Two sides of the coin: Combining imaging and spectroscopy to reveal the hidden universe

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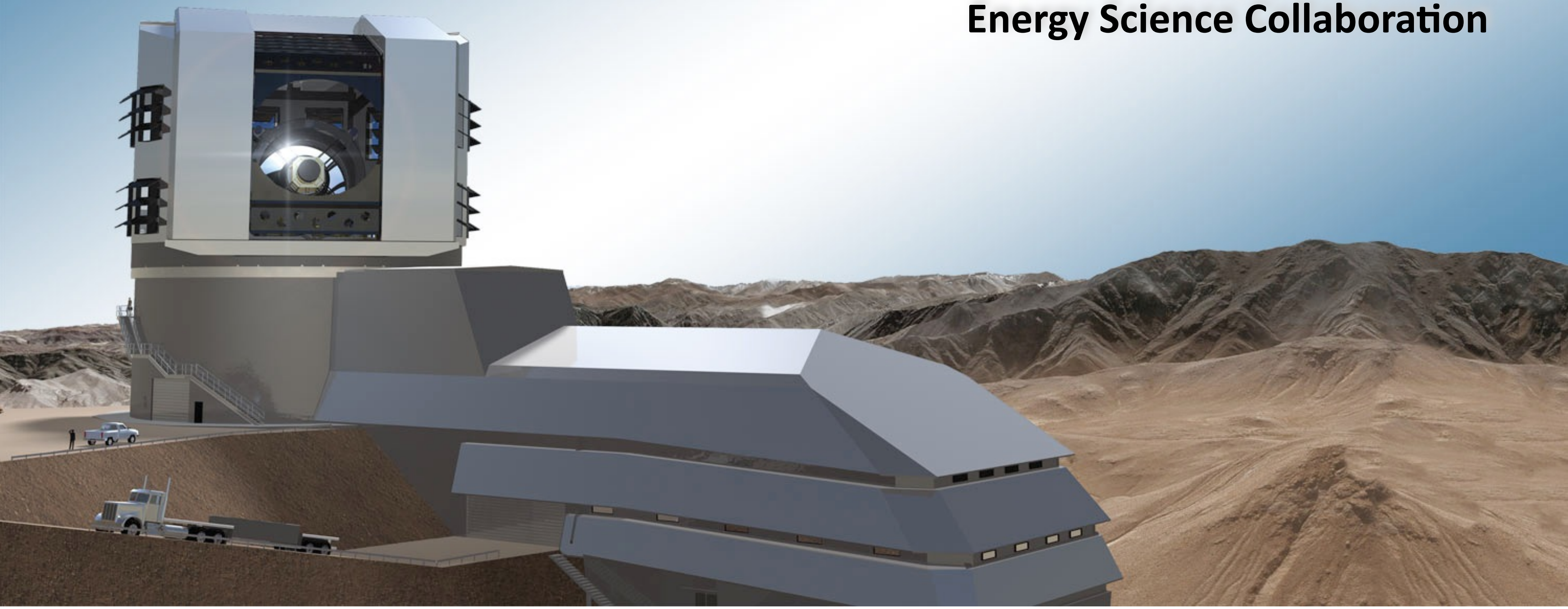


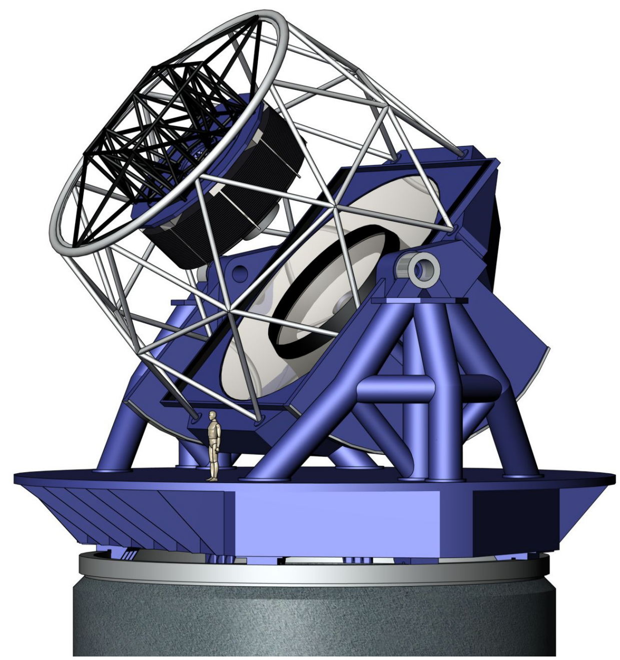
Outline

- **Unlocking the potential of imaging surveys with spectroscopy: requirements for training photometric redshifts for LSST**
- **Using imaging and spectroscopy of SDSS galaxies to explore hidden properties of our Galaxy: Milky Way Analogs in SDSS and MaNGA**

- **See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* (http://arxiv.org/abs/1309.5384, 1309.5388) and Milky Way papers led by Tim Licquia for much more**

A brief review of LSST

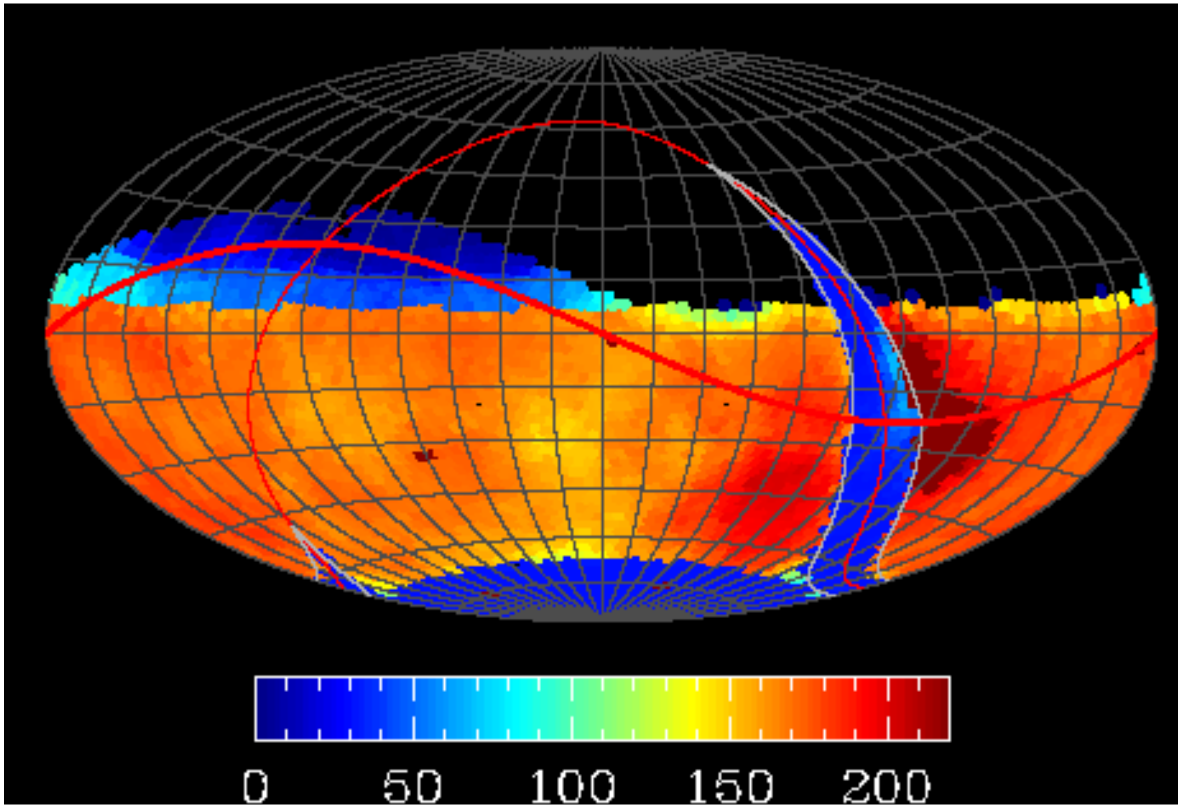
- 8m diameter (6.7m effective), f/1.23 telescope, deep imaging in 6 filters (*ugrizy*)
- 2x15 sec images of 9.6 sq. deg. at a time
  - 900 visits per night, cover visible sky every 3 nights
- 10-year total survey: combine >800 visits per pointing for extremely deep imaging over 50% of sky
- Science enabled:
  - Cosmology (dark matter, dark energy, testing GR, etc.)
  - Mapping the Milky Way
  - Revealing the Transient Universe
  - Inventory of the Solar System



LSST: A dedicated 10-year survey

- 5σ point-source depth (1 visit): 23.9 (*u*), 25.0 (*g*), 24.7 (*r*), 24.0 (*i*), 23.3 (*z*), 22.1 (*y*)
- Depth at end of the survey: 26.3 (*u*), 27.5 (*g*), 27.7 (*r*), 27.0 (*i*), 26.2 (*z*), 24.9 (*y*)

- **40 trillion observations of 40 billion objects**
- Status: construction start approved by NSF & DOE
  - 'First stone' laid last month
- Survey start late 2022



LSST needs multi-object spectroscopy like what PFS can provide

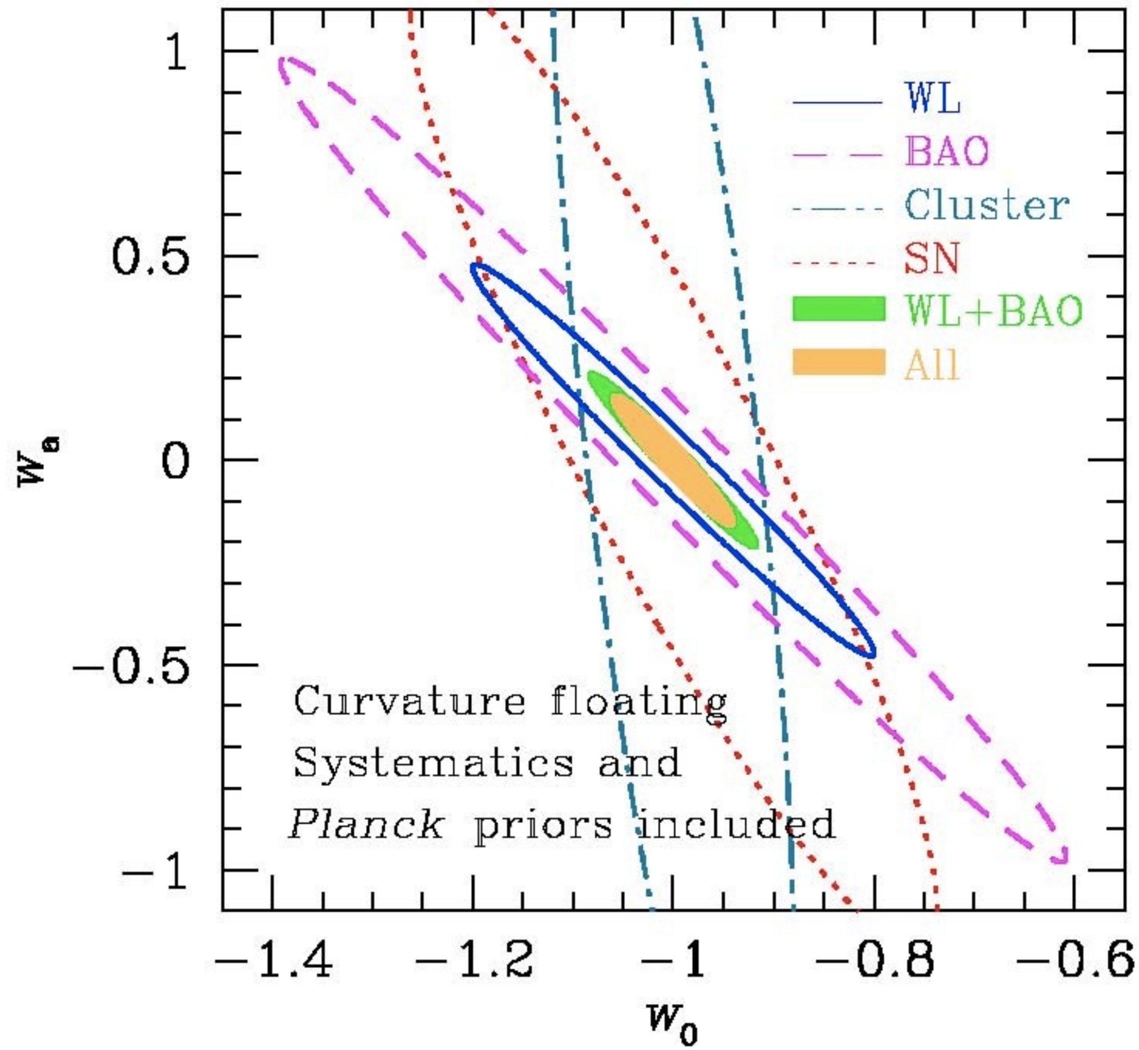
- **Matheson et al. white paper analyzed spectroscopic use cases:**

Problem[a]	Depth[b]	λ^d	R[e]	Σ_{Target}[f]
Superluminous SNe	$16 < r < 25$	$0.4 - 2.5\mu m$	2000	0.05 deg^{-2}
Cataclysmic variables	$16 < r < 25$	$0.4 - 2.5\mu m$	2000	10 deg^{-2}
Galaxy stellar dynamics	$16 < r < 25$	$0.4 - 0.9\mu m$	2000–5000	...
Galaxy stellar abundances:				
[Fe/H], [α/Fe], [C/Fe]	$16 < r < 25$	$0.37 - 0.9\mu m$	2000	...
individual α elements	$16 < r < 25$	$0.37 - 0.9\mu m$	5000	...
"all" individual elements	$16 < r < 25$	$0.37 - 0.9\mu m$	20,000+	...
Brown dwarf masses	$K \sim 15$	$1.0 - 1.6\mu m$	50,000	...
Brown dwarf weather	$K \sim 15$	$1.0 - 1.6\mu m$	5,000	...
Massive galaxy survey	$20 < i < 25$	$0.4 - 1.3\mu m$	4000	1000 deg^{-2}
Topology of reionization survey	$z_{AB} \sim 26 - 27$	5000 - $1\mu m$	1000 - 4000	up to 10 $arcmin^{-2}$
Dwarf satellite galaxies	$r < 24$	4000 - 9000Å	4000	10,000 deg^{-2}
IGM tomography	$i < 25 - 26$	3500 - 10000 Å	2000	10 $arcmin^{-2}$
Quasar redshift survey	$i < 24$	3800 - 12600	1000 - 2000	500 deg^{-2}
Reverberation mapping	$r < 24$	4000 - 10000	> 1000	1000 deg^{-2}
$z > 6$ quasars (other rare AGN)	$Y < 24$	0.8 - 2.5 μm	> 2000	single object
Lyα blobs	$i < 24$	3200 - 6000 Å	2000	single object
Weak Lensing/LSS cross-corr. cal.	$20 < i < 23$	$0.4–1.0\mu m$	4000	1000 deg^{-2}
Weak Lensing/LSS photo-z train.	$22 < i < 25$	$0.4–2.0\mu m$	4000	1000 deg^{-2}
Weak Lensing/LSS supplemental	$i \sim 25$	$0.4–2.0\mu m$	4000	10 deg^{-2}
Cluster Cosmology photo-z cal.	$22 < i < 25$	$0.4–1.5\mu m$	4000	100 deg^{-2}
Strong Lensing cosmology	$i \sim 25$	$1–2\mu m$	2000	1/10 deg^{-2}
SNIa Cosmology: SN follow-up	$gri \sim 19–24$ mag	$0.4–1.0\mu m$	1000	5 deg^{-2}
SNIa Cosmology: Host follow-up	$20 < i < 25$ mag	$0.4–1.0\mu m$	4000	30 deg^{-2}

Green = MOS

LSST constrains dark energy in many ways… all will rely on redshift information

- 4 major probes of dark energy: weak lensing, baryon acoustic oscillations, cluster counts, & type Ia supernovae (plus strong lensing, etc.)
- For all of these, we want to measure observables as a function of redshift

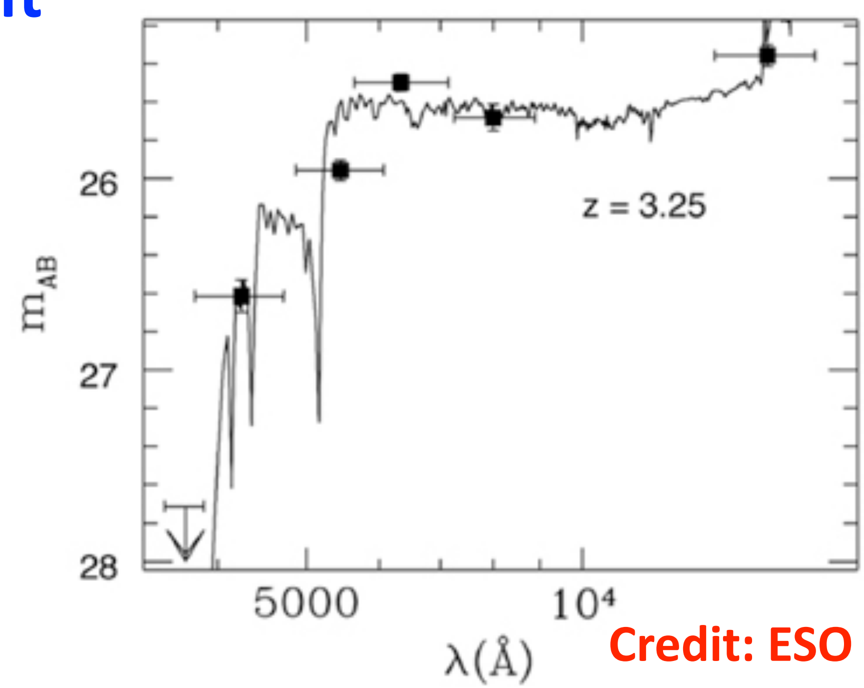


LSST Science Book

Spectroscopy provides ideal redshift measurements – but is infeasible for large samples

- **At LSST depths (*i*<25.3), ~190 hours on a 10m telescope to determine a redshift (~75% of time) spectroscopically**
- **With a next-generation, 5000-fiber spectrograph would take >50,000 10m telescope-years to measure redshifts for LSST "gold" weak lensing sample (4 billion galaxies)!**

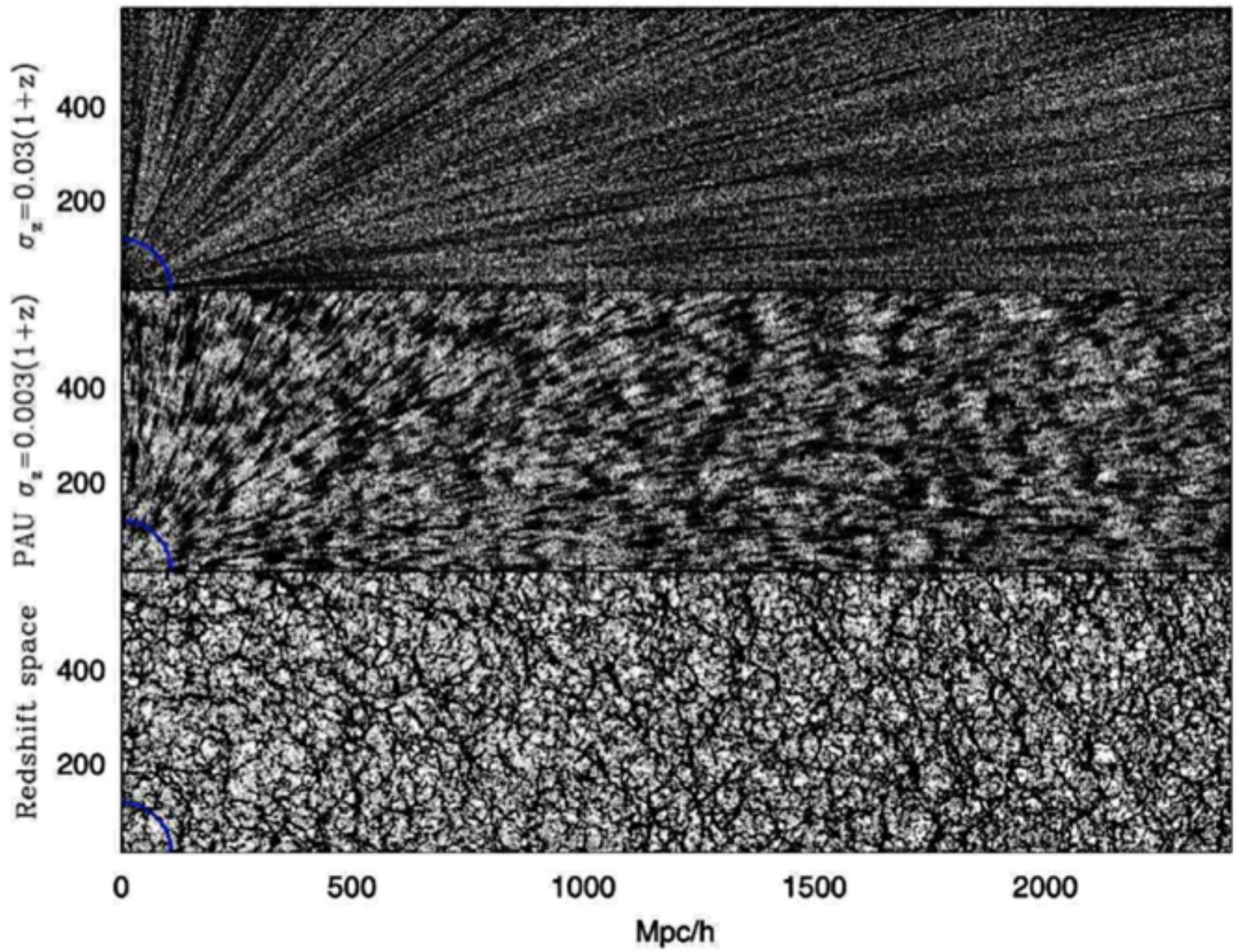
- **Alternative: use broad spectral features to determine *z* : a photometric redshift**
- **Advantage: high multiplexing**
- **Disadvantages: lower precision, calibration uncertainties**



Credit: ESO

Two spectroscopic needs for photo-z work: training and calibration

- Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters



Benitez et al. 2009

  - Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

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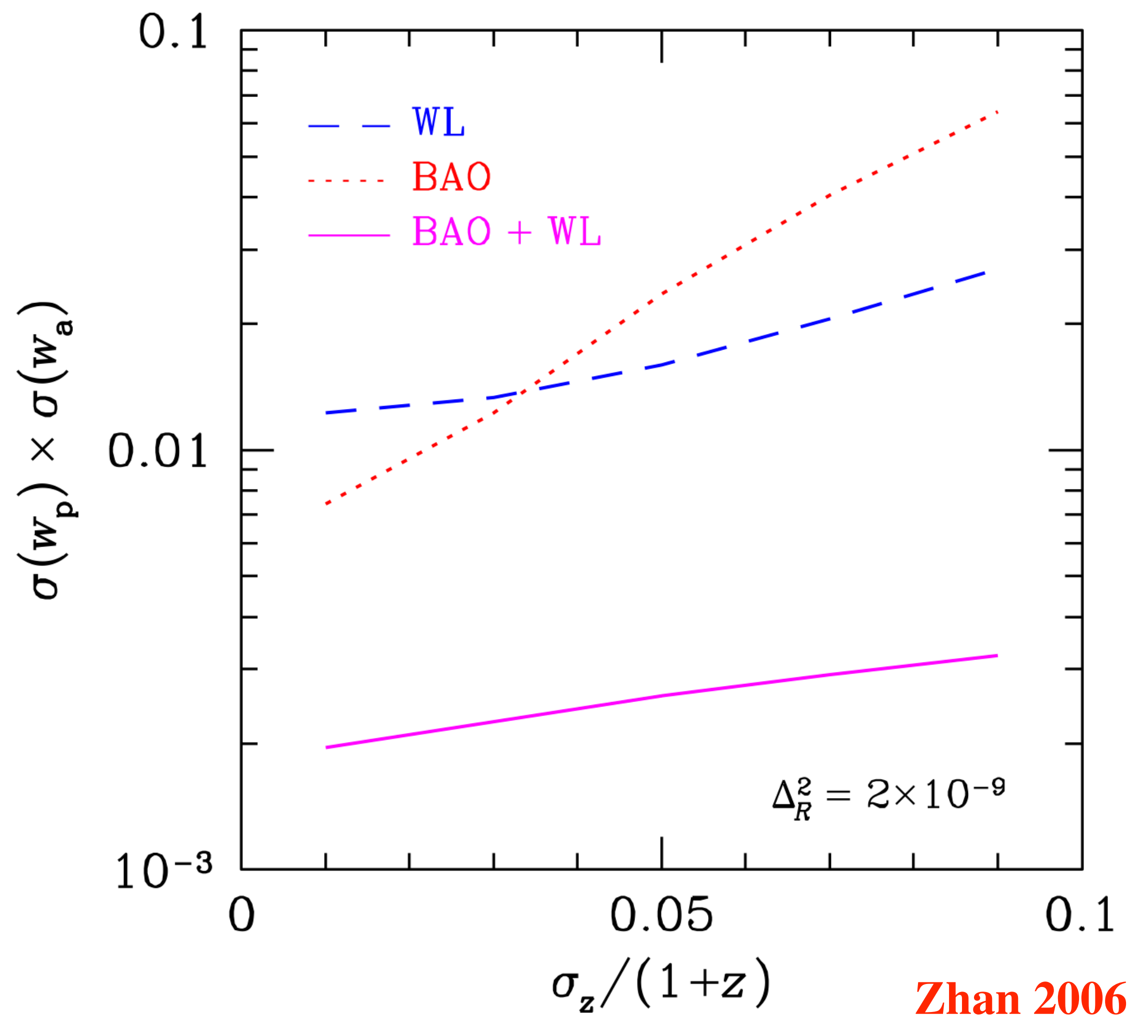
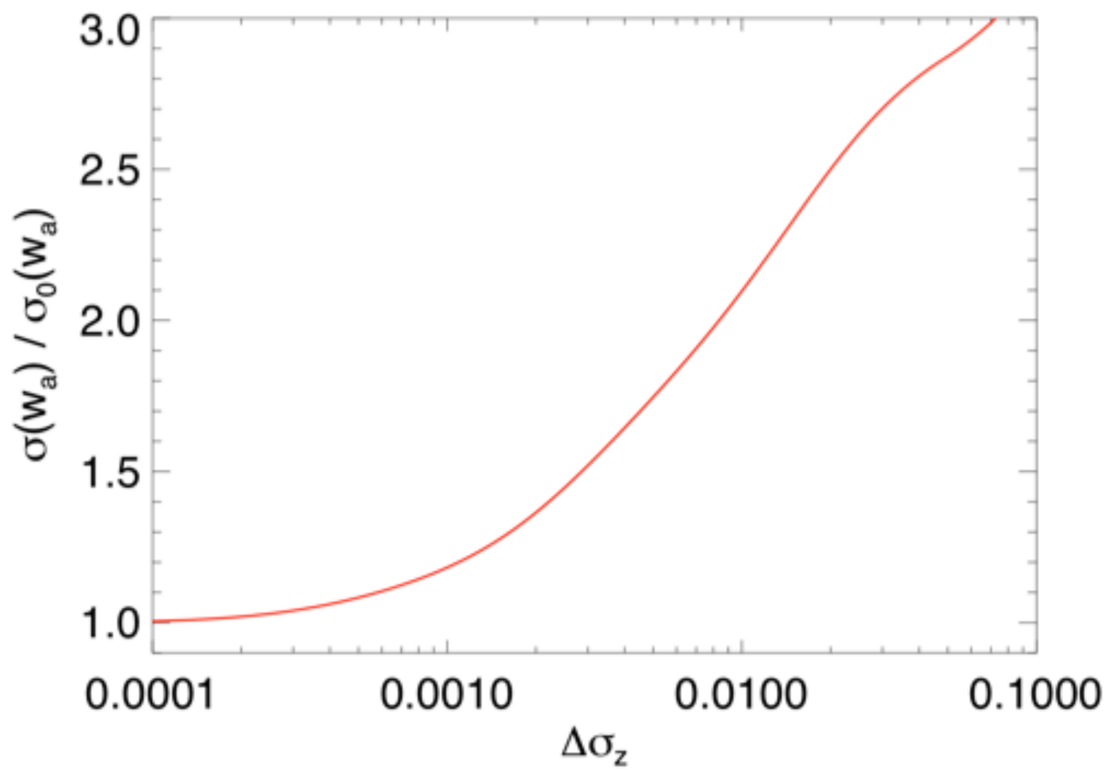


  - Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

Two spectroscopic needs for photo-z work: training and calibration

LSST DESC Dark Energy Science Collaboration

- For weak lensing and supernovae, individual-object photo-*z*'s do not need high precision, but the calibration must be accurate - i.e., bias and errors need to be extremely well-understood



Newman et al. 2013

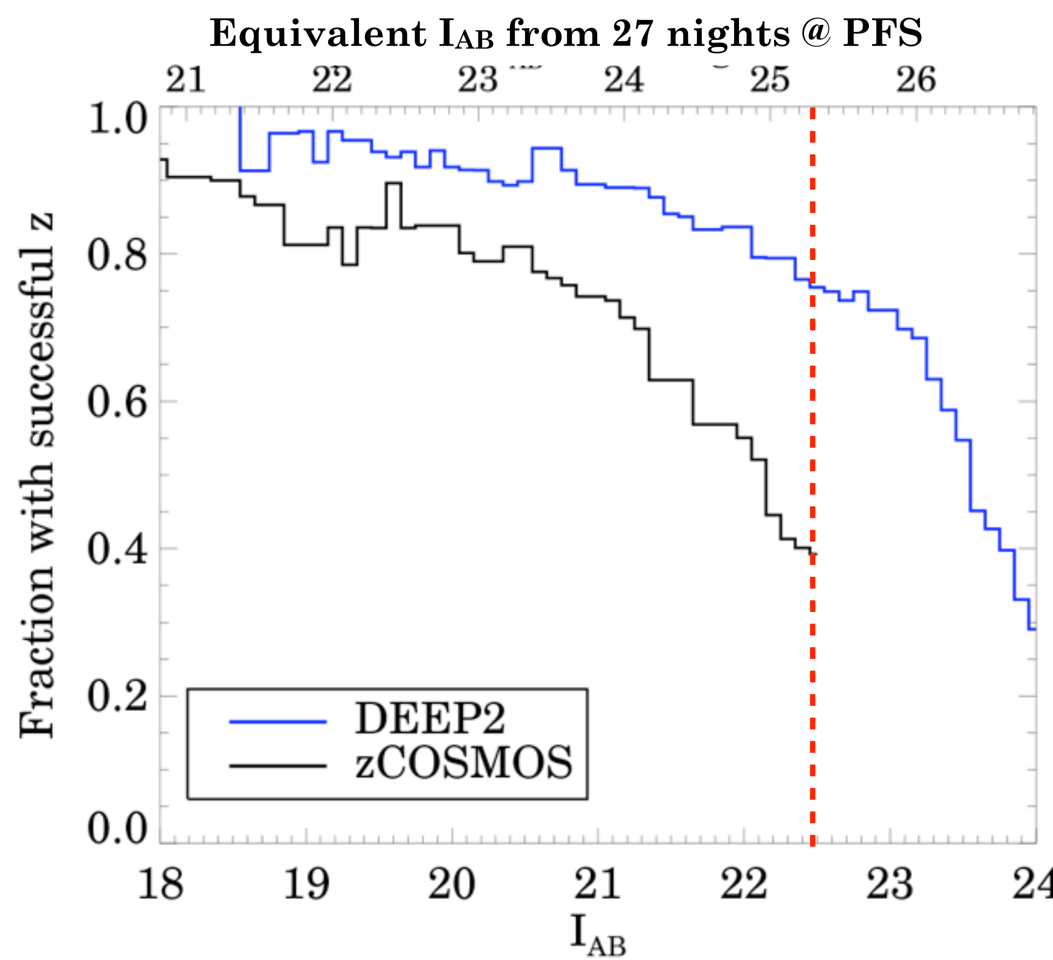
- *uncertainty in* bias, $\sigma(\delta_z) = \sigma(\langle z_p - z_s \rangle)$, and in scatter, $\sigma(\sigma_z) = \sigma(RMS(z_p - z_s))$, must both be $\lesssim 0.002(1+z)$ for Stage IV surveys

Biggest concern: incompleteness in training/ calibration datasets

- In current deep redshift survey (to i~22.5/R~24), 25-60% of targets fail to yield secure (>95% confidence) redshifts

- Redshift success rate depends on galaxy properties - losses are systematic, not random

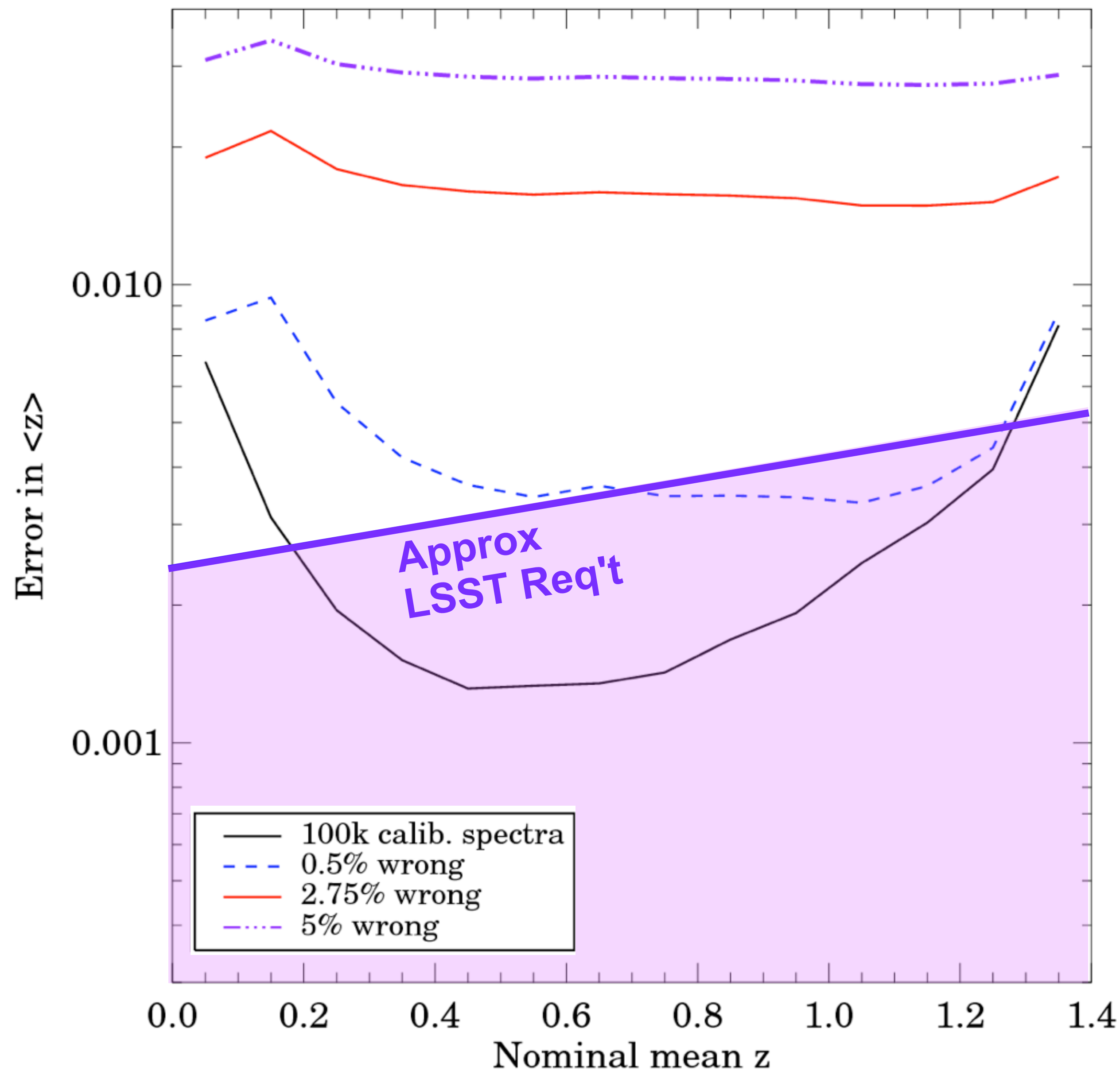
- Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations



Data from DEEP2 (Newman et al. 2013) and zCOSMOS (Lilly et al. 2009)

Note: even for 100% complete samples, current false-z rates can compromise calibration accuracy

- **Only the highest-confidence redshifts should be useful for precision calibration: lowers spectroscopic completeness further when restrict to only the best**



Based on simulated redshift distributions for ANNz-defined DES bins in mock catalog from Huan Lin, UCL & U Chicago, provided by Jim Annis

Spectroscopic training set requirements

- Goal: make δ_z and $\sigma(\sigma_z)$ so small that systematics are subdominant
- Many estimates of training set requirements (Ma et al. 2006, Bernstein & Huterer 2009, Hearin et al. 2010, LSST Science Book, etc.)
- General consensus that roughly 20k-30k extremely faint galaxy spectra are required to characterize:
  - Typical z_{spec}-z_{phot} error distribution
  - Accurate catastrophic failure rates for all objects with $z_{phot} < 2.5$
  - Characterize all outlier islands in z_{spec}-z_{phot} plane via targeted campaign (core errors easier to determine)
- Those numbers of redshifts are achievable with GMT, if multiplexing is high enough

What qualities do we desire in our training sets?

- **Sensitive spectroscopy of faint objects (to i=23.7 for DES, 25.3 for LSST)**

  - Need a combination of large aperture and long exposure times; >20 Keck-nights (=4 GMT-nights) equivalent per target, minimum

- **High multiplexing**

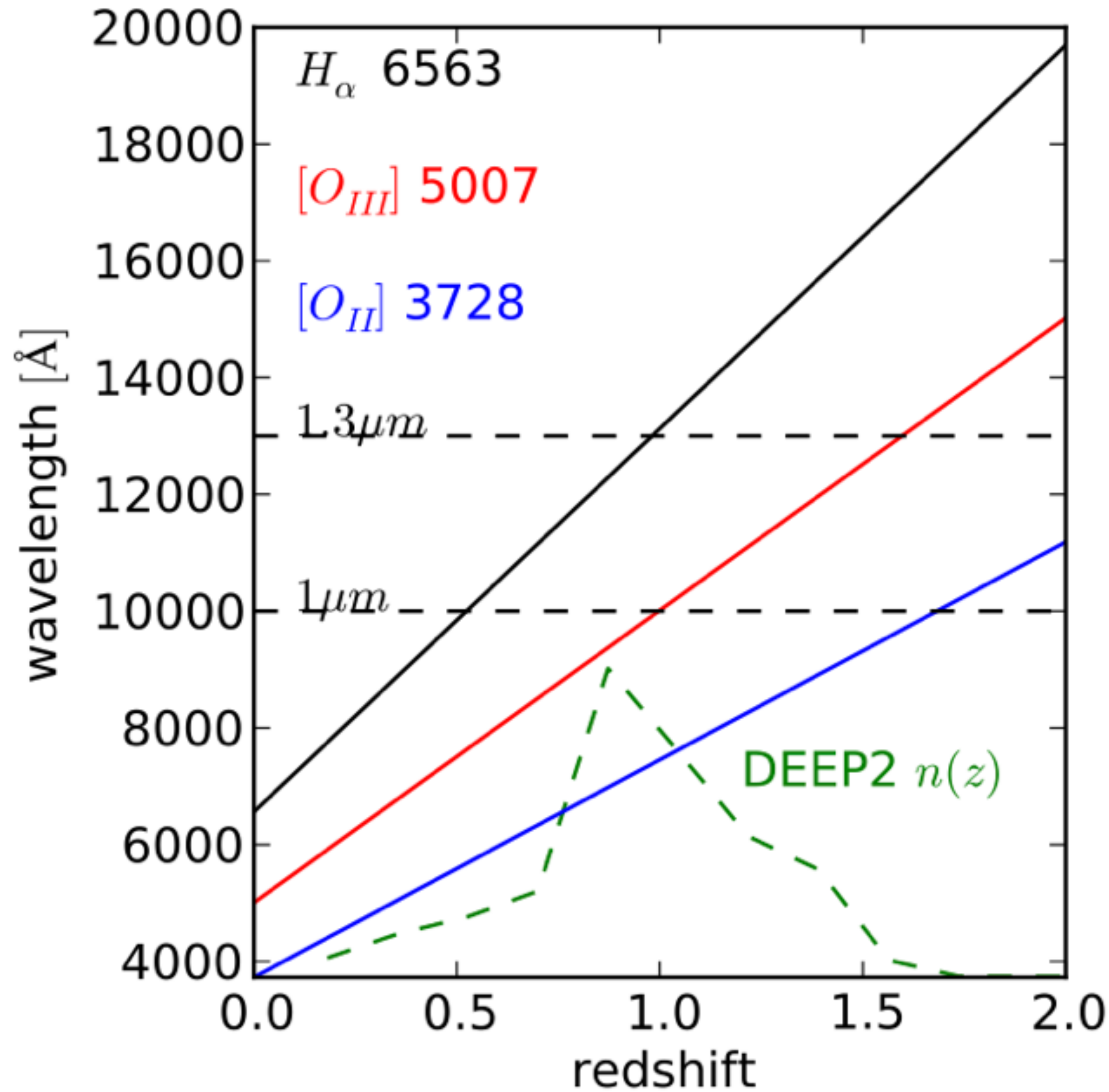
  - Obtaining large numbers of spectra is infeasible without it

What qualities do we desire in our training sets?

- **Coverage of full ground-based window**

  - Ideally, from below 4000 Å to ~1.5µm

    - Require multiple features for secure redshift

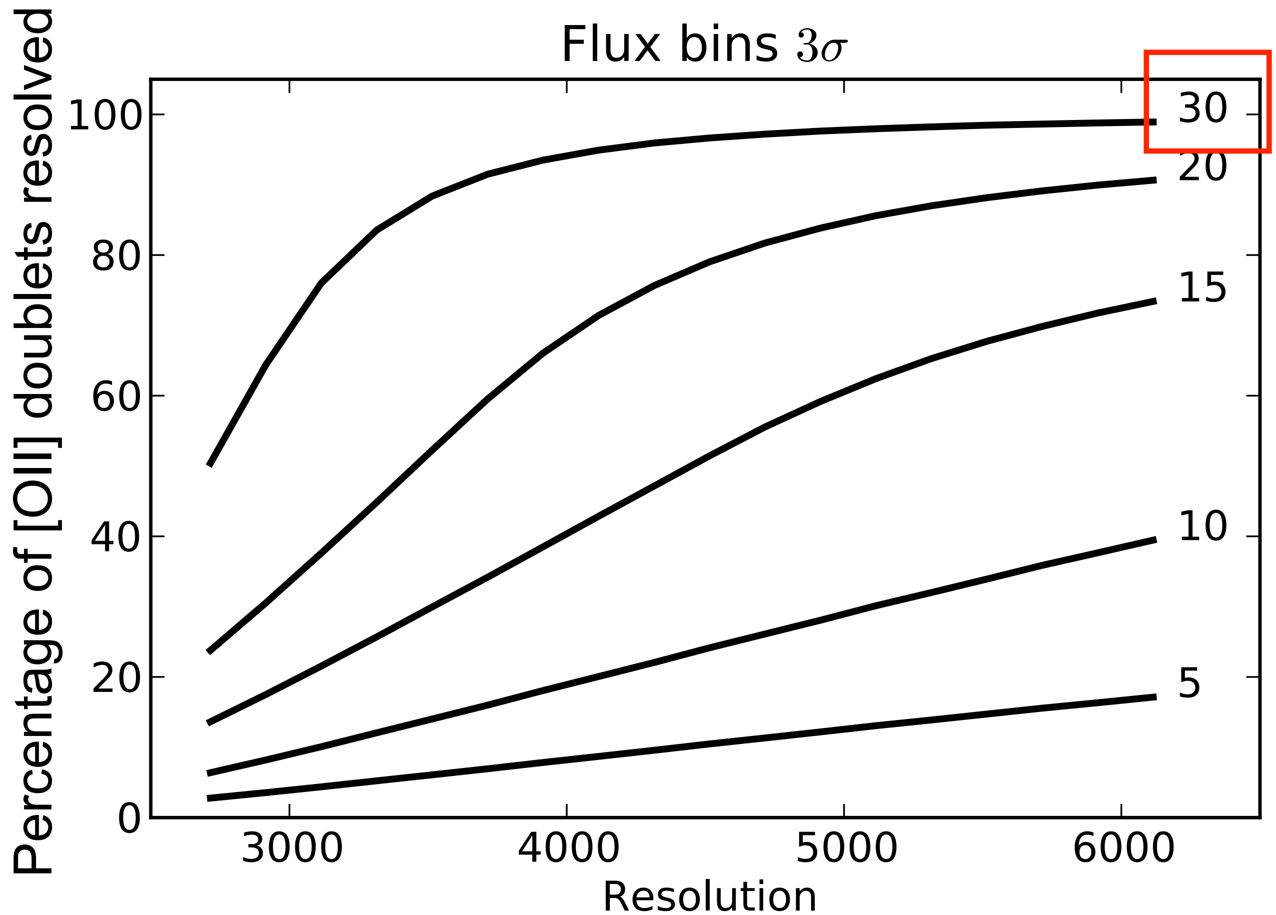


Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

- **Significant resolution (R>~4000) at red end**

  - Allows redshifts from [OII] 3727 Å doublet alone, key at *z*>1



Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

- **Field diameters > ~20 arcmin**

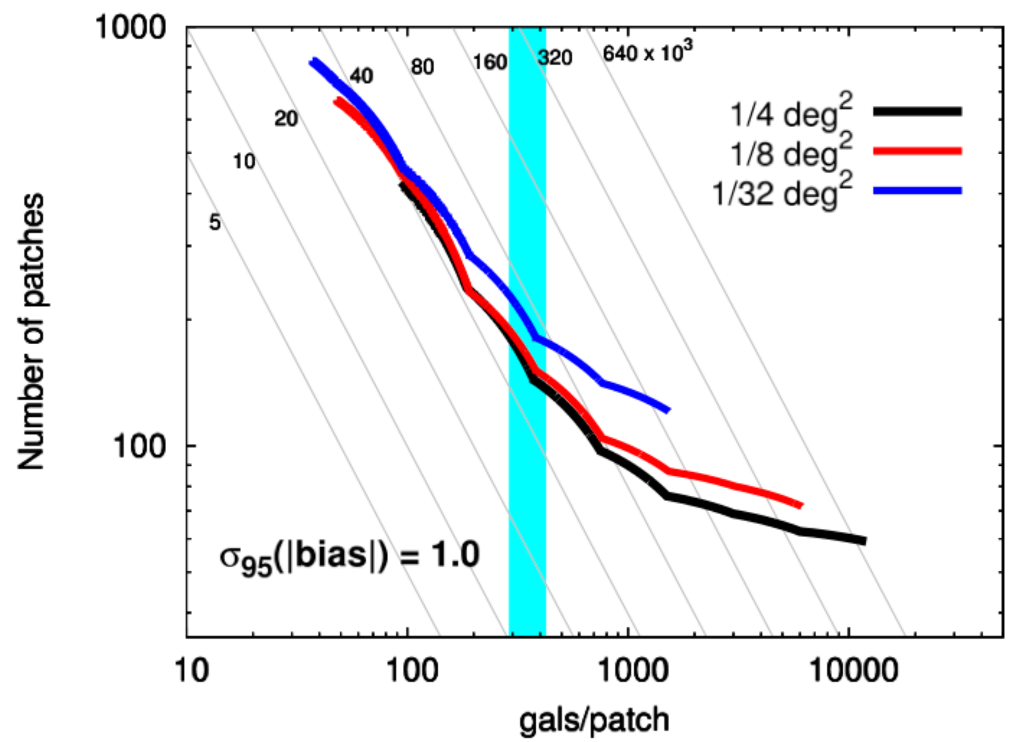
  - Need to span several correlation lengths for accurate clustering measurements (key for galaxy evolution science and cross-correlation techniques)

  - $r_0 \sim 5\ h^{-1}$ Mpc comoving corresponds to ~7.5 arcmin at z=1, 13 arcmin at z=0.5

- **Many fields**

  - Minimizes impact of sample/ cosmic variance.

    - e.g., Cunha et al. (2012) estimate that 40-150 ~0.1 deg^2 fields are needed for DES for sample variance not to impact errors (unless we get clever)



Cunha et al. 2012

Summary of (some!) potential instruments

Telescope / Instrument	Collecting Area (m^2)	Field area ($arcmin^2$)	Multiplex	Limiting factor
Keck / DEIMOS	76	54.25	150	Multiplexing
VLT / MOONS	58	500	500	Multiplexing
Subaru / PFS (≈MSE)	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE (≈4MOST)	13	11300	1000	Multiplexing
GMT/MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / MOSAIC	978	39-46	160-240	Multiplexing

Table 2-1. *Characteristics of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Assuming that we wish for a survey of ~15 fields of at least 0.09 deg^2 each yielding a total of at least 30,000 spectra, we also list what the limiting factor that will determine total observation time is for each combination: the multiplexing (number of spectra observed simultaneously); the total number of fields to be surveyed; or the field of view of the selected instrument. For GMT/MANIFEST+GMACS and VLT/OPTIMOS, a number of design decisions have not yet been finalized, so a range based on scenarios currently being considered is given.*

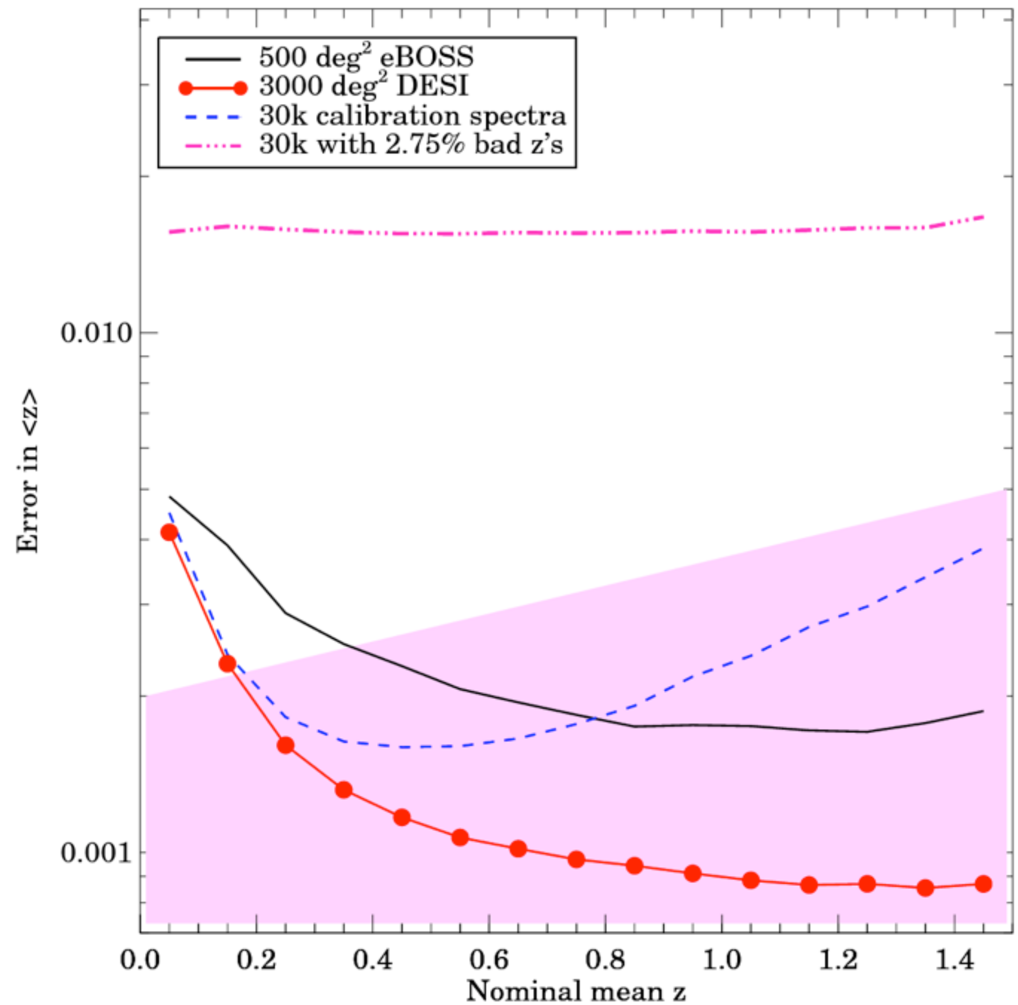
Time required for each instrument

Telescope / Instrument	Total time(y), DES / 75% complete	Total time(y), LSST / 75% complete	Total time(y), DES / 90% complete	Total time(y), LSST / 90% complete
Keck / DEIMOS	0.51	10.22	3.19	63.89
VLT / MOONS	0.20	4.00	1.25	25.03
Subaru / PFS (≈MSE)	0.05	1.10	0.34	6.87
Mayall 4m / DESI	0.26	5.11	1.60	31.95
WHT / WEAVE (≈4MOST)	0.45	8.96	2.80	56.03
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.60 - 4.71
TMT / WFOS	0.09	1.78	0.56	11.12
E-ELT / MOSAIC	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.10 - 4.65

Table 2-2. *Estimates of required total survey time for a variety of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Calculations assume that we wish for a survey of ~15 fields of at least 0.09 deg² each, yielding a total of at least 30,000 spectra. Survey time depends on both the desired depth (i=23.7 for DES, i=25.3 for LSST) and completeness (75% and 90% are considered here). Exposure times are estimated by requiring equivalent signal-to-noise to 1-hour Keck/DEIMOS spectroscopy at i~22.5. GMT / MANIFEST + GMACS estimates assume that the full optical window may be covered simultaneously at sufficiently high spectral resolution; in some design scenarios currently being considered, that would not be the case, increasing required time accordingly.*

Wide-field MOS surveys also enable photo-z calibration via cross-correlations

- Galaxies of all types cluster together: trace same dark matter distribution
- Enables reconstruction of *z* distributions via spectroscopic/ photometric cross-correlations (Newman 2008)
- For LSST calibration, require >100k objects over >100 deg^2, spanning full z range
- >500 degrees of overlap with DESI-like survey would meet LSST science requirements (>3000 sq deg of overlap expected).



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

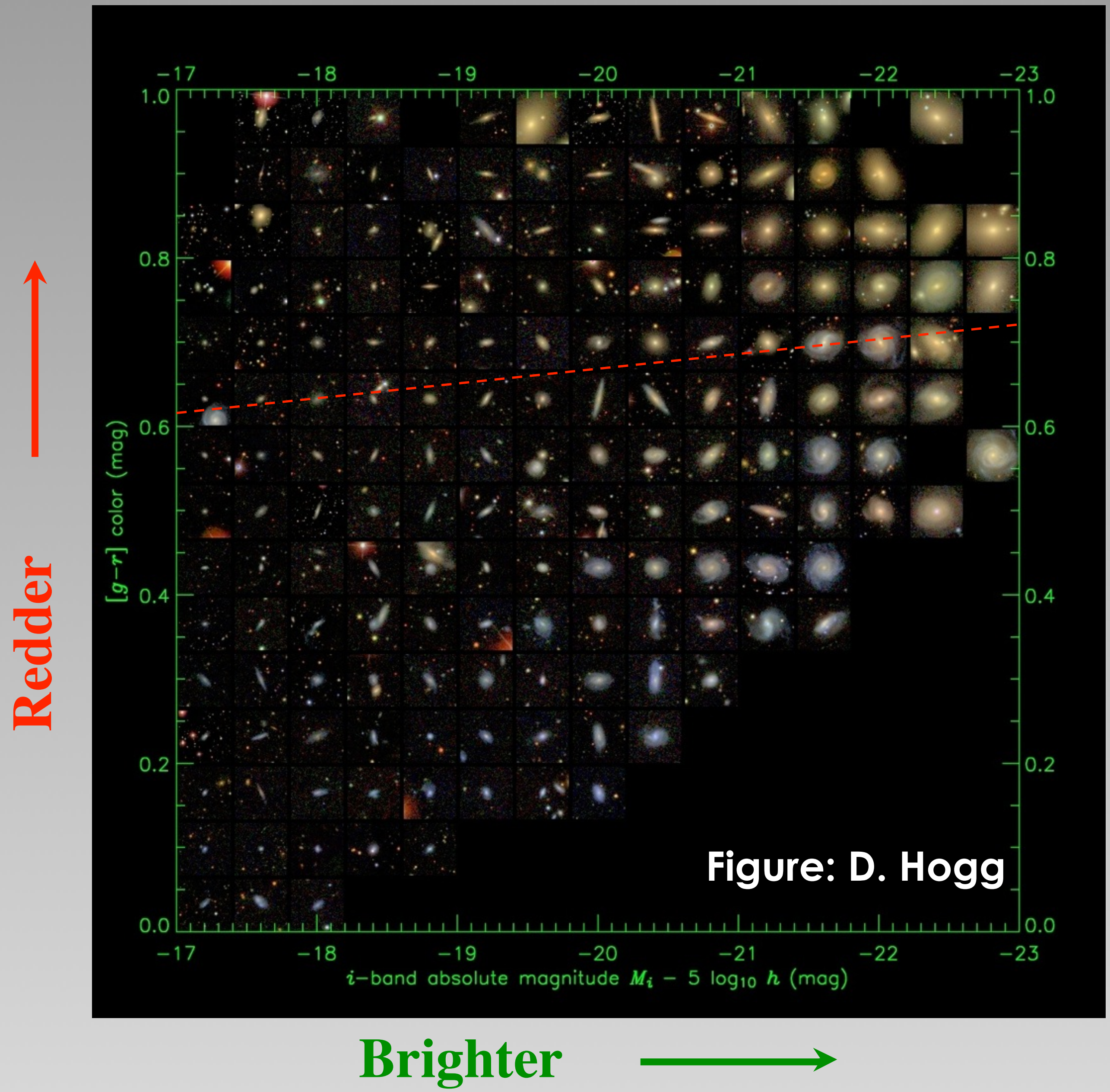
Exploring the Milky Way via its extragalactic analogs

Licquia and Newman, 2015; Licquia, Newman, & Brichmann, submitted; Licquia & Newman 2015a,b in prep.

Image: A face-on MW analog of typical color, SDSS J083909.27+450747.7
MOSAIC camera, 4m Mayall telescope at Kitt Peak
Armin Rest (STScI) & Brittany McDonald (McMaster University)

Color and luminosity are key tools for classifying galaxies

- The easiest (often only) attributes we can measure for most galaxies: need only redshift + photometry
- Depend primarily on a galaxy's history of star formation



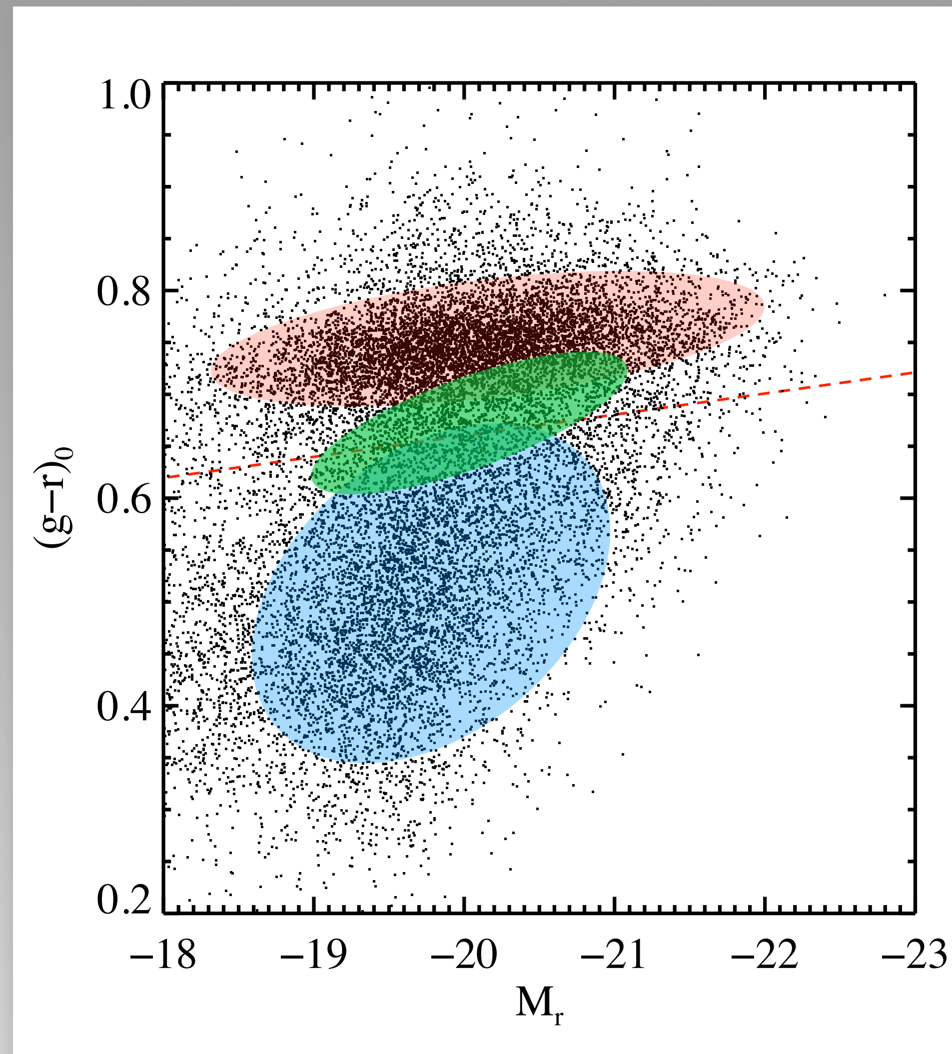
Color and luminosity are key tools for classifying galaxies

- Most galaxies are too far away to see detailed shapes.

- We can still classify them by color: quiescent "red sequence", star-forming "blue cloud", and transitional "green valley"

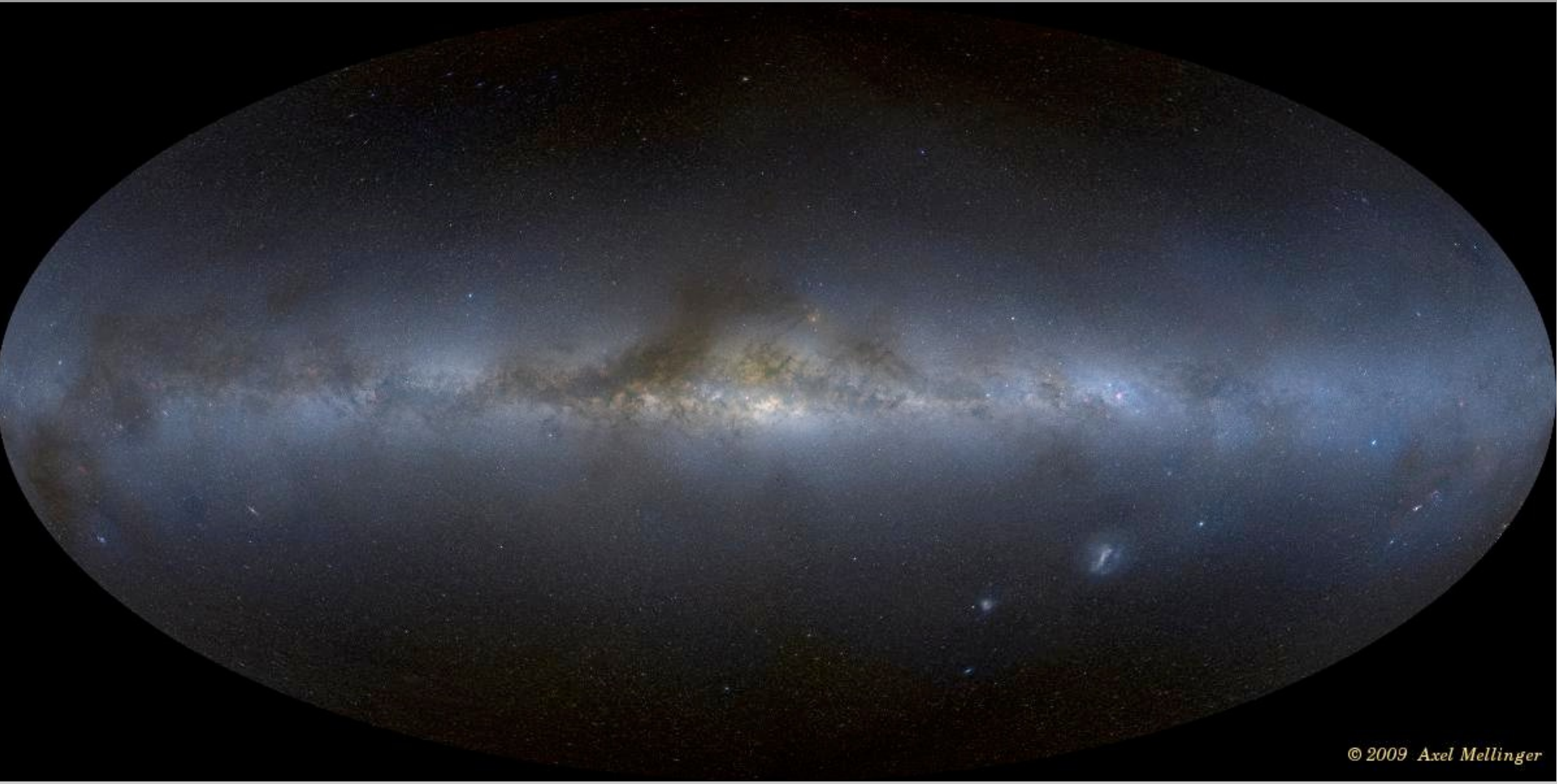
- Where would the Milky Way fall on this diagram?

Redder



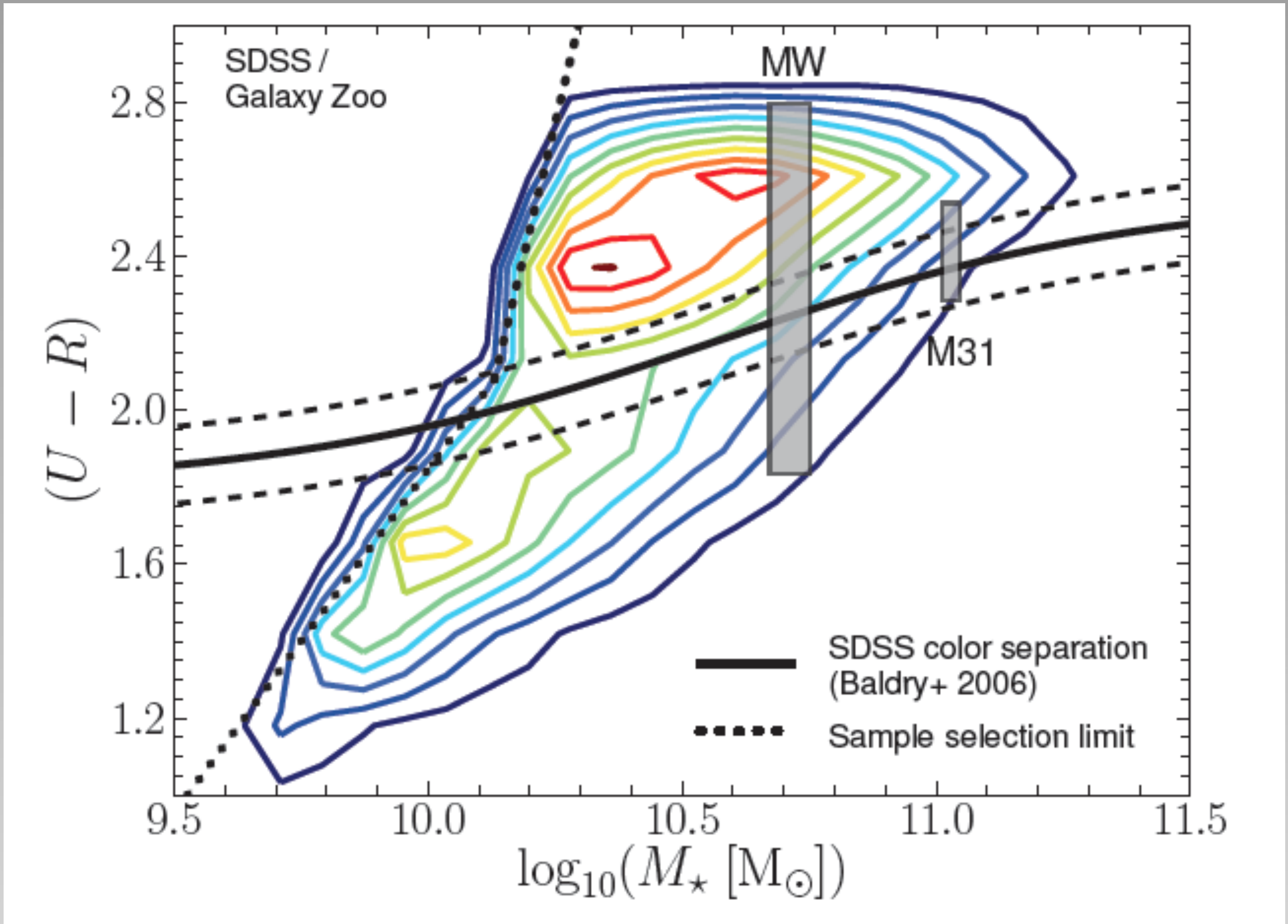
Brighter

Our location within the Milky Way makes determining its overall color difficult



• Note colors in this photographic panorama: MW looks white at night because low-light vision is black-and-white

Inspiration: Mutch et al. 2011



New method: find analogs of the Milky Way and measure their colors

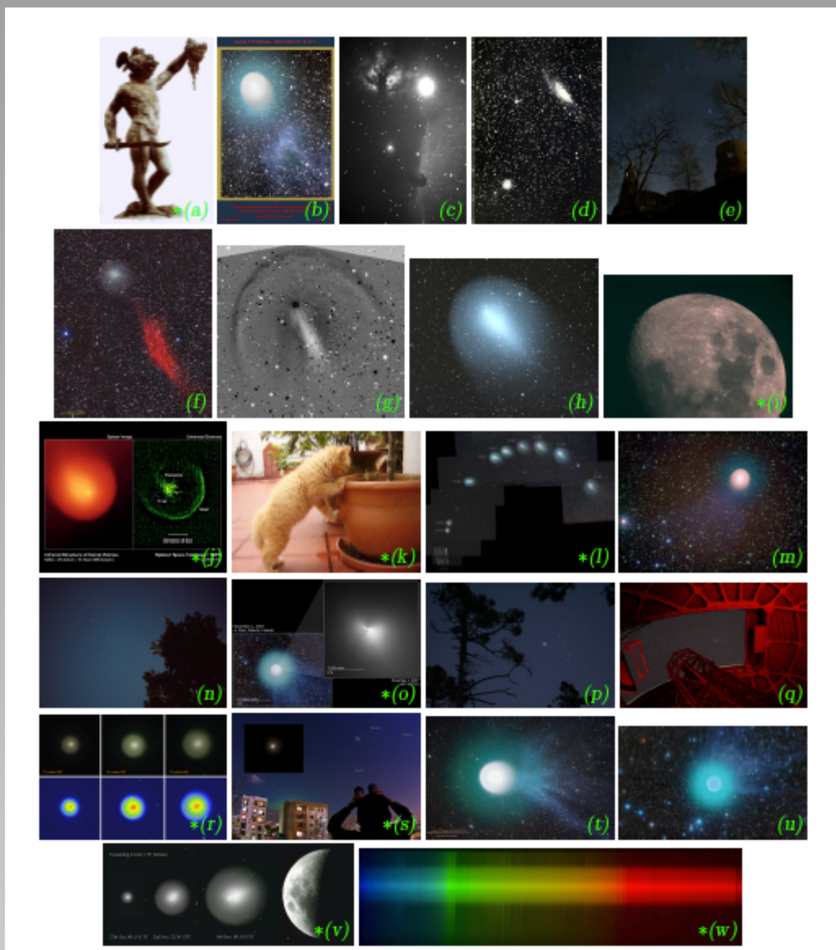
- We identify galaxies in SDSS sample matching Milky Way (given uncertainties) in total mass of stars (M_*) and rate of making new stars (SFR)

- Then we can determine their color and luminosity

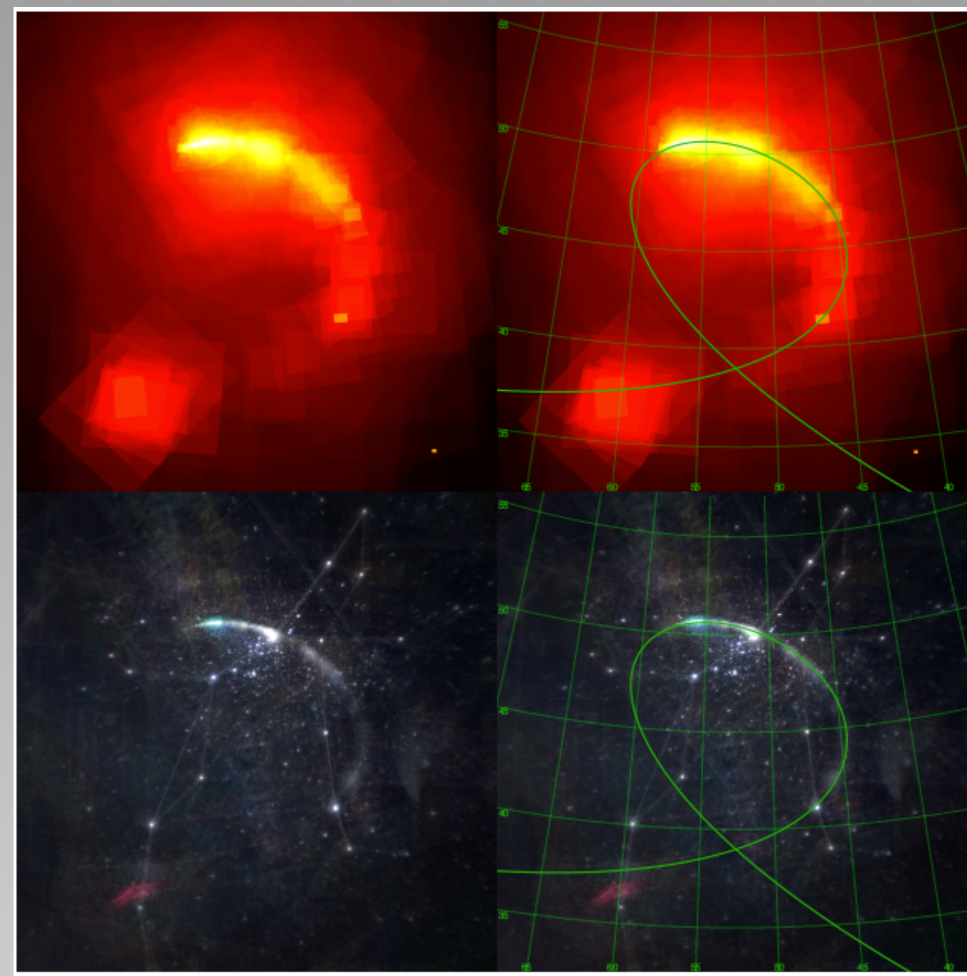
- The first problem: there are many estimates of the MW M_* and SFR…

Images from SDSS; colored to highlight contrasts, not what eye would see

We combine these measurements with a Hierarchical Bayesian meta-analysis



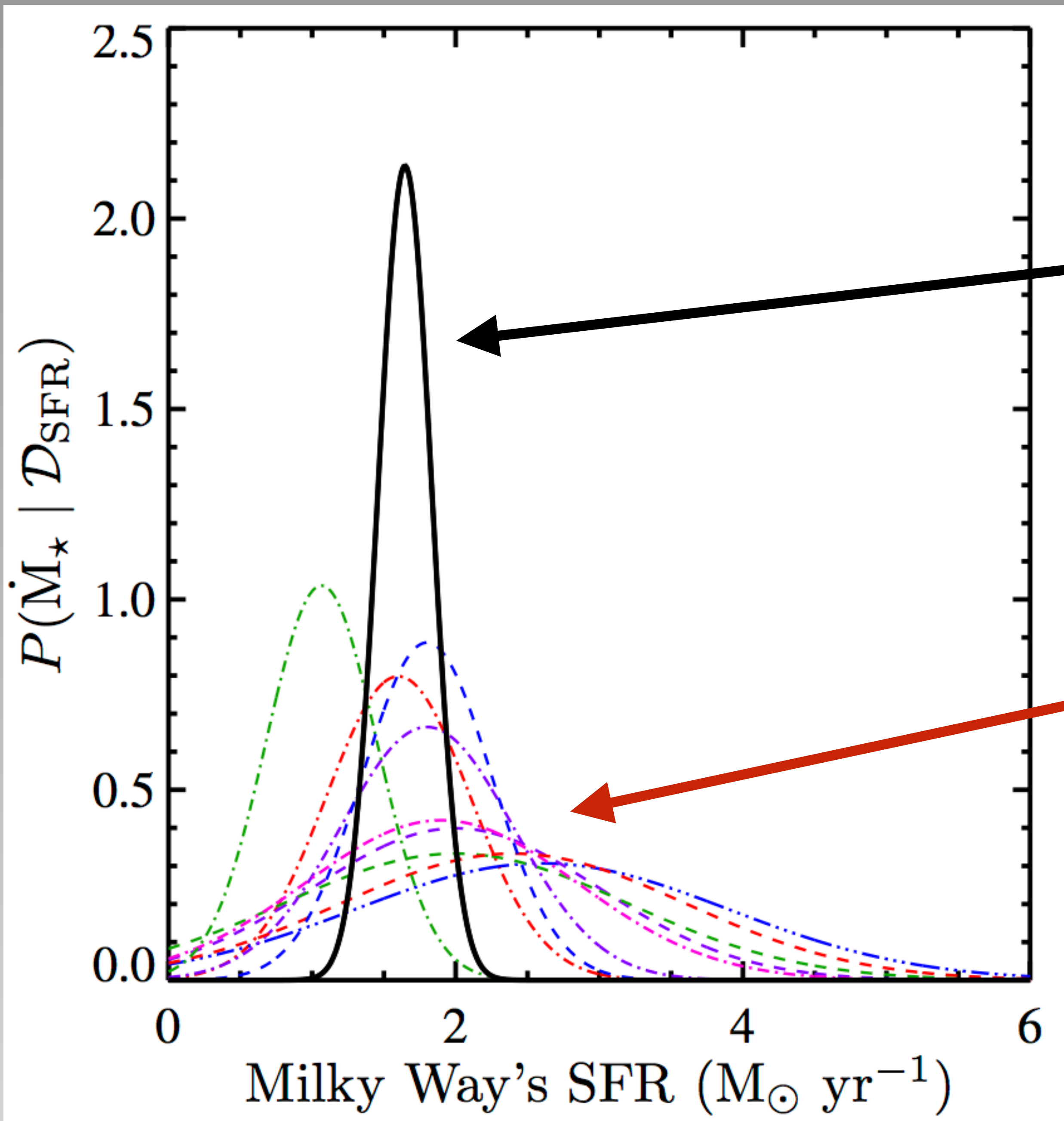
Yahoo! Search: “Comet Holmes”



Orbit reconstruction

Dustin Lang & David Hogg (2011)

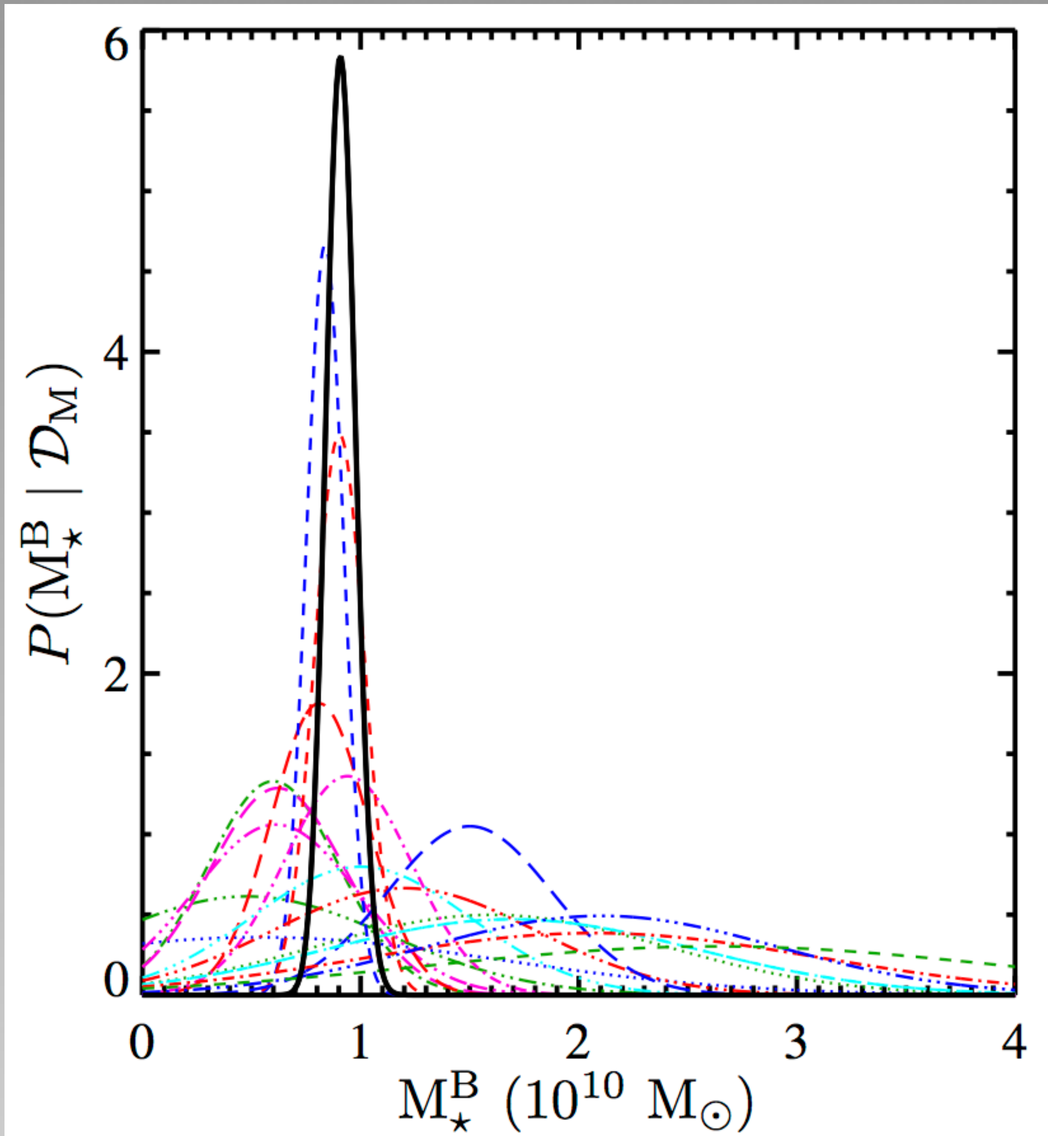
Meta-Analysis of SFR Values



Aggregate Result:
$\dot{M}_\star = 1.65 \pm 0.19\ M_\odot\ yr^{-1}$

Compilation of MW SFR values on same normalization from Chomiuk & Povich (2010)

Meta-Analysis of Stellar Mass Values



Aggregate Result:

$M_{\star,B}$ = 0.91 ± 0.07 x 10^{10} $M_\odot$

- We compiled bulge mass measurements and remapped them to common assumptions
- We combine this with the Bovy & Rix (2013) disk, remapped to the same R_0 & definition of stellar mass used for other galaxies:

$M_{\star,D}$ = 5.17 ± 1.11 x 10^{10} $M_\odot$

to get:

$M_\star$ = 6.08 ± 1.14 x 10^{10} $M_\odot$

B/T = 0.15 ± 0.02

Selecting Milky Way analogs

Milky Way Measurements

Total Stellar Mass ($M_\star$)

Star Formation Rate ($\dot{M}_\star$)

ugriz mags & colors

SDSS Galaxy Measurements

Total Stellar Mass ($M_\star$)

MPA-JHU

Star Formation Rate ($\dot{M}_\star$)

MPA-JHU

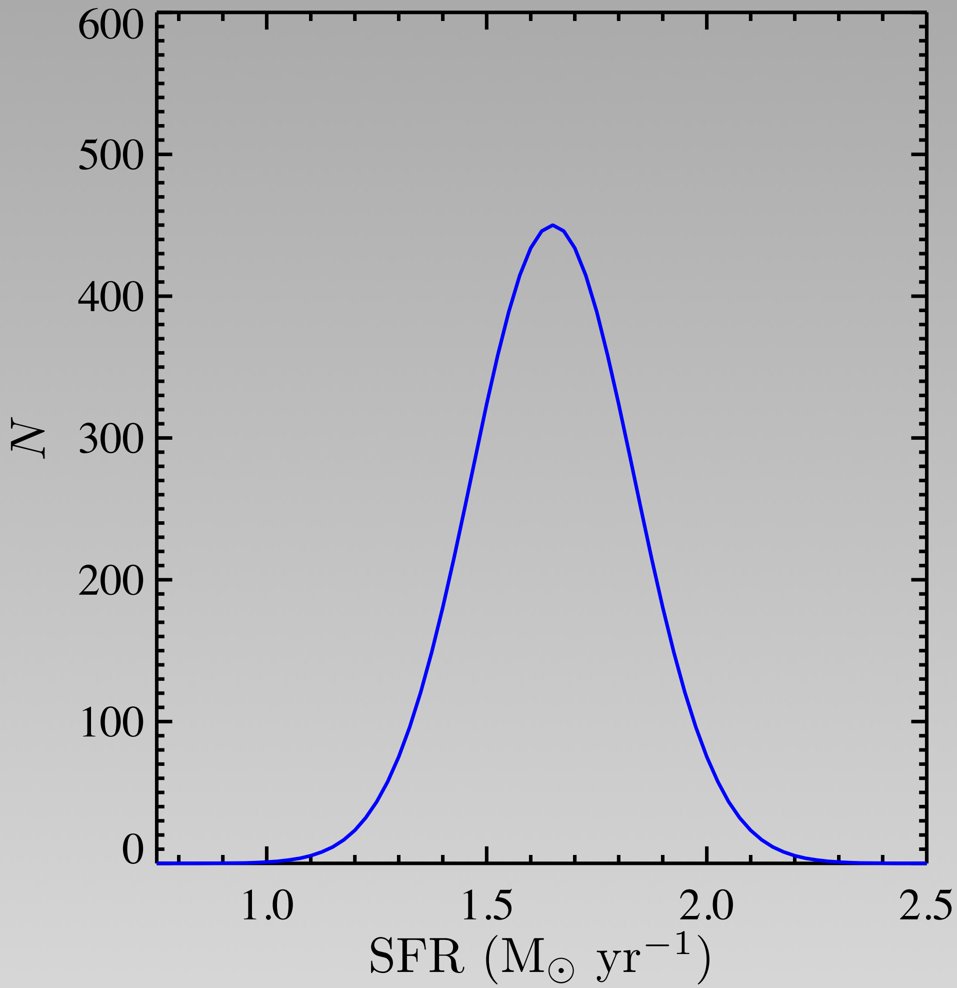
ugriz mags & colors

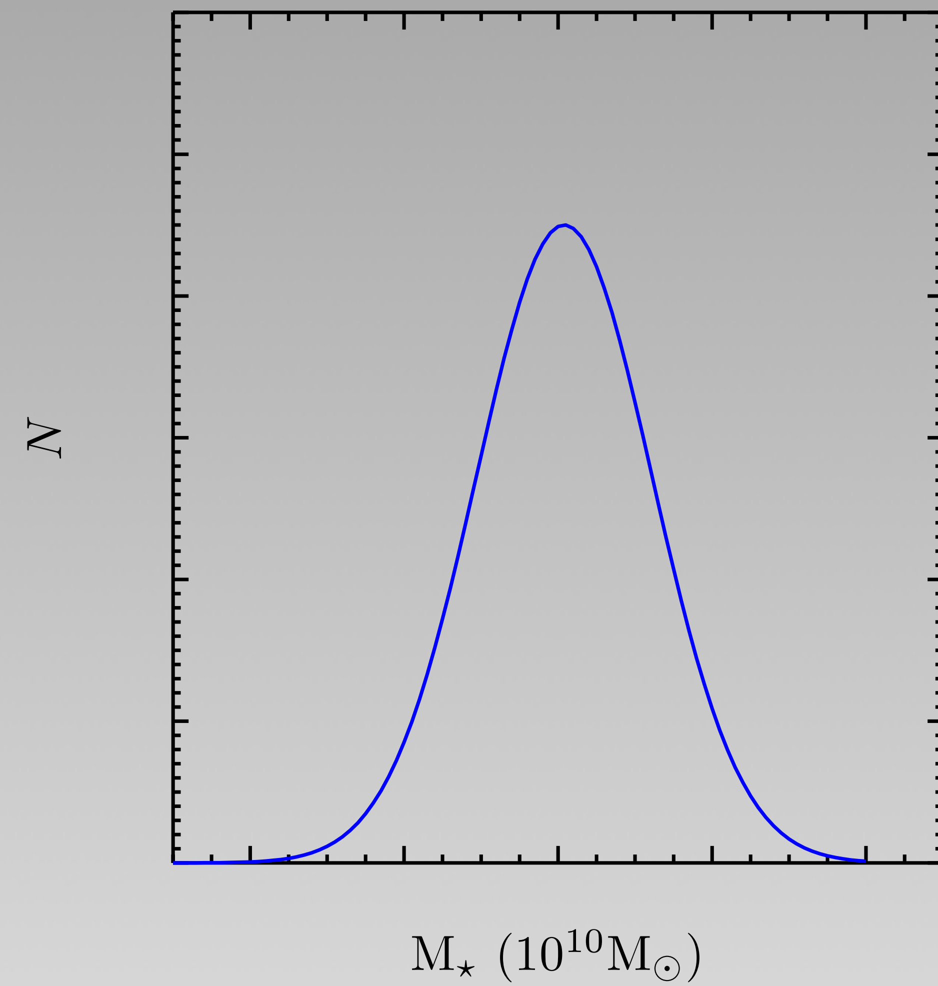
The Mass Properties of the Milky Way

Licquia & Newman 2015
(arXiv:1407.1078)

$\dot{M}_\star = 1.65 \pm 0.19\ M_\odot$ yr-1

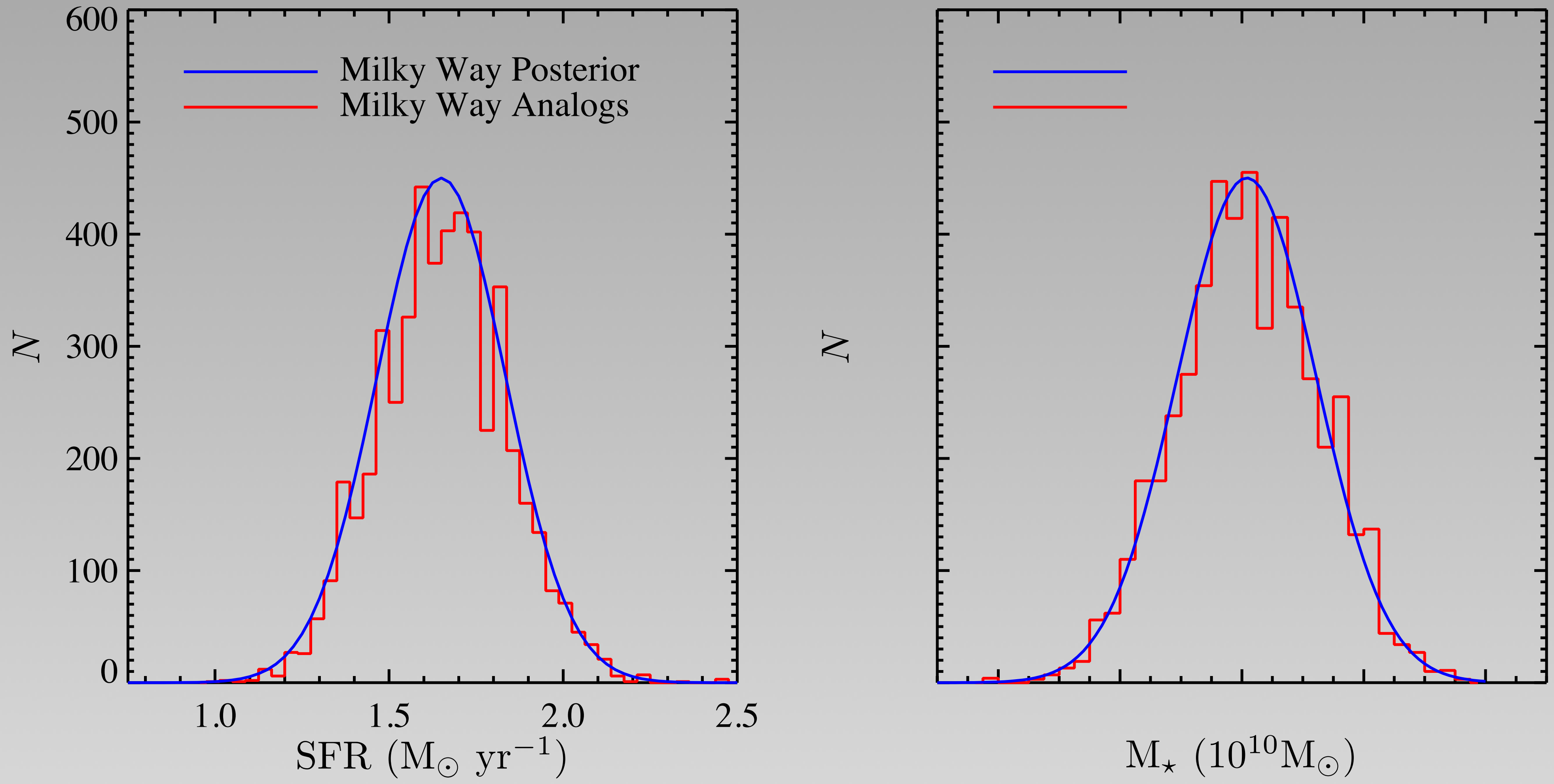
$M_\star = 6.08 \pm 1.14 \times 10^{10}\ M_\odot$



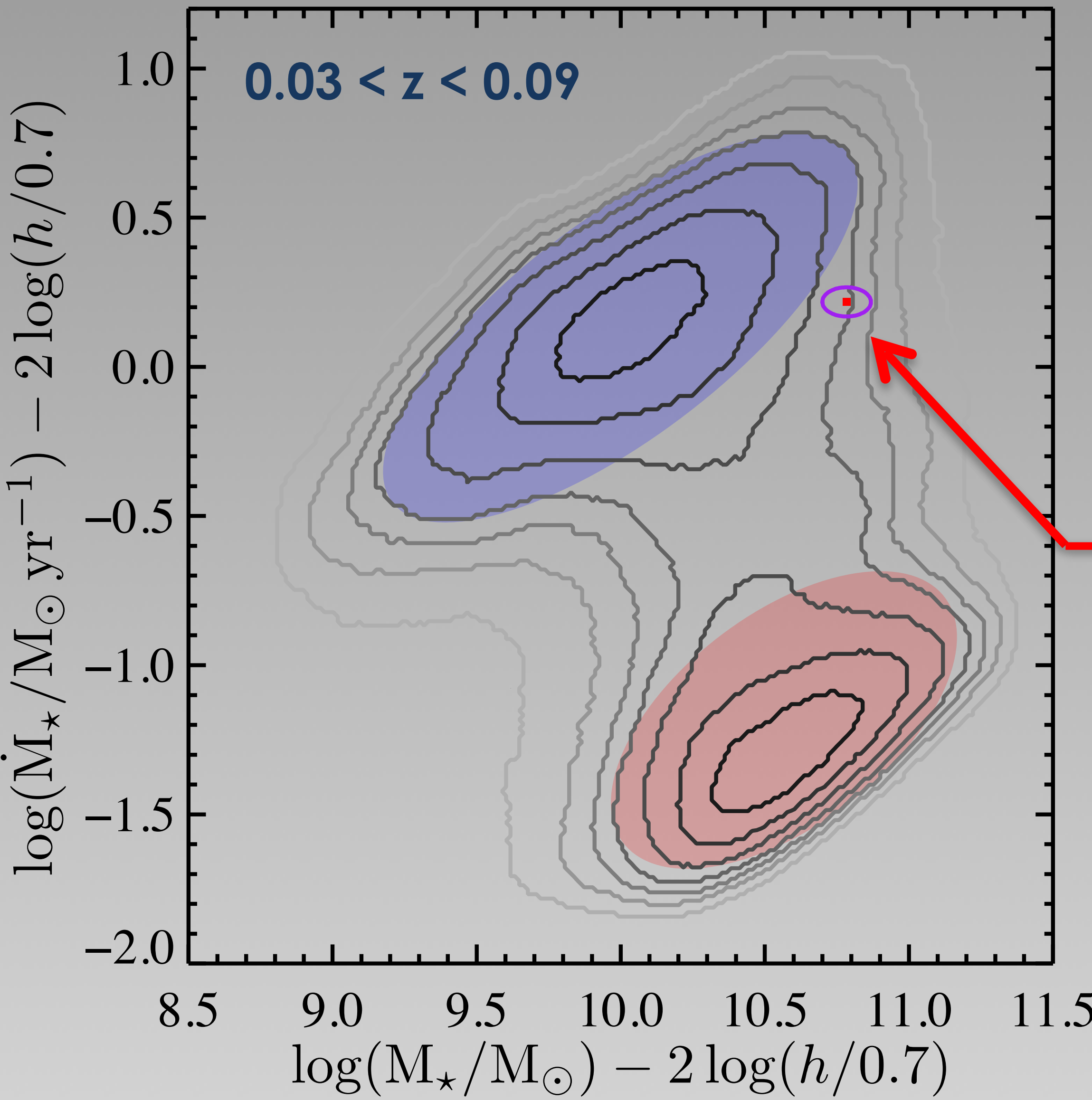


A Sample of Milky Way Analogs

5,000 SDSS galaxies whose distribution of masses & SFRs match the Galactic posterior PDFs



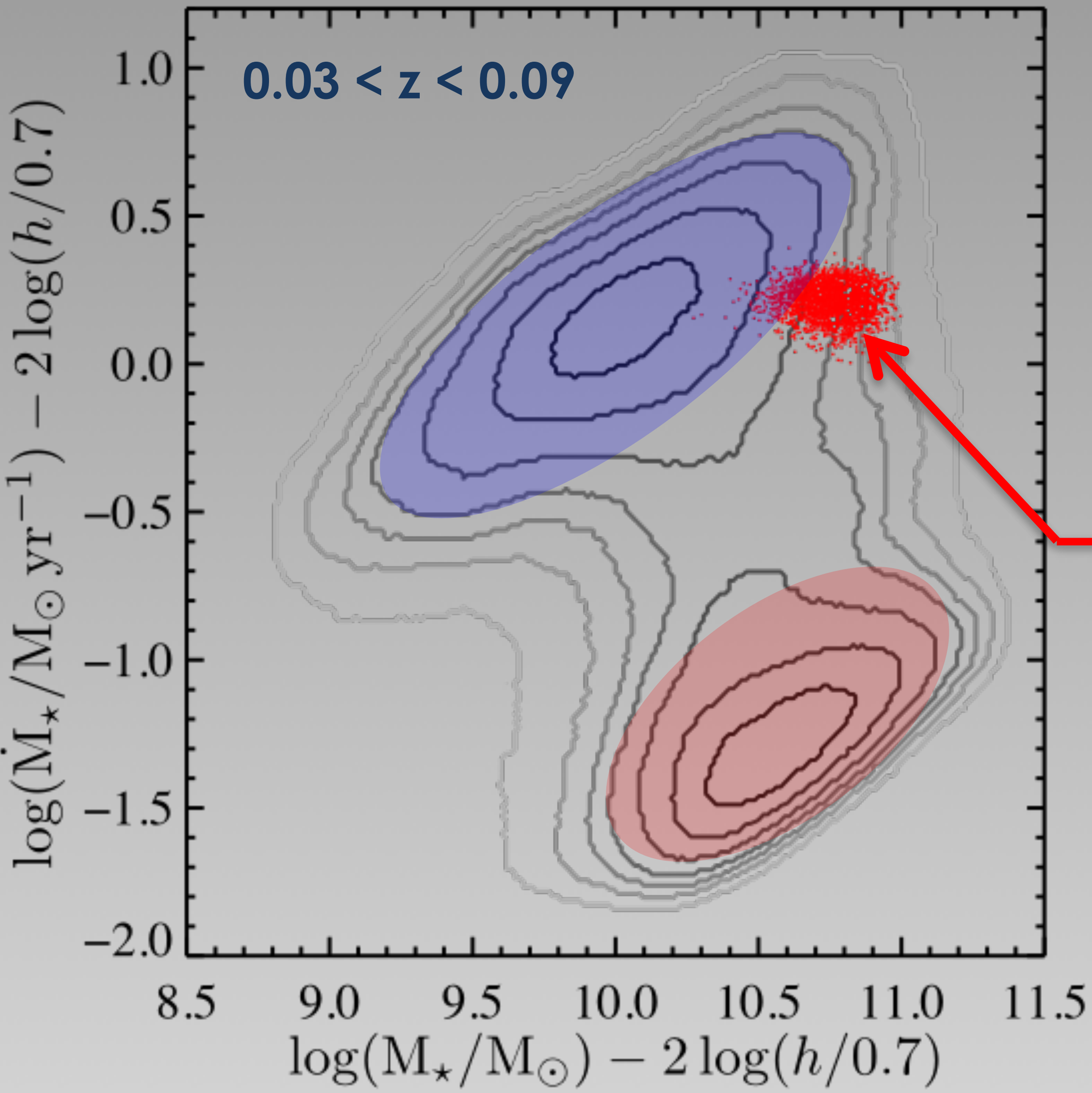
A Sample of Milky Way Analogs



The SFR–Stellar Mass Plane of SDSS Galaxies

Milky Way Posterior

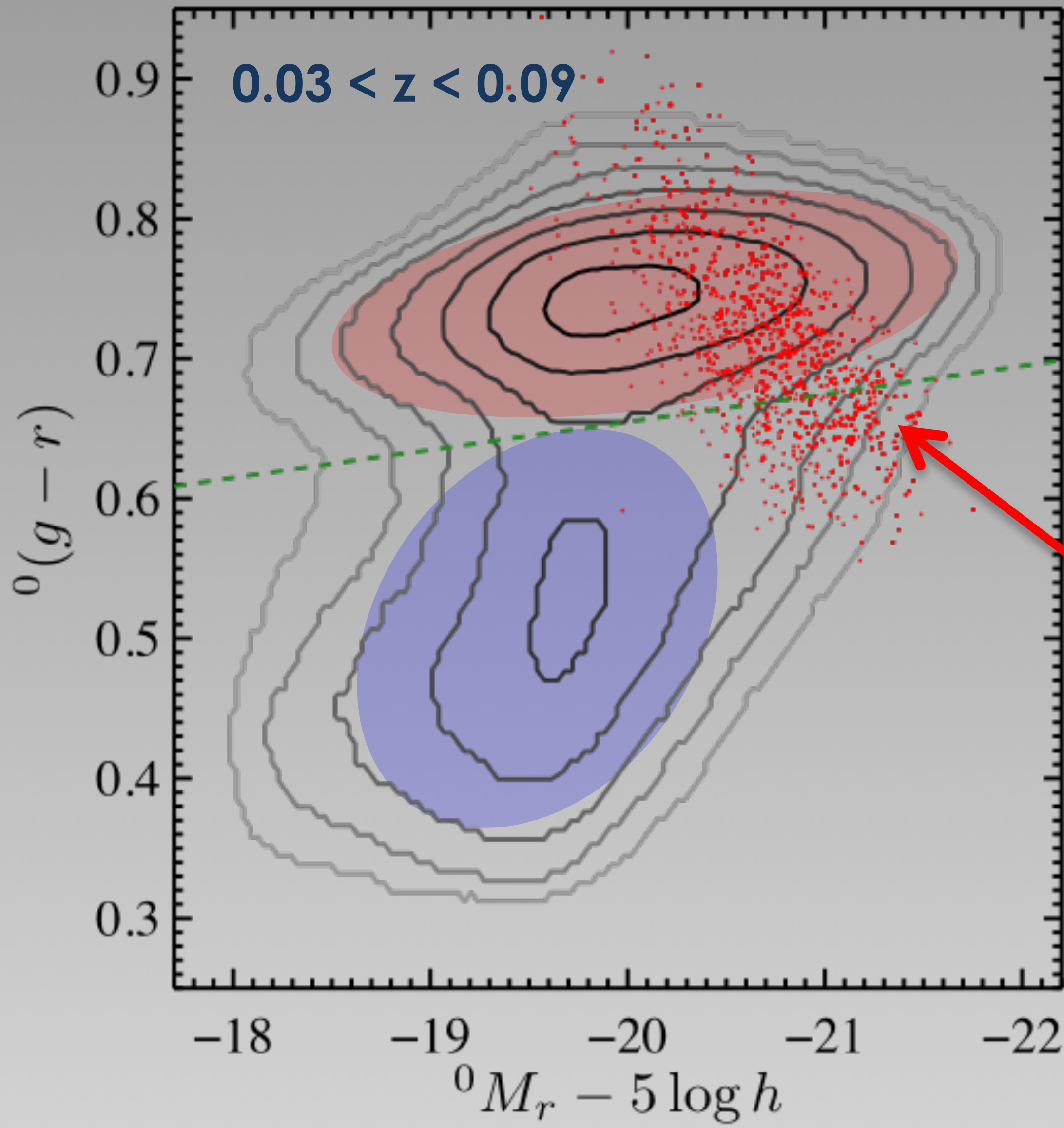
A Sample of Milky Way Analogs



The SFR–Stellar Mass Plane of SDSS Galaxies

5,000 Milky Way Analogs

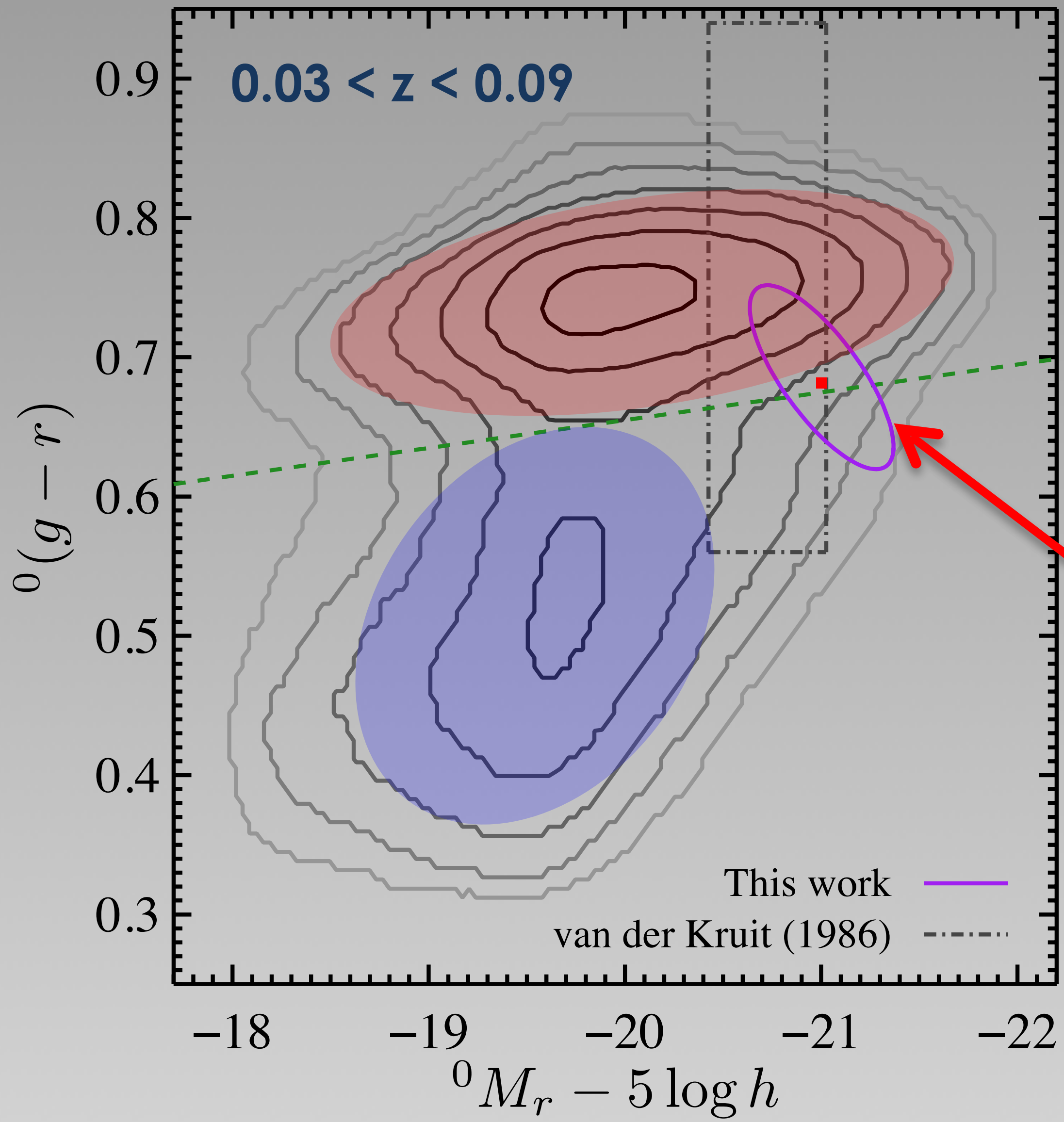
A Sample of Milky Way Analogs



The Color–Magnitude Diagram

5,000 Milky Way Analogs

The Milky Way on the CMD

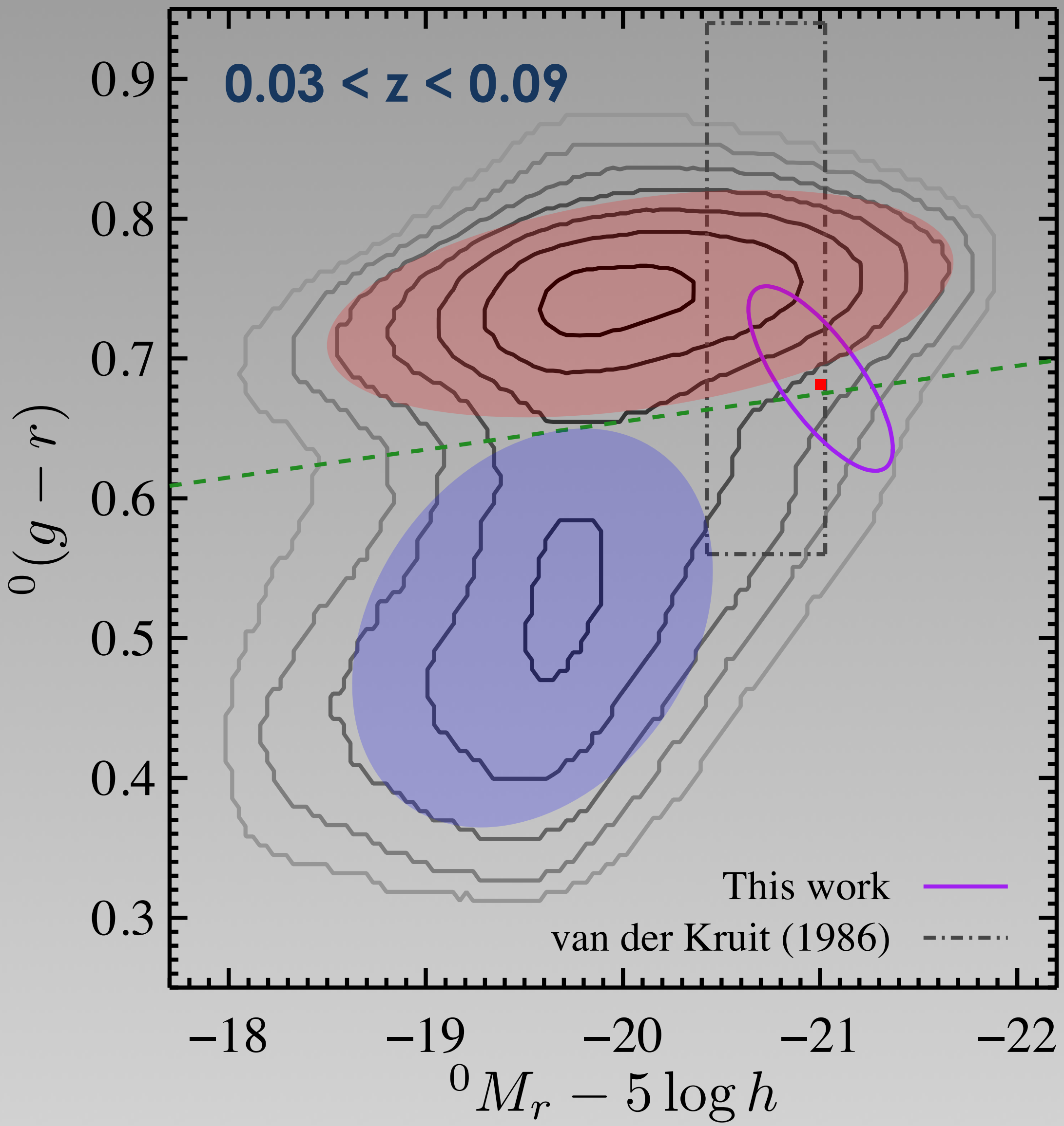


The Color–Magnitude Diagram

New Constraints on Milky Way Photometric Properties

(corrected for systematics)

The Milky Way on the CMD



- We can predict any property for the MW that we can measure in SDSS: absolute magnitudes, colors, AGN duty cycles, pseudobulge rate, etc. E.g.,

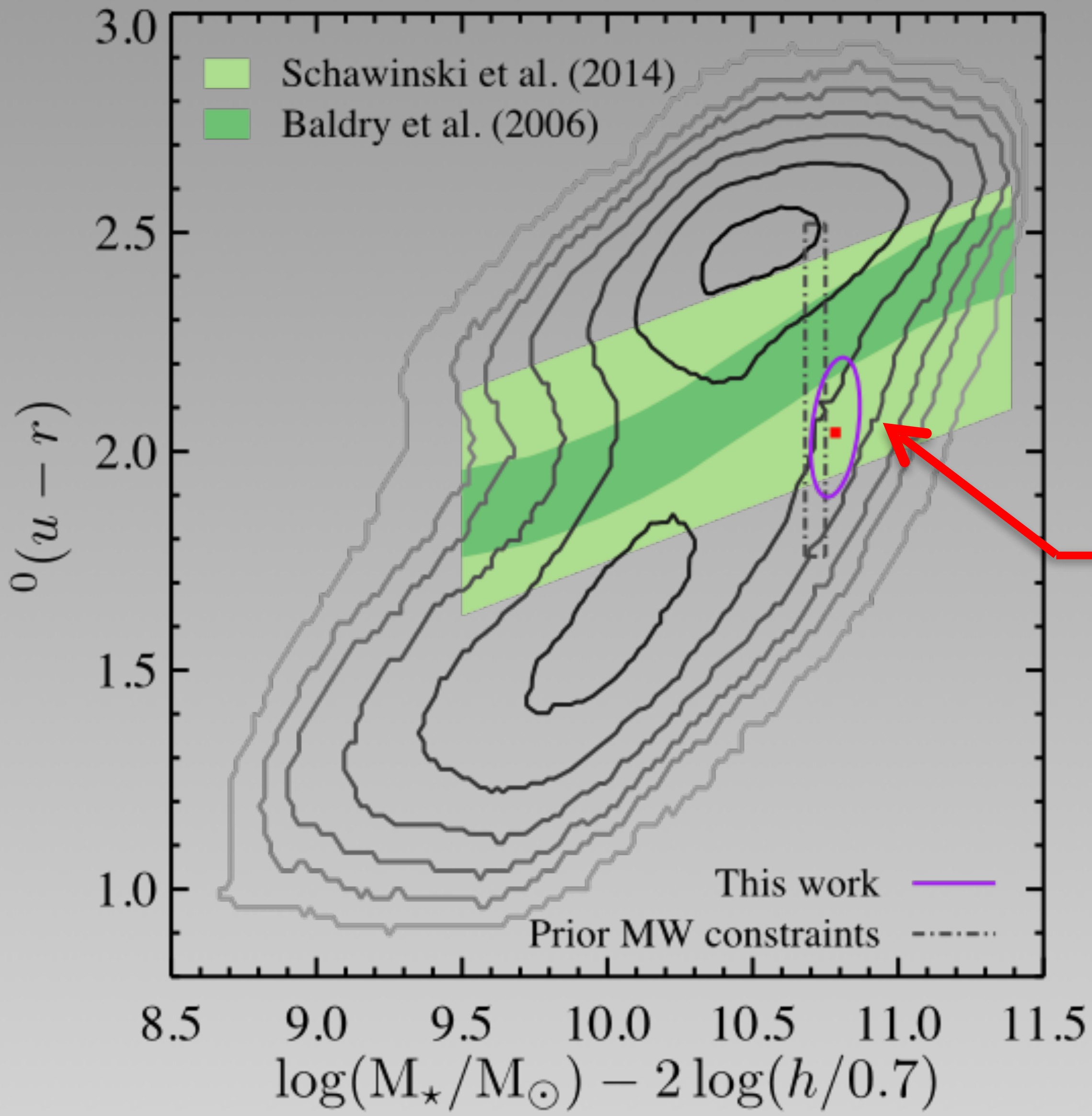
$$^{0.1}M_r - 5\log h = -21.07^{+0.40}_{-0.33}$$

$$^{0.1}(g-r) = 0.703^{+0.071}_{-0.061}$$

- Compare to luminosity of typical bright galaxy:

$$^{0.1}M_{*,r} - 5\log h = -20.73$$

Is the Milky Way a Green Valley galaxy?



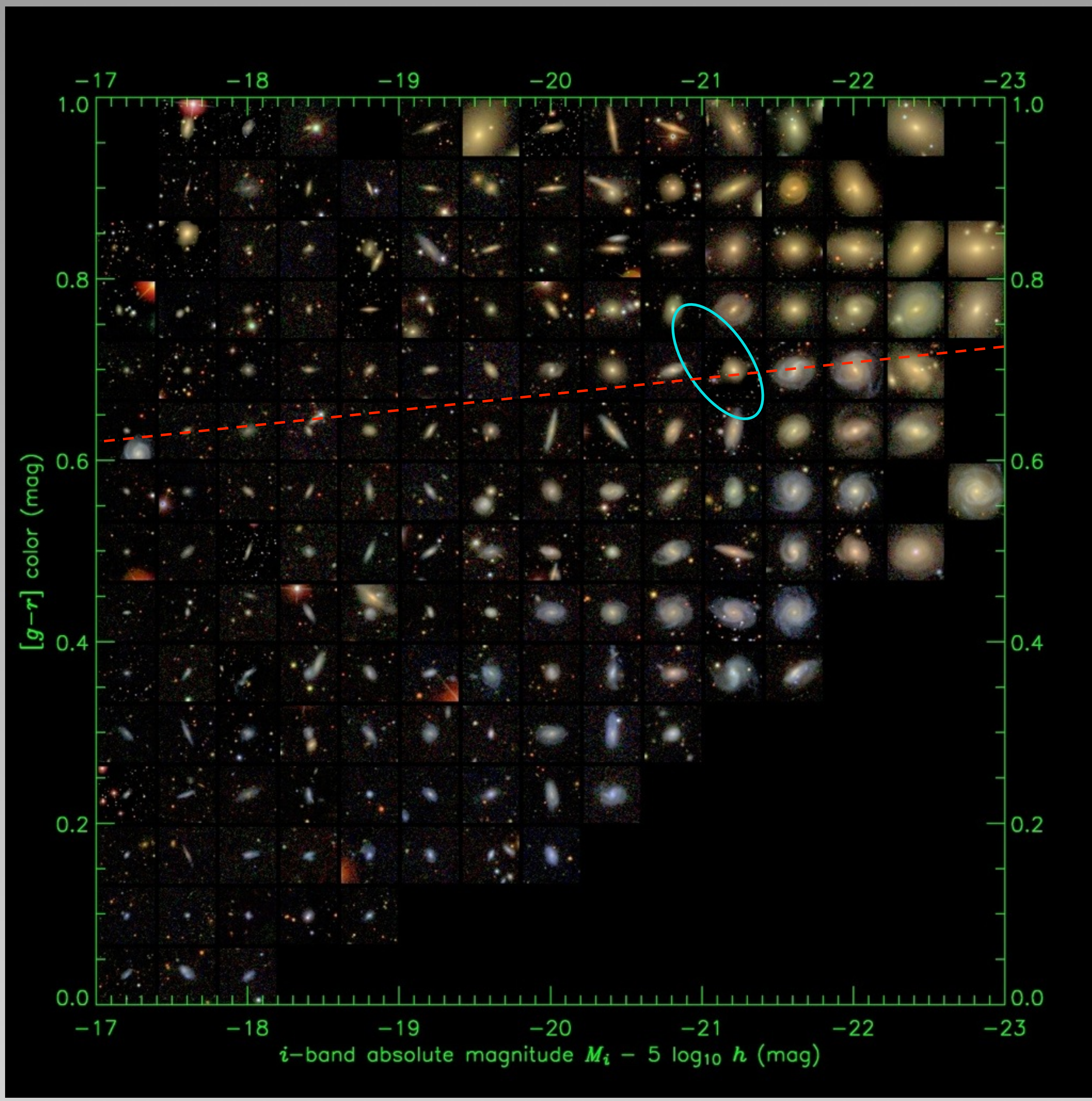
The Color–Mass Diagram

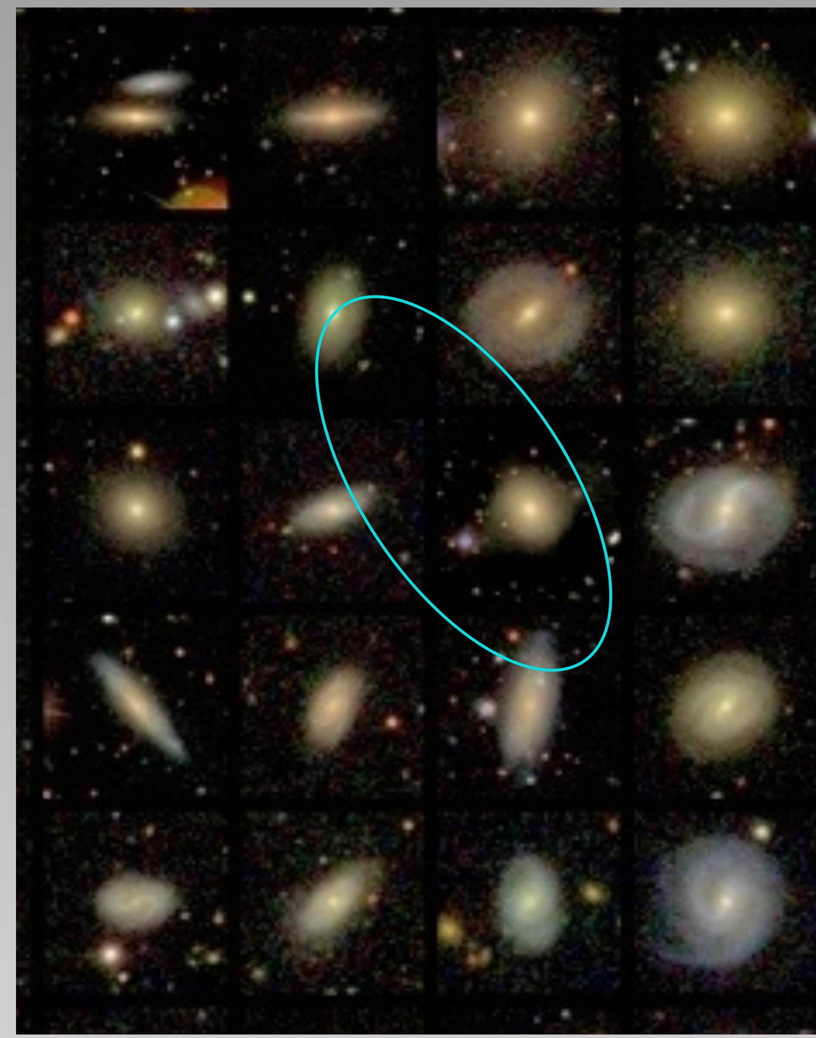
New Constraints on Milky Way Photometric Properties

(corrected for systematics)

The Milky Way on the optical color-magnitude diagram

Redder

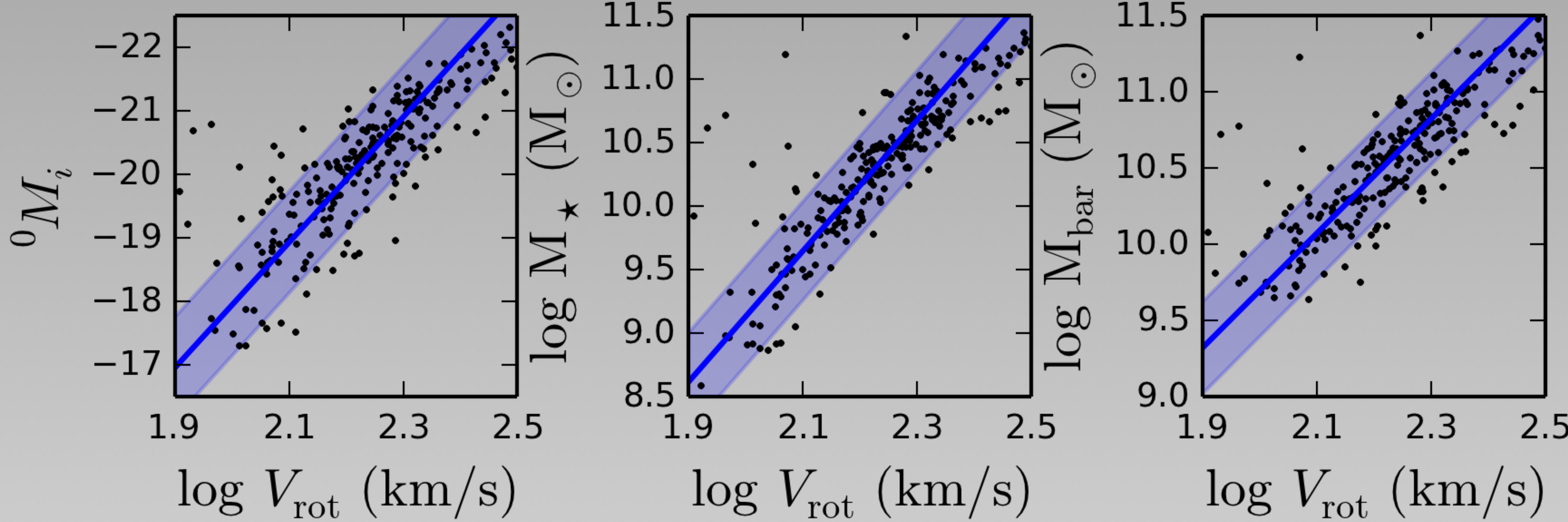




Brighter

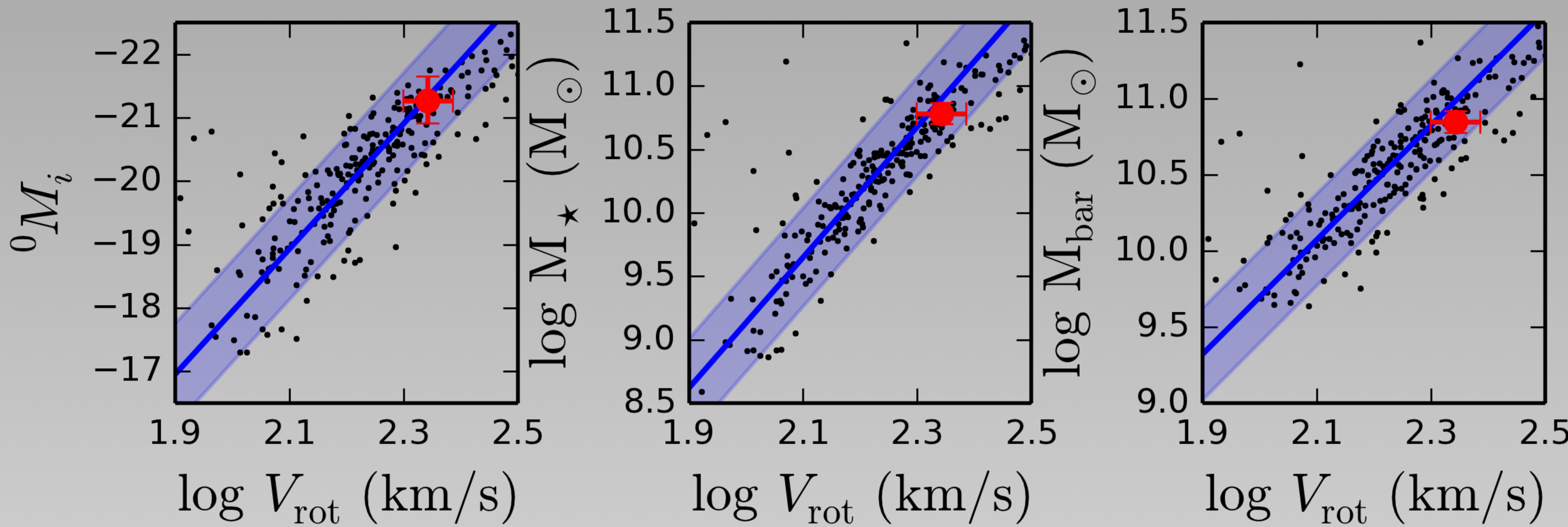
The Milky Way vs. the Tully-Fisher Relation

V_{rot} measured from 21cm linewidths (SFI++ catalog, Springob+07)



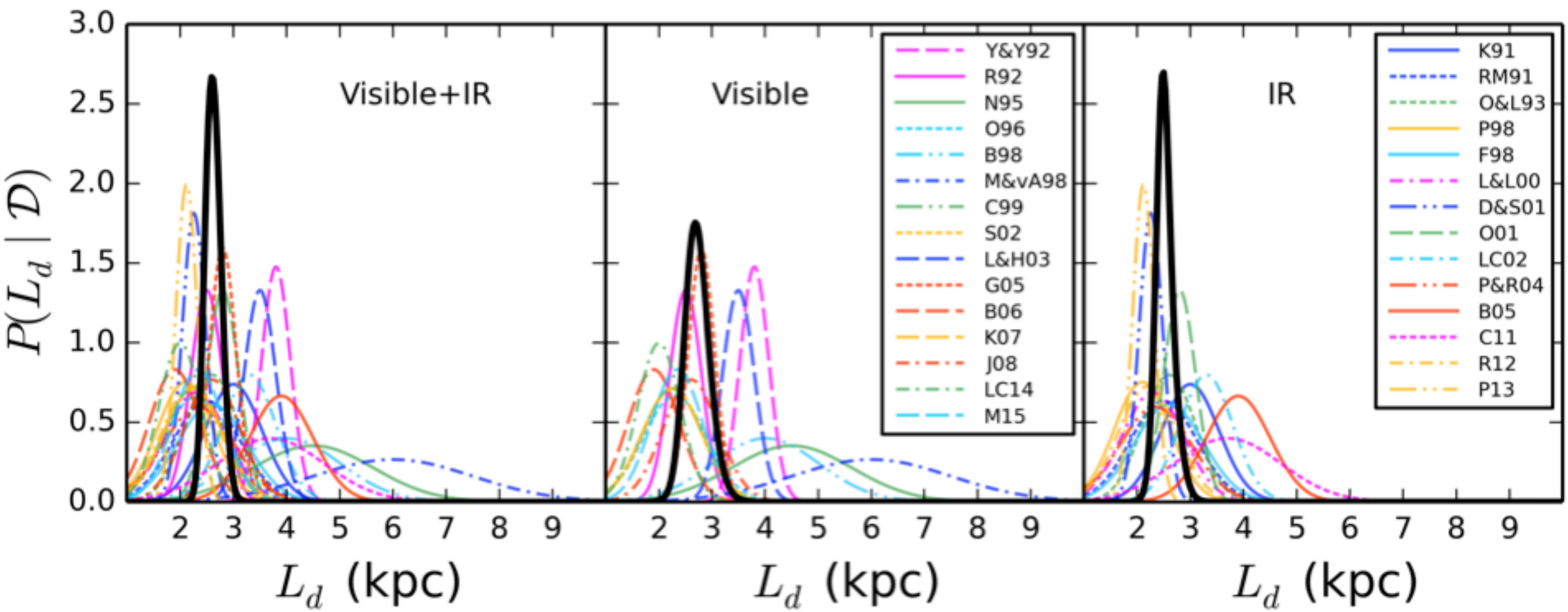
The Milky Way vs. the Tully-Fisher Relation

V_{rot} measured from 21cm linewidths
(SFI++ catalog, Springob+07)



The Milky Way is typical in TFR space!

Licquia & Newman 2015a: Hierarchical Bayesian meta-analysis of scale length measurements



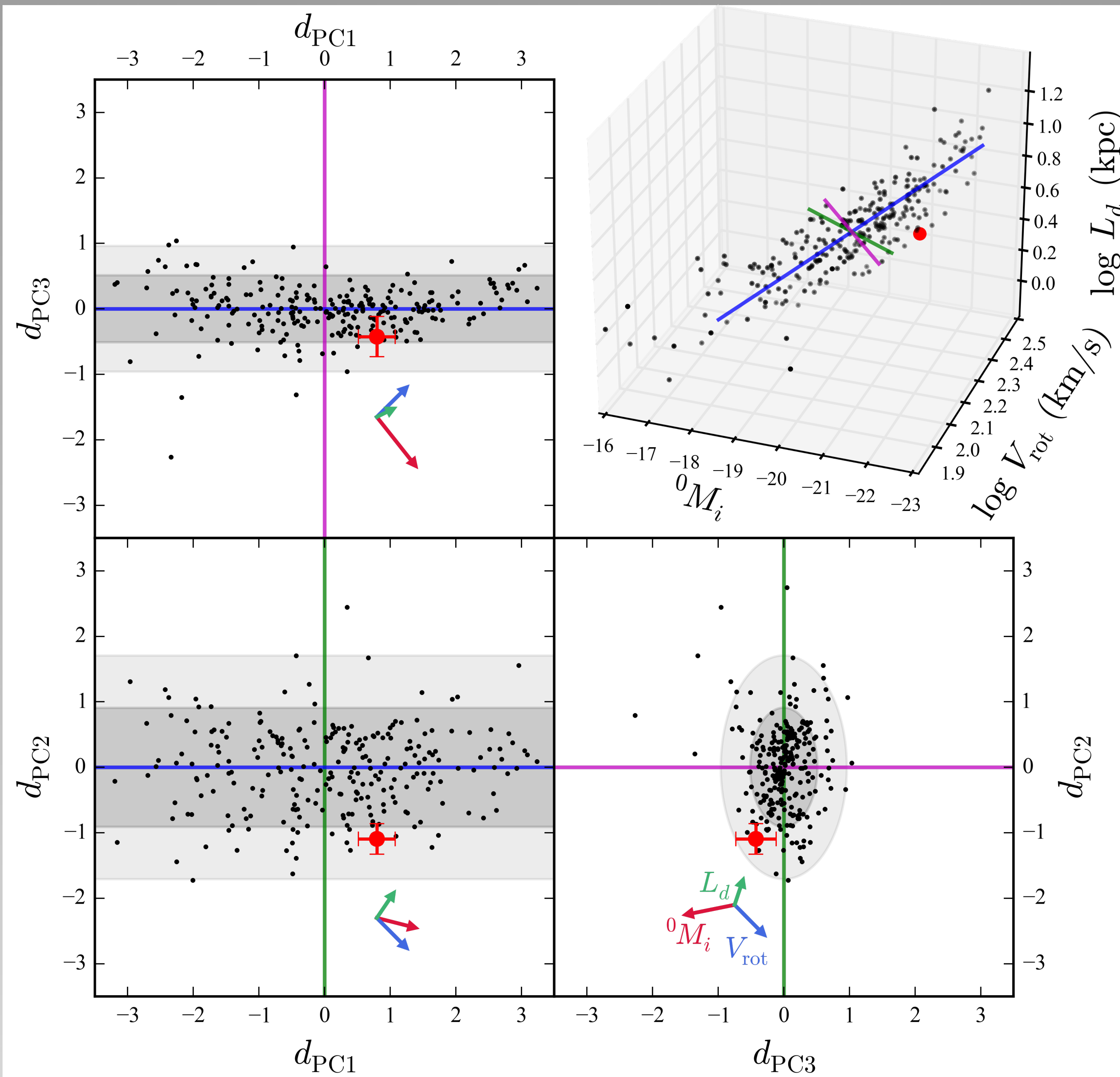
Ultimately, we find the Galactic scale length to be $L_d = 2.71 \pm 0.23$ kpc measured from starlight in the visible, $L_d = 2.50^{+0.17}_{-0.14}$ kpc measured from starlight in the IR, and $L_d = 2.61 \pm 0.15$ kpc when combining data from both wavelength regimes.

vs. mass scale length from Bovy & Rix: 2.15 +/- 0.14 kpc

The Milky Way is somewhat off the Luminosity-Velocity-Size relation of spirals

- The Milky Way disk scale length is roughly half of what you would expect for its luminosity/ mass and v_{circ}

- It is further from the relation than 87-92% of galaxies (depending on band or mass measure used): a bit <2σ off



Milky Way Analogs in MaNGA

Up to 25 ancillary IFUs → ~50 MWAs total

https://trac.sdss.org/wiki/MANGA/Survey/AncillaryPrograms2014/Newman_MWAnalogs

Stars and gas:
- Star formation history
- Star formation efficiency
- Kinematics
- Asymmetric Drift

Ionized gas:
- Metallicity gradients
- Ionization state
- Kinematics

Spectral bulge/disk decompositions:
pseudobulges vs. classical bulges?

Conclusions

- Photo-z's are critical for dark energy experiments
- Incompleteness or incorrect redshifts in spectroscopic samples will cause systematic errors in photo-z applications
- Cross-correlation methods can calibrate photometric redshifts even using incomplete samples of only bright galaxies & QSOs
- Minimum LSST photo-z training survey, ~75% complete:
  - 15 widely-separated pointings, ~30,000 spectra to i = 25.3, ~1.1 years on PFS (can do galaxy evolution science simultaneously!)
- The Milky Way is an ~L* galaxy with an SFR below the star-forming main sequence; it is compact by a factor of ~2 compared to its peers

- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments*, http://arxiv.org/abs/1309.5384, 1309.5388; Licquia & Newman 2015, http://arxiv.org/abs/1407.1078