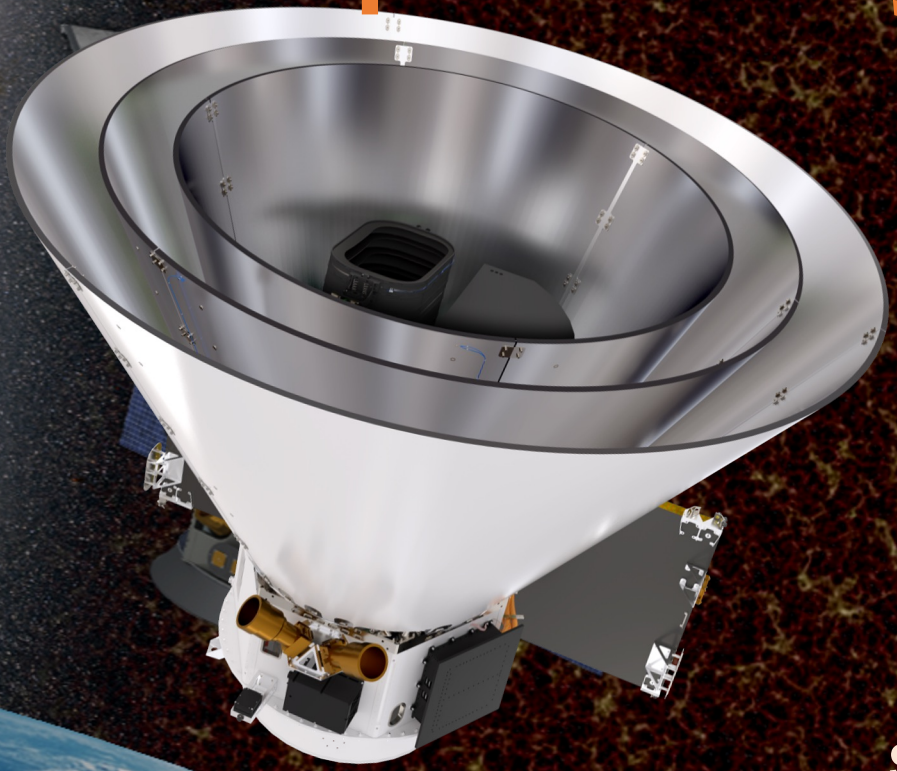
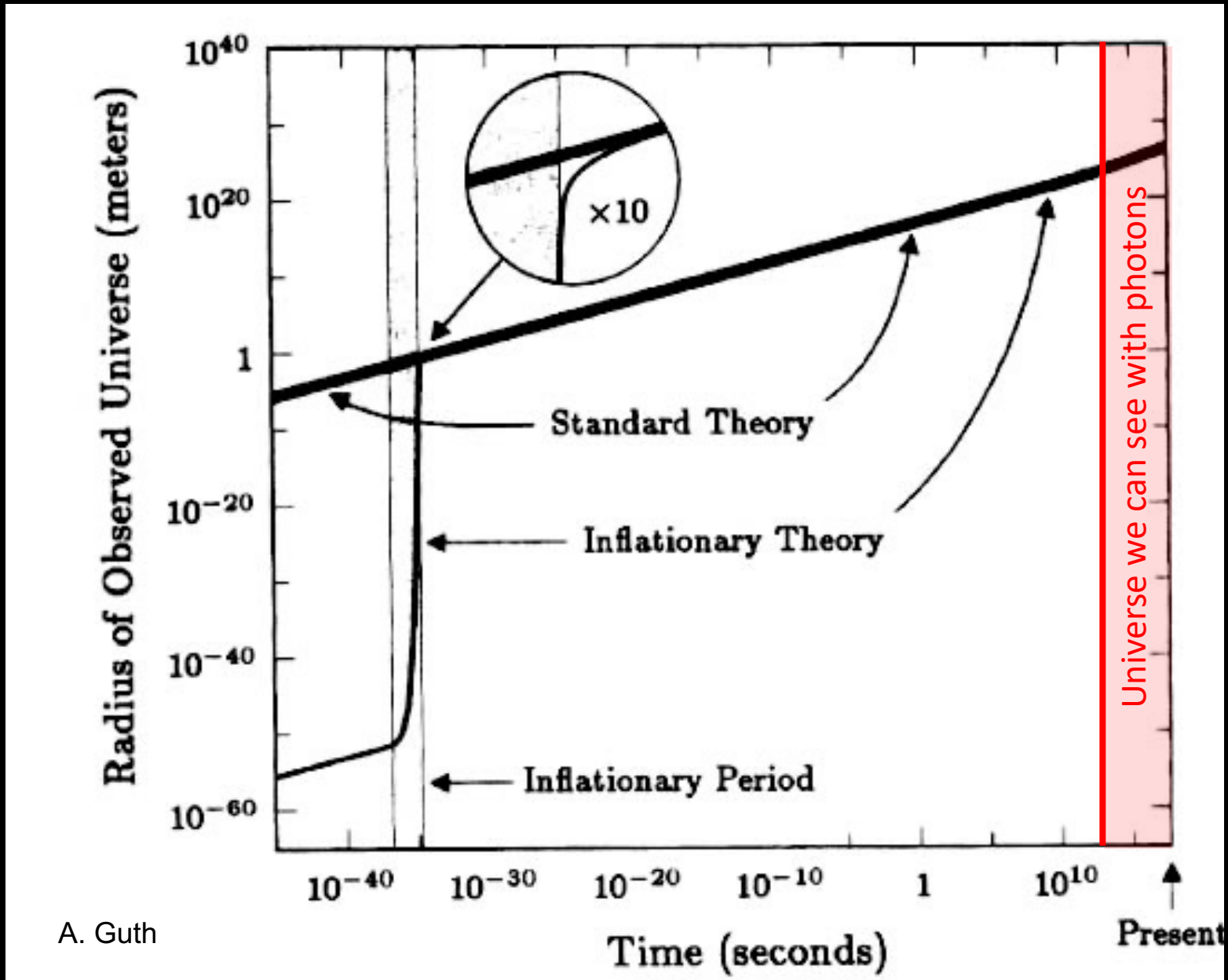
SPHEREx: NASA's Near-Infrared Spectroscopic All-Sky Survey



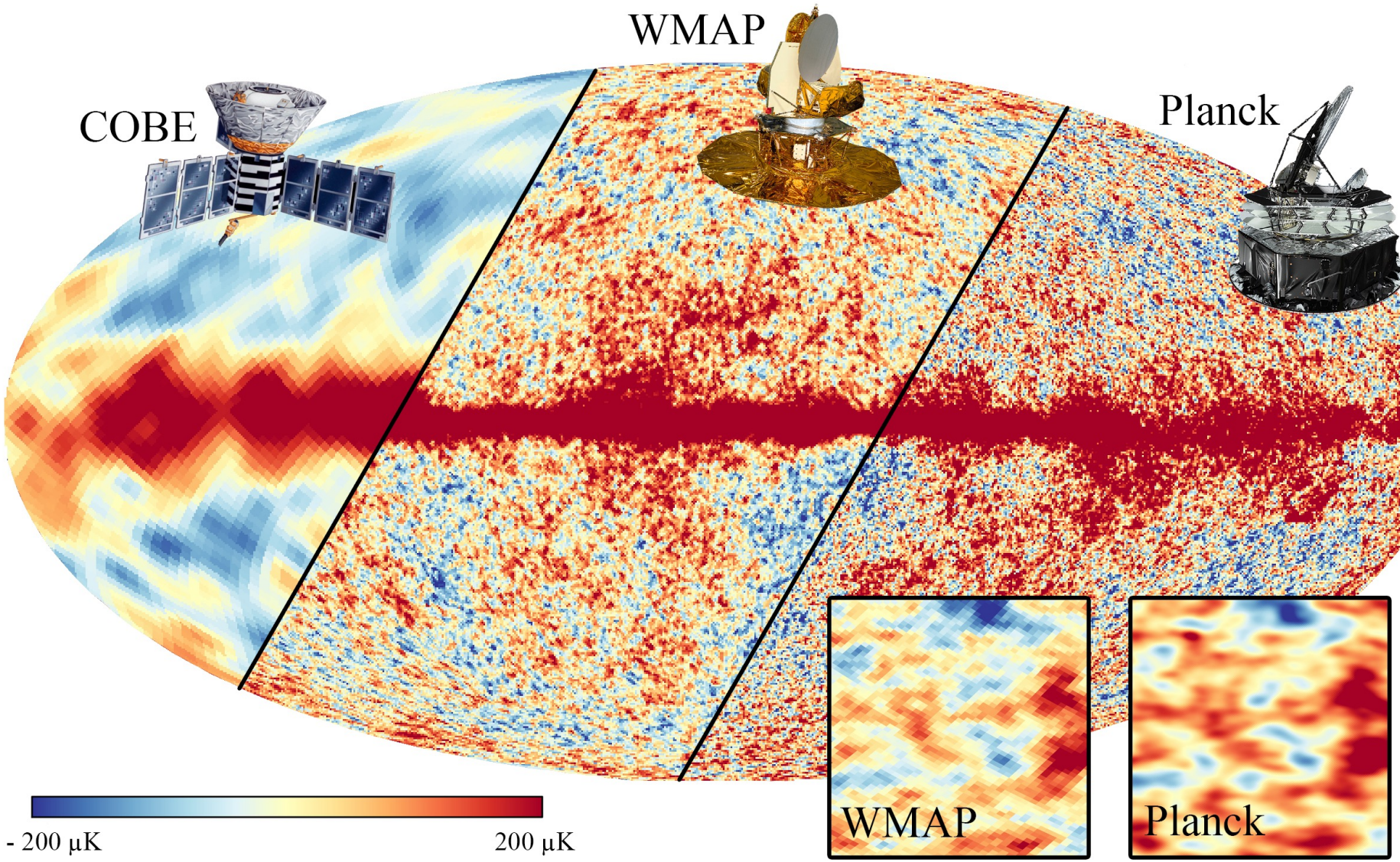
Brendan Crill
SPHEREx Pipeline Architect
Jet Propulsion Laboratory / California Institute of Technology

June 9, 2023

Inflation

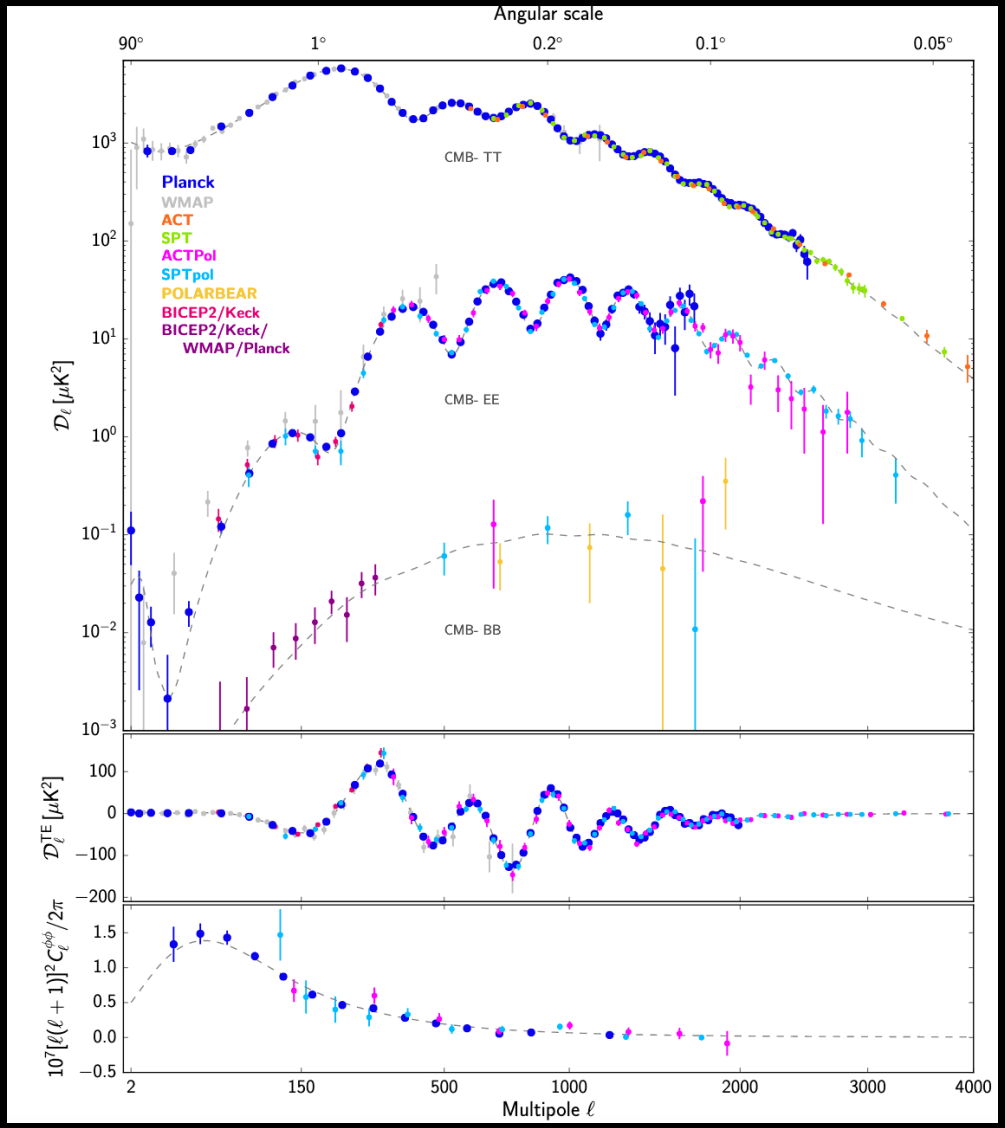


A. Guth



J. Gudmundsson

6 parameter ΛCDM model: now 5 of 6 known to better than 1%



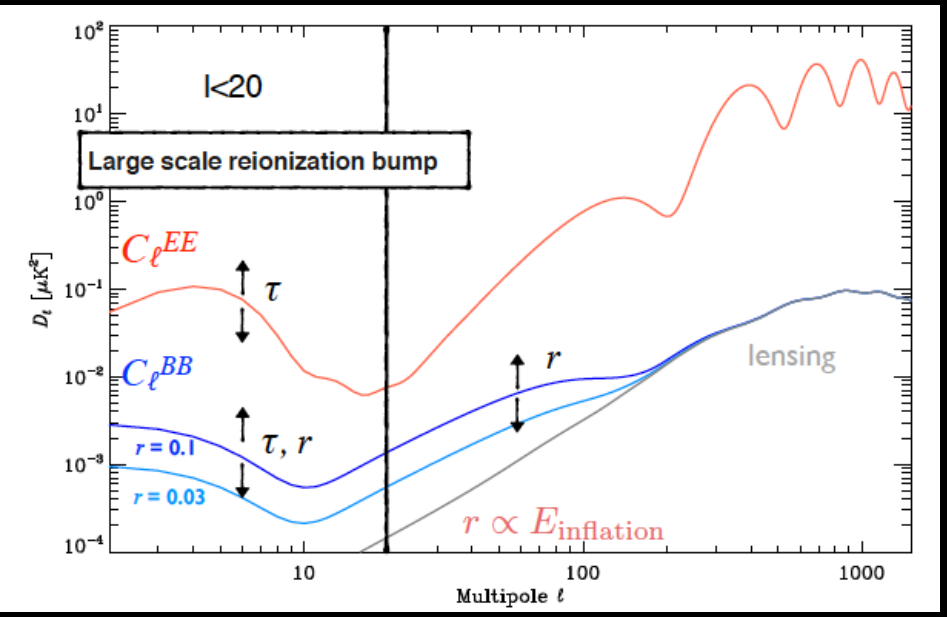
Temperature and polarization fluctuations

Temperature / polarization cross correlation

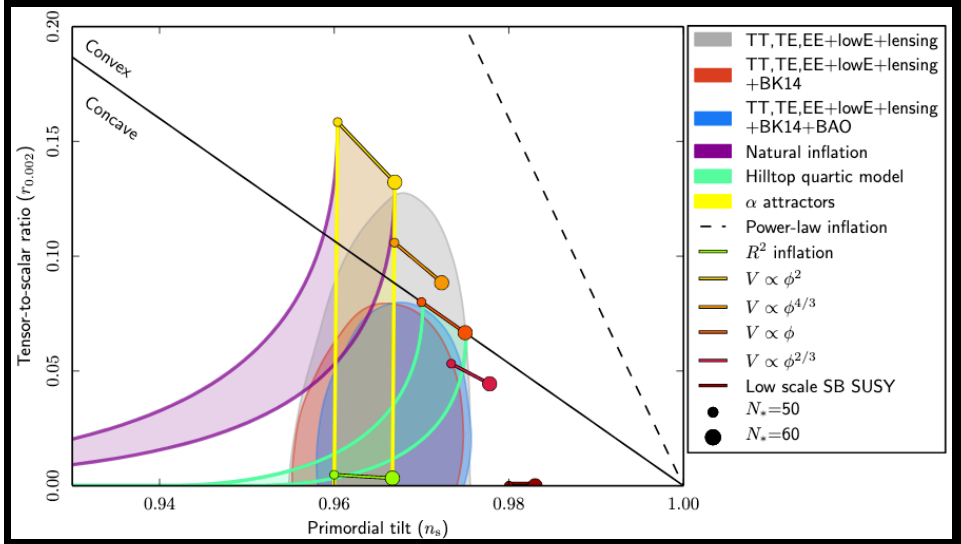
Weak lensing of CMB

Planck Collaboration (2019)

Primordial B-mode polarization

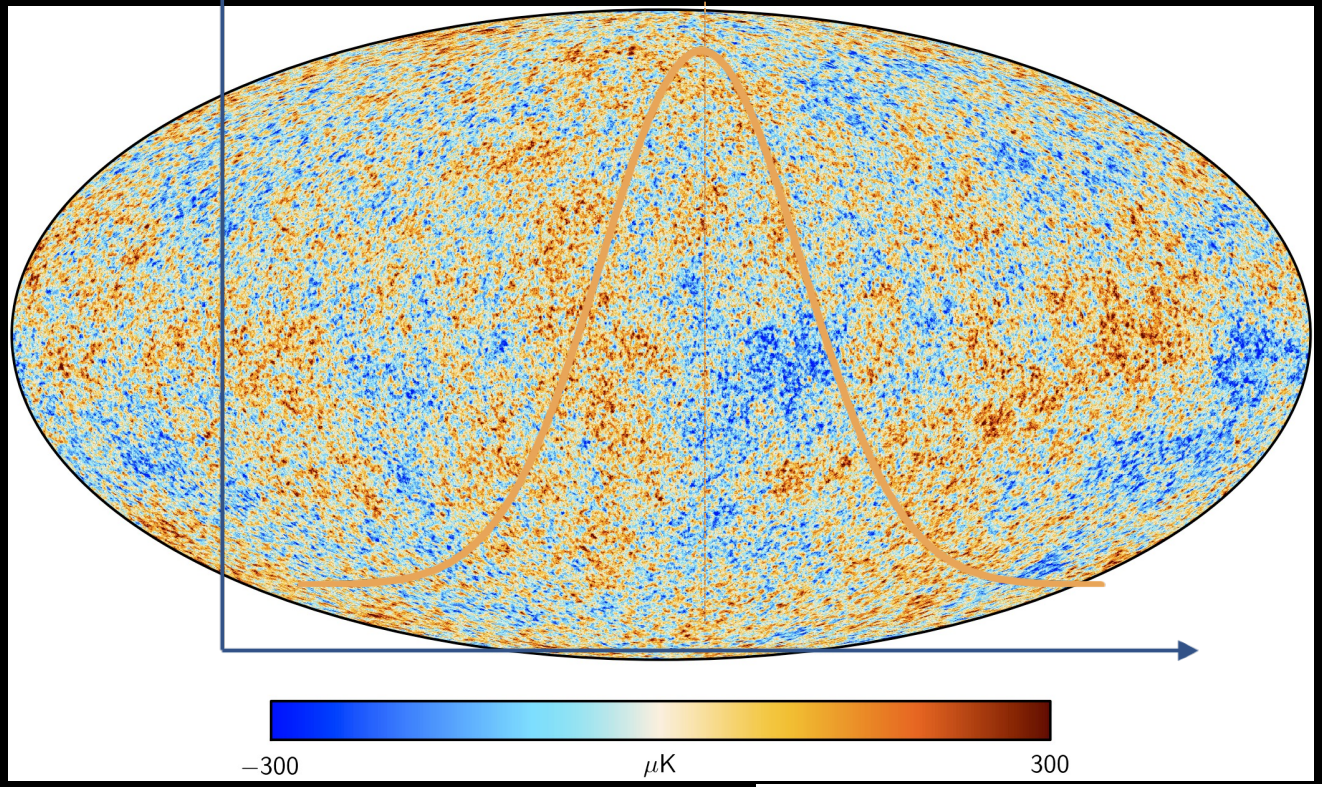


A. Mangilli



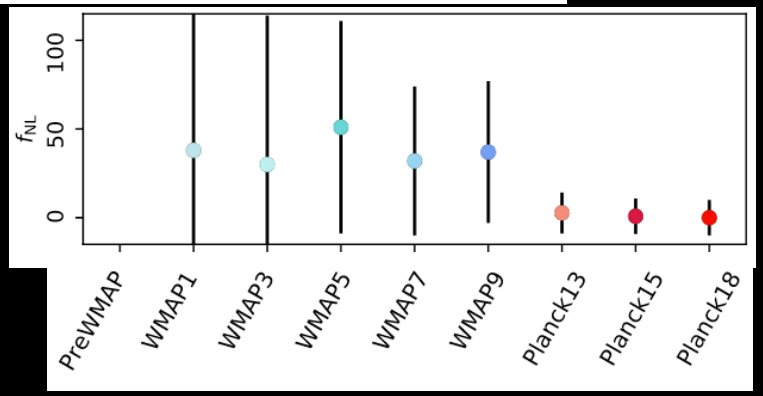
Planck Collaboration (2019)

Were the primoridal fluctuations Gaussian-distributed?



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

CMB: $f_{NL} < 10.8$ (2σ)
(CMB Cosmic Variance 1σ limit is around f_{NL} of ~3-4)



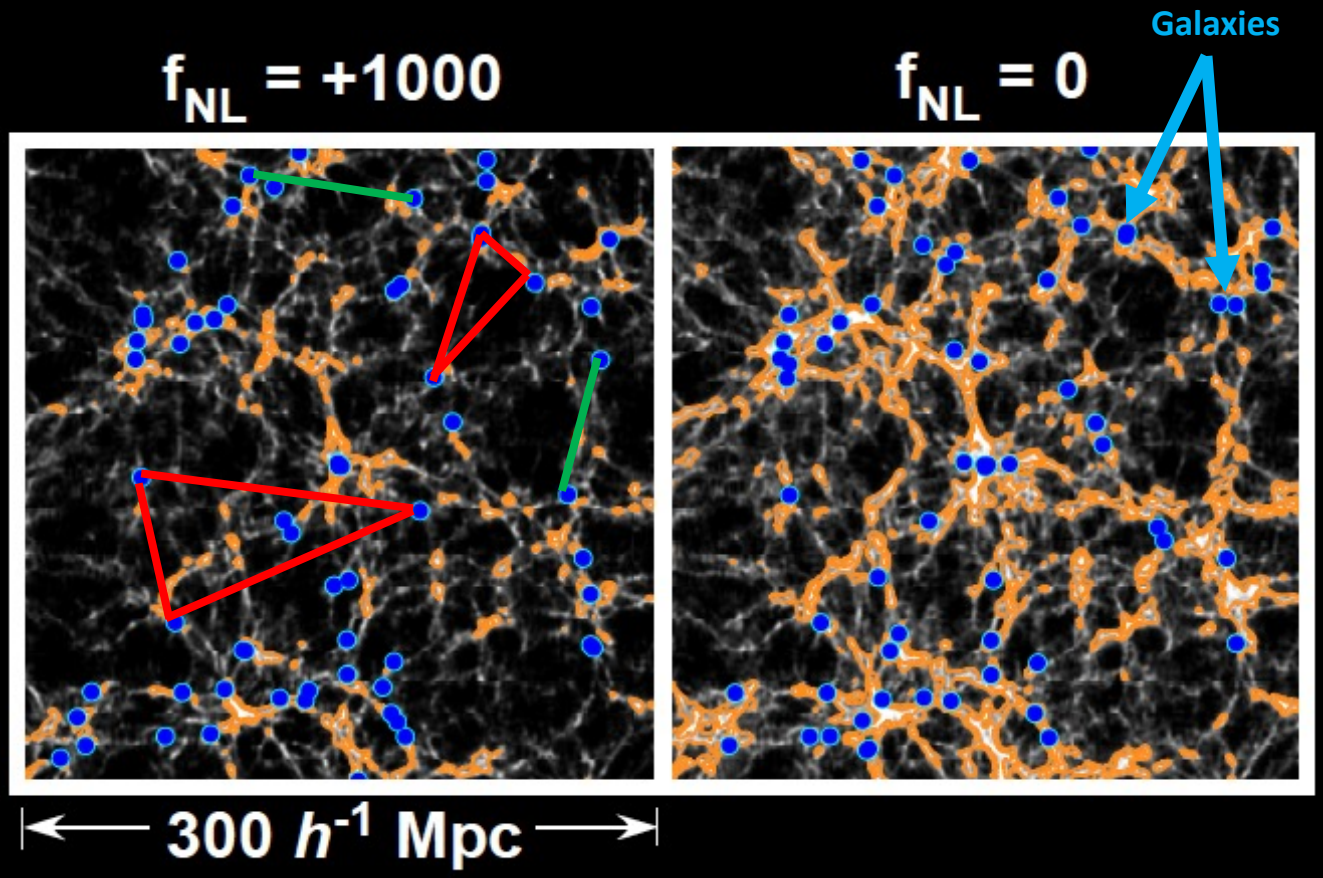
Planck Collaboration (2019)

Gaussianity can also be probed by Large Scale Structure measurements

Quantified by 3D correlations between galaxies:

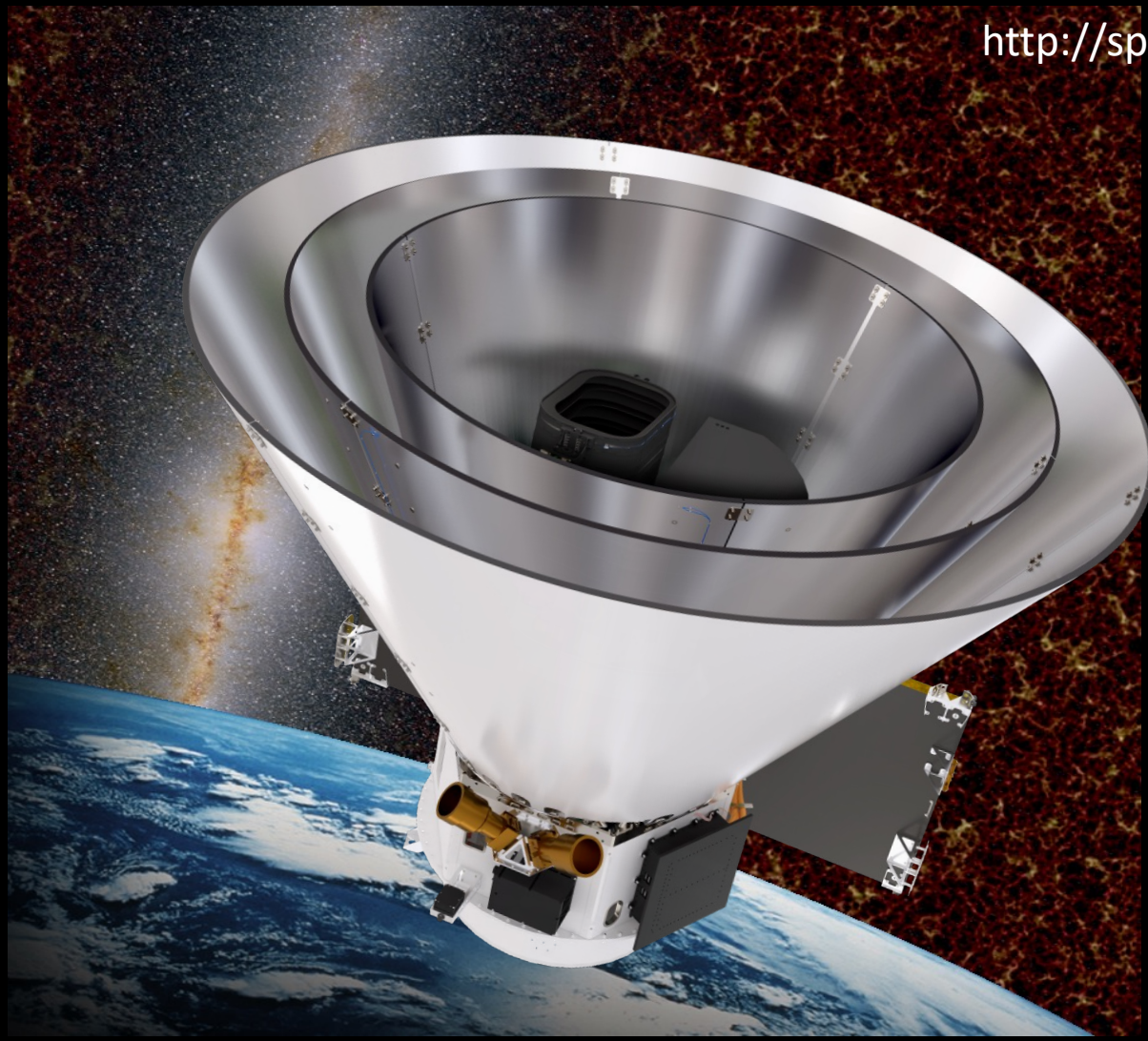
Pairs (2-point func)
- Power spectrum

Triples (3-point func)
- Bispectrum



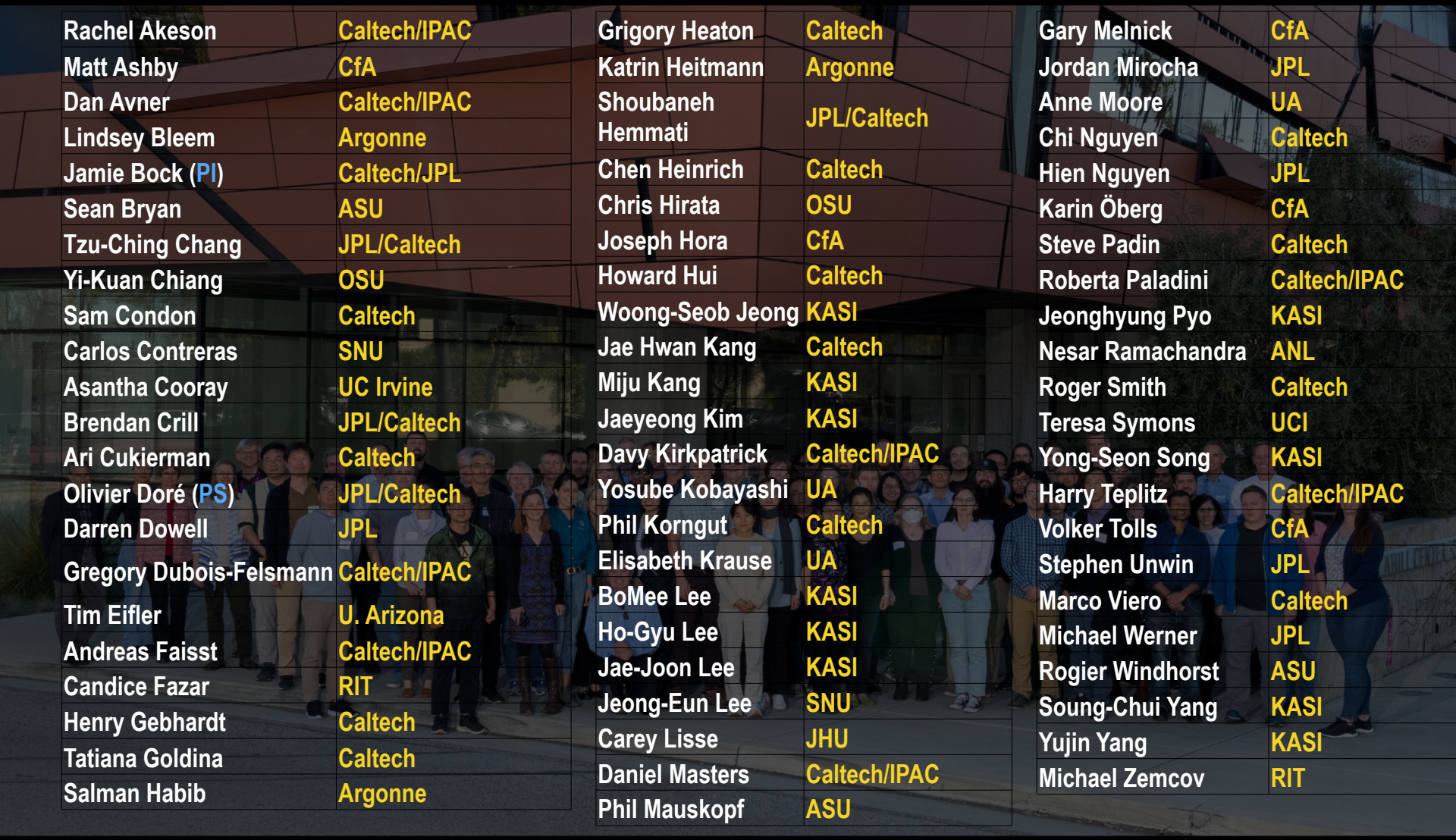
SPHEREx: An All-Sky Spectral Survey

http://spherex.caltech.edu



Jet Propulsion Laboratory
California Institute of Technology

SPHEREx Science Team



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Jamie Bock (PI)	Caltech/JPL
Sean Bryan	ASU
Tzu-Ching Chang	JPL/Caltech
Yi-Kuan Chiang	OSU
Sam Condon	Caltech
Carlos Contreras	SNU
Asantha Cooray	UC Irvine
Brendan Crill	JPL/Caltech
Ari Cukierman	Caltech
Olivier Doré (PS)	JPL/Caltech
Darren Dowell	JPL
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Candice Fazar	RIT
Henry Gebhardt	Caltech
Tatiana Goldina	Caltech
Salman Habib	Argonne
Grigory Heaton	Caltech
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Chen Heinrich	Caltech
Chris Hirata	OSU
Joseph Hora	CfA
Howard Hui	Caltech
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Jaeyeong Kim	KASI
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Phil Korngut	Caltech
Elisabeth Krause	UA
BoMee Lee	KASI
Ho-Gyu Lee	KASI
Jae-Joon Lee	KASI
Jeong-Eun Lee	SNU
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Gary Melnick	CfA
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Anne Moore	UA
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Marco Viero	Caltech
Michael Werner	JPL
Rogier Windhorst	ASU
Soung-Chui Yang	KASI
Yujin Yang	KASI
Michael Zemcov	RIT

SPHEREx Team

SPHEREx's Three Science Investigations

How did the Universe begin?

Probe inflation through studies of primordial non-Gaussianity

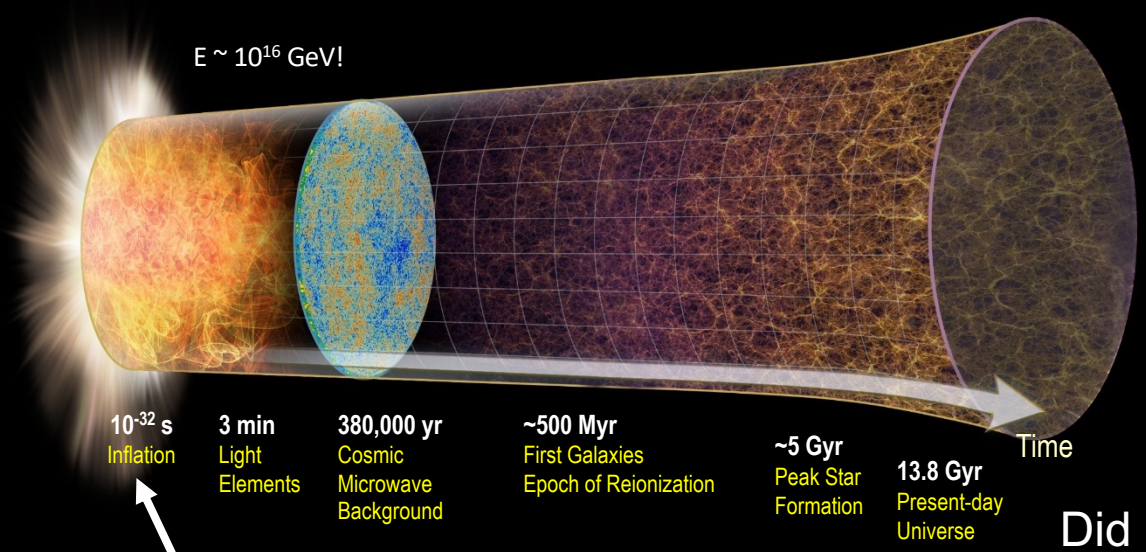
How did Galaxies begin?

Study the history of the cosmic light production through NIR background fluctuations

What are the conditions for Life to begin?

Survey the Milky Way for water and other Biogenic Ices

How did the Universe Begin?

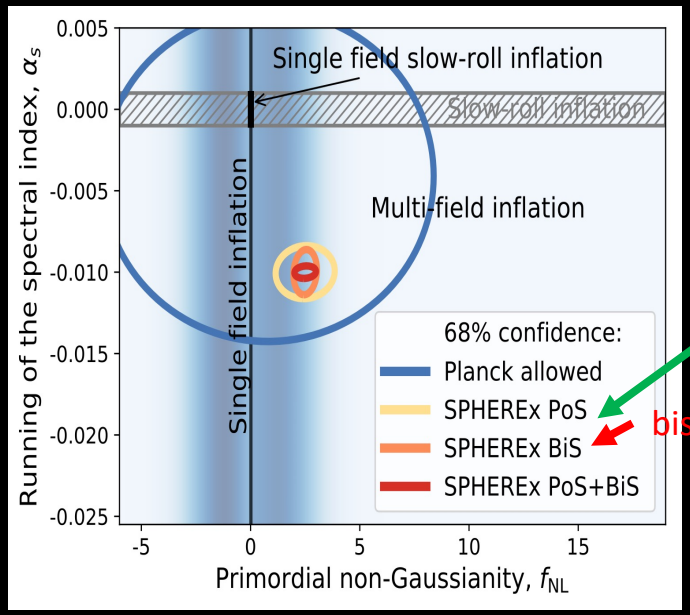


2020 Astro Decadal:
"The search for primordial non-Gaussianity, either to detect a signal or to constrain f_{NL} to be below 1… is particularly important"

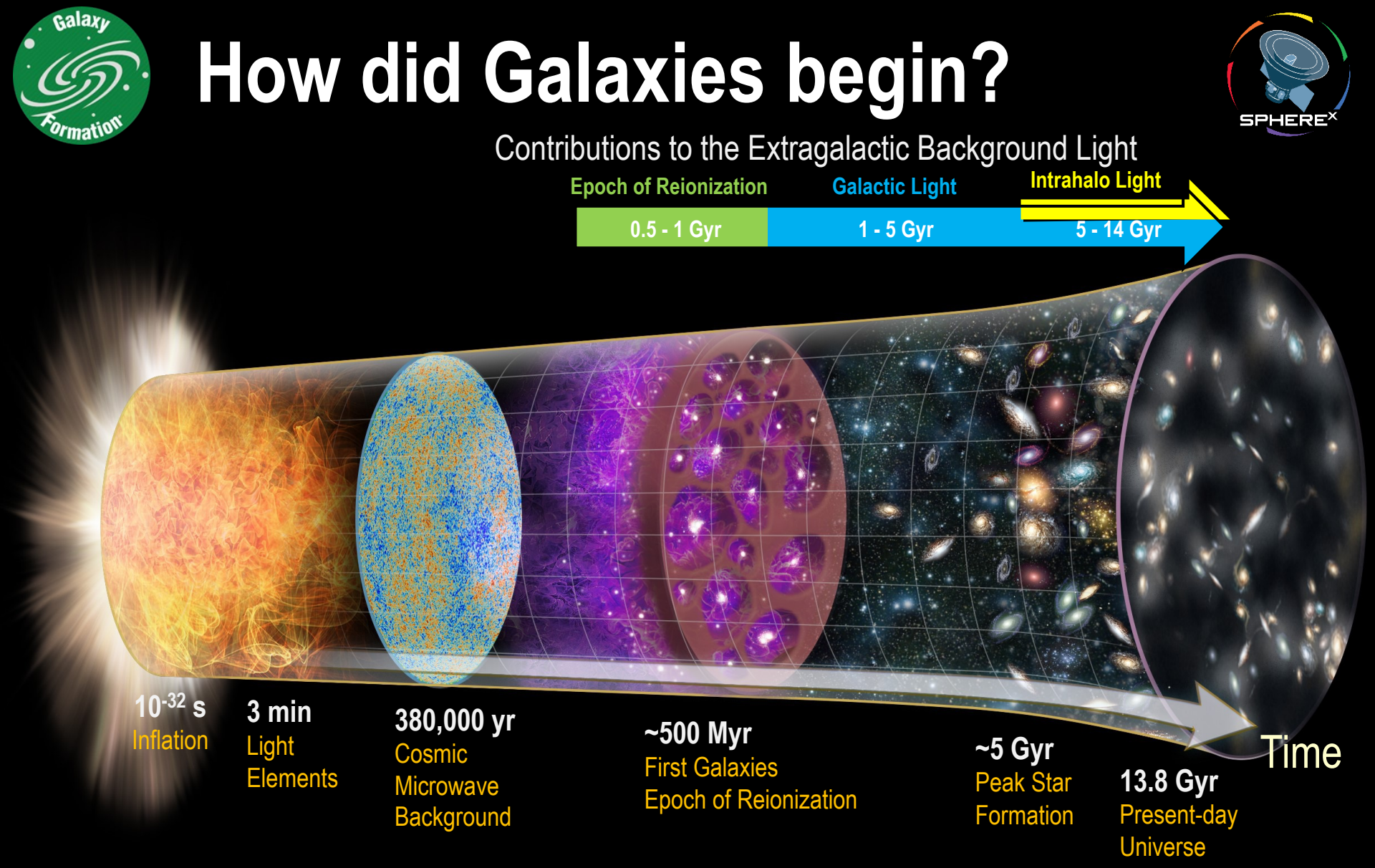
Probing ***Inflation*** with Non-Gaussianity (f_{NL})

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

Did Multiple Fields Drive Inflation?



How did Galaxies begin?

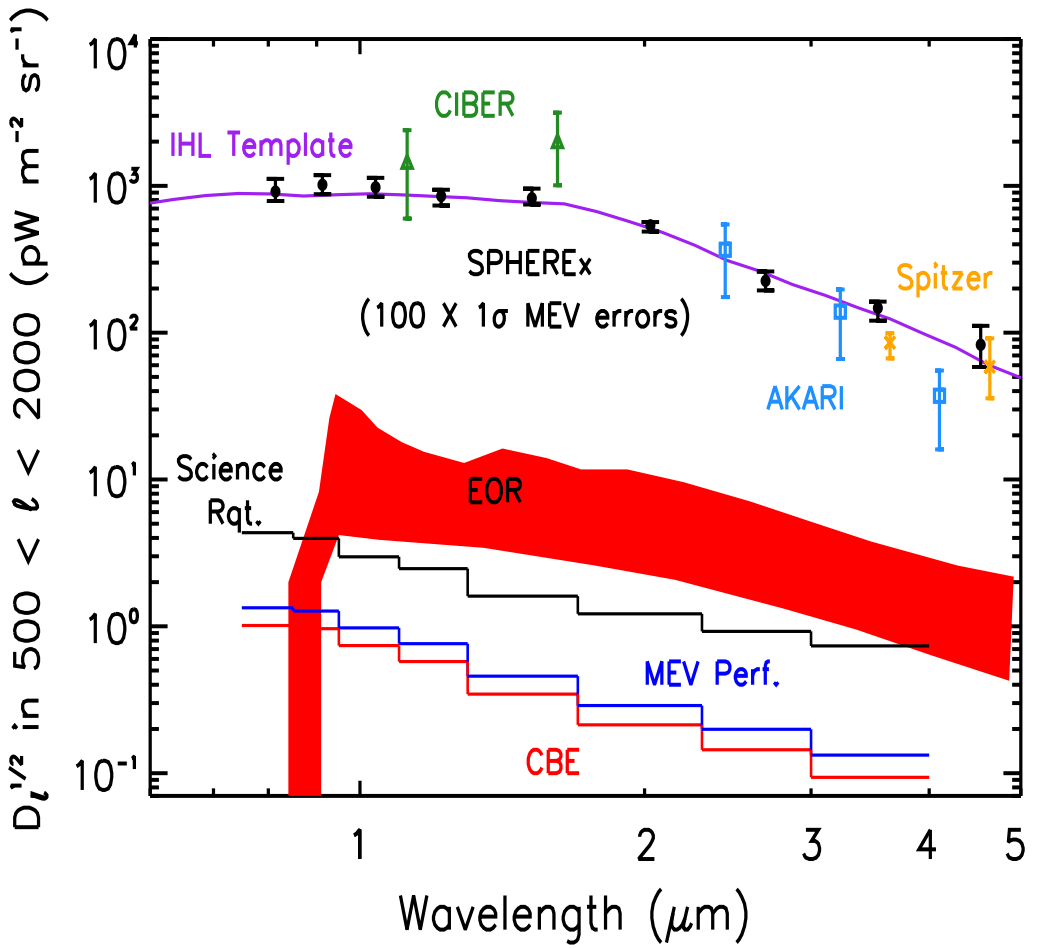


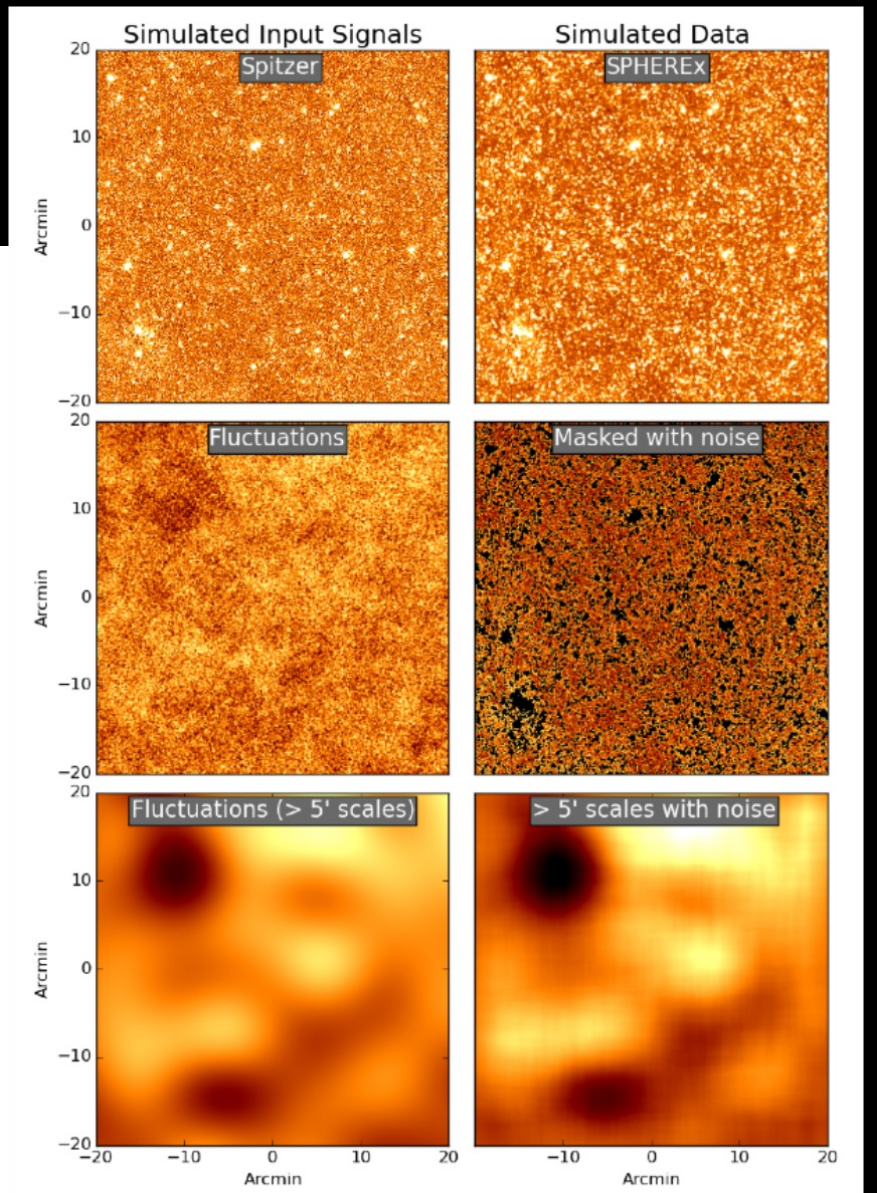
SPHEREx measures the total light emitted by galaxies

NIR Clustering Fluctuations

Intrahalo light (z ~ 0-2)
or
Early Galaxies (z ~ 6-8)?

Amplitude of clustering power spectrum

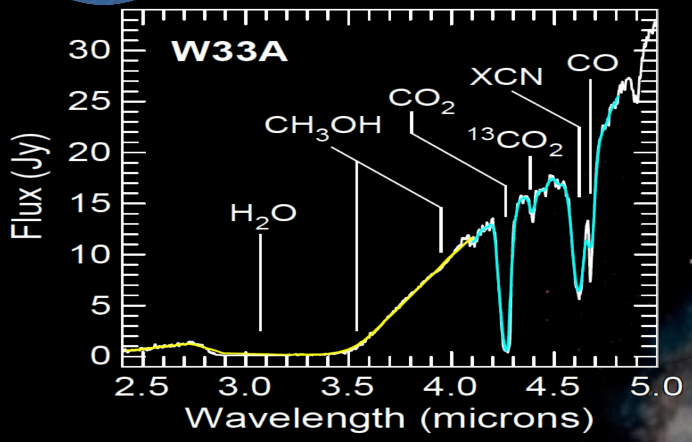




What are the conditions for life to begin?

More than 99 % interstellar water is locked in ice
‘Follow the Water’ means ‘Follow the Ice’

SPHEREx Surveys Ices in All Phases of Star Formation



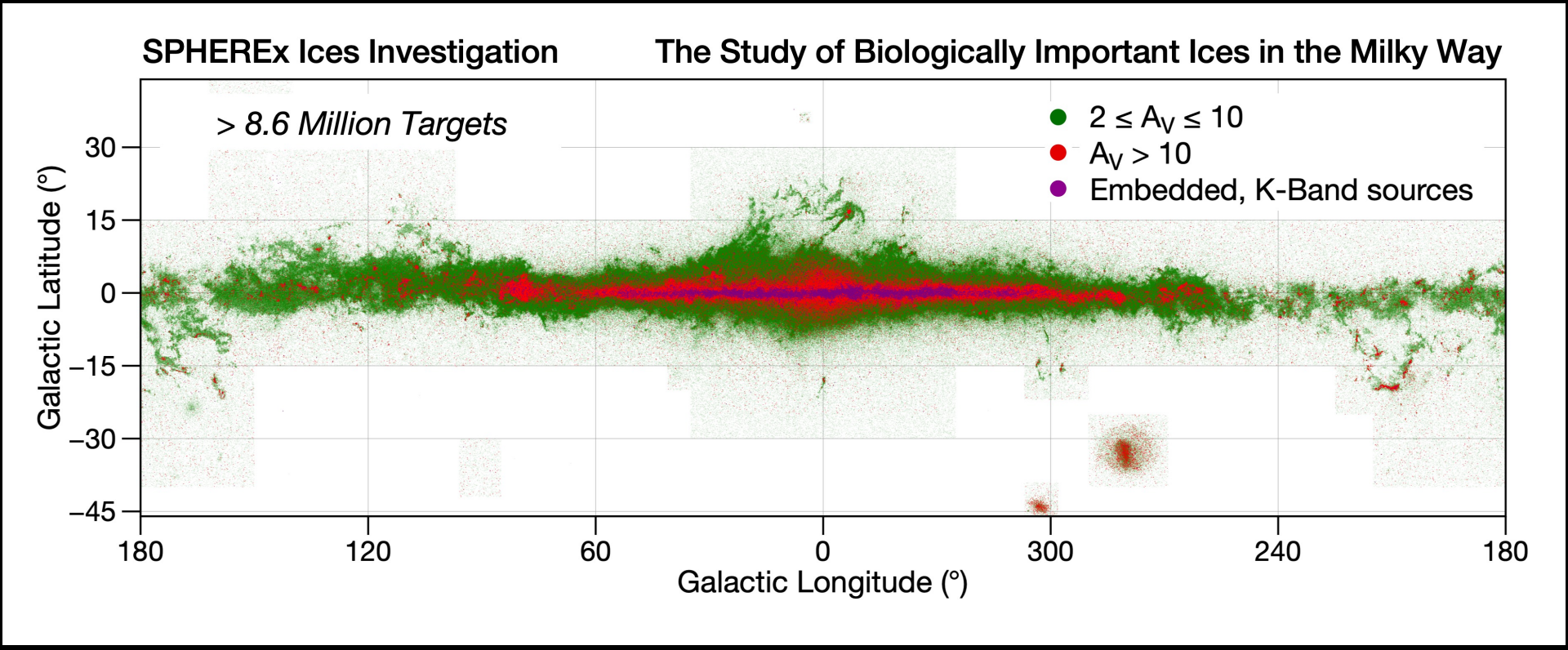
Young Stellar Envelopes

Dense Clouds

Protoplanetary Disks

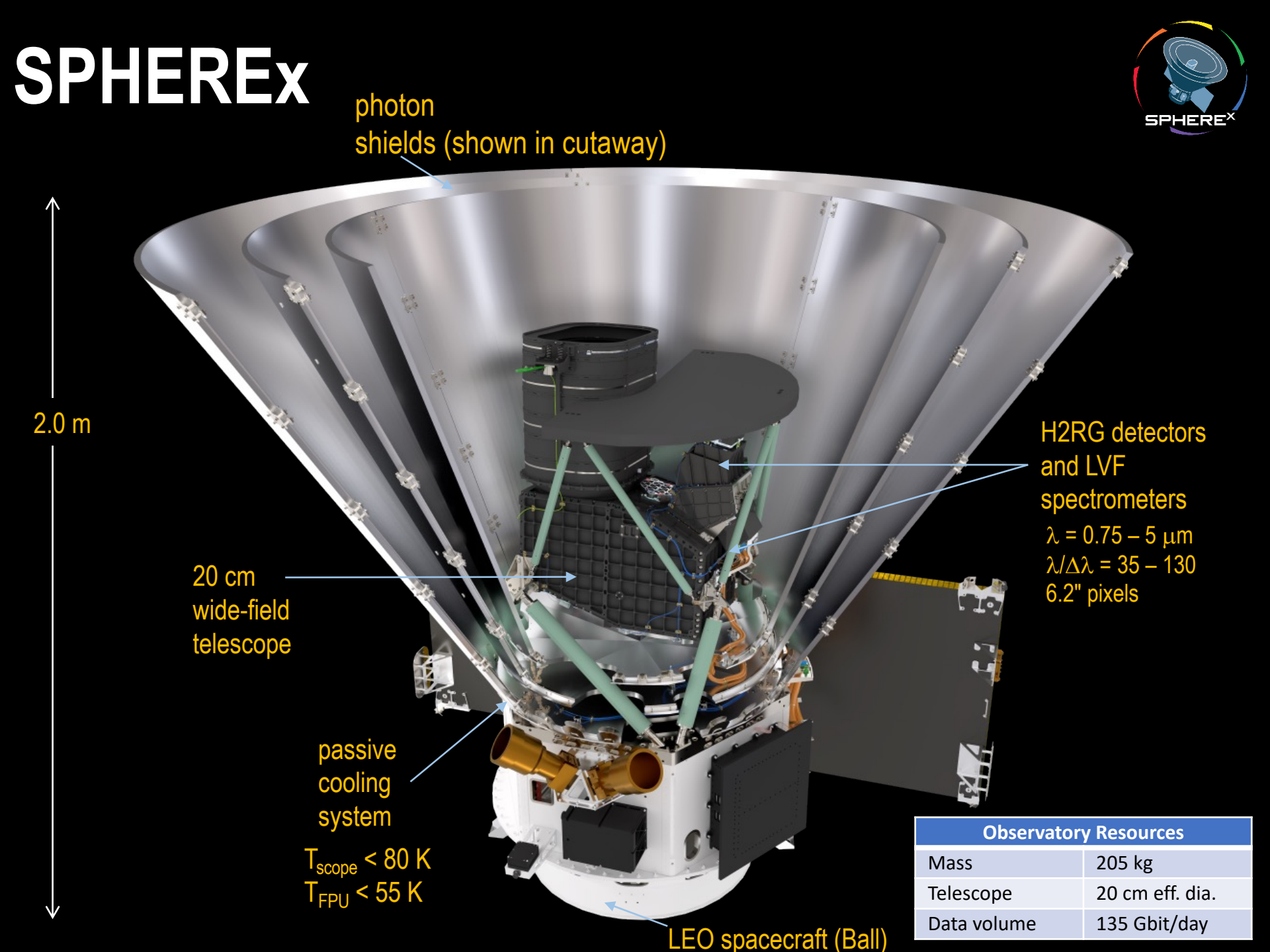
Young Solar Systems

SPHEREx Ices Targets



Ashby et al (2023)

SPHEREx



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

NASA's Astrophysics/Heliophysics Explorer Program

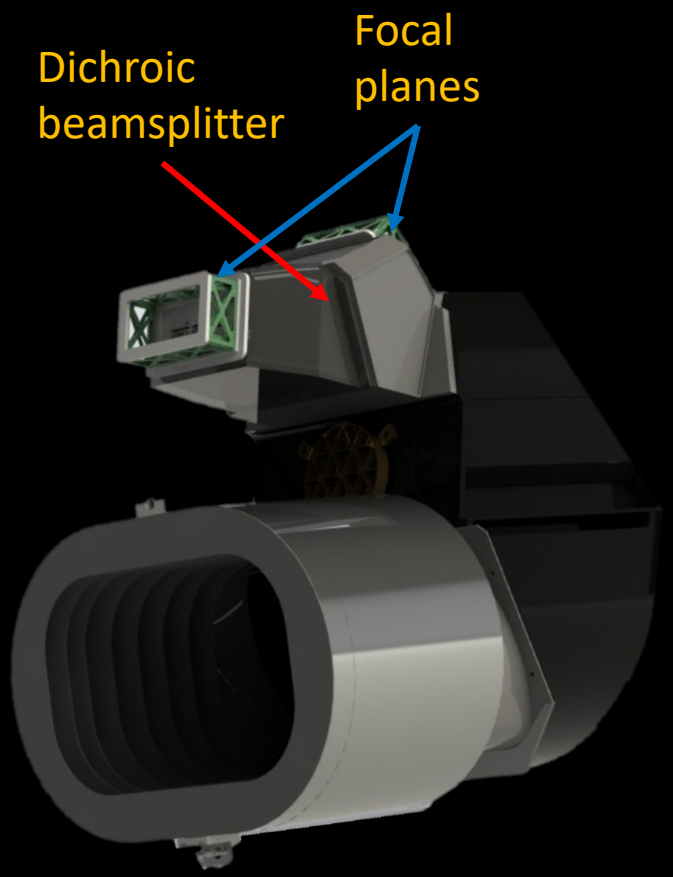
MIDEX: <= $250M (not including launch)
SMEX: <= $145M
Risk "class C" → no redundancy

Astrophysics mission
Heliophysics mission

- ~2 Astrophysics MIDEX missions per decade
- PI-led, competitively selected
- SPHEREx selected in February 2019

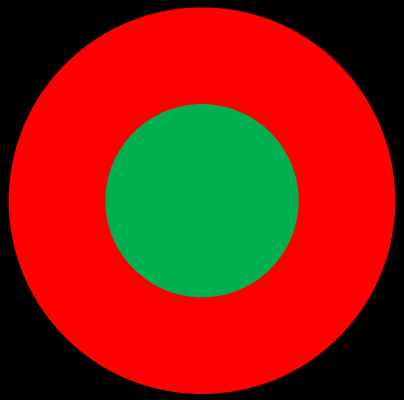
Wide-Field Telescope: Large AΩ Product

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



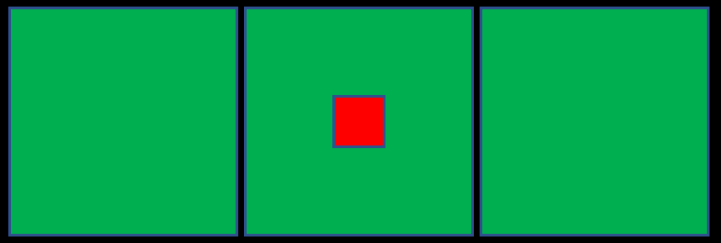
WISE vs. SPHEREx

Mirror Area: WISE has 4x more



WISE: 40 cm
SPHEREx: 20 cm

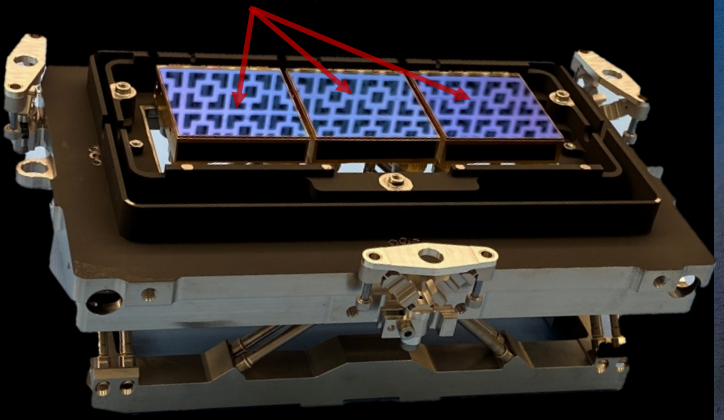
Field of View: SPHEREx has 65x more

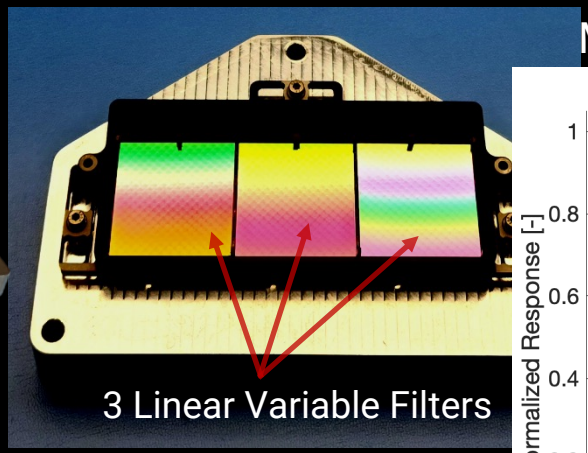


WISE: 0.61 sq. deg
SPHEREx: 39.6 sq. deg.

AΩ Product: SPHEREx has 16x more

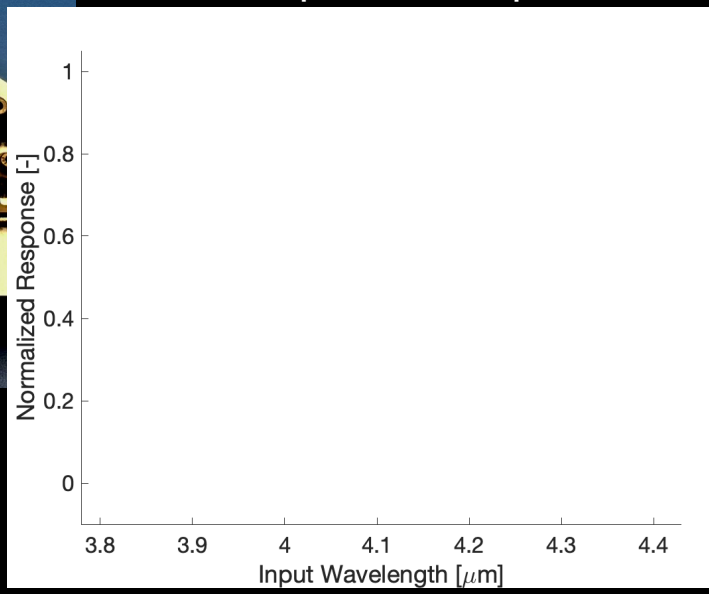
High-Throughput LVF Spectrometer

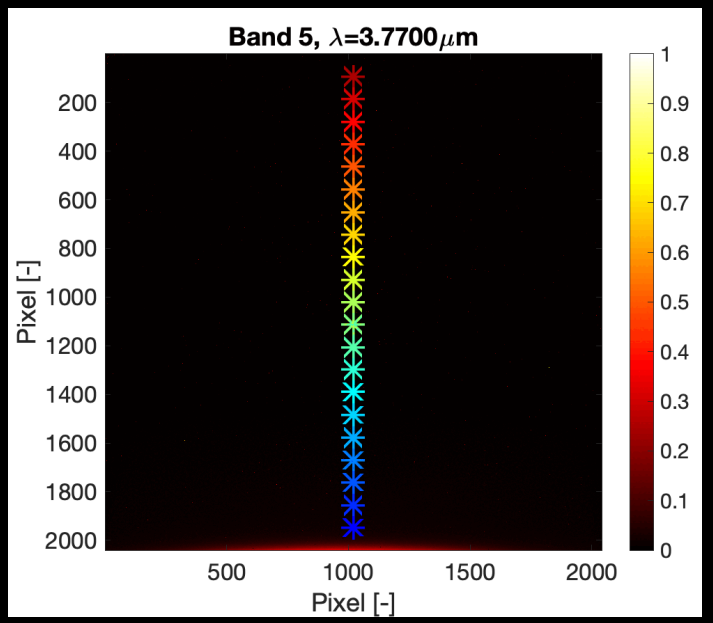




Mid-wave focal plane assembly

Measured Spectral Response

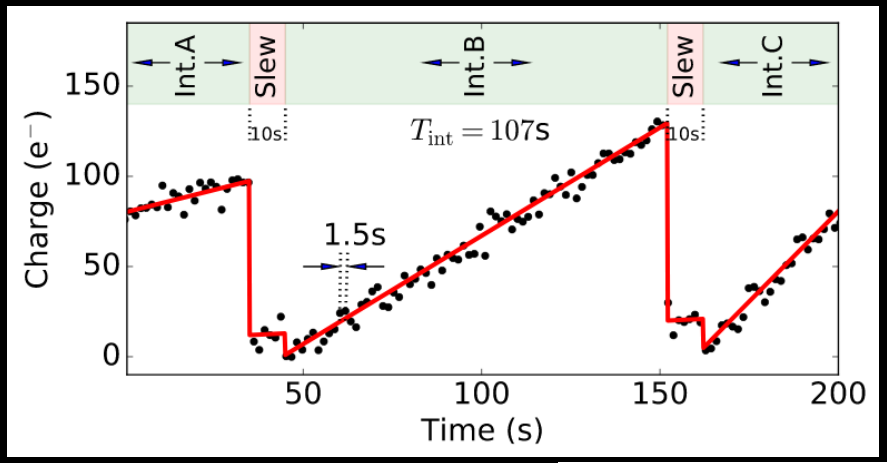




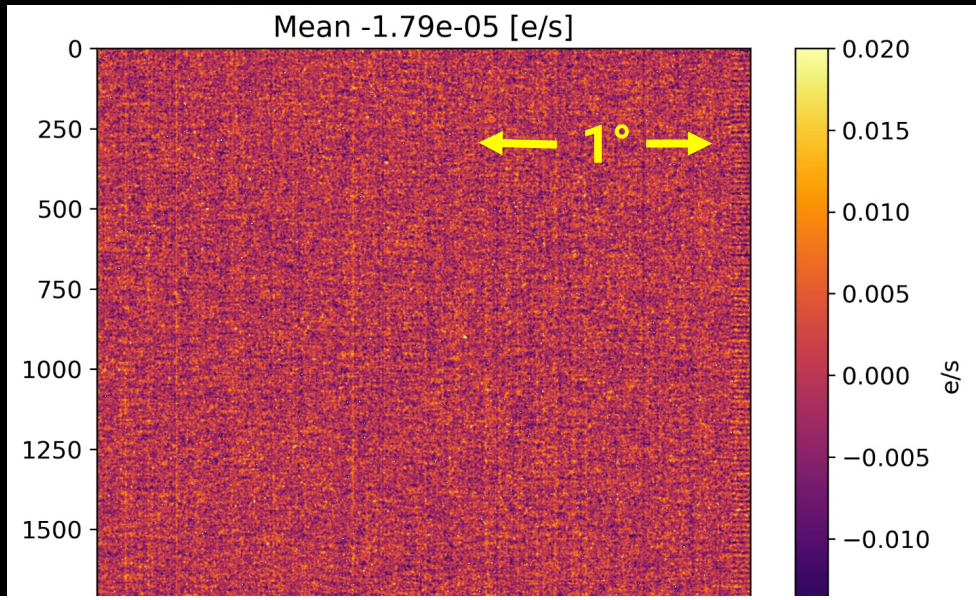
All 6 LVF/H2RG pairs have passed environmental and optical/dark performance testing

Custom H2RG Readout

Custom SUR algorithm:
photocurrents measured onboard –
transients flagged



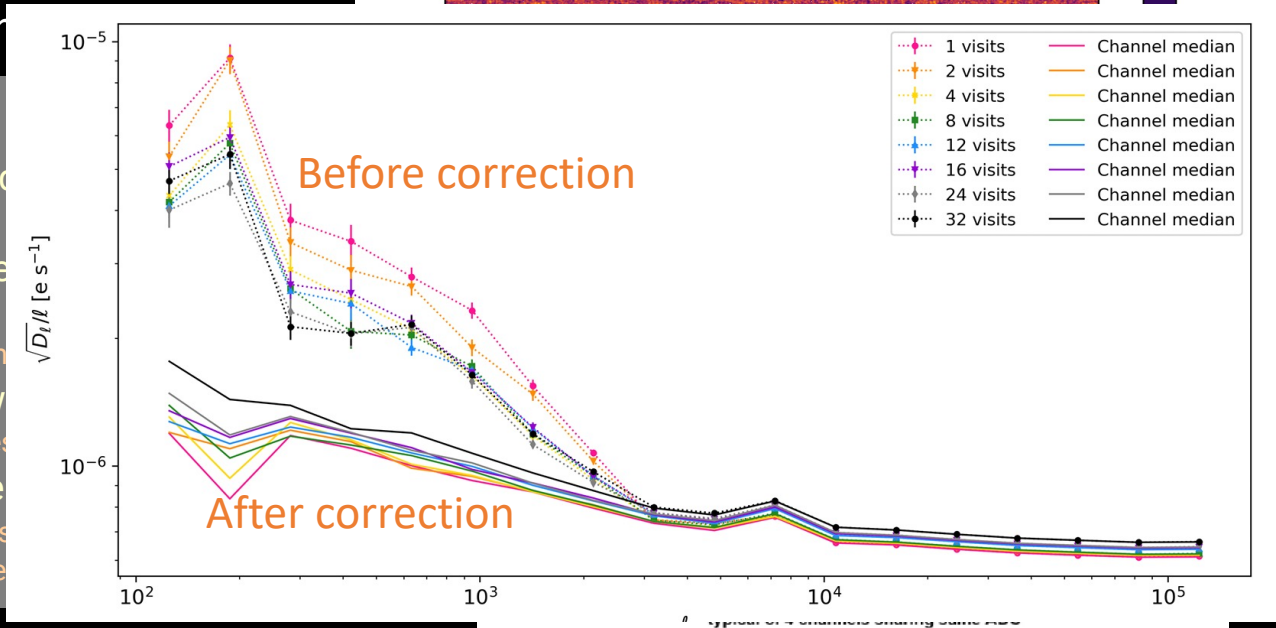
Demonstrated noise



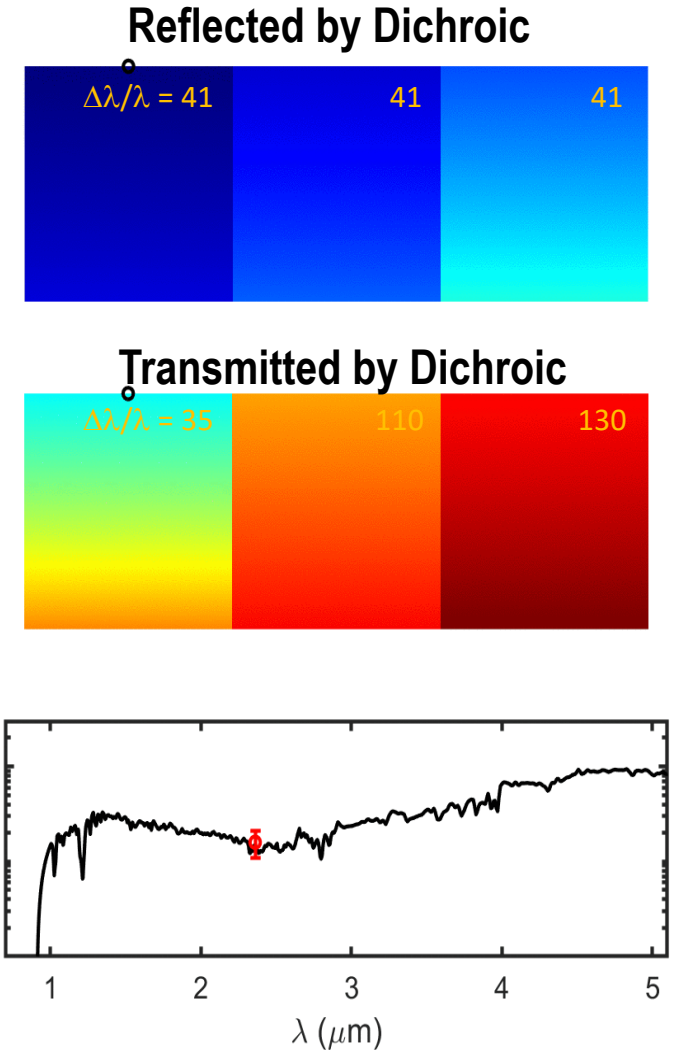
Zem

Steps to Remove Spatial 1/f

- Use VIDEO8: custom ASIC
  - Low amplifier noise (< 2 e-)
- Switch inputs to ground inte
  - "Phantom pixels" in data stream
  - Removes amplifier drift and 1/f n
- "Row Chopping" to skip row
  - Mixes 1/f noise to high frequencies
- Subtract residual offset in e
  - Sources most of the remaining nois
  - Can use reference pixels or channe

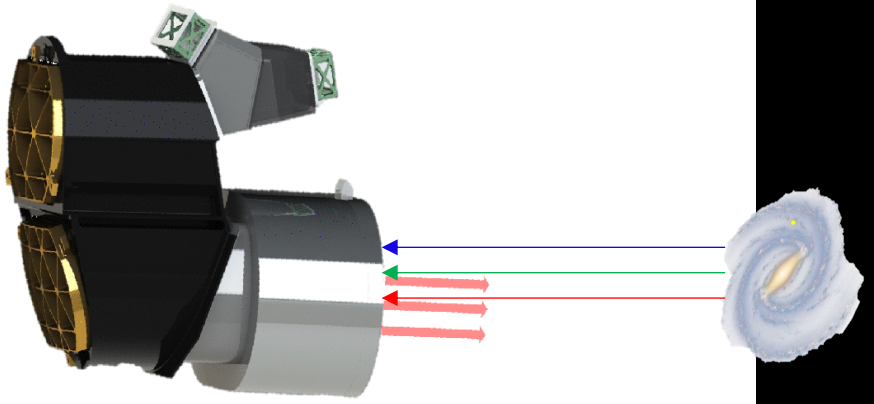


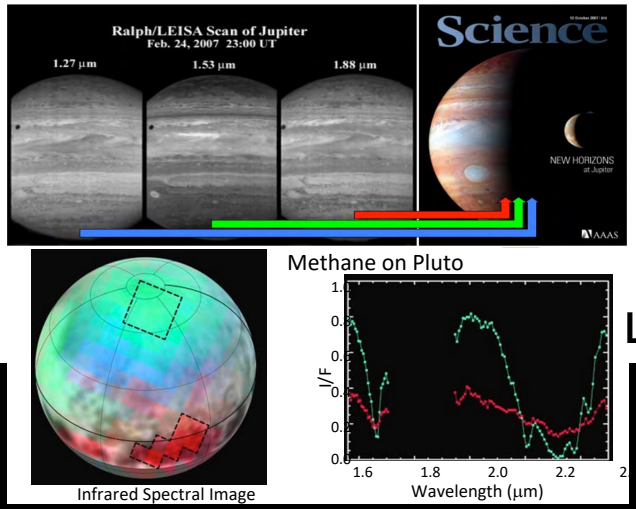
Spectroscopy with Linear Variable Filters



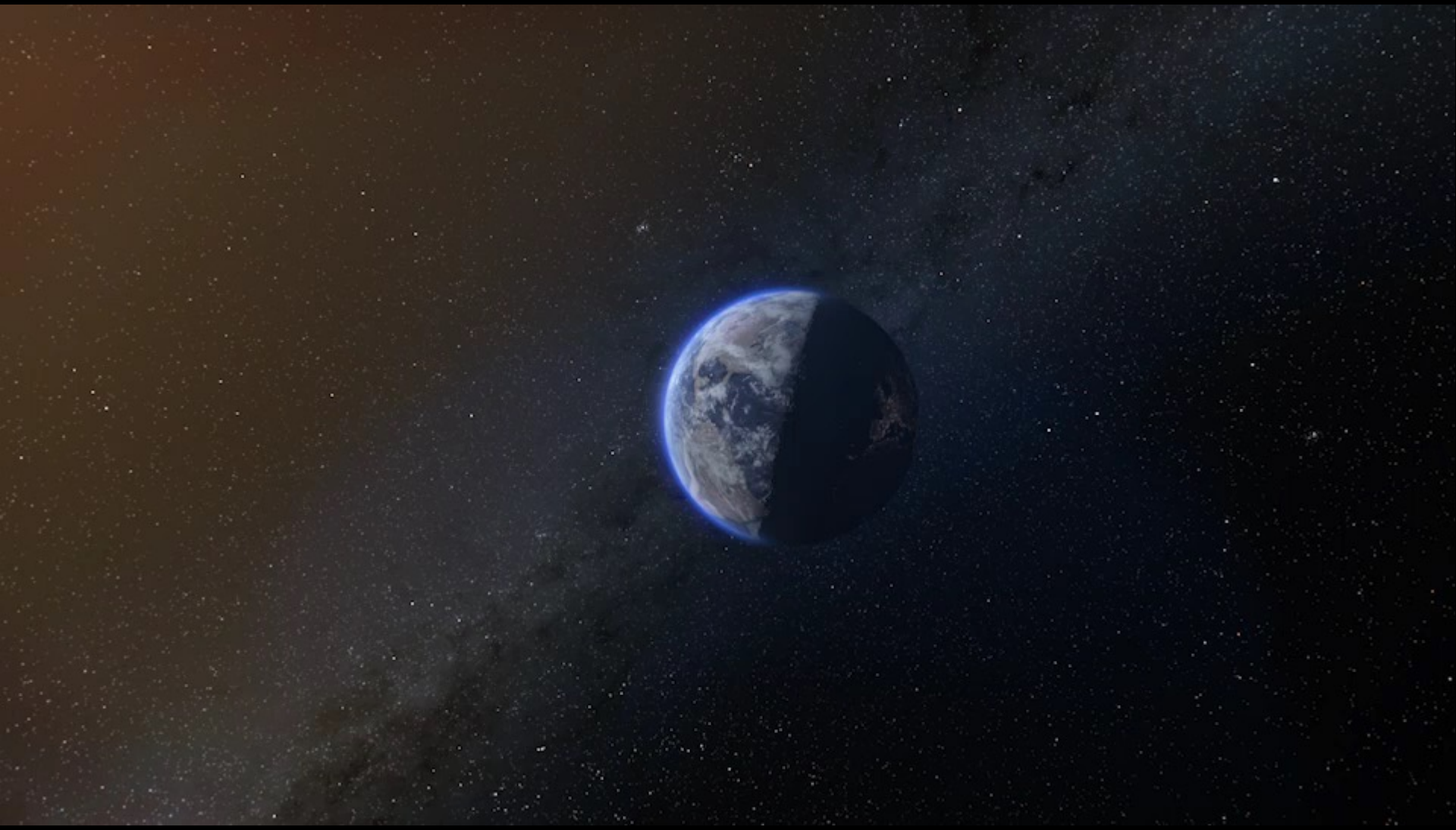
A complete spectrum in 51 exposures
Each exposure ~112s

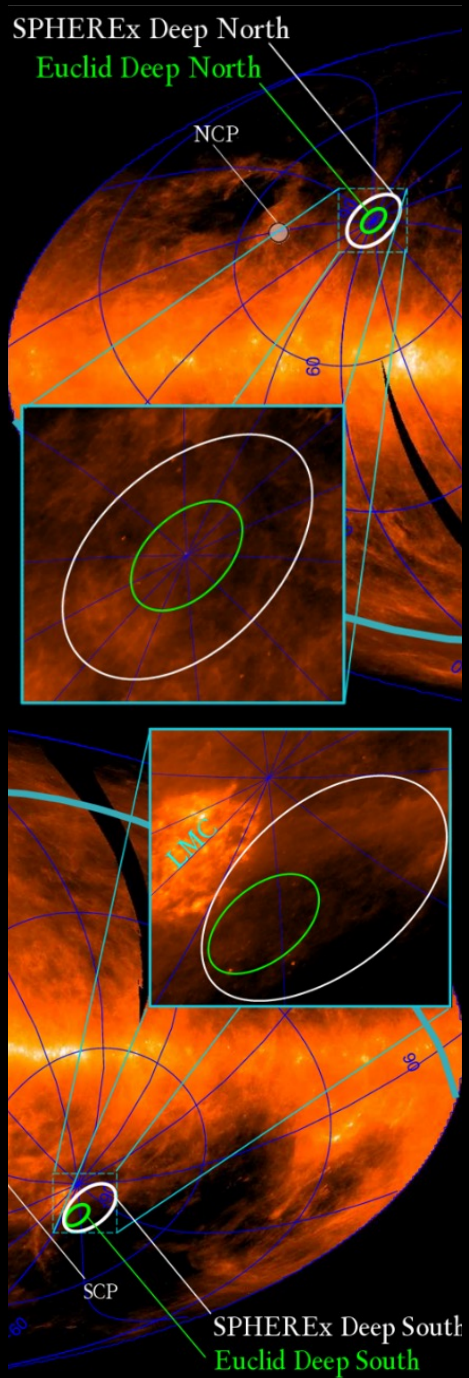
Shifting the spacecraft pointing modulates the wavelength at which an object is observed.

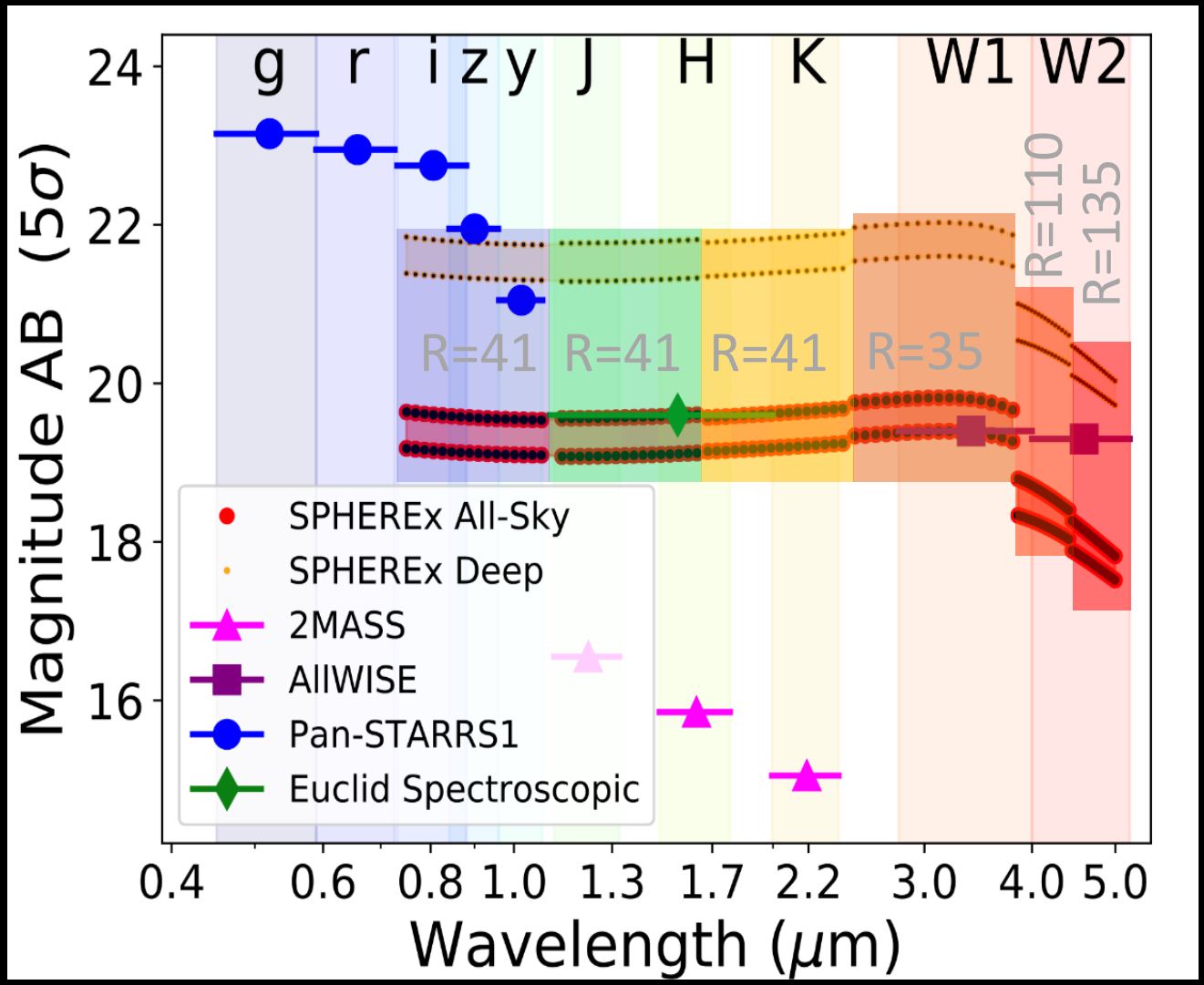




LEISA - New Horizons

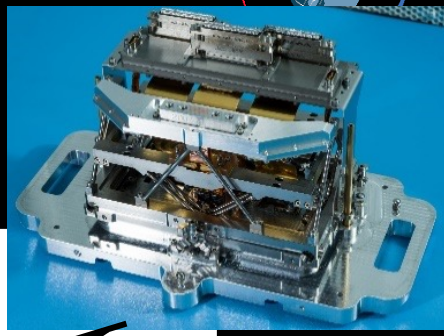



SPHEREx Deep North
Euclid Deep North
NCP
LMC
SCP
SPHEREx Deep South
Euclid Deep South


g
r
i
z
y
J
H
K
W1
W2
R=41
R=41
R=41
R=35
R=110
R=135
SPHEREx All-Sky
SPHEREx Deep
2MASS
AllWISE
Pan-STARRS1
Euclid Spectroscopic
Magnitude AB (5σ)
Wavelength (μm)
24
22
20
18
16
0.4
0.6
0.8
1.0
1.3
1.7
2.2
3.0
4.0
5.0

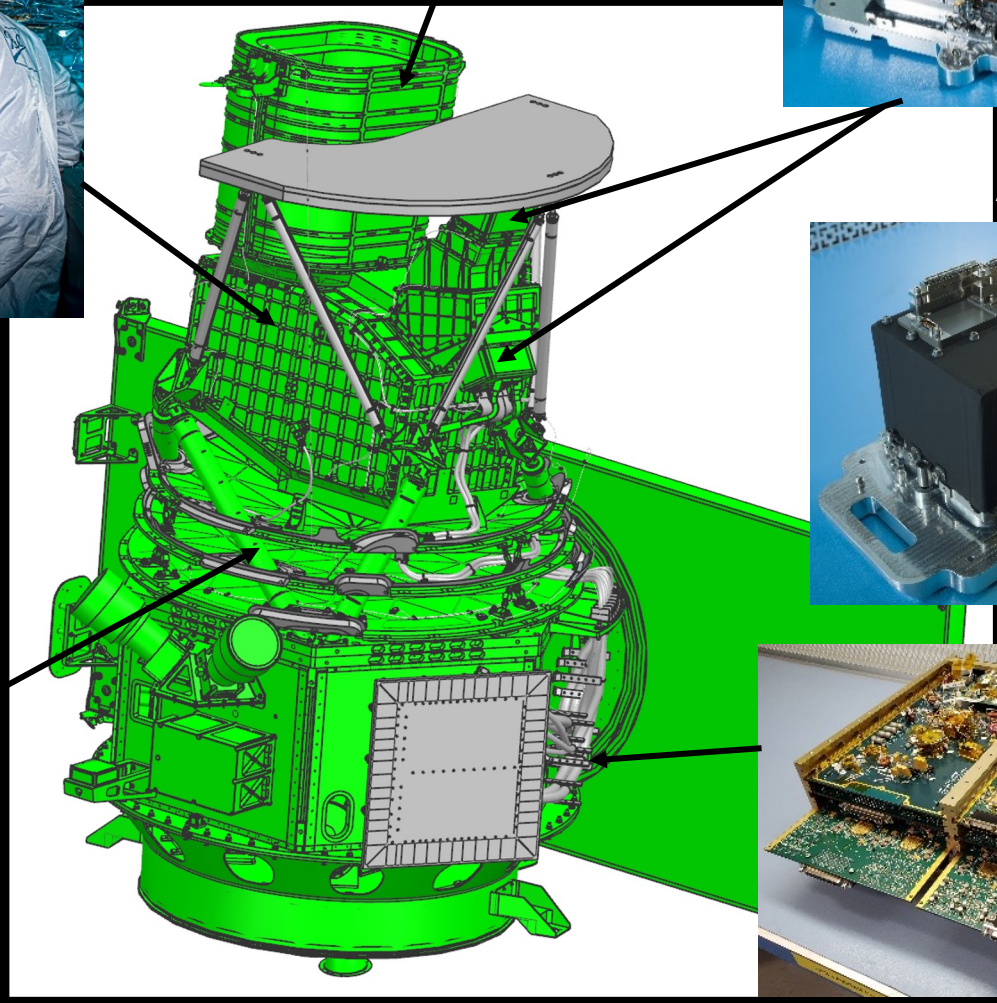
Hardware Received

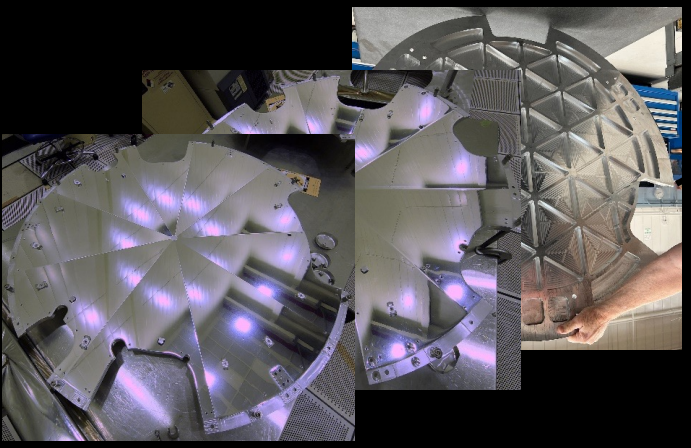
Cover



Focal Plane Assemblies

Telescope





V-Groove Coolers

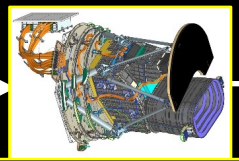
Instrument Electronics

Ongoing Instrument Tests

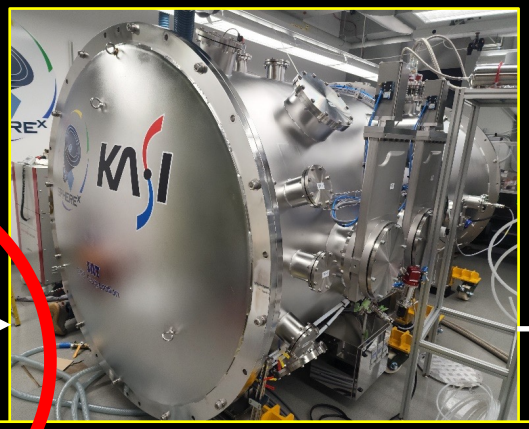
Telescope Cryo Focus

Vibe

Focus Repeatability

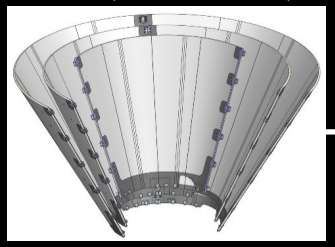


Instrument Sub-Assembly



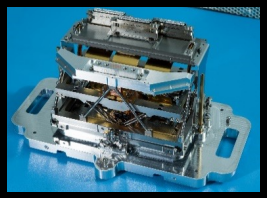
Custom Cryogenic Test Chamber (tested)

Photon Shields
(in fabrication)

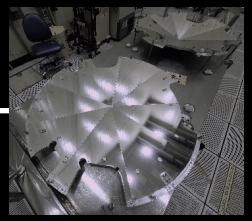


Deliver to Spacecraft March 2024

Focus → Vibe → Focus → Calibration



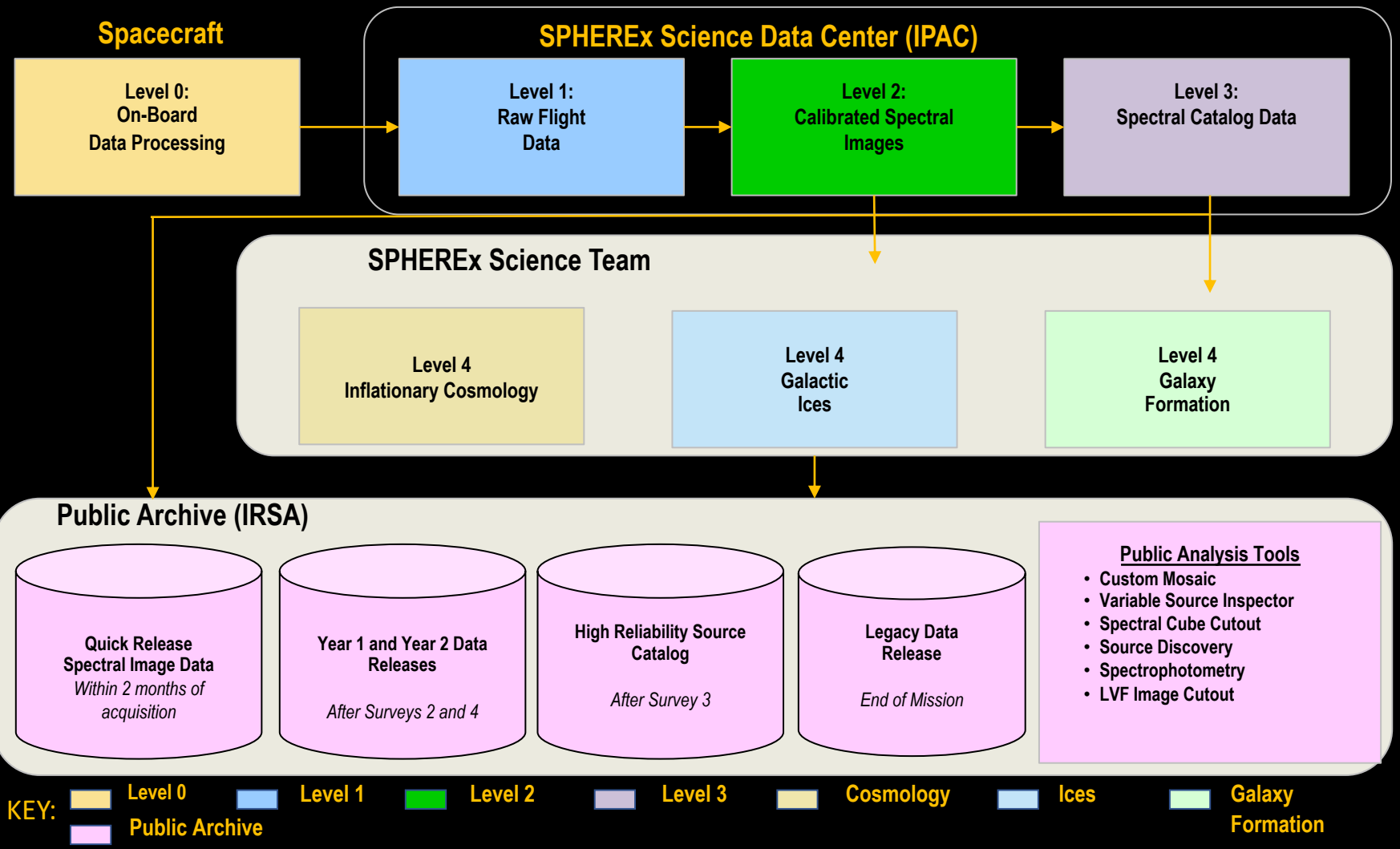
Focal Plane Assemblies
(tested)



Thermal Sub-System
(in assembly)

Flight Electronics
(in board-level test)

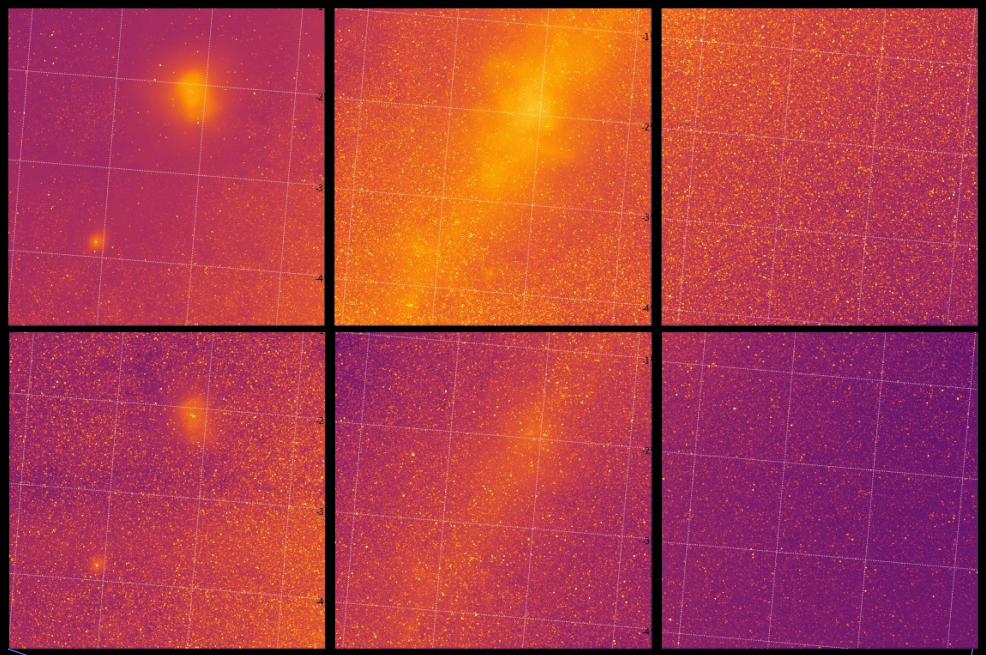
Science Data Flow

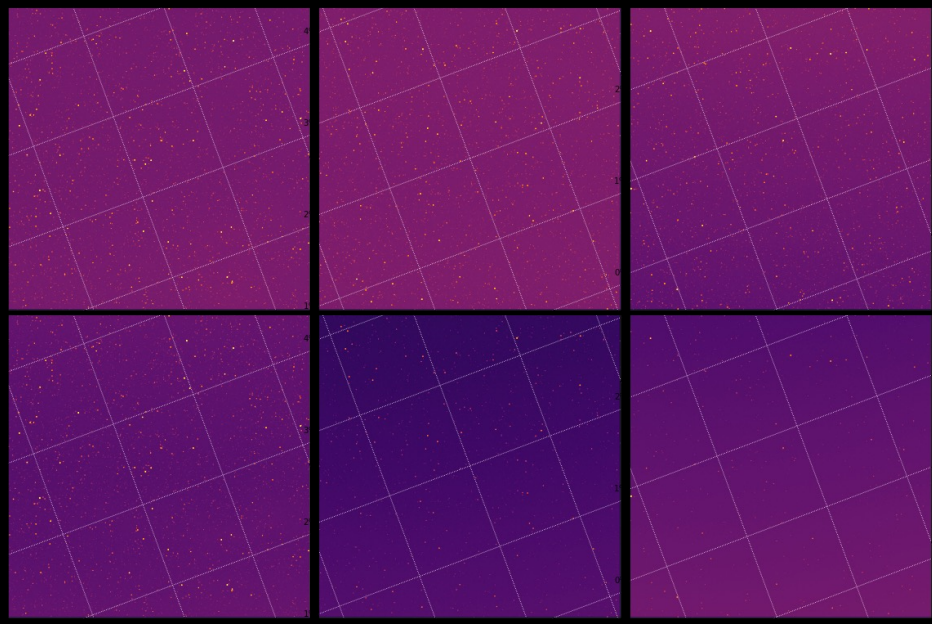


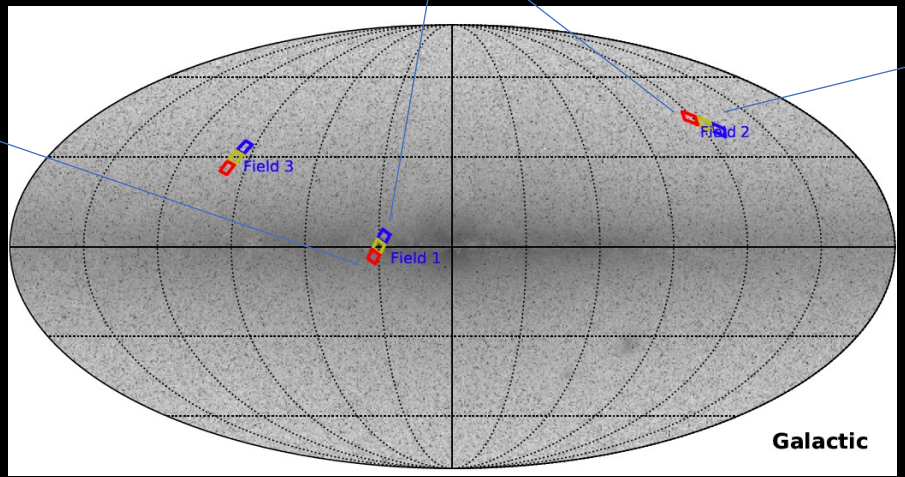
Simulated Spectral Images (2 pointings)

Crowded field in the Galactic plane

The COSMOS field





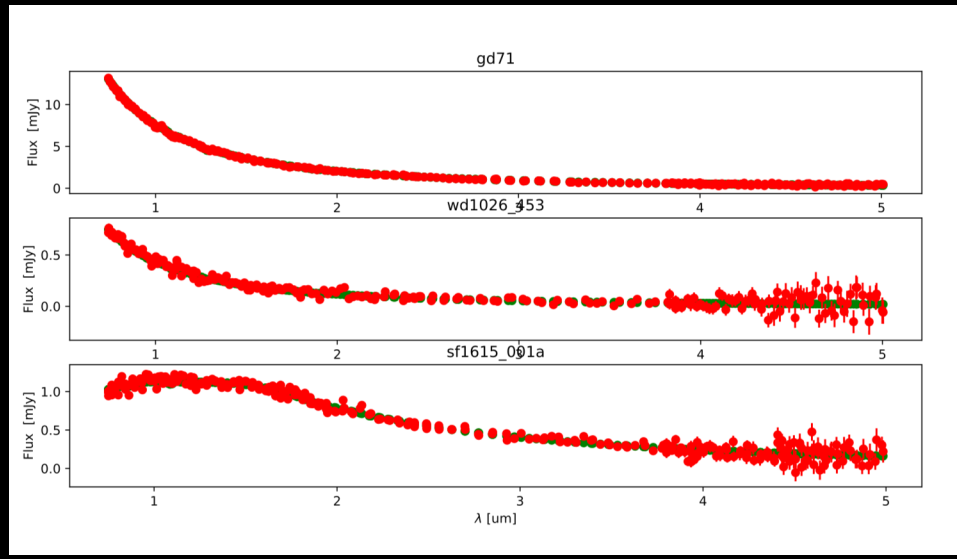


Spectrophotometry with SPHEREx

- Source spectra built up with a series of narrow-band photometric measurements
  - For galaxies, stars, etc.
- SPHEREx uses ”forced photometry” on location of previously known sources
  - Source position priors from external catalogs:

    PanSTARRS/ Gaia/ WISE and eventually LSST
- Baseline method: TRACTOR software run on each spectral image separately

- Over the course of the mission accumulate full set of spectrophotometric measurements (102 data points) for each source:



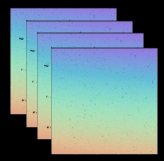
- Survey plan yields complete spectra for a typical source in ~20 days
- Deep field sources can have 100x or more the coverage!

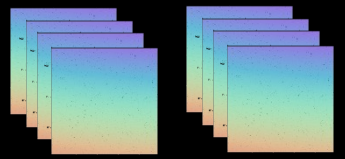
SPHEREx Data Products

- **Quick Release Spectral Images**
  - On order 500 exposures/day
  - Public release on a rolling basis within 2 months of acquisition
- **Year 1 and Year 2 full releases**
  - Re-release of all previous spectral images reprocessed with latest calibration
  - All-Sky data cubes for visualization
- **High Reliability Source Catalog (8 months after survey 3 complete)**
- **Legacy Data Release (end of mission)**

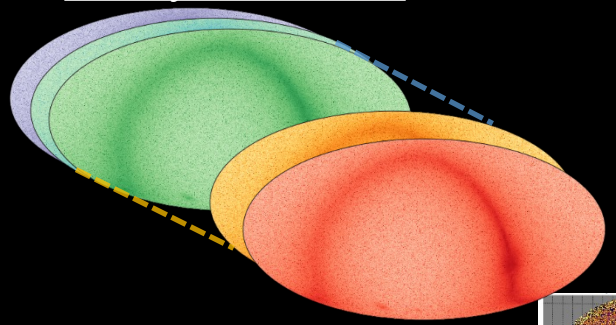
Quick Release Spectral Image Data

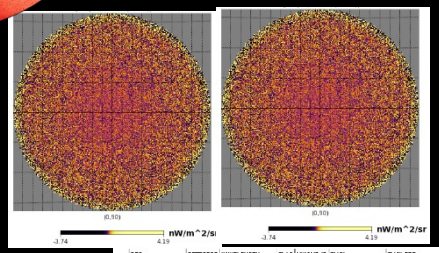
Year 1 and Year 2 Spectral Images





All-sky Data Cube

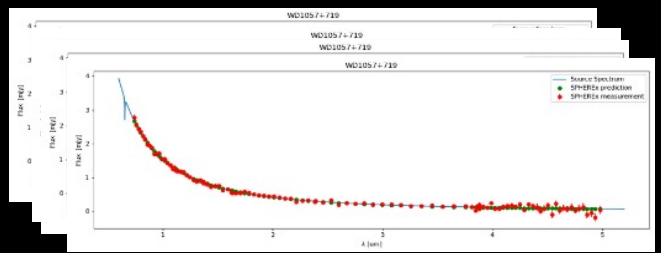




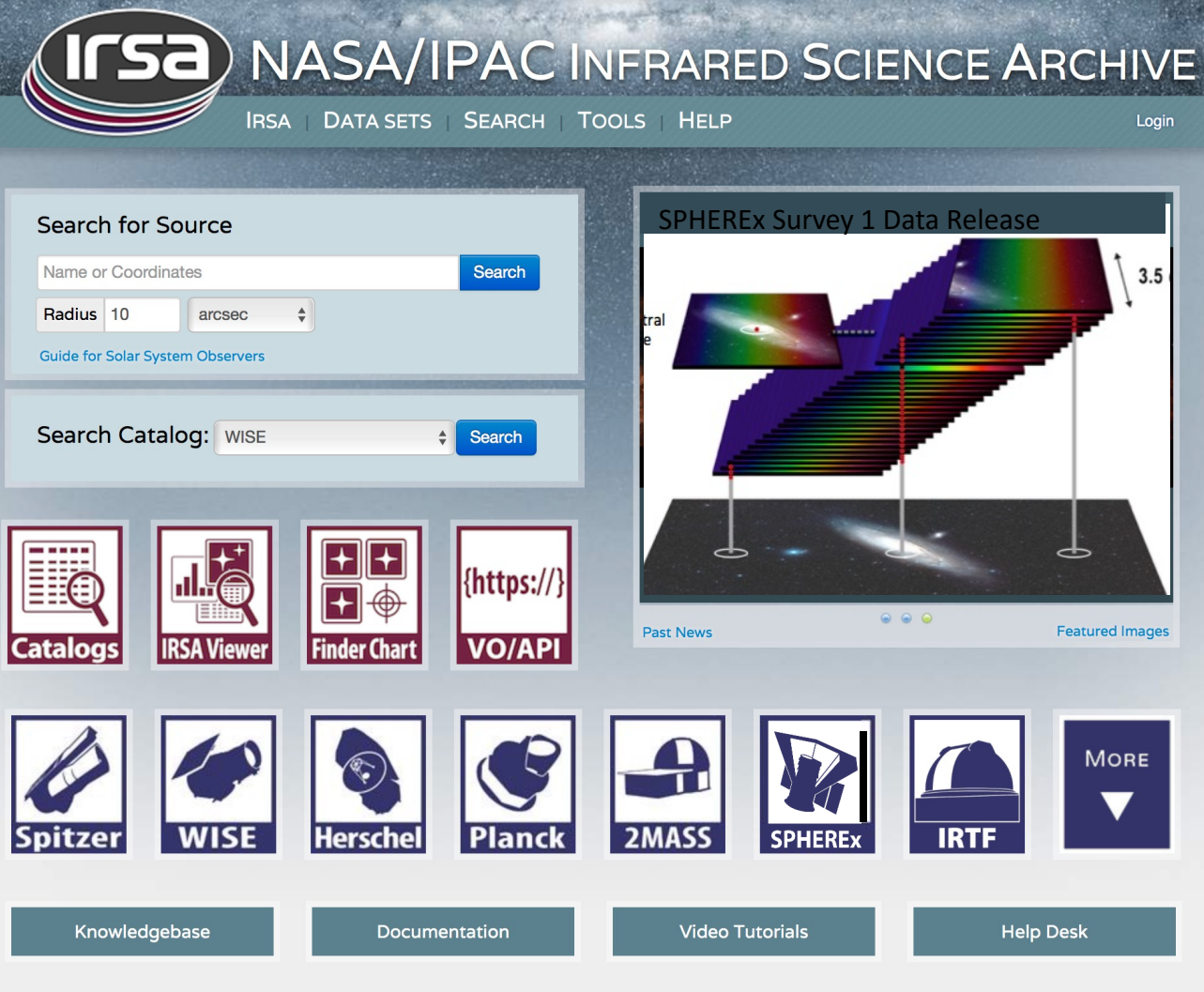
Legacy Data Products

Legacy Deep Field Mosaics
Legacy Galaxy Catalog
Legacy Stellar Type/Ice Column Density Catalog

High Reliability Source Catalog



Public Archive



How will SPHEREx measure 3D Large Scale Structure?

Exquisite measurements of galaxy redshifts!

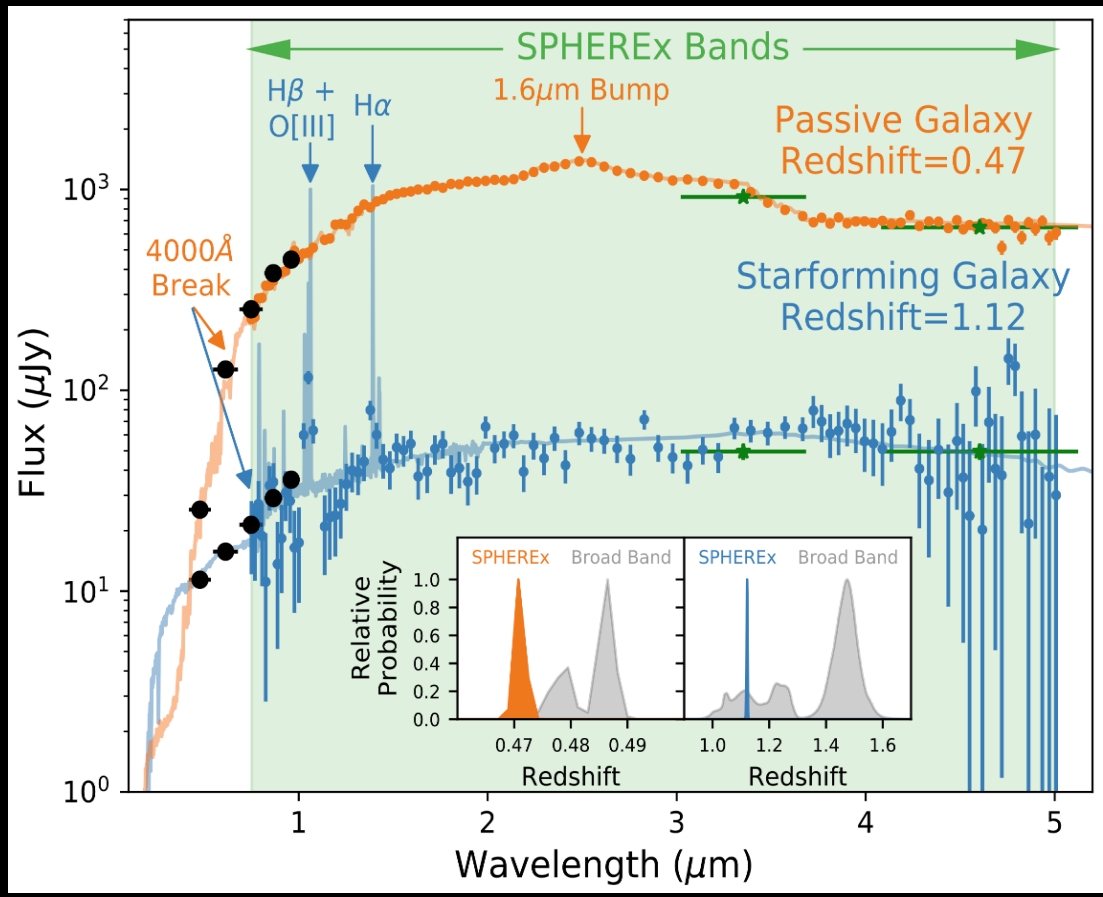
Detected galaxies	> 1 billion
Galaxies $\Delta z/(1+z) < 10\ \%$	> 450 million
Galaxies $\Delta z/(1+z) < 0.3\%$	> 10 million

We select known sources using the full-sky catalogs from PanSTARRS/DES/LSST and obtain SPHEREx spectra for each
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

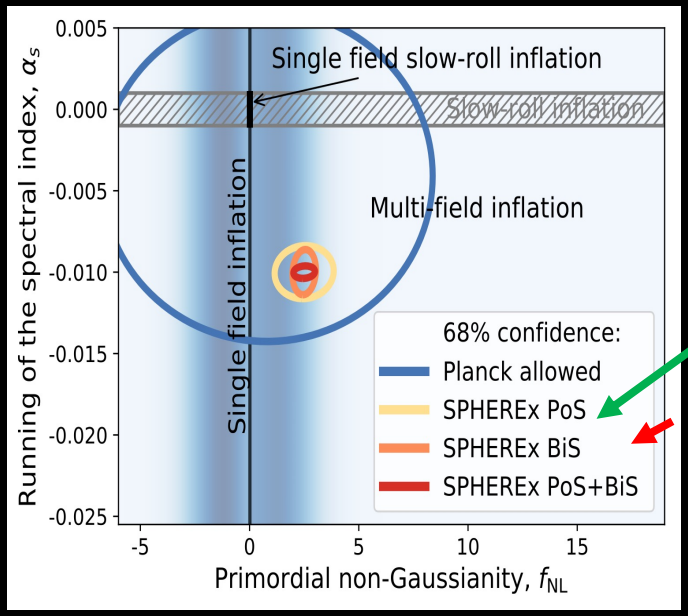
Key spectral features:
Hα, 1.6 μm bump, 1.875 μm Pα, 3.3 μm PAH

We simulated this process using COSMOS model spectra (Stickley et al. 2016) and more recently with empirical templates and more realistic emission lines (Feder et al 2023 in prep)



How did the Universe Begin?

Did Multiple Fields Drive Inflation?



power spectrum

bispectrum

Probing ***Inflation*** with Non-Gaussianity (f_{NL})

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

A spectrum for every 6” pixel on the sky

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

IRAS*
COBE
ROSAT
2MASS
GALEX
WMAP
Planck
WISE

***More than 800,000 total citations**

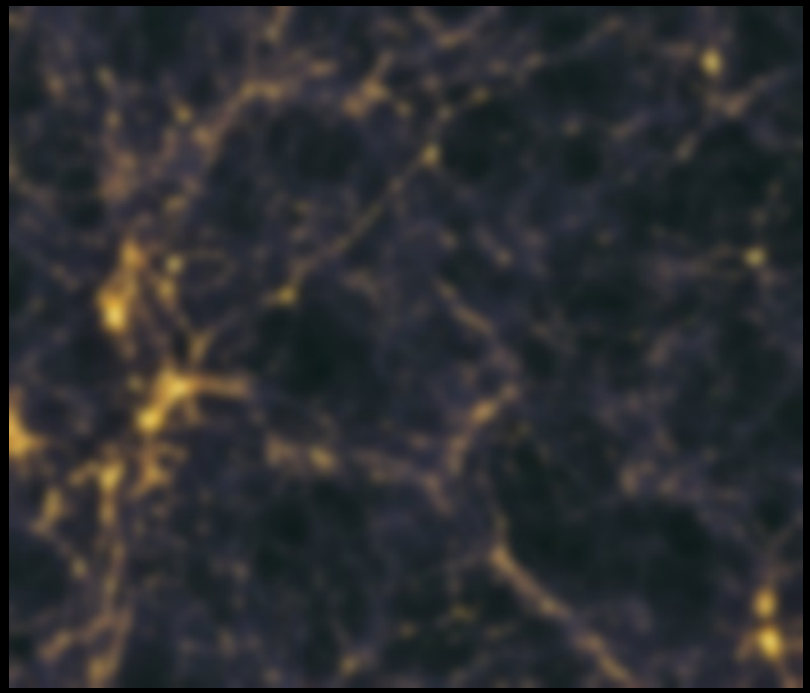
Stay Tuned:

- 2025 Launch
  - Major data releases every year
- SPHEREx designed for a major impact in three science areas:
  - Inflation: a galaxy redshift survey with large effective volume and deep redshift accuracy
  - Galaxy Formation: Deep regions, multi-band imaging
  - Interstellar Ices: Galactic Plane, resolved spectra to 5 μm
- *What will you do with the SPHEREx data?*

For more information see http://spherex.caltech.edu

Studying the Cosmic History of Light Production

SPHEREx 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
- Power spectrum/component separation methods used on CIBER, Spitzer, Herschel, Planck data