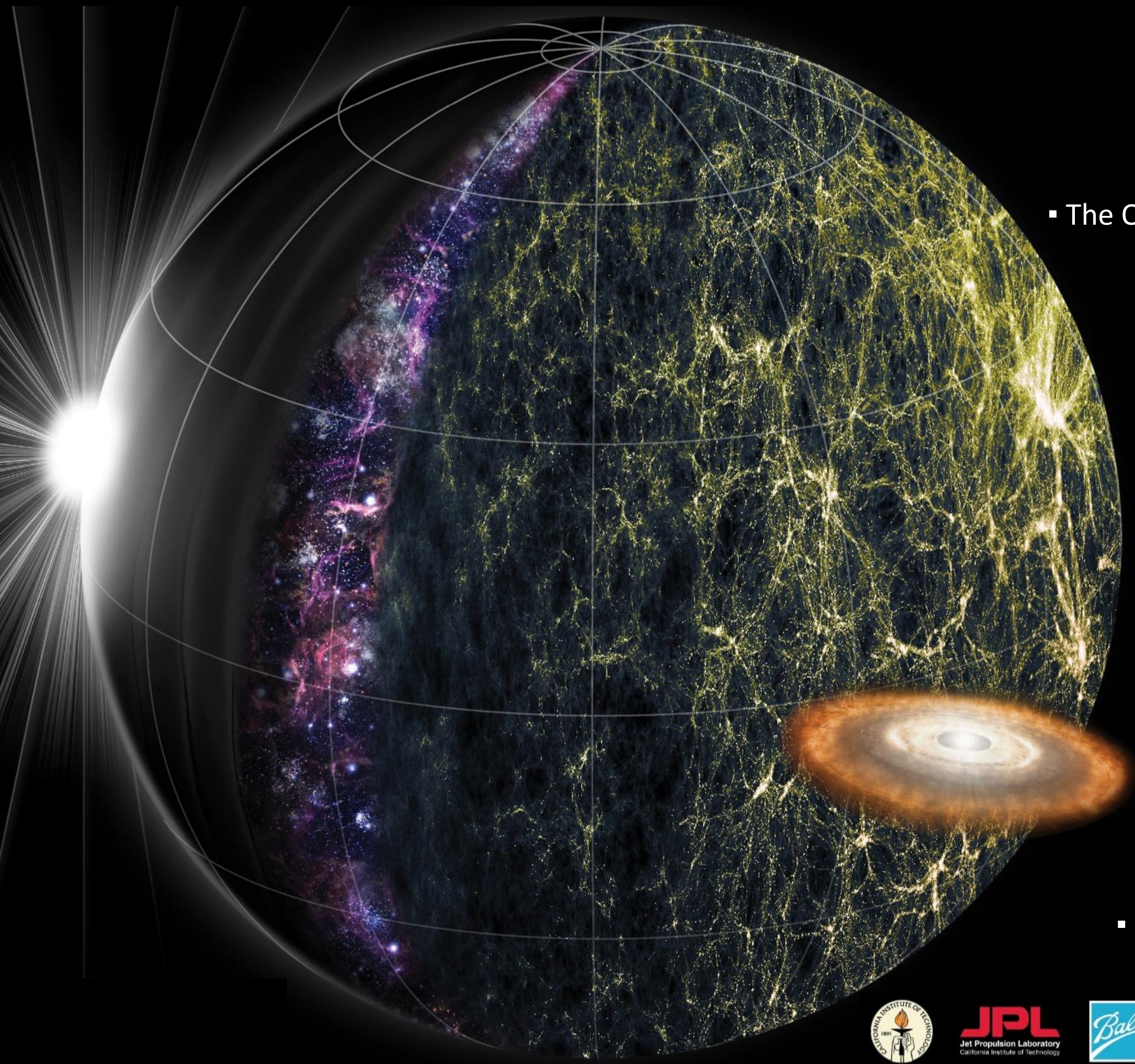
# SPHEREx: An All-Sky Spectral Survey



**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

JPL Jet Propulsion Laboratory California Institute of Technology
Ball
ipac
CfA
UCI
THE OHIO STATE UNIVERSITY

# 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"

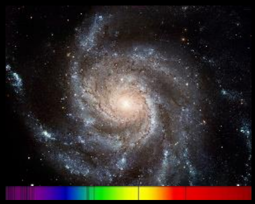
# SPHEREx Creates an All-Sky Legacy Archive

*A spectrum for every 6" pixel on the sky*

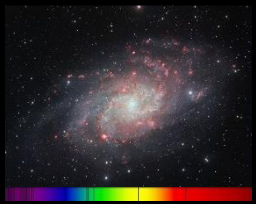
## Galaxies

**Detected**
> 1 billion

**Medium-Accuracy Spectra**
> 100 million



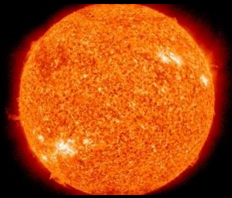
**High-Accuracy Spectra**
10 million



**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**
2 – 300?

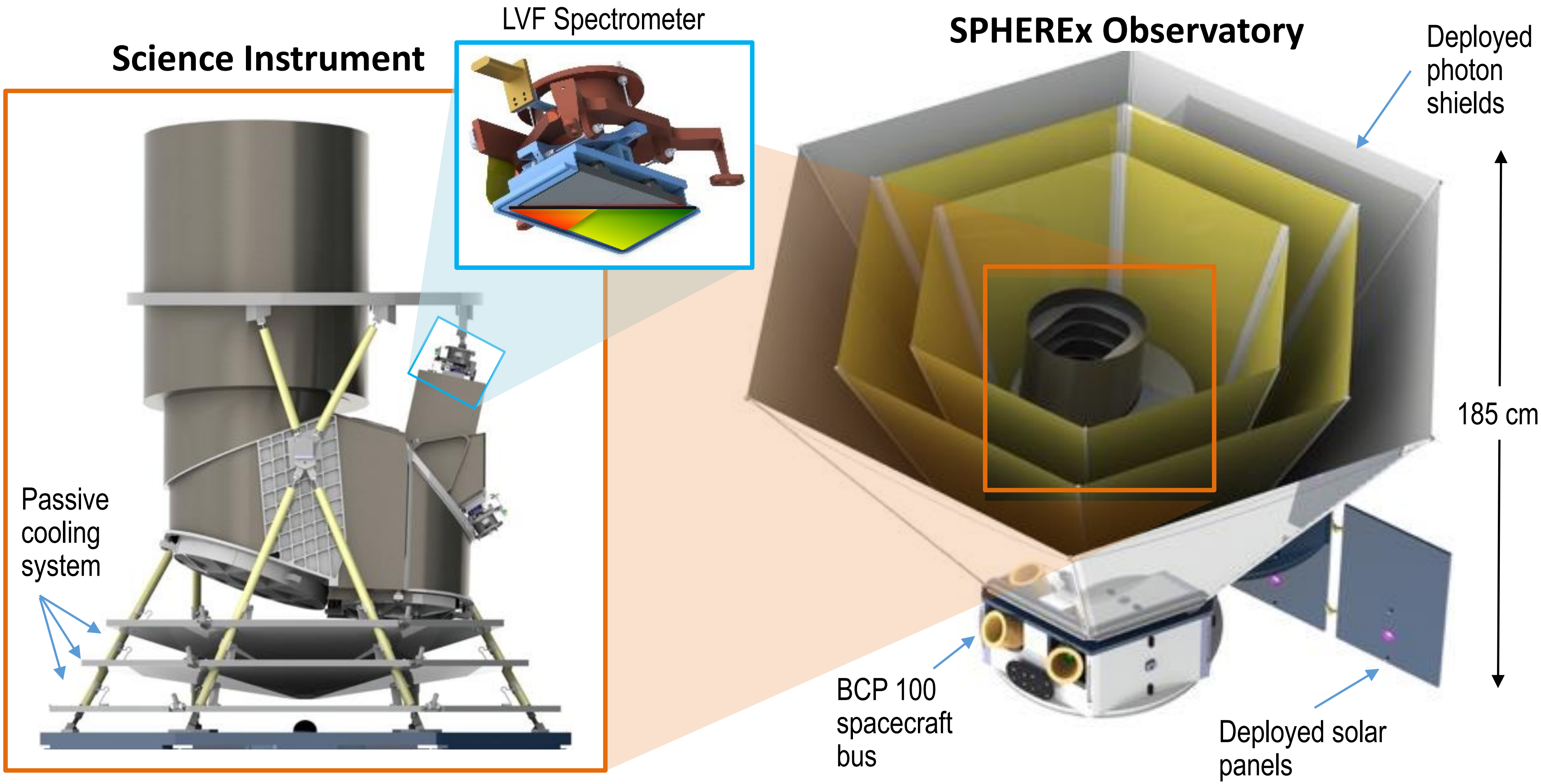
**Asteroid & Comet Spectra**
10,000

**Galactic Line Maps**
PAH, HI, $H_2$

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

**COBE**
**IRAS**
**GALEX**
**WMAP**
**Planck**
**WISE**

# SPHEREx Overview



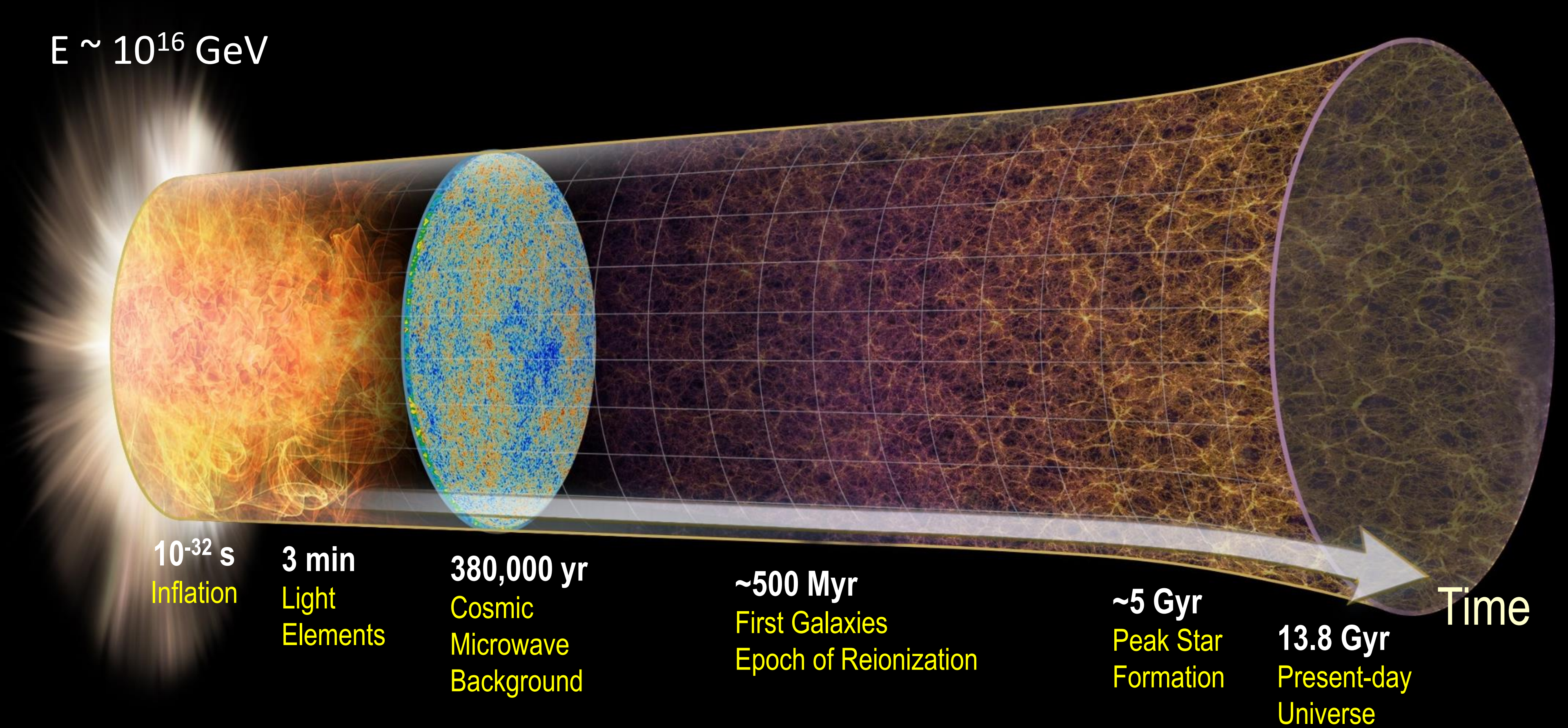

- 20 cm telescope effective diameter
- 3.5° x 7° field of view
- 6.2" pixel size
- 0.75 – 5 μm wavelength range
- $\lambda/\Delta\lambda$ = 40-135 resolving power

**Wide-Field Linear Variable Filter Spectroscopy**

- No moving parts
- Space-proven method
- Spectra produced by pointing the spacecraft
- Complete spectral sky survey every 6 months

*Note: SMEX configuration parameters given throughout*

# *How Did the Universe Begin?*




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

# How Do We Probe Inflation Physics? Observables

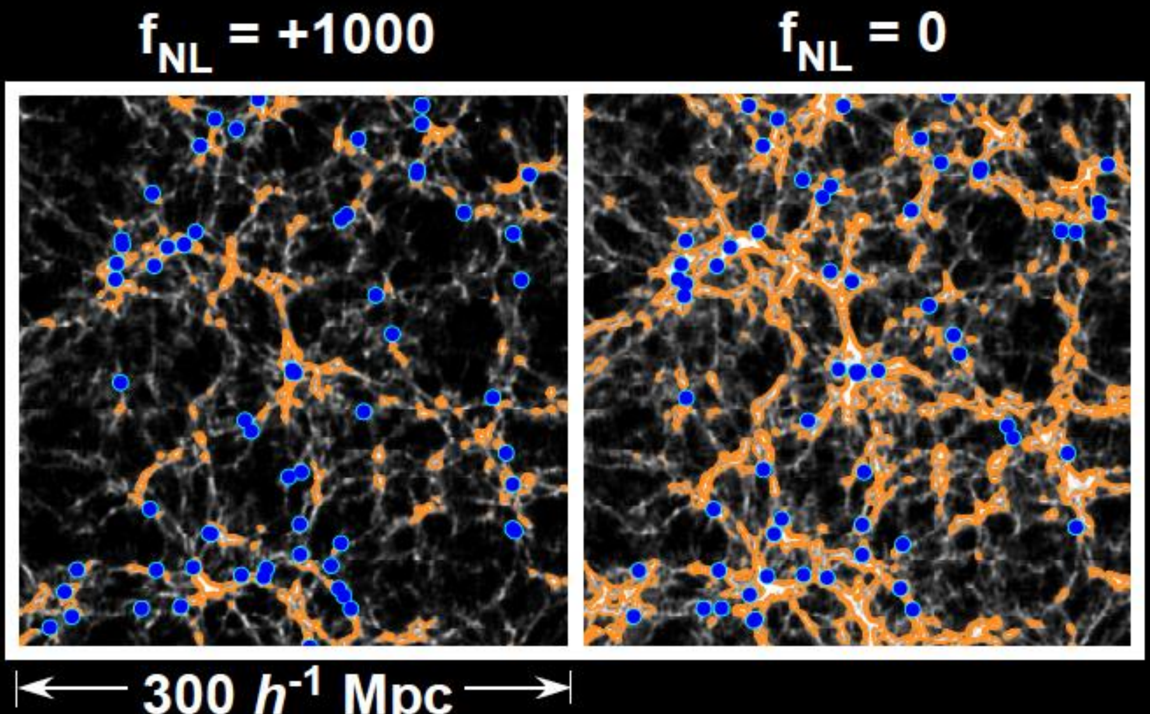
Inflationary gravitational waves – CMB “B-mode” polarization
Spectral index of fluctuations – CMB and large-scale structure
**Non-Gaussianity** – Sensitive to **Inflaton field** (single- or multi-field)

$$\phi = \phi_{linear} + f_{NL}\,\phi^2{}_{linear}$$

$$CMB:\ \ f_{NL} < 10.8\ (2\sigma)$$

Local $f_{NL}$; Planck 2015 results

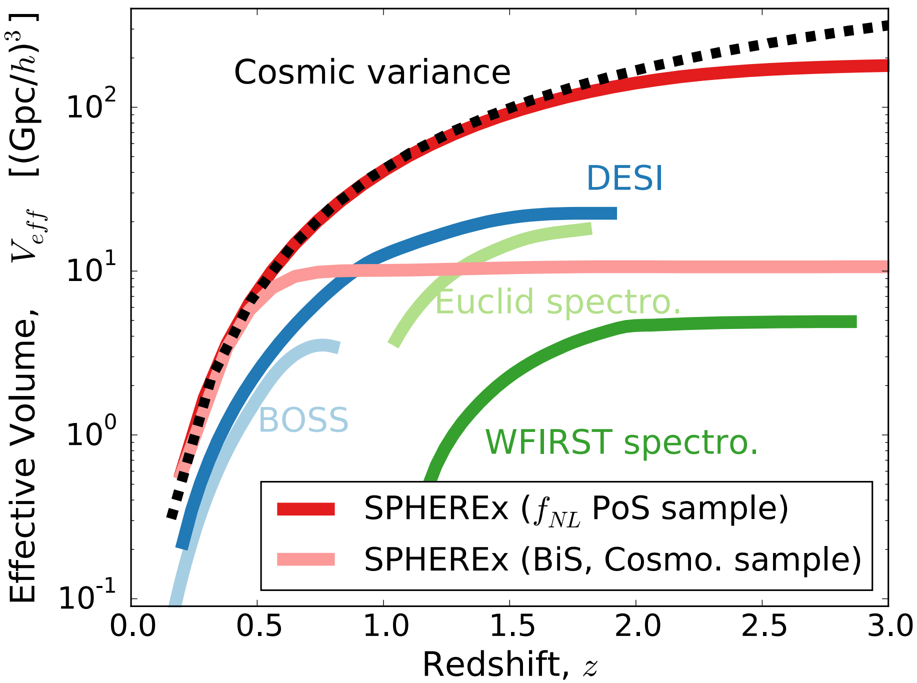
*Large-Scale Structure will give best non-Gaussianity measurements*



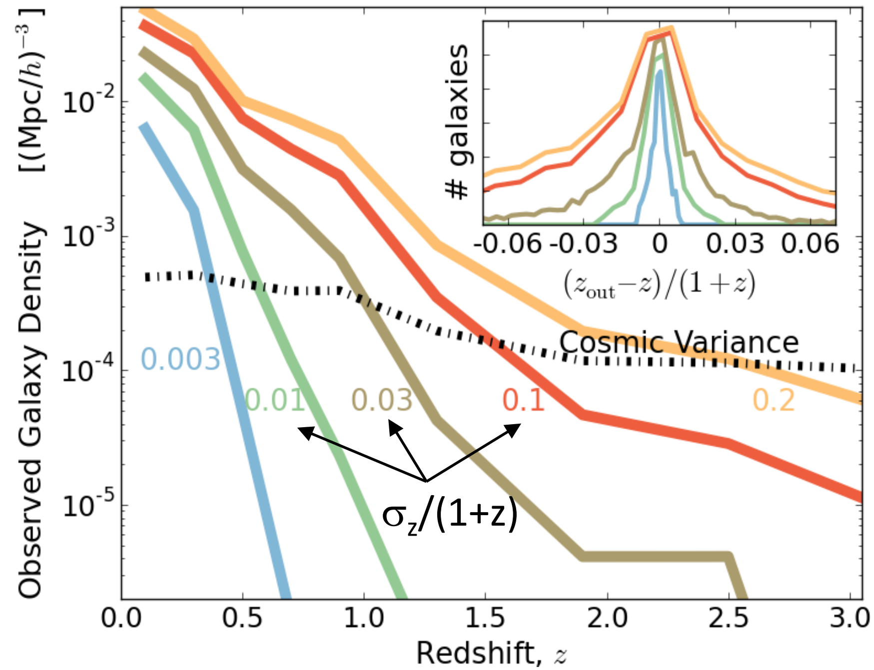

Non-Gaussianity appears on largest spatial scales – <u>need large volume survey</u>

# SPHEREx Large Volume Galaxy Survey

## SPHEREx Surveys Maximum Cosmic Volume




## Catalog Split into Redshift Accuracy Bins



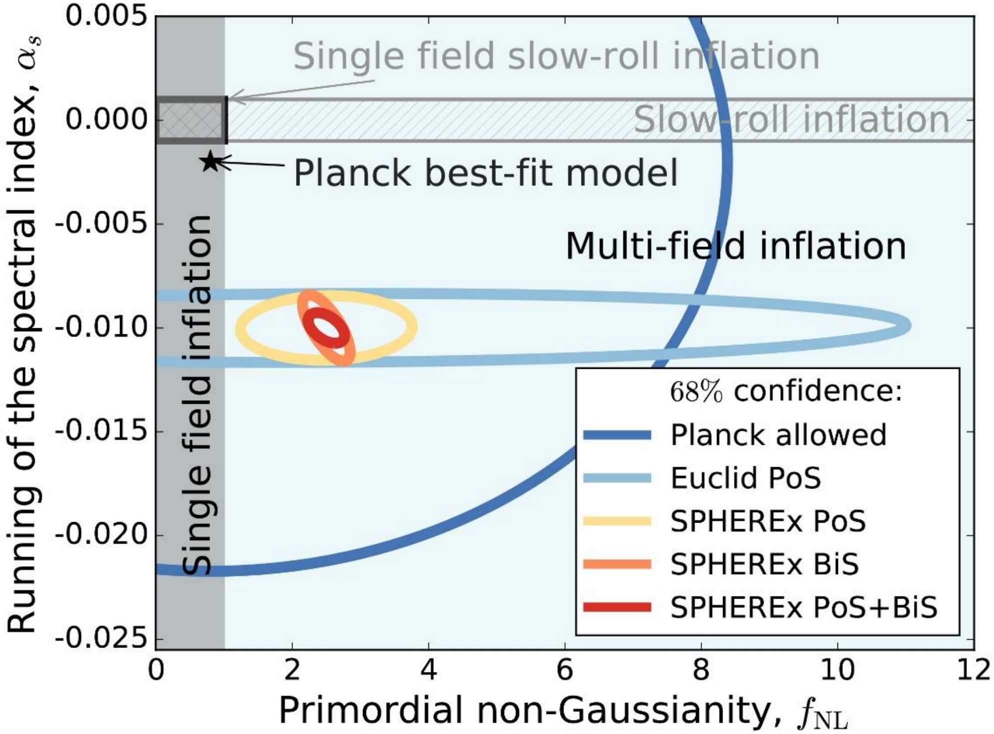

**SPHEREx Large-Volume Redshift Catalog**

- 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

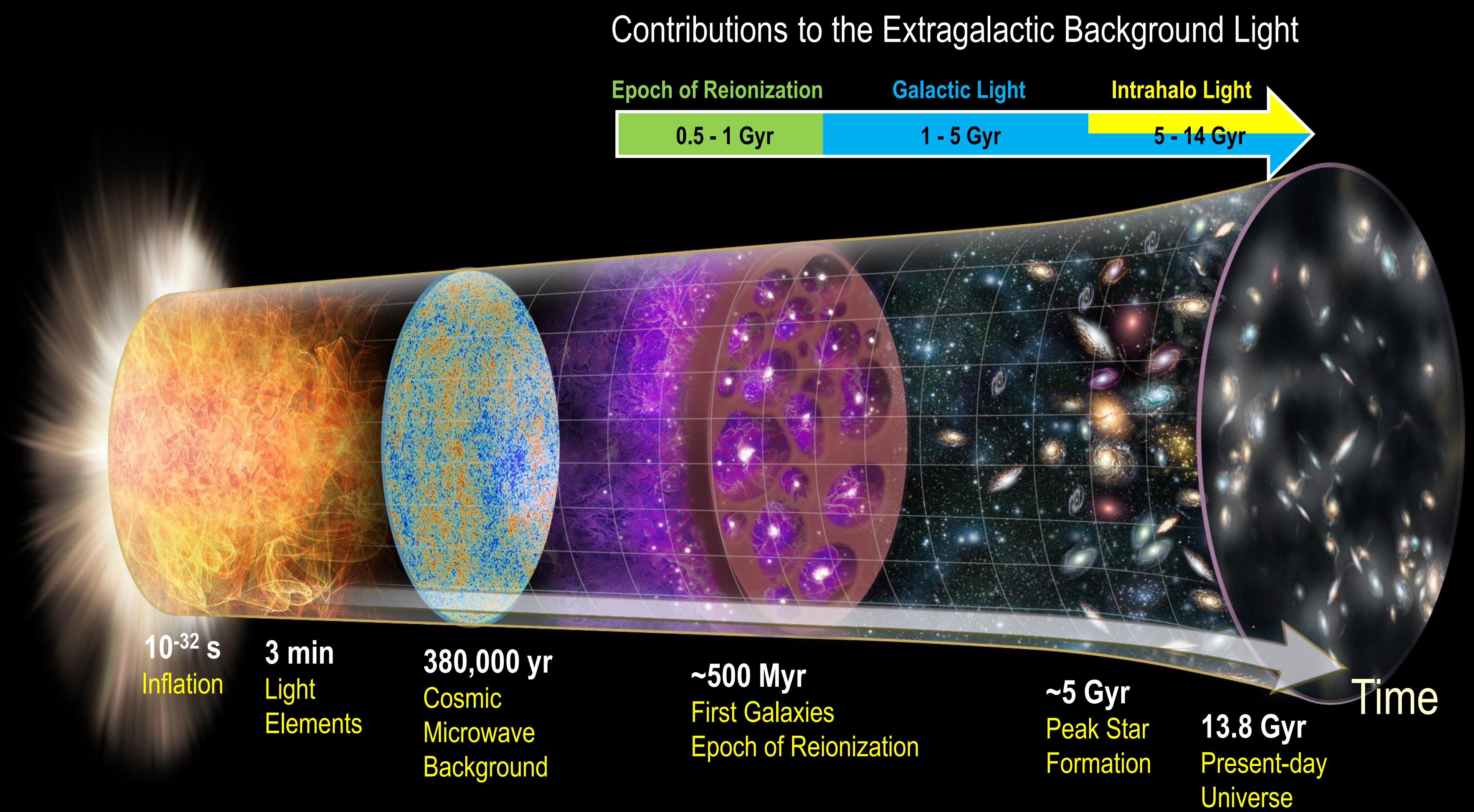
# SPHEREx Tests Inflationary Non-Gaussianity




| $1\sigma$ errors statistical (with systematics) | SPHEREx (MEV) | | | Euclid | Current |
|---|---|---|---|---|---|
| | PoS | BiS | PoS+BiS | PoS | |
| $f_{NL}$ 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 $\alpha_s$ ($\times 10^{-3}$) | 1.0 | 1.0 | 0.49 | 1.1 | 7.5 |
| Curvature $\Omega_k$ ($\times 10^{-4}$) | 7.6 | 9.5 | 6.6 | 7.0 | 20 |
| Dark Energy figure of merit | 381 | NC | NC | 309 | 14 |

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

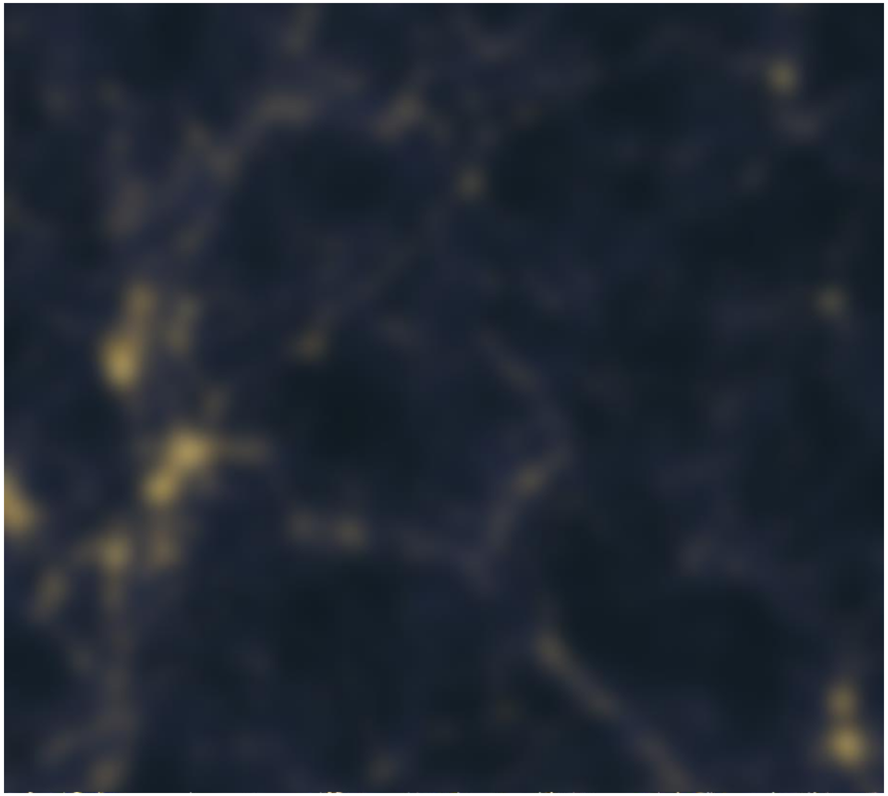
# How Did Galaxies Begin?




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

# Measuring Cosmic Light Production

## Two Ways to Measure Cosmic Light Production



**1) Individual Galaxies & Redshifts**

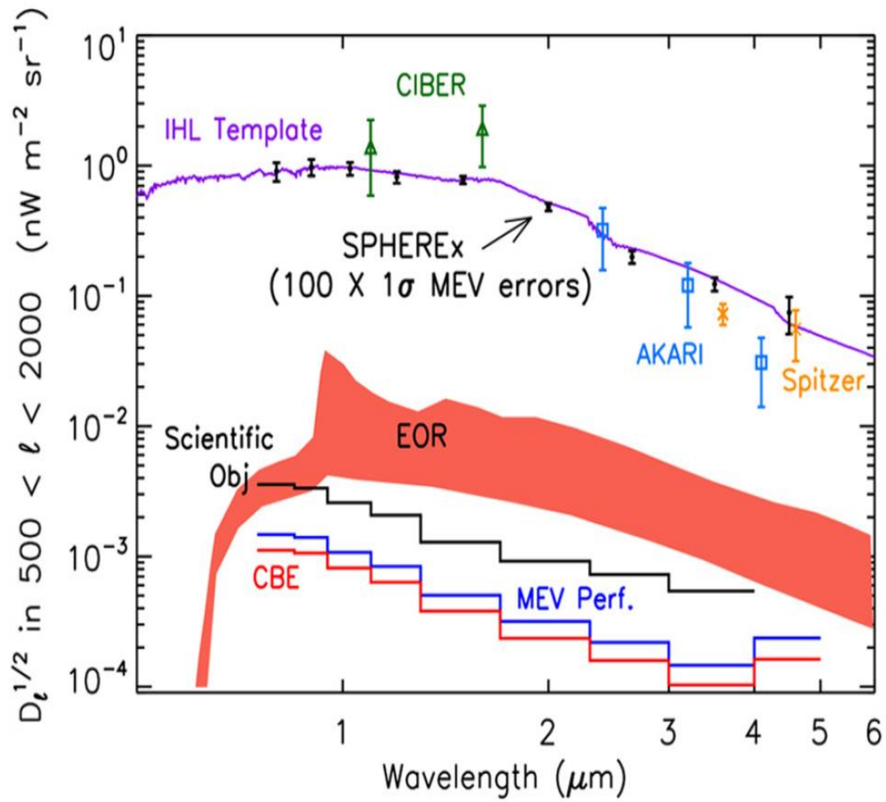
*Large telescope for point source sensitivity*

**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*

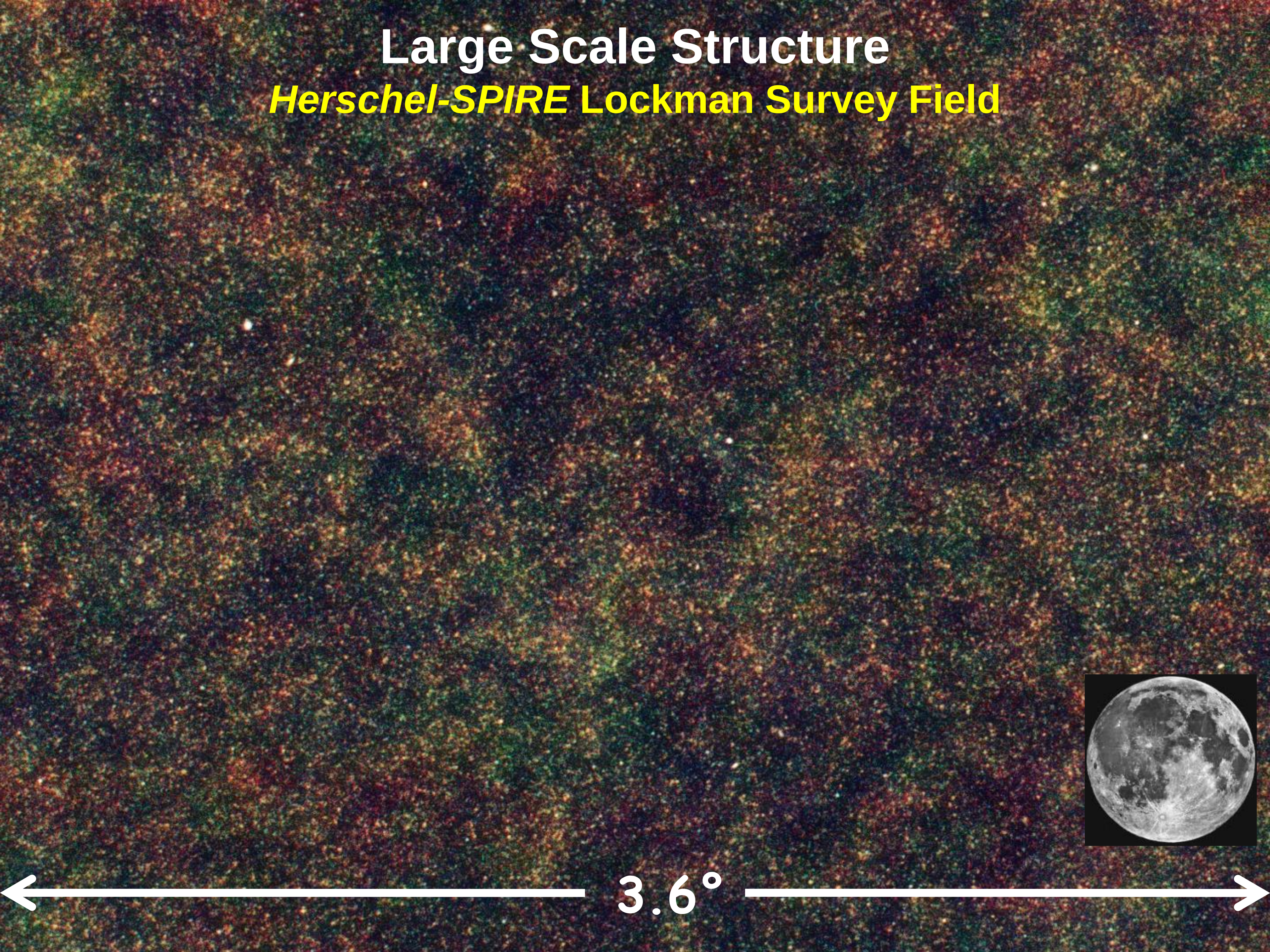
**3) Intra Halo Light**

*Tidally stripped stars at z = 0 - 2*

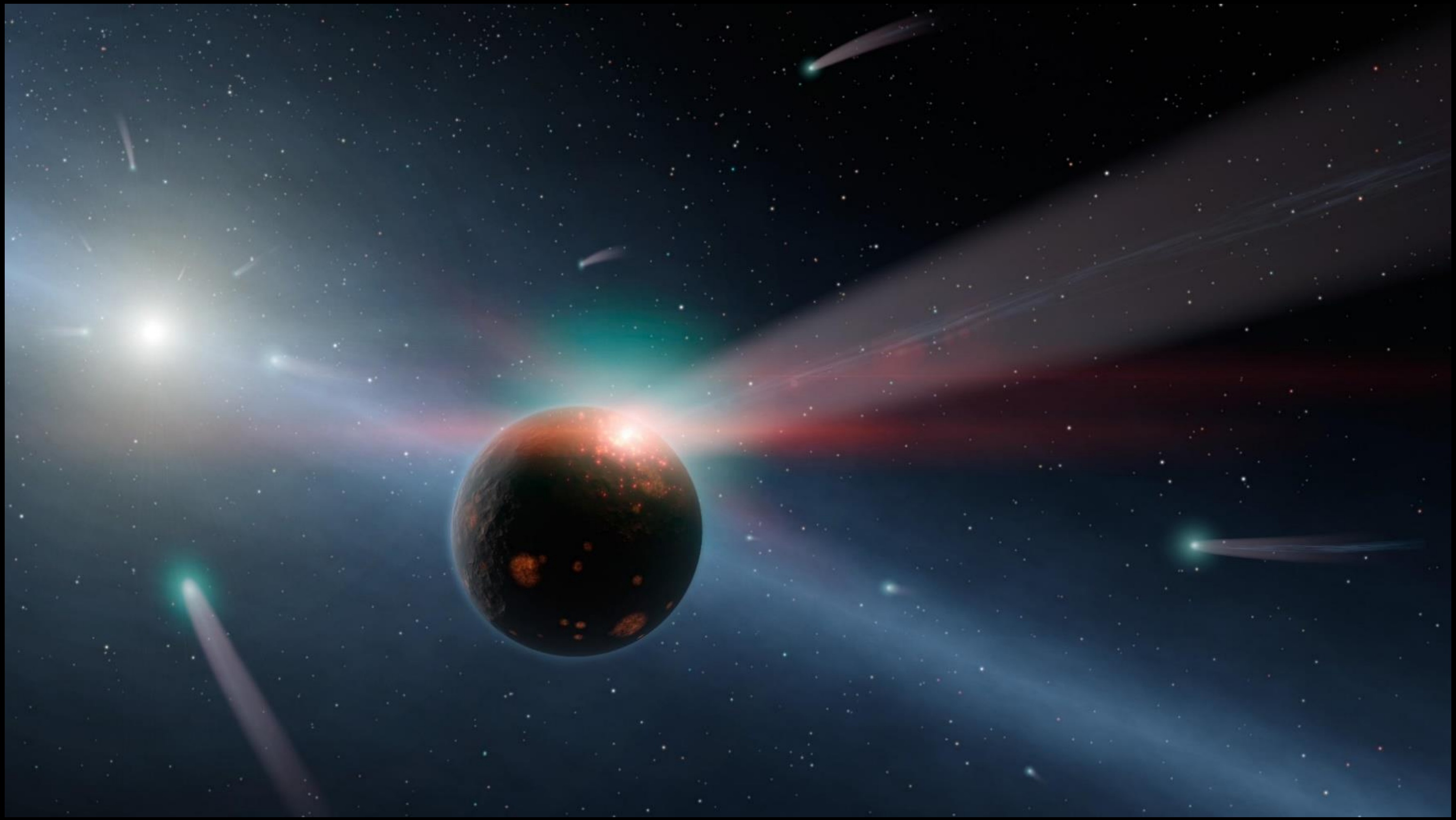
**4) Surprises?**

# Large Scale Structure

## *Herschel-SPIRE* Lockman Survey Field



# What Are the Conditions for Life Outside the Solar System?



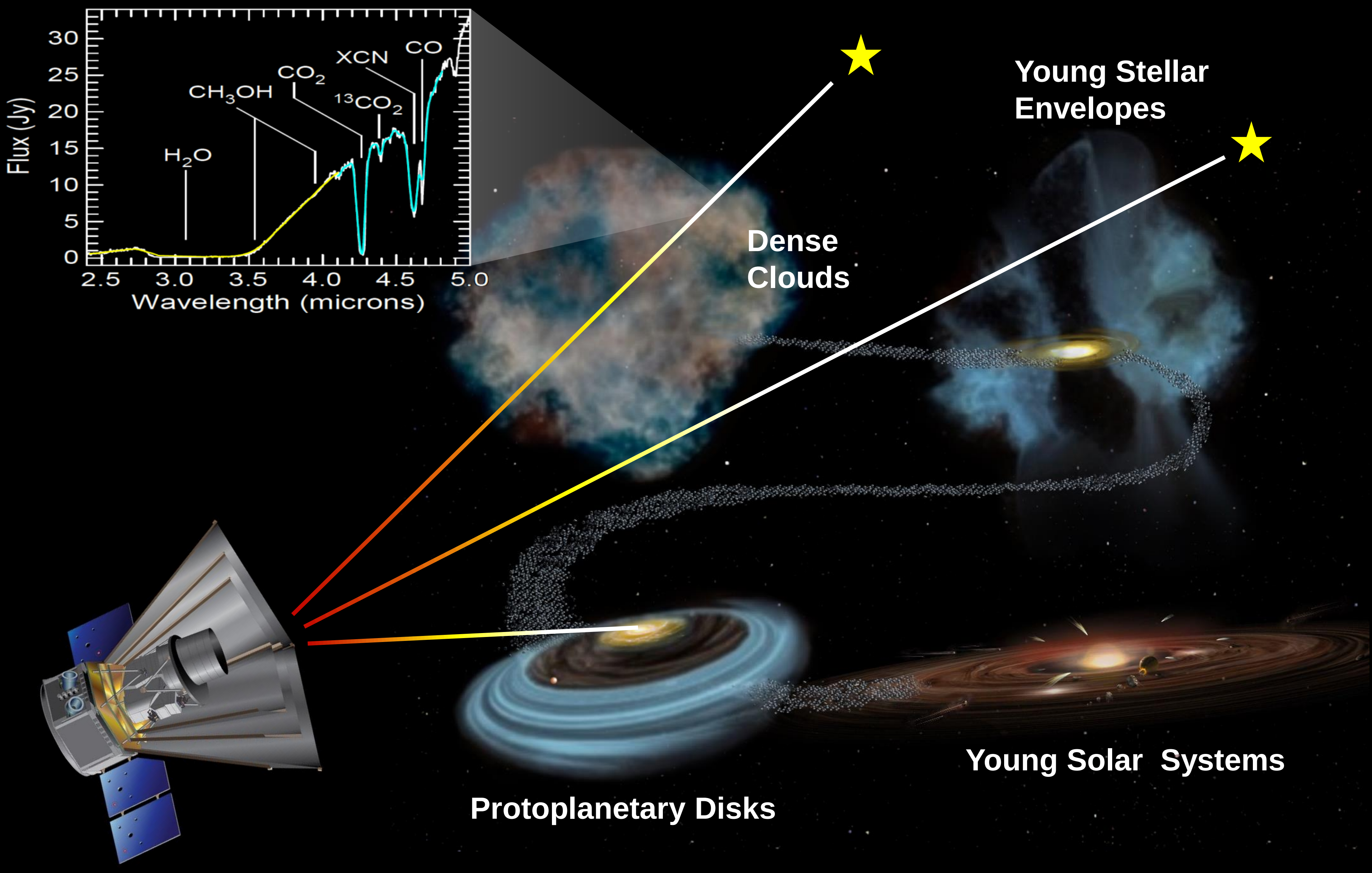
Sourced by **interstellar ices**, rich in biogenic molecules: $H_2O$, CO, $CO_2$, $CH_3OH$…

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

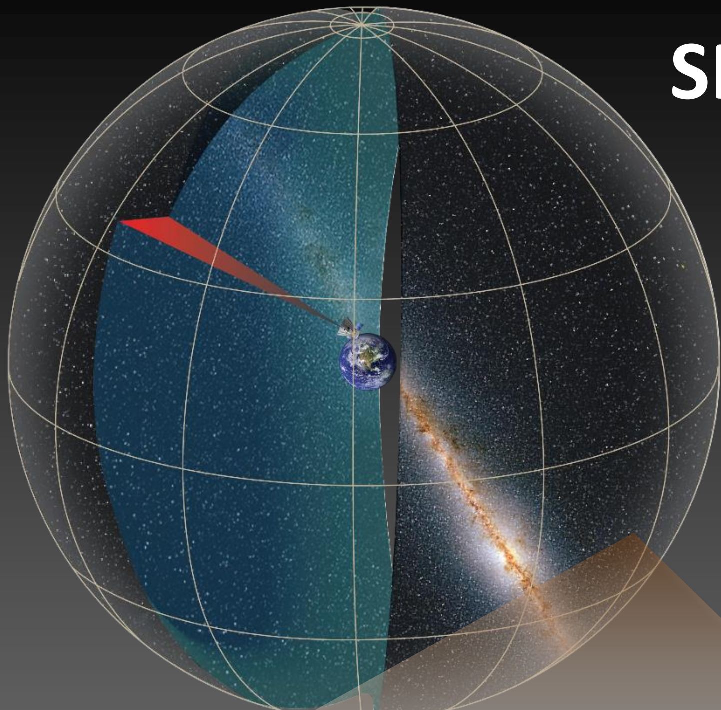
Did water arrive from the late bombardment (~500 MY) or before?

*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*

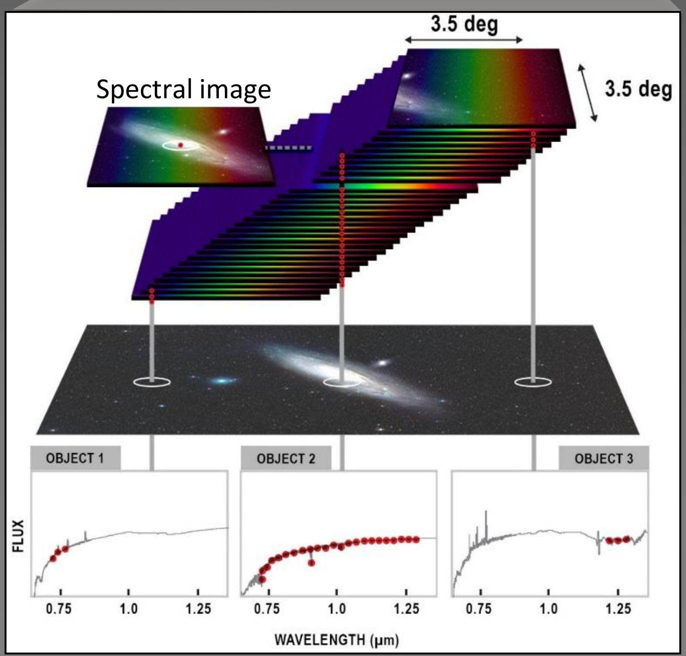
# SPHEREx Surveys Ices in All Phases of Star Formation



# SPHEREx All-Sky Spectral Survey



1.3 *trillion* voxels per survey!




## Archive 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 $\sigma(z)/(1+z) < 0.03$** | 120 million | Study (H, CO, O, S, $H_2O$) line and PAH emission by galaxy type. Explore galaxy and AGN life cycle | |
| **Galaxies $\sigma(z)/(1+z) < 0.003$** | 10 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** | 1-300 | 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 | A.Cox (2015) 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) |

# How Does SPHEREx Advance My PAG's Science?

## PhysPAG: Test Inflationary Birth of the Universe

Archive
- Low-z galaxy redshift survey complements Euclid & WFIRST
- Tests of large-scale gravitation via growth of structure & lensing
- Find X-ray counterparts in eROSITA all-sky survey

## ExoPAG: Survey Ices in Early Stages of Planet Formation

Archive
- IR spectro-photometry on Kepler & TESS host stars
- Survey $10^8$ stars - disks, hot dust, brown dwarfs, etc

## COPAG: Galaxy Evolution via Clustering Fluctuations

Archive
- Survey for $z > 7$ quasars
- Survey $10^8$ galaxies
- Galaxy cluster spectra with X-ray and mm-wave data

# What Would *You* Do with the SPHEREx Archive?

**SPHEREx science paper:**
Doré *et al*. arXiv 1412.4872 (82 citations)

## SPHEREx Archive Community Workshop

Feb 2016, California Institute of Technology

Exoplanet masses    X-ray synergies

**Charter:** Identify new science, tools and data products

Attended by over 50 non-SPHEREx scientists

**White paper:** Doré *et al*. arXiv 1606.07039 (84 pp, 68 authors)

## Astrophysics with the SPHEREx All-Sky Spectral Survey

A Community Workshop on the Scientific Synergies Between the SPHEREx Survey and Concurrent Astronomical Observatories

January 30-31, 2018

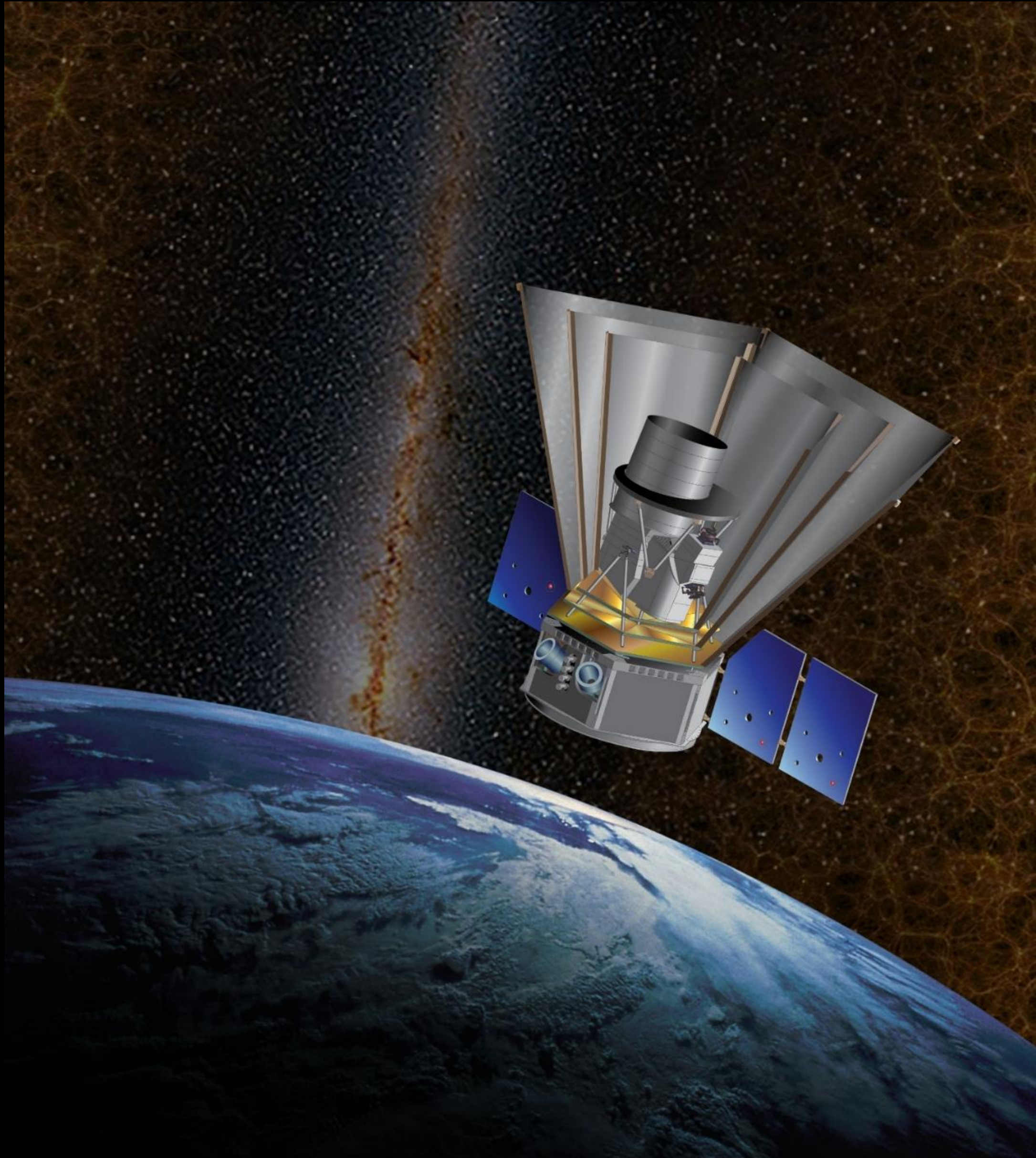
Harvard-Smithsonian Center for Astrophysics

*SPHEREx AAS poster session Thursday!*

# Thanks for Listening!

## SPHEREX Science Team

| | | |
|---|---|---|
| **Jamie Bock** | Caltech/JPL | Principal Investigator |
| **Matt Ashby** | CfA | Interstellar ices |
| **Peter Capak** | IPAC | Galaxy redshifts |
| **Asantha Cooray** | UC Irvine | Extragalactic backgrounds |
| **Elisabeth Krause** | JPL/U. Arizona | Cosmology |
| **Brendan Crill** | JPL | Pipeline architect |
| **Olivier Doré** | JPL | Project Scientist |
| **Chris Hirata** | Ohio State | Cosmology |
| **Woong-Seob Jeong** | KASI | KASI PI |
| **Phil Korngut** | Caltech | Instrument Scientist |
| **Dae-Hee Lee** | KASI | Instrumentation |
| **Phil Mauskopf** | Arizona State | Survey planning |
| **Gary Melnick** | CfA | Interstellar ices |
| **Roland dePutter** | Caltech | Cosmology |
| **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 |
| **Mike Zemcov** | RIT | Data pipeline |
| | | |
| **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 |

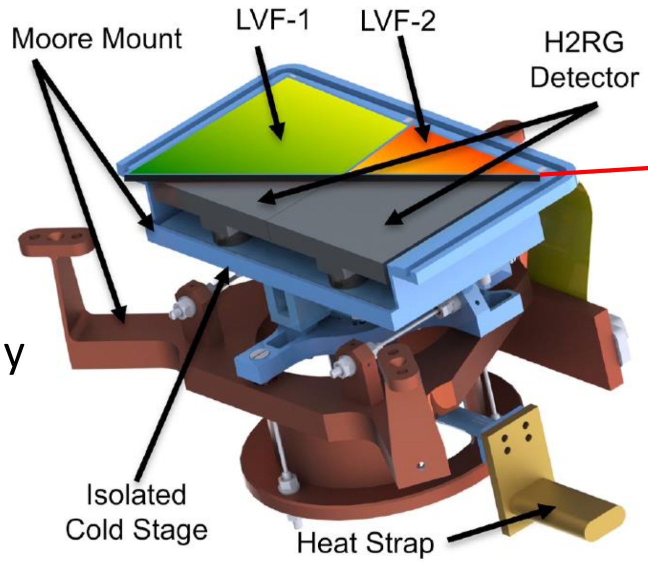


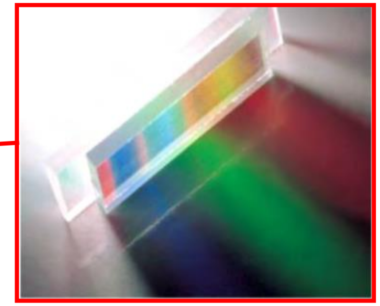
spherex.caltech.edu

# Backup

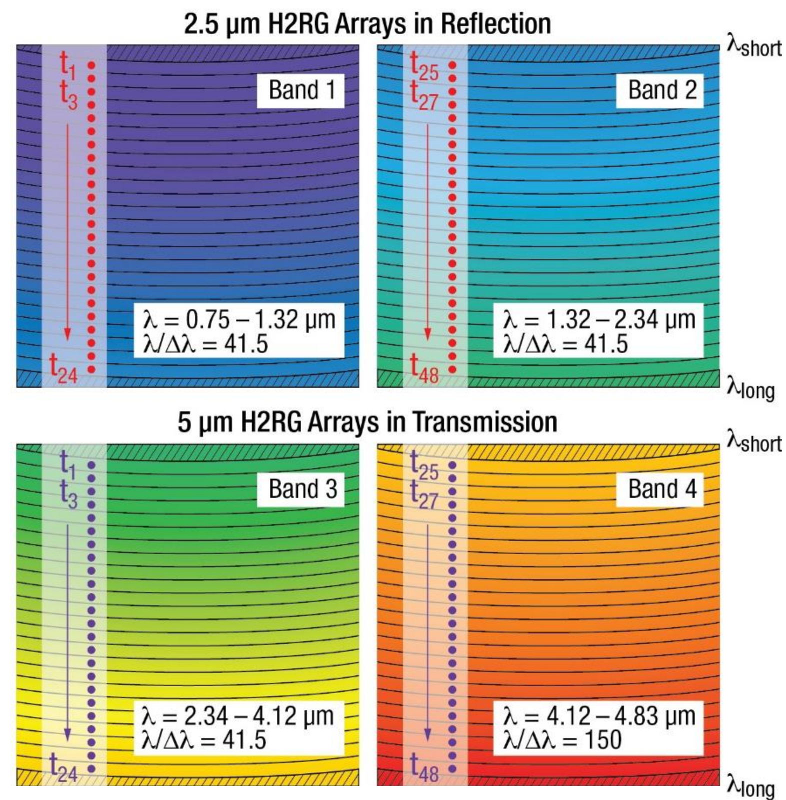
# High-Throughput LVF Spectrometer

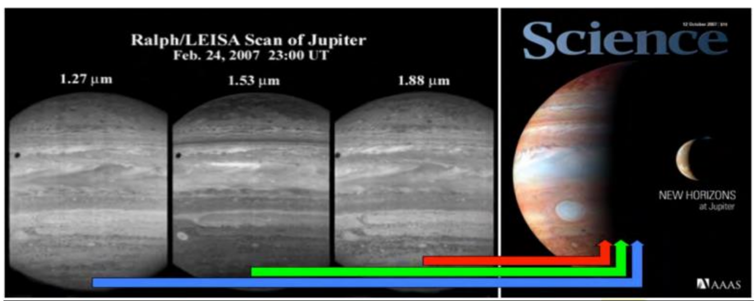
Focal Plane Assembly

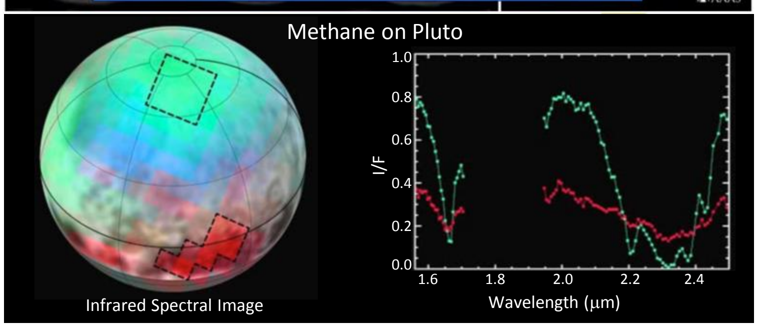


Linear Variable Filter



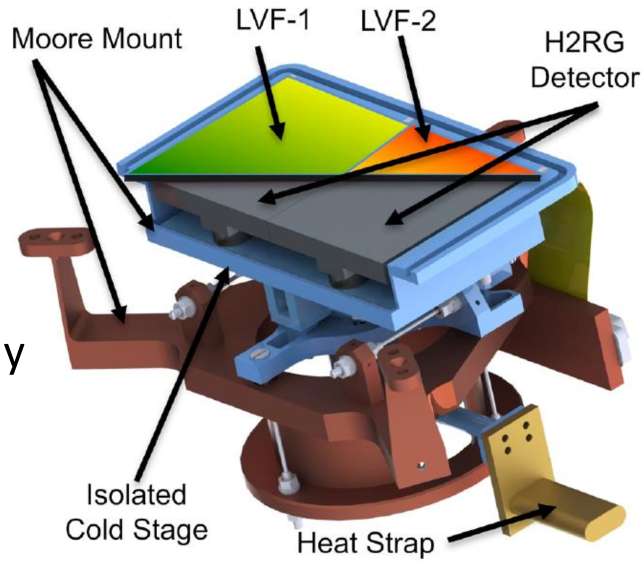



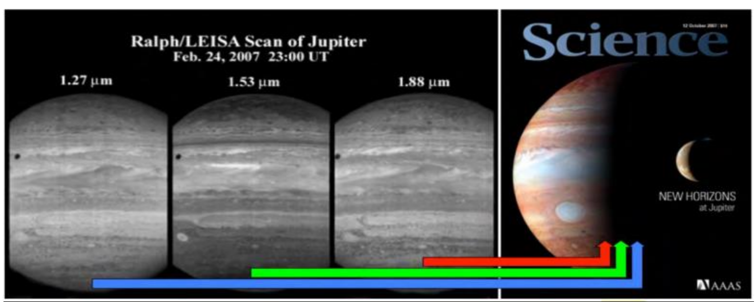

LVFs used on ISOCAM, HST-WFPC2, New Horizons LEISA, and OSIRIX-Rex

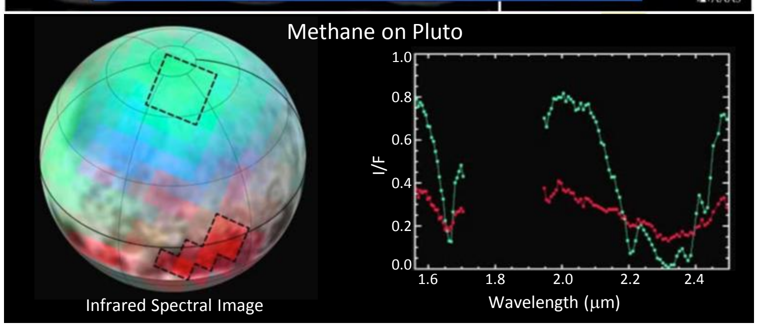
Spectra obtained by stepping source over the FOV in multiple images: **no moving parts**

# High-Throughput LVF Spectrometer

Focal Plane Assembly

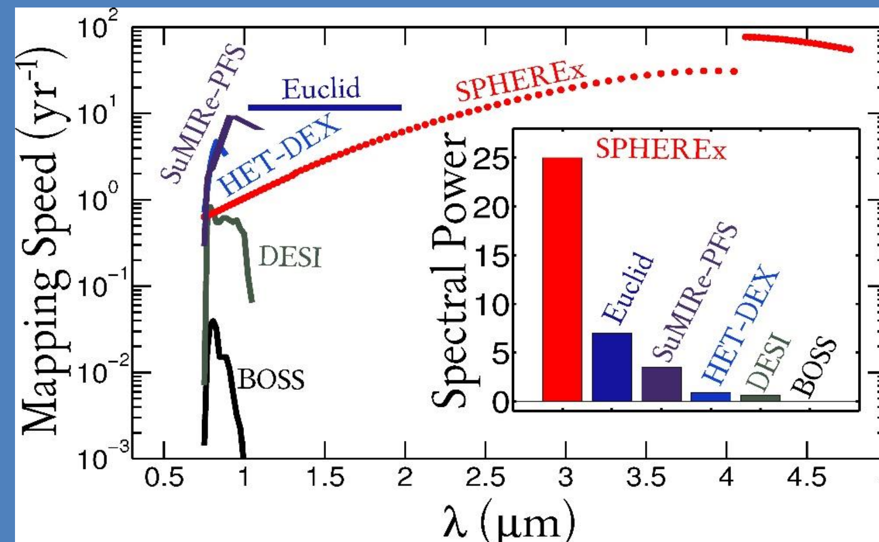



LVFs used on ISOCAM, HST-WFPC2, New Horizons LEISA, and OSIRIX-Rex

## How Does LVF Spectroscopy Compare?




**Speed** ≡ 1/(time to map full sky to $\delta F = 10^{-18}$ Wm$^{-2}$)

- Speed means how quickly an instrument maps the sky to detect a line at a fixed wavelength

**Power** ≡ ∫ Speed $(d\lambda/\lambda)$

- Power means how quickly an instrument maps the sky to detect a line over a log spectral band

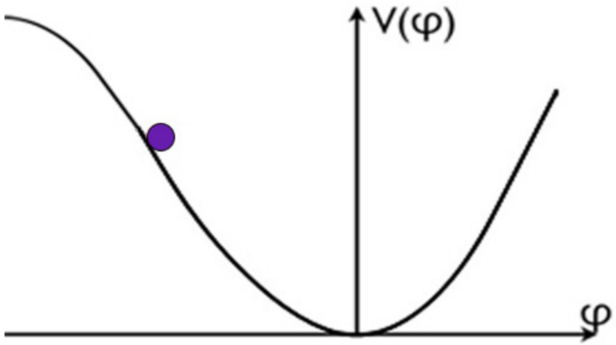
SPHEREx performs well, especially in IR

- despite power scaling with telescope diameter as $d^2$
- large throughput (AΩ product)
- photon noise limited with low space backgrounds

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

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

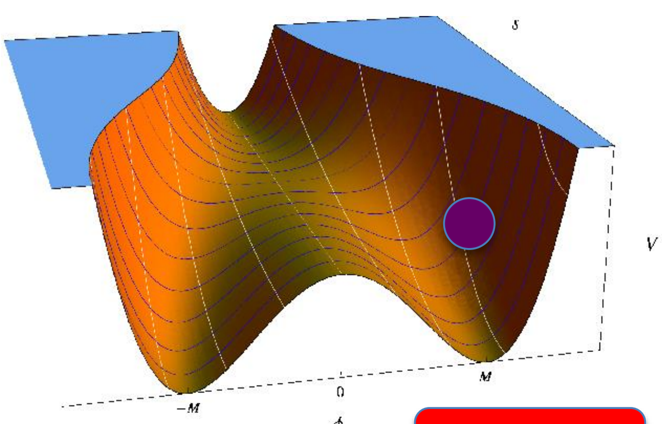
## Single-Field Inflation:



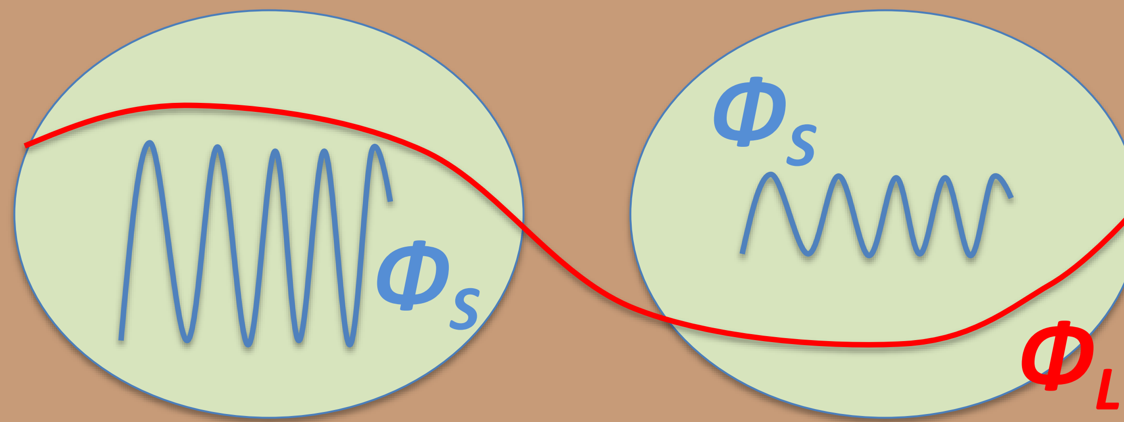

*Squeezed limit consistency condition by Maldacena (2003):*

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

## Multi-Field Inflation:




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




### Non-Gaussianity Produces Two Signatures

**Enhanced power on large spatial scales $\Phi_L$**

**Modulated small-scale power $\Phi_S$ on large scales $\Phi_L$ due to non-linear mode coupling**

- measured with power spectrum and bispectrum

# Redshifts with SPHEREx

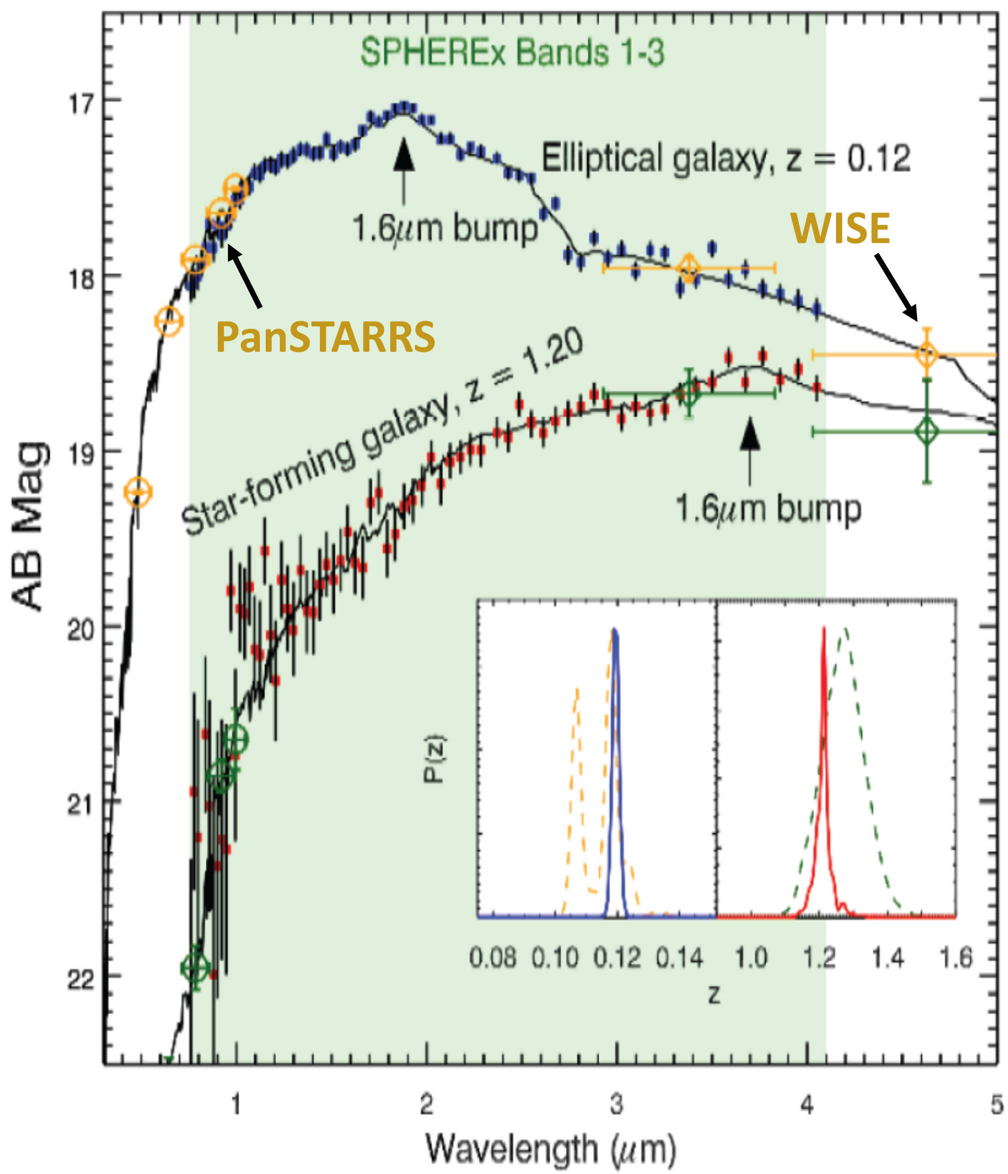
We extract the spectra of *known* sources using the full-sky catalogs from PanSTARRS/DES.
Controls blending and confusion

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)

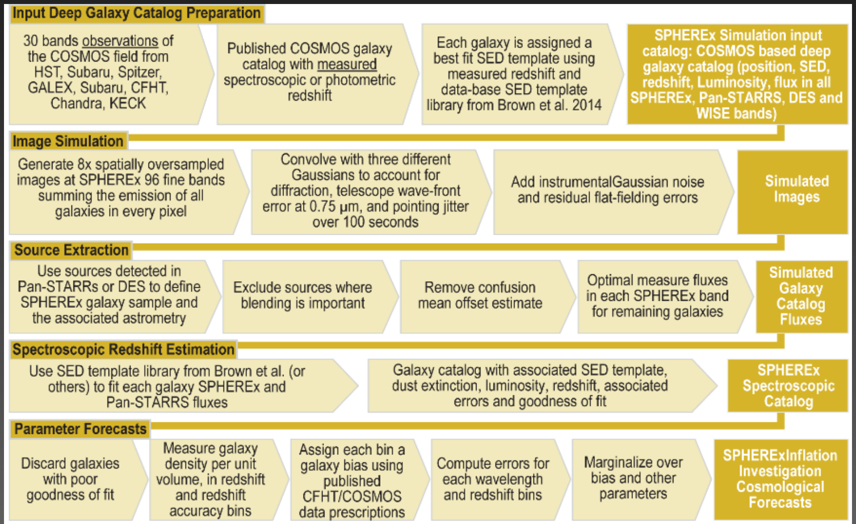
We simulated this process using the COSMOS data set using the same process as Euclid/WFIRST (Capak et al.).

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

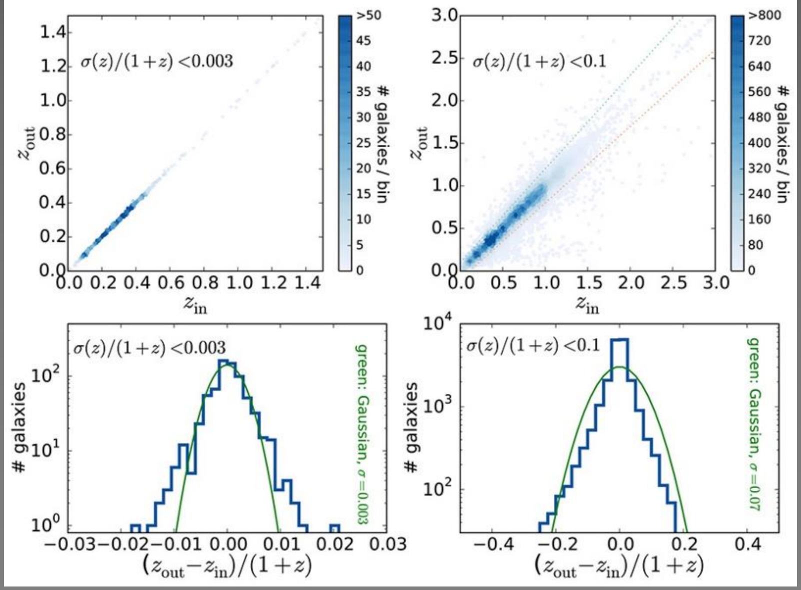


# Testing Redshift Reliability

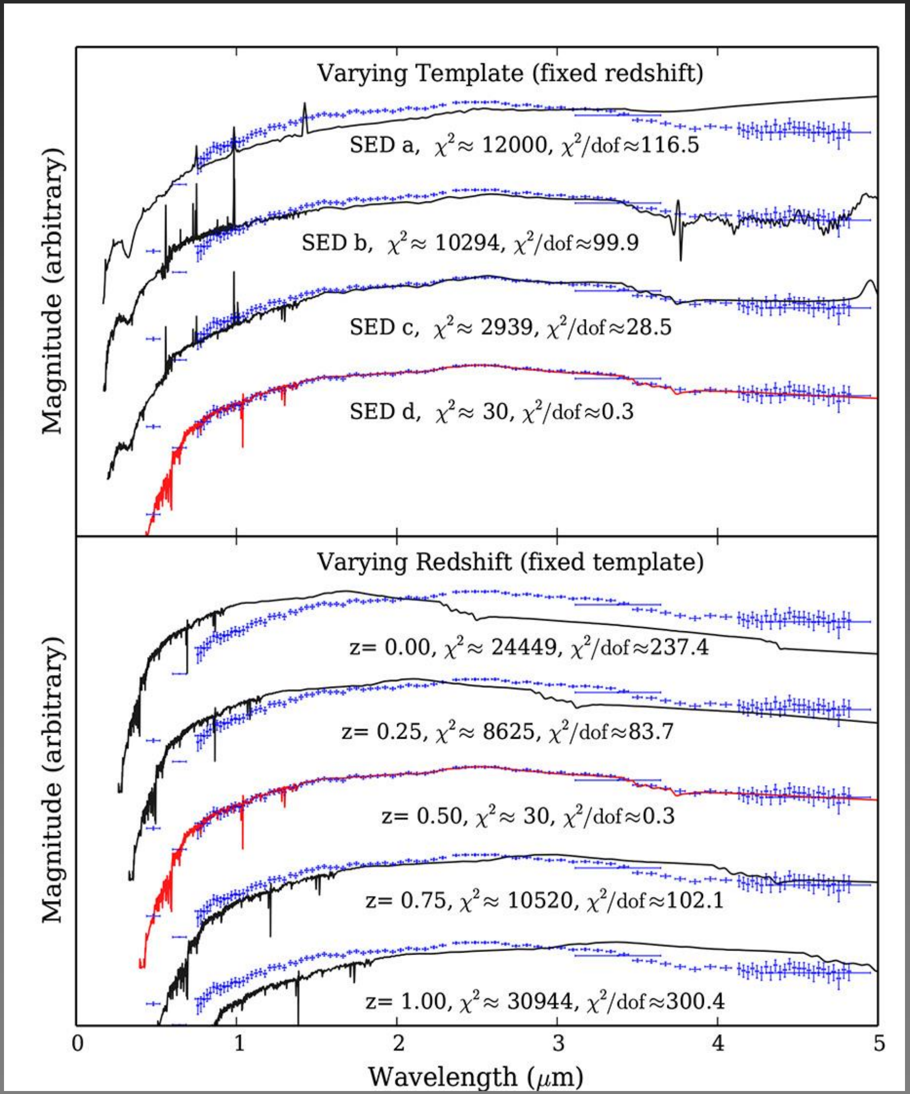
## Inject Real Galaxies into SPHEREx Pipeline




## Resulting Redshift Errors

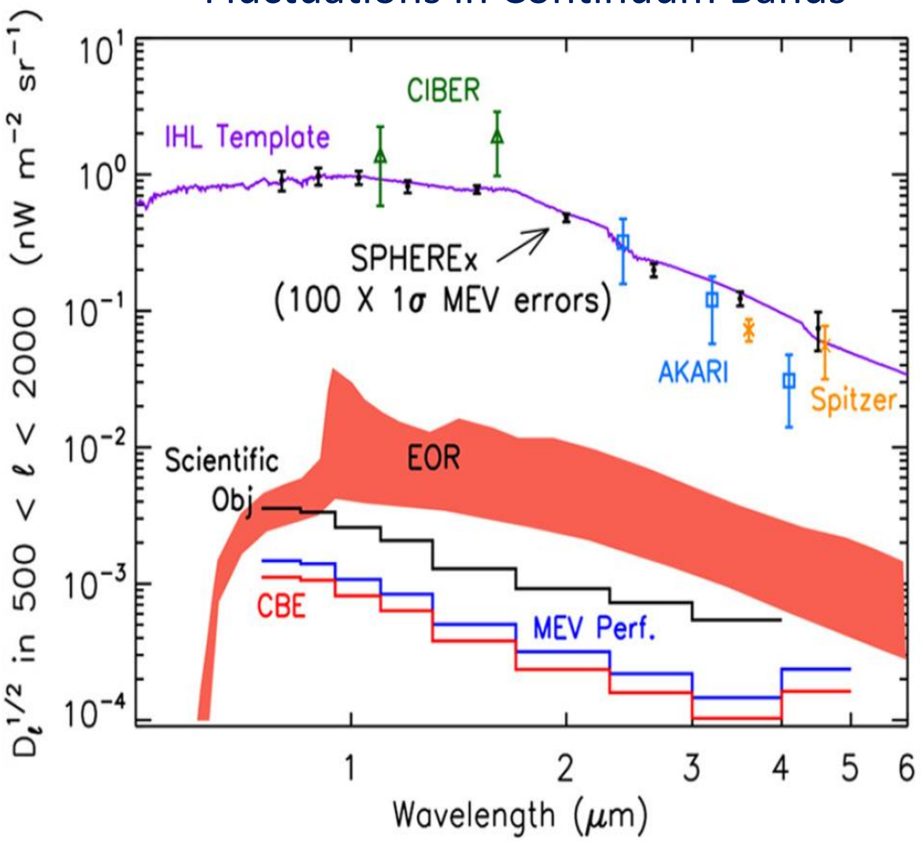



## Example Template and Redshift Fits



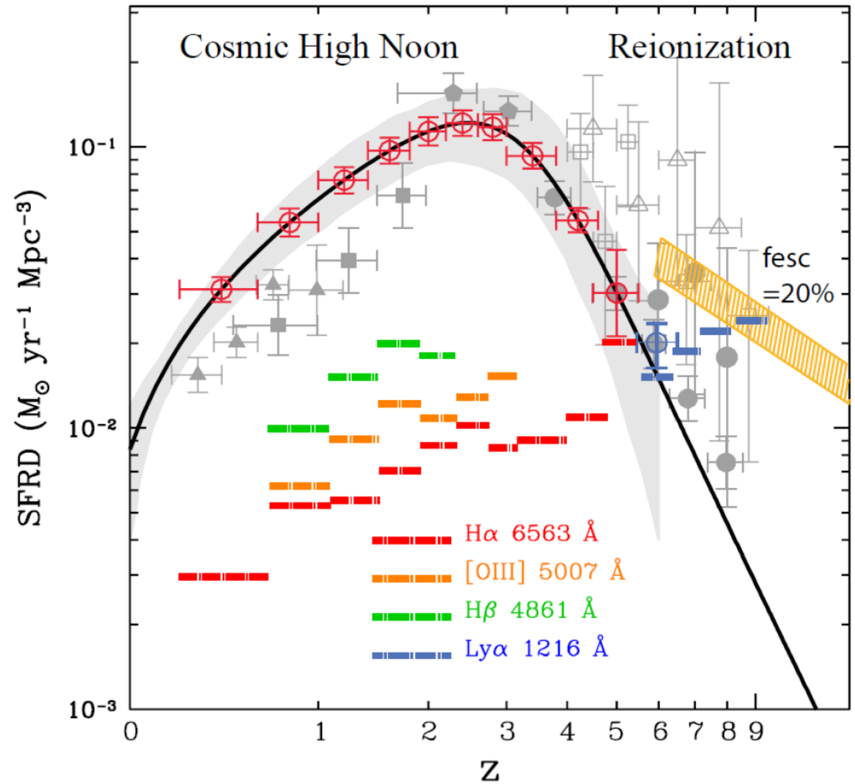
# SPHEREx Measures Large-Scale Fluctuations

## 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

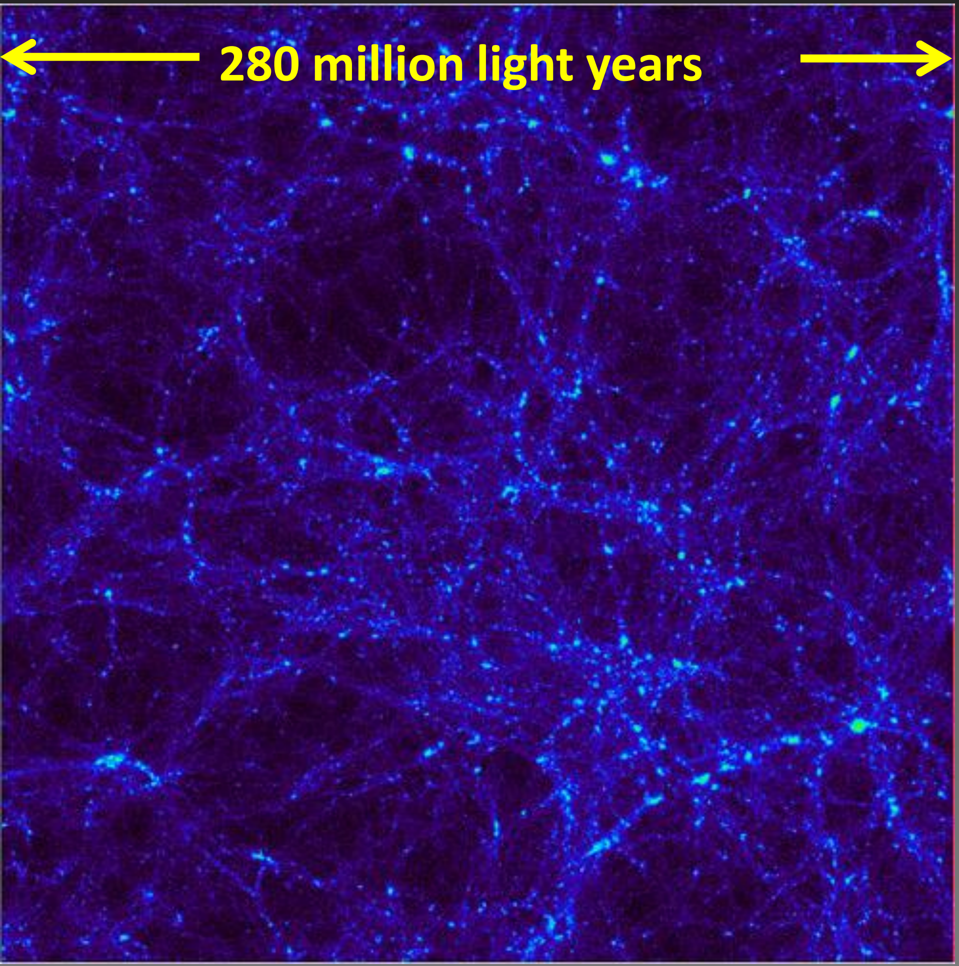
## Fluctuations in Lines



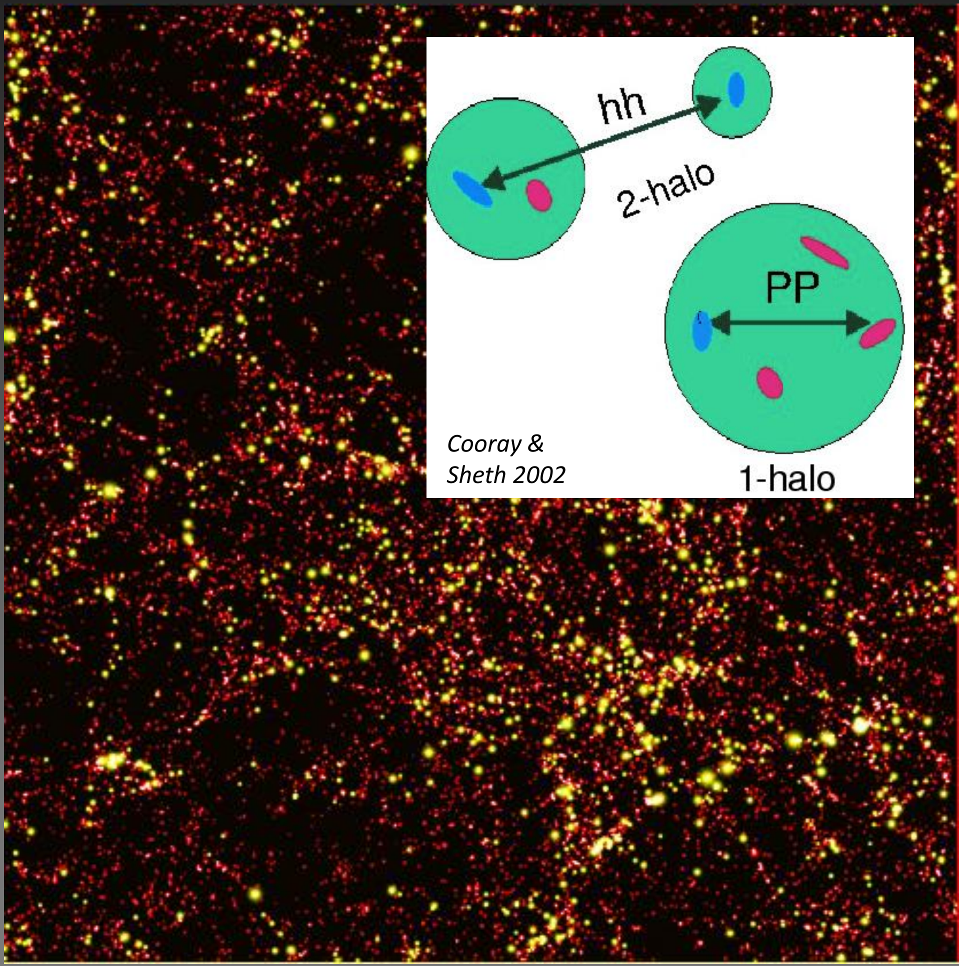

- Emission lines encode clustering signal at each redshift over cosmic history
- Amplitude gives line light production
- Multiple lines trace star formation history
  - High S/N in Hα for z < 5; OIII and Hβ for z < 3
  - Lyα probes EoR models for z > 6

# Relating Galaxies to Dark Matter

Dark Matter from Numerical Simulation (z = 2)




Dark Matter Clumps Color-Coded by Mass



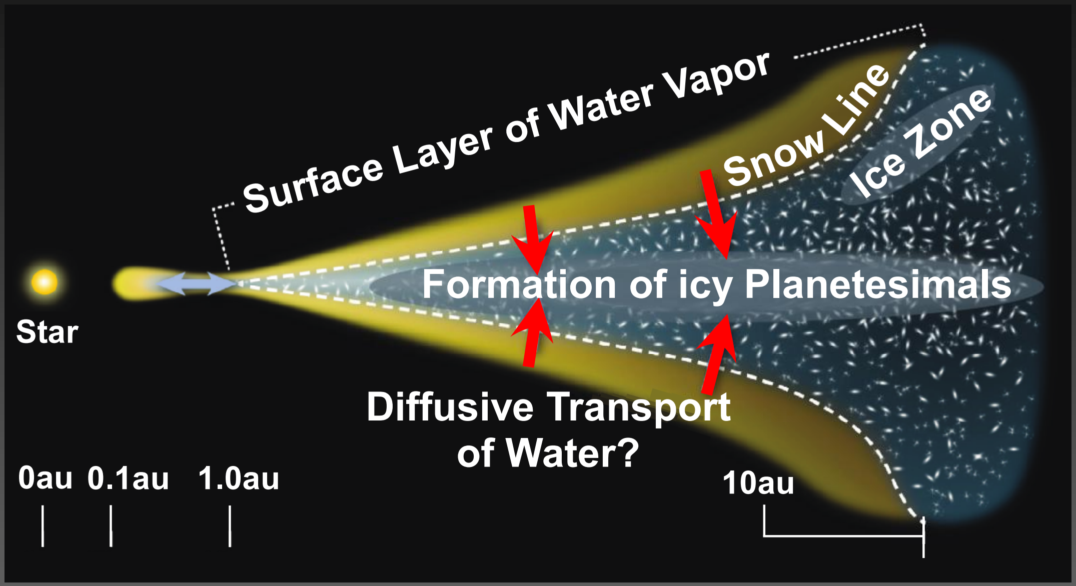

**Large scales:** Light traces dark matter
**Med scales:** Non-linear clustering
**Small scales:** Poisson fluctuations

Measure light production
Galaxy formation within a halo
Galaxy counts

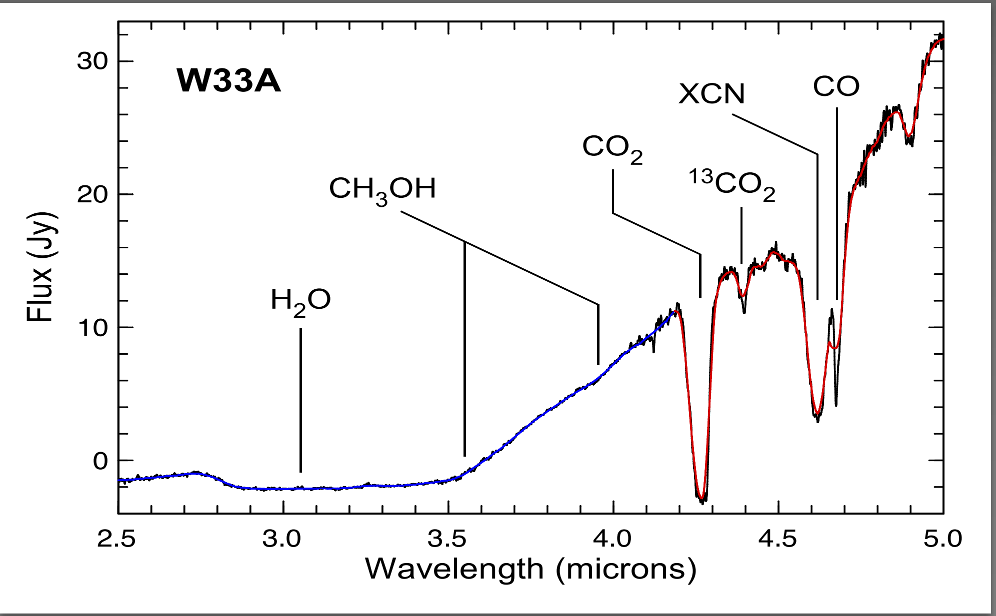
# Why Study Ices?

- **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 $\lambda$s to study ices: 2.5 - 5 $\mu$m**
  - 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

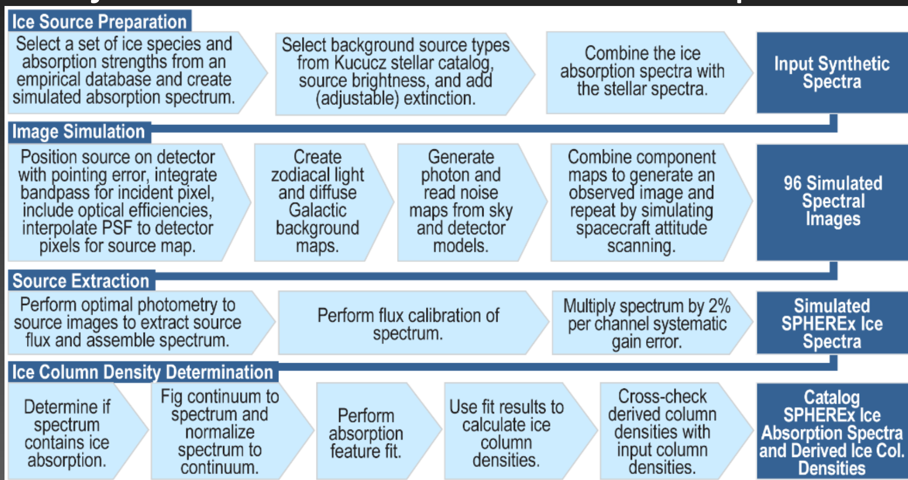



ISO absorption spectrum

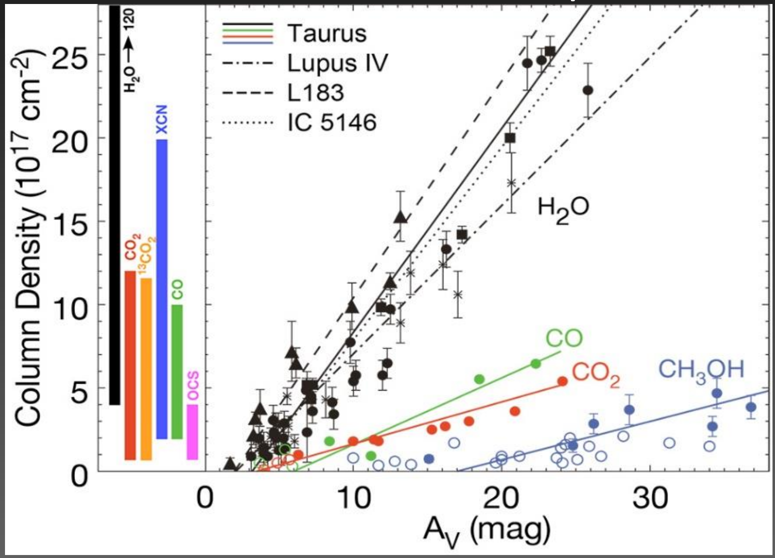


# SPHEREx Galactic Ice Survey

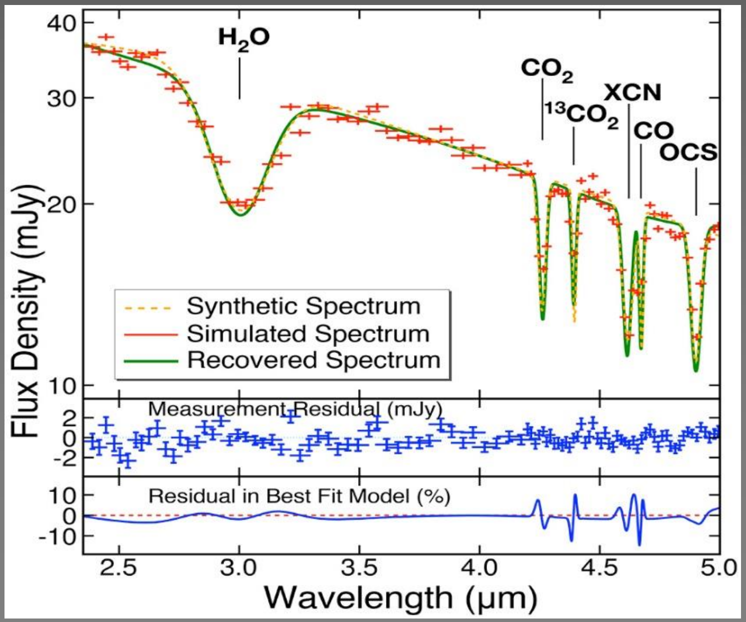
## Inject Simulated Ice Sources into Pipeline




## Reliable Columns of Ice Species




## Estimate Errors on Absorption Depth




## Expect ~1 Million High-Quality Ice Detections