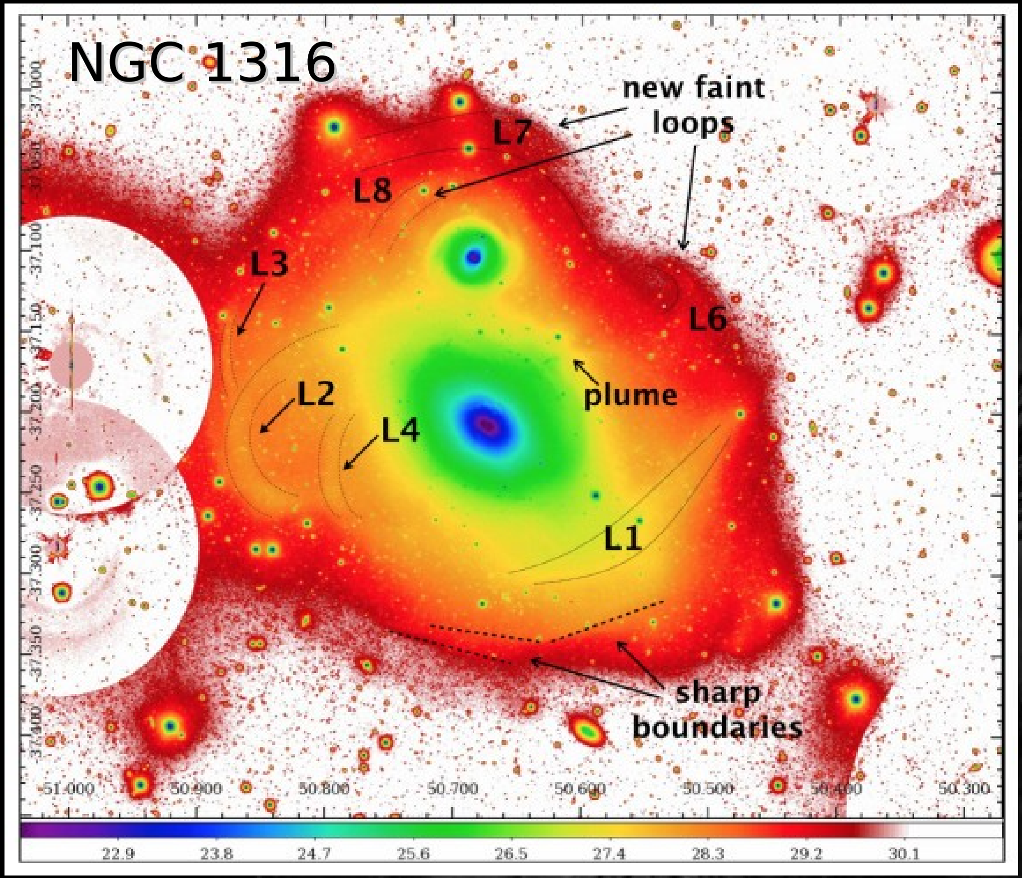
FINE STRUCTURES IN VEGAS DATA

- **VEGAS**: *VST survey of Early-type GAlaxies in the Southern hemisphere* offers imaging down to $\mu_g \sim 31$ mag/arcsec^2
  (see talk by Iodice, Spavone & Cattapan)

- We expect to identify fine structures in all ETGs

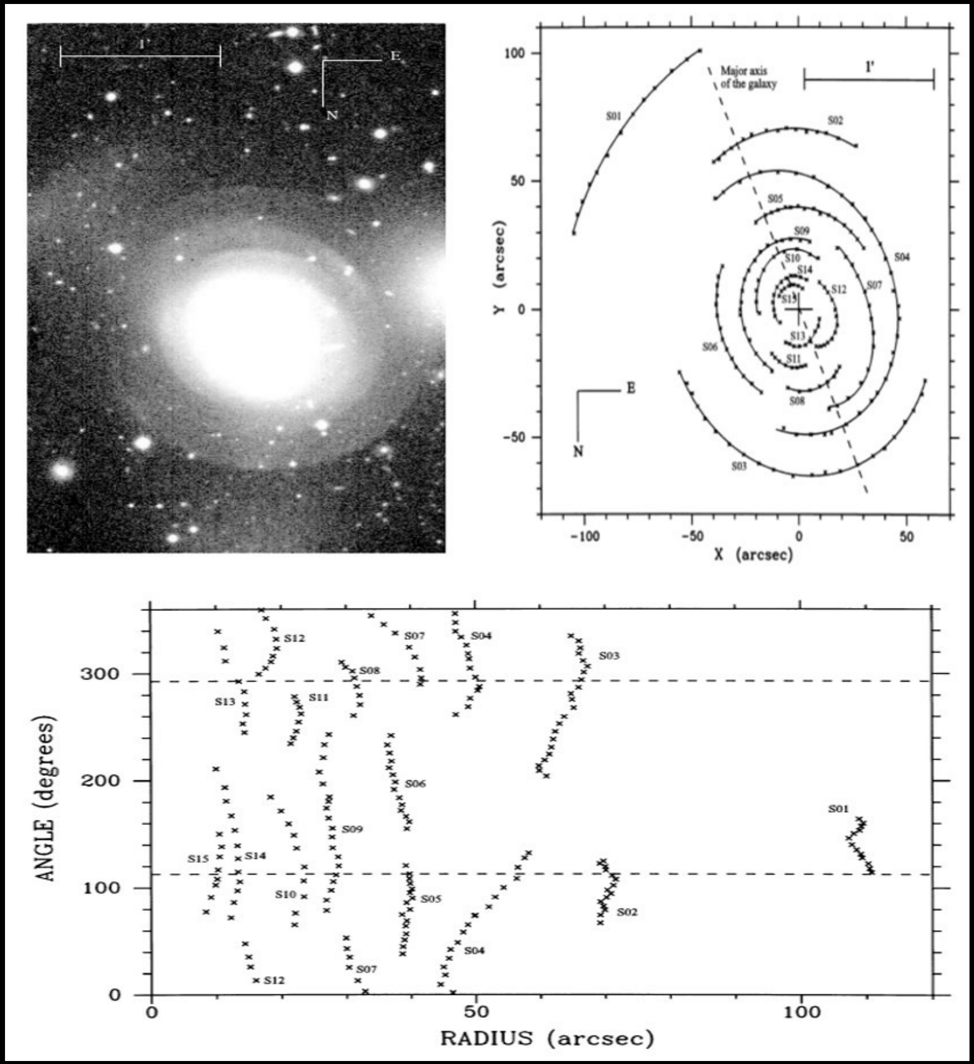
- 17 ETGs in VEGAS host cores
  (Ferrarese et al. 2006;
  Lauer et al. 2007;
  Richings et al. 2011;
  Rusli et al. 2013)

- What we want: automated/sistematic fine structure detection routine



[Iodice 2017]

PREVIOUS WORKS



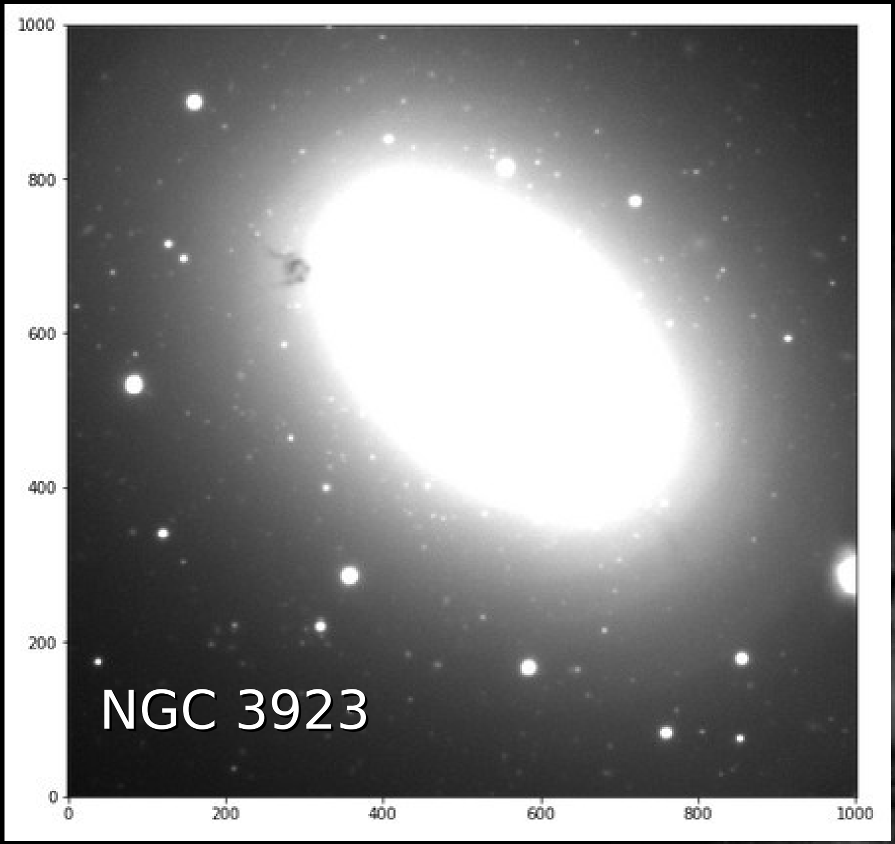
[Wilkinson 2000]

- ✪ The first info we need are:
  - ▸ shells number
  - ▸ shells radii
  - ▸ shells angular apertures

- ✪ Previous studies → “by hand”
  (e.g. Wilkinson et al. 2000)

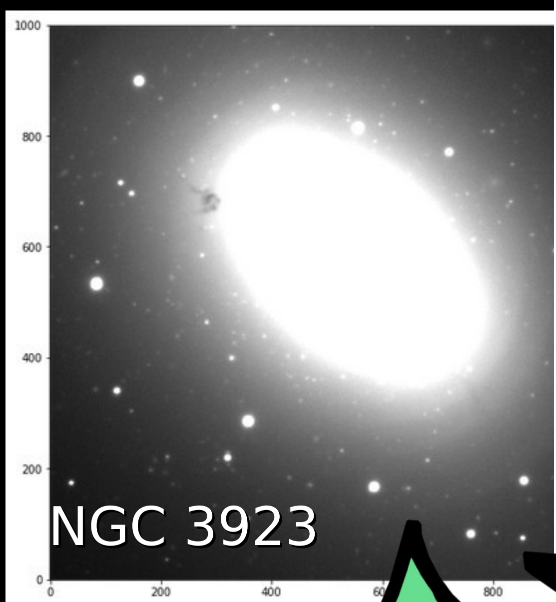
DETECTION ROUTINE

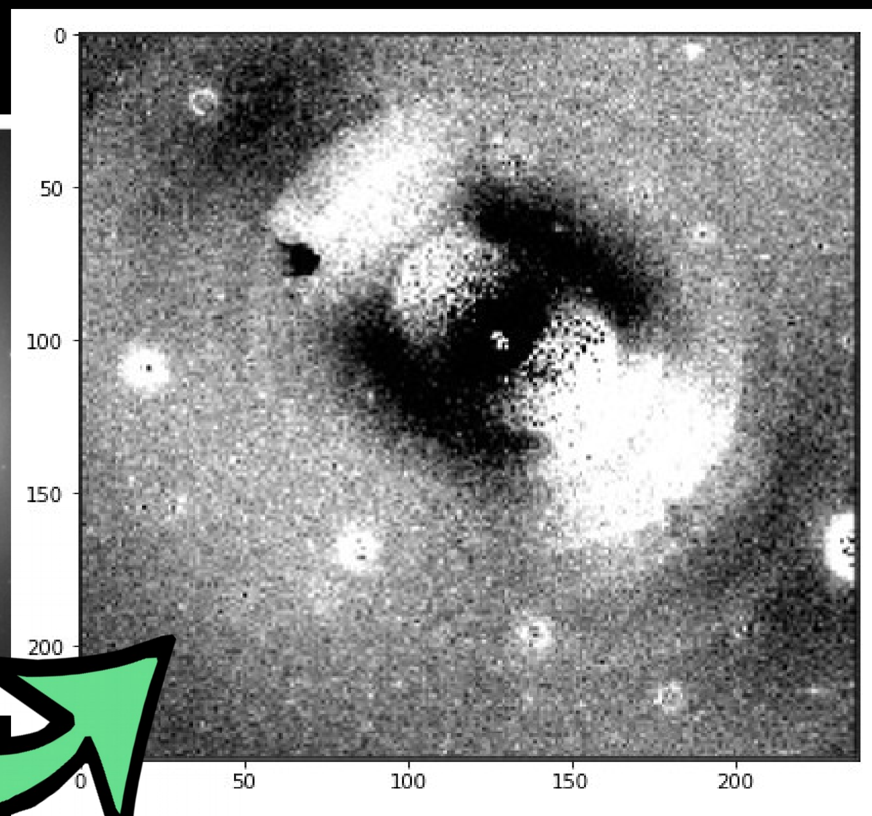
✪ Automated detection of shells in the VEGAS deep images

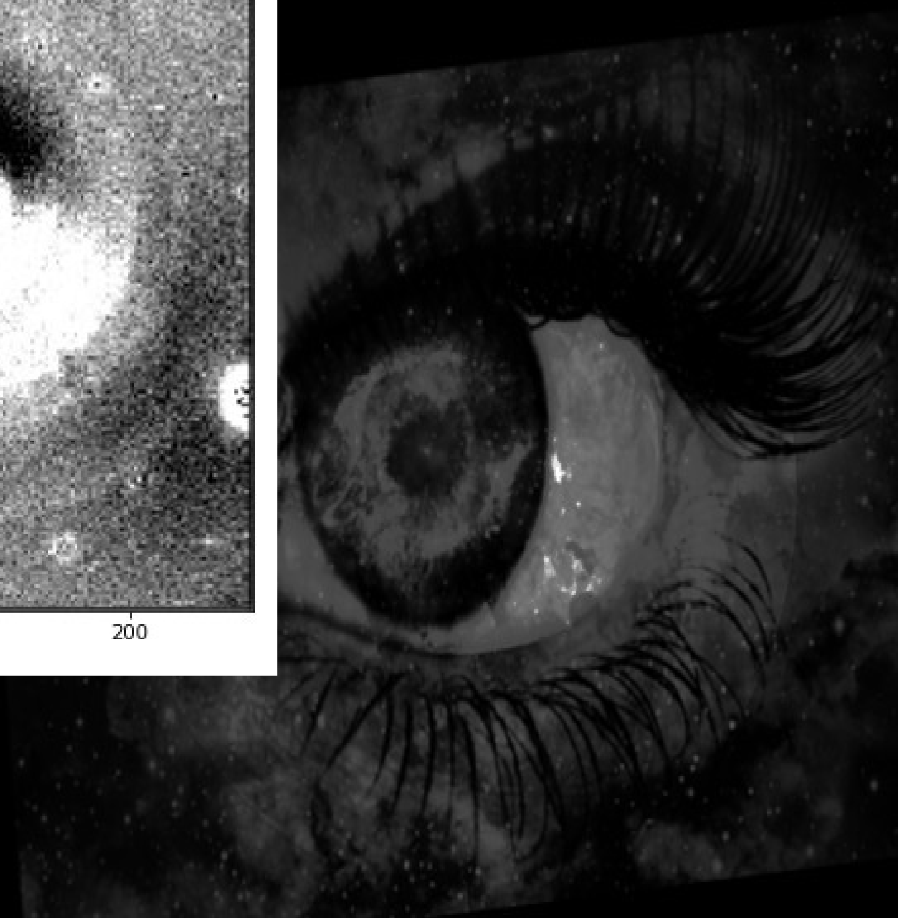


DETECTION ROUTINE

- ✪ 2D model subtraction (GALFIT) + star removal (J. Kypriotakis, *in prep.*)

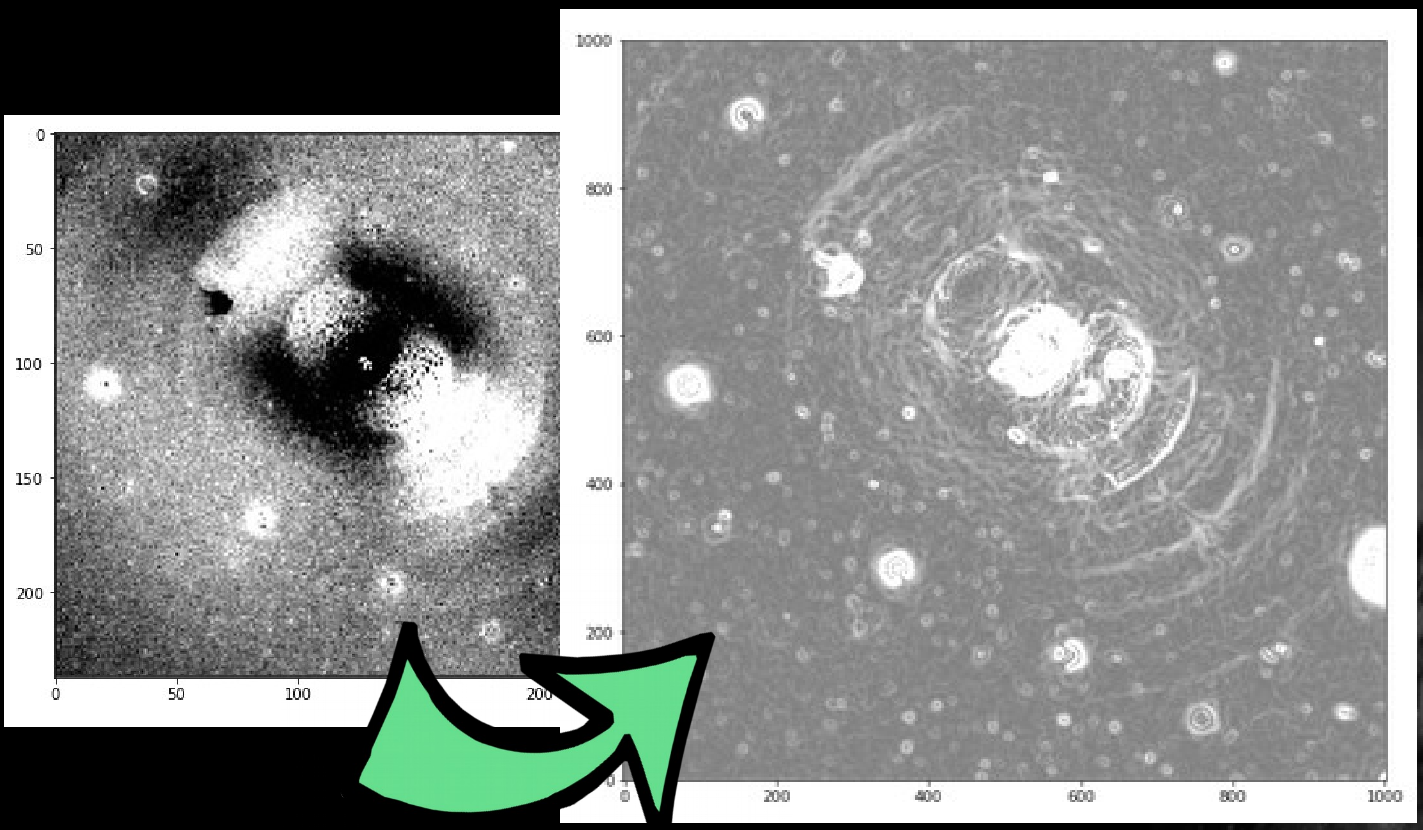






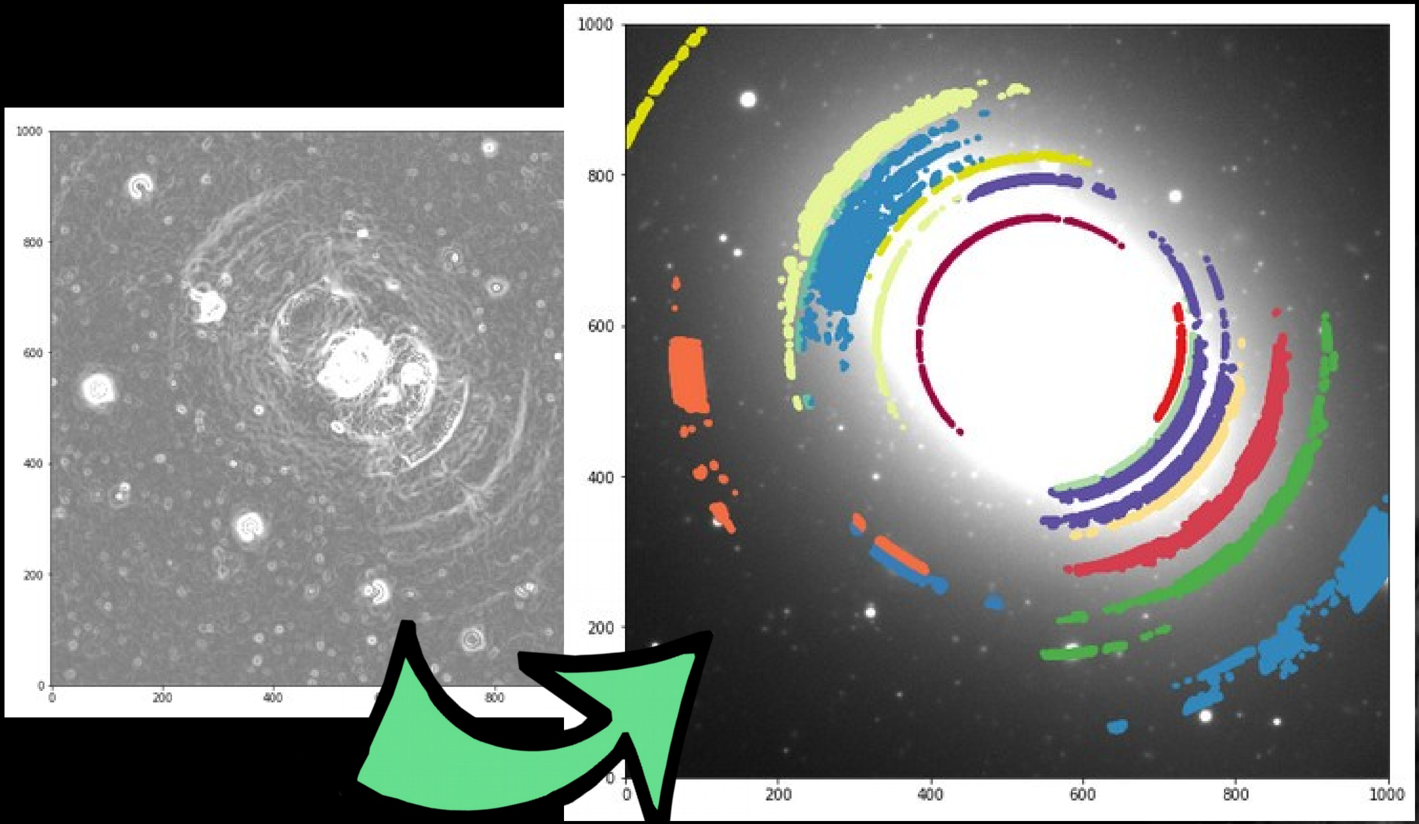
DETECTION ROUTINE

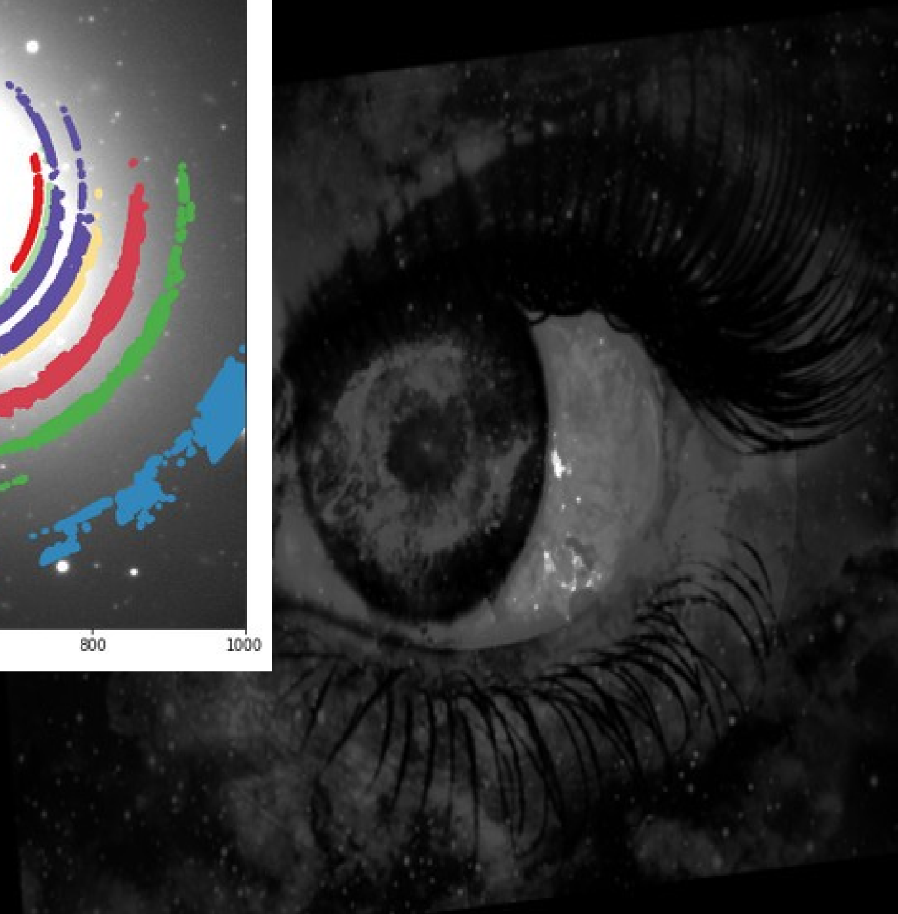
- Edge detection (Gaussian Gradient Model) but experimenting with filament search *(Panopouplou et al. 2017)*



DETECTION ROUTINE

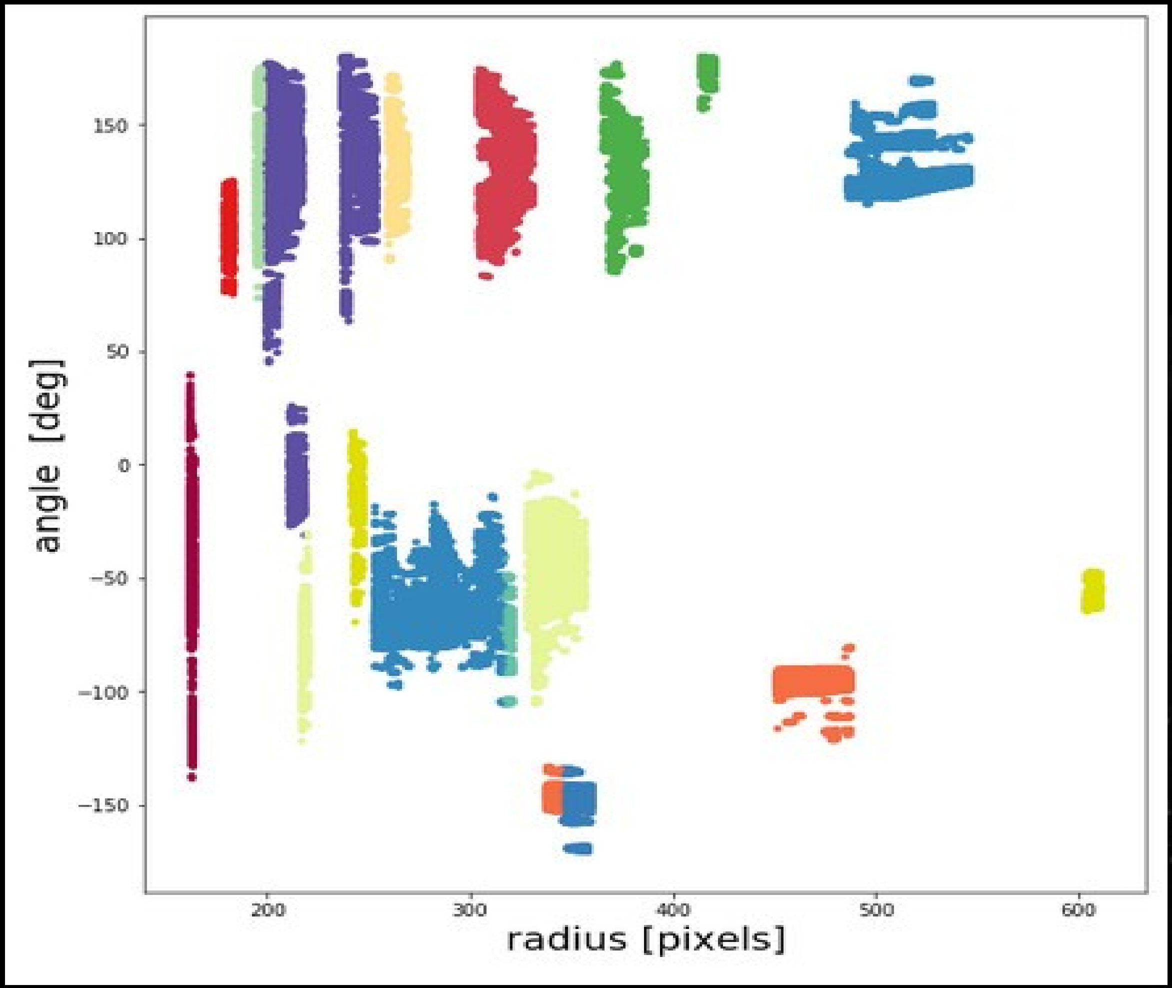
- Clustering analysis



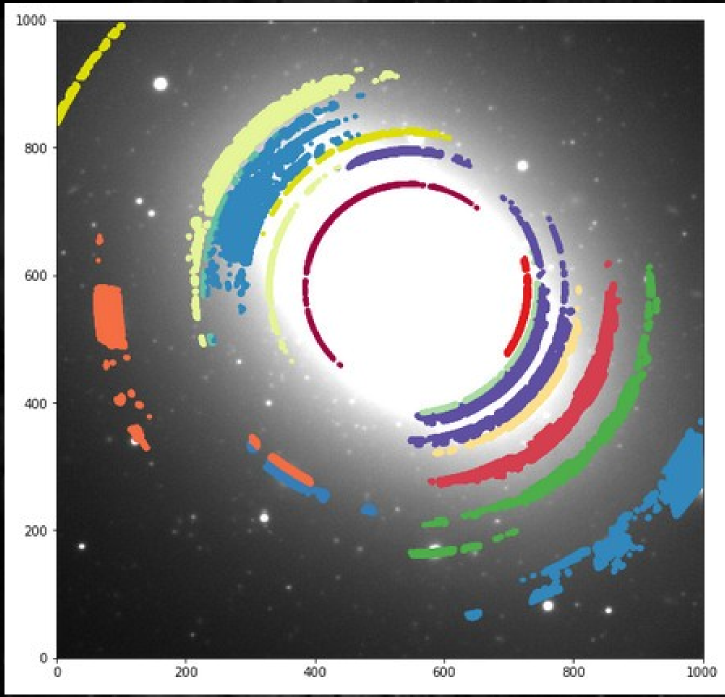


DETECTION ROUTINE

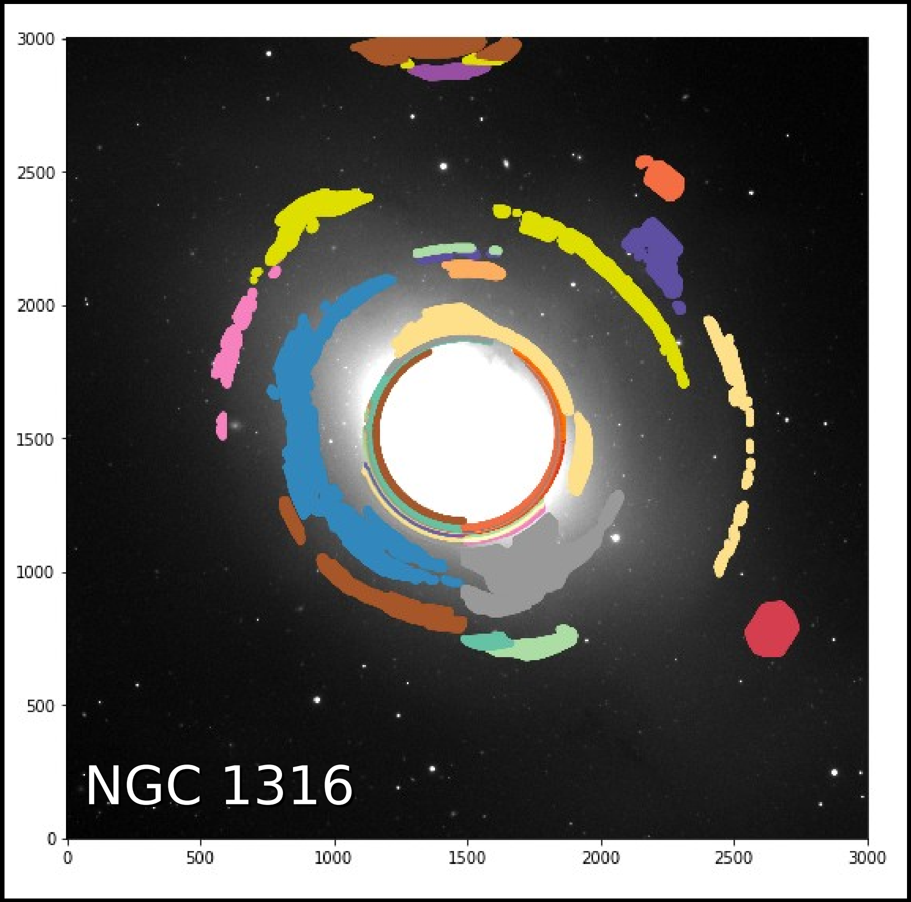
- In polar coordinates → shells are vertical (further screening if necessary)

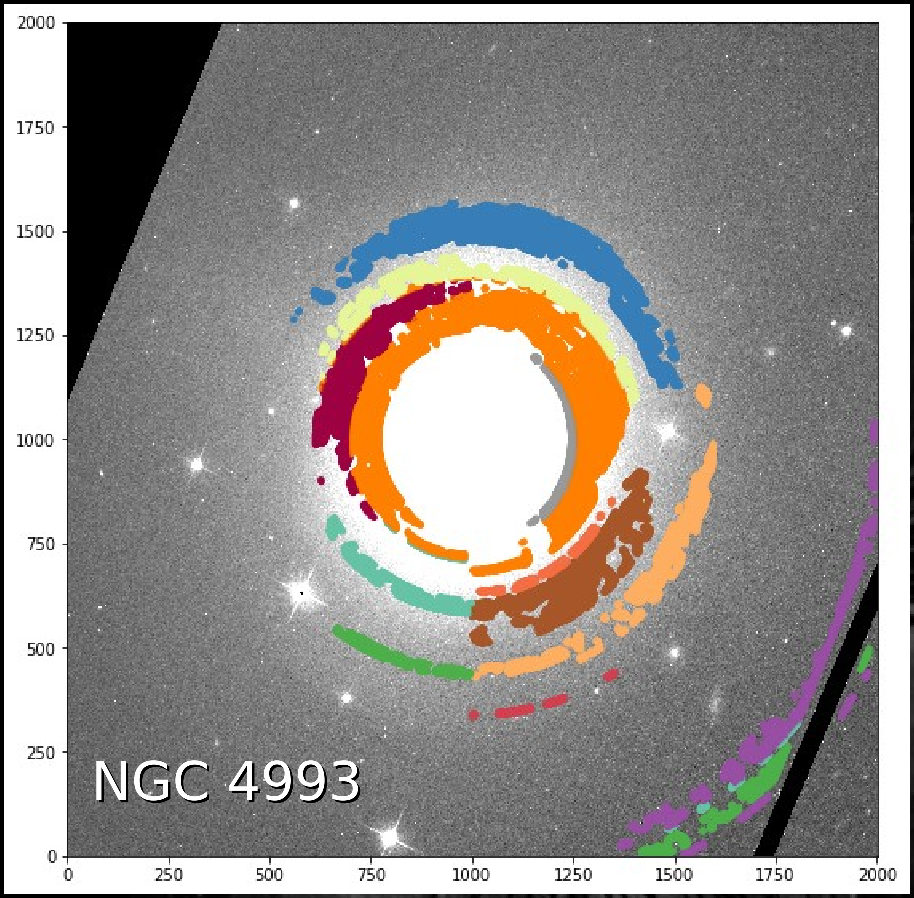


- Now trivial to automatically get:
  - shells number
  - shells radii
  - shells angular apertures



COUPLE MORE EXAMPLES





TAKE-HOME POINTS

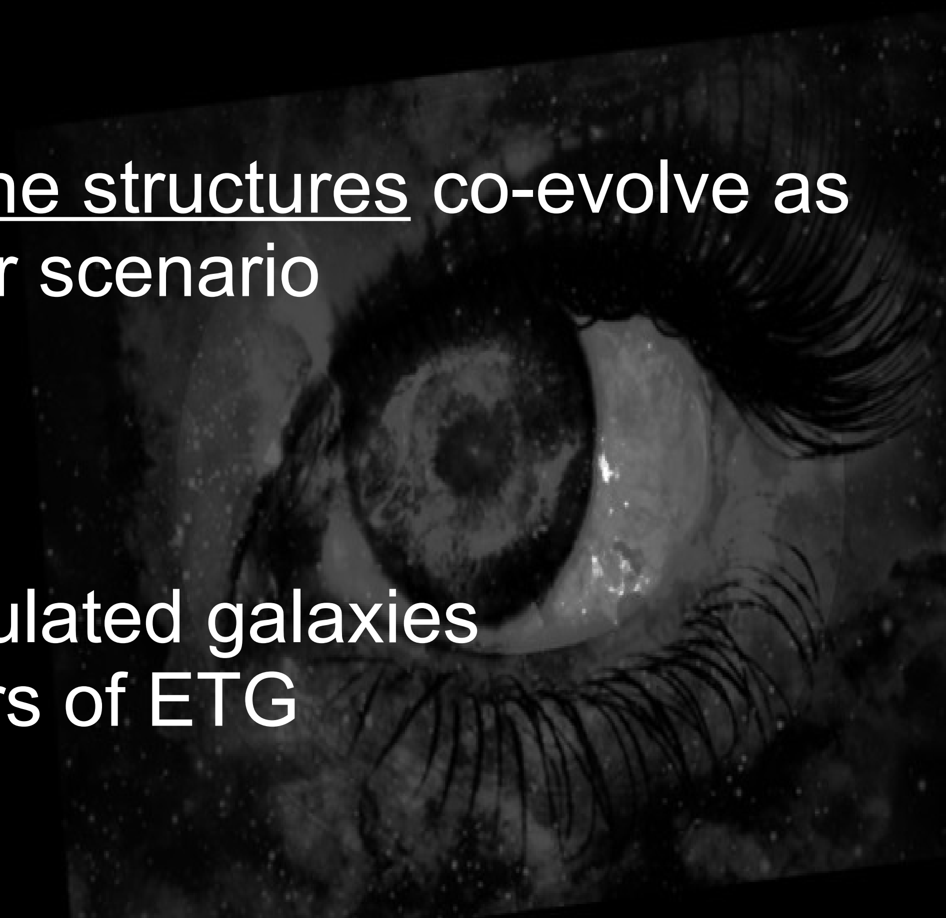
- ✪ Fine structures are one – of the few – ways to date ETGs

- ✪ Cores (= massive ETGs) and fine structures co-evolve as expected by hierarchical merger scenario

- ✪ Compare fine structures:

  real galaxies *vs* simulated galaxies

  → get statistical age / progenitors of ETG



THANK YOU

(FOR NOT FALLING ASLEEP ...)

COLLABORATORS (spot your friends!)

✪ Fine Structure:

- ► *E. Iodice & VEGAS collaboration – INAF*
- ► *A. Zezas & J. Andrews – University of Crete*
- ► *P.-A. Duc & MATLAS collaboration – Strasbourg Observatory*
- ► *T. Bitsakis – UNAM*

✪ Cores:

- ► *A. Graham – Swinburne University*
- ► *E. Bortolas – INAF*