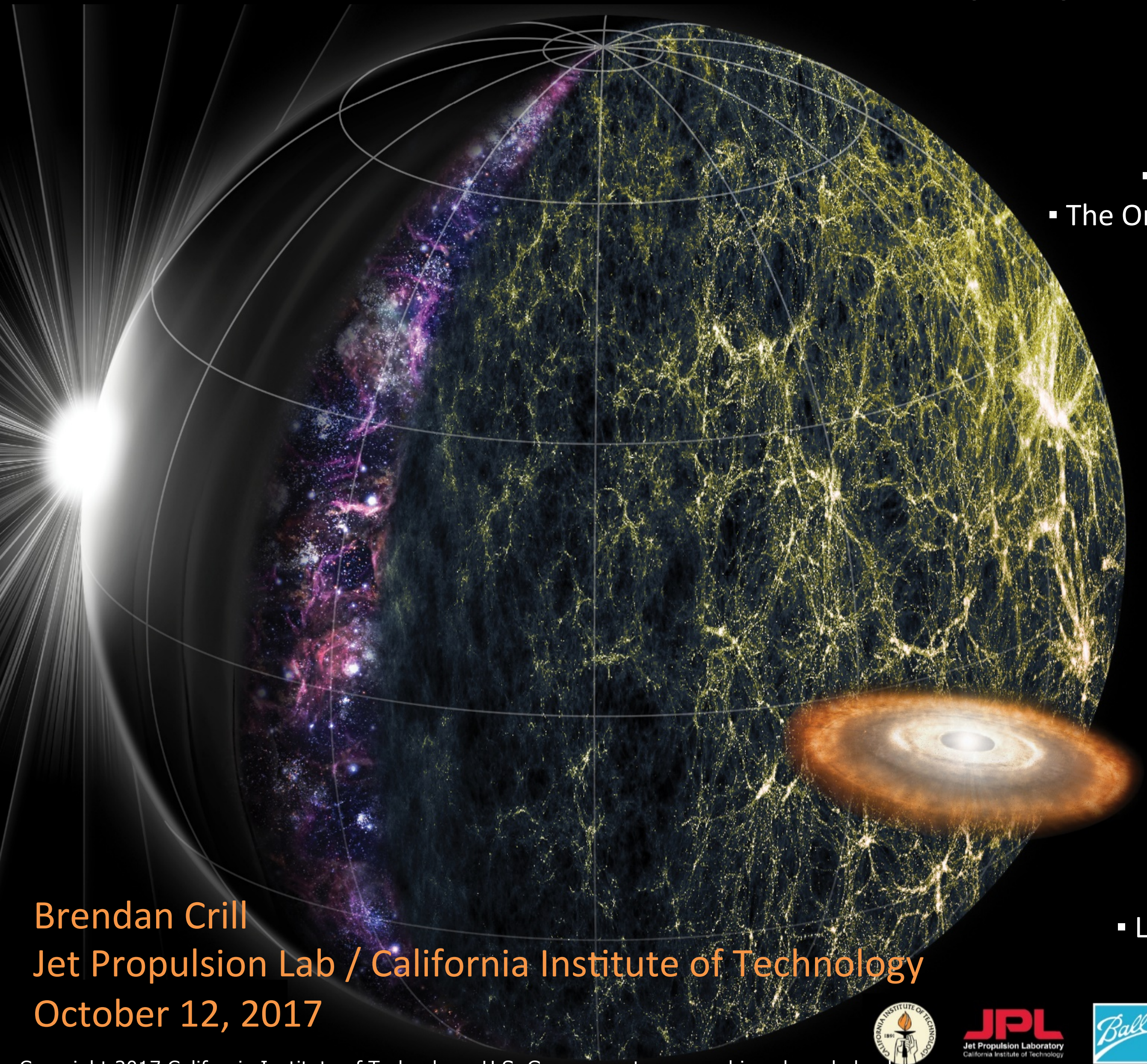
SPHEREx: An All-Sky Spectral Survey



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

Brendan Crill
Jet Propulsion Lab / California Institute of Technology
October 12, 2017

SPHEREx Science Team

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Peter Capak	IPAC	Galaxy redshifts
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Elisabeth Krause	JPL/U. Arizona	Cosmology
Brendan Crill	JPL	Pipeline architect
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Phil Korngut	Caltech	Instrument Scientist
Dae-Hee Lee	KASI	Instrumentation
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Gary Melnick	CfA	Interstellar ices
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Yong-Seon Song	KASI	Cosmology
Harry Teplitz	IPAC/Caltech	Data Archive
Volker Tolls	CfA	Ices pipeline
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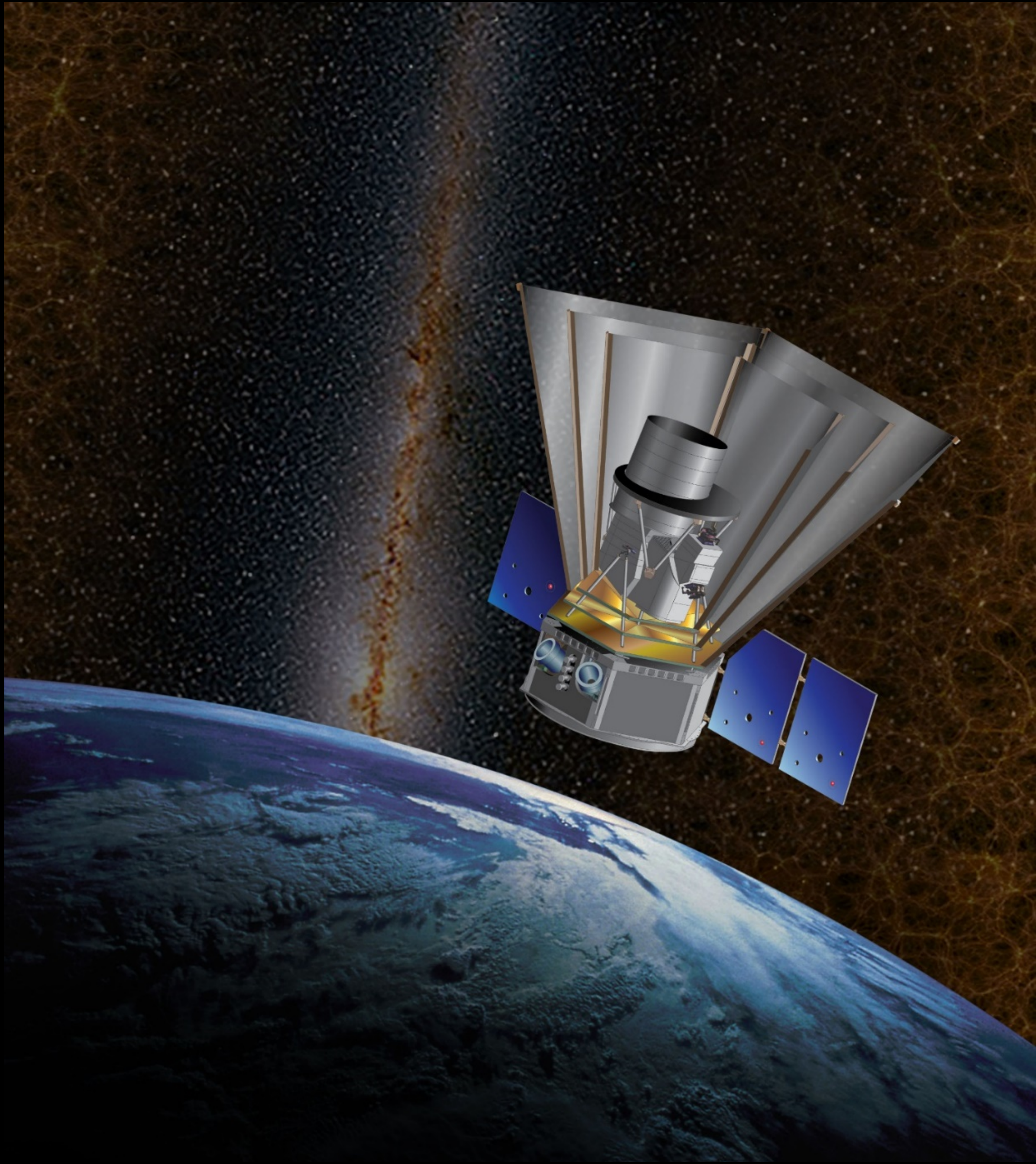
Lindsey Bleem	Argonne	Galaxy clusters
Roger Smith	Caltech	Detector arrays
Tim Eifler	JPL/U. Arizona	LSST/DESI synergies
Salman Habib	Argonne	Cosmology simulations
Katrin Heitmann	Argonne	Cosmology simulations
Karin Sandstrom	UCSD	Star formation
Carey Lisse	JHU	Solar system
Daniel Masters	Caltech	Spectral redshift fitting
Hien Nguyen	JPL	Instrumentation
Karin Oberg	CfA	Ice properties
Rogier Windhorst	Arizona State	JWST synergies



What are the Most Important Questions in Astrophysics?

As Stated in the NASA 2014 Science Plan

How Did the Universe Begin?

“Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity”

How Did Galaxies Begin?

“Explore the origin and evolution of the galaxies, stars and planets that make up our universe”

What are the Conditions for Life Outside the Solar System?

“Discover and study planets around other stars, and explore whether they could harbor life”

SPHEREx Creates an All-Sky Legacy Archive

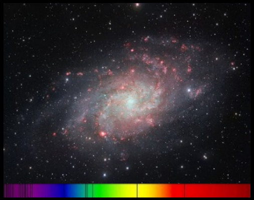
A spectrum (0.8 to 5 micron) for every 6" pixel on the sky

Galaxies

Detected
> 1 billion

Medium-Accuracy Spectra
> 100 million

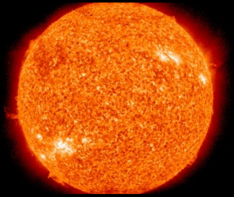
High-Accuracy Spectra
10 million



Clusters
25,000

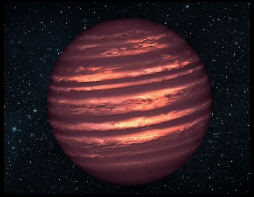
Stars

Main Sequence Spectra
> 100 million



Dust-forming
10,000

Brown Dwarfs
> 400



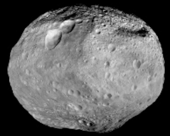
Cataclysms
> 1,000

Other

Quasars
> 1.5 million

Quasars z >7
1 – 300?

Asteroid & Comet Spectra
10,000



Galactic Line Maps
PAH, HI, H_2

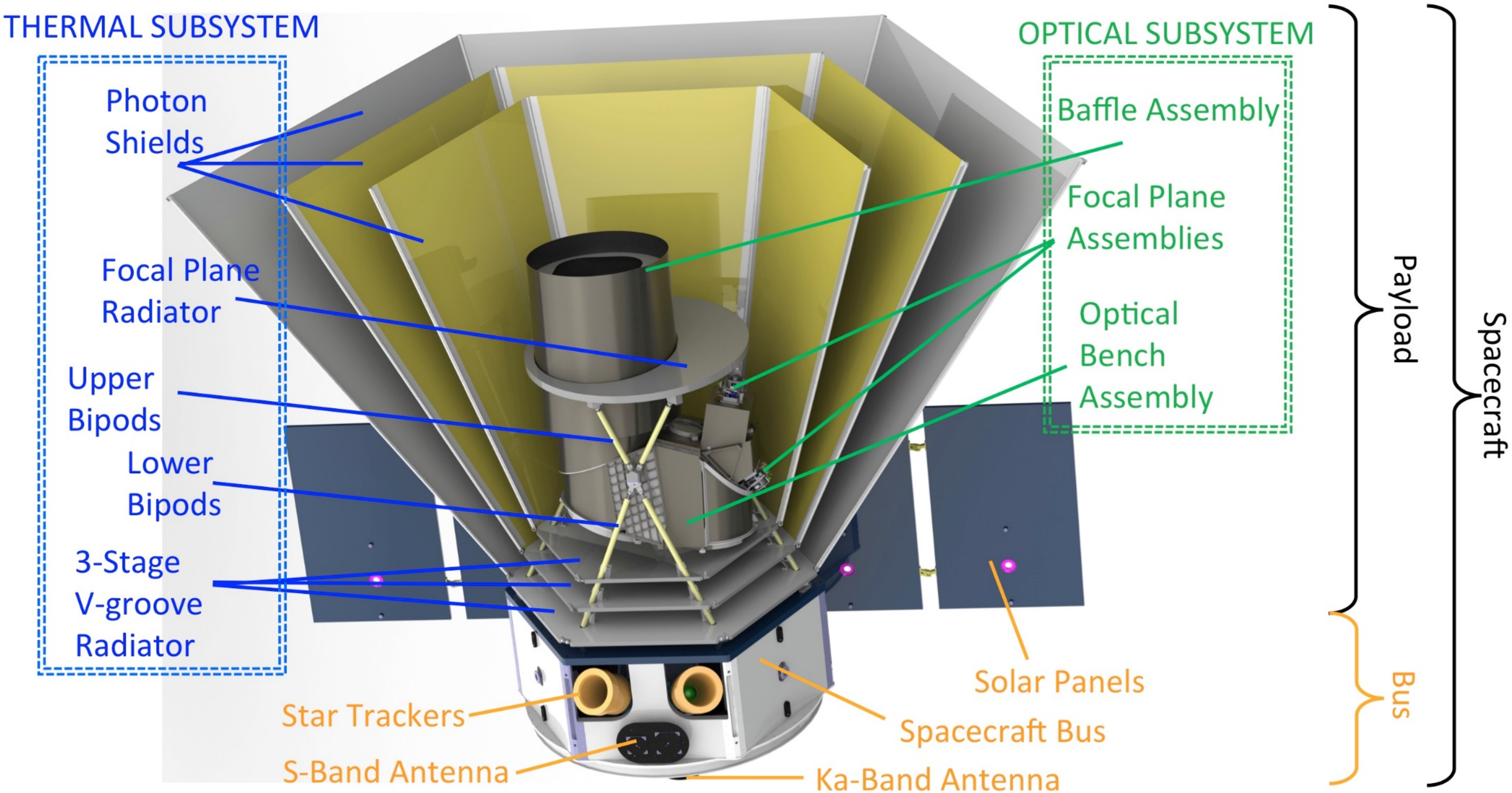
All-Sky surveys demonstrate high scientific returns with a lasting data legacy used across astronomy For example:

COBE
IRAS
GALEX
WMAP
Planck
WISE

More than 400,000 total citations

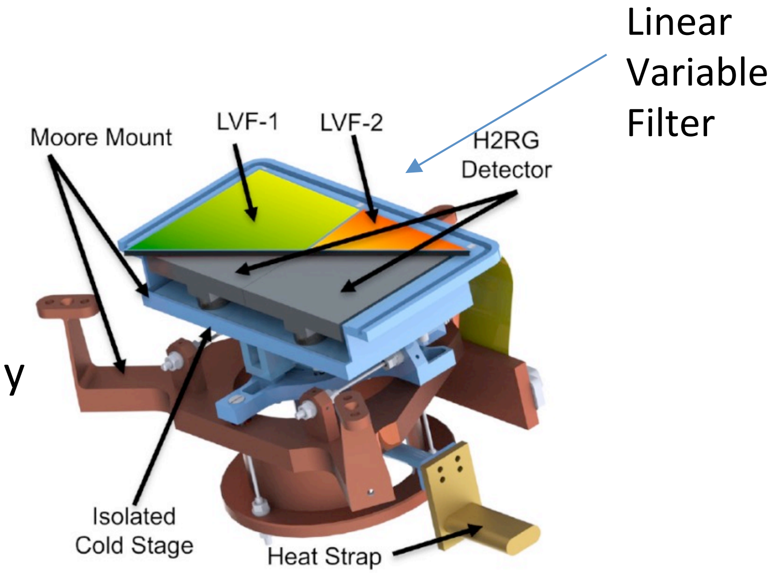
SPHEREx Overview

Passively cooled telescope (80K 30cm diameter primary) and near-infrared detectors (55K) in Low-earth Orbit

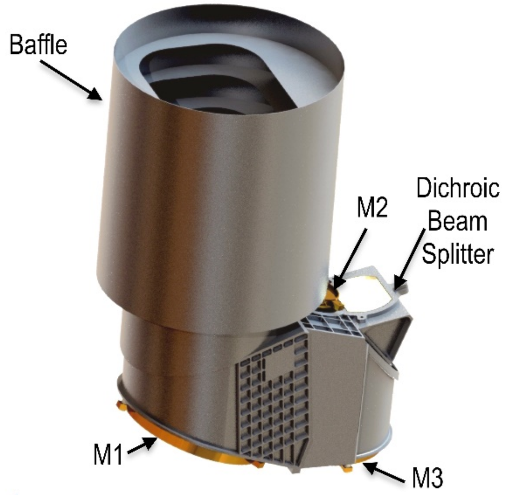


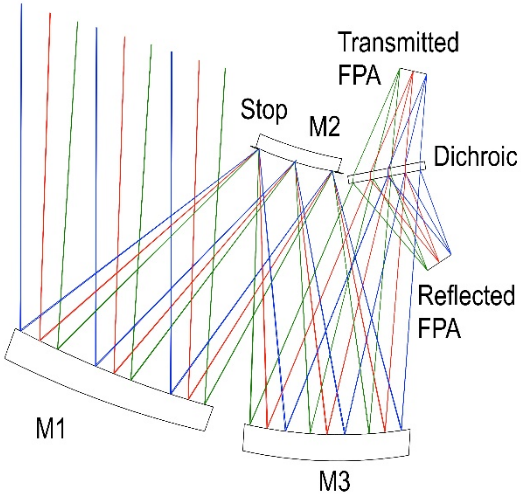
Wide-field telescope with High-Throughput Linear Variable Filter (LVF) Spectrometer

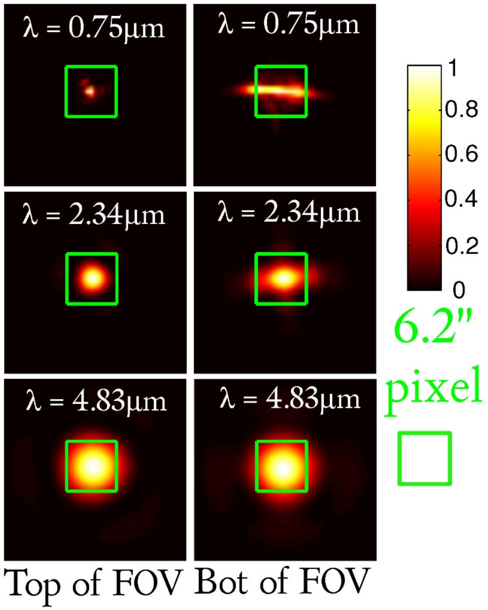
Focal Plane Assembly



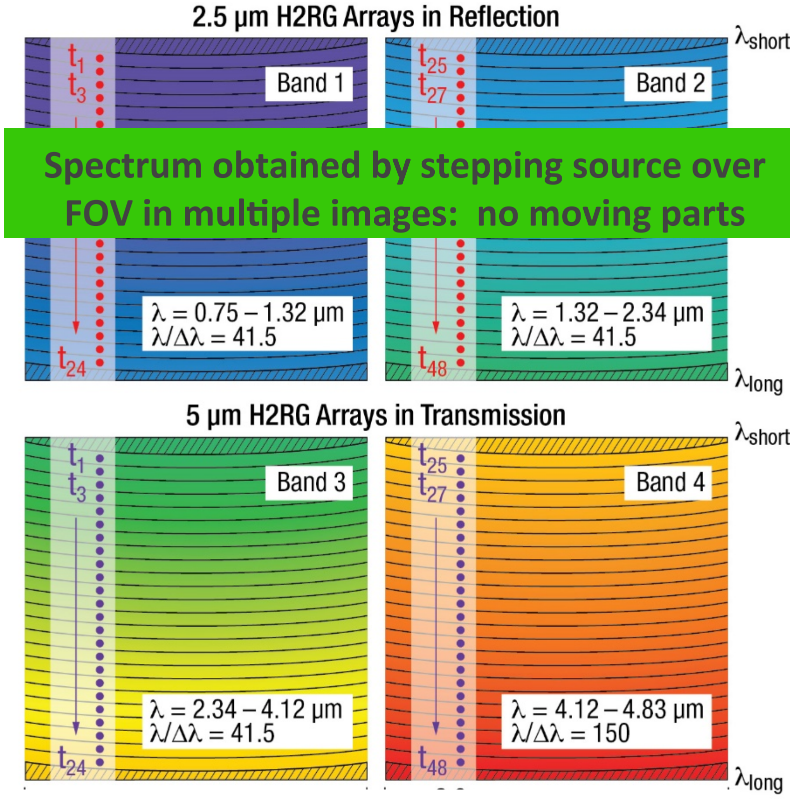
Three-mirror astigmat





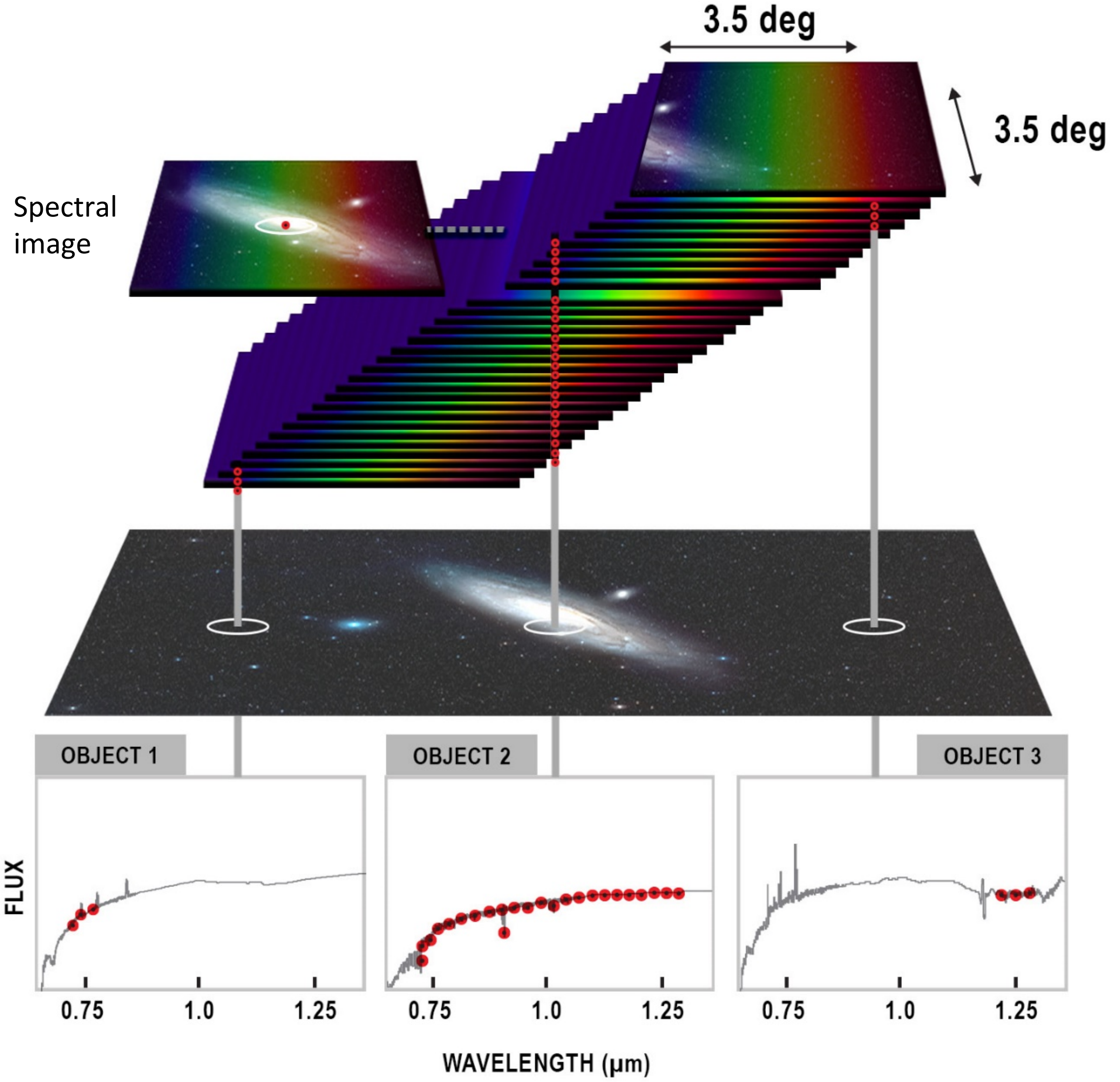


PSF undersampled: 6 arcsecond resolution set by pixel size in all bands



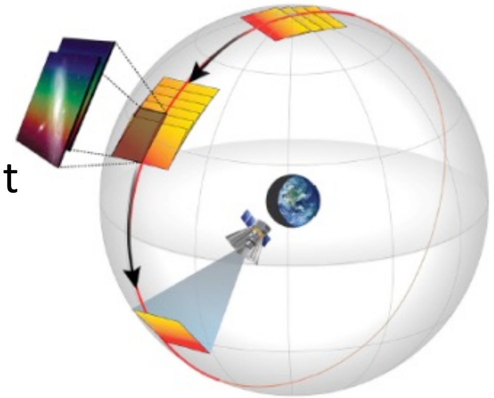
Spectrum obtained by stepping source over FOV in multiple images: no moving parts

Mapping the Sky with LVFs

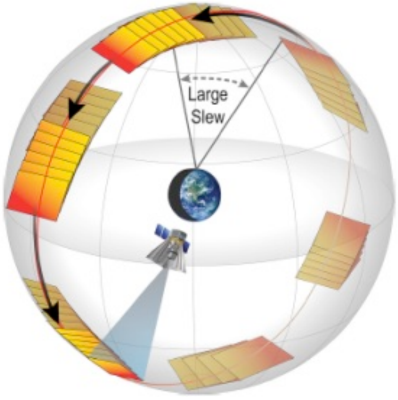


A complete spectrum is made from a series of images

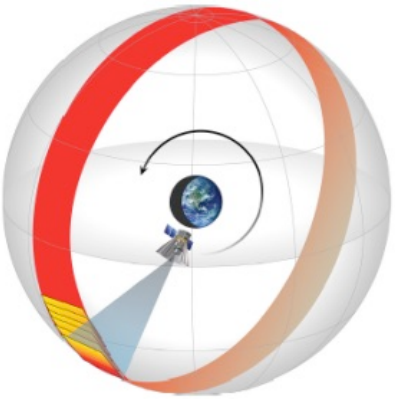
1 orbit



2 orbits

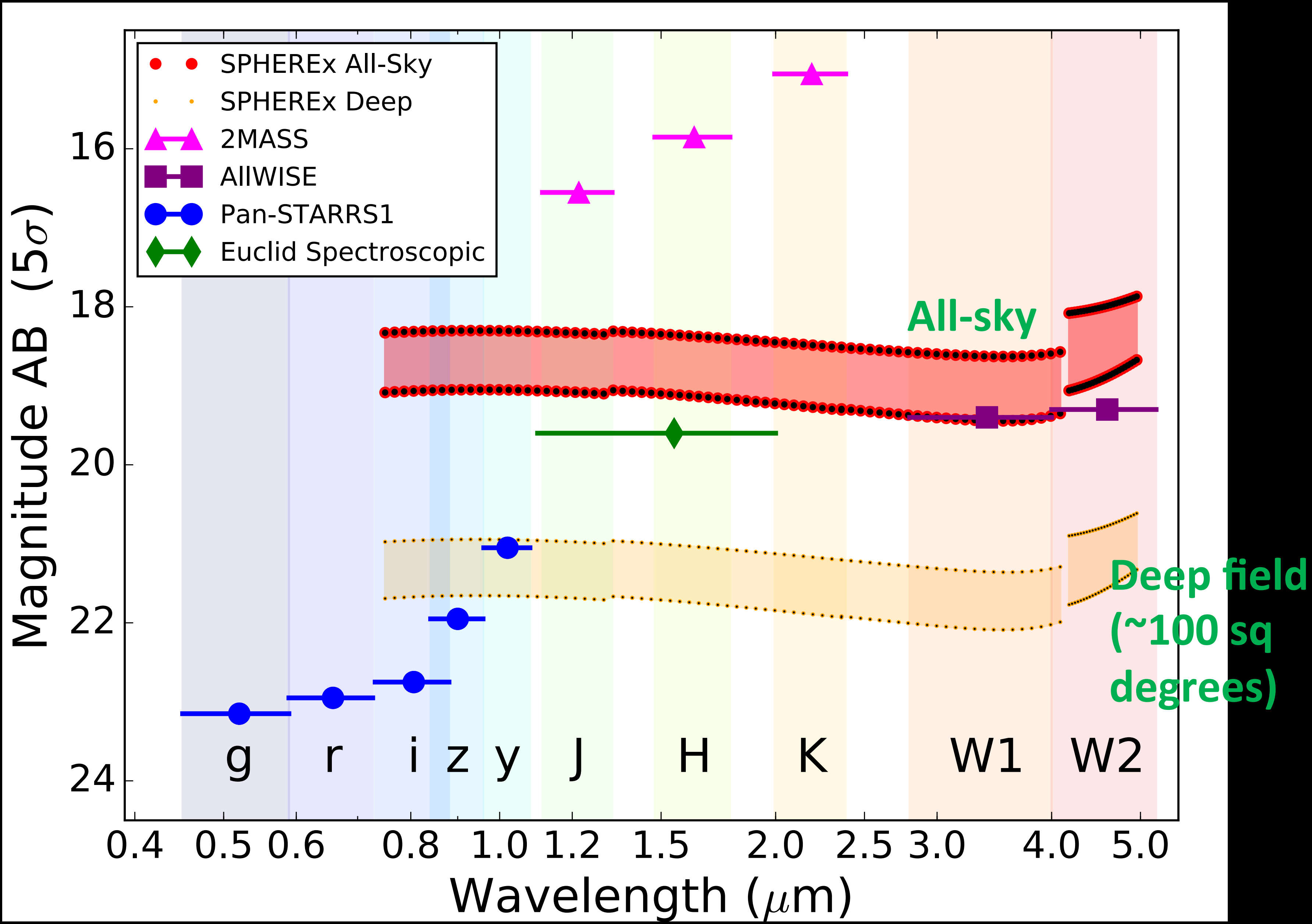


N orbits



SPHEREx maps the sky over multiple orbits with large and small slews

SPHEREx sensitivity after 4 years



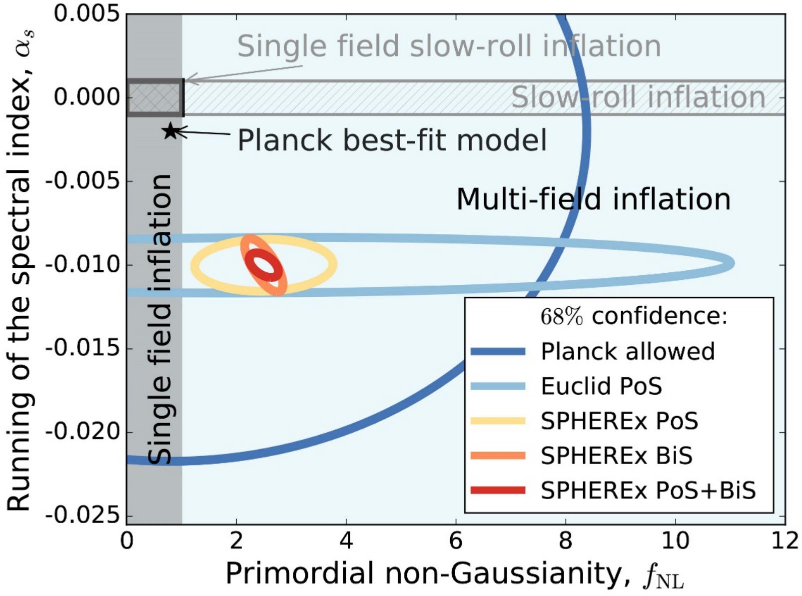
SPHEREx Cosmology Goals

Inflation

SPHEREx Large-Volume Redshift Catalog

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

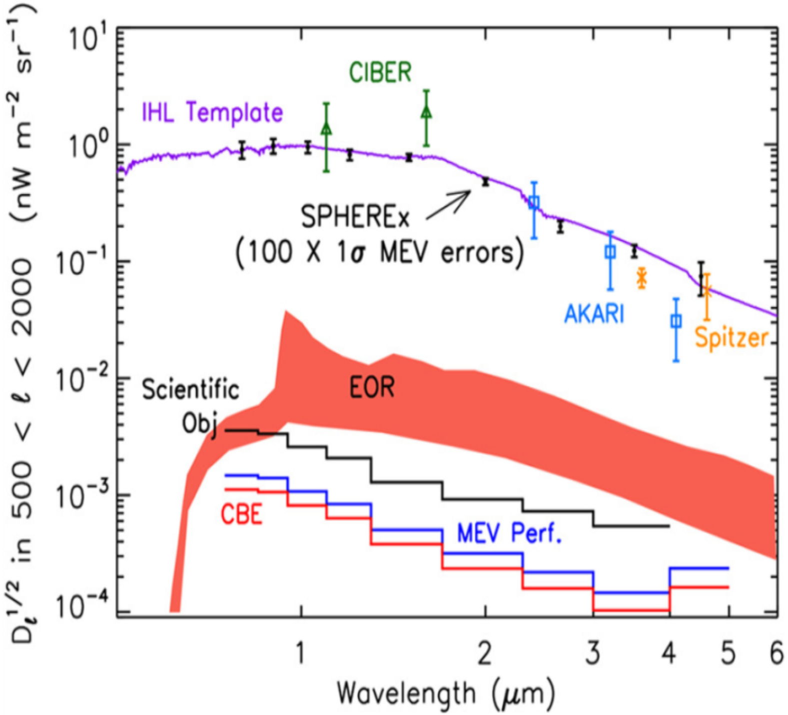
- **Constrains inflation through highly sensitive measurements of statistical non-Gaussianity in large scale structure**



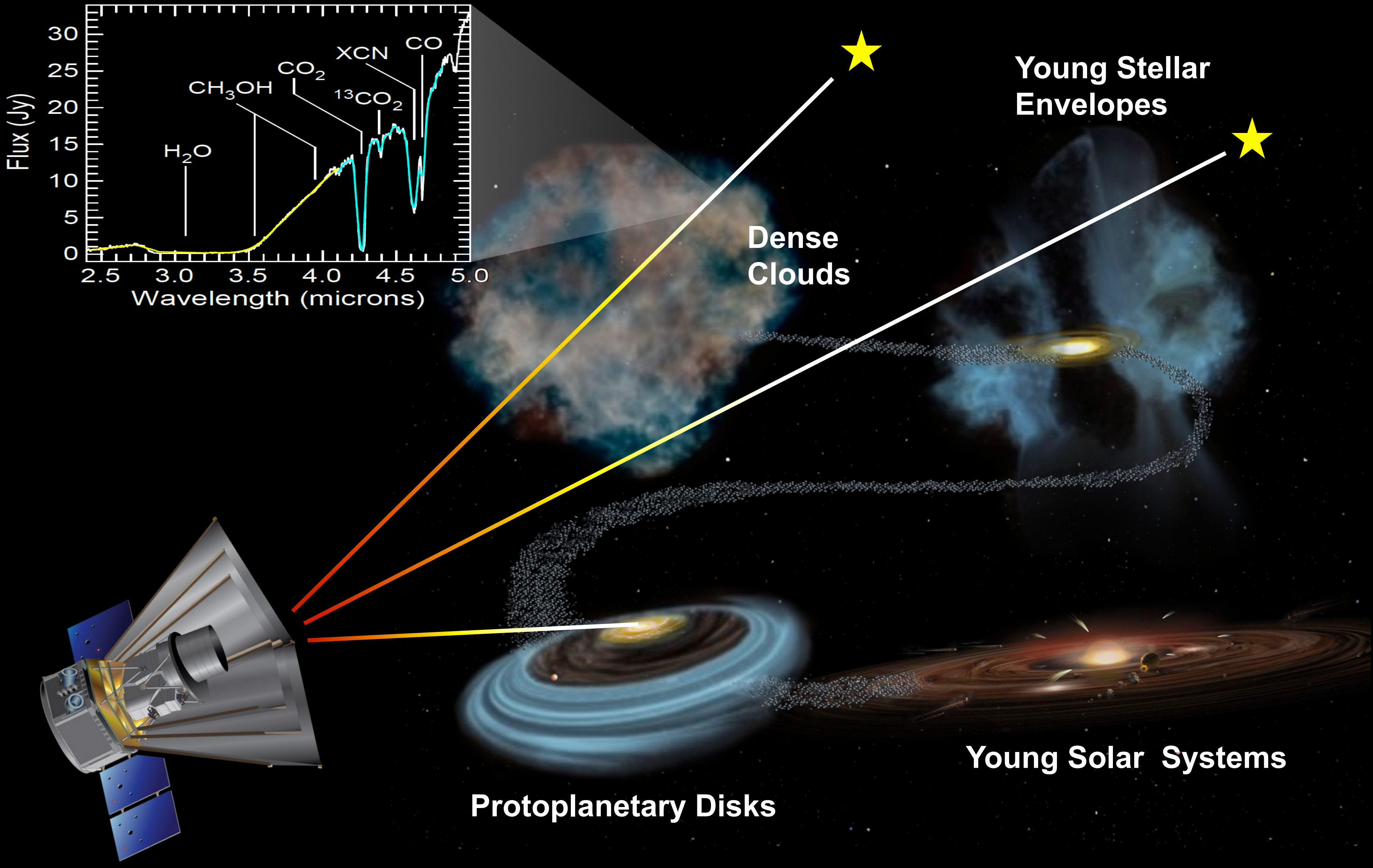
Galaxy Formation

Deep field survey: Extragalactic Background Light

- SPHEREx has ideal wavelength coverage and high sensitivity for studying large-scale fluctuations
- Multiple bands enable correlation tests that are sensitive to redshift history
- Method demonstrated on Spitzer & CIBER



SPHEREx Surveys Ices in All Phases of Star Formation



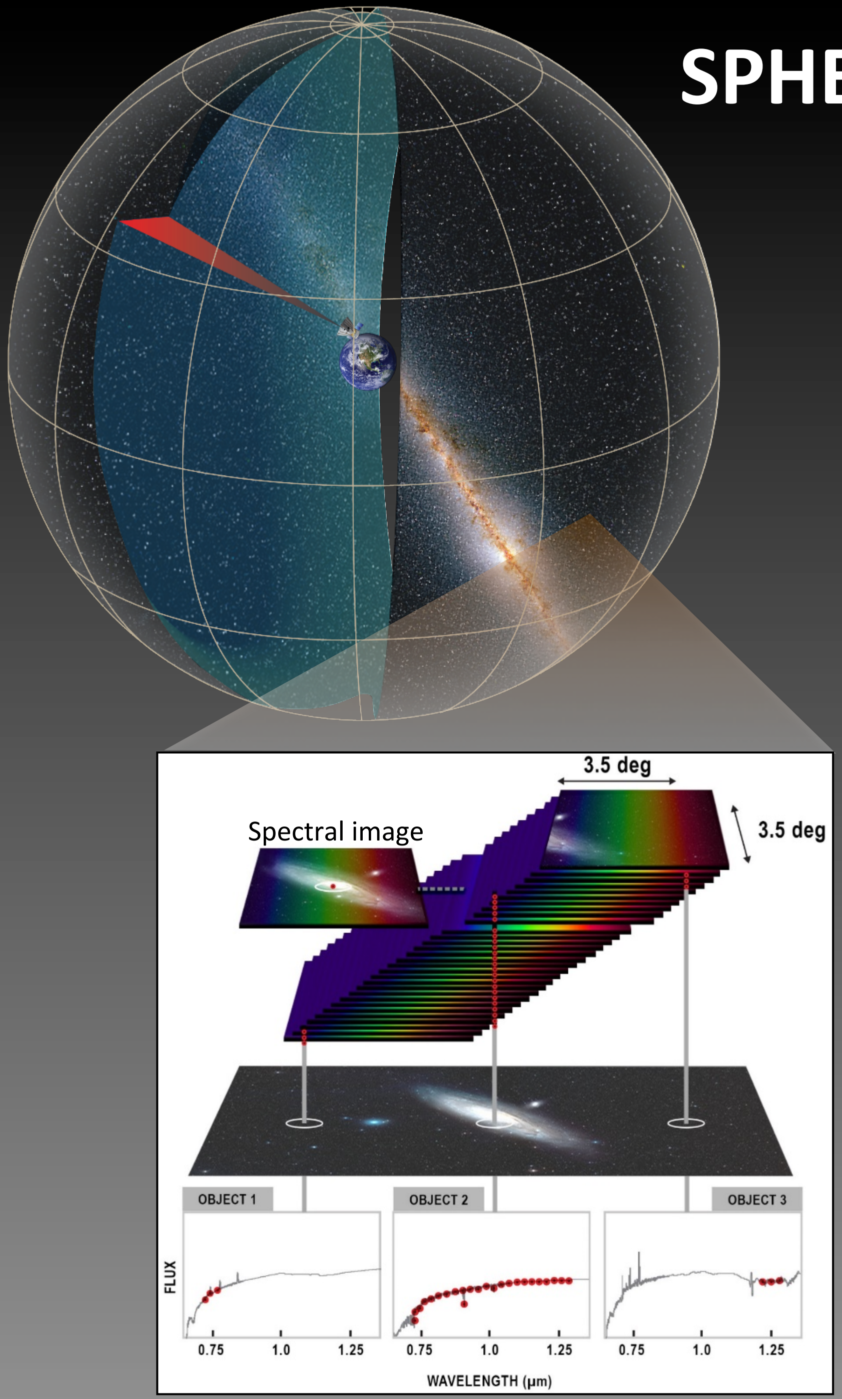
Young Stellar Envelopes

Dense Clouds

Protoplanetary Disks

Young Solar Systems

SPHEREx Data Products & Tools



Planned Data Releases

Survey Data	Date (Launch +)	Associated Products
Survey 1	1 – 8 mo	S1 spectral images/data cube
Survey 2	8 – 14 mo	S1/2 spectral images/data cube Early release catalog
Survey 3	14 – 20 mo	S1/2/3 spectral images/data cube
Survey 4	20 – 26 mo	S1/2/3/4 spectral images/data cube
Final Release		Legacy catalogs and maps

Available Data Tools: Served through IRSA at IPAC

Analysis Tool	Function
Image lookup	Find image at location and time
SED estimator	Find spectrum of a known source
Data cube viewer	View spectrum of any sky region
On-the-fly mosaic	Images within specified time
Variable sources	Spectra over all 4 surveys
Moving sources	SEDs for known moving objects

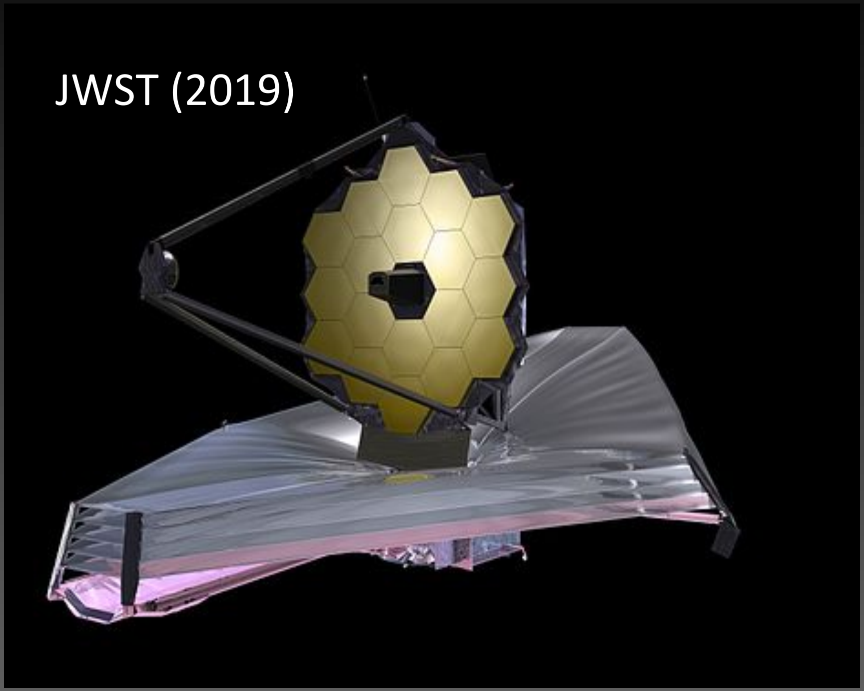
Legacy Catalogs and Maps

Catalog	#	Function
Core science catalogs	> 450 M > 20,000	Galaxy types & redshift Ice sources
Deep field maps		Image mosaics
Stars	> 100 M	SEDs of known stars
Galaxies	1.4 B	SEDs of known galaxies
Clusters	25,000	SEDs of cluster members
Asteroids	10,000	SEDs of known objects
Galaxy maps		Image and line mosaics

more releases, tools and catalogs under consideration

SPHEREx synergy w/ other NASA missions

SPHEREx planned to launch in 2022



TESS stars + SPHEREx spectrophotometry + GAIA parallaxes = huge improvement in stellar radii

(yesterday's talk by Dan Stevens)

JWST follow-up of unusual objects in SPHEREx archive, for example:

- High redshift quasars
- Objects with interesting ice features
- Etc..

… and complements cosmology with Euclid (2020) and WFIRST (mid 2020's)

What Would *You* Do with the Archive?

New Ideas from the 2016 Workshop

Object	# Sources	Legacy Science	Reference
X-ray all-sky survey	> 100,000	Detect eROSITA source SEDs and spectroscopic redshifts	Dore et al. 2016
Missing baryons	> 10,000	In conjunction with CMB, detect kSZ signal in galaxy groups and clusters	Dore et al. 2016 Ferraro et al. 2016
Exoplanet characterization	> 1000	With GAIA, determine precise radii for host stars	Dore et al. 2016
Deuterated PAHs		Probe and possible map deuterated PAHs, complete inventory of D in local ISM	Dore et al. 2016 Doney et al. 2015
Lowest metallicity stars	~1000	Identify low-mass stars by their IR signatures, map distribution in Galaxy	Dore et al. 2016
Asteroids and comets	10,000 / 100	Spectrally classify numerous asteroids; CO/CO$_2$ ratios in comets	Dore et al. 2016
Nearby galaxies	>100 million	Spectrally image galaxies to trace stellar populations, star formation, etc	2MASS catalogs
New idea here!	TBD		

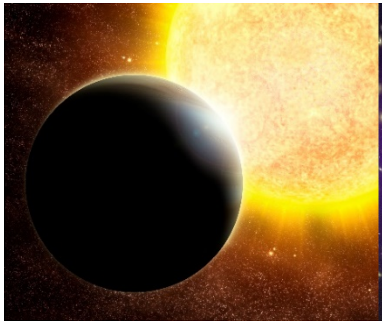
2018 Workshop Jan 30-31 at CfA

2016 Workshop: Over 50 non-SPHEREx scientists

Charter: Identify new science, tools and data products

2014 SPHEREx science paper: Over 60 citations

Workshop white paper: 84 pages, 68 authors



Exoplanet masses

X-ray synergies

- SPHEREx’s all-sky spectrophotometric survey in the near-infrared creates a a lasting data legacy that is widely useful across astronomy

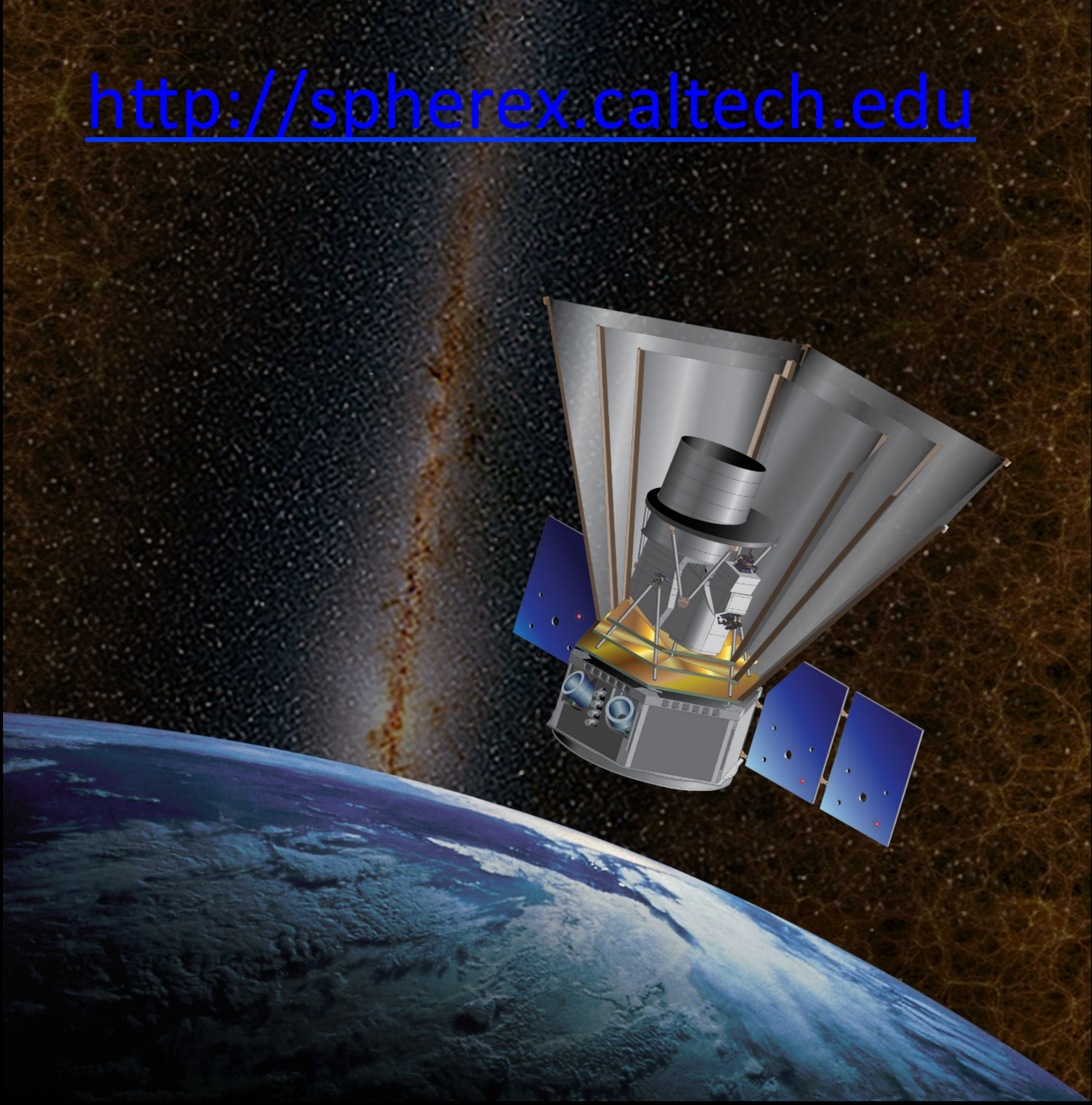
- SPHEREx’s unique survey aims to address fundamental questions in:
  - The nature of inflation
  - The history of galaxy formation
  - Abundance, composition, and evolution of ices in our galaxy.

- MidEx competition wraps up late in calendar year 2018

- If SPHEREx is selected, launch is planned for late 2022

SPHEREx

http://spherex.caltech.edu

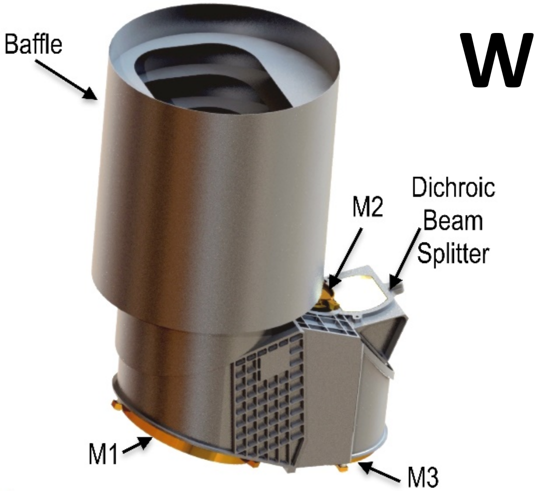


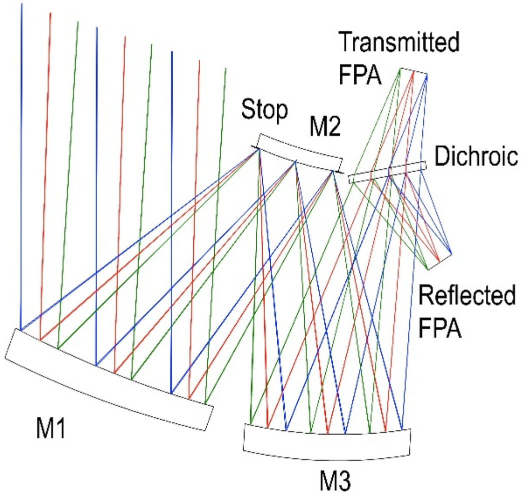
Thanks
for your
Attention!

BACKUP

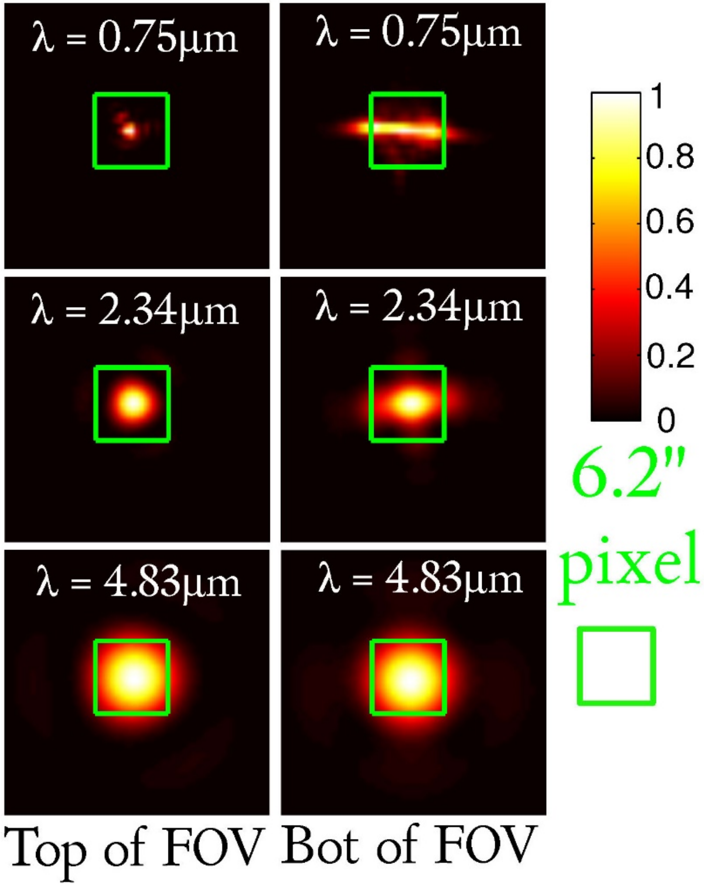
Wide-Field Telescope

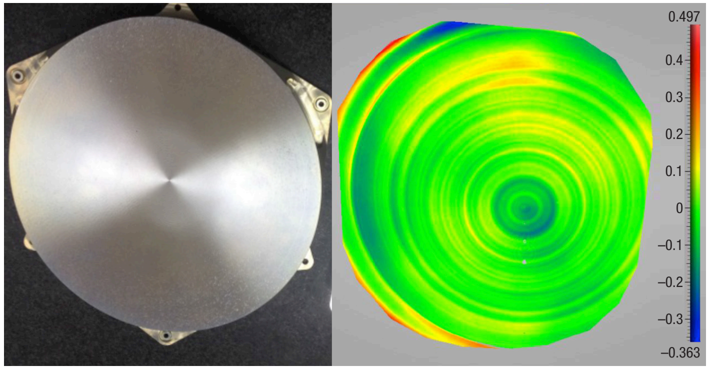
Three-mirror astigmat





Spot diagrams





Demo of flight free-form mirror giving 44 nm rms vs. 80 nm req't

The PSF is under sampled. We use ~8000 bright stars per image to determine

- Astrometry to < 1" per image
- PSF FWHM to < 1 % per image

SPHEREx core science uses known source positions

Redshifts with SPHEREx

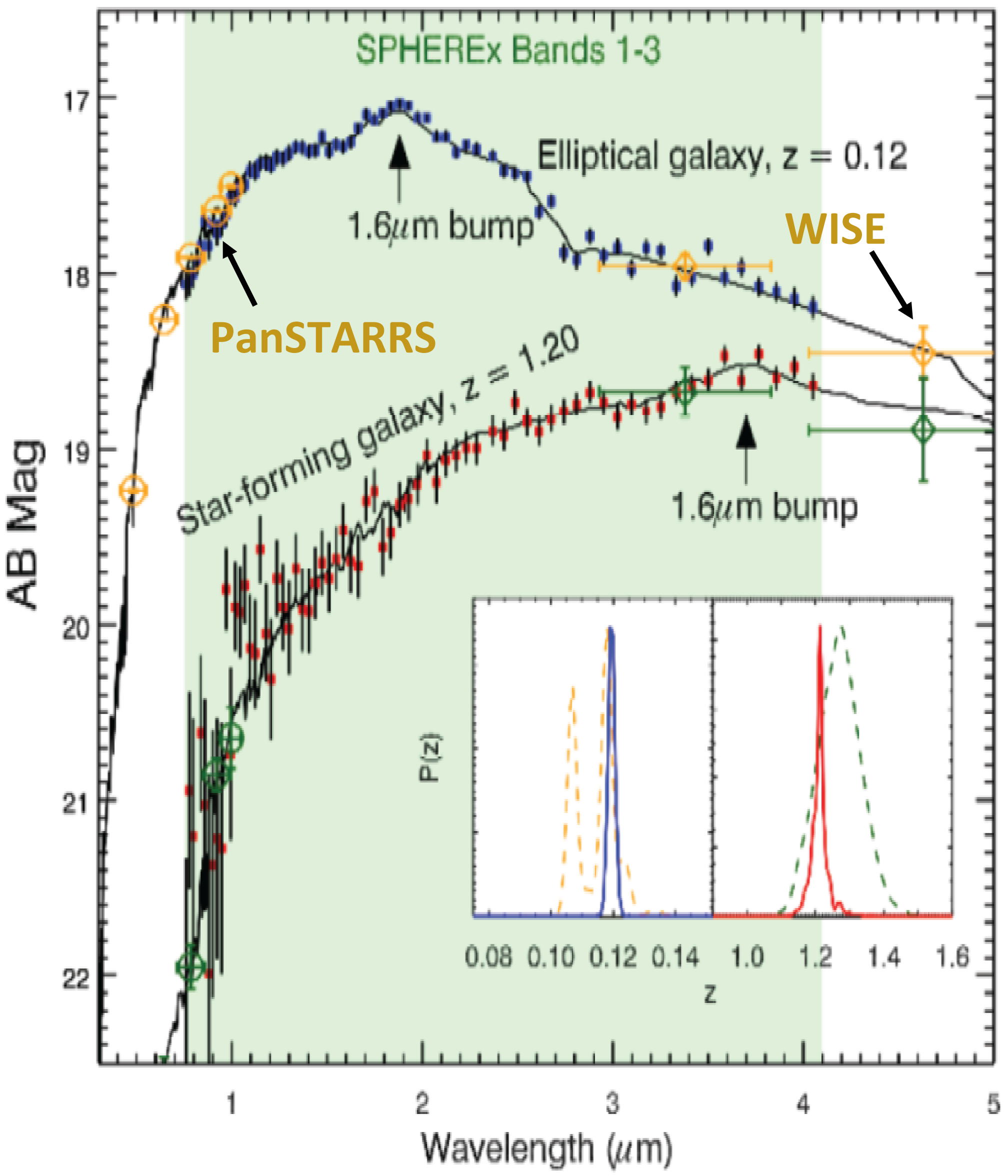
We extract the spectra of *known* sources using the full-sky catalogs from PanSTARRS/DES.
Controls blending and confusion

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)

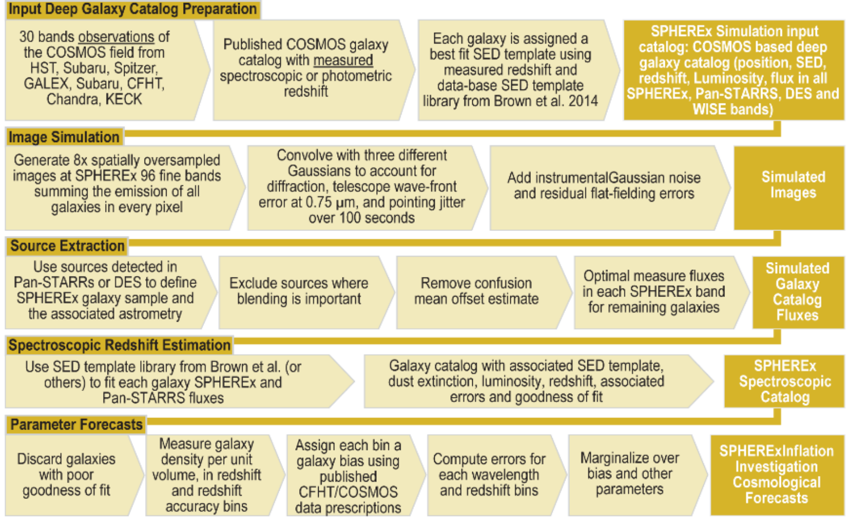
We simulated this process using the COSMOS data set using the same process as Euclid/WFIRST (Capak et al.).

The power of low-resolution spectroscopy has been demonstrated with PRIMUS (Cool++14), COSMOS (Ilbert++09), NMBS (van Dokkum++09).



Testing Redshift Reliability

Inject Real Galaxies into SPHEREx Pipeline



Input Deep Galaxy Catalog Preparation

30 bands observations of the COSMOS field from HST, Subaru, Spitzer, GALEX, Subaru, CFHT, Chandra, KECK

Published COSMOS galaxy catalog with measured spectroscopic or photometric redshift

Each galaxy is assigned a best fit SED template using measured redshift and data-base SED template library from Brown et al. 2014

SPHEREx Simulation input catalog: COSMOS based deep galaxy catalog (position, SED, redshift, Luminosity, flux in all SPHEREx, Pan-STARRS, DES and WISE bands)

Image Simulation

Generate 8x spatially oversampled images at SPHEREx 96 fine bands summing the emission of all galaxies in every pixel

Convolve with three different Gaussians to account for diffraction, telescope wave-front error at 0.75 μm, and pointing jitter over 100 seconds

Add instrumentalGaussian noise and residual flat-fielding errors

Simulated Images

Source Extraction

Use sources detected in Pan-STARRs or DES to define SPHEREx galaxy sample and the associated astrometry

Exclude sources where blending is important

Remove confusion mean offset estimate

Optimal measure fluxes in each SPHEREx band for remaining galaxies

Simulated Galaxy Catalog Fluxes

Spectroscopic Redshift Estimation

Use SED template library from Brown et al. (or others) to fit each galaxy SPHEREx and Pan-STARRS fluxes

Galaxy catalog with associated SED template, dust extinction, luminosity, redshift, associated errors and goodness of fit

SPHEREx Spectroscopic Catalog

Parameter Forecasts

Discard galaxies with poor goodness of fit

Measure galaxy density per unit volume, in redshift and redshift accuracy bins

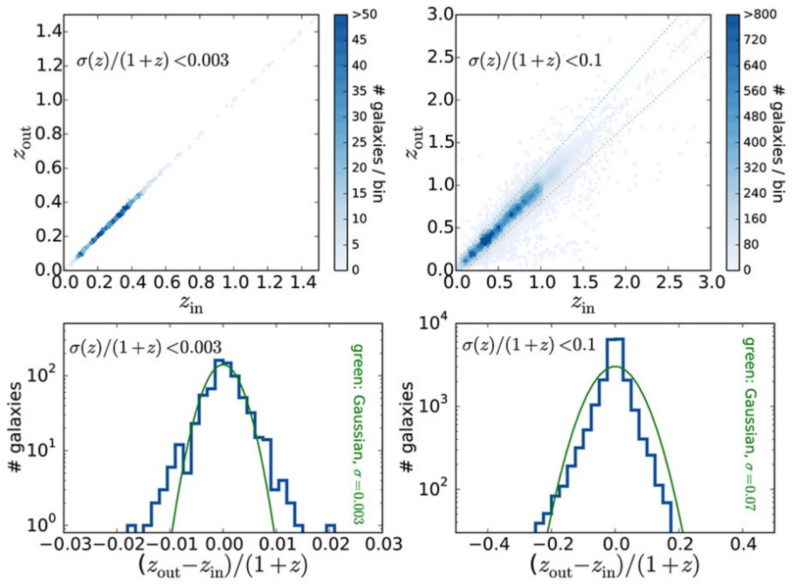
Assign each bin a galaxy bias using published CFHT/COSMOS data prescriptions

Compute errors for each wavelength and redshift bins

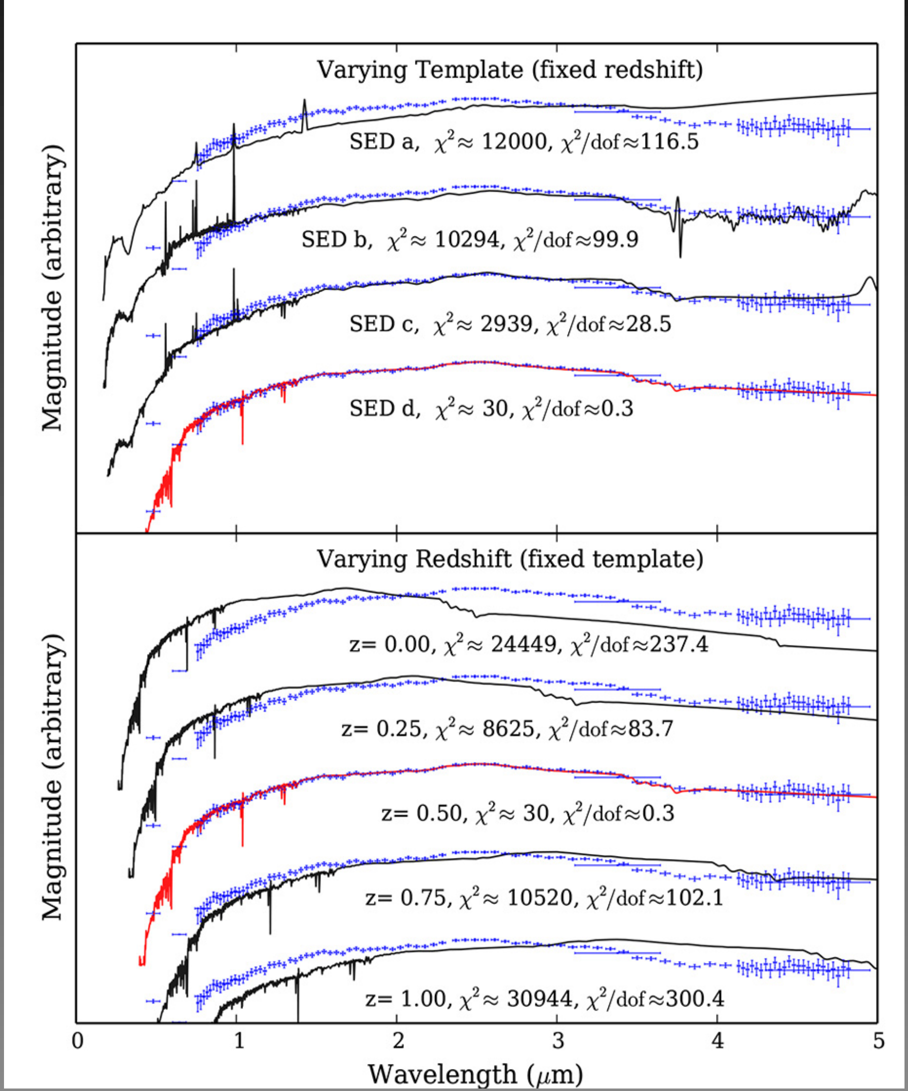
Marginalize over bias and other parameters

SPHERExInflation Investigation Cosmological Forecasts

Resulting Redshift Errors

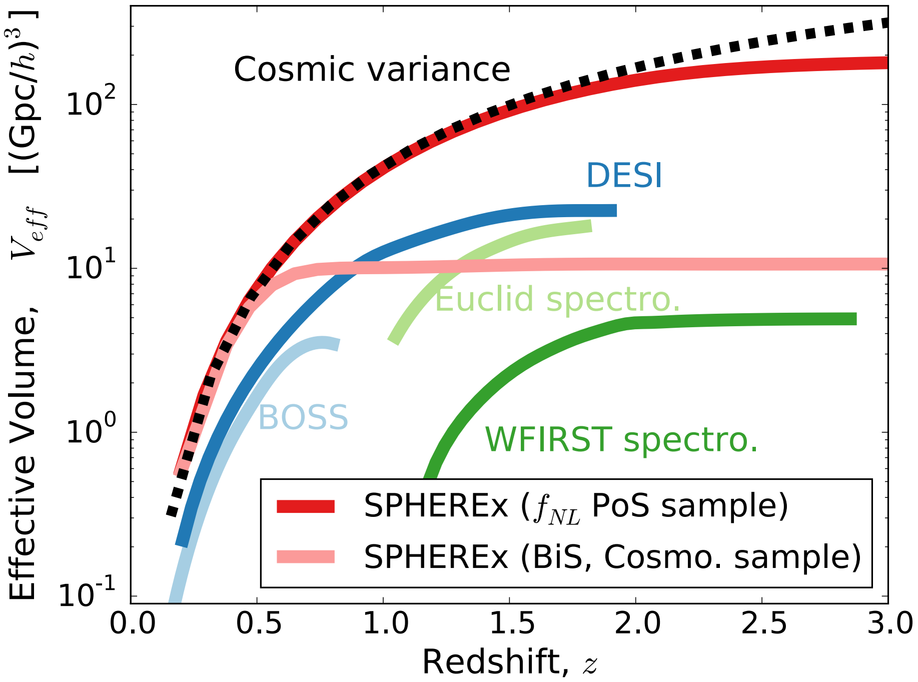


Example Template and Redshift Fits

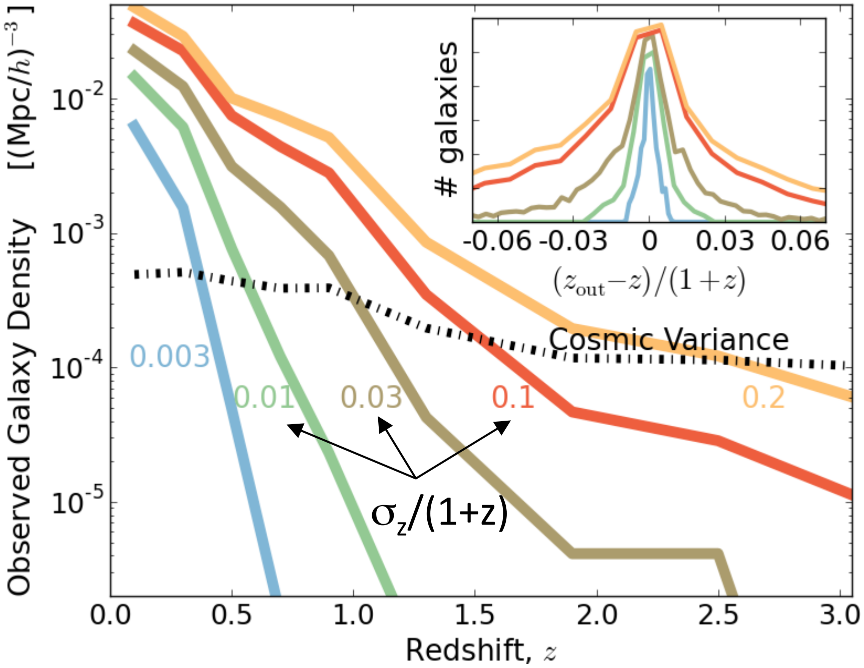


SPHEREx Large Volume Galaxy Survey

SPHEREx Surveys Maximum Cosmic Volume



Catalog Split into Redshift Accuracy Bins



SPHEREx Large-Volume Redshift Catalog

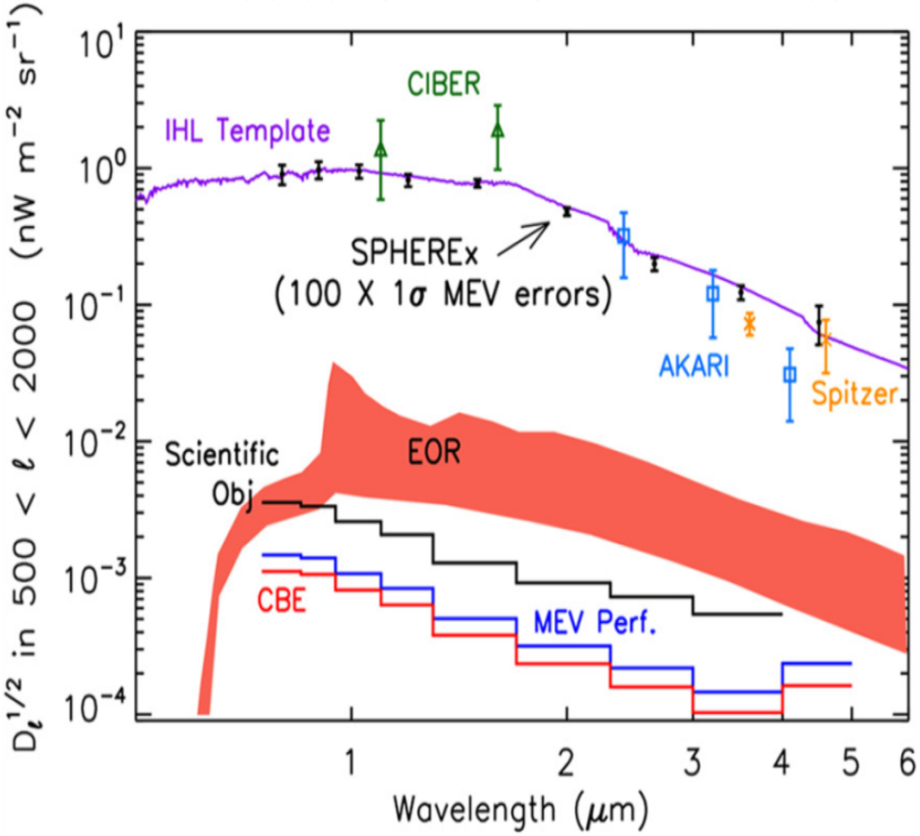
- Largest effective volume of any survey, near cosmic limit
- Excels at z < 1, complements dark energy missions (Euclid, WFIRST) targeting z ~ 2
- SPHEREx + Euclid measures gravitational lensing and calibrates Euclid photo-zs

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

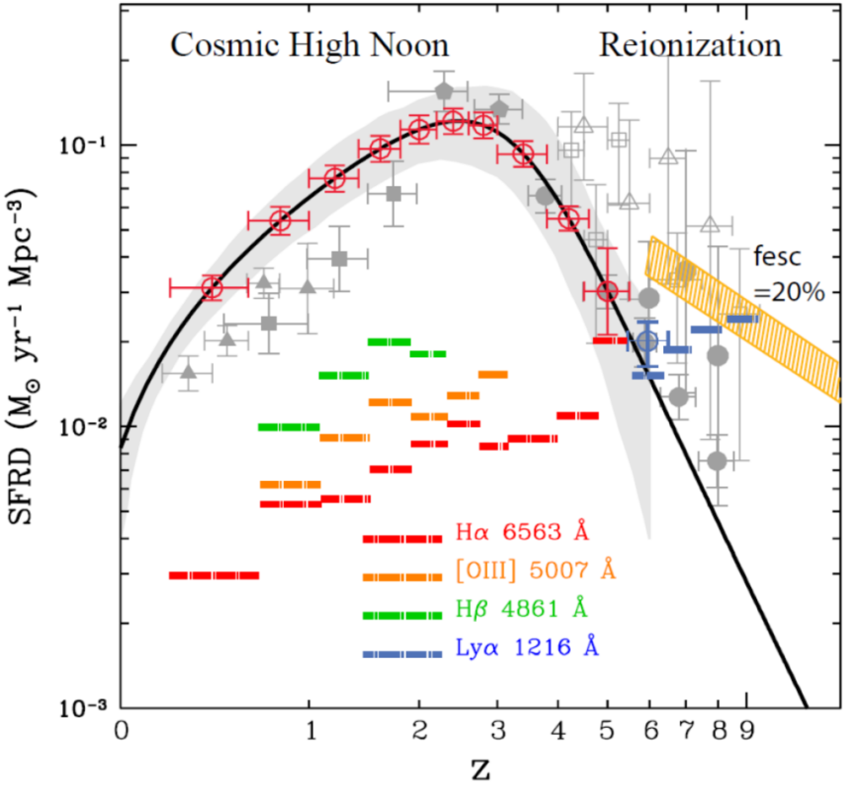
SPHEREx Measures Large-Scale Fluctuations

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

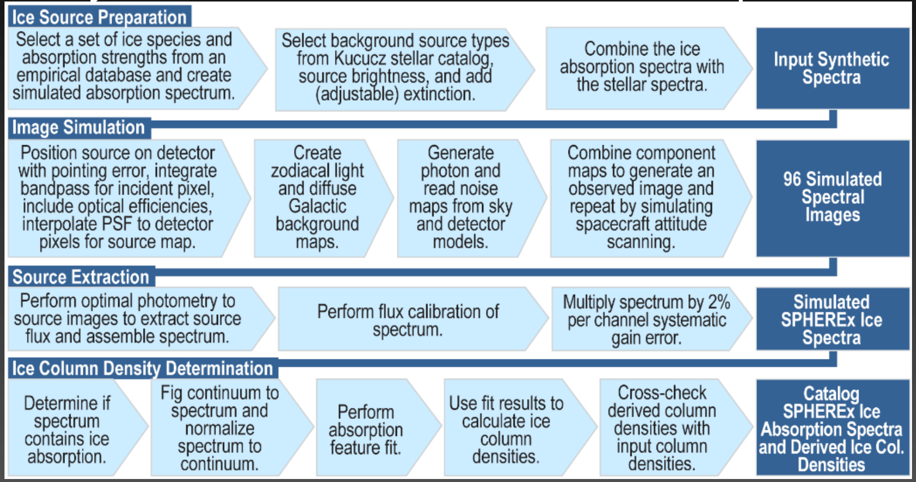
Fluctuations in Lines



- 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
  - Lyα probes EoR models for z > 6
  - Hα and Lyα crossover region 5 < z < 6

SPHEREx Galactic Ice Survey

Inject Simulated Ice Sources into Pipeline



Ice Source Preparation

Select a set of ice species and absorption strengths from an empirical database and create simulated absorption spectrum.

Select background source types from Kucucz stellar catalog, source brightness, and add (adjustable) extinction.

Combine the ice absorption spectra with the stellar spectra.

Input Synthetic Spectra

Image Simulation

Position source on detector with pointing error, integrate bandpass for incident pixel, include optical efficiencies, interpolate PSF to detector pixels for source map.

Create zodiacal light and diffuse Galactic background maps.

Generate photon and read noise maps from sky and detector models.

Combine component maps to generate an observed image and repeat by simulating spacecraft attitude scanning.

96 Simulated Spectral Images

Source Extraction

Perform optimal photometry to source images to extract source flux and assemble spectrum.

Perform flux calibration of spectrum.

Multiply spectrum by 2% per channel systematic gain error.

Simulated SPHEREx Ice Spectra

Ice Column Density Determination

Determine if spectrum contains ice absorption.

Fig continuum to spectrum and normalize spectrum to continuum.

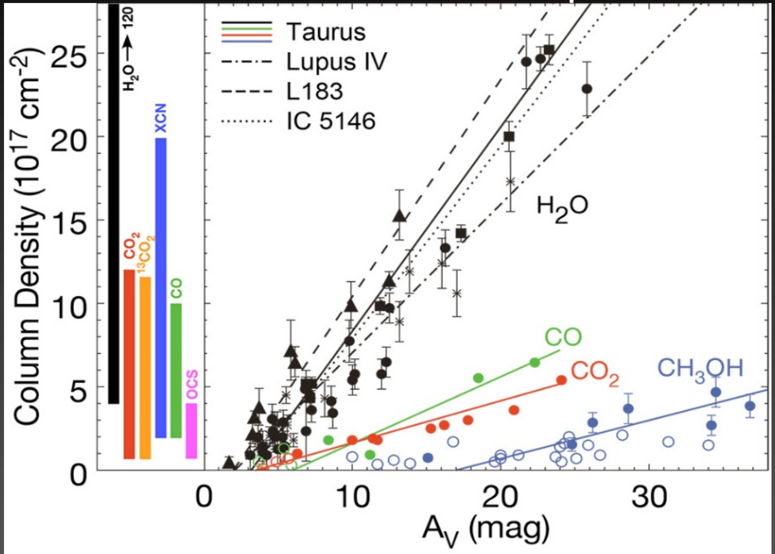
Perform absorption feature fit.

Use fit results to calculate ice column densities.

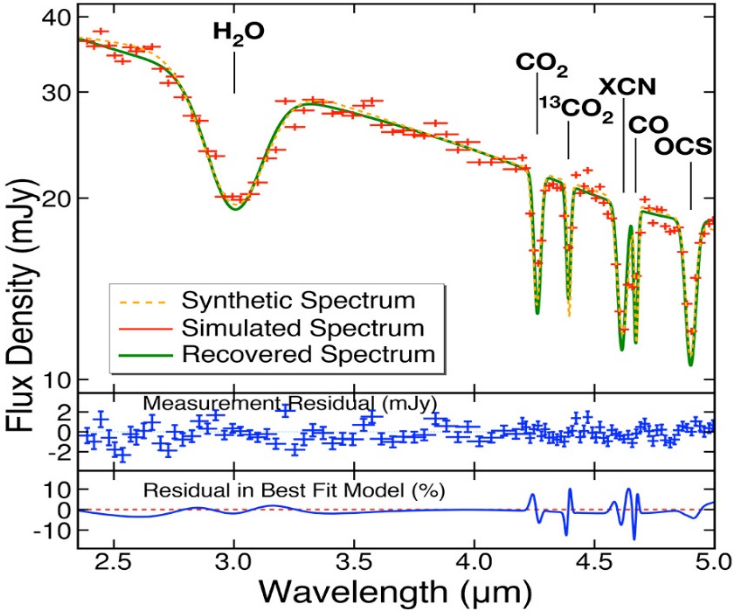
Cross-check derived column densities with input column densities.

Catalog SPHEREx Ice Absorption Spectra and Derived Ice Col. Densities

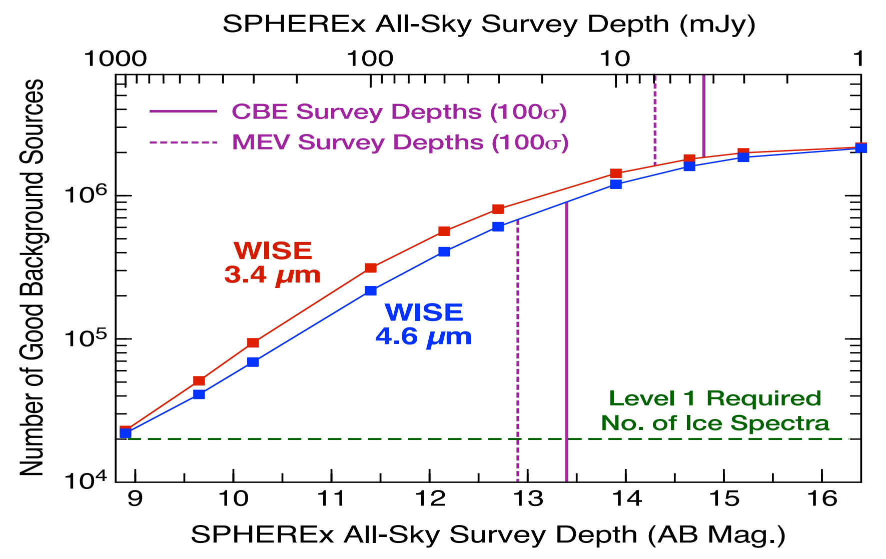
Reliable Columns of Ice Species



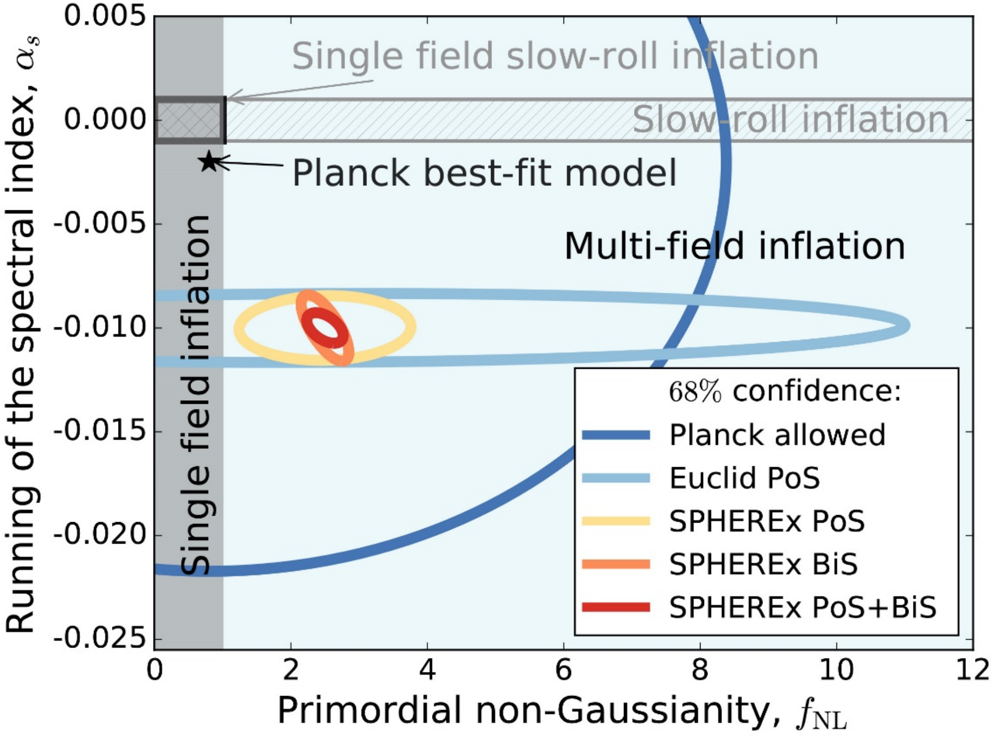
Estimate Errors on Absorption Depth

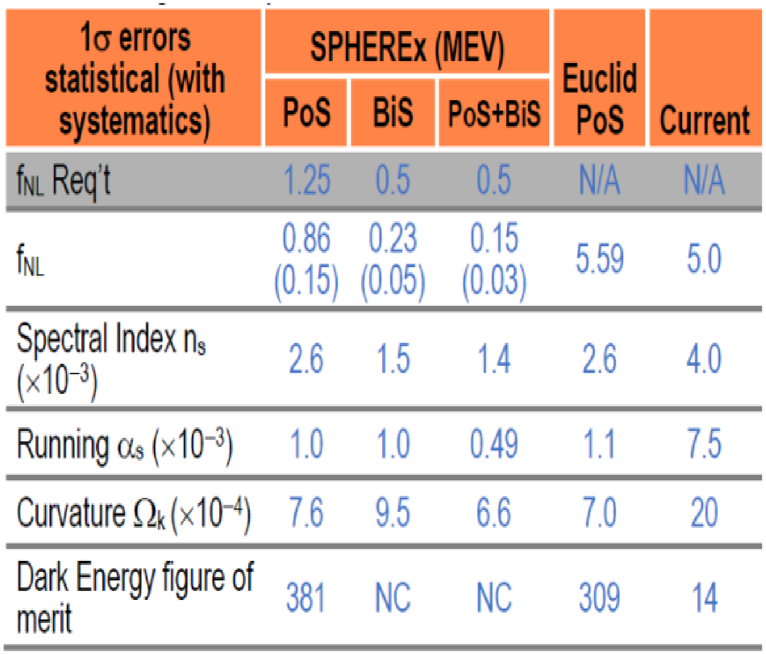


Expect ~1 Million High-Quality Ice Detections



SPHEREx Tests Inflationary Non-Gaussianity

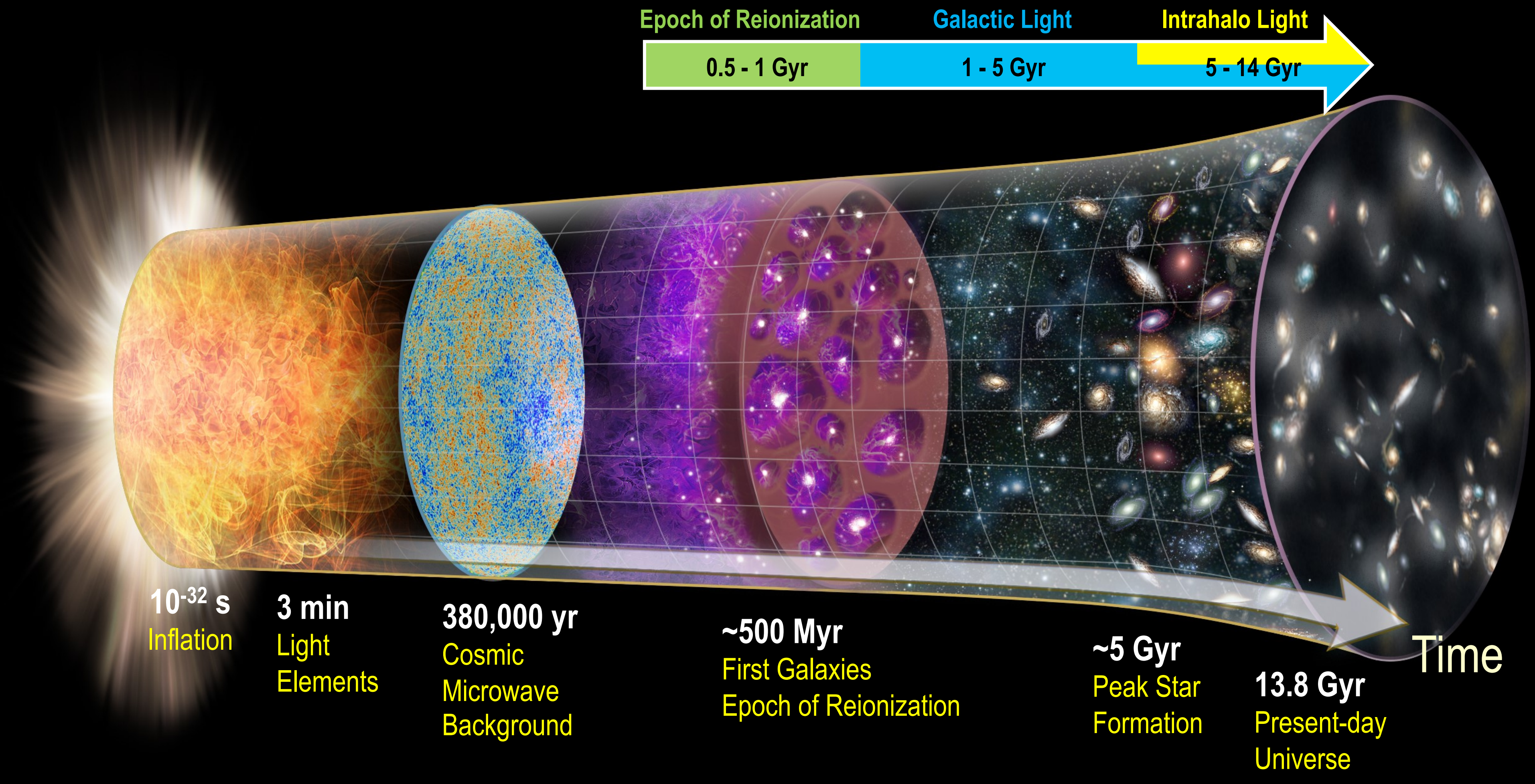




1σ errors statistical (with systematics)	SPHEREx (MEV)			Euclid PoS	Current
	PoS	BiS	PoS+BiS		
f_{NL} Req't	1.25	0.5	0.5	N/A	N/A
f_{NL}	0.86 (0.15)	0.23 (0.05)	0.15 (0.03)	5.59	5.0
Spectral Index n_s ($\times 10^{-3}$)	2.6	1.5	1.4	2.6	4.0
Running α_s ($\times 10^{-3}$)	1.0	1.0	0.49	1.1	7.5
Curvature Ω_k ($\times 10^{-4}$)	7.6	9.5	6.6	7.0	20
Dark Energy figure of merit	381	NC	NC	309	14

- Projected SPHEREx sensitivity is $\Delta f_{NL} < 0.5$ (1σ)
  - Two independent tests via power spectrum and bispectrum
- Competitively tests running of the spectral index
- SPHEREx low-redshift catalog is complementary for dark energy

How Did Galaxies Begin?



Contributions to the Extragalactic Background Light

Epoch of Reionization	Galactic Light	Intrahalo Light
0.5 - 1 Gyr	1 - 5 Gyr	5 - 14 Gyr

10^{-32} s
Inflation

3 min
Light Elements

380,000 yr
Cosmic Microwave Background

~500 Myr
First Galaxies
Epoch of Reionization

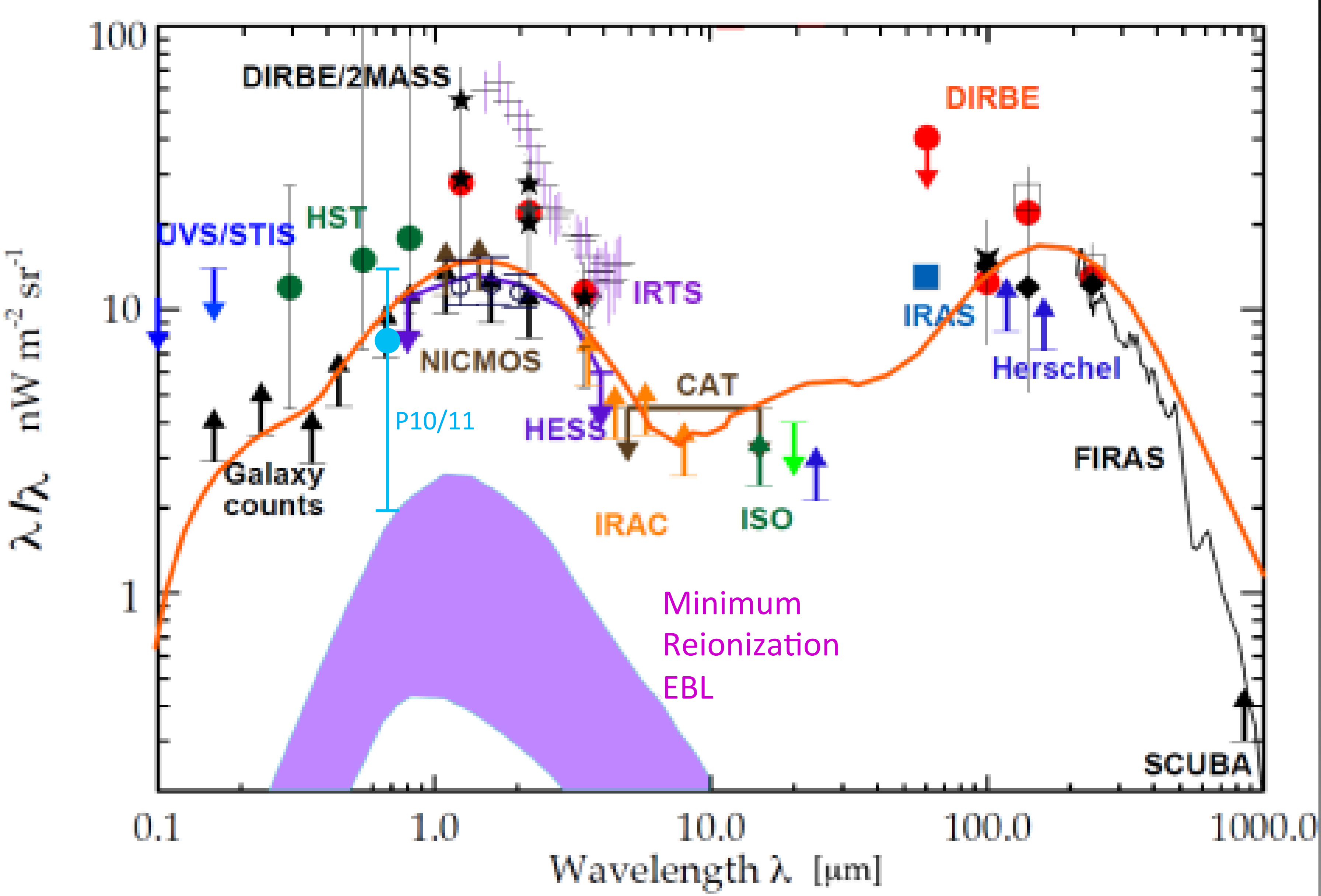
~5 Gyr
Peak Star Formation

13.8 Gyr
Present-day Universe

Time

SPHEREx extragalactic background light measurements determine the total light emitted by galaxies

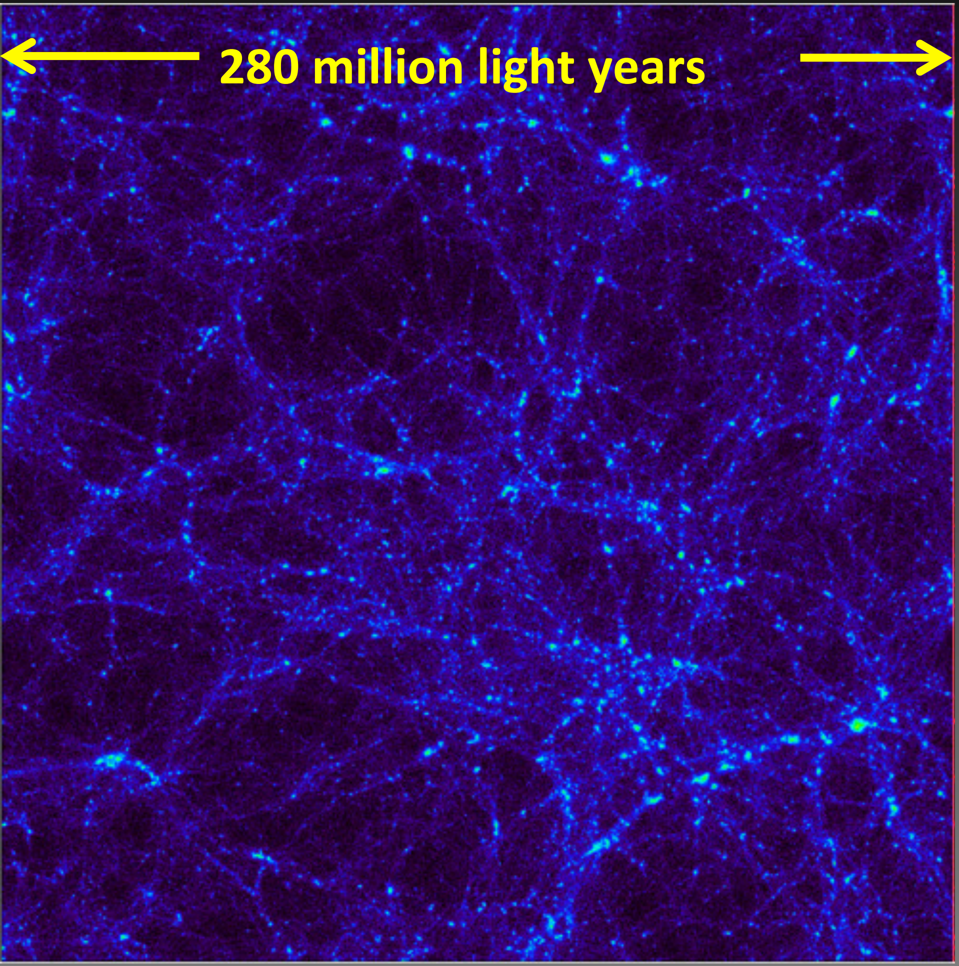
Current Absolute EBL Measurements



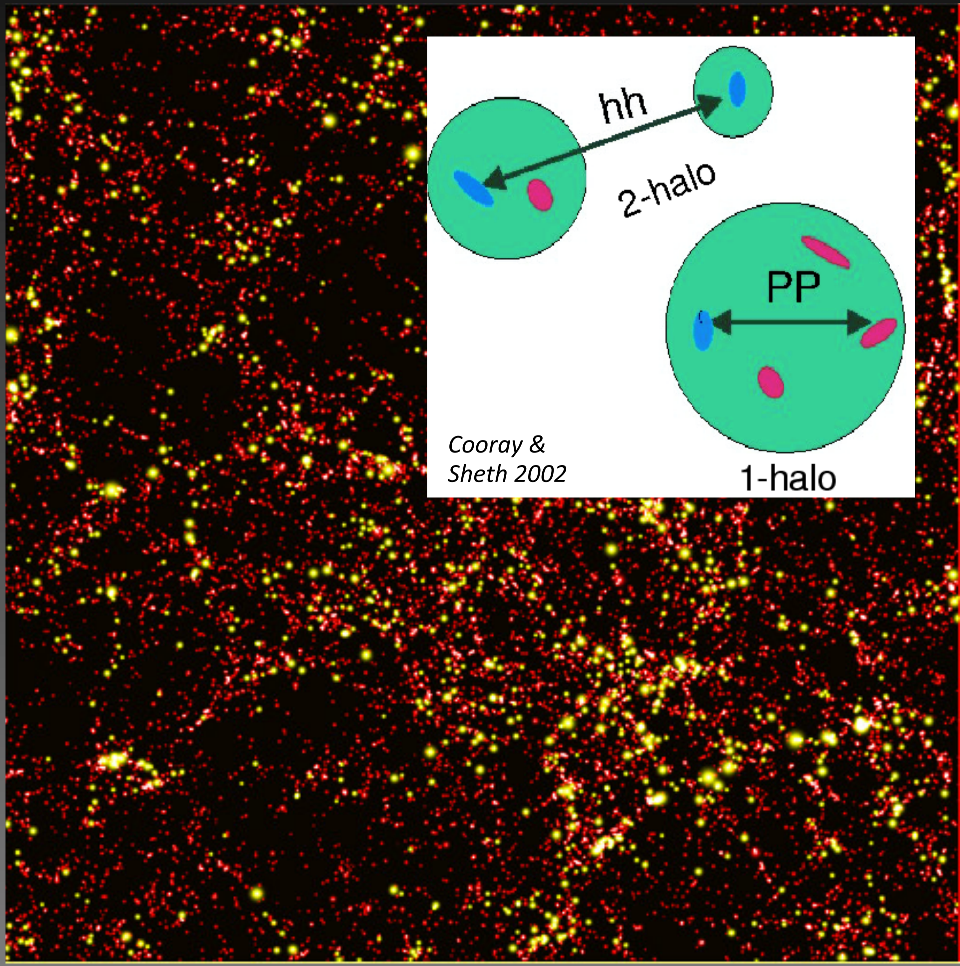
Problem with Absolute Photometry: Foregrounds!

Relating Galaxies to Dark Matter

Dark Matter from Numerical Simulation (z = 2)



Dark Matter Clumps Color-Coded by Mass

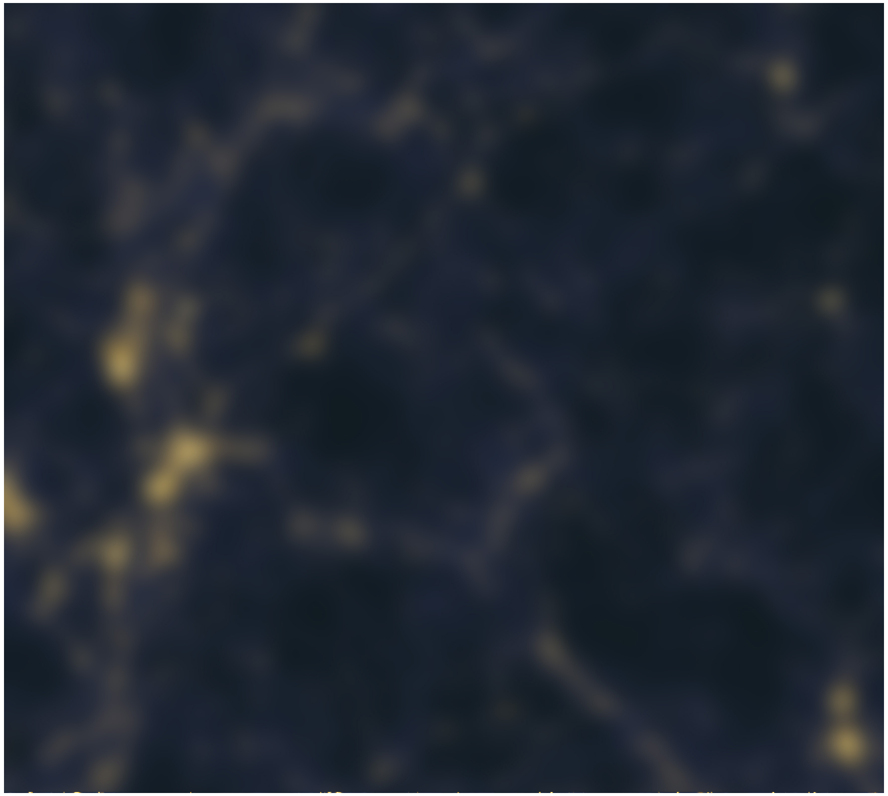


Cooray & Sheth 2002

Large scales:	Light traces dark matter	Measure light production [since we “know” P(k)]
	Measure P(k) precisely → cosmography	
Med scales:	Non-linear clustering	Galaxy formation within a halo
Small scales:	Poisson fluctuations	Galaxy counts

Measuring Cosmic Light Production

Two Ways to Measure Cosmic Light Production



1) Individual Galaxies & Redshifts

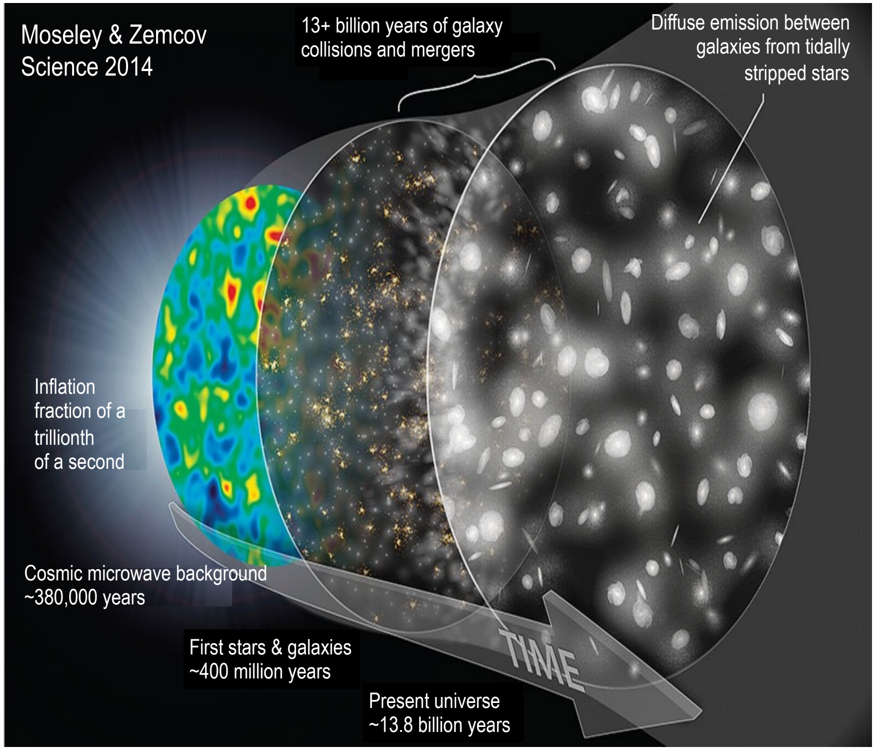
Large telescope for point source sensitivity

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

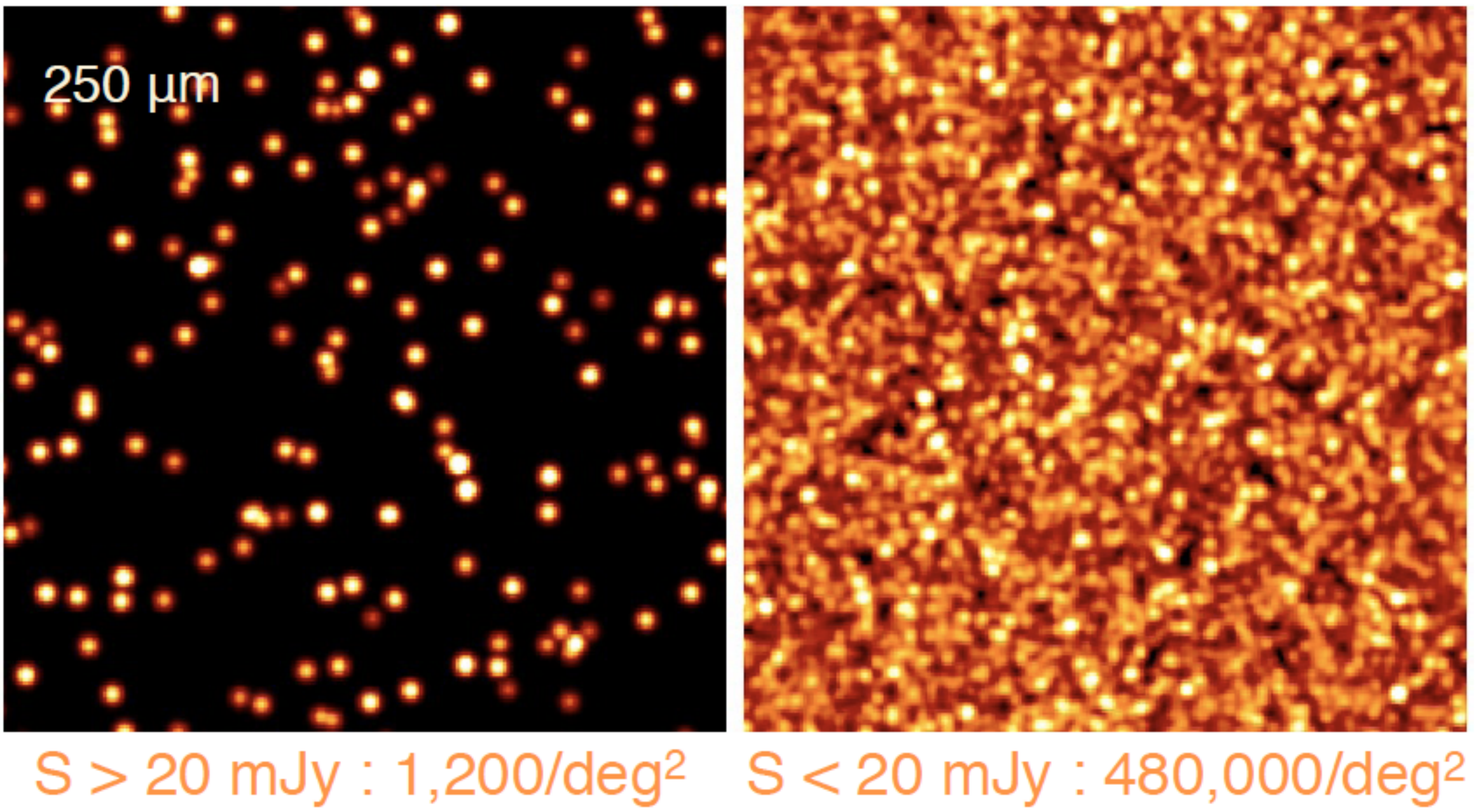
3) Inter Halo Light

Tidally stripped stars at z = 0 - 2

4) Surprises?

Continuum Intensity Mapping

How to Fully Exploit Far-Infrared Herschel Maps?

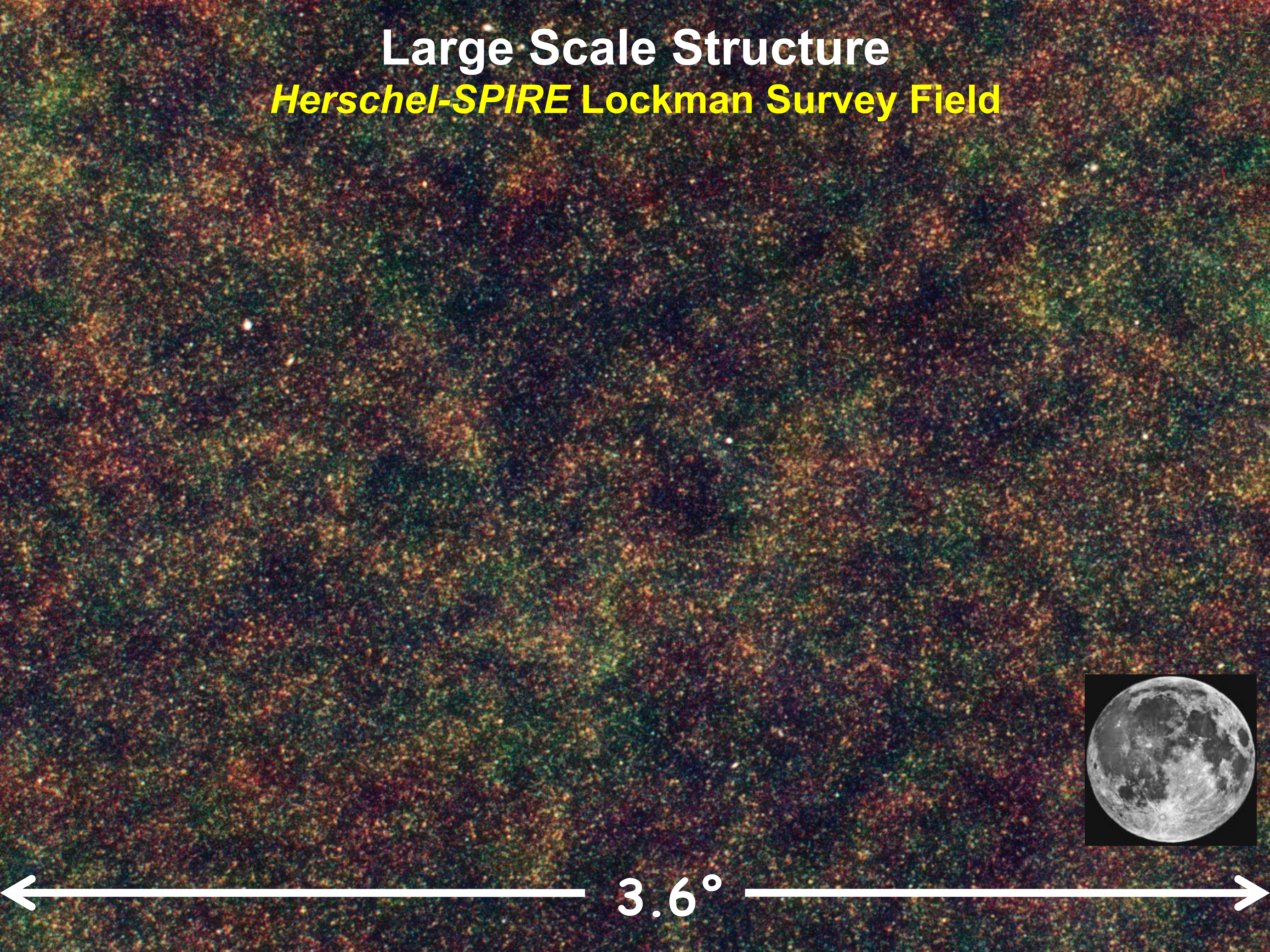


S > 20 mJy : 1,200/deg^2 S < 20 mJy : 480,000/deg^2

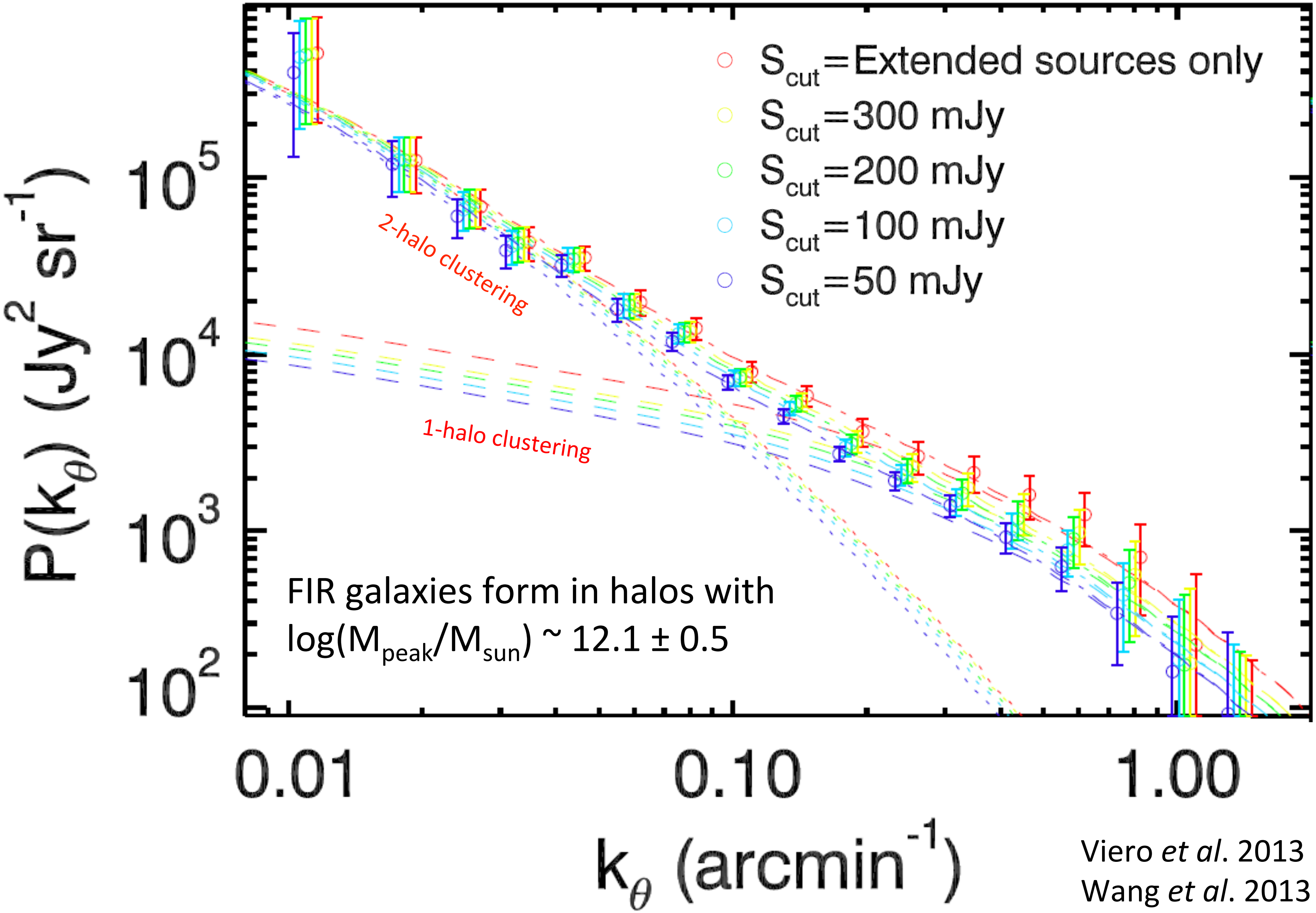
Slide courtesy Marco Viero

Large Scale Structure

Herschel-SPIRE Lockman Survey Field



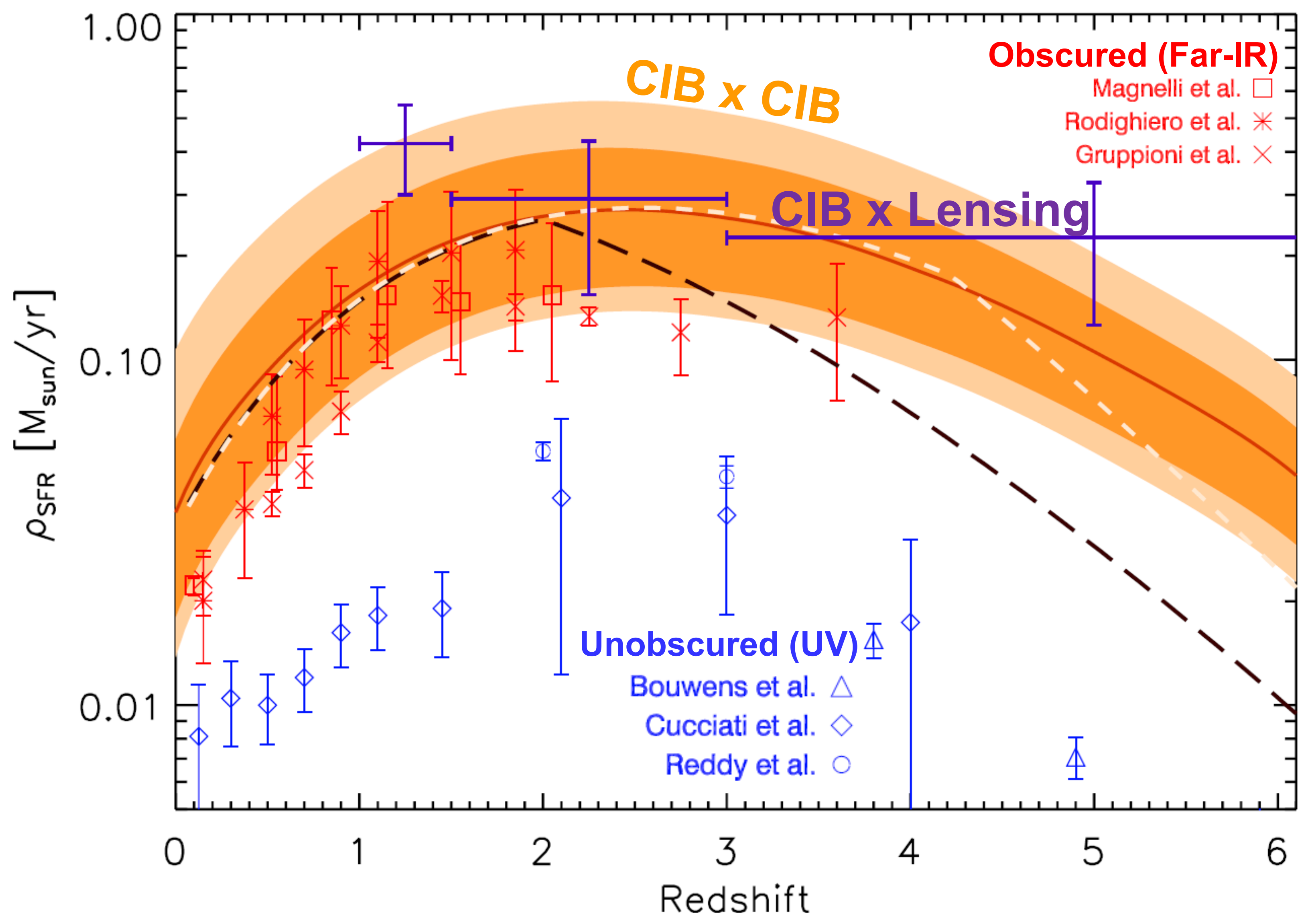
Spatial Power Spectrum Shows Clustering



FIR galaxies form in halos with $\log(M_{peak}/M_{sun}) \sim 12.1 \pm 0.5$

Viero *et al*. 2013
Wang *et al*. 2013

Probing High-z Star Formation

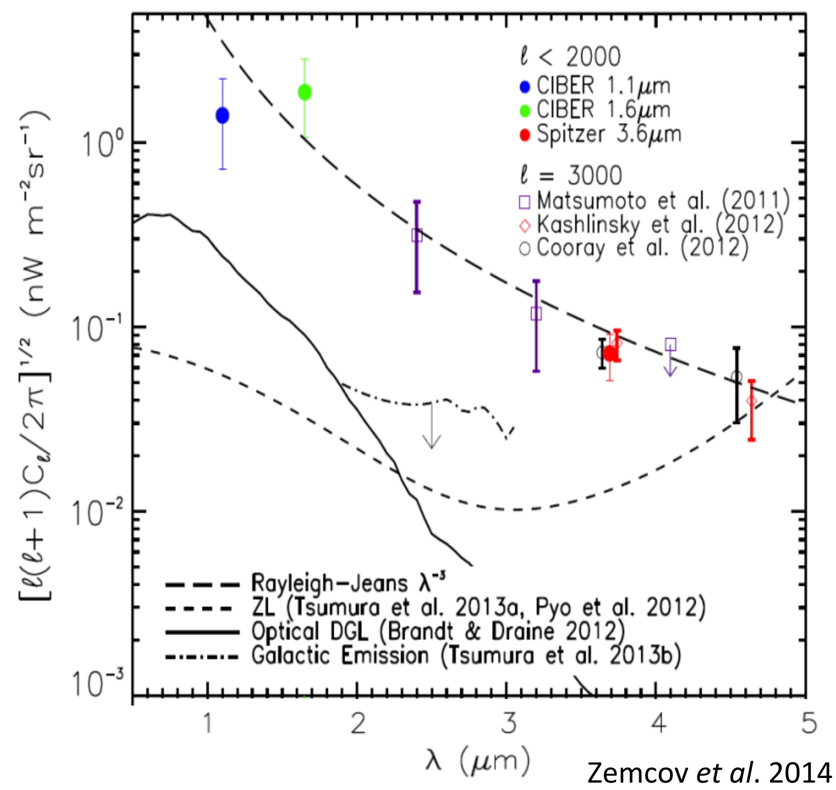


Planck 2013 - ESLAB

Near-Infrared Clustering Fluctuations

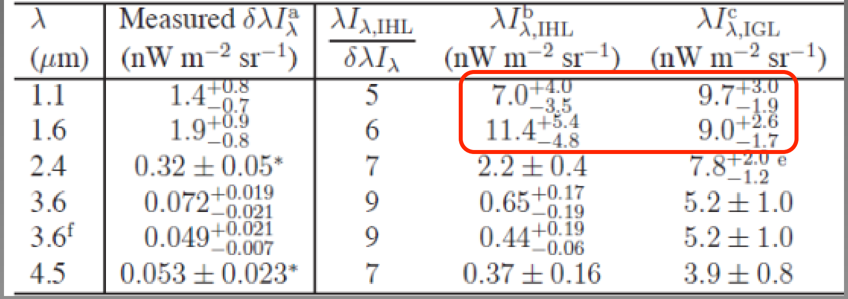
IHL (at redshift 0-2) or EOR (at redshift 6-8)?

Amplitude of clustering power spectrum

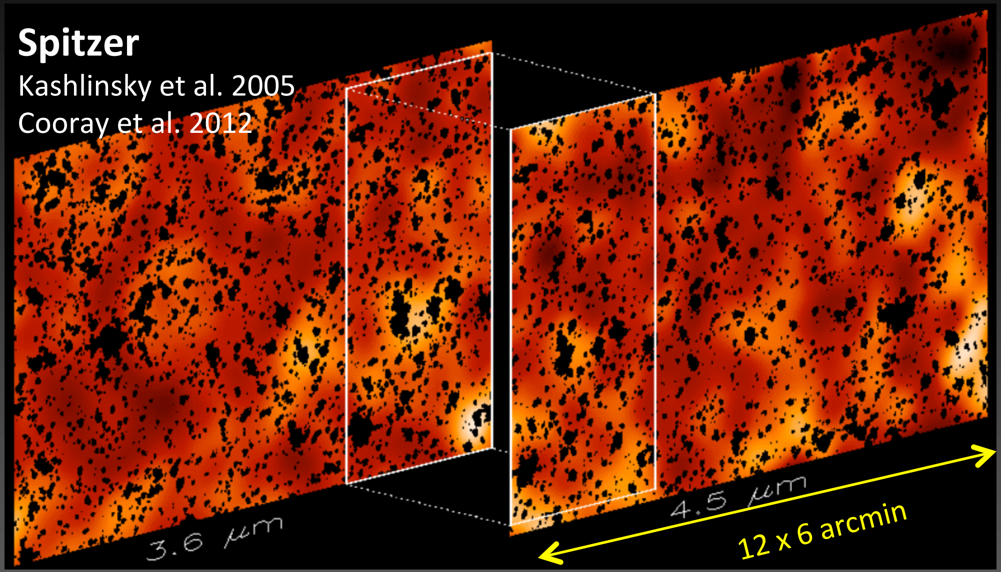


Zemcov *et al.* 2014

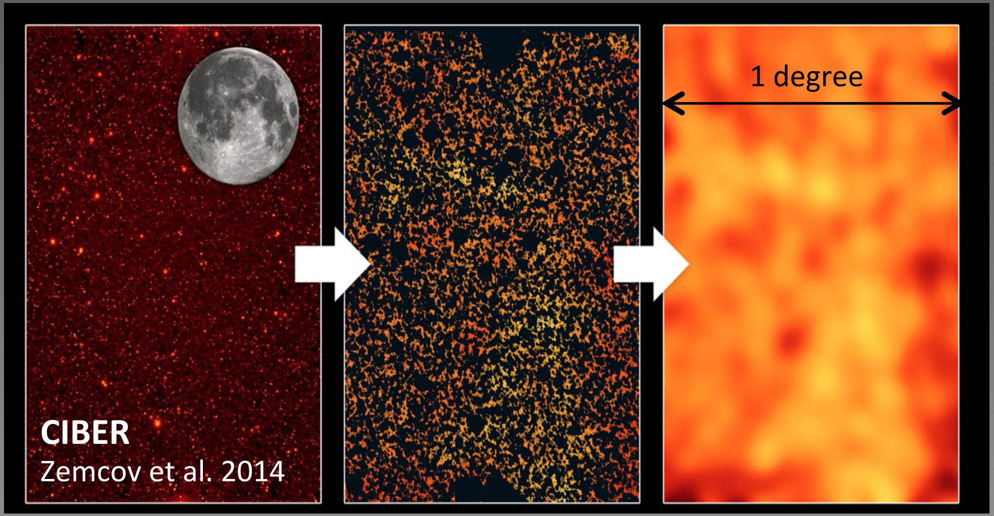
Inferred Extragalactic Background



λ (μm)	Measured $\delta\lambda I_\lambda^{a}$ (nW m^{-2} sr^{-1})	$\frac{\lambda I_{\lambda,\mathrm{IHL}}}{\delta\lambda I_\lambda}$	$\lambda I^{b}_{\lambda,\mathrm{IHL}}$ (nW m^{-2} sr^{-1})	$\lambda I^{c}_{\lambda,\mathrm{IGL}}$ (nW m^{-2} sr^{-1})
1.1	$1.4^{+0.8}_{-0.7}$	5	$7.0^{+4.0}_{-3.5}$	$9.7^{+3.0}_{-1.9}$
1.6	$1.9^{+0.9}_{-0.8}$	6	$11.4^{+5.4}_{-4.8}$	$9.0^{+2.6}_{-1.7}$
2.4	$0.32 \pm 0.05^{*}$	7	2.2 ± 0.4	$7.8^{+2.0\ e}_{-1.2}$
3.6	$0.072^{+0.019}_{-0.021}$	9	$0.65^{+0.17}_{-0.19}$	5.2 ± 1.0
3.6^{f}	$0.049^{+0.021}_{-0.007}$	9	$0.44^{+0.19}_{-0.06}$	5.2 ± 1.0
4.5	$0.053 \pm 0.023^{*}$	7	0.37 ± 0.16	3.9 ± 0.8



Spitzer
Kashlinsky et al. 2005
Cooray et al. 2012



CIBER
Zemcov et al. 2014

What Are the Conditions for Life Outside the Solar System?

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

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

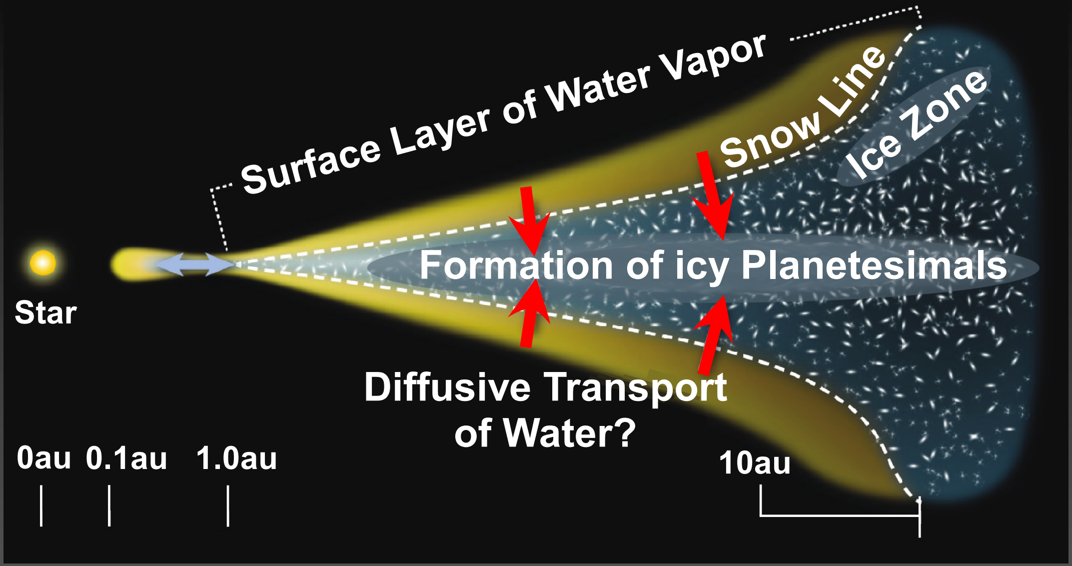
Did water arrive from the late bombardment (~500 MY) or before?

SPHEREx will measure the H_2O, CO, CO_2, CH_3OH ice content in clouds and disks, determining how ices are inherited from parent clouds vs. processed in disks

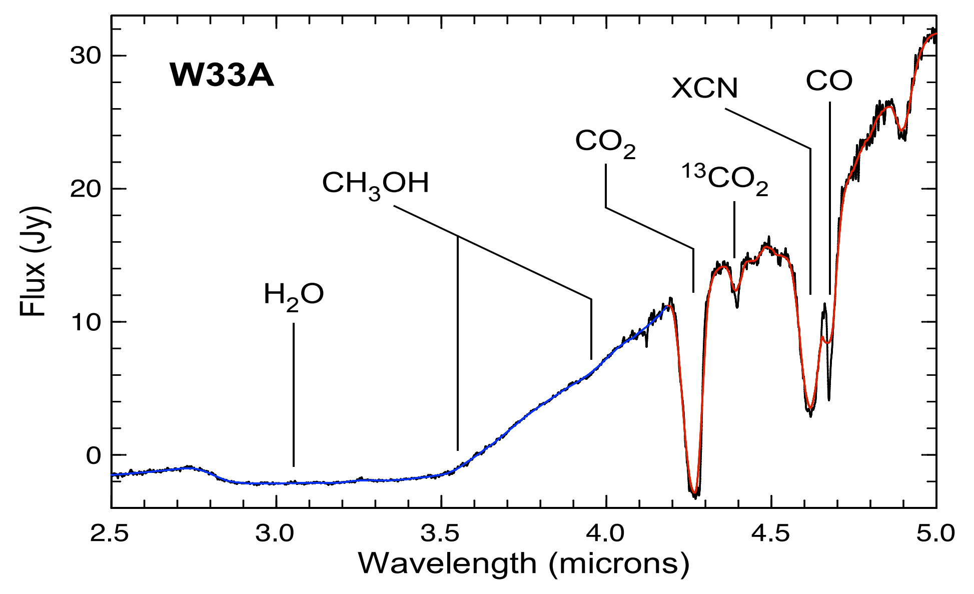
Why Study Ices?

- **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 $^{13}CO_2$

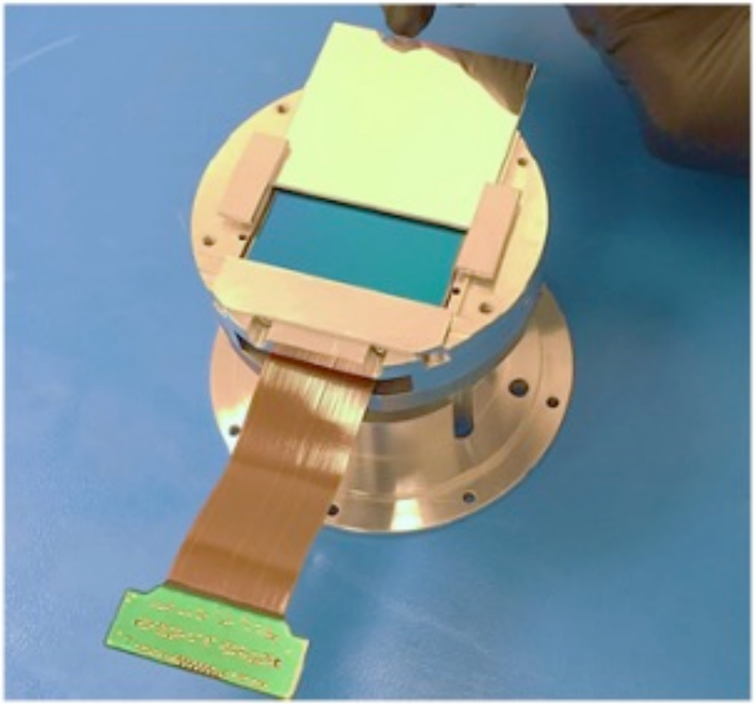
Schematic of a protoplanetary disk



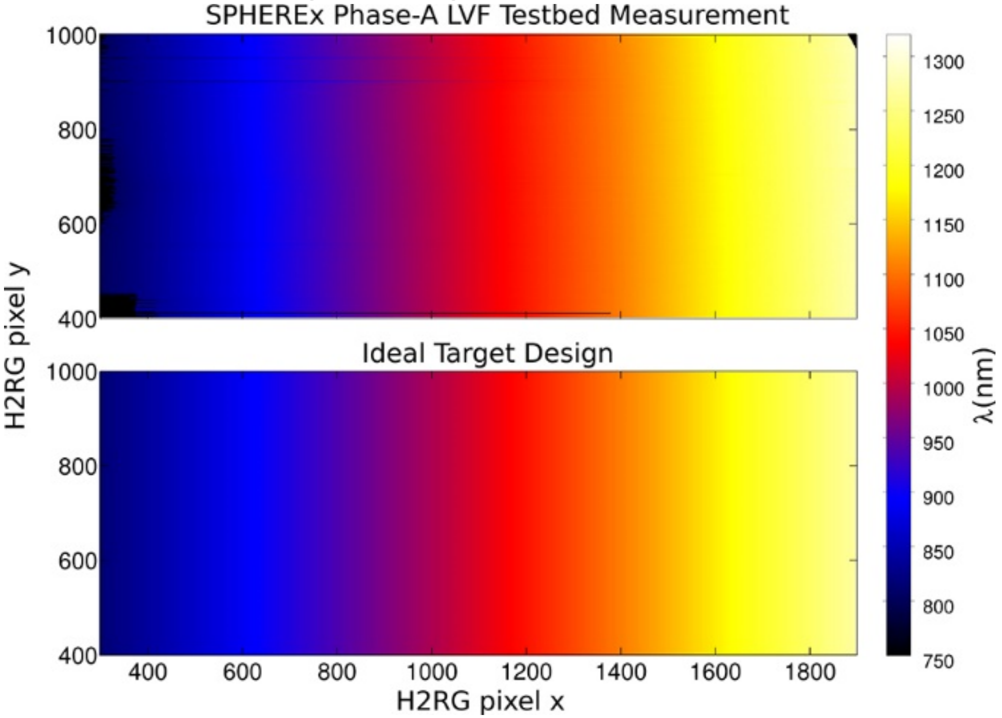
ISO absorption spectrum



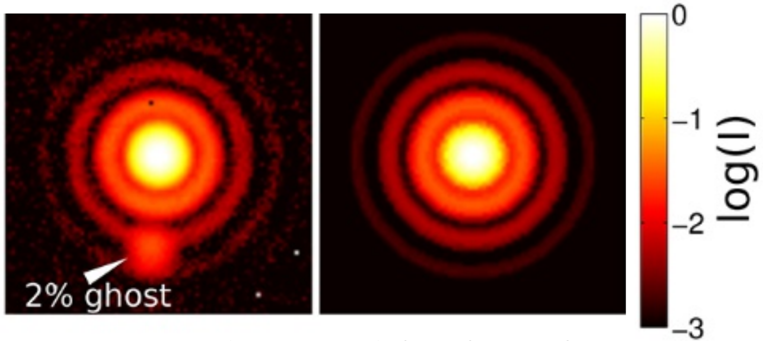
Demonstrating the Band 1 LVF Spectrometer



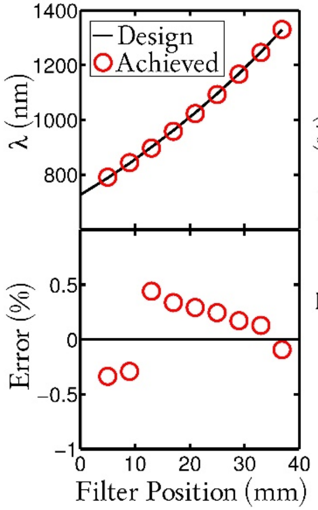
Wavelength Progression and Resolution

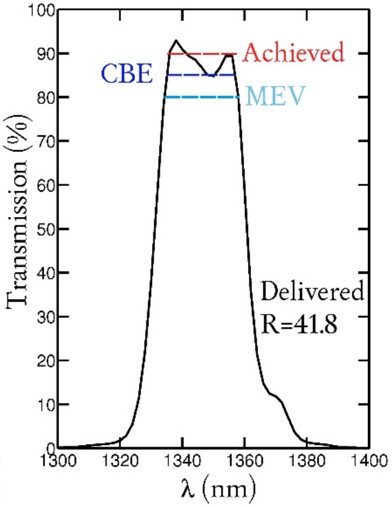


2 % Reflections Between Detector & LVF

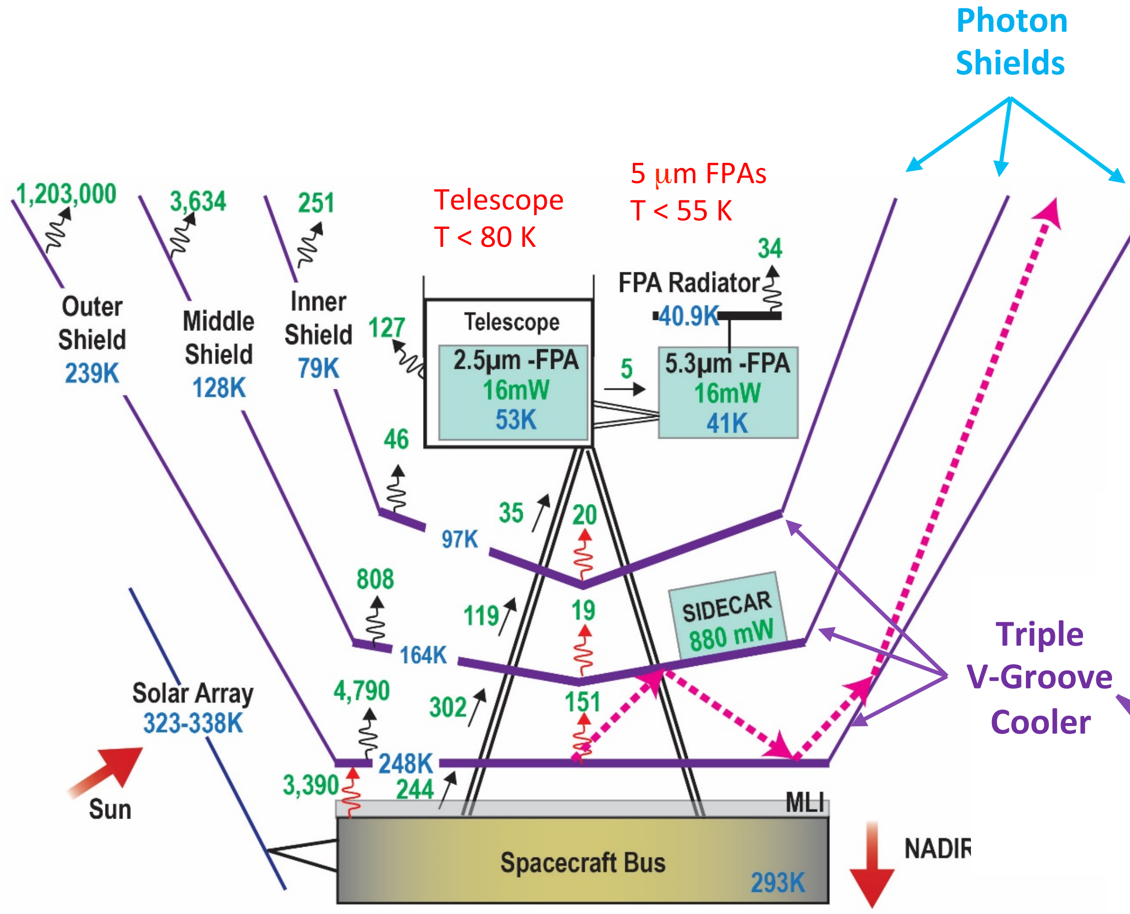


Measured Model without ghost





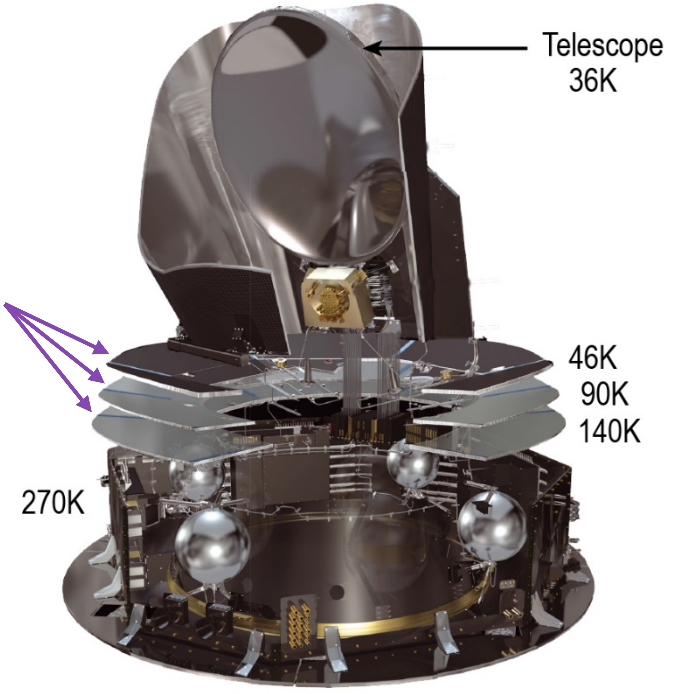
SPHEREx Passive Cooling System



Cooling Design for SPHEREx in Low-Earth Orbit

Passive Cooling Examples

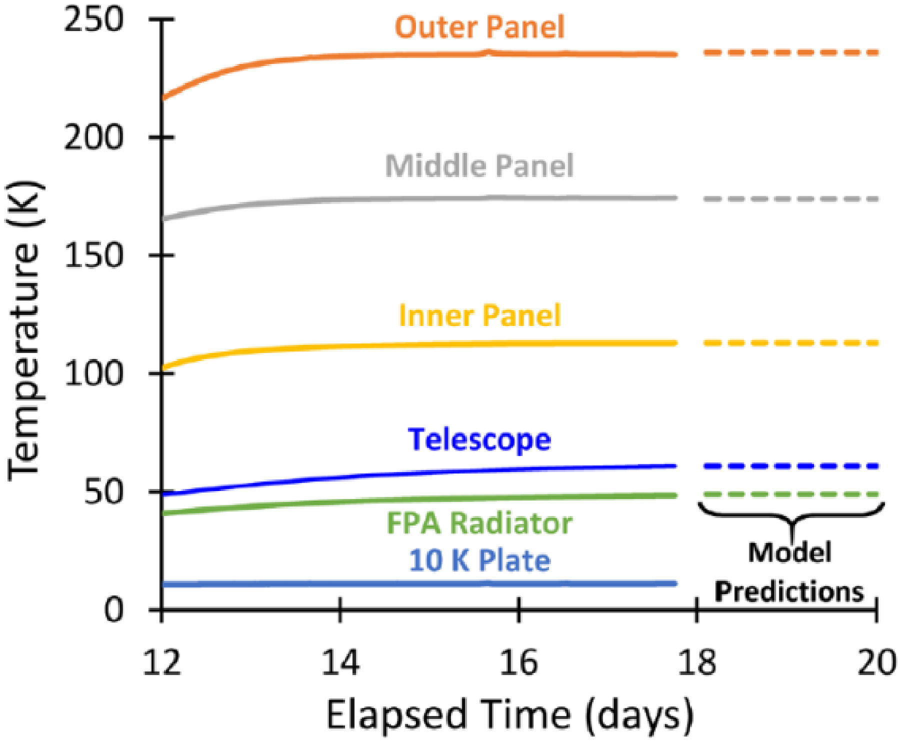
Mission	Orbit	Temp	Notes
COBE	LEO Sun-Sync	45 K	DIRBE post-cryo Volz et al. 1992
WISE	LEO SS	74 K	Mirror post-cryo
Spitzer	Earth-trail	27.5 K	Mirror post-cryo
Planck	L2	36 K	Telescope Planck et al. 2011

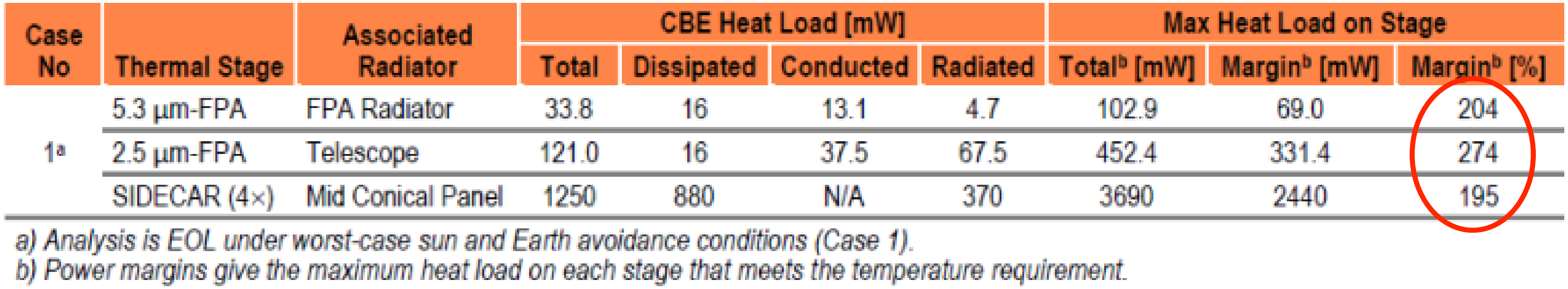


JPL Passive Cooling Design for Planck at L2

Thermal System Prototype Testing

¼ Scale Thermal Test



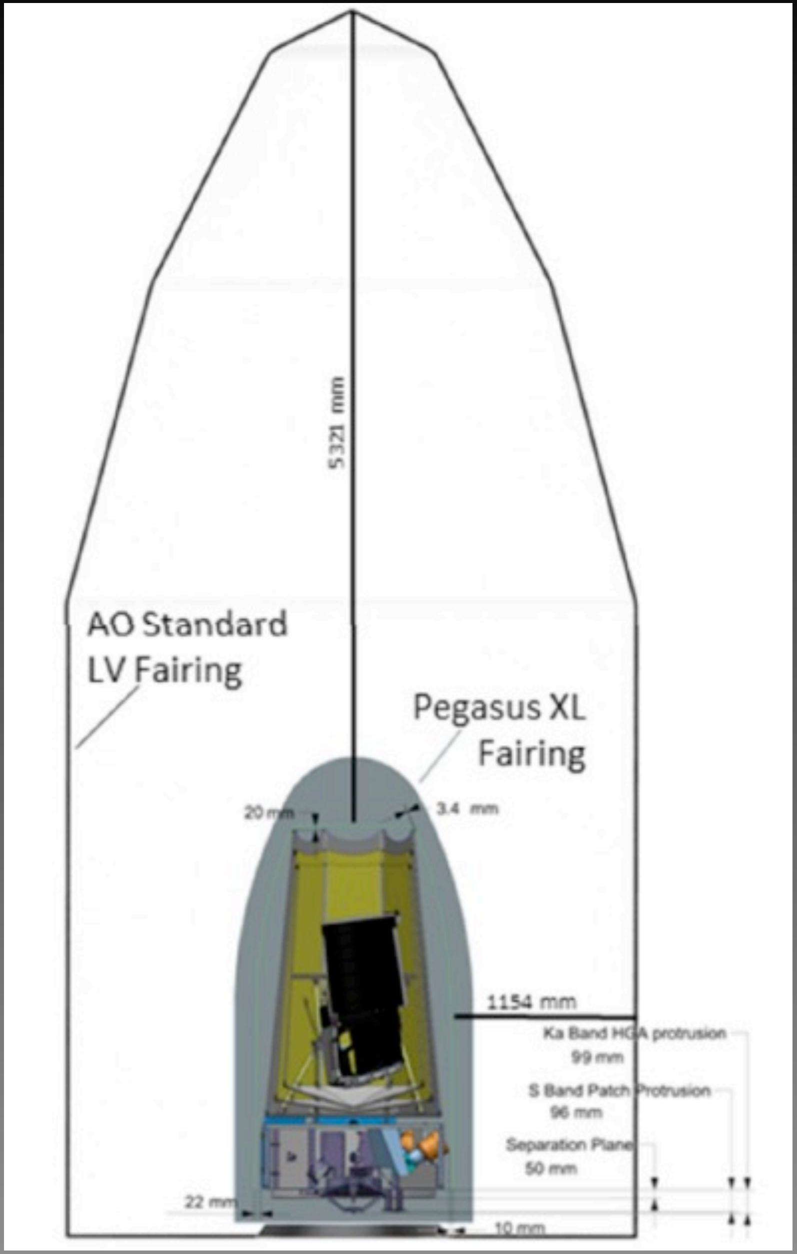


Case No	Thermal Stage	Associated Radiator	CBE Heat Load [mW]				Max Heat Load on Stage		
			Total	Dissipated	Conducted	Radiated	Total[b] [mW]	Margin[b] [mW]	Margin[b] [%]
1[a]	5.3 μm-FPA	FPA Radiator	33.8	16	13.1	4.7	102.9	69.0	204
	2.5 μm-FPA	Telescope	121.0	16	37.5	67.5	452.4	331.4	274
	SIDECAR (4×)	Mid Conical Panel	1250	880	N/A	370	3690	2440	195

a) Analysis is EOL under worst-case sun and Earth avoidance conditions (Case 1).
b) Power margins give the maximum heat load on each stage that meets the temperature requirement.

To meet
T ≤ 55 K
T ≤ 80 K
T ≤ 200 K

Falcon IX vs. Pegasus Launch

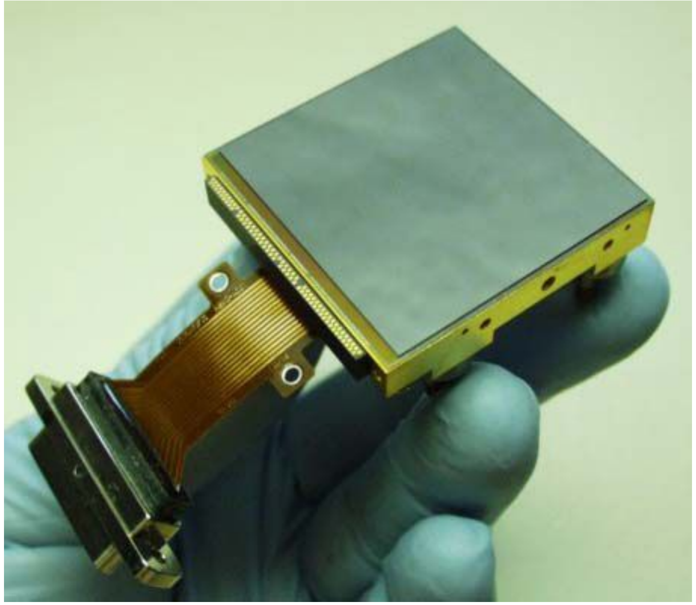


Falcon IX: 2865 kg to LEO sun-sync

1564 % mass margin

Pegasus: 240 kg to LEO sun-sync

Hawaii-2RG Detector Arrays

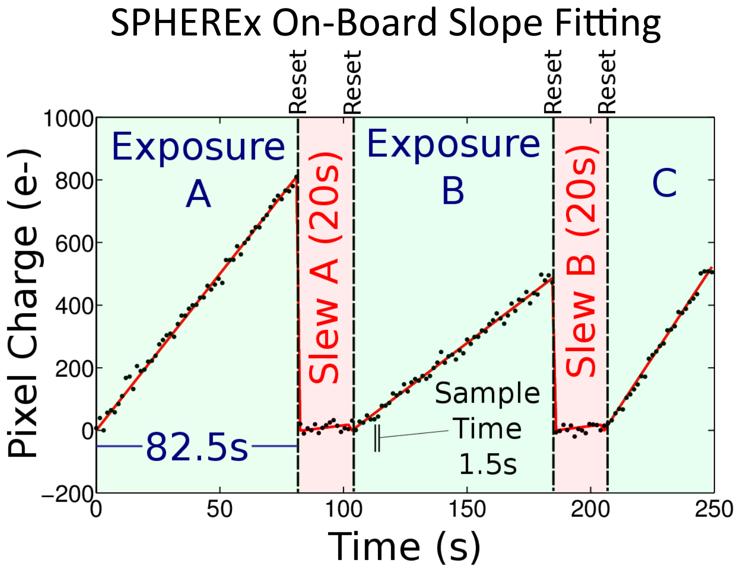


Teledyne H2RG arrays

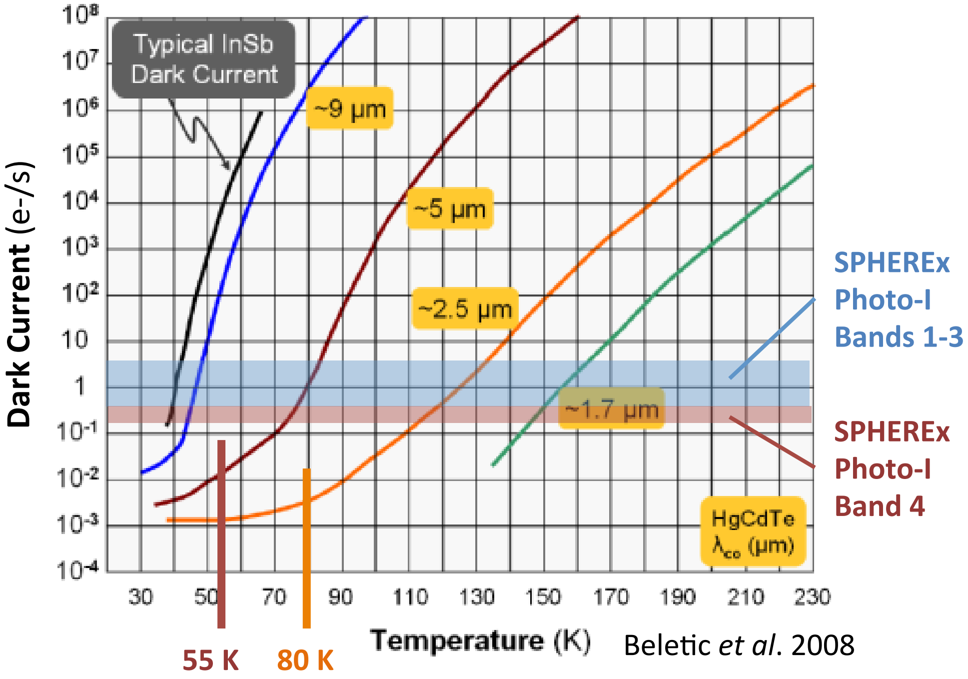
- H1RGs flown on HST (1.7um), OCO (2.5um), WISE (5um) (TRL 9)
- H2RGs and SIDECAR for JWST (TRL 6)
- H2RGs wide use in ground-based astronomy

‘Off-the-Shelf’ Array Specifications

Parameter	**2.5 μm Arrays**		**5 μm Arrays**	
	Spec	**Typical**	**Spec**	**Typical**
CDS Read Noise	18 e^-	10.5 e^-	15 e^-	10.5 e^-
Detector QE	70 %	75 %	75 %	75 %
Dark Current	0.05 e^-/s	0.01 e^-/s	0.05 e^-/s	0.01 e^-/s



SPHEREx On-Board Slope Fitting



Beletic *et al.* 2008