Dust and Molecular Gas in Early-Type Galaxies

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EAO, Hilo May 2019

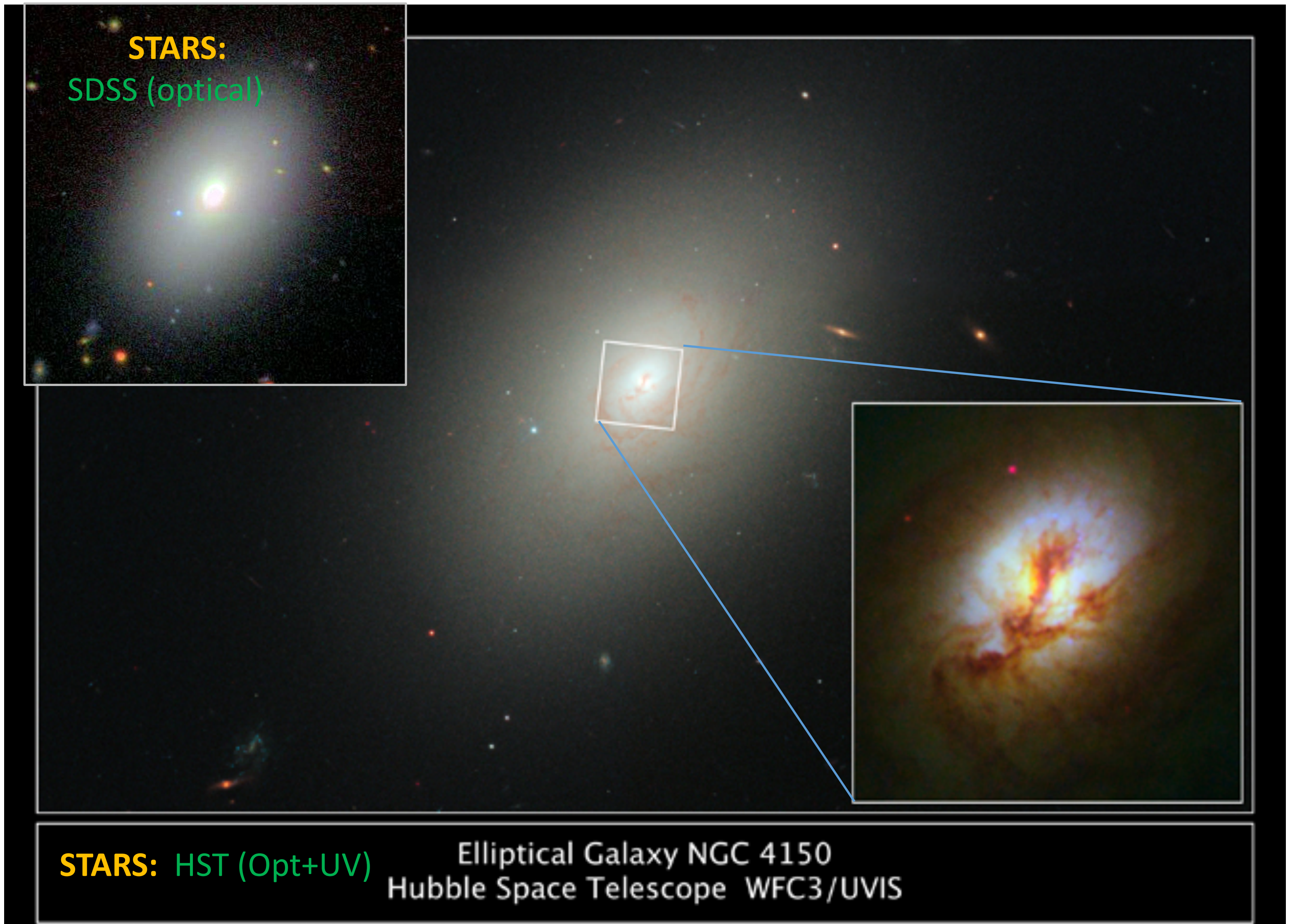
Outline of talk

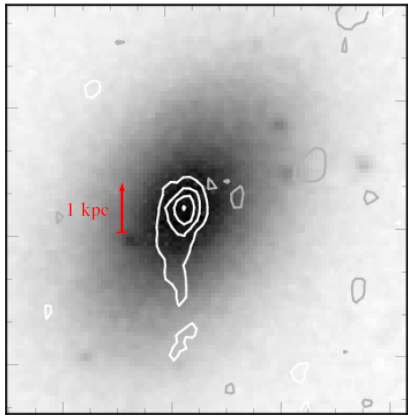
- **Motivation** – For studying gas and dust in ETGs
- **Observations** – Past, *Herschel Space Observatory*
- **Kinematics** – *SAMI* IFU observations
- **Environment** – Comparison of GAMA and Virgo
- ***ALMA*** – follow-up of 5 dusty ETGs
- ***KiDS*** – data and future
- **Summary**

Motivation for studying gas and dust in ETGs

- Smoking gun of past galaxy evolution – through ISM content, kinematics and structure (e.g. *Davis et al. 2011*)
- Environmental effects on ISM (e.g. *Young et al. 2011; Agius et al. 2015*)
- Survivability of dust and dust heating mechanisms
- Gas-to-dust ratios in different galaxy types (cosmological inferences, e.g. *Camps et al. 2016*)
- ETGs represent endpoints of galaxy evolution? (e.g. *Eales et al. 2018*)

Multiwaveband data
Elliptical **NGC4150**



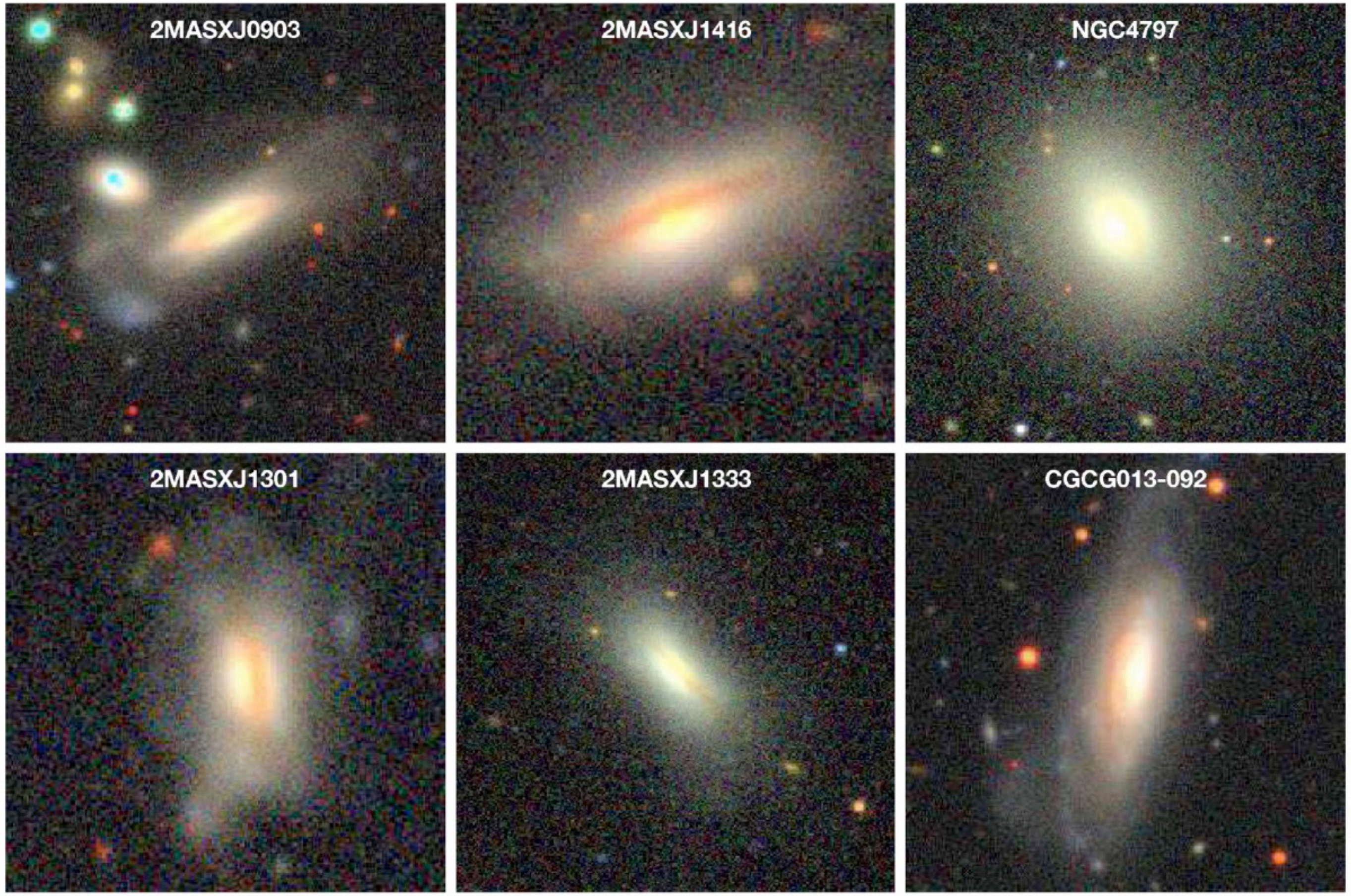


MOLECULAR GAS:
CO (radio)

Crockett et al.
Young et al.

Gas and dust origins in ETGs?

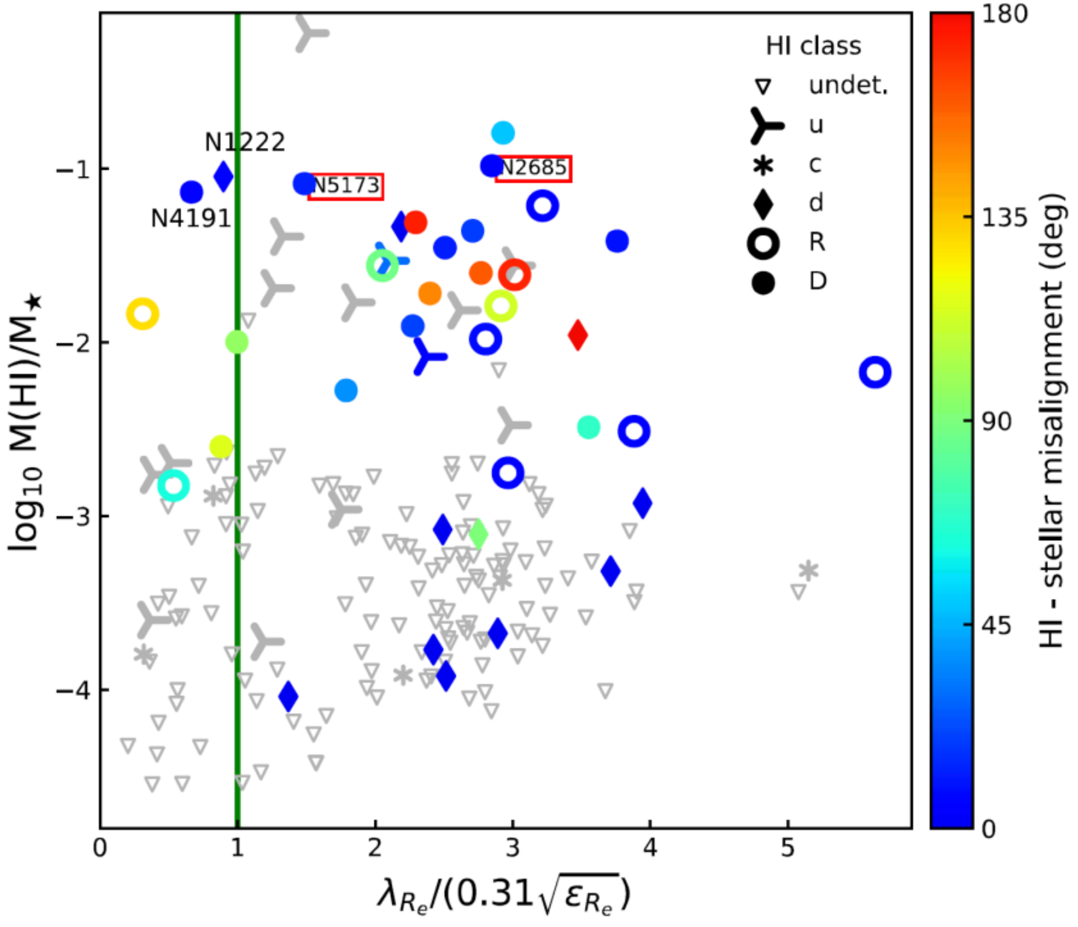
- Stellar mass loss?
- Major or minor mergers?
- Cold gas accretion?



Examples of minor mergers
(*van der Voort et al. 2018*)

ISM variety in ETGs – e.g. (M_{HI}/M_*)

(*Young et al. 2018*)



Molecular gas in ETGs

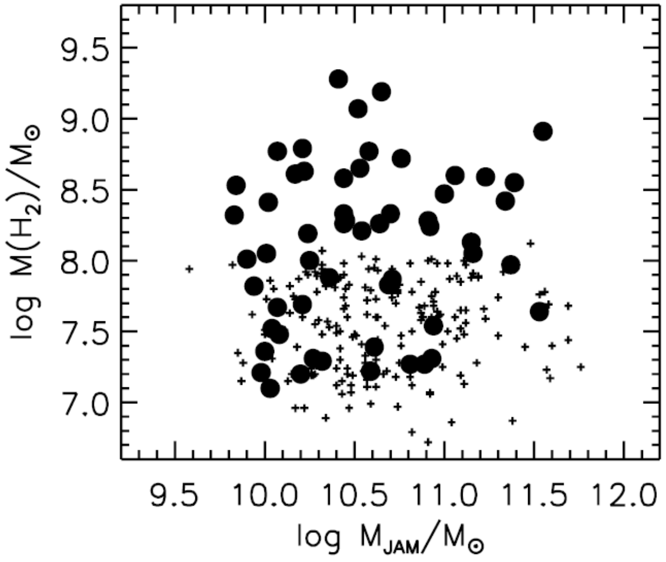
- Previous relations (ATLAS^{3D}, IRAM, CARMA):

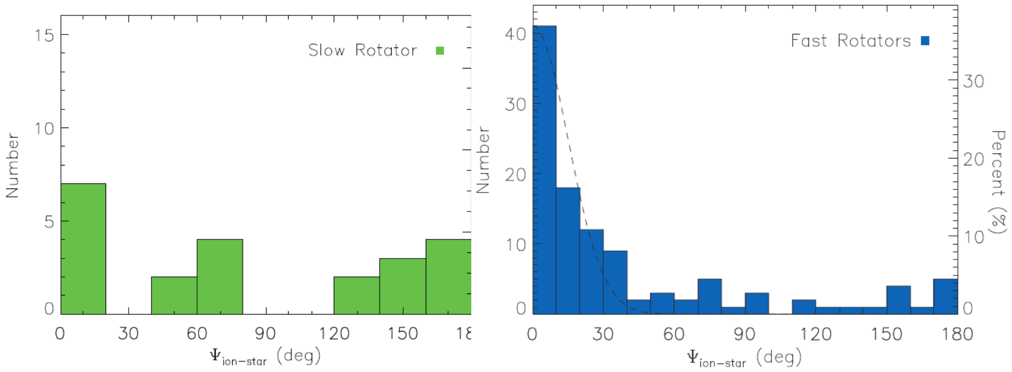
  (*Young et al. 2011*)
  - ~22% detections, Log($M(H_2)/M_\odot$)=7.1 to 9.3
  - Lack of $M(H_2)$ versus M_{gal} relations.
  - More CO detected in fast rotating ETGs
  - Most CO gas rich found in rare environments

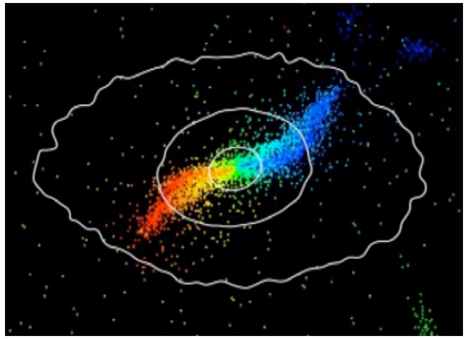
  (*Davis et al. 2011*)
  - Ionized gas follows molecular (CO) gas distribution
  - <u>Kinematic misalignments</u> of CO (& ion) versus stars, particularly in slow rotators:
  - Misalignments indicate external origin

- Simulations: Misaligned gas disks can survive

  ~2Gyr (*van de Voort et al. 2015*)

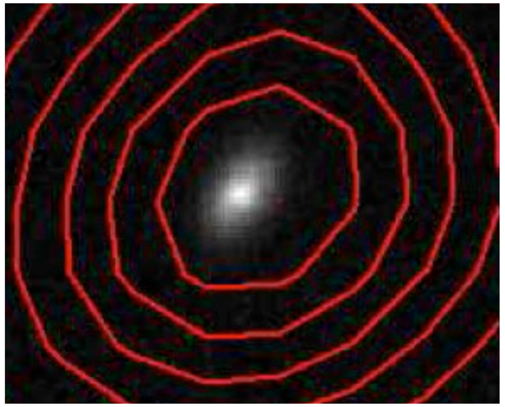






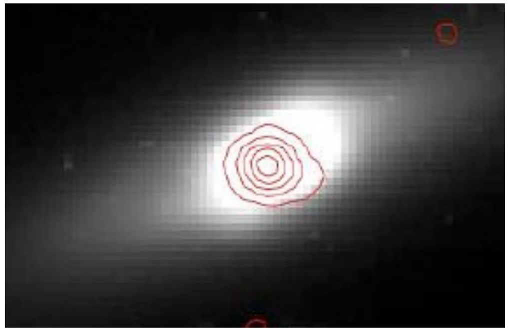
Dust in ETGs

- Earlier results (ATLAS^{3D} (*abs*), Scuba, ISO (*em*), Spitzer):
  - 16% dust features in optical images (*Krajnovic et al. 2011*)
  - Lack of far IR versus optical trend (*Temi et al. 2007*)
  - Dust detected in 24%(Es), 62%(S0s) in HRS, 62 ETGs (*Smith et al. 2012*)



- Sample from early H-ATLAS/GAMA

  (*Agius et al. 2013/15*):
  - Dust detected in 29% of 771 ETGs
  - Plus Herschel, Virgo cluster survey (HeViCS)



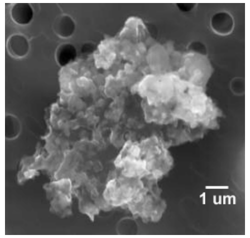
Large surveys

GAMA: Galaxy and Mass Assembly Survey (Multi-waveband)

http://www.gama-survey.org/

H-ATLAS: Herschel Astrophysical Terahertz Large Area Survey (Sub-mm)

Detects dust emission



http://www.h-atlas.org/

Good for observing complete samples, e.g. E/S0 galaxies

ETG Study (*Agius, Sansom et al. 2015*)

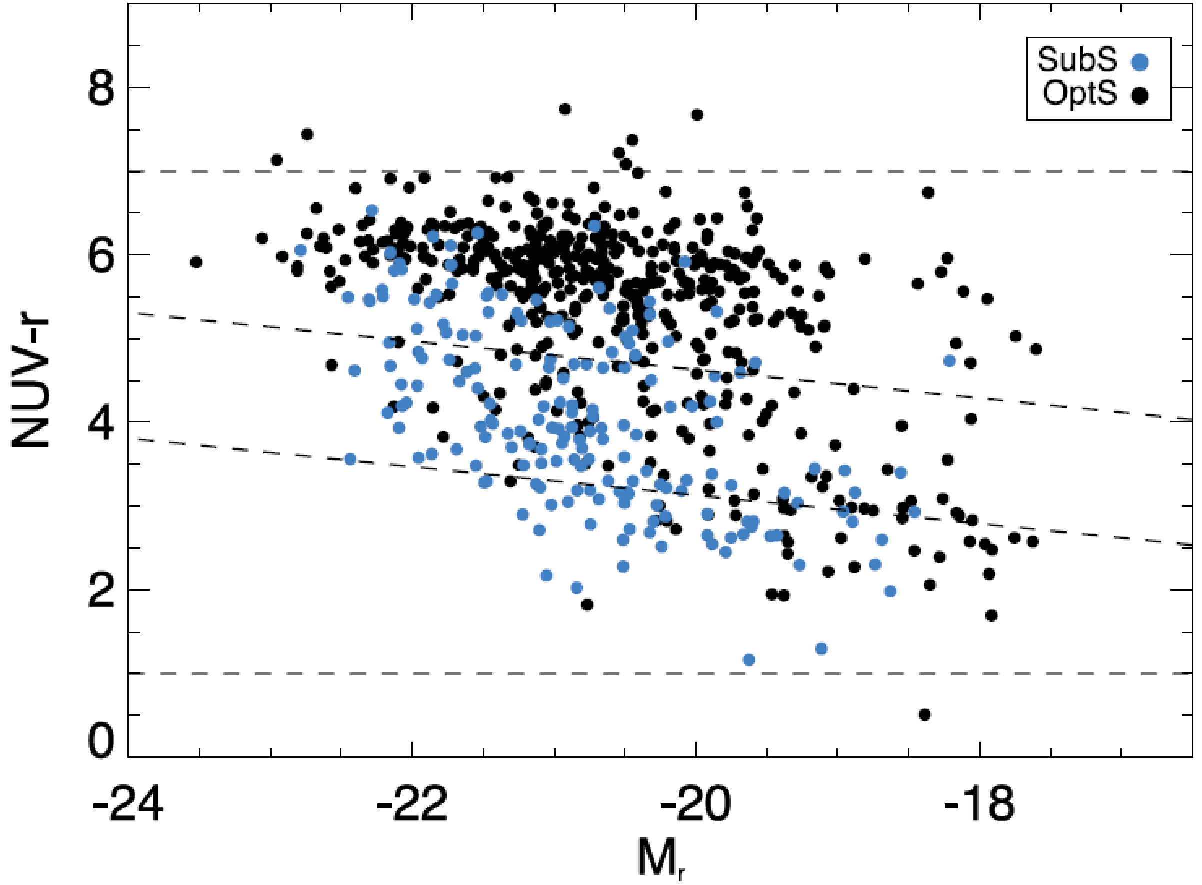
- Out to **z<0.06**, mostly field/group environments
- (**E, S0, Sa**) from GAMA *morphologies* (SDSS images; *Kelvin et al. 2014*)
- **H-ATLAS/GAMA** – 3 equatorial field areas
- Removed: *Contaminants, lenses, AGN, flat, small galaxies, 20 spiral*
- 771 ETGs *complete* down to **M_r = –17.4 mag** (≈SMC)
- **220 submm detections** out of 771 ETGs (**29%**)
- Investigate dust (M_d, T) versus:
  - Stellar Mass (M_*)
  - Star formation (UV, optical colours, Hα)
  - Types
  - Environment

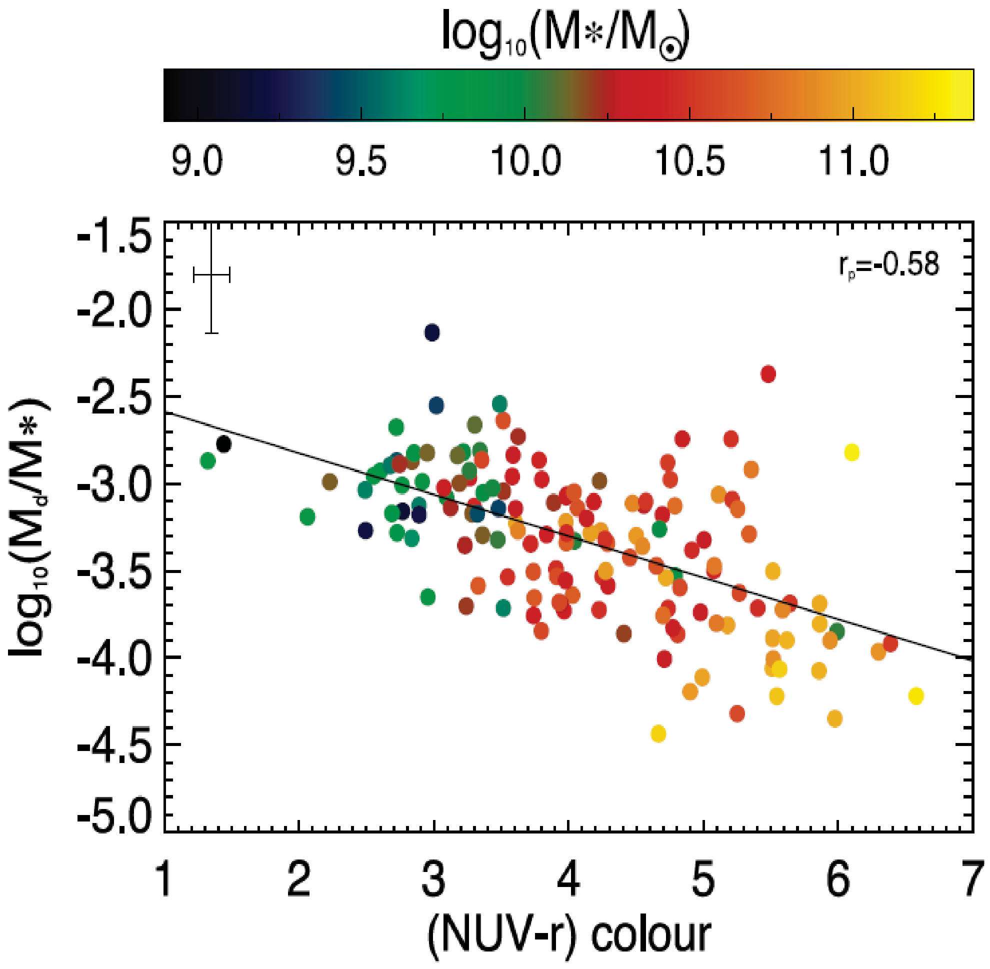
What trends did we find?...

Downsizing in ETGs

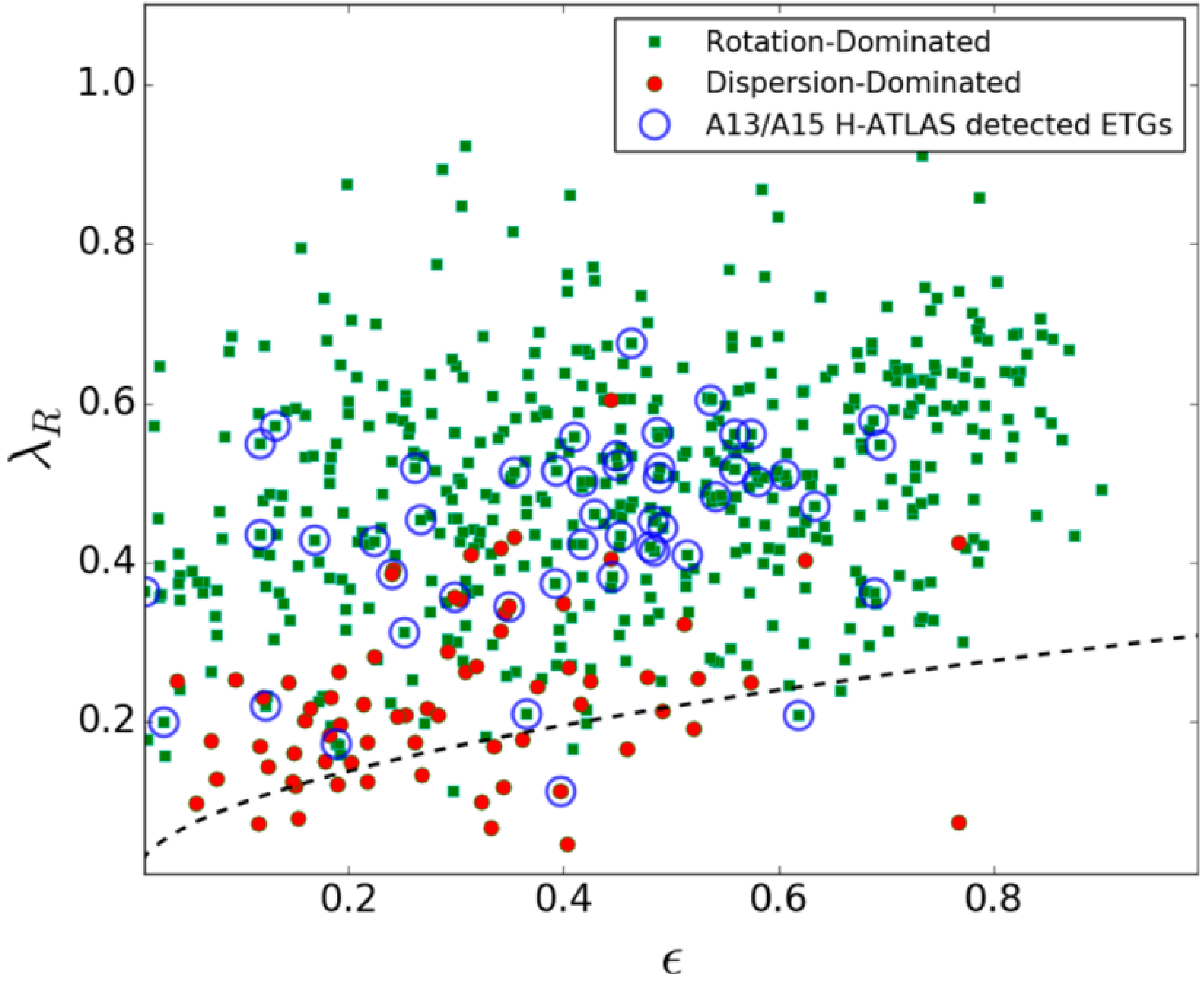
Herschel-ATLAS results (*Agius et al. 2013*)

● = Submm detected





Kinematics of some ETGs *(Bassett et al. 2017)*



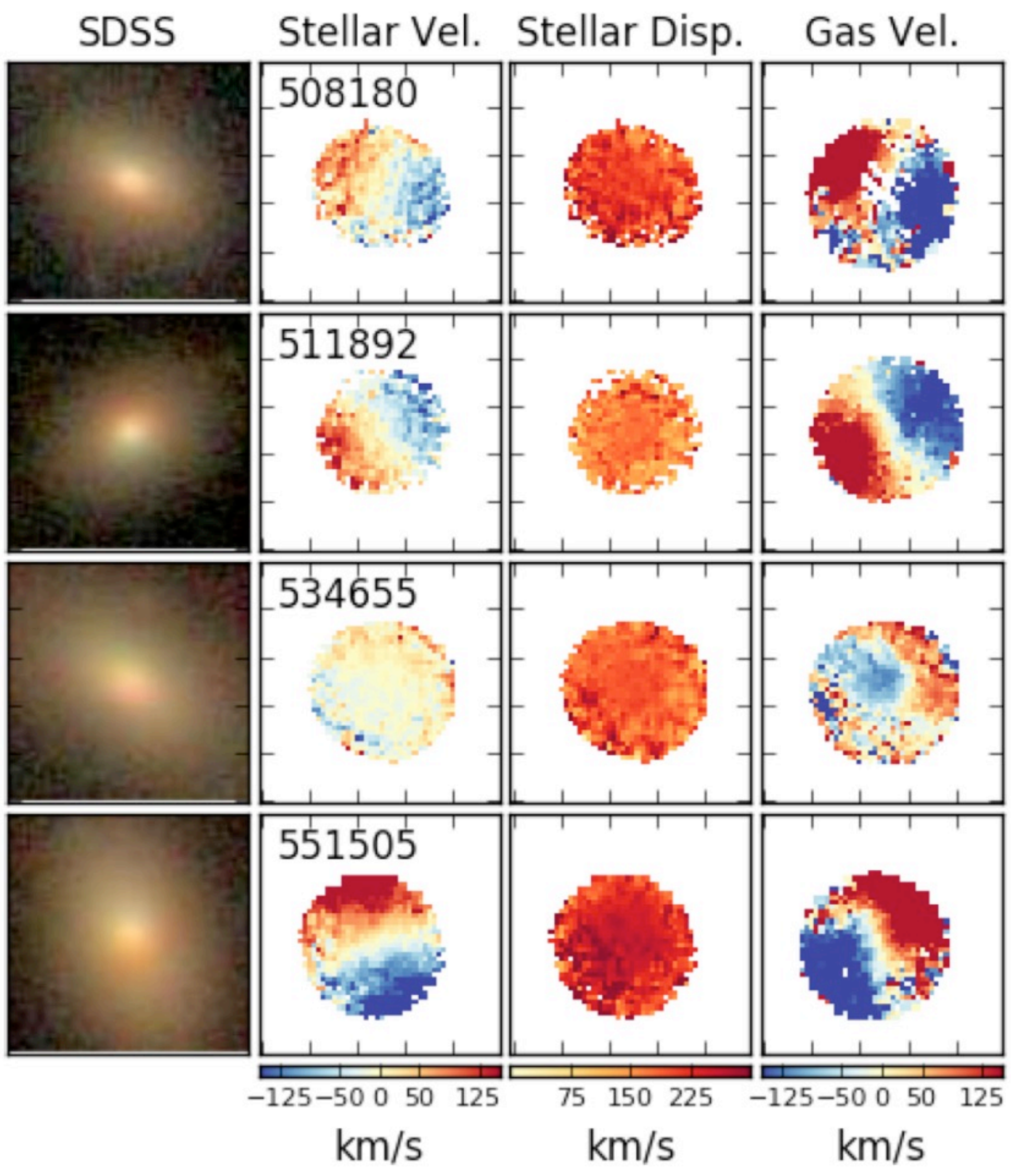
- 49 out of 220 submm detected ETGs observed with SAMI optical IFU
- Kinematically classified
- *Emsellem et al. 2011* --------
- $$\lambda_R = \frac{\sum_{k=1}^{n} F_k R_k |V_k|}{\sum_{k=1}^{n} F_k R_k \sqrt{V_k^2 + \sigma_k^2}}$$ (*n* spaxels)
- Only 4 are dispersion-dominated, dusty ETGs

  (σ>110 km/s; $\sigma > V_c$)

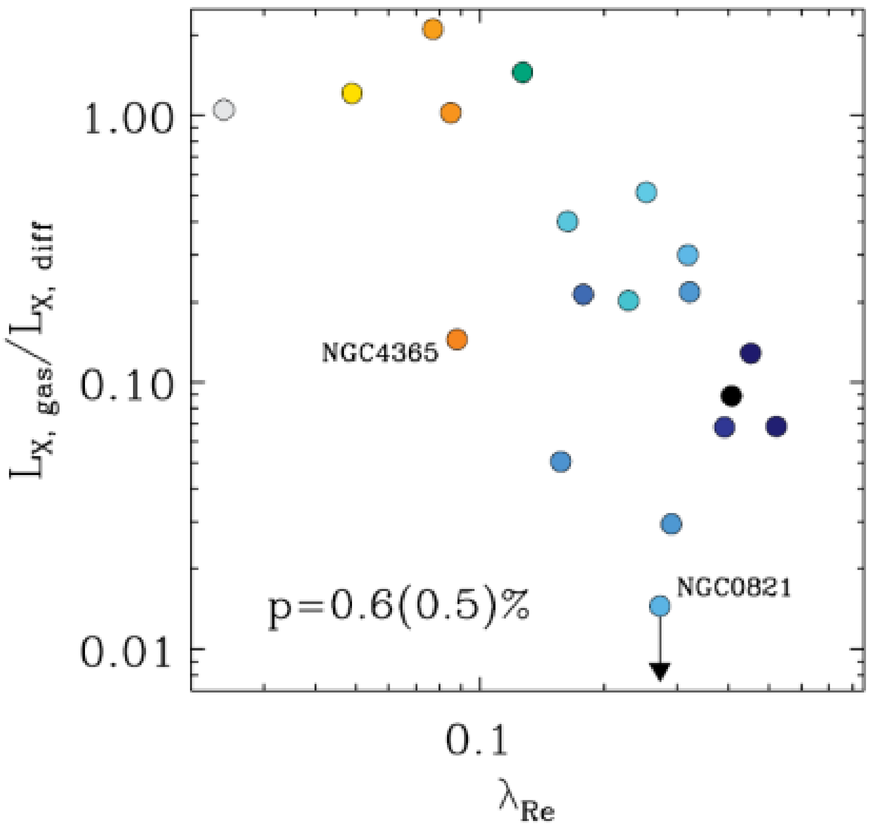
Kinematics of some ETGs

- 4 dispersion dominated, dusty ETGs, out of 49 ETGs observed with SAMI
- Measured stars and ionized gas
- Star-to-gas space and kinematic misalignments, suggestive of merger.

(Bassett et al. 2017)



Survival of dust in ETGs



(Sarzi et al. 2013)

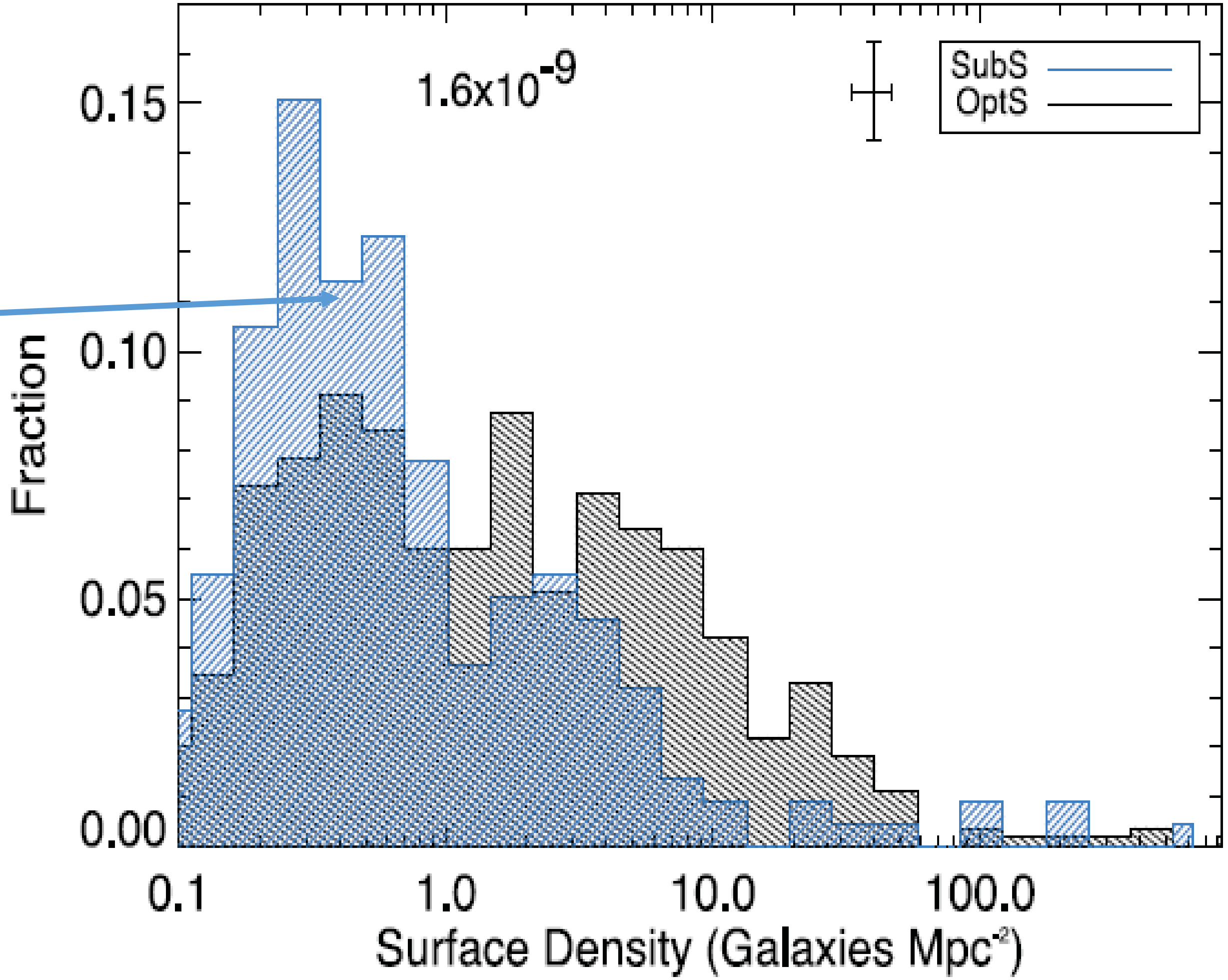
- 49 representative H-ATLAS ETGs - mostly rotation dominated (*Bassett et al. 2017*)
- Fast rotators have less hot, X-ray gas (e.g. *Sarzi et al. 2013*)
- Dispersion dominated ETGs (σ>150 km/s), with X-ray halos – expect dust destruction in τ_{dust} < 0.02Gyr
- **Dust is more likely to survive longer in fast rotating ETGs**

  ⇒ *Seen in HRS and H-ATLAS samples*

Environment densities in sub-mm

detected and un-detected ETGs (*Agius et al. 2013*)

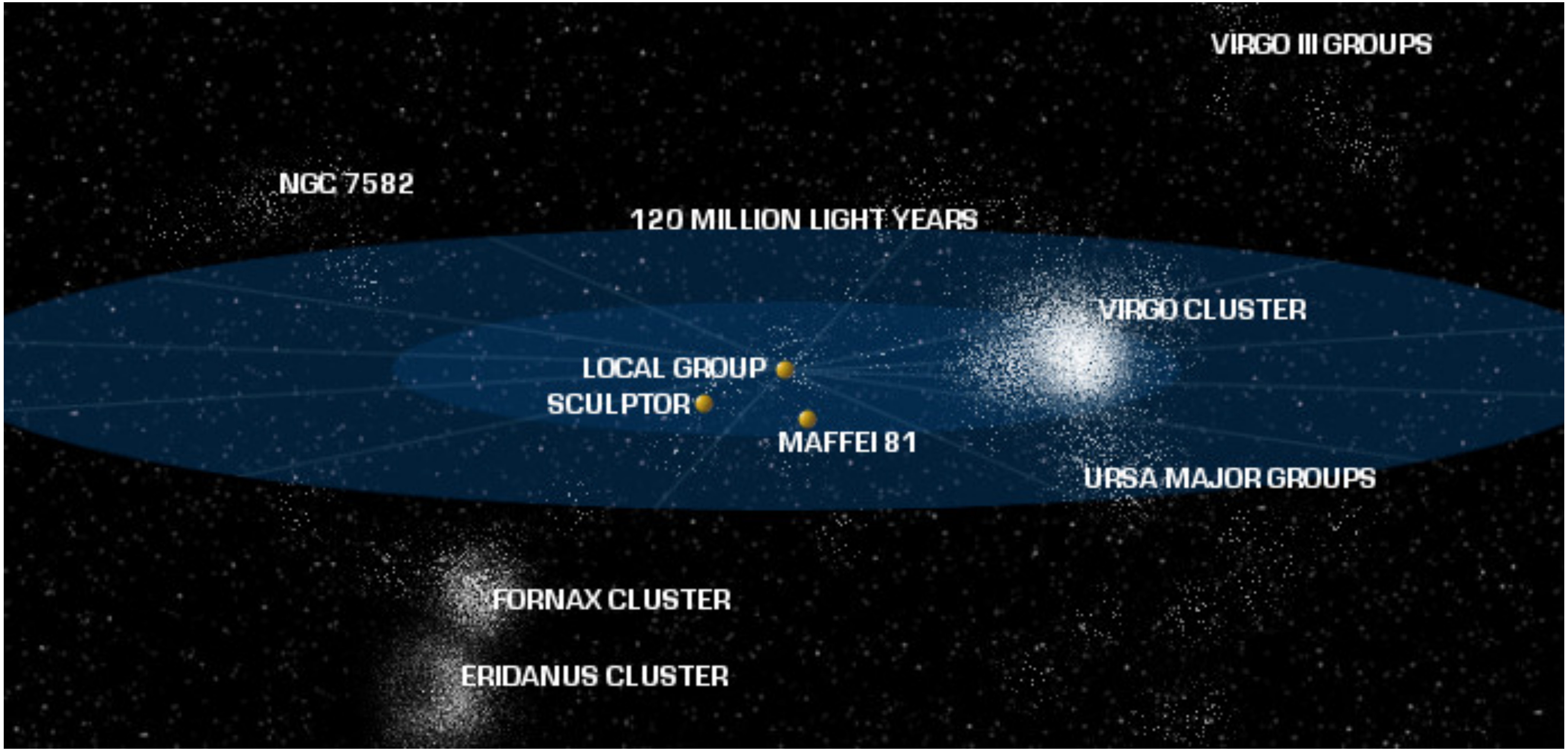
Dusty ETGs tend to lower density environments



What about denser environments?

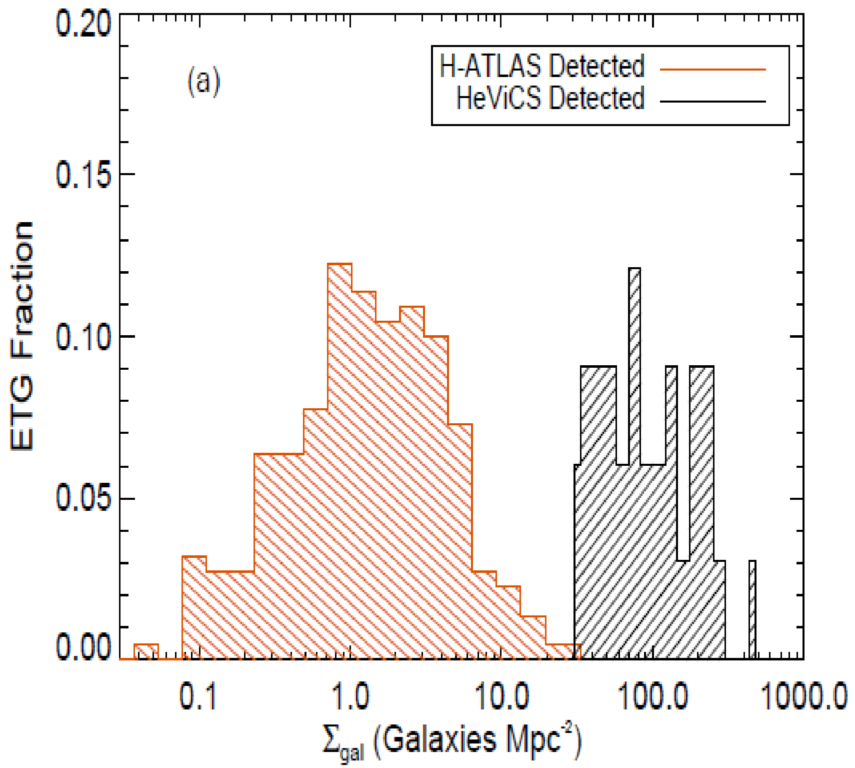
Virgo Supercluster region

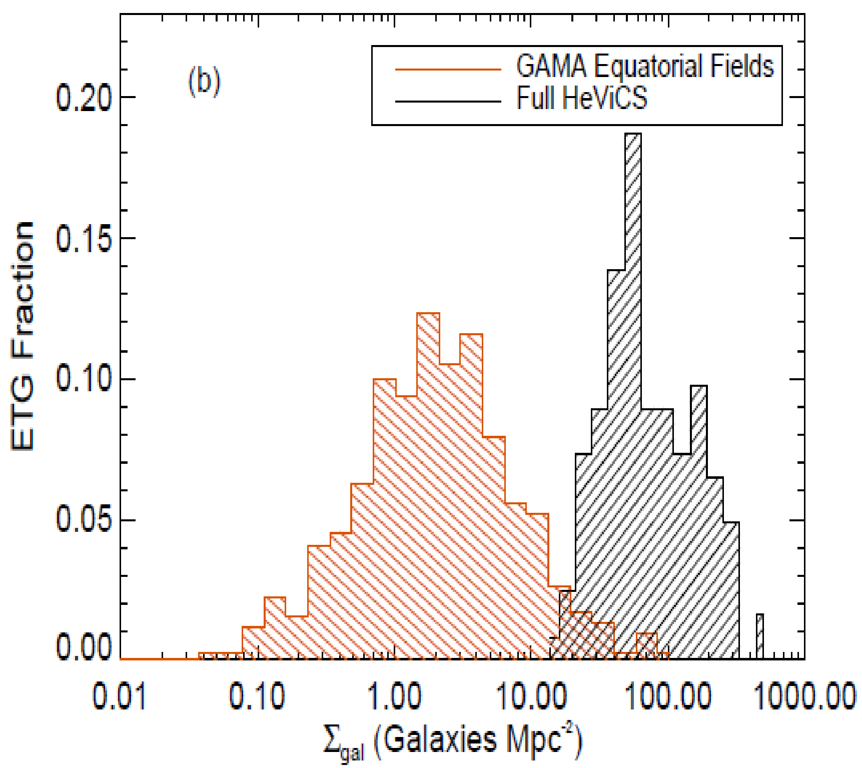
(*1 ly =0.307 parsecs*)



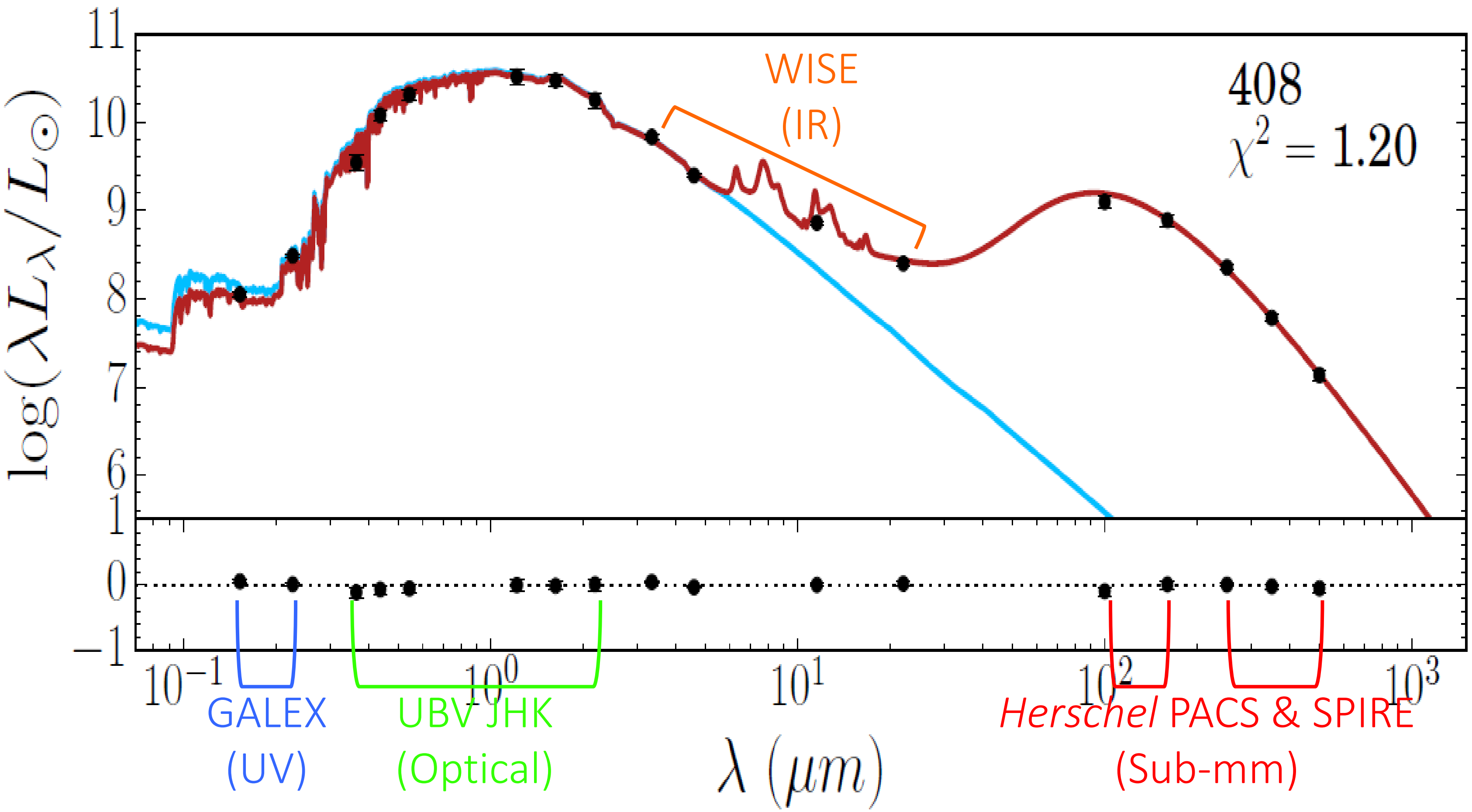
GAMA and Virgo Cluster ETGs

(Agius et al. 2015)



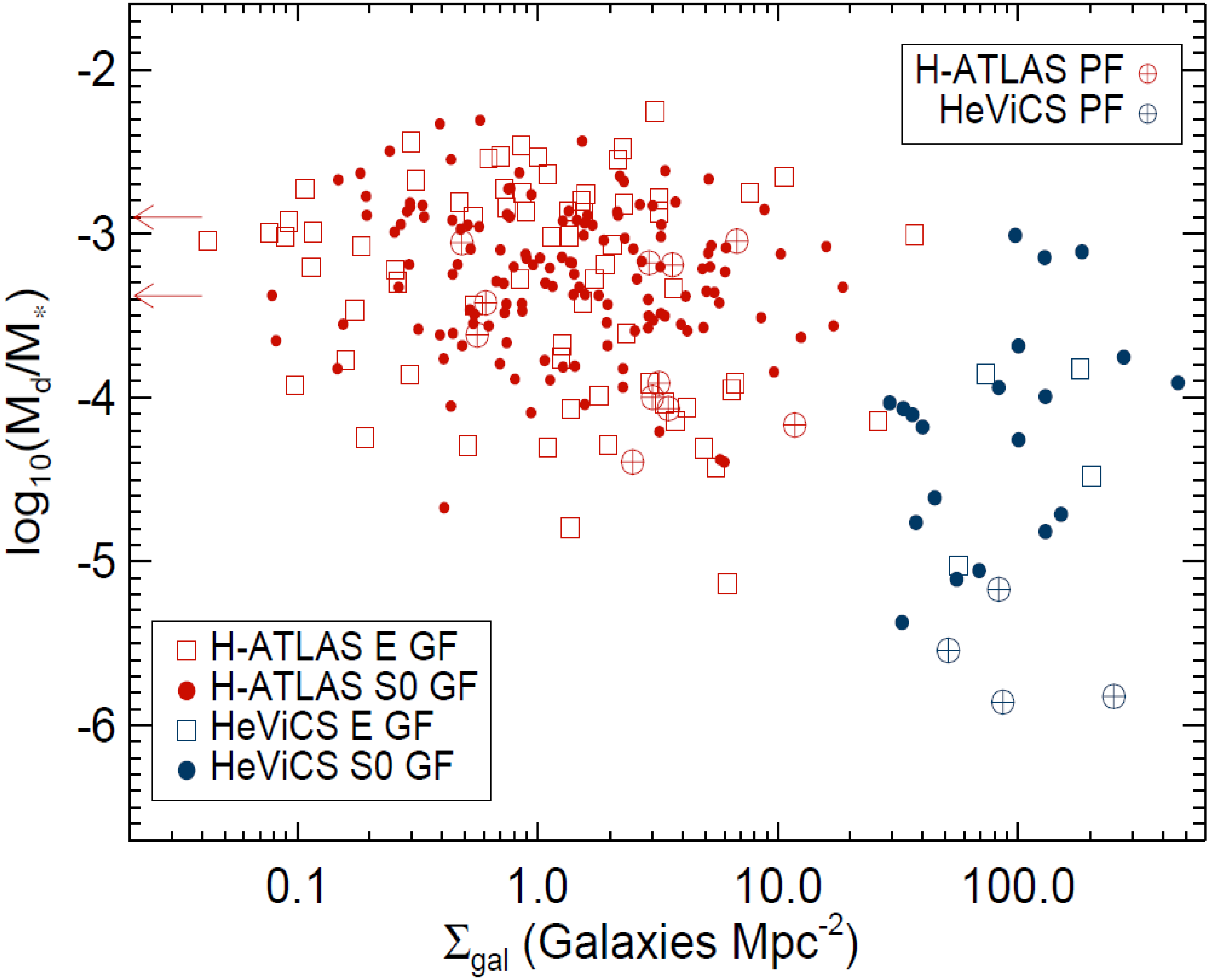


Spectral Energy Distributions + Fitting



⇨SFR, M_*, M_d etc.

Comparison with Virgo cluster *(Agius et al. 2015)*

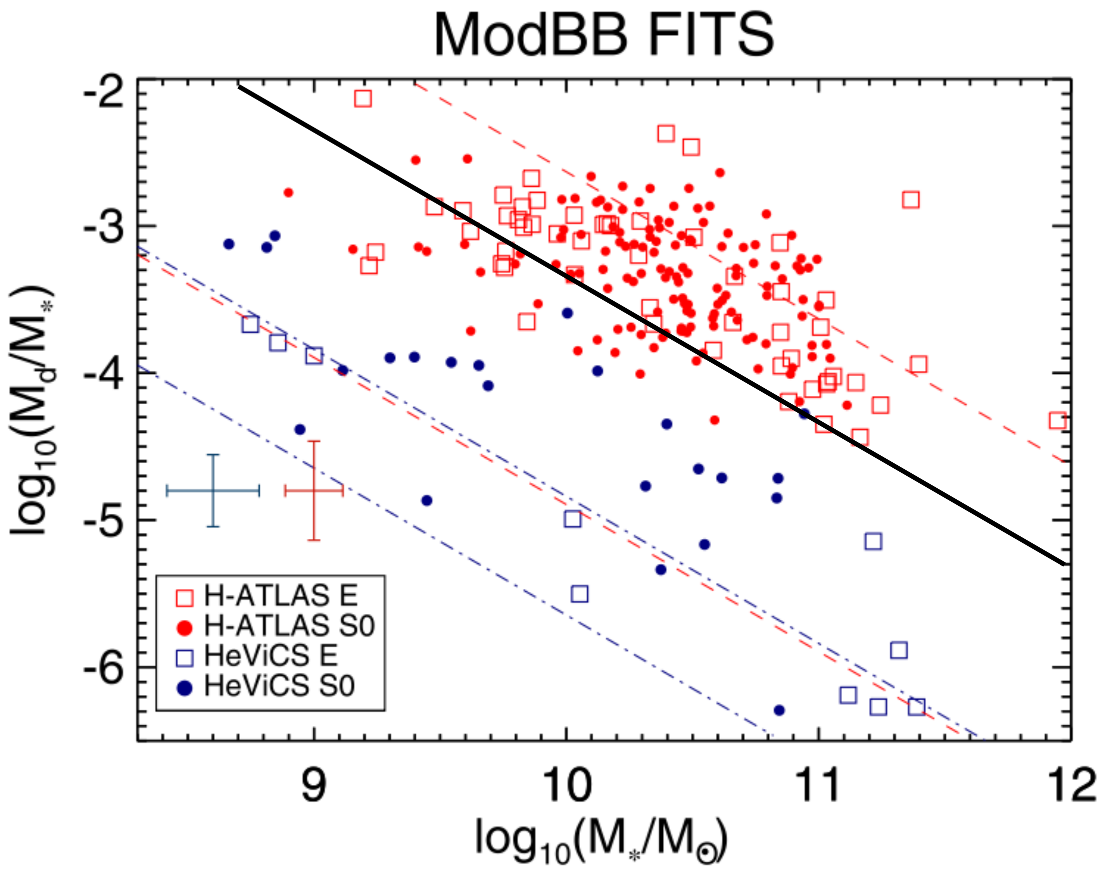


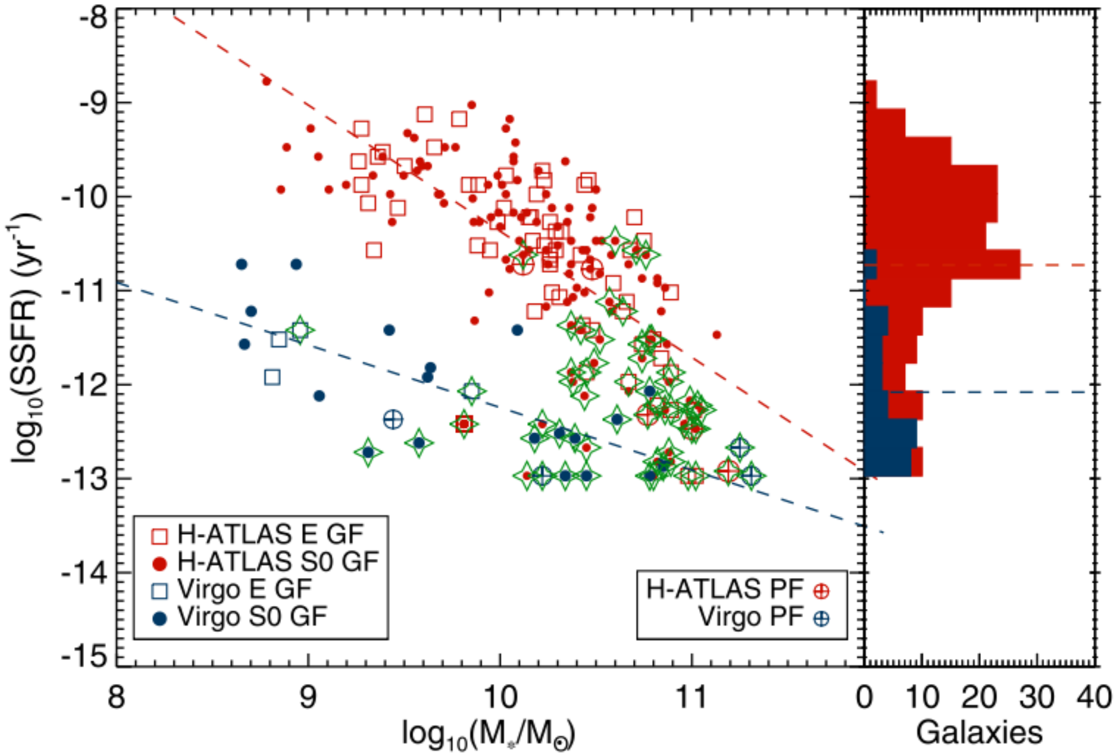
Specific dust-to-star mass ($Log(M_d/M_*)$) versus Environmental density (Σ_{gal})

Comparison with Virgo Cluster

Lower Dust Masses and Star Formation Rates in ETGs in Virgo Cluster

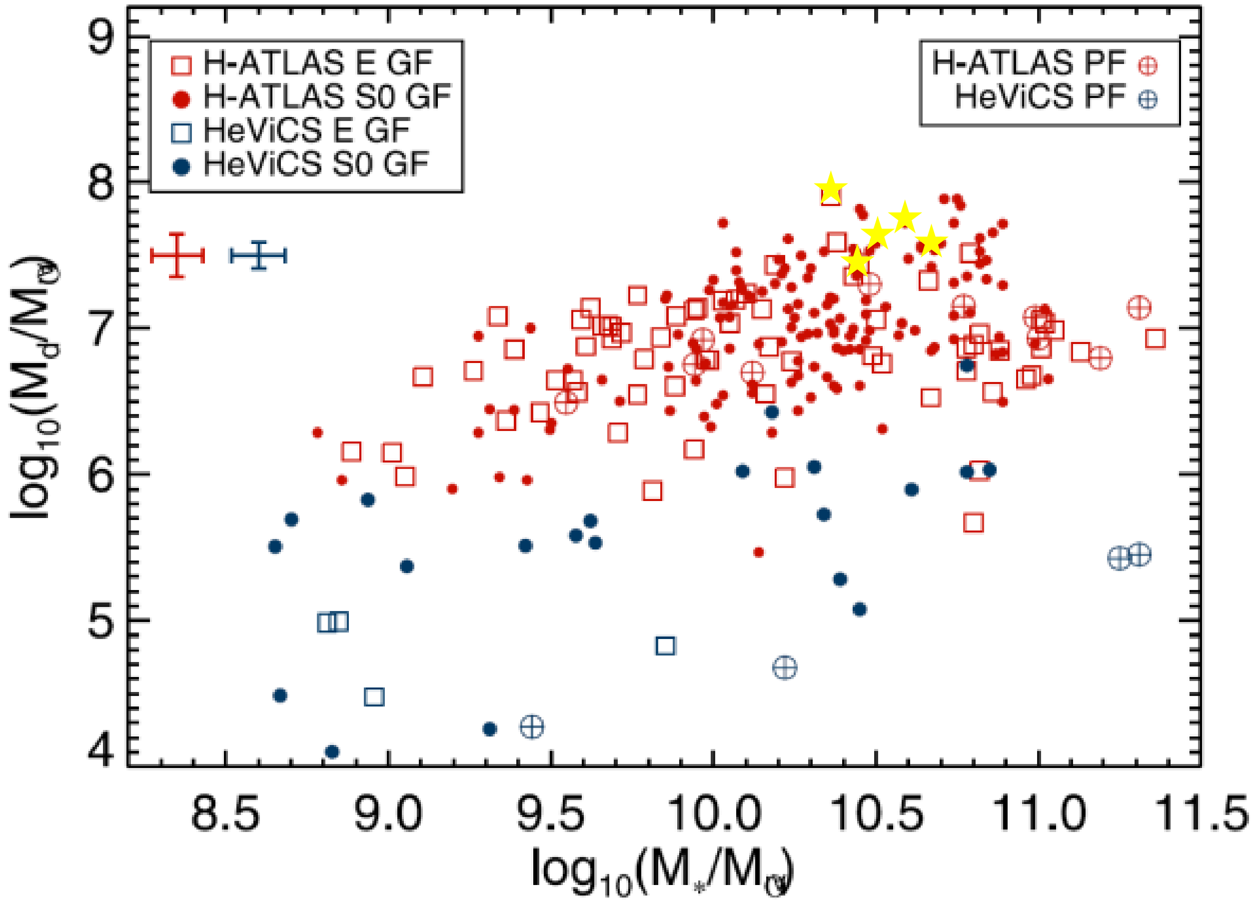
(Agius et al. 2015)





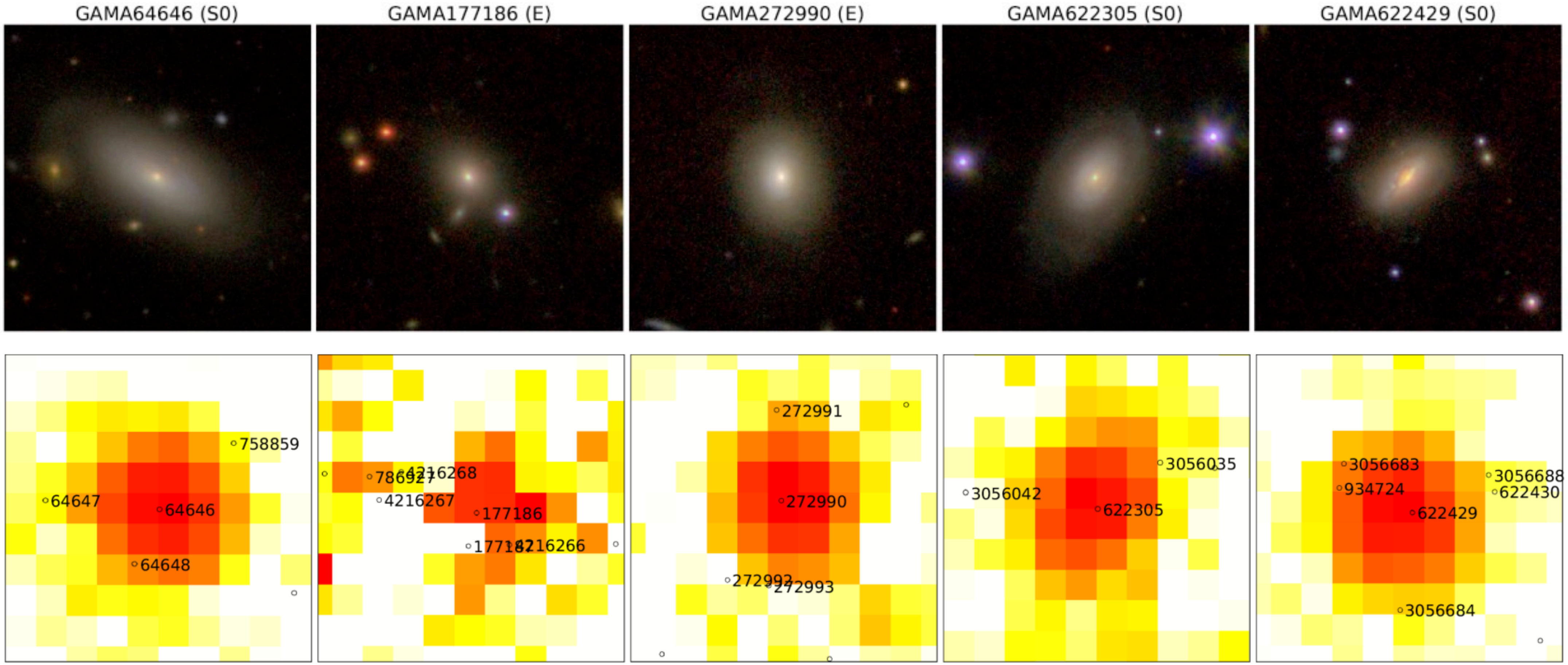
Comparison of GAMA with Virgo cluster

(Agius et al. 2015)



H-ATLAS ETGs: 5 targets in yellow observed with ALMA

5 dusty ETGs
(Morphologies from GAMA catalogue)



KiDS
(gr)

H-ATLAS
(250μm)

1′ × 1′

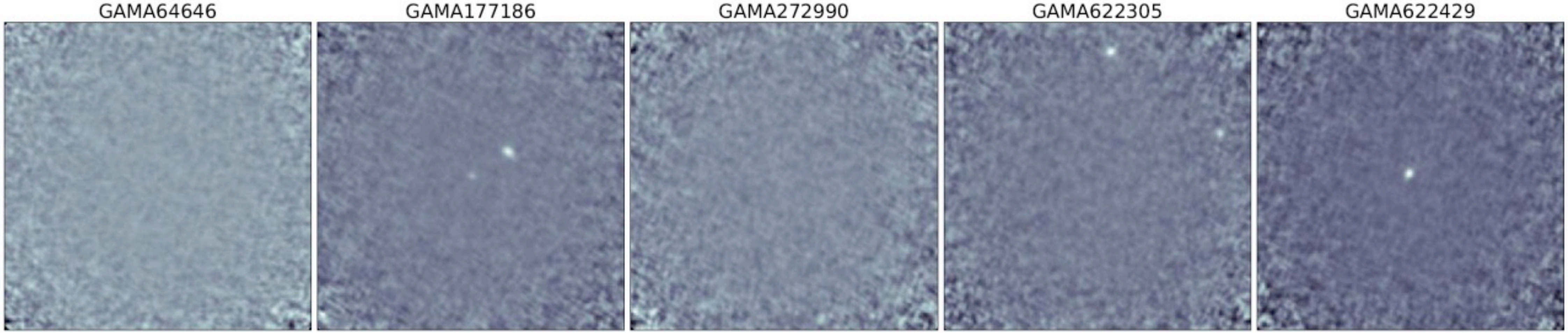
Resolving dust and gas

ALMA (*almaobservatory.org*)

- Interferometry ⇒ data cube (*x, y, vel*)
- Dust emission - **from continuum**
- Molecular gas - **from line transitions in molecules**, $^{12}CO(2\text{-}1)$ transition at 230 GHz (1.3mm) for low density gas

- Data processing: ALMA calibrations + cleaning + PB corrections (CASA) + moments and spectra (IDL, python).

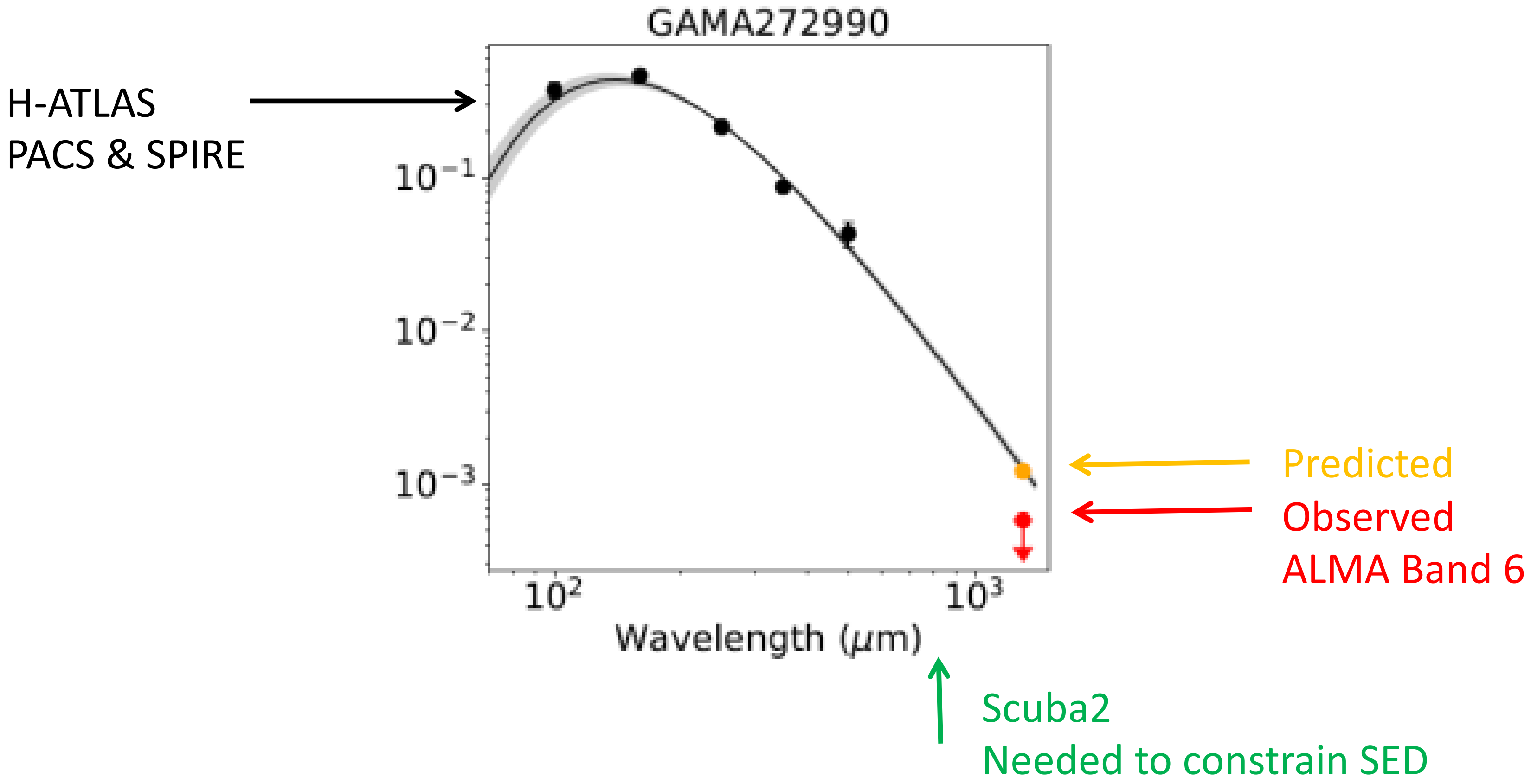
ALMA continuum detections



- No detections in GAMA64646 and GAMA272990
- Unresolved, faint source at centre of GAMA177186, plus brighter submm source ~4” NW (probably contributed to H-ATLAS fluxes).
- Two serendipitous point sources at ~13” N and W of GAMA622305
- Unresolved source at centre of GAMA622429 – could be AGN.

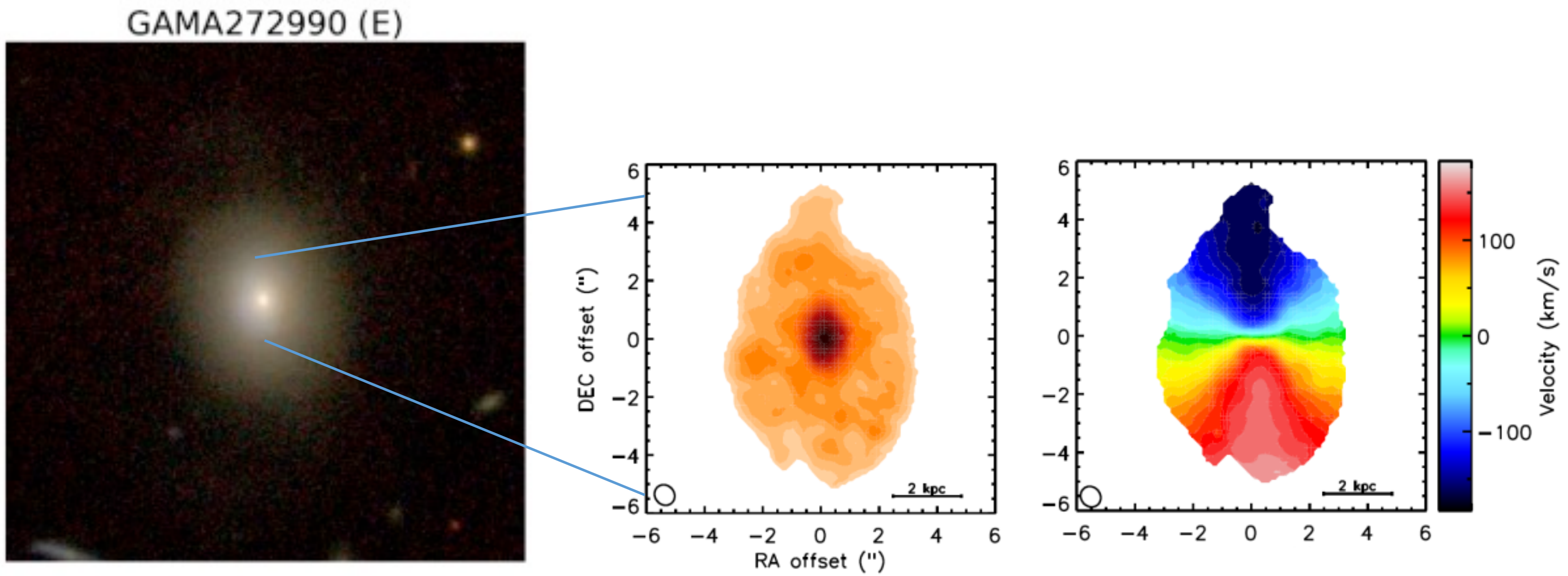
Dust

- Lack of extended ALMA continuum: LAS and sensitivity limitations (if dust is extended)
- E.g.



Results from ALMA *(Sansom et al. 2018)*

E.g. $^{12}CO(2\text{-}1)$ in GAMA 272990 - an Elliptical galaxy



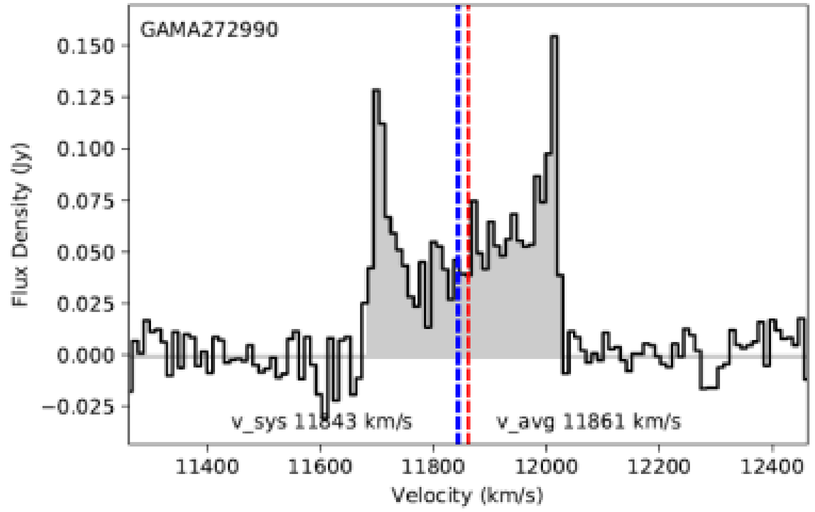
KiDS optical image (r-band, 1'x1')

Moment 0 (^{12}CO flux)

Moment 1 (^{12}CO velocity)

Molecular gas:
Flux to Luminosity and Mass conversions

- Measure line flux as $S\Delta v$ (*Jansky kms* $^{-1}$) from spectra:



- $L_{CO} = (c^2/2k) D_L^2 \{S\Delta v\} \upsilon_{rest}^{-2} (1+z)^{-1}$

(K km s^{-1} pc^2) (Mpc^2) (Jy kms^{-1}) (GHz^{-2})

- Conversion from $L_{CO(2\text{-}1)}$ to $L_{CO(1\text{-}0)}$ (for M-L relation of *Solomon et al 1987*)
  E.g. *Young et al. 2011,* 1:1 if same excitation T
- Conversion from CO to H_2 mass (α_{CO} or X_{CO})
  Metal dependant, e.g. *Remy-Ruyer et al. 2014*
- Conversion from M_{H_2} to M_{Total} (for Helium, metals)

$$M_{Total} = 1.37 \alpha_{CO} \frac{L_{CO(1-0)}}{L_{CO(2-1)}} L_{CO(2-1)}$$

Molecular gas-to-dust mass ratios etc.

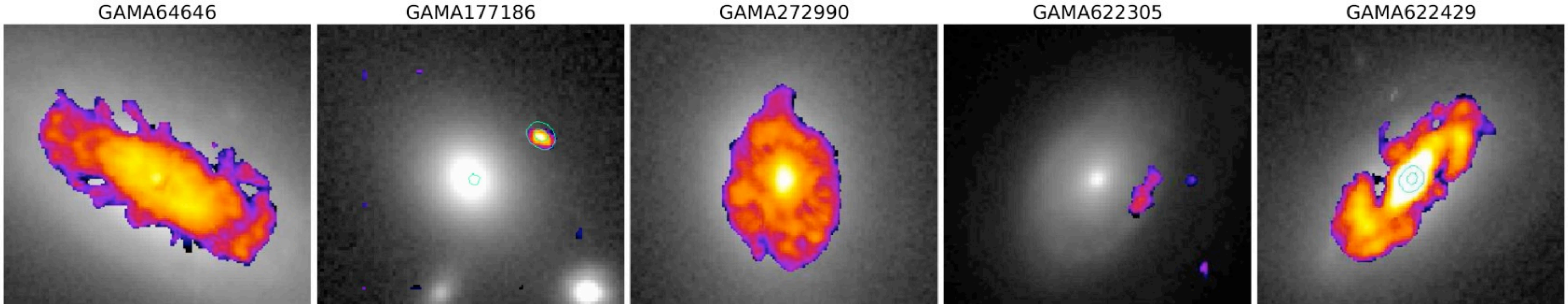
(*Sansom et al. 2018*)

ETG GAMA ID	MAGPHYS M_* ($M_\odot$)	MAGPHYS M_d ($M_\odot$)	$\pm$	MAGPHYS SFR ($M_\odot$/yr)	ALMA M_{mol} ($M_\odot$)	$\pm$	$\frac{M_{mol}}{M_*}$	$\frac{M_{mol}}{M_d}$	$\pm$	(M_{mol}/SFR) t_{depl} (yr)
64646	7.80E+10	3.3E+7	4.2E+6	1.066	3.2E+9	2.4E+8	0.0410	98	14	3.0E+9
177186	1.68E+10	1.9E+7:	4.0E+6	-	3.5E+8	4.8E+7	-	18:	5	-
272990	3.34E+10	2.3E+7	3.3E+6	0.608	2.4E+9	1.6E+8	0.0719	106	17	3.9E+9
622305	4.27E+10	3.9E+7	6.8E+6	0.490	6.6E+7:	1.3E+7	0.0015:	2:	1	1.3E+8:
622429	2.97E+10	4.2E+7	3.4E+6	4.245	7.1E+9	4.4E+8	0.2391	168	17	1.7E+9

M_{mol} > MWG

Results from ALMA (*Sansom et al. 2018*)

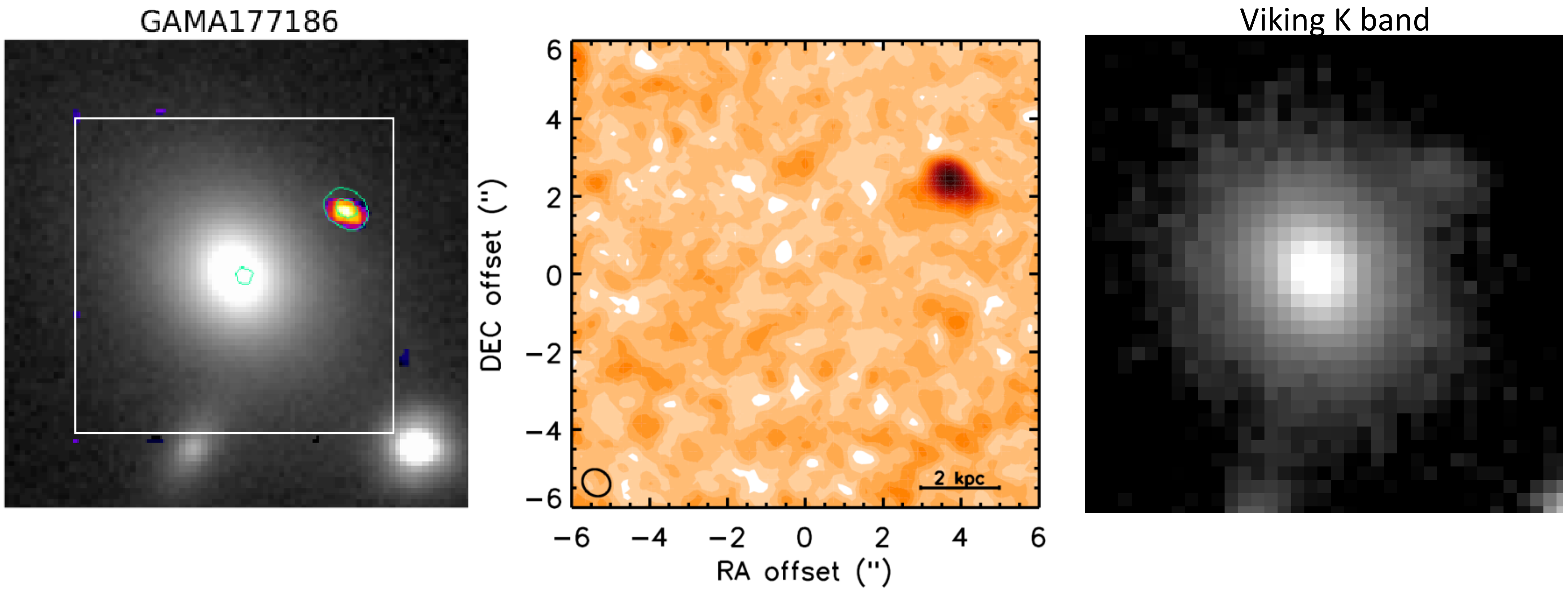
Overlays by David Glass (PT PhD student at UCLan)



KiDS optical images (greyscale); ^{12}CO Moment 0 maps (false colour); Continuum (green contours)
(17”x17”)

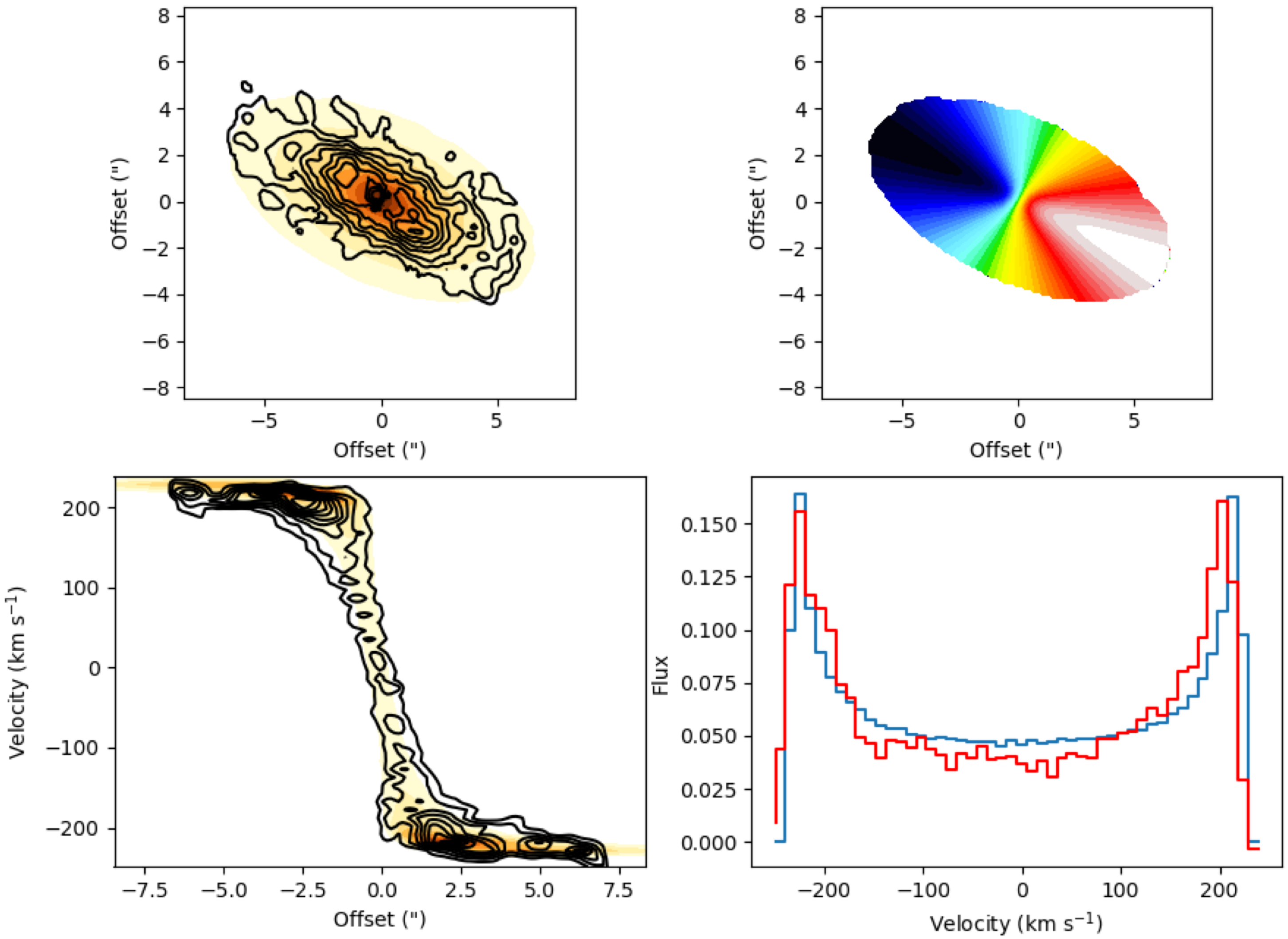
M_{mol} ~ few ×10^9 $M_{\odot}$ in 3 ETGs

Offset molecular gas in GAMA177186



Moment 0 map around systemic v_{gal} shows noise, except for offset source.
Line emission – but which line? If not CO(2-1) then maybe background galaxy at z>2

Future: Kinematic analysis of ALMA CO



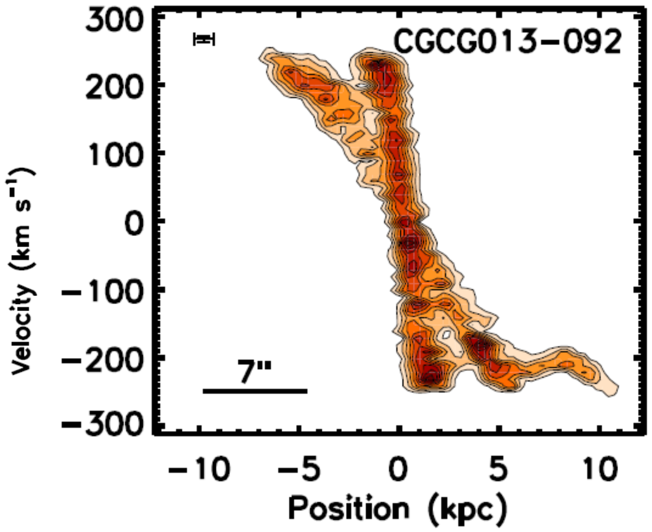
GAMA 64646

Software:
KinMS (Davis+13)

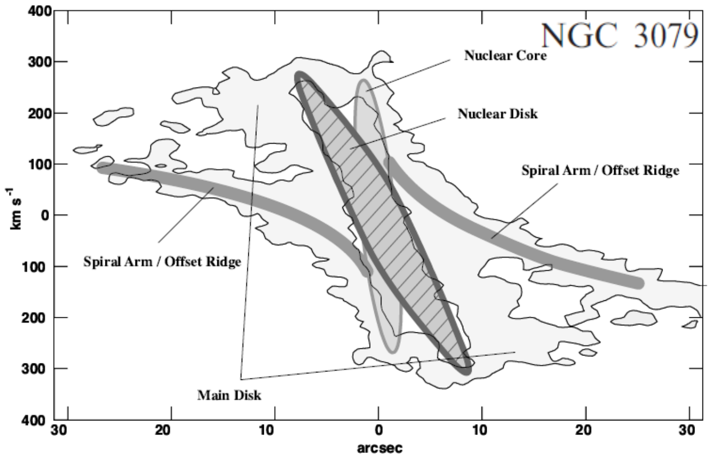
Manual tuning of parameters

Empirical arc tan model of exp disk

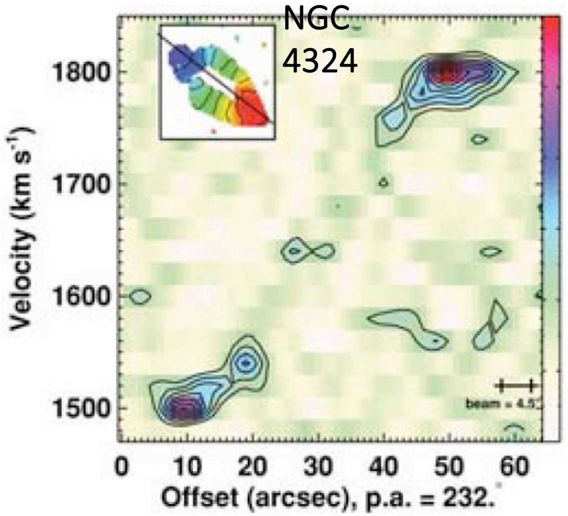
Examples of information in PV diagrams



X-structure
Typical of a bar
(disc+ring)
(e.g. *van de Voort et al. 2018*)



Ridges
Typical of spirals
(e.g. *Koda et al. 2002*)



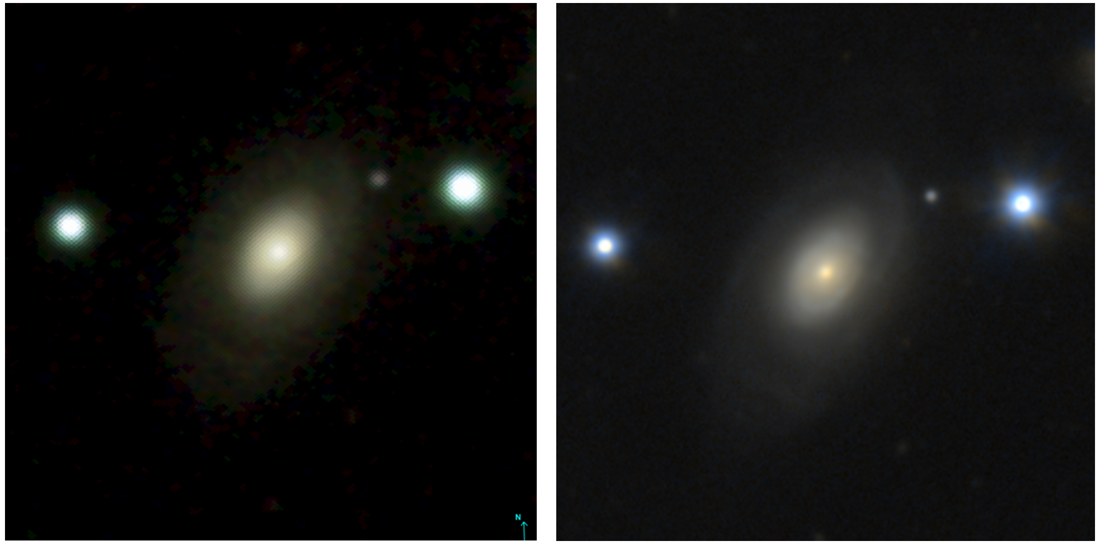
Max and min
Typical of rings
(e.g. *Alatalo et al. 2013*)

Future: GAMA/KiDS/GalaxyZoo

- KiDS – Kilo Degree Survey with VST

  (*de Jong et al. 2013*)

  KiDS improved depth and resolution over SDSS:

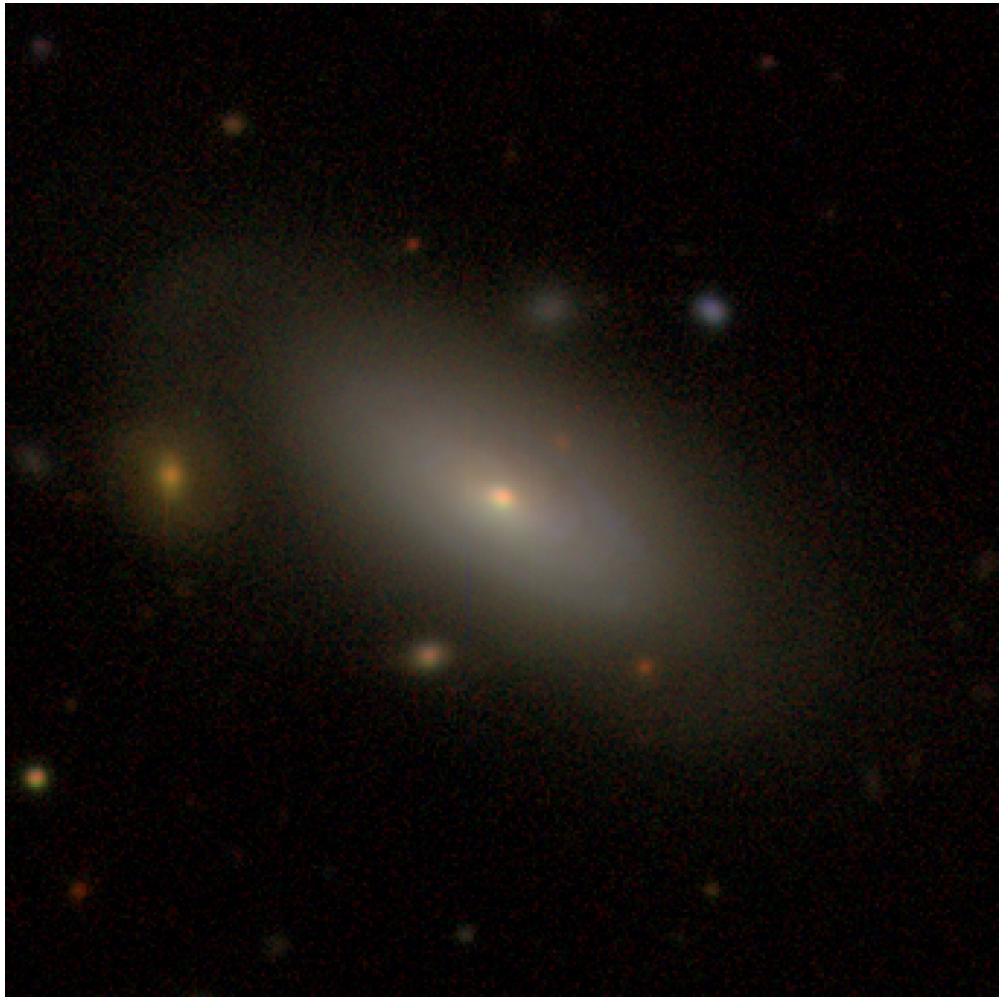


- GAMA_morphs in equatorial fields

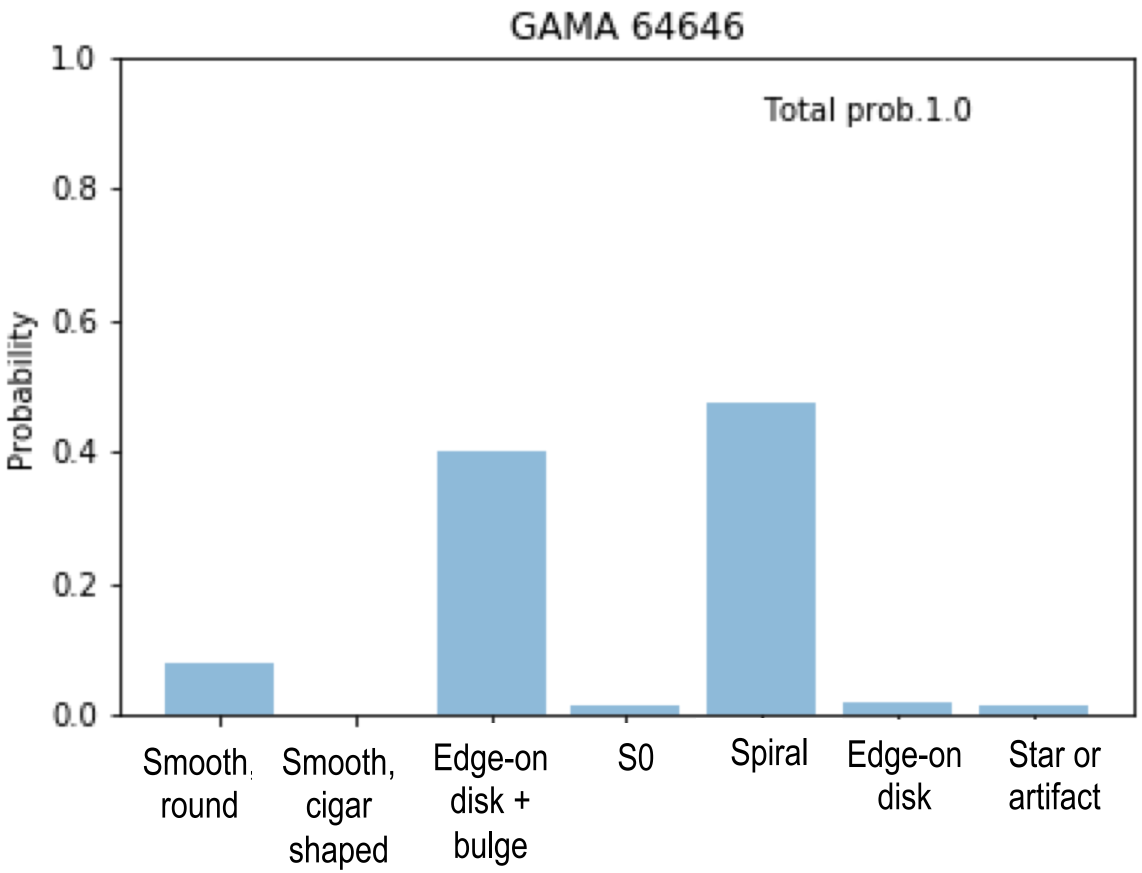
  Composite g,r colour KiDS images created by Kelvin et al. (LJMU)
  Decision tree for GZ GAMA-KiDS
  Into Galaxy Zoo (Jan 2017), completed (Feb 2018), ~50000 galaxies
  At least 40 attempts per galaxy
  Results reduced and cleaned (Bamford et al.), ongoing bias corrections

- Can we use GZ GAMA-KiDS results to distinguish ETGs (E and S0)?

Sharper Images - Different Classifications



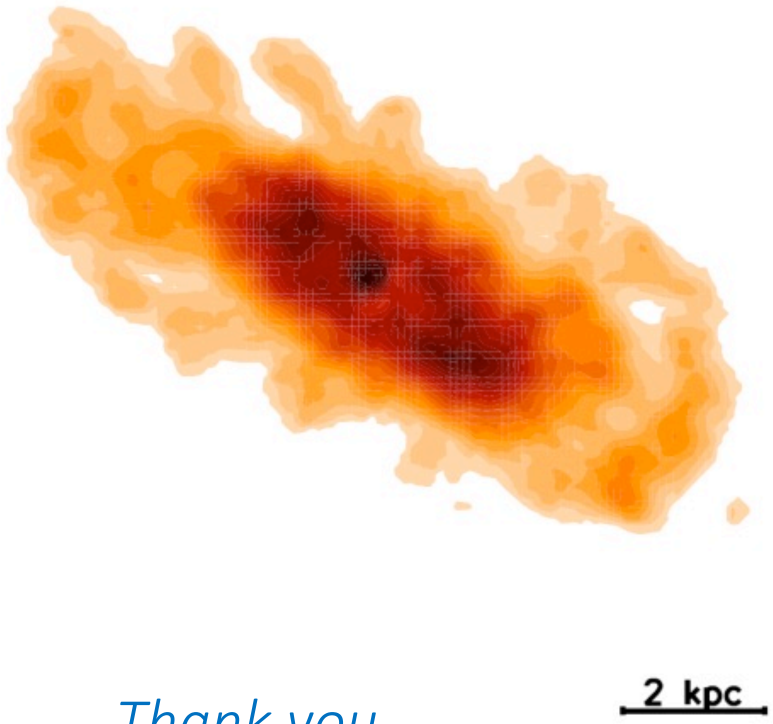
(GAMA64646, KiDS optical 1.1’ x 1.1’ – Galaxy Zoo)



Probabilistic classification
(e.g. *Hart et al. 16; Casteels et al. 2013*)

Summary

- **H-ATLAS revealed 220 (29%) dusty ETGs in GAMA equatorial fields**
  - Lower mass galaxies more affected (downsizing in ETGs)
  - Mostly green valley galaxies (*see also Kelvin et al. 2018; Eales et al. 2018*)
  - Dust mass correlates poorly with stellar mass
  - In rarer environments
- **49 observed with SAMI**
  - Mostly fast rotators
  - Predict a lack of x-ray halos – hence dust can survive
- **Virgo cluster ETGs –** less dusty
- **ALMA follow-up of 5 dusty ETGs from H-ATLAS/GAMA**
  - None with extended dust (LAS & sensitivity limits)
  - One offset continuum contamination in G177186
  - 3 with massive molecular gas reservoirs (M_{Mol} ~ few × 10^9 $M_{\odot}$)
  - Next: KinMS analysis of CO
- **GAMA/KiDS/GalaxyZoo –** morphological possibilities



Thank you