# The SPHEREx All-Sky Infrared Spectral Survey: Science Overview

*Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer*


Olivier Doré

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*California Institute of Technology*


**http://spherex.caltech.edu**

***SPHEREx Team***

# SPHEREX SCIENCE TEAM

| | |
|---|---|
| Rachel Akeson | Caltech/IPAC |
| Matt Ashby | CfA |
| Jamie Bock (PI) | Caltech/JPL |
| Lindsey Bleem | Argonne |
| Peter Capak | Caltech/IPAC |
| Tzu-Ching Chang | JPL/Caltech |
| Asantha Cooray | UC Irvine |
| Brendan Crill | JPL/Caltech |
| Olivier Doré (PS) | JPL/Caltech |
| Tim Eifler | U. Arizona |
| Salman Habib | Argonne |
| Katrin Heitmann | Argonne |
| Shoubaneh Hemmati | JPL/Caltech |
| Chris Hirata | OSU |
| Woong-Seob Jeong | KASI |
| Davy Kirkpatrick | Caltech/IPAC |
| Phil Korngut | Caltech |

& strong and experienced engineering team @ JPL and Ball

| | |
|---|---|
| Elisabeth Krause | U. Arizona |
| Carey Lisse | JHU |
| Daniel Masters | JPL/Caltech |
| Phil Mauskopf | ASU |
| Gary Melnick | CfA |
| Hien Nguyen | JPL |
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| Roger Smith | Caltech |
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| Volker Tolls | CfA |
| Stephen Unwin | JPL |
| Michael Werner | JPL |
| Rogier Windhorst | ASU |
| Yujin Yang | KASI |
| Michael Zemcov | RIT |

Image Credit: Illustris TNG

# SPHEREX TEAM @ CCA TODAY

Lindsey Bleem (ANL)
Cluster catalog lead

Jamie Bock (Caltech/JPL)
PI

Tzu-Ching Chang (JPL/Caltech)
Intensity mapping lead

Asantha Cooray (UCI)
Extra-galactic background light lead

Phil Korngut (Caltech)
Instrument scientist

Cassey Lisse (JHU/APL)
Solar system object lead

Gary Melnick (CfA)
Ices investigation lead

Roberta Paladini (Caltech/IPAC)
Pipeline scientist

Jennifer Rocca (JPL)
Principal system engineer

# SPHEREX DESIGNED TO ADDRESS THE MOST IMPORTANT QUESTIONS IN ASTROPHYSICS

- How did the Universe begin?
  - ➡ Probe the physics of the young inflationary Universe through the 3D spatial distribution of galaxies

- How did Galaxies begin?
  - ➡ Study the cosmic history of light production through near-infrared background fluctuations

- What are the Conditions for Life Outside the Solar System?
  - ➡ Survey the Milky Way for water ices and other biogenic molecules

SPHEREx probes the origin of the Universe, galaxies, and life

We will do so by constructing the first all-sky near-infrared spectral survey

# SPHEREX: AN ALL-SKY SPECTRAL SURVEY

SPHEREx Dataset:

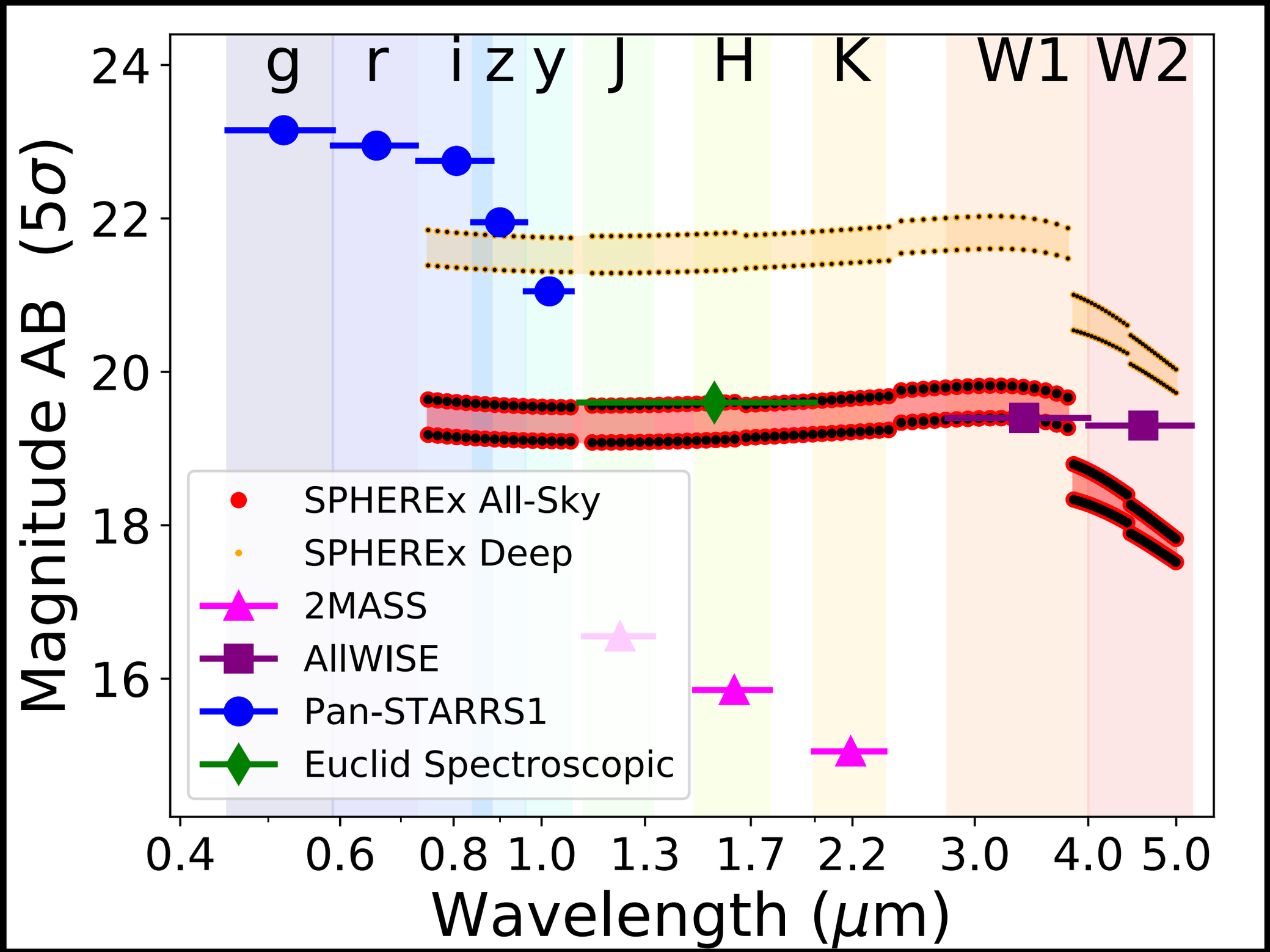
- For every 6.2” pixel over the entire sky:

  ➡ R=35-41 spectra spanning 0.75 μm < λ < 3.82 μm

  ➡ R=110-130 spectra spanning 3.82 μm < λ < 5.0 μm

- ≃ all-sky survey with 96 fine photometric bands

# SPHEREX SURVEY DEPTH




Deep survey

All-sky survey

# Marveling at the Heavens with SPHEREx

Camille Flamarion 1888

# SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE

**Galaxies**

**Detected**
> 1 billion

**Med. Accuracy z's**
> 100 million

**High Accuracy z's**
10 million

**Clusters**
25,000

**Stars**

**Main Seq. Spectra**
> 100 million

**Dust-forming**
10,000

**Brown Dwarfs**
> 400

**Cataclysms**
> 1,000

**Other**

**Quasars**
> 1 million

**Quasars z >7**
3 – 300?

**Asteroid Spectra**
10,000

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

➡ All-Sky surveys demonstrated high scientific returns with lasting data legacy used across astronomy (COBE, IRAS, GALEX, WMAP, Planck, WISE)

➡ Many exciting discoveries will come from the community

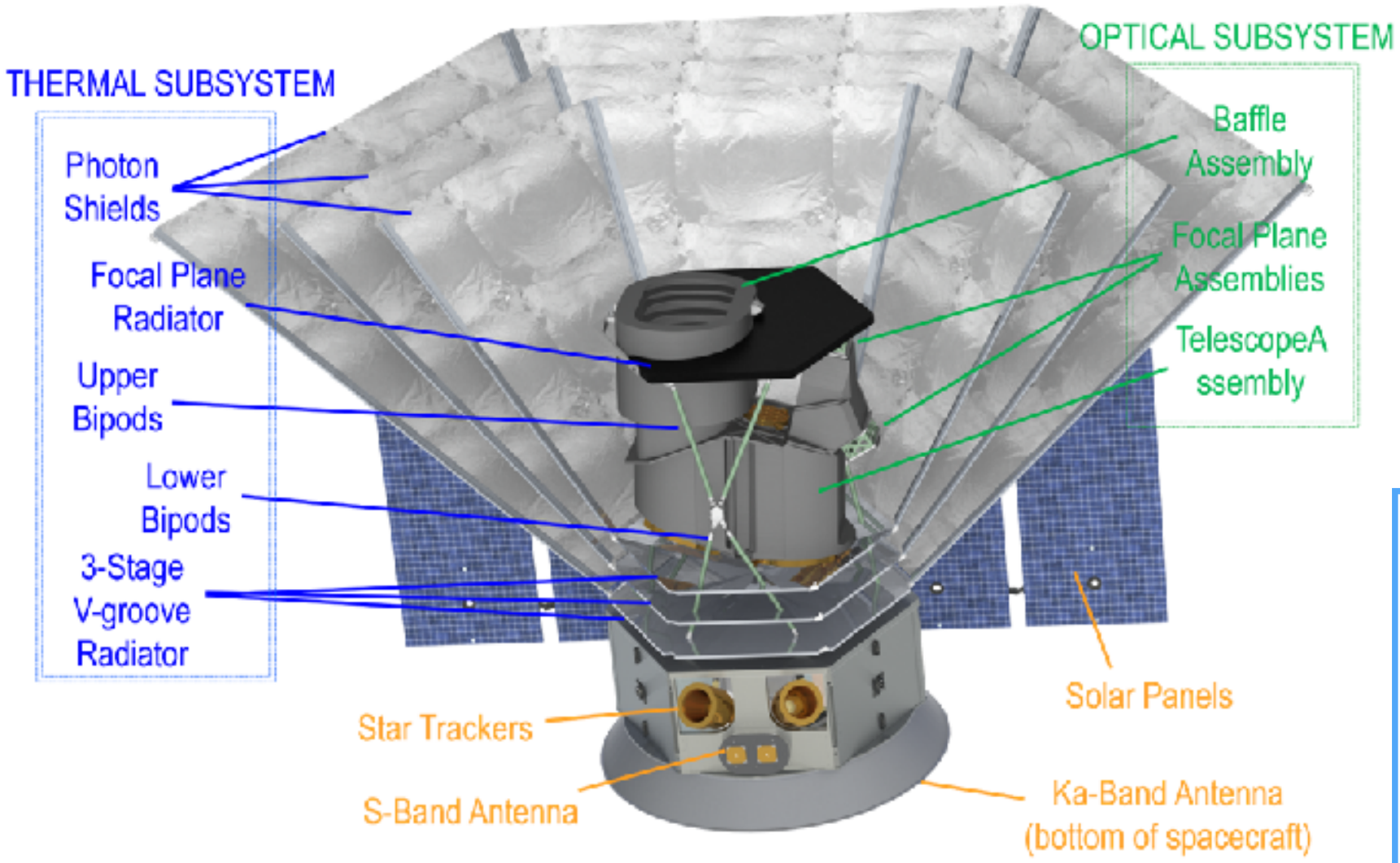
OD++16,18

# AGGRESSIVE DATA RELEASE PLAN
## *"CONVEYOR BELT MODEL"*

- L : Launch late 2023
- L+1 : End of commissioning
- L+2n: Every ~2 months after, for 24 months
  - ➡ Release spectral images data (L2 product)
- L+6n+ε: Every 6 months, we complete a full sky survey
  - ➡ Release local wavelength maps
- L+12n+ε: Every 12 months, complete two full sky surveys
  - ➡ Release source catalogs
- L+24+1yr: End of nominal mission + 1yr of analysis
  - ➡ Release L4 (science) catalogs (galaxy, ices, maps, legacy catalogs)

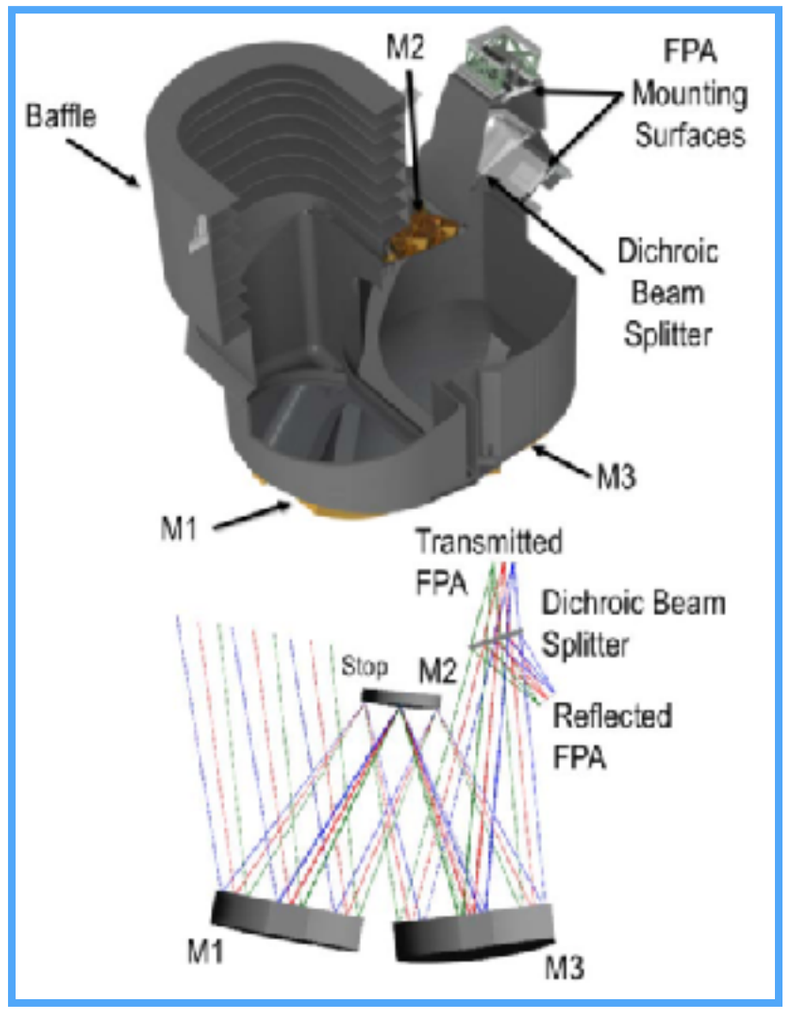
- Archive hosted by IRSA at IPAC/Caltech (http://irsa.ipac.caltech.edu)
  - ➡ Will also host tools to do on the fly mosaic, forced photometry on a catalog, time variable sources photometry, etc.

# SPHEREx: An Innovative Architecture Based on Mature Technologies

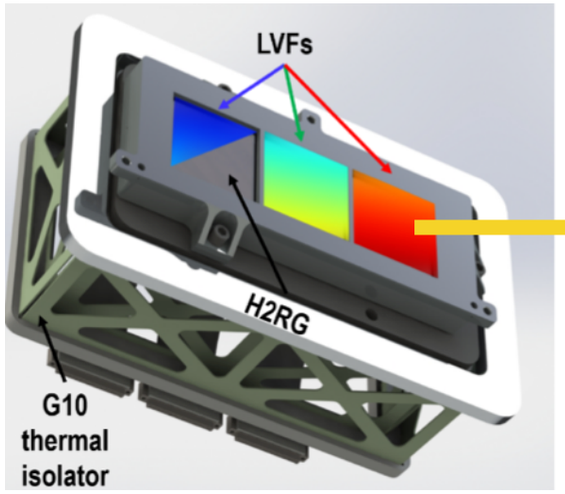


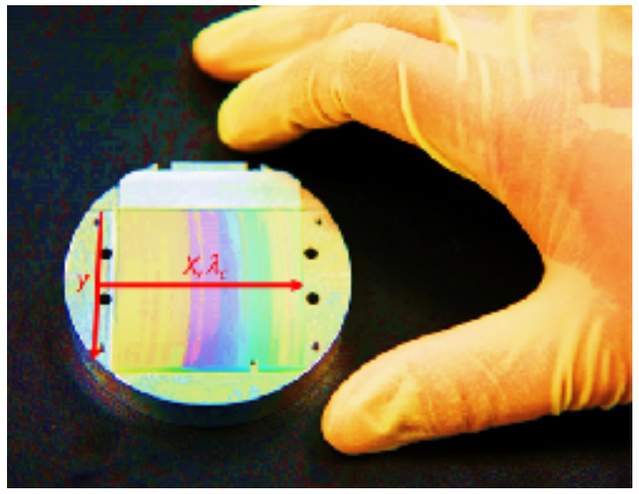

| Parameter | Value |
|---|---|
| Telescope eff. diameter | 20 cm |
| Field of view | 3.5 x 11 deg.$^2$ |
| Pixel size | 6.2 arcsec |
| Wavelength range | 0.75 – 5 μm |
| Resolving power $\lambda/\Delta\lambda$ | 35-130 |

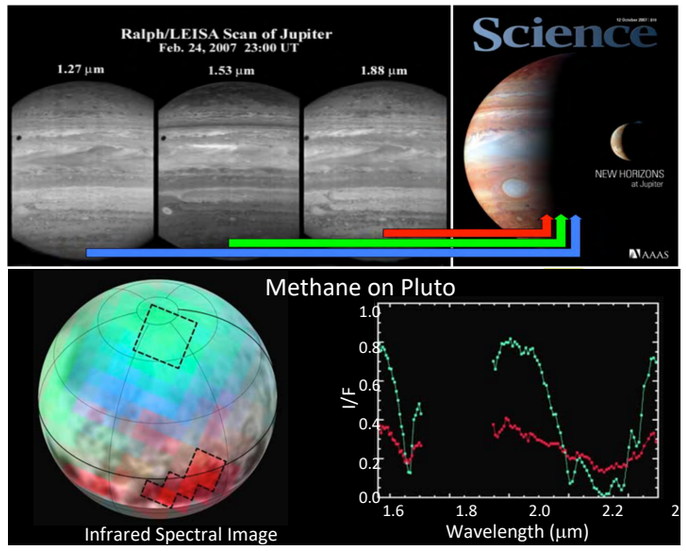
## Wide field telescope



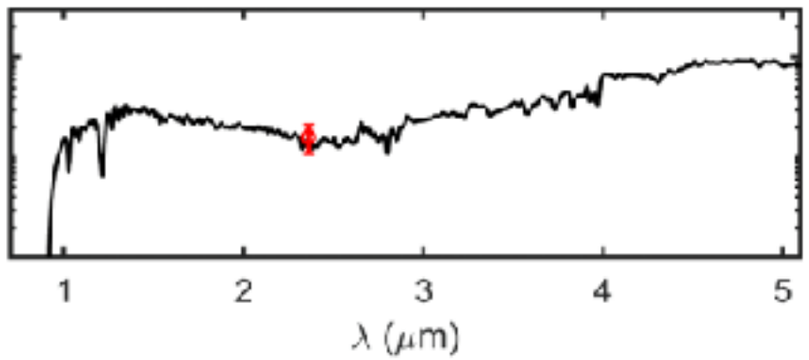
# High-Throughput Linearly Variable Filters Spectroscopy

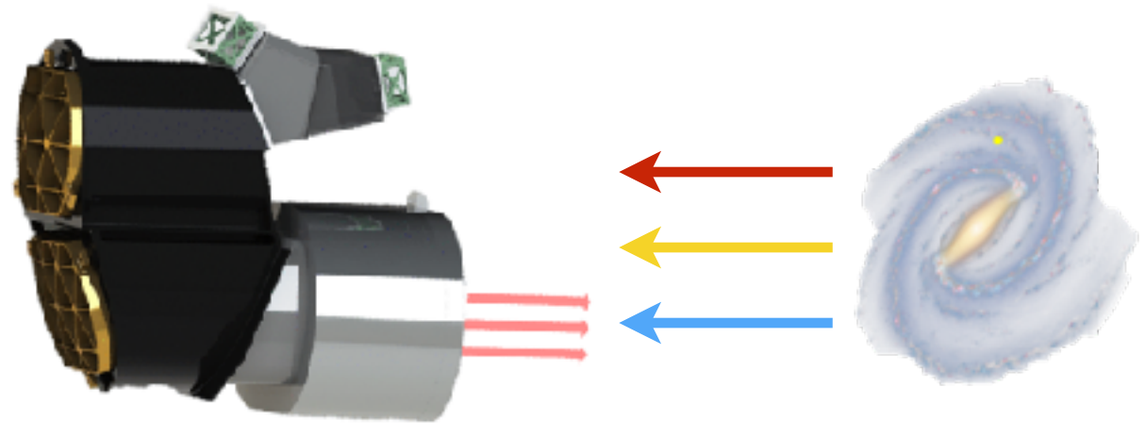


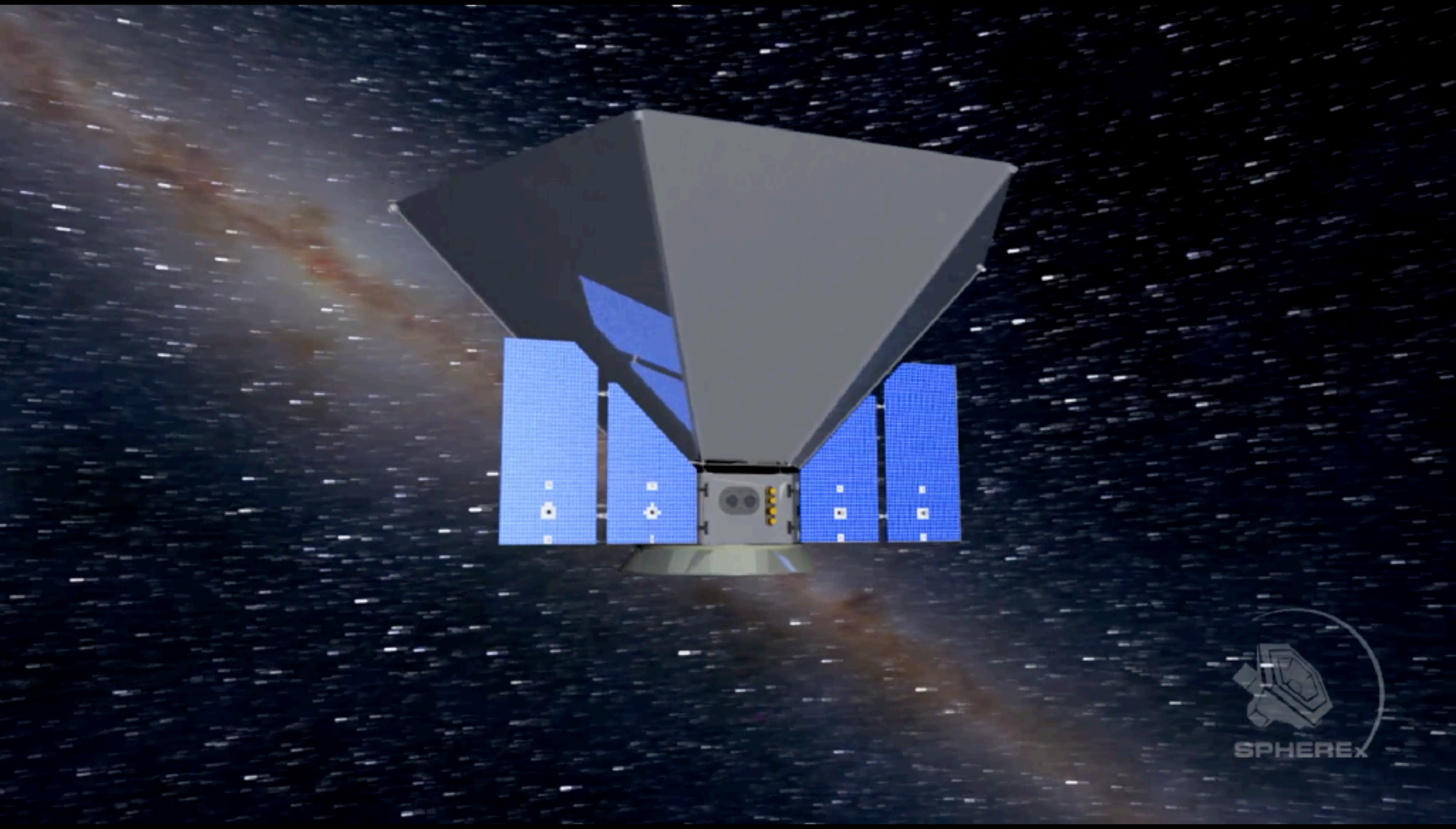

LVF used on ISOCAM, HST-WPC2, New Horizons LEISA, OSIRIS-REx



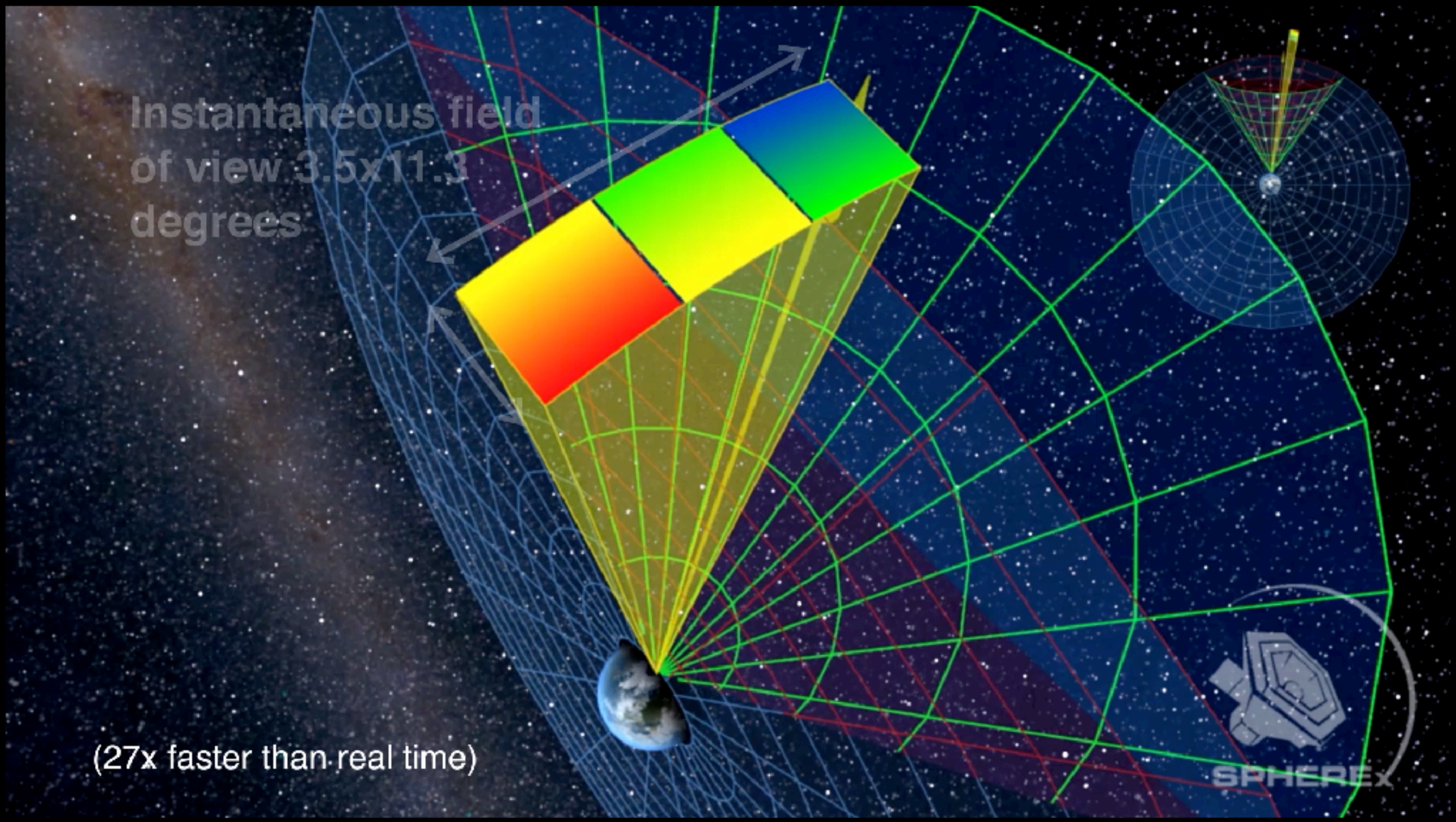



Spectra obtained by stepping sources over the FOV in multiple images: no moving parts

# SPHEREX AVOIDANCE CRITERIA

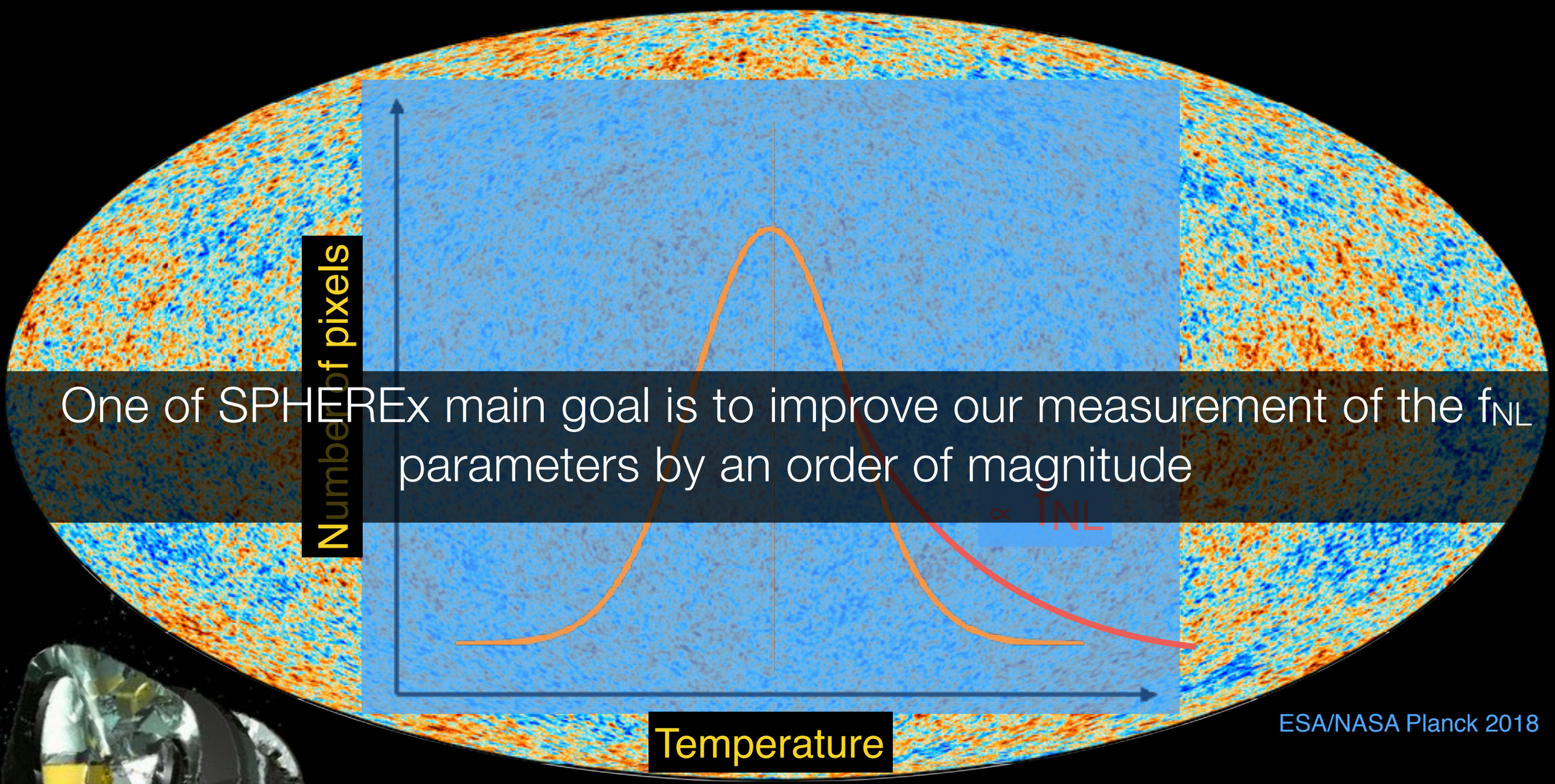


# PRE-PROGRAMED SCANNING STRATEGY

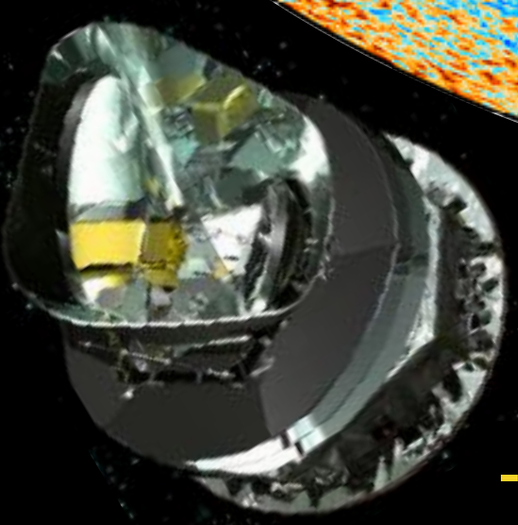


# INFLATION INVESTIGATION

# PLANCK MAP IS GAUSSIAN



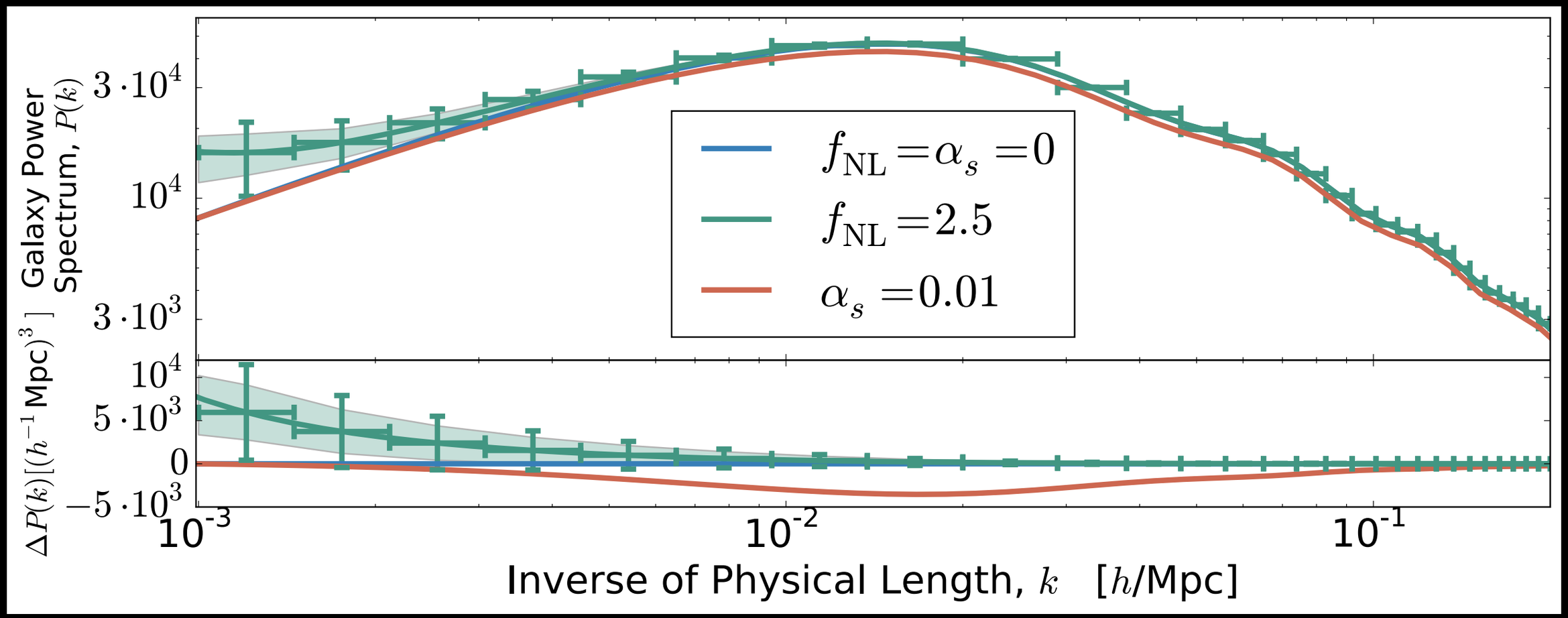

One of SPHEREx main goal is to improve our measurement of the $f_{NL}$ parameters by an order of magnitude



-300 μK +300

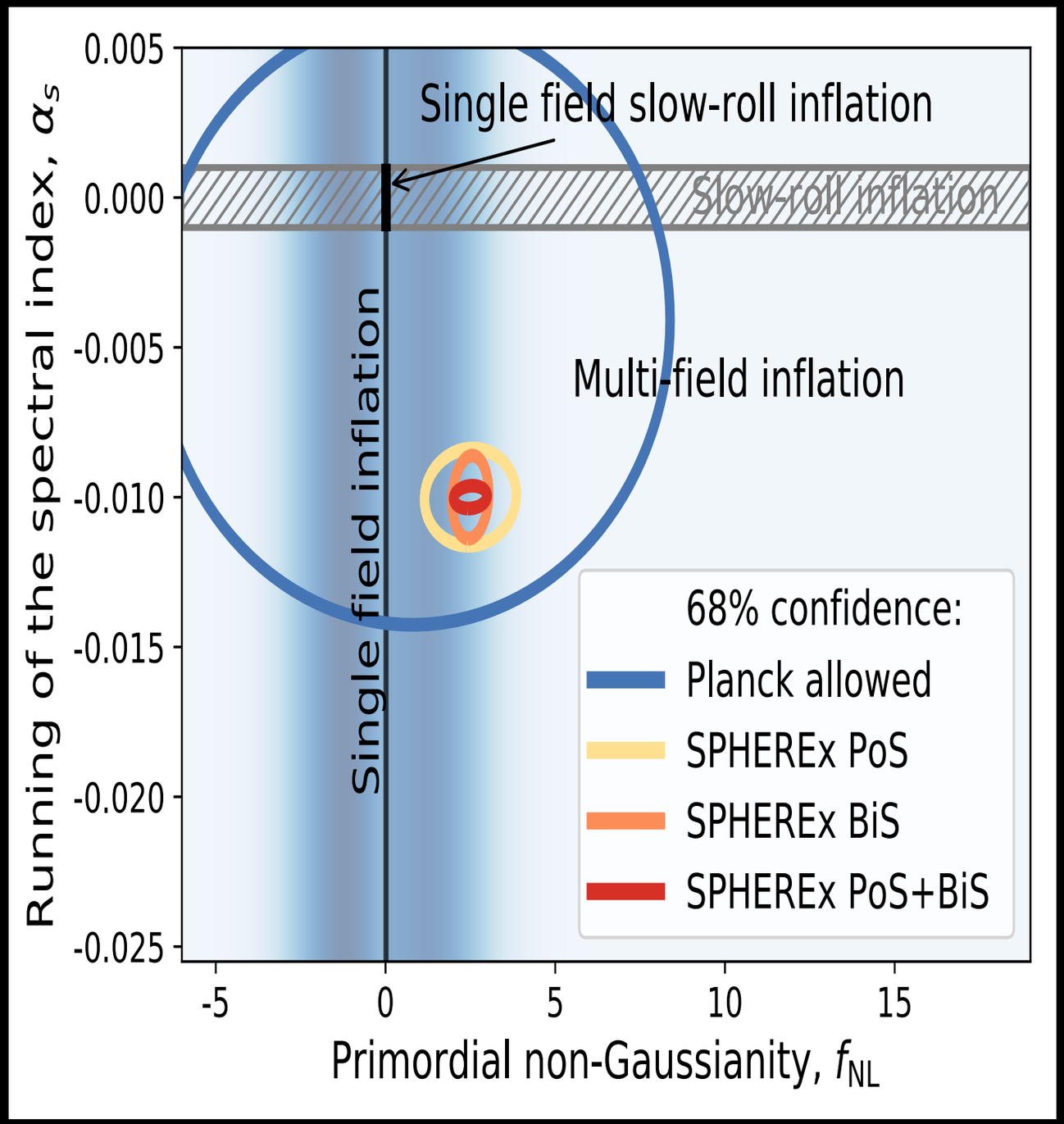
ESA/NASA Planck 2018

# POWER SPECTRUM MEASUREMENT




3D clustering of galaxies selected in external catalogs but with spectra/redshift measured in SPHEREx

# SPHEREX AND INFLATION




- SPHEREx produces a unique 3-D galaxy survey
  - ➡ Optimized for large scales to study inflation
  - ➡ Two ~independent tests of non-Gaussianity
- SPHEREx improves non-Gaussianity accuracy by a factor of ~10
  - ➡ Improves $\Delta f_{NL} \sim 5$ accuracy today to $\Delta f_{NL} < 0.5$
- Discriminates between models
  - ➡ Single-field inflation $f_{NL} << 1$
  - ➡ Multi-field inflation $f_{NL} \gtrsim 1$

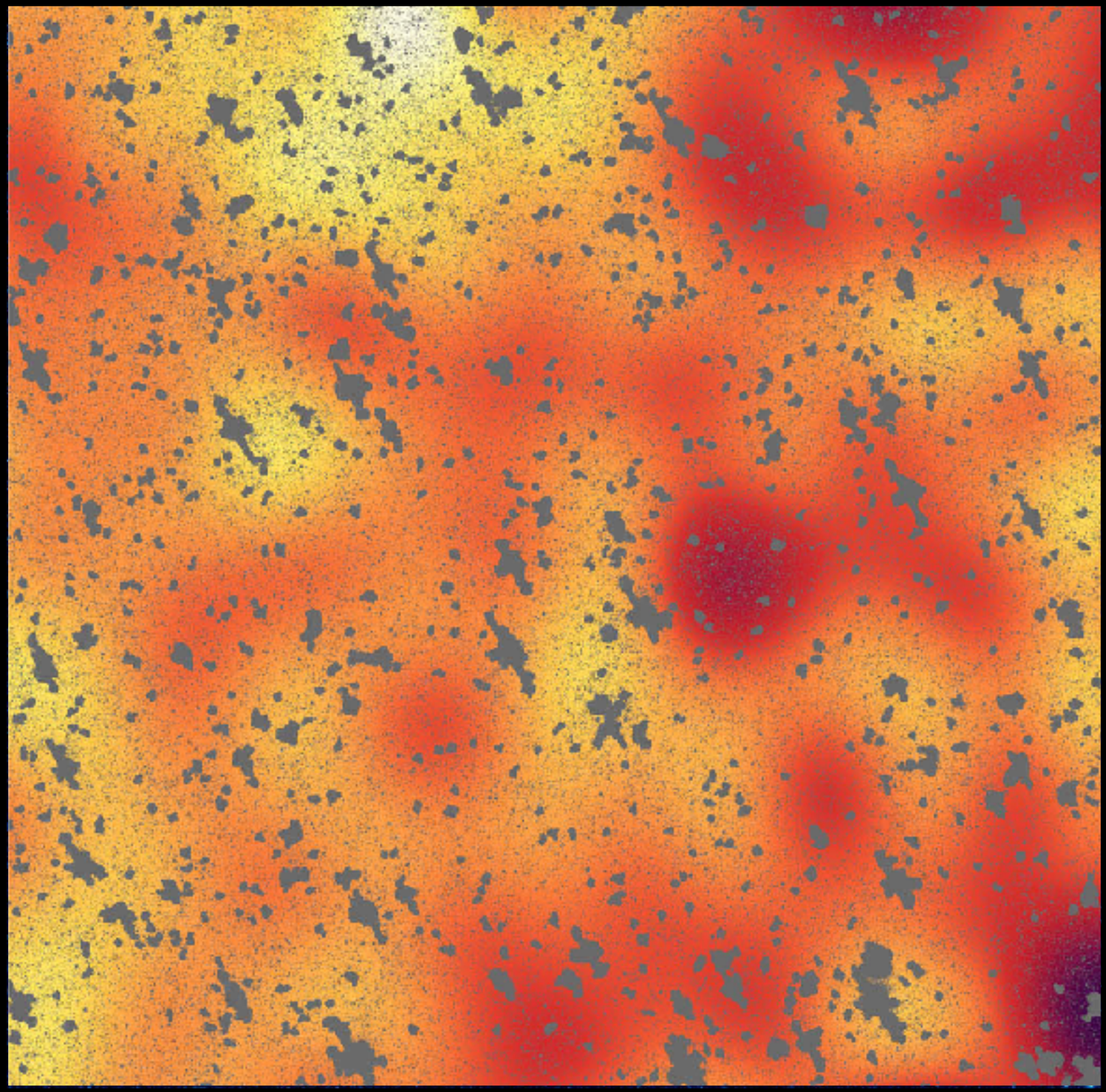
# MAIN SYSTEMATICS EFFECTS FOR LARGE-SCALE CLUSTERING MEASUREMENT

- Allocated systematic budget level set at the δn/n = 0.2% rms/dex ($\Delta^2(k)=k^3P(k)/2\pi^2 \propto (\delta n/n)^2$)
  - ➡ ~mmag controls of all systematic effects over ~30 deg. scales

- Dominant expected systematic effects (for cosmology):
  - ➡ Galactic extinction: 3 mmag rms before mitigation and δn/n = 0.06% rms/dex after mitigation
  - ➡ Selection non-uniformity: 0.2 mag rms before mitigation and δn/n = 0.06% rms/dex after mitigation
  - ➡ Redshift errors due to non-uniform noise: 0.2 mag rms before mitigation and δn/n = 0.017% rms/dex after mitigation
  - ➡ Calibration stability: <1% drift over 4 surveys and δn/n = 0.05% rms/dex after mitigation
  - ➡ Non-uniformity in external catalogs: 0.1% rms/dex after mitigation

# EXTRA-GALACTIC BACKGROUND LIGHT INVESTIGATION

# MAPPING EXTRA-GALACTIC BACKGROUND LIGHT




Spitzer @ 3.6 μm

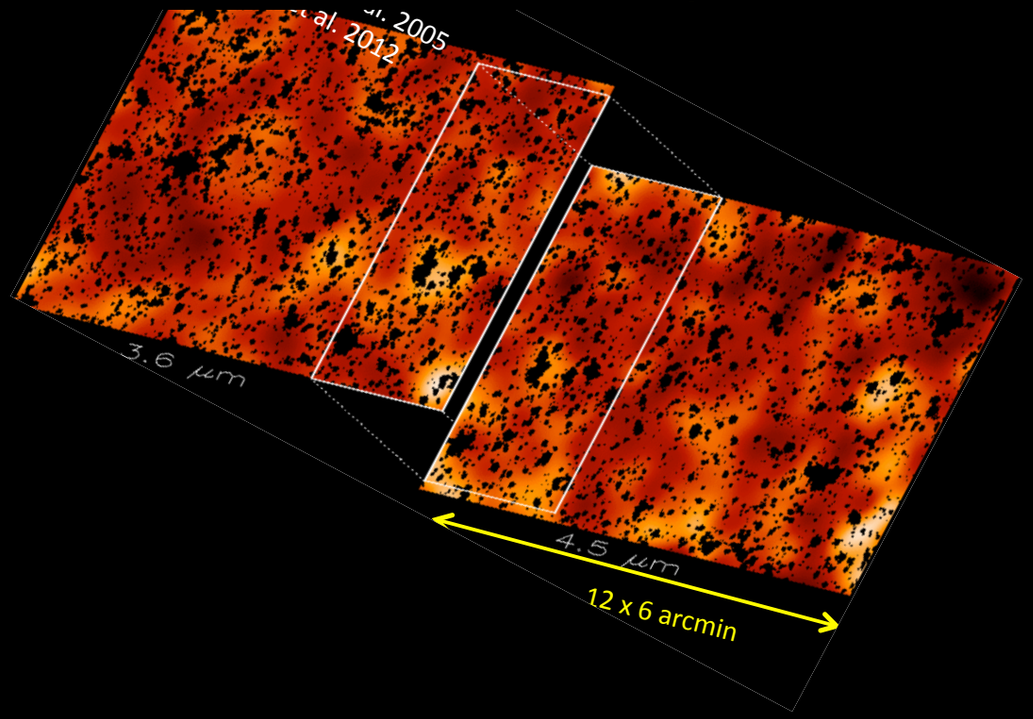
Cooray++07

# HOW DID GALAXIES BEGIN?

*MEASURING THE SPECTRA OF THE INTEGRATED COSMIC LIGHT THROUGH NIR FLUCTUATIONS*

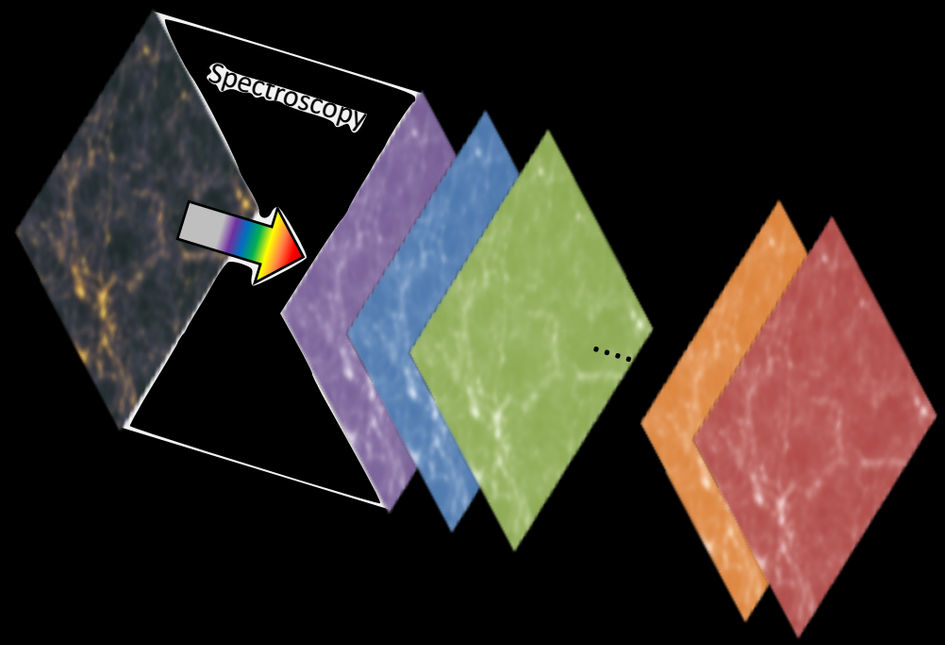
Spitzer (but also DIRBE, Planck, Akari, or Herschel)

*NIR in 2 bands and 72 sq. arcmin*




SPHEREx

*Extends to 96 bands and 200 sq. deg.*

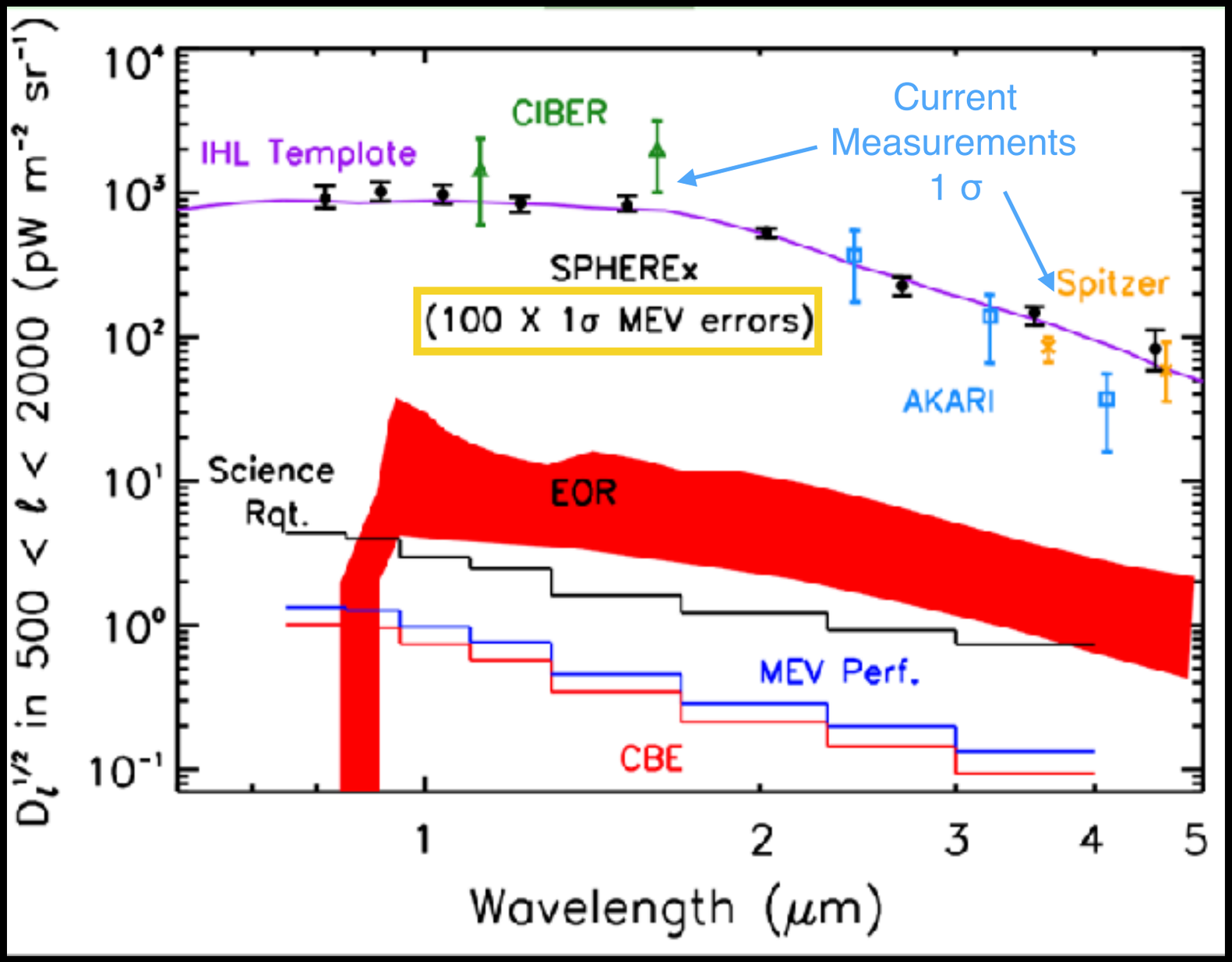



- SPHEREx observes every orbits ~200 sq. deg near the ecliptic poles
  - ➡We can reliably map light fluctuations over these *deep fields*

- Fluctuations receive contributions from all galaxies (incl. the dwarf galaxies responsible for reionization), but also from stars from stripped galaxies, etc.
  - ➡SPHEREx will measure the *spectra* of these fluctuations
  - ➡These spectra allow the extraction of the emission from the first galaxies (Feng++19)

# PROBING THE EPOCH OF REIONIZATION

Fluctuations in 9 broad continuum bands



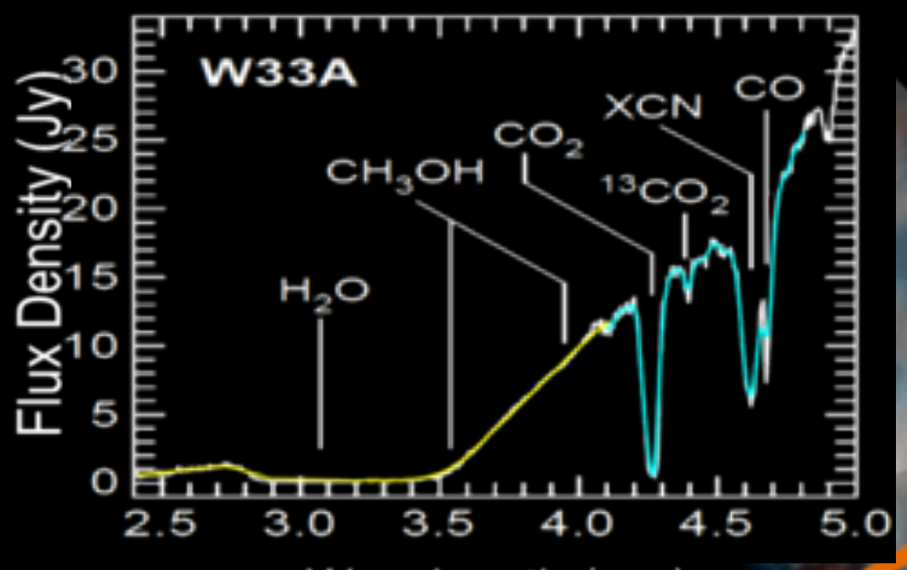

Can also extend to higher spectral resolution to do line intensity mapping (Tzu-Ching's talk this afternoon)

# SYSTEMATIC EFFECTS FOR DIFFUSE LIGHT MAPPING

- Dark current
  - ➡ Control to <0.1 $e^-$/s
- Thermal stability
  - ➡ < 10 mK p-p in 150 s exposure
- Stray-light from earth
  - ➡ <1% ZL with baffling
- Extended PSF inside or outside FOV
- Detector persistence

# ICE INVESTIGATION

# WHAT ARE THE CONDITION FOR LIFE OUTSIDE THE SOLAR SYSTEM?
## *SPHEREX SURVEYS ICES IN ALL PHASES OF STAR FORMATION*







SPHEREx will measure ice abundance towards >> 20,000 sources (currently ~200 known) and determine how water and biogenic ices evolve from molecular clouds to young stars to proto-planetary disks

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

- Sourced by biogenic molecules: $H_2O$, CO, $CO_2$, $CH_3OH$…

- Where do these molecules (in particular $H_2O$) come from:
  - ➡Did earth's water come from the Oort cloud, Kuiper belt or closer?
  - ➡Did water arrive from the late bombardment (~500 MY) or before?

- More than 99 % interstellar water is locked in ice:
  - ➡'Follow the Water' means 'Follow the Ice'

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

# SYSTEMATIC EFFECTS FOR ICES INVESTIGATION

- SNR > 100 per spectral channel!
- Variable sources
  - ➡ Remove sources that fail consistency over 4 surveys
- Bright source and persistence
  - ➡ Mask non-linear and persistent pixels
- Relative photometric calibration
  - ➡ Calibration on spectral standard and flat fields
  - ➡ Control at 2% bin to bin

# SPHEREX THREE LEGACY CATALOGS

- Spectral catalog of comets and asteroids (lead C. Lisse)

- Star catalog (lead  R. Akeson)
  - ➡ Precise spectra of stars of target planet-bearing stars from the Kepler, K2, TESS, Gaia, and other transit and radial velocity surveys
  - ➡ Atlas of spectra of late M dwarfs and all accessible brown dwarfs, down to the coolest Y dwarfs, to facilitate the study of our lowest mass stellar neighbors

- Spectral catalog of clusters of galaxies (lead L. Bleem)

- Support immediate community utilization of SPHEREx data

OD++16,18

# SUMMARY

- SPHEREx will create the first all sky near-infrared spectroscopic survey:
  - ➡ A quickly released public dataset of lasting legacy
  - ➡ Many discoveries will come from the community

- SPHEREx offers a simple and very robust design and modus operandi:
  - ➡ Naturally enables a high control of systematics thanks to multiple built-in redundancy, the CMB way

- SPHEREx will enable multiple and powerful studies:
  - ➡ Primordial non-Gaussianity to learn about Inflation
  - ➡ Extra-galactic background light from z=0 till the reionization era
  - ➡ Origin of water and biogenic ices in young stellar objects and proto-planetary systems
  - ➡ …

- SPHEREx has strong synergies with current and future observatories
  - ➡LSST, DESI, JWST, WFIRST, Euclid, SDSS-V, TESS, e-ROSITA, SO, CMB-S4…

- A very exciting decade ahead!

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# FIN