Optical/NIR Imaging Surveys

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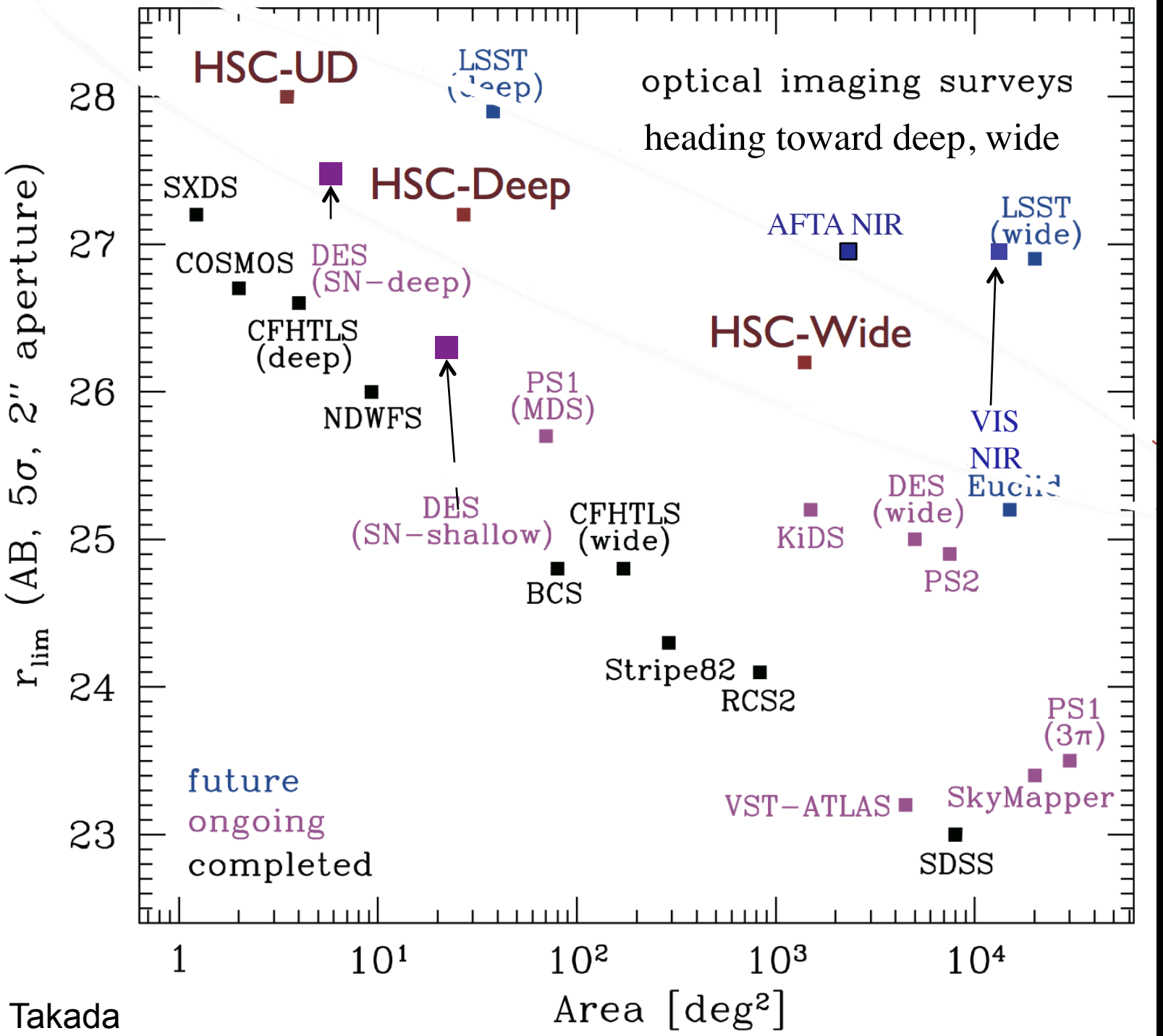
Cosmology in the Era of Extremely Large Telescopes
June 10, 2013

New Generation of Large Imaging Surveys

- Science Goals (varying, but common themes):
  - Cosmology/Dark Energy
  - Galaxy Formation and Evolution
  - Time-Domain Studies
  - Local (Galactic) Structure
  - …
- Billions of targets for ELT Follow-up
- Immense synergies to be exploited

Brief Survey of New Imaging Surveys

- Dark Energy Survey (2013-18)
- Hyper Suprime-cam surveys (2014-18)
- LSST (2021-31)
- Euclid (2020-26)
- WFIRST/AFTA (early 2020's?)
- With apologies to PanSTARRS, Skymapper,…
- Dates are notional survey start dates, based on recent information from participants/proponents


optical imaging surveys
heading toward deep, wide
HSC-UD
LSST (deep)
HSC-Deep
SXDS
COSMOS
DES (SN−deep)
CFHTLS (deep)
NDWFS
PS1 (MDS)
DES (SN−shallow)
CFHTLS (wide)
BCS
Stripe82
RCS2
AFTA NIR
LSST (wide)
HSC-Wide
VIS
NIR
Euclid
DES (wide)
KiDS
PS2
PS1 (3π)
SkyMapper
VST−ATLAS
SDSS
future
ongoing
completed
r_{lim} (AB, 5σ, 2″ aperture)
Area [deg²]
28
27
26
25
24
23
1
10¹
10²
10³
10⁴

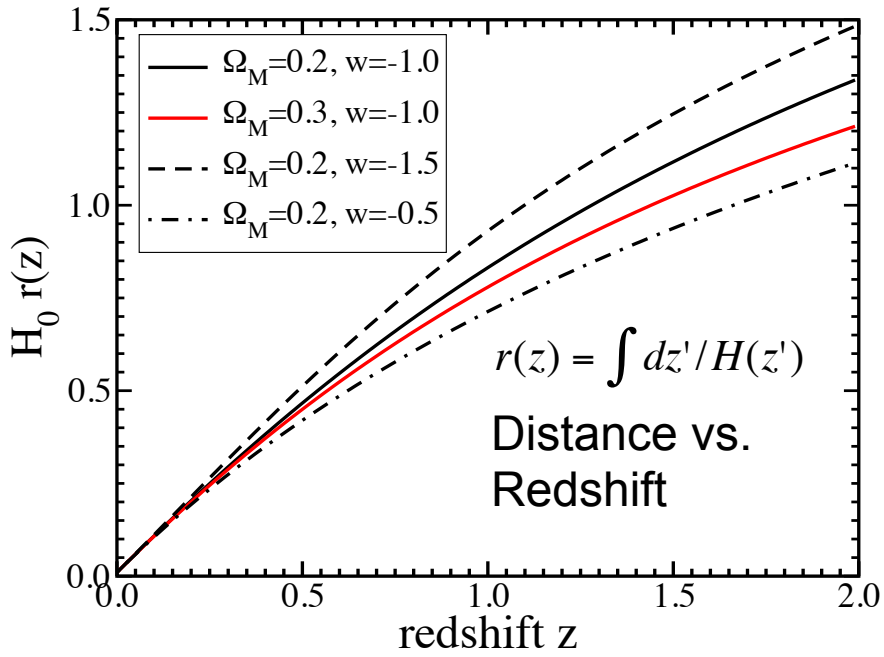
Takada

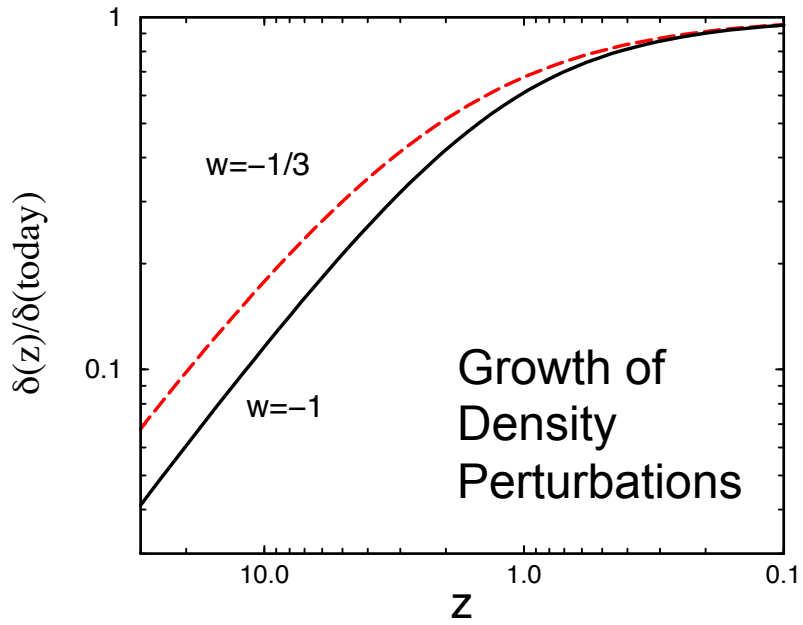
Dark Energy

- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - What is the DE equation of state parameter *w* and (how) does it evolve?

What can we probe?

Require both to disentangle Dark Energy from Modified Gravity





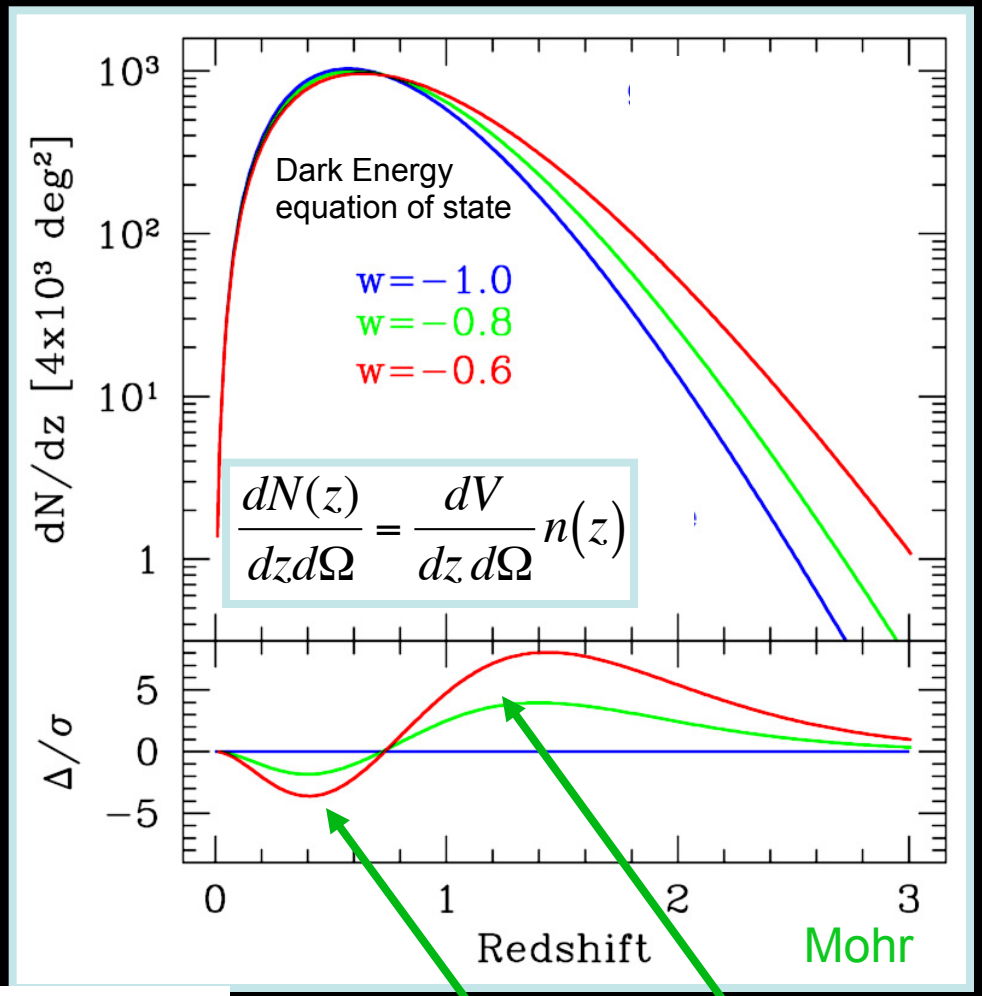
- Weak Lensing cosmic shear — Distances+growth
- Supernovae — Distances
- Baryon Acoustic Oscillations — Distances and H(z)
- Cluster counting — Distances+growth
- Redshift Distortions — Growth

I. Clusters

- Clusters are proxies for massive halos and can be identified optically to redshifts z>1
- Galaxy colors provide photometric redshift estimates for each cluster
- Observable proxies for cluster mass: optical richness, SZ flux decrement, weak lensing mass, X-ray flux

- Challenge: determine mass-observable relation *p(O|M,z)* with sufficient precision

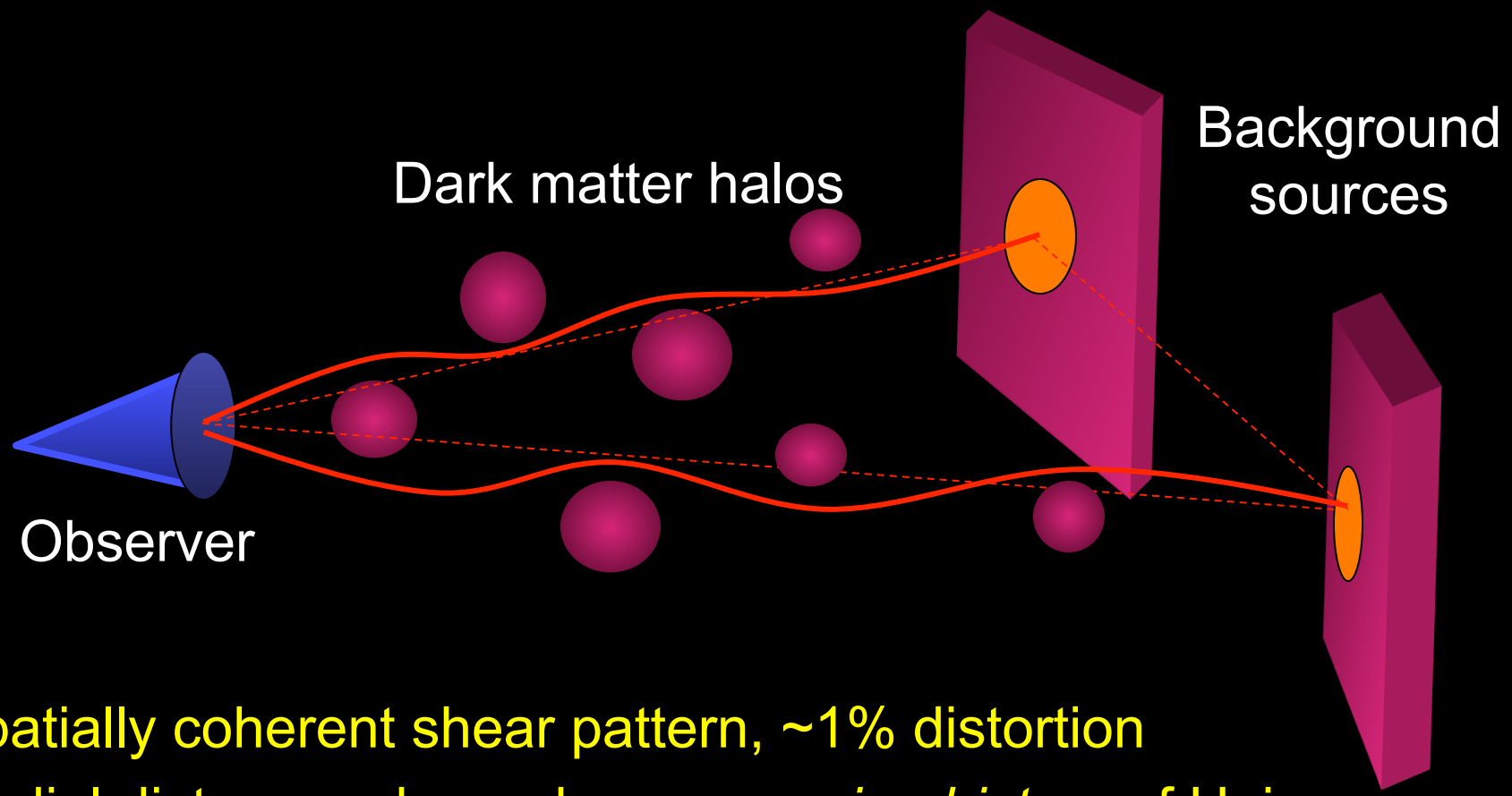
Number of clusters above mass threshold



$$\frac{d^2N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z) dO \int p(O \mid M,z) \frac{dn(z)}{dM} dM$$

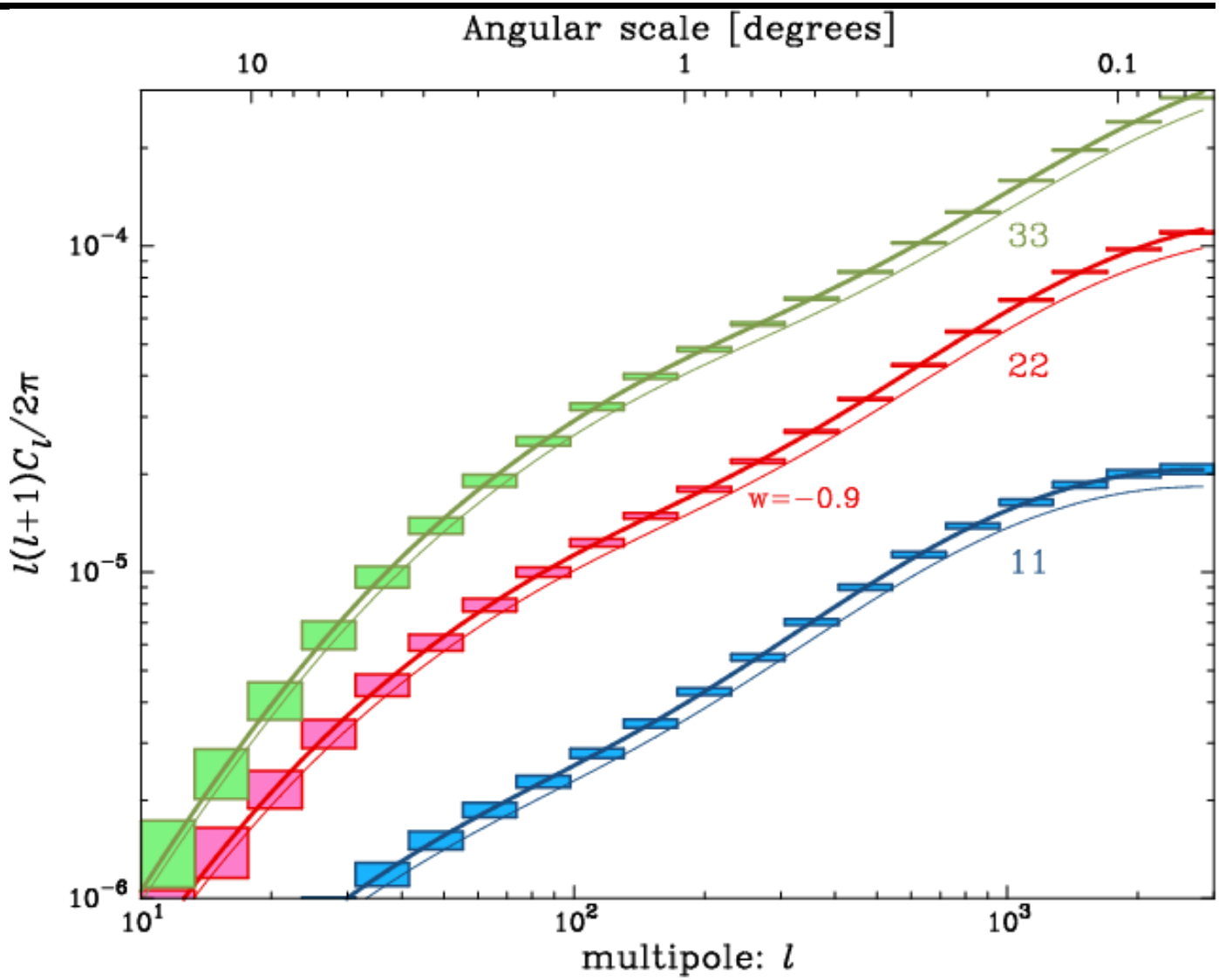
Volume Growth

II. Weak Lensing: Cosmic Shear

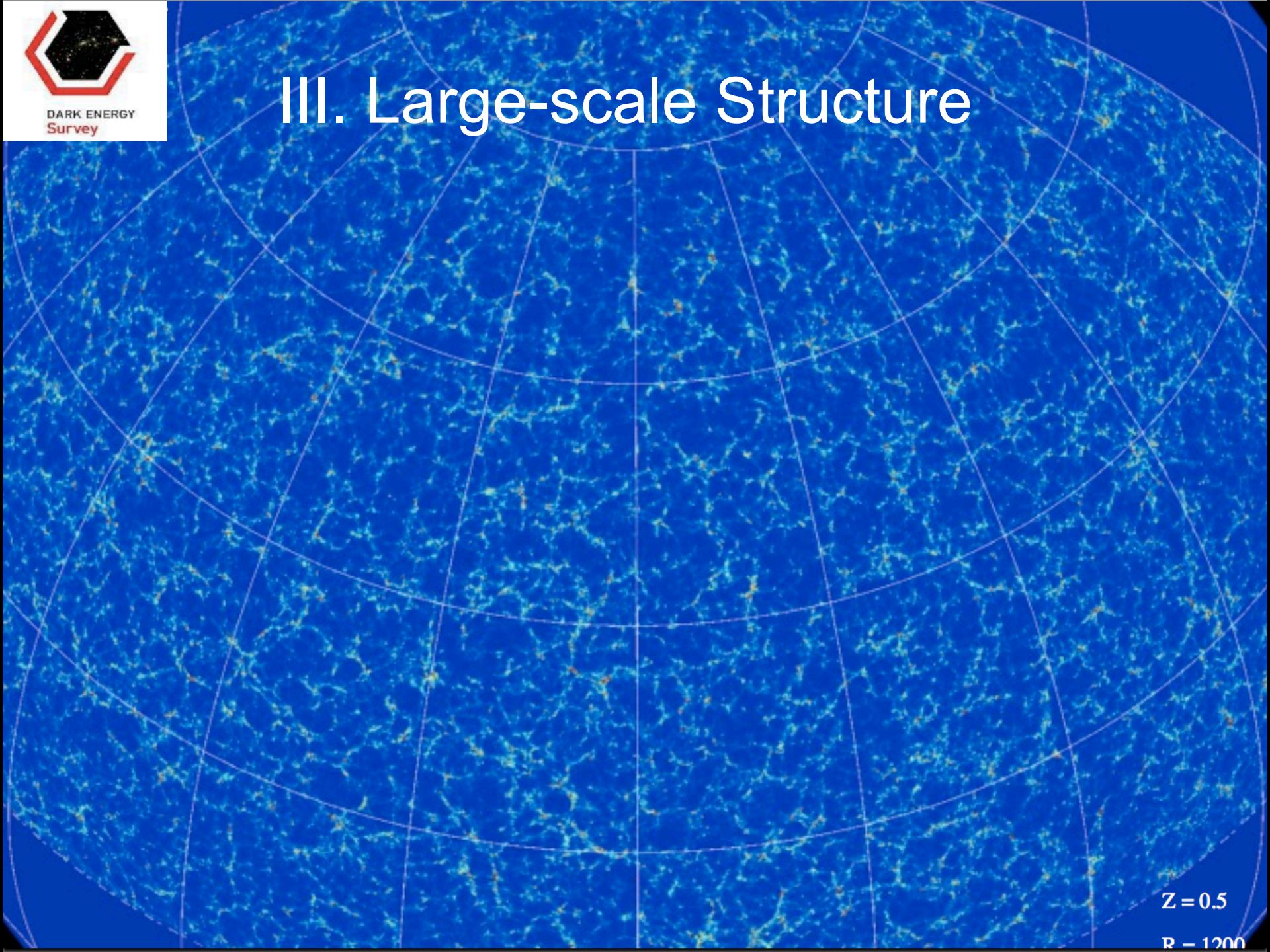


- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

Cosmic Shear Tomography



III. Large-scale Structure

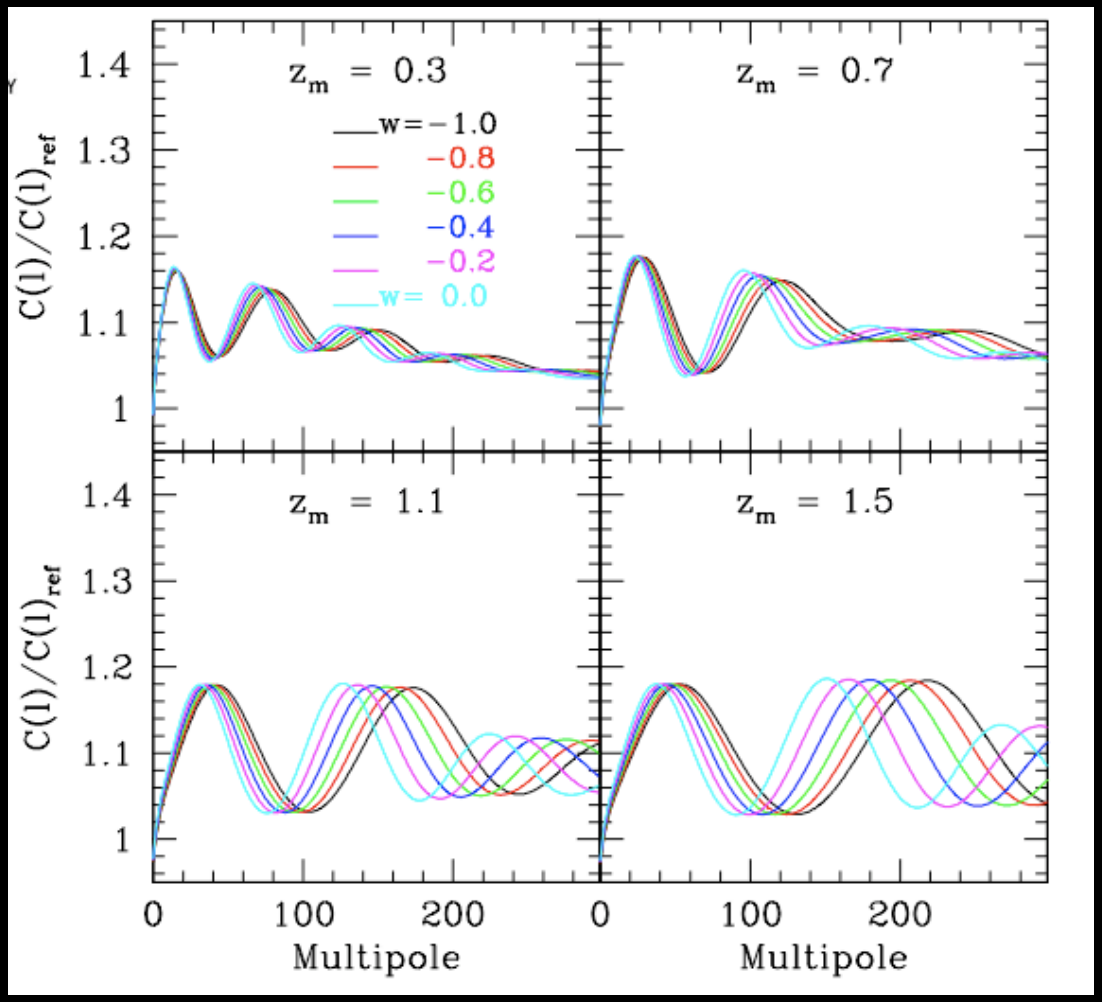


Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins (relative to model without BAO)

Photometric surveys provide angular measure

Radial modes require spectroscopy



Fosalba & Gaztanaga

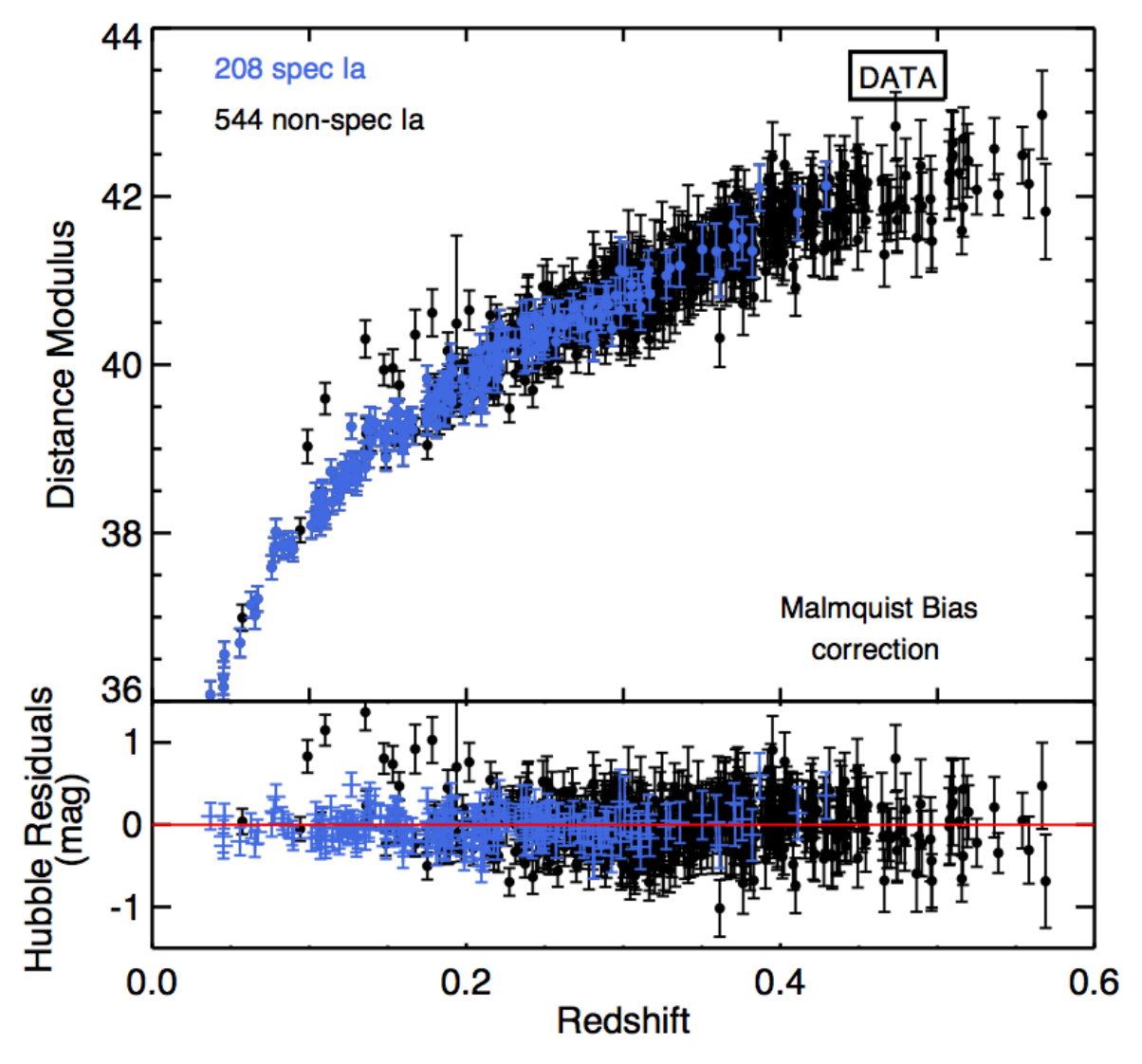
IV. Supernovae

B. Dilday

SDSS-II: 500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III

Photometric SN Cosmology

- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts
- Future surveys will have SN spectra for only a small subsample



Campbell, etal

VST and VISTA

250 nights: VIKING

440 nights: KiDS

VISTA

4m telescope

0.6 sq.deg. InfraRed camera

16 2kx2k detectors

0.35" pixels

VST

2.6m telescope

1 sq.deg. optical camera (OmegaCAM)

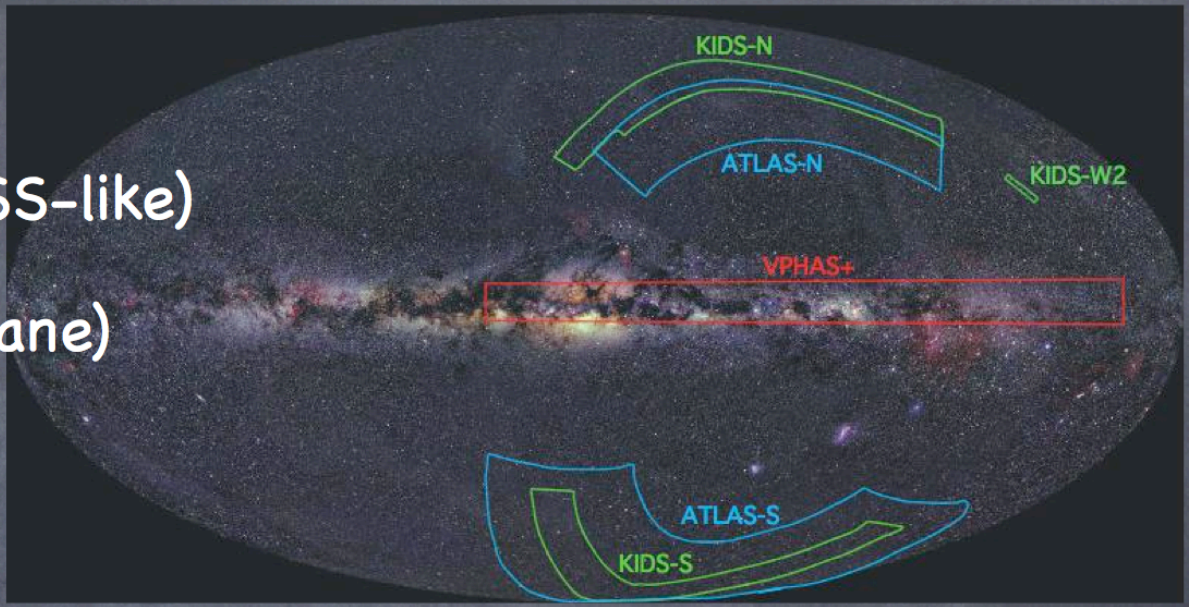
32 2kx4k detectors

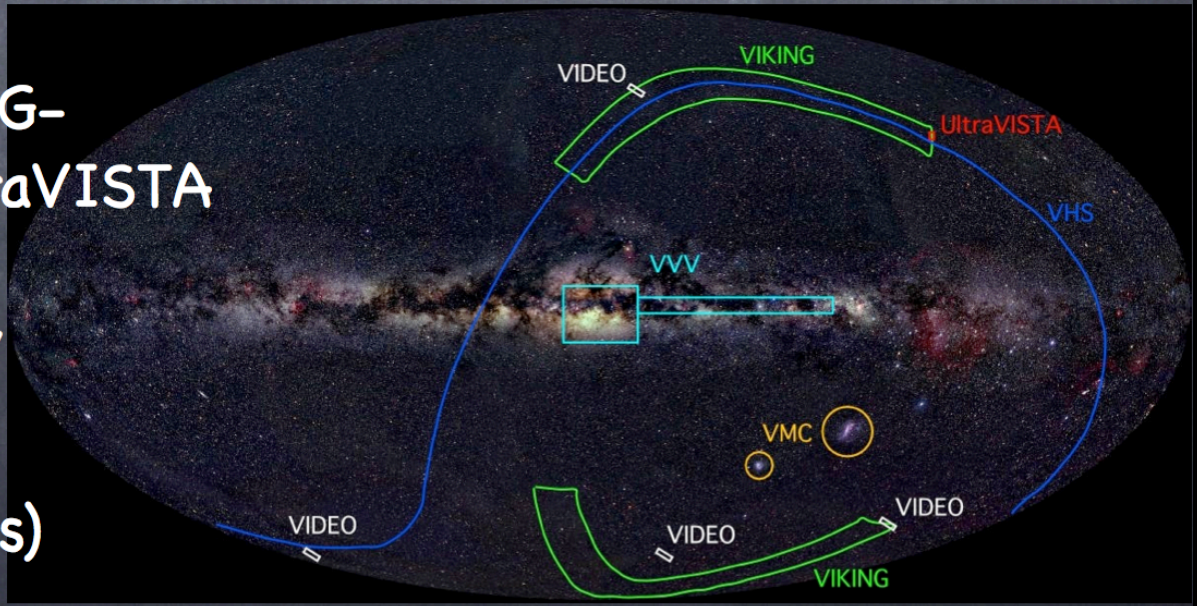
0.21" pixels

Kuijken

ESO Public Surveys

- VST:
  - ATLAS (SDSS-like)
  - VPHAS+ (plane)
  - KiDS
- VISTA:
  - VHS-VIKING-VIDEO-UltraVISTA
  - VVV (plane, variables)
  - VMC (Clouds)

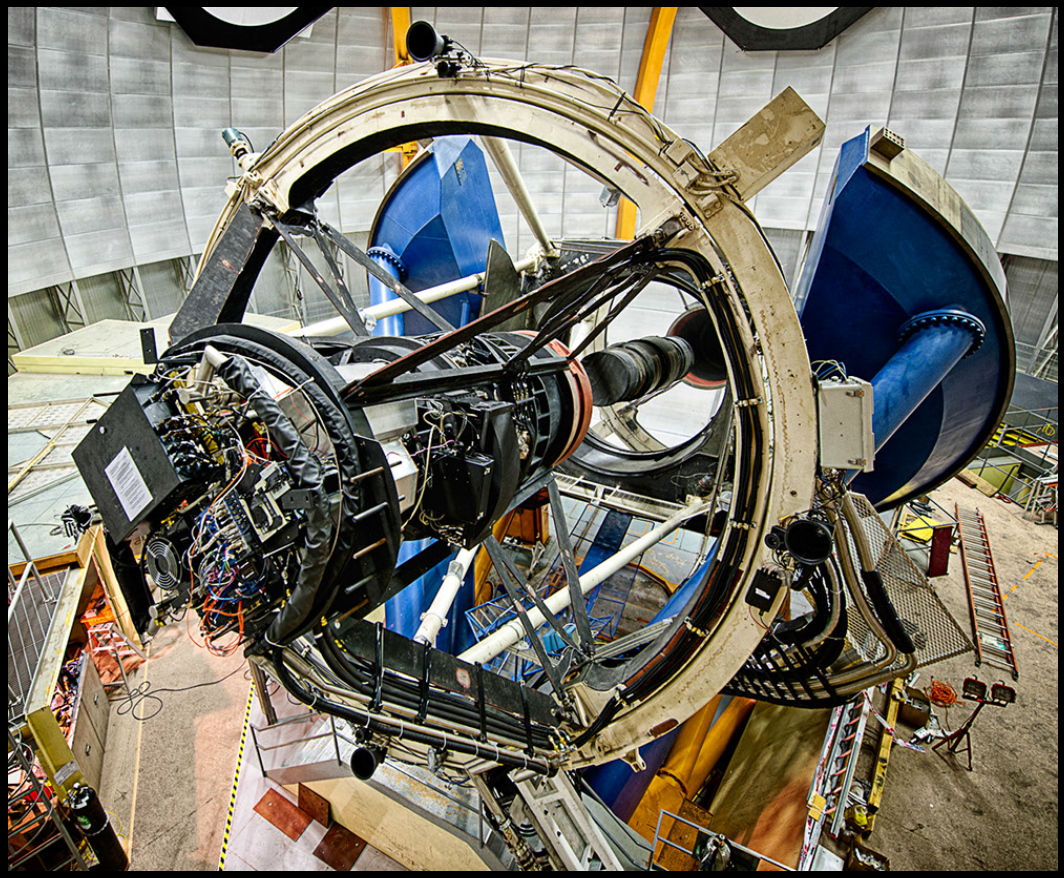




The Dark Energy Survey

- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband imaging surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat *griz* (SNe)
- New 3 deg^2 FOV camera on the Blanco 4m telescope
  - Survey 2013-2018 (525 nights)
  - Facility instrument for astronomy community (DES 30% time)

DECam on the Blanco 4m at CTIO



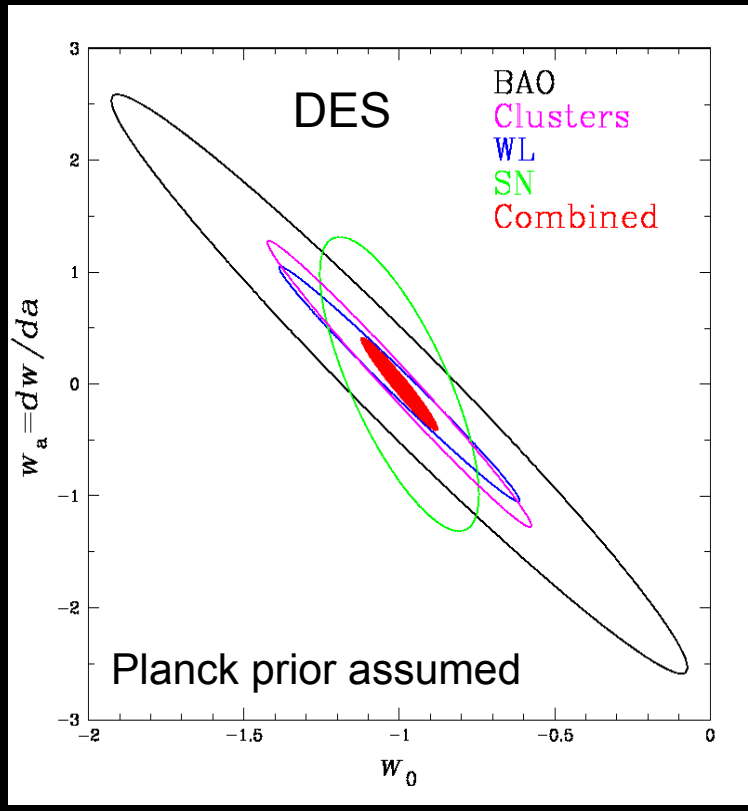
www.darkenergysurvey.org
darkenergydetectives.org

DES Science Summary

Four Probes of Dark Energy

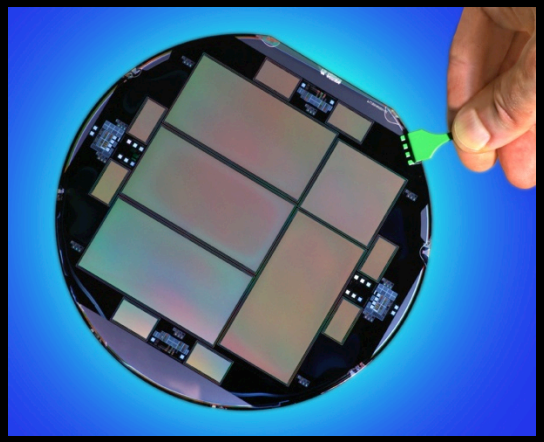
- Galaxy Clusters
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Forecast Constraints on DE Equation of State

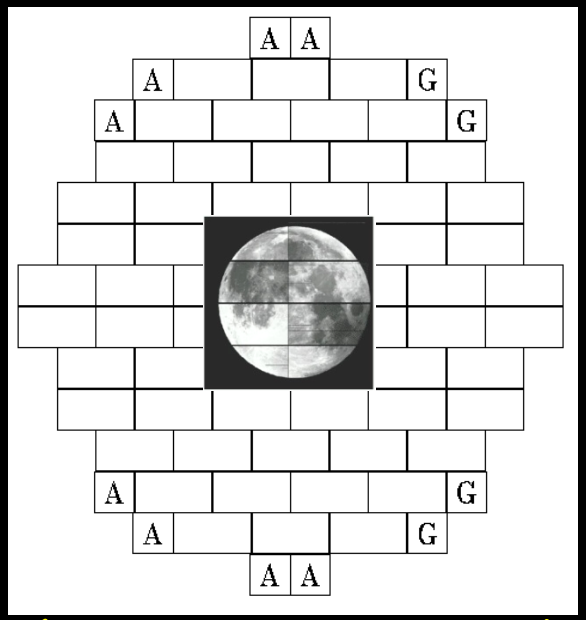


DETF Stage III Experiment

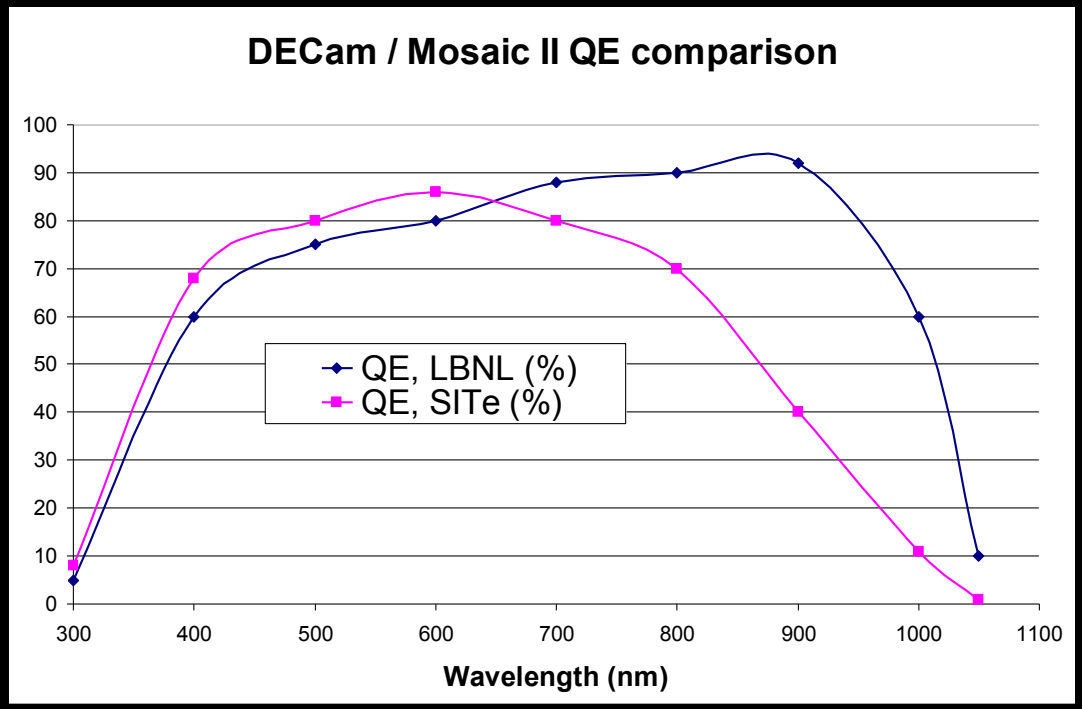
DECam CCDs



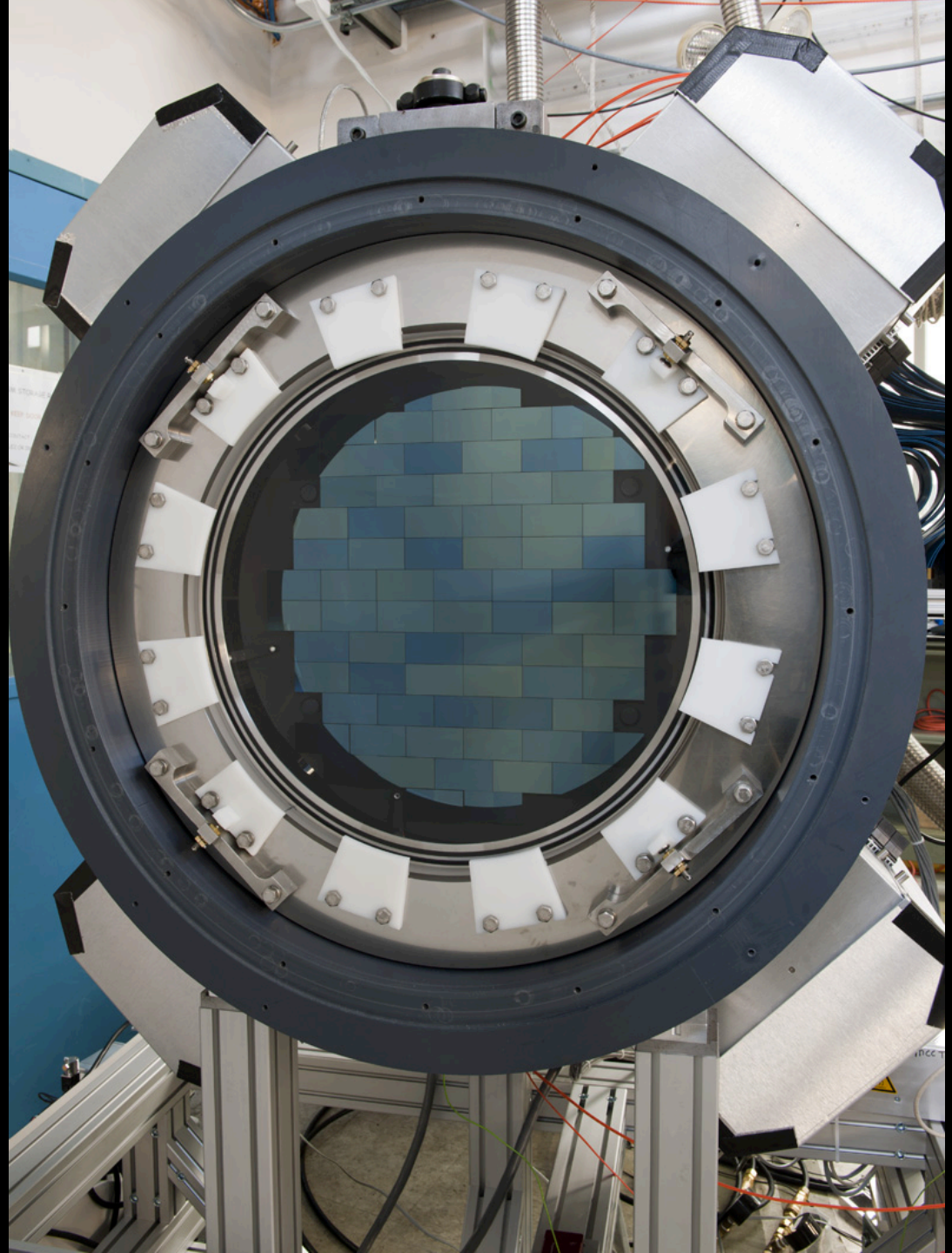
- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels



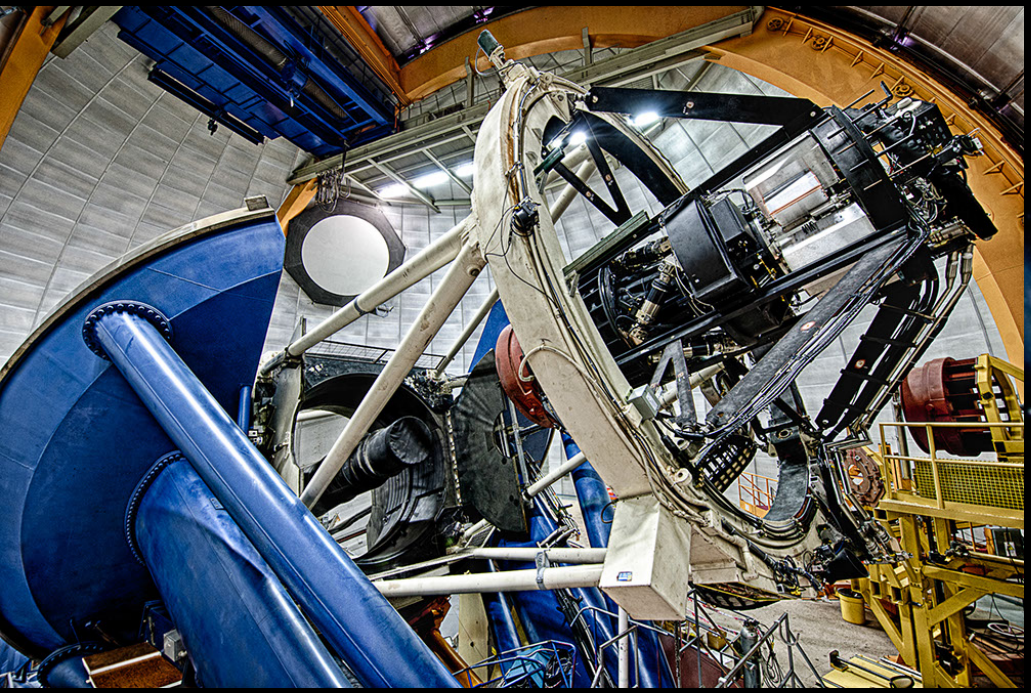
2.2 deg



570-Mpix DECam imager



DECam First Light



September 12, 2012

Covered in 258 publications in 36 countries, plus Jay Leno’s monologue

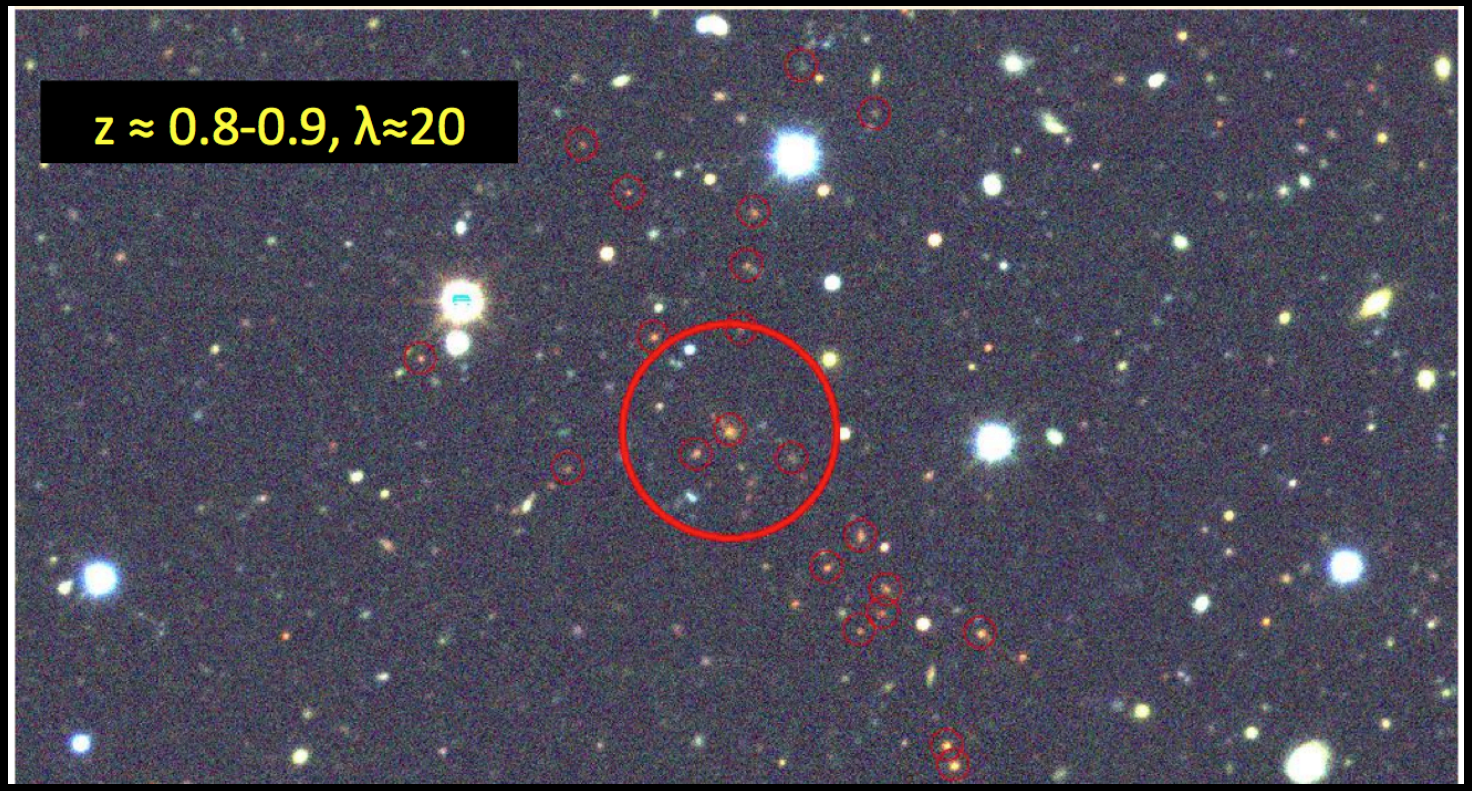
DARK ENERGY SURVEY

DECam
1x1deg
grizY co-add
image of SPT
cluster
z=0.32

~50,000 galaxies
in this image

DARK ENERGY
SURVEY

High Redshift Cluster Discovered by DES

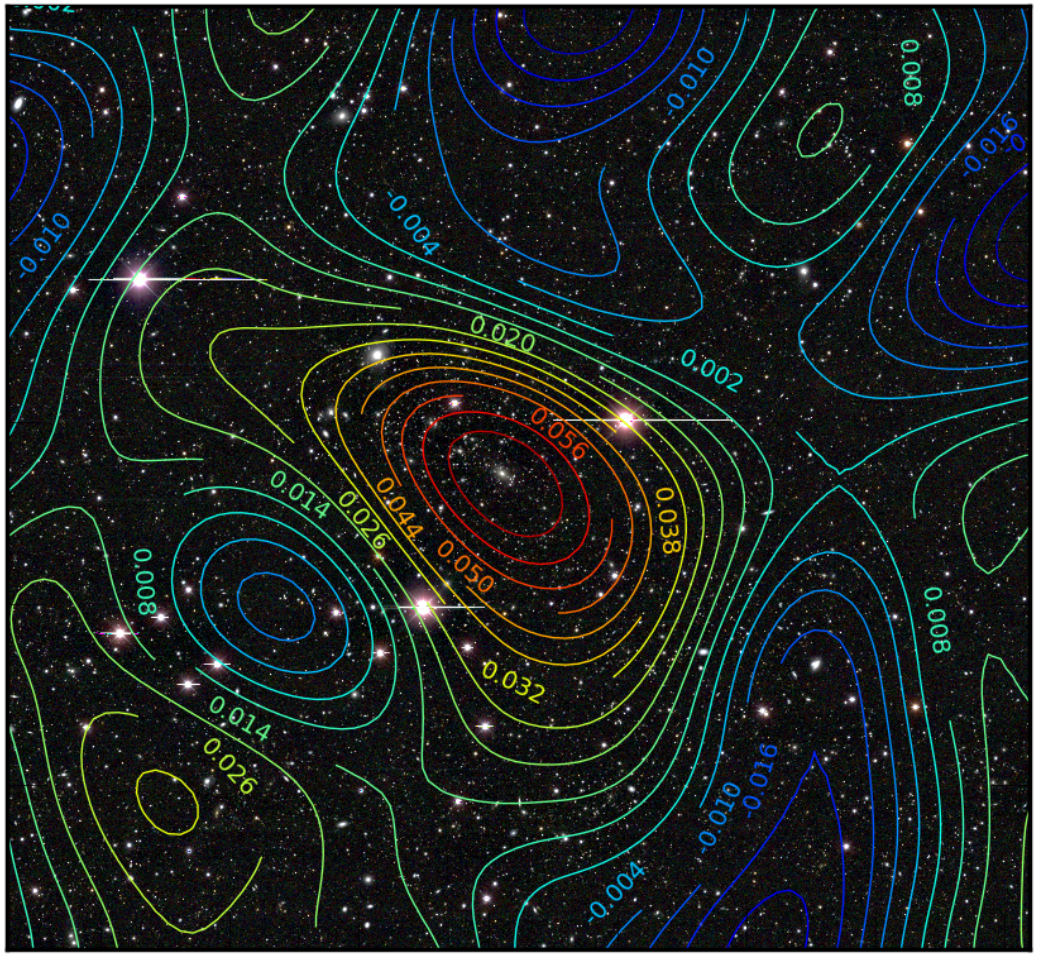


from DES Science Verification data in November

Cluster Weak Lensing

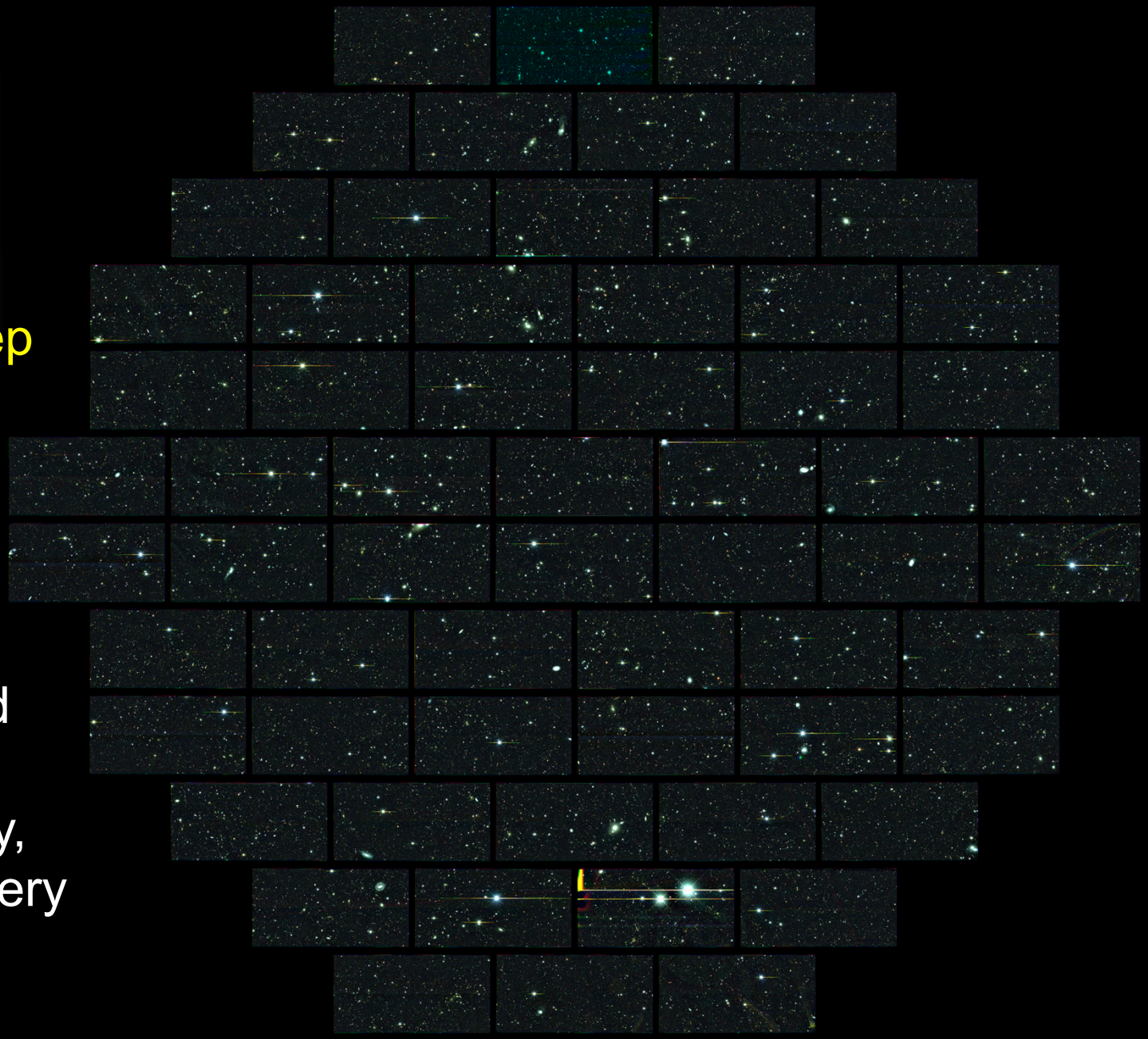
- Stacked (statistical) Weak Lensing cluster shear profiles will calibrate cluster mass-observable relations

- Preliminary cluster mass map from DES Science Verification data



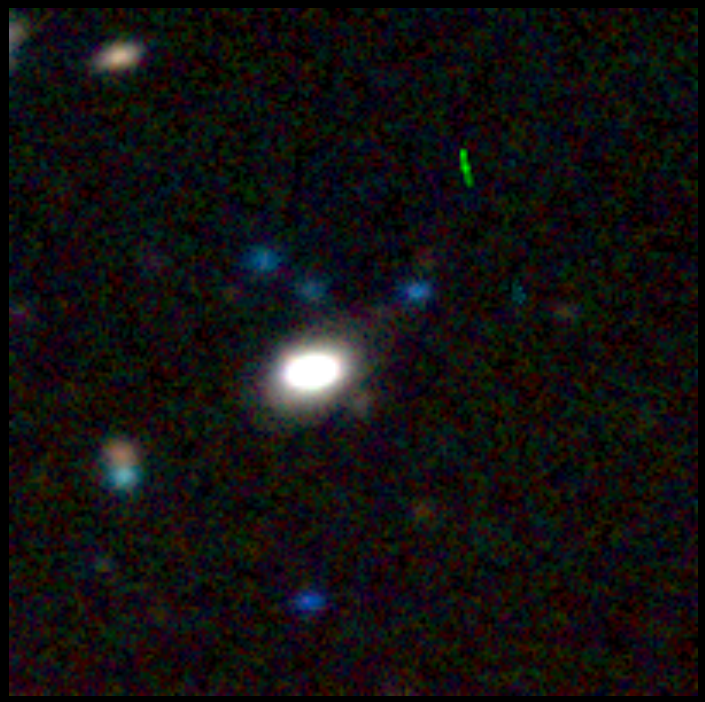
DARK ENERGY SURVEY

DECam composite image of deep SN field

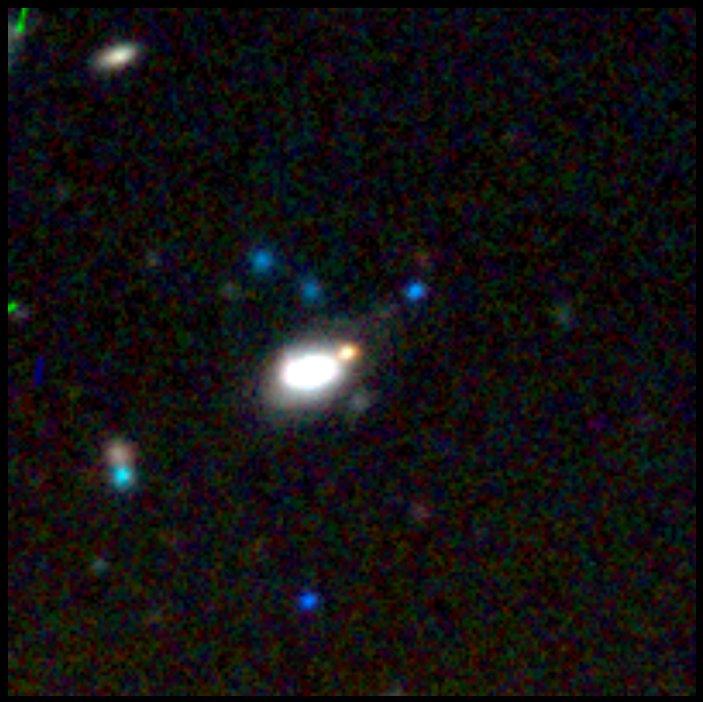


will be visited many times during survey, resulting in very deep co-add

First Confirmed SNe from DES



Nov. 7

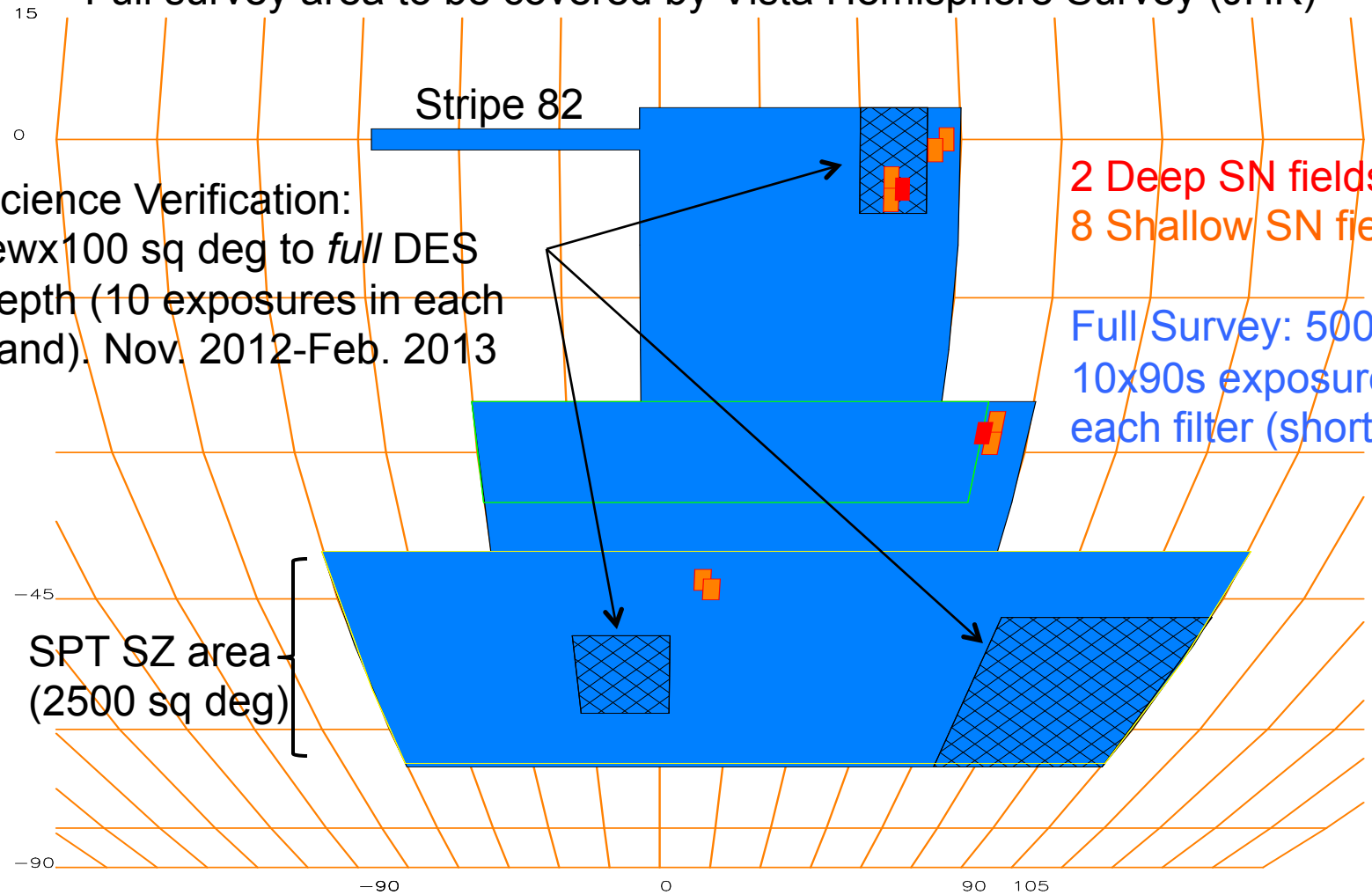


Dec. 15

SN Ia at z=0.2 confirmed at AAO
100 nights on AAO awarded for follow-up (OzDES)

DES Survey Strategy

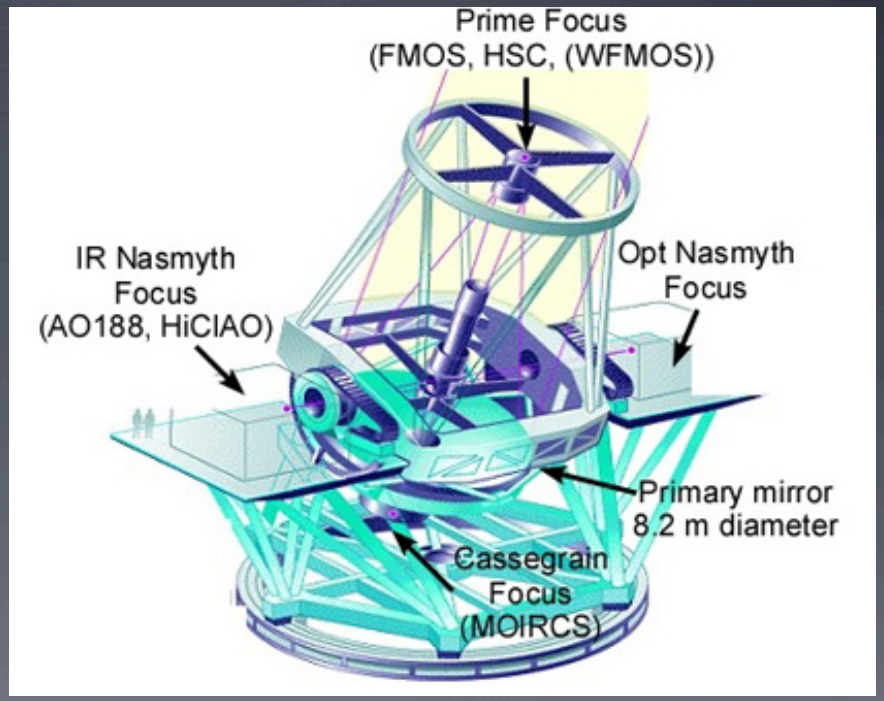
Full survey area to be covered by Vista Hemisphere Survey (JHK)

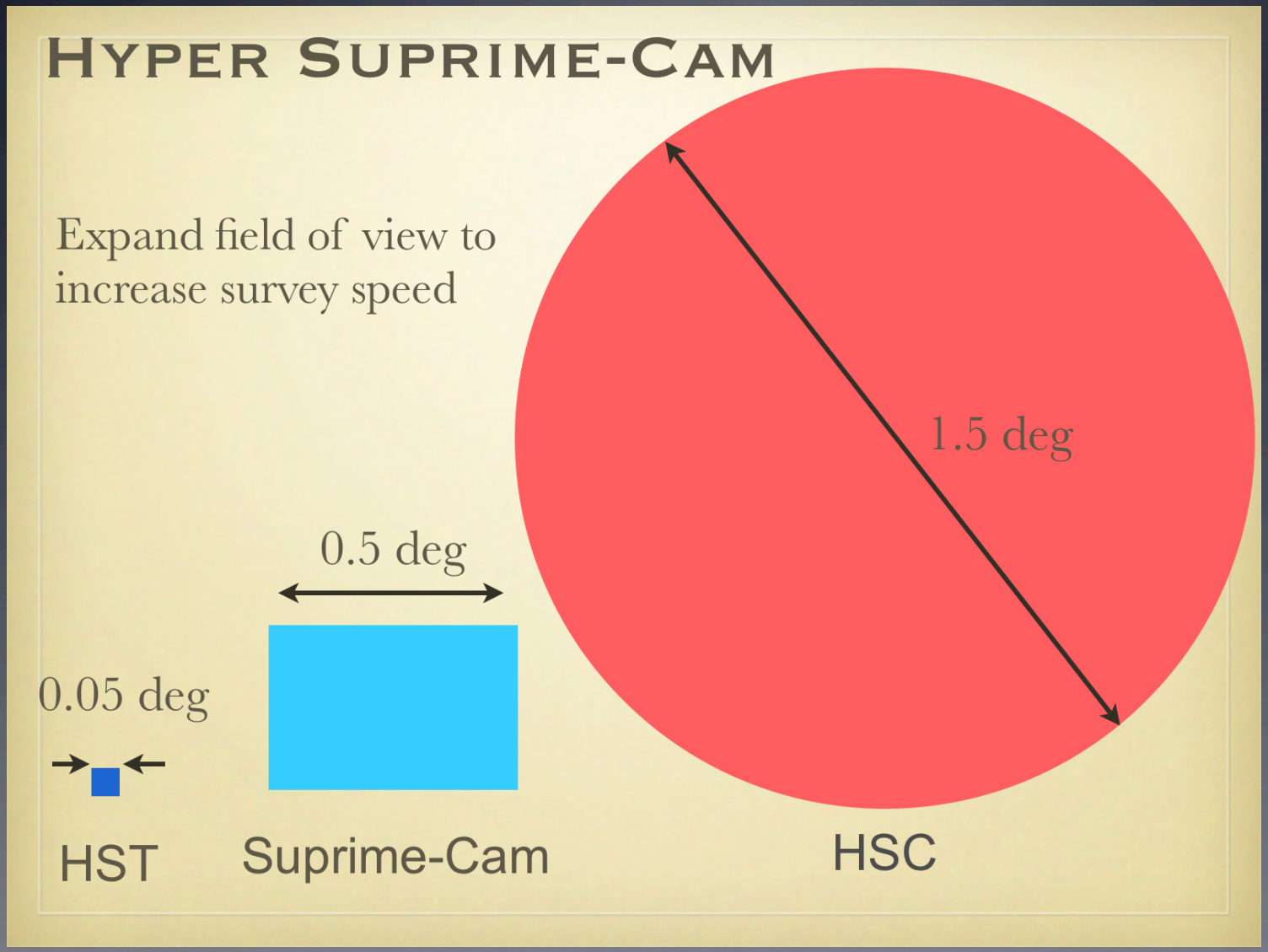


Science Verification:
fewx100 sq deg to *full* DES depth (10 exposures in each band). Nov. 2012-Feb. 2013

Subaru telescope

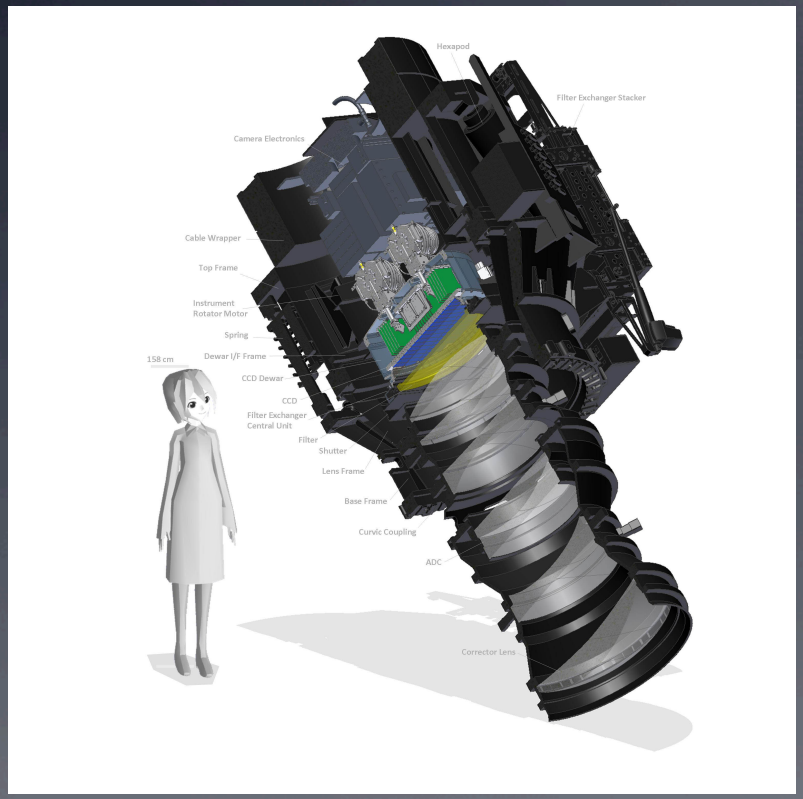
- 8.2 meter primary mirror
- Mauna Kea
- Excellent imaging conditions





Picture credit: S. Miyazaki

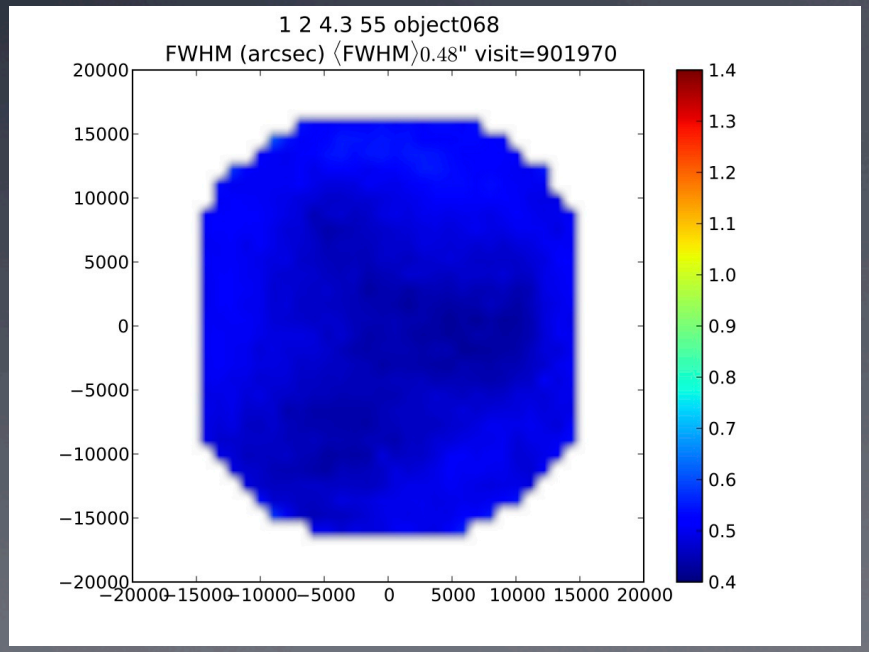
HSC is on the telescope!



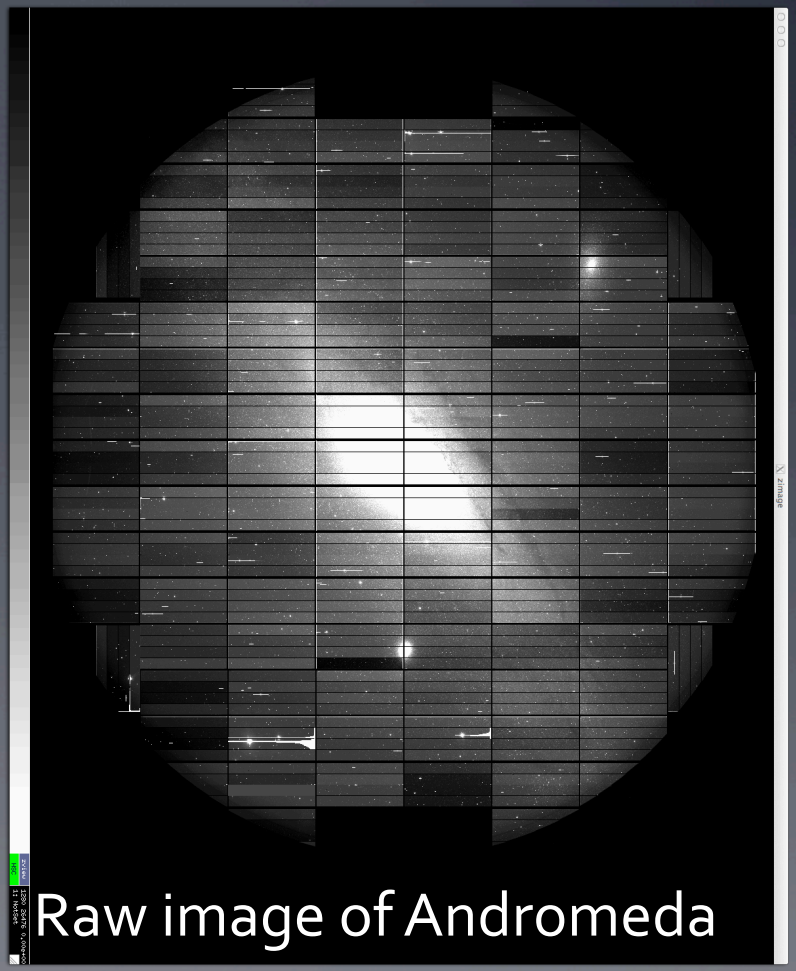
First Light Sept. 2012

Looking good!

Seeing variation across FOV



104 Science, 4 Guide, 8 Focus CCDs
870 Megapixels (0.17”/pixel)



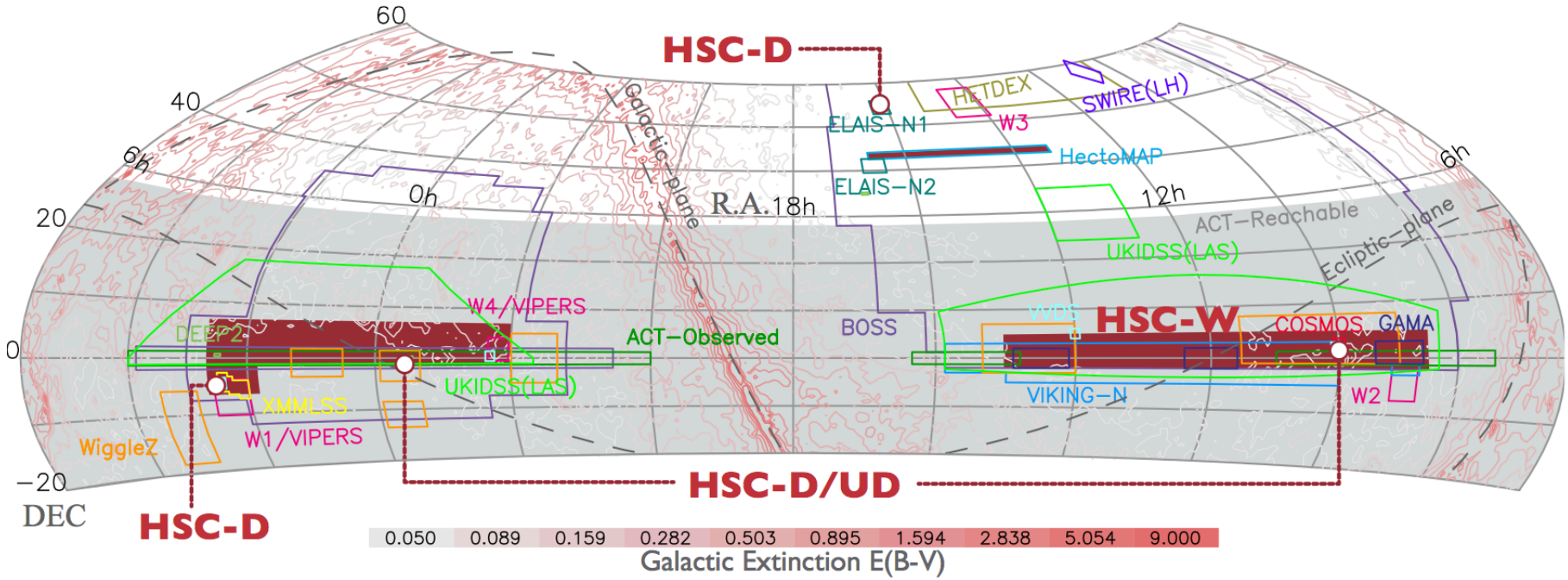
3-layer HSC survey

- Wide: ~1400 deg^2, i<25.8 (grizy)
  - ➜ Weak lensing, z<1.5 galaxy populations
- Deep: ~26 deg^2, 1 mag deeper, 5 wide+3 NB filters
  - ➜ Ly-α emitters, quasars, deeper galaxy populations, lensing systematics, …
- Ultradeep: 3 deg^2, 1 mag deeper, 5 wide+6 NB filters
  - ➜ Supernovae, galaxies to z<7

✓ Important synergies: CMB (ACT+ACTPol), redshifts (BOSS + assorted other), NIR, u band, …

✓ Surveys starting 1st semester of 2014 (300 nights over 5 yrs)

HSC Survey Fields



- The HSC fields are selected based on …
  - Synergy with other data sets: SDSS/BOSS, The Atacama Cosmology Telescope CMB survey (from Chile), X-ray (XMM-LSS), spectroscopic data sets
  - Spread in RA
  - Low dust extinction

Takada

The Large Synoptic Survey Telescope

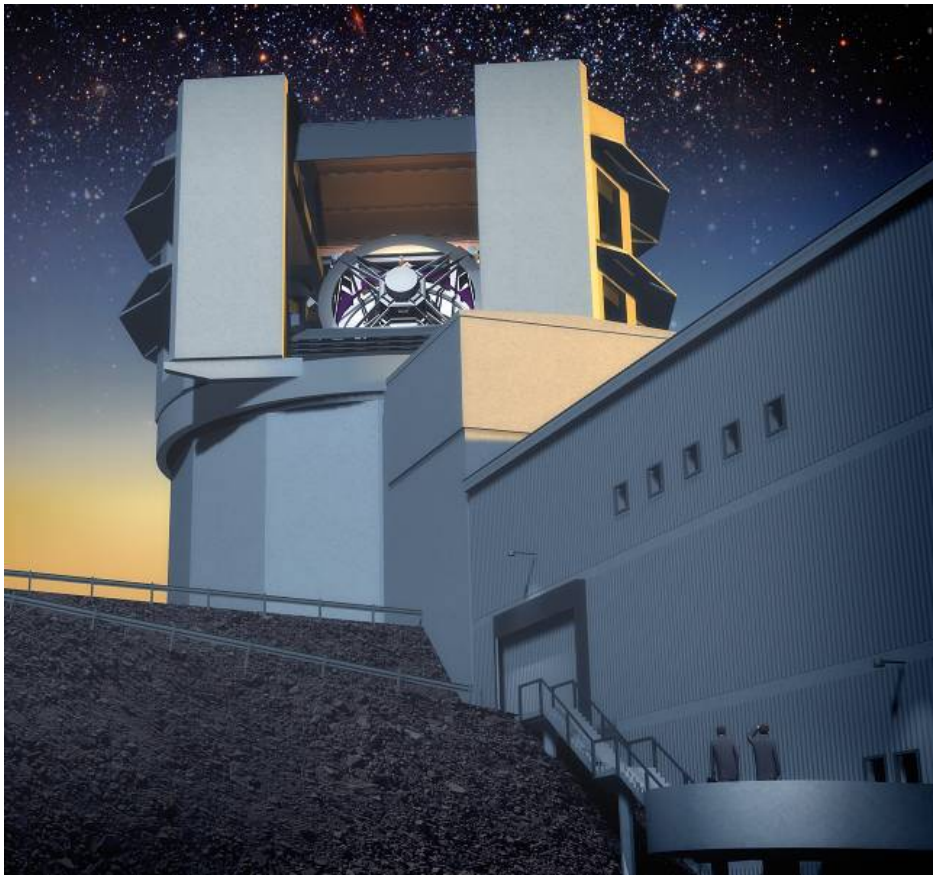
Steven M. Kahn

Sidney Wolff

Victor Krabbendam

Nadine Kurita

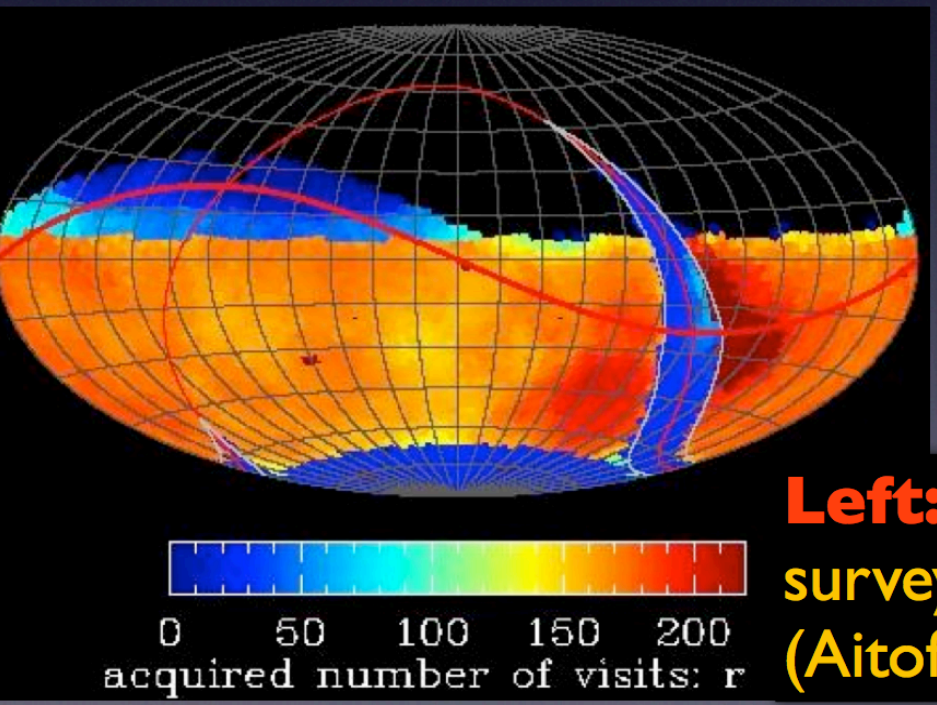
Zeljko Ivezic



Cerro Pachon, Chile

Basic idea behind LSST: **a uniform sky survey**

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PB of data: about a billion 16 Mpix images, enabling **measurements for 20 billion objects!**



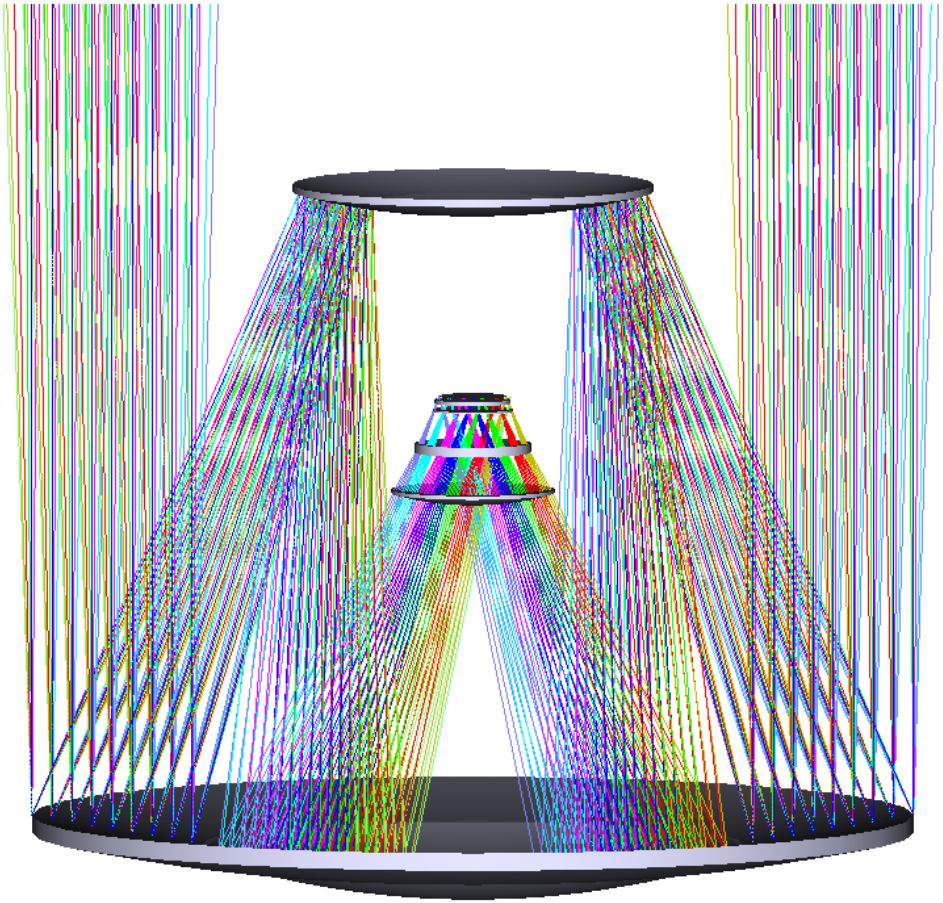
LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

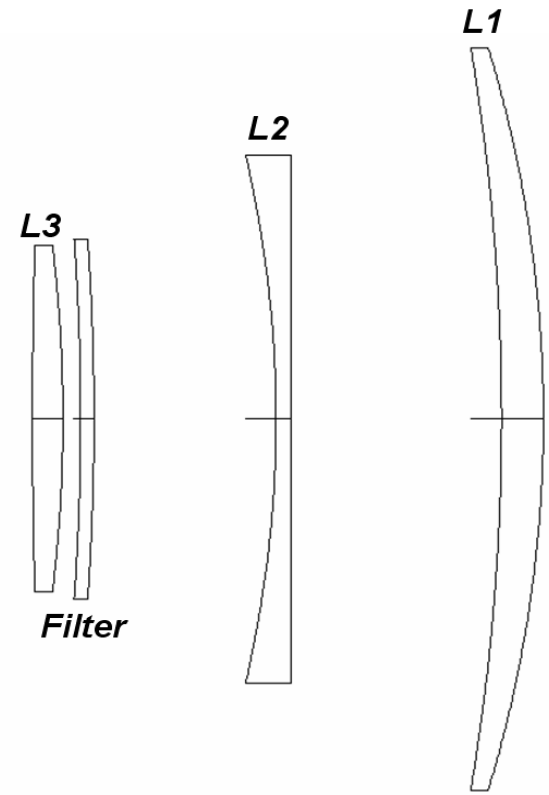
Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

Summary of High Level Requirements

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320-1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.9; g = 25.0; r = 24.7; I = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 2% absolute, < 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	< 60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

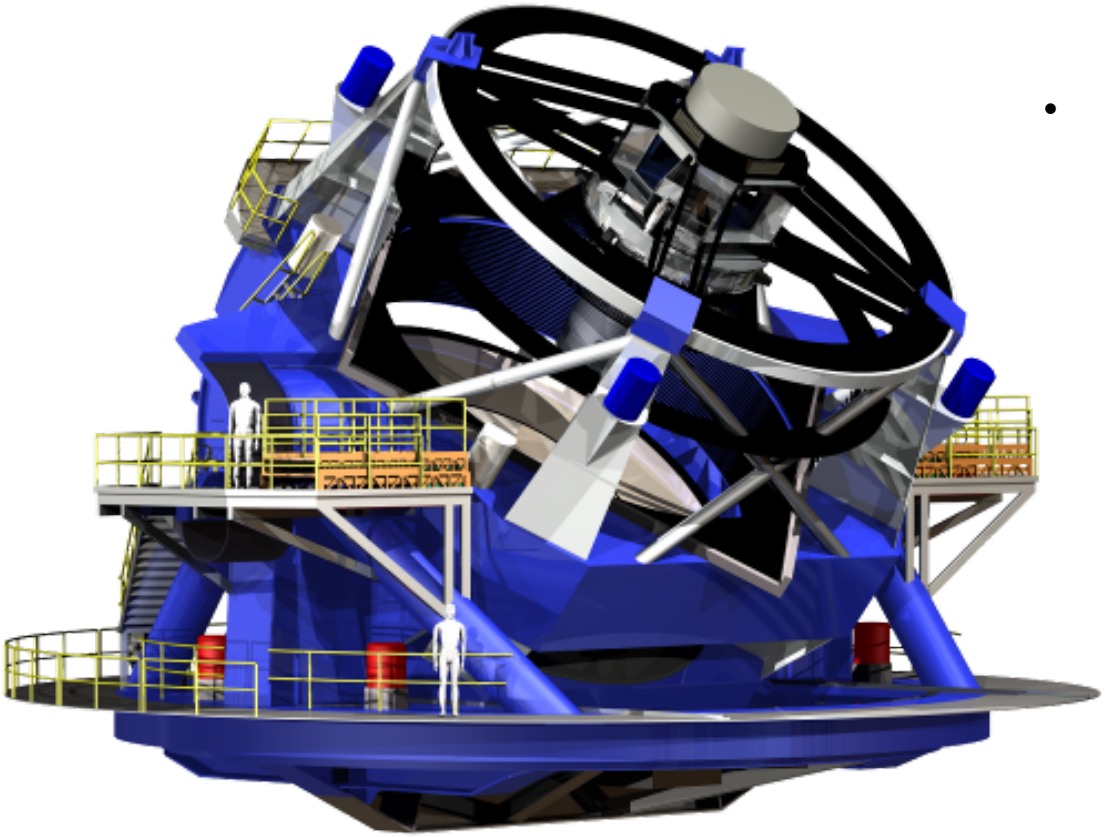
The modified Paul-Baker optical design provides a large field of view with high image quality.





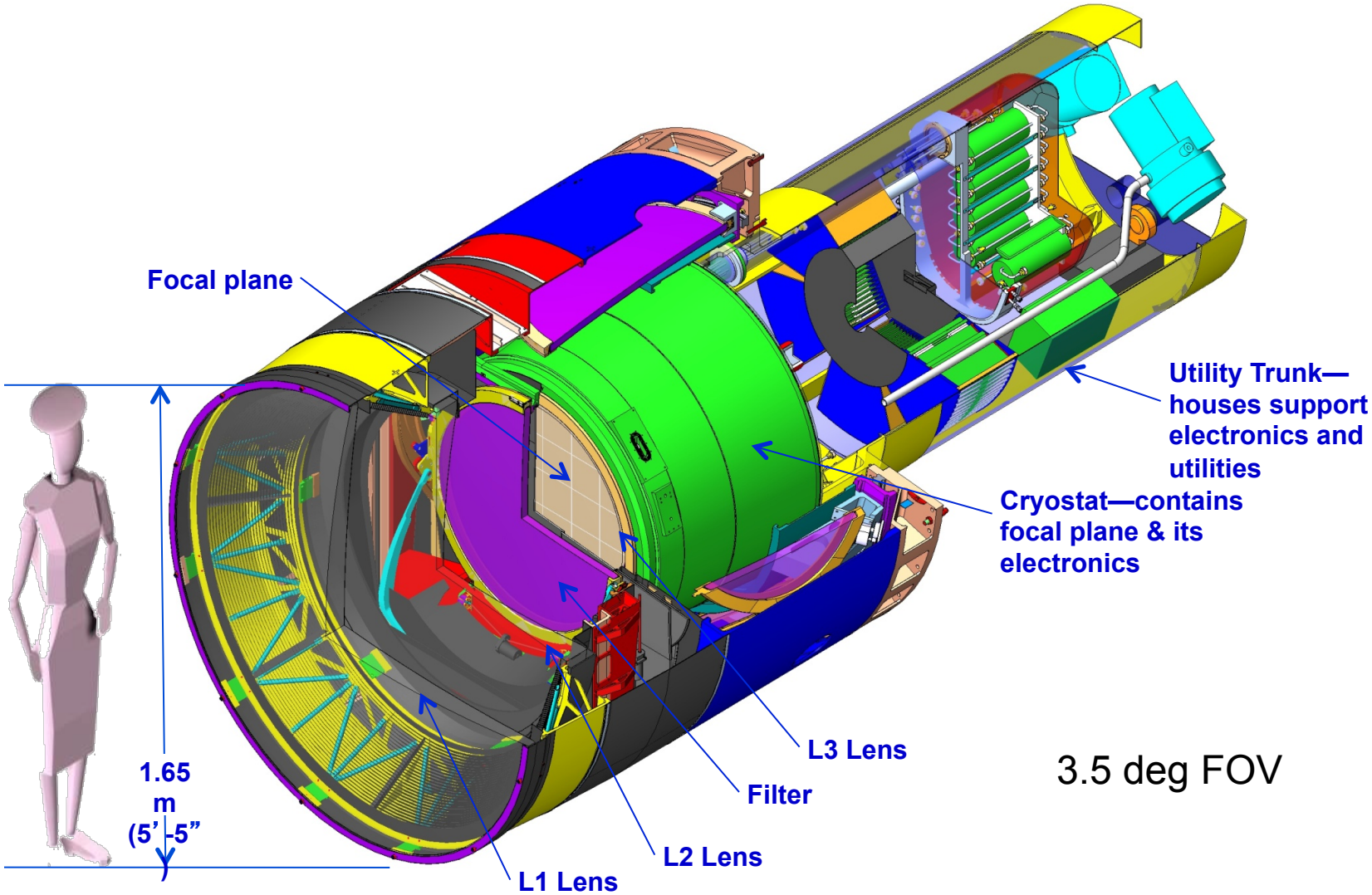
8.4m primary mirror diameter, 6.7m effective aperture

The telescope mount has been optimized for fast slew and settle.



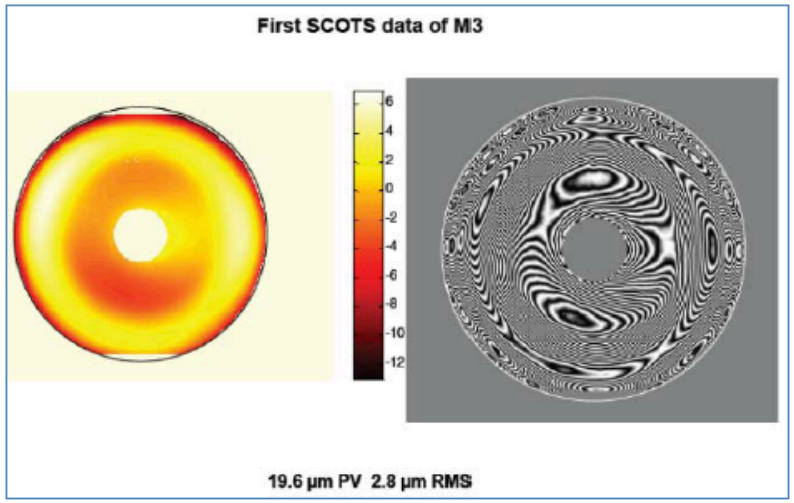
- Points to new positions in the sky every 37 seconds
- Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 seconds

The 3.2 billion pixel camera enables a 9.6 square degree field in a tight enclosure.



3.5 deg FOV

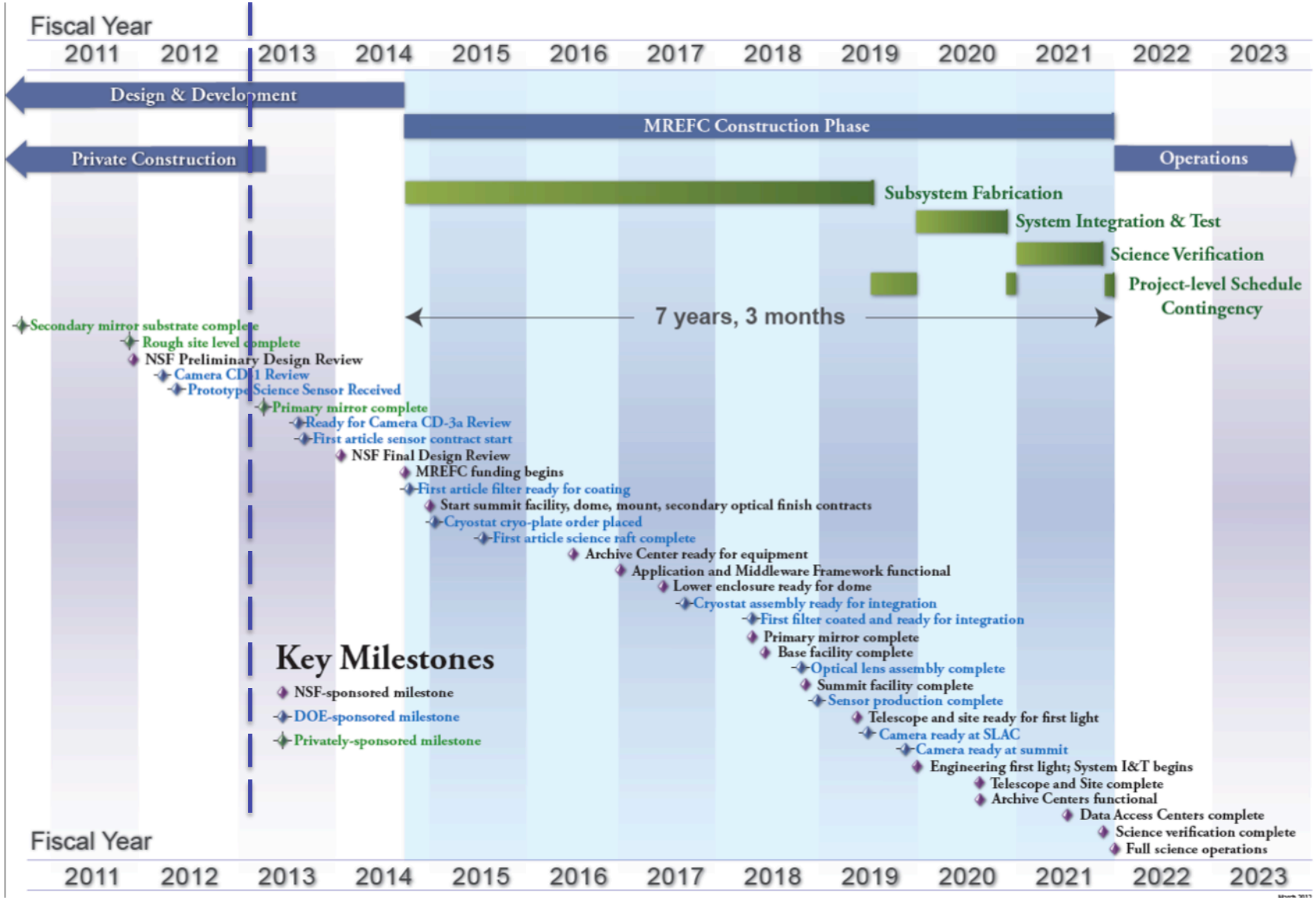
Recent Progress: M1/M3



- Final Optical Polishing has commenced – the final and most challenging step.
- Final acceptance testing scheduled for late 2013.
- 5 tons of excess material already removed to generate rough optical surface of M1/M3.
- Loose abrasive grinding resulted in initial optical shapes.

- Interferogram shows surface deviations on the order of microns, aiming for nanometers.
- Work enabled by private funds.

Project timeline enables “first light” in 2019, survey start 2022



Euclid Mission: baseline and options

SURVEYS **In ~6 years**		
	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**	
	Weak Lensing		Photo-z		BAO

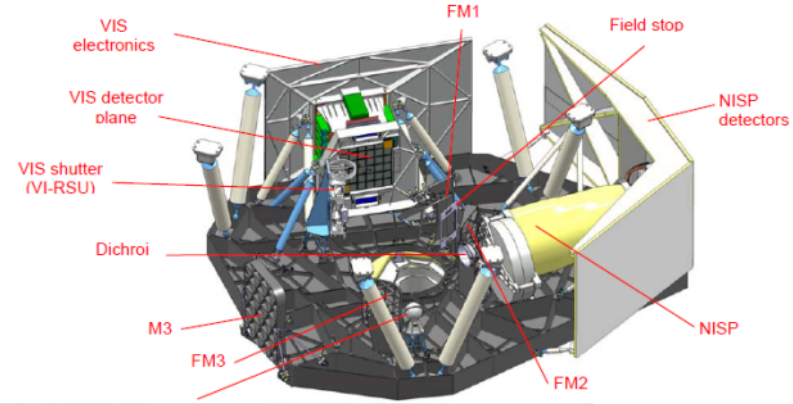
Ref: Euclid RB Laureijs et al arXiv:1110.3193

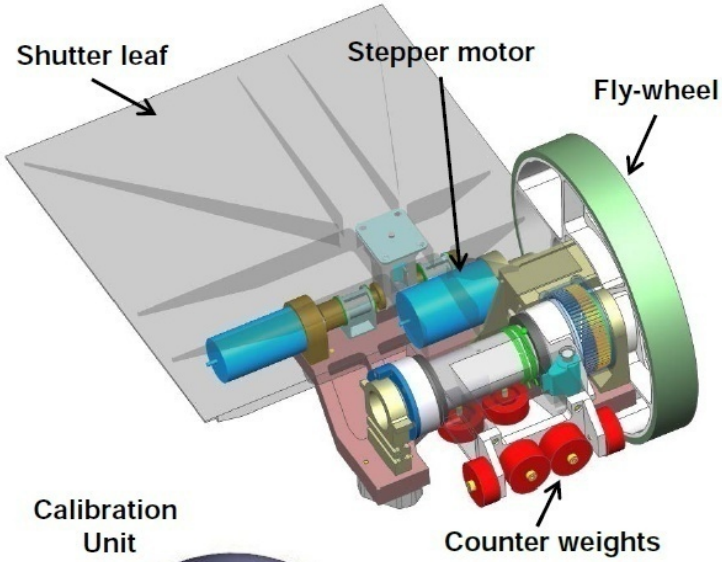
Euclid slides from Yannick Mellier

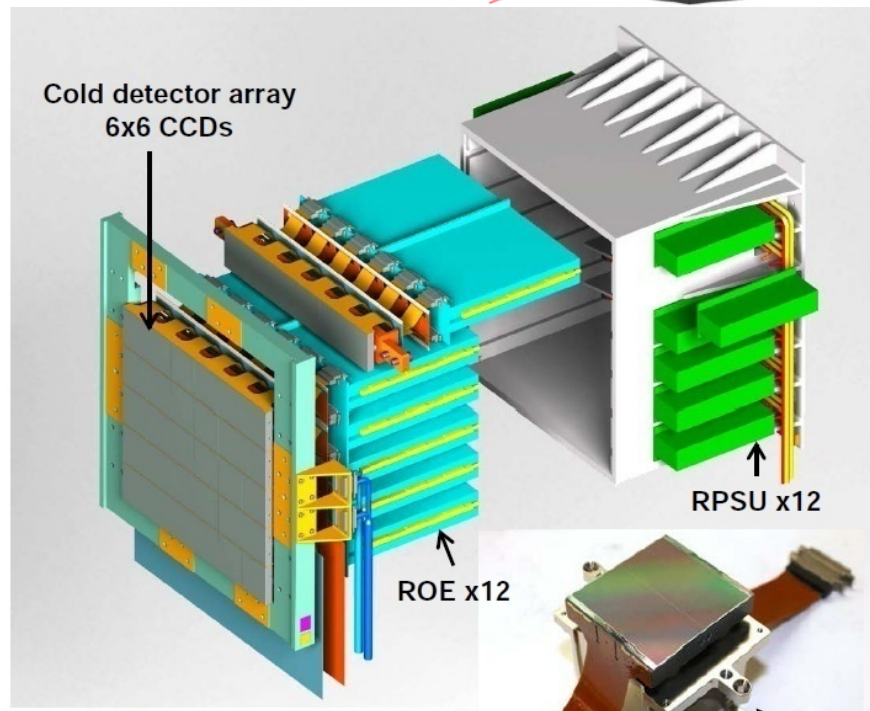
The VIS instrument

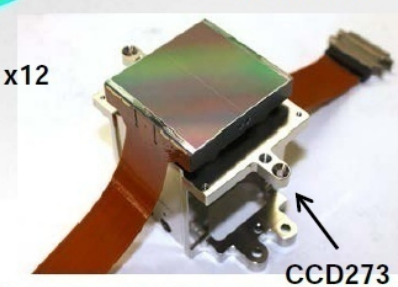
Courtesy: S. Pottinger, R. Cole, M. Cropper and the VIS team

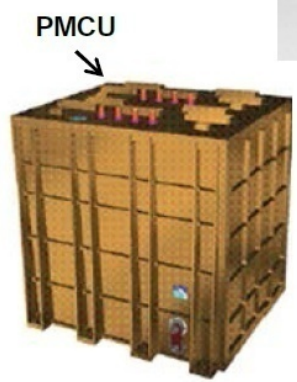
- large area imager – a 'shape measurement machine'
- 36 4kx4k CCDs with 12 micron pixels
- 0.1 arcsec pixels on sky
- bandpass 550-900 nm (wide band channel)
- limiting magnitude for wide survey of magAB = 24.5 for 10σ (extended)
- data volume – 520Gbit/day

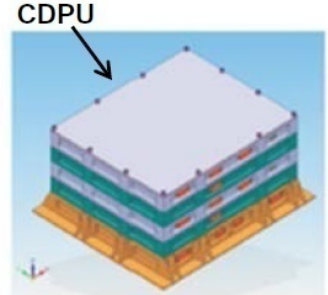


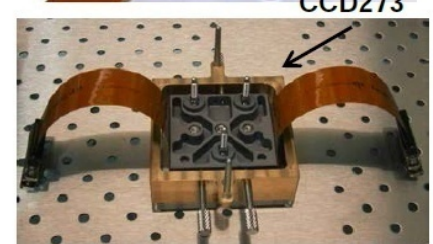






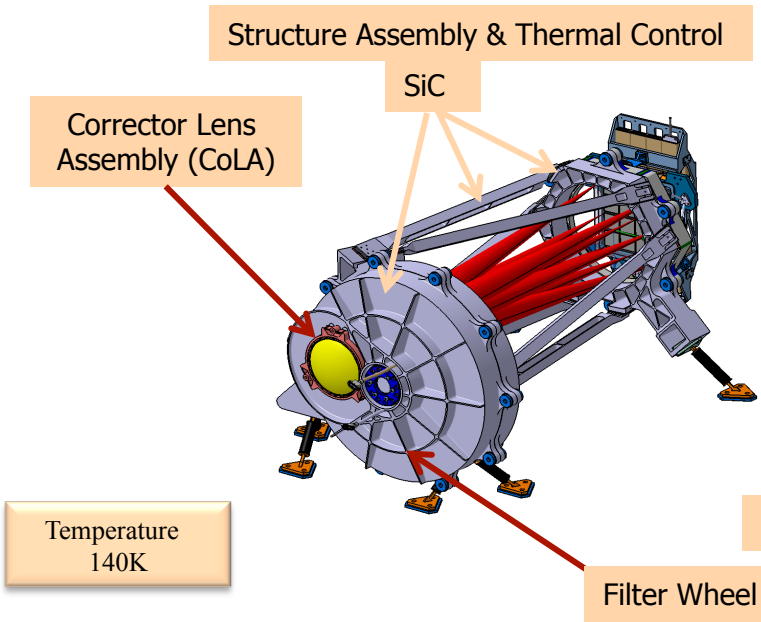


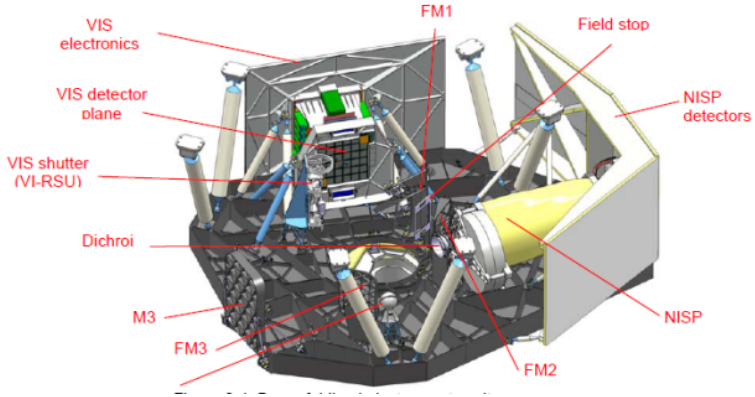


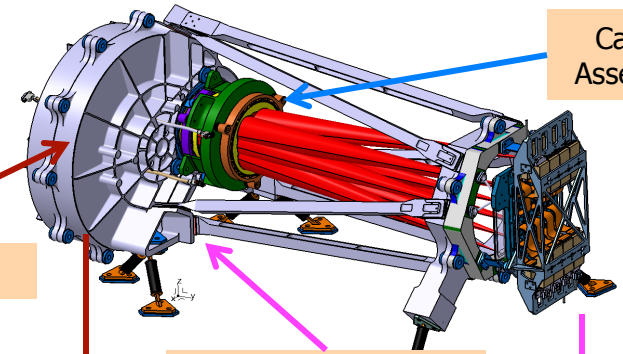


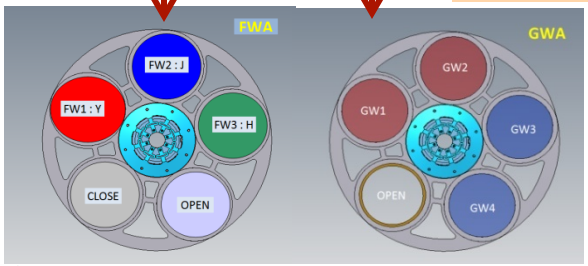
The NISP Instrument

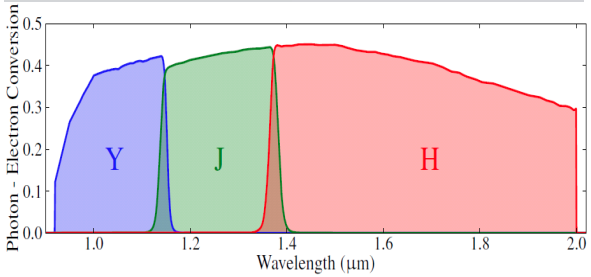
Courtesy: T. Maciaszek and the NISP team

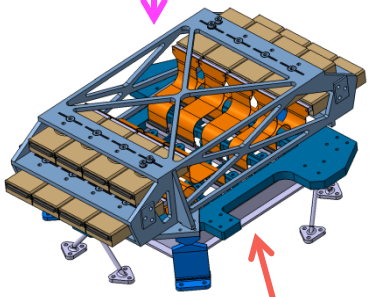












16 H2RG DETECTORS (provided by ESA/NASA)

16 2kx2k H2GR NIR detectors

0.3 arcsec/pixel

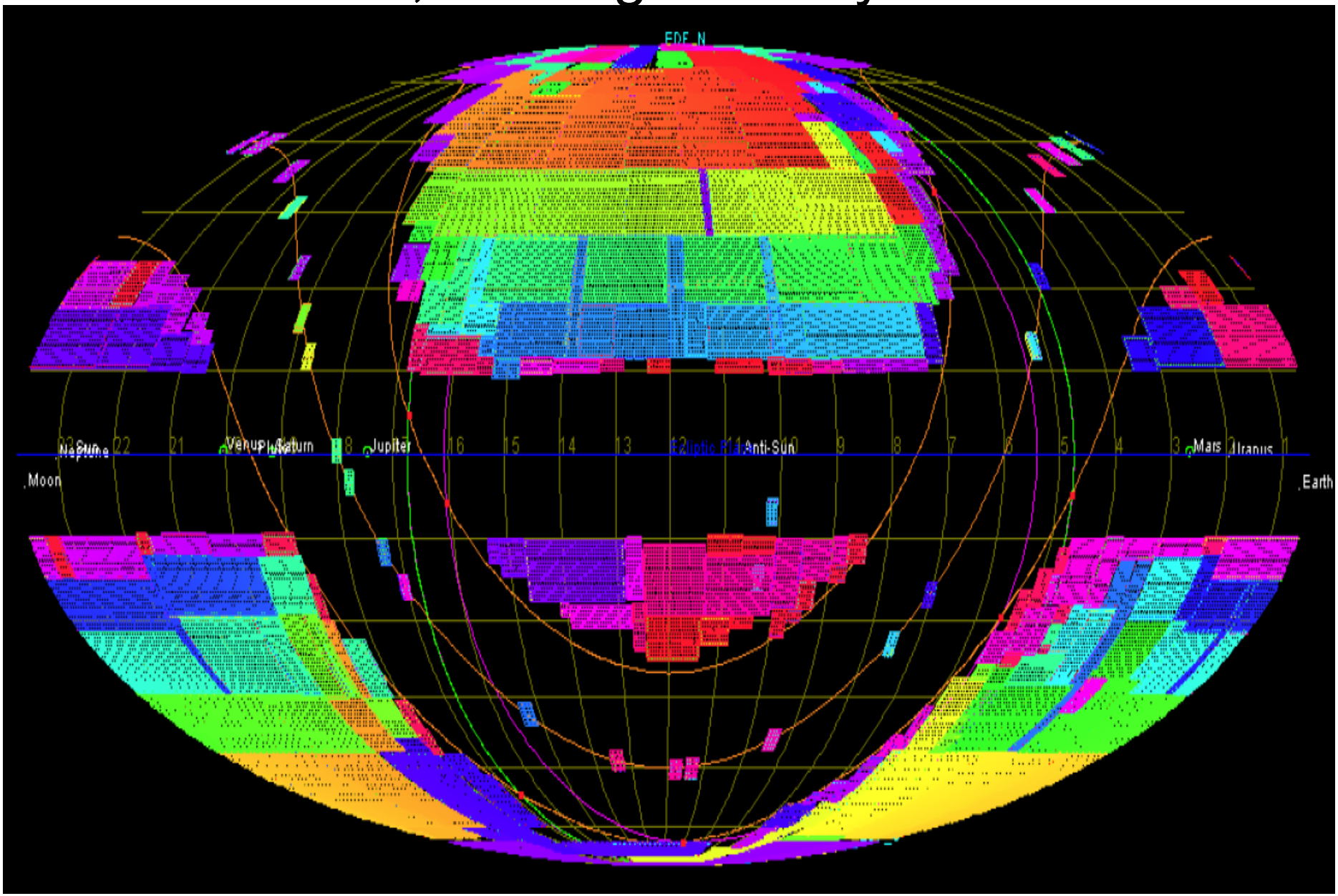
3 NIR filters: H,J,H,

4 Grisms (2 « B»; 2 « R »)

Lim. mag: AB 24.0 ; 5 σ pt source

Data volume:180 Gbit/day

15,000 deg^2 in 5.5 years



Ground Based Data: photo-z

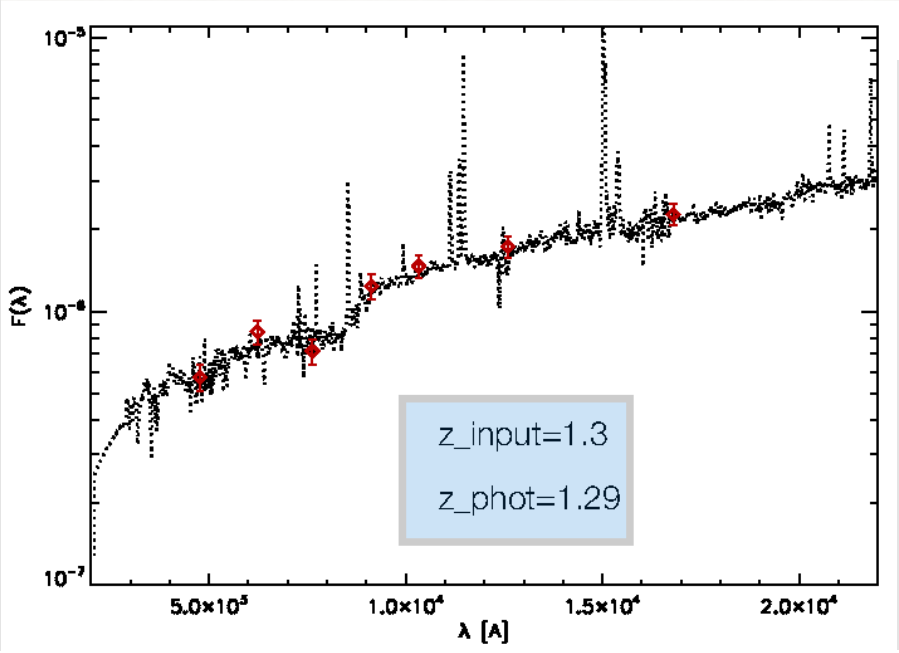
Photometric redshifts with Euclid

Requirements: accuracy

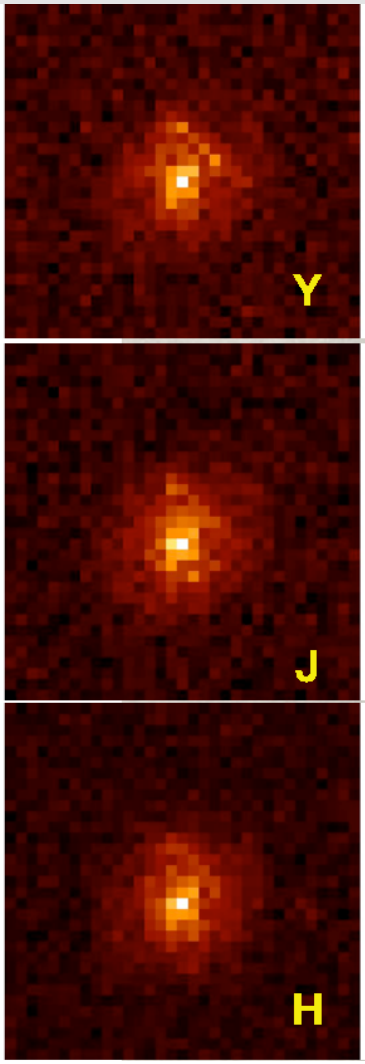
= 0.05x(1+z)

→ 4 optical band needed

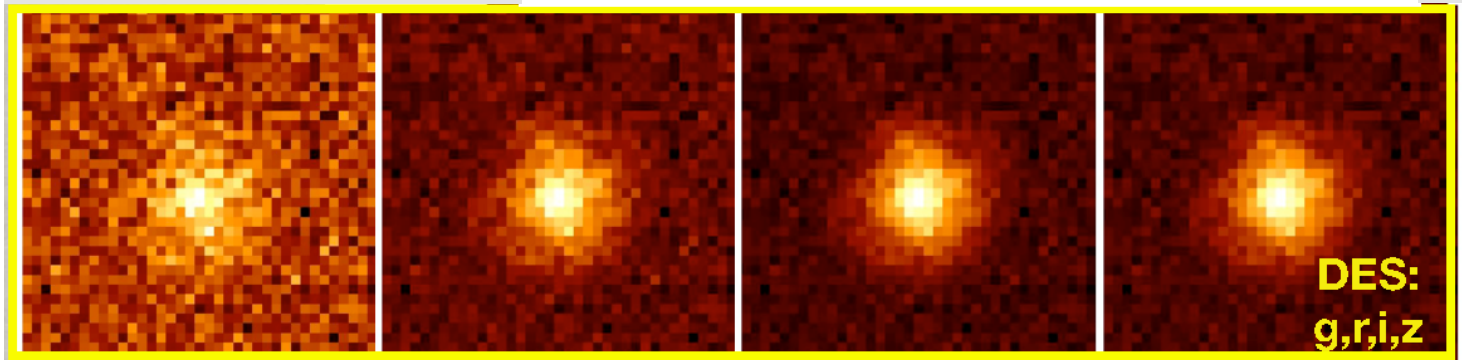
→ U-band not needed.



Nearinfrared data from Euclid NIR images.



Visible data obtained from ground based telescopes



Euclid Legacy:

a gold mine for astronomy for 2020-2040

Objects	Euclid	Before Euclid
Galaxies at 1<z<3 with precise mass measurment	~$2x10^8$	~$5x10^6$
Massive galaxies (1<z<3))	Few hundreds	Few tenss
H α Emitters with metal abundance measurements at z~2-3	~$4x10^7/10^4$	~10^4/~10^2 ?
Galaxies in clusters of galaxies at z>1	~$2x10^4$	~10^3 ?
Active Galactic Nuclei galaxies (0.7<z<2)	~10^4	<10^3
Dwarf galaxies	~10^5	
T_{eff} ~400K Y dwarfs	~few 10^2	<10
Lensing galaxies with arc and rings	~300,000	~10-100
Quasars at z > 8	~30	None

Astrophysics Focused Telescope Assets (AFTA)

Presentation to P. Hertz April 19, 2013

Neil Gehrels (GSFC)	SDT Co-Chair
David Spergel (Princeton)	SDT Co-Chair
Kevin Grady (GSFC)	Study Manager & Project Team

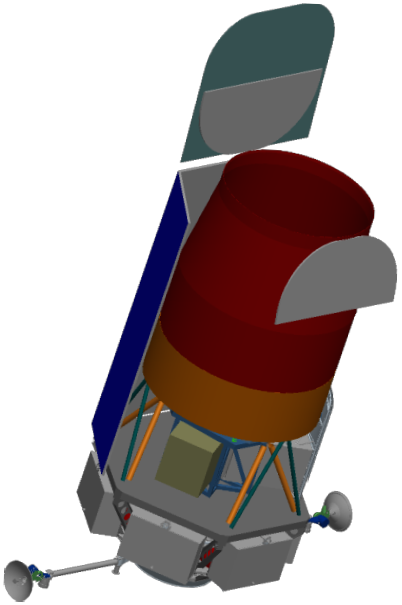
SCIENCE DEFINITION TEAM

James Breckinridge, Caltech
Megan Donahue, Michigan State Univ.
Alan Dressler, Carnegie Observatories
Chris Hirata, Caltech
Scott Gaudi, Ohio State Univ.
Thomas Greene, Ames
Olivier Guyon, Univ. Arizona
Jason Kalirai, STScI
Jeremy Kasdin, Princeton
Warren Moos, Johns Hopkins
Saul Perlmutter, UC Berkeley / LBNL
Marc Postman, STScI
Bernard Rauscher, GSFC
Jason Rhodes, JPL
Yun Wang, Univ. Oklahoma
David Weinberg, Ohio State U.
Joan Centrella, NASA HQ Ex-Officio
Wes Traub, JPL Ex-Officio

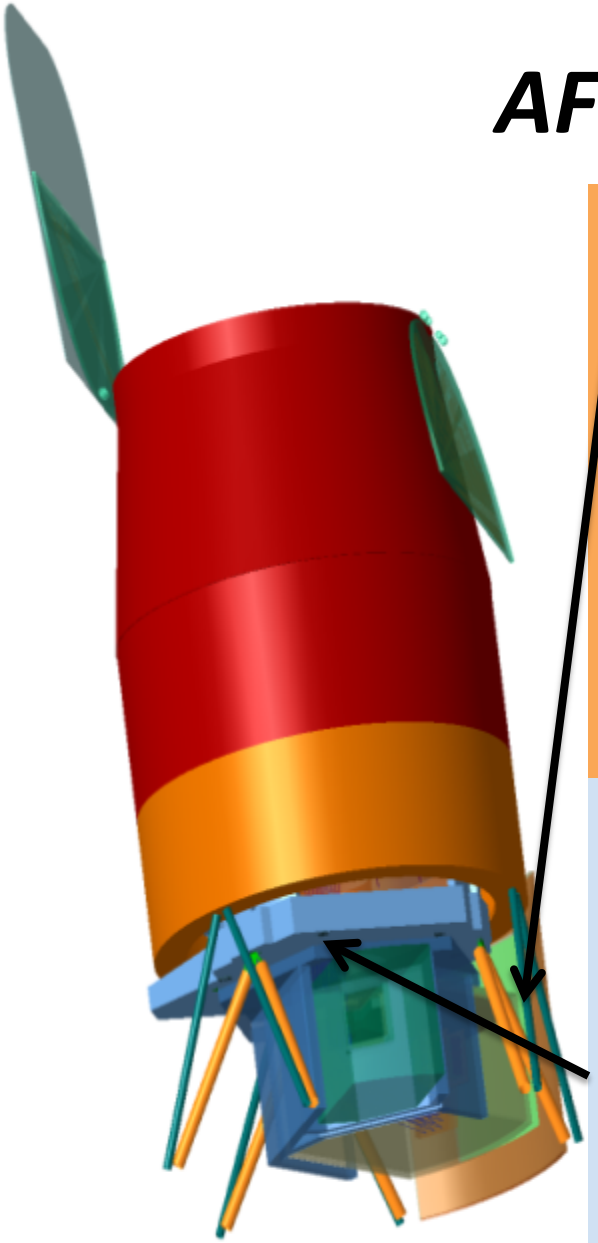
“Discover how the universe works, explore how it began and evolved, and search for Earth-like planets”
NASA Strategic Plan (p. 14)

AFTA-2.4m

- Dark energy
  * Accelerating expansion of the universe
  * Growth of structure
- Exoplanet microlensing
- Exoplanet coronagraphy (optional)
- Galactic and extragalactic astronomy
- Guest Investigator & Observer program



AFTA Instruments



Wide-Field Instrument

- *Imaging & spectroscopy over 1000s sq deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 micron bandpass
- 0.28 sq deg FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 4 filter imaging, grism + IFU spectroscopy

Coronagraph (study option)

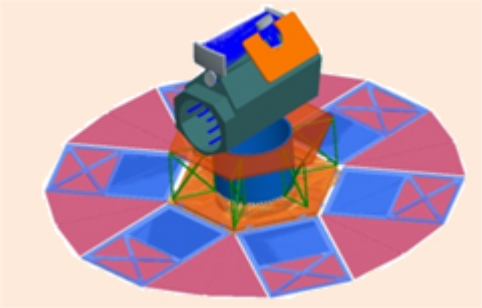
- *Imaging of ice & gas giant exoplanets*
- *Imaging of debris disks*
- 400 – 1000 nm bandpass
- 10^{-9} contrast
- 100 milliarcsec inner working angle at 400 nm

Requires focused tech. development ASAP for 2021 launch

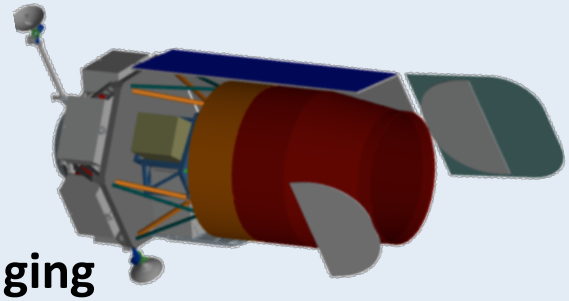
Evolution of WFIRST Concepts to AFTA

- **DRM1**
  - 1.3 meter off-axis telescope
  - 150 Mpixels, 0.4 deg^2
  - 5 year mission (15% GO time)

- **DRM2**
  - 1.1 meter off-axis telescope
  - 234 Mpixels, 0.6 deg^2
  - 3 year mission (15% GO time)

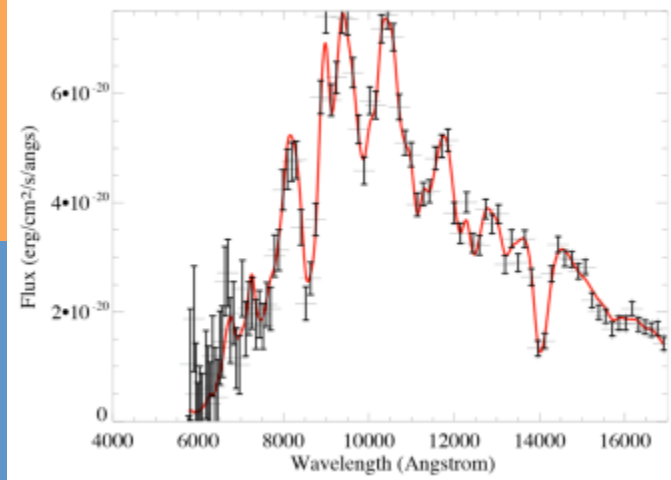


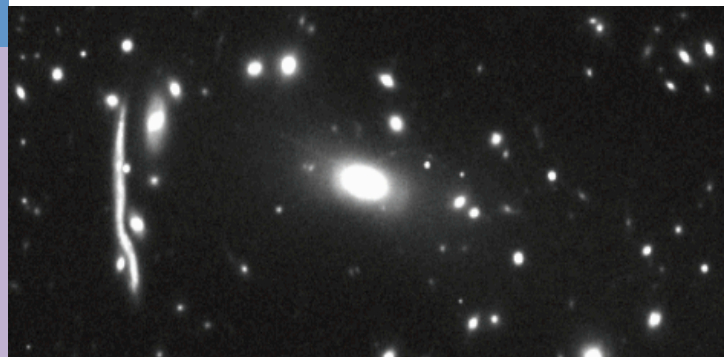
- **2.4m AFTA**
  - 2.4 meter on-axis telescope
  - 288 Mpixels, 0.3 deg^2
  - Additional IFU for SN slit spectroscopy
  - Additional coronagraph for exoplanet imaging
  - 5 year mission (25% GO time)



AFTA is a more capable dark energy mission than previous DRMs

- **Larger telescope + integral field channel enable high S/N spectrophotometry**
  - **More supernovae out to higher redshift**
  - **Systematic errors addressed: eliminate K-correction, improved calibration, measure SN spectral diagnostics.**
- **Deeper weak lensing survey**
  - **3x fainter, 1.9x smaller PSF, 2x n_{eff}**
  - **more accurate lensing maps to higher redshift**
  - **Better sampling for higher-order WL statistics**
  - **Lensing masses for 40,000 M ≥ $10^{14} M_{sun}$ clusters in the 2000 deg^2 area of the high-latitude survey**
- **Much deeper galaxy redshift survey at 1 < z< 2, [OIII] extends redshift range to z =3.**
  - **Can use multiple tracers.**
  - **Improve redshift-space distortion measurements, test systematics.**
  - **Better measurements of high-order clustering.**





Frontiers of Knowledge

As envisioned in NWNH, AFTA uses multiple approaches to measure the growth rate of structure and the geometry of the universe to exquisite precision. These measurements will address the central questions of cosmology

Imaging Survey

Map over 2000 square degrees of high latitude sky

500 million lensed galaxies (70/arcmin^2)
40,000 massive clusters

Supernova Survey

wide, medium, & deep imaging + IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

Trace the Distribution of Dark Matter Across Time

- Why is the universe accelerating?
- What are the properties of the neutrino?
- What is Dark Matter?

Measure the Distance Redshift Relationship

BAO

Red shift space distortion

Spectroscopic Survey

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

Multiple measurement techniques each achieve 0.1-0.4% precision

AFTA and Euclid have complementary strengths for dark energy studies

AFTA:

Deep Infrared Survey (2000 sq. deg)

Lensing:

- High Resolution (70 -250 gal/arcmin^2)
- 5 lensing power spectrum

Supernovae:

- High quality IFU spectra of 2700 SN

Redshift survey

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

Euclid:

Wide optical Survey (15000 sq. deg)

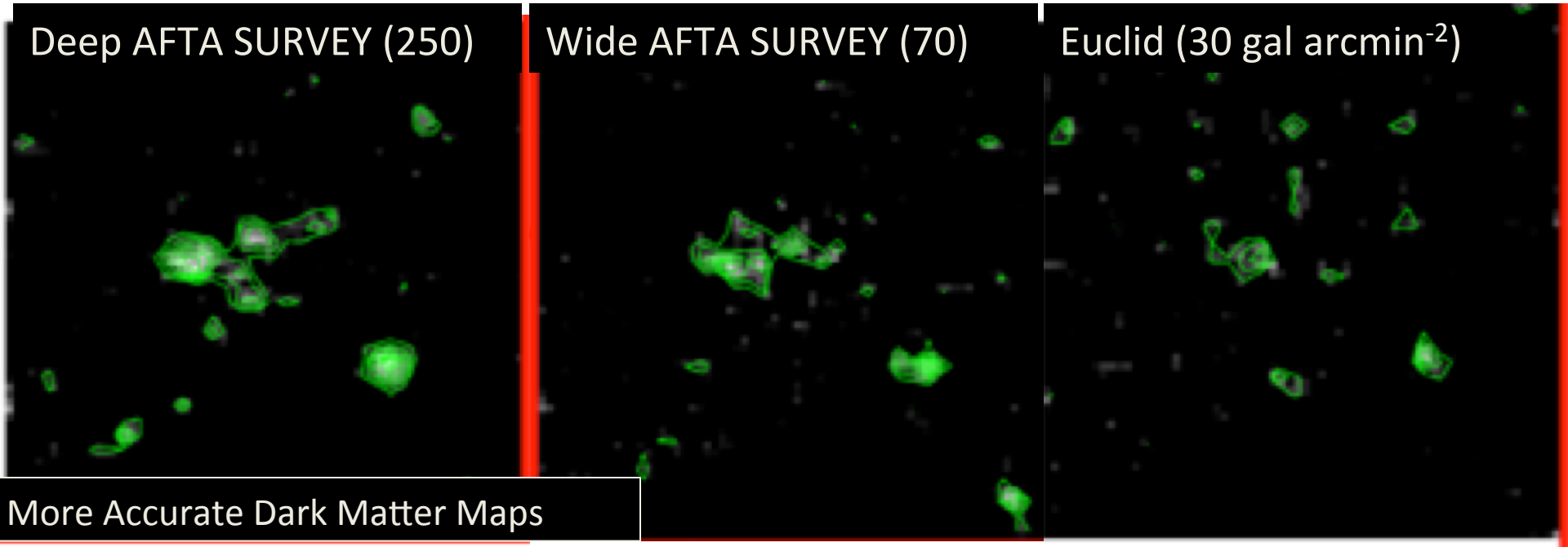
Lensing:

- Lower Resolution (30 gal/arcmin^2)
- 1 lensing power spectrum

No supernovae program

Redshift survey:

- Low number density of galaxies
- Significant number of low redshift galaxies



More Accurate Dark Matter Maps

AFTA and Euclid have complementary strengths for dark energy studies

AFTA:

Deep Infrared Survey (2000 sq. deg)

Lensing:

- High Resolution (70 -250 gal/arcmin^2)
- 5 lensing power spectrum

Supernovae:

- High quality IFU spectra of 2700 SN

Redshift survey

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

Euclid:

Wide optical Survey (15000 sq. deg)

Lensing:

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Redshift survey:

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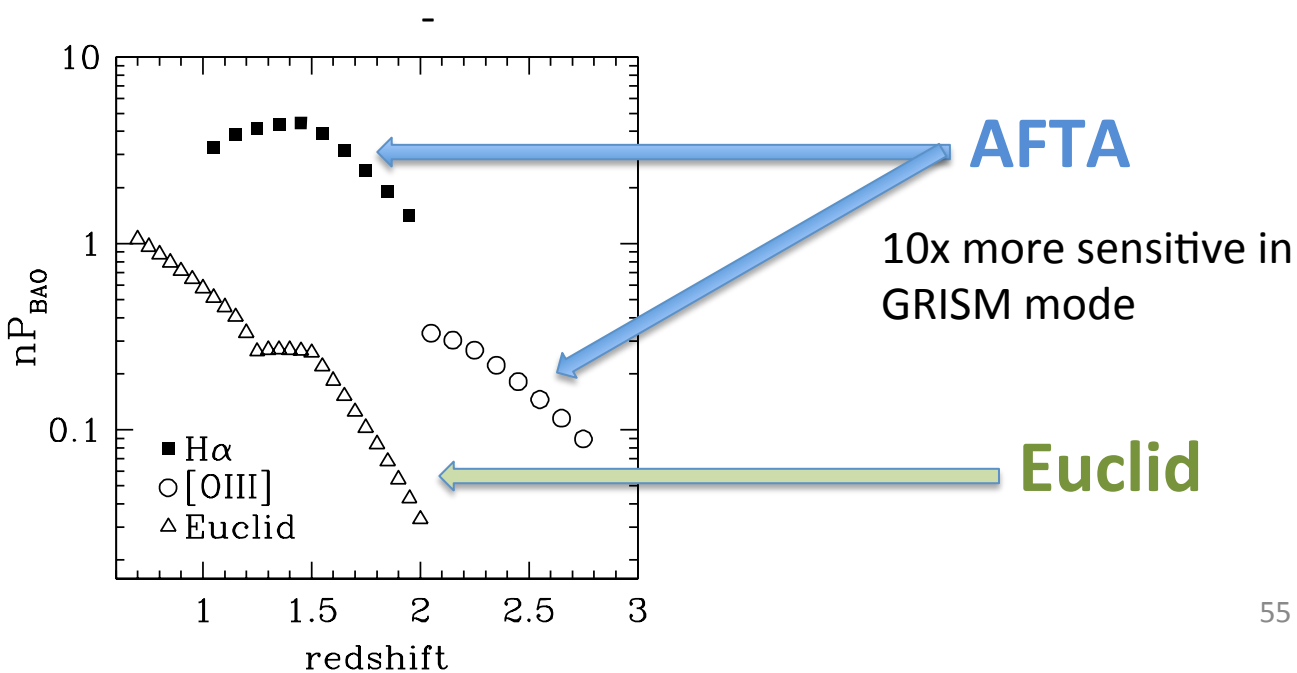
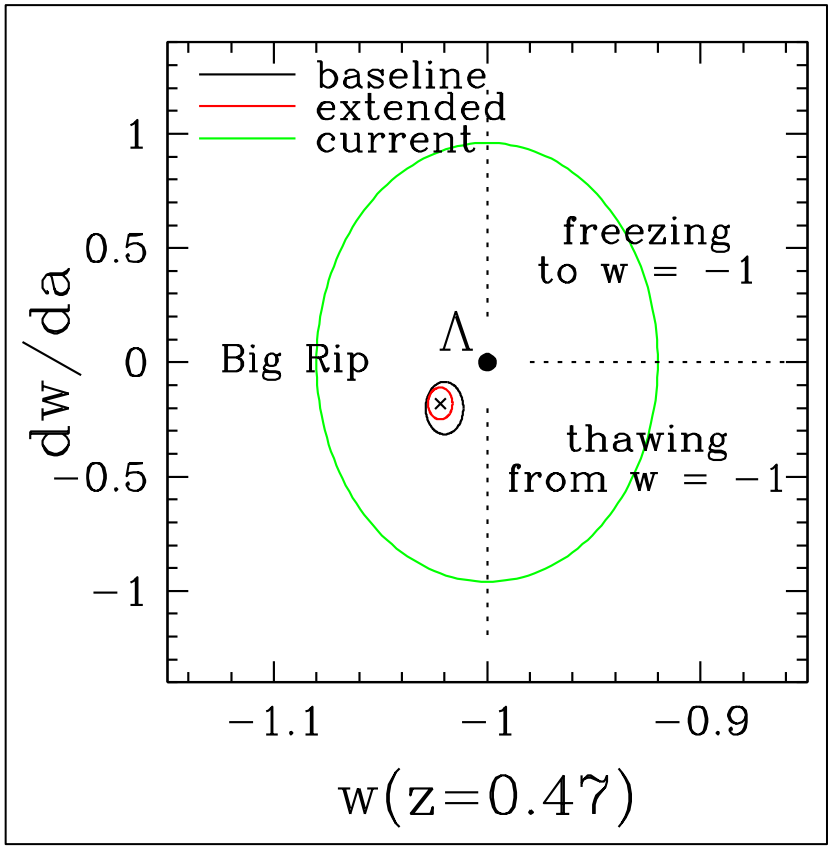


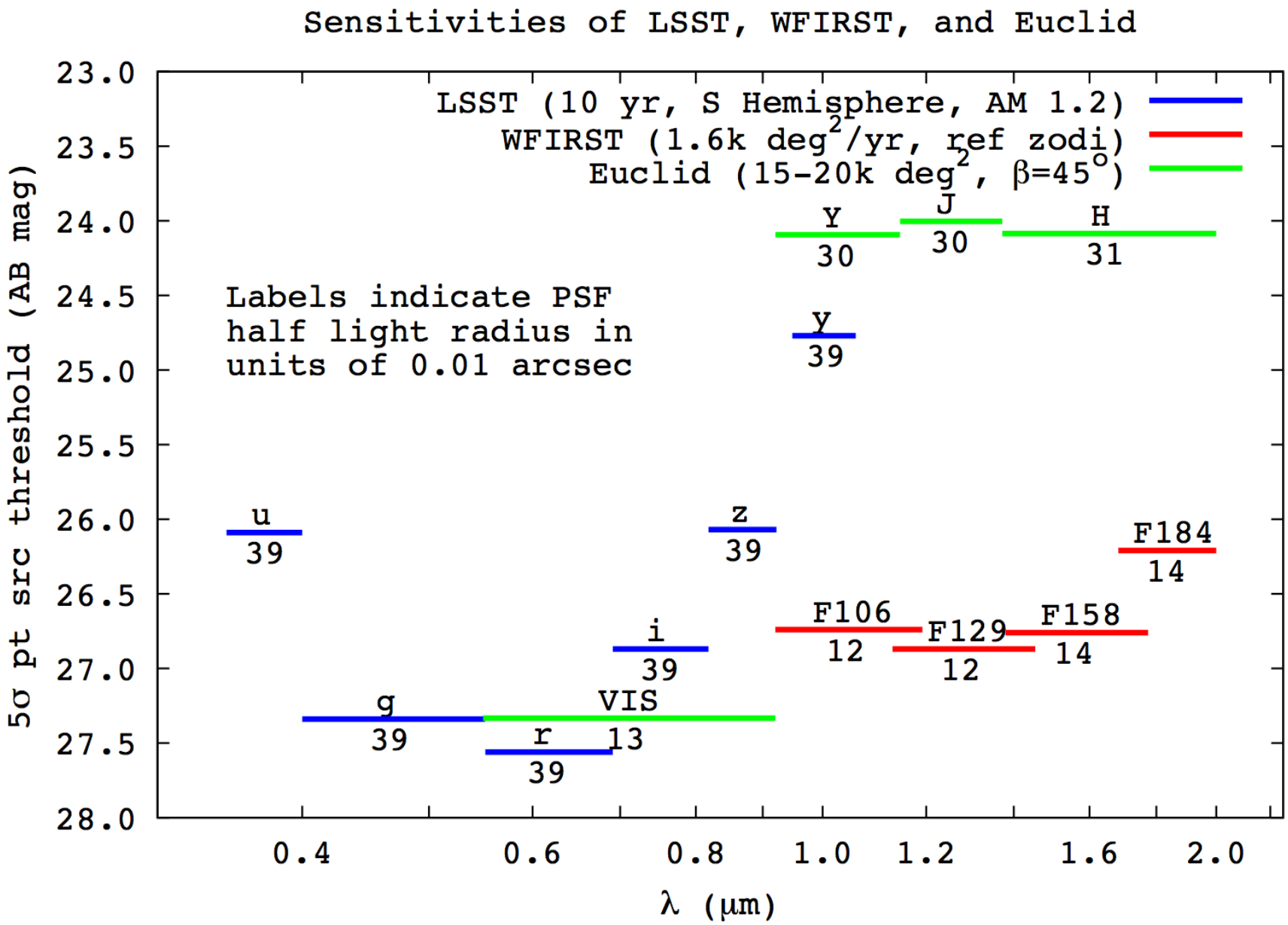
AFTA will have the sensitivity and the control of systematics to enable a major discovery of the nature of dark energy!

By measuring the relationship between distance and redshift, we will be able to determine the properties of dark energy.

These properties are often characterized by w and its time derivative, dw/da.

If w < -1, the universe will someday by torn apart in a “big rip” that destroys spacetime.




Sensitivities of LSST, WFIRST, and Euclid
LSST (10 yr, S Hemisphere, AM 1.2)
WFIRST (1.6k deg^2/yr, ref zodi)
Euclid (15-20k deg^2, β=45°)
Labels indicate PSF half light radius in units of 0.01 arcsec
u 39
g 39
r 39
i 39
z 39
y 39
Y 30
J 30
H 31
VIS 13
F106 12
F129 12
F158 14
F184 14
5σ pt src threshold (AB mag)
λ (μm)
23.0
23.5
24.0
24.5
25.0
25.5
26.0
26.5
27.0
27.5
28.0
0.4
0.6
0.8
1.0
1.2
1.6
2.0

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		
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				

Synergies with ELTs

- Wider, faster, deeper optical/NIR surveys on the way
- Deep imaging surveys require large, deep(?) spectroscopic samples for photo-z calibration (see Jeff Newman's talk)
- Imaging surveys provide sources for value-added follow-up: radial velocities, line strengths, unusual objects…
- Time-domain surveys: rapid follow-up for identification/ characterization
- Multi-layered follow-up program, with varying depth, sample size, spectral resolution, and timescale requirements: wide, fast, *deep* spectroscopy needed
- Piecemeal vs. coherent program?