The NRO-1 2.4-m Telescope:

A game-changing opportunity to accomplish priority science programs of "New Worlds New Horizons"

-- Alan Dressler, presentation to the Committee on Astronomy & Astrophysics
June 4, 2012

NASA hopes to use the first of the NRO telescopes to further the scientific goals of the New Worlds, New Horizons Decadal Survey, in keeping with a four-decade tradition of using A&A Decadals as roadmaps for the Astrophysics program of the Science Mission Directorate.

The presentation today at this first meeting of the NRC Committee on Astronomy & Astrophysics recognizes the CAA's primary and key role: stewardship of the NWNH Decadal Survey --- the responsibility to further the science goals of the Survey through the decade in the context of changing resources, scientific priorities, and developing astronomical facilities in the U.S. and the world. Furthermore, in this particular case, the CAA is an appropriate body to help organize the astronomical community to the task of taking full advantage of this remarkable opportunity.

My presentation is based on the work of a small group asked by NASA HQ to provide a preliminary answer to the question "Can a 2.4-m NRO-developed telescope make substantial progress on the priority science goals of the NWNH survey?" This group included Matt Mountain, David Spergel, Alan Dressler, Marc Postman, Jeremy Kasdin, and Erin Elliott.

The New Worlds New Horizons Decadal Survey recommended 1.5-m wide-field infrared space telescope --- WFIRST --- as its highest priority space mission for the 2010-2020 time frame. The recommendation to the Decadal Survey Committee from the Electromagnetic Observations from Space Panel was based on the recognition that, among the >50 proposals for new space initiatives, several of the highest priority science programs needed essentially the same space facility:

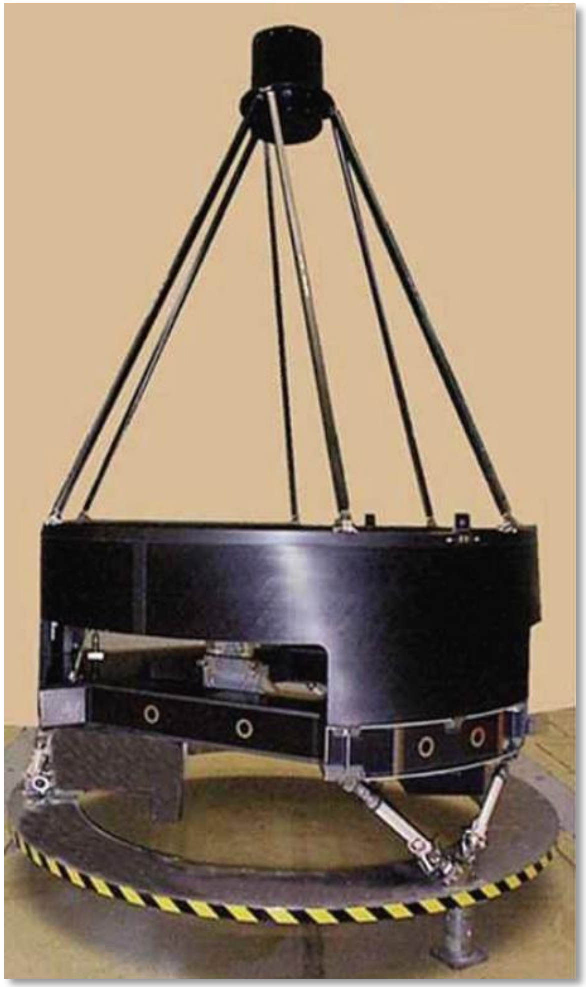
"Subjects as disparate as the history of the acceleration of universe, the discovery of exoplanets in habitable zones and beyond, the history of the assembly of the Milky Way and the evolution of galaxies in the first billion years all stood to benefit from the dramatic increase in the number of infra-red sensitive pixels -- roughly 200 million -- that one could reasonably hope to place in orbit." --- Dr. Paul Schechter, testimony to the House Appropriations Subcommittee, March 22, 2012

Schechter's point is key: The NWNH vision of the WFIRST mission was a 1.5-m telescope with a large-area IR camera. Although the description of WFIRST in NWNH included a strawman concept for the telescope (essentially the JDEM-Omega design), it is not the telescope that defines WFIRST, but neither is WFIRST just a collection of science goals. The hardware that is the key is a wide-field IR camera in space, capable of carrying out a diverse program of Dark Energy, Planet-finding, Surveys, and GO science.

Picture of the "dynamic test unit"courtesy of Exelis via Gary Matthews

Brief Summary of New Asset

- Two 2.4-m telescopes have been transferred to NASA:
  - Designed as a TMA system but tertiary mirror is not applicable for science mission
  - Primary mirror is f/1.2, on-axis system
  - Compact design is similar to the dynamic test unit shown here
  - Thermal control heaters are already on the shell
  - 6 struts position the secondary mirror
    - 6 actuators at the base of the SM struts
    - 1 focus actuator on the SMA for fine focus
  - Long struts to spacecraft bus provide approximately 1.5m of available space for aft optics, instruments, etc.

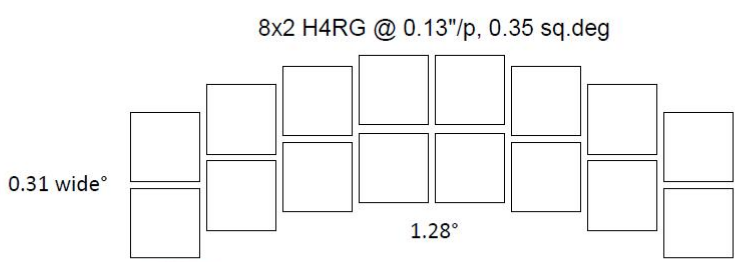


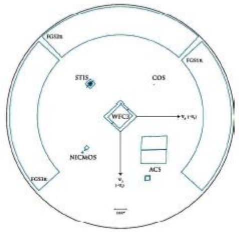
Preliminary Instrument Design:

- Based on existing telescope primary and secondary mirrors without changes
- Initial wide-field instrument shown; 2nd wide-field instrument would be a mirror image
  - 3 mirror camera, folded, with filter at pupil
- Filter & prism wheels (not shown) in ea. wide field instrument
- Fits within instrument volume implied by existing struts

Potential Payload Overview:
- 2 wide field instruments
- 2 small, finer sampled instruments

GSFC study

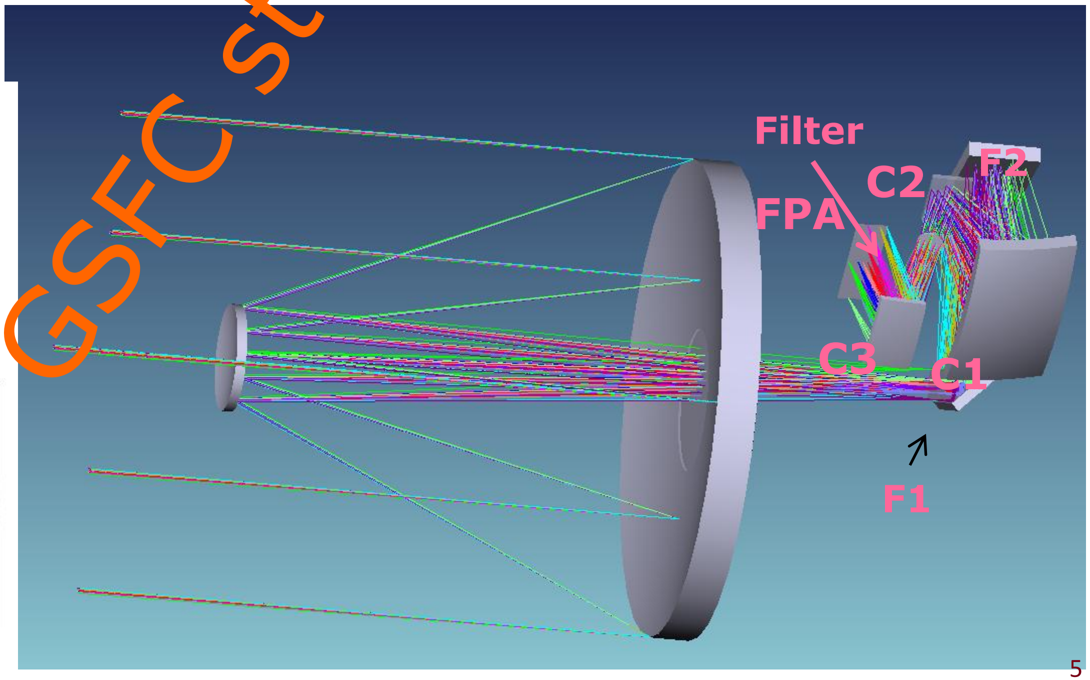




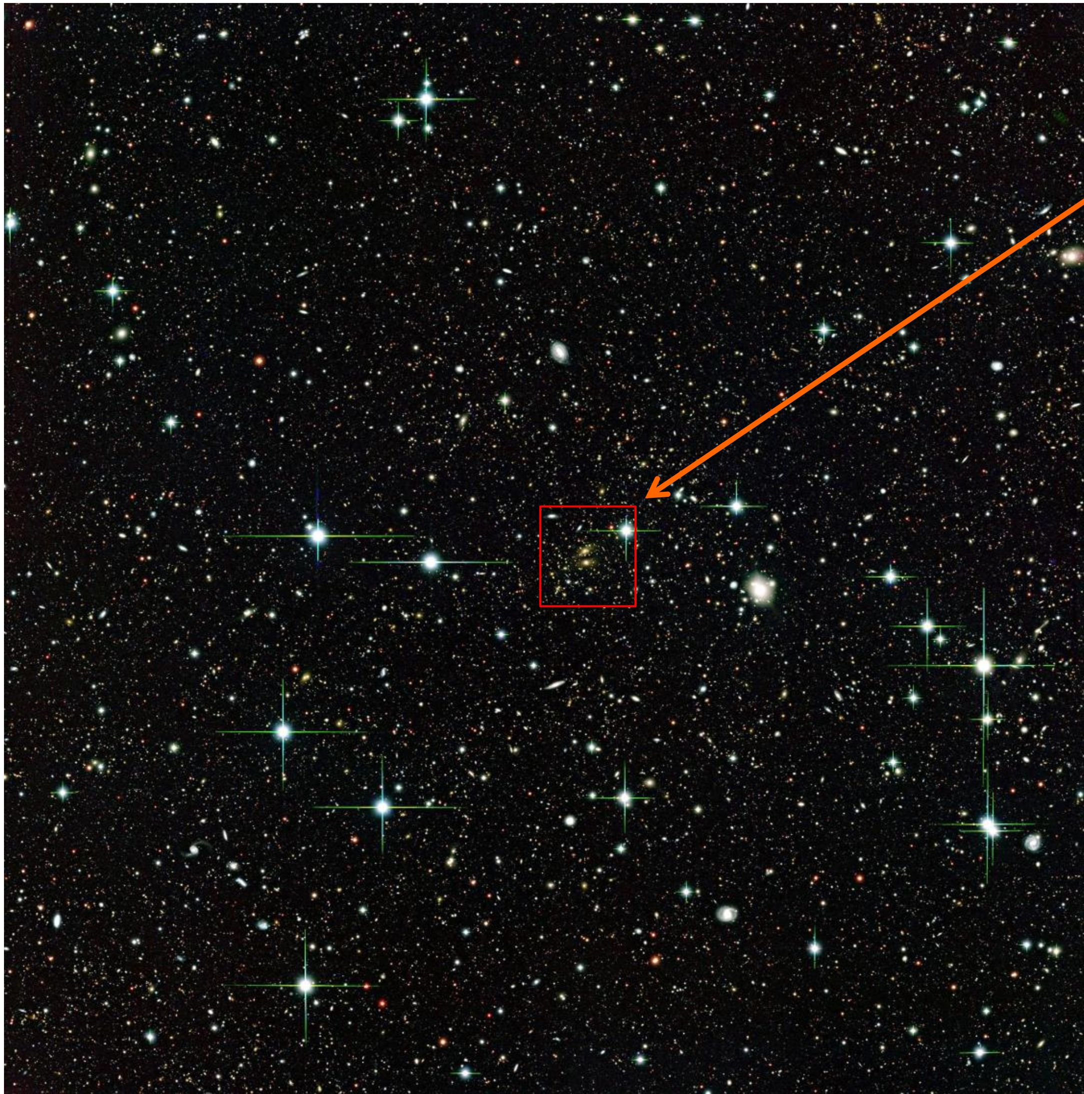
HST [all instruments]

JWST [all instruments]

Moon (average size seen from Earth)



100x the Area as HST's WFC3/IR cam



0.25 sq deg FOV

HST WFC3/IR FOV

Existing telescope has a 2.4-m f/1.2 primary with a 9% obscuration secondary that produces a 1/20 wave near-IR optical system at about f/8 <u>assembled and tested.</u>

A preliminary 3-mirror design uses 16 Hawaii 4RG HgCdTe IR-detectors (10µm pixels) to cover 0.25 sq deg at 0.11"/pixel, compared to this telescope's 0.15" diffraction limit at 1.5µm

This is slightly better sampling than the SDT 1.5-m WFIRST with 0.18" pixels for a 0.24" diffraction limit.

A preliminary look at how the NRO-1 telescope will accomplish the two “core program” goals, Dark Energy surveys and Microlensing planet-finding:

Chris Hirata: Extragalactic Survey Programs – Imaging (Weak Lensing) and Redshift (BAO) -- with the 2-4m NRO-1 telescope

Assumptions:

- 2.4-m, obstructed, with mask at real exit pupil
- H4RG detectors @ 0.0975"/p (1 pix = 10 μm)
  - Same sampling relative to the diffraction spot as WFIRST-DRM1.
  - Assumed that a read noise of 20 e/CDS (with 5 e floor) reached for the mature devices.
- Area = 0.25 deg^2 --- this is 20 detectors.
- Fore optics @ 250 K
- 4 filters for survey mode (F105/F129/F159/F194), similar to 2012 WFIRST DRM.
  - But with λ_{max} = 2.175 μm (where it gets painful).
  - Compare to red cutoff of 2.0 μm (WFIRST 2011 IDRM) or 2.4 μm (current WFIRST).
- Copied the WFIRST DRM1 observing sequence, but with longer exposures for the imaging mode (270 s) to get below the read noise at the lower frame rate.
- This is only a preliminary sensitivity calculation – would need a serious study to understand the issues involved.

Chris Hirata: (cont.)

Increasing complementarity with EUCLID

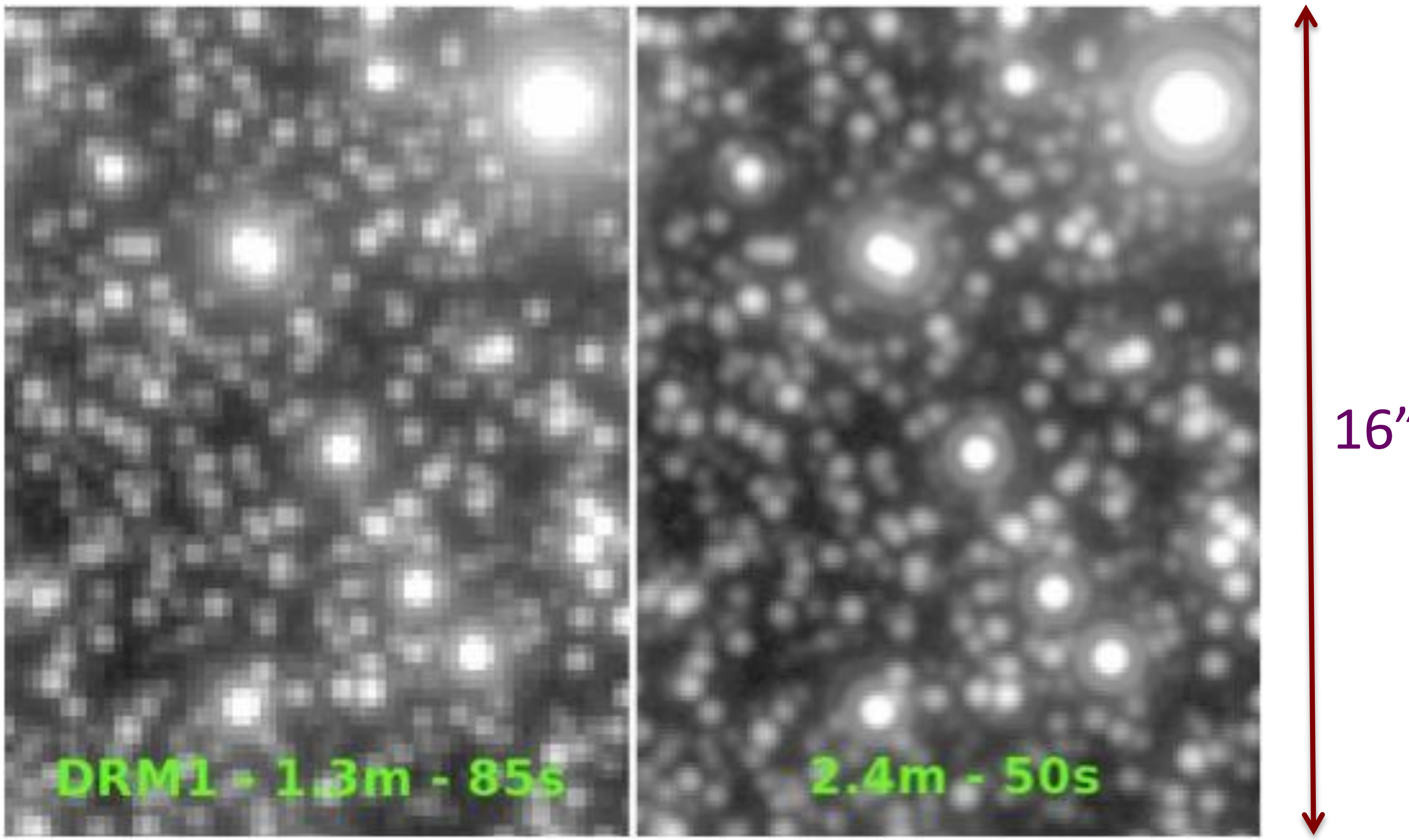
Summary: Extragalactic Surveys

	WFIRST DRM1	WFIRST DRM2	Big Telescope
Implementation	1.3 m unobs 36 H2RG 0.18”/p	1.1 m unobs 14 H4RG 0.18”/p	2.4 m obs 20 H4RG 0.0975”/p
Imaging Survey* [4 filters for all; depths are 5σ isolated pt src]	0.92—2.40 μm 26.0—26.2 mag AB 2800 deg²/yr EE50 = 0.15—0.21”	0.92—2.40 μm 25.8—26.0 mag AB 2900 deg²/yr EE50 = 0.18—0.25”	0.92—2.17 μm 26.9—27.3 mag AB 1080 deg²/yr EE50 = 0.11—0.14”
Weak Lensing [reddest 3 filters]	30, 33, 32 gal/am²	24, 26, 25 gal/am²	79, 82, 72 gal/am²
Redshift Survey [≥7σ Hα detections]	z = 1.28—2.66 4900 gal/deg² 2900 deg²/yr	z = 1.59—2.66 2900 gal/deg2 4400 deg²/yr	z = 1.13 – 2.20 4900 gal/deg² 4000 deg²/yr

* The big telescope could in principle support an accelerated imaging mode matching the WFIRST DRM1 survey rate of 2800 deg²/yr. This reaches depth of 25.8—26.0 mag AB and 26/31/32 galaxies per arcmin². This survey is heavily read noise limited (90 s exposures) so may not be the best use of a big telescope.

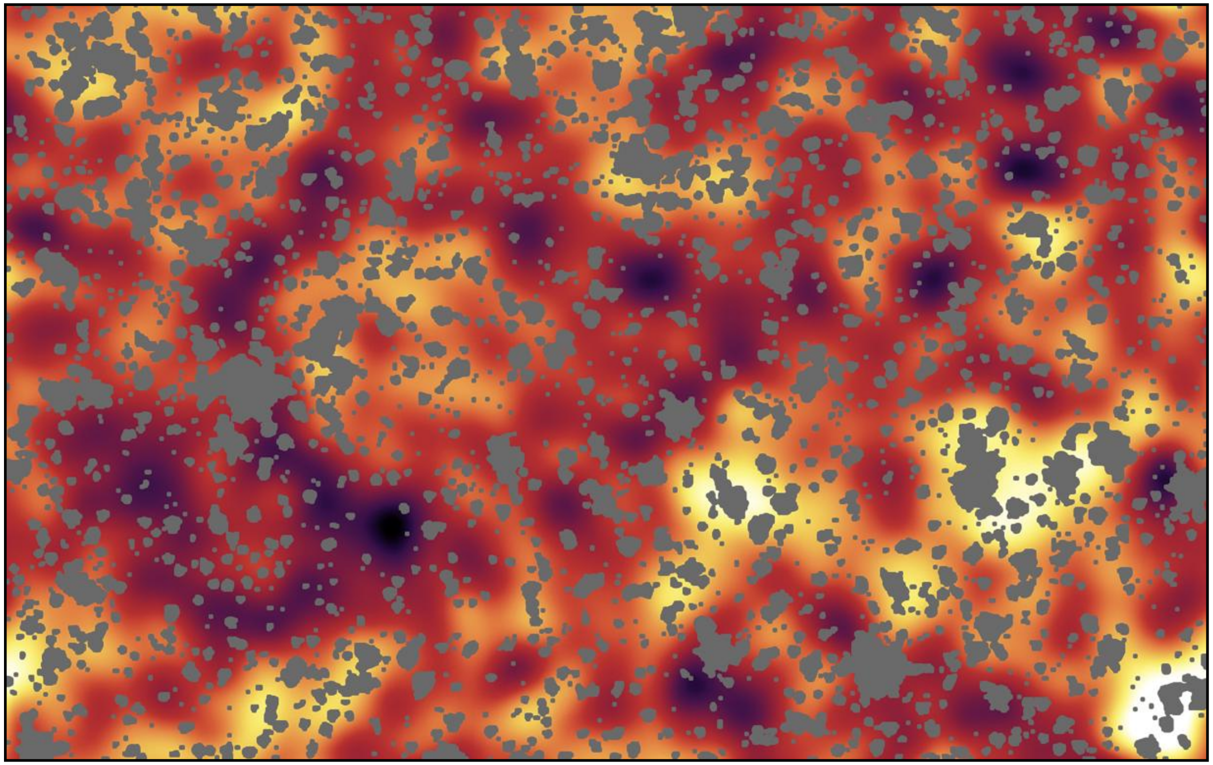
From Matthew Penny (OSU) and David Bennet (NDU): Microlensing planet-finding: a demographic survey complementing Kepler mission, R > 1AU – beyond the snow line!

Performance of NRO-1 2.4-m compared to SDT WFIRST (DRM1) . The images compare an "equal-duration, equal-area" survey of a Galactic Bulge field (assuming a 2.4-m field of 0.25 sq deg). The total area covered in 15-minute cycles is 2.5-deg, with 7 DRM1 fields or 10 2.4-m fields.



From Daniel Stern’s talk at “Science with a Wide-Field IR Space Telescope”

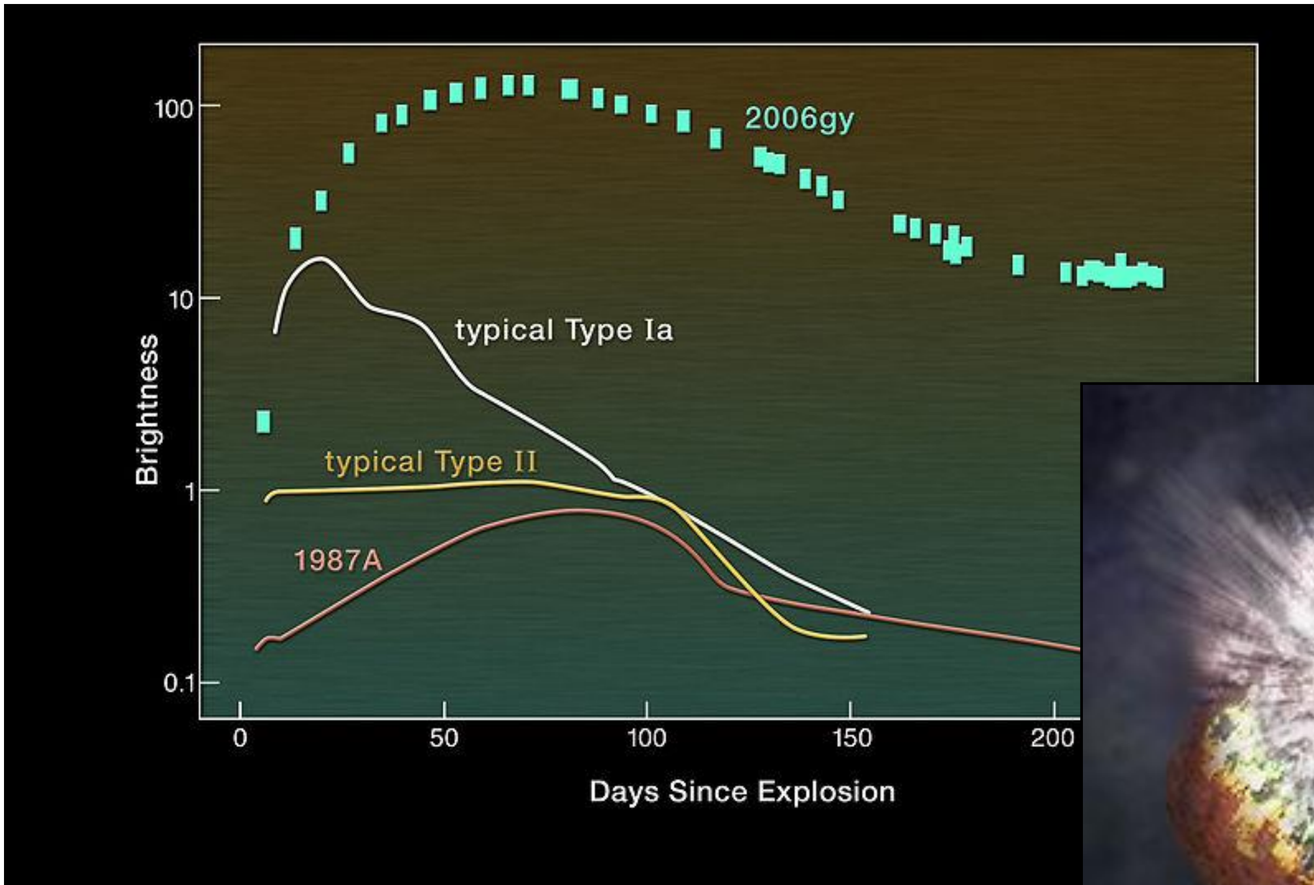
diffuse infrared background in the near-IR is a probe of primordial star formation at z > 8. WFIRST or NRO-1 2.4-m trumps JWST because of the more than an order-of-magnitude greater entendue



clustered emission from **first** generation of star formation in the Universe;
expected at near-infrared wavelengths (controversial claims already by Spitzer)

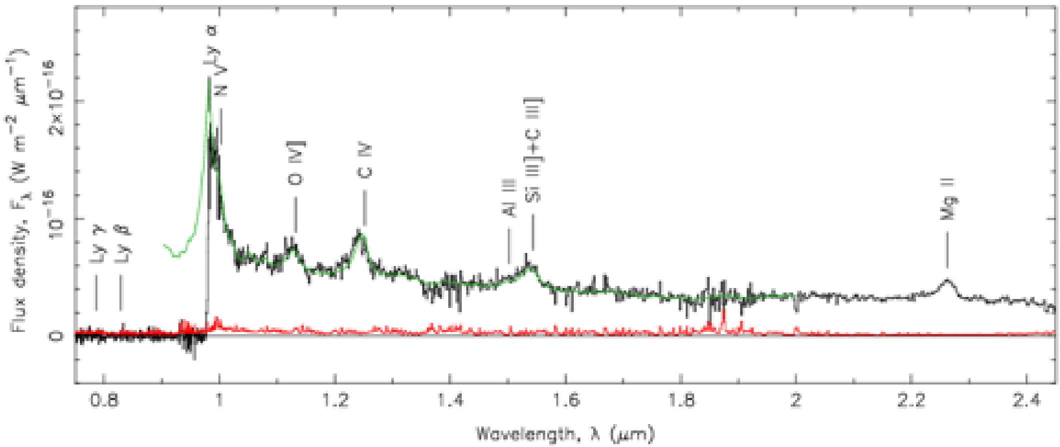
From Daniel Stern’s talk at “Science with a Wide-Field IR Space Telescope”

population III supernovae (see Ranga-Ram Chary’s talk): Could be hard to find with JWST – greater entendue of NRO-1 could make the difference.



From Daniel Stern's "Science with a Wide-Field IR Space Telescope" talk
high-redshift quasars

WFIRST will revolutionize studies of cosmic dawn
- measure the first epoch of black hole formation in the universe
- probe earliest phases of structure formation
- unique probes of the intergalactic medium
- probe the epoch(s) of reionization
- WFIRST will identify the rarest, most distant luminous quasars – NOT JWST science!



QSO at z=7.085. [From Mortlock et al. (2011; Nature, **474**, 616).]

From Daniel Stern's talk at "Science with a Wide-Field IR Space Telescope"

high-redshift quasars

WFIRST will revolutionize studies of cosmic dawn

- surveys to date have identified 15 quasars at $z \geq 6$, including 1 at $z \geq 7$
- ambitious current surveys (e.g., UKIDSS, VISTA) expect to reach ~100 quasars at $z \geq 6$ in next few years, including 1-2 at $z \geq 8$
- WFIRST will identify 1000's of quasars at $z \geq 6$, and push out to z~10+

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

Table 1: Number of high-redshift quasars predicted for various ground- and space-based near-infrared surveys, based on the quasar luminosity function of Willott et al. (2010). Note: For the WFIRST wide survey, we only consider the 4730 deg2 (out of 11,000 deg2 total) that are imaged with at least two exposures in both filters.

LF

Green et al. 2011, WFIRST IDRM (arXiv:1108.1374)

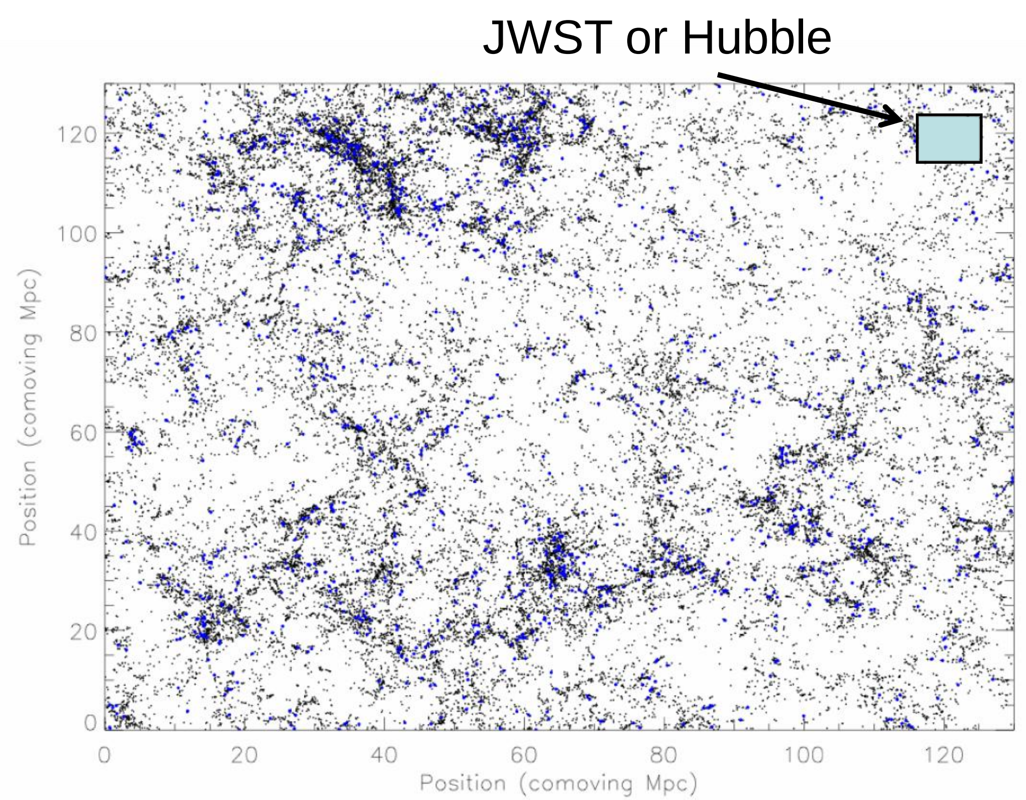
From Daniel Stern's talk at "Science with a Wide-Field IR Space Telescope"

LBGs and LAEs to z~10

WFIRST will be an unprecedented probe of the z~7+ universe

- cosmic variance and issue for HST/JWST studies of LSS at z~7+
- expect large change in LAE LF at reionization; deep grism survey should be sensitive to LAE's during the epoch(s) of reionization; map reionization
- brightest LBGs amenable to detailed study: UV slopes, HeII 1640 emission, early IMF

Fantastic source catalog for JWST spectroscopy!



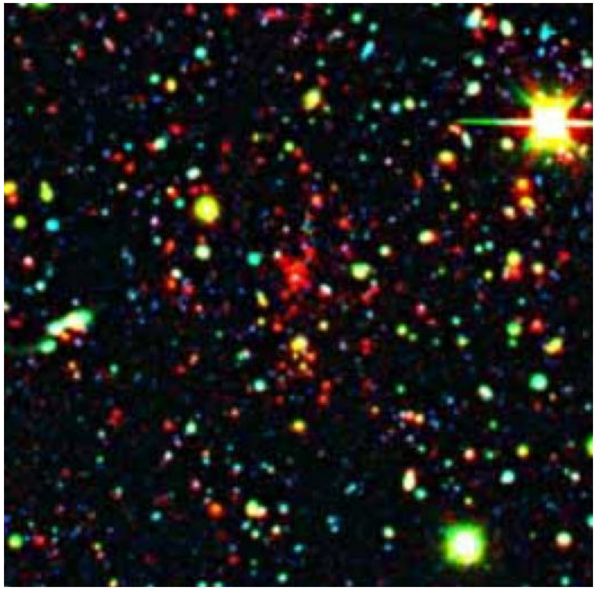
Simulated large scale structure at z=6.6. Black dots are collapsed haloes, blue dots are LAEs. The cyan box in the upper right corner shows the field of view of Hubble/ACS, illustrating that Hubble (and JWST) has much too small of a field of view to study the spatial distribution of z~7+ galaxies. [From Tivli et al. 2008.]

From Daniel Stern's talk at "Science with a Wide-Field IR Space Telescope"

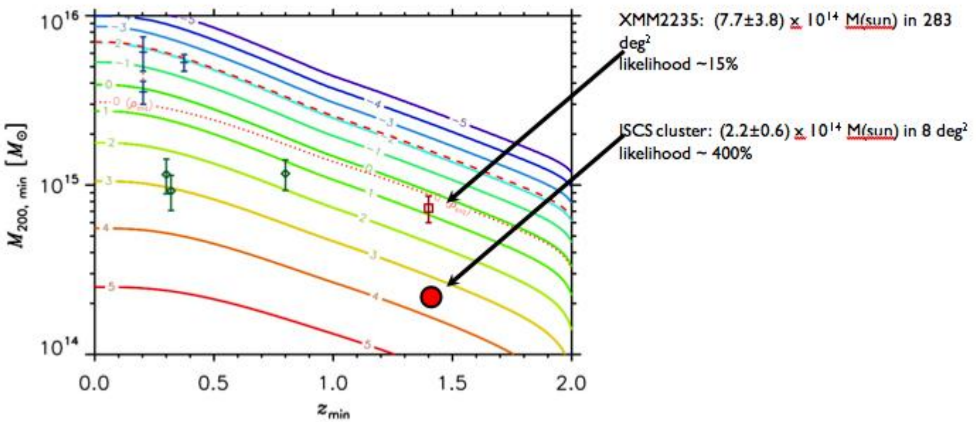
galaxy clusters at z>1

WFIRST will be an extremely powerful tool for finding and confirming clusters at z>1

- interesting cosmologically, for growth of structure
- interesting cosmologically, for probing non-Gaussianity ("pink elephants")
- interesting cosmologically, for efficient identification of type Ia supernovae
- interesting for galaxy evolution
- synergy with eROSITA and SZ surveys

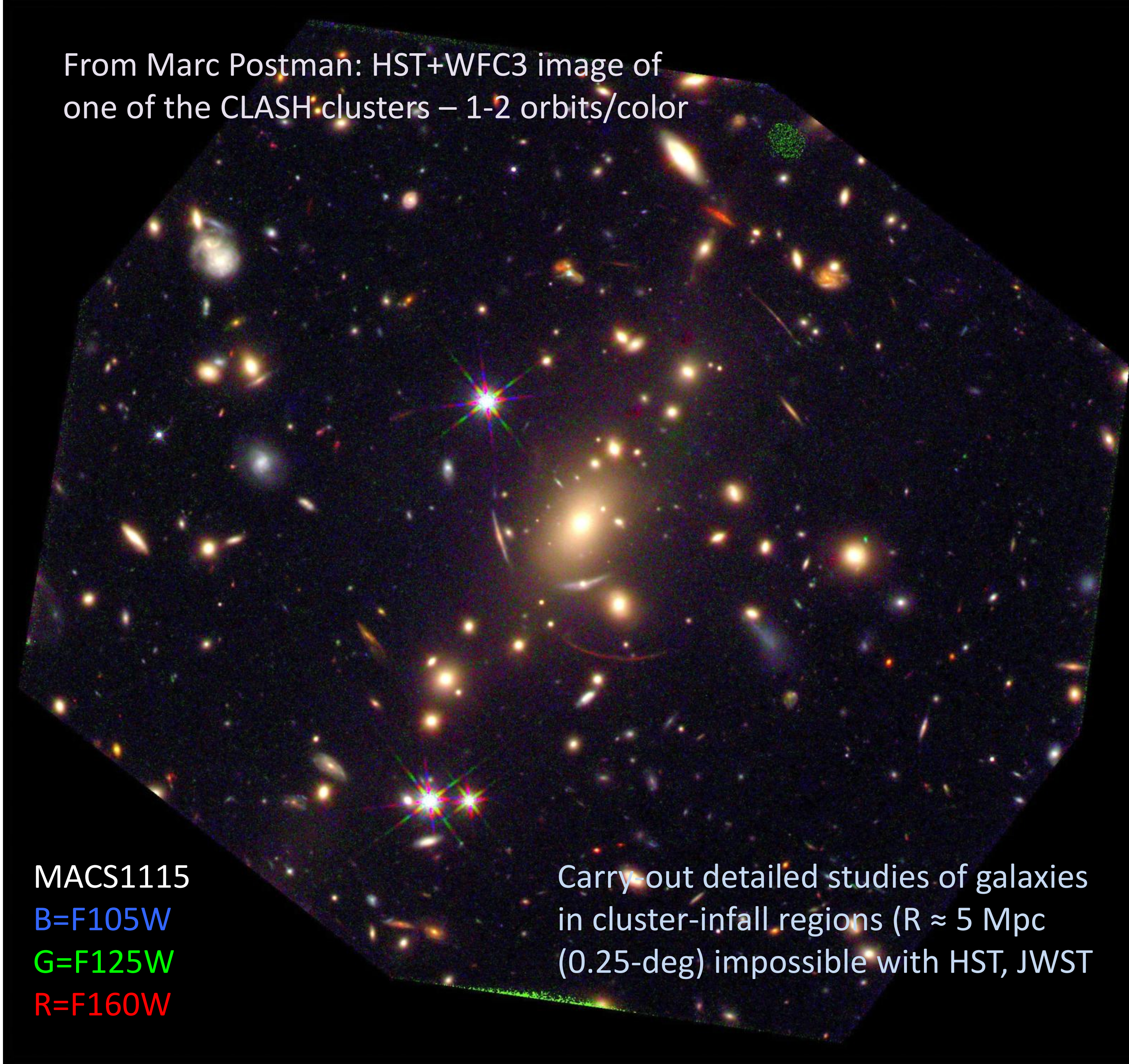


IR-selected galaxy cluster at z=1.413. From Brodwin, Stern et al. (2011; ApJ, **732**, 33).



constraints on non-Gaussianity

Holz & Perlmutter 2012, submitted (arXiv:1004.5349)
Hoyle, Jimenez, & Verde 2011, PhysRevD, **83**, 3502


From Marc Postman: HST+WFC3 image of
one of the CLASH clusters – 1-2 orbits/color
MACS1115
B=F105W
G=F125W
R=F160W
Carry-out detailed studies of galaxies
in cluster-infall regions (R ≈ 5 Mpc
(0.25-deg) impossible with HST, JWST

From Jason Kalirai’s talk at “Science with a Wide-Field IR Space Telescope

Stellar Populations in the Local Volume

Snapshot of WFIRST Survey Science Opportunities inside the Milky Way

1.) Towards the next generation of population synthesis models

- Stretch the color-magnitude diagram
- Better ages and metallicities for nearby calibrators
- Color-magnitude relation and LF of RG and AGB phases in IR bandpasses
- Easy to develop science case using current pencil beam probes

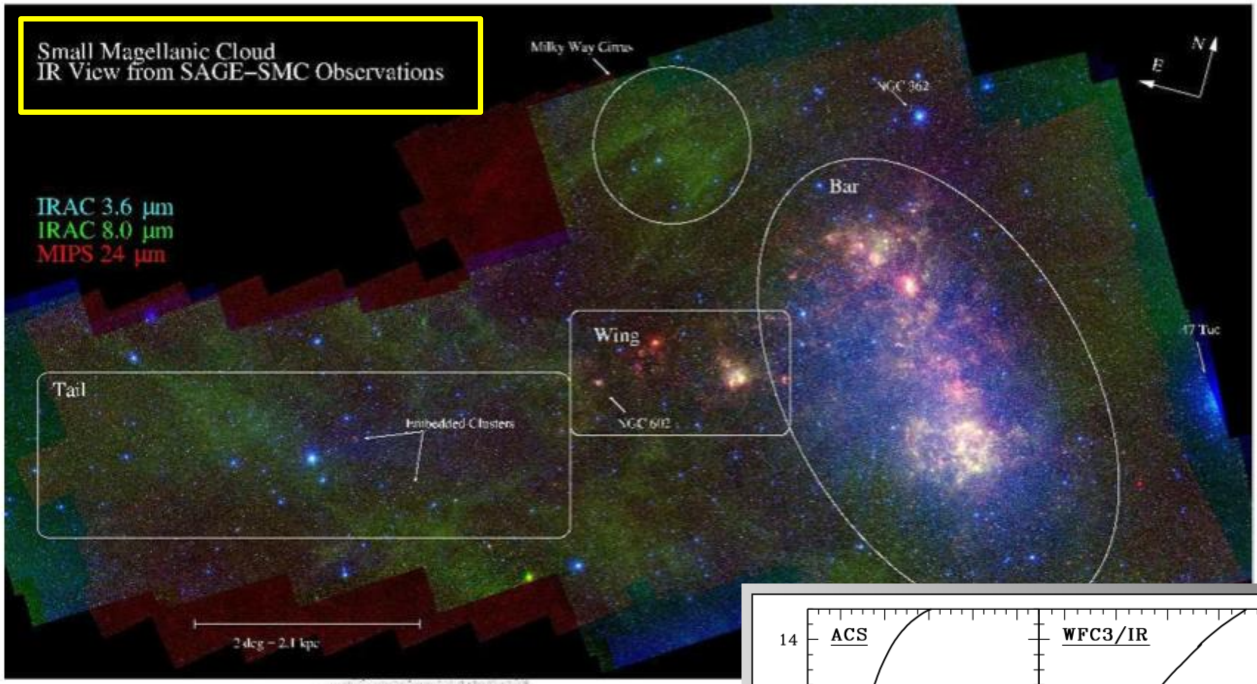
2.) A complete stellar census and the Galactic mass budget

- Stellar mass function is steep, dominated by cool stars
- Map the IMF in different environments
- The H-burning limit as a function of stellar properties
- L and T dwarfs, structure of low mass dwarfs

3.) Stellar remnants as fossils

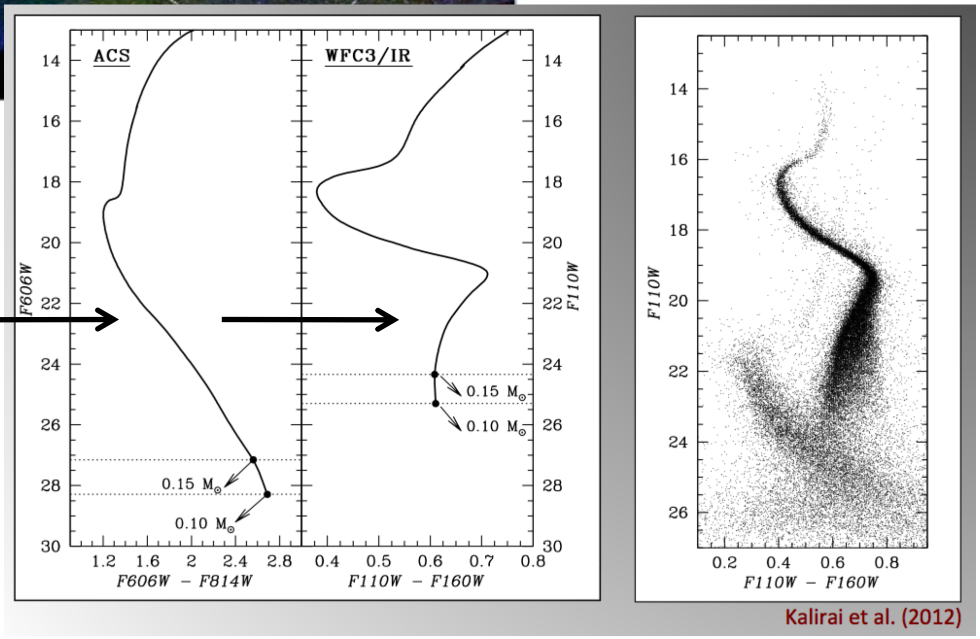
- 98% of all stars will end their lives as white dwarfs
- Cooling ages and temperatures from photometry
- Luminosity functions hold clues on the evolved stellar mass function and Galactic SFR
- Population II IMF through halo searches

resolved stellar populations in nearby galaxies

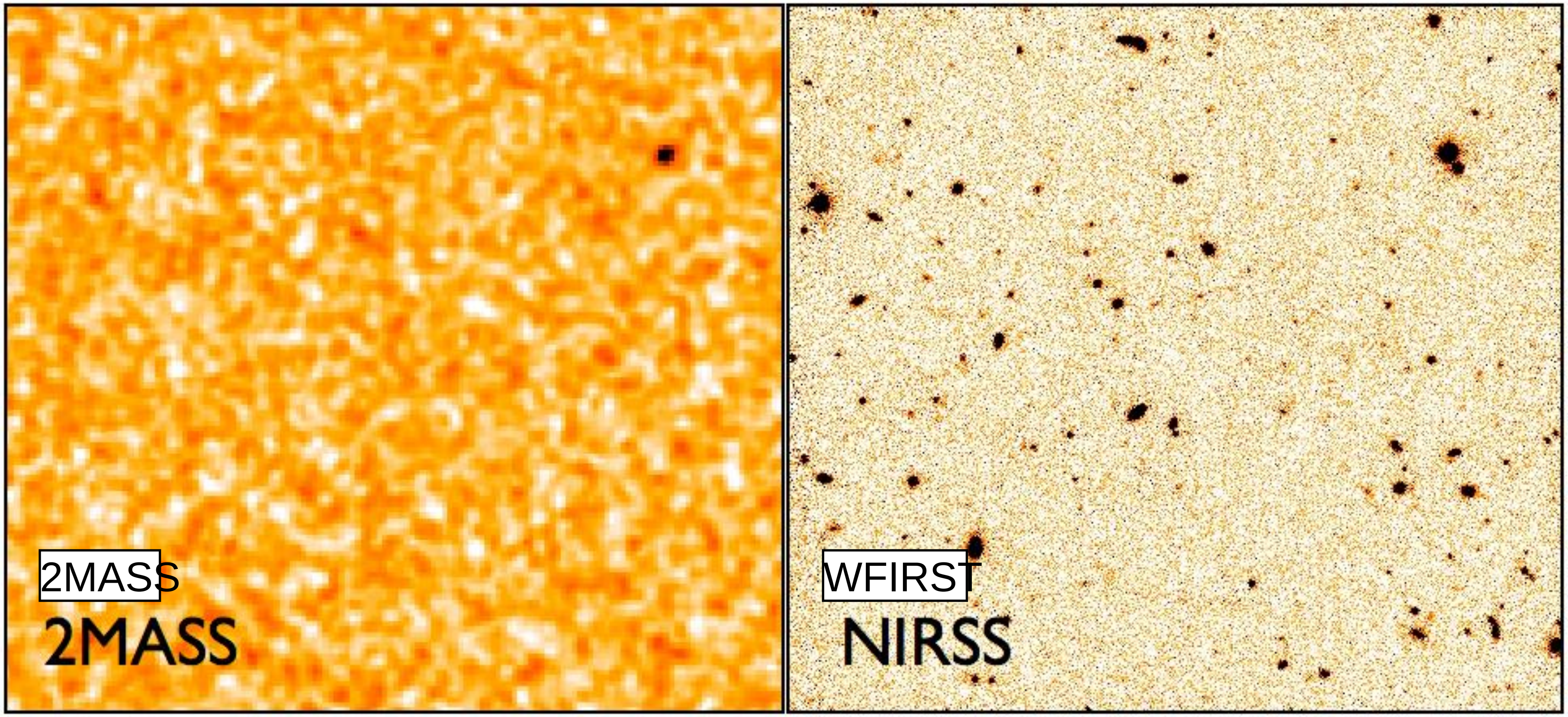


IR color map of SMC is rich in structure that can be identified as distinct stellar populations with color-magnitude diagrams that include near-IR colors (from D. Stern talk)

J. Kalirai: adding IR colors greatly improves precision of age, metal abundance measurements for old stellar populations



All these programs, and many more, will be possible because of the F < 0.1 μJy (> 26 AB mag) reached by NRO-1 for wide-fields. This flux limit is, by the way, a perfect match to the LSST optical surveys: together, astronomers will have a broad photometric catalog that will be powerful for galaxy formation and evolution studies



Coronagraphy with the NRO-1 2.40-m Telescope

Recent advances allow high-contrast imaging at small angles with on-axis telescopes

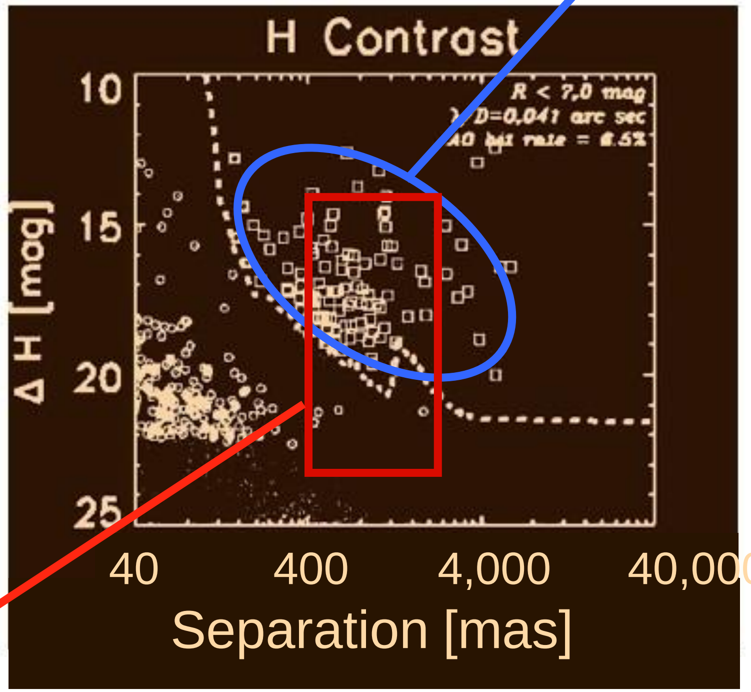
- Uncorrected contrast of up to 10^{-5}, Corrected (with DM) to 10^{-8} or better
- Corrected contrast limited by telescope stability
- Another order of magnitude possible via post-processing
- Inner working angles from 2.5-3 λ/D depending on contrast
- Experimental verification of designs and approach in place

Rich Scientific Opportunities

- Exozodi characterization at inner solar system
- Characterization of RV and Transiting planets
- Protoplanetary disks, brown dwarfs, Hot Jupiters
- Explores habitable zones around up to 30 nearby GFK stars and many more nearby M stars.
- Technology pathfinder for future large telescopes

Compliments ground systems (GPI, SPHERE, Subaru) – Observes in unexplored search space.

Gemini Planet Imager



Repurposed Telescope

dots - all planets
circles - RV
squares - GPI

Image from GPI website (planetimager.org/pages/science_planets.html)

The NRO-1 2.4-m telescope: accomplishing the WFIRST science program of New Worlds New Horizons– and more (and better):

- The 2.4-m telescope will better resolve distant galaxies and has the potential to measure their shapes to higher precision. This telescope can match or improve measurements of weak lensing and redshift surveys, and constrain the distribution of dark matter.
- The 2.4-m telescope's higher resolution will enable it to detect and characterize supernova at higher red-shift, strengthening the third leg of the Dark Energy program.
- By reducing confusion in deep fields, the 2.4-m telescope will be more sensitive to micro-lensing events – more targets, and more accurate photometry.
- The 2.4-m telescope's will be a Hubble-like near-IR telescope, delivering 0.1-0.2 arcsec imaging at 0.1μJy for studies of the stellar populations of nearby galaxies, multi-color surveys of evolving galaxies $1<z<5$, quasars up to $z=10$, large-scale structure at $z=7$, the growth of structure $z < 4$, surveys for and studies of cool stars, star formation in the Galactic plane, and on…
- As well as carrying out its core program, and serving the broad astronomical community through deep and broad surveys and a diverse GO program, the 2.4-m wide-field infrared space telescope will support and complement JWST in its primary goals of the study of the early universe and the formation of stars and their planetary systems. NRO-1 and JWST will continue the tradition started at Palomar with the Schmidt and Hale Telescopes by providing the traditional wide-field "surveyor" for deep follow-up studies by JWST.
- Combining the 2.4-m aperture with its superb on-axis image quality with advances in high-contrast imaging could be a huge step forward in exoplanet research: Jovian-planet finder; Exo-zodi mapper, and even explorer of the habitable zones of the nearest GFK stars searching for Earth-sized worlds.

Some of the issues that need further, detailed study

The Question: Can the science goals of NWNH be suitably mapped onto the existing NRO-1 2.4-m optical telescope assembly (OTA) being made available to NASA with a minimum of changes?

The issues include:

- How to package a wide-field IR camera.

  Area > 0.25 deg? Two cameras? Slightly better sampling?
- The system temperature of the existing OTA, existing coating and long-wavelength cutoff – impact on science program?
- L2 or Geo-sync orbit: does this enable a more cost-effective launch options and data transmission advantages?
- What is the expected stability of optical system given the option to control alignment and more complex optical train compared to SDT WFIRST concept. Will active control compensate for a Geo-Sync orbit and how important is "knowledge" of PSF compared to the ability to control the PSF?

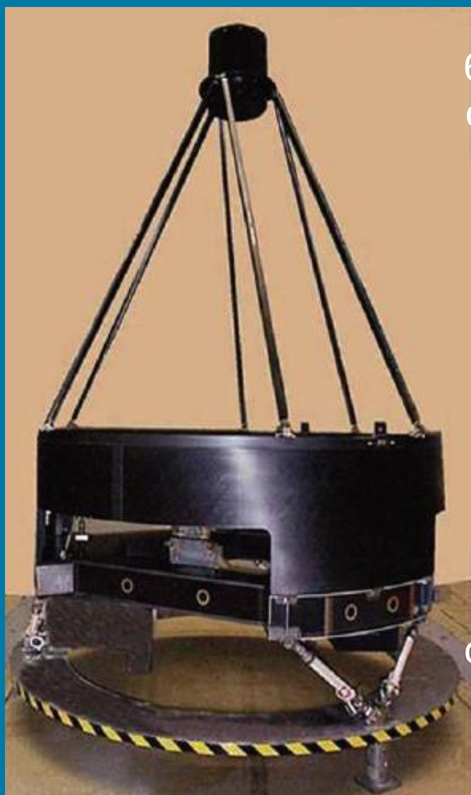
Some issues that need to further detailed study (cont.)

- What spacecraft is required? Heritage design? Schedule and cost?

- Possible "secondary" on-axis instrument, for example, small optical channel or coronagraph.

- Is it possible to cap the cost to launch at $1B, assuming a launch before 2022?

2.4m telescope and possible orbit



6 dof control of secondary

Polynomial Expansion of Wavefront in Polar Coordinates (ρ, θ)

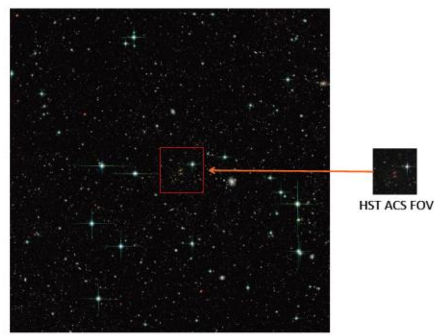
radial	angular	optics name	lensing name
ρ^0	1	piston	time delay
ρ^1	$\sin\theta; \cos\theta$	tilt	deflection
ρ^2	1	defocus	(magnification)$^{-1}$
ρ^2	$\sin 2\theta; \cos 2\theta$	astigmatism	shear
ρ^3	$\sin\theta; \cos\theta$	coma	1-flexion
ρ^3	$\sin 3\theta; \cos 3\theta$	trefoil	3-flexion

exquisite control of ellipticity errors
(uncertainty < 0.0002, Schecter)

Active WFS and control

wide FOV configuration

A.W x 2 WFIRST



WFIRST 0.25 sq deg FOV

Giga-pixel arrays

high data rates

~300K

operate at design temperature

launch infrastructure

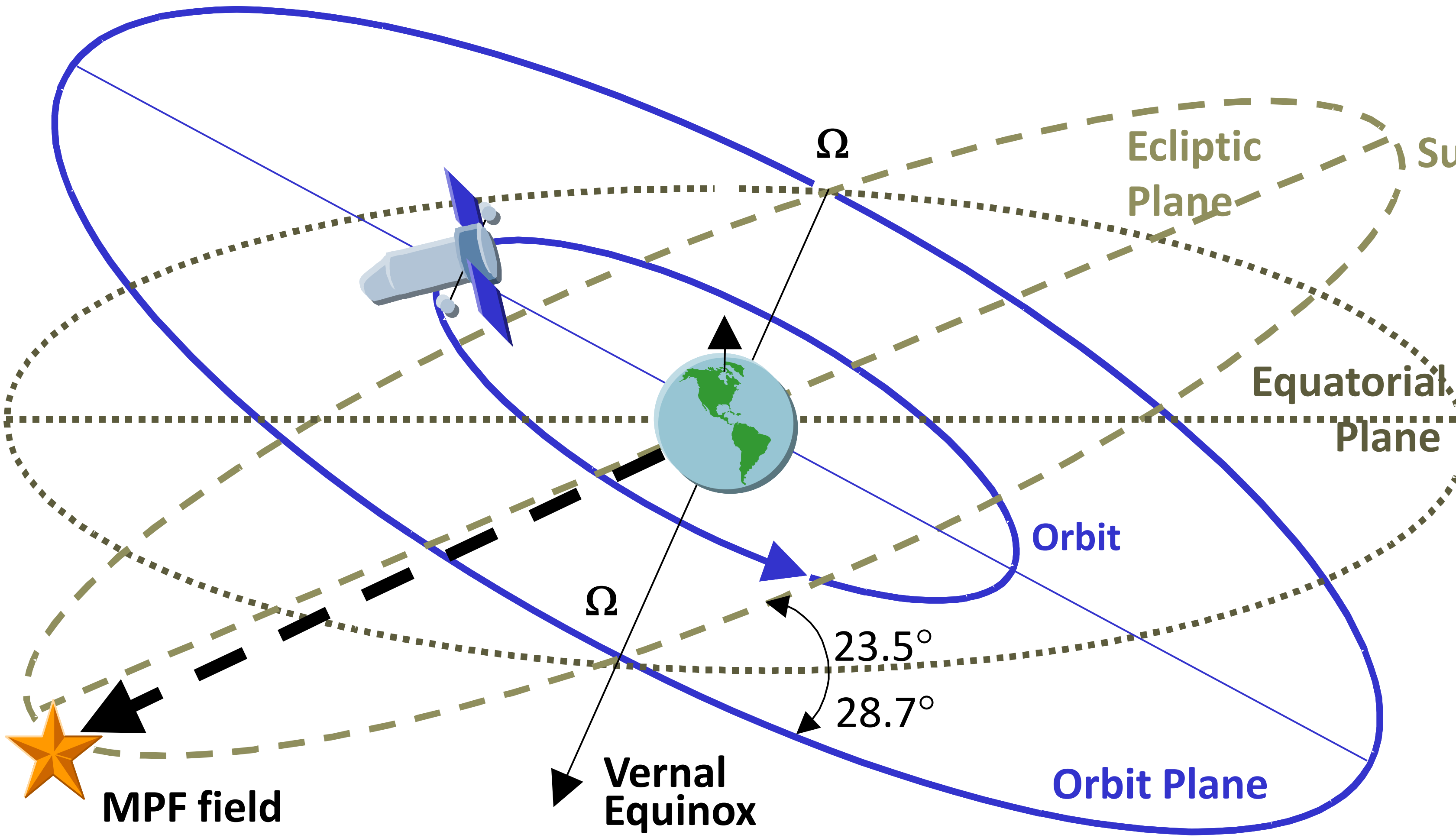
GEO

active stability

simplified flight & science operations

other peoples money

MPF in Geosynchronous Orbit



MPF's orbit allows continuous view of Galactic bulge planet search field and continuous data data downlink to a dedicated ground station in White Sands.

My personal perspective:

Prior to the disclosure of this NRO opportunity, NASA's WFIRST Science Definition Team, led by Paul Schechter and Jim Green, had made great progress in developing the WFIRST mission well beyond the original notions laid out by the EOS Panel and NWNH Decadal Survey Reports. Two design reference missions that could meet and exceed NWNH science goals, within time frame and budget, are well advanced.

However, it is my opinion that, if one of the "new opportunity" NRO 2.4-m telescopes can match or improve on performance, cost, and schedule for the full WFIRST science program --- DE, Exoplanets, IR Surveys, and GO --- this new opportunity supercedes and essentially replaces previous proposals for the WFIRST telescope, but not of course for the wide-field IR camera – the heart of the project. I personally cannot imagine shelving a 2.4-m telescope to pursue one of the current SDT designs unless it could be demonstrated the 2.4-m would fail <u>qualitatively</u> to accomplish the WFIRST science. In that case, NASA and the community would face a difficult decision about whether to go ahead with implementing some reduced WFIRST program, and/or something else covered in NWNH (but not the highest priority)

The present preliminary report suggests that this is not the case and that the potential exists to have greater capability for the WFIRST science, enable additional scientific opportunities, match or reduce cost, and improve schedule, and that this possibility should be pursued as vigorously as possible by the astronomical community.