Galaxy Science with LSST

Matt Jarvis

(Oxford & UWC)

With thanks to

Nathan Adams, Rebecca Bowler & Peter Hatfield

Galaxy Science with LSST and the need for other data

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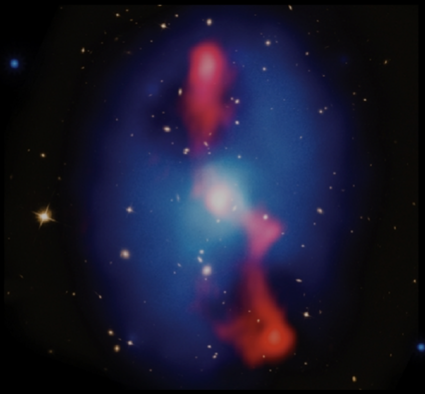
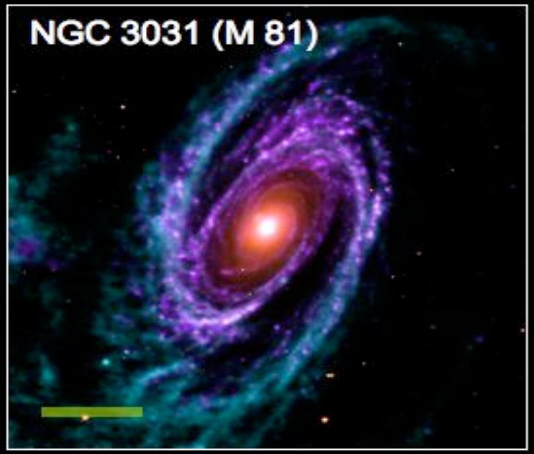
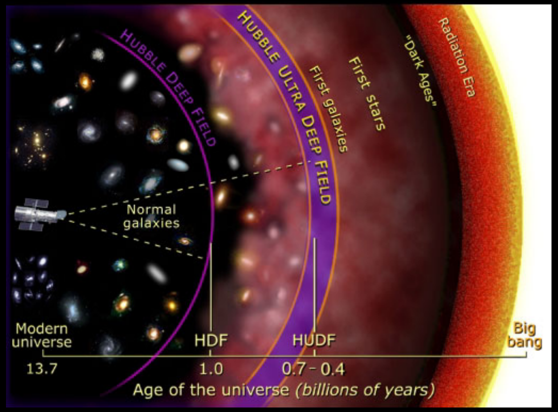
Questions in Galaxy Formation and Evolution

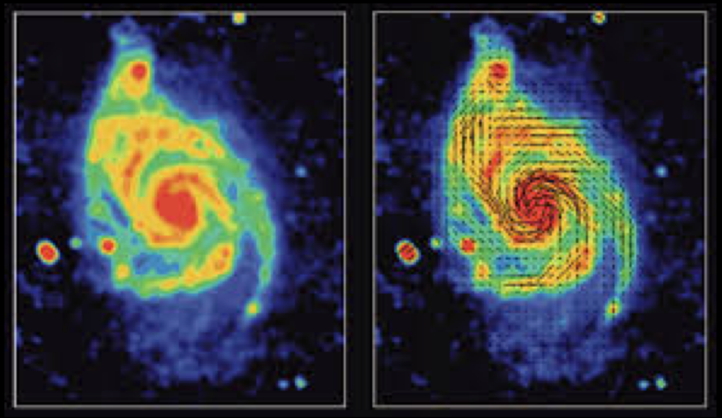
How are BHs fueled and how does accretion onto BHs affect the evolution of galaxies?





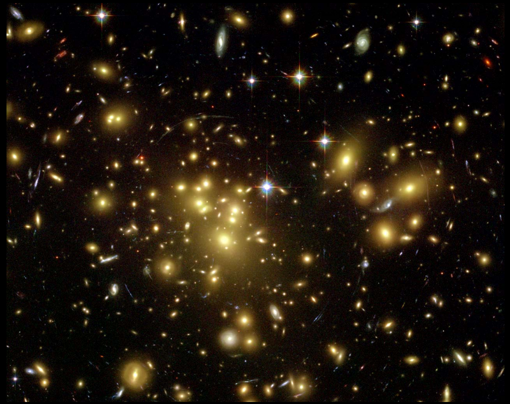
How and when were the first galaxies formed?





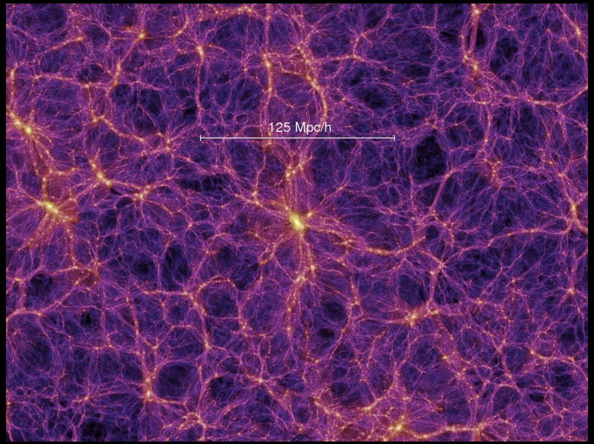
How do magnetic fields influence galaxy structure and growth

How do we go from gas to stars in galaxies?



What is the environmental influence?

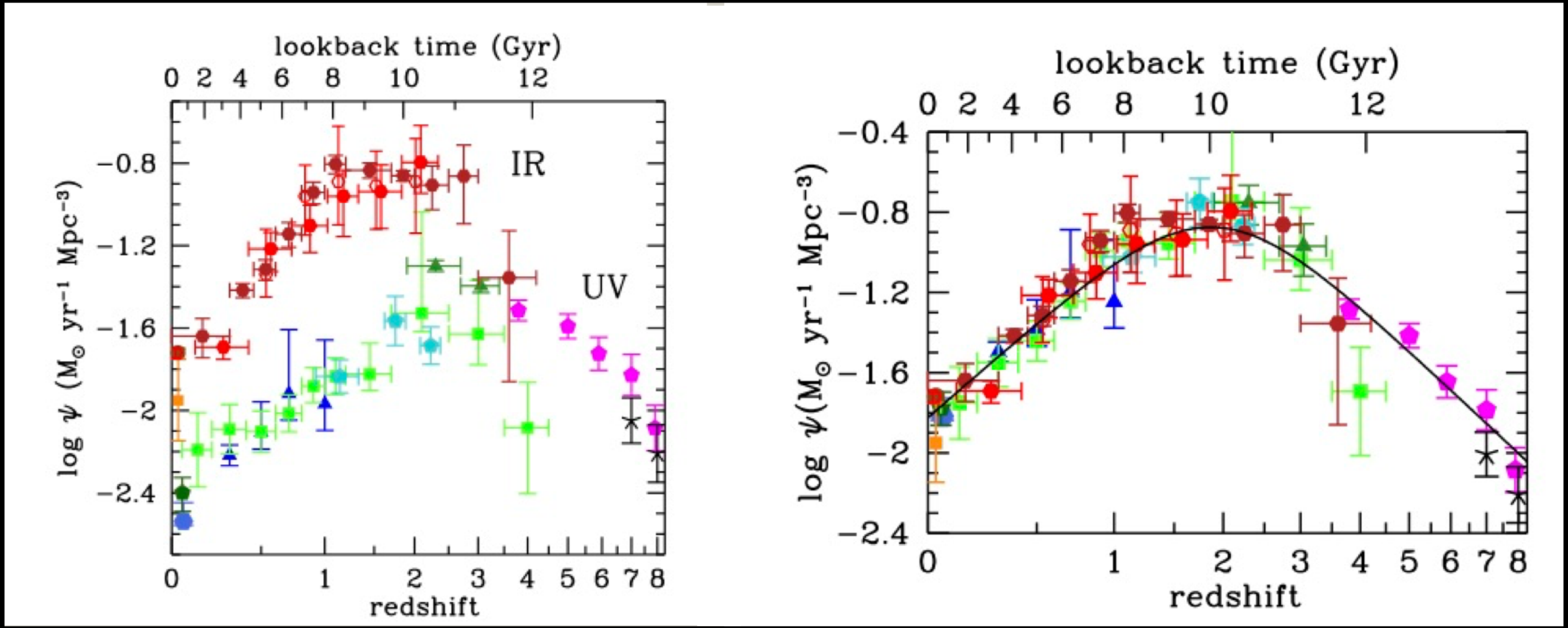
How do Baryons trace and affect the Dark Matter distribution?



The cosmic history of star formation

Dust Uncorrected

Dust Corrected

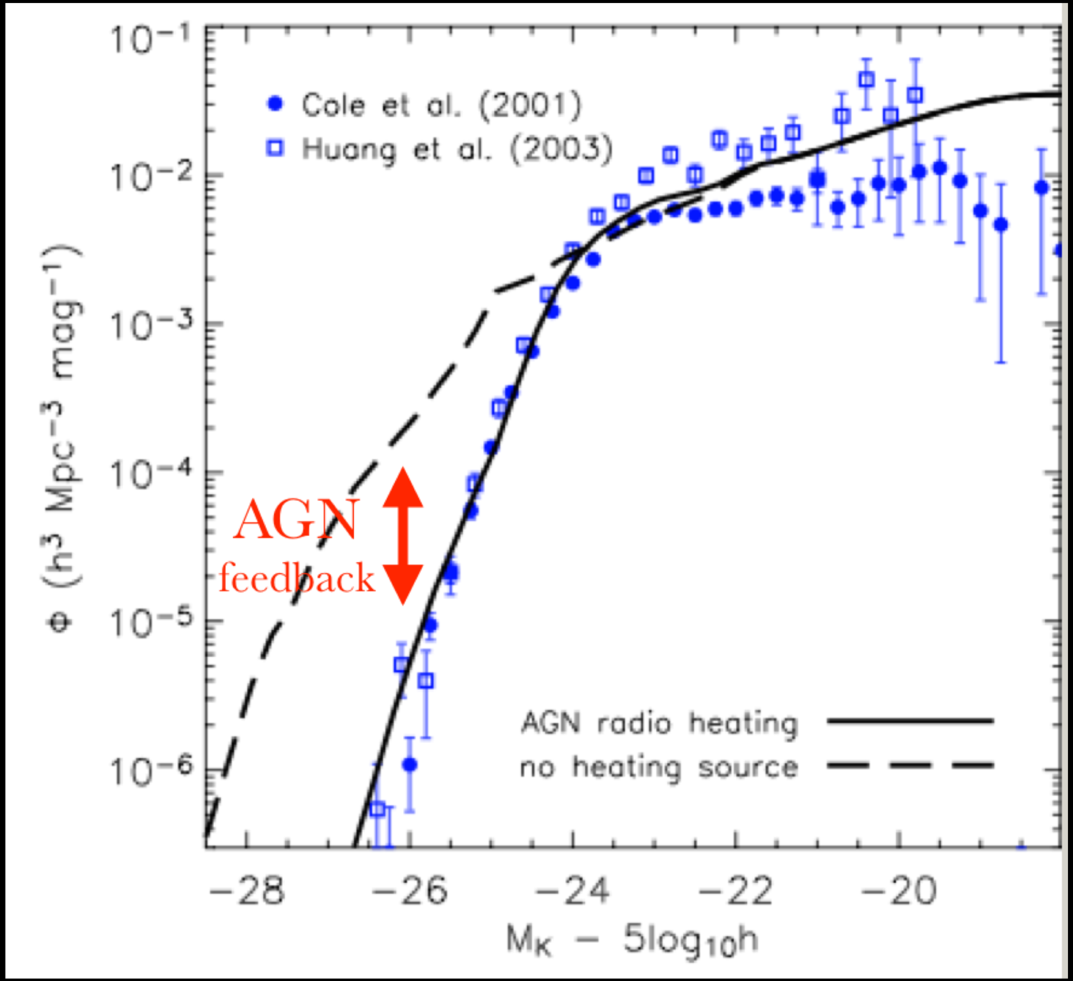


Madau & Dickinson 2014

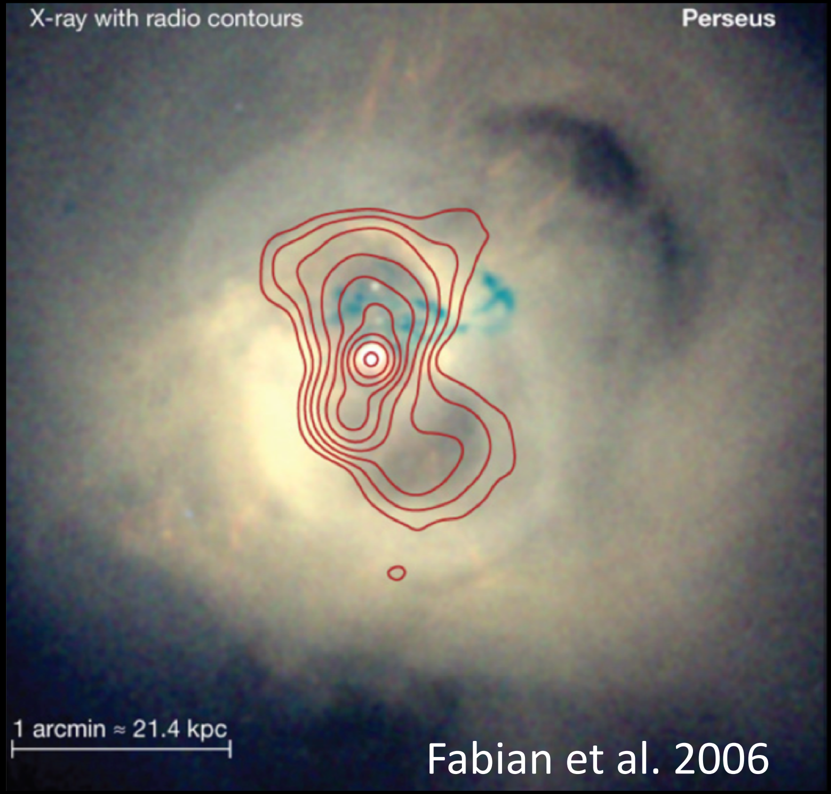
SFR density uncertain due to dust

Given this right data can do this as a function of stellar mass, halo mass and proximity to AGN

Galaxy & AGN evolution and Feedback



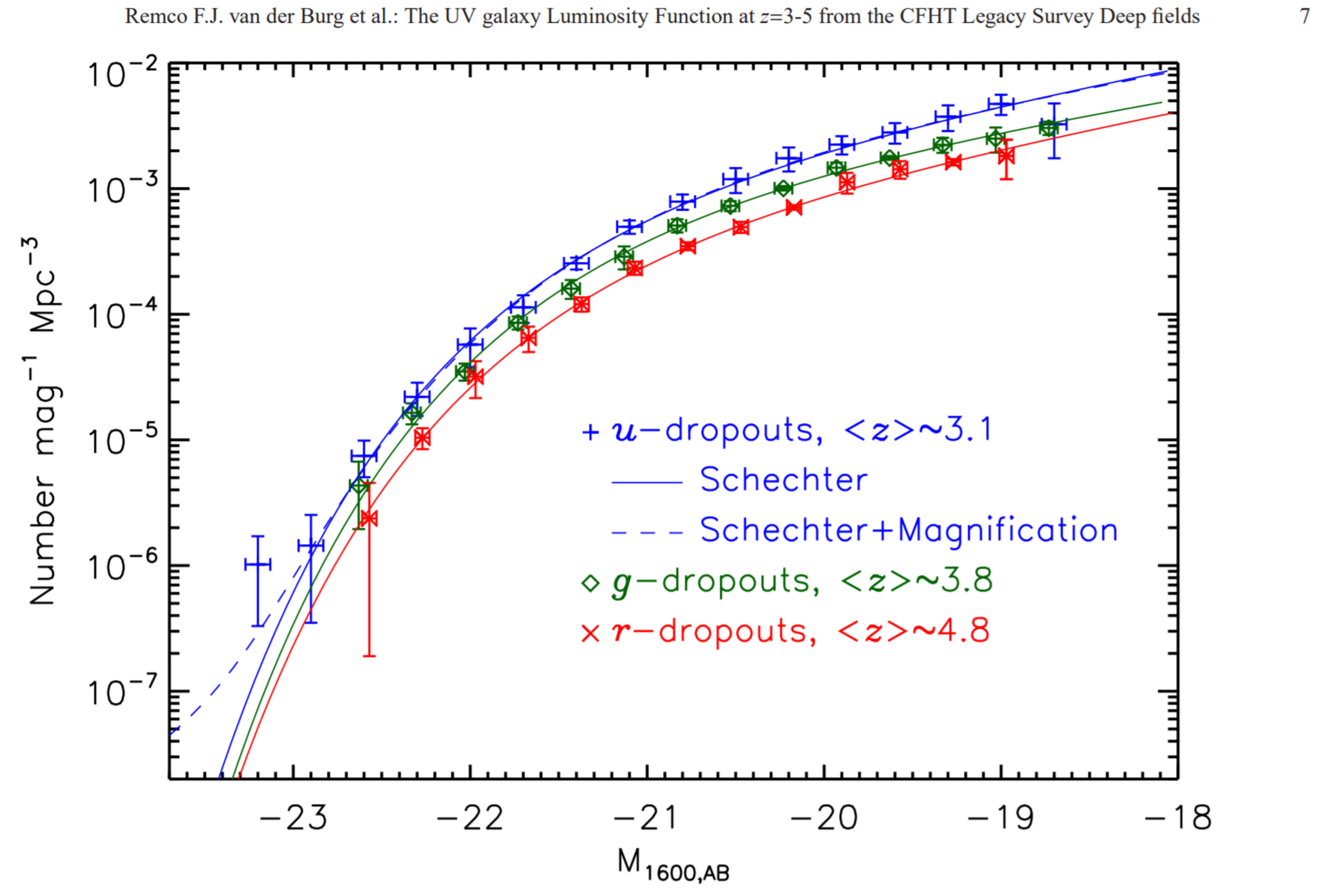
Exponential cut-off at the bright end of the luminosity function



Fabian et al. 2006

The Galaxy Luminosity Function

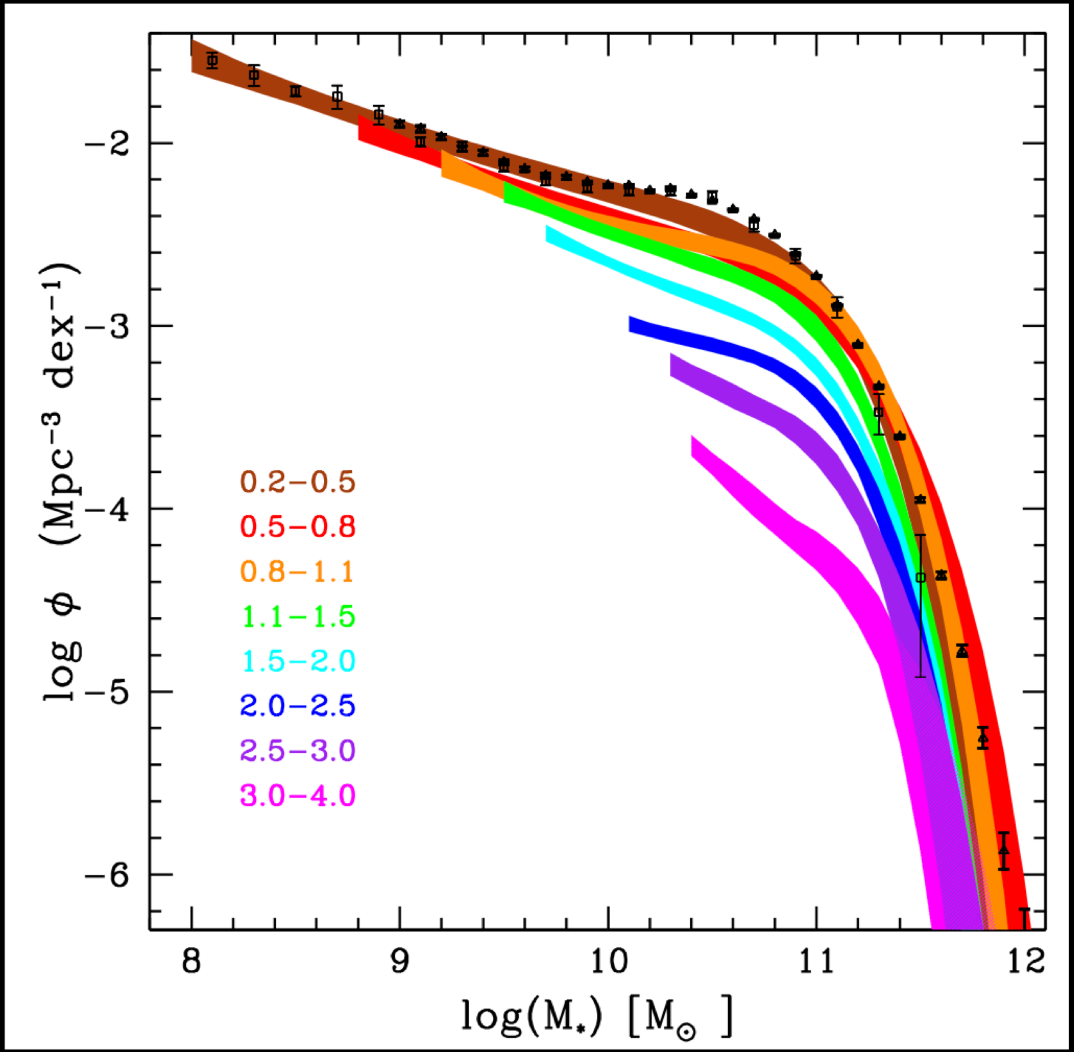
- One of simplest ways of describing a galaxy population.
- Is the volume density of galaxies as a function of luminosity.
- Evolution of bright end → Growth of massive galaxies, AGN feedback, UV ionising background.



van der Burg et al 2010

The Galaxy Luminosity -> Mass Function

- Can also determine the mass function
- But need to ensure you are sampling wavelengths where the bulk of the stellar mass is emitting
- At z>1.5 LSST is not enough



Ilbert et al. 2013

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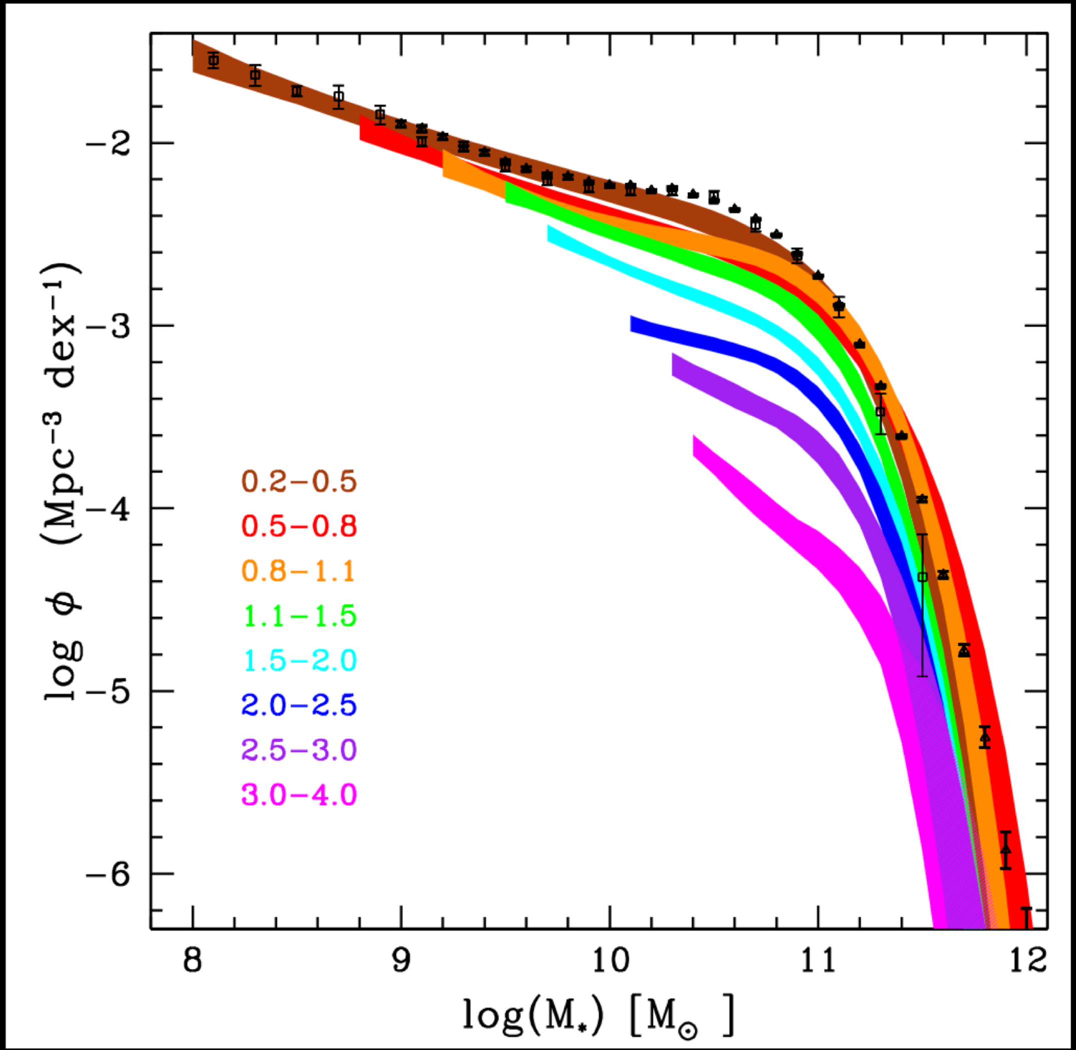


Need redshifts, absolute magnitudes (therefore k-corrections) and if we want the mass function we also need to probe bulk of the stellar mass

Ilbert et al. 2013

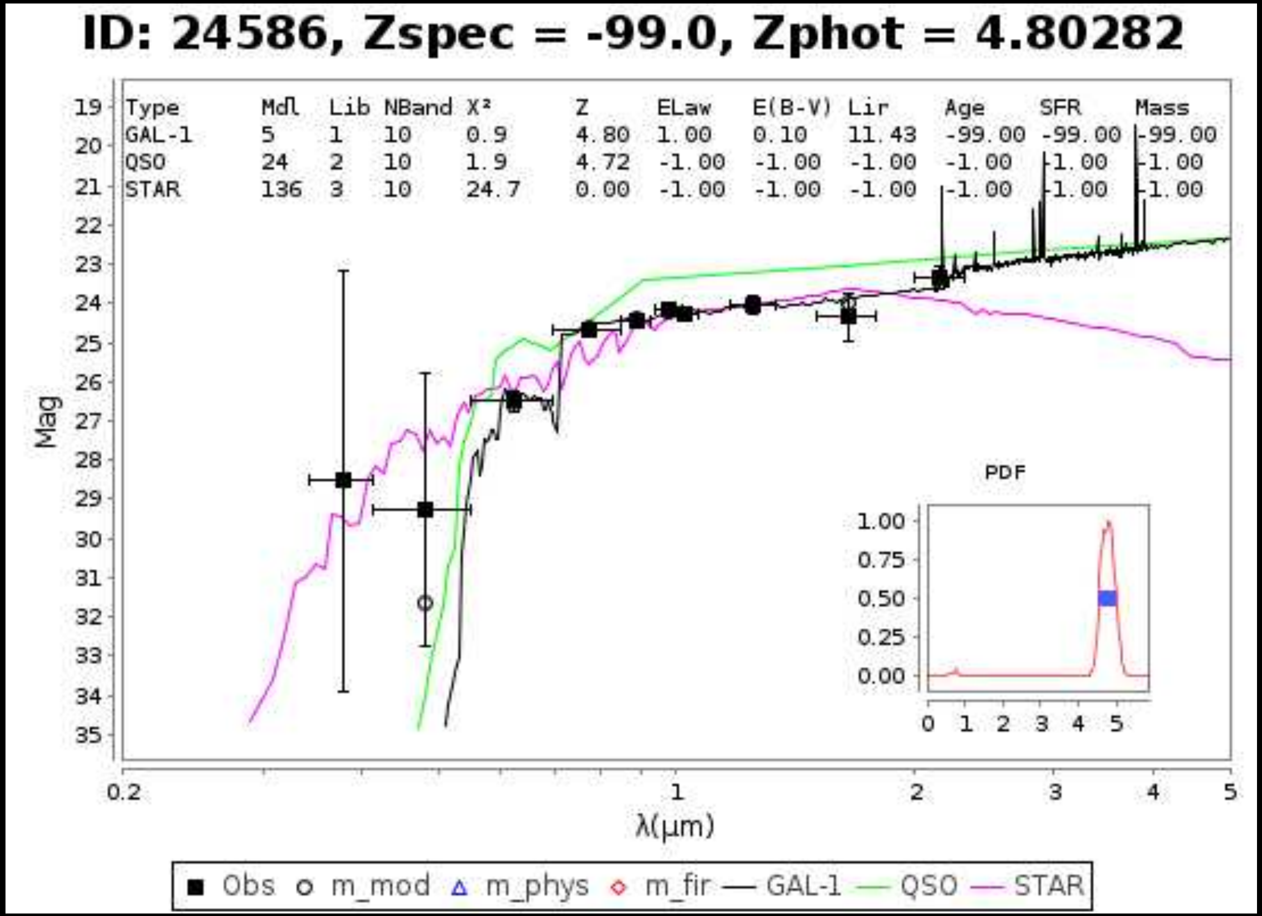
Photometric Redshifts

- Estimates of redshift & basic galaxy properties
- Performed by fitting Spectral Energy Distributions to photometry.
- Requires: Photometry, SED Template Set, Filter Transparency.

- **SED Templates:**
- 1) Bruzual & Charlot 2003 / GALAXEV (Simulations)
- 2) Brown et al 2013 (Observations)

Photometric Redshifts: Template fitting

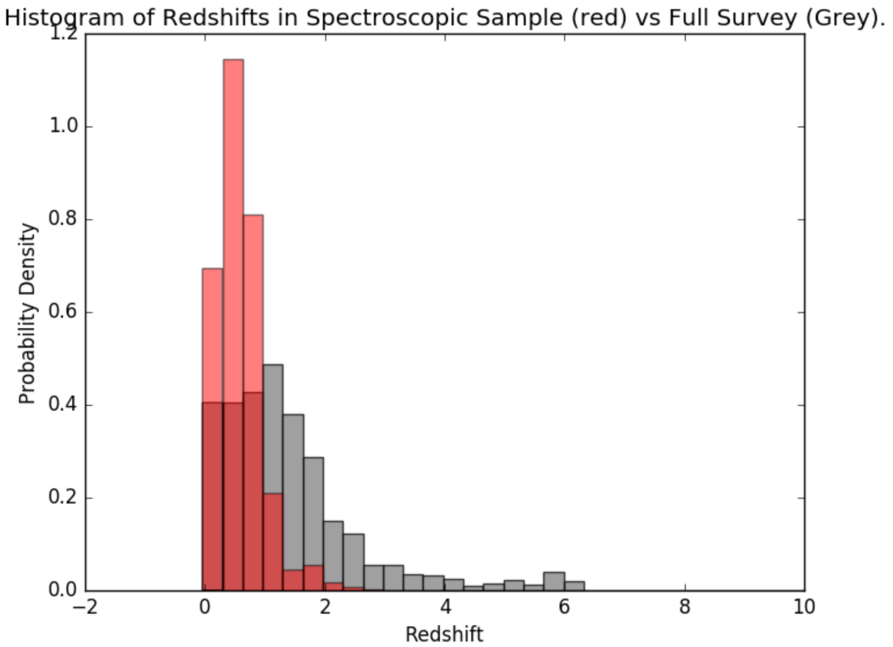
- Many variables & priors to control.
- Flexible template sets, extinction models etc.
- Checks for Stars and QSO's.

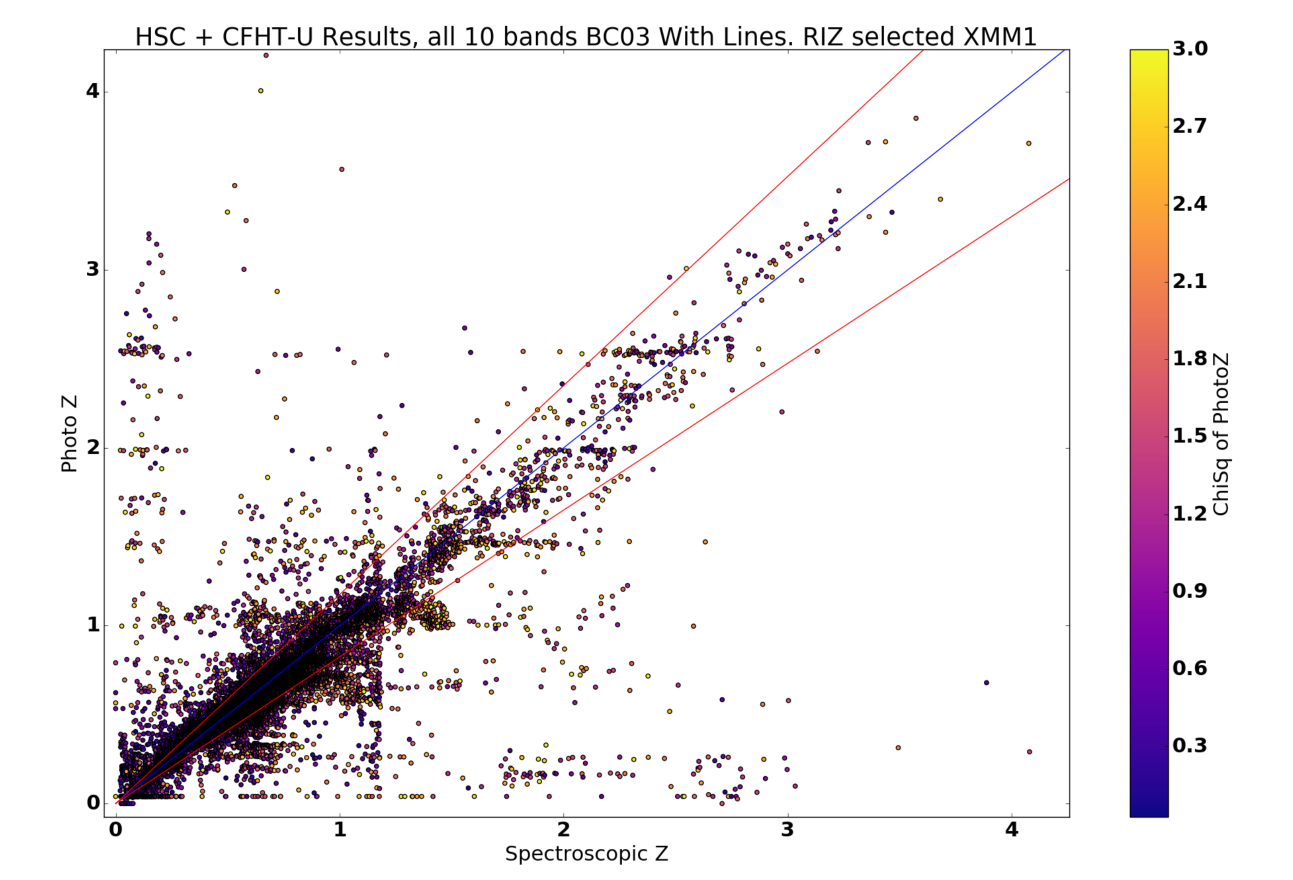


Photometric Redshifts

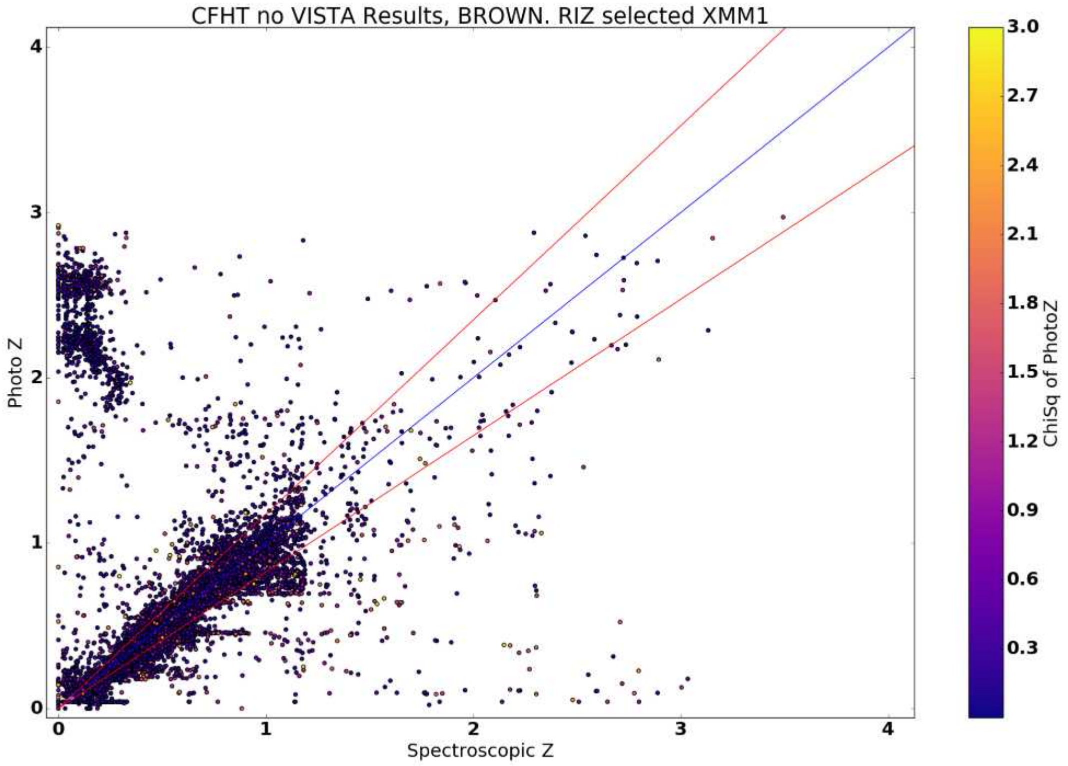
Example

- ~20,000 galaxies with Spec-zs
- 93% success rate
- Success: (1+z) estimate within 15%

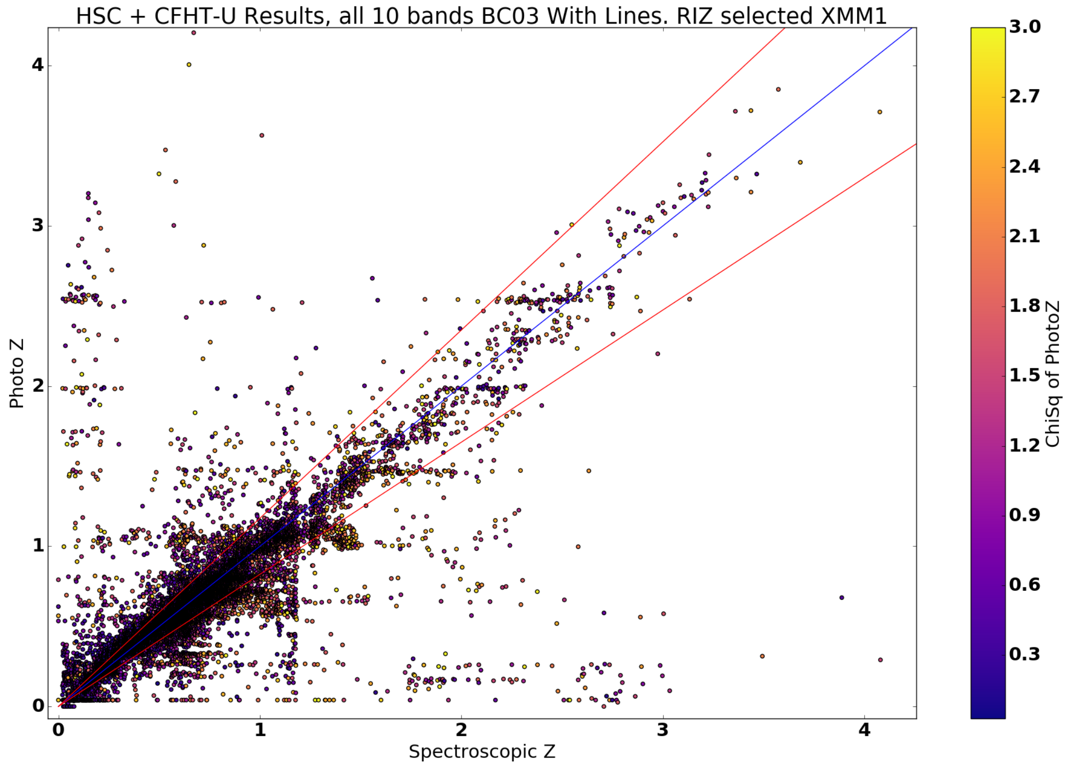




Why near-infrared is needed

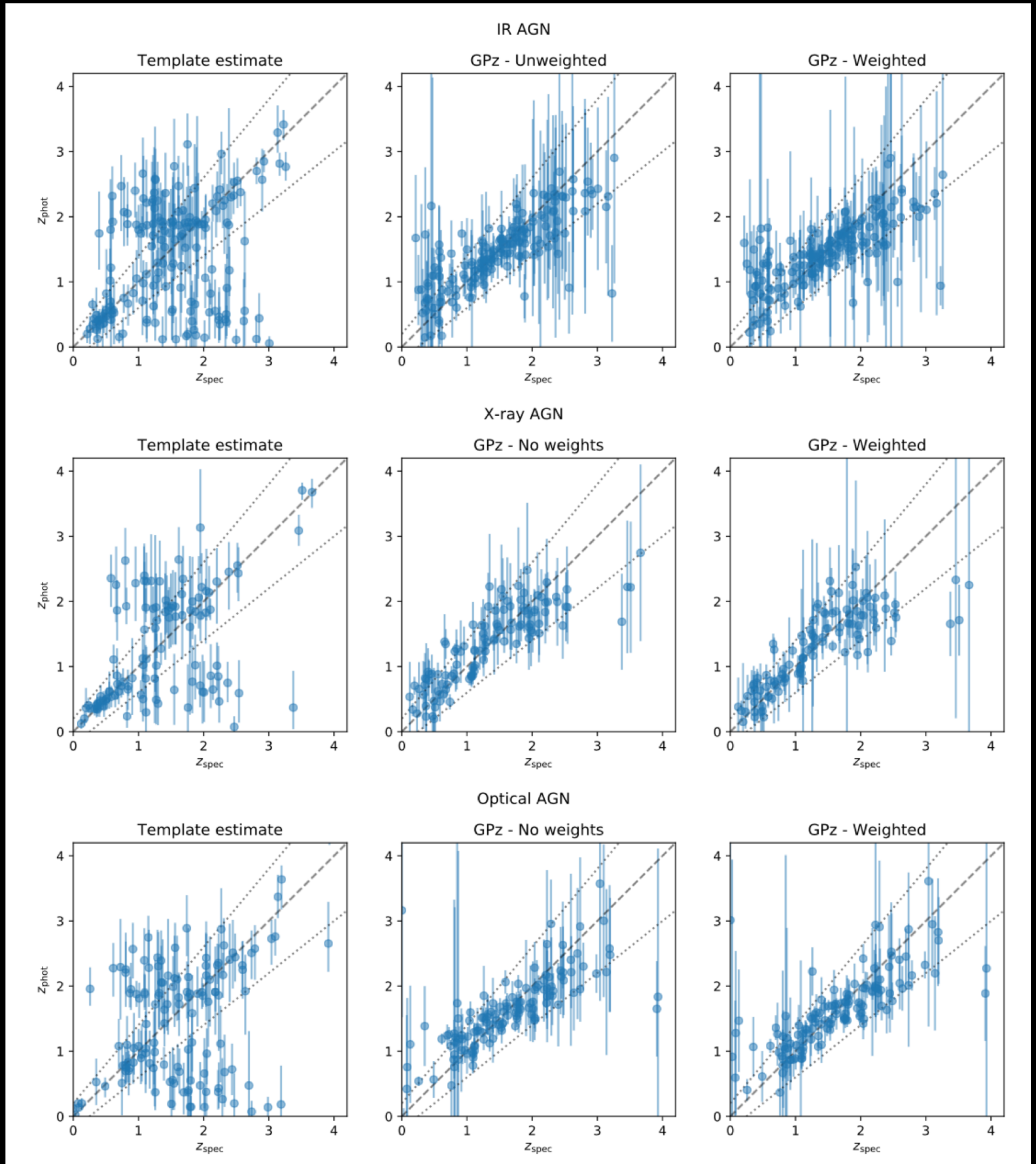


Only visible CFHT data,
85% success



Using CFHT & HSC & VISTA,
93% success

Photo-z testing on radio surveys (mainly AGN)



Duncan, Jarvis, Brown & Rottgering 2018

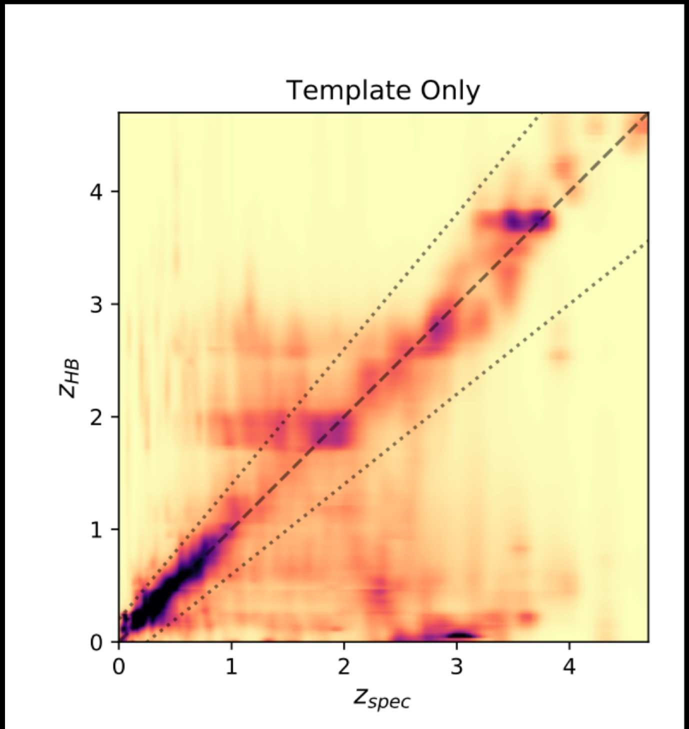
For GPz see

Almosallam et al. 2016a,b

Gomes, Jarvis, Almosallam & Roberts 2018

https://github.com/OxfordML/GPz

Photo-z testing on radio surveys (mainly AGN)



Duncan, Jarvis, Brown & Rottgering 2018

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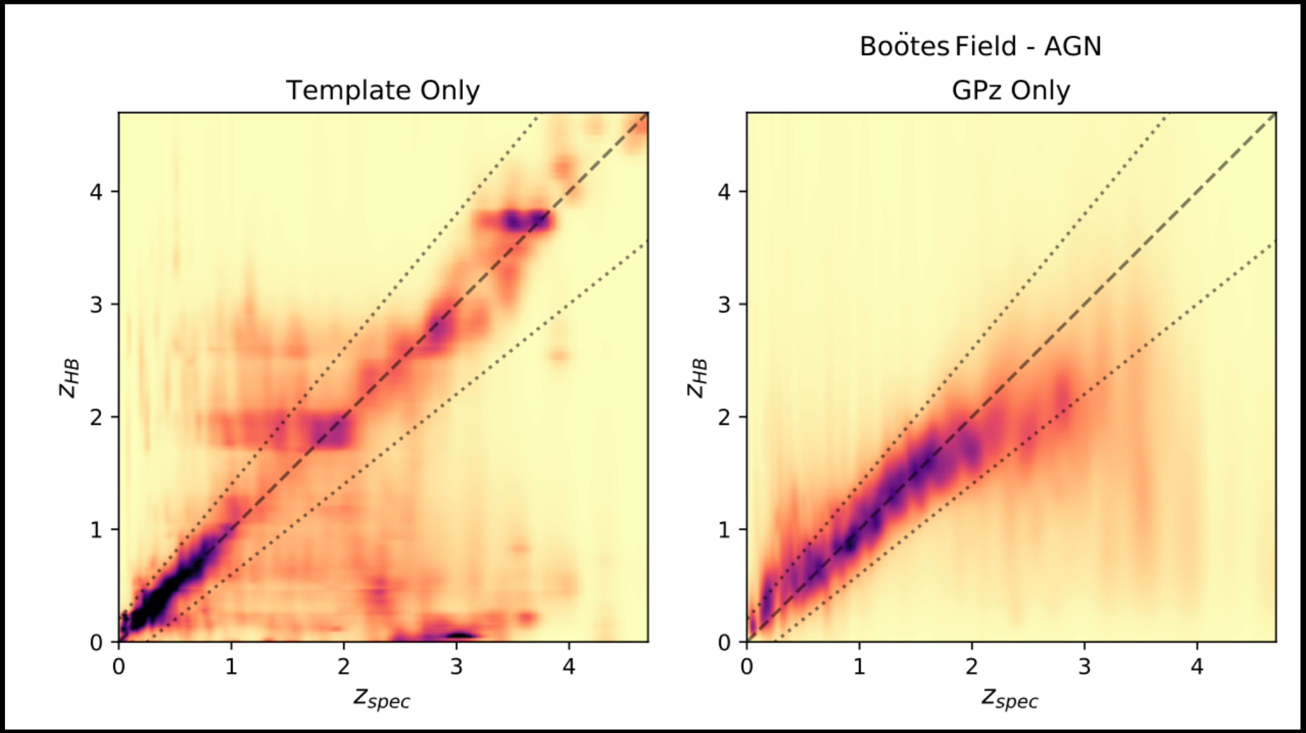
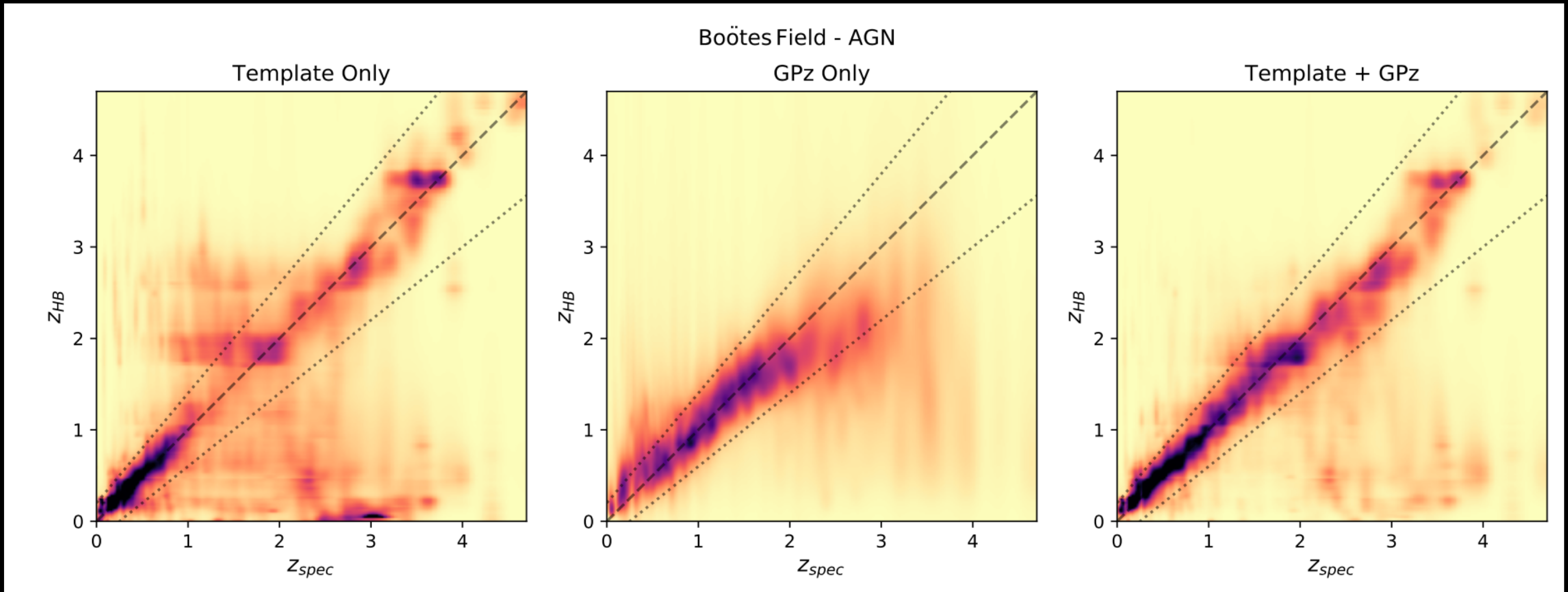


Duncan, Jarvis, Brown & Rottgering 2018

Photo-z testing on radio surveys (mainly AGN)



Duncan, Jarvis, Brown & Rottgering 2018

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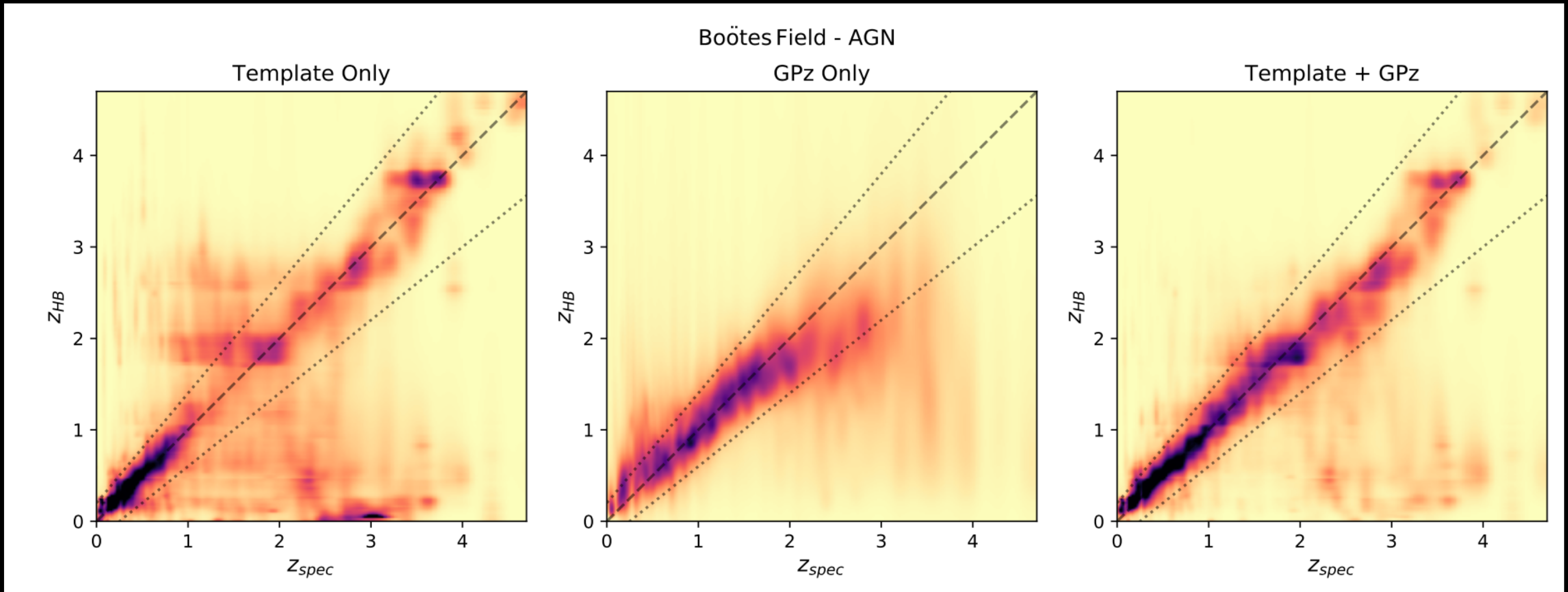
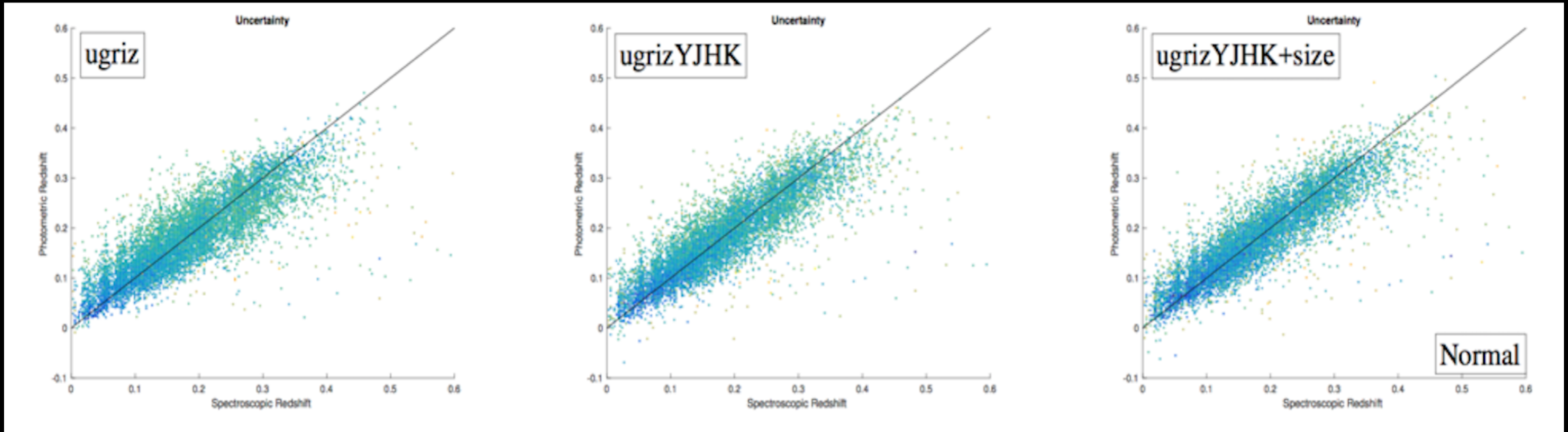


Duncan, Jarvis, Brown & Rottgering 2018

Further development of GPz and the template suite will continue to improve this

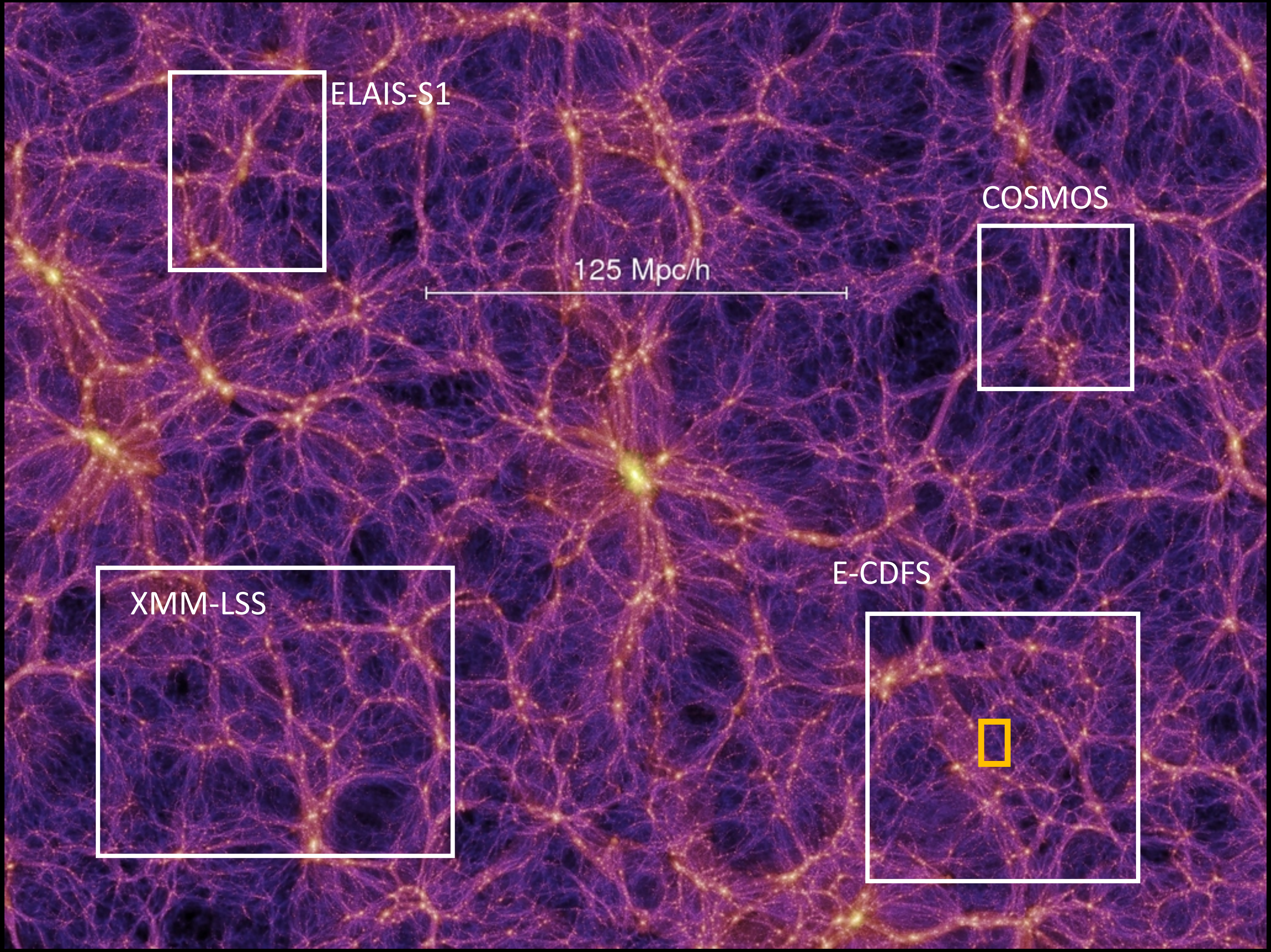
Why stop at colour information?



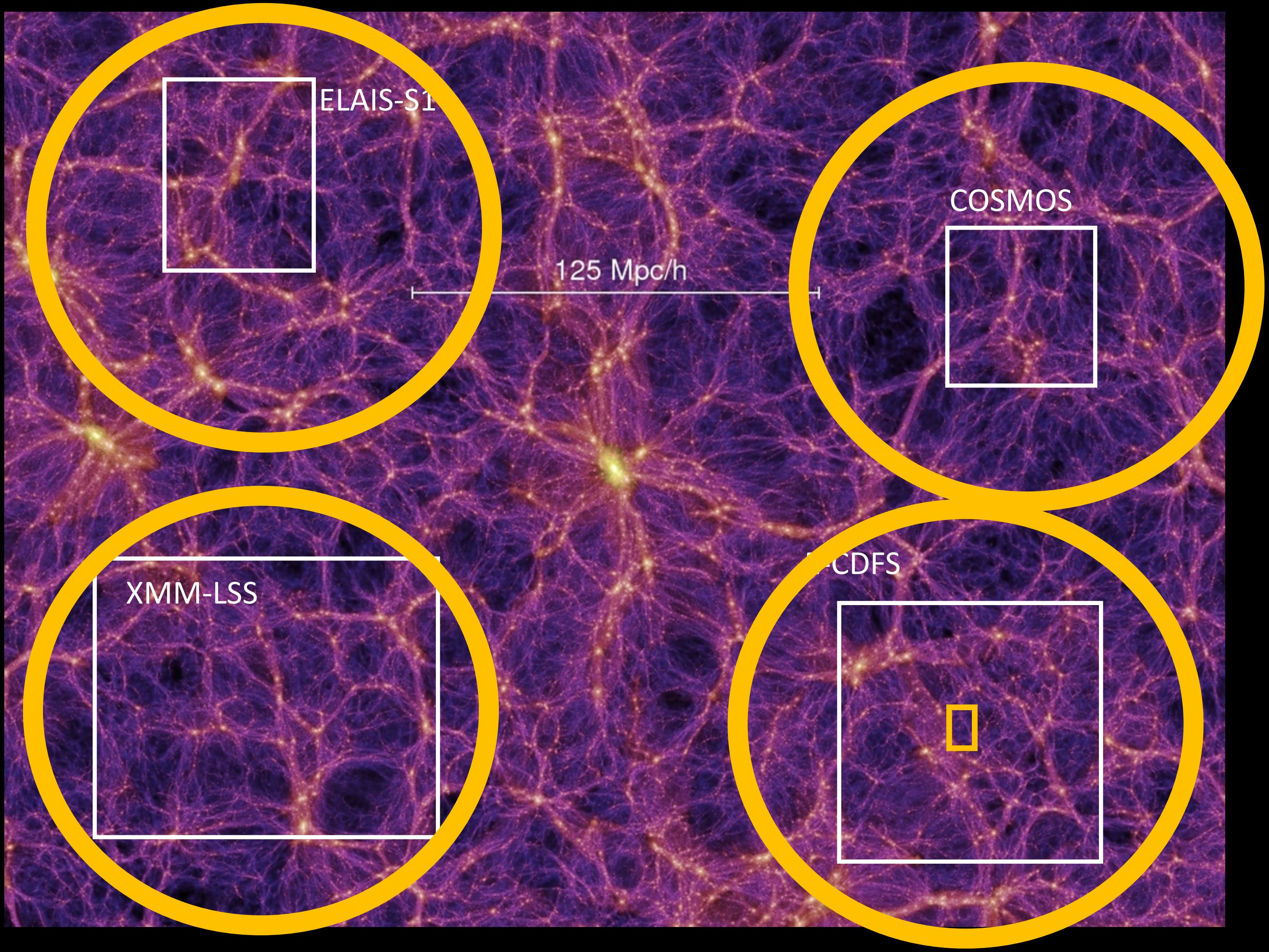
CSL Method	Filters	RMSE	NBIAS	MLL	$FR_{0.15}$	$FR_{0.05}$	Variance	Model Variance	Noise Variance
Normal	ugriz	0.0478	-0.0027	1.7714	99.1941	84.7809	0.0023	6.90E-06	0.0023
	ugrizYJHK	0.0438	-0.0024	1.8075	99.4523	87.7778	0.0018	6.80E-06	0.00184
	ugrizYJHK+size	0.042	-0.0024	**1.8792**	99.4366	89.1471	0.0018	7.20E-06	0.00180
Normalized	ugriz	0.0476	0.0001	1.7115	99.2958	84.8279	0.0015	6.68E-06	0.0015
	ugrizYJHK	0.0443	0.0001	1.7893	99.4366	87.8091	0.0013	6.99E-06	0.0013
	ugrizYJHK+size	**0.0418**	-0.0001	1.8188	**99.507**	**89.6401**	**0.0011**	**6.06E-06**	**0.0011**

Gomes, Jarvis, Almosallam & Roberts 2018.

Multi-wavelength survey strategy

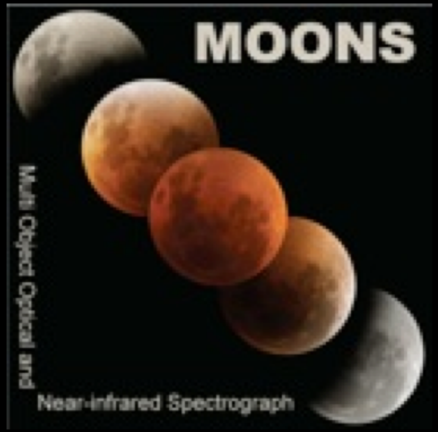


Multi-wavelength survey strategy



Multi-wavelength coverage of the Deep Drilling fields

LSST, DES, HSC,
CFHTLS, VST-VOICE



UltraVISTA+VIDEO,
VEILS

JWST/Euclid/WFIRST

HerMES/H-GOODS

4MOST

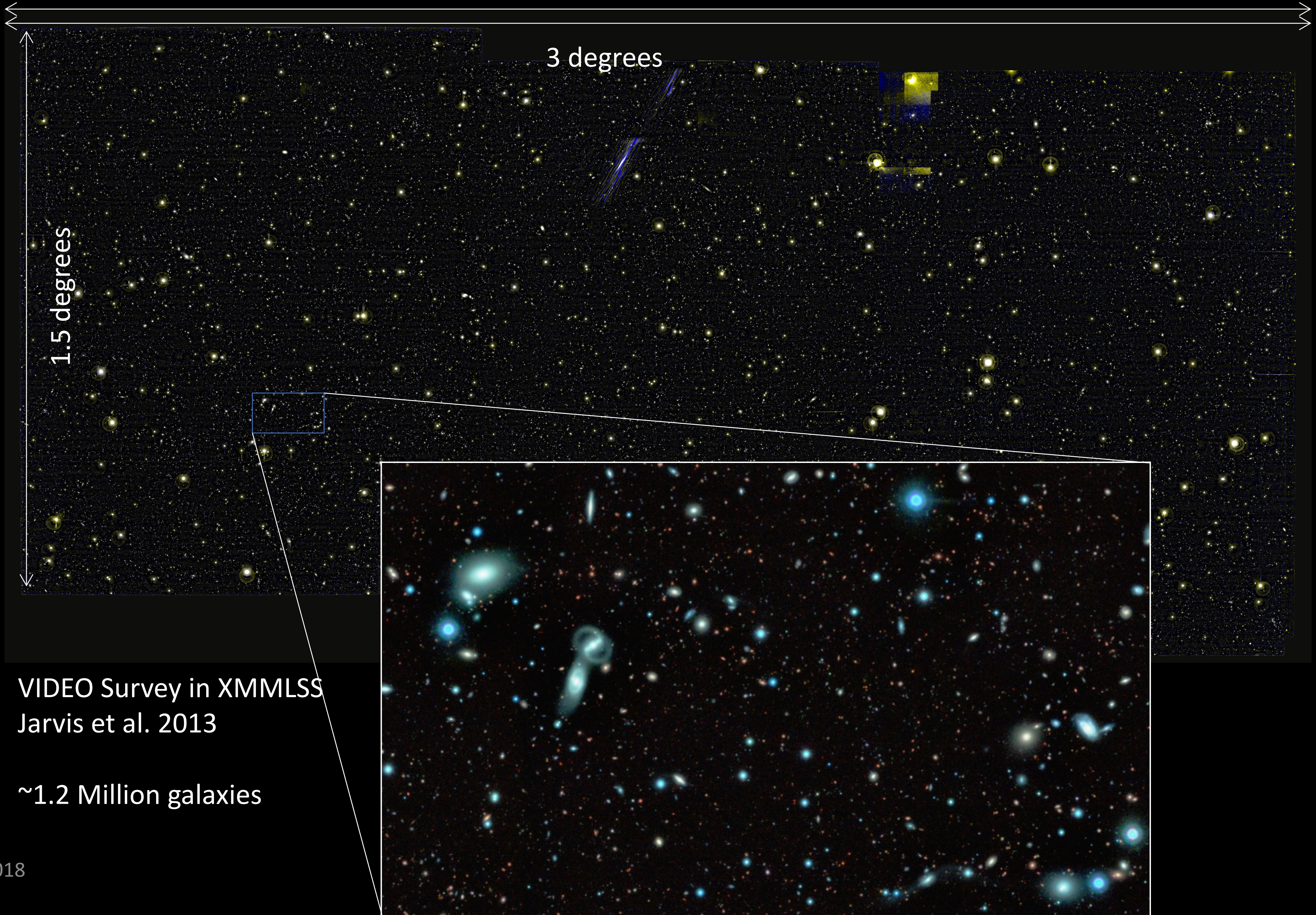
SCOSMOS/SERVS/SpUDS etc

MeerKAT, SKA

SuMIRe
Prime Focus
Spectrograph

Chandra, XMM

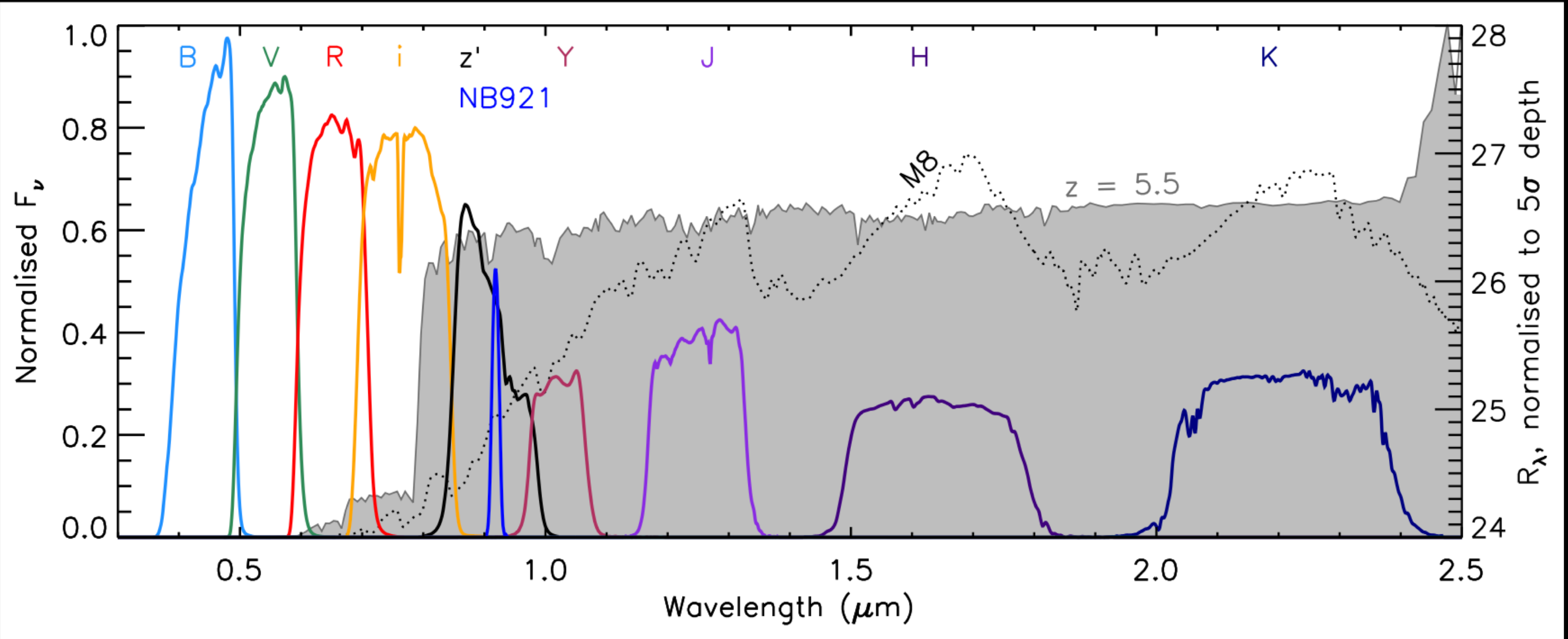
Multi-λ data is already in place over the ex-gal DD fields



VIDEO Survey in XMMLSS
Jarvis et al. 2013

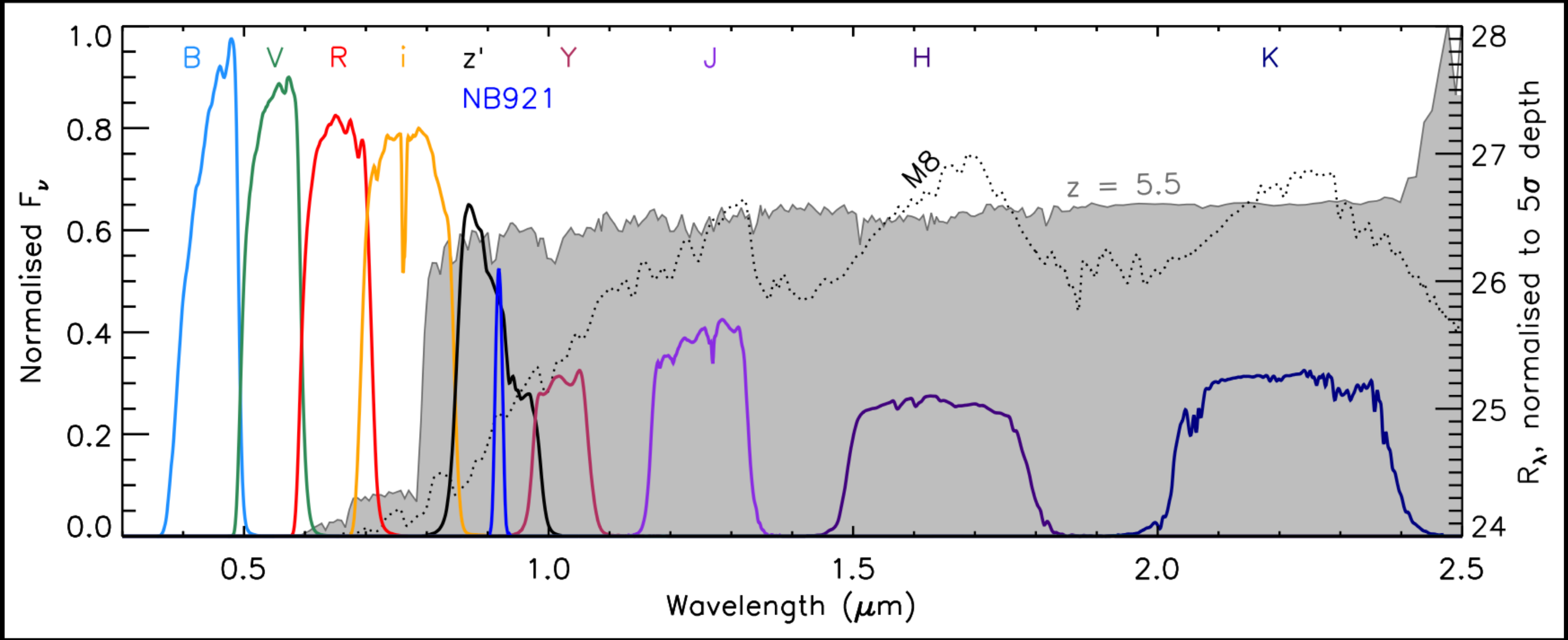
~1.2 Million galaxies

Finding high-z galaxies



Deep near-IR data is needed to select z>7 candidate galaxies & AGN

Finding high-z galaxies

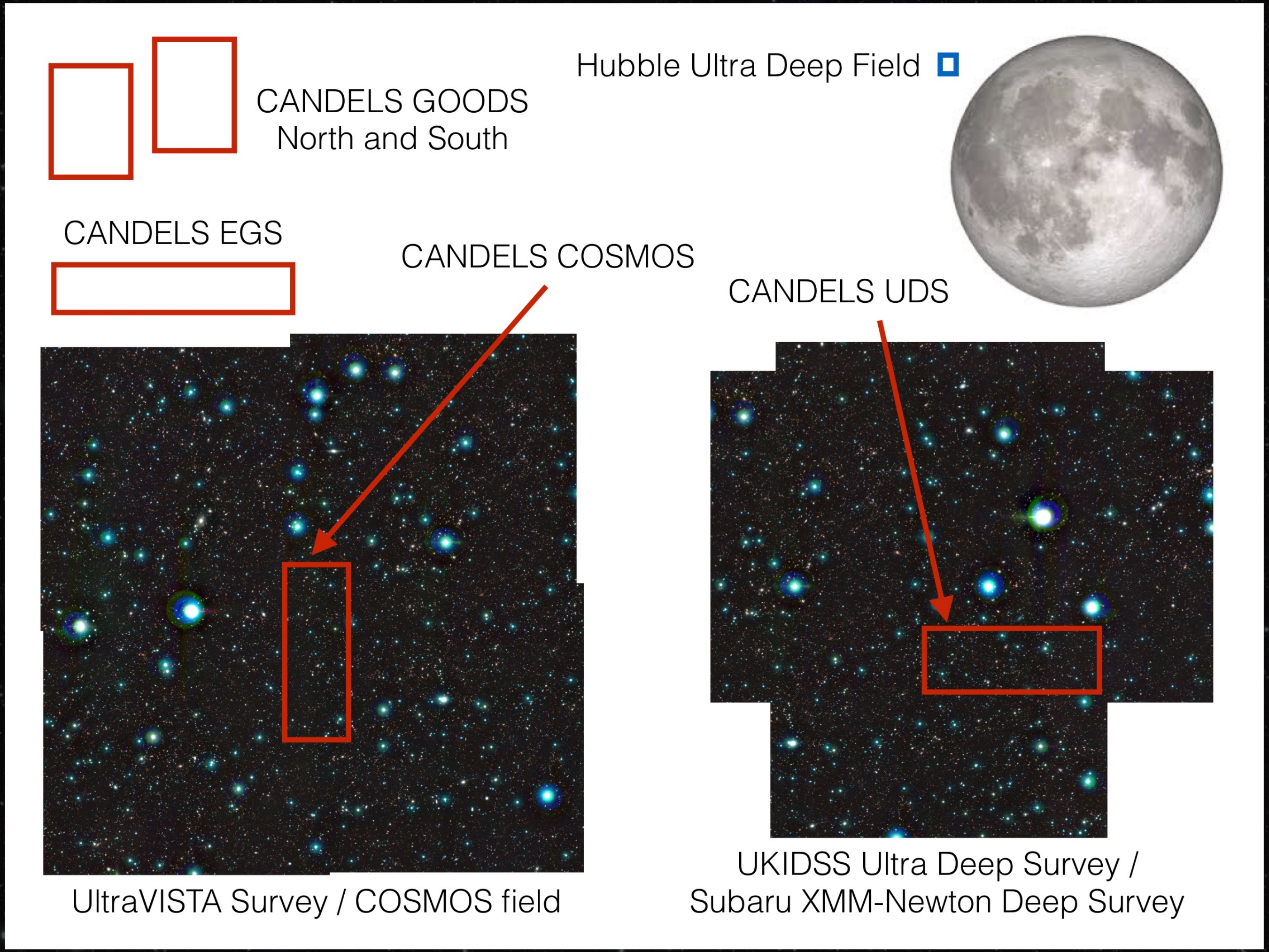


Deep near-IR data is needed to select z>7 candidate galaxies & AGN

Deep optical (LSST) data is essential to

1. Measure the strong Lyman-break
2. Remove contaminant low-z galaxies
3. Remove cool galactic brown dwarfs that will be detected in redder

Current leading surveys for searching for high-z galaxies

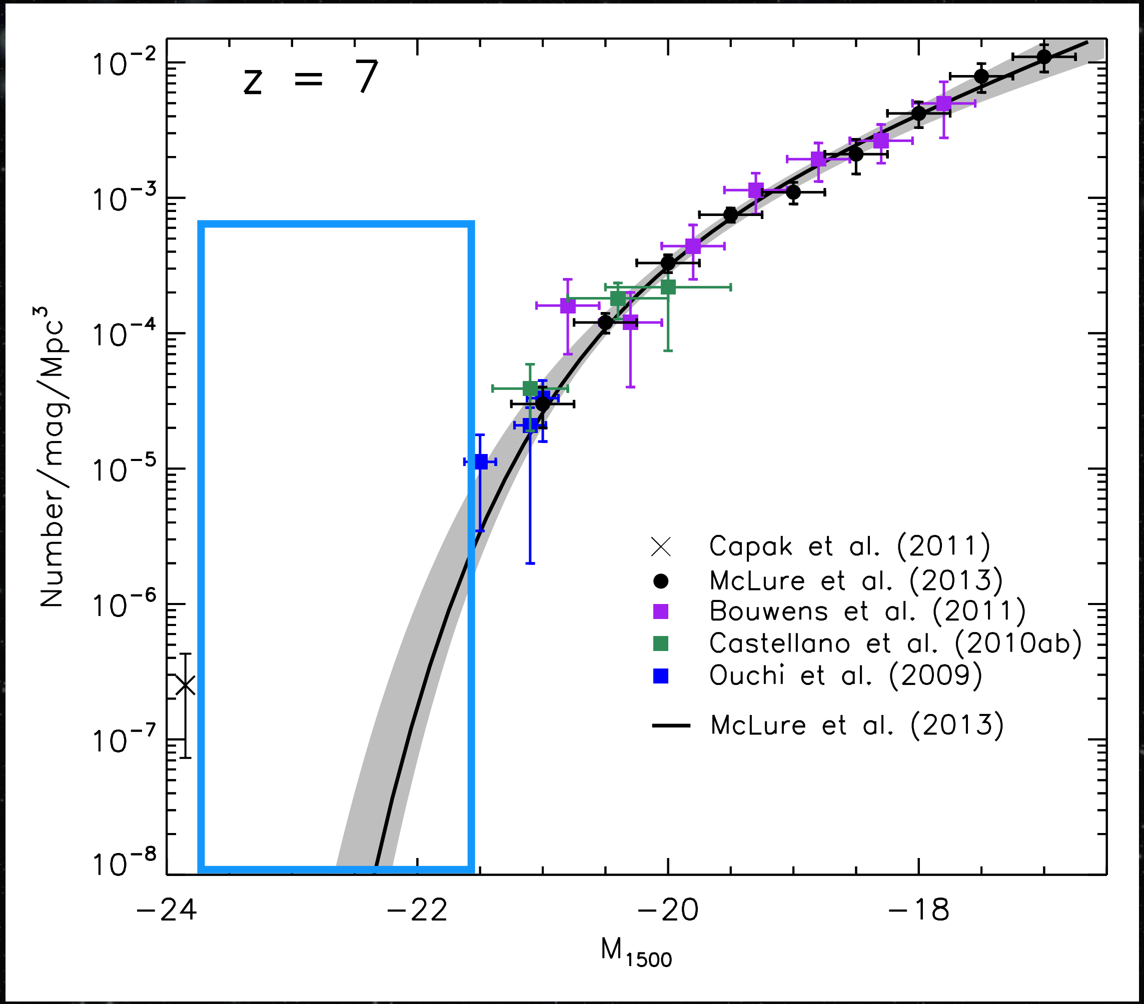


COSMOS
ugriz/CFHTLS
z/Subaru
NB/Subaru
YJHKs/UltraVISTA
3.6 4.5micron/SPLASH

UDS
BVRiz/Subaru
NB/Subaru
Y/VISTA VIDEO
JHK/UKIDSS UDS
3.6 4.5micron/SPLASH

The bright end of the z~7 galaxy LF

Need wide-area, near-IR surveys!

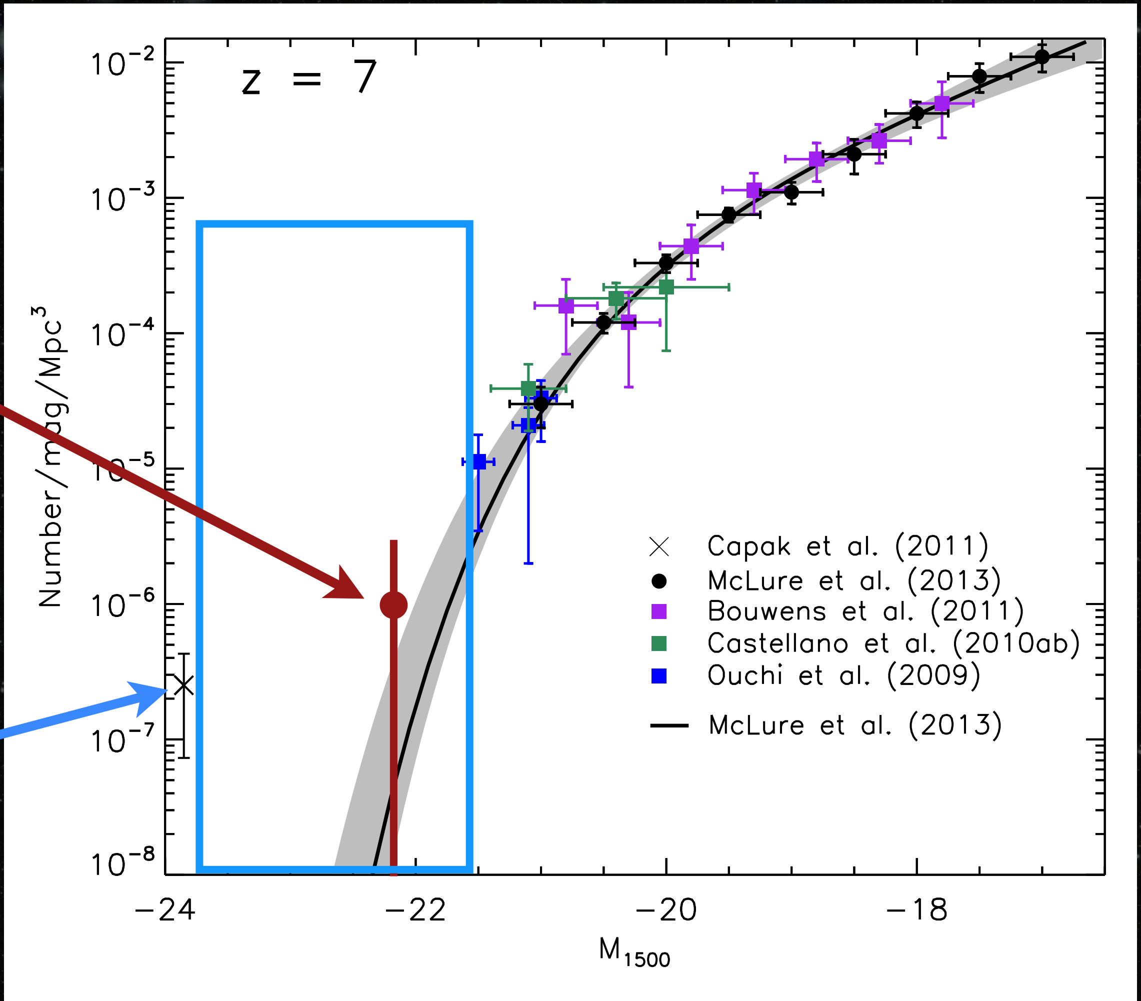


The bright end of the z~7 galaxy LF

Need wide-area, near-IR surveys!

Brightest point from full CANDELS only ~ 1 galaxy

Previous CFHT/ UKIRT data not deep enough ("LBGs" all at z ~ 2)

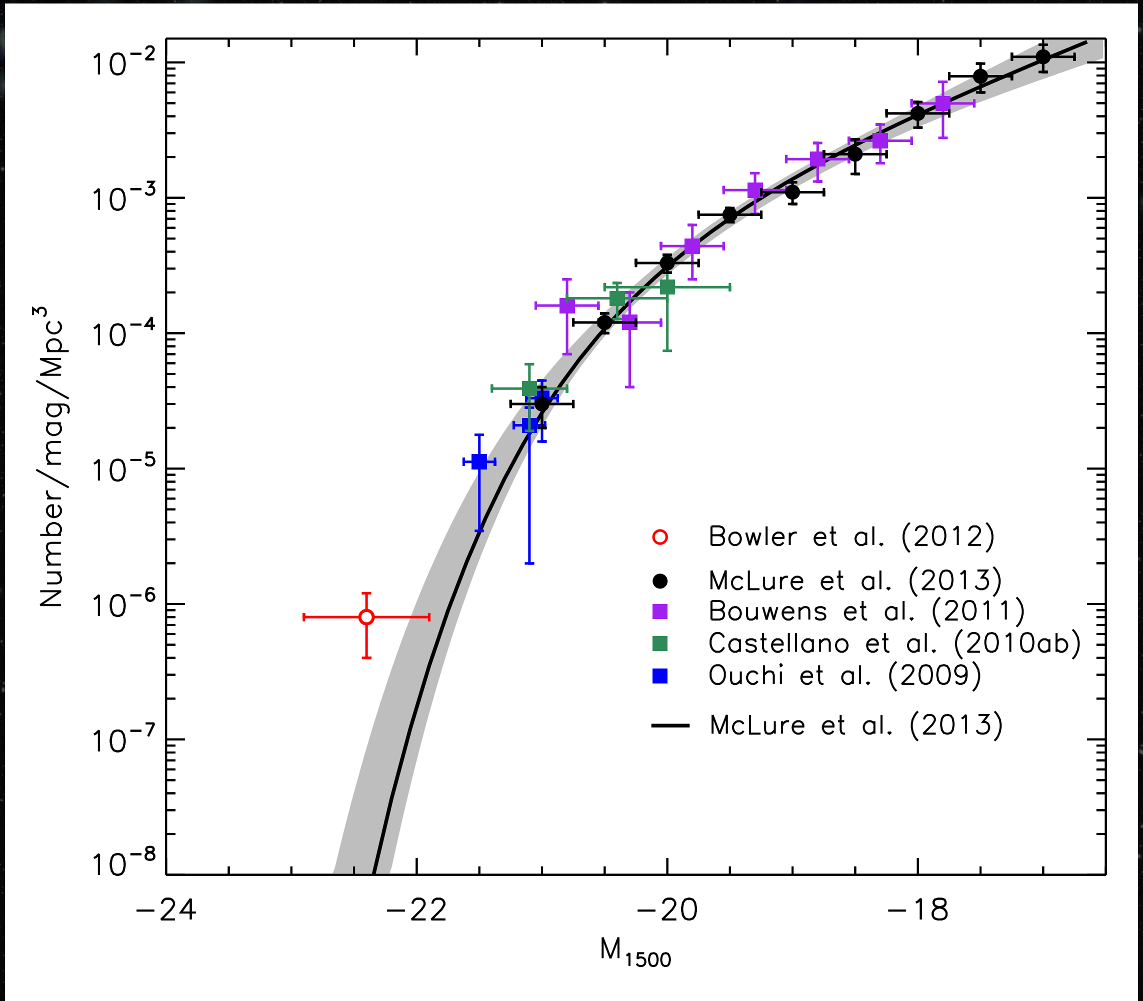


The bright end of the z~7 galaxy LF

UltraVISTA DR1

1 sq. degree

10 galaxies



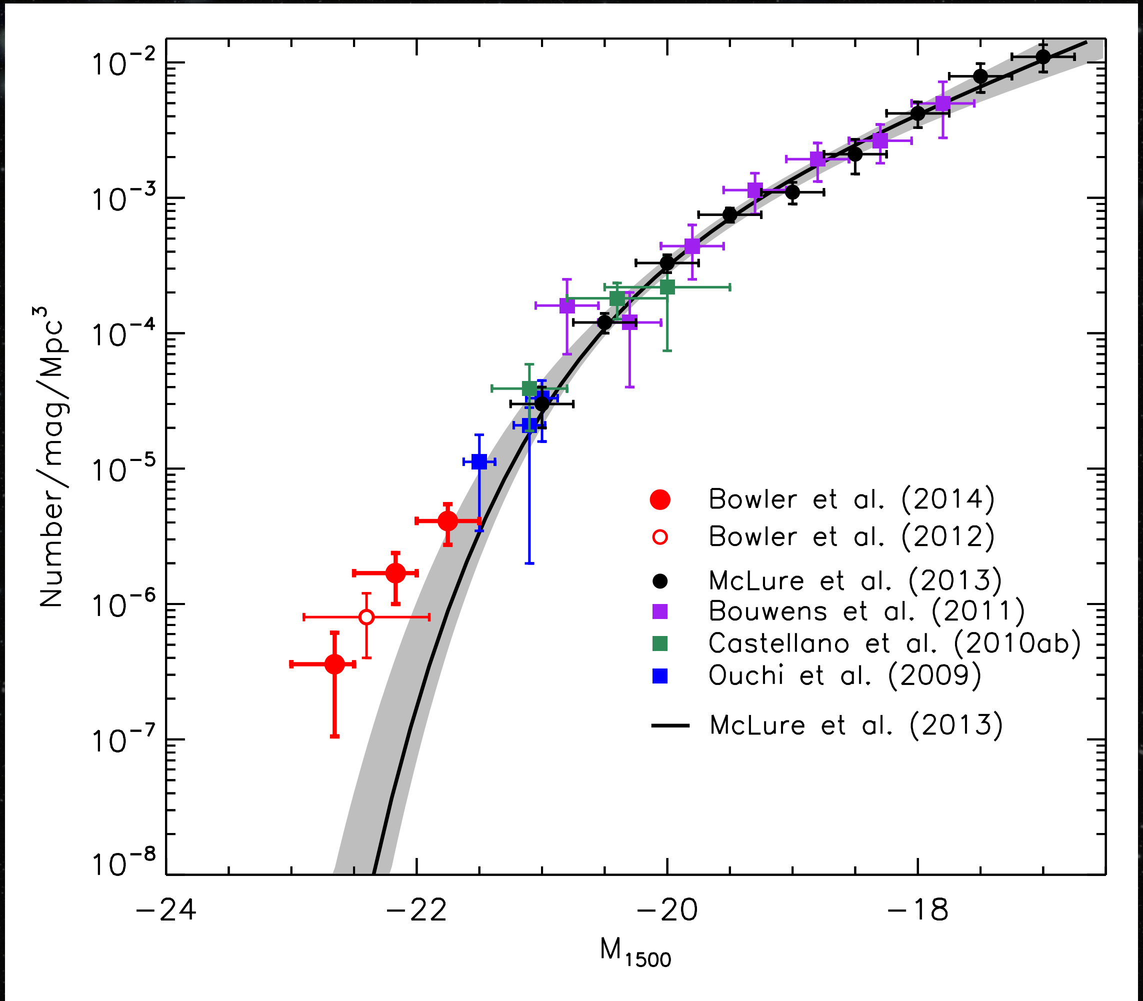
The bright end of the z~7 galaxy LF

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

34 galaxies (including 9/10 Bowler et al. 2012 objects)

0.5-1 mag deeper near-IR data than DR1



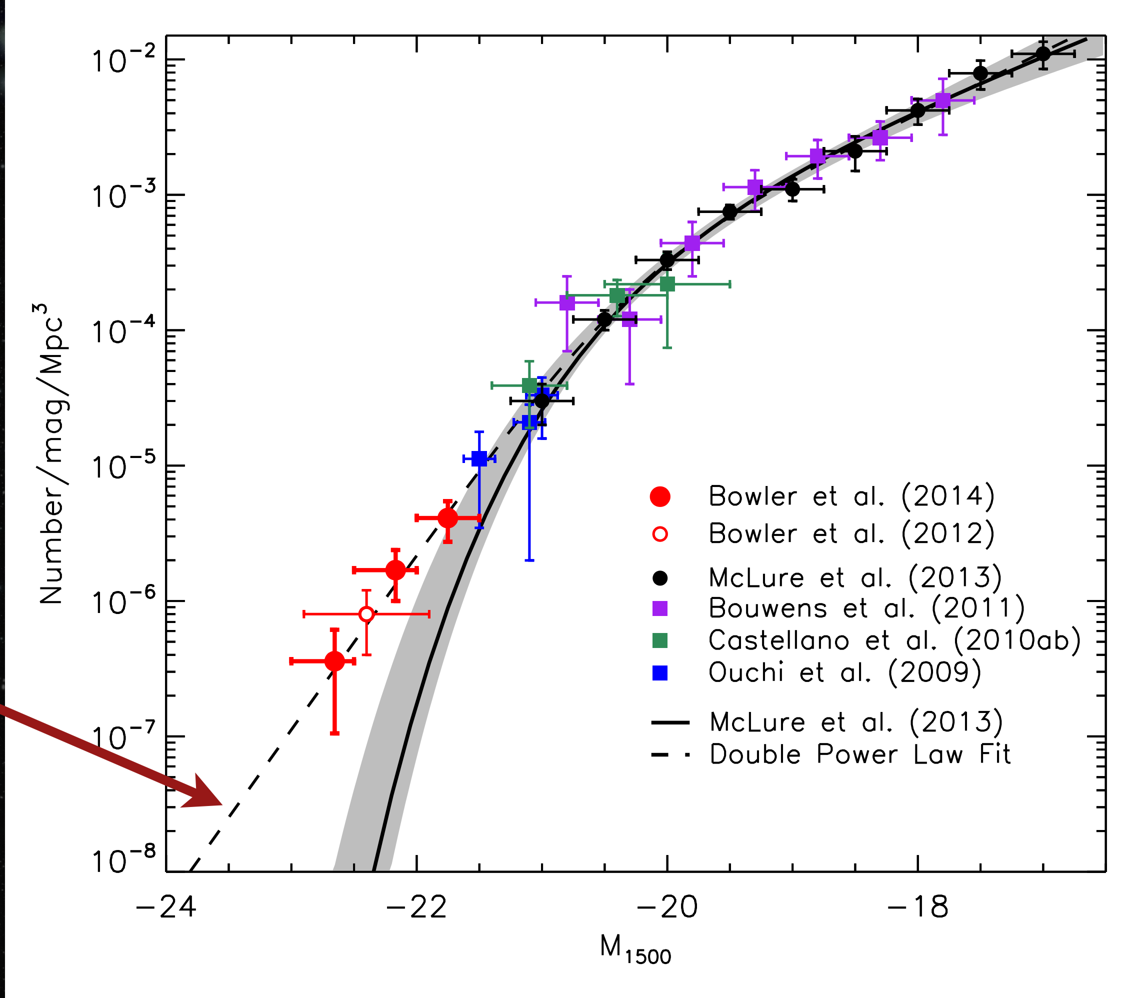
The bright end of the z~7 galaxy LF

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

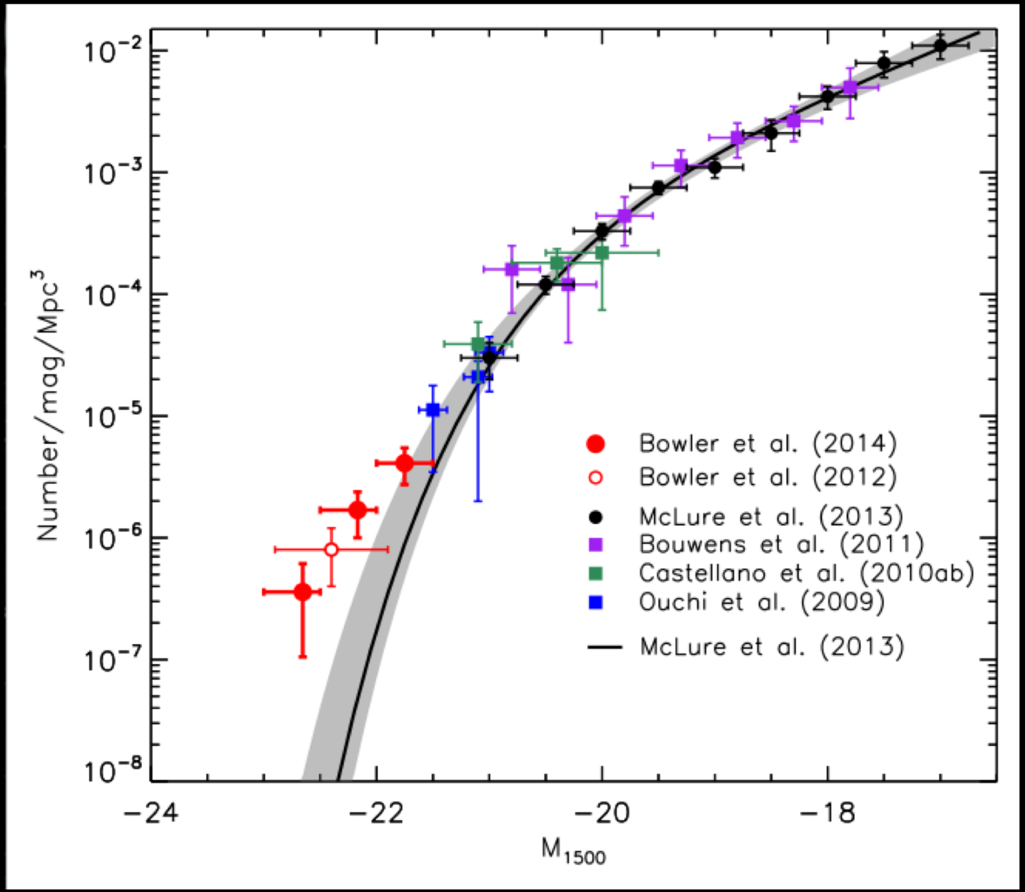
Best-fit is not the usually assumed exponential decline (Schechter) but a **double power-law**

Inefficient AGN feedback? Reduced dust?



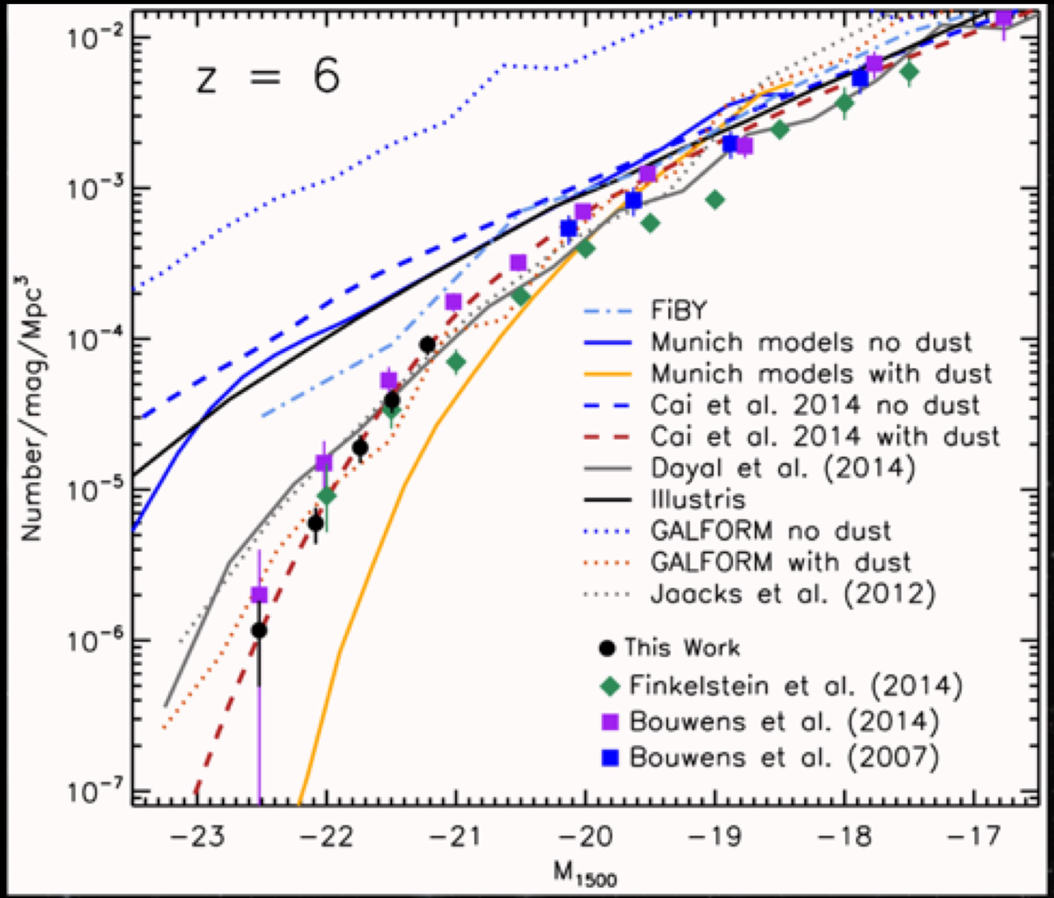
[redacted]

High-z galaxies LFs compared to models



Data

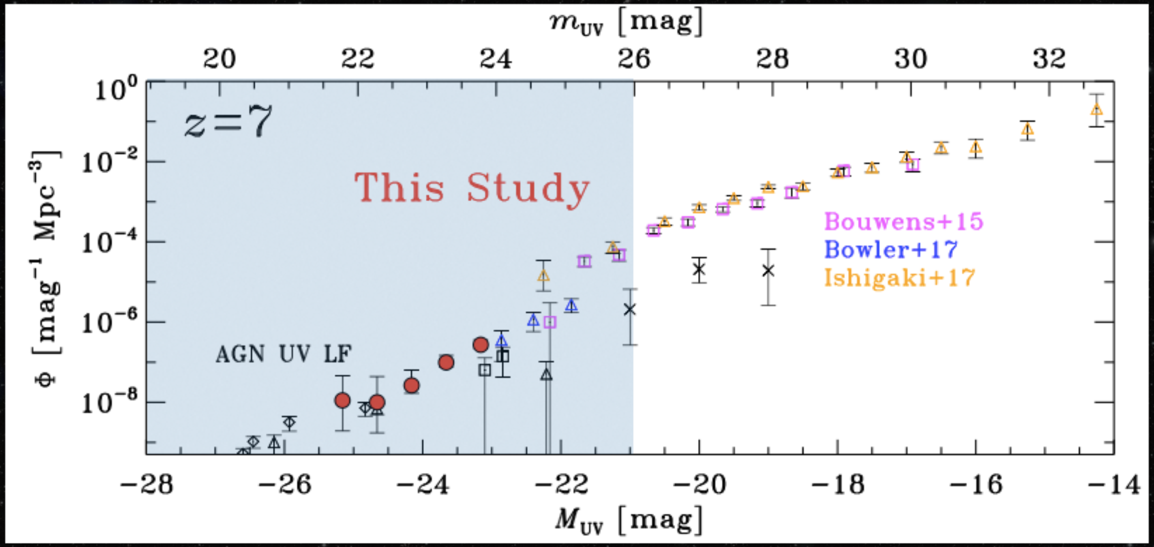
Bowler et al. 2015



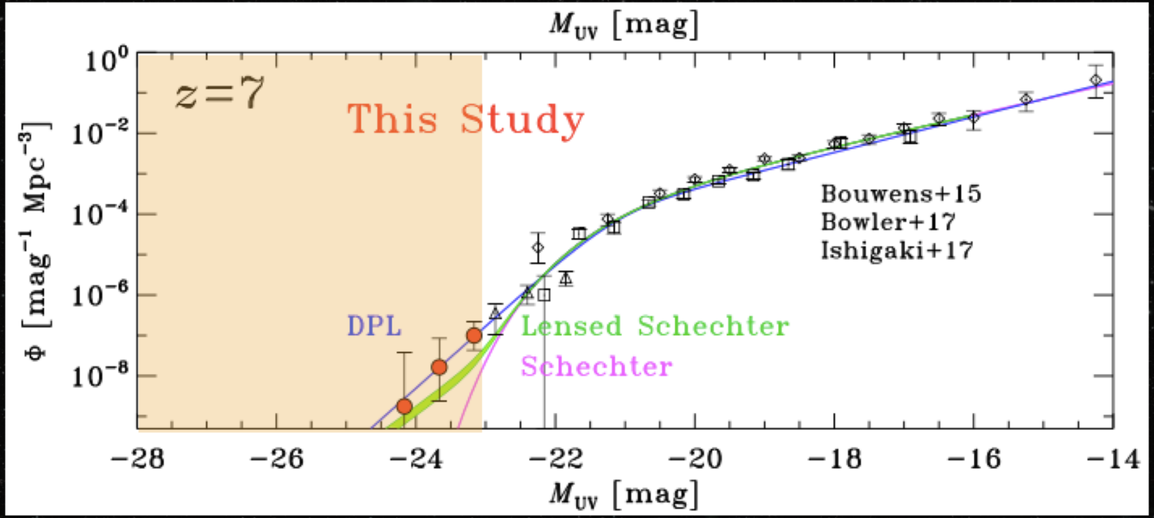
Models

Results from HSC-UltraDeep Survey

Results from wide, deep and ultra-deep HSC data to 2016



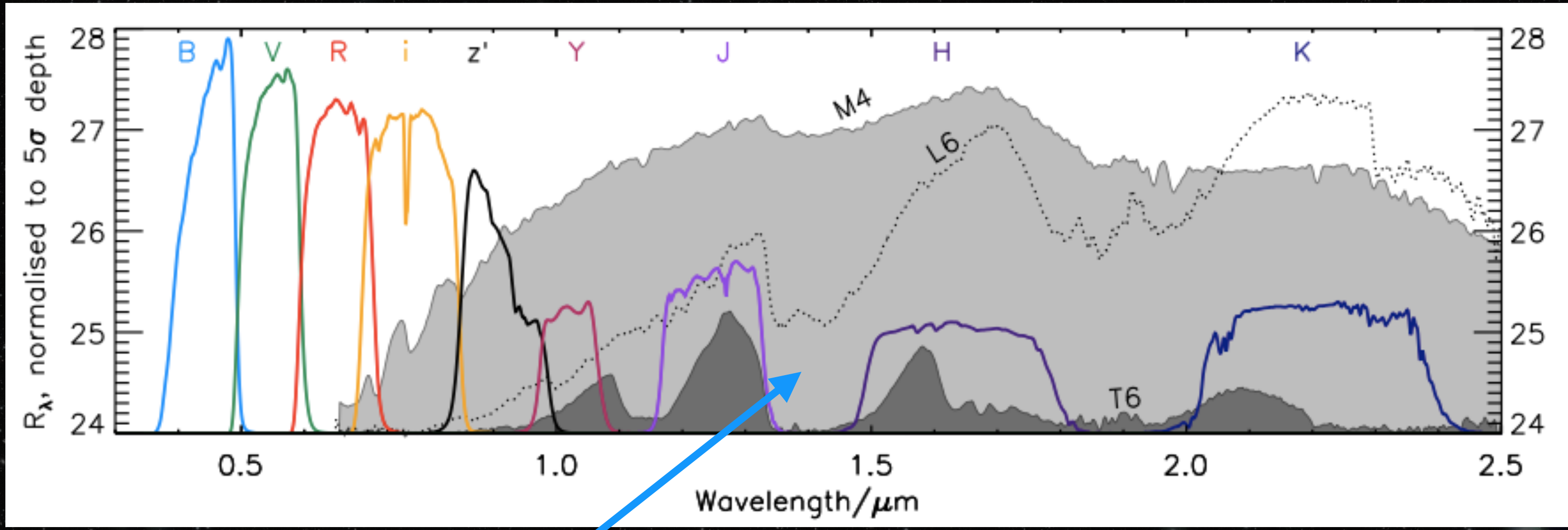
With AGN LF subtracted:



- No removal of brown dwarfs which dominate in this magnitude regime
- AGN LF is uncertain

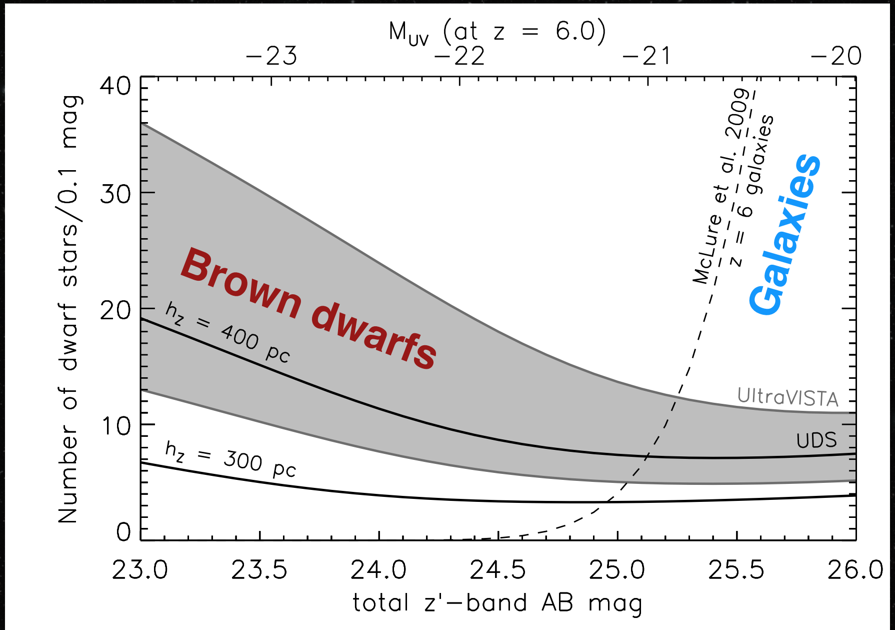
Ono et al. 2017

Contamination by cool galactic brown dwarfs



Water + methane absorption

★ M, L and T dwarfs outnumber bright z ~ 7 galaxies and can mimic their colours with inadequate depth + filter sampling



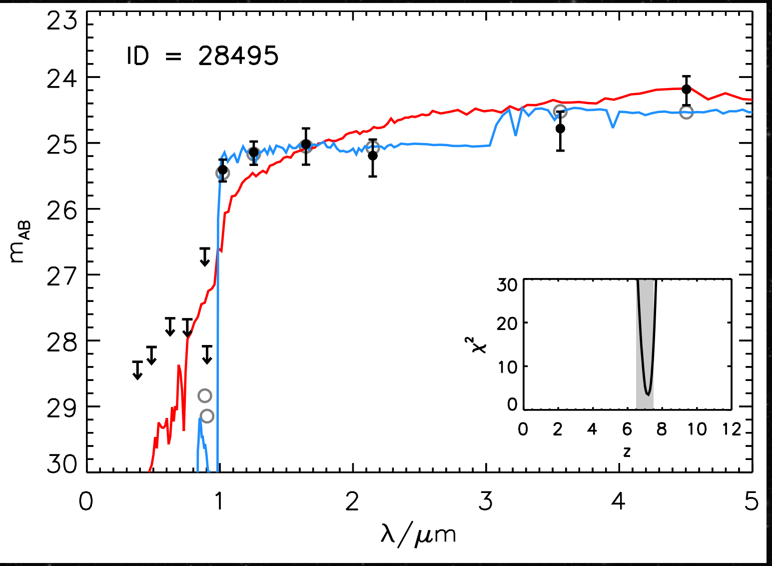
Bowler et al. 2015

Clean Selection of high-z galaxies

★ Deep **optical + near-infrared** photometry constrains high-z nature

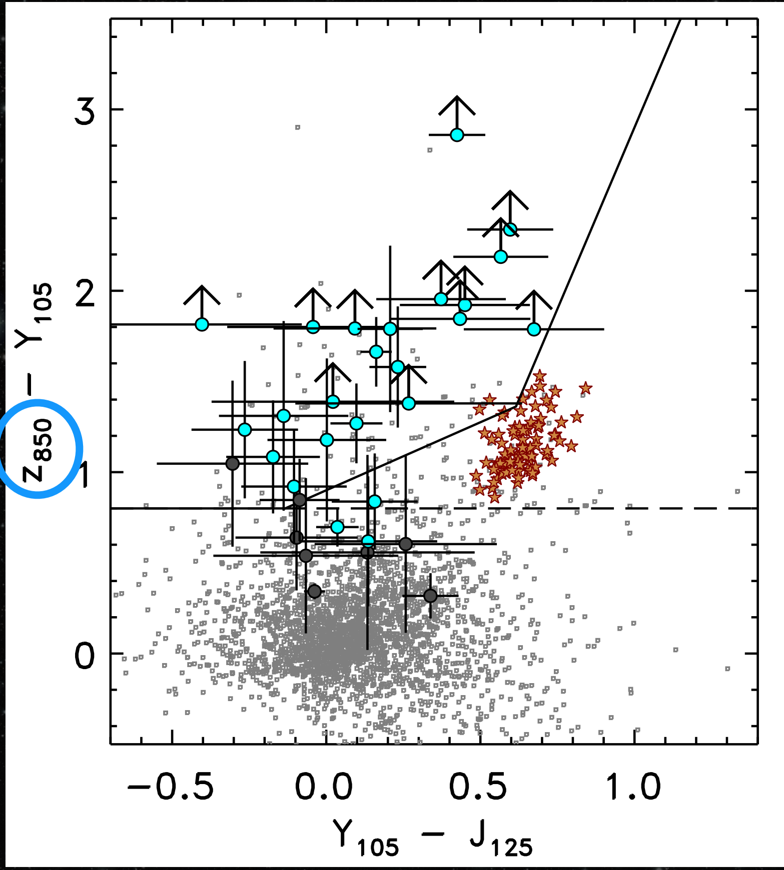
Strong break + blue continuum

Spitzer/IRAC removes red interlopers



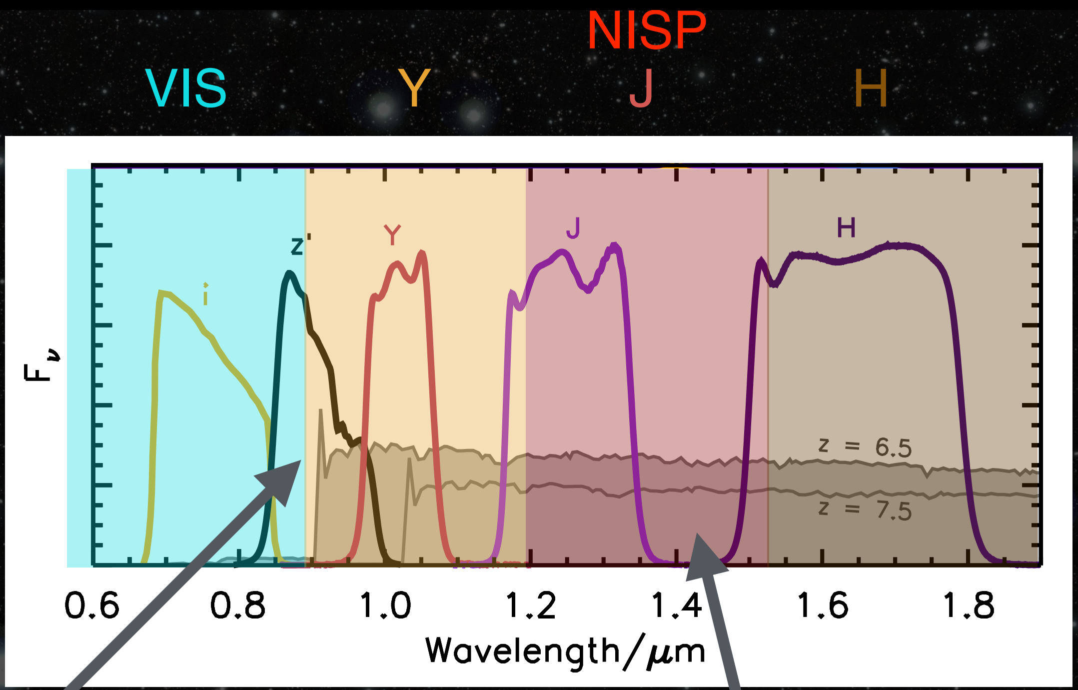
High-z galaxy

Low-z galaxy



Finkelstein et al. 2010

Finding high-z galaxies with LSST + Euclid



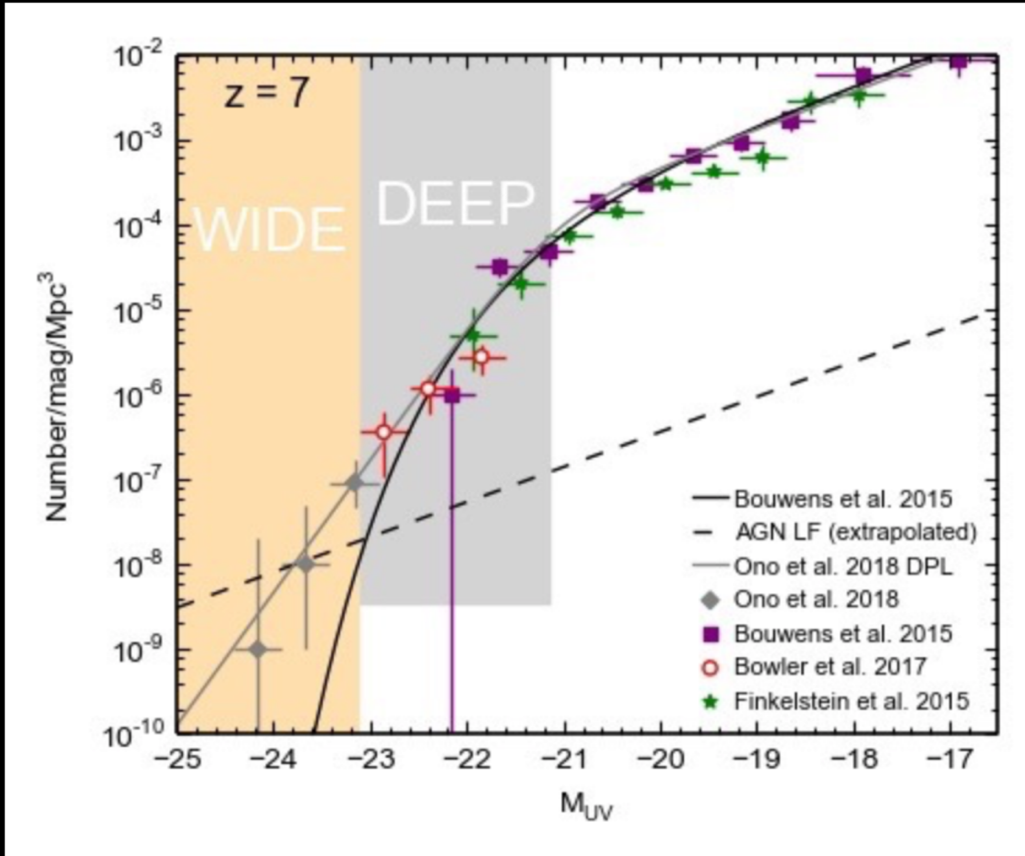
Lyman-alpha emission

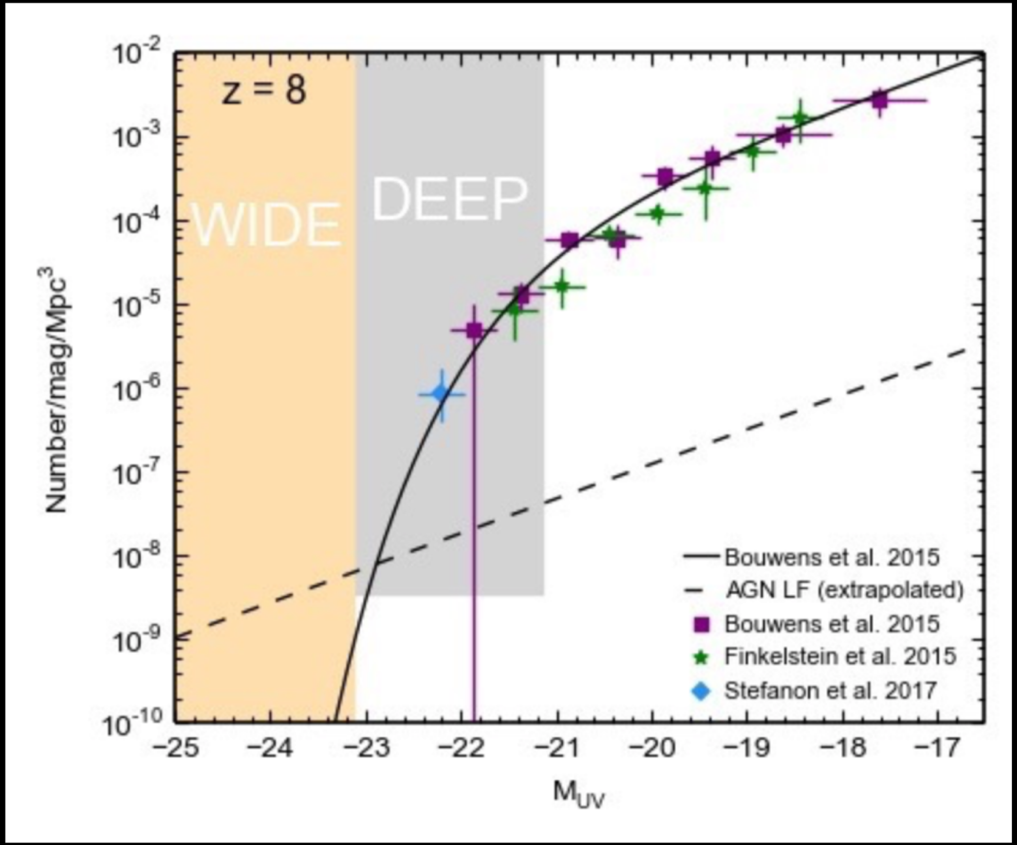
Lyman-break galaxy

Grism spectroscopy will detect
Lyman-a from z = 6.5 -> 9

VIS-filter dropouts: z ~ 7 galaxies
Y-filter dropouts: z ~ 8 galaxies
J-filter dropouts: z ~ 9 galaxies

The power of LSST + Euclid for measuring the z>7 LF



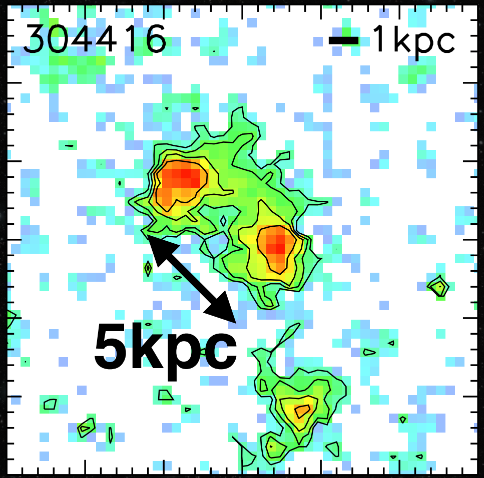


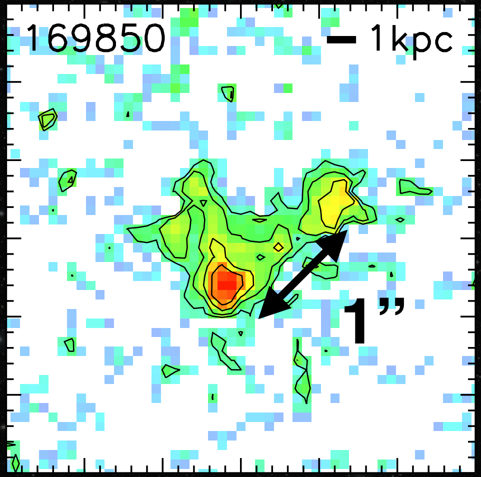
Predicted number counts in the Euclid DEEP

Redshift	6	7	8	9	10
Lyman-break Galaxies	50,000	10,000	2,000	100s?	10s?
High-z AGN	200	50	10	3?	1?

How big are z>7 galaxies?

Cycle 22 HST follow-up of bright LBGs reveal sizes/ morphologies that are elusive in ground-based data





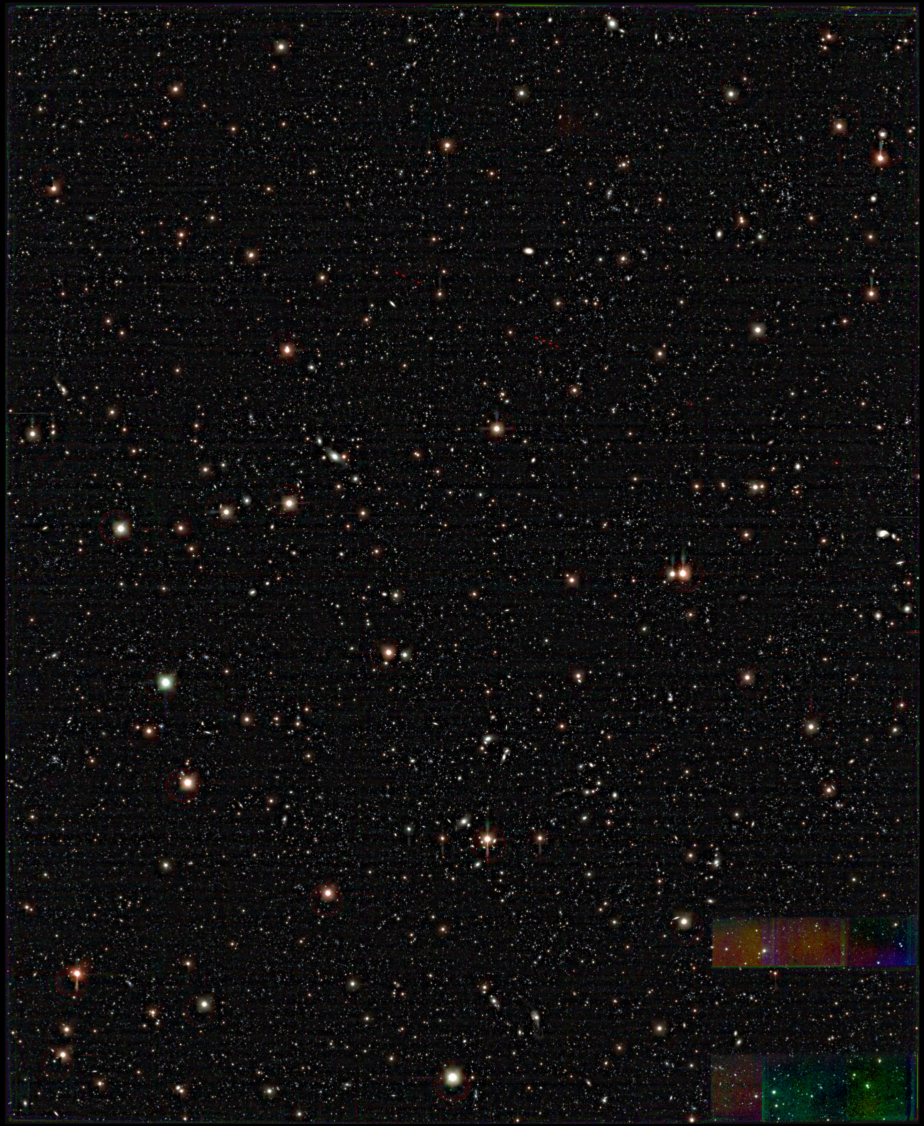
- ⋆ The brightest Lyman-break galaxies at z ~ 7 are resolved
- ⋆ Diminishes worry over brown dwarf contamination

Bowler et al. 2017a

Clustering of galaxies to high-z

- **Deep wide-field surveys** allow us to track galaxy evolution over the history of the Universe
- Understanding the ***clustering*** of galaxies gives important information about large scale structure, how galaxies and baryons trace matter, and galaxy environment
- A powerful approach to modelling galaxy clustering is the ***Halo Occupation Distribution*** (HOD) phenomenology

1. The HOD Model
2. Clustering in VIDEO
   a) HOD and stellar mass to halo mass ratios
   b) Cross correlations
   c) Comparison to simulations

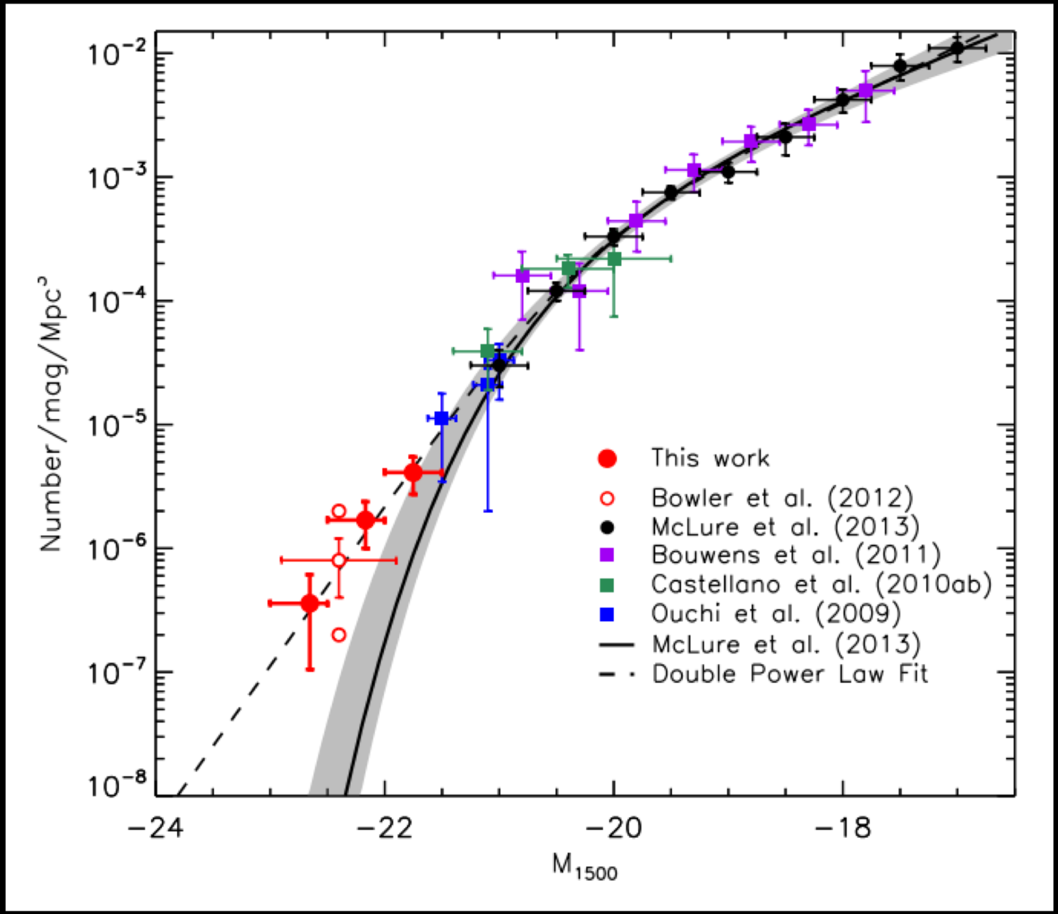


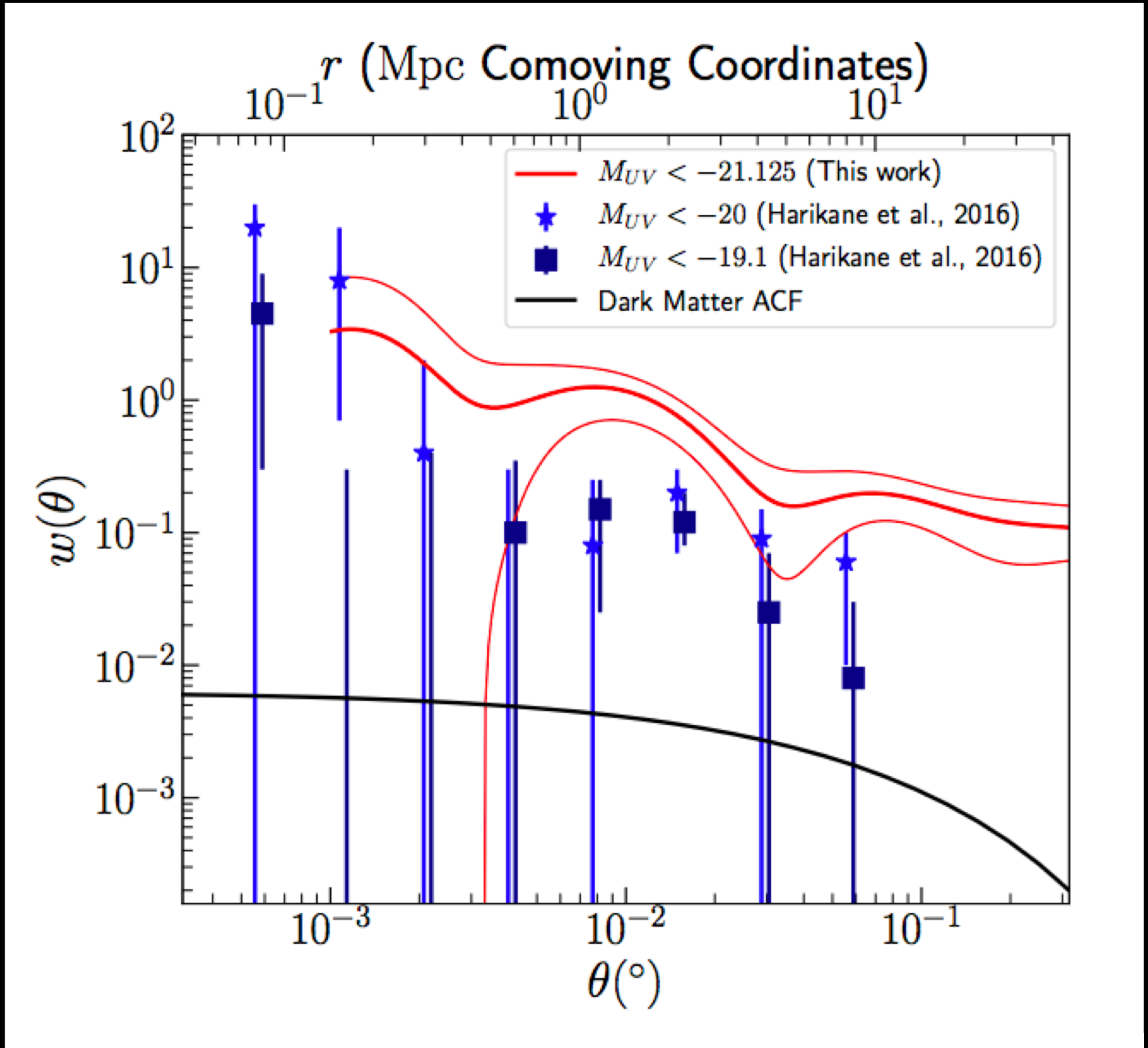
VIDEO-XMM3

The galaxy-halo connection in the VIDEO Survey at 0.5<z<1.7, Hatfield et al., MNRAS 2016
Environmental Quenching and Galactic Conformity in the Galaxy Cross-Correlation Signal, Hatfield & Jarvis, MNRAS 2017
The environment and host haloes of the brightest z~6 Lyman-break galaxies, Hatfield et al. MNRAS, 477, 3760

Clustering at z~6

- z~6 clustering of LBGs – onset of quenching?





$$-2\log\mathcal{L} = \chi^2_{\phi} + \Sigma\chi^2_{\omega(\theta)} + \Sigma\chi^2_{\Delta\Sigma}$$

Hatfield et al. 2017, MNRAS, 477, 3760

Summary

- Highlighted a few science cases for LSST but the data will form the basis of massive number of studies in the coming decade
- The areal coverage of even the Deep Drilling Fields is immense compared to where we are now
- So rare object science and science requiring “large” contiguous areas will be unique to LSST
- The key is the photo-zs and characterization of objects (star/galaxy/AGN/hydbrid)
- New non-optical/nearIR data will also be crucial to gain a complete understanding
    - In addition to Euclid and WFIRST which will help with photo-zs and morphology
    - X-SERVS (Chen et al. 2018)
    - MeerKAT (HI and radio continuum – Jarvis et al. 2017)
    - Herschel and Spitzer data already in place
    - Follow-up with ALMA and JWST will be key for detailed studies