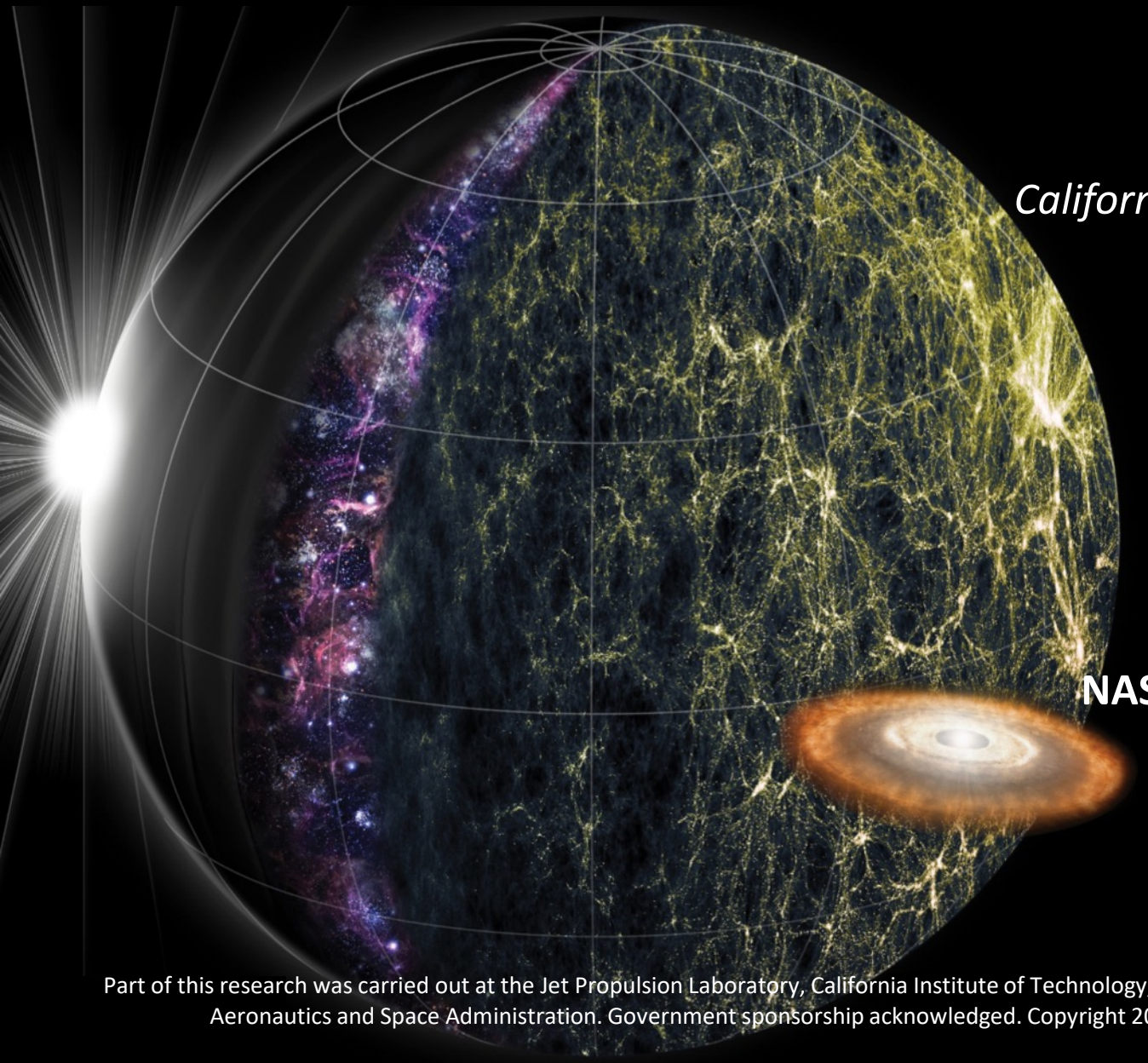
SPHEREx: Near-IR all-sky spectral survey



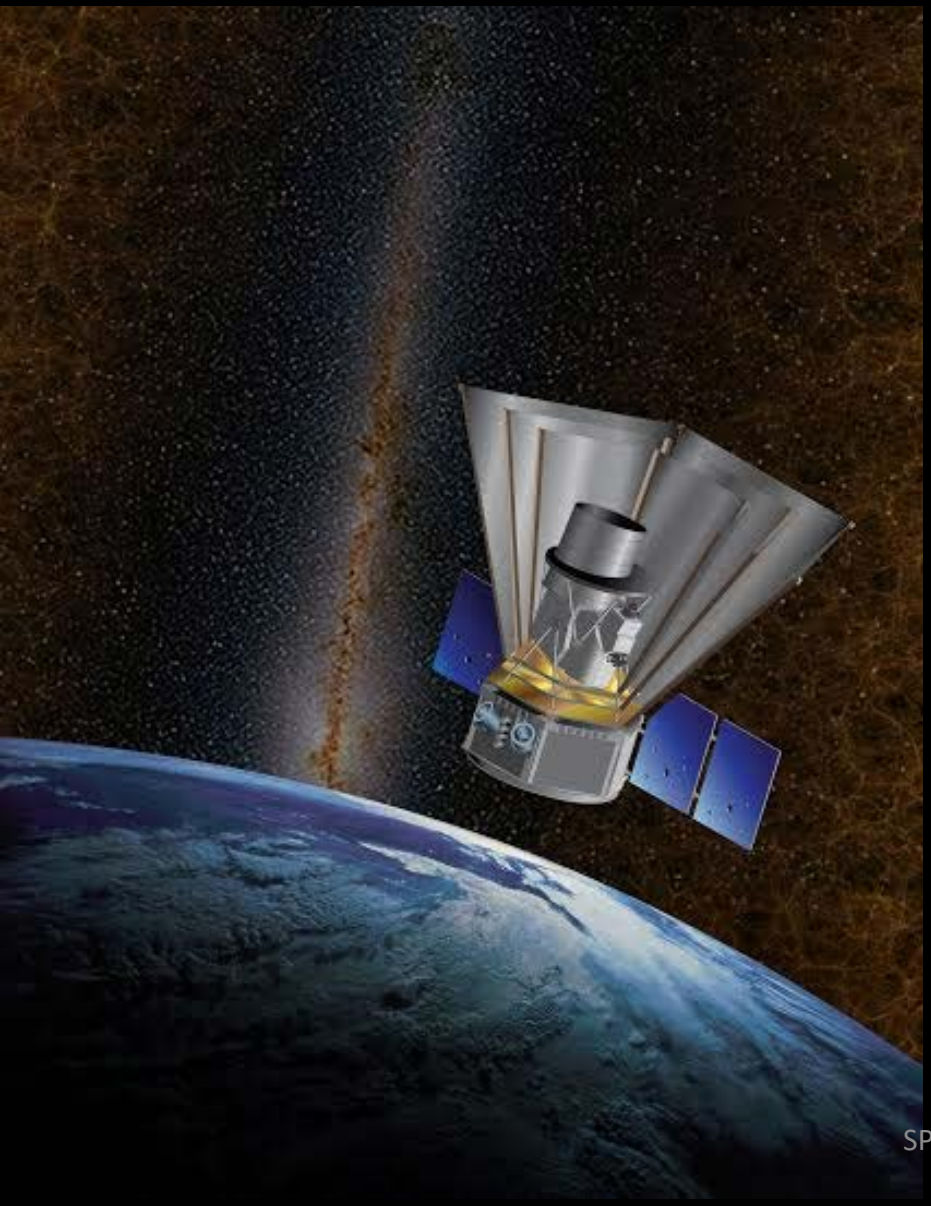
Stephen Unwin
Jet Propulsion Laboratory
California Institute of Technology

for the SPHEREx Science, Instrument, Mission & Management teams

NASA Ames Research Center
September 21, 2016

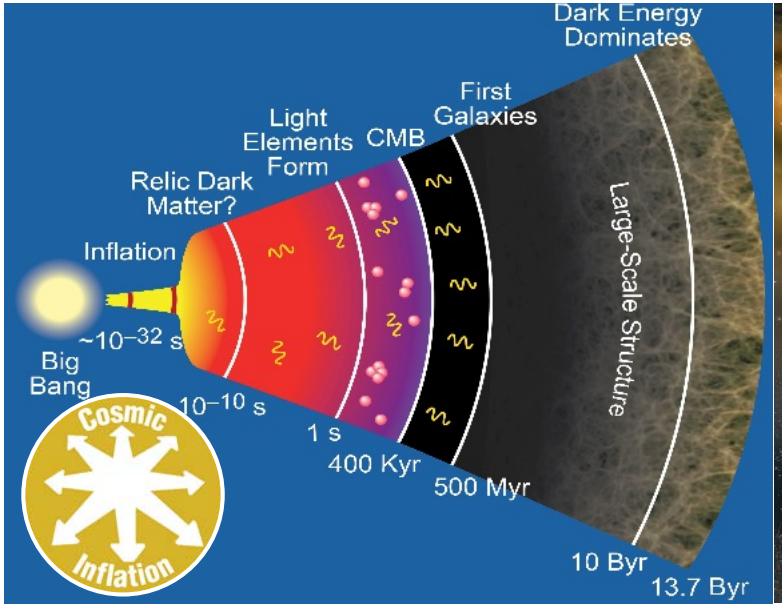
Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged. Copyright 2016. All rights reserved.

SPHEREx: An All-Sky Spectral Survey

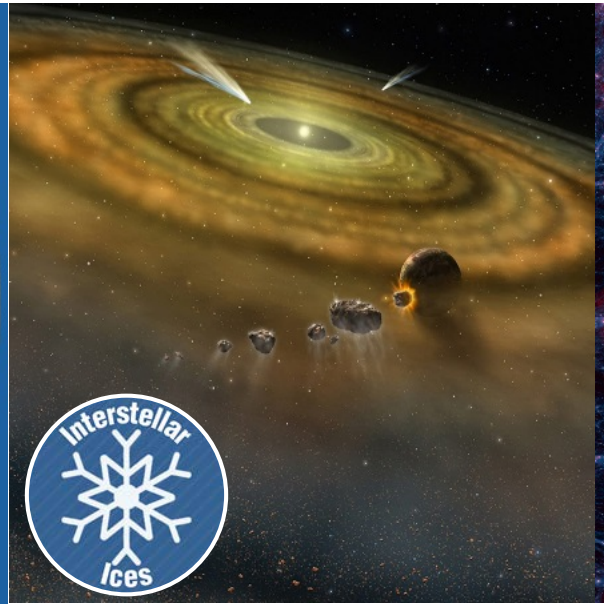


Science Goals and mission outline

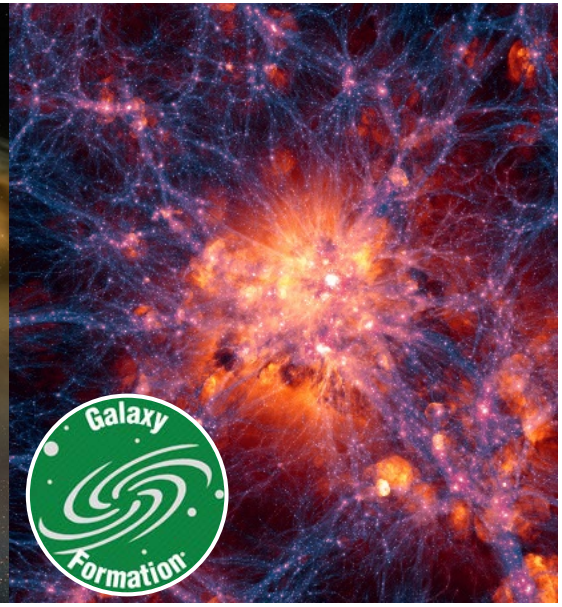
SPHEREx: Major Science Themes



Probe the earliest epochs in the Universe's history

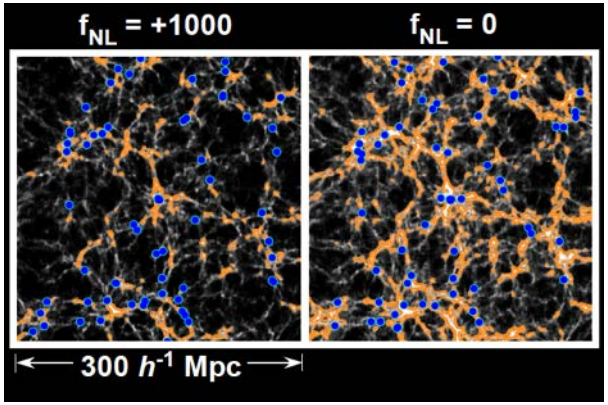


Survey the ice content in our own Galaxy.

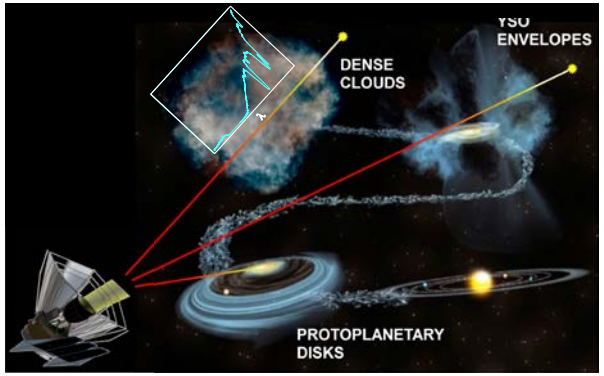


Measure the history of light production and constrain galaxy formation.

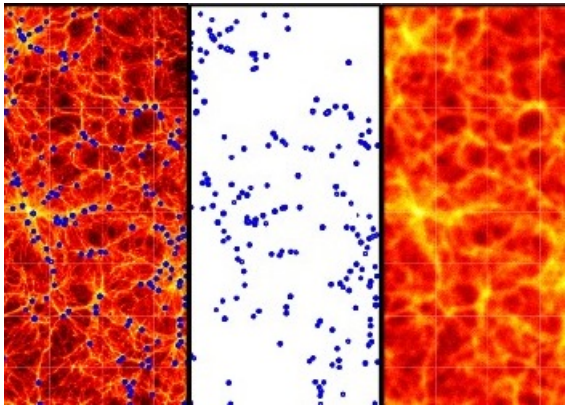
SPHEREx: Observable Signatures



F_nl is an inflation parameter which can be quantified by measuring its imprint on the 3D clustering of galaxies at late times.

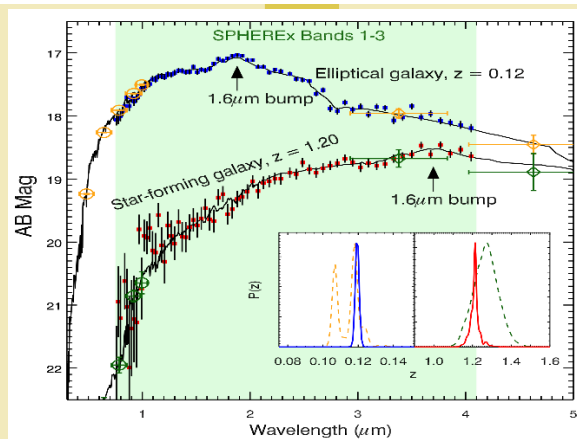


By looking along lines of sight towards stars in the Galactic plane, we can measure ice absorption features in dense clouds.

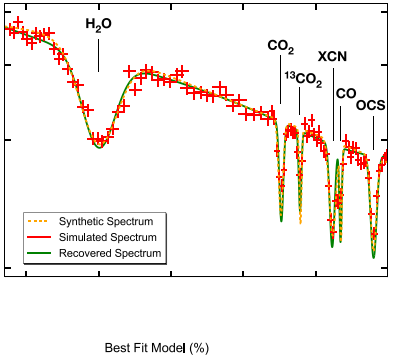


By Mapping deep regions from space with a large FOV, you can map diffuse structure as well as Galaxies.

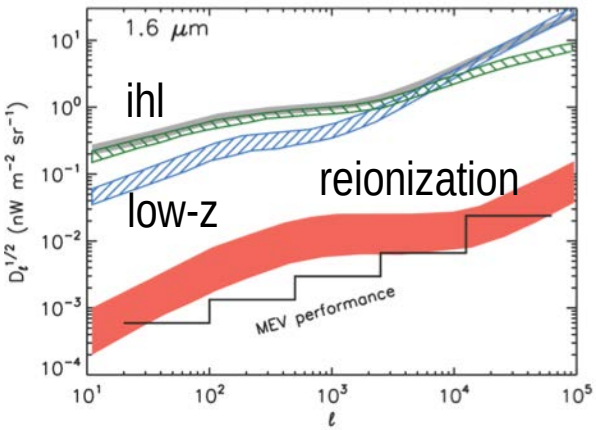
SPHEREx: Major Science Themes



Spectroscopy on the 1.6um bump allows for redshift determination of a large sample of galaxies to be used in both a power spectrum and bispectrum analysis.

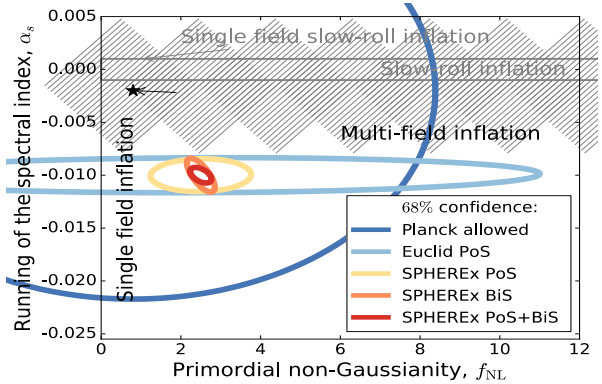


Many biogenic ice species have broad lines in the NIR and have yet to be surveyed systematically.

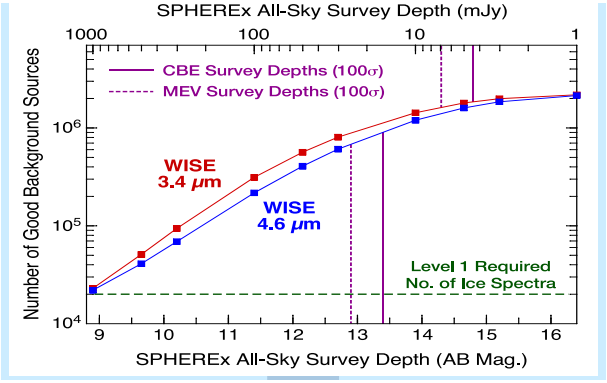


The spatial power spectrum of diffuse emission contains signal from various epochs, measuring at many wavelengths enables disentangling of the contributions.

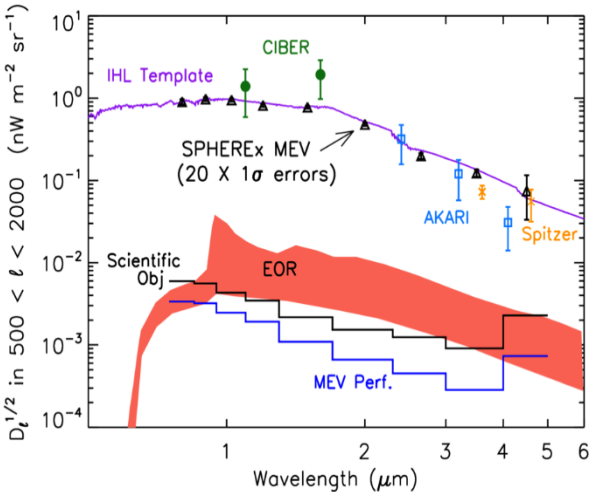
SPHEREx: Major Science Themes



Projected Constraints on f_nl compared to other experiments.



Projected number counts of ice sources.



Projected uncertainties on the amplitude of clustered signal in the spatial power spectrum.

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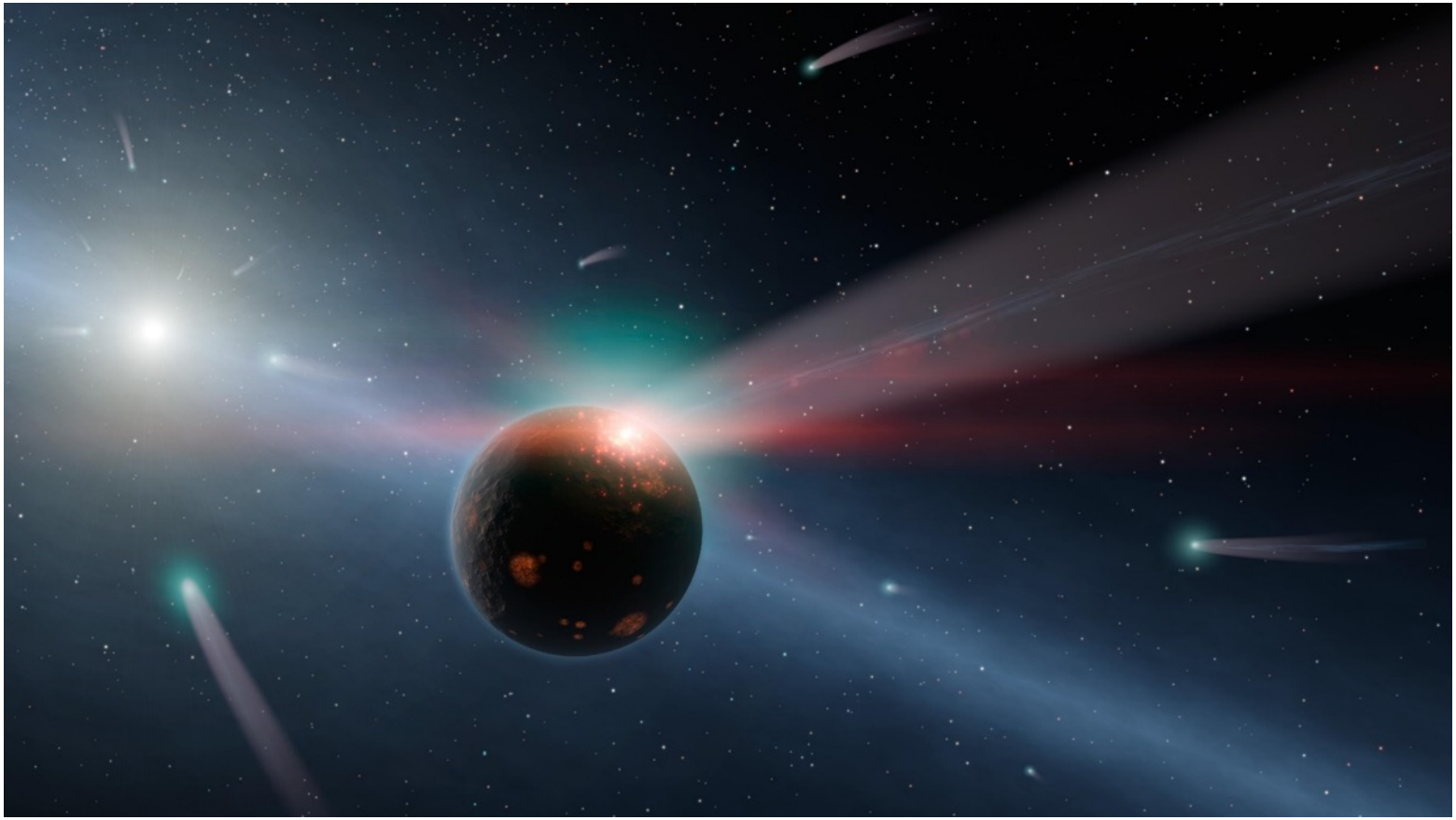
How Did the Earth's Water Originate?



Sourced by **<u>interstellar</u>** **<u>ices</u>**, rich in biogenic molecules: H_2O, CO, CO_2, CH_3OH…

Current debate: did water come from the Oort cloud, Kuiper belt or closer in?

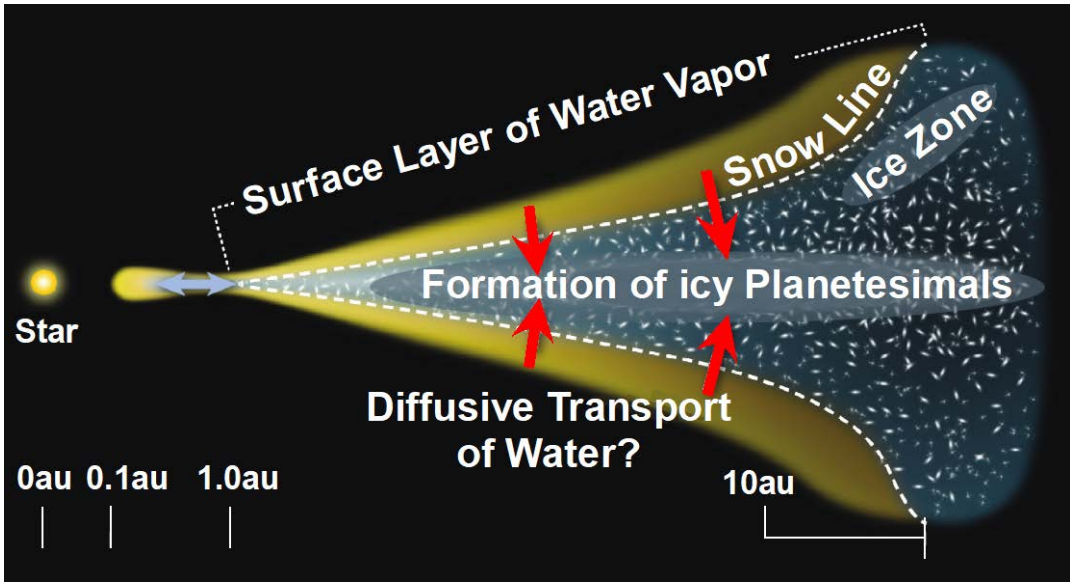
Did water arrive from the late bombardment (~500 MY) or before?

- D/H of earth's oceans is 10x solar
- D/H varies between comet families, KBOs and asteroids

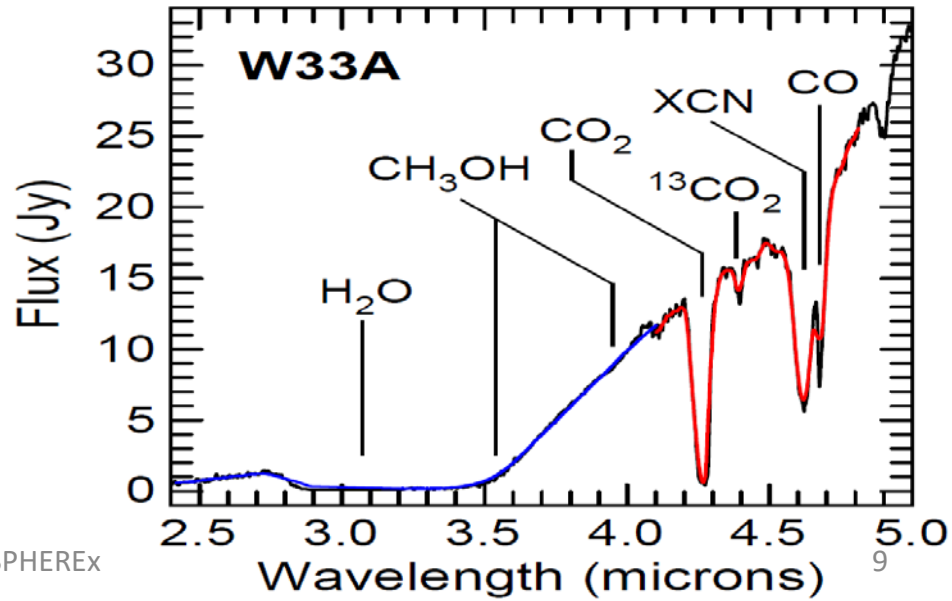
Why Study Ices?

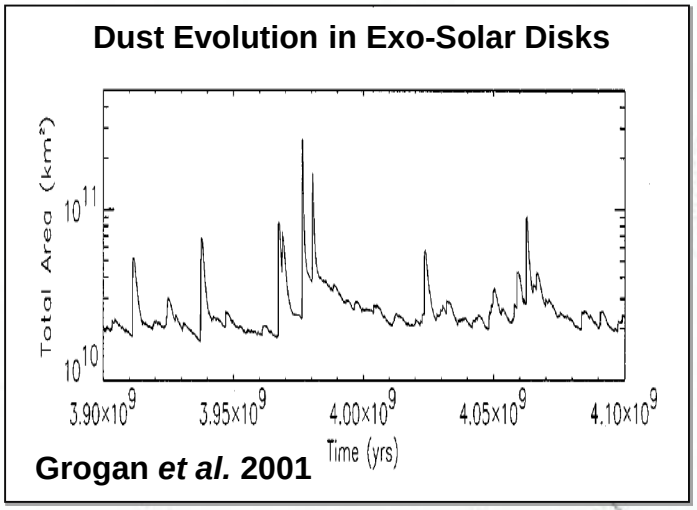
- **Gas and dust in molecular clouds are the reservoirs for new stars and planets**
  - In molecular clouds, water is 100-1000x more abundant in ice than in gas
  - Herschel observations of the TW Hydrae disk imply the presence of 1000s of Earth oceans in ice (Hogerheijde *et al*. 2011)
  - Models suggest water and biogenic molecules reside in ice in the disk mid-plane and beyond the snow line
- **Ideal λs to study ices: 2.5 - 5 μm**
  - Includes spectral features from H_2O, CO and CO_2
  - Plus chemically important minor constituents NH_3, CH_3OH, X-CN, and $^{13}CO_2$

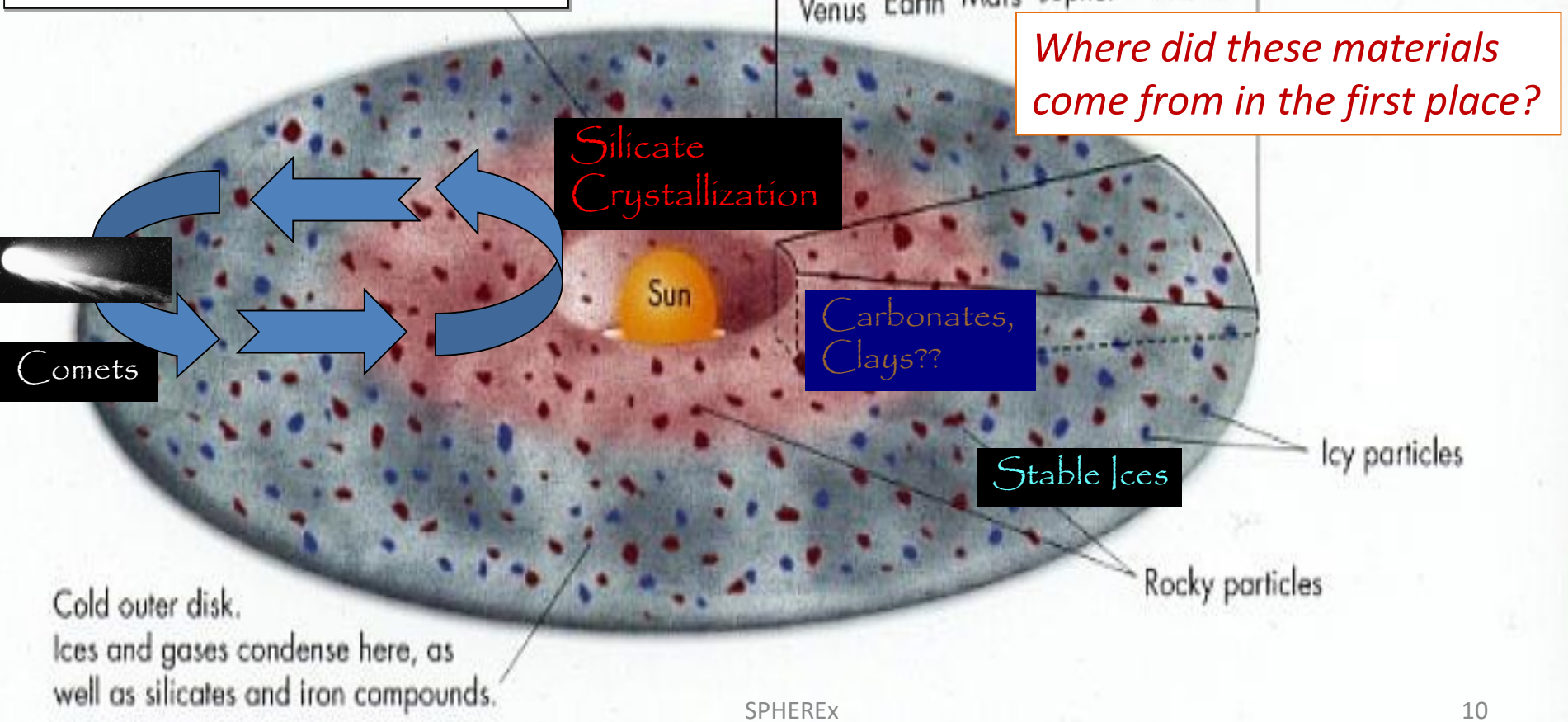
Schematic of a protoplanetary disk



ISO absorption spectrum



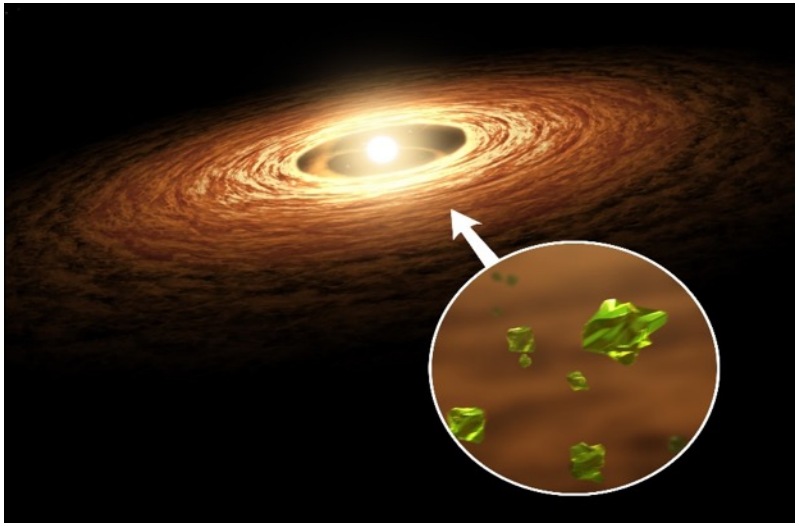




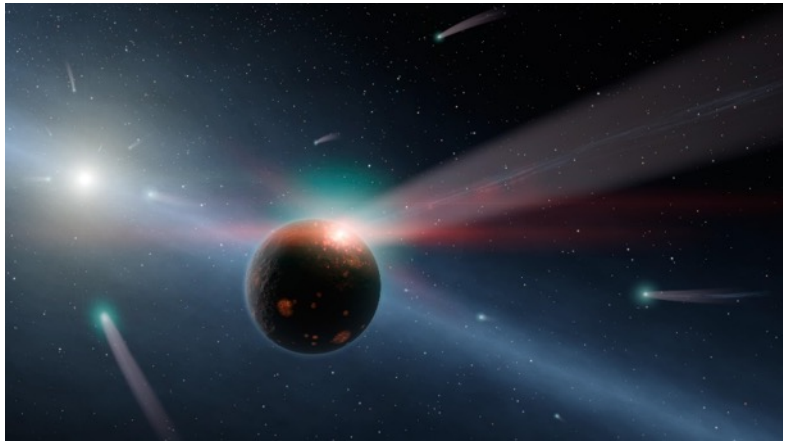
Where did these materials come from in the first place?

Dusty Disrupted Protoplanetary Disks from *Spitzer*

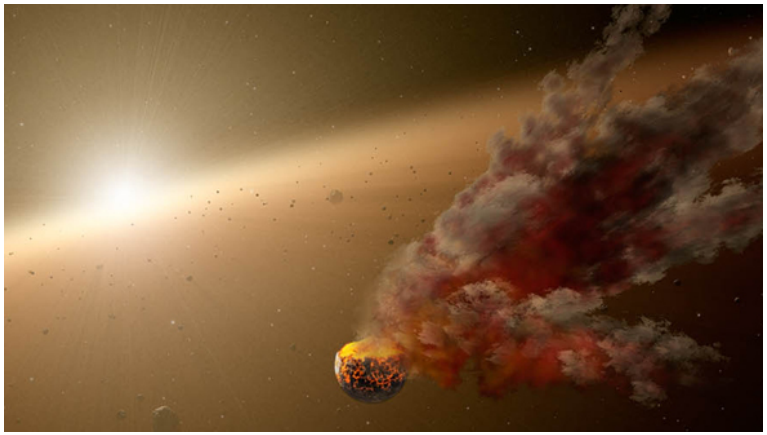
Evidence of collision event in young solar system HD 172555 based on spectra with amorphous silica and SiO (tektites)



Crystalline silicate in dust flare up of EX Lupi may indicate the production of crystals found in comets (fosterite)

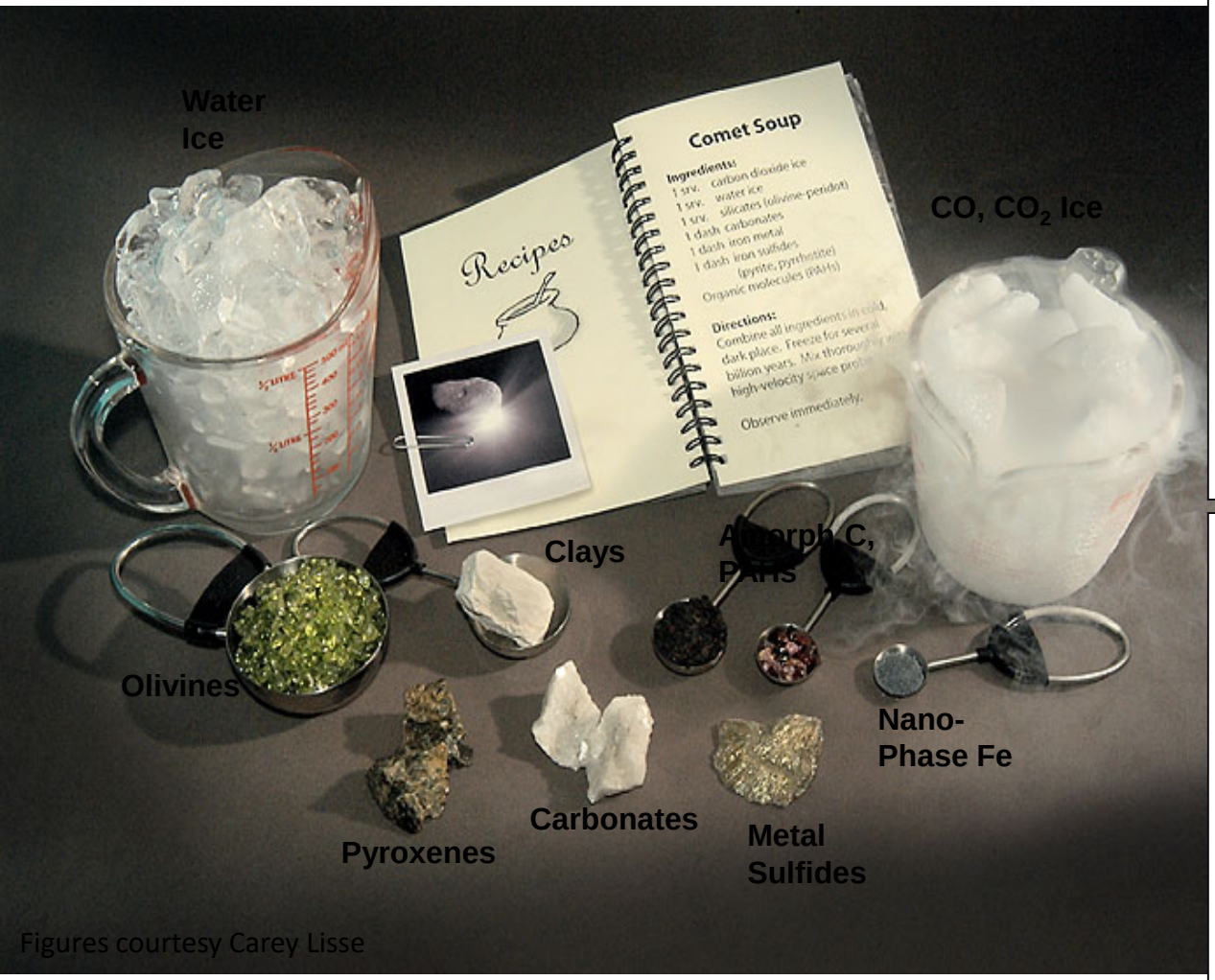


Late bombardment signature in Eta Corvi (H_2O ice, silicates, organics, ala KBO)

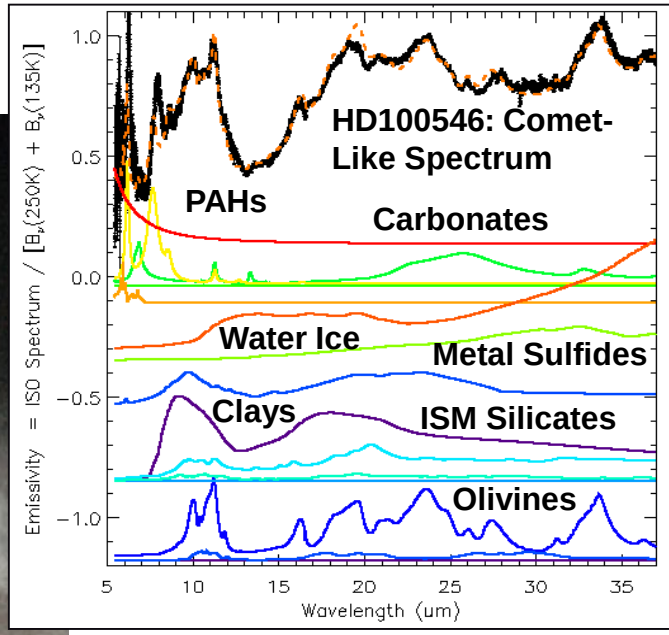


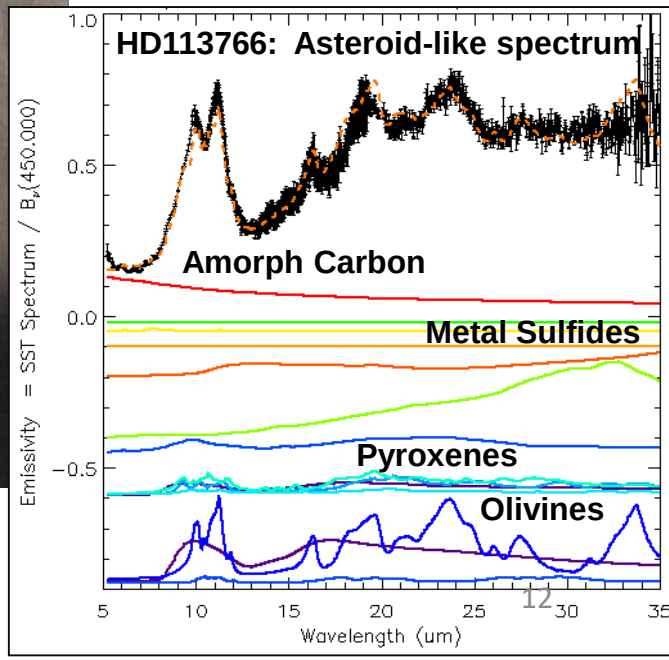
Dust flare-up in star NGC 2547-ID8 recently detected as a transient event

What is Going on in Disrupted Disks? Spectroscopy is Key



Figures courtesy Carey Lisse





SPHEREx will Determine the <u>Ice</u> <u>Properties</u> of such Protoplanetary Disk Systems

SPHEREx Galactic Ice Survey

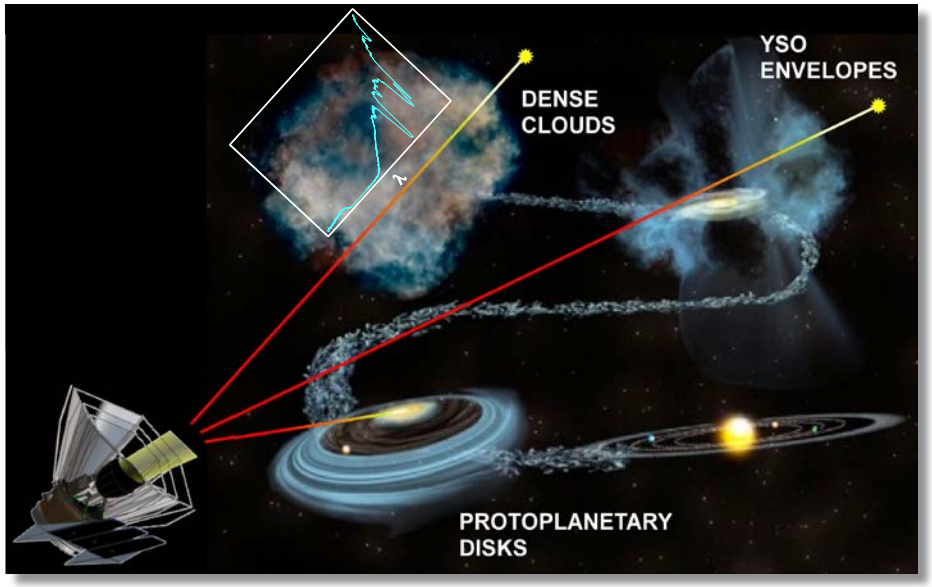
SPHEREx will be a game changer to resolve long-standing questions about the amount and evolution of key biogenic molecules through all phases of star and planet formation

- SPHEREx increases the number of ice spectra from ~200 to >> 20,000
- Band 4 spectral resolving power $\lambda/\Delta\lambda$ = 150 chosen to isolate the absorption from each ice species

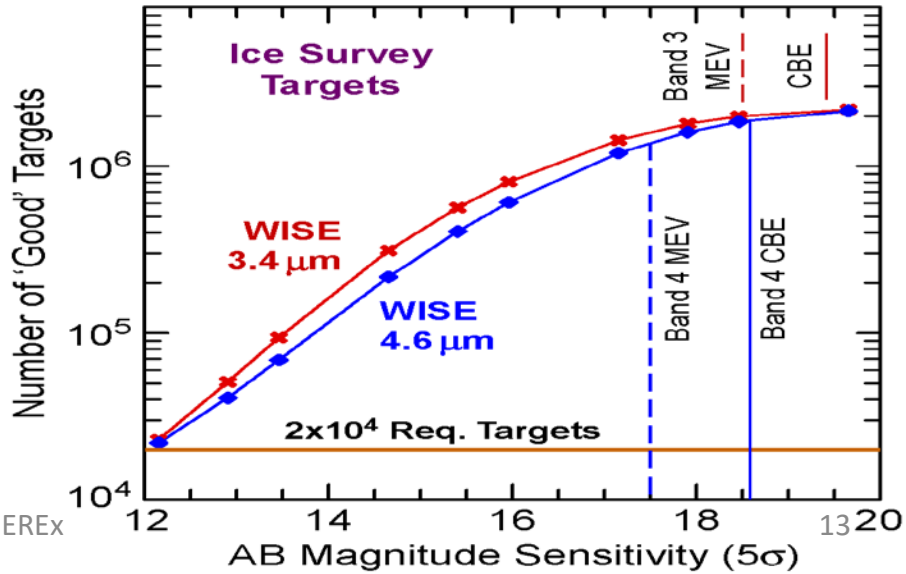
The SPHEREx ice catalog will:

- Contain molecular clouds, YSOs, and 1000s of protoplanetary disks
- Determine the role of environment (T, n, radiation field, cosmic rays) in forming ices
- Determine if ices in disks come from the parent cloud or are reformed
- Measure the abundance of water and biogenic ices in disks that is available to new planets

Ices in each Phase of Star Formation



One Million Targets with |b| < 1°



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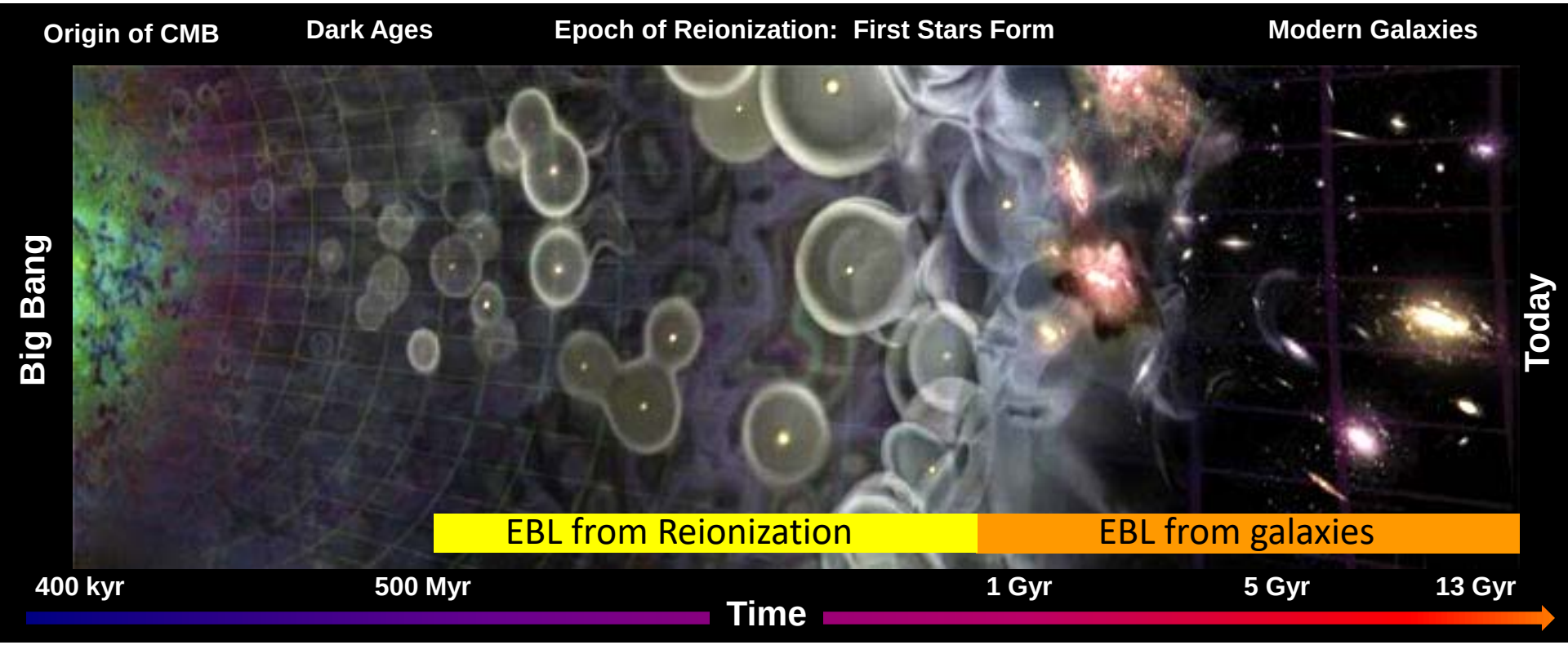
Why Study the Extragalactic Background Light?



Epoch of Reionization

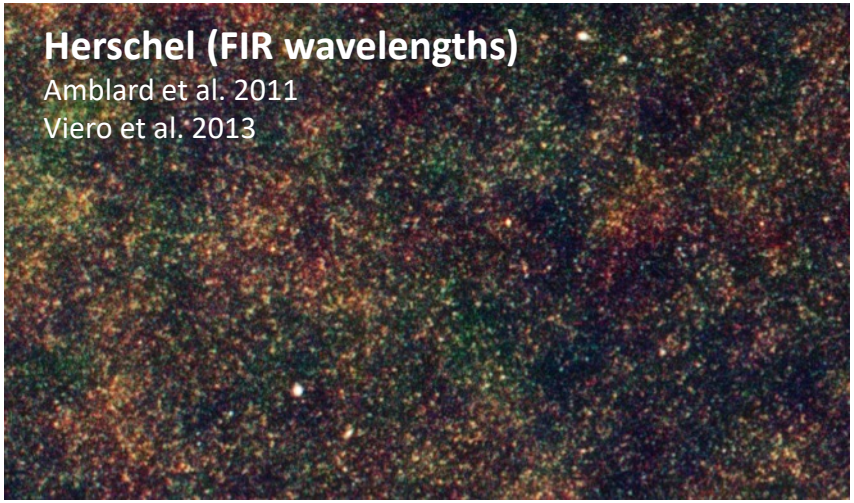
When did it begin?
When did it end?
What were the first sources like?

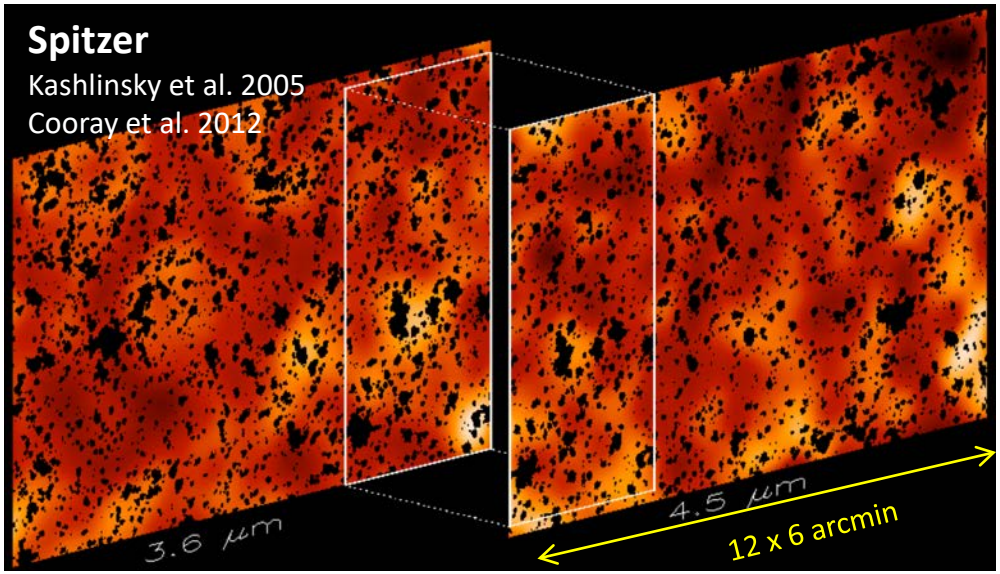
Observables

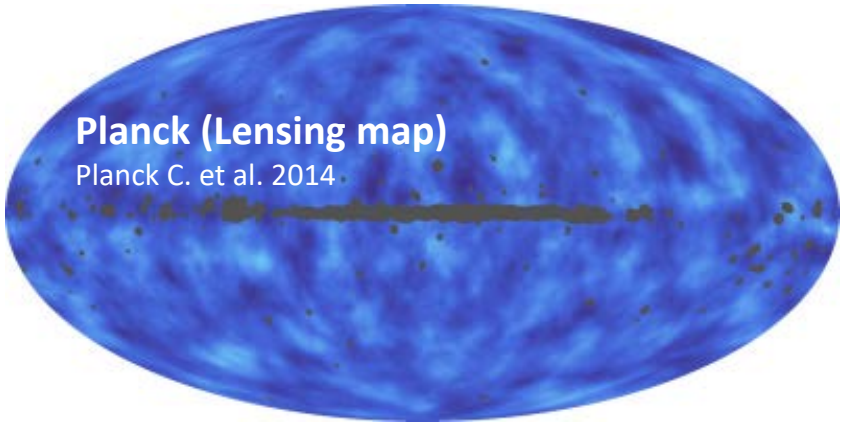
Free Electrons: Scatter CMB photons
Neutral Gas: HI 21 cm, Ly absorption
Galaxies: Stellar light, line emission

Problem with Absolute Photometry: Foregrounds!

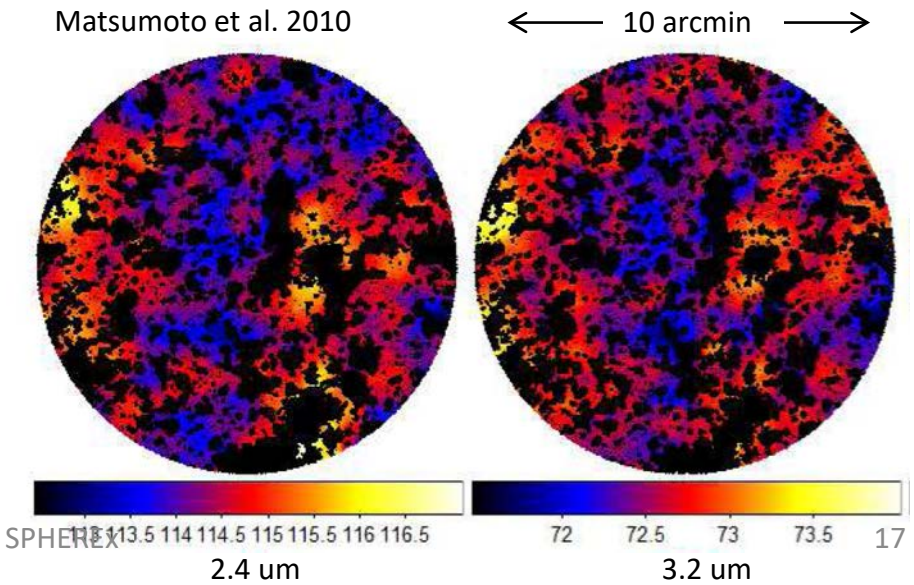
Instead: Probe EBL by Studying *Spatial Variations*







Akari
Matsumoto et al. 2010

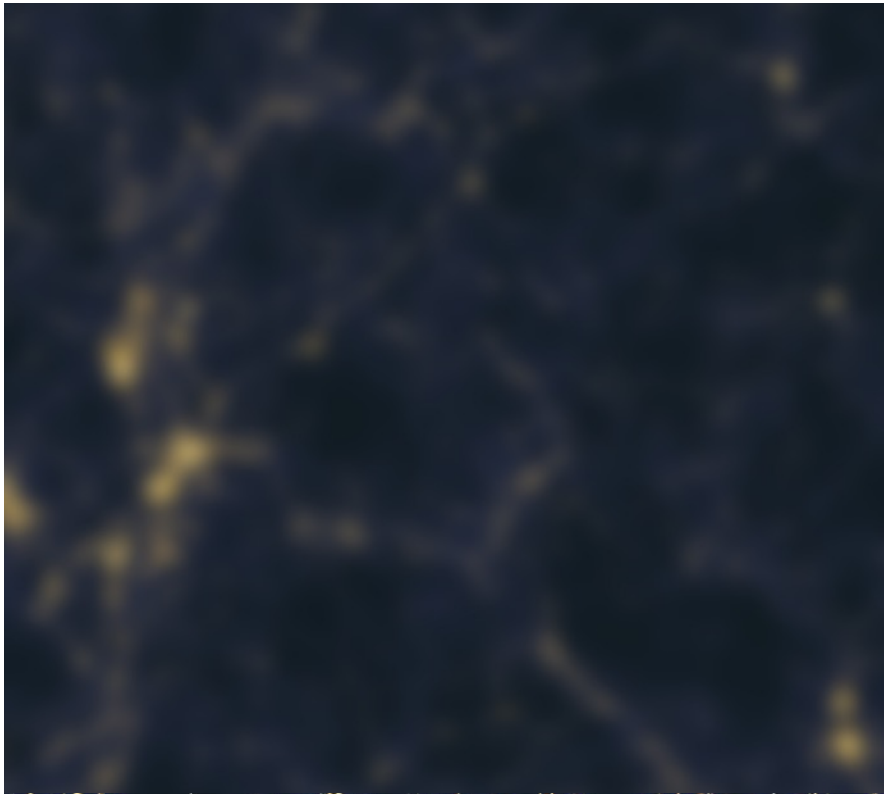


Successful Applications at Longer Wavelengths

- Herschel EBL: Viero et al. 2013
- Planck EBL: Planck C. et al. 2013
- Planck EBL x CMB Lensing: Planck C. et al. 2014
- Herschel EBL x CMB Lensing: Many

Measuring Cosmic Light Production

Two Ways to Measure Cosmic Light Production



1) Individual Galaxies & Redshifts

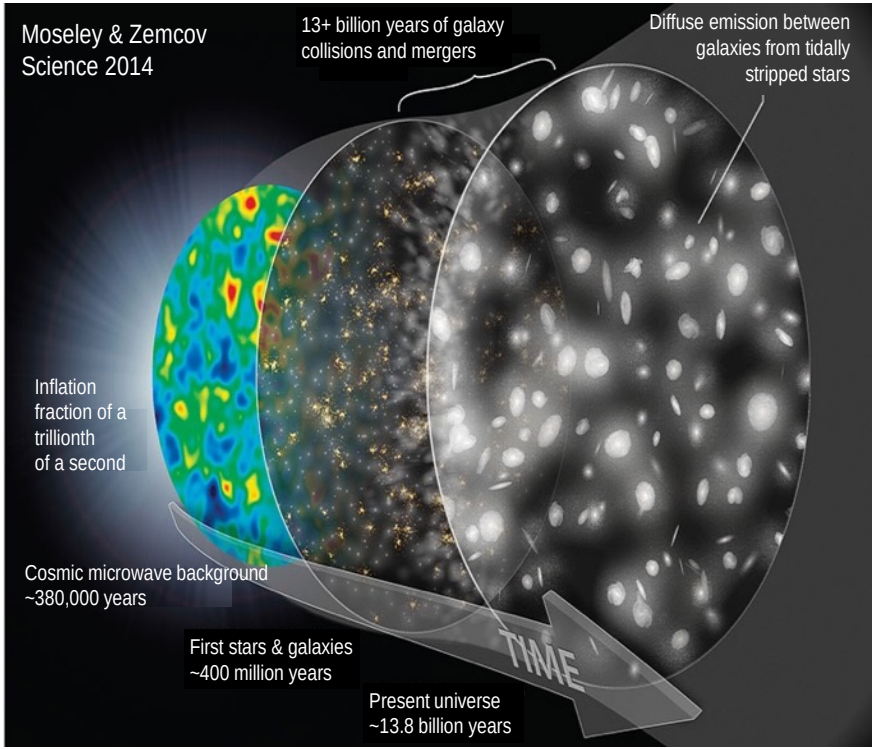
Large telescope for point source sensitivity

2) Large-Scale Patterns in the Background

Small telescope with fidelity on degree scales

→ the **amplitude** of large-scale (clustering) fluctuations proportional to **total light production**

What Constitutes Cosmic Light Production?



1) Photon Production in Galaxies

Nucleosynthesis & black holes, peaks at z ~ 2

2) First Stars and Galaxies

Epoch of Reionization z > 6

3) Intra Halo Light

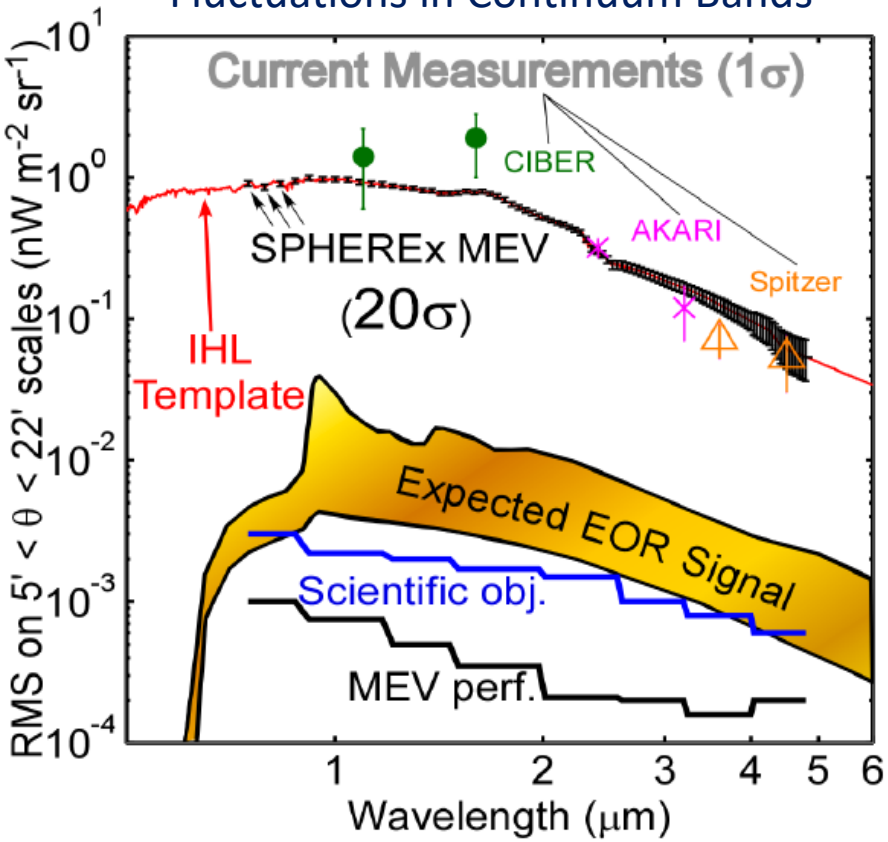
large telescope for point source sensitivity

4) Surprises?

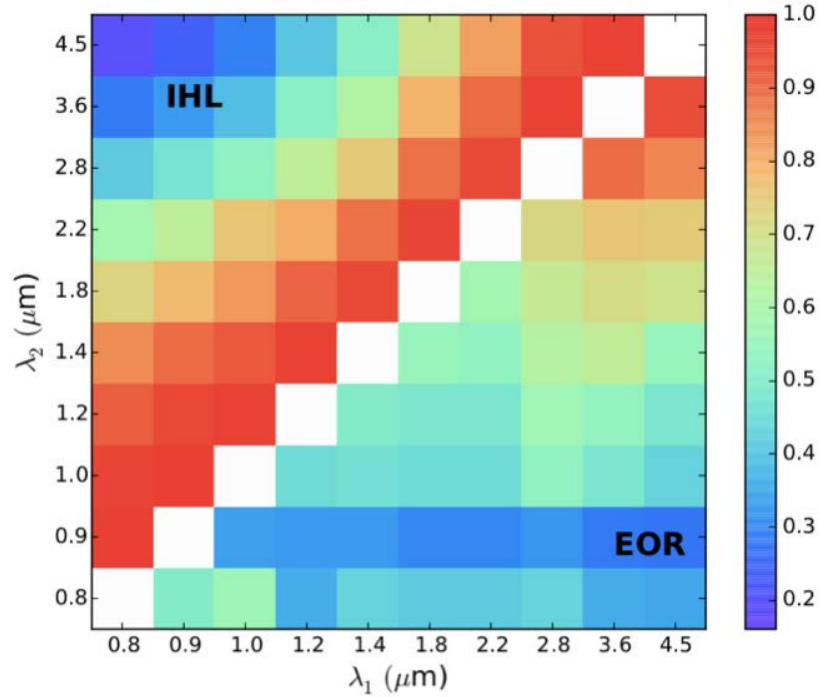
E.g. Light from particle decay

SPHEREx Measures Large-Scale Fluctuations

Fluctuations in Continuum Bands



Separating the components



Wavelength cross-correlation structure for the Intra-Halo Light (IHL) and EOR components

- SPHEREx has ideal wavelength coverage and high sensitivity
- Multiple bands enable correlation tests sensitive to redshift history
- Method demonstrated on Spitzer & CIBER

- Calculated at multipole ℓ=1000 for 10 broad photometric bands
- Exploiting these distinct correlation structures at many multipoles enables separating these signals

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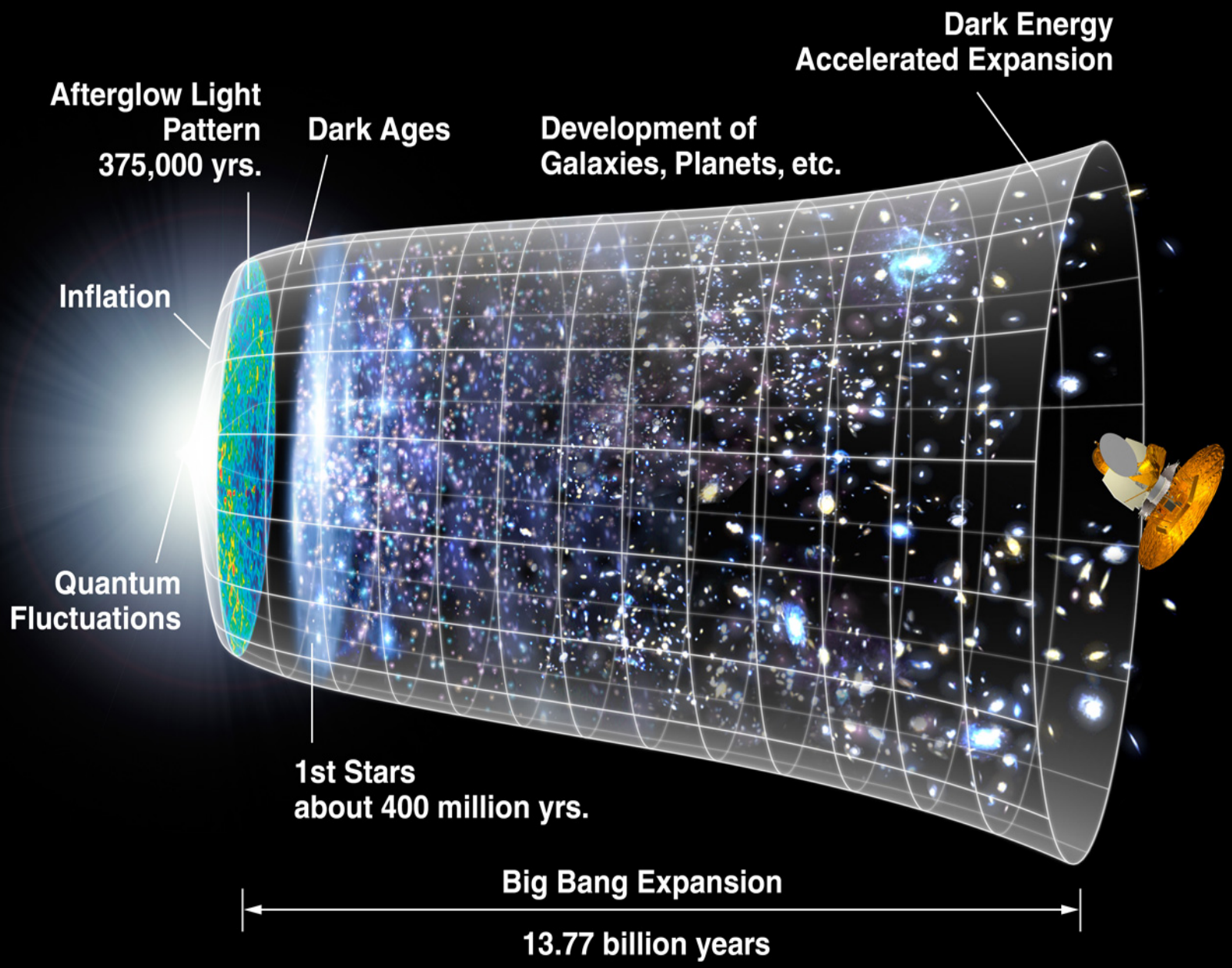
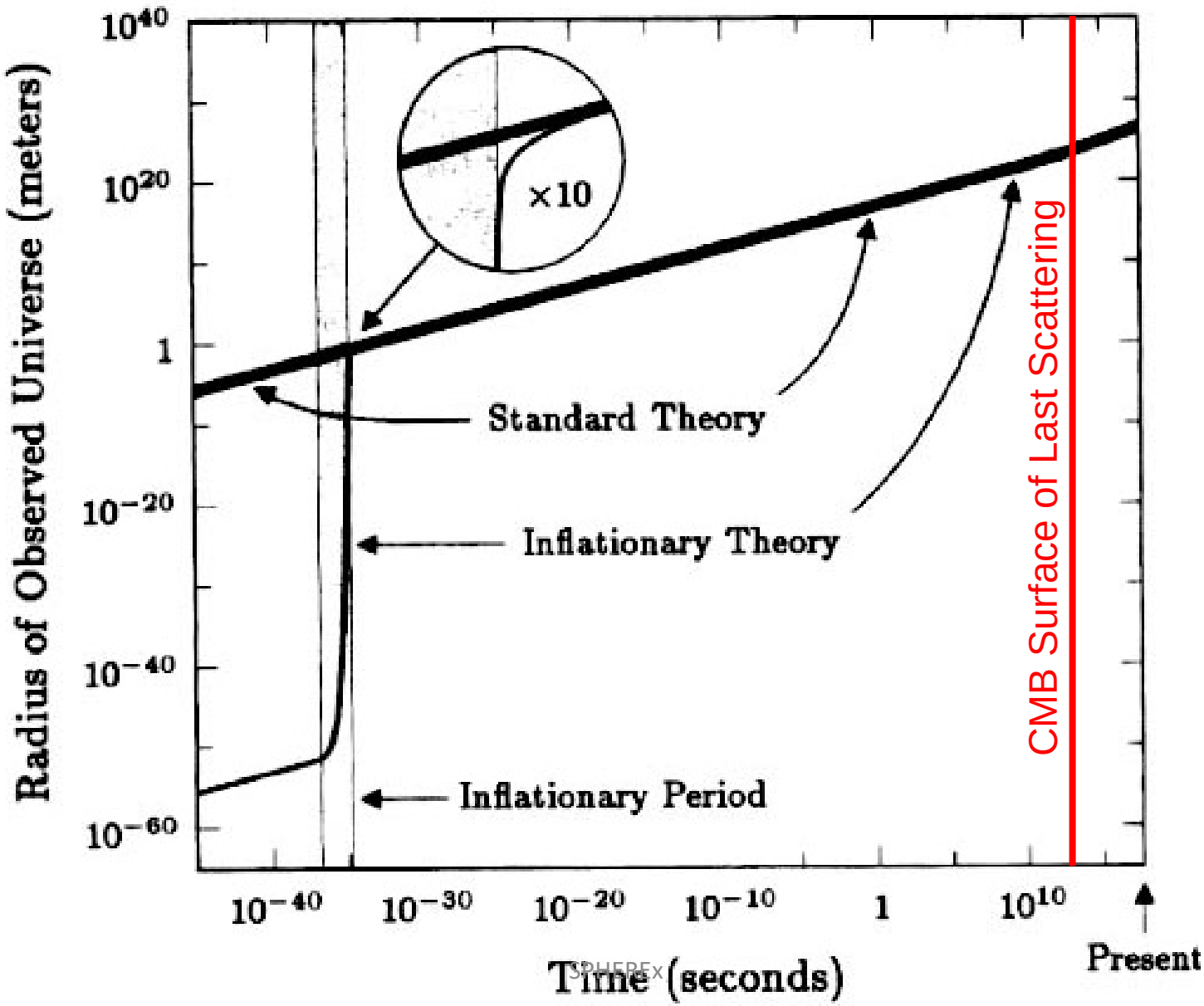


NASA/WMAP Science Team

The Remarkable Theory of Inflation

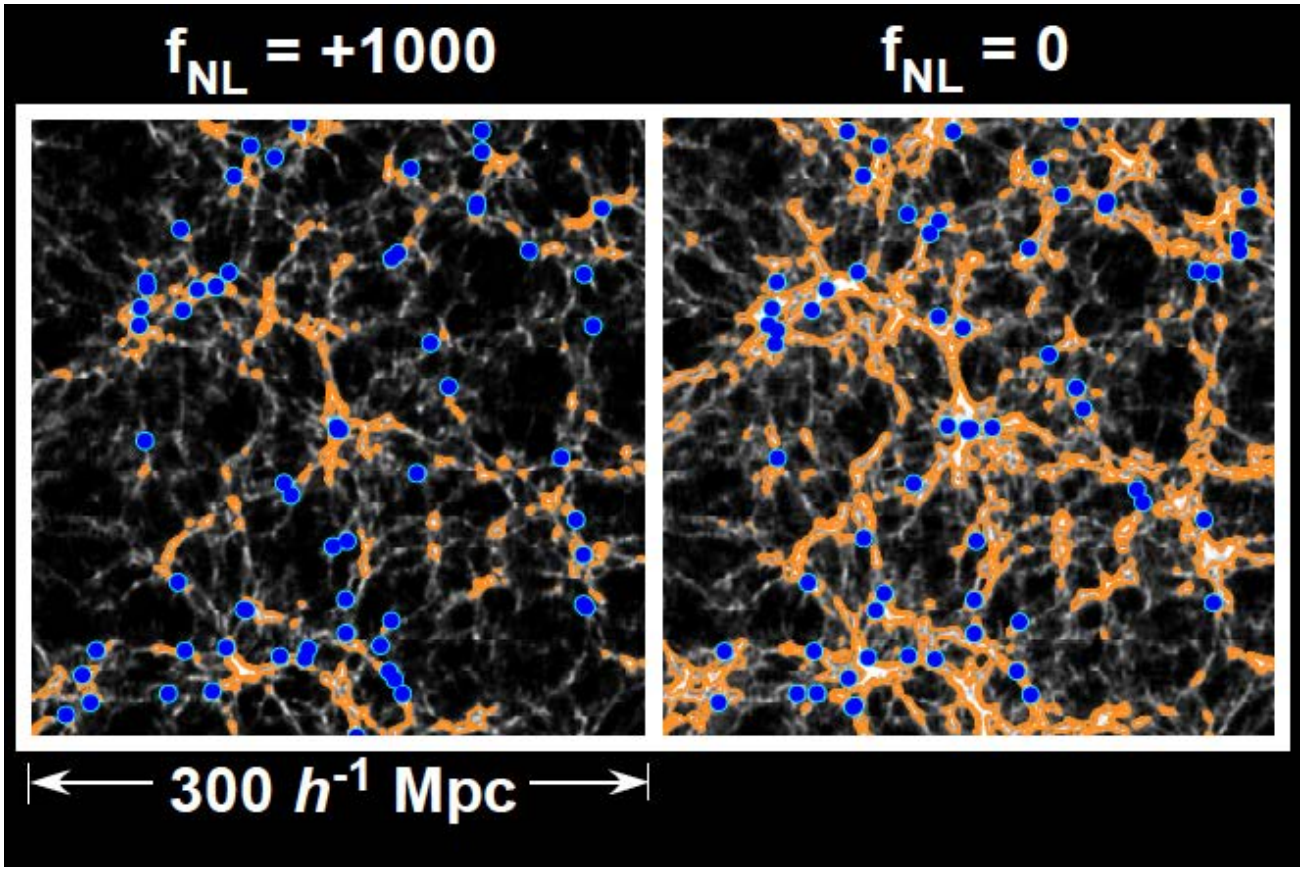


A. Guth

How Do We Probe Inflation Physics? Observables

Inflationary gravitational waves – CMB "B-mode" polarization
Spectral index of fluctuations – CMB and large-scale structure
Non-Gaussianity – Sensitive to **Inflaton field** (single- or multi-field)

Large-Scale Structure will give best non-Gaussianity measurements

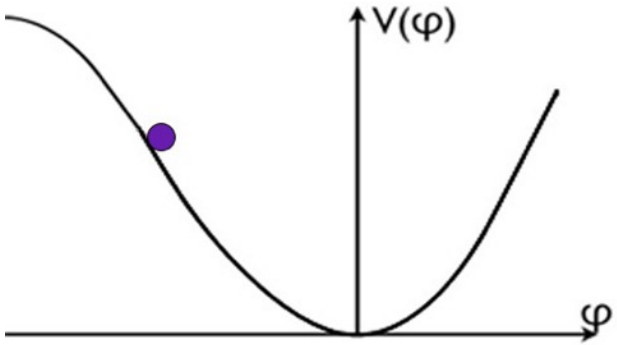


Non-Gaussianity appears on largest spatial scales – <u>need large volume survey</u>

Measuring Primordial Non-Gaussianity to $\sigma(f_{NL}) < 1$

A test to distinguish between single- and multi-field Inflation

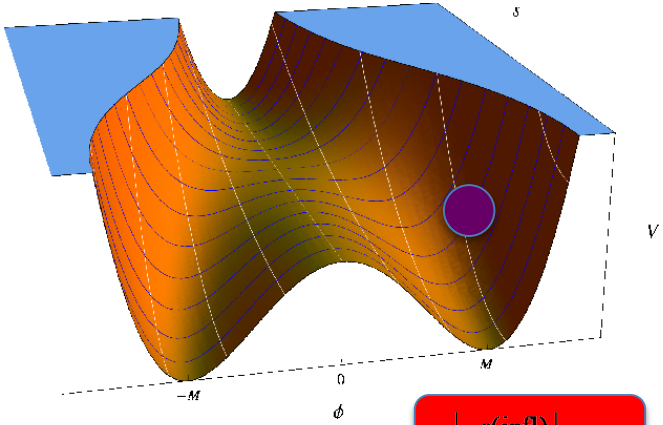
Single-Field Inflation:



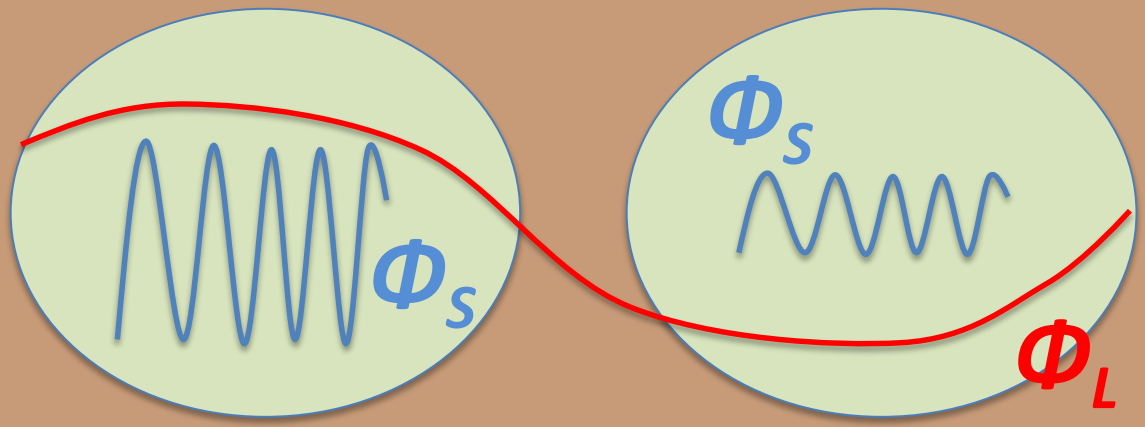
Squeezed limit consistency condition by Maldacena (2003):

$$f_{NL}^{(\mathrm{infl})} \sim (n_s - 1) << 1$$

Multi-Field Inflation:



$$\left| f_{NL}^{(\mathrm{infl})} \right| \geq 1$$



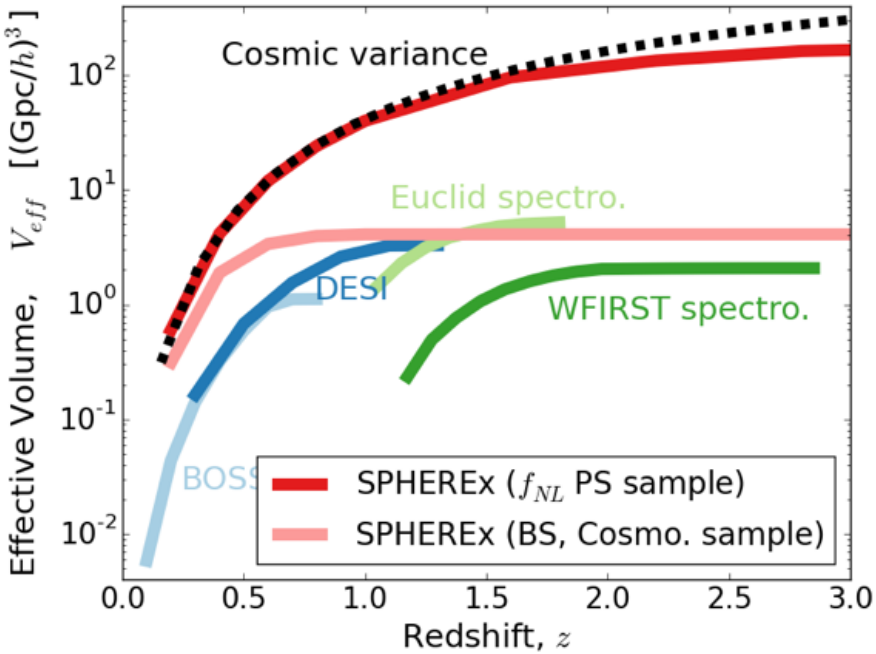
Non-Gaussianity Produces Two Signatures

Enhanced power on large spatial scales Φ_L
- measured with power spectrum

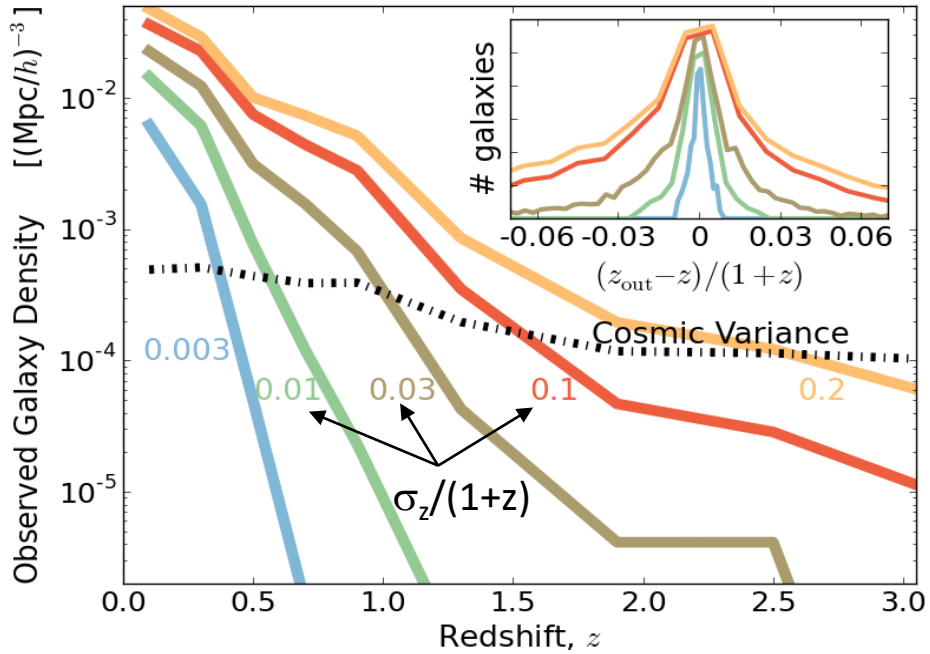
Modulated small-scale power Φ_S on large scales Φ_L due to non-linear mode coupling
- measured with bispectrum

SPHEREx Large Volume Galaxy Survey

SPHEREx Surveys Maximum Cosmic Volume



Catalog Split into Redshift Accuracy Bins



SPHEREx Large-Volume Redshift Catalog

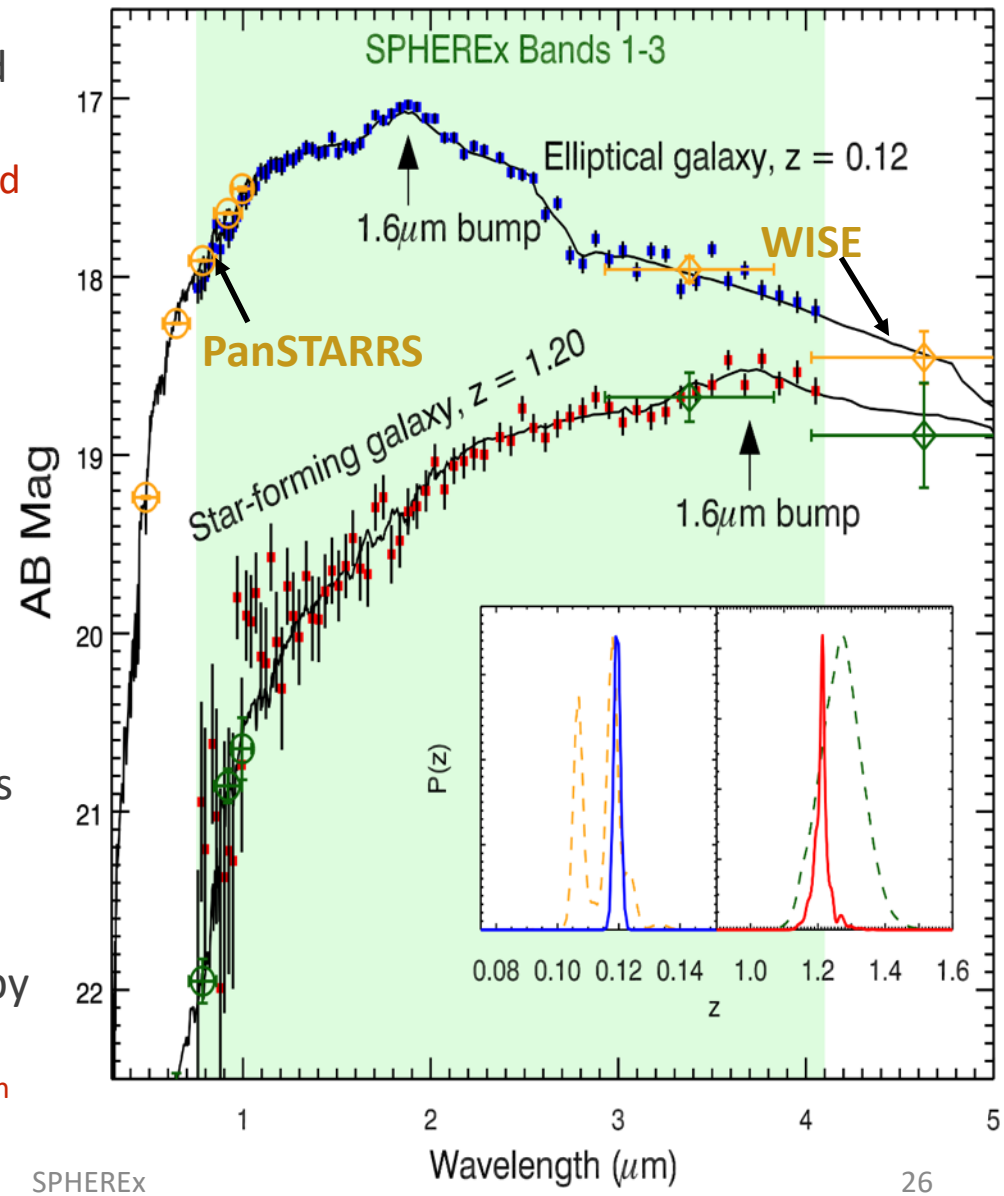
- Largest effective volume of any survey, near cosmic limit
- Excels at z < 1, complements dark energy missions (Euclid, WFIRST) targeting z ~ 2
- SPHEREx + Euclid measures gravitational lensing and calibrates Euclid photo-zs

Survey Designed for Two Tests of Non-Gaussianity

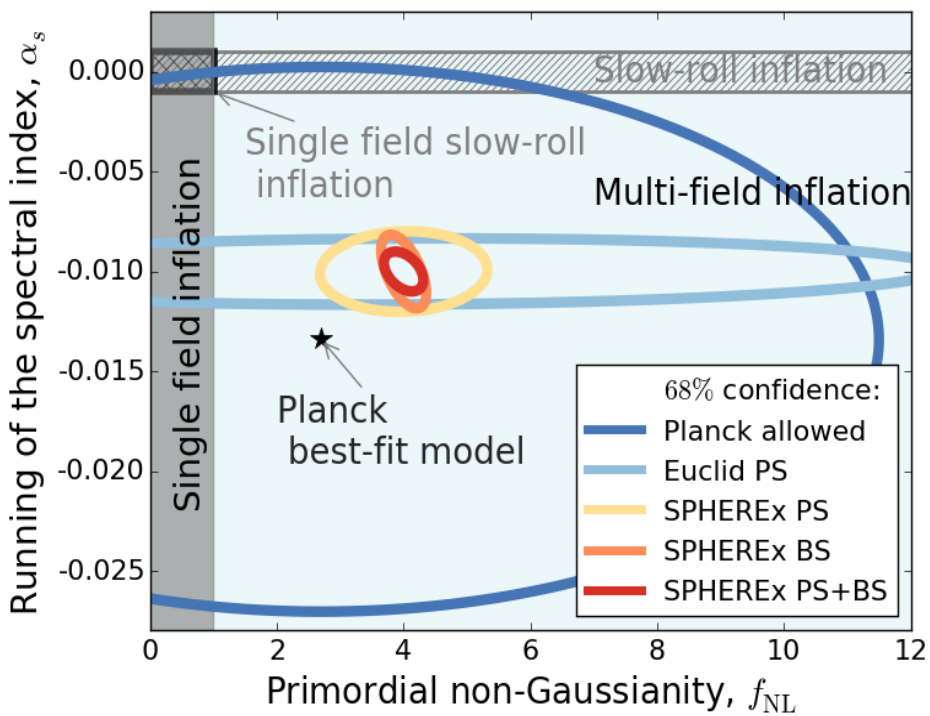
- Large scale power from **power spectrum**: large # of low-accuracy redshifts
- Modulation of fine-scale power from **bispectrum**: fewer high-accuracy redshifts

Redshifts with SPHEREx

- We extract the spectra of *known* sources using the full-sky catalogs from WISE and PanSTARRS/DES
  - Blending and confusion easily controlled
- We compare this spectra to a template library (robust for low redshift sources):
  - For each galaxy: redshift & type
  - Multiple types test galaxy bias effects
- The 1.6 µm bump is a well known universal photometric indicator
  - Simpson & Eisenhardt 99
- We simulated this process using the COSMOS data set using the same process as Euclid/WFIRST
  - Capak et al.
- The power of low-resolution spectroscopy has been demonstrated
  - PRIMUS (Cool++14), COSMOS (Ilbert++09), NMBS (van Dokkum++09)



SPHEREx Tests Inflationary Non-Gaussianity

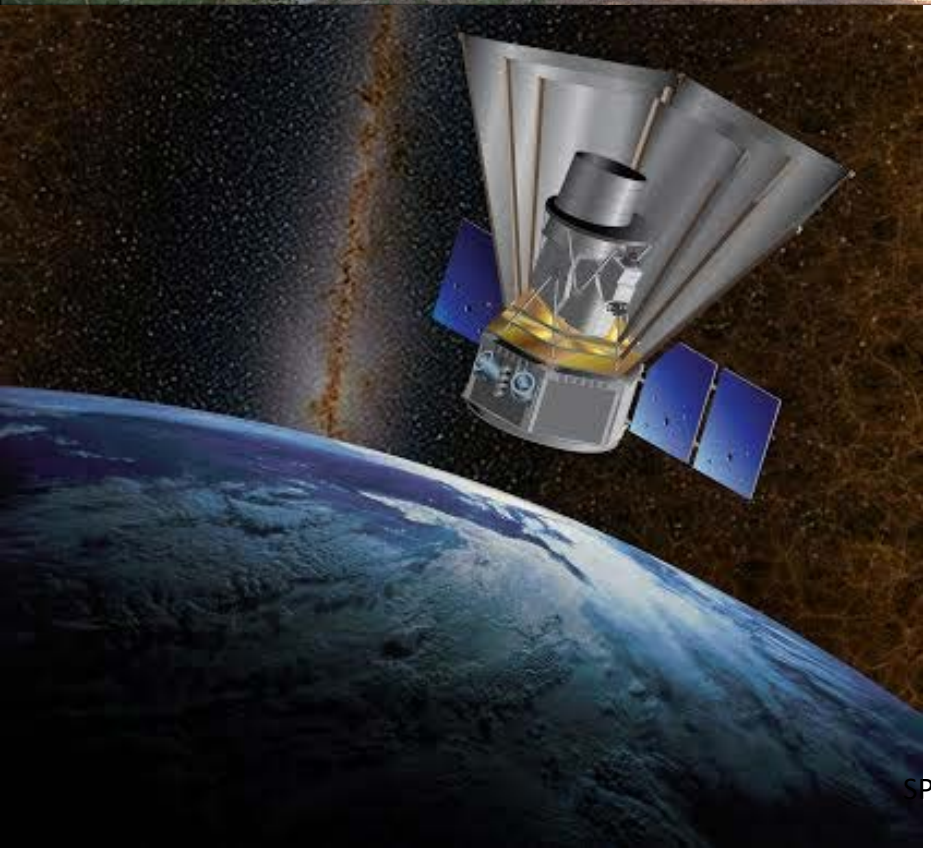


1σ errors	SPHEREx (MEV)			Euclid	Current
	PS	BS	PS+BS		
f_{NL} Req't	1.0	0.5	0.5	N/A	N/A
f_{NL}	0.87	0.23	0.20	5.59	5.8
Spectral Index n_s (x 10^{-3})	2.7	2.3	2.2	2.6	5.4
Running α_s (x10^{-3})	1.3	1.2	0.65	1.1	17
Curvature Ω_k (x10^{-4})	9.8	9.5	6.6	7.0	66
Dark Energy figure of merit	202	NC	NC	309	14

- Non-Gaussianity distinguishes between multi- and single-field models
- Projected SPHEREx sensitivity is $\delta f_{NL} < 1$ (2σ)
  - Two *independent tests* via power spectrum and bispectrum
- Competitively tests running of the spectral index
- SPHEREx low-redshift catalog is complementary for dark energy

SPHEREx: An All-Sky Spectral Survey

Workshop at
Caltech
February 2016



Exploration of Legacy Science
Arxiv:1606.07039

Science Impacts of the SPHEREx All-Sky Optical to Near-Infrared Spectral Survey:

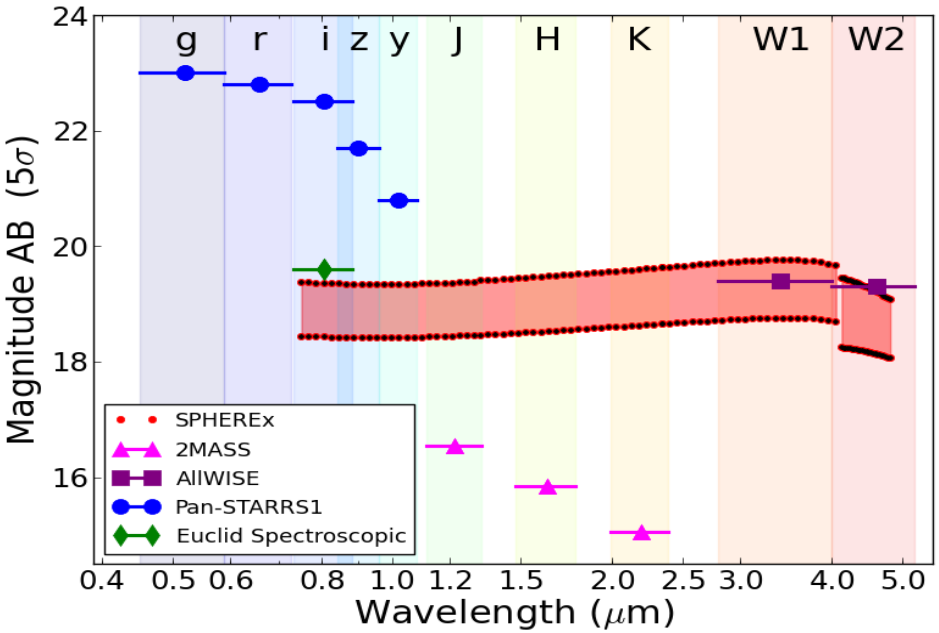
Report of a Community Workshop Examining Extragalactic, Galactic, Stellar and Planetary Science

Olivier Doré[1,21], Michael W. Werner[1,21], Matt Ashby[26], Pancha Banerjee[23], Nick Battaglia[16], James Bauer[1], Robert A. Benjamin[34], Lindsey E. Bleem[36,37], Jamie Bock[21], Adwin Boogert[2], Philip Bull[1,21], Peter Capak[8], Tzu-Ching Chang[3], Jean Chiar[38], Seth H. Cohen[30], Asantha Cooray[28], Brendan Crill[1,21], Michael Cushing[4], Roland de Putter[21], Simon P. Driver[32], Tim Eifler[21], Chang Feng[28], Simone Ferraro[19], Douglas Finkbeiner[31], B. Scott Gaudi[18], Tom Greene[5], Lynne Hillenbrand[21], Peter A. Höflich[6], Eric Hsiao[6], Kevin Huffenberger[6], Rolf A. Jansen[30], Woong-Seob Jeong[7], Bhavin Joshi[30], Duho Kim[30], Minjin Kim[7], J.Davy Kirkpatrick[8], Phil Korngut[21], Elisabeth Krause[9], Mariska Kriek[25], Boris Leistedt[10], Aigen Li[40], Carey M. Lisse[11], Phil Mauskopf[30], Matt Mechtley[30], Gary Melnick[26], Joseph Mohr[35,41], Jeremiah Murphy[6], Abraham Neben[13], David Neufeld[24], Hien Nguyen[1,21], Elena Pierpaoli[23], Jeonghyun Pyo[7], Jason Rhodes[1,21], Karin Sandstrom[15], Emmanuel Schaan[16], Kevin C. Schlaufman[22], John Silverman[12], Kate Su[33], Keivan Stassun[17], Daniel Stevens[18], Michael A. Strauss[16], Xander Tielens[39], Chao-Wei Tsai[20], Volker Tolls[26], Stephen Unwin[1], Marco Viero[9], Rogier A. Windhorst[30], Michael Zemcov[27,1]

Editors and corresponding authors: Olivier Doré[1,21], Michael Werner[1,21]

0607039v1 [astro-ph.CO] 22 Jun 2016

SPHEREx Creates an All-Sky Legacy Archive



Notable Features of the SPHEREx All-Sky Survey

- High S/N spectrum for every 2MASS source
- Solid detection of faintest WISE sources
- Catalogs ideal for JWST observations

And added from the Workshop:

- Redshifts for the all-sky eRosita X-Ray survey
- Photo baselines for wide-field transient survey
- Mapping 3D distribution of Galactic ices

Legacy Science Opportunities: A Few Examples

Object	# Sources	Legacy Science	Reference
Detected galaxies	1.4 billion	Properties of distant and heavily obscured galaxies	Simulation based on COSMOS and Pan-STARRS
Galaxies σ(z)/(1+z) < 0.03	120 million	Study (H, CO, O, S, H_2O) line and PAH emission by galaxy type. Explore galaxy and AGN life cycle	
Galaxies σ(z)/(1+z) < 0.003	9.8 million	Cross check of Euclid photo-z. Measure dynamics of groups and map filaments.	
QSOs	> 1.5 million	Understand QSO lifecycle, environment, and taxonomy	Ross et al. (2013) plus simulations
QSOs at z > 7	0-300	Determine if early QSOs exist. Follow-up spectro-scopy probes EOR through Lyα forest	
Clusters with ≥ 5 members	25,000	Redshifts for all eRosita clusters. Viral masses and merger dynamics	Geach et al., 2011, SDSS counts
Main sequence stars	>100 million	Test uniformity of stellar mass function within our Galaxy as input to extragalactic studies	2MASS catalogs
Mass-losing, dust forming stars	Over 10,000 of all types	Spectra of M supergiants, OH/IR stars, Carbon stars. Stellar atmospheres, dust return rates, and composition of dust	Astro-physical Quantities, 4th edition [ed. A.Cox] p. 527
Brown dwarfs	>400, incl. >40 of types T and Y	Atmospheric structure and composition; search for hazes. Informs studies of giant exoplanets	dwarfarchives. org and J.D. Kirkpatrick, priv. comm.
Stars with hot dust	>1000	Discover rare dust clouds produced by cataclysmic events like the collision which produced the Earth's moon	Kennedy & Wyatt (2013)
Diffuse ISM	Map of the Galaxy	Study diffuse emission from interstellar clouds and nebulae; (H, CO, S, H_2O and PAH emission)	GLIMPSE survey (Churchwell et al. 2009)

SPHEREx Team

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Yong-Seon Song	KASI
Stephen Unwin	JPL
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Michael Zemcov	Caltech

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Tim Eifler	JPL
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Yan Gong	UC Irvine
Elisabeth Krause	Stanford
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Hien Nguyen	JPL
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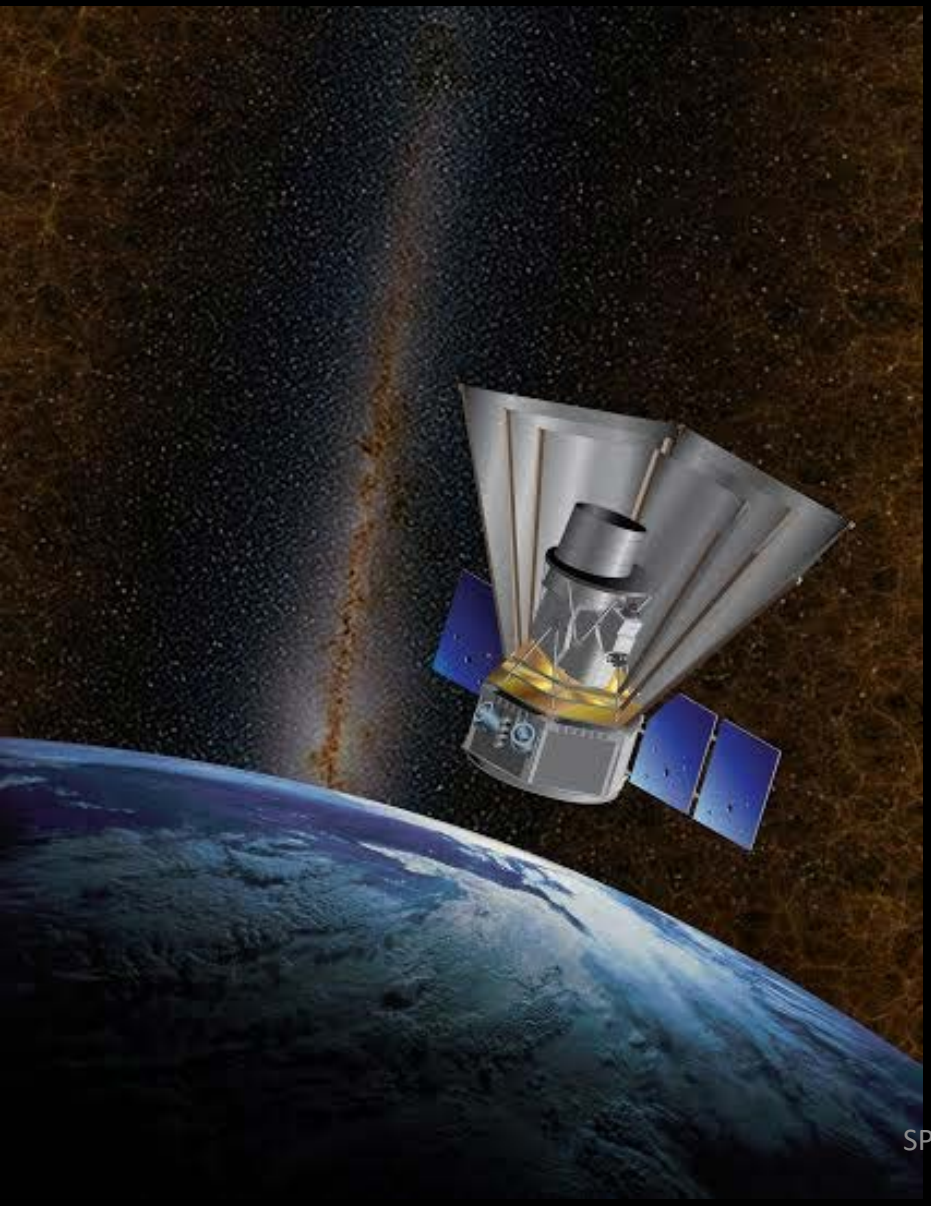
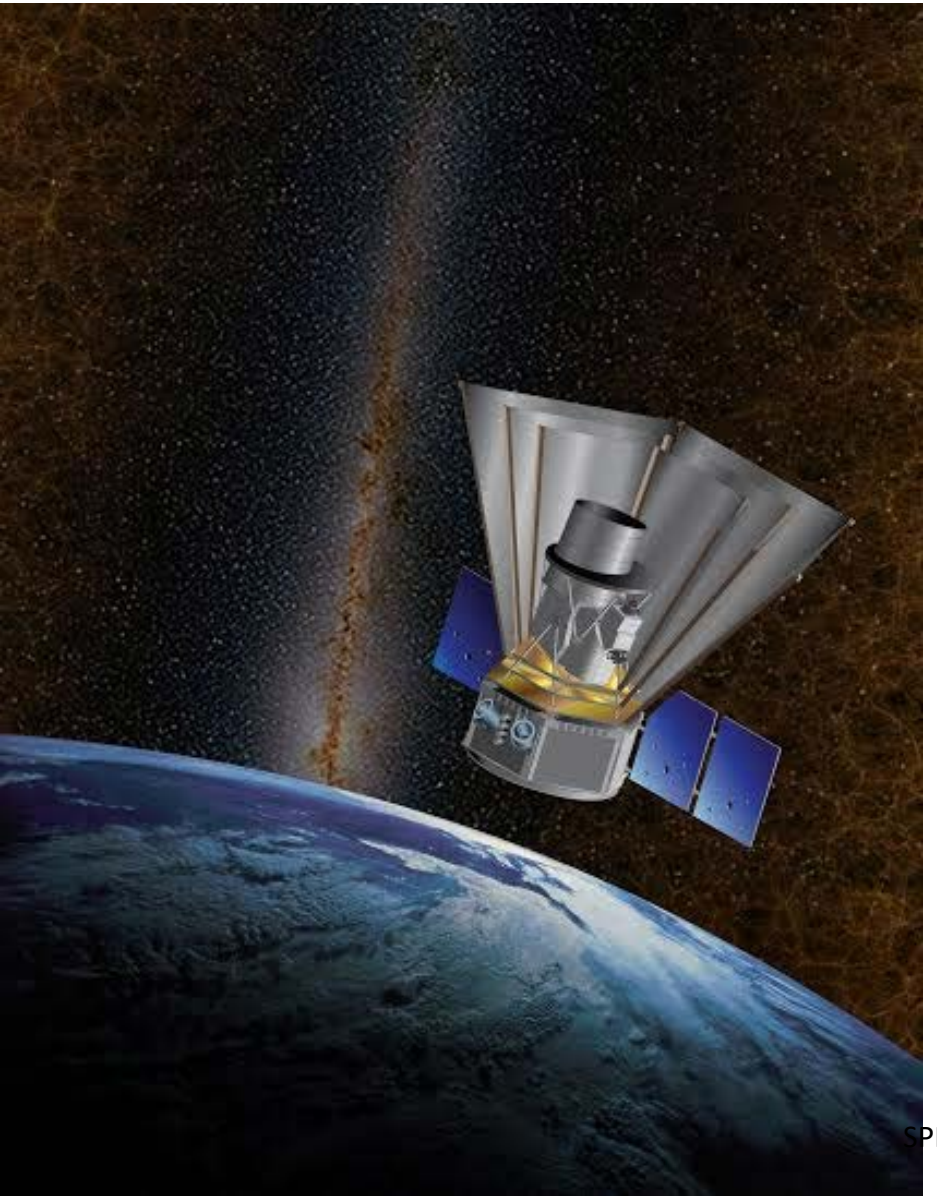
Volker Tolls	CfA
Salman Habib	Argonne
Katrin Heitmann	Argonne
Marco Viero	Stanford

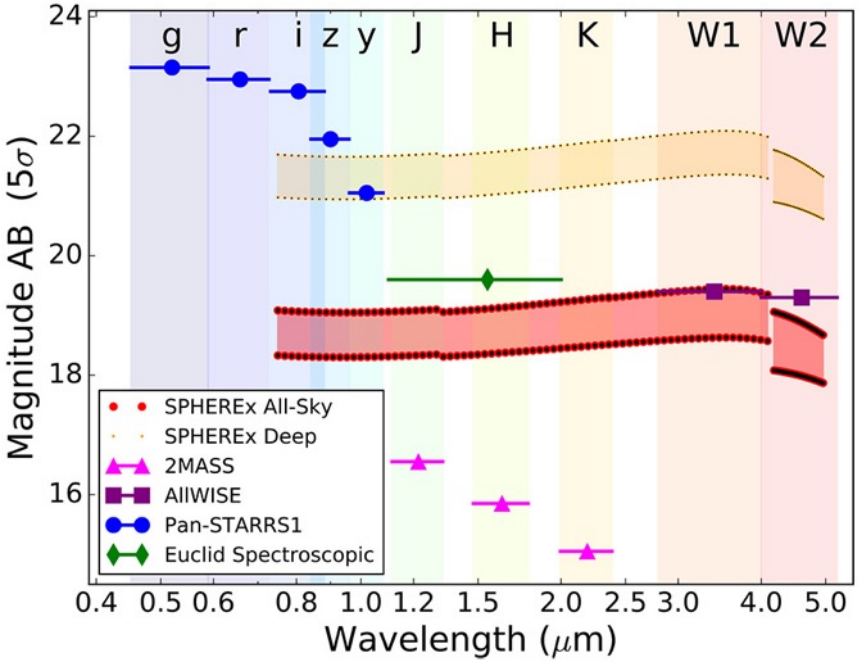
SPHEREx: An All-Sky Spectral Survey

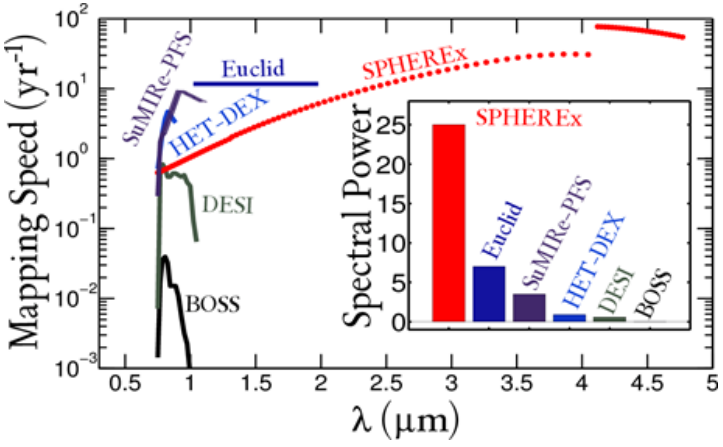


The Mission

SPHEREx: An All-Sky Spectral Survey

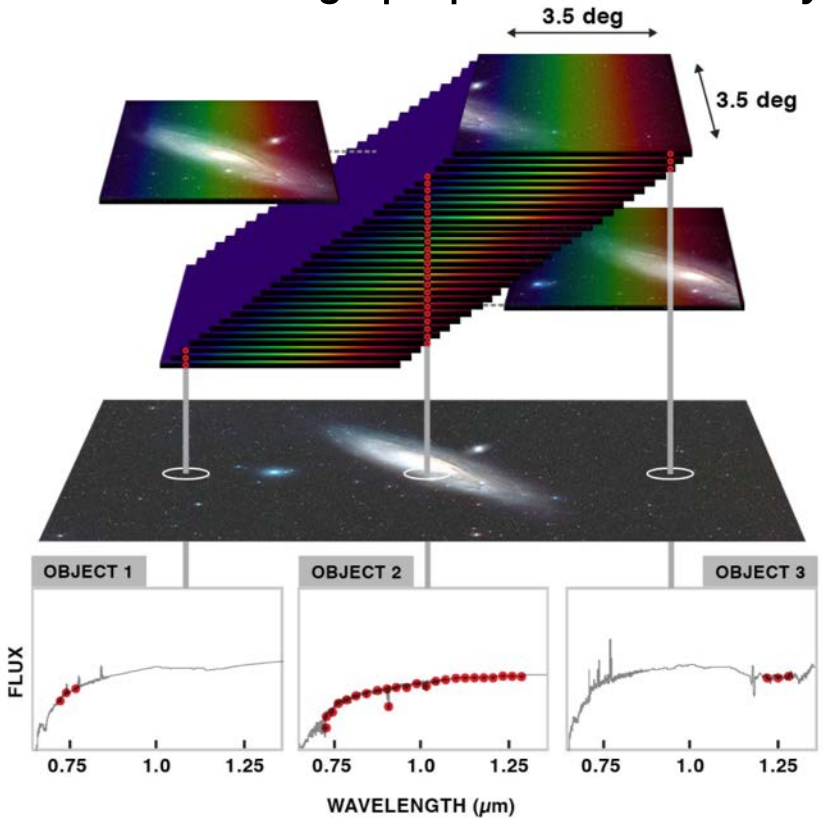




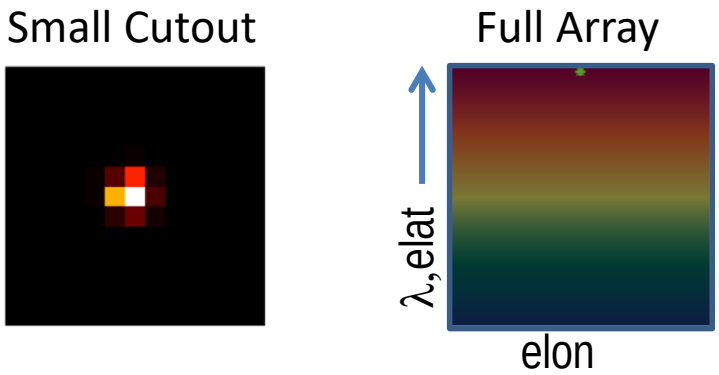


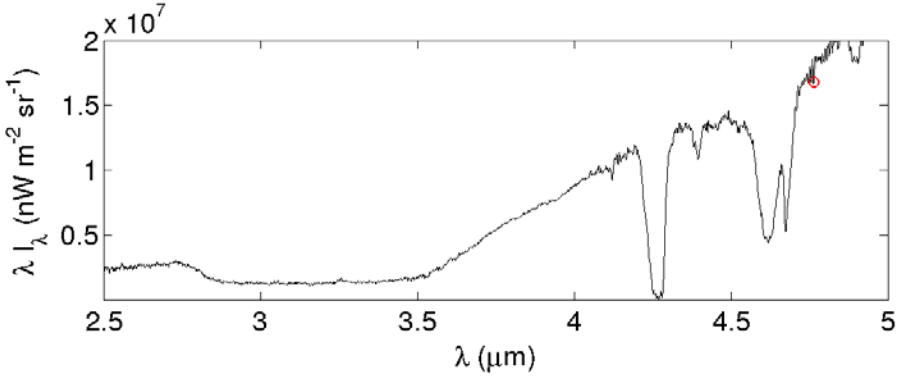
Spectroscopy with a Linear Variable Filter (LVF)

Building up Spectra in a Survey



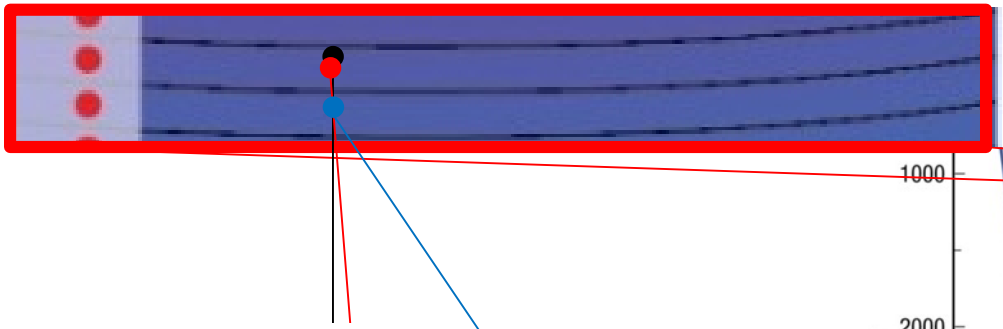
Scanning a single source

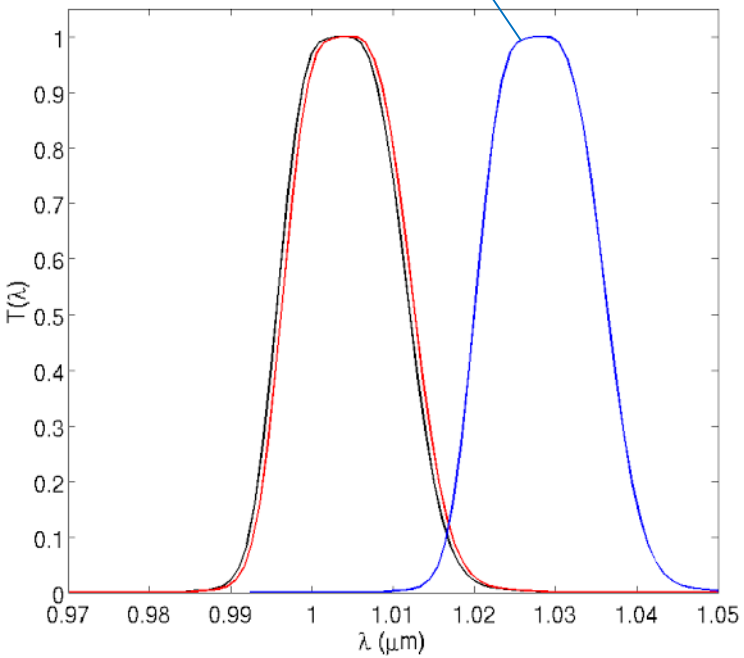


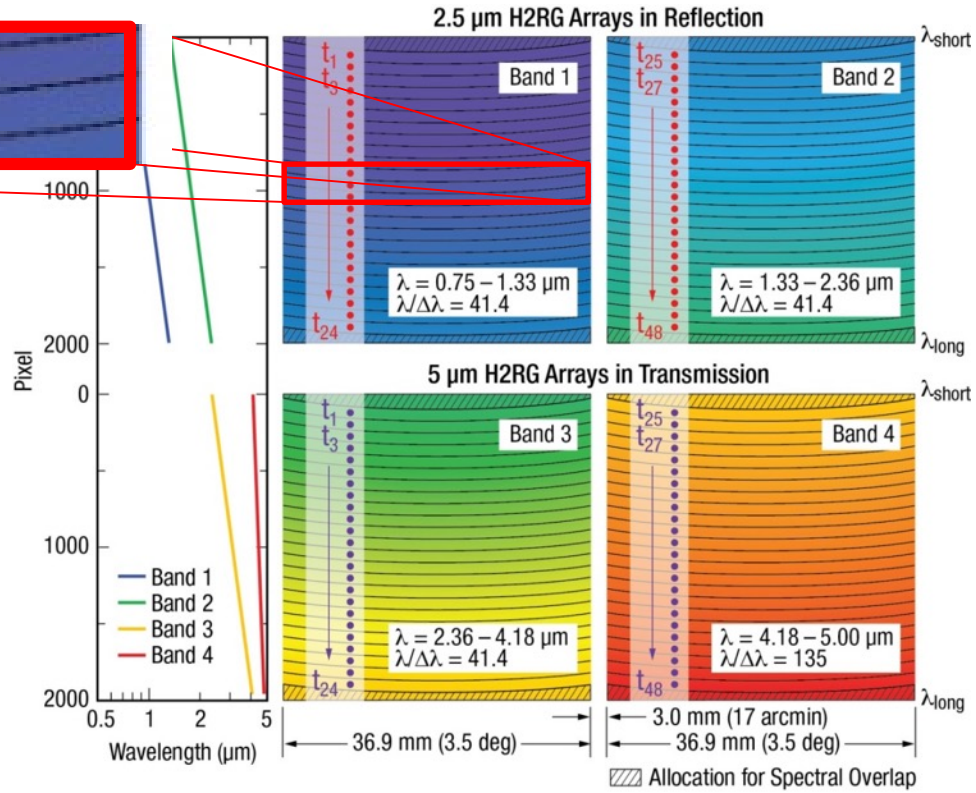


SPHEREx has 4 focal planes, each with an LVF mounted directly over the detectors. This defines the spectral response of each pixel. By scanning the FOV using the spacecraft attitude, a spectrum is assembled for every point on the sky.

Spectroscopy with a Linear Variable Filter (LVF)



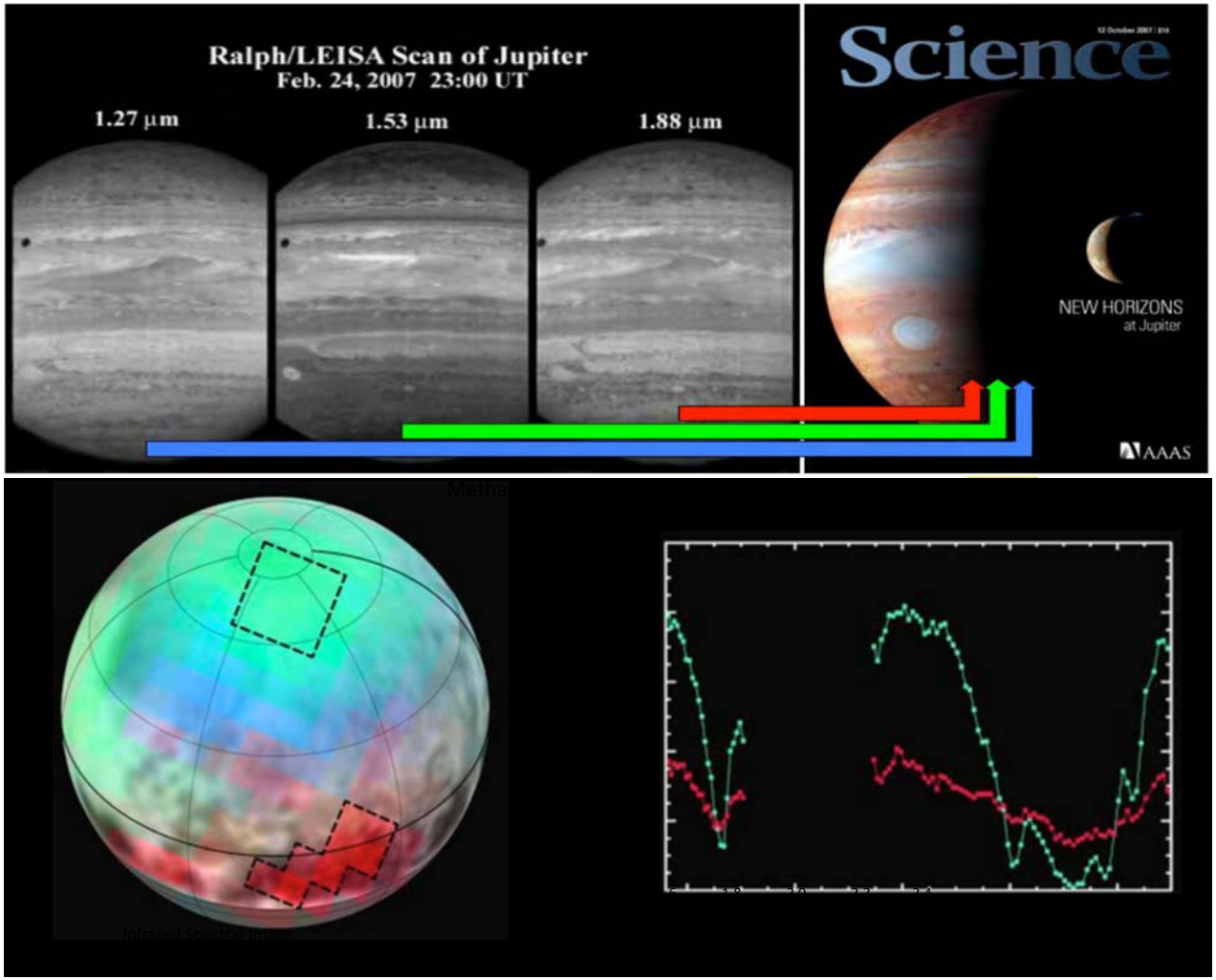




Each array has 24 independent spectral channels across it although the wavelength varies continuously.

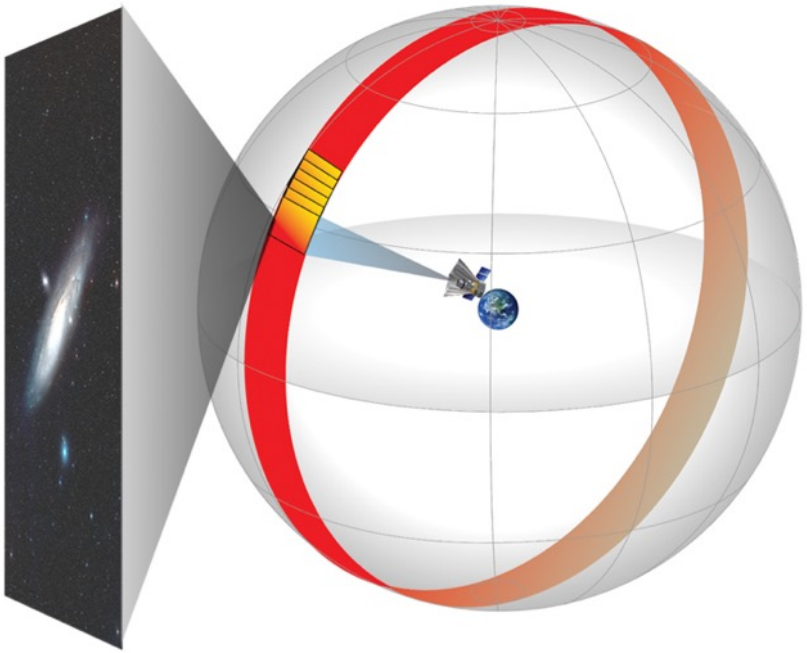
R =41.4 for bands 1-3 and R=135 for band 4

Spectroscopy with a Linear Variable Filter (LVF)



This technique for spectroscopy has already seen application in space

Orbit and Survey Strategy

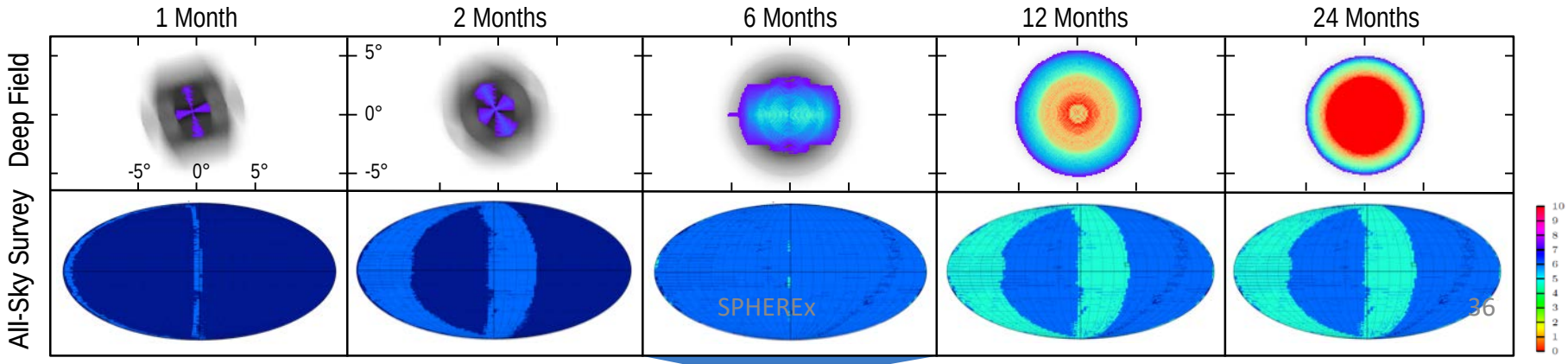


SPHEREx takes a Sun Synchronous Polar Low Earth Orbit at 600km altitude.

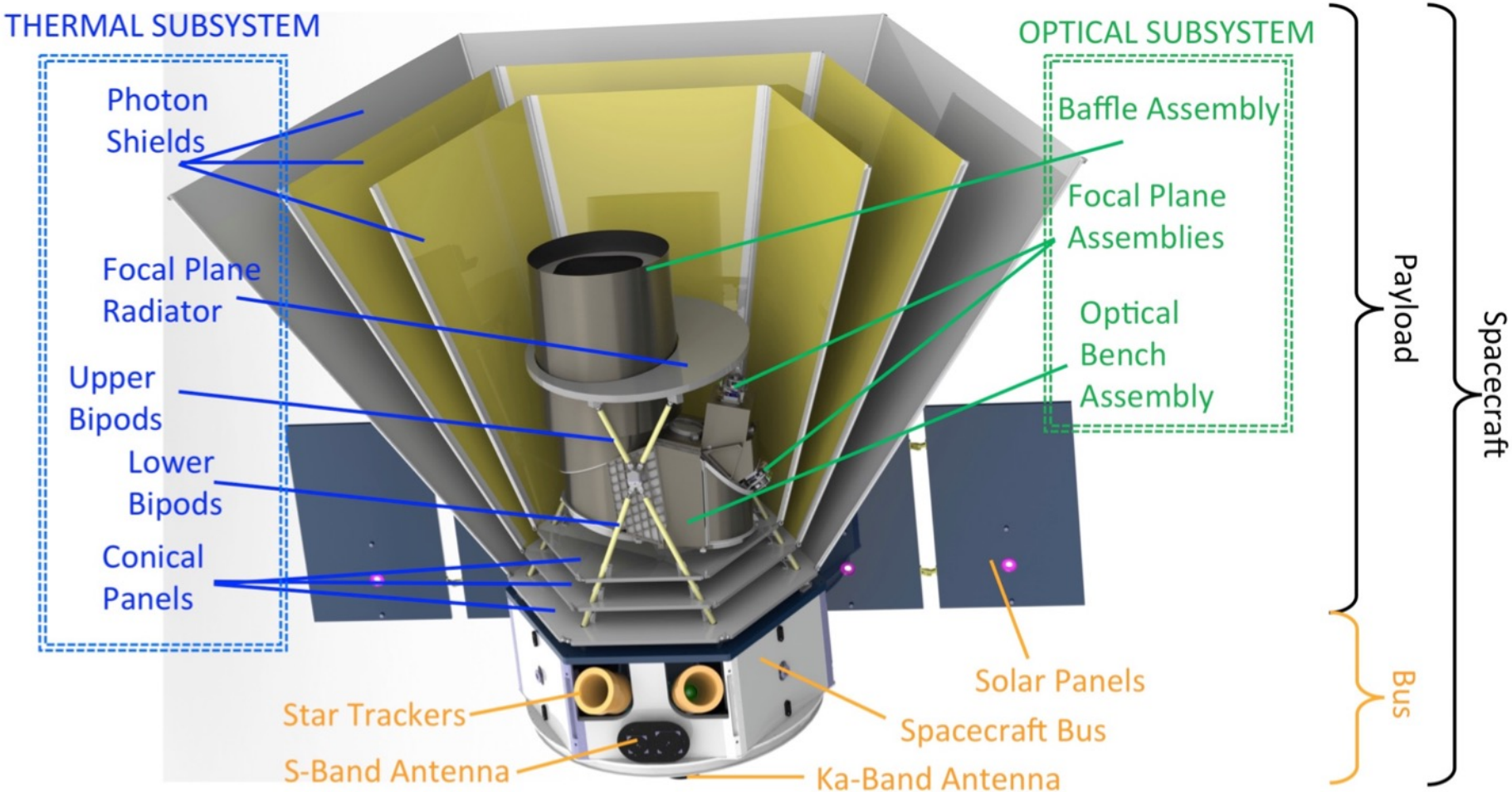
Each orbit contains a series of small steps and large slews to build up the spectral/spatial coverage

Survey the whole sky in 6 months as the orbit processes

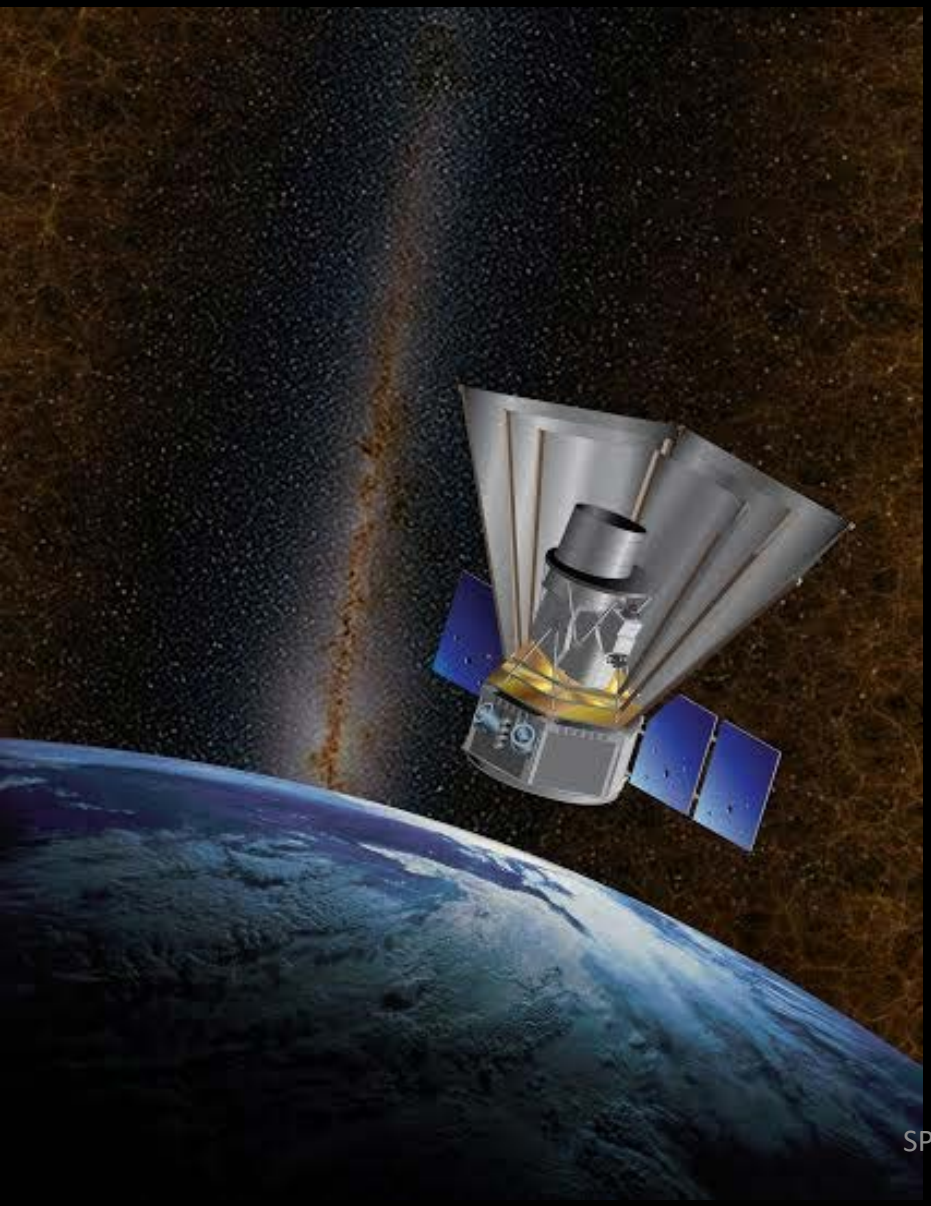
Natural Deep regions at the Ecliptic Poles



Spacecraft Overview

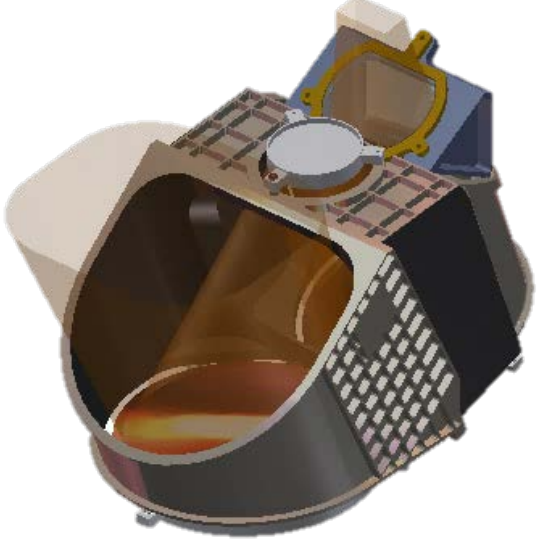


SPHEREx: An All-Sky Spectral Survey

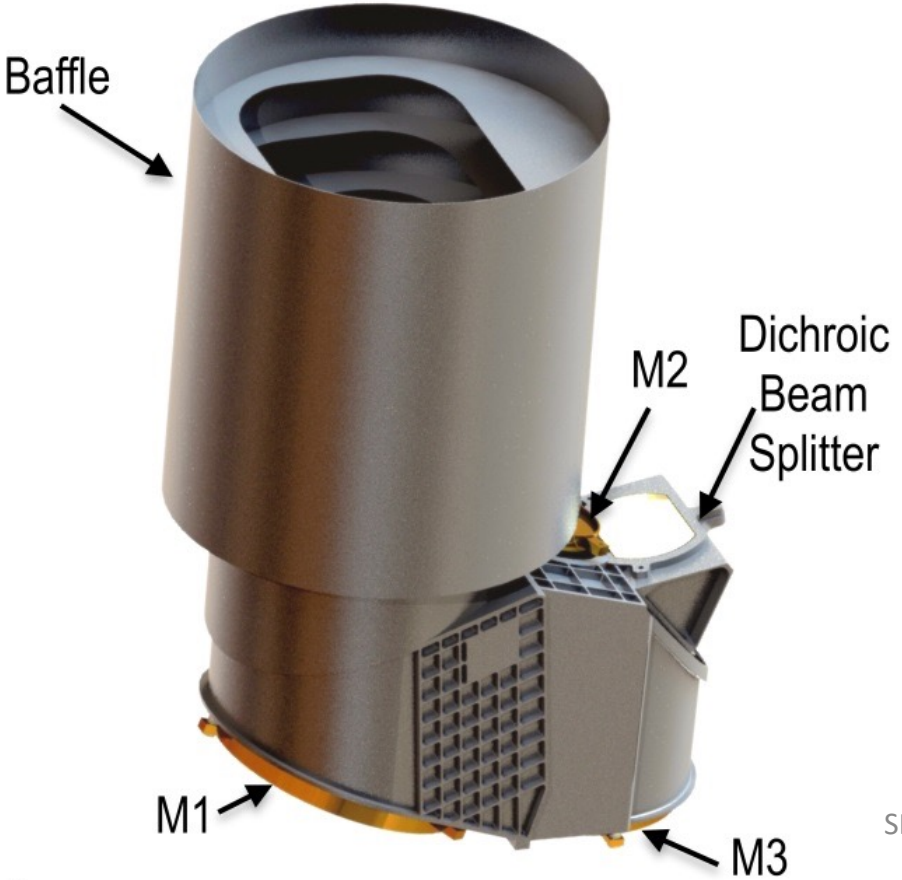


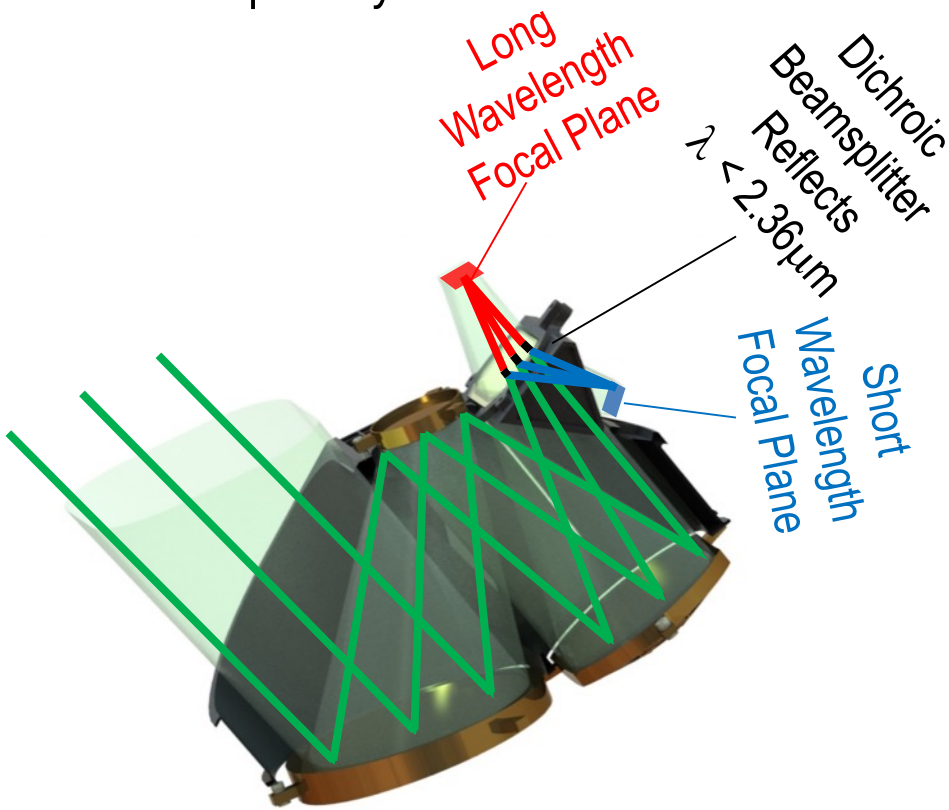
Optics

Telescope Optical and Mechanical design

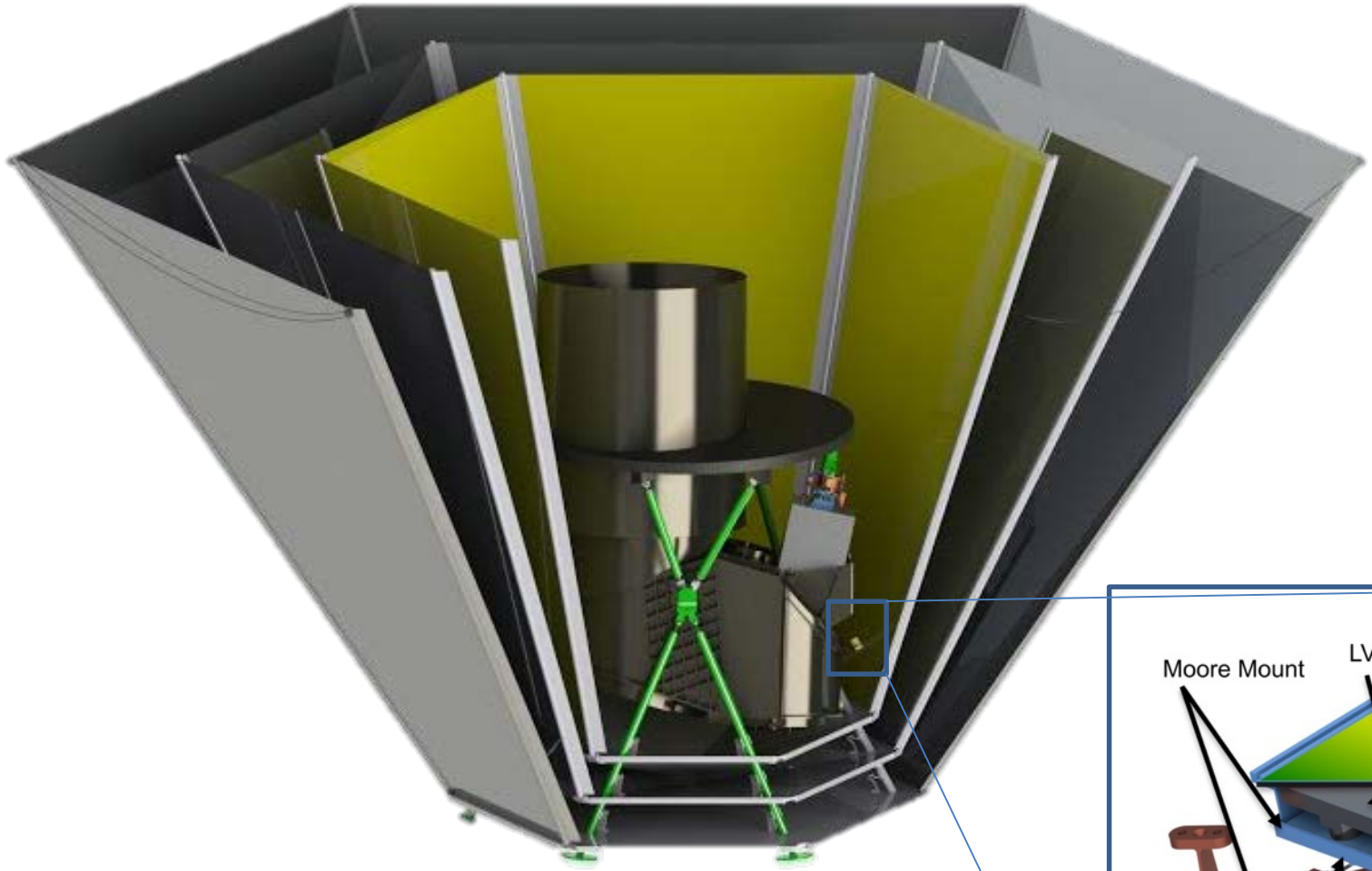


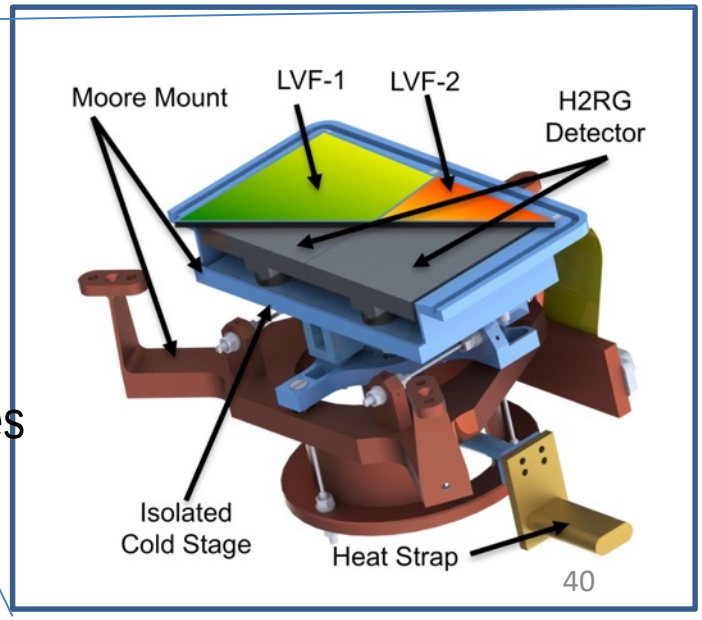
Reflective Triplet design with a dichroic to make 2 3.5 x 7 deg FOVs.
Housing and alignment done cryogenically by L3
20cm Free-form primary mirror





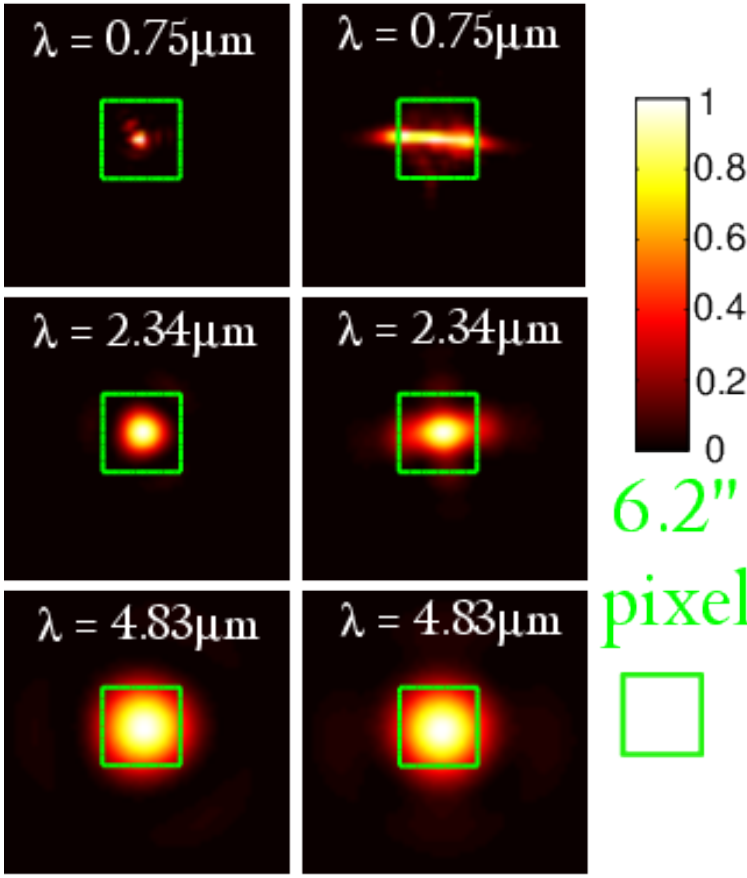
Focal Plane Assemblies





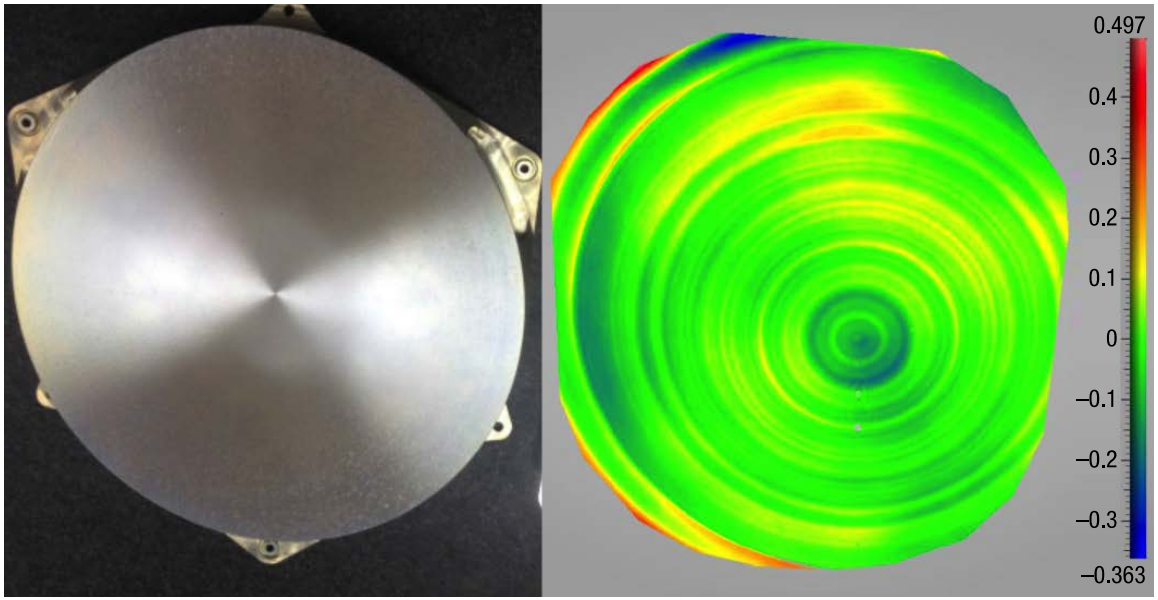
Moore Mounts allow for the thermal isolation and 6 degrees of freedom for focus adjustment.
They mount the LVFs 100um above the FPA surface

Telescope Optical and Mechanical performance



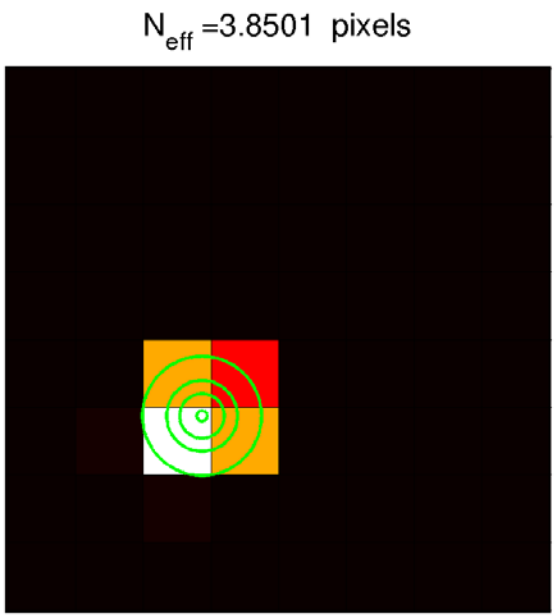
Simulated Optical PSFs
SPHEREx under-samples its PSF to maximize throughput

Corning Fabricated Demonstration Primary

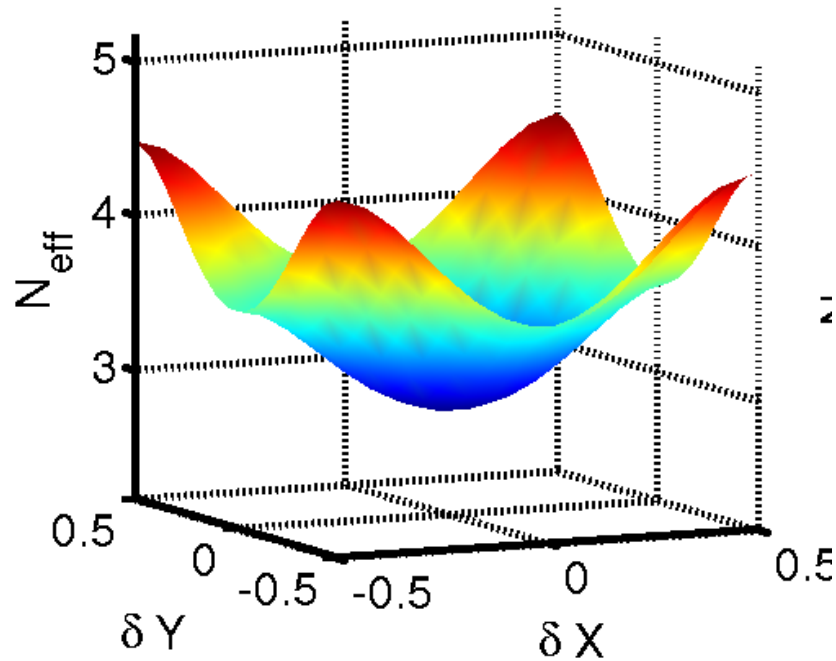


Demo of flight free-form mirror giving 44 nm rms
80 nm rms is the requirement

Effective Number of Pixels

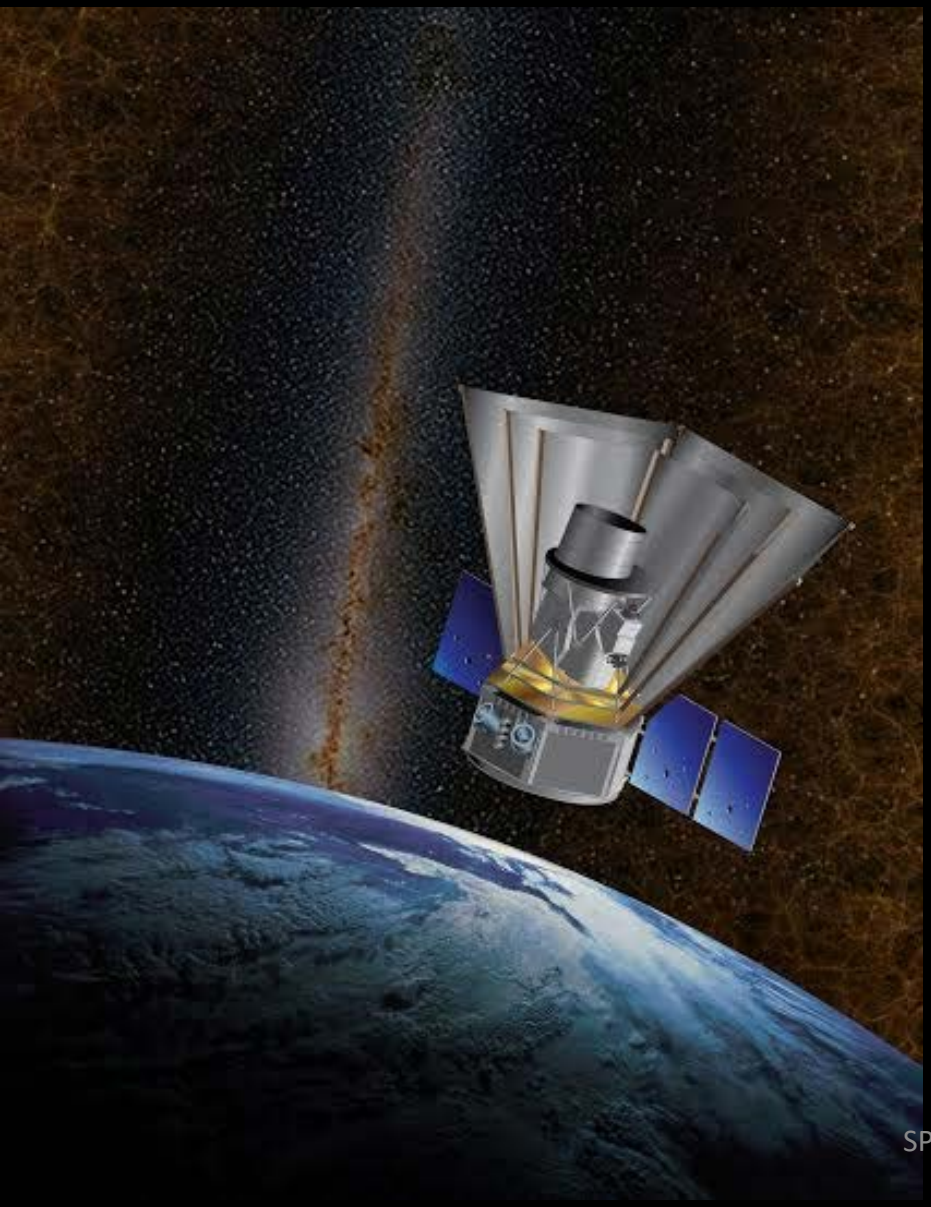


$$N_{eff} = \sum_{i,j} \frac{1}{w_{i,j}^2} \qquad \delta F = \sqrt{N_{eff}}\,[\delta F_1]$$



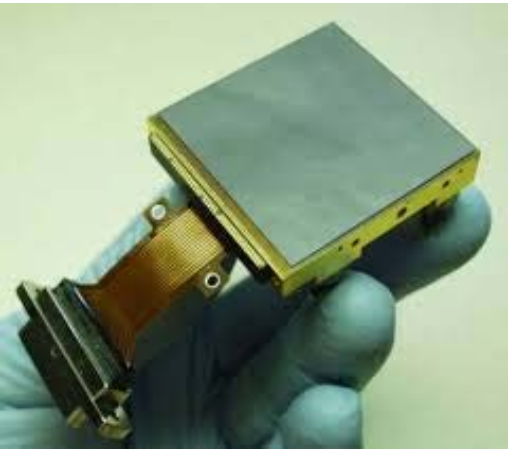
- Sensitivity Scales as the square root of Neff.
- Depends on alignment of source and pixel grid.
- Step1 assumed infinitely fast pointing wobble.

SPHEREx: An All-Sky Spectral Survey



Detectors, readout and data

Detectors and Data path



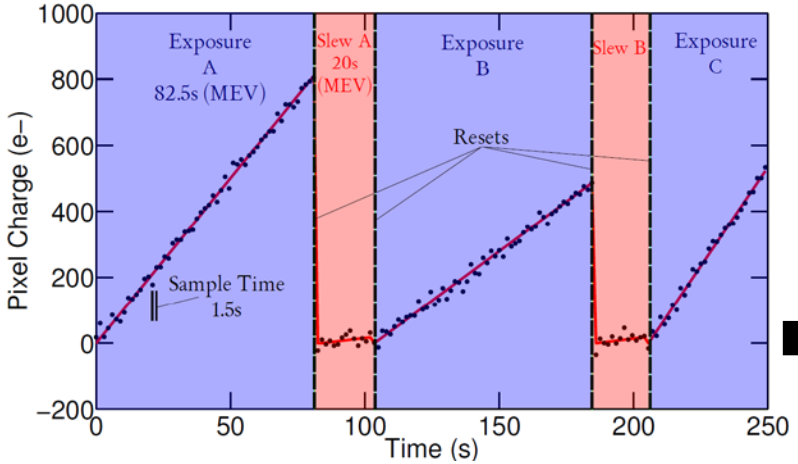
4 Teledyne 2k x 2k H2RGs, two with 2.5um cutoffs and two at 5.3um cutoffs.

Cryo harness

4 Cryogenic Sidecars for low power multiplexing and ADC

Cryo harness

FPGAs



Sample up the ramp for photocurrent map, cosmic ray flags, saturation

Per exposure data package

RAD750 compression and storage

Ka-band Telemetry system

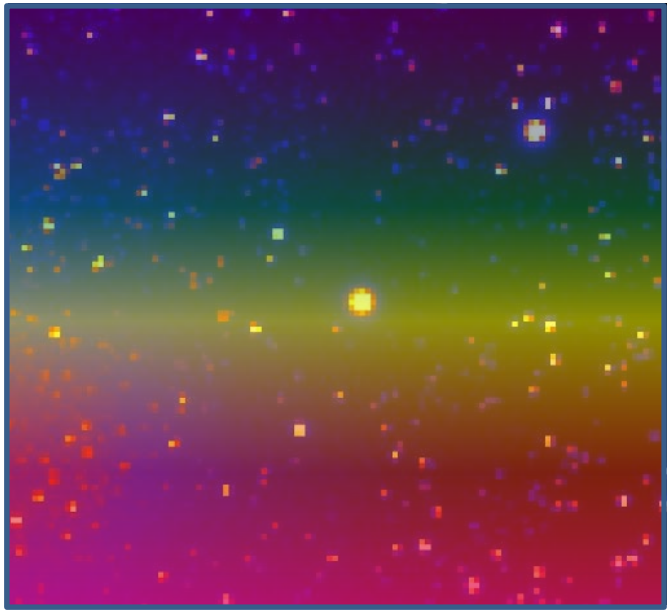
NASA Near Earth Network (NEN)

300Mb/s downlink requires only ~5 minutes per day to return all the data to the ground stations. Additionally maintain 3 days of storage on-board. Data is shipped from the ground stations to Caltech for the SPHEREx science center.

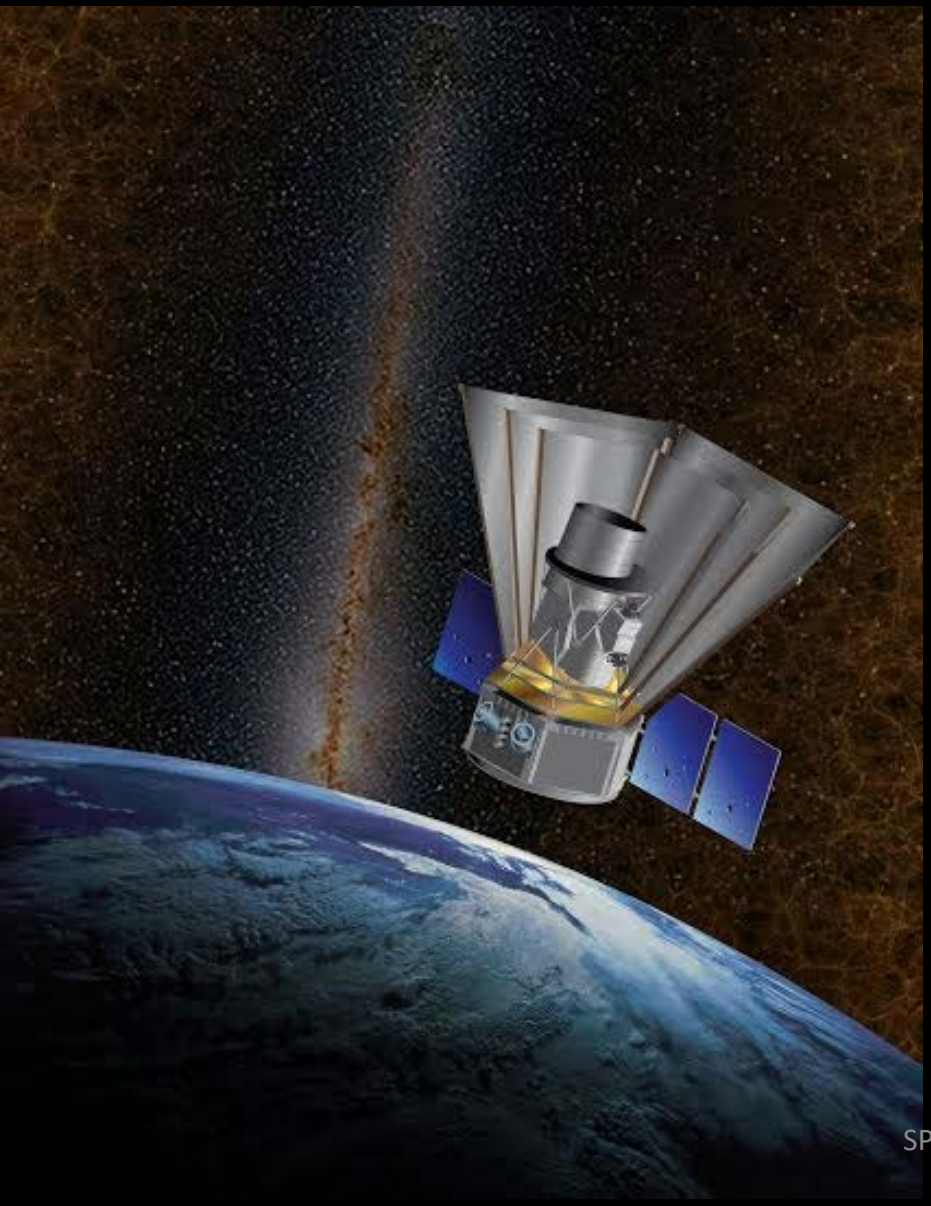
Data Release Plan

Survey / Data Release	Date	Data Volume	Products
Survey 1 starts	L+1 mo		
Survey 1 end	L+8 mo		
DR1	L+10 mo	6.4 TB	Survey 1 spectral images
Early Science	L+10 mo		
Survey 2 end	L+14 mo		
DR2	L+16 mo	12.8 TB	Survey 1/2 spectral images High Reliability Catalog
Survey 3 end	L+20 mo		
DR3	L+22 mo	16.0 TB	Survey 1/2/3 spectral images
Survey 4 end	L+26 mo		
DR4	L+28 mo	22.4 TB	Survey 1/2/3/4 spectral images
DR5	L+34 mo	25.6 TB	Final Galaxy Catalog, final stellar catalog, final mosaics

Simulated Spectral Image



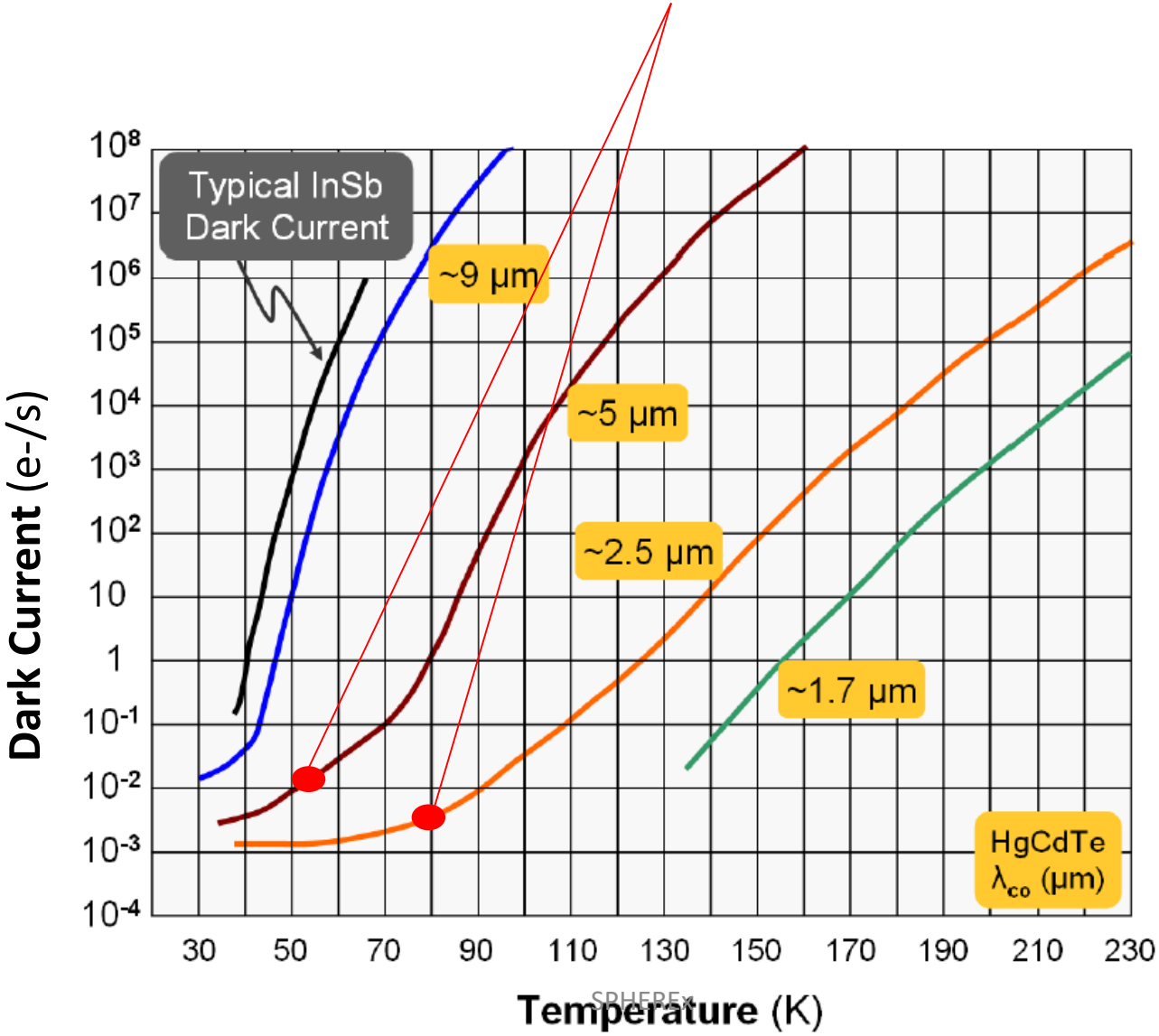
SPHEREx: An All-Sky Spectral Survey



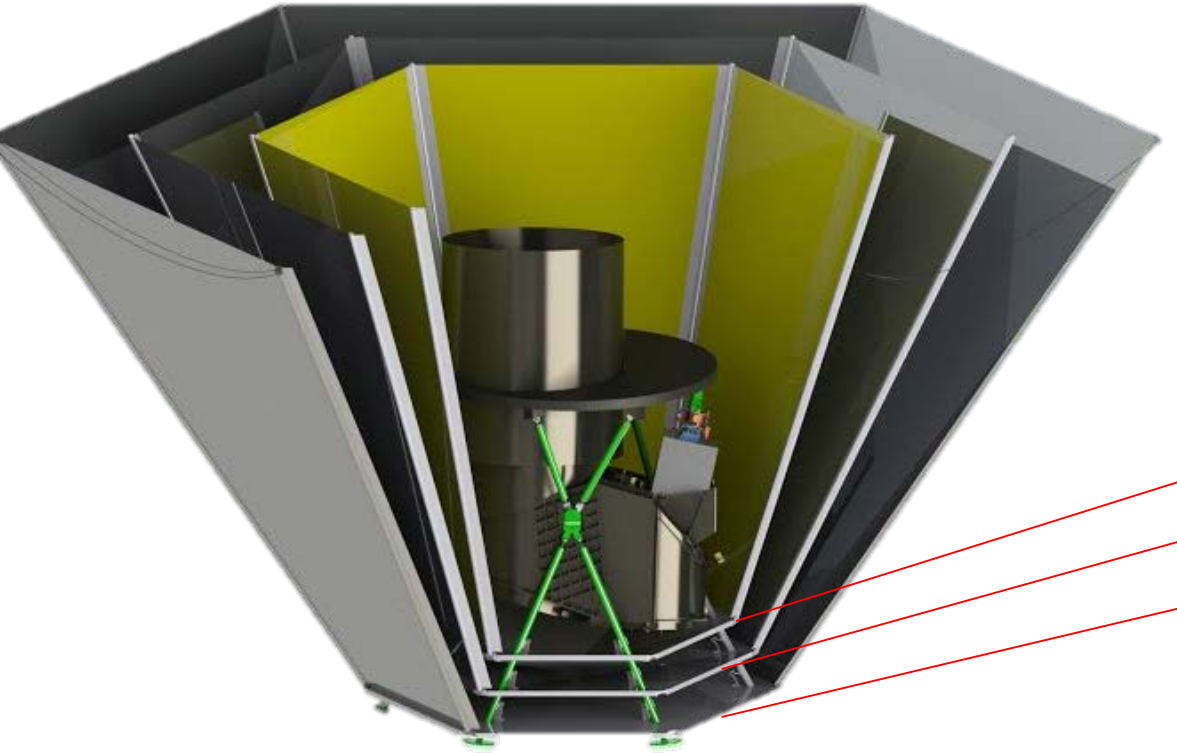
Thermal sub-system

SPHEREx Passive Cooling System

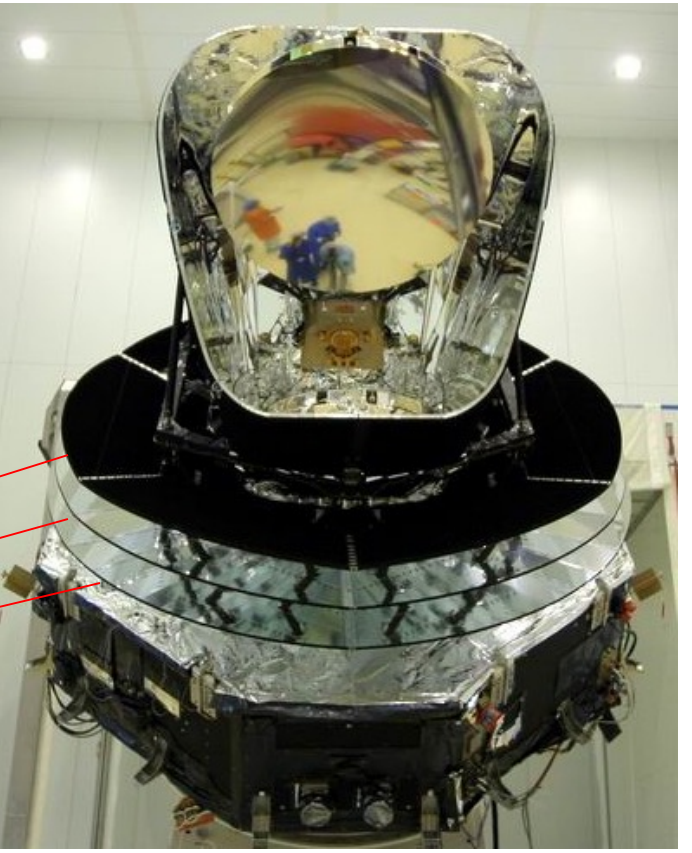
Requirements on thermal Performance are driven by the Dark Current of the Detectors



SPHEREx Passive Cooling System



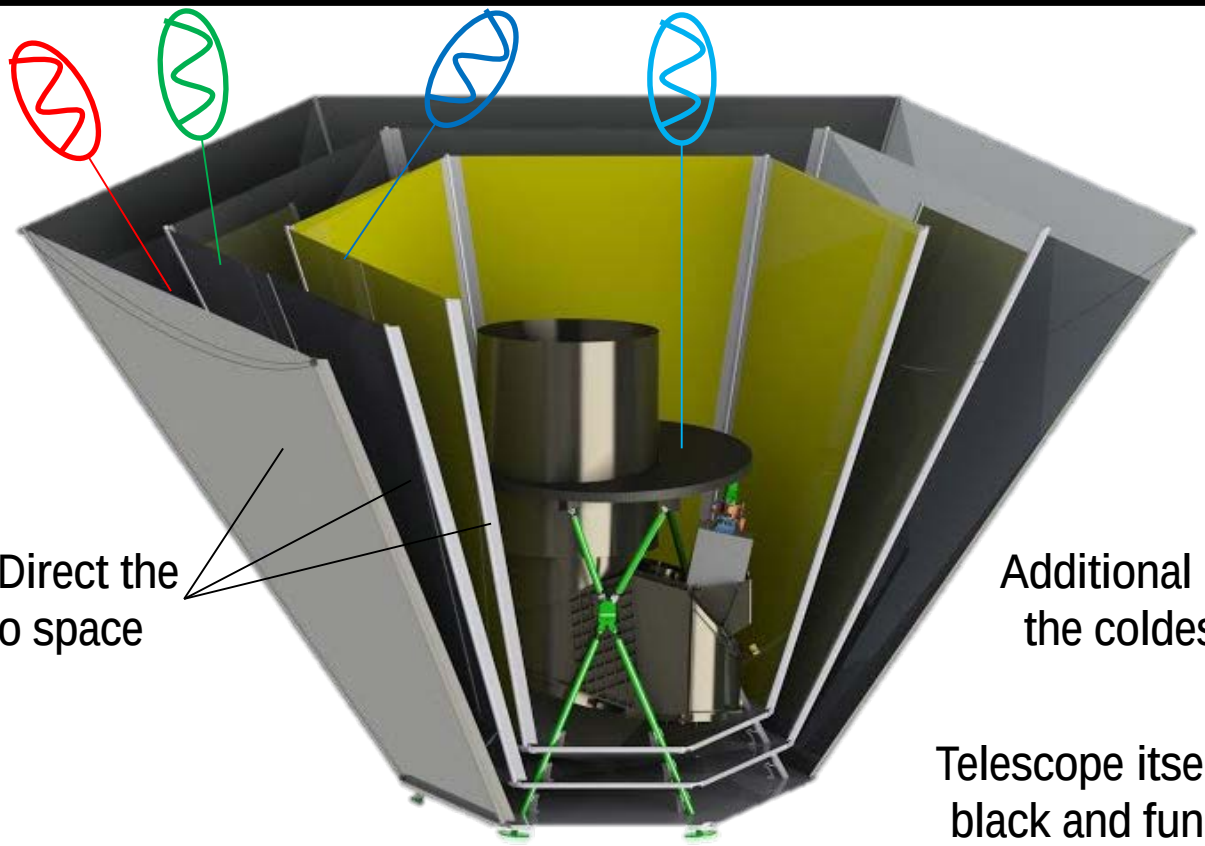
SPHEREx has the same V-grooves as Planck, adapted for low-Earth orbit



Planck 3-stage V-groove radiator for L2

SPHEREx Passive Cooling System- Radiator Scheme

Space (Infinite Heatsink (2.7K))



Photon Shields Direct the radiation out to space

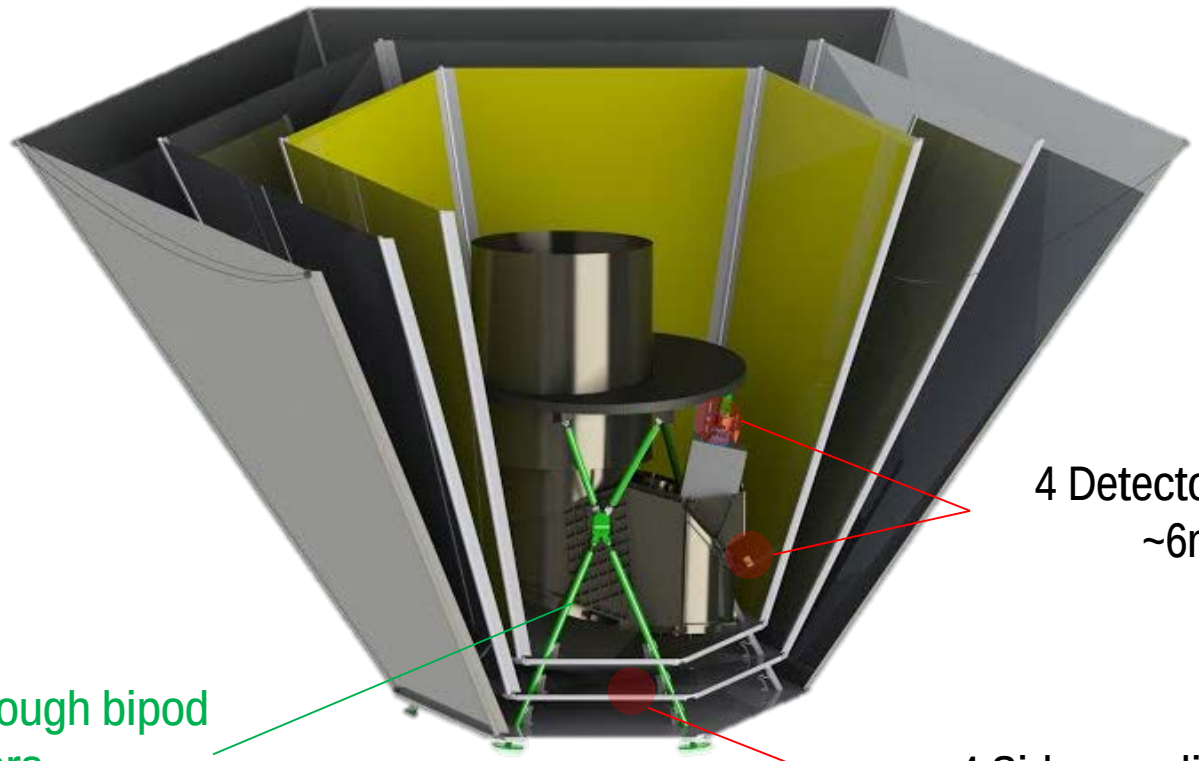
Additional FPA radiator for the coldest components

Telescope itself is painted black and functions as a radiator

3 Stage conical Panel V-grooves radiate away the energy

SPHEREx Passive Cooling System- Dissipative Loads

Space (Infinite Heatsink (2.7K))



4 Detectors dissipating ~6mW each

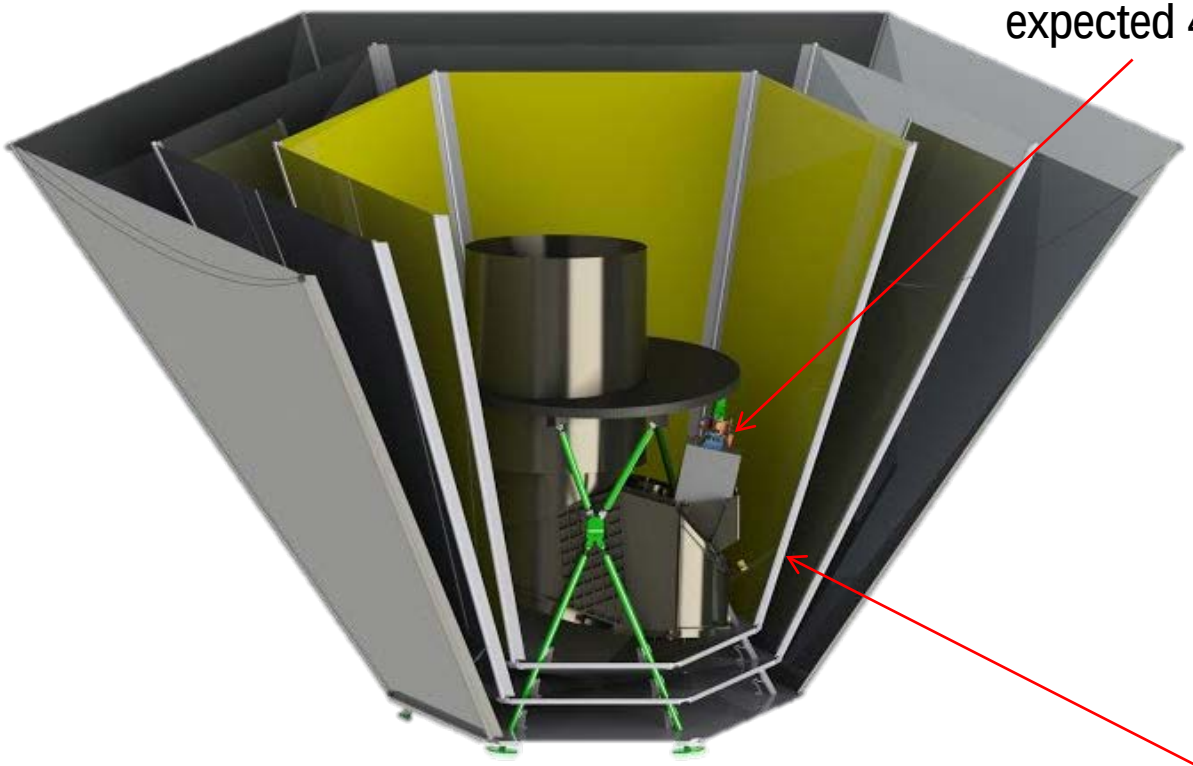
Conduction through bipod isolators

4 Sidecars dissipating ~300mW each

SPHEREx Passive Cooling System

Space (Infinite Heatsink (2.7K))

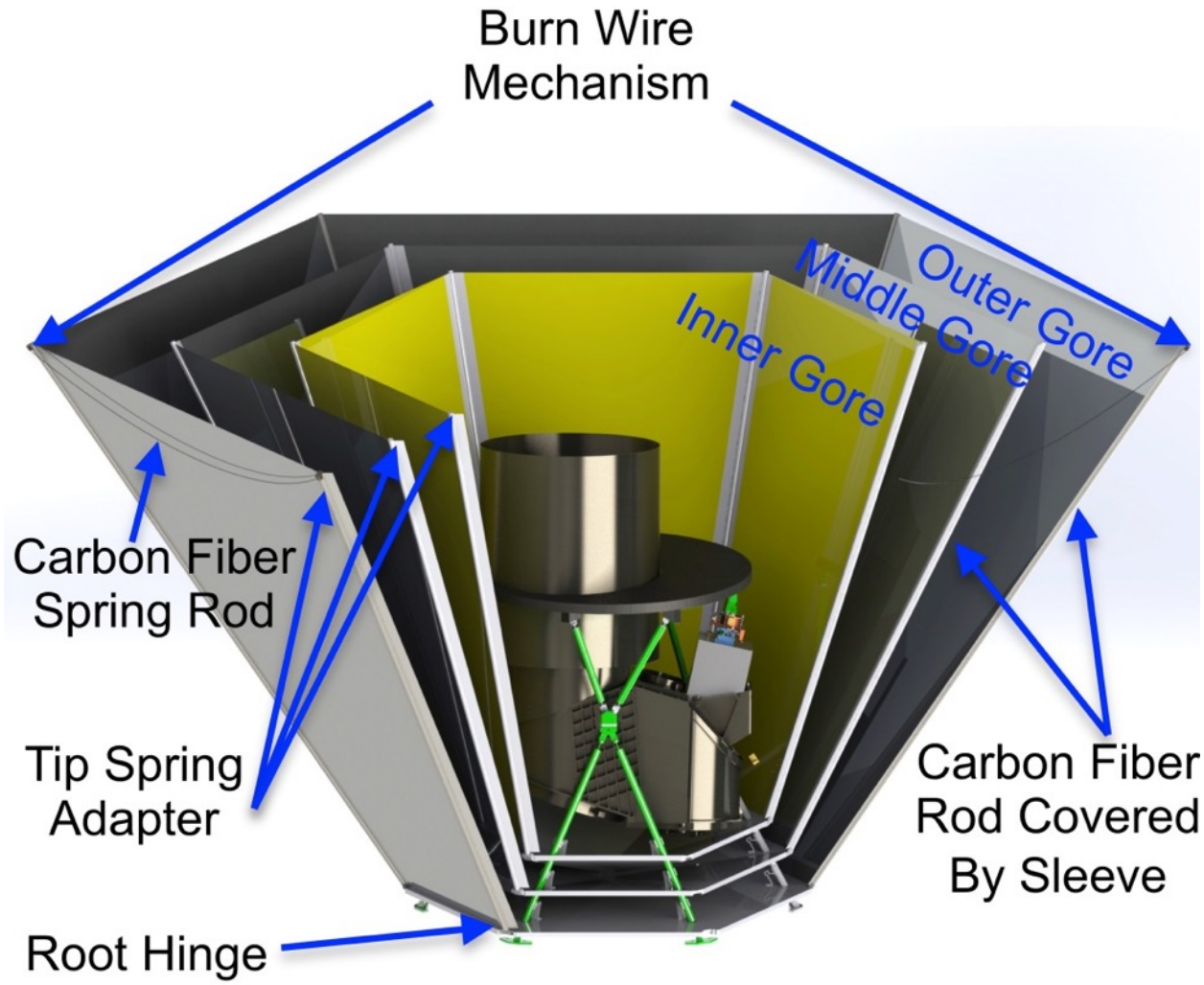
5.3um Radiator Requirement < 55K
expected 41K



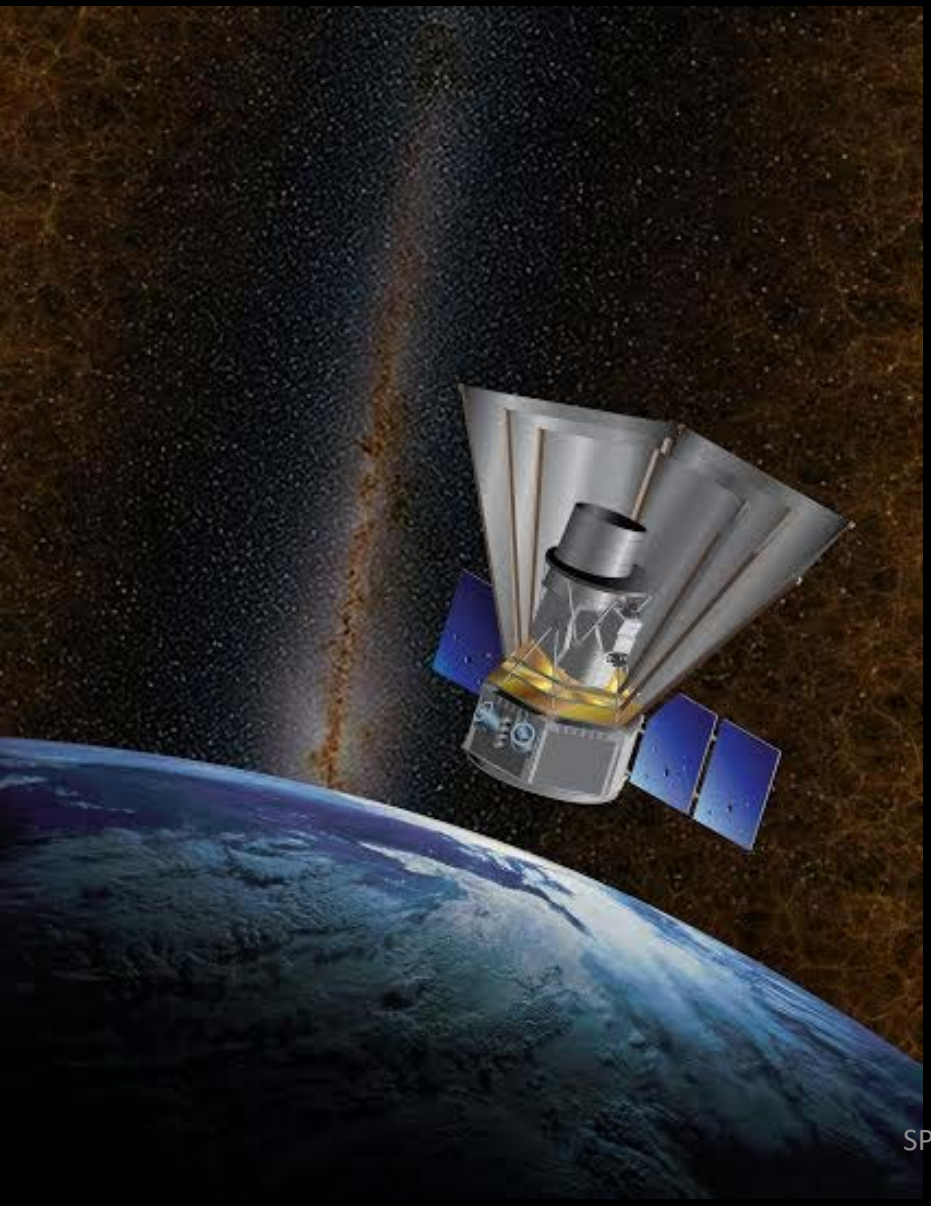
2.5um Detectors
Requirement < 80K
expected 54K

SPHEREx Passive Cooling System: Deployment

A system of Spring rods, hinges and a burn wire release mechanism allow for deployment once we are in orbit



Summary



- SPHEREx will measure f_nl really well
- SPHEREx will greatly increase our knowledge of ice absorbers in a wide range of envirionments
- SPHEREx will revolutionize our understanding of fluctuations in the NIR background

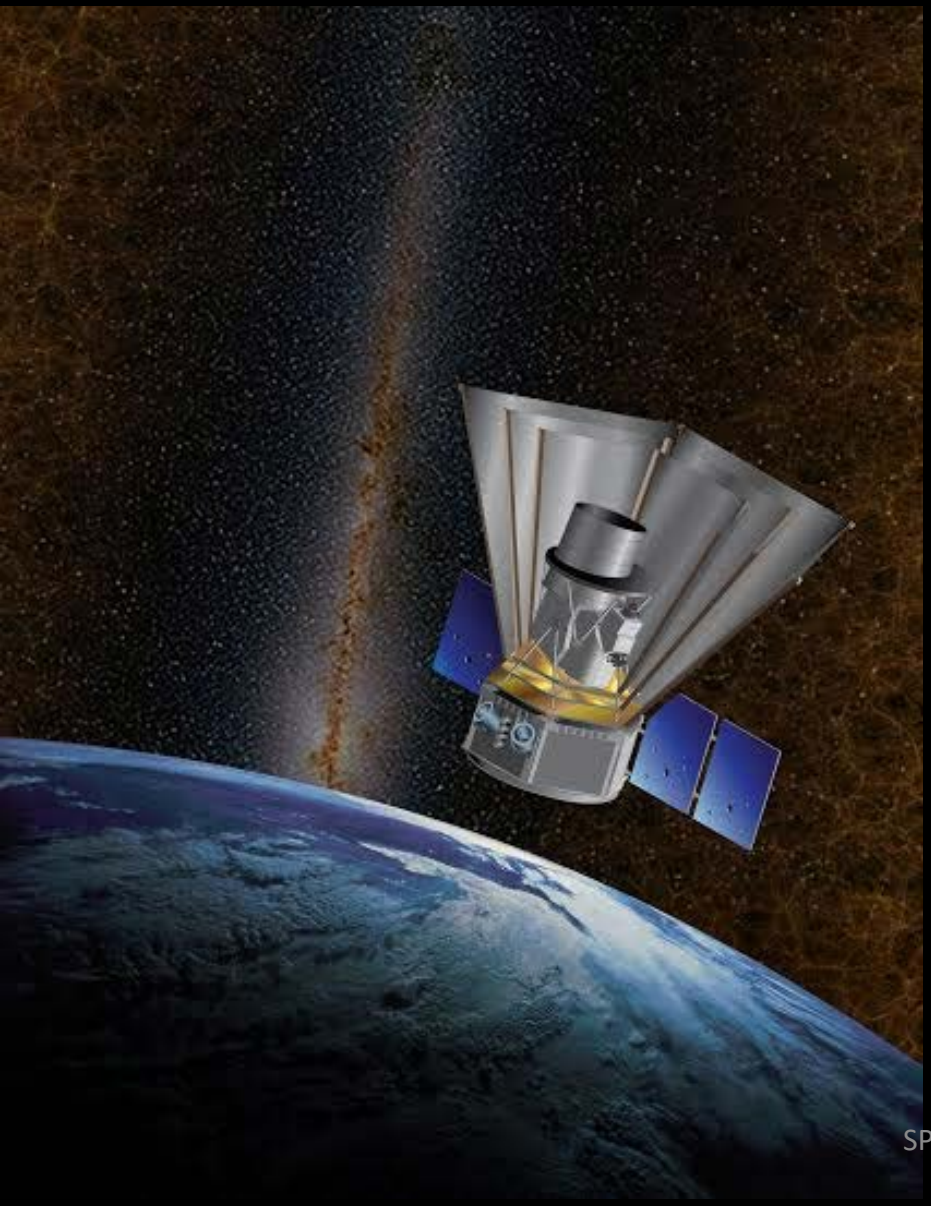
- The legacy of the all sky survey will provide spectra for the whole community

- The spacecraft implementation is robust with large margins

- Testbed work has demonstrated technology readiness

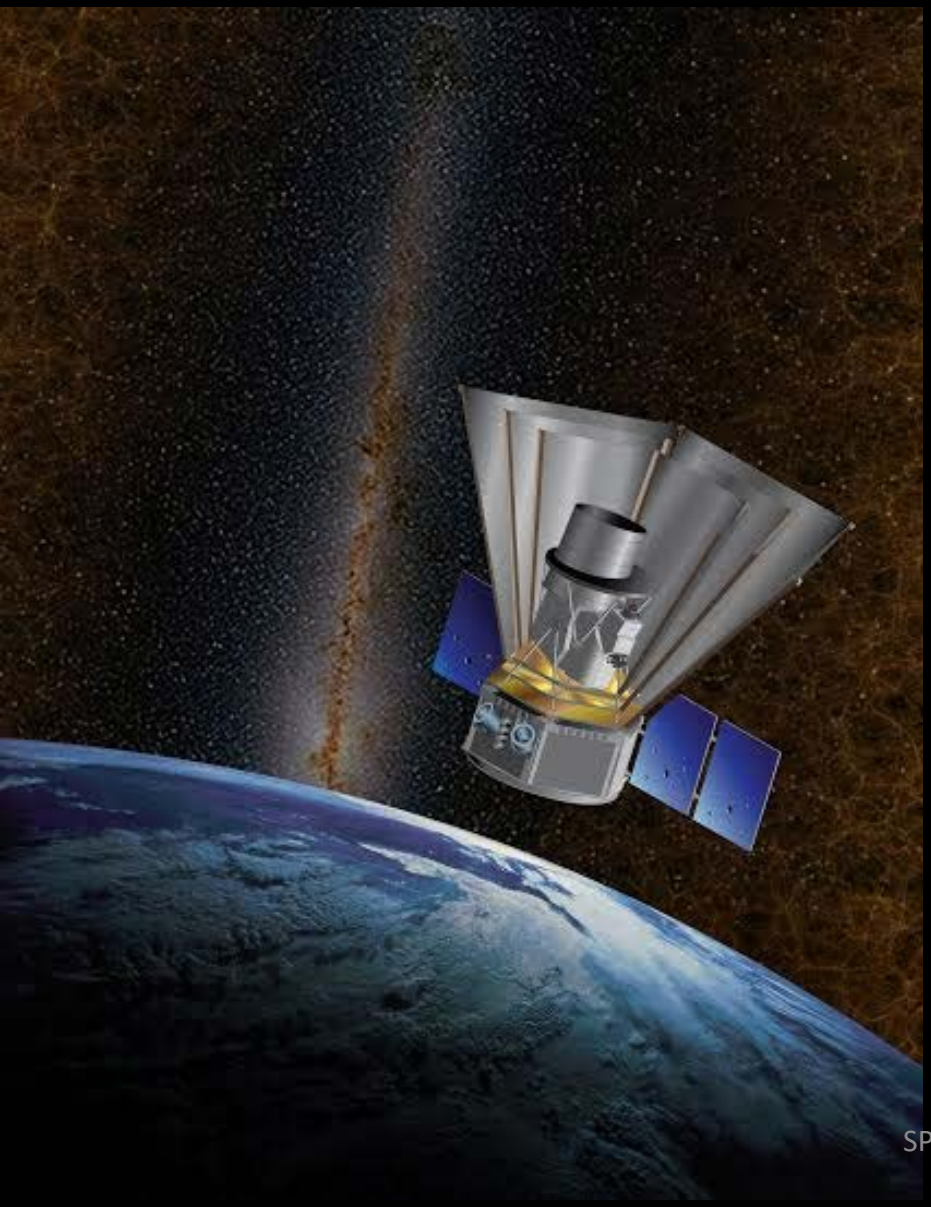
Backup

Backup



Phase A Demonstrations

SPHEREx: An All-Sky Spectral Survey



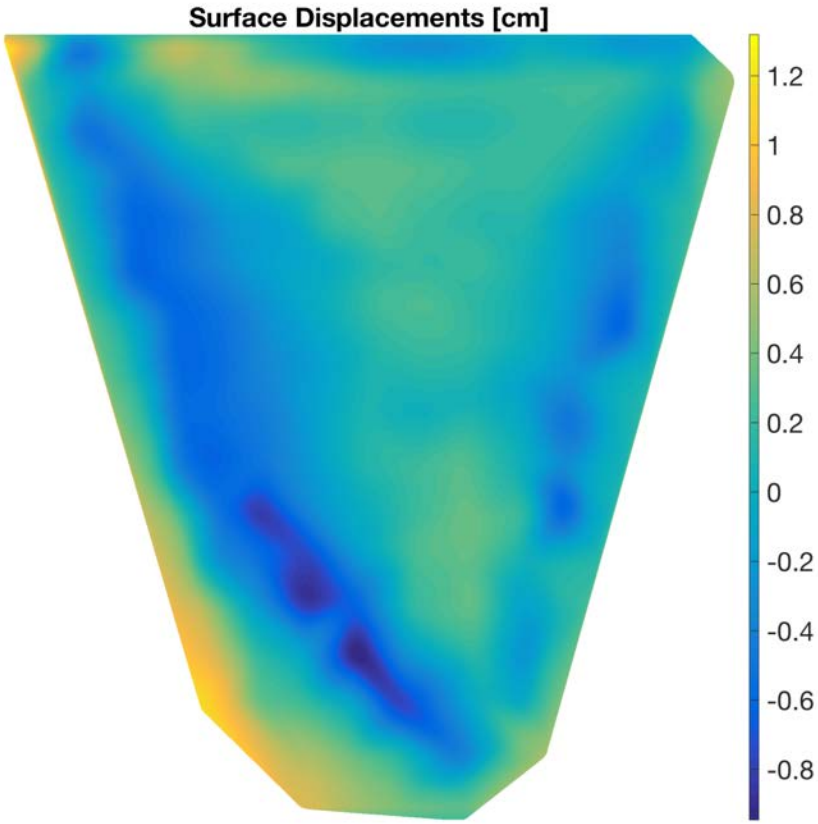
Phase A Demonstrations:

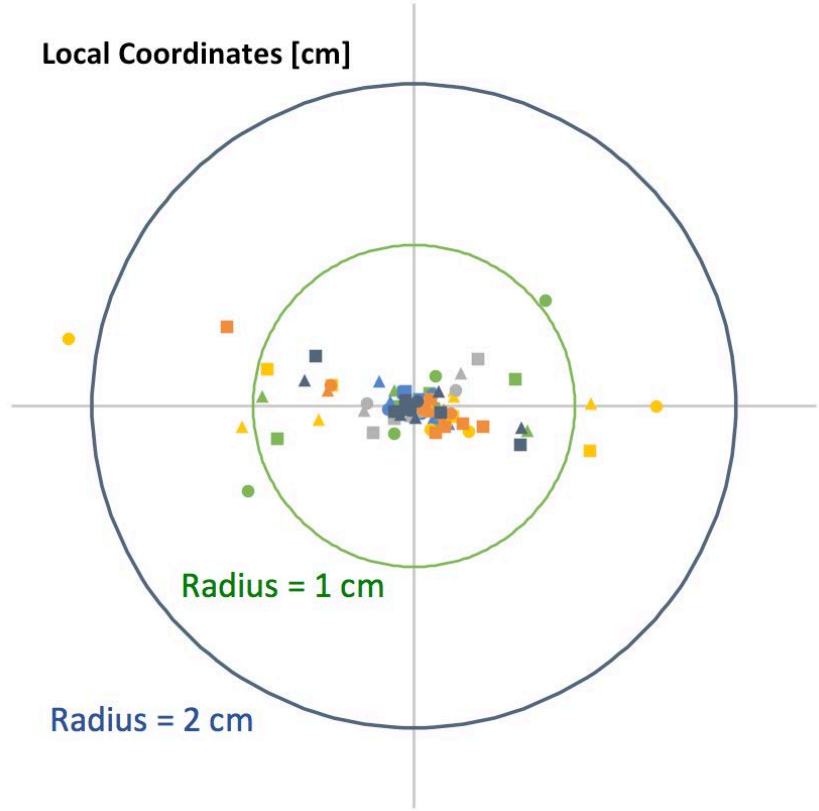
Deployment

Photon Shield deployment after vibration test

Spar Tip Position Measurements

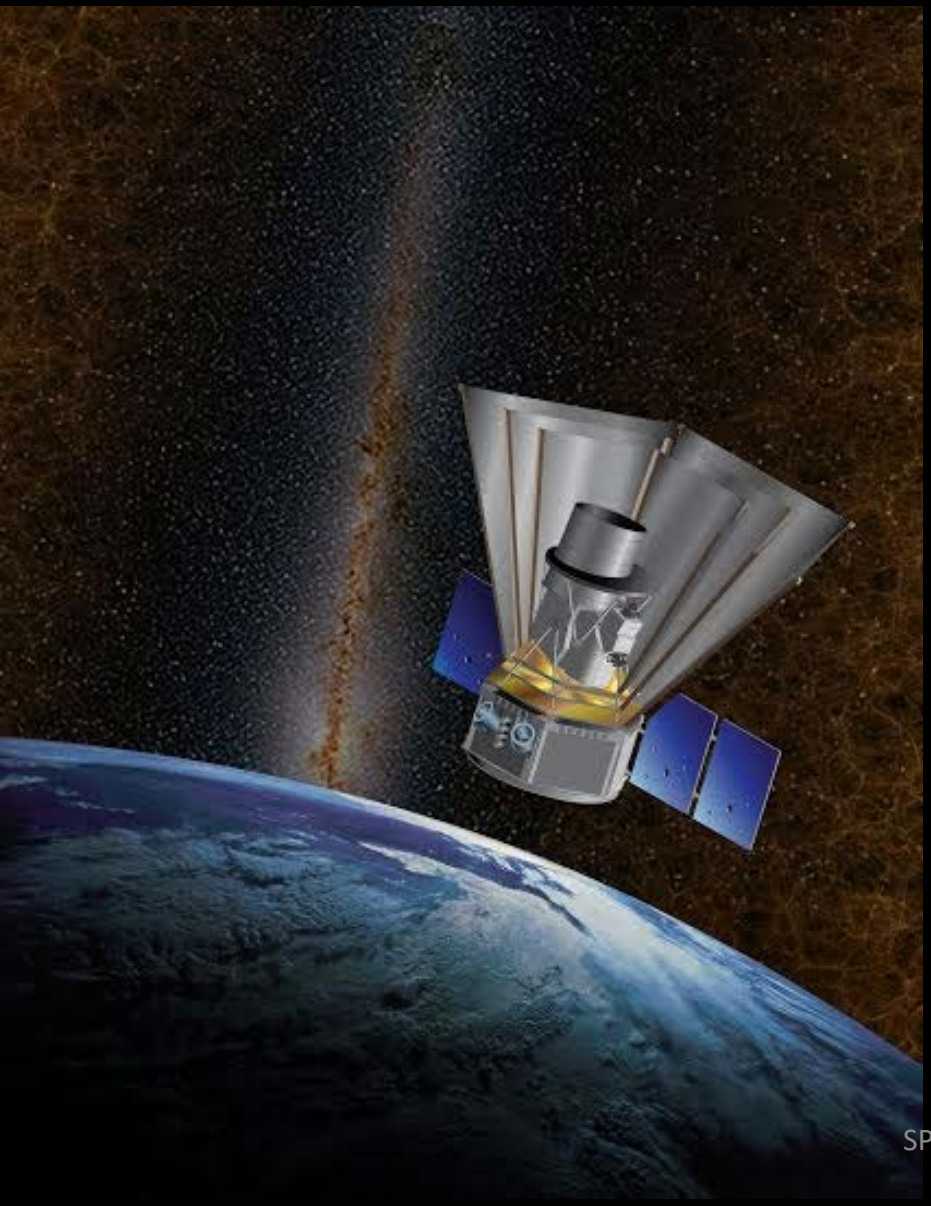
Requirement is within 4cm Radius





Surface RMS photogrammetry measurements

SPHEREx: An All-Sky Spectral Survey

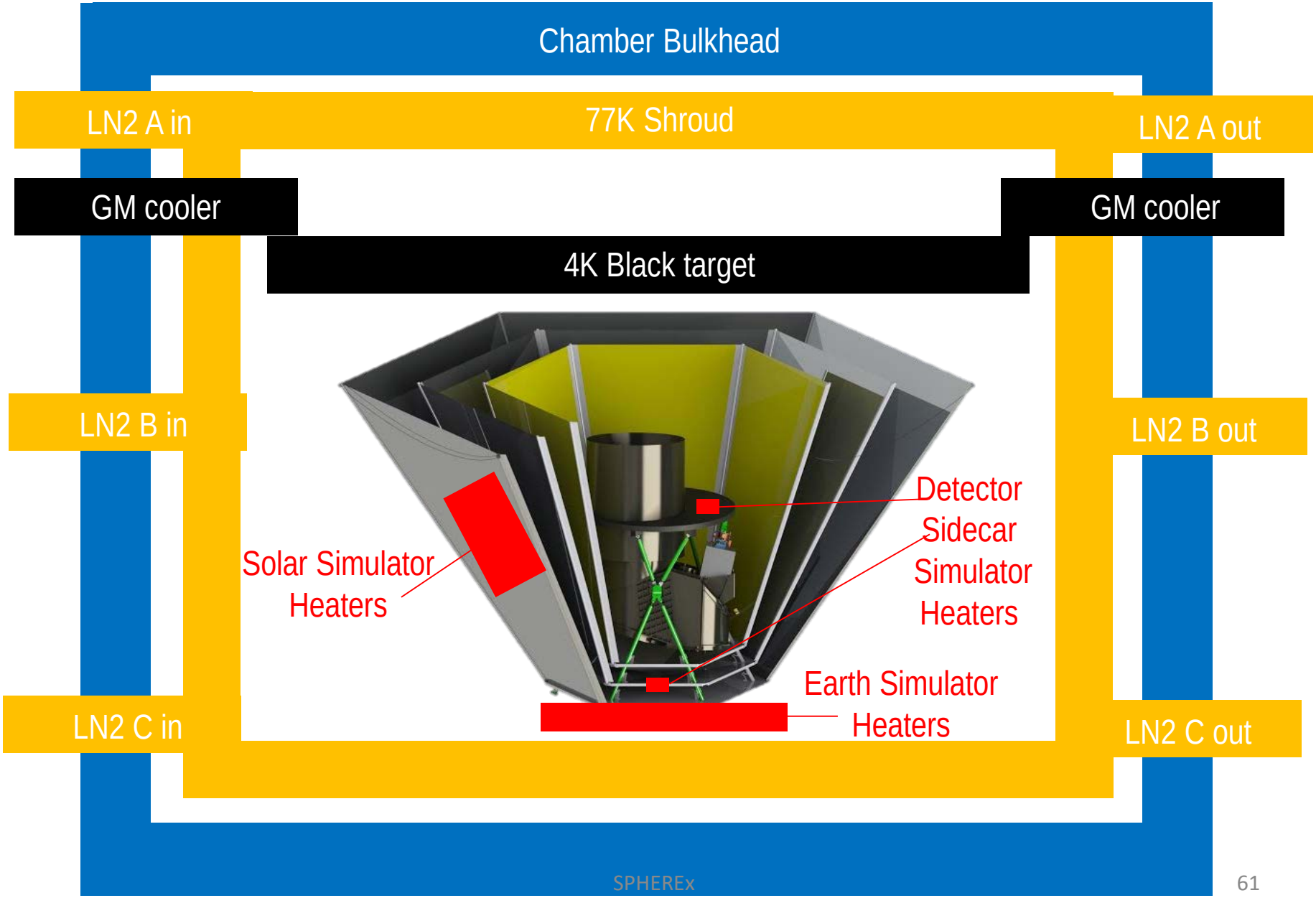


Phase A Demonstrations:

Thermal

Thermal Testbed Outline

Cool Down a ¼ scale model to demonstrate radiative cooling and thermal model

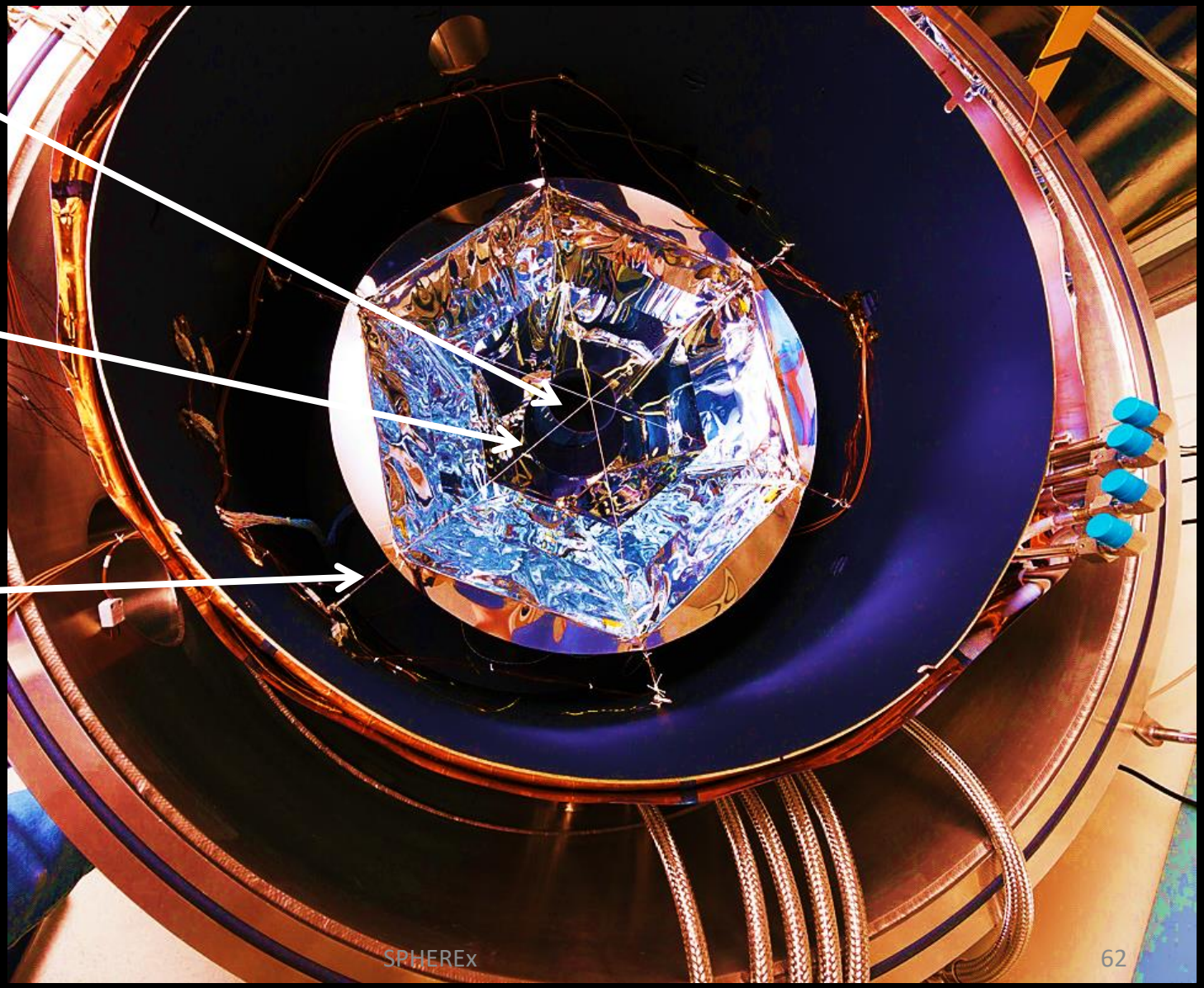


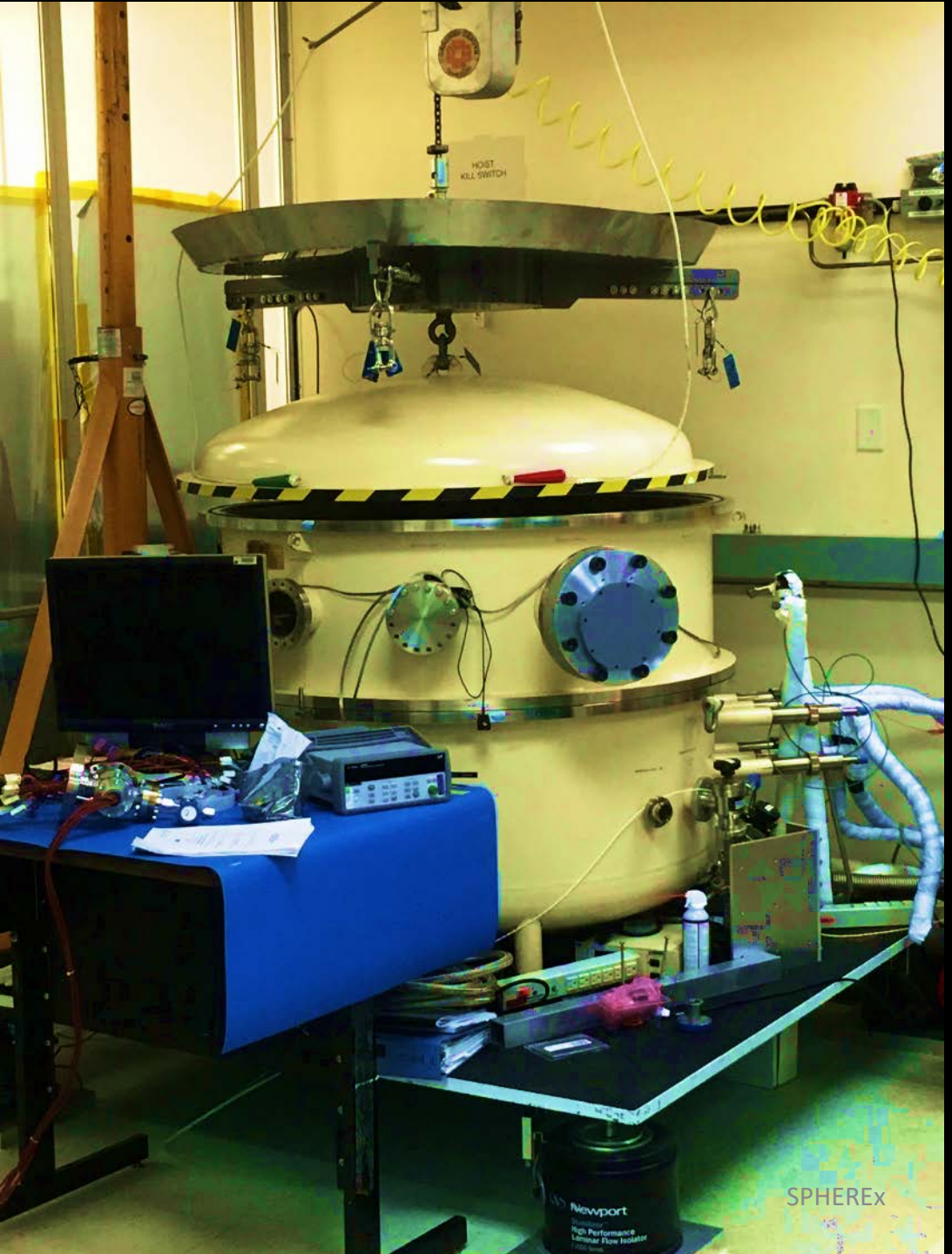
¼ scale model in the shroud

Optics thermal sim

FPA radiator thermal sim

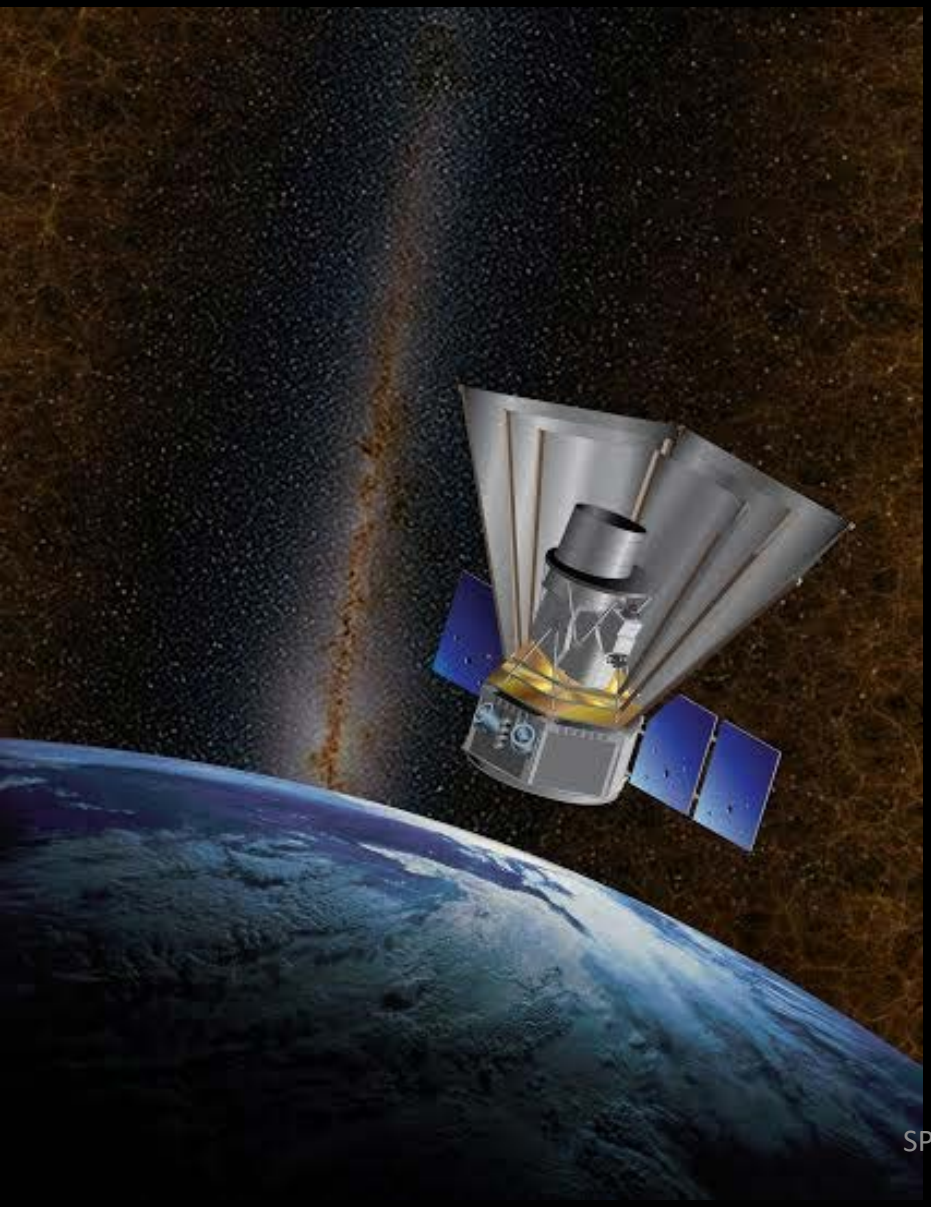
Target suspension





External view of the chamber

SPHEREx: An All-Sky Spectral Survey



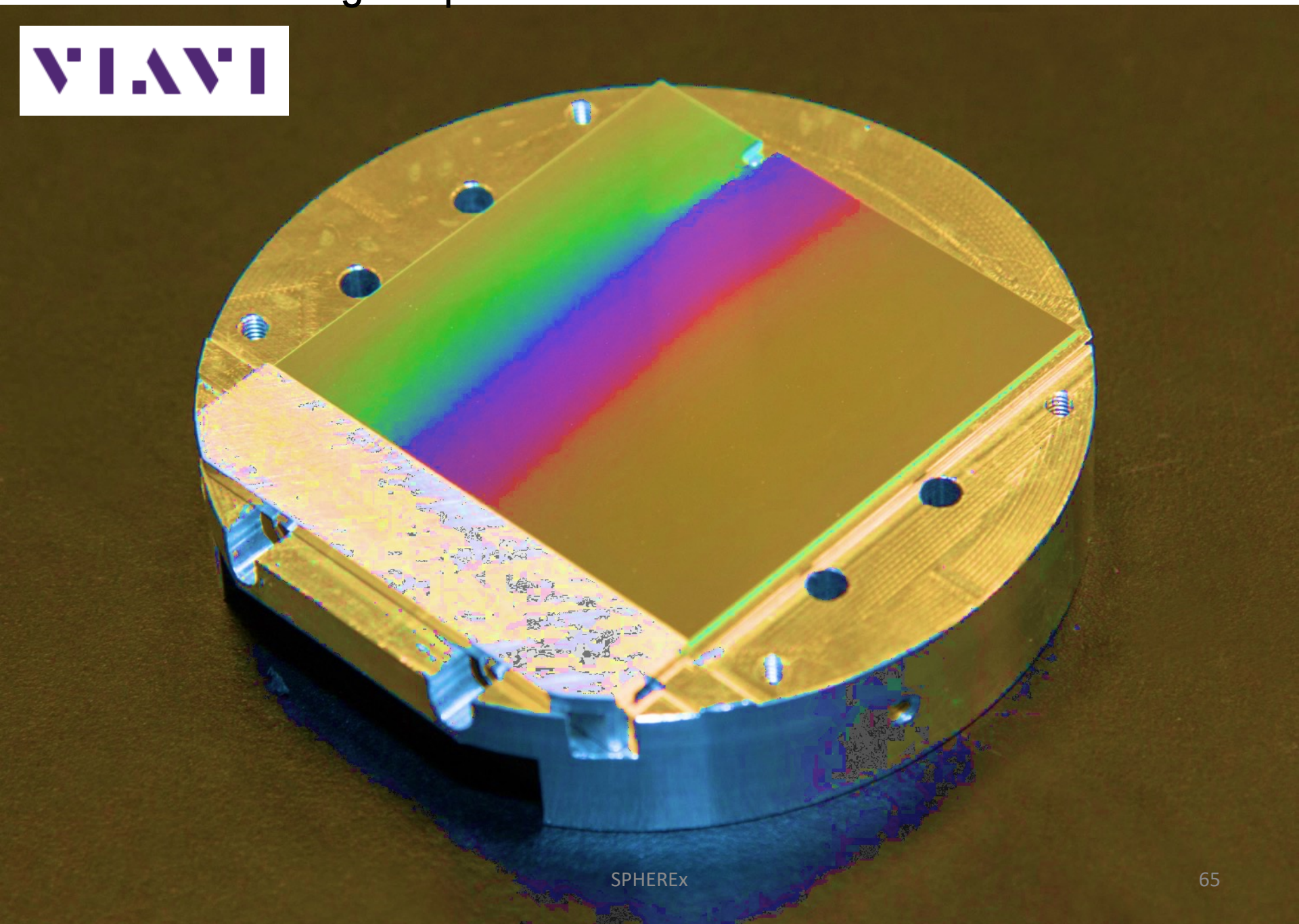
Phase A Demonstrations:

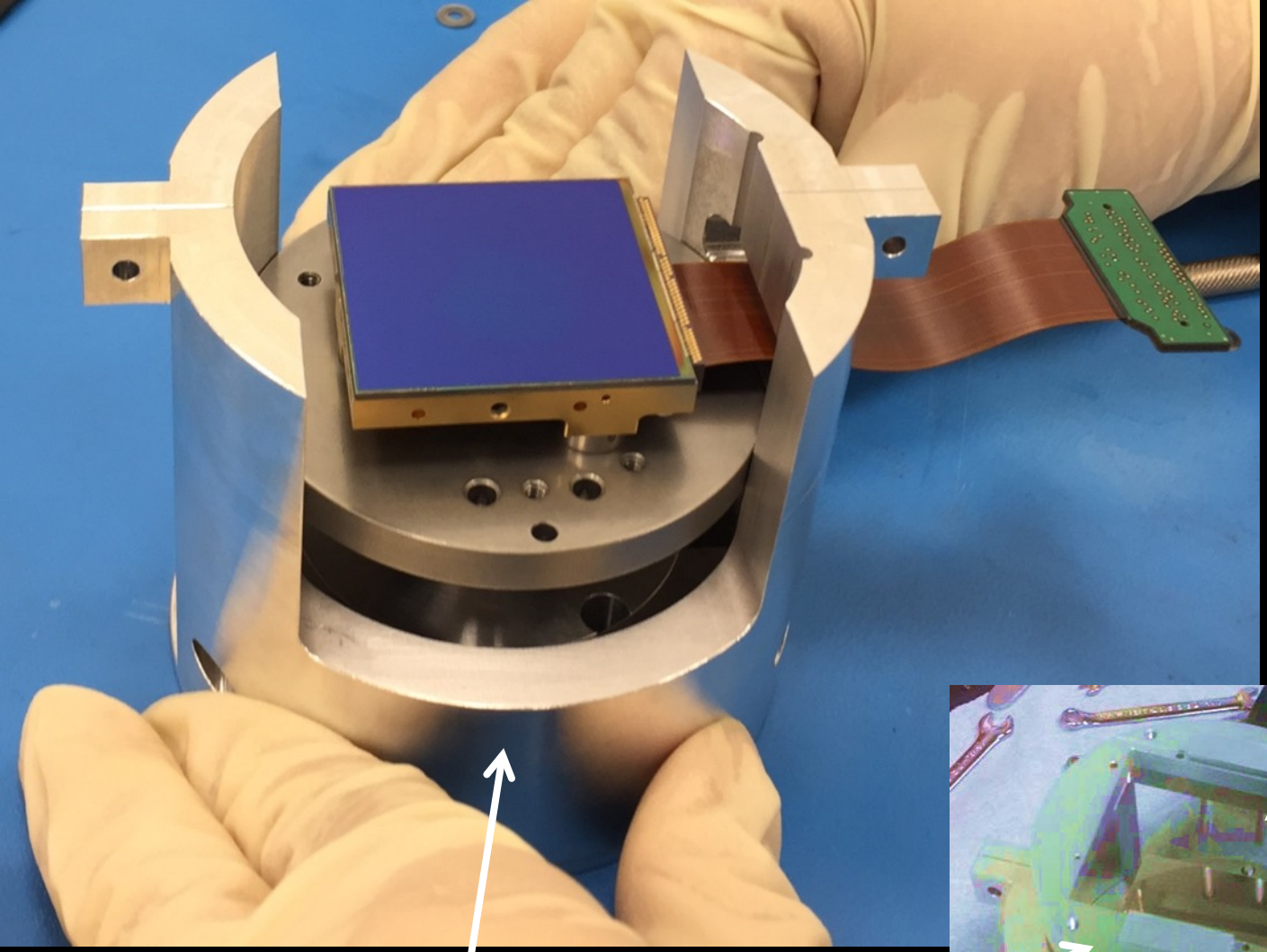
LVF Spectroscopy Lead: Phil Korngut

Goals:

- Fabricate custom SPHEREx band1 LVF to flight specifications
- Couple to H2RG with small separation
- Couple H2RG+LVF to the lab optically
- Measure the Wavelength Progression
- Verify Reflectances to quantify ghosts
- Verify Resolution performance

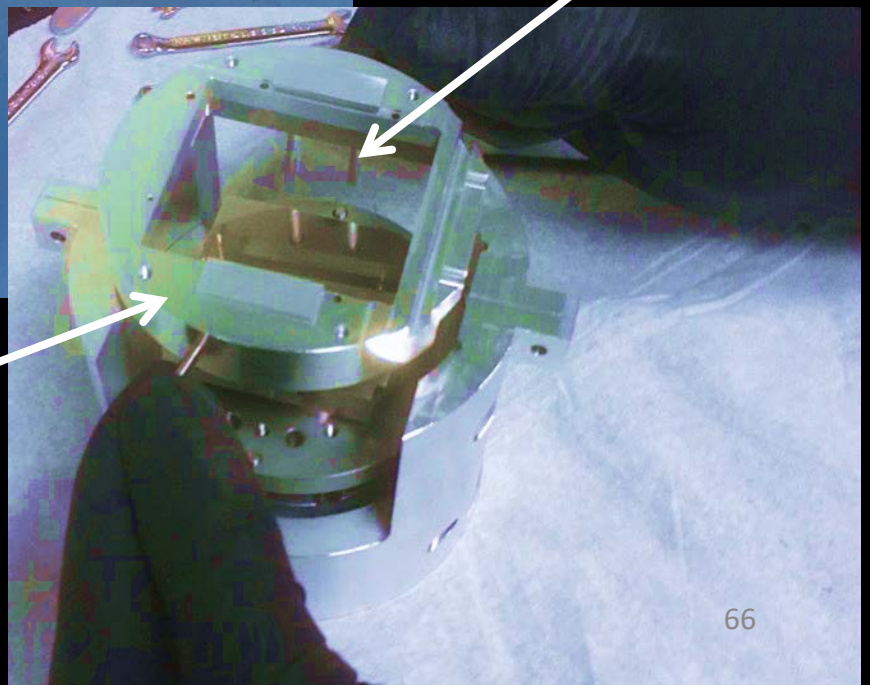
Flight Spec SPHEREx band 1 LVF



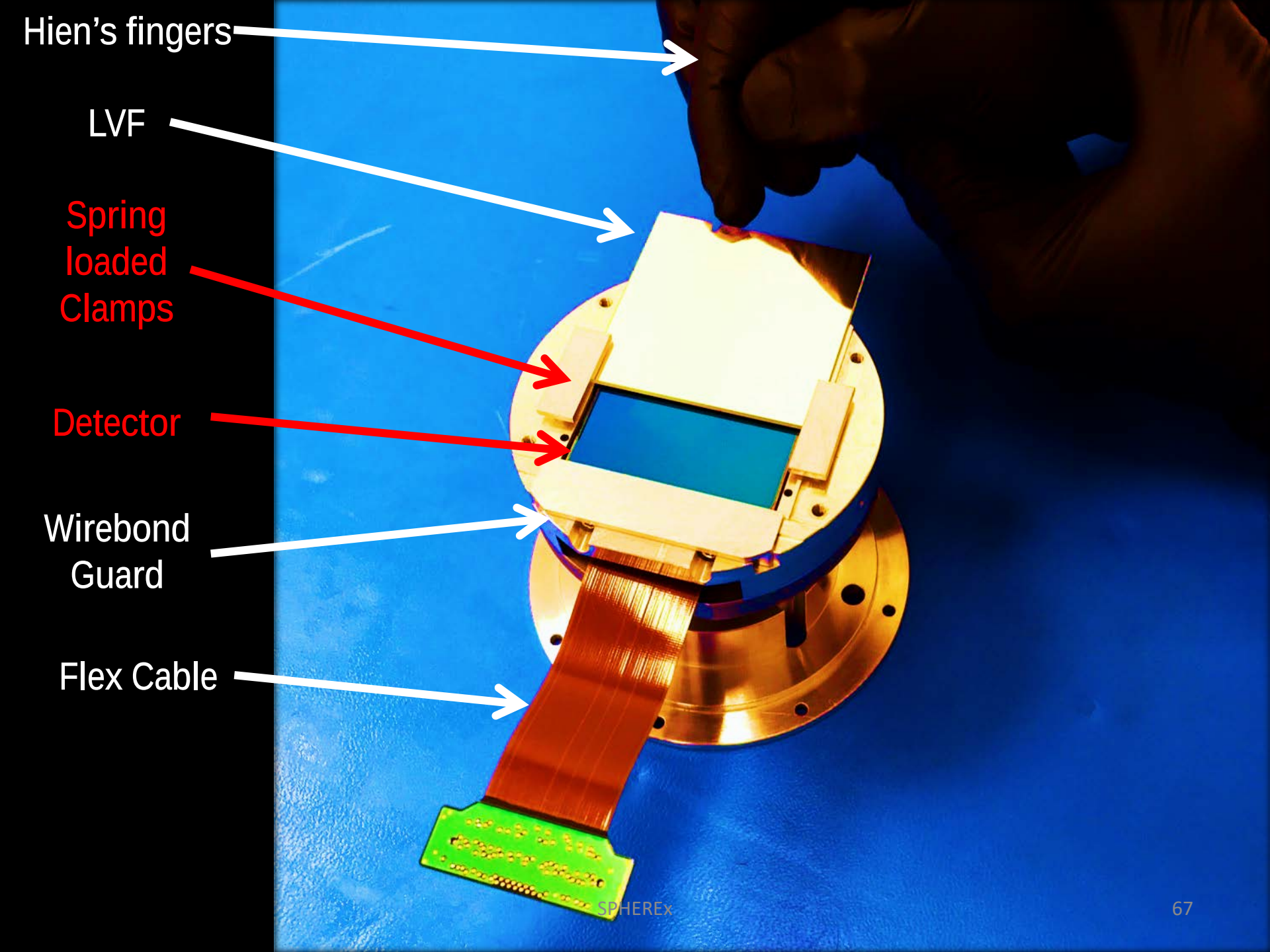


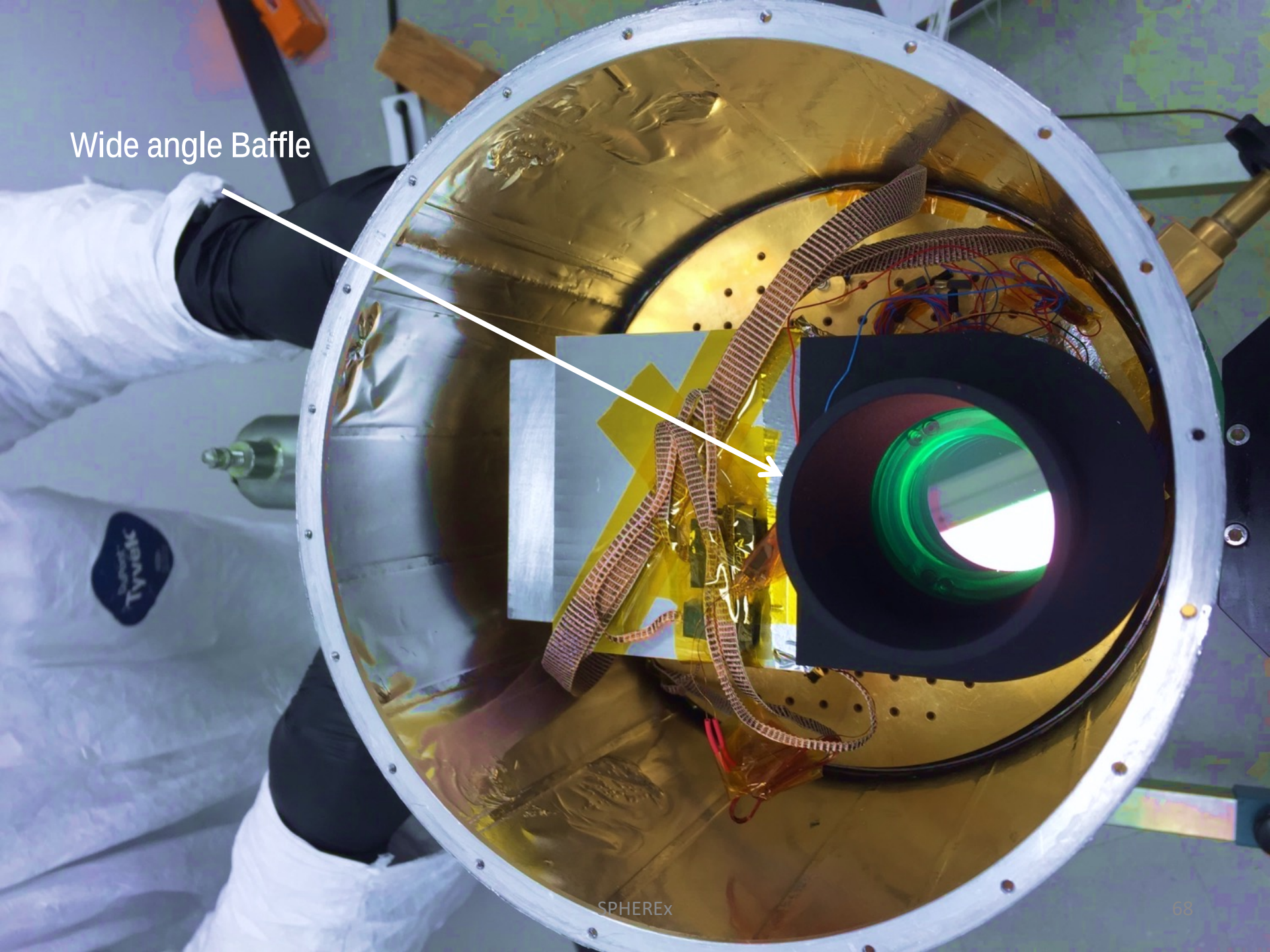
Assembly adapted from CIBER2 FPA design (Larry Wade and Alicia Lanz).

Spring clamp



Clamshell precision machined LVF holder and guide

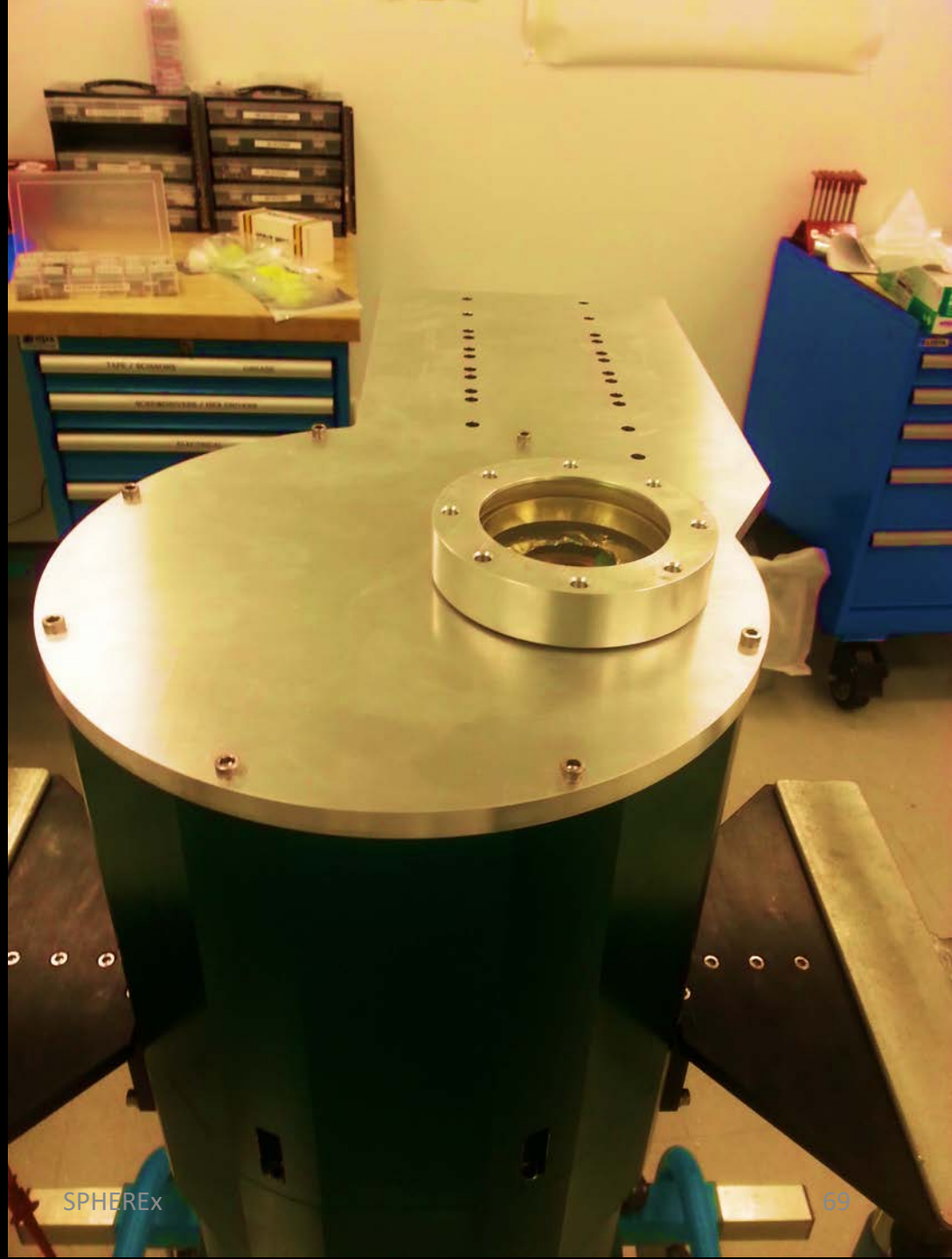

Hien's fingers
LVF
Spring loaded Clamps
Detector
Wirebond Guard
Flex Cable


Wide angle Baffle

Adapted 2 stage IR labs dewar for the cryo.

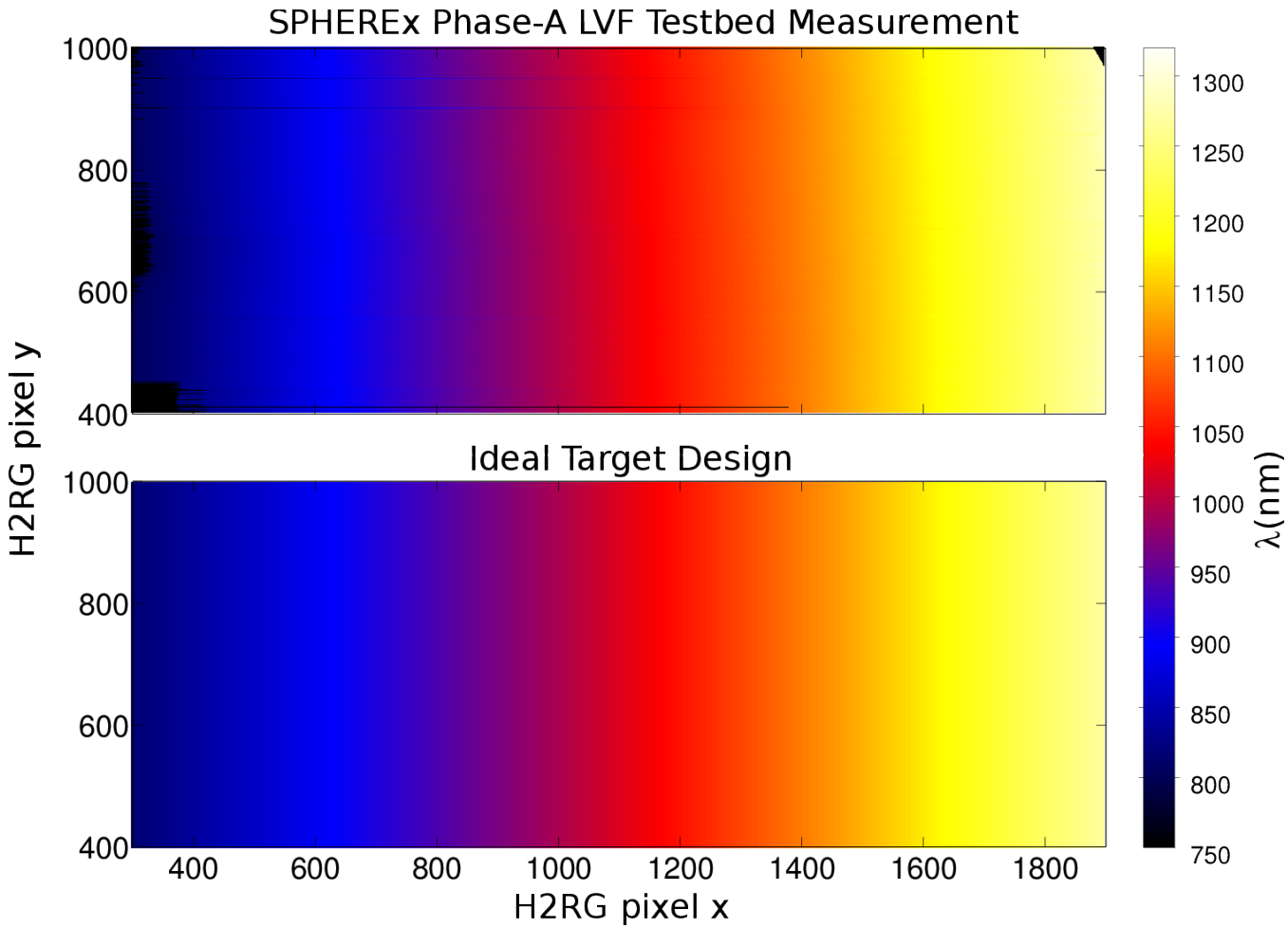
Bulkhead includes optical bench mount.

Zerodur Window



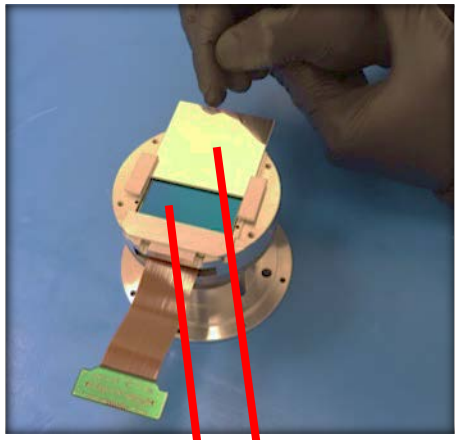
LVF + H2RG System Spectral Calibration

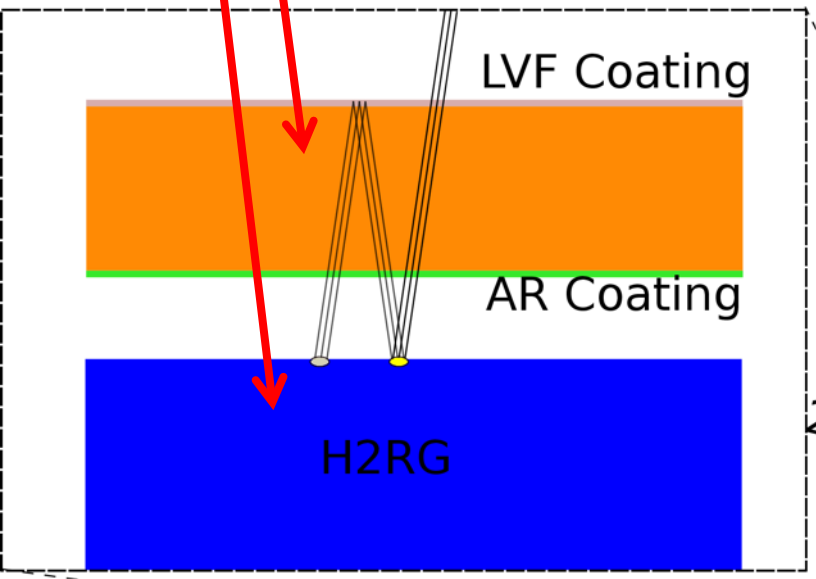
zero free parameters or prior knowledge

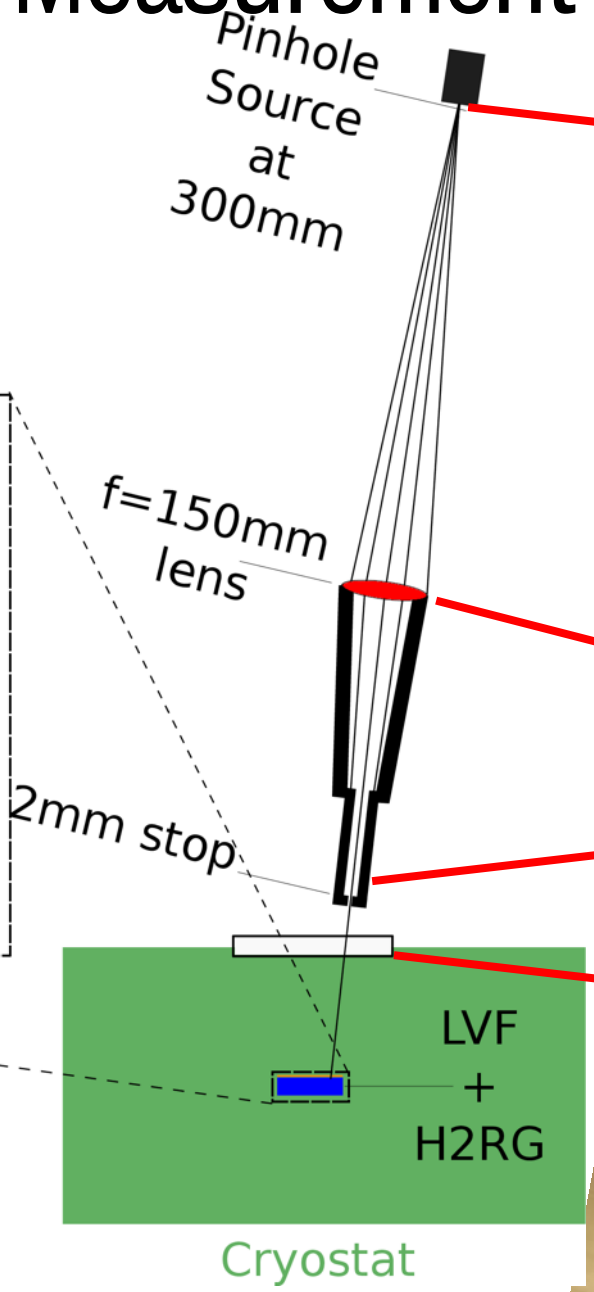


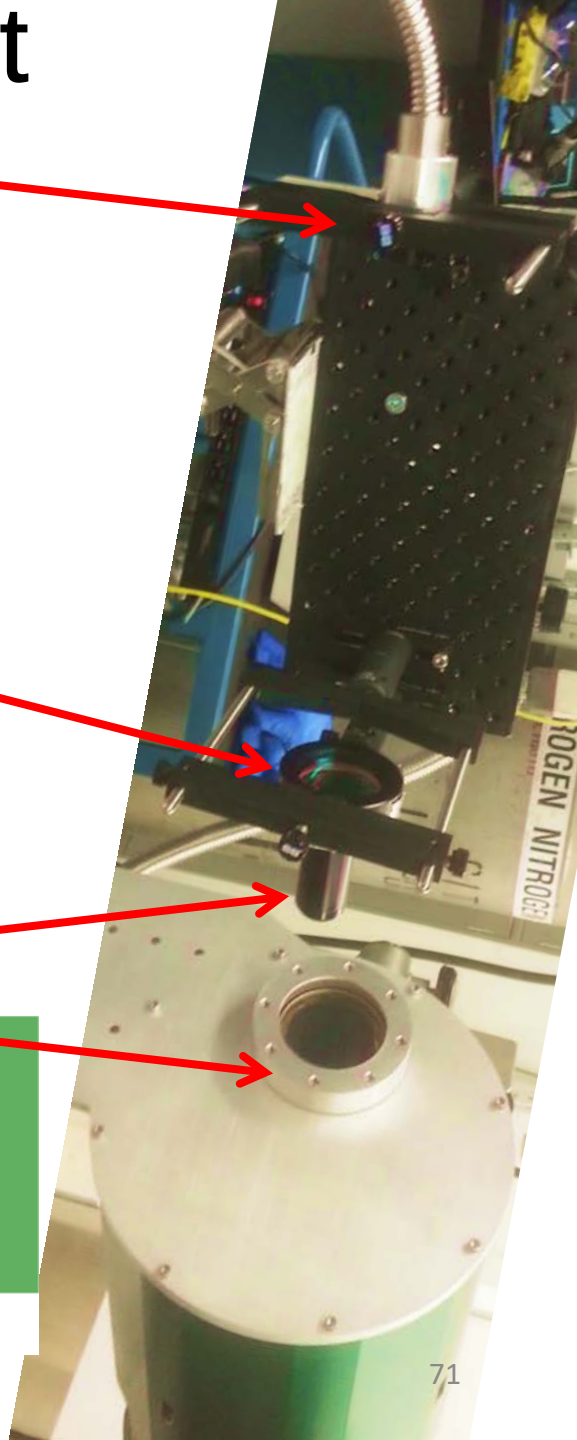
They are almost identical!

Ghost Measurement Setup

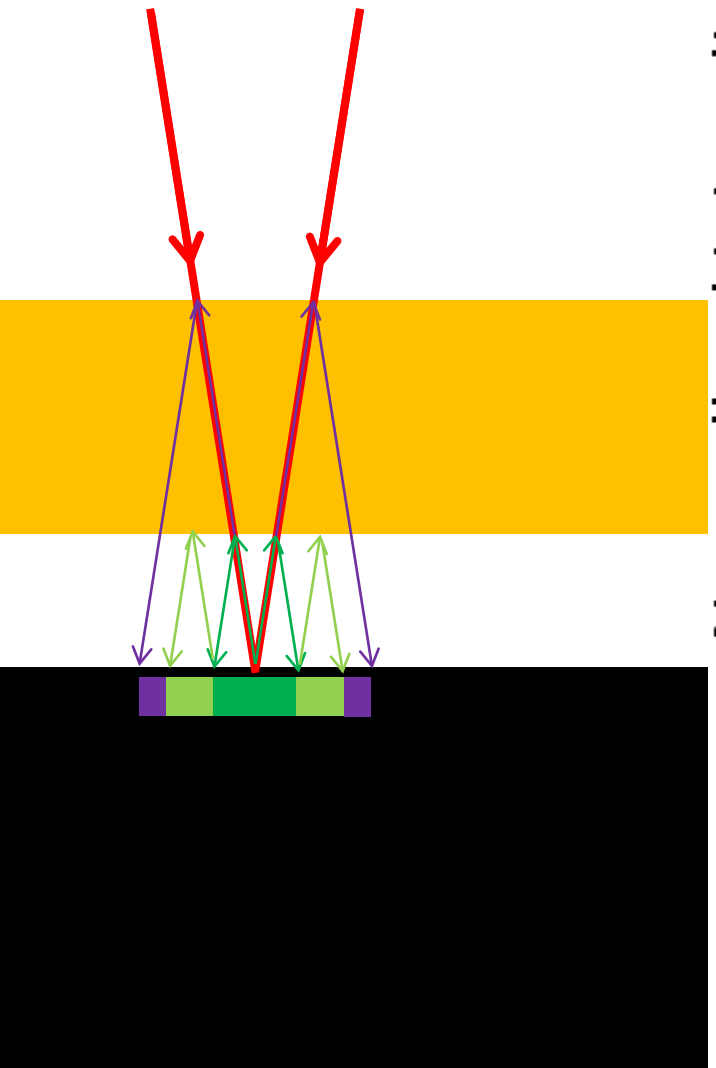
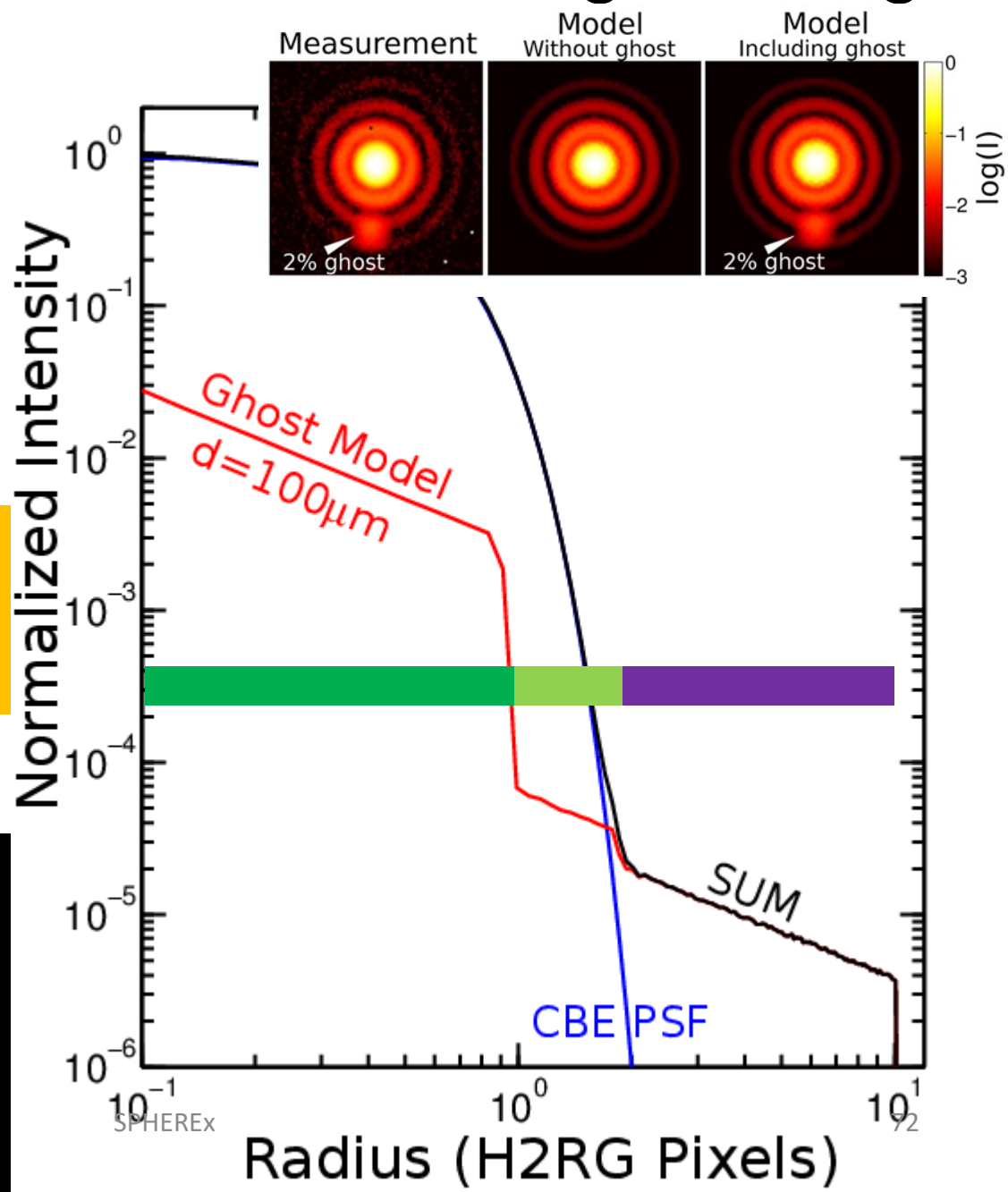








Goal is to bring nearly parallel rays in to the array at a high angle of incidence.

Implications for SPHEREx Flight design

Flight Model for an f/3 telecentric light cone, flipped LVF and 100um gap