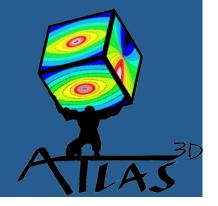
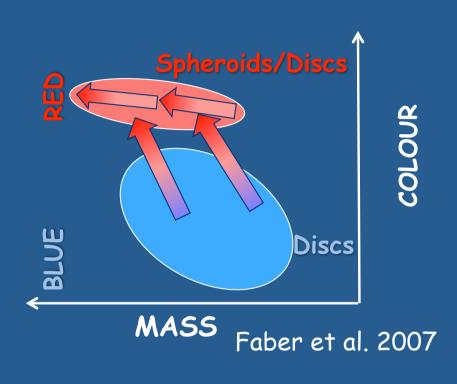
# ATLAS<sup>3D</sup>: IFU driven synergy of multi-wavelength observations

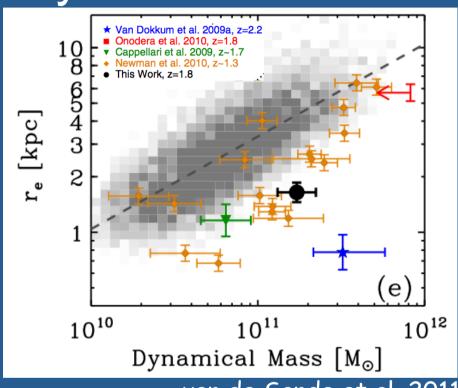
Davor Krajnović





## Hierarchical Galaxy Formation

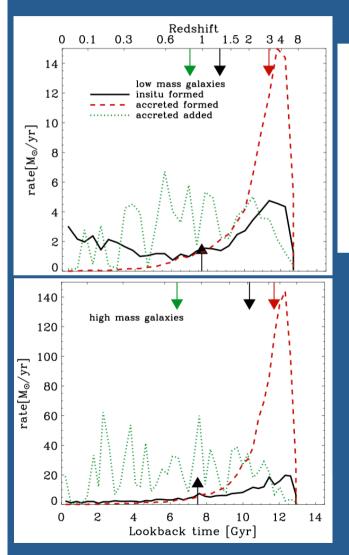




van de Sande et al. 2011

- Bimodal galaxy colour distribution needs merging + feedback to jump from blue to red (Baldry et al. 2004, Bell et al. 2004)
- Red sequence is a mixture of remnants from gas-rich (blue cloud) and gas-poor (red sequence) mergers (e.g.Cattaneo et al. 2006)
- Stellar densities (or sizes) have evolved (decreased) with time

## Two phase formation scenario



Oser et al. (2010)

TABLE 2
THE ASSEMBLY OF STARS IN MASSIVE GALAXIES

	In-situ	Accreted
Epoch	$6\gtrsim z\gtrsim 2$	$3 \gtrsim z > 0$
Baryonic mass source	cold gas flows	minor & major mergers
Size of region	$r_{1/2}pprox 2{ m kpc}$	$r_{1/2} pprox 7 \mathrm{kpc}$
Energetics	Dissipational	Conservative

- Distinction between *in-situ* and *ex-situ* star-formation (SF)
- SF in small galaxies continues today

## Key questions of galaxy formation

- What controls star formation?
- What controls mass assembly?
- What is the relation between these?
- How do we tackle these questions?!?

Goal: determine the key evolutionary processes and understand them in the cosmological context





## Project

M<sub>K</sub> < -21.5 D < 42 Mpc |δ - 29| < 35° |b| > 15°

- Parent sample: 871 nearby galaxies
- Morphological selection: No spiral arms (DSS/SDSS)
- No colour cut
- Observe a complete volume limited sample of ETGs: 260
- Mass range:  $\sim 7 \times 10^9 5 \times 10^{11} \, M_{sun}$

(0056)	00698	100676	·· 100719	CC782	C1024	IC3631	NGC0448	NGC0474	NGC0502	NGC0509	NGC0516	NG00524
		1								-		
SD NG00525	SD/c NGC0651	SO NGCO680	50 NGC0770	5b NGC0821	SC NGC0936	SO NGC1023	'50 NGC112'	50 NGC1222	5C NGC1248	50 NGC1266	, 50 NGC1289	90 VGC1665
50	€.	1	E	ŧ	50	50	50	-50	50	50	50	50
NGC2481	NCC2549	NGC2577	NDC2592	NGC2594	NGC2679	NGC2685	NGC2695	NGC2698	NCC2699	NGC2764	NGC2768	NGC2778
1												
90/c, NGC2824	S0 NGC2B52	SO NGC2859	E NGC2880	90/a NGC2850	S0 NGC2962	90 NGC2974	90 NGC3032	SO NGC3073	E NGC309R	SC NG03156	E NG3.3182	E \\G0.3193
200												
SD NGC 1225	So NGC3230	50 NGC3245	90 NGC3248	SD NGC3301	SO NGC3377	NG03379	SO NGCASR4	50 8003400	SC NGC3412	SC NG03414	90/a NGC3457	E NGC3458
E	50	50	50	50/0	E	Ę	50	50	5C	50	E	50
NGC3489	NGC3499	NGC3522	NGC3530	NGC3595	NCC3599	NGC3605	NGC 3607	NGC3608	NGC3610	NGC 361 3	NGC3819	VGC3826
50	\$0/c	1	50/a	50	SO	ε	50	E	E	E	SO	SO.
NGC 36 50	NCC3640	NGC3641	NGC3648	NCC3658	MCC3665	NGC 3674	NGC 3694	NGC 3757	NGC 3796	NCC3838	NC23941	NCC 3945
02 BBB8000M	NCC4025	NCC4036	SO NOC4078	S0 NGC4111	S0 NCC4119	90 NOC4143	E. NGC4150	S0 NCC4168	90/d NCC4179	90/a N004191	S0 NG24203	90 NGC4215
SD NGC4233	90 NGC4249	50 NGC4251	90 NGC4255	S0 NGC4259	S0 NGC4261	90 NGC4282	90 NGC4284	E HGC4267	SC . NGC4268	90 NGC4270	S0 NGC4278	90 9004281
			-									
SD	50 NGC+324	SO NGC4.339	50	50	E	so	50	50 NGC4371	50/e	50 NGC4527	E	SO
NGC+283	NGC+324	NGC4339	NGC4340	NGC4342	NGC4348	NGC4350	NGC4365	NGC4371	NGC4574	NGC4377	NGC4379	NGCA382
	50		so	so	śo	so	r.	30	6	SC	so	SO
NGC4367	NGC+40B	NGC4417	NGC4425	NGC4429	NGC4454	NGC4435	NGC4442	NGC4452	NGC4458	NGC4459	NG24461	NGC4472
								1		4		
E NGC4473	NGC4474	50 NGC4476	50 NGC4477	S0 NGC4478	NGC44B3	NGC4486	90 NGC4486A	100 NGC44B9	NGC4494	SC NGC4503	NG24521	E 1GC4526
E NGC4528	50 NGC4546	50 NGC4550	90 NGC4551	E NGC4552	SQ NGC4564	E NGC4570	E NGC4578	E NGC4596	E NGC4608	SC NGC4512	90/a NG04521	90 VGC4623
						-						
50	50	SQ .	Ε	E	E	50 NGC4684	50	30	30 NGC4697	50	E	30 NGC4/53
NGC4624	NGU+658	NGC463B	NGC#643	NGC4649	NGC4660	NGC4004	NGC4690	NGC4694	NGC-469	NGC4/10	N654733	165.4755
.80	E	so	80		E	- 80	90	30		80		80
NGC4754	NGC4752	NGC4833	NGC5103	NGC5173	NGC5 198	NGC5273	NGC5308	NGC5322	NGC5342	NG05353	NG25355	VGC5358
	* )											en la
NGC5379	50 NGC5422	50/e NGC5473	50/e NGC5475	E NGC5481	NGC5485	50 NGC5493	90 NGC5500	NGC55D7	SC NGC5557	SC NGC5574	NG05576	VGC3582
	/		•									
NGC5611	SU NGC5631	50 NGC563B	Sa NGC5687	L NGC5770	SU NGC5813	90 NGC5831	L NGC5838	SU NGC5839	L NGC5845	SC NG05846	L NG05354	VGC5864
SD NGC5866	50 NGC5859	NGC6010	50 NG06014	S0 NG05017	E NGC8149	E NGC627E	. 50 • NGC6547	50 NGC6548	E NGC8703	- NGC6798	S0 NG07280	S0 VGC7332
50	50	50/0	50	E	50	50	50	50	5C	50	50	50
NGC7454	NCC7457	N0C7485	NDC7693	NGC7710	P00016080	PCC028887	P0C029321	PGC035754	PGC042549	PCD344433	P0C050395	P00051753
	sn .	so	50	so	. 50	S0/o	5075	50		\$0/a	50 /a	50/6
PGC054452		PGC058114	PC8061468	°GC071531		UGC33960	50/5 UGC04551	UGC05408	UG006062	UGC06176	50/a UGC08876	SO/e UGC09519
												*
20	, 50	so	S0/a	E	E	E	50	SO	SC	sc	90/a	90

# Comprehensive approach

ODSERVATIONS								
Optical Spectra	Optical imaging	Radio	mm	NIR spectra	Archive			
SAURON IFU	MegaCam, INT	WRST, EVLA	IRAM 30m Carma	NIFS, SINFONI	2MASS, SDSS, HST, Spitzer, Chandra, Galex, Herschel			

	MODELLING AND SIMULATIONS								
Dynamics	Stellar populations	High-res sim. binary mergers	High-res sim. of gas in ETGs	Cosmological simulations	Semi- Analytic Models				

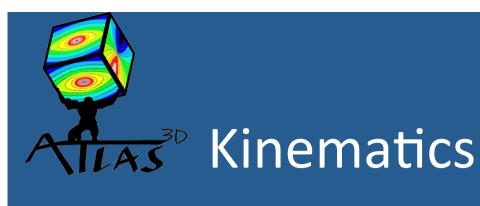


PIs: Michele Cappellari (Oxford), Eric Emsellem (ESO), Davor Krajnović (ESO), Richard McDermid (Gemini)

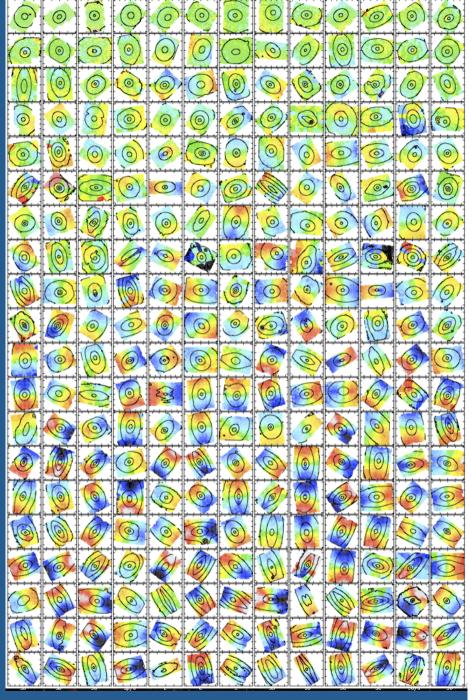
#### Researchers:

Katey Alatalo, Estelle Bayet, Leo Blitz, Maxime Bois, Frederic Bournaud, Martin Bureau, Alison Crocker, Jean-Charles Cuillandre, Roger Davies, Tim Davies, Tim de Zeeuw, Pierre-Alain Duc, Etienne Ferriere, Jesus Falcon-Barroso, Sadegh Khochfar, Harald Kuntschner, Pierre-Yves Leblanche, Leo Michel-Dansac, Raffaella Morganti, Thorsten Naab, Kristina Nyland, Ludwig Oser, Tom Oosterloo, Marc Sarzi, Nicholas Scott, Paolo Serra, Kristen Shapiro, Remco van den Bosch, Glenn van de Ven, Gijs Verdoes-Kleijn, Anne-Marie Weijmans, Lisa Young

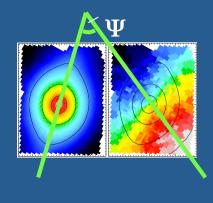
(36 researchers in ~16 institutes)

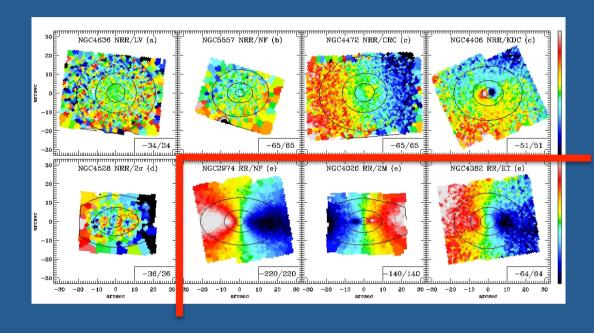


- Large variety of kinematic features
- Classification of velocity structures
- Measurement of stellar angular momentum



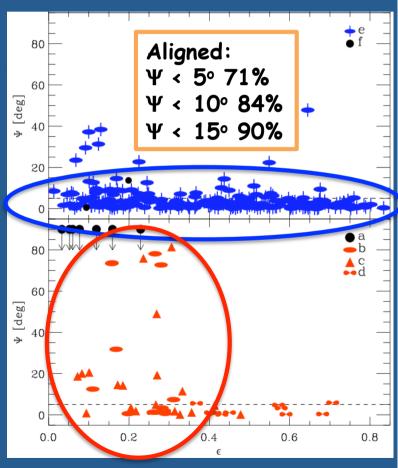
#### Kinematics



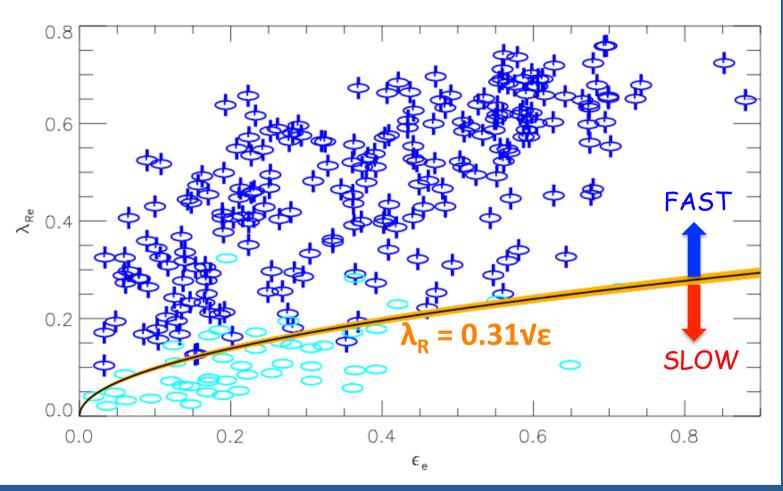


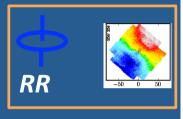


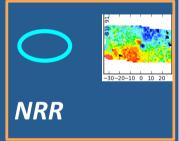
- RR: aligned → nearly axisymmetric systems (+ bars!)
- NRR: (also) misaligned → triaxial systems



## Proxy for angular momentum



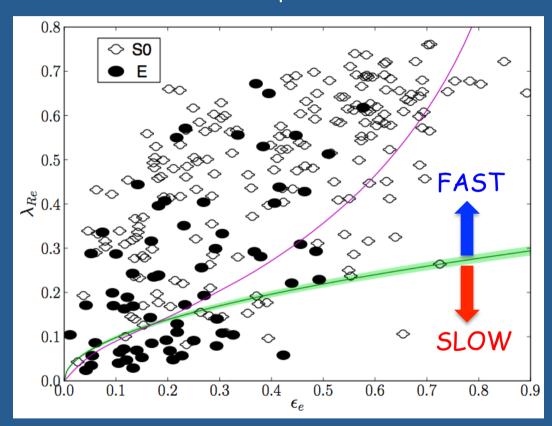




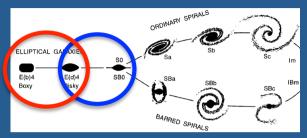
- $\lambda_R$  depends on the flattening ( $\epsilon$ )
- Emsellem, et al. 2011, Paper III
- 85% of all nearby ETGs are fast rotators

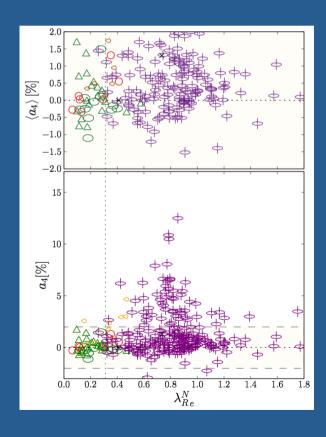
# $\lambda_R$ vs Hubble classes

Emsellem et al. 2011, Paper III

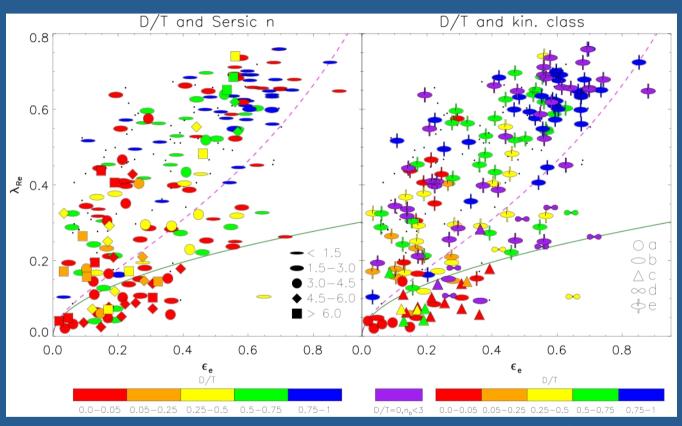


- 66% of E are FR
- 20% of FR are E
- FR ≈ S0 + E(d)
- SR = true ellipticals





## Are there discs in ETGs?



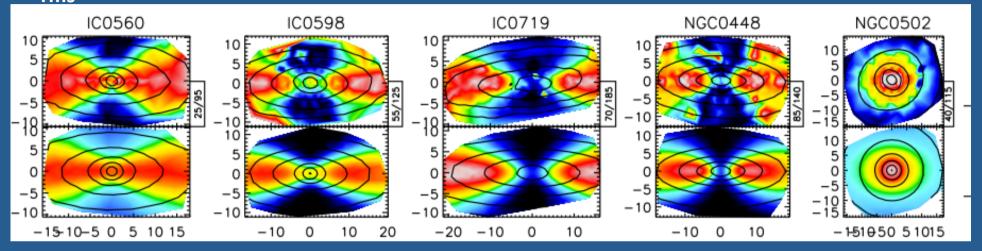
Sersic +
exponential
fits to 180
non-barred
ATLAS<sup>3D</sup>
objects (r
band SDSS
+INT
imaging)

Krajnović et al. 2012, Paper XVII

- Exponential components in ETGs can be associated with regular rotation
- FR: two comp. systems or 1 comp. of low Sersic n
- SR: 1 comp. systems with large Sersic n

## **Dynamics**

 $V_{rms} = V(v^2 + \sigma^2)$ 

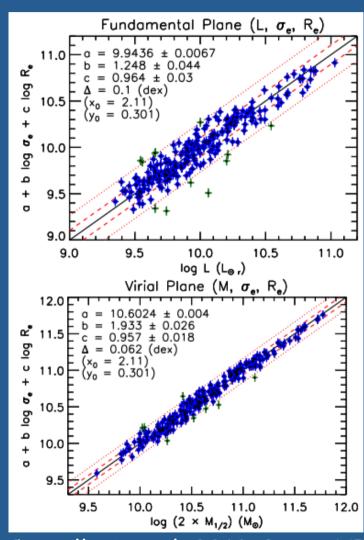


Cappellari et al. 2012, Paper XIX

- Dynamical models for all sample galaxies accurate dynamical masses
- MGE (Emsellem et al. 1994)+ JAM (Cappellari et al. 2008) models: two parameters:  $(\beta_7, i)$
- Mass follows light models: kinematics well reproduced:
  - DM is not important or traces light precisely

## Role of DM and the Virial Plane

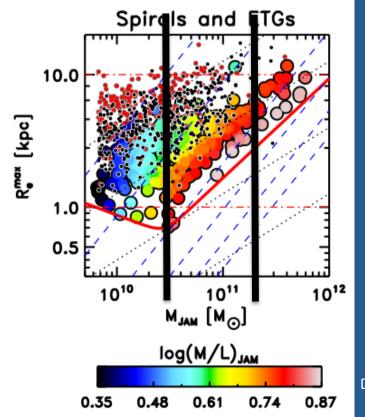
- 12 16% of DM within R<sub>e</sub> on average (depending on the DM parameterisation and model quality)
- $f_{DM} < 39\%$  for 90% of models
- From FP to VP
  - $-L \rightarrow M$
  - Reduction in observed scatter:32 -> 19 %
  - Scatter in FP due to variations in M/L
  - b~2, close to virial prediction
  - Tilt of FP due to M/L variations
- Galaxies are virialized stellar systems



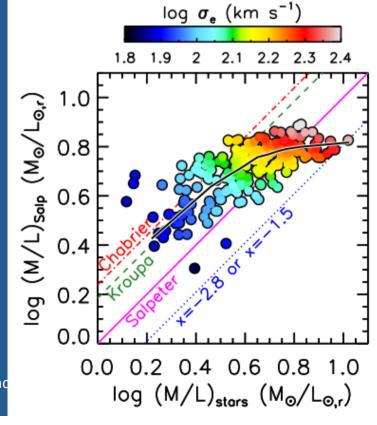
Cappellari et al. 2012, Paper XIX

## Connecting ETGs to spirals

- Two characteristics masses:  $3x10^{10}$  and  $2x10^{11}$  M<sub>sun</sub>
- $\sigma$  best predictor of properties (M/L, H $\beta$ , colour, concentration...)
- Parallel sequence to spiral galaxies
  - overlap for low M/L, break in similarities at large M/L (M or  $\sigma$ )
  - largest M/L ETGs have no counterpart in spirals
- Systematic variation of IMF from Kroupa to Salpeter as function of sigma (M/L)



Cappellari et al. 2012, Paper XX



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### Gas observations

- WRST HI interferometry
  - ~2500 hours (198 galaxies 32 from literature)
  - All galaxies visible from WRST  $(\delta>10^{\circ}+15')$  from Virgo)
- IRAM 30 m single dish
  - Full sample
- Carma CO interferometry
  - 500 hours
  - Flux limited sample of IRAM detections (40 galaxies – 10 from literature)







## HI gas: large scale structures

Detection: strong environmental

dependence: 10% (virgo) vs

**40%** (field)

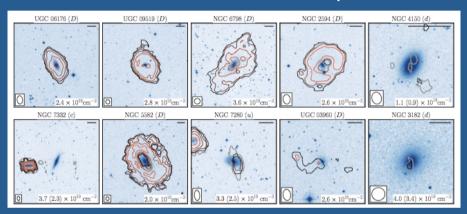
Disc/ring: 64%

Unsettled: 8%

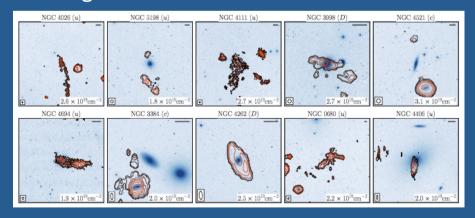
• Clouds: 28%

- A continuum of morphologies:
  - clouds unsettled discs
- Weak trend with luminosity
  - Less HI
  - mostly more perturbed

#### Serra et al. 2012, Paper X



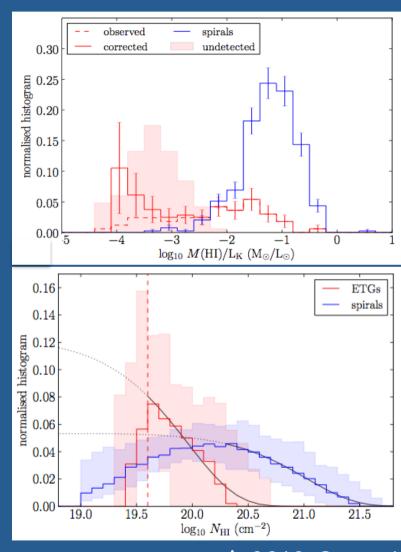
#### 10 galaxies in least dense environment



10 galaxies in densest environment

## HI: ETGs vs Spirals

- HI provides material for star formation in ETGs
- Overlap with spirals in M(HI) and M(HI)/L<sub>K</sub>
  - $-\log M(HI) = 7-10 M_{sun}$
- less HI than spirals, but
- many ETGs have similar amount of HI as spirals
- but smaller column densities in ETGS



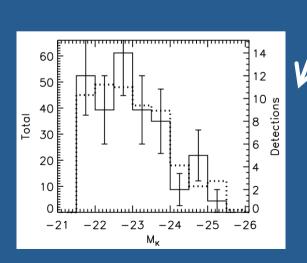
## Molecular gas

Young et al, 2011, Paper IV

#### **IRAM 30m Single Dish Survey**

- Detection rate: 22%
- Molecular gas masses in range 10<sup>7</sup> to 10<sup>9</sup> Msun
- Upper limits down to 6.3x10<sup>6</sup> Msun
- $-\;\;$  Molecular gas fractions: 7% to 0.02% (Msun/L $_{ extsf{k}}$ )
- No detections of molecular gas in slow rotators

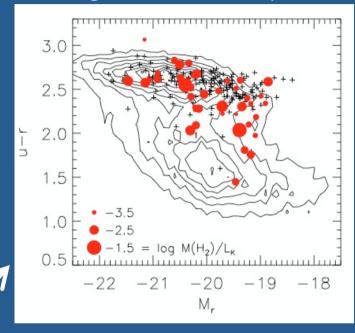
Detection rate independent of luminosity!

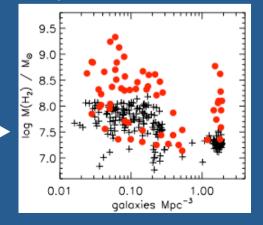


Red and dead? Not really

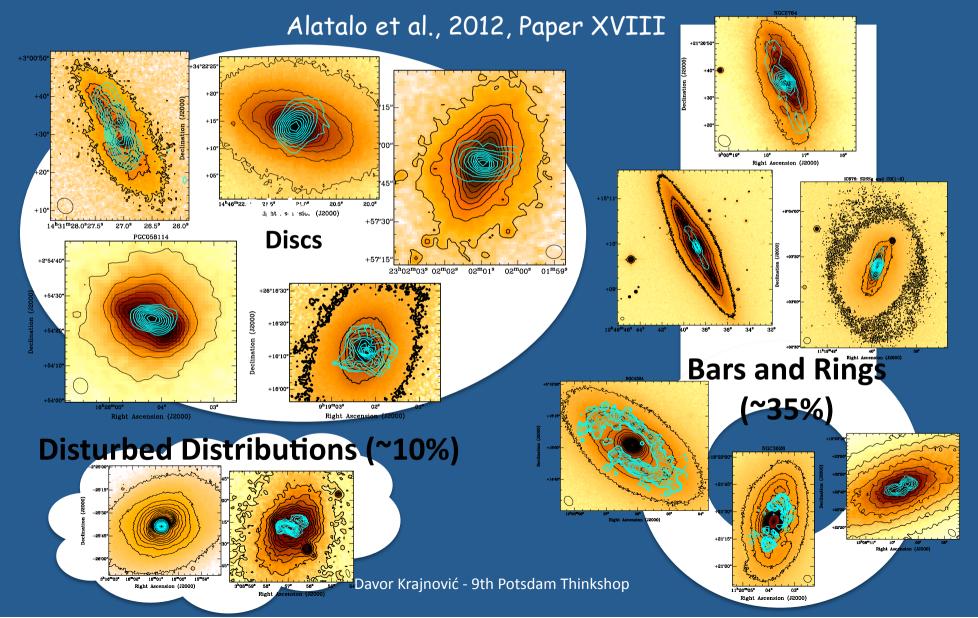
Detection rate also seems to be independent of environment!







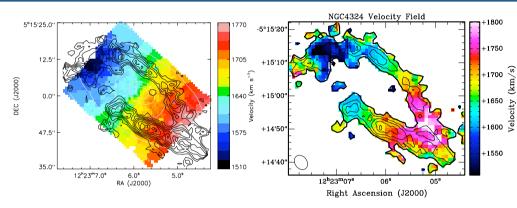
# CO gas morphologies

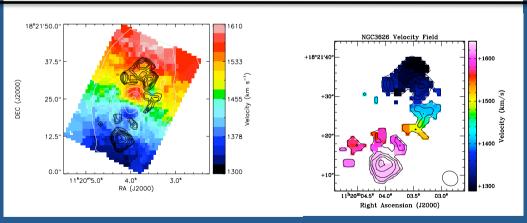


## What is the origin of gas?

- Internal (e.g. stellar mass loss)
  - gas rotates like stars
- External (e.g. cold accretion)
  - all possible orientation (in axisymmetric system coand counter-rotation
- Molecular, atomic and ionised gas often seen to make one single structure (e.g. Morganti et al. 2006, Oosterloo et al. 2010)
- Use large sample in a statistical sense



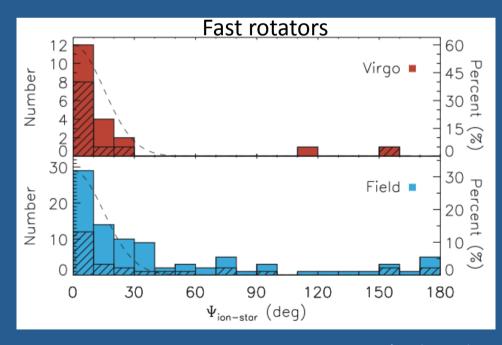


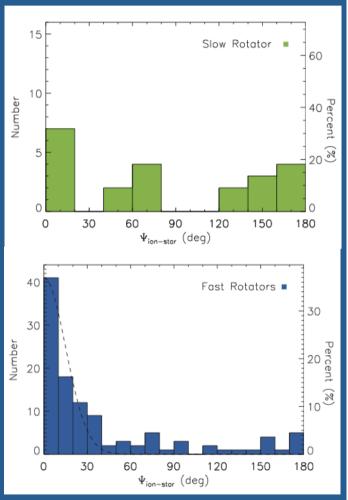


Davis et al. 2011, Paper X

## Alignment with stars

- FR gas mostly aligned, but not all...
- SR aligned and misaligned (similar numbers)
- For FR strong environmental dependence (Virgo/non-Virgo)
- Evidence for at least 46% of objects to have external gas origin





Davis et al., 2011, Paper X

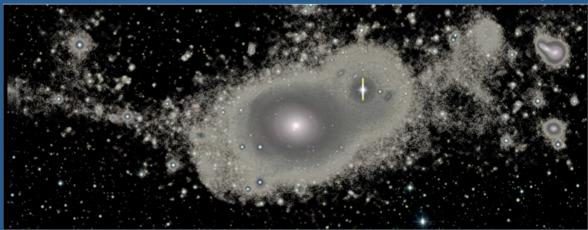
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## Deep imaging

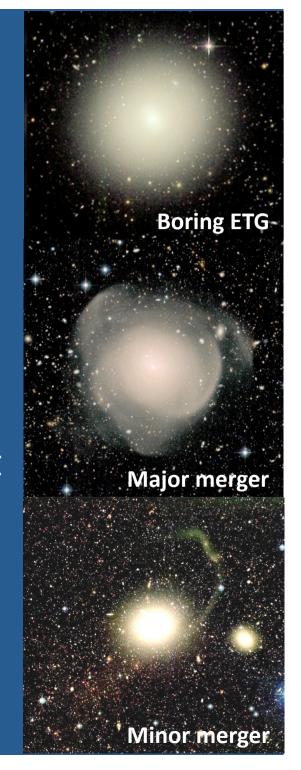
- Multi-band imaging with MegaCam
- Depth: up to 28.5 29 mag/"2 in g band
- ~400 hours of CFHT time (LP starting now)

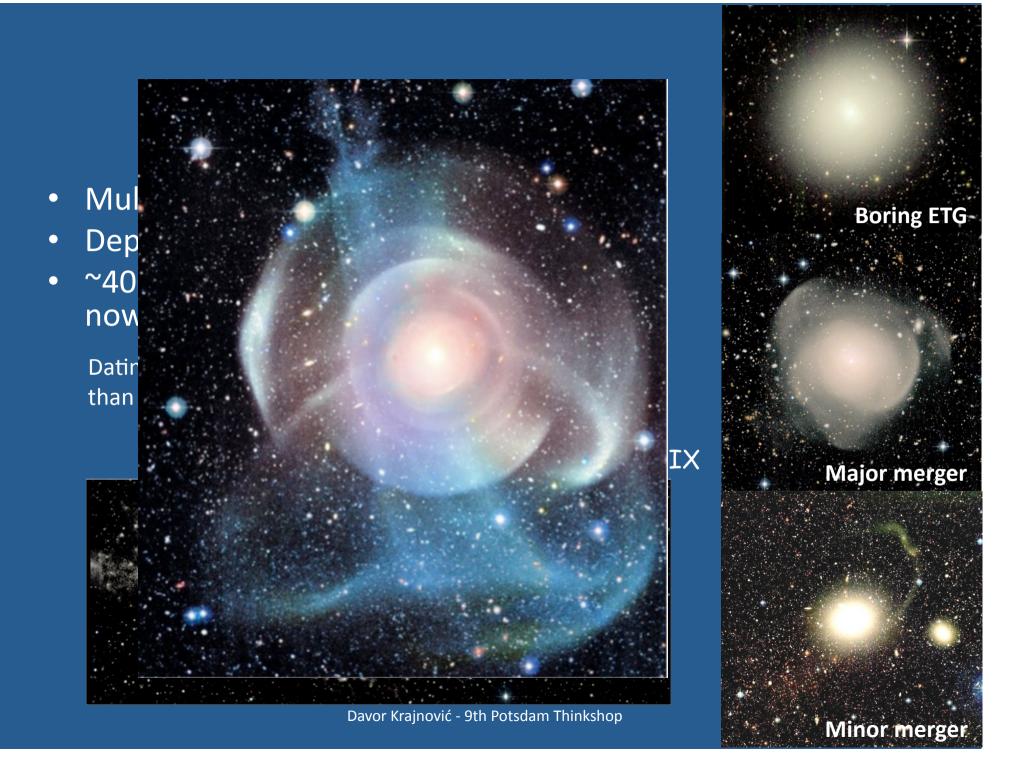
Dating the merger: major wet, not younger than 1 Gyr, but merger happened after z<0.5

Duc et al. 2011, Paper IX



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### Outlook

- Synergy of multi-wavelength observations is not a new concept, and it really works!
- Parallelism and continuity in physical parameters between early-type and spiral galaxies (Paper VII)

