STUDYING GALAXY STELLAR CORES

CONSTRAINING THE COEVOLUTION OF EARLY-TYPE GALAXIES AND THEIR SMBHs

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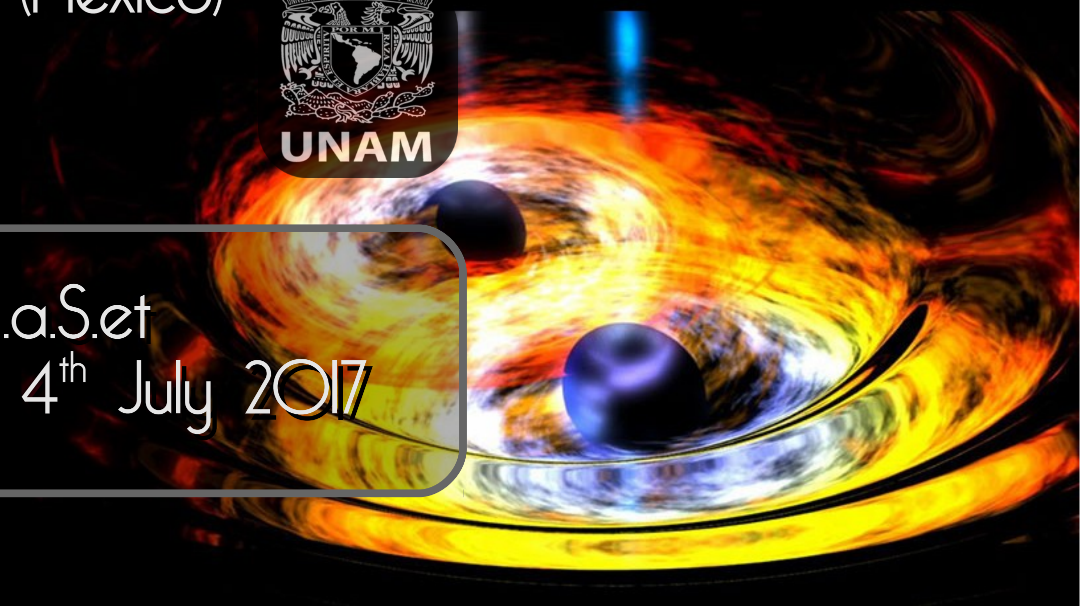

Hel.a.S.et
Heraklion - 4th July 2017

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PART I – THE LARGEST CORES

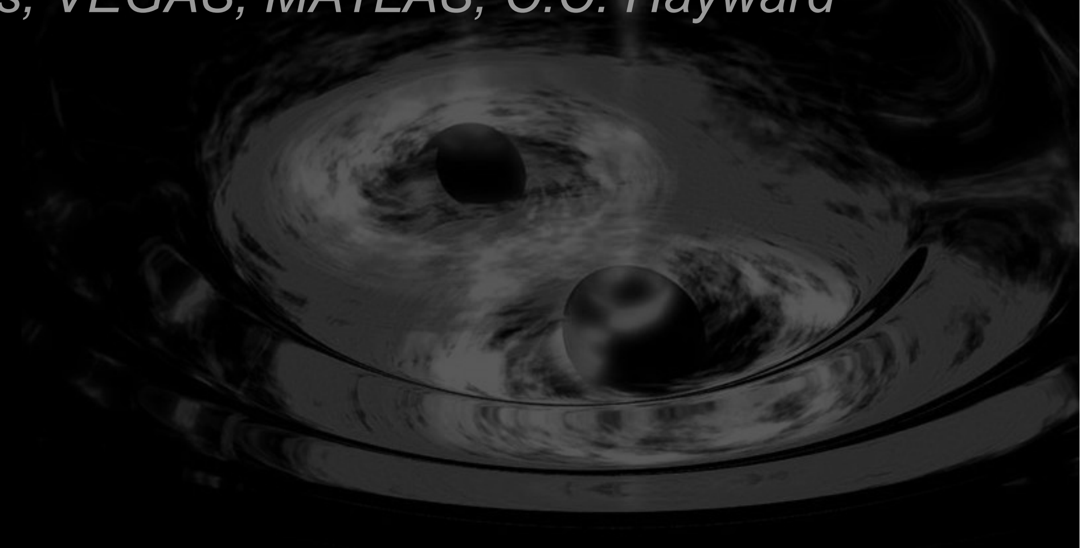
Collaborators: A. Graham, B. Dullo

- What is a “core” ? Cores & Super-Massive Black Holes (SMBHs)
- Testing the binary-SMBH scenario for core formation

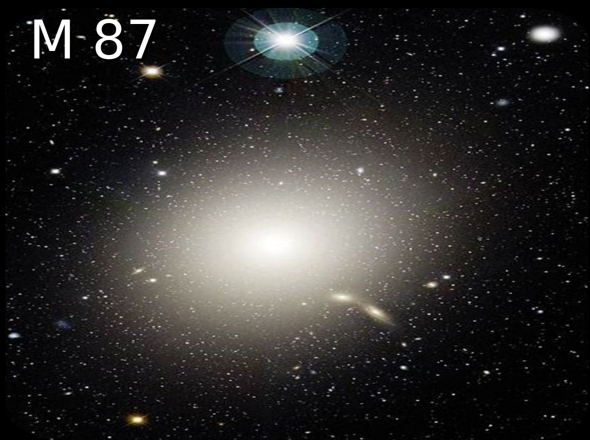
PART II – CORES AND FINE STRUCTURES

Collaborators: A. Zezas, T. Bitsakis, VEGAS, MATLAS, C.C. Hayward

- Fine structure in early-type galaxies
- Co-evolution of fine structure and cores



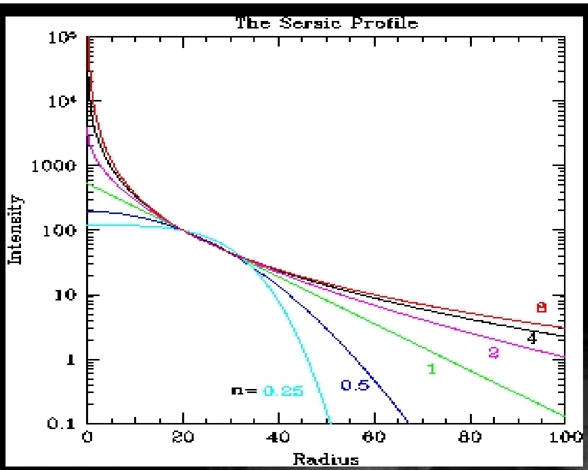
PART I - LIGHT PROFILES OF EARLY-TYPE GALAXIES



[Image credit: J.C. Cuillandre]

- Early type (ETGs): Elliptical (E) + Lenticular (S0)
- Spheroids described by a Sersic profile (n > 2)

$$\Sigma(r) = \Sigma_e \, exp \left[-k \, (r/r_e)^{1/n} \right]$$

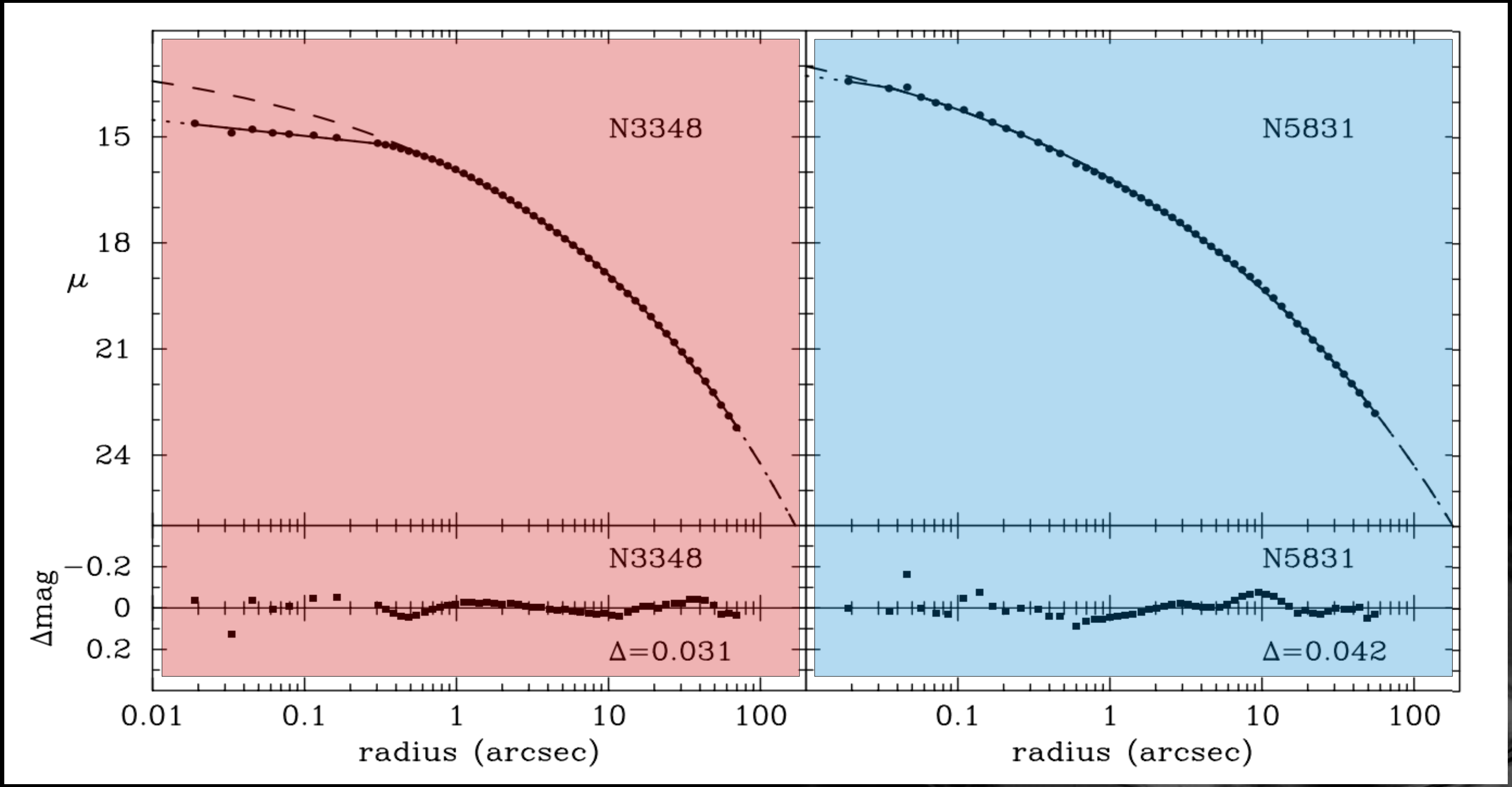


[Image credit: Peng 2010]

- Luminous ($M_B \lesssim$ -20.5) ETGs long known to host cores (central flattening of profile)
  (e.g. King & Minkowski 1966, 1972; King 1978; Young et al. 1978; Duncan & Wheeler 1980; Begelman et al. 1980; Kormendy 1985; Lauer 1985)

ETGs DICHOTOMY

- From this point of view, ETGs broadly separate in:
  - ▸ "Sersic" (in literature: "power-law" galaxies) ↔ $M_B \lesssim -20.5$
  - ▸ "core-Sersic" (in literature: "core" galaxies) ↔ $M_B > -20.5$



[Graham et al. 2003]

THE CORE-SERSIC MODEL

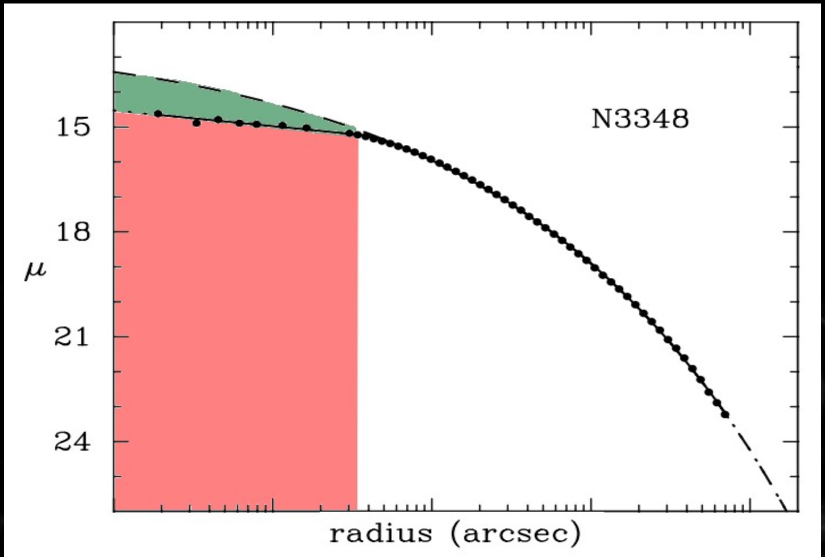
- core-Sersic model → empirical description of core galaxies light profiles
  (Graham et al. 2003; Trujillo et al. 2004)

$$I(r) = I' \left[1 + \left(\frac{r_b}{r}\right)^{\alpha}\right]^{\gamma/\alpha} \exp\left[-b_n \left(\frac{r^{\alpha} + r_b^{\alpha}}{r_e^{\alpha}}\right)^{1/(n\alpha)}\right]$$

- ▸ smooth connection of a Sersic (overall bulge) + power-law (core)
- ▸ transition at break radius r_b
- ▸ far from r_b: *second term* ~ inner power-law, *third term* ~ Sersic
- ▸ α regulates “smoothness” of transition
- ▸ b_n is a normalization factor: can be defined to for r_e to be the effective radius of the Sersic part

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)

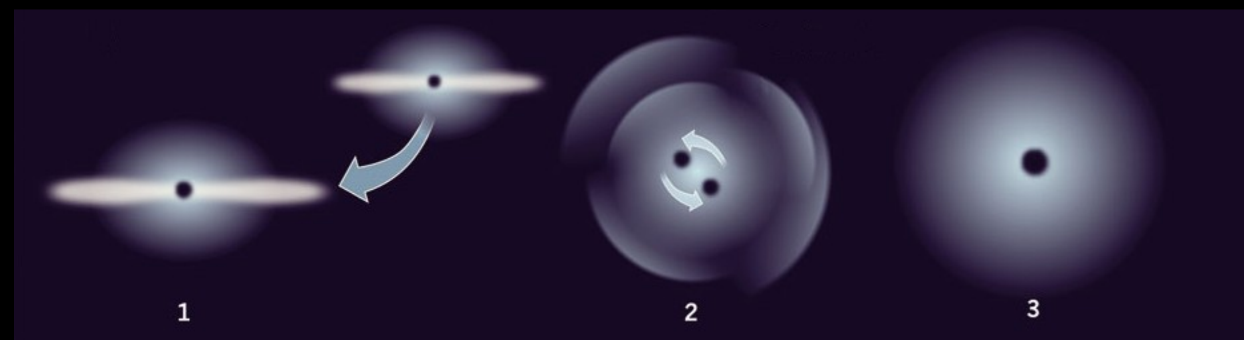


- *NOTE:*
  core mass (M_{core}) $= M(r < r_{core})$
  mass deficit (M_{def}) $= M_{core\text{-}Sersic} - M_{sersic}$

→ WHAT'S THE PHYSICAL CONNECTION WITH THE SMBH?

BINARY SMBH SCOURING SCENARIO

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

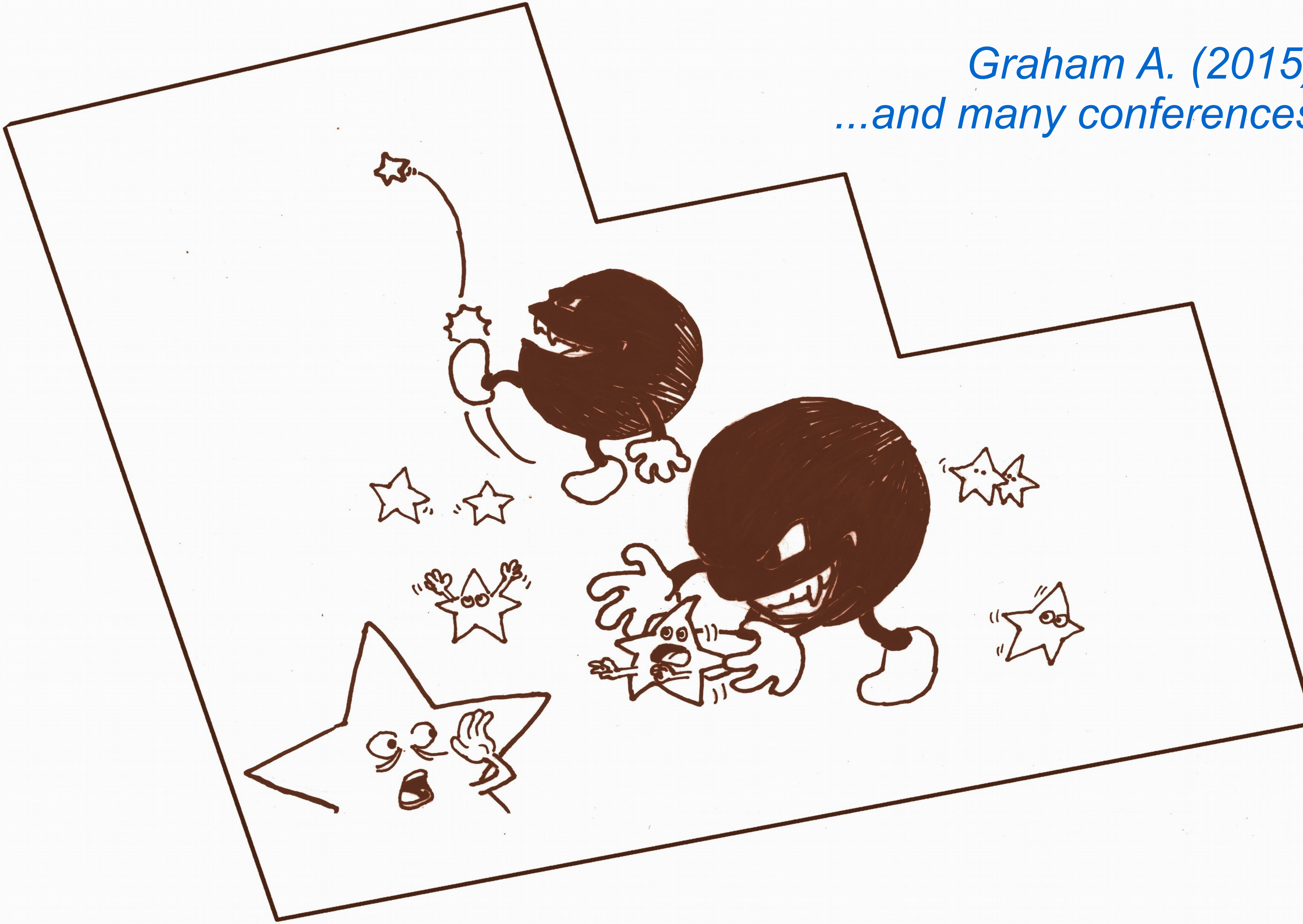


[Adapted from Cappellari 2011]

- 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)*
  - ▸ This month news: first “visual” (VLBI) SMBH binary with separation ~7 pc! *(0402+379, Bansal et al. 2017)*

→ AND IN OPTICAL IT SHOULD LOOK LIKE THIS:

Graham A. (2015)
...and many conferences



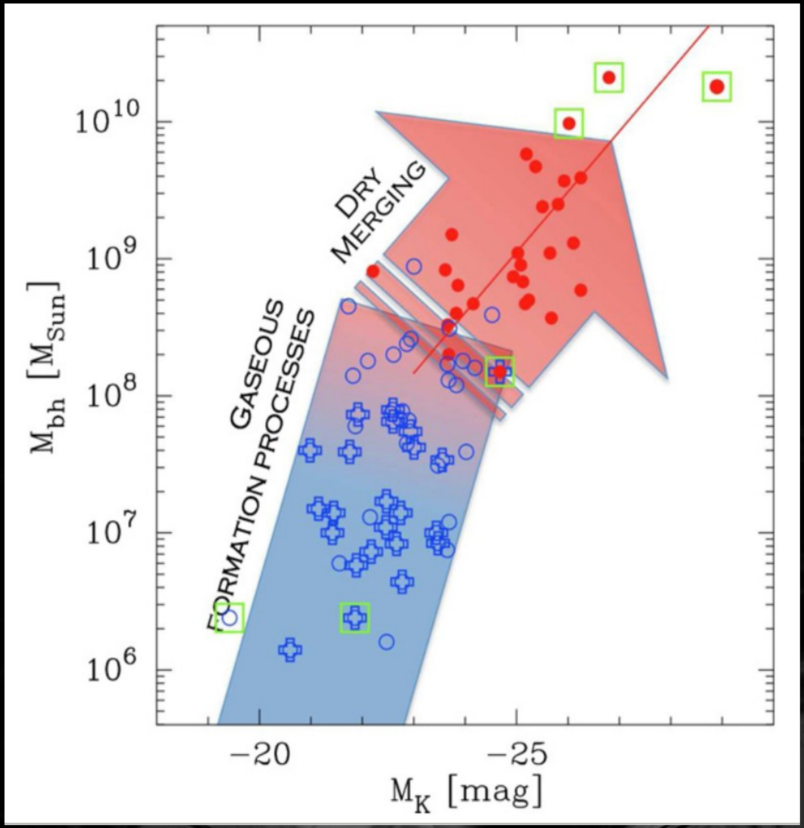
WFPC2 captures a SMBH binary kicking stars out of the bulge

FORMATION SCENARIOS

- 2 different formation channels for Sersic and core-Sersic galaxies:
  (Graham & Scott 2013)
  - Sersic ⟷ wet mergers
  - core-Sersic ⟷ dry mergers

- Transition at M_B ~ -20.5 mag

- NOTE: dry mergers produce flatter relation
  (M_{STARS} and M_{BH} simply sum up)



[Graham & Scott 2013]

WHAT'S AT STAKE

✪ SMBH scouring is a convincing scenario for the galaxy / SMBH co-evolution, *BUT:*

- *caveat :* triaxial potential can refill the core
- scaling relations not very tight
- extremely large cores not explained !
  (> 1kcp; e.g. Hyde et al. 2008; Postman et al. 2012; Lopez-Cruz et al. 2014)

ALTERNATIVES:

✪ multiple (>2) scouring SMBHs
(Kulkarni & Loeb 2012)

✪ recoiling SMBHs
(e.g. Redmount & Rees 1989; Merrit et al. 2004; Boyan-Kolchin et al. 2004; Gualandris 2008)

✪ AGN-driven gas outflows re-arrange the gravitational potential
(Martizzi et al. 2012)

✪ In-falling perturber (captured satellite) excavates the core
(Goerdt et al. 2010)

HOW TO TEST THE CORE FORMATION SCENARIOS ?

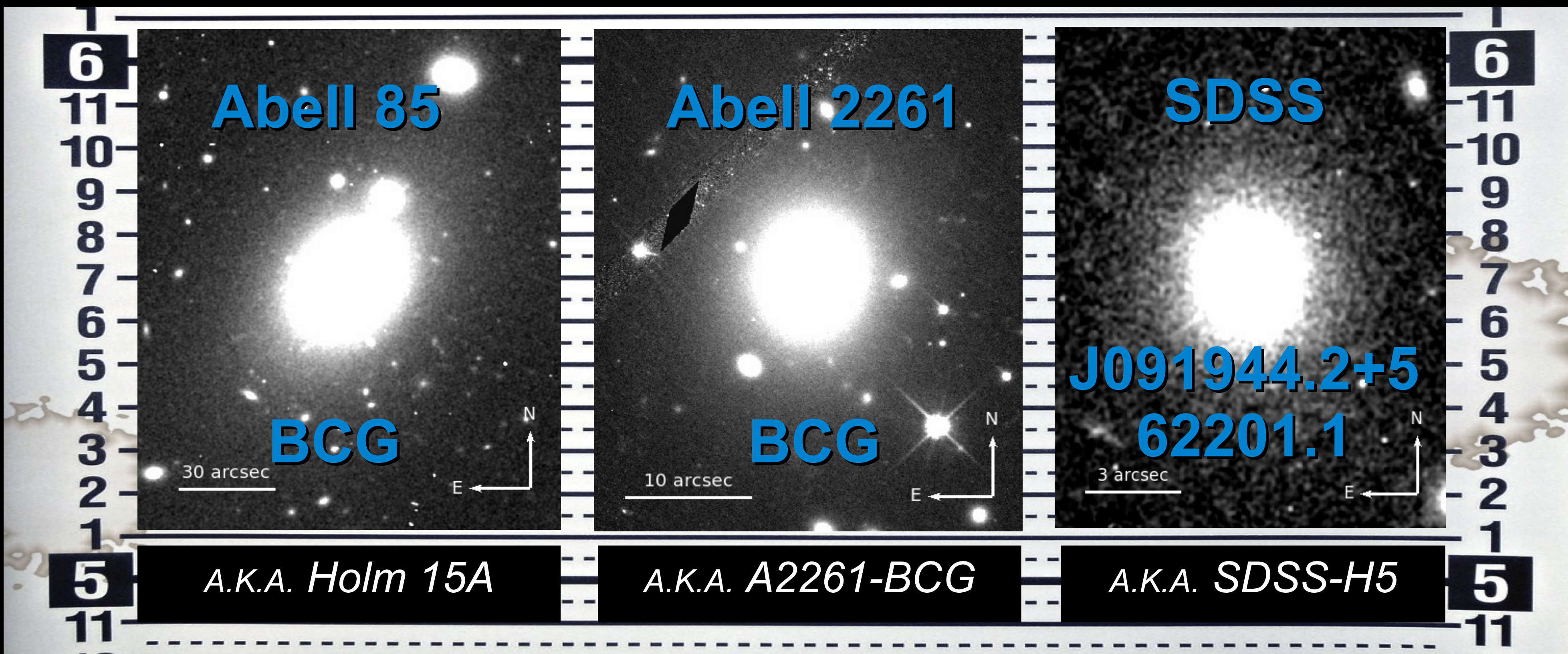
- ✪ Ideal benchmarks: most massive ETGs
  - ▸ "extreme" conditions → expected to host largest cores and SMBHs
  - ▸ size compensate for resolution → cores detectable at large distances

- ✪ We searched in the literature for galaxies claimed to report the largest cores

- ✪ Aim → check if reported cores are compatible with SMBH scouring scenario

→ WE IDENTIFIED 3 CANDIDATES FOR THIS STUDY ...

THE LARGEST KNOWN CORES: THE SUSPECTS



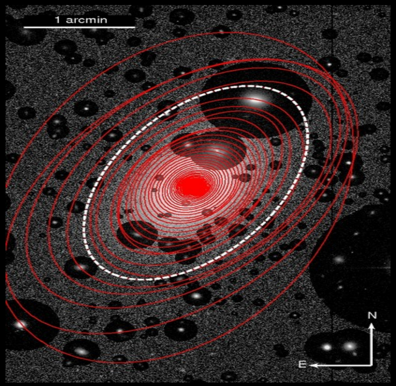
- R_{CORE} ~ 4.57 kpc (Lopez-Cruz et al. 2014)
- R_{CORE} ~ 3.2 kpc (Postman et al. 2012)
- R_{CORE} ~ 1.5 kpc (Hyde et al. 2008)

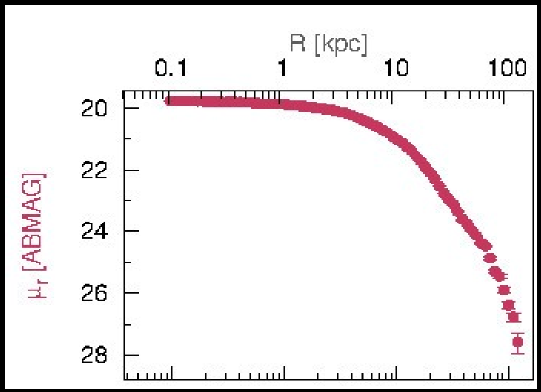
THESE CORES ARE TOO LARGE FOR SMBH SCOURING – ARE THEY REAL?

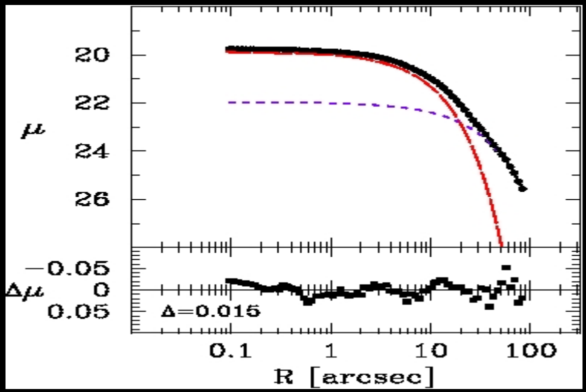
METHOD

✪ Fit the 1D and 2D light profiles of the galaxies exploring core and core-less models

1D FIT







trace isophotes

extract light profile

fit

2D FIT

image

model

residual

METHOD

GALFIT-CORSAIR

2D fitting of core-Sersic model based on GALFIT

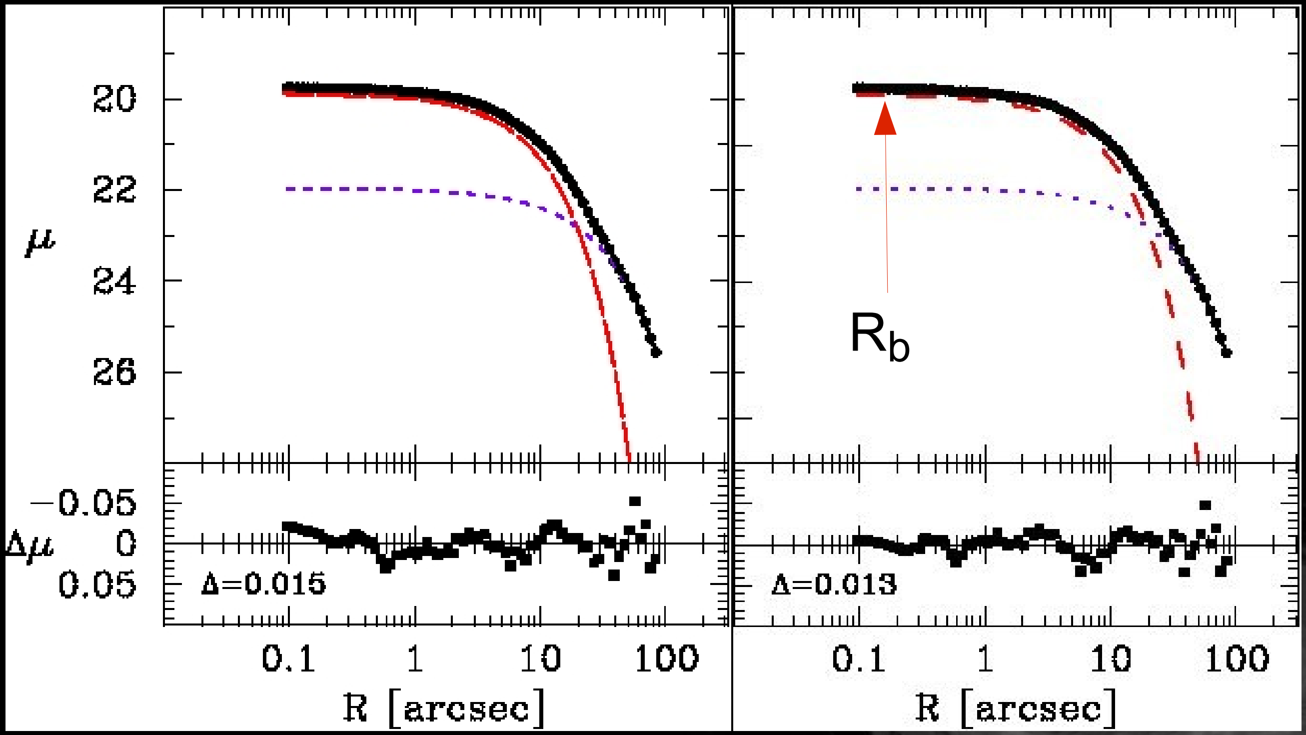
www.astronomy.swin.edu.au/~pbonfini/galfit-corsair

2D FIT

image model residual

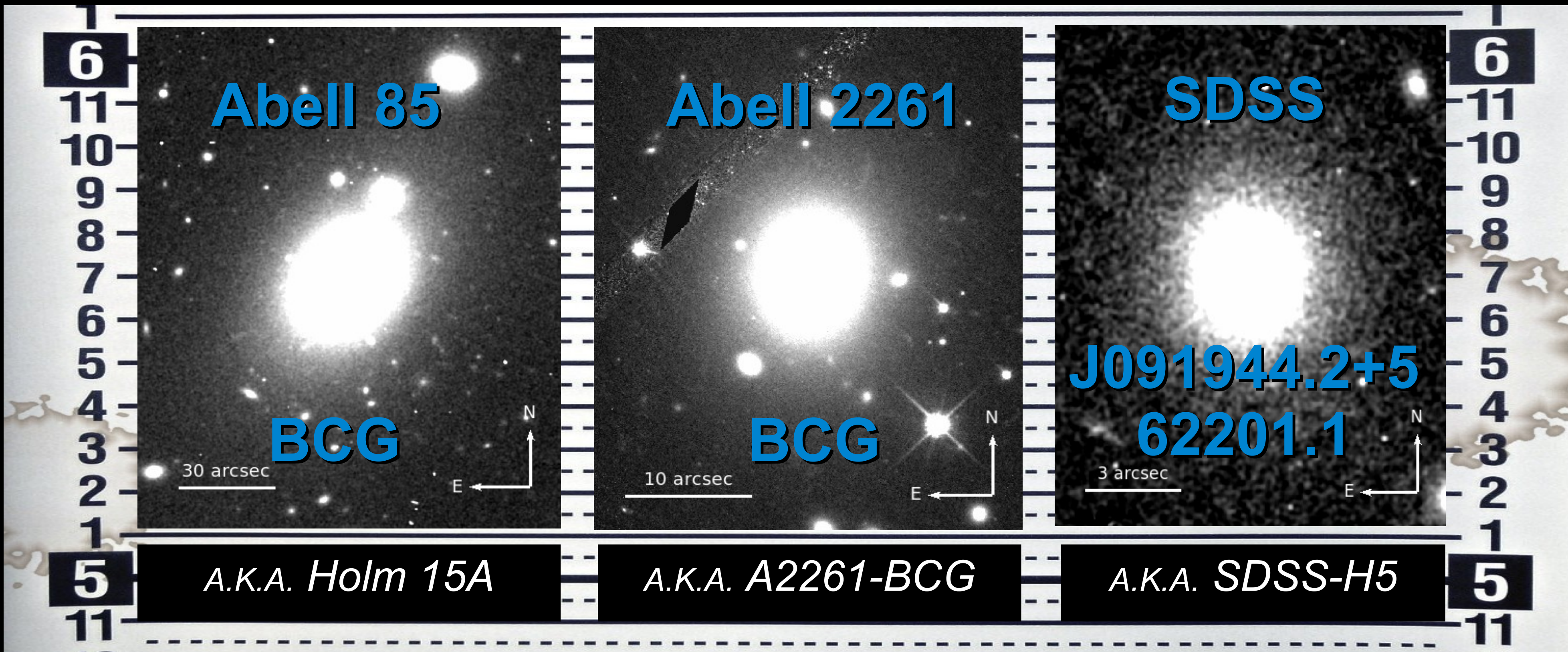
EXAMPLE OF CORE/CORE-LESS ARGUMENT - HOLM 15A

- Fit 1: core-less → Sersic (spheroid) + exponential (halo) — $N_{d.o.f.} = 5$
- Fit 2: core → core-Sersic (spheroid) + exponential (halo) — $N_{d.o.f.} = 7$



▸ core minimized
▸ Sersic part of the fits essentially equivalent → we adopt the simplest

THE LARGEST KNOWN CORES: RESULTS



NO CORE

CORE CONFIRMED!
▸ R_{CORE} ~ 3.2 kpc

CORE CONFIRMED!
▸ R_{CORE} ~ 0.55 kpc

✪ core of SDSS-H5 now in the average, but core of A2261-BCG is exceptional!

→ *HOW CAN WE EXPLAIN A2261-BCG ?*

RECORD CORE

A2261-BCG

- Enormous mass deficit M_{def} ($= M_{core\text{-}Sersic} - M_{sersic}$) = 1.8e11 $M_{\odot}$

▸ $M_{def} / M_{BH} \sim 5 - 6$

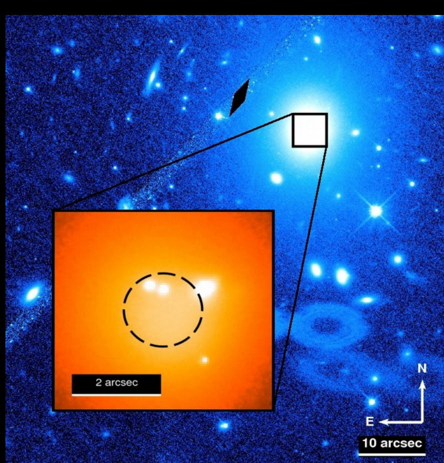
$M_{BH} \sim 3e10\ M_{\odot}$ ← $M_{BH} \longleftrightarrow M_{BULGE}$

(Scott et al. 2013)

Assuming: $M_{def} \sim 0.5\ N\ M_{BH}$

(Merritt 2006)

→ $N \sim 10 – 12$
major dry mergers !



- What then? → We consider the “stalled perturber” scenario:
(Goerdt et al. 2006; Read et al. 2006a; Inoue 2009, 2011)

▸ a captured object spirally in-falls

▸ dynamical friction transfer momentum to stars

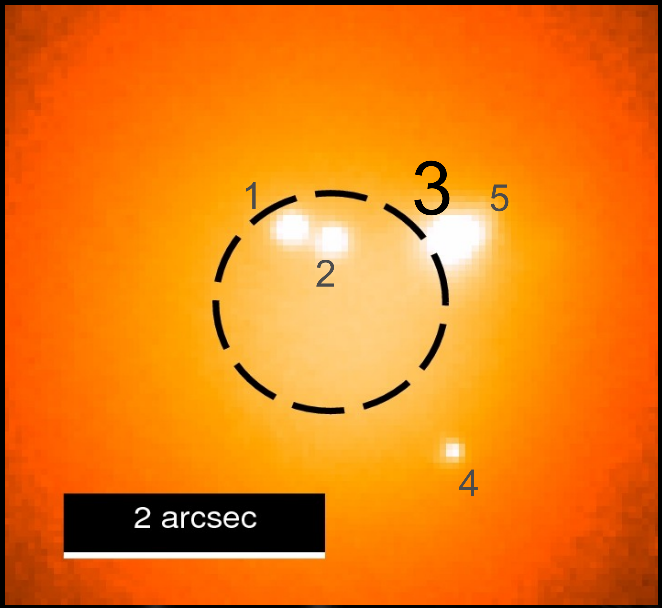
▸ once core is created, perturber orbit stalls

STALLED PERTURBER

✪ Hypothesis from theoretical predictions:
1) Object stalls at core radius → knots 1, 2, 3

2) M_{ENC} ~ Mass perturber
(M_{ENC} = mass enclosed [pre-depletion] in core)
(Goerdt et al. 2006; Read et al. 2006a)

→ knots 3 satisfies these conditions
Possible responsble for core of A2261-BCG!



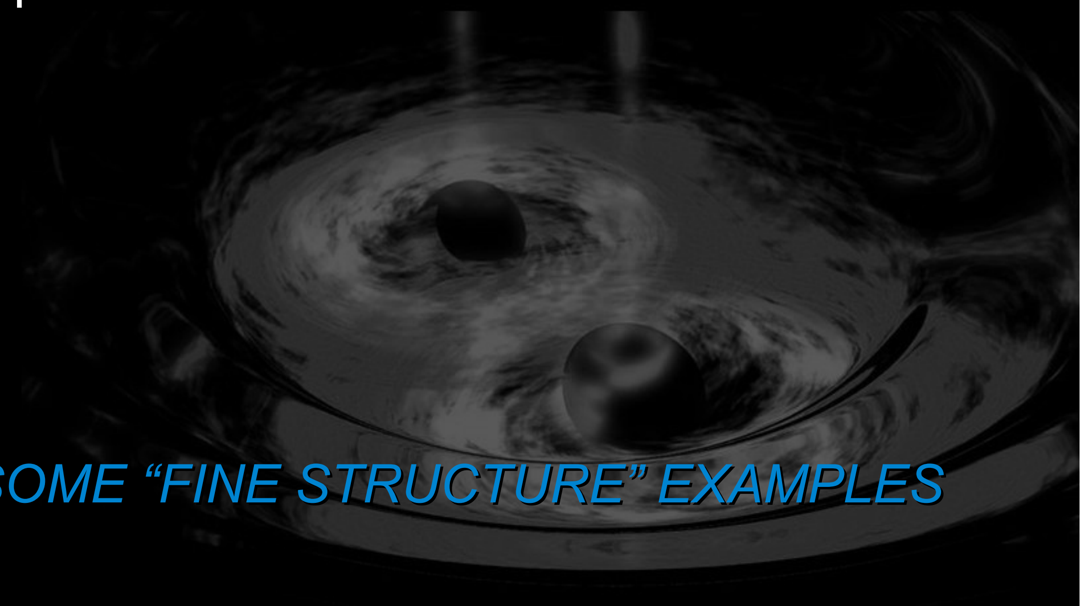
The results presented so far are reported in a series of 3 papers:
Bonfini P. 2014, PASP, 126, 935
Bonfini, Dullo & Graham 2015, ApJ, 807, 136
Bonfini & Graham 2016, ApJ, 829, 81

PART II – CONNECTING CORES AND FINE STRUCTURES

- ✪ The idea is to connect the evolution of cores and that of the ETG morphology *(collaboration with A. Zezes & T. Bitsakis among others)*

- ✪ Following the merger event which created the ETG:
  - ▸ core progressively excavated by SMBH binary
  - ▸ galaxy potential relaxes and interaction features fade away

- ✪ To do so, we need to measure, in a sample of core ETGs:
  - ▸ depleted mass
  - ▸ significance of fine structure

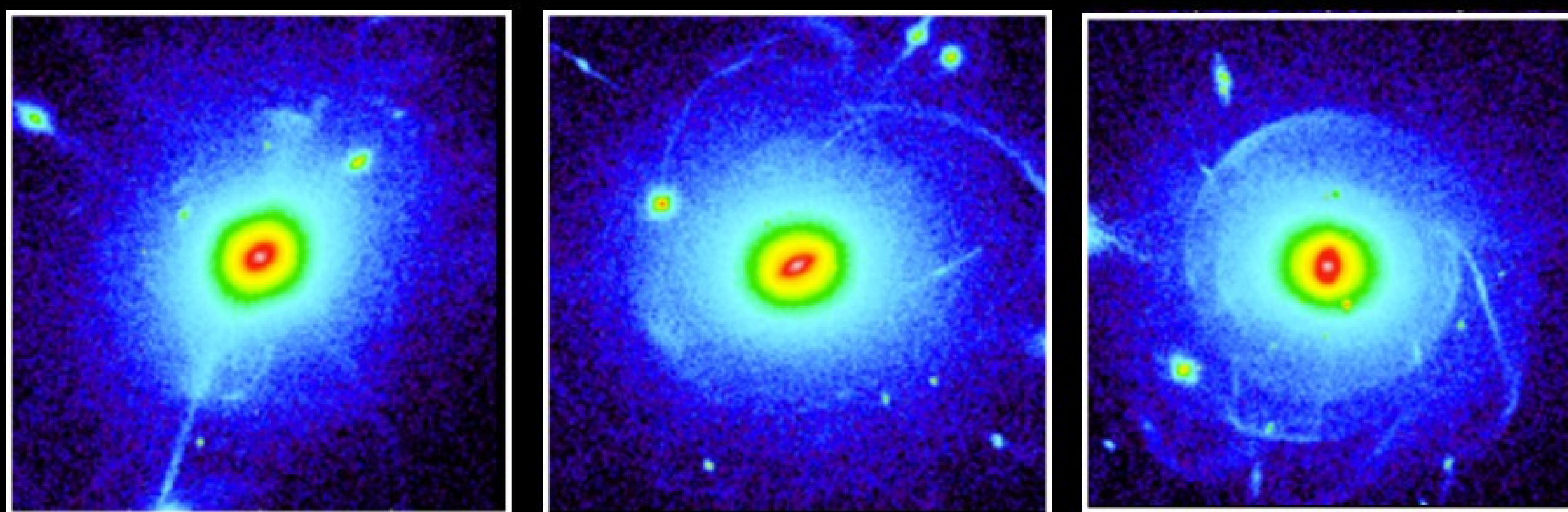


→ LET'S SEE SOME "FINE STRUCTURE" EXAMPLES

FINE STRUCTURES IN ETGs

- Fine structures include diverse features: shells, ripples, plumes, rings, streams, ...

TAILS **STREAMS** **SHELLS**



[Credit: MATLAS collaboration]

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

- Shells are most probable connected with dry mergers → ideal for this project

TIMESCALE COMPARISON

- On average:

  - core formation → ~1 Gyr
    (Khan et al. 2012a, b, Colpi 2014)

  - fine structures → ~1-2 Gyr
    (Hibbard & Mihos 1995; Feldmann et al. 2008; Johnston et al. 2001, 2008; Michel-Dansac et al. 2010; Peirani et al. 2010; Torrey et al. 2015; Duc 2016; Paudel et al. 20107)

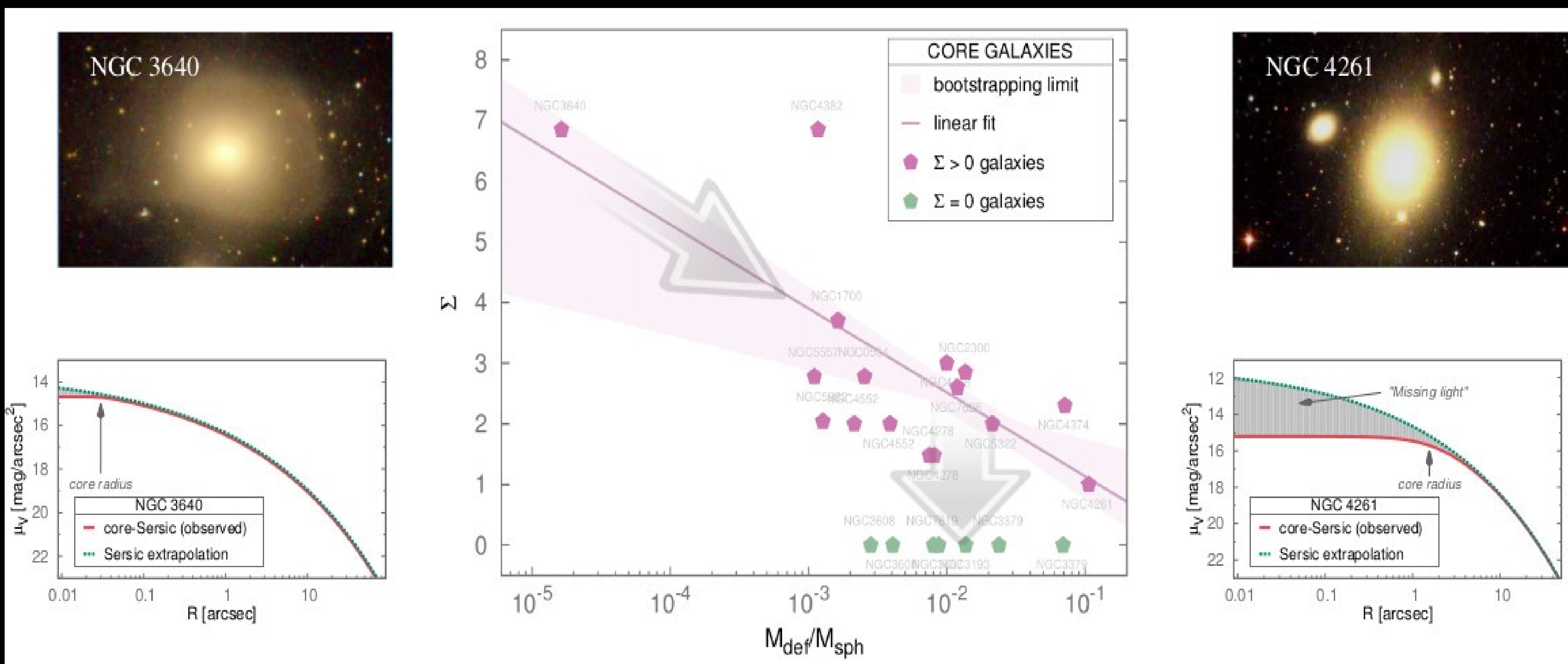
→ TIMESCALES ARE COMPARABLE !

- The 2 features must co-exist at least within first Gyr (after 1 Gyr, fine structure evolves independently)

→ WHAT'S THE EVOLUTIONARY TRACK?

EVOLUTIONARY TRACK

- Σ (Schweizer et al. 1990) → visual indicator of fine structure
- Depleted masses → Richings et al. (2011) and Dullo & Graham (2014)



Bonfini, Bitsakis, Zezas et al., submitted to MNRAS

SUMMARY

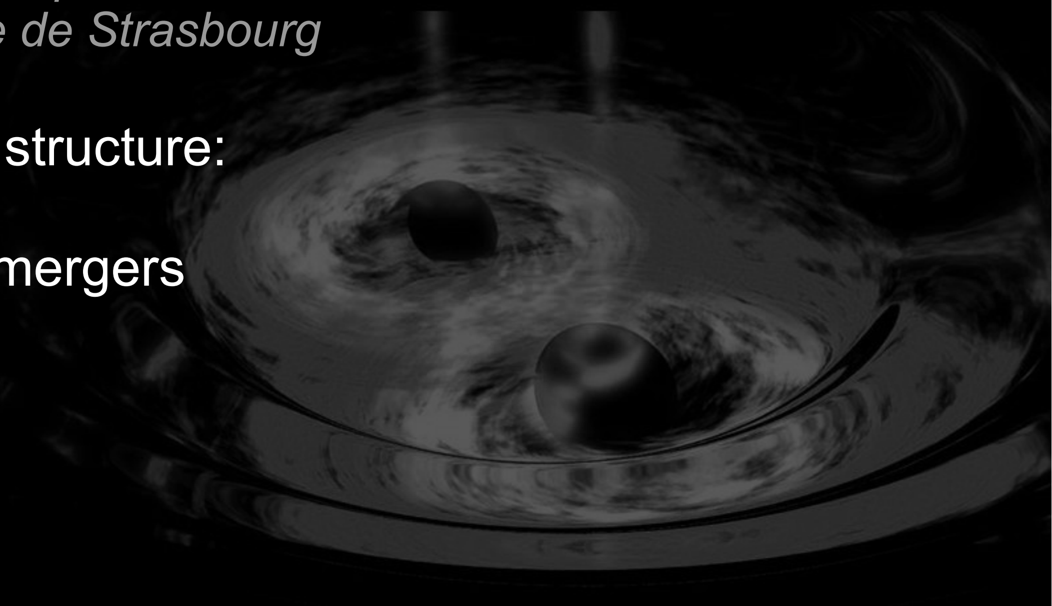
- ✪ Holm 15A → Flat inner profiles can mmick large cores

- ✪ A2261-BCG → Largest core known (?) excavated by infalling satellite

- ✪ Fine structure / core

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

  ▸ Define a more robust estimator for fine structure:
  - independent of depth
  - able to distinguish between dry/wet mergers
  A. Zezas – University of Crete
  T. Bitsakis – IRyA



THANK YOU

Gratzy !