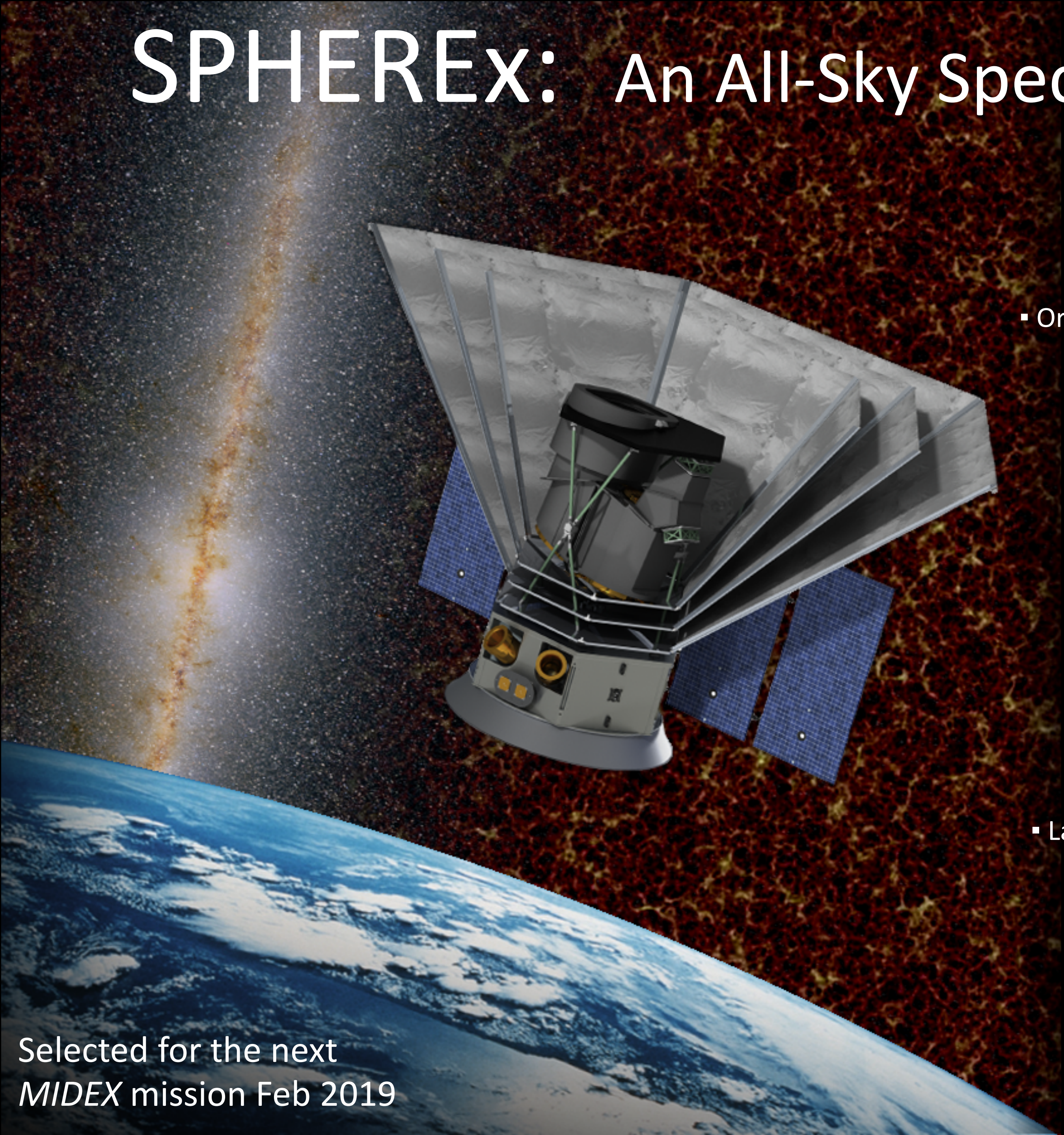
SPHEREx: An All-Sky Spectral Survey



Designed to Explore

- Origin of the Universe
- Origin and History of Galaxies
- 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

Elegantly Simple

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

Jamie Bock
Caltech/JPL
2 June 2020

Selected for the next *MIDEX* mission Feb 2019

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"

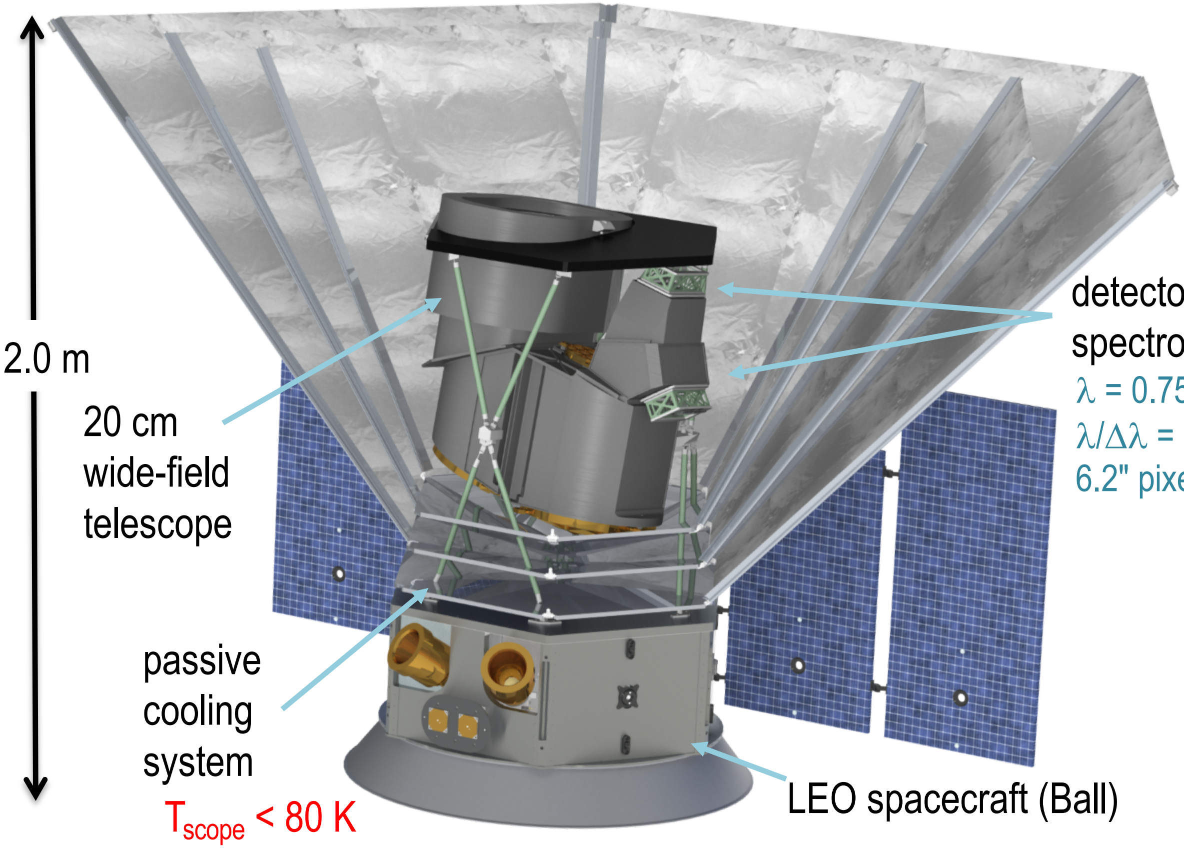
How Did Galaxies Begin?

"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 in a Nutshell



deployed photon shields (shown cutaway)

2.0 m

20 cm wide-field telescope

passive cooling system

$T_{scope} < 80$ K

$T_{FPU} < 55$ K

detectors and LVF spectrometers

$\lambda = 0.75 - 5\ \mu m$

$\lambda / \Delta\lambda = 35 - 130$

6.2" pixels

LEO spacecraft (Ball)

AO LV 1 Fairing

AO LV 2 Fairing

Observatory Resources*	
Mass	205 kg
Telescope	20 cm eff. dia.
Data volume	135 Gbit/day

**In phase A*

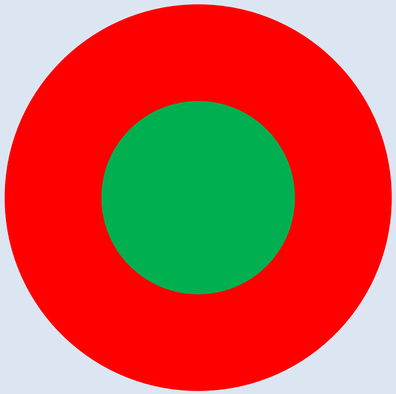
SPHEREx resources are well within the MIDEX family

Wide-Field Telescope: Large AΩ Product

- 3-Mirror off-axis anastigmat
- 20 cm effective aperture
- 3.5° x 11.3° FOV
- 25 million 6.2 arcsecond pixels

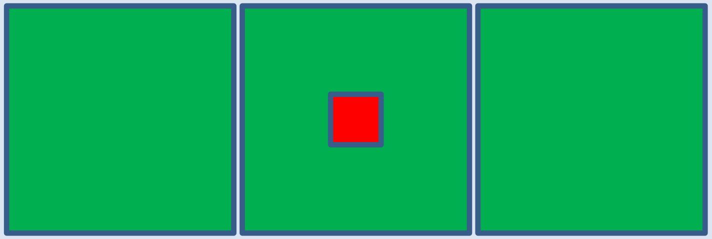
WISE vs. SPHEREx

Mirror Area: WISE has 4x more



WISE: 40 cm
SPHEREx: 20 cm

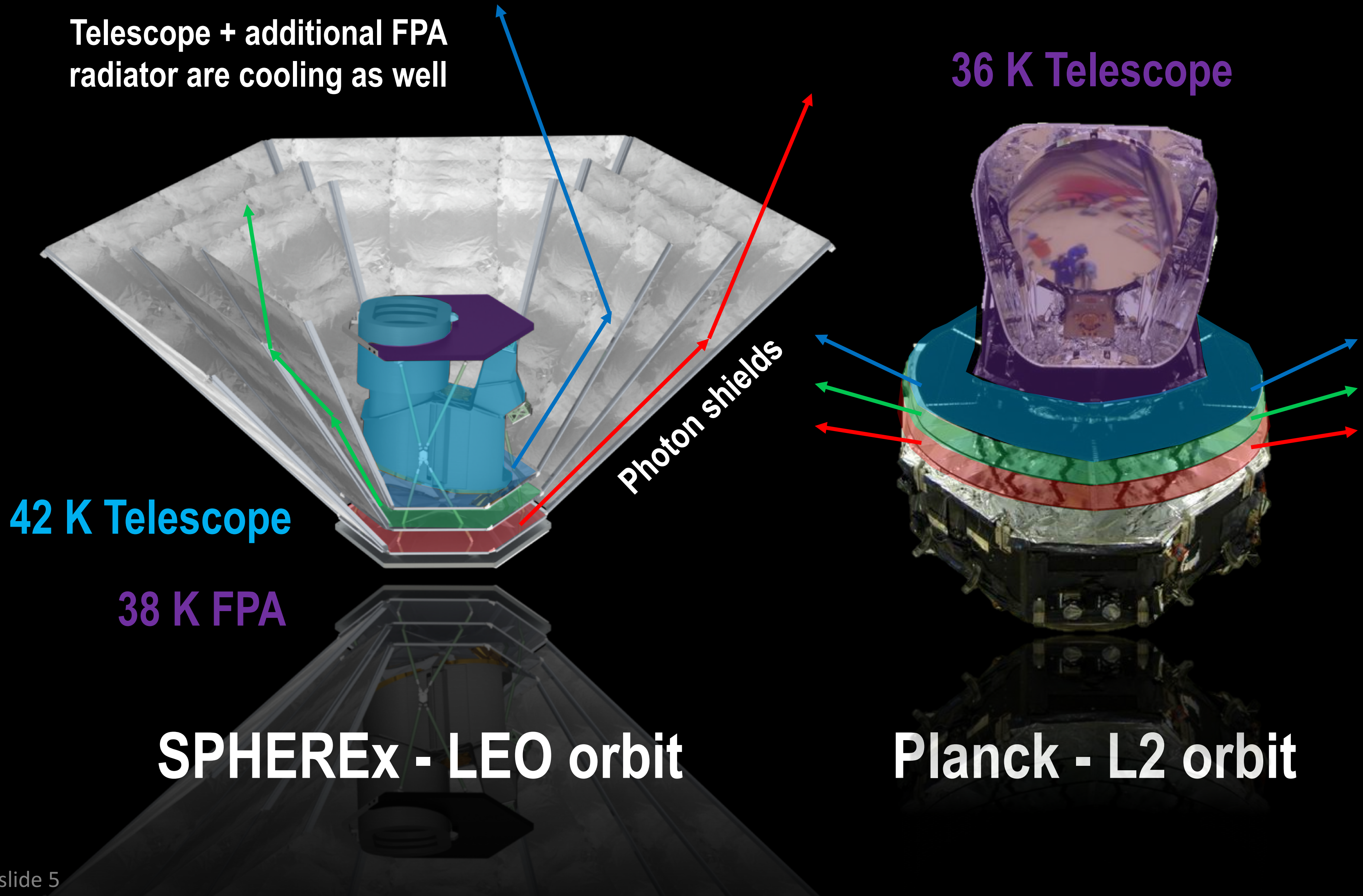
Field of View: SPHEREx has 65x more



WISE: 0.61 sq. deg
SPHEREx: 39.6 sq. deg.

AΩ Product: SPHEREx has 16x more

V-Groove Passive Cooling System



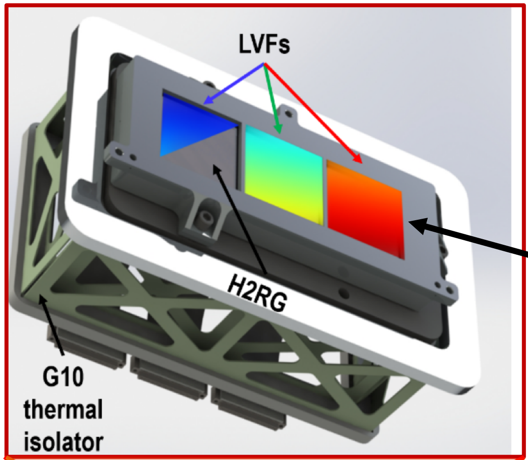
Telescope + additional FPA radiator are cooling as well

SPHEREx - LEO orbit

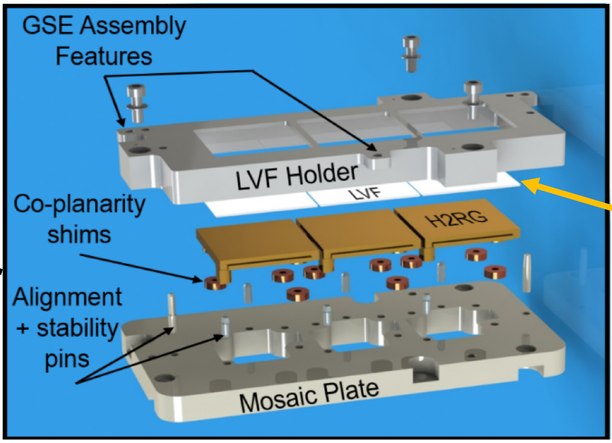
Planck - L2 orbit

High-Throughput LVF Spectrometer

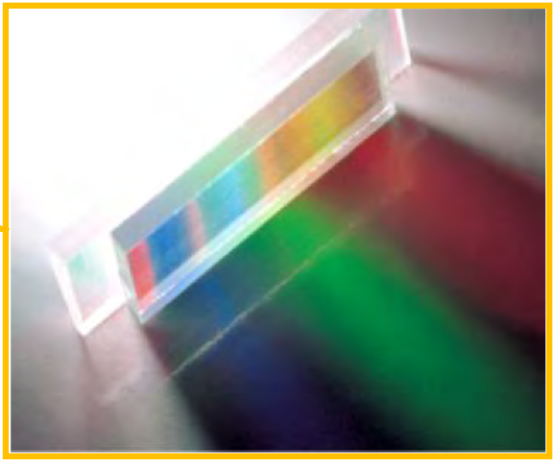
Focal Plane Assembly

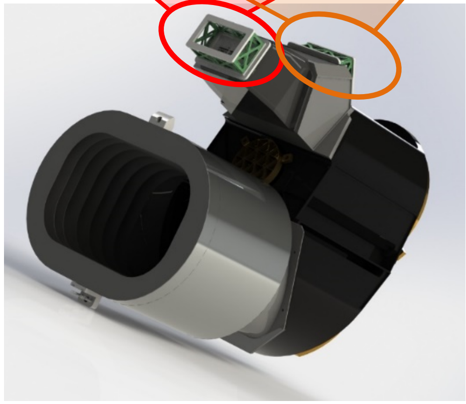


LVF Assembly

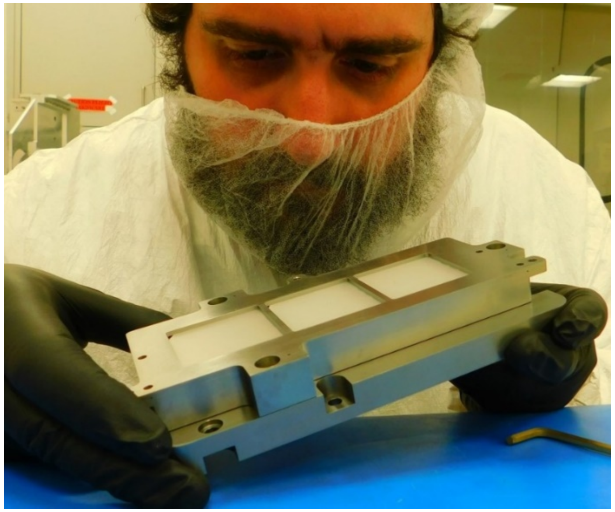


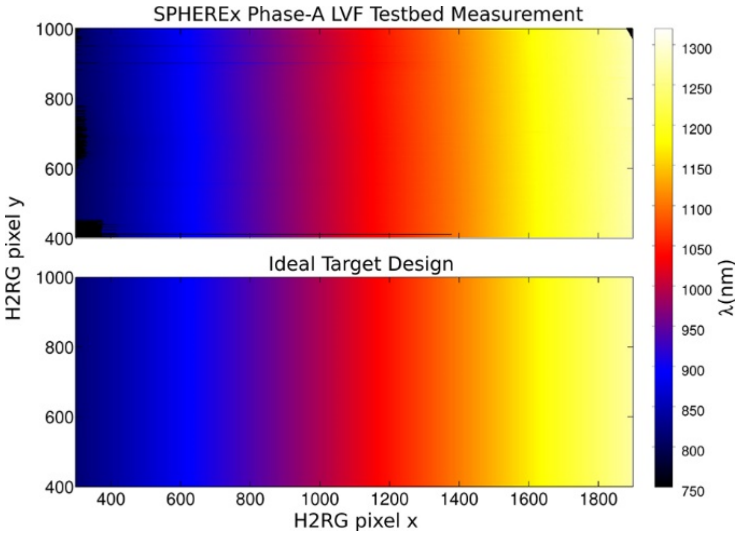
Linear Variable Filter





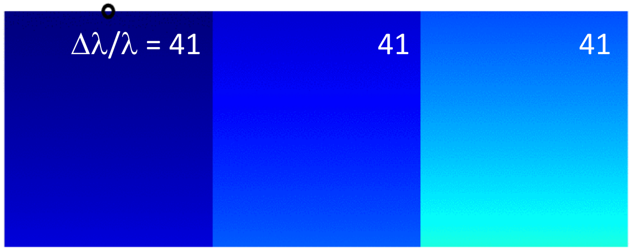
SPHEREx telescope



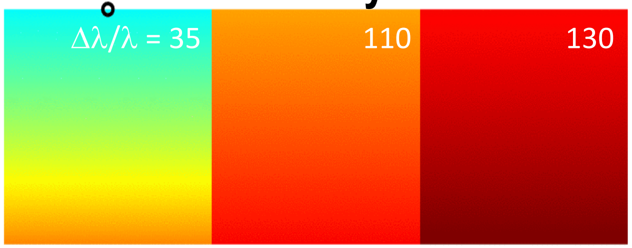


Spectroscopy with Linear Variable Filters

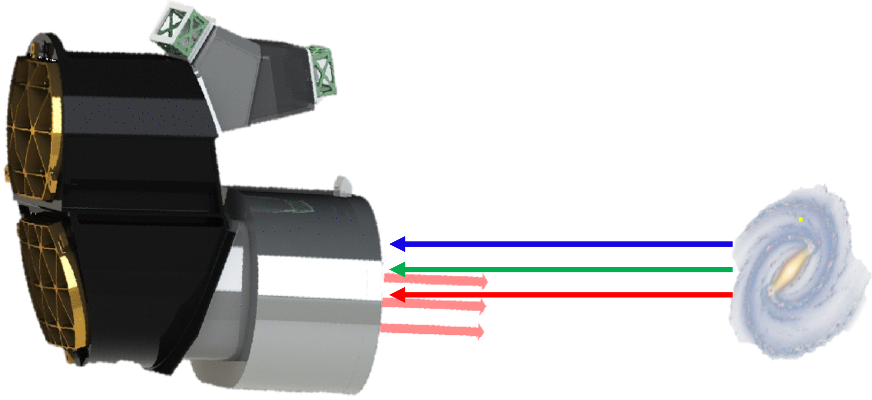
Reflected by Dichroic

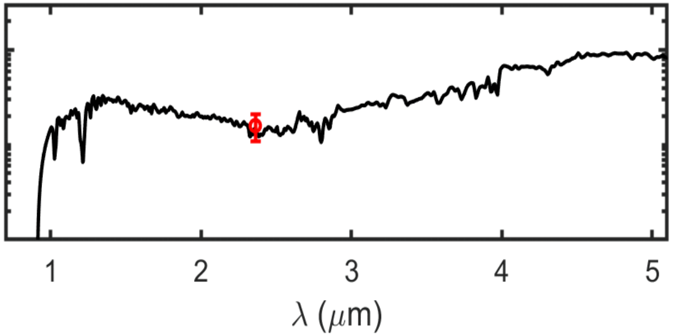


Transmitted by Dichroic

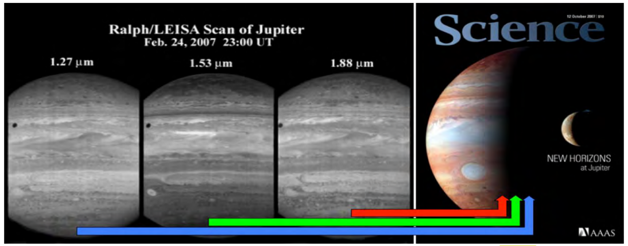


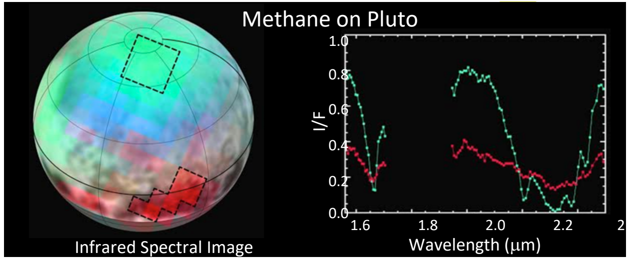
Shifting the spacecraft pointing modulates the wavelength at which an object is observed.





A complete spectrum in 48 exposures
Each exposure takes ~150s
1 complete spectrum every 6 months

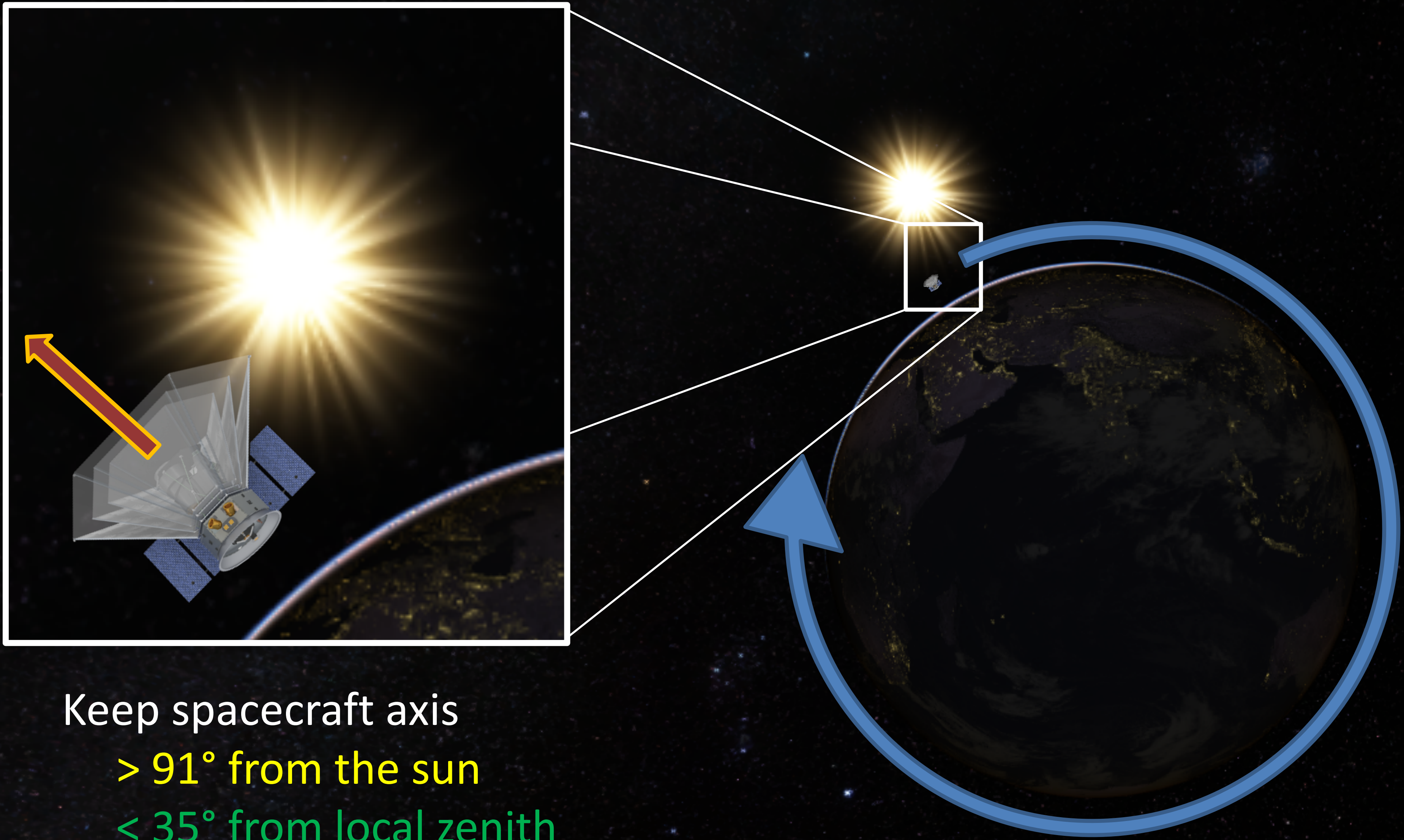




LVF surveys
somewhat novel to astrophysics but have been used for great results in planetary

LEISA - New Horizons

SPHEREx in Low Earth Orbit



Keep spacecraft axis

> 91° from the sun

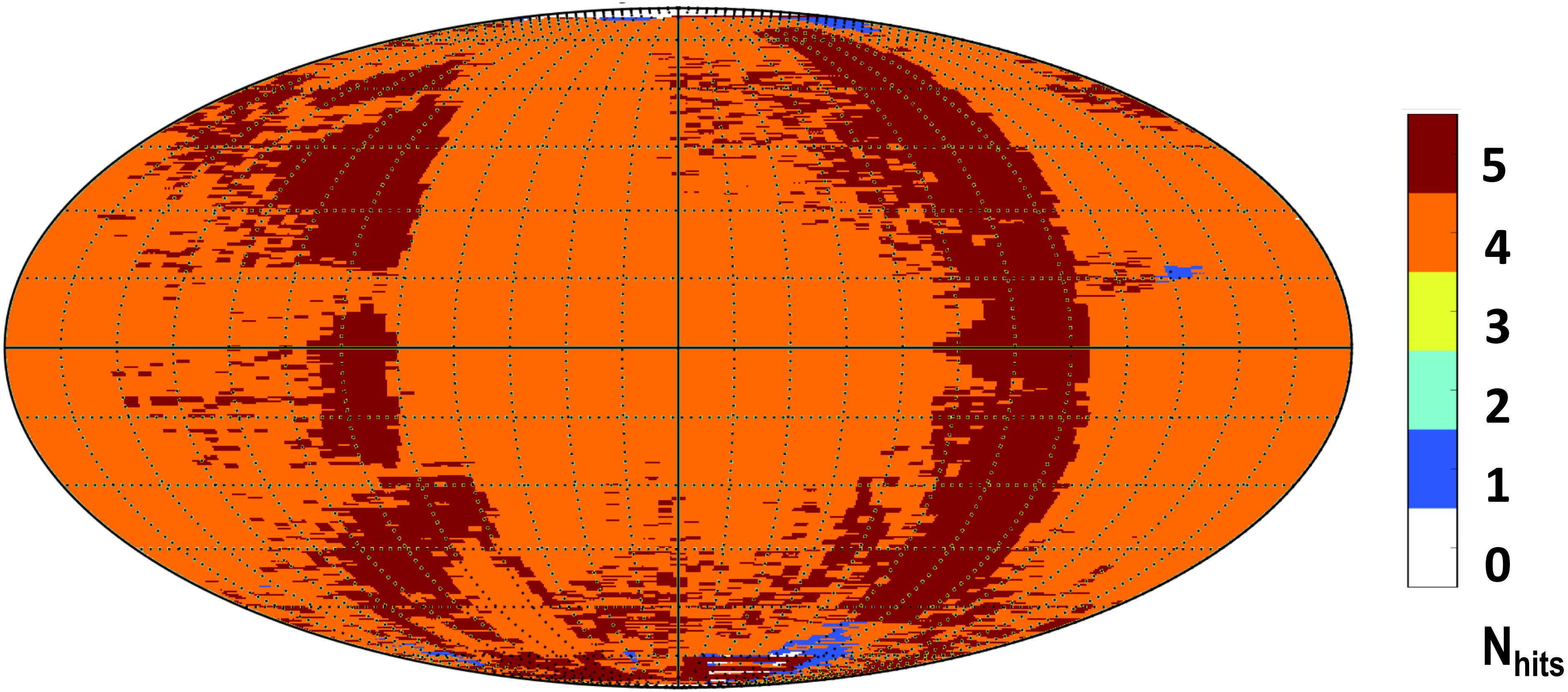
< 35° from local zenith

“Terminator” orbit follows the sunrise-sunset line

SPHEREx Sky Coverage for 1 Wavelength

25 Months

= *4 complete surveys*



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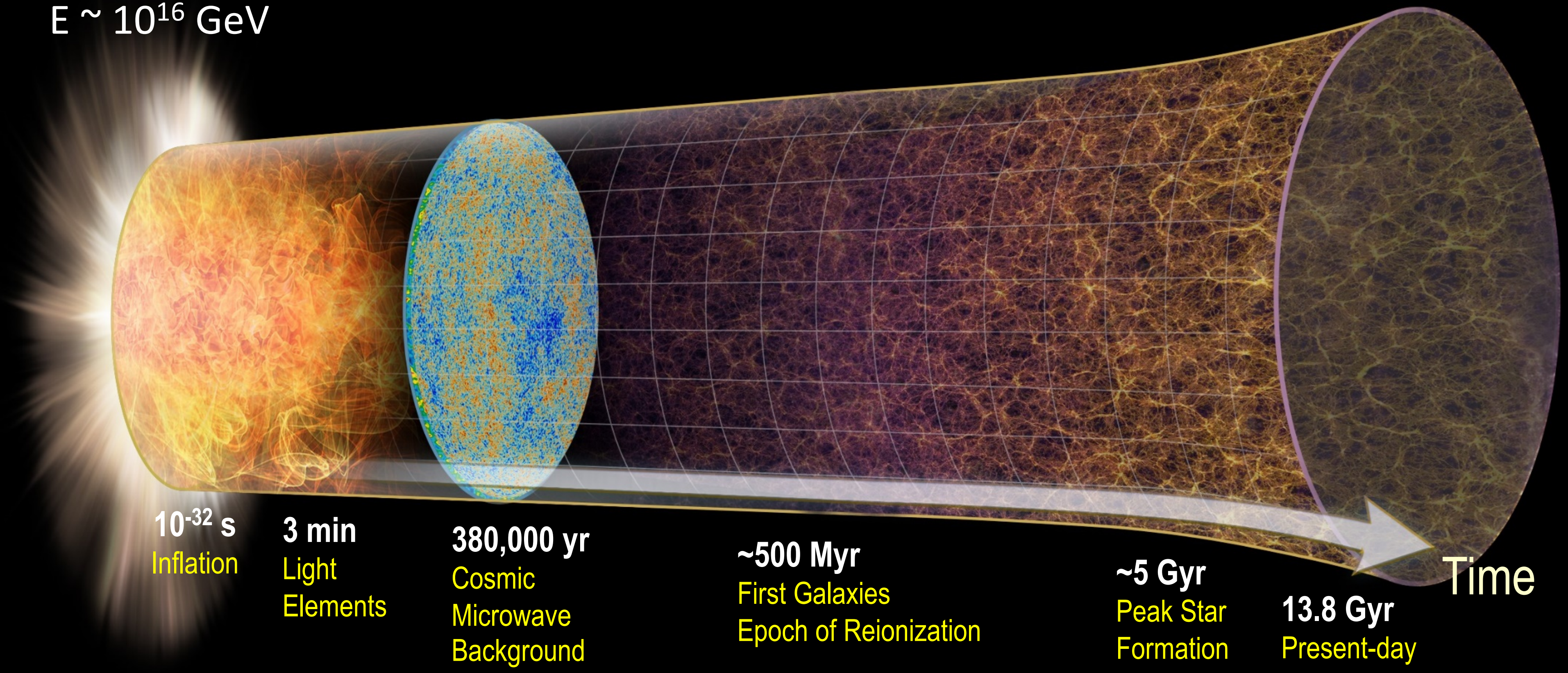
Q1: How Did the Universe Begin?



E ~ 10^{16} GeV

10^{-32} s
Inflation

3 min
Light Elements

380,000 yr
Cosmic Microwave Background

~500 Myr
First Galaxies
Epoch of Reionization

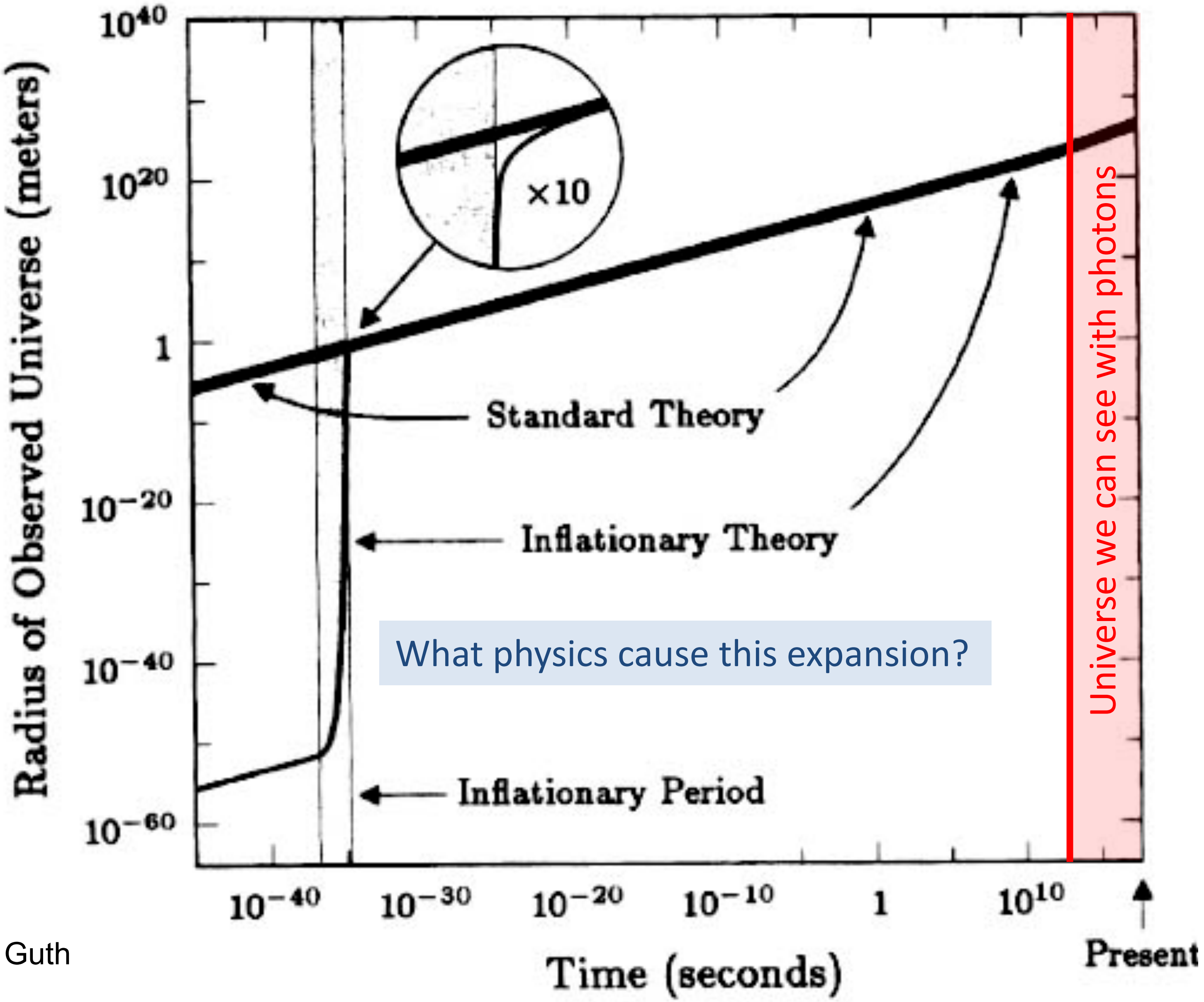
~5 Gyr
Peak Star Formation

13.8 Gyr
Present-day Universe

Time

SPHEREx observes the 3D distribution of galaxies,
uses Non-Gaussianity *to probe inflation physics*

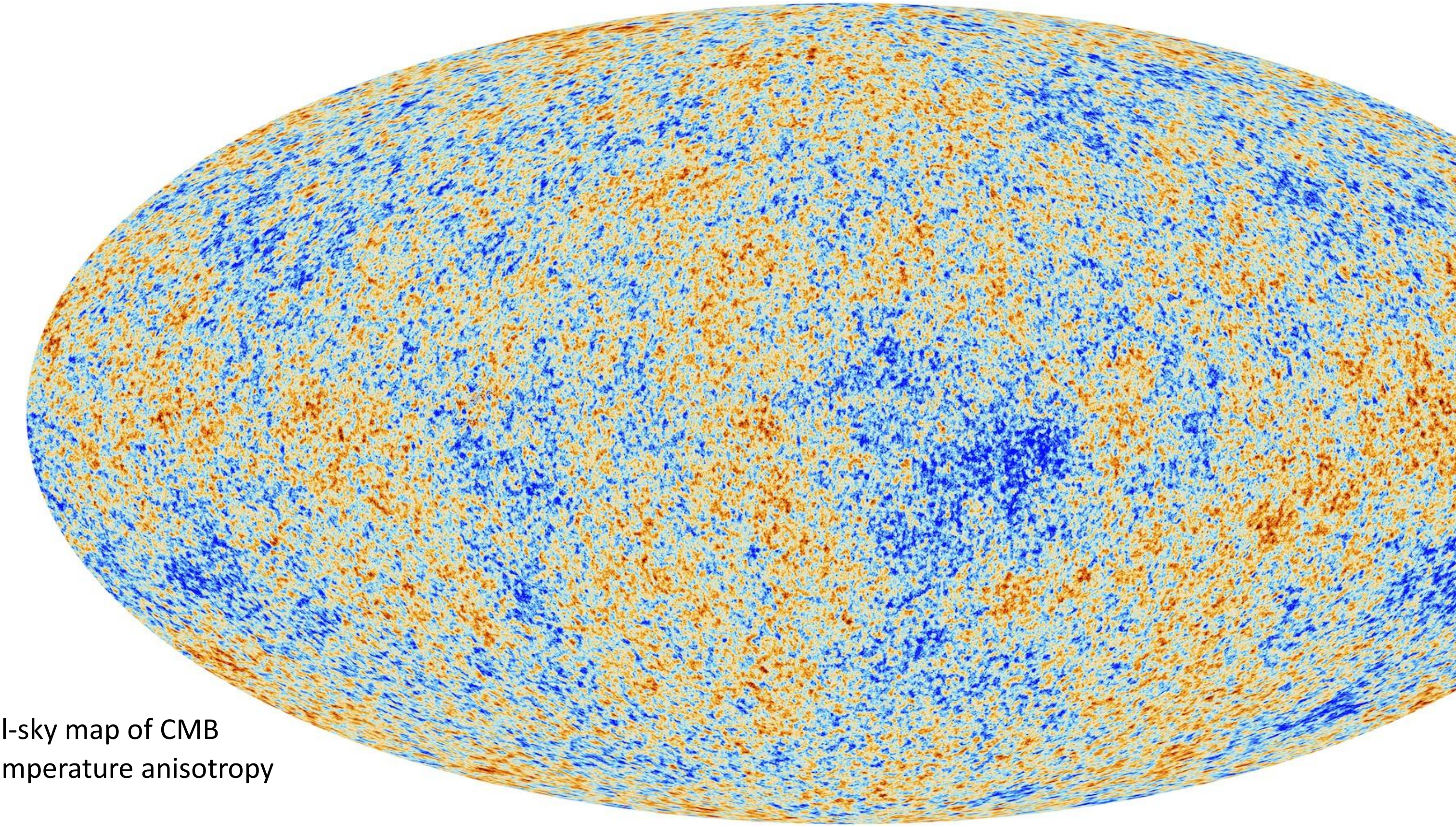
The Remarkable Theory of Inflation



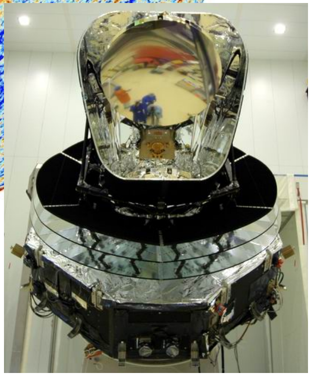
What physics cause this expansion?

A. Guth

Inflation Passes All Tests to Date!



All-sky map of CMB temperature anisotropy



The Planck Satellite

From precise CMB measurements:

√ Universe is geometrically flat

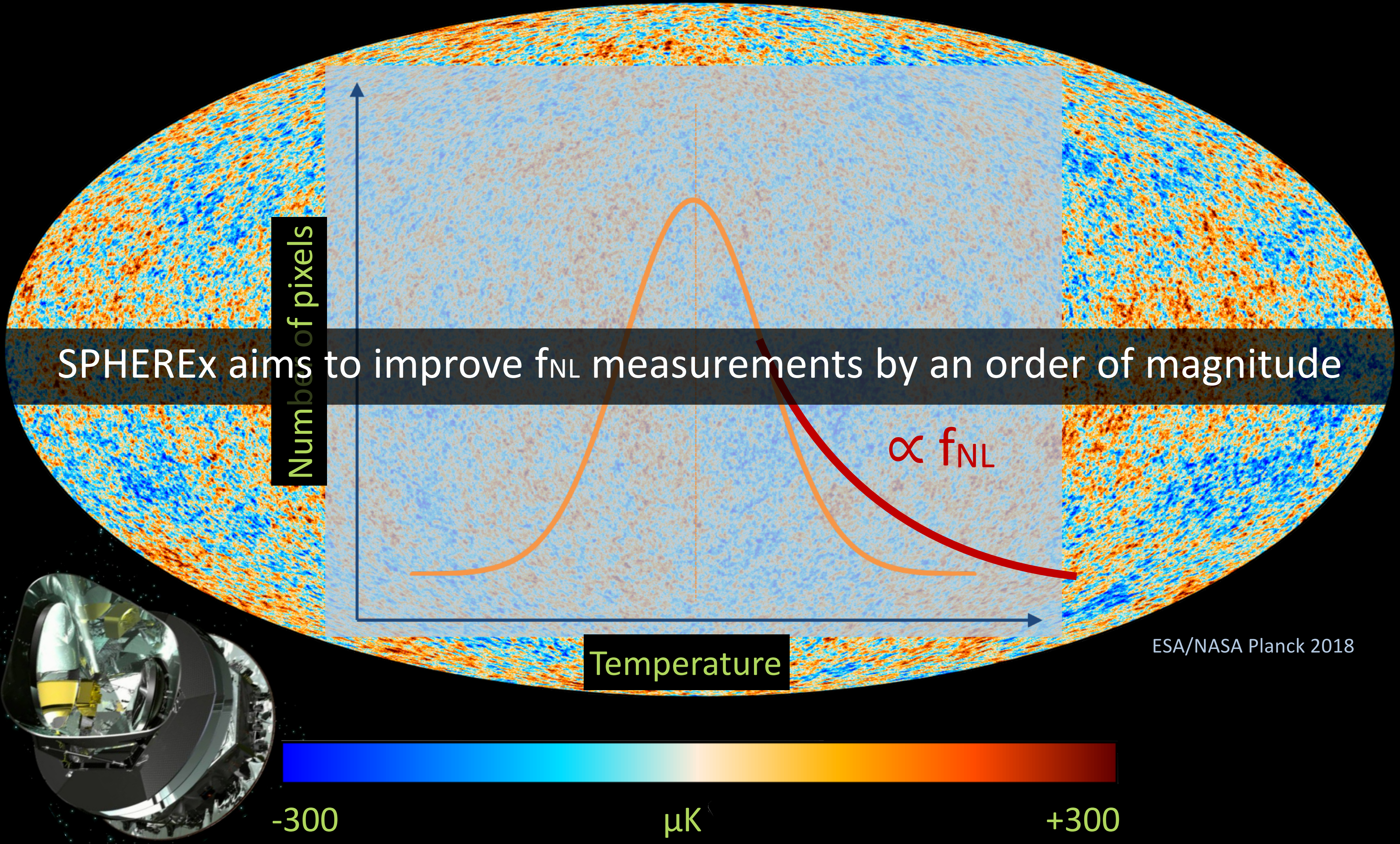
√ There are coherent structures larger than the classical horizon

√ Fluctuations have a nearly “scale invariant” spectrum

√ Fluctuations are in phase

√ Fluctuations have Gaussian statistics

Planck CMB Map has Gaussian Statistics



SPHEREx aims to improve f_{NL} measurements by an order of magnitude

ESA/NASA Planck 2018

How Do We Probe Inflation Physics? Observables

1. **Inflationary gravitational waves** – CMB polarization
2. **Non-Gaussianity** – Sensitive to **Inflaton field**, single- or multi-field

CMB Non-Gaussianity: $f_{NL} < 10.8$ (2σ) limited by cosmic noise

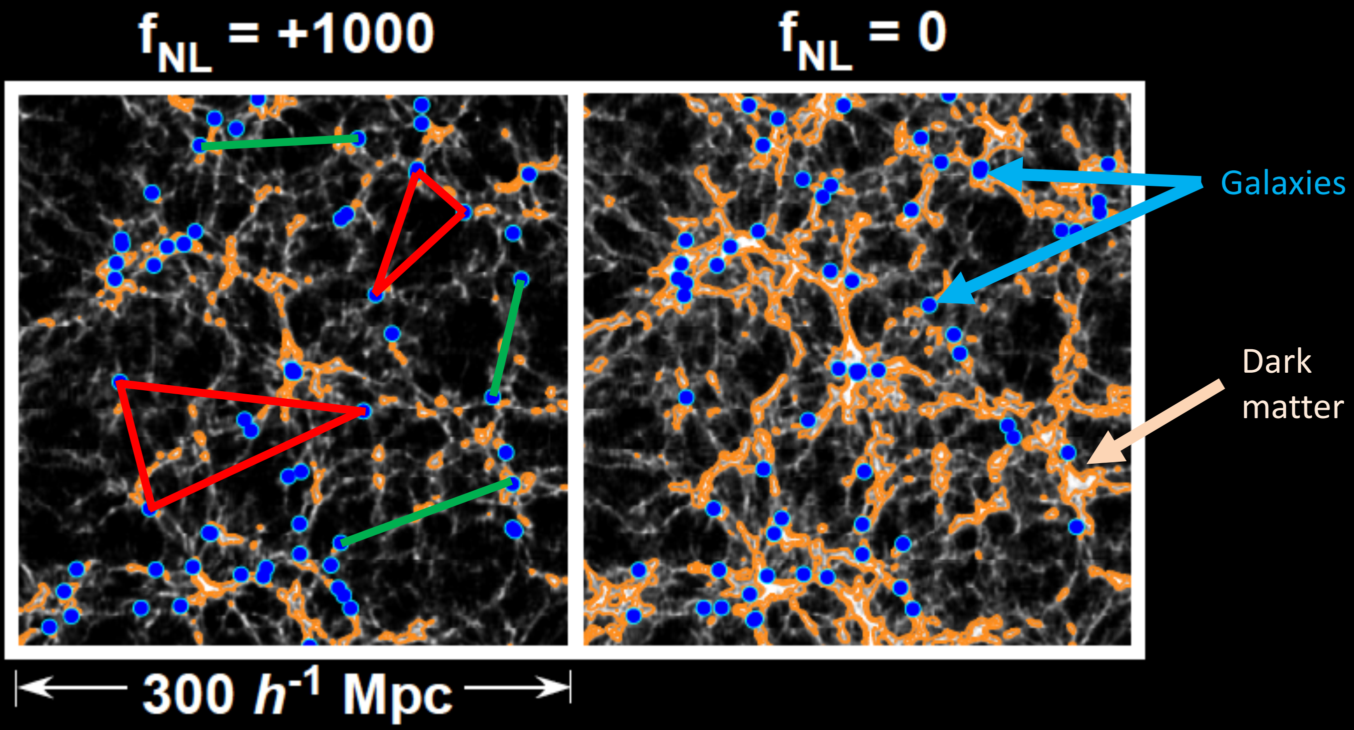
Planck
2015 results

Large-Scale Structure will give best non-Gaussianity measurements

Quantified by 3D correlations between galaxies:

Pairs (2-point func)

Triples (3-point func)



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

Redshifts with SPHEREx

We extract the spectra from *known* galaxy positions

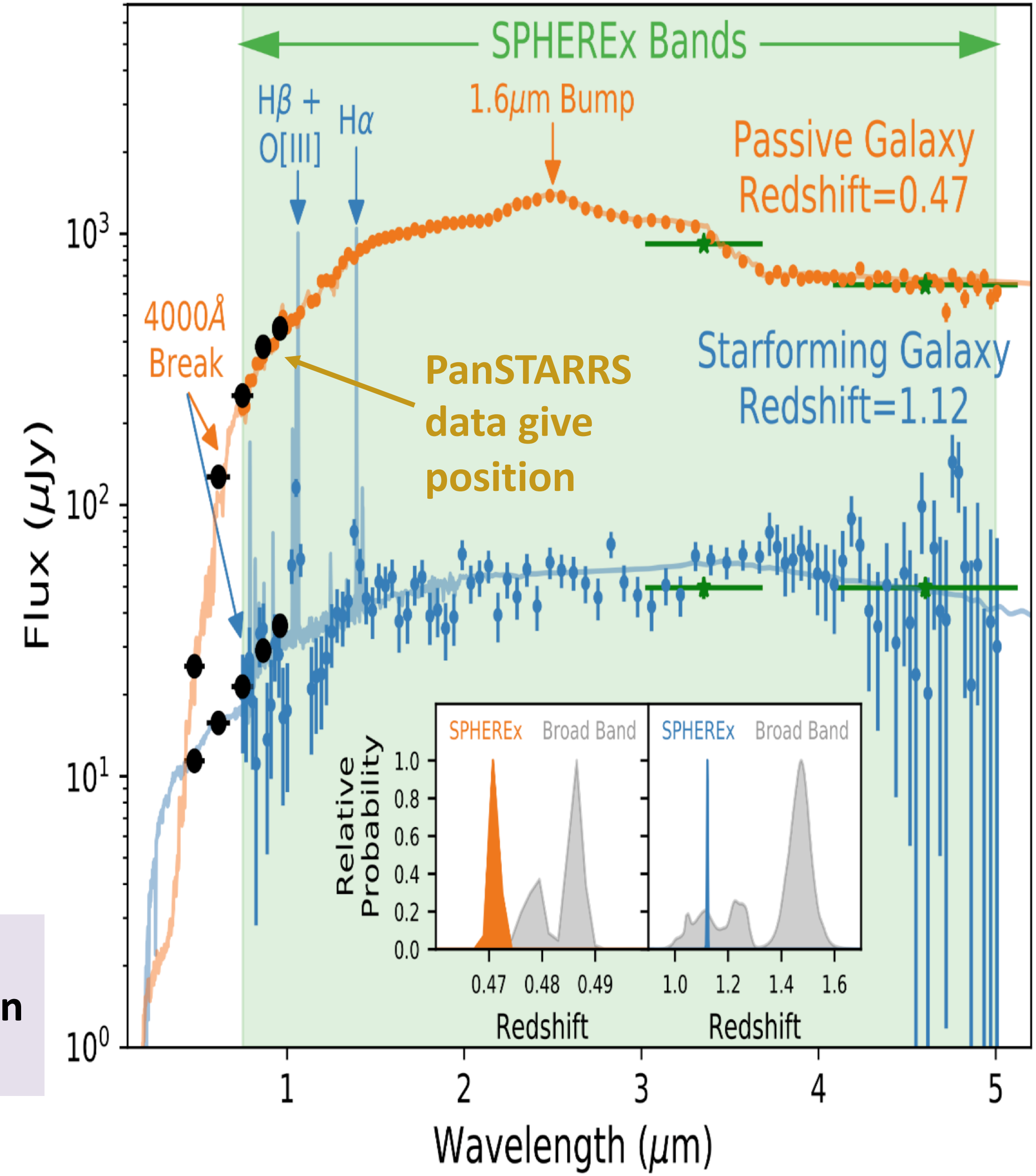
Controls blending and confusion

We compare each spectrum to a template library:

For each galaxy: redshift, type and redshift error

Many self-consistency tests using SPHEREx data, spectral models, and external redshift catalogs

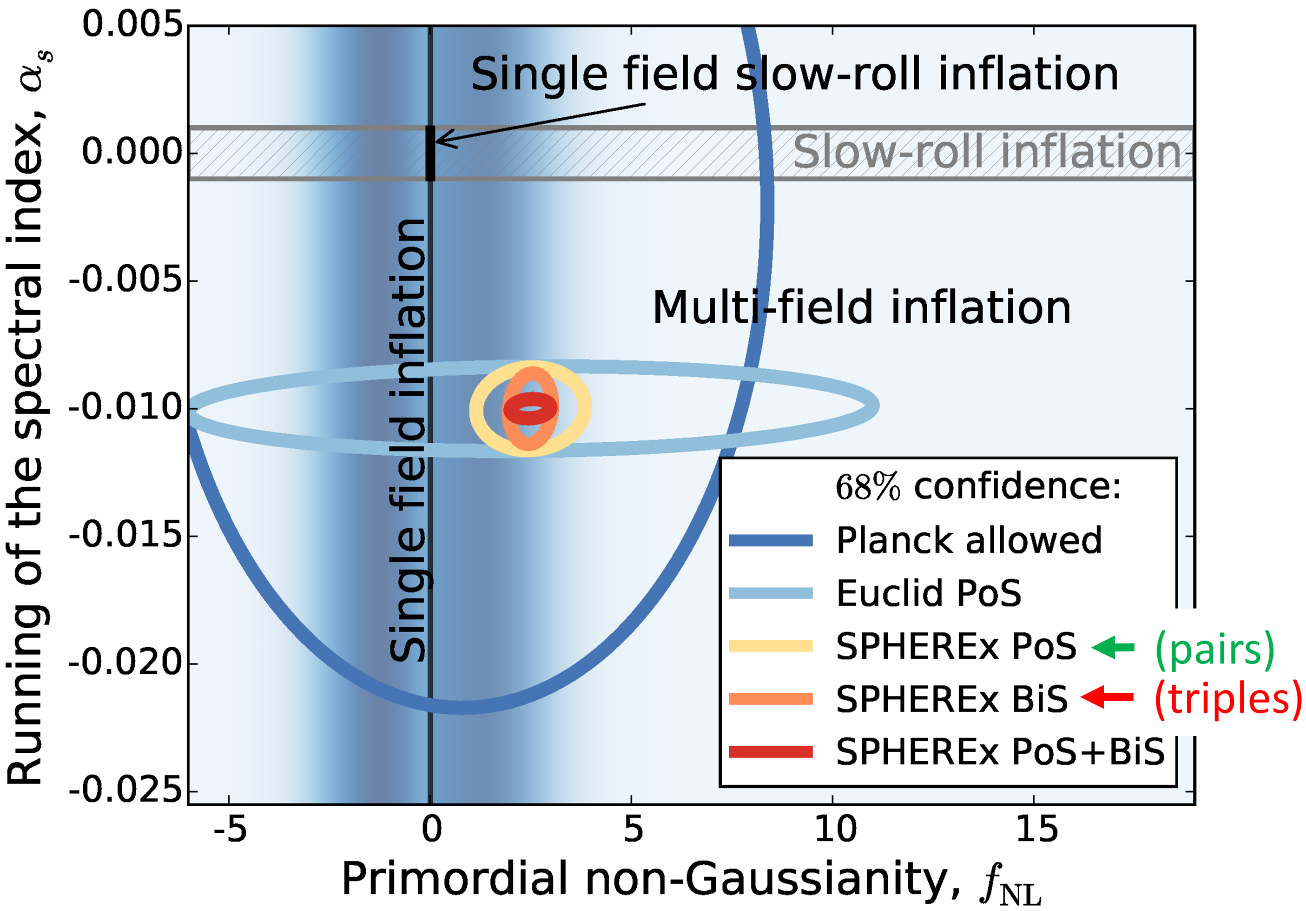
Detected galaxies	**> 1 billion**
Galaxies $\Delta z/1+z < 10\ \%$	**> 450 million**
Galaxies $\Delta z/1+z < 0.3\%$	**> 10 million**



Visualization by Salman Habib, ANL

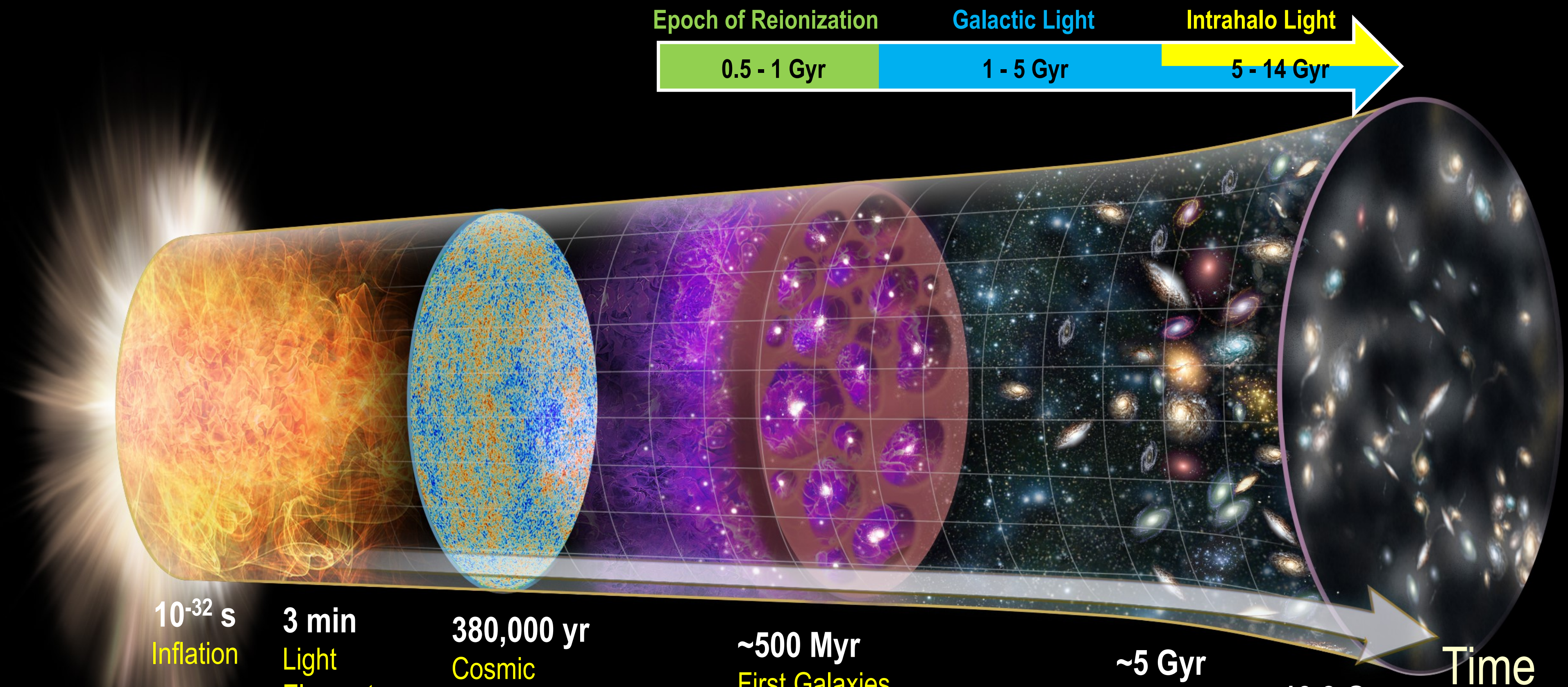
SPHEREx Tests Inflationary Non-Gaussianity

- Single-field models predict $f_{\rm NL} < 0.01$
- Multi-field models predict $f_{\rm NL} \gtrsim 1$
- Non-inflationary models (Steinhardt et al.) predict $f_{\rm NL} \sim 1$



- SPHEREx sensitivity is $\Delta f_{\rm NL} < 0.5$ (1σ)

Q2: 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

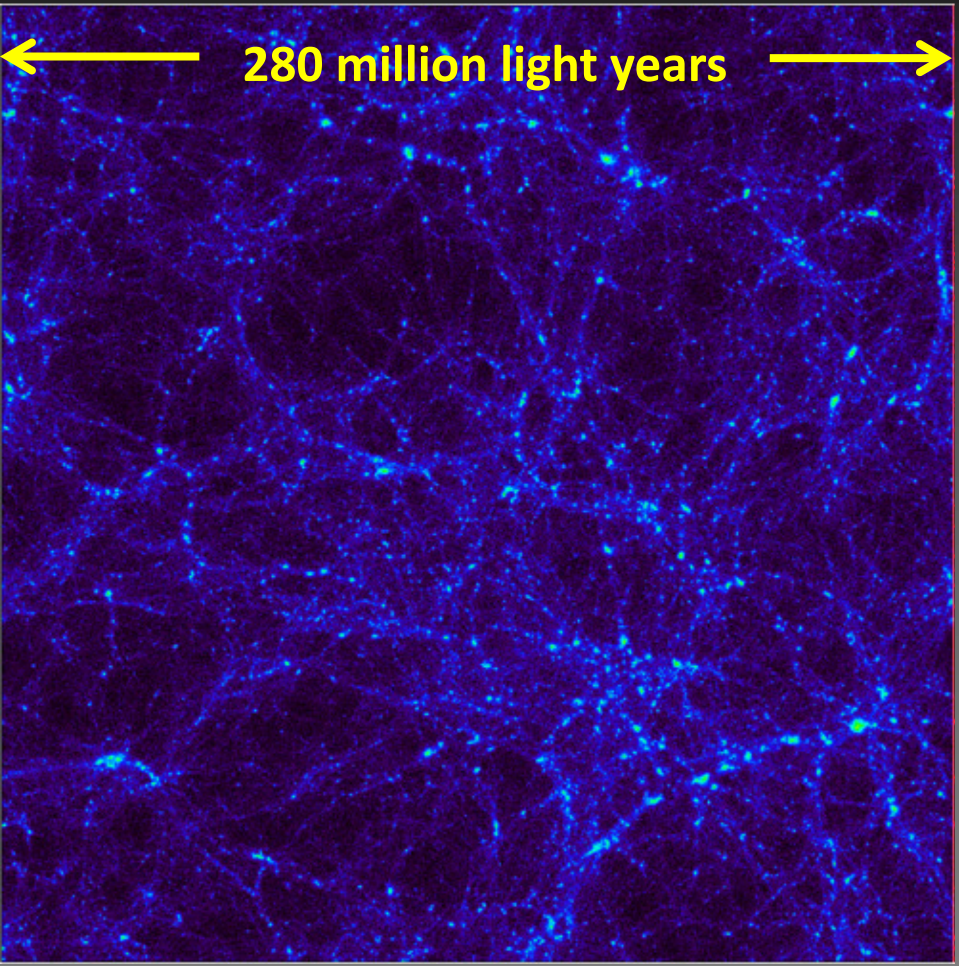
13.8 Gyr
Present-day
Universe

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

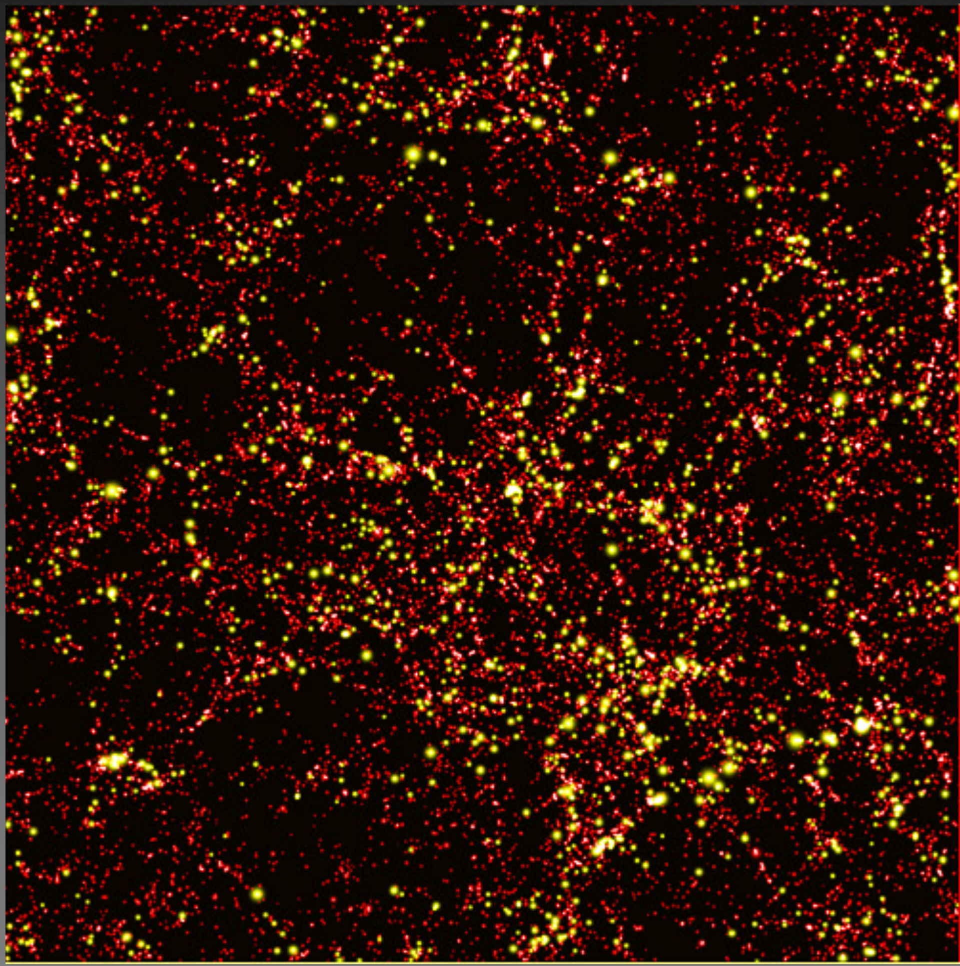
Problem with Absolute Photometry: Foregrounds!

Relating Galaxies to Dark Matter

Dark Matter from Numerical Simulation (z = 2)



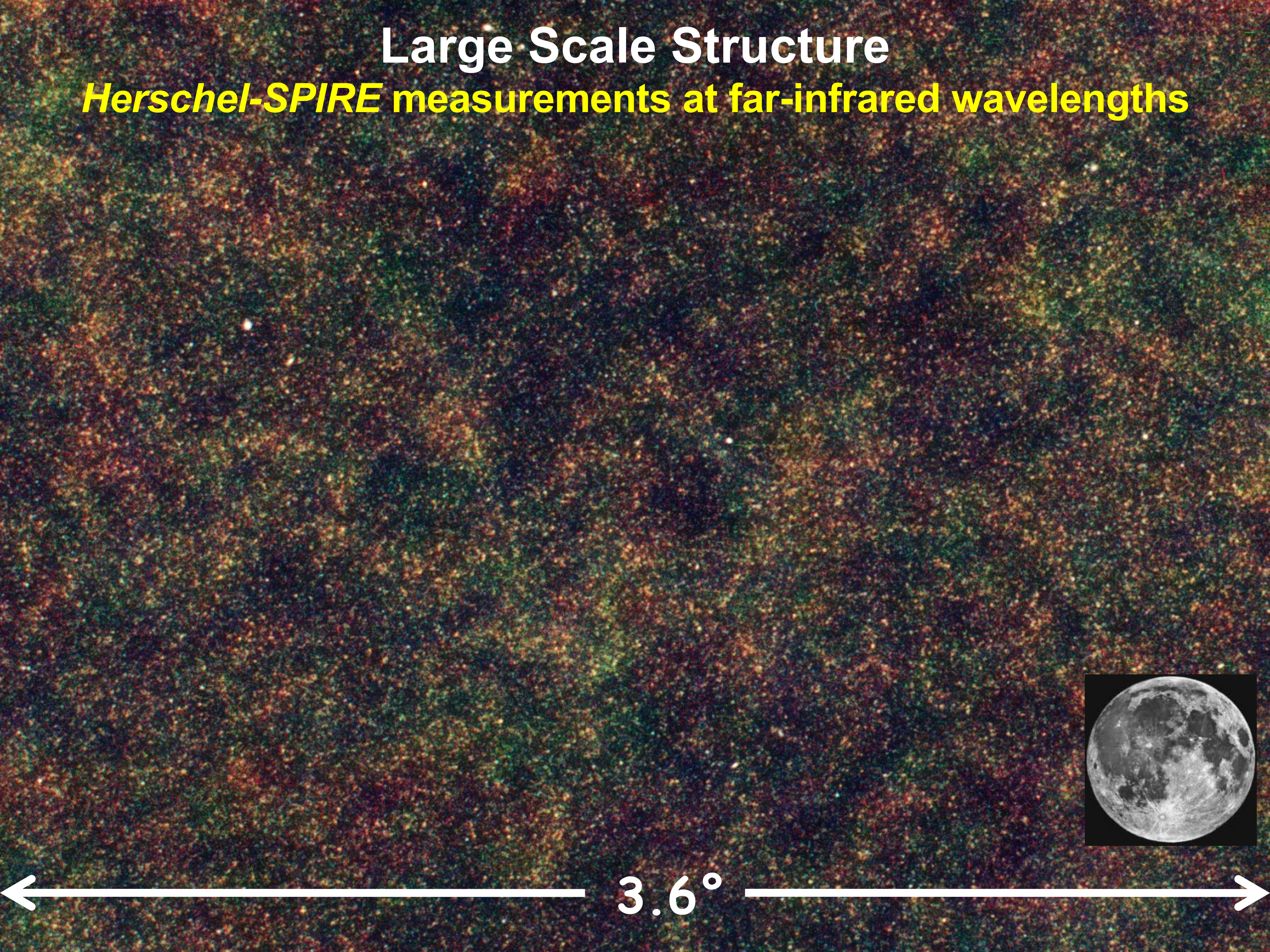
Dark Matter Clumps Color-Coded by Mass



On large scales: Light traces dark matter → Use to measure light production

Large Scale Structure

Herschel-SPIRE measurements at far-infrared wavelengths



Near-Infrared Clustering Measurements

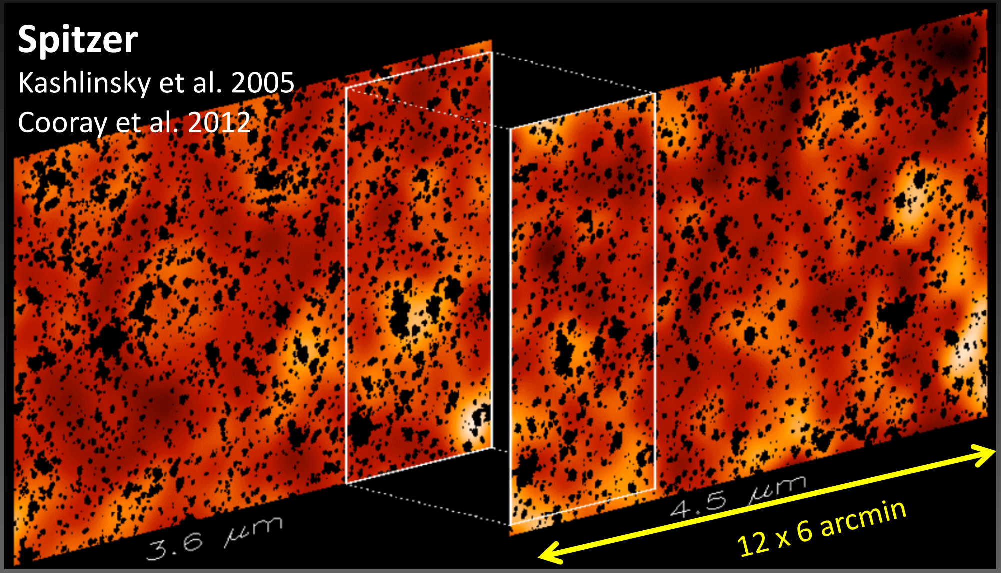
Both measurements show large clustering signal

- Exceeds light produced by known galaxy populations

First stars (redshifts > 6)?

Intra halo light (redshifts 0 – 2)?

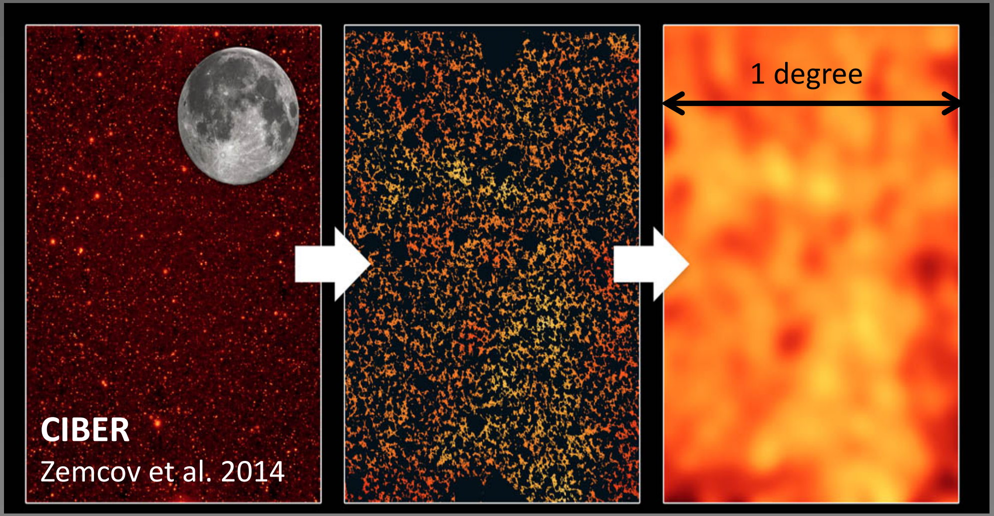
SPHEREx: multi-wavelength measurements!



Spitzer

Kashlinsky et al. 2005

Cooray et al. 2012

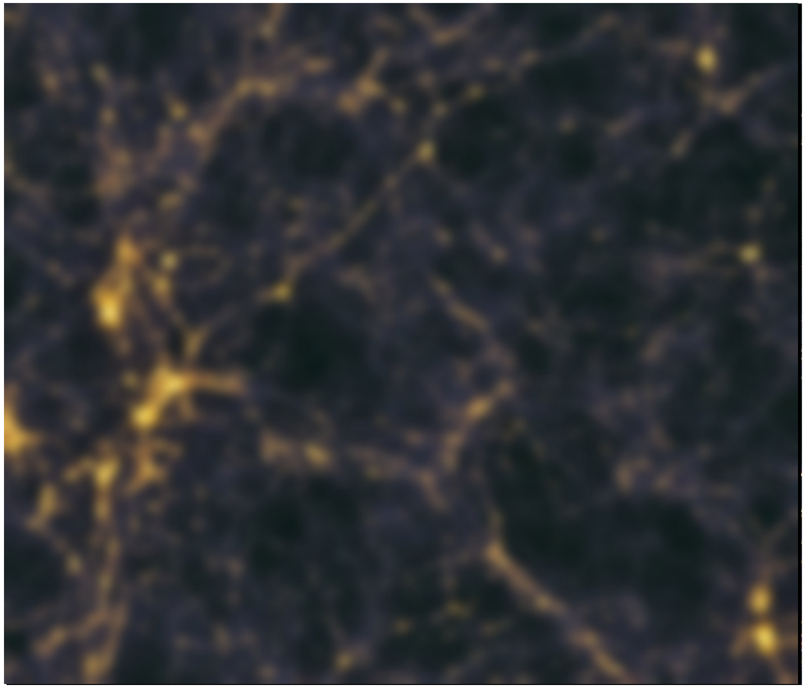


CIBER

Zemcov et al. 2014

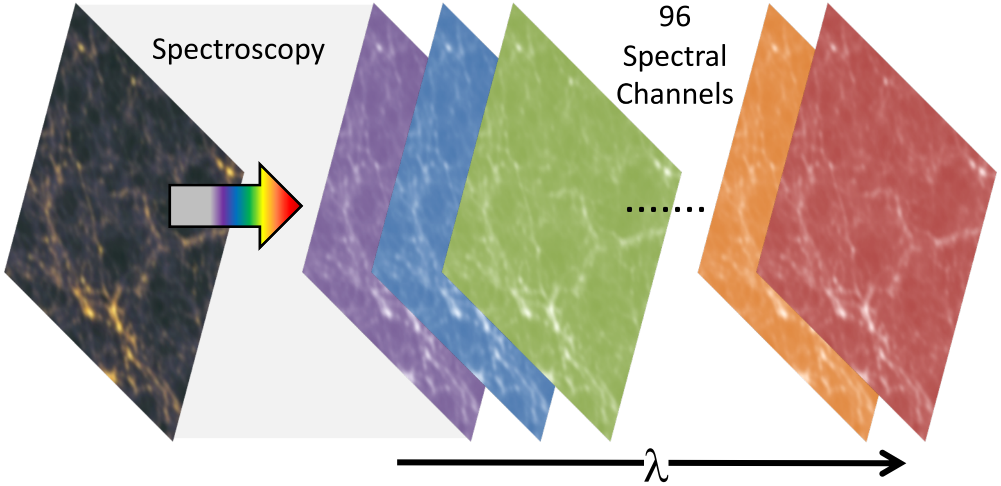
Surveying Cosmic History of Galaxies

Intensity mapping measures light emitted by *everything that gravitationally clusters*



- Traces faint light associated with dark matter
  - Emission from all galaxies
  - Dwarf galaxies responsible for reionization
  - Diffuse emission from stripped stars
  - Dark matter decay (?)
- Complements galaxy-by-galaxy surveys
- Method used on CIBER, Spitzer, Herschel, Planck

Spectroscopy is key for untangling cosmic history



Q3: What Are the Conditions for Life Outside the Solar System?

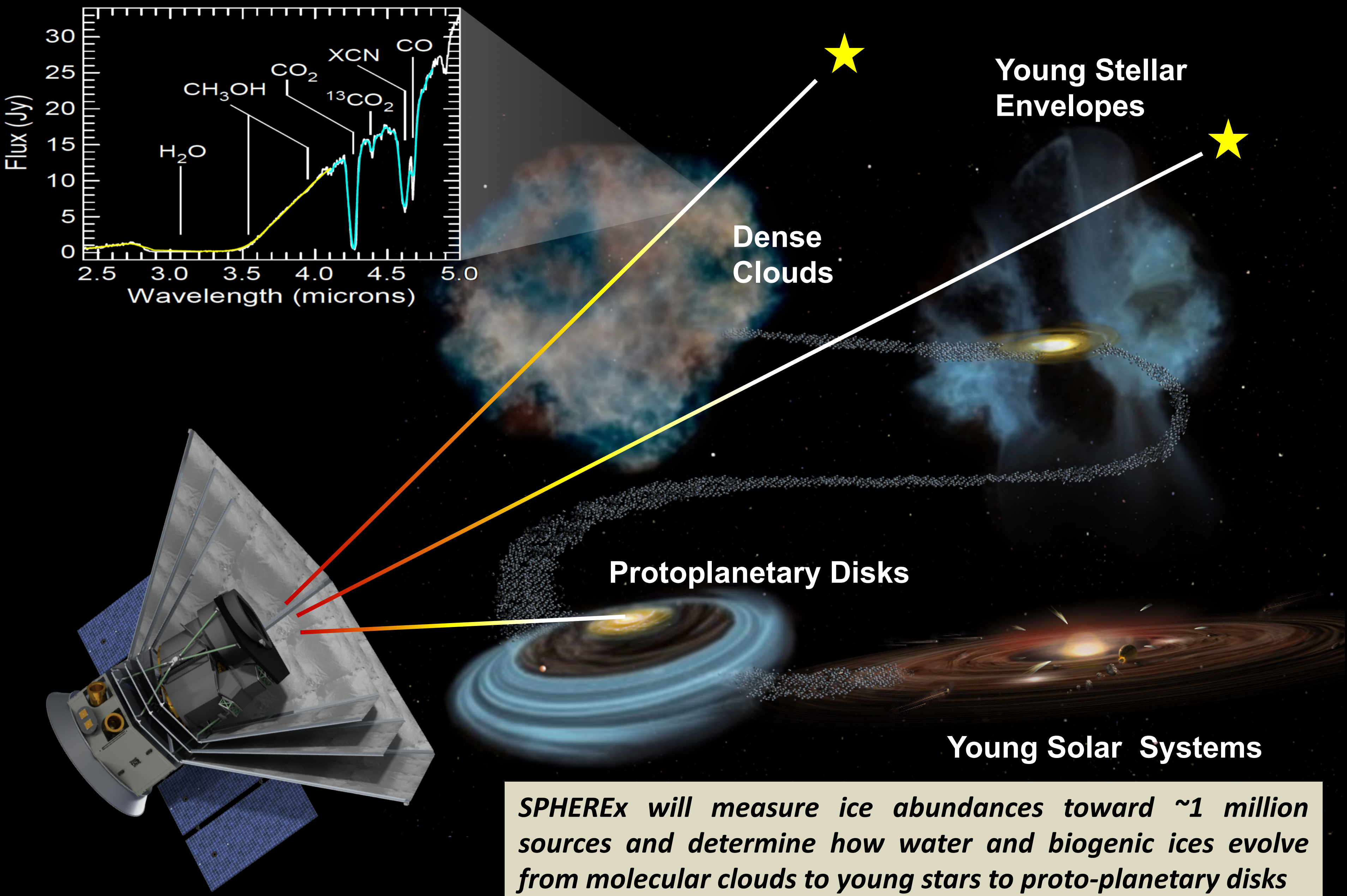
Sourced by **interstellar ices**, rich in biogenic molecules: H_2O, CO, CO_2, CH_3OH…

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

Did water arrive from asteroids or comets?

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

SPHEREx Surveys Ices in All Phases of Star Formation



SPHEREx will measure ice abundances toward ~1 million sources and determine how water and biogenic ices evolve from molecular clouds to young stars to proto-planetary disks

SPHEREx Creates an All-Sky Legacy Archive

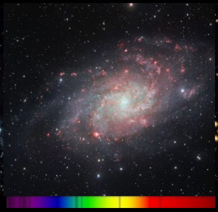
A spectrum for every 6" pixel on the sky

Galaxies

Detected
> 1 billion

Medium-Accuracy Spectra
> 100 million

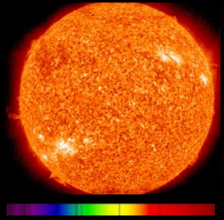
High-Accuracy Spectra
> 10 million



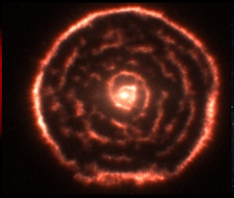
Clusters
100,000

Stars

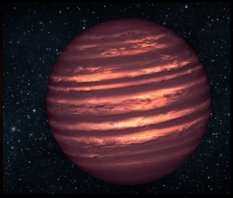
Main Sequence Spectra
> 100 million



Dust-forming
10,000



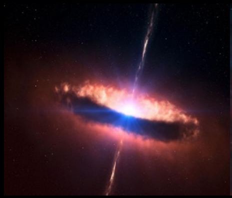
Brown Dwarfs
> 400



Cataclysms
> 1,000

Other

Quasars
> 1.5 million

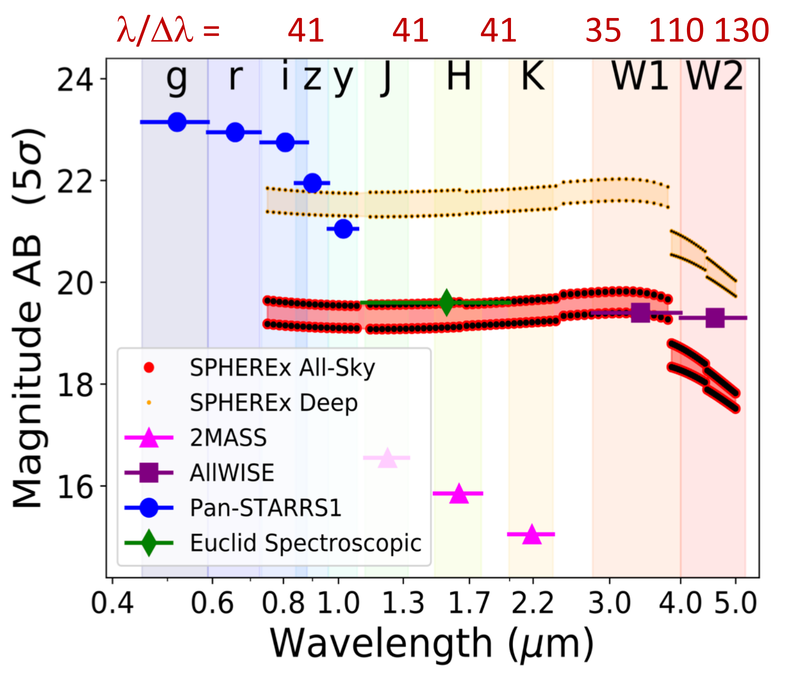


Quasars z >7
3 – 300?

Asteroid & Comet Spectra
100,000

Galactic Line Maps
PAH, HI, H_2

SPHEREx Survey Depth



What Would *You* Do with the Archive?

2018 Workshop at CfA
Synergies with NASA Missions

2020 Workshop at CCA
Collaborative Opportunities

2016 Workshop: Survey Science Ideas

Object	**# Sources**	**Legacy Science**
X-ray all-sky survey	> 100,000	Detect eROSITA source SEDs and spectroscopic redshifts
Exoplanet characterization	10,000 of 600,000	With GAIA, determine precise radii for host stars
Deuterated PAHs		Probe and possible map deuterated PAHs, complete inventory of D in local ISM
Lowest metallicity stars	~1000	Identify low-mass stars by their IR signatures, map distribution in Galaxy
Asteroids and comets	100,000	Spectrally classify numerous asteroids; CO/CO_2 ratios in comets
Nearby galaxies	>100 million	Spectrally image galaxies to trace stellar populations, star formation, etc
Your idea here!	TBD	

Three workshops: Over 120 non-SPHEREx scientists

Charter: Identify new science, tools and data products

Two examples of new science from the workshops

Exoplanet masses X-ray synergies

SPHEREx science: Doré et al. 2014

SPHEREx workshops: Doré et al. 2016 & 2018

SPHEREx Science Team

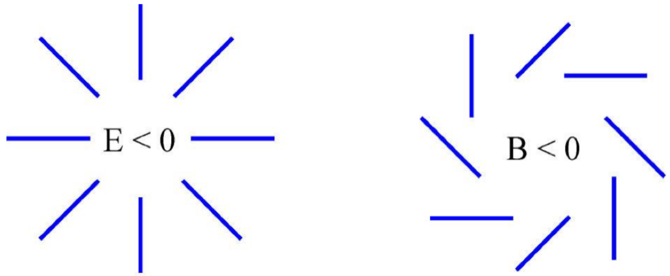
Jamie Bock	Caltech/JPL	Principal Investigator
Rachel Akeson	IPAC	Stellar catalog
Matt Ashby	CfA	Interstellar ices
Lindsey Bleem	Argonne	Galaxy cluster catalog
Peter Capak	IPAC	Galaxy redshifts
Tzu-Ching Chang	JPL	Intensity mapping
Asantha Cooray	UC Irvine	Extragalactic backgrounds
Brendan Crill	JPL	Pipeline architect
Roland de Putter	Caltech	Cosmology
Olivier Doré	JPL	Project Scientist
Tim Eifler	U. Arizona	LSST/DESI synergies
Salman Habib	Argonne	Cosmology simulations
Katrin Heitmann	Argonne	Cosmology simulations
Chris Hirata	Ohio State	Cosmology
Woong-Seob Jeong	KASI	KASI PI
Davy Kirkpatrick	IPAC	Brown dwarfs
Phil Korngut	Caltech	Instrument Scientist
Elisabeth Krause	U. Arizona	Cosmology
Carey Lisse	JHU	Solar system catalog
Daniel Masters	Caltech	Spectral redshift fitting
Phil Mauskopf	Arizona State	Survey planning
Gary Melnick	CfA	Interstellar ices
Hien Nguyen	JPL	Instrumentation
Karin Öberg	CfA	Ice properties
Roger Smith	Caltech	Detector arrays
Yong-Seon Song	KASI	Cosmology
Harry Teplitz	IPAC/Caltech	Data Archive
Volker Tolls	CfA	Ices pipeline
Steve Unwin	JPL	Interstellar ices
Mike Werner	JPL	Legacy science
Rogier Windhorst	Arizona State	JWST synergies
Yujin Yang	KASI	Survey science
Mike Zemcov	RIT	Data pipeline

Thanks for listening!

Backup

BICEP-Keck Constraints on Inflationary Gravitational Waves

r = tensor to scalar ratio, i.e. amplitude of inflationary gravitational-wave background



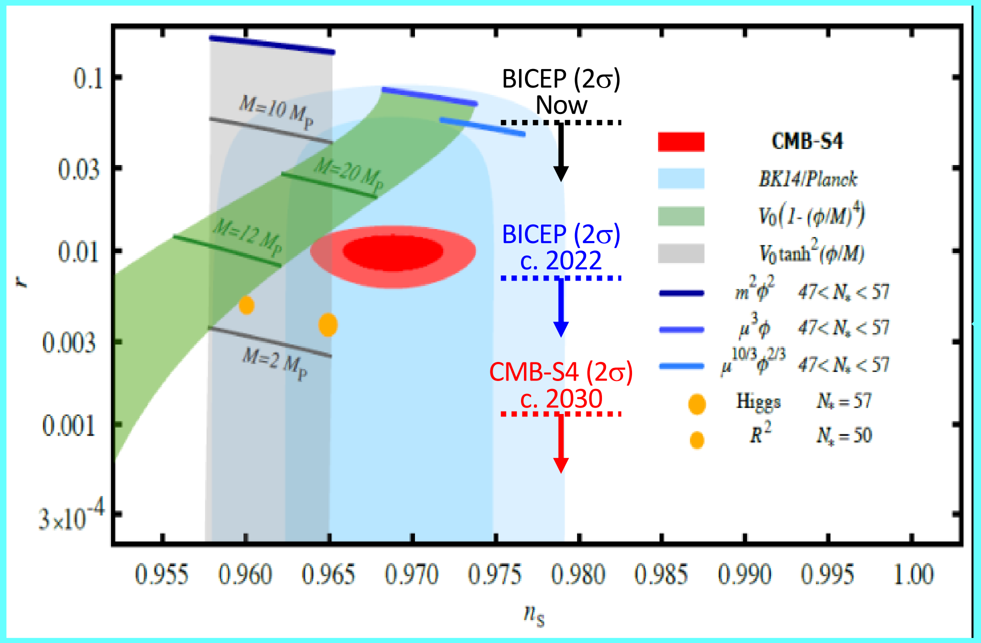
February 2020: BICEP Array first light!

All published polarization constraints on Inflationary Gravitational Waves

Experiment	Year	Bands [GHz]	σ(r)
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
Planck	2018	30…353	~0.2
BK15	2018	95,150,220 + P	0.020
Polarbear	2019	150 + Planck	0.32
BK18	2020	95,150,220 + P	0.010 (est)

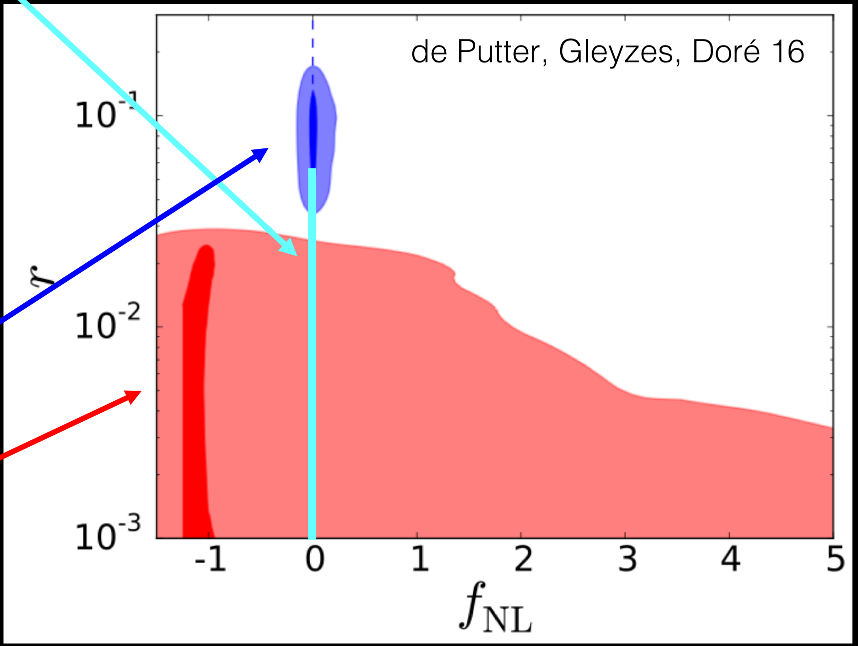
Non-Gaussianity and B-Modes are Complementary

Single-field models
from CMB-S4 Science paper



Primordial non-Gaussianity discriminates between models

- Single-field inflation → $f_{NL} << 1$
- Multi-field inflation → $f_{NL} \gtrsim 1$
- Cyclic models → $f_{NL} \sim 1$ (Steinhardt, Ijjas)



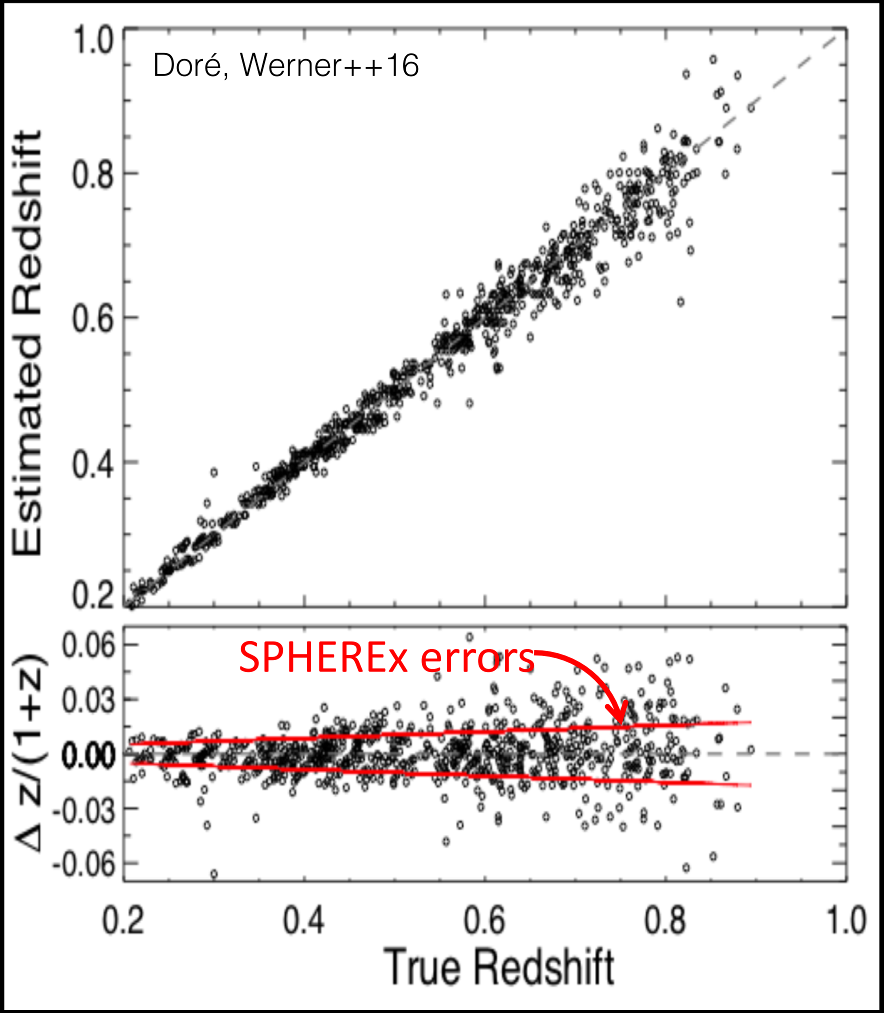
Multi-field models

- Multi-field with primordial perturbations generated by inflaton
- Primordial perturbations generated by second field (i.e. spectator-dominated models)

Cosmology with CMB-S4 + SPHEREx

- Galaxy x CMB lensing
  SPHEREx gives galaxy bias
  Measures the growth of structure D_G over a wide redshift range
    -- Probes gravity on large scales
    -- Constrains the amplitude A_{lens}
- Baryonic Kinetic SZ Effect
  SNR ~ 55 using precision redshift sample and CMB map
  SNR >100 cross-correlating lower-accuracy sample and T^2
    -- e.g. Doré *et al*. 2003
- Galaxy Cluster Redshifts
  CMB-S4 and eROSITA will find 100,000+ massive clusters
  SPHEREx will also find ~100,000
  SPHEREx provides redshifts
    -- *$\sigma_z / (1 + z) < 0.03$ for $z < 0.9$*
    -- *Virial masses for large samples*

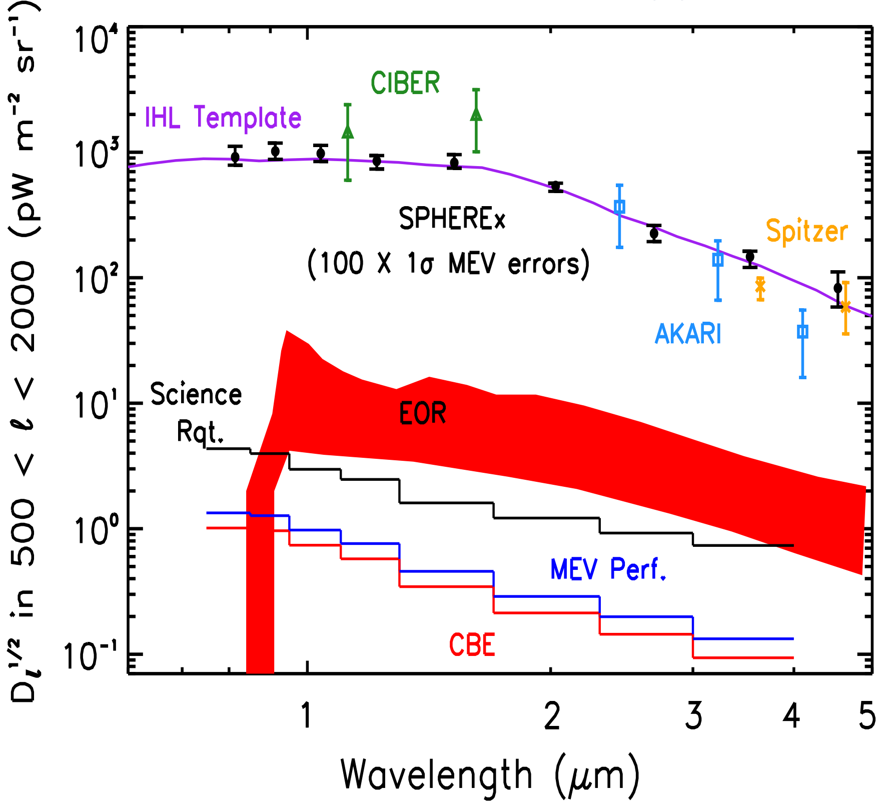
SPHEREx Cluster Redshift Errors*



*Simulated by Lindsey Bleem, ANL

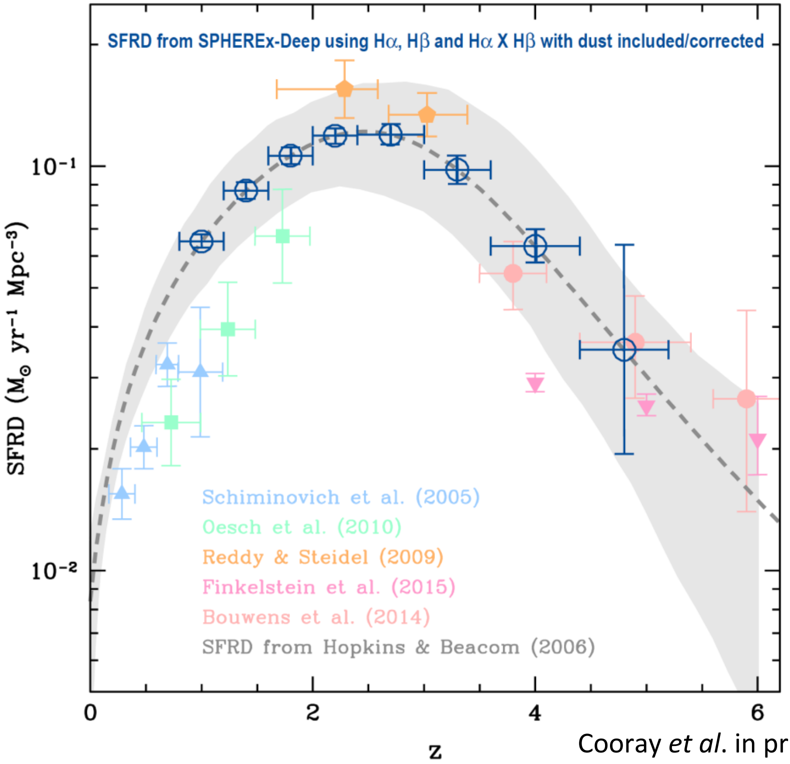
SPHEREx Measures Large-Scale Fluctuations

Continuum Anisotropy



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

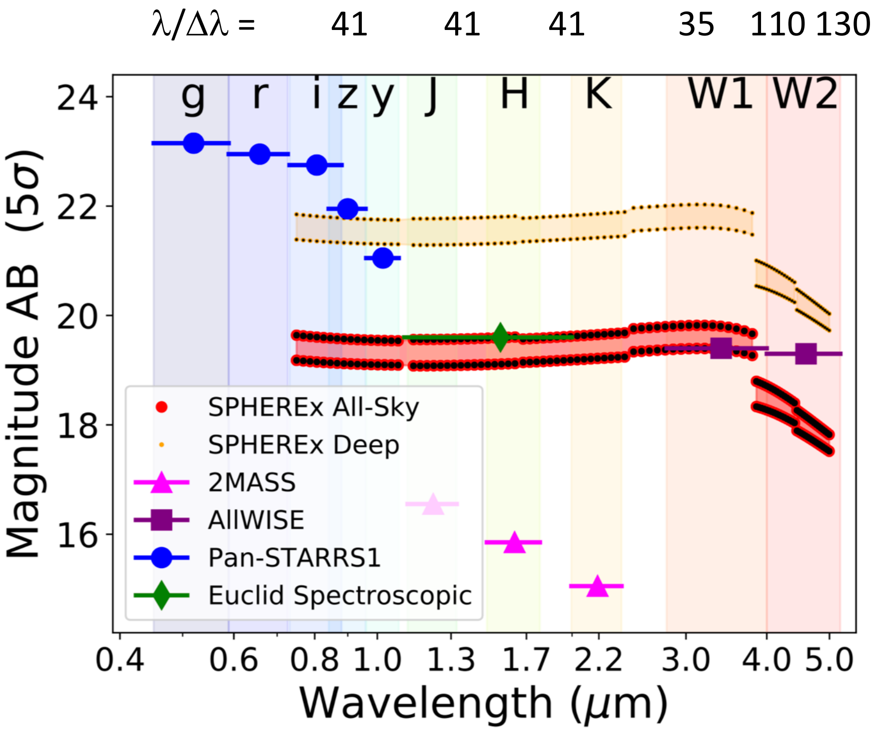
Line Tomography



Cooray *et al*. in prep

- 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
- Example above uses Hα + Hβ to solve for SFRD and dust attenuation simultaneously

SPHEREx All-Sky Survey Data Products & Tools



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

Users have access to data exploration, analysis, and visualization tools

- On-the-fly Mosaics
- Photometry on Known Position
- Spectral Data Cube Extractor
- Variable Source Extractor
- Source Discovery

Plus: Legacy Catalogs

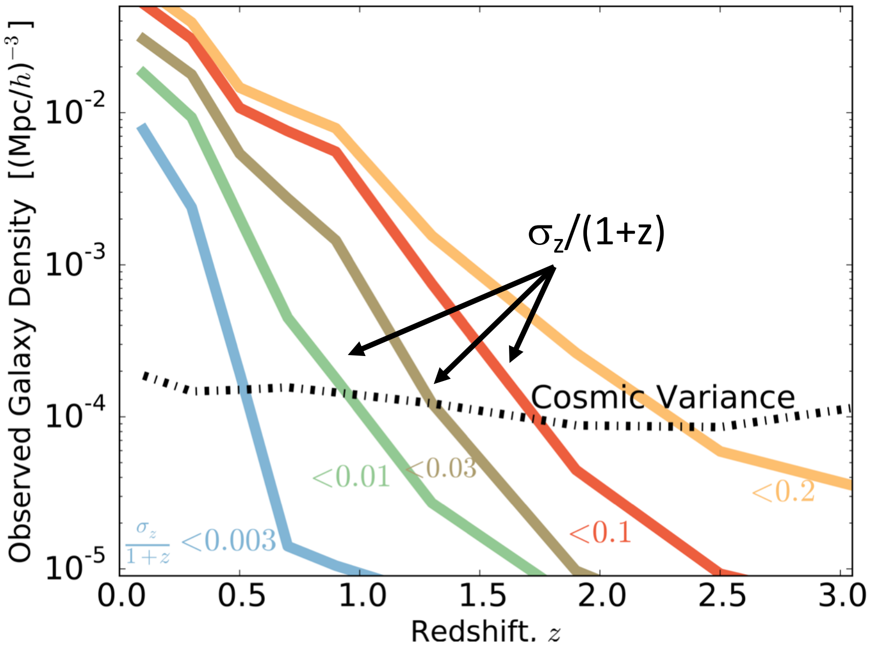
- Exoplanet Target Stars
- Solar System Objects
- Galaxy Clusters

Estimated source numbers

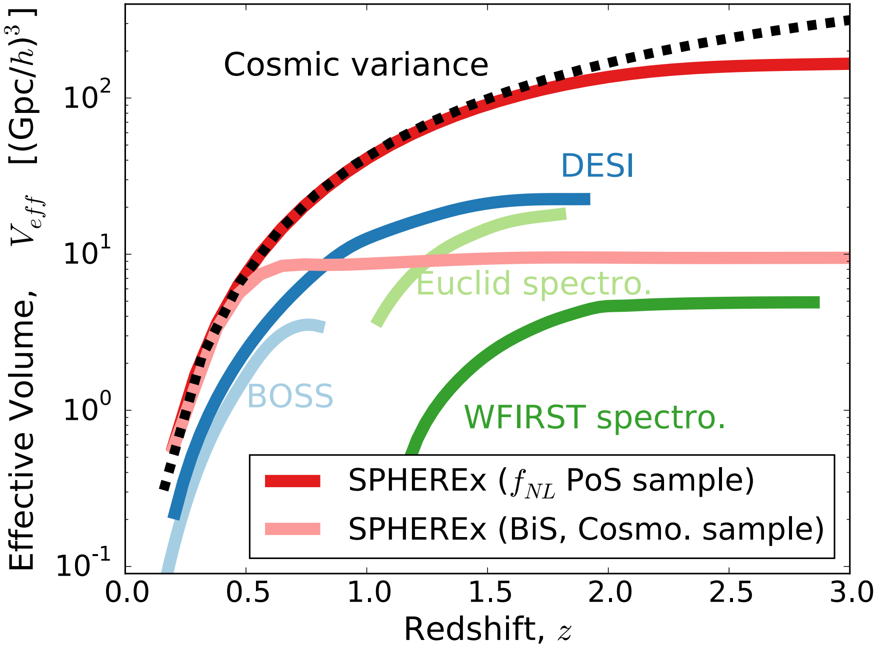
Detected galaxies	> 1 billion
Galaxy spectra $\Delta z/1+z < 10\,\%$	> 450 million
Galaxy spectra $\Delta z/1+z < 0.3\%$	> 10 million
Quasar spectra	> 1.5 million
Main sequence stars	> 100 million
Exoplanet target stars	> 600,000
Low-mass stars (LTY)	> 400
X-ray counterparts	> 100,000
Clusters	> 100,000
Asteroids & comets	> 100,000

SPHEREx Large Volume Galaxy Survey

Catalog Split into Redshift Accuracy Bins



SPHEREx Surveys Maximum Cosmic Volume



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

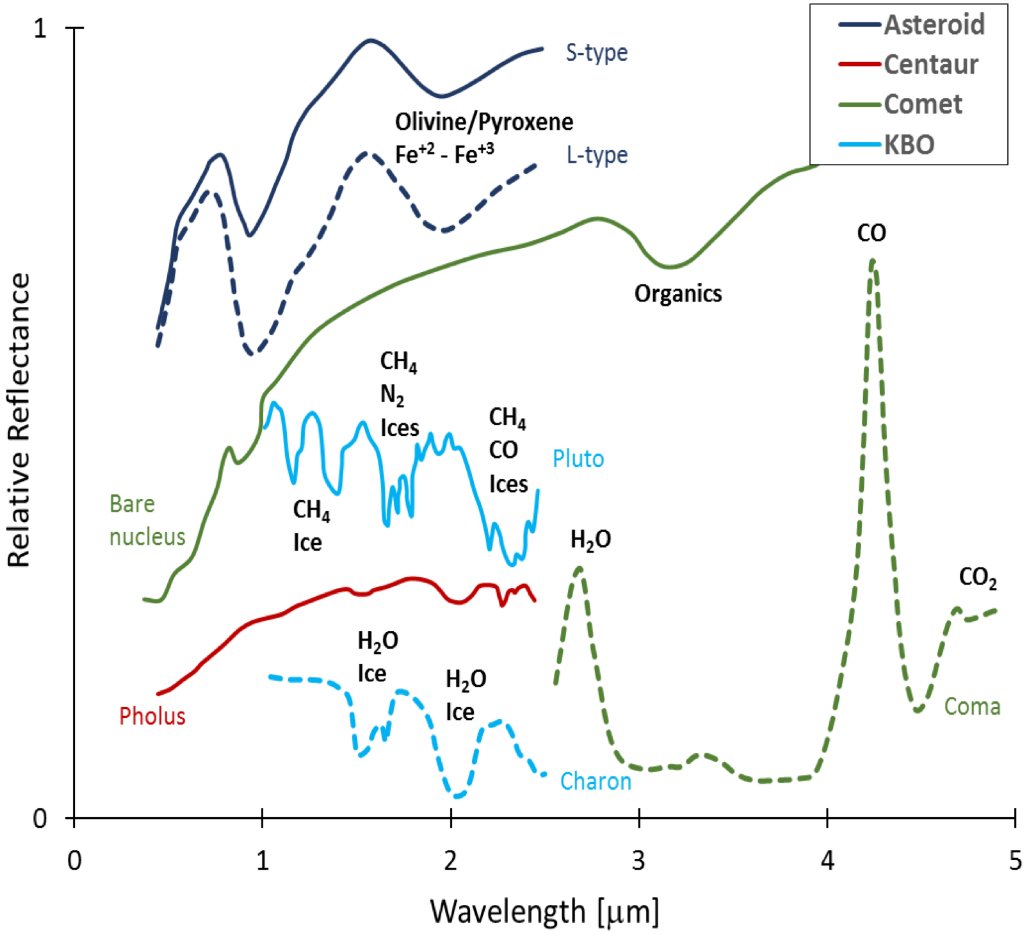
SPHEREx Solar System Science

SPHEREx spectrally surveys solar system objects over the full sky $6 < K_{AB} < 19$:

- 100,000 asteroids
- 100s of comets and Centaurs
- 1000s of Jovian Trojans
- 10s of the largest KBOs

Selected exciting investigations:

- Distinguish the size, albedo, and composition of the **Main Belt Asteroids** – necessary for future resource utilization, hazard mitigation, supporting the NASA *OSIRIS-Rex* and *PSYCHE* missions.
- Determine the chemical abundances of **Comets**, the most pristine leftovers from the era of formation of our solar system
- Determine the composition of the **Trojan Asteroids** in support of the NASA *LUCY* mission, and help determine if they are captured KBOs
- Obtain bi-yearly measurements of **Outer Moons & KBOs**, allowing us to search for changes in their surfaces & atmospheres



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Space Observations Key to Controlling Systematic Errors

Systematic	Mitigation/Control	Amplitude	Conversion to $\delta n/n$	Technique Reference	Coherent on large scales?	$\delta n/n$% rms/dex
Galactic extinction	Observe in infrared, template deprojection	0.003 mag rms before mitigation	1.4 /mag	e.g., Pullen & Hirata (2013)	Yes	0.064
Noise selection non-uniformity	Inject simulated objects into real data; template deprojection	0.2 mag rms before mitigation	0.017/mag	Suchyta et al. (2016), Huff et al. (2014)	Yes	0.017
Noise redshift non-uniformity			0.062/mag			0.06
Non-uniformity in external catalogs	Above + select from SPHEREx data, cross-calibrate, flux cut selection	NA	NA	All of the above	Yes	0.1
Source blending in redshift estimates	Control effective PSF FWHM; mask blended sources in Pan-STARRS/ DES/WISE catalog	NA	NA	Laidler et al. (2007), Lang et al. (2016)	No	Counted in end-to-end simulations
Source blending in clustering measurement	Small-scale correction using forward modeling and mock catalogs	Within cosmic variance	NA	Hahn et al. (2017)	No	Negligible
Detector hysteresis	Mask pixels based on photometric history	~0.13% pixels lost per exposure	NA	Smith et al. (2008), Rauscher et al. (2014)	No	Negligible
Cosmic rays	Flag contaminated pixels; do not observe in SAA	~0.22% pixels lost per exposure	NA	Zemcov et al. (2016)	No	Negligible
Absolute calibration	Calibrate on spectral standards and flat-field; overlapping bands	Control <3% to meet <6% science req't	0.32% × (cal. err.)$^{1/2}$		Yes	0.056
Channel-to channel calibration	Calibrate on spectral standards and flat-field	Control <2% bin-bin to meet <6% science req't	0.19% × (cal. err.)$^{1/2}$	Fixsen et al. (2000)	Yes	0.027
Calibration stability	Monitor calibration on orbital timescales using deep fields	<1% drift over 4 surveys	5% × drift	Cutri et al. (2018)	Yes	0.05
PSF and astrometry knowledge	Centroid and sub-pixel stack on 2MASS stars	<0.5% photometric error	NA	Bock et al. (2013)	No	Counted in calibration budget and simulations

SPHEREx Systematic Error Control Strategy:

Infrared Observations from Space mitigate large-scale errors from atmosphere and Galactic extinction

Stable In-Flight Calibration controls gain and PSF/astrometry errors on orbital to annual timescales

Catalog-Driven Galaxy Selection mitigates galaxy confusion – just discard known blends

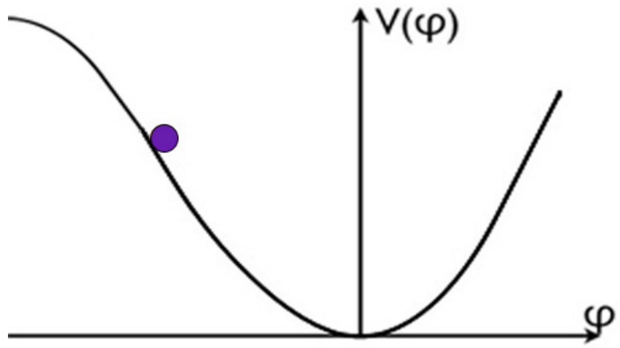
Redshift Validation use known spec-zs to test redshift errors, split by type, location, etc

For details see: Doré *et al*. arXiv 1412.4872

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

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

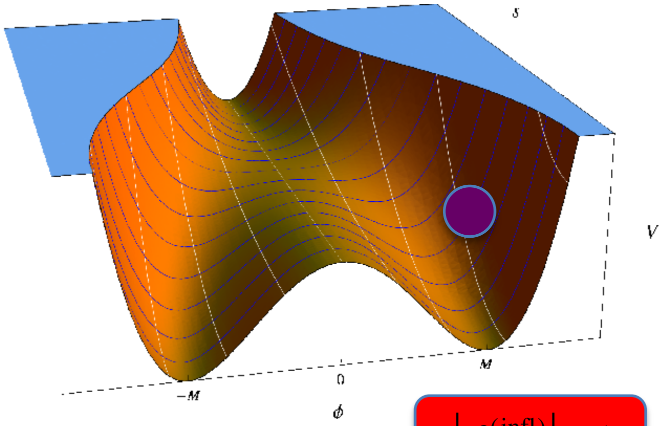
Single-Field Inflation:



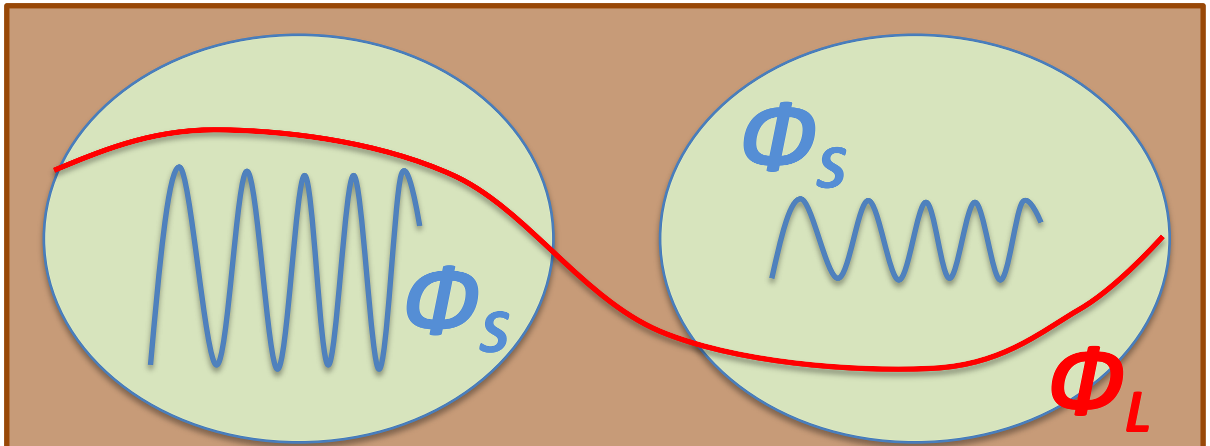
Squeezed limit consistency condition by Maldacena (2003):

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

Multi-Field Inflation:



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



Non-Gaussianity Produces Two Signatures

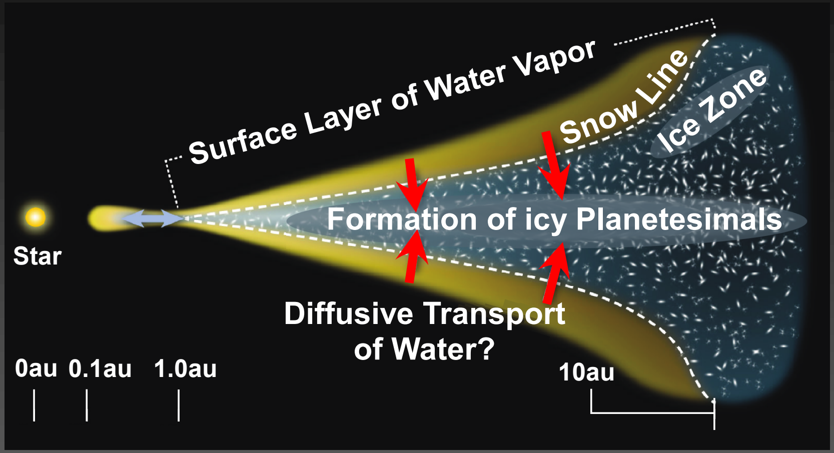
Enhanced power on large spatial scales Φ_L

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

- measured with power spectrum and bispectrum

SPHEREx Galactic Ice Survey

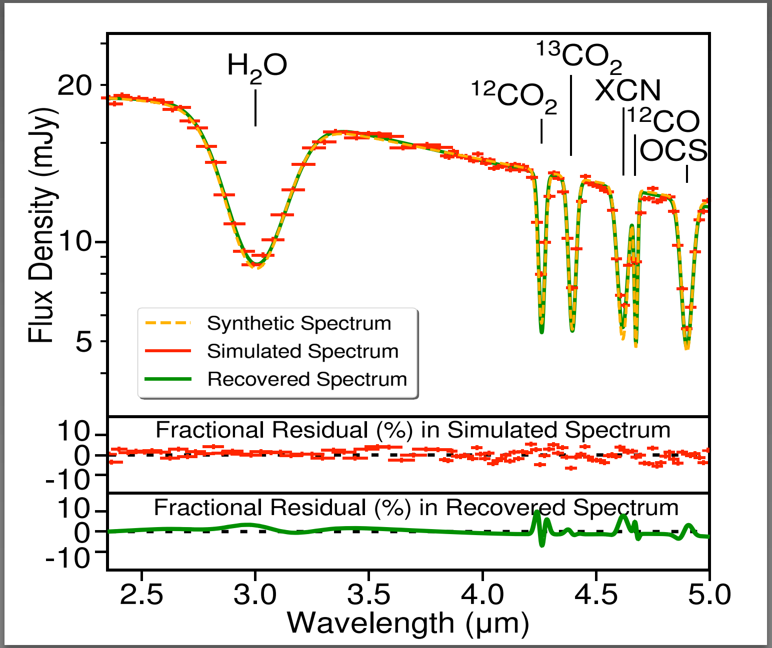
Schematic of a Protoplanetary Disk



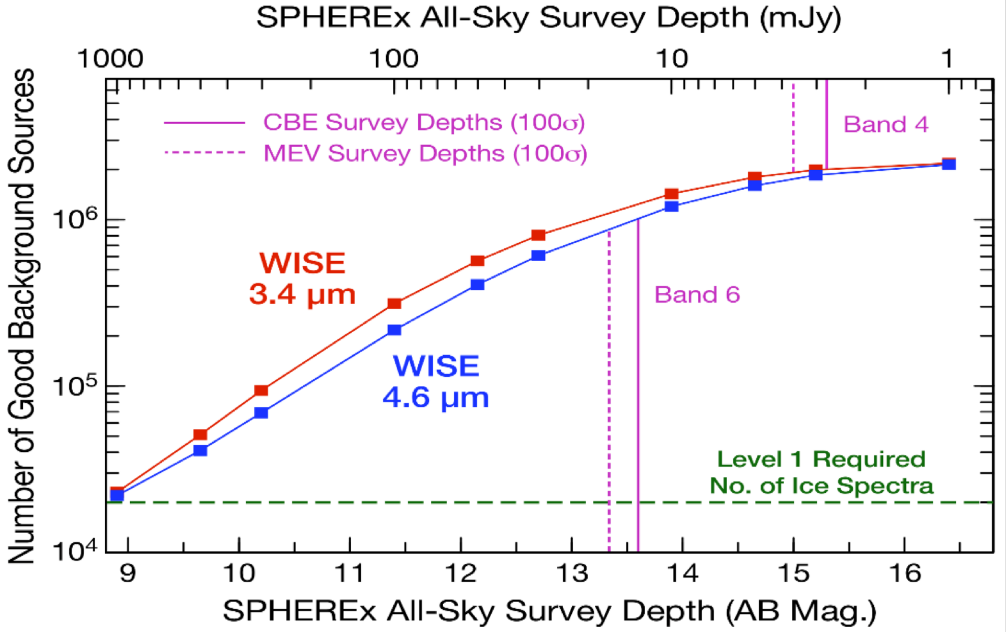
"High-quality ice source" means

- Embedded behind dust
- Bright (SNR > 100 per channel)
- Isolated

Estimate Errors on Absorption Depth



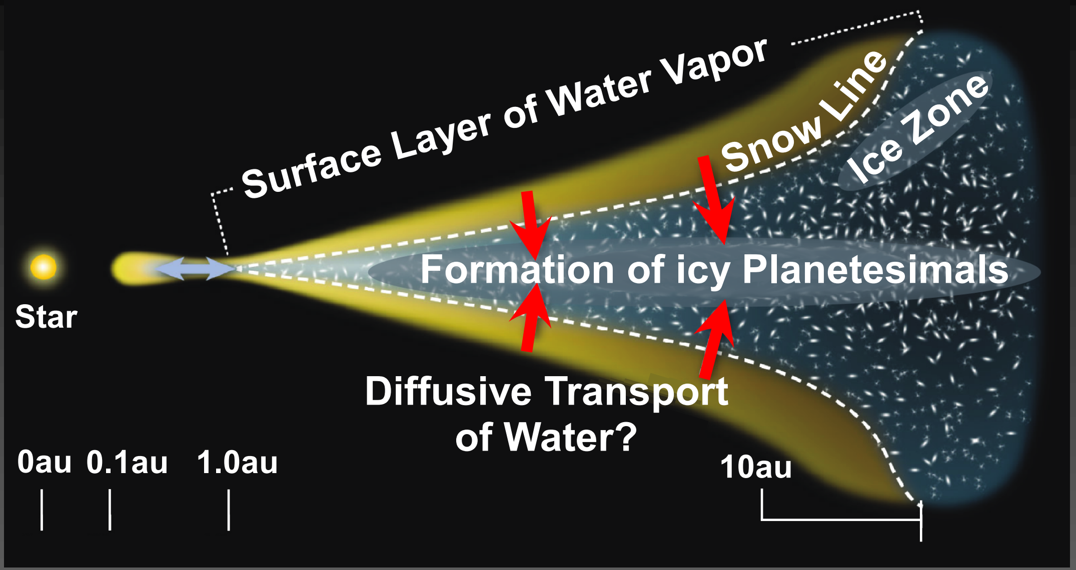
Expect ~1 Million High-Quality Ice Detections



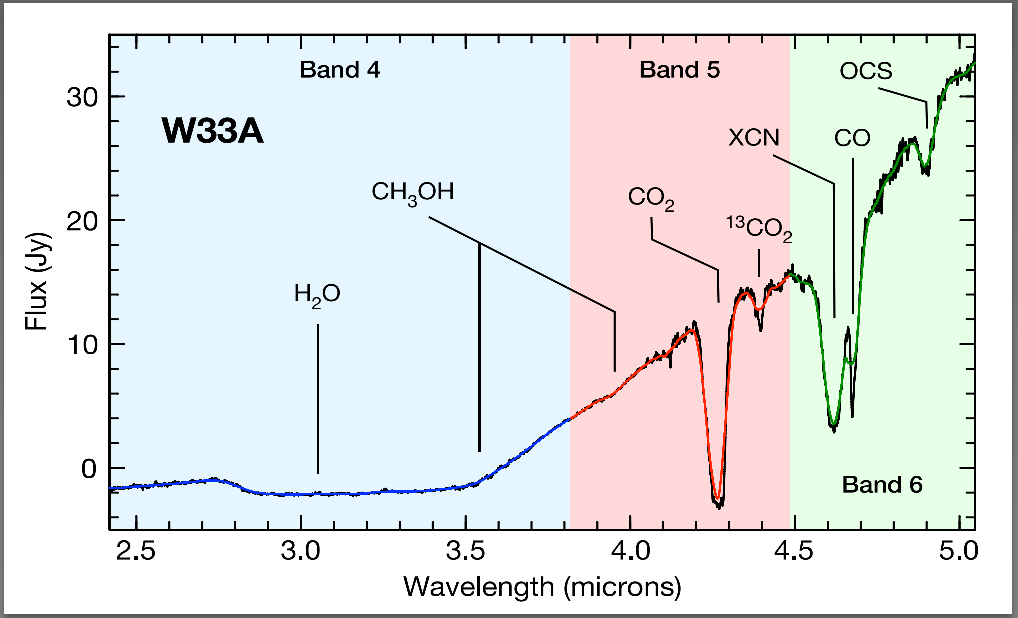
Why Study Ices?

- **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



Testing Redshift Reliability

Inject Real Galaxies into SPHEREx Pipeline

Input Deep Galaxy Catalog Preparation

- 30 band observations of the COSMOS field from HST, Subaru, Spitzer, GALEX, Subaru, CFHT, Chandra, Keck
- Published COSMOS photometric catalog with measured spectroscopic or photometric redshift and stellar types
- Each galaxy and star is assigned a best fit SED template using measured redshift and data-based SED template library
- **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's 96 spectral channels 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 150 seconds
- Add instrumental noise plus overall and source-by-source calibration errors (Table M.5.3-4)
- **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
- Measure fluxes in each SPHEREx band using forward modeling with *Tractor*
- **Simulated Galaxy Catalog Fluxes**

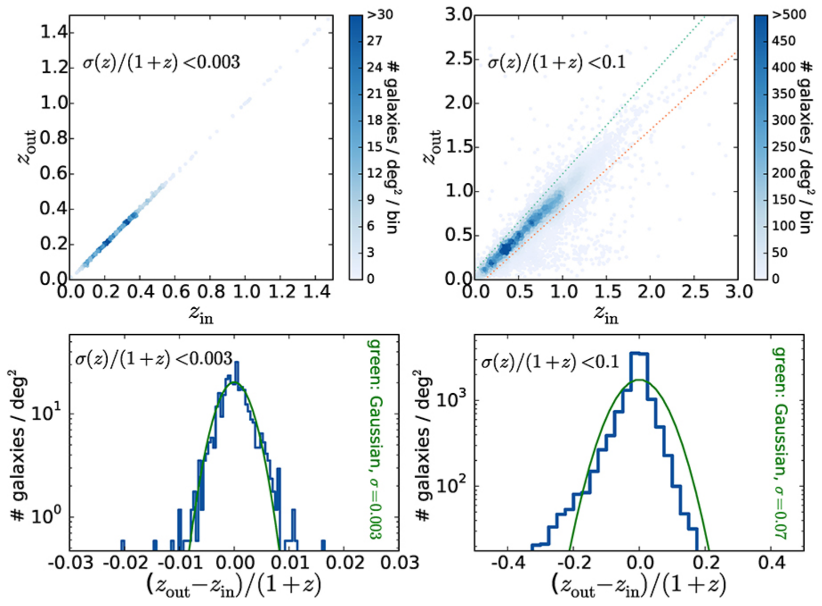
Spectroscopic Redshift Estimation

- Use SED template library from Brown et al. (or others) to fit each galaxy's SPHEREx and Pan-STARRS fluxes
- Galaxy catalog with associated SED template, dust extinction, luminosity, redshift, associated errors and goodness of fit
- **SPHEREx Spectroscopic Catalog**

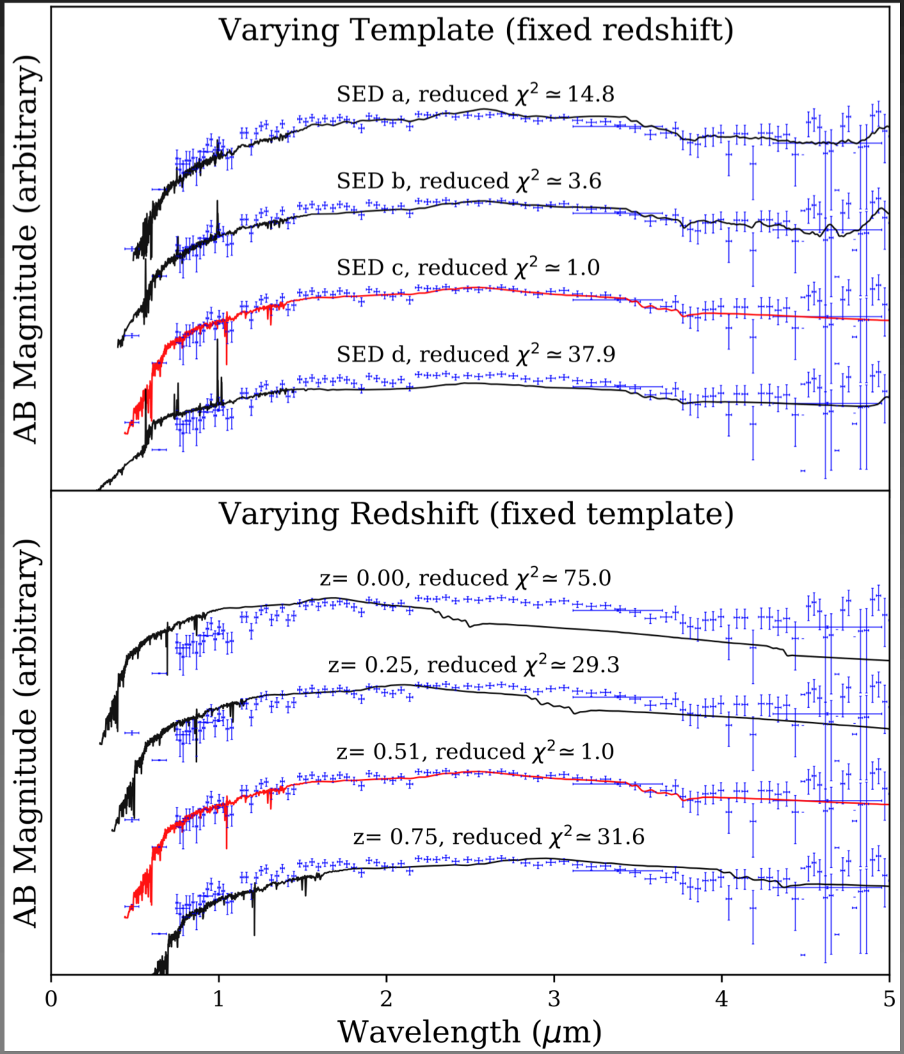
Parameter Forecasts

- Discard galaxies with poor goodness of fit
- Compute errors on PoS and BiS in 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
- **SPHEREx Inflation Investigation Cosmological Forecasts**

Resulting Redshift Errors



Example Template and Redshift Fits



CMB-S4: CMB Lensing Cross-Correlation

- The SPHEREx galaxy clustering measurement covers the full sky and is cosmic variance limited on large scales

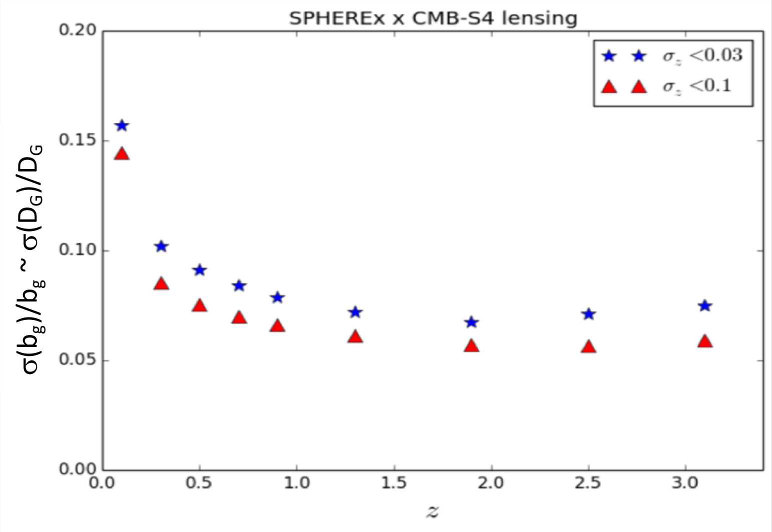
- SPHEREx determines galaxy bias b_g from the galaxy power spectrum analysis

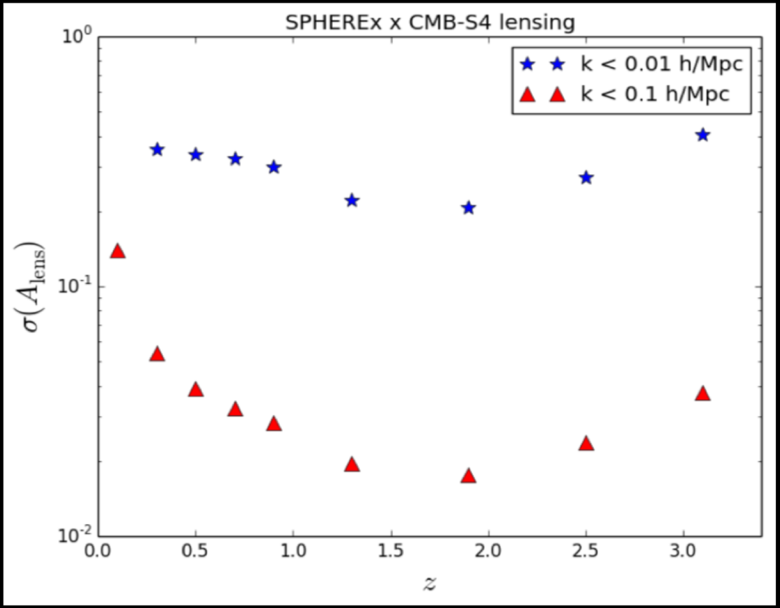
- Given b_g, Galaxy x CMB lensing:

  Measures the growth of structure D_G over a wide redshift range

  -- Probes gravity on large scales

  -- Constrains the amplitude A_{lens}





Calculation by E. Schaan

Doré, Werner++16

CMB-S4: kSZ Cross-Correlation

- SPHEREx + CMB-S4 greatly increase our ability to measure the baryon component of the kinematic Sunyaev-Zel'dovich effect

- Using the velocity reconstruction method, and using only the two highest redshift accuracy (~24.5M galaxies)

  S/N~55 assuming half the sky (CMB map noise of 14 μK-arcmin)

- Using direct cross-correlation between T^2 and δ_{gal} (Doré++03, Hill++16, Ferraro++16) allows a statistical measurement with less stringent requirements on redshift errors:

  S/N > 100 can be achieved by combining SPHEREx with future CMB experiments

Calculation by S. Ferraro & E. Schaan

Doré, Werner++16