

From Planets to Dark Energy: Forecasting the Astronomical Landscape for WFIRST

David Weinberg, Ohio State University



Credit: Jeff Sullivan
Photography

©Jeff Sullivan

From Planets to Dark Energy: Forecasting the Astronomical Landscape for WFIRST

David Weinberg, Ohio State University



From Planets to Dark Energy: Forecasting the Astronomical Landscape for WFIRST

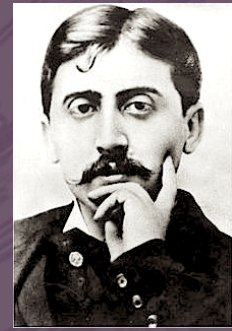
David Weinberg, Ohio State University

- I. Planets
- II. Stars
- III. Galaxies
- IV. Dark Energy

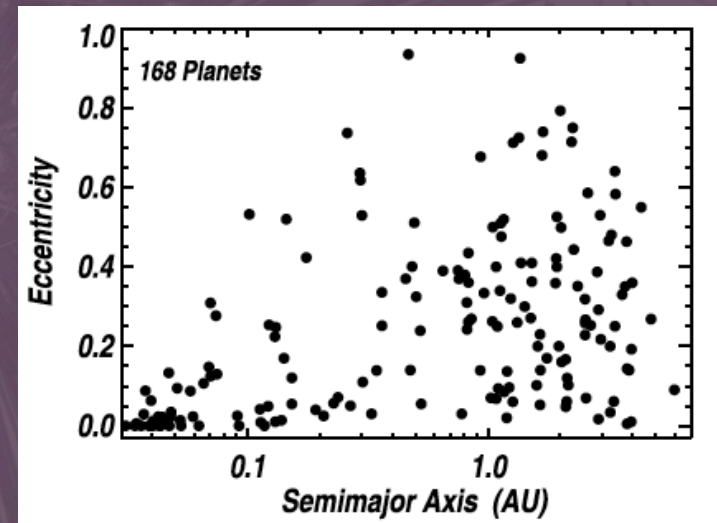
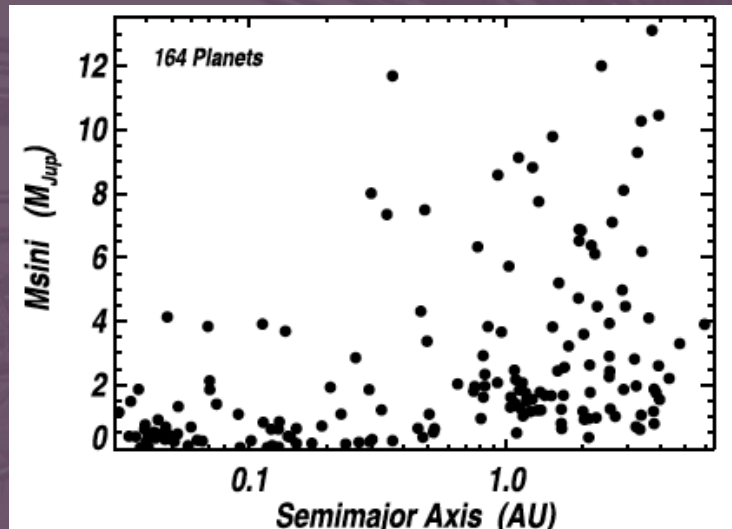




Planets – *il y a dix ans*

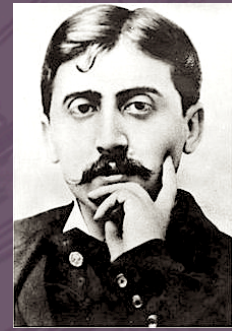


- Hot and warm Jupiters surprisingly common
- Many high eccentricity planets

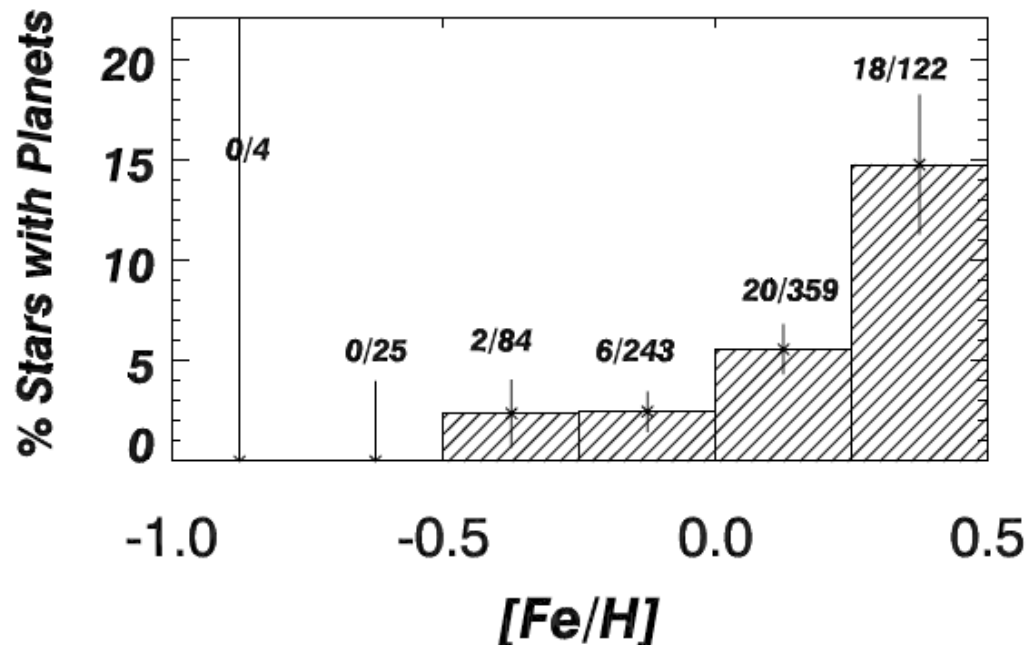


Butler, Marcy, Wright, Fischer et al. 2006

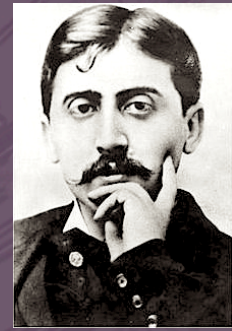
Planets – *il y a dix ans*



- Hot and warm Jupiters surprisingly common
- Many high eccentricity planets
- Super-Earths an emerging population
- Planet-metallicity correlation

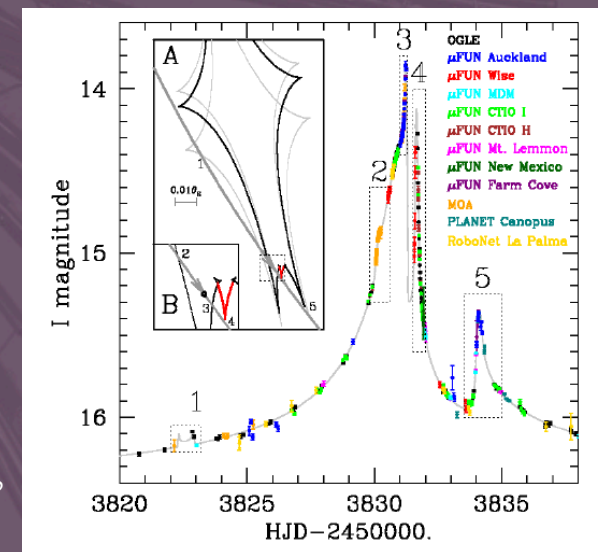
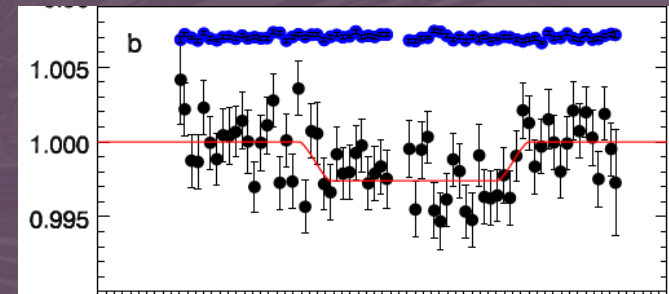


Planets – *il y a dix ans*



- Hot and warm Jupiters surprisingly common
- Many high eccentricity planets
- Super-Earths an emerging population
- Planet-metallicity correlation
- Handful of transit discoveries, transit spectrophotometry, secondary eclipse photometry
- Handful of microlensing discoveries, first Jupiter/Saturn analog

Deming, Seager, Richardson,
& Harrison 2007

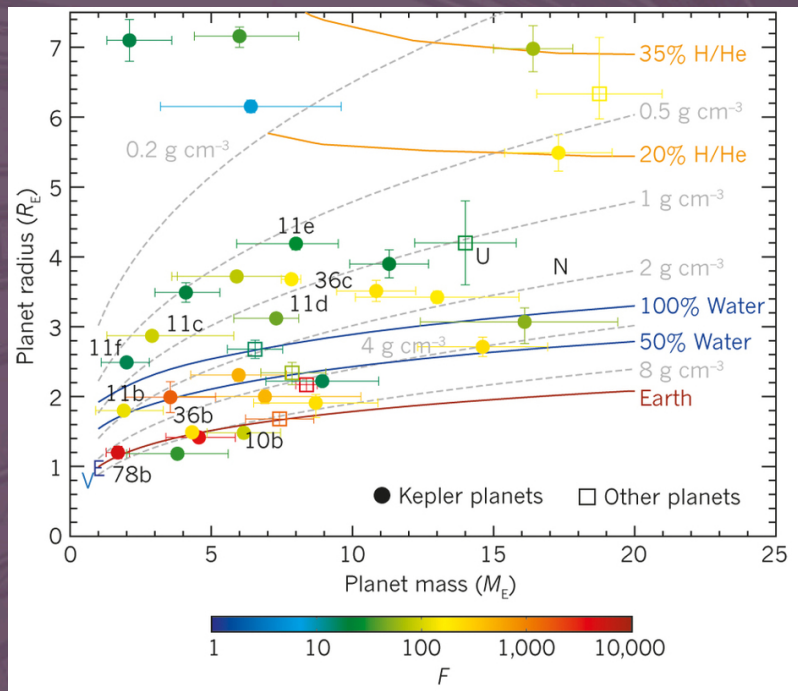


Gaudi, Bennett, Udalski,
Gould et al. 2008

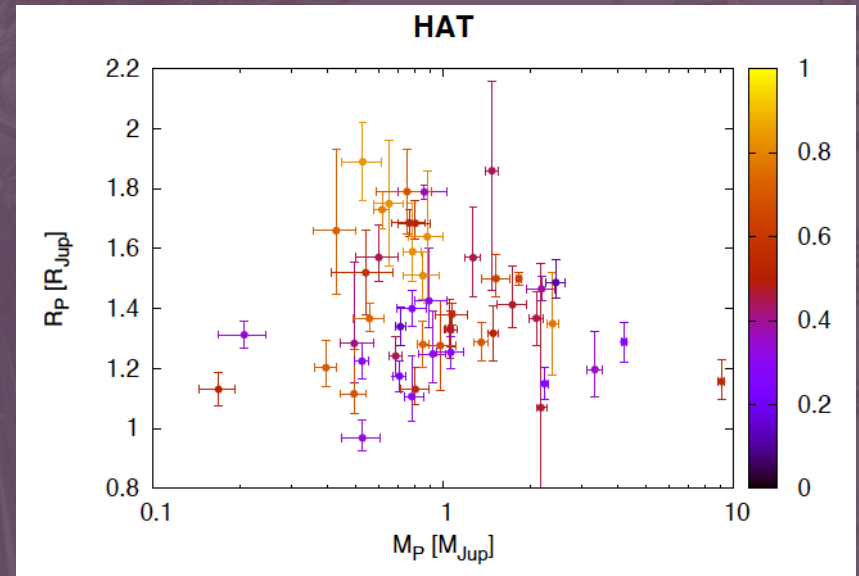
Planets – 2017

Kepler, transit surveys, sub m/sec RV, microlensing, ALMA

- Earth(ish) size planets are common, diversity of compositions, inflation of hot Jupiters



Lissauer, Dawson, & Tremaine 2014

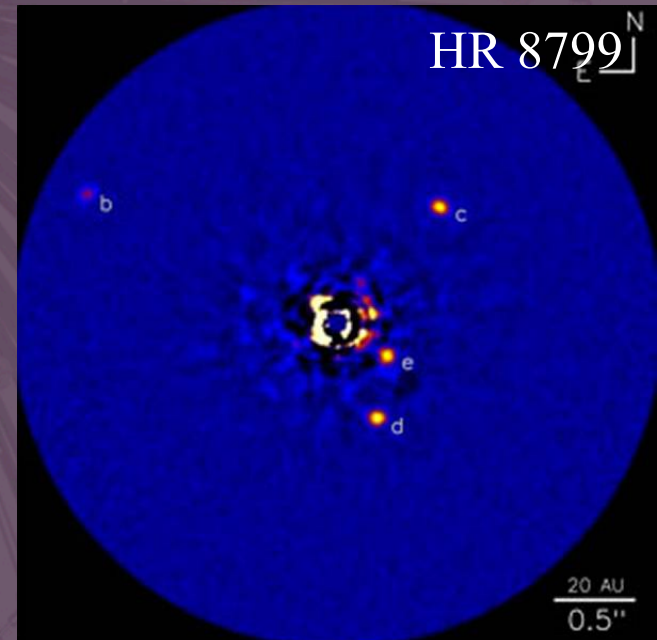
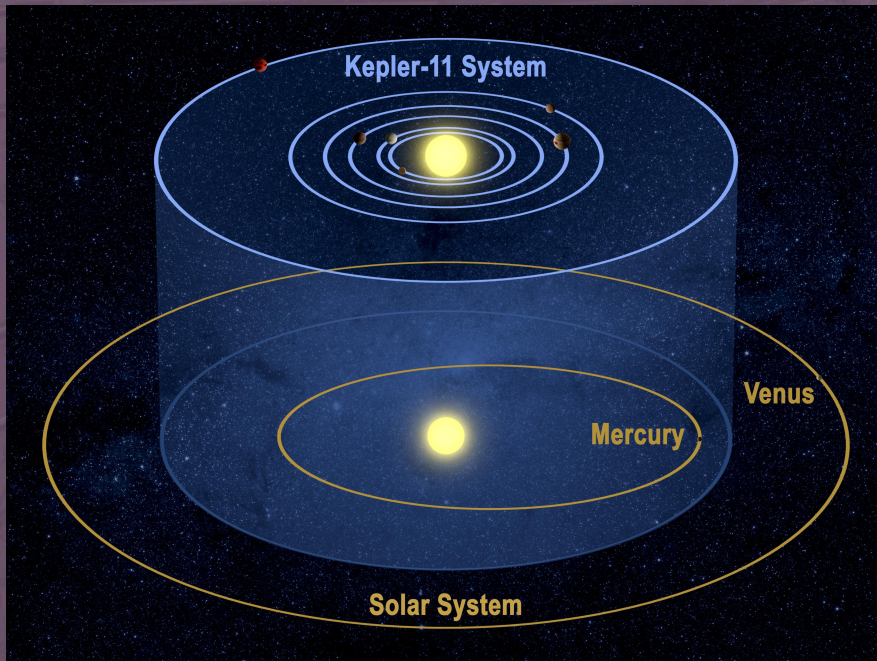


Hartman, Bakos, Bhatti, Penev et al. 2016

Planets – 2017

Kepler, transit surveys, sub m/sec RV, microlensing, ALMA

- Earth(ish) size planets are common, diversity of compositions, inflation of hot Jupiters
- Compact multi-planet systems surprisingly common
- Direct imaging planets rare, cold Neptunes common



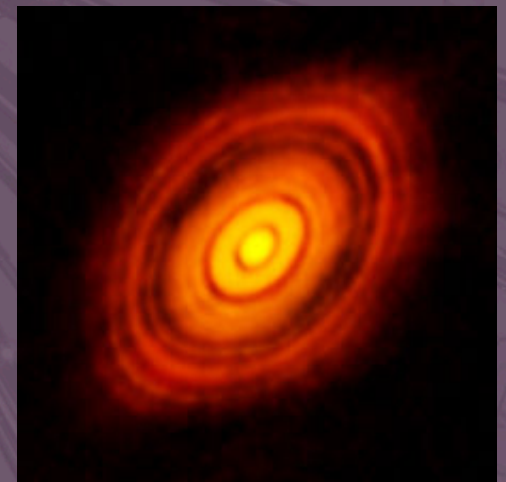
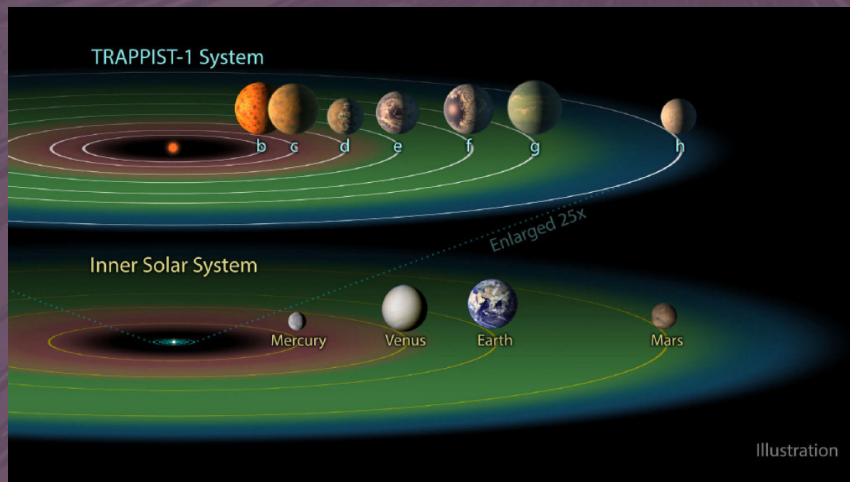
Planets – 2017

Kepler, transit surveys, sub m/sec RV, microlensing, ALMA

- Earth(ish) size planets are common, diversity of compositions, inflation of hot Jupiters
- Compact multi-planet systems surprisingly common
- Direct imaging planets rare, cold Neptunes common
- Potentially habitable worlds, many with M-dwarf hosts
- Complex structures in proto-planetary disks

HL Tau

Trappist-1

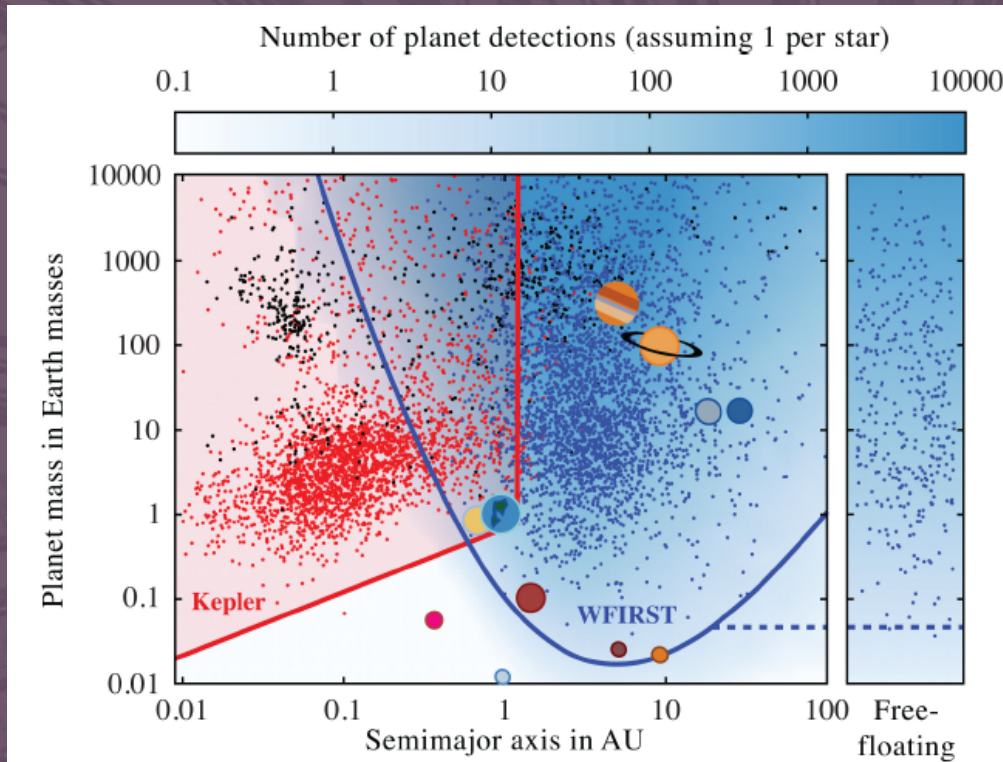




Planets – 2027

- Excellent demographics within \sim few AU (transit, RV) and giant planets beyond 20-30 AU (direct imaging)
- Microlensing demographics at 1-10 AU, free floating
- Detailed correlations of planet properties vs. star properties
- Many detailed multi-wavelength proto-planetary disk maps
- Many habitable worlds discovered
- Detailed study of some planetary atmospheres with *JWST* transit spectroscopy

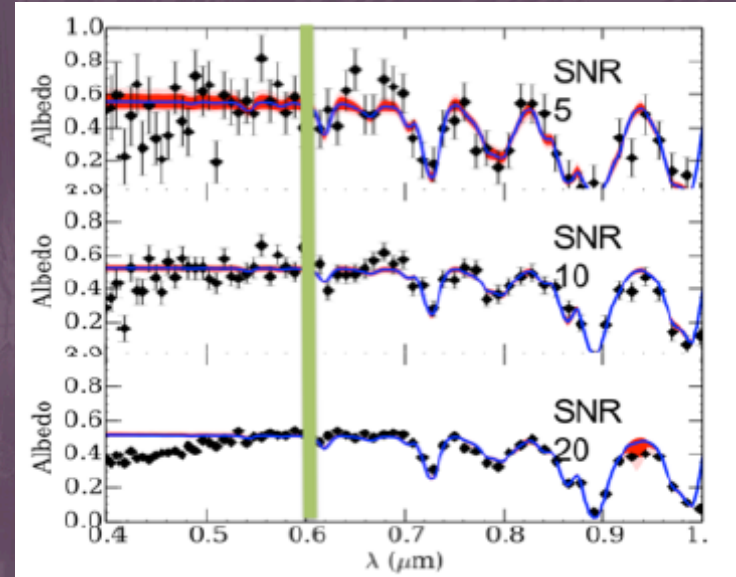
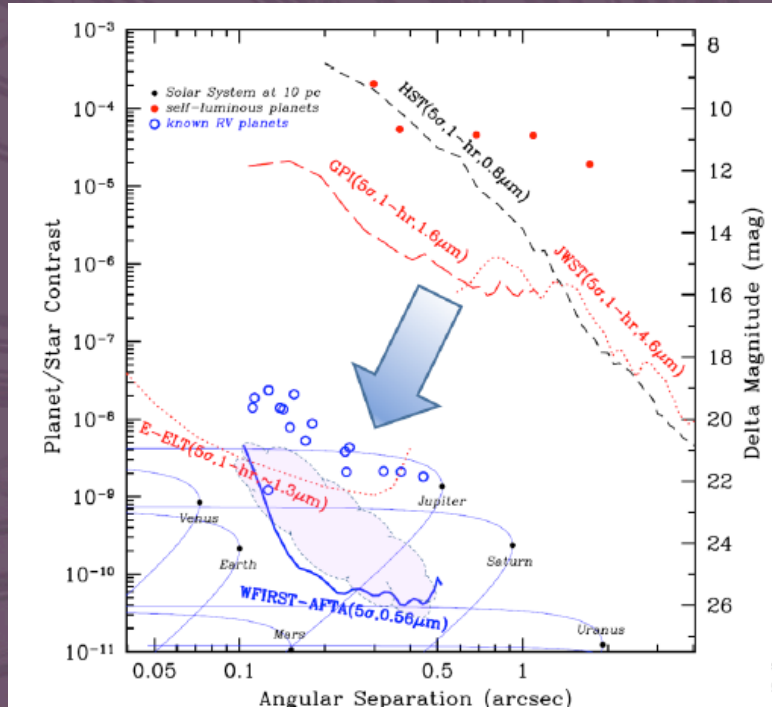
Planets with WFIRST: Demographics



Kepler + WFIRST: Demographics from sub-Earth to super-Jupiter, 0.01 – 20 AU, plus free floating.

The fundamental data for understanding planet formation.

Planets with WFIRST: Characterization

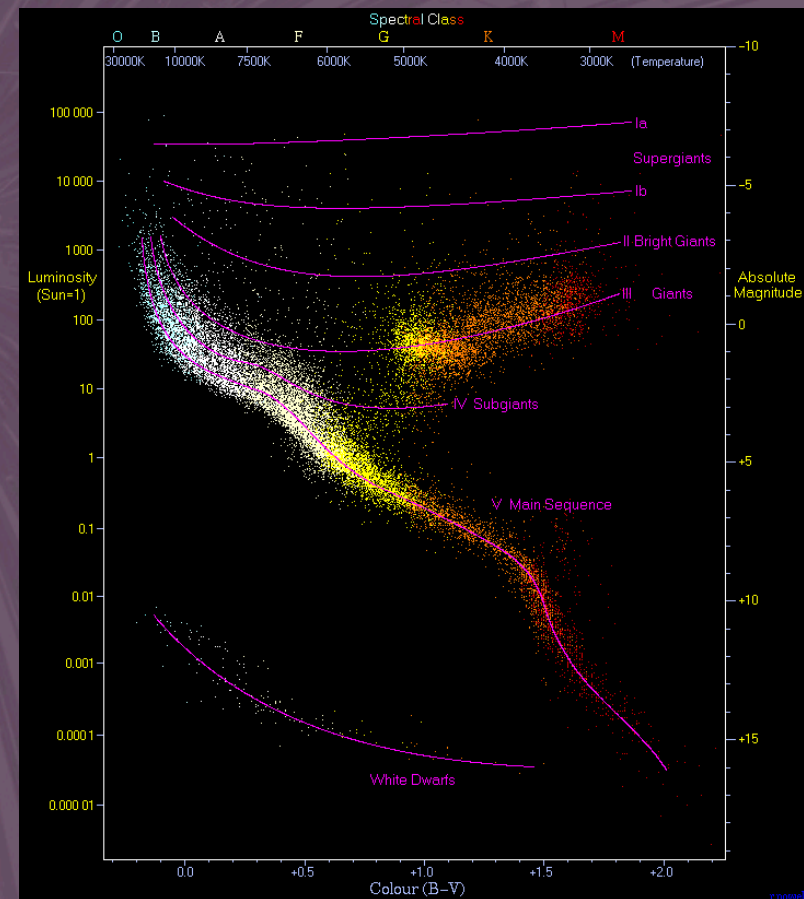
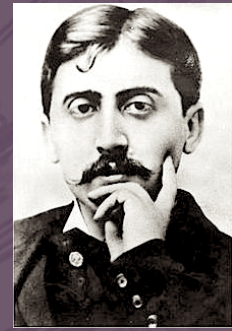


Spectra of giant planets, maybe super-Earths.

Path to the future: atmospheres and signatures of life on other worlds.

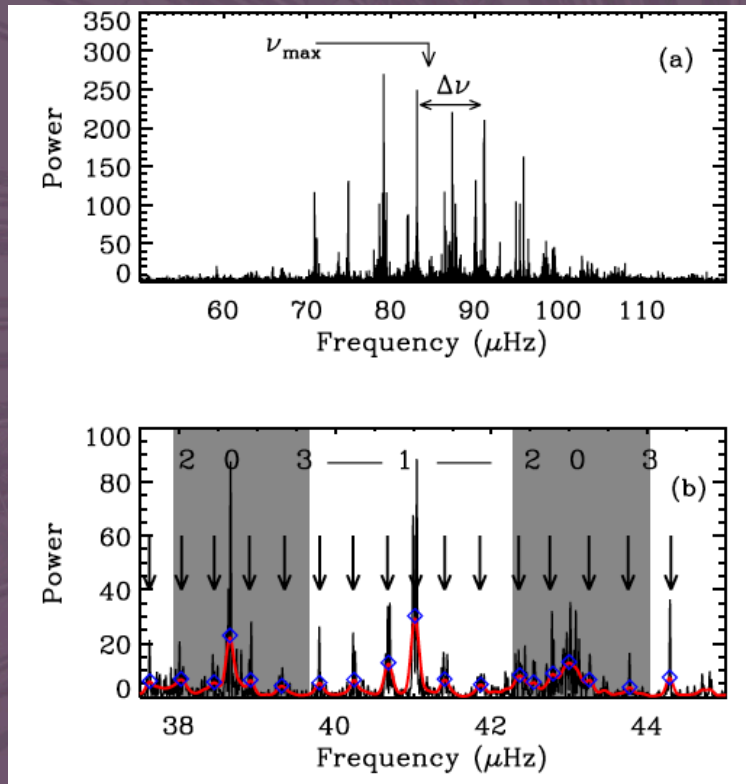
Stars – *il y a dix ans*

- Fairly tidy story, developed over a century.
- Interesting complications: binary evolution, rotation, magnetic fields.
- Core collapse SN mechanism?
- SNIa progenitors?

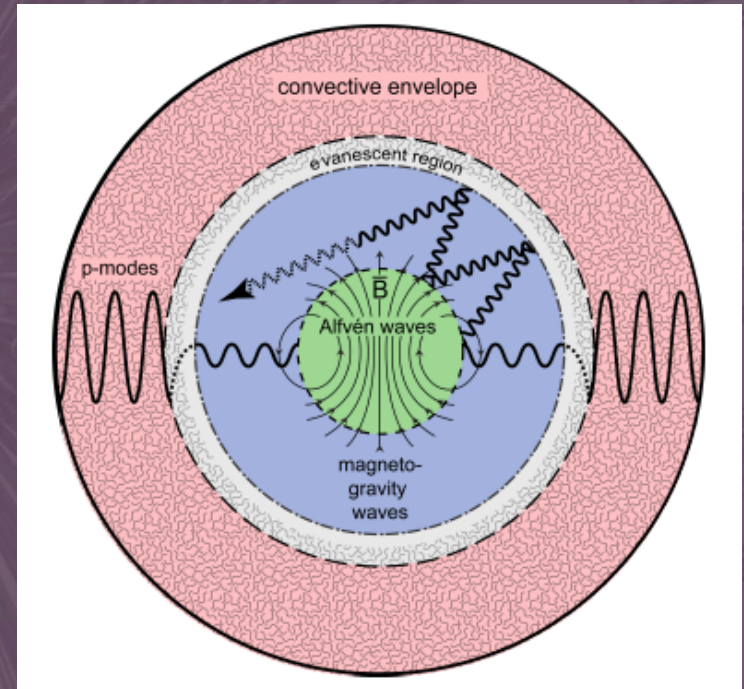


Stars – 2017

- Giants pulsate. *Kepler* asteroseismology of 10,000+ giants. Precision probe of the interior structure of evolved stars.



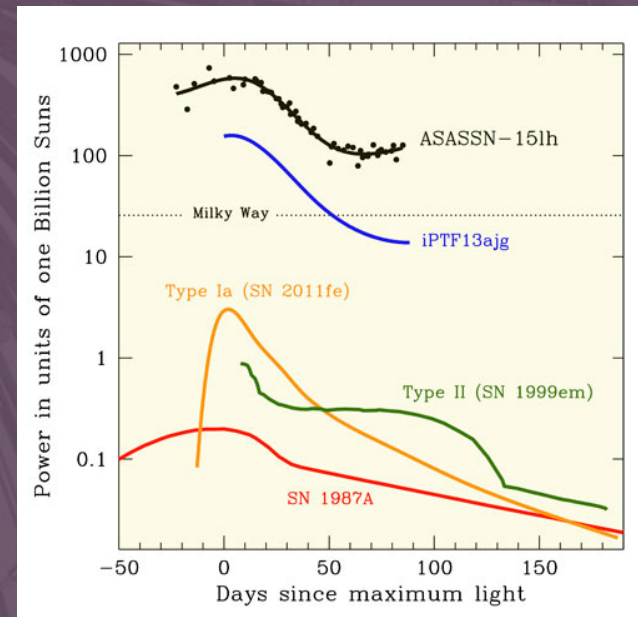
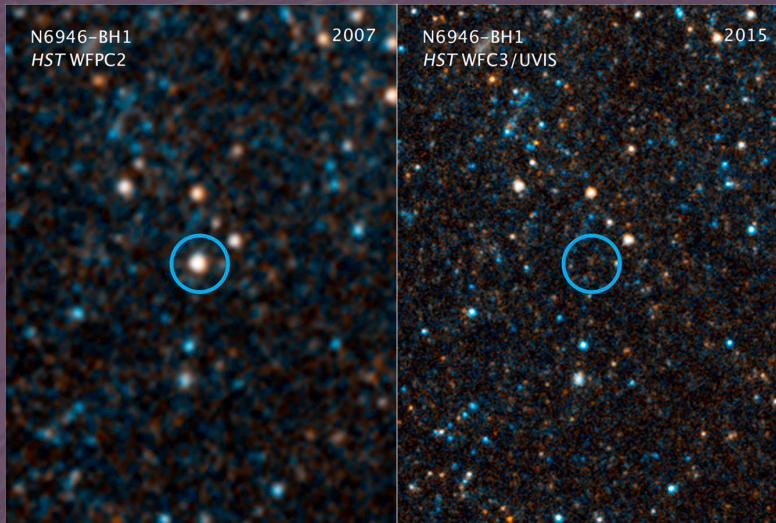
Stello, Huber, Bedding, Benomar et al. 2013



Fuller, Cantiello, Stello, Garcia, & Bildsten 2015

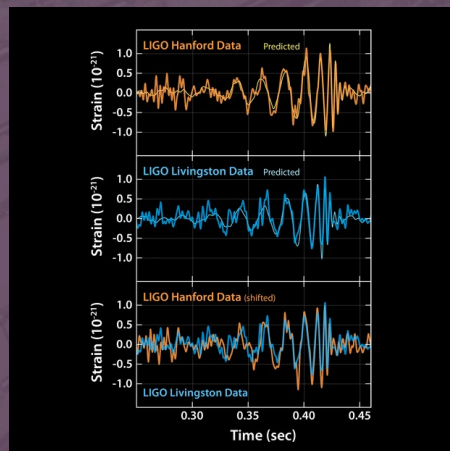
Stars – 2017

- Giants pulsate. *Kepler* asteroseismology of 10,000+ giants. Precision probe of the interior structure of evolved stars.
- Wild variety of stellar fates
 - Low mass and metal-enriched white dwarfs
 - Tidal disruptions by supermassive black holes
 - Super-luminous and sub-luminous supernovae
 - Direct collapse to black hole



Stars – 2017

- Giants pulsate. *Kepler* asteroseismology of 10,000+ giants. Precision probe of the interior structure of evolved stars.
- Wild variety of stellar fates
 - Low mass and metal-enriched white dwarfs
 - Tidal disruptions by supermassive black holes
 - Super-luminous and sub-luminous supernovae
 - Direct collapse to black hole
- Gravitational waves from 20 – 30 M_{sun} black hole mergers!





Stars – 2027

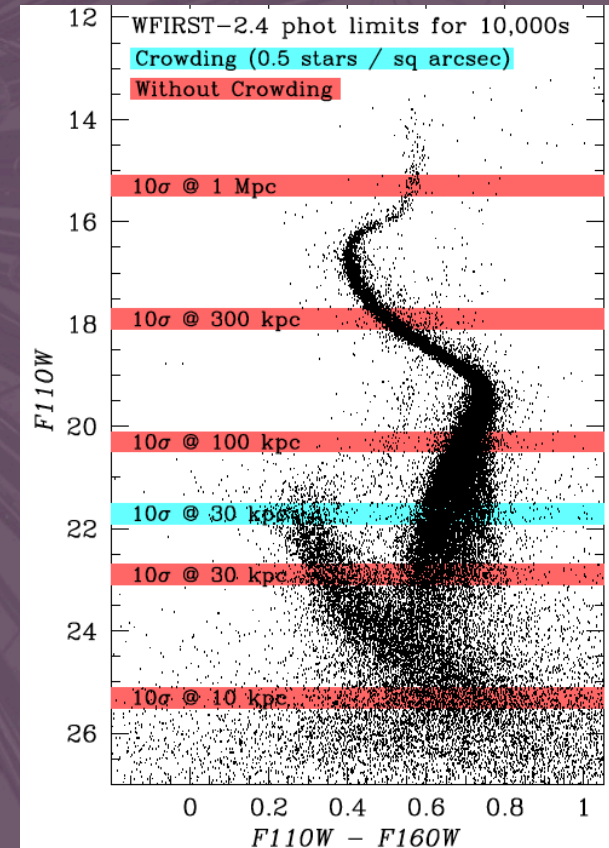
- Much more precision knowledge of stellar interiors (Gaia, TESS, PLATO, APOGEE, GALAH)
- Much better maps of stellar populations throughout the Milky Way and the Local Group
- A still wilder variety of stellar fates (ASAS-SN, ZTF, LSST)
- Good statistics on gravitational waves from BH and NS mergers (Progenitors? Electromagnetic signatures?)

Stars with WFIRST

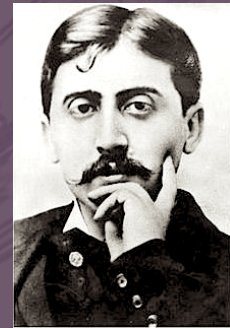


- Asteroseismology of 1 million red giants in the bulge and disk (from microlensing survey)
- Comprehensive white dwarf luminosity functions of the disk, halo, star clusters
- Evolution of supernova populations over most of cosmic history
- Near-IR stellar populations throughout the Local Group

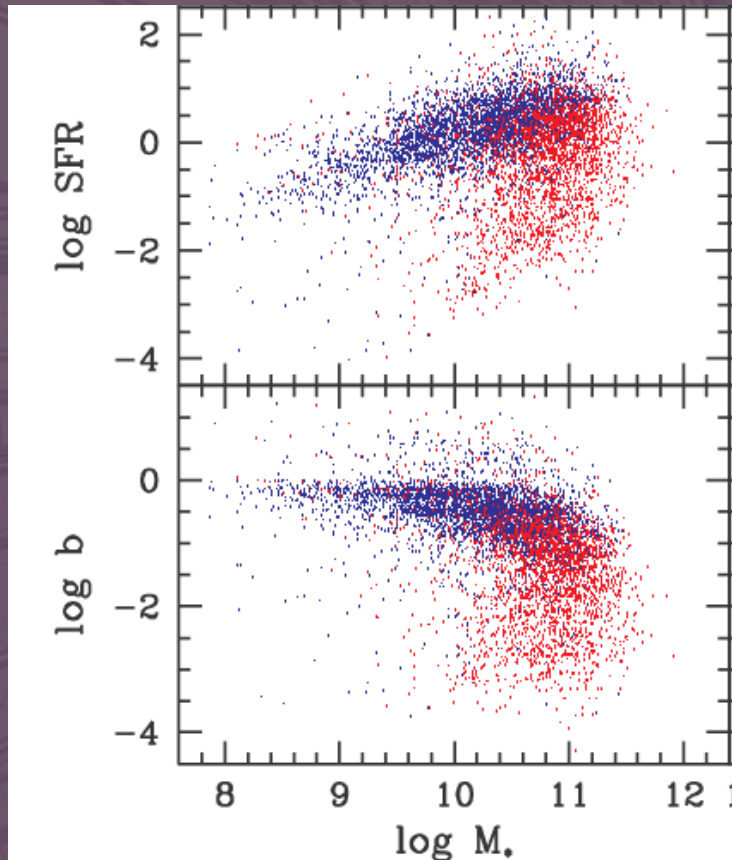
J. Kalirai based on Kalirai, Richer, Dotter, Anderson et al. 2012



Galaxies – *il y a dix ans*

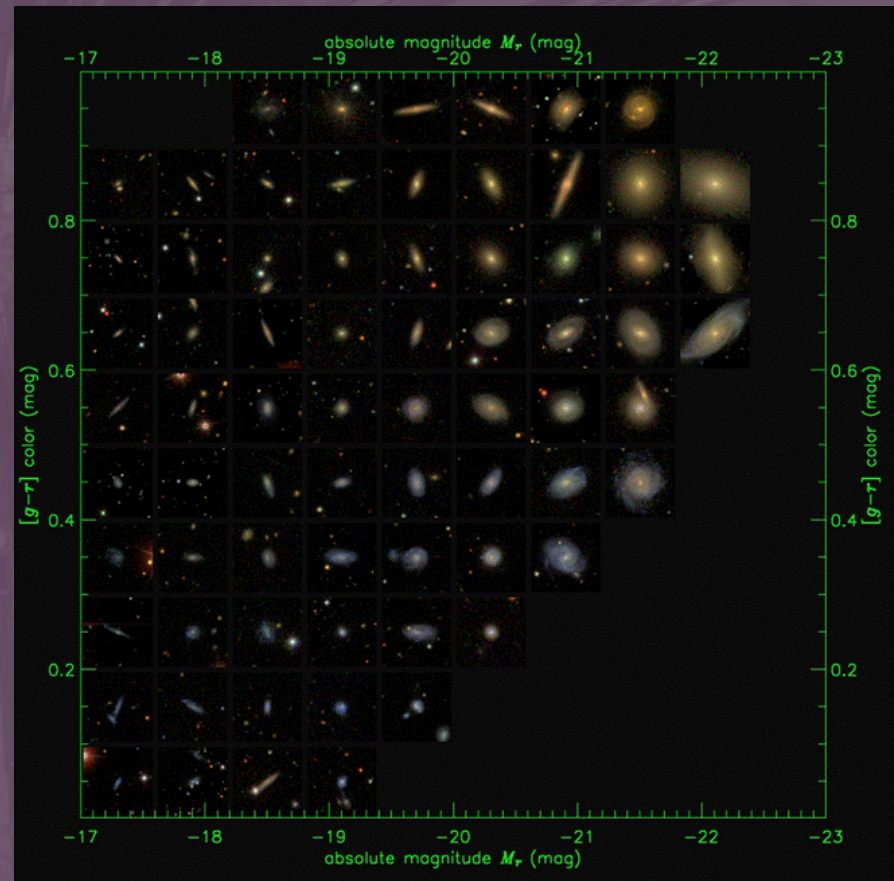


- Detailed local demographics from SDSS+

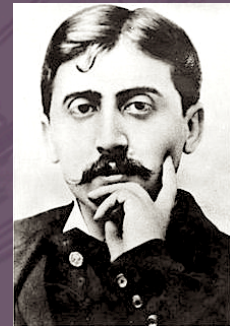


Salim, Charlot, Rich,
Kauffmann et al. 2005

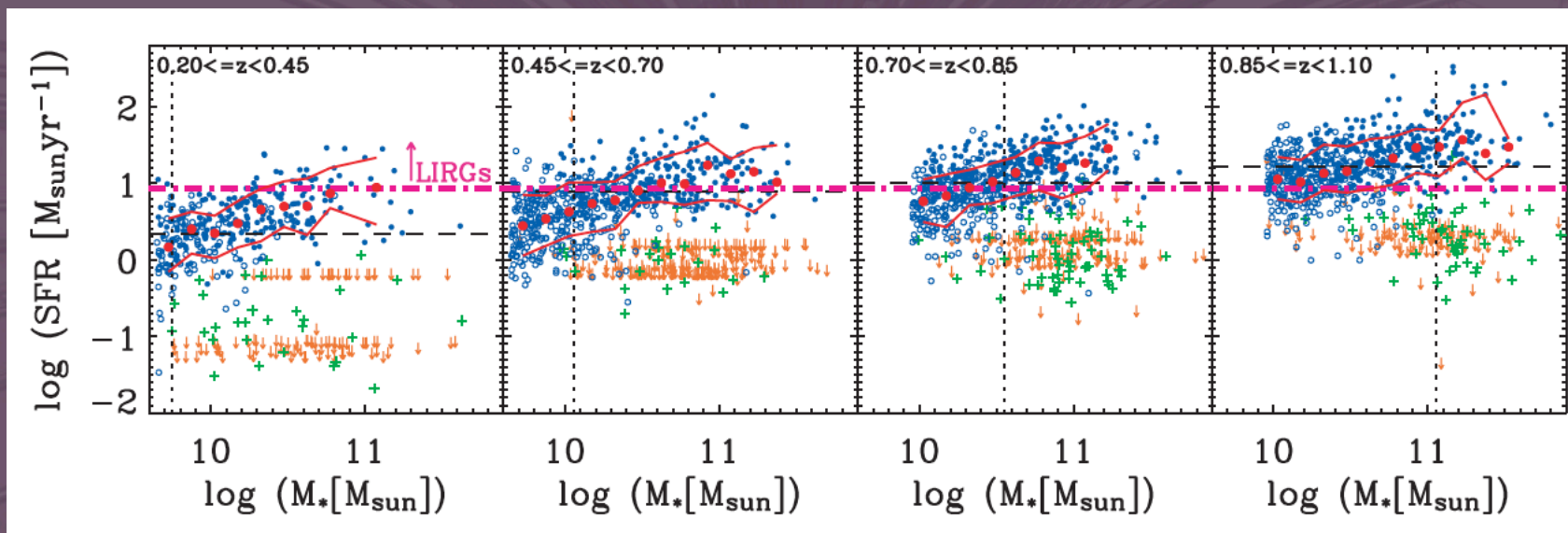
Blanton, Hogg, et al.



Galaxies – *il y a dix ans*

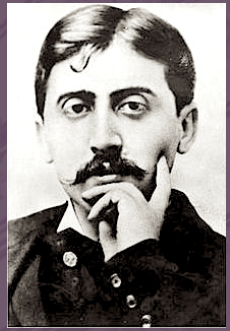


- Detailed local demographics from SDSS+
- Extending to $z \sim 0.5 - 3$ with *HST*, DEEP2, etc.

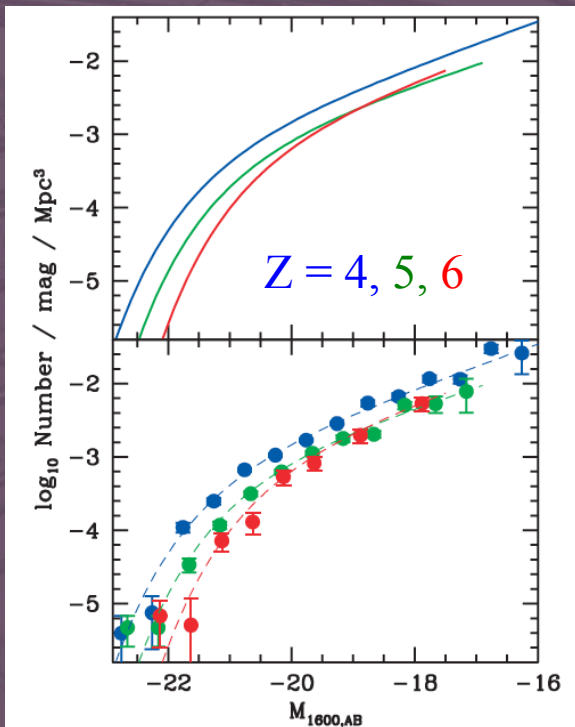


Noeske, Weiner, Faber, Papovich et al. 2007

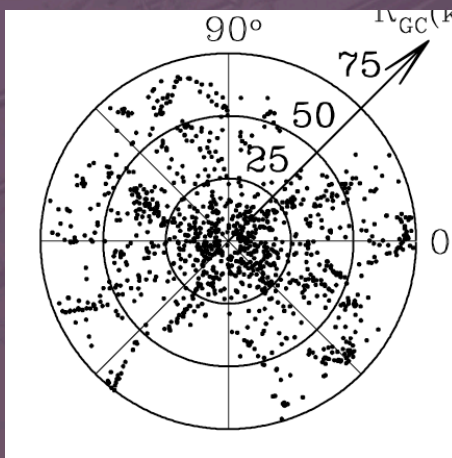
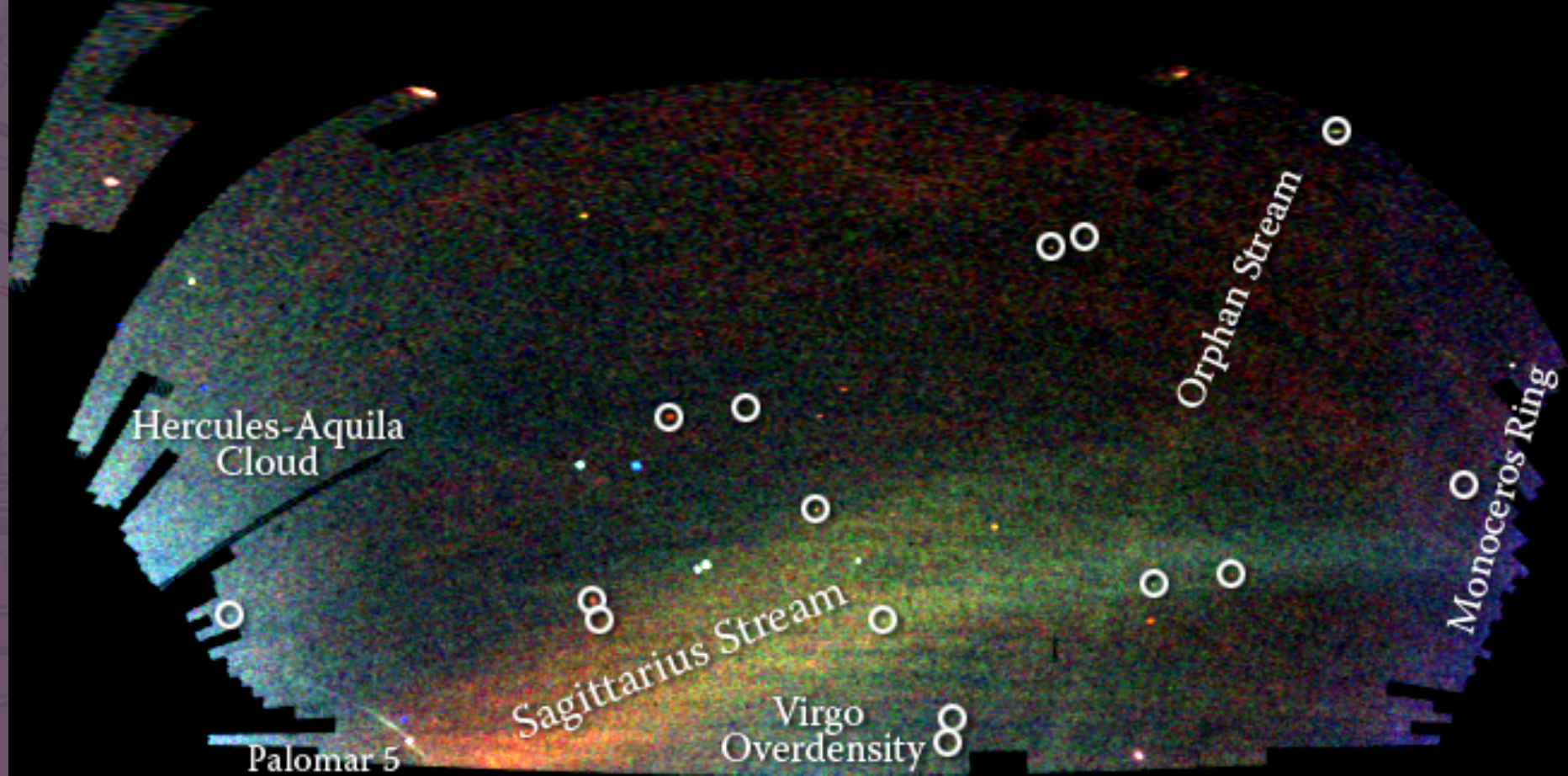
Galaxies – *il y a dix ans*



- Detailed local demographics from SDSS
- Extending to $z \sim 0.5 - 3$ with *HST*, DEEP2, etc.
- UV luminosity functions at $z = 6$!

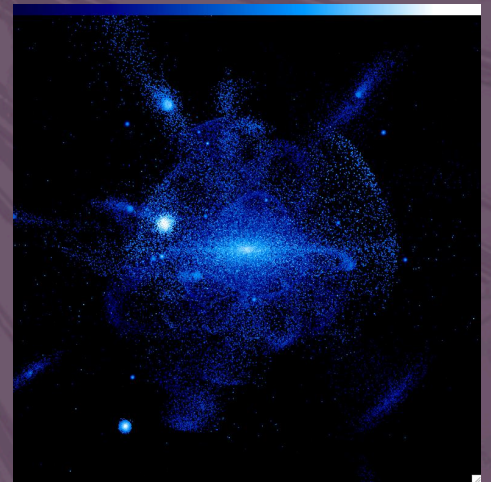


Bouwens, Illingworth, Franx,
& Ford 2007



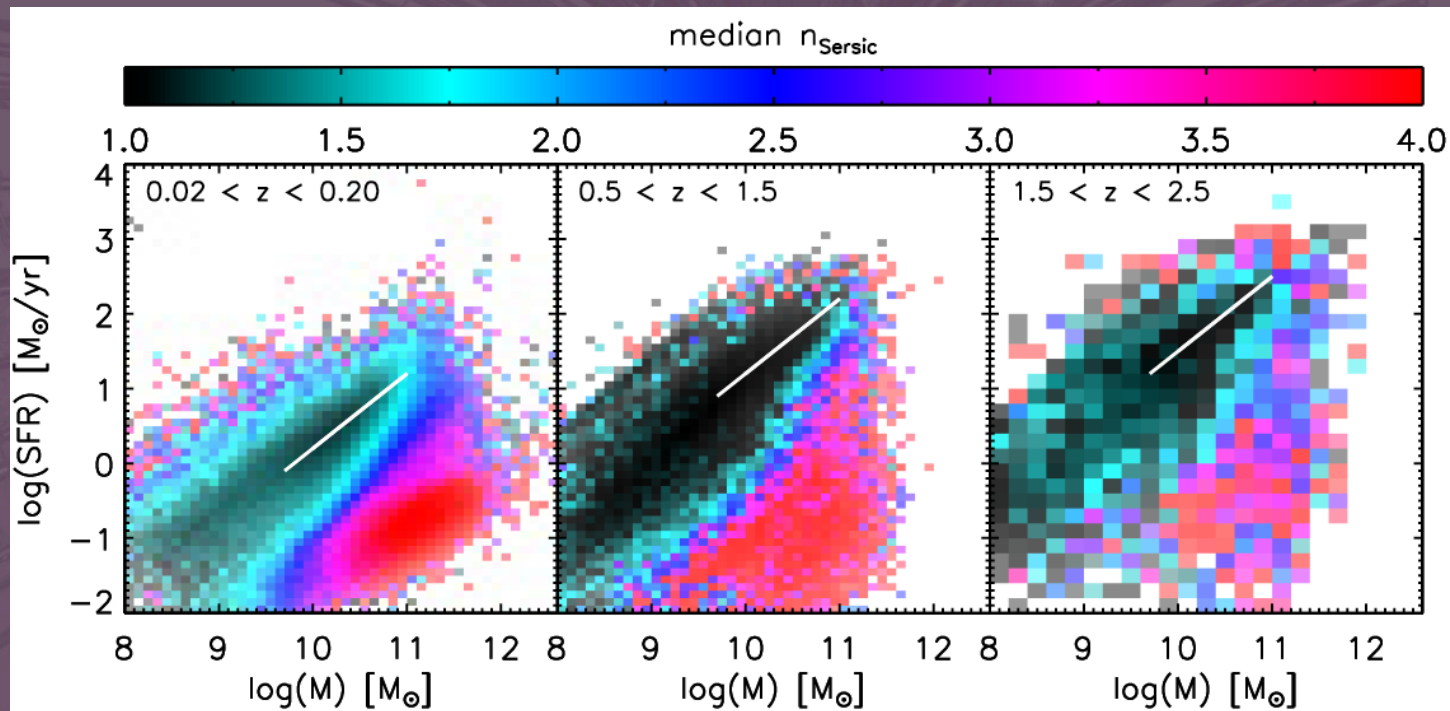
Bullock & Johnston 2005

Bullock, Kravtsov & Weinberg 2001



Galaxies – 2017

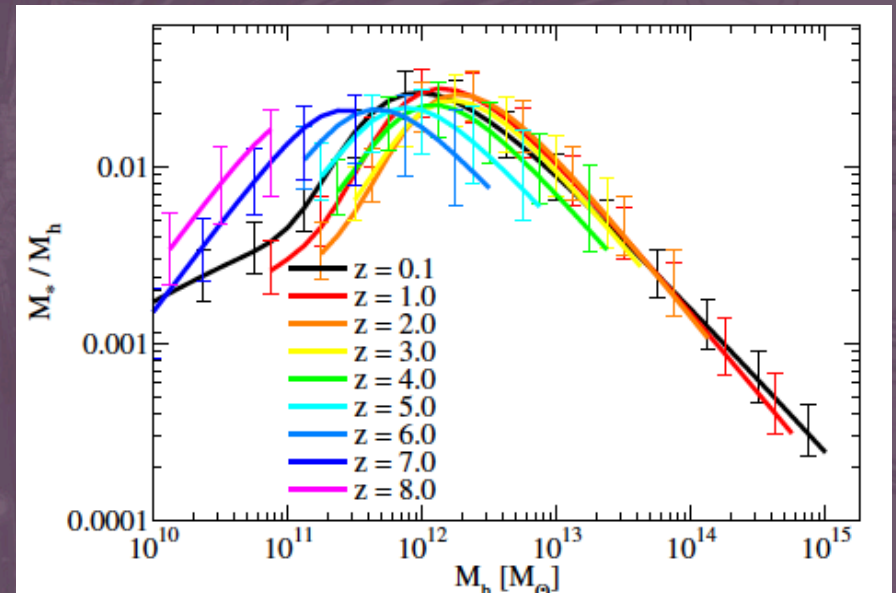
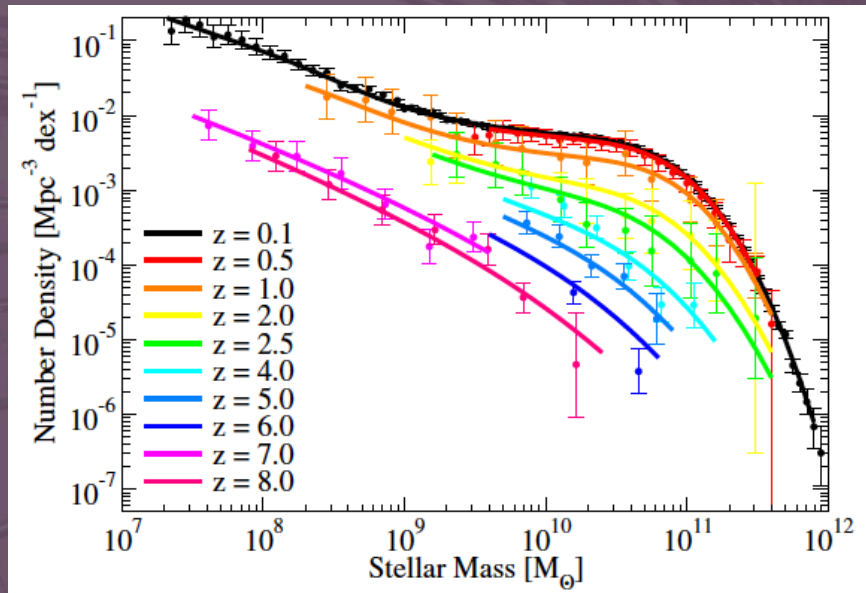
- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content



Wuyts, Forster Schreiber, van der Wel, Magnelli et al. 2011

Galaxies – 2017

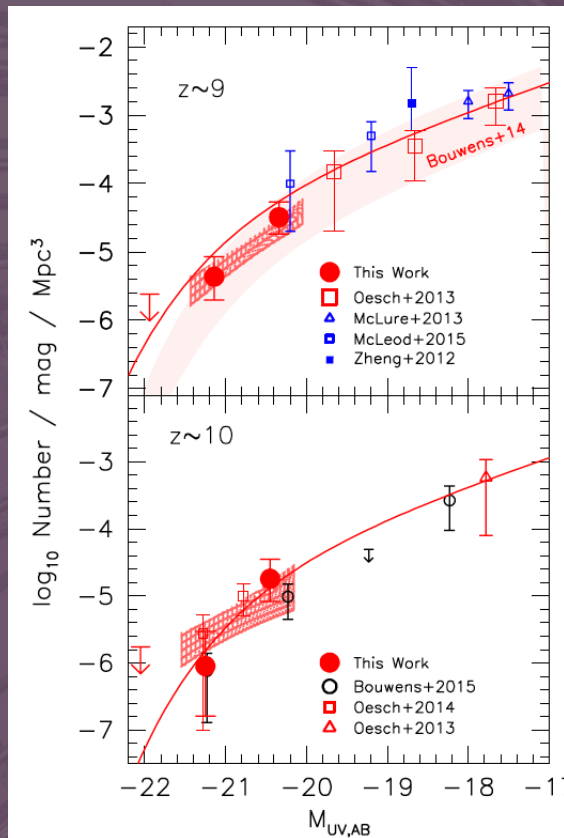
- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content



Behroozi, Wechsler & Conroy 2013

Galaxies – 2017

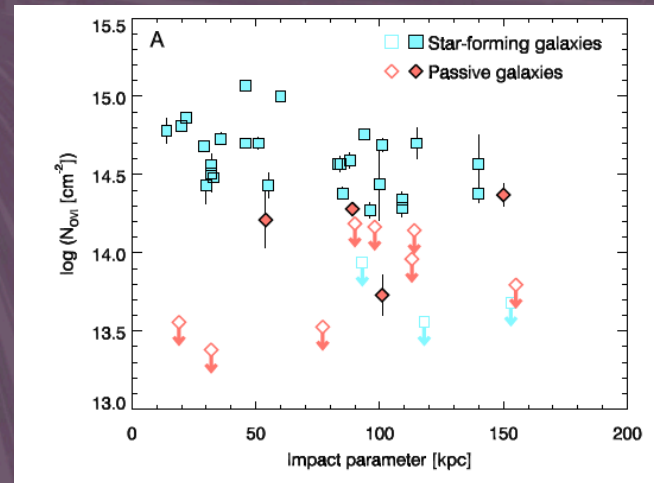
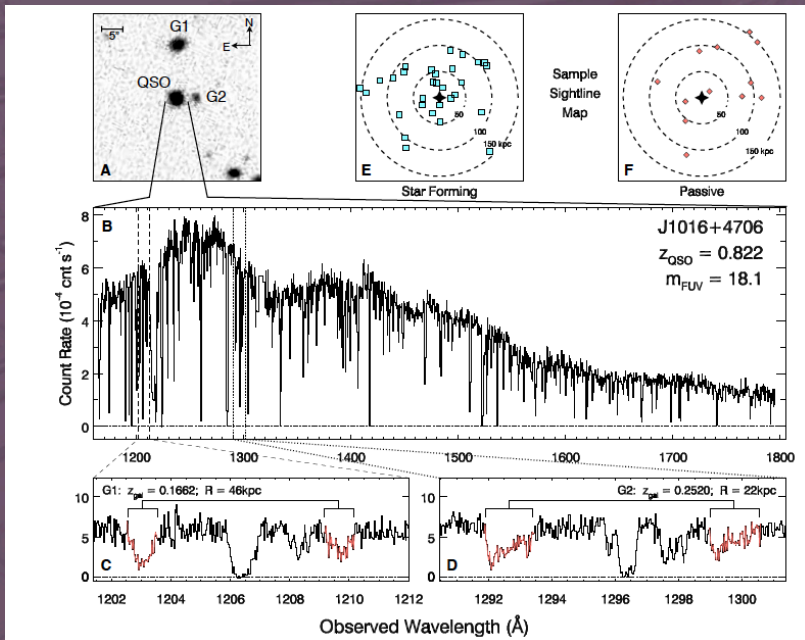
- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content
- Luminosity functions at $z = 8 - 10$, sources of reionization?



Bouwens, Oesch, Labbe,
Illingworth et al. 2016

Galaxies – 2017

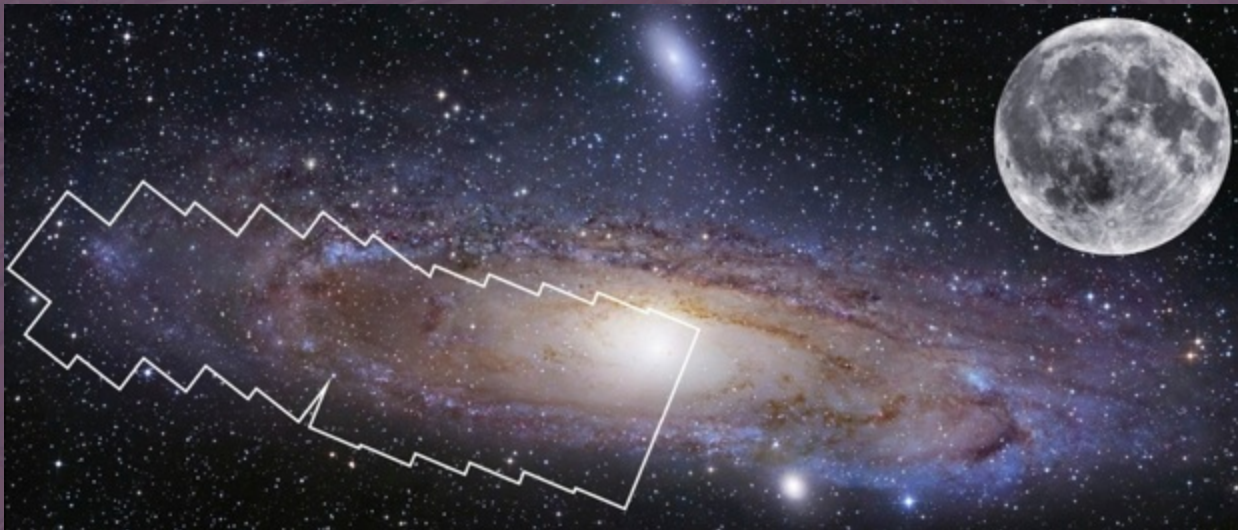
- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content
- Luminosity functions at $z = 8 - 10$, sources of reionization?
- Quasar probes of circumgalactic medium (CGM) – ubiquitous cool gas in galaxy halos



Tumlinson, Thom, Werk,
Prochaska et al. 2011

Galaxies – 2017

- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content
- Luminosity functions at $z = 8 - 10$, sources of reionization?
- Quasar probes of circumgalactic medium (CGM) – ubiquitous cool gas in galaxy halos
- Resolved stellar maps of nearest neighbors, large IFU surveys



Panchromatic
Hubble
Andromeda
Treasury

Dalcanton++

PAndAS survey

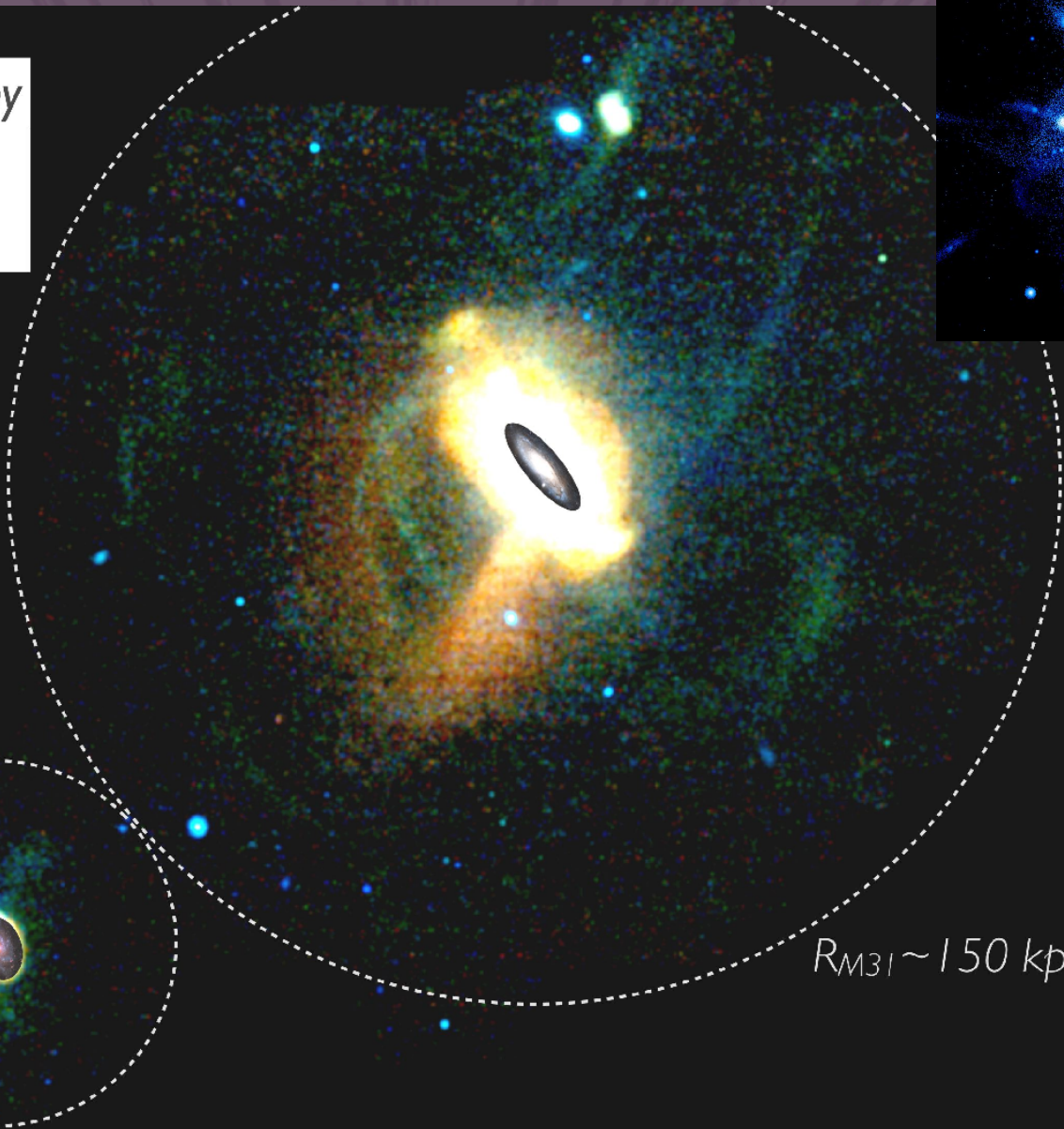
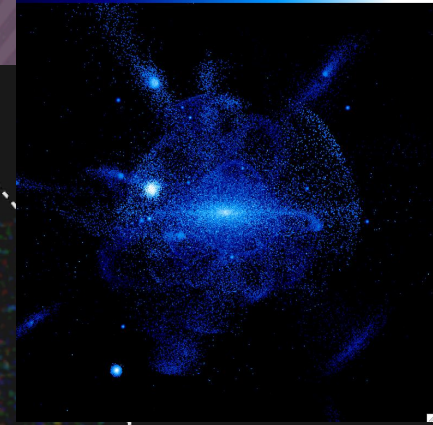
[Fe/H] ~ -2.3

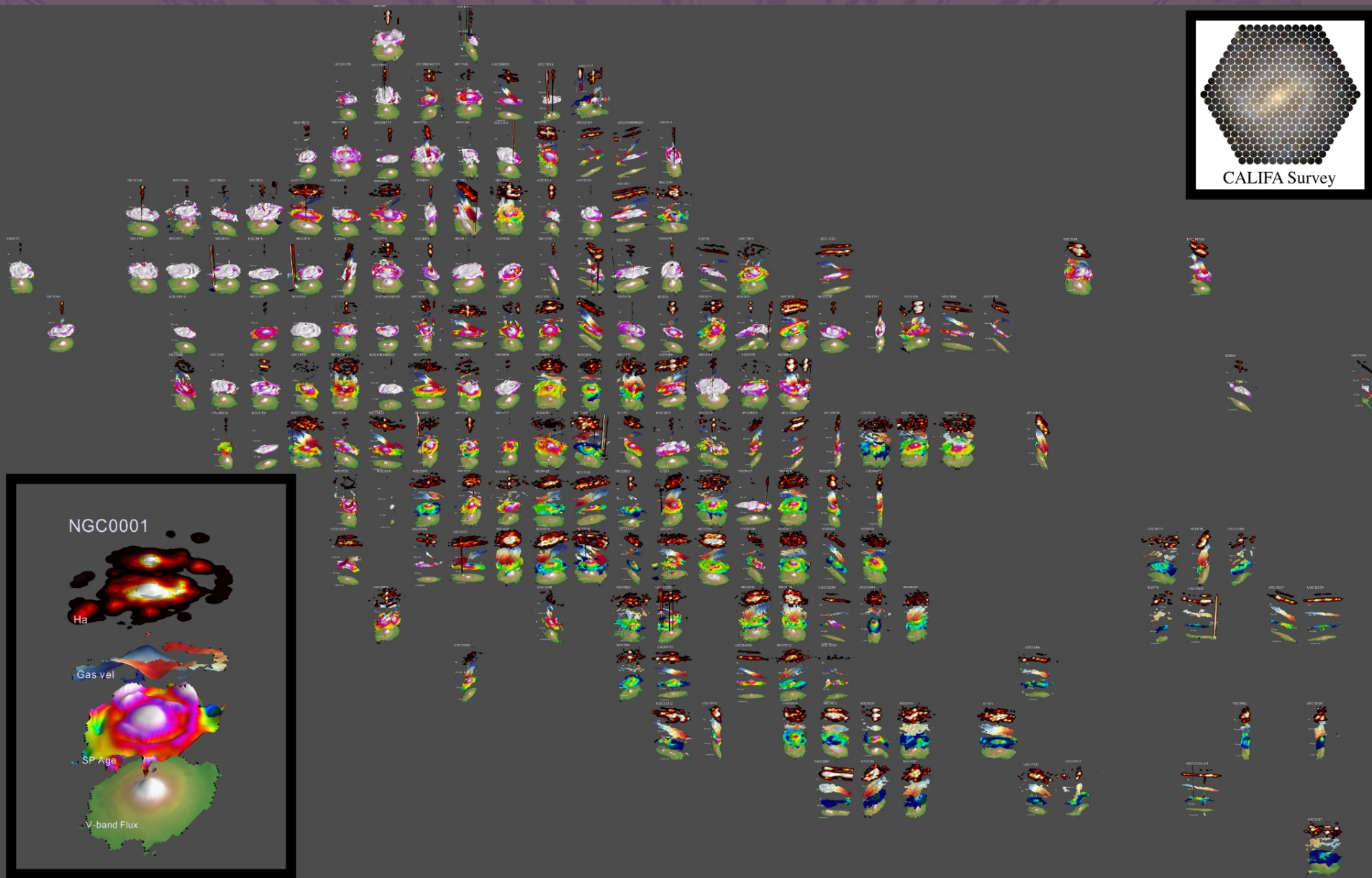
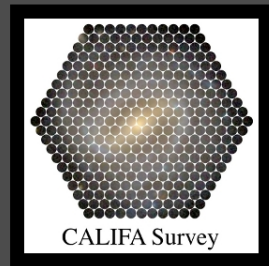
[Fe/H] ~ -1.4

[Fe/H] ~ -0.7

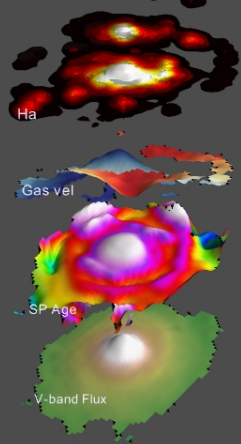
$R_{M33} \sim 50$ kpc

$R_{M31} \sim 150$ kpc



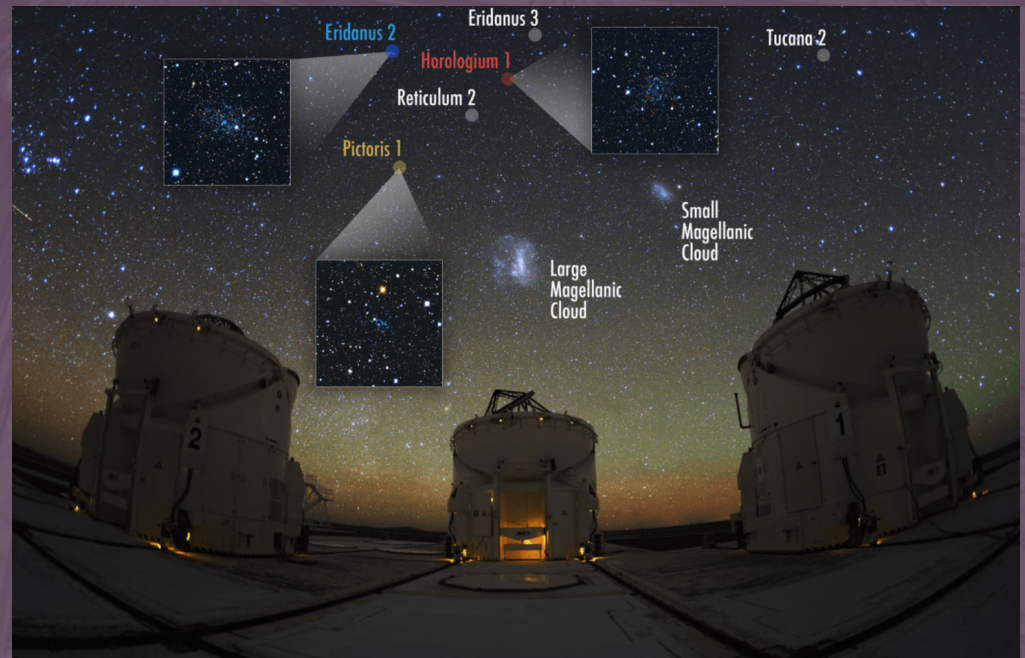


NGC0001



Galaxies – 2017

- Detailed demographics from $z \sim 0 - 4$, including size, morphology, dynamics, gas content
- Luminosity functions at $z = 8 - 10$, sources of reionization?
- Quasar probes of circumgalactic medium (CGM) – ubiquitous cool gas in galaxy halos
- Resolved stellar maps of nearest neighbors, large IFU surveys
- More than 3-dozen Milky Way satellites



Galaxies – 2027

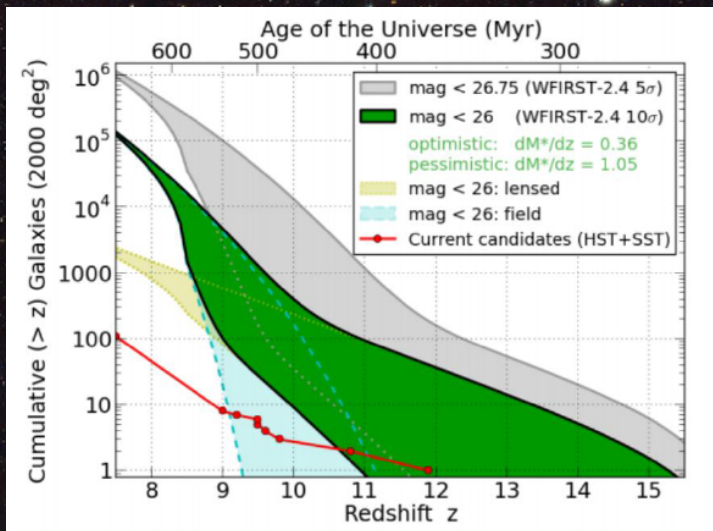


- Excellent demographics of faint galaxies at high- z from *JWST*
- Maps of many galaxies at pc to kpc scales in stars, SFR, metallicity, multi-phase gas
- Better empirical/physical picture of the CGM?
- Hundreds of Milky Way satellites?

Galaxies with WFIRST



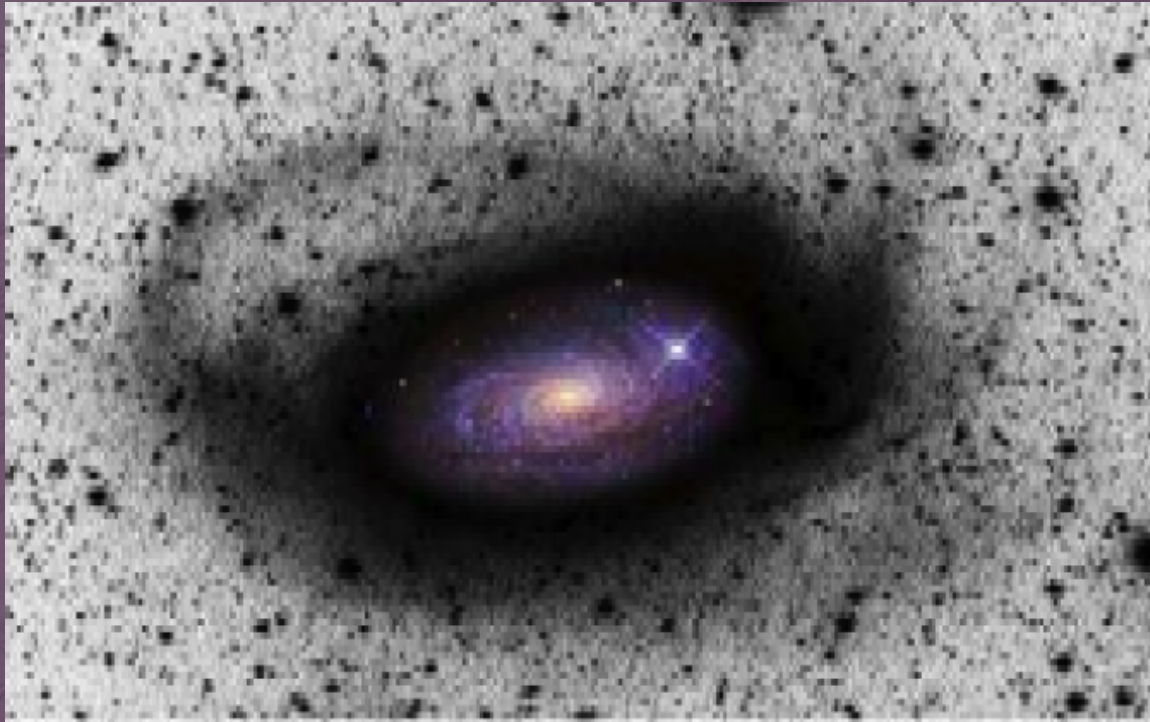
- Comprehensive demographics of the $z > 6$ universe
- Precise stacked dark matter profiles of galaxies in fine bins of luminosity, morphology, redshift, etc.



Galaxies with WFIRST



- Comprehensive demographics of the $z > 6$ universe
- Precise stacked dark matter profiles of galaxies in fine bins of luminosity, morphology, redshift, etc.
- Assembly histories of many nearby galaxies
- Ultra-faint and LSB galaxies throughout the Local Volume



Why is the universe accelerating?

A breakdown of General Relativity on cosmological scales?

Dynamical dark energy that varies in space and time?

A cosmological constant, with a very surprising magnitude?

To address these questions, measure the history of cosmic expansion and growth of structure with the highest achievable precision over a wide range of redshift.

The Biggest Cosmological Breakthroughs (last 200 years)

1859: Precession of Mercury

Newtonian gravity is incomplete.

1921: Distance to the Andromeda Nebula

The universe is big! Galaxies are basic unit.

1929: Hubble's law

The universe is expanding, as General Relativity naturally predicts.

1930s – 1970s: Dark matter

The dominant form of matter in the universe is invisible.

1960s: Cosmic microwave background and big bang nucleosynthesis

The universe began with a hot big bang.

1980s – 2000s: Large scale structure and CMB anisotropies

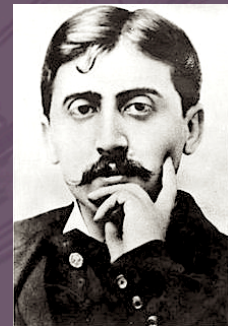
Cosmic structure formed by gravitational instability.

Dark matter is non-baryonic. Space is Euclidean.

Late 1990s: Cosmic acceleration

Gravity is repulsive over cosmological distances.

WFIRST seeks the next great cosmological discovery.



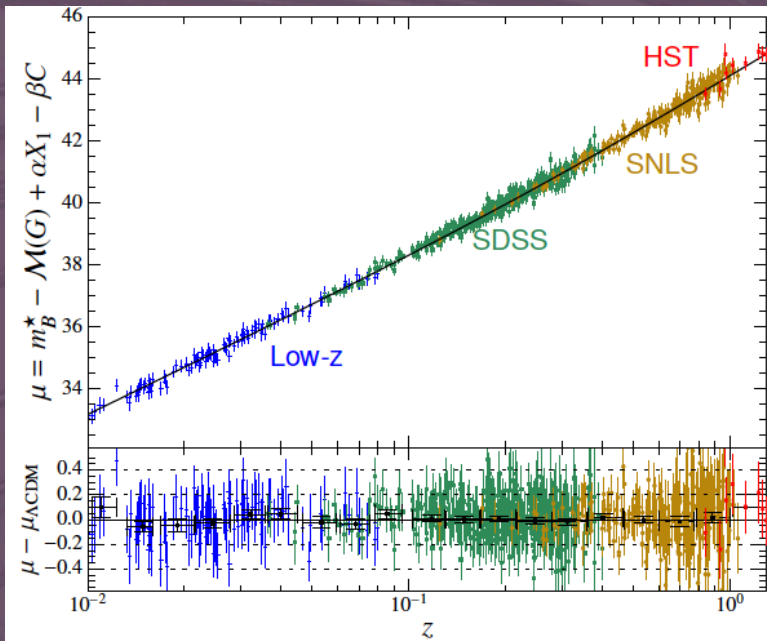
Dark Energy – *il y a dix ans*

- Good consensus on flat Λ CDM
 $\Omega_m \approx 0.27$, $\sigma_8 \approx 0.8$, $H_0 \approx 70$ km/s/Mpc
WMAP3, SNIa, galaxy clustering, first BAO, direct H_0
- Expansion history precision 5 - 10%
- Growth of structure precision 10 – 20%
- “Stage III” dark energy experiments just beginning
(DES, BOSS, CFHT Legacy Survey)

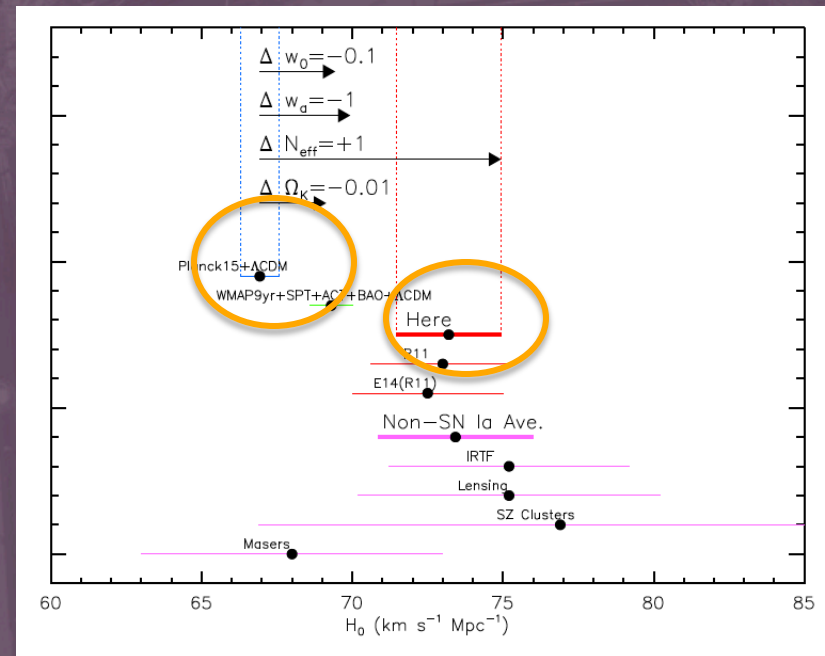
Dark Energy – 2017

Planck CMB + Λ CDM: $\Omega_m = 0.316 \pm 0.009$, $\sigma_8 \approx 0.831 \pm 0.013$
 $H_0 = 67.3 \pm 0.7$ km/s/Mpc

- Expansion history (SNIa and BAO) agree at 1-2%
- Direct H_0 disagrees, e.g., $H_0 = 73.2 \pm 1.7$ km/s/Mpc (R16)



Betoule, Kessler, Guy, Mosser++ 2014



Riess, Macri, Hoffmann, Scolnic++ 2016

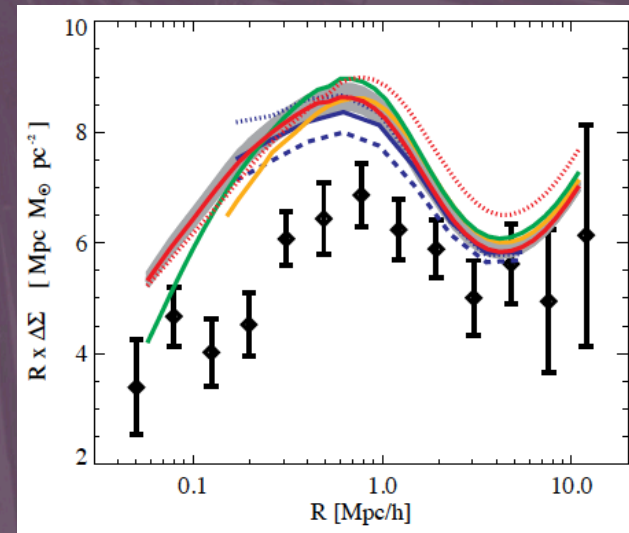
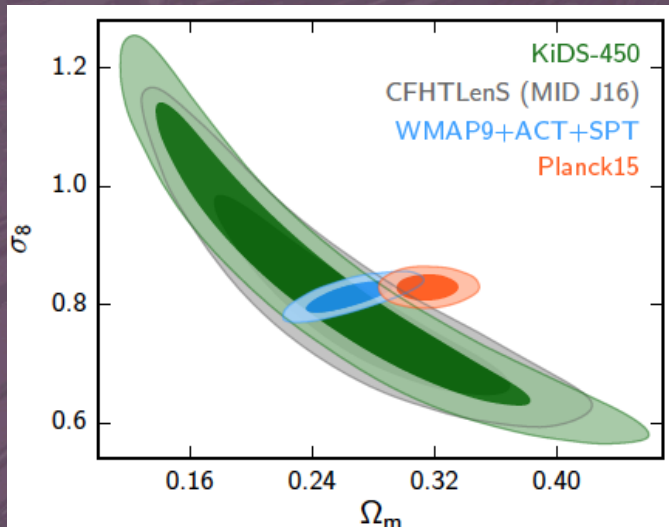
Dark Energy – 2017

Planck CMB + Λ CDM: $\Omega_m = 0.316 \pm 0.009$, $\sigma_8 \approx 0.831 \pm 0.013$
 $H_0 = 67.3 \pm 0.7$ km/s/Mpc

- Expansion history (SNIa and BAO) agree at 1-2%
- Direct H_0 disagrees, e.g., $H_0 = 73.2 \pm 1.7$ km/s/Mpc (R16)
- Growth of structure precision 5 – 10%

Many but not all measurements disagree w/ Planck+ Λ CDM

Hildebrandt,
Viola,
Heymans,
Joudaki
et al. 2017



Leauthaud,
Saito,
Hilbert,
Barreira
et al. 2017

Dark Energy – 2017

Planck CMB + Λ CDM: $\Omega_m = 0.316 \pm 0.009$, $\sigma_8 \approx 0.831 \pm 0.013$
 $H_0 = 67.3 \pm 0.7$ km/s/Mpc

- Expansion history (SNIa and BAO) agree at 1-2%
 - Direct H_0 disagrees, e.g., $H_0 = 73.2 \pm 1.7$ km/s/Mpc (R16)
 - Growth of structure precision 5 – 10%
- Many but not all measurements disagree w/ Planck+ Λ CDM
- Big near-term advances in weak lensing expected from Dark Energy Survey, Subaru Hyper-Suprime Camera



Dark Energy – 2027

Three plausible scenarios

1. Current tensions confirmed by Stage III experiments + ACT/SPT CMB data.
We are deep into trying to understand their origin.
2. Current tensions dissipate, but new ones have emerged at the 1% level. Confirmation and characterization are high priority.
3. Precision has improved to sub-percent level, all results consistent with Λ CDM.

DESI, Euclid, LSST, WFIRST all have important roles to play, partly overlapping, partly complementary.

Dark Energy with WFIRST



The ultimate supernova cosmology experiment

Unique in precision, redshift range, control of measurement and astrophysical systematics.

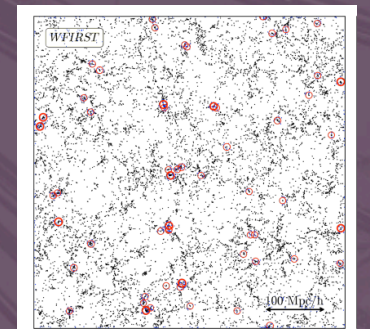
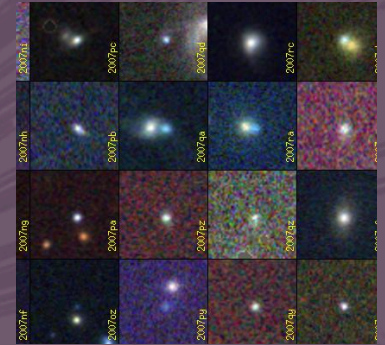
The best controlled weak lensing experiment

Unique in depth, detail, and control of measurement and astrophysical systematics.

The densest large scale map of structure at $z = 1-2$

Only WFIRST can map this redshift range at the density needed to reveal details of structure.

Per unit time, WFIRST is most powerful supernova, weak lensing, and $z = 1-2$ spectroscopic facility.



Cosmological tensions – historical templates?

Early 1990s: “Excess large scale power”

$\Omega = 1$? Theoretical elegance.

$\Omega = 0.3$? Simplest interpretation of observations.

New physics: $\Omega_m = 0.3, \Omega_{tot} = 1$

Mid 1990s: “The age crisis”

Systematic errors in H_0 ? Systematic errors in star cluster ages?

New physics: Cosmic acceleration implies $t_0 \approx 1/H_0$

Mid 2000s: WMAP1 σ_8 vs. cluster mass-to-light ratios

Systematics in M/L predictions? New physics?

Astrophysical systematics in CMB polarization foregrounds

Observational Probes of Cosmic Acceleration

Physics Reports 530, 87-255 (2013), arXiv:1201.2434



David Weinberg



Michael Mortonson



Daniel Eisenstein



Chris Hirata



Adam Riess



Eduardo Rozo

Contents	
1. Introduction	89
1.1. History	90
1.2. Theories of cosmic acceleration	91
1.3. Looking forward	93
2.1. Basic equations	96
2.2. Model parameters and constraints	98
2.3. CMB anisotropies and large scale structure	99
2.4. Parameter degeneracies and CMB constraints	100
2.5. Overview of methods	100
3. Type Ia supernovae	109
3.1. General principles	109
3.2. The current state of play	109
3.3. Observational considerations	112
3.4. Systematic uncertainties and strategies for amelioration	113
3.5. Space vs ground	114
3.6. Prospects	115
4. Baryonic acoustic oscillations	115
4.1. General principles	115
4.2. The current state of play	116
4.3. Theory of BAO	119
4.3.1. Linear theory	119
4.3.2. Non-linear evolution and galaxy clustering bias	120
4.3.3. Reconstruction	122
4.3.4. Fitting to data	124
4.4. Observational considerations	125
4.4.1. Statistical errors	125
4.4.2. From BAO to dark energy	126
4.4.3. Sampling density	127
4.4.4. Spectroscopic v. photometric redshifts	128
4.4.5. Traces of structure	128
4.5. Systematic uncertainties and strategies for amelioration	129
4.5.1. Measurement systematics	129
4.5.2. Astrophysical systematics	130
4.5.3. Cosmological systematics	131
4.6. Space vs ground	131
4.7. Prospects	132
5. Weak lensing	133
5.1. General principles: an overview	134
5.2. Weak lensing principles: mathematical discussion	135
5.2.1. Deflection of light in cosmology	135
5.2.2. Cosmic shear, magnification, and flexion	137
5.2.3. Power spectra and correlation functions	137
5.2.4. Method I: cosmic shear power spectrum*	139
5.2.5. Method II: power spectrum tomography*	140
5.2.6. Method III: galaxy-galaxy lensing*	140
5.2.7. Method IV: cosmography*	141
5.2.8. Method V: non-Gaussian statistics*	142
5.3. The current state of play	142
5.3.1. Cosmic shear	143
5.3.2. Galaxy-galaxy lensing as a cosmological probe	144
5.3.3. Lensing outside the optical band	146
5.4. Observational considerations and survey design	146
5.4.1. Statistical errors	146
5.4.2. The galaxy population for optical surveys	148
5.4.3. Instrumental residuals and their calibration	148
5.4.4. Lensing in the radio	150
5.4.5. Lensing of the CMB	151
5.5. Measuring shear	151
5.5.1. The reduction problem	152
5.5.2. Shape measurement algorithms*	153
5.5.3. Shape measurement errors*	156
5.5.4. Noise rectification and selection biases*	156
5.5.5. Determining the PSF and instrument properties	157
5.6. Astrophysical systematics	158
5.6.1. Intrinsic alignments*	158
5.6.2. Theoretical uncertainties in the matter power spectrum*	161
5.7. Systematic errors and their amelioration: summary	162
5.8. Advantages of a space mission	163
5.9. Prospects	163
6. Clusters of galaxies	166
6.1. General principles	166
6.2. The current state of play	168
6.3. Observational considerations	170
6.3.1. In period numbers and cosmological sensitivity	170
6.3.2. Cluster finding	174
6.3.3. Calibrating the observables: mass relation	176
6.4. Systematic uncertainties and strategies for amelioration	179
6.4.1. Redshift uncertainties	179
6.4.2. Contamination and incompleteness: the tails of $P(X, M, z)$	179
6.4.3. Calibrating the core of $P(X, M, z)$	180
6.4.4. Theoretical systematics	180
6.5. Space vs ground	183
6.6. Prospects	184
7. Alternative methods	186
7.1. Measurement of the Hubble constant at $z \approx 0$	186
7.2. Redshift-space distortions	188
7.3. The Alcock-Paczynski test	191
7.4. Alternative distance indicators	192
7.5. Standard sirens	193
7.6. The Ly α forest as a probe of structure growth	194
7.7. Other tests of modified gravity	195
7.8. The integrated Sachs-Wolfe effect	196
7.9. Cross-correlation of weak lensing and spectroscopic surveys	197
7.10. Strong gravitational lensing	198
7.11. Galaxy ages	198
7.12. Redshift drift	199
7.13. Alternative methods: summary	199
8. A balanced program on cosmic acceleration	200
8.1. A fiducial program	200
8.2. Forecasting constraints	202
8.3. Results: forecasts for the fiducial program and variations	206
8.3.1. Constraints in single $w(z)$ models	206
8.3.2. Constraints on structure growth parameters	210
8.3.3. Dependence on the $w(z)$ model and binning of data	212
8.3.4. Constraints on $w(z)$ in the general model	214
8.4. Forecasts for clusters	223
8.5. Forecasts for alternative methods	223
8.5.1. The Hubble constant	223
8.5.2. The Alcock-Paczynski test	223
8.5.3. Redshift-space distortions	225
8.5.4. Distances	226
8.6. Observative and aggregate precision	226
8.7. Prospects with many probes	230
9. Conclusions	232
Appendix. Glossary of acronyms and facilities	236
References	238

Personal reasons for enthusiasm

Cosmic acceleration: biggest cosmological discovery during my academic life

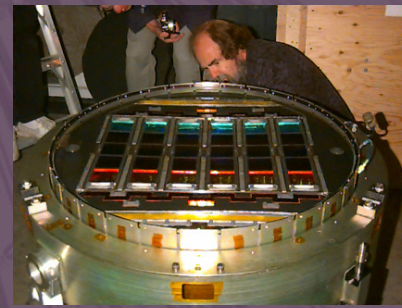
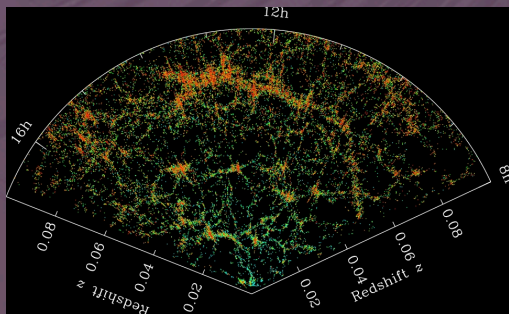
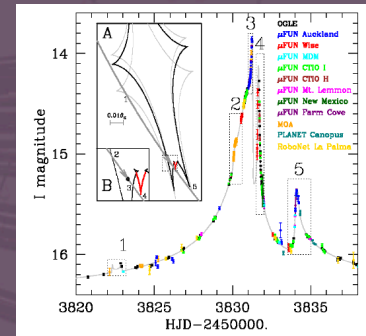
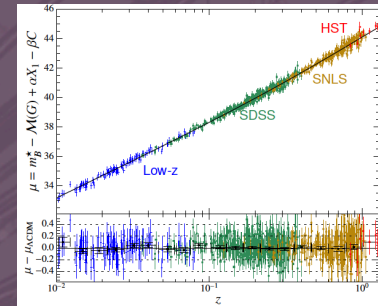
WFIRST can make unique contributions to understanding it

Microlensing: a beautiful way to find planets

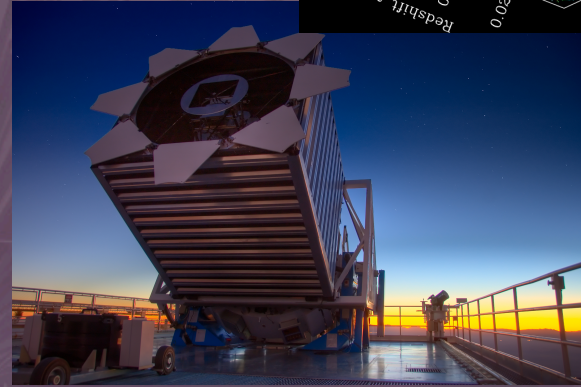
Unique tool for understanding planet formation

The Sloan Digital Sky Survey in space

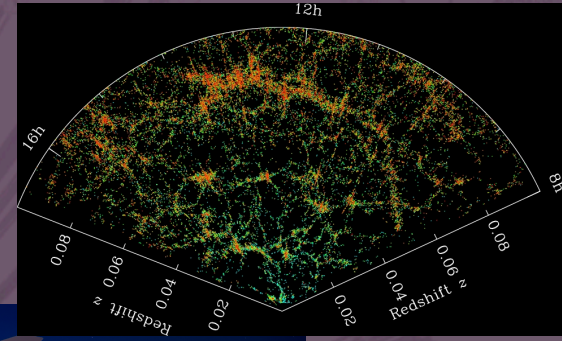
Promises enormous, broad-ranging scientific impact



Hubble + SDSS



=



WFIRST

