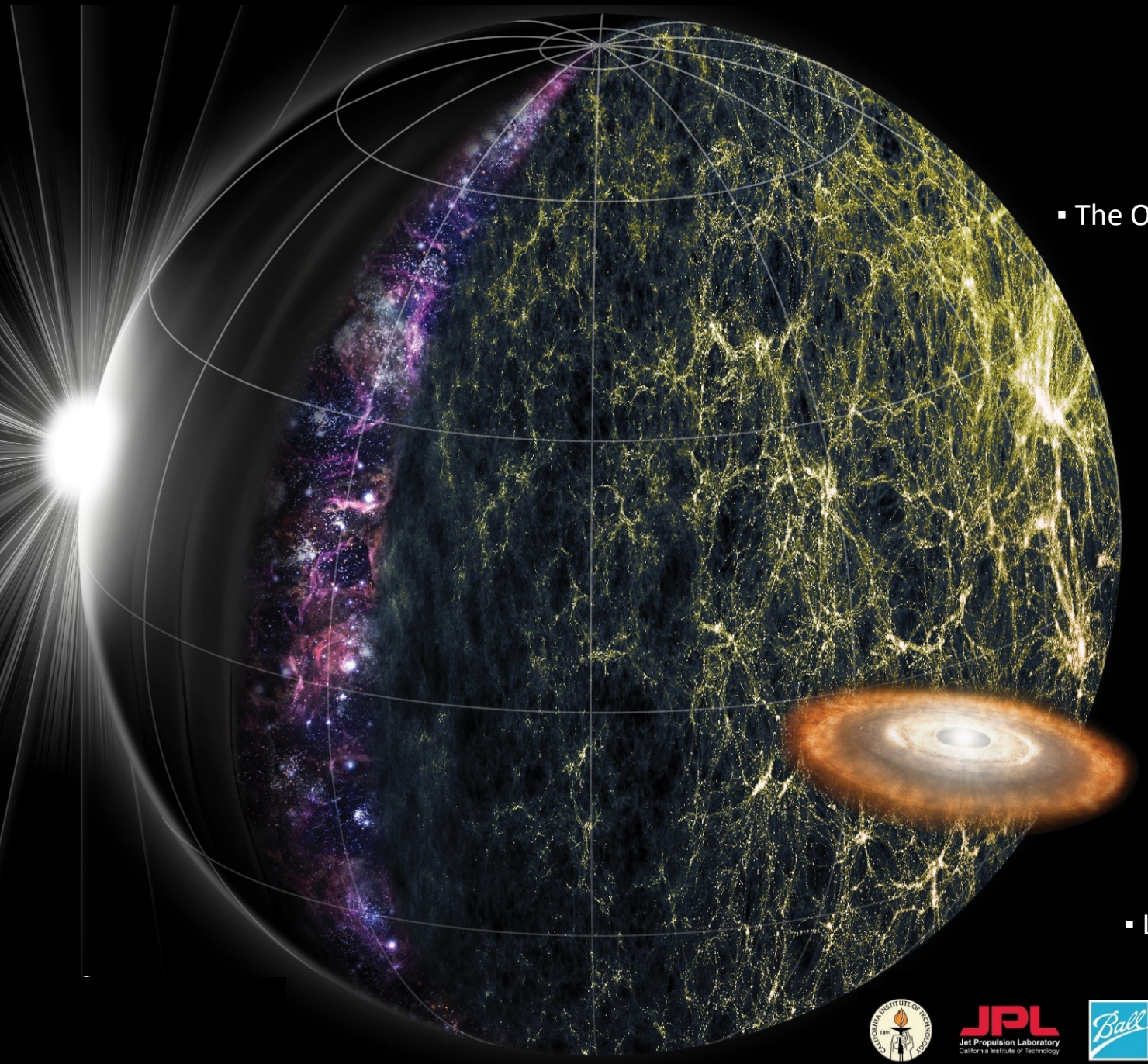
SPHEREx: An All-Sky Spectral Survey



Designed to Explore

- The Origin of the Universe
- The Origin and History of Galaxies
- The Origin of Water in Planetary Systems

The First All-Sky Near-IR Spectral Survey

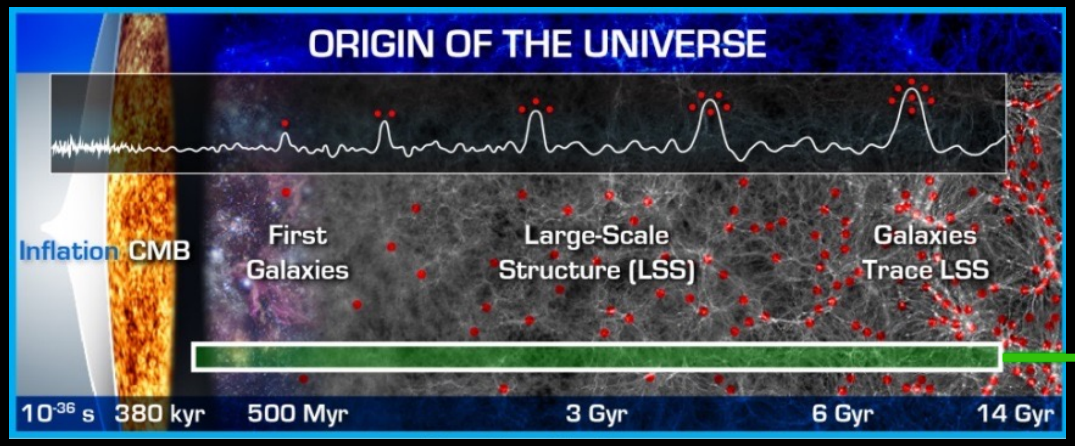
A Rich Legacy Archive for the Astronomy Community with 100s of Millions of Stars and Galaxies

Low-Risk Implementation

- Single Observing Mode
- No Moving Parts
- Large Technical & Scientific Margins

Caltech JPL Jet Propulsion Laboratory California Institute of Technology Ball ipac CfA UCI The Ohio State University

SPHEREx Addresses Three Main Astrophysics Questions



Time Since Big Bang

Time Since Big Bang

Stages of Star Formation

Map the large scale structure of galaxies to study the process of Inflation in the early universe, addressing NASA's objective to *Probe the origin and destiny of the Universe.*

Measure the total light production from stars and galaxies across cosmic history, addressing NASA's objective to *Explore the origin and evolution of galaxies.*

Determine how interstellar ices bring water and organics into proto-planetary systems, furthering NASA's objective to *Explore whether planets around other stars could harbor life.*

SPHEREx Team

Science Team

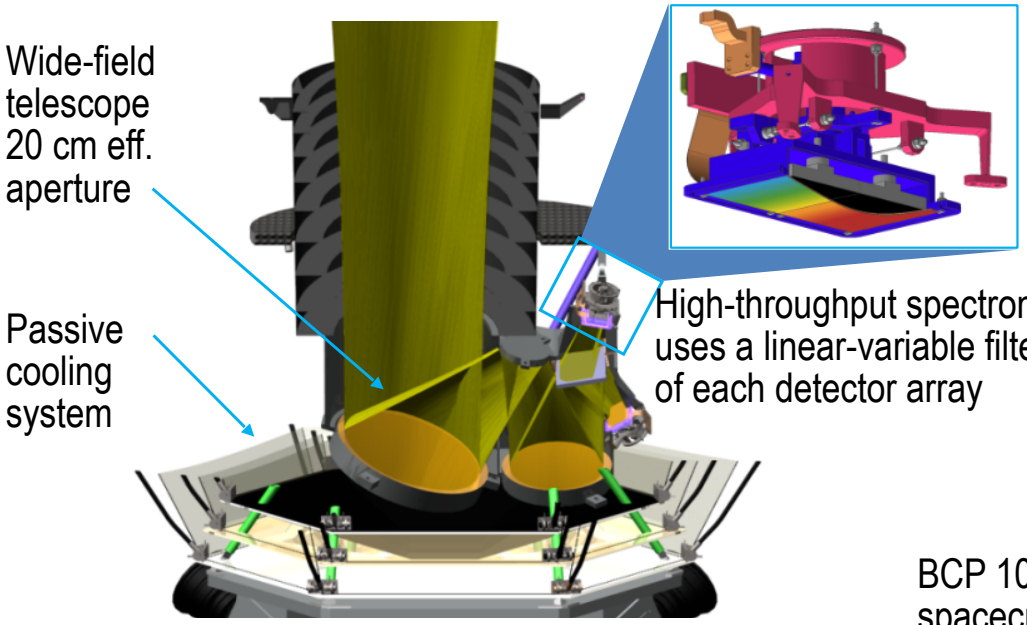
Name	Institution	Role	Responsibility
Jamie Bock	Caltech/JPL	PI	Principal investigator, overall management
Matt Ashby	CfA	Co-I	Pipeline development
Peter Capak	IPAC	Co-I	Galaxy spectral fitting modules
Asantha Cooray	UC Irvine	Co-I	Galaxy Formation L4 lead
Olivier Doré	JPL/Caltech	PS	Project scientist; Inflationary Cosmology L4 lead
Chris Hirata	OSU	Co-I	Inflation and Cosmology studies
Woong-Seob Jeong	KASI	Co-I	KASI PI
Phil Korngut	Caltech	Co-I	Deputy instrument scientist
Dae-Hee Lee	KASI	Co-I	Ground test equipment
Gary Melnick	CfA	Co-I	Galactic Ice L4 lead
Roger Smith	Caltech	Co-I	Detector array development
Yong-Seon Song	KASI	Co-I	Cosmology interpretation
Stephen Unwin	JPL	Co-I	Galactic ice science
Michael Werner	JPL	Co-I	Legacy survey science
Michael Zemcov	Caltech	Co-I	Instrument scientist

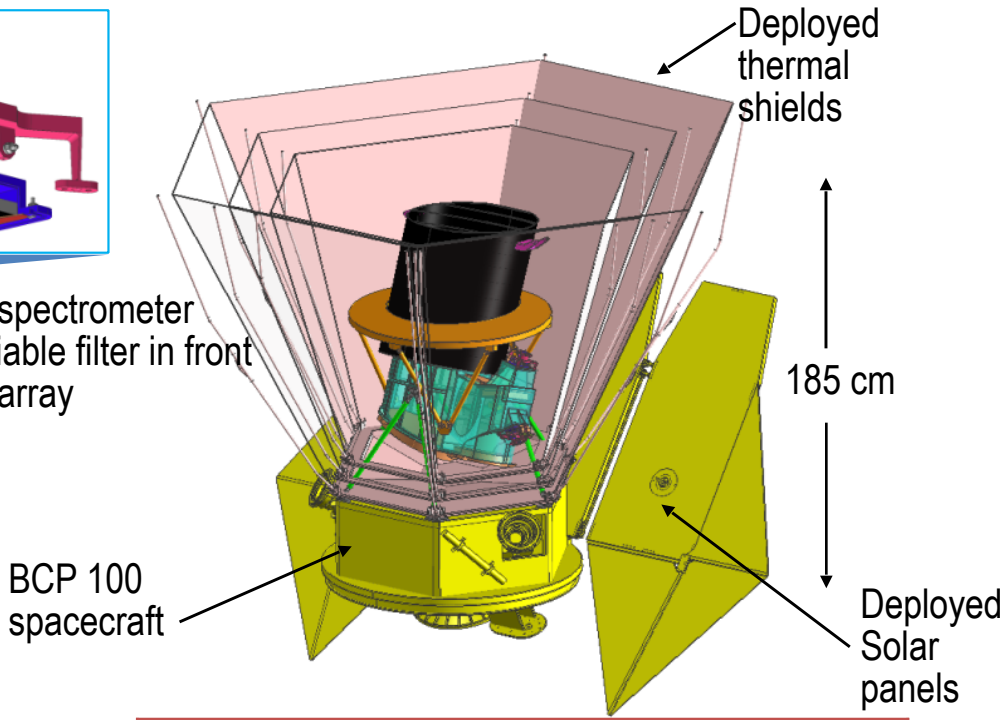
Collaborators

Name	Institution
Roland de Putter	JPL
Tim Eifler	JPL
Nicolas Flagey	IfA
Yan Gong	UC Irvine
Elisabeth Krause	Stanford
Daniel Masters	Caltech
Phil Mauskopf	ASU
Bertrand Menneson	JPL
Hien Nguyen	JPL
Karin Öberg	CfA
Anthony Pullen	CMU
Alvise Raccanelli	JHU
Volker Tolls	CfA
Salman Habib	Argonne
Katrin Heitmann	Argonne
Marco Viero	Stanford

Competed in Dec 2014 SMEX; Selected by NASA for a Phase-A study in July 2015.
Phase A report due in July 2016.
Phase A down-selection ~ December 2016

SPHEREx: Simple Instrument, Large Margins



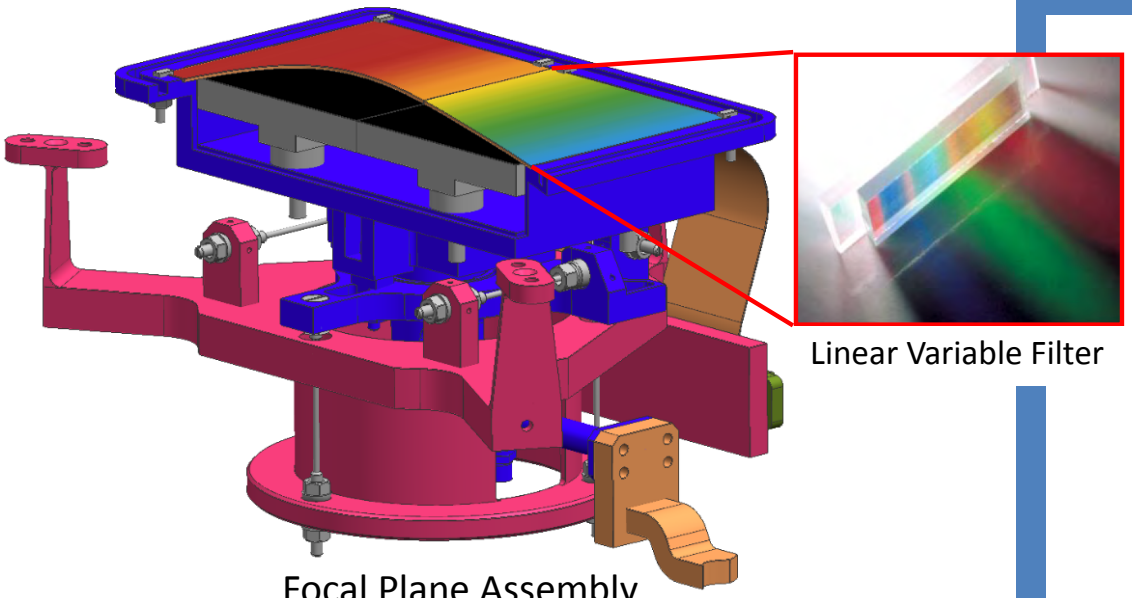


Parameter	Value
Telescope Effective Aperture	*20 cm*
Pixel Size	*6.2" x 6.2"*
Field of View	*2 x (3.5° x 7.0°); dichroic*
Spectrometer	*Linear-Variable Filters*
Resolving Power and Wavelength Coverage	*R=41.5 λ=0.75 - 4.1 µm* *R=150 λ=4.1 - 4.8 µm*
Arrays	*2 x Hawaii-2RG 2.5 µm* *2 x Hawaii-2RG 5.3 µm*
Point Source Sensitivity (MEV Performance)	*18.5 AB mag (5σ) with 300% margin to req't*
Cooling	*All-Passive*
2.5 µm Array and Optics Temperature (Req't)	*80 K with 700% margin on total heat load*
5.3 µm Array Temperature (Req't)	*55 K with 450% margin on total heat load*
Payload Mass	*68.1 kg (CBE+31% Ctg)*
Payload Power	*27.8 W (CBE+30% Ctg)*

Parameter	Performance	Margin
Spacecraft	*Ball BCP 100*	N/A
Science Data Downlink	*73 Gb/day*	97%
Pointing Stability	*2.1" (1σ) over 200 s*	43%
Pointing Control	*22.7" (1σ)*	164%
Pointing Agility	*70º in 116 s (large slews)* *8.8' in 6 s (small steps)*	29% 233%
Observatory Mass	*173.6 kg (MEV)*	53%
Observatory Power	*171.8 W (MEV)*	36%
Solar Array Power Output (EOL)	*234 W*	N/A

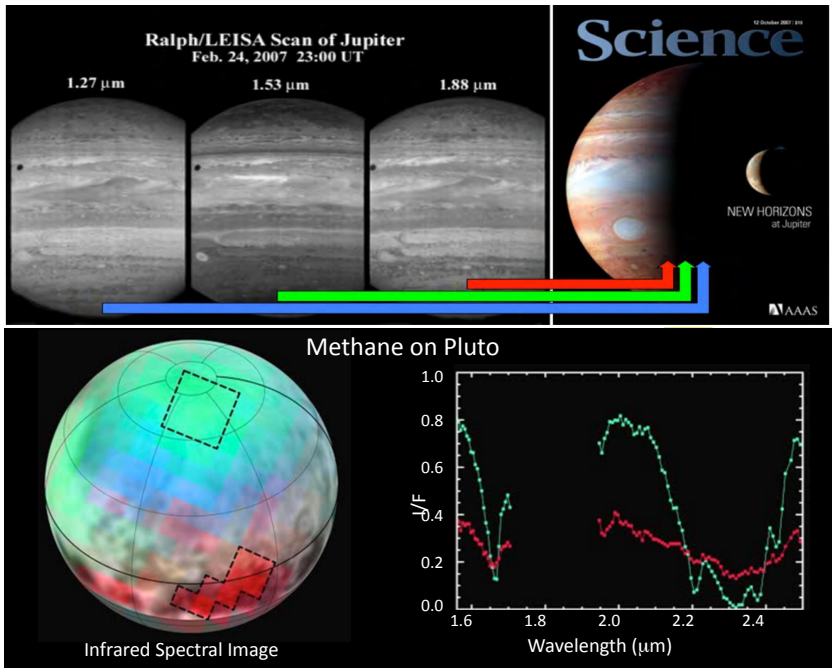
Margins: Thermal Science

High-Throughput LVF Spectrometer

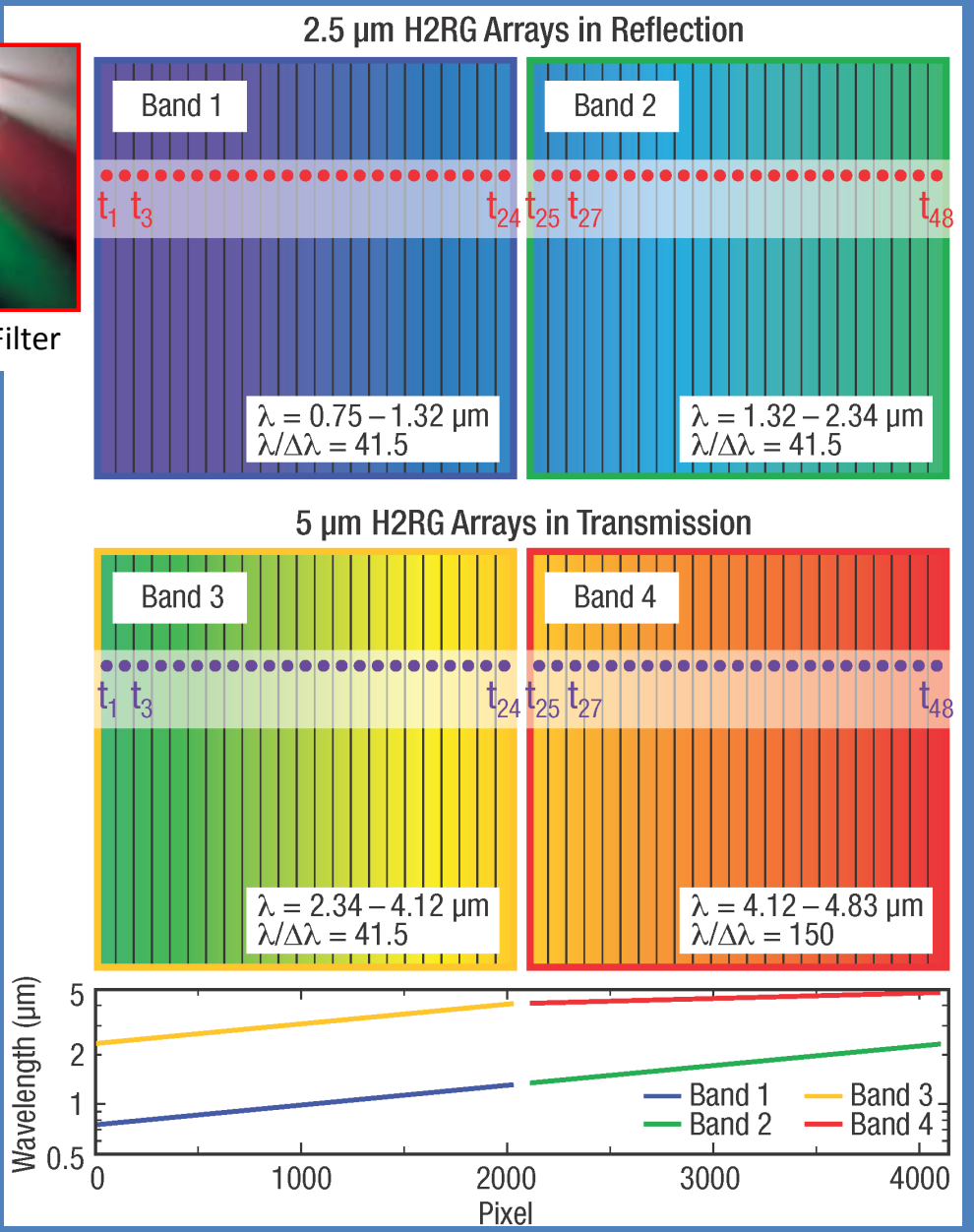


Linear Variable Filter

Focal Plane Assembly

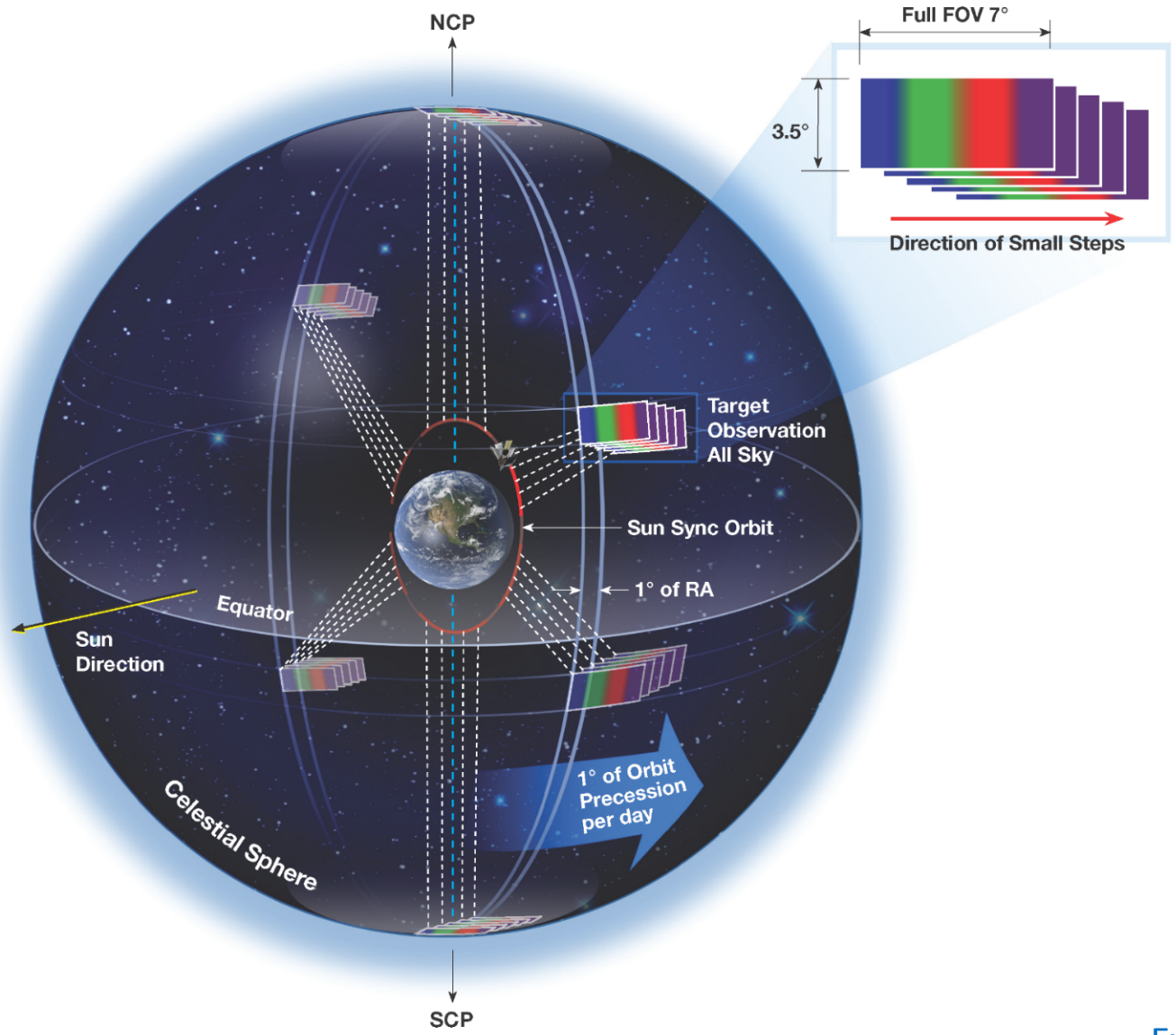


LVFs used on ISOCAM, HST-WFPC2,
New Horizons LEISA, & OSIRIX-Rex (2016 launch)



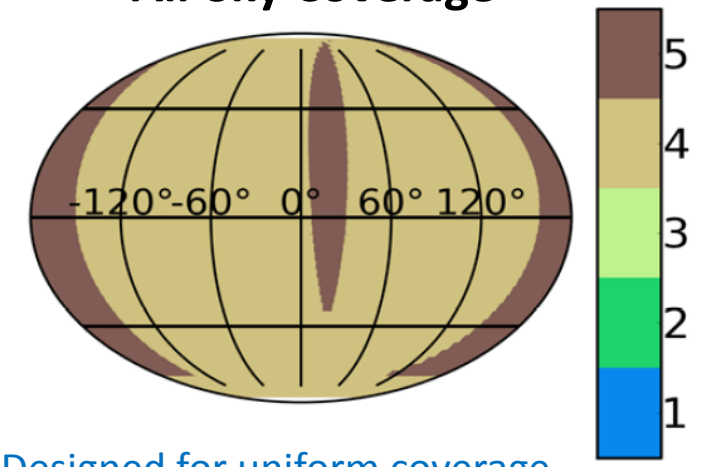
Spectra obtained by stepping source over the
FOV in multiple images: **no moving parts**

Mapping the Full Sky with SPHEREx



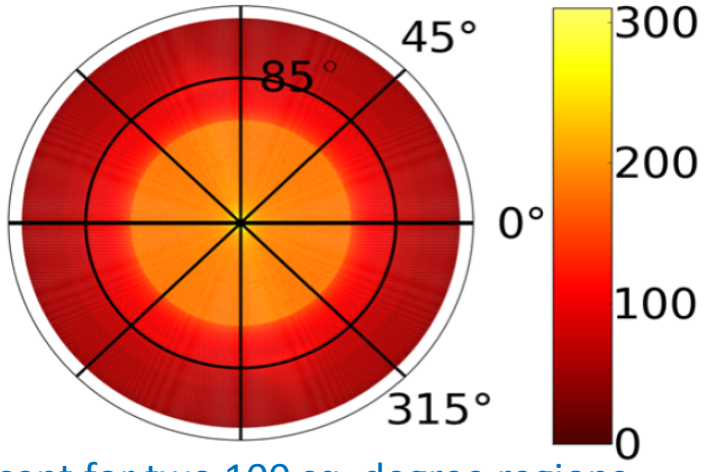
SPHEREx observes the sky simply by pointing the spacecraft over multiple orbits to obtain complete spectra.

All-Sky Coverage



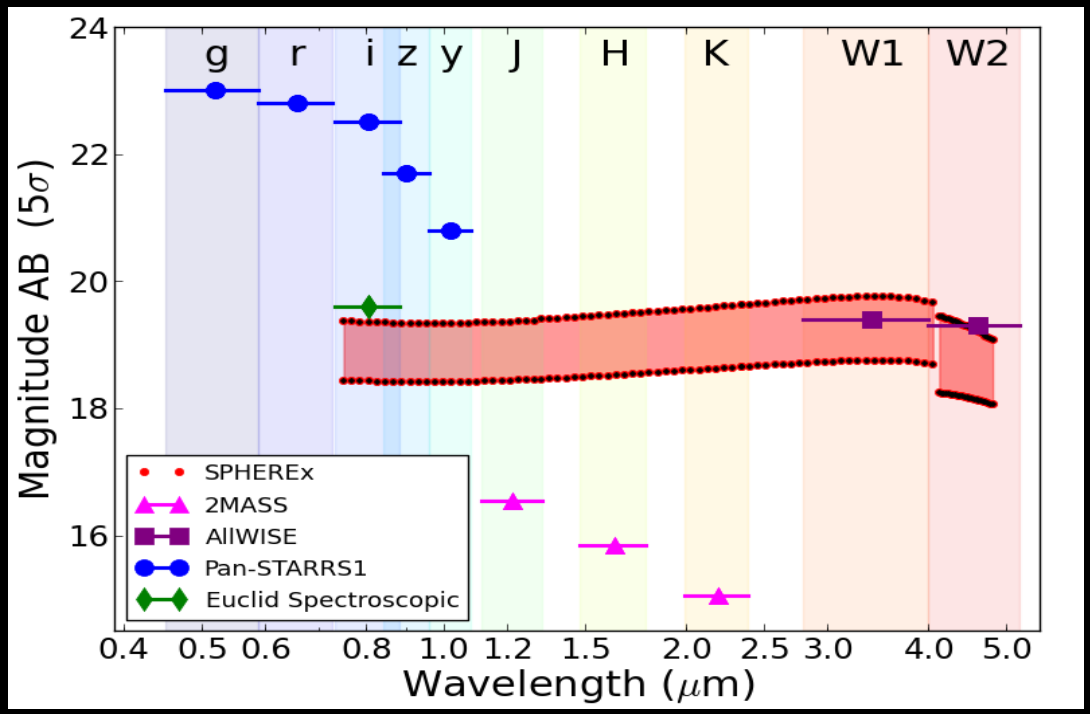
Designed for uniform coverage after 25 months of observations with 4 independent surveys.

Deep Surveys at Poles



Except for two 100 sq. degree regions At the poles with are ~30x deeper.
An opportunity for unique science

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

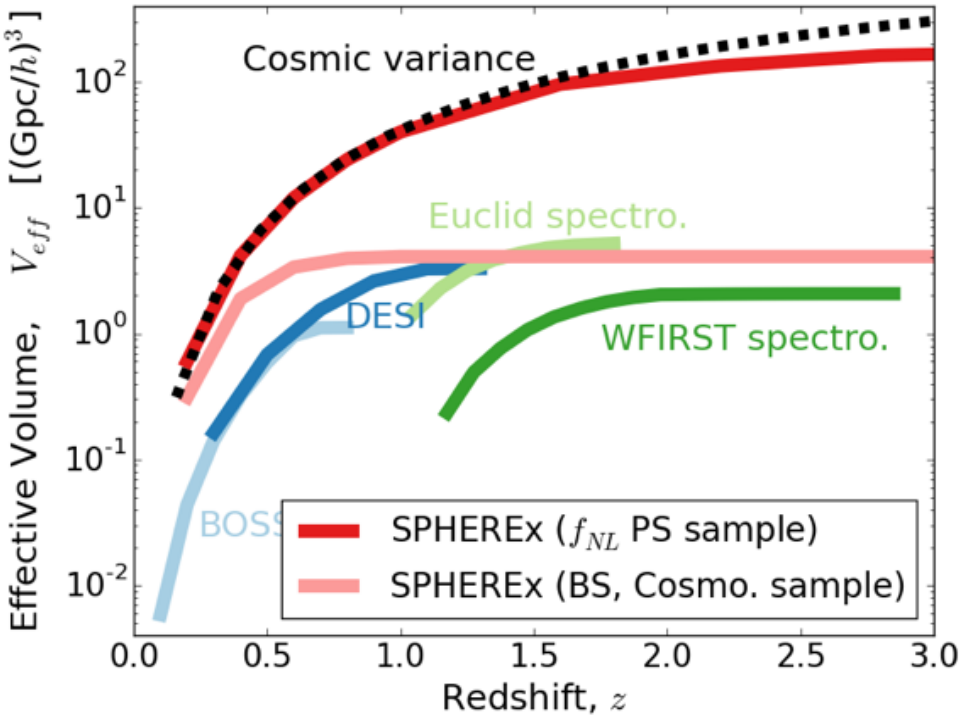
New ideas recently brought to our attention

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

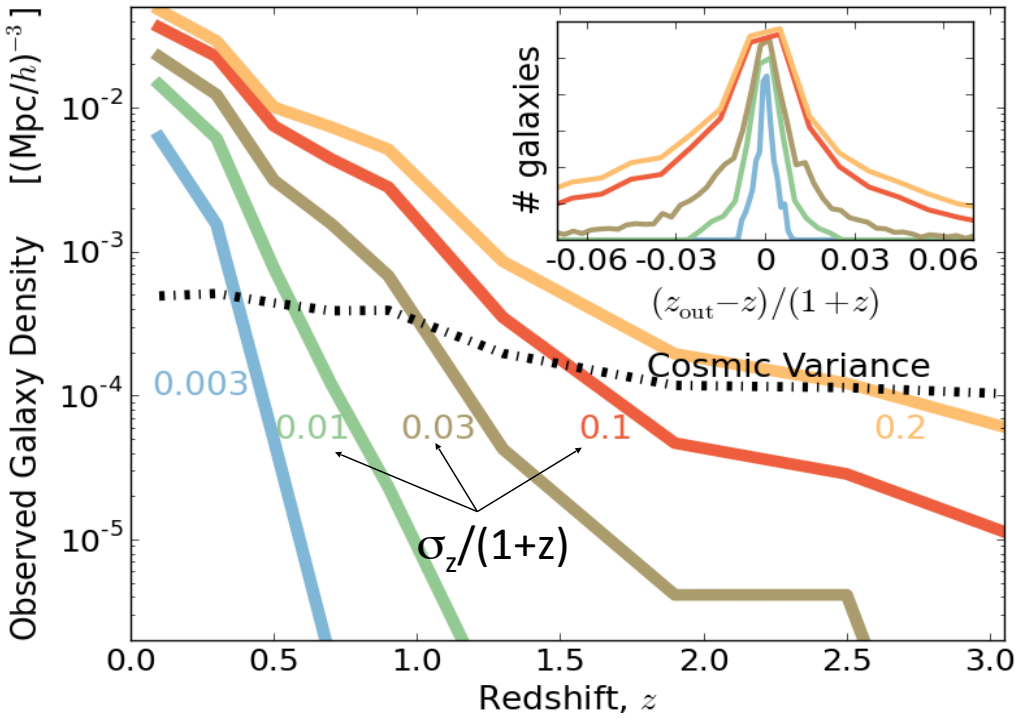
Object	# Sources	Legacy Science	Reference
Detected galaxies	*1.4 billion*	*Properties of distant and heavily obscured galaxies*	*Simulation based on COSMOS and Pan-STARRS*
Galaxies σ(z)/(1+z) < 0.03	*120 million*	*Study (H, CO, O, S, H_2O) line and PAH emission by galaxy type. Explore galaxy and AGN 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 Large Volume Galaxy Survey

SPHEREx Surveys Maximum Cosmic Volume



Catalog Split into Redshift Accuracy Bins



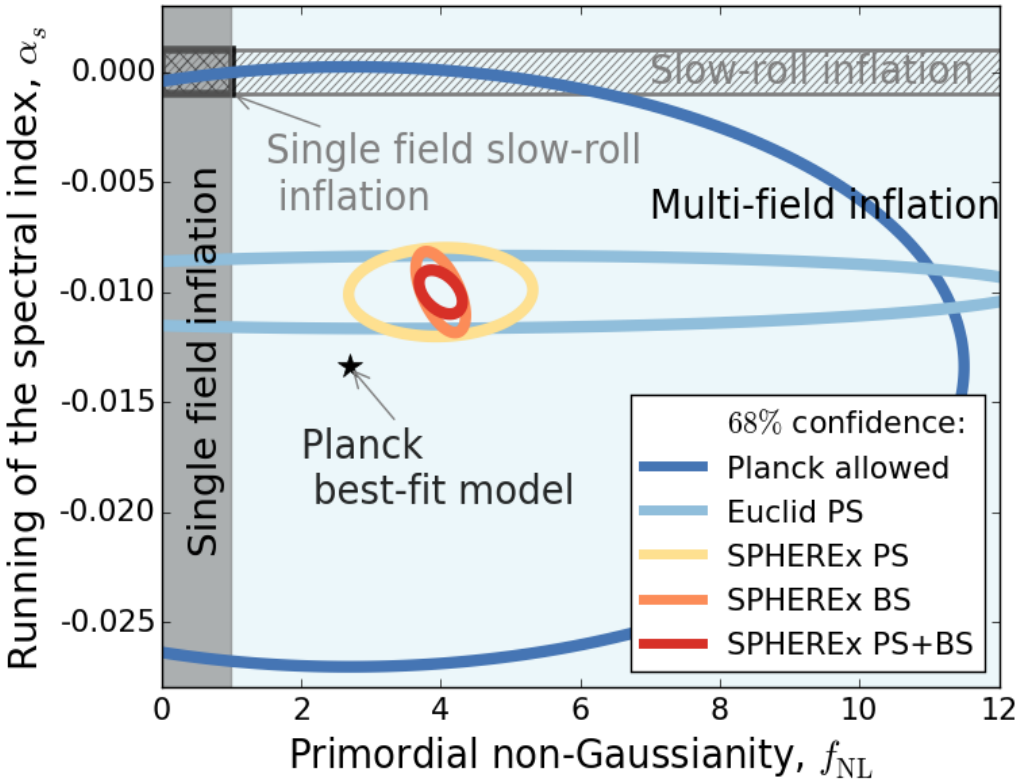
SPHEREx Large-Volume Redshift Catalog

- 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

SPHEREx Tests Inflationary Non-Gaussianity

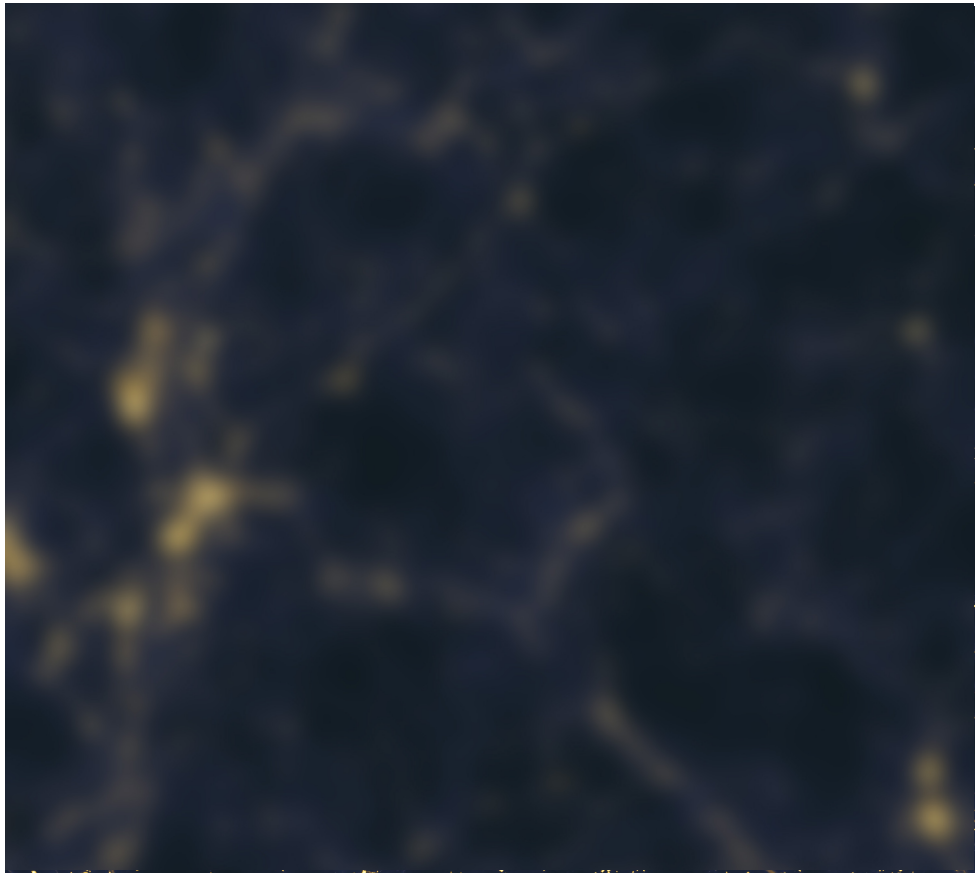


1σ errors	SPHEREx (MEV)			Euclid	Current
	PS	BS	PS+BS		
f_{NL} Req't	1.0	0.5	0.5	N/A	N/A
f_{NL}	0.87	0.23	0.20	5.59	5.8
Spectral Index n_s (x 10^{-3})	2.7	2.3	2.2	2.6	5.4
Running α_s (x10^{-3})	1.3	1.2	0.65	1.1	17
Curvature Ω_k (x10^{-4})	9.8	9.5	6.6	7.0	66
Dark Energy figure of merit	202	NC	NC	309	14

- 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 Measures Cosmic Light Production

Two Ways to Measure Cosmic Light Production



1) Individual Galaxies & Redshifts

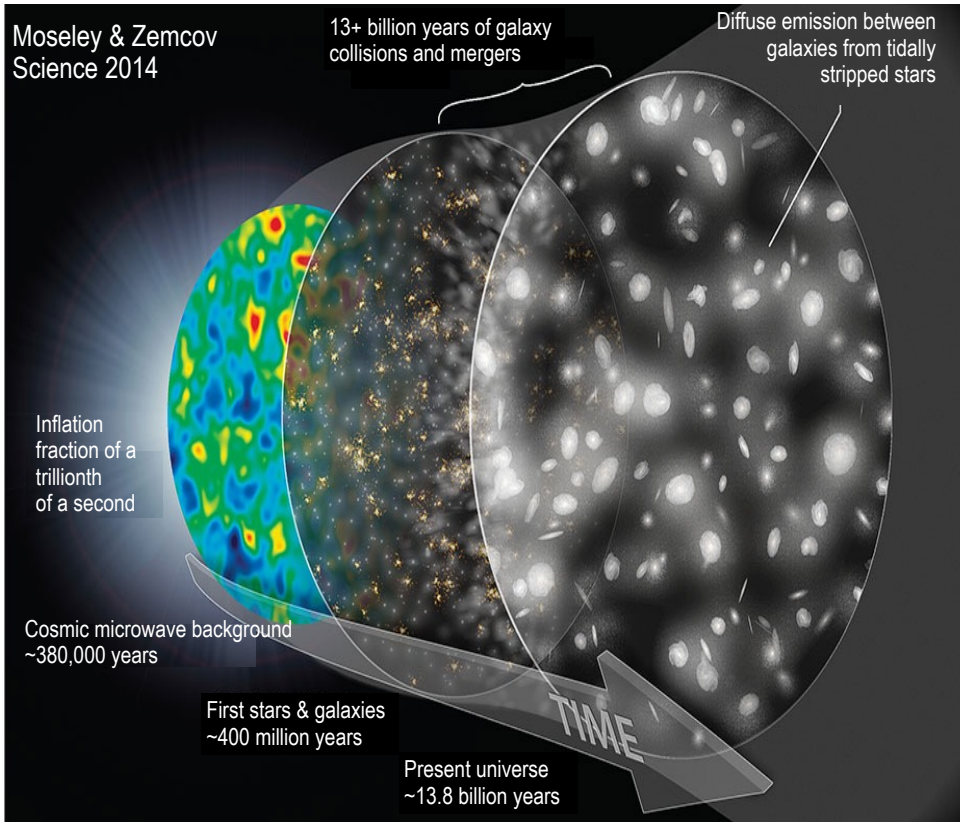
Large telescope for point source sensitivity

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

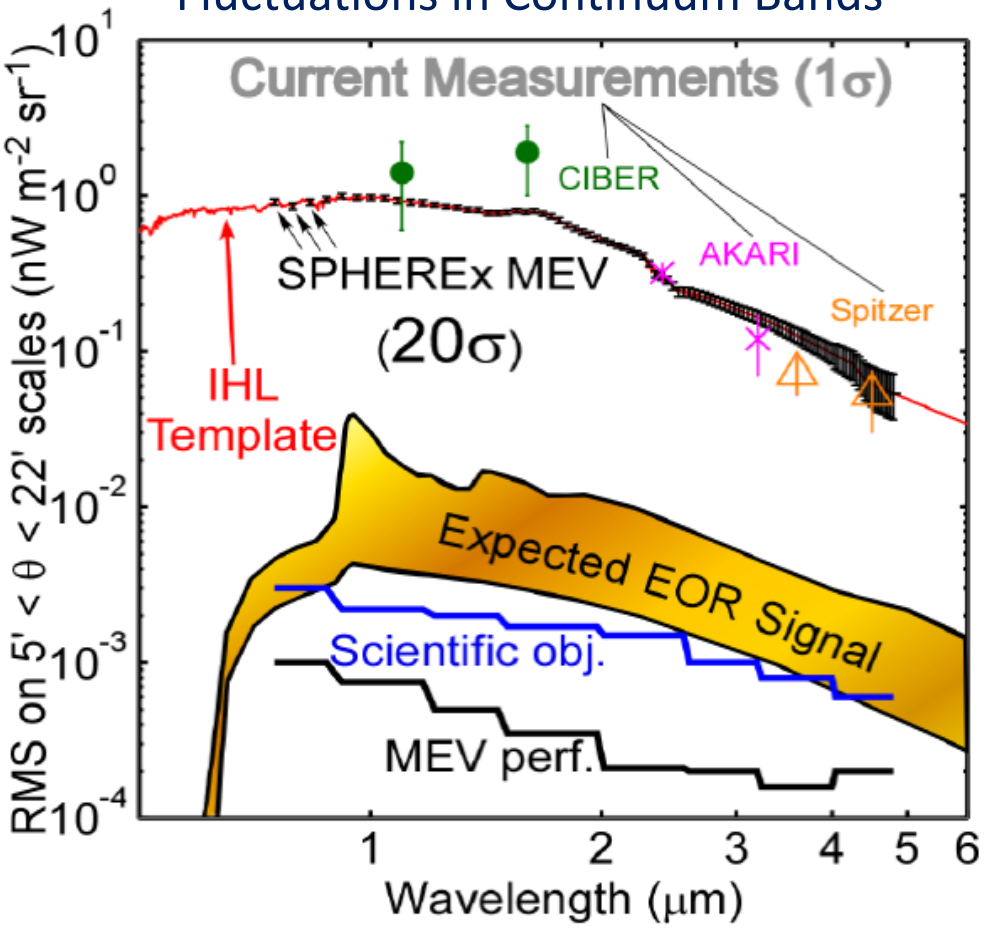
large telescope for point source sensitivity

4) Surprises?

E.g. Light from particle decay

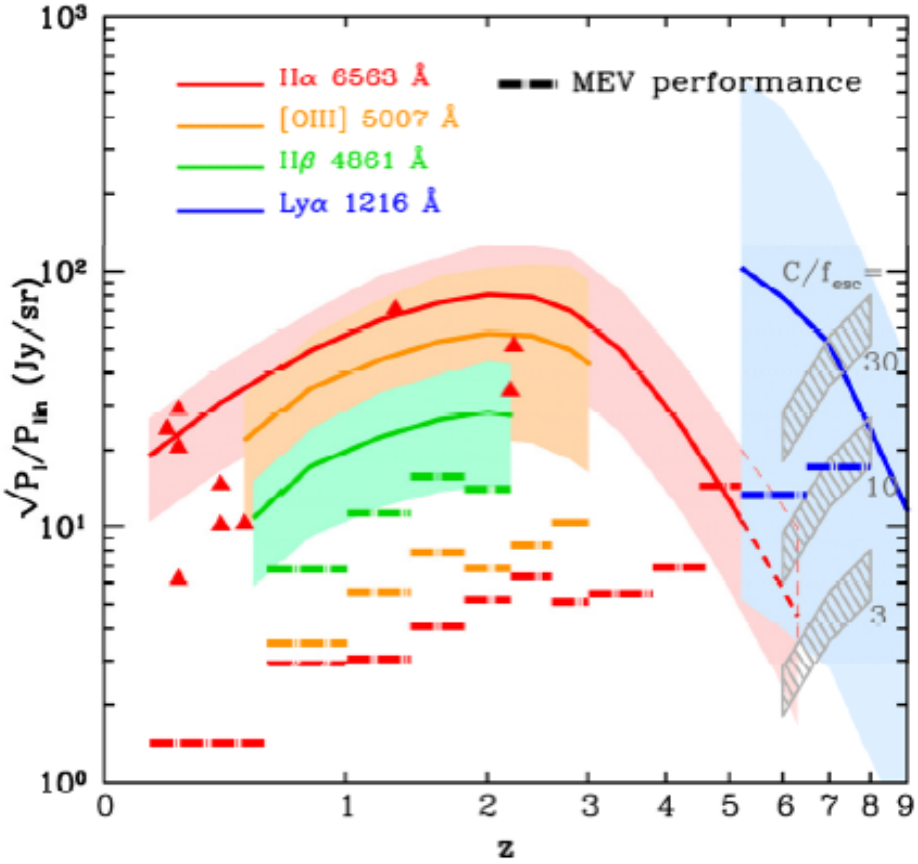
SPHEREx Measures Large-Scale Fluctuations

Fluctuations in Continuum Bands



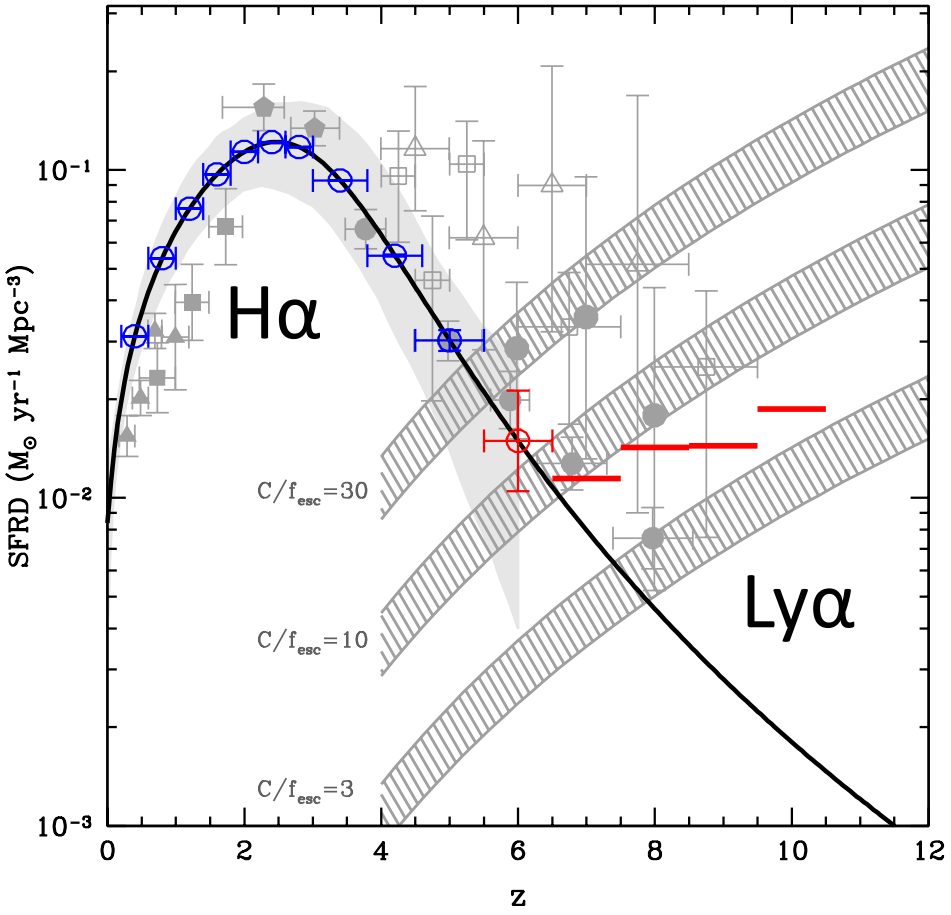
- SPHEREx has ideal wavelength coverage and high sensitivity
- Multiple bands enable correlation tests sensitive to redshift history
- Method demonstrated on Spitzer & CIBER

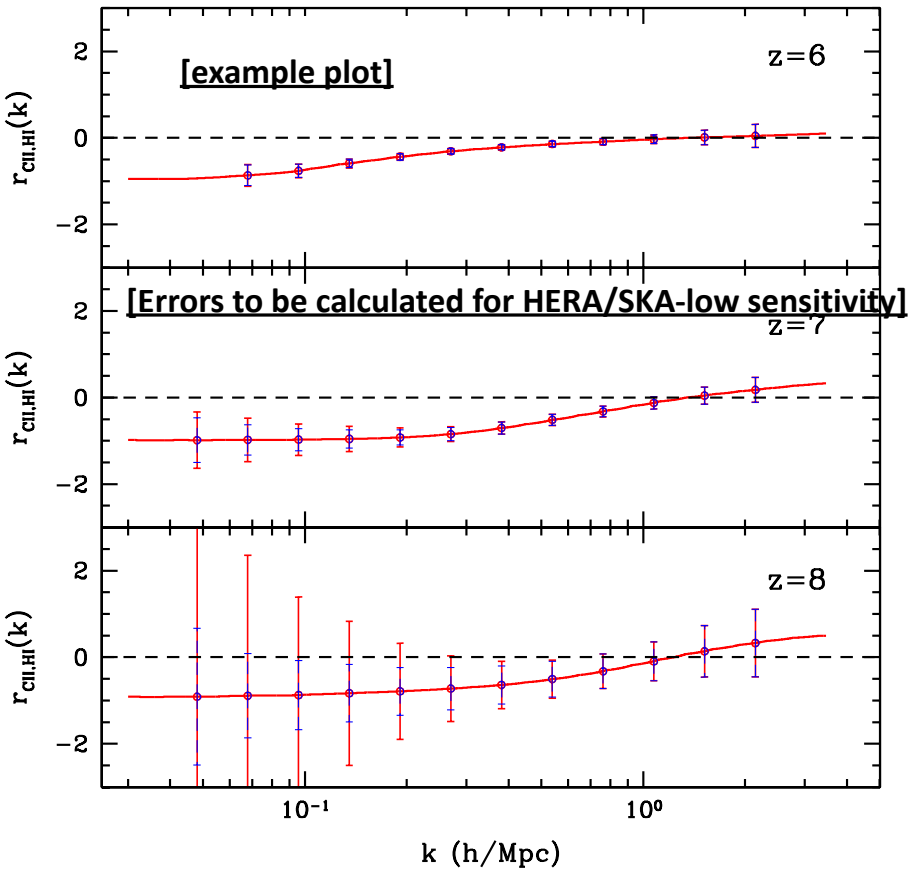
Fluctuations in Spectral Lines



- Emission lines encode clustering signal at each redshift over cosmic history
- Amplitude gives line light production
- Multiple lines trace star formation history
  - High S/N in Hα for z < 5; OIII and Hβ for z < 3
  - Lya probes EoR models for z > 6
  - Hα and Lyα crossover region 5 < z < 6

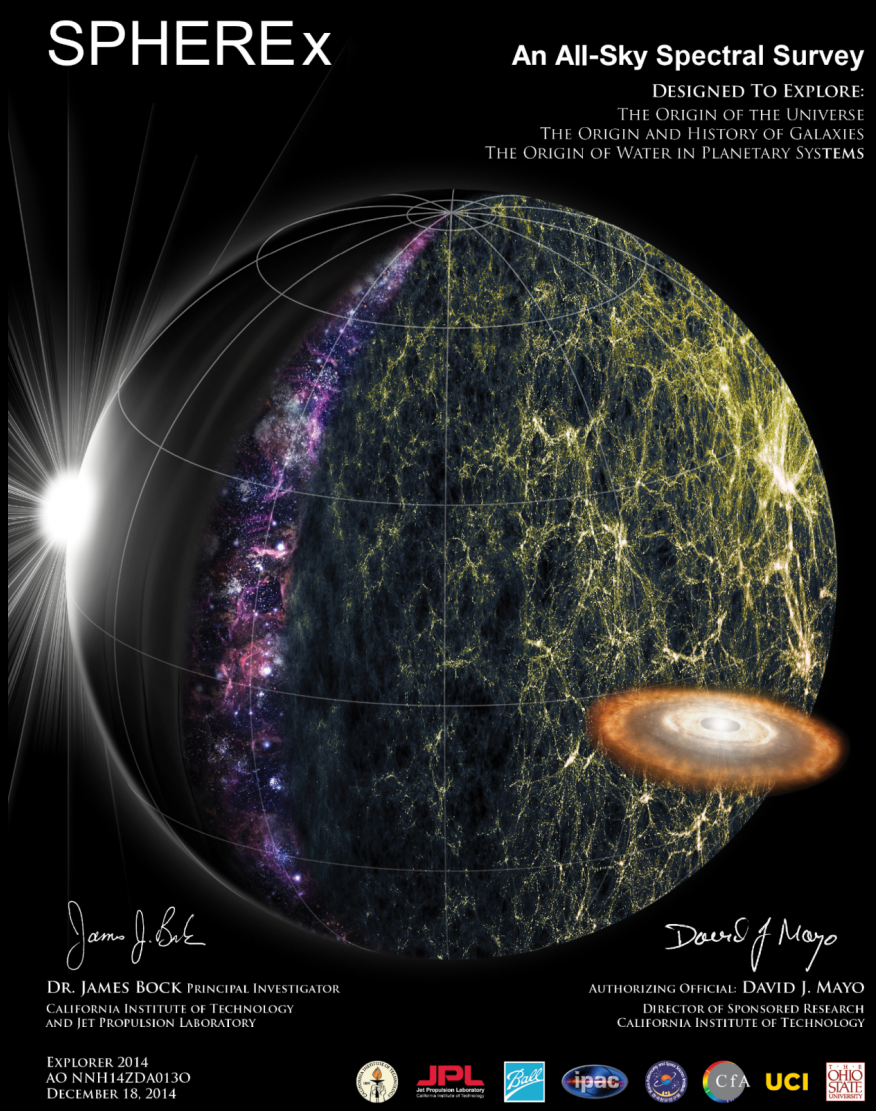
SPHEREx Studies Reionization [with 21-cm]





(a) **SPHEREx will map Lyα emission during reionization** over the whole sky.
(b) Apart from z~6, SPHEREx alone will not have sensitivity for a detection of the power spectrum [for Hopkins & Beacom SFRD].

(a) SPHEREx Lyα intensity maps ideal for cross-correlation with 21-cm fluctuations
(b) Correlation coefficient negative at large scales to positive at small scales.
(c) Direct measure of bubble sizes!



NASA Small Explorer in Phase-A Study

All-sky near-IR spectral survey

- Unprecedented measurements of the Non-Gaussian signature from Inflation
- Survey of the role of organic ices in molecular clouds and young stellar systems
- Probing galaxy formation through precise measurements of extragalactic background light anisotropy
- Rich spectral catalog for the astronomy community

Summary paper: Doré *et al*. arXiv 1412.4872

What can you do?

Perform theory predictions and write papers on your sciences with SPHEREx.

Provide input to the SPHEREx Science Team on data requirements and tools for your sciences with SPHEREx data

Details soon at http://spherex.caltech.edu