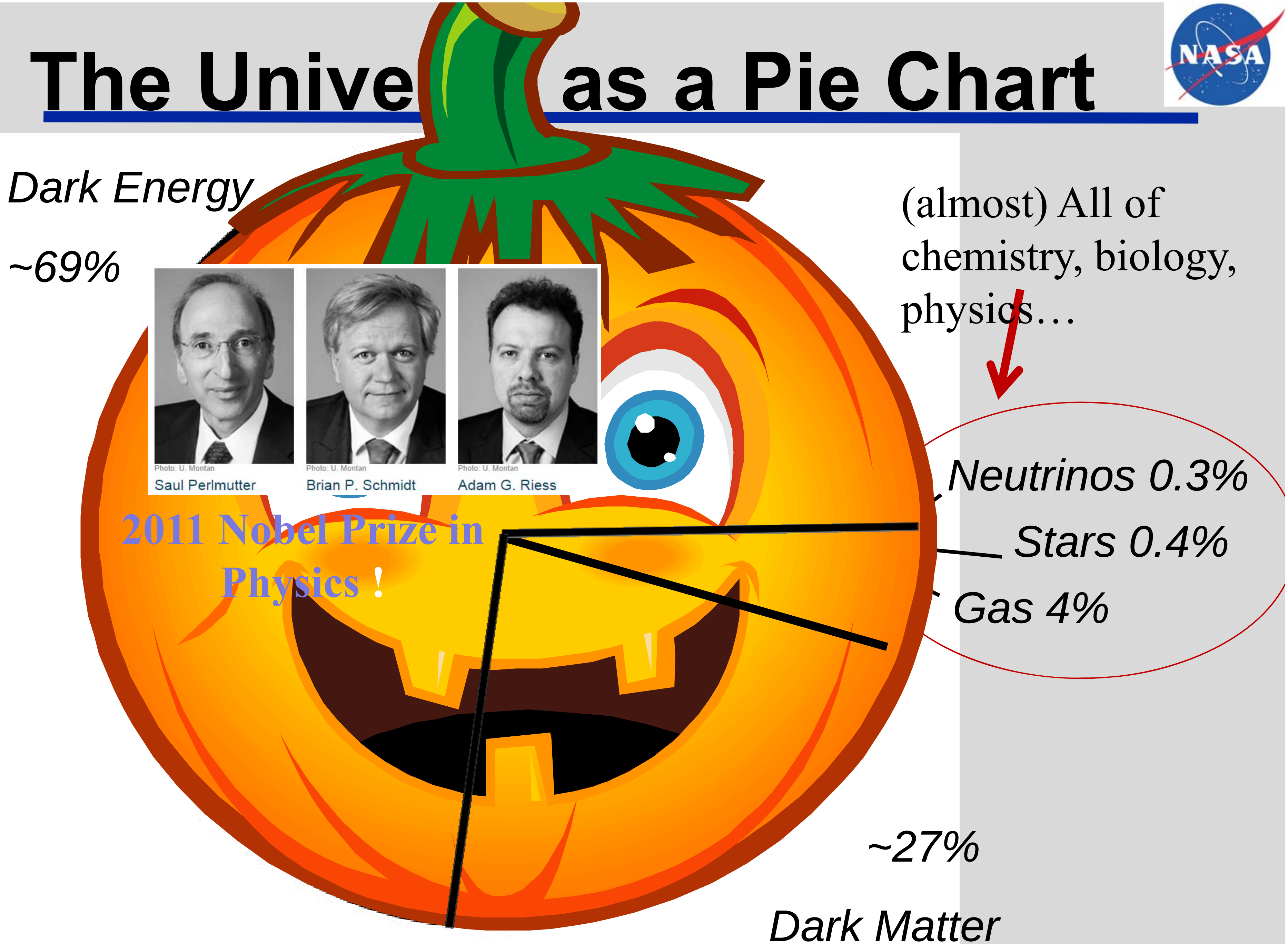
Euclid and WFIRST-AFTA: NASA's Ambitious Dark Energy Program

Jason Rhodes (JPL)

IPMU Seminar

Oct 31, 2014

The Unive as a Pie Chart

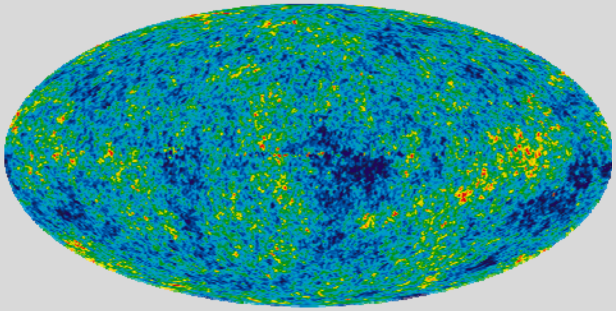


Top level questions

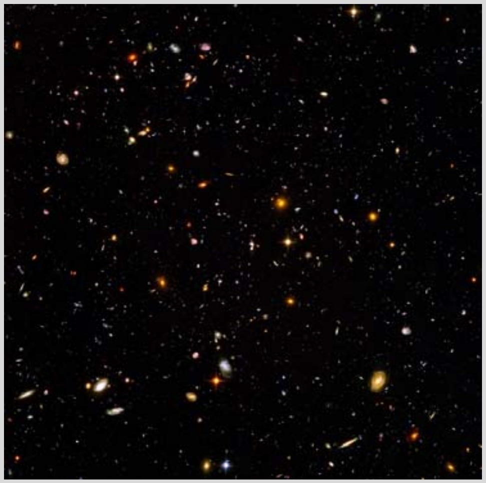
1. **Is cosmic acceleration caused by a new energy component or by the breakdown of General Relativity (GR) on cosmological scales?**
2. **If the cause is a new energy component, is its energy density constant in space and time, or has it evolved over the history of the universe?**

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!*

Probes of DE

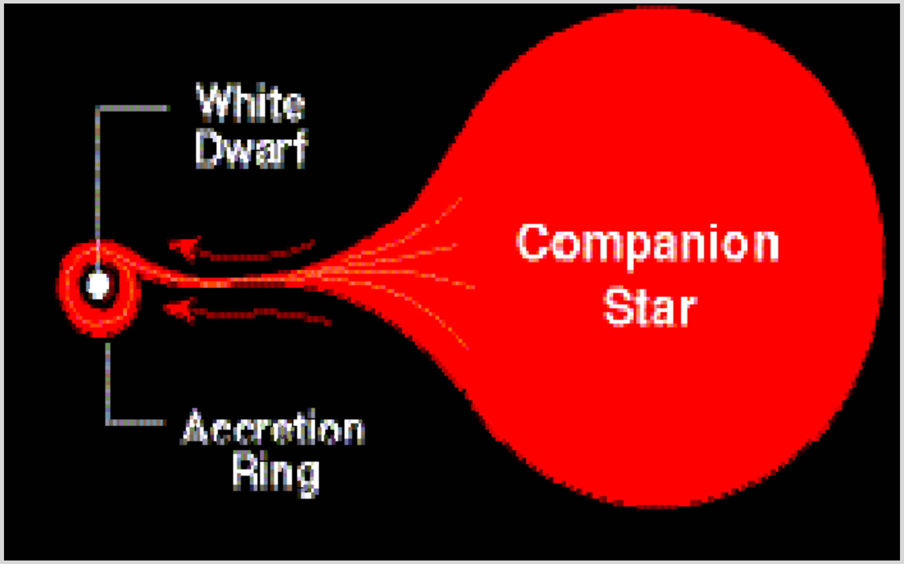
Comparison of expansion history and growth of structure helps distinguish dark energy and modified gravity models

- Supernovae type IA, which act as standard candles to measure the expansion history
- Weak gravitational lensing, the apparent distortion of galaxy shapes by foreground dark matter
  - Measures primarily growth of structure
- Galaxy clustering
  - Baryon acoustic oscillations (BAO), which act as a standard ruler to measure the expansion history
  - Redshift space distortions (RSD) which measure the growth of structure

Dark energy studies are done statistically, and require great precision and attention to systematics

Wide field space missions allow for large statistics and control of systematics

Standard Candles



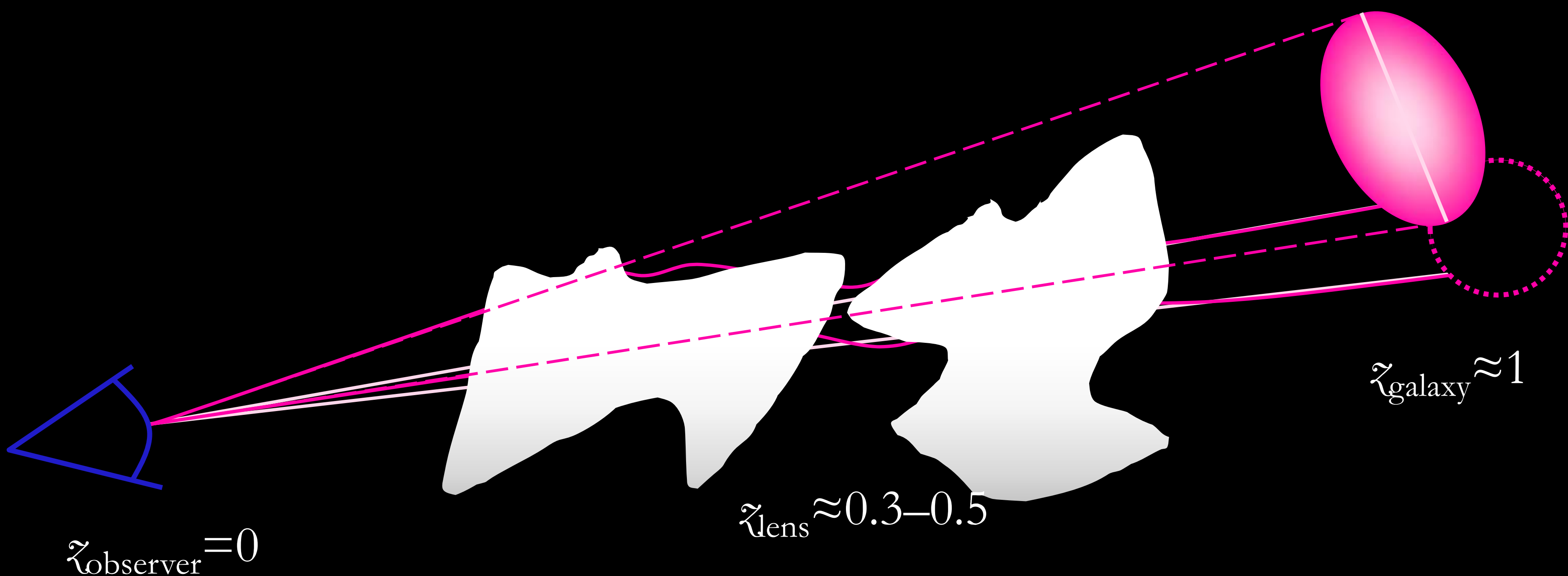
Supernova 1994D, HST, NGC 4526

When the white dwarf accretes enough mass, it explodes. That is a *Supernova Type Ia*. They can outshine the rest of the galaxy, so they are easy to see.

SNIa have a well-defined relationship between the brightness of the explosion and the length of time the ensuing fireball lasts.

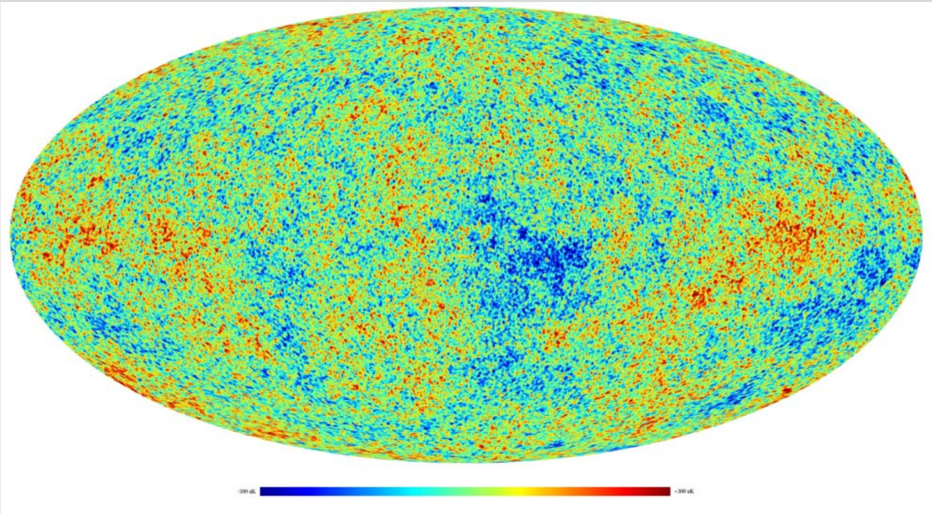
We know how bright they are *intrinsically*, so they are standard candles.

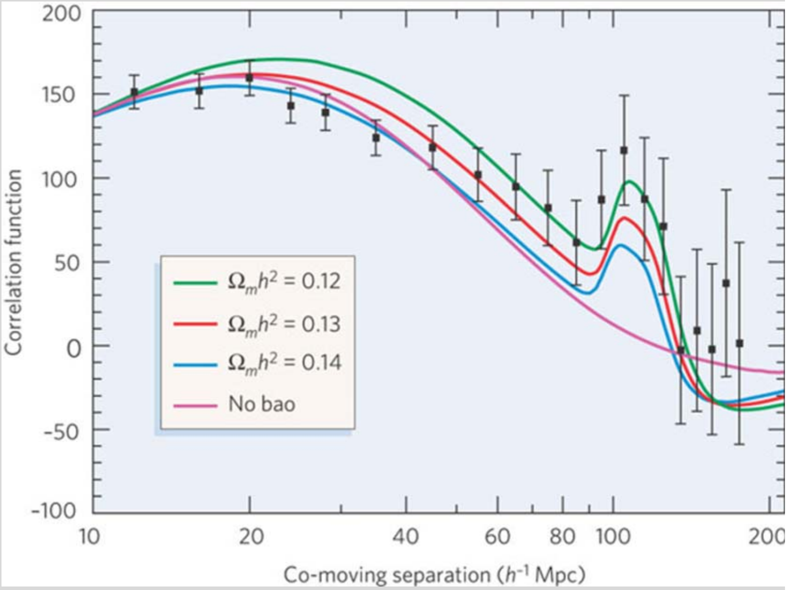
Gravitational Lensing



If there is any intervening large-scale structure, light follows the distorted path (exaggerated). Background images are magnified and sheared by ~2%, mapping a circle into an ellipse. Like glass lenses, gravitational lenses are most effective when placed half way between the source and the observer.

Galaxy Clustering:BAO





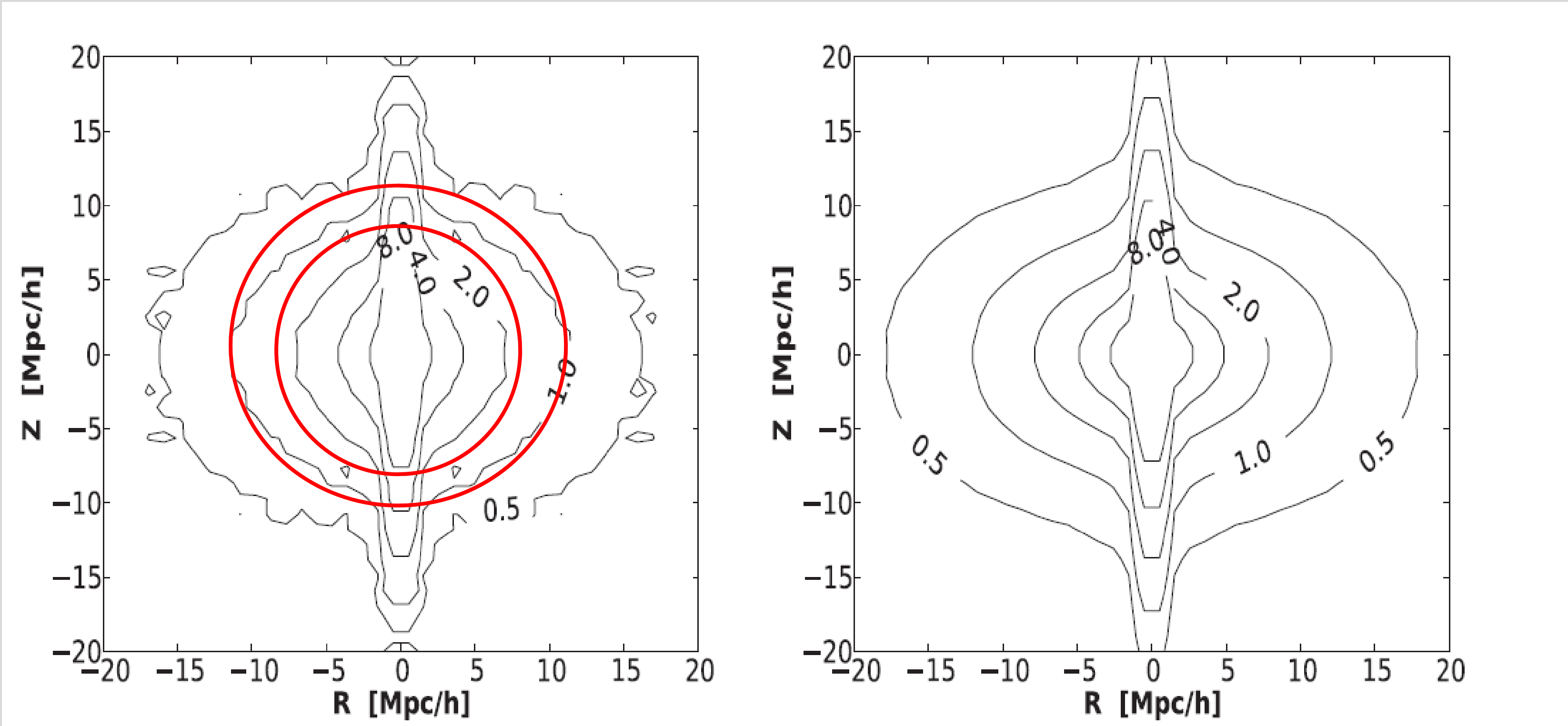
CMB

Clustering of Galaxies

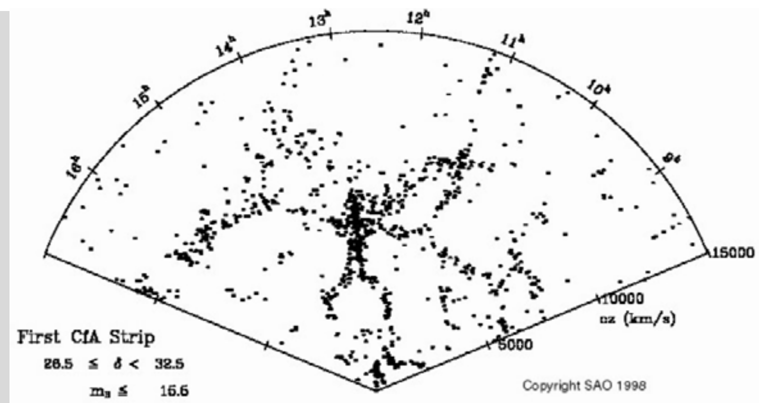
Bennett, Nature

Baryon Acoustic Oscillations make use of the clustering scale of galaxies as a *standard ruler* to measure the expansion history

RSD



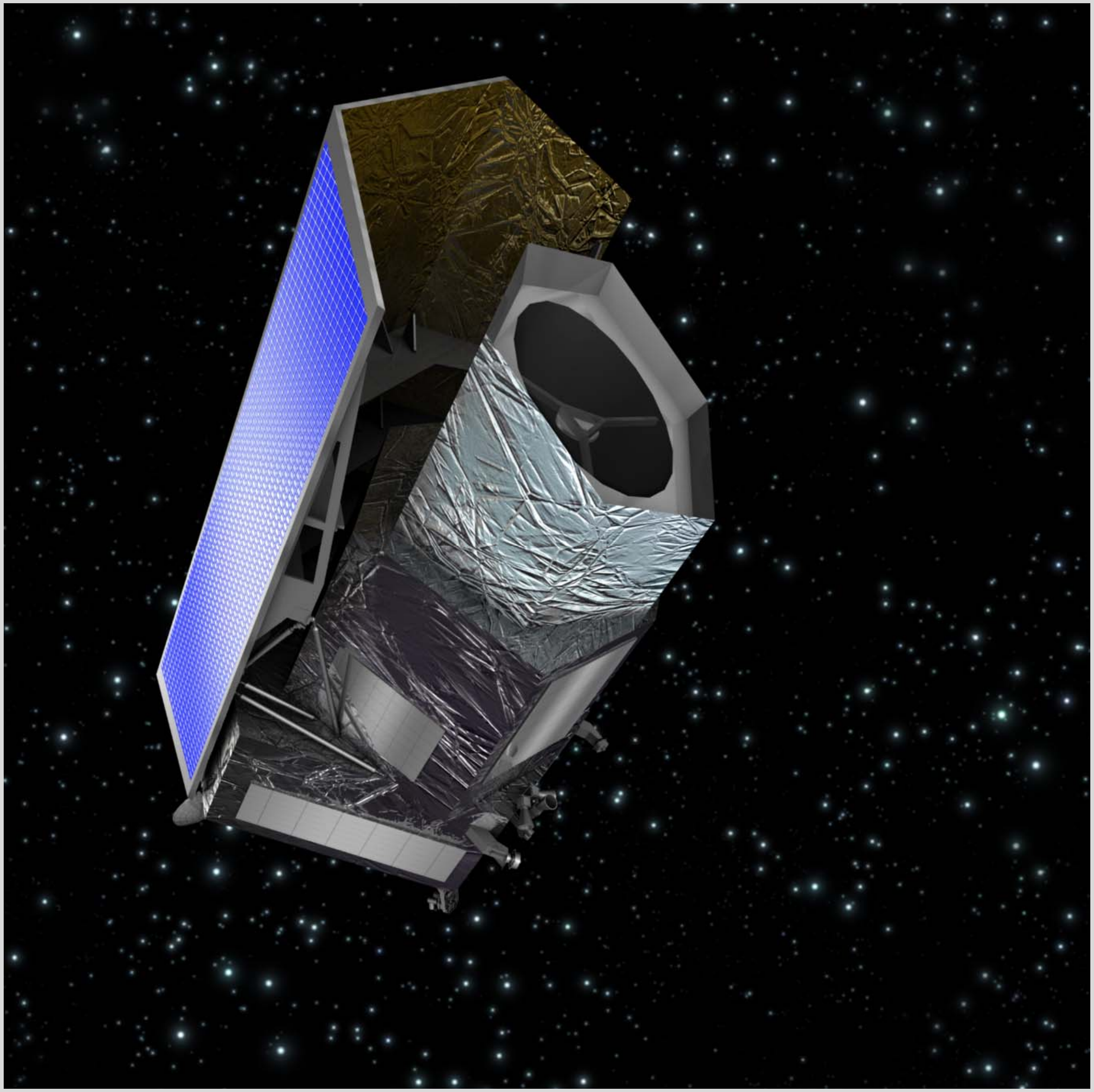
White et al 2011

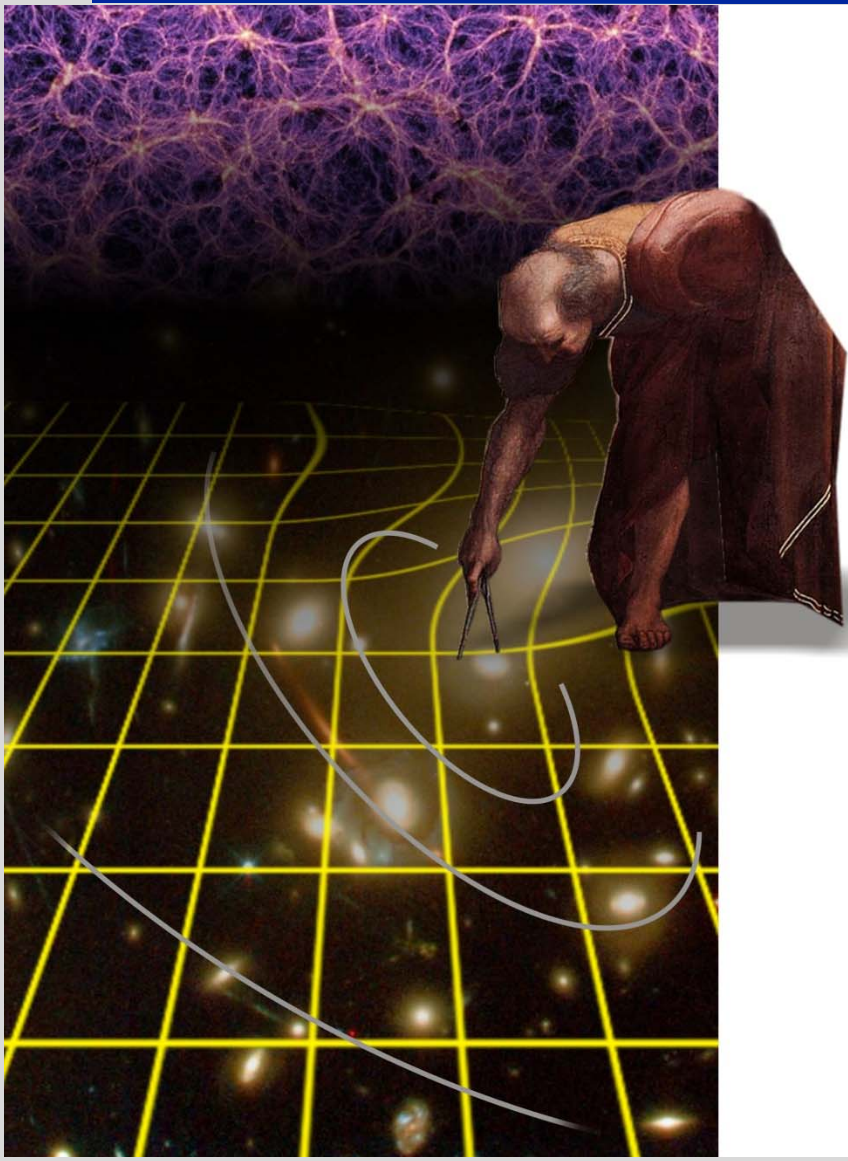


De Lapperent et al 1985

Redshift Space Distortions make use of the relative motions of galaxies as a measure of the growth of structure

Euclid





Euclid: Mapping the geometry of the Dark Universe

2004: Dark Universe Mission proposed as a Theme to ESA's Cosmic Vision programme

Oct 2007: DUNE and SPACE jointly selected for an ESA Assessment Phase

April 2010: Formation of single Euclid Consortium

July 2011: Final Euclid Proposal- Red Book

Oct 2011: **Final Approval of Euclid**

Fall 2012: NASA Joins, selects 40 additional US participants for funding (54 total in US)

2012-2020: Implementation phase (1300+ member consortium)

2020: Launch

2020-2026:Science operations

Euclid goals

Understand the nature of Dark Energy and Dark Matter by:

•Measuring w_0 *and* w_a to 2% and 10%, respectively

•Measuring γ to 2%

•Testing CDM, and measuring the sum of the neutrino masses to 0.04eV

•Improving by a factor of 20 the determination of the initial condition parameters compared to Planck

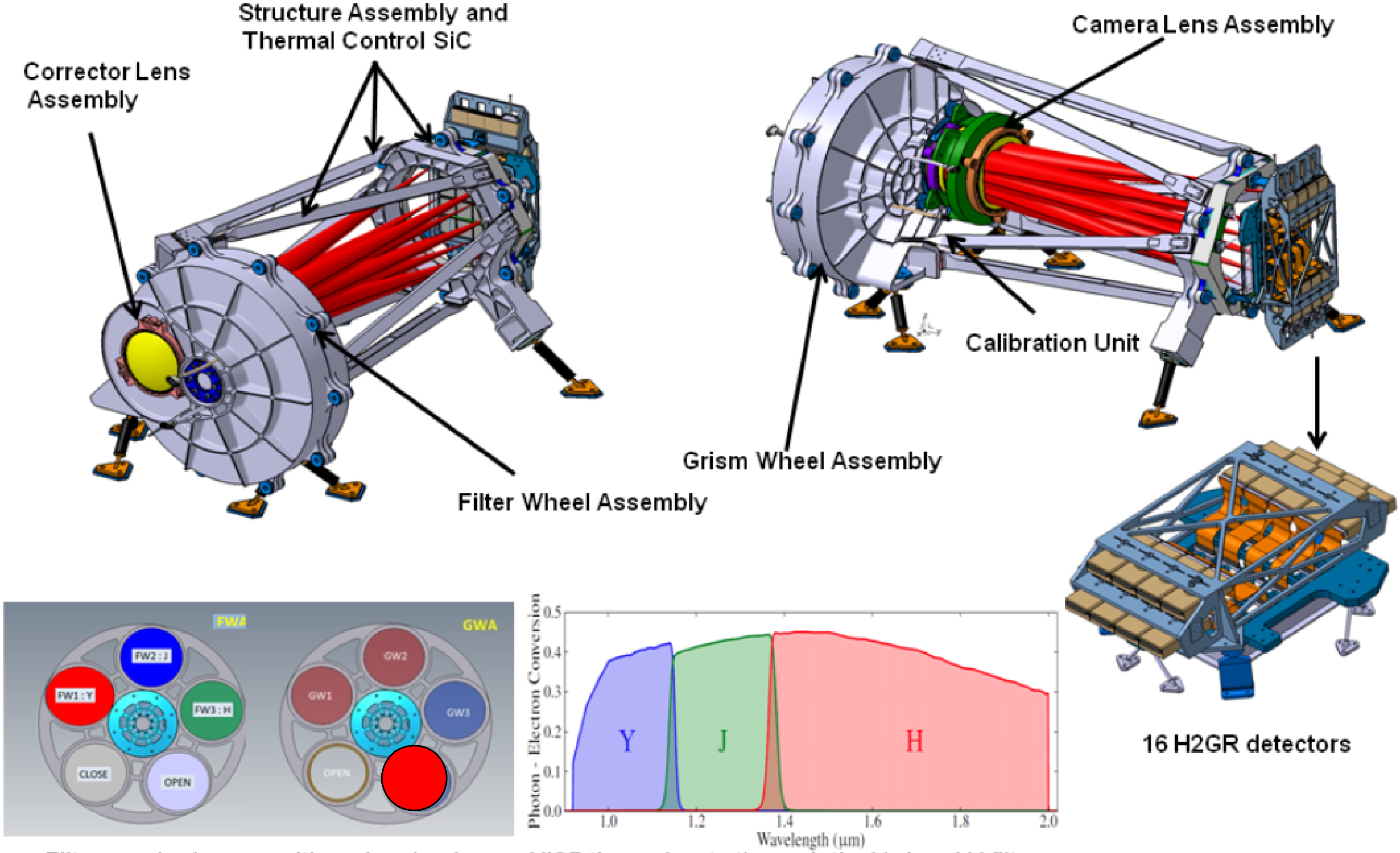
Responsive to **some** of the *scientific* goals outlined in US Decadal Survey Panel Reports:

- How did the universe begin?
- Why is the universe accelerating?
- What is dark matter?
- What are the properties of neutrinos?

Euclid concept

- Optimized for two complementary cosmological probes:
  - —Weak Gravitational Lensing
  - —Galaxy Clustering (Baryonic Acoustic Oscillations & Redshift Space Distortions)
- 15,000 square degree survey
  - —Imaging (WL):
    - High precision visible photometry (shapes)
    - NIR Photometry (photo-z)
  - —Near infrared grism spectroscopy (galaxy clustering)
- 40 square degree survey
  - —2 mags deeper than wide
  - —Calibration and galaxy evolution
- Not optimized for SN

Euclid NISP

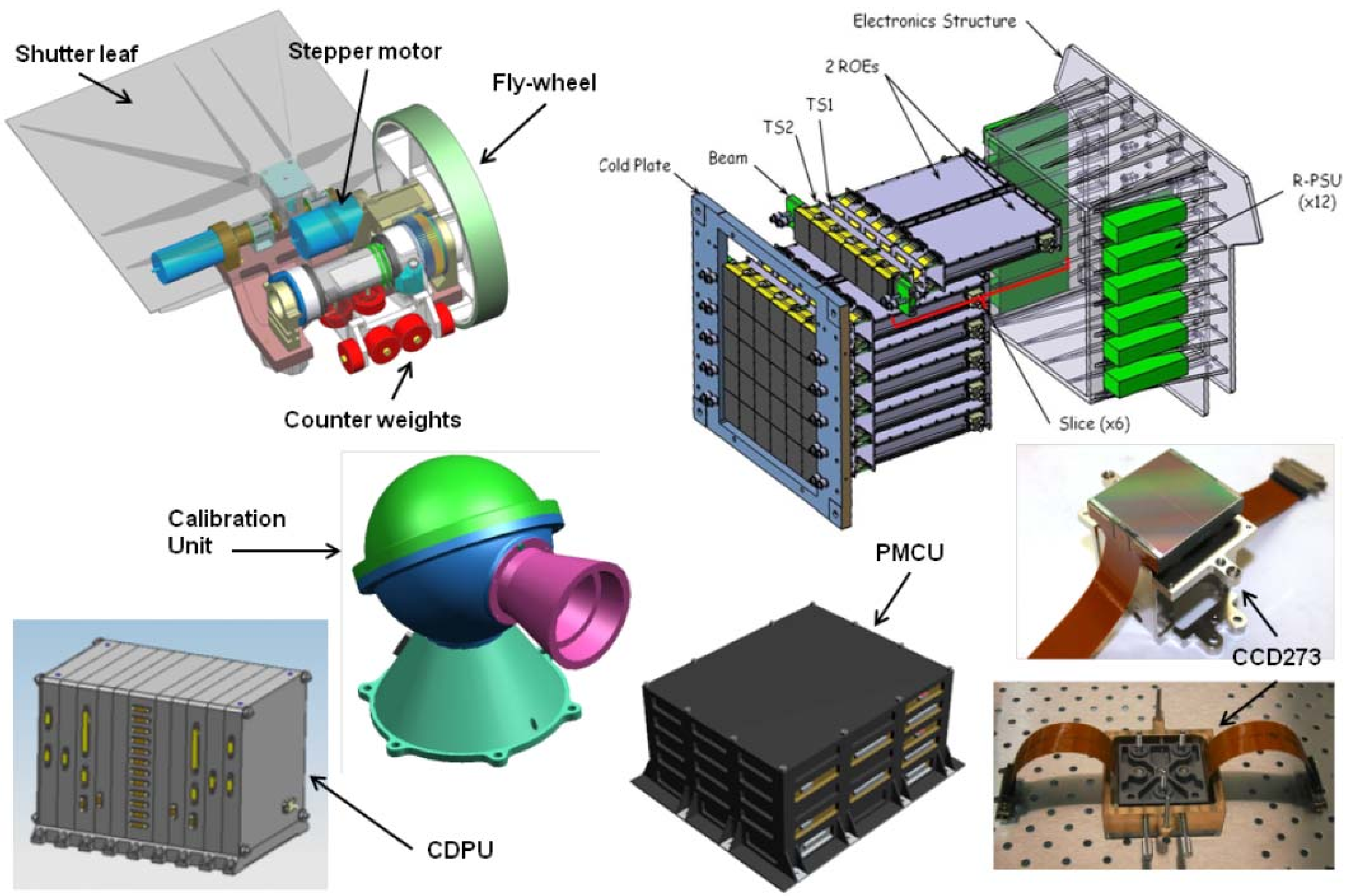


Filters and grisms positions in wheels

NISP throughputs through the Y, J and H filters

Overview of the subsystems composing the NISP instrument(the warm electronic subsystem is not shown on this figure). The red cones inside the mechanical assembly show the light beams illuminating the near infrared detectors. – Courtesy Euclid Consortium/NISP team

Euclid VIS



Overview of the subsystems composing the VIS instrument – Top, from left to right: Shutter Unit; an expanded view of the Focal Plane Array, with the 36 CCD273 at the front, the Focal Plane Structure, the ReadOut Electronics, the electronic structure and the Power Supply units. Bottom, from left to right: Control and Data Procesing Unit; the Calibration Unit; the Power and Mechanisms Control Unit; and views of a CCD273 of the VIS camera. Courtesy Euclid Consortium/VIS team

Euclid Mission

SURVEYS **in 6.25 yrs**		
	Area (deg2)	Description
Wide Survey	**15,000 deg^2**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg^2**	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux
	Shapes + Photo-z of *n* = 1.5 x10^9 galaxies ?				***z* of *n*=5x10^7 galaxies**
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Ref: Euclid RB arXiv:1110.3193

~2 billion shapes and 50 million spectra

Euclid Dark Energy Probes- WL

- Euclid weak lensing covers wide area (15,000 square degrees)
  - Single very wide optical filter
  - One visit per area on sky
  - 3-4 exposures at each point on sky (~50% of sky has 3 exposures)
  - Very good sampling on areas with 4 exposures
  - 25-35 galaxies per square arcminute
  - Requires external ground based photometry for photo-zs
  - Uses NIR photometry from Euclid for photo-z

Euclid Dark Energy Probes- Galaxy Clustering (1)

- Euclid Galaxy Clustering covers same 15,000 square degrees

- Uses Hα line only (work underway on using others)

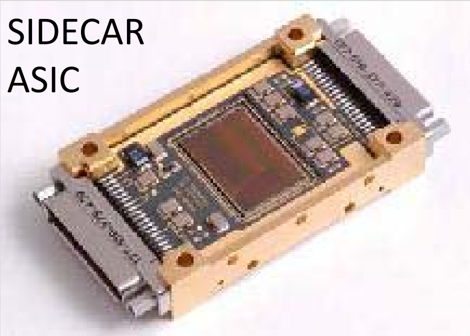
1. Recent work (e.g. Colbert et al 2013 - arxiv:1305.1399; Sobral et al 2012- arxiv:1202.3436) found a lower density of Hα emitters than was assumed at the time of the 2011 Euclid Red Book
2. Ground based experiments (e.g. DESI) will do better at low-z than anticipated several years ago

↓

Euclid as designed would not meet requirements, and would make some redundant measurements; **redesign to focus on redder (higher z) range underway**

NASA's Euclid Partnership Agreement with ESA

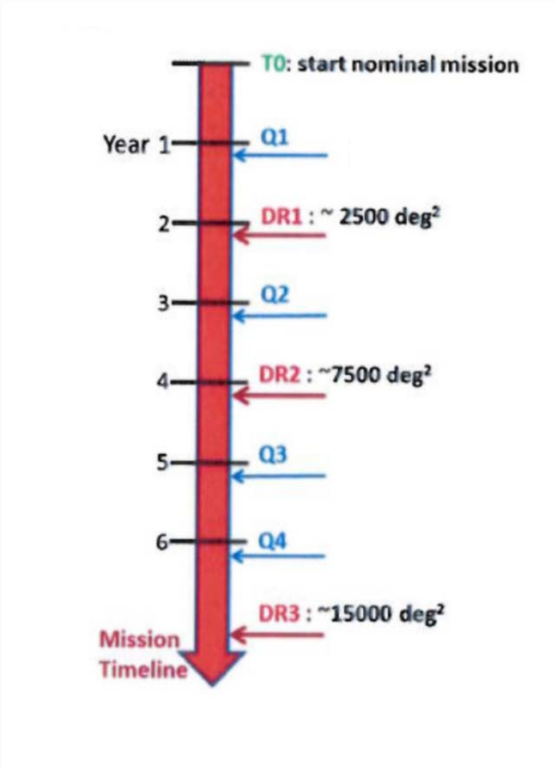
- ESA Responsibilities
  - — Mission, Spacecraft, Launch vehicle
- Euclid Consortium (EC) responsibilities
  - — 2 Instruments, Science Data Centers, science
- ESA/NASA MOU signed January 10, 2013
  - — NASA responsible for Sensor Chip Systems (SCS) for Near Infrared Spectrometer and Photometer (NISP) Instrument. ($45M)
    - Teledyne H2RG HgCdTe detector, SIDECAR ASIC, and flexible cryogenic cable. (16 FM and 4 FS)
  - — NASA gets 40 new EC member slots, selected through NRA. ($50M lifetime science team cost); brings to 54 the number of US scientists working on Euclid
  - — JPL Project Office (PM Ulf Israelsson, PS Michael Seiffert, Deputy PS Jason Rhodes)
  - — Detector char. at GSFC DCL [PCOS Program Office MM Tom Griffin]
  - — US Science Lead Jason Rhodes (ESA Euclid Science Team & Consortium Board)



SIDECAR™ (system image, digitizing, enhancing, controlling, and retrieving) ASIC (Application Specific Integrated Circuit)

Euclid Public Data Releases

- Q2 2020 launch, 6 months on-orbit verification, followed by 6 years of science survey operations
- "Quick release" of small survey areas at 14, 38, 62, 74 months after start of mission
  - Small areas only, not suitable for cosmology
- Survey will be released in stages:
  - 26 months after start (2500 deg^2, ~2023)
  - after 50 months (7500 deg^2, cumulative, ~2025)
  - after 86 months (15000 deg^2, cumulative)
- Euclid Consortium have immediate access to all data



Euclid Science Reach

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	[illegible]	0.015	0.150	430
Euclid All	0.009	0.02[illegible]	2.0	0.013	0.048	1540
Euclid+Planck	0.007	[illegible]	2.0	0.007	0.035	4020
Current (09/2011)	0.[illegible]	[illegible].580	100	0.100	1.500	~10
Improvement Fa[illegible]	[illegible]	**30**	**50**	**>10**	**>50**	**>300**

[illegible]esses many aspects of the current cosmological paradigm

“Blue Book” update coming late 2015

From Euclid Red Book :

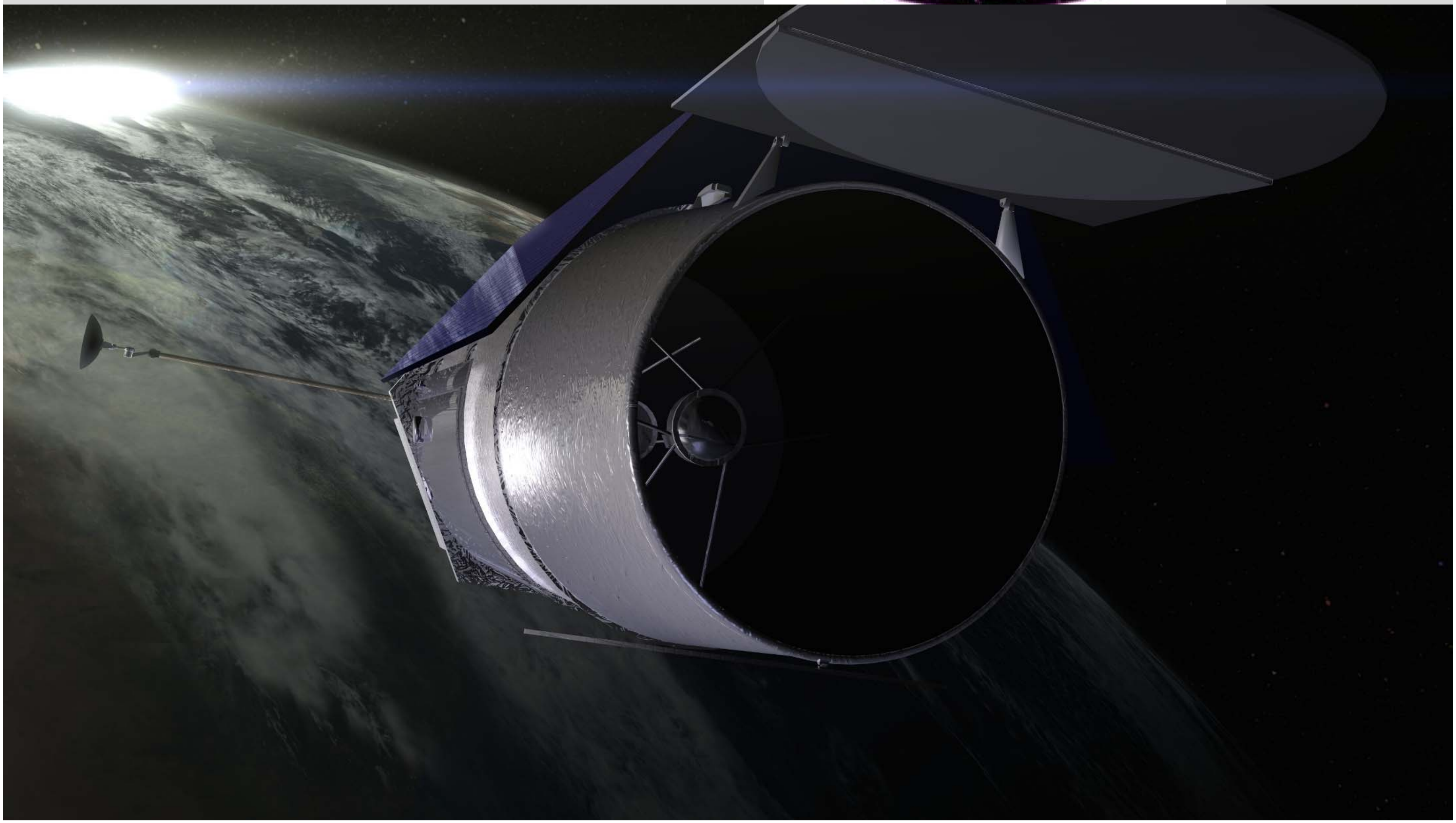
sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983

WFIRST-AFTA

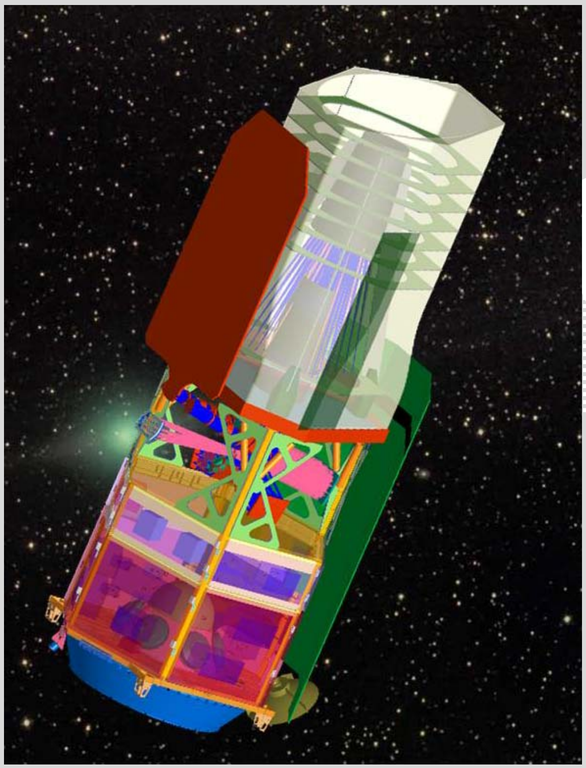
Wide-Field Infrared Survey Telescope

WFIRST

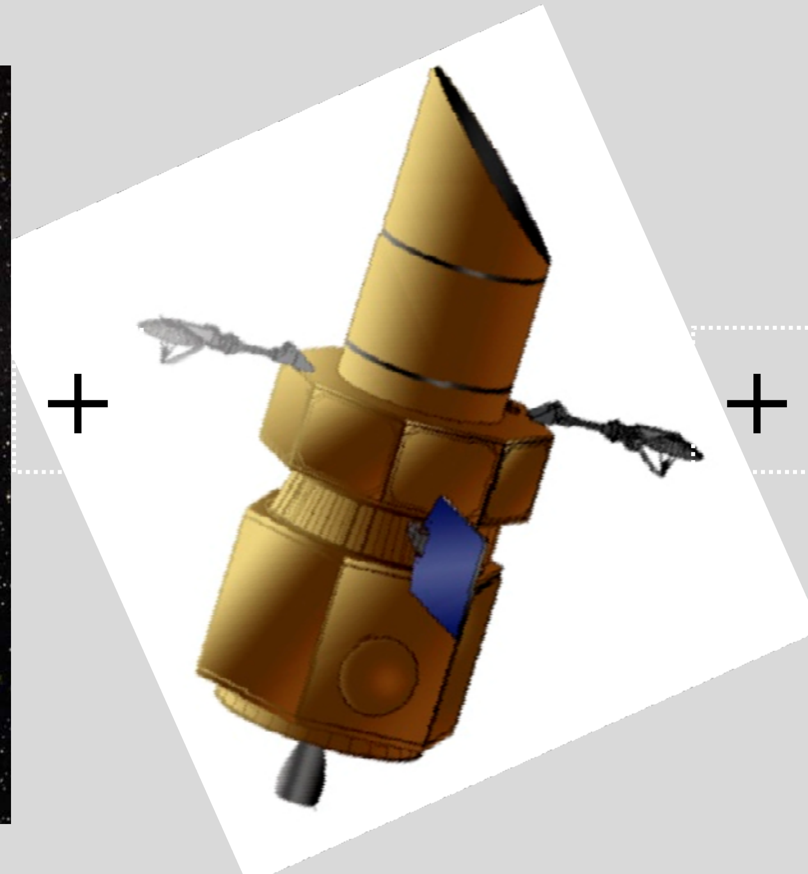
Dark Energy - Exoplanets - NIR Surveys



WFIRST =



+



+

JDEM-Ω

MPF

NIRSS

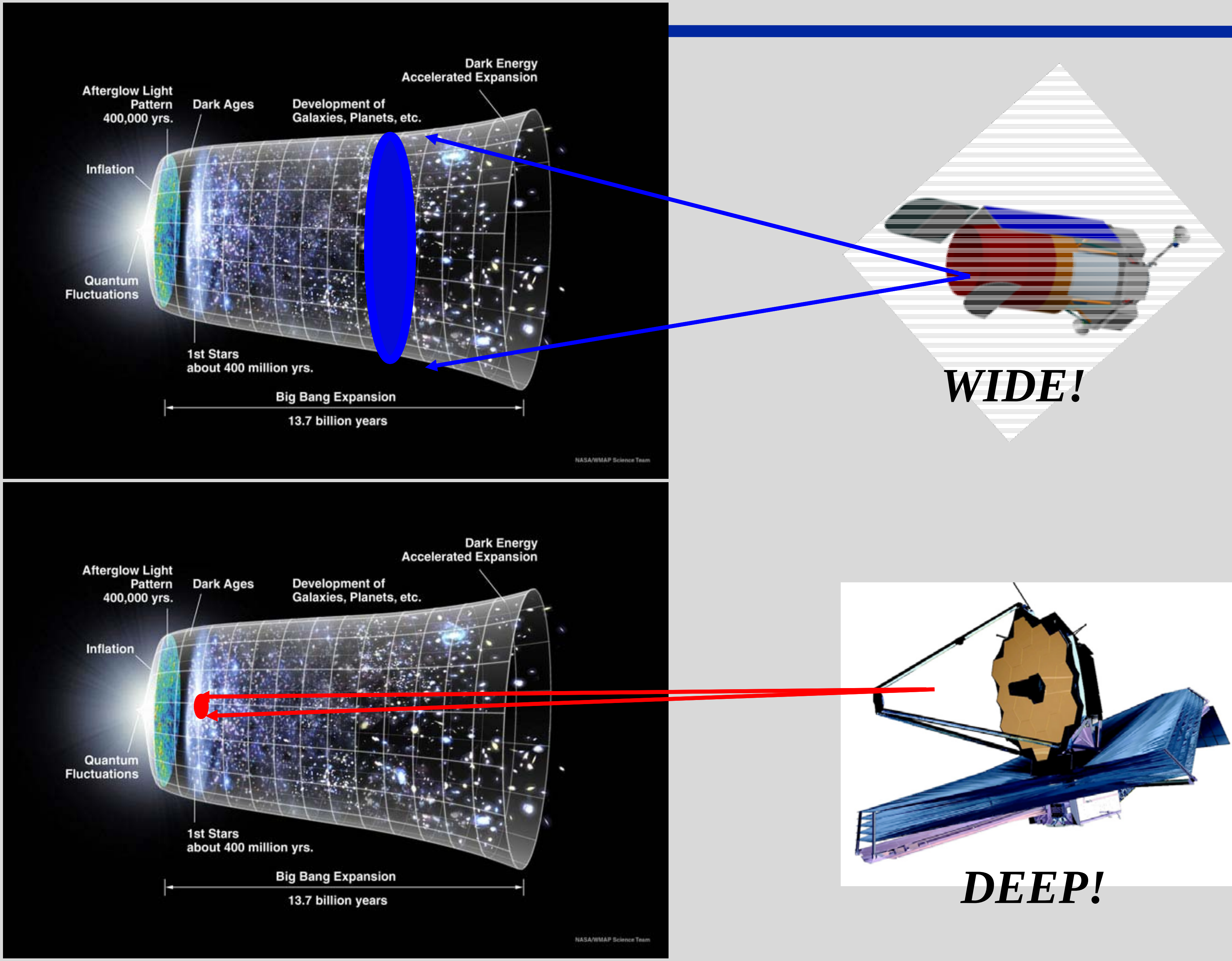
WFIRST - AFTA

Wide Field Infrared Survey Telescope-Astrophysics Focused Telescope Asset

- AFTA is the version of WFIRST that uses a 2.4 m telescope
- This asset comes from the NRO (i.e. a spy agency!)
- Offers a fundamentally new regime of DE (and other) research
- Includes a coronagraph to image exoplanets

A wide field HST

AFTA Complements JWST



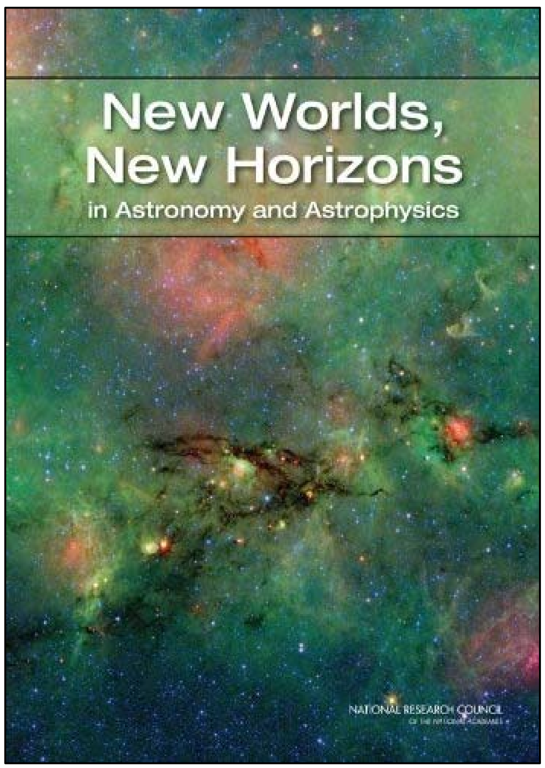
WFIRST-AFTA's Guest Observer Program Addresses Decadal Survey

<u>Frequently discussed</u>

#1 Large-Scale Priority - Dark Energy, Exoplanets

#1 Medium-Scale Priority - New Worlds Tech. Development (prepare for 2020's planet imaging mission)

<u>But, WFIRST-AFTA provides improvement over IDRM in many other areas….</u>



<u>5 Discovery Science Areas</u>

- ID & Characterize Nearby Habitable Exoplanets ✓
- Time-Domain Astronomy ✓
- Astrometry ✓
- Epoch of Reionization ✓
- Gravitational Wave Astrometry

<u>20 Key Science Questions</u>

- Origins **(7/7 key areas)**
- Understanding the Cosmic Order **(6/10 key areas)**
- Frontiers of Knowledge **(3/4 key areas)**

Status

- Science Definition Team (SDT) working hard at developing the mission, along with Exoplanet Program office at JPL and WFIRST Study office at G...
- Significant WFIRST-AFTA ... by Congress for FY13 and ... President's FY15 budget.
  - This includes $2M for prep...
- Funding is being used for ... rapid start and allow a sho...
  - Hardware
  - Requirements
  - Simulations
- Project / SDT driving toward fastest, cheapest implementation of mission

Jason's best guess: 2024 for a 10 year mission

Report available at http://wfirst.gsfc.nasa.gov/ (look at right hand column 'Latest News')

WFIRST-AFTA SDT

Co-Chairs

- David Spergel, Princeton University
- Neil Gehrels, NASA GSFC

Members

- Charles Baltay, Yale University
- Dave Bennett, University of Notre Dame
- James Breckinridge, California Institute of Technology
- Megan Donahue, Michigan State University
- Alan Dressler, Carnegie Institution for Science
- Scott Gaudi, Ohio State University
- Tom Greene, NASA ARC
- Olivier Guyon, Steward Observatory
- Chris Hirata, Ohio State University
- Jason Kalirai, Space Telescope Science Institute
- Jeremy Kasdin Princeton University
- Bruce MacIntosh, Stanford University
- Warren Moos, Johns Hopkins University
- Saul Perlmutter, University of California Berkeley
- Marc Postman, Space Telescope Science Institute
- Bernie Rauscher, NASA GSFC
- Jason Rhodes, NASA JPL
- David Weinberg, Ohio State University
- Yun Wang, University of Oklahoma

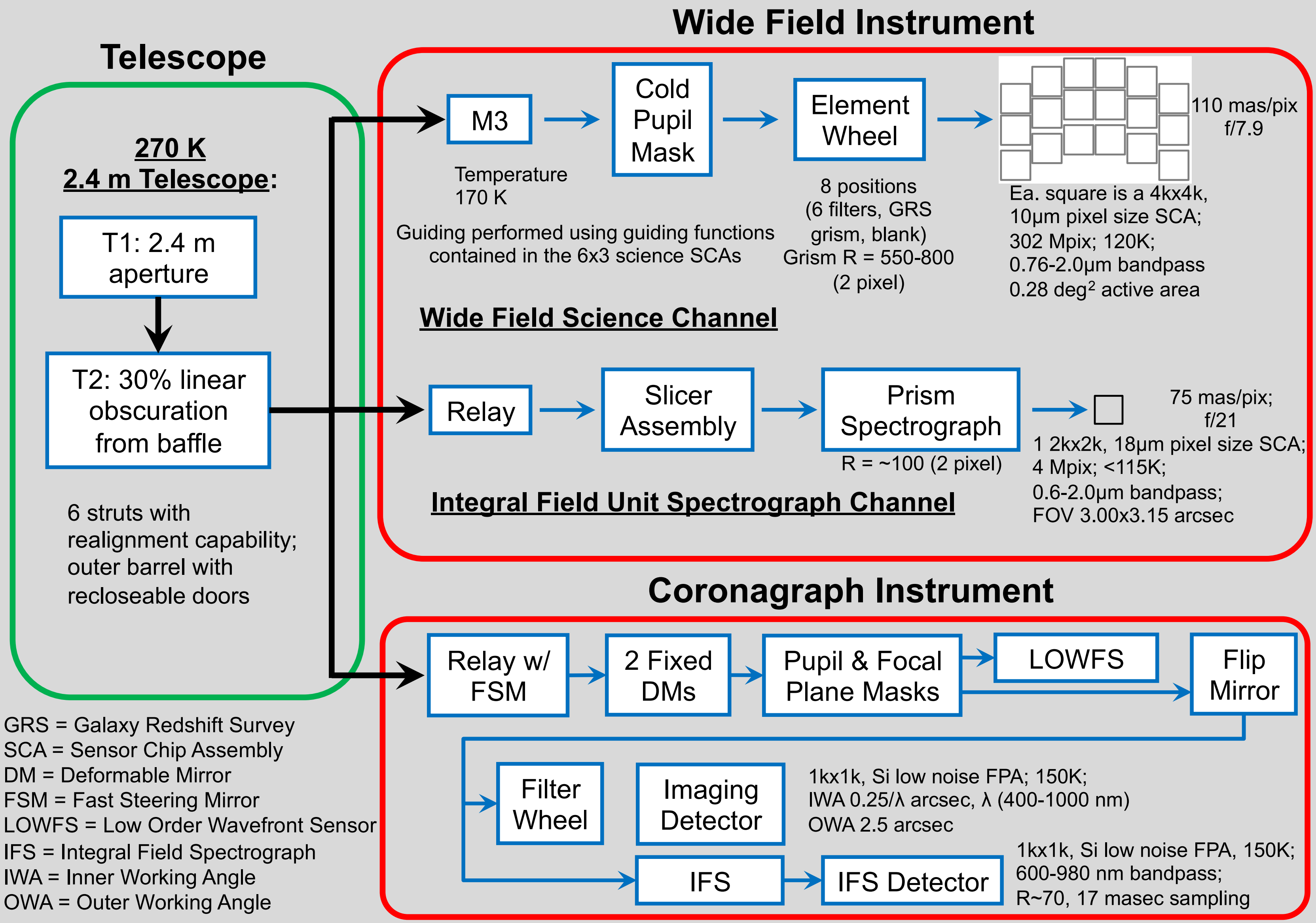
Ex Officio

- Dominic Benford, NASA HQ
- Mike Hudson, Canadian Space Agency
- Yannick Mellier, European Space Agency
- Wes Traub, NASA JPL
- Toru Yamada, Japan Aerospace Exploration Agency

Consultants

- Matthew Penny, Ohio State University
- Dmitry Savransky, Cornell University
- Daniel Stern, NASA JPL

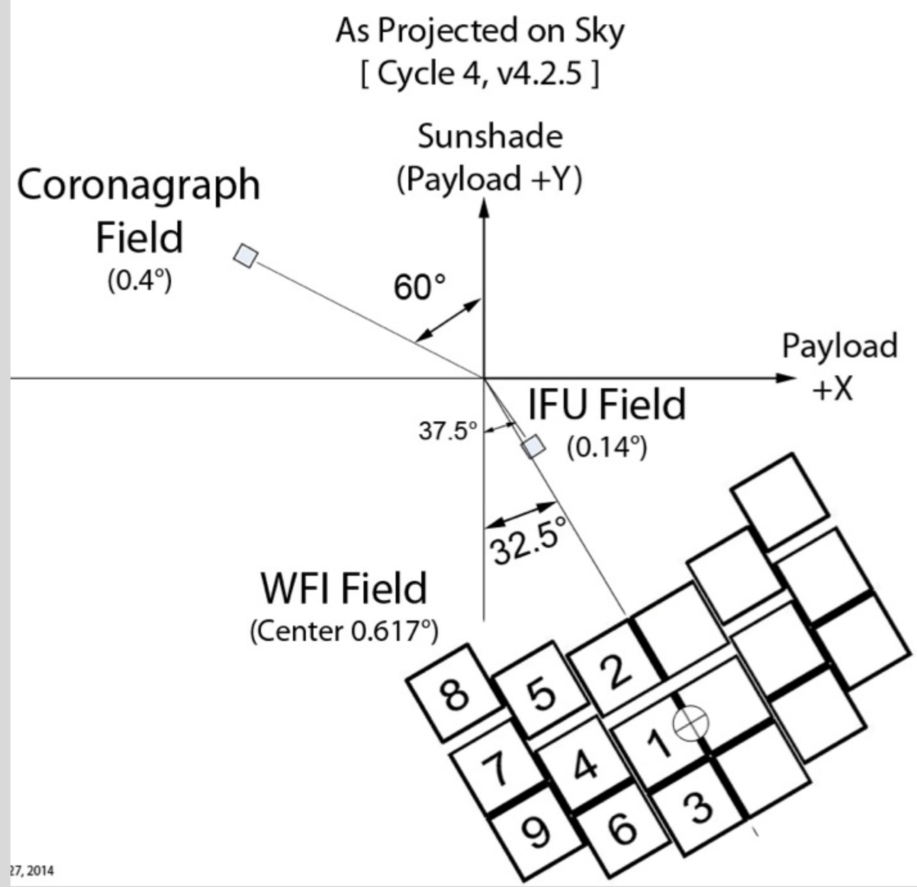
WFIRST-AFTA Payload Optical Block Diagram



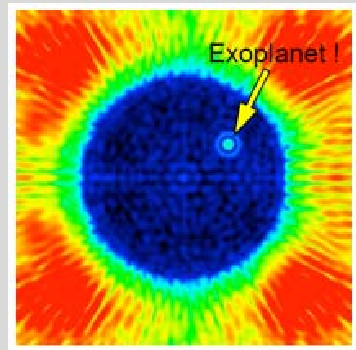
Optical Field Layout

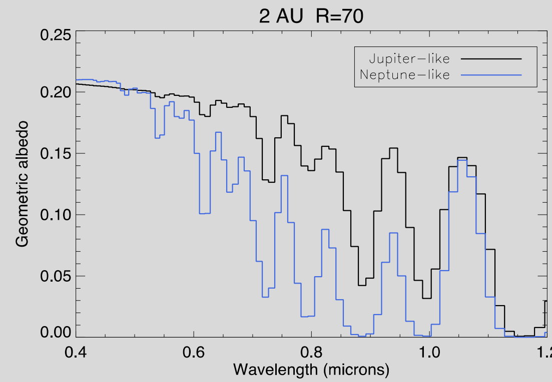
- **The Wide Field Instrument has two optical channels**
  - **The wide field channel uses the telescope along with 2 fold mirrors and a conic tertiary mirror in the instrument, to complete a folded three mirror anastigmat optical system.**
  - **The wide field instrument includes an integral field unit, used for supernova spectroscopy and GO spectroscopy**
- **The coronagraph is a small field system in a separate field of view**

Channel Field Layout for WFIRST-AFTA Instruments



WFIRST-AFTA Coronagraph Capability





[redacted]

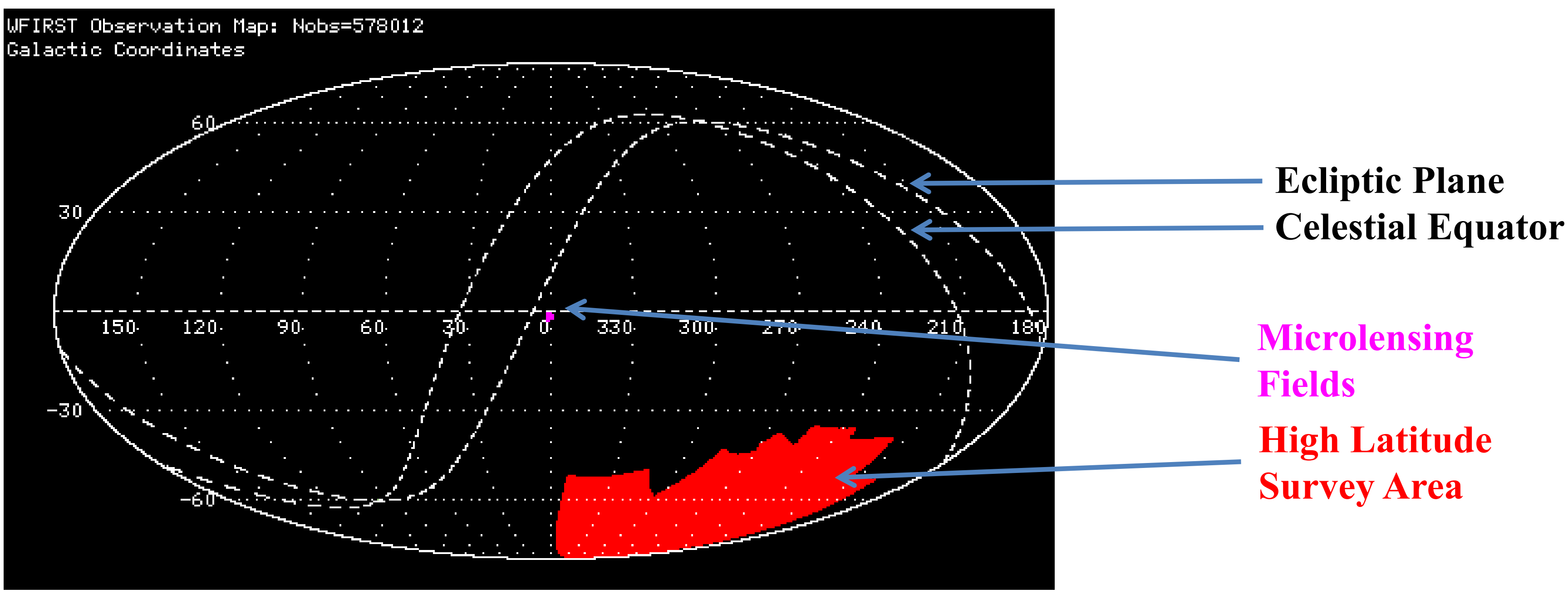
[redacted]

[redacted]

Bandpass	400 – 1000 nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	~3λ/D
Outer working angle	0.75 – 1.8 arcsec	By 48x48 DM
Detection Limit	Contrast ≤ 10^{-9} (after post processing)	Cold Jupiters, Neptunes, and icy planets down to ~2 RE
Spectral Resolution	~70	With IFS, R~70 across 600 – 980 nm
Spatial Sampling	17 mas	Nyquist for λ~430nm

Example Observing Schedule: Properties

- This timeline is an **existence proof** only, not a final recommendation.
- Unallocated time is 1.43 years (includes GO program)
- High latitude survey (HLS: imaging + spectroscopy): 1.96 years
  - **2401 deg^2** @ ≥3 exposures in all filters (2440 deg^2 bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.62 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission



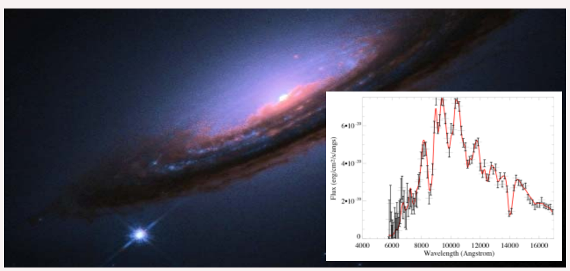
WFIRST-AFTA Dark Energy Roadmap

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

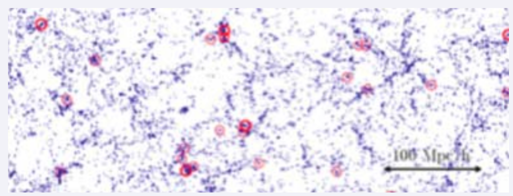
20 million Hα galaxies, z = 1–2
2 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

400 million lensed galaxies
40,000 massive clusters

standard ruler

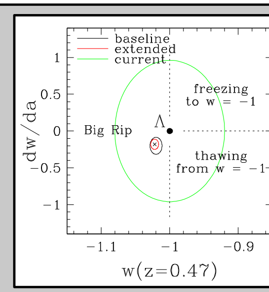
distances	expansion rate
z = 1–2 to 0.4%	z = 1–2 to 0.72%
z = 2–3 to 1.3%	z = 2–3 to 1.8%



dark matter clustering
z < 1 to 0.16% (WL); 0.14% (CL)
z > 1 to 0.54% (WL); 0.28% (CL)
1.2% (RSD)

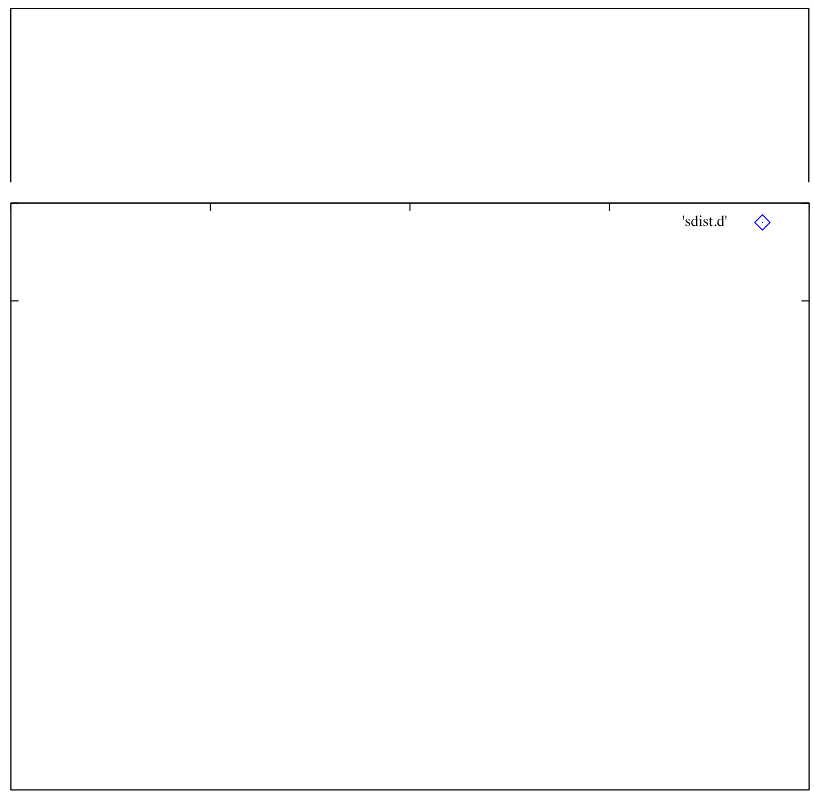
history of dark energy
+
deviations from GR

w(z), ΔG(z), Φ_{REL}/Φ_{NREL}



The Supernova Survey

- Three tiered survey for low, medium, and high redshift Type Ia supernovae out to redshift of 1.7
- Use the Wide Field Instrument for supernova discovery with a 5 day cadence, the Integral Field Spectrometer (IFU) for lightcurves from spectrophotometry, no need
- 2700 supernovae, distance error bin including best estimate of sys
- Low infrared background in space allows unique high redshift survey not possible from the ground
- High S/N spectra with the IFU allow reduced systematic errors to match high precision achievable with 2.4 m



Weak Lensing with WFIRST

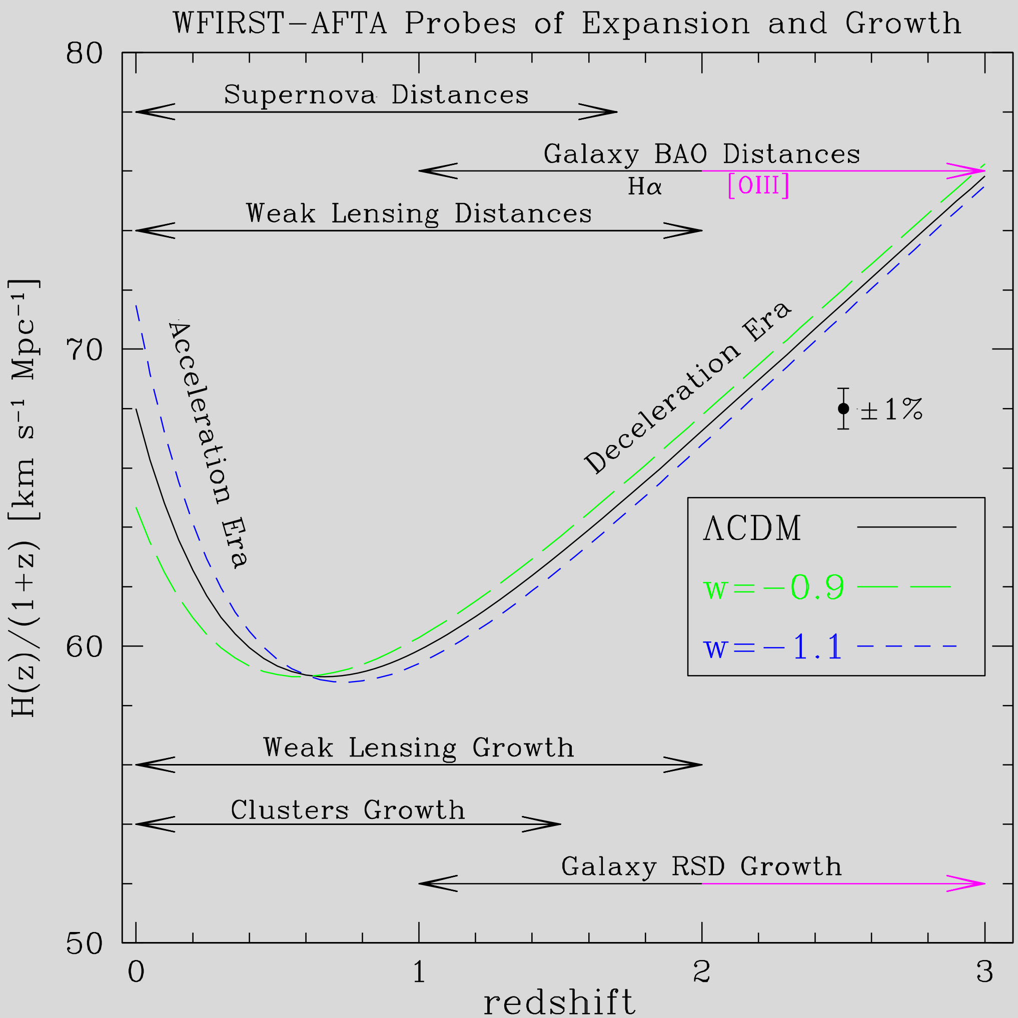
- Powerful probe of matter distribution in the Universe
  - Shapes for >400 million galaxies (50/arcmin^2 over 2400 deg^2).
  - Precision of 0.12% on amplitude of matter clustering from cosmic shear; comparable power from cluster-galaxy and galaxy-galaxy lensing.
  - High number density enables high-resolution mass maps
- Systematic error control
  - Shapes measured in 3 filters, with total of 6 passes over the sky: rich opportunity for null tests, auto- and cross-correlations, and internal calibration. *Crucial* for believing high-precision measurements.
  - Small and stable PSF with 2.4 m space telescope reduces systematic errors in the PSF model and their impact on galaxy ellipticity measurement
  - Dither pattern recovers full sampling, even rejecting cosmic rays at GEO rate

WFIRST-AFTA Galaxy Redshift Survey

- Wide and Deep Galaxy Redshift Survey:
  - ~20 million Hα galaxies ($1<z<2$)
  - ~2 million [OIII] emission line galaxies ($2<z<3$)
  - Baseline survey area 2,400 deg^2
- High Precision Measurement of Cosmic Expansion History and Growth History:
  - Model-independent measurement of cosmic expansion rate H(z) & cosmic structure growth rate $f_g(z)\sigma_8(z)$ at a few % level with dz=0.1
  - Cumulative precision of H(z) and $f_g(z)\sigma_8(z)$ at sub percent levels
- High Galaxy Number Density Allows Tight Control of Systematic Effects:
  - Good sampling of cosmic large scale structure
  - Enables subdividing data into subsets for crosschecks
  - Enables higher order statistics
  - More robust to Hα luminosity function uncertainties

WFIRST-AFTA Dark Energy

- **The WFIRST-AFTA Dark Energy program probes the expansion history of the Universe and the growth of cosmic structure with multiple methods in overlapping redshift ranges.**
- **Tightly constrains the properties of dark energy, the consistency of General Relativity, and the curvature of space.**
- **The High Latitude Survey is designed with sub-percent control of systematics as a paramount consideration.**



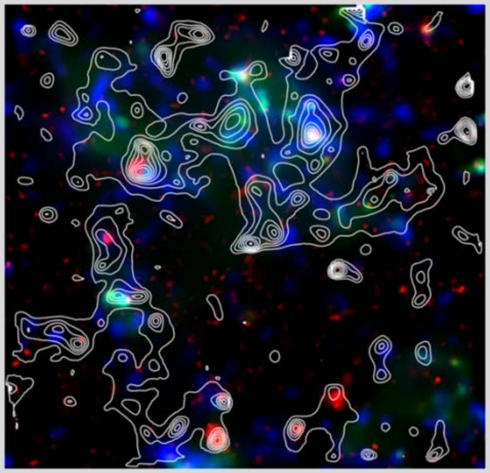
"For each of the cosmological (dark energy) probes in NWNH, WFIRST/AFTA exceeds the goals set out in NWNH"
NRC - *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*

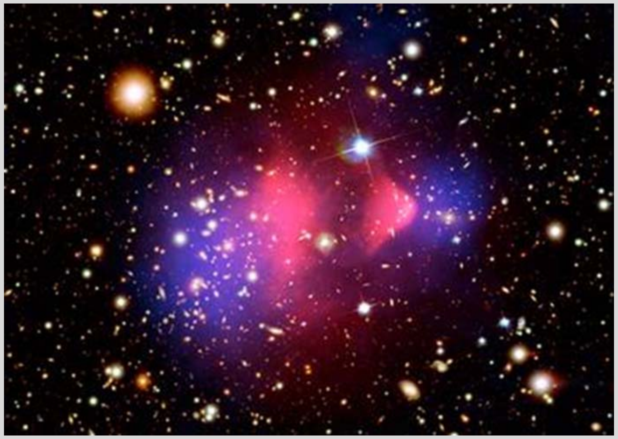
WL: A completely different regime

- WL with AFTA survey would reach >50 galaxies per square arcminute
  — vs ~30 w/Euclid, and even fewer from the ground
- With a deeper survey AFTA could reach HUDF depths of **>250** galaxies per square arcminute

This is a fundamentally different WL regime that is not possible from the ground or with a 1.3 meter class telescope due to PSF size.

- Much better calibration data
- *Much* better for understanding dark matter





WFIRST-AFTA Exoplanet Science

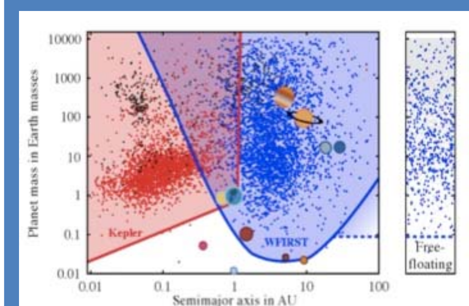
The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbors.

Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

3000 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

Complete the Exoplanet Census

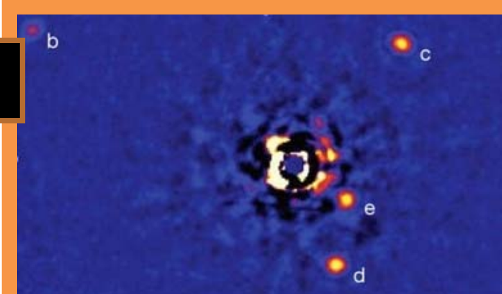


High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of 10^{-9} on angular scales > 0.1”
R=70 spectra and polarization between 400-1000 nm

Detailed characterization of up to a dozen giant planets.
Discovery and characterization of several Neptunes
Detection of massive debris disks.

Discover and Characterize Nearby Worlds



- **How do planetary systems form and evolve?**
- **What are the constituents and dominant physical processes in planetary atmospheres?**
- **What kinds of unexpected systems inhabit the outer regions of planetary systems?**
- **What are the masses, compositions, and structure of nearby circumstellar disks?**
- **Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?**

Toward the "Pale Blue Dot"

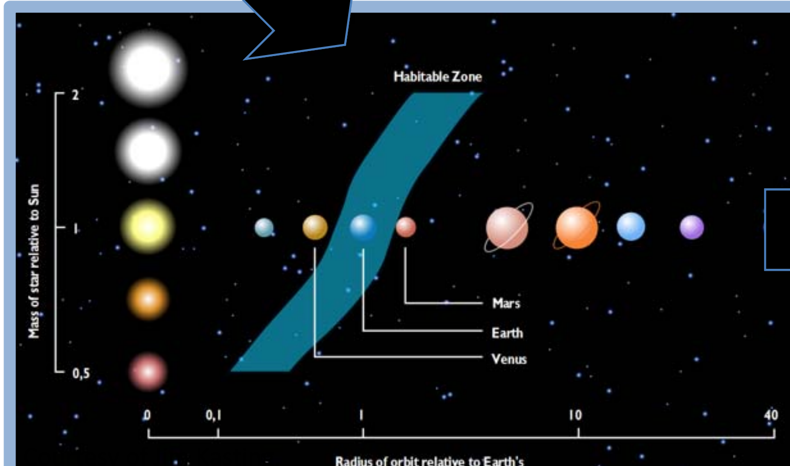
WIFRST will lay the foundation for a future flagship direct imaging mission capable of detection and characterization of Earth-like planets.

Microlensing Survey

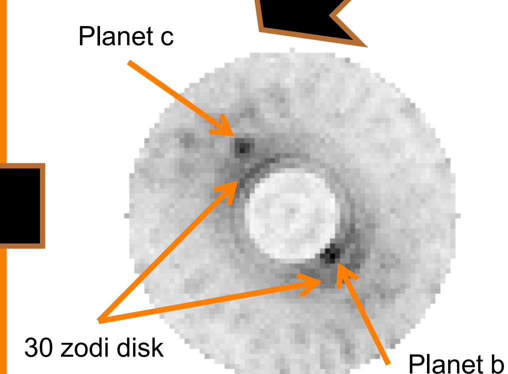
- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler's estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

High Contrast Imaging

- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight.*



Science and technology foundation for the New Worlds Mission.

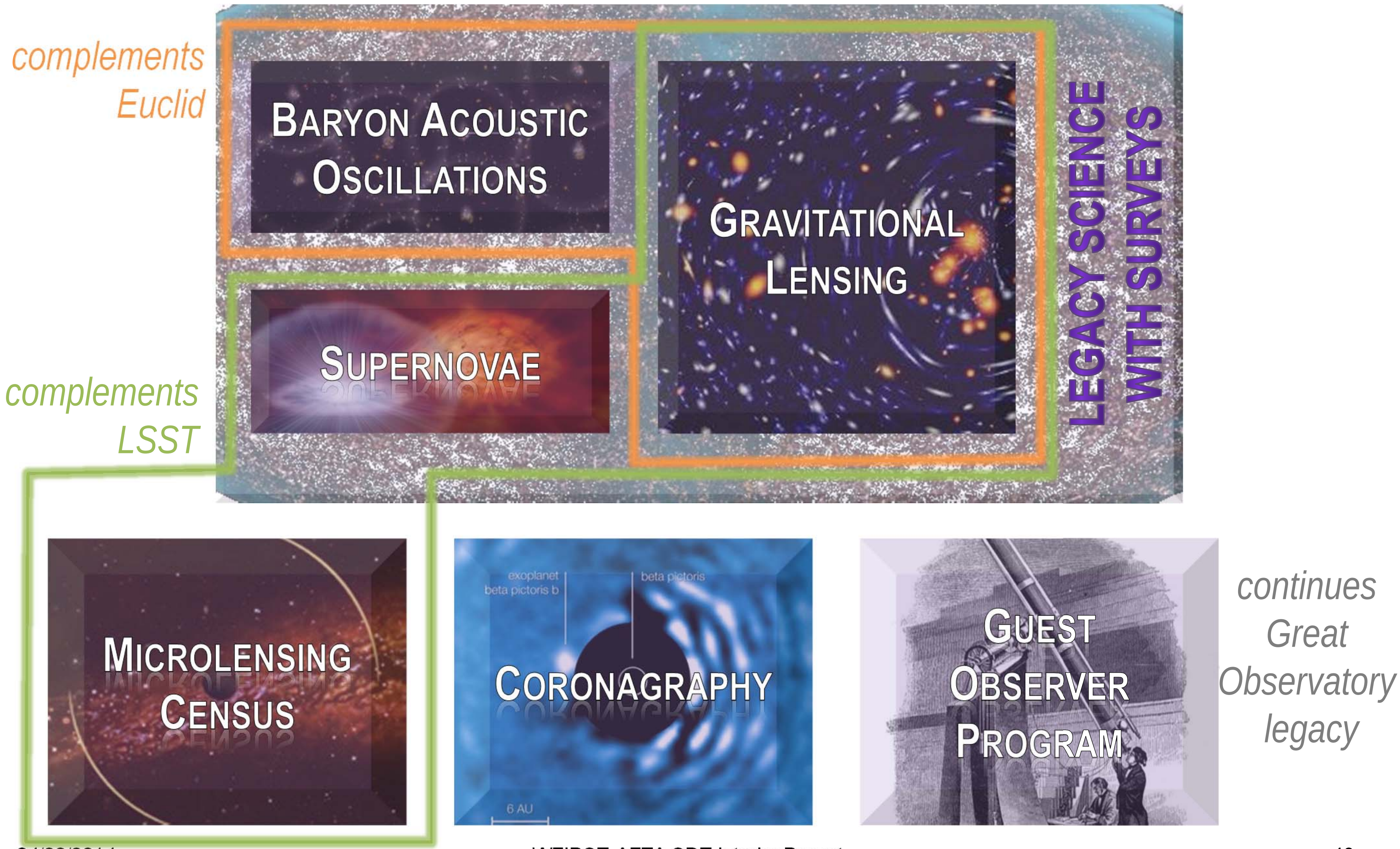


Simulated WFIRST-AFTA coronagraph image of the 47 UMa planetary system

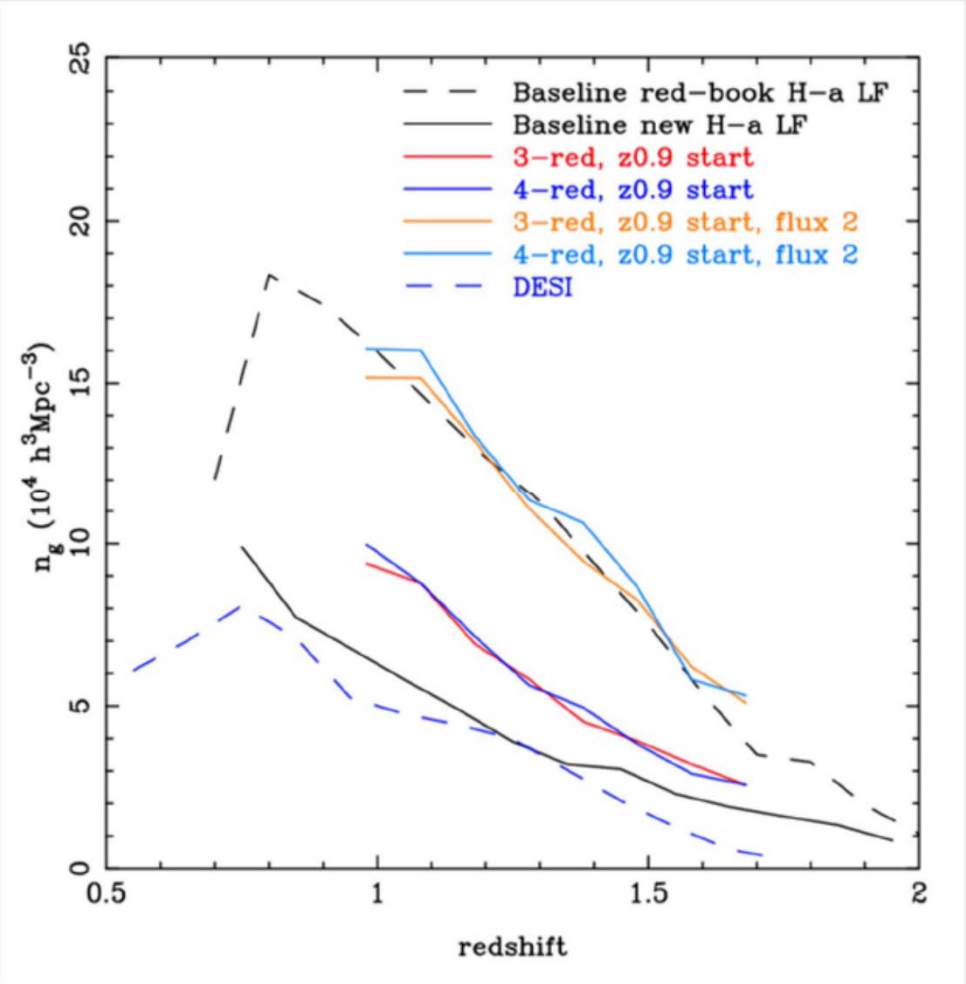
[redacted]

BACKUP

WFIRST-AFTA Science



Euclid Dark Energy Probes- Galaxy Clustering (2)



This has led to a change in the Euclid design from 2 Red and 2 Blue grisms. The wide (15,000 square degree) cosmology survey will use only red grisms; 3 R/1B will be used in deep (40 square degree) survey.

- Provides better measurements (systematics) and recovers surface density of emitters
- Smaller redshift range covered; low z from the ground
- Ancillary (galaxy evolution) science maintained via deep survey blue grism observations

Executive Summary

- "HST quality" NIR imaging over 1000's of square degrees
- 2.5x deeper and 1.6x better resolution than IDRM*
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science of NWNH
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Aerospace CATE cost is 8% larger than IDRM (w/o launcher, w/ risks). Coronagraph adds 16% (including 1 extra year of operations), but addresses the top medium scale priority of NWNH.
- Use of donated telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public.

* IDRM = 2011 WFIRST mission designed to match NWNH