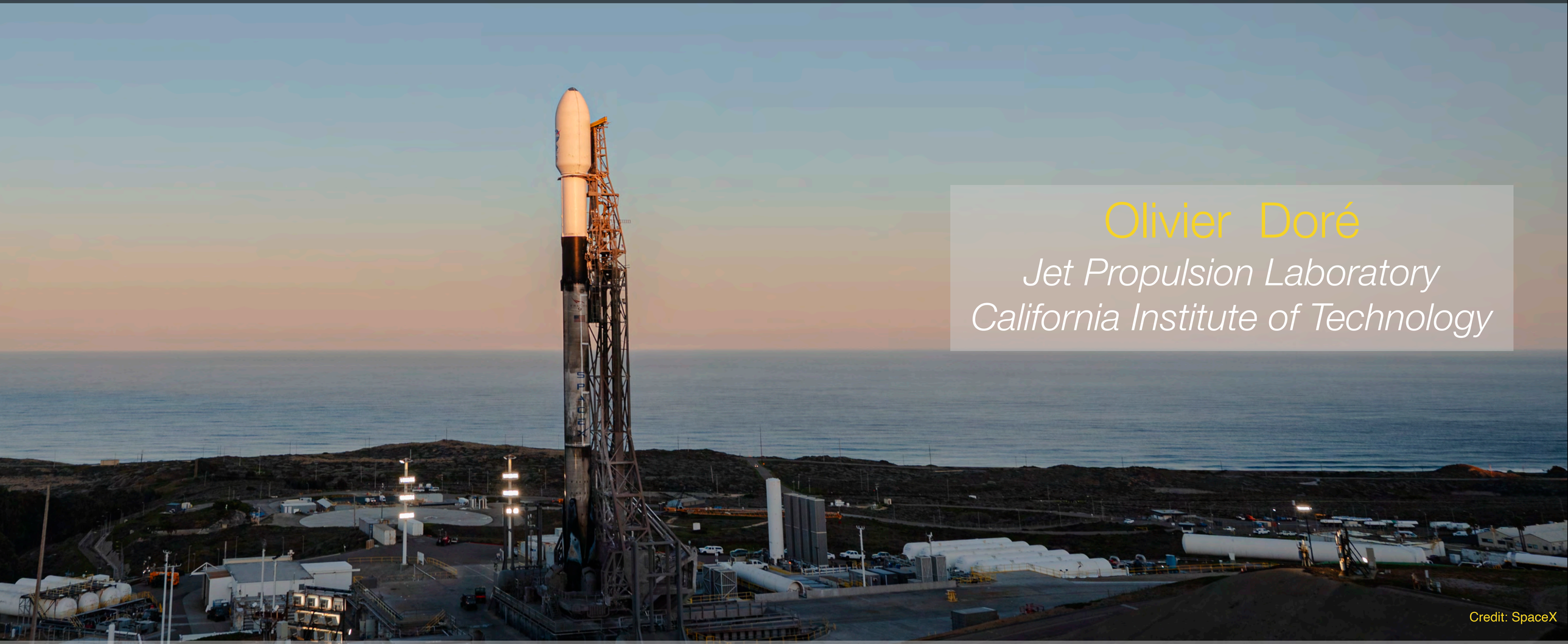
SPHEREx Is Mapping the Universe



Olivier Doré
Jet Propulsion Laboratory
California Institute of Technology

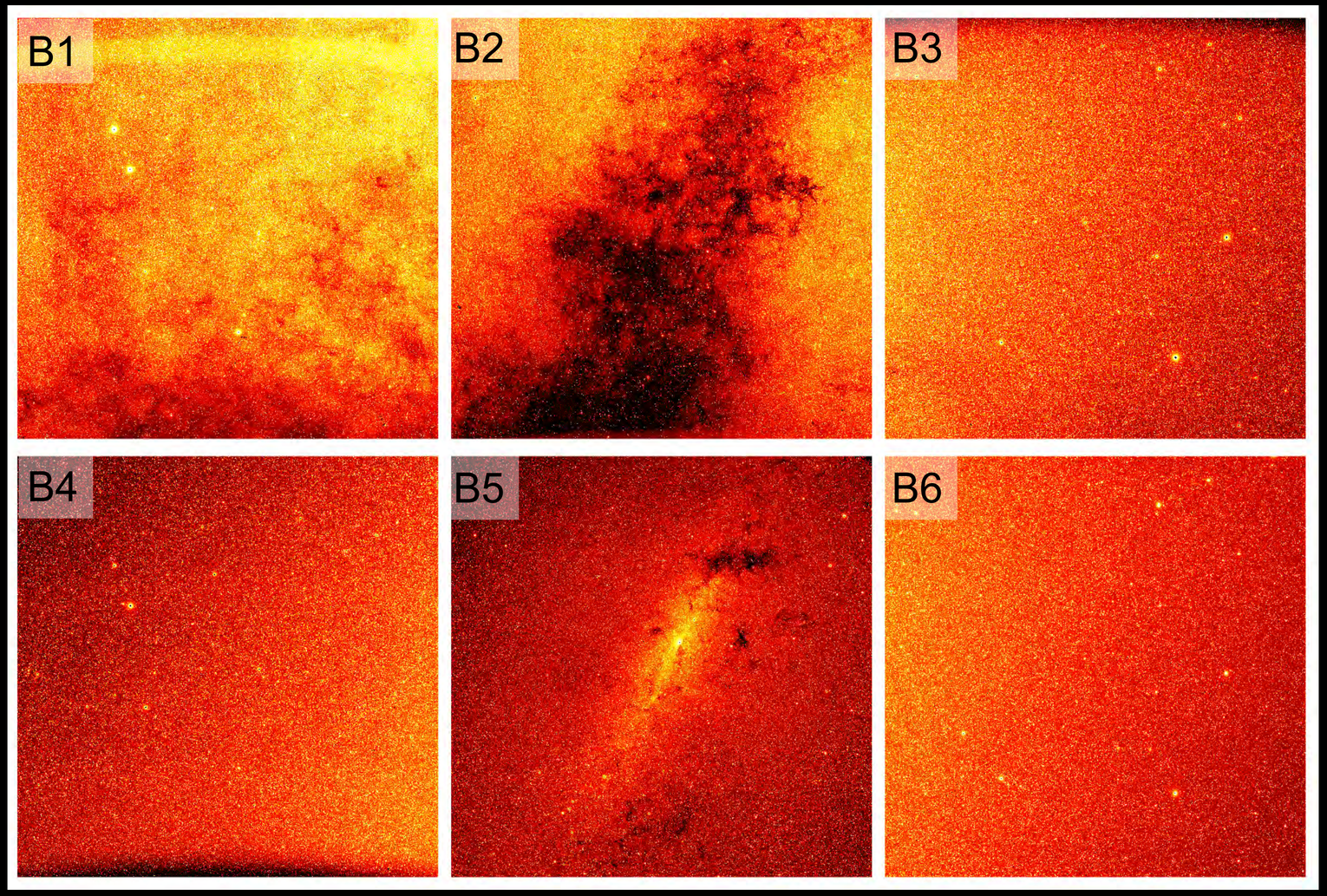
Credit: SpaceX

Jet Propulsion Laboratory
California Institute of Technology

https://spherex.caltech.edu

SPHEREx Team

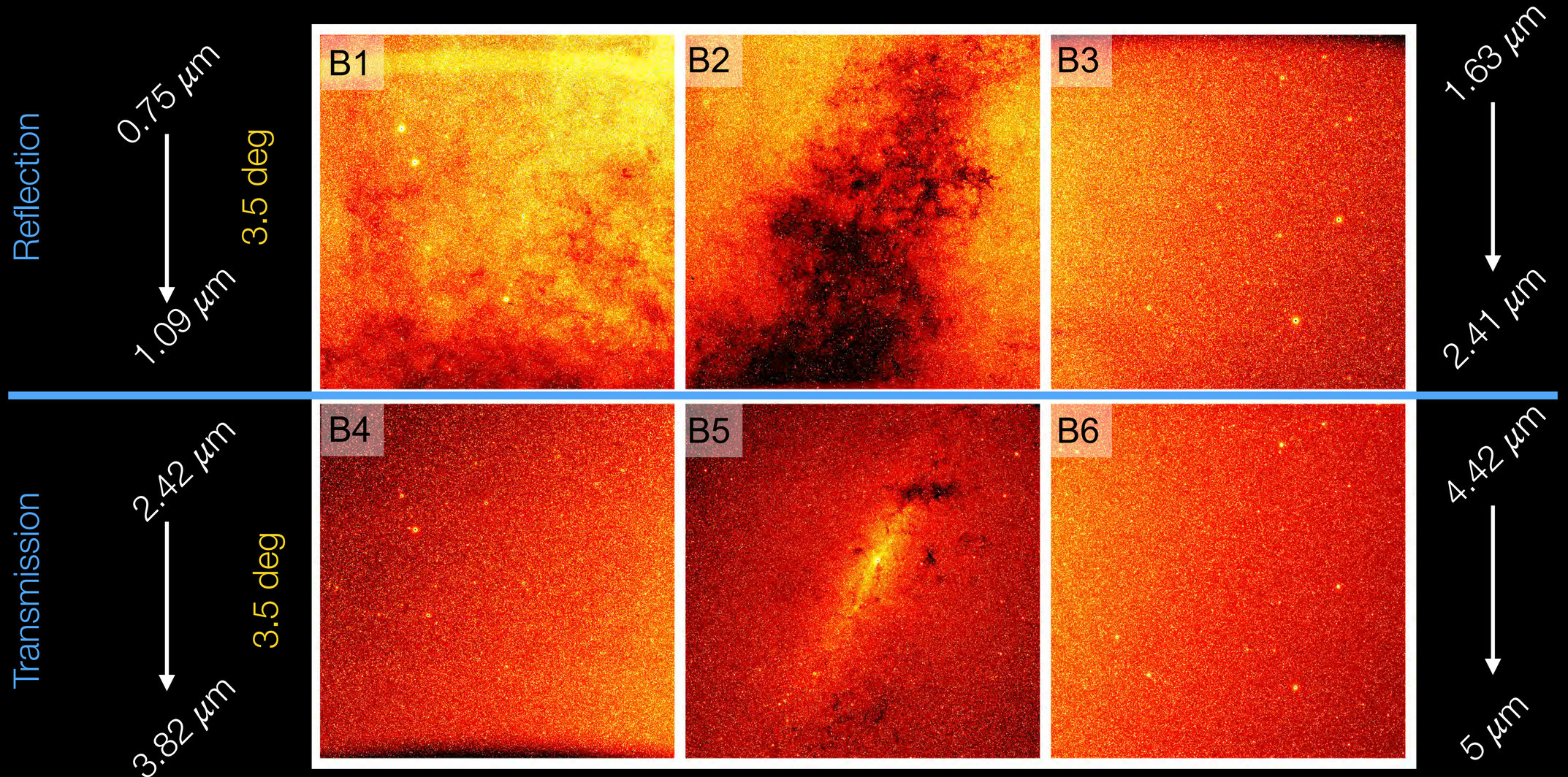
SPHEREX IS WORKING BEAUTIFULLY



Example of a raw level1 exposure near the *Galactic Center*, i.e. before any flat field or dark current correction.
1 of **563950** exposures (~600/day) we collected with 0 instrument collection failure as of 10/02.

Plot: Phil Korngut

SPHEREX DATA ARE INCREDIBLY RICH



These 6 exposures are spectral images of a contiguous area

Plot: Phil Korngut

SPHEREX IS DESIGNED TO ADDRESS THE MOST IMPORTANT QUESTIONS IN ASTROPHYSICS

- A NASA MIDEX Astrophysics mission selected on Feb. 19 2019
  - ➡ Same mission class as e.g. Swift, WMAP, WISE, TESS, and UVEX

- What are the Conditions for Life Outside the Solar System?
  - ➡ Survey the Milky Way for water ices and other biogenic molecules
- How did Galaxies begin?
  - ➡ Study the cosmic history of light production through near-infrared background fluctuations
- How did the Universe begin?
  - ➡ Probe the physics of the young inflationary Universe through the 3D spatial distribution of galaxies

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

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

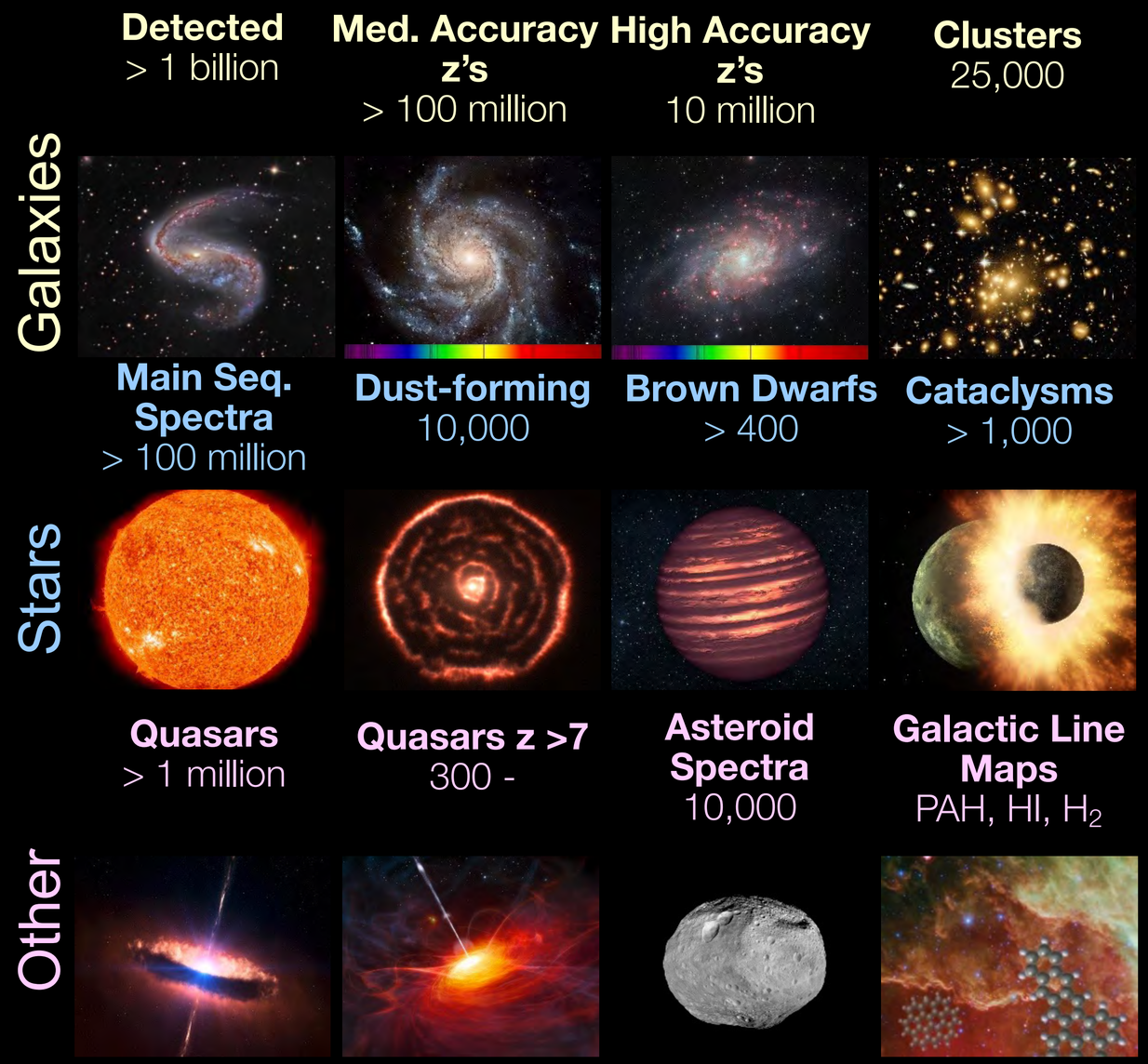
WHAT KIND OF DATASET IS SPHEREX PRODUCING?

- 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

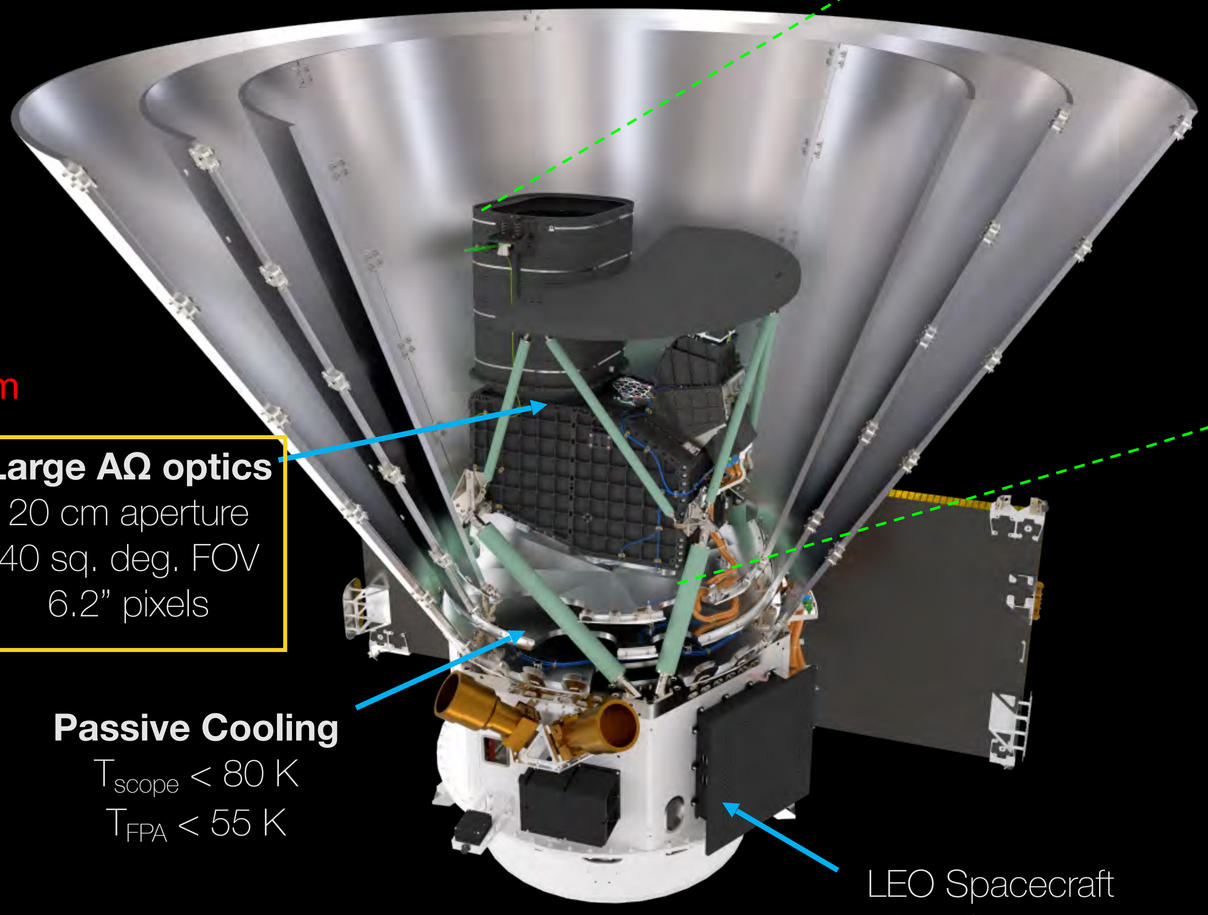
SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE



- All-Sky surveys demonstrated high scientific returns with lasting data legacy used across astronomy (COBE, IRAS, GALEX, WMAP, Planck, WISE)
- Great potential for follow-up with NASA's observatories
- Many exciting discoveries will come from the community
  - Data served through the InfraRed Science Archive (IRSA) at IPAC/Caltech

OD++16,18

SPHEREX OBSERVATORY AT A GLANCE

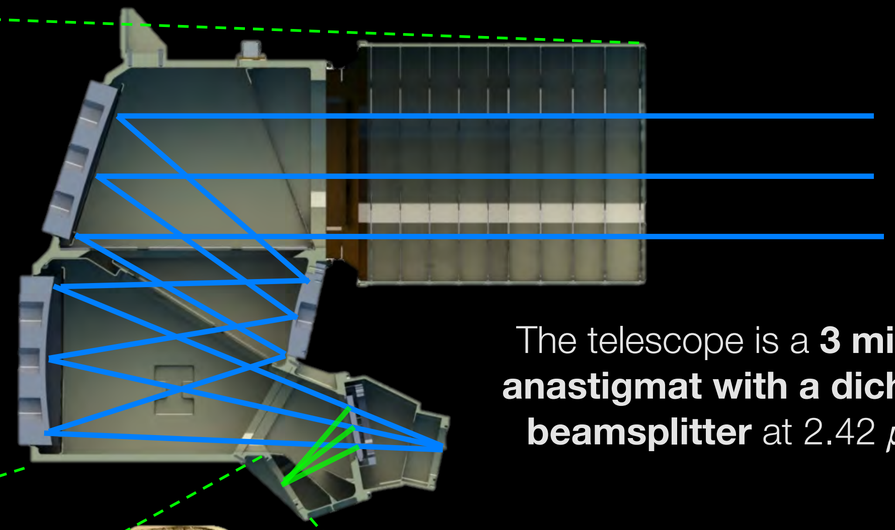


2 m

Large AΩ optics
20 cm aperture
40 sq. deg. FOV
6.2” pixels

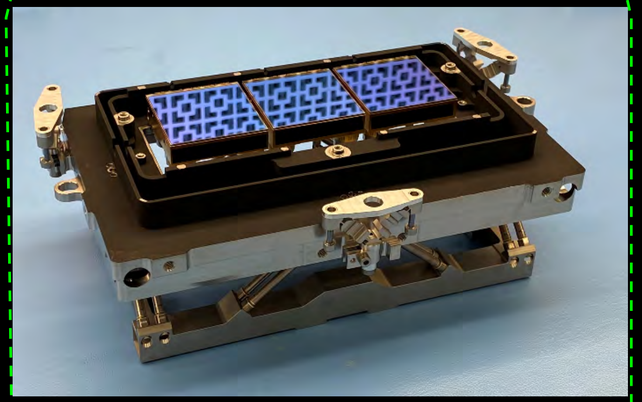
Passive Cooling
$T_{scope} < 80$ K
$T_{FPA} < 55$ K

LEO Spacecraft
BAE Systems
(ex Ball Aerospace)



The telescope is a **3 mirror anastigmat with a dichroic beamsplitter** at 2.42 μm.

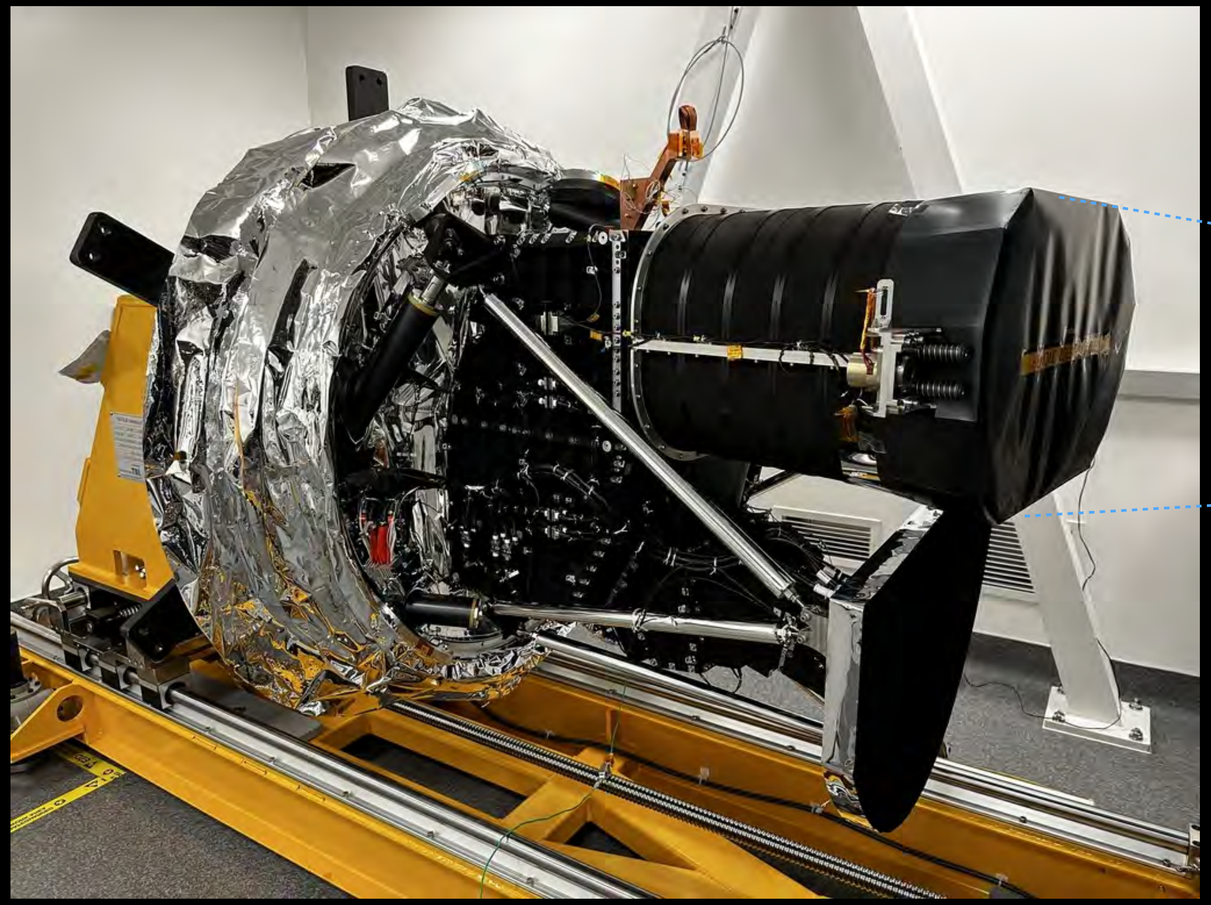
Linear Variable Filter Spectroscopy
λ = 0.75 – 5 μm
λ/Δλ = 35 – 130
Spread across the two focal planes.



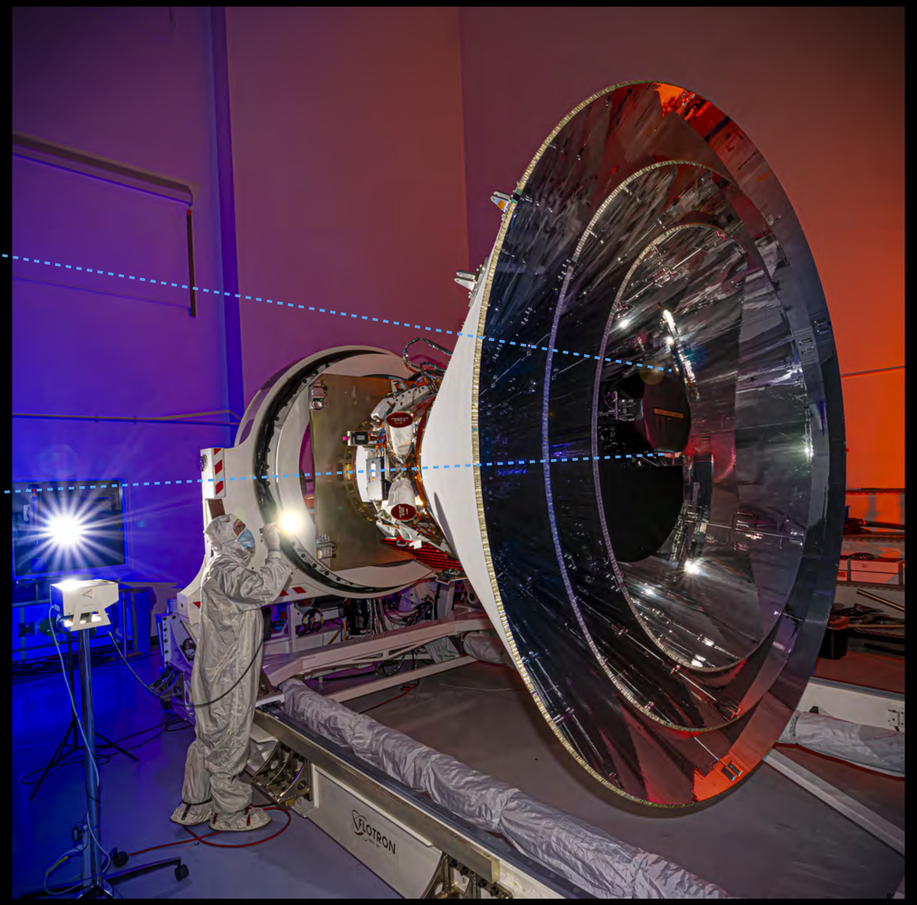
Mosaics of 2x3 H2RG arrays located directly behind the LVFs generate the spectral images.

Bock++25

OBSERVATORY LEVEL TESTING



Telescope and instrument integration and testing finished at Caltech in Feb. 2024



Full observatory assembly (Apr. 2024) at BAE Systems in Boulder, CO

Credit: Caltech, BAE Systems

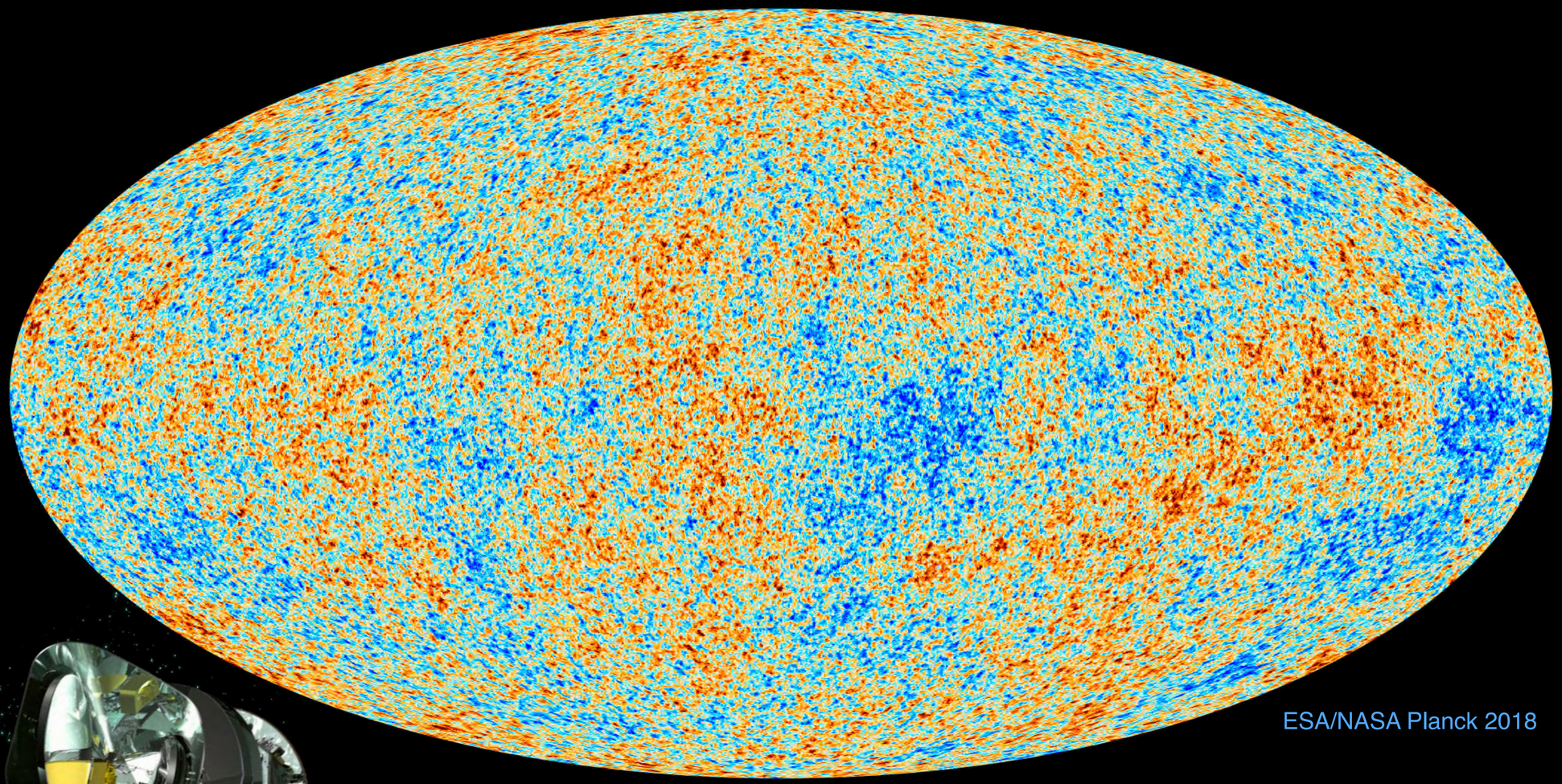
Credit: SpaceX, BAE Systems

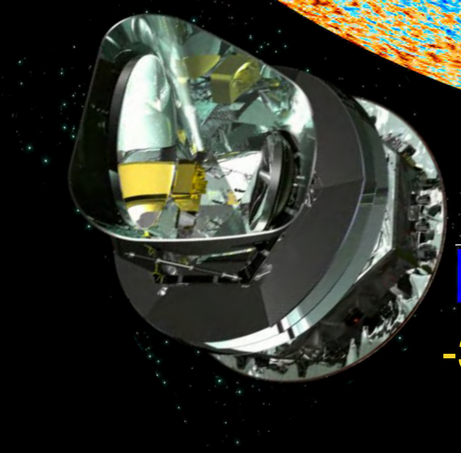
Credit: SpaceX, BAE Systems

On the landing pad….

INFLATION INVESTIGATION

PLANCK MAP OF THE YOUNG UNIVERSE

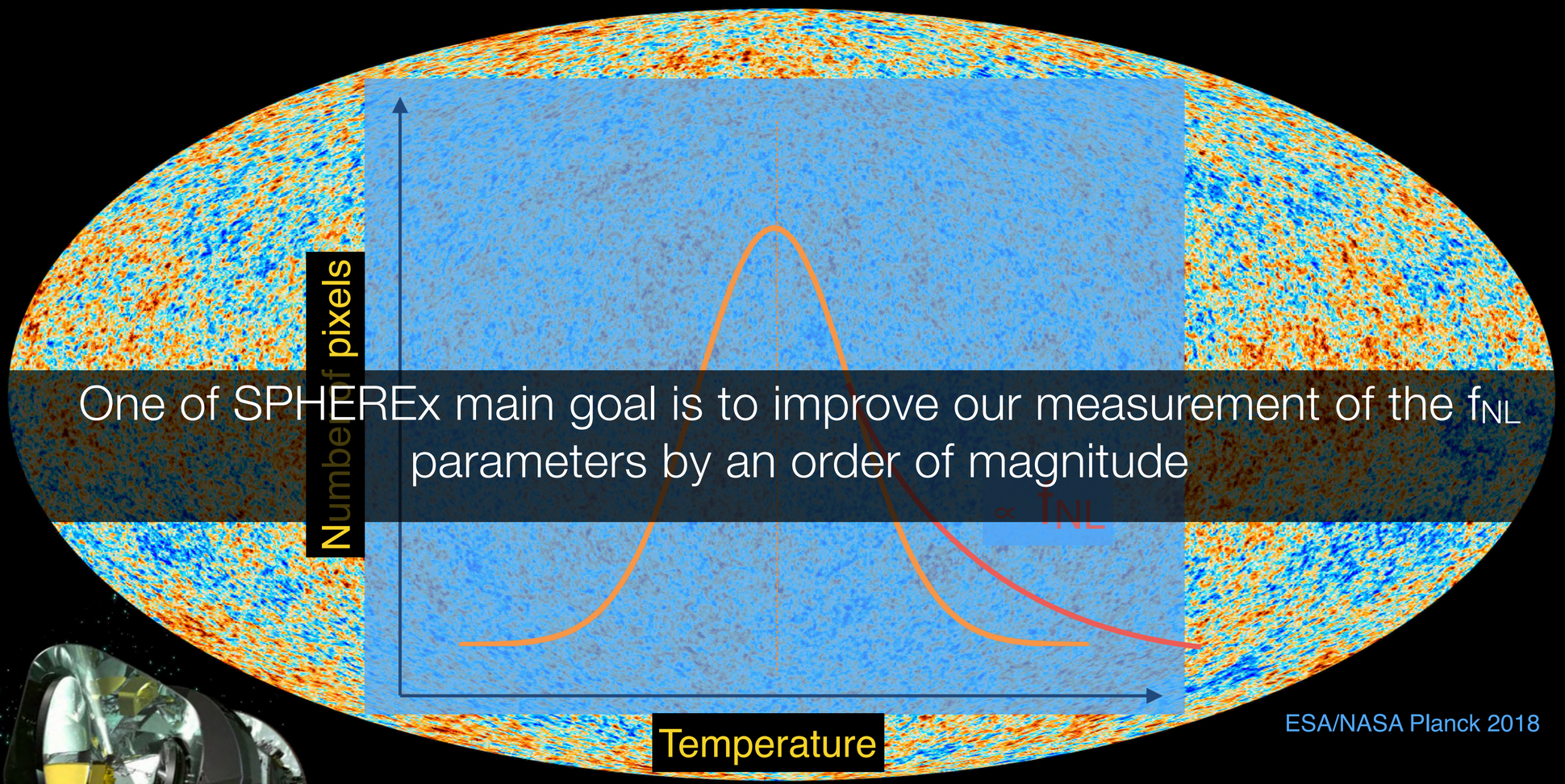




-300 μK +300

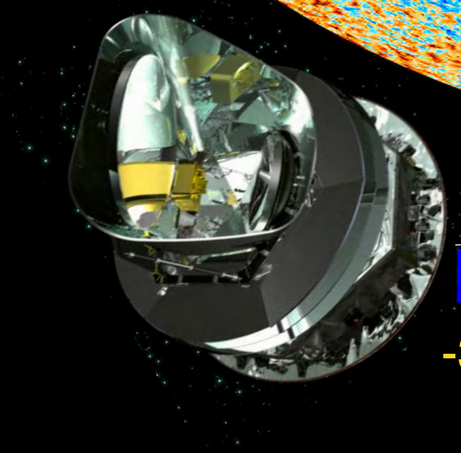
ESA/NASA Planck 2018

PLANCK MAP IS GAUSSIAN



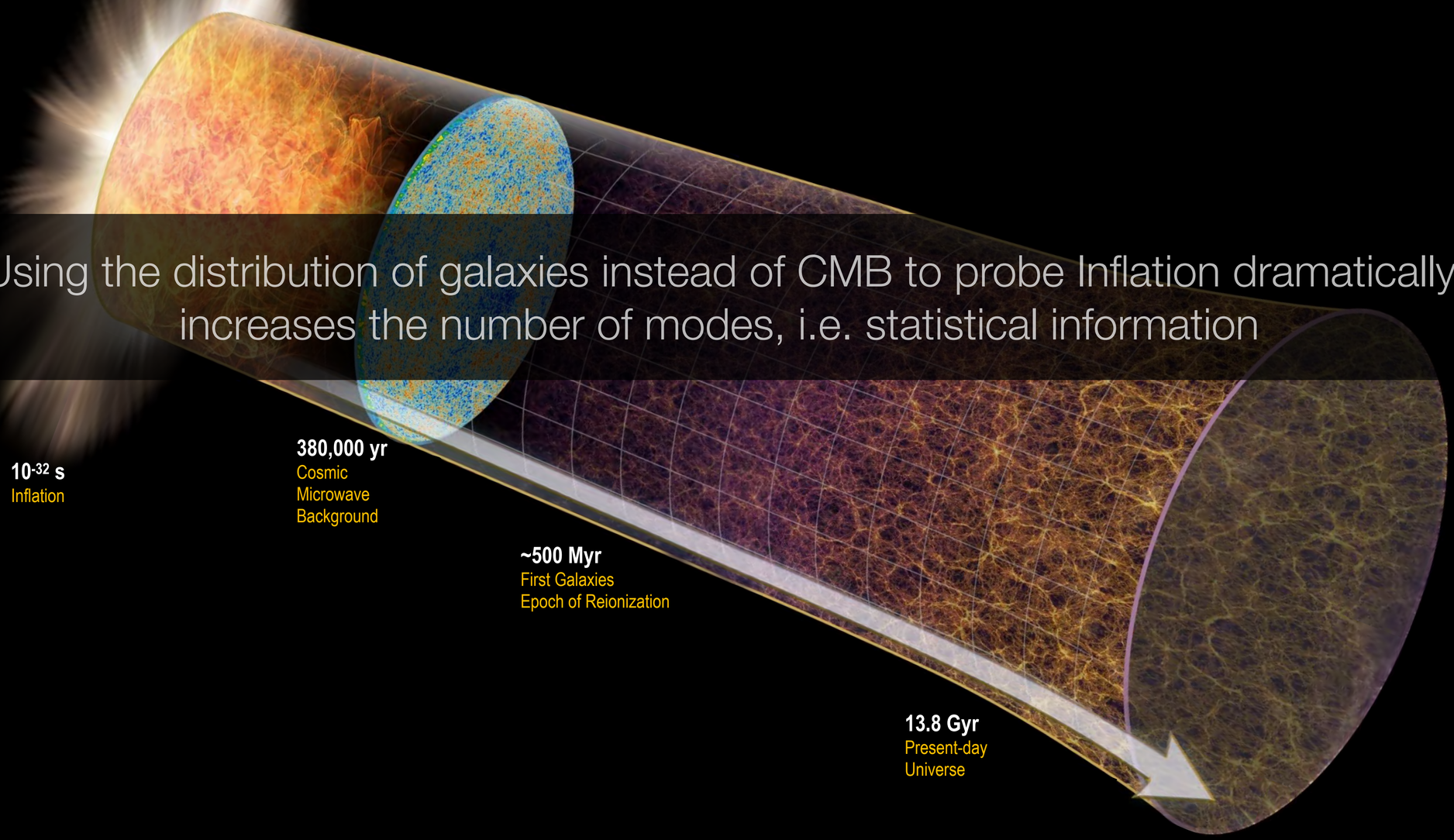
One of SPHEREx main goal is to improve our measurement of the f_{NL} parameters by an order of magnitude

ESA/NASA Planck 2018



-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

PRIMORDIAL NON-GAUSSIANITY INTRODUCES MODE COUPLING

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

- Peak-background split insights:

$$\Phi = \Phi_{Long} + \Phi_{Short}$$

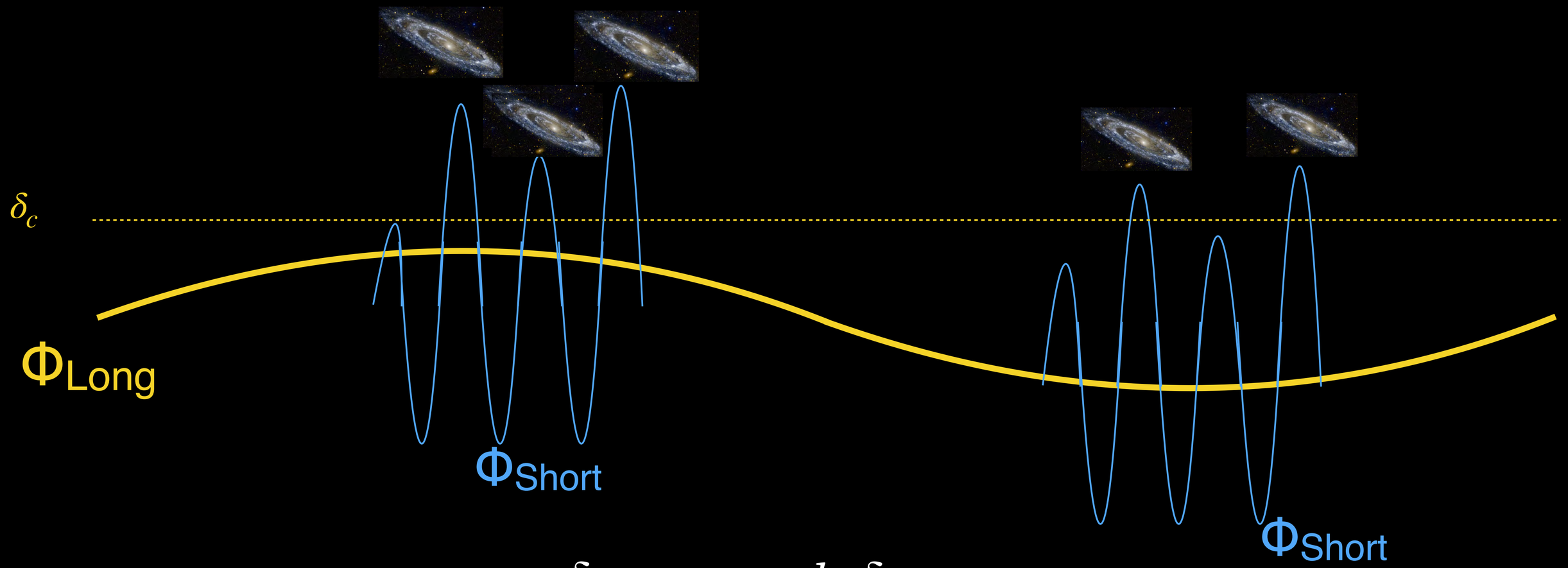
$$\Phi = \Phi_{Long} + f_{NL}^{loc}\ \Phi_{Long}\Phi_{Short} + f_{NL}^{loc}\ \Phi_{Short}^2 + \cdots$$

Slosar++07, Desjacques++16

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

$f_{NL} = 0$

No mode coupling



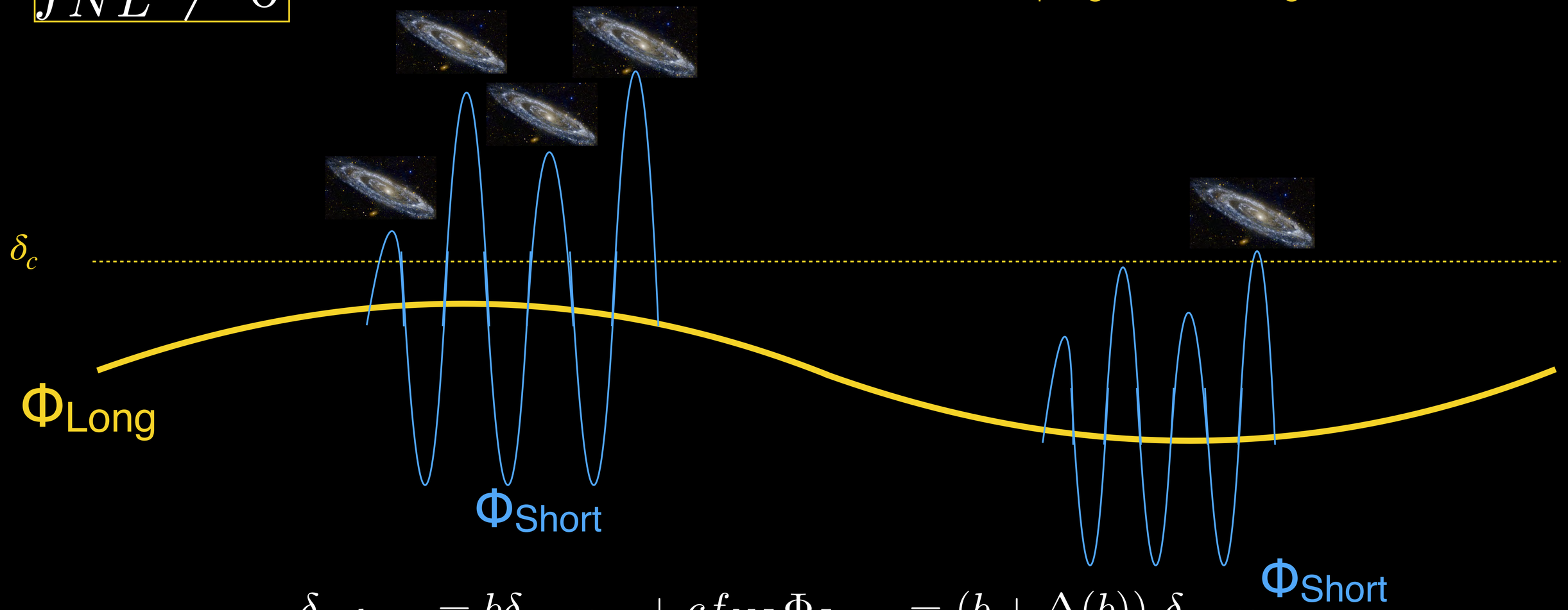
$$\delta_{galaxy} = b\ \delta_{matter}$$

Galaxy bias (linear)

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

$f_{NL} \neq 0$

Coupling between long and short modes



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

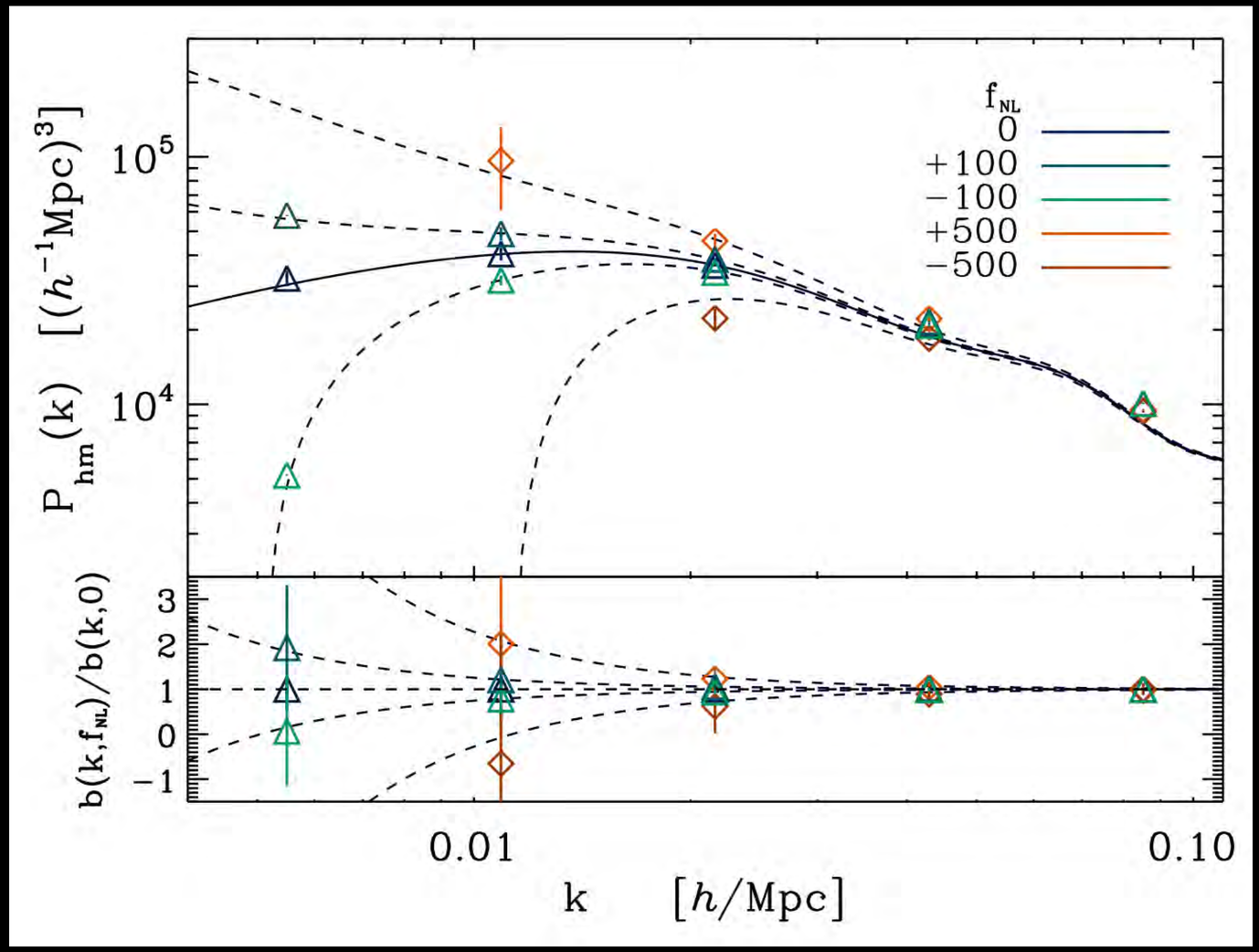
$$\Delta(b) \propto \ (b-1)\frac{f_{NL}}{k^2}$$

Scale dependent
galaxy bias (assuming universal bias rel.)

PRIMORDIAL NON-GAUSSIANITY AND BIASING

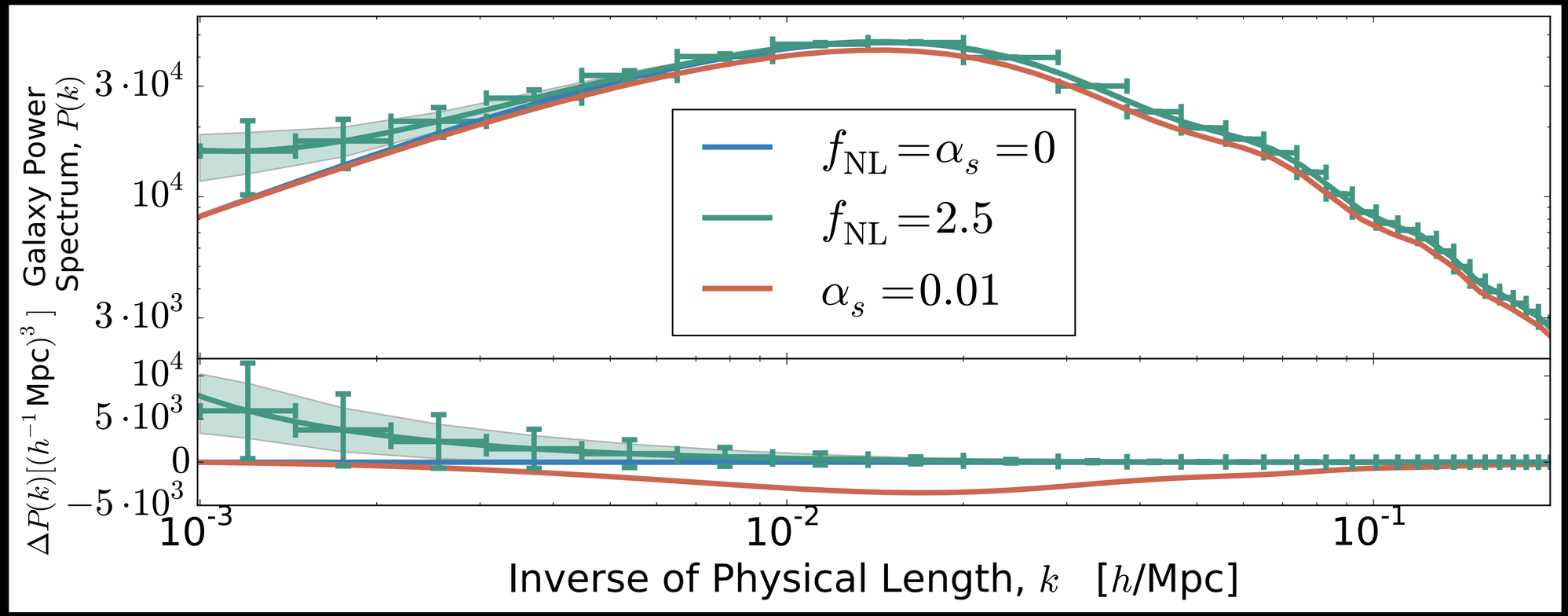
$$b_{NG}^{loc}(q) \propto f_{NL}^{loc} \frac{1}{T(q)q^2}$$

bias(k) *bias(k) $P_{mm}(k)$*



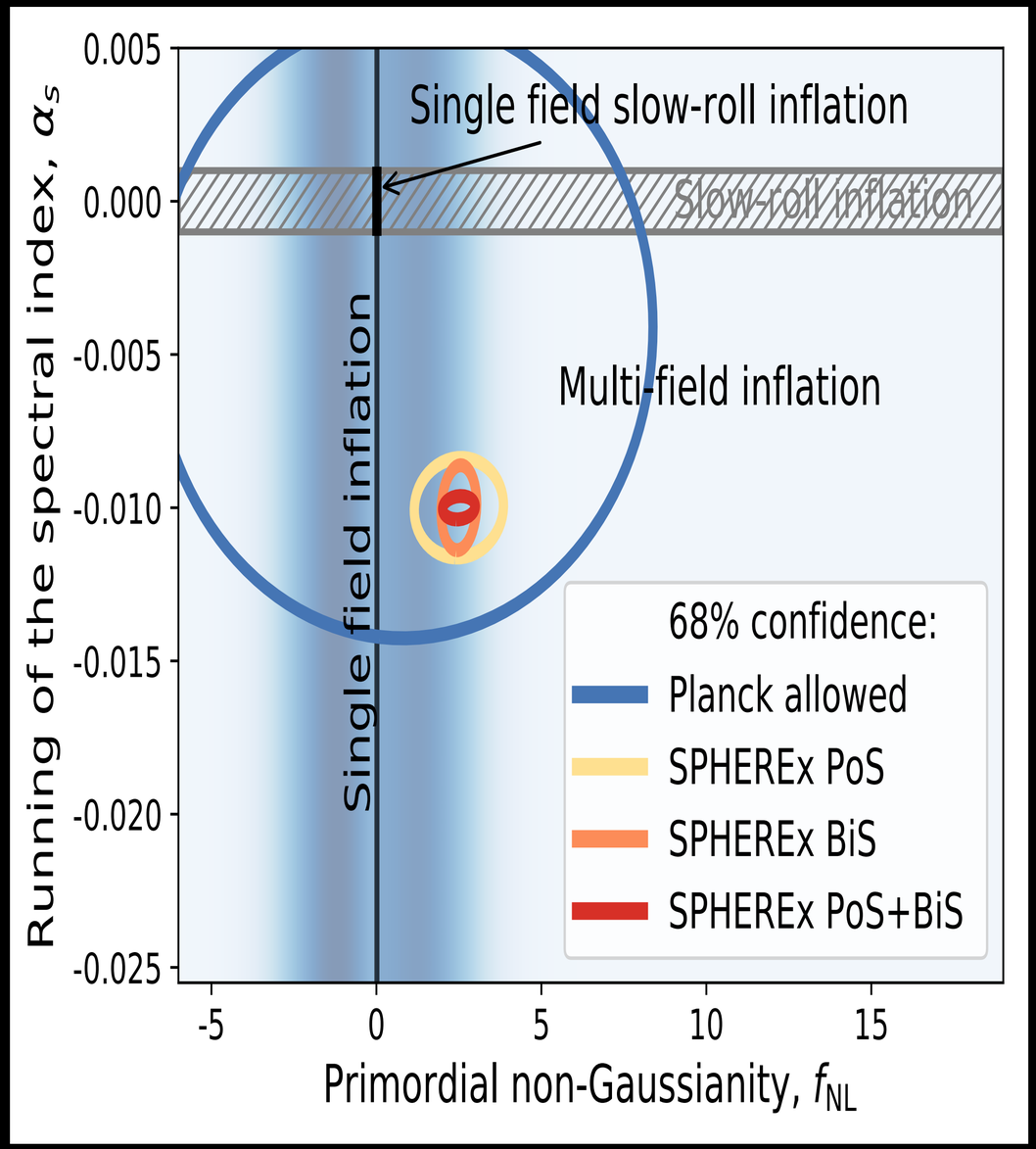
Dalal, OD, Huterer, Shirokov 07

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 Δf_{NL}~ 5 accuracy today to Δf_{NL}< 0.5
- Discriminates between models
  - ➡ Single-field inflation $f_{NL} << 1$
  - ➡ Multi-field inflation $f_{NL} \gtrsim 1$
- Measuring f_{NL} is one of the three observational ways we have to learn about inflation
  - ➡ Characterizing primordial perturbations/power spectrum: n_s, α_s, features…
  - ➡ Energy scale of inflation with CMB B-modes: r
  - ➡ Complexity of inflation (field(s) interactions, etc.: f_{NL}

MEASURING GR CORRECTIONS

Standard density plus RSD

Lensing

Doppler

Non-integral potential terms

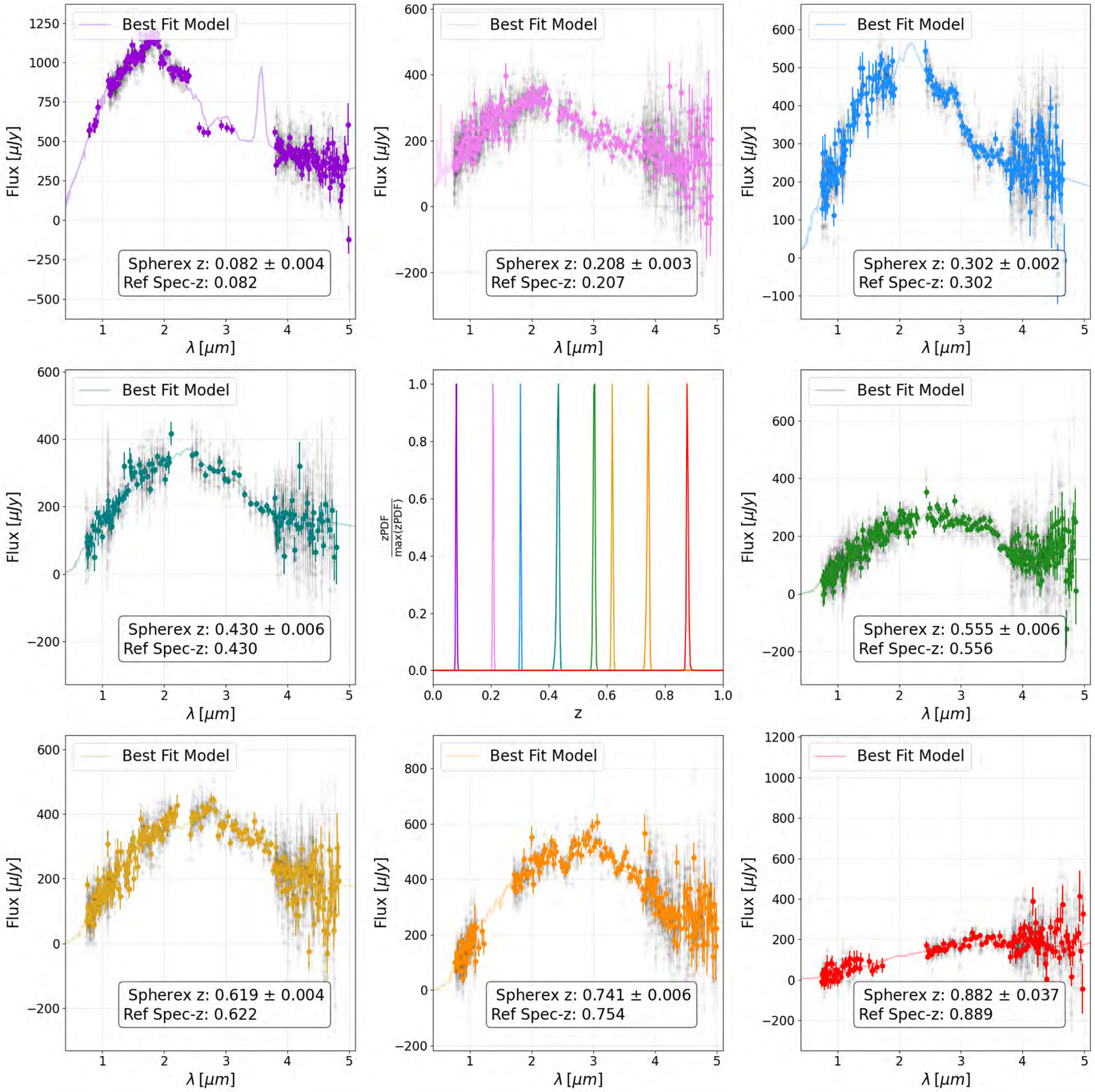
Shapiro effect

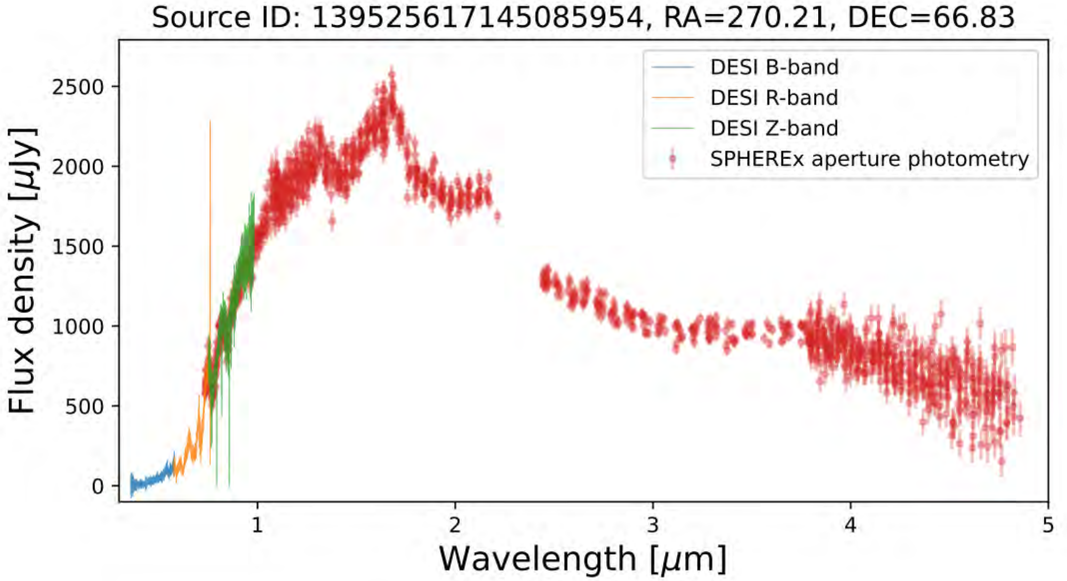
Integrated Sachs-Wolfe

$$\delta_{\rm g}^{\rm rel}(\hat{\mathbf{n}}, z) = b_1 D_{\rm m} - \frac{1}{\mathcal{H}}\frac{\partial \vec{v}}{\partial x}\cdot\hat{\mathbf{n}}$$
$$- (2-5s)\kappa$$
$$- \mathcal{A}_1(\vec{v}-\vec{v}_o)\cdot\hat{\mathbf{n}} + (2-5s)\vec{v}_o\cdot\hat{\mathbf{n}}$$
$$+ \mathcal{A}_1(\Psi-\Psi_o) + \left(\mathcal{A}_1\mathcal{H}_0 - \frac{2-5s}{x}\right)V_o$$
$$- (2-5s)\Phi + \Psi + \frac{1}{\mathcal{H}}\dot{\Phi} + (b_{\rm e}-3)\mathcal{H}V$$
$$- \frac{2-5s}{x}\int_{\tau_0}^{\tau(z)}(\Psi(\tau')+\Phi(\tau'))\,d\tau'$$
$$- \mathcal{A}_1\int_{\tau_0}^{\tau(z)}(\dot{\Psi}(\tau')+\dot{\Phi}(\tau'))\,d\tau'. \qquad (3)$$

Wen++24, 25 (in prep.)

Galaxy Spectra and Redshift Validation



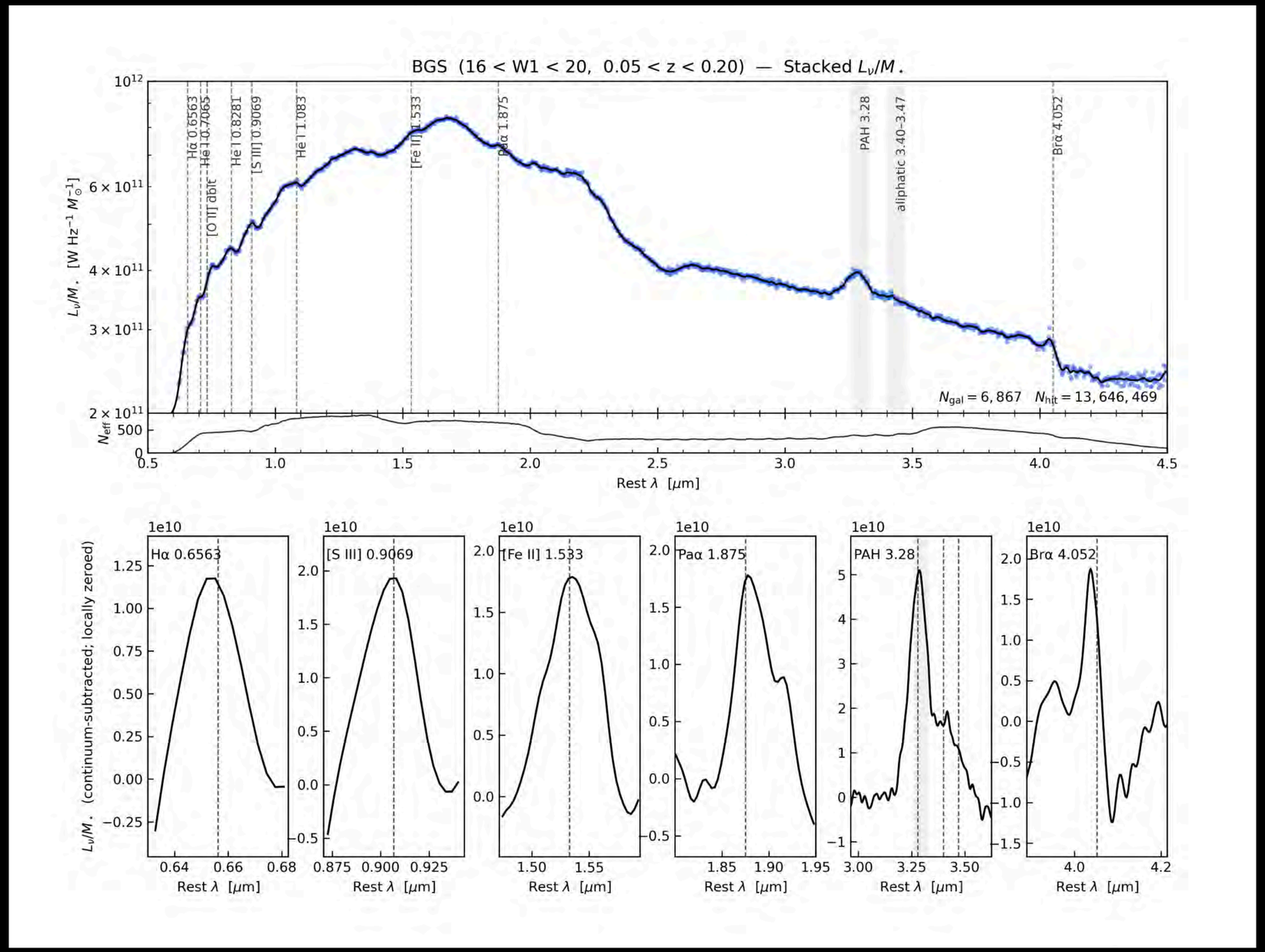


The first sample of galaxy spectra were used to test the SED and redshift fitting pipeline.

Excellent agreement with reference spectra from the ground is observed.

Plot: Sean Bruton

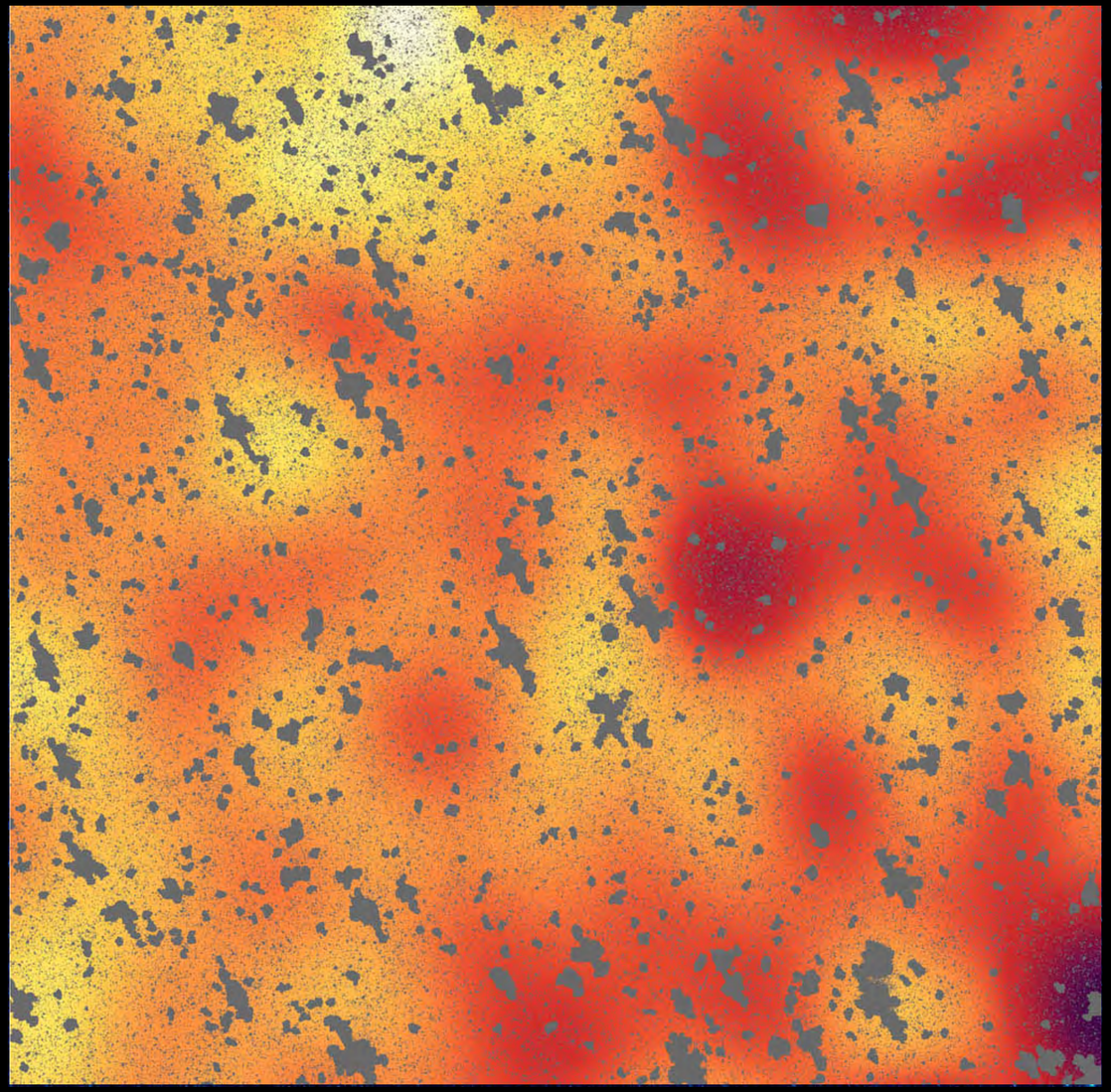
STACKED DESI BGS GALAXIES



Plot: Asantha Cooray (UCI)

EXTRA-GALACTIC BACKGROUND

MAPPING EXTRA-GALACTIC BACKGROUND LIGHT



8.5 arcmin

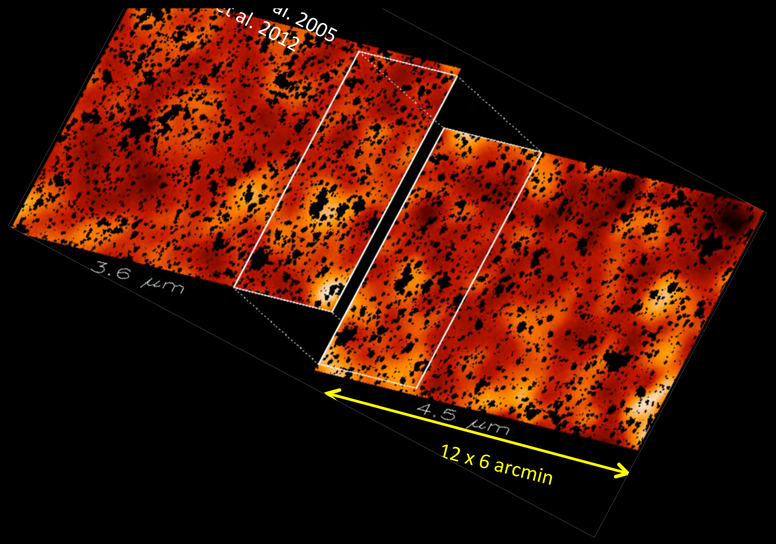
Spitzer @ 3.6 μm

Cooray++07

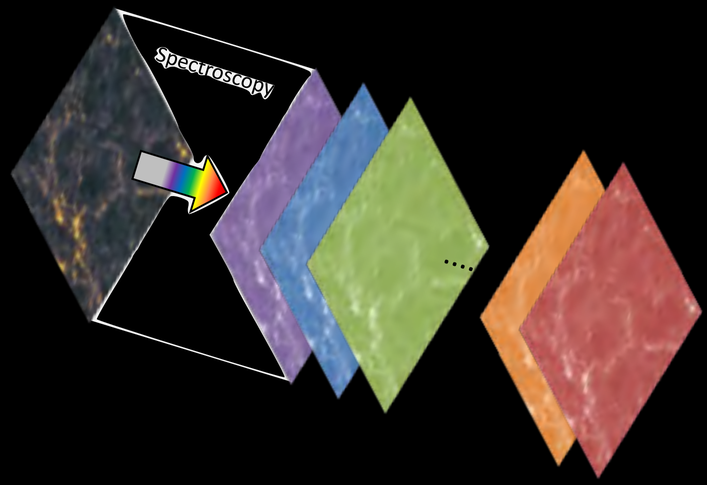
HOW DID GALAXIES BEGIN?

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 102 bands and 200 sq. deg.



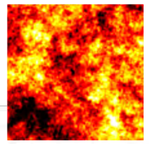
- SPHEREx observes every orbits ~2 x 100 sq. deg near the ecliptic poles
  ➡We can reliably map light fluctuations over these *deep fields*

- 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)

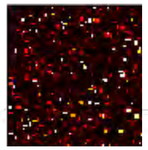

NEP Deep field - 25 square degrees
0.75μm < λ < 1.5μm
2.0μm < λ < 3.0μm
4.0μm < λ < 5.0μm

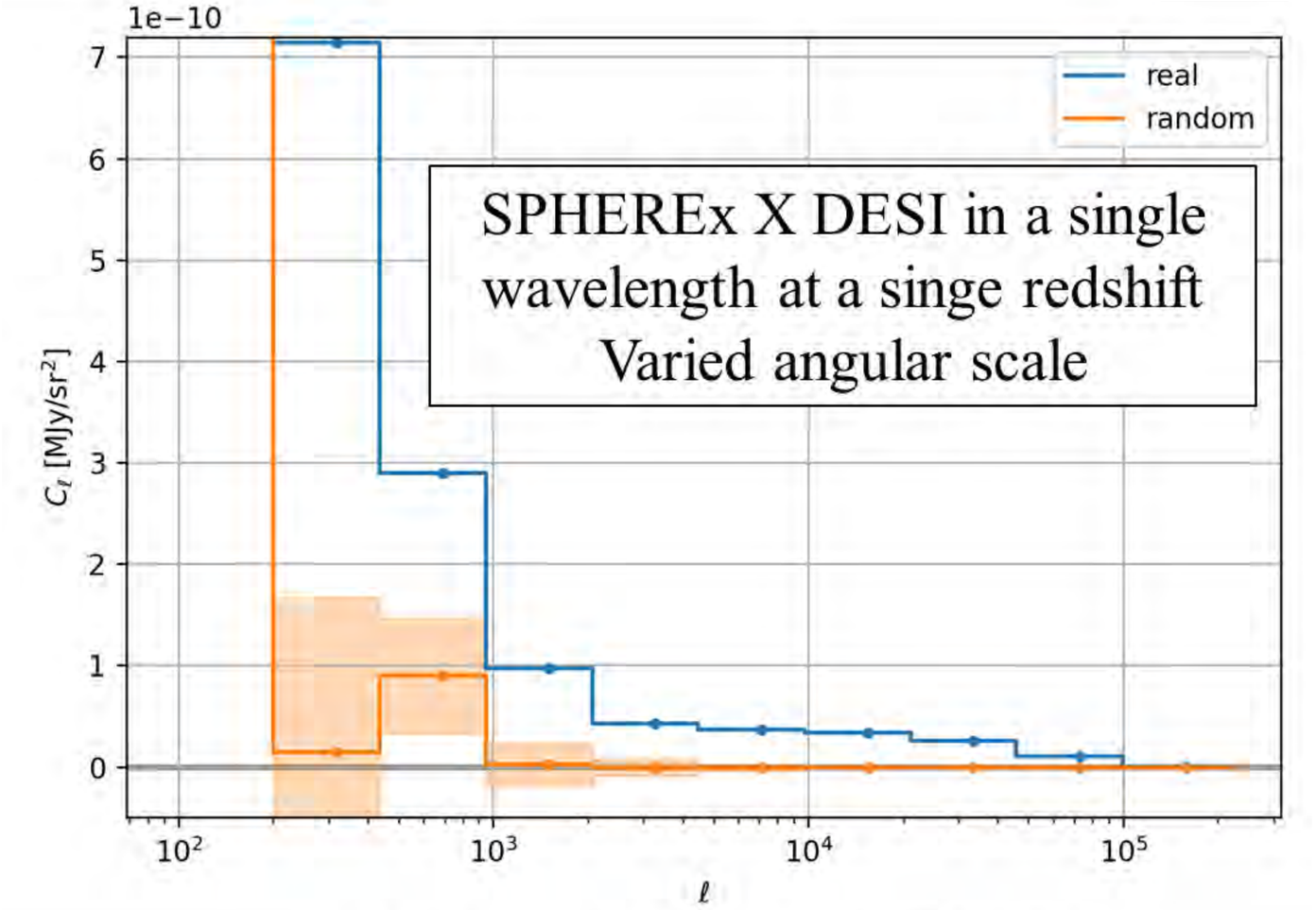
EBL early Science, Cross Correlation

“Puffy” large structure



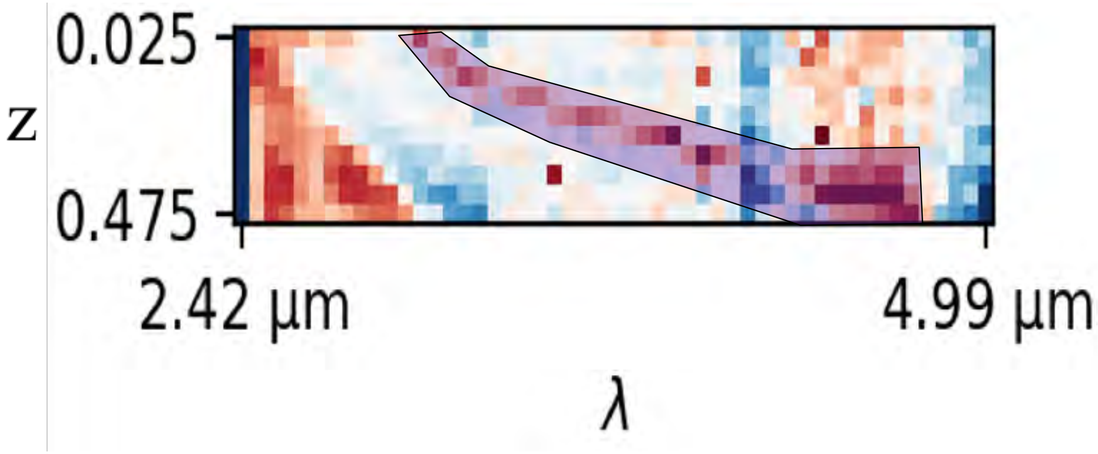
Compact sources





Multipole (~ 1/ Angular Scale)

SPHERE x DESI at a fixed angular scale

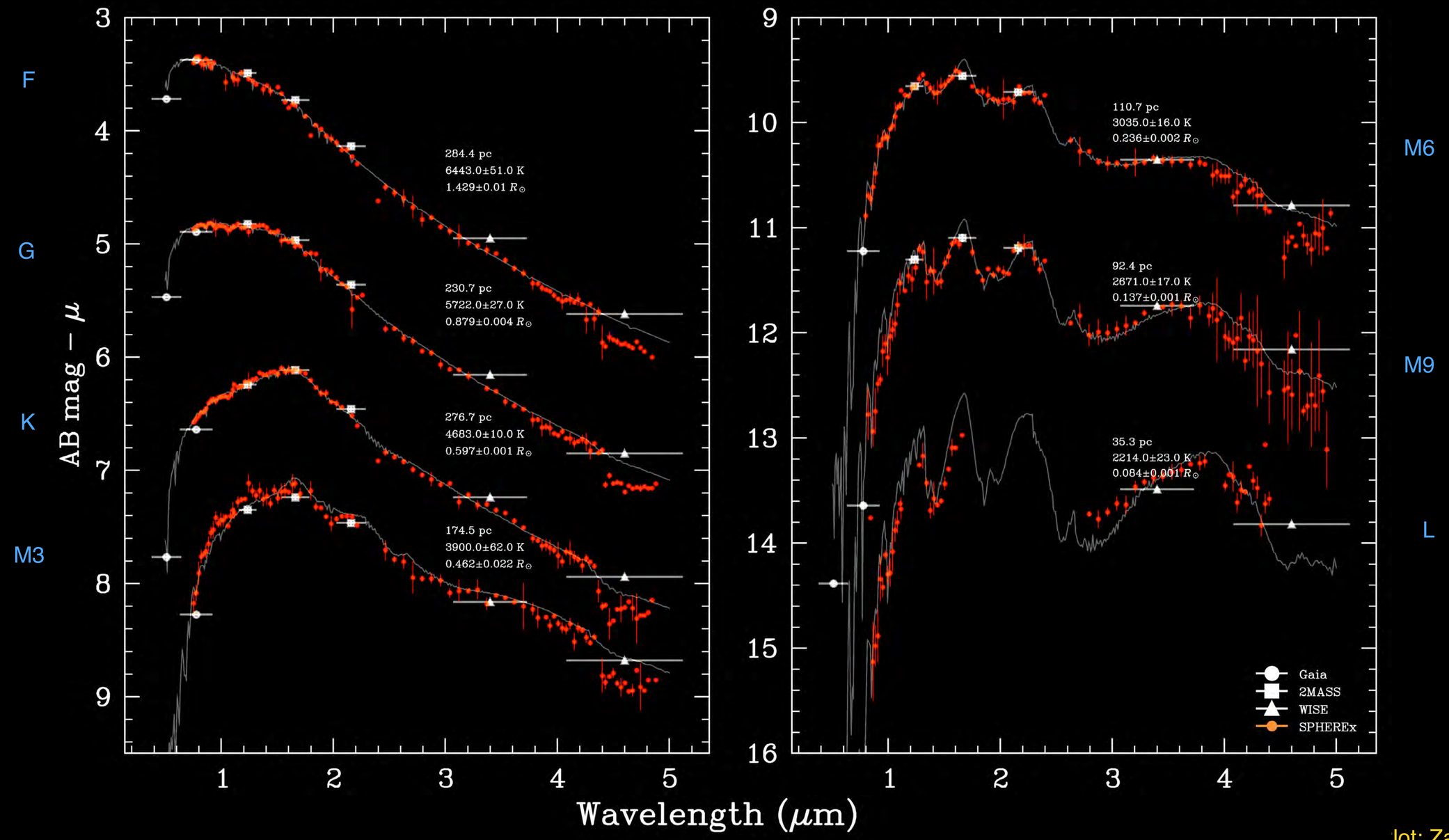


PAH emission evolution through cosmic time!

Work from Shuang-Shuang Chen (Caltech Grad student)

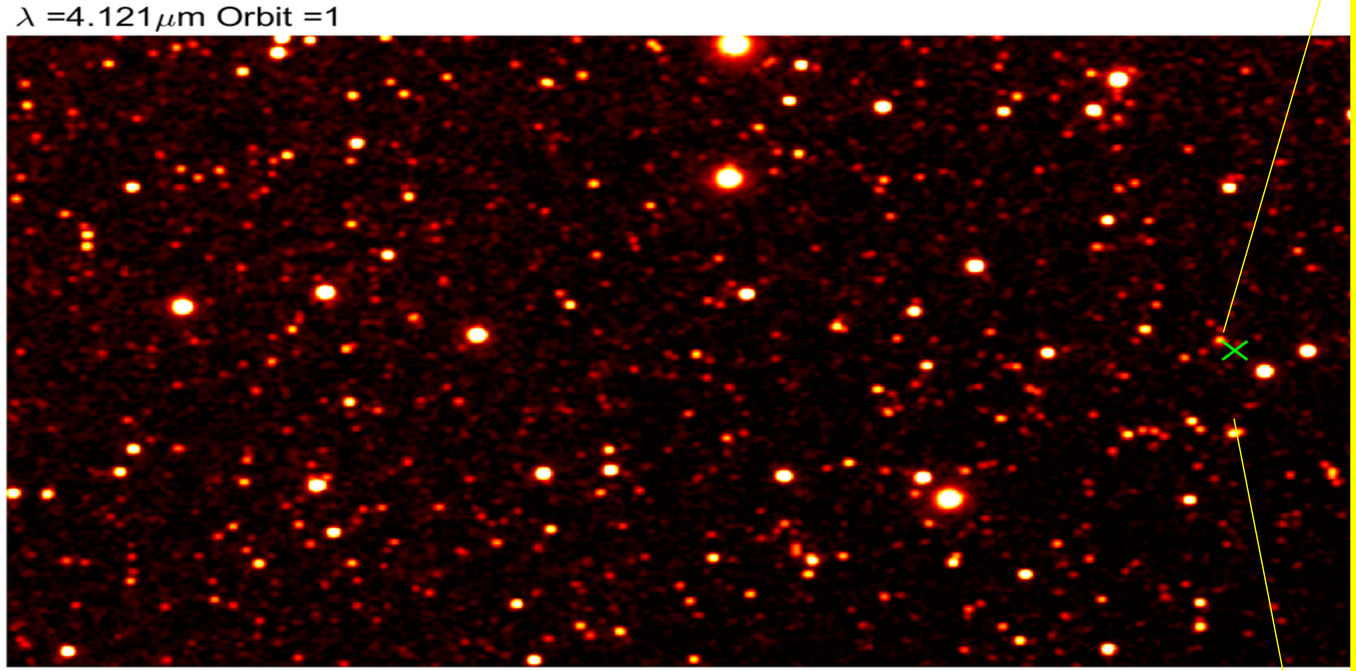
LEGACY SCIENCE

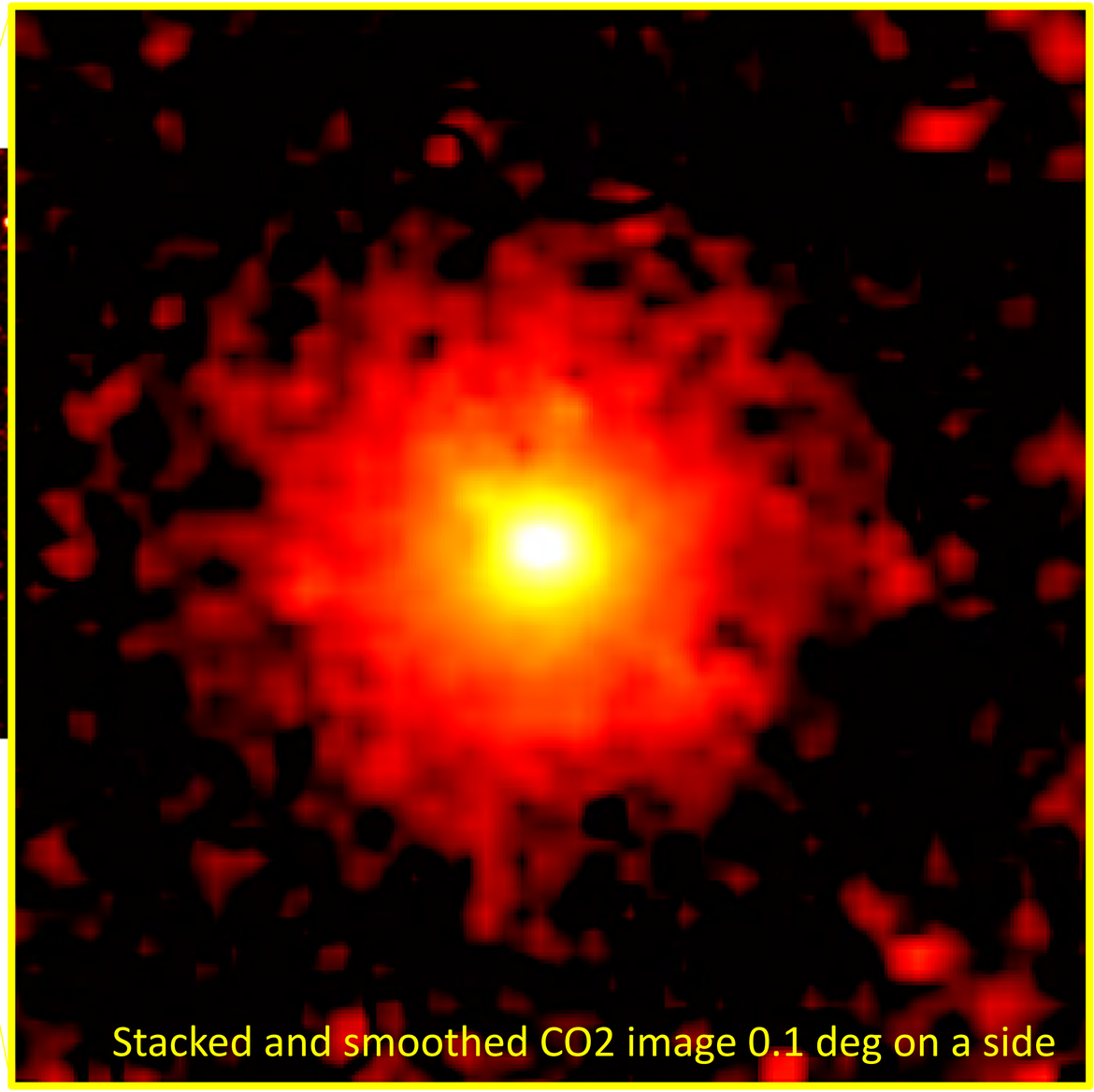
PRELIMINARY SCIENCE: MAIN SEQUENCE STELLAR SPECTRA



lot: Zafar Rustamkulov

Solar System: SPHEREx discovers a CO2 coma in the interstellar object



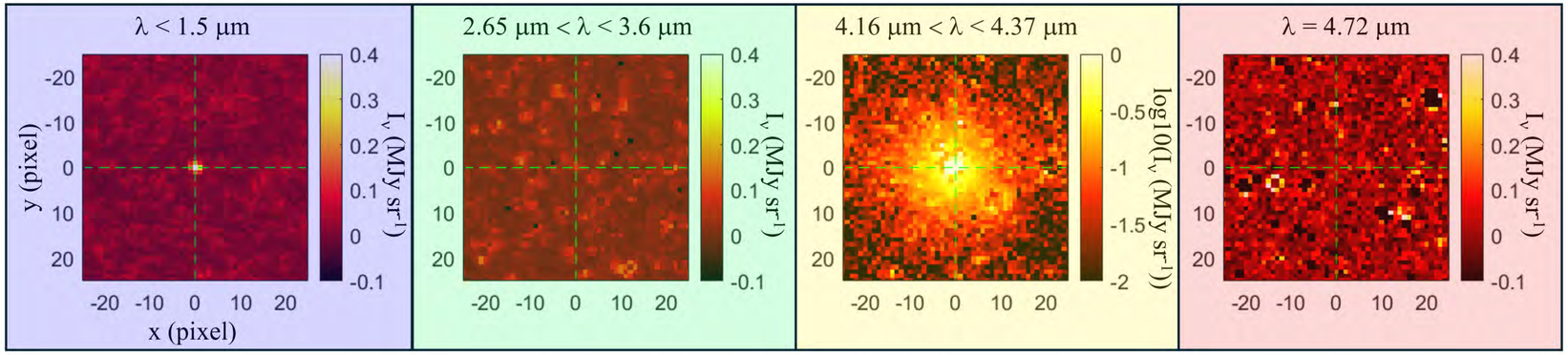


Published in RNAAS: Lisse et al, SPHEREx Discovery of Strong Water Ice Absorption and an Extended Carbon Dioxide Coma in 3I/ATLAS

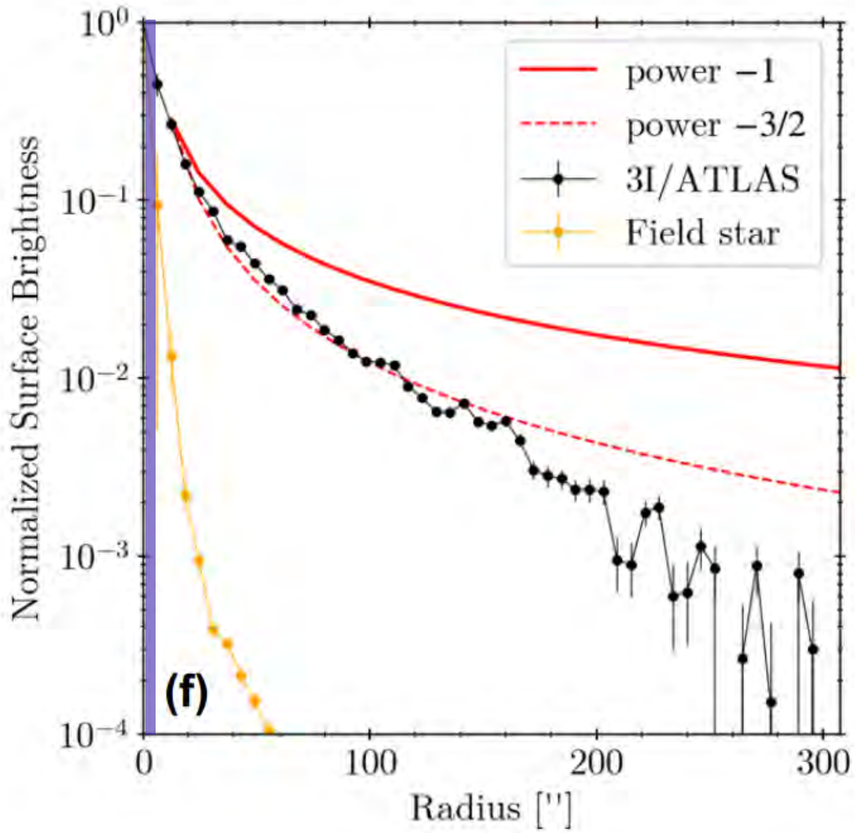
Submitted 10 days after completion of observations

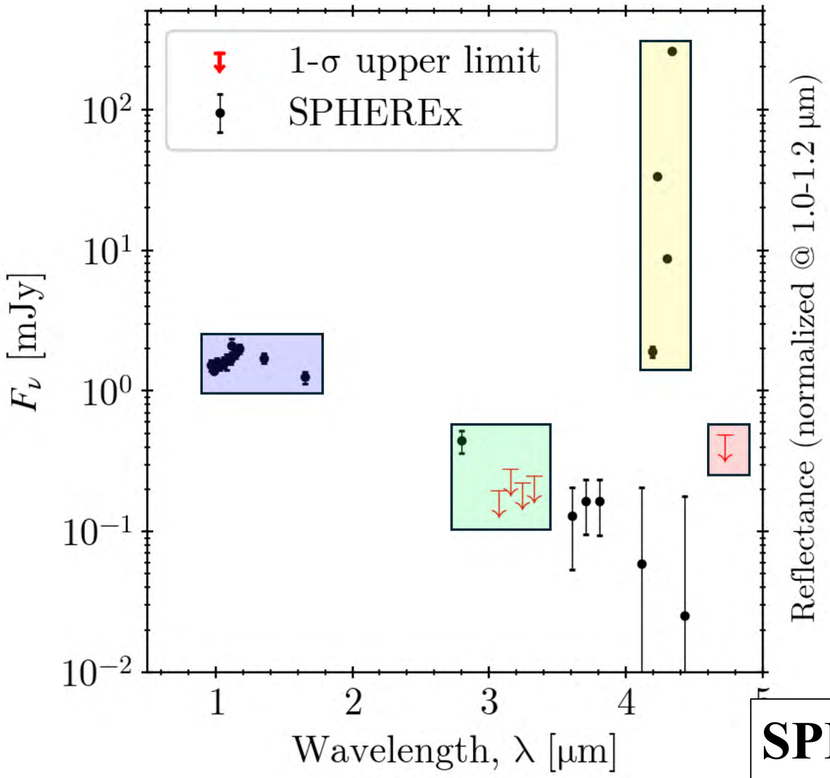
More detailed publication in preparation

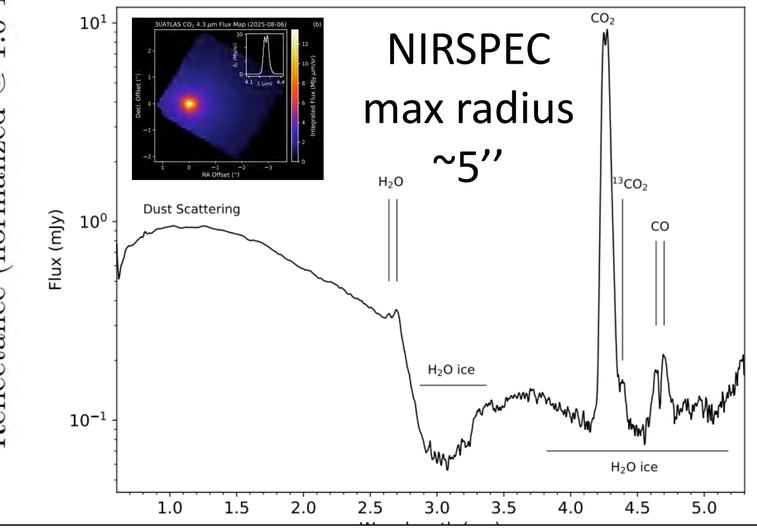
Imaging Spectroscopy of 3I Atlas: Discovery of an enormously bright CO_2 coma and water ice absorption in the core.



Enormously Extended CO2 Emission







Beautiful JWST NIRSPEC data confirm results in the core ~3 days later

SPHEREx will Observe 3I again in Nov/Dec after perihelion (Oct 29).

SUMMARY

- SPHEREx launched on March 11st 2025 and is working beautifully
  - ➡ Observatory is meeting or exceeding its requirements

- SPHEREx is creating the first all sky near-infrared spectroscopic survey:
  - ➡ Continuous data release has started
  - ➡ 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:
  - ➡ Origin of water and biogenic ices in young stellar objects and proto-planetary systems
  - ➡ Extra-galactic background light from z=0 till the reionization era
  - ➡ Primordial non-Gaussianity to learn about Inflation
  - ➡ …

- SPHEREx is transforming our understanding of everything from Earth's atmosphere to the dawn of the Universe — and all that lies in between
  - ➡ Already some discoveries. We are just beginning.