Intensity Mapping with SPHEREx

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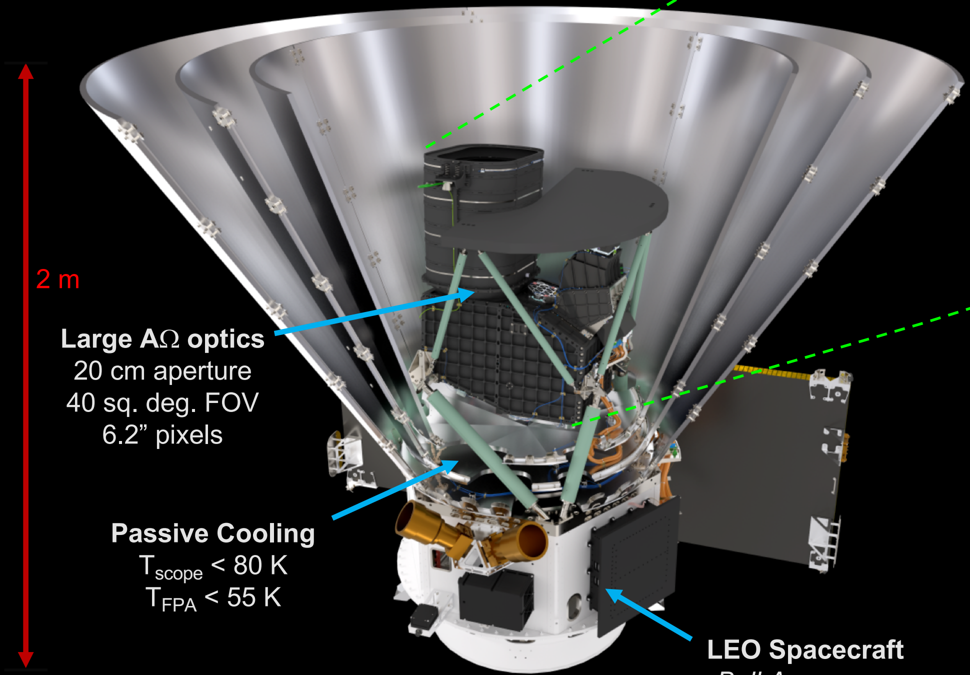
Yujin Yang	KASI
Michael Zemcov	RIT

NASA MIDEX Satellites

- Competed mission - roughly 2 opportunities per decade in astrophysics
- Proposed science, not agency directed
- PI cost cap for MIDEX ~ $300M (FY2022), SMEX ~ $145M (FY2020)
- SPHEREx was selected for Phase B (implementation) in 2019

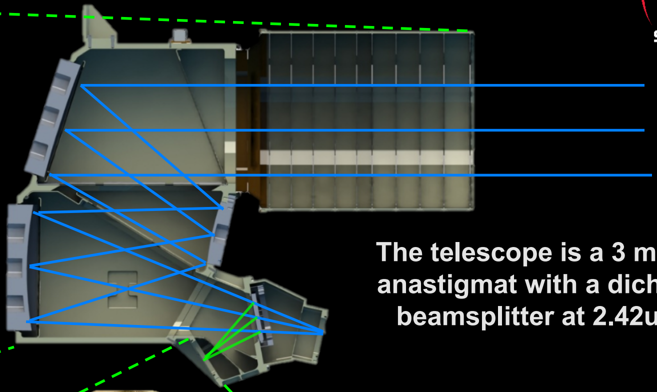
What is SPHEREx?



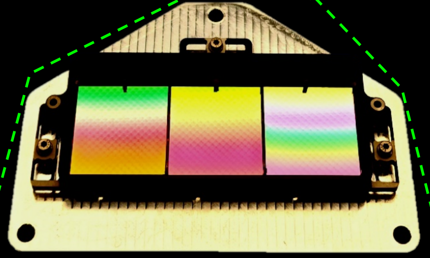
Large AΩ optics
20 cm aperture
40 sq. deg. FOV
6.2” pixels

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

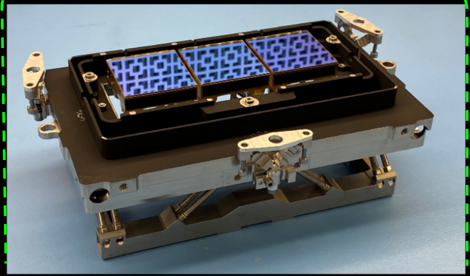
LEO Spacecraft
Ball Aerospace
Now BAE Systems



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

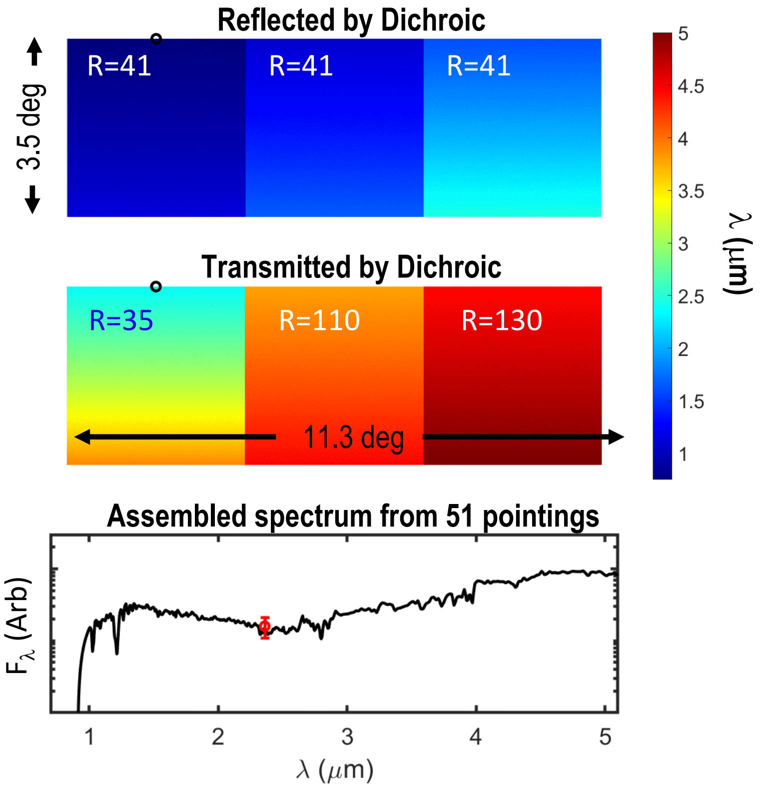


Linear Variable Filter Spectroscopy
$\lambda = 0.75 - 5\ \mu m$
$\Delta\lambda/\lambda = 35 - 130$
Spread across the two focal planes.

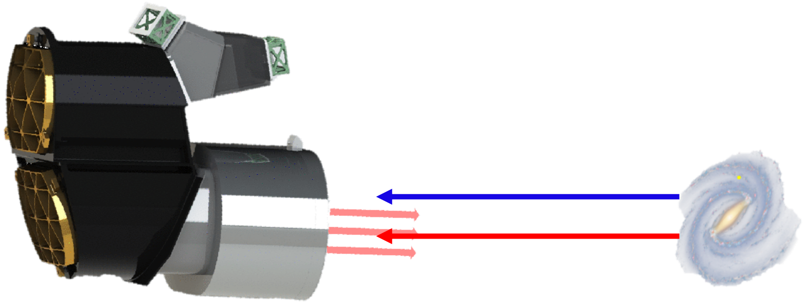


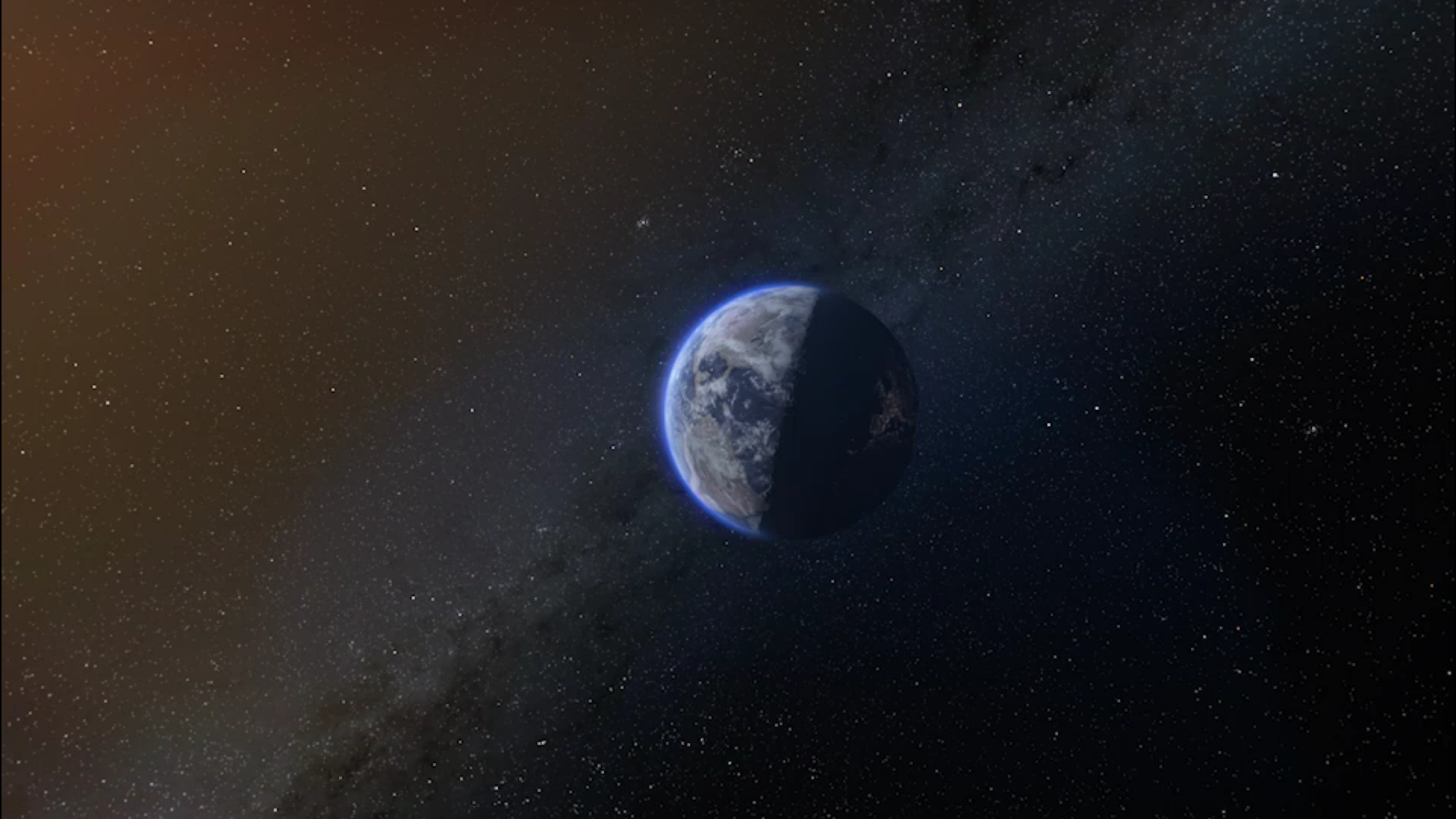
Mosaics of 2x3 H2RG arrays located directly behind the LVFs generate the spectral images.

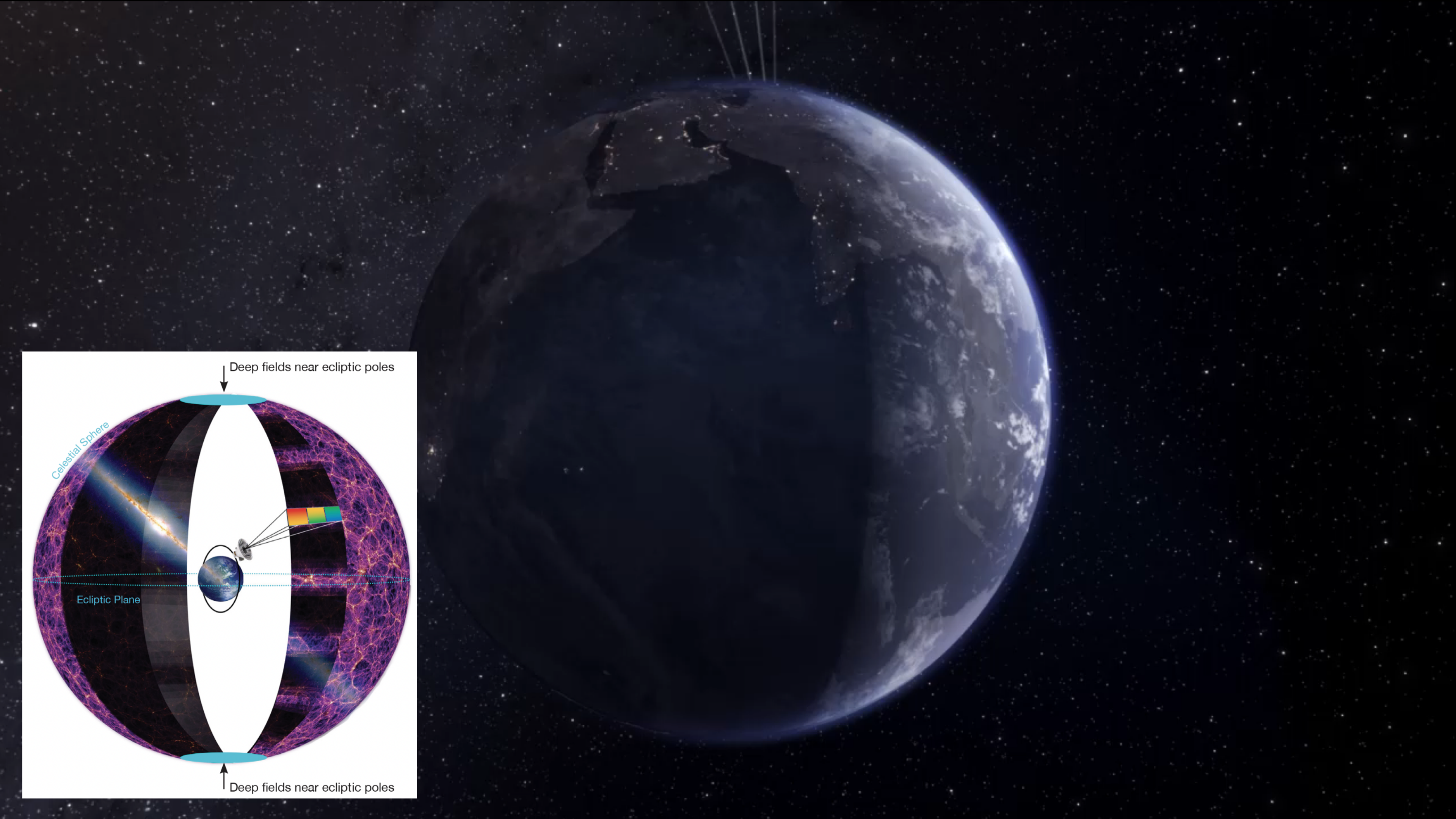
Getting Spectral Images



- 6 x 2048 x 2048 H2RG Arrays
- Linear-Variable Filters
  - $\lambda = 0.75 - 5\ \mu m$
  - $\lambda/\Delta\lambda = 35 - 130$






Deep fields near ecliptic poles
Celestial Sphere
Ecliptic Plane
Deep fields near ecliptic poles

Target Science for SPHEREx

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?

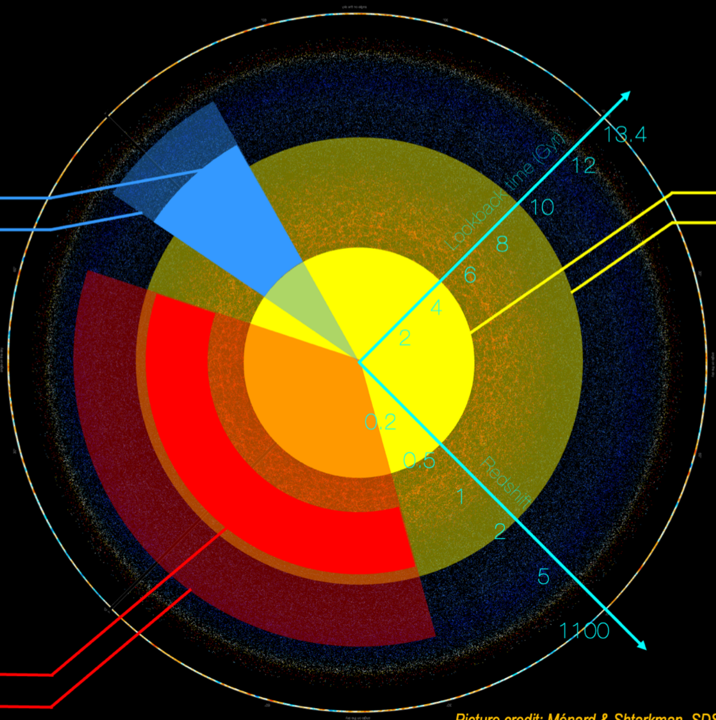
Survey the Milky Way for water ices and other biogenic molecules

By constructing the first all-sky near-infrared spectral survey

- ***For every 6.2" pixel over the entire sky:***
  - ***R = 35-41 spectra spanning 0.75 to 3.82 um***
  - ***R = 110-130 spectra spanning 3.82 to 5.0 um***
- ***All-sky survey with 102 fine photometric bands***

Redshift Catalog from SPHEREx

Roman
BAO and lensing survey
Science targets dark energy
2,000 sq. deg. area
25M spec-zs
2B photo-zs



Picture credit: Ménard & Shtarkman, SDSS

Euclid
BAO and lensing survey
Science targets dark energy
15,000 sq. deg. area
30M spec-zs
2B photo-zs

SPHEREx
All-sky spectroscopic survey
Science targets inflation

$$30,000\mathrm{deg}^2$$

$$19M; \frac{\sigma_z}{1+z} < 0.03$$

$$445M; \frac{\sigma_z}{1+z} < 0.1$$

$$810M; \frac{\sigma_z}{1+z} < 0.2$$

Measuring Cosmic History of Light Production

Spectroscopy is Key for Untangling Cosmic History

In otal Light

Jordan will tell us about modeling and parameters inference

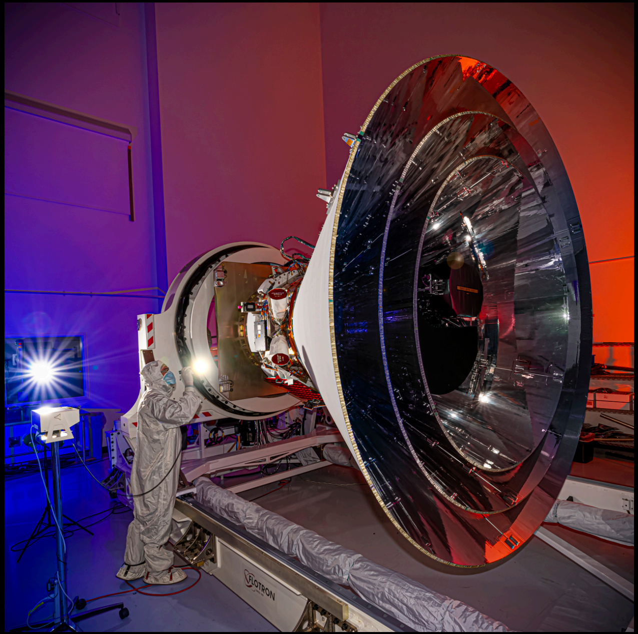
Spectral Decomposition Determ

- Emission from all galaxies
- Dwarf galaxies responsible for
- Diffuse emission from stripped
- Dark matter decay (?)

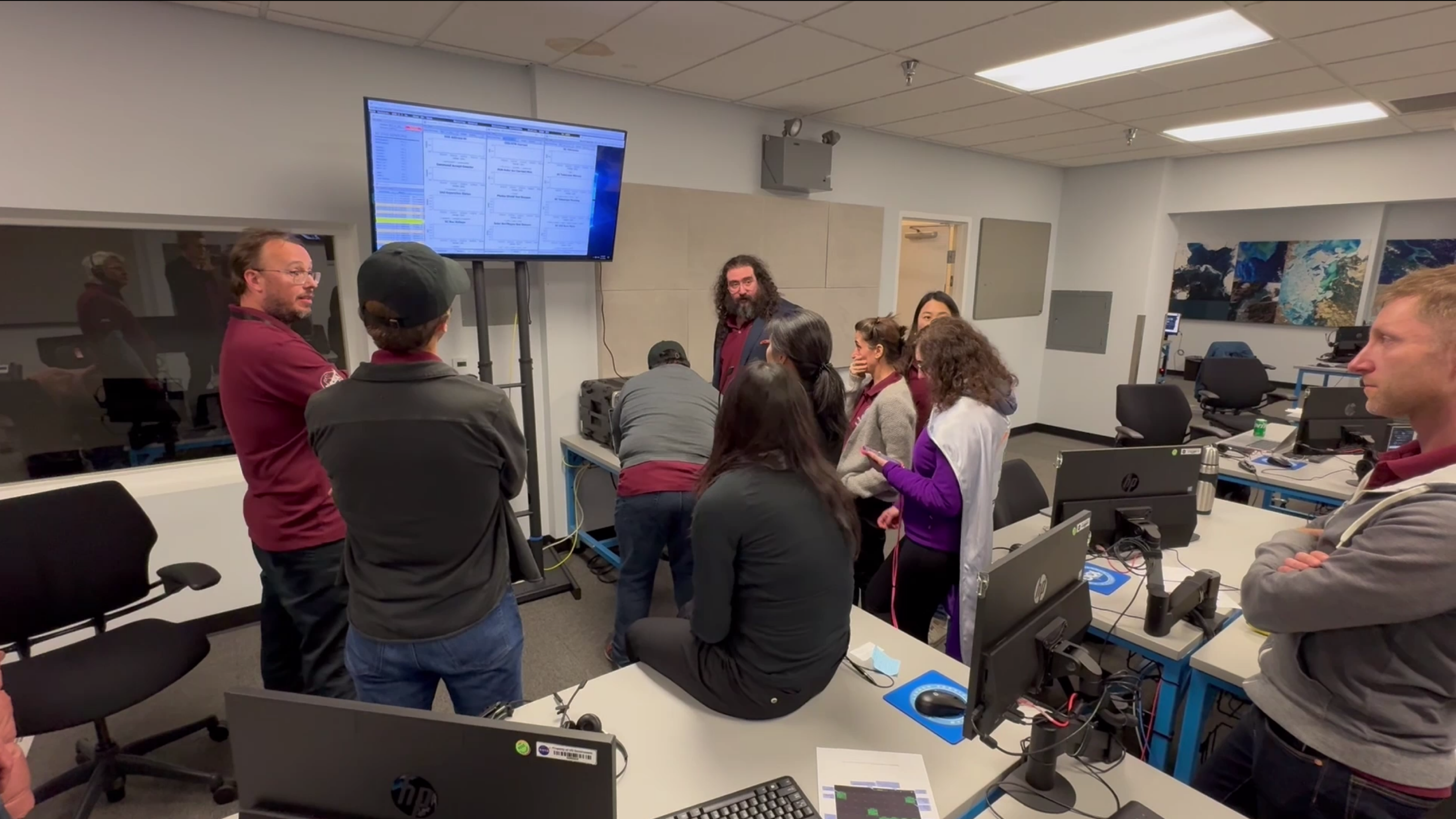
• Complements galaxy-by-galaxy surveys

Intensity Mapping captures the light emitted from everything that gravitationally clusters

Spacecraft integration (2024)




SPEED
0
KM/H
ALTITUDE
0.1
KM
STAGE 1 TELEMETRY
STARTUP
LIFTOFF
MAX-Q
MECO
BOOSTBACK
FAIRING
T - 00:00:03
SPHEREX / PUNCH



JPL Earth Orbiting Mission Operation Center

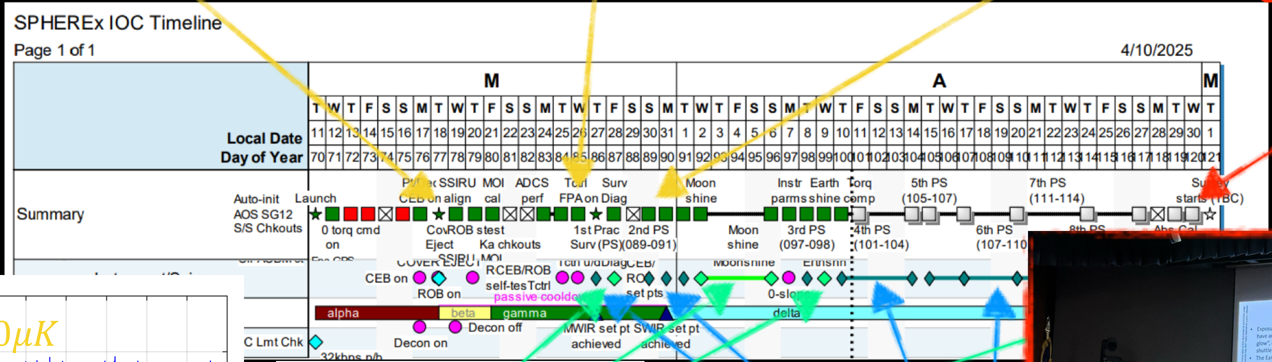
In-Orbit Checkout

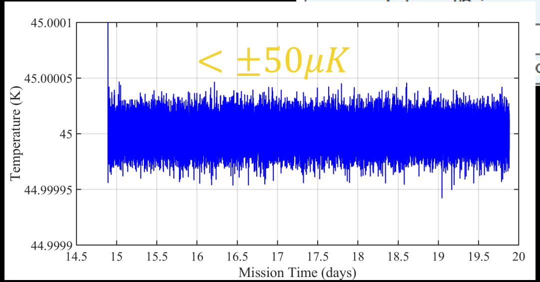
3/18: Cover Eject

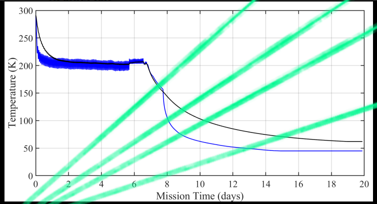
3/26: Detector turn on

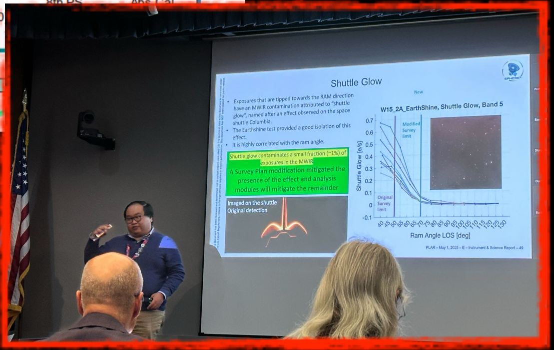
3/30: Focal Plane Temperature at Target: 62K/45K

Start of Science Survey





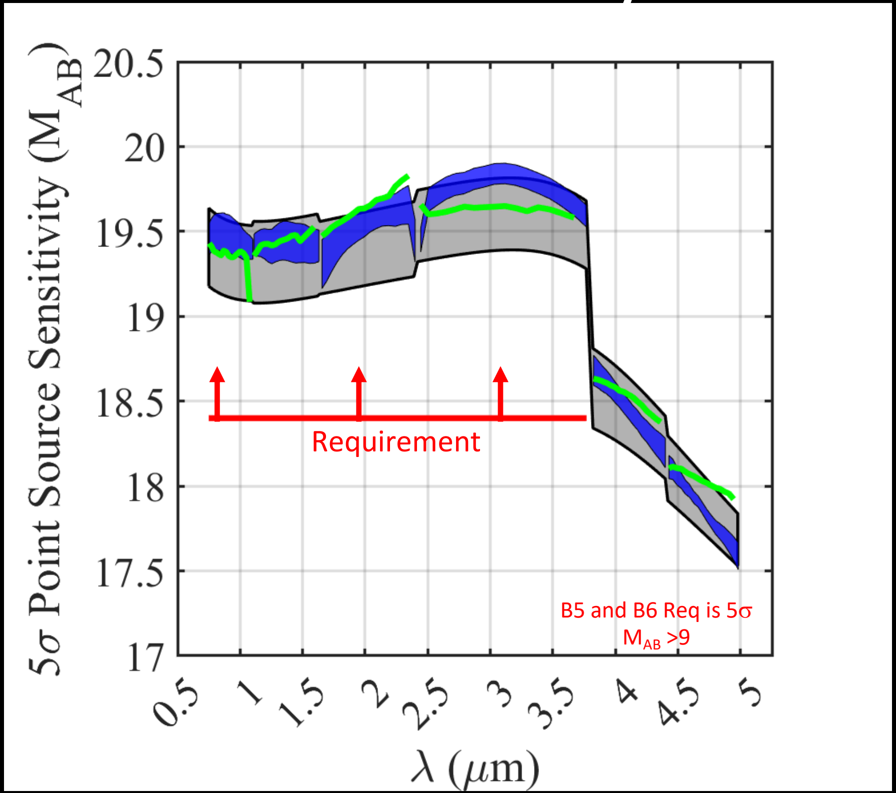




Systematics Experiments

Practice Surveys with multiple configurations

SPHEREx Sensitivity



CSR –Level Estimate ca. 2018

- Vendor negotiated detector specifications
- Vendor negotiated efficiencies
- Simulated Optical Performance
- Simulated Spacecraft ADCS Performance
- Modelled Sky Brightness

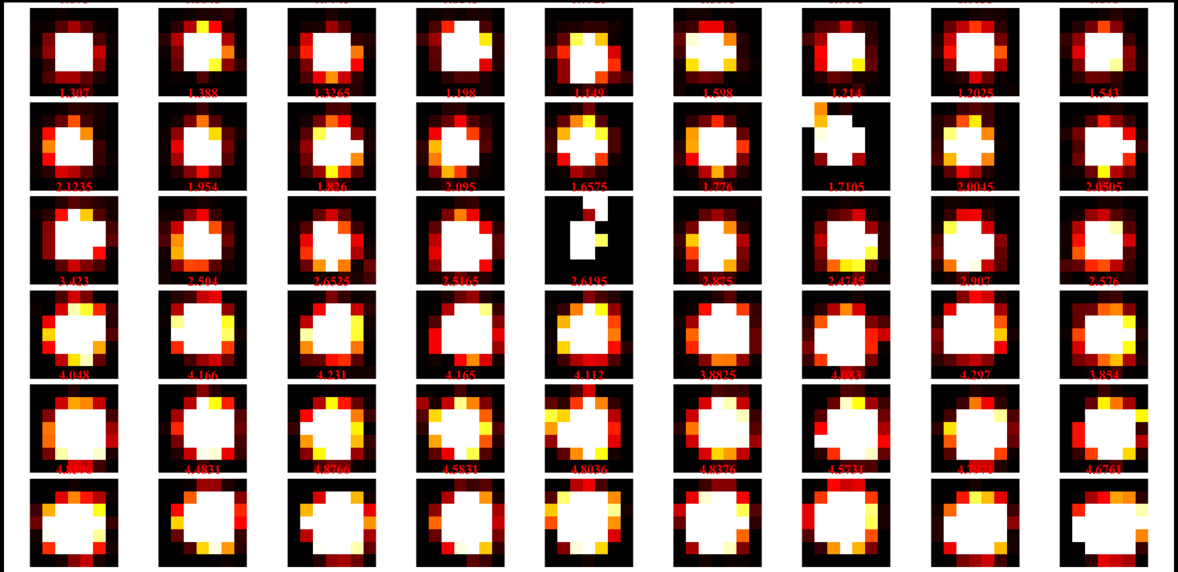
Instrument I&T Completion ca. 2023

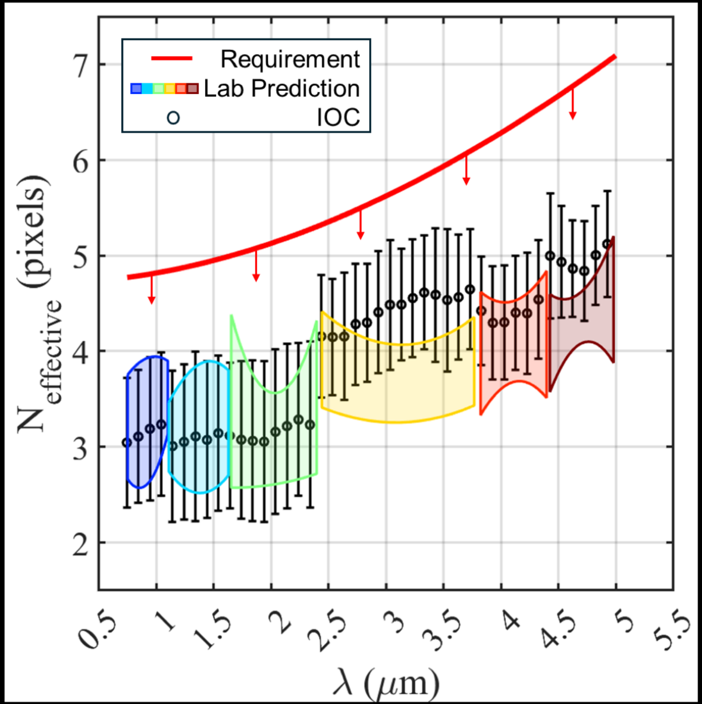
- Lab measured detector performance
- Component measured efficiencies
- Measured Focus + Simulated Optical Performance
- Simulated Spacecraft ADCS Performance
- Modelled Sky Brightness

IOC Data with No Modeled components

- Neffective (PSF) from stars including pointing
- Noise from differences
- Absolute Calibration from Standard Stars
- Sky averaged Photocurrent

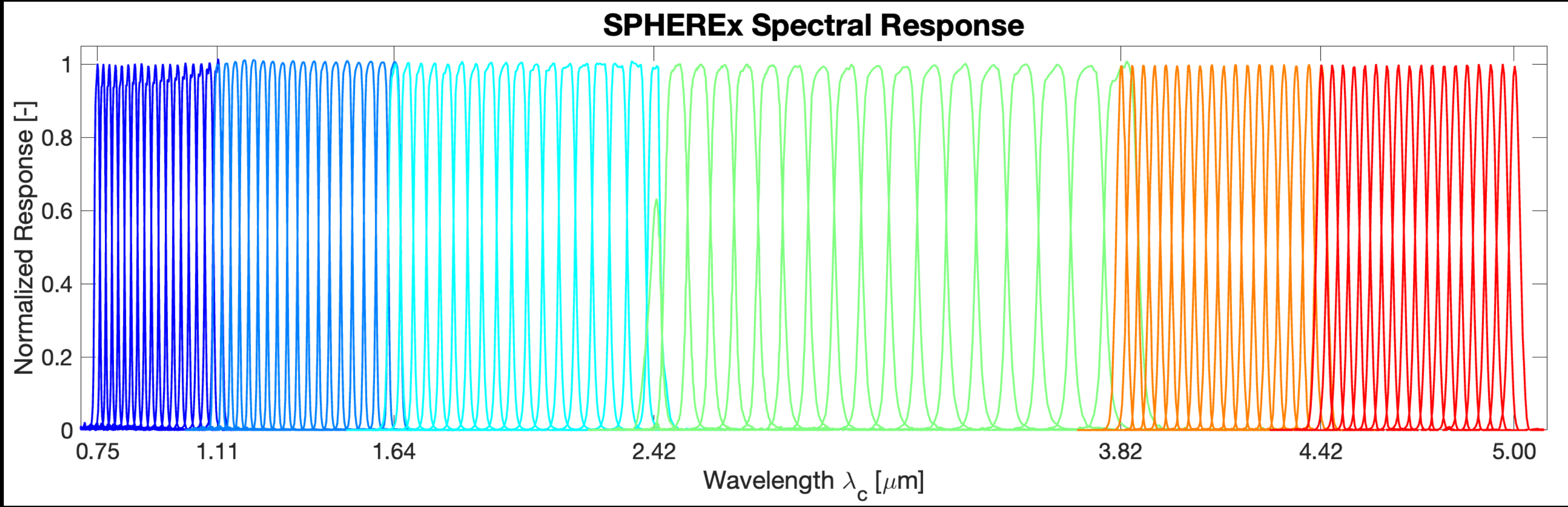
Optical Performance



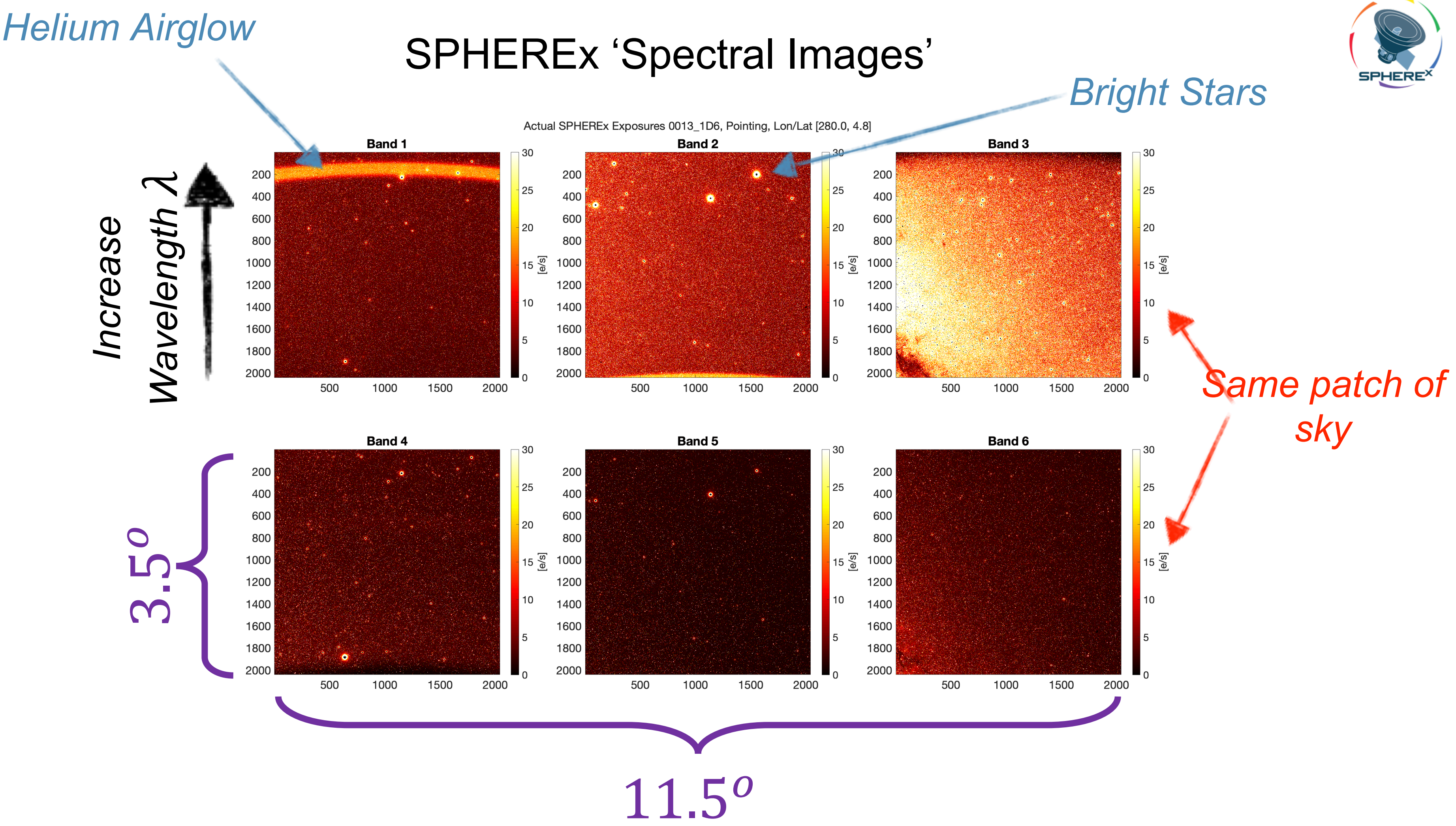


Calculate the beam volume in Neff using ~1M bright isolated stars

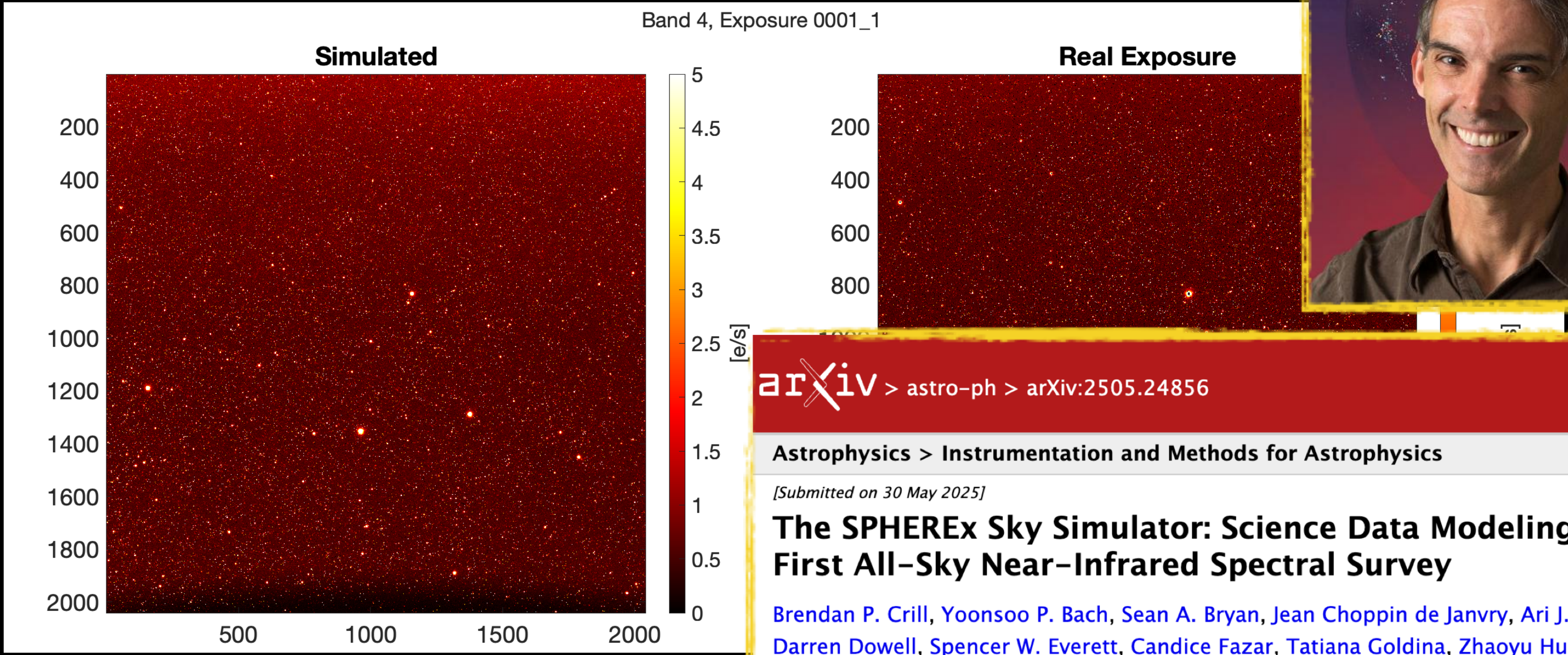
Spectral Response



SPHEREx ‘Spectral Images’



SPHEREx Sky Simulator



arXiv > astro-ph > arXiv:2505.24856

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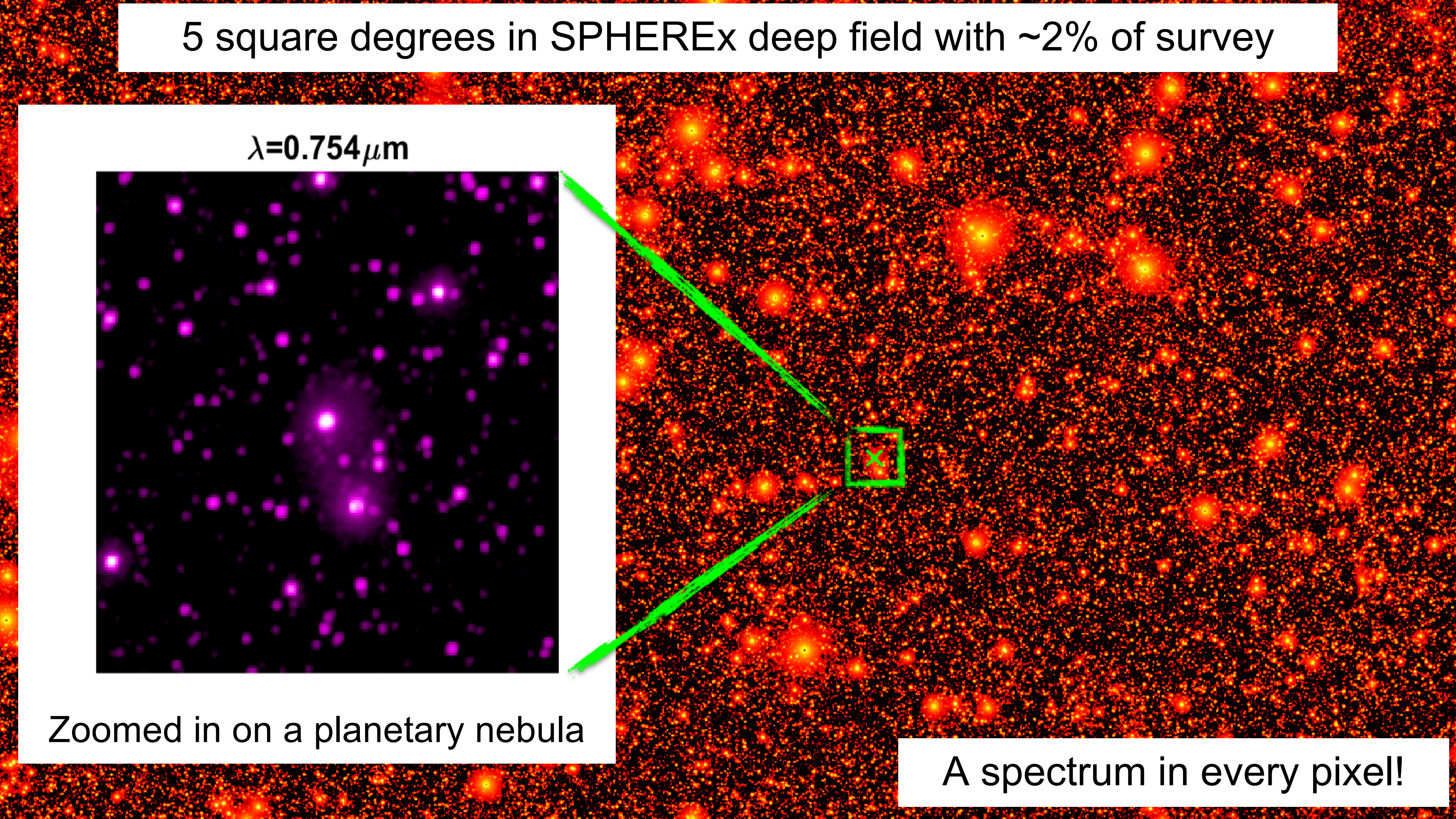
Astrophysics > Instrumentation and Methods for Astrophysics

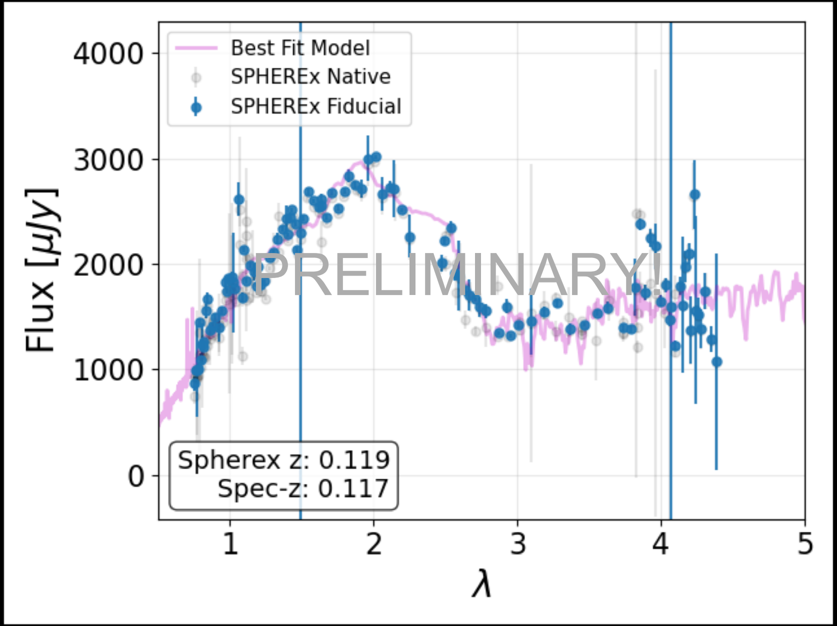
[Submitted on 30 May 2025]

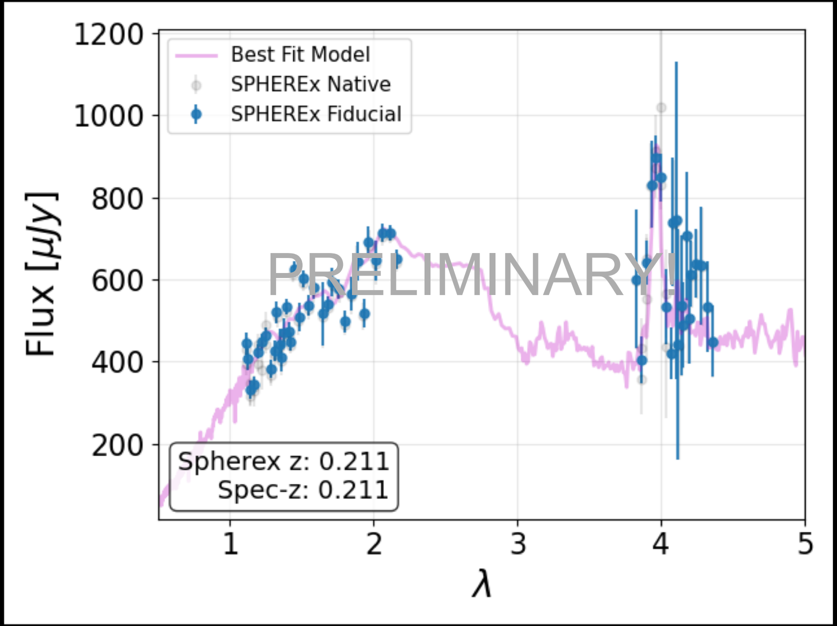
The SPHEREx Sky Simulator: Science Data Modeling for the First All-Sky Near-Infrared Spectral Survey

Brendan P. Crill, Yoonsoo P. Bach, Sean A. Bryan, Jean Choppin de Janvry, Ari J. Cukierman, C. Darren Dowell, Spencer W. Everett, Candice Fazar, Tatiana Goldina, Zhaoyu Huai, Howard Hui, Woong-Seob Jeong, Jae Hwan Kang, Phillip M. Korngut, Jae Joon Lee, Daniel C. Masters, Chi H. Nguyen, Jeonghyun Pyo, Teresa Symons, Yujin Yang, Michael Zemcov, Rachel Akeson, Matthew L. N. Ashby, James J. Bock, Tzu-Ching Chang, Yun-Ting Cheng, Yi-Kuan Chang, Asantha Cooray, Olivier Doré, Andreas L. Faisst, Richard M. Feder, Michael W. Werner


5 square degrees in SPHEREx deep field with ~2% of survey
λ=0.754μm
Zoomed in on a planetary nebula
A spectrum in every pixel!

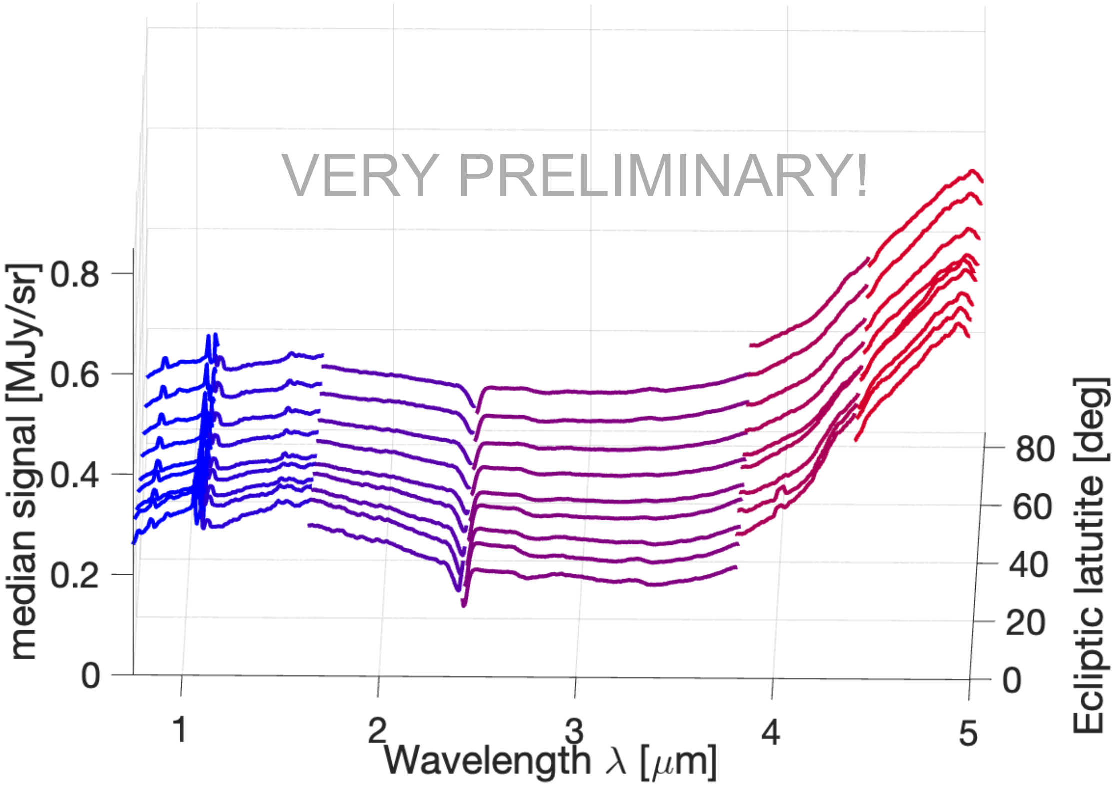
Redshift estimation



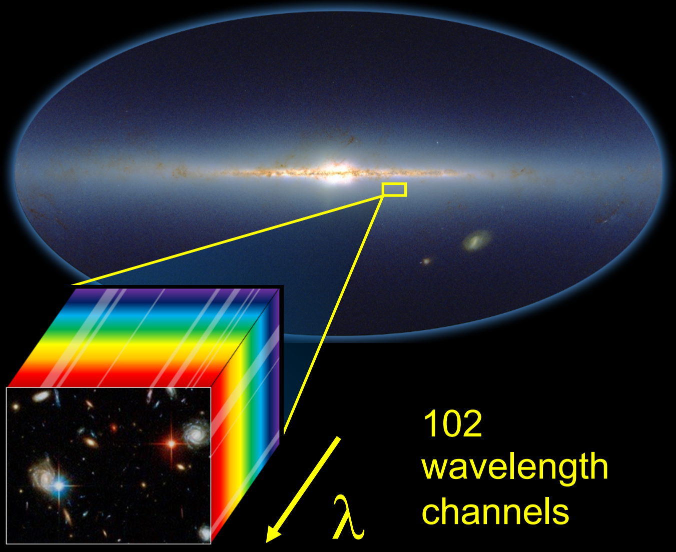


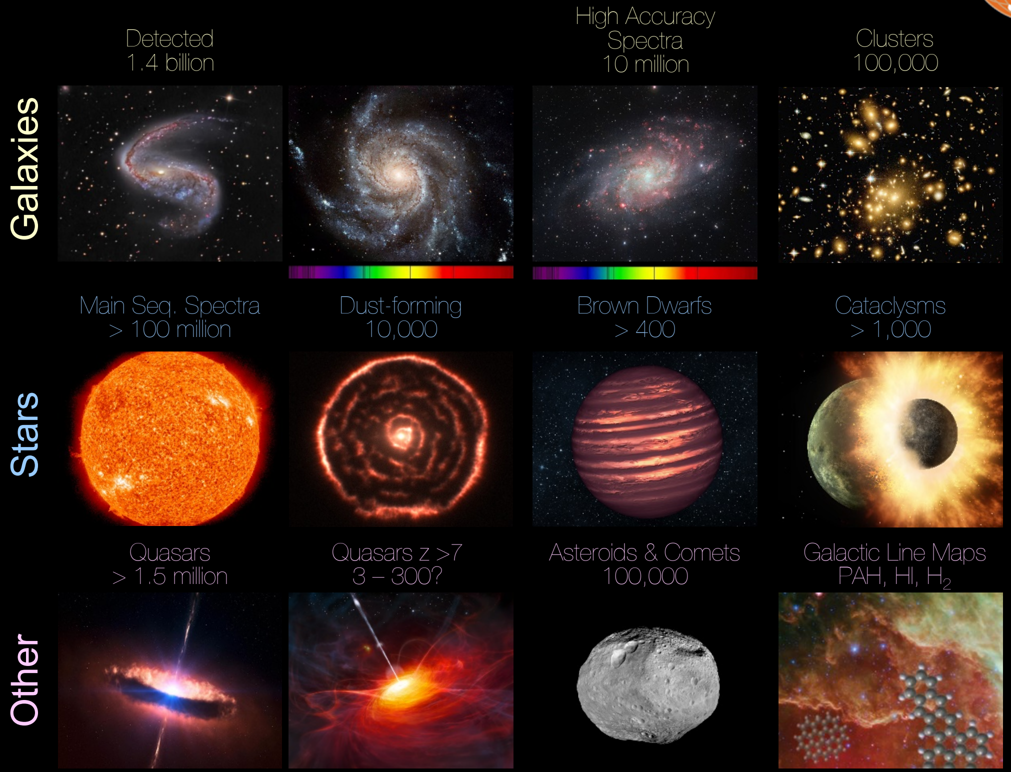
SPHEREx Cosmology Team

3 days of (commissioning) data…



Legacy Archive!





SPHEREx provides a new and unique dataset

a complete near-infrared spectrum for every 6″ pixel on the sky

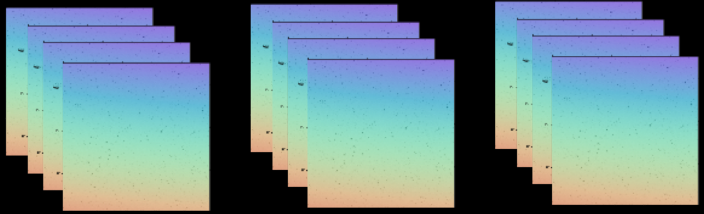
SPHEREx will provide an all-sky spectral archive

Delivered to the NASA/IPAC Infrared Science Archive (IRSA)

→ Enables a wide range of community science with well-calibrated data products

Calibrated Spectral Image Data

- Available in archive within 2 months
- Reprocessed images released after Year 1 and Year 2

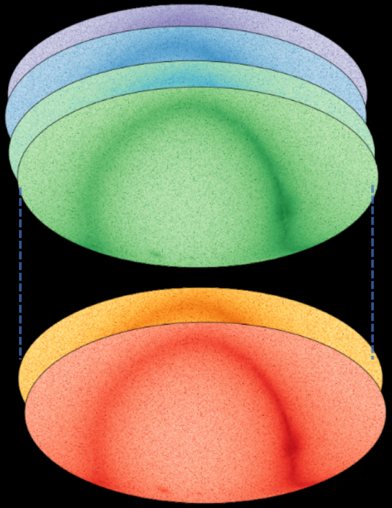


Archive functionality

- User-driven Spectrophotometry
- Custom Mosaics
- LVF Image Cutout
- General search, retrieval and visualization

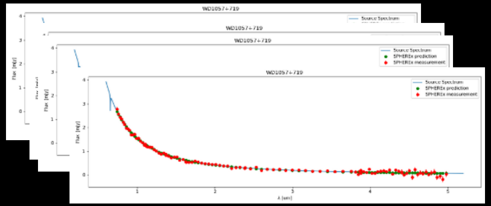
102 All-sky Data Cubes

- Released after Year 1 and 2



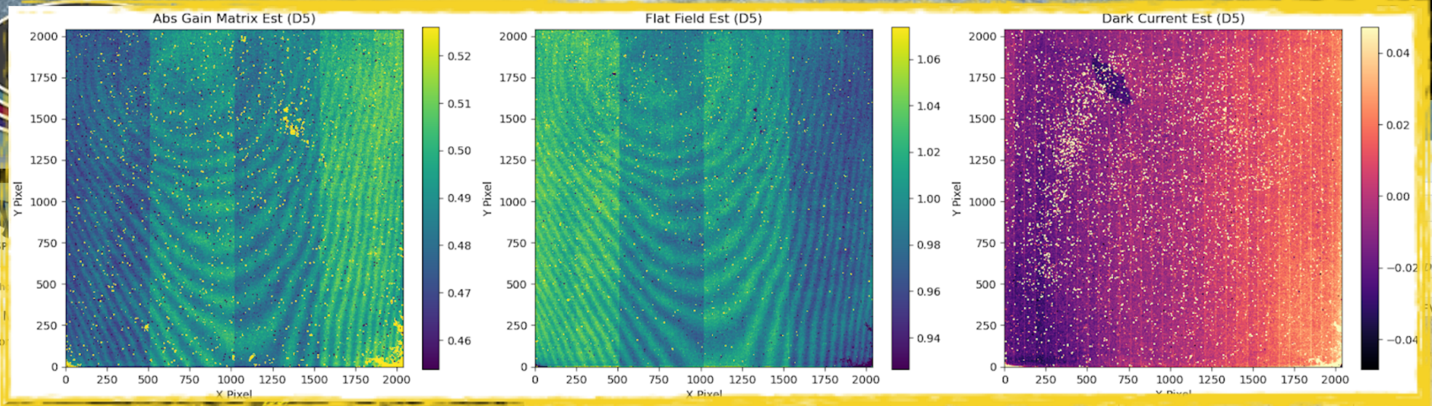
High Reliability Source Catalog

- Photometry in 102 spectral channels
- Sources selected from input catalog



Legacy Data Products

- Released at end of mission
- Legacy Deep Field Mosaics
- Legacy Galaxy Catalog
- Legacy Stellar Type/Ice Column Density Catalog



- *Flatfield*
- *Darkcurrent*
- *Photometric Calibration*
- *Nonlinearity*
- *Persistence Masks*
- *Astrometry*
- *Source Mask*
- *Exposure-Average PSFs*
- *...*

SSDC Data Product Specification — SSDC–DP–017

SPHEREx Explanatory Supplement — Version 0.1, 2024-05-14

SSDC–DP–017

SPHEREx Explanatory Supplement

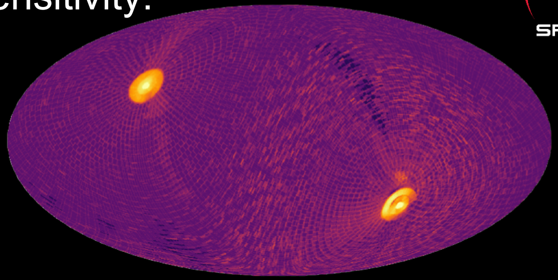
Version: 0.1

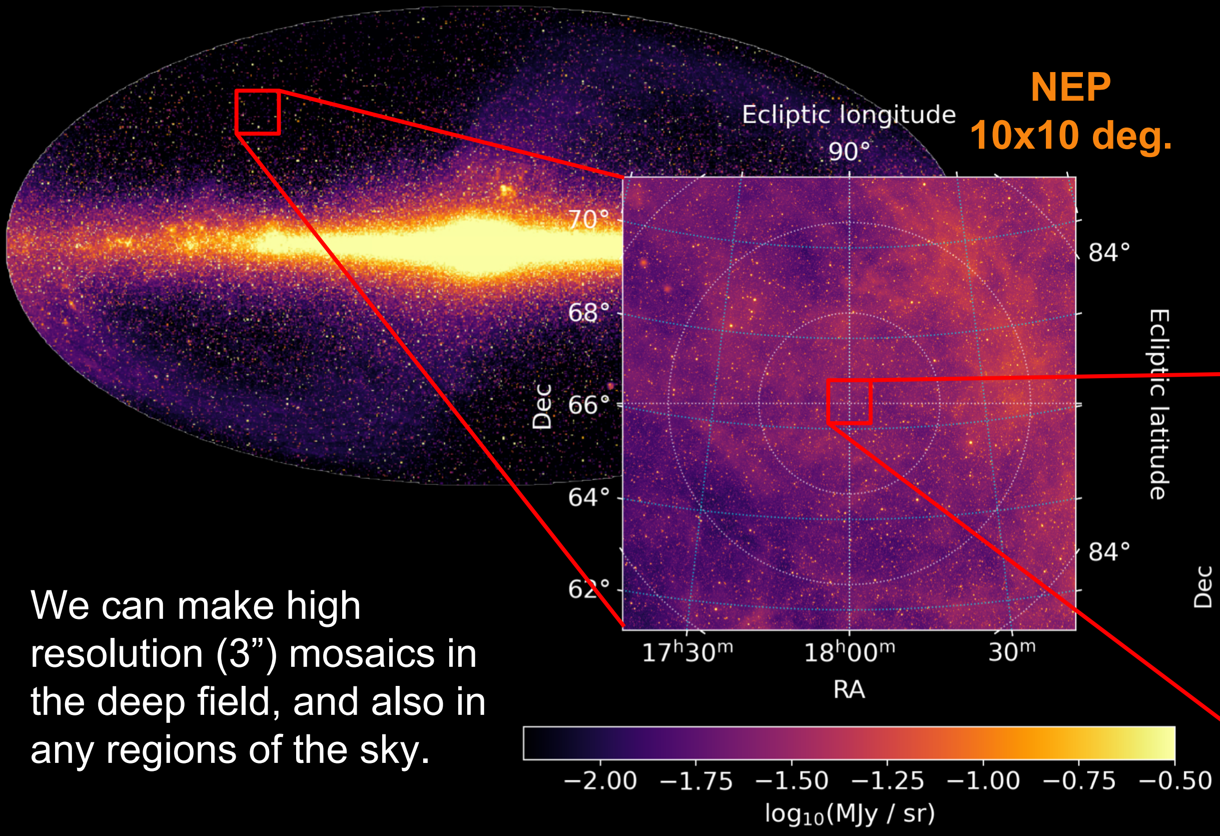
Authors:
SSDC (Rachel Akeson, Gregory Dubois-Felsmann, Andreas Faisst, Tamim Fatahi, Tatiana Goldina, Yuna Kwon, Dan Masters, Christina Nelson, Roberta Paladini, Gaby Torrini, Phani Velicheti)
Project POC (Matthew Ashby, Brendan Crill, Olivier Doré, C. Darren Dowell, Candice Fazar, Howard Hui, Phil Korngut, Michael Zemcov)

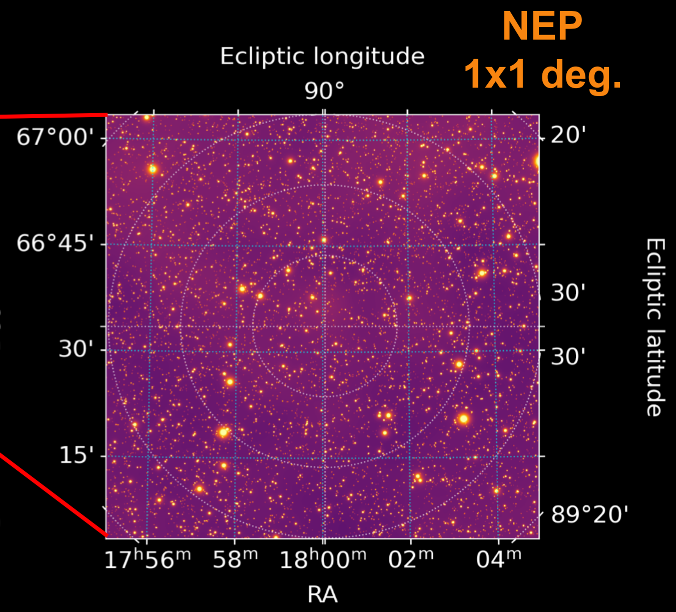
EBL Analysis Pipeline

Deep field mosaic maps

Sensitivity:





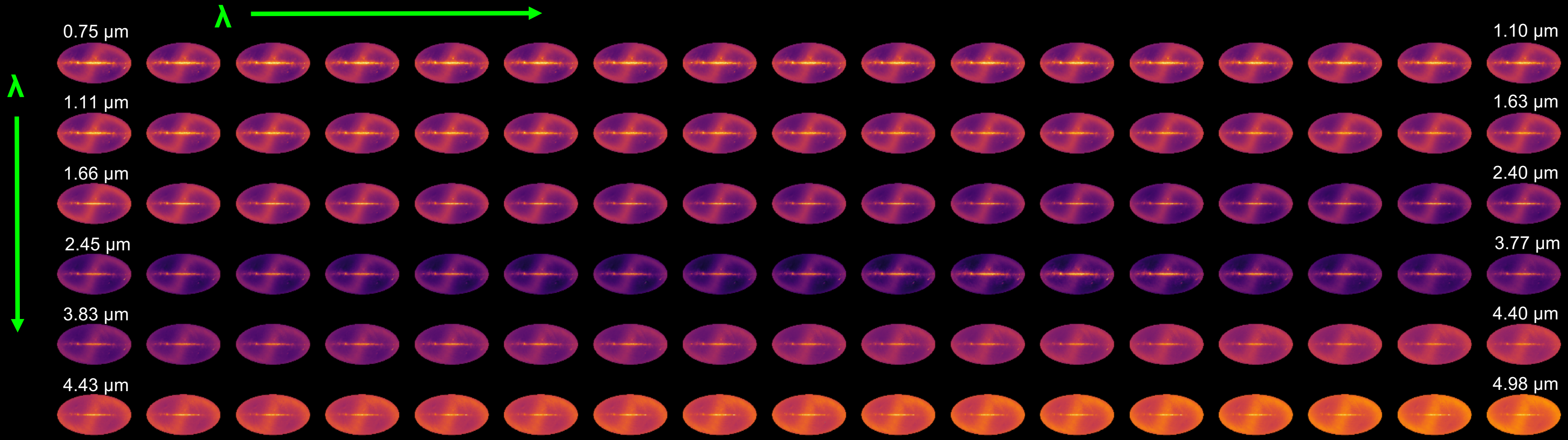


We can make high resolution (3”) mosaics in the deep field, and also in any regions of the sky.

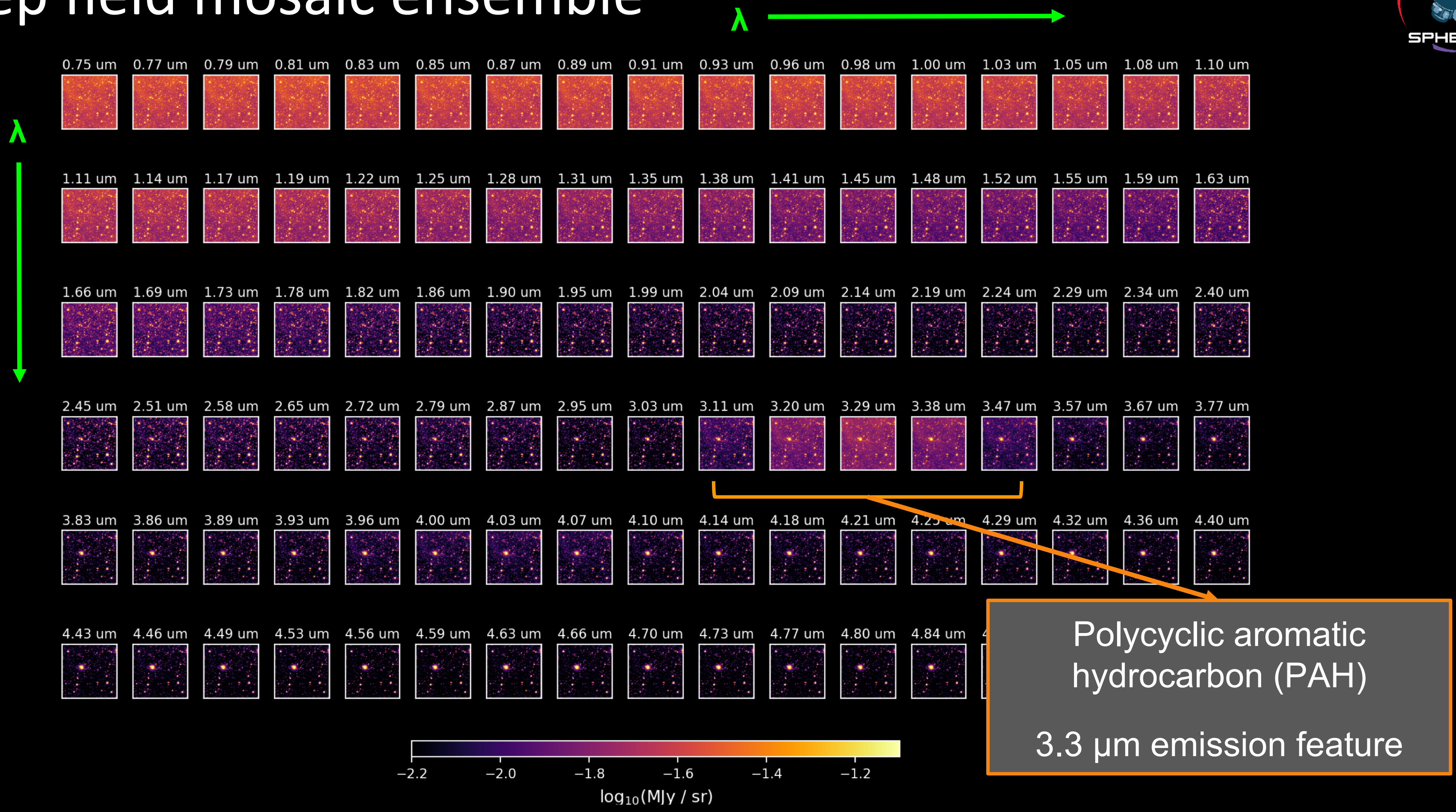
Full sky mosaic ensemble

102 NIR wavelengths to study the whole sky

Giulia Murgia
(Caltech)

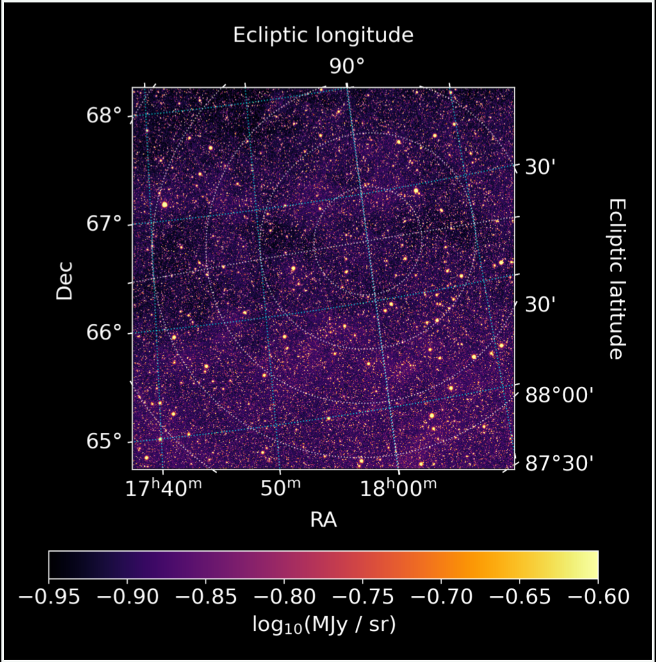


Deep field mosaic ensemble



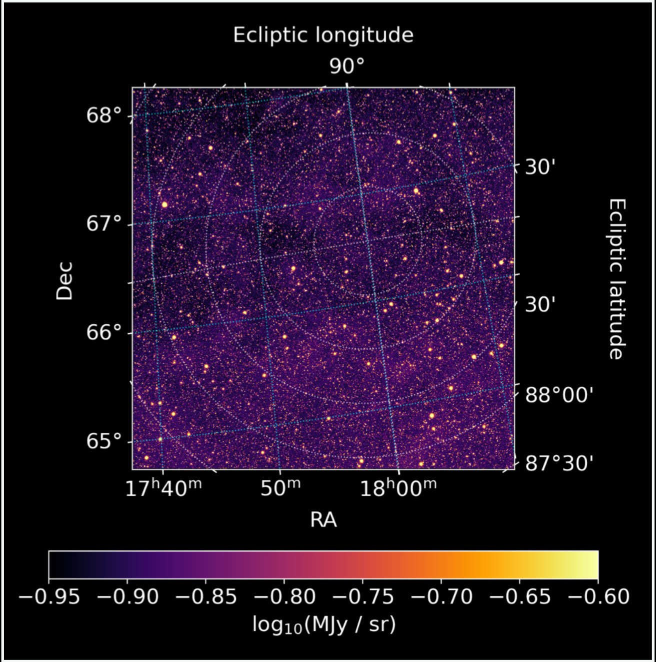
What's in the data?

Typical SPHEREx exposure (simulated)

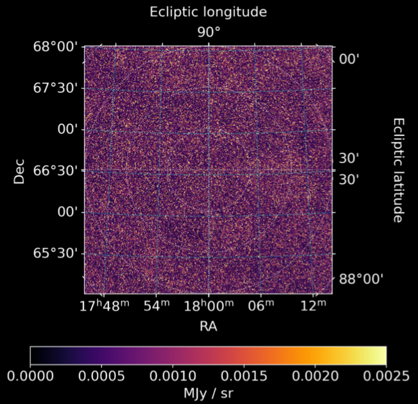


What’s in the data?

Typical SPHEREx exposure (simulated)



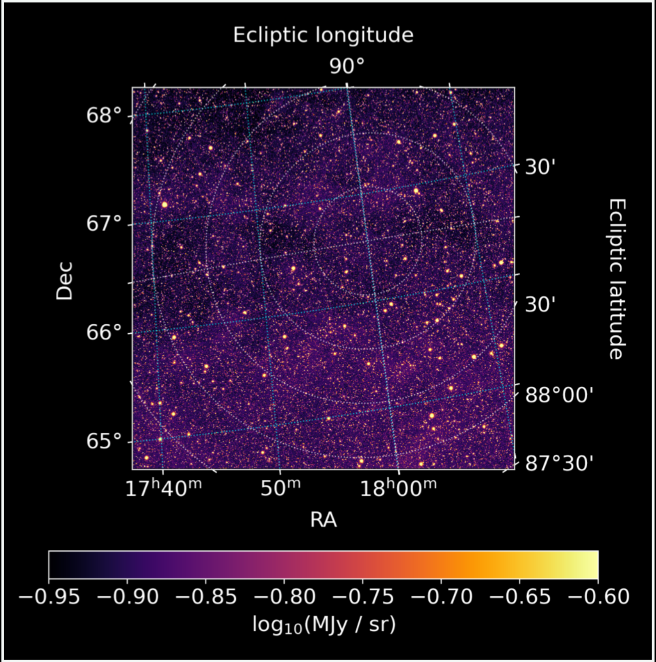
Extragalactic background light (EBL)



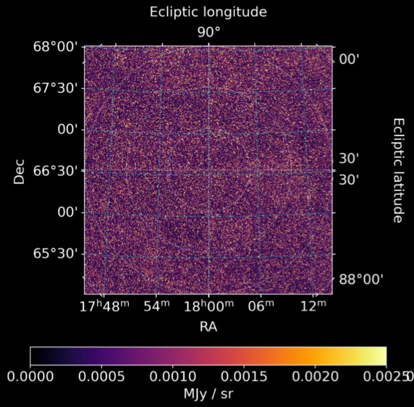
- ➔ Total light emitted by all galaxies since the epoch of reionization
- ➔ **Our target signal!**

What's in the data?

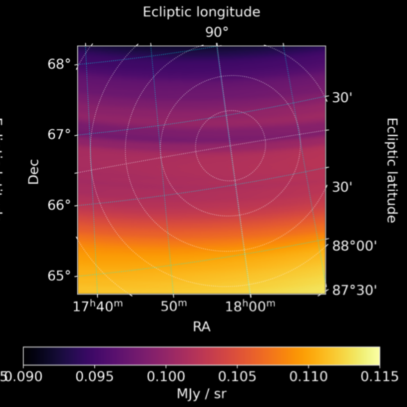
Typical SPHEREx exposure (simulated)



Extragalactic background light (EBL)



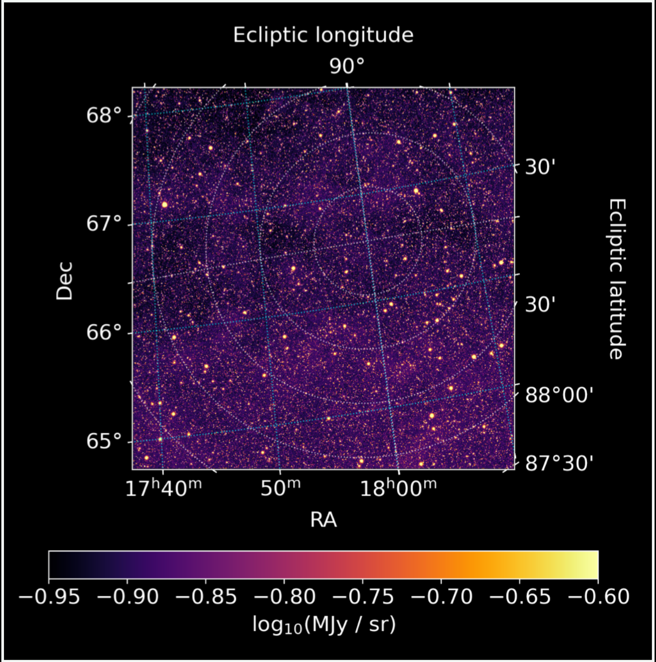
Zodiacal light



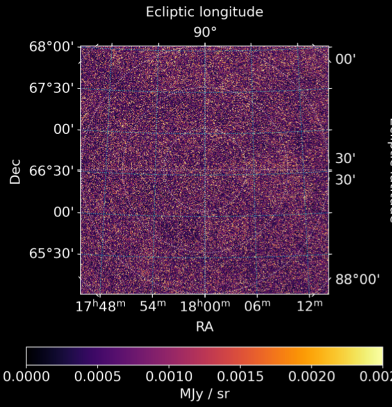
- ➔ Brightest foreground
- ➔ Smooth and time-varying
- ➔ Apply a spatial filter

What's in the data?

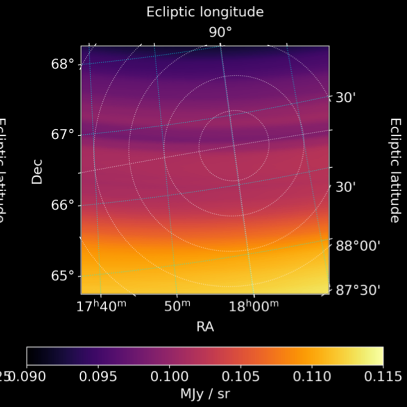
Typical SPHEREx exposure (simulated)



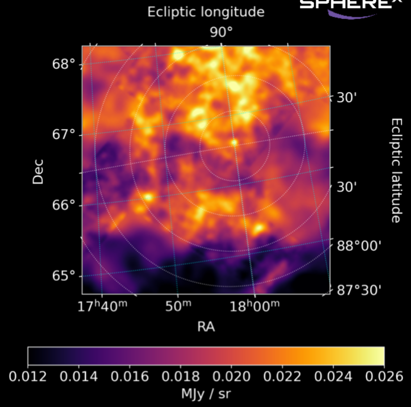
Extragalactic background light (EBL)



Zodiacal light



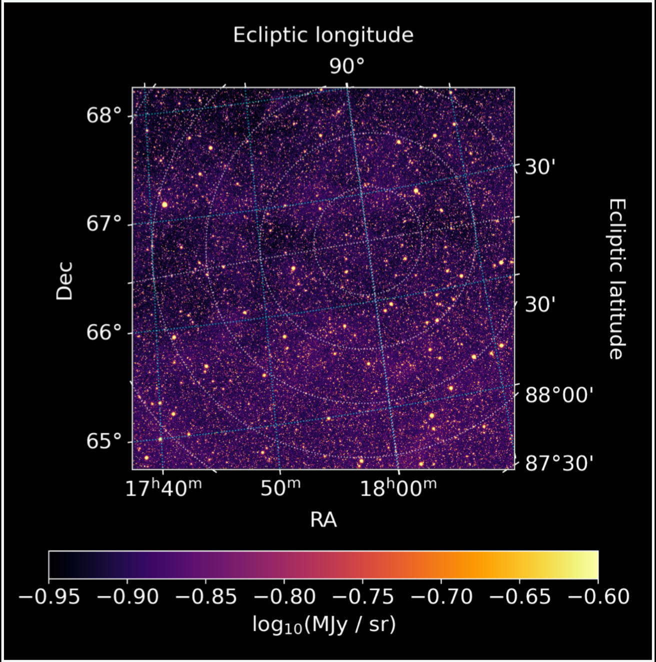
Diffuse Galactic light (DGL)



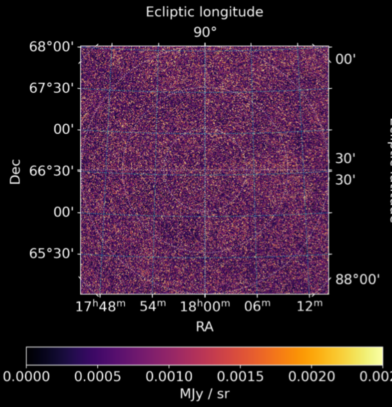
- ➔ Reflected starlight from dust in the Milky Way
- ➔ Deproject based on estimated templates

What's in the data?

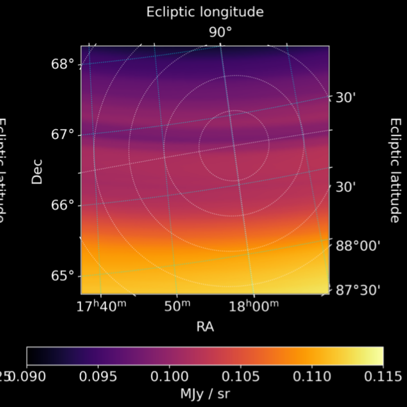
Typical SPHEREx exposure (simulated)



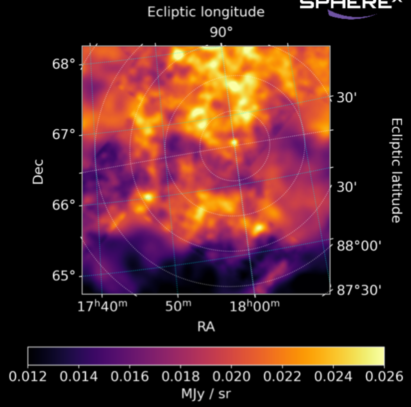
Extragalactic background light (EBL)



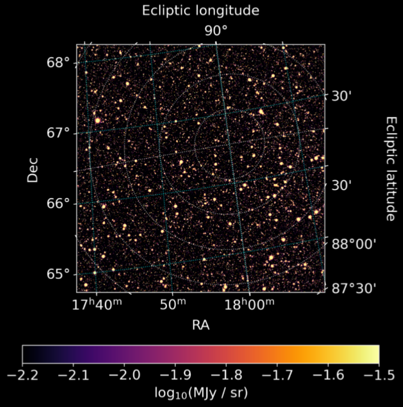
Zodiacal light



Diffuse Galactic light (DGL)



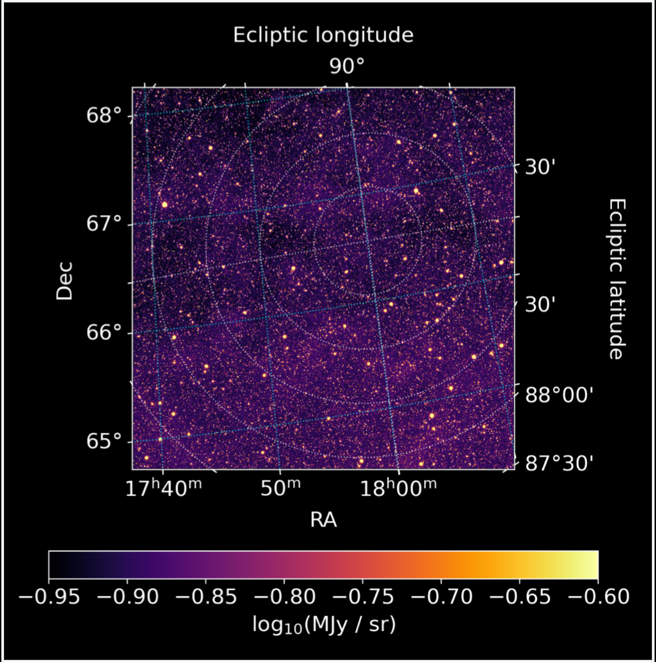
Stars



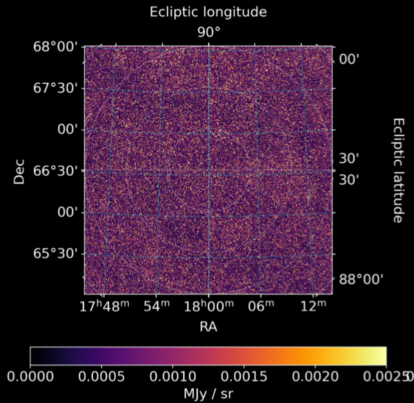
- ➔ Apply a source mask
- ➔ Deproject to further remove residuals outside the mask

What's in the data?

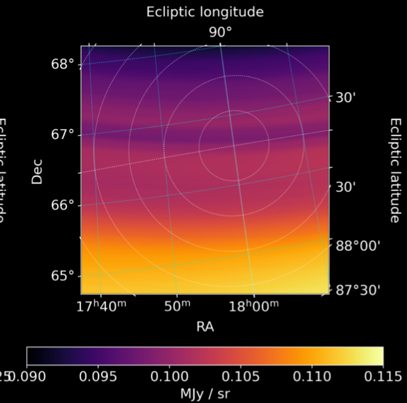
Typical SPHEREx exposure (simulated)



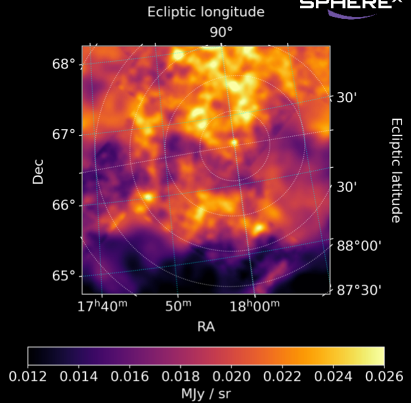
Extragalactic background light (EBL)



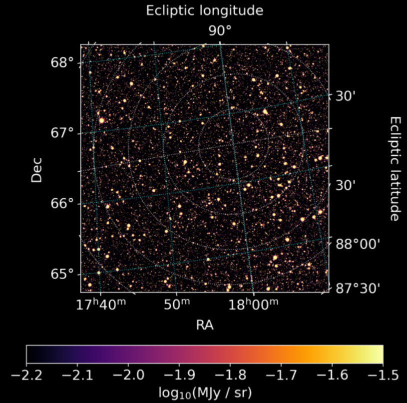
Zodiacal light



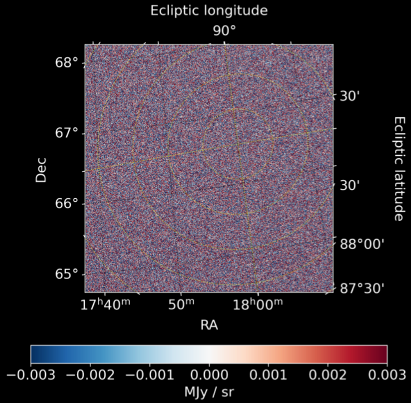
Diffuse Galactic light (DGL)



Stars



Noise



➔ Photon noise + read noise

What's in the data?

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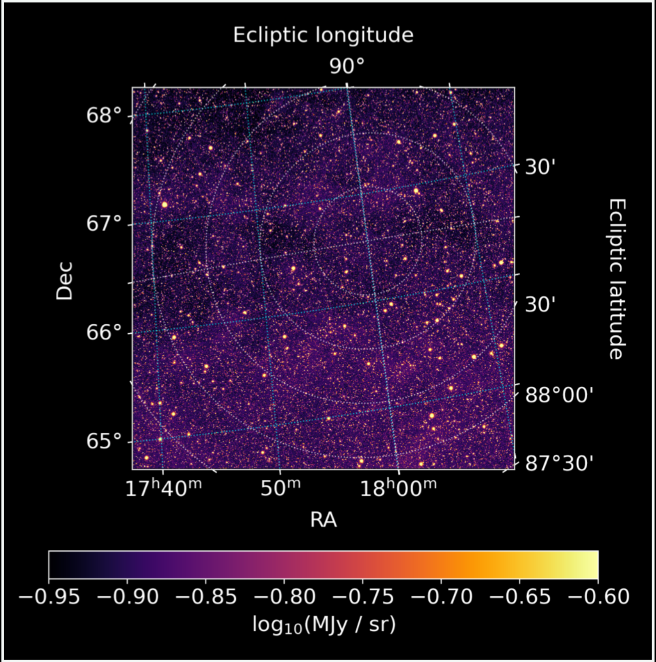

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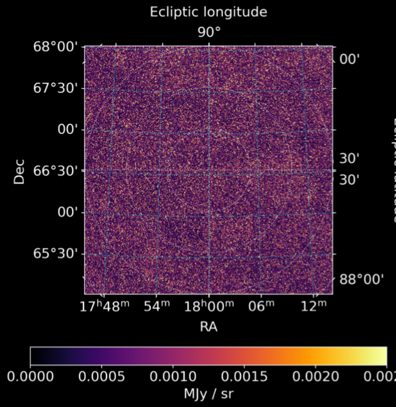
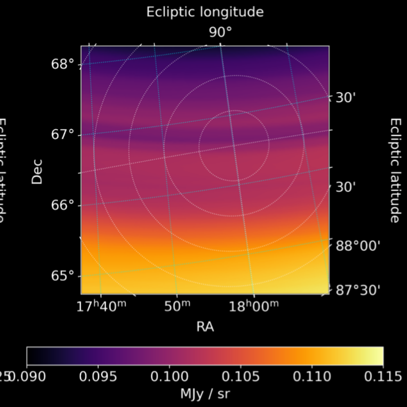


Zodiacal light



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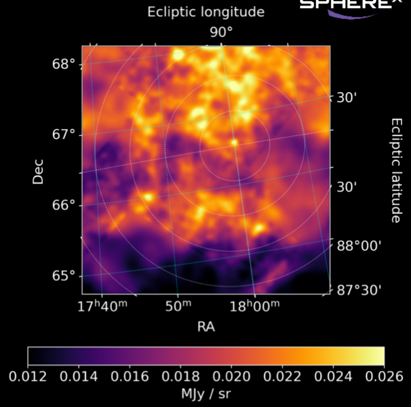
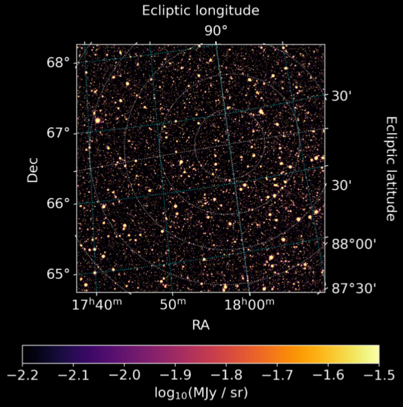
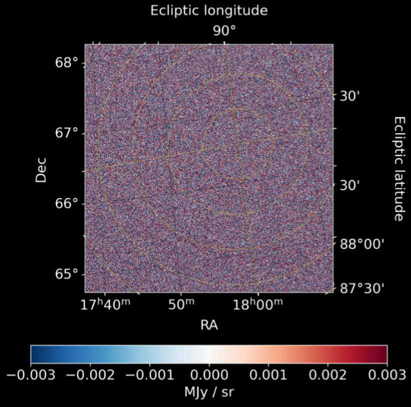


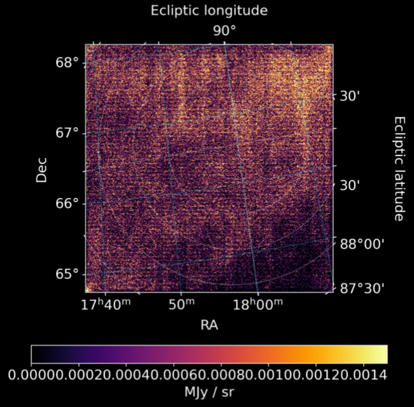
Stars



Noise



Dark current



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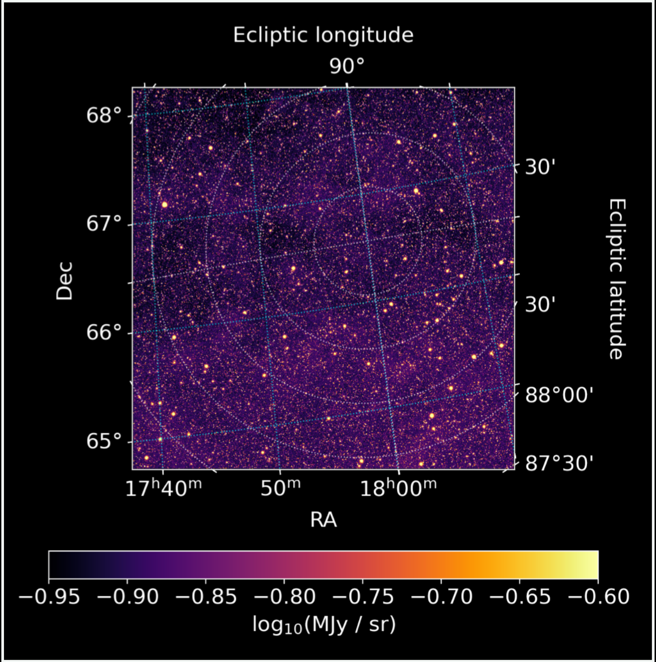
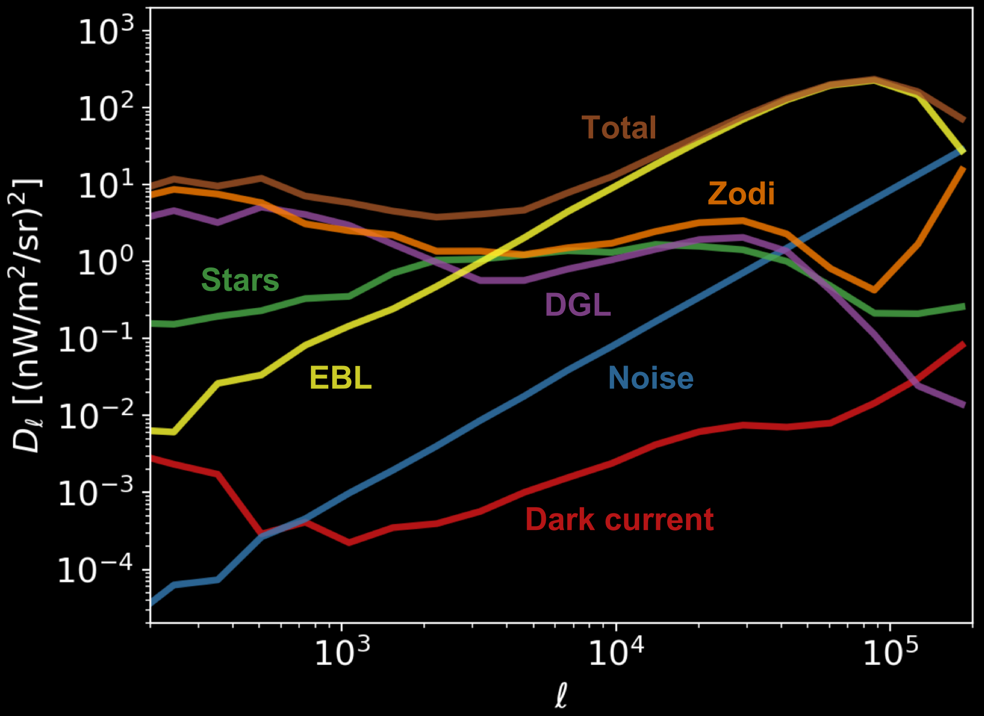


Auto power spectrum



What’s in the EBL map?

Spiral galaxies

Elliptical galaxies

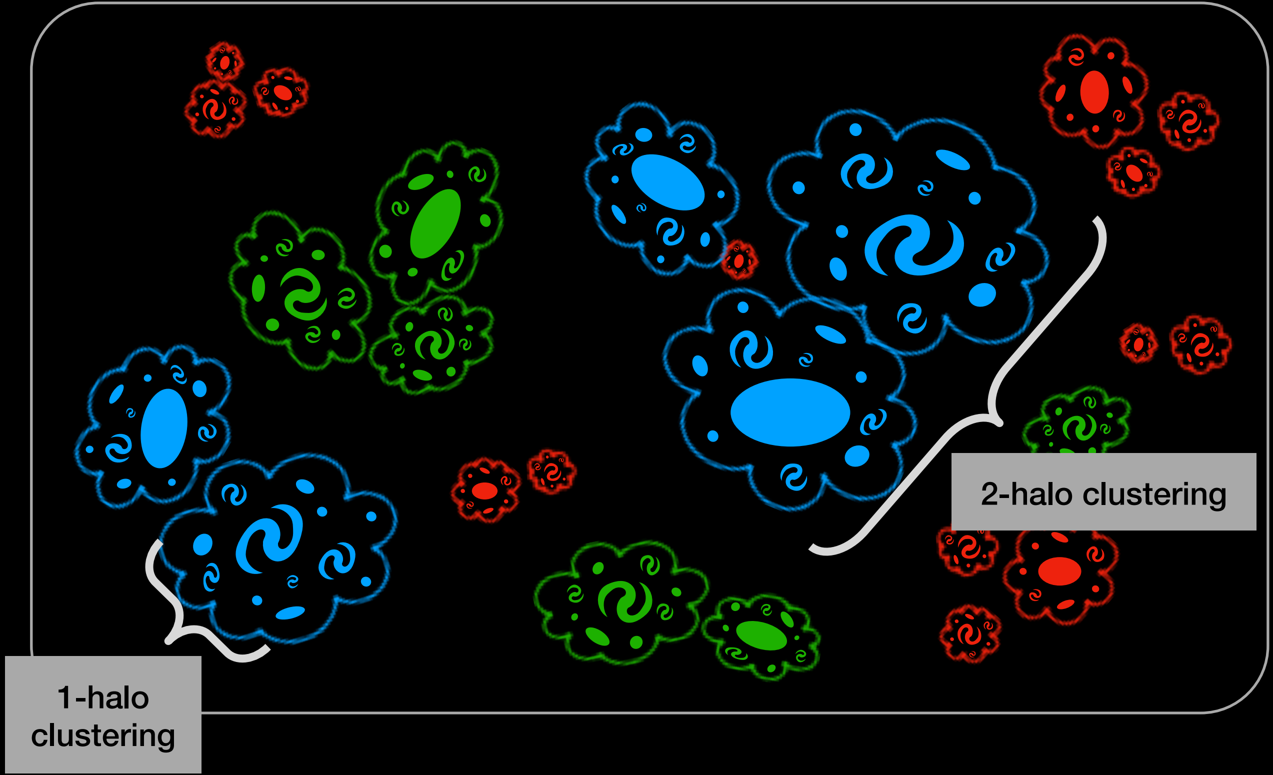
Intra halo light (IHL)

Dwarf galaxies

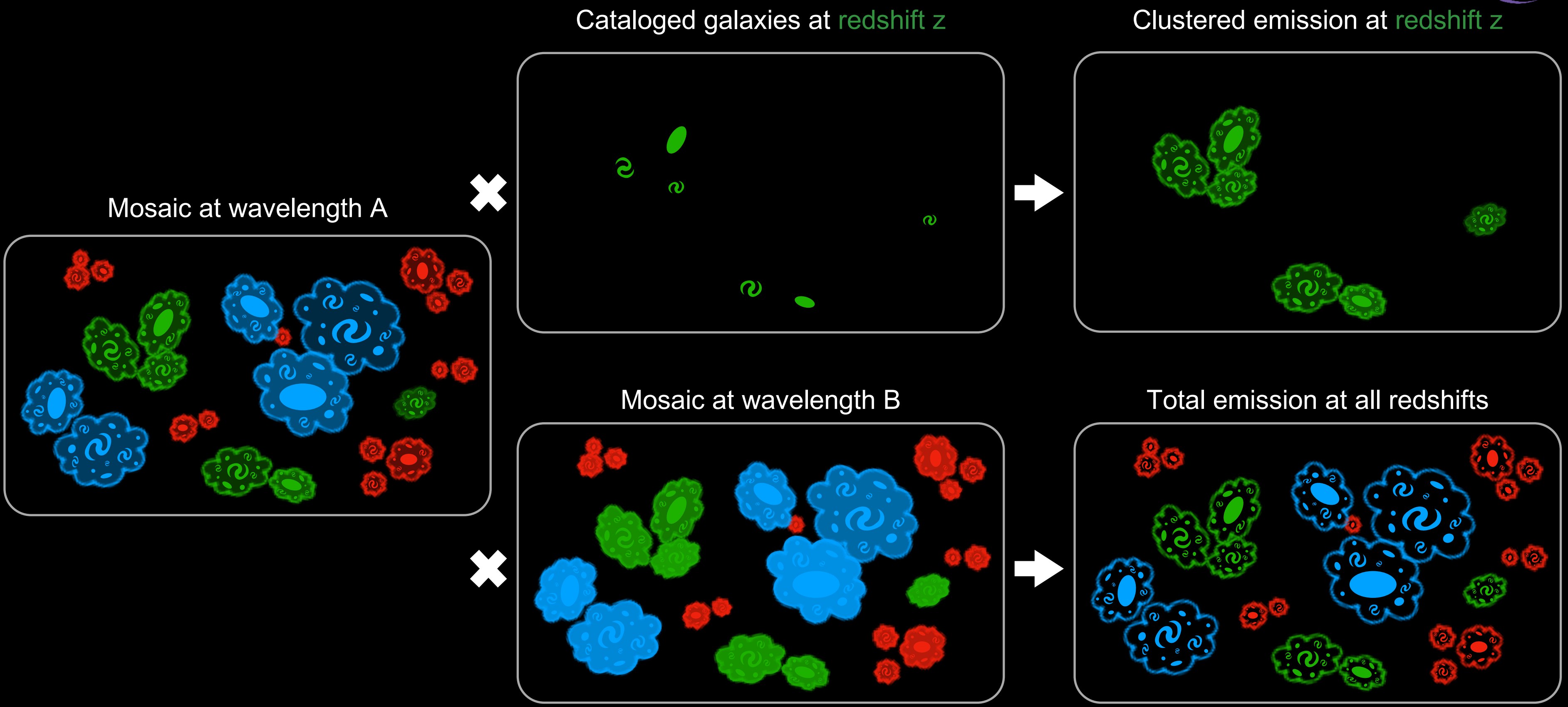
Low redshift

Mid redshift

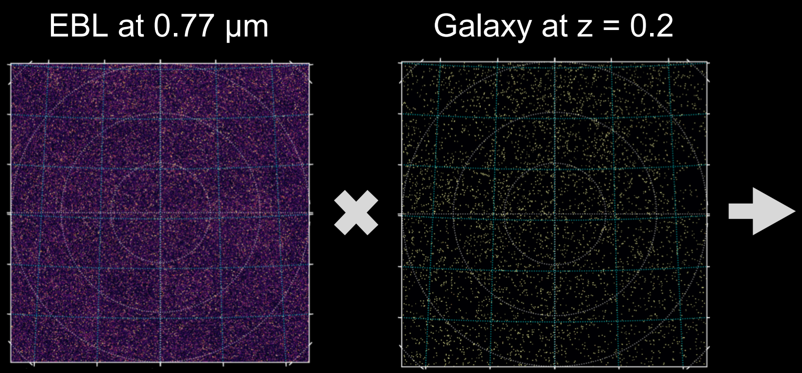
High redshift

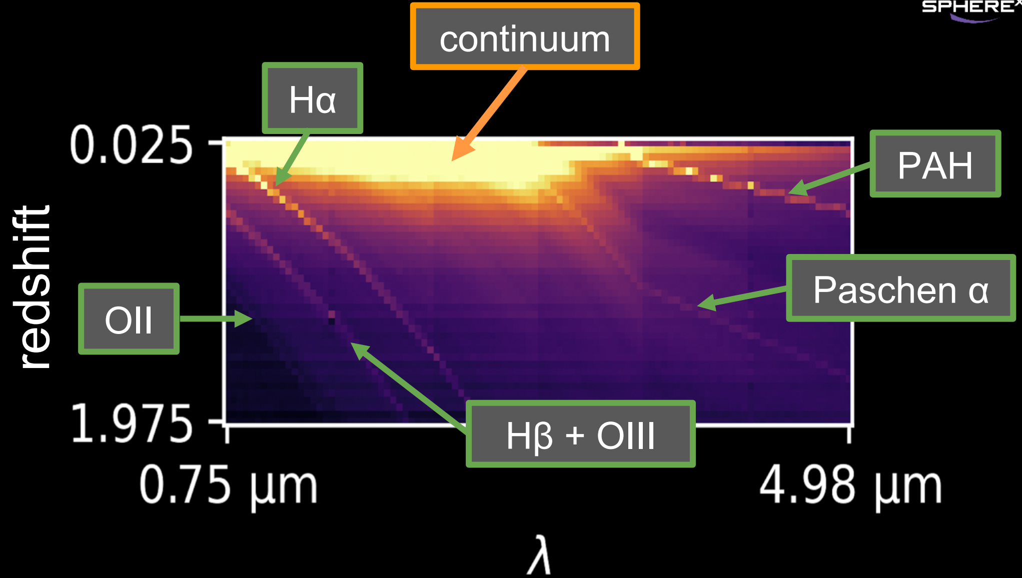


Cross correlation



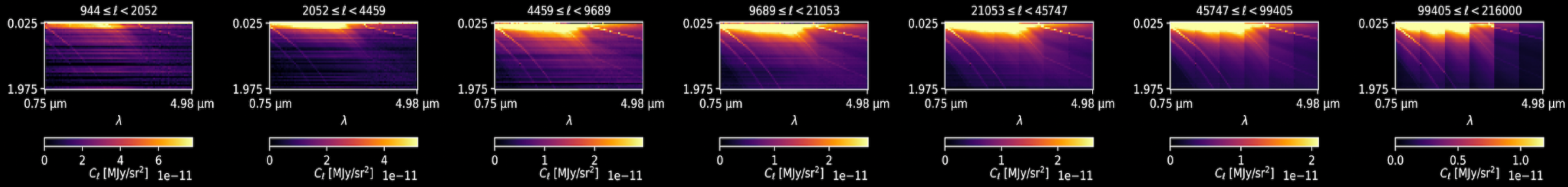
Science 1: galaxy cross spectrum





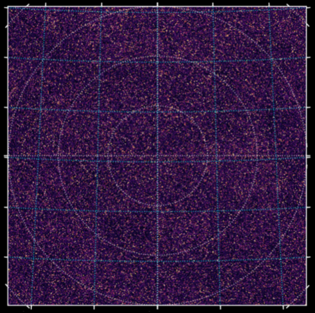
Large angular scales →

Small angular scales

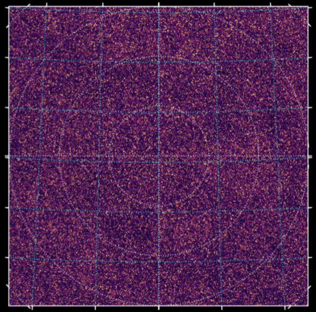


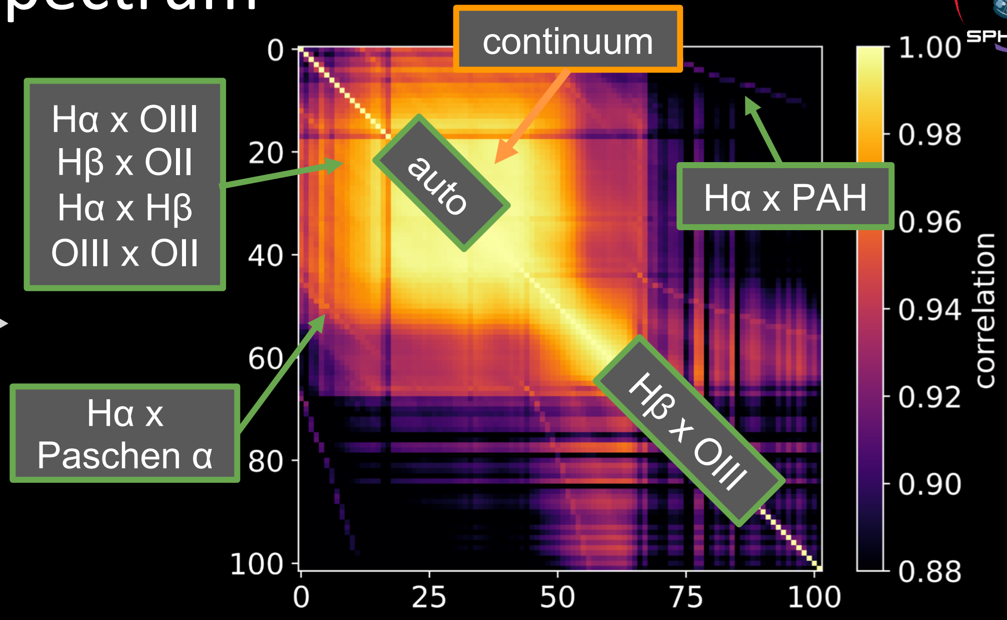
Science 2: internal cross spectrum

EBL at 0.77 µm



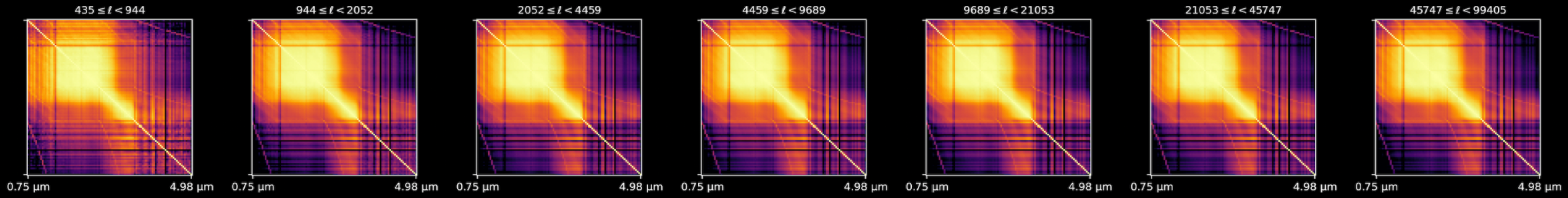
EBL at 3.11 µm





Large angular scales →

Small angular scales



Real data gallery

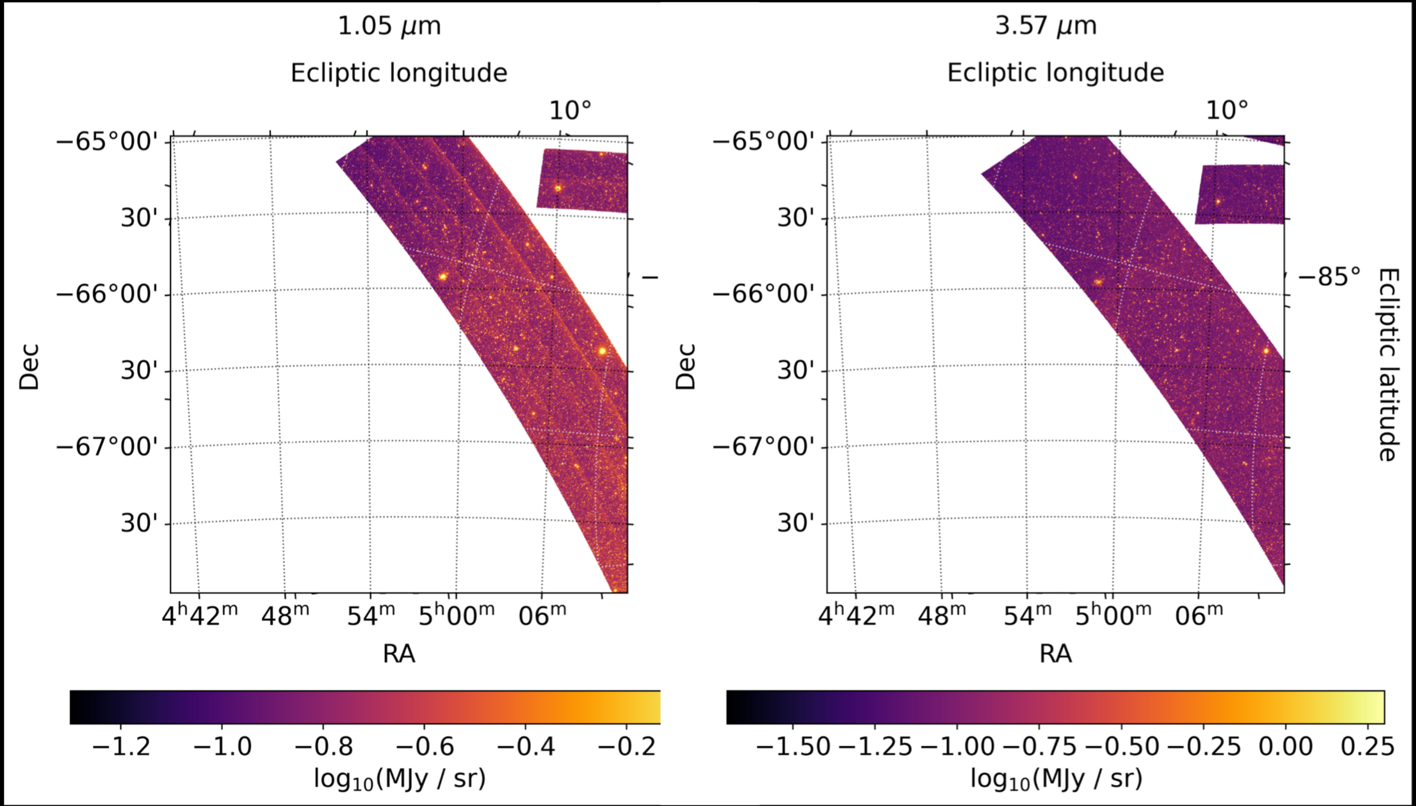
SPHEREx is mapping the sky!

Wavelength varies across the detector → spectral variations

Ari Cukierman (Caltech)

Band 1

Band 4



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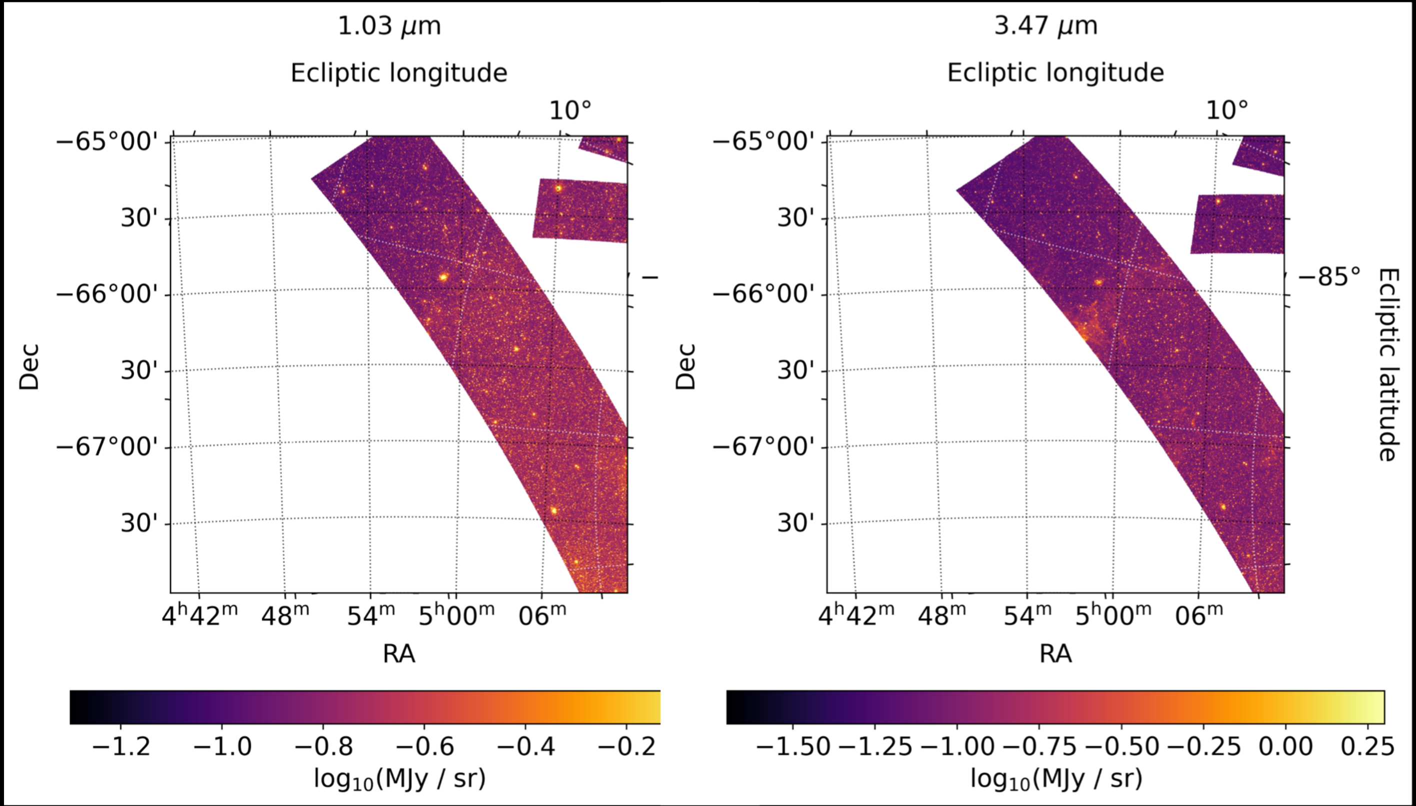

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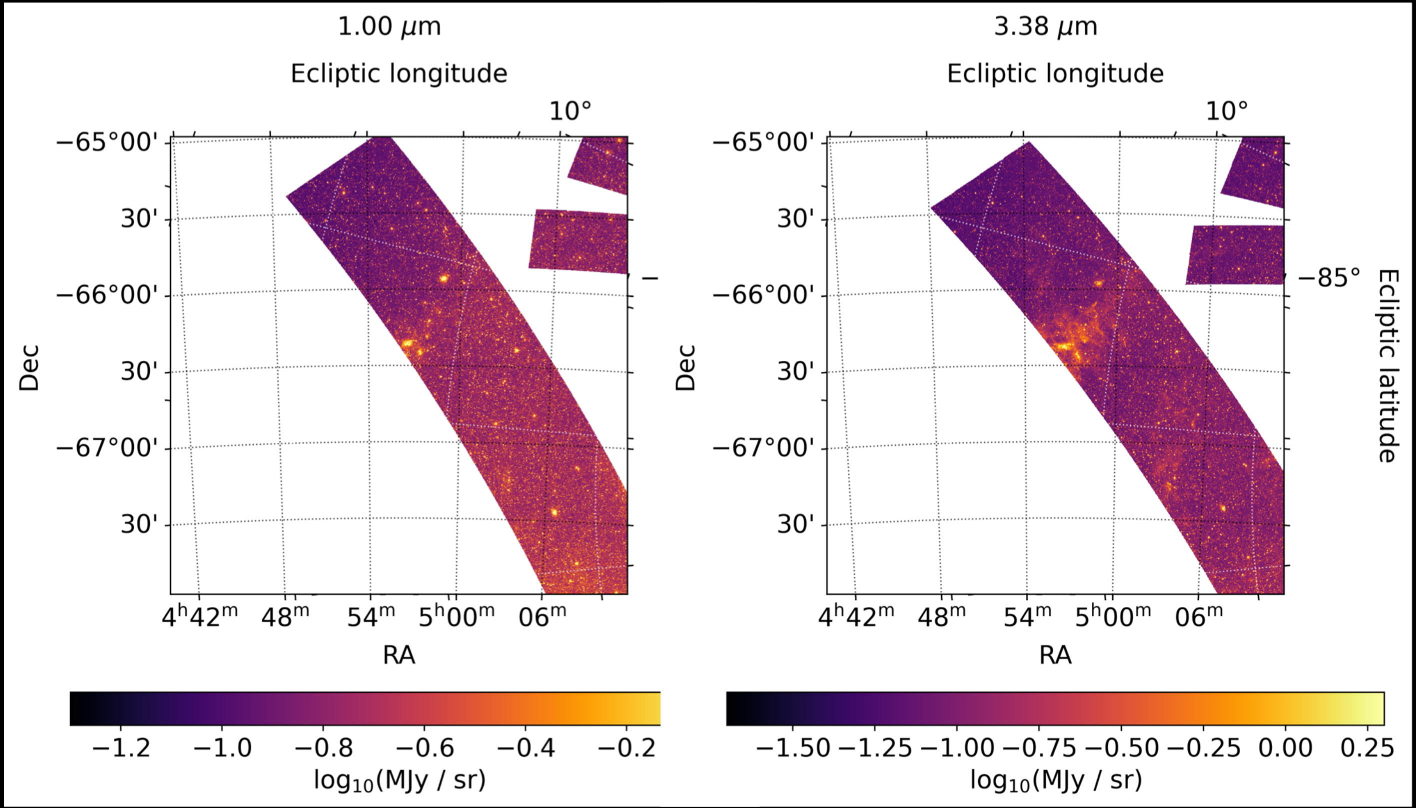

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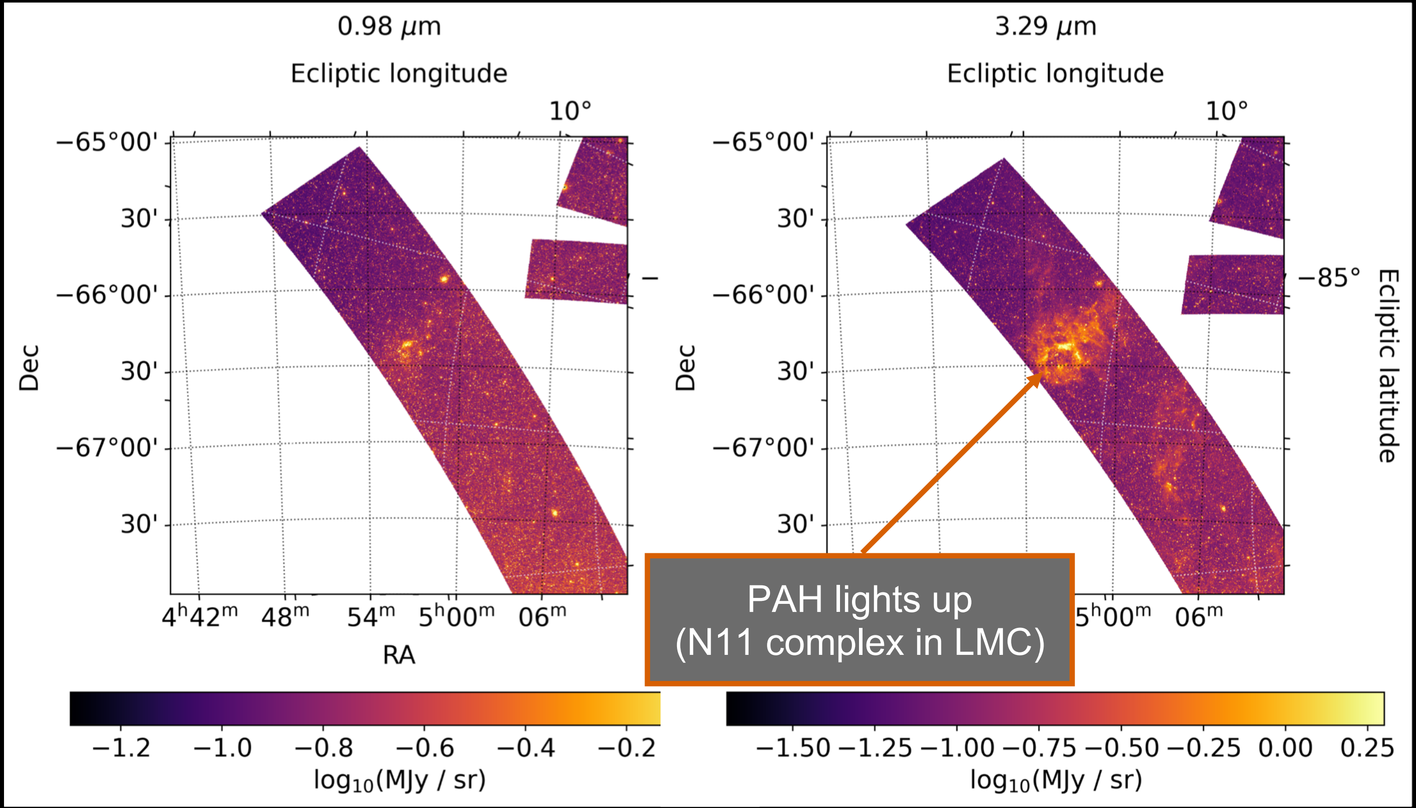
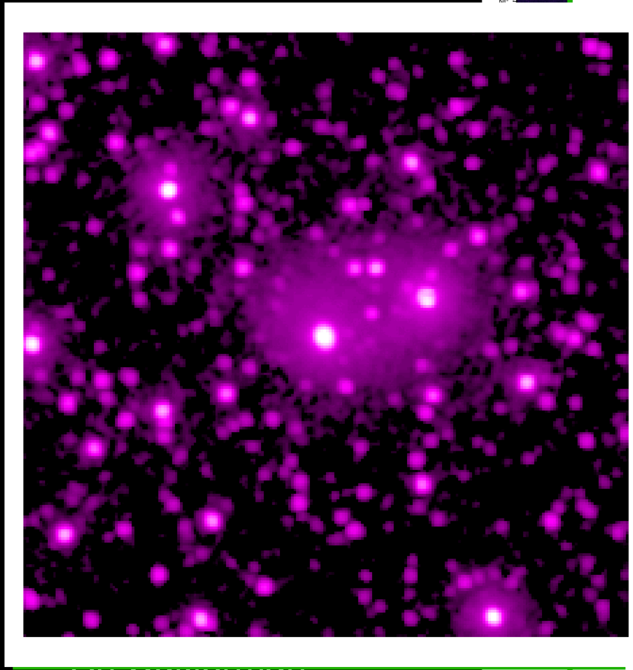
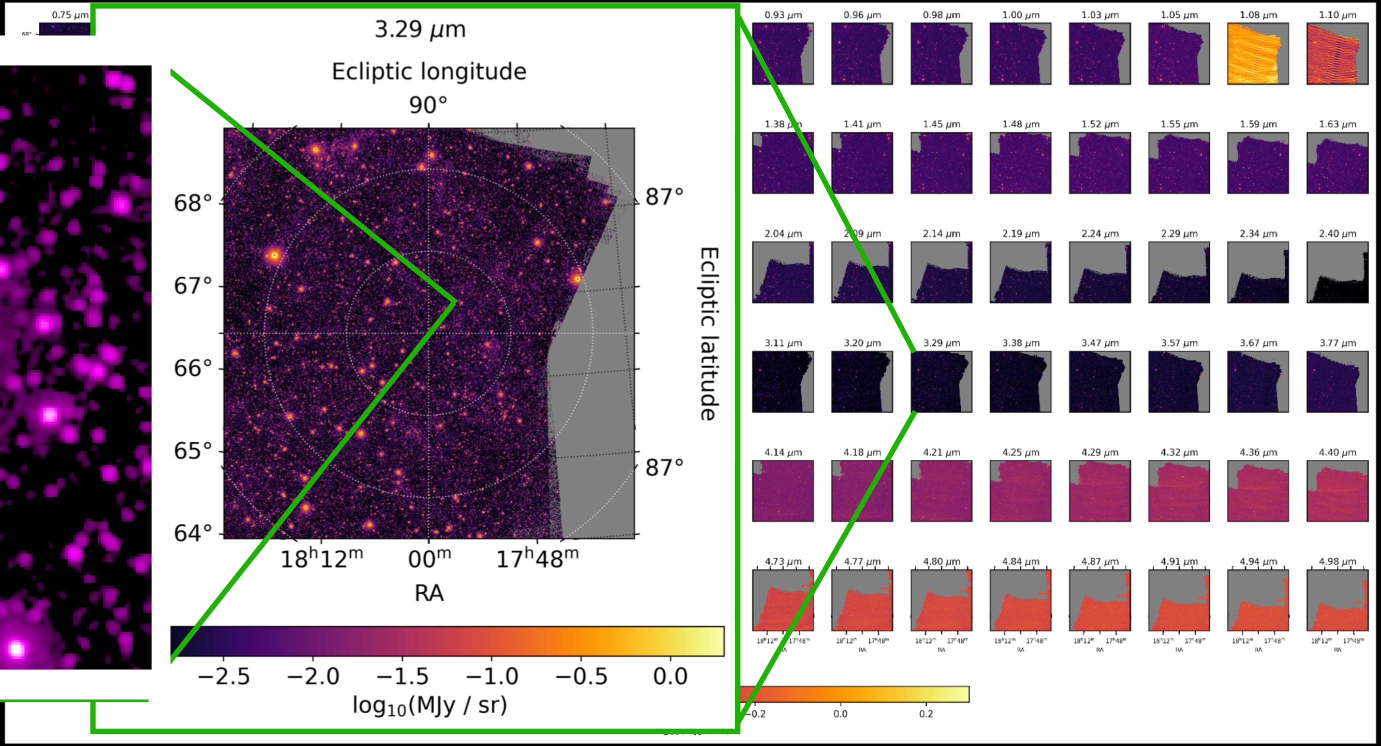


Real data gallery

Mosaic ensemble in the deep field (coverage as of May 13)

Cat's Eye Nebula

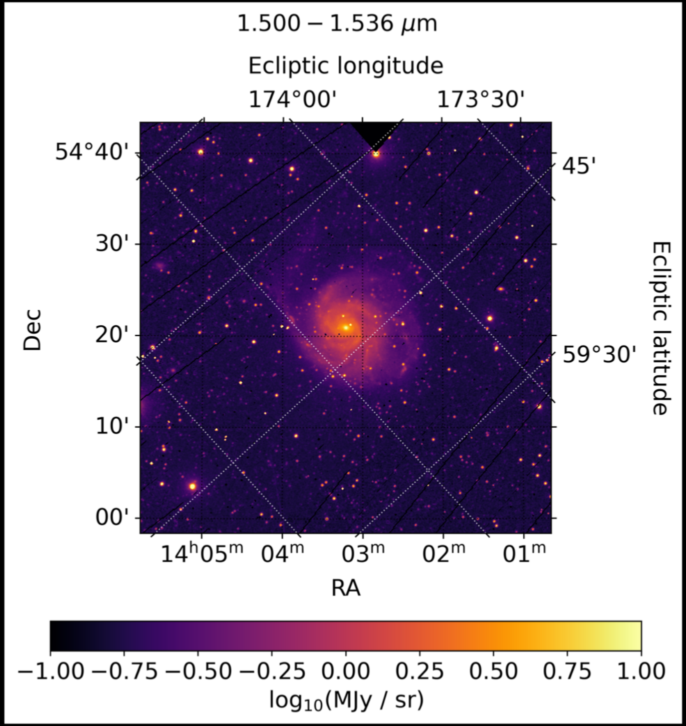




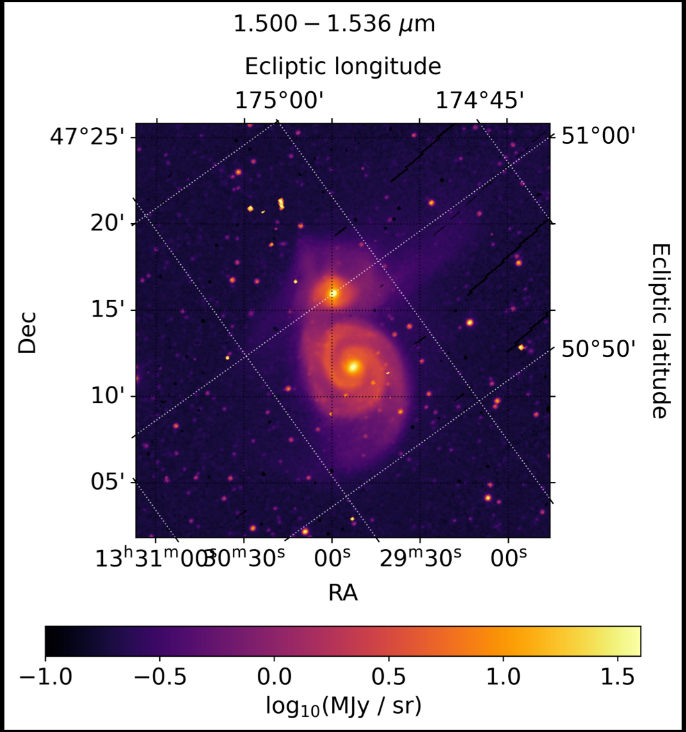
(Caltech)

Real data gallery

Pinwheel galaxy (M101)



Whirlpool galaxy (M51)

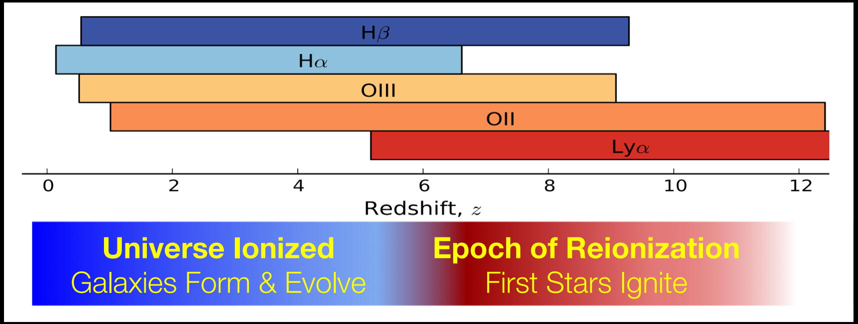


EBL Modeling and Parameter Inference: science, approach, status

Target lines and signals

We catch classic rest-optical SFR tracers over much of cosmic history, e.g., Balmer lines, [O III], and [O II]. Lya enters the SPHEREx band at z~5.5.

Emission Lines Observable by SPHEREx



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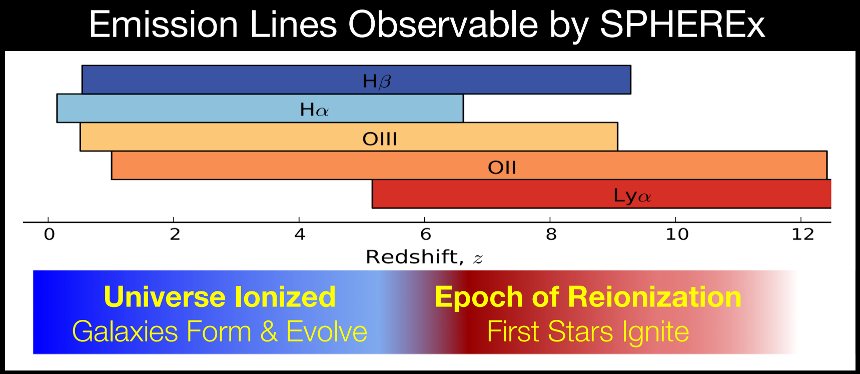
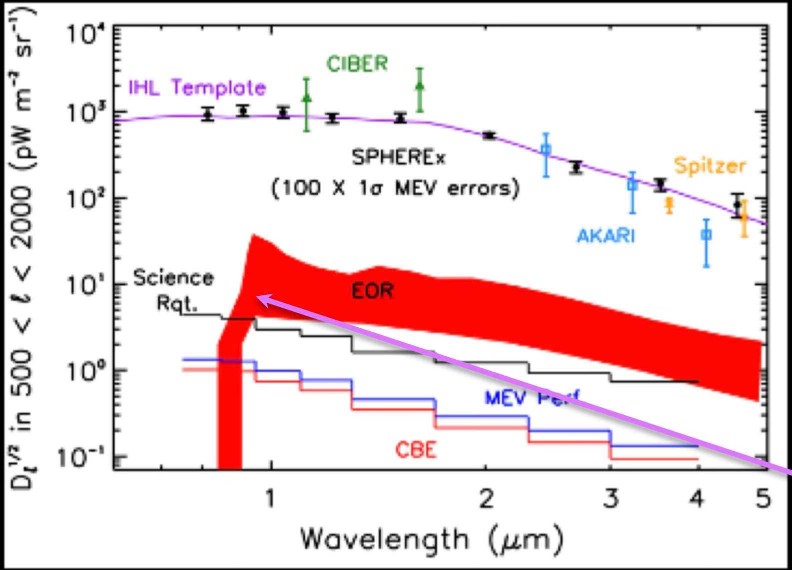




Must bin to ~10 bands to achieve the sensitivity needed to detect EoR galaxy population (in nominal 2 yr mission).

Not doing LIM in this regime, but we are still sensitive to spectral features, e.g., Lyman break, at this resolution!

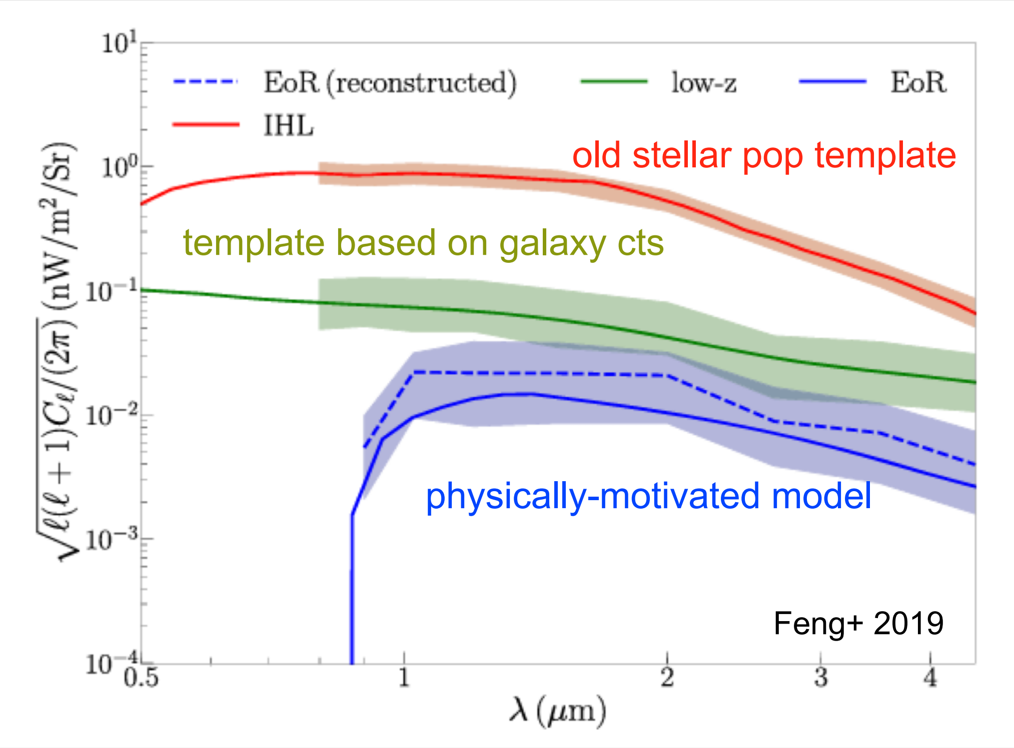
Prospects for EoR recovery

The sharp feature at ~1 micron helps isolate the EoR contribution from the total signal.

Strong contributions from IHL and low-z galaxies have distinct spatial structure and SED.

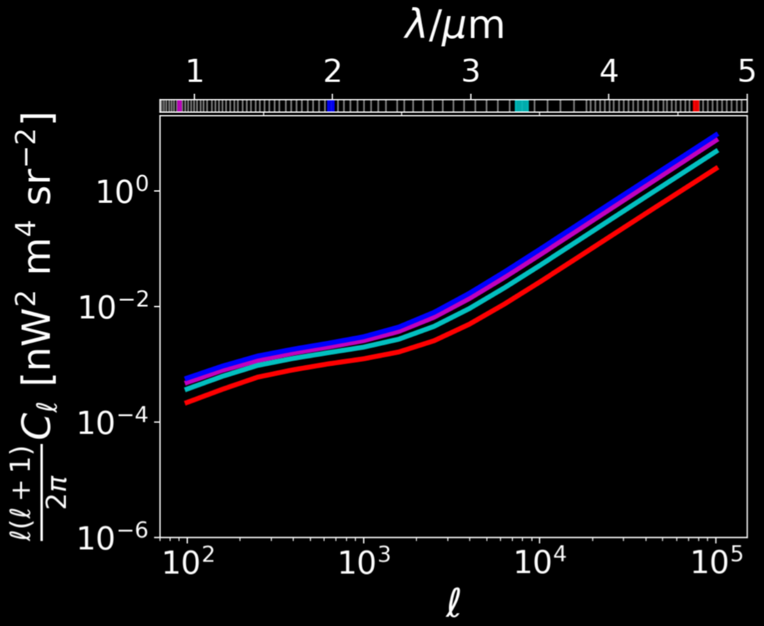
IHL and low-z galaxies are of course interesting in their own right; more on that shortly.

power on ~ 10 arcminute scales



Modeling Requirements

1. We need fast models that we can use to fit measured power spectra and cross spectra and turn into insights about galaxies near and far.



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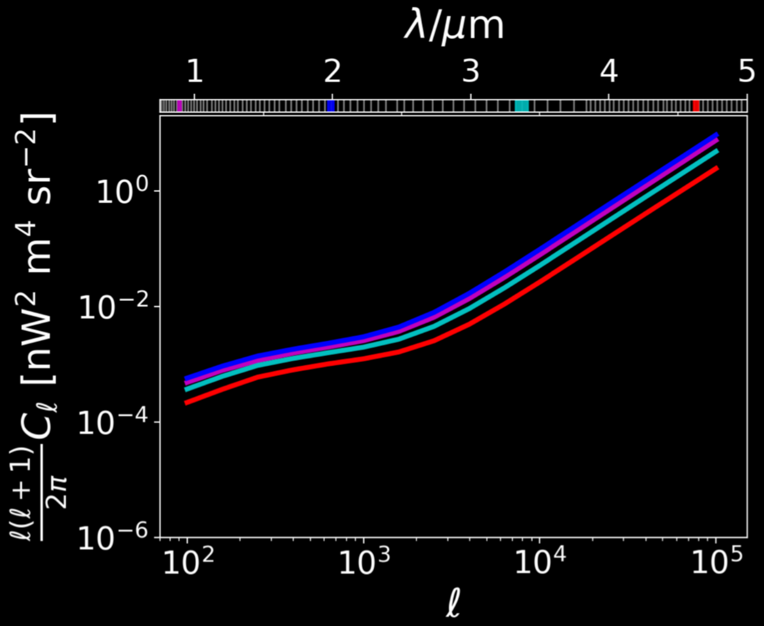
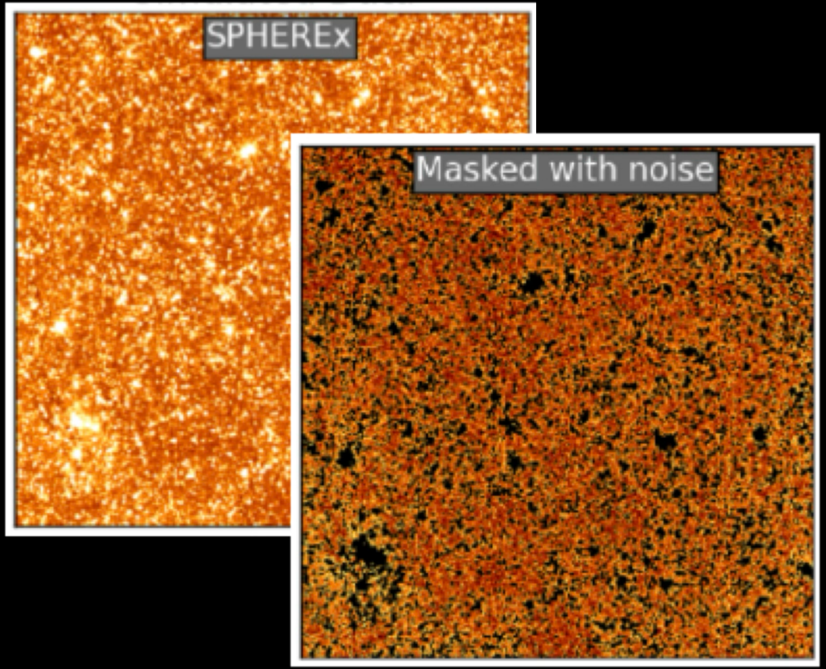


2. We need synthetic SPHEREx maps in order to validate our data analysis pipeline (e.g., test filtering, masking, M_{kk} matrices, etc.)



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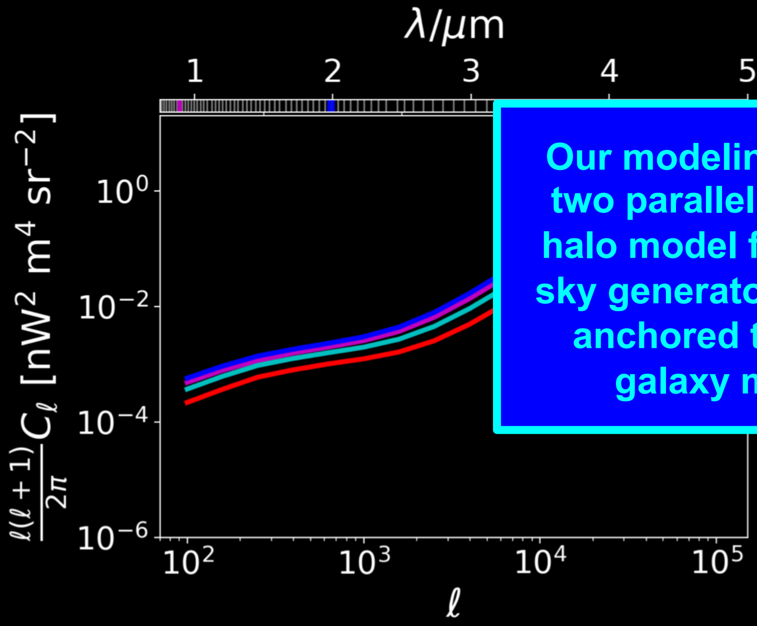
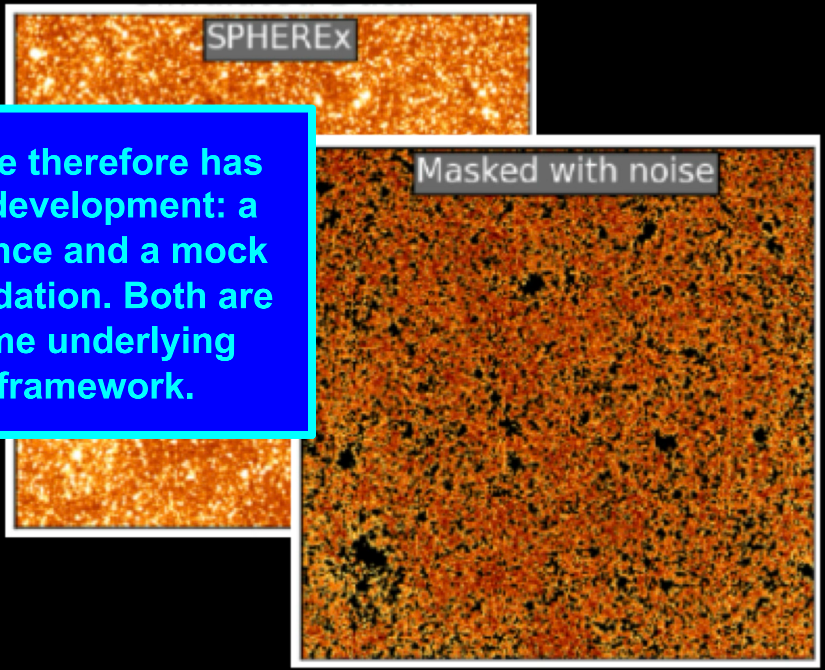


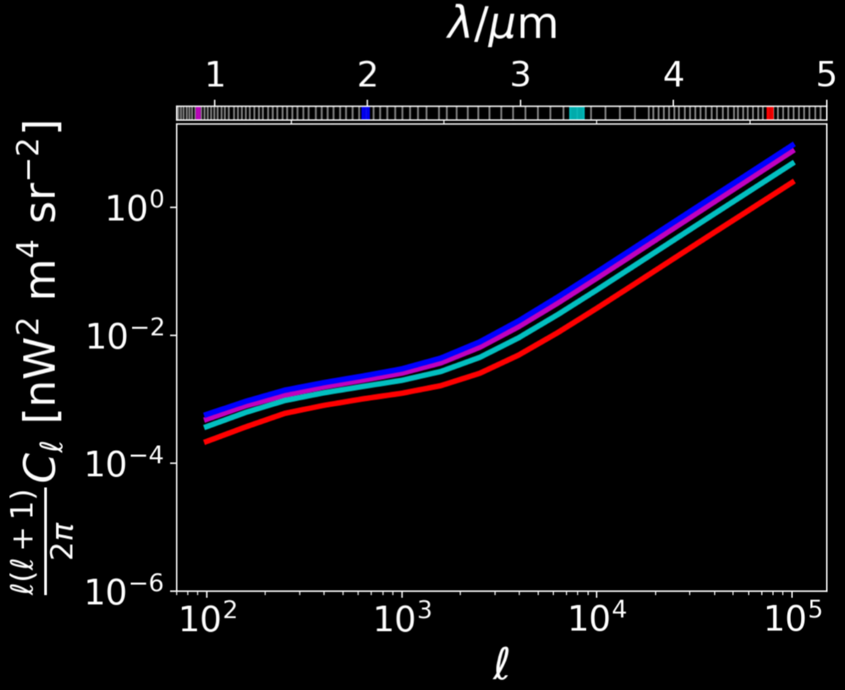


Our modeling pipeline therefore has two parallel lines of development: a halo model for inference and a mock sky generator for validation. Both are anchored to the same underlying galaxy modeling framework.

New approach: all sources, all redshifts, one model

Semi-empirical galaxy model fed into a custom halo model. Key details:

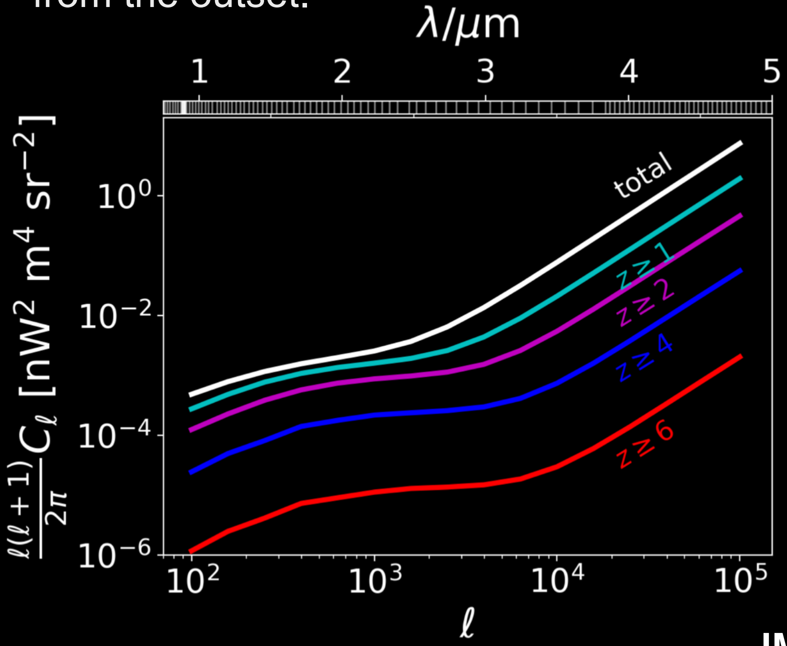
- Continuum emission is a signal of interest for us, so we must model, e.g., stellar mass, SFHs, metallicity, and dust. This also means we have a full integral over *z* to compute for each channel.
- 1-halo contributions from satellites and intrahalo light (IHL) are both likely to be important.
- Many potential source populations, including both star-forming and passive galaxies, centrals and satellites, & IHL means lots of “inter-population” cross-terms, adding to expense.



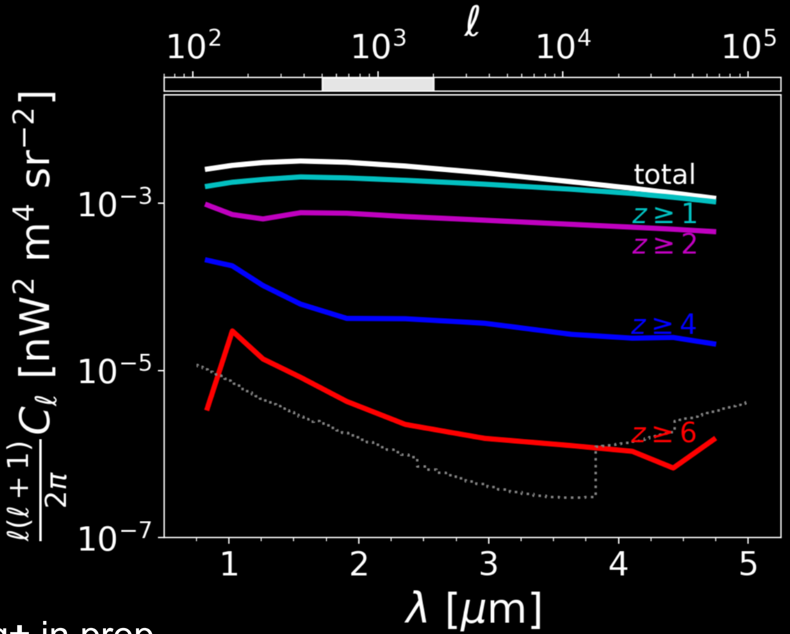
example autos from **JM**, Chang**+** in prep

Advantages of this approach

Self-consistent treatment of all relevant sources in one framework. Anchored to pre-existing constraints: joint likelihood capabilities built-in from the outset.



Can build more flexible templates for component separation, e.g., target cosmic noon instead of EoR w/ early data.

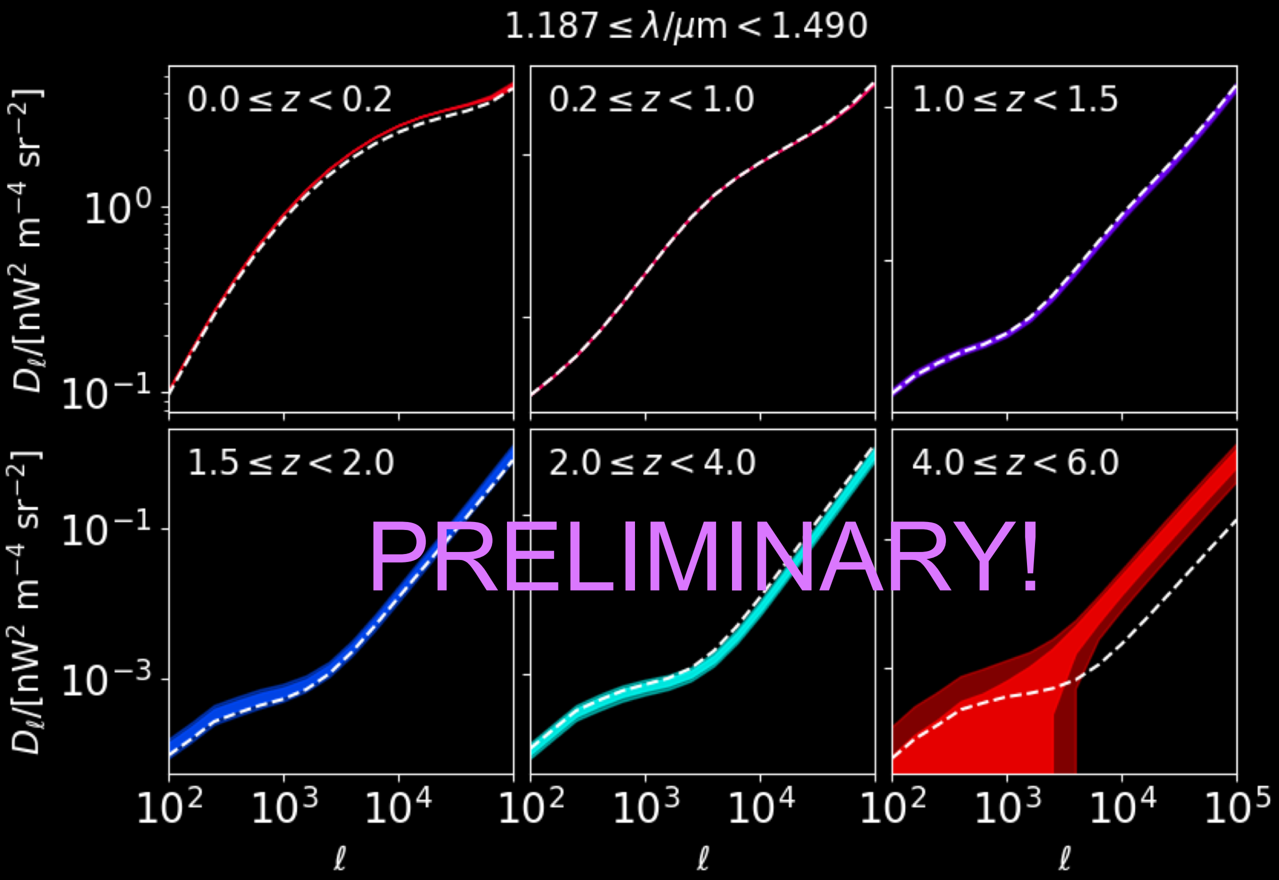


JM, Chang**+** in prep

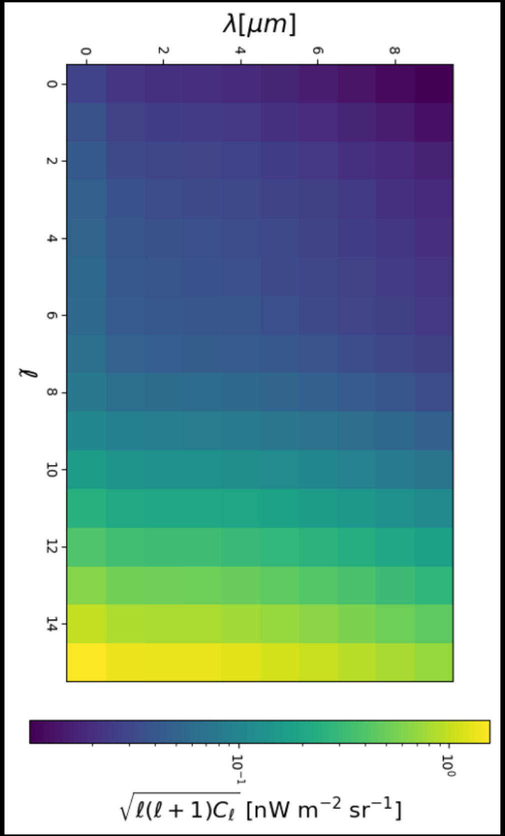
Ongoing work: inference & component separation

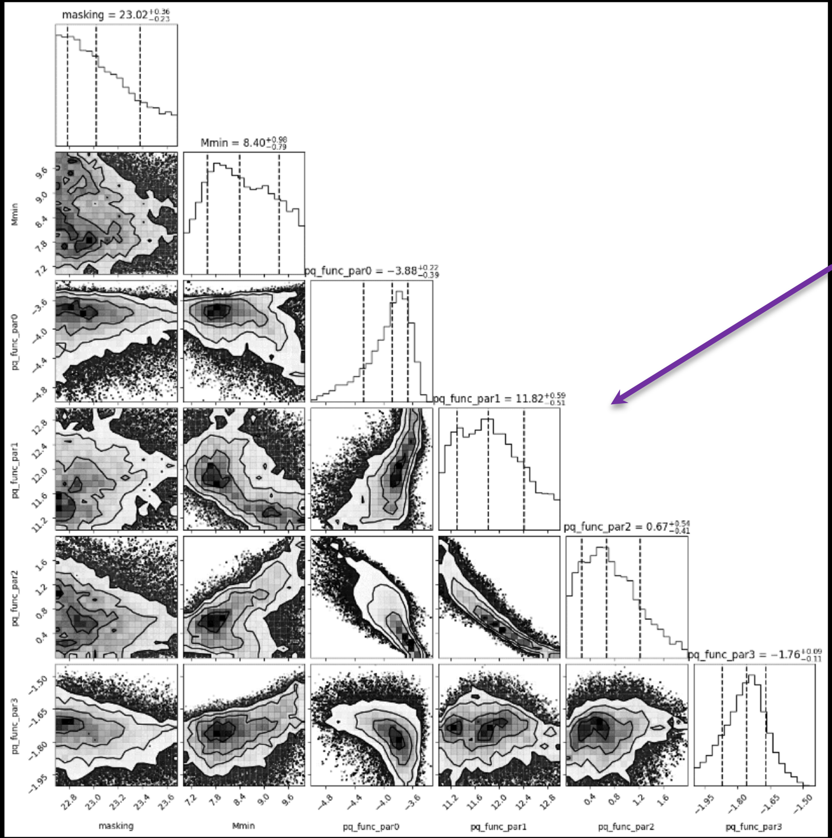
Example here:

- Templates based on redshift rather than source population.
- Flexible shapes (in ell, wavelength) allowed, determined via SVD of EBL model database (i.e., sampled prior vol)
- Mock fit to shallow data comparable to ~6 months of data, rather than full 2 yr survey.
- Binned to 10 bands.



Ongoing work: inference & component separation



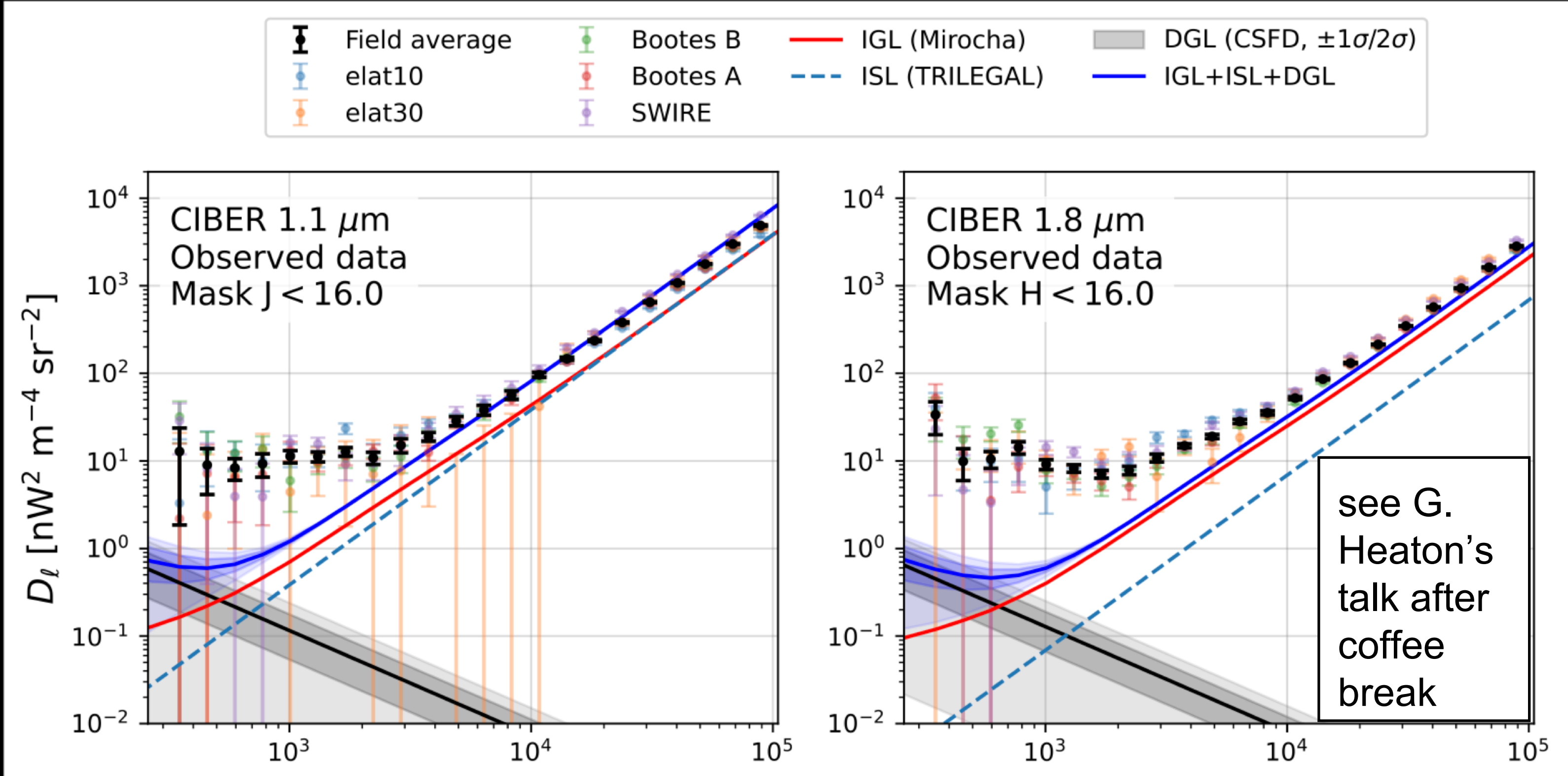


CNN-based emulator (á la Breitman+ 2024) w/ EBL instead of 21-cm

Proof of concept with SMHM parameters, EBL-only fit.

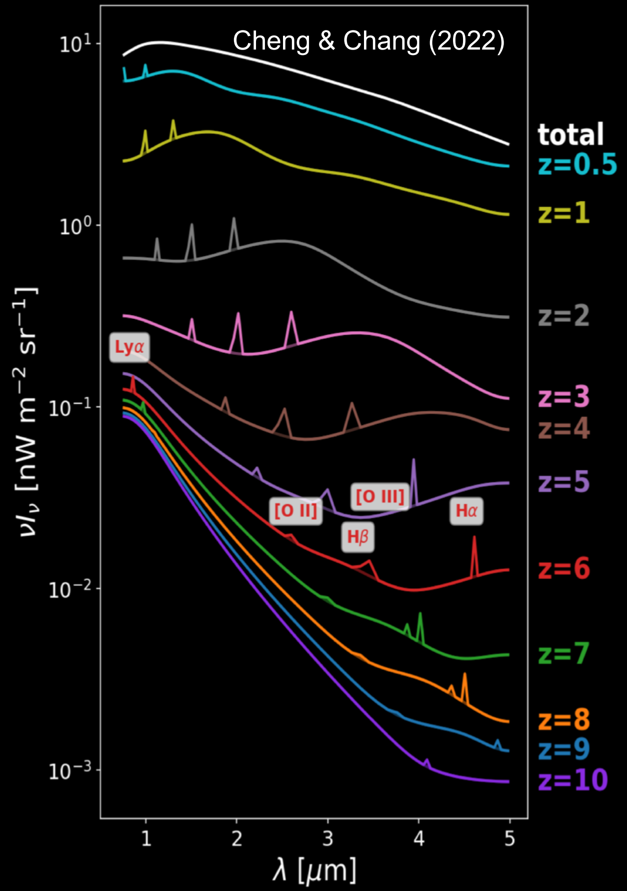
Sean Lewis (Yale)
2024 JPL SURF

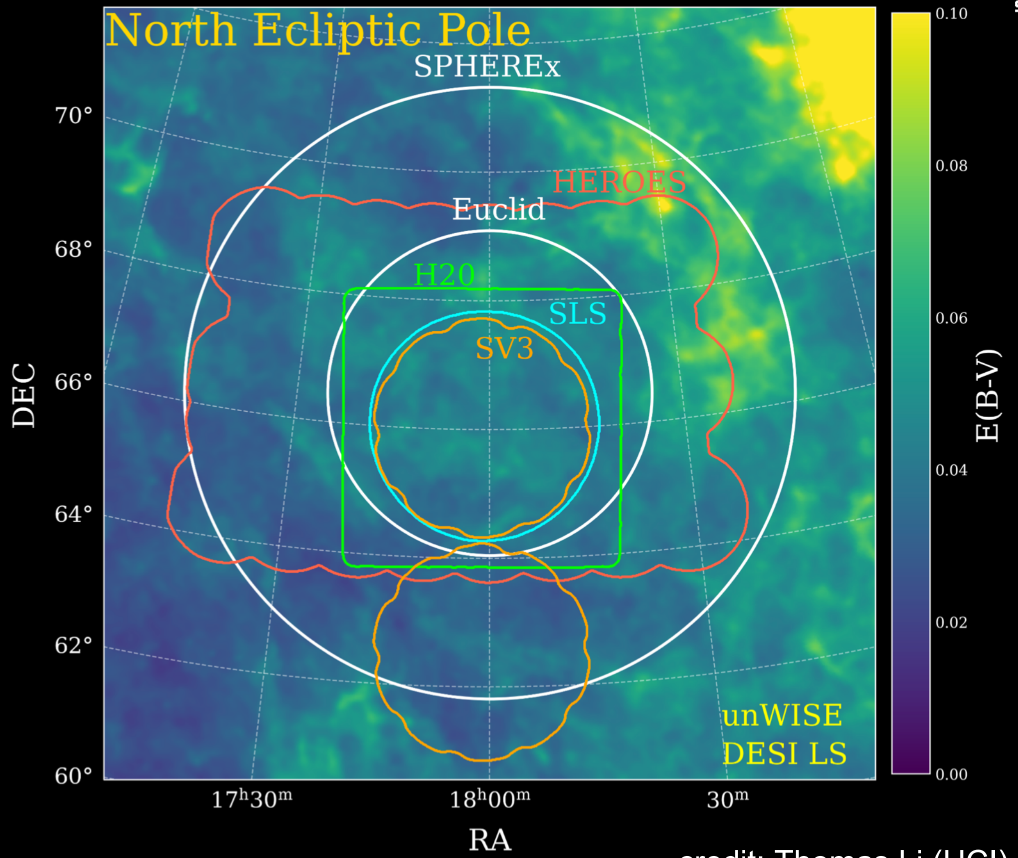
Ongoing work: validation on existing EBL measurements



Feder et al. 2025 (2501.17933)

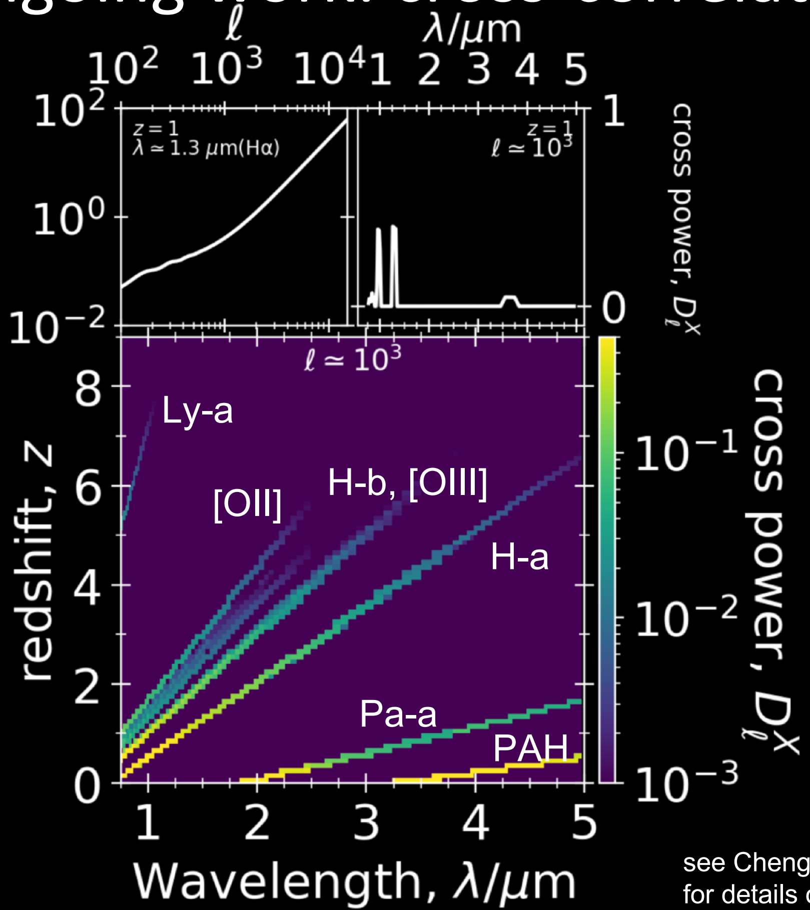
Ongoing work: cross-correlation inference





credit: Thomas Li (UCI)

Ongoing work: cross-correlation inference

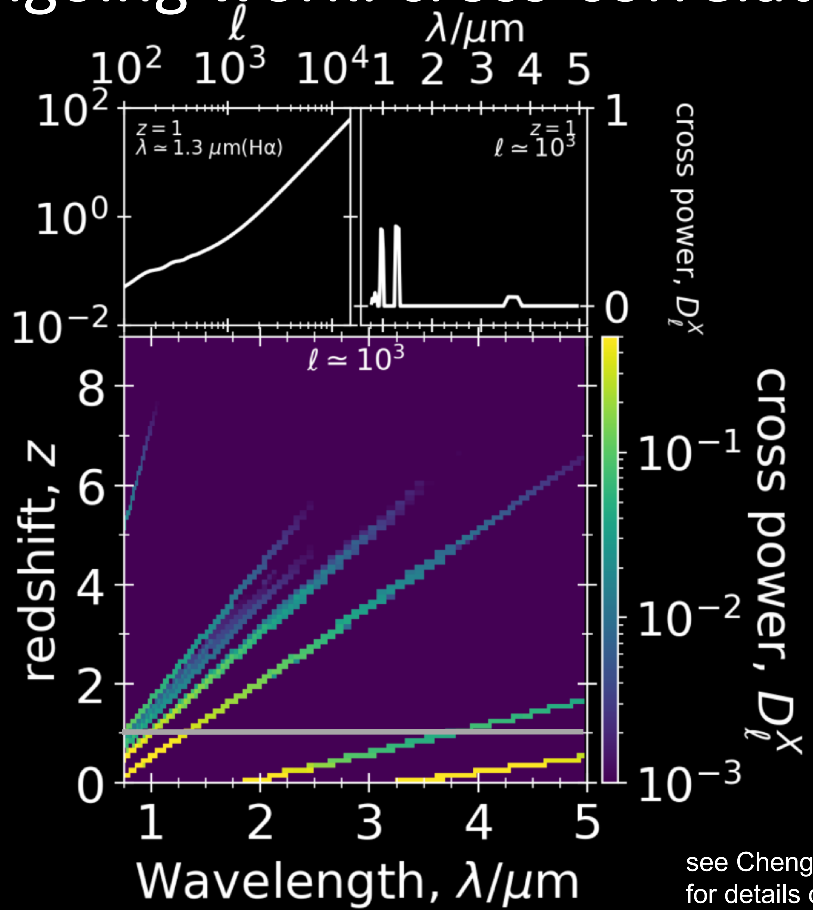


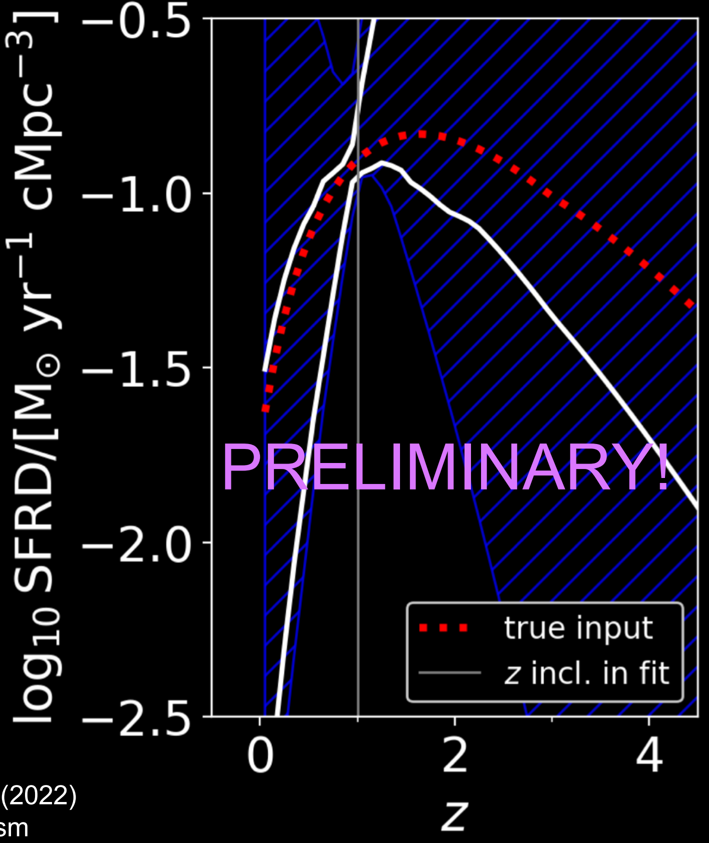
What do we learn from cross-correlations?

- Here, exploring potential for SFRD constraint via SPHEREx x Euclid.
- Basic idea is simple: use Balmer lines as SFR tracer.
- Can in principle jointly constrain SFRD and dust correction through use of multiple lines in single z bin.
- (Extra information from, e.g., line luminosity functions, only helps, but is not being included here.)

see Cheng & Chang (2022) for details on formalism

Ongoing work: cross-correlation inference





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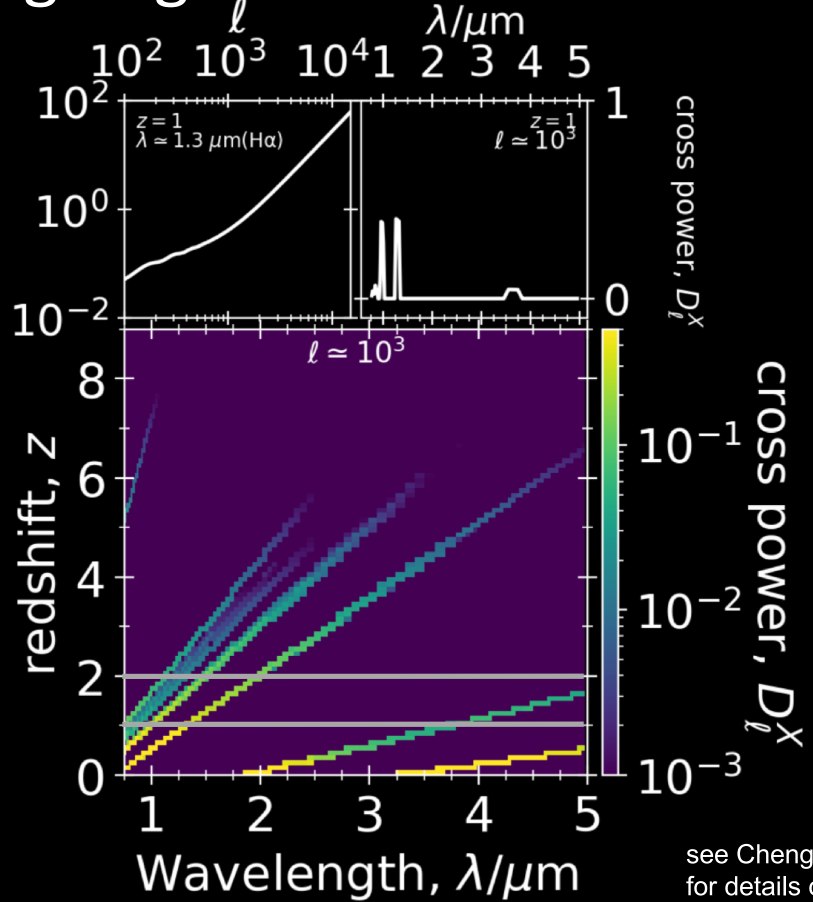

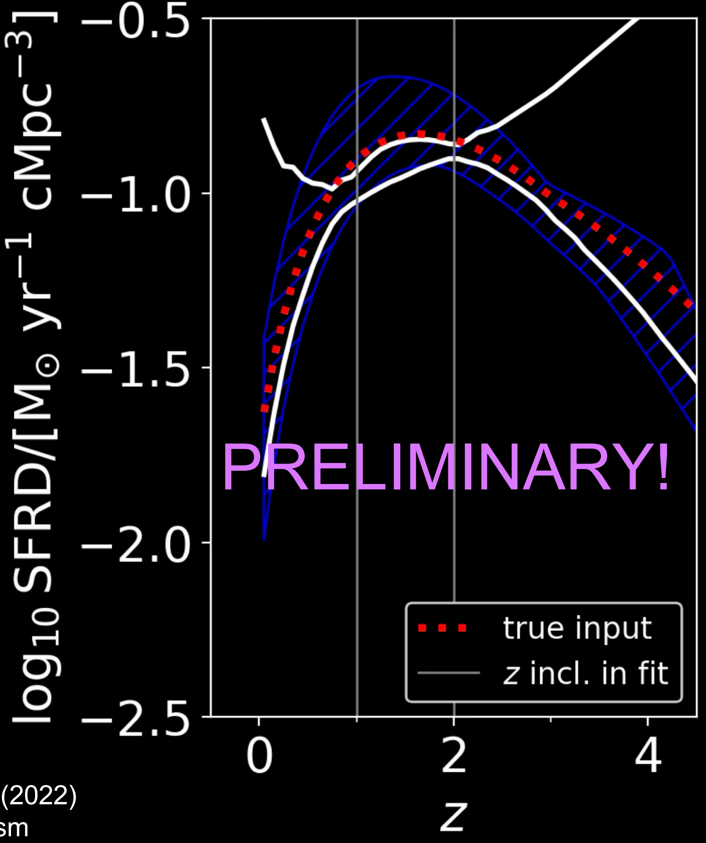

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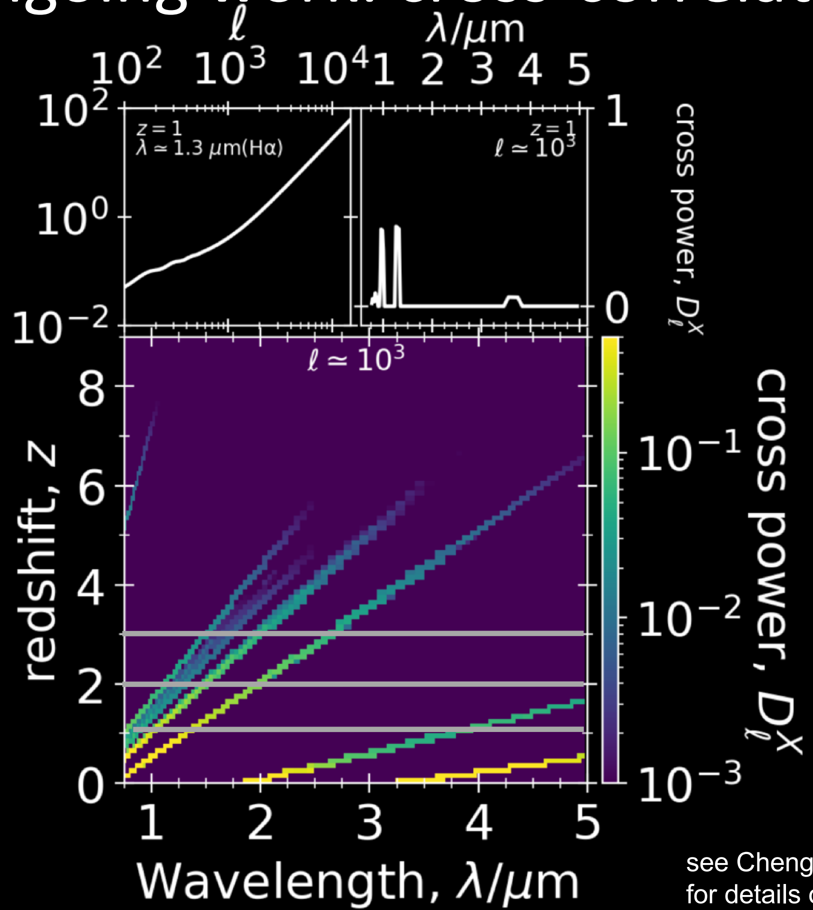
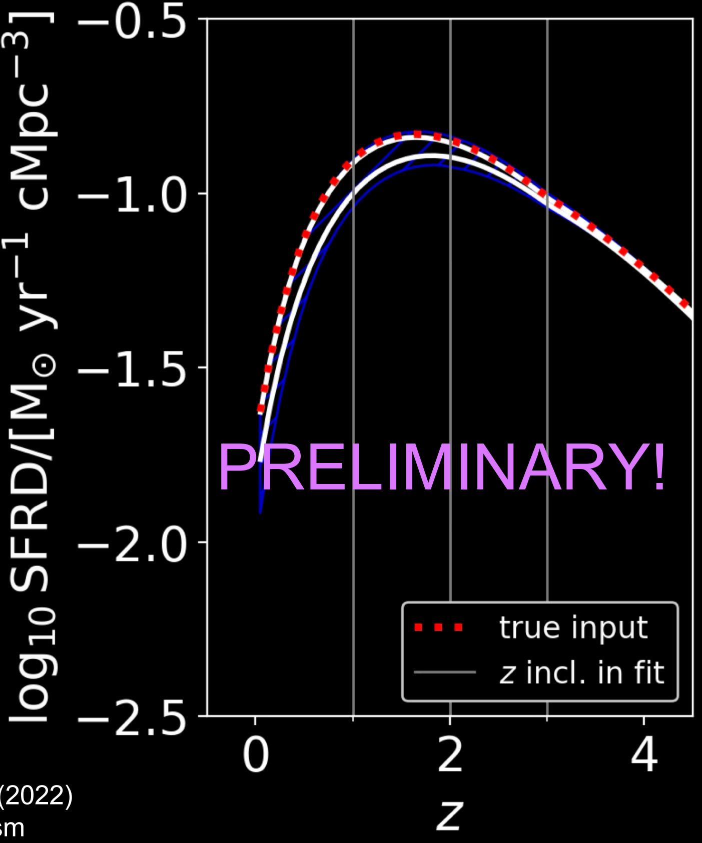


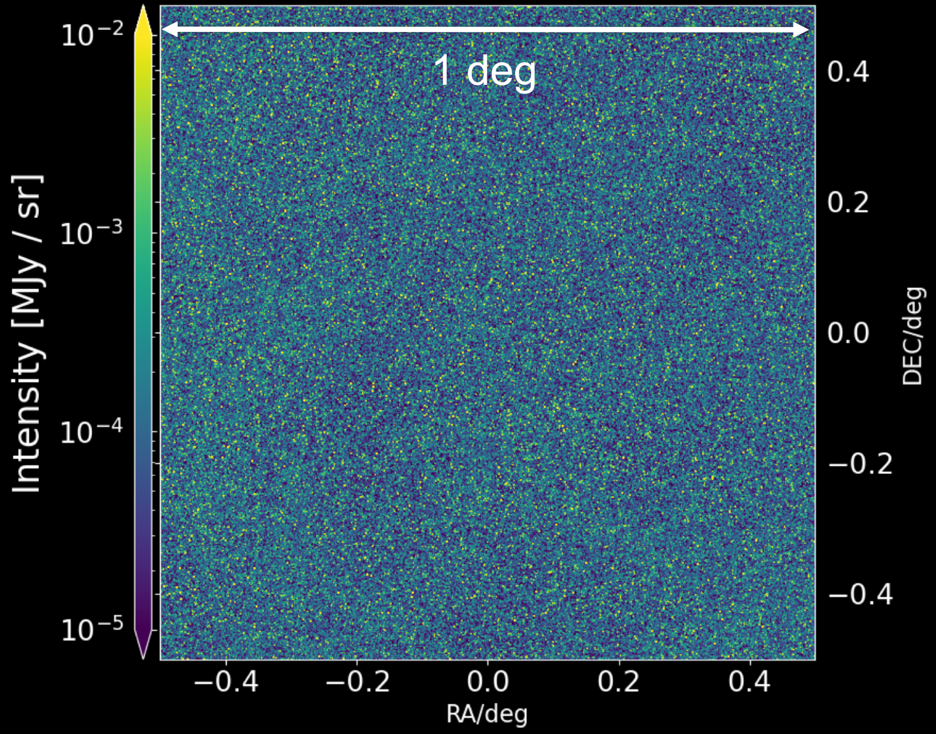


see Cheng & Chang (2022) for details on formalism

Mock skies

Key considerations:

Map of point-source star-forming galaxies.
Halos $M_h > 10^{10}$ M_{sun}, $z < 2$. 3" pixel scale.

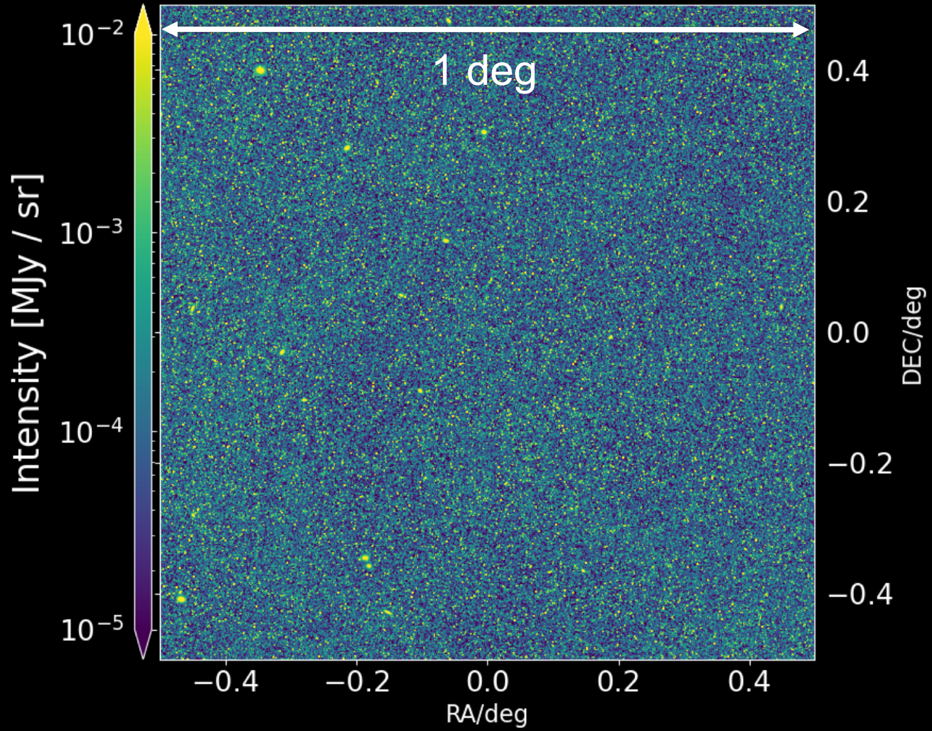


Mock skies

Key considerations:

- Our resolution is 3-6’’. This means we resolve (some) galaxies.

We follow Williams+2018, and draw from empirical mass- size and n_{sers} distributions.



Mock skies

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- Quiescent galaxies too!

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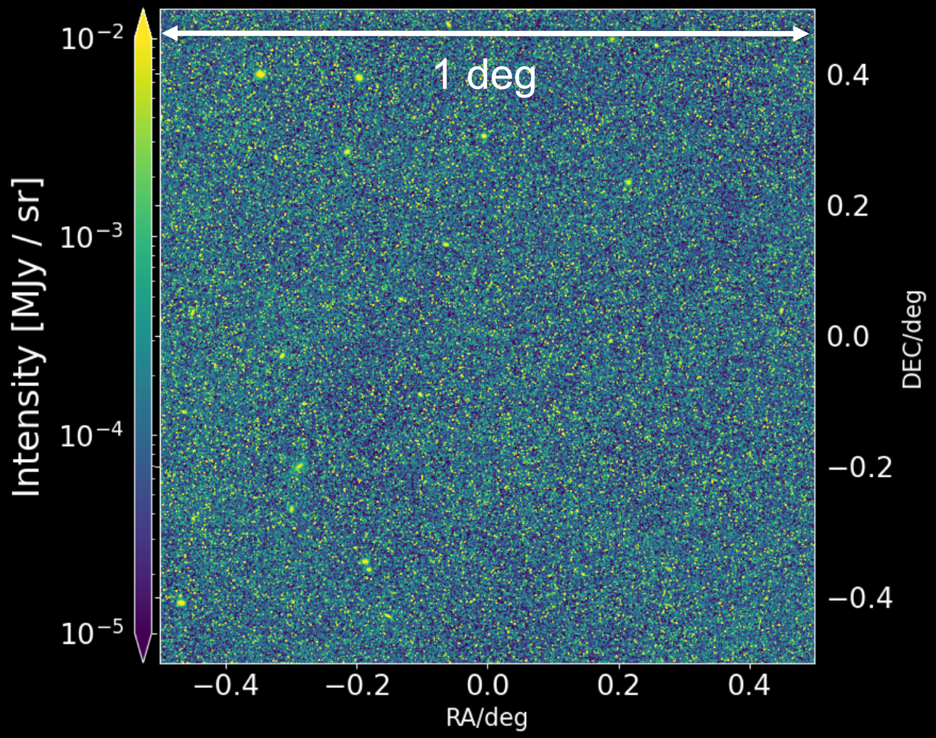


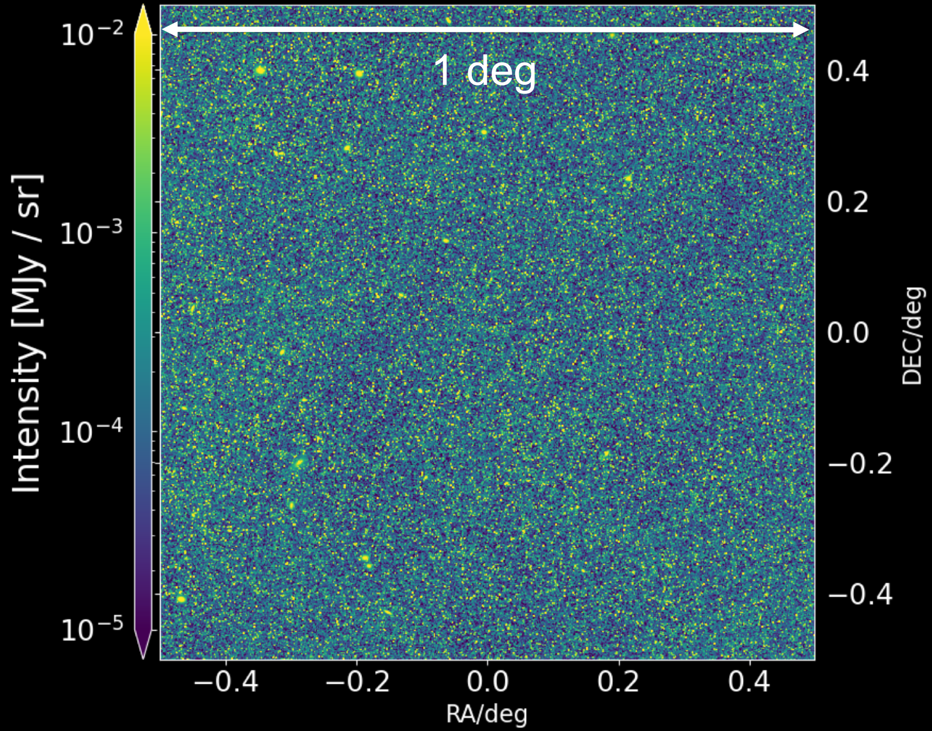
populations.

Mock skies

Key considerations:

- Our resolution is 3-6''. This means we resolve (some) galaxies.
- Quiescent galaxies too!
- Satellites likely provide non-trivial contribution to fluctuations (Cheng & Bock '22, Jun+ 2025).

Draw from Tinker & Wetzel (2008) subhalo mass function and populate with galaxies.

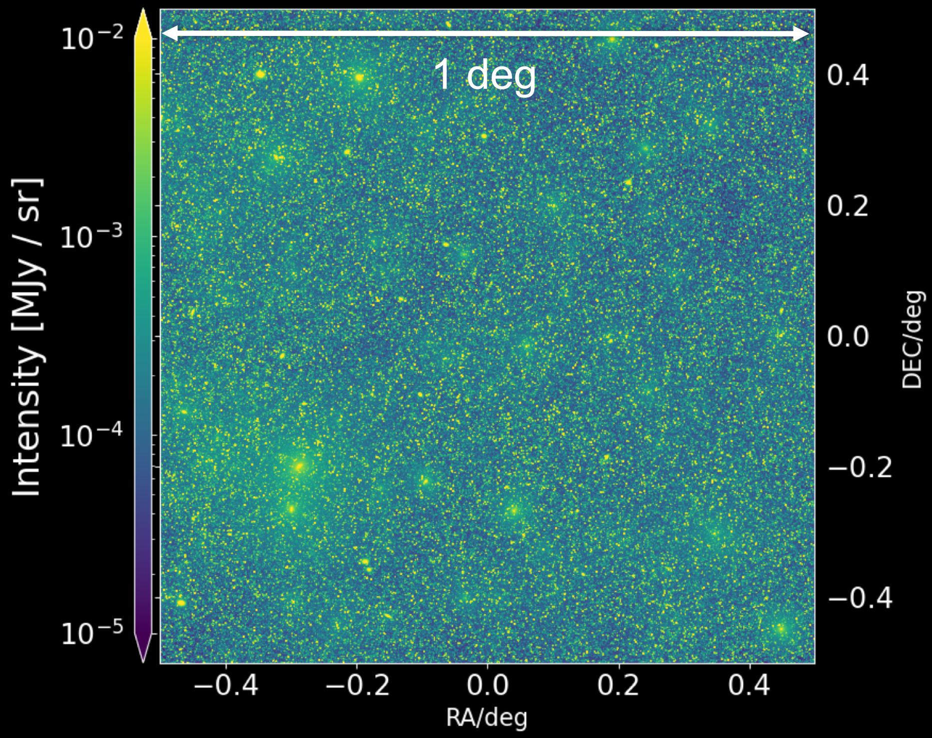


Mock skies

Key considerations:

- Our resolution is 3-6''. This means we resolve (some) galaxies.
- Quiescent galaxies too!
- Satellites likely provide non-trivial contribution to fluctuations (Cheng & Bock '22, Jun+ 2025).
- Intrahalo light may be the dominant source of fluctuations on intermediate scales [see Cooray+ 2012, Zemcov+ 2014]. If it extends out to the virial radius of halos, it is resolved out to high redshift.

'Paint' in IHL as projected NFW profile, luminosity scales w/ Mh [here: Purcell '07-like]

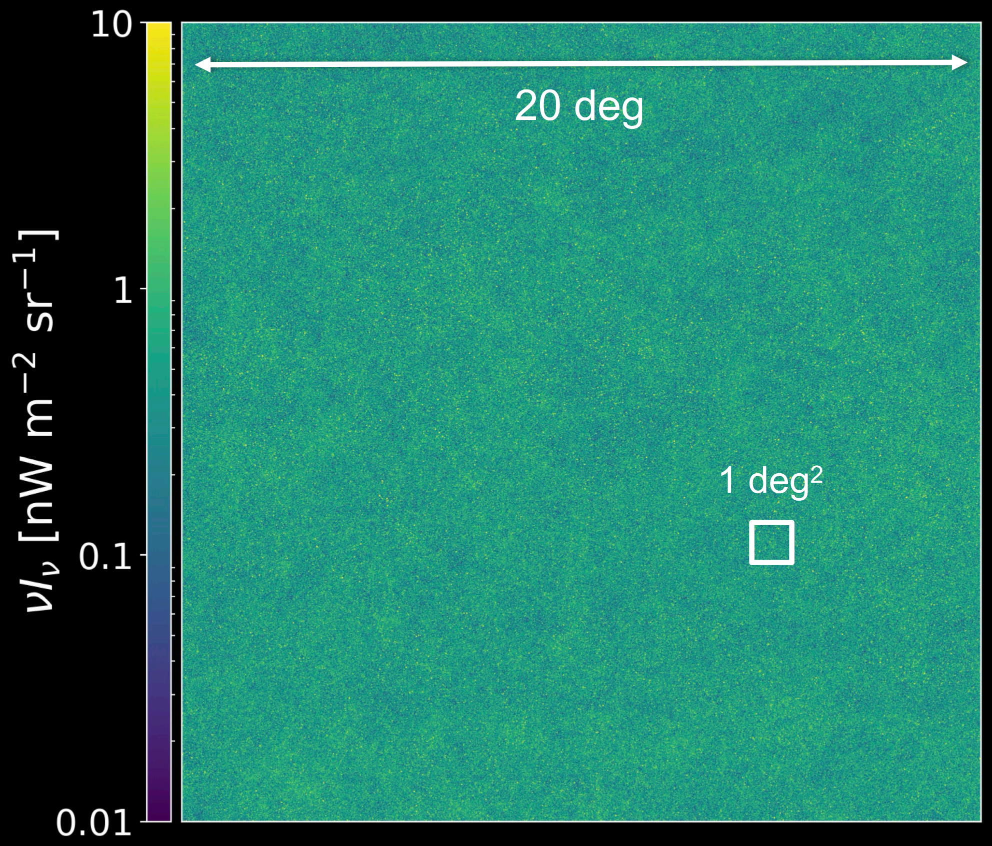


Ongoing work: biasing, optimization, mock deep field

Our default approach is based on log-normal density fields. Plots in previous slides just employed Poisson-sampling but we're working on a biasing scheme.

In the meantime, we're also setup to start from N-body halo catalogs (e.g., MICECAT; Crocce+ 2015, $z<1.4$), as shown to the right. This gives us halo biases for free, but there are mass resolution and/or area limitations.

Either way, mocks get expensive, so we have yet to run a full deep field area (100 deg^2) with all source populations, through the EoR, for all spectral channels...but, we can run with a few of these options! Optimization is a slog, but we've been making steady progress.



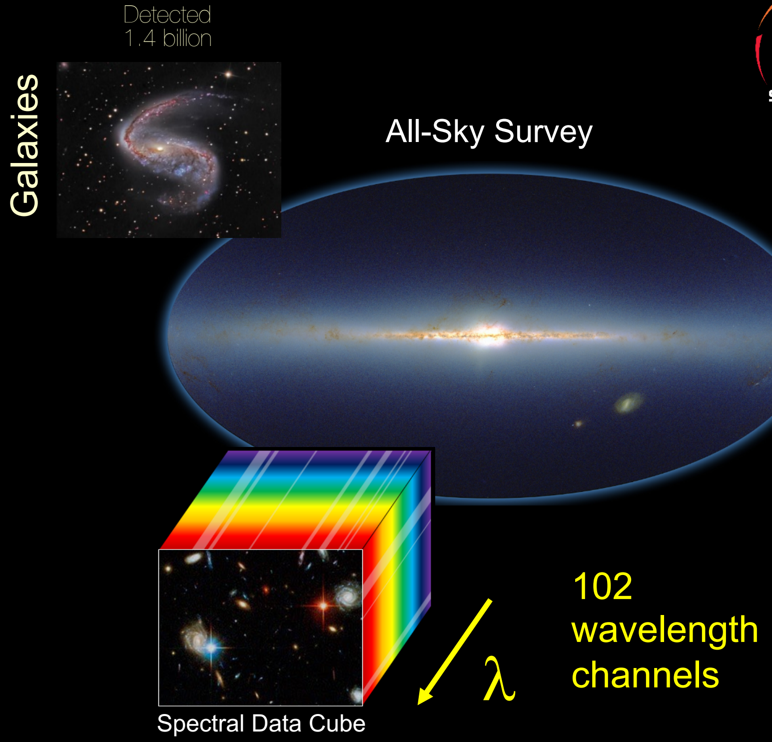
Summary & Opportunities

Summary: SPHEREx is working *brilliantly*.

Data: use our maps and catalogs! Cross correlate, stack, admire. Great synergies w/ CO, [CII], 21-cm, e.g., relationship between star formation and gas (or dust) content, properties of faint galaxies, and EoR.

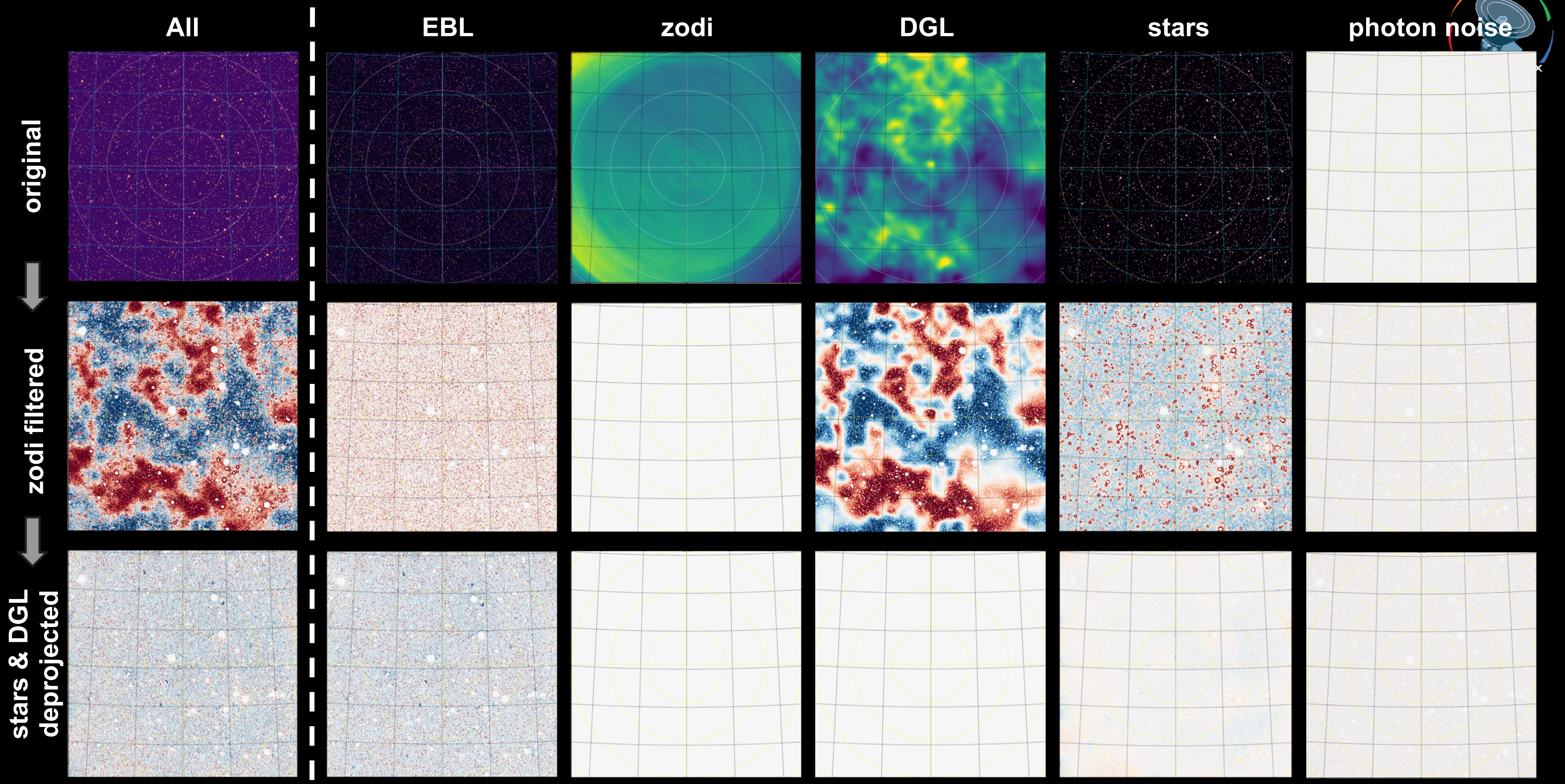
Forecasting: we're happy to share mocks -- perhaps you can synthesize your favorite signal without much trouble? (M_h, SFR, M_{stell}, A_V generated too)

Likelihoods: we'll provide model-dependent constraints on, e.g., SFRD, satellite galaxies & IHL, and the non-ionizing emissivity of EoR galaxies. $b_I \, dI/dz$ is the most model-independent quantity we measure (in cross). Fertile grounds for joint likelihood analyses!

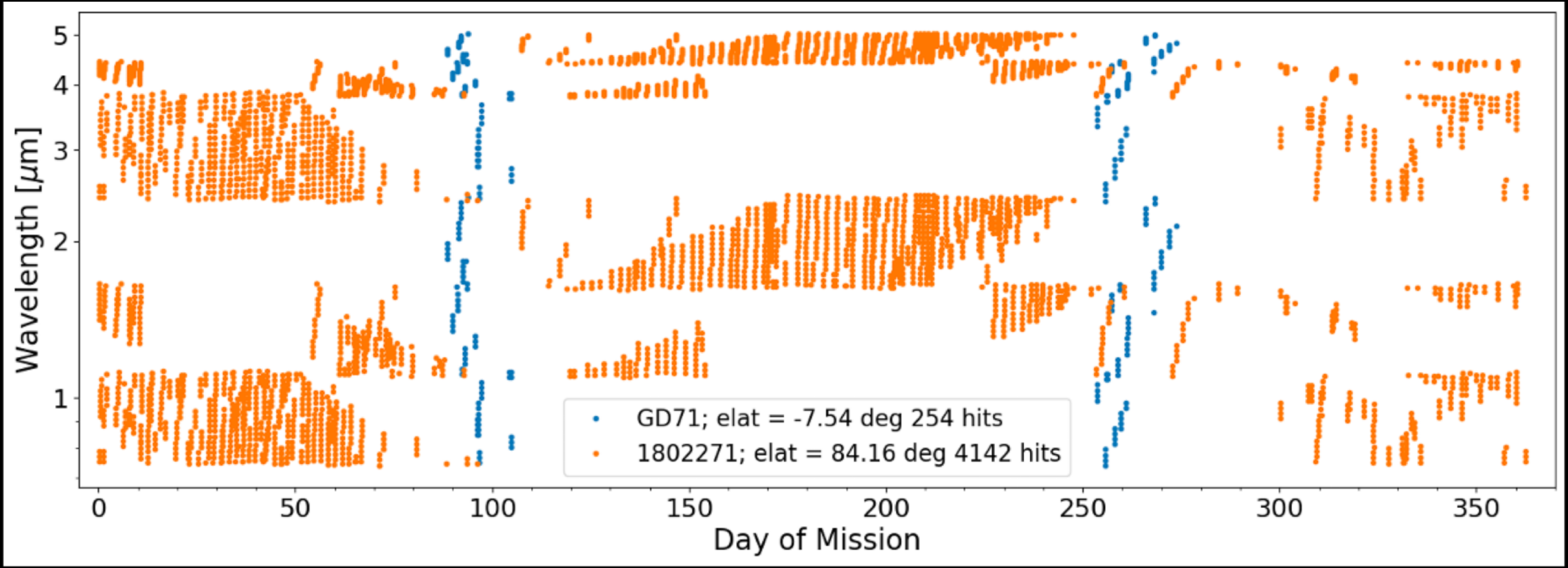


SPHEREx provides a new and unique dataset
a complete near-infrared spectrum for every 6″ pixel on the sky

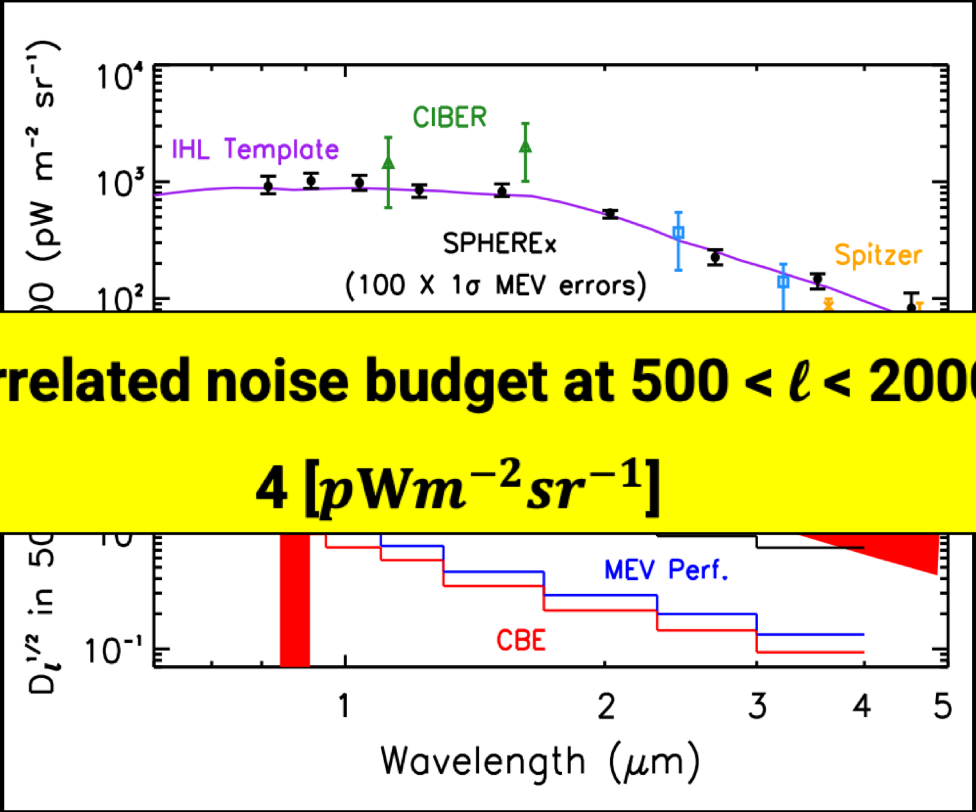
Backup slides


All
EBL
zodi
DGL
stars
photon noise
original
zodi filtered
stars & DGL deprojected

Time domain astronomy with SPHEREx?



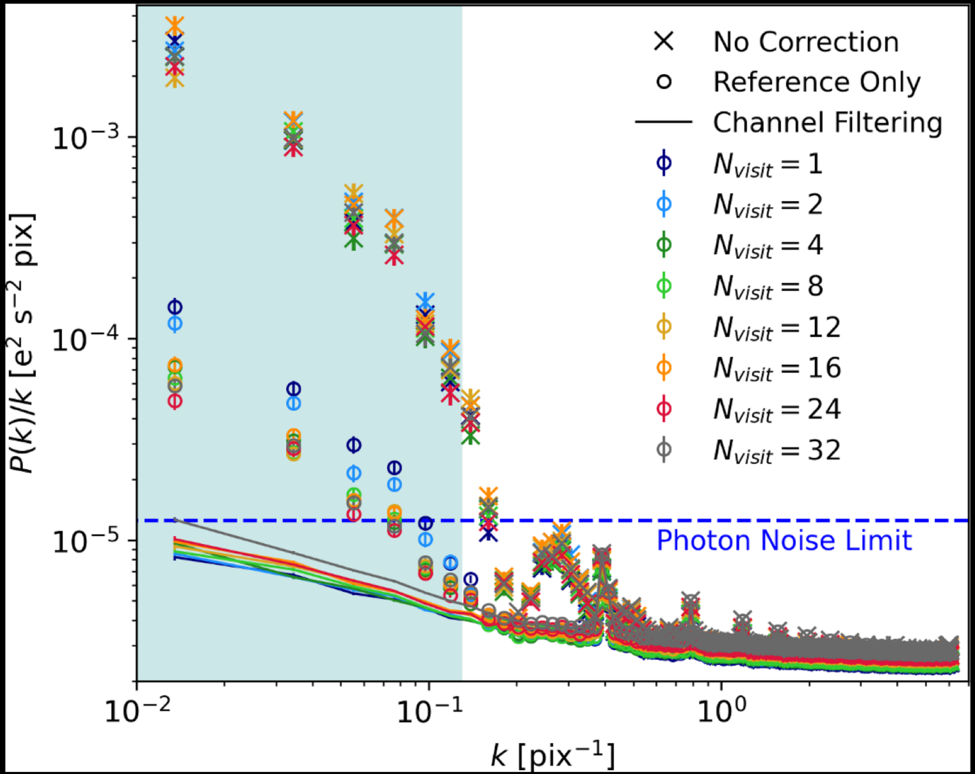
Correlated Noise Budget



Correlated noise budget at $500 < \ell < 2000$

$4\ [pWm^{-2}sr^{-1}]$

Row Chopping, Channel Filtering to reduce noise



Individual exposure integration time fixed by survey length (2 surveys a year

More reference readings = longer single frame interval

➔ fewer samplings per exposure

➔higher per pixel noise

➔higher noise at all frequencies!