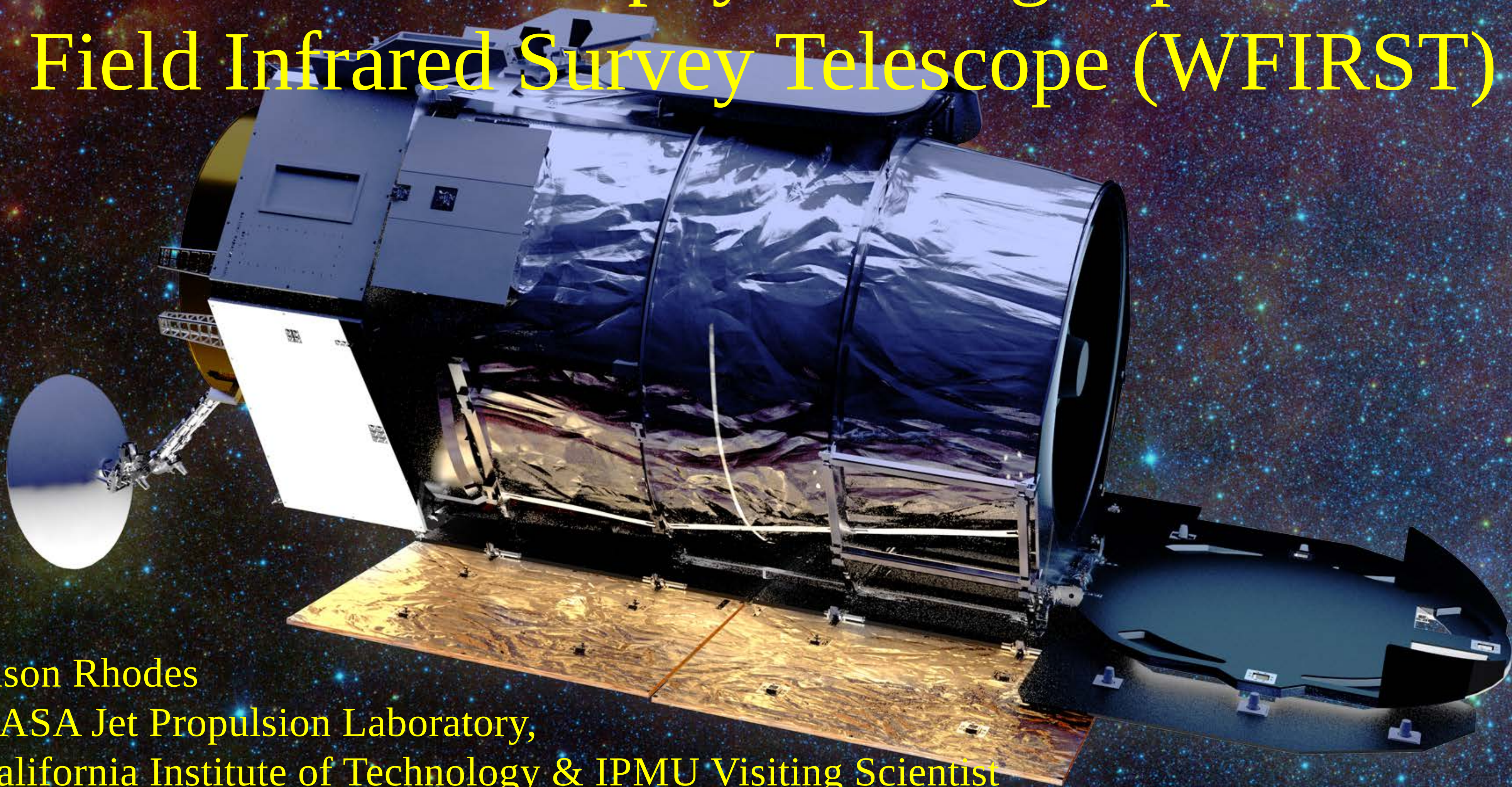
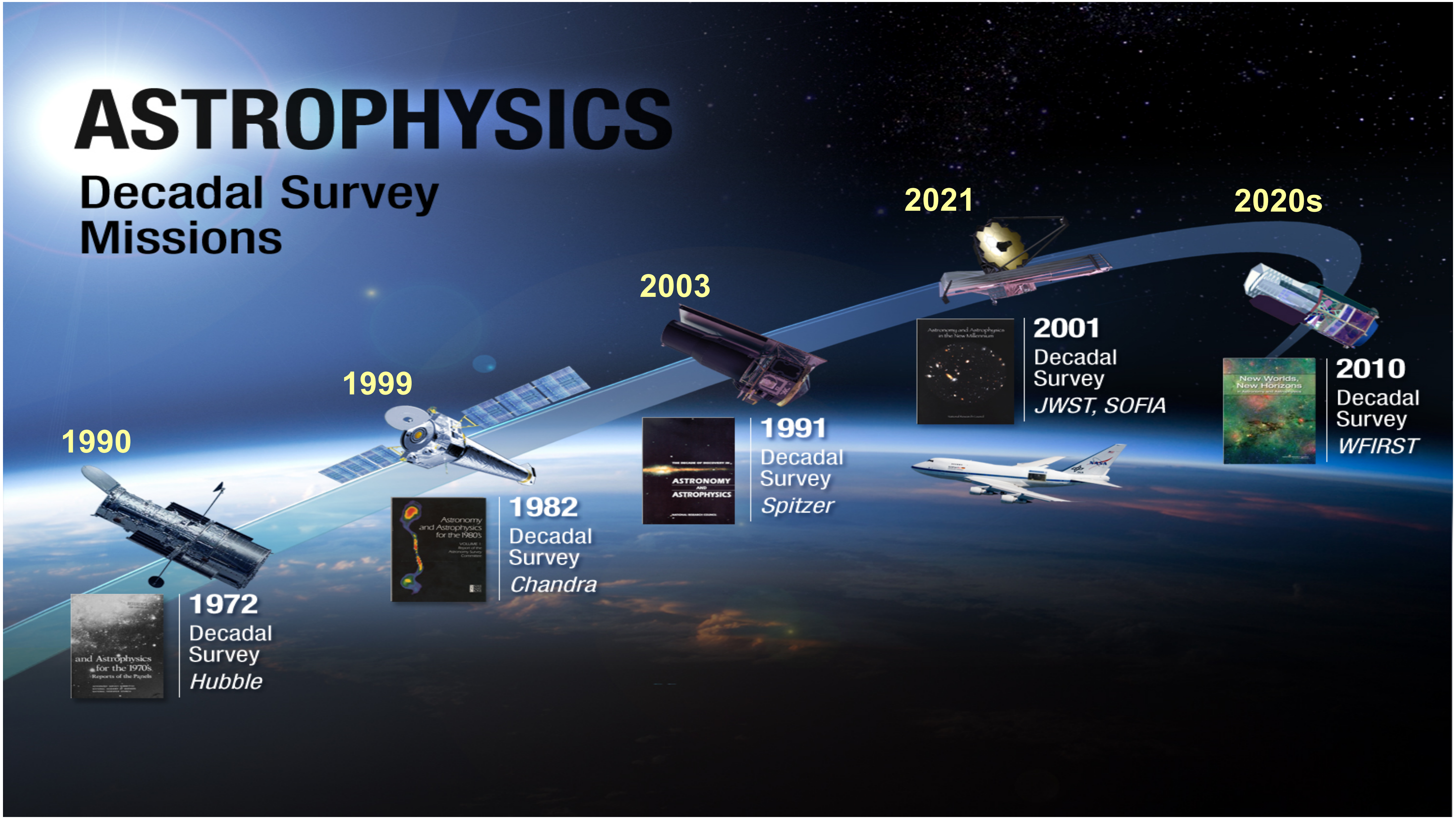
NASA's Next Astrophysics Flagship: The Wide Field Infrared Survey Telescope (WFIRST)



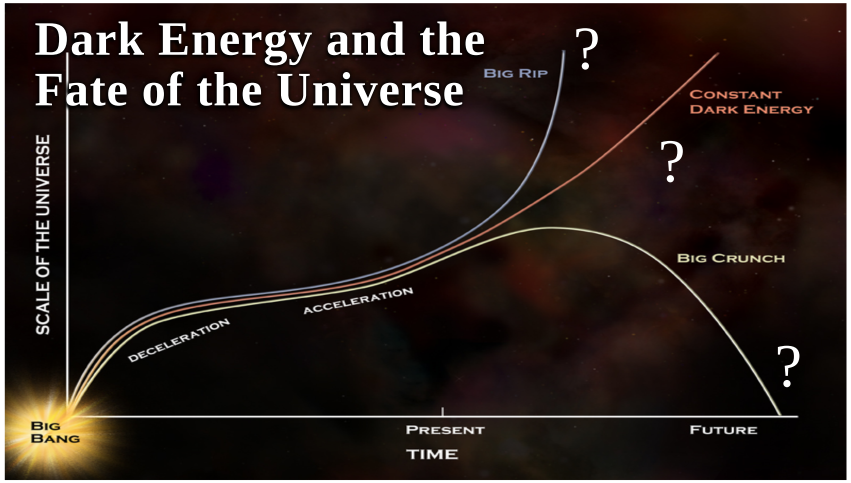
Jason Rhodes
NASA Jet Propulsion Laboratory,
California Institute of Technology & IPMU Visiting Scientist
September, 25 2019

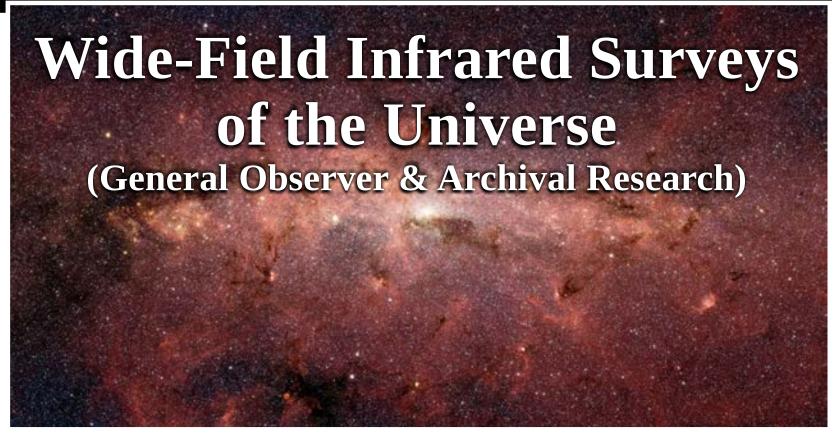
#NASAWFIRST

Jet Propulsion Laboratory
California Institute of Technology

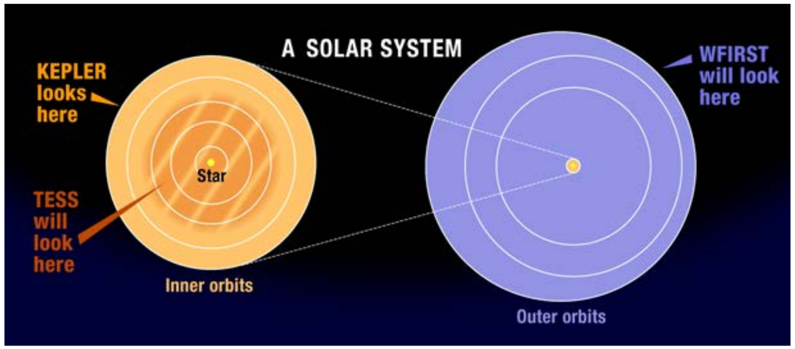

ASTROPHYSICS
Decadal Survey Missions
1990
1972 Decadal Survey
Hubble
1999
1982 Decadal Survey
Chandra
2003
1991 Decadal Survey
Spitzer
2021
2001 Decadal Survey
JWST, SOFIA
2020s
2010 Decadal Survey
WFIRST
and Astrophysics for the 1970's
Astronomy and Astrophysics for the 1980's
ASTRONOMY AND ASTROPHYSICS
New Worlds, New Horizons

Guidance from NWNH



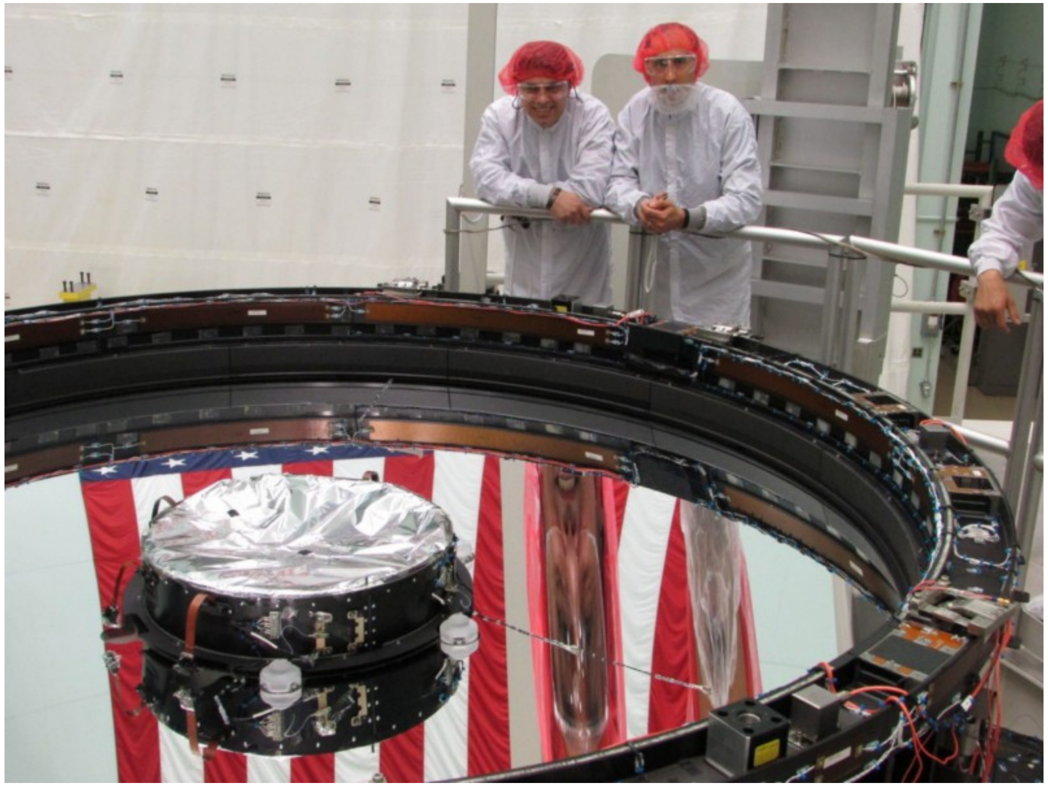


The full distribution of planets around stars



A Bigger WFIRST

- Uses repurposed 2.4 m telescope from the another government agency
- Three science pillars: dark energy, exoplanets, infrared surveys
- Science done with Wide Field Instrument (WFI), with 18 H4RG detectors

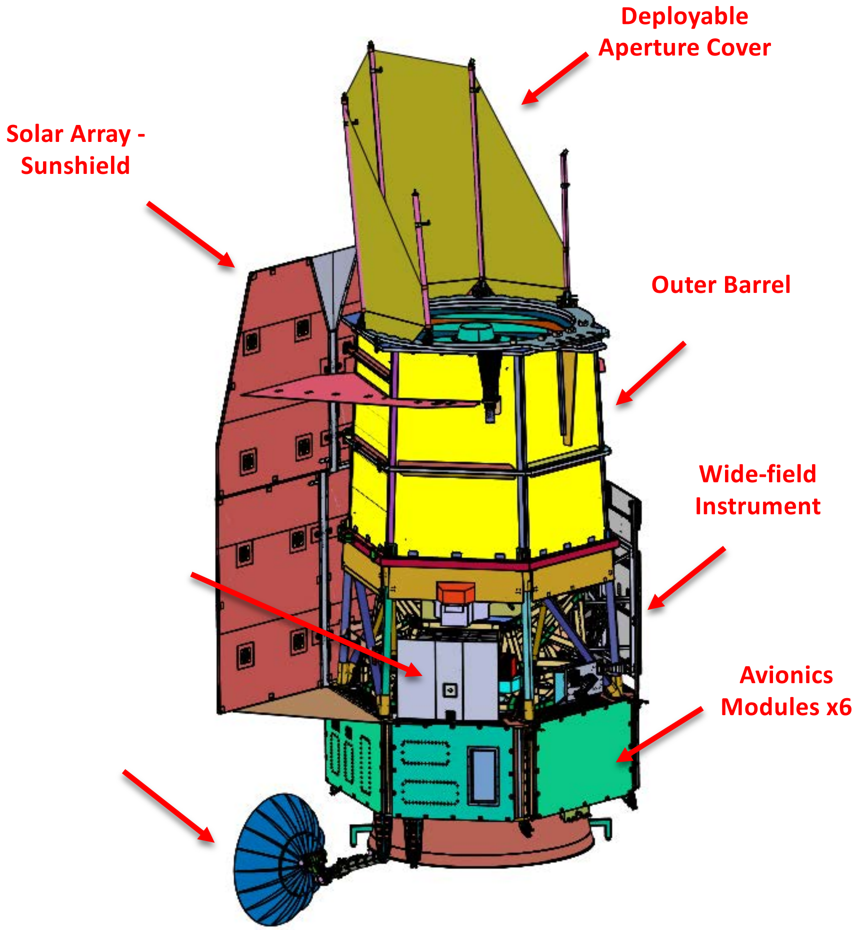


Harris Corporation / TJT Photography

- Coronagraph Instrument (CGI) is a tech demo that will be ~1000x better than previous coronagraphs
- Designed to be Starshade ready
- Designed to be serviceable
- 5 year primary mission at L2
- 10+ year extended mission possible

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

Top-level Observatory Overview



Key Features

Telescope: 2.4m aperture

Instruments:

Wide Field Imager / Slitless Spectrometer

Internal Coronagraph

Data Downlink: 275 Mbps

Data Volume: 11 Tb/day

Orbit: Sun-Earth L2

Launch Vehicle: 3 options

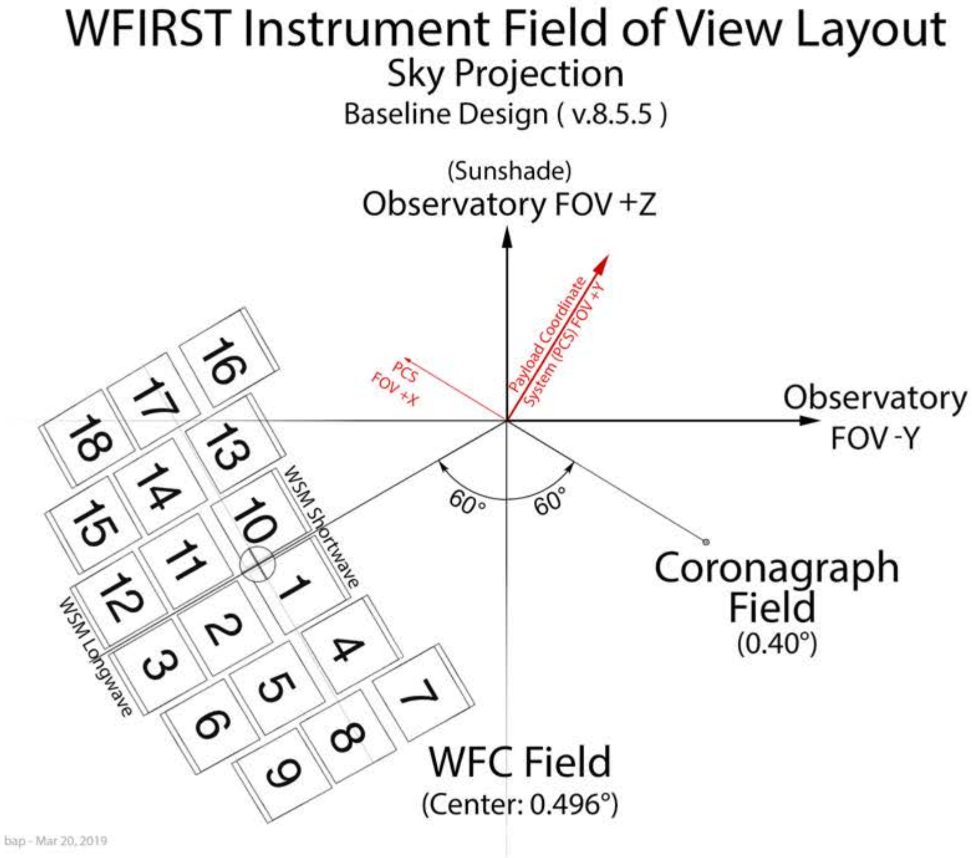
Mission Duration: 5 yr, 10yr goal

Serviceability: Observatory designed to be robotically serviceable

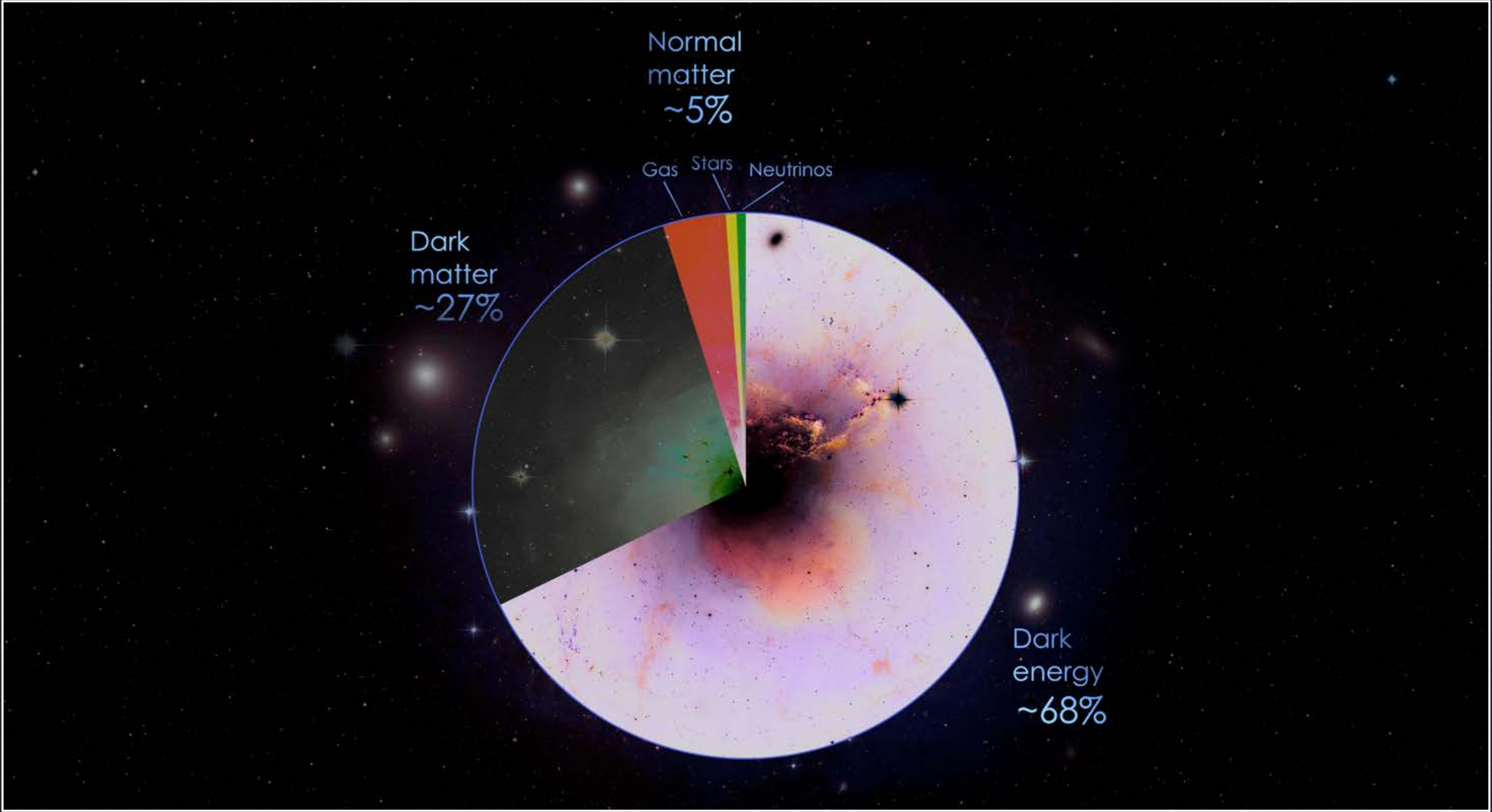
Starshade compatible

Wide Field Instrument

- 0.25 square degree FOV
- 18 4k by 4k NIR detectors
- 0.1” pixels
- Heritage from HST, JWST, Euclid
- ‘100 Hubbles for the 2020s’ : https://arxiv.org/abs/1902.05569



The Universe as a Pie Chart

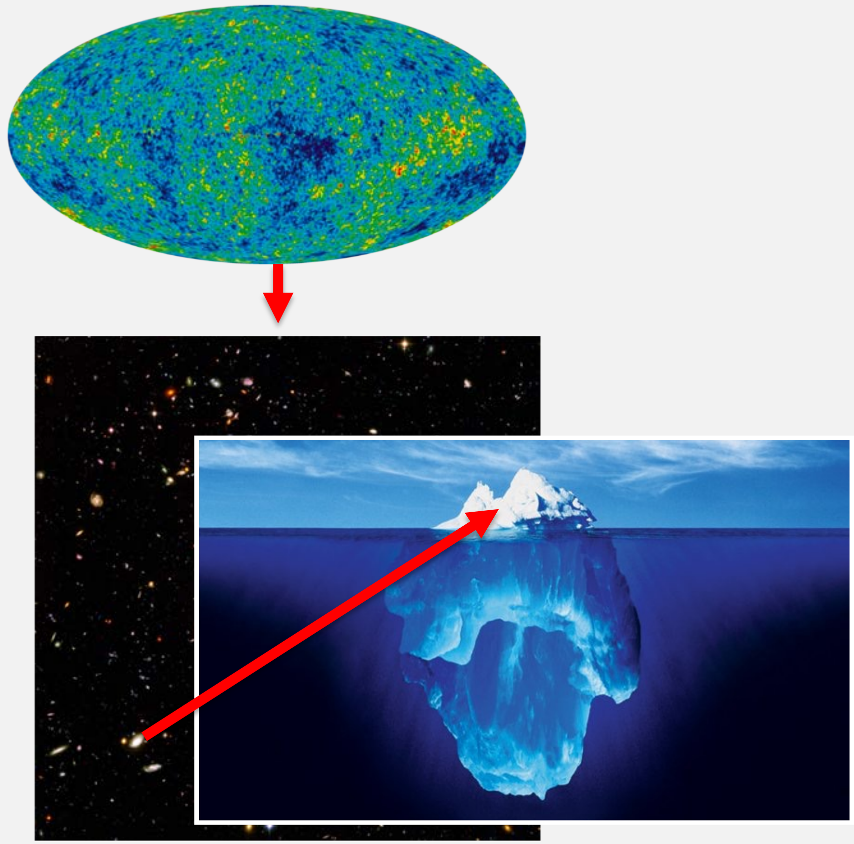


Consequences of DE

Dark Energy affects the:

- Expansion history of the Universe
  - How fast did the Universe expand?
  - Also called the geometry of the Universe

- Growth of structures
  - How do structures (which are mostly dark matter) evolve and grow over time
  - Attractive gravity competes with repulsive dark energy

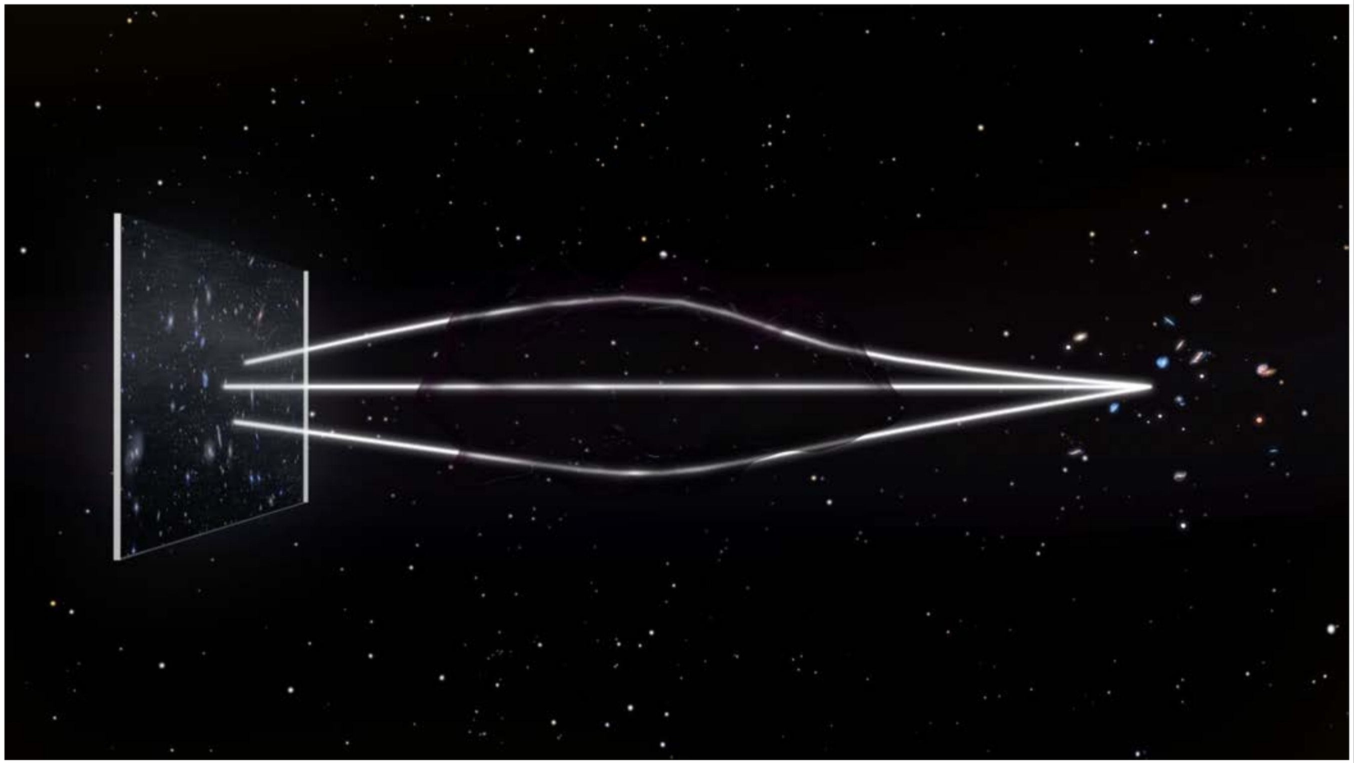


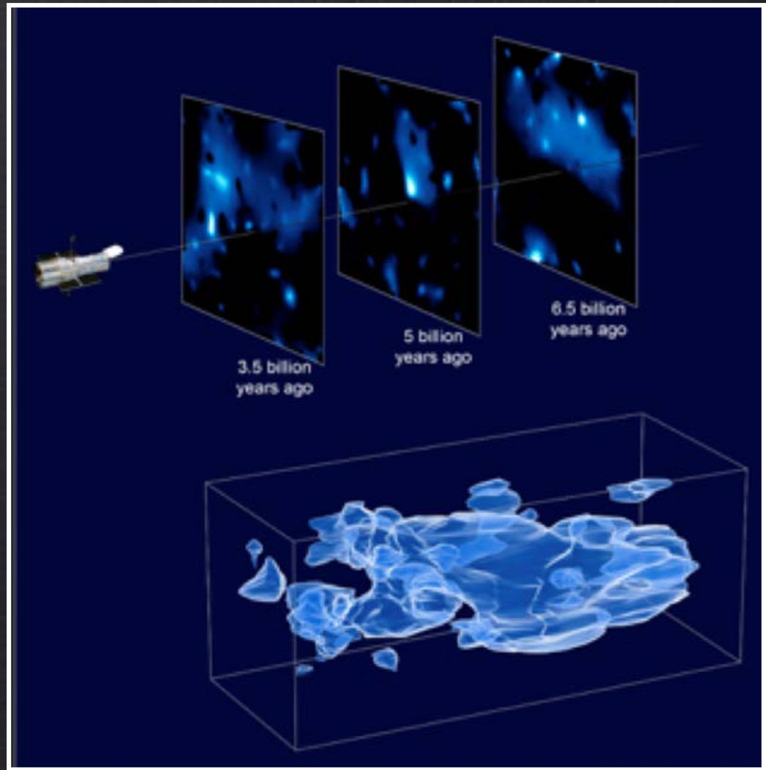
If Einstein’s General Relativity is wrong, modified gravity theories could explain the accelerating expansion.

This would change the above effects differently, *so we must measure them both!*

WFIRST will

measure galaxy shapes to map dark matter and measure the growth of galaxies over the Universe's life

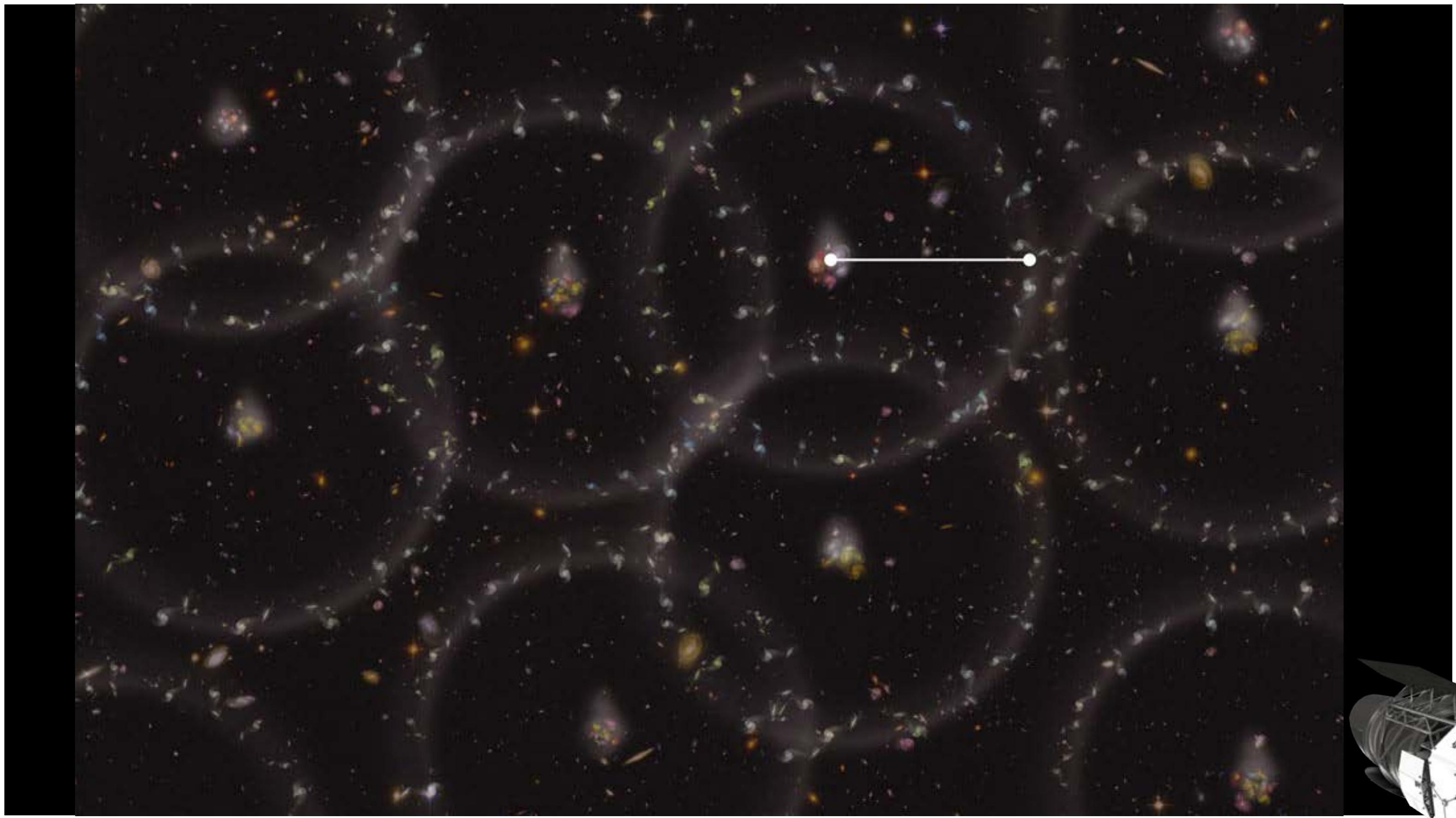


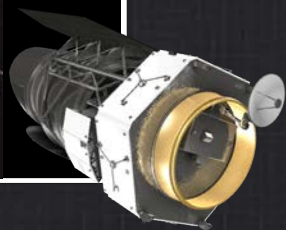


From Massey, Rhodes, et al 2007

WFIRST will

map the positions of galaxies to establish a cosmic standard ruler to measure the Universe's expansion history

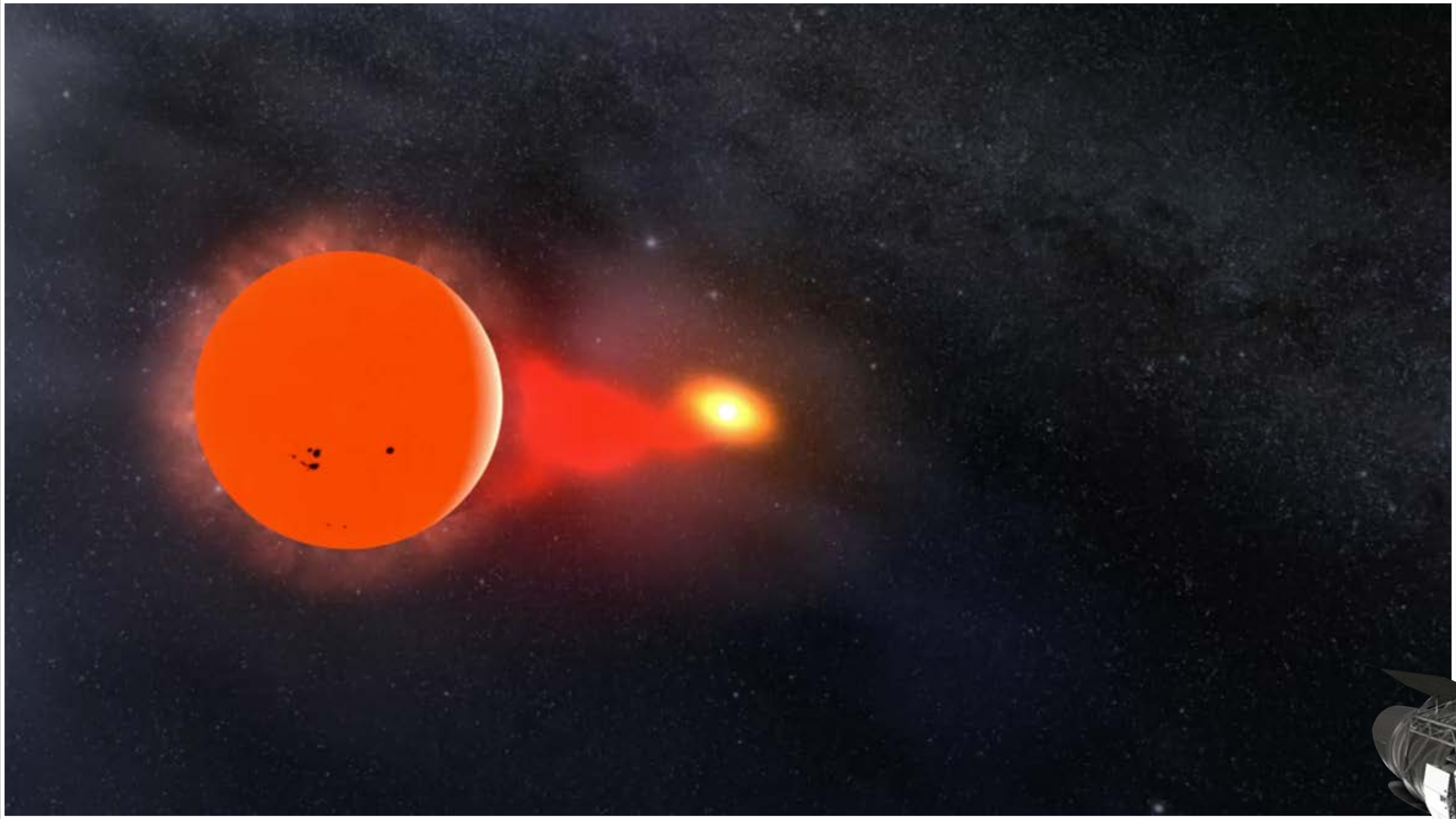


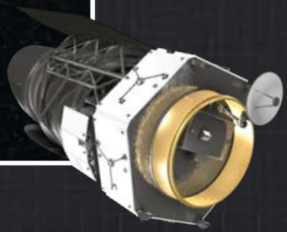


#WFIRST

WFIRST will

discover exploding stars (supernovae) across cosmic time
to establish precise distances to galaxies





#WFIRST

WFI Filters & dispersers

Band	Element name	Min (µm)	Max (µm)	Center (µm)	Width (µm)	R
R	F062	0.48	0.76	0.620	0.280	2.2
Z	F087	0.76	0.977	0.869	0.217	4
Y	F106	0.927	1.192	1.060	0.265	4
J	F129	1.131	1.454	1.293	0.323	4
H	F158	1.380	1.774	1.577	0.394	4
F	F184	1.683	2.000	1.842	0.317	5.81
Wide	W146	0.927	2.000	1.464	1.030	1.42
GRS	G150	1.0	1.93	1.465	0.930	461λ(2pix)
PRS	P120	0.75	1.80	0.975	1.05	80-180 (2pix)

Weak lensing photo-z

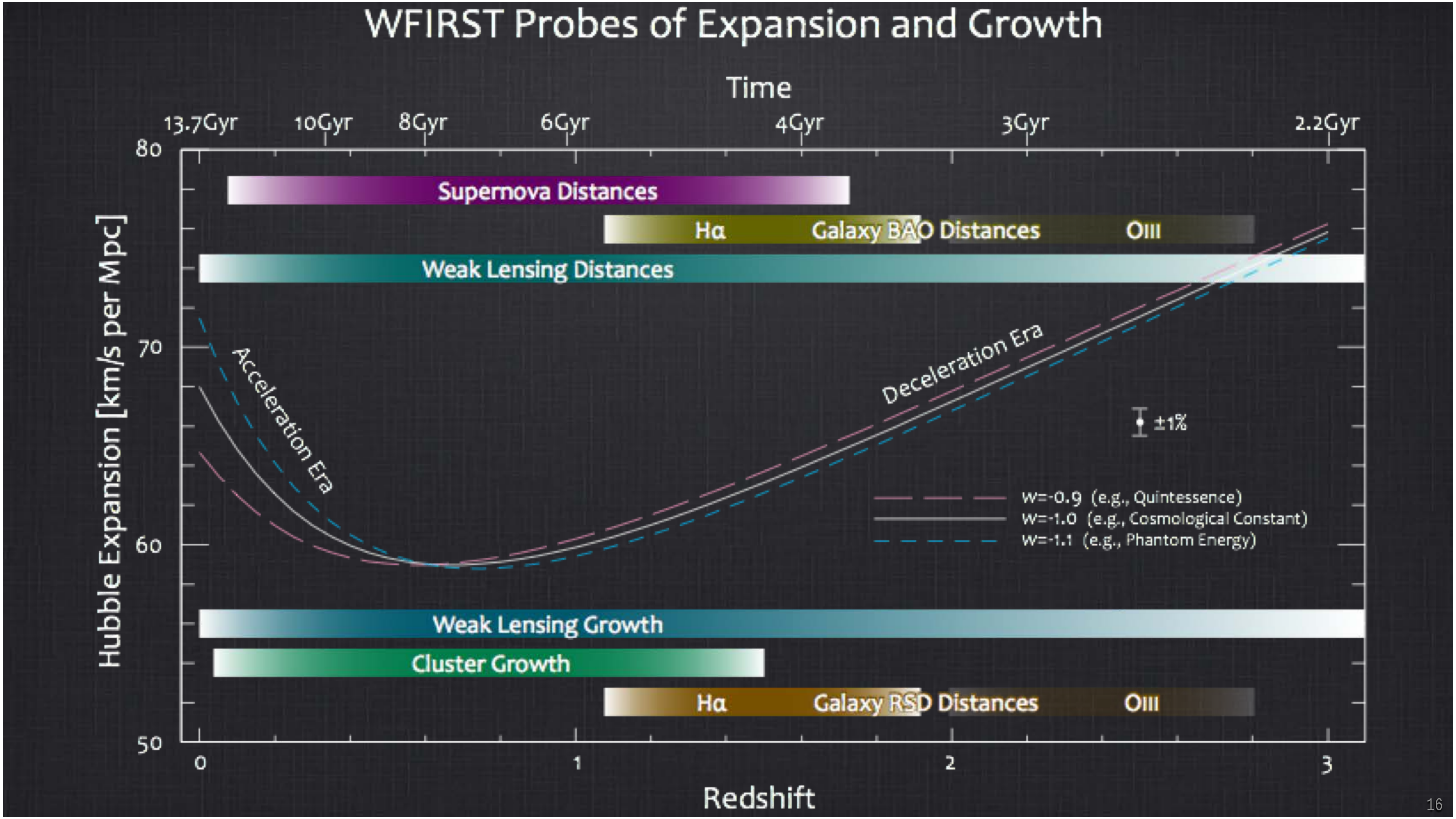
Weak lensing shapes

Grism for galaxy resdshift survey

Prism for SN follow up

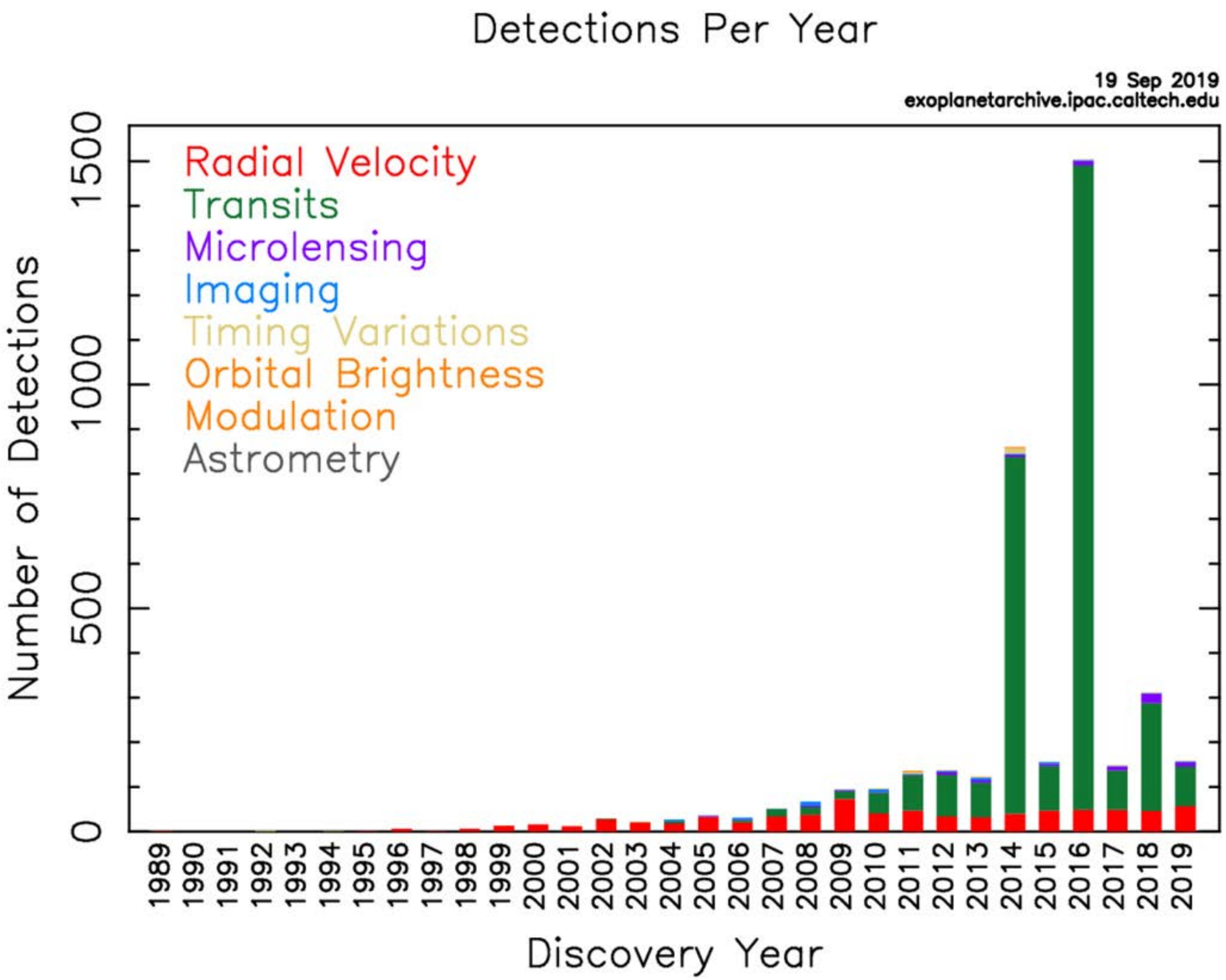
	LSST	Euclid	WFIRST
Proposed lifetime	2022 - 2032	2022 - 2028	2025 - 2031
Mirror size (m)	6.5 (effective diameter)	1.2	2.4
Survey size (sq deg)	20,000	15,000	2,227
Median z (WL)	0.9	0.9	1.2
BAO specz range	NA	~1-2	~1-3
Depth (AB mag)	~27.5	~24.5	~27
FoV (sq deg)	9.6	0.5 (Vis) 0.5 (NIR)	0.28
Filters	u-g-r-i-z-y	Y-J-H-Vis	Y-J-H-F184
Cosmological probes	WL, SN, LSS, GC	WL, LSS, GC	WL, LSS, SN, GC

WL: Weak Lensing, LSS: Large Scale Structure/Galaxy Clustering, SN: Supernova, GC: Galaxy Clusters

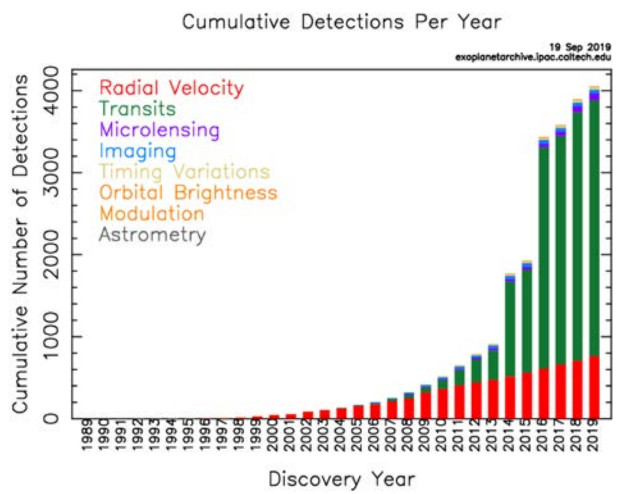


WFIRST Probes of Expansion and Growth
Time
13.7Gyr
10Gyr
8Gyr
6Gyr
4Gyr
3Gyr
2.2Gyr
80
70
60
50
Hubble Expansion [km/s per Mpc]
Supernova Distances
Hα
Galaxy BAO Distances
OIII
Weak Lensing Distances
Acceleration Era
Deceleration Era
±1%
W=-0.9 (e.g., Quintessence)
W=-1.0 (e.g., Cosmological Constant)
W=-1.1 (e.g., Phantom Energy)
Weak Lensing Growth
Cluster Growth
Hα
Galaxy RSD Distances
OIII
0
1
2
3
Redshift

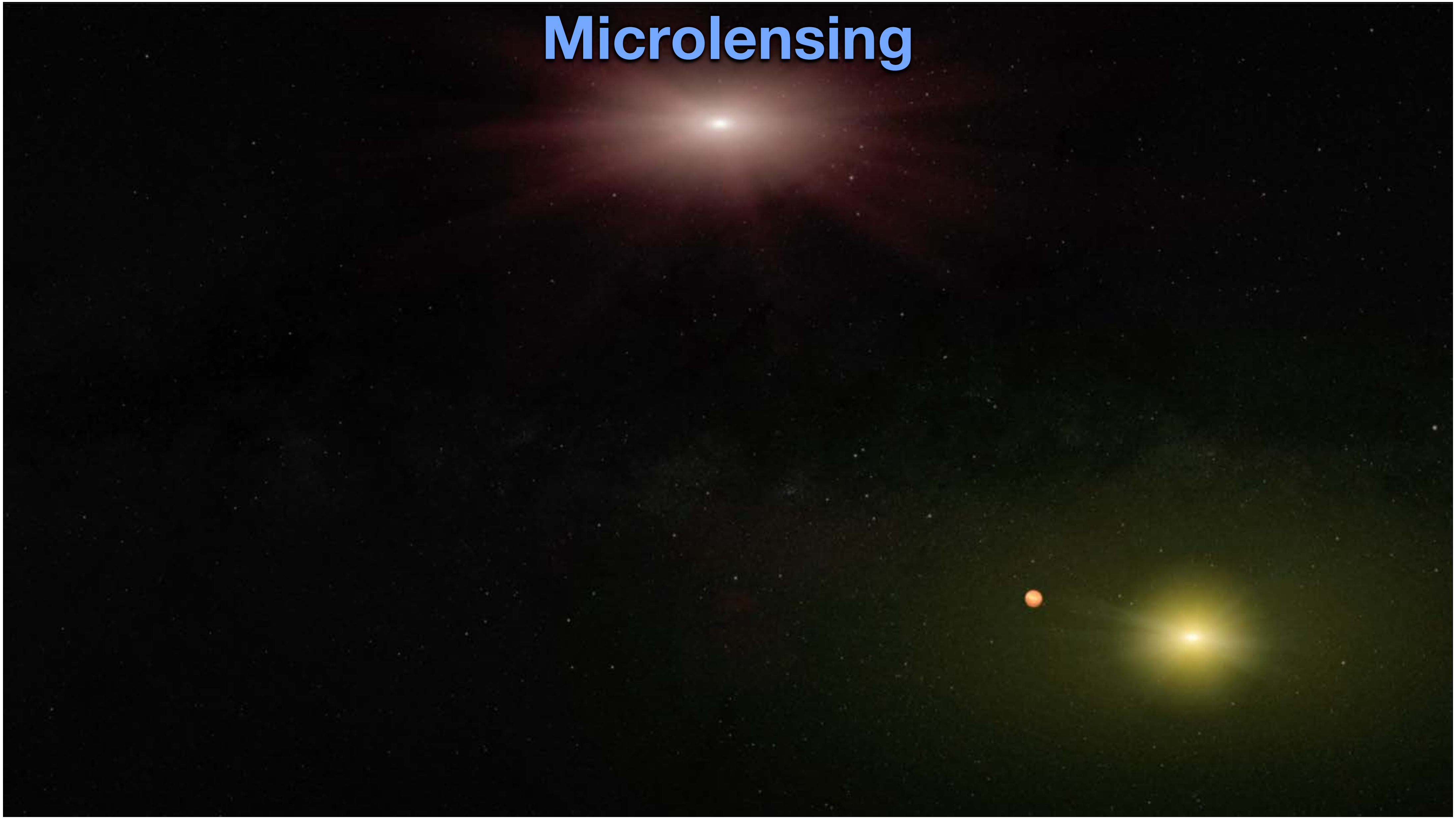
Exoplanet Detections

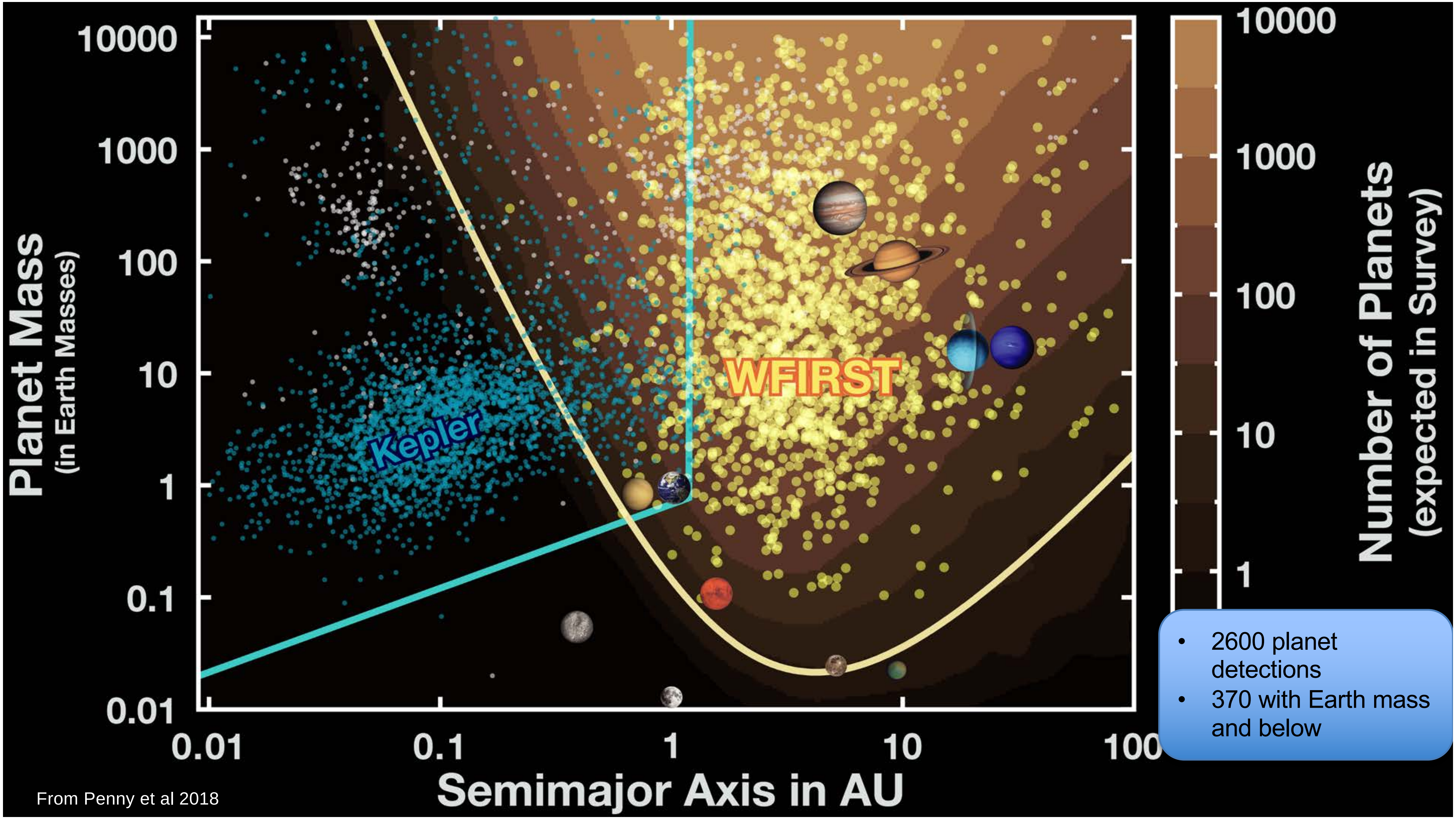


- Exoplanet detection is increasing exponentially
- These methods are largely missing outer solar system analogs

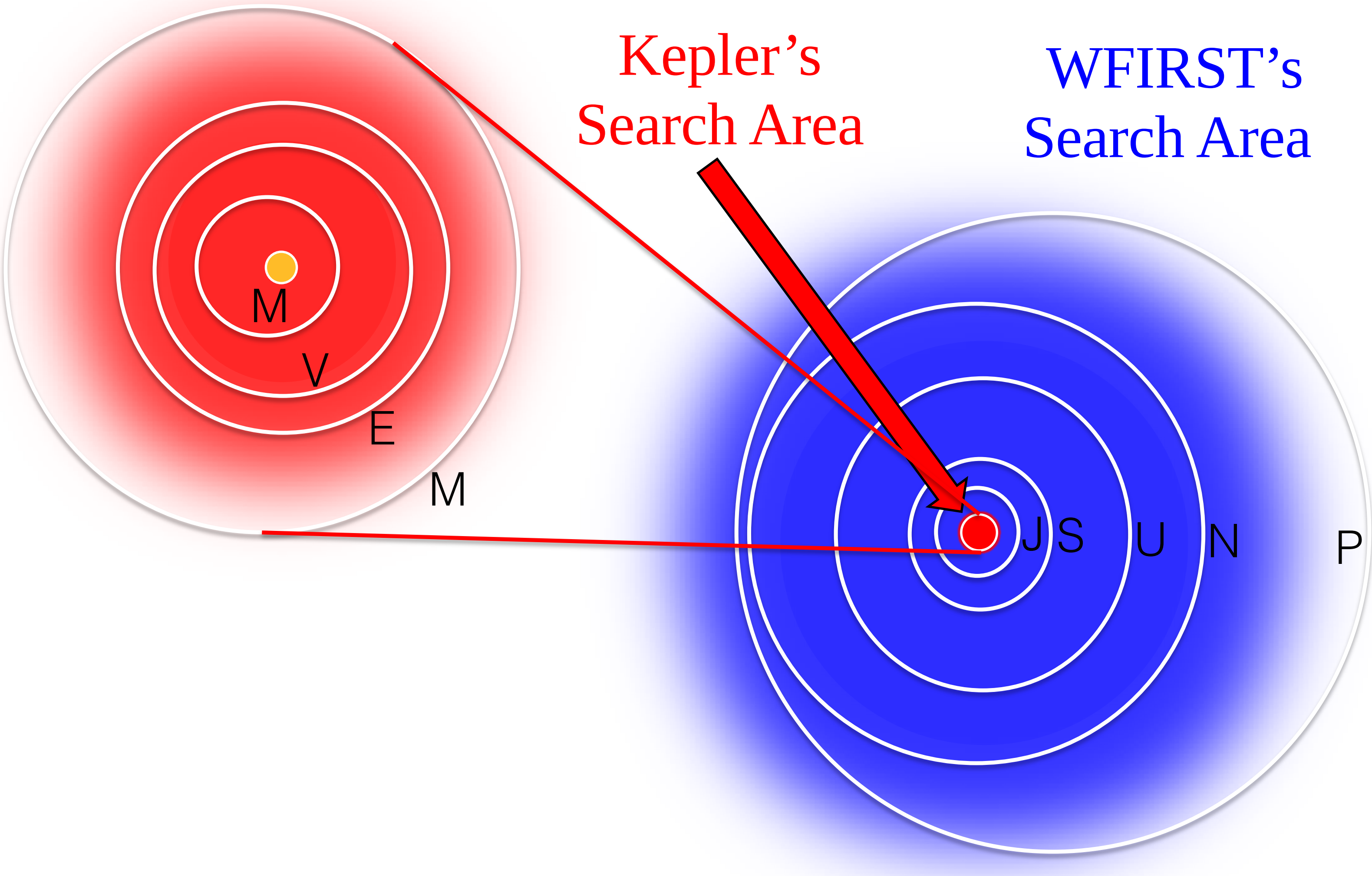


Microlensing

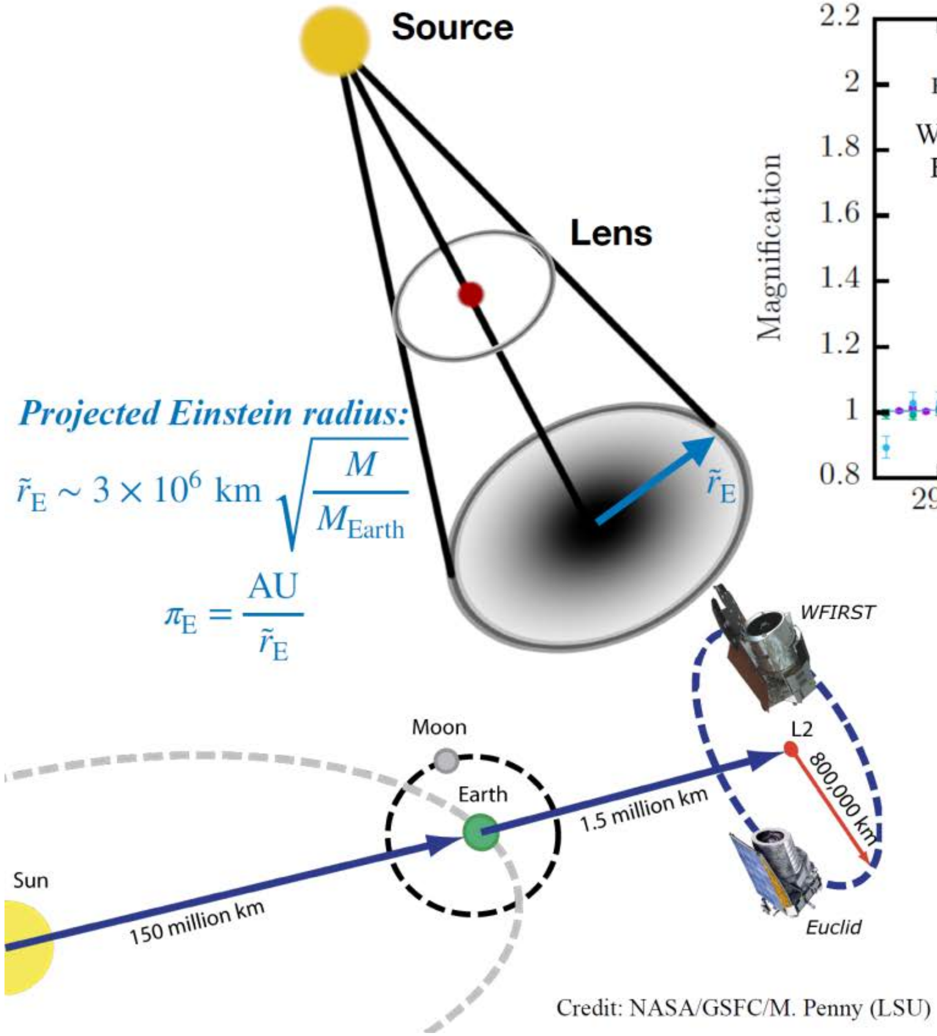



Planet Mass
(in Earth Masses)
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Semimajor Axis in AU
Kepler
WFIRST
10000
1000
100
10
1
Number of Planets
(expected in Survey)
• 2600 planet detections
• 370 with Earth mass and below
From Penny et al 2018

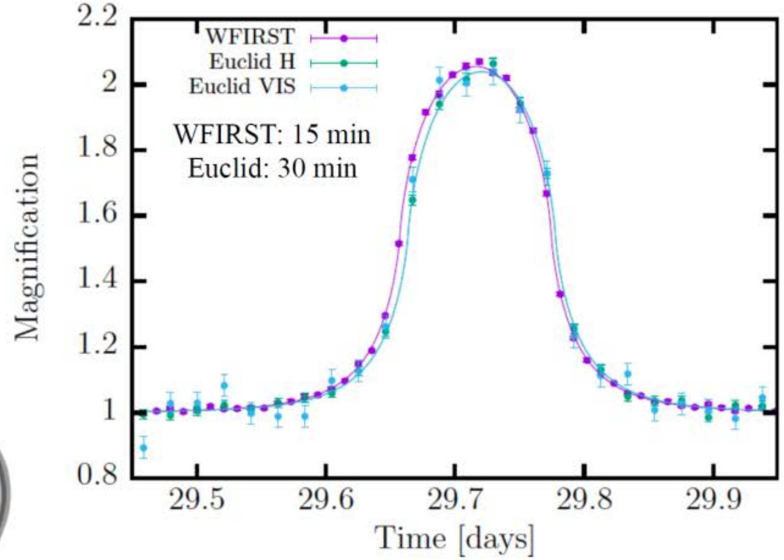
WFIRST Complements Kepler



Microlensing with *Euclid* & *WFIRST:* Masses of Free-Floating Planets



Credit: NASA/GSFC/M. Penny (LSU)

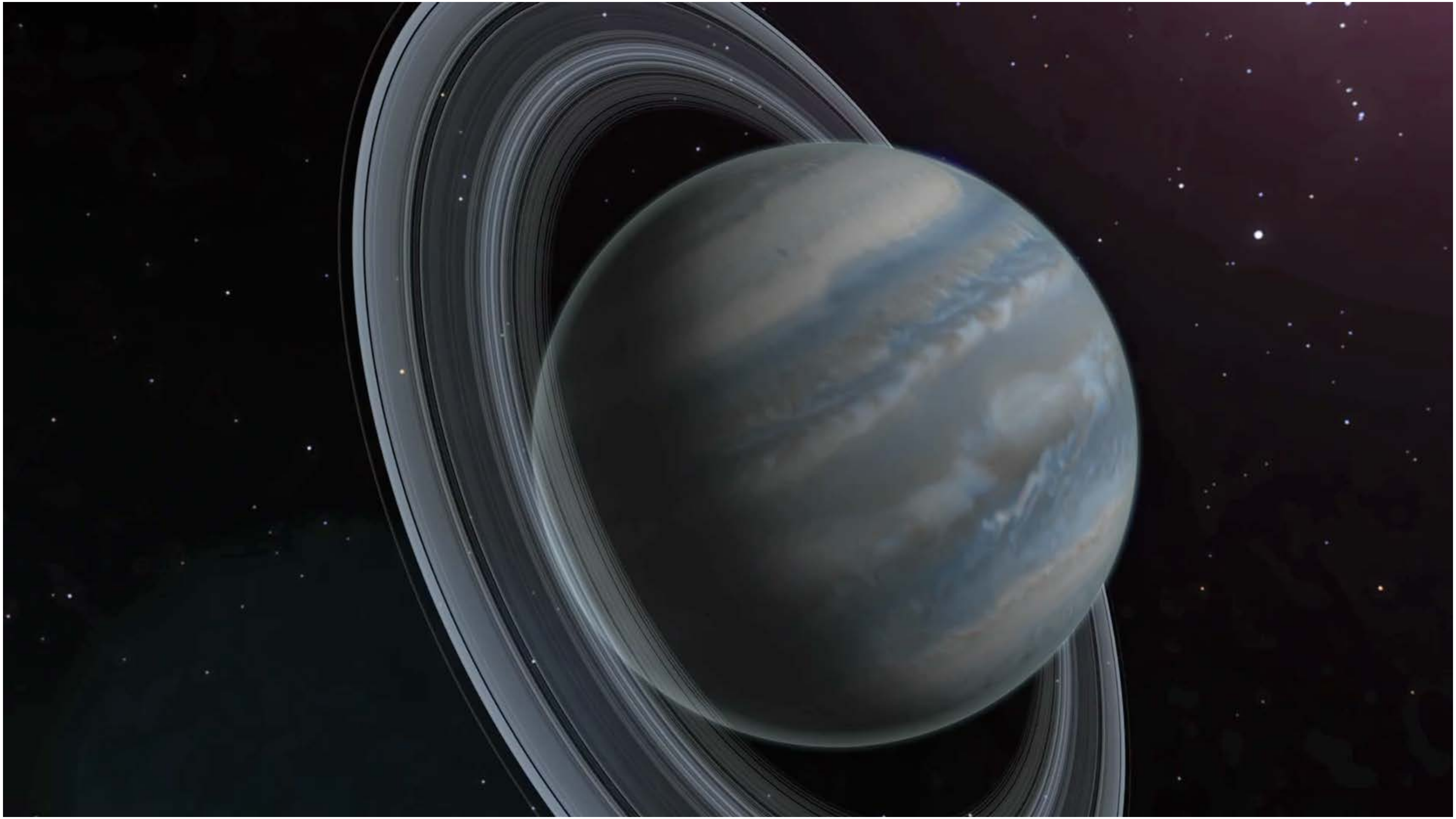


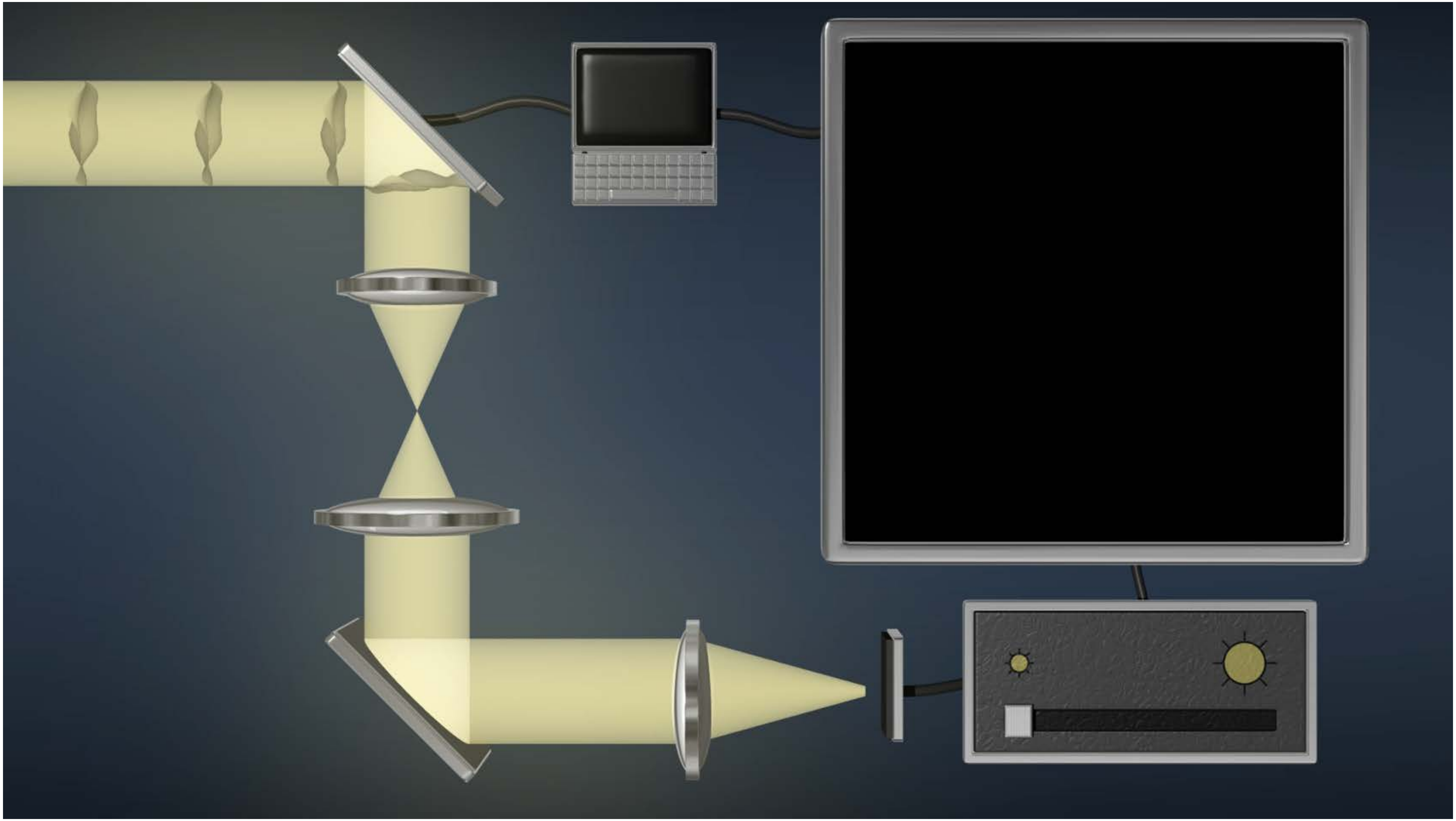
Credit: M. Penny (LSU), S. Johnson (OSU)

$$\pi_E = 61.8 \pm 19.3$$
$$\theta_E = 6.6 \pm 1.3\mu\mathrm{as}$$

$$M = \frac{\theta_E}{\kappa \pi_E}$$

$$M = 0.44 \pm 0.16 M_{\mathrm{Earth}}$$

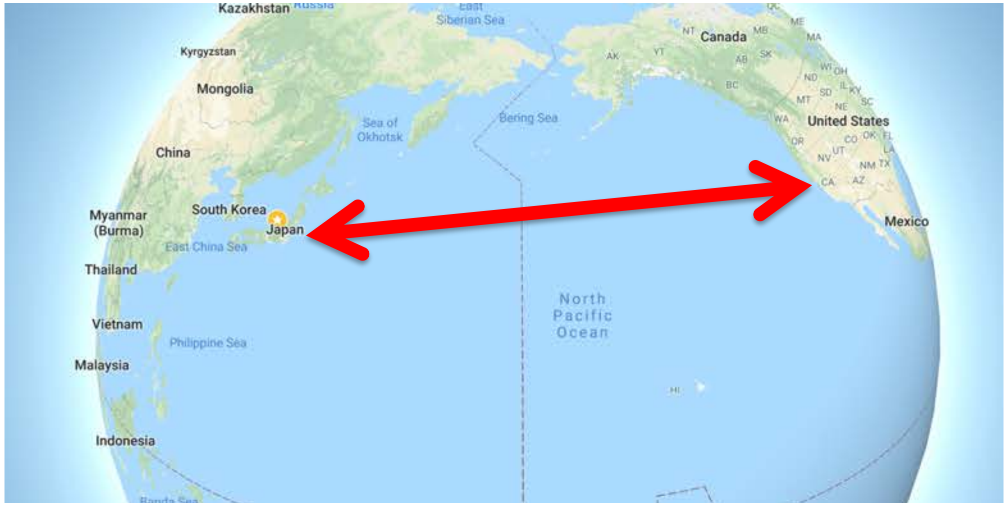




[redacted]

A Firefly and a Spotlight

Seeing an exoplanet around a star is like trying to see a firefly near a spotlight in Los Angeles… when you are in Japan



Credit: S Gaudi

Seeing an Earth-like exoplanet in the habitable zone around a Sun-like star is like trying to see a firefly near ONE THOUSAND spotlights in Los Angeles… when you are in Japan!

Coronagraphy- Powers of 10

Contrast Ratio (planet light to star light)

10^{-5} – 10^{-6} 1 part in 100,000 to 1,000,000

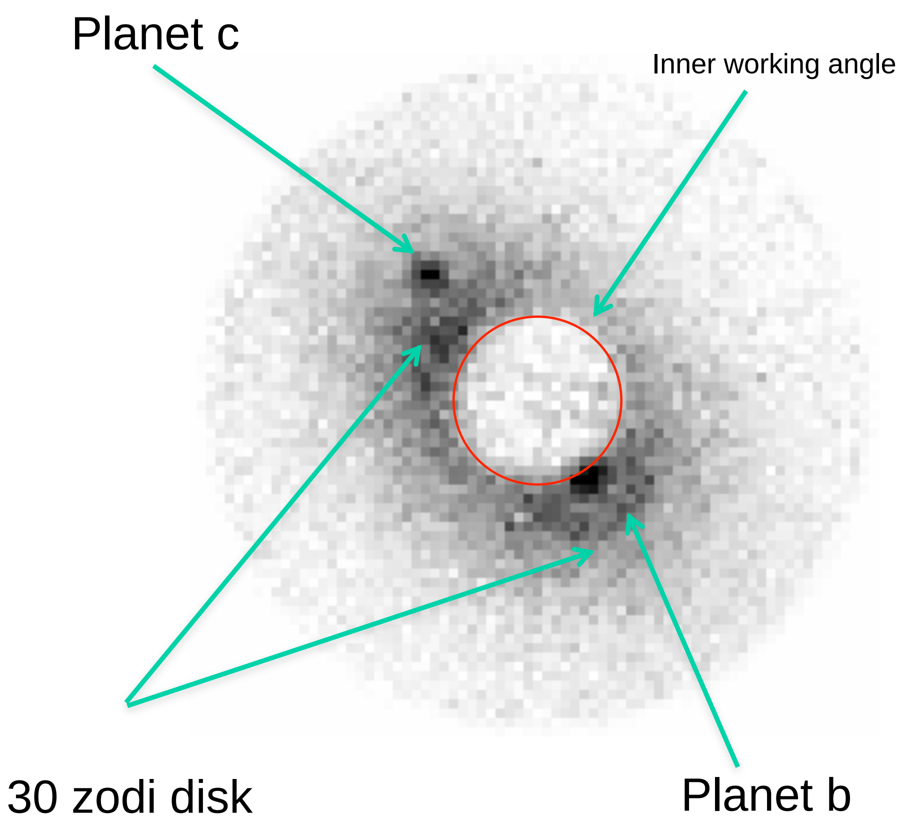
What we can get from coronagraphs now and in the near future

10^{-9} 1 part in 1,000,000,000

What WFIRST's coronagraph is being designed to achieve (already demonstrated in lab- idealized conditions)

10^{-10} 1 part in 10,000,000,000

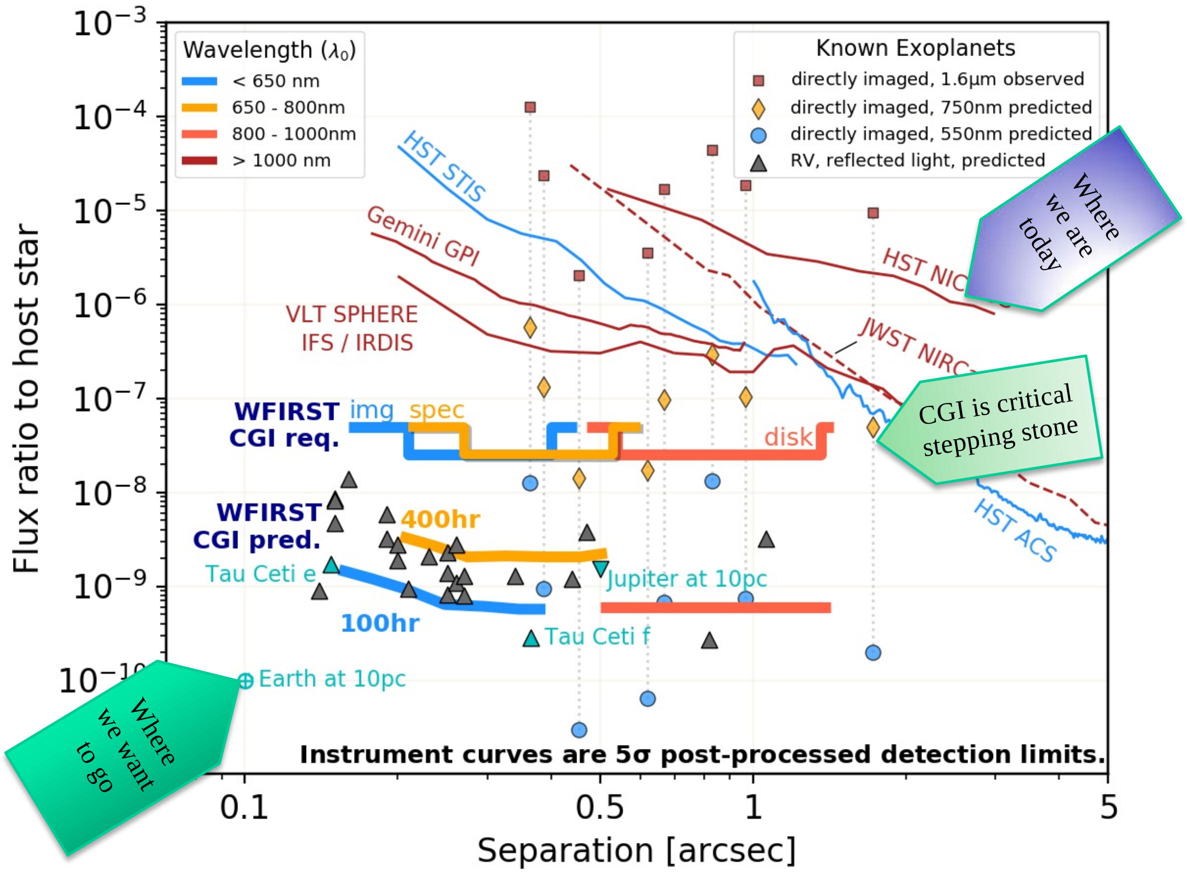
What we need to see another Earth (with a future mission like HabEx or LUVOIR)



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

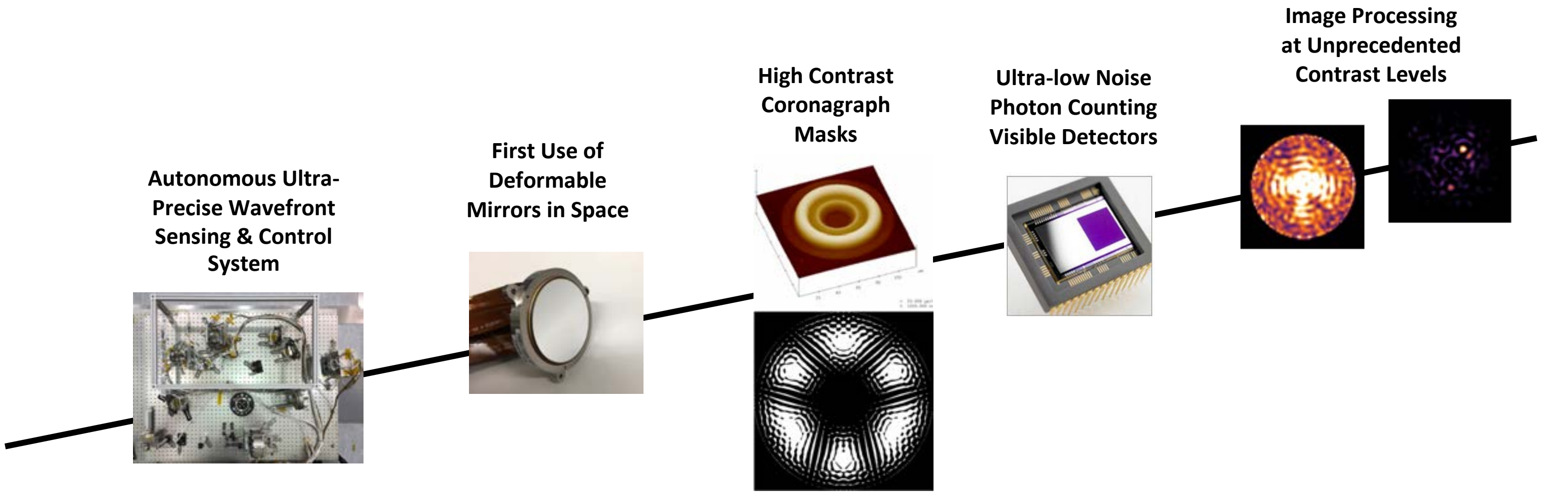
CGI is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets

- **CGI projected capabilities represent a 1000 fold compared to current capabilities**
  - **Enabled by active control of optical wavefront errors and pointing**
- **Dozens of planets within reach of characterization**
- **exoEarths in Habitable zone further x10-100 improvement in contrast and x2 in spatial resolution**
- **CGI is a major stepping stone that will obtain optical spectra of mature exoJupiters**



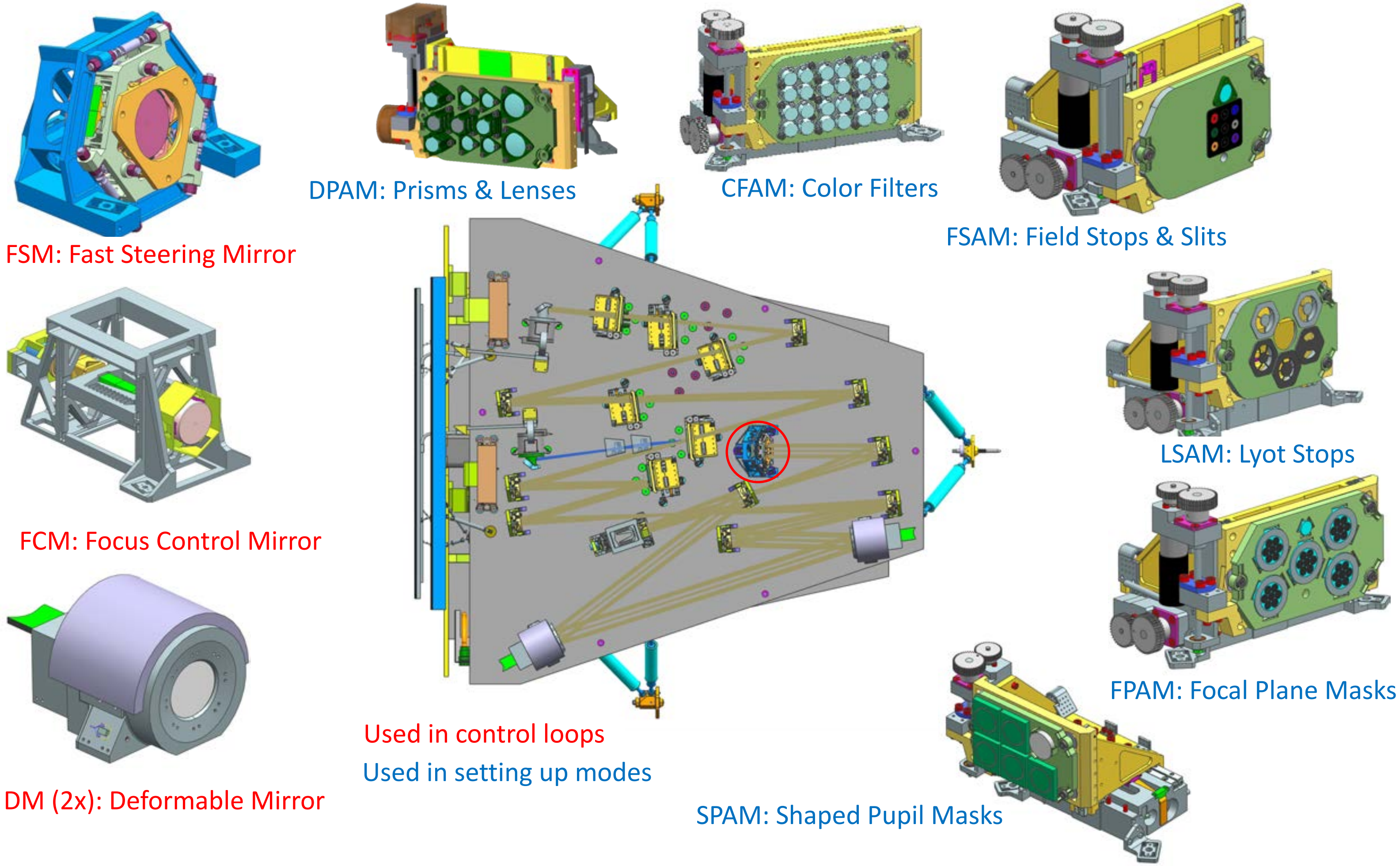
WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

CGI Tech Demonstrations Along the Beam Path

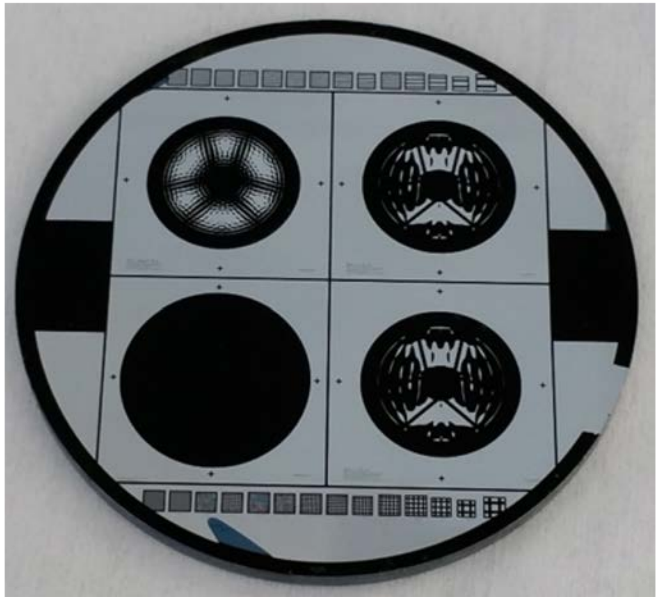


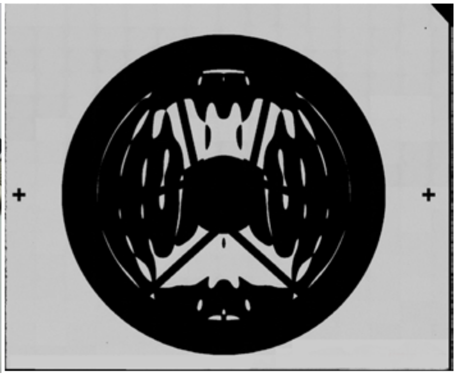
- CGI will premiere in space many key technologies required for the characterization of rocky planets in the Habitable Zone, significantly reducing the risk and cost of future possible missions such as HabEx and LUVOIR
- CGI is a direct & necessary predecessor to these missions, and is a *crucial* step in the exploration of Sun-like planetary systems

Actuators and Mechanisms

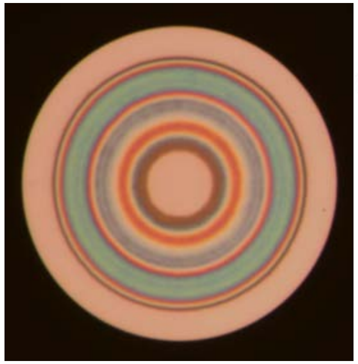


Recent Fabrications of Coronagraph Masks
(Images not to scale)

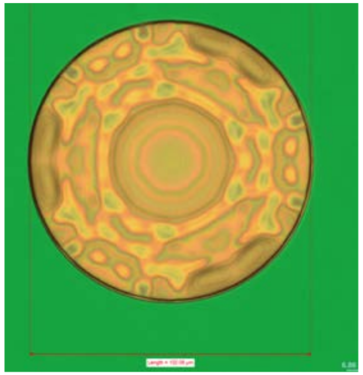


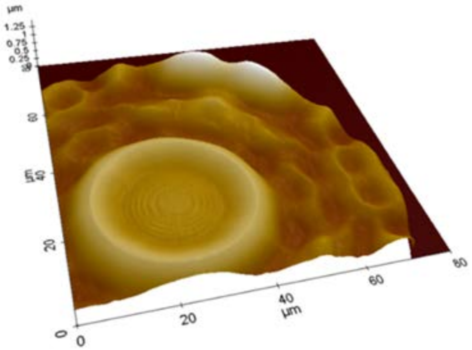


Typical Shaped Pupil Masks fabricated at JPL
Ref: SPIE Proc 10400, 2017



AHLC6_R3C3



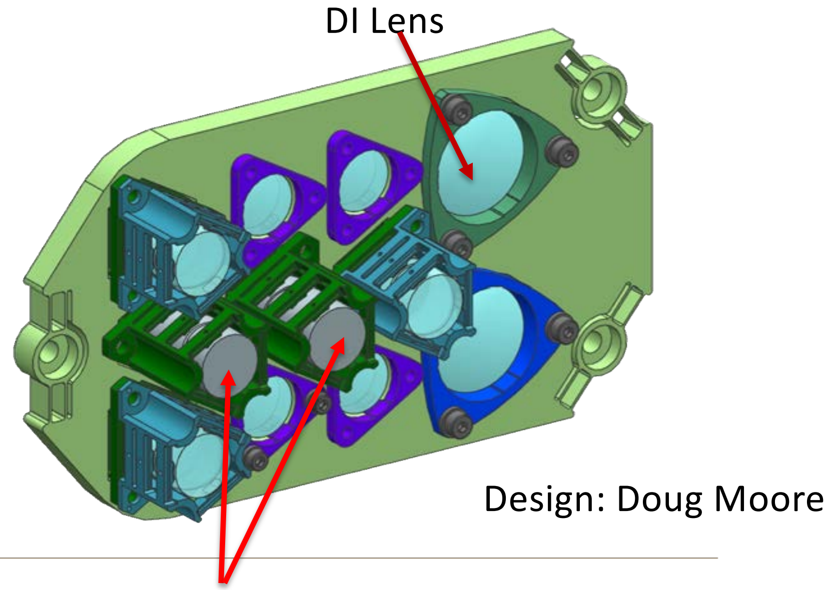


Typical Hybrid Lyot Masks fabricated at JPL
Ref: SPIE Proc 11117, 2019

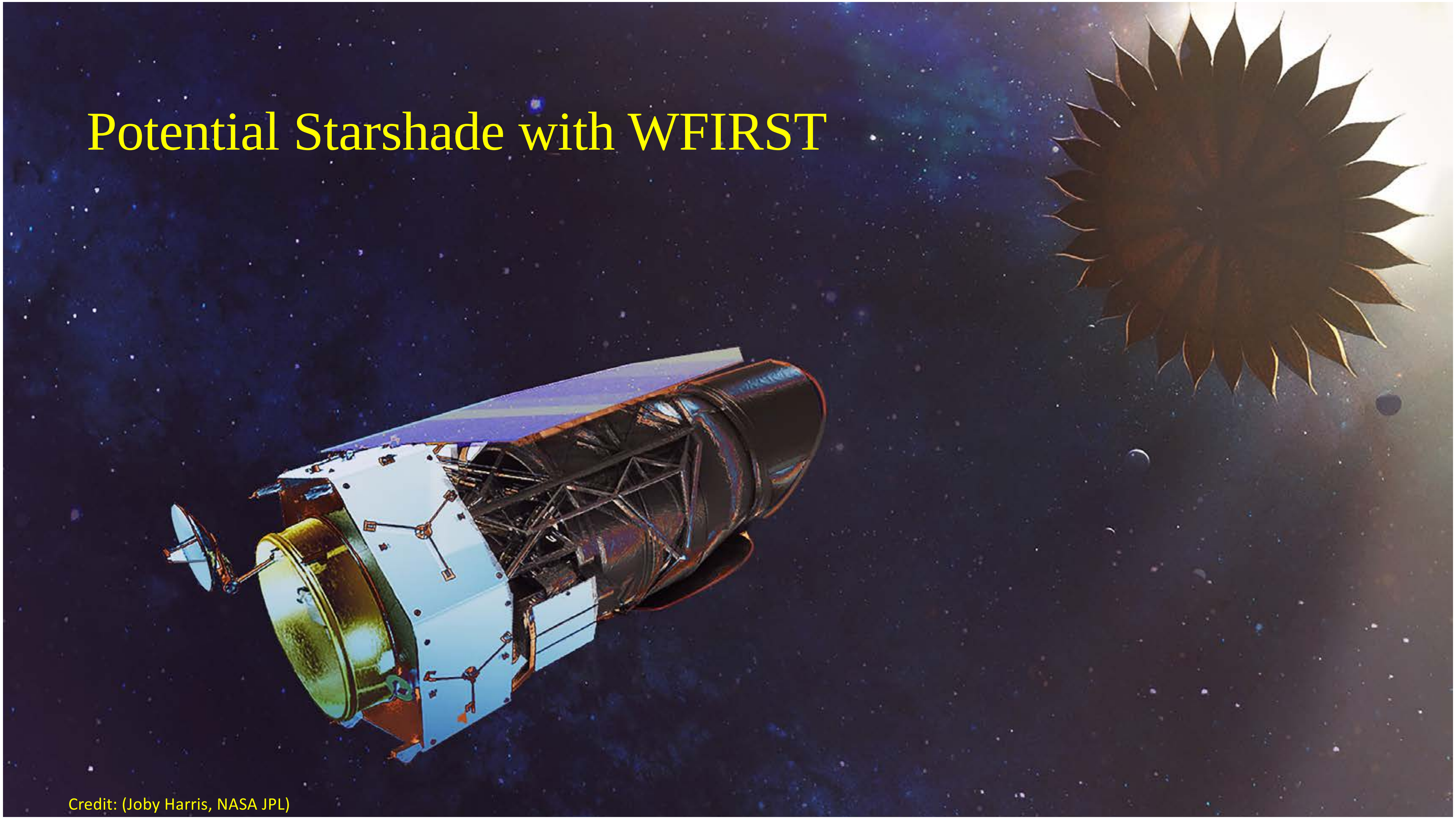
Substrates are JAXA contribution

JAXA contributions of polarizer elements

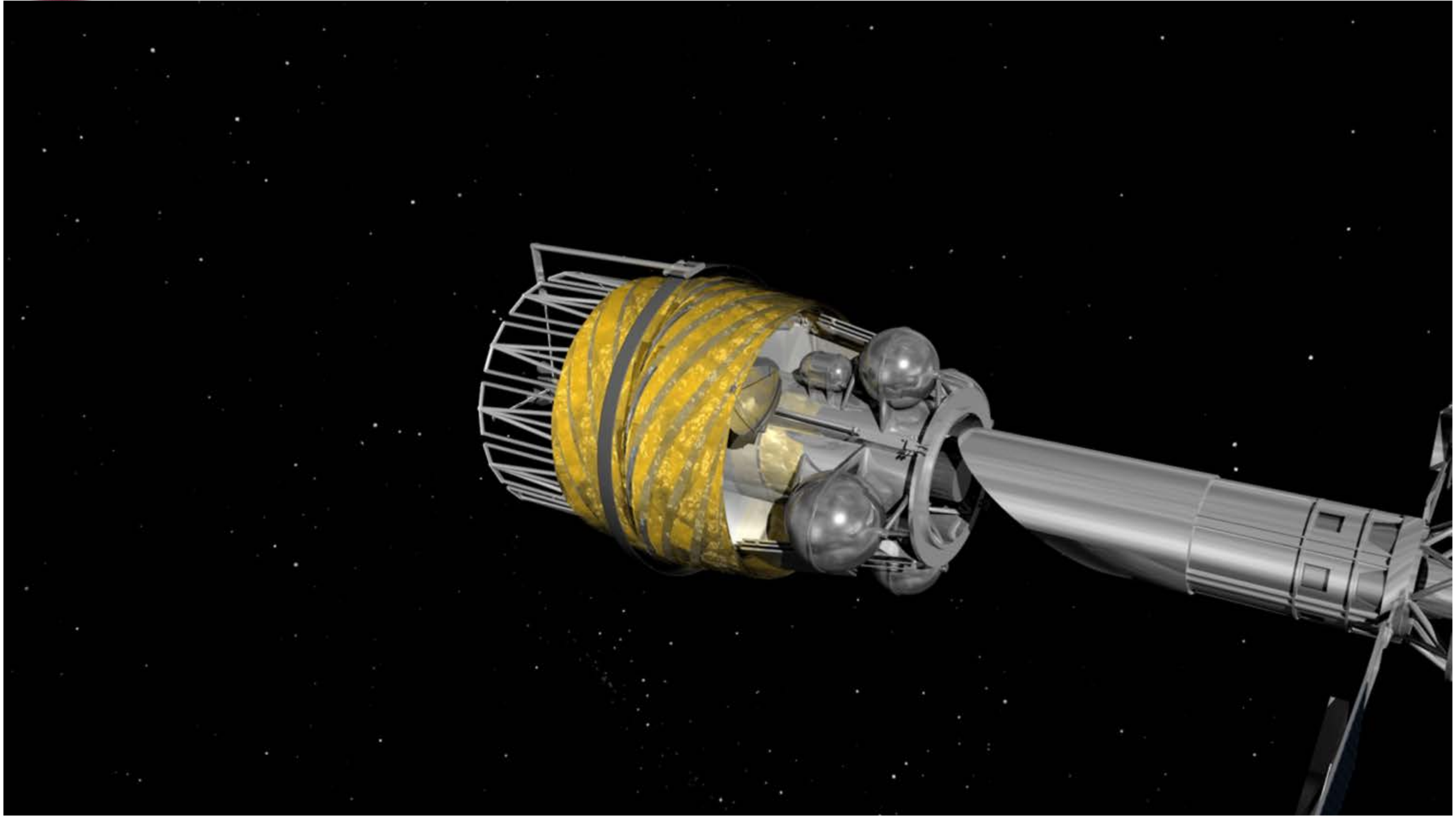
Items to be delivered	EM	FM
DI Lens doublet for position 1 on DPAM	3 each	3 each
Polarizer Elements for position 2 on DPAM	3 each	3 each
Polarizer Elements for position 3 on DPAM	3 each	3 each



Polarization Optical elements from JAXA
Polarization module tubes designed and assembled on a mounting plate at JPL


Potential Starshade with WFIRST
Credit: (Joby Harris, NASA JPL)

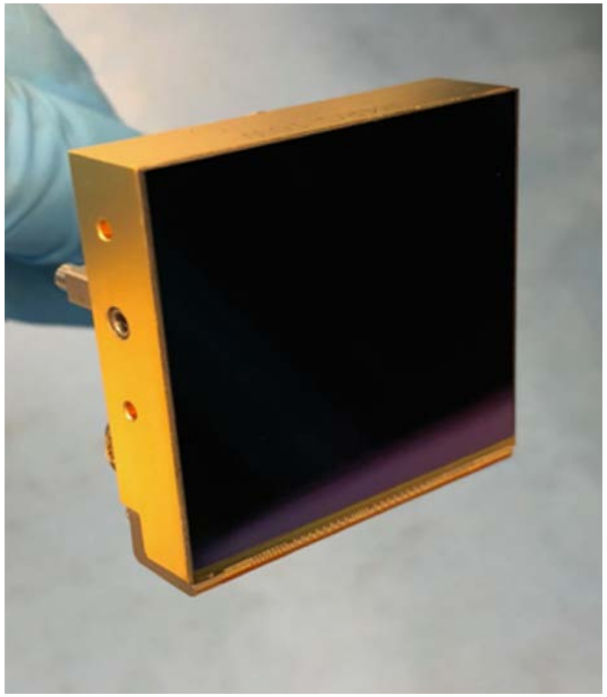
Starshade



WFIRST Status

- WFIRST remains on the plan approved at the beginning of Phase B in 2018
- Lifecycle cost range $3.2B -$3.9B
- Launch in late 2025

- Major Milestones for 2019
  - Progress through all element Preliminary Design Reviews (5 of 6 done)
  - Flight build of significant items (primary mirror, H4RG detectors)
  - Mission Preliminary Design Review in October/November 2019
  - Expected move to Phase C early 2020



Teledyne H4RG detector

Observing Program Overview

Source: WFIRST Science Requirements Document (SRD), Reference Survey Material & Requirements

Observing Program	Program Attributes	Notional Time Allocation	Current Time Estimate
HLIS	Survey Speed: 0.20 sq-deg/hour Reference Survey: 2000 sq-deg, 2 passes, 4 filters Baseline Survey: 1700 sq-deg, 2 passes, 4 filters	Survey Time: 352 days Deep-field observations: 39 days Total: 391 days	291-342 days* (1700-2000 sq-deg)
HLSS	Survey Speed: 0.34 sq-deg/hour Reference Survey: 2000 sq-deg, 4 passes, Grism Baseline Survey: 1700 sq-deg, 4 passes, Grism	Survey Time: 211 days Deep-field observations: 23 days Total: 234 days	169-199 days* (1700-2000 sq-deg)
SNS	Survey Area: 5 sq-deg, up to 6 filters + Prism Survey Cadence: 30 hours every 5 days over 2 year period	Survey Time: 183 days	
EMS	Reference Survey Coverage: 731.7 sq-deg-days Baseline Survey Coverage: 585.4 sq-deg-days Survey Area: 2 sq-deg Survey Cadence: 15 minutes	Survey Time: 372 days	
GO	Full sky availability throughout the mission	Program Time: 456 days	
EC	90 days of observing to support technology demonstration	Program Time: 90 days	
		TOTAL: 1726 days (4.73 years)	
	Schedule Reserve (Used for Mission Overheads)	99 days (0.27 years)	* Using MEV slew durations

Partnerships

JAXA	Coordinated, contemporaneous ground-based observations on Subaru Ground station for telemetry and tracking Polarization optics for the CGI Microlensing data from the MOA project & new PRIME observatory
DLR	Precision mechanisms for the CGI
ESA	Star trackers, possibly other S/C components EMCCD detectors for the CGI (e2v in UK) Ground station for telemetry and tracking
CNES	Superpolished optics for the CGI Grism data processing Cosmology simulations

WFIRST and Subaru

Subaru and WFIRST: A Partnership for the 2020s

An Activity White Paper for submission to the 2020 Decadal Survey

Jason Rhodes (Jet Propulsion Laboratory, California Institute of Technology; Jason.d.rhodes@jpl.nasa.gov), Takahiro Sumi (Osaka University), David Bennett (NASA/GSFC), Peter Capak (IPAC/Caltech), Olivier Doré (JPL), A. Fukui (NAOJ), Jeremy Kasdin (Princeton University), Bryan Holler (STScI), Takayuki Kodama (Tohoku), Yusei Koyama (NAOJ), Noriyuki Matsunaga (The University of Tokyo), Stefanie Milam (NASA/GSFC), Hironao Miyatake (Nagoya), Shogo Nishiyama (Miyagi University of Education), Masami Ouchi (University of Tokyo), James Rhoads (NASA/GSFC), Dan Scolnic (Duke University), Daisuke Suzuki (JAXA), Nao Suzuki (IPMU), Masaomi Tanaka (Tohoku University), Motohide Tamura (U. Tokyo and Astrobiology Center), Tsuyoshi Terai (NAOJ), David Weinberg (Ohio State), Ben Williams (University of Washington), Toru Yamada (JAXA), Fumi Yoshida (PERC/Chitech)

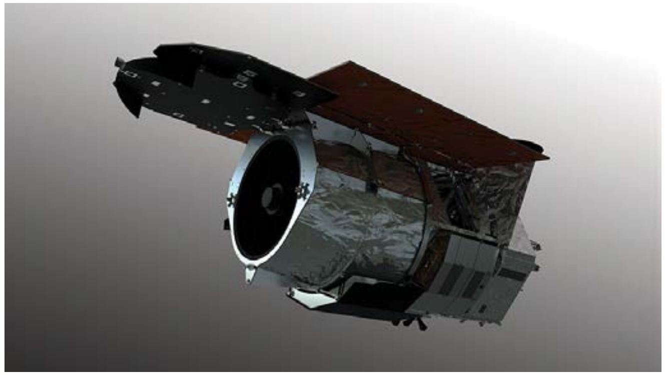
Steering Group:

- Takahiro Sumi (Chair of WFIRST JAXA Working Group)
- Toru Yamada (JAXA WFIRST Representative)
- Yusei Koyama (Subaru Representative)
- Tadayuki Kodama (Chair of the Subaru Science Advisory Committee)
- David Spergel (WFIRST WFI Adjutant Scientist)
- Julie McEnery (WFIRST Deputy Project Scientist)
- Jason Rhodes (WFIRST Deputy Project Scientist)

Program	Instrument	Total nights
(S3) microlensing concurrent	HSC and ULTIMATE	17
(S3) microlensing NIR Spectroscopic ToO	Subaru IRD	11.2
(S3) microlensing concurrent	ULTIMATE	3.4
(S4) CGI follow-up and support	SCExAO/CHARIS/IRD	25
(S5) SN follow up	PFS	25
(S5) Live SN monitoring	PFS	20
(S6) Optical Imaging follow-up of SNe fields	HSC	8
(S6) Spectroscopic follow-up of SNe fields	PFS	8
(S6) Narrow band survey of SNe fields	HSC/PFS	6-10
(S6) Ultra Deep Fields	HSC	33
(S7) Spec-z follow-up for photo-z calibration*	PFS	25-50
(S7) Intermediate-band follow-up for photo-z* *calibration*	HSC	60
(S7)Lensing and structure growth	PFS/HSC	~Tens (TBD)
(S8) Galaxy Halo Pre-imaging	HSC	10
(S9) Bulge HVSs (characterization)	PFS	0.5
(S9) Bulge HVSs (characterization)	ULTIMATE (MOS)	0.5
(S9) Bulge HVSs (survey)	ULTIMATE- (Imaging)	2.5
(S9) Microlensed Bulge Objects	IRCS/IRD	15
(S10) TNOs	HSC	6
(S10) Other Minor Bodies	HSC	10
(S10) Irregular Satellites	HSC	6

JAXA/NAOJ/NASA

- Collaborative agreement is imminent
- Japanese scientists can become part of current (and future) Science Investigation Teams
- Want to enable collaboration on WFIRST
  - — Especially with Subaru
  - — Especially for early career scientists
- For further information and engagement contact (leads in red):
  - — Toru Yamada (JAXA), Yas Murata (JAXA)
  - — Cosmology: Hironao Miyatake (Nagoya), Masahiro Takada (IPMU)
  - — Supernova: Takashi Moriya (NAOJ)
  - — Exoplanet Microlensing: Takahiro Sumi (Osaka), Daisuke Suzuki (JAXA)
  - — Coronagraph: Motohide Tamura (NAOJ), Naoshi Murakami (Hokudai)

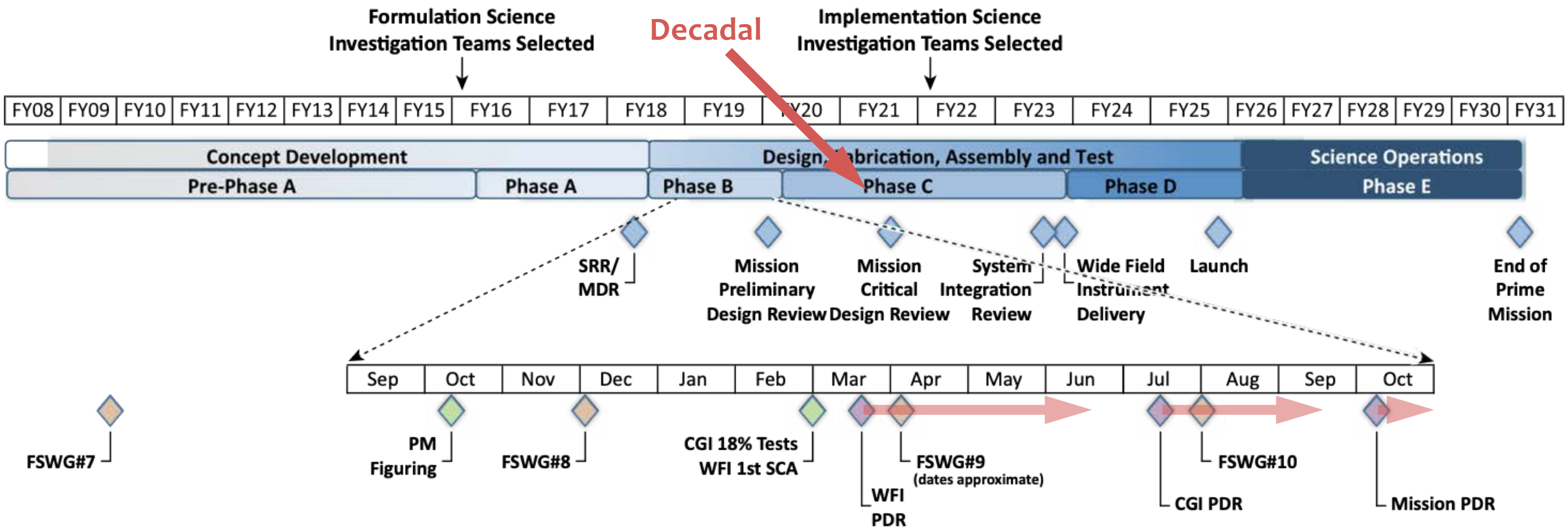


Opportunities with WFIRST

- 2020 Decadal Survey will consider a separate Starshade mission to fly with WFIRST
- 25% General Observer (GO) in 5 year prime mission
- ~100% GO in extended mission
- All prime survey science teams will be competed in ~2021
- All data released immediately- no proprietary period
- CGI available via a Participating Scientists Program
- Baseline mission includes contributions from ESA (including EMCCD for CGI from e2v in UK), France (CNES), Germany (DLR), Japan (JAXA, NAOJ)

Additional Slides

2019 Events



Formulation Science Investigation Teams Selected
Decadal
Implementation Science Investigation Teams Selected
FY08 FY09 FY10 FY11 FY12 FY13 FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31
Concept Development
Design, Fabrication, Assembly and Test
Science Operations
Pre-Phase A
Phase A
Phase B
Phase C
Phase D
Phase E
SRR/ MDR
Mission Preliminary Design Review
Mission Critical Design Review
System Integration Review
Wide Field Instrument Delivery
Launch
End of Prime Mission
Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct
FSWG#7
PM Figuring
FSWG#8
CGI 18% Tests WFI 1st SCA
WFI PDR
FSWG#9 (dates approximate)
CGI PDR
FSWG#10
Mission PDR

Observing Program Overview

NOTIONAL OBSERVING PROGRAM LAYOUT

Assuming 09/11/2025 launch, 90-day commissioning and orbit insertion by 12/31/2025

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MISSION YEAR 1 (2026)	HLS GO	EMS	EMS	HLS GO	EC HLS	GO PA/C	HLS EC	EMS	EMS	HLS EC	GO EC	HLS GO PA/C
MISSION YEAR 2 (2027)	EC GO	EMS	EMS	HLS EC	HLS GO PA/C	SNS HLS	SNS GO	SNS HLS	SNS GO	SNS GO	SNS HLS	SNS HLS PA/C
MISSION YEAR 3 (2028)	SNS HLS	SNS GO	SNS HLS	SNS GO HLS	SNS GO PA/C HLS	SNS HLS	SNS HLS	SNS GO	SNS HLS	SNS GO HLS	SNS GO HLS	SNS GO PA/C
MISSION YEAR 4 (2029)	SNS HLS	SNS HLS	SNS GO	SNS GO HLS	SNS HLS GO	HLS PA/C	GO HLS	EMS	EMS	HLS	GO HLS	HLS PA/C
MISSION YEAR 5 (2030)	HLS GO	EMS	EMS	HLS GO	HLS GO	GO PA/C	HLS	EMS	EMS	GO HLS	HLS	GO PA/C

LEGEND

HLS	High Latitude Survey (Imaging & Spectroscopy)
SNS	Supernova Survey (Imaging & Spectroscopy)
EMS	Exoplanet Microlensing Survey
GO	General Observer Program
EC	Exoplanet Coronagraphy Program
PA/C	Payload Alignment/Calibration

- Notional Observing Program activities are represented in each month as a *percentage of time dedicated to that activity*
- Durations range from 1 week (25%) to 4 weeks (100%) →

25%
25%
25%
25%

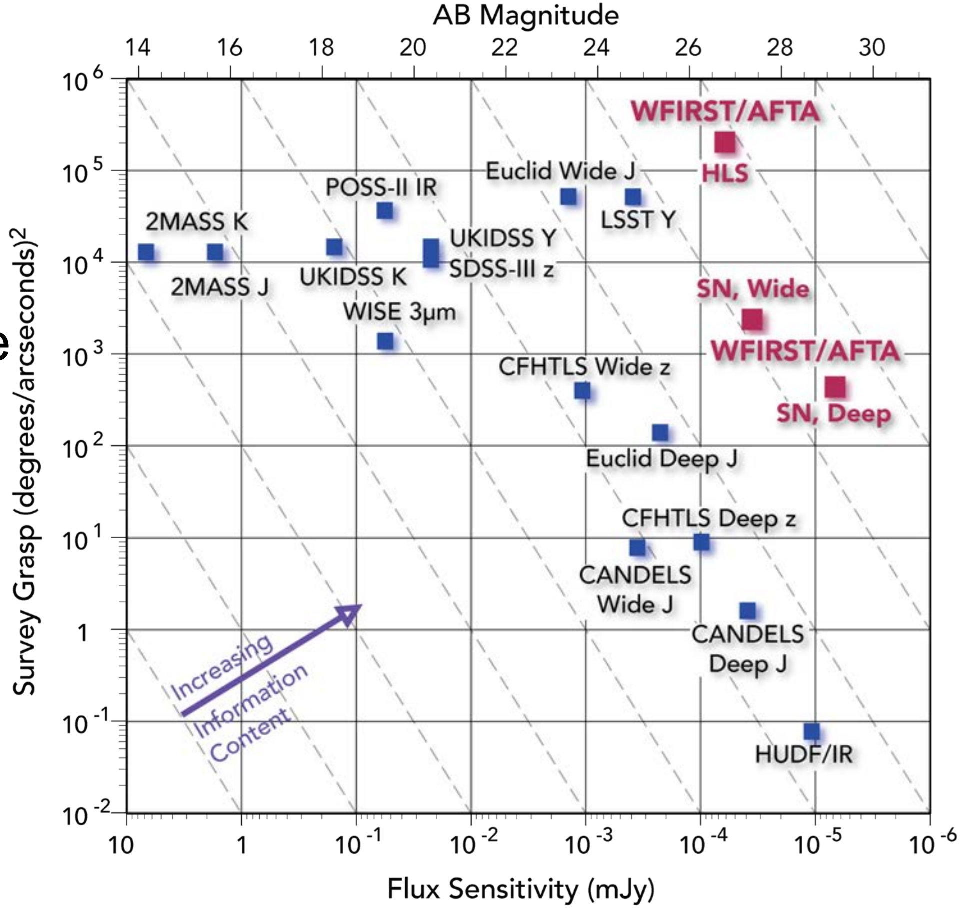
- Routine mission overheads (e.g. large slews between observing programs, momentum unloads, station-keeping) are interleaved with the observing program activities

DE SURVEY COMPLEMENTARITY AT A GLANCE

STAGE IV	LSST	WFIRST	Euclid	DESI
Start, duration	2022, 10 yr	~2025, 5 (-10) yr	2021, 6 yr	2019, 5 yr
Area (sq. deg.)	20,000 (S)	2,000 (S)	15,000 (N+S)	14,000 (N)
FOV (sq. deg.)	10	0.281	0.53	7.9
Diameter (m.)	6.7	2.4	1.3	4
Photometric Survey	6 bands (u,g,r,i,z,y)	6 bands (Z,Y,J,H,F,184,W149)	4 bands (VIS,Y,J,H)	
Photometric Galaxies (w/ shapes) (#/arcmin^2)	~30 in 6 bands (ugrizy)	~68 in 4 bands (YJHF184)	~30-35, in 1 band (VIS)	
SN1a	10^4-10^5/yr z=0-0.7 photometric	2700 z=0.1-1.5 IFC spectroscopy		
Spectroscopic Survey		Grism R=550-800 1-2 µm	Grism R=250 1.1-2 µm	Fibers R=4000 0.36-0.98 µm
Spectroscopic Galaxies		ELGs z=0.5-1.8 (Ha/ ~20M) z=0.9-2.8 (OIII/ ~2M)	ELGs, z~0.7-2.1 (20M)	LRGs+ELGs z~0.6-1.7 (20-30M) QSOs/Lya 1.9<z<4 (1M)

WFIRST Surveys

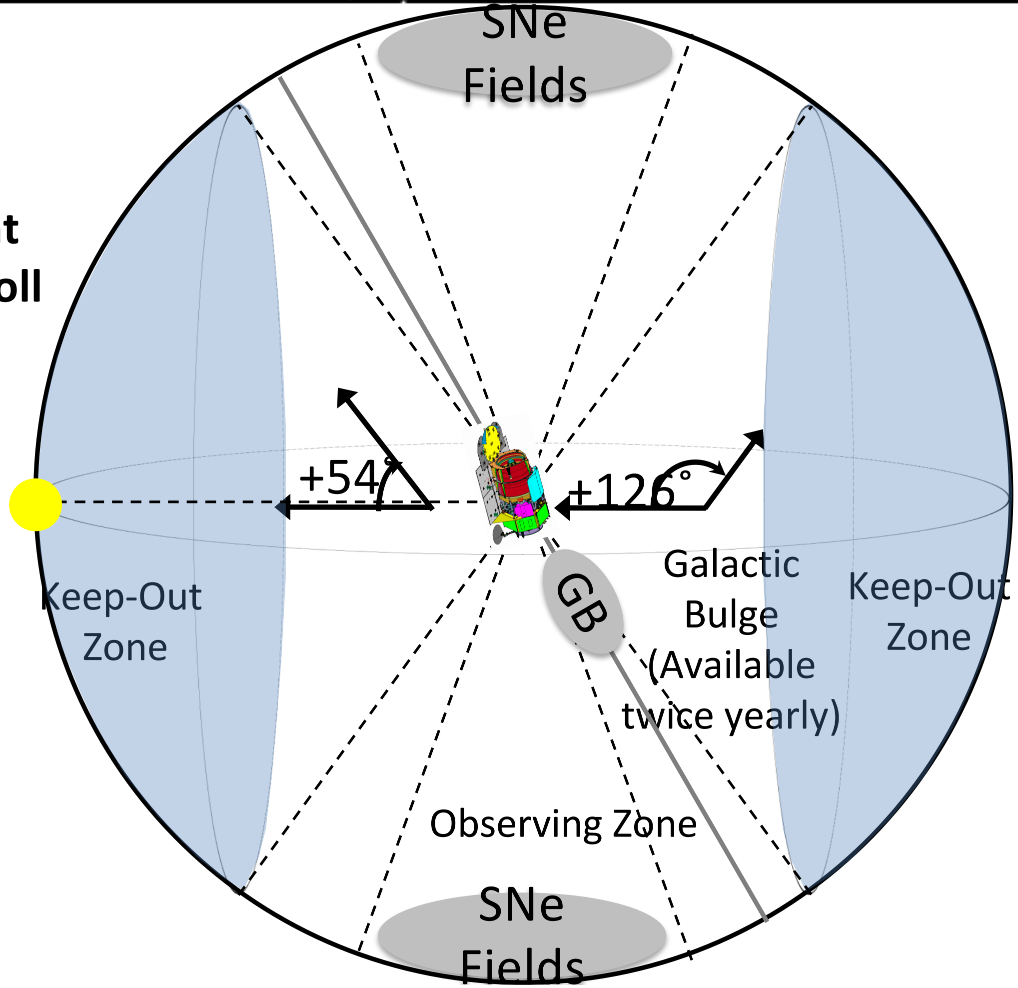
- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



Near Infrared Surveys

Field of Regard (FOR)

Observing Zone:
- **54˚-126˚ off Sun Line**
- **360˚ about Sun Line**
- **±15˚ about line of sight (LOS) off max power roll angle**



SNe fixed fields ±20˚ off of the ecliptic poles, located in continuous viewing zone

Earth/Moon LOS avoidance angles are a minor sporadic constraint

HLS/GO/Coronagraph observations can be optimized within the full Observing Zone

Microlensing can observe inertially fixed fields in the Galactic Bulge (GB) for 72 days twice a year