WFIRST & Euclid

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Overview

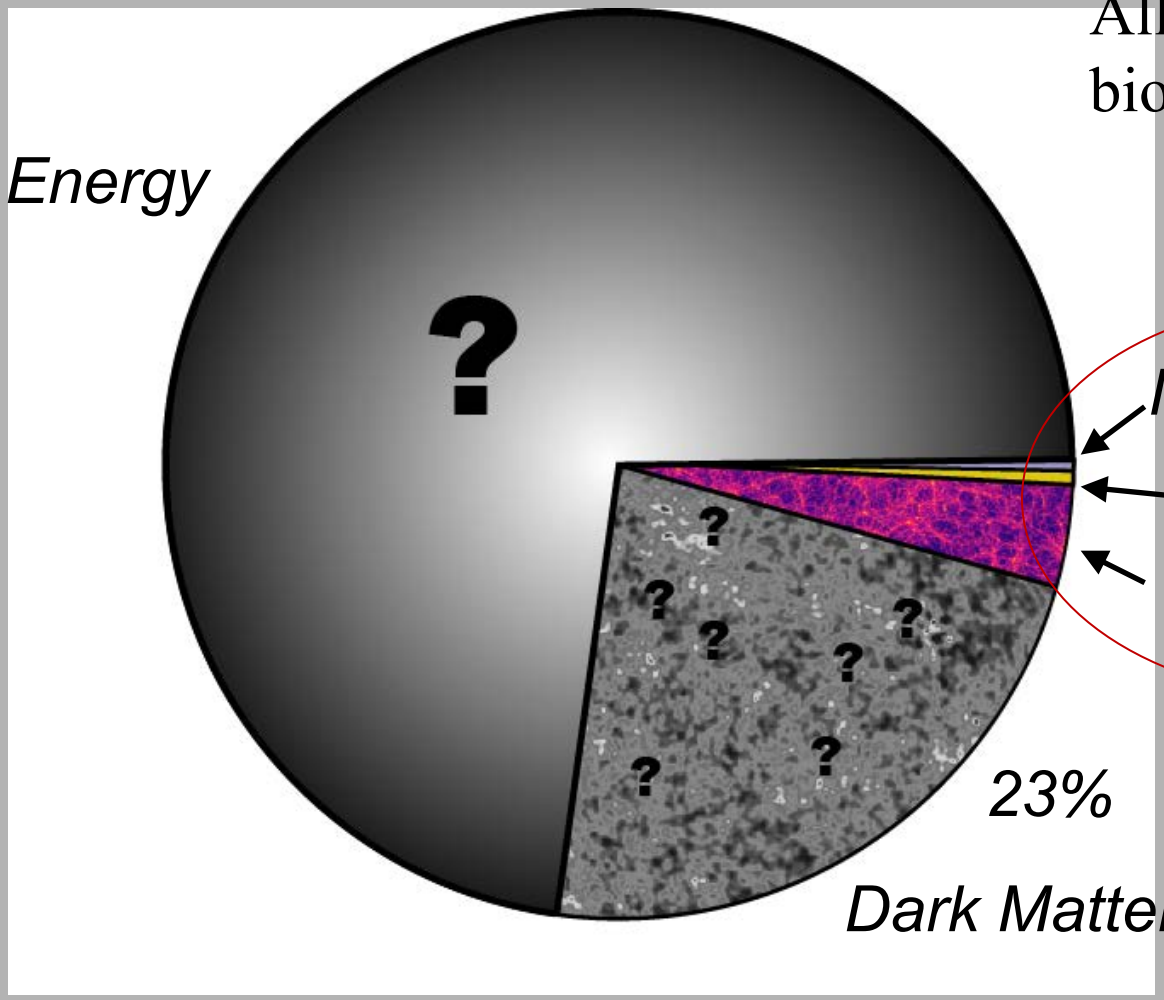
Fundamental Scientific Questions

- Dark Matter and Energy
- The abundance of Earth-like planets
- The Evolution of Galaxies & Near Infrared Survey Science

The Missions:

- Euclid- ESA Cosmic Visions
- Wide Field Infrared Survey Telescope - NASA

The Components of the Universe



Dark Energy

73%

All of chemistry, biology, physics…

Neutrinos 0.3%

Stars 0.4%

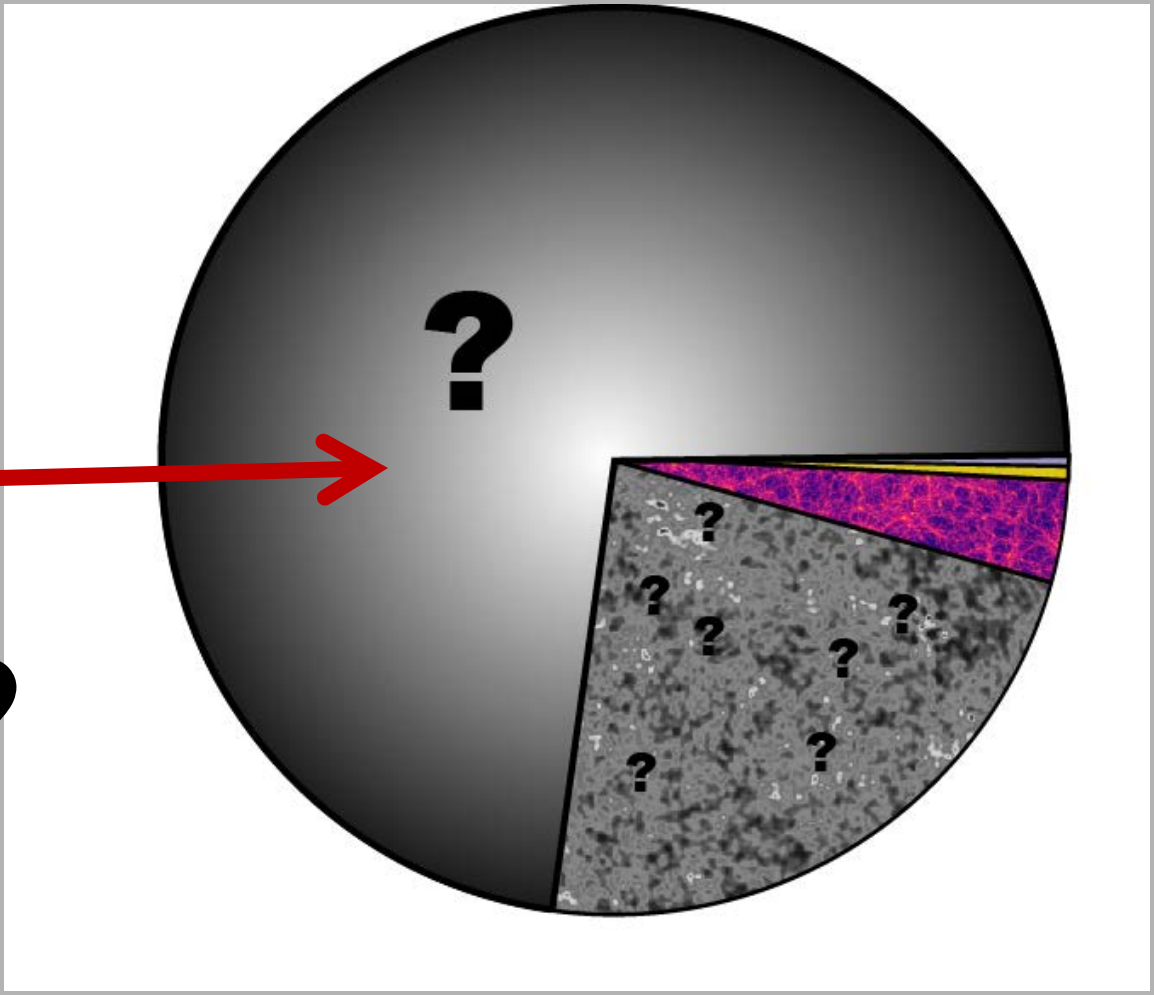
H, He Gas 4%

23%

Dark Matter

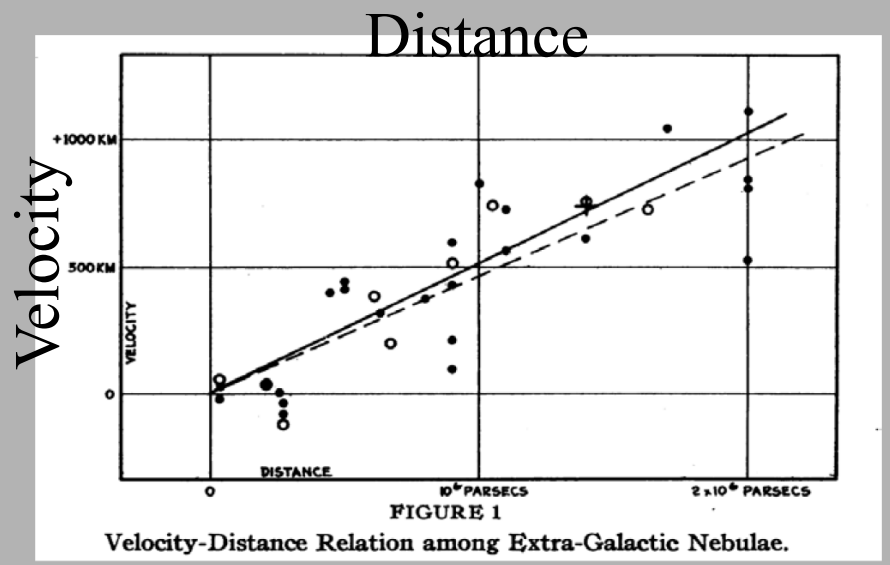
The Next Piece of the Pie

What is that stuff????



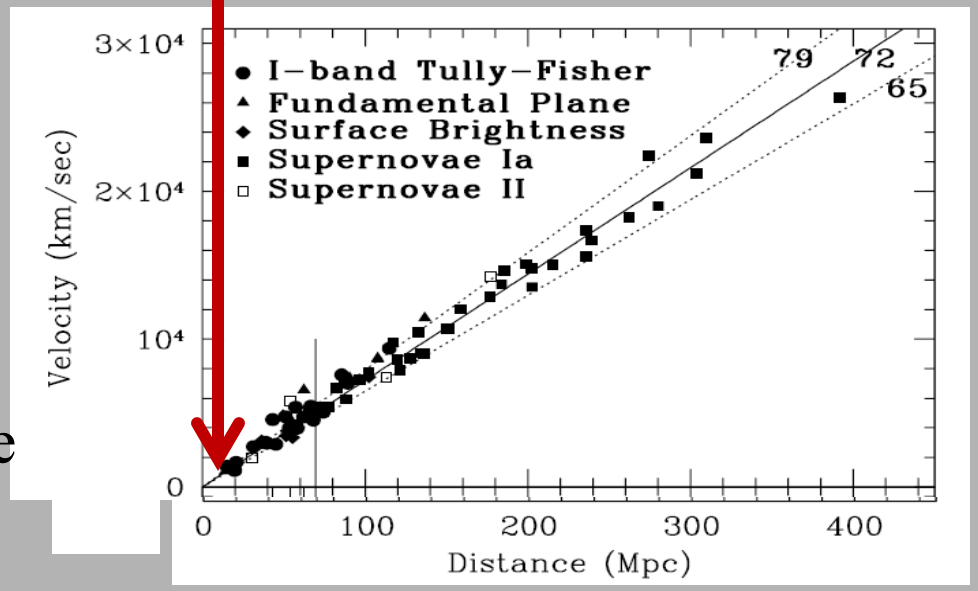
One of the most compelling and important questions in science!

The Universe is Expanding



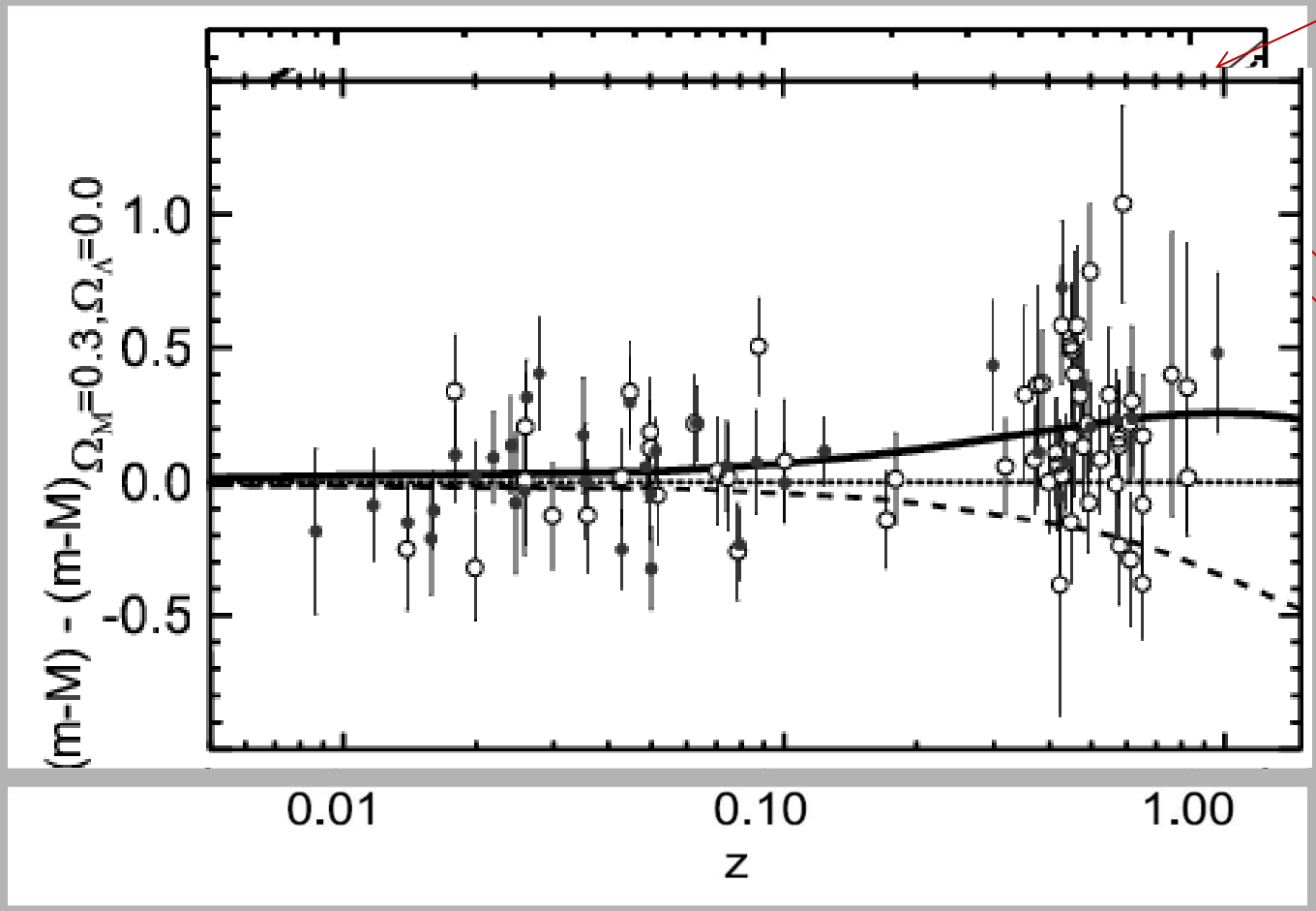
Hubble, 1929

The farther away something is, the faster it is moving away, *in all directions!*



Hubble Space Telescope

The Expansion is *Accelerating!*



Universe with *something* (dark energy) making the expansion accelerate "recently"

Universe with just mass

Perlmutter & Schmidt, 2003

Einstein's Equation

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Gravity or space curvature

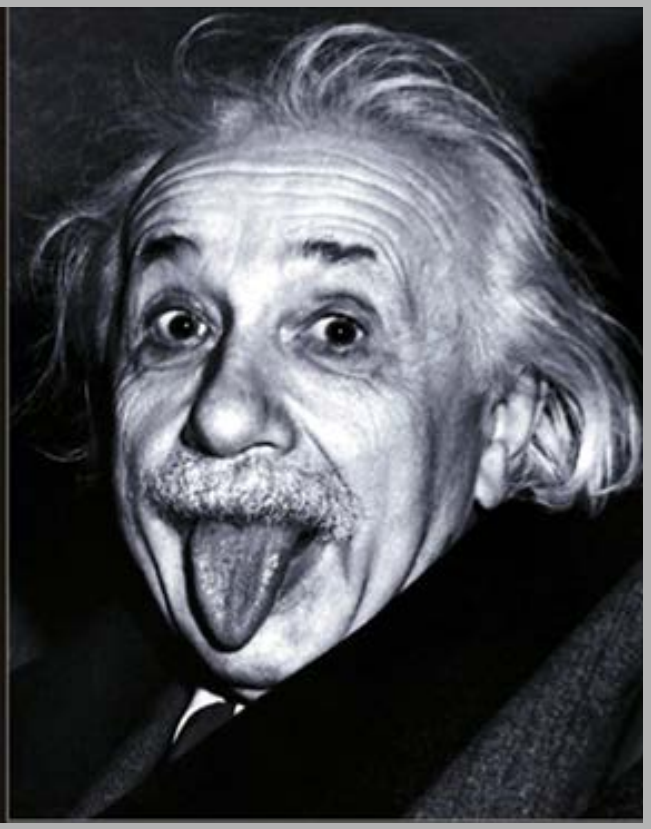
Mass and energy

Cosmological constant or Dark Energy (but maybe not actually a constant)

- Λ term on right hand side introduced to allow for a 'steady state' Universe
- Don't need it if the Universe is expanding but decelerating

We could also be "wrong" about the left hand side (gravity). *We will test this* as we attempt to measure dark energy.

Einstein's Blunder (?)



- Einstein added the cosmological constant Λ so his equations would work for a static universe
- Before Hubble, it was assumed that the universe was static- that was aesthetically pleasing
- When the expansion of the Universe was discovered, the equations held without Λ
- Einstein called Λ his 'biggest blunder'

In 1998, when the accelerating expansion was discovered, Λ was reintroduced!

Einstein's 'biggest blunder' is going to win somebody a Nobel Prize!

Two Effects

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 the dark matter structures (like the ones we recently measured with Hubble) 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!*

Future of the Universe

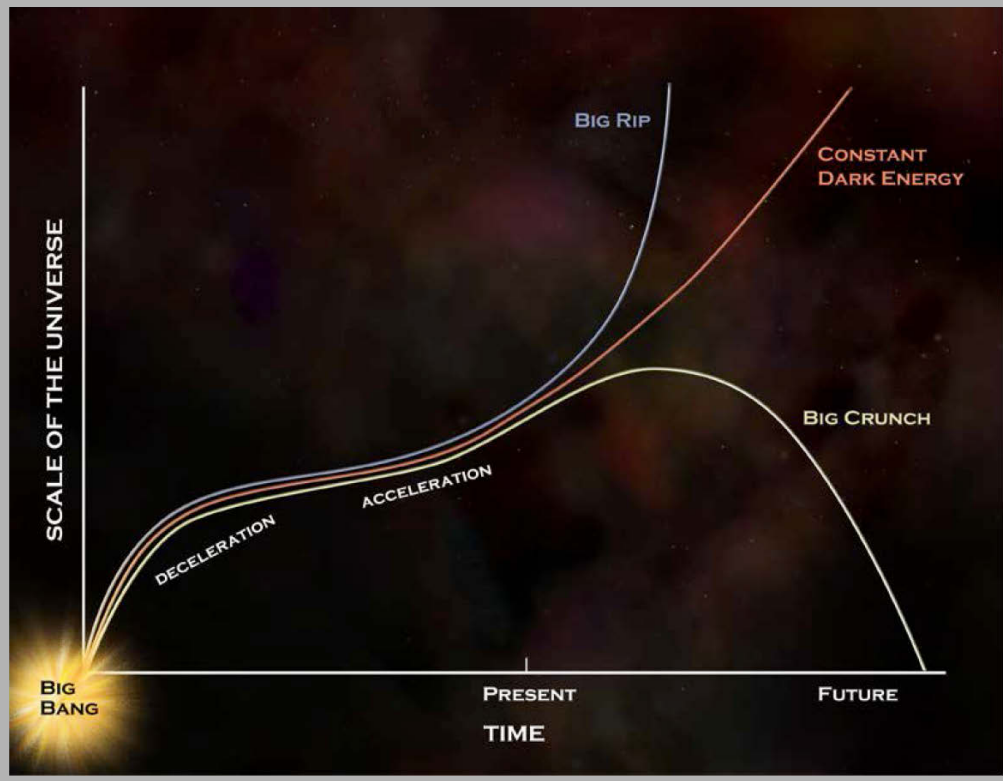
Universes with Dark Energy and

$-1 < w < -1/3$:

- eternal expansion
- other galaxies eventually disappear beyond the horizon
- gravitationally bound objects stay bound

Universes with Dark Energy and $w < -1$:

- DE density becomes infinite
- bound objects torn asunder!
- even atoms broken apart!
- **the "Big Rip" !!**
- **if $w = -1.5$**, Big Rip happens in **22 billion years**.

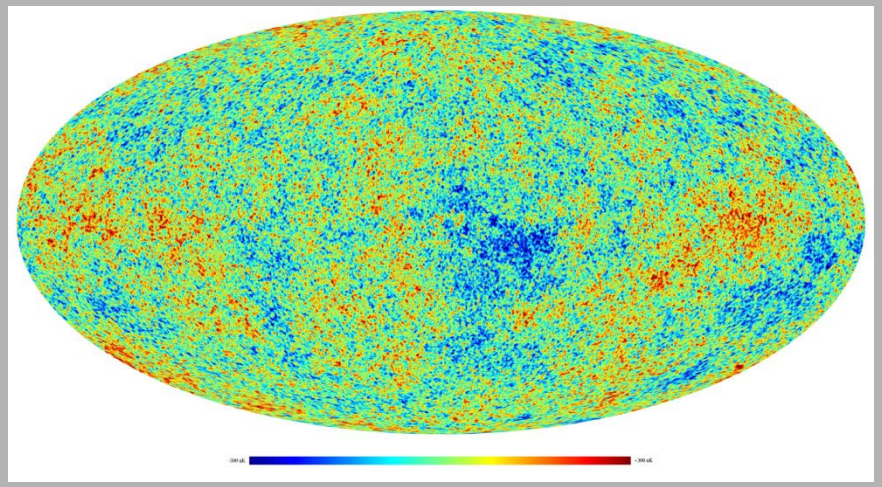


Three Primary Dark Energy Probes

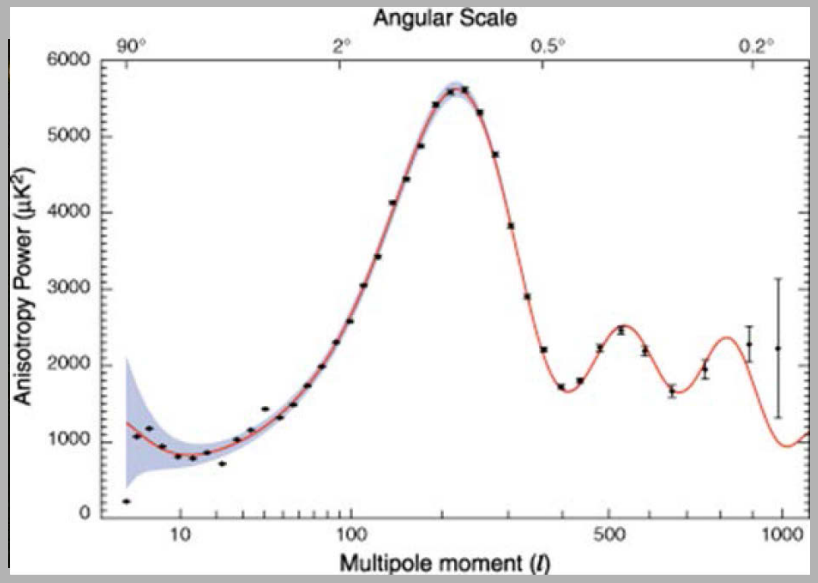
Weak lensing can measure the expansion history *and* the growth of structure *simultaneously*

Supernova Ia are standard candles that measure the expansion history

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



CMB

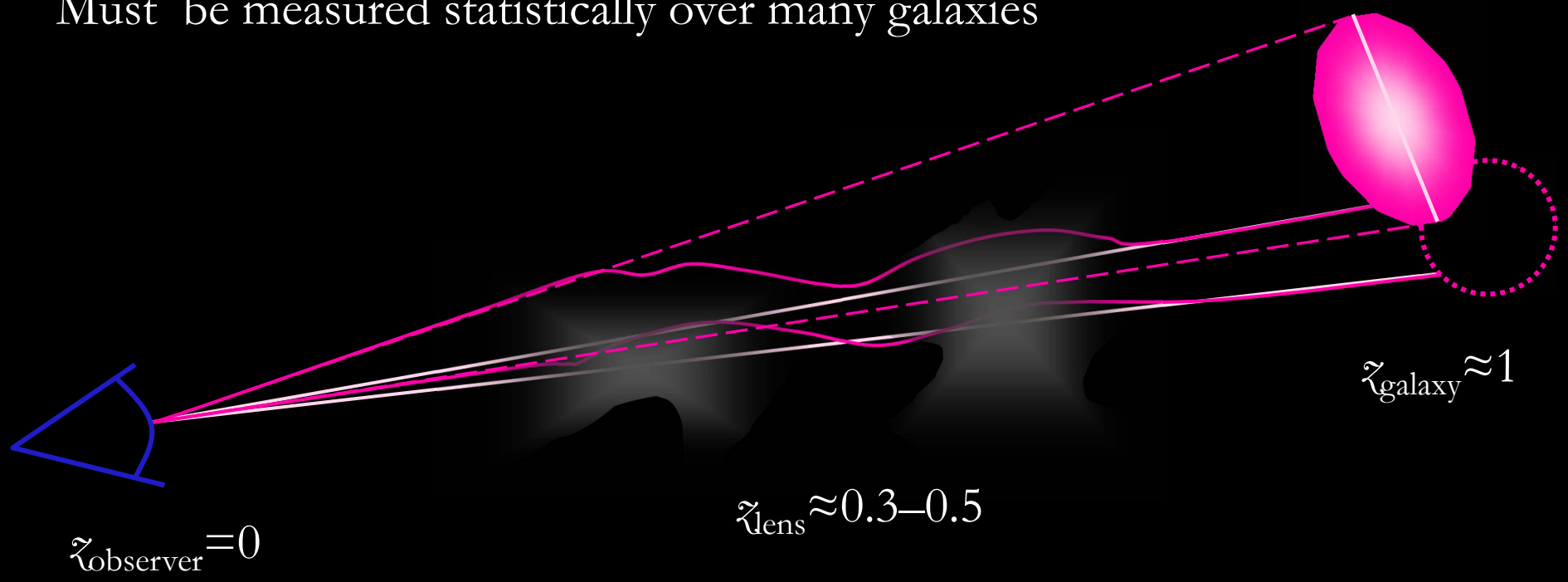


Clustering of Galaxies

Weak Gravitational Lensing

Weak lensing effect cannot be measured from any individual galaxy.

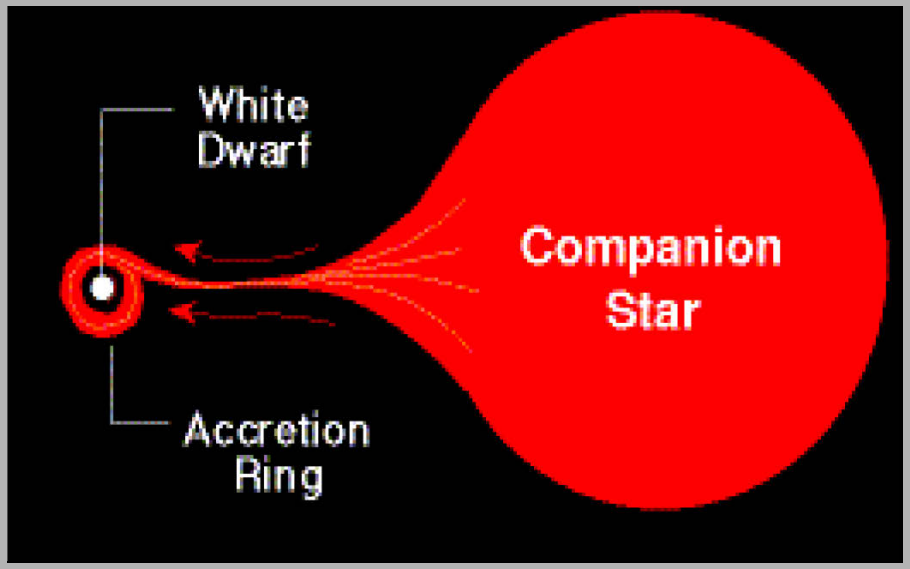
Must be measured statistically over many galaxies



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.

Standard Candles

Supernovae Ia are thought to be white dwarf stars that reach critical mass through gobbling up gas from a nearby



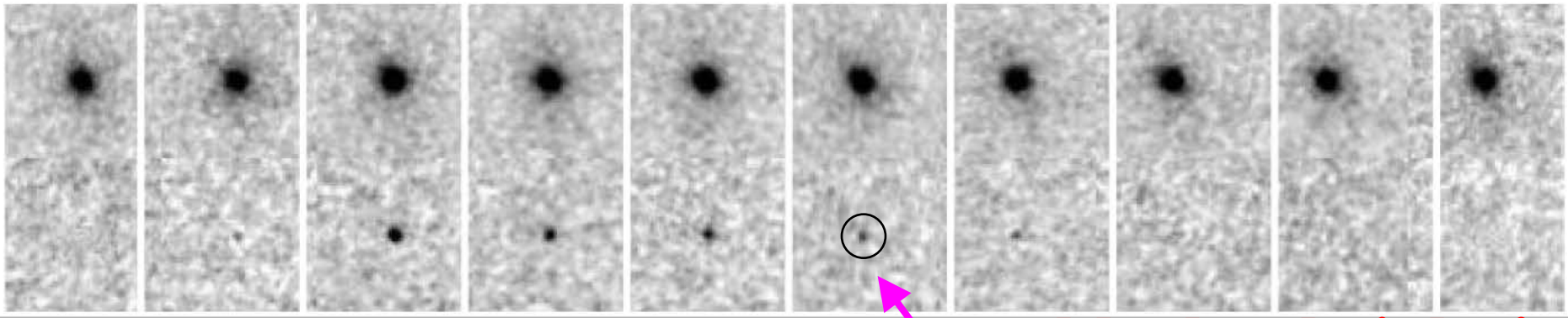
SuperNova 1994D, HST, NGC 4526

- When critical mass is reached, a thermonuclear runaway explosion results, and consumes the entire white dwarf star
- By measuring the timescales of rise and fall in brightness of the supernovae, one can estimate its intrinsic brightness and use it as a standard candle

How to Find Supernovae

- **30 hour visit every 5 days for 2 years**
  - **about 2000 SNe total**
- **Measure photometry to 0.05%**
  - **Light curve (in multiple filters) gives intrinsic brightness**
- **Spectra to confirm that SNe are Ia**
- **Systematics: photometric calibration, extinction, evolution**

Time →

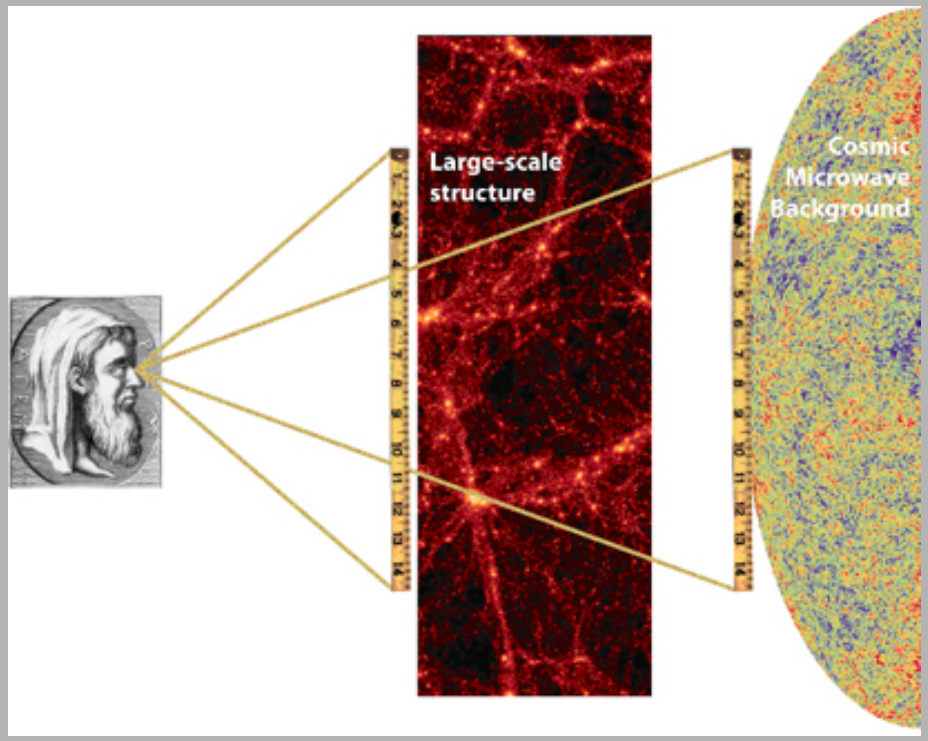


Kirschner, Science, 300, 1916 (2003)

black = bright !

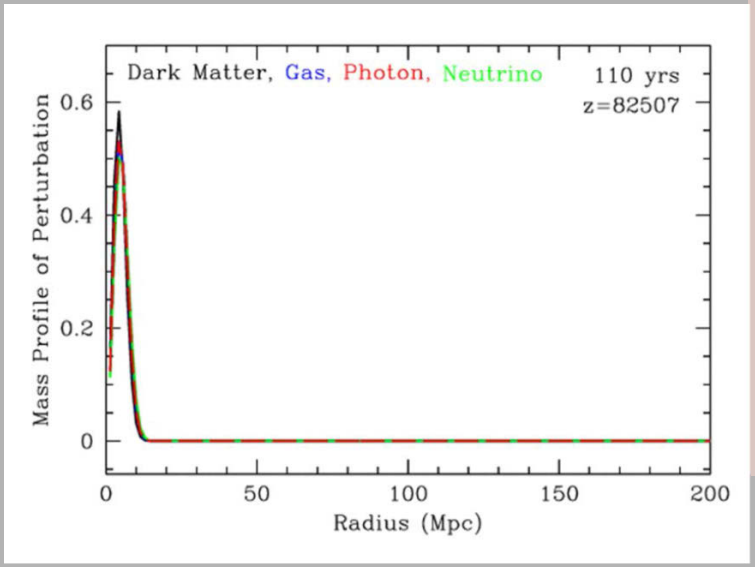
Standard ruler: baryonic acoustic oscillations (BAO)

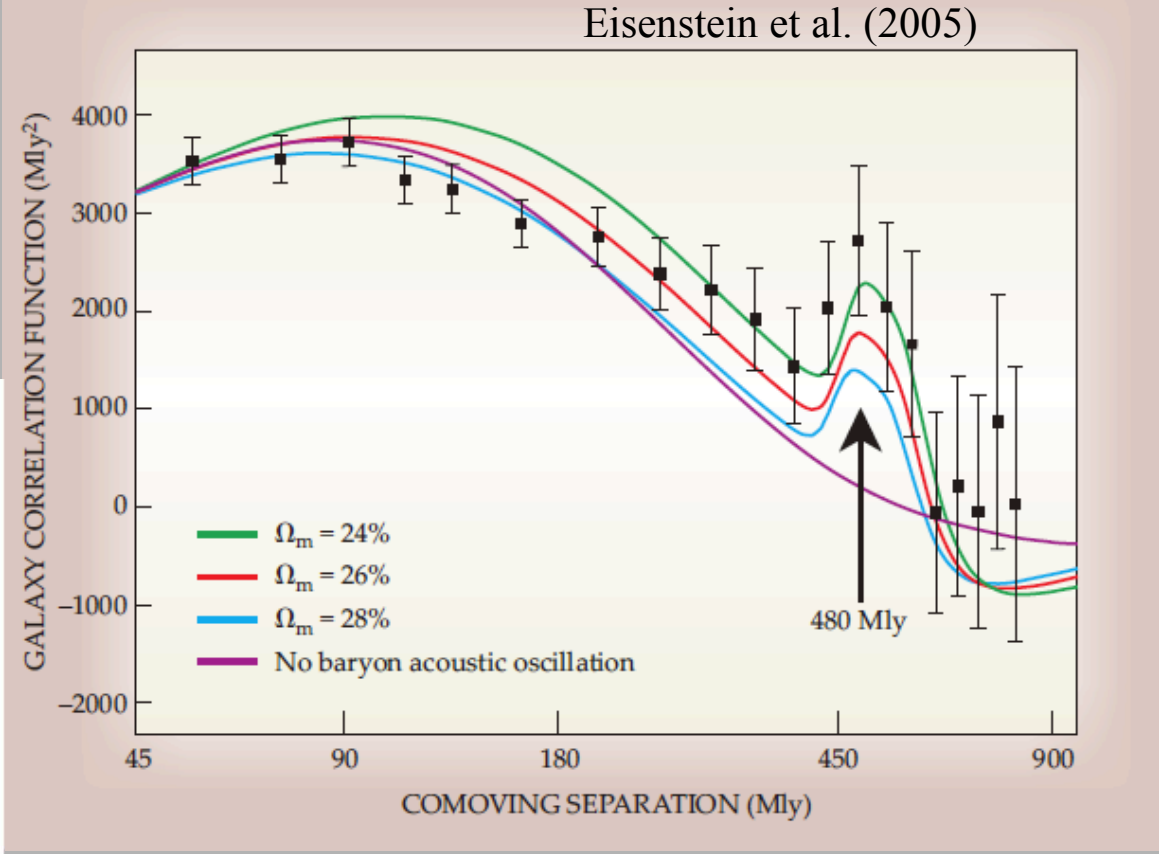
- **In early Universe, sound waves could ripple through plasma like ripples on a pond**
- **Fixed scale imposed when the Universe became transparent (seen in CMB data; 1 part in 10,000)**
- **Fluctuations grew to large structures (DM, galaxies, everything)**



BAO

Spectacular confirmation of this prediction from the Sloan Digital Sky Survey – 50,000 galaxies with positions and spectra.





The basic picture of structure formation through gravity is confirmed.

Dark energy is required. Without it, the 480 million light-years would be a smaller number.

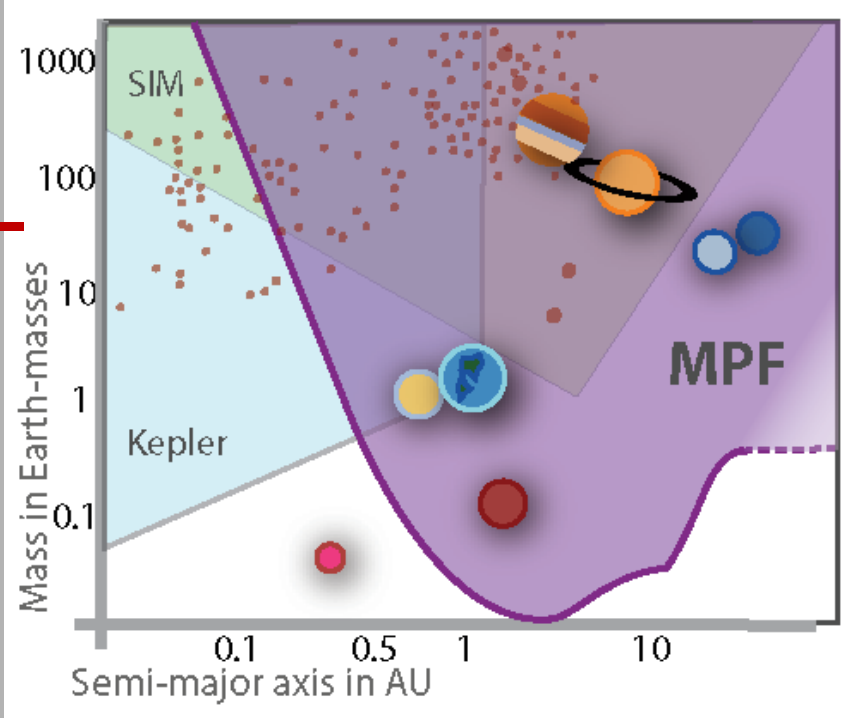
Are We Alone?

The search for planets is fundamental to the search for alien life

Multiple techniques exist for finding planets

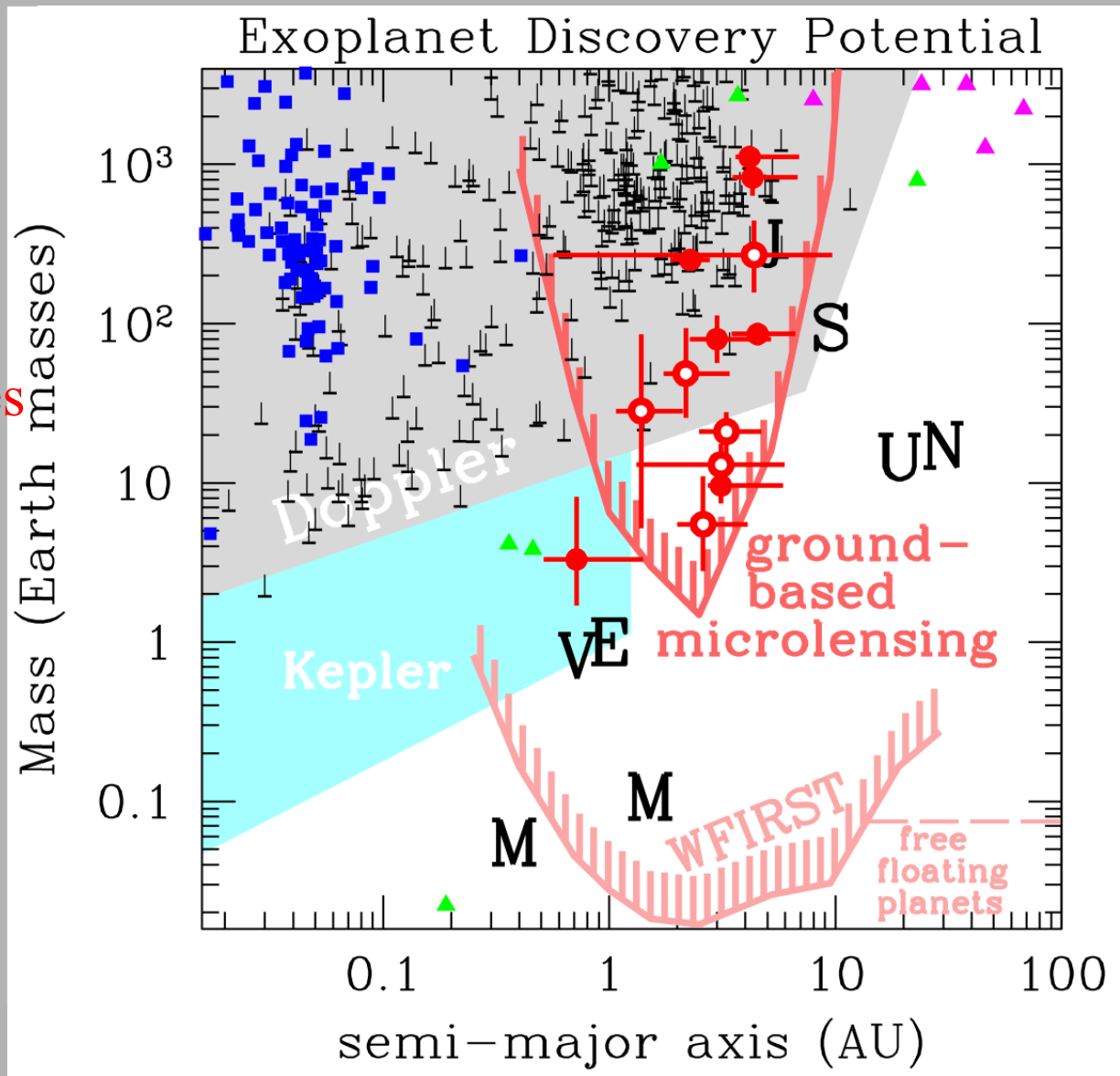
Gravitational microlensing allows a statistical census for planets near the "interesting" region:

We want to find Earth-like planets in the habitable zone



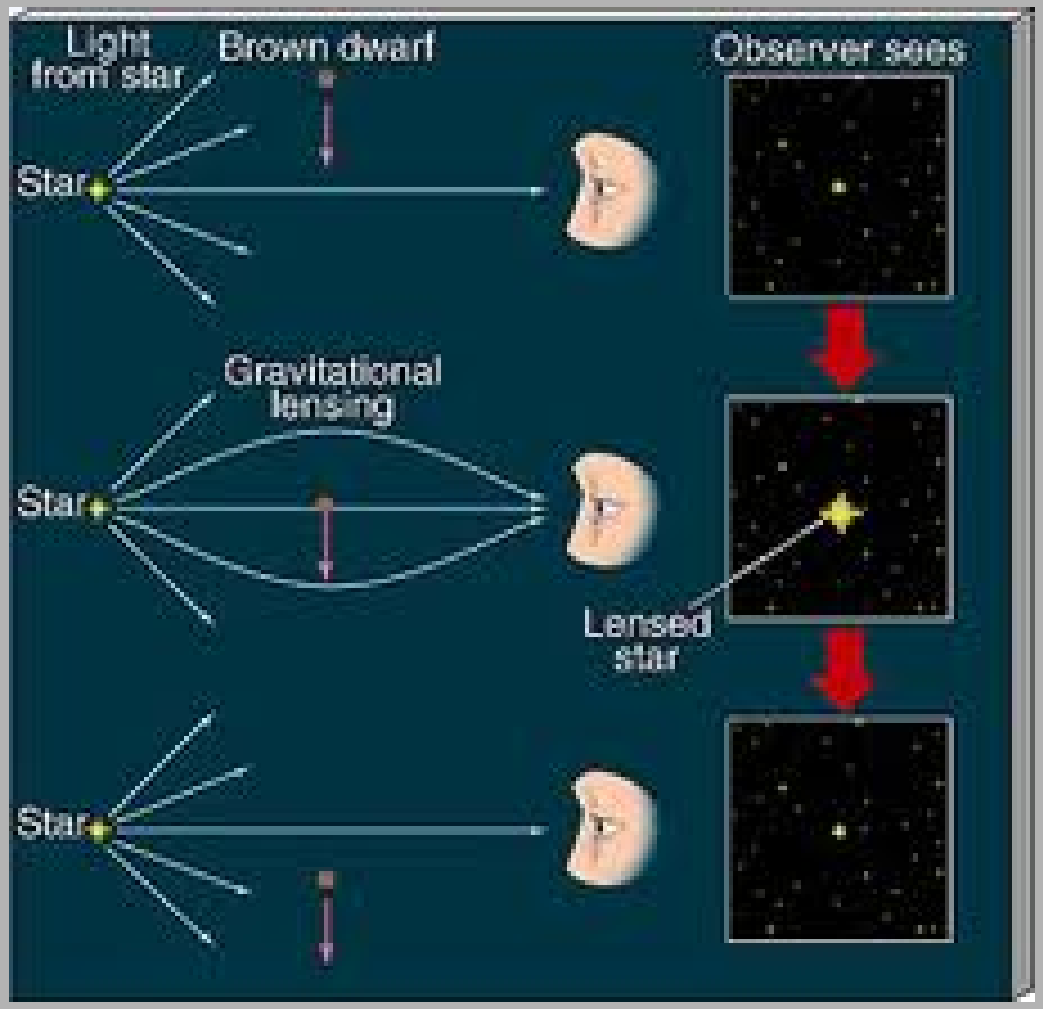
Planet Discoveries by Method

- ~400 Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
  - cool, low-mass planets
- Direct detection, and timing are magenta and green triangles



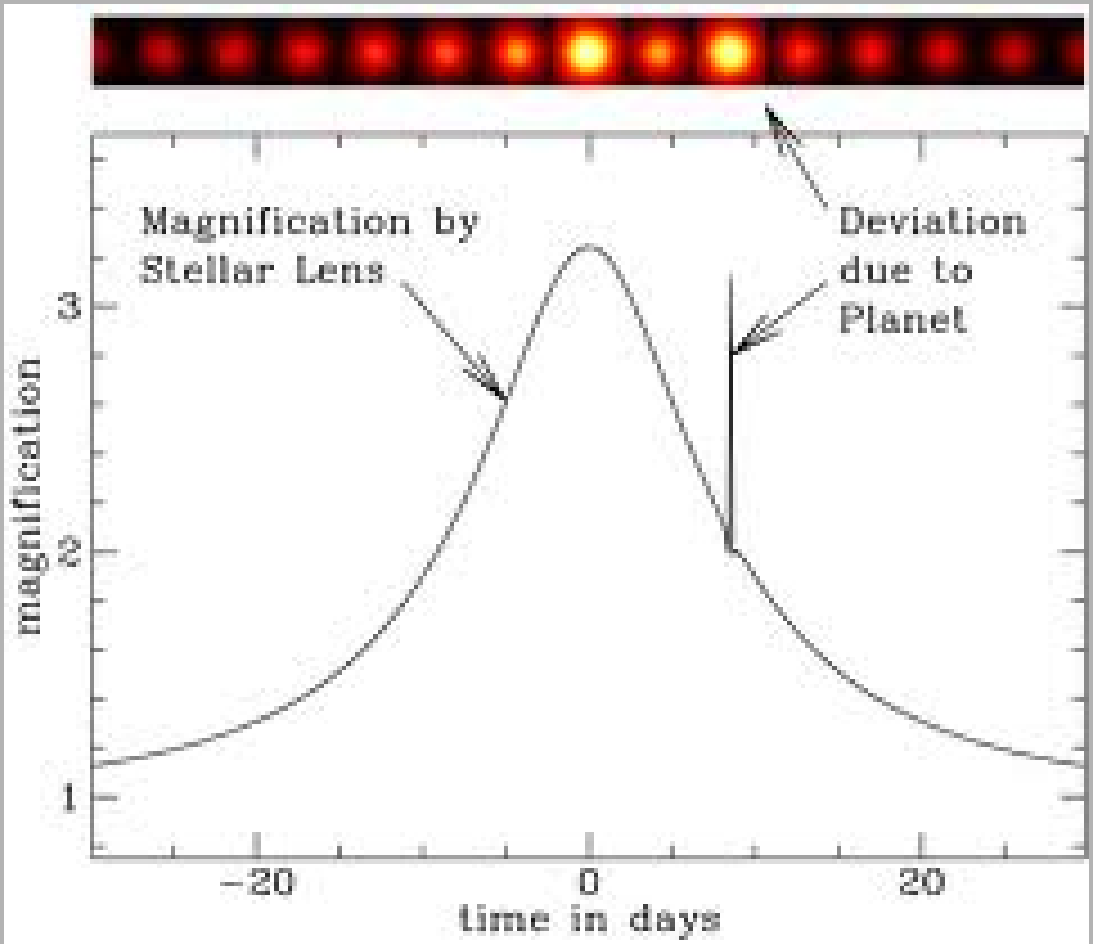
Microlensing Phenomenology

- When the path of a foreground star crosses near a background star, its gravity bends and focuses the light from the background star.
- The background star is the 'source', and the foreground star is the 'lens'.
- The result is a time-dependent magnification of the light we receive from the 'source' star.



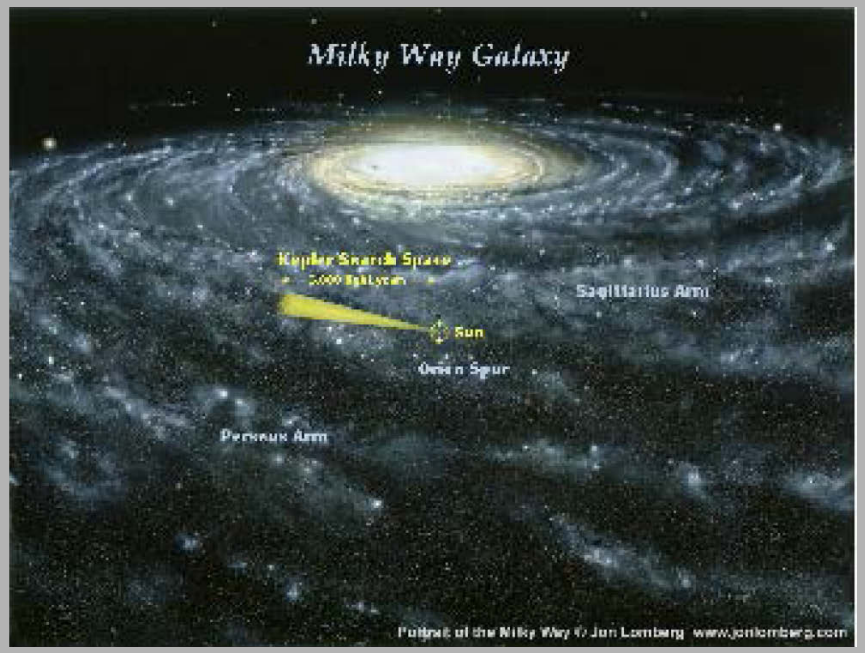
Stellar and exoplanetary microlensing

- **Typical time scale for a stellar event is 1 to 2 months.**
- **If the 'lens' star has a planet, its gravity may also contribute to lensing the light from the 'source'.**
- **This produces a secondary peak in the light curve.**
- **Typical exoplanetary deviation lasts only hours to days.**



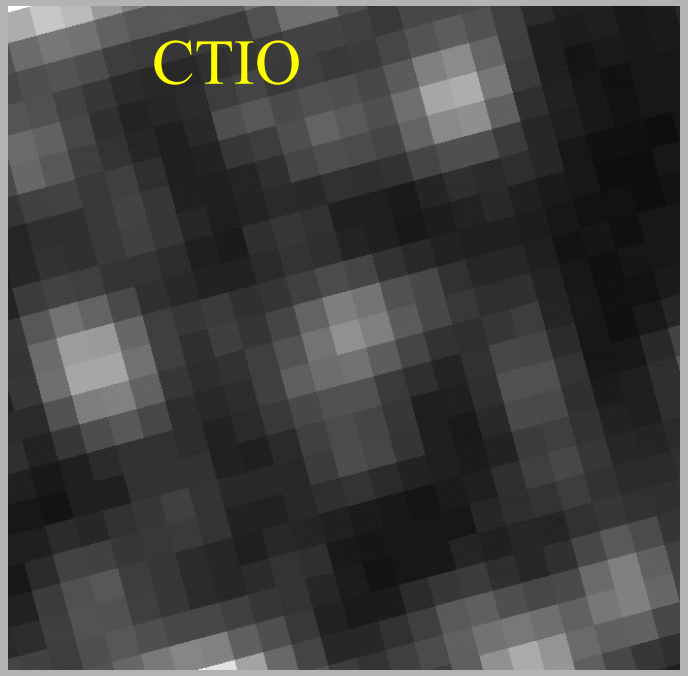
Exoplanet surveys

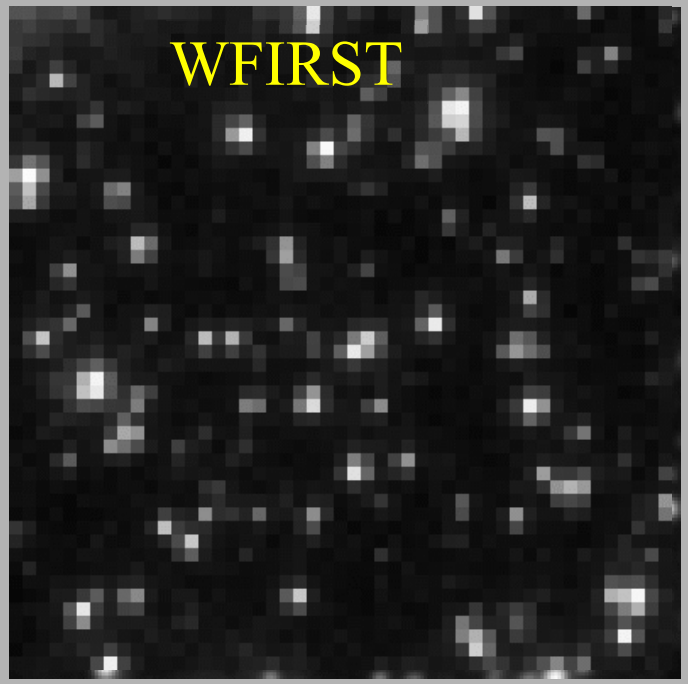
- **Exoplanetary microlensing is a low probability phenomenon.**
- **In order to monitor many potential events, we need**
  - **A Wide-field survey**
  - **Pointed at a region that is dense in stars, e.g. the galactic bulge**
- **High-cadence continuous sampling**
- **IR telescope, because**
  - **Can see farther through dust, and**
  - **Most stars are M stars, which strongly radiate in the IR**



Typical 'Source' star is a giant or dwarf in the bulge.
Typical 'Lens' star is a red main-sequence star in the foreground disk or bulge

Why do we need a space-based survey?





- **Space-based imaging is needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection**
- **High Resolution + large field + 24 hr duty cycle**

- **Space observations needed for sensitivity at a range of separations and mass determinations.**

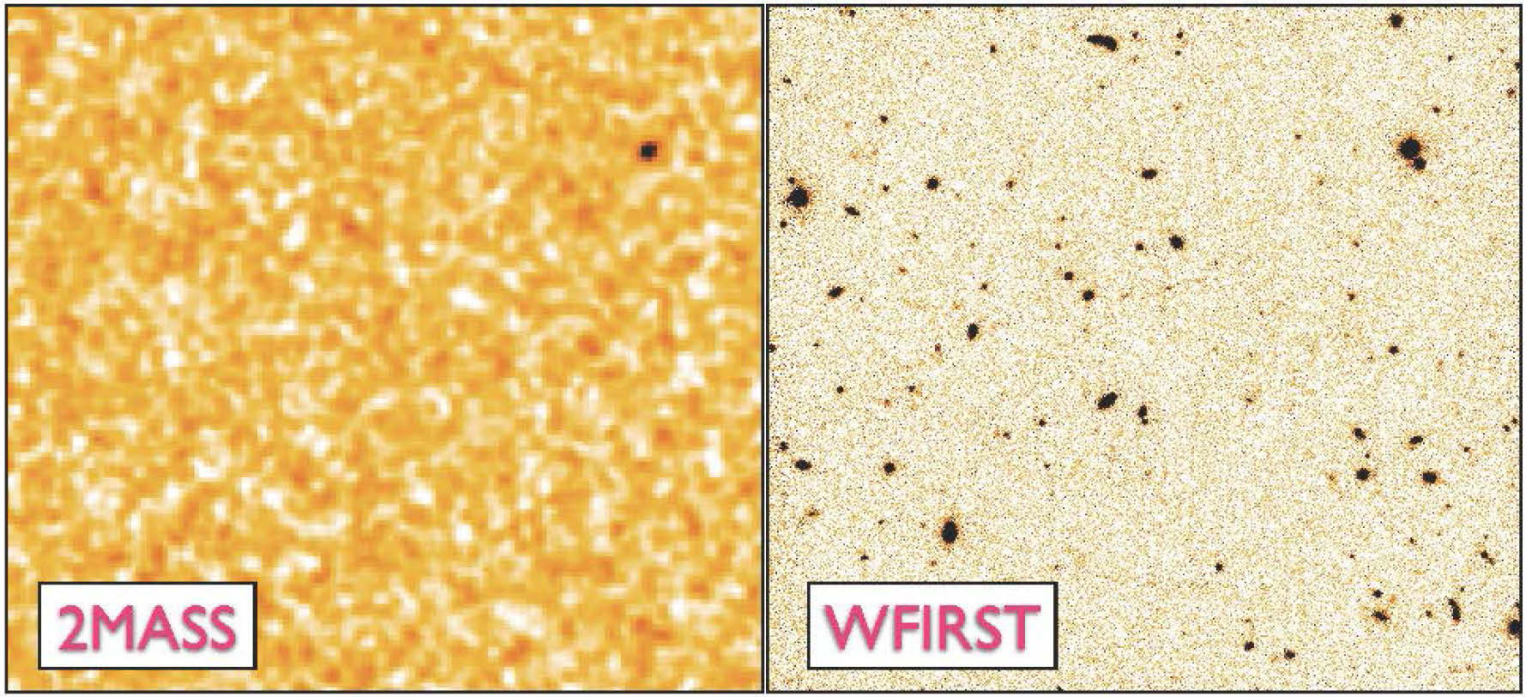
Why Space-based Microlensing?

- **Microlensing requires extremely crowded fields**
- **Source stars only resolvable from space**
- **Ground-based surveys need high lensing magnification to resolve most source stars**
  - **Limits sensitivity to near the Einstein ring**
  - **Space-based microlensing sensitive from 0.5 AU - ∞**
- **Space-based microlensing allows detection of most lens stars**
  - **Allows direct determination of star and planet masses**

Why microlensing

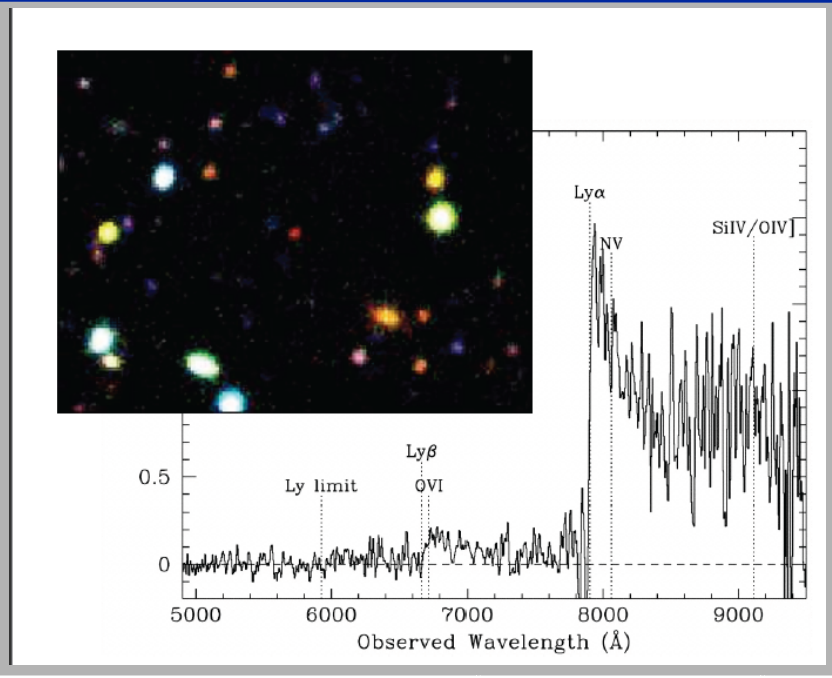
- **Measuring the 'demographics' of planets beyond the 'snow line' – out past 1 AU.**
- **I.e., what is the distribution of planet masses and separations?**
  - **—RV is sensitive to close-in planets more massive than Neptune.**
  - **—Kepler is sensitive to planets inward of 1 AU.**
- **Frequency of habitable earth-like planets**
- **Frequency of free-floating (ejected?) planets**
- **Frequency of massive moons**
- **All these items are important to test planet formation theories.**

NIR Survey Science



- Targets for JWST and TMT/ELT's.
- Compliments WISE, Planck, DES/Pan-STARRS/LSST, eROSITA/ART-XC, ...

High Redshift Quasars



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

High Redshift Quasars

- WFIRST or Euclid will identify quasars at z>6 in unprecedented numbers

- Science afforded by high-redshift quasars (QSOs):
    - probe the epoch of reionization in several ways:
    - luminous background probes for studying intervening universe
    - Lyα profiles probe state of local gas (e.g., Strömgren sphere radii)
    - QSO luminosity function (QLF) gives contribution to ionizing budget
    - radio-loud QSOs provide additional 21 cm probe of reionization
    - early history of black hole growth
    - proxy for early galaxy growth / growth of large-scale structure (LSS)
    - large numbers of high-redshift QSO pairs

- brightest (e.g., tip of the luminosity function + lensed) galaxies will likely be selected by the same color criteria. Such sources buy significant additional science, such as early IMF, metallicities, ages of first galaxies (c.f., substantial panchromatic literature on cB58, a strongly lensed z~3 LBG)

Normal Galaxies

- new near infrared surveys will detect vast numbers of normal galaxies
- near-IR data buys improved photometric redshifts: necessary for weak lensing cosmology program, but also essential for studying galaxy evolution
- though WFIRST resolution < HST resolution, still expect to resolve most (~80%) of sources brighter than H ~ 25
- grism/spectroscopy data data too...
- depth slightly lower than COSMOS, but covering >1000x greater area
- near-IR very powerful for identifying massive galaxies at z>1
- very powerful tool for studying high z galaxy clusters:

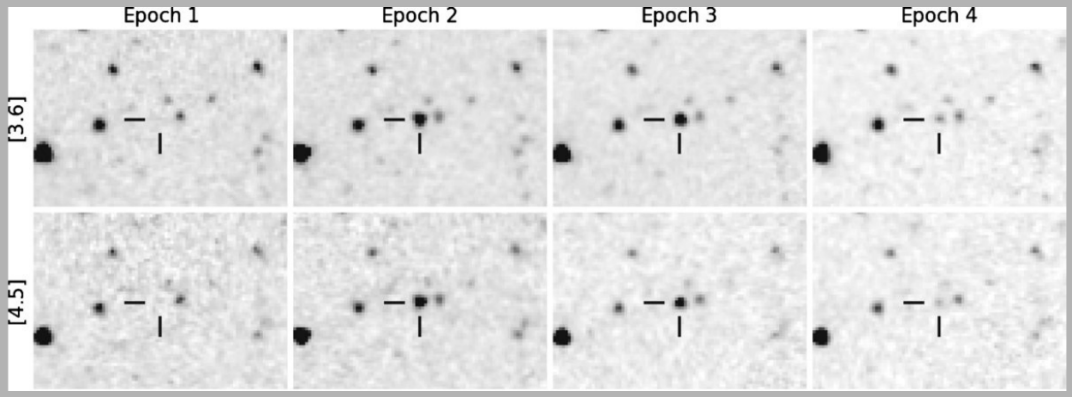
Galactic Plane

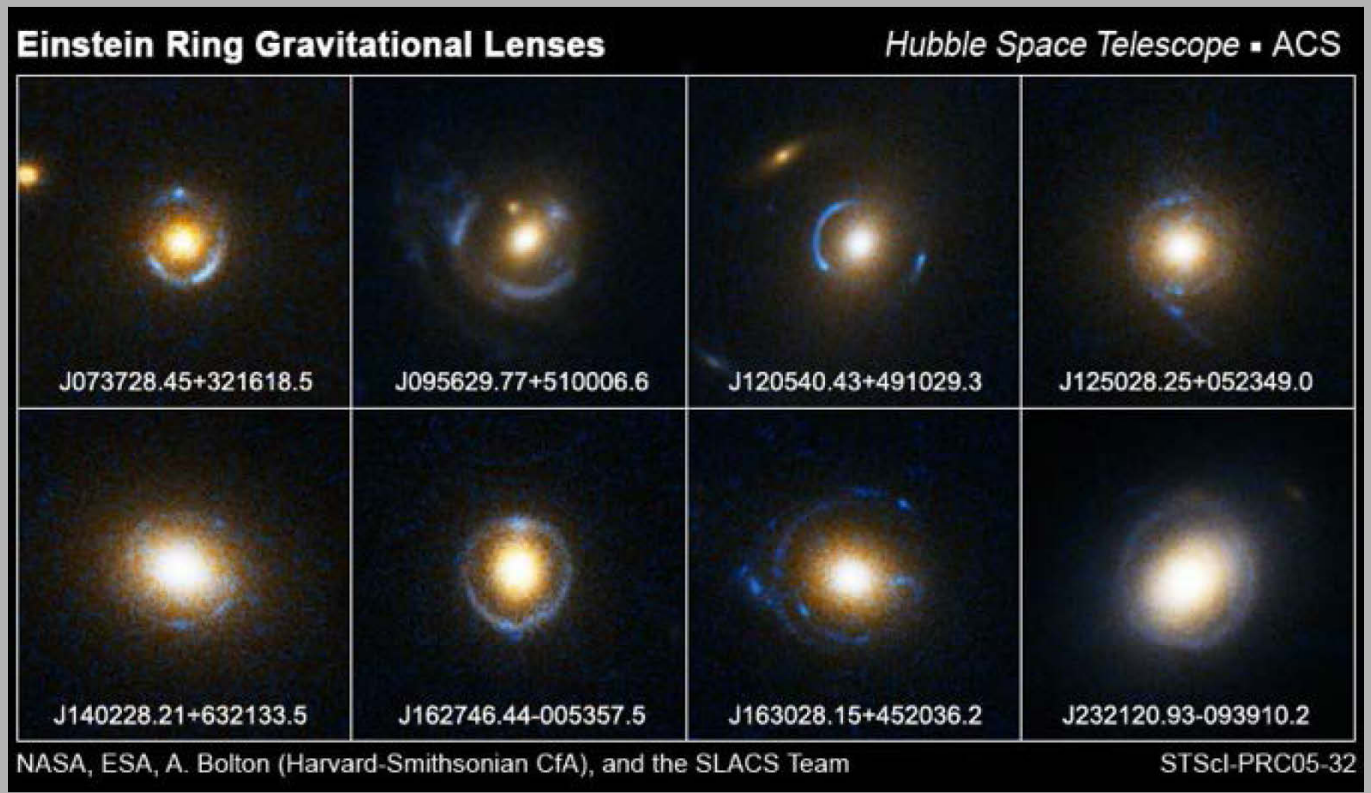
- science from WFIRST Galactic Plane Survey:
  - structure of the Milky Way Galaxy: edge of the disk, shape and extent of the Galactic warp, study IMF to H-burning limit as function of environment, tidal streams, probe time-domain (e.g., variable sources, moving sources; e.g., identify the deuterium instability region)
  - identify proto-stars
  - find low-mass BD's: star/planet boundary
  - find cool WD's: history of the Milky Way Galaxy

- 2-epoch studies of Galactic clusters:
  - identify members through proper motions

Serendipity

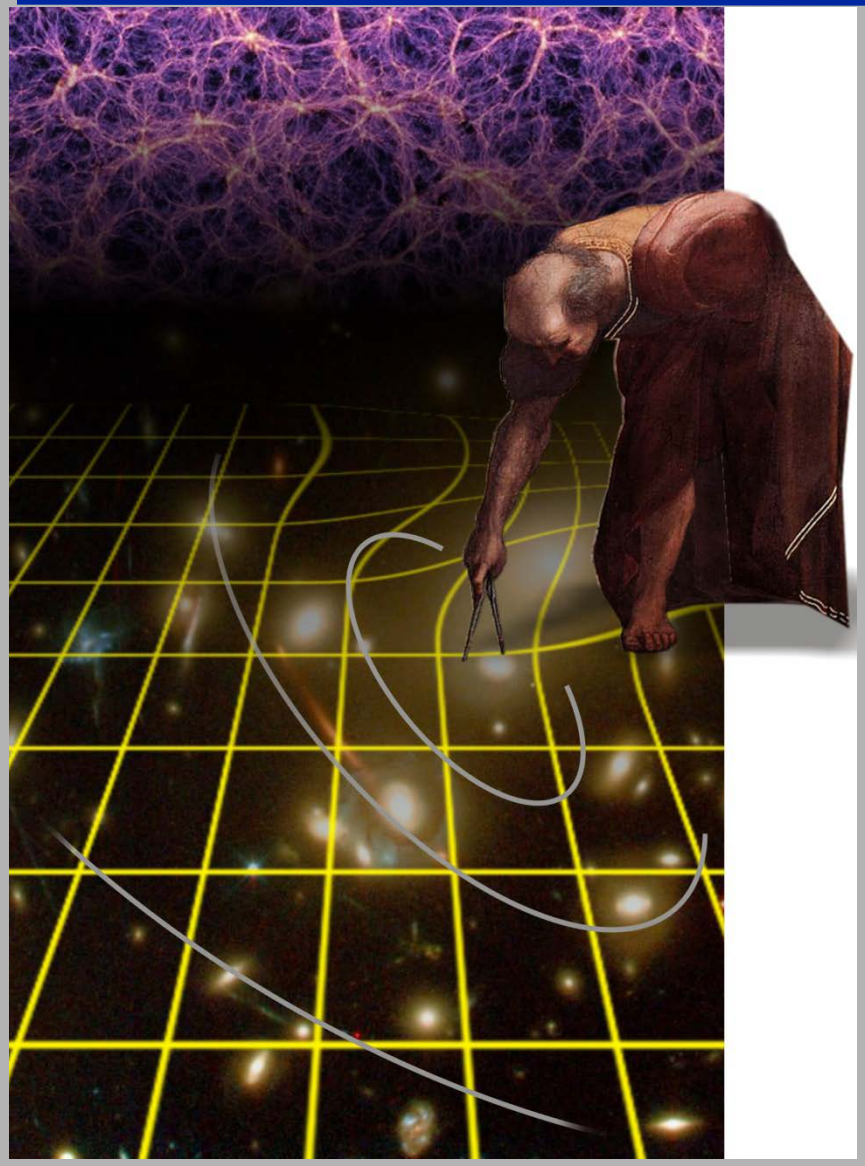
- Variable and rare objects
- Strong gravitational lenses
- ???





- most variable source in Spitzer Deep, Wide-Field Survey
- • a dust-enshrouded supernova at z~0.2 (SN 2007va)
- • ηCarinae analog

The Missions



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

2010-2011: Definition phase

April 2010: Formation of single Euclid Consortium

December 2010: NASA Call for 2 US Euclid Science Teams

July 2011: Final Euclid Proposal- Red Book

Oct 2011: Cosmic Vision Selection

2012-2017: Implementation phase

2017-2018: launch

Euclid concept

- High-precision survey mission to map the geometry of the Dark Universe
- Optimized for two complementary cosmological probes:
  - Weak Gravitational Lensing
  - Baryonic Acoustic Oscillations

  Additional probes: clusters, redshift space distortions, ISW
- Full extragalactic sky survey with 1.2m telescope at L2:
  - Imaging:
    - High precision imaging at visible wavelengths
    - Photometry/Imaging in the near-infrared
  - Near Infrared Spectroscopy
- Synergy with ground based surveys
- Legacy science for a wide range of areas in astronomy
- Survey Data public after one year

Euclid goals

Understand the nature of Dark Energy and Dark Matter by:

•Measuring the DE equation of state parameters w_0 *and* w_a to a precision of 2% and 10%, respectively, using both expansion history and structure growth.

•Measuring the growth factor exponent γ with a precision of 2%, enabling to distinguish General Relativity from the modified-gravity theories

•Testing the Cold Dark Matter paradigm for structure formation, and measure the sum of the neutrino masses to a precision better than 0.04eV when combined with Planck.

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

Euclid Mission Baseline

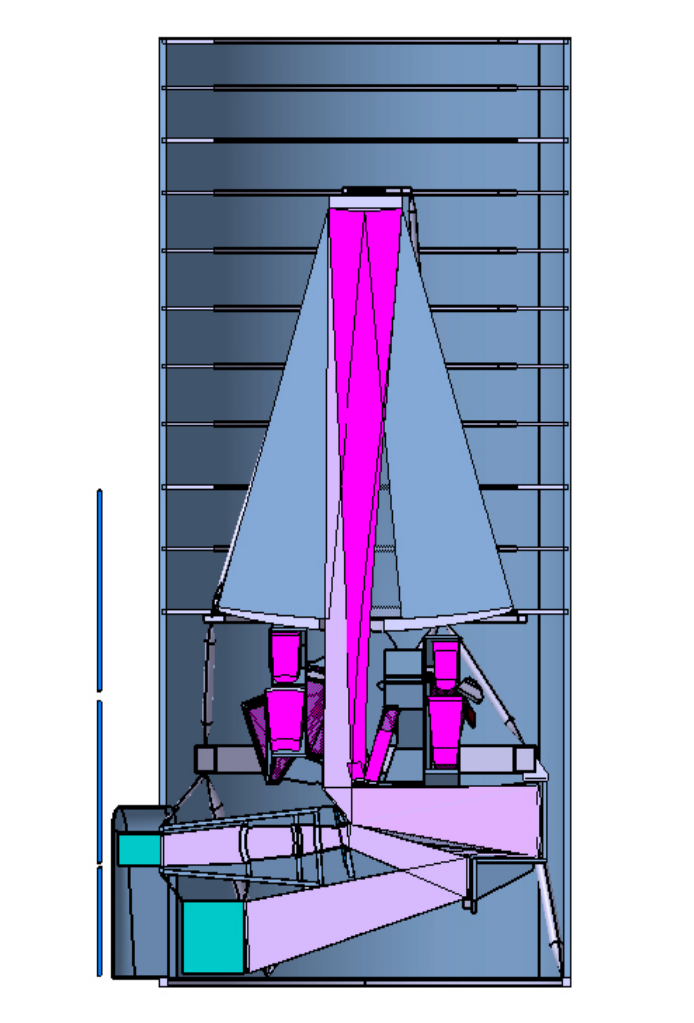
Mission elements:

- L2 Orbit
- 4-5 year mission
- Telescope: three mirror astigmat (TMA) with 1.2 m primary
- Instruments:

– VIS: Visible imaging channel: 0.5 deg^2, 0.10'' pixels, 0.16'' PSF FWHM, broad band R+I+Z (0.5-0.9mu), 36 CCD detectors, galaxy shapes

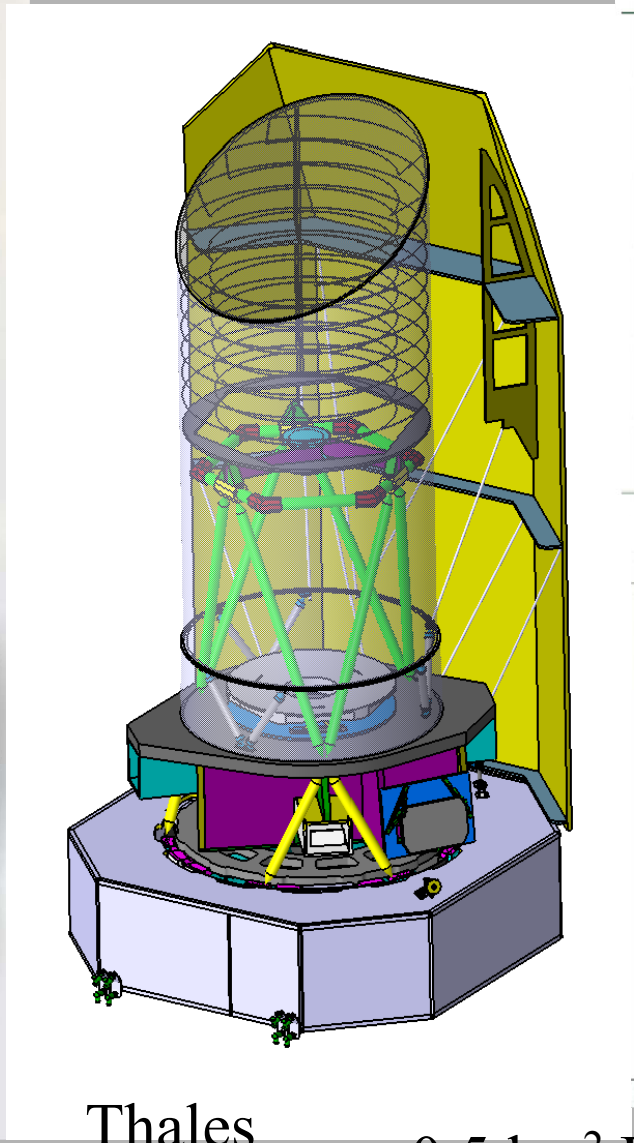
– NISP: NIR channel: 0.5 deg^2, 16 HgCdTe detectors, 1-2mu:

  - Photometry: 0.3'' pixels, 3 bands Y,J,H, photo-z's
  - Spectroscopy: slitless, R=500, redshifts

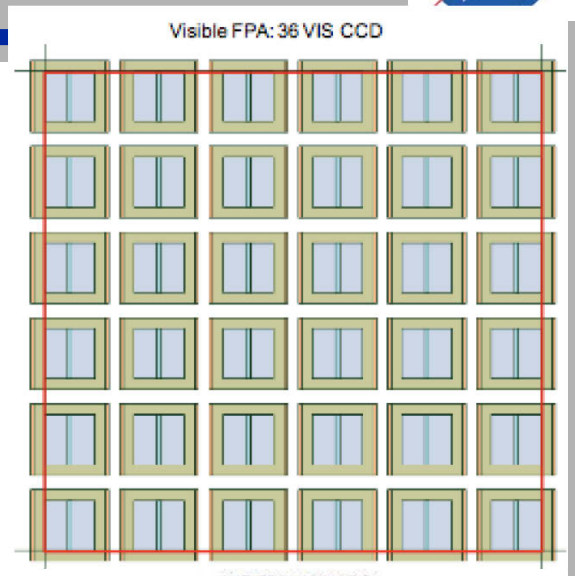


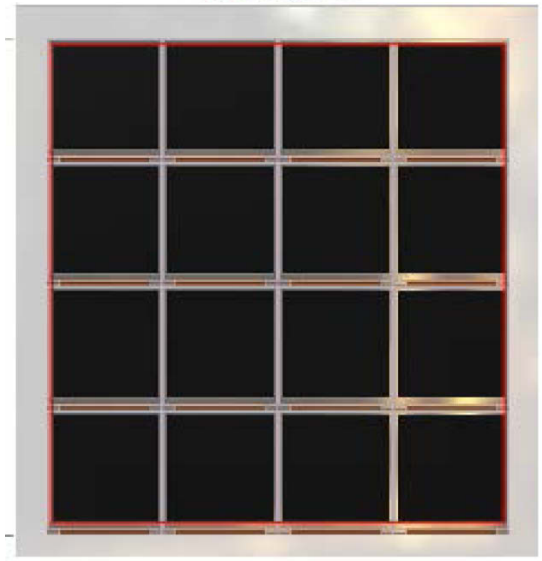
Hardware

Astrium



Thales

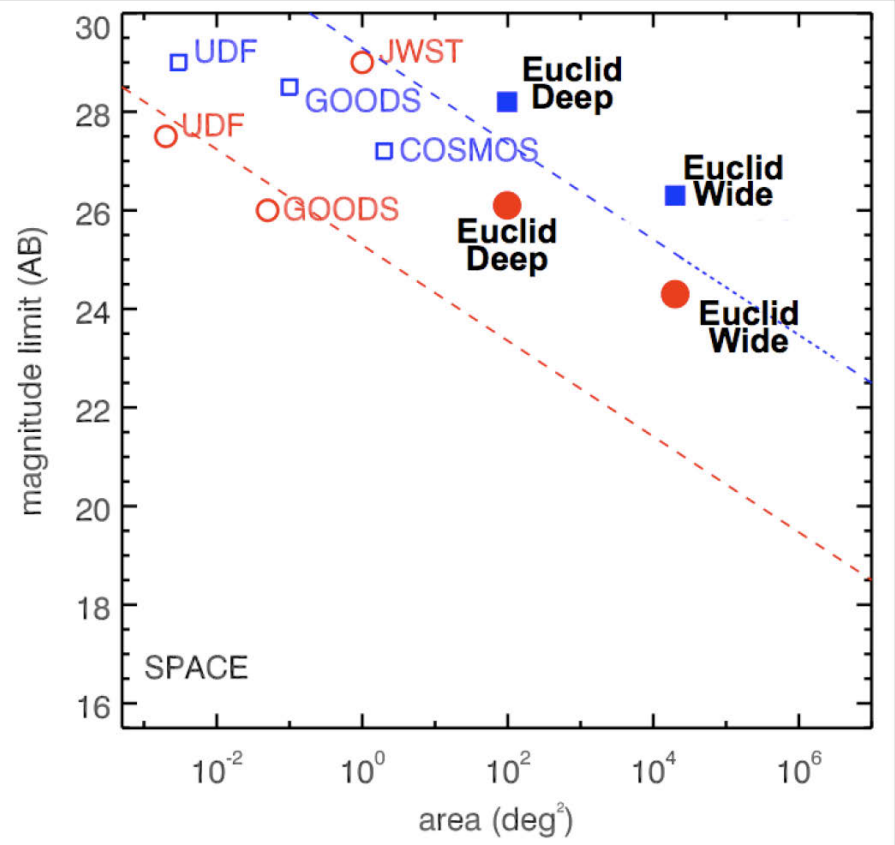




0.5deg^2 FOV in optical/NIR

Deep Fields and Legacy

- Deep Fields: 40 deg^2 at ecliptic poles two mags deeper. Ideal for calibration, high-z science and possibly transients
- Wide Survey Legacy: 2 billion galaxies imaged in optical/NIR, ~70 Million NIR galaxy spectra, full extragalactic sky coverage, Galactic sources
- Synergies with other facilities: JWST, Planck, e-Rosita, GAIA, DES, Pan-STARSS, LSST, etc.
- All data publicly available through a legacy archive promoting "SDSS-like" explosion of science applications



Euclid has the capability to do a very good microlenasing survey, if survey time is made available
Likely requires an extended mission

Impact on Cosmology

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary^	0.01	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.02	2	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2	0.007	0.035	4020
Current*	0.2	0.58	100	0.1	1.5	~10
Factor Improvement	**30**	**30**	**50**	**>10**	**>50**	**>300**

$f = d\ln\delta_m/d\ln a \propto \Omega_m^{\gamma}$

$w(a)=w_p+w_a(a_p-a)$

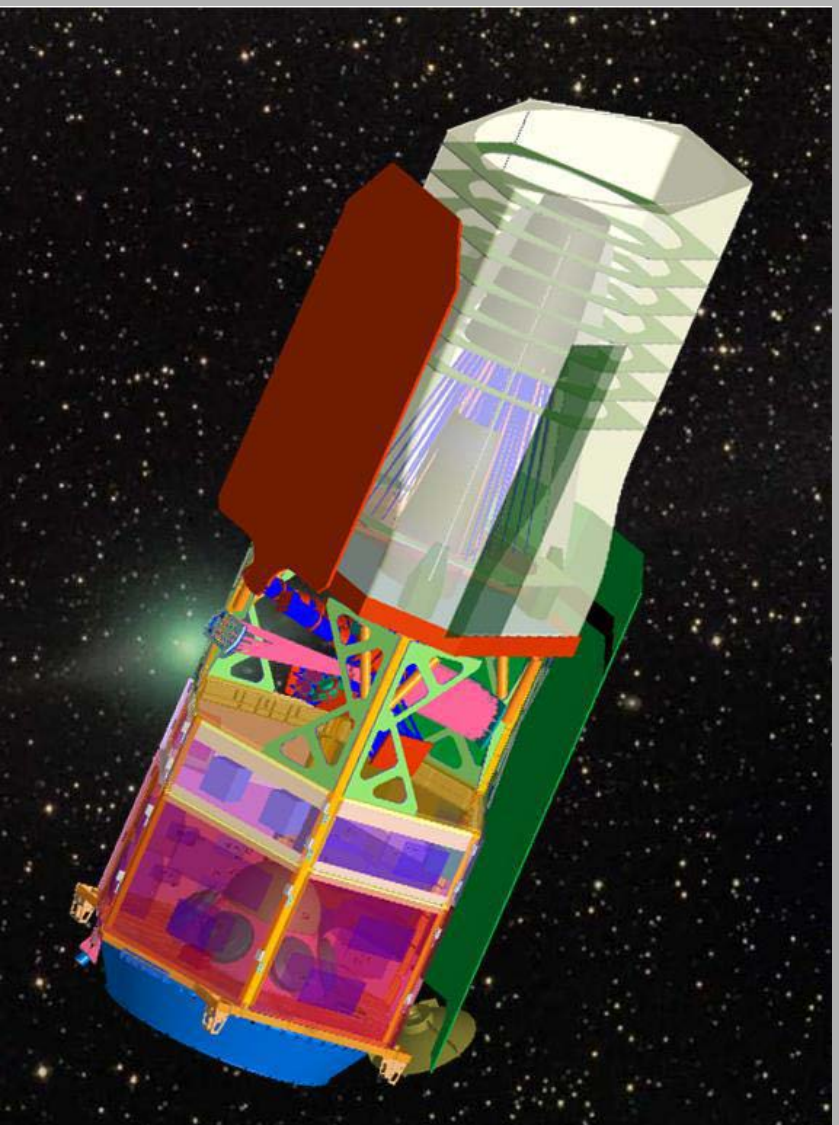
$FoM=1/(dw_p dw_a)$

Primary: Five year survey with weak lensing and galaxy clustering from 15,000 deg^2 of optical/NIR imaging and slitless spectroscopy (RIZ > 24.5, YJH > 24) and DES/PS2 ground-based data

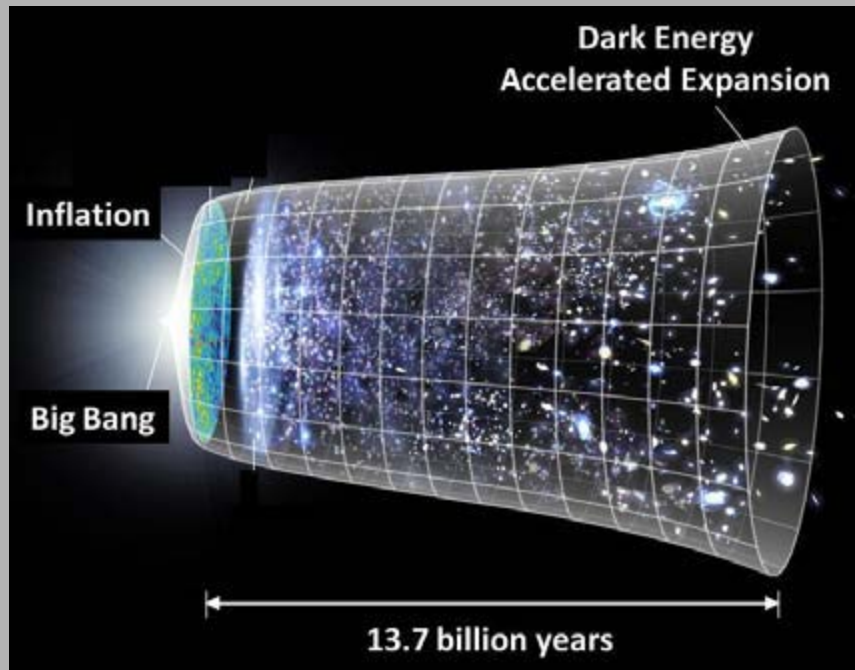
All: Including RSD, ISW and clusters from same survey data

WFIRST

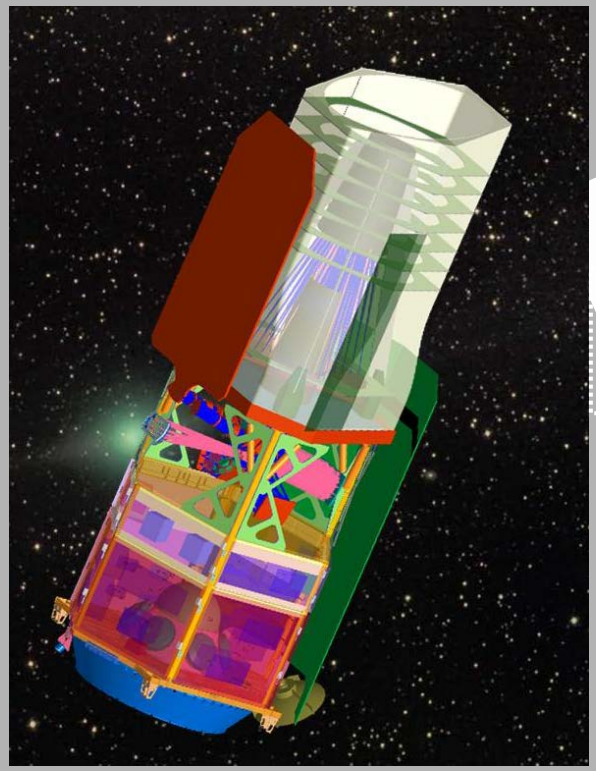
Wide Field Infrared Survey Telescope



- Dark energy and modified gravity
- Microlensing searches for exoplanets
- Near infrared survey for galaxy formation and evolution



WFIRST =



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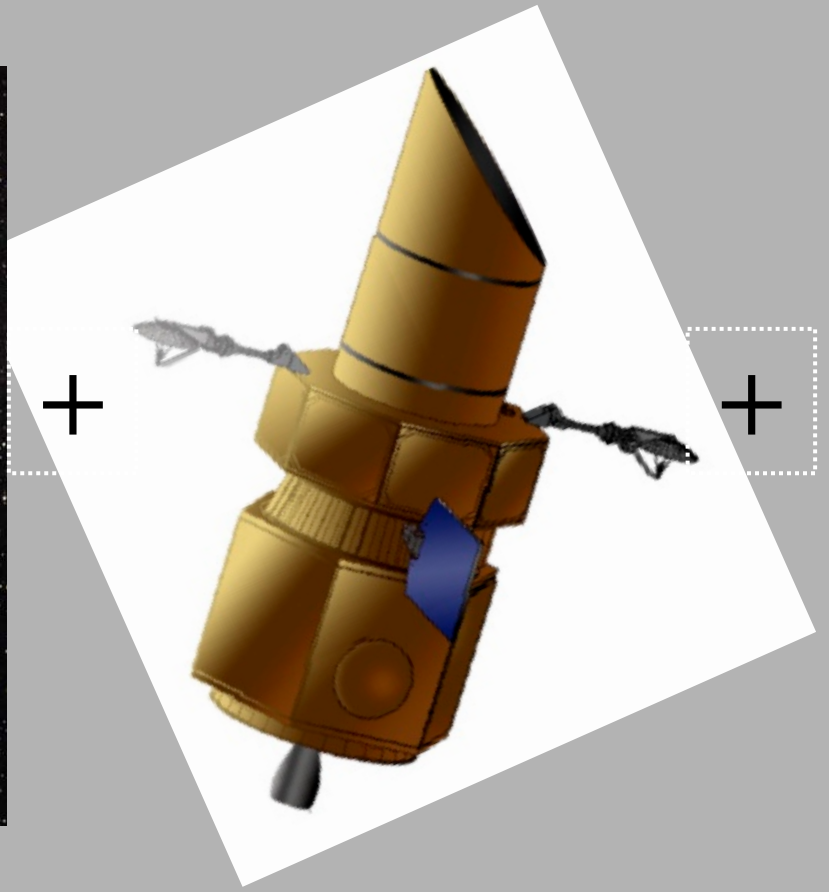


+

JDEM-Ω

MPF

NIRSS

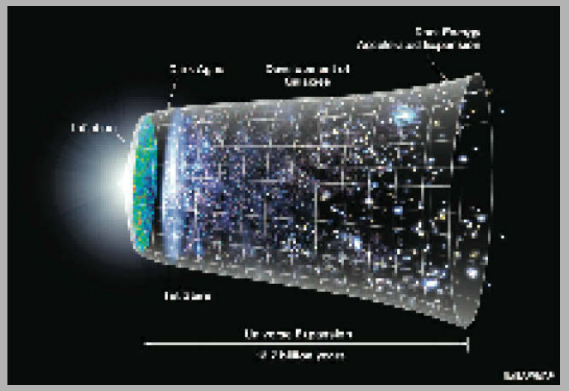
WFIRST History and Philosophy

- Several high-priority science areas required similar hardware
  - Near infrared (500nm -2+ micron) detectors w ~100Mpix
  - 1-1.5 meter mirror
  - Stable platform in space
- Most robust and capable design was from JDEM, a NASA/DOE dark energy mission
  - JDEM had several incarnations- JDEM Ω was the one chosen as a baseline
  - Imaging and spectroscopy up to 2 microns on a 1.3m telescope
- Astro2010 top large space recommendation: do WFIRST to accomplish as many of the JDEM, NIRSS, and MPF goals as possible

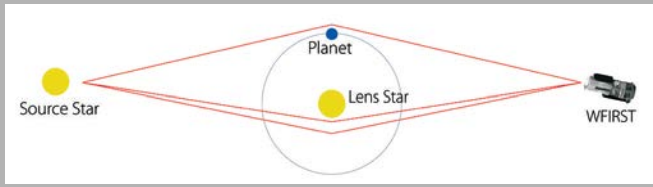
WFIRST Summary

❖ WFIRST is the highest ranked large space mission in NWNH, and plans to:

- complete the statistical census of Galactic planetary systems using microlensing
- determine the nature of the dark energy that is driving the current accelerating expansion of the universe
- survey the NIR sky for the community

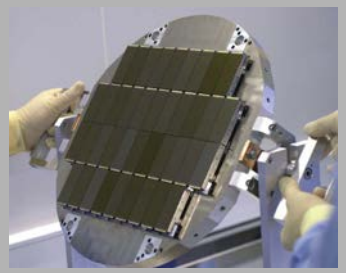


❖Earth-Sun L2 orbit, 5 year lifetime, 10 year goal



❖The current Interim Design Reference Mission has

- 1.3 m unobstructed telescope
- NIR instrument with ~36 HgCdTe detectors
- >10,000 deg^2 5-sigma NIR survey at mag AB=25



❖The time is ripe for WFIRST:

- Space-qualified large format HgCdTe detectors are US developed technology and flight ready

WFIRST Status

- Science Definition Team has delivered interim report and associated design reference mission
- Must be sold to OMB (Congress) and the OSTP (President)
- Negotiations with ESA will likely take place after Euclid downselect
- Could start an 84 month development and implementation cycle as soon as 2013 (funding permitting)

WFIRST – Science Objectives

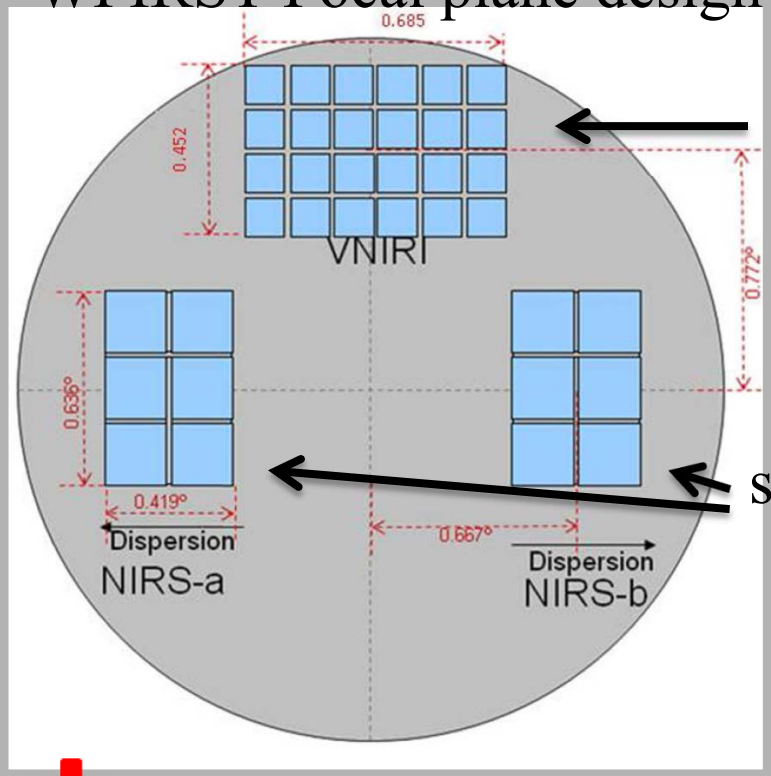
1) Complete the statistical census of planetary systems in the Galaxy, from habitable Earth-mass planets to free floating planets, including analogs to all of the planets in our Solar System except Mercury.

2) Determine the expansion history of the Universe and its growth of structure in order to test explanations of its apparent accelerating expansion including Dark Energy and possible modifications to Einstein's gravity.

3) Produce a deep map of the sky at NIR wavelengths, enabling new and fundamental discoveries ranging from mapping the Galactic plane to probing the reionization epoch by finding bright quasars at $z>10$.

WFIRST – A **Survey** Telescope

WFIRST Focal plane design

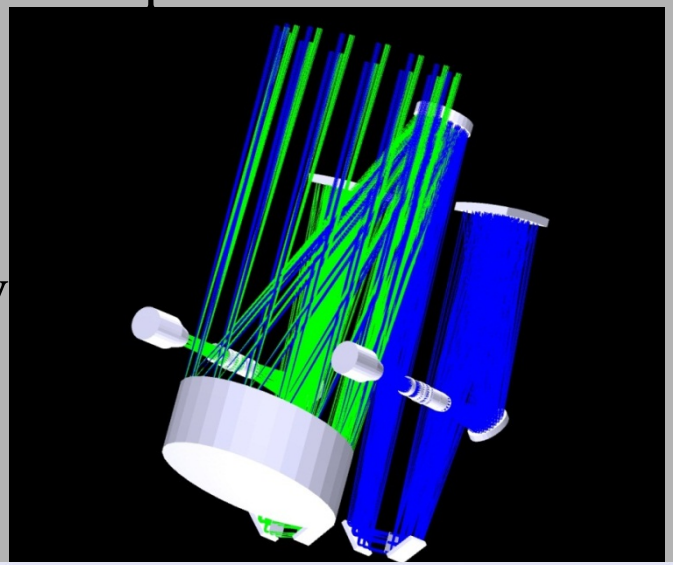


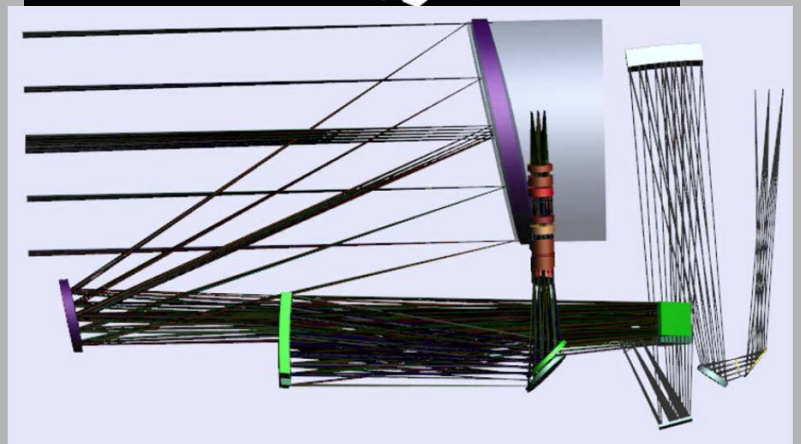
imaging

spectroscopy

Approximate HST/JWST field of view. These telescopes cannot do WFIRST wide surveys.

Off-axis design gives high throughput and excellent point spread function





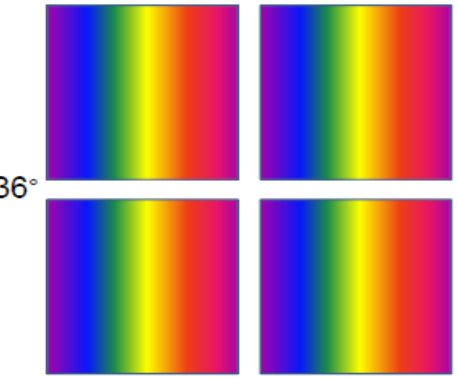
Channel field layout for WFIRST IDRM

The Fields of view of the imaging channel (ImC), spectroscopy channels (SpCs), and guiding modes (FGS) are shown to scale with the Moon, HST, and JWST. Each square is a 4Mpix vis-NIR sensor chip assembly (SCA)

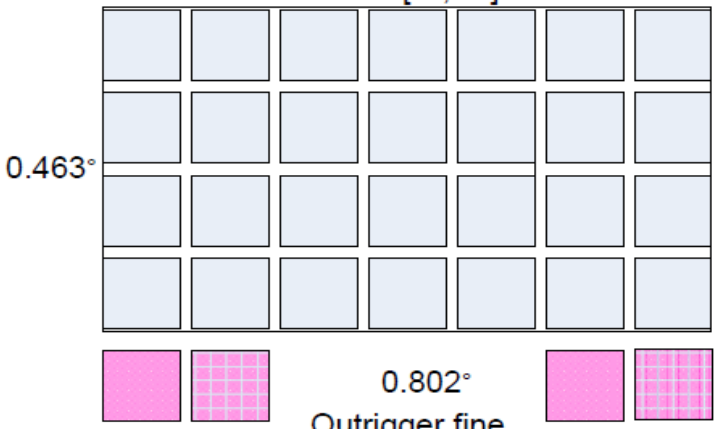
Moon (average size seen from Earth)

ImC: 7x4 @ 0.18"/p; SpC 2(2x2)@0.45"/p
[xfield center, yfield center, degrees]

SpC-B [-0.9275°,0°]

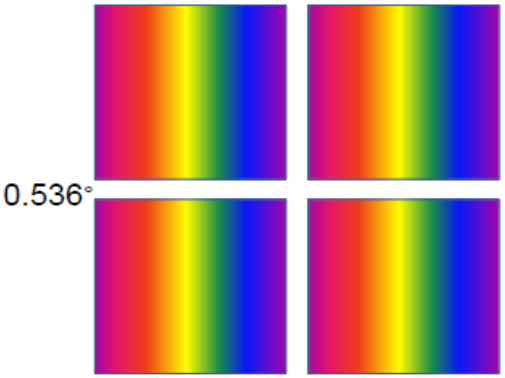


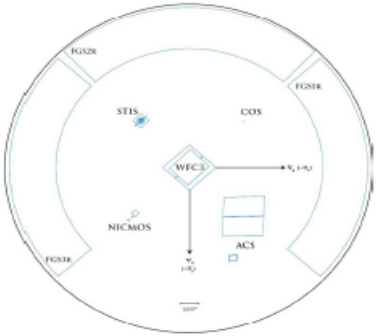
ImC: [0°, 0°]



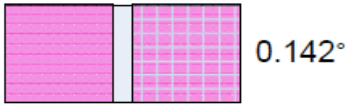
Outrigger fine guidance sensors

SpC-A [0.9275°,0°]





HST [all instruments]



Auxiliary Fine Guidance System: 2@0.25"/p [0°, -0.6°]

JWST [all instruments]

Exoplanet Survey Capability

- **Planet detection to 0.1 Earth mass (M_{Earth})**
- **Detects ≥ 30 free floating planets of 1 M_{Earth} in a 500 day survey***
- **Detects ≥ 125 planets of M_{Earth} (in 2 year orbits) in a 500 day survey***
- **Detects ≥ 25 habitable zone† planets (0.5 to 10 M_{Earth}) in a 500 day survey ***

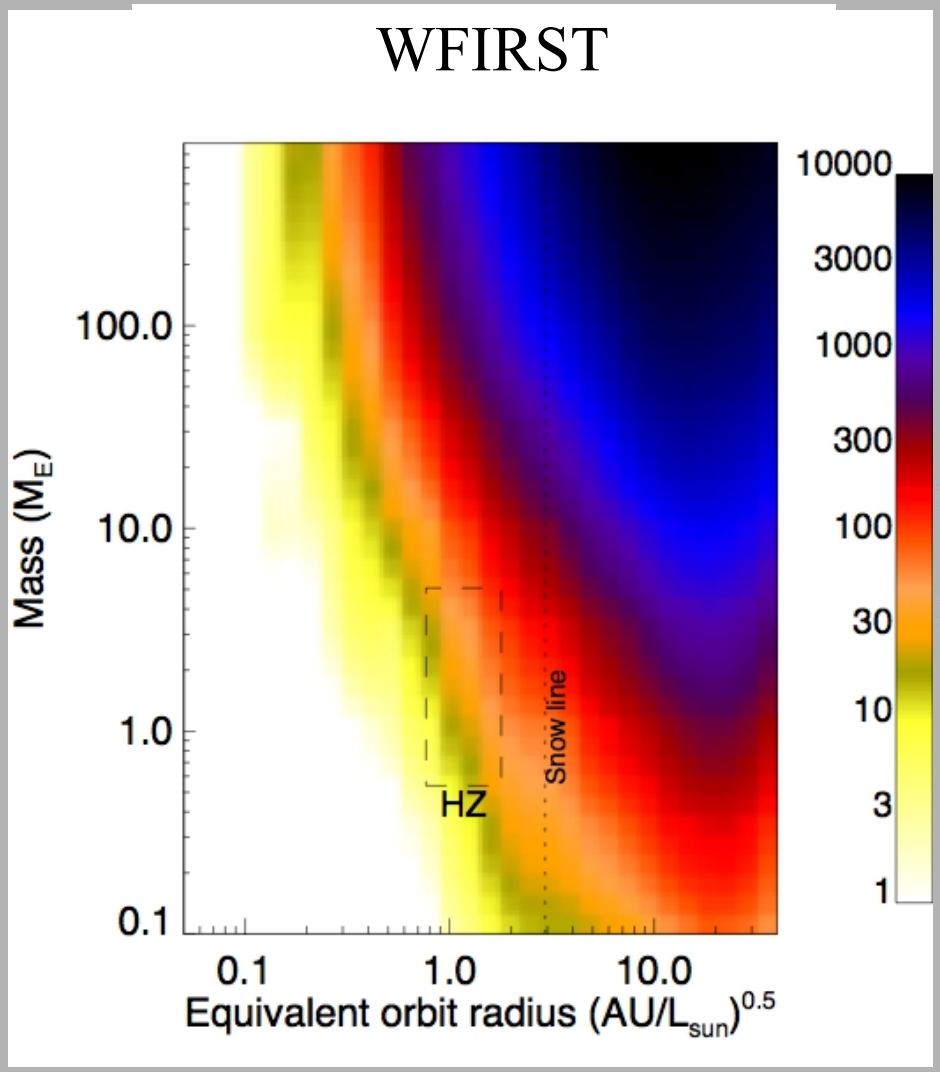
*** Assuming one such planet per star; "500 day surveys" are concurrent**

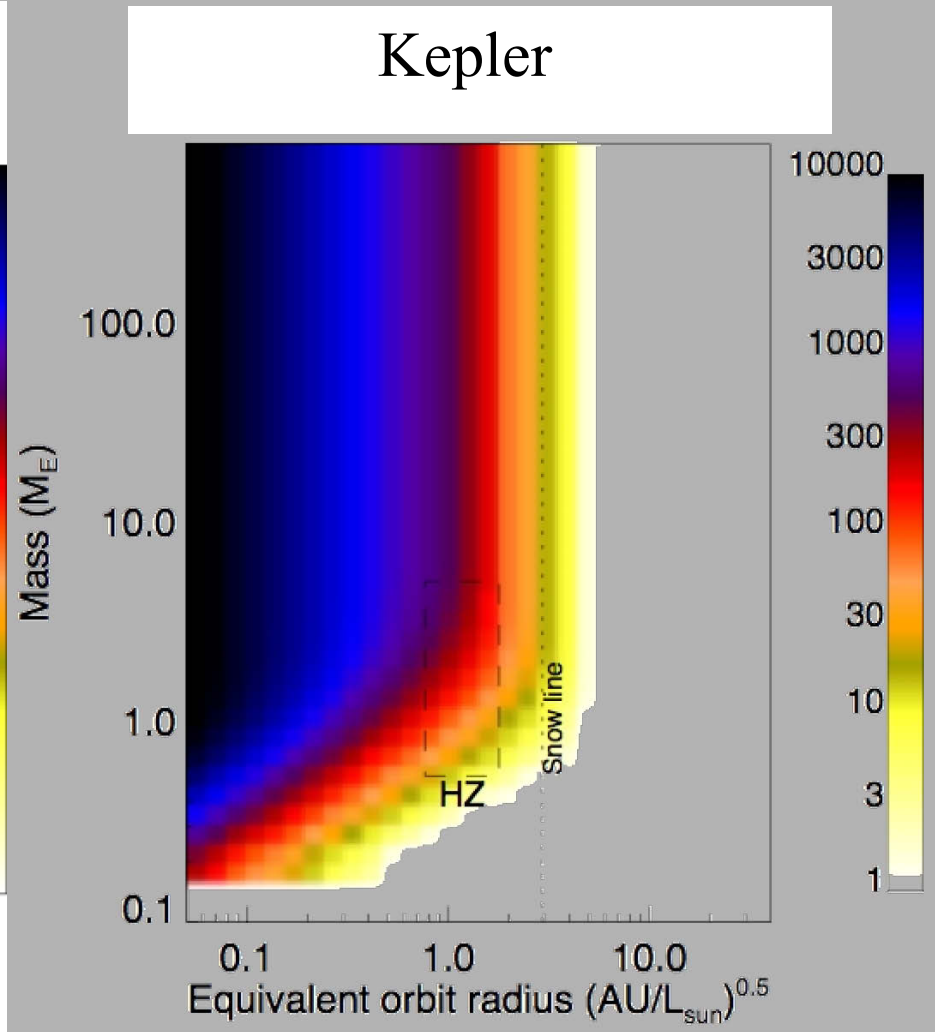
† 0.72-2.0 AU, scaling with the square root of host star luminosity

Data Set Rqts include:

✓Observe ≥ 2 square degrees in the Galactic Bulge at ≤ 15 minute sampling cadence;
✓Minimum continuous monitoring time span: ~60 days;
✓Separation of ≥4 years between first and last observing seasons.

Microlensing – Transit Comparison





Figures from B. MacIntosh of the ExoPlanet Task Force

Dark Energy Survey Capabilities

- **BAO/RSD: ... "WIDE" survey mode**
  - **11,000 deg^2/dedicated year**
  - **Redshift errors $\sigma_z \leq 0.001(1+z)$, over redshift range $0.7 \leq z \leq 2$**
- **Weak Lensing: ... "DEEP" survey mode**
  - **2700 deg^2/dedicated year**
  - **Effective galaxy density $\geq$30/amin^2, shapes resolved plus photo-zs**
- **SNe-Ia Survey:**
  - **>100 SN per Δz= 0.1 bin for most bins $0.4 < z < 1.2$, per dedicated 6 months**
  - **Redshift error $\sigma_z \leq 0.005$ per supernova**

NIR Survey Capability

- **Identify ≥100 quasars at redshift z>7**
- **Obtain broad-band NIR spectral energy distributions of ≥10^9 galaxies at z>1 to extend studies of galaxy formation and evolution**
- **Map the structure of the Galaxy using red giant clump stars as tracers**

Data Set Rqts include:

✓High Latitude data from Imager and Spectrometer channels during BAO/RSD and WL Surveys;

- Image 2500 deg^2 in 3 NIR filters to mag AB=25 at S/N=5

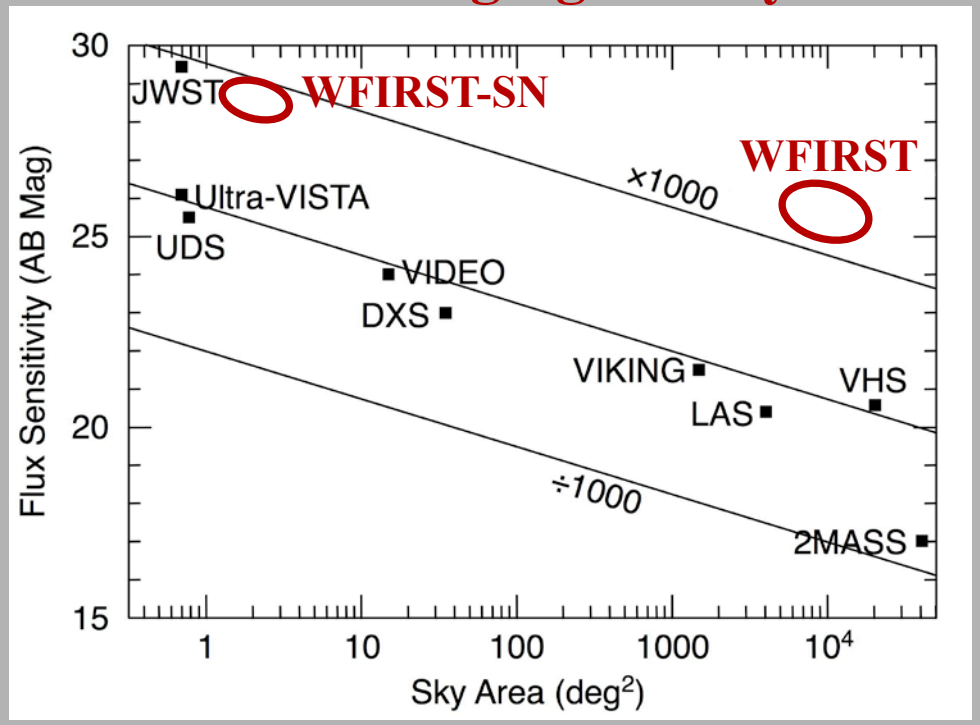
✓Galactic Plane Survey (~0.5 yr, per EOS Panel);

- Image 1500 deg^2 of the Galactic Plane in 3 NIR filters

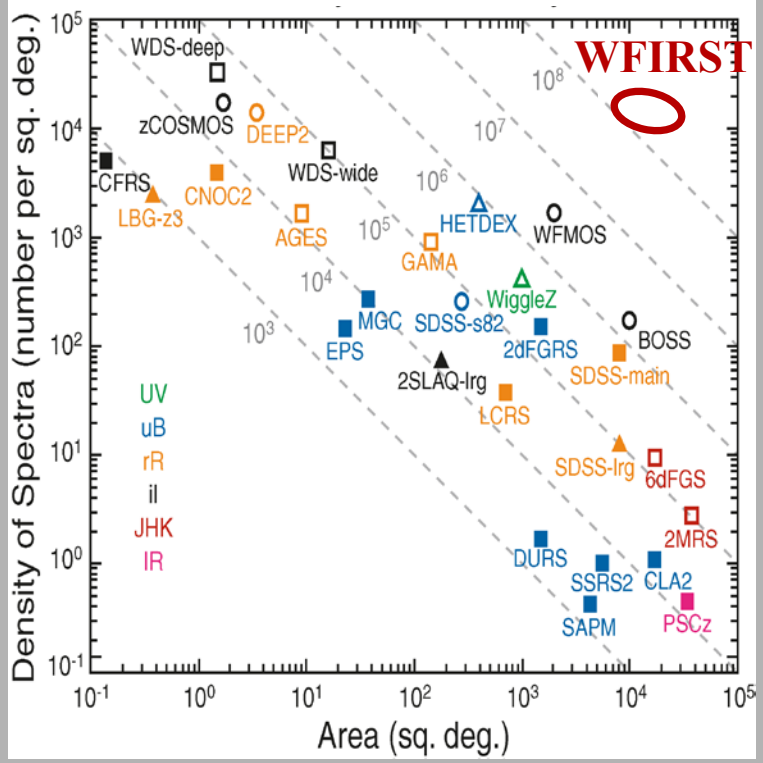
✓Guest Investigator observations (~1 yr, per EOS Panel) will supplement

WFIRST NIR Surveys

NIR Imaging Surveys



NIR Redshift Surveys



WFIRST provides a factor of 100 improvement in IR surveys

Science Return

Mission Performance: EOS Panel vs WFIRST IDRM

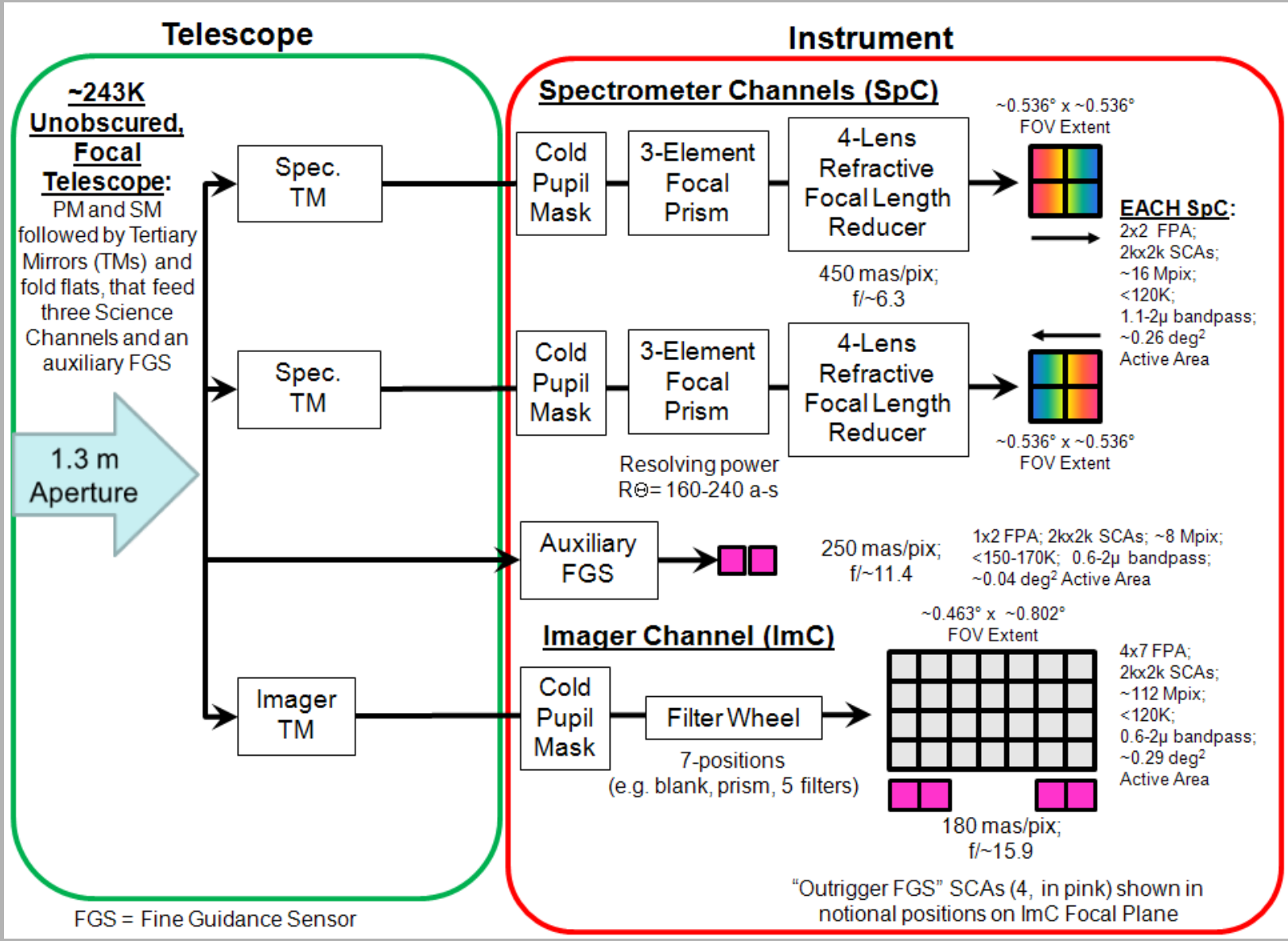
Science Investigation	EOS Panel Report	WFIRST IDRM
WL Survey	4000 deg^2	2700 deg^2/yr
BAO Survey	8000 deg^2	11,000 deg^2/yr
SNe	Not Mentioned	1200 SNe per 6 months
Exoplanet Microlensing	500 total days	500 total days
Galactic Plane Survey	0.5 yr GP Survey	0.5 yr GP Survey
Guest Investigators	1 year GI observations	1 year GI observations

Dark Energy Performance: NWNH Main Report vs WFIRST IDRM

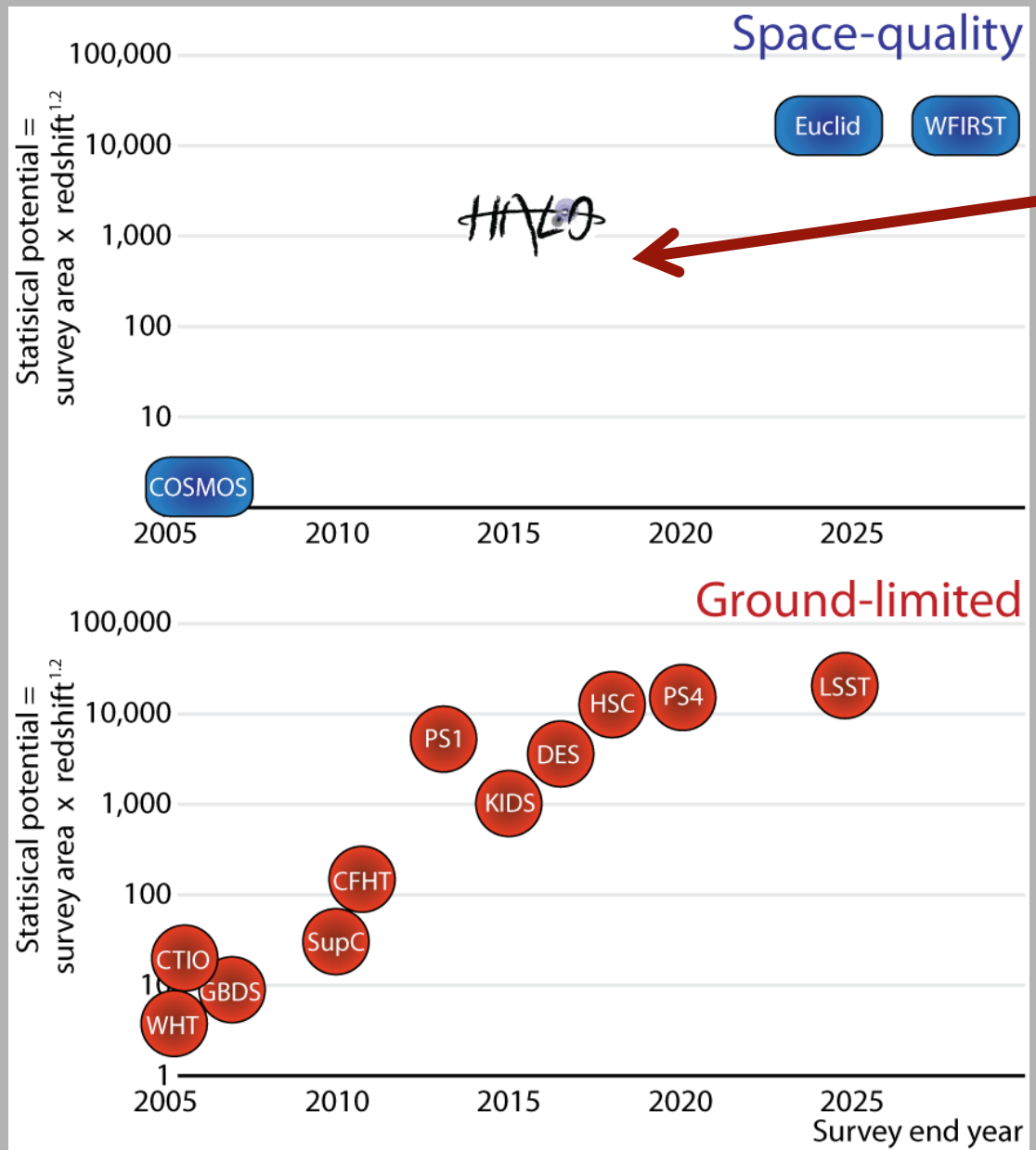
DE Technique	NWNH Main Report	WFIRST IDRM 5 yr mission	WFIRST IDRM 5 yr Dark Energy*
WL Galaxy Shapes	2 billion	300 million (1 yr)	600 million (2 yr)
BAO Galaxy Redshifts	200 million	60 million (1 yr)	120 million (2 yr)
Supernova SNe-Ia	2000	1200 (1/2 yr)	2400 (1 yr)

***Including 5 year extended mission**

WFIRST IDRM
Payload Optics Block Diagram



The future of weak lensing



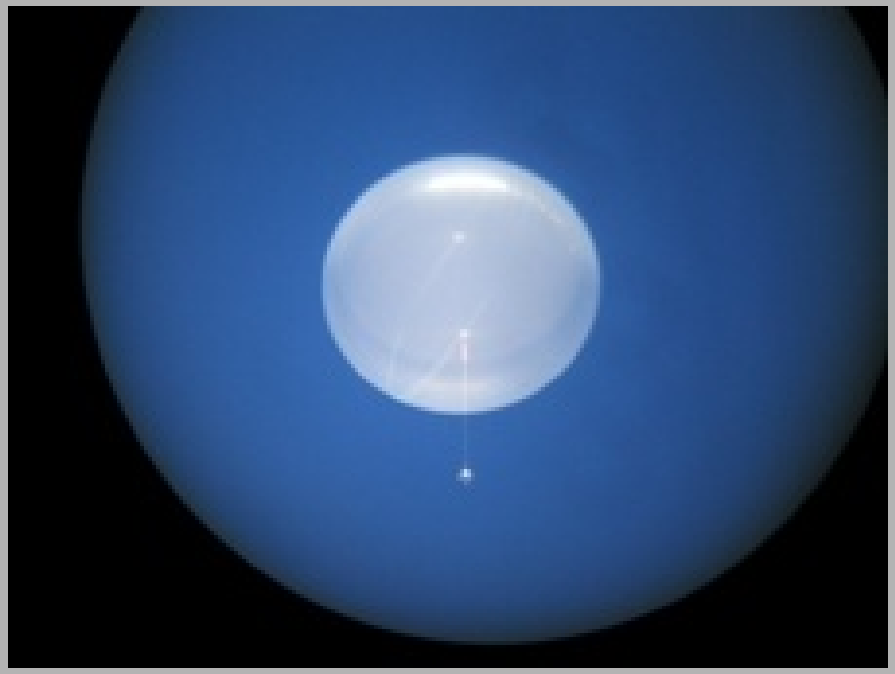
Without something here, we have a two decade gap!

Fundamentally limited by systematics

Solution: Use a Balloon

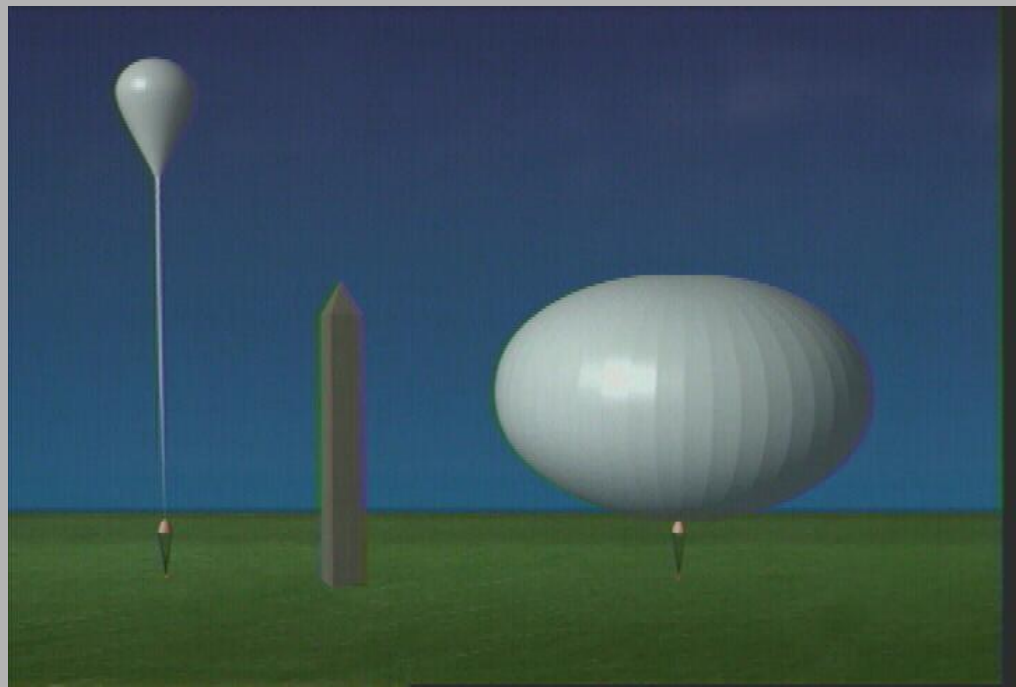
NASA's Ultra Long Duration Balloon program had a 54 day Antarctic Flight last year

Pictures courtesy Columbia Scientific Balloon Facility



ULDB- Ultra Long Duration Balloon

- Superpressure balloons require no ballast for diurnal cycle
- 7million cubic foot balloon flown (14 and 22 MCF planned)
- 14MCF have ~2000 pound payload
- 20 day circumnavigations from Australia are baselined for science within a few years
- 100 day flights are on the drawing board



http://sites.wff.nasa.gov/code820/uldb.html

High Altitude Lensing Observatory

Jason Rhodes (Principal Investigator) Jeff Booth (Project Manager)

JPL: Paul Brugarolas, Ben Dobke , Eric Jullo, Kurt Liewer, Chris Paine, Michael Seiffert, Ali Vanderveld, James Wu **Caltech**: Richard Ellis, Sergio Pellegrino, Roger Smith , Harry Teplitz(IPAC) **Wallops Flight Facility:** Raymond Lanzi, David Stuchlick, **NOAJ(Japan):** Satoshi Miyazaki **ETH Zurich:** Adam Amara, Simon Lilly, Udo Wehmeier **Edinburgh (UK):** Tom Kitching, Richard Massey, John Peacock **Durham (UK):** Ray Sharples, Paul Clark, Richrd Meyers **UKATC:** David Lunney, David Henry, Naidu Bezawada

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The Challenge

- Demonstrate weak lensing capability from a balloon

  - Requires small and stable PSF
    - Near diffraction limited
    - Thermal/mechanical control of entire system
    - Sub arcsecond pointing stability over entire exposure

- Technology exists, but must be implemented within the *cost constraints of balloon program*

HALO: The High Altitude Lensing Observatory

2011-2014

Single night flights; single detector;N2 cooling, standard balloon

Stage 1

2012-2016

Multiple flights of ~100 days; 50 CCDs; TEC cooling; ULDB; dark energy constraints

Stage 2

Partners: UK (Durham and Edinburgh),e2v(UK), Switzerland (ETH), Wallops Flight Facility (US), Caltech

Two Stages

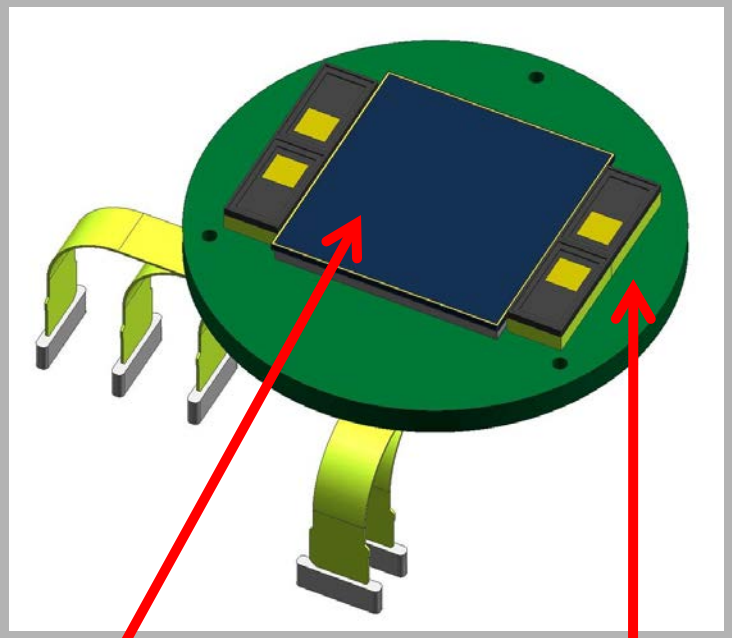
1. Stage 1 (2011-2013)
   - Technology demonstration
   - 60cm telescope w/ single science and 4 guide CCDs
   - Goals are to demonstrate capabilities
   - Two single night flights in US after 2.5 years construction
   - Strong and weak lensing of galaxy clusters
   - Enables Stage 2 and *multiple other science goals*

2. Stage 2 (2012?-2016?)
   - Constrain dark matter and dark energy properties with low systematics
   - 1.2m telescope with 50 science CCDs
   - Multiple long duration (up to 100 days each) flights

HALO- Stage 1

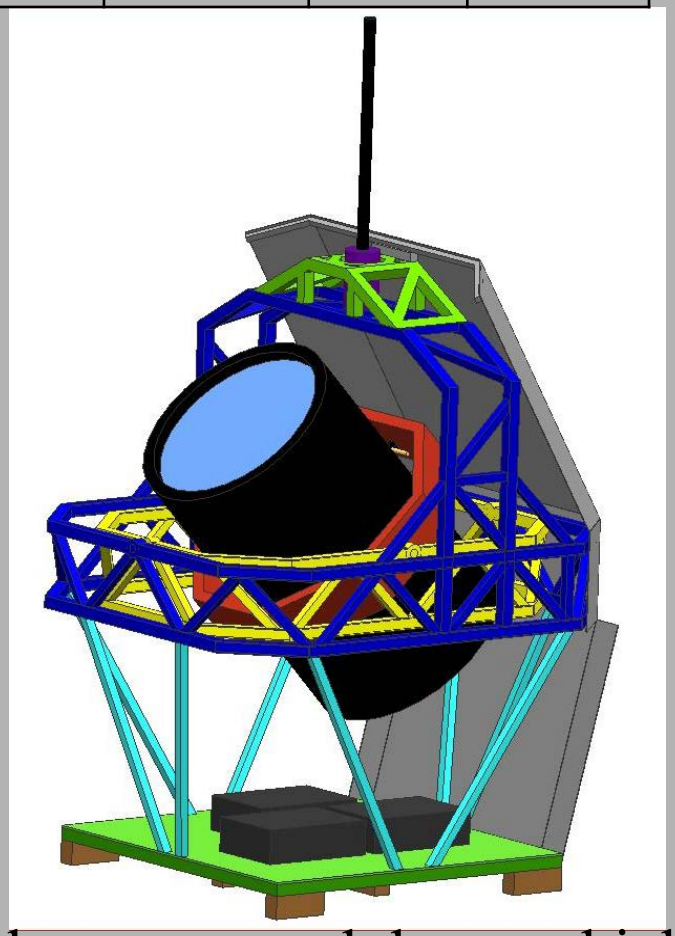
Aperture	Focal Length	Science CCD	Guide CCDs	Exposure Cadence	Filter	Flight Altitude	Data volume
60 cm	20.6 m	e2v 6kx6x CCD 15 µm device, 0.15"/pixel	4 e2v 13 µm devices, 0.13"/pixel	400 s	500–900 nm	30-35 km	25 Gb

Focal Plane



Science CCD

Guide CCDs



Telescope, gondola, sunshields

What's New

- HST and JWST have small fields of view
  - COSMOS took 10% of HST time for 2 years
  - HALO stage 1 will have a 200 arcmin^2 FOV (20 times HST/ACS)

- Sub –arcsecond pointing has been done – **with bright sources**
  - SUNRISE recently demonstrated 0.05" pointing stability
  - Stratoscope II (1970s) sub-arcsecond stability planetary observations
  - HALO will use faint guide stars, cost less than SUNRISE and be lighter than Stratoscope