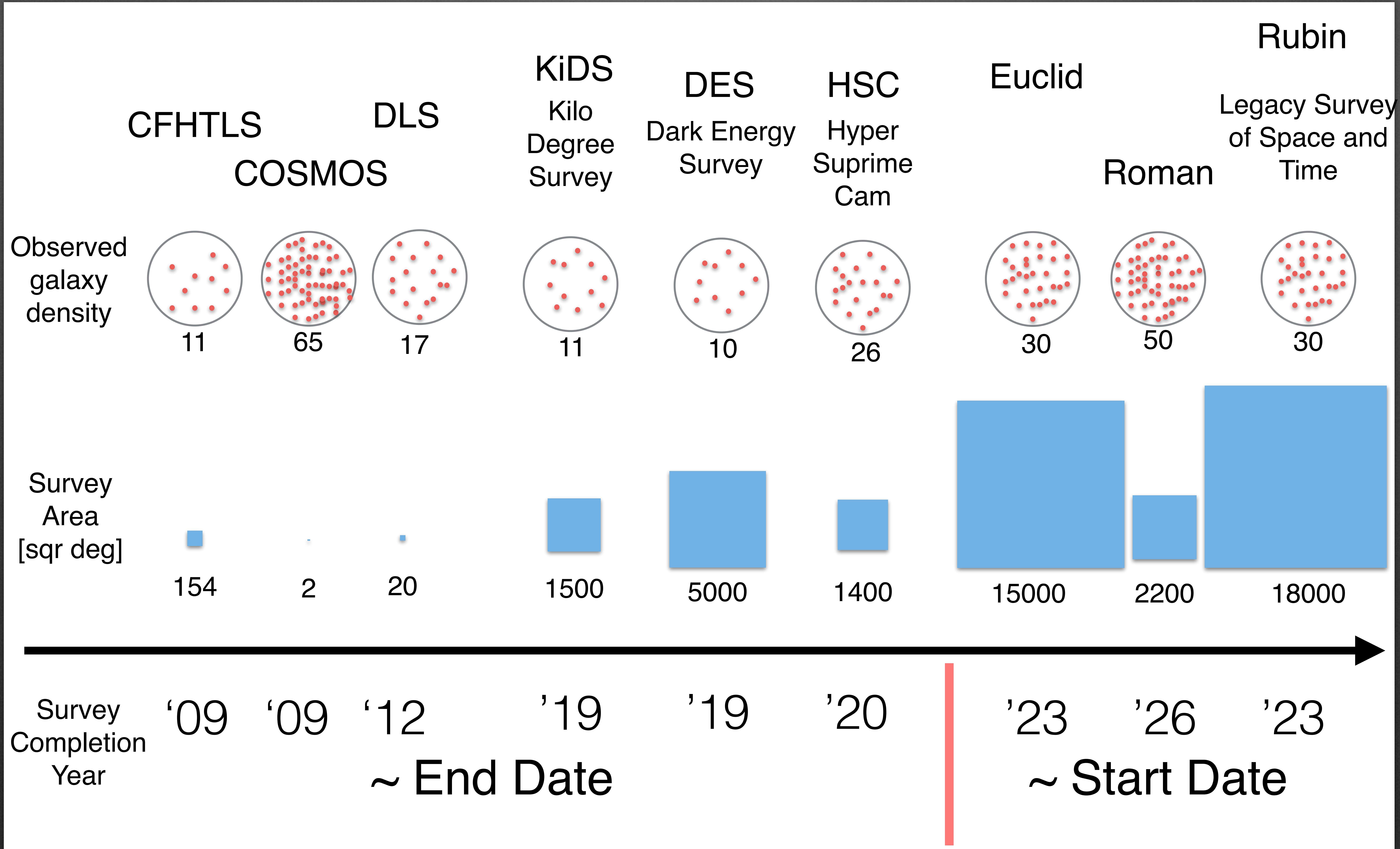
Synergies between Rubin Observatory and the Roman Space Telescope

Tim Eifler
Arizona Cosmology Lab
Steward Observatory / University of Arizona

Imaging surveys (some have spectro instruments)



NANCY GRACE ROMAN SPACE TELESCOPE

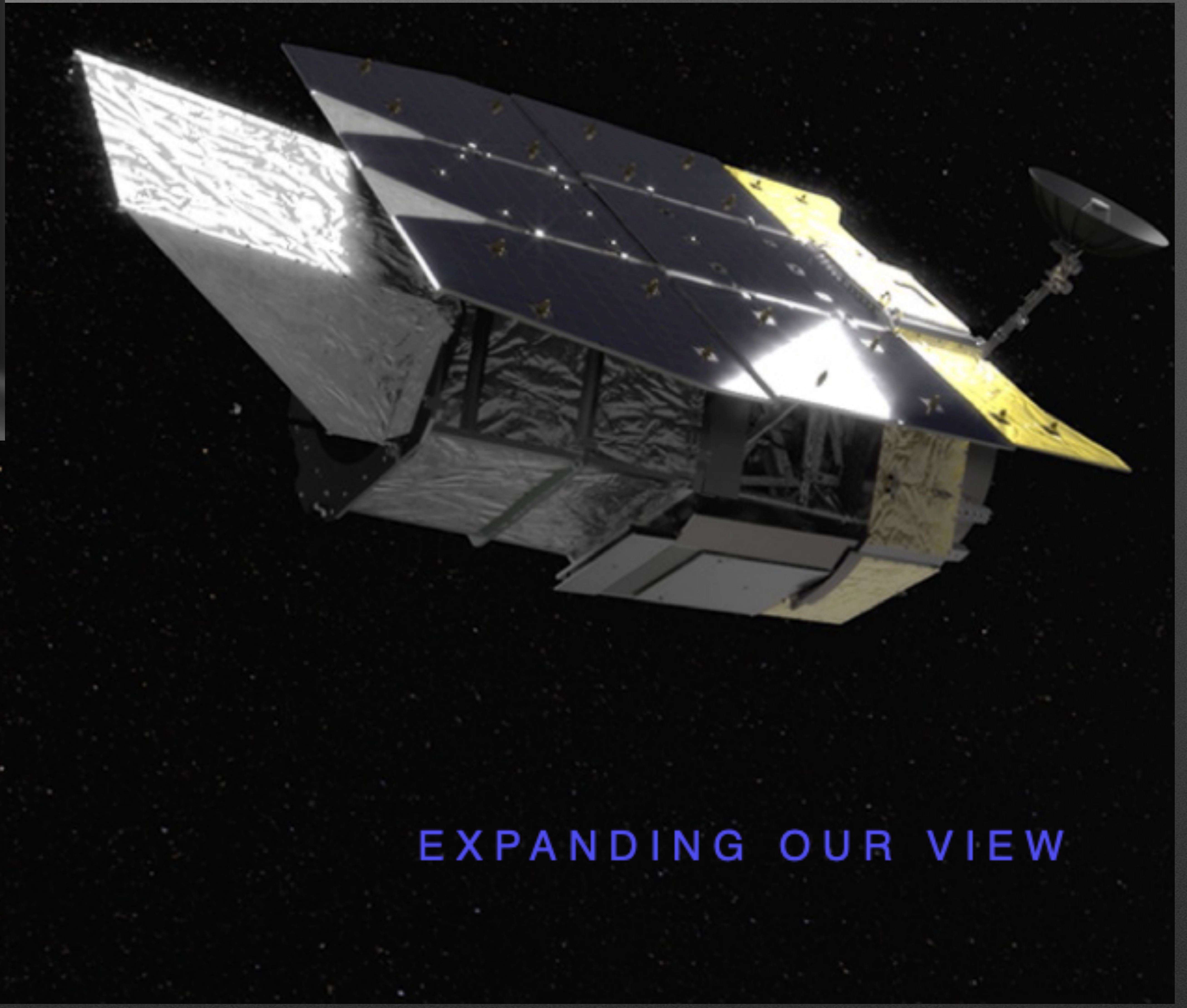
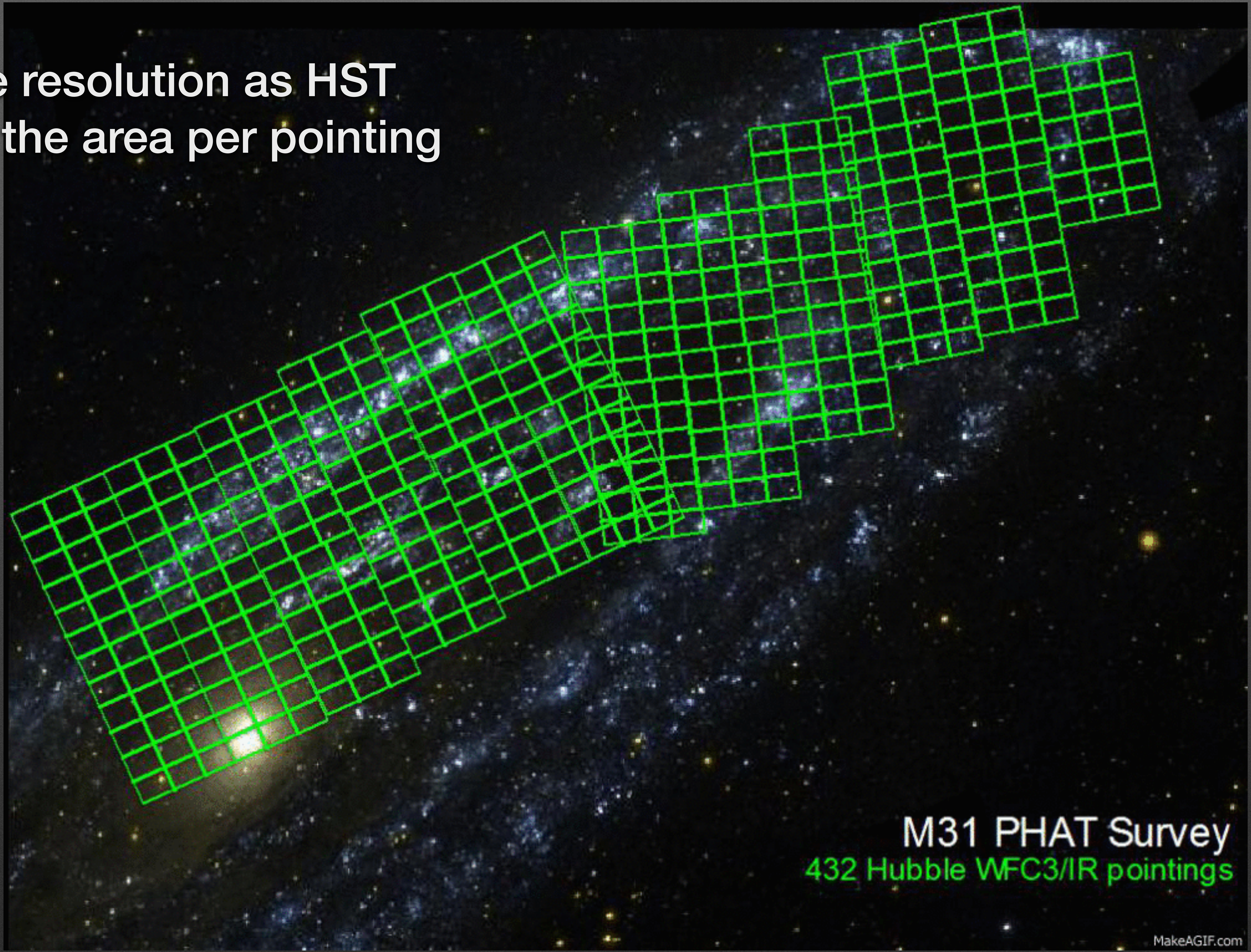
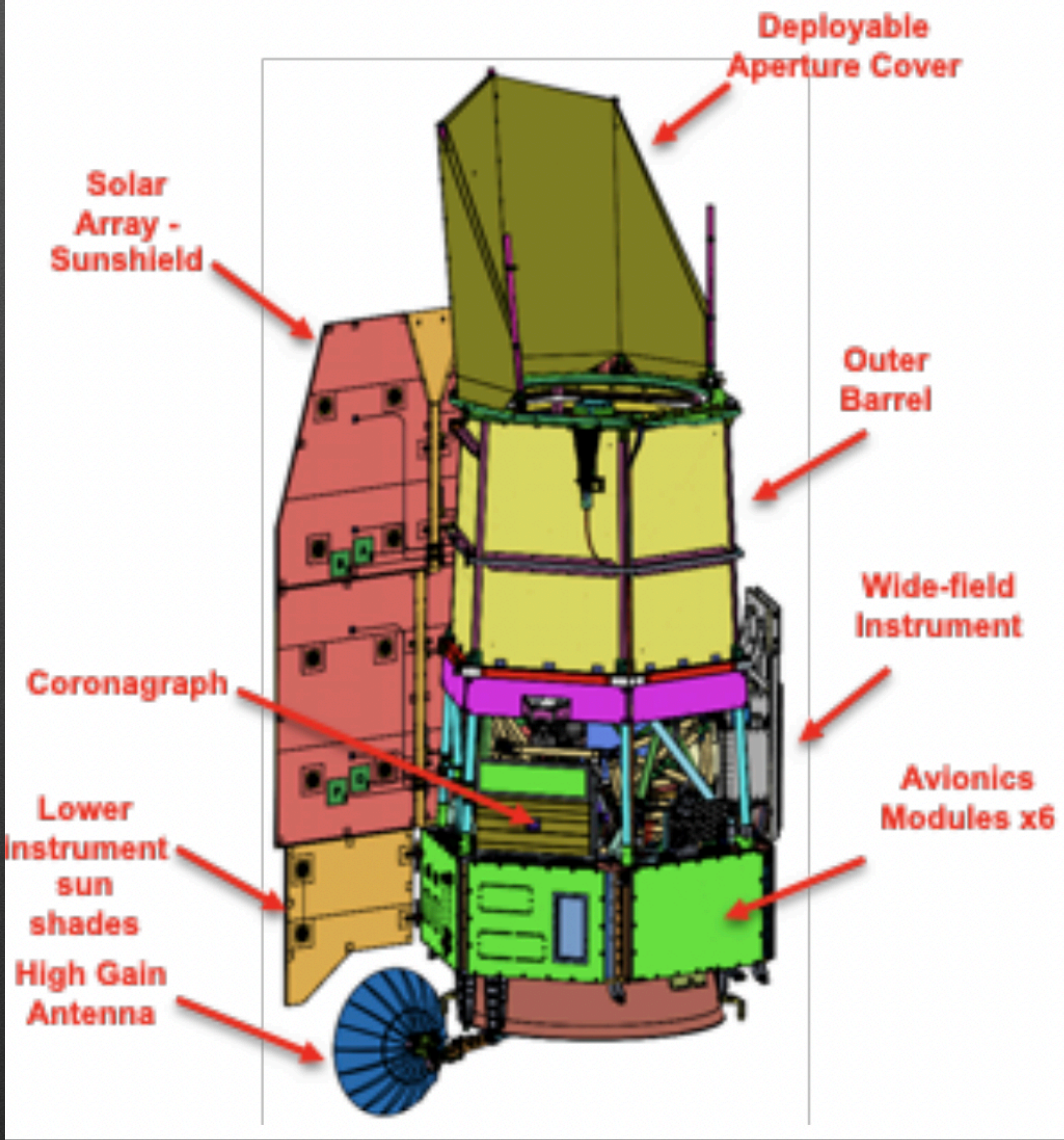


Image credit: NASA

- Same resolution as HST
- 200x the area per pointing



Observatory and Instruments



Key Features

Telescope: 2.4m aperture

Instruments:

Wide Field Imager / Slitless Spectrometer

Internal Coronagraph

Data Downlink: 250-500 Mbps

Data Volume: 11 Tb/day

Orbit: Sun-Earth L2

Launch Vehicle: 3 options

Mission Duration: 5 yr, 10yr goal

Serviceability: Observatory designed to be robotically refuelable

Credit: Roman Project

Core Community Surveys

Notional Survey	Target region	Primary spectral elements	On-sky time in notional survey plan
High Latitude Wide Area Survey (core community survey)	Extragalactic sky, ~ 2000 deg^2	Y106, J129, H158, F184, and Grism	~ 24 months
High Latitude Time Domain (core community survey)	5-20 deg^2 in the continuous field of regard,.	TBD filters + Prism	~ 6 months
Galactic Bulge Time Domain (core community survey)	2 deg^2 in a low-extinction area near Galactic center	W149 filter (occasional use of other filters)	~ 13 months
General Astrophysics Surveys	Full sky is available	All WFI elements	~ 15 months
Coronagraph Instrument Tech Demo Observations	Selected nearby stars	Coronagraph Instrument	~ 3 months

White Paper input to shape CCS

Roman Core Community Survey White Papers

Optimizing the Roman HLWAS

Roman Core Community Survey: High Latitude Wide Area Survey (Imaging)

Scientific Categories: Large scale structure of the universe

Submitting Authors: Tim Eifler (UArizona, timeifler@arizona.edu), Christopher Hirata (Ohio State University, hirata.10@osu.edu)

Co-authors/Endorsers: Rachel Bean (Cornell University), Jayashree Behera (Kan
Karim Benabed (Institut d'astrophysique de Paris), Jonathan Blazek (Northeastern Un
(Caltech/JPL), Ami Choi (NASA GSFC), Brendan Crill (JPL), Olivier Doré (JPL/Ca
(CNRS/IN2P3), Eric Gawiser (Rutgers University), Sven Heydenreich (UC Santa Cru
Shirley Ho (CCA, Flatiron Institute), Bhuvnesh Jain (UPenn), Buell T. Jannuzi (UArizo
(Princeton University), Elisabeth Krause (UArizona), Anja von der Linden (Stony Broo
(Kavli IPMU), Vivian Miranda (Stony Brook University), Hironao Miyatake (Nagoya
Miyazaki (Subaru, NAOJ), Paulo Montero-Camacho (Tsinghua U/PCL), Catalina Moral
sity of Costa Rica), Andrés A. Plazas Malagón (SLAC/ KIPAC), Anna Porredon (Univ
Brant Robertson (UC Santa Cruz), Lado Samushia (Kansas State University), Robyn E
Tomomi Sunayama (UArizona), Masahiro Takada (Kavli IPMU), Ting Tan (LPNHE/CN
(Ohio State University)

Abstract:
We outline possible survey strategies for the imaging component of the Nancy Grace Roman Space Telescope (Roman) High Latitude Wide Area Survey (HLWAS) that consider synergies with ground-based experiments, most prominently Rubin Observatory's Legacy Survey of Space and Time (LSST).

The *reference design* for the Roman HLWAS ensures excellent systematics control by covering 2000 deg^2 in 4 bands (and the grism). Alternatively, Roman could cover the LSST area of 18,000 deg^2 in the W-band (i.e. the F146 filter spanning 0.93-2.00μm). While the latter strategy significantly boosts the statistical constraining power of Roman, it is also more susceptible to systematic effects, e.g., shear calibration and photo-z estimation.

The most promising way to increase statistical constraining power while retaining systematics control is a two-tier HLWAS: to split the time between a "medium" tier, which resembles the reference survey but with a reduced area, and a "wide" tier in a single filter. We outline several options for the wide tier option that cover the trade space of systematics control vs statistical information content.

NANCY:
Next-generation All-sky Near-infrared Community surveY

Roman Core Community Survey Category: High Latitude Wide Area Survey

Scientific Categories: *Solar system astronomy; stellar physics and stellar types; stellar populations and the interstellar medium; galaxies; the intergalactic medium and the circumgalactic medium, supermassive black holes and active galaxies; large scale structure of the universe*

Submitting Authors: Jesse Han <jesse.han@cfa.harvard.edu>, Arjun Dey <arjun.dey@noirlab.edu>

Affiliation: Harvard-Smithsonian Center for Astrophysics, NOIRLab

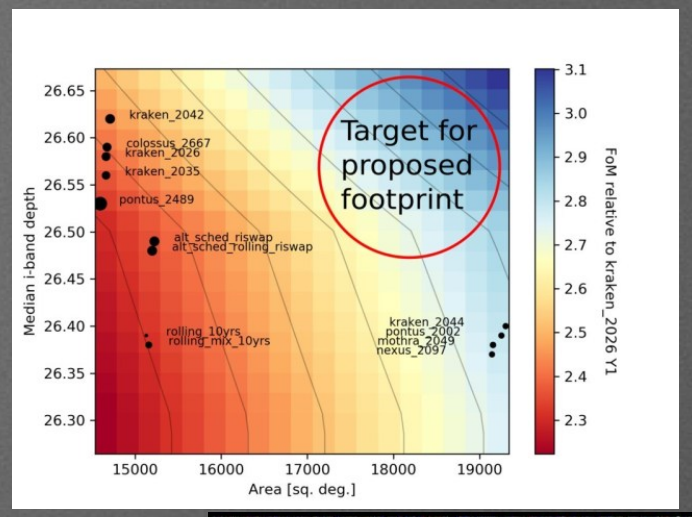
How do we optimize the Roman survey?

How do we explore synergies with other surveys, e.g. LSST?

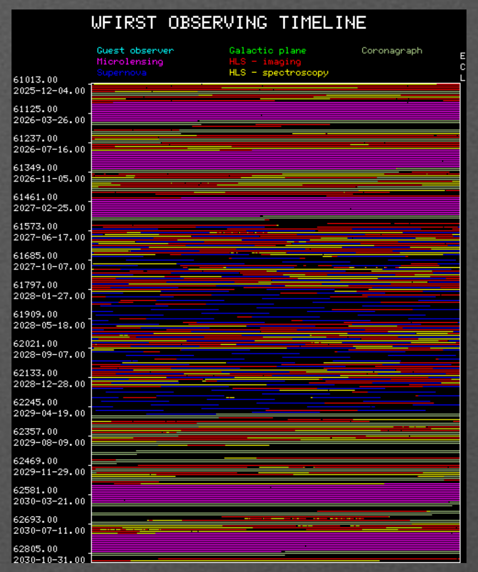
We need simulated likelihood analyses…
many of them…

Multi-Probe Forecasts Roman+LSST

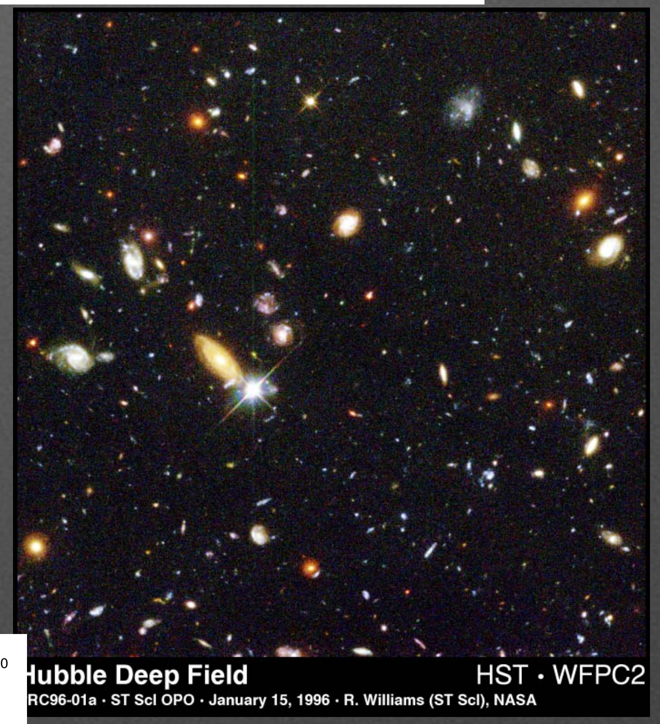
LSST survey scenario + Exposure Time Calculator *(Hirata ++ 2012)*
Creates realistic survey area, depth combination



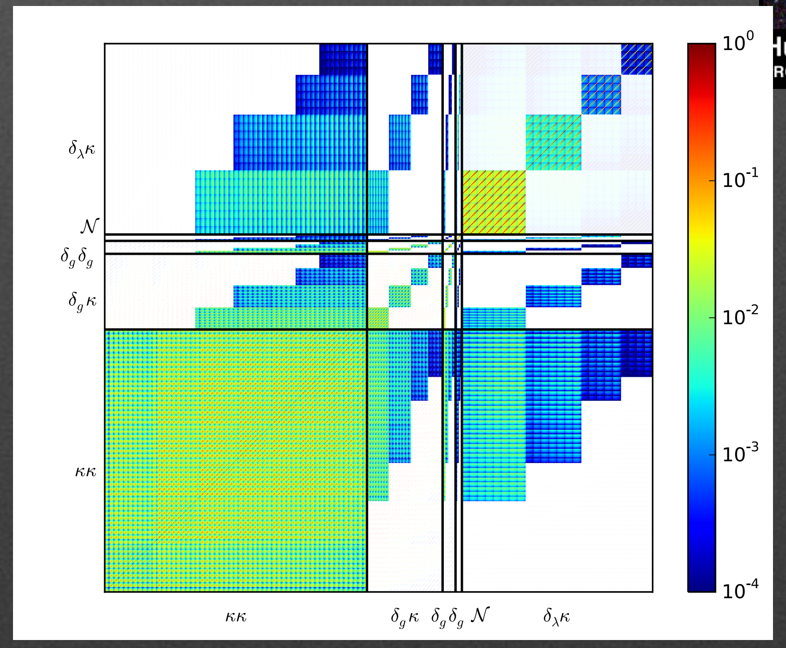
+



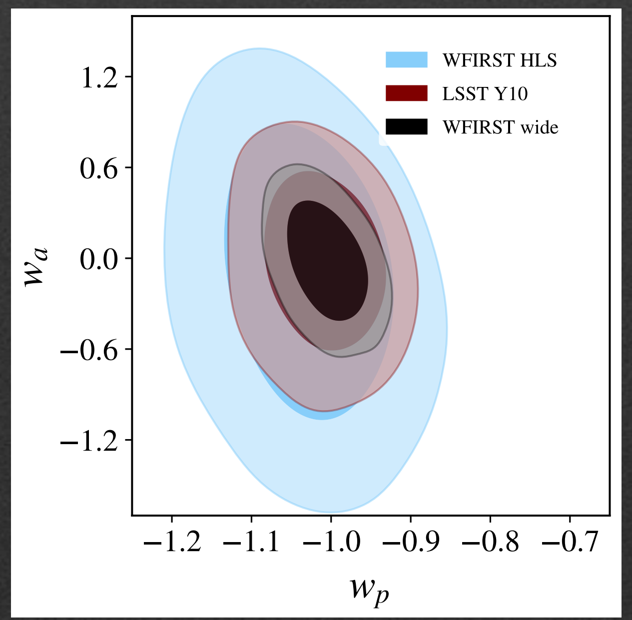
CANDELS Roman catalog *(Hemmati et al 2018)*
Extract “realistic” redshift distribution for lensing and clustering sample (also for galaxy clusters)



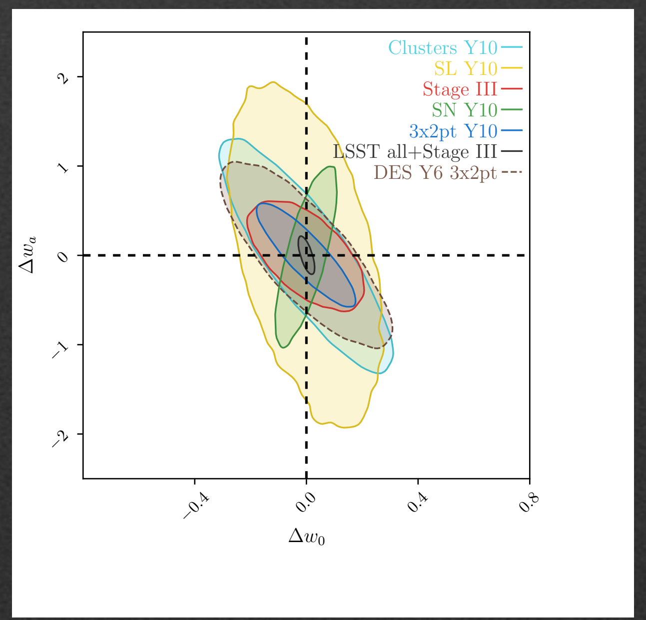
CosmoLike Multi-Probe Covariance
Krause & Eifler (2017)



CosmoLike Likelihood Analysis
Eifler, Miyatake, Krause et al (2021)
Eifler, Simet, Krause et al (2021)



+



Same code used in the LSST-DESC SRD:
DESC, Mandelbaum, Eifler et al 2019

Simulated Multi-Probe Analysis

First choose some probes…

- Cosmic shear
- Galaxy-Galaxy Lensing
- Galaxy Clustering
- Cluster Number Counts
- Cluster Weak Lensing
- Galaxy Clustering (Spectro)
- SN1a

- 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

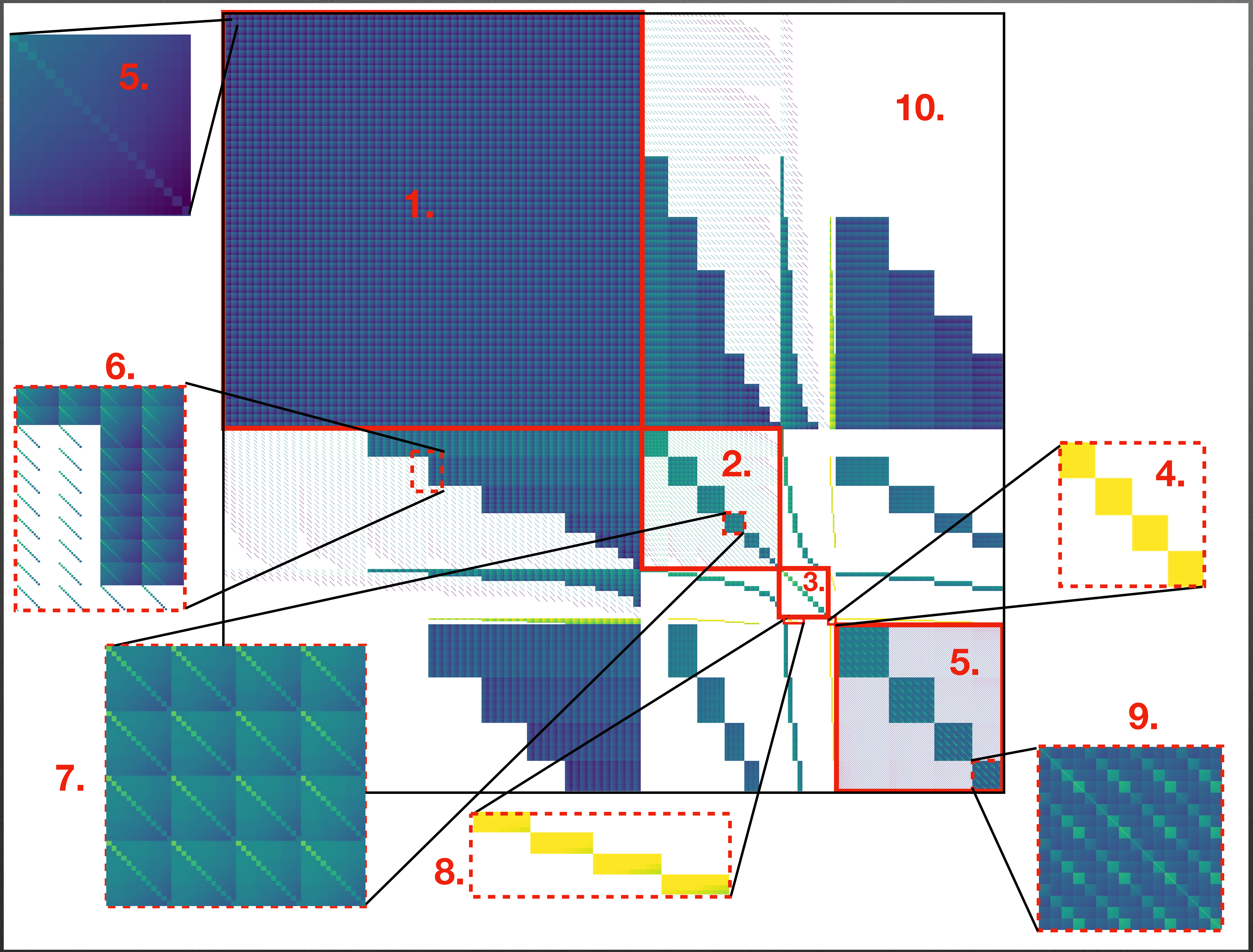
- Cosmic shear
- Galaxy-Galaxy Lensing
- Galaxy Clustering
- Cluster Number Counts
- Cluster Weak Lensing
- Galaxy Clustering (Spectro)
- SN1a

- 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)

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>**

Problem 1: Probes are correlated



1. Cosmic Shear
2. Galaxy-Galaxy Lensing
3. Galaxy Clustering
4. Cluster Number Counts
5. Cluster Lensing

Problem 2: Probes have systematics

- Weak Lensing (cosmic shear)
  - 10 tomography bins
  - 25 l bins, 30 < l < 4000
- Galaxy clustering (photometric)
  - 10 tomography bins (different from sources, higher number density)
- Galaxy-galaxy lensing
  - galaxies from clustering (as lenses) with shear sources
- Clusters - number counts + shear profile
  - so far, 5 richness, 4 z-bins
  - tomographic cluster lensing (500 < l < 15000)
- Galaxy clustering (spectroscopic)
  - k_min=0.001, kmax=0.3, 100 bins
  - 7 redshift, 10 \mu bins
- SN1a (see Hounsell et al 2018)

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

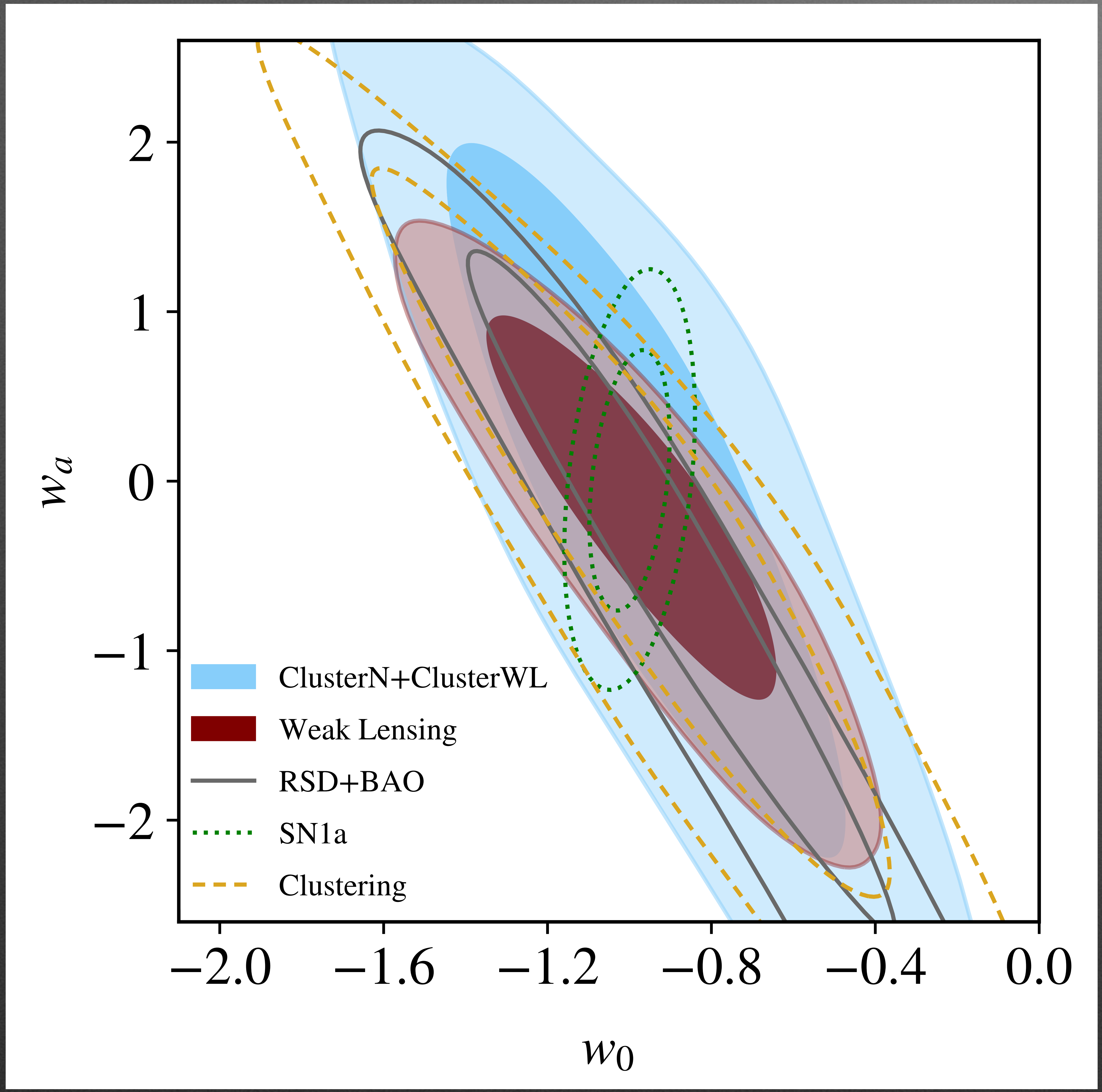
b_1, photo-z (lenses)

N-M relation
c-M relation
off-centering

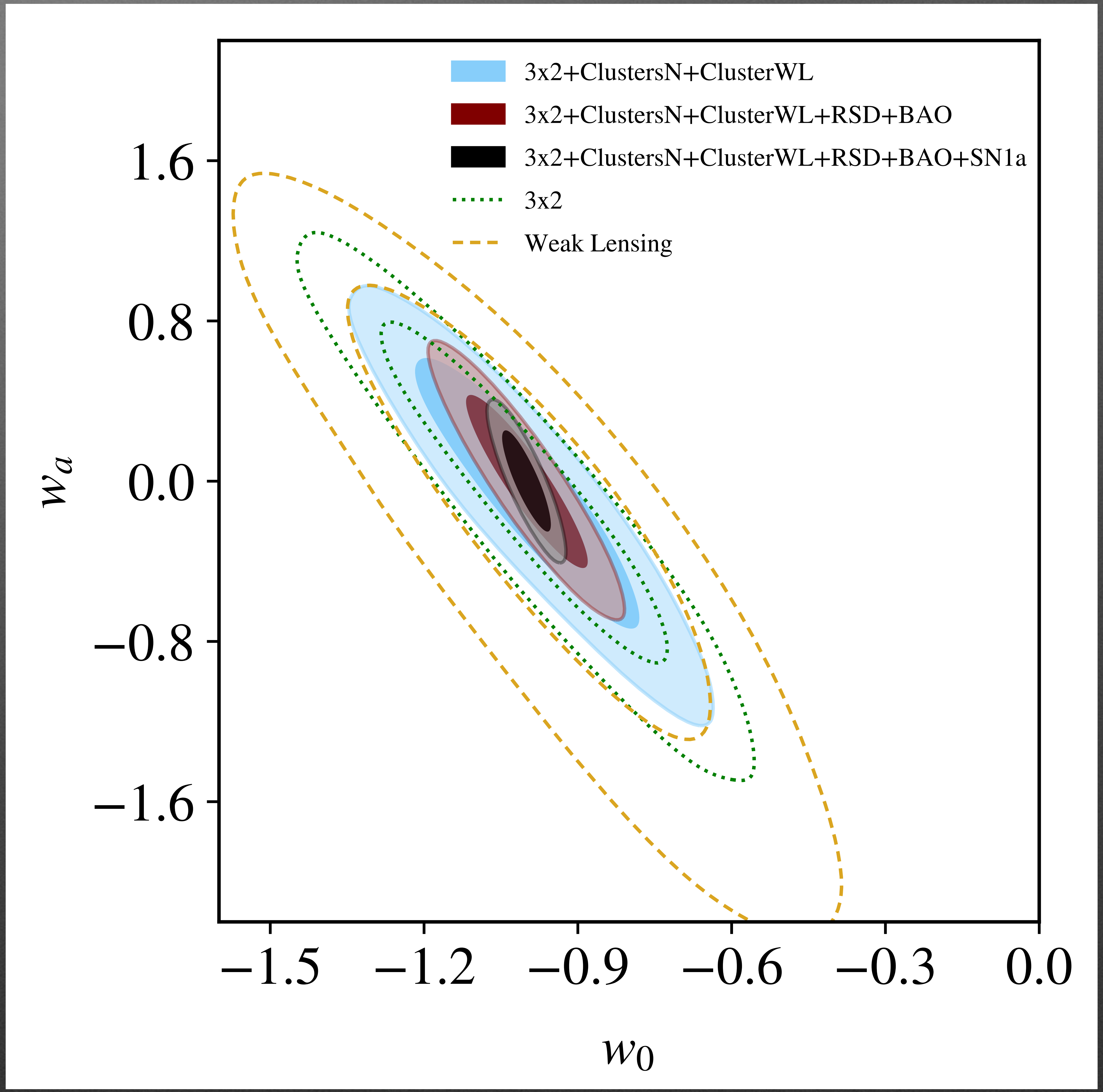
Shot-noise
Redshift
Peculiar velocity

Multi-probe results - Roman only

TE et al 2021



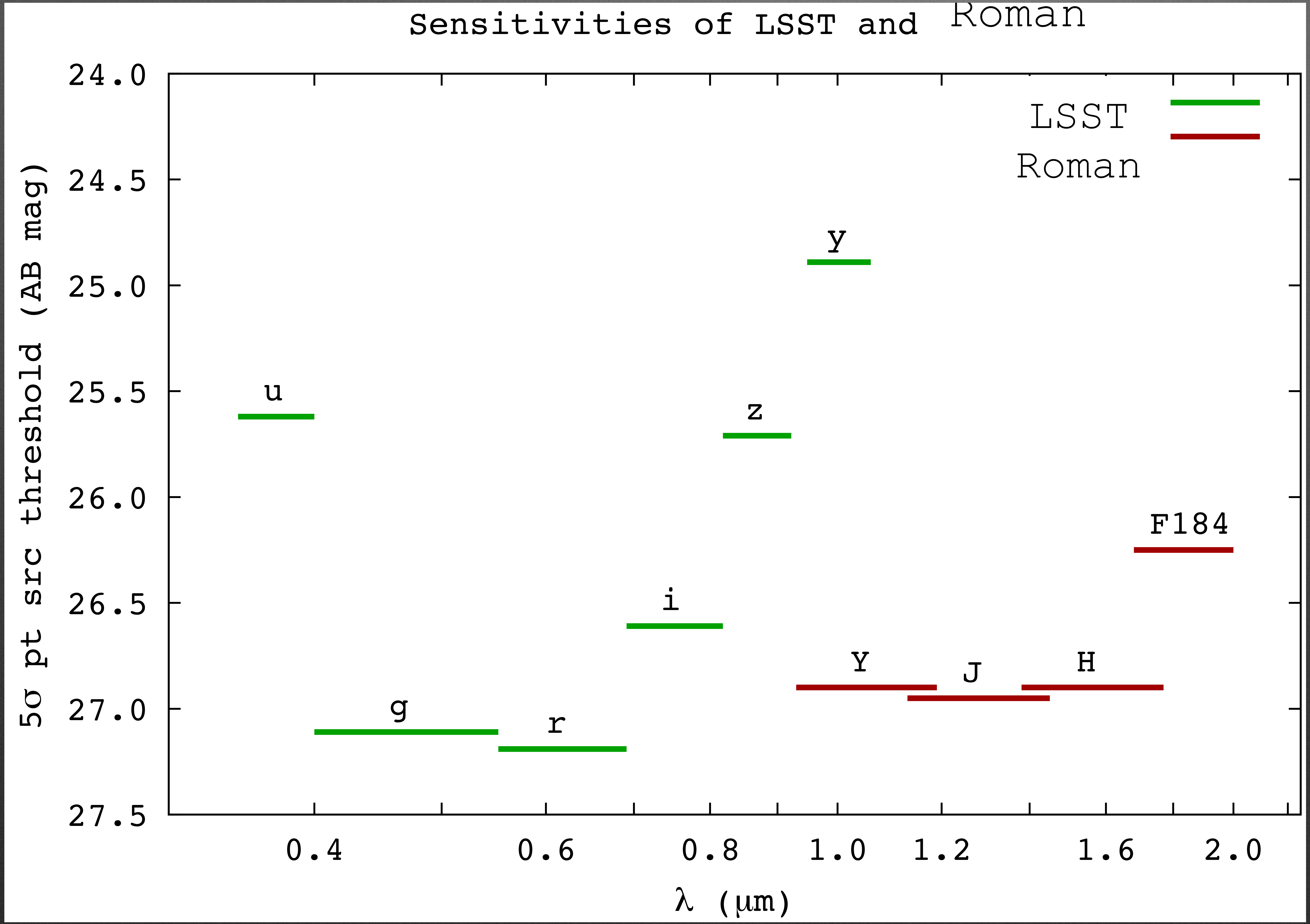
Single probe Analyses



Multi-probe analyses

Let’s explore synergies of Roman and LSST…

Roman+LSST overlap in wavelength



Credit: Chris Hirata

Roman Space Telescope Imaging Capabilities

Telescope Aperture (2.4 meter)	Field of View (45′x23′; 0.28 sq deg)	Pixel Scale (0.11 arcsec)	Wavelength Range (0.5-2.3 μm)

Filters	F062	F087	F106	F129	F146	F158	F184	F213
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	0.93-2.00	1.38-1.77	1.68-2.00	1.95-2.30
Sensitivity (5σ AB mag in 1 hr)	28.5	28.2	28.1	28.0	28.3	28.0	27.5	26.2

Roman Space Telescope Spectroscopic Capabilities

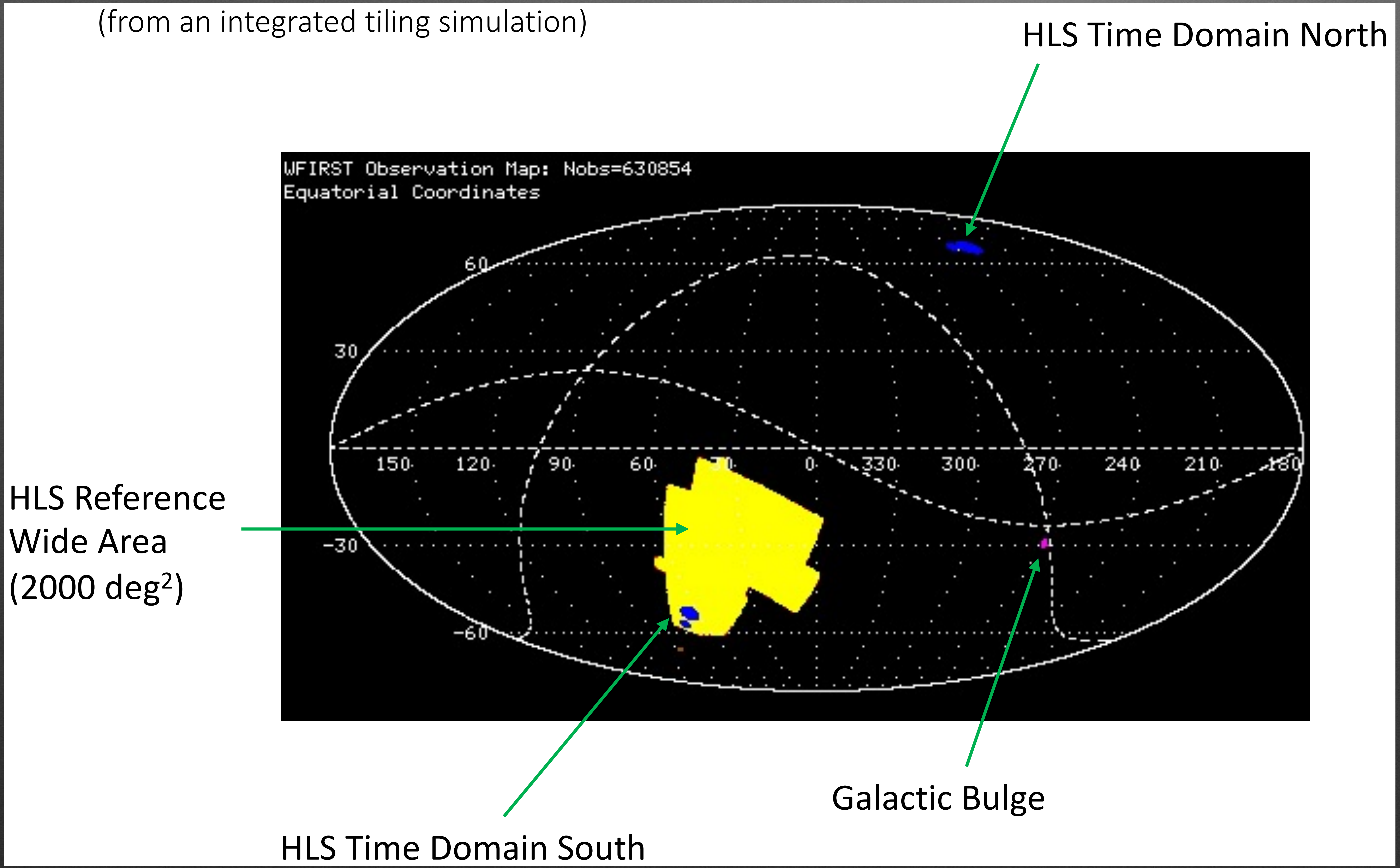
	Field of View (sq deg)	Wavelength (μm)	Resolution	Sensitivity (AB mag) (10σ per pixel in 1hr)
Grism	0.28 sq deg	1.00-1.93	461	20.5 at 1.5 μm
Prism	0.28 sq deg	0.75-1.80	80-180	23.5 at 1.5 μm

Roman Space Telescope Coronagraphic Capabilities

	Wavelength (μm)	Inner Working Angle (arcsec)	Outer Working Angle (arcsec)	Detection Limit*	Spectral Resolution
Imaging	0.5-0.8	0.15 (exoplanets) 0.48 (disks)	0.66 (exoplanets) 1.46 (disks)	10^{-9} contrast (after post-processing)	47-75
Spectroscopy	0.675-0.785				

https://roman.gsfc.nasa.gov/science/Roman_Reference_Information.html

Roman reference design survey



Are there alternatives relying on ground based data?

Let's explore Roman strategies based on synergies with LSST

Can be improved further with Roman+Subaru (HSC/PFS) synergies

Roman Space Telescope Imaging Capabilities

Telescope Aperture (2.4 meter)	Field of View (45′x23′; 0.28 sq deg)	Pixel Scale (0.11 arcsec)	Wavelength Range (0.5-2.3 μm)

Filters	F062	F087	F106	F129	F146	F158	F184	F213
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	0.93-2.00	1.38-1.77	1.68-2.00	1.95-2.30
Sensitivity (5σ AB mag in 1 hr)	28.5	28.2	28.1	28.0	28.3	28.0	27.5	26.2

Roman Space Telescope Spectroscopic Capabilities

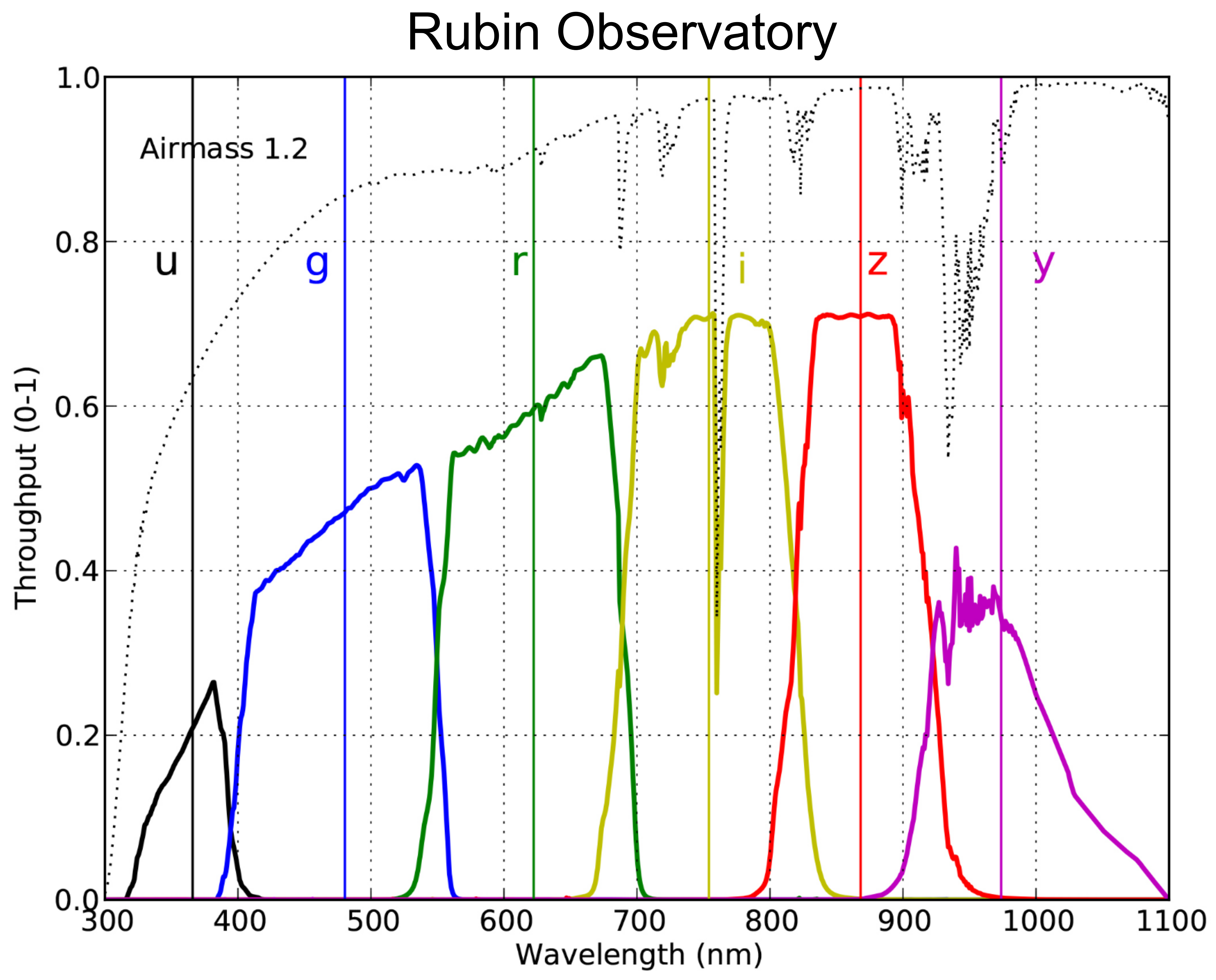
	Field of View (sq deg)	Wavelength (μm)	Resolution	Sensitivity (AB mag) (10σ per pixel in 1hr)
Grism	0.28 sq deg	1.00-1.93	461	20.5 at 1.5 μm
Prism	0.28 sq deg	0.75-1.80	80-180	23.5 at 1.5 μm

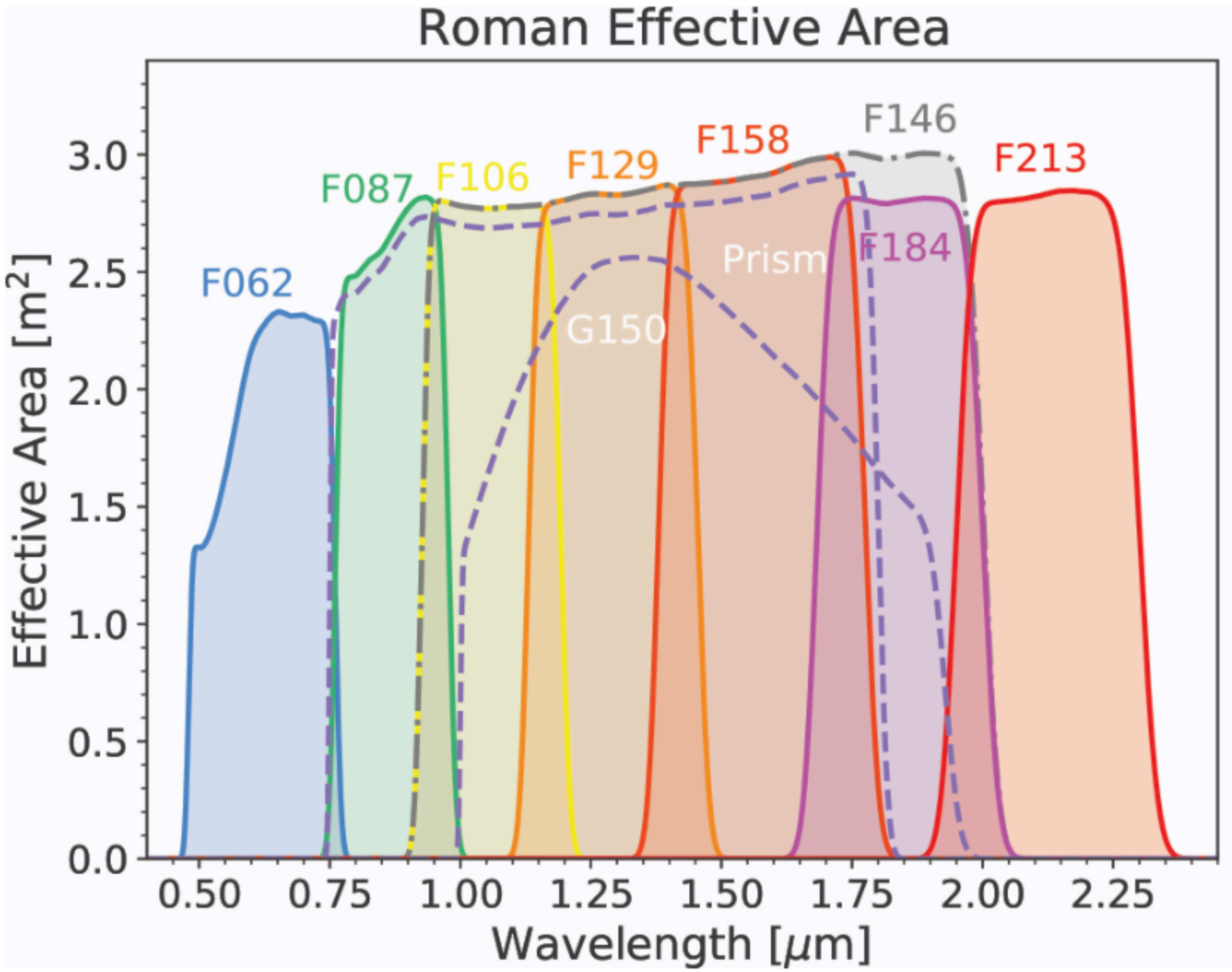
Roman Space Telescope Coronagraphic Capabilities

	Wavelength (μm)	Inner Working Angle (arcsec)	Outer Working Angle (arcsec)	Detection Limit*	Spectral Resolution
Imaging	0.5-0.8	0.15 (exoplanets) 0.48 (disks)	0.66 (exoplanets) 1.46 (disks)	10^{-9} contrast (after post-processing)	47-75
Spectroscopy	0.675-0.785				

https://roman.gsfc.nasa.gov/science/Roman_Reference_Information.html

Roman “wide survey” idea - Synergies with Rubin

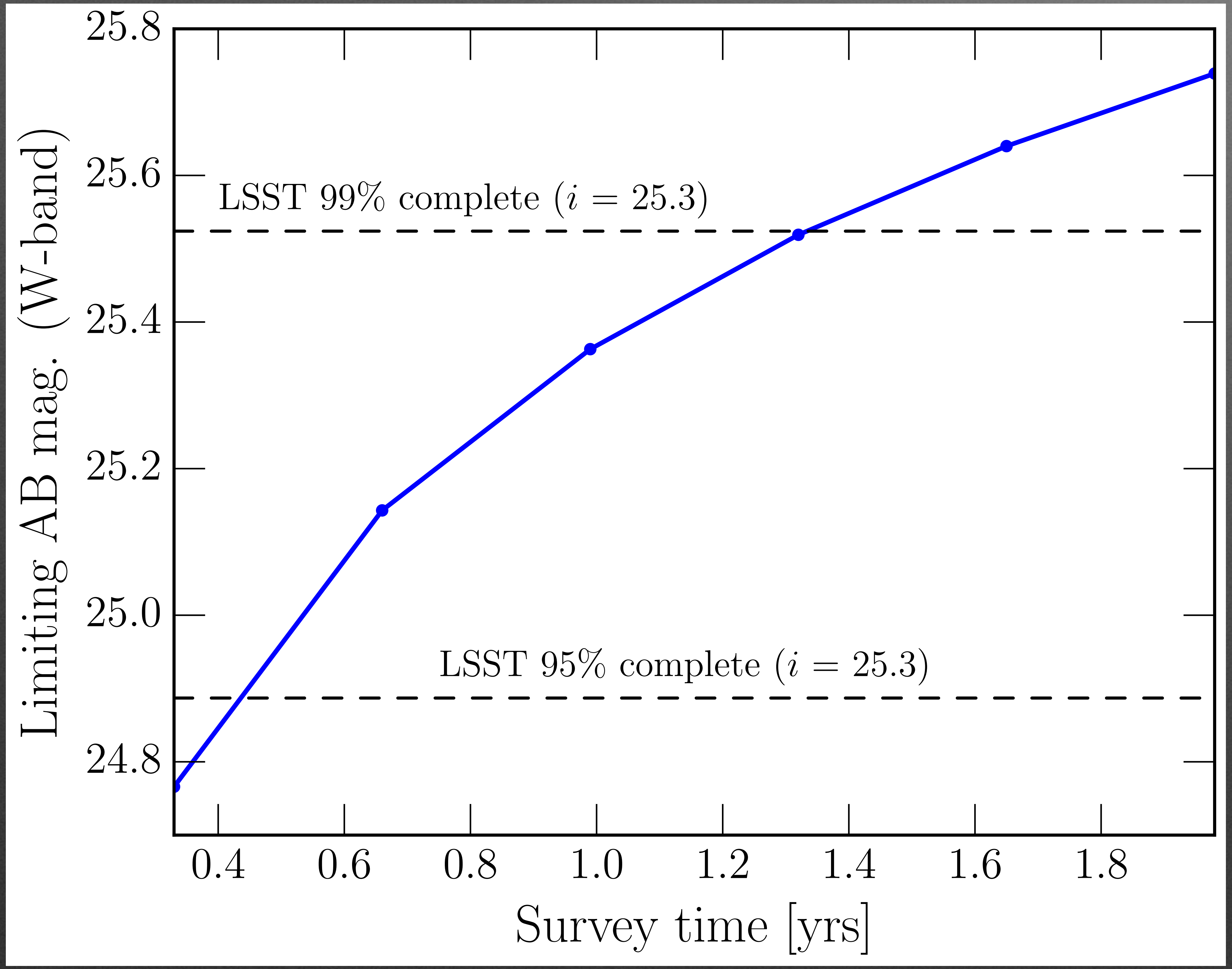


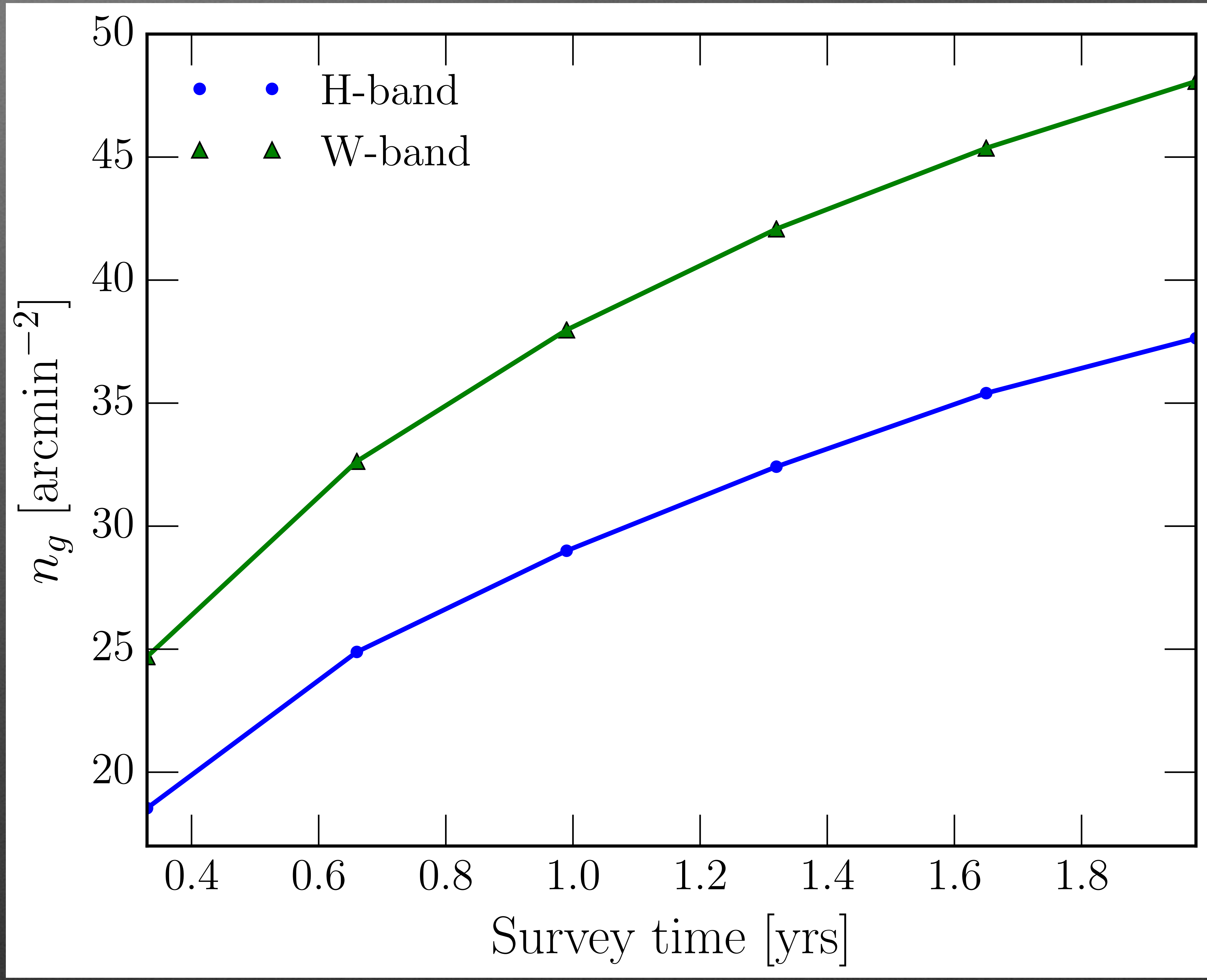


This concept combines the Roman W-band with the 6 LSST bands for photo-z

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

Eifler, Simet, Krause et al 2021

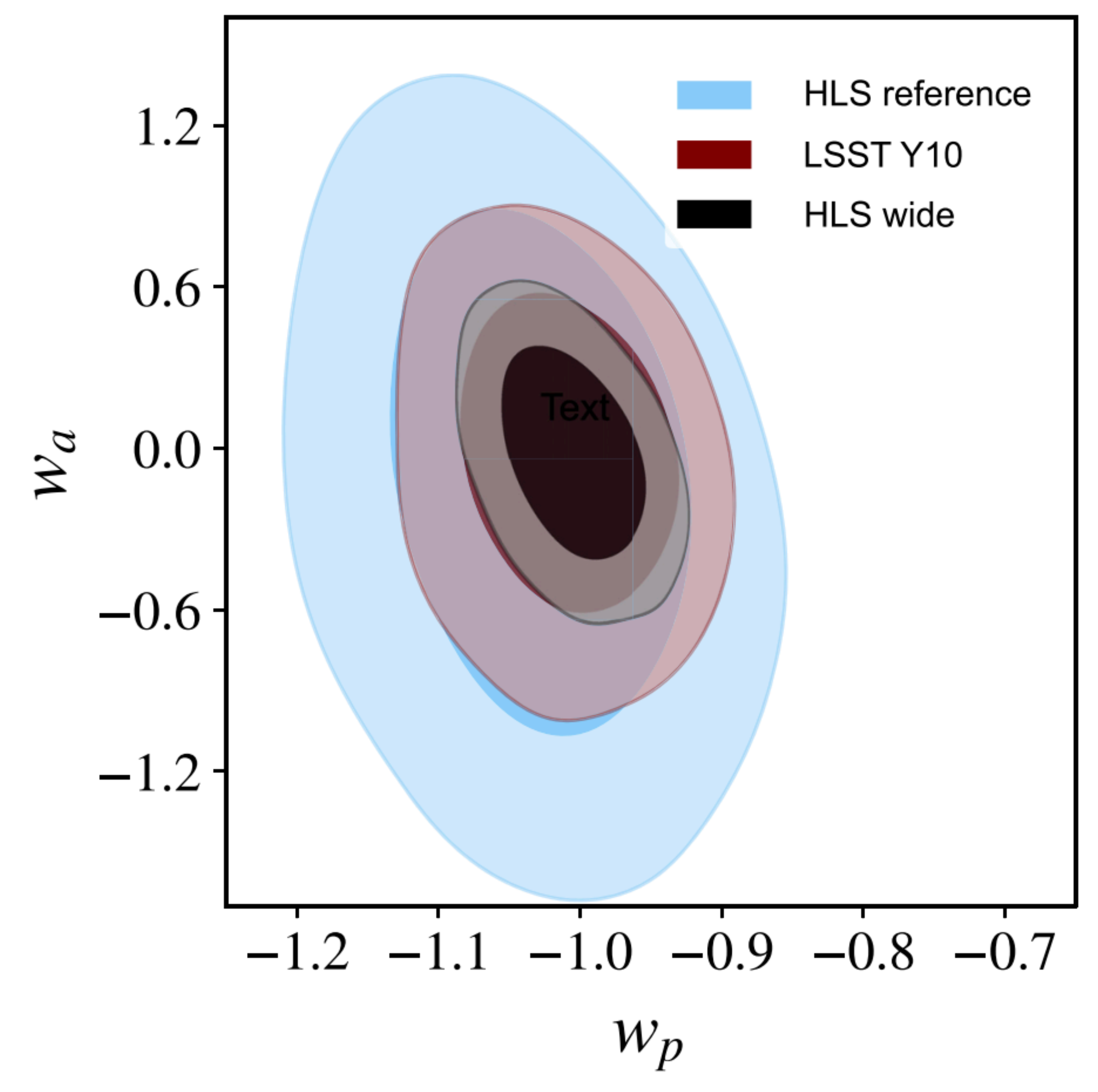




In 5 months Roman can cover LSST area in the W-band with 95% LSST completeness

In 1.5 years Roman can reach similar depth with W-band as for the reference survey design across entire LSST area

Multi-probe Roman+LSST



Analysis is 3x2pt only, (no clusters, spec-z, SN)

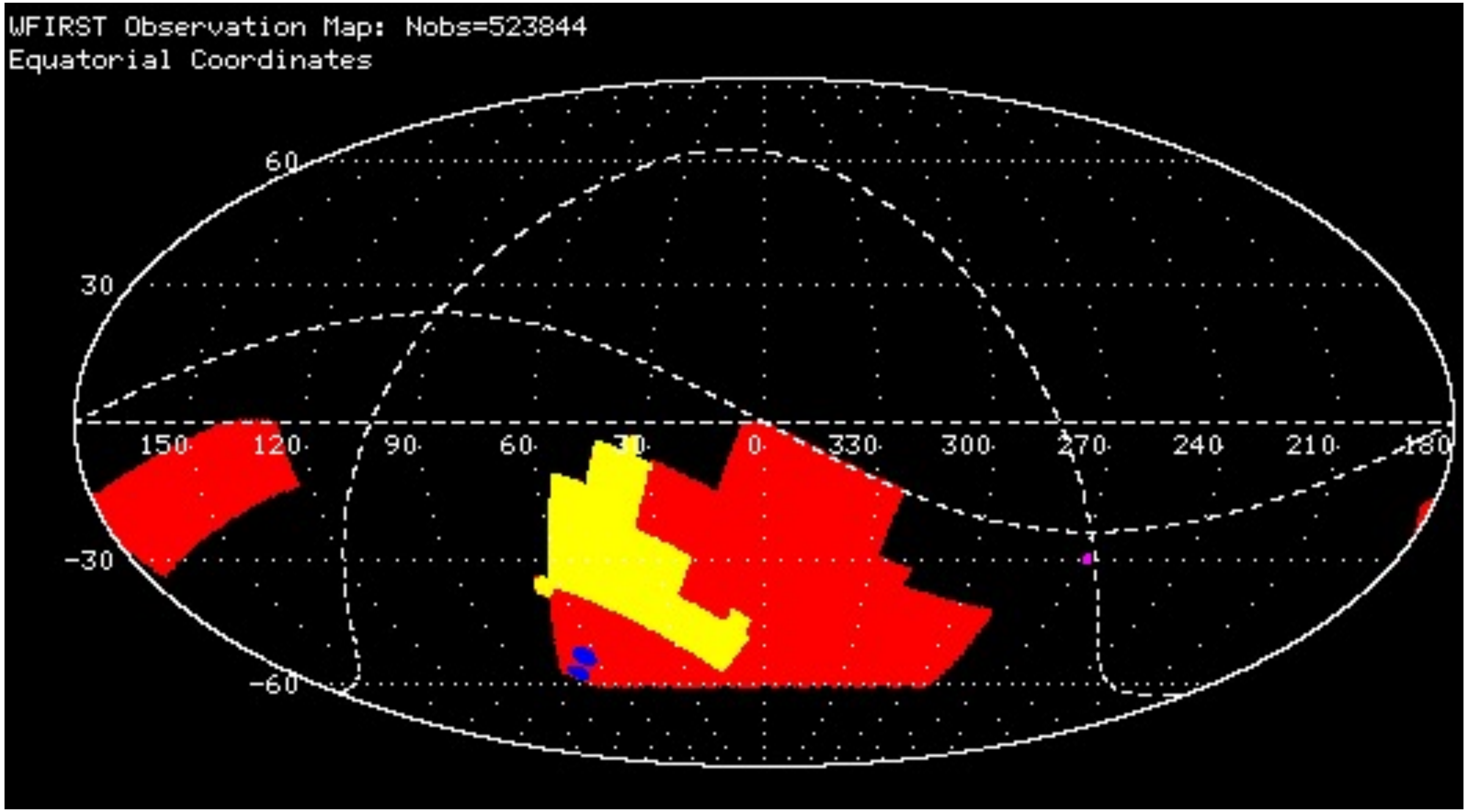
Includes ~56 dims of systematics modeling:

- Shear calibration
- Galaxy bias
- Photo-z
- Intrinsic Alignment
- Baryons

FoM (Roman wide + Rubin)=2.4 x FoM (LSST only)

FoM (Roman wide + Rubin) = 5.5 x FoM (Roman Reference survey)

Compromise between statistical power and systematics control?



This example had an H band only survey (red, 5000 deg²) with Y/J/H/F184/grism coverage in a smaller region (yellow).

- Example: Consider hybrid 5000 deg^2 survey in H-band
- Less statistical power than Roman 18k survey
- H-band is not affected by wavelength dependent PSF
- Have 1000 deg^2 calibration area in 4 bands
- Still exquisite systematics control

Summary

- Roman is on track for launch in Oct 2026
- High Latitude Survey (2000 deg^2) is designed for exquisite systematics control, but should be considered an example, not a final strategy.
- Wide Roman covering LSST area to LSST Y10 WL depth (95%) can be done in 4-5 months with the W-Band
- W-band all-sky survey takes ~1 year. Get an all-sky high-resolution map of the entire visible sky.
- 1.5 year Roman W-band survey can cover LSST area with 50 galaxies/arcmin^2 and increase FoM by a factor of 5.5 over reference survey (Disclaimer: increased risk for systematics compared to reference survey)
- Goal: Find sweet spot of systematics control and statistical power before launch

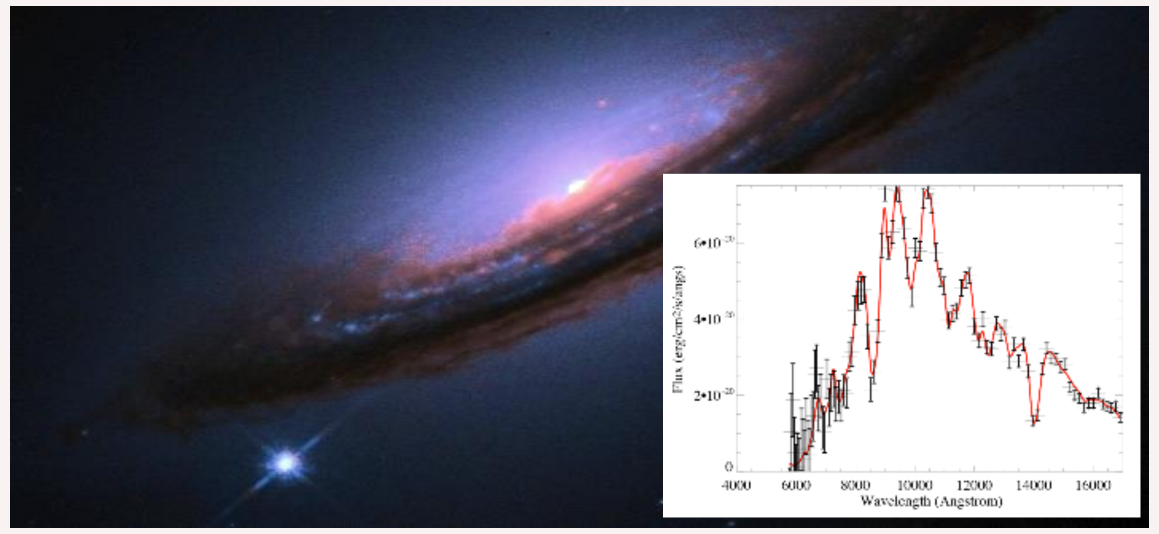
Roman - Dark Energy Plan

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%



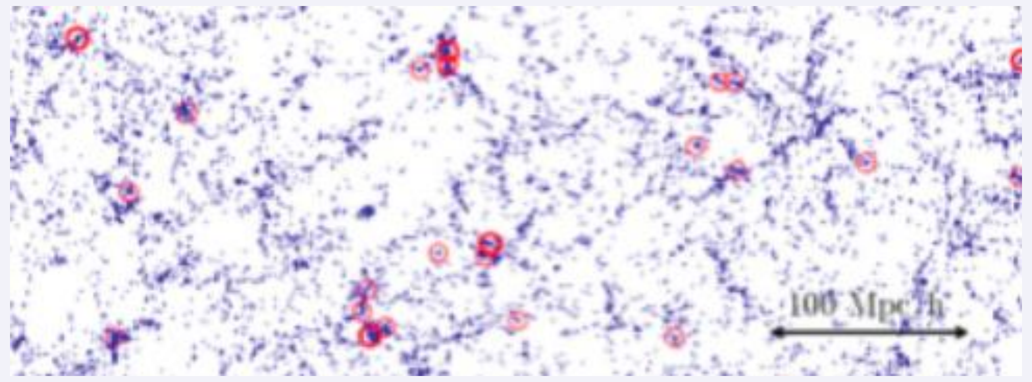
High Latitude Survey

spectroscopic: galaxy redshifts

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

standard ruler

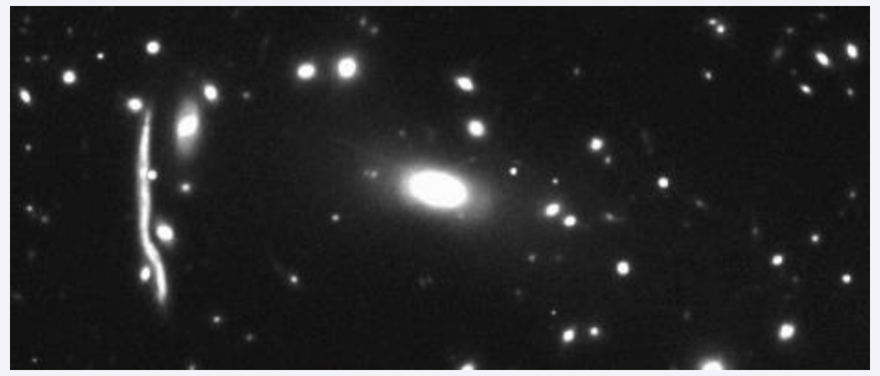
distances	expansion rate
z = 1–2 to 0.5%	z = 1–2 to 0.9%
z = 2–3 to 1.3%	z = 2–3 to 2.1%



imaging: weak lensing shapes

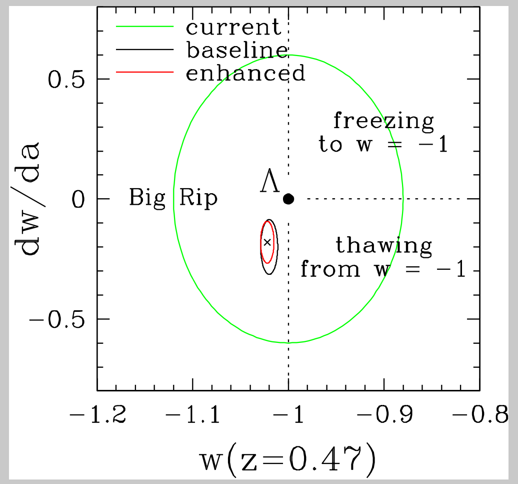
380 million lensed galaxies
40,000 massive clusters

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



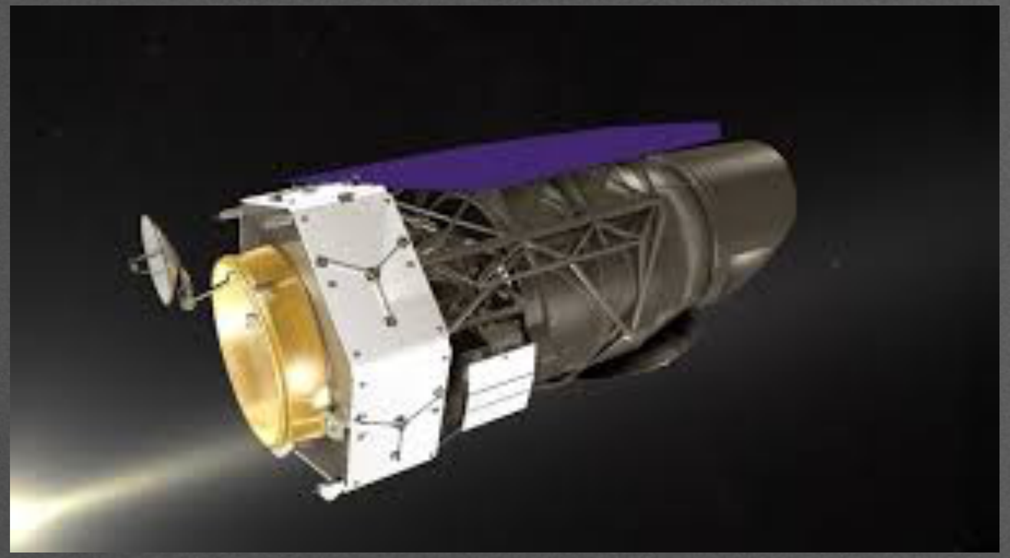
history of dark energy
+
deviations from GR

$w(z)$, $\Delta G(z)$, Φ_{REL}/Φ_{NREL}



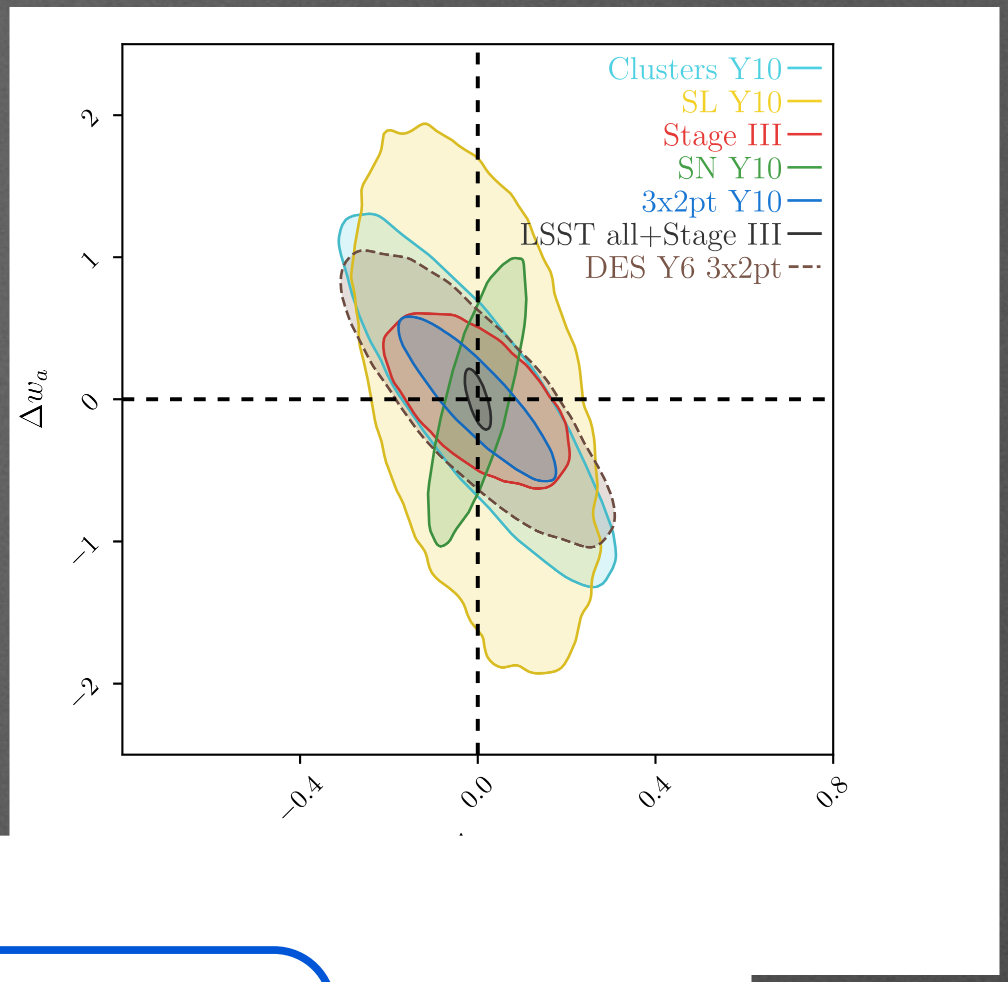
Talk focusses on Imaging Component

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

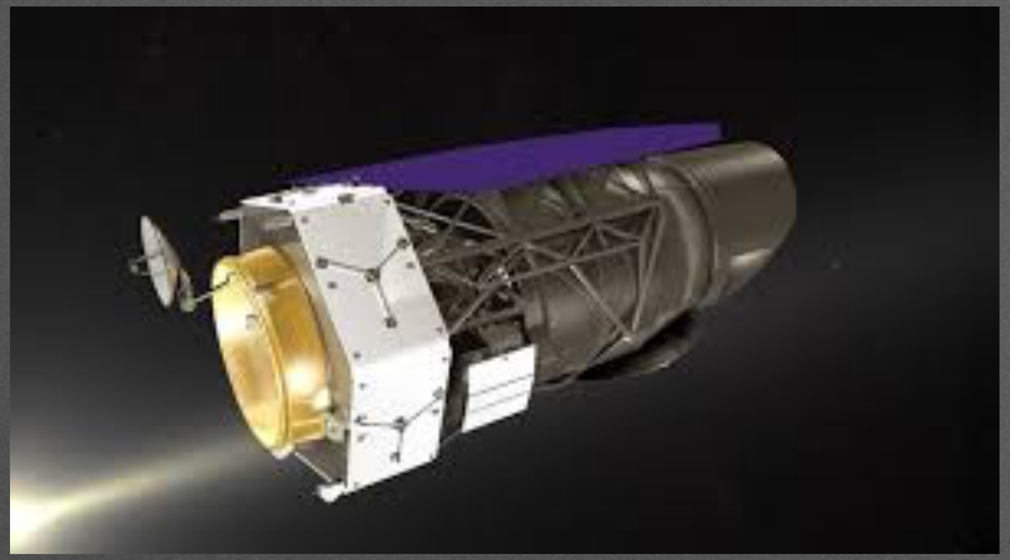
$$p\left(\boldsymbol{\pi}|\hat{\mathbf{d}}\right) \propto p\left(\boldsymbol{\pi}\right)\mathcal{L}\left(\hat{\mathbf{d}}|\mathbf{m}\left(\boldsymbol{\pi}\right), C\right)$$

Enhanced modeling via
- Observations
- Simulations
- Theory

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

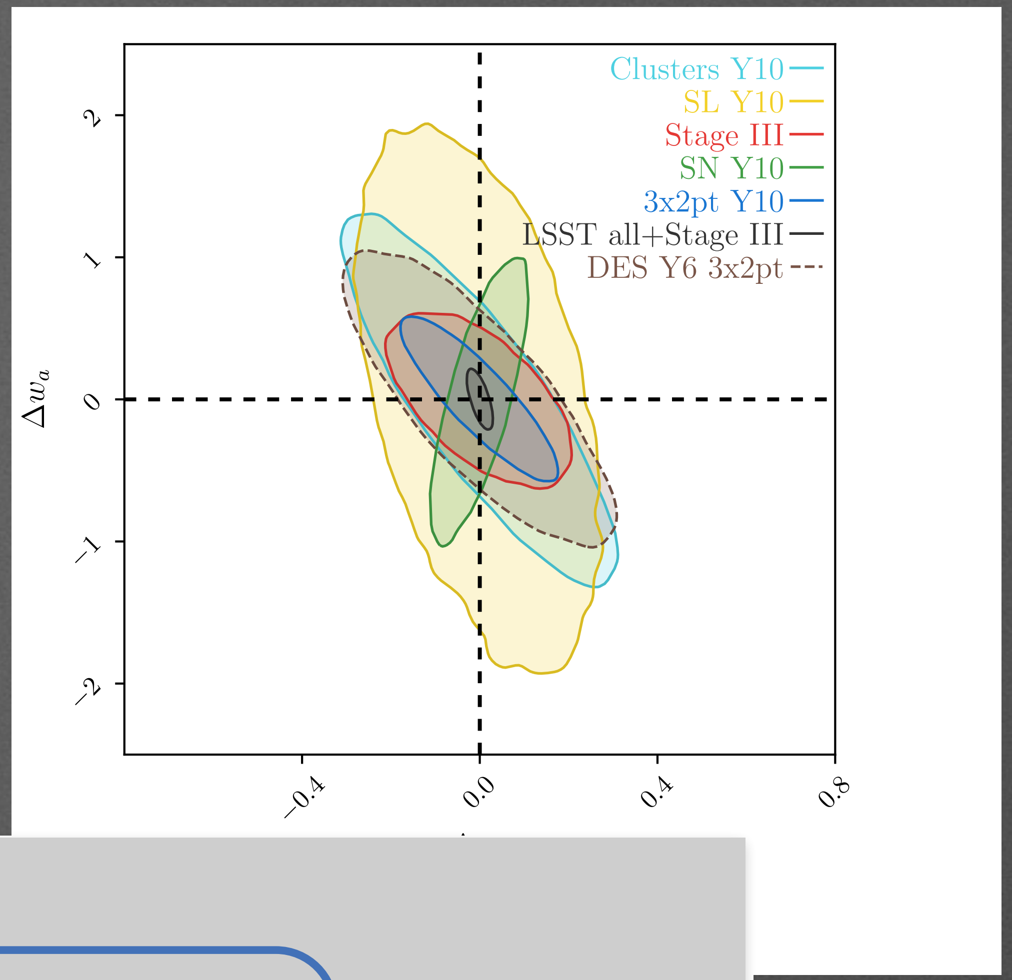
Statistics II - Covariances
- cosmology dependent Signal + constant Noise
- large and complicated, non-(block) diagonal
- different methods for derivation

The Challenge



reduced data and catalogs

summary statistics



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

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

Enhanced modeling via
- Observations
- Simulations
- Theory

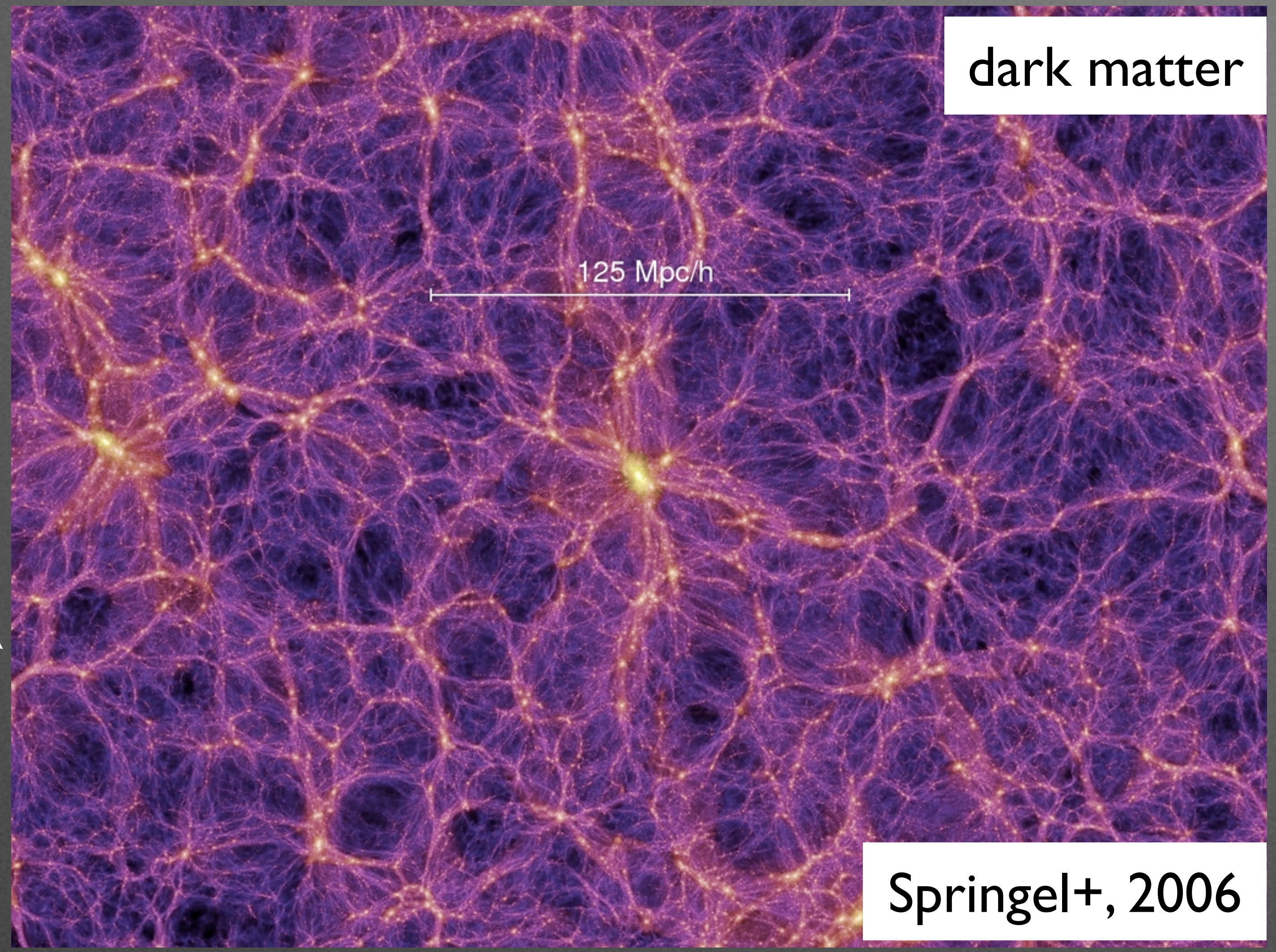
Statistics I - Likelihood function
- Multivariate Gaussian vs other parameterizations
- Non-parametric forms
- Approximate Bayesian Computation

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

Theory - Data connection in a nutshell

Physics
+ model parameters

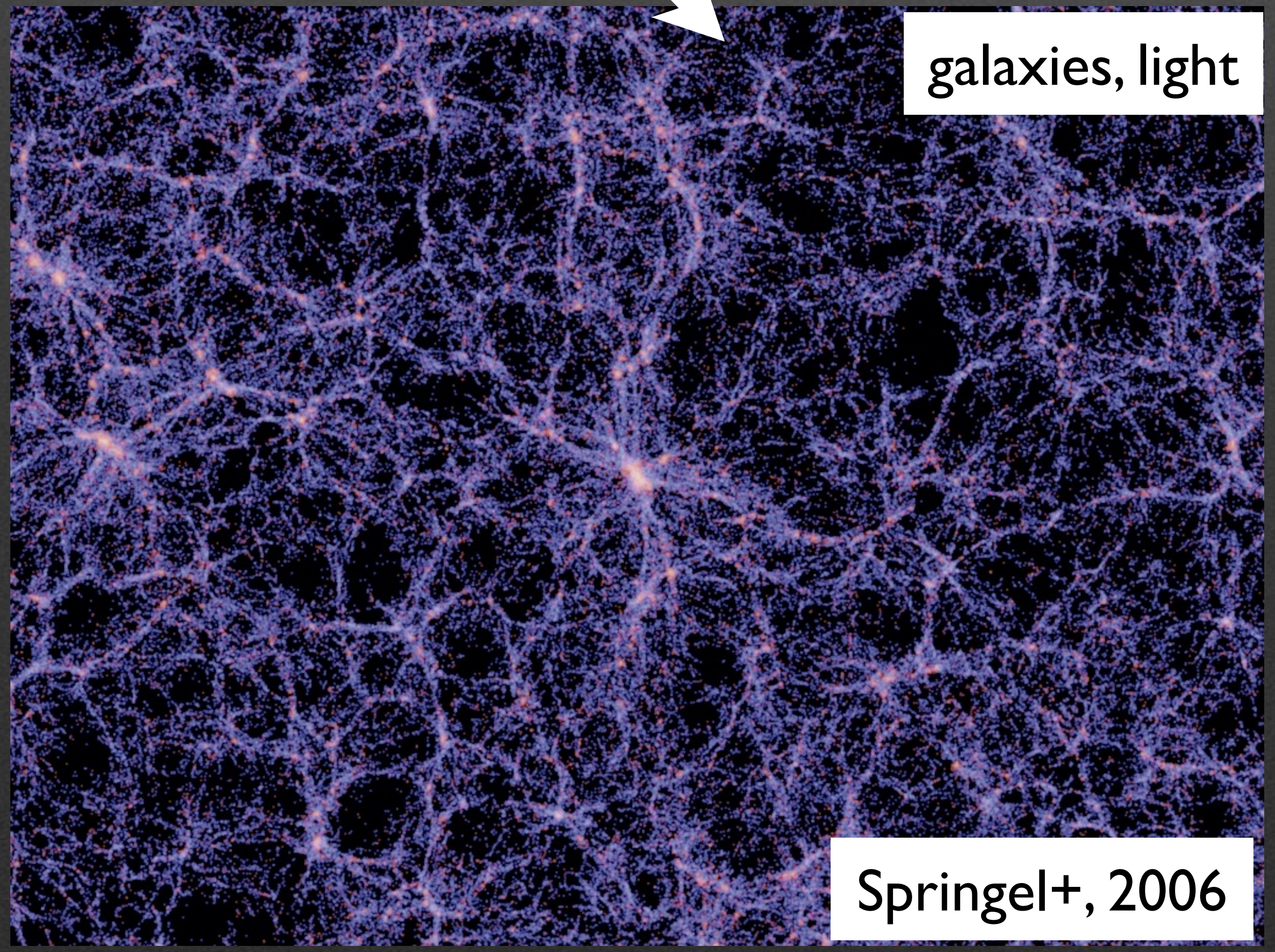
generate initial conditions, evolve



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

galaxy formation models

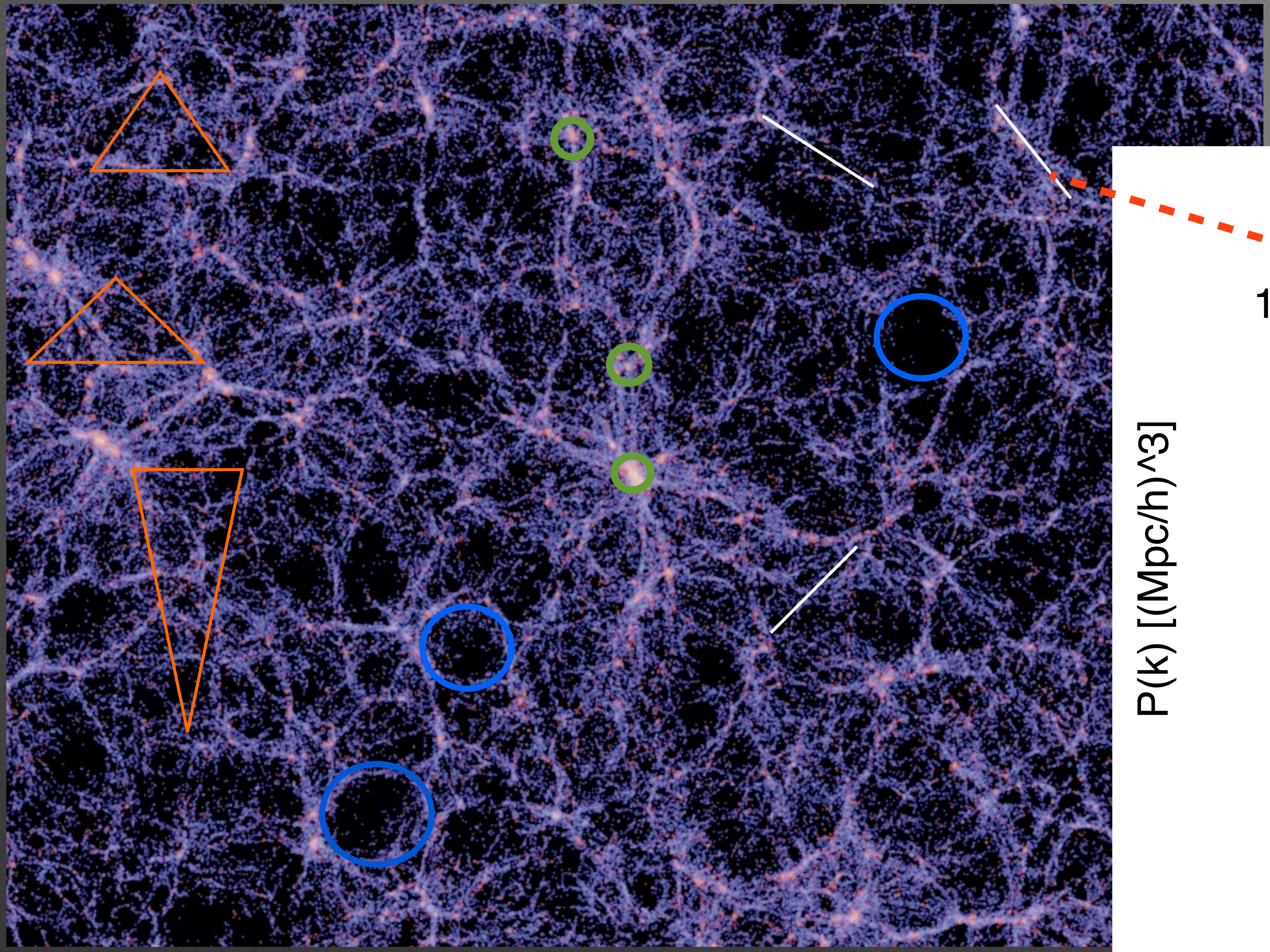
?

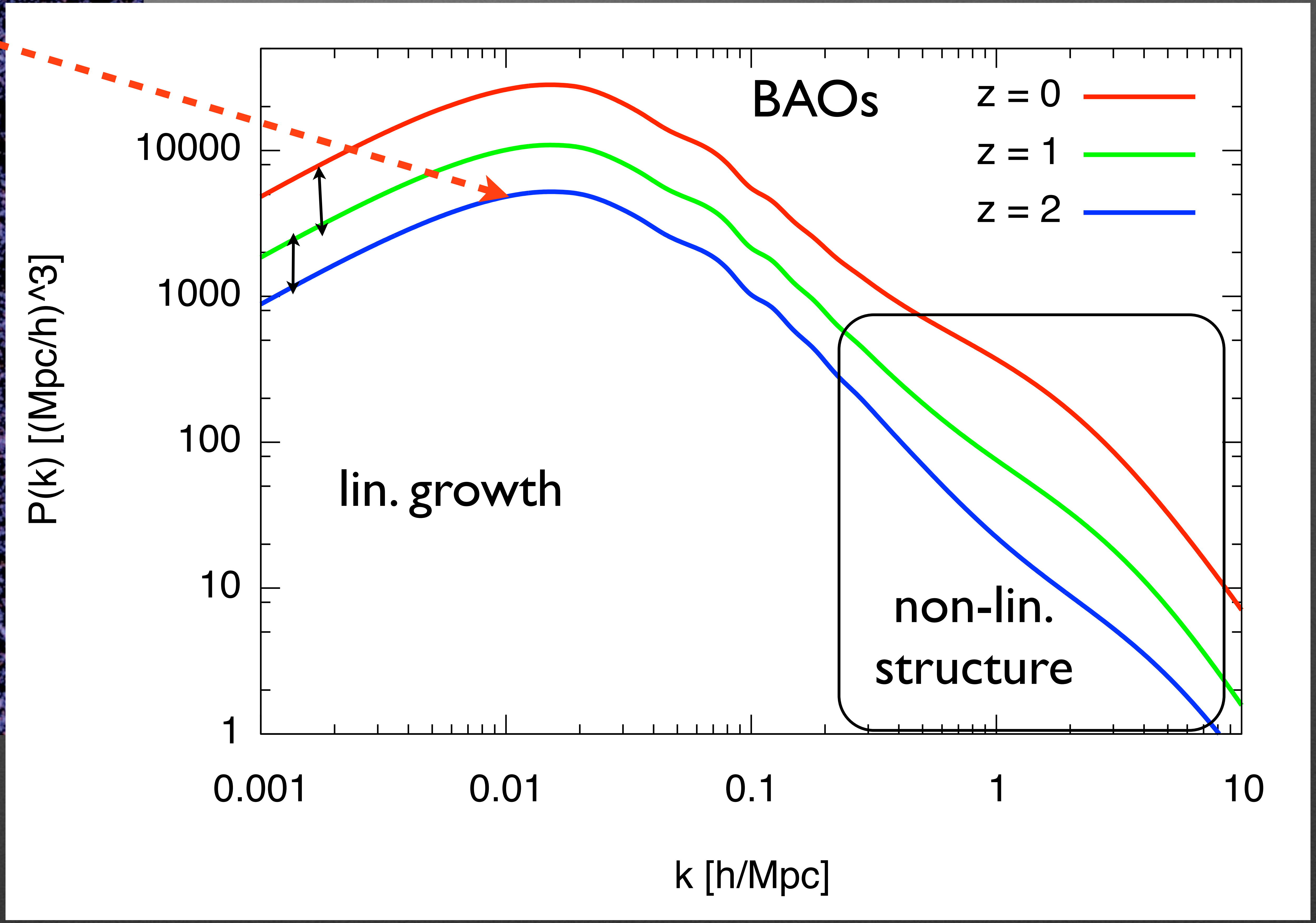


Obs

Sys ?

Tracers of the density field





clusters,peaks (over densities),

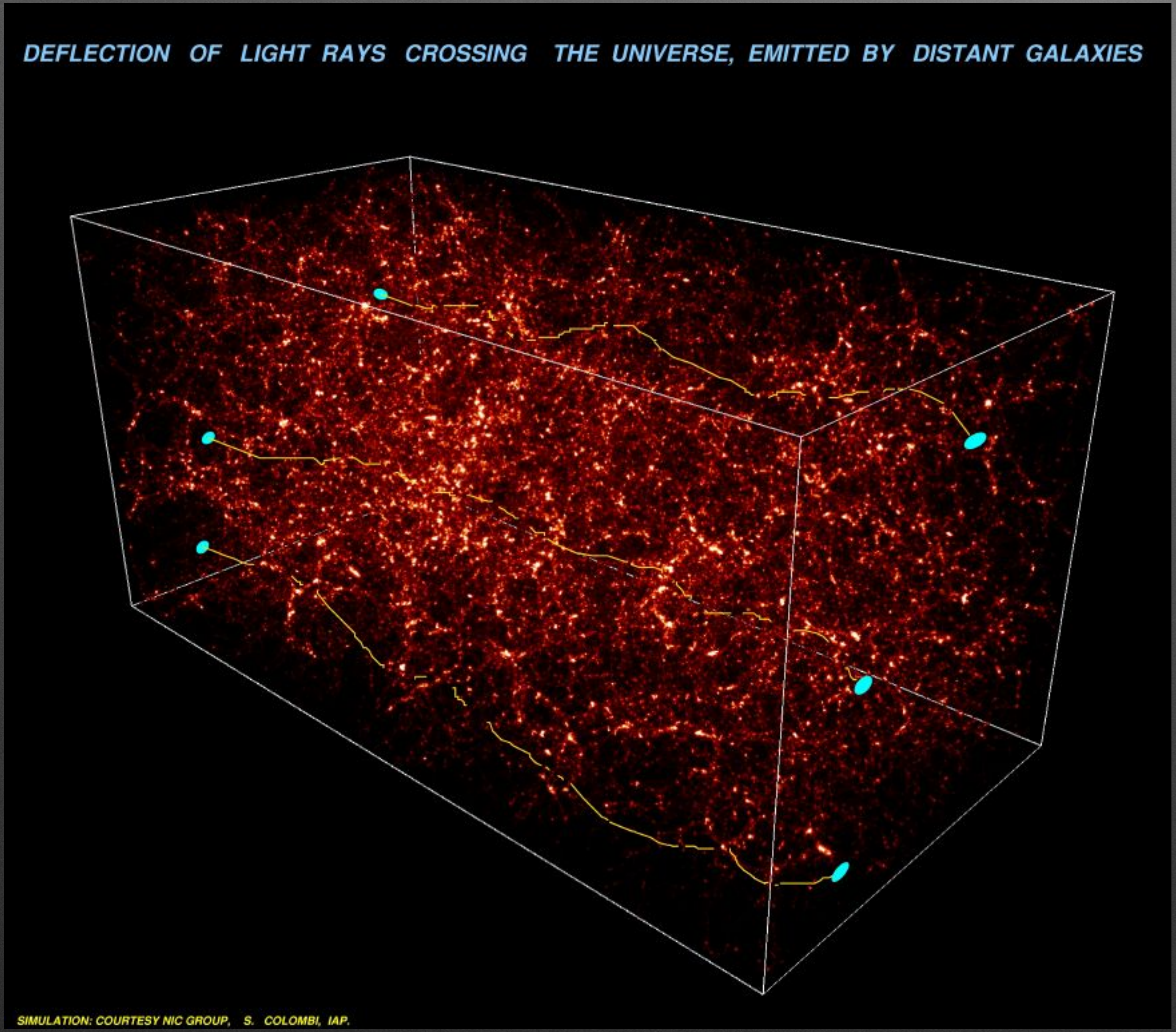
voids (under densities)

two-point correlations
(galaxy positions, shapes)

three-point correlations,...

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

Weak Lensing

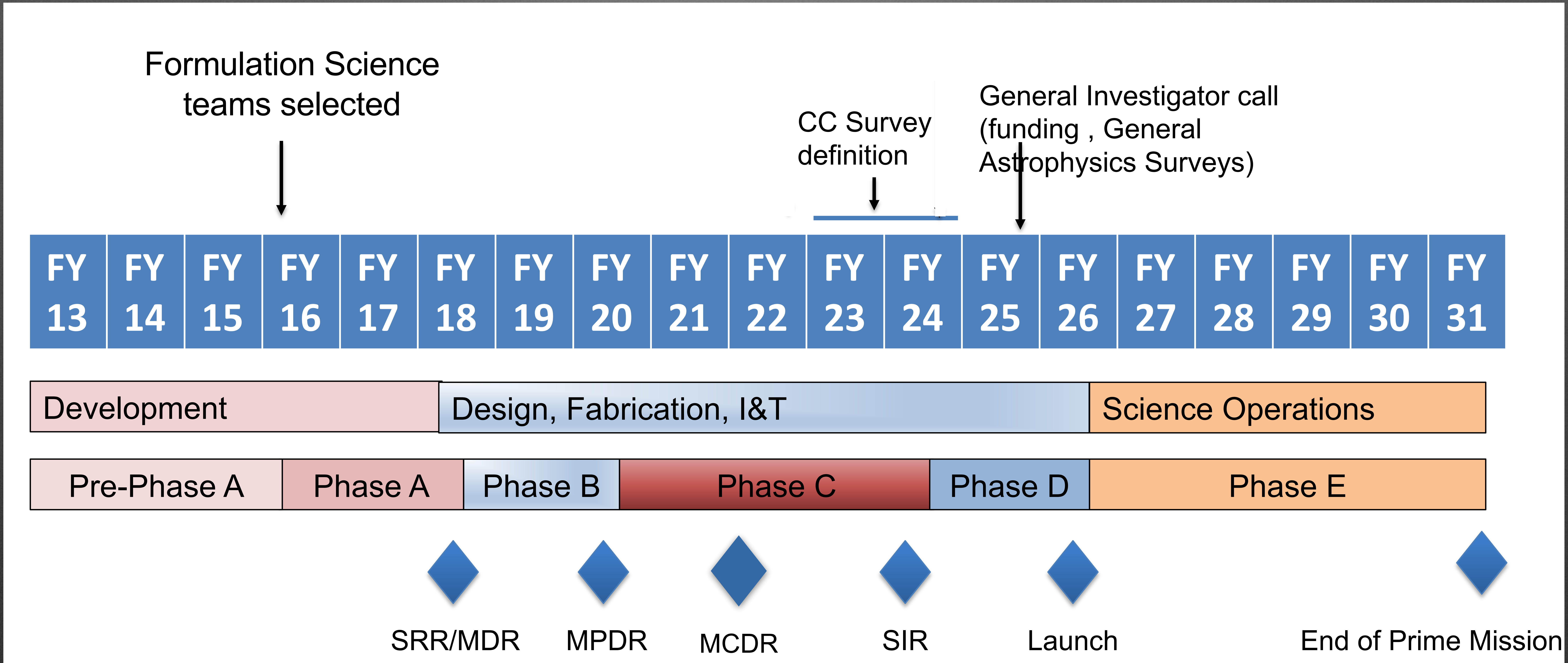


Light rays are distorted by dark matter density field of the Universe

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

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

Roman timeline



Roman passed Critical Design Review and is now in its systems integration phase.

Extended Mission possible, no expendables