WFIRST Science Definition Team and Project Interim Report Presentation to the Astrophysics Sub-Committee

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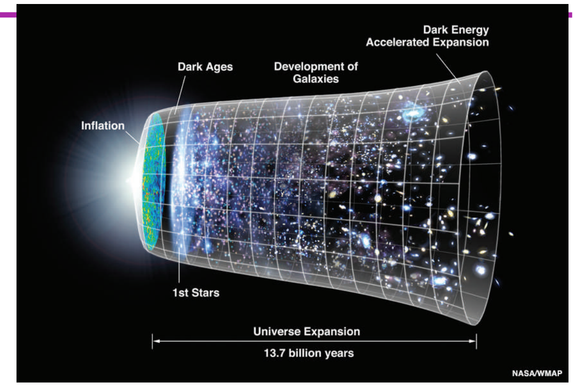
* These viewgraphs should not be read as a substitute for the full report.

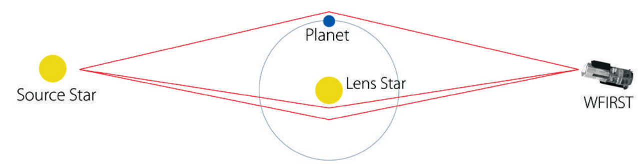
July 13, 2011

WFIRST Summary



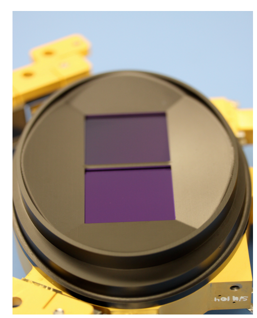
❖ WFIRST is the highest ranked large space mission in NWNH, and plans to:
- complete the statistical census of Galactic planetary systems using microlensing
- determine the nature of the dark energy that is driving the current accelerating expansion of the universe
- survey the NIR sky for the community

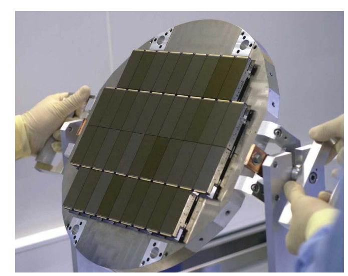
❖ Earth-Sun L2 orbit, 5 year lifetime, 10 year goal



❖ The current Interim Design Reference Mission has
- 1.3 m unobstructed telescope
- NIR instrument with ~36 HgCdTe detectors
- >10,000 deg^2 5-sigma NIR survey at mag AB=25

❖ The time is ripe for WFIRST:
- Space-qualified large format HgCdTe detectors are US developed technology and flight ready





SDT Charter

"The SDT is to provide science requirements, investigation approaches, key mission parameters, and any other scientific studies needed to support the definition of an optimized space mission concept satisfying the goals of the WFIRST mission as outlined by the Astro2010 Decadal Survey."

"In particular, the SDT report should present assessments about how best to proceed with the WFIRST mission, covering the cases that the Euclid mission, in its current or modified form, proceeds to flight development, or that ESA does not choose Euclid in the near future."

WFIRST – Science Objectives

1) Complete the statistical census of planetary systems in the Galaxy, from habitable Earth-mass planets to free floating planets, including analogs to all of the planets in our Solar System except Mercury.

2) Determine the expansion history of the Universe and its growth of structure in order to test explanations of its apparent accelerating expansion including Dark Energy and possible modifications to Einstein's gravity.

3) Produce a deep map of the sky at NIR wavelengths, enabling new and fundamental discoveries ranging from mapping the Galactic plane to probing the reionization epoch by finding bright quasars at $z>10$.

SDT Findings #1

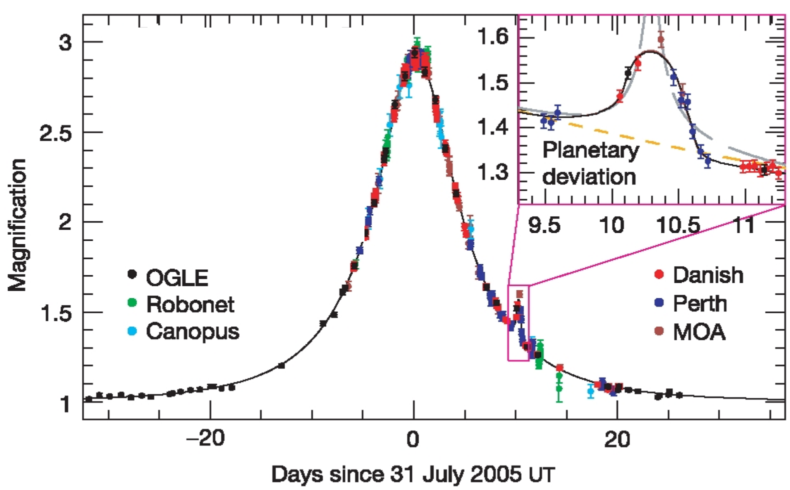
WFIRST should include all of the science objectives and utilize all of the techniques outlined in the NWNH recommendations:

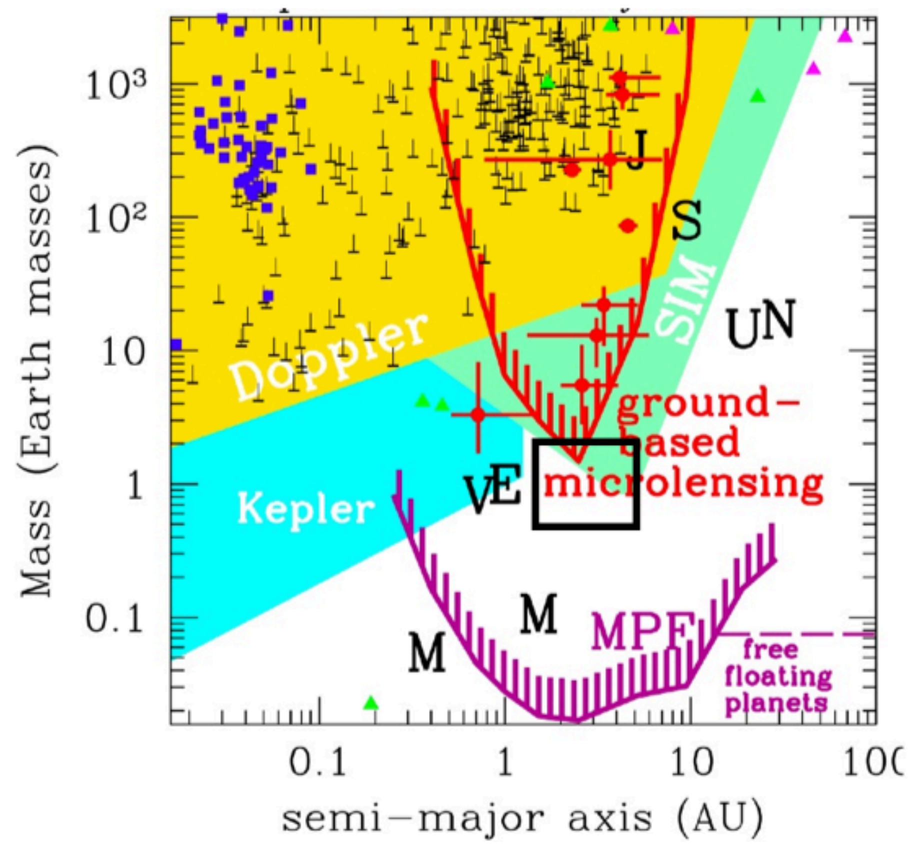
A: Baryon Acoustic Oscillation (BAO) Galaxy Redshift Survey
B: Exoplanet (ExP) Microlensing Survey
C: Supernova SNe-Ia Survey
D: Weak Lensing (WL) Galaxy Shape Survey
E: Near Infrared Sky Survey – w/Survey of the Galactic plane
F: Guest Investigator Program
G: *Redshift Space Distortions, or RSD, acquired in parallel with BAO for free*

The WFIRST IDRM is compliant with the NWNH recommendation for groundbreaking observations in Dark Energy, Exoplanet and NIR sky surveys

Exoplanet Microlensing Technique

- Monitor Galactic bulge in NIR
- Detect microlensing events of background stars by foreground stars + planets
- Also detects free-floating planets
- Complementary to transit techniques (such as Kepler)





Exoplanet Survey Capability

- Planet detection to 0.1 Earth mass (M_{Earth})
- Detects ≥ 30 free floating planets of 1 M_{Earth} in a 500 day survey*
- Detects ≥ 125 planets of M_{Earth} (in 2 year orbits) in a 500 day survey*
- Detects ≥ 25 habitable zone† planets (0.5 to 10 M_{Earth}) in a 500 day survey *

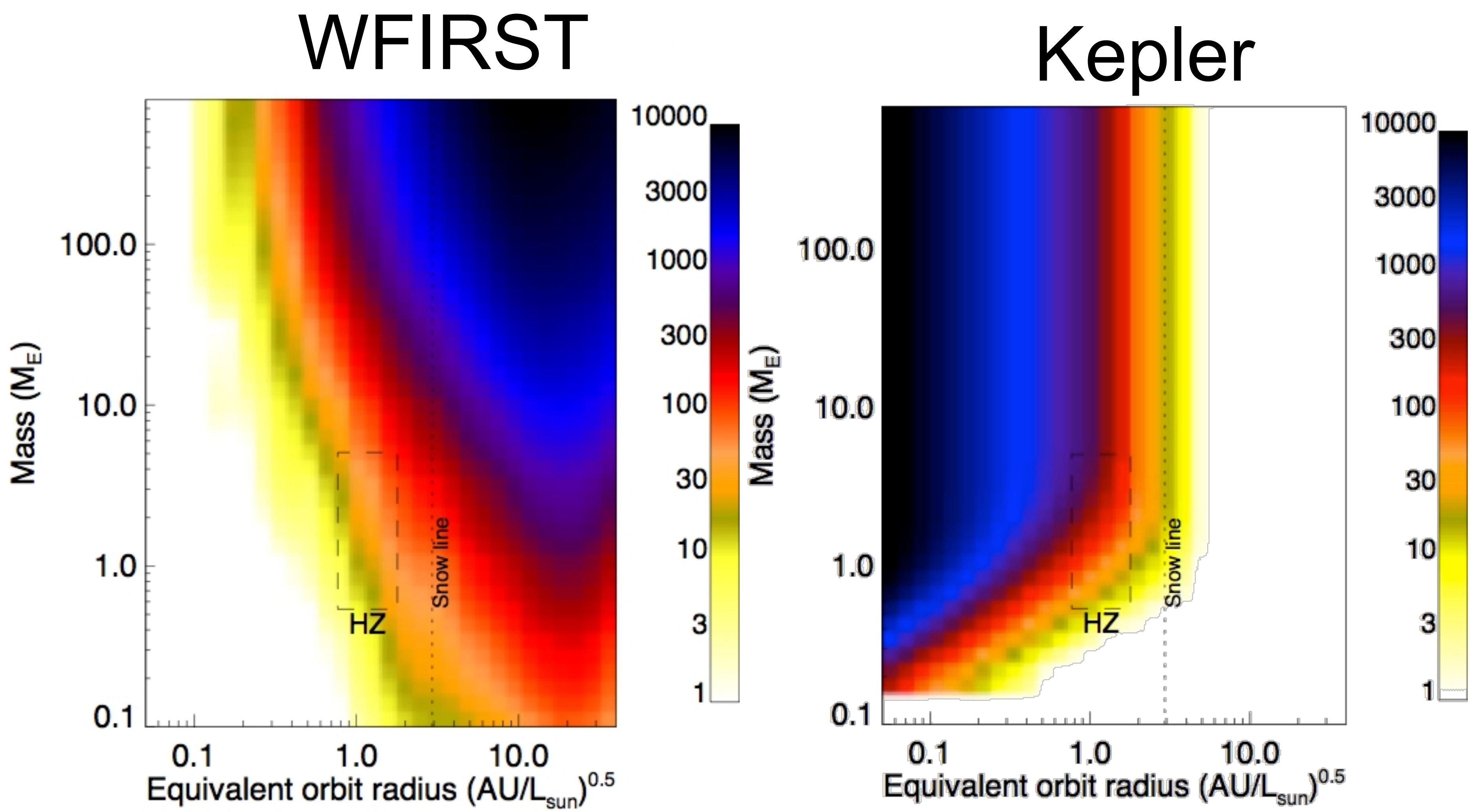
* Assuming one such planet per star; "500 day surveys" are concurrent

† 0.72-2.0 AU, scaling with the square root of host star luminosity

Data Set Rqts include:

✓Observe ≥ 2 square degrees in the Galactic Bulge at ≤ 15 minute sampling cadence;
✓Minimum continuous monitoring time span: ~60 days;
✓Separation of ≥4 years between first and last observing seasons.

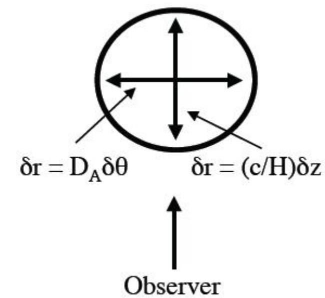
Microlensing – Transit Comparison



Figures from B. MacIntosh of the ExoPlanet Task Force

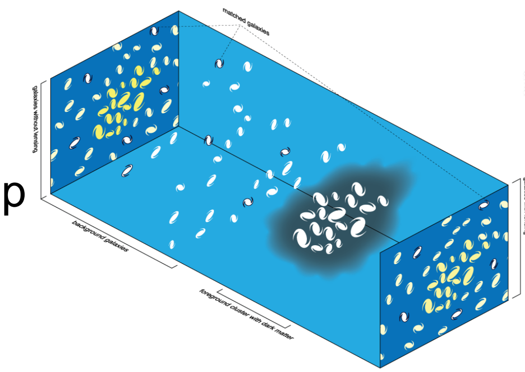
Dark Energy Techniques

- Three most promising techniques each provide different physical observables and unique information:

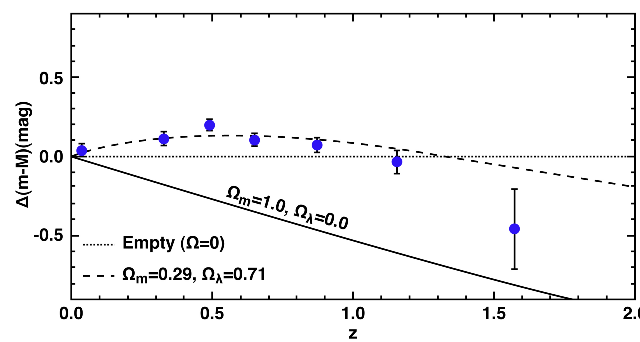


Baryon Acoustic Oscillation (BAO)
- Emission line galaxies positioned in 3D using strong Hα line
- Spectroscopic redshift survey in NIR

Weak Lensing (WL)
- Precision shape measurement of galaxy shap
- Photo-z redshifts



Type Ia Supernovae (SNe)
- Type Ia supernovae detected into NIR



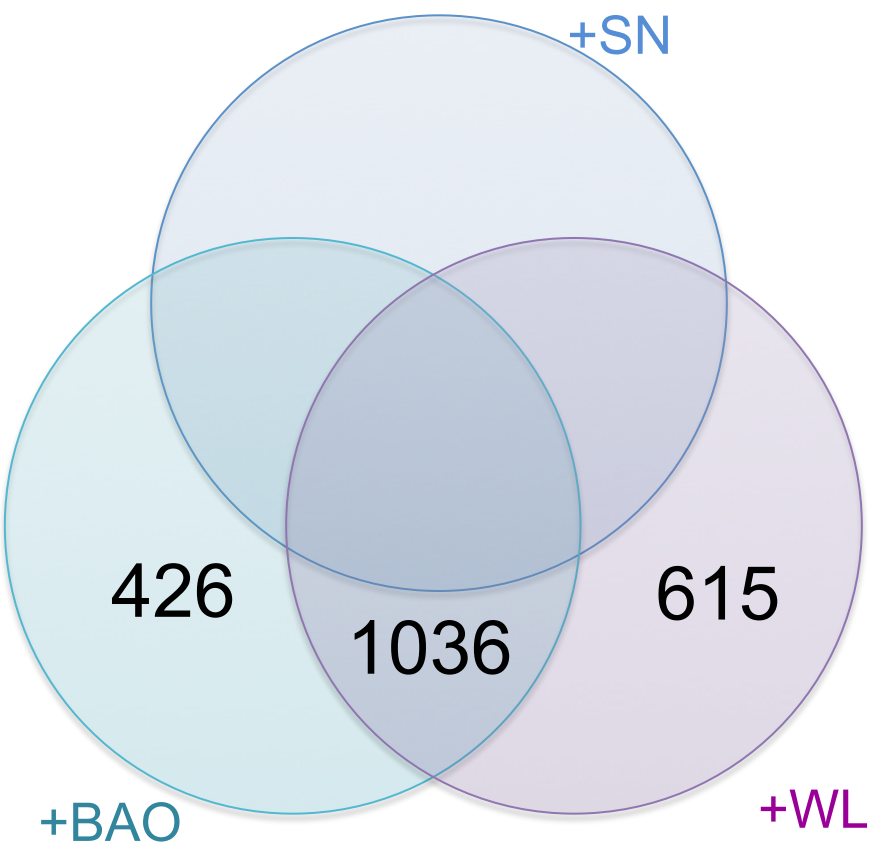
- Redshift Space Distortions (RSD)
  – Distortions in Hubble flow
  – Galaxy redshifts from BAO survey can give growth of structure info

Dark Energy Survey Capabilities

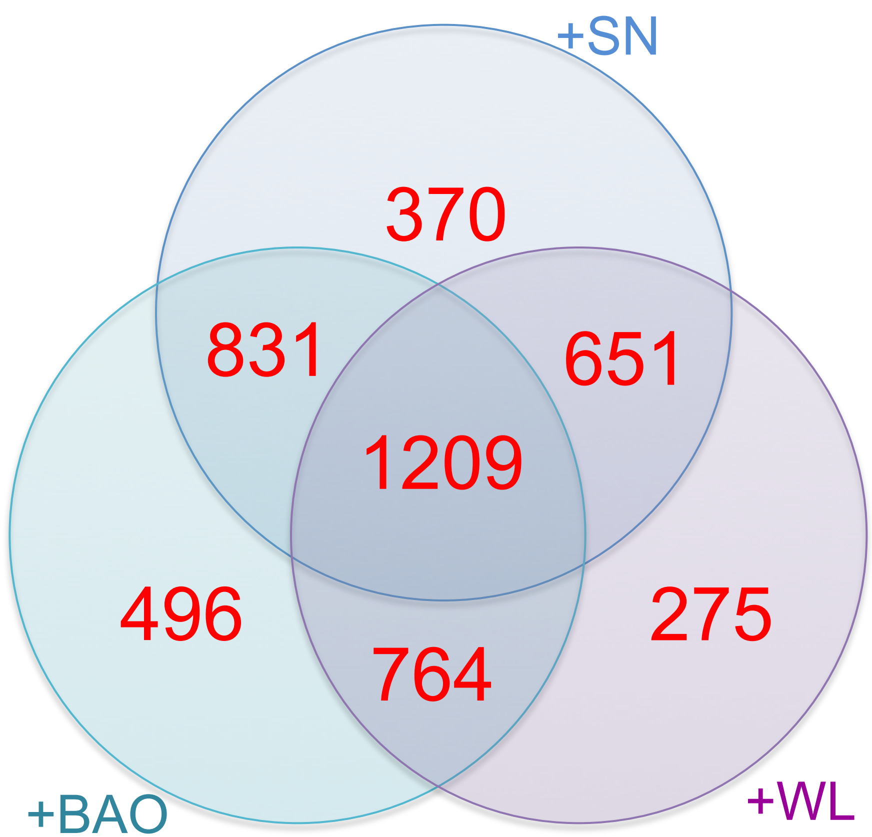
- BAO/RSD: ... “WIDE” survey mode
  - 11,000 deg^2/dedicated year
  - Redshift errors $\sigma_z \leq 0.001(1+z)$, over redshift range $0.7 \leq z \leq 2$
- Weak Lensing: ... “DEEP” survey mode
  - 2700 deg^2/dedicated year
  - Effective galaxy density $\geq 30/amin^2$, shapes resolved plus photo-zs
- SNe-Ia Survey:
  - >100 SN per $\Delta z = 0.1$ bin for most bins $0.4 < z < 1.2$, per dedicated 6 months
  - Redshift error $\sigma_z \leq 0.005$ per supernova

Comparison with EUCLID (DETF FoM)

EUCLID Optimistic:
5 year Dark Energy Measurement



WFIRST Optimistic:
2.5 year Dark Energy Measurement



NIR Survey Capabilities

- Identify ≥100 quasars at redshift $z>7$
- Obtain broad-band NIR spectral energy distributions of ≥1e9 galaxies at $z>1$ to extend studies of galaxy formation and evolution
- Map the structure of the Galaxy using red giant clump stars as tracers

Data Set Rqts include:

✓High Latitude data from Imager and Spectrometer channels during BAO/RSD and WL Surveys;

- Image 2500 deg^2 in 3 NIR filters to mag AB=25 at S/N=5

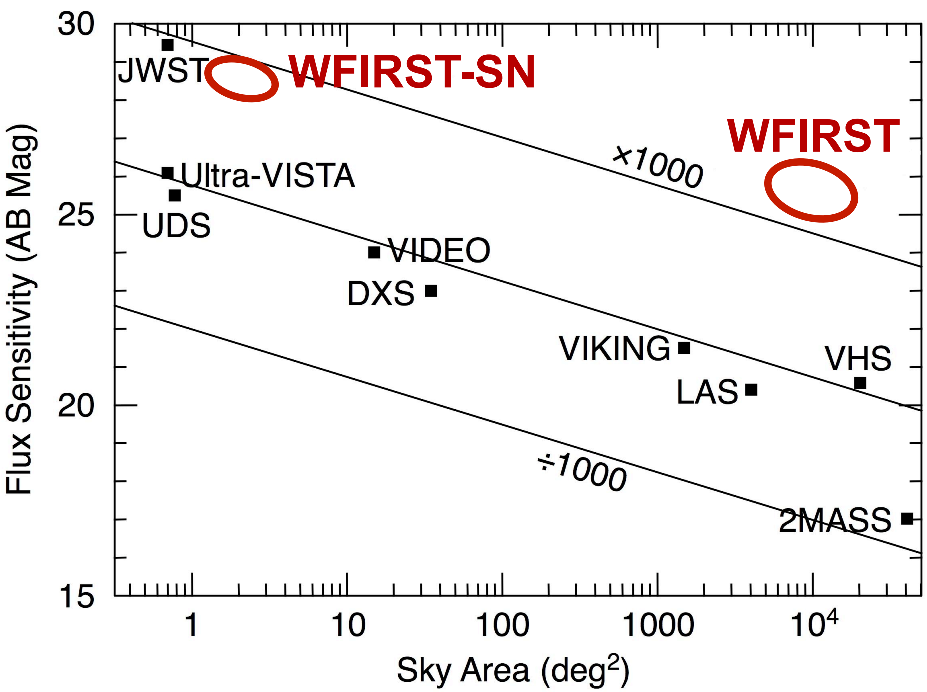
✓Galactic Plane Survey (~0.5 yr, per EOS Panel);

- Image 1500 deg^2 of the Galactic Plane in 3 NIR filters

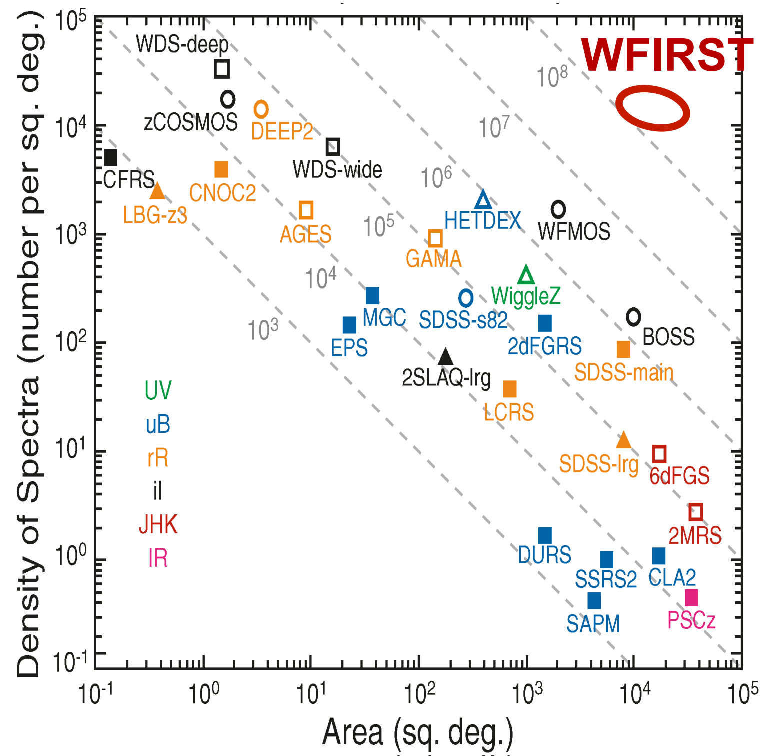
✓Guest Investigator observations (~1 yr, per EOS Panel) will supplement

WFIRST NIR Surveys

NIR Imaging Surveys



NIR Redshift Surveys



WFIRST provides a factor of 100 improvement in IR surveys

Guest Investigator (GI) Studies with WFIRST

WFIRST will be a unique platform for a broad range of astrophysical studies. The NWHM report strawman schedule allocates ~1 yr of the baseline 5 yr mission for competed Guest Investigator (GI) programs. Examples of potential such programs include:

- (time domain) surveys of the outer Solar System (Kuiper belt)
- follow-up of exoplanet transits (imaging and spectroscopic)
- wide-field (time domain) imaging of Galactic globular and open clusters
- deep imaging of Galactic supernova remnants
- transient surveys
- GI studies of galaxies in the nearby volume
- wedding cake galaxy evolution surveys (e.g., GI programs would fill in layers of the wedding cake missed by the dark energy surveys; imaging and spectroscopic)
- deep studies of massive, high-redshift galaxy clusters
- clustering of $z>7$ Lyman-alpha emitters
- environments of $z\sim10$ quasars

Science Return

Mission Performance: EOS Panel vs WFIRST IDRM

Science Investigation	EOS Panel Report	WFIRST IDRM
WL Survey	4000 deg^2	2700 deg^2/yr
BAO Survey	8000 deg^2	11,000 deg^2/yr
SNe	Not Mentioned	1200 SNe per 6 months
Exoplanet Microlensing	500 total days	500 total days
Galactic Plane Survey	0.5 yr GP Survey	0.5 yr GP Survey
Guest Investigators	1 year GI observations	1 year GI observations

Dark Energy Performance: NWNH Main Report vs WFIRST IDRM

DE Technique	NWNH Main Report	WFIRST IDRM 5 yr mission	WFIRST IDRM 5 yr Dark Energy*
WL Galaxy Shapes	2 billion	300 million (1 yr)	600 million (2 yr)
BAO Galaxy Redshifts	200 million	60 million (1 yr)	120 million (2 yr)
Supernova SNe-Ia	2000	1200 (1/2 yr)	2400 (1 yr)

***Including 5 year extended mission**

Science Return Summary

- WFIRST meets or comes close to meeting the time allocations and sky coverages given in the EOS Panel Report.

- For Dark Energy, WFIRST has fewer galaxies surveyed and SNe monitored than called for in the NWNH Main Report. The NWNH numbers were taken from the JDEM-IDECS RFI with 5 years of Dark Energy observations and were never feasible for WFIRST or JDEM-Omega (even with 5 years of DE).

- Still, the WFIRST IDRM has excellent performance compared to overall NWNH objectives as reviewed by the SDT. The FoM numbers are good for all science areas.

SDT Findings #2

How would WFIRST change if Euclid is selected?

- Due to the importance of the scientific questions and need for verification of the results, WFIRST should proceed with all of its *observational capabilities* intact regardless of the ESA decision on Euclid.

- The WFIRST design incorporates significant advantages with regard to BAO (fixed prism) and WL (unobscured telescope). Supernovae and exoplanet microlensing surveys are most effectively pursued in the infrared.

- The actual *observation program* would likely be altered in light of Euclid's selection or in response to any Euclid results prior to WFIRST's launch.

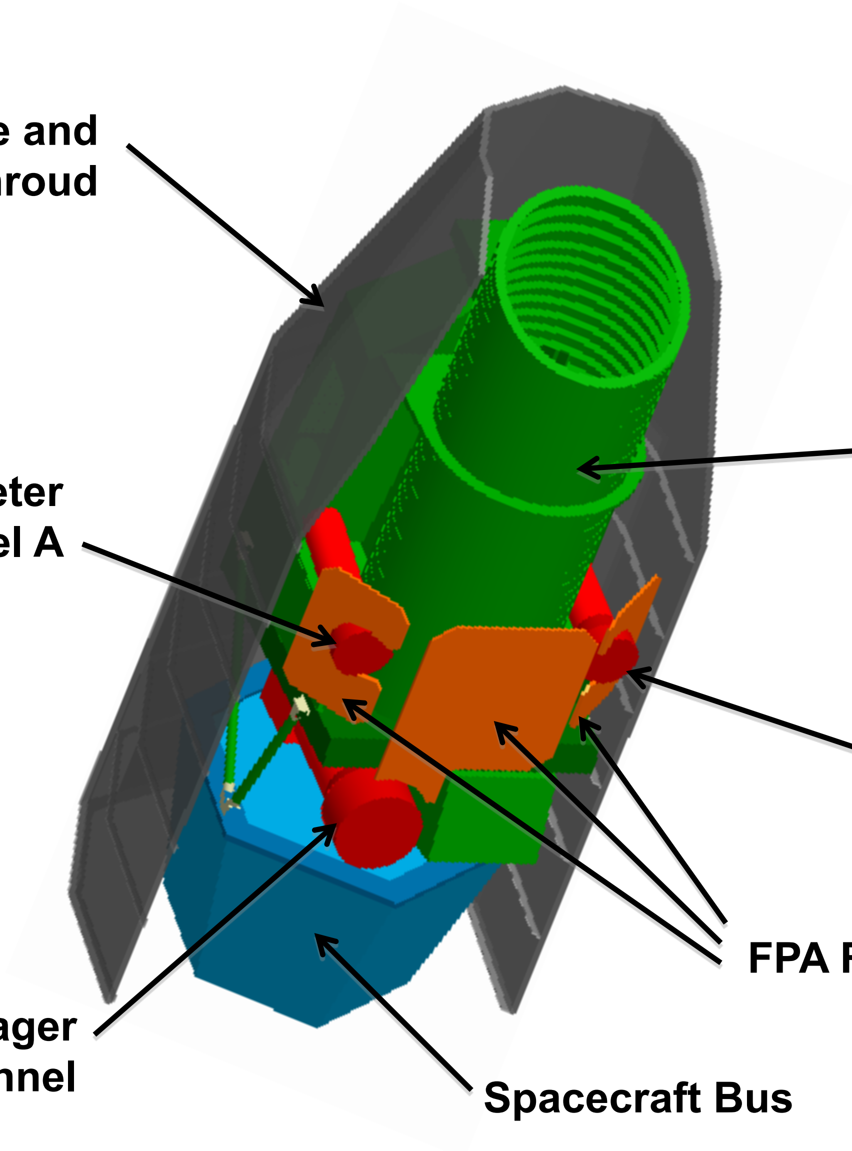
SDT Findings #3

Should NASA and ESA decide to pursue a joint mission or program, all of the scientific approaches and broad objectives currently included in WFIRST must be included in the joint mission or program.

Future Study Areas

- IDRM design/analysis cycle underway and continuing into FY12.
- Re-assessment of Euclid when Red Book is published.
- Assessment of collaboration opportunities with ESA once the status of Euclid is clarified in October 2011.
- Study of technical feasibility and scientific trades of increasing maximum wavelength beyond 2 microns.
- Study of technical feasibility and scientific trades of substituting a slit spectrometer or IFU for SN spectroscopy.

WFIRST IDRM
Observatory Layout



Key Hardware Changes

WFIRST IDRM vs JDEM-Omega

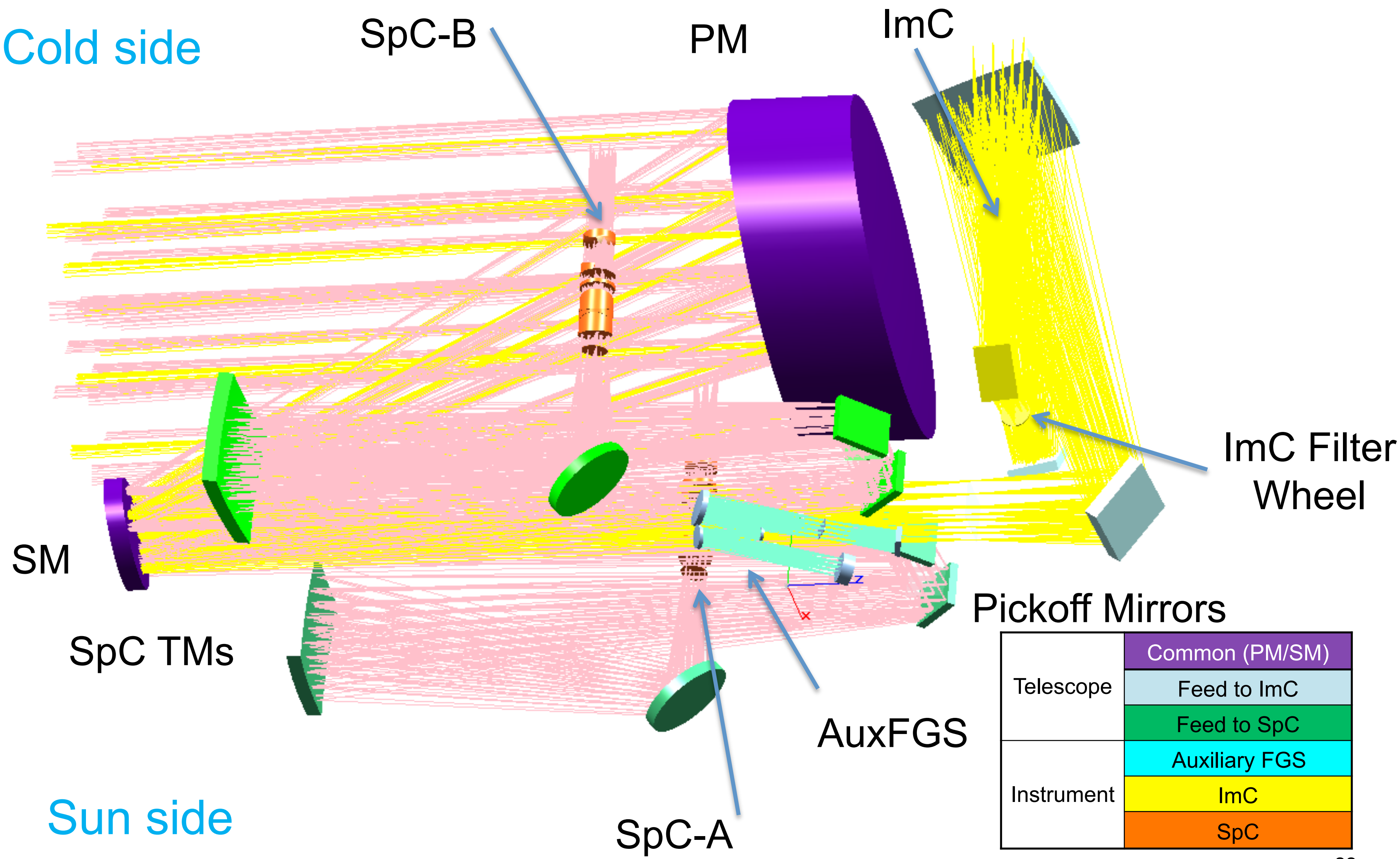
- 1.3m unobscured telescope vs 1.5m obscured for JDEM-Omega.
  Better imaging performance. Faster integration times. Comparable cost.

- 4 detectors moved from Spectrometer to Imager, and Spectrometer pixel scale increased.
  Increased sky coverage for Imager while keeping Spectrometer sky coverage constant.

- Larger Field of Regard (range of pitch angles off the sun)
  Increased sky availability to meet Exoplanet Galactic Bulge field monitoring requirements in tandem with SNe field monitoring

- Focal designs for ImC/SpC vs afocal SpC design for JDEM-Omega
  Allowed removal of large, complex 4 asphere collimator feed to SpC

IDRM Payload Optics – Ray trace



Telescope	Common (PM/SM)
	Feed to ImC
	Feed to SpC
Instrument	Auxiliary FGS
	ImC
	SpC

Channel field layout for WFIRST IDRM-1

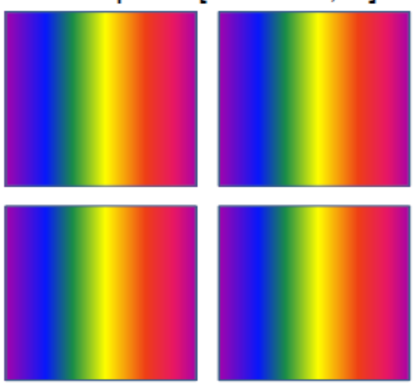
Moon (average size seen from Earth)

The Fields of view of the imaging channel (ImC), spectroscopy channels (SpCs), and guiding modes (FGS) are shown to scale with the Moon, HST, and JWST. Each square is a 4Mpix vis-NIR sensor chip assembly (SCA)

ImC: 7x4 @ 0.18"/p; SpC 2(2x2)@0.45"/p
[xfield center, yfield center, degrees]

SpC-B [-0.9275°,0°]

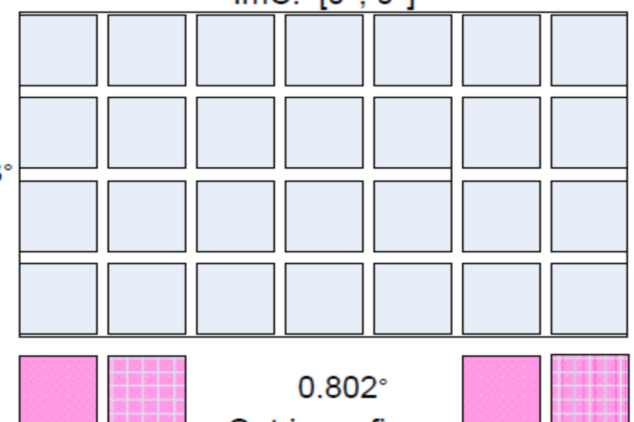
0.536°



0.536°

ImC: [0°, 0°]

0.463°

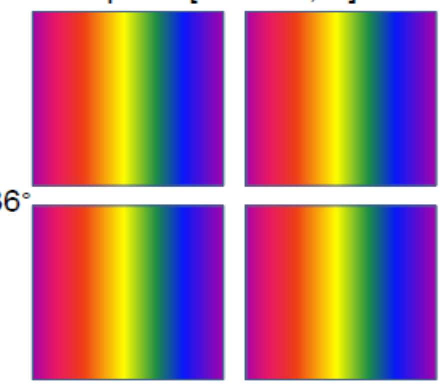


0.802°

Outrigger fine guidance sensors

SpC-A [0.9275°,0°]

0.536°

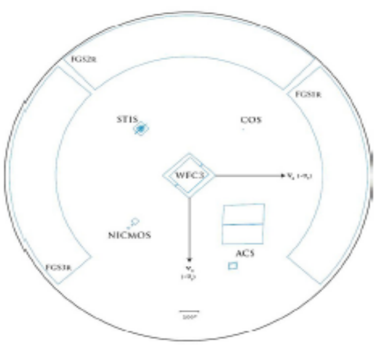


0.536°

0.142°

0.31°

Auxiliary Fine Guidance System: 2@0.25"/p [0°, -0.6°]



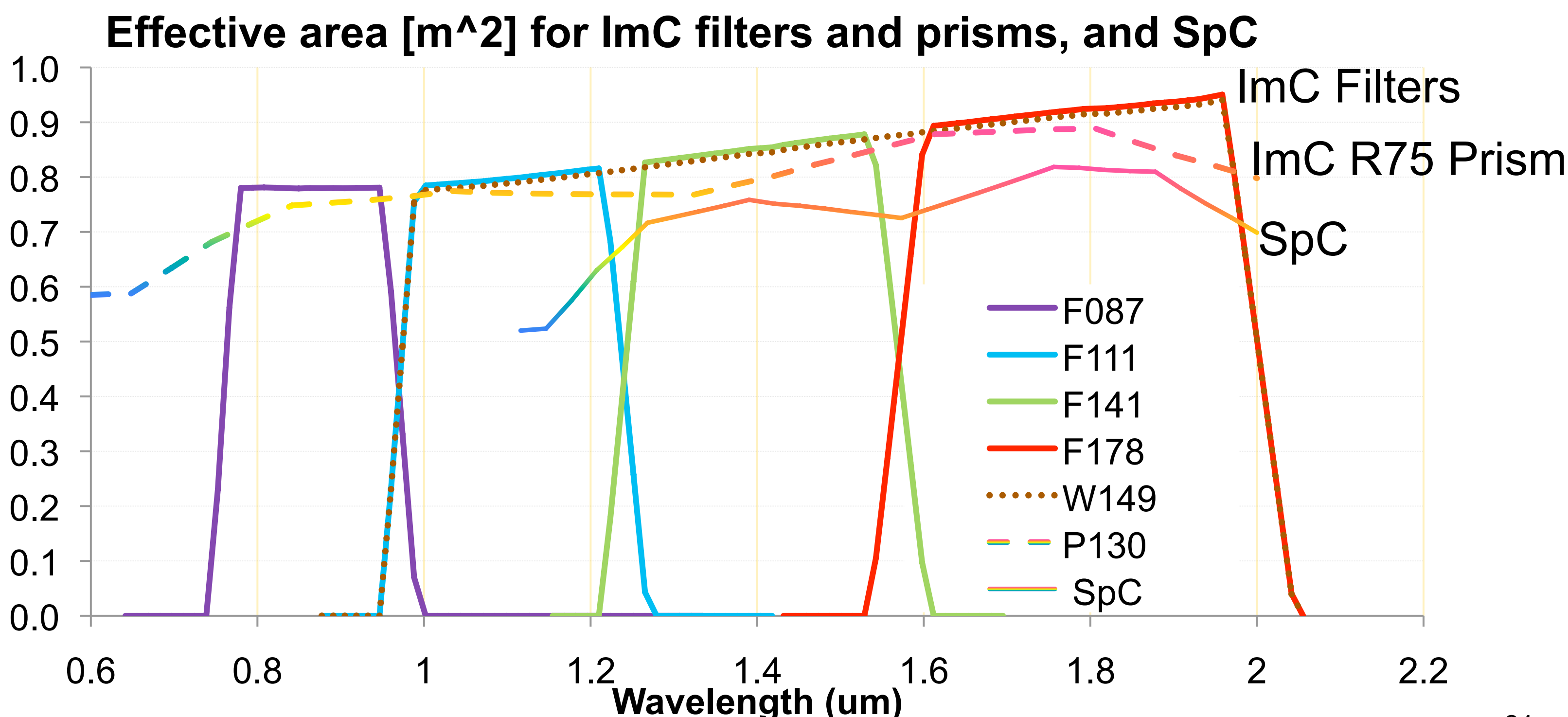
HST [all instruments]

JWST [all instruments]

Throughput

- Plot shows effective areas for each instrument configuration: Each of 2 identical Spectrometer channels (SpCs), and each element in the Imager filter wheel, per filter table below.

name	min	max	center	type
F087	0.760	0.970	0.865	ImC filter
F111	0.970	1.240	1.105	ImC filter
F141	1.240	1.570	1.405	ImC filter
F178	1.570	2.000	1.785	ImC filter
W149	0.970	2.000	1.485	ImC filter
P130	0.6	2	1.3	R75 ImC prism
SpC	1.114	2	1.557	R200 SpC prism



One Page Flow Down - Purpose

- Substantiate that the IDRM can achieve the science objectives mandated by NWNH.
- Trace WFIRST's Science Objectives to a set of derived Survey and Data Set requirements, and flow these down to a responsive Interim Observatory Design and Ops Concept
- IDRM is an **Interim** Reference Design
  - o Design implementation is not prescriptive and is preliminary
  - o Multiple designs can meet the science requirements

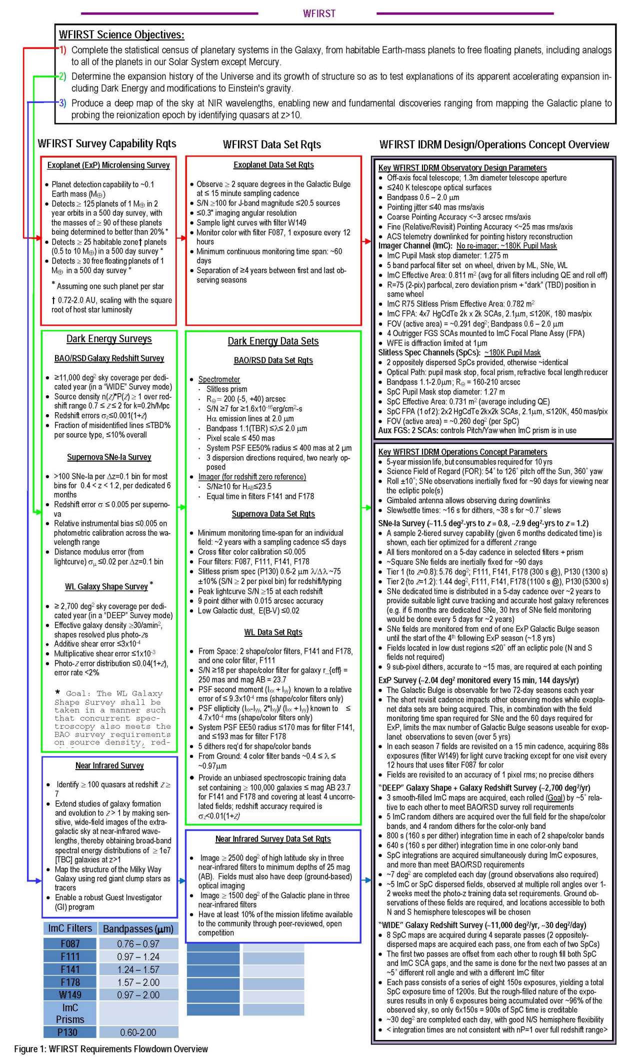
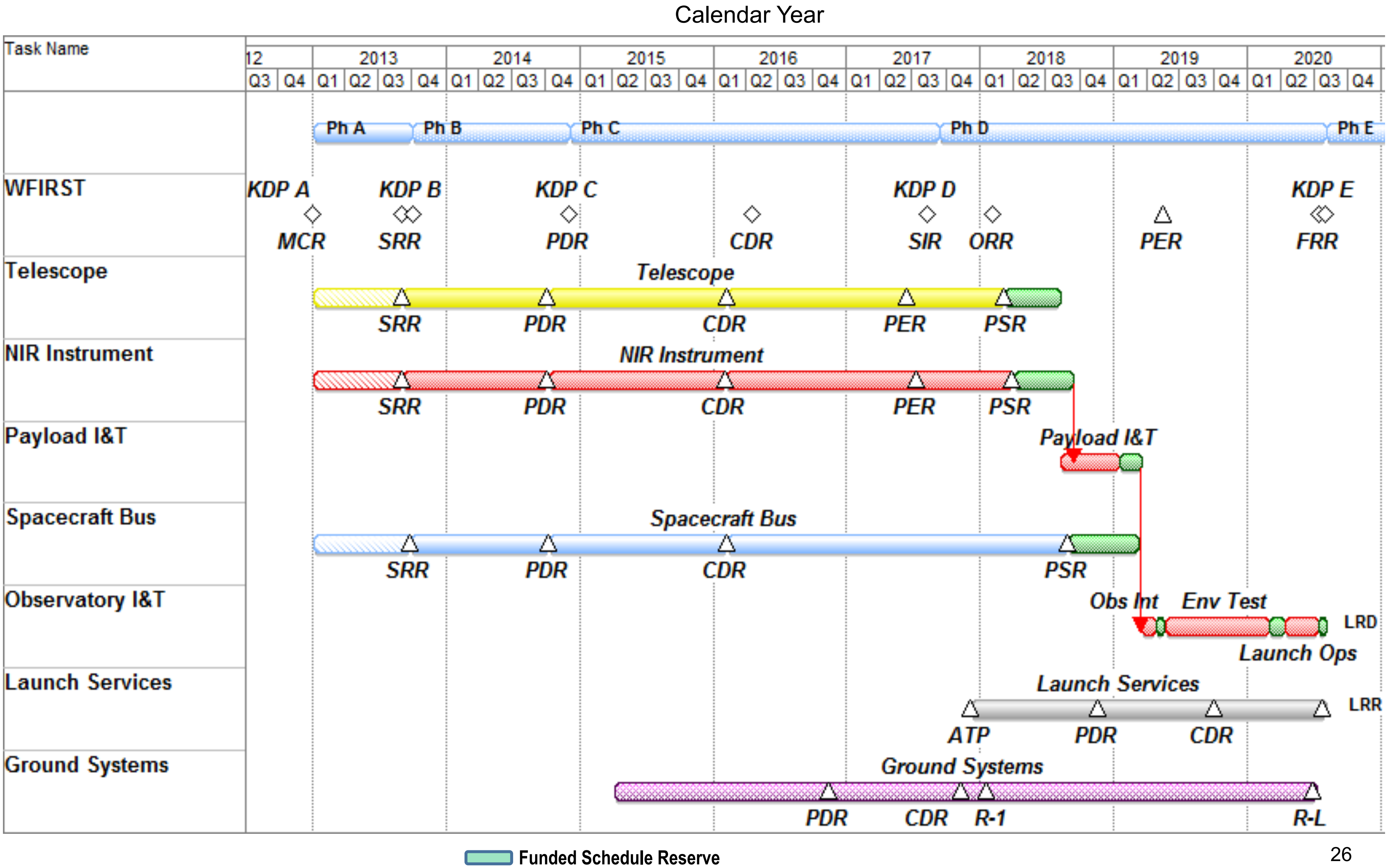


Figure 1: WFIRST Requirements Flowdown Overview

1-pager_v6

WFIRST IDRM Schedule Estimate



Summary

- WFIRST has broad science capabilities
  - The most pressing fields in astrophysics all require a near infrared survey capability. WFIRST can satisfy all of the observational requirements . Our biggest problem is dividing up the observing time: proof of its scientific viability
- WFIRST is technologically mature
  - We could start development as soon as funding is available
- WFIRST is cost effective
  - $1.6B is a lot of money, but this cost estimate has been independently verified with the latest methodology and is credible
  - Given that WFIRST is the decadal #1 priority, and the broad science return in multiple areas, we believe that WFIRST is a bargain

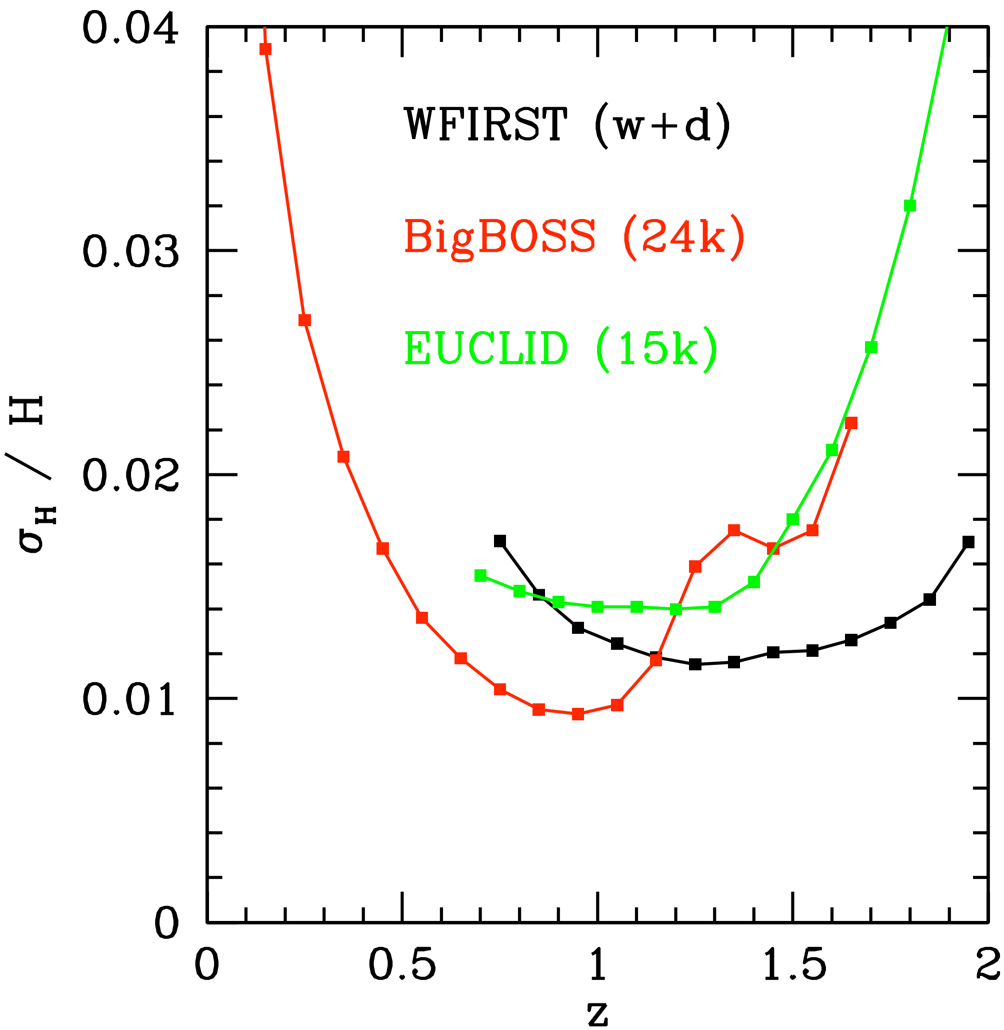
- *WFIRST can move astrophysics forward into new frontiers of knowledge, and do it in less than a decade*

Backup Charts

WFIRST Interim Design Reference Mission Cost Estimate

- NWNH Astro 2010 ICE for the WFIRST life cycle cost estimate (LCCE) using JDEM Omega as the basis of estimate was $1.6B
- WFIRST IDRM incorporates only minor optimizations of JDEM Omega
  - These optimizations were made with cost control in mind
- WFIRST Project is in the process of developing the LCCE for the IDRM using multiple estimating techniques (grassroots, modeled, analogy)
- This LCCE is based on the IDRM development schedule shown on the previous page. This schedule is almost identical to the submitted JDEM Omega schedule, which received favorable review by NWNH.
  - Since only minor optimizations have been made to JDEM Omega to arrive at the WFIRST IDRM, it is highly likely that this schedule will remain at the 70% confidence level.
- In parallel with the Project's cost estimation efforts, an ICE of the IDRM will be performed this summer.
  - Complete early September
  - Cost increases based on increased schedule duration are unlikely because of IDRM schedule validation against NWNH ICE WFIRST 70% schedule assessment

Example Dark Energy Performance



DETF FoM Venn diagrams

Conservativ
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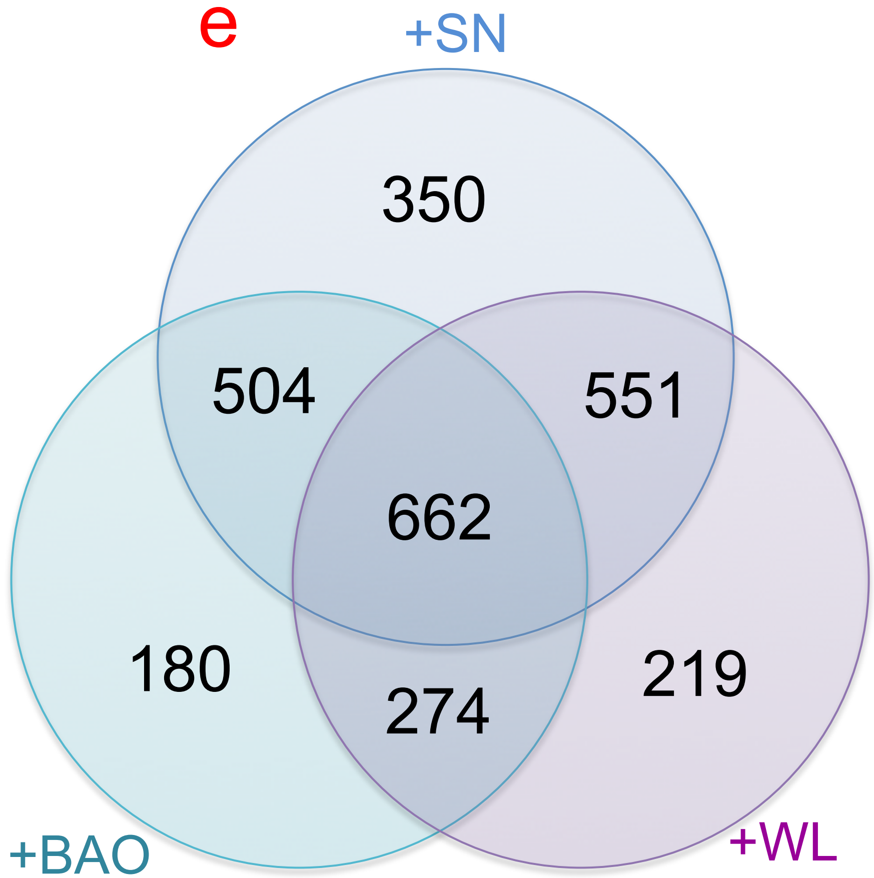
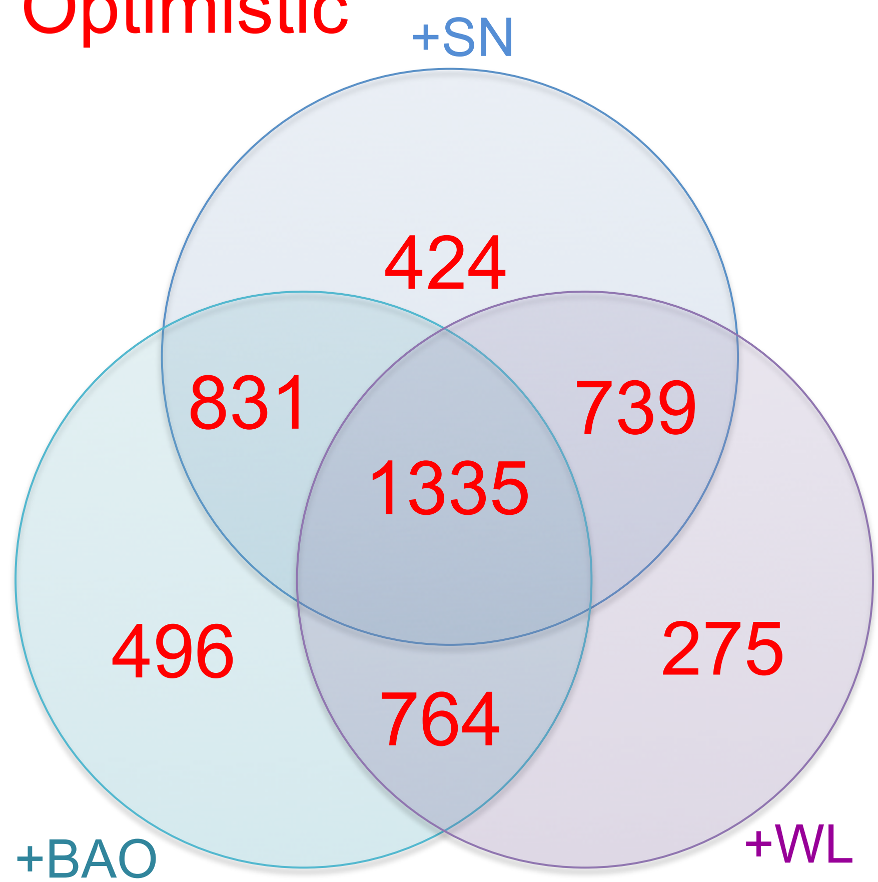


Planck+StageIII priors
Weak Lensing 12months wide
BAO 12 months deep,
12 months wide
Supernova 6 months slitless

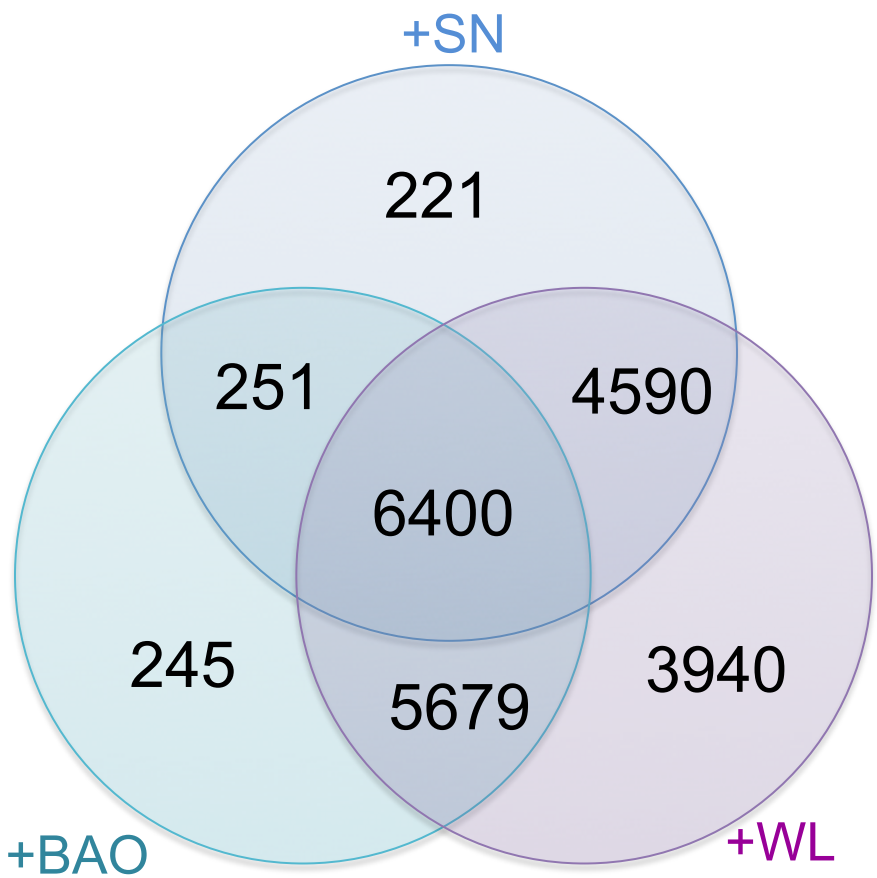
Optimistic

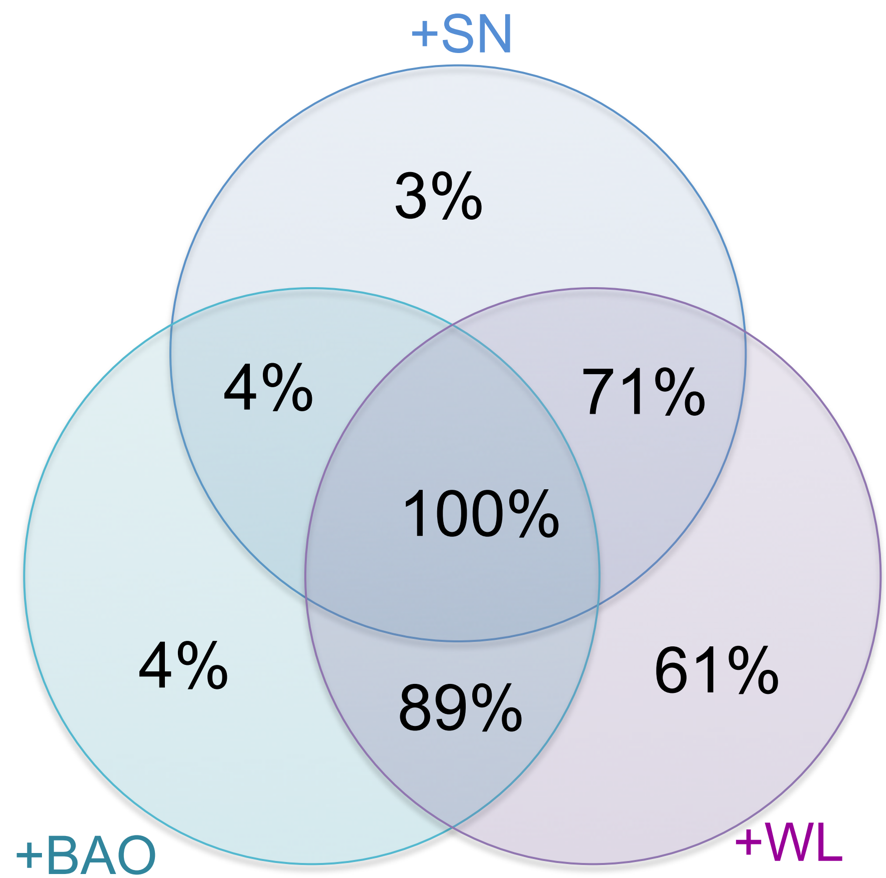


Planck+StageIII priors
Weak Lensing
BAO+RSD
Supernova

Conservative γ figure of merit = $1/\sigma(\gamma)$

- Stage III baseline 221





GI Studies of Nearby Young Stellar Clusters

- WFIRST can survey nearby clusters to a depth that crosses the brown dwarf/planet mass boundary at 10 – 15 M(Jupiter)
- Important for understanding brown dwarf formation mechanisms
- Will probe recent results indicating that free-floating planets are very common
- Target clusters are generally out of the Galactic Plane; WFIRST can survey to depths and areas not achievable from the ground. In particular, large areas must be surveyed to get adequate statistics because mass segregation will result in wide distribution of the low-mass targets

Sample program (based on UKIDDS survey, but much deeper):

- 10 clusters, 1400 deg^2 total, 3 NIR spectral bands, 1 band repeated for proper motion
- 6 min. per pointing implies a total time of ~2000 hr.
- Reaches depth of K = 23.4 (5σ; UKIDDS reaches 18.7)
- Proper motions determined to 7 mas (RMS) to confirm cluster membership
- Reaches ~ 5 M(Jupiter) for 6 young clusters + Pleiades.

Reaches 10 – 15 M(Jupiter) for Hyades, Coma Ber, and Praesepe (all ~ 600 Myr)

GI Studies of Galaxies in the Nearby Volume

• Follow-on to many successful HST/Spitzer Treasury/Legacy Programs

• First wide-field + high resolution studies of resolved nearby stellar populations

– 1 hr. exposure with WFIRST reaches MSTO to 0.4 Mpc, RC/HB to 2.5 Mpc, TRGB to 10 Mpc

– 1 month GU program can map ~100 galaxies over their full extent in 3 filters (incl. LMC/SMC, M31/M33, etc.)

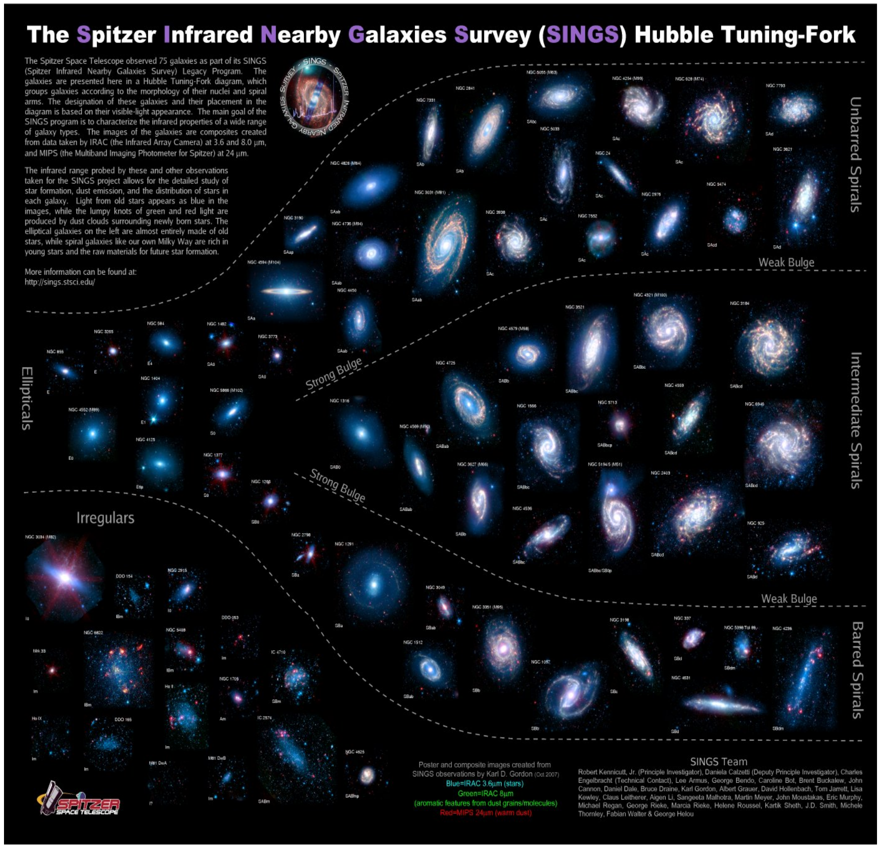
GI Studies of Galaxies in the Nearby Volume

Science:

Cover all structural components in a homogeneous way (thin disk, thick disk, bar, bulge, halo, warp, stellar streams, globular clusters, etc.)

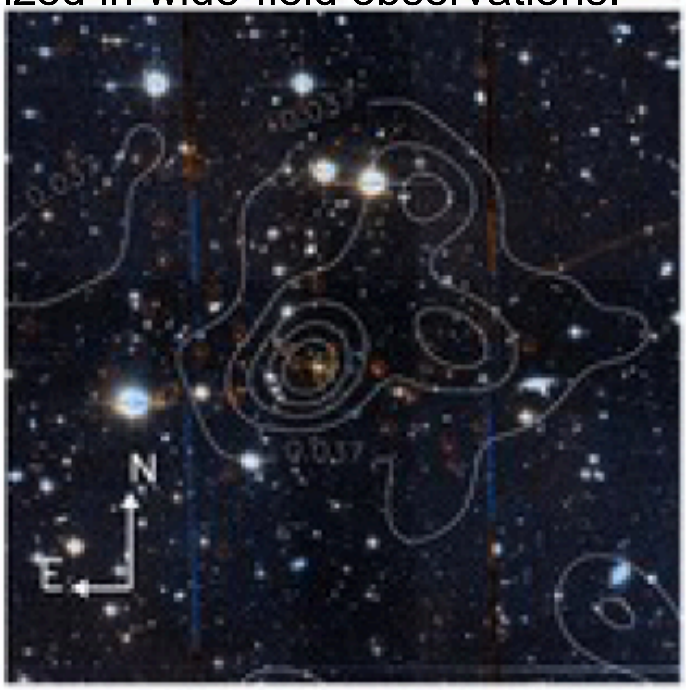
Use substructure + streams in halos to constrain hierarchical formation models
Study topics across a wide range of subject areas (stellar astrophysics, mass function, star formation, star formation histories, galaxy structure, interactions, accretion, galaxy formation, interstellar
medium, globular cluster populations, etc.)

Complementarity to LSST at higher resolution (0.2” vs. 0.7”); blending limits LSST to < 1 Mpc
1 hr. WFIRST reaches comparable depth to the 10 yr. LSST survey

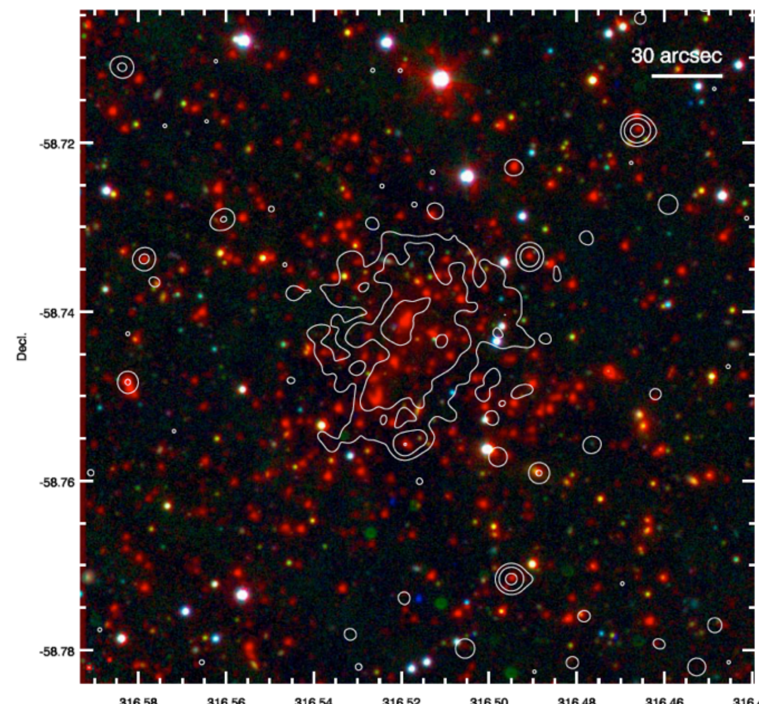


GI Studies of Galaxy Clusters

- Discovery of high-redshift clusters. In particular, the number of massive (~1e15 Msun), high-redshift (z>1) galaxy clusters tests structure formation models. Recent results are revealing tension with the non-Gaussian density fluctuations implied by “vanilla” L-CDM models.
- Deep follow-up GI programs could provide robust weak lensing mass measurements: mass maps, including clumps and filaments, to the virial radius and beyond. Test predictions of cosmological structure formation models. Mass-sheet systematics are minimized in wide-field observations.



Jee et al. (2011): weak-lensing maps of 22 z>1 HST clusters (F775W and F850LP)

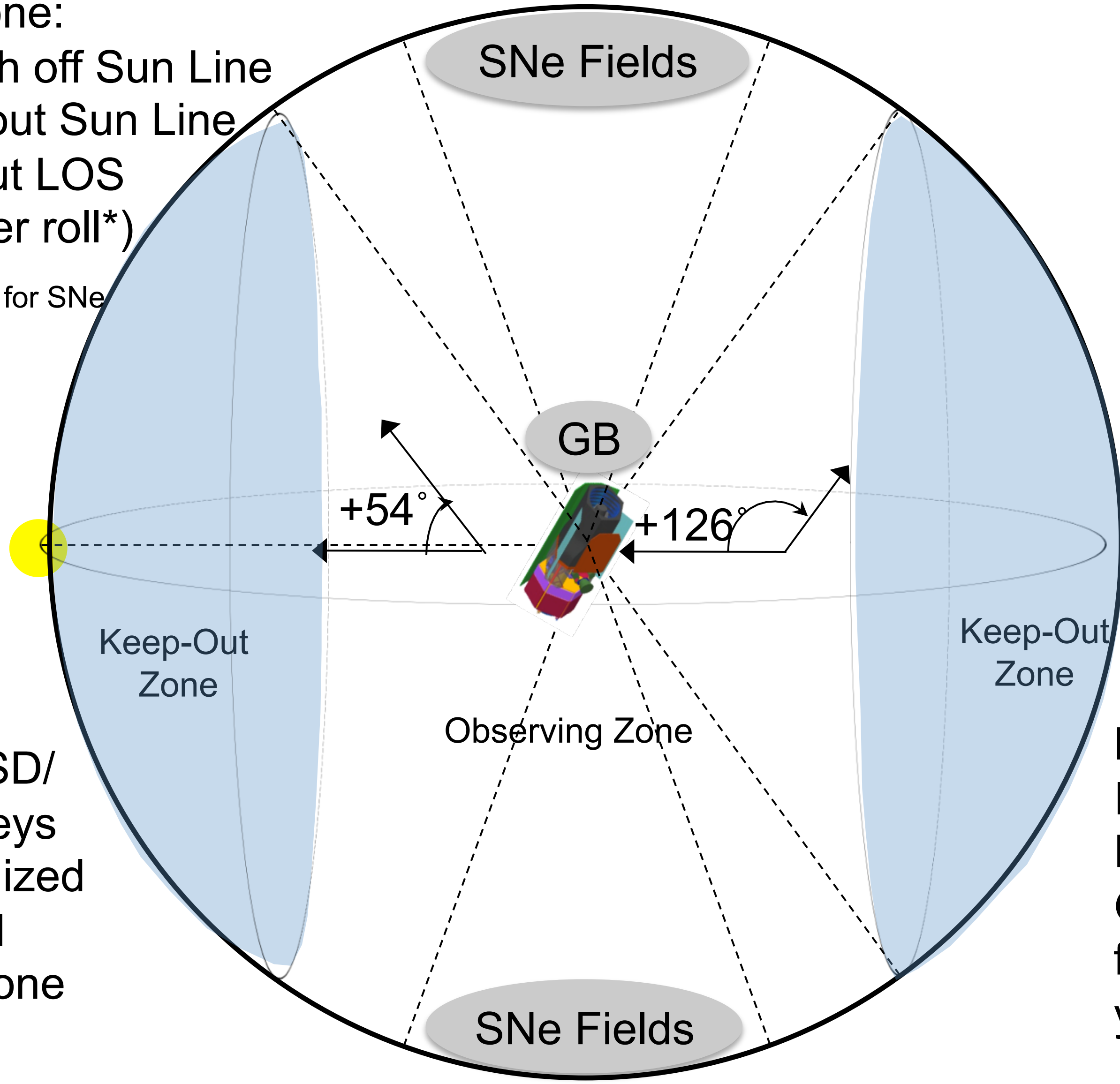


Foley et al. (2011): most massive z>1 cluster known currently (found by SPT)

WFIRST's Central Line of Sight (LOS) Field of Regard (FOR)

Observing Zone:
54°-126° Pitch off Sun Line
360° Yaw about Sun Line
±10° roll about LOS
(off max power roll*)

* Larger roll allowed for SNe



SNe Inertially Fixed Fields must be within 20° of one of the Ecliptic Poles, and can be rotated every ~90 days

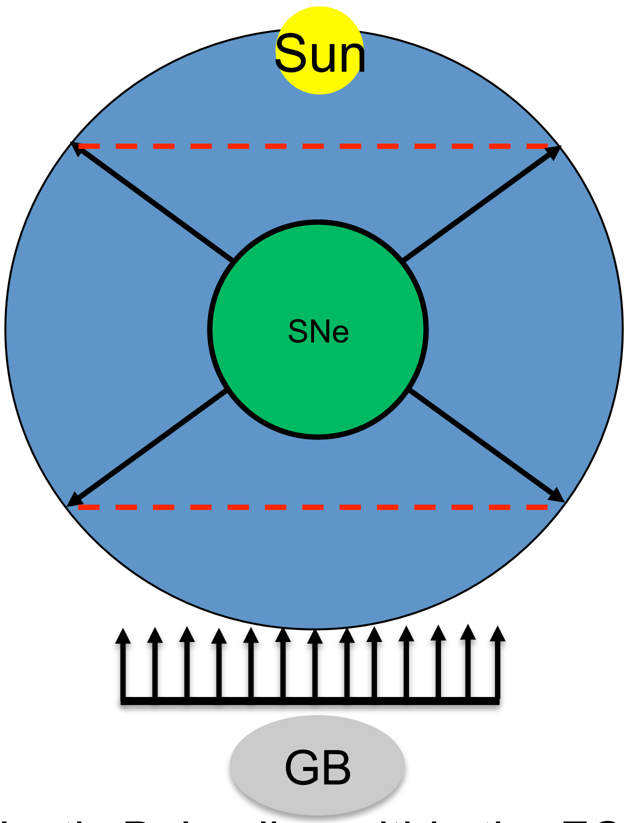
WL/ BAO-RSD/ GI/ GP Surveys can be optimized within the full Observing Zone

ExP can observe Inertially Fixed Fields in the Galactic Bulge (GB) for 72 days twice a year

WFIRST's FOR and its Motion

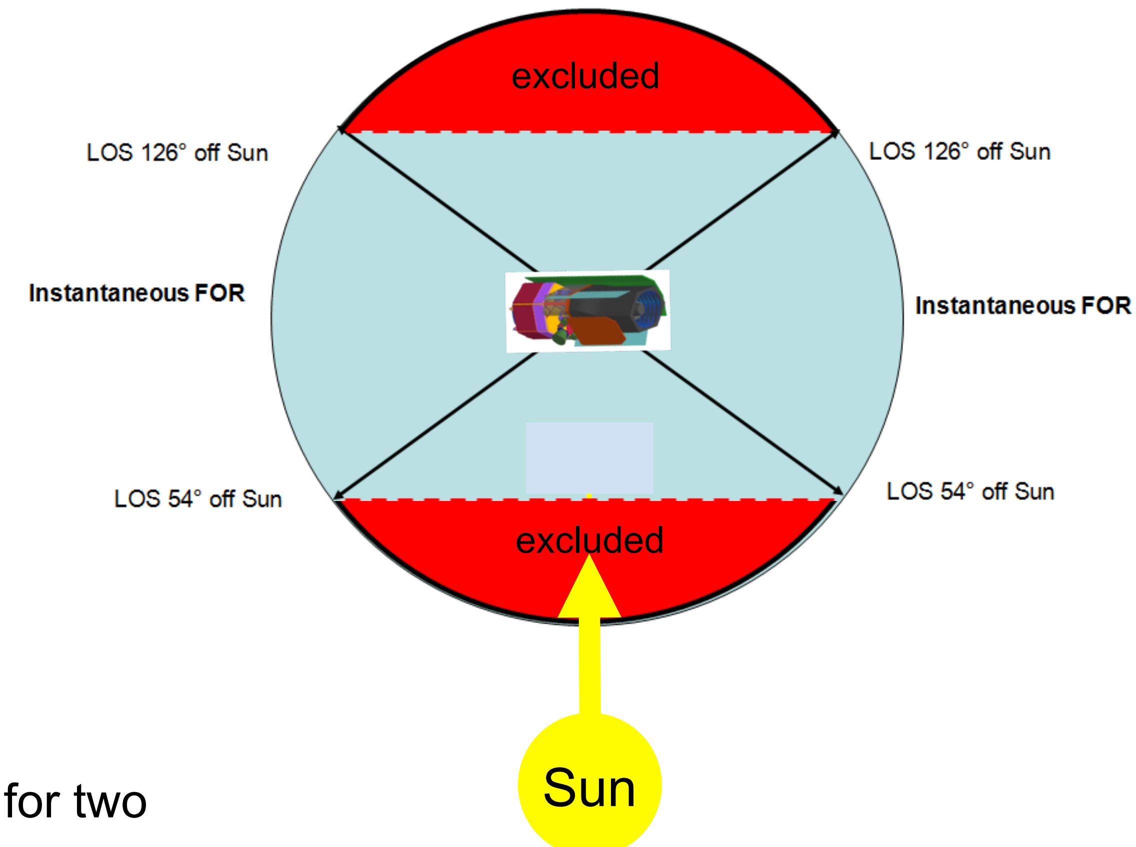
<Views are looking normal to the ecliptic plane>

Orbital motion covers full sky twice/year; SNe fields near ecliptic poles always accessible



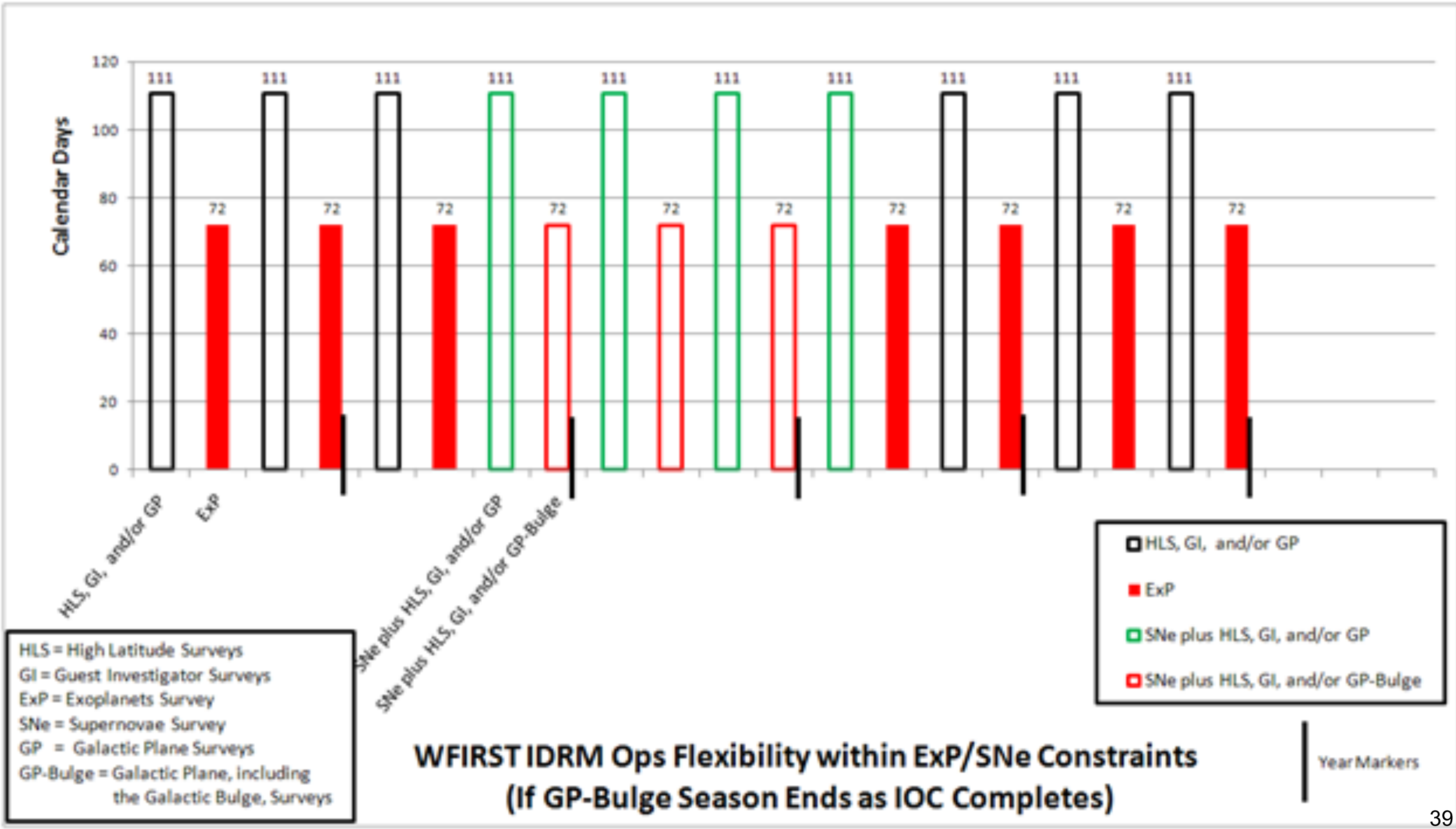
Galactic Bulge lies within the FOR for two 72-day seasons each year

Instantaneous FOR is a 360° band with a width of 72° driven by Sun angles



Capabilities Yield Flexible Ops Concept

WFIRST Exhibits Excellent Observing Mode Flexibility in Sample Ops Concept Meeting ExP and SNe Field Monitoring Rqts



WFIRST IDRM vs JDEM Omega

Engineering Design Changes (1 of 2)

Design Change IDRM vs JDEM Omega	**Pros**	**Cons**
1.3m unobscured (JDEM was 1.5m obscured)	Same sensitivity at smaller diameter primary mirror	Alignment tolerance tighter, but achievable
	More light in the core of the image Better weak lensing signal	Payload wider Tighter fairing accommodation, but achievable
	Larger total field of view Larger imager area Same spectrometer area	
	Design margins are improved Aberration residuals are smaller compared to the budget	
	Stray light rejection improved Capability to point closer to sun	
	Roughly equivalent cost	

WFIRST IDRM vs JDEM Omega

Engineering Design Changes (2 of 2)

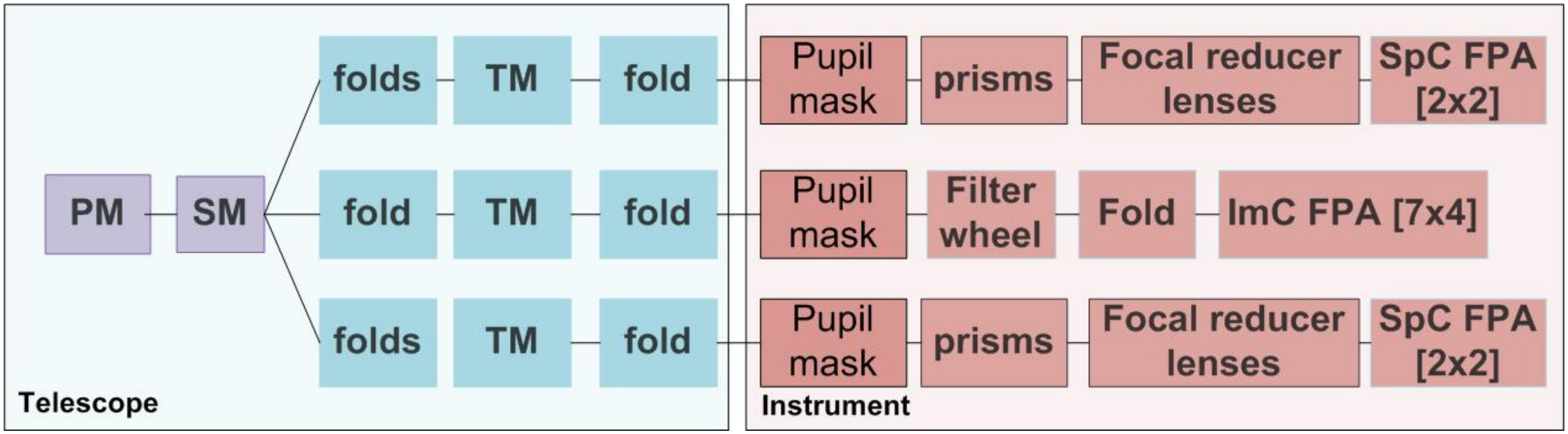
Design Change IDRM vs JDEM Omega	Pros	Cons
Shifted 4 SCAs from spectrometer channel to imager channel	1/6 increase in survey speed for all imaging science	Spectrometer gets faster Focus budget gets tighter, but achievable
	BAO science not significantly impacted	
Changed from hybrid (afocal spectrometer, focal imager) to all focal by putting powered prisms in spectrometer channel	Allows removal of 4-asphere collimators in telescope feed to spectrometer channels Mass and volume savings	Flight qualification optics glass necessary Thought to be low risk for WFIRST spectral band pass at L2 environment
	Telescope optics become simpler 3 similar tertiaries 3 similar focal interfaces	

WFIRST High-z Quasar Return Estimate/Comparison

Survey	Area (deg^2)	Depth (5-sigma, AB)	z>7 QSO's	z>10 QSO's
UKIDSS-LAS	4000	Ks=20.3	8	-
VISTA-VHS	20,000	H=20.6	40	-
VISTA-VIKING	1500	H=21.5	11	-
VISTA-VIDEO	12	H=24.0	1	-
Euclid, wide (5 yr.)	15,000	H=24.0	1406	23
WFIRST, deep (1 yr.)	2700	F3=25.9	904	17
WFIRST, wide (1 yr.)	(4730)	F3 = 25.3-25.5	1148	21

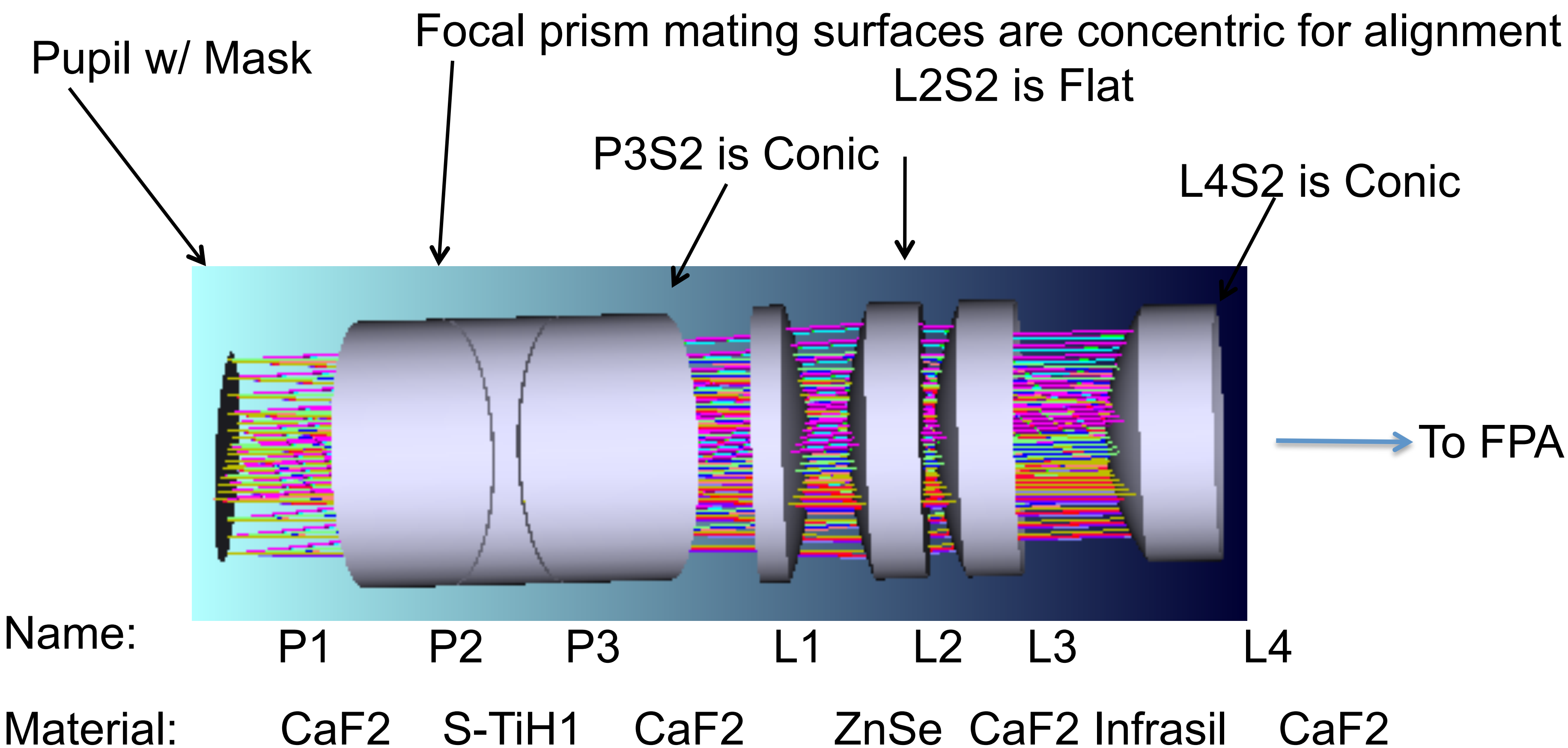
Returns of quasar's at z>7 and z>10 for multiple surveys. Note: For the WFIRST wide survey, we only consider the 4730 deg^2 (out of 11,000 deg^2 total for a 1 yr wide survey) that are imaged with at least two exposures in both filters.

Optical element description

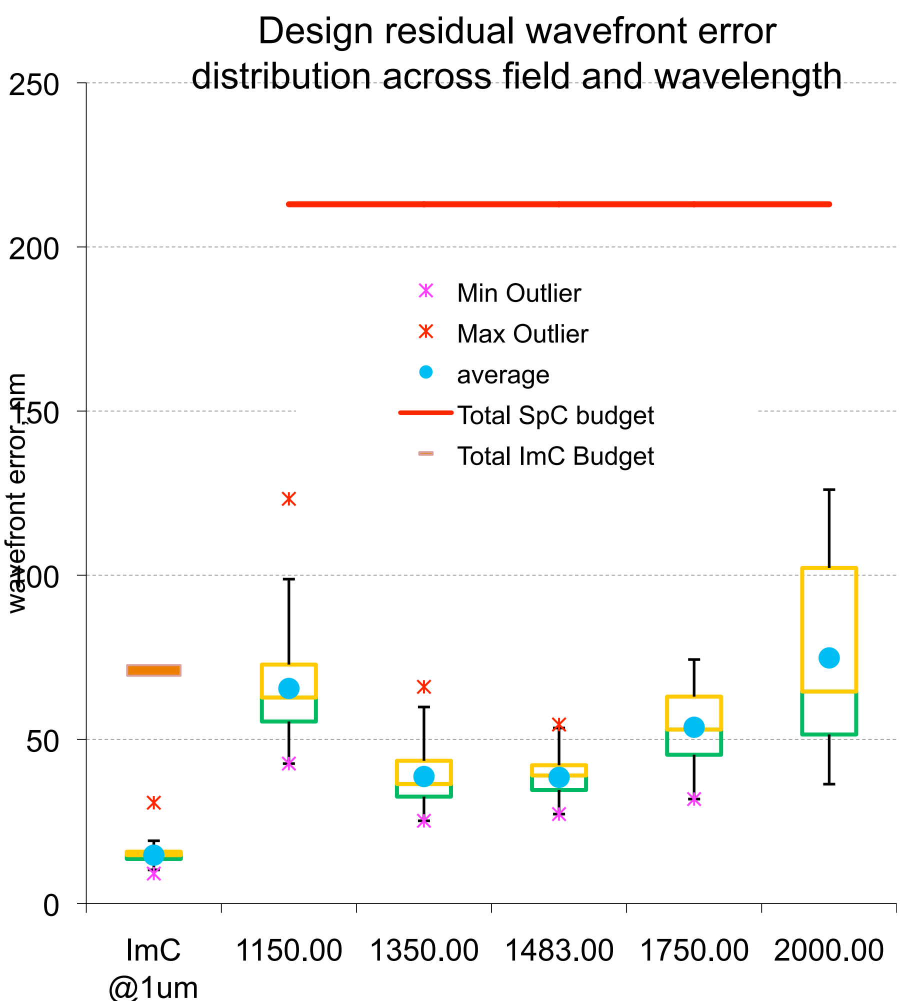


- Telescope is 3 channel, 1.3m unobscured three mirror anastigmat
- Interfaces are each f/16 focal, well corrected pupils; readily testable, well understood
  - Mechanical, thermal, optical interface all at pupils

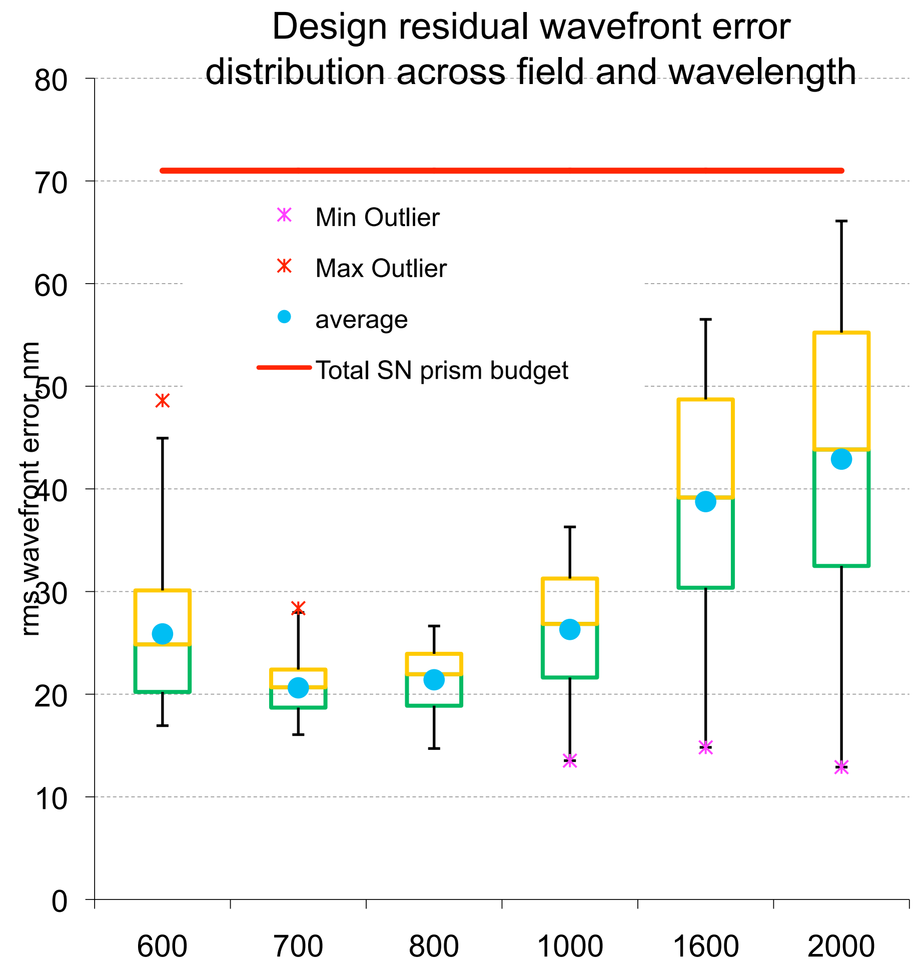
SpC detail: 14 surfaces, 11 spheres, 2 conic, 1 flat



Robust optical performance margins

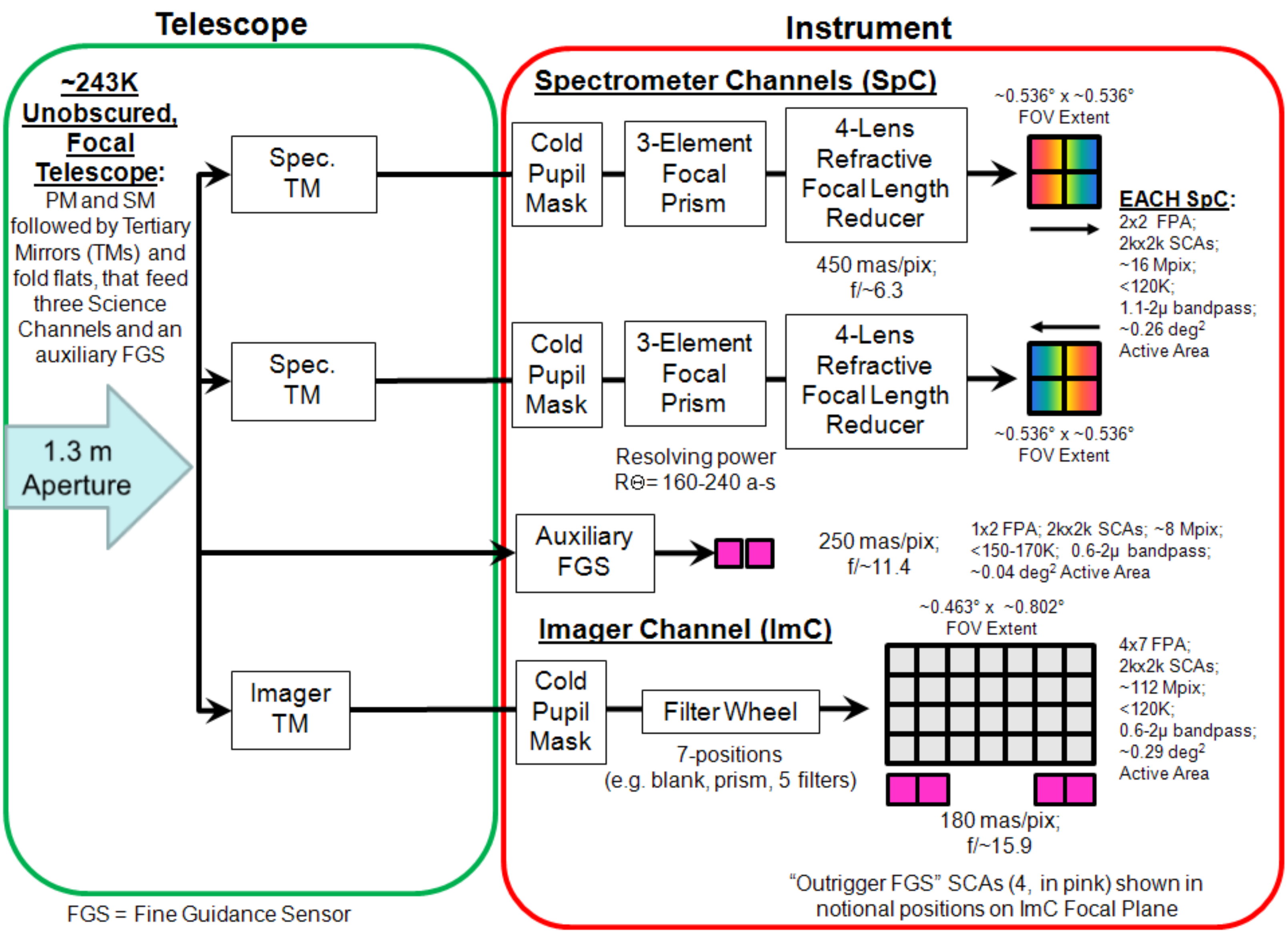


Spectrometer wavefront error distribution at wavelength shown (unless titled imC for Imaging Channel)

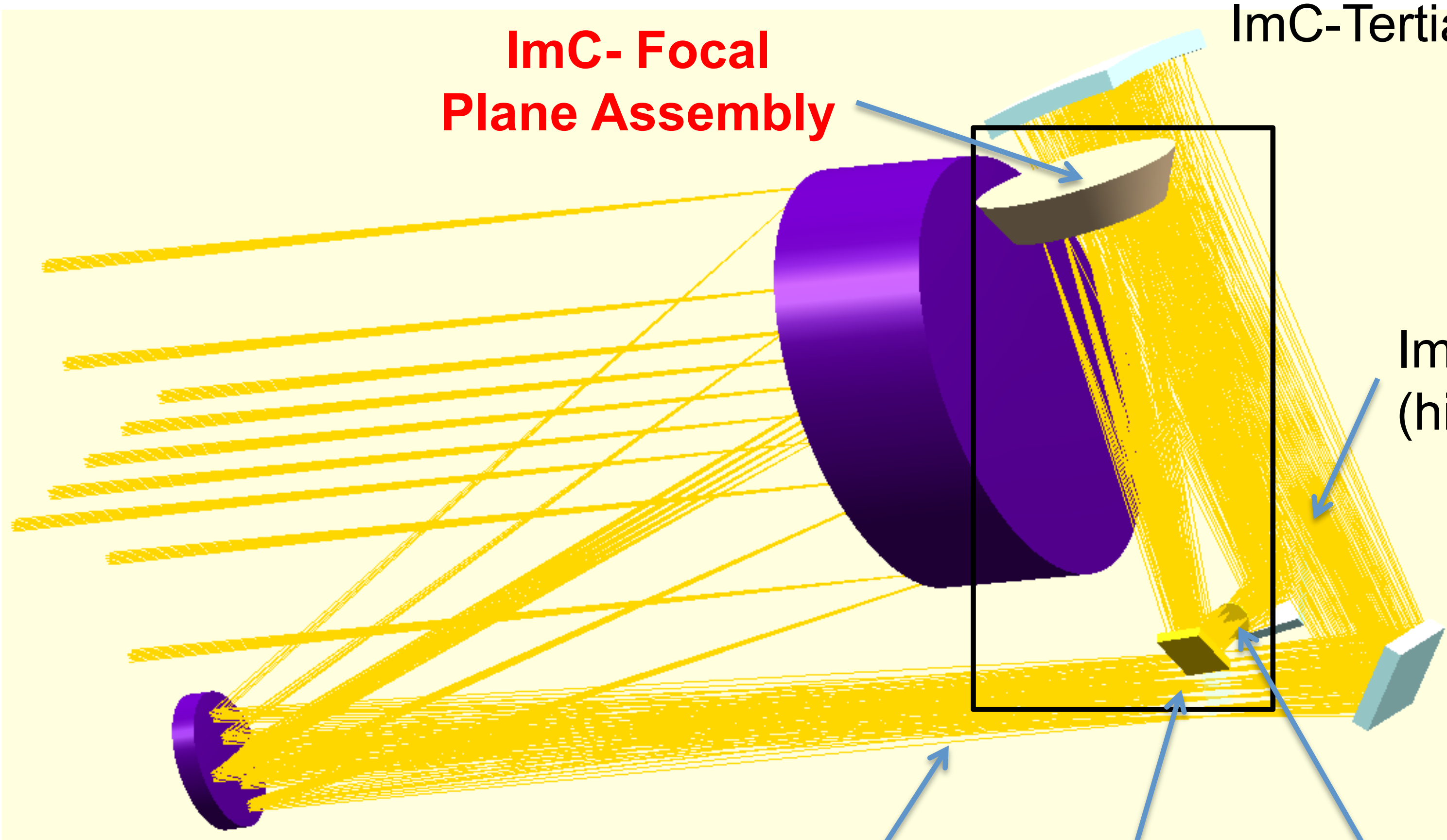


SN prism wavefront error distribution

WFIRST IDRM
Payload Optics Block Diagram

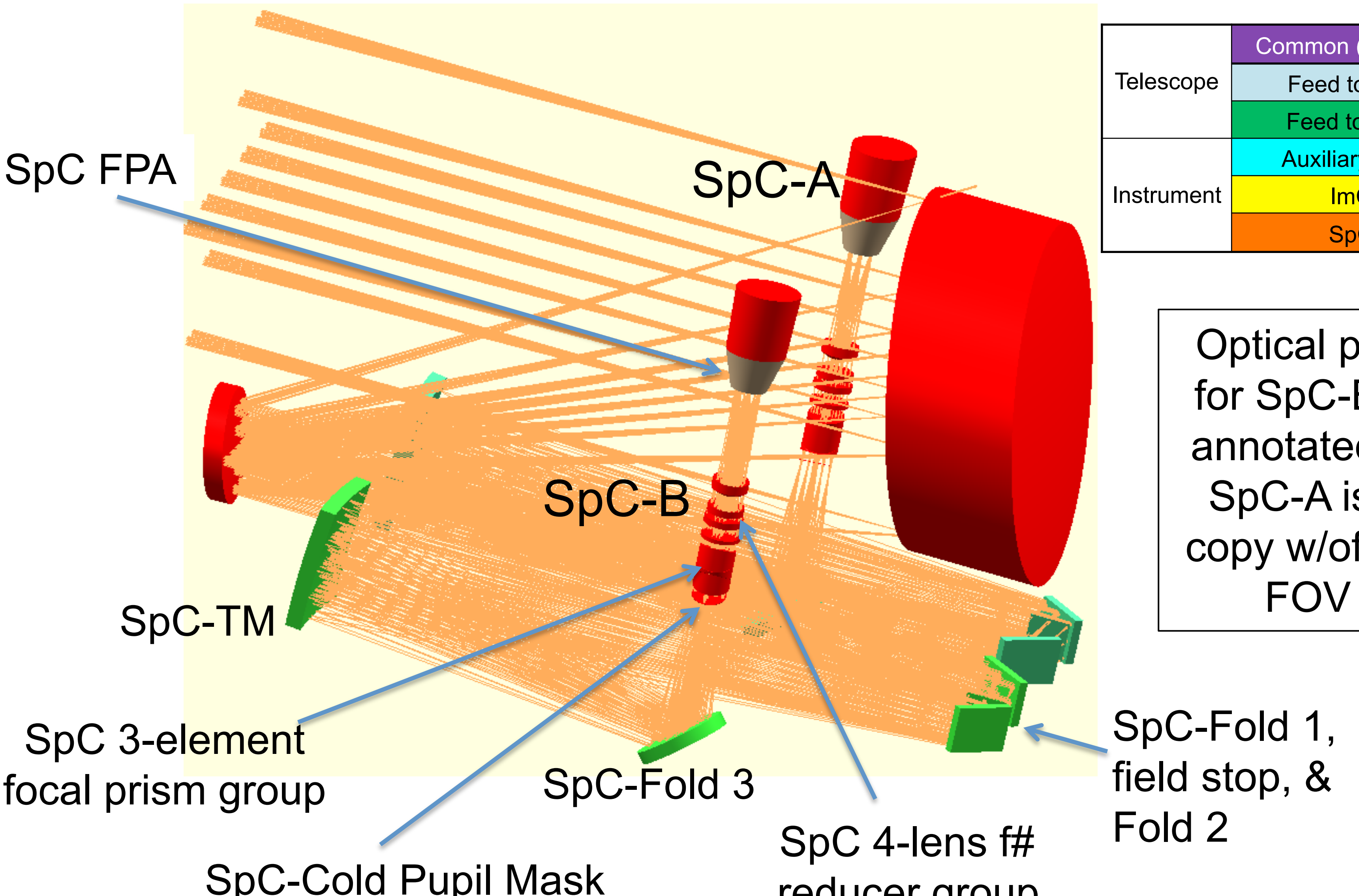


IDRM ImC – Ray trace



Telescope	Common (PM/SM)
	Feed to ImC
	Feed to SpC
Instrument	Auxiliary FGS
	ImC
	SpC

IDRM SpC – Ray trace



Telescope	Common (PM/SM)
	Feed to ImC
	Feed to SpC
Instrument	Auxiliary FGS
	ImC
	SpC

Optical path for SpC-B is annotated ... SpC-A is a copy w/offset FOV