Survey with WFIRST-AFTA

Jan. 25-27, 2015 SSG Workshop. High-1 Resort

Changbom Park (Korea Institute for Advanced Study)

WFIRST-AFTA Science Definition Team Interim Report (April 30, 2014)

David Spergel, What is WFIRST-AFTA (Nov. 20, 2014)

Josh Frieman, Dark Energy and WFIRST-AFTA

The Wide-Field Infrared Survey Telescope (WFIRST)

A NASA mission responding to the 2010 National Research Council New Worlds, New Horizons (NWNH) Astronomy and Astrophysics Decadal Survey top priority recommendation in the large space mission category.

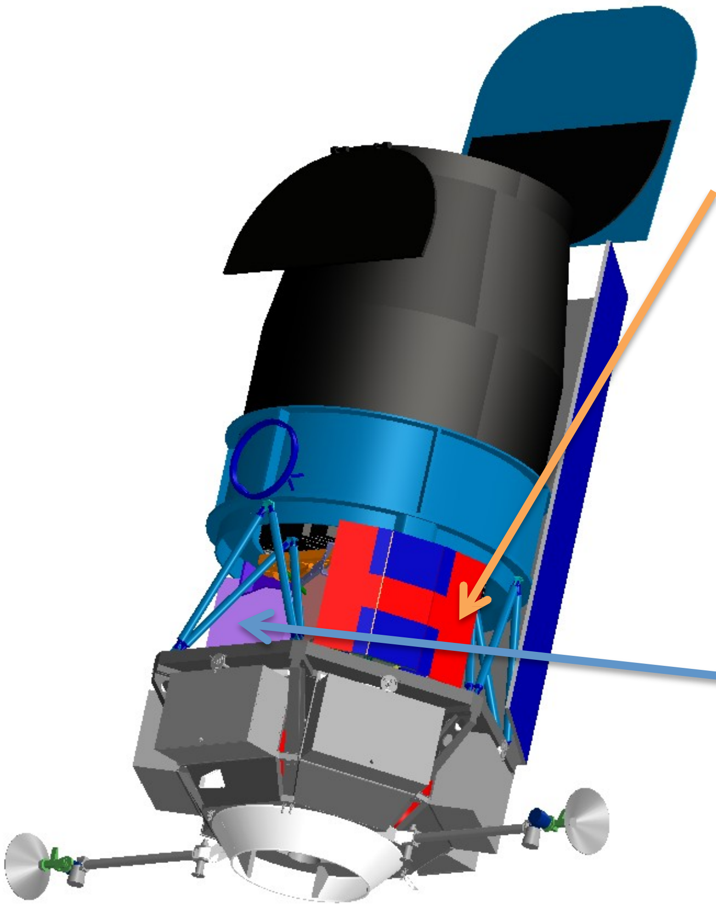
WFIRST includes science objectives in exoplanet exploration, dark energy research and Galactic and Extragalactic surveys.

WFIRST is a combination of three proposed telescopes:
the Microlensing Planet Finder (MPF), the Joint Dark Energy Mission/Omega (JDEM-Omega) and the Near-Infrared Sky Surveyor (NIRSS).

Science Definition Team Cochairs
Spergel, Princeton University
Neil Gehrels, NASA GSFC

WFIRST-AFTA Observatory & Instruments

- **Telescope** – Two, 2.4 m, two-mirror telescopes provided to NASA.



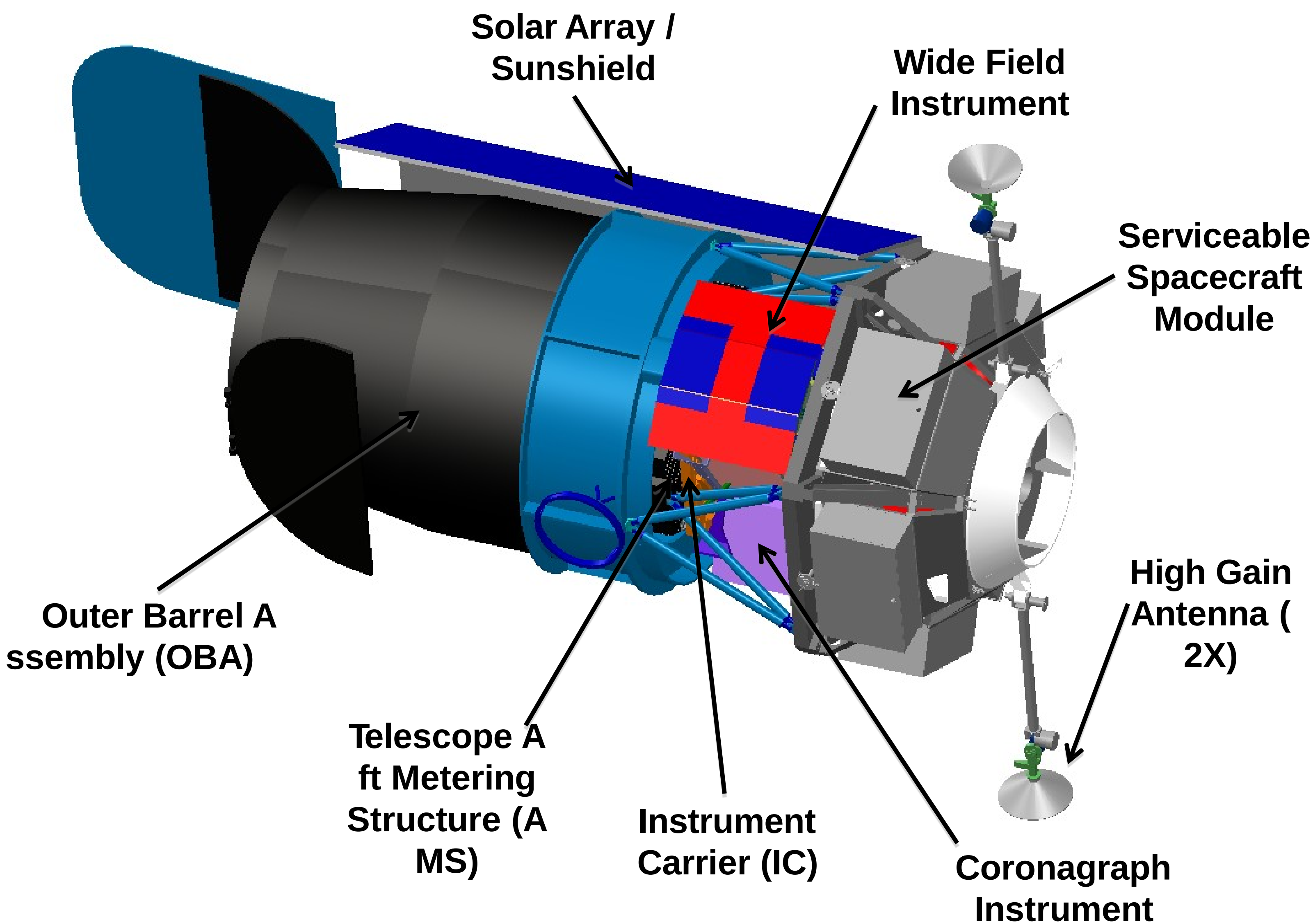
Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 micron bandpass
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 4kx4k H4RG HgCdTe detectors
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

- *Imaging of ice & gas giant exoplanets*
- *Imaging of debris disks*
- 400 – 1000 nm bandpass
- d10^{-9} contrast (after post-processing)
- 100 milliarcsec inner working angle at 400 nm

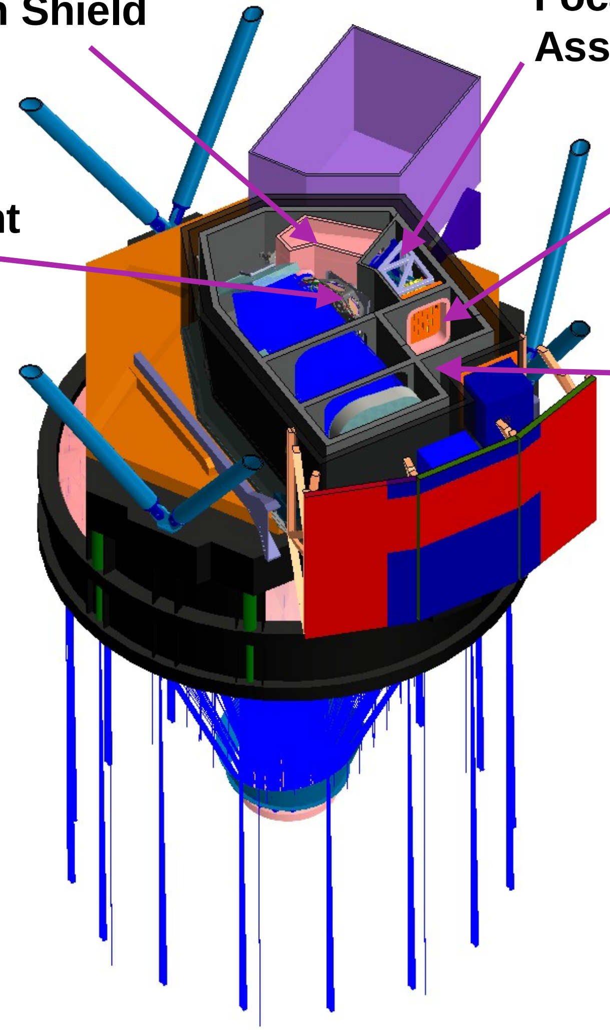
WFIRST-AFTA Observatory Layout



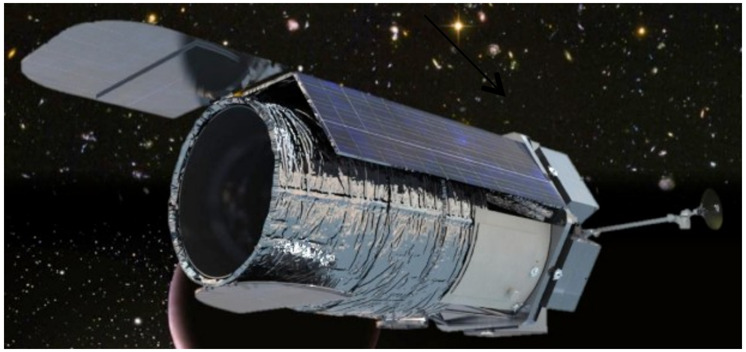
Wide Field Instrument

<u>Key Features</u>

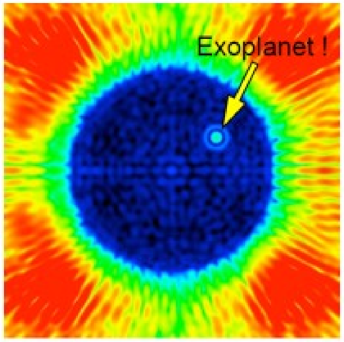
- Single wide field channel in strument for <u>both imaging and spectroscopy</u>
  - 3 mirrors, 1 powered
  - 18 4K x 4K HgCdTe detectors cover 0.76 - 2.0 μm
  - 0.11 arc-sec plate scale
  - Grism used for GRS survey c overs 1.35 – 1.95 μm with R between 645 - 900
- IFU channel for SNe spectra , single HgCdTe detector co vers 0.6 – 2.0 μm with R~75
- Single element wheel for filters and grism



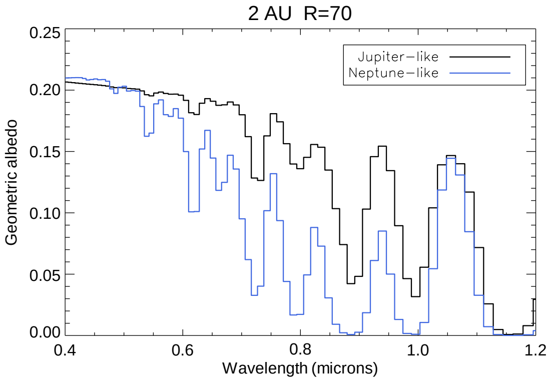
WFIRST-AFTA Coronagraph Capability



Coronagraph Architecture: Primary : Occulting Mask (OMC) Backup: Phase Induced Amplitude Apodization (PIAA)



Exoplanet Direct Imaging

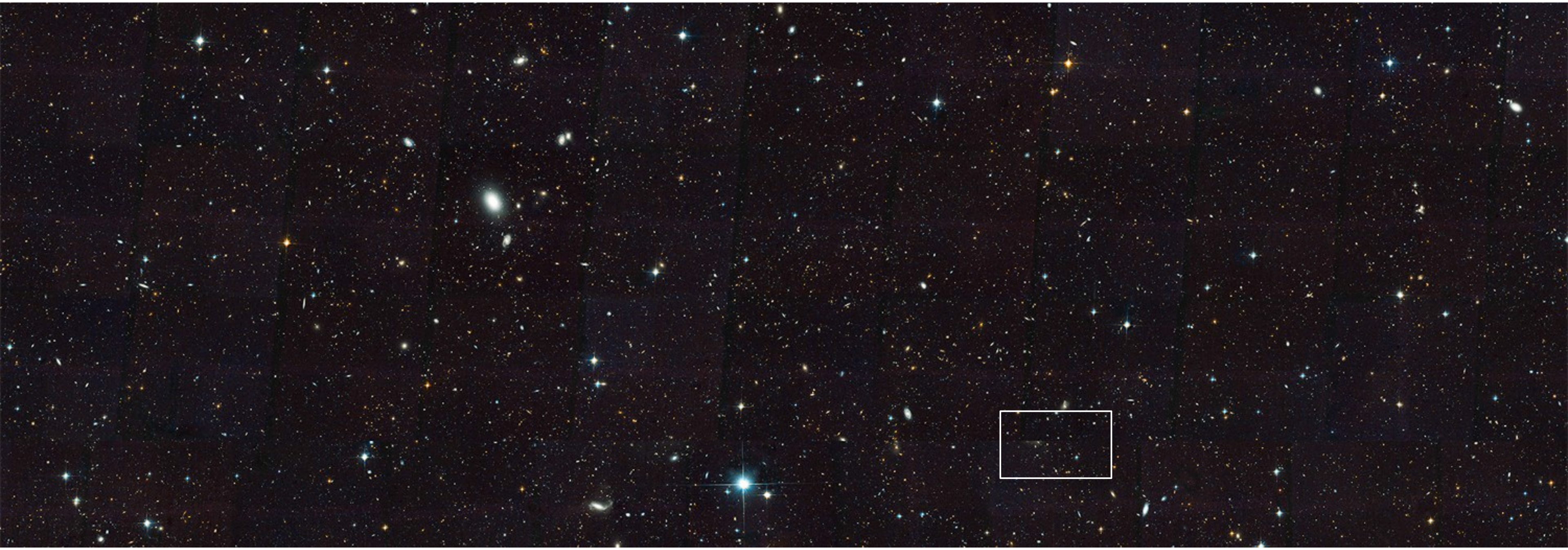


Exoplanet Spectroscopy

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 d 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

WFIRST-AFTA vs Hubble

WFIRST-AFTA Deep Field
>1,000,000 galaxies in each image



Hubble Ultra Deep Field - IR
~5,000 galaxies in one image

WFIRST-AFTA Design Reference Mission Capabilities from the 2013 SDT Report

WFIRST-2.4 Design Reference Mission Capabilities						
Imaging Capability	0.281 deg^2		0.11 arcsec/pix		0.6 – 2.0 μm	
Filters	Z087	Y106	J129	H158	F184	W149
Wavelength (μm)	0.760-0.977	0.927-1.192	1.131-1.454	1.380-1.774	1.683-2.000	0.927-2.000
PSF EE50 (arcsec)	0.11	0.12	0.12	0.14	0.14	0.13
Spectroscopic Capability	Grism (0.281 deg^2)			IFU (3.00 x 3.15 arcsec)		
	1.35 – 1.95 μm, R = 550-800			0.6 – 2.0 μm, R = ~100		

Baseline Survey Characteristics					
Survey	Bandpass	Area (deg^2)	Depth	Duration	Cadence
Exoplanet Microlensing	Z, W	2.81	n/a	6 x 72 days	W: 15 min Z: 12 hrs
HLS Imaging	Y, J, H, F184	2000	Y = 26.7, J = 26.9 H = 26.7, F184 = 26.2	1.3 years	n/a
HLS Spectroscopy	1.35 – 1.95 μm	2000	0.5×10^{-16} erg/s/cm^2 @ 1.65 μm	0.6 years	n/a
SN Survey				0.5 years (in a 2-yr interval)	5 days
Wide	Y, J	27.44	Y = 27.1, J = 27.5		
Medium	J, H	8.96	J = 27.6, H = 28.1		
[illegible]	[illegible]	[illegible]	[illegible]		

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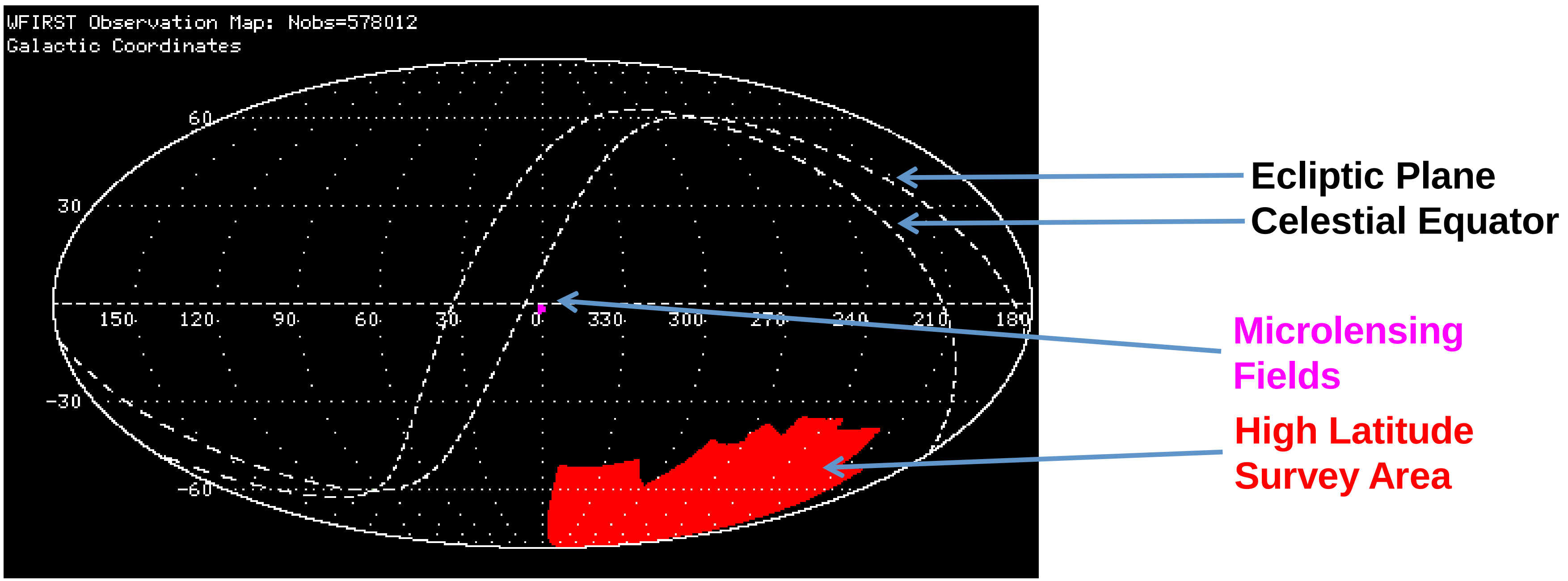
Medium	J, H	8.96	J = 27.6, H = 28.1		
Deep	J, H	5.04	J = 29.3, H = 29.4		
IFU Spec	7 exposures with S/N=3/pix, 1 near peak with S/N=10/pix, 1 post-SN reference with S/N=6/pix Parallel imaging during deep tier IFU spectroscopy: Z, Y, J, H ~29.5, F184 ~29.0				

Guest Observer Capabilities

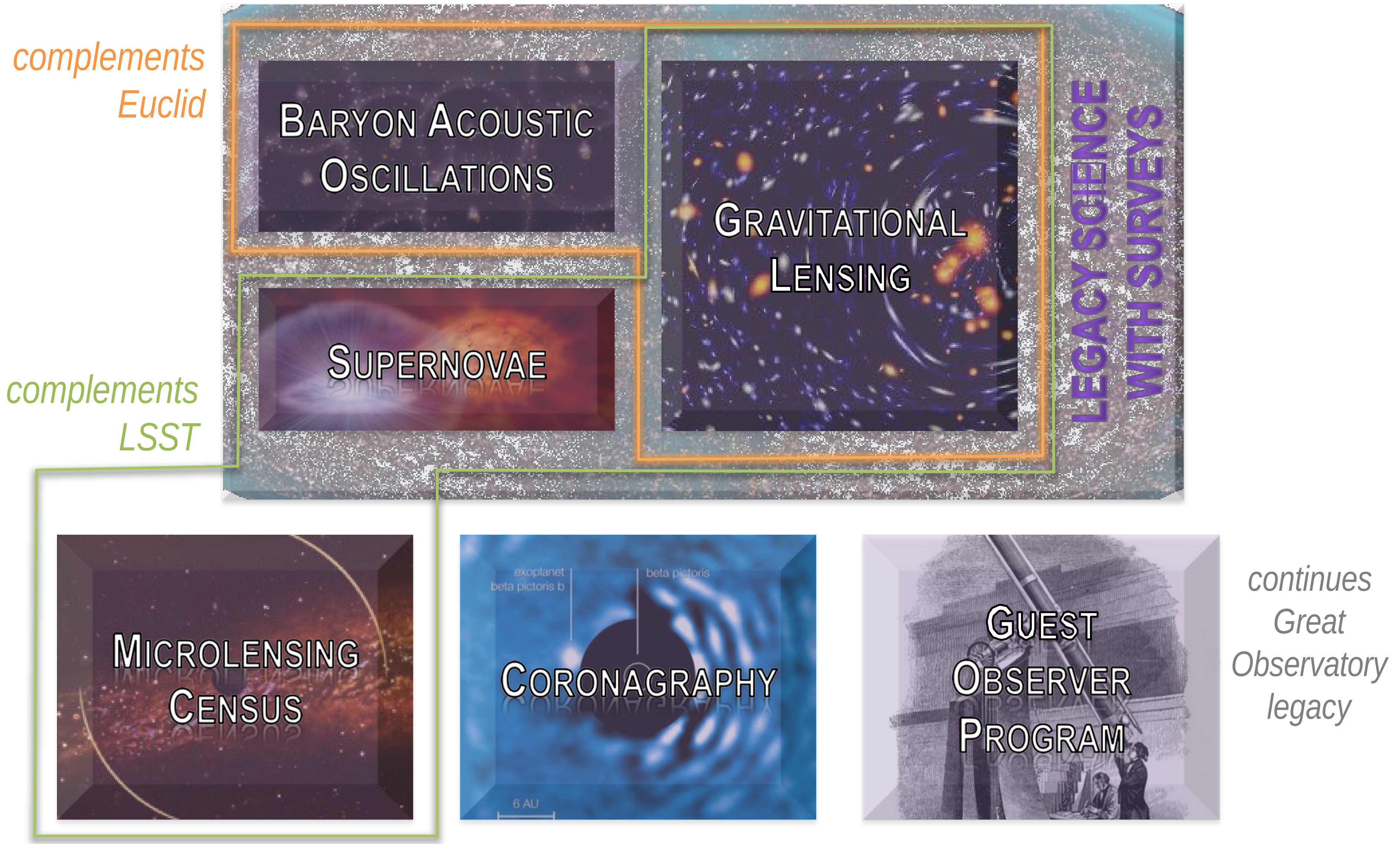
1.4 years of the 5 year prime mission

Example Observing Schedule (not final)

- Unallocated time is 1.43 years (includes GO program)
- High latitude survey (HLS: imaging + spectroscopy): ~2 years
  - **2401 deg²** @ e3 exposures in all filters (2440 deg² bounding box)
- 6 microlensing seasons (~1 years, after lunar cutouts)
- SN survey in ~0.6 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission



WFIRST-AFTA Science



Dark Energy & Cosmology

Questions:

1. Why is the Universe accelerating? Caused by a new energy component or by the breakdown of GR on cosmological scales?
2. If the cause is a new energy component, is its energy density constant in s pace and time, or has it evolved over the history of the universe?

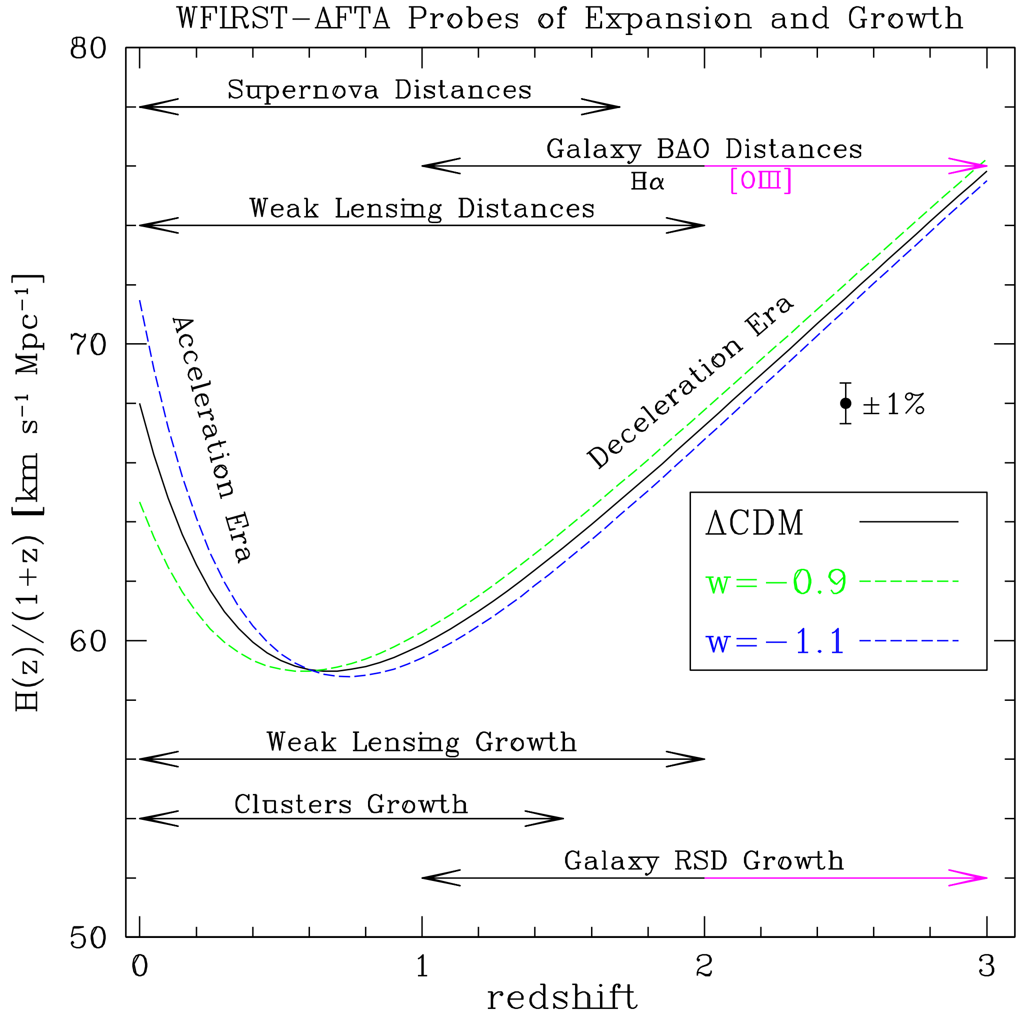
WFIRST-AFTA: Uses multiple methods to measure the history of cosmic exp ansion and structure growth

→ tightly constraining the properties of dark energy, the consistency of GR, and the curvature of space.

1. Supernova Survey: Standard ruler. Distance measurements, $z = 0 – 1.7$.
2. Weak Lensing Survey: Growth of structure from cosmic shear, galaxy-galaxy lensing, abundance of massive clusters.
3. Galaxy Redshift Survey: Distance and expansion rate from BAO, growth of structure from redshift-space distortions. Neutrino effects on galaxy PS.

WFIRST-AFTA Dark Energy

- Expansion history of the Universe and the growth of cosmic structure with multip le methods in overlapping redshift ranges.
- Tightly constrains the prope rties of dark energy, the con sistency ofGR, and the curvature of space.



"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 Horiz ons in Astronomy and Astrophysics***

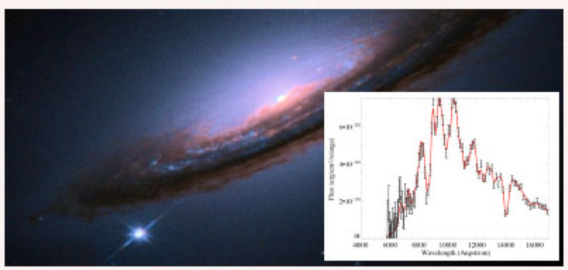
The WFIRST-2.4 Dark Energy Roadmap

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

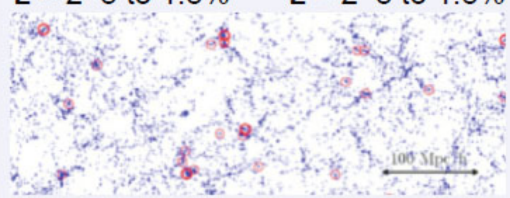
20 million Hα galaxies, $z = 1–2$
2 million [OIII] galaxies, $z = 2–3$

imaging: weak lensing shapes

500 million lensed galaxies
40,000 massive clusters

standard ruler

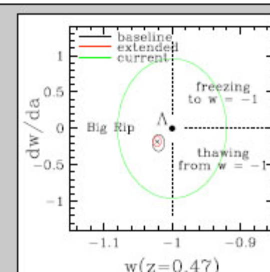
distances	expansion rate
$z = 1–2$ to 0.4%	$z = 1–2$ to 0.72%
$z = 2–3$ to 1.3%	$z = 2–3$ to 1.8%



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

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



WFIRST-AFTA & Euclid Complementary for Dark Energy

WFIRST-AFTA

Deep Infrared Survey (2400 deg^2)

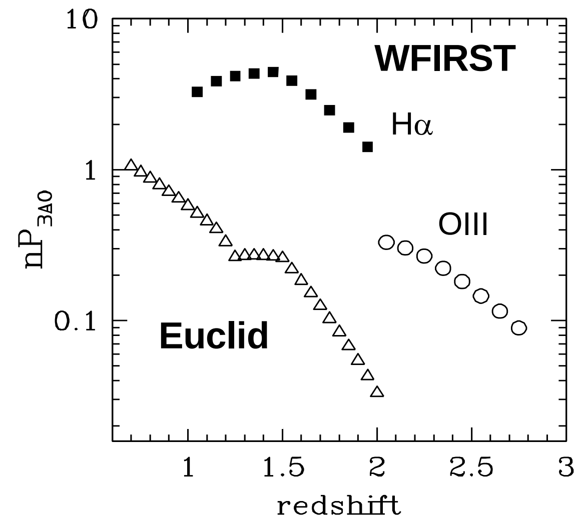
Lensing

- High Resolution (2.5x the Euclid # density of galaxies)
- Galaxy shapes in IR
- 5 lensing power spectra

Supernovae:

- High quality IFU spectra of >2000 SN Redshift survey

- High number density of galaxies
- Redshift range extends to z = 3



Euclid

Wide Optical and Shallow Infrared Survey (15000 deg^2)

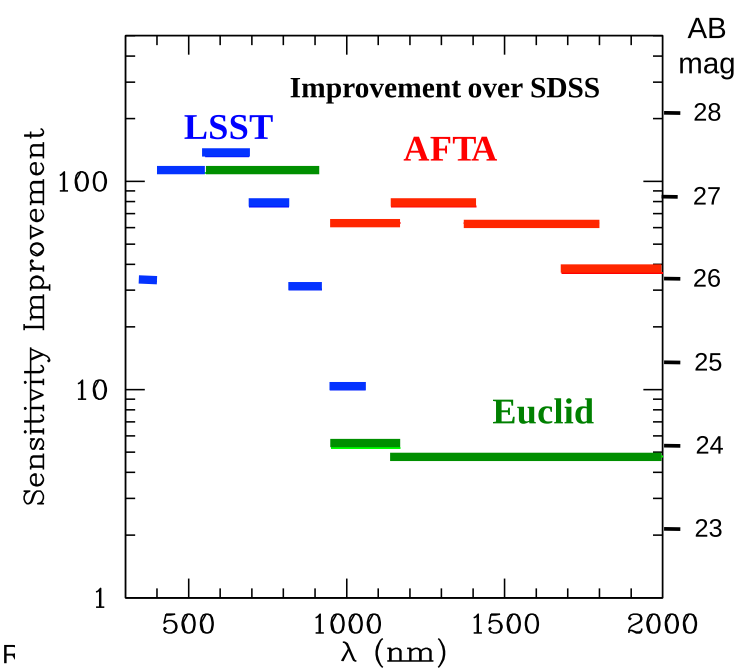
Lensing:

- Lower Resolution
- Galaxy shapes in optical
- 1 lensing power spectrum

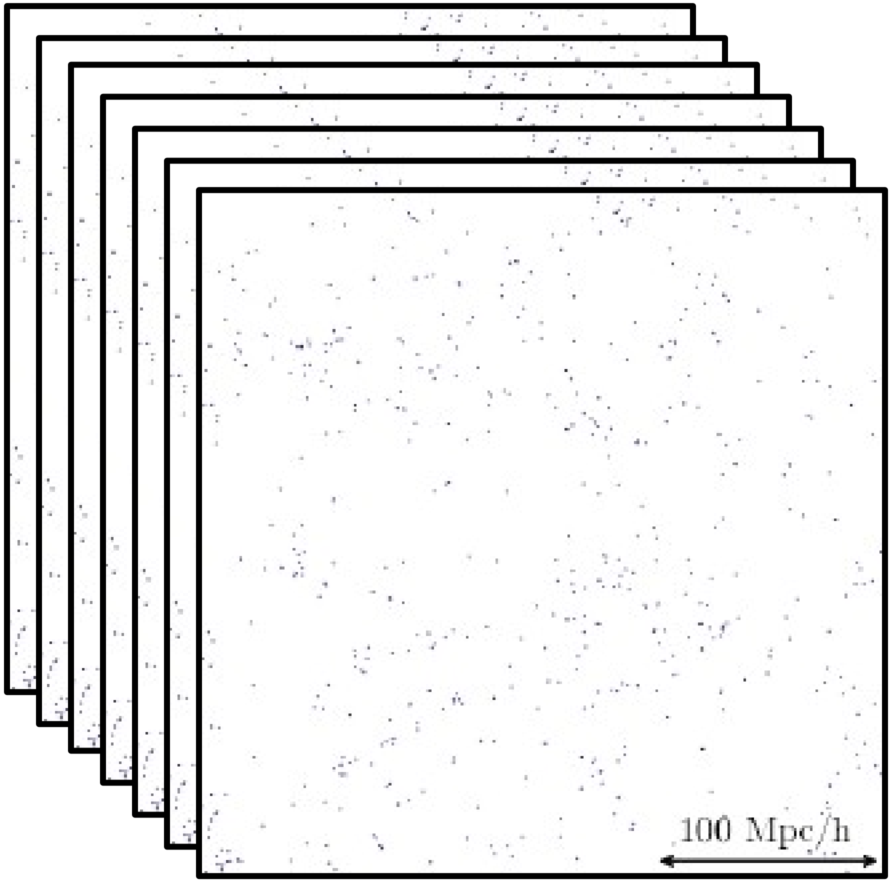
No supernova program

Redshift survey:

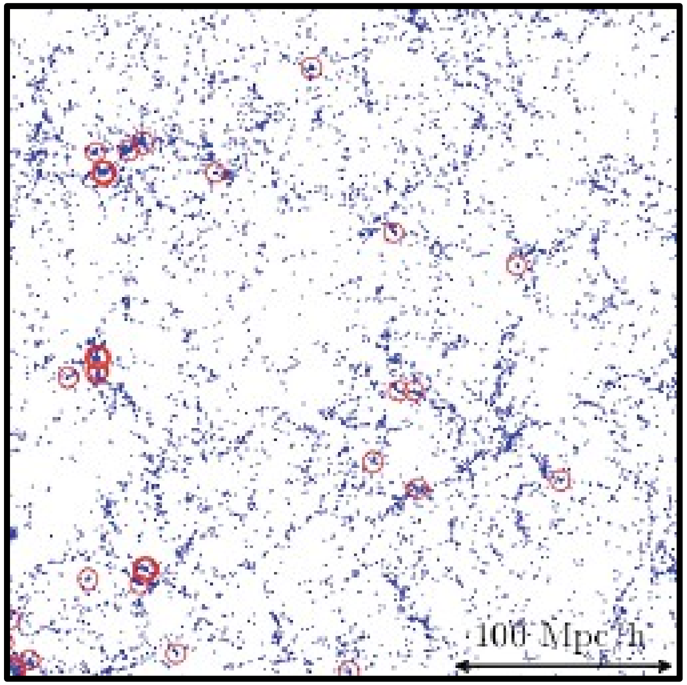
- Low number density of galaxies
- Redshift range z = 0.7 - 2



Detailed 3D Map of Large Scale Structure at z = 1-2



Large scale structure simulation showing 0.1% of the total WFIRST-AFTA Galaxy Redshift Survey Volume



Euclid
15,000 deg² @ 1700 gal/deg²

WFIRST
2,400 deg² @ 12,600 gal/deg²

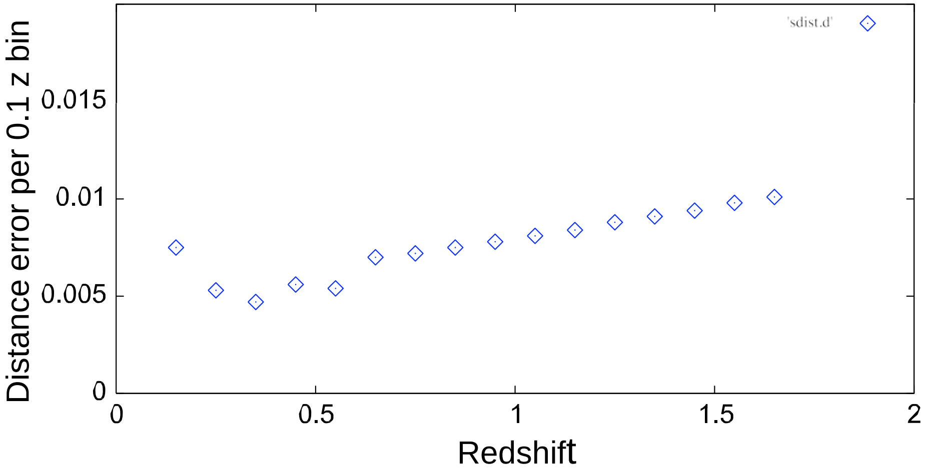
Large scale structure simulations from 2013 SDT Report – courtesy of Ying Zu

Thin and thick red circles mark clusters with masses exceeding 5 x 10^{13} M_{Sun} and 10^{14} M_{Sun}, respectively

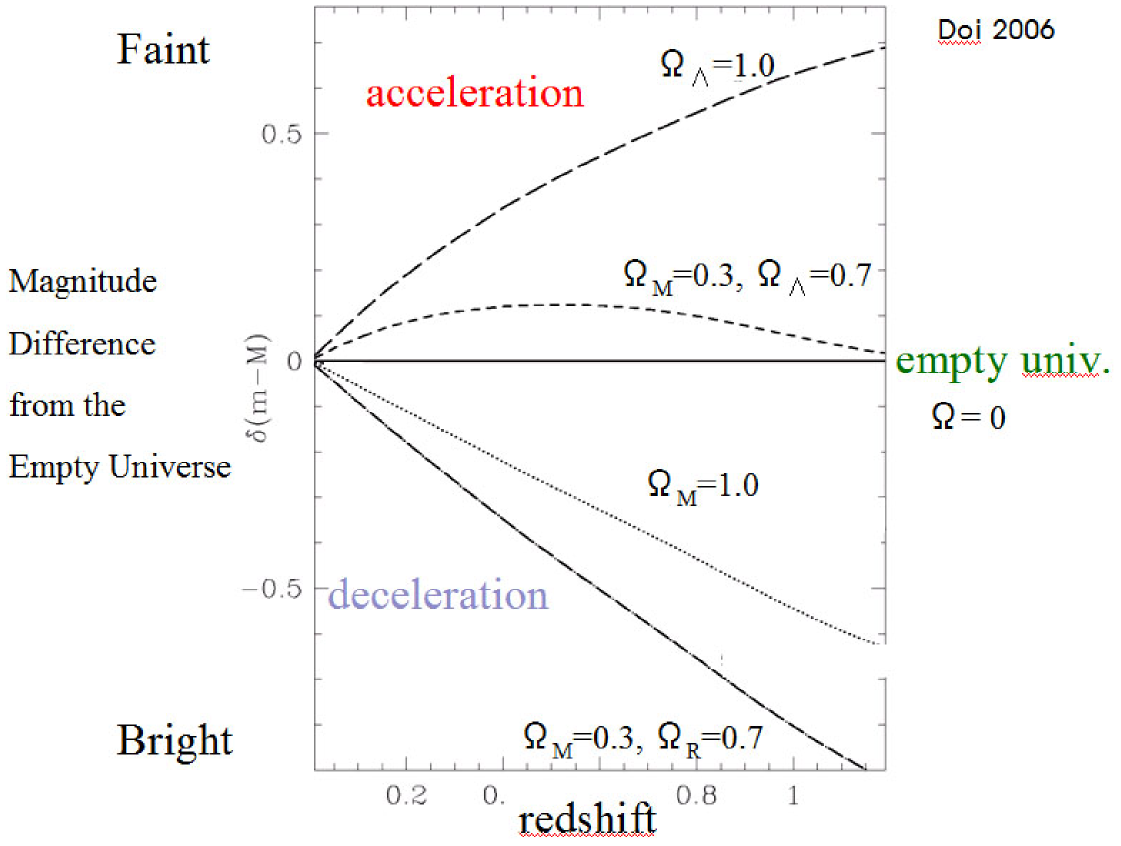
The Supernova Survey

- Three tiered survey for low, medium, and high redshift Type Ia supernovae out to redshift of 1.7
- Use the Wide Field Instrument for SN discovery with a 5day cadence, the IFS for lightcurves from spectrophotometry
- 2700 supernovae, distance errors 0.5 % to 1.0 % per 0.1 redshift bin including best estimate of systematic errors

- 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



©, z dependence of apparent magnitude of a standard candle



$$m(z) - M_B = -5\log(H_0) + 25 + 5\log[H_0 D_L(z, \Omega_m, \Omega_{DE}, w)] + K_{Bx} + A$$

$$d_L = cH_0^{-1}(1+z)\int_0^z dz[(1+z)^3(\Omega_M) + (1-\Omega_M)(1+z)^{3(1+w)}]^{-1/2}$$

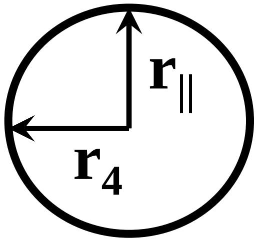
WFIRST-AFTA Galaxy Redshift Survey

- 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 -- 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

Geometric methods using LSS

$$r_{\|} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z) D_A(z) \Delta\theta$$ (=r d¸)



where

$$D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)}$$

$$\mathbf{H(z)} = \sqrt{\frac{\Omega_m h^2}{1-\Omega_X}} \sqrt{\Omega_m (1+z)^3 + \Omega_X \exp\left[3 \int_0^z \frac{1+w(z)}{1+z} dz\right]}$$

Standard rulers (Actual objects or Features in PS/CF)

→ measure ”z & ”¸ → H(z) & D_A(z) → ©$_m$, ©¸ , w

BAO

Acoustic oscillation amplitude : depends on ©$_b$

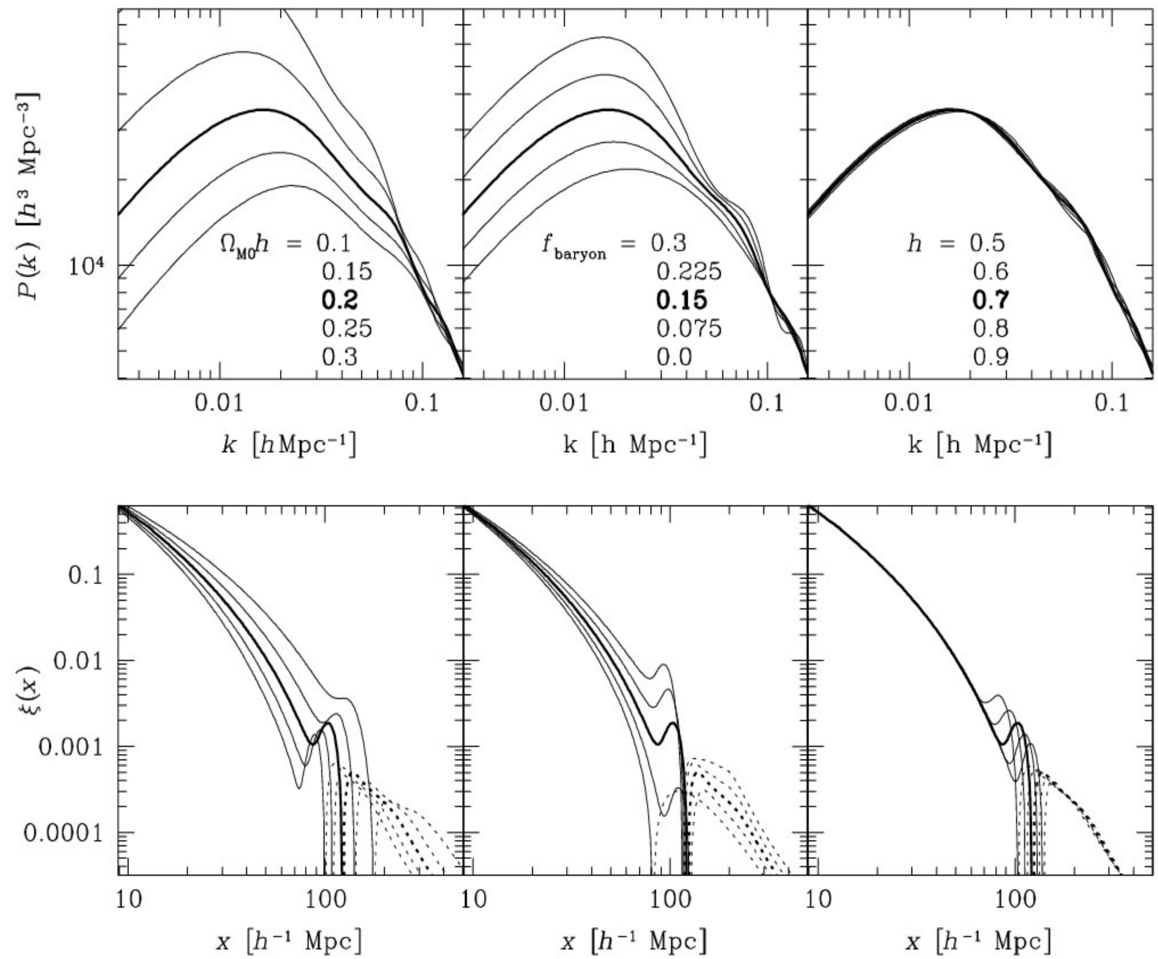
oscillation scale = comoving sound horizon 's' at t_{dec}

k_A = 2À/s depends strongly on ©$_m$, weakly on ©$_b$ not on DE

→ Curvature of space, Baryonic mass

Baryonic oscillation in PS

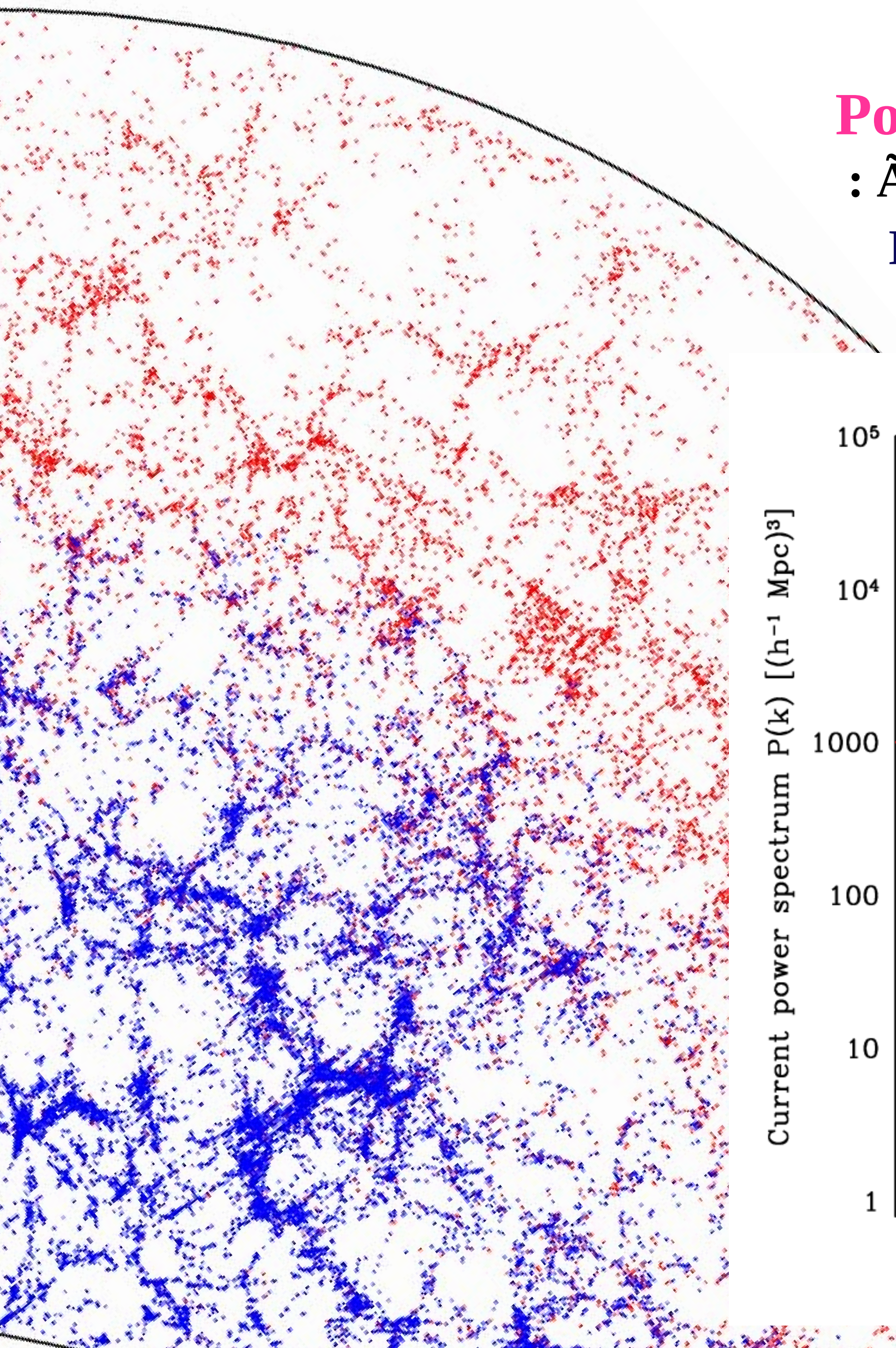
Baryonic bump in CF

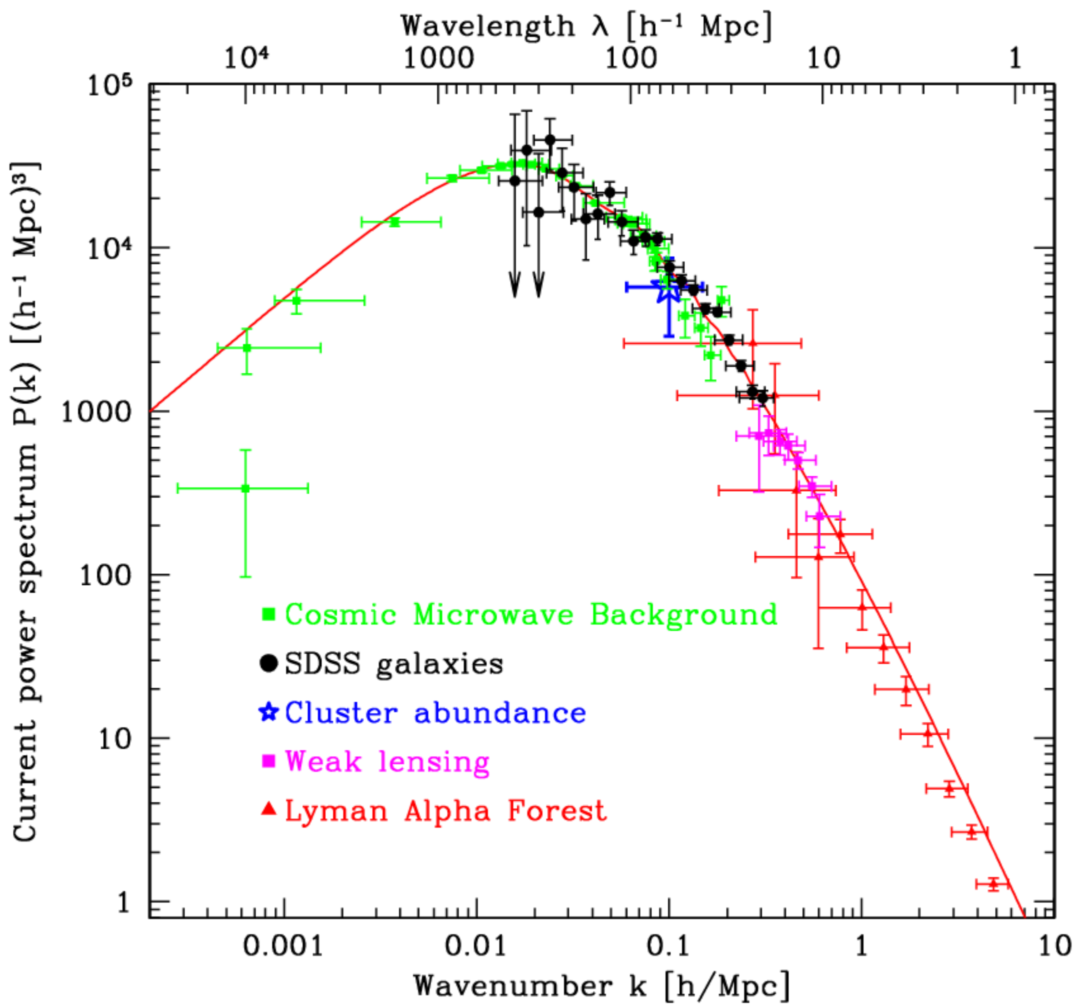


Power Spectrum from CMB & LSS

: Ã$_8$(amplitude), ©$_m$ (equality scale)

But biasing relative to matter (Ã$_8$)





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 l ensing.
  - 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 c alibration. *Crucial* for believing high-precision measurements.
  - Small and stable PSF with 2.4 m space telescope reduces sys tematic errors in the PSF model and their impact on galaxy elli pticity measurement
  - Dither pattern recovers full sampling, even rejecting cosmic rays at GEO rate

Clusters of galaxies

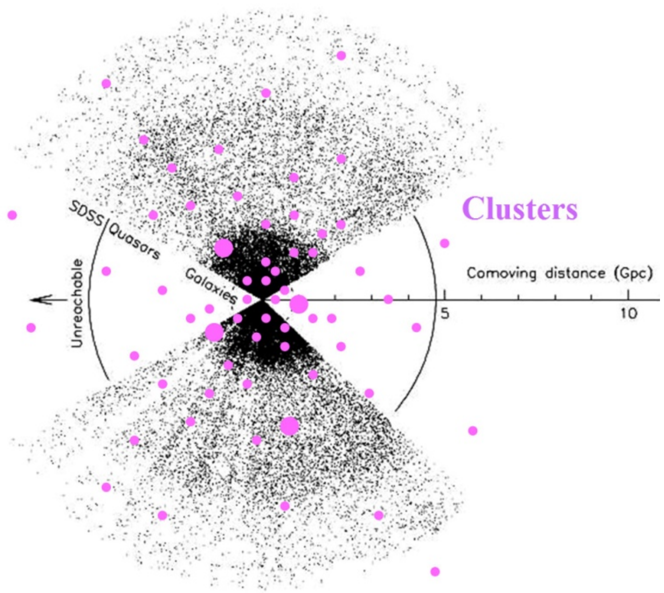
Cluster # count

A census of clusters by X-ray or SZ effect as a function of redshift and mass

Compared with model predictions to derive cosmological parameters

abundance $d^2N/dMdz$

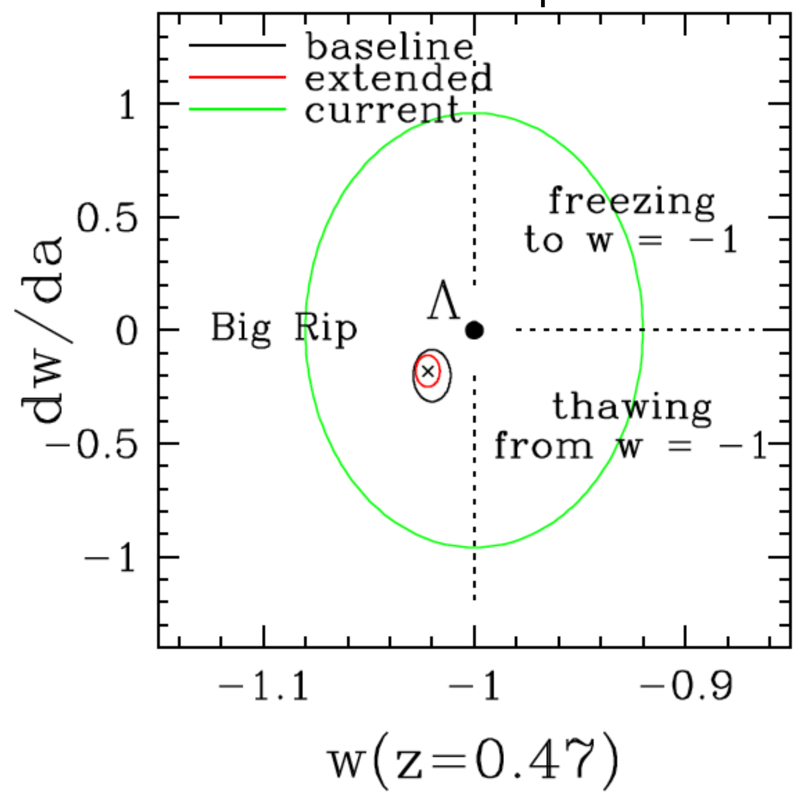
$$\frac{d^2N}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2(z)\,(1+z)^2 \int_0^\infty dM\, \frac{dn}{dM}(M,z)\, f(M,z)$$



Potential for Discovery

WFIRST-AFTA will improve cosmological measurements by 1-2 orders of magnitude over current data, with greater redshift leverage, control of systematics, and cross-checks of methods.

From 2013 SDT Report



Forecast dark energy constraints from baseline & extended programs, compared to current knowledge. Distinct regions of plane represent fundamentally different physics.

Current/Planned Wide-Field Spectroscopic Galaxy Surveys

Instrument	Telescope	Ref	Nights/ year	No. Galaxies	sq deg	Ops Start
SDSS I+II	APO 2.5m	1	dedicated	85K LRG	7600	2000
Wiggle-Z	AAT 3.9m	2	60	239K	1000	2007
BOSS	APO 2.5m	3	dedicated	1.4M LRG + 160K Ly-α	10000	2009
HETDEX	HET 9.2m	4	60	1M	420	2014
eBOSS	APO 2.5m	-	dedicated	600K LRG + 70K Ly-α	7000	2014
MS-DESI	NOAO 4m	5	tbd	32M + 2M Ly-a	18000	2018
SUMIRE PFS	Subaru 8.2m	6	20	4M	1400	2018
4MOST	VISTA 4.1m	7	dedicated	6-20M bright objects	15000	2019
EUCLID	1.2m space	8	dedicated	52M	14700	2021

1 Eisenstein et al AJ 122, 2267 (2001) & astro-ph/0501171 (2005); Hogg et al ApJ 624, 54 (2005);
2 Drinkwater et al MNRAS 401, 1429 (2010); Scrimgeour et al arXiv 1205.6812 (2012)
3 Eisenstein et al AJ 142, 72 (2011); Bolton et al arXiv 1207.7326 (2012); http://www.sdss3.org/dr9/
4 Hill et al ASP Conf Series vol 399, 115 (2008) ** but 1/7 fill factor
5 Abdalla et al arXiv 1209.2451 (2012), Schlegel et al arXiv 1106.1706 (2011)
6 Ellis et al arXiv 1206.0737 (2012)
7 de Jong et al arXiv 1206.6885 (2012); primarily follpw-up of GAIA stellar samples
8 Amiaux et al arXiv 1209.2228 (2012)

WFIRST	2.4m space		0.6 year	22M	2000	2024

Dark Energy Landscape in 2024

- DES, HSC long done
- DESI, PFS wrapping up
- LSST in ~3rd year of survey operations
- Euclid in mature operation
- WFIRST launches
  - Is WFIRST to Euclid as Planck is to WMAP?
  - Multiplicity of experiments and probes suggests there will be a n umber of tensions to resolve, due to systematics and/or departur es from ΛCDM.

SDSS vs WFIRST

1. WMAP vs Planck
2. Not just DE