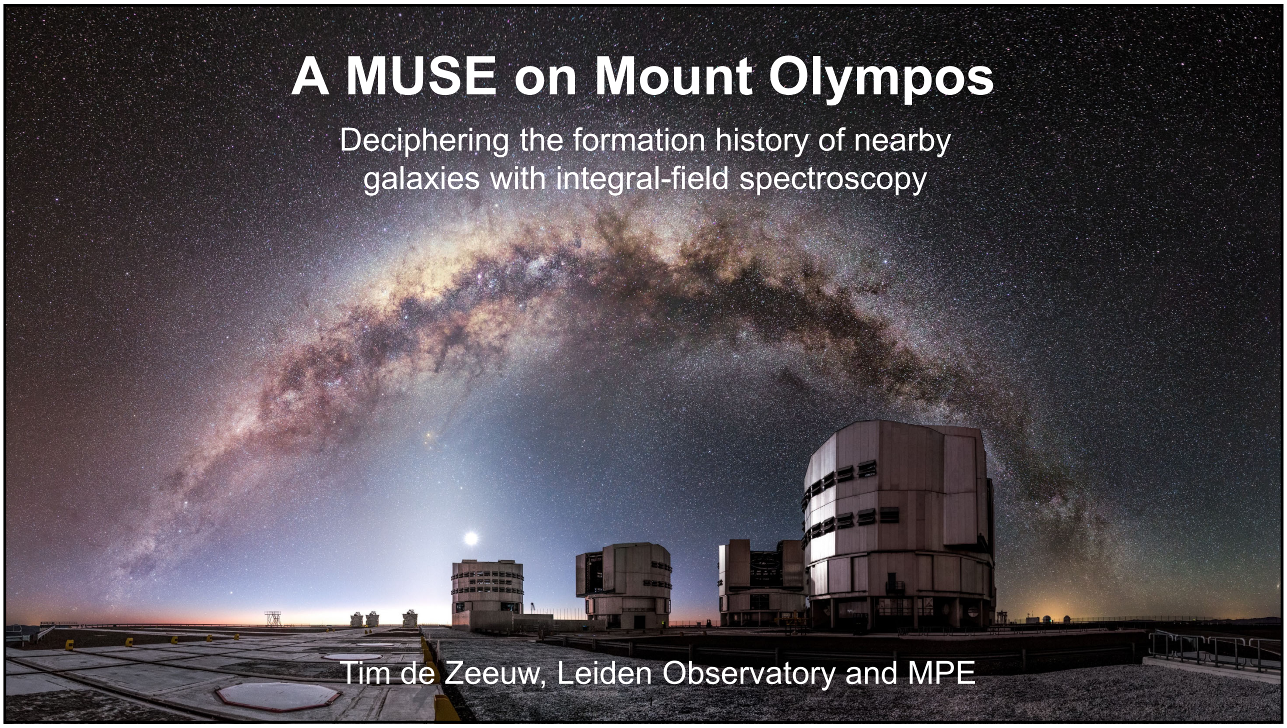


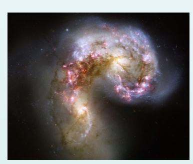
A MUSE on Mount Olympos

Deciphering the formation history of nearby galaxies with integral-field spectroscopy

Tim de Zeeuw, Leiden Observatory and MPE

Galaxy Formation and Evolution

- Galaxies form by hierarchical accretion/merging
  - Matter clumps through gravitation
  - Primordial gas starts forming first stars
  - Stars produce heavier elements (‘metals’)
  - Subsequent generations of stars contain more metals
  - Massive galaxies form by assembly of smaller units
- Galaxy encounters still occur
  - Deformation, stripping, merging
  - Galaxies continue to evolve
- Central black hole also influences evolution

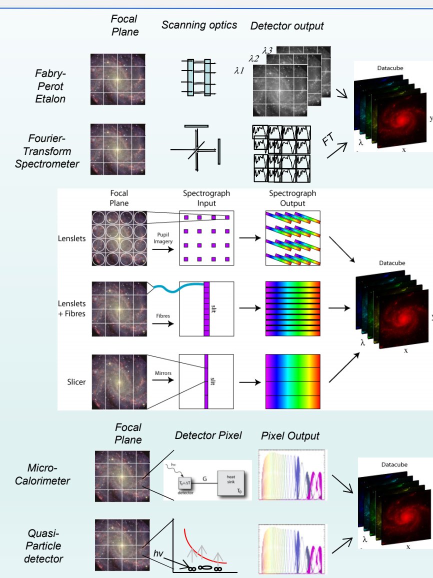


Observational Approaches

- Study very distant galaxies
  - Observe evolution (far away = long ago)
  - Objects faint and small: little information
- Study nearby galaxies
  - Light is not resolved in individual stars
  - Objects large & bright: structure accessible
  - Infer evolution through archaeology
  - Fossil record is cleanest in early-type galaxies
- Study resolved stellar populations
  - Ages, metallicities and motions of stars
  - Archaeology of Milky Way and its nearest neighbours

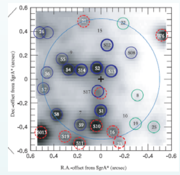
Spectroscopy over an Area

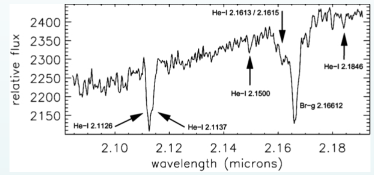
- Three techniques
  - Scanning spectrometer
    - Fabry-Perot
    - Fourier Transform
  - Integral-field spectrograph
    - Lenslets
    - Lenslets + fibers
    - Image slicer (most efficient)
  - Energy-resolving detector
    - Micro-calorimeter
    - Quasi particle detector
- Eisenhauer & Raab
  - 2015 ARAA 53, 155

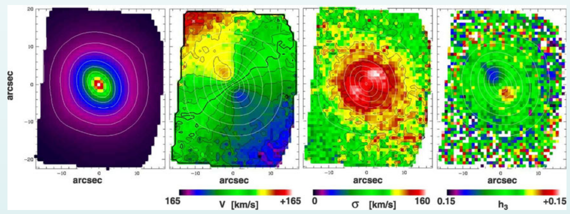


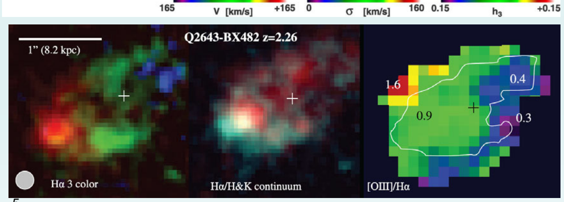
Early Examples

- Galactic Centre
  - Stellar radial velocities
  - SINFONI@VLT (8.2m)
    - slicer
- E/S0 galaxies
  - Absorption-line kinematics
  - SAURON@WHT (4.2m)
    - FOV 33"-41", 1"x1" pixels
    - 4810-5350Å, R~1500
    - lenslets
- Galaxies at z~2
  - Emission line kinematics
  - SINFONI & KMOS@VLT
    - slicer/multi-object









The SAURON and ATLAS^{3D} projects

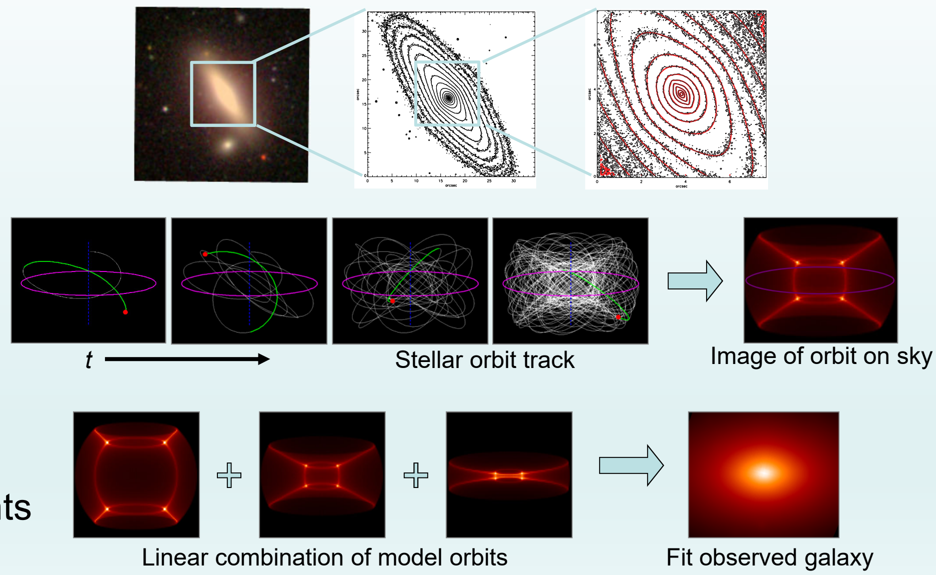
- SAURON was built for specific science project
  - Census of 72 representative nearby E & S0 galaxies and Sa bulges
  - PI's Bacon, Davies, de Zeeuw
- Follow-up: ATLAS^{3D}
  - Same instrument, for a volume-limited sample of 260 E/S0's
  - Much auxiliary data, including neutral and molecular gas
  - PI's Cappellari, Emsellem, Krajnovic, McDermid
- Selected results
  - Detailed dynamical models & accurate M/L's
  - New galaxy classification scheme based on kinematics
  - Recent star formation in ~20% of early-type galaxies
  - Slope of Initial Mass Function varies with galaxy mass

Schwarzschild's Orbit Superposition Method

Mass model

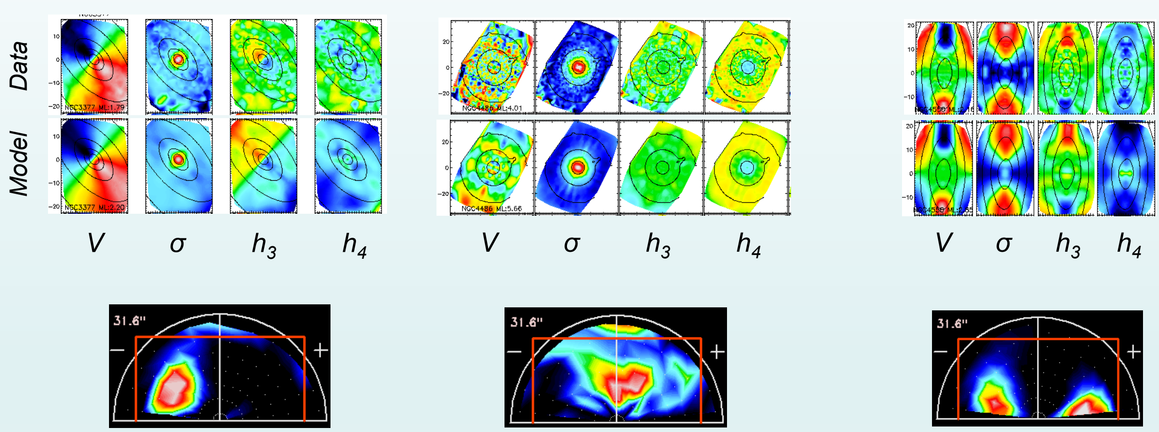
Orbit integration

Fit data constraints



Dynamical Decomposition

NGC 3377 | M87 | NGC 4550



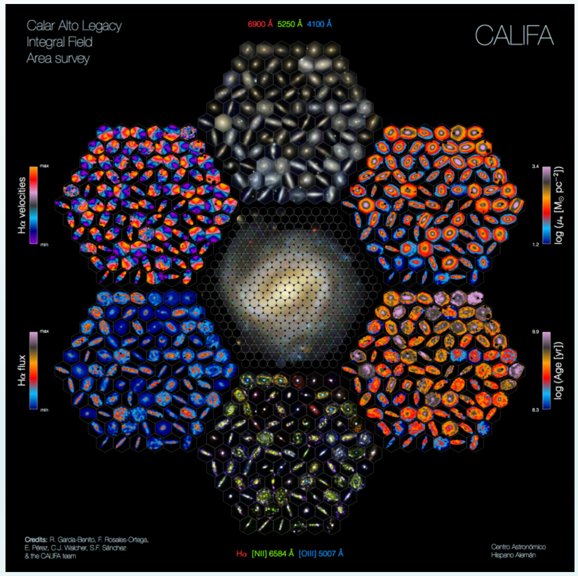
Normal rotation

No mean rotation

Counter-rotating discs with different scale-heights

Post SAURON (1)

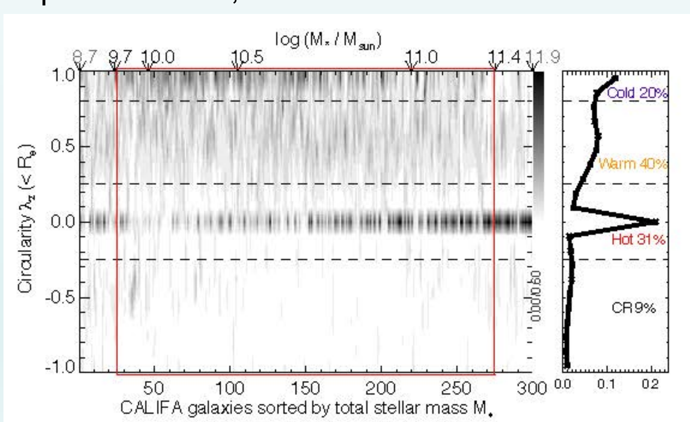
- CALIFA@Calar Alto (3.5m)
  - PMAS/PPAK
  - 2.7" fibers
  - FOV 64"x74" (60%)
  - R~850 or 1650
  - 3700-7000Å
  - 600 galaxies, all Hubble types
  - PI: S.F. Sanchez
- Galaxy Survey (2010-2016)
  - Much analysis done
  - Including dynamical models



Dynamical Decomposition

- Orbit superposition models for 250 CALIFA galaxies
  - Range of factor 50 in mass, both early- and late-types
  - Three main components: cold, warm and hot

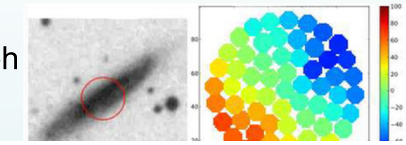
Orbital circularity
$\lambda_z = L_z / L_{z,c}(r)$

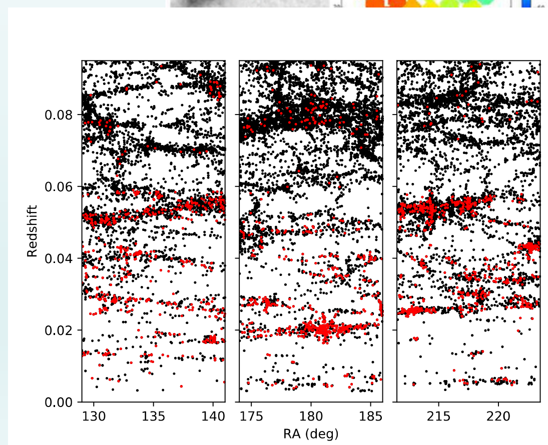


Zhu, van de Ven et al. 2017, 2018

Post SAURON (2)

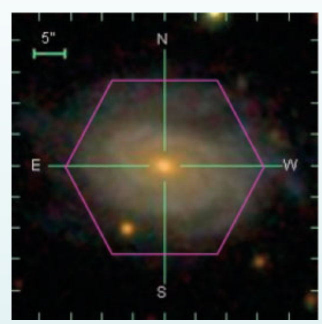
- SAMI@Anglo-Australian Telecope (3.9m)
  - Sydney-AAO Multi-object Integral field spectrograph
    - 13 hexabundles placed in 1º diameter FoV
    - Coupled to AAOmega spectrograph on AAT
  - Hexabundle
    - 61 1.6" fibers, fill factor 75%
    - FoV 15″ diameter
    - Blue: R~1800, 3700-5800Å
    - Red: R~ 4250, 6300-7400Å
- Galaxy Survey (2013-2021)
  - 3068 galaxies
  - Properties as function of environment
  - PI: S. Croom

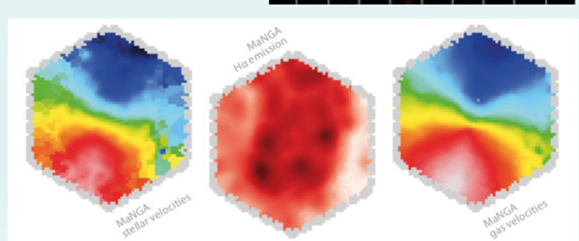


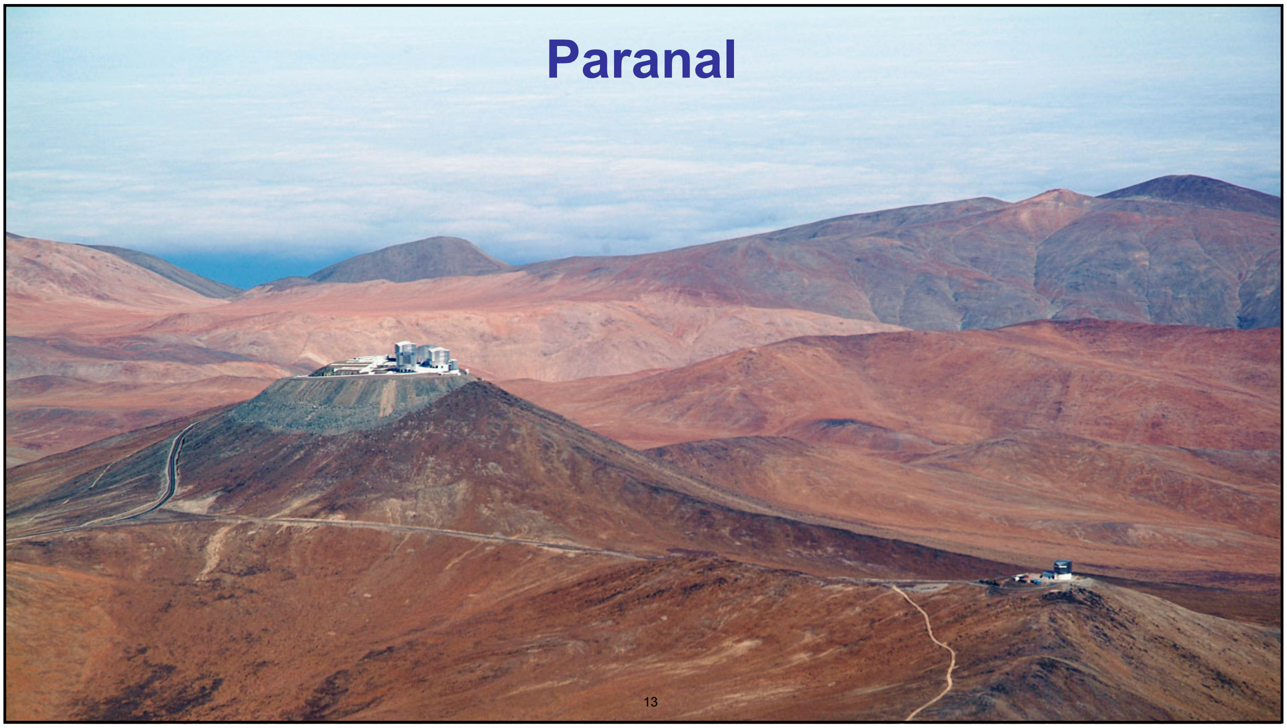


Post SAURON (3)

- MANGA@Apache Point Observatory (2.5m)
  - 17 fiber bundles per 7□ plate
  - Total number of fibres: 1423
  - FOV 12"-32", 2" fibers
  - R~2000, 3600-9800Å
- Galaxy Survey (2014-2020)
  - 10000 galaxies in 2700□, z~0.03
  - ~3 hour exposures reach 1.5-2.5 R_e
  - P.I. K. Bundy

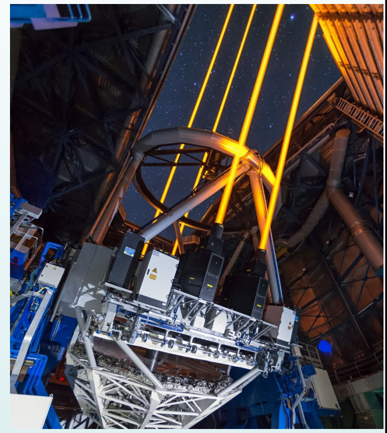




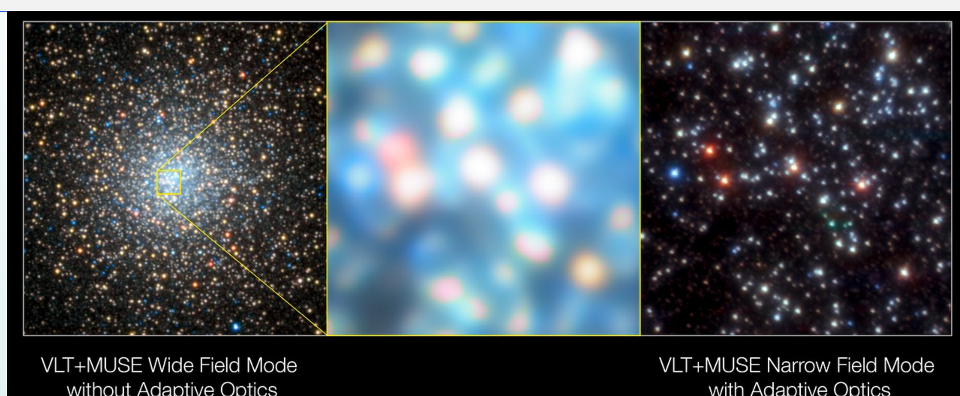

Paranal
13

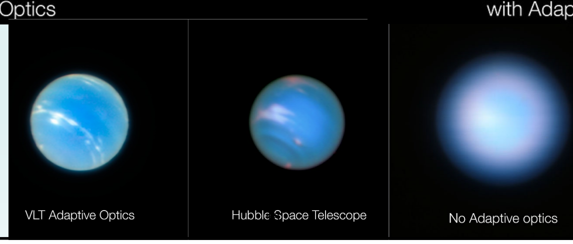
A MUSE for the VLT

- Multi-Unit Spectrographic Explorer (PI: Bacon)
  - WFM: 60"x60" with 0.2"x0.2" elements
  - NFM: 7"x7" with 0.025"x0.025" elements
  - 90000 spectra, 4650-9300 Å, with R~1500-3000
  - Image slicer ⇒ 35% throughput, including UT4
  - www.eso.org/public/videos/ann17025a/
- Coupled to Adaptive Optics Facility with 4LGSF
  - WFM: GLAO improves FWHM by up to factor of two
  - NFM: 10% Strehl @ 6500 Å; 25% Strehl @ 8500 Å

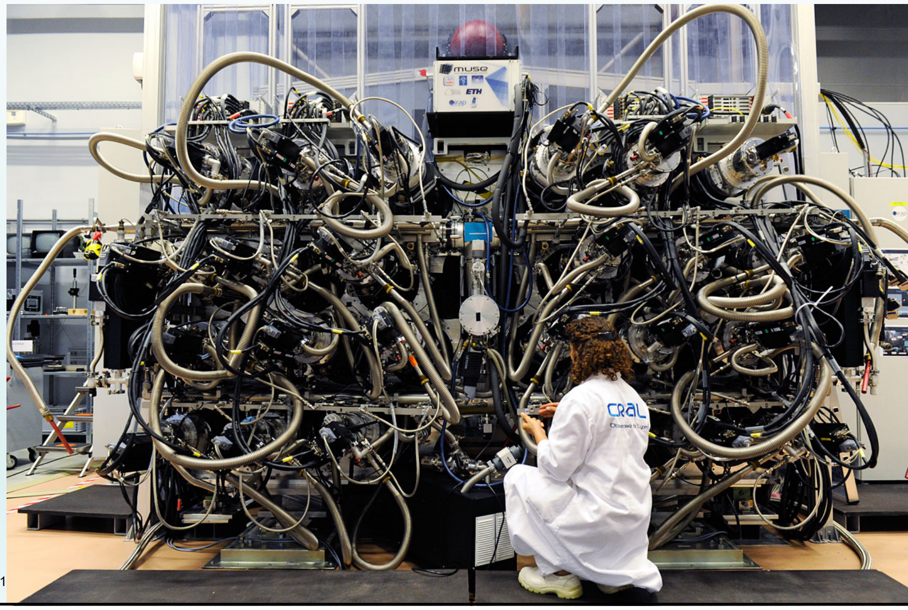


MUSE





Pre-integration Lyon, Sep 2013



University of Crete, 21

MUSE Arrives on Paranal Oct 2013

Re-integration Oct-Dec 2013

University of Cr

From Basecamp to UT4: 18 Jan 2014

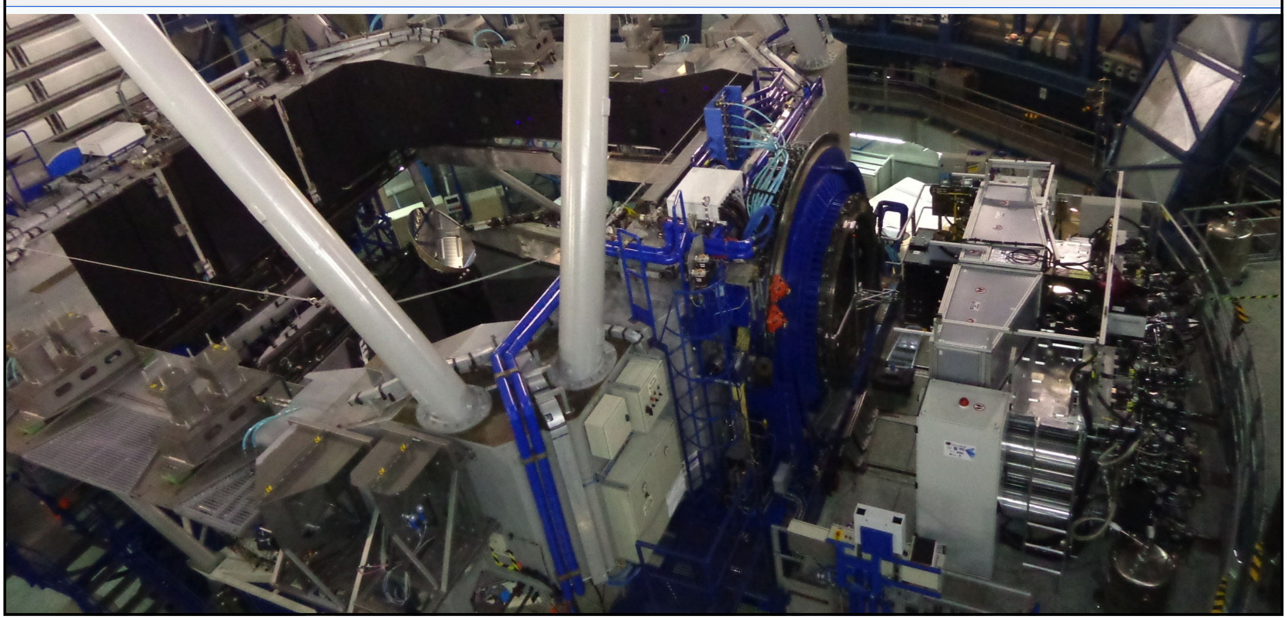
University of Crete, 21

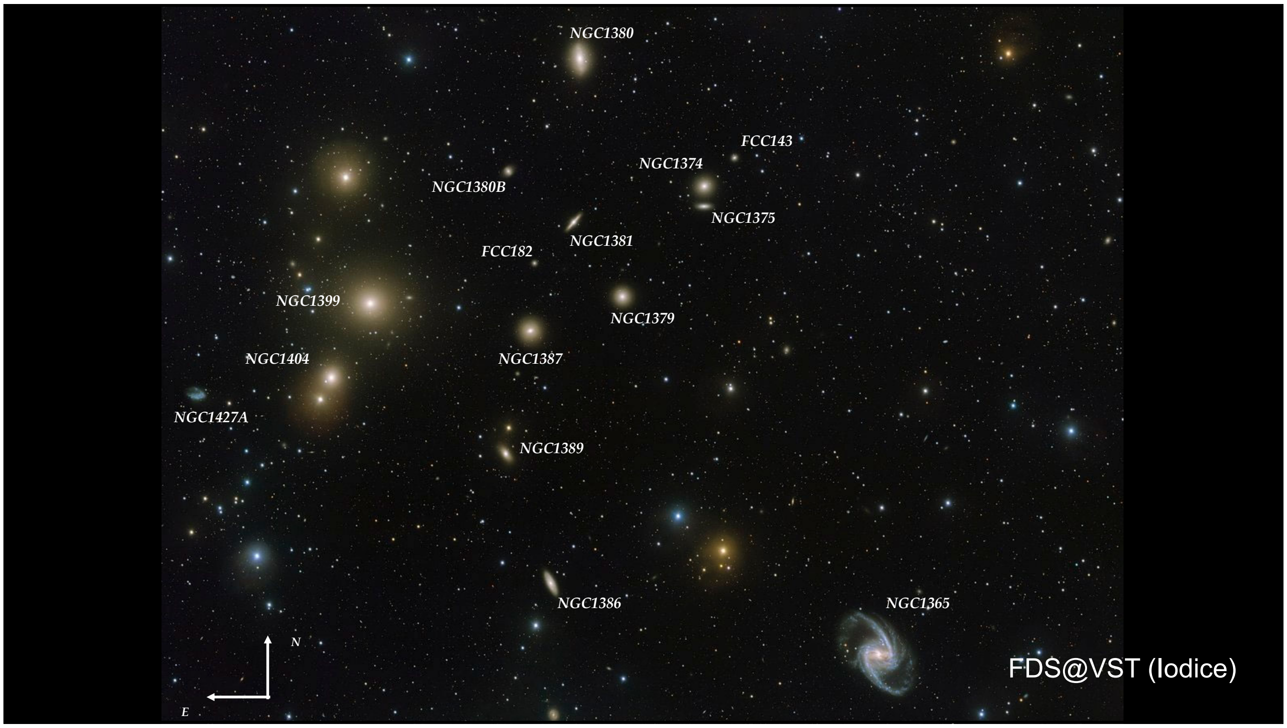
Moment of Maximum Terror

University of Crete, 21 October 2021

21

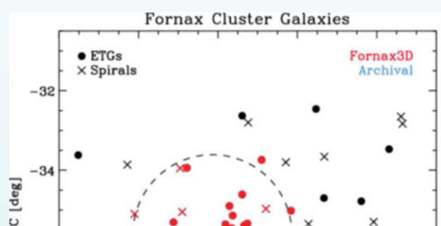
MUSE on UT4





Fornax3D

- Magnitude-limited study of galaxies inside the virial radius of Fornax
  - 33 galaxies ($m_B \leq 15$)
  - 1-3 MUSE pointings per galaxy (~100 hrs)
  - S/N=25 @ m_B=25 (binned), reaching 2-3 R_e
- Goals (Sarzi et al. 2018, A&A, 616, 121)
  - Internal orbital structure of stellar components
  - Stellar populations and IMF, into outskirts
  - Properties of the ISM, GCs, NSCs, PNe
  - Influence of environment/interactions
- Team
  - Sarzi, Iodice, Coccato, Corsini, Falcon-Barroso, Fahrion, Gadotti, Lyubenova, Martin-Navarro, McDermid, Pinna, Poci, van de Ven, de Zeeuw, Zhu

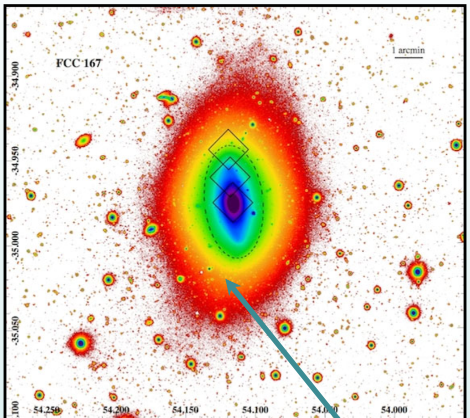


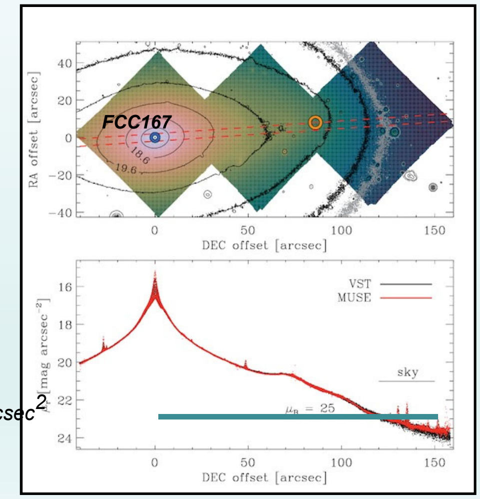
University of Crete, 21 October 2021

24

Survey Design

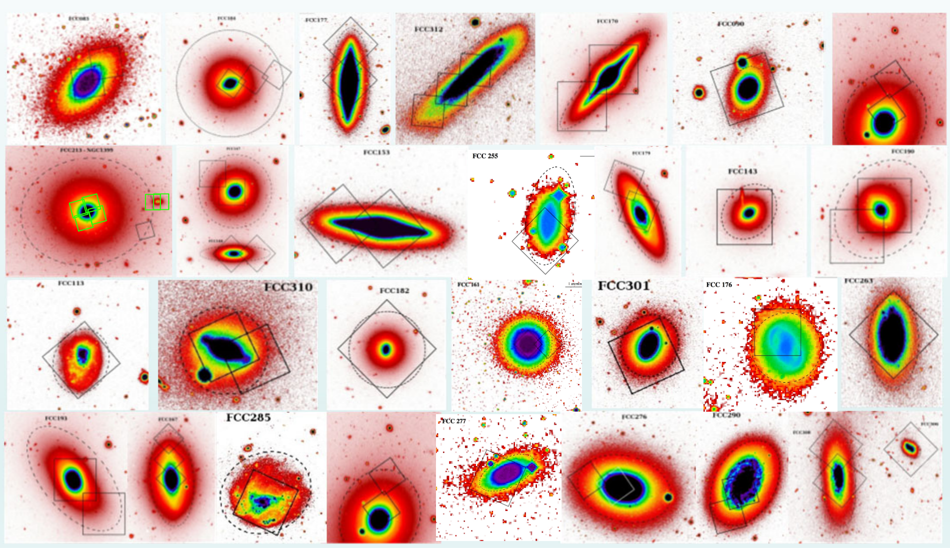
1hr *1hr* *1.5hr*





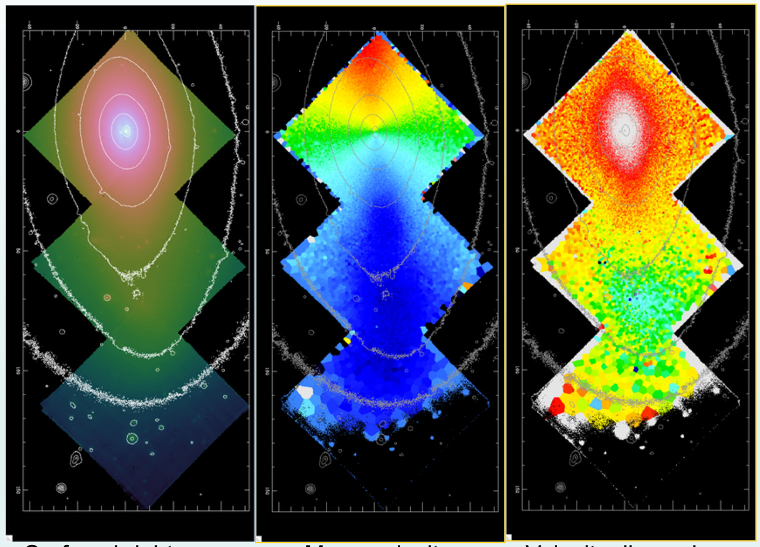
μ_B=25 mag/arcsec^2

Fornax3D Pointings



Imaging: Fornax Deep Survey with VST (Iodice)

FCC167: Stellar Kinematics



Surface brightness Mean velocity Velocity dispersion

Many Projects

- Structure and stellar populations in edge-on objects (Pinna)
- Properties of the GC systems and the role of NSCs (Fahrion)
- Census of Planetary Nebulae (Sarzi, Galàn de Anta, Spriggs)
- Properties of gas and dust, relation with CO (AlFoSc+F3D, Zabel)
- IMF and stellar populations in outskirts (Martín-Navarro)
- Metallicity gradients in late-type galaxies (Lara-Lopez)
- Construction of dynamical models which include the stellar population properties (Poci, McDermid / Ding, Zhu, van de Ven)
- Tracing the assembly history of the cluster using the kinematics structure and stellar population properties of the galaxies (Iodice)

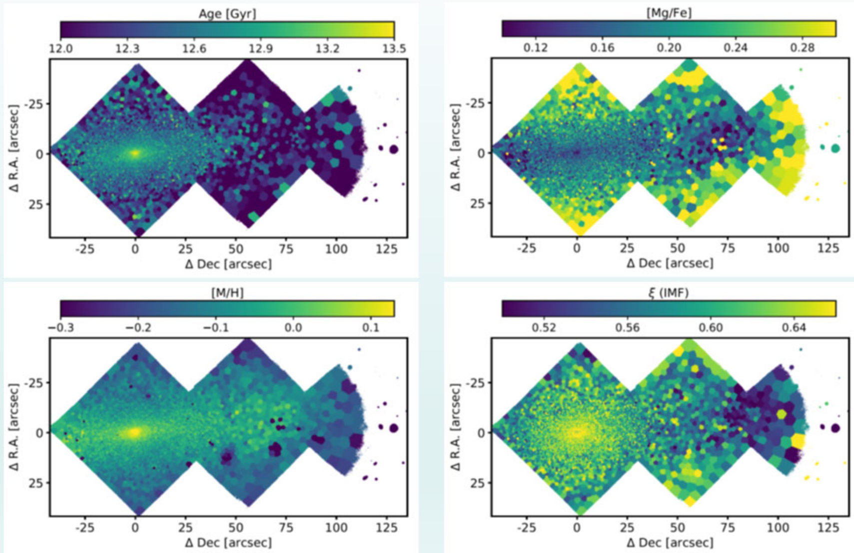
FCC 167: Stellar Populations

Age

Mg/Fe

M/H

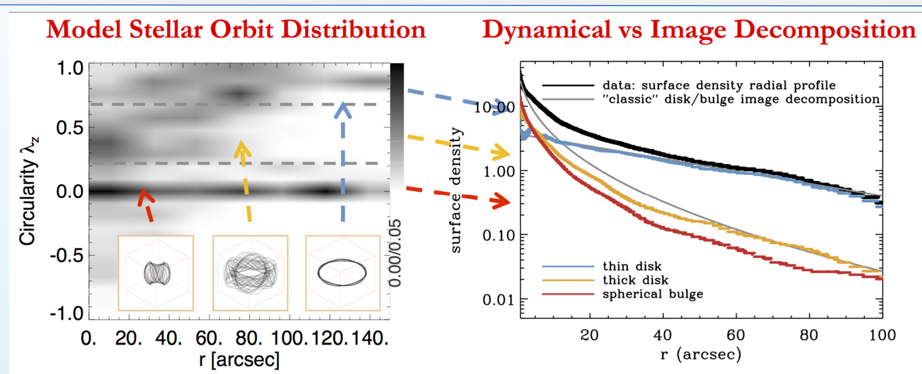
ξ



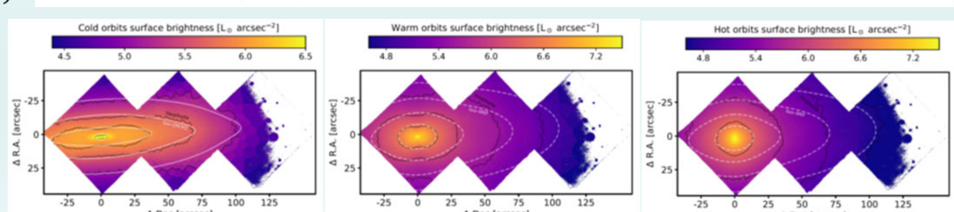
Related to slope of IMF
Larger $\xi \Rightarrow$ more low-mass stars

Martín-Navarro et al, 2019, A&A 626, 124 & astro-ph/2107.14243

FCC 167: Dynamical Decomposition

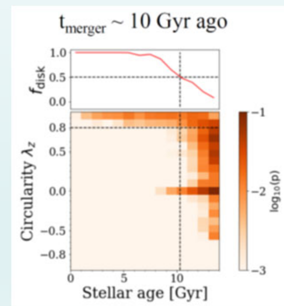


Label orbits by circularity parameter $\lambda_z = L_z / L_{z,c}(r)$



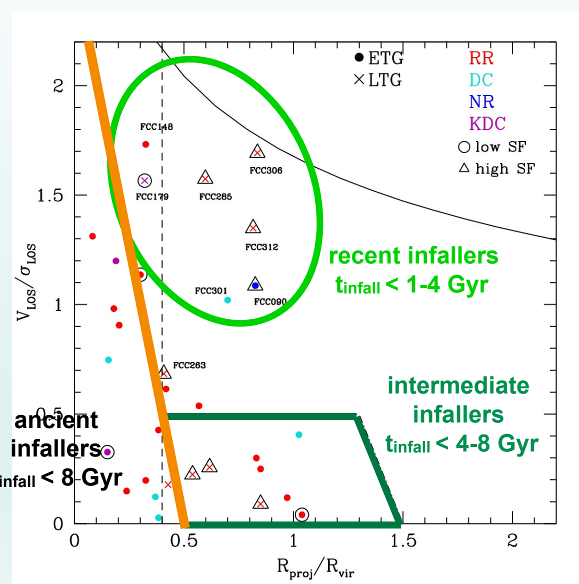
Assembly Histories of E/S0 Galaxies

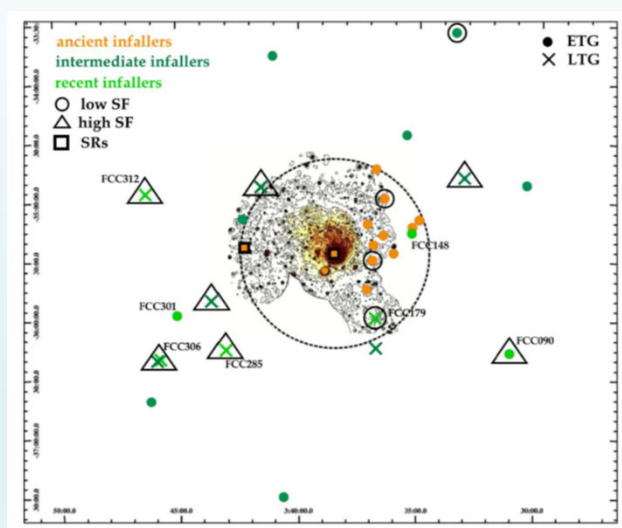
- Two independent approaches to model kinematics and stellar population properties together, ‘coloring the orbits’
- Age vs stellar velocity dispersion relation for three edge-on objects
  - Poci et al. 2021 A&A 647, 125
- Orbit superposition model for FCC 167
  - Disc undisturbed since ~10 Gyr, range of metallicities
  - Warm material extends out to ~2 R_e: inner stellar halo
  - Merger that formed it must have occurred 10 Gyr ago
  - Comparison with simulations: 3.7 x 10^{10} $M_\odot$ accreted
  - Similar to ancient mergers observed in MW and M31
- Modeling of 18 more galaxies ongoing



Zhu et al. 2021, submitted

Infall History and Environment





Rhee et al. 2017; Iodice et al 2019 A&A 627, 136

Conclusions

- Integral field spectroscopy of nearby galaxies
  - Multi-object study of scaling relations and role of environment in large samples
  - Superior sensitivity, spectral range and angular resolution of MUSE to dissect nearby galaxies with dynamical models including stellar population properties
  - This allows deriving the assembly history of individual objects and connect these with the evolution of the cluster
- Links the z~2 emission-line work done by a number of groups and the *in-situ* studies of the Milky Way and its nearest neighbours
  - This is only one of many areas where MUSE is providing major steps forward