Dynamics of Galaxies and Clusters with FORS

Magda Arnaboldi (ESO)

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Outline

- Motivation
- How to observe stellar halos: CDI and MSIS (PN.S@WHT & FORS1/2@VLT)
- The ePN.S survey: diversity of early-type galaxies' halos
- The extended halos in cD and group dominant galaxies
- Conclusions

Motivation

In ΛCDM, galaxies form from infall of baryons in the grav. potential generated by the dark matter halos

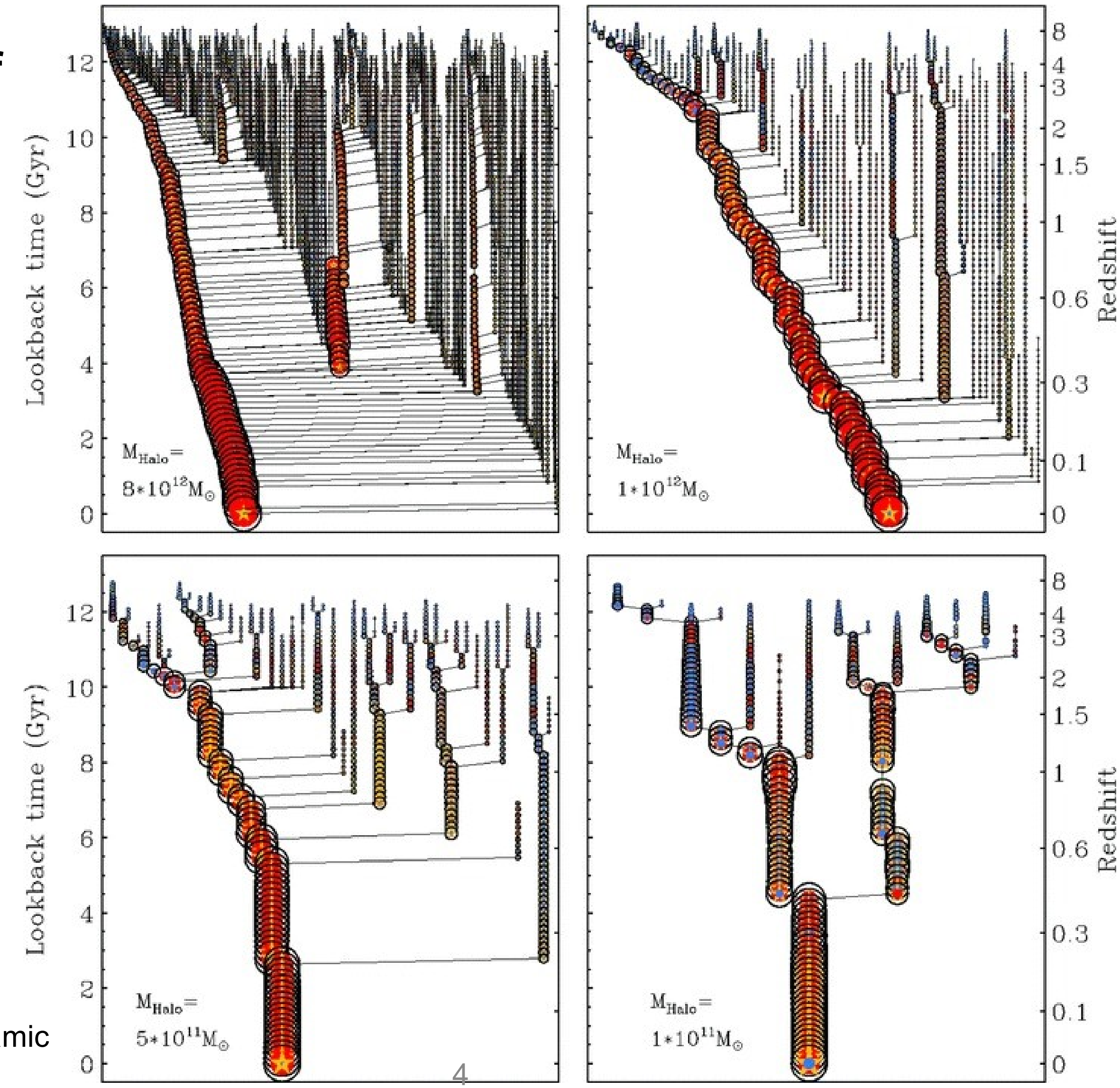
- When and how did the stellar halos form? Are they spherical/axisymmetric/triaxial?
- How is dark matter distributed in each halo? What is its density profile/scaling relations?
- On what time scale do baryons fall in their dark matter halos?
- How do halos acquire angular momentum? Does it depend on mass/environment?
- How do halos and baryons exchange angular momentum? Is there a bimodality between fast and slow rotators?

Motivation

- **DM halos continue to grow by accretion, with about half or more of their mass acquired since z=1.**

- **Two phase formation scenario**

- initial assembly phase:
  rapid star formation fueled by the infall of cold gas (z>1.5) or through major merger events
- size growth through minor mergers
- dark matter shows a mild radial anisotropy, <u>while accreted stars are strongly radially biased.</u>
- Radially anisotropy monotonically increasing with radius



Hirschmann et al. 2012
cosmological hydrodynamic zoom simulations

Trujillo+2006
van Dokkum+2010
Oser+2010
Muñoz-Cuartas+2011
Rodriguez-Gomez+2016
Qu+2017

Motivation

In ΛCDM galaxies form from infall of baryons in the grav. potential generated by the dark matter halos

- When and how did the stellar halos form? Are they spherical/axisymmetric/ triaxial?
- How is dark matter distributed in each halo? What is its density profile/scaling relations?
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- How do halos acquire angular momentum? Does it depend on mass/environment?
- How do halos and baryons exchange angular momentum? Is there a bimodality between fast and slow rotators?

✓ In the nearby universe these questions can be tacked from imaging & kinematics observations and dynamical modelling of a complete magnitude limited sample of galaxies

✓ Key requirements are that the measurements for tracers – of light and motions - extend to very large radii

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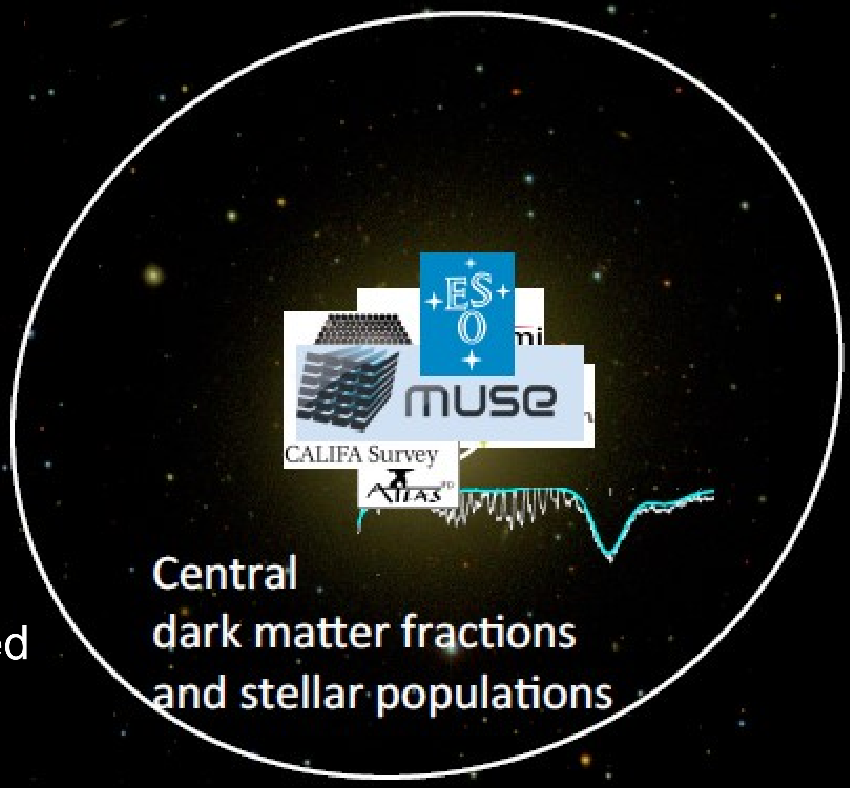
Summary observational goals

PNs are kinematical probes in galaxies

PNe kinematic tracers of stars:

- Late phase of intermediate mass stars
- Bright [OIII] emitters: easily detectable
- PN and stellar kinematics agree in the overlap regions

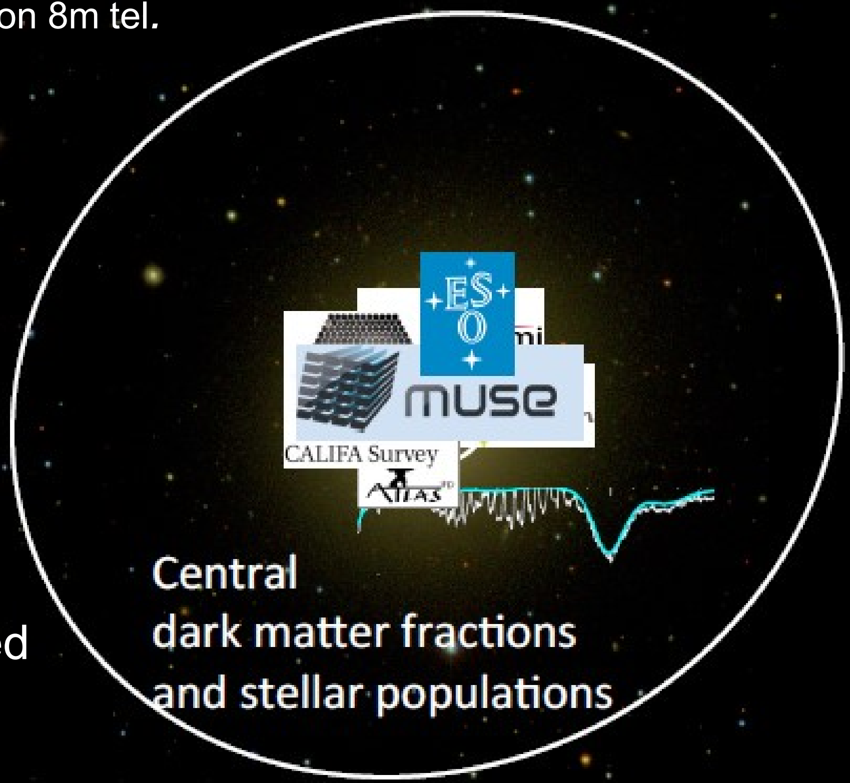


Central regions constrained from abs. line spec. meas. LS & IFU

Summary observational goals

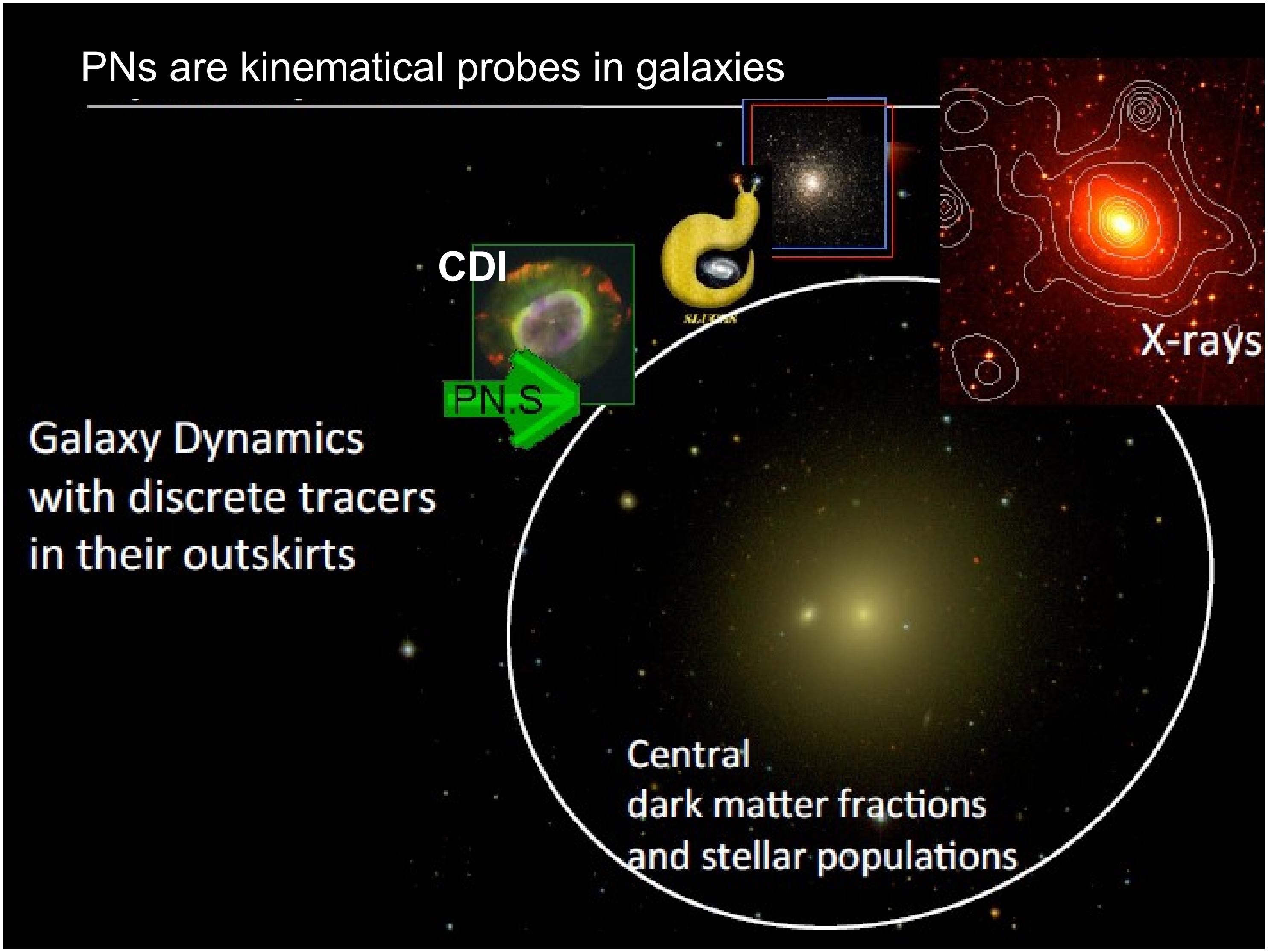
PNs are kinematical probes in galaxies

F([OIII]$_{5007}$)=2.4 x 10^{-14} erg/s/cm^2 @M31
F([OIII]$_{5007}$)=9.6 x 10^{-17} erg/s/cm^2 @Virgo
F([OIII]$_{5007}$)=2.2 x 10^{-18} erg/s/cm^2 @Coma => it corresponds to ~2 photons/min on 8m tel.



Central regions constrained from abs. line spec. meas. LS & IFU

Summary observational goals

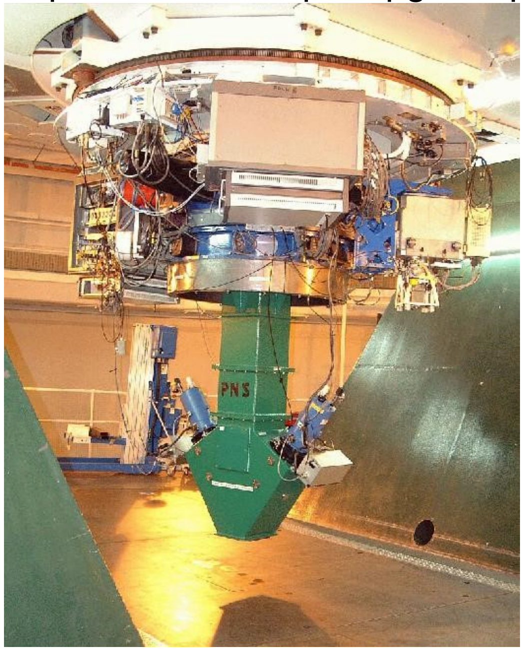


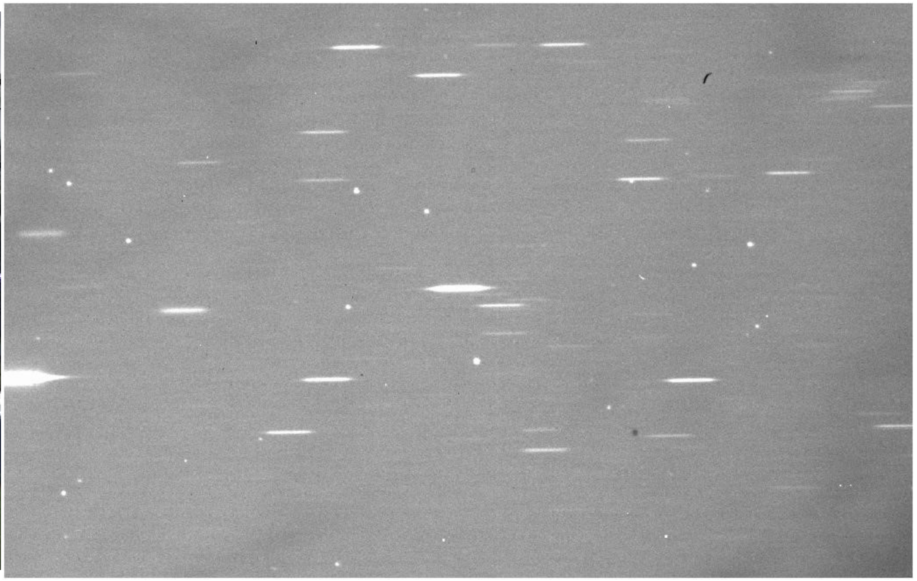
CDI:PN.S@WHT & FORS@VLT

PN.S implements counter dispersed imaging (CDI) in the Right/Left arms.

Emission line appears as dots, continuum emitters appear as strikes.

http://www2011.mpe.mpg.de/opinas/research/DynamicsGroup/pns/





CDI: narrow band filter plus grism and no slits; successfully implemented with FORS1/2 for observations of galaxies in SH

http://www.eso.org/sci/facilities/paranal/instruments/fors.html

Counter Dispersed Imaging

Counter Dispersed Imaging

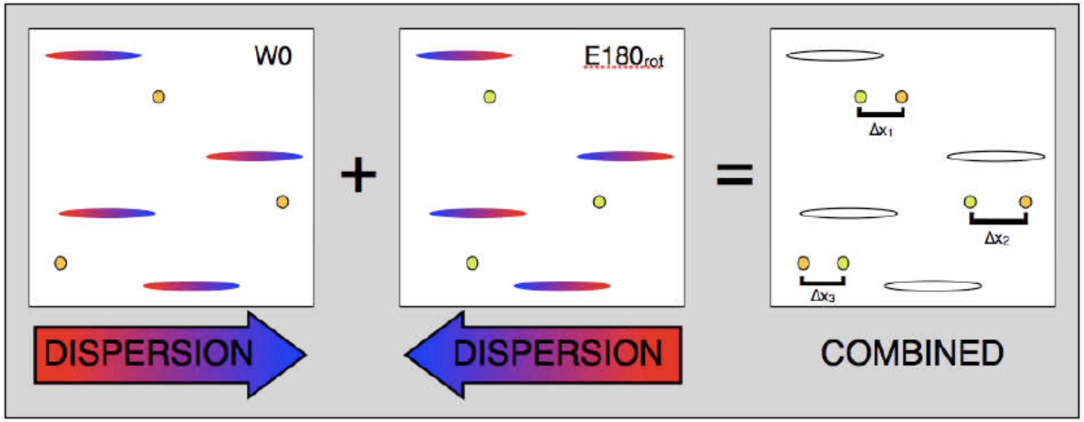
- Narrow band filter plus grism, two exposures per pointing, one of these rotated by 180 degrees

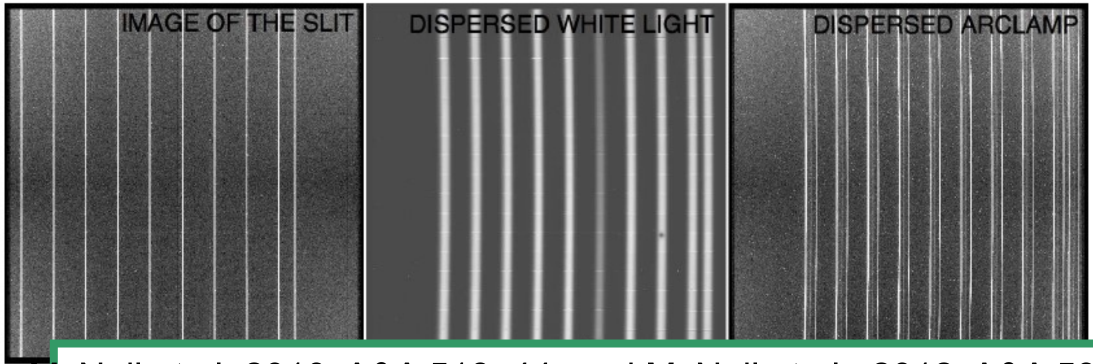
- Carried out at FORS1/FORS2@VLT

- It yields m_{5007},x,y,v_{los} for PNs in the field

- See works by R. Mendez and A Teodorescu for alternative obs. strat. – RHM+2008

- FOV 7'x7'; 0.3'' pix^{-1}, 0.54 Å pix^{-1}, Spec res 10000.





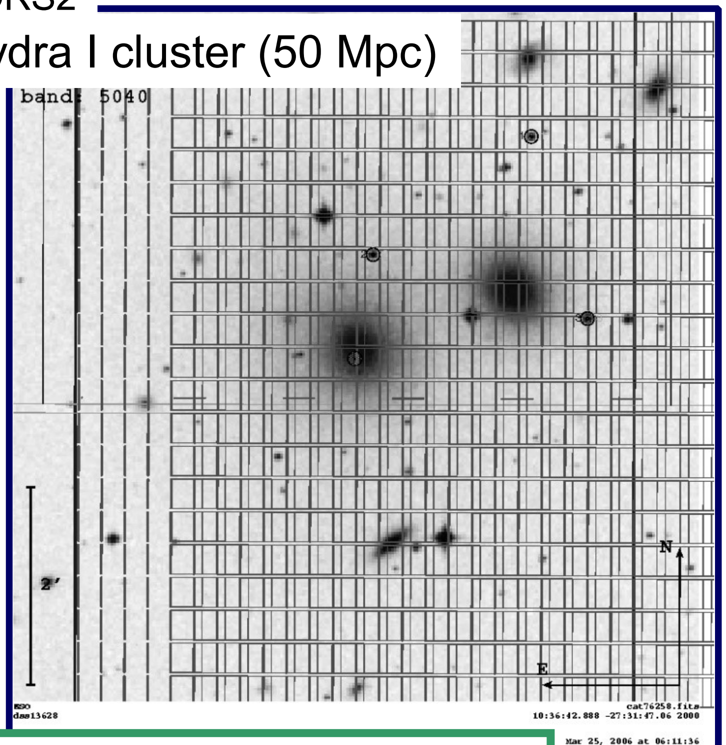
McNeil et al. 2010, A&A 518, 44, and McNeil et al. 2012, A&A 539, 11

Multi Slit Imaging Spectroscopy

MSIS allows a blind search: it combines a mask of parallel multiple slits with a narrow band filter, centred on redshifted [OIII] 5007 Å line at the cluster mean systemic velocity, plus a grism to obtain spectra of all PNs that lie behind the slits.

FORS2

Hydra I cluster (50 Mpc)

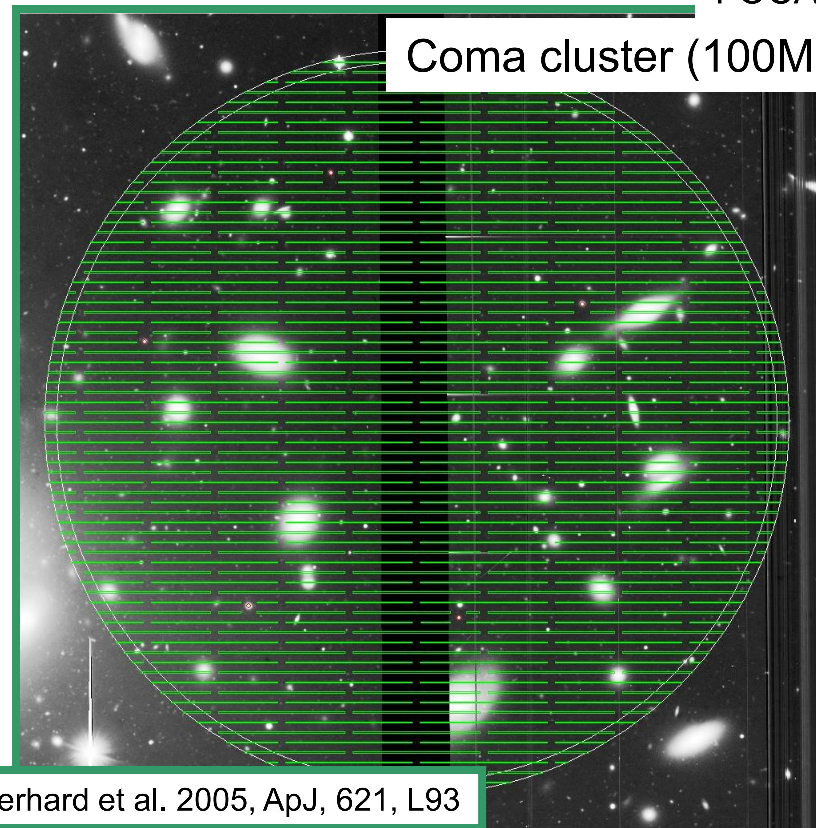


Ventimiglia et al. 2011, A&A, 528, 24

See also Hilker + [2018A&A...619A..70H](2018A&A...619A..70H)

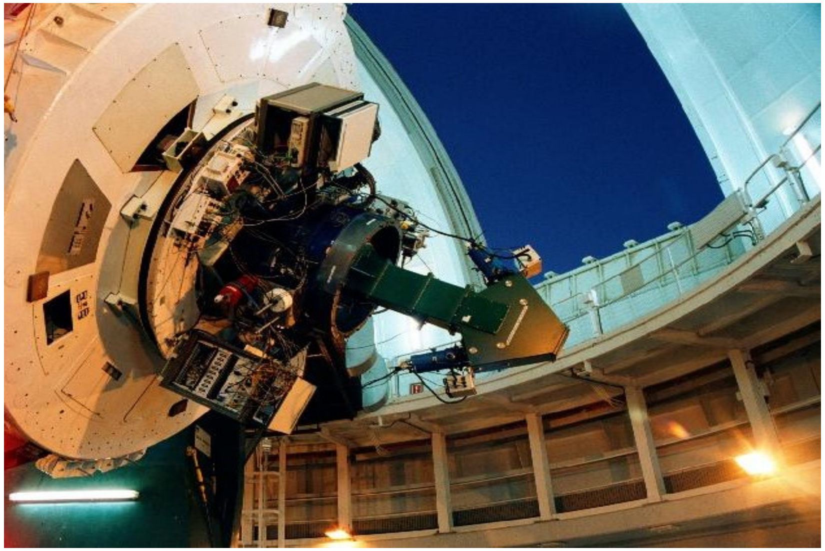
FOCAS

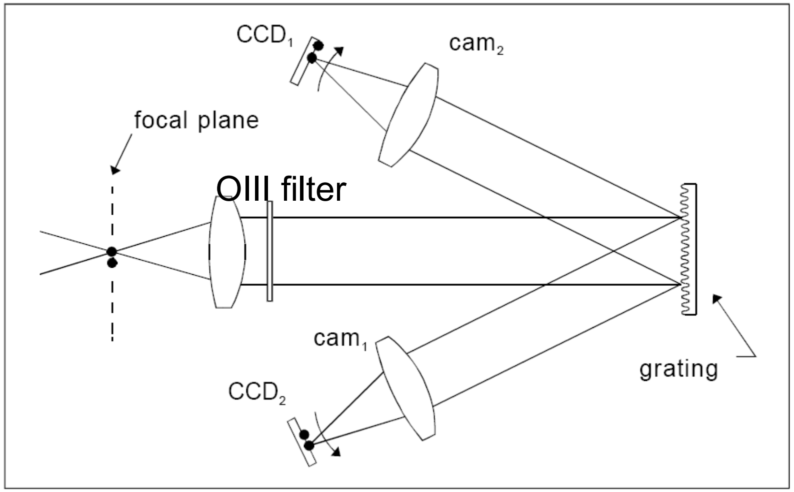
Coma cluster (100Mpc)



Gerhard et al. 2005, ApJ, 621, L93

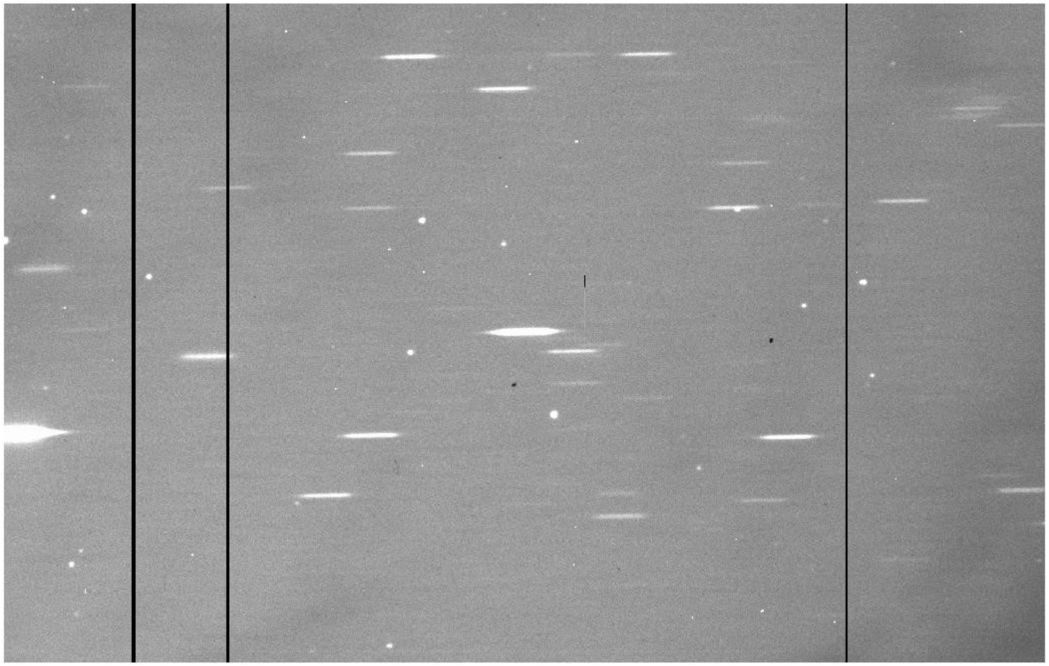
Planetary Nebulae Spectrograph





(Douglas et al 2002, PASP, 114, 1234)

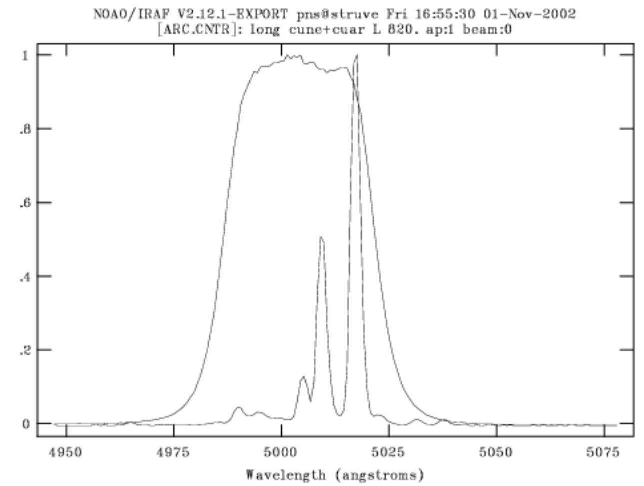
Positions and velocities of the PNe are measured with a single exposure!!!

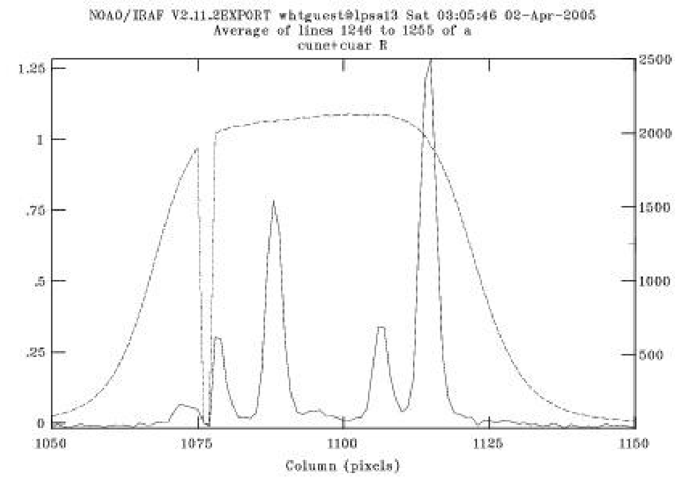


CCD1 and CCD2 blinking: →

Planetary Nebulae Spectrograph

- Cassegrain focus f/10.942
- FoV 11’x10’
- Angular scale 0”.3 pix^{-1}
- Grating 600g/mm, 0.77Å pix^{-1}
- Operating range 4950-5070 Å
- 4 filters: A (5000Å), B(5034Å), C(5050Å), with FWHM 31-35 Å and AB (5026Å) FWHM 43 Å
- Overall efficiency 0.37, σ_{ins} = 20 kms^{-1}
- Mounted on WHT, a 4 meter class telescope





Observing technique vs. PN [OIII] science

Obs. tech	[OIII] detect. < 20 Mpc	[OIII] detect. > 20 Mpc	Hα det.	PNLF studies	σ_{inst}	PN V_{exp}	2D velocity field
NB imaging (30-60 Å)	yes	no	no	Yes	-	-	-
Spectroscopic follow-up	yes	no	no	Yes	150 m/s	yes	yes
CDI	yes	no	no	Yes	37 km/s	no	yes
MSIS	yes	yes	no	Yes	>154 km/s	no	yes
PN.S	yes	no	yes	no(+)	20 km/s	no	yes

Observing technique vs. PN [OIII] science

Obs tec	Dynamics of BCGs/ETG/S0s	Dynamics of spirals/irr/dwarfs	PNLF shape	PN population
Imaging +Spectr. follow-up	Yes , within 20 Mpc distance	Yes in principle, but expected contamination from HII regions	Yes, 2.5 mags down with 8m tel	Yes
CDI	Yes , within 20 Mpc distance	Yes in principle, but expected contamination from HII regions	Yes, only 1.5 mag	Yes
MSIS	Yes, massive ETGs within 100 Mpc	No	Yes, only 0.5 mag	Massive ETGs within 100 Mpc
PN.S	Yes , within 20 Mpc distance	Yes, science case for Hα arm	Yes(-), only 1.5 mag	Yes

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Extended PN Survey in ETGs

PN.S
CDI

Extended Planetary Nebulae Survey
P.I. Magda Arnaboldi

Kinematics, dynamics, angular momentum, mass in ETG halos; D ~ 25 Mpc; 80-700 PNs per galaxy out to ~6Re; Homogenous analysis

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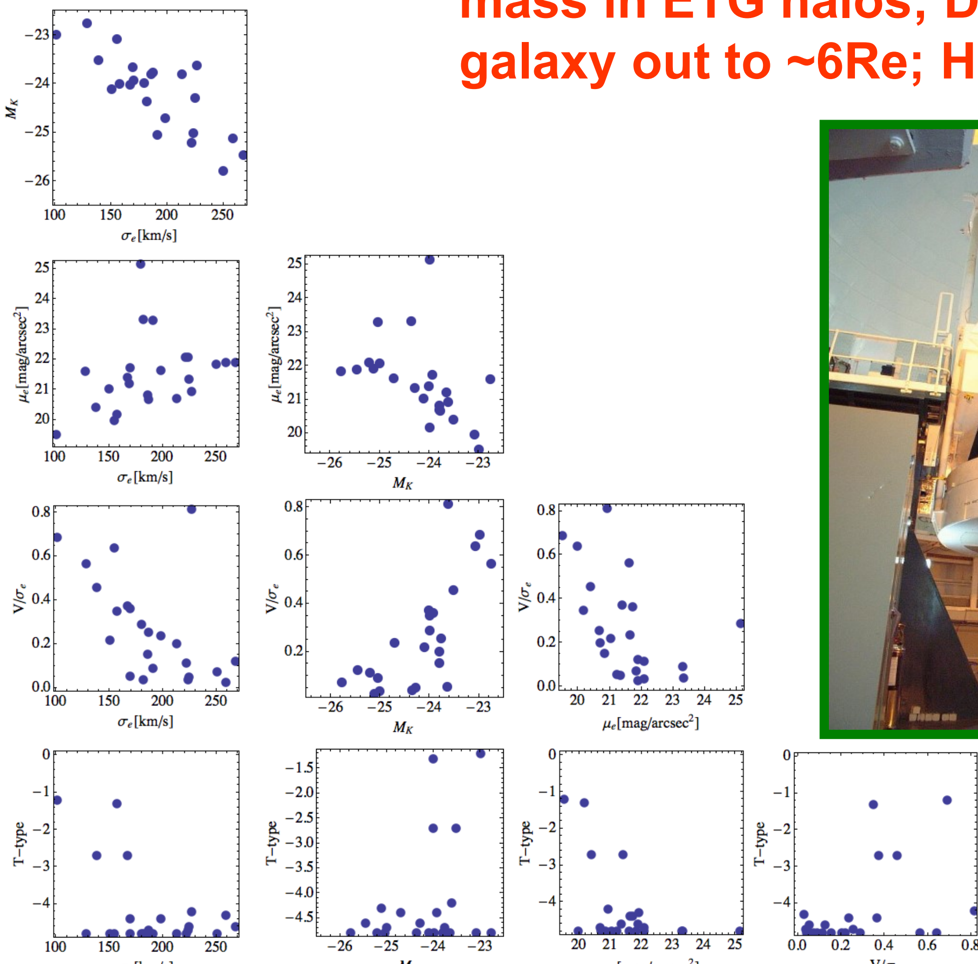
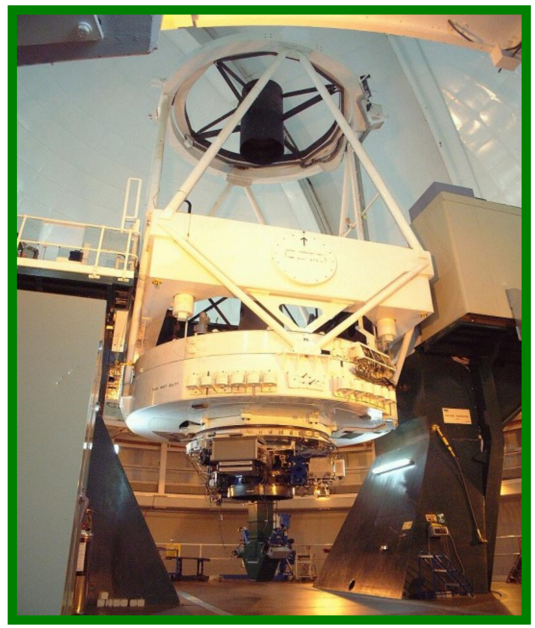




Arnaboldi+2017, 2019 in prep

Extended PN Survey in ETGs

CDI PN.S

- 33 nearby (distance to ~25 Mpc) early type galaxies with a wide range of structural parameters (luminosity, central velocity dispersion, ellipticity, boxy/diskyness)
- Magnitude limited sample
- 24 fast and 9 slow rotators
- 80-700 PNs per galaxy
- Kinematics out to [3 - 13 Re], median ~6 Re
- > 60 ref papers

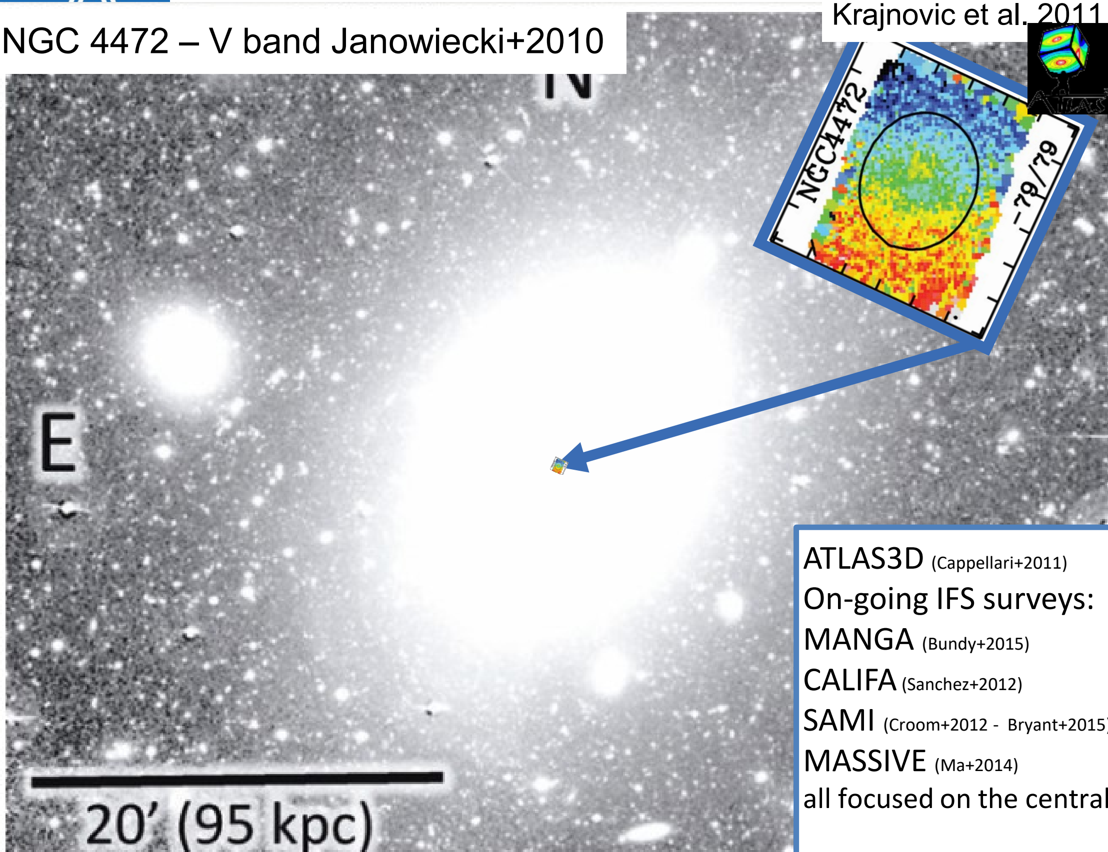
Kinematics, dynamics, angular momentum, mass in stellar halos

Galaxy NGC	M_K[(a)] mag	D[(b)] Mpc	class[(c)]	N_{PNe}[(d)]	PA_{phot}[(e)]	ϵ[(f)]
0584	-24.16	20.1	F	33	63	0.339 ± 0.007
0821	-23.99	23.4	F	40	31.2	0.35 ± 0.1
1023	-24.01	11.4	F	48	83.3	0.63 ± 0.03
1316	-25.93	20	F	109	50	$0.29 \pm 0.016^*$
1344	-23.92	18.4	F	30	167	0.333 ± 0.013
1399	-24.99	18.5	S	328	110	$0.1 \pm 0.004^*$
2768	-24.71	21.8	F	63	91.6	0.57 ± 0.06
2974	-23.62	21.4	F	38	44.2	0.37 ± 0.03
3115	-26.52	9.68	F	93	43.5	0.607 ± 0.016
3377	-22.76	10.9	F	35.5	46.3	0.33 ± 0.12
3379	-23.80	10.3	F	40	68.2	$0.13 \pm 0.01^*$
3384	-23.52	11.3	F	32.5	53	0.5 ± 0.03
3489	-22.99	12.1	F	22.5	70.5	0.45 ± 0.04
3608	-23.65	22.3	S	29.5	82	$0.2 \pm 0.04^*$
3923	-25.04	22.9	S	86.4	48	0.271 ± 0.009
4278	-23.80	15.6	F	31.5	39.5	$0.09 \pm 0.01^*$
4339	-22.49	16	F	30	15.7	$0.07 \pm 0.01^*$
4365	-25.21	23.3	S	128.1	40.9	$0.24 \pm 0.02^*$
4374	-25.12	18.5	S	113.7	128.8	$0.05 \pm 0.01^*$
4472	-25.78	17.1	S	194.4	154.7	$0.19 \pm 0.03^*$
4473	-23.77	15.3	F	47.7	92.2	0.43 ± 0.03
4494	-24.11	16.6	F	49	176.3	$0.14 \pm 0.02^*$
4552	-24.29	15.8	S	94.9	132	$0.11 \pm 0.01^*$
4564	-23.08	15.8	F	20.5	48.5	0.53 ± 0.04
4594	-25.16	9.8	F	102	88	0.521 ± 0.003
4636	-24.36	14.3	S	183.35	144.2	$0.23 \pm 0.06^*$
4649	-25.46	16.8	F	128.1	91.3	$0.16 \pm 0.01^*$
4697	-23.93	10.9	F	68.4	67.2	0.32 ± 0.04
4742	-22.51	15.5	F	14.4	80	0.351 ± 0.013
5128	-23.94	3.8	F	162.6	30	$0.069 \pm 0.05^*$
5846	-25.01	24.2	S	59	53.3	$0.08 \pm 0.03^*$
5866	-24.00	14.9	F	36	125	0.58 ± 0.08
7457	-22.38	12.9	F	36	124.8	0.47 ± 0

ePN.S: Probing ETG halo kinematics with PNe

NGC 4472 – V band Janowiecki+2010

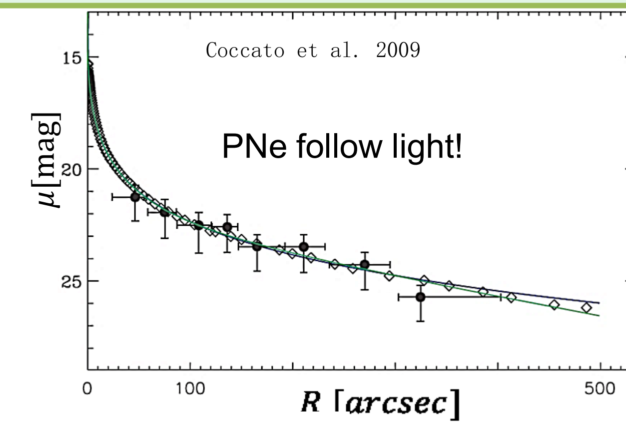
Krajnovic et al. 2011

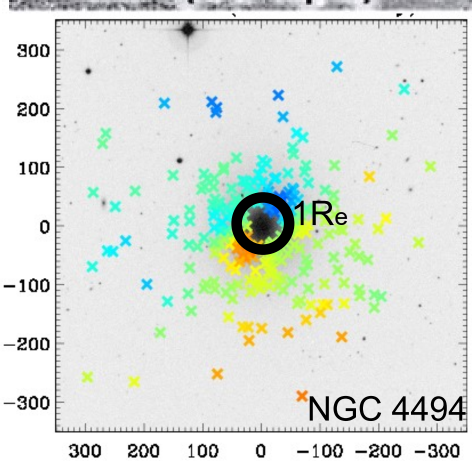


Rationale:

- >50% of the stellar angular momentum
- 95% of the total mass
- **dark matter** dominates
- halo **mostly accreted** (ex-situ) star material
- long settling time scales (~1 Gyr): signatures of the formation processes preserved

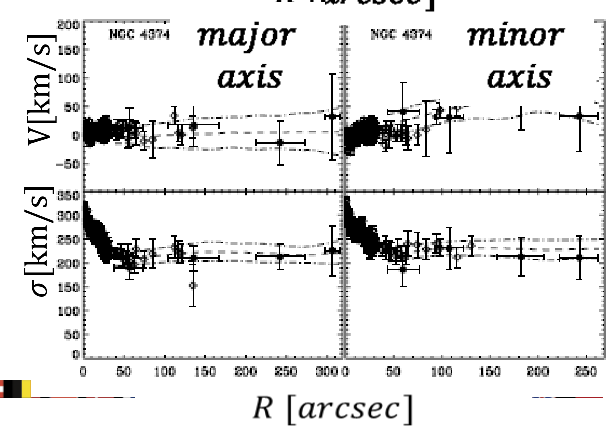
ATLAS3D (Cappellari+2011)
On-going IFS surveys:
MANGA (Bundy+2015)
CALIFA (Sanchez+2012)
SAMI (Croom+2012 - Bryant+2015)
MASSIVE (Ma+2014)
all focused on the central 1-2 Re





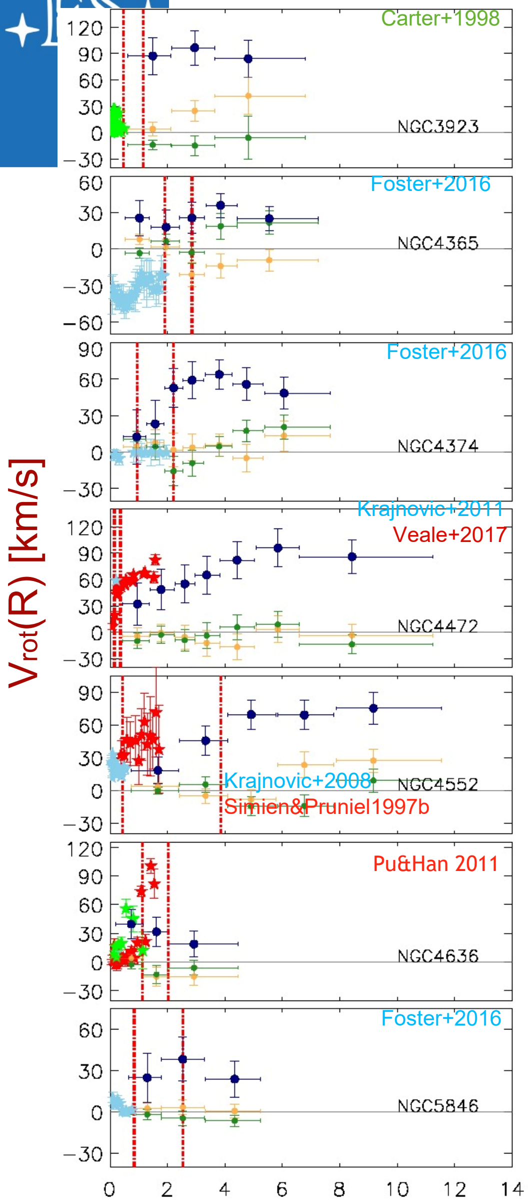
PNe kinematic tracers of stars:

- Bright [OIII] emitters: easily detectable
- PN and stellar kinematics agree in the overlap regions

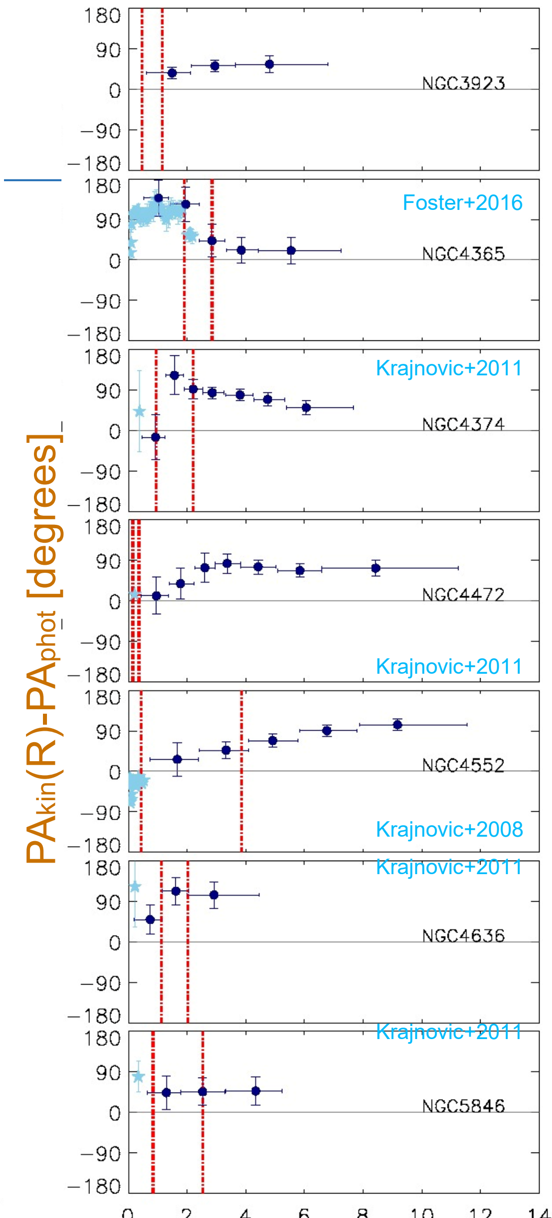


Slow Rotators

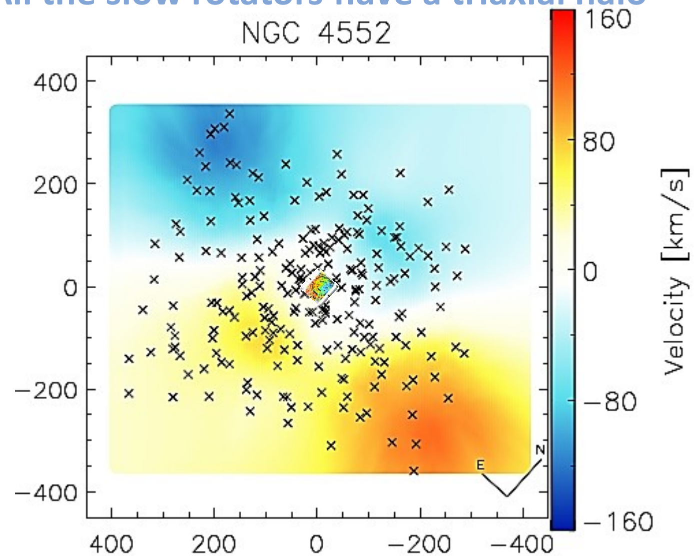
- **Flat velocity dispersion profiles**
- **Increased but still modest rotational support at large radii**
- **Twists or misalignments of the PAkin are commonly observed**
- **All the slow rotators have a triaxial halo**



Major Axis Distance / Re



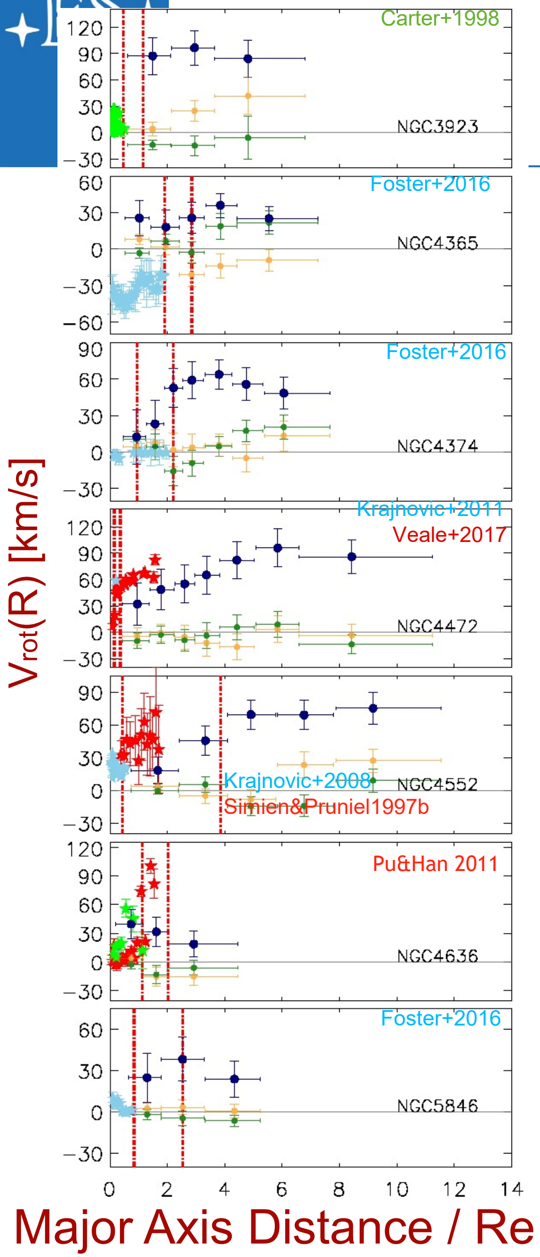
Major Axis Distance / Re

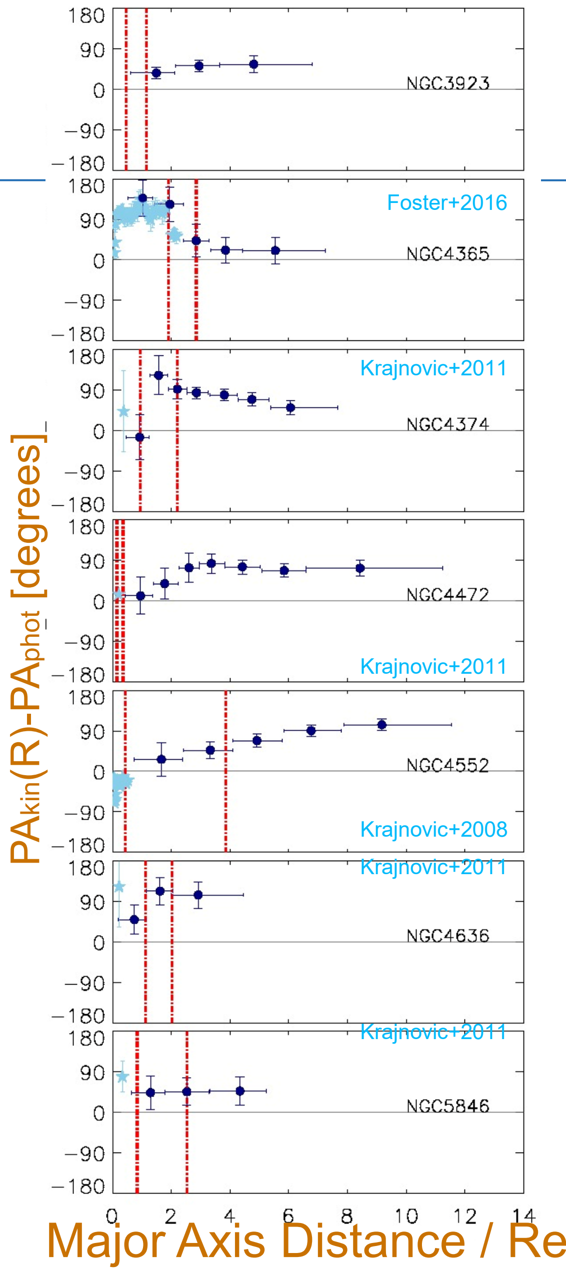


Pulsoni et al. 2018, A&A, 618, 94

$$f(R,\varphi) = V_{sys} + V_{rot}(R)\cos[\varphi - PA_{kin}(R)] + \text{higher order harmonics}$$

Slow Rotators





- Flat velocity dispersion profiles
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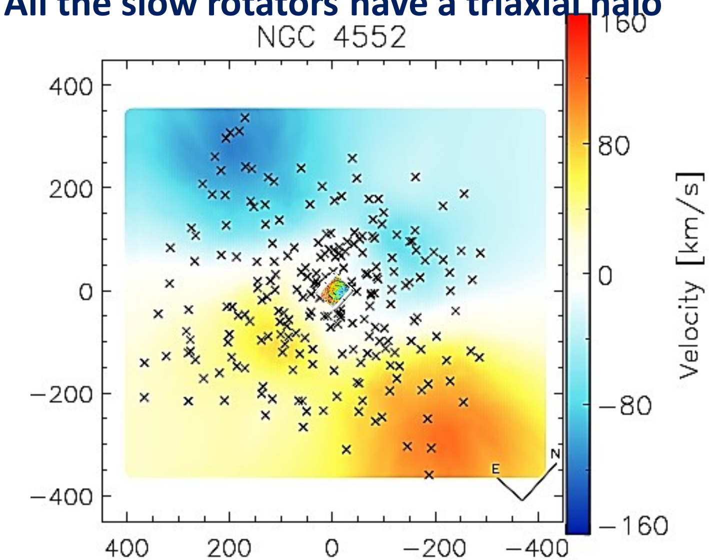
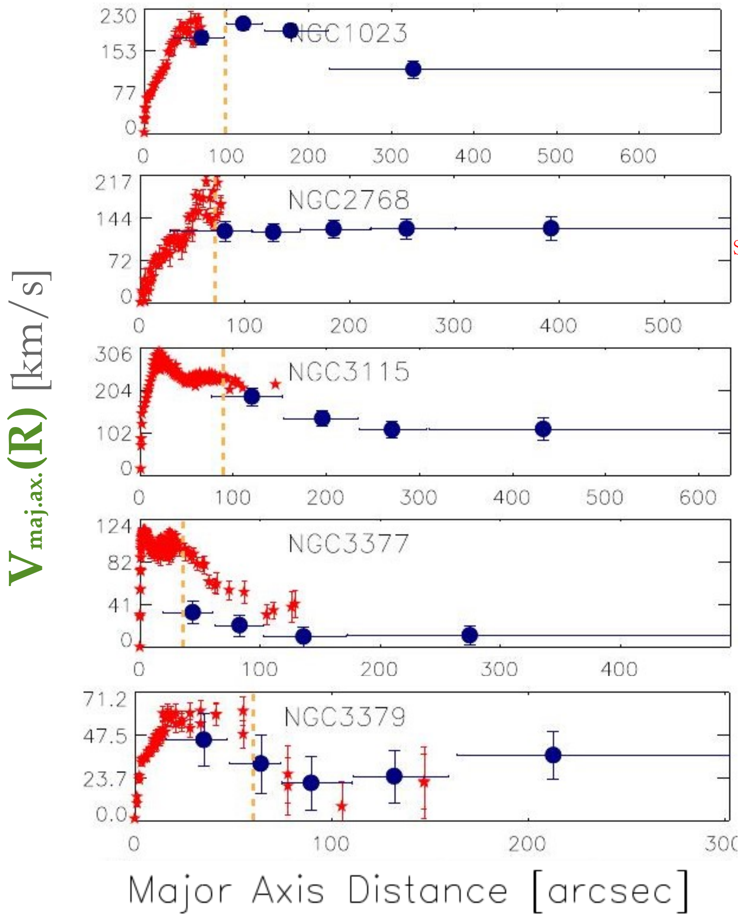


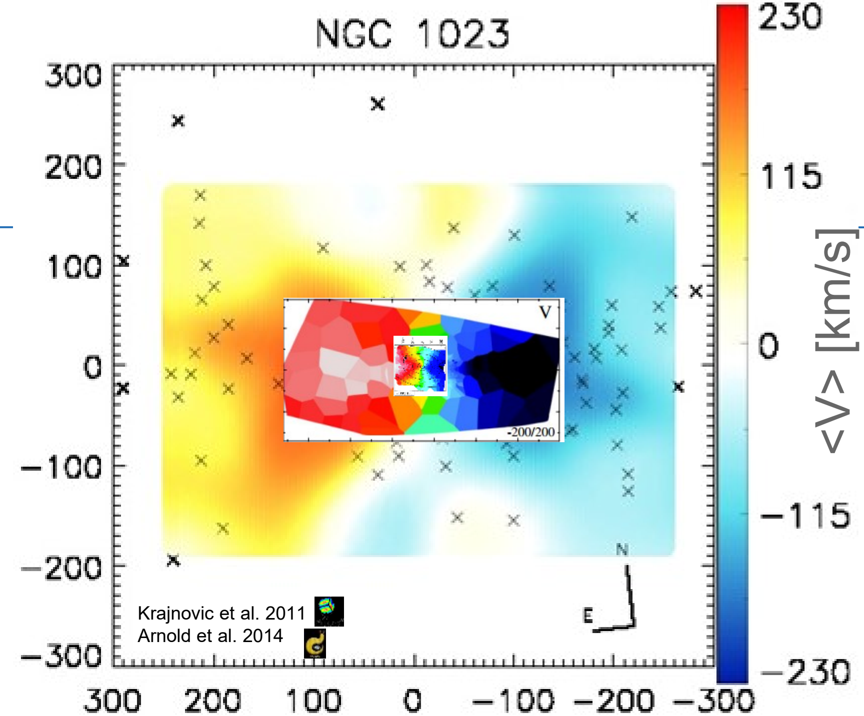
Pulsoni et al. 2018, A&A, 618, 94

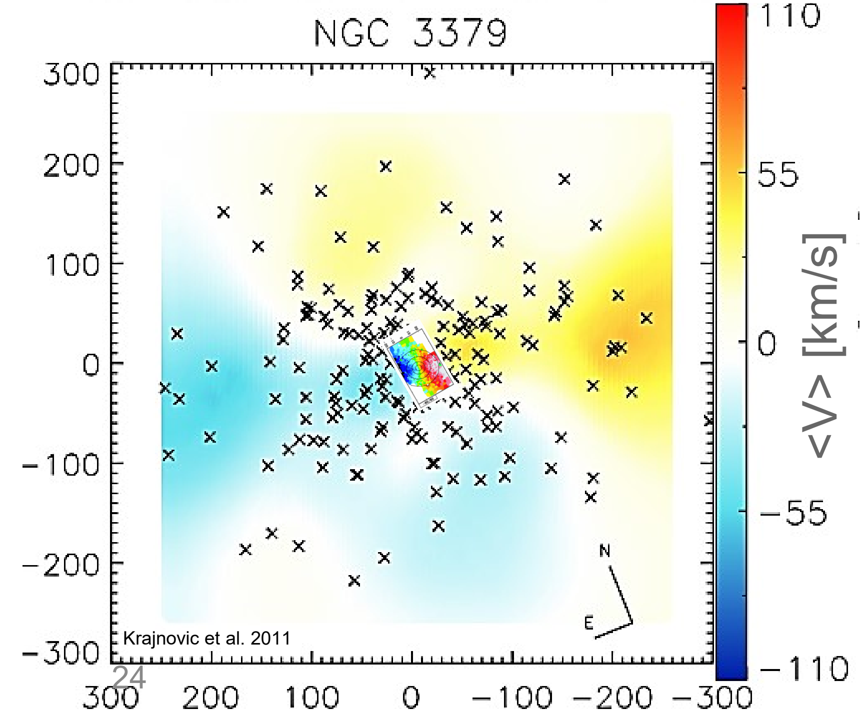
$$f(R,\varphi) = V_{sys} + V_{rot}(R)\cos[\varphi - PA_{kin}(R)] + \text{higher order harmonics}$$

Fast Rotators

- **Declining rotation profiles along the major axis from fading disc structure (but 30% are dominated by rotation at large R)**







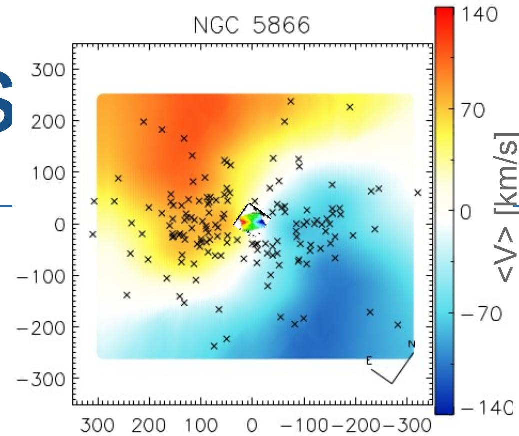
References for the photometry:
Krajnovic+2013, Cortesi+2013

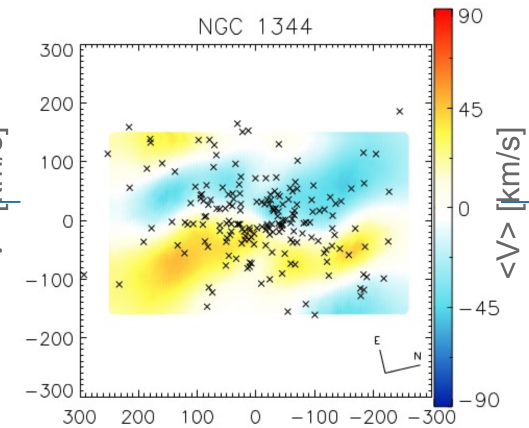
$$\tilde{V}(R,\phi) = V_{maj.ax.}(R)\cos(\phi - PA_{phot})$$

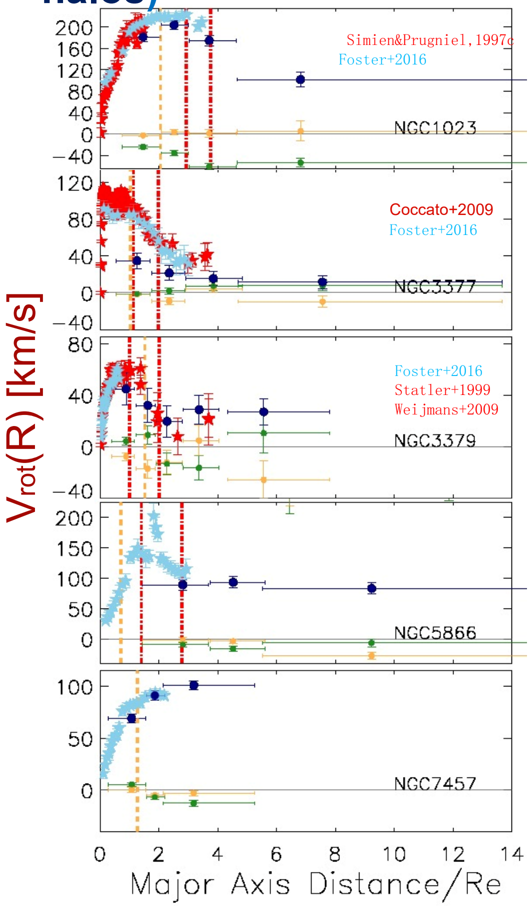
Fast Rotators

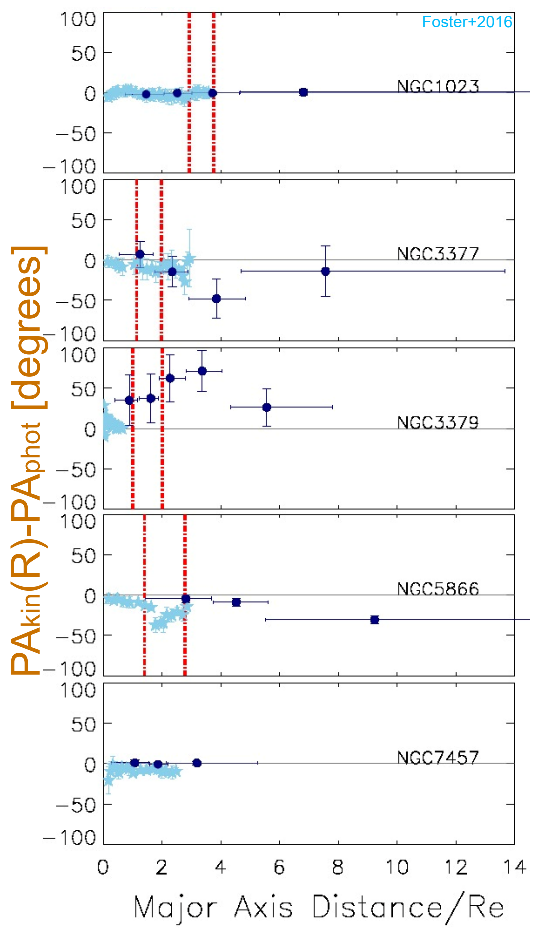
- **Declining rotation profiles along the major axis from fading disc**

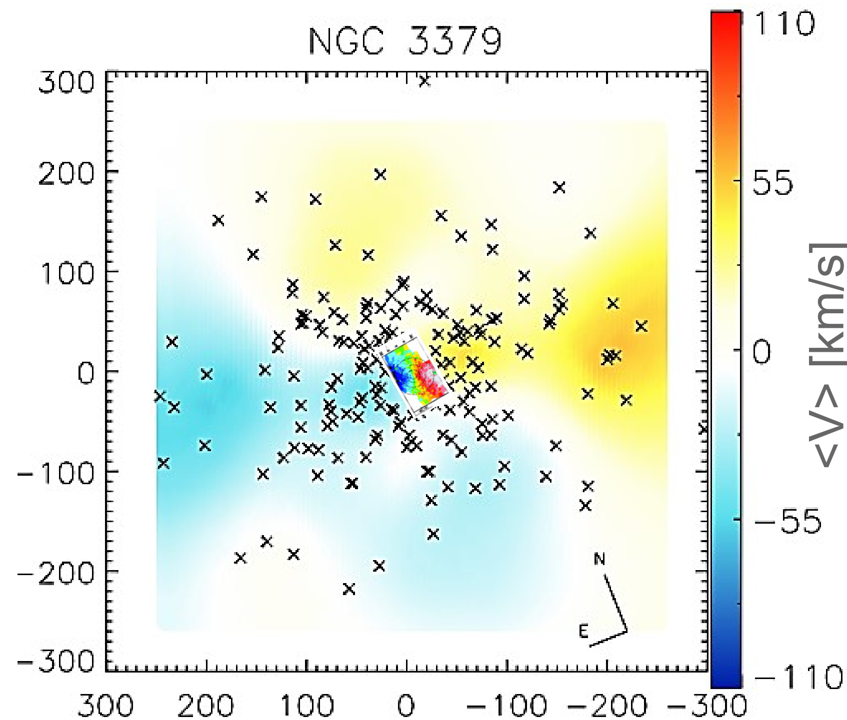
- **40% of the fast rotators display a kinematic twist or a constant misalignment (triaxial halos)**





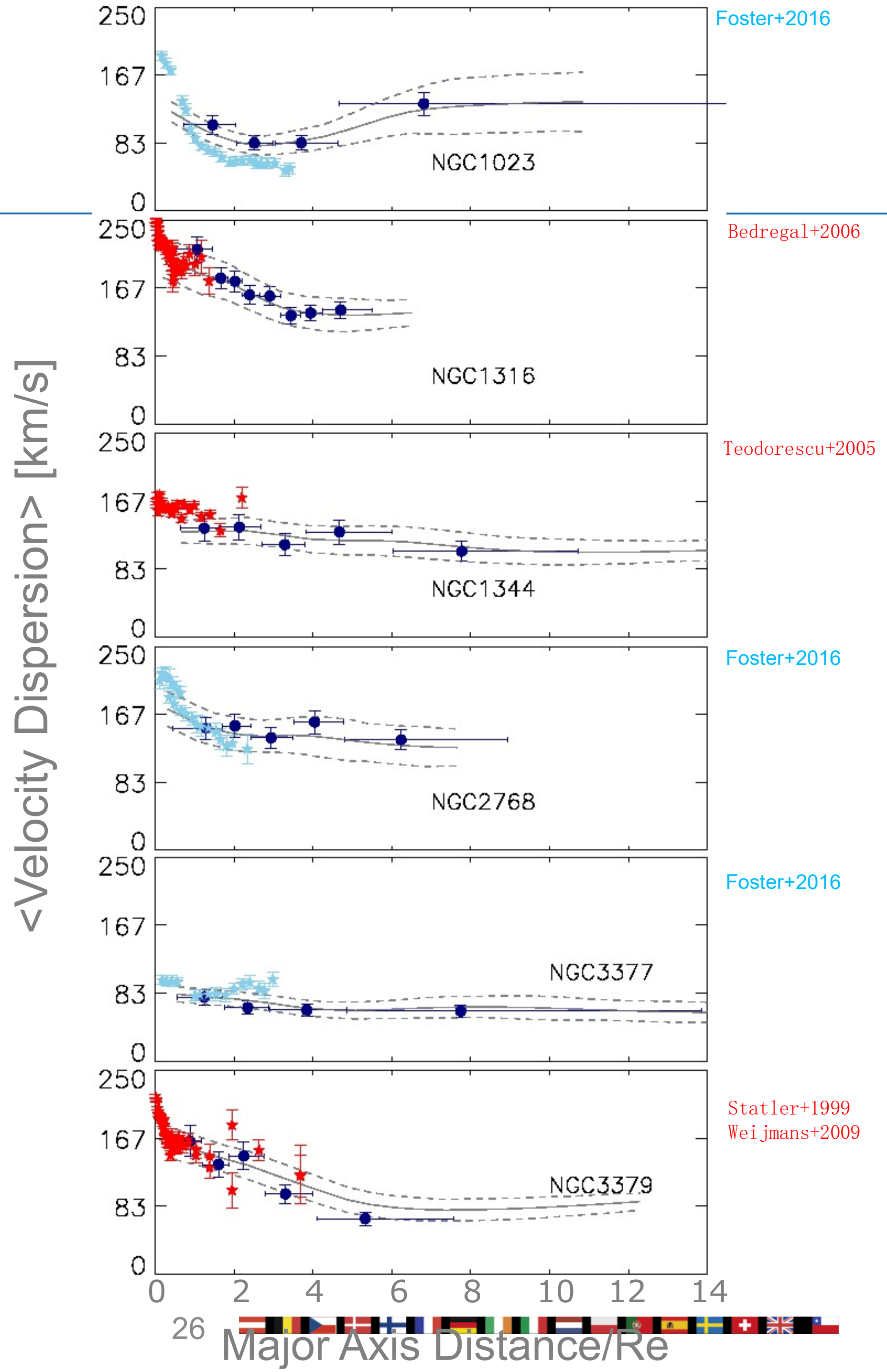






Fast Rotators

- Declining rotation profiles along the major axis from fading disc structure (but 30% are dominated by rotation at large R)
- 40% of the fast rotators display a kinematic twist or a constant misalignment (triaxial halos)
- **Velocity dispersion profiles are found to be either constant or decreasing with radius.**



Take away points: halo kinematics

Pulsoni et al. 2018, A&A, 618, 94

- **PNe are reliable probes for the kinematics of the ETG halos. The wider spatial sampling of the ePN.S survey yields new information about the nature of ETGs.**
- **ETGs halos have more diverse kinematic properties than in the central regions.**

SLOW ROTATORS

- onset of rotation in the halo

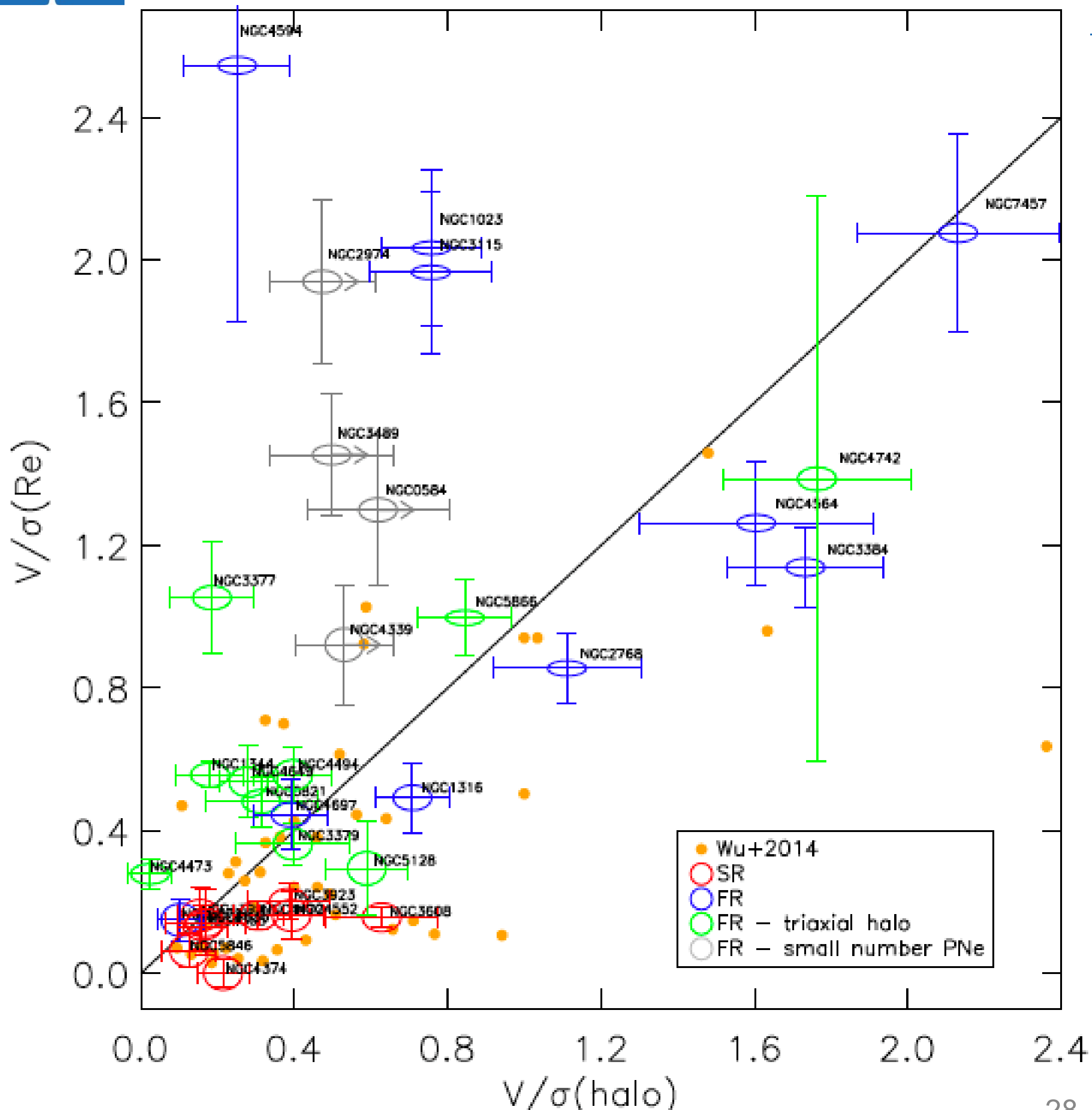
FAST ROTATORS

- 70% with slowly rotating outer spheroid (fading disc in outer spheroid
- 30% rapidly rotating at large radii (extended disc component or rapidly rotating outer spheroid
- 40% triaxial fast rotators (kinematic twists or misalignments, consistent with photometric twist; see below)

For the fast rotators this diversity is consistent with the variety of processes that might drive their evolution (e.g. minor mergers, wet major mergers, gas accretion, interaction with environment..., Duc+2011, Naab+2014, Penoyre+2017, Smethurst+2018)

Halo Vs Central Kinematics

Pulsoni et al. 2018, A&A, 618, 94



SLOW ROTATORS

- onset of rotation in the halo

FAST ROTATORS

- 70% with slowly rotating outer spheroid
- 30% rapidly rotating at large radii (extended disk component or rapidly rotating outer spheroid)
- 40% (10\24) ePN.S fast rotators with evidence of triaxial halo, consistent with presence of photometric twists

Kinematic Transition Radius

Pulsoni et al. 2018, A&A, 618, 94

$R_T \pm \Delta R_T$ is quantified using

(A) the radial interval between V_{rot}^{max} and $V_{rot}^{max} - 50 km/s$

OR

(B) the radial range between $V_{rot} = 0$ and $V_{rot} = 50$ km/s

OR

(C) the radial range in which PA_{kin} changes significantly.

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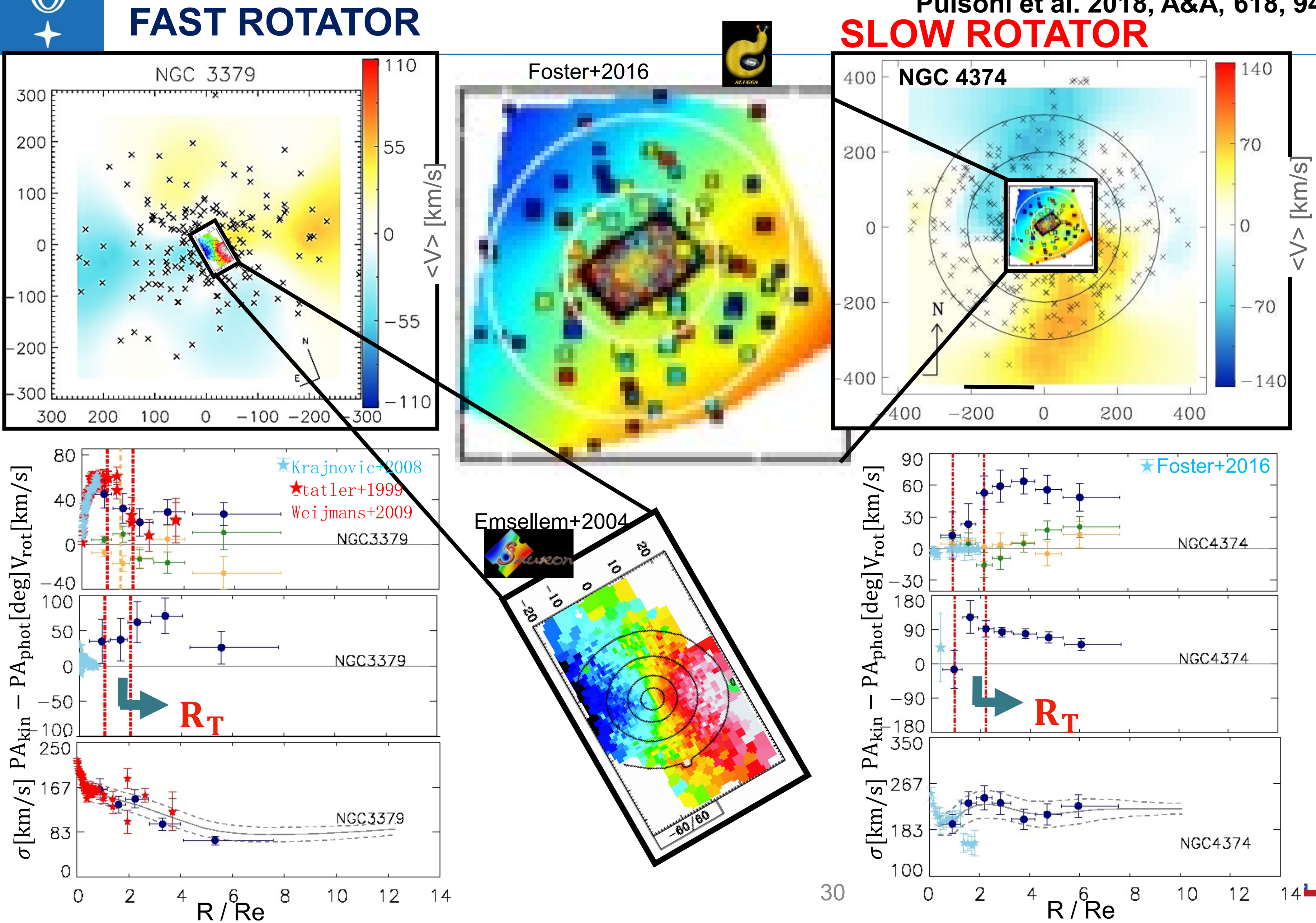

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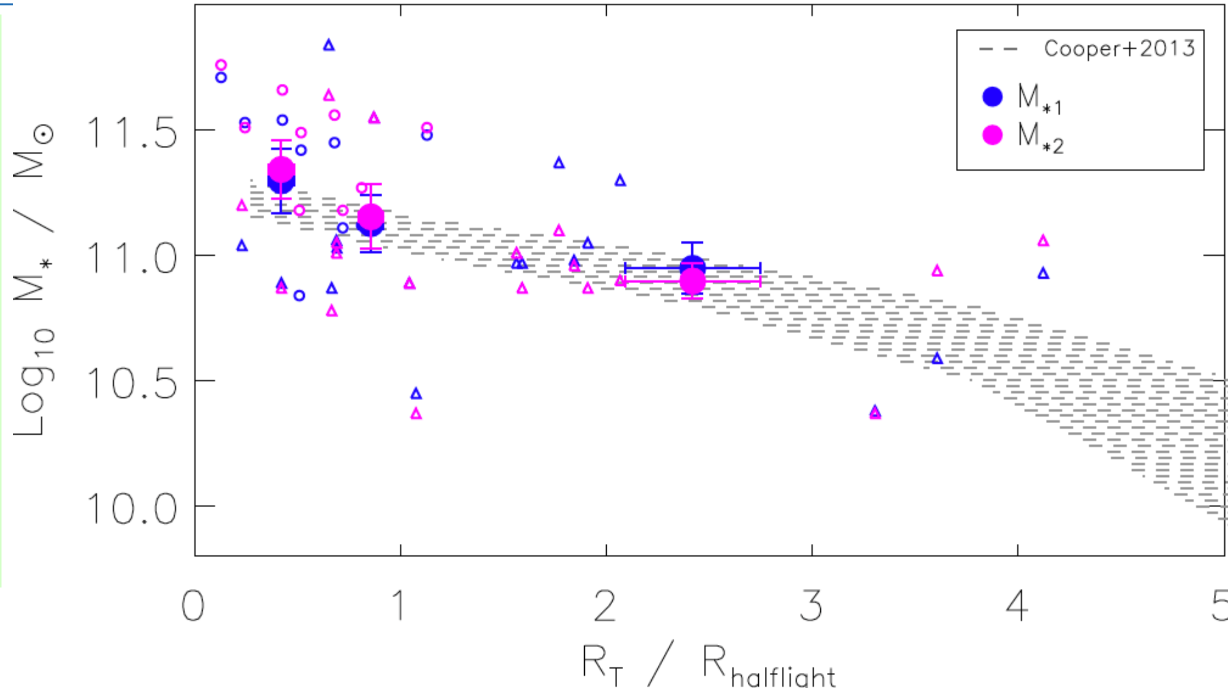
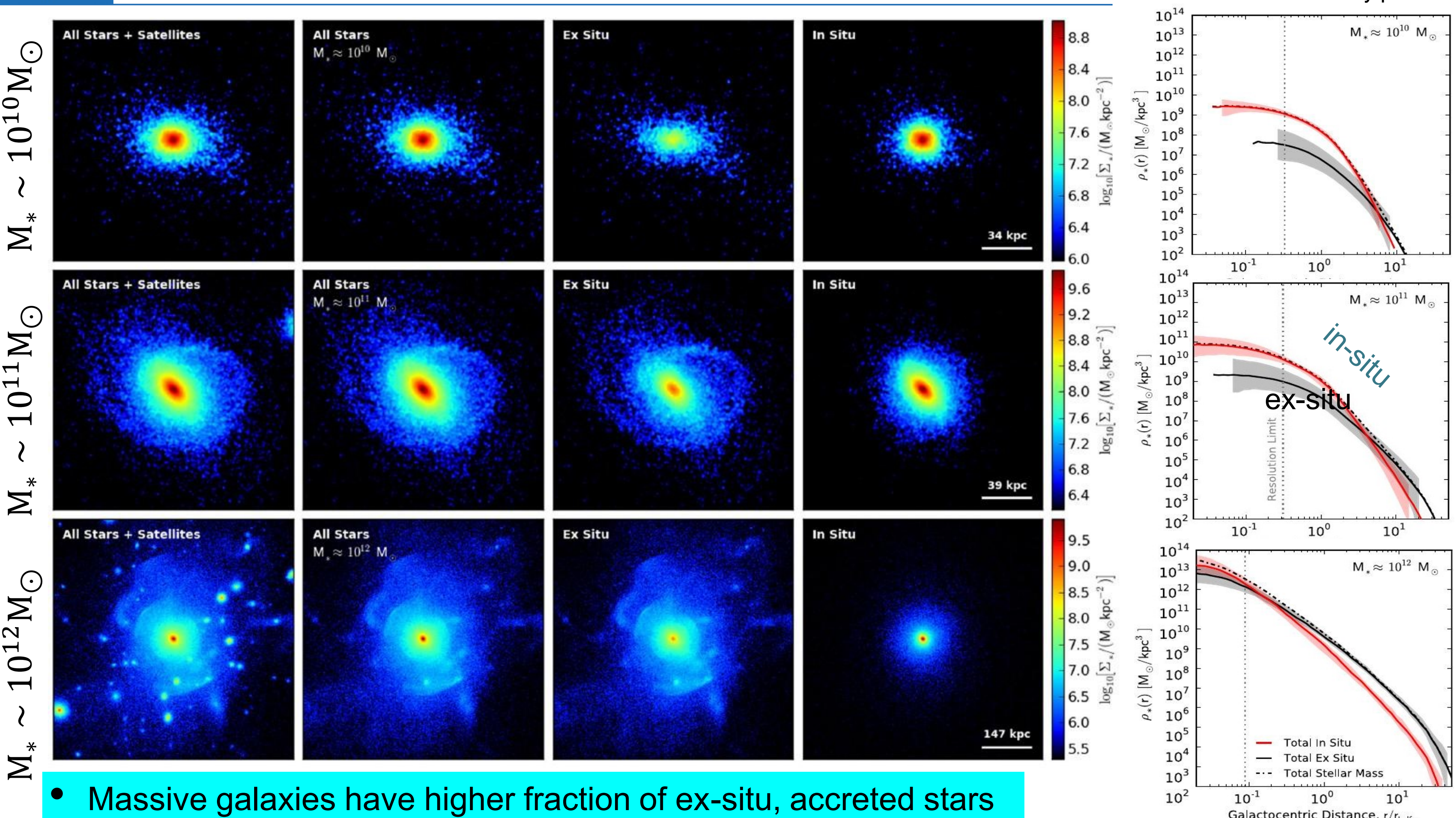


- The kinematic transition from central regions to halos of ETGs **correlates inversely with mass**
- Interpretation: R_T marks the transition between the inner regions, dominated by the **in-situ stellar component**, and the **halo, which is mostly accreted**

Ex-situ vs. in-situ stars (two phase formation scenario)



- Massive galaxies have higher fraction of ex-situ, accreted stars
- Low mass galaxies are mostly made of in-situ stars
- The prominence of the accreted halo depends on mass

Rodriguez-Gomez et al.2016
Illustris simulations

Take away points: ETGs with PN.S

- PNe are reliable tracers for the kinematics of stars, hence they can be used to probe the outer regions of the halos where the surface brightness is too low for absorption line measurements.

  ePN.S survey: 33 ETGs, kinematics out to ~6Re.

- ETGs have more diverse kinematic properties than in the central regions. For ePN.S sample we find:

- SLOW ROTATORS	**onset of rotation in the halo**
- FAST ROTATORS	**70% slowly rotating halo**
	30% rapidly rotating halo
	40% triaxial halo
	(consistent with photometric twists)

- For the fast rotators this diversity is consistent with the variety of processes that might drive their evolution (e.g. minor mergers, wet major mergers, gas accretion, interaction with environment..., Duc+2011, Naab+2014, Penoyre+2017, Smethurst+2018)

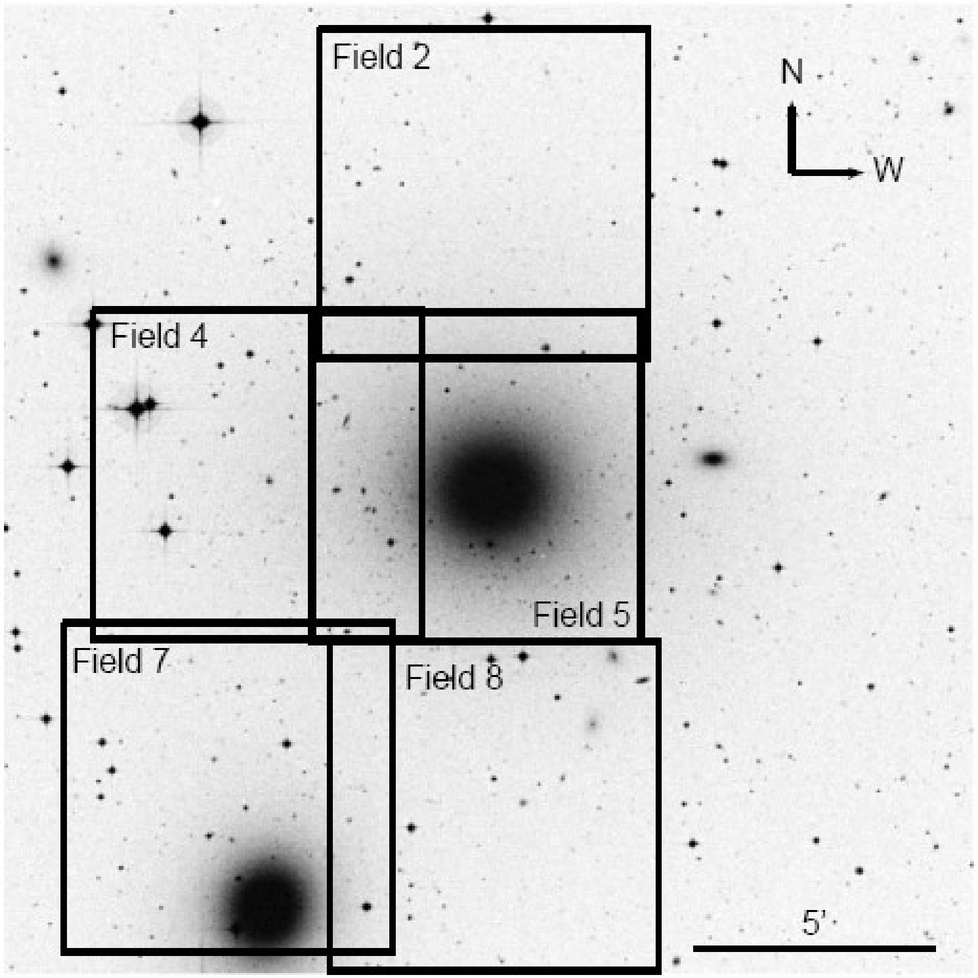
- Kinematic transition radius anti-correlates with stellar mass, in agreement with cosmological simulations. (e.g. Cooper 2013, Rodriguez-Gomez+2016). The fast rotators with triaxial halo are among the most massive galaxies for which the accreted halo is expected to be more prominent.

Outline

- Motivation
- How to observe stellar halos: CDI and MSIS (PN.S@WHT & FORS1/2@VLT)
- The ePN.S survey: diversity of early-type galaxies' halos
- **The extended halos in cD and group dominant galaxies**
- Conclusions

Halos in BCGs : the Fornax cluster

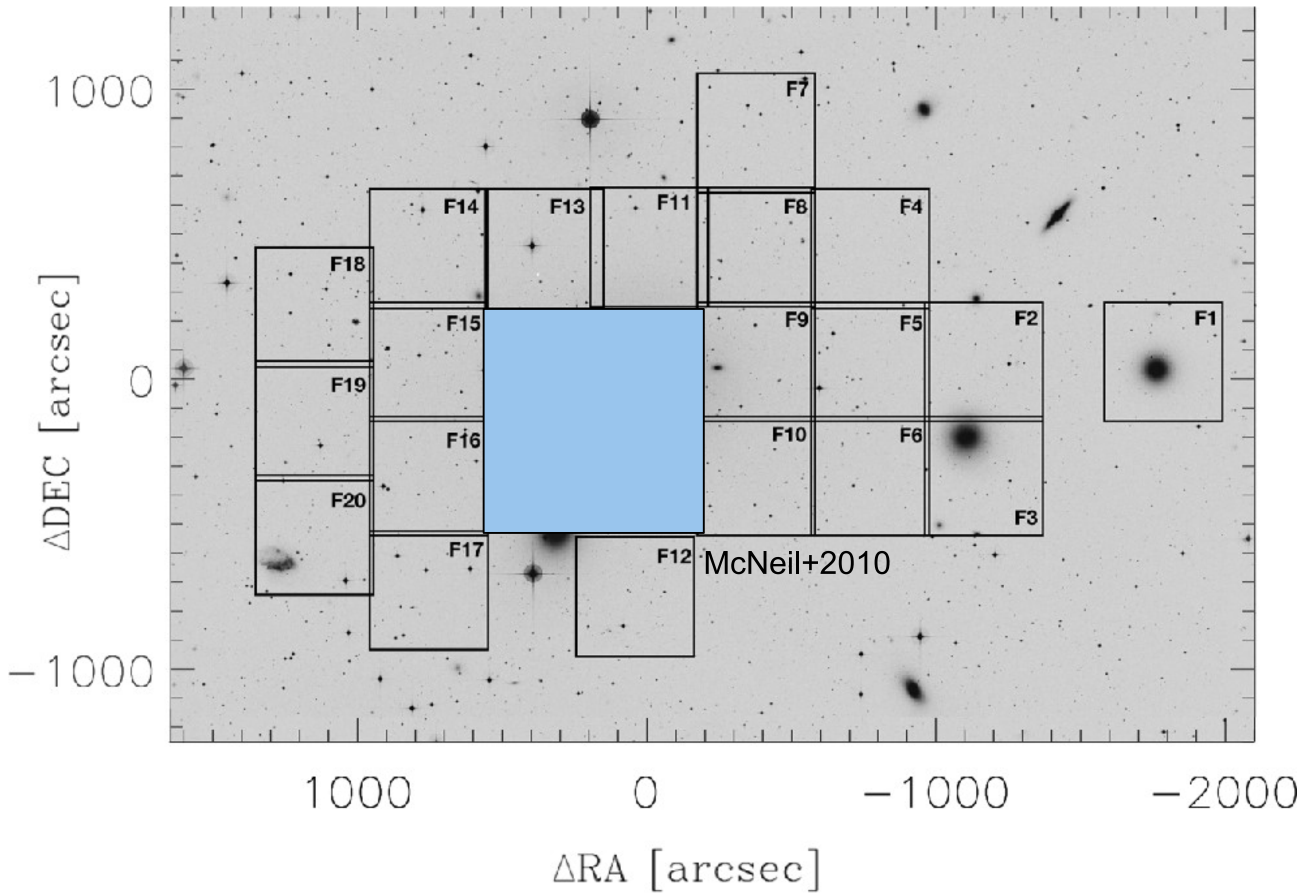
CDI with FORS1@VLT
Mosaicing of several pointings.



E. McNeil et al., 2010, A&A, 518 44

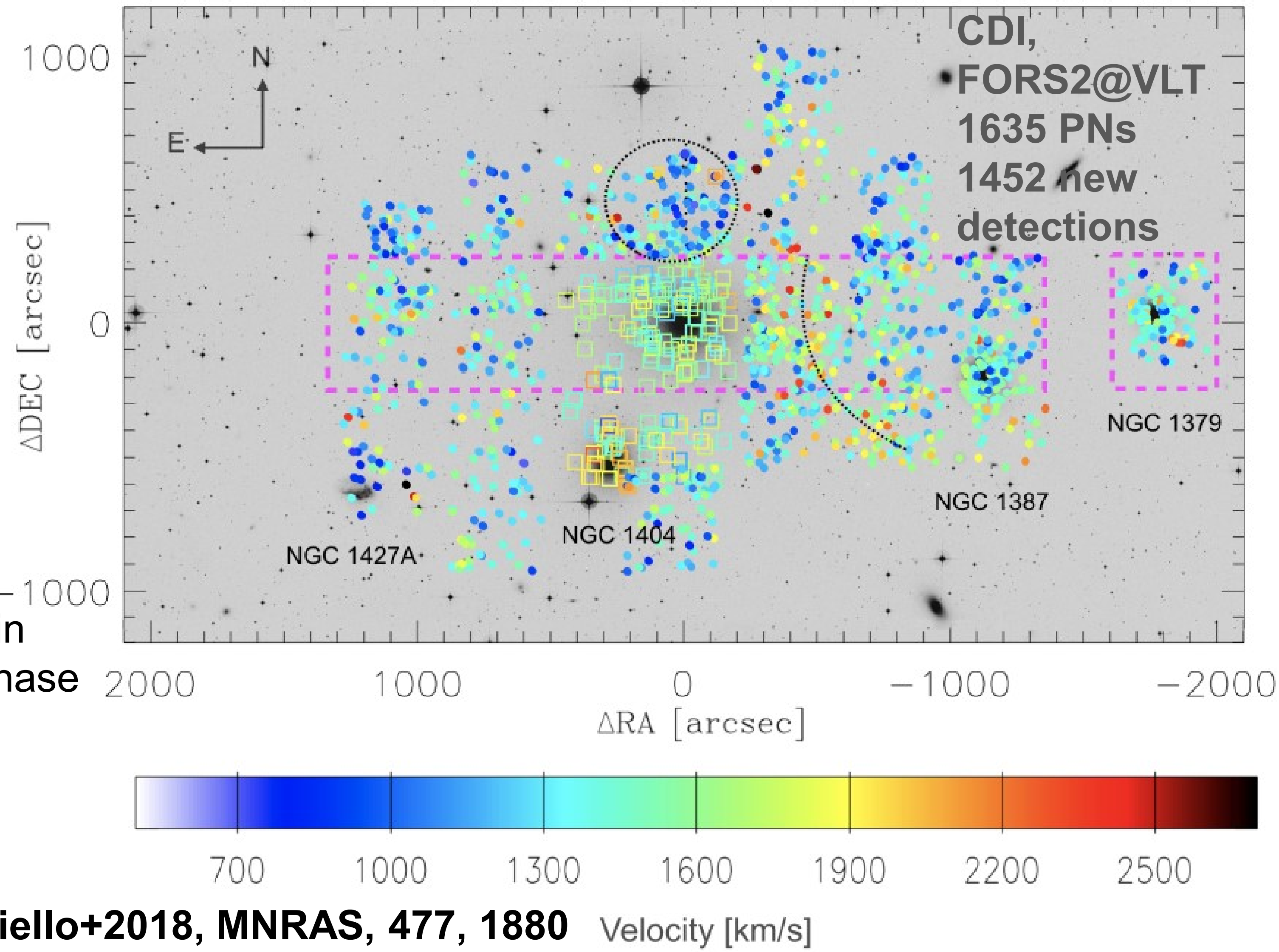
Halos in BCGs : the Fornax cluster

CDI with FORS2@VLT Mosaicing of several pointings.



Spiniello+2018, MNRAS, 477, 1880

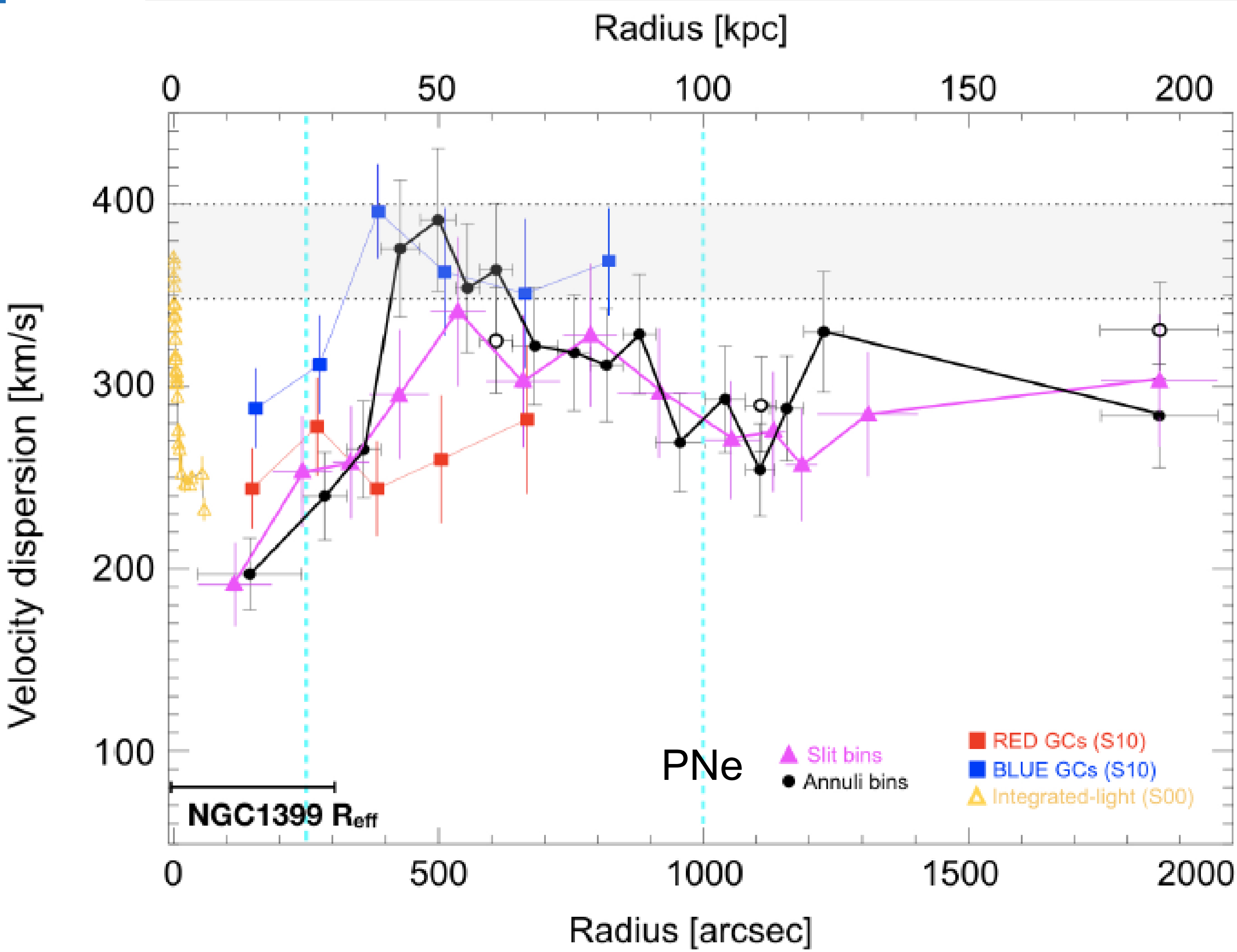
Halos in BCGs: the Fornax cluster



Correlation between structures in light and phase space

Spiniello+2018, MNRAS, 477, 1880

Measuring velocities out to 200 kpc



- R<25kpc: PNs share the dynamical of the central galaxy
- 40 kpc < R < 100 kpc σ_{PNe} rises to clust gal. σ. Contamination from subhaloes
- R> 100 kpc: σ_{PNe} profile flattens; and $\sigma_{ICPN} = \sigma_{cl}$ -80km/s
- The PNe share the same potential of the Fornax cluster but have different spat. distrib. than cluster galaxies

Spiniello+2018, MNRAS, 477, 1880

Take away points: halos in BCGs

- Smooth components around BCGs imply accretion events older than 5 Gyr
- Strong blue gradient down to B-V=0.6 at R> 50-70 kpc in Virgo cluster. HST CMD of resolved stellar population in the ICL indicate [Fe/H] < -1.5
- Galaxy progenitors of outermost halos/IGL/ICL have total stellar mass < 10^8 $M_{sun.}$ Outer halos formed by minor mergers with mass ratios < 1:10. This channel contributes ~ 10% of total light
- Accretion events with mass ratios > 1:10 are clearly identifiable; stellar mass ~ LMC(M49) - 1.5x M33 (M87); leave substructures in phase space, not phase mixes; accreted ~ 1Gyr ago.
- ICL stars in Fornax cluster comes preferentially from satellites on radial orbits that are plunging into the cluster potential

Conclusions

- ETGs have more diverse kinematic properties than in the central regions. For the fast rotators this diversity is consistent with the variety of processes that might drive their evolution (e.g. minor mergers, wet major mergers, gas accretion, interaction with environment, etc.)
- The stars in the very outermost regions of BGCs come from low mass satellites $\sim 10^8$ Msun. Orbital radial anisotropy strongly increases with radius.
- Forward look for FORS
  - Effective complementarity with MUSE for galaxy dynamics studies
  - <u>Enlarge FOV</u>
  - Increase in spectra resolution => constrain satellites' masses
  - Increase efficiency in the blue => enable chemistry using Pne in halos