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 **ATLAS3D** 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: ATLAS3D**
  - 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

Linear combination of model orbits

Stellar orbit track

Image of orbit on sky

Fit observed galaxy

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
\[ \lambda_z = \frac{L_z}{L_{z,c}(r)} \]

Zhu, van de Ven et al. 2017, 2018
Post SAURON (2)

- SAMI@Anglo-Australian Telescope (3.9m)
  - Sydney-AAO Multi-object Integral field spectrograph
    - 13 hexabundles placed in 1° 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
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/](http://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

MUSE Arrives on Paranal Oct 2013
Re-integration Oct-Dec 2013

From Basecamp to UT4: 18 Jan 2014
Moment of Maximum Terror

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 $R_e$

  - 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
Survey Design

1hr 1hr 1.5hr

μB=25 mag/arcsec²

FCC167

Fornax3D Pointings

Imaging: Fornax Deep Survey with VST (Iodice)
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

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


FCC 167: Dynamical Decomposition

Model Stellar Orbit Distribution

Dynamical vs Image Decomposition

Label orbits by circularity parameter $\chi_E = L_E / L_{PE}(r)$

University of Crete, 21 October 2021
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\_\text{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

Infall History and Environment

- Recent infallers: t_{\text{infall}} < 1-4 Gyr
- Intermediate infallers: t_{\text{infall}} < 4-8 Gyr
- Ancient infallers: t_{\text{infall}} < 8 Gyr

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 \textit{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