WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

LSST
Large Synoptic Survey Telescope

Cosmology with WFIRST - Synergies with ground-based surveys

Tim Eifler
(Steward Observatory/
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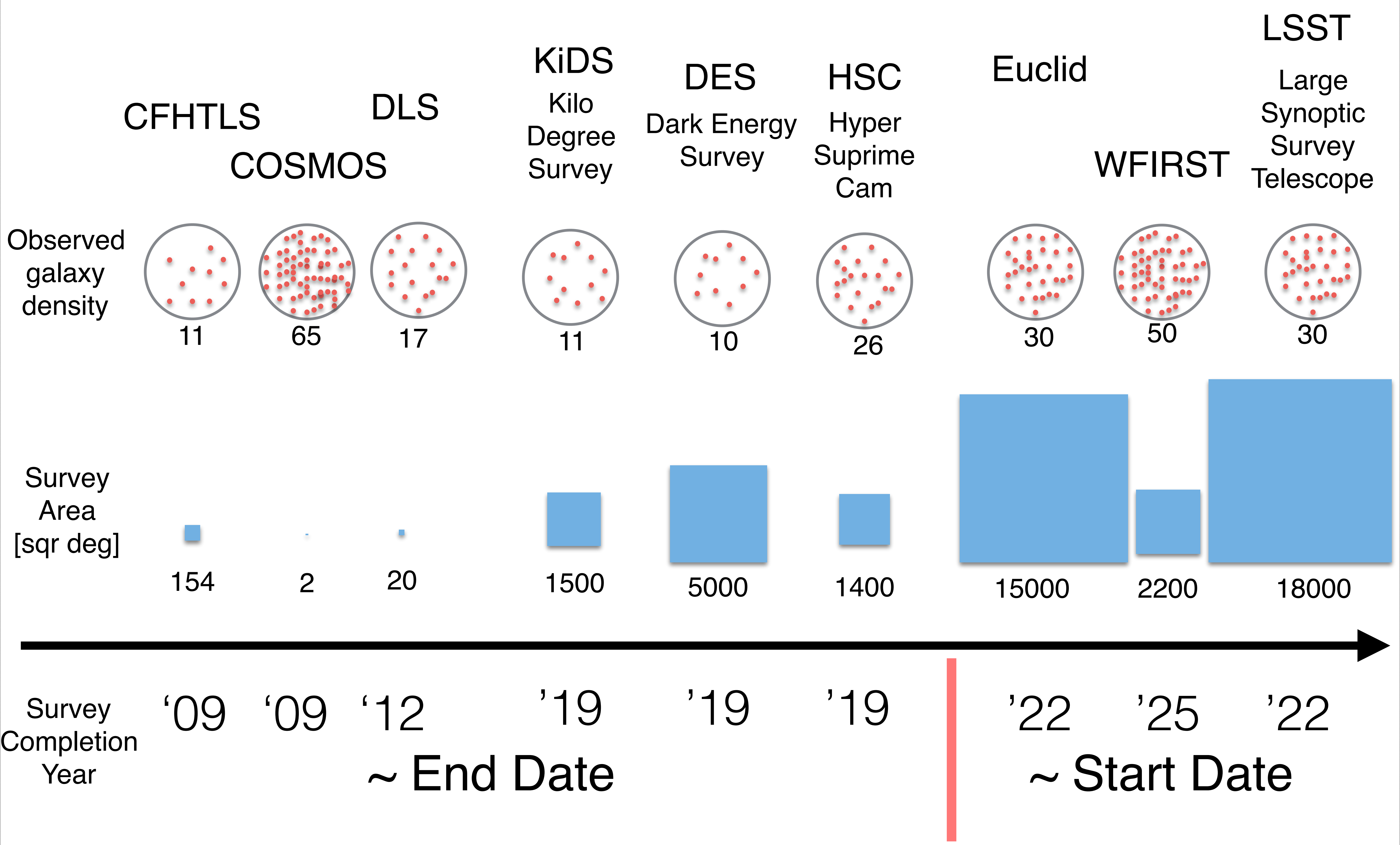
Partnering space and ground observatories - Synergies in cosmology from LSST and WFIRST

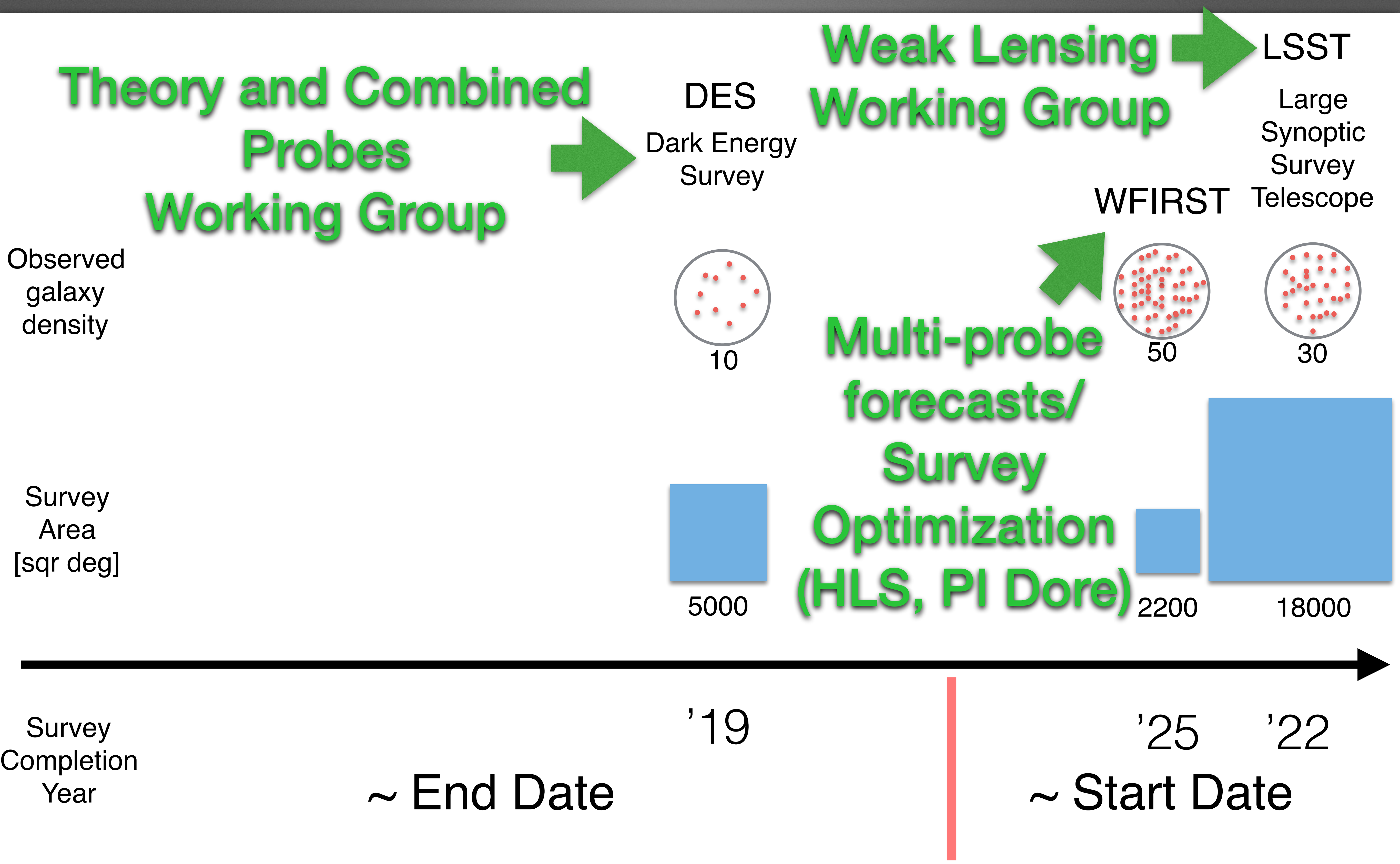
Thematic areas: 7. Cosmology and Fundamental Physics

Authors: Tim Eifler[1] (U. of Arizona), Melanie Simet (UC Riverside), Chris Hirata (OSU), Chen Heinrich (JPL/Caltech), Shoubaneh Hemmati (IPAC/Caltech), Rachel Mandelbaum (CMU), Mike Jarvis (UPenn), Elisabeth Krause (U. of Arizona), O. Doré (JPL/Caltech), Hironao Miyatake (U. of Nagoya), Bhuvnesh Jain (UPenn), David Spergel (Princeton), Vivian Miranda (U. of Arizona), Xiao Fang (U. of Arizona), Anja von der Linden (Stony Brook), Masahiro Takada (Kavli IPMU), Naoki Yoshida (U. of Tokyo/Kavli IPMU), Masato Shirasaki (NAOJ), Catherine Heymans (U. of Edinburgh), Robert Schuhmann (U. of Edinburgh), Joe Zuntz (U. of Edinburgh)

Photometric Dark Energy Surveys



Photometric Dark Energy Surveys

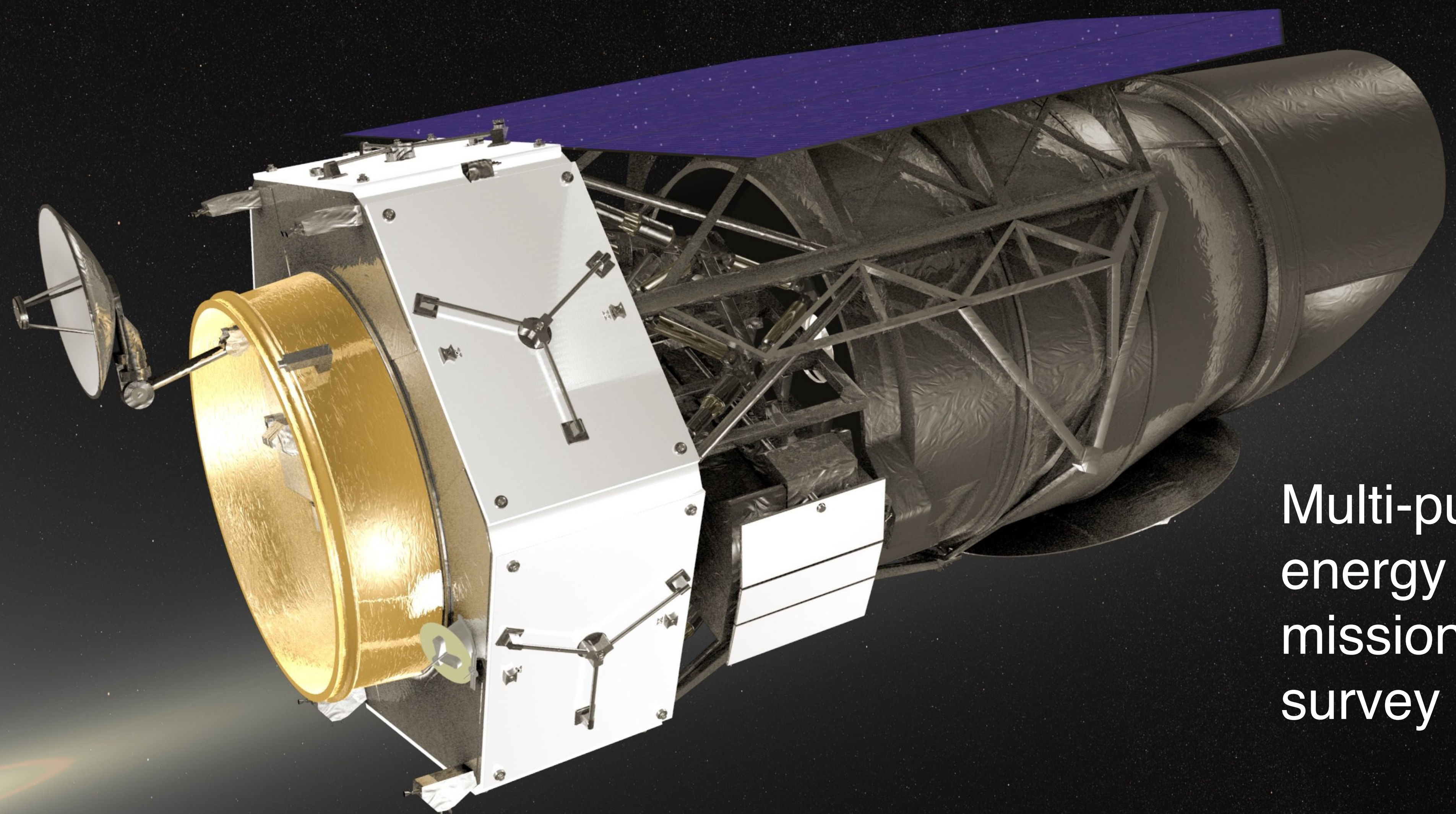


WFIRST

WWF

Top-ranked space mission of the 2010 US Decadal Survey

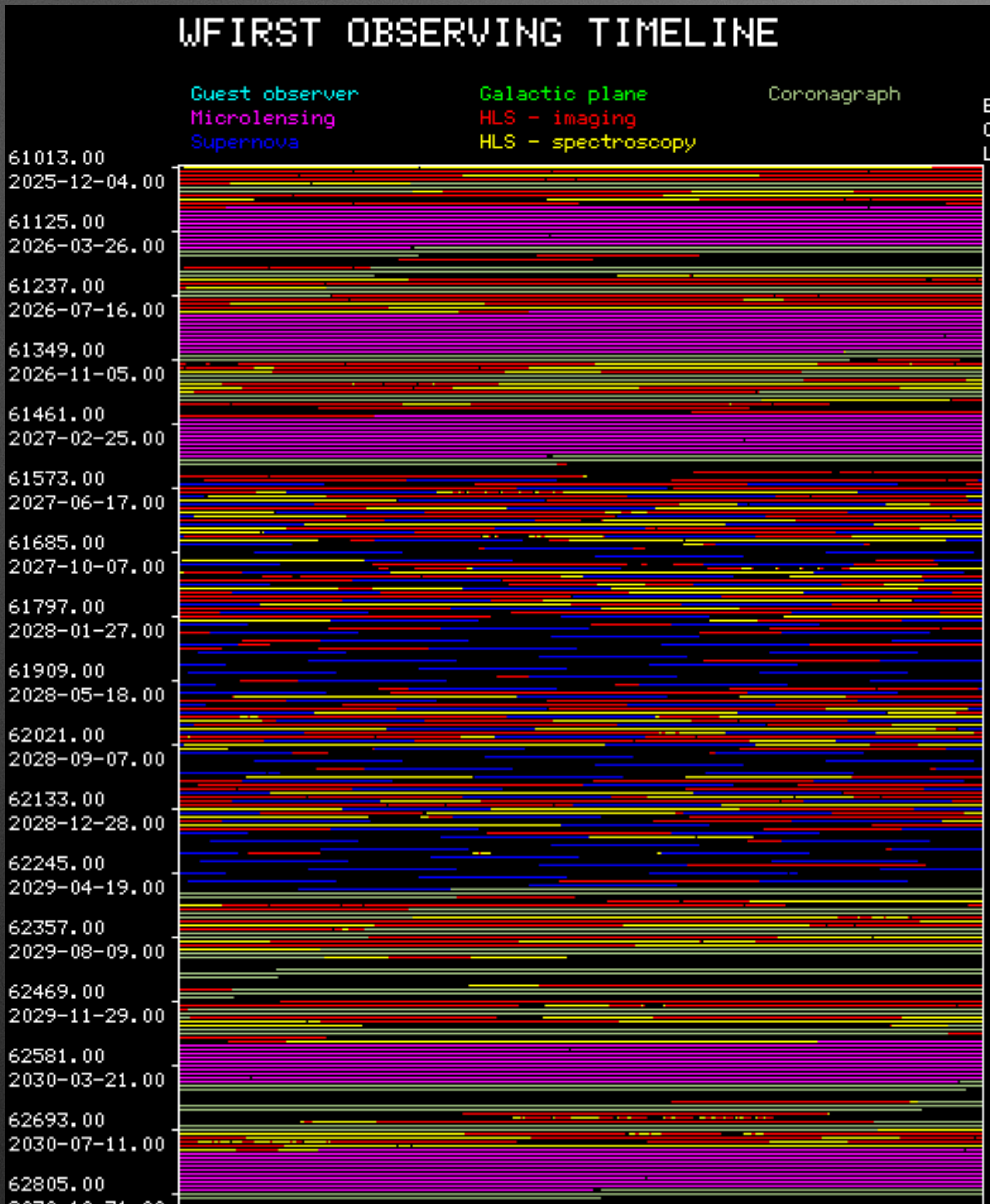
Launch ~2025
Currently in Phase B



Multi-purpose (Dark energy to exoplanet) mission with wide-field survey capabilities.

2.4m Hubble-sized telescope (repurposed from NRO)

WFIRST Example Survey



- Exposure time calculator (Hirata et al 2012)
- Includes slew time, shutter, filter change, etc
- WFIRST is multi-purpose survey:
  - HLS Spectro
  - HLS imaging
  - SN
  - Microlensing
  - Guest Observer
  - Galactic plane
  - Coronograph

WFIRST Imaging Capabilities

Telescope Aperture (2.4 meter)	Field of View (45′x23′; 0.28 sq deg)	Pixel Scale (0.11 arcsec)	Wavelength Range (0.5-2.0 μm)

Filters	R062	Z087	Y106	J129	H158	F184	W146
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	1.38-1.77	1.68-2.00	0.93-2.00
Sensitivity (5σ AB mag in 1 hr)	28.50	28.02	27.95	27.87	27.81	27.32	28.33

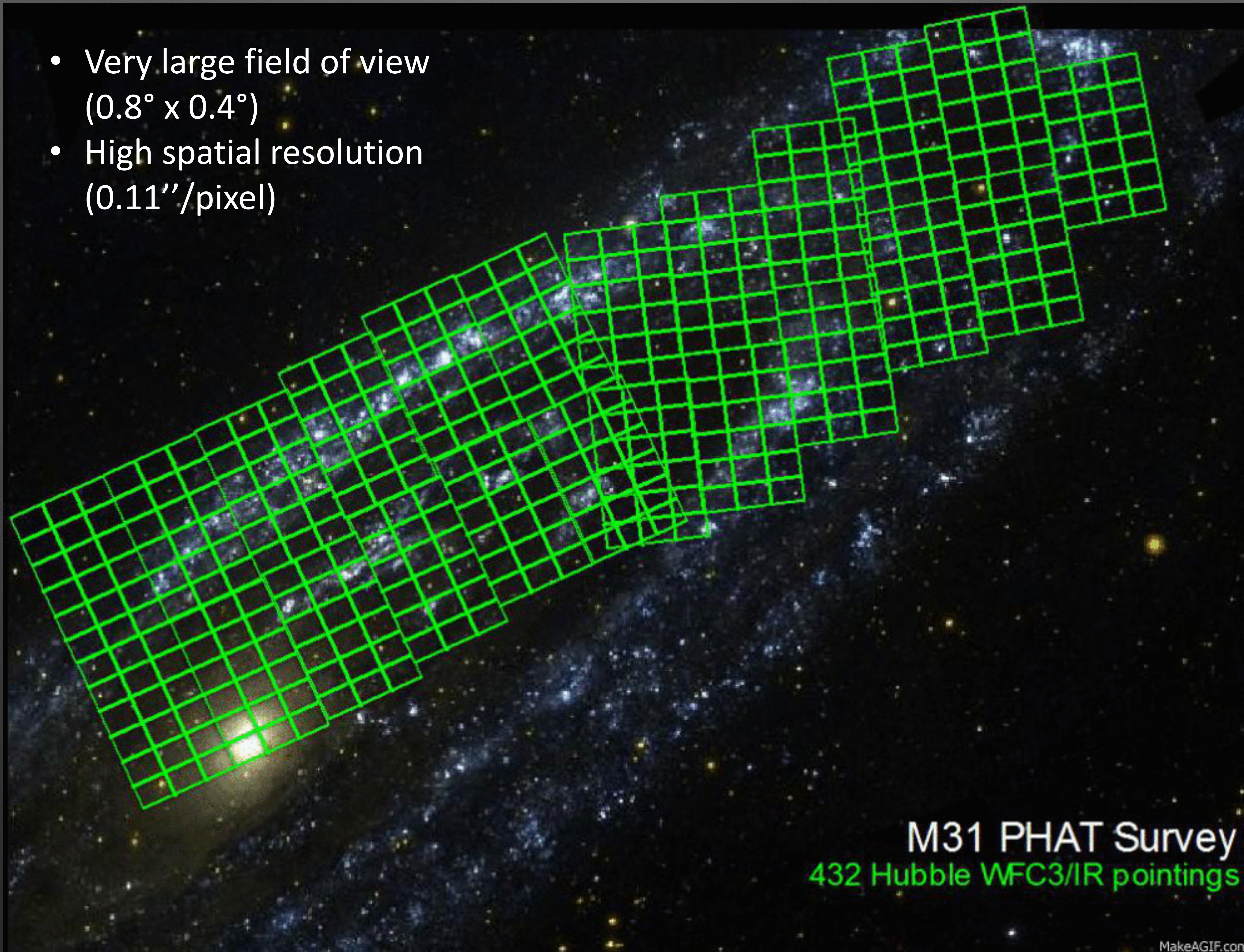
WFIRST Spectroscopic Capabilities

	Field of View (sq deg)	Wavelength (μm)	Resolution	Sensitivity (10σ AB mag in 1000s)
Grism	0.28 sq deg	1.00-1.89	435-865	20.4 at 1.5 μm
~~Integral Field Channel~~	~~3.00 x 3.15 arcsec~~	~~0.42-2~~	~~80-120~~	~~24.2 at 1.5 μm~~

WFIRST Coronagraphic Capabilities

	Wavelength (μm)	Inner Working Angle (arcsec)	Outer Working Angle (arcsec)	Detection Limit	Spectral Resolution
Imaging & Spectroscopy	0.4-1	0.15 (exoplanets) 0.9 (disks)	0.9 (exoplanets) 3.0 (disks)	10^{-9} contrast (after post-processing)	~50

- Very large field of view (0.8° x 0.4°)
- High spatial resolution (0.11’’/pixel)



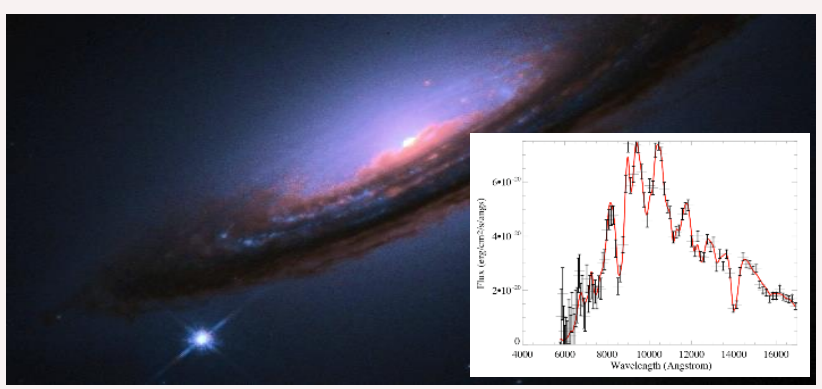
WFIRST - Dark Energy Plan

Supernova Survey

wide, medium, & deep imaging
+
~~IFU spectroscopy~~

2700 type Ia supernovae
z = 0.1–1.7

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

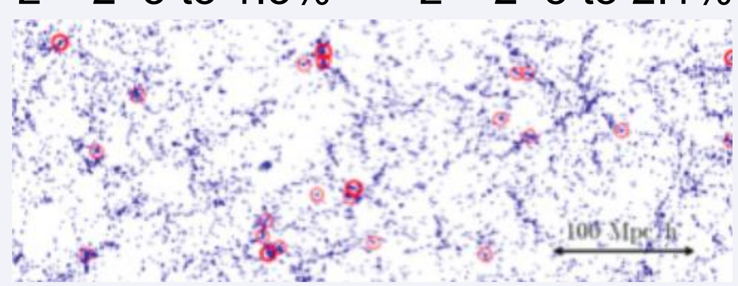
16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

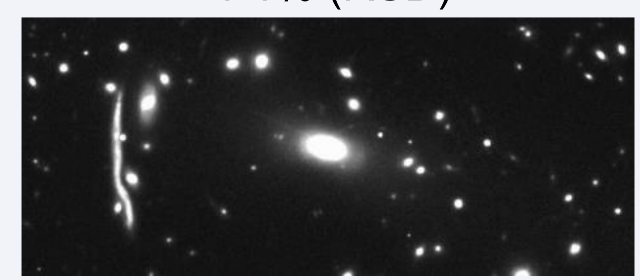
380 million lensed galaxies
40,000 massive clusters

standard ruler

distances	expansion rate
z = 1–2 to 0.5%	z = 1–2 to 0.9%
z = 2–3 to 1.3%	z = 2–3 to 2.1%

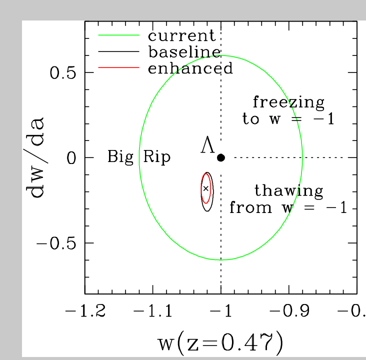


dark matter clustering
z < 1 to 0.21% (WL); 0.24% (CL)
z > 1 to 0.78% (WL); 0.88% (CL)
1.1% (RSD)

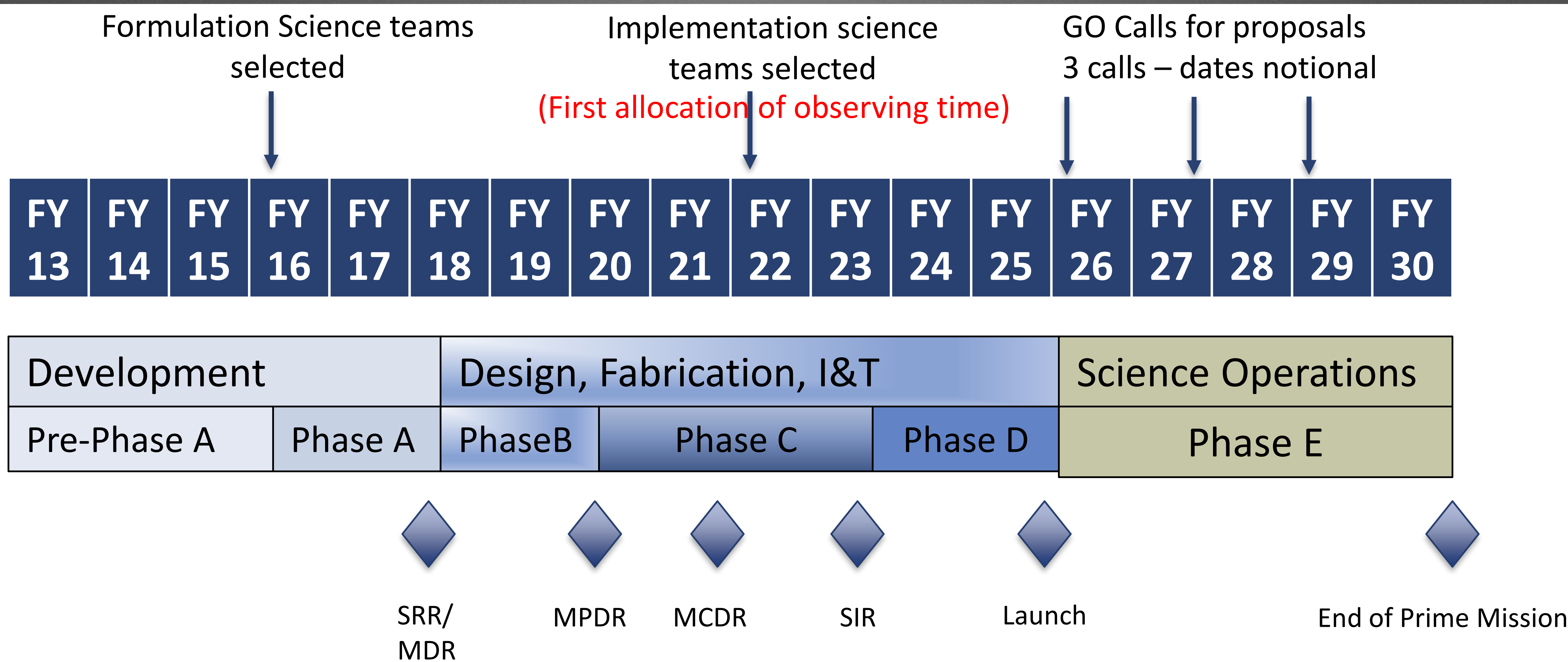


history of dark energy
+
deviations from GR

w(z), ΔG(z), Φ_{REL}/Φ_{NREL}



WFIRST Schedule

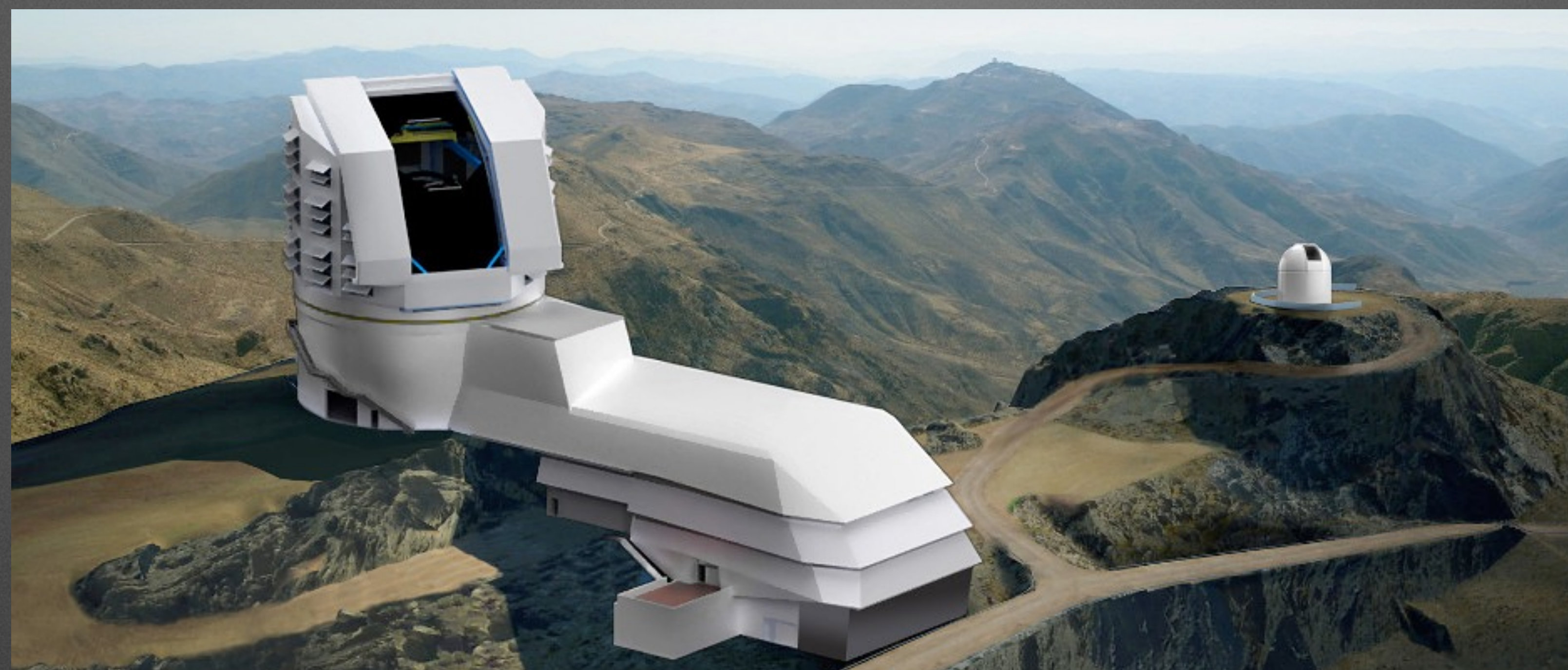


Extended Mission can be expected

As of Feb 19…WFIRST is well on track.

LSST

Large Synoptic Survey Telescope



LSST: The Experiment

- largest planned LSS survey
- map visible sky every 3 nights
- high priority in P5, decadal survey
- construction started 2015
- commissioning first light 2019
- survey duration 2022-2032

LSST: Science Collaborations

- Solar System
- Stars, Milky Way, Local Volume
- Transients
- Galaxies
- Active Galactic Nuclei
- Informatics and Statistics
- Dark Energy

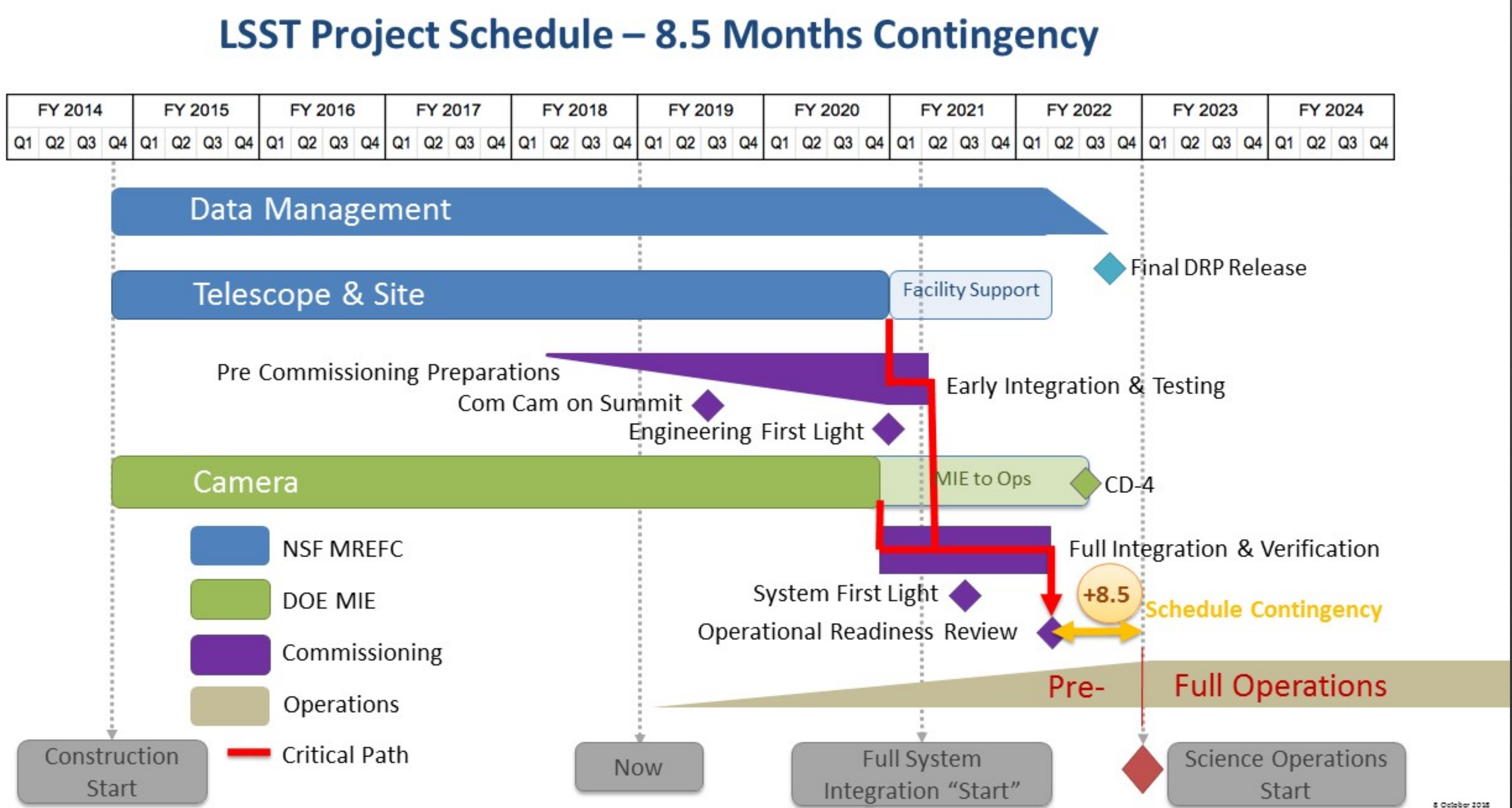
The LSST Dark Energy Science Collaboration

Prepare for and carry out cosmology analyses with the LSST survey

- 6 key cosmology Working Groups (WG)
  Galaxy Clustering, Galaxy Clusters, Strong Lensing, Supernovae, Weak Lensing; Theory & Joint Probes
- “Enabeling Analyses” WGs: understand LSST system + systematics

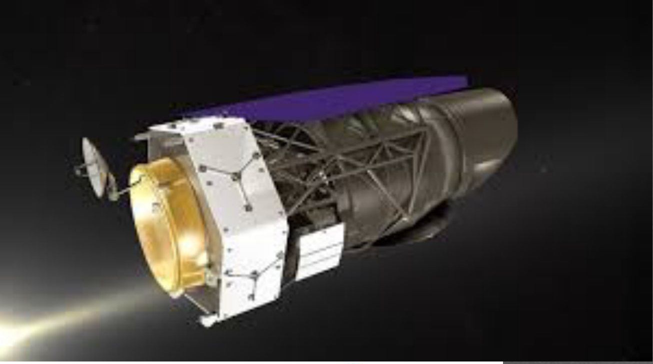
lots of work until first data, lots to learn from ongoing surveys!

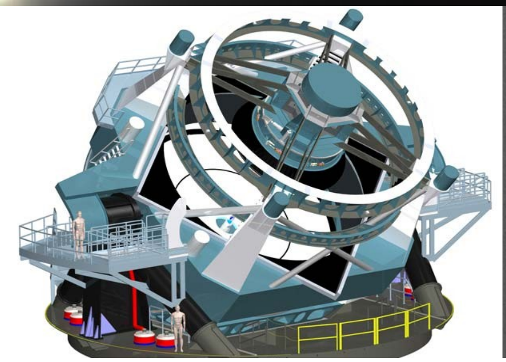
LSST Schedule



How do we optimize WFIRST/LSST?

How do we explore synergies?

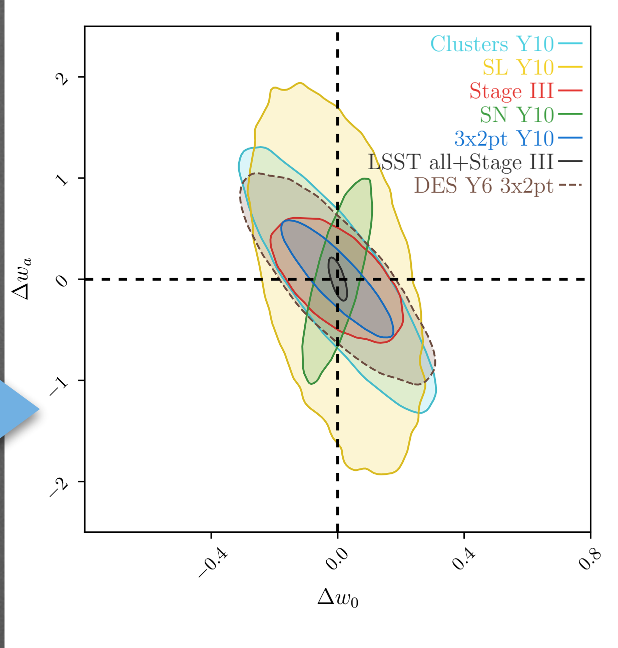




The Challenge

reduced data and catalogs → summary statistics →

→



Independent probes
e.g., SN1a as priors

Large model vector (CMB+LSS)
Self-consistent modeling of all observables as a function of
1) cosmological parameters (~10)
2) nuisance parameters (XXX)

large data vector

posterior probability

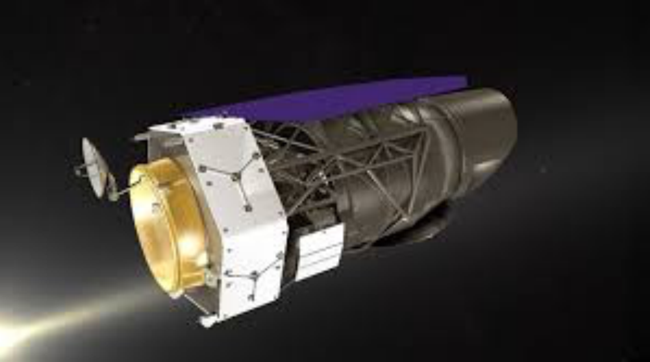
$$p\left(\boldsymbol{\pi}|\hat{\mathbf{d}}\right) \propto p\left(\boldsymbol{\pi}\right)\mathcal{L}\left(\hat{\mathbf{d}}|\mathbf{m}\left(\boldsymbol{\pi}\right),\boldsymbol{C}\right)$$

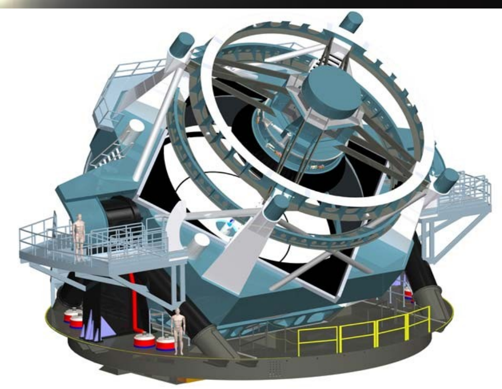
Enhanced modeling via
- Observations
- Simulations
- Theory

Statistics I - Likelihood function
- Multivariate Gaussian vs other parameterizations
- Non-parametric forms
- Approximate Bayesian Computation

Statistics II - Covariances
- cosmology dependent Signal + constant Noise
- large and complicated, non-(block) diagonal
- different methods for derivation

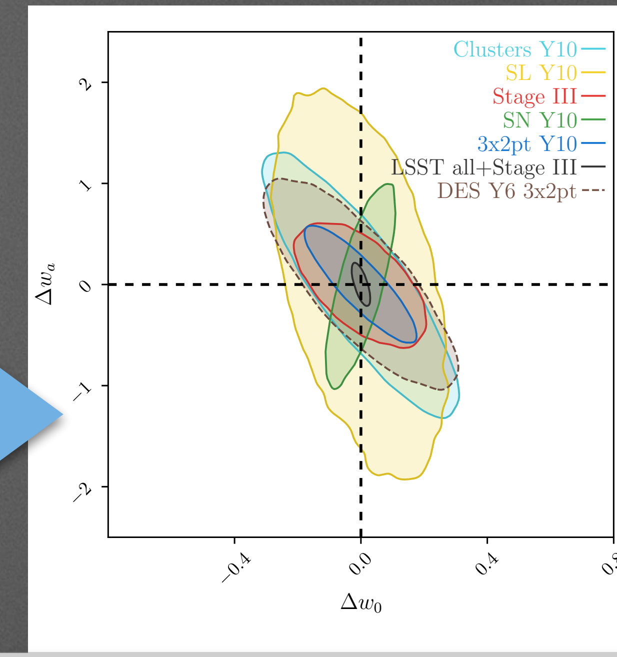
The Challenge





reduced data and catalogs → summary statistics →

→



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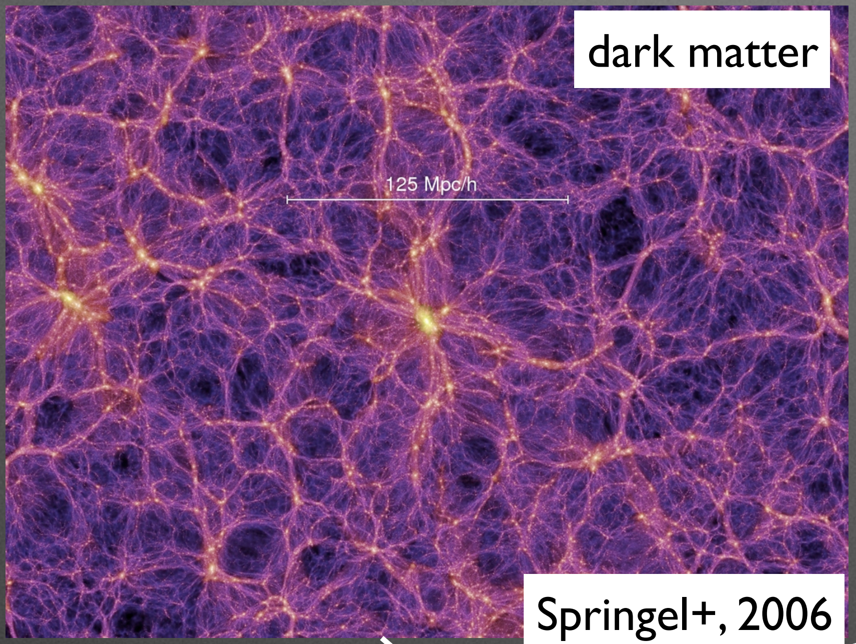
Theory - Data connection in a nutshell

Physics
+ model parameters

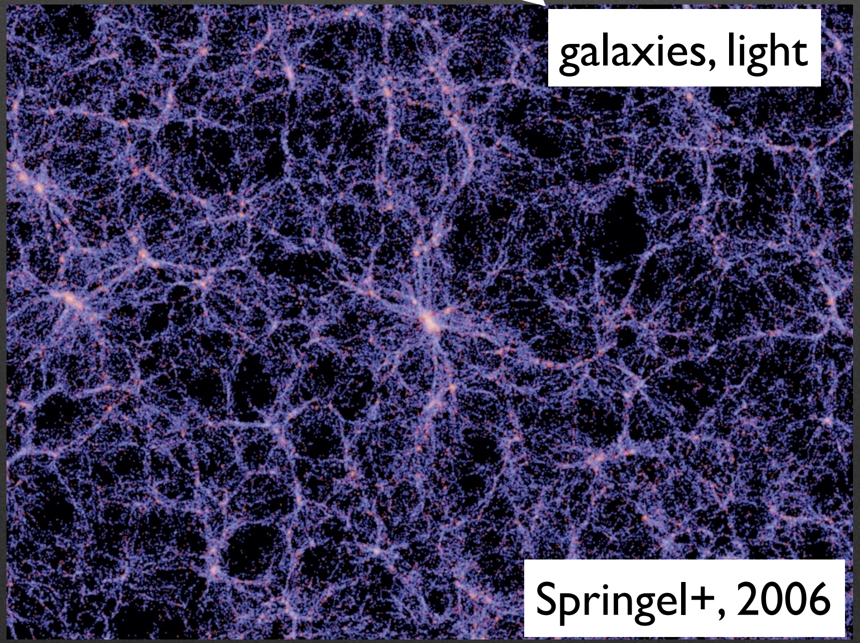
generate initial conditions, evolve



Baryons, galaxy bias, Intrinsic alignment, Cluster Mass Observable Relation

galaxy formation models

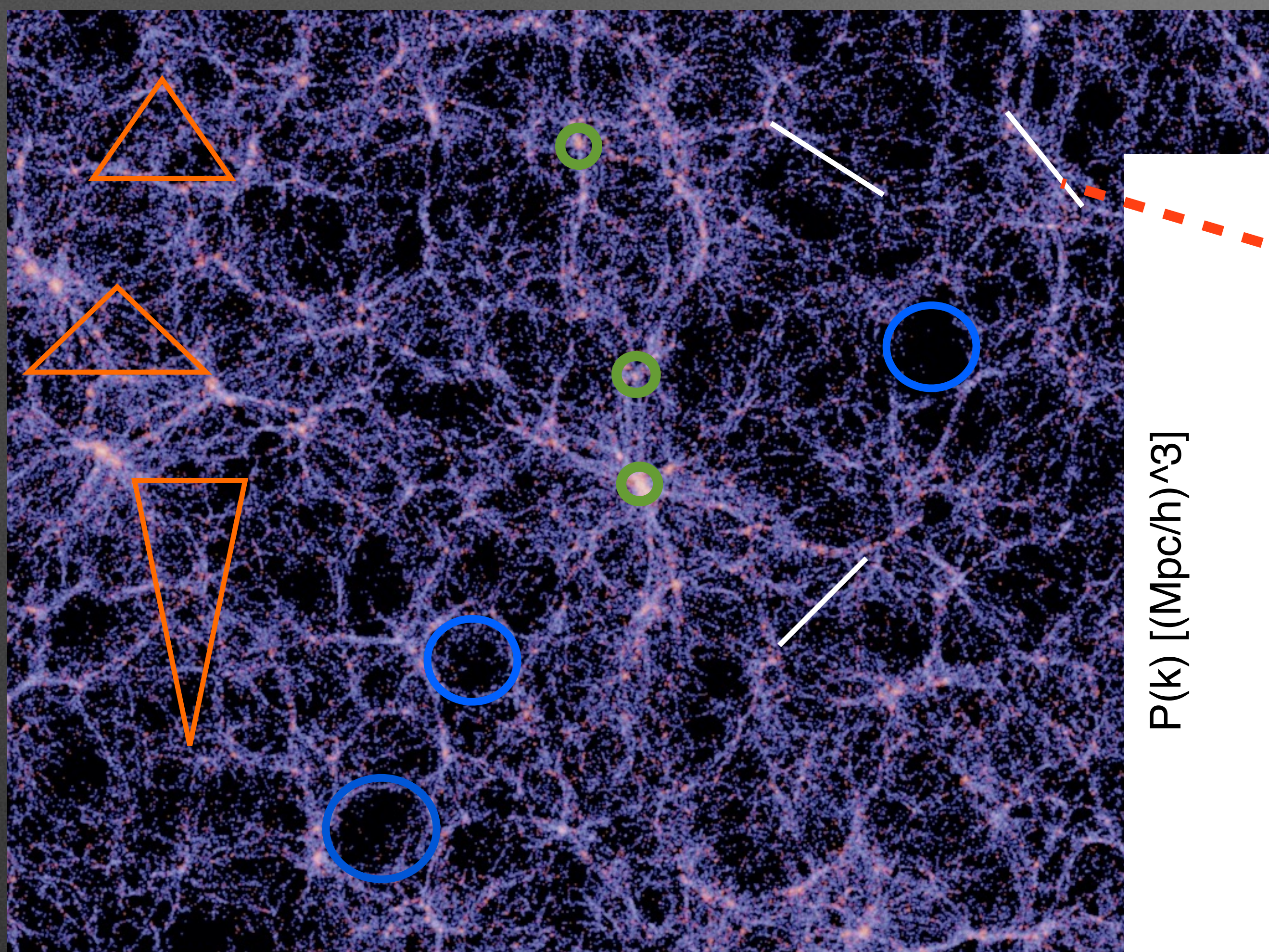
?

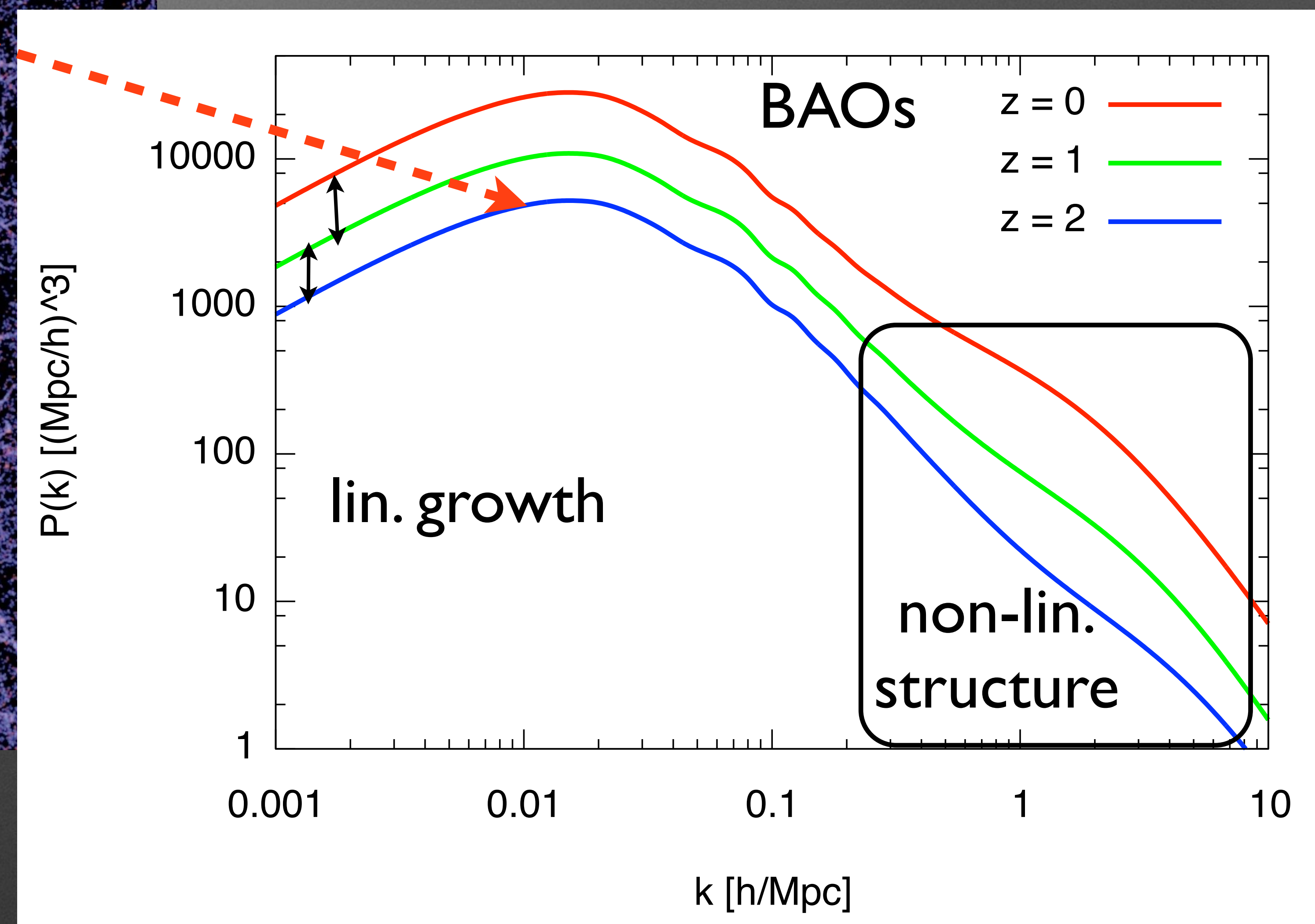


Obs

Sys ?

Tracers of the density field

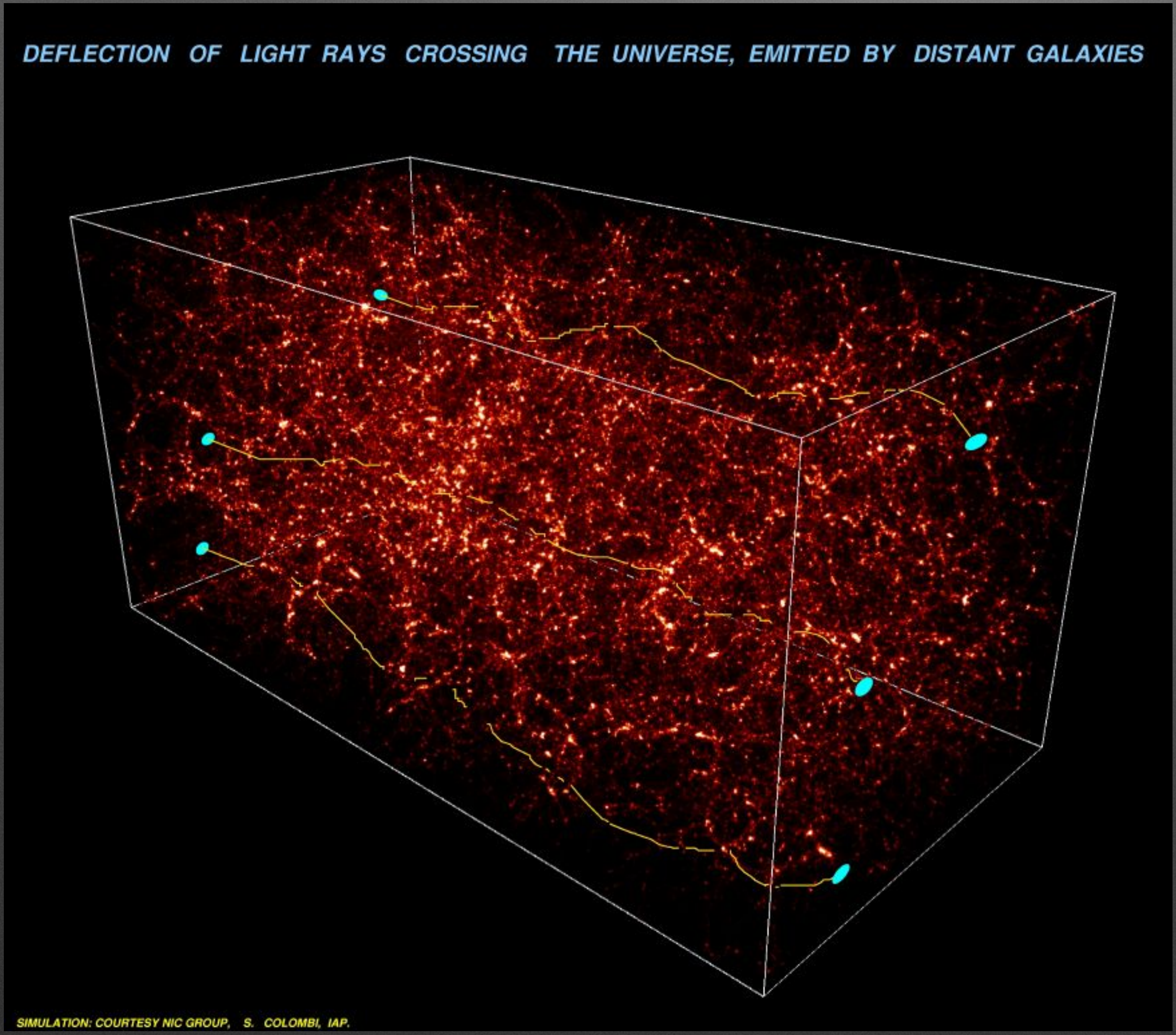




- clusters,peaks (over densities),
- voids (under densities)
- two-point correlations (galaxy positions, shapes)
- three-point correlations,...

$$C_\ell^{AB} = \int \frac{d\chi}{\chi^2}\, W_A(\chi) W_B(\chi)\, P_m\left(k = \frac{\ell + 1/2}{\chi}, \chi\right),$$

Weak Lensing

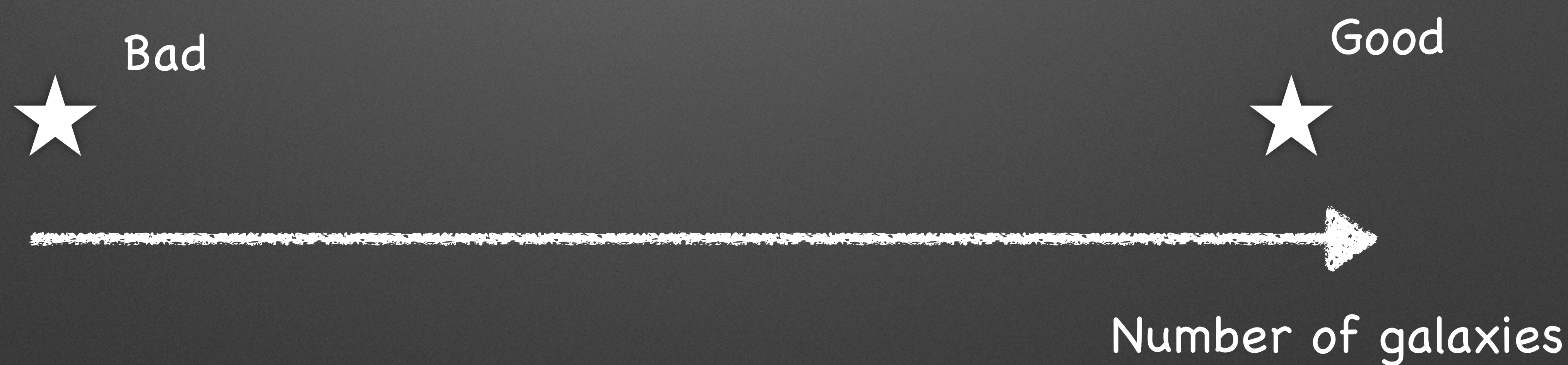


Light rays are distorted by dark matter density field of the Universe

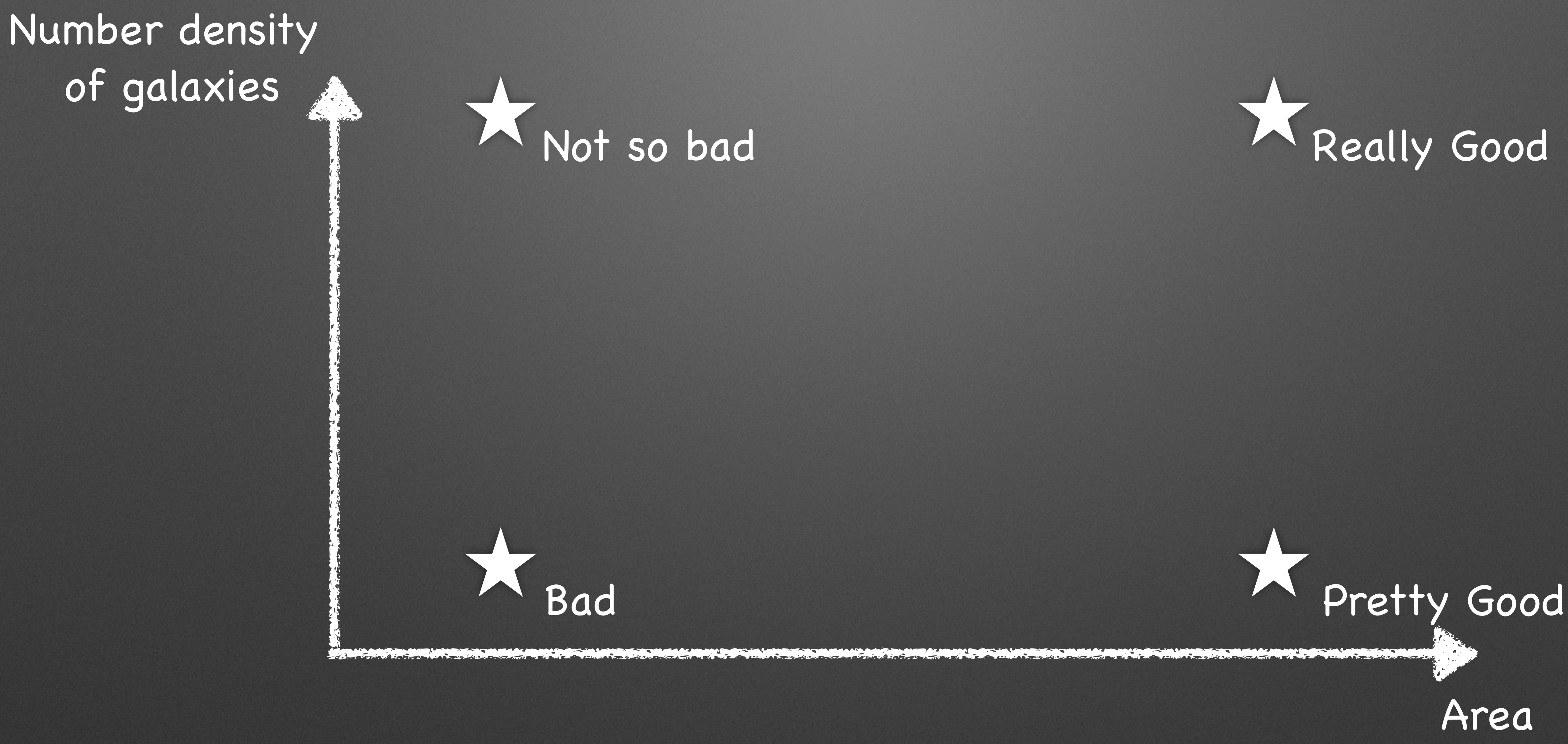
Statistical properties of the distortion reflect statistical properties of the projected density field

$$C_\ell^{AB} = \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi) P_m\left(k = \frac{\ell + 1/2}{\chi}, \chi\right).$$

Survey Optimization I



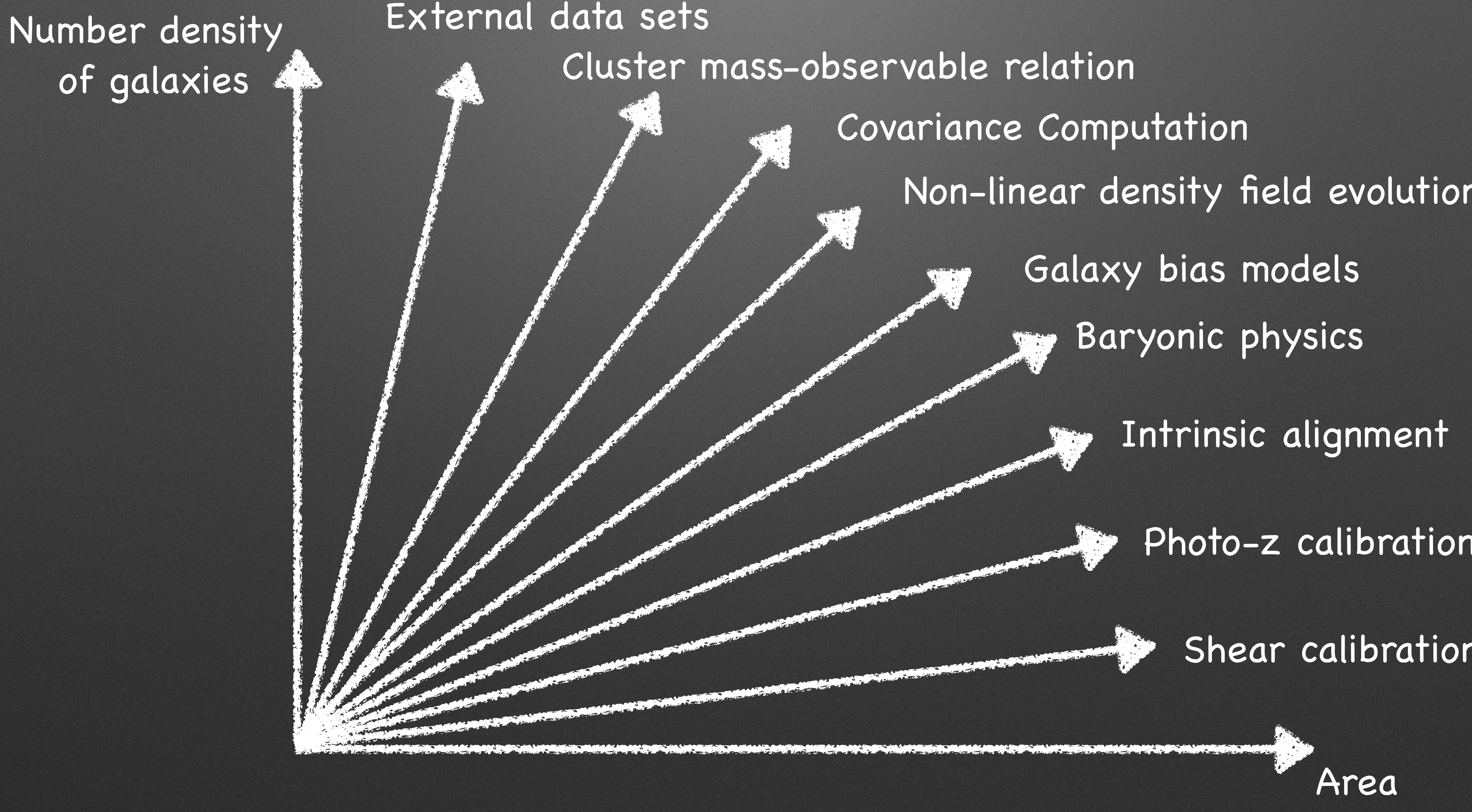
Survey Optimization II



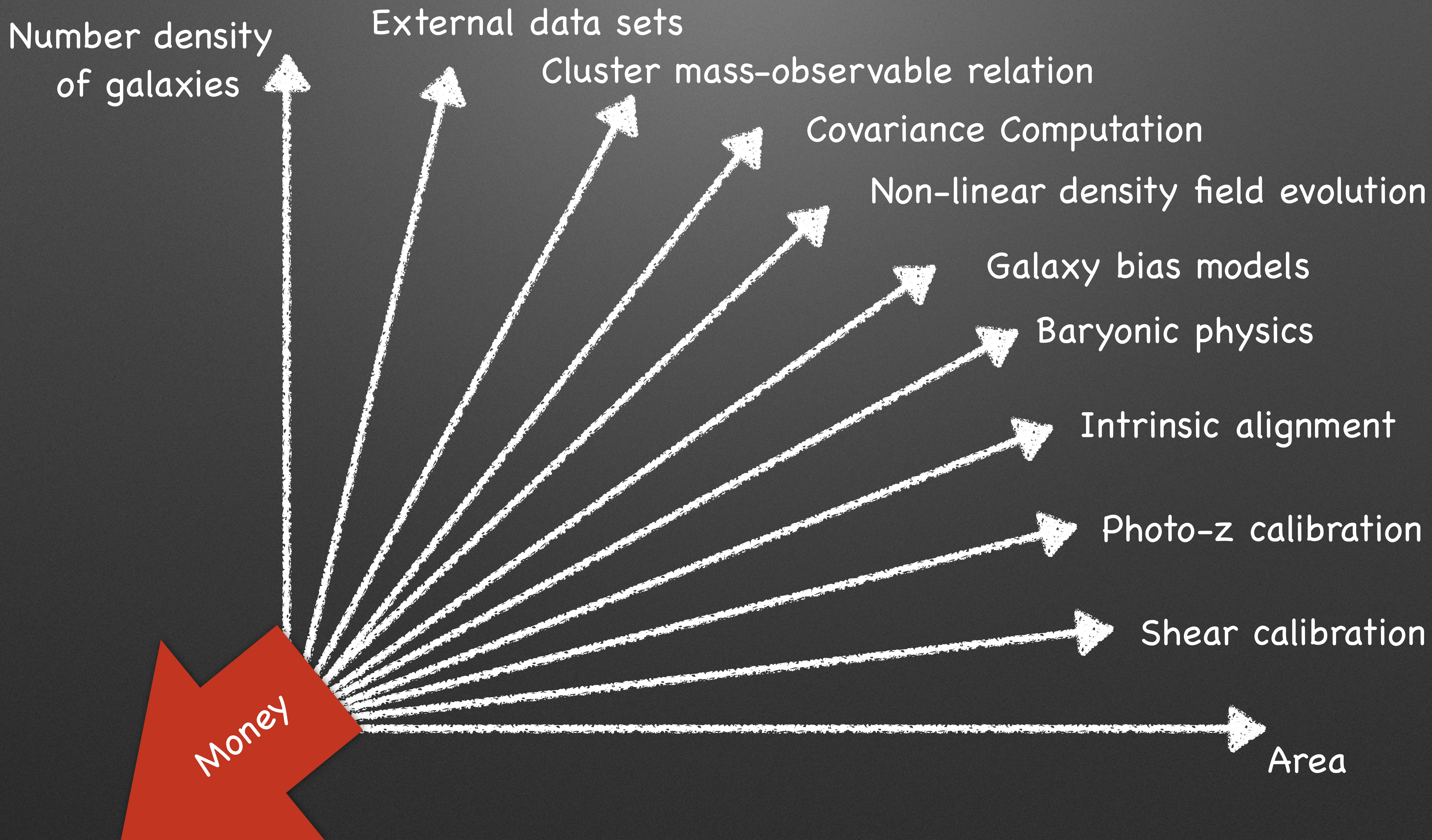
Statistical error bars only (slightly simplified):

- Area is more important than depth
- Even more true since non-gaussian Covariances became fashionable

Today's Survey Optimization III



Today's Survey Optimization III



How do we optimize WFIRST/LSST?

Simulated Multi-Probe Analysis

First choose some probes…

- Cosmic shear
- Galaxy-Galaxy Lensing
- Galaxy Clustering
- Cluster Number Counts
- Cluster Weak Lensing

- Cluster Clustering
- Peak Statistics
- Voids
- Magnification
- Higher-order statistics (many position, shape, magnification combinations are possible)
- All can be correlated with CMB (again many combinations are possible)

Simulated Multi-Probe Analysis

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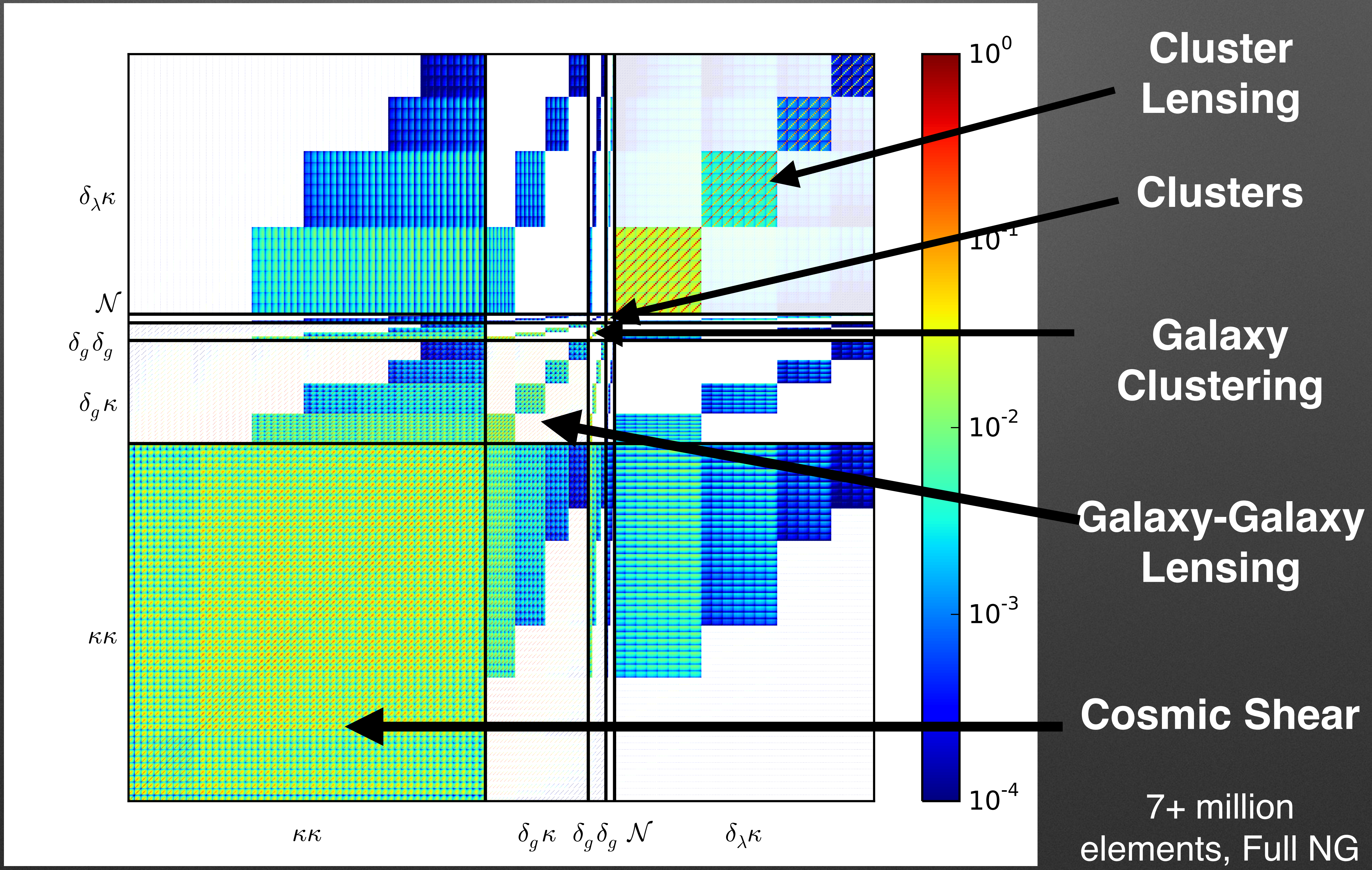
Many analysis choices are necessary beyond "choosing probes": (e.g. scales, redshifts, binning, galaxy samples, etc) that depend on:

- data quality
- **modeling precision/accuracy of physics, systematics, statistical errors <u>in finite time</u>**

Challenge of the coming decade

Problem 1: Probes are correlated



7+ million elements, Full NG

details: Krause&TE '17

Problem 2: Probes have systematics

- Weak Lensing (cosmic shear)
  - 10 tomography bins
  - 25 l bins, 25 < l < 5000

shear calibration,
photo-z (sources)
IA, Baryons

- Galaxy clustering
  - 4 redshift bins (0.2-0.4,0.4-0.6,0.6-0.8,0.8-1.0)
  - compare two samples: σ_z <0.04, redMaGiC
  - linear + quadratic bias only : l bins restricted to R> 10 Mpc/h
  - l bins restricted to R>0.1 MPC/h

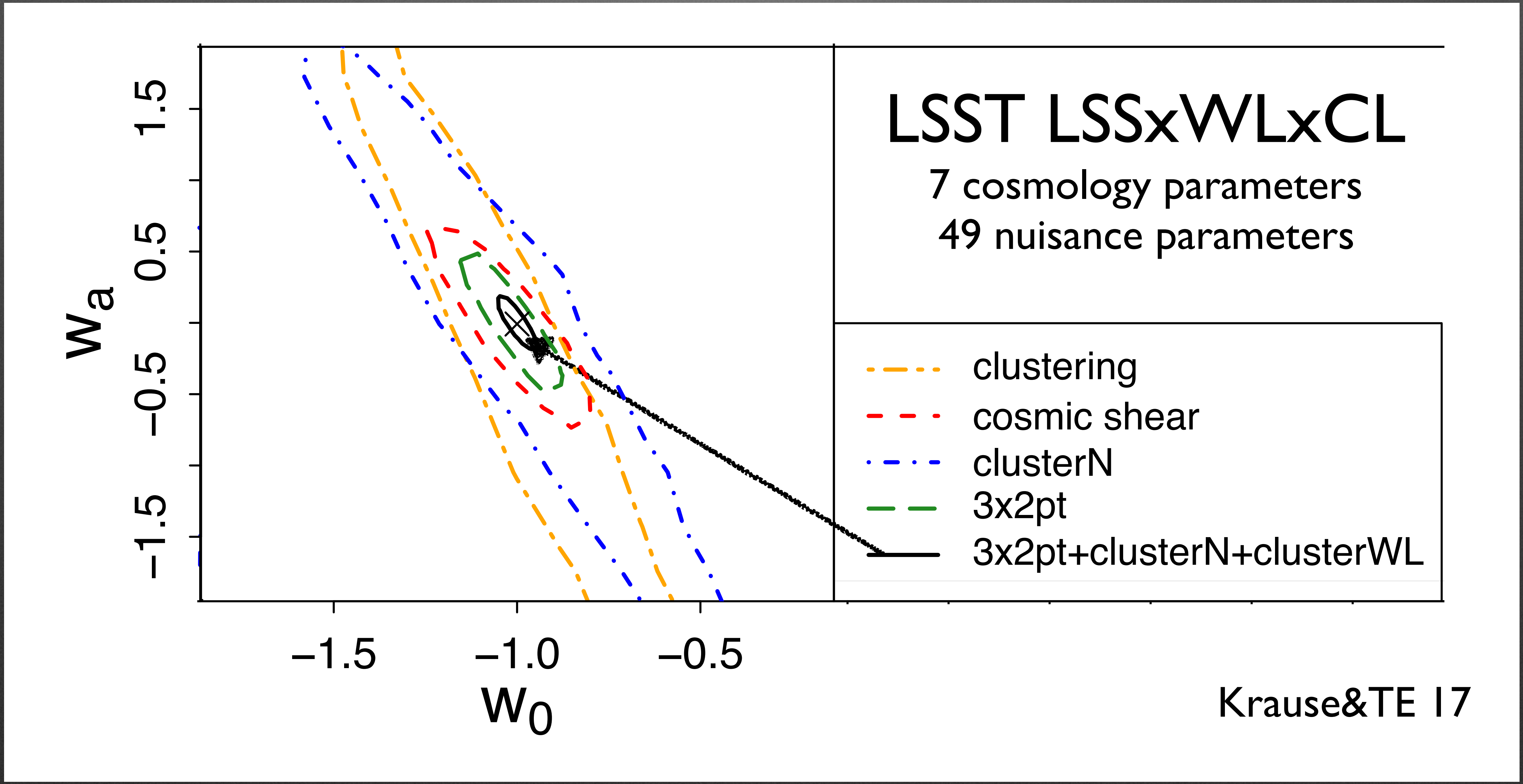
b_1, b_2,...
photo-z (lenses)

HOD modeling

- Galaxy-galaxy lensing
  - galaxies from clustering (as lenses) with shear sources
- Clusters - number counts + shear profile
  - so far, 8 richness, 4 z-bins (same as clustering)
  - tomographic cluster lensing (500 < l < 10000)

N-M relation
c-M relation
off-centering

The Power of Combining Probes with LSST



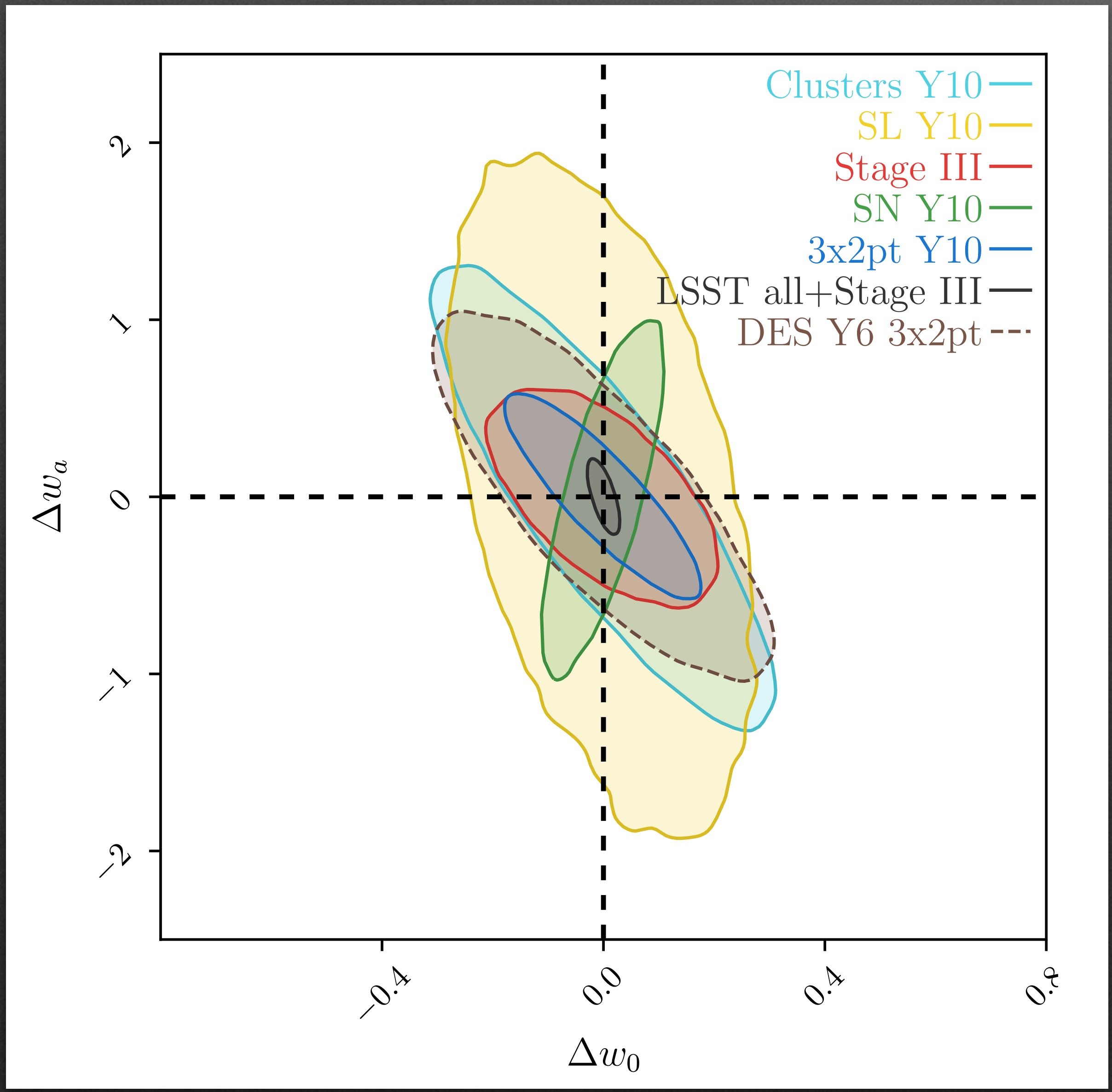
The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document

The LSST Dark Energy Science Collaboration, Rachel Mandelbaum, Tim Eifler, Renée Hložek, Thomas Collett, Eric Gawiser, Daniel Scolnic, David Alonso, Humna Awan, Rahul Biswas, Jonathan Blazek, Patricia Burchat, Nora Elisa Chisari, Ian Dell'Antonio, Seth Digel, Josh Frieman, Daniel A. Goldstein, Isobel Hook, Željko Ivezić, Steven M. Kahn, Sowmya Kamath, David Kirkby, Thomas Kitching, Elisabeth Krause, Pierre-François Leget, Philip J. Marshall, Joshua Meyers, Hironao Miyatake, Jeffrey A. Newman, Robert Nichol, Eli Rykoff, F. Javier Sanchez, Anže Slosar, Mark Sullivan, M. A. Troxel

(Submitted on 5 Sep 2018)

The Large Synoptic Survey Telescope (LSST) Dark Energy Science Collaboration (DESC) will use five cosmological probes: galaxy clusters, large scale structure, supernovae, strong lensing, and weak lensing. This Science Requirements Document (SRD) quantifies the expected dark energy constraining power of these probes individually and together, with conservative assumptions about analysis methodology and follow-up observational resources based on our current understanding and the expected evolution within the field in the coming years. We then define requirements on analysis pipelines that will enable us to achieve our goal of carrying out a dark energy analysis consistent with the Dark Energy Task Force definition of a Stage IV dark energy experiment. This is achieved through a forecasting process that incorporates the flowdown to detailed requirements on multiple sources of systematic uncertainty. Future versions of this document will include evolution in our software capabilities and analysis plans along with updates to the LSST survey strategy.

Comments: 32 pages + 60 pages of appendices. This is v1 of the DESC SRD, an internal collaboration document that is being made public and is not planned for submission to a journal. Data products for reproducing key plots are available at the LSST DESC Zenodo community, this https URL; see "Executive Summary and User Guide" for instructions on how to use and cite those products
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as: **arXiv:1809.01669 [astro-ph.CO]**
(or **arXiv:1809.01669v1 [astro-ph.CO]** for this version)



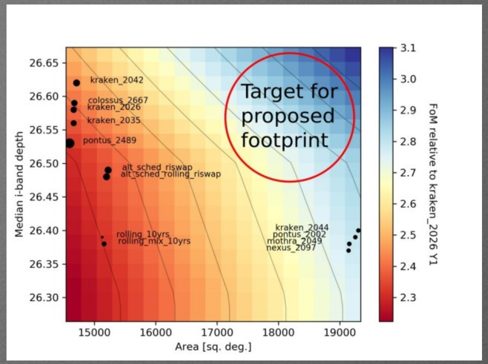
- Some aspects to be improved:
- linear bias
- Baryon mitigation via scale cuts
- Gaussian photo-z

Soon: Explore science return for different survey strategies/ systematics scenarios.

How do we explore synergies of LSST and WFIRST?

Multi-Probe Forecasts WFIRST+LSST

LSST survey scenario + Exposure Time Calculator (Hirata et al 2012)
Creates realistic survey area, depth combination



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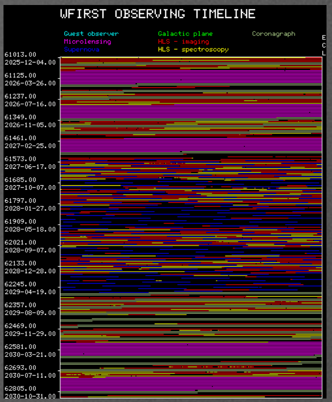
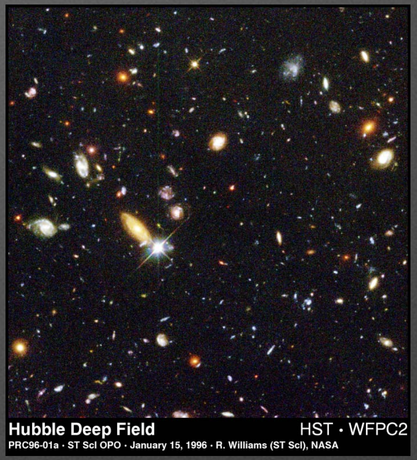
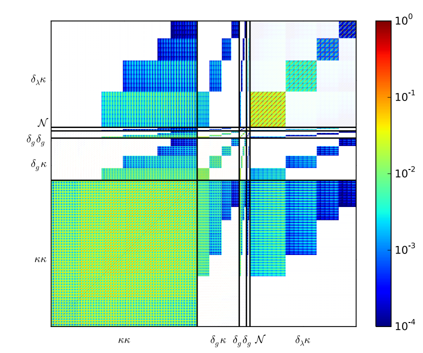


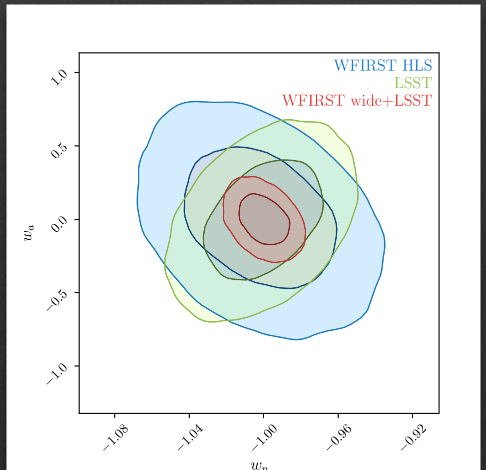
CANDELS WFIRST catalog (Hemmati et al 2018)
Extract "realistic" redshift distribution for lensing and clustering sample (also for galaxy clusters)



CosmoLike Multi-Probe Covariance
Krause & Eifler (2017)

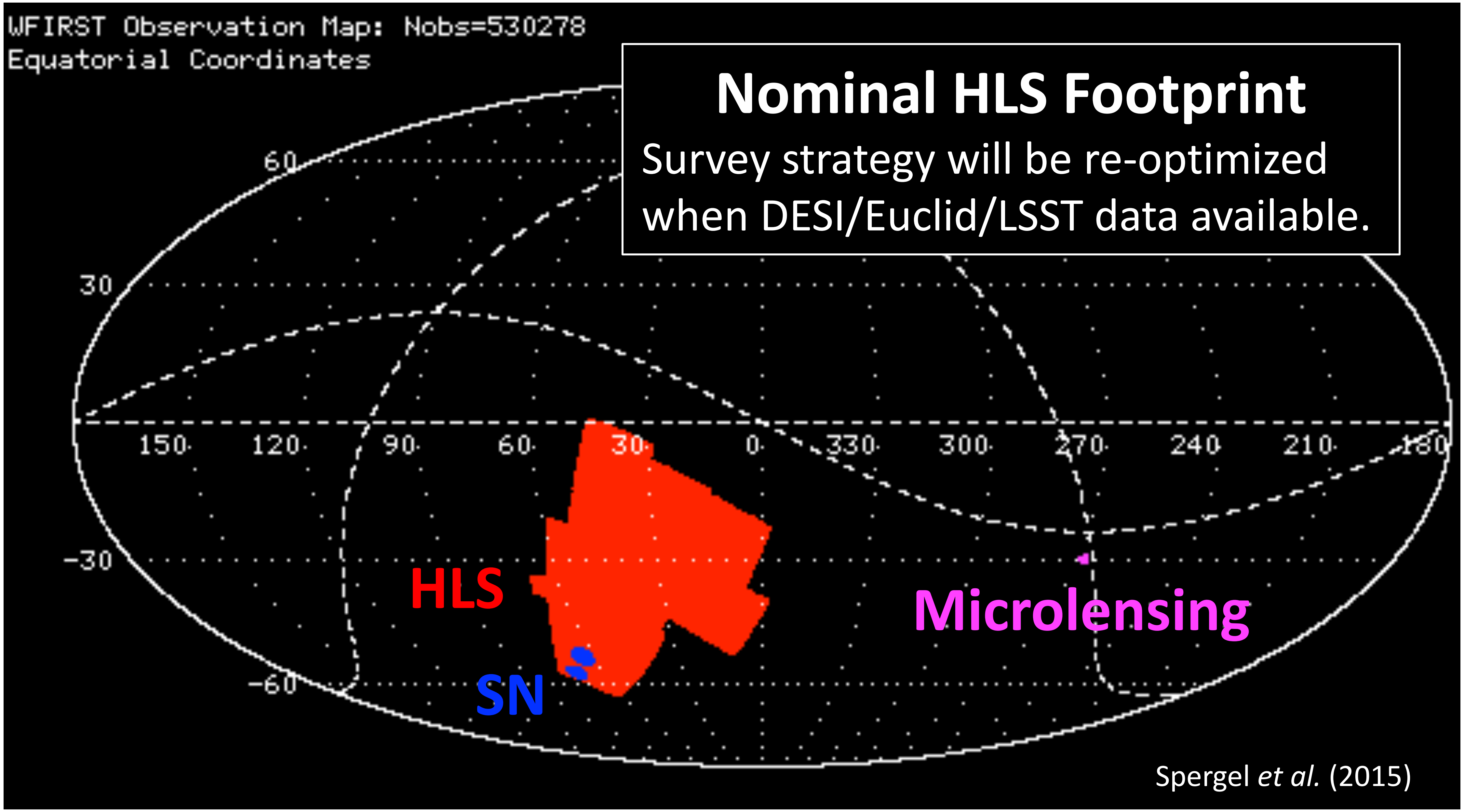


CosmoLike Likelihood Analysis
Eifler et al in prep



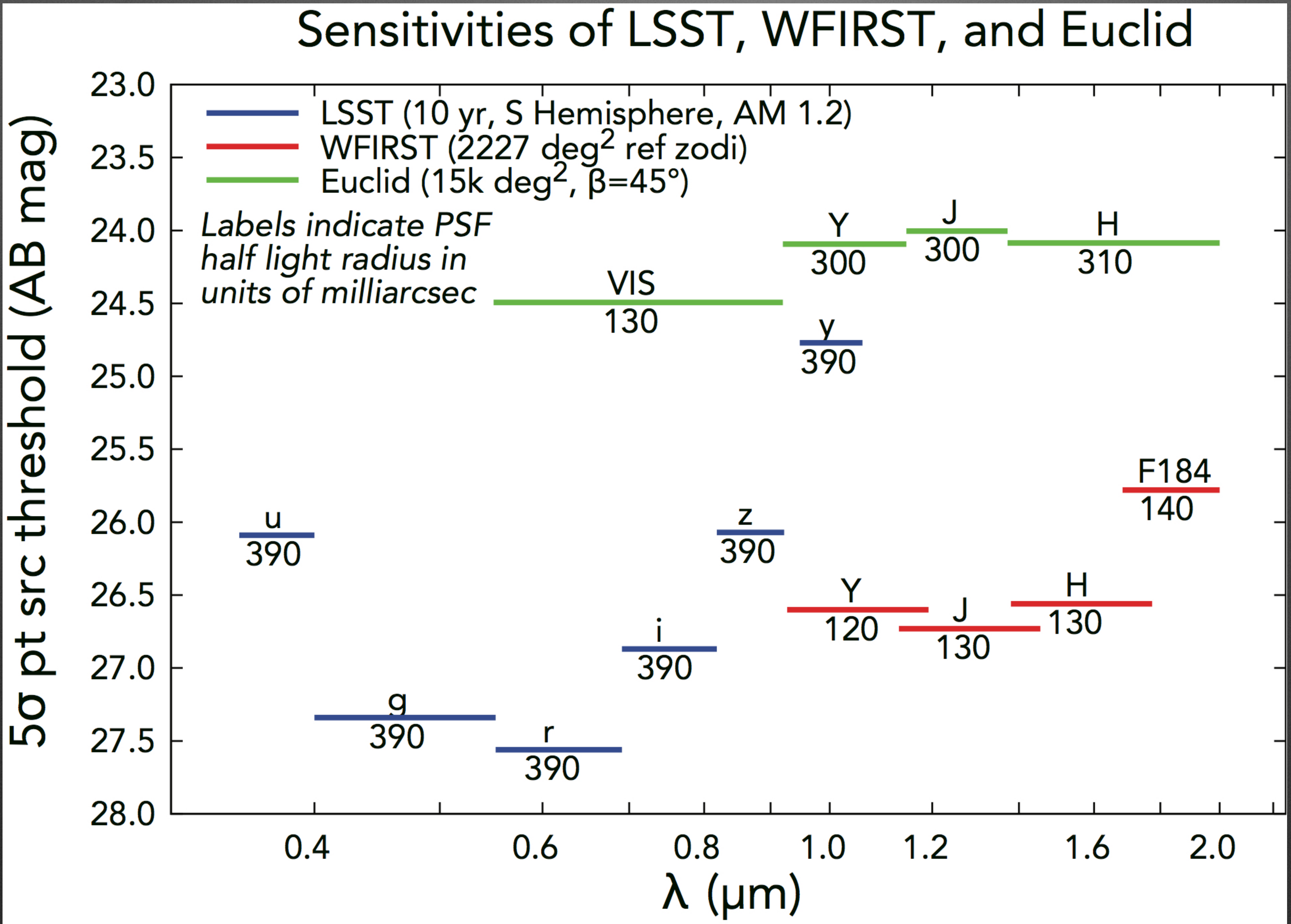
Also used in the LSST-DESC SRD and the DESC Observations Strategy TF:
- DESC, Mandelbaum, Eifler et al 2019
- Lochner et al 2019

WFIRST High Latitude Survey (HLS)



- Nominally 1.5yr over ~2,000 deg^2 in southern sky (c.f. Euclid: 15,000 deg^2 over 6yr)
- Cosmological probes: (i) near-IR spectroscopic galaxy clustering (BAO+RSD)
  f>1x10^{-16} ergs/s/cm^2 (c.f. Euclid: 2x10^{-16} ergs/s/cm^2)
  (ii) gravitational weak lensing shear measurements
  Y, J, H, (F184) to AB ~26.5 (5σ point src) (c.f. Euclid VIS AB~24.5)

Overlap in wavelength



But W-band

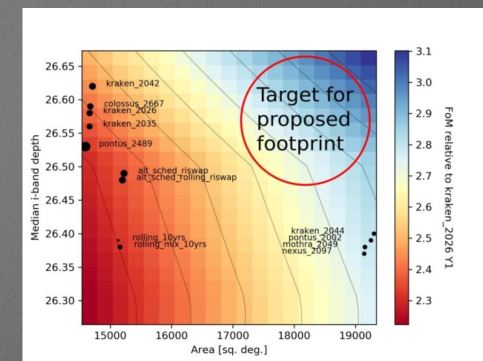
WFIRST Imaging Capabilities							
Telescope Aperture (2.4 meter)		**Field of View** (45′x23′; 0.28 sq deg)		**Pixel Scale** (0.11 arcsec)		**Wavelength Range** (0.5-2.0 μm)	
Filters	**R062**	**Z087**	**Y106**	**J129**	**H158**	**F184**	**W146**
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	1.38-1.77	1.68-2.00	0.93-2.00
Sensitivity (5σ AB mag in 1 hr)	28.50	28.02	27.95	27.87	27.81	27.32	28.33

WFIRST Spectroscopic Capabilities				
	Field of View (sq deg)	**Wavelength (μm)**	**Resolution**	**Sensitivity (10σ AB mag in 1000s)**
Grism	0.28 sq deg	1.00-1.89	435-865	20.4 at 1.5 μm
~~Integral Field Channel~~	~~3.00 x 3.15 arcsec~~	~~0.42-2~~	~~80-120~~	~~24.2 at 1.5 μm~~

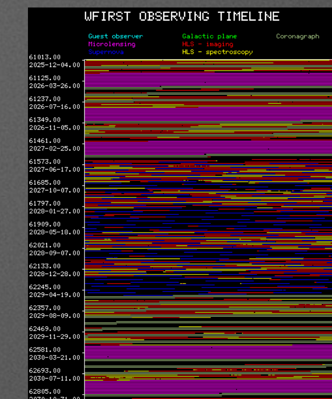
WFIRST Coronagraphic Capabilities					
	Wavelength (μm)	**Inner Working Angle (arcsec)**	**Outer Working Angle (arcsec)**	**Detection Limit**	**Spectral Resolution**
Imaging & Spectroscopy	0.4-1	0.15 (exoplanets) 0.9 (disks)	0.9 (exoplanets) 3.0 (disks)	10^{-9} contrast (after post-processing)	~50

Multi-Probe Forecasts WFIRST+LSST

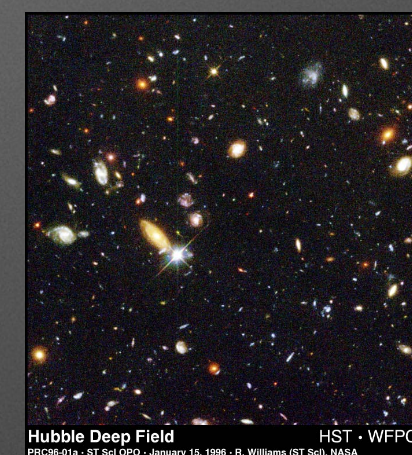
LSST survey scenario + Exposure Time Calculator (Hirata et al 2012)
Creates realistic survey area, depth combination



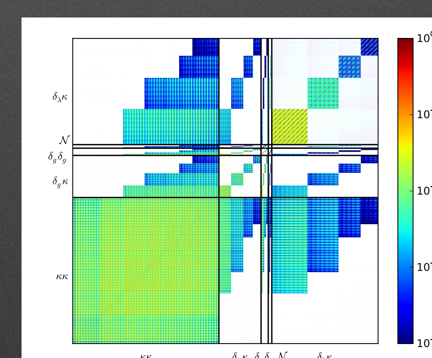
+



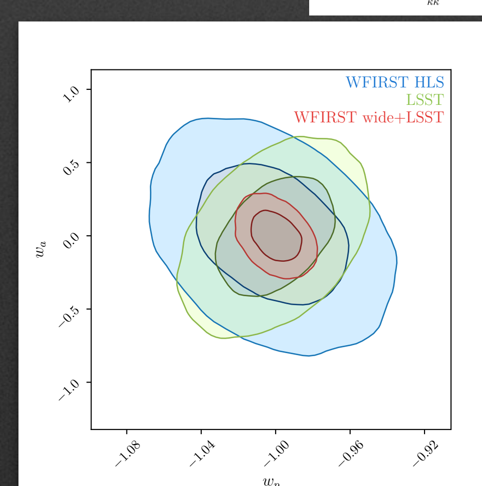
CANDELS WFIRST catalog (Hemmati et al 2018)
Extract "realistic" redshift distribution for lensing and clustering sample (also for galaxy clusters)



CosmoLike Multi-Probe Covariance
Krause & Eifler (2017)



CosmoLike Likelihood Analysis
Eifler et al in prep

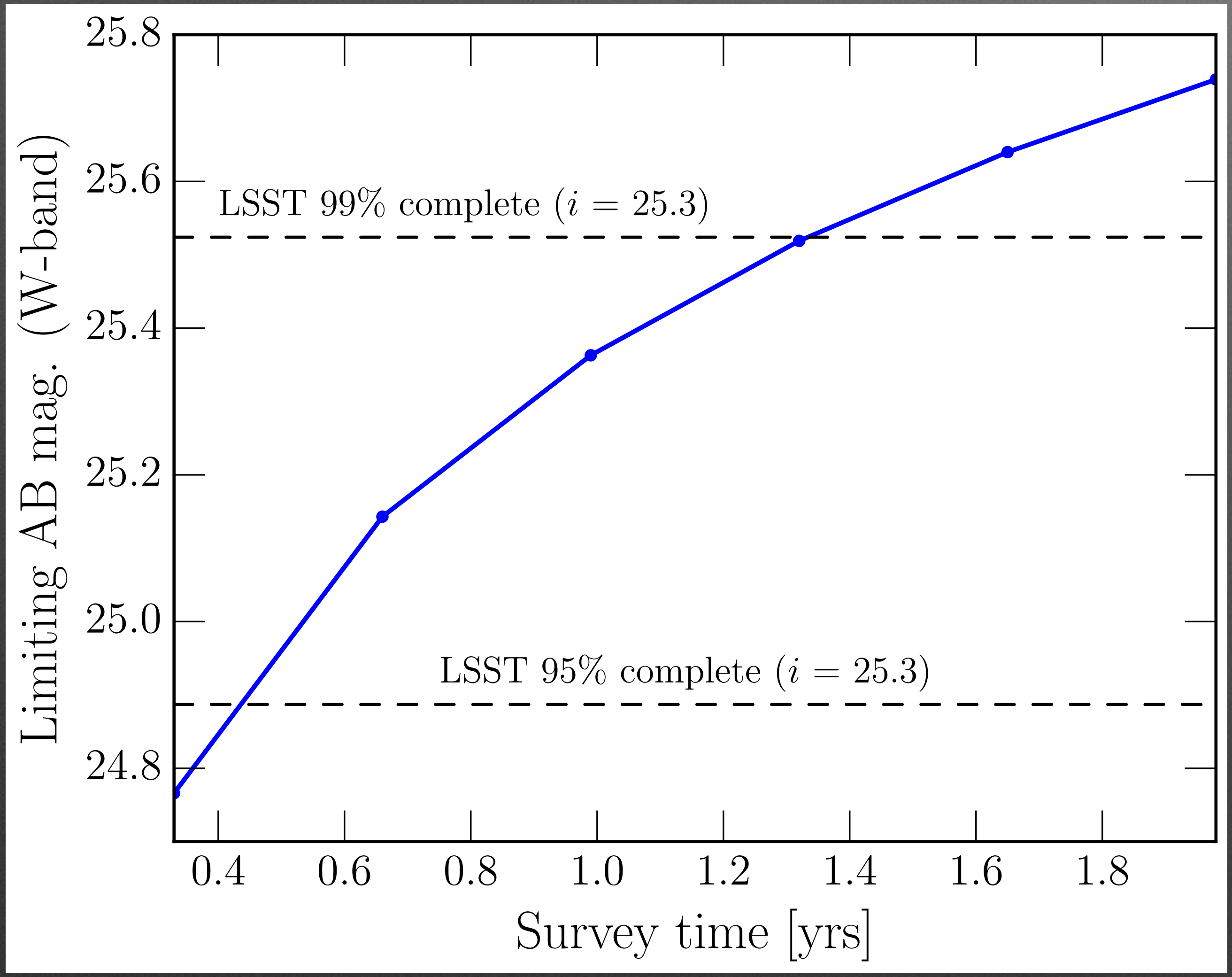


Also used in the LSST-DESC SRD and the DESC Observations Strategy TF:

- DESC, Mandelbaum, Eifler et al 2019
- Lochner et al 2019

Explore WFIRST W-band Wide Survey, 18000 deg^2

Based on exposure time calculator, Hirata et al 2012



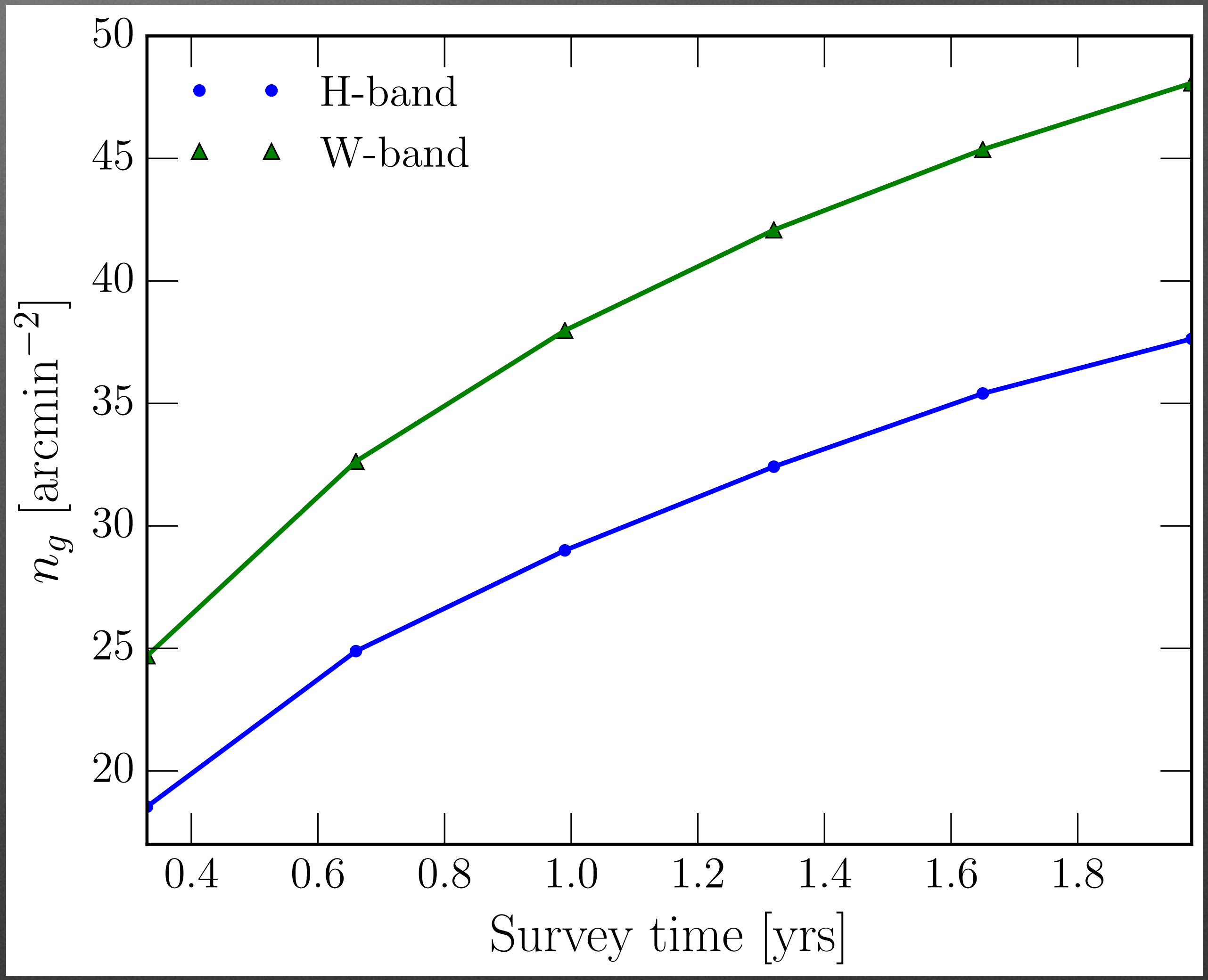
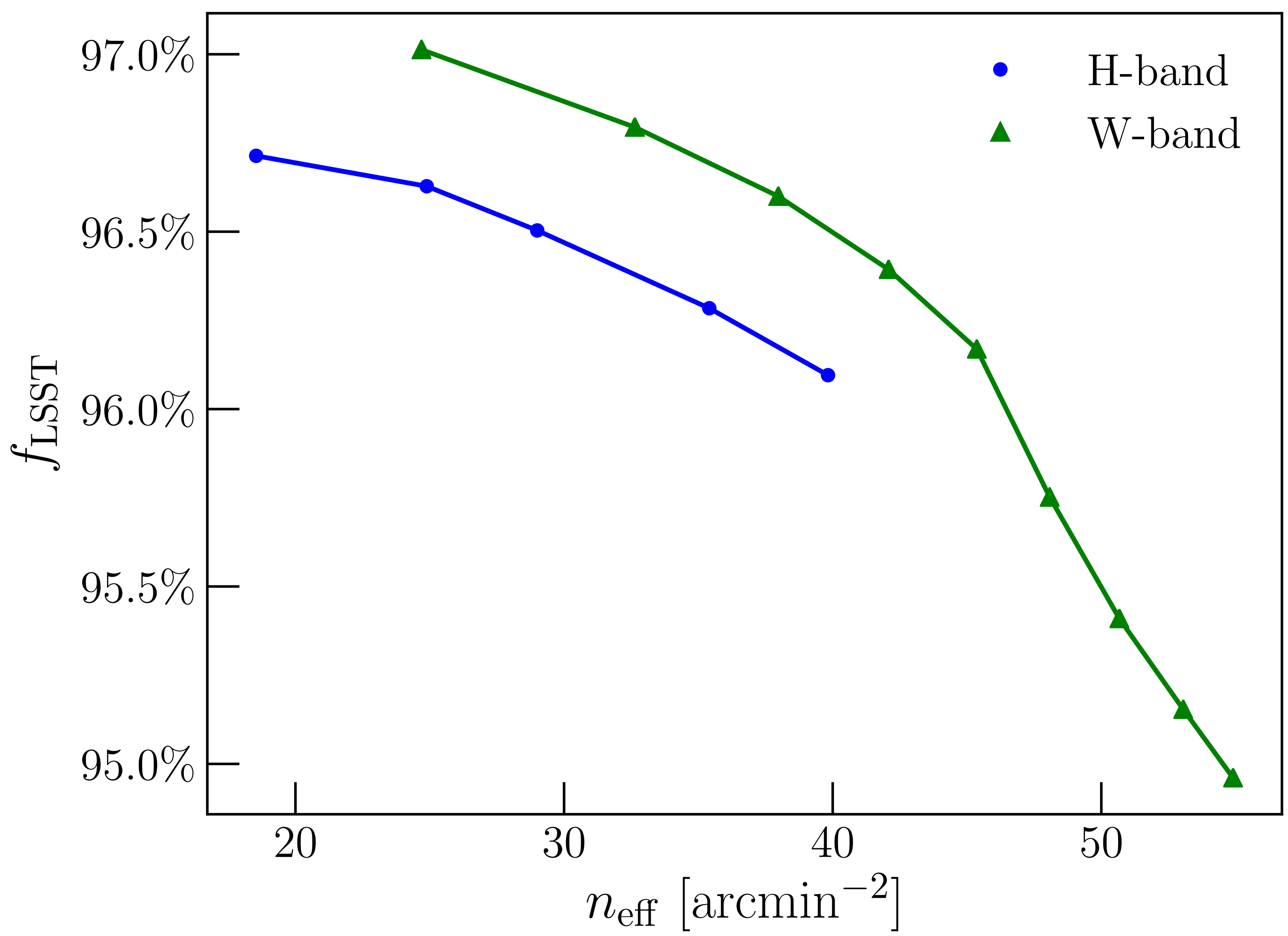
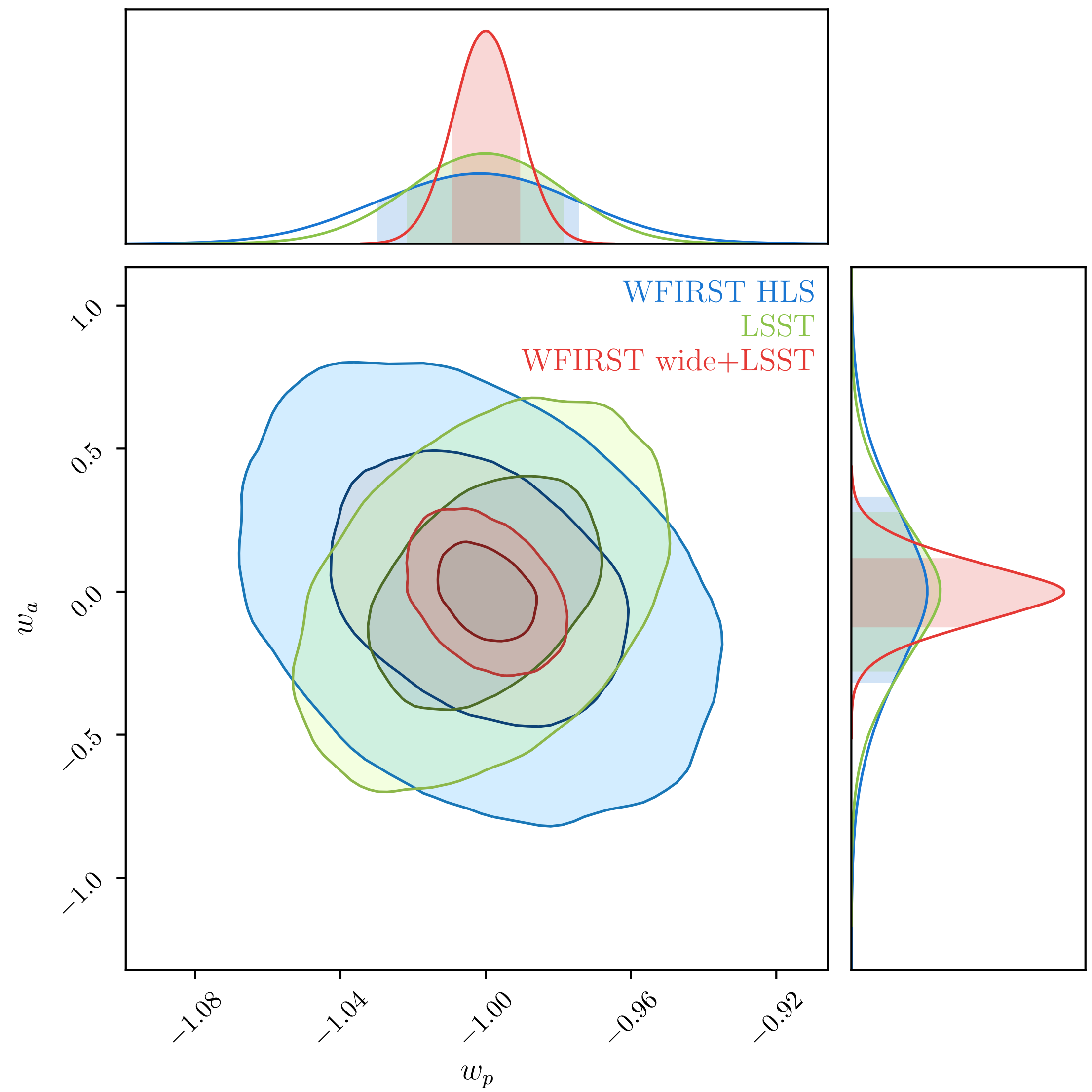


Figure 2: *Left:* Limiting magnitude of a 18,000 deg^2 WFIRST W-band survey as a function of survey time. We also show the LSST weak lensing samples 95% and 95% completeness thresholds as dashed lines. *Right:* The number density of a weak lensing galaxy sample for a 18,000 deg^2 WFIRST survey when conducted in W or H-band, respectively, again as a function of survey time.

Multi-probe LSST+WFIRST

Based on CosmoLike, Krause & Eifler 2017





Lensing+Clustering
No clusters… yet.

2020 decadal white papers

- Decadal 2020 survey coming up
- Several WFIRST WPs
- HLS survey (Dore et al)

Partnering space and ground observatories - Synergies in cosmology from LSST and WFIRST

Thematic areas: 7. Cosmology and Fundamental Physics

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Summary

- WFIRST is on track for launch in 2025
- High Latitude Survey (2000 deg^2) is designed for exquisite systematics control
- Wide WFIRST covering LSST area to LSST Y10 WL depth can be done in 5 months - interesting.
- Multi-data and multi-probe analysis are the future (CMB, space+ground optical, NIR, UV, radio…) for systematics control and maximum information content