CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

On the nature of cluster UDGs

Internal dynamics and stellar content of ultra-diffuse galaxies in the Coma cluster prove their evolutionary link with dE/dS0 galaxies

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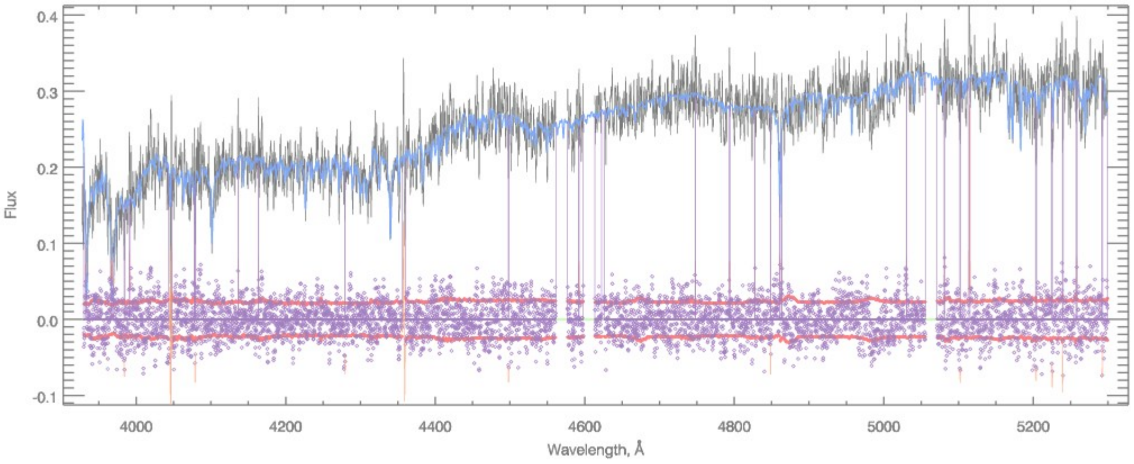
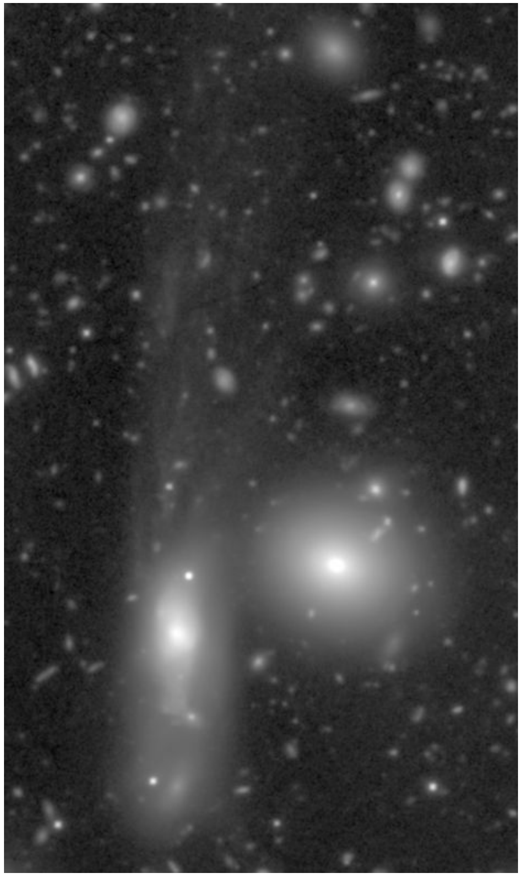


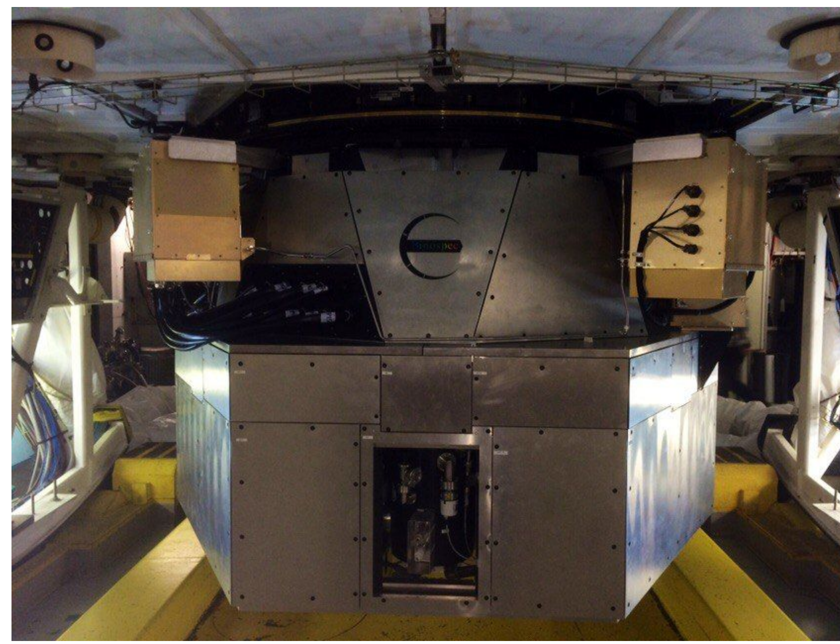


Diversity of the Local Universe – SAO RAS – 2019/Oct/2

MMT: a 6.5-m telescope in Arizona

Binospec @ MMT: overview

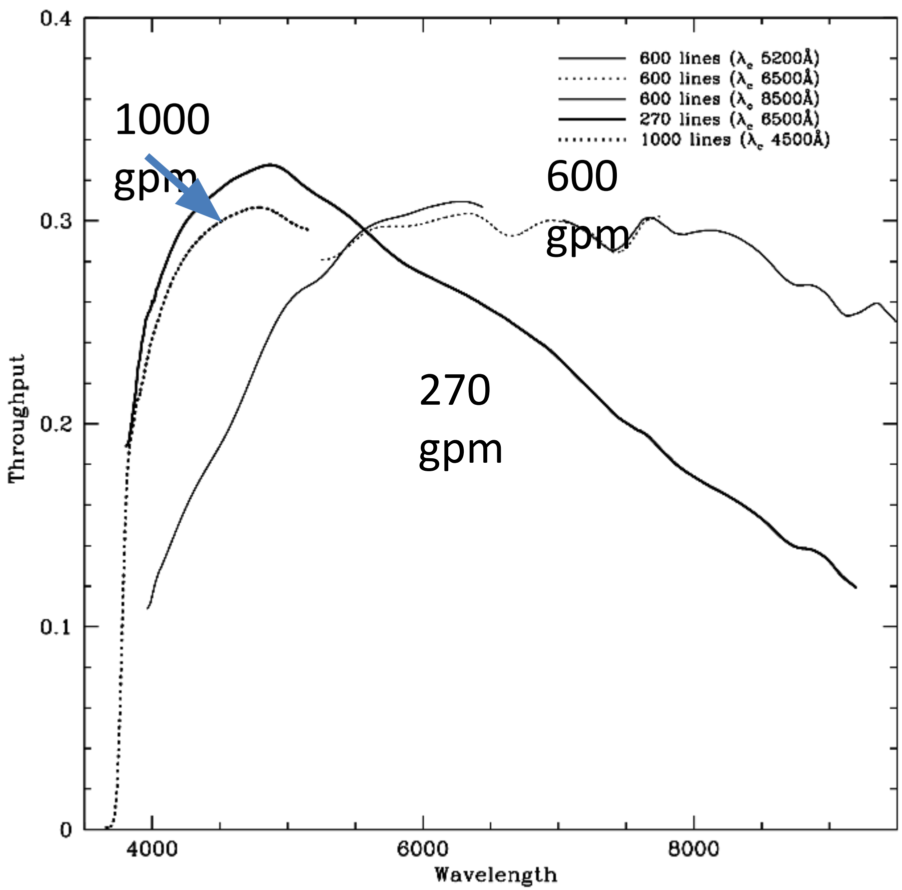
- Dual-unit optical spectrograph @ MMT f/5
  - imaging (*SDSS griz*): 2*15’x8’ fields
  - spectroscopy:
    - 200mm collimated beam
    - 270/600/1000 gpm gratings
    - λ=0.37-1.05μm R=1300-4500
    - long-slit: 15’ long slit
    - MOS: 10 masks; 2*15’x8’ FoV

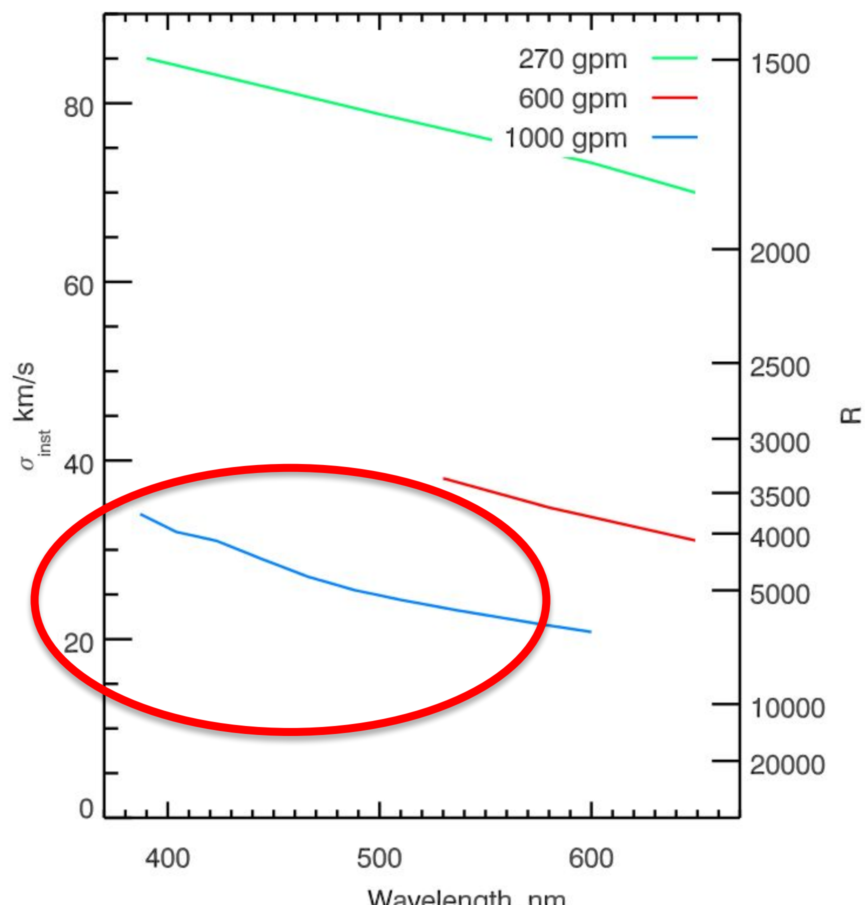


- First light in Nov/2017
- Queue operations started in Feb/2018

Binospec: a niche for low SB targets

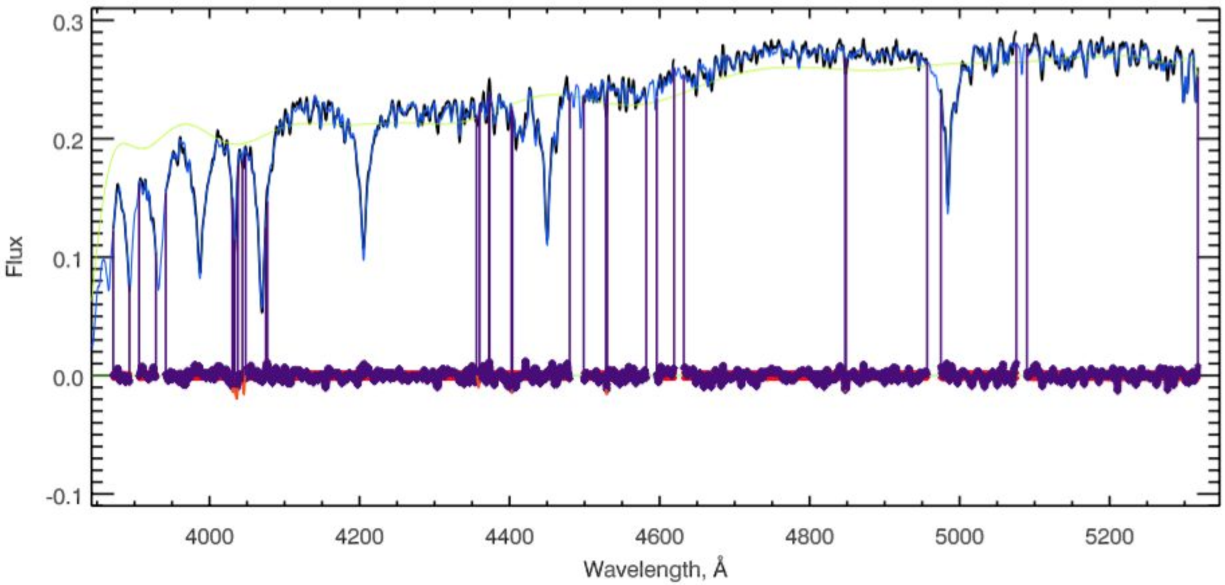
- 1000gpm: high throughput at R>4000 at 375<λ<550nm
  - feature rich wavelength range in old stellar populations
  - ideal instrument to study nearby low surface brightness galaxies

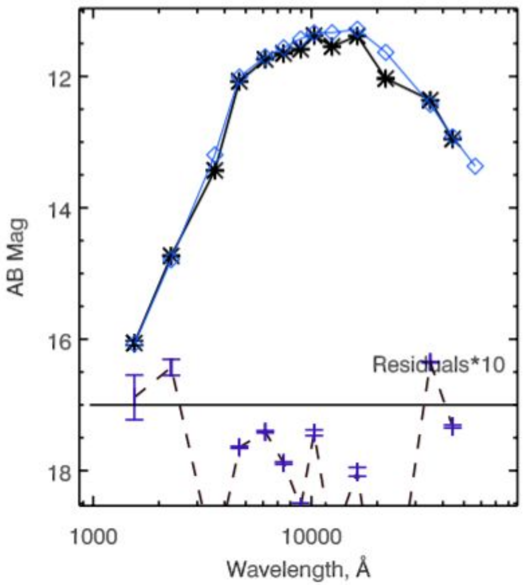




Spectroscopic data analysis

- NBursts/NBursts+phot full spectrum fitting technique (Chilingarian et al. 2007)
  - fitting a spectrum against a grid of stellar population models (SSPs or more complex models, e.g. a "leaky box" with consistent chemical evolution of iron and α-elements)
  - simultaneous fitting of internal kinematics and a parameterized star formation history
  - IDL package originally based on PPxF (Cappellari & Emsellem 2004); heavily modified afterwards
  - simultaneous fitting of broad-band photometry and spectroscopic data
- Jeans Axisymmetric Modeling (Cappellari 2008) assuming that total mass follows stellar mass with a constant factor.
  - archival data from Subaru Suprime Cam; CFHT Megaprime; NOAO
  - mass-to-light conversion using profiles of stellar population parameters derived with NBursts





Ultra-diffuse galaxies in Coma

Chilingarian et al. 2019 in pres (ApJ)s. arXiv:1901.05489

- Sandage & Binggeli (1984): “A new type of very large diameter (10000 pc), low central surface brightness (>25 B mag/arcsec) galaxy, that comes in both early (i.e., dE) and late (i.e., Im V) types, has been isolated, but there are, as yet, no known examples in the local neighborhood”
- van Dokkum et al. (2015): re-discovery of this galaxy type in the Coma cluster and re-branding it as “ultra-diffuse galaxy” (μ_{0R}>24.0 mag/arcsec^2; r_e>1.5kpc)
- Koda et al. (2015) and Yagi et al. (2016) identified 700+ Coma UDGs (μ_{0R}>24.0 mag/arcsec^2; r_e>0.7kpc)
- Lack of good spectroscopic measurements: only two UDGs have spectroscopic measurements of stellar velocity dispersion in integrated light: DF44 (30h with Deimos; 17h with KCWI; van Dokkum et al. 2016, 2019) and NGC1052-DF2 (3h with KCWI; Danieli et al. 2019)
  - Dynamical status and dark matter content claims remain speculative
- Formation and evolution:
  - Same as dwarf ellipticals (dEs): SN feedback + environment (Conselice 2018)
  - More exotic scenarios: early quenching of “underdeveloped” galaxies at z=2 (Yozin & Bekki 2015); strong star-formation driven outflows (Di Cintio et al. 2017)

Coma UDGs: observations

- Filler targets for the diffuse post-starburst program (see below)
  - UDGs from the Yagi et al. (2015) sample
  - Faint galaxies from Adami et al. (2008)
  - slits NOT parallel to major axes
  - **2h** of integration time
- Out of 30+ objects we kept 9, for which we could measure velocity dispersion from integrated light spectra and stellar population parameters
  - 6 galaxies from the Yagi et al. (2015) sample
  - 2 spatially extended galaxies with bluer colors from Adami et al. (2008)
- Challenging data analysis because of low signal-to-noise ratios:
  - σ, age, [Fe/H] measurements from an optimally extracted integrated spectrum (S/N=3-5 for 5 objects) or several bins along the slit binned to S/N=5 for 3 objects
  - spatially resolved radial velocity profile along the slit for S/N=2-3 while keeping velocity dispersion and stellar population parameters fixed

UDG in 2h with a 6.5-m telescope?

- Analytic estimates of σ uncertainties from pixel fitting:

$$\chi^2 = \sum_{N_\lambda} \frac{\{F_i - P_{1p}[T_i(\mathrm{SFH}) \otimes \mathcal{L}(v, \sigma, h_3, h_4) + P_{2q}]\}^2}{\Delta F_i^2},$$

$$\text{where} \quad T_i(\mathrm{SFH}) = \sum_{N_{\mathrm{bursts}}} k_i T_i(t_n, Z_n),$$

$$\frac{\partial \chi^2}{\partial \sigma} = 0$$

- Keep aside your childhood nightmares and compute the derivative for a Gaussian LOSVD and Gaussian error statistics. After all, the convolution is just a linear integral transform!
- After simple although bulky calculations:

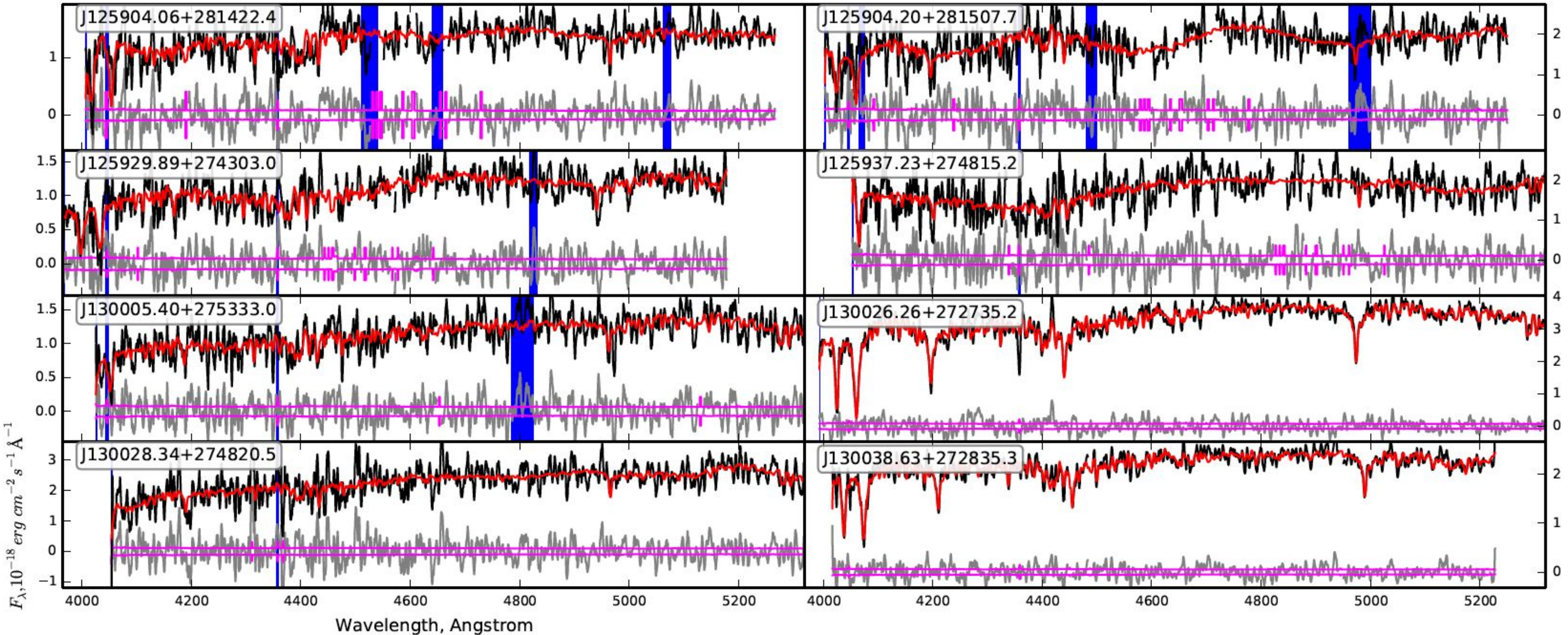
absorption line depth, spectral resolution

$$\Delta\sigma = \frac{\sigma}{\mathrm{SNR}\sqrt{\sum_{N_\lambda}(T_i \otimes (\mathcal{L}(v,\sigma) - \mathcal{L}(v,\sigma)\frac{\Delta\lambda^2}{\sigma^2}))^2}} = \frac{\sigma}{\mathrm{SNR}}\Big(\sum_{N_\lambda}\big(\frac{\partial T_i}{\partial \lambda} \otimes \mathcal{L}(v,\sigma)\big)^2\Big)^{-1/2}$$

- The code to compute this is 7 lines long (IDL)
- Let's plug in some numbers (Keck versus us):
  - DF44, Deimos, 30h, SNR=14, Hα, σ=44 km/s, [Fe/H]=-1.2 dex: Δσ=7 km/s
  - Binospec, 2h, SNR=4, blue, σ=20 km/s, [Fe/H]=-1.0 dex: Δσ=7 km/s

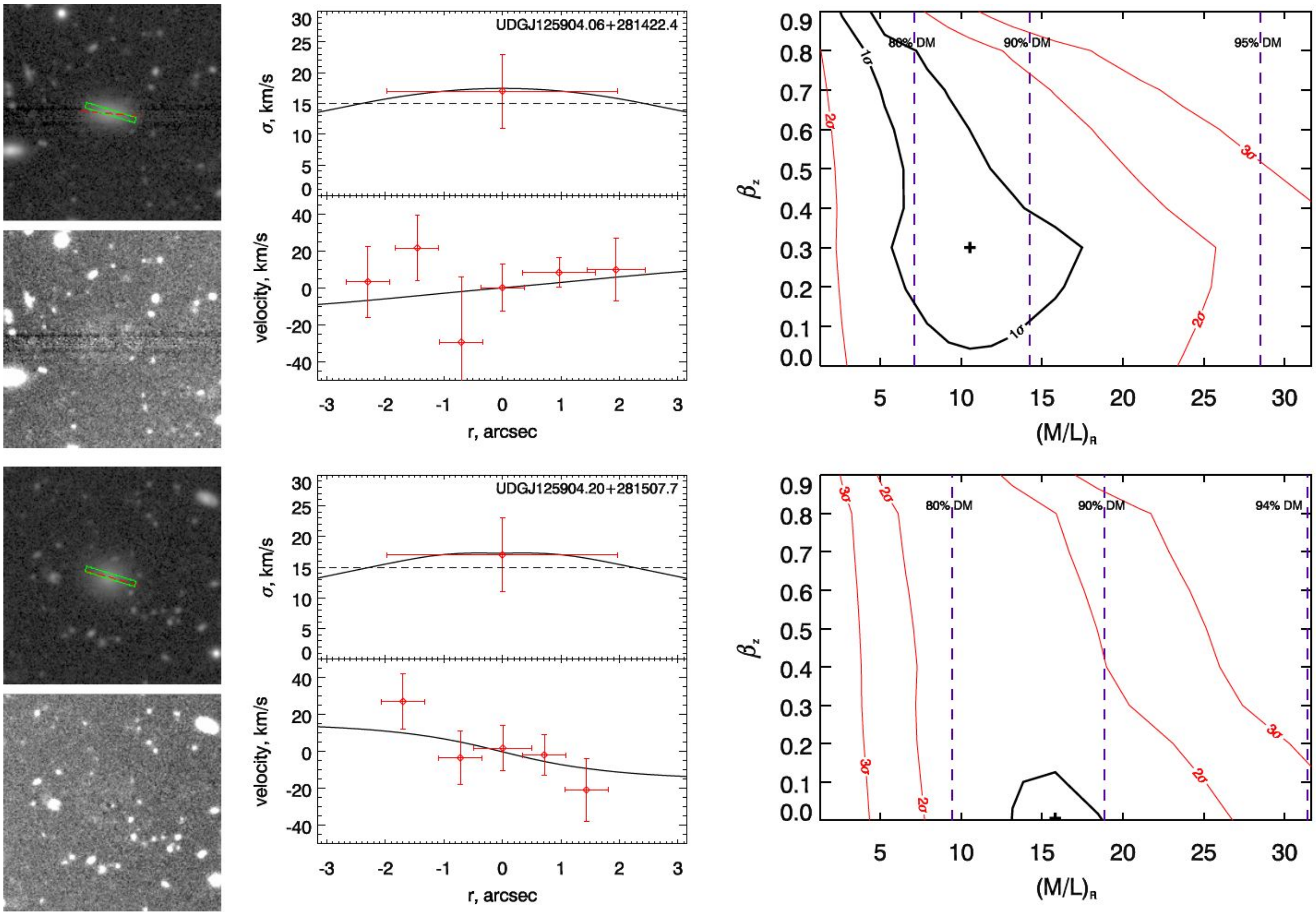
Coma UDGs: results

- 2 Adami et al. galaxies: intermediate-age (1.5-2 Gyr); moderately metal-poor (-0.90…-0.75 dex)
- 4 UDGs: old (>5.5 Gyr); metal-poor (-1.4…-0.93 dex)
- 2 UDGs: 3Gyr and 6Gyr; metal-rich (-0.3 and -0.6 dex)
- 2 UDGs exhibit major axis rotation; 1 has a stellar nucleus



Coma UDGs: results

- Very diverse dynamical and stellar population properties



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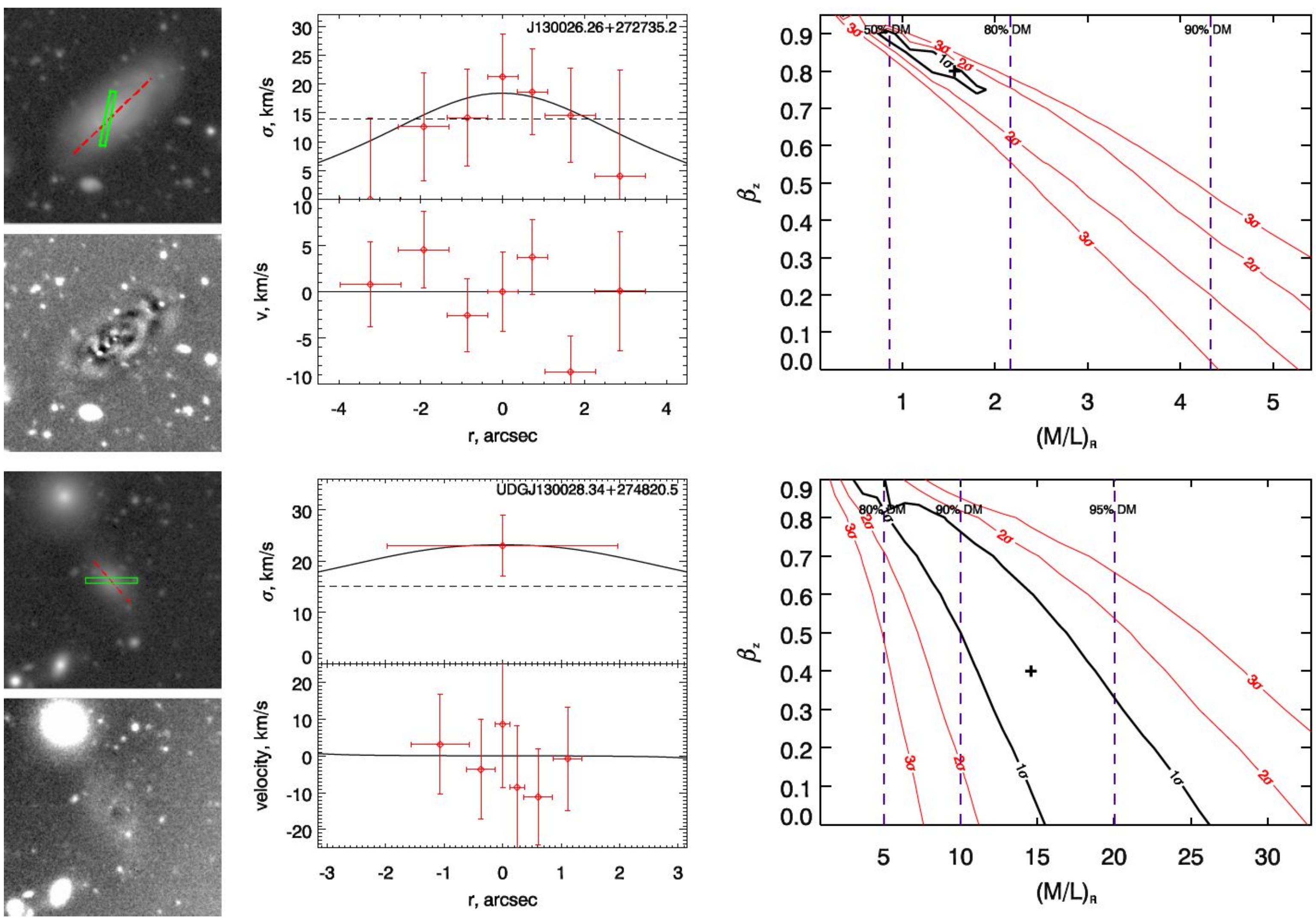
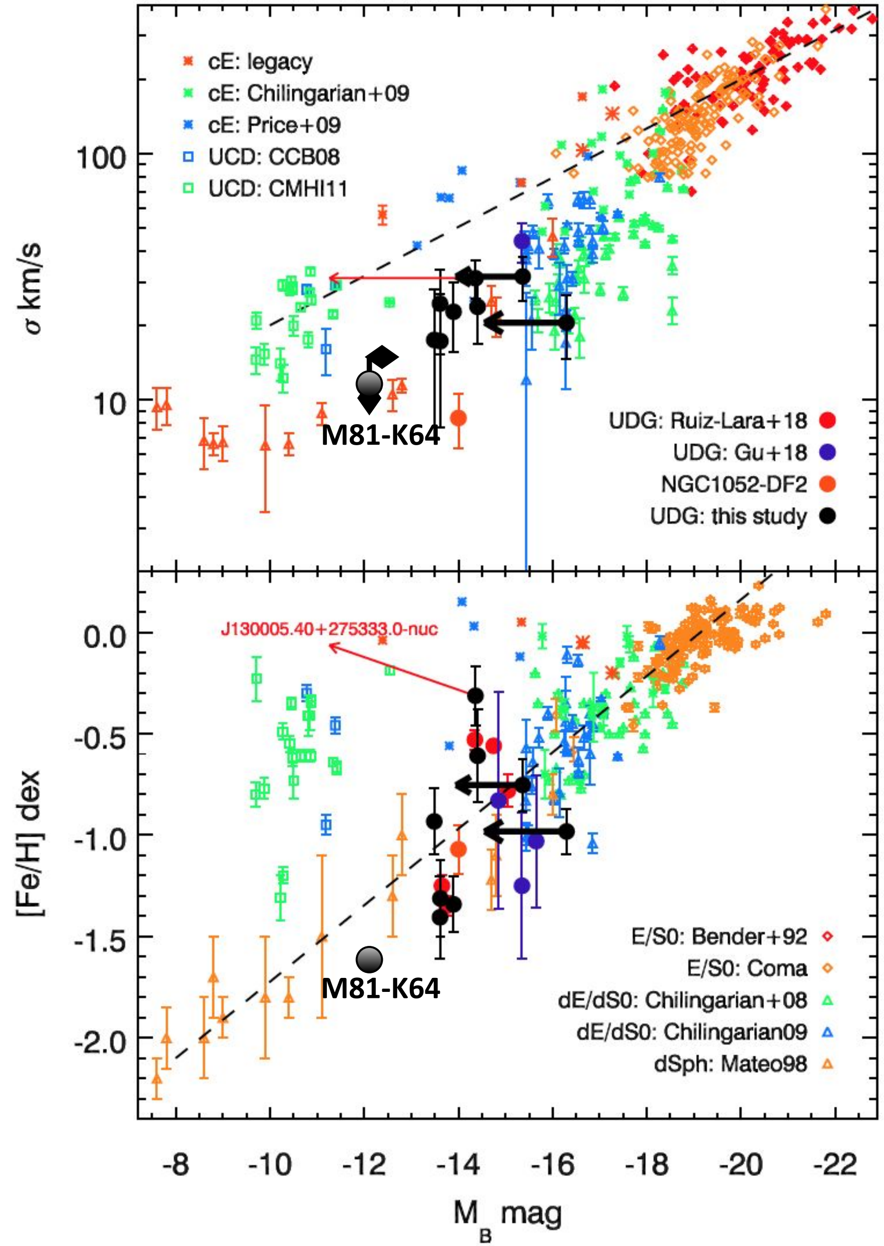


Coma UDGs: results

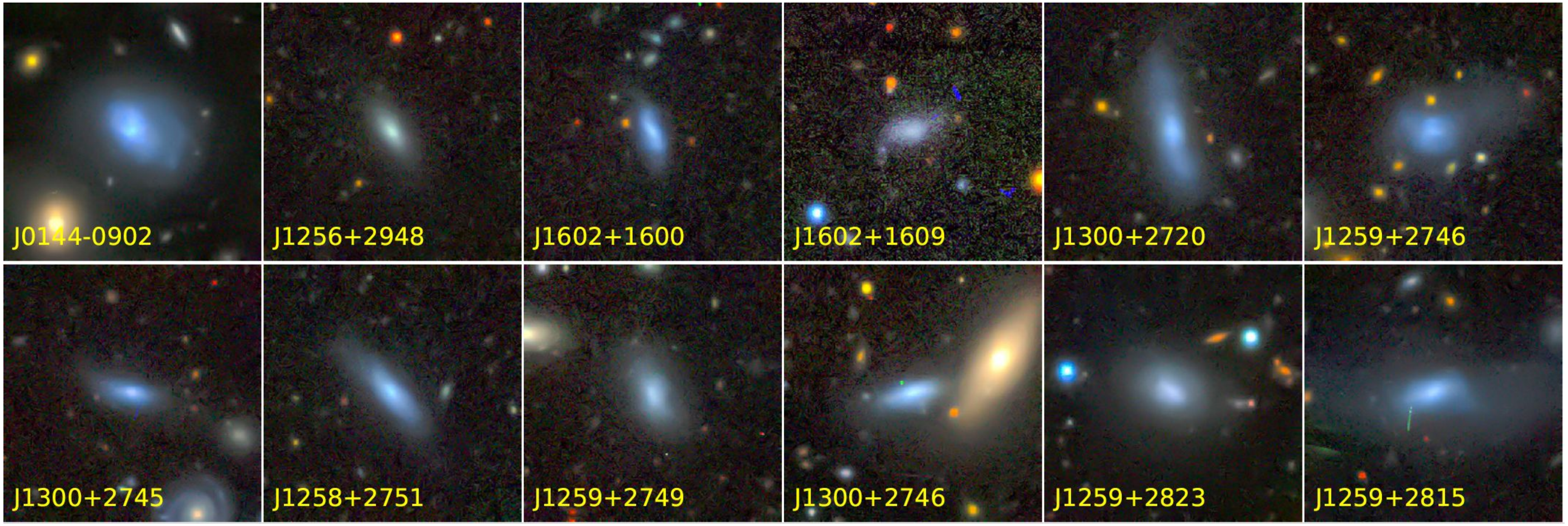
- The observed galaxies form a heterogeneous population
  - rotating and non-rotating
  - nucleated and non-nucleated
  - dark matter fractions 50-85%
  - follow the mass-metallicity relation established by dEs and dSphs
  - follow the Faber-Jackson relation
- The nucleated UDG is metal-rich and exhibits minor axis rotation: either triaxial or tidally stripped
- Similar properties to brighter dE/dS0 galaxies, slightly more DM
- They can all be formed using classical dE formation scenarios



Diffuse post-starburst galaxies

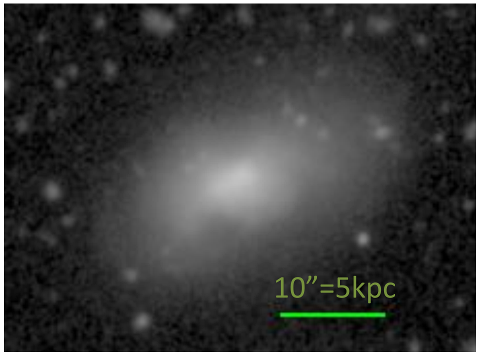
as a smoking gun of UDG formation

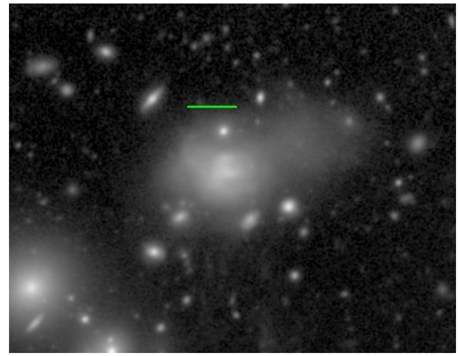
- diffuse extended post-starburst galaxies were identified in SDSS using RCSED (http://rcsed.sai.msu.ru/)
- selection criteria: extended (r>5”), blue (*g*-*r*<0.5 mag), no emission lines
- 10 objects in Coma, 2 in Abell2147, 1 in a group
- Discovered while demonstrating RCSED capabilities to a colleague
  - All in SDSS main galaxy sample, hence it is a complete magnitude limited sample

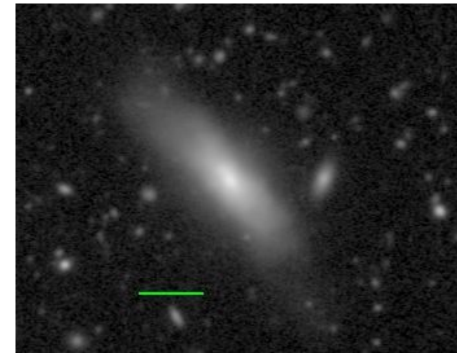


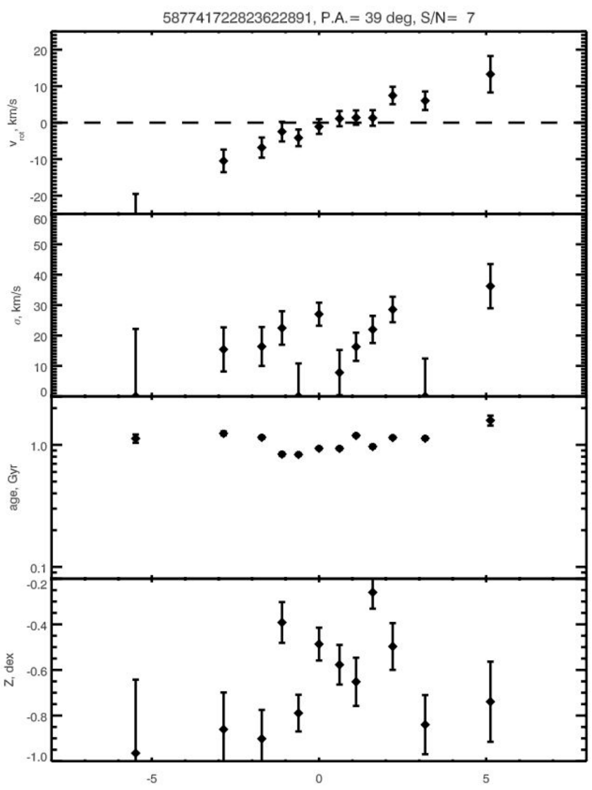
Diffuse PSGs: results (preliminary)

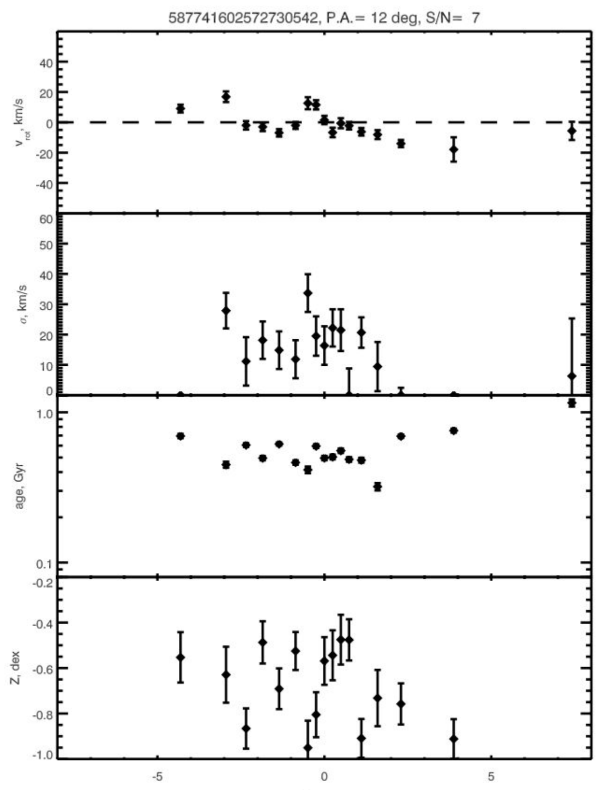
- can measure σ=10km/s at SNR=5/pix that corresponds to m_R=24.5 mag/arcsec^2

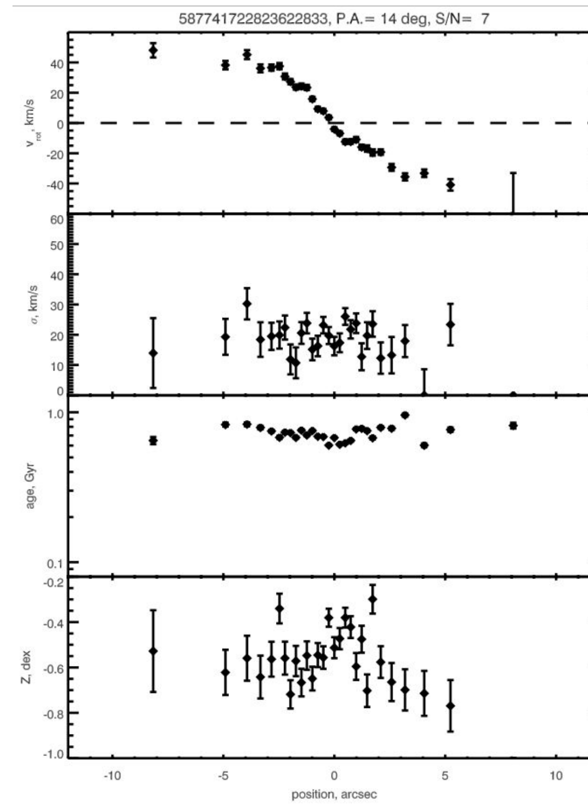












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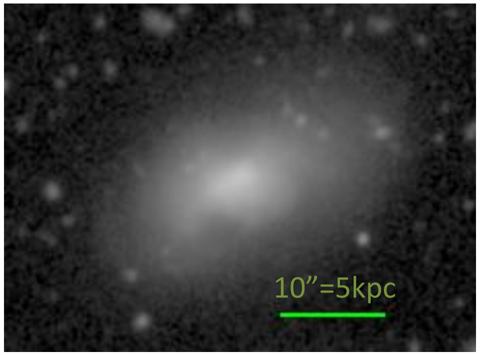

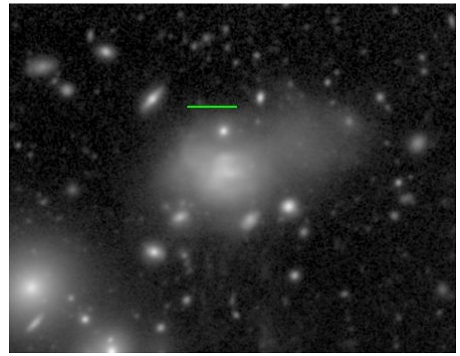

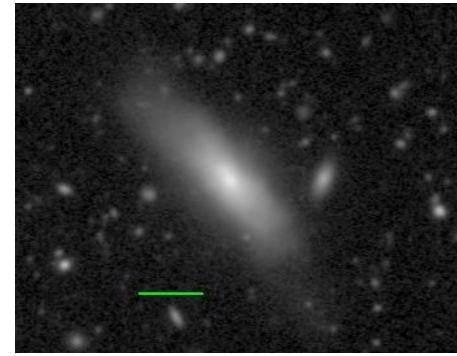

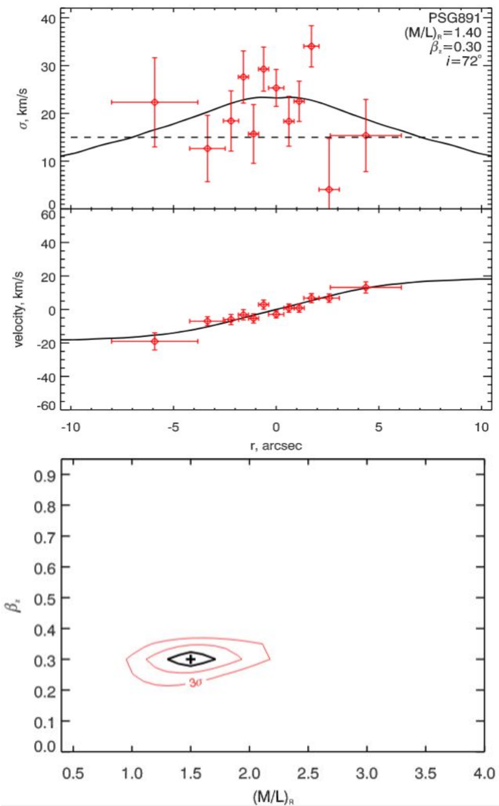

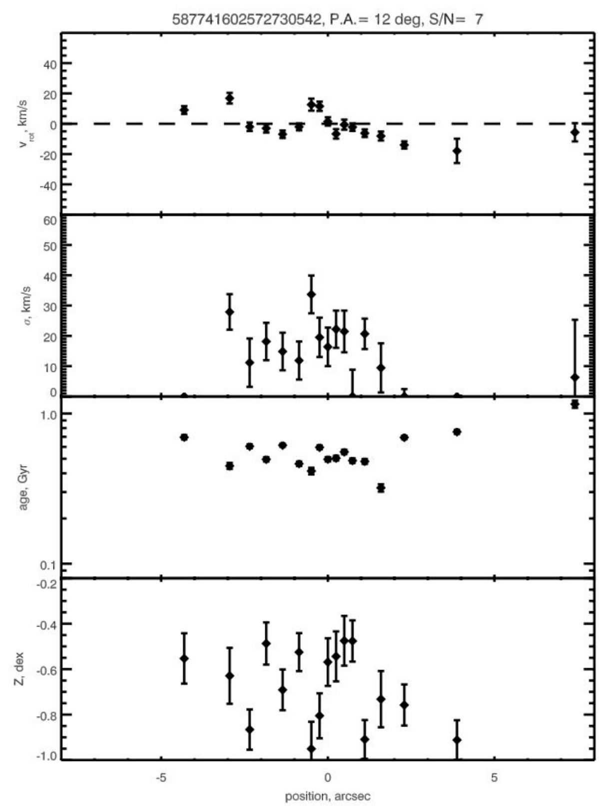

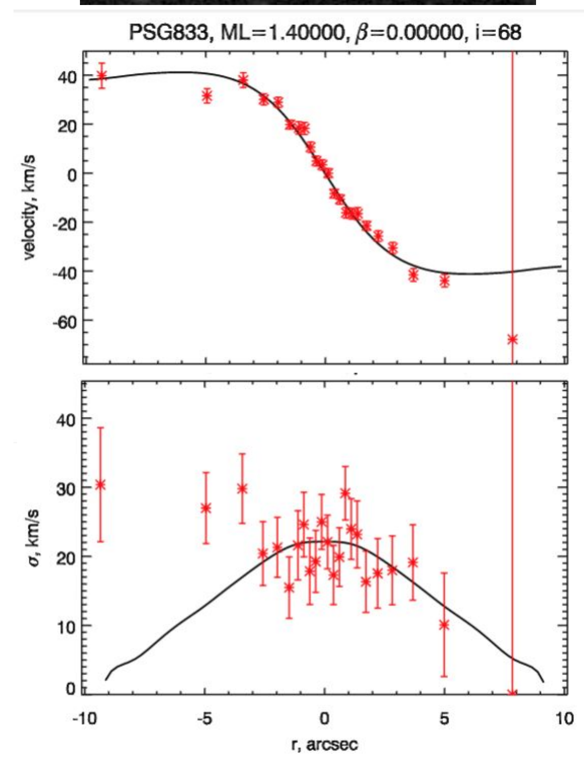

Diffuse PSGs: results (preliminary)

- 9 or 11 galaxies show regular rotation and low velocity dispersions
  - 1 is highly anisotropic
  - 1 has bizarre kinematics and irregular shape (it is also the youngest of all)
- young stellar populations (truncation ages of 300-800Myr)
- 5 galaxies show multi-component kinematics
- 4 galaxies exhibit clear signs of recent ram pressure stripping:
  - straight tails with a comet-like morphology in the youngest objects
  - asymmetric stellar ages across the disk
- M/L ratios from dynamical modeling: 0.8-2.4 (*R* band; Solar units)
  - 50-85% of dark matter by mass within 2 effective radii (similar to "normal" UDGs)
- Future evolution of diffuse PSGs
  - galaxies have zero gas left and no current star formation
  - little old stellar population (from deep Spitzer IRAC photometry)
  - they will age and drop the V-band surface brightness by a factor of 20-50 in 5Gyr and become legit UDGs, thus explaining one of the UDG formation channels without involving exotic scenarios

UDGs: take-away message

- UDGs fill a gap between dEs found in clusters and much fainter dSphs found in groups in various properties
  - mass-metallicity and Faber-Jackson relations
  - the dark matter fraction (increases when mass decreases)
  - fainter objects tend to be more anisotropic
- We found a population of diffuse extended post-starburst galaxies in clusters: in terms of sizes and stellar densities they clearly lie in the UDG regime. They are rotating disks. They were quenched by ram pressure stripping, which induced the final burst of star formation and then caused the stellar disk expansion. <u>At least some old UDGs were formed like that</u>.
- All current fights about distinctions between UDGs, dEs, dSphs make no sense: there is a continuum of dynamical and stellar population properties
- More observations are needed, but given currently available data, there is no need in involving exotic galaxy formation scenarios to explain the nature of UDGs: the dE formation channels are good enough.