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

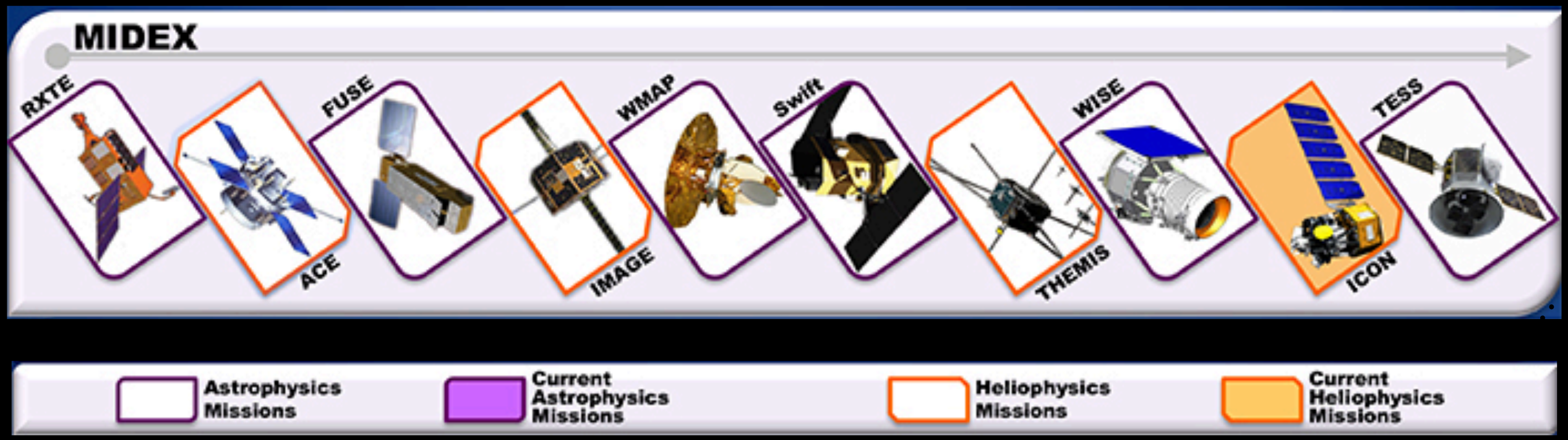
Jet Propulsion Laboratory

California Institute of Technology

http://spherex.caltech.edu

SPHEREx Team

ASTROPHYSICS & HELIOPHYSICS MID-EXPLORERS MISSIONS



Competed. PI led. <$250M. ~1 per decade in each category. Fast schedule.

SPHEREx is scheduled to launch in early 2024.

https://explorers.gsfc.nasa.gov/

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

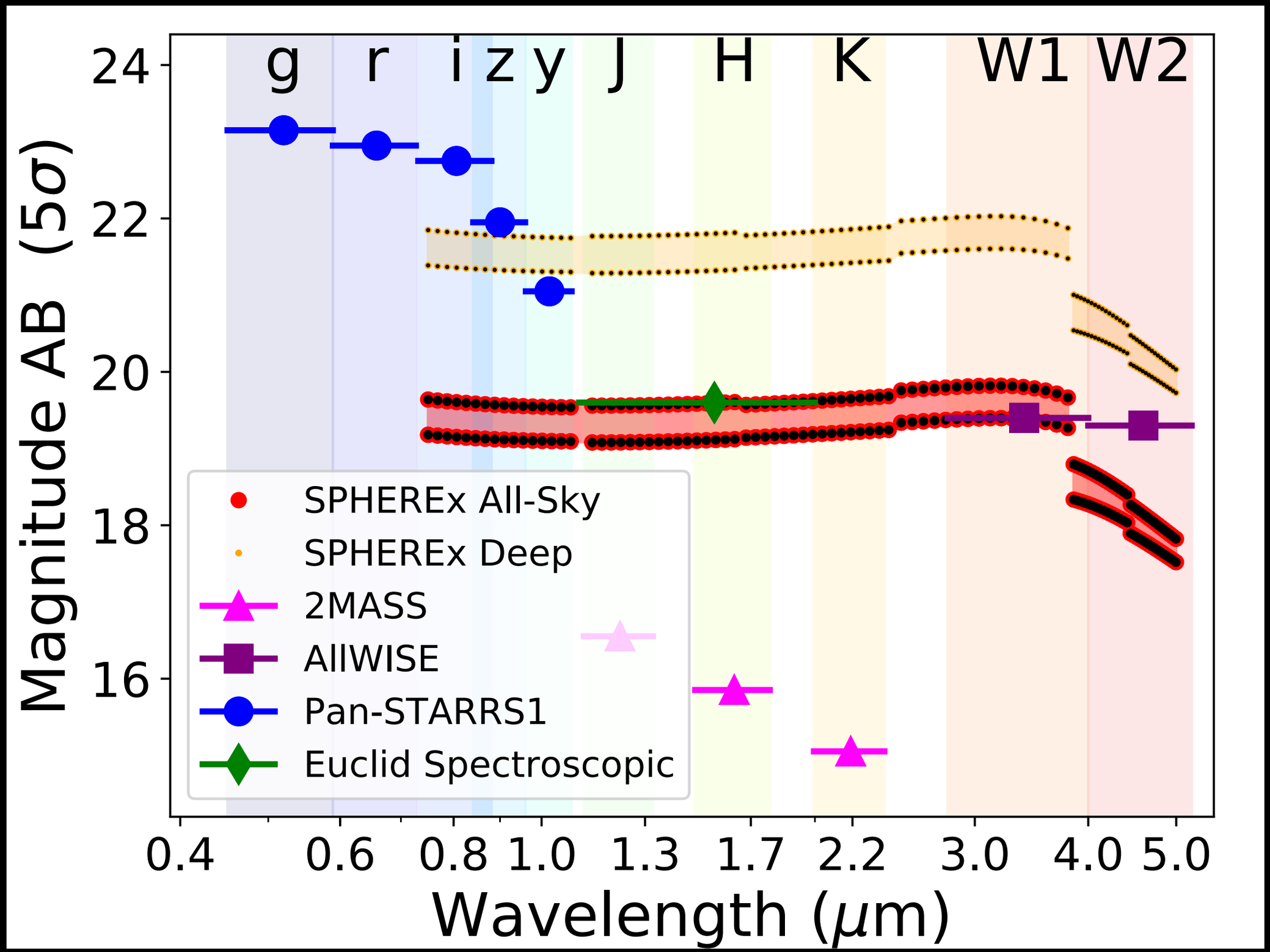
We will do so by constructing the first all-sky near-infrared spectral survey

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 102 fine photometric bands

SPHEREX SURVEY DEPTH



Deep survey

All-sky survey

Marveling at the Heavens with SPHEREx

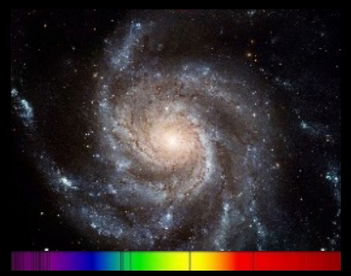
Camille Flamarion 1888

SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE

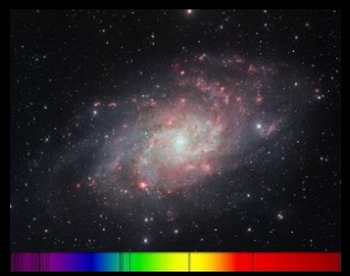
Galaxies

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

SPHEREX SCIENCE TEAM

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

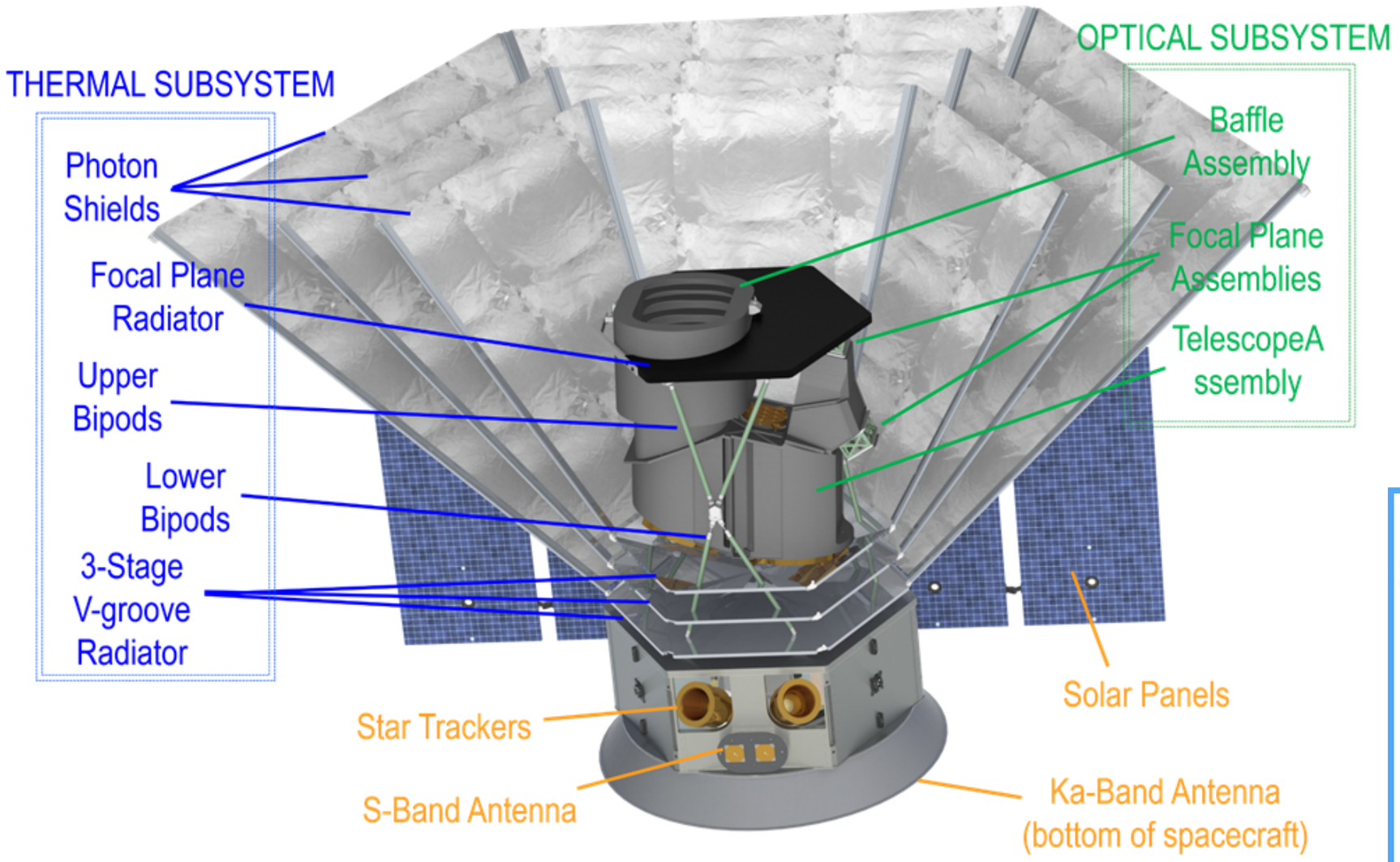
Rachel Akeson	Caltech/IPAC
Matt Ashby	CfA
Jamie Bock (PI)	Caltech/JPL
Lindsey Bleem	Argonne
Peter Capak	Caltech/IPAC
Tzu-Ching Chang	JPL/Caltech
Asantha Cooray	UC Irvine
Brendan Crill	JPL/Caltech
Olivier Doré (PS)	JPL/Caltech
Tim Eifler	U. Arizona
Salman Habib	Argonne
Katrin Heitmann	Argonne
Shoubaneh 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
Karin Öberg	CfA
Roger Smith	Caltech
Yong-Seon Song	KASI
Harry Teplitz	Caltech/IPAC
Volker Tolls	CfA
Stephen Unwin	JPL
Michael Werner	JPL
Rogier Windhorst	ASU
Yujin Yang	KASI
Michael Zemcov	RIT

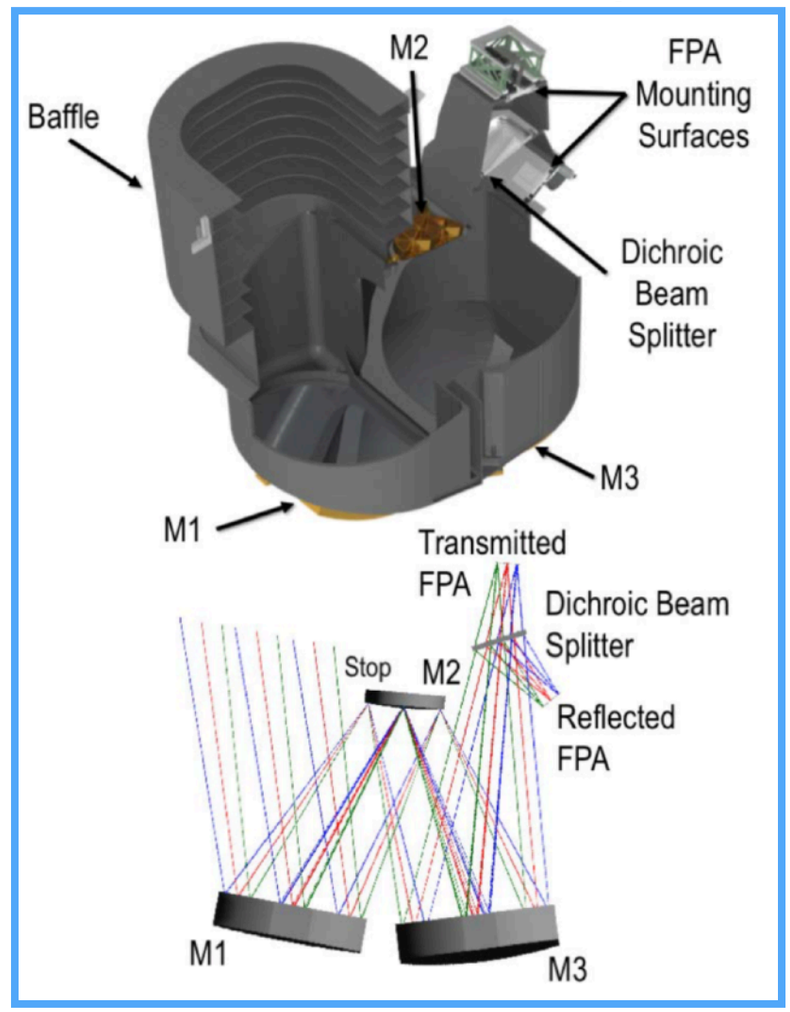
Image Credit: Illustris TNG

SPHEREx: An Innovative Architecture Based on Mature Technologies

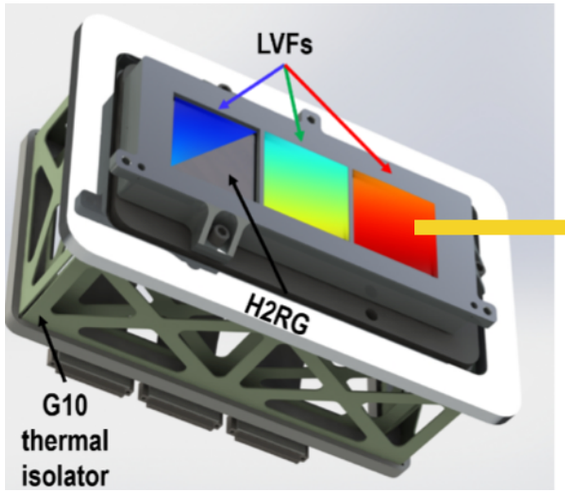


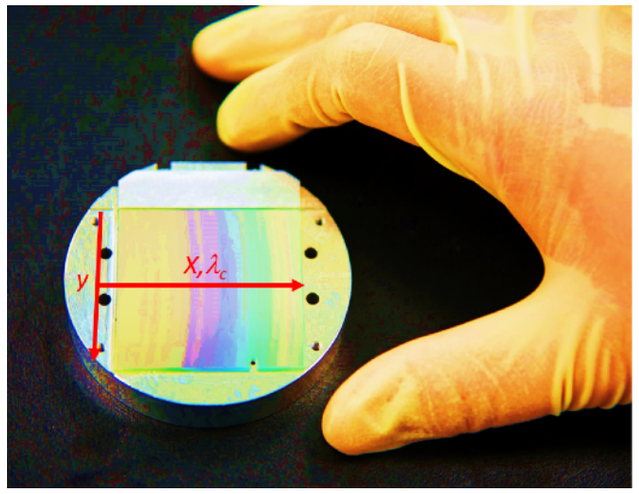
Parameter	Value
Telescope eff. diameter	20 cm
Field of view	3.5 x 11 deg.^{2}
Pixel size	6.2 arcsec
Wavelength range	0.75 – 5 μm
Resolving power $\lambda/\Delta\lambda$	35-130

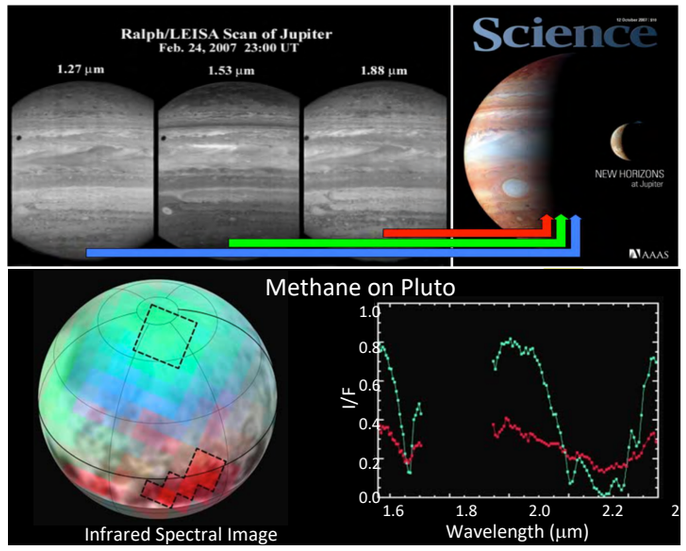
Wide field telescope



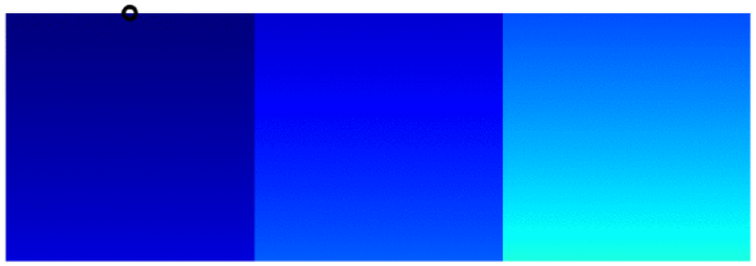
High-Throughput Linearly Variable Filters Spectroscopy

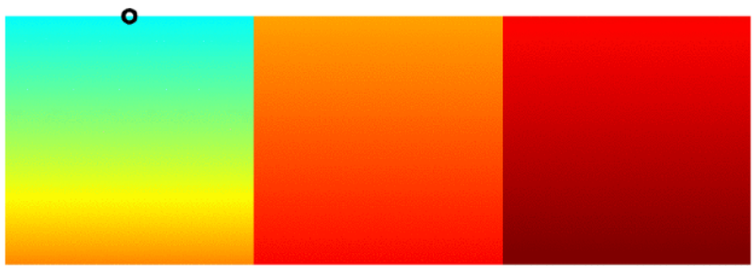


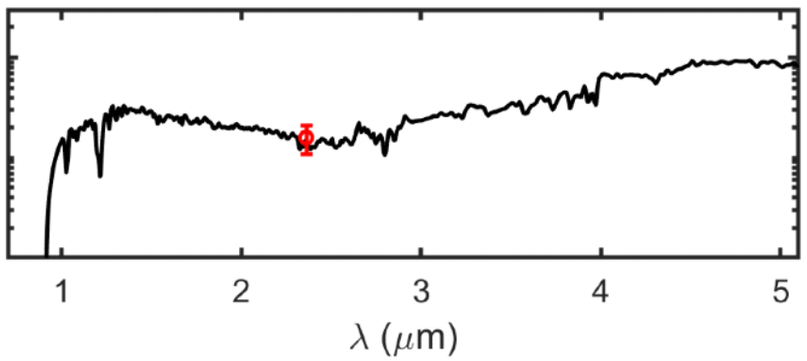


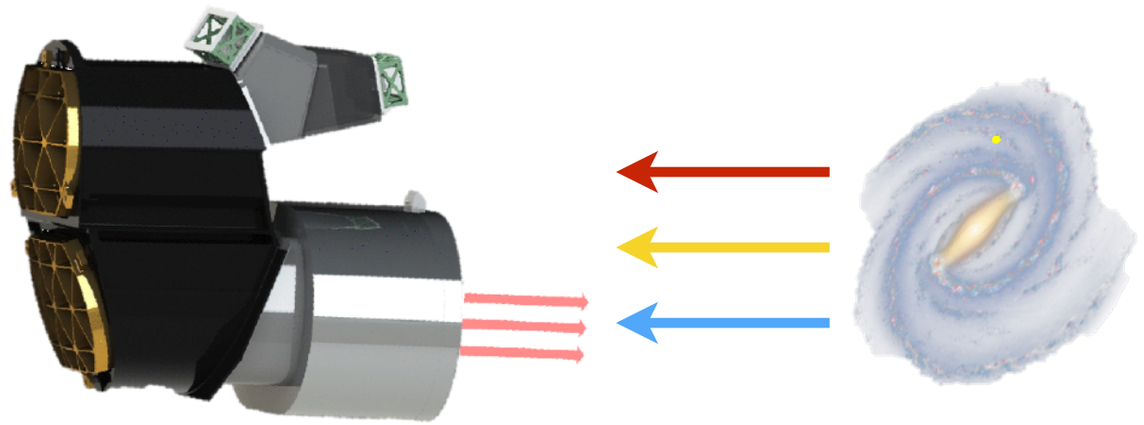


LVF used on ISOCAM, HST-WPC2, New Horizons LEISA, OSIRIS-REx





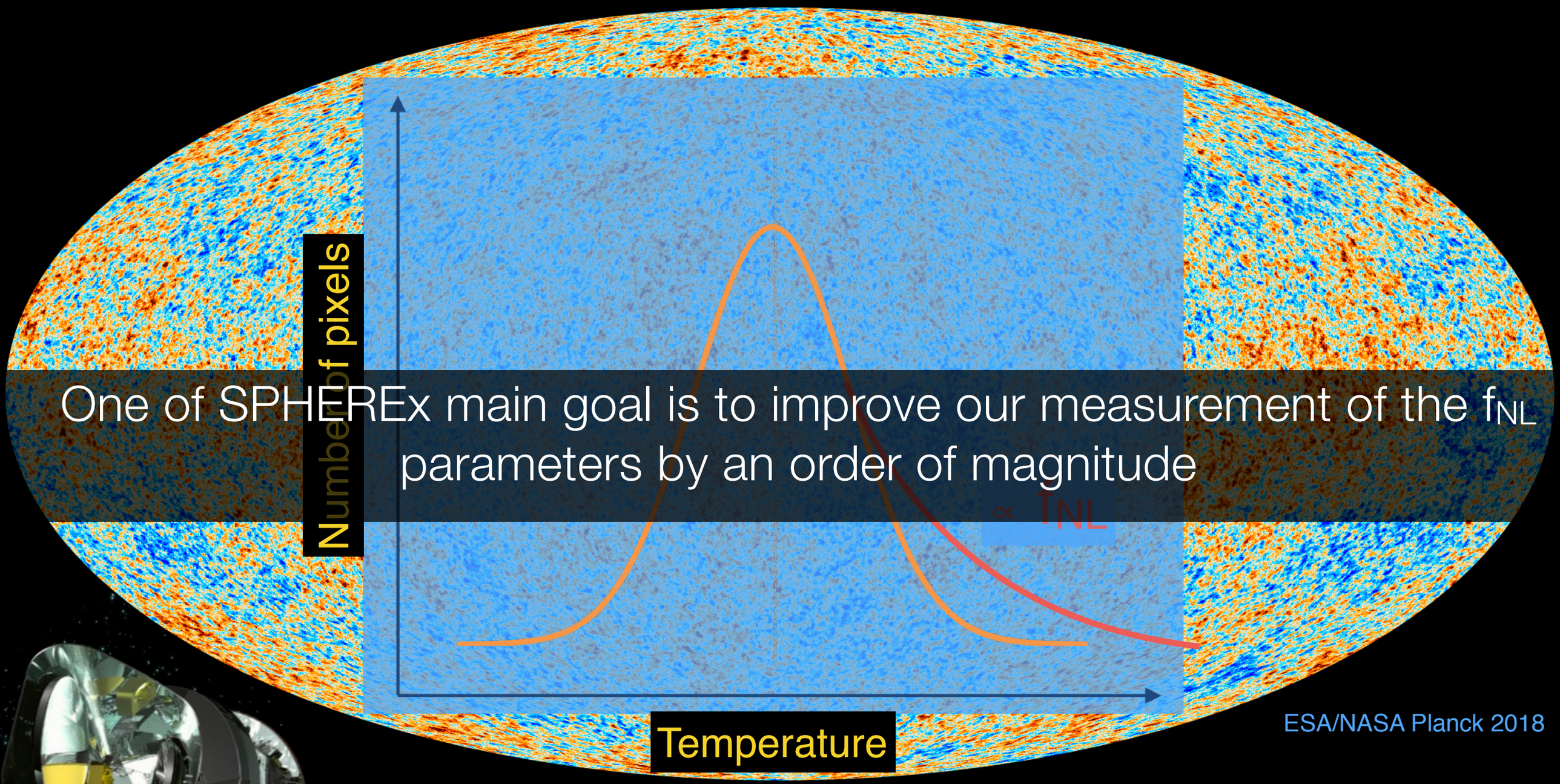




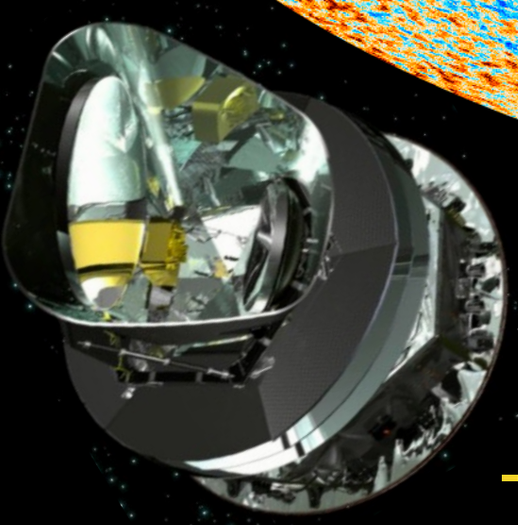
Spectra obtained by stepping sources over the FOV in multiple images: no moving parts

INFLATION INVESTIGATION

PLANCK MAP IS GAUSSIAN

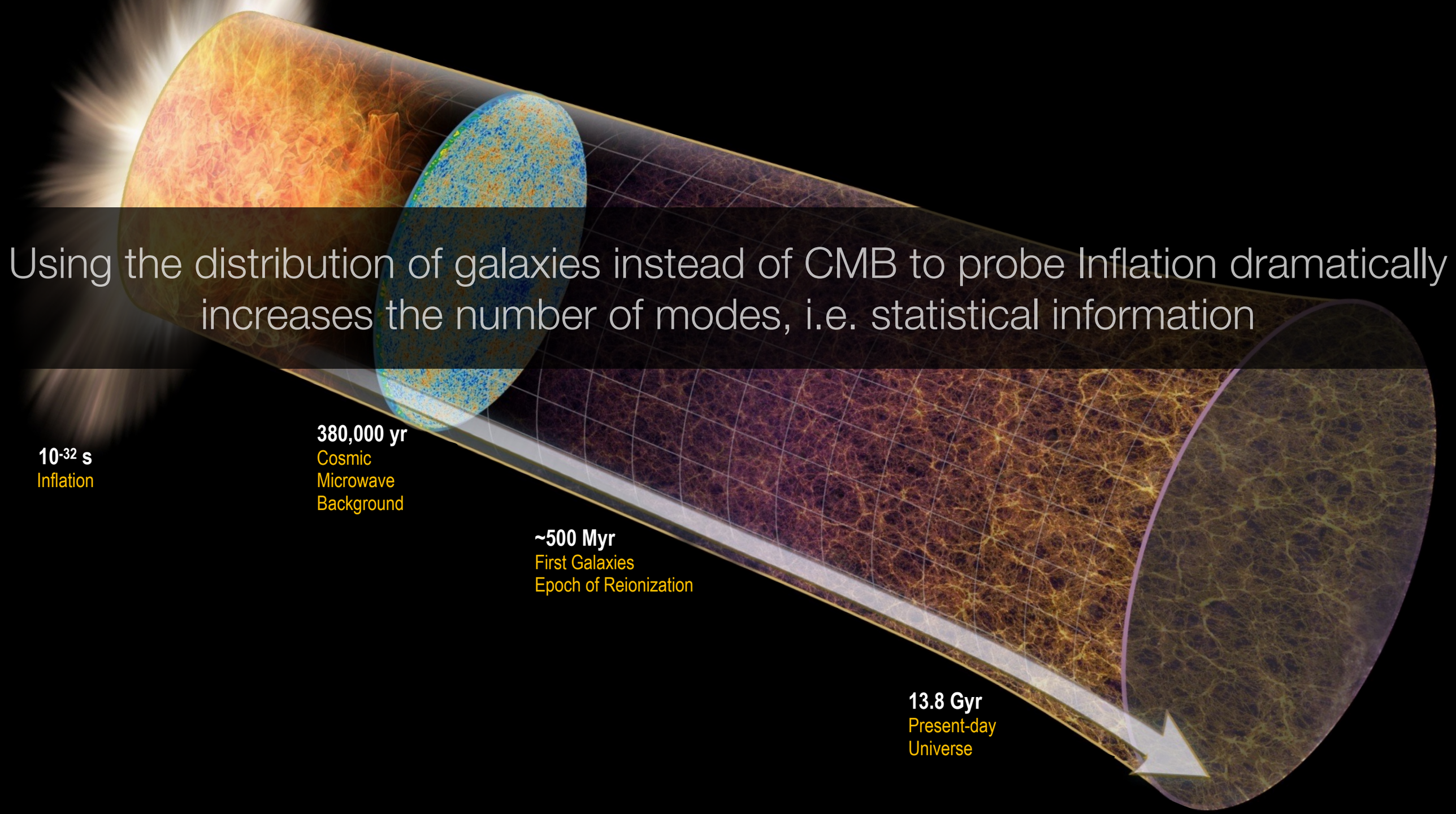


One of SPHEREx main goal is to improve our measurement of the f_{NL} parameters by an order of magnitude



-300 μK +300

PROBING INFLATION THROUGH GALAXY LARGE-SCALE STRUCTURES



Using the distribution of galaxies instead of CMB to probe Inflation dramatically increases the number of modes, i.e. statistical information

CMB CONSTRAINTS ON PRIMORDIAL NON-GAUSSIANITY

- Measuring f_{NL} is a unique probe of inflation:
  - ➡Probes interactions in the primordial Lagrangian
  - ➡Distinguish between single field and multi-field inflation

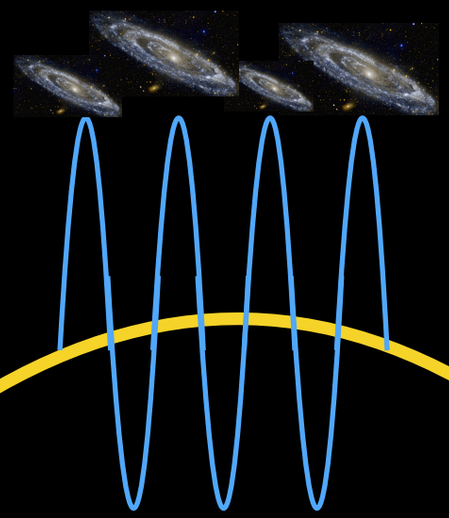
$$\Phi = \Phi_G + f_{NL}^{loc} \ \Phi_G^2$$

- Current limit using Planck (T+P) bispectrum:
  - ➡$f_{NL} = 0.8 \pm 5$ (68%)

- Future limits with a perfect CMB experiment (T+P, $l<3000$):
  - ➡$f_{NL} \lesssim 2$ (68%)

Planck 2015. XVII

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING



$\Phi_{\rm Short}$

$\Phi_{\rm Long}$

$$f_{NL} = 0$$

No mode coupling

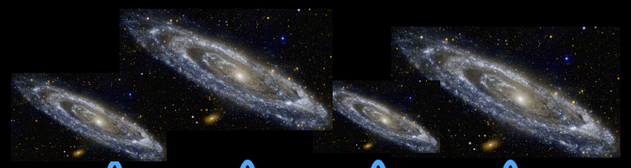
$\Phi_{\rm Short}$

$$\delta_{galaxy} = b\ \delta_{matter}$$

Galaxy bias (linear)

Slosar et al. 07

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

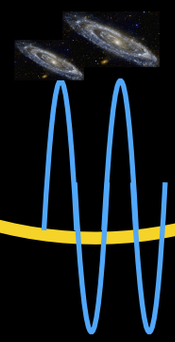


Φ_{Short}

Φ_{Long}

$$f_{NL} \neq 0$$

Mode coupling introduced



Φ_{Short}

$$\delta_{galaxy} = b\delta_{matter} + cf_{NL}\Phi_{Long} = (b + \Delta(b))\ \delta_{matter}$$

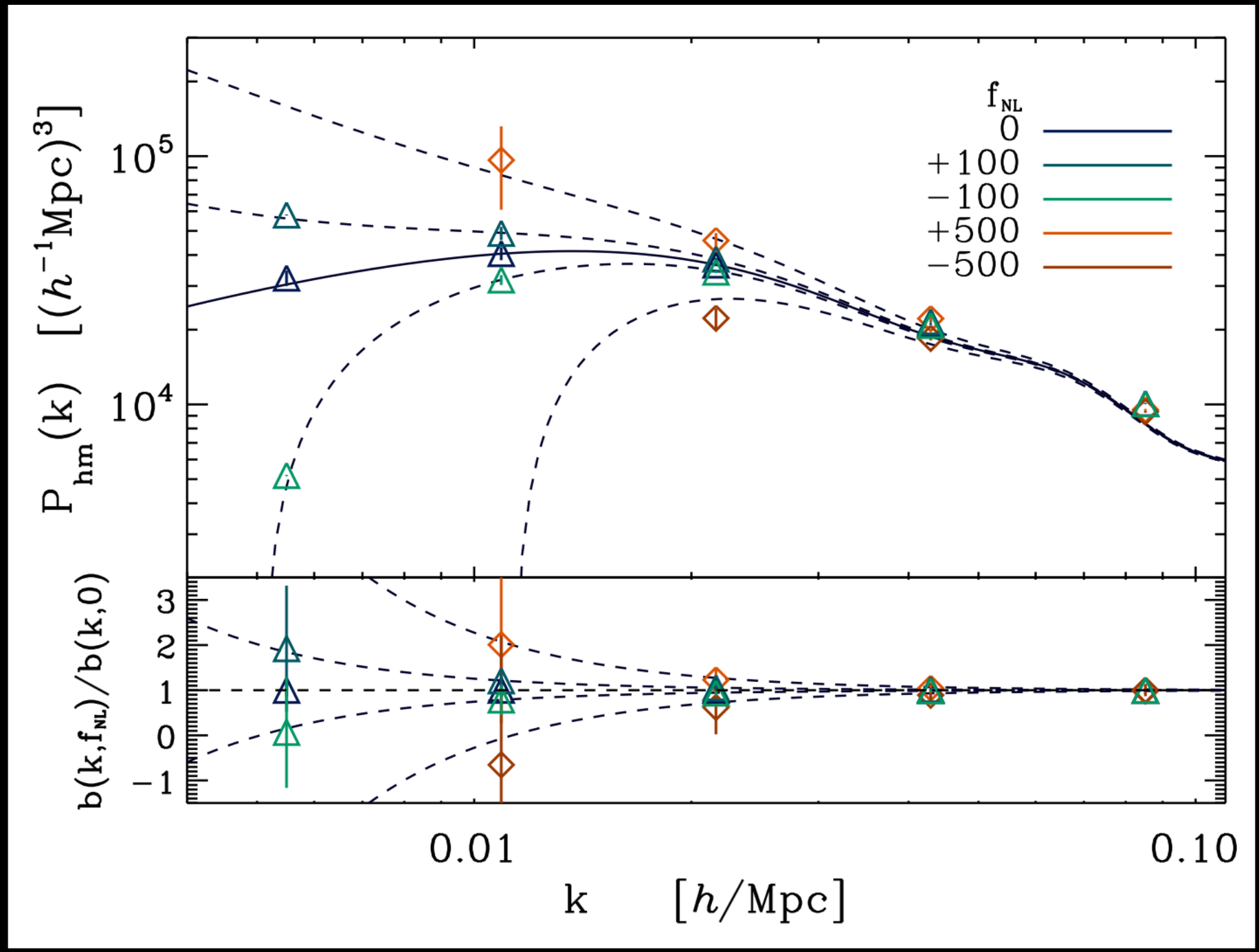
$$\Delta(b) \propto \ (b-1)\frac{f_{NL}}{k^2}$$

Scale dependent galaxy bias

PRIMORDIAL NON-GAUSSIANITY AND BIASING

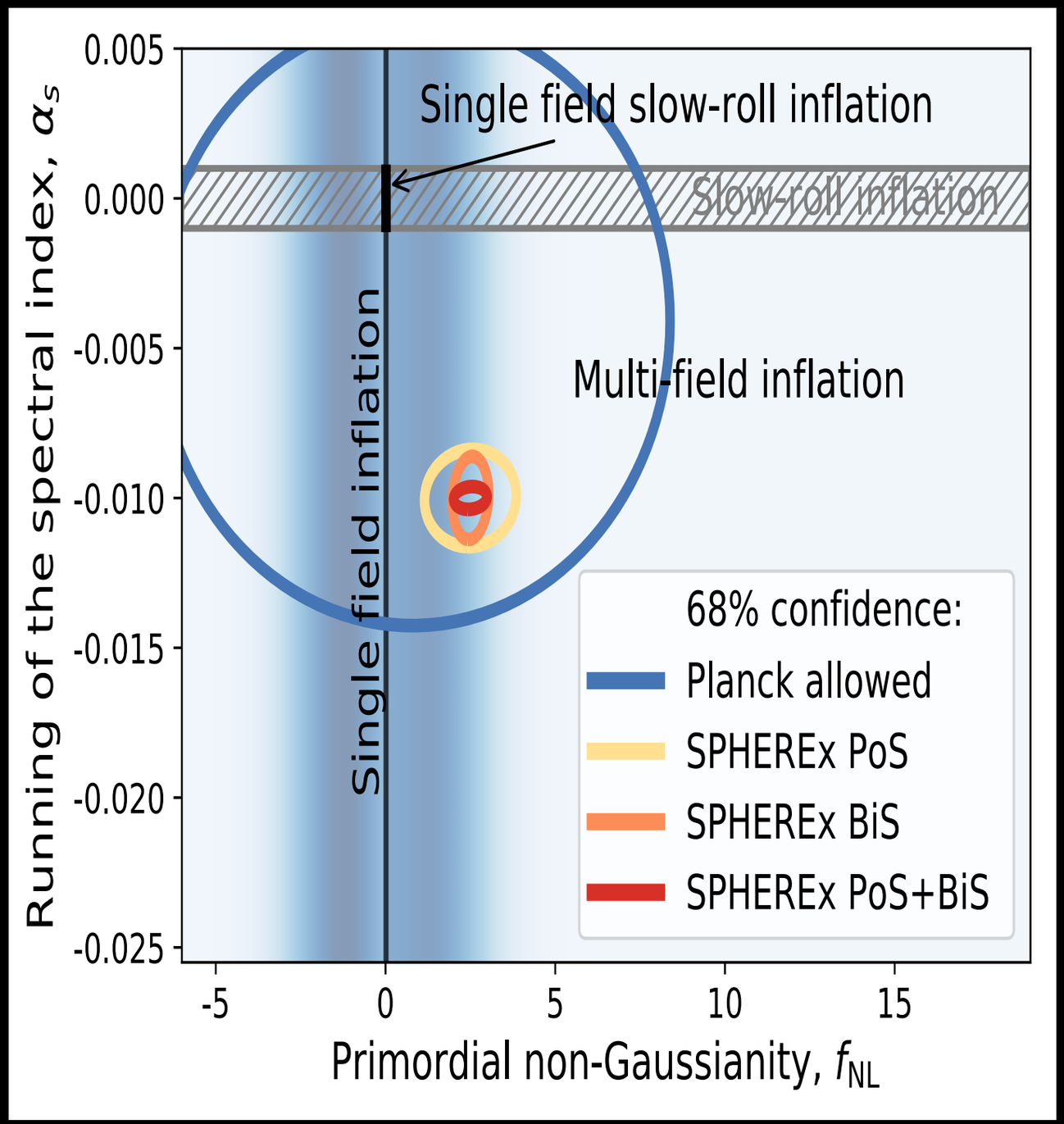
$$b_{NG}^{loc}(q) \propto f_{NL}^{loc} \frac{1}{T(q)q^2}$$

bias(k) bias(k) Pmm(k)



Dalal, OD, Huterer, Shirokov 07

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 $f_{NL} \gtrsim 1$

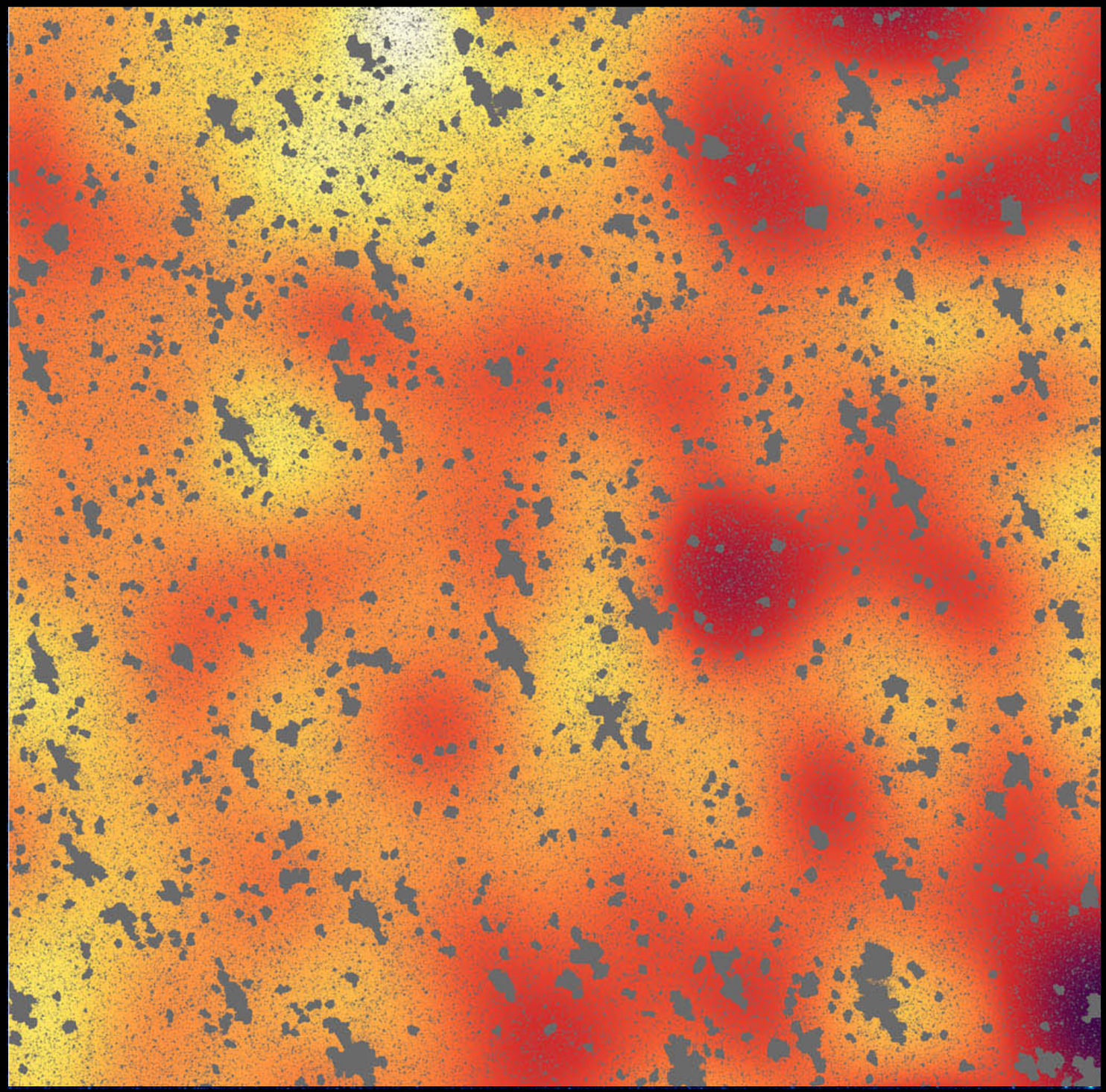
MAIN SYSTEMATICS EFFECTS FOR LARGE-SCALE CLUSTERING MEASUREMENT

- 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

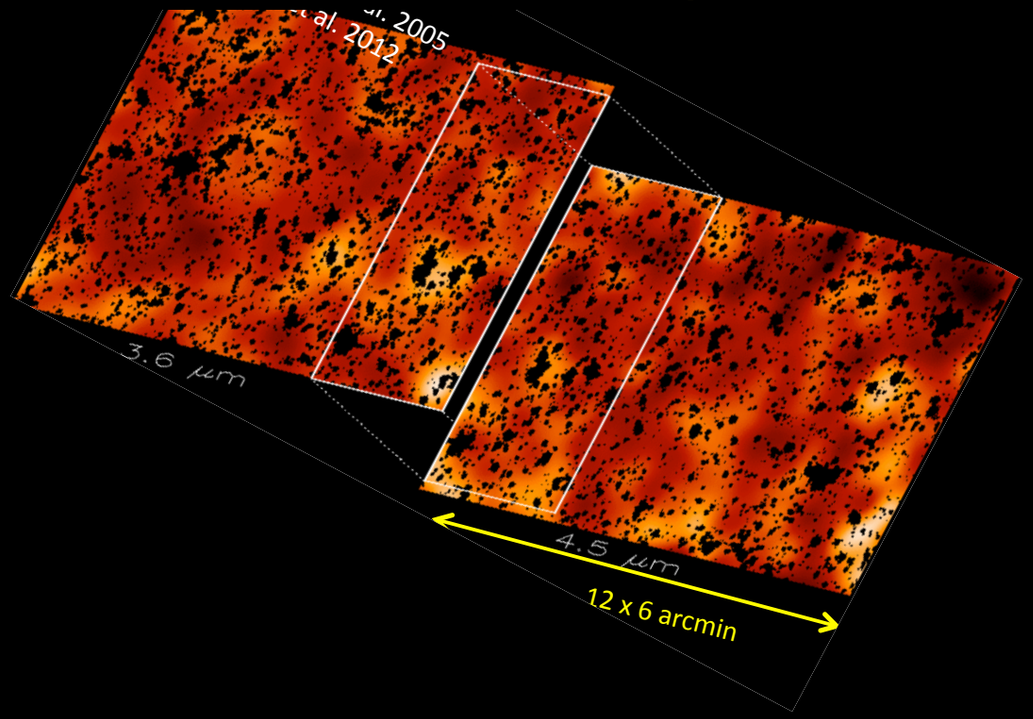
Cooray++07

HOW DID GALAXIES BEGIN?

MEASURING THE SPECTRA OF THE INTEGRATED COSMIC LIGHT THROUGH NIR FLUCTUATIONS

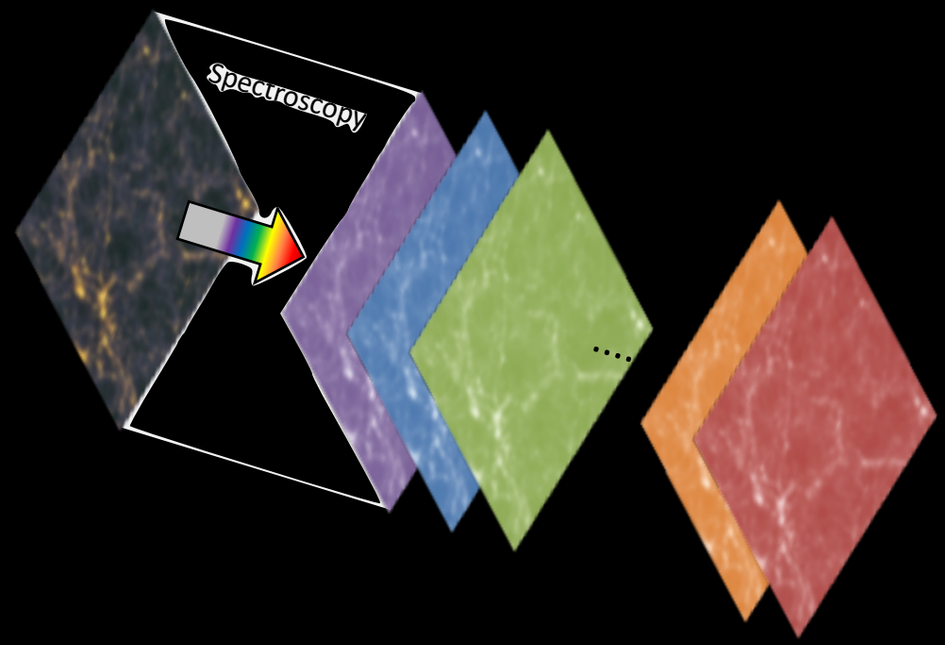
Spitzer (but also DIRBE, Planck, Akari, or Herschel)

NIR in 2 bands and 72 sq. arcmin



SPHEREx

Extends to 96 bands and 200 sq. deg.

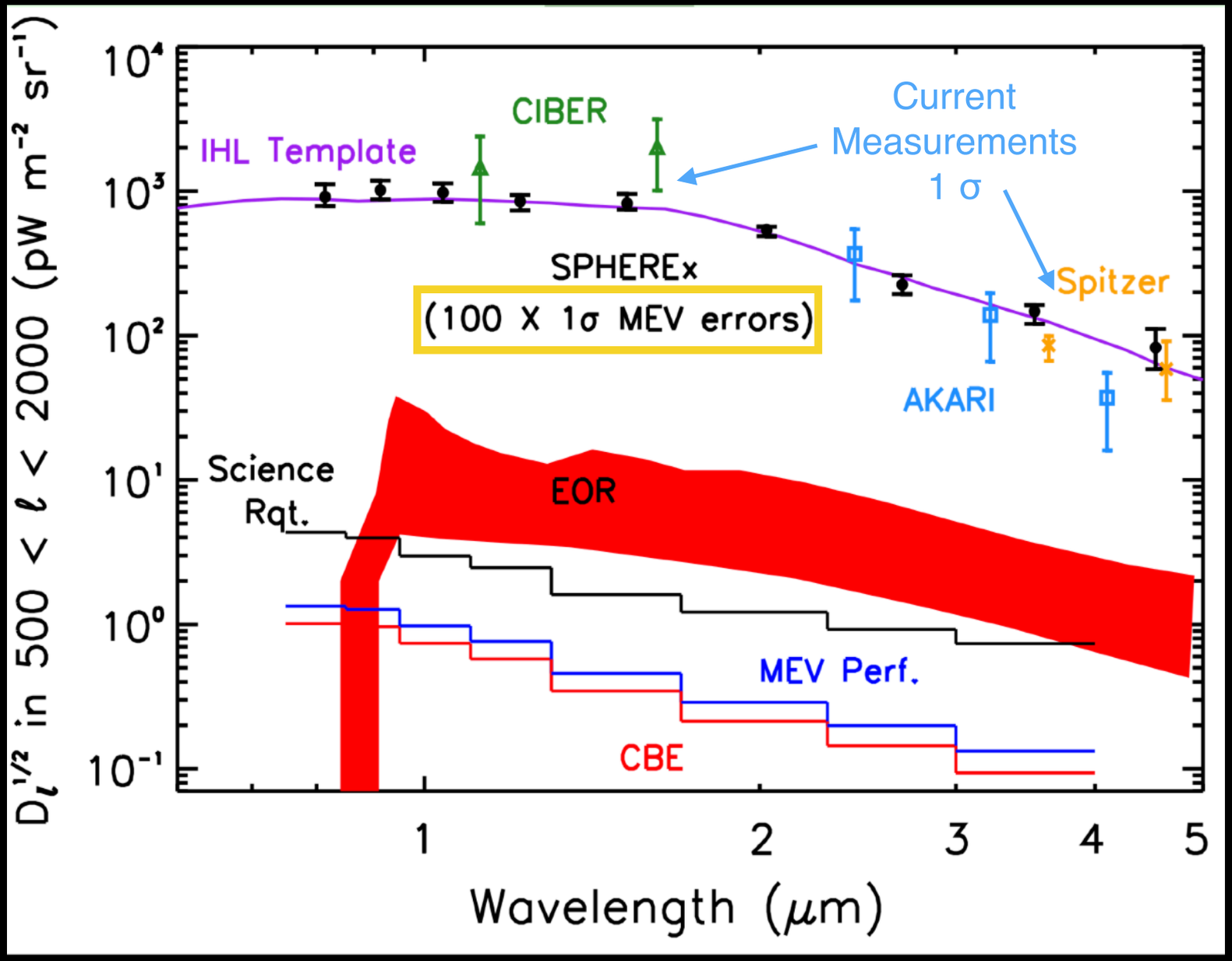


- SPHEREx observes every orbits ~200 sq. deg near the ecliptic poles
  - ➡We can reliably map light fluctuations over these *deep fields*

- 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

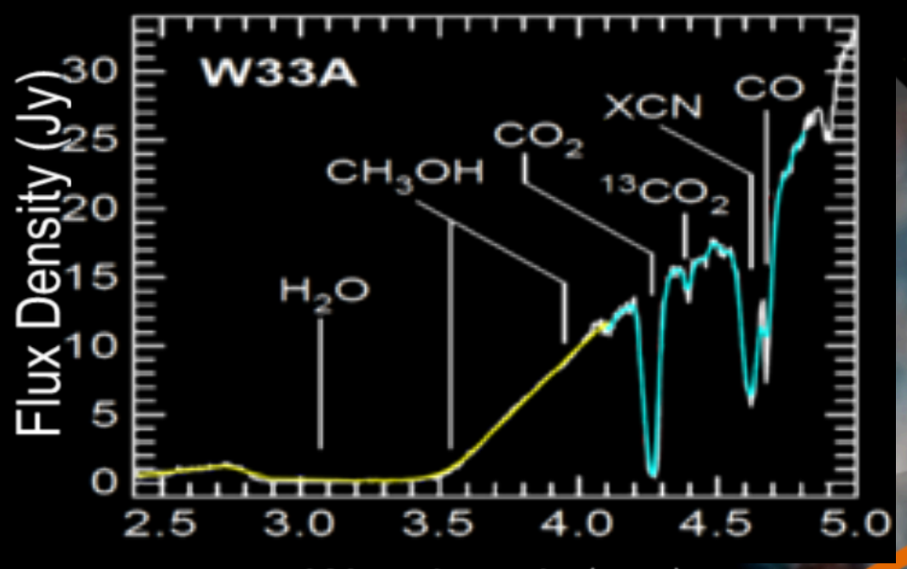
SYSTEMATIC EFFECTS FOR DIFFUSE LIGHT MAPPING

- 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…

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

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

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

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:
  - ➡ 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!

FIN