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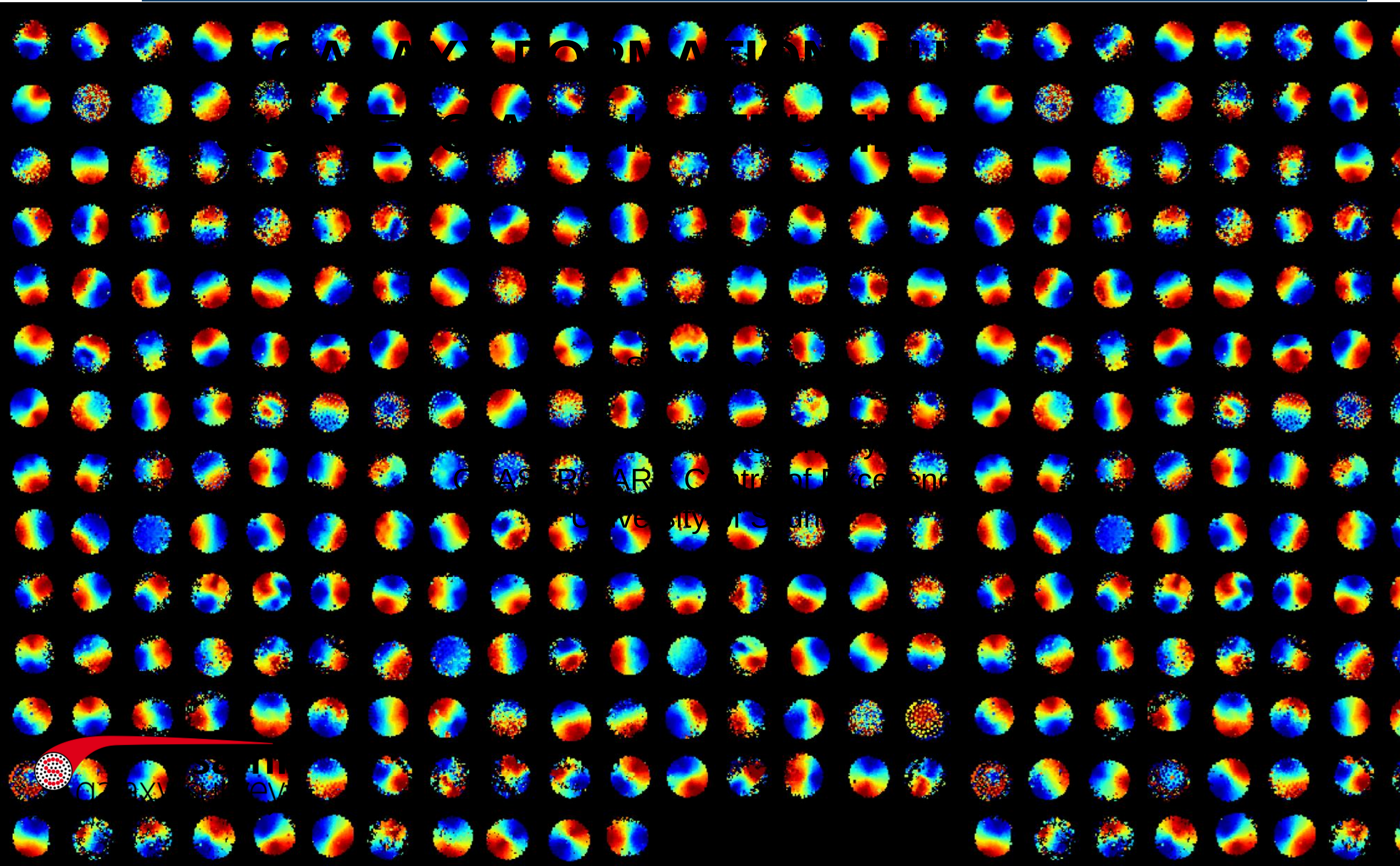
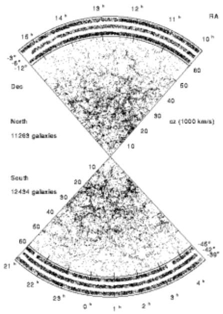
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS



The last 2 decades and the next one…

› Nineties



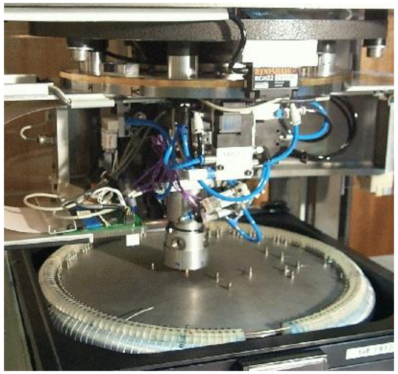
Las Campanas

2dFGRS, 2QZ

Certainly not a complete list!!!

› Noughties

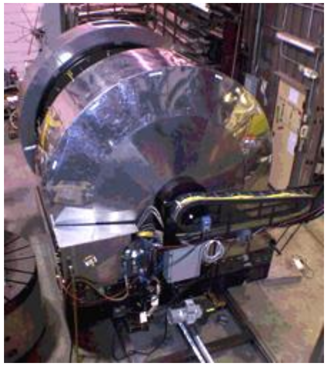
SDSS-I and II



6dFGS

2SLAQ,WiggleZ

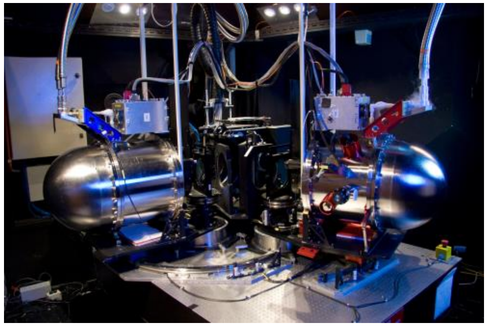
VVDS, zCOSMOS



DEEP-2

The last 2 decades and the next one…

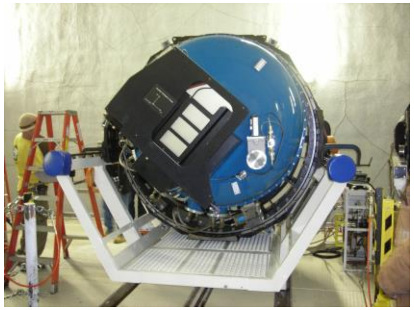
- Now



GAMA

SDSS-III, IV

VIPERS



MOSDEF

- Next…..

Outline

My personal view, trying not to repeat other talks…

1. Capturing complexity – Challenges for galaxy formation.

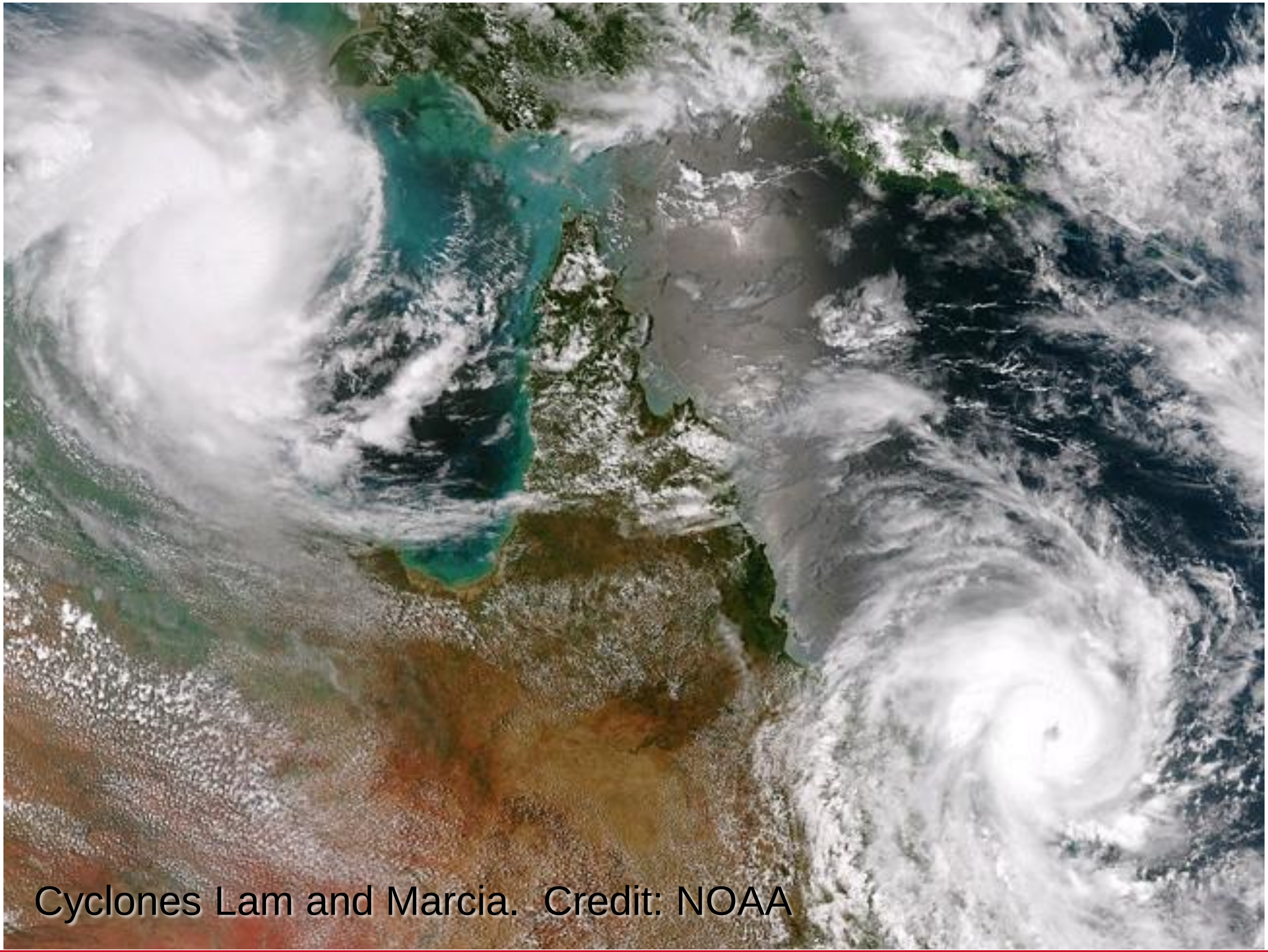
2. The IFU revolution.

3. New dimensions – where next?

Can we understand this?

Arp 274, credit: NASA

Can we understand this?



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What would solving galaxy formation look like?

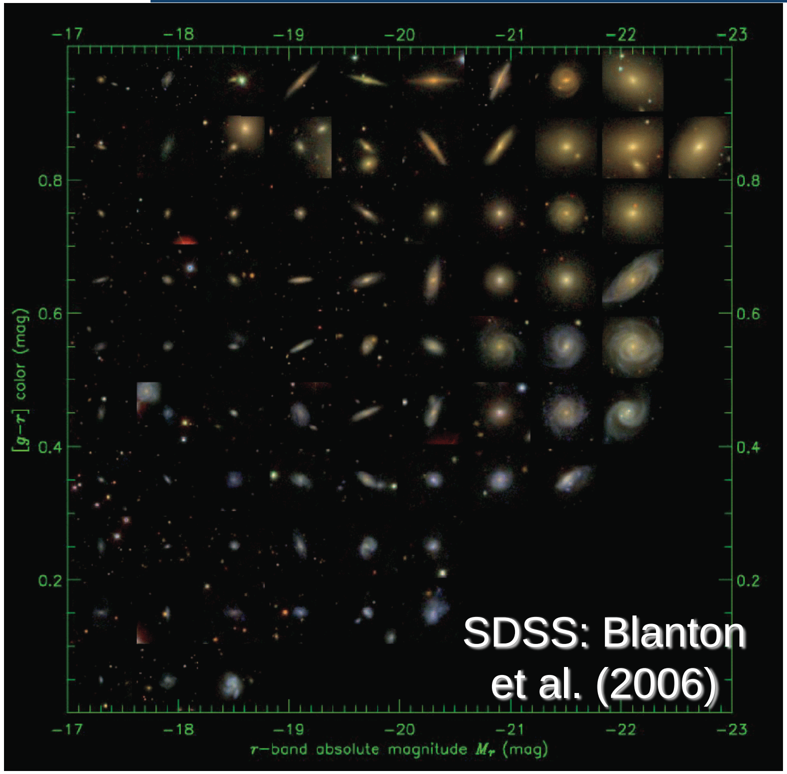
- Will we ever get there?

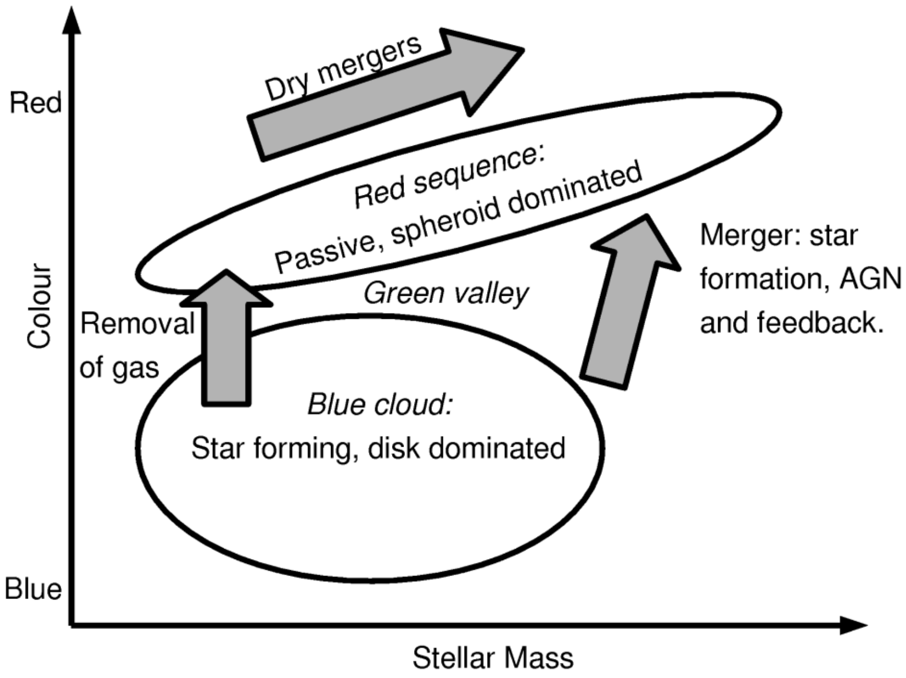
- If complexity is central, we can’t expect a set of simple physical relationships or laws. Is a match to simulations the only solution?

- What are the most vital observations and theory?

- How do we get to robust testable predictions from simulations?

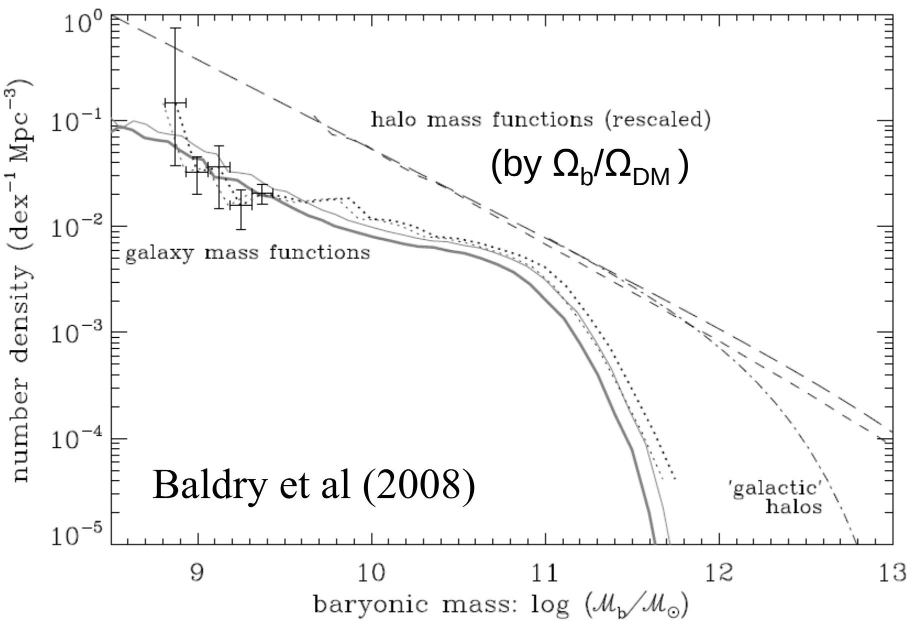
The problem: transformations

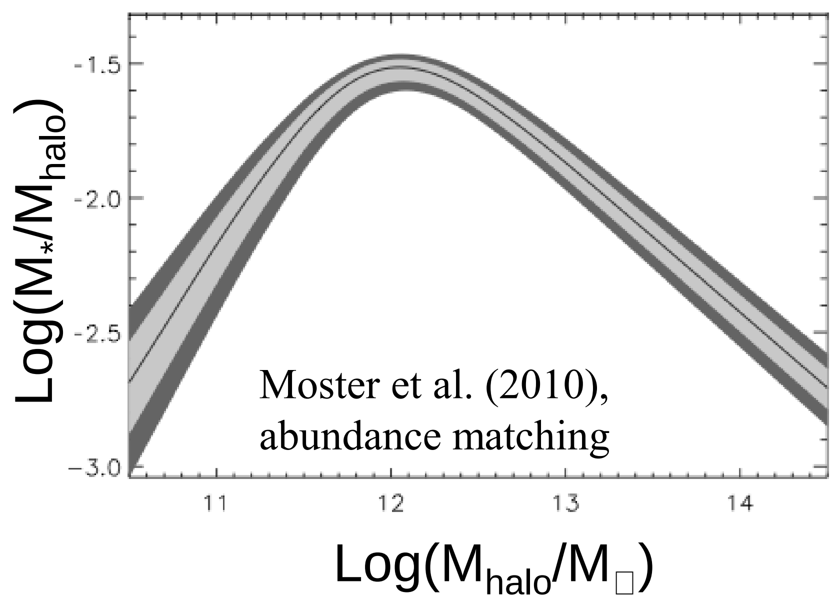




- Colour: blue ➔ red...
- Morphology: disk ➔ spheroid...
- Activity: Starforming ➔ passive....

The problem: mapping DM to stellar mass



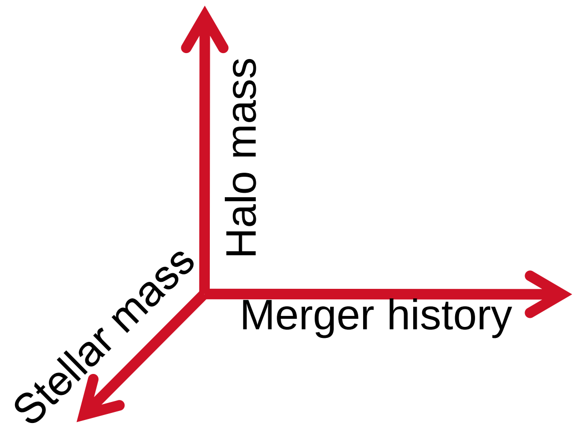


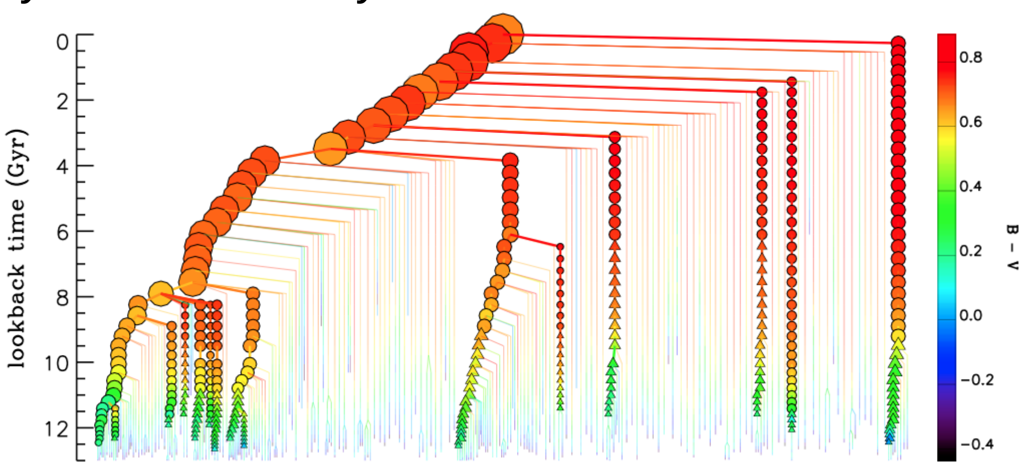
› Non-linear mapping of halo mass function to galaxy stellar mass function.

Multiple drivers

› What are the fundamental drivers of galaxy properties?

- Stellar mass.
- Halo mass.
- Environment – i.e. more than just halo mass.
- Central vs. satellite.
- Merger/accretion history.
- Intrinsic stochasticity (disk instability, local instability, secular evolution, other parameters?).





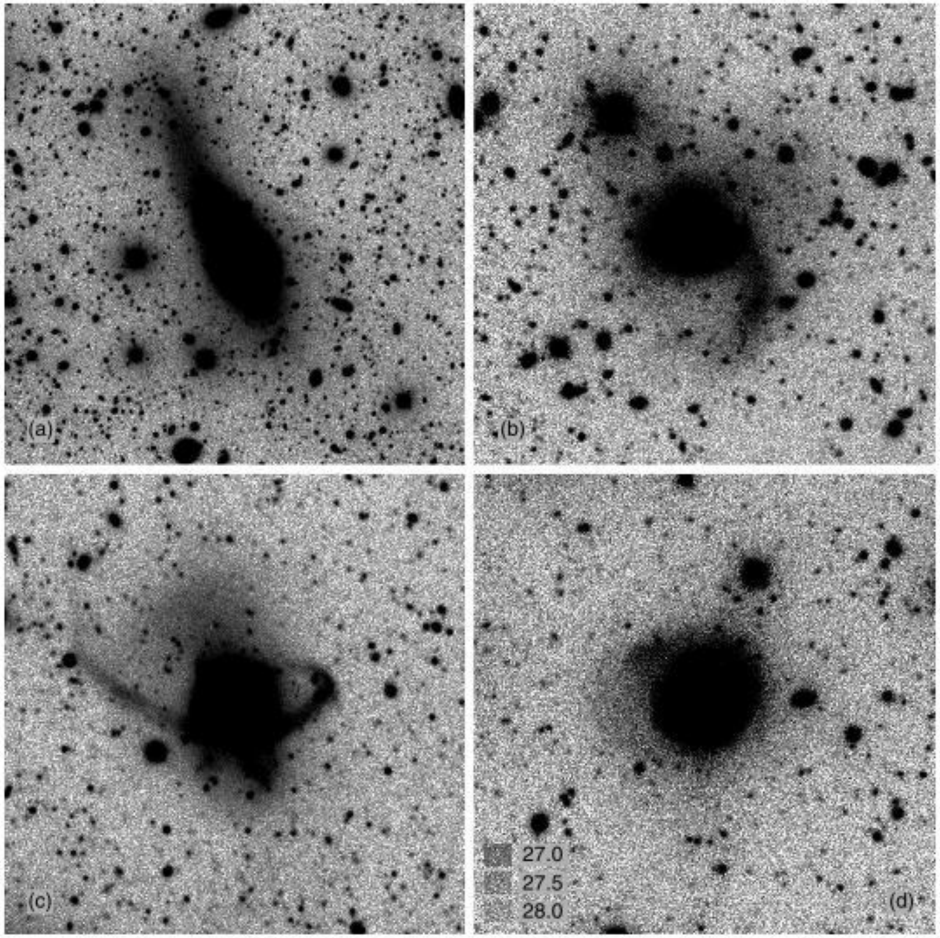
De Lucia &Blaizot (2007)

Measuring the drivers

- **Stellar mass.** Relatively easy… (but IMF!)
  - integrated photometry + SED fitting.
- **Halo mass**:
  - Group catalogues from spectroscopic surveys.
  - Gravitational lensing from imaging surveys.
- **Environment.** What is environment…???
  - Redshift survey defining local density, walls, filaments etc.
  - X-ray for gas density/temperature (in groups/clusters).
- **Central vs satellite.** Is this well defined? particularly at low mass.
  - Group catalogues from spectroscopic surveys.
- **Merger/accretion history… how???**

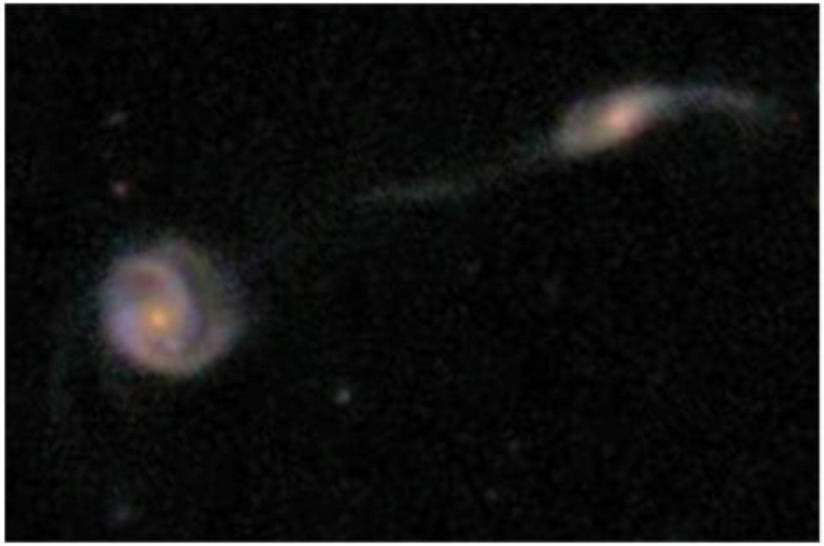
Viewing merger history

- Deep imaging to see merger remnant features (e.g. van Dokkum 2005).
- Next generation deep imaging surveys – VST, DES and then onto LSST – will be hugely valuable for this.

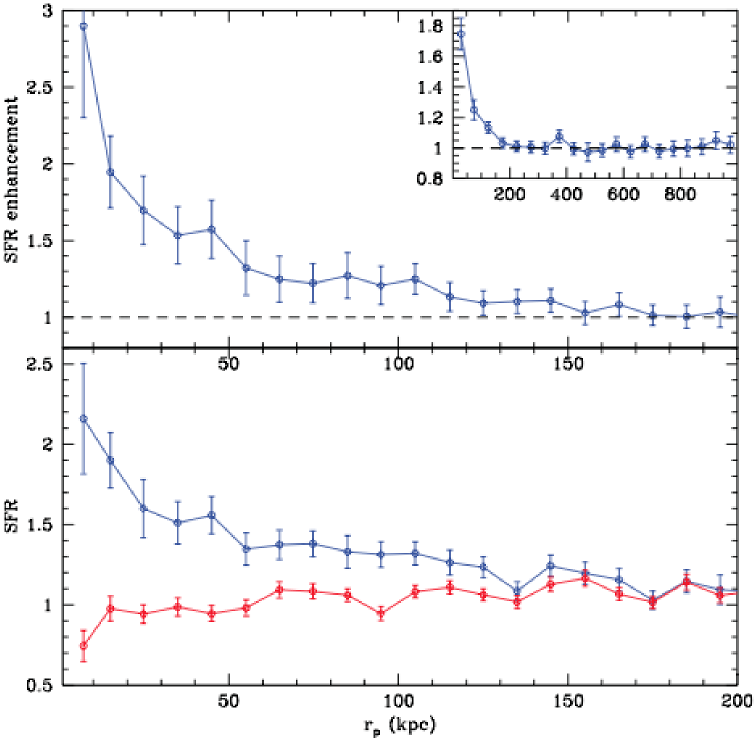


Viewing merger history

- Close pairs for future mergers (e.g. Ellison et al. 2010, 2011), although only a small fraction of galaxies in such pairs.
- Ideally MOS with high completeness and sampling rate is required – e.g. GAMA.



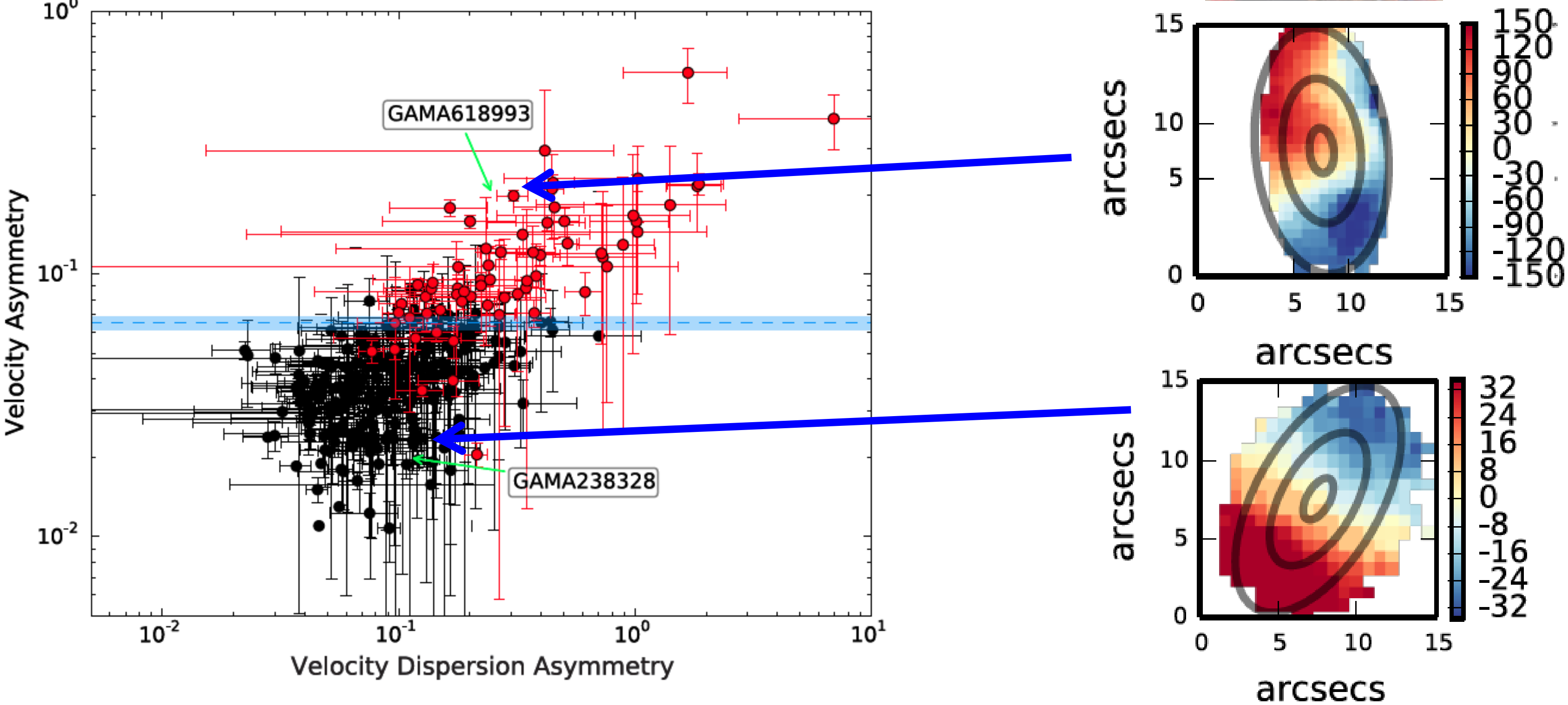
Ellison et al. 2011



Viewing merger history

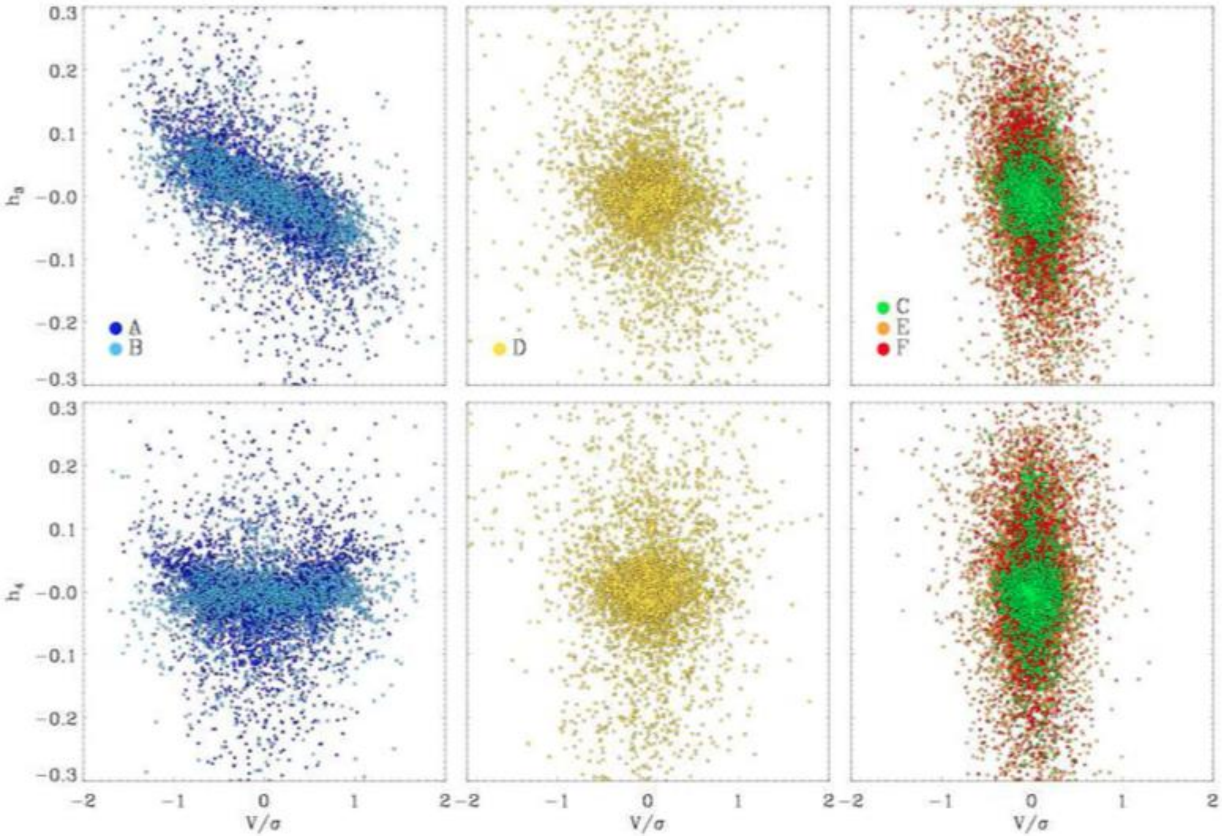
› Dynamical disturbance:

- SAMI Galaxy Survey (Bloom et al. in prep).
- See also Shapiro et al. (2008) using SINFONI.



Viewing merger history

› Stellar motions encode the merger history. Can we sub-divide based on stellar kinematics? Certainly fast/slow rotators, but finer resolution is possible (Naab et al. 2014).

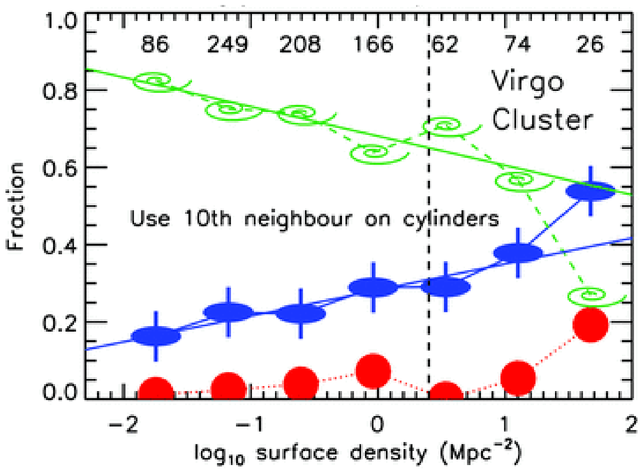


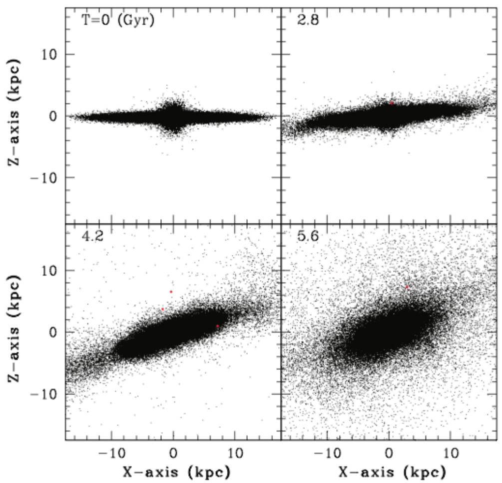
Many galaxy properties…

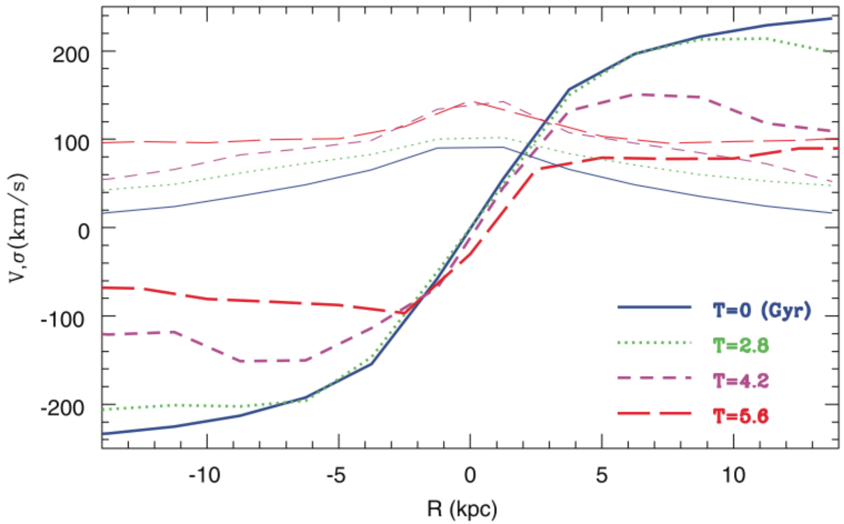
- **Star formation history.** Quantified as mean stellar age, colour or full SFH.
- **Current star formation.** What does "current" mean?
- **Morphology**. Visually and/or kinematically (strongly related). Disk/bulge or concentration or kinematically.
- **Angular momentum**. Random motion vs. regular rotation.
- **Gas content.** How much gas do galaxies contain? What state is this in, e.g. molecular, neutral, ionized
- **Metallicity.** [Fe/H], [α/Fe]… etc.
- and many more…

Science drivers example: Morphological transformation

› Possibly multiple paths for S0 formation.
  - Fading, plausible for some S0s from TF relation (e.g. Bedregal 2006), but not all.
  - Environmental dependence (e.g. Dessler 1980; Cappellari et al 2011).
  - Galaxy-galaxy tidal interaction in groups a likely contender (Bekki & Couch 2011).

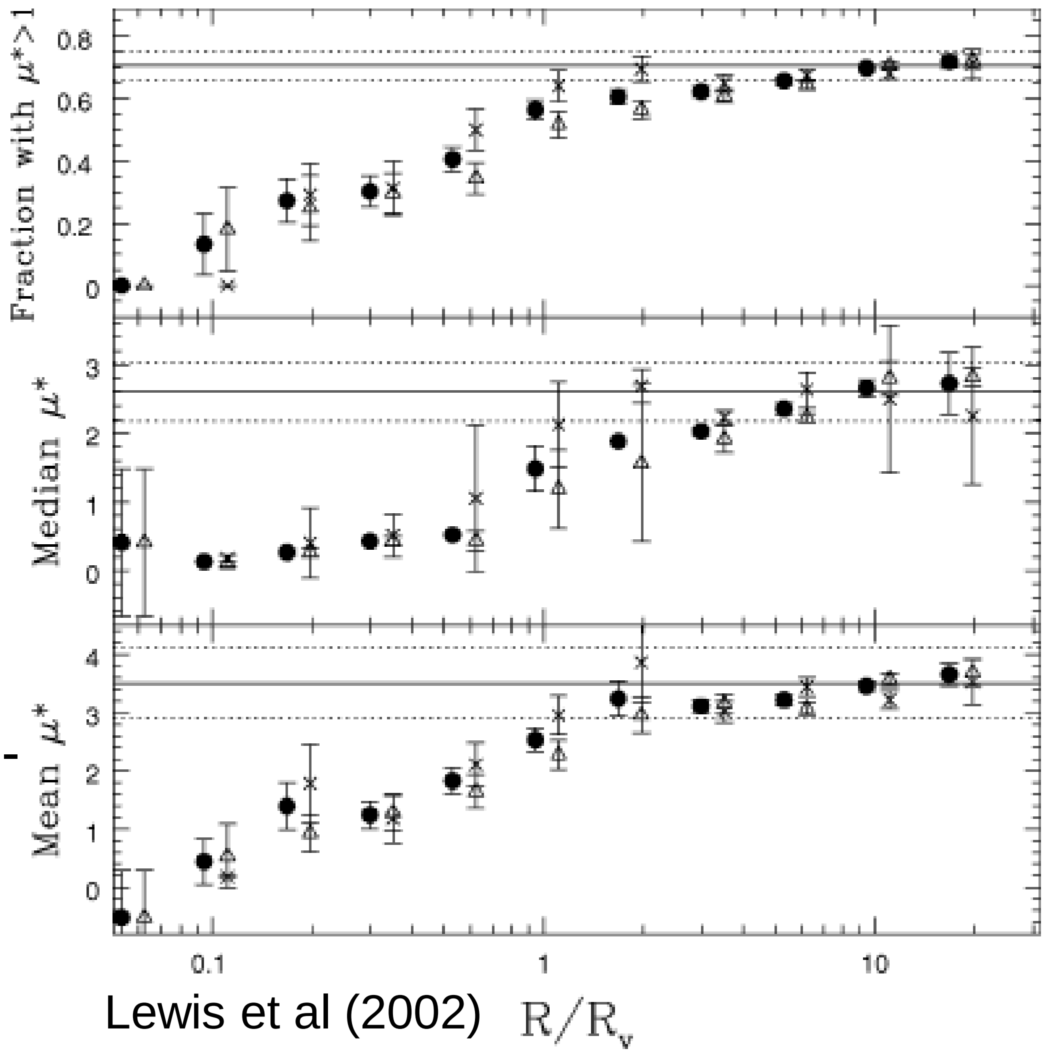






Science driver example: Quenching

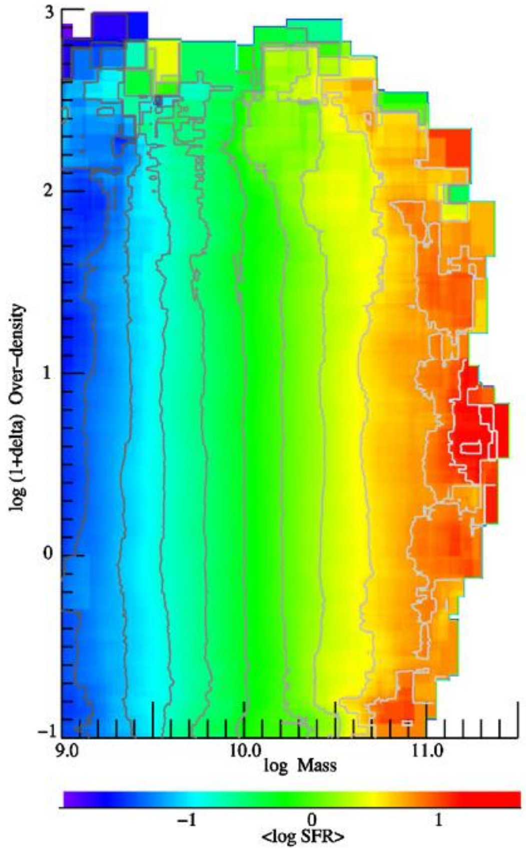
- Clear quantification of the suppression of SF in high density regions (e.g. Lewis et al. 2002).
- Consistent with (but does not explain) the well known morphology-density relation.
- When/where does the processing happen? “Group pre-processing?”
- What is the mechanism? Ram-pressure stripping? Strangulation? Age?
- Relative impact of feedback and environment?



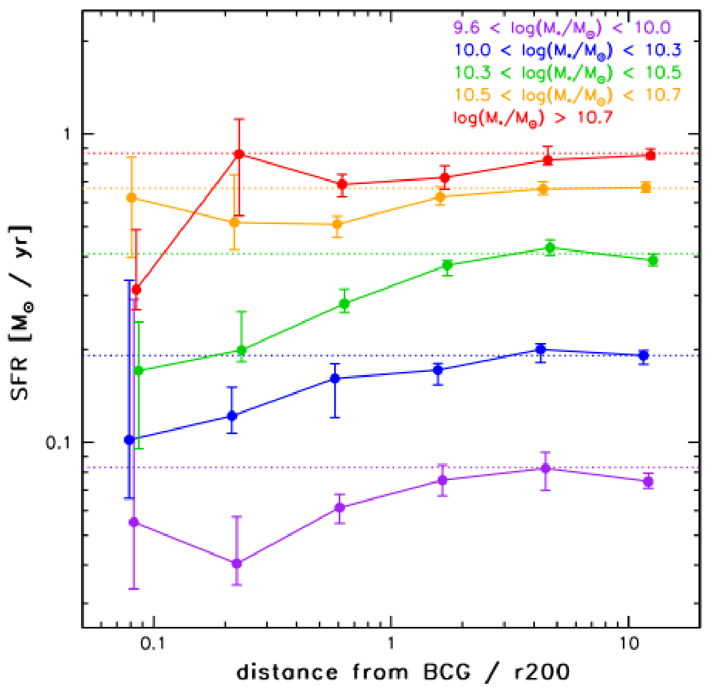
Lewis et al (2002)

Science drivers example: Quenching

› Quenching star formation: what are the physical processes?



Peng et al. (2010, 2012)
-> **FAST**

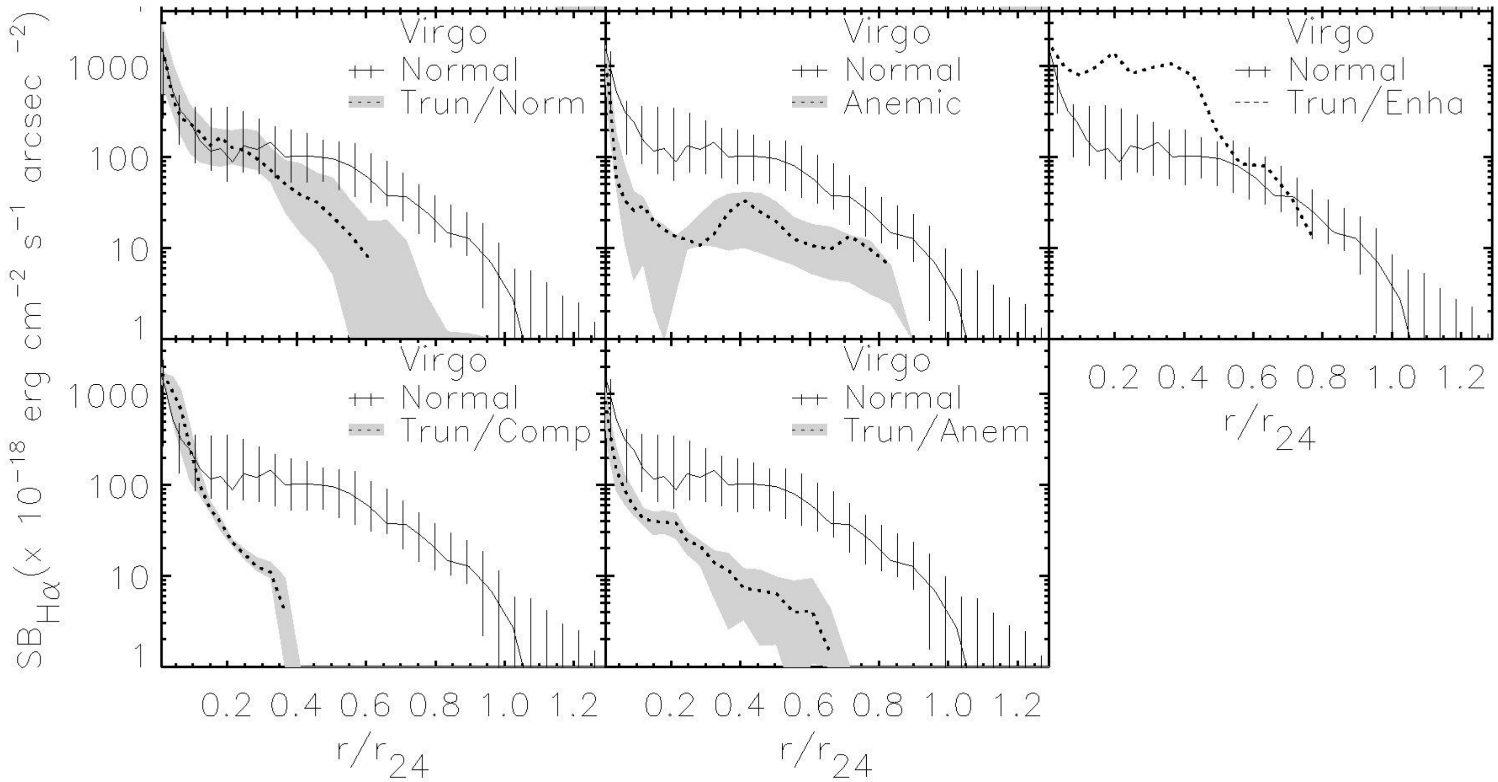


Von der Linden et al. (2010), see also Weinmann et al. (2010)

-> **SLOW**

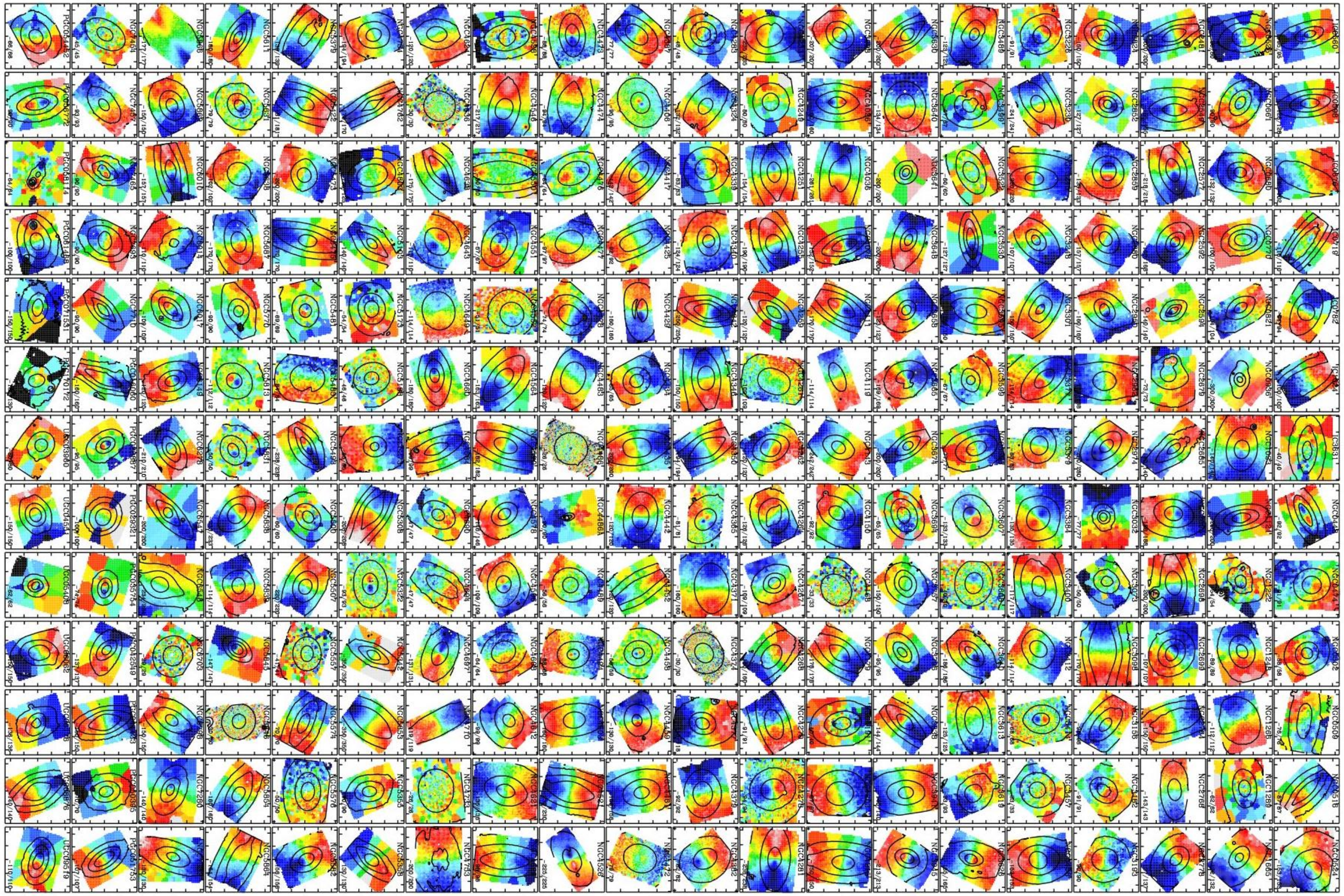
Science drivers example: Quenching

› But… where is star formation happening?



› E.g. Koopmann & Kenney (2004): Hα imaging in Virgo, ~50% of spirals truncated compared to field.

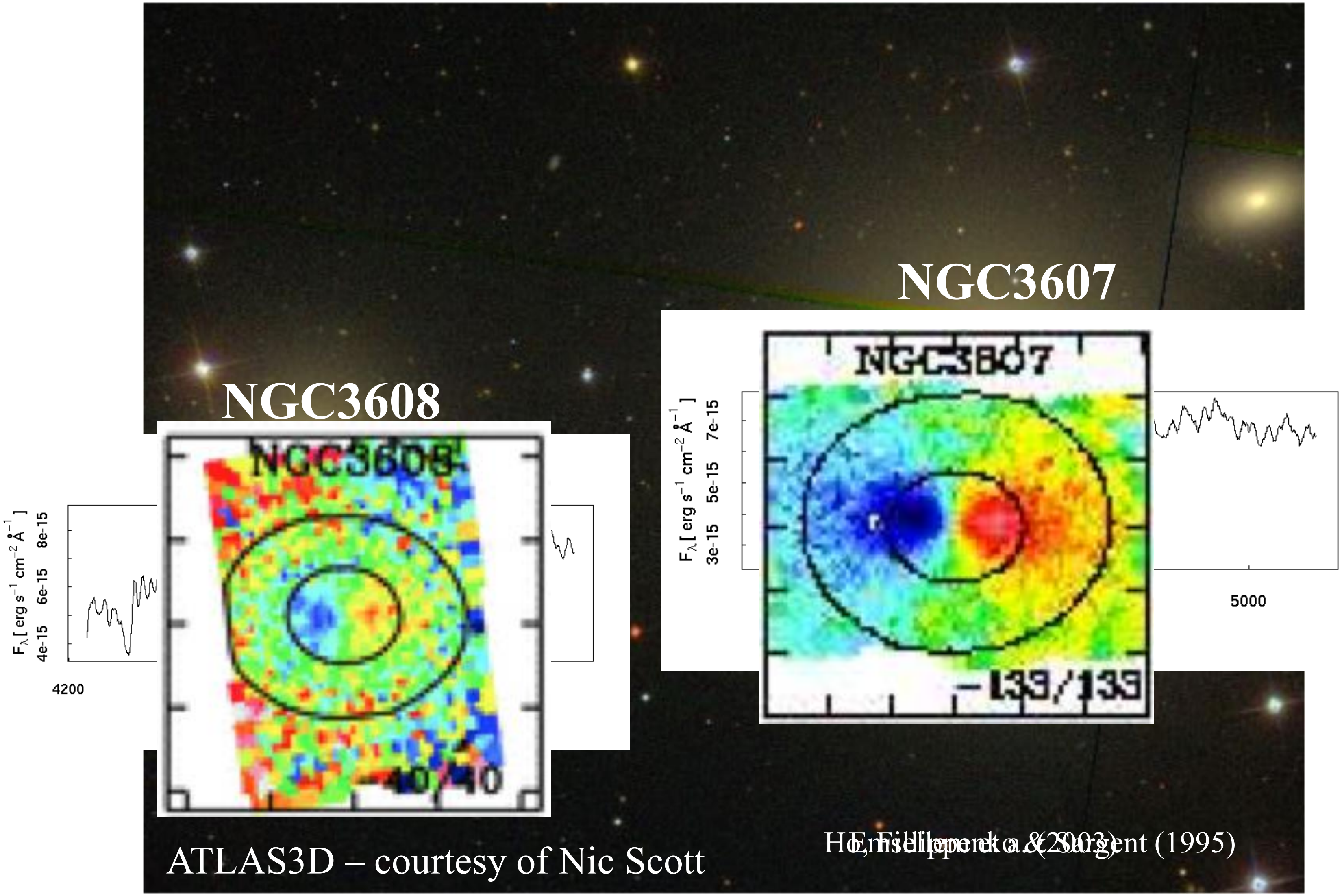
The IFU revolution: ATLAS 3D



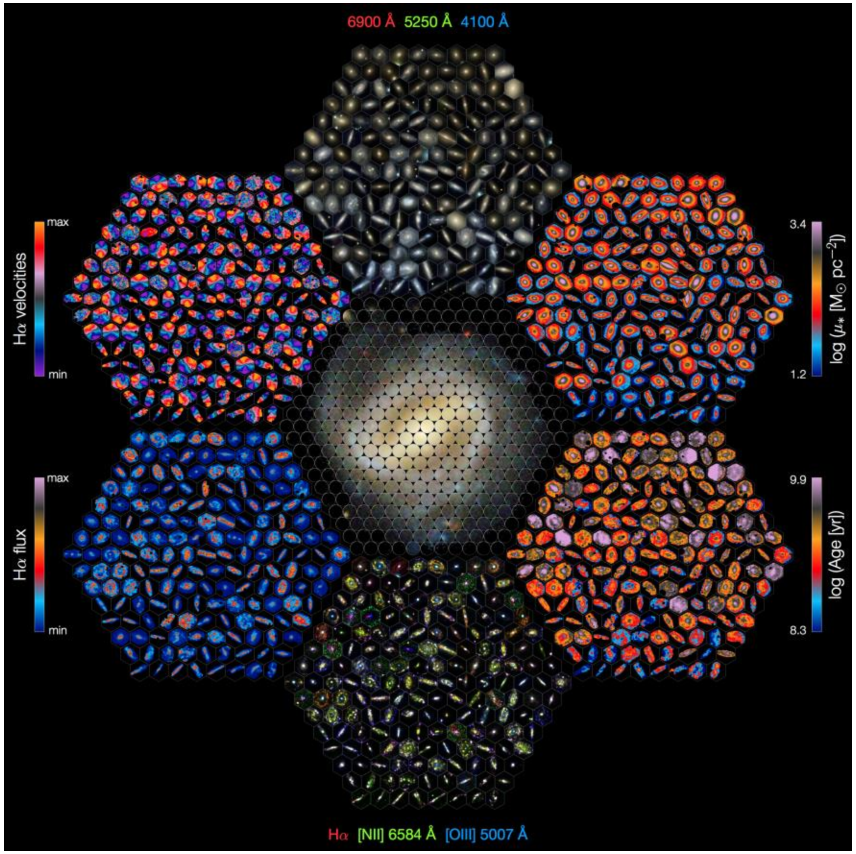
Krajnovic et al (2011)

260 local early type galaxies in a volume limited sample.

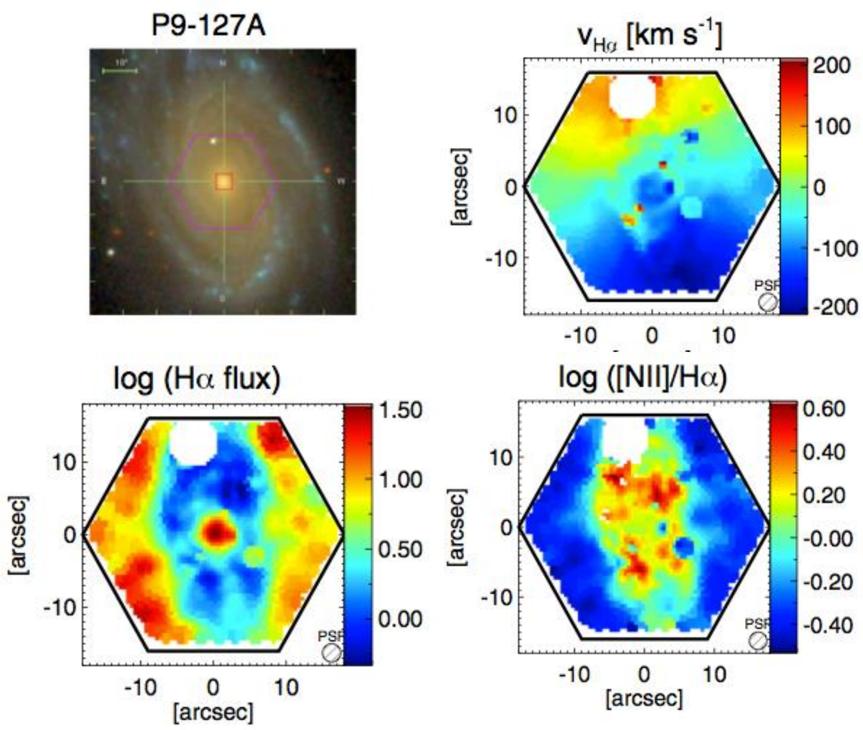
The power of extra dimensions



CALIFA, MANGA



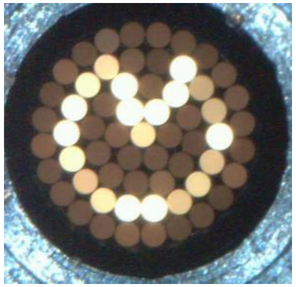
CALIFA: 600 local galaxies (all types), diameter limited, Sanchez et al (2012). Complete in 2015. See talk by Jesus Falcon-Barroso.



MANGA: 10,000 local galaxies (all types), Bundy et al. (2015), 2014 to 2020. See Anne-Marie Weijmans talk.

The Sydney-AAO Multi-object IFS (SAMI)

- 1 degree diameter field-of-view.
- 13 x 61 fibre IFUs using hexabundles (Bland-Hawthorn et al. 2011; Bryant et al. 2014).
- Fused fibre bundles; high fill factor, 75%.
- 15” diameter IFUs, 1.6” diameter fibres.
- Feeds AAT’s AAOmega spectrograph.
- First light July 2011.
- Instrument description: Croom, Lawrence, Bland-Hawthorn et al. (2012).



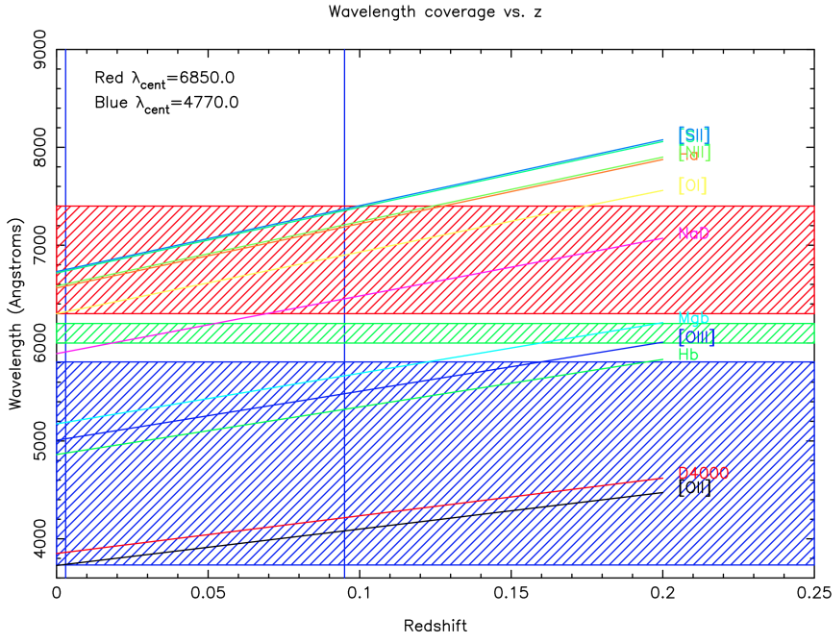
astrophotonics

The SAMI Galaxy Survey

- Using the upgraded SAMI instrument (Feb 2013).
- Started in March 2013, due to complete in 2016.
- 3400 galaxies in ~200 nights.
- Primary fields are the Galaxy And Mass Assembly (GAMA; Driver et al. 2010) regions.
  - Three 4x12 deg equatorial regions at 9hr, 12hr and 15hr RA.
  - Deep, complete, spectroscopy to r=19.8 to define environment.
  - Robust group catalogue (Robotham et al. 2011).
  - GALEX, SDSS, VST, UKIDSS, VISTA, WISE, Herschel imaging.
  - HI 21cm from ALFALFA (half the area), and in the future ASKAP.
- 8 cluster fields targeted in the South Galactic Cap to probe the highest density environments (~600 gals).

Survey parameters

› Wavelength coverage/resolution:
  - Blue: 3700-5800A, R~1750, sigma=70km/s
  - Red: 6300-7400A, R~4500, sigma=30km/s



› Galaxy sizes:
  - median major axis Re=4.4” (IFU to 1.7Re).
  - 10-90% range 1.8-9.4”

› S/N:
  - Median at 1 Re, V-band continuum S/N=15, per spaxel, per A.
  - 10-90% range S/N= 2 – 37.

› Chose to include dwarfs (to log(M*)<8.2), although lower S/N.

› Flux calibration: better than 5% over full spectral range (high fill factor, + calibration star observed with galaxies).

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SAMI Galaxy Survey team

James Allen, Sydney
Ivan Baldry, Liverpool JMU
Luke Barnes, Sydney
Amanda Bauer, AAO
Simona Bekeraitė, AIP
Kenji Bekki, ICRAR
Mike Birchall, AAO
Joss Bland-Hawthorn, Sydney
Jess Bloom, Sydney
Alyson Brooks, Rutgers
Sarah Brough, AAO
Julia Bryant, Sydney, target sel WG chair
Gerald Cecil, North Carolina
Michelle Cluver, AAO
Matthew Colless, ANU
Luca Cortese, Swinburne
Warrick Couch, AAO
Rob Crain, Leiden Observatory
Scott Croom, Sydney, PI
Darren Croton, Swinburne
Roger Davies, Oxford
Catherine de Burgh-Day, Melbourne
Francesco Di Mille, Sydney/AAO
Michael Drinkwater, UQ, QC WG chair
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Michael Goodwin, AAO
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Madusha Gunawardhana, Sydney
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I-ting Ho, University of Hawaii
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Lisa Kewley, ANU, Science coordinator
Iraklis Konstantopoulos, AAO, DB WG chair
Baerbel Koribalski, CSIRO
David Lagattuta, Swinburne
Maritza Lara-Lopez, AAO
Jon Lawrence, AAO
Geraint Lewis, Sydney
Joe Liske, European Southern Observatory
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Nuria Lorente, AAO
Smriti Mahajan, Queensland
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Martin Meyer, ICRAR/UWA
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Simon Mutch, Swinburne
Peder Norberg, Durham
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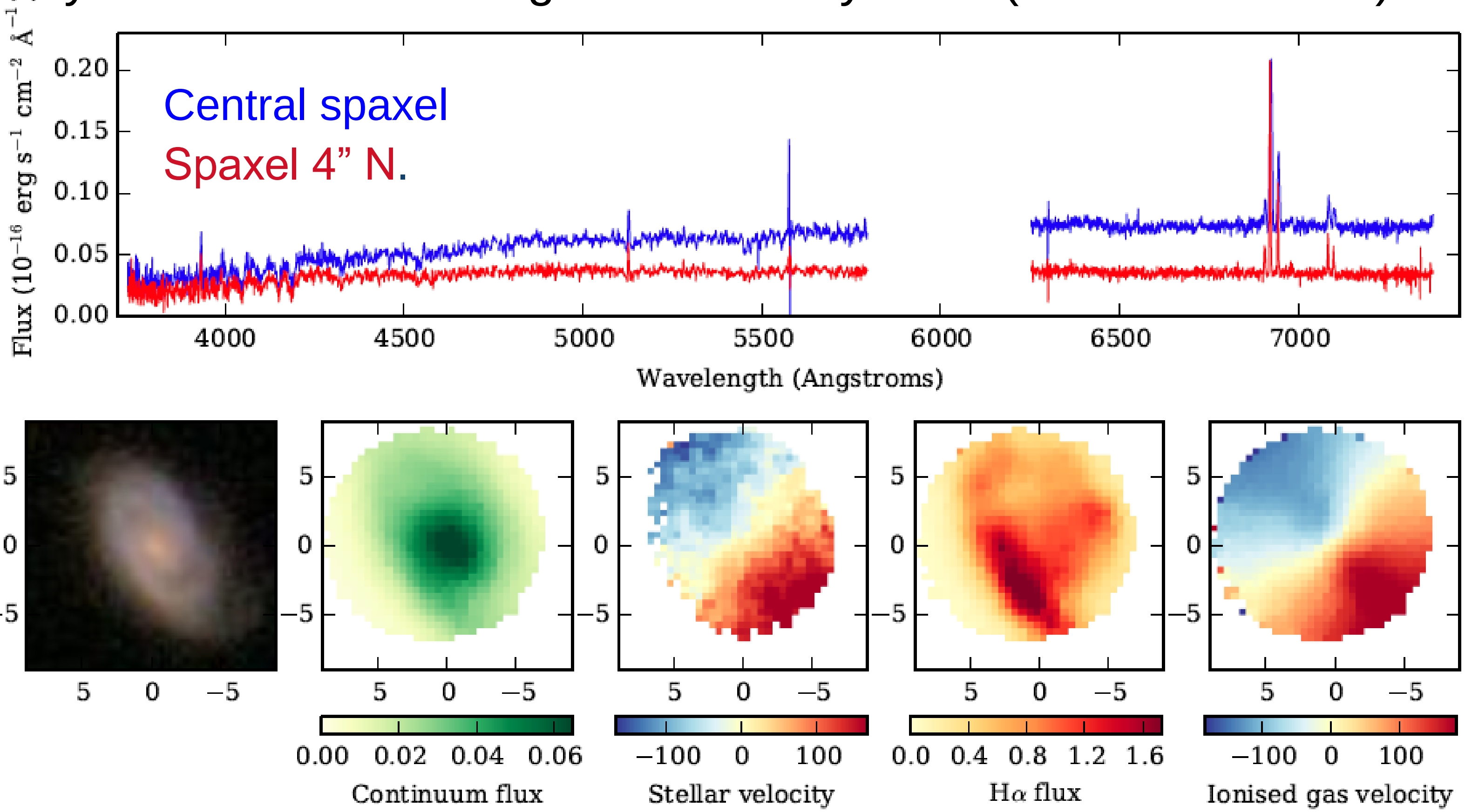
Matt Owers, AAO
Quentin Parker, Macquarie/AAO
Gregory Poole, Swinburne
Chris Power, ICRAR/UWA, sims WG chair
Michael Pracy, Sydney
Justin Read, ETH Zürich/Leicester
Samuel Richards, Sydney
Aaron Robotham, St Andrews/UWA
Elaine Sadler, Sydney
Sebastian F. Sanchez, Inst de Astro de Andalucia
Adam Schaefer, Sydney
Julia Scharwaechter, ANU
Nic Scott, Sydney
Rob Sharp, ANU, DR WG Chair
Rachel Somerville, Rutgers
Chris Springob, ICRAR/UWA
Sarah Sweet, Queensland
Edward Taylor, Melbourne
Chiara Tonini, Swinburne
Jakob Walcher, AIP
Rachel Webster, Melbourne
Lutz Wisotzki, AIP
Ivy Wong CSIRO
Tiantian Yuan, ANU

Science drivers

- **What are the physical processes responsible for galaxy transformations?**
  - Morphological and kinematic transformations; suppression of star formation; internal vs. external; secular vs. fast; ram pressure stripping; harassment, strangulation; galaxy–group/cluster tides; galaxy-galaxy mergers; galaxy-galaxy interactions…
- **How does mass and angular momentum build up?**
  - The galaxy velocity function; stellar mass in dynamically hot and cold systems; galaxy merger rates; halo mass from velocity-field shear; Tully-Fisher relation…
- **Feeding and feedback: how does gas get into galaxies, and how does it leave?**
  - Winds and outflows; feedback vs. mass; triggering and suppression of SF; gas inflow; metallicity gradients; the role of AGN…

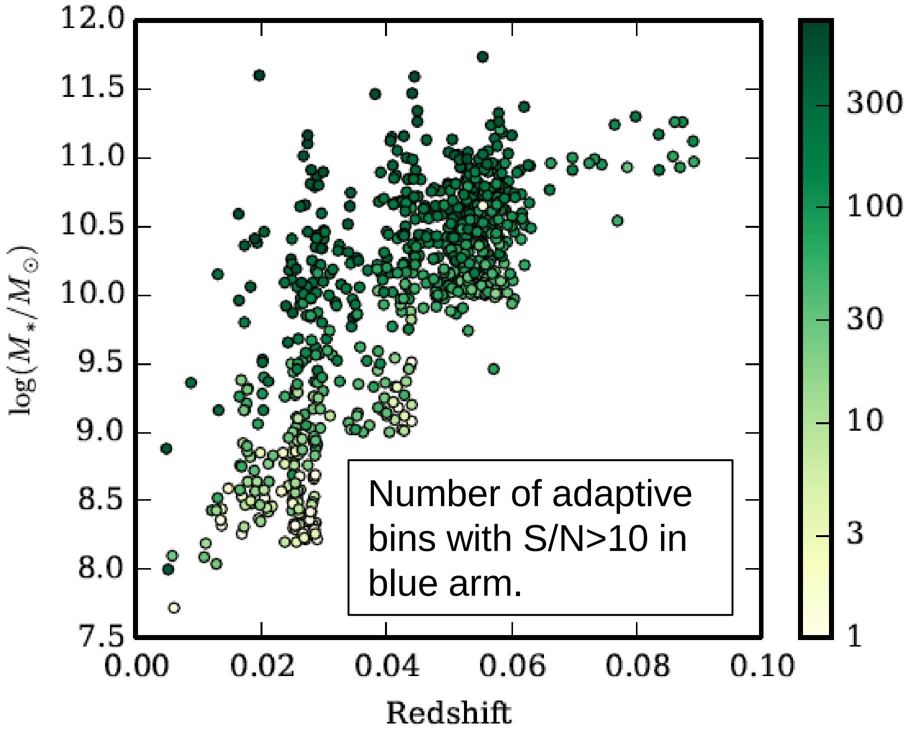
Survey status

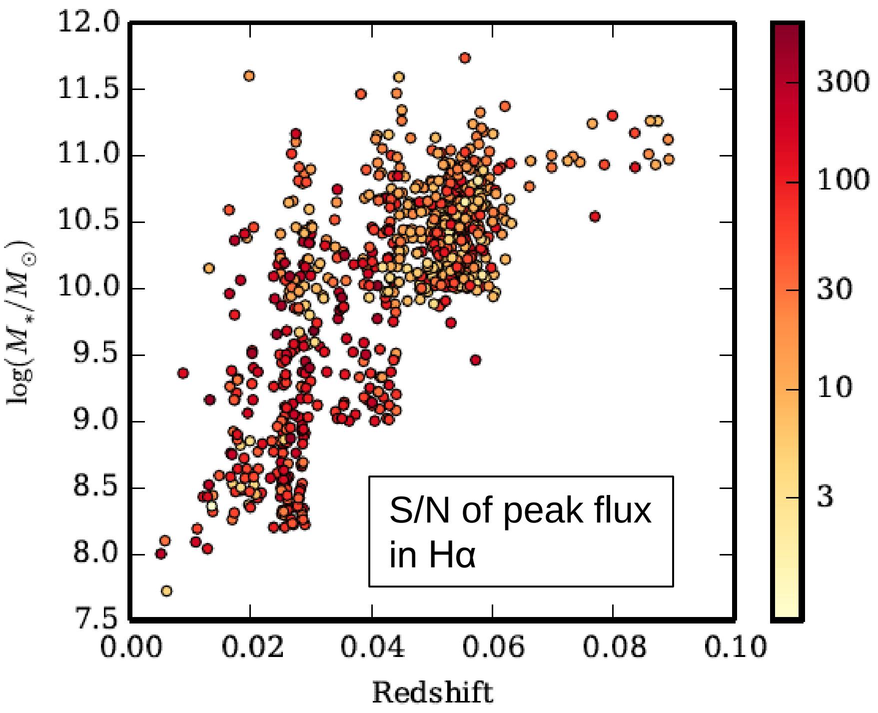
- Just over 1000 galaxies (plus ~100 pilot galaxies from 2012).
- All reduced uniformly through full pipeline (currently v0.8).
- Early data release – 100 galaxies in July 2014 (Allen et al. 2015)



Survey status

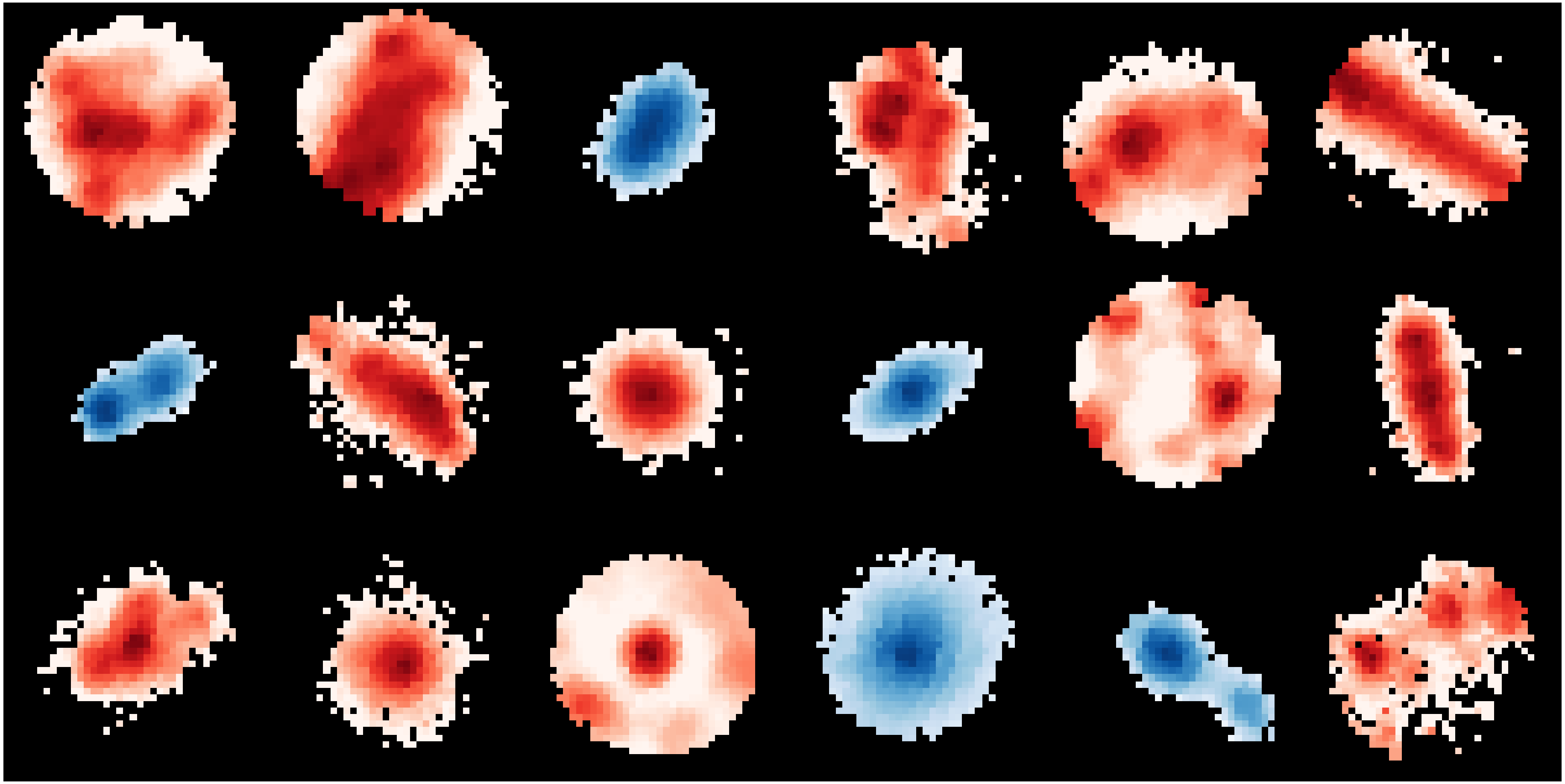
- Just over 1000 galaxies (+100 pilot galaxies from 2012).
- Median number of S/N>10 bins is 93. 10-90th percentile range 9-298 bins.



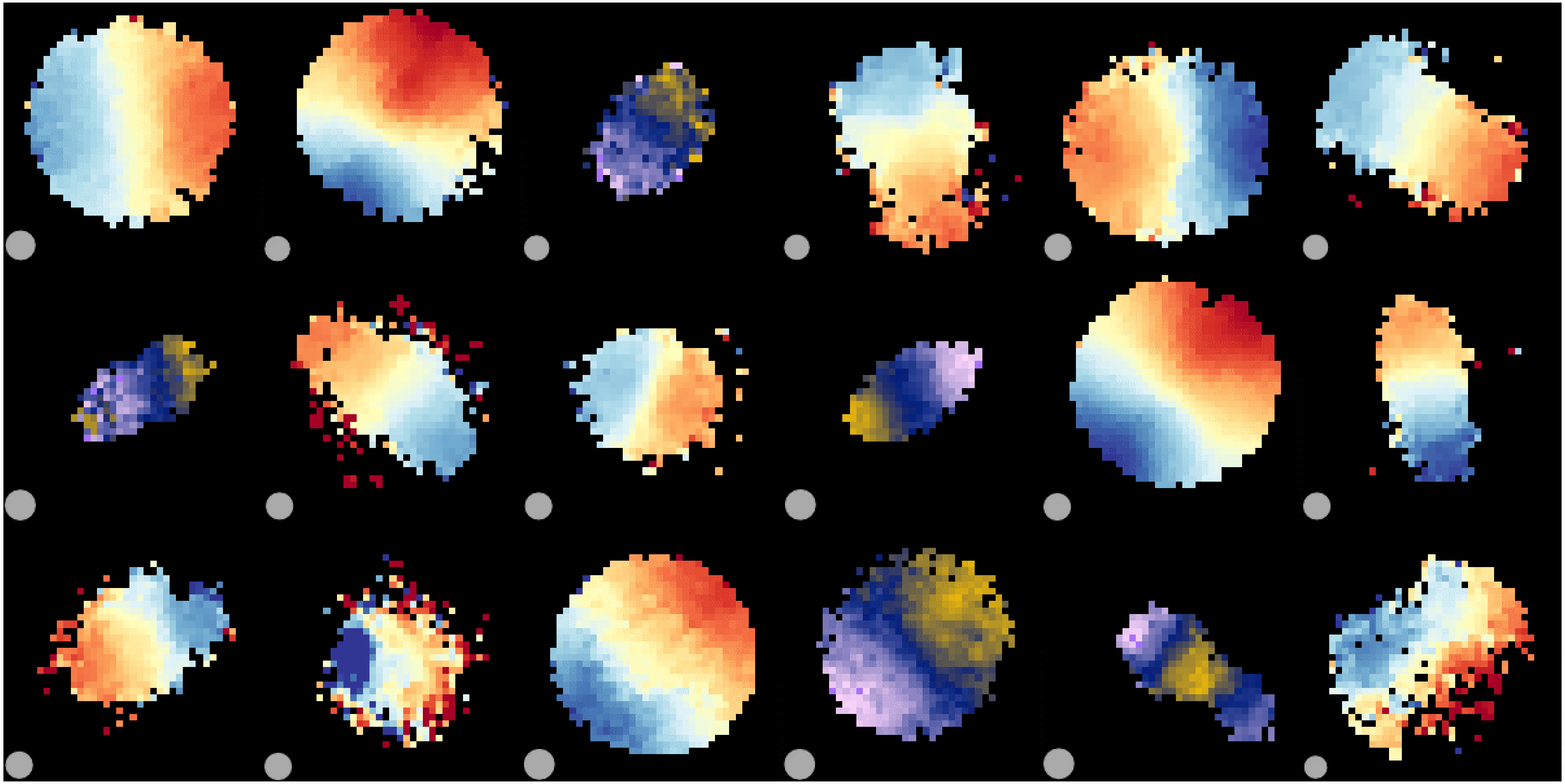


SAMI Early Data Release

SAMI Early Data Release

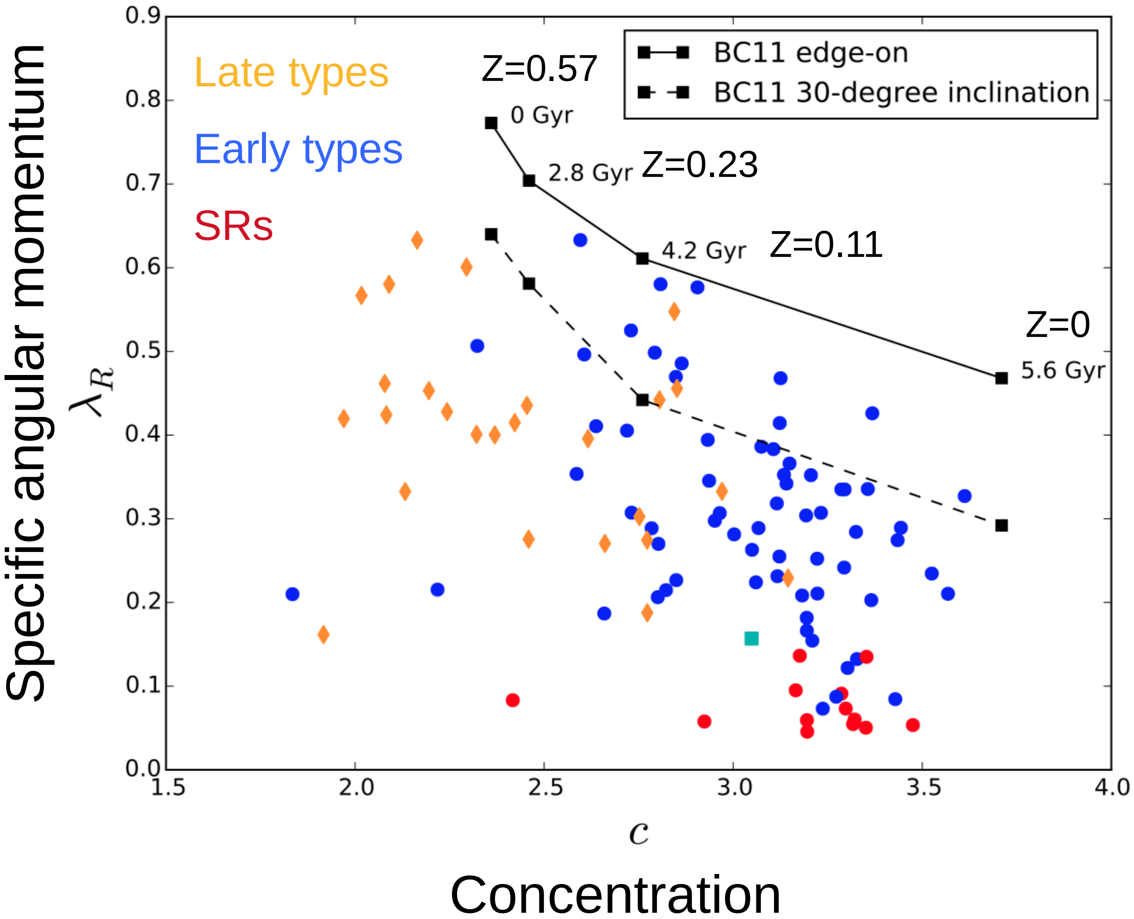


SAMI Early Data Release



SAMI Science: angular momentum and galaxy transformation

Pilot cluster data:



- Dynamical processes driving morphological transformations. E.g. tidal interaction in groups (Bekki & Couch 2011).
- Fogarty et al., Cortese et al., in prep.
- Really need galaxies at the redshifts appropriate for the evolutionary tracks. Particularly given the higher dispersion in high-z galaxies.

SAMI Science: decomposing winds

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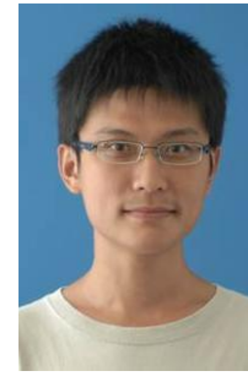
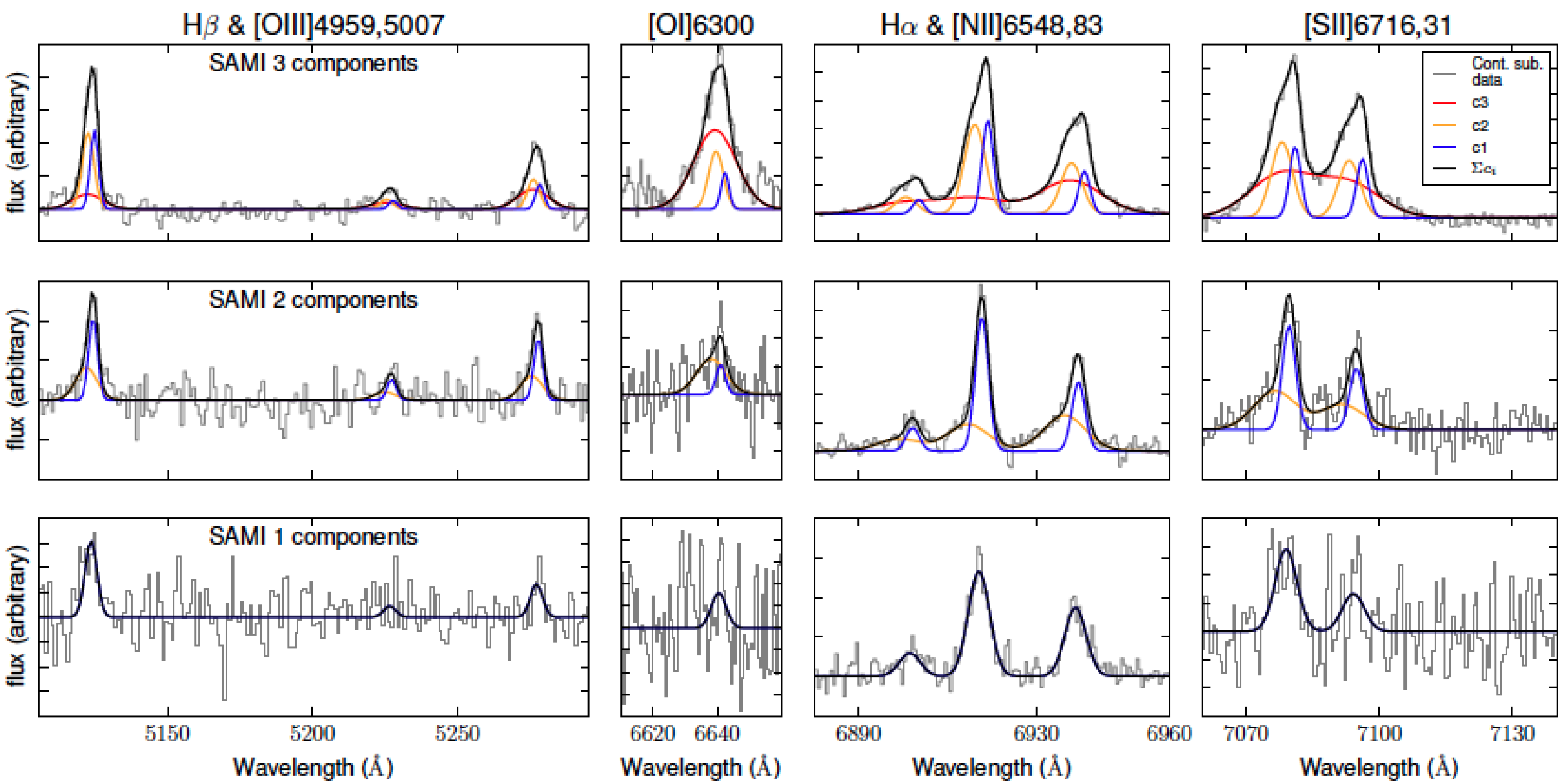
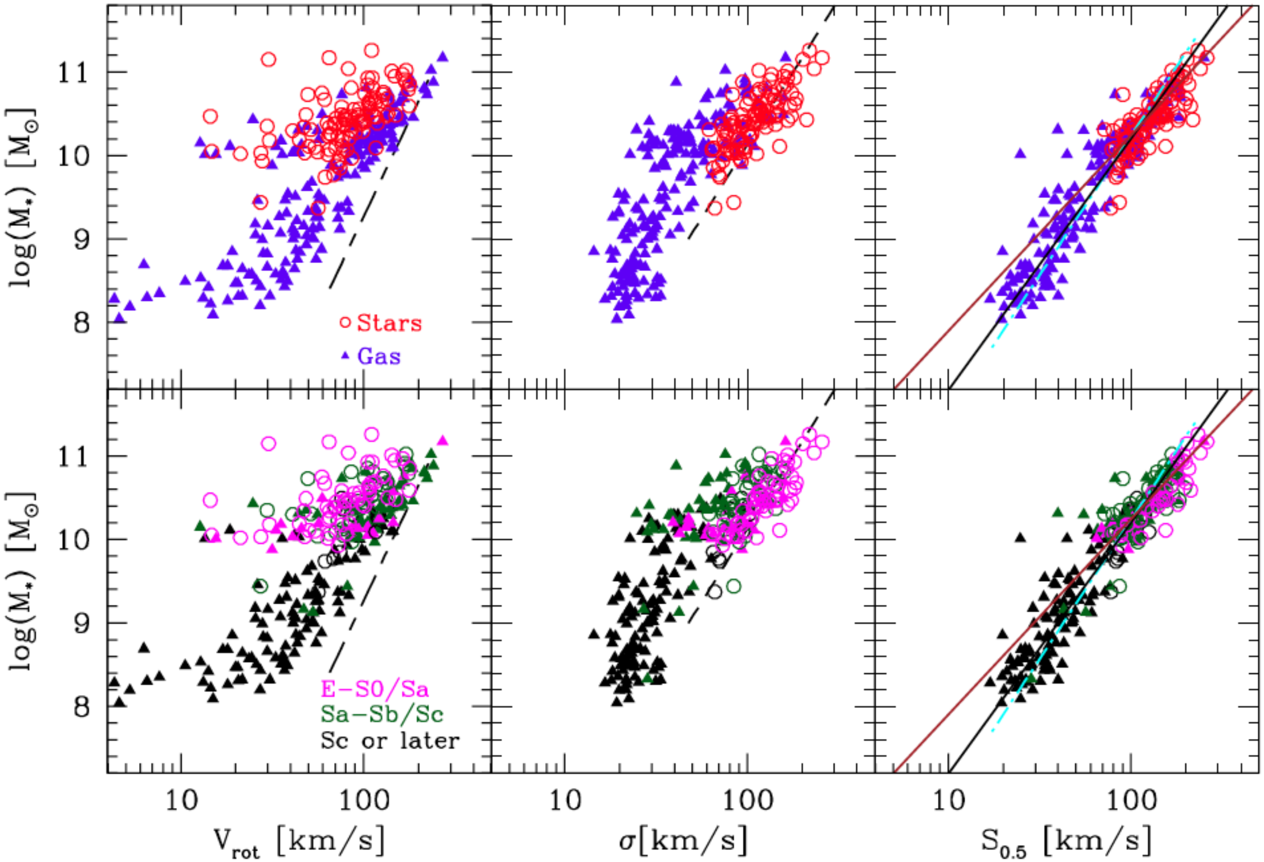


- Wind in a "normal" SF galaxy, log(M_*)=10.8, SFR~10 $M_\odot$/yr (Ho et al. 2014). Uses LZIFU fitting pipeline.
- SAMI can directly characterize the frequency and strength of winds.



SAMI Science: Universal scaling relations

- ***All*** galaxies fall on the same tight relation when combining V_{rot} and σ using $S_{0.5}=(0.5V_{rot}^2+\sigma^2)^{1/2}$ (Kassin+ 2007) within 1 Re.
- Scatter ~0.1 dex in $S_{0.5}$ or 0.3 dex in M_* (Cortese et al. 2014).



Where next?

- The problem is complexity.
- How many parameters does galaxy formation depend on? We need to probe an n-dimensional parameter space:
  - Stellar mass; halo mass; physical environment (cluster, filament, void etc); merger history…+++?
- These drive the dependent parameters:
  - Star formation history; morphology; angular momentum; gas content; metallicity…+++?
- How much stochasticity at a given point in this space (e.g. driven by individual interactions)? Depends on the measurement you are making. E.g. Hα star formation traces a very short time-scale, so large stochastic variation.

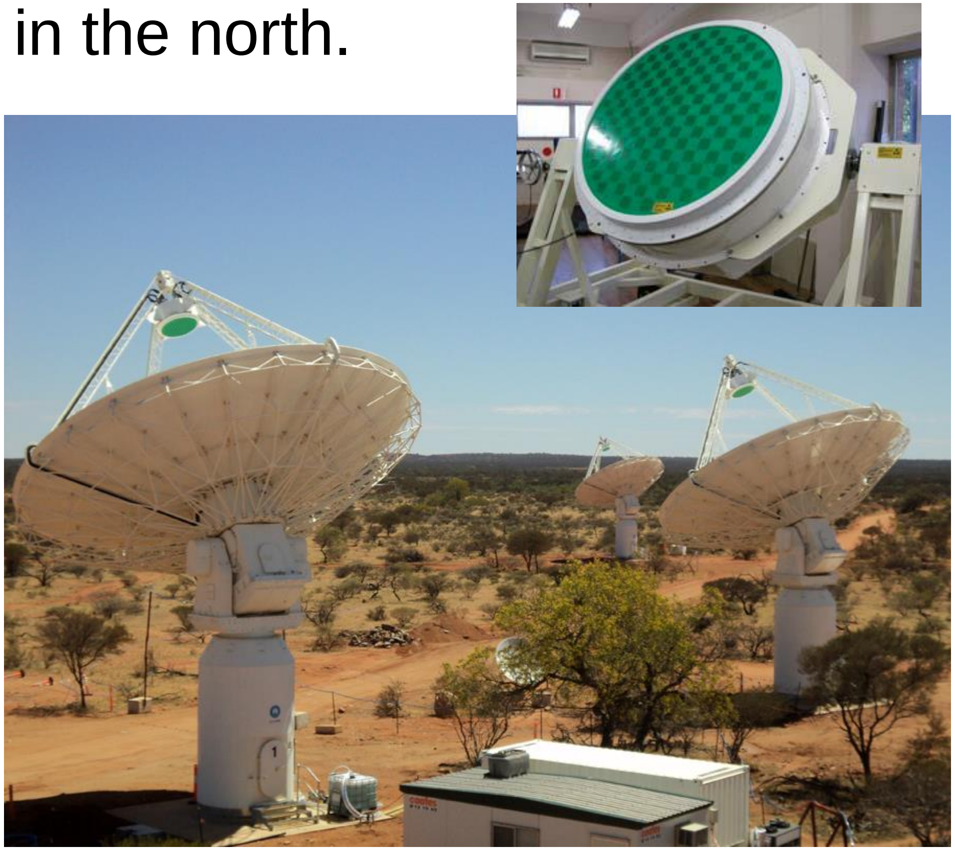
What is needed?

- Extra dimensions in parameter space push us to at least an order of magnitude more galaxies: Hector (see Julia Bryant's talk).
- Detailed understanding of environment. Expansion of GAMA like surveys, e.g. 4MOST/WAVES (see Roelof de Jong's talk and Simon Driver's talk).
- Gas content: next generation of radio surveys for HI emission, ASKAP, and then on to SKA phase 1…++
- Molecular gas via ALMA, but still one at a time…
- Need to gather the best multi-wavelength data (UV to far-IR), probably the most important reason for this is dust. GAMA is doing this.

MOS of neutral gas in galaxies

- Next generation HI surveys will start in the next few years.
- WALLABY (all sky) & DINGO (deep) Surveys with ASKAP.
- Also WNSHS on Westerbork in the north.

- ASKAP: Australian SKA Pathfinder:
  - 36x12m antennae.
  - 30 sq deg field of view with phased array feeds.
  - ~500 HI detections per field (8 hour integration).



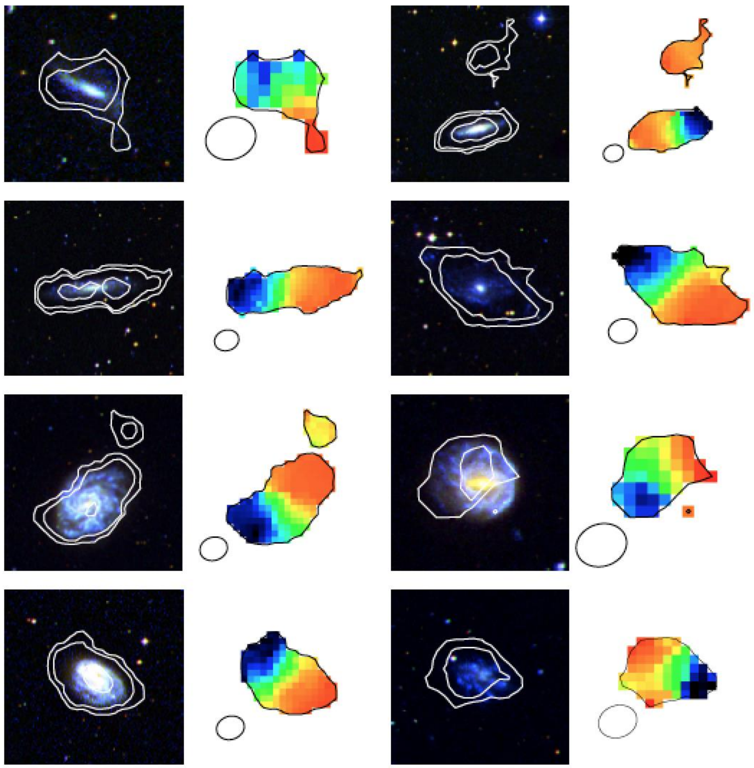
MOS of neutral gas in galaxies

› WALLABY parameters:

- survey time: ~one year on sky.
- sky coverage: $-90^{o} < \delta < +30^{o}$ (max. $+50^{o}$)
- Velocity range: −2,000 to 77,000 km/s (z = 0.26)
- Spatial resolution: 30" (+ 10" cutouts)
- Spectral resolution: 4km/s
- line sensitivity: ~1.5 mJy/beam per channel

› Approximately 600,000 galaxies with median z ~ 0.05 and max z~0.26.

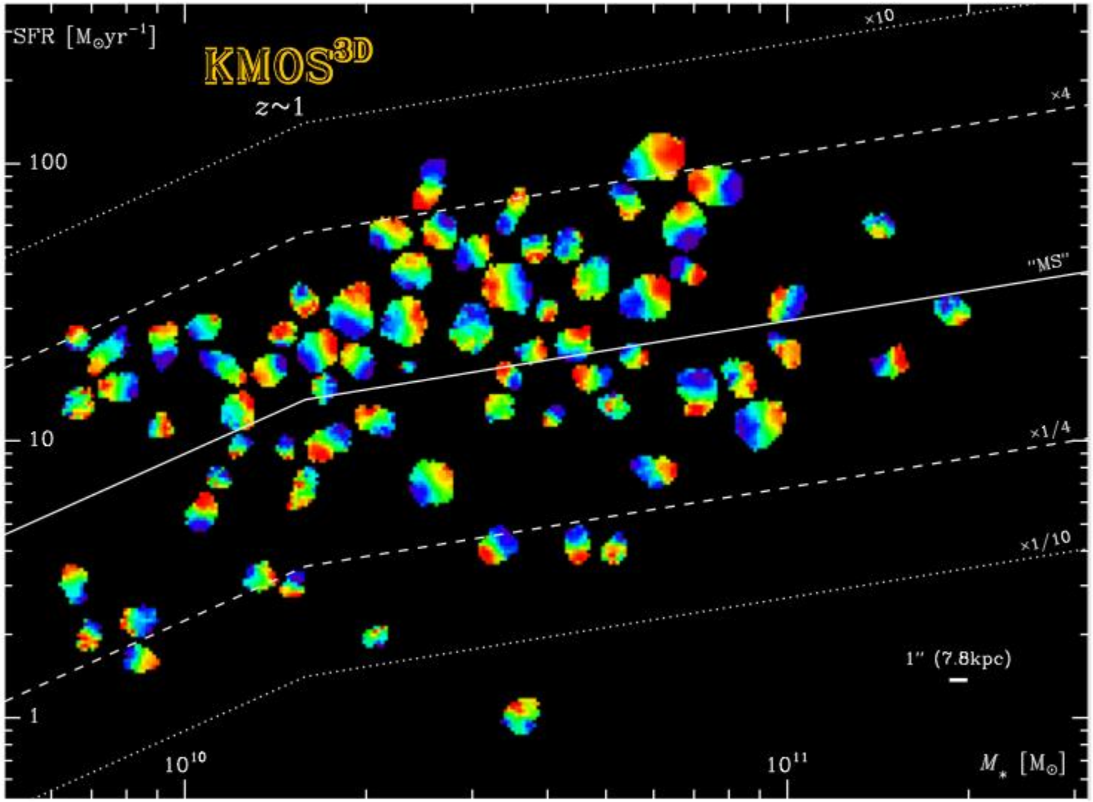
› ***30 sq deg field-of-view IFU!!!!***



Serra, Koribalski, Kilborn et al., in prep.

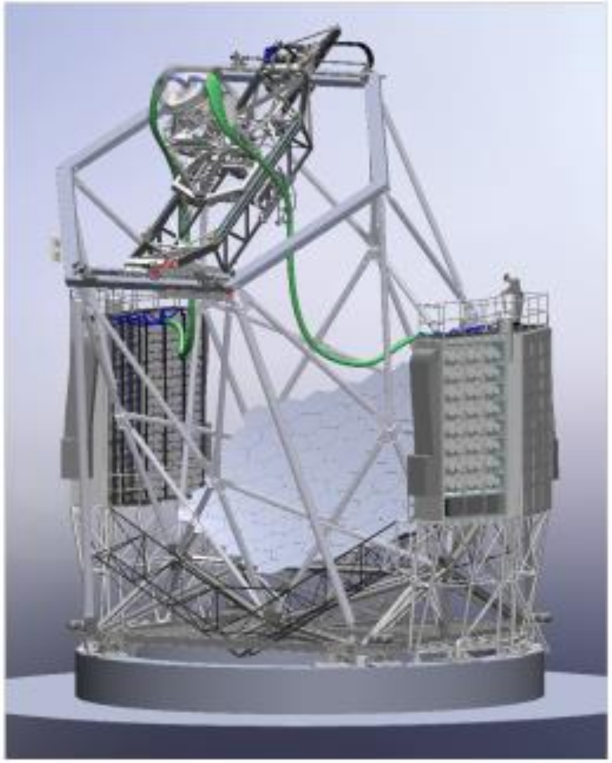
Expanding the reach of IFUs

- The natural region for expansion is in redshift, e.g. z>1. KMOS is already doing this (e.g. Wisnioski et al. 2014).
- Emission line kinematics for several thousand galaxies at, z~1-2.
- Hard/impossible to get resolved stellar kinematics at high redshift.
- Surface brightness dimming kills us.



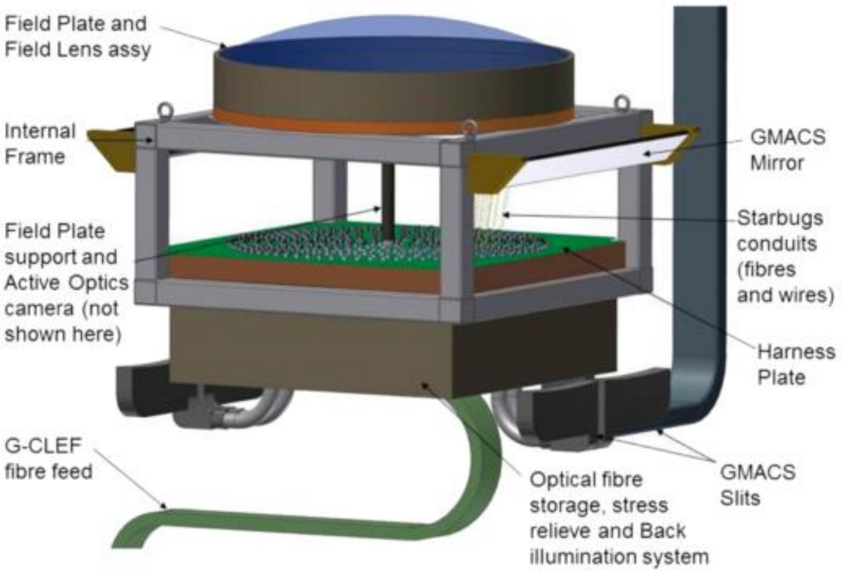
Monolithic multi-object IFUs

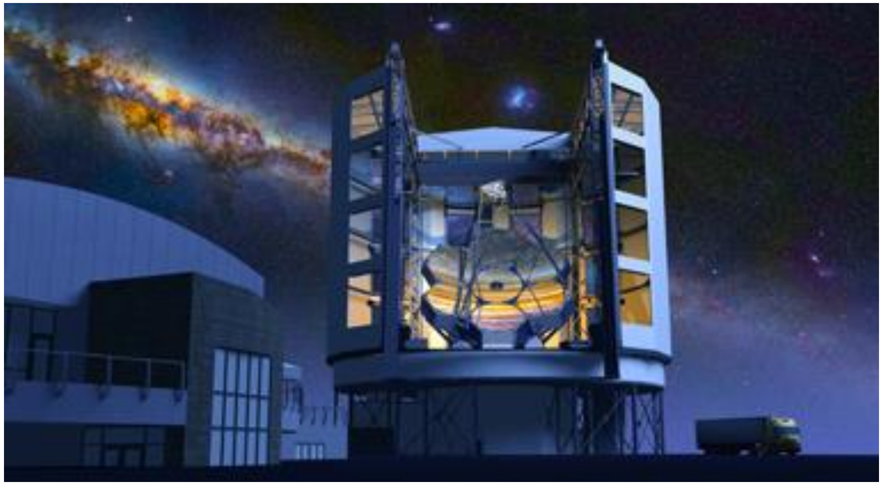
› Areal coverage for instruments like MUSE and VIRUS (see Gary Hill's talk) make them effectively multi-object systems.



MOS IFS on the GMT

- 24m GMT planned to be commissioned in 2021.
- Largest field of view possible (with corrector) is 20 arcmin diameter.
- Facility fibre system: MANIFEST.
- Use autonomous starbugs (see Julia Bryant and Andrew Hopkins talks).
- Can feed a number of different other GMT facility instruments, e.g. GMACS, G-CLEF, NIRMOS
- Do ***NOT*** want diffraction limited AO.





MOS IFS on the GMT

› What's possible with GMT, particularly with stellar continuum?

› Sizes:

- z=0.05 ->0.97 kpc/", SAMI, 1.6" fibres
- z=0.3 -> 4.4 kpc/" 4.5x smaller than SAMI
- z=0.5 -> 6.1 kpc/" 6.3x smaller than SAMI

› GMT GLAO performance (van Dam et al. 2014):

Wavelength (μm)	0.440	0.550	0.640	0.790	1.215	1.654	2.179
FWHM (mas)							
No correction	573.3	552.9	533.2	510.9	451.8	403.6	374.0
Averaged-wavefronts reconstructor	537.3	518.9	502.8	470.9	392.8	337.0	268.8
Minimum-variance reconstructor	478.0	447.3	420.7	383.0	268.1	203.6	161.2

MOS IFS on the GMT

- What's possible with GMT, particularly with stellar continuum?
- Back of envelope calculation scaling from known SAMI performance, assuming 0.4" fibres for GMT:
  - z=0.05, S/N at median Re surface brightness is ~16/A in 4 hours on AAT.
  - z=0.30, S/N at median Re surface brightness is ~16/A in 8 hours on GMT.
  - z=0.50, S/N at median Re surface brightness is ~10/A in 8 hours on GMT.
- Clearly plausible.
- Better resolution and smaller IFU fibres? Need to think about Multi-object AO…
- Go to near-IR and CaT?
- Direct measurement of the growth of the Hubble sequence.

Summary

- We are already doing the 3rd/4th generation of major galaxy redshift surveys.
- Integral field spectroscopy gives qualitatively different data.
- First generation of MOS IFU surveys now underway.
- Early data release now public, see: www.sami-survey.org
- Crucial to combine surveys:
  - IFU data + deep spectroscopy for environments and/or halo mass + HI surveys for gas mass + multi-wavelength for dust and multiple SF estimates.
- Pushing to high-z for gas ***and stars*** requires ELTs.