The GOGREEN survey

Michael Balogh
GOGREEN and GCLASS Data Release Workshop
August 24-28, 2020

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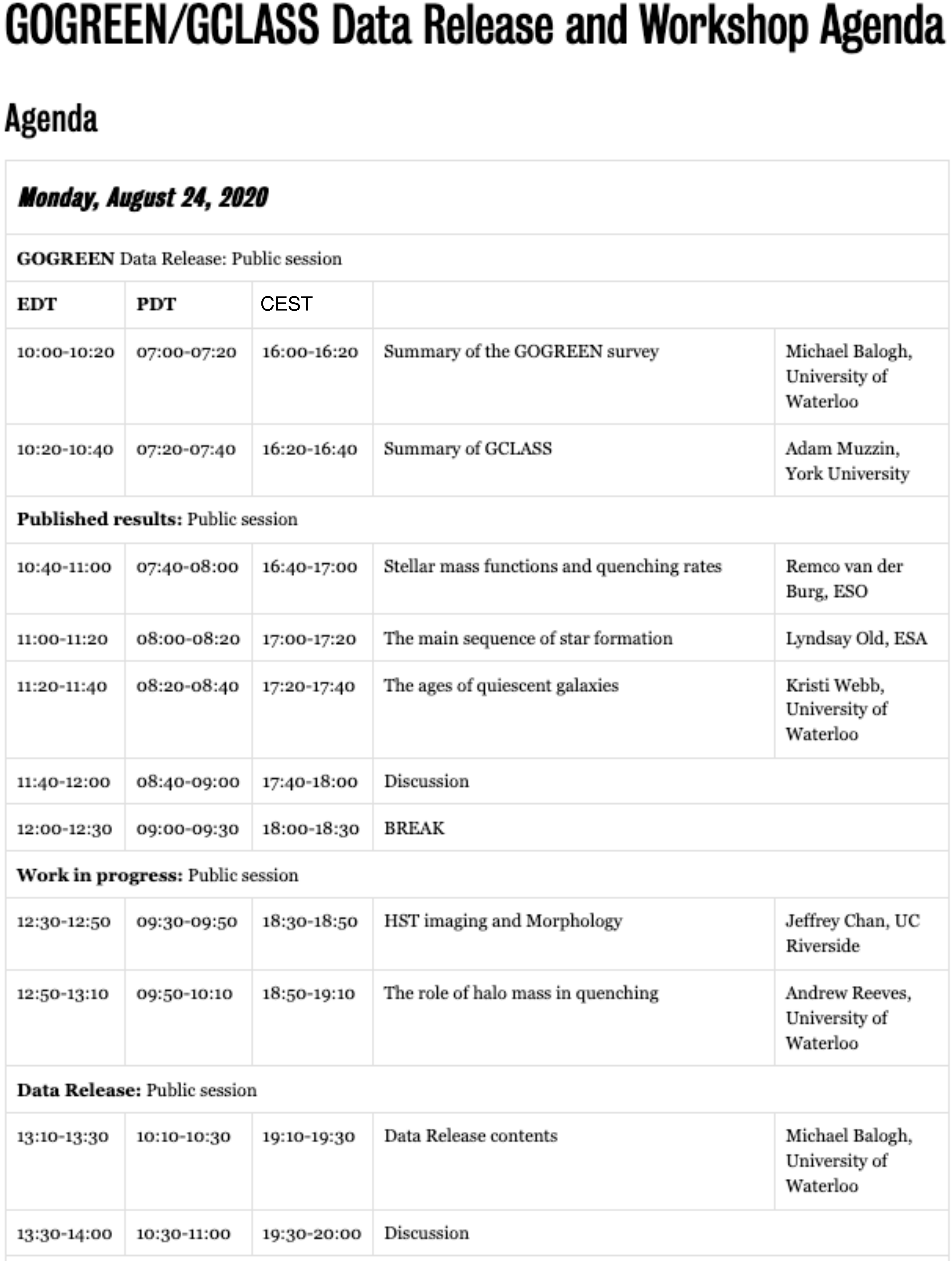
GOGREEN
http://gogreensurvey.ca/

WATERLOO CENTRE FOR ASTROPHYSICS



GOGREEN/GCLASS Data Release and Workshop Agenda

Agenda

Monday, August 24, 2020

GOGREEN Data Release: Public session				
EDT	**PDT**	CEST		
10:00-10:20	07:00-07:20	16:00-16:20	Summary of the GOGREEN survey	Michael Balogh, University of Waterloo
10:20-10:40	07:20-07:40	16:20-16:40	Summary of GCLASS	Adam Muzzin, York University
Published results: Public session				
10:40-11:00	07:40-08:00	16:40-17:00	Stellar mass functions and quenching rates	Remco van der Burg, ESO
11:00-11:20	08:00-08:20	17:00-17:20	The main sequence of star formation	Lyndsay Old, ESA
11:20-11:40	08:20-08:40	17:20-17:40	The ages of quiescent galaxies	Kristi Webb, University of Waterloo
11:40-12:00	08:40-09:00	17:40-18:00	Discussion	
12:00-12:30	09:00-09:30	18:00-18:30	BREAK	
Work in progress: Public session				
12:30-12:50	09:30-09:50	18:30-18:50	HST imaging and Morphology	Jeffrey Chan, UC Riverside
12:50-13:10	09:50-10:10	18:50-19:10	The role of halo mass in quenching	Andrew Reeves, University of Waterloo
Data Release: Public session				
13:10-13:30	10:10-10:30	19:10-19:30	Data Release contents	Michael Balogh, University of Waterloo
13:30-14:00	10:30-11:00	19:30-20:00	Discussion	

Meeting is being recorded and will be posted publicly

Feel free to put questions in the chat – they may be answered directly there or we can return to them during the discussion session

Tuesday, August 25, 2020

Work in progress (continued): Public session				
EDT	**PDT**	CEST		
10:00-10:20	07:00-07:20	16:00-16:20	Cluster Dynamics	Andrea Biviano, Trieste
10:20-10:40	07:20-07:40	16:20-16:40	Transition galaxies	Karen McNab, University of Waterloo
10:40-11:00	07:40-08:00	16:40-17:00	Predictions from simulations	Egidius Kukstas, LJMU
11:00-12:00	08:00-09:00	17:00-18:00	Discussion	

The GOGREEN team

Management team
Postdocs/students

Michael Balogh, Waterloo (PI)
Kristi Webb, PhD
Andrew Reeves, PhD
Karen McNab, MSc
Matthew Pereira Wilson
Adam Muzzin, York
Gregory Rudnick, Kansas
Gillian Wilson, UC Riverside
M. Victoria Alonso, Cordoba
Andrea Biviano, Trieste
Pierluigi Cerulo, Concepcion
Jeffrey Chan, UC Riverside
Kevin Cooke, Kansas

Michael Cooper, UC Irvine
Gabriella De Lucia, Trieste
Ricardo Demarco, Concepcion
Alexis Finoguenov, Helsinki
Ben Forrest, UCR
David Gilbank
Pascale Jablonka, EPFL
Kristen Jones, Kansas
Egidius Kukstas, Liverpool JM
Joel Leja, Harvard CfA
Chris Lidman, ANU
Ian McCarthy, Liverpool JM
Sean McGee, Birmingham

Hernan Muriel, Cordoba
Julie Nantais, Andrés Bello
Allison Noble, ASU
Lyndsay Old, ESA
Irene Pintos-Castro, Toronto
Bianca Poggianti, INAF/Padova
Heath Shipley, McGill
Remco van der Burg, ESO
Benedetta Vulcani, INAF/Padova
Howard Yee, Toronto
Dennis Zaritsky, Arizona

Bob Abraham, Toronto; Richard Bower, Durham; Charlie Conroy, CfA Harvard; Warrick Couch, AAO; Erica Ellingson, Boulder; Henk Hoekstra, Leiden; Mark David Lacy, NRAO; Diego Garcia Lambas, Cordoba; Matt Owers, AAO; Laura Parker, McMaster ; Alessandro Rettura, JPL; Ian Smail, Durham; Jason Surace, Caltech IPAC; Jeremy Tinker, NYU; Carlos Valotto, Cordoba; Tracy Webb, McGill; Andrew Wetzel, UC Davis; Jon Willis, Victoria

with help from:

Callum Bellhouse, INAF/Padova; Kevin Boak, Waterloo; Anna Davidson, Kansas; Nicole Drakos, UCSC; Sean Fillingham, U Washington; Caelan Golledge, Kansas; Stephen Gwyn, NRC/CADC, Grayson Petter, Kansas; Melinda Townsend, Kansas

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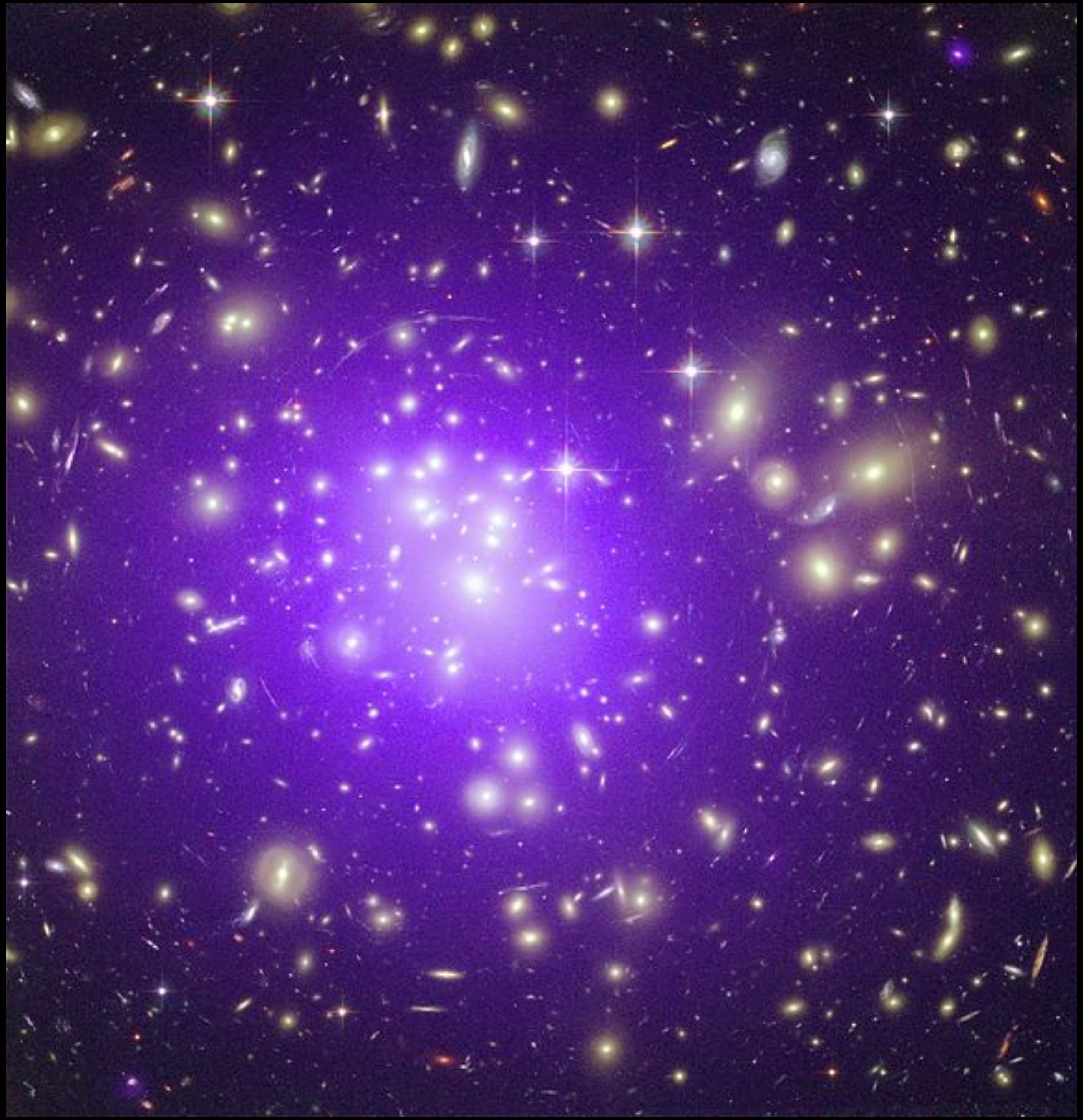
Scientific Motivation

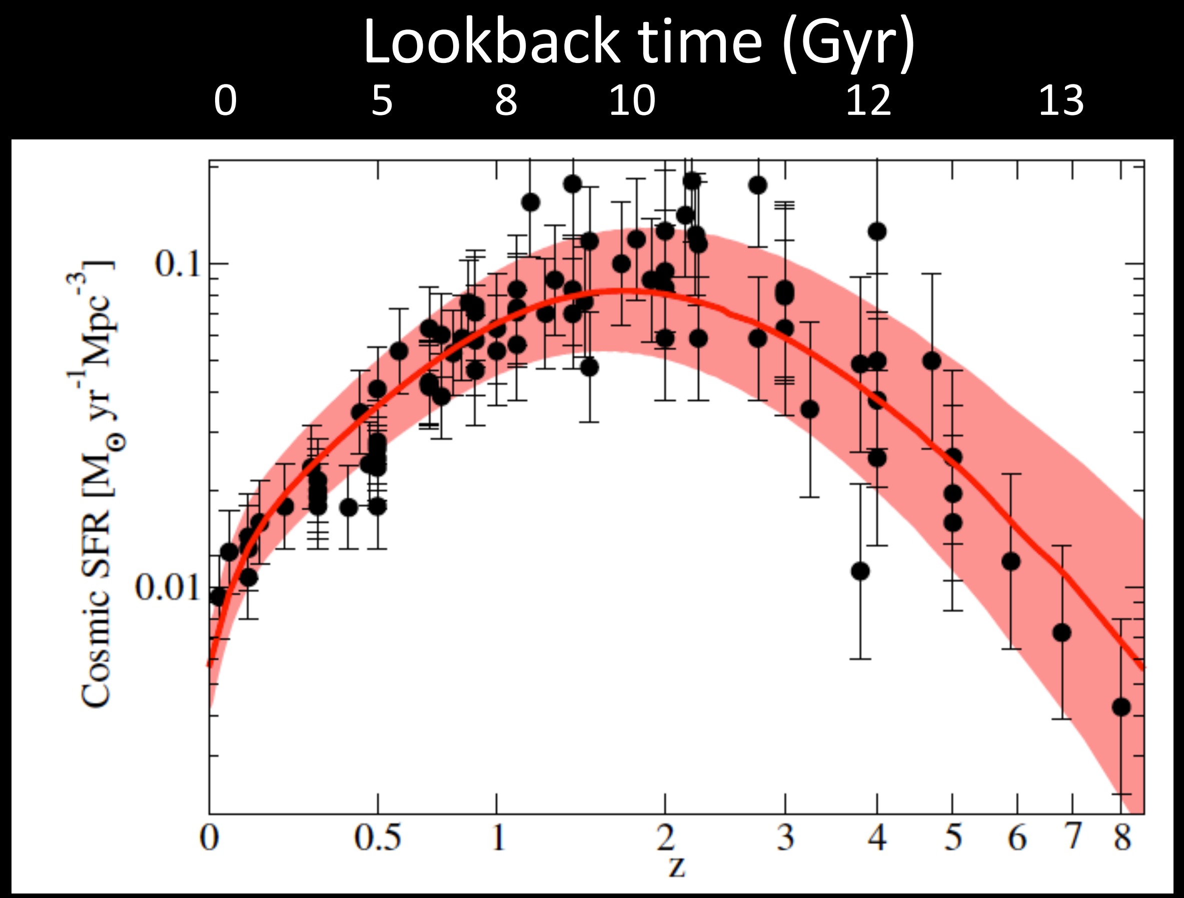
Why study Galaxy clusters?

- Rich environments with many galaxies at the same distance.
- Nearly all baryons directly observable
- Cosmologically sensitive
- Examples of extreme environments and rare processes
- Mass and baryon accretion history reasonably well understood from theory

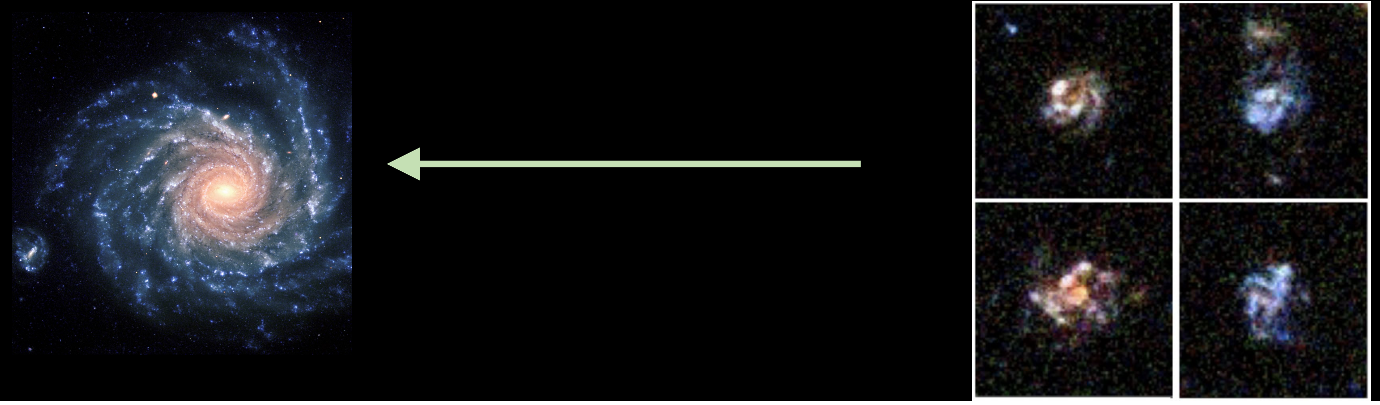


Abell 1689: X-ray: NASA/CXC/MIT/E.-H Peng et al.; Optical: NASA/STScI

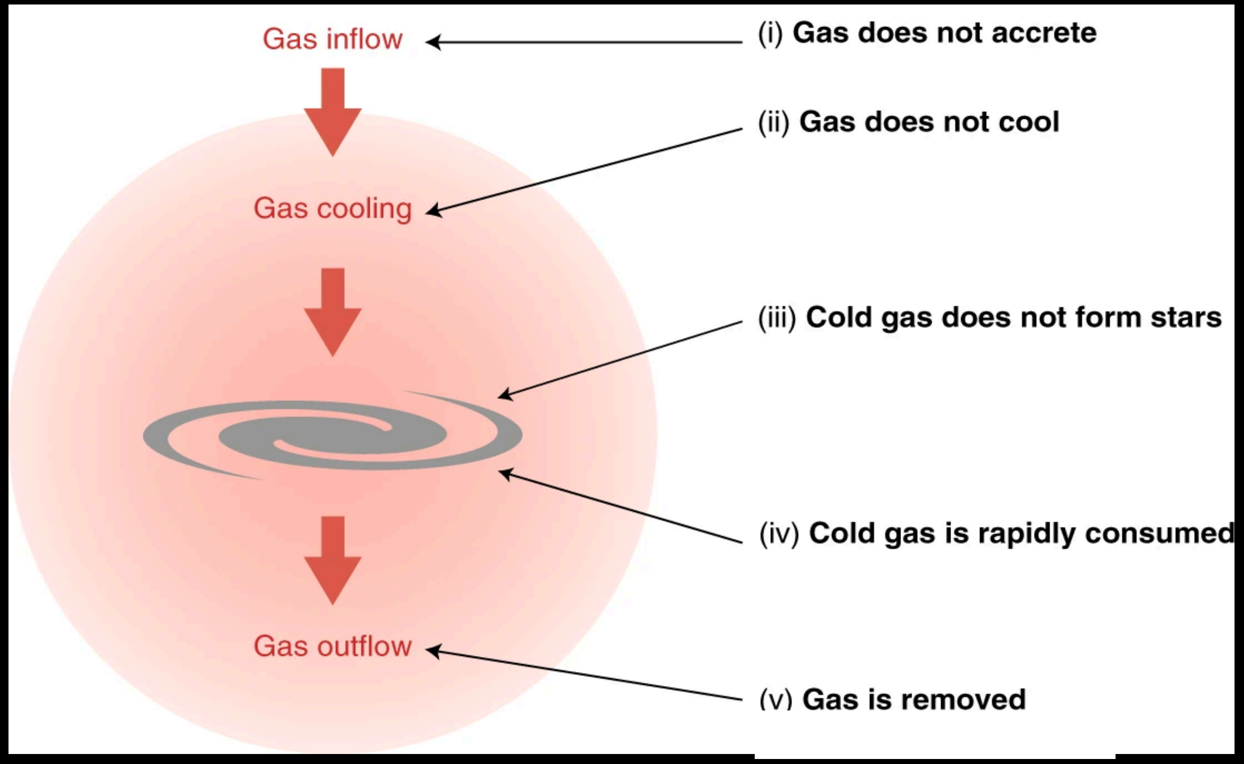
Insights into galaxy evolution



Behroozi et al. (2010)

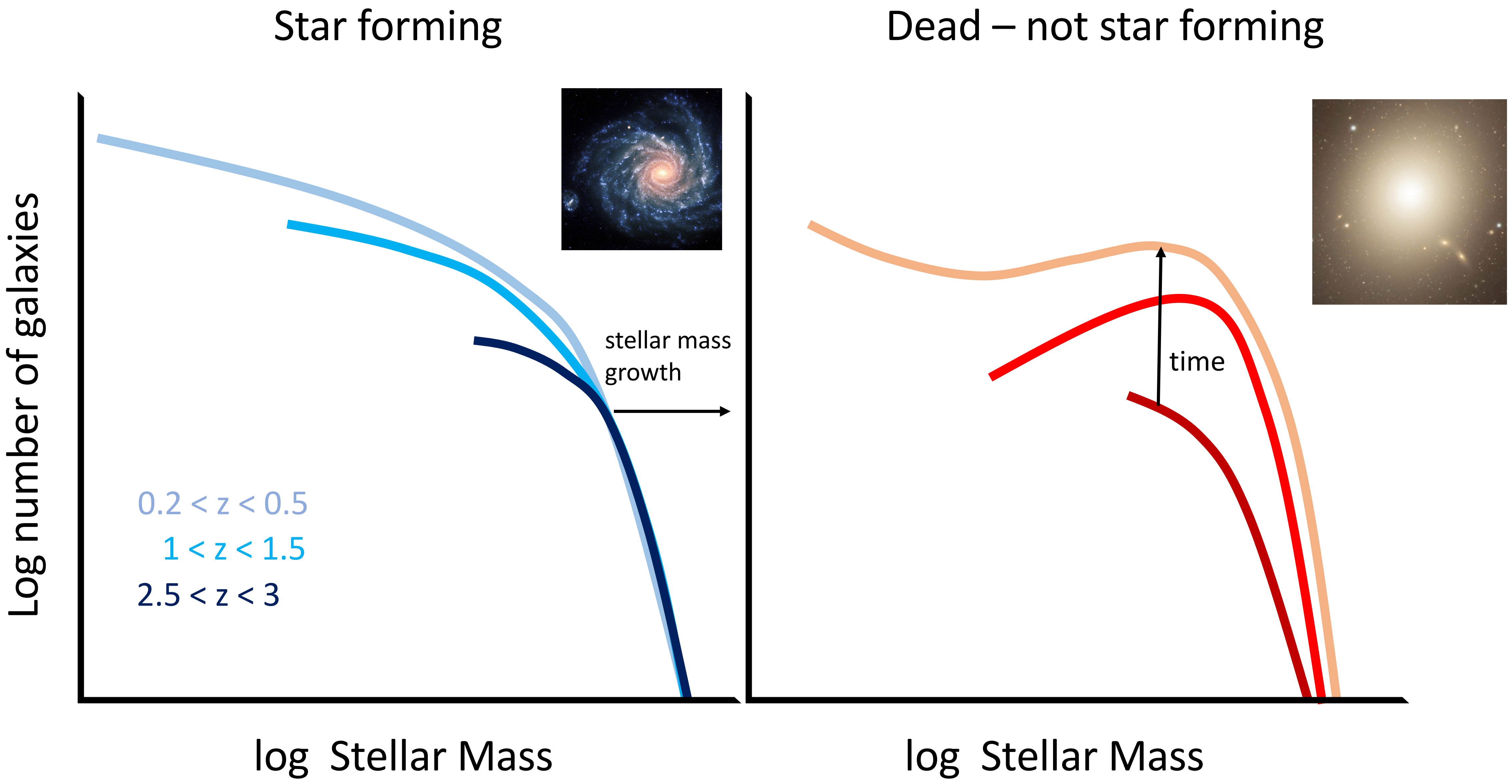


Star formation in the Universe has been declining for the past 10 billion years – must ultimately be related to the baryon cycle



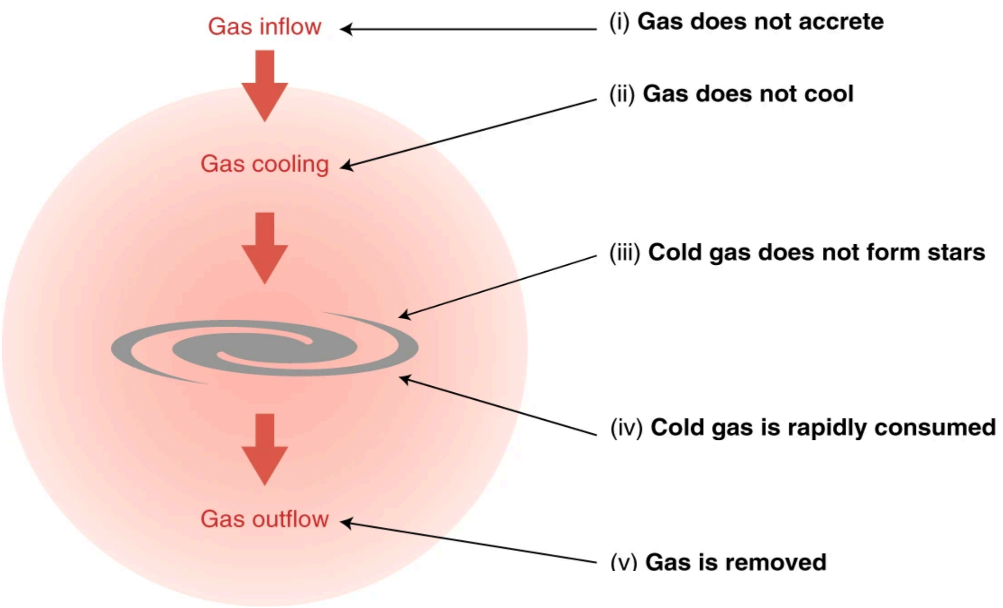
Adapted from Man+Belli 2018

Quenching: galaxies eventually stop forming stars, and the number of dead galaxies builds up



Much of this quenching is likely related to various feedback processes that disrupt the gas flow

- *Strongly mass dependent*



Adapted from Muzzin+2013, based on ULTRAVISTA photometry of the COSMOS field

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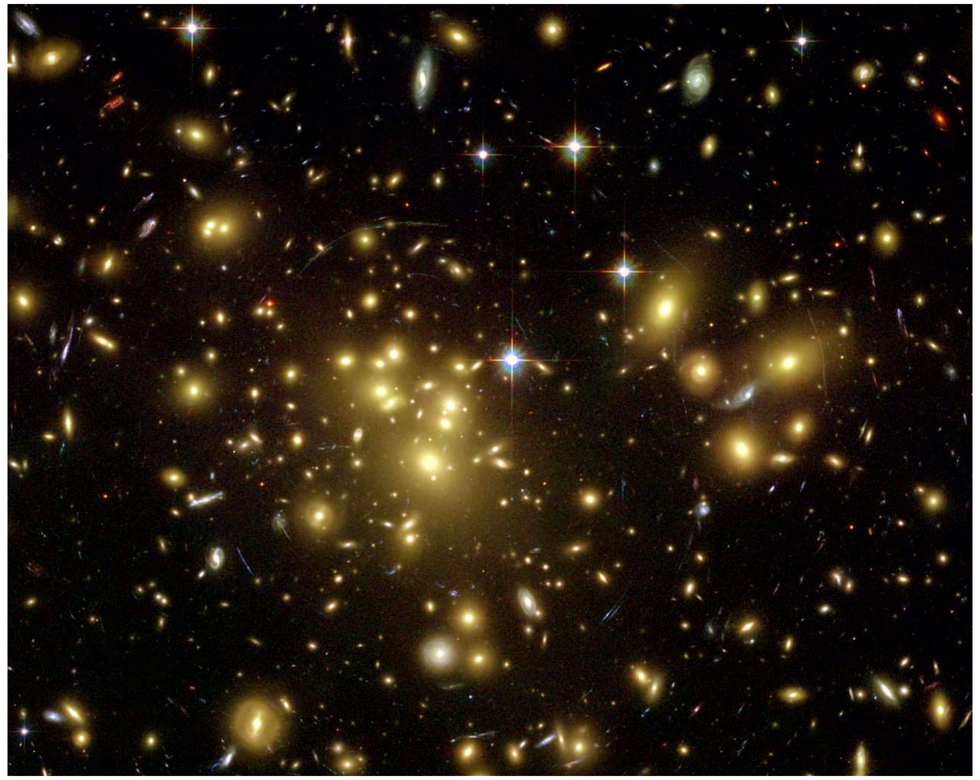
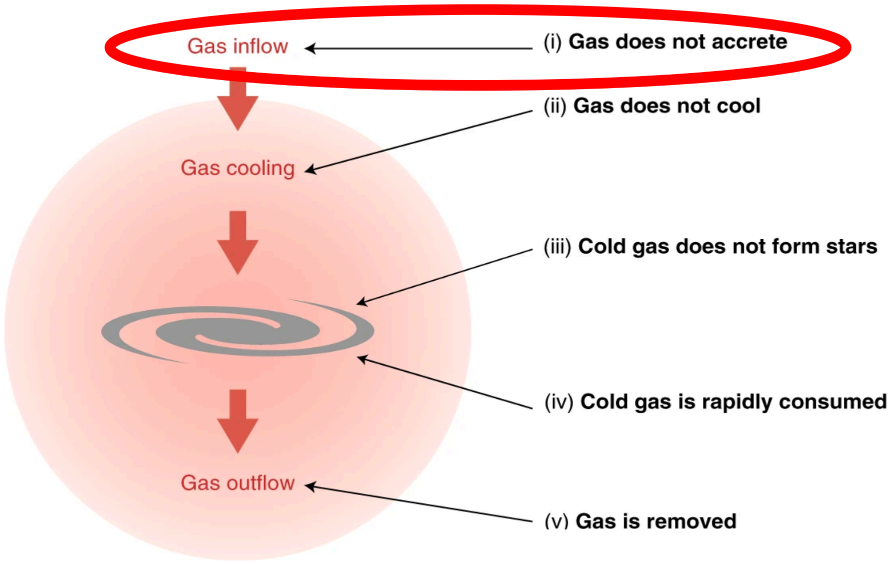
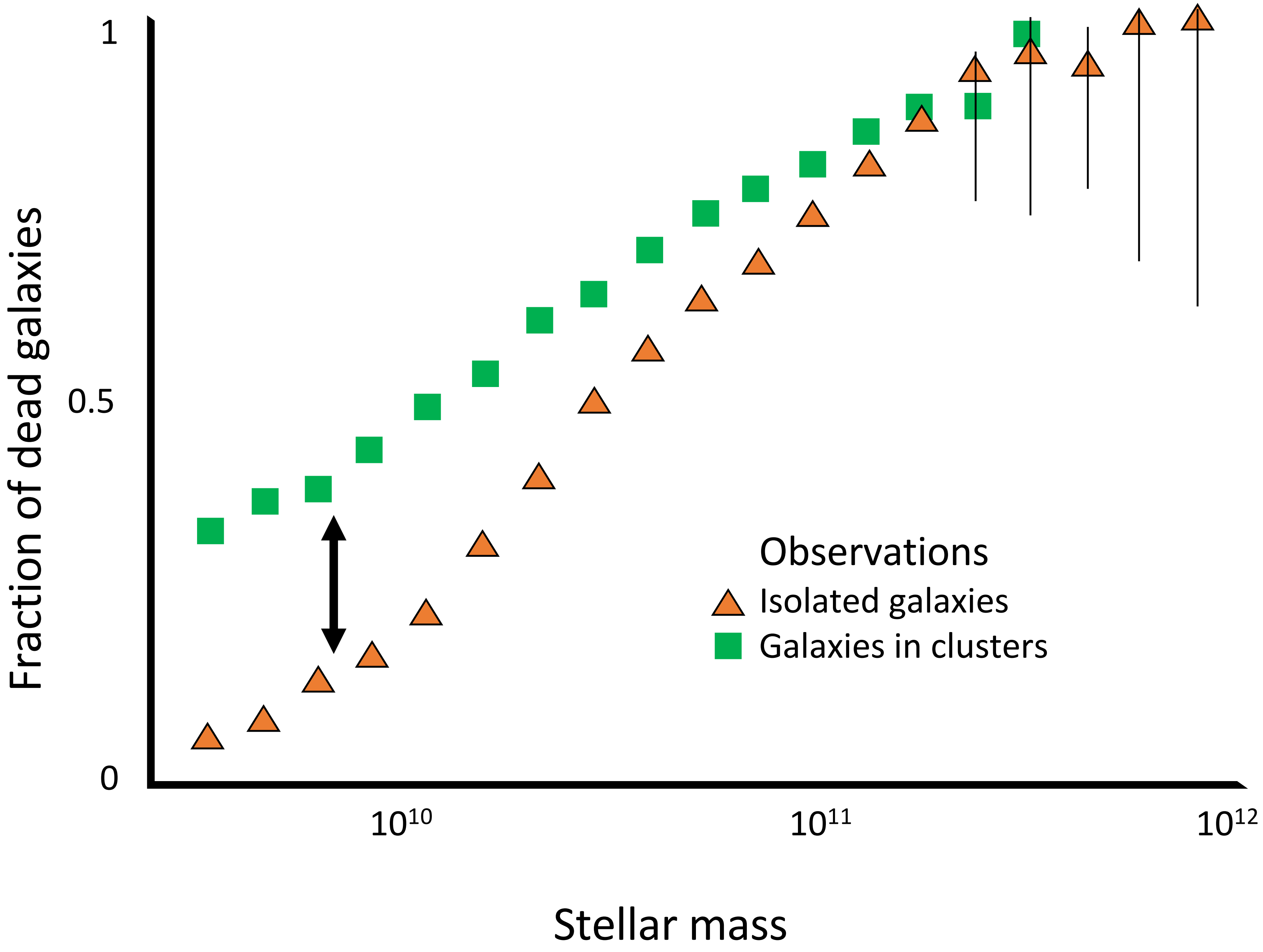


A satellite galaxy loses its source of fresh gas from cosmological accretion. Many of the other complex physical processes (e.g. SFR, feedback) are likely unaffected



But galaxies that are satellites of a more massive host halo are more likely to be quenched. i.e. SFR history also depends on the large scale *environment*.



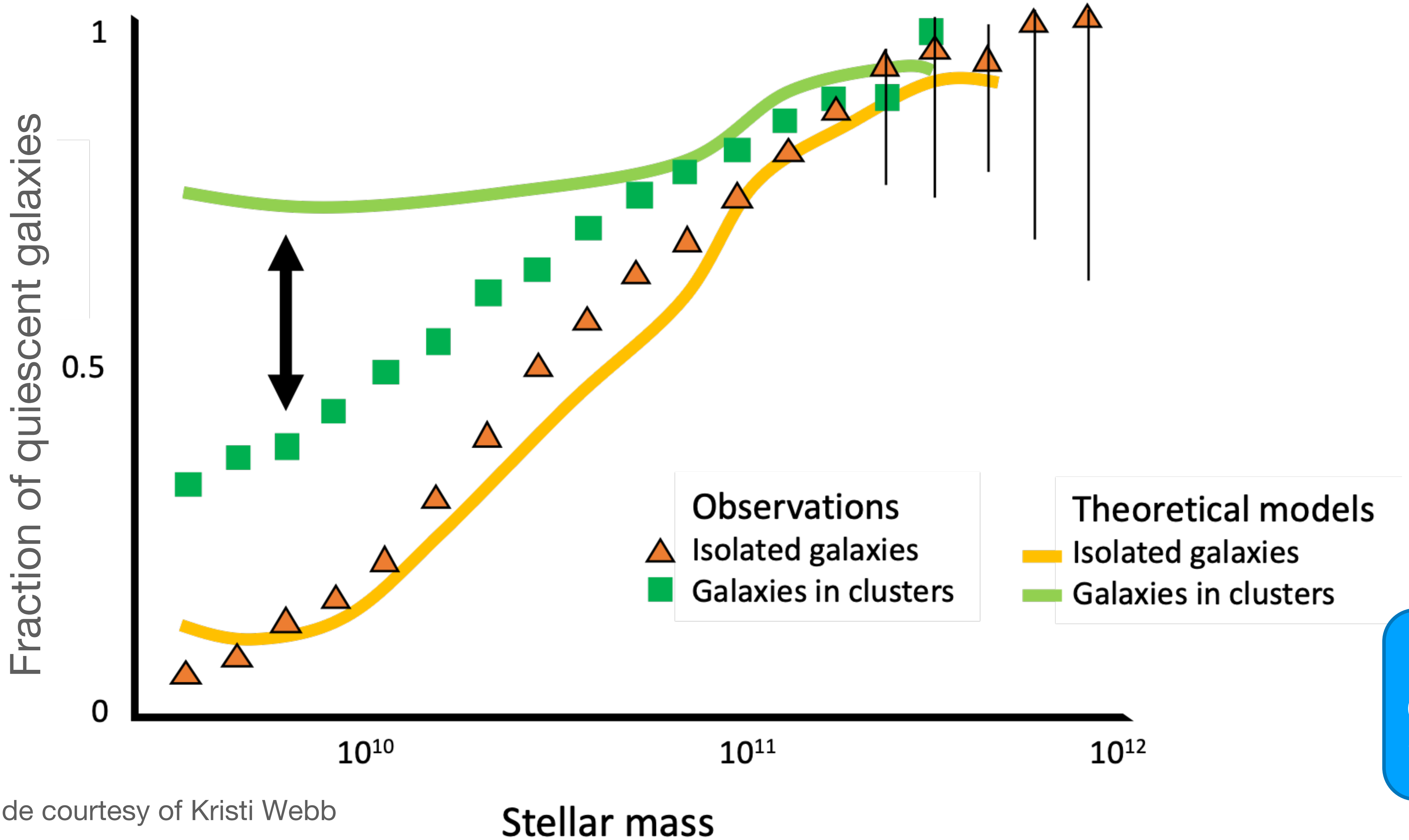
Adapted from Hirschmann+2014

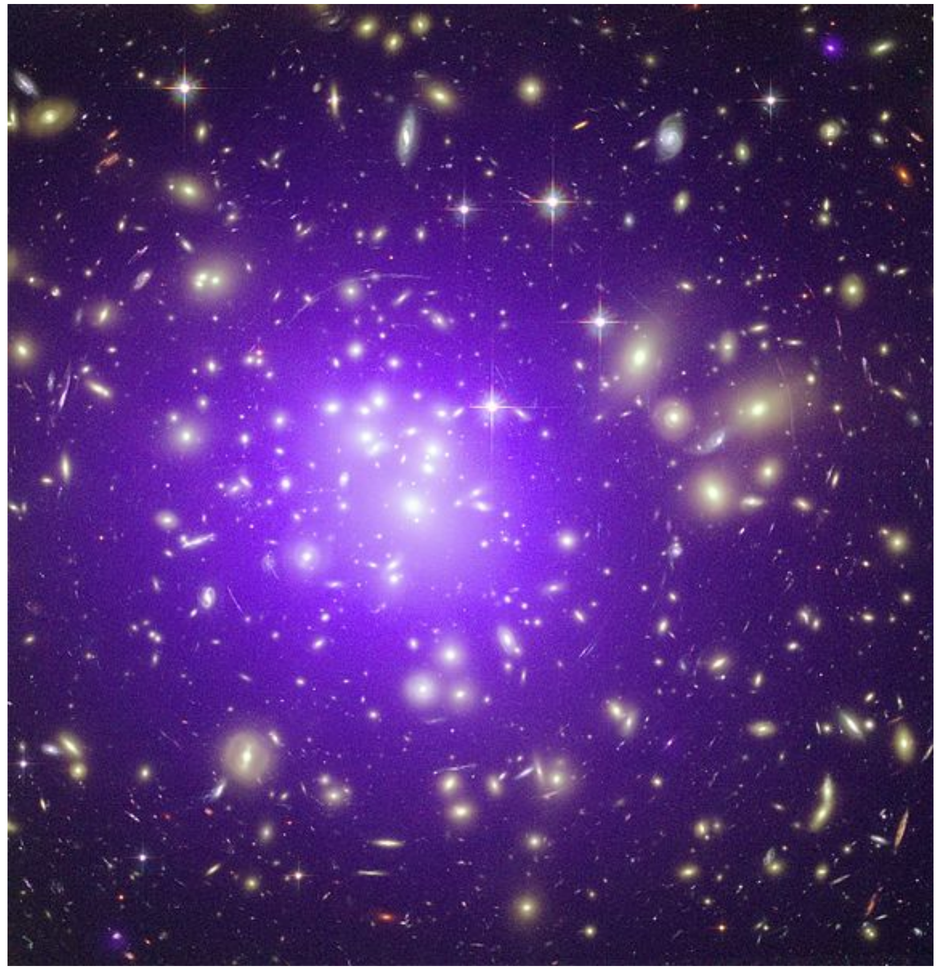
Galaxies in clusters are more likely to be quenched

No shortage of ideas:

- Ram pressure stripping
- Merging/harassment
- Tidal stripping

…but theoretical models consistently *overpredict* the number of quenched satellites





Redshift evolution can be an important discriminator because the properties of the infalling population are very different

Slide courtesy of Kristi Webb

Adapted from Hirschmann+2014, Guo+2011 SAM+Millenium theoretical models

Survey Strategy and Design

GOGREEN and GCLASS

but mostly GOGREEN

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Some spectroscopic cluster surveys at z>0.2

Mean redshift

Survey	**Year**	**Redshift**	**Number of clusters**	**Number of redshifts**	**Reference**
CNOC	1996	0.2-0.5	16	2600	Yee et al. (1996)
EDisCs	2008	0.4-1.0	26	~2500	Milvang-Jensen et al. (2008)
IMACS	2013	0.2-0.5	5	6000	Oemler et al. (2013)
VLT-CLASH	2014	0.2-0.6	13	30,000	Rosati et al. (2014)
SPT-GMOS	2016	0.3-0.8	>60	2200	Bayliss et al. (2016)
XXL	2018	<0.6	164	2500	Guglielmo et al. (2018)
GCLASS	2012	0.8-1.3	10	1250	Muzzin et al. (2012)
MaDCoWS	2019	0.7-1.5	38	~1000 (?)	Gonzalez et al. (2018)
GOGREEN	2020	1-1.5	21	1500	Balogh et al. (2020)

$z<1$

$z>1$

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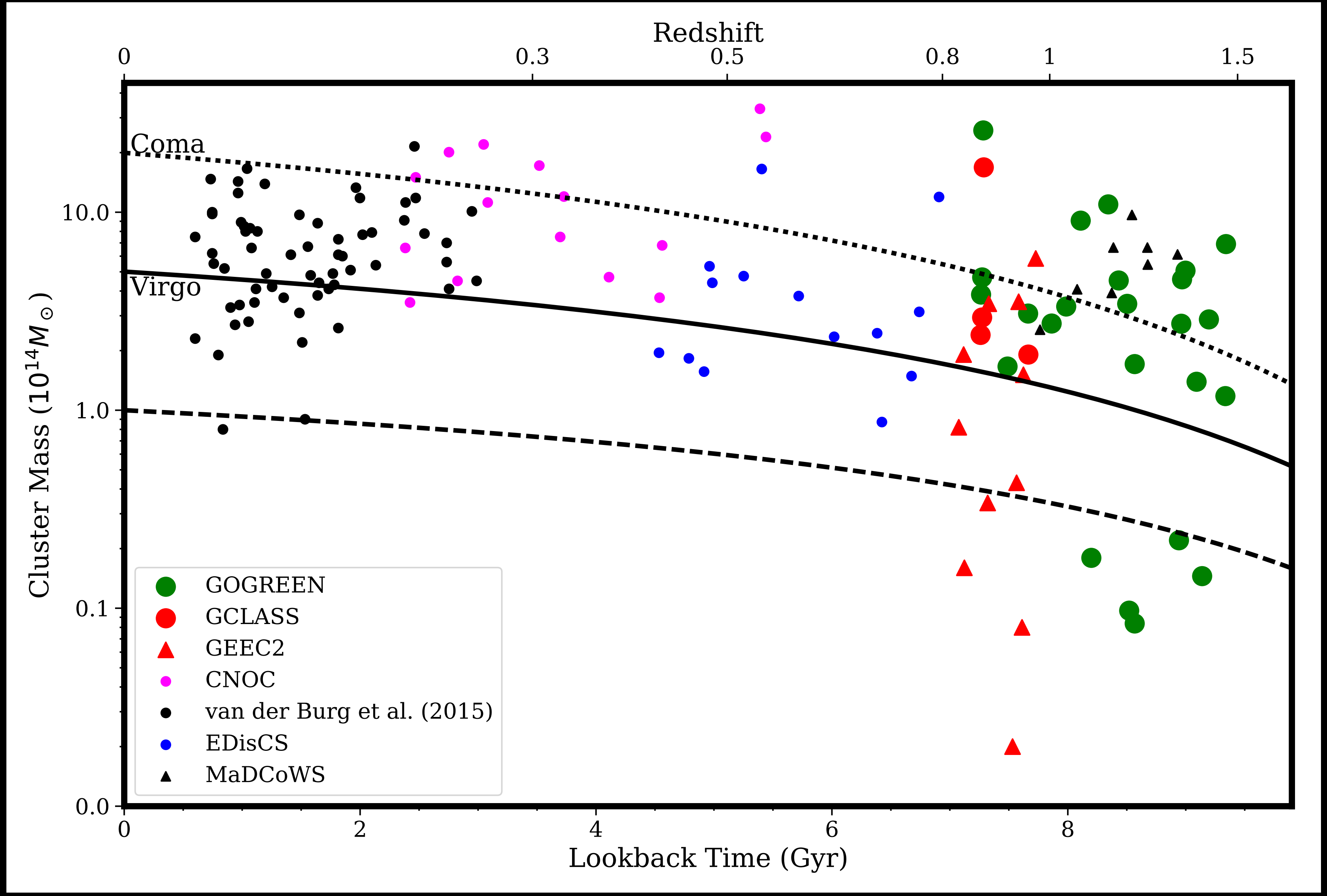
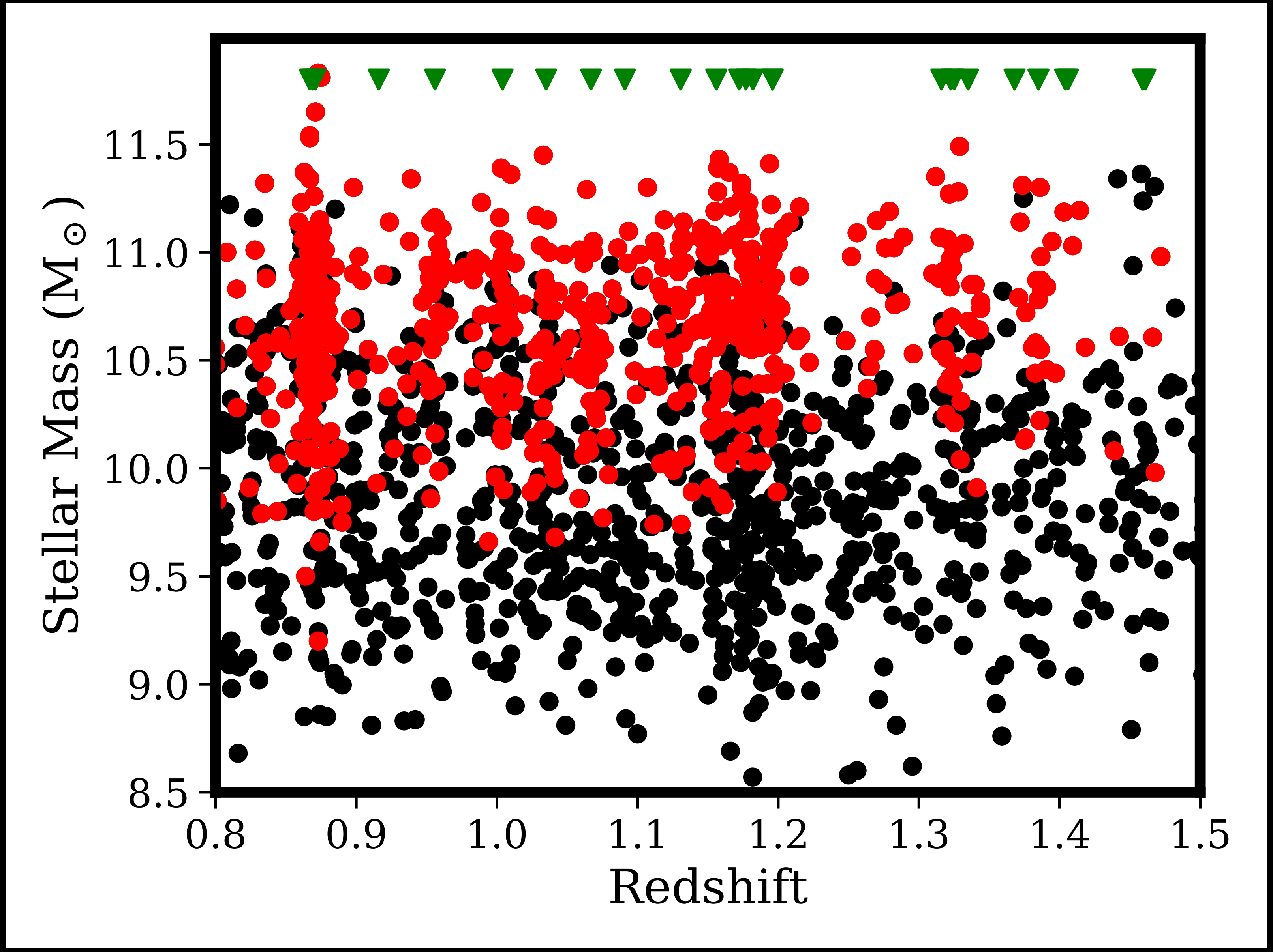
GOGREEN and GCLASS

Gemini GMOS spectroscopy of 26 clusters

Providing a wide baseline in key parameters:

- Redshift
- Halo mass
- Stellar mass





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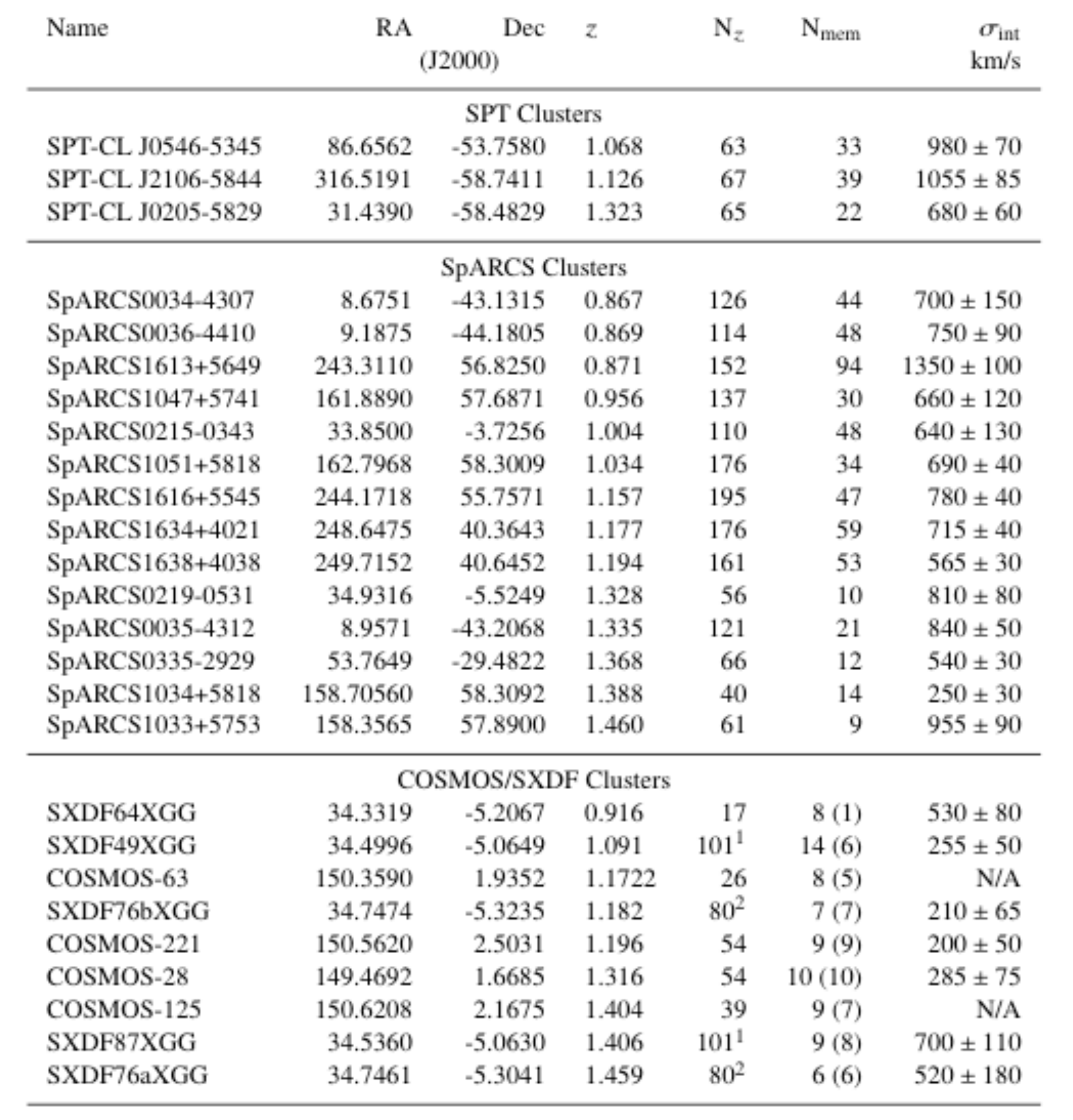
GOGREEN: a 530h Gemini LLP



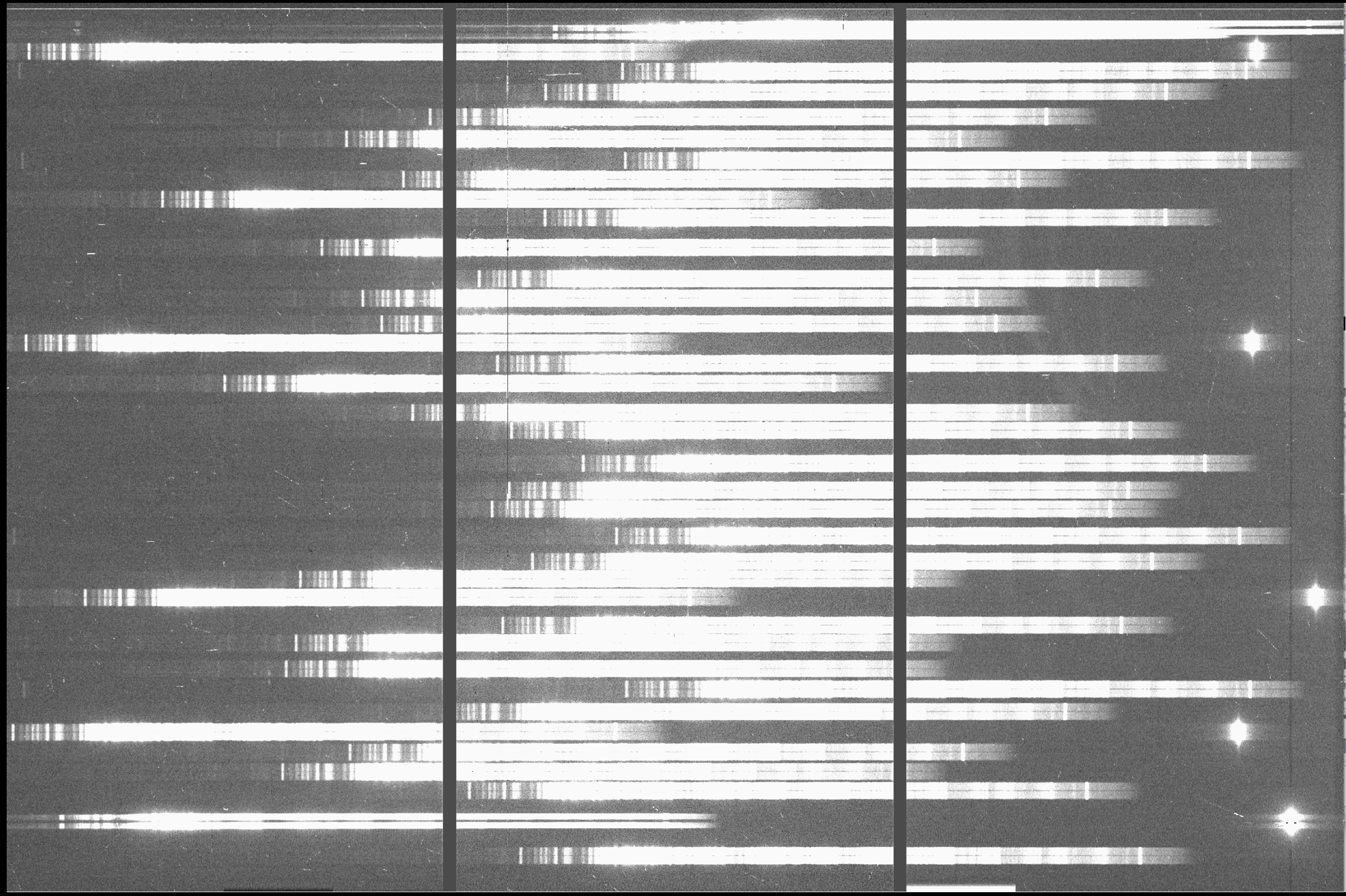
Name	RA	Dec	z	N$_z$	N$_{mem}$	σ_{int}
	(J2000)					km/s
SPT Clusters						
SPT-CL J0546-5345	86.6562	-53.7580	1.068	63	33	980 ± 70
SPT-CL J2106-5844	316.5191	-58.7411	1.126	67	39	1055 ± 85
SPT-CL J0205-5829	31.4390	-58.4829	1.323	65	22	680 ± 60
SpARCS Clusters						
SpARCS0034-4307	8.6751	-43.1315	0.867	126	44	700 ± 150
SpARCS0036-4410	9.1875	-44.1805	0.869	114	48	750 ± 90
SpARCS1613+5649	243.3110	56.8250	0.871	152	94	1350 ± 100
SpARCS1047+5741	161.8890	57.6871	0.956	137	30	660 ± 120
SpARCS0215-0343	33.8500	-3.7256	1.004	110	48	640 ± 130
SpARCS1051+5818	162.7968	58.3009	1.034	176	34	690 ± 40
SpARCS1616+5545	244.1718	55.7571	1.157	195	47	780 ± 40
SpARCS1634+4021	248.6475	40.3643	1.177	176	59	715 ± 40
SpARCS1638+4038	249.7152	40.6452	1.194	161	53	565 ± 30
SpARCS0219-0531	34.9316	-5.5249	1.328	56	10	810 ± 80
SpARCS0035-4312	8.9571	-43.2068	1.335	121	21	840 ± 50
SpARCS0335-2929	53.7649	-29.4822	1.368	66	12	540 ± 30
SpARCS1034+5818	158.70560	58.3092	1.388	40	14	250 ± 30
SpARCS1033+5753	158.3565	57.8900	1.460	61	9	955 ± 90
COSMOS/SXDF Clusters						
SXDF64XGG	34.3319	-5.2067	0.916	17	8 (1)	530 ± 80
SXDF49XGG	34.4996	-5.0649	1.091	101^1	14 (6)	255 ± 50
COSMOS-63	150.3590	1.9352	1.1722	26	8 (5)	N/A
SXDF76bXGG	34.7474	-5.3235	1.182	80^2	7 (7)	210 ± 65
COSMOS-221	150.5620	2.5031	1.196	54	9 (9)	200 ± 50
COSMOS-28	149.4692	1.6685	1.316	54	10 (10)	285 ± 75
COSMOS-125	150.6208	2.1675	1.404	39	9 (7)	N/A
SXDF87XGG	34.5360	-5.0630	1.406	101^1	9 (8)	700 ± 110
SXDF76aXGG	34.7461	-5.3041	1.459	80^2	6 (6)	520 ± 180

TOTAL 2257 705

GOGREEN Spectroscopy

- 3-year 438h Gemini LP started in 2014. Extended to 530h over 10 semesters on both telescopes
- Red-sensitive detectors allow us to extend sample to z=1.5
- 99% of original allocation executed
- Last data taken July 2019

Image credit: Gemini/NSF/AURA



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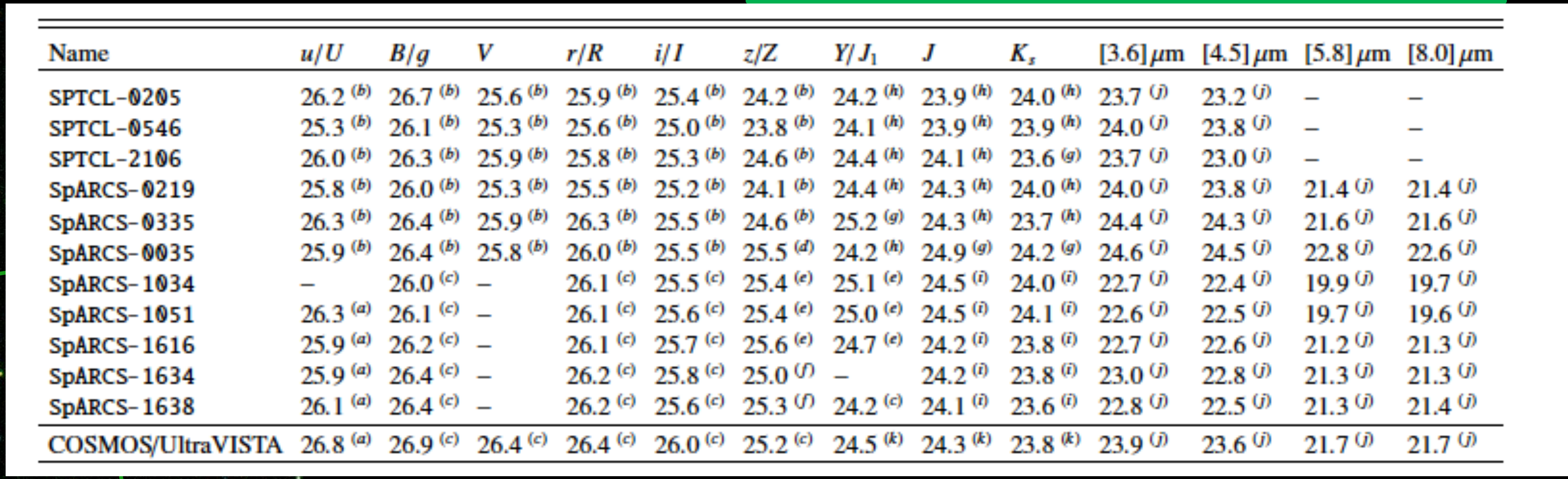
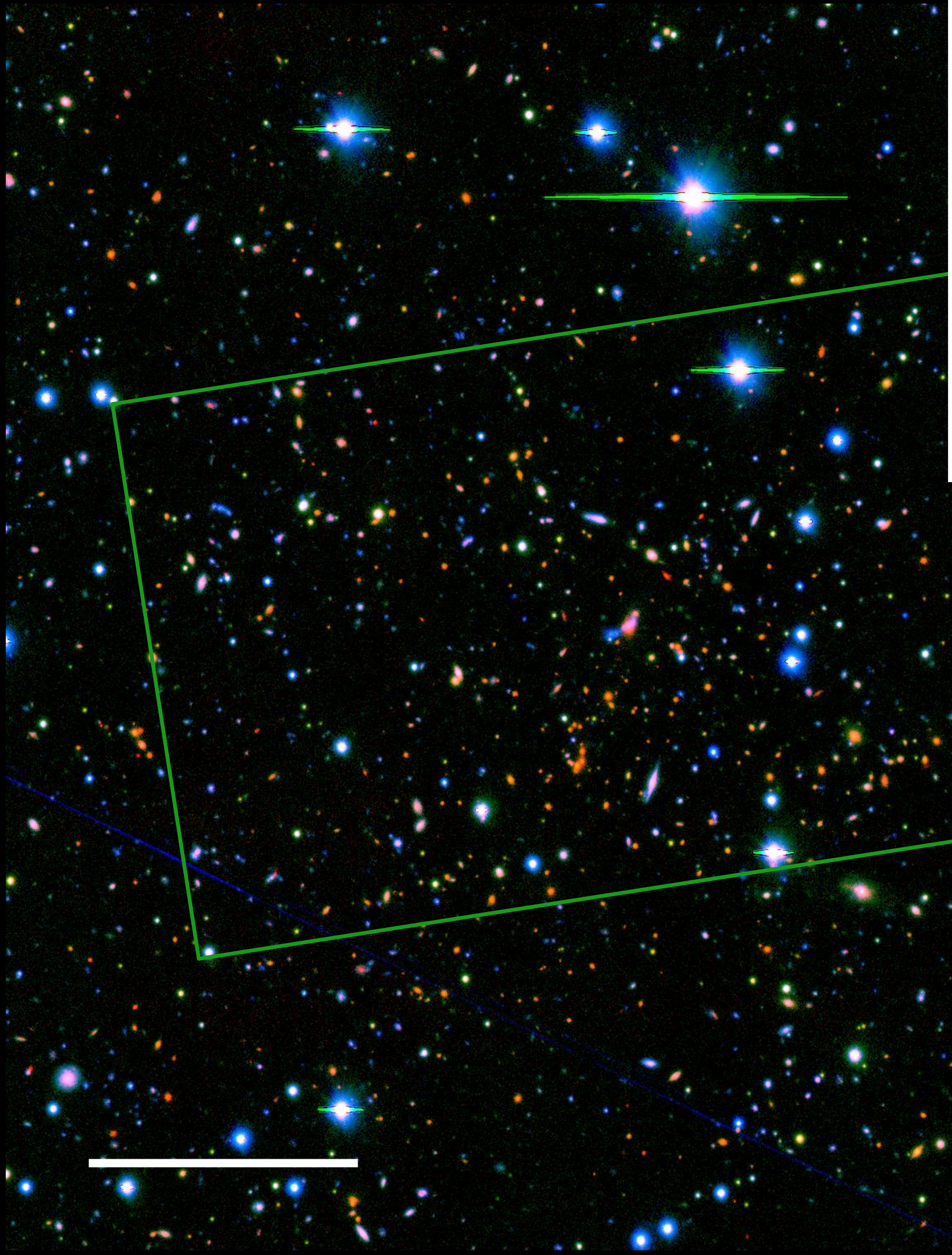
Deep multiwavelength imaging

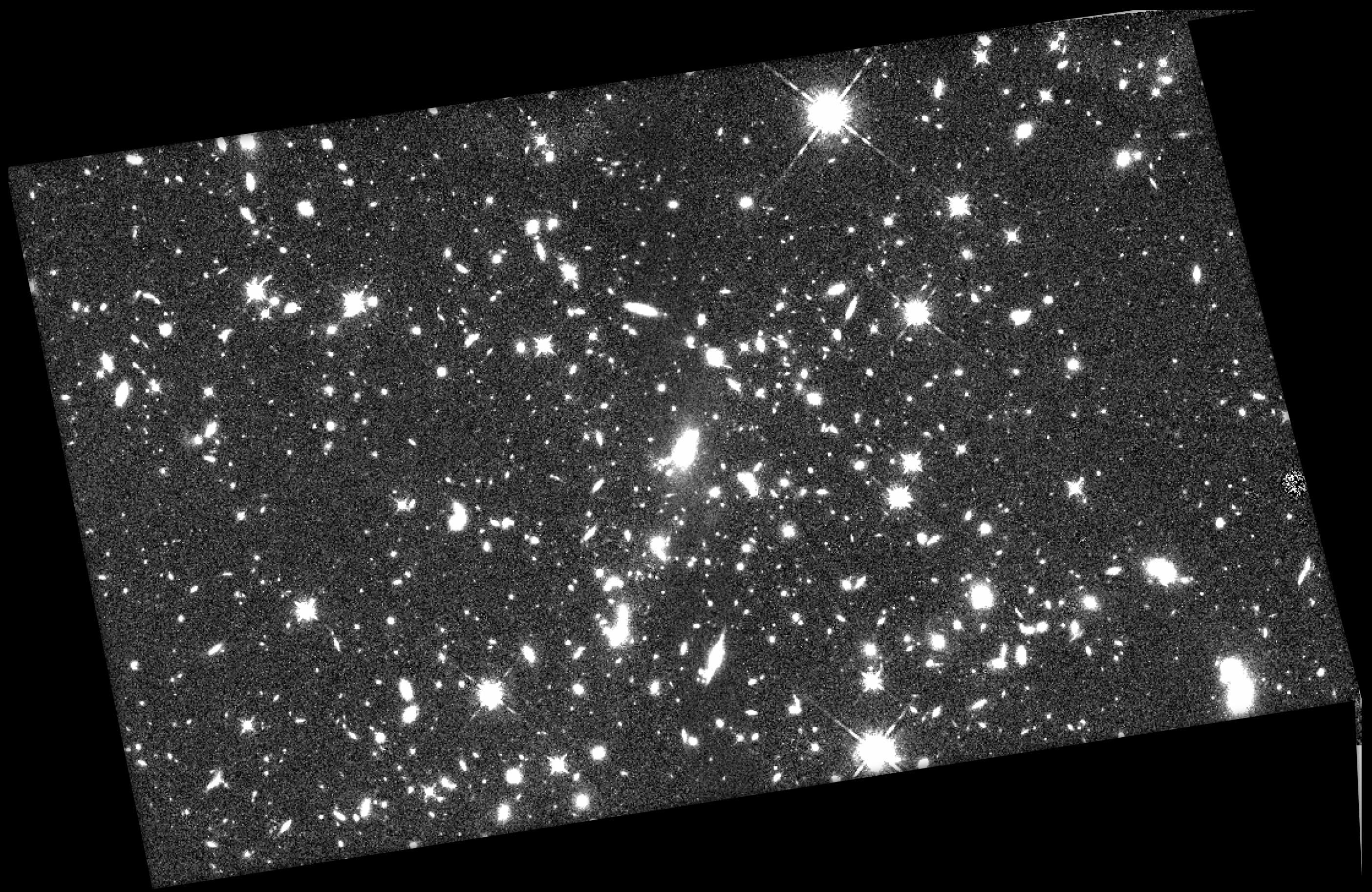
~40 proposals, to 8 telescopes, over 4 years

14-band coverage for most clusters, including IRAC and HST F160W

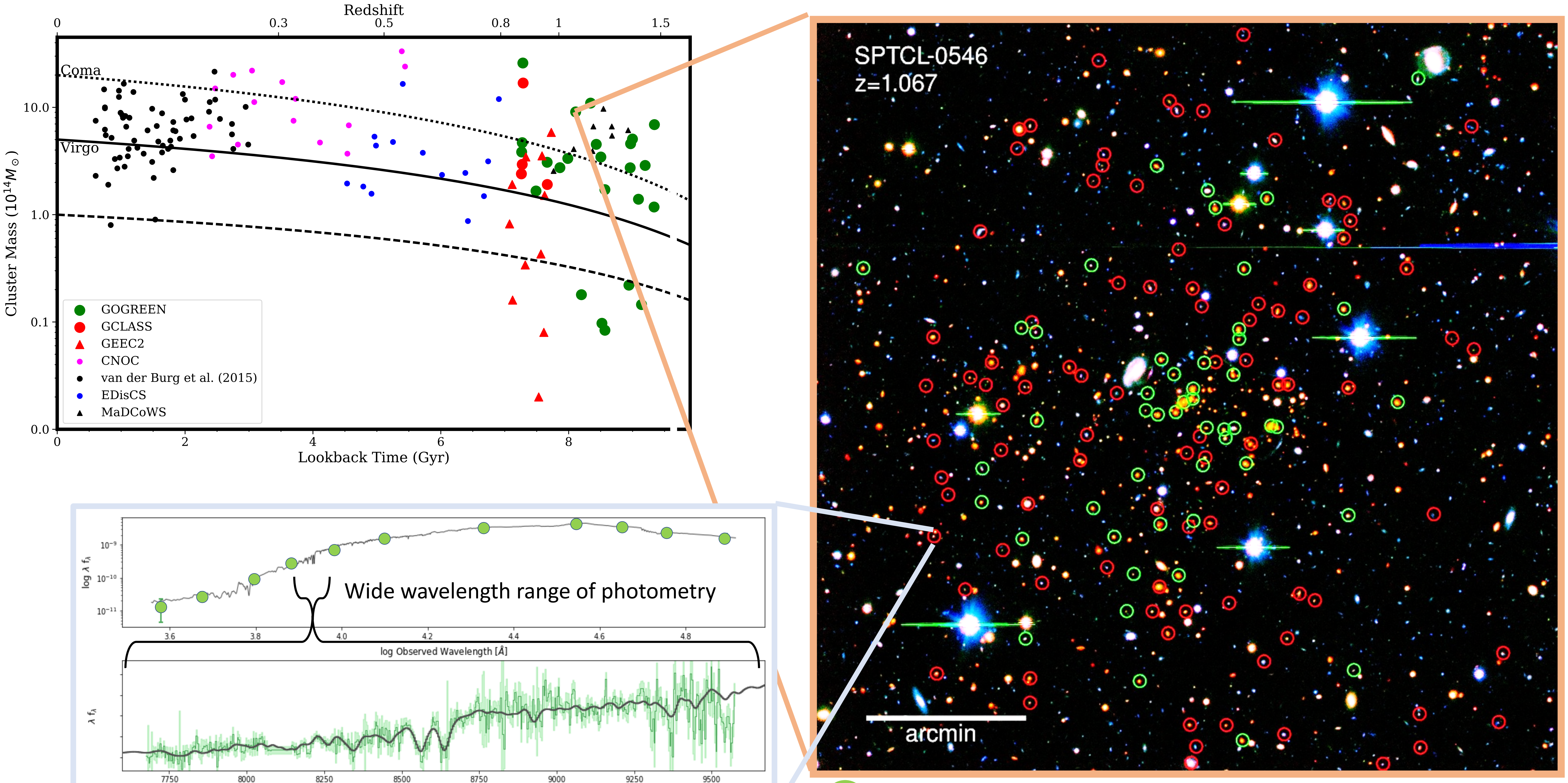


Name	u/U	B/g	V	r/R	i/I	z/Z	Y/J_1	J	K_s	[3.6] μm	[4.5] μm	[5.8] μm	[8.0] μm
SPTCL-0205	26.2 $^{(b)}$	26.7 $^{(b)}$	25.6 $^{(b)}$	25.9 $^{(b)}$	25.4 $^{(b)}$	24.2 $^{(b)}$	24.2 $^{(h)}$	23.9 $^{(h)}$	24.0 $^{(h)}$	23.7 $^{(j)}$	23.2 $^{(j)}$	–	–
SPTCL-0546	25.3 $^{(b)}$	26.1 $^{(b)}$	25.3 $^{(b)}$	25.6 $^{(b)}$	25.0 $^{(b)}$	23.8 $^{(b)}$	24.1 $^{(h)}$	23.9 $^{(h)}$	23.9 $^{(h)}$	24.0 $^{(j)}$	23.8 $^{(j)}$	–	–
SPTCL-2106	26.0 $^{(b)}$	26.3 $^{(b)}$	25.9 $^{(b)}$	25.8 $^{(b)}$	25.3 $^{(b)}$	24.6 $^{(b)}$	24.4 $^{(h)}$	24.1 $^{(h)}$	23.6 $^{(g)}$	23.7 $^{(j)}$	23.0 $^{(j)}$	–	–
SpARCS-0219	25.8 $^{(b)}$	26.0 $^{(b)}$	25.3 $^{(b)}$	25.5 $^{(b)}$	25.2 $^{(b)}$	24.1 $^{(b)}$	24.4 $^{(h)}$	24.3 $^{(h)}$	24.0 $^{(h)}$	24.0 $^{(j)}$	23.8 $^{(j)}$	21.4 $^{(j)}$	21.4 $^{(j)}$
SpARCS-0335	26.3 $^{(b)}$	26.4 $^{(b)}$	25.9 $^{(b)}$	26.3 $^{(b)}$	25.5 $^{(b)}$	24.6 $^{(b)}$	25.2 $^{(g)}$	24.3 $^{(h)}$	23.7 $^{(h)}$	24.4 $^{(j)}$	24.3 $^{(j)}$	21.6 $^{(j)}$	21.6 $^{(j)}$
SpARCS-0035	25.9 $^{(b)}$	26.4 $^{(b)}$	25.8 $^{(b)}$	26.0 $^{(b)}$	25.5 $^{(b)}$	25.5 $^{(d)}$	24.2 $^{(h)}$	24.9 $^{(g)}$	24.2 $^{(g)}$	24.6 $^{(j)}$	24.5 $^{(j)}$	22.8 $^{(j)}$	22.6 $^{(j)}$
SpARCS-1034	–	26.0 $^{(c)}$	–	26.1 $^{(c)}$	25.5 $^{(c)}$	25.4 $^{(e)}$	25.1 $^{(e)}$	24.5 $^{(i)}$	24.0 $^{(i)}$	22.7 $^{(j)}$	22.4 $^{(j)}$	19.9 $^{(j)}$	19.7 $^{(j)}$
SpARCS-1051	26.3 $^{(a)}$	26.1 $^{(c)}$	–	26.1 $^{(c)}$	25.6 $^{(c)}$	25.4 $^{(e)}$	25.0 $^{(e)}$	24.5 $^{(i)}$	24.1 $^{(i)}$	22.6 $^{(j)}$	22.5 $^{(j)}$	19.7 $^{(j)}$	19.6 $^{(j)}$
SpARCS-1616	25.9 $^{(a)}$	26.2 $^{(c)}$	–	26.1 $^{(c)}$	25.7 $^{(c)}$	25.6 $^{(e)}$	24.7 $^{(e)}$	24.2 $^{(i)}$	23.8 $^{(i)}$	22.7 $^{(j)}$	22.6 $^{(j)}$	21.2 $^{(j)}$	21.3 $^{(j)}$
SpARCS-1634	25.9 $^{(a)}$	26.4 $^{(c)}$	–	26.2 $^{(c)}$	25.8 $^{(c)}$	25.0 $^{(f)}$	–	24.2 $^{(i)}$	23.8 $^{(i)}$	23.0 $^{(j)}$	22.8 $^{(j)}$	21.3 $^{(j)}$	21.3 $^{(j)}$
SpARCS-1638	26.1 $^{(a)}$	26.4 $^{(c)}$	–	26.2 $^{(c)}$	25.6 $^{(c)}$	25.3 $^{(f)}$	24.2 $^{(c)}$	24.1 $^{(i)}$	23.6 $^{(i)}$	22.8 $^{(j)}$	22.5 $^{(j)}$	21.3 $^{(j)}$	21.4 $^{(j)}$
COSMOS/UltraVISTA	26.8 $^{(a)}$	26.9 $^{(c)}$	26.4 $^{(c)}$	26.4 $^{(c)}$	26.0 $^{(c)}$	25.2 $^{(c)}$	24.5 $^{(k)}$	24.3 $^{(k)}$	23.8 $^{(k)}$	23.9 $^{(j)}$	23.6 $^{(j)}$	21.7 $^{(j)}$	21.7 $^{(j)}$





HST F160W



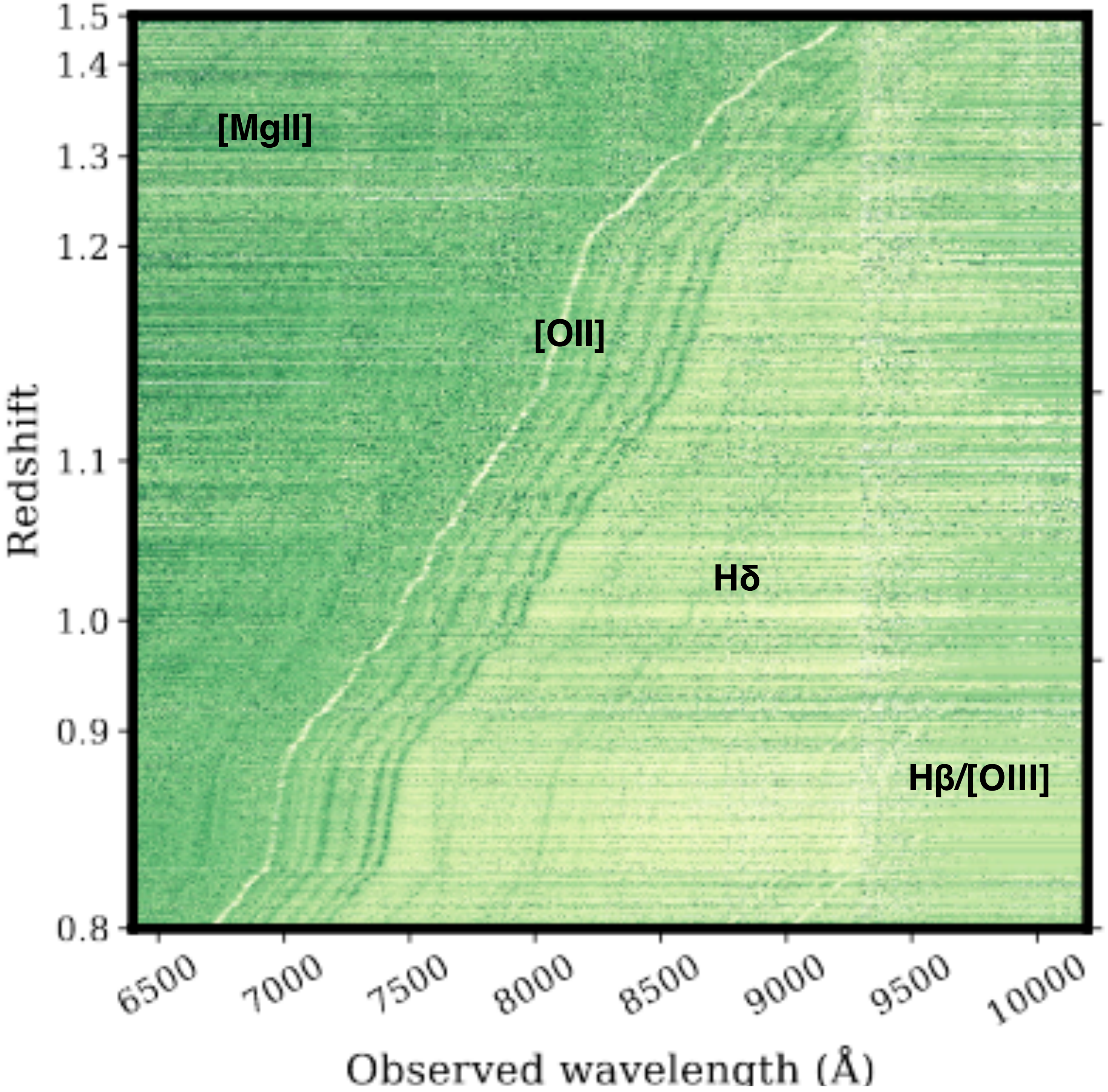
Wide wavelength range of photometry

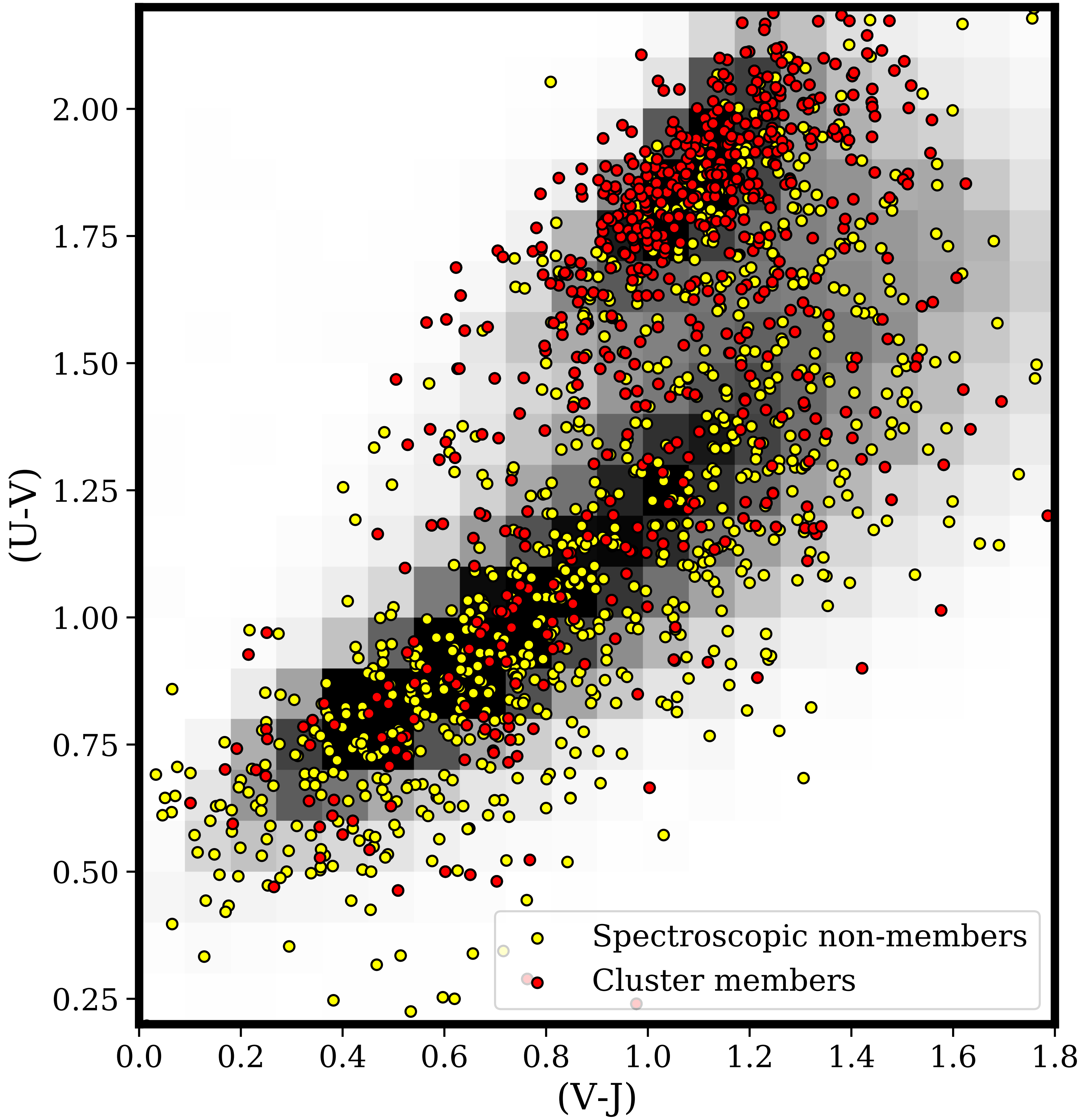
○ Cluster member

○ Non-member

Rest-frame optical spectroscopy

GOGREEN + GCLASS = ~2800 redshifts





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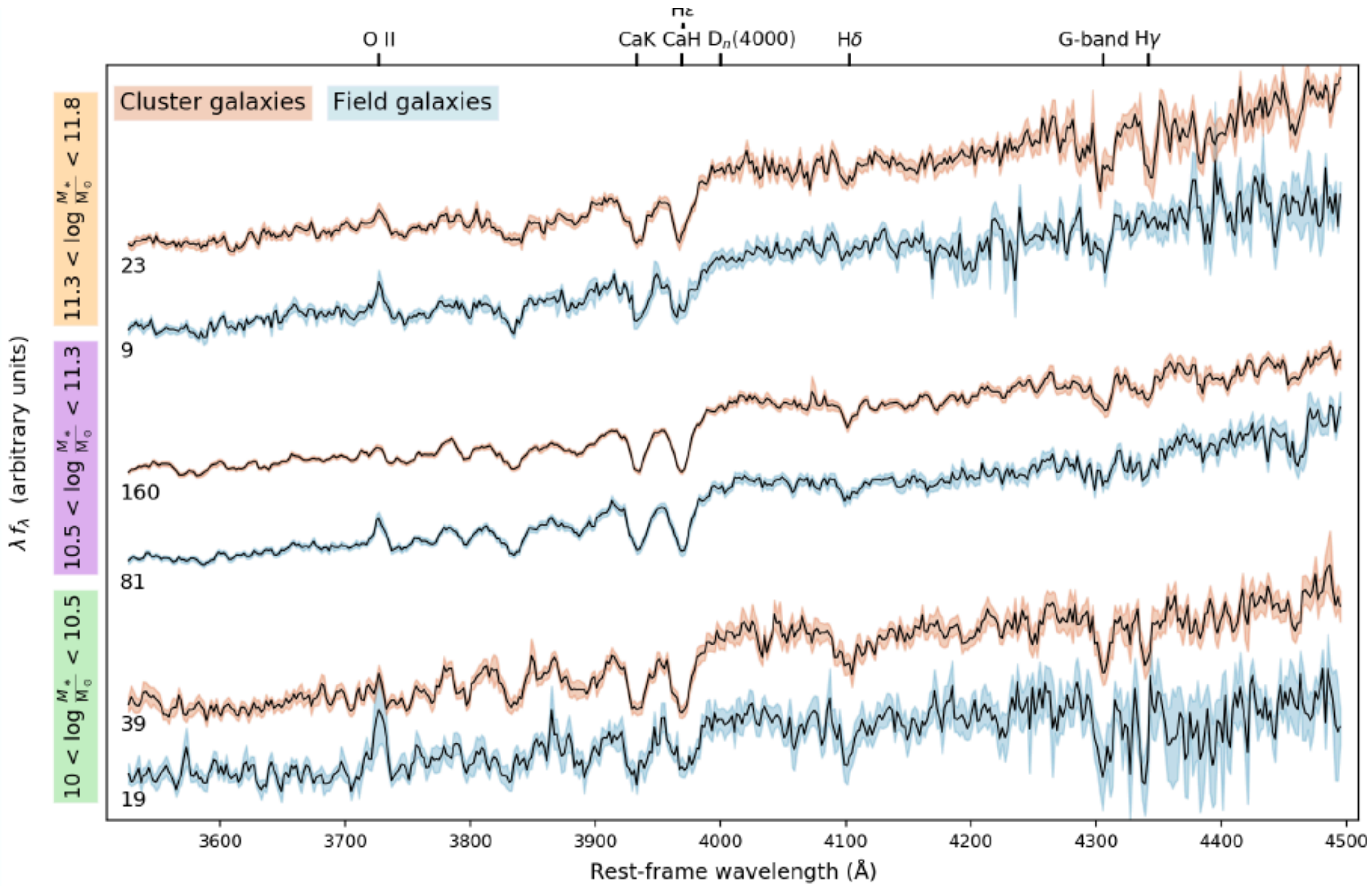
Spectroscopy covers key spectral features



Combined spectra of quiescent galaxies within mass and environment selections, shown within the wavelength region included in the SFH fitting procedure. The spectra in each subsample were de-redshifted, re-binned to a common wavelength sampling, flux normalized about 4120 Å, and then averaged. The uncertainty in the co-added spectra was determined from bootstrapping. Prominent spectral features are labelled on the top axis, and number of galaxies in each co-add are indicated on the left.

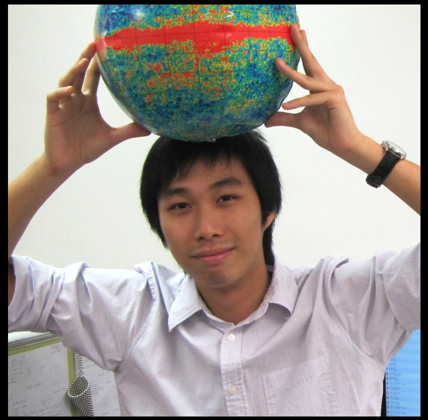
Webb et al. (2020, submitted)

First results

1. Luminosity functions for six clusters (Chan et al. 2019, ApJ, 880, 119)
2. Stellar mass functions in clusters (van der Burg et al. 2020 A&A, 638, 112)
3. SFR-mass relation and its dependence on environment (Old et al. 2020 MNRAS, 493, 5987)
4. Ages of the quiescent galaxy population (Webb et al. 2020, submitted)

In Preparation

- The role of halo mass in environmental quenching at z=1 (Andrew Reeves et al.)
- The morphology of quenched cluster galaxies in GOGREEN (Jeffrey Chan et al.)
- Transition galaxies in GOGREEN (Karen McNab et al.)
- Dynamics and mass profiles of clusters at 0.8<z<1.5 (Andrea Biviano et al.)



Jeffrey Chan

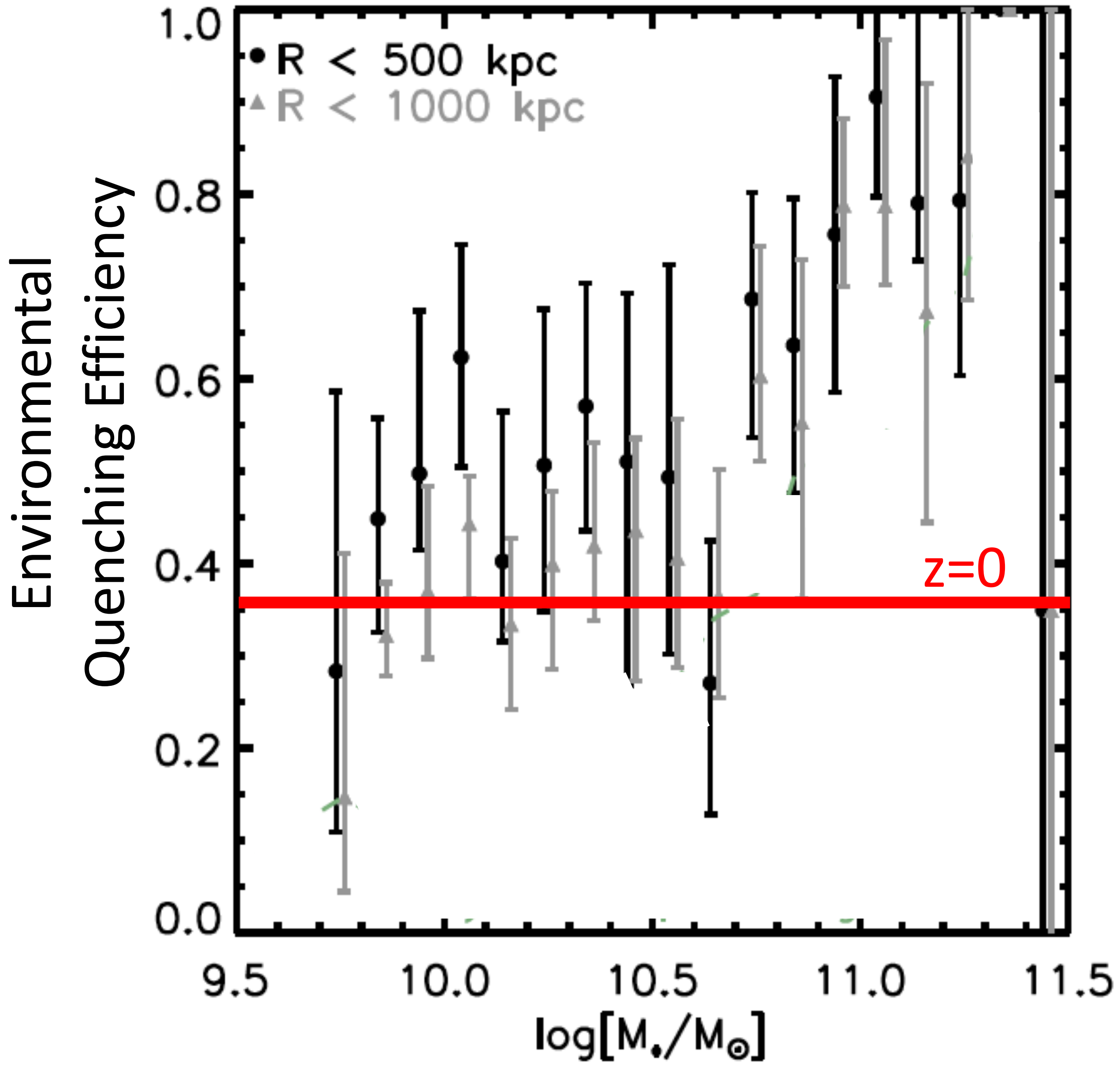
Remco van der Burg

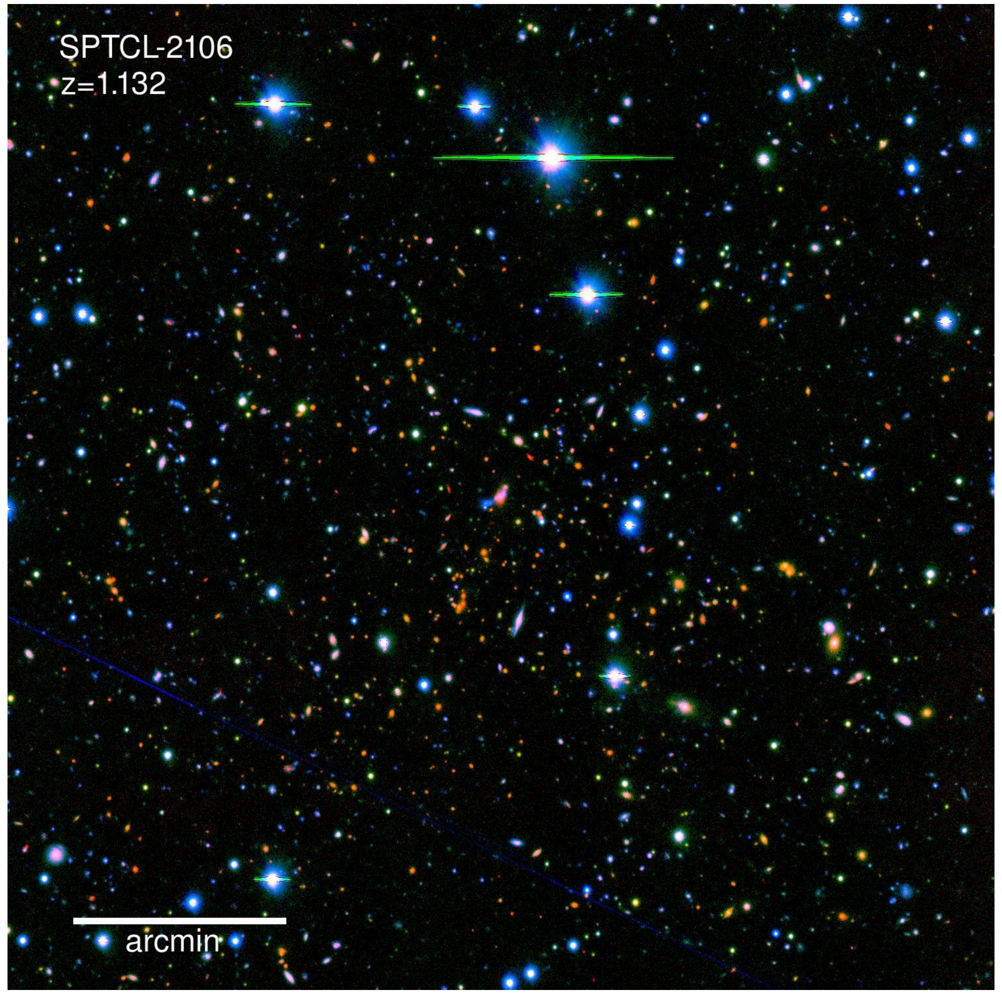
Lyndsay Old

Kristi Webb

More on this at 10:40 EDT!

High fraction of quenched galaxies





- ❖ Environmental quenching is even more effective at z=1 than at z=0
- ❖ Depends on stellar mass – unlike at z=0

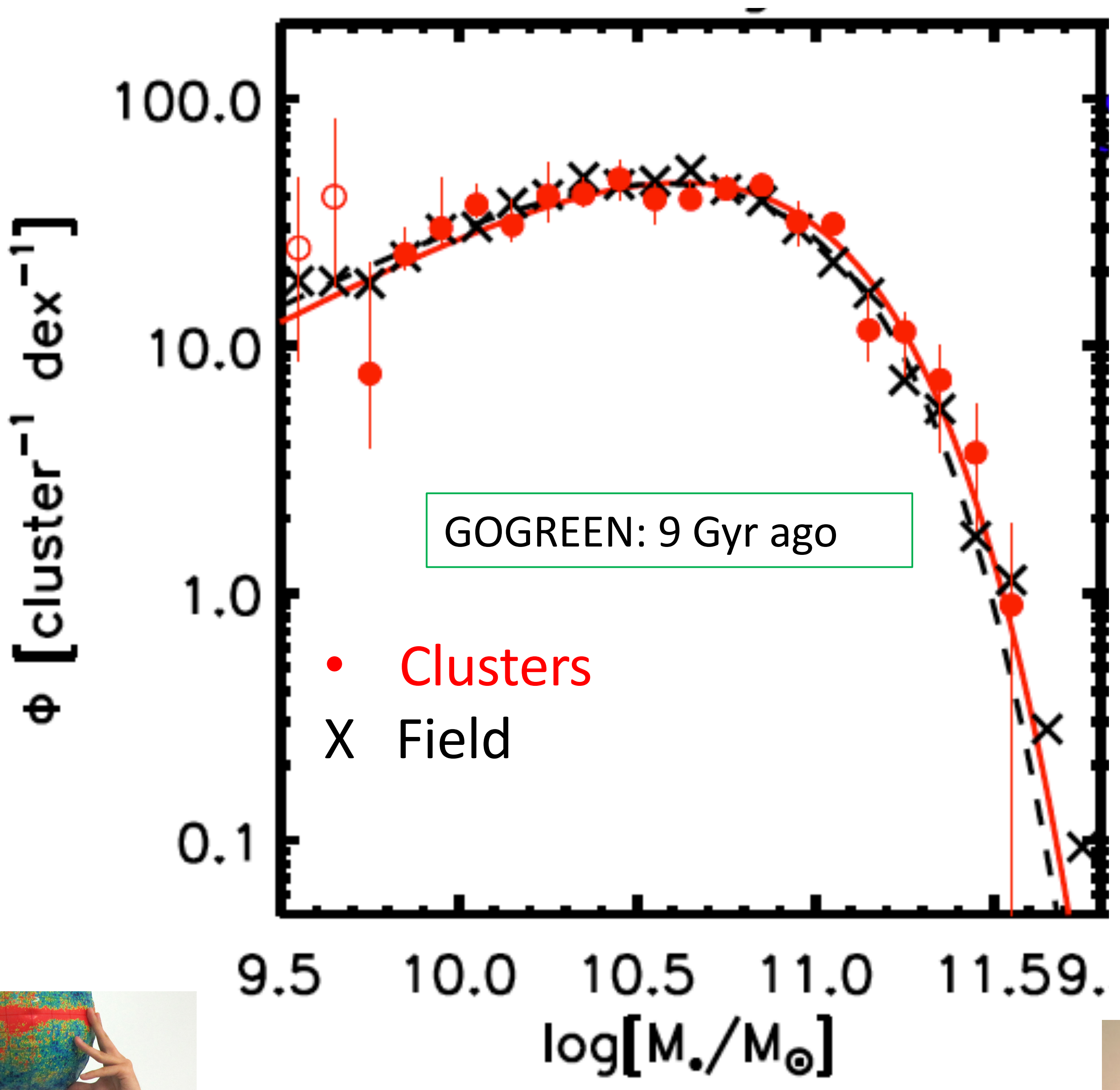
van der Burg et al. (2020)

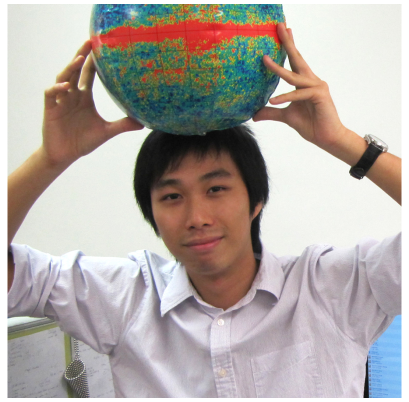
See also Muzzin et al. (2012); Balogh et al. (2016)

More on this at 10:40 EDT!

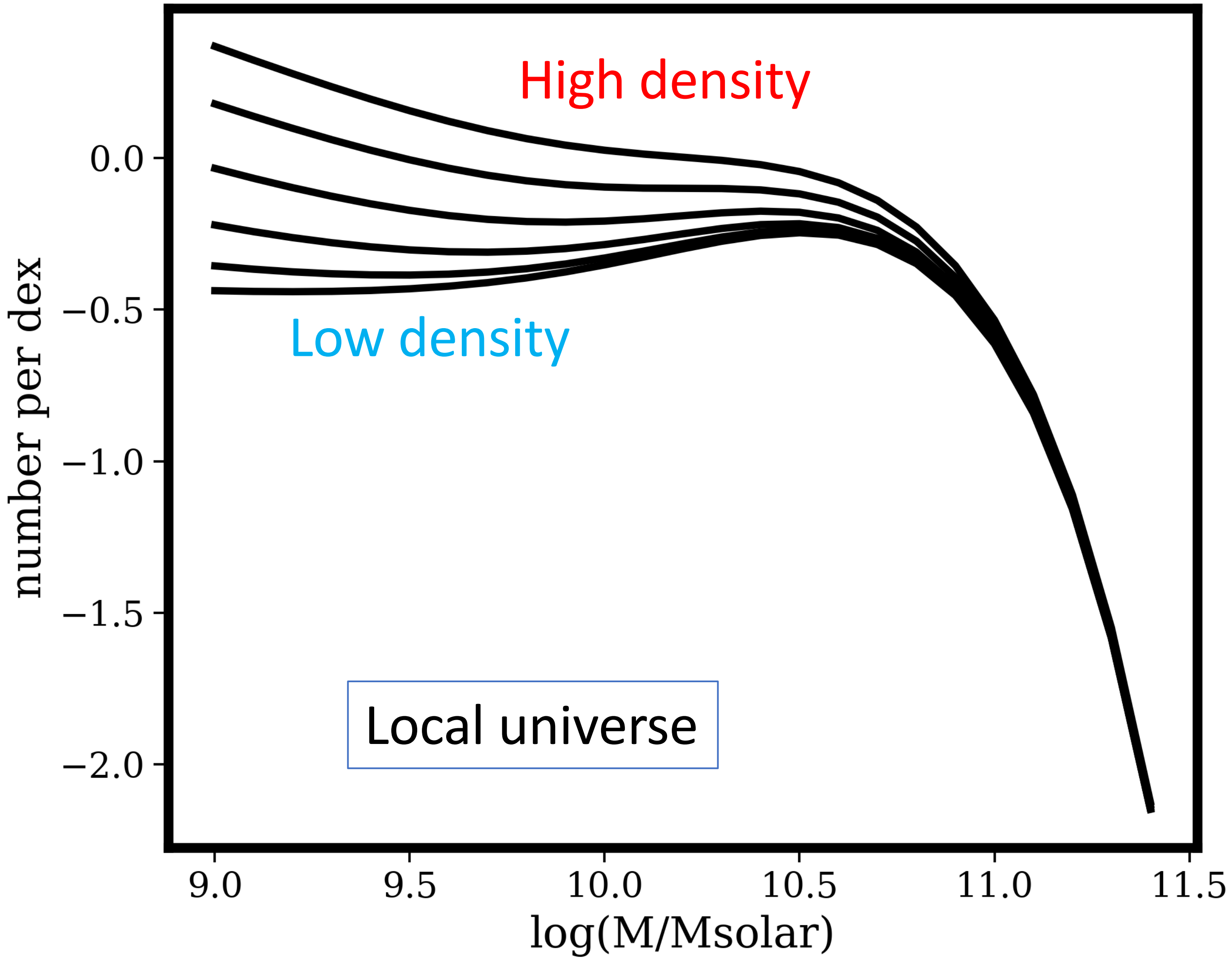
Stellar mass functions

Stellar mass function of dead galaxies in clusters is identical to that in the field; in stark contrast from what is observed locaslly





Chan et al. (2019)
van der Burg et al. (2020)

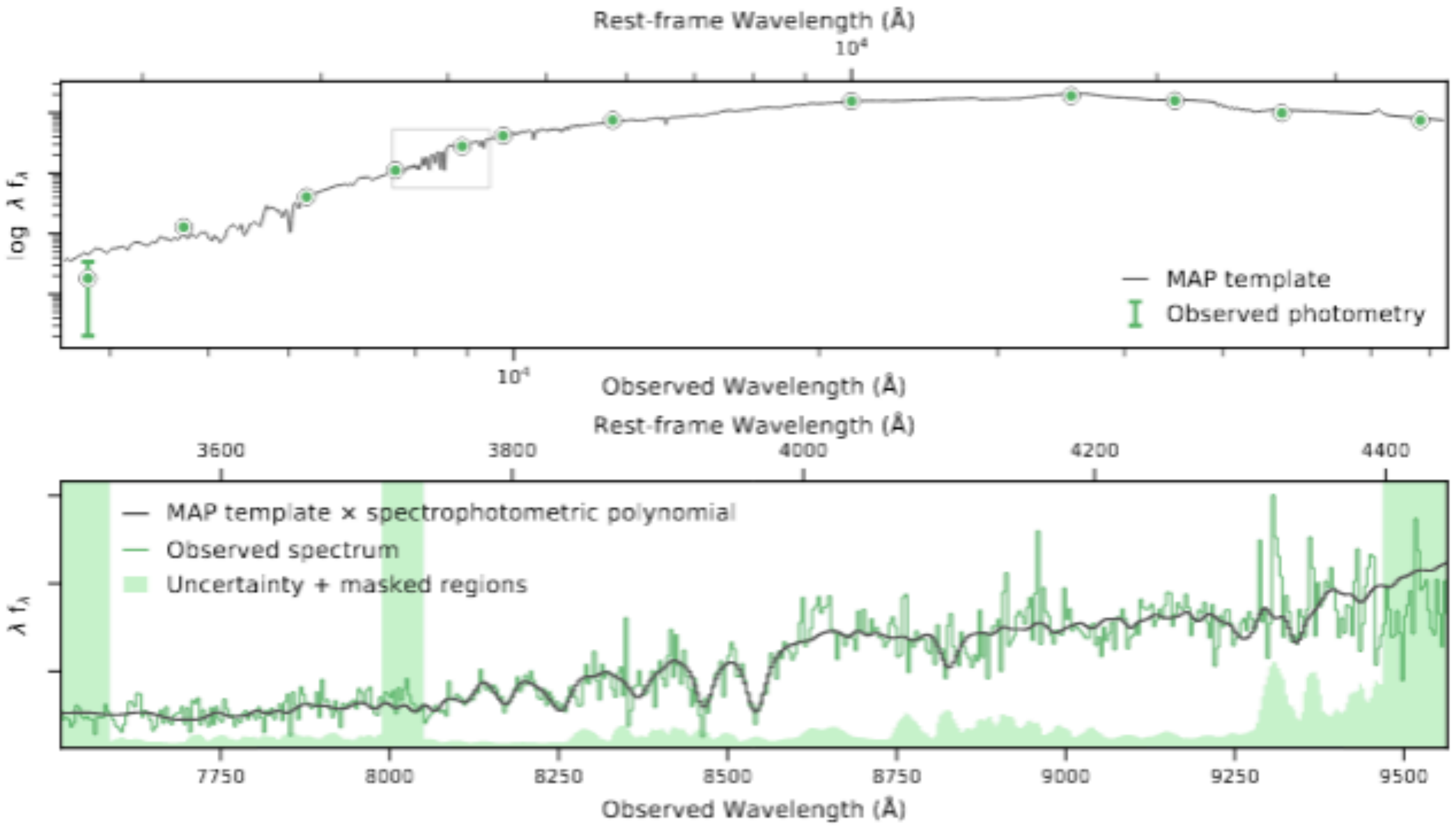


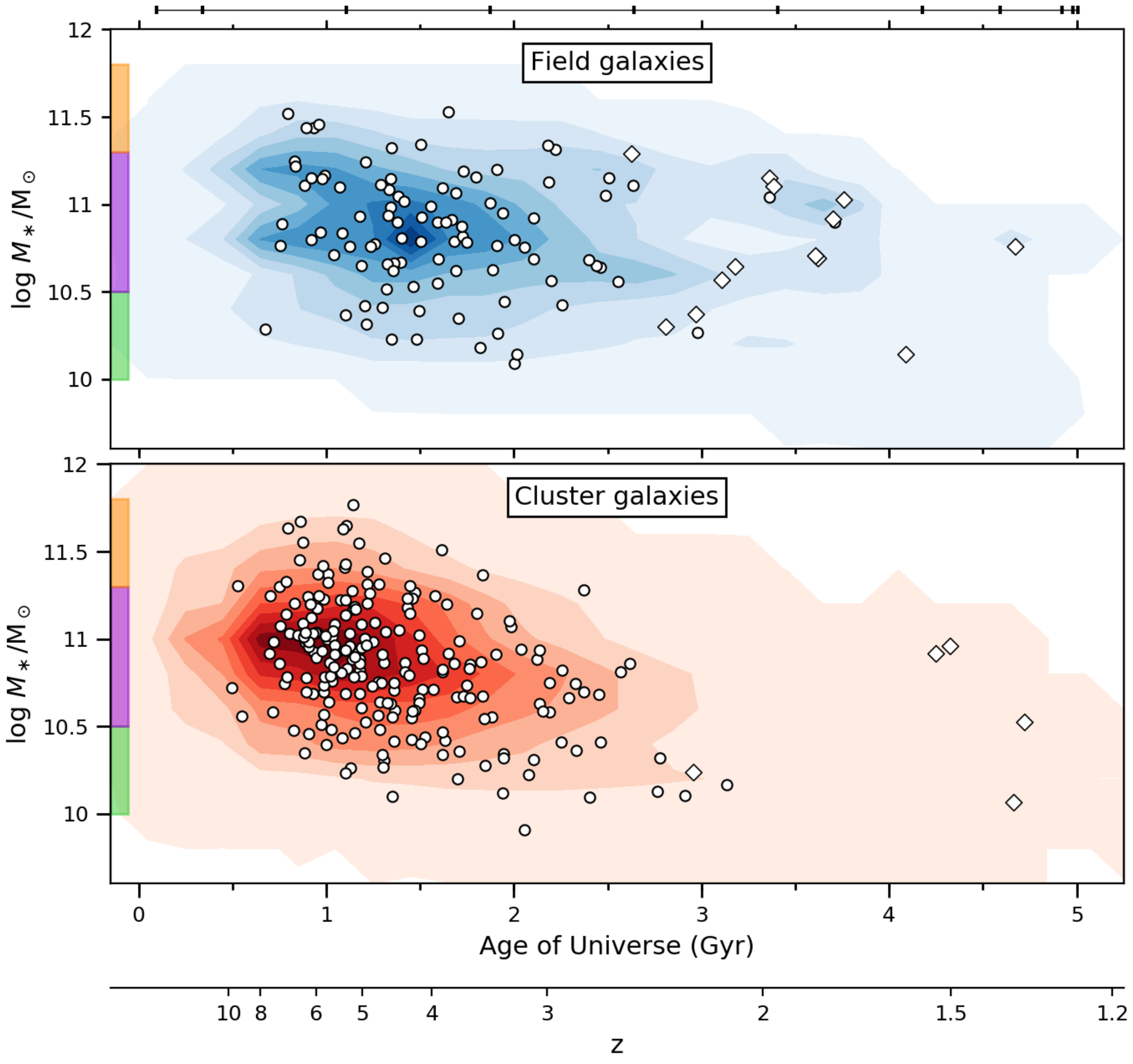
Baldry et al. (2006)

More on this at 11:20 EDT!

Quiescent galaxy ages

The median age of cluster quiescent galaxies is only 0.3 Gyr older than that of field quiescent galaxies



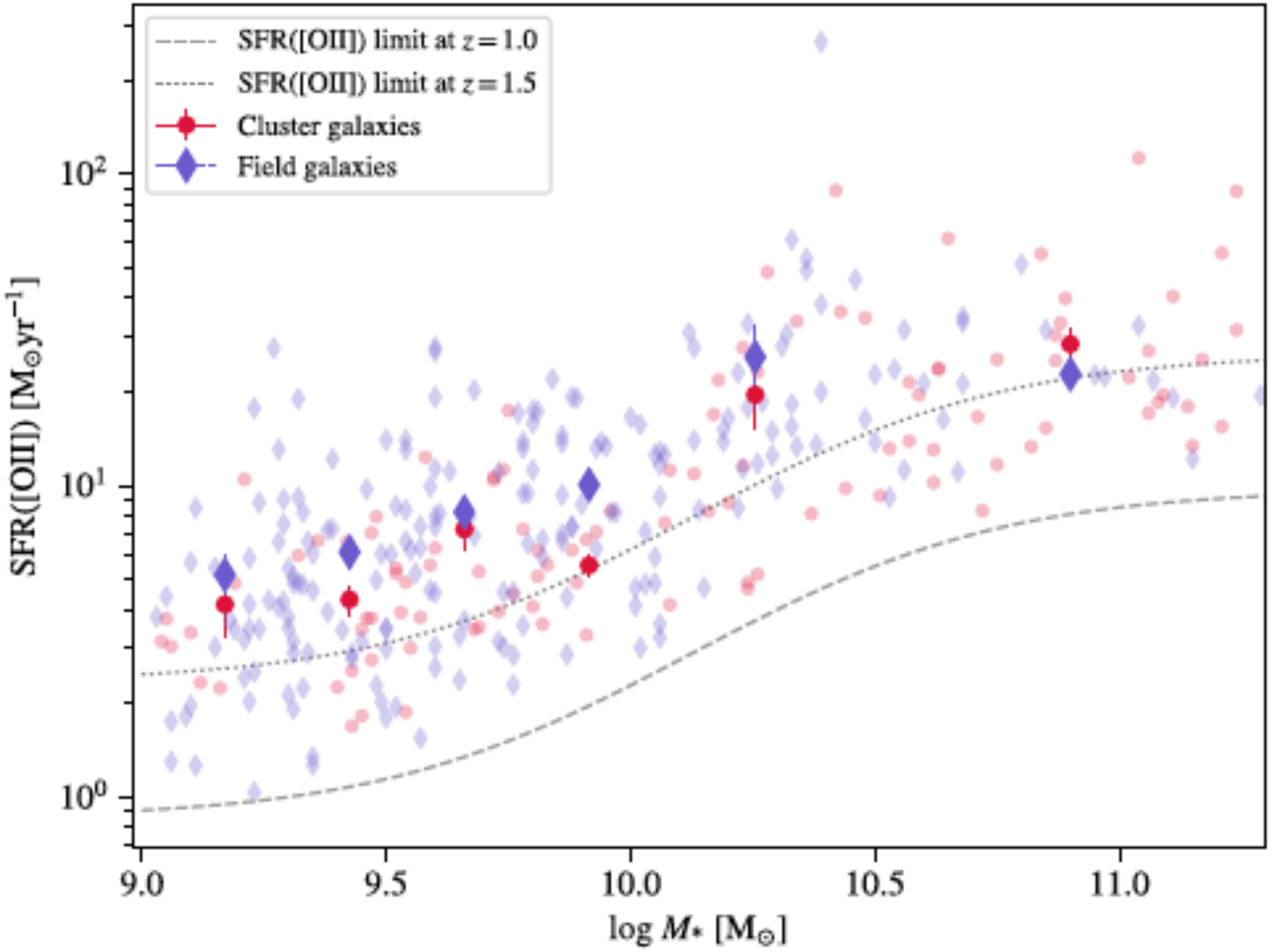


Webb et al. (2020, submitted)

More on this at 11:00 EDT!

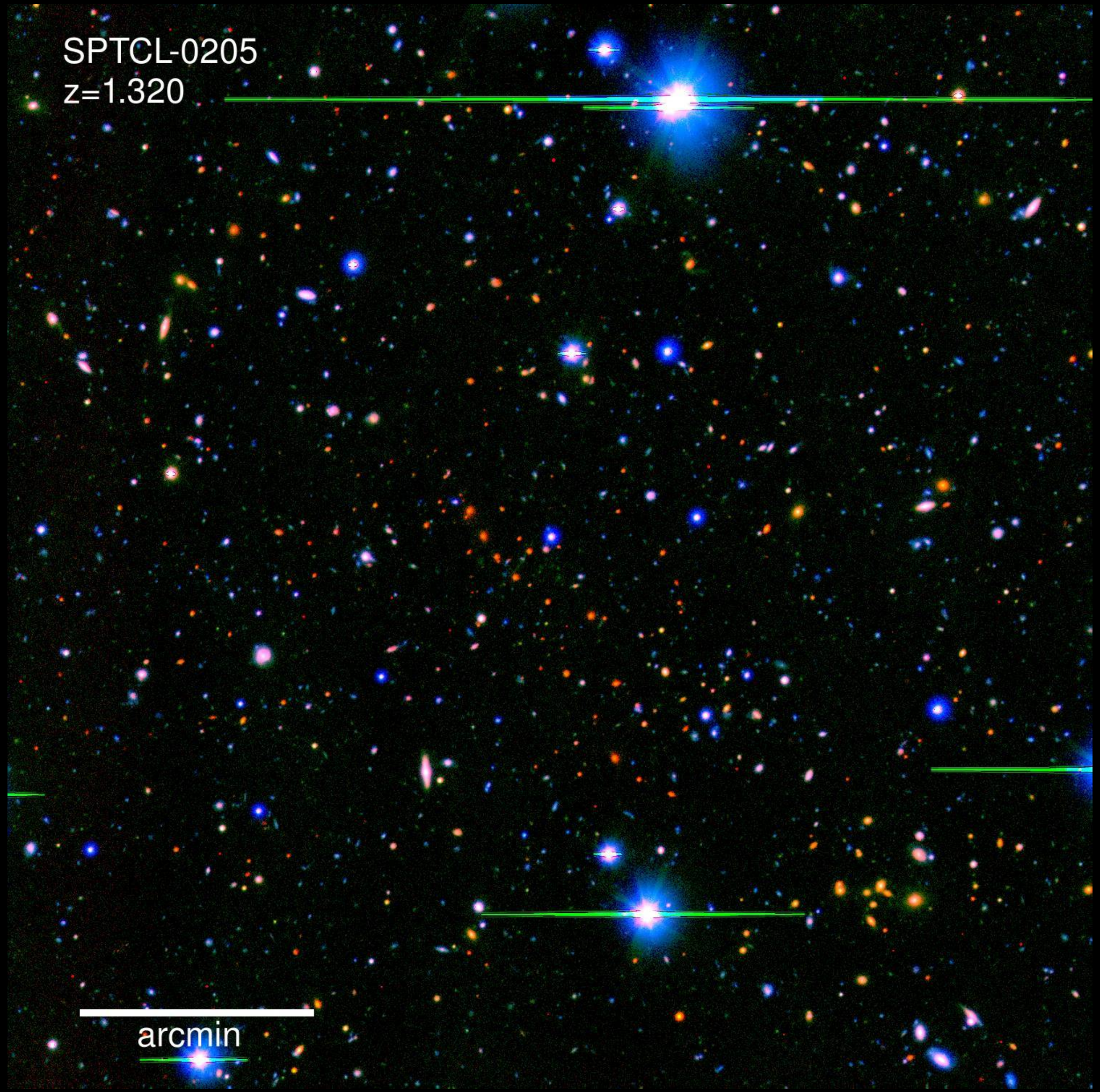
Star formation rates

The SFR of galaxies in the clusters are at most slightly lower than those in the field. Similar to what is seen at low redshift



Old et al. (2020)

z=1.3



z>1 clusters have a substantial population of dead galaxies, but their origin is very different from those that dominate at z<1.

z=0

Russ Carroll, Robert Gendler, and Bob Frank

http://gogreensurvey.ca/

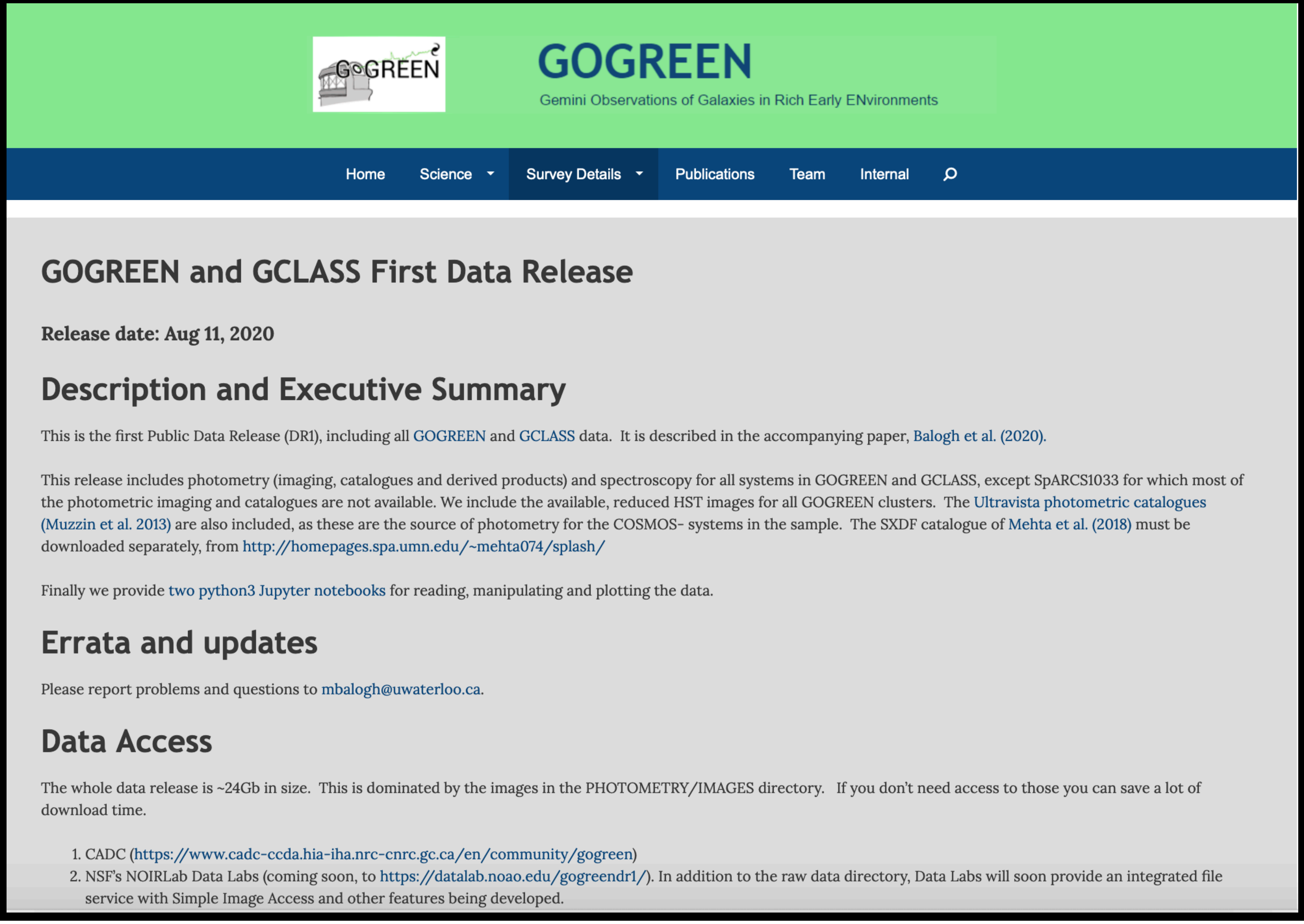
More on this at 13:10 EDT!

gogreensurvey.ca for more information

Full GOGREEN and GCLASS data released Aug 11, 2020:

http://gogreensurvey.ca/data-releases/data-packages/gogreen-and-gclass-first-data-release/

Survey Description: Balogh et al. (2017)
Data Release: Balogh et al. (2020, submitted)



GOGREEN and GCLASS First Data Release

Release date: Aug 11, 2020

Description and Executive Summary

This is the first Public Data Release (DR1), including all GOGREEN and GCLASS data. It is described in the accompanying paper, Balogh et al. (2020).

This release includes photometry (imaging, catalogues and derived products) and spectroscopy for all systems in GOGREEN and GCLASS, except SpARCS1033 for which most of the photometric imaging and catalogues are not available. We include the available, reduced HST images for all GOGREEN clusters. The Ultravista photometric catalogues (Muzzin et al. 2013) are also included, as these are the source of photometry for the COSMOS- systems in the sample. The SXDF catalogue of Mehta et al. (2018) must be downloaded separately, from http://homepages.spa.umn.edu/~mehta074/splash/

Finally we provide two python3 Jupyter notebooks for reading, manipulating and plotting the data.

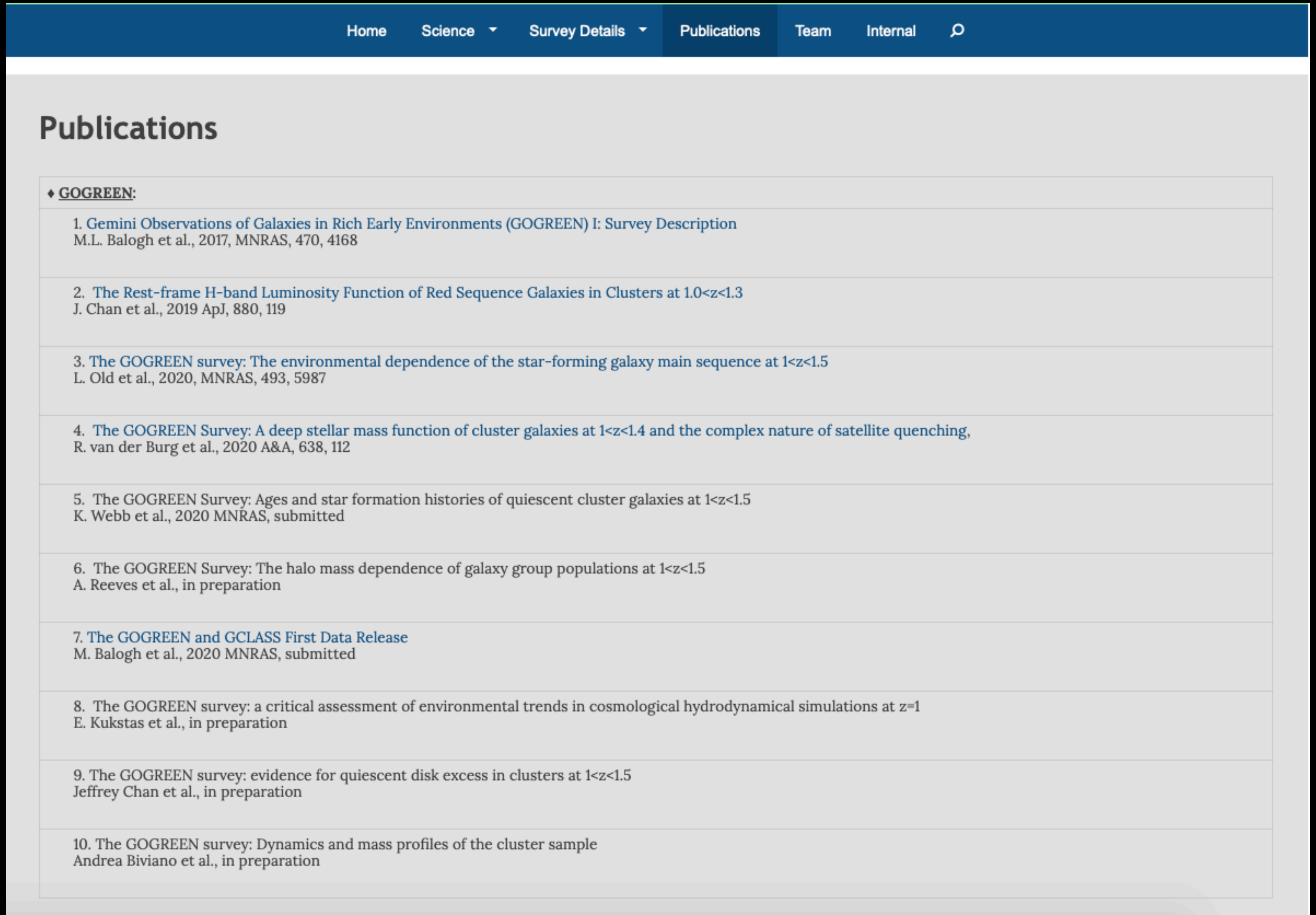
Errata and updates

Please report problems and questions to mbalogh@uwaterloo.ca.

Data Access

The whole data release is ~24Gb in size. This is dominated by the images in the PHOTOMETRY/IMAGES directory. If you don't need access to those you can save a lot of download time.

1. CADC (https://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/community/gogreen)
2. NSF's NOIRLab Data Labs (coming soon, to https://datalab.noao.edu/gogreendr1/). In addition to the raw data directory, Data Labs will soon provide an integrated file service with Simple Image Access and other features being developed.



Publications

♦ GOGREEN:

1. Gemini Observations of Galaxies in Rich Early Environments (GOGREEN) I: Survey Description
M.L. Balogh et al., 2017, MNRAS, 470, 4168

2. The Rest-frame H-band Luminosity Function of Red Sequence Galaxies in Clusters at 1.0<z<1.3
J. Chan et al., 2019 ApJ, 880, 119

3. The GOGREEN survey: The environmental dependence of the star-forming galaxy main sequence at 1<z<1.5
L. Old et al., 2020, MNRAS, 493, 5987

4. The GOGREEN Survey: A deep stellar mass function of cluster galaxies at 1<z<1.4 and the complex nature of satellite quenching,
R. van der Burg et al., 2020 A&A, 638, 112

5. The GOGREEN Survey: Ages and star formation histories of quiescent cluster galaxies at 1<z<1.5
K. Webb et al., 2020 MNRAS, submitted

6. The GOGREEN Survey: The halo mass dependence of galaxy group populations at 1<z<1.5
A. Reeves et al., in preparation

7. The GOGREEN and GCLASS First Data Release
M. Balogh et al., 2020 MNRAS, submitted

8. The GOGREEN survey: a critical assessment of environmental trends in cosmological hydrodynamical simulations at z=1
E. Kukstas et al., in preparation

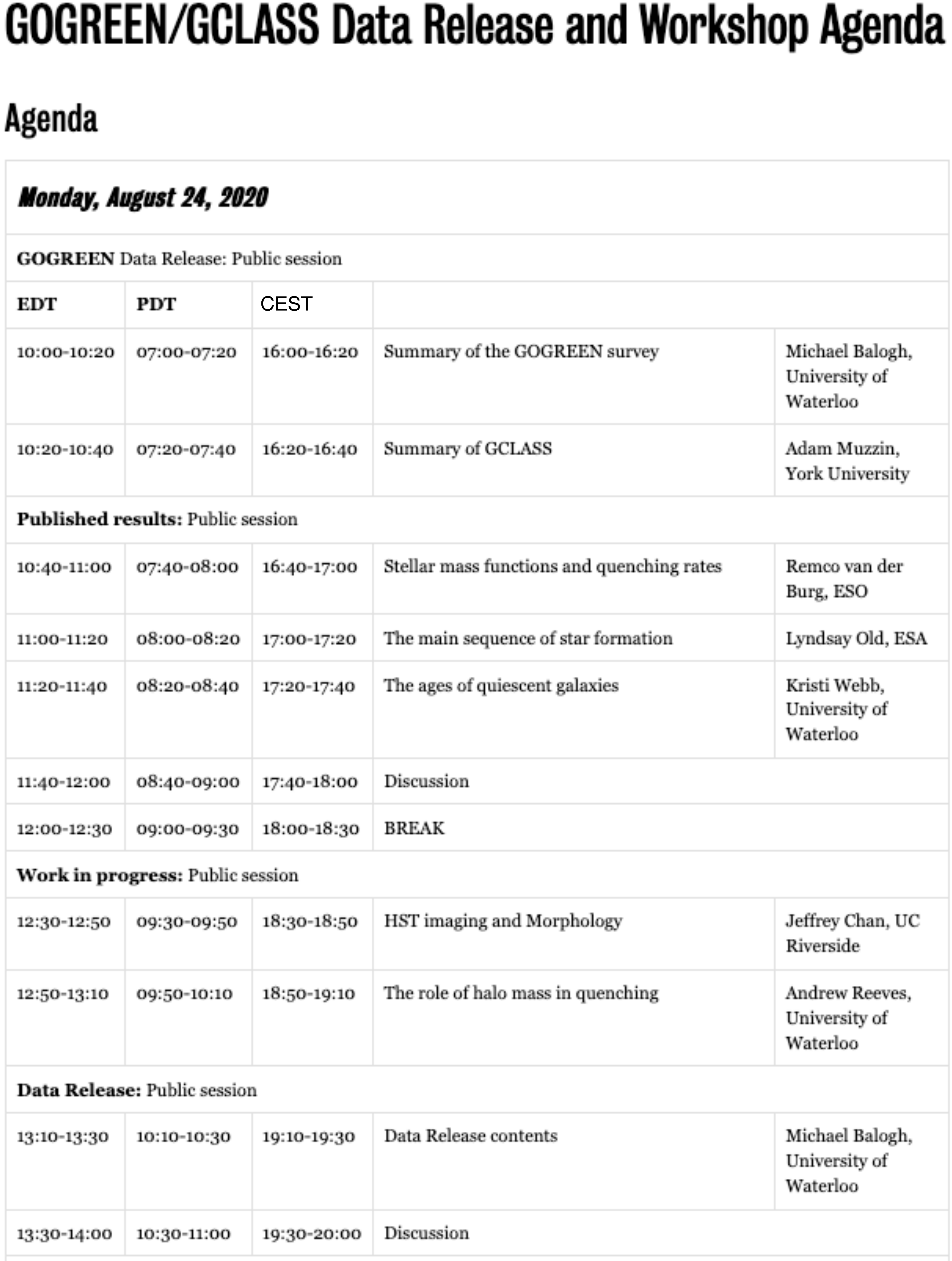
9. The GOGREEN survey: evidence for quiescent disk excess in clusters at 1<z<1.5
Jeffrey Chan et al., in preparation

10. The GOGREEN survey: Dynamics and mass profiles of the cluster sample
Andrea Biviano et al., in preparation

UNIVERSITY OF WATERLOO

GOGREEN
http://gogreensurvey.ca/

WATERLOO CENTRE FOR ASTROPHYSICS



GOGREEN/GCLASS Data Release and Workshop Agenda

Agenda

Monday, August 24, 2020

GOGREEN Data Release: Public session				
EDT	**PDT**	CEST		
10:00-10:20	07:00-07:20	16:00-16:20	Summary of the GOGREEN survey	Michael Balogh, University of Waterloo
10:20-10:40	07:20-07:40	16:20-16:40	Summary of GCLASS	Adam Muzzin, York University
Published results: Public session				
10:40-11:00	07:40-08:00	16:40-17:00	Stellar mass functions and quenching rates	Remco van der Burg, ESO
11:00-11:20	08:00-08:20	17:00-17:20	The main sequence of star formation	Lyndsay Old, ESA
11:20-11:40	08:20-08:40	17:20-17:40	The ages of quiescent galaxies	Kristi Webb, University of Waterloo
11:40-12:00	08:40-09:00	17:40-18:00	Discussion	
12:00-12:30	09:00-09:30	18:00-18:30	BREAK	
Work in progress: Public session				
12:30-12:50	09:30-09:50	18:30-18:50	HST imaging and Morphology	Jeffrey Chan, UC Riverside
12:50-13:10	09:50-10:10	18:50-19:10	The role of halo mass in quenching	Andrew Reeves, University of Waterloo
Data Release: Public session				
13:10-13:30	10:10-10:30	19:10-19:30	Data Release contents	Michael Balogh, University of Waterloo
13:30-14:00	10:30-11:00	19:30-20:00	Discussion	

Tuesday, August 25, 2020

Work in progress (continued): Public session				
EDT	**PDT**	CEST		
10:00-10:20	07:00-07:20	16:00-16:20	Cluster Dynamics	Andrea Biviano, Trieste
10:20-10:40	07:20-07:40	16:20-16:40	Transition galaxies	Karen McNab, University of Waterloo
10:40-11:00	07:40-08:00	16:40-17:00	Predictions from simulations	Egidius Kukstas, LJMU
11:00-12:00	08:00-09:00	17:00-18:00	Discussion	

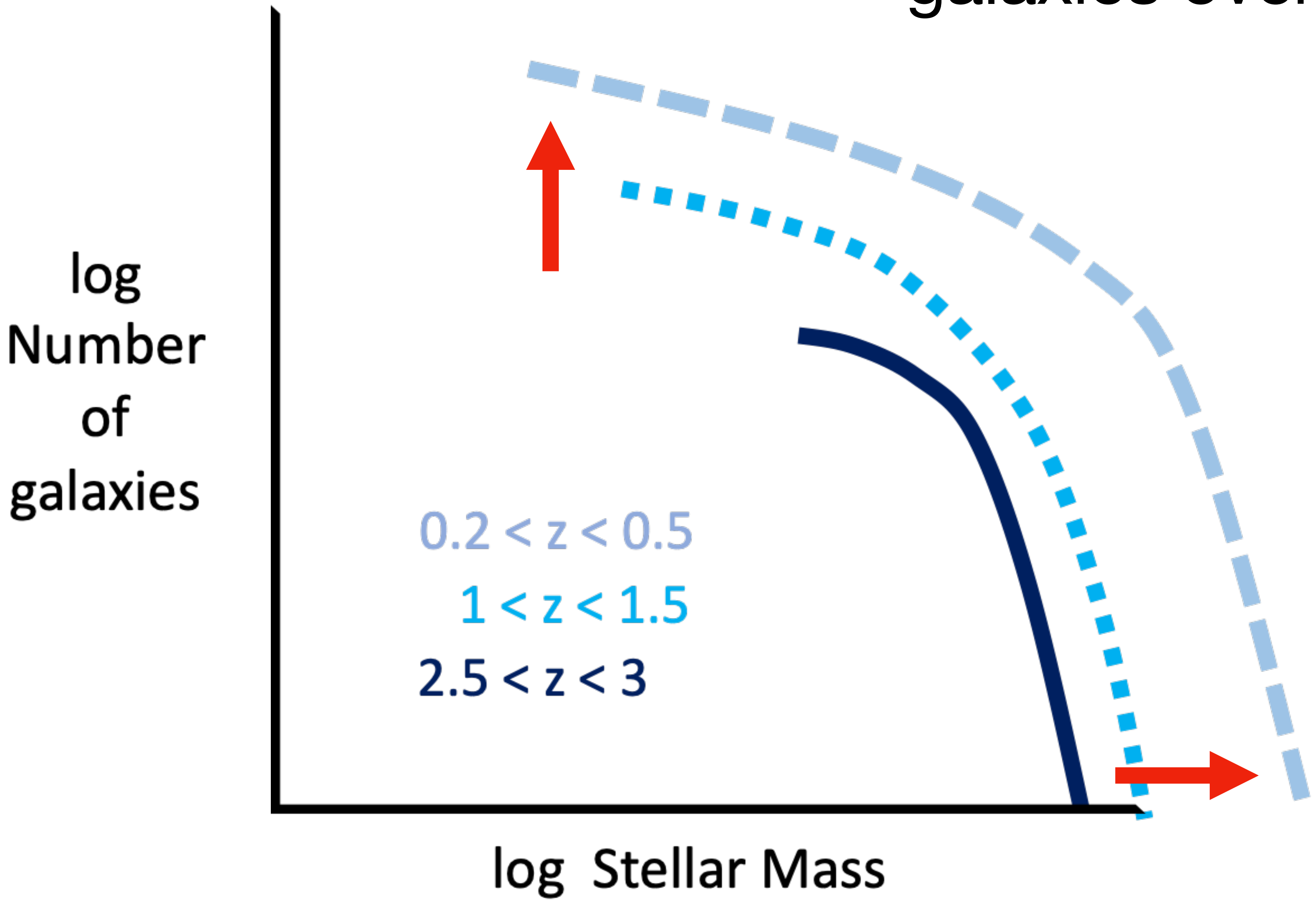
More to come today and tomorrow including some work in progress

END

Runts, rejects and extras

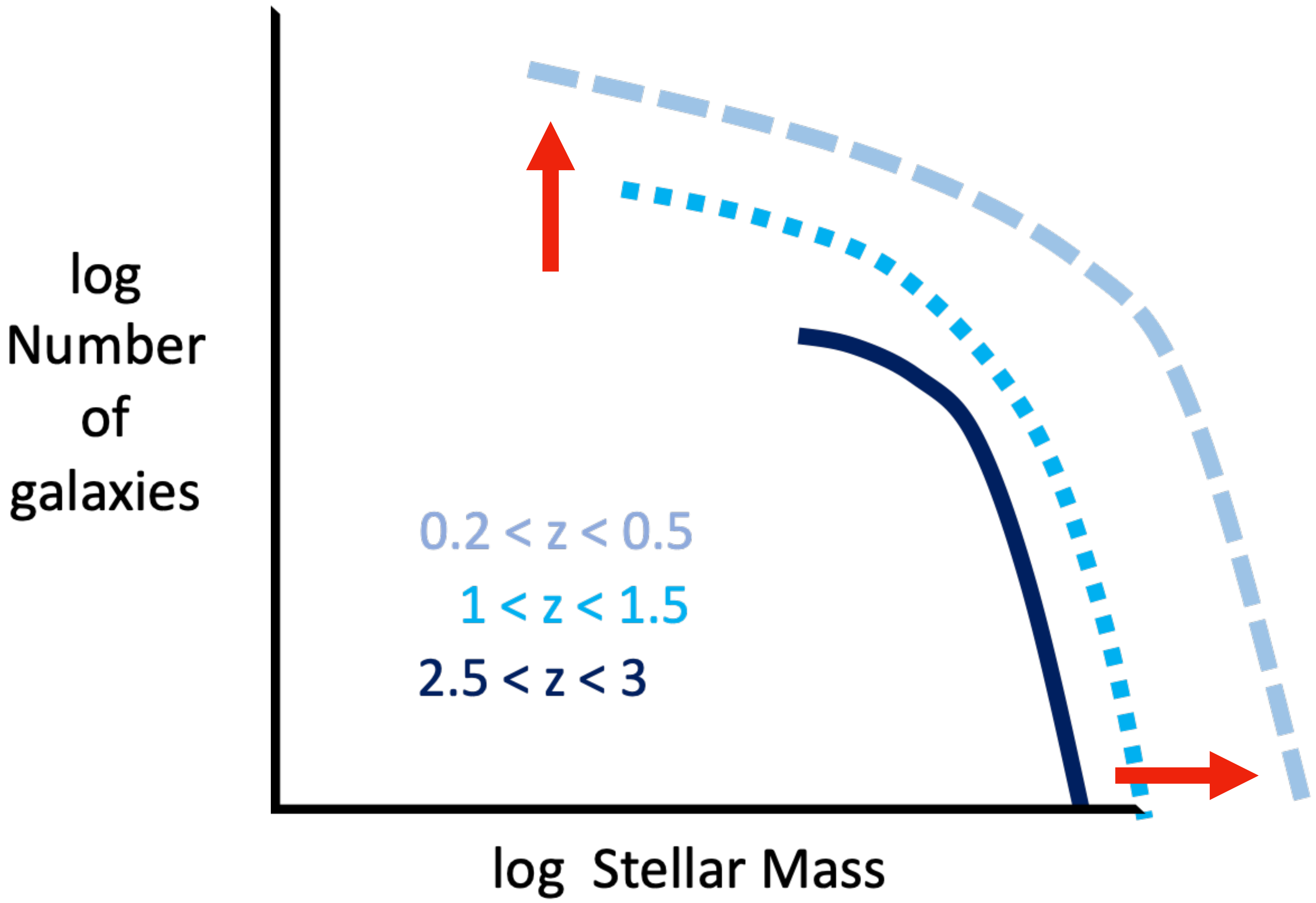
Galaxy formation and evolution is driven by star formation

Naively expect that galaxies keep getting bigger and bigger, and there will be more galaxies over time

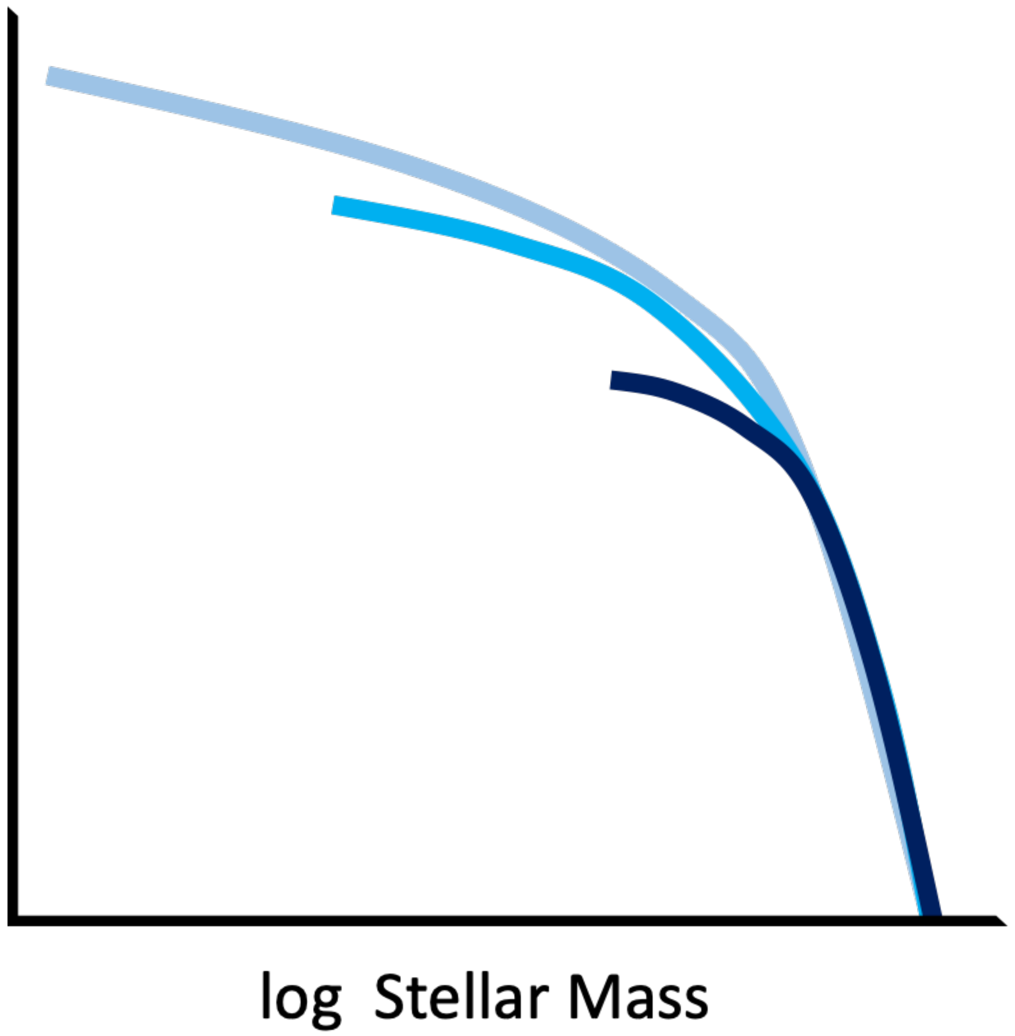


Slide courtesy of Kristi Webb

Galaxy formation and evolution is driven by star formation



Observations show that the distribution of star forming galaxies doesn't evolve like this!

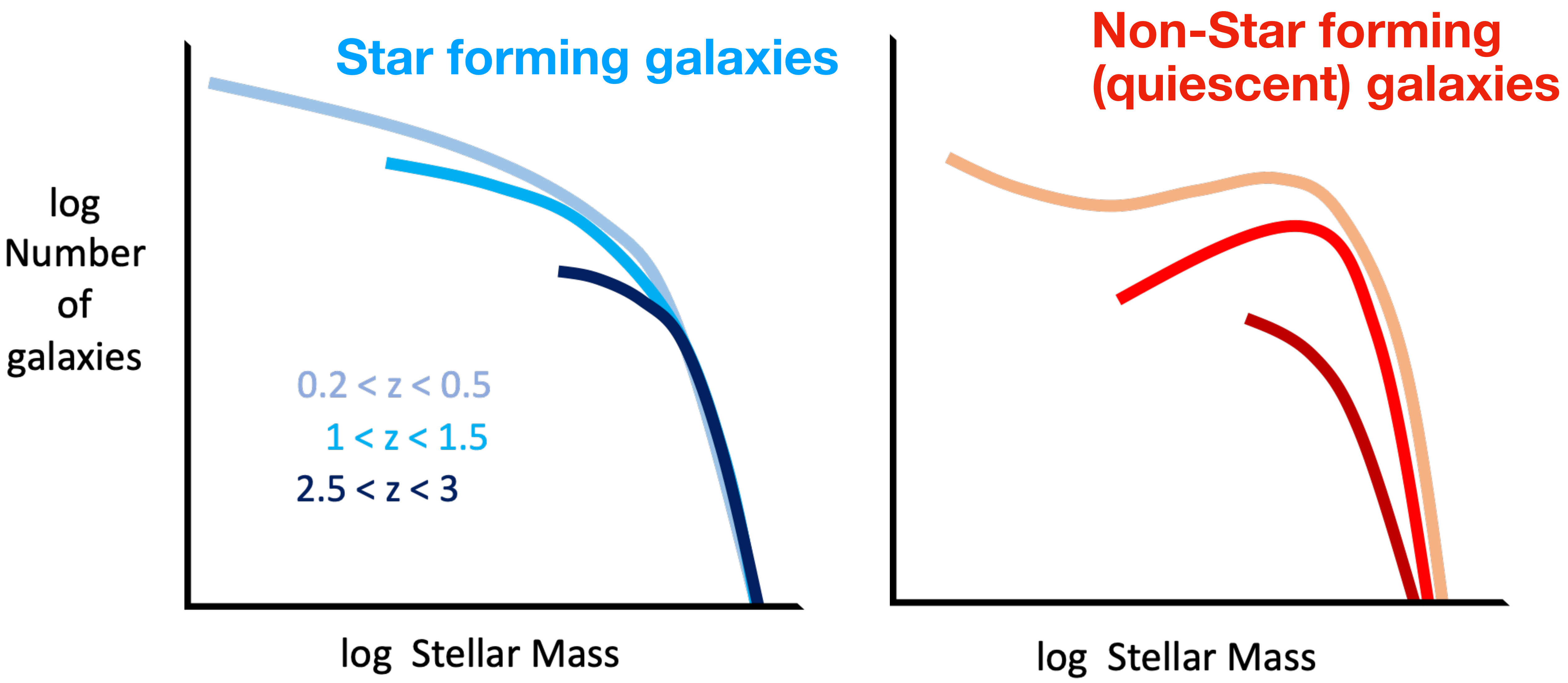


Adapted from Muzzin+2013, based on ULTRAVISTA photometry of the COSMOS field

Slide courtesy of Kristi Webb

Galaxies stop forming stars (quench).

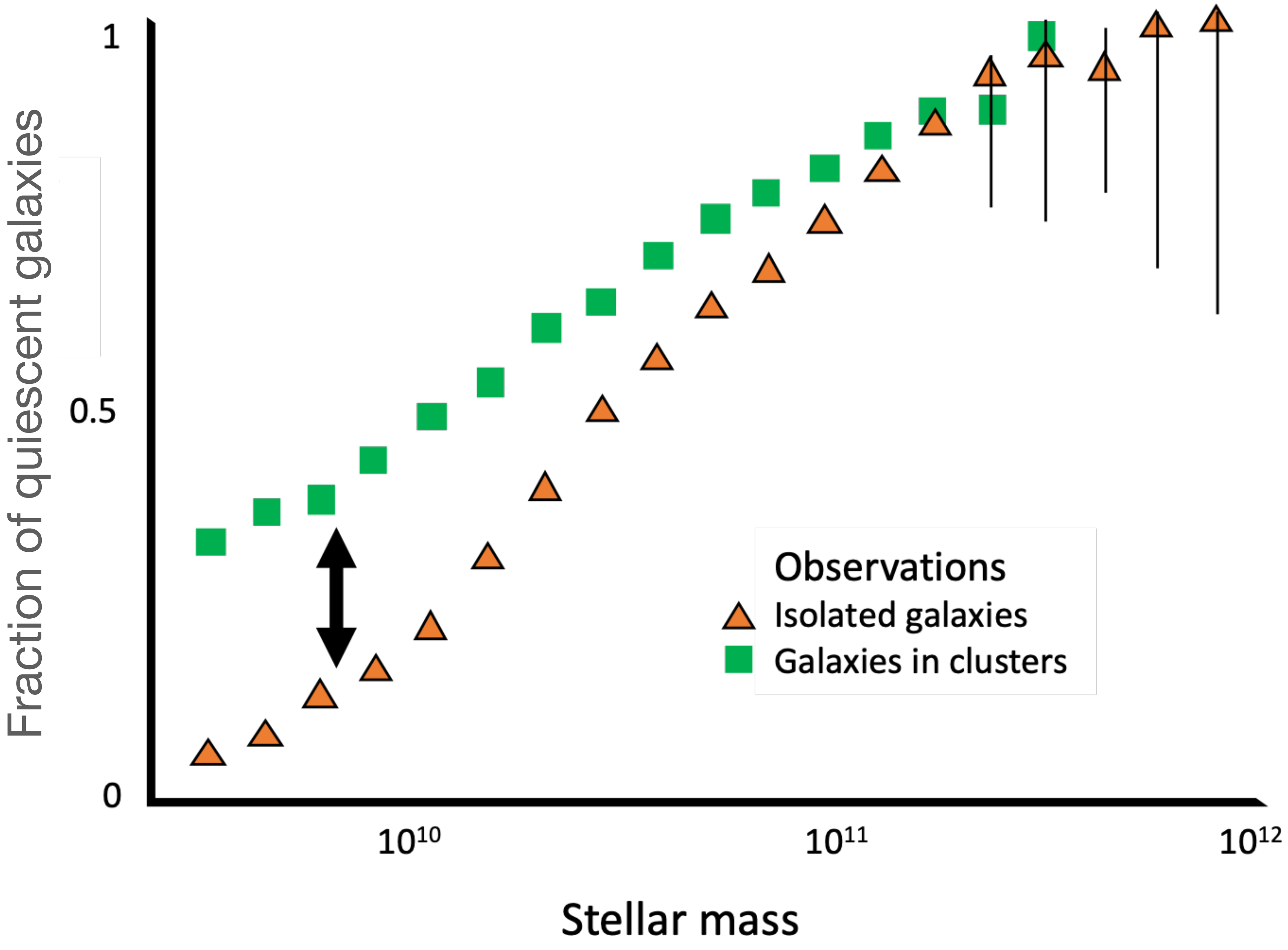
There are more of these quenched galaxies at higher stellar masses and at later times.



Adapted from Muzzin+2013, based on ULTRAVISTA photometry of the COSMOS field

Slide courtesy of Kristi Webb

Galaxies in clusters are more likely to be quenched



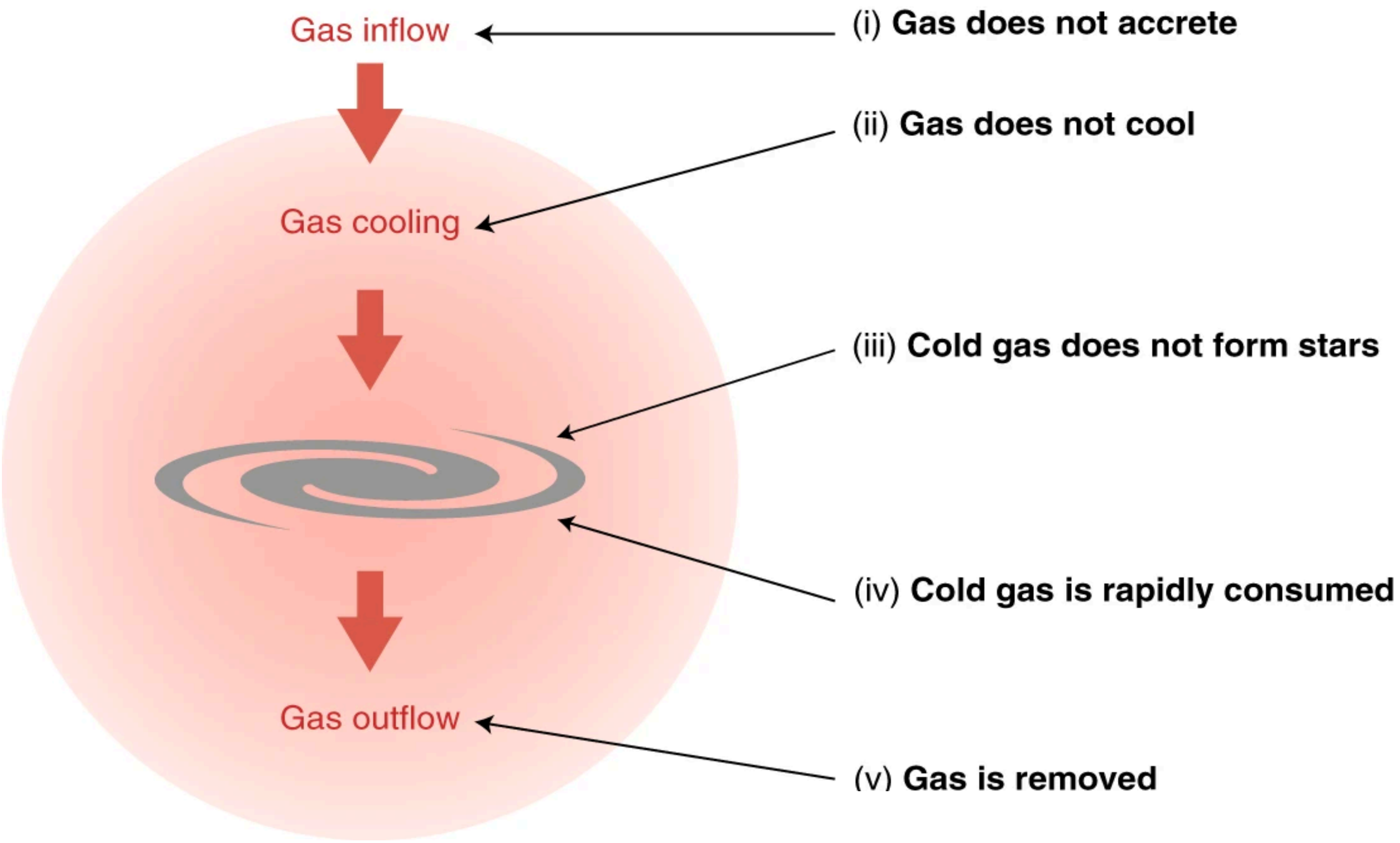
Slide courtesy of Kristi Webb

Adapted from Hirschmann+2014

Insight into galaxy evolution: What causes quenching?

Since at least redshift $z \approx 2$, the population of galaxies without significant star formation has been building up.

The physical process or processes responsible for this "quenching" of star formation are not well understood.



Gas inflow

Gas cooling

Gas outflow

(i) **Gas does not accrete**

(ii) **Gas does not cool**

(iii) **Cold gas does not form stars**

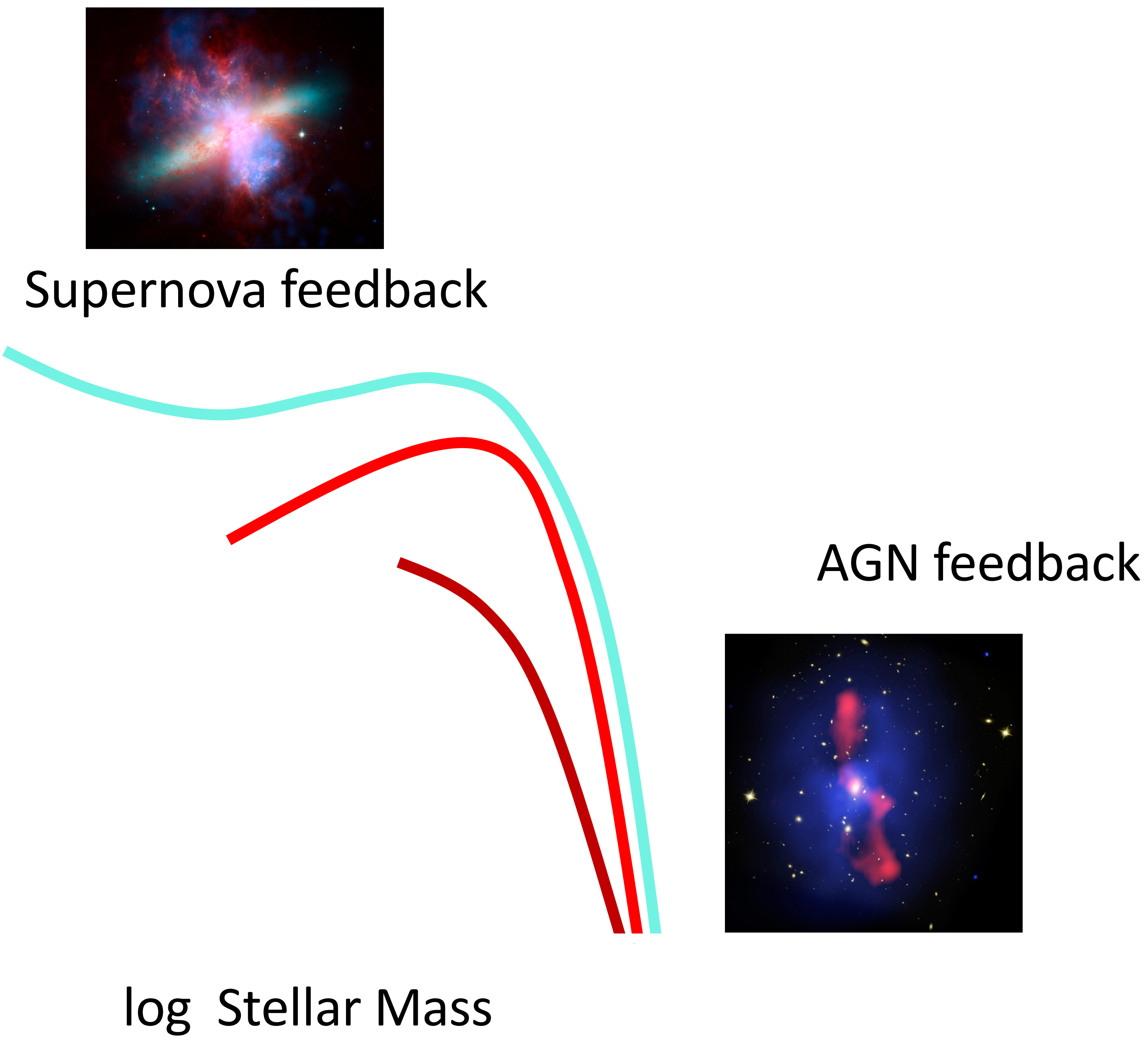
(iv) **Cold gas is rapidly consumed**

(v) **Gas is removed**

Adapted from Man+Belli 2018

Quenching: driven by feedback

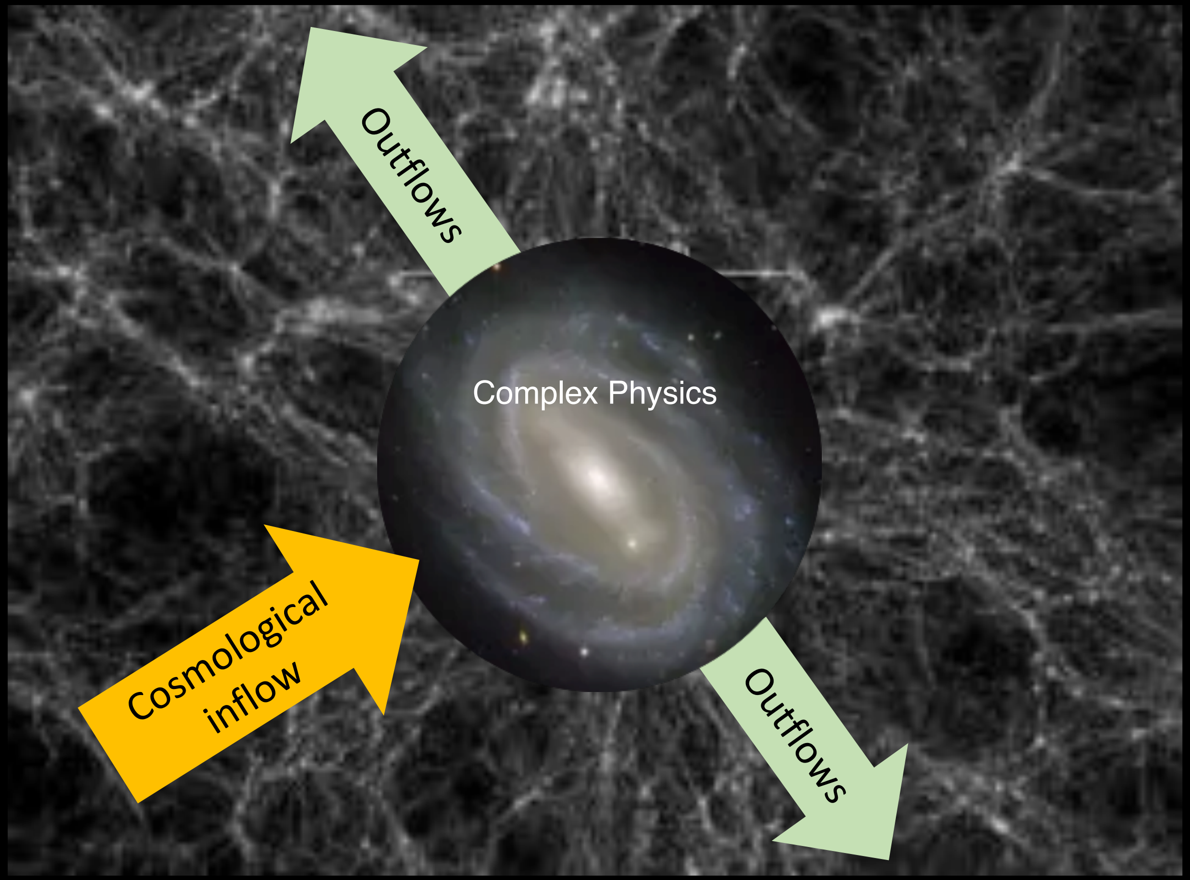
log
Number of
galaxies



Isolated Galaxies

Star formation rates are determined by a variety of processes occurring over a wide range of time and spatial scales.

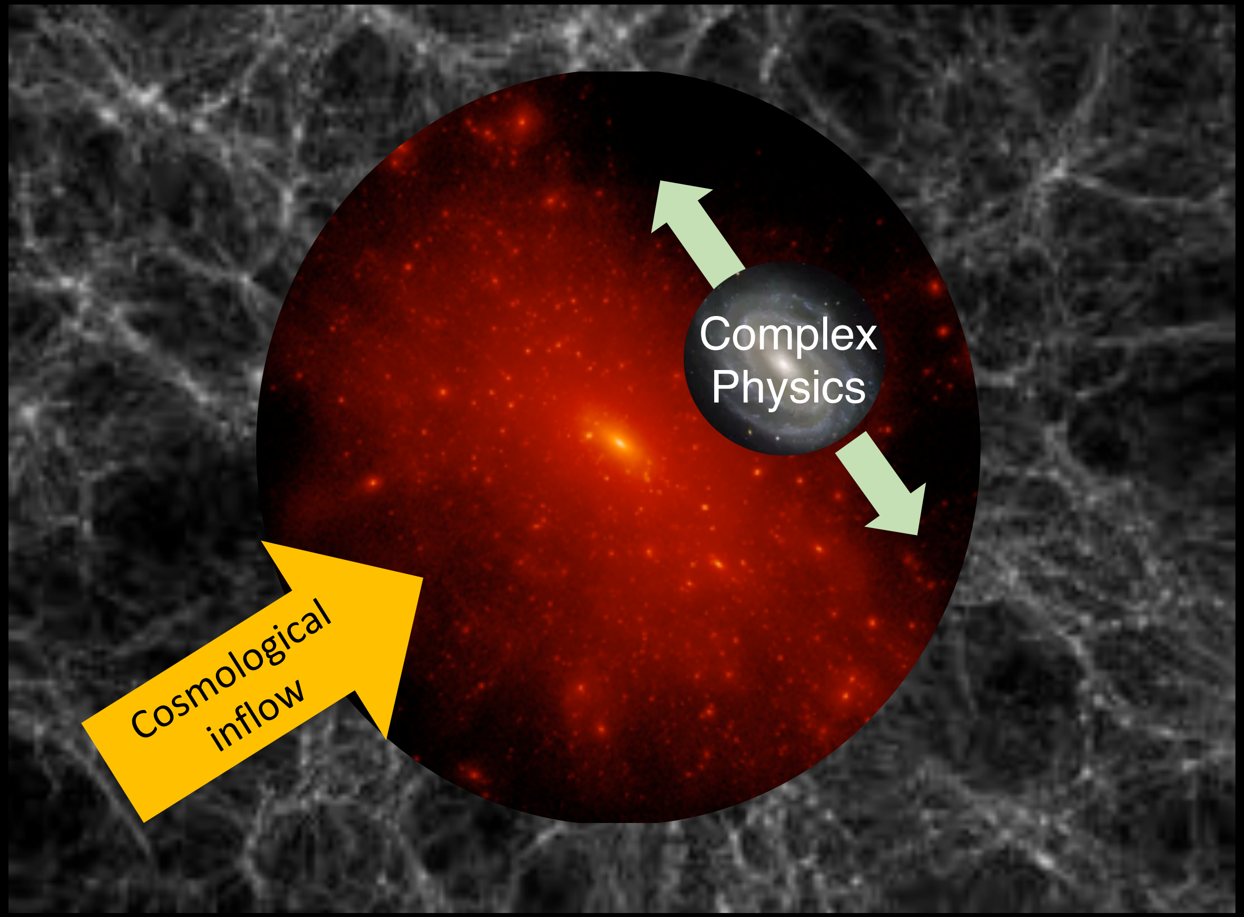
Central galaxy



Cluster Galaxies

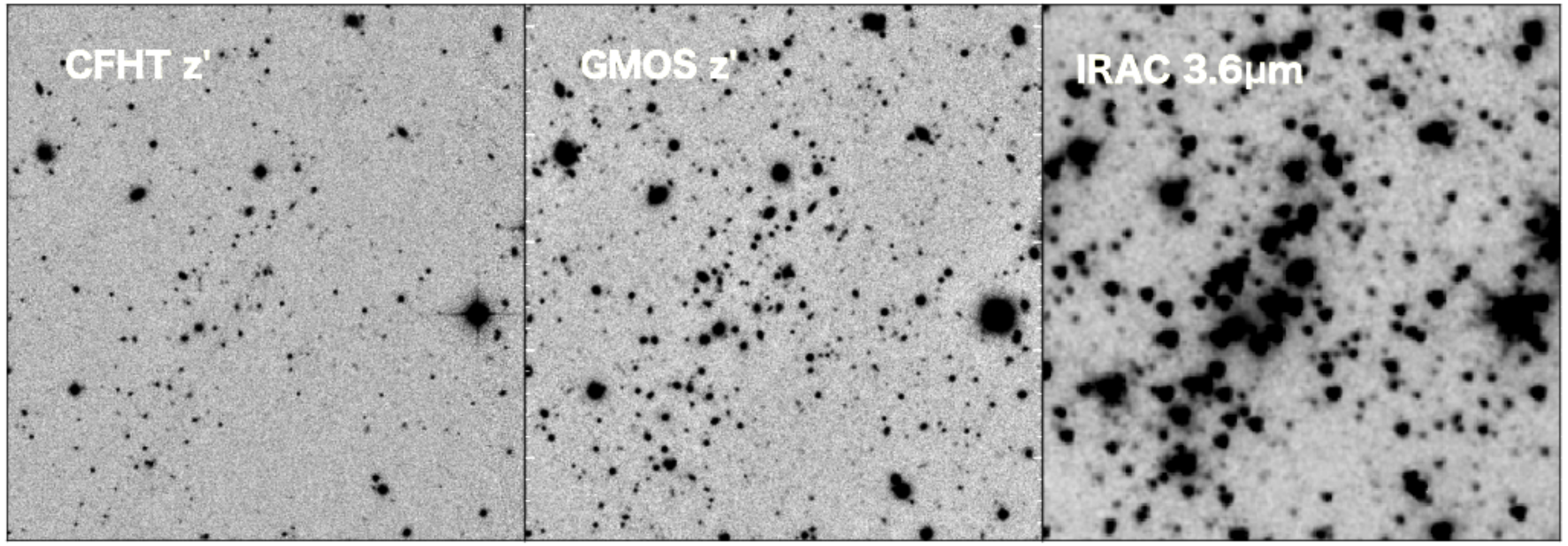
A satellite galaxy loses its source of fresh gas from cosmological accretion. Many of the other complex physical processes (e.g. SFR, feedback) are likely unaffected

Satellite galaxy

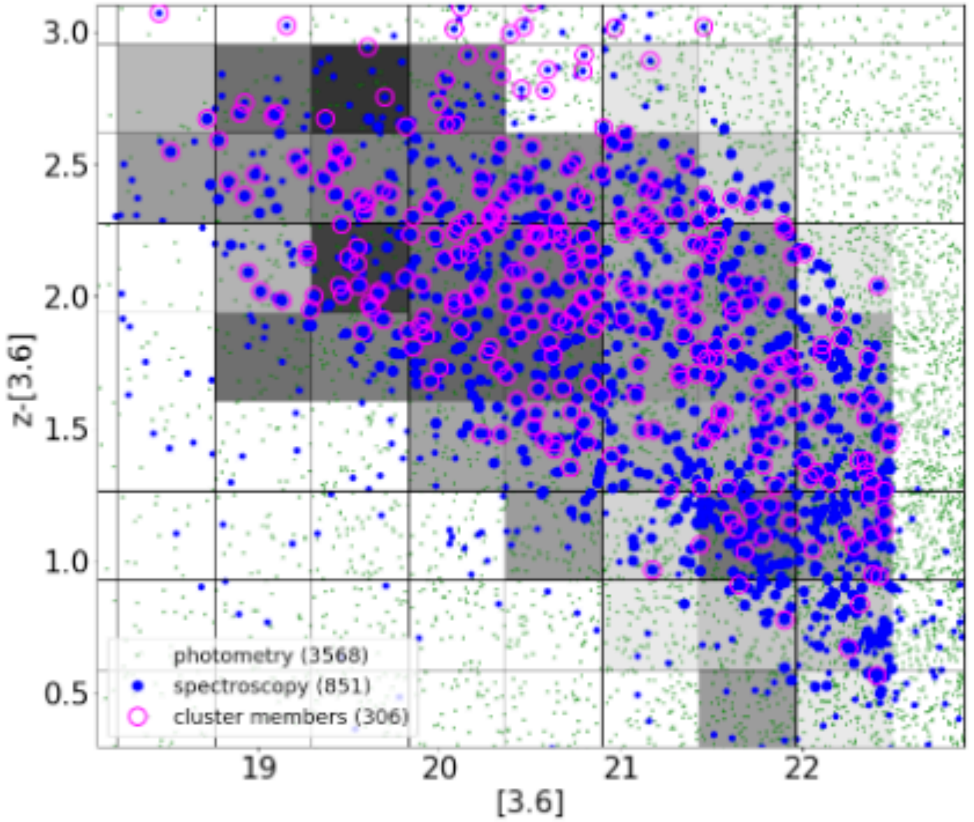


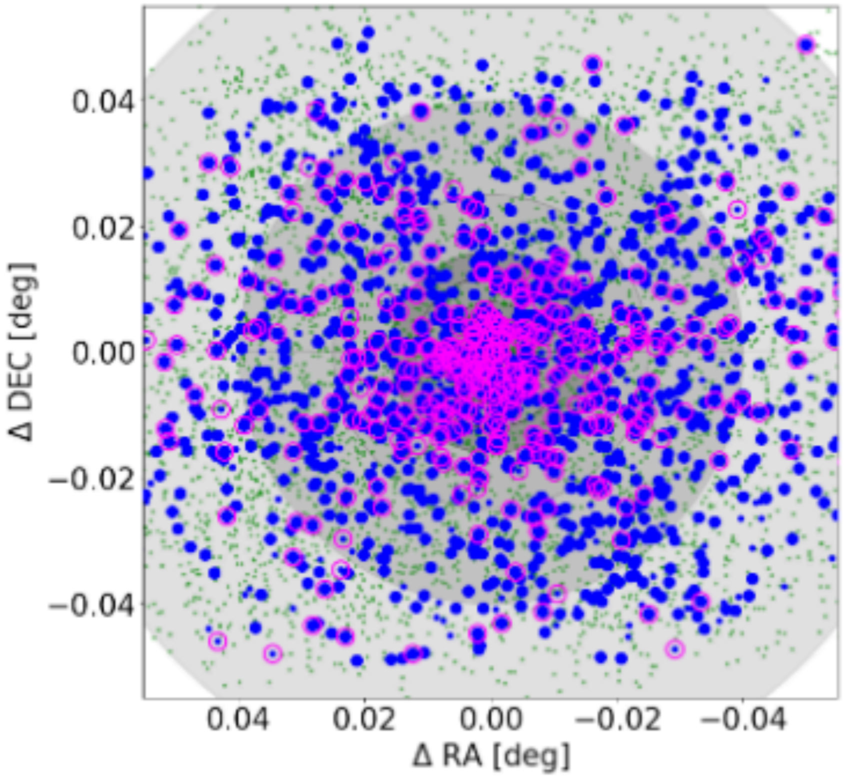
Data Quality and Completeness

Selection



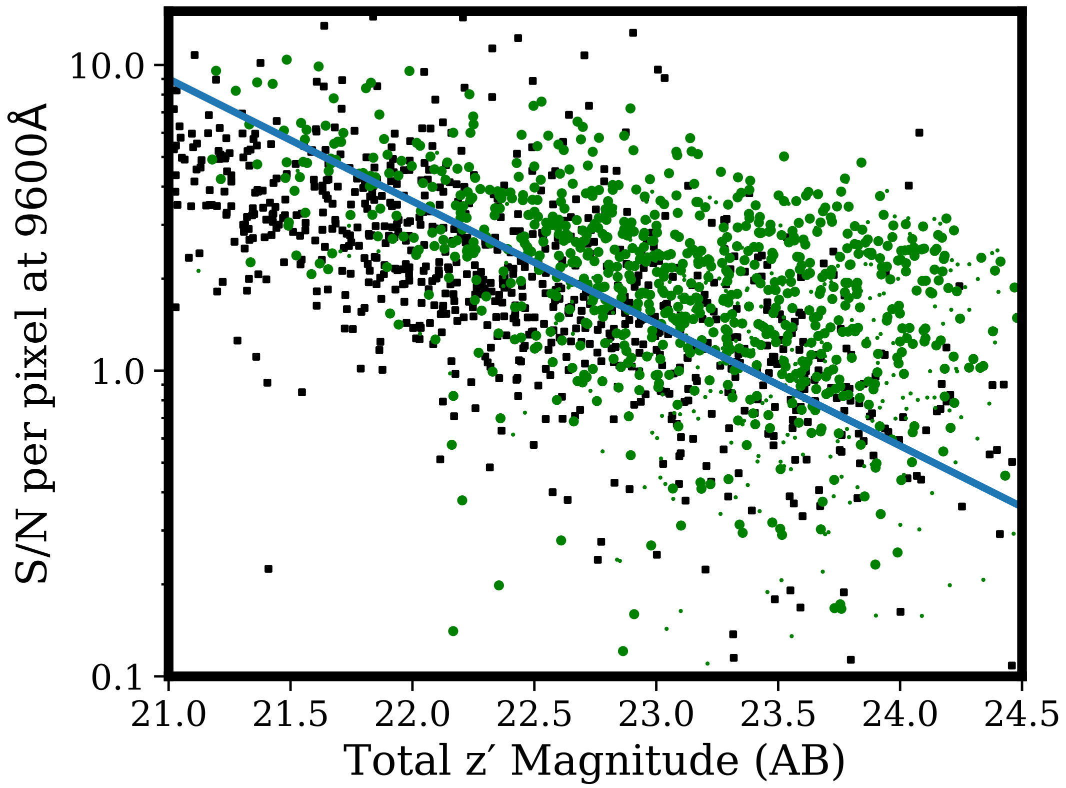
Targets selected based on z-[3.6] colour. Excellent at excluding foreground galaxies

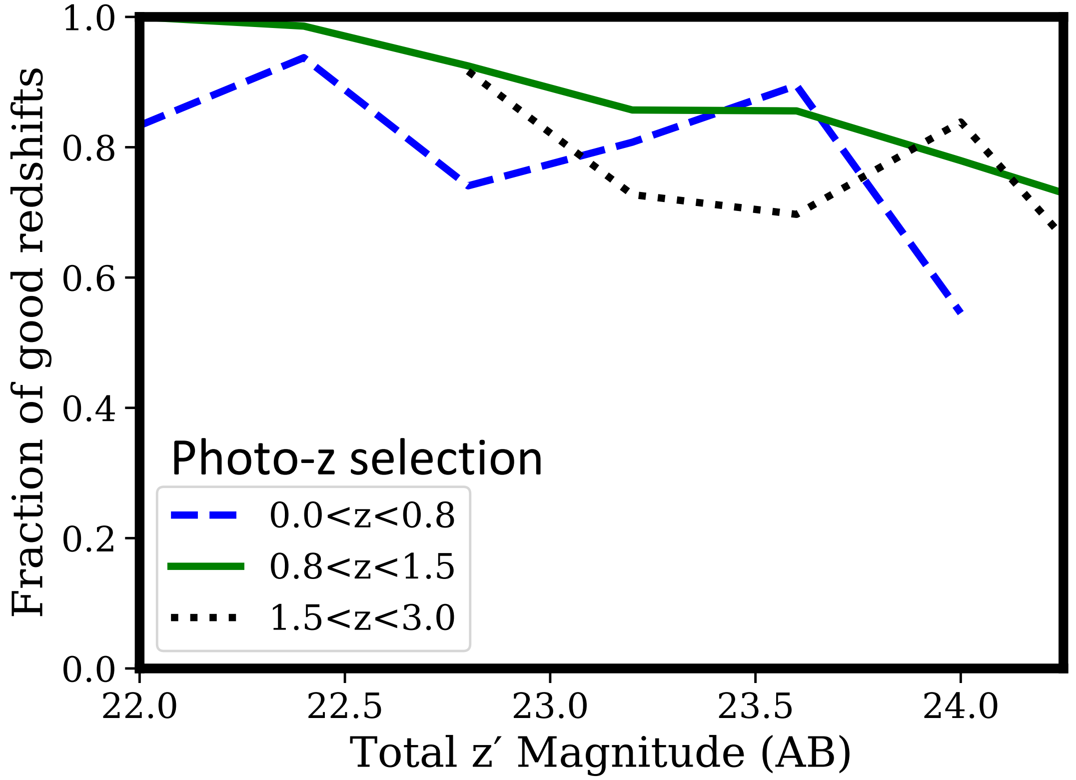




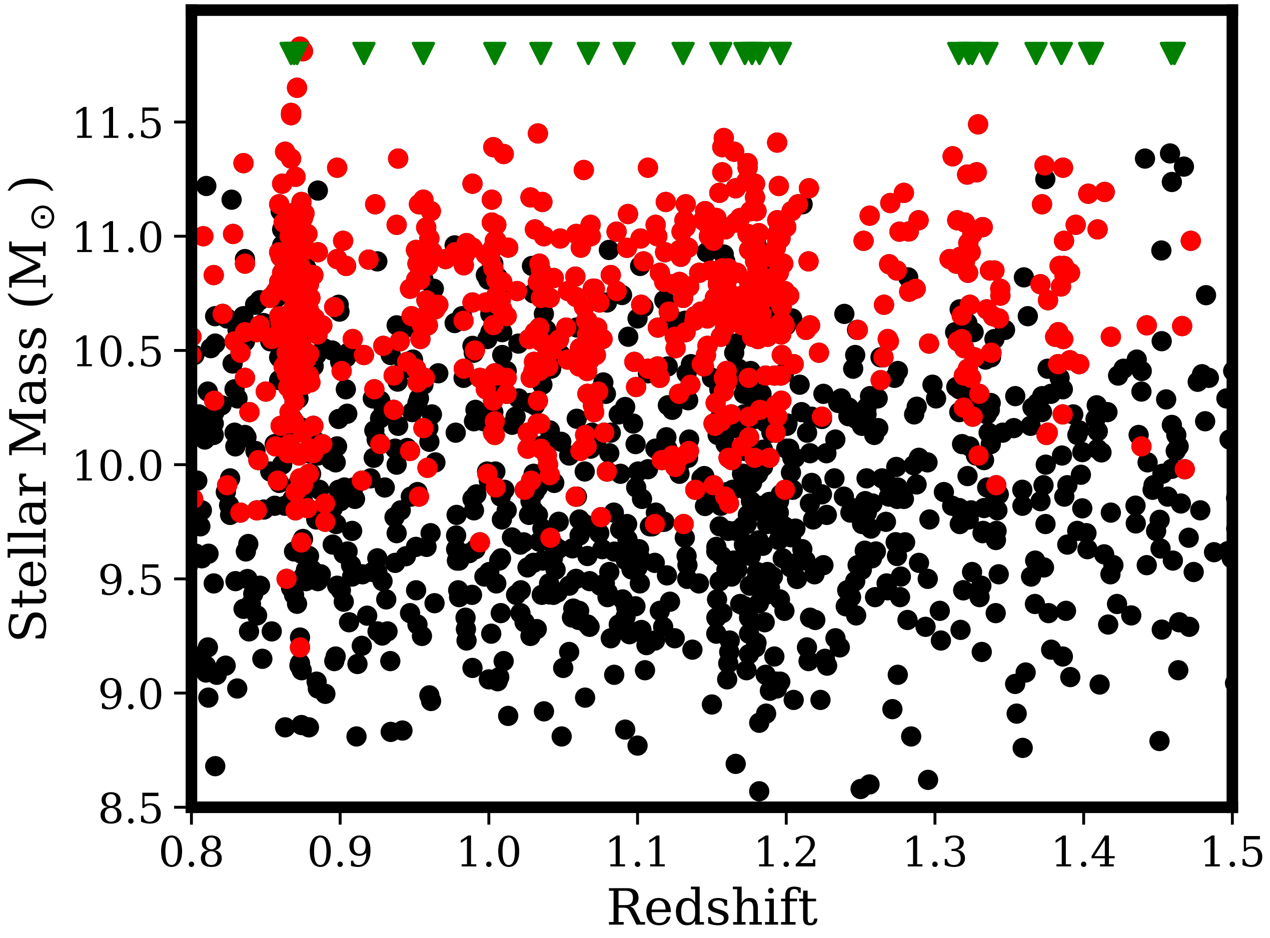
Balogh et al. (2017, 2020)

Redshifts





Faint galaxies z′>23.5 observed on multiple masks to build up exposure time



Balogh et al. (2020)