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Science Data Simulations for SPHEREx

Brendan Crill

Jet Propulsion Lab / California Institute of Technology

SPHEREx: All-Sky NIR spectral survey

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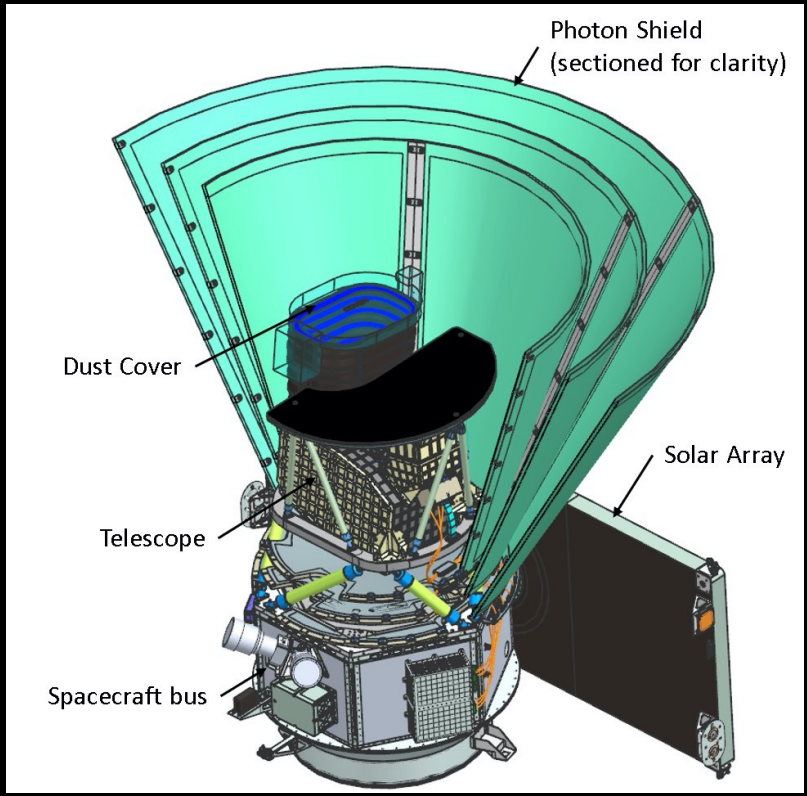

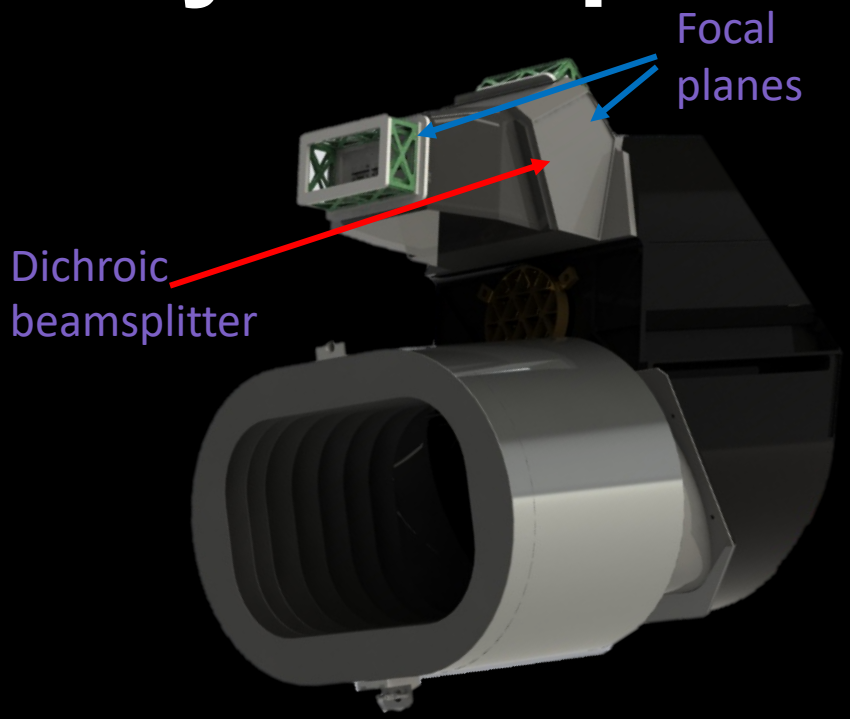

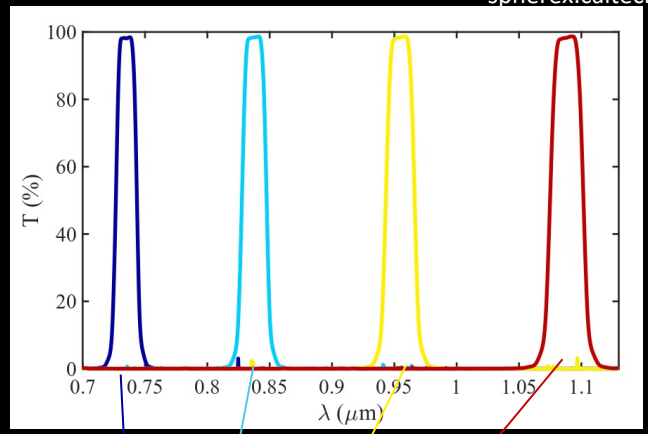

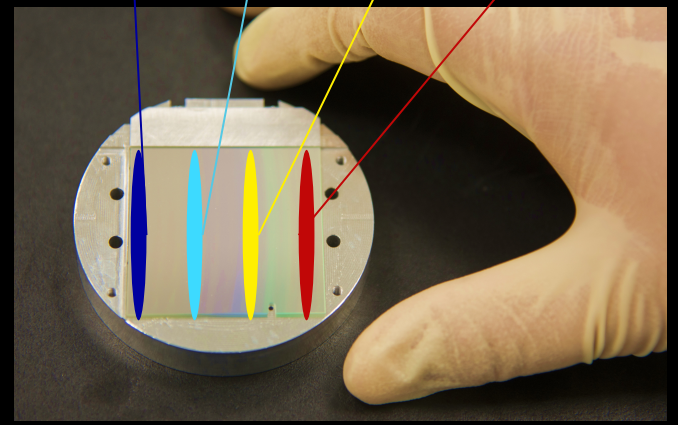

- NASA Medium Explorer mission: selected in 2019, launch-ready in 2024
- Currently in Detailed Design phase: Critical Design Review in Fall 2021

- 3-mirror off-axis anastigmat
- 20 cm effective aperture
- 3.5° × 11.3° FOV
- Two 1 × 3 mosaics of H2RG detectors on either side of a dichroic
- 25 million 6.2” pixels

- Linear Variable Filters mounted in front of detectors

Spectroscopy with SPHEREx

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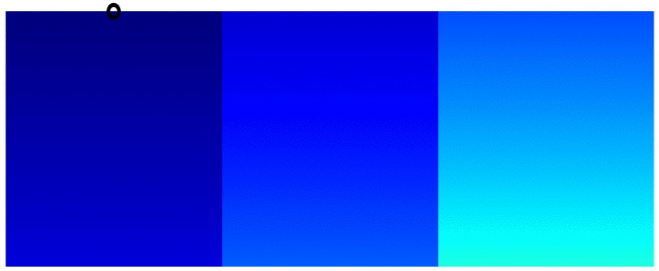
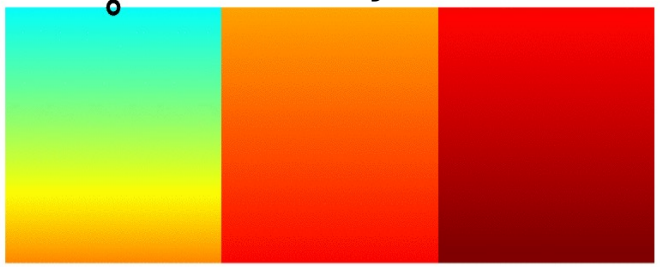
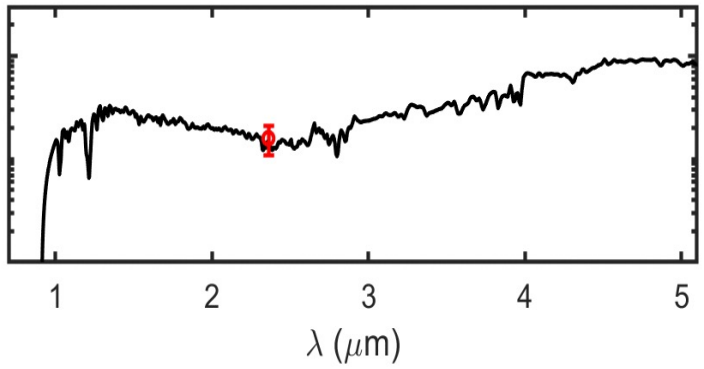
Reflected by Dichroic

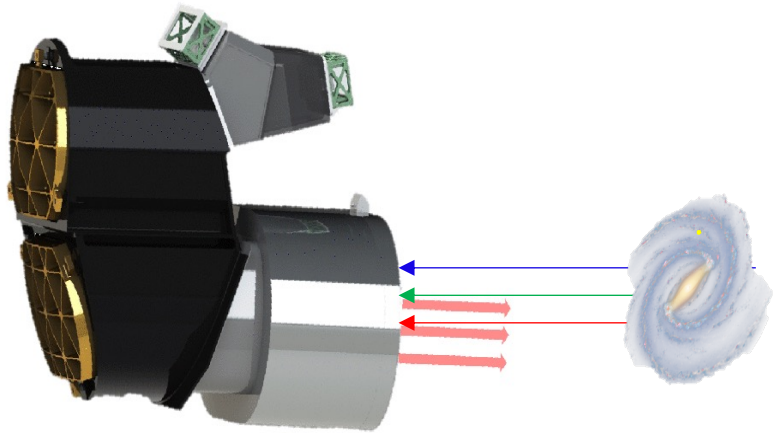


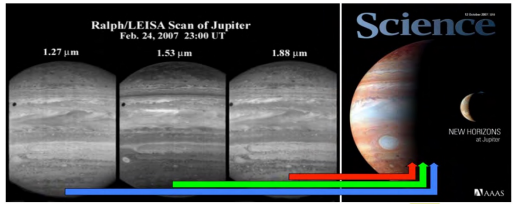
Transmitted by Dichroic

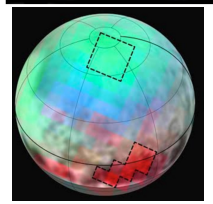




Shifting the spacecraft pointing modulates the wavelength at which an object is observed.

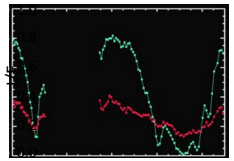






Infrared Spectral Image

Methane on Pluto



Ralph/LEISA - New Horizons

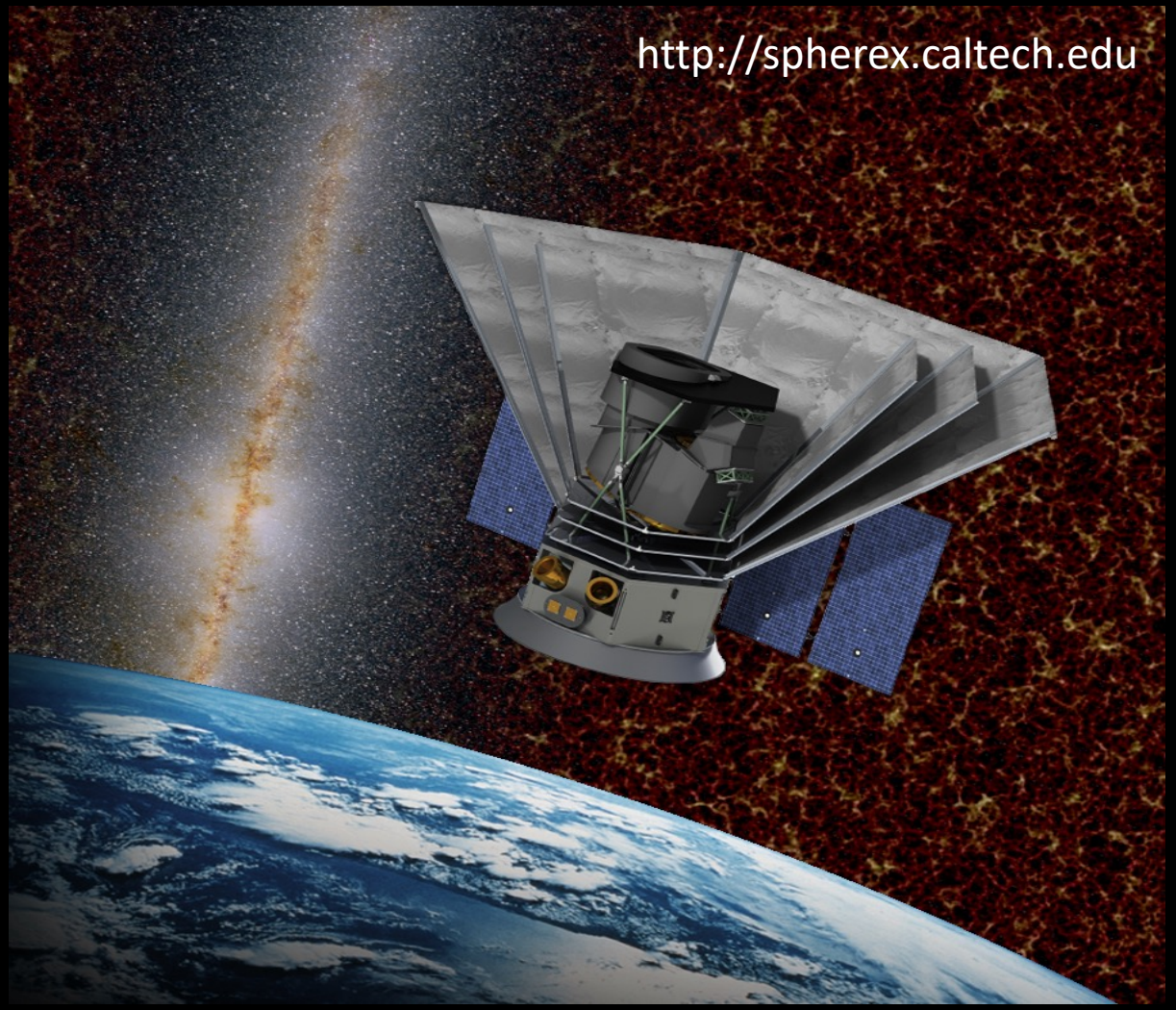
A complete spectrum in 51 exposures

Each exposure ~112s

SPHEREx operates in Low Earth Orbit; full spectrum of entire sky built up over the course of a year

SPHEREx Science Team

Jamie Bock (PI)	Caltech/JPL
Rachel Akeson	IPAC
Matt Ashby	CfA
Lindsey Bleem	Argonne
Sean Bryan	Arizona State
Joyce Byun	U. Arizona
Tzu-Ching Chang	JPL
Yi-Kuan Chiang	Ohio State
Asantha Cooray	UC Irvine
Brendan Crill	JPL
Olivier Doré (PS)	JPL
Darren Dowell	JPL
Gregory Dubois-Felsmann	IPAC
Tim Eifler	U. Arizona
Andreas Faisst	IPAC
Salman Habib	Argonne
Grigory Heaton	Caltech
Chen Heinrich	Caltech
Katrin Heitmann	Argonne
Chris Hirata	Ohio State
Woong-Seob Jeong	KASI
Jae Hwan Kang	Caltech
Davy Kirkpatrick	IPAC
Phil Korngut	Caltech
Elisabeth Krause	U. Arizona
BoMee Lee	KASI
Carey Lisse	JHU
Daniel Masters	Caltech
Phil Mauskopf	Arizona State
Gary Melnick	CfA
Hien Nguyen	JPL
Karin Öberg	CfA
Steve Padin	Caltech
Roberta Paladini	IPAC
Milad Pourrahmani	IPAC
Roger Smith	Caltech
Yong-Seon Song	KASI
Teresa Symons	RIT
Harry Teplitz	IPAC/Caltech
Volker Tolls	CfA
Steve Unwin	JPL
Michael Werner	JPL
Rogier Windhorst	Arizona State
Yujin Yang	KASI
Mike Zemcov	RIT



SPHEREx

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Jet Propulsion Laboratory
California Institute of Technology

SPHEREx's three Science Themes

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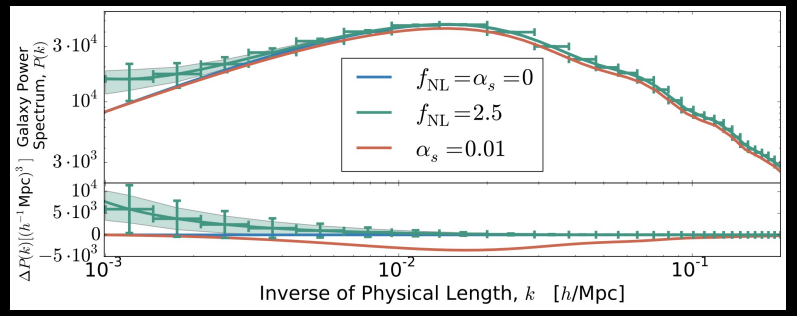
- Science goal: constrain inflation through primordial non-Gaussianity as measured in 3D galaxy power spectrum and bispectrum

Key Systematics:

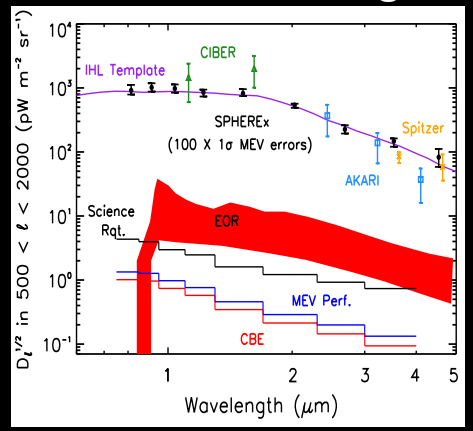
- PSF reconstruction
- Photometric stability
- Absolute calibration



- Science goal: understand galaxy formation via power spectra of Extragalactic Background Light

Key Systematics

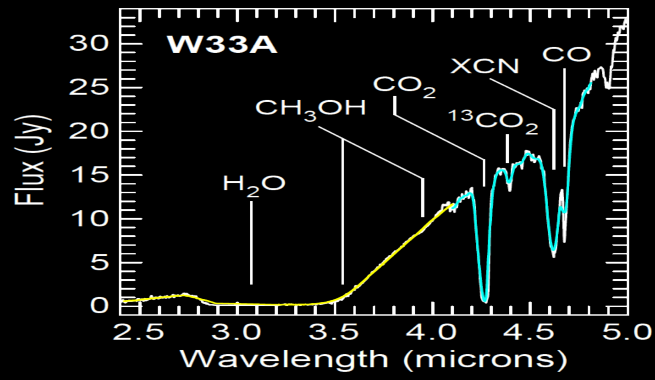
- Extended PSF / ghosting
- Readout crosstalk
- Image persistence
- Correlated noise, dark current
- Time-variable backgrounds



- Science goal: inventory biogenic ices in the Galaxy via absorption features towards stars

Key systematics

- PSF reconstruction
- Crowded field photometry
- Relative calibration
- Spectral features in ISM
- Nonlinearity/Saturation



SPHEREx Sky Simulator

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Software for generating simulated SPHEREx image and catalog science data

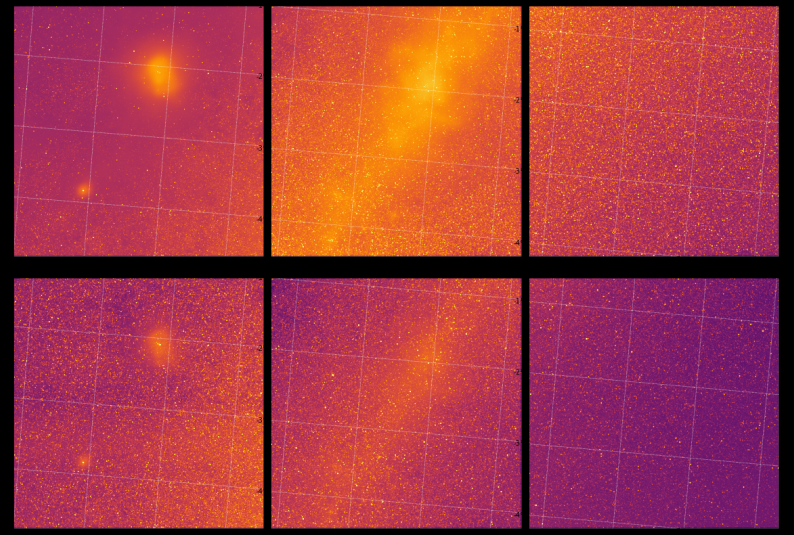
Purpose of the SPHEREx Sky Simulator

1. Support instrument trade studies and requirements definition
2. Create simulated data to assist in developing science software
3. Prototype and Validate science data pipeline software
4. Evaluate effects of systematic errors on science results

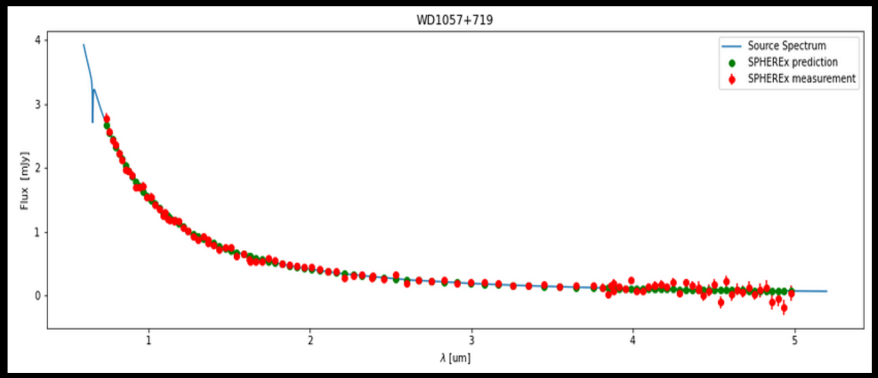
Requirements on the Simulator

- realistic representation of SPHEREx observations
- high performance - scalable to High Performance Computing (HPC) environments to enable large numbers of simulations
- portable to different platforms
- well-documented, strict version control
- Flexible; i.e., easy to introduce additional instrumental effects

Produces either 1. simulated exposures:



or 2.spectral catalog data:



Software Management Approach

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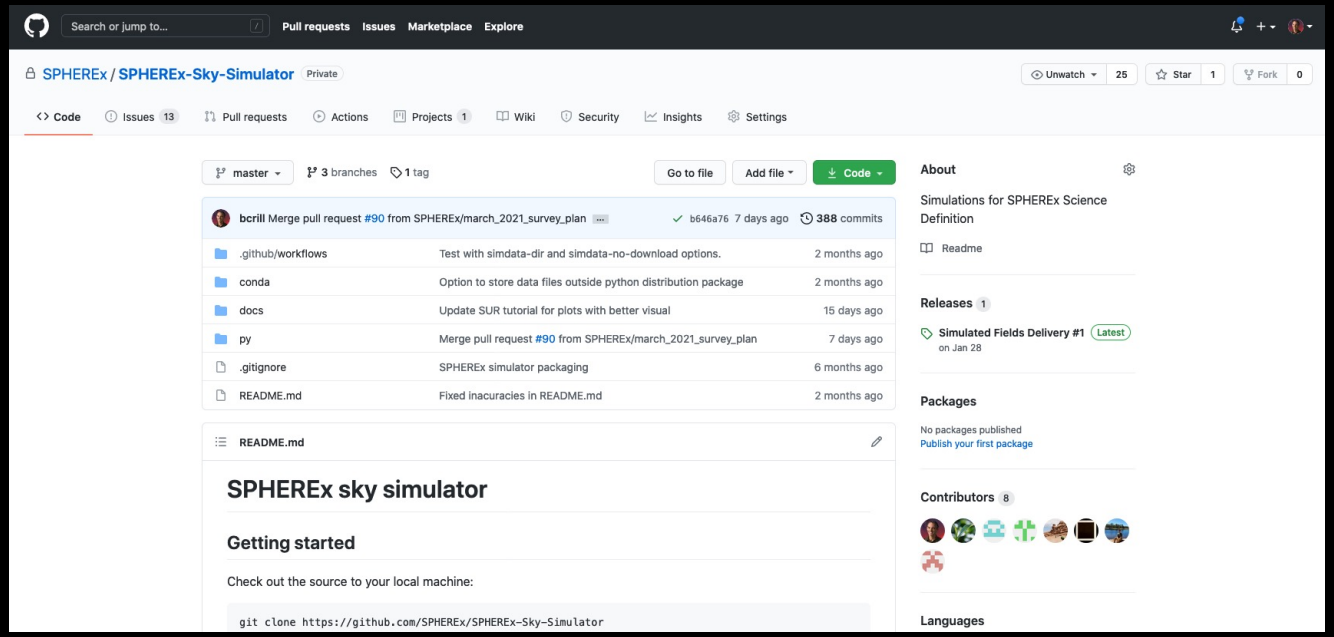
- Based around github
- Around ~5 SPHEREx team members are actively contributing, we assign each other pull requests to review
- Github actions configured to test commits
- Large binaries are stored outside of github repo and automatically downloaded at install time



Sky Simulator Architecture

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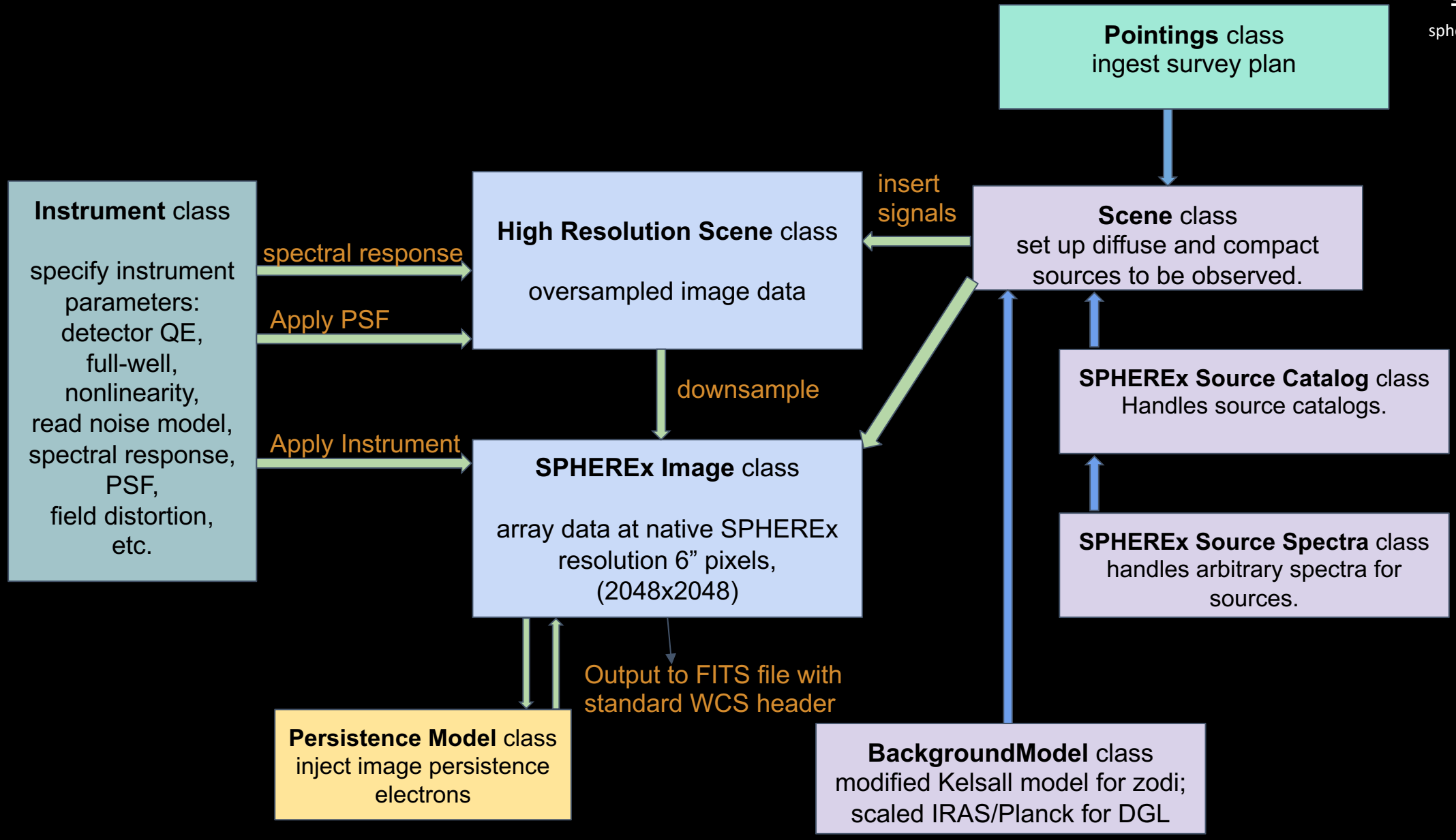
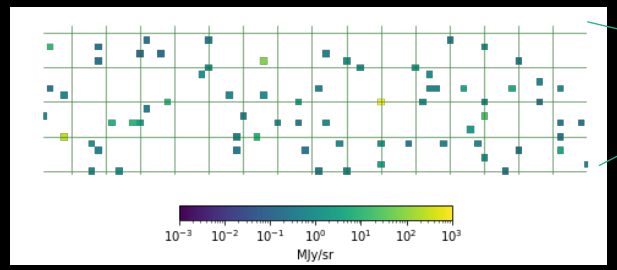
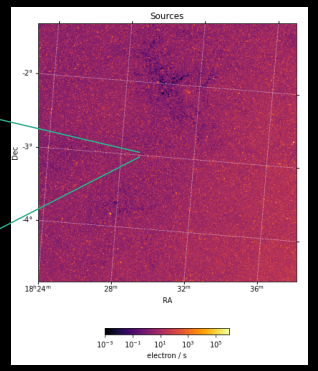


Example

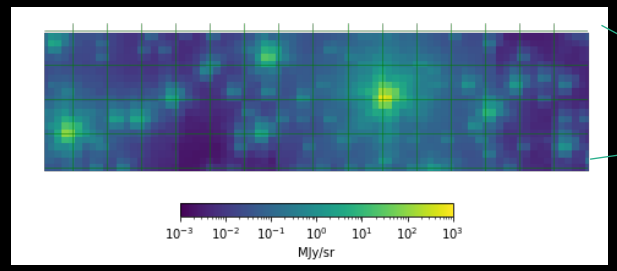
1. create a WCS given spacecraft orientation
2. Compact sources (convolved with spectral response) inserted into oversampled image

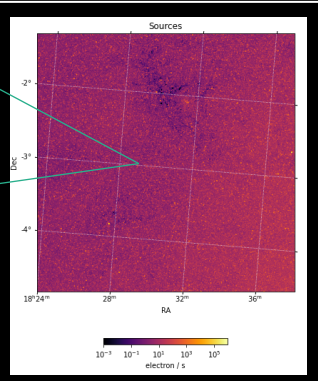




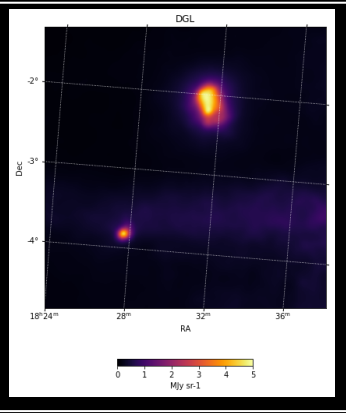
Green grid shows SPHEREx native resolution

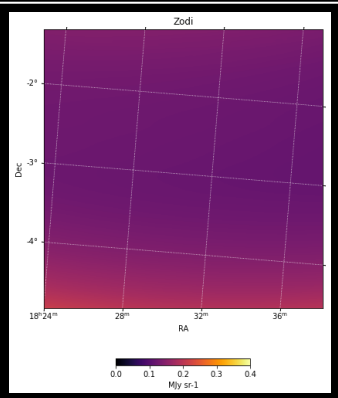
3. Convolve with PSF



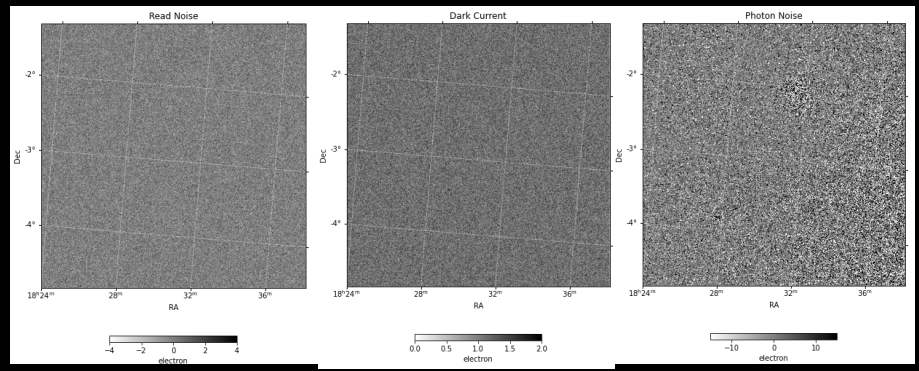


4. Insert sub-pixel systematics
5. Downsample to SPHEREx resolution
Insert diffuse signals (convolved w/spectral response)

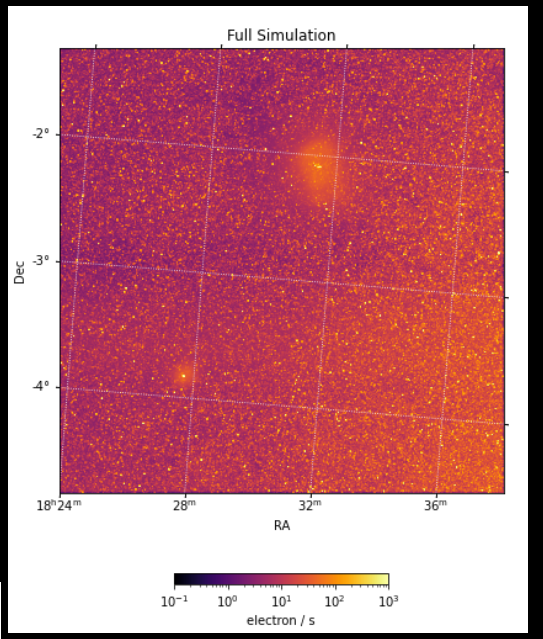




6. Appy instrument: perform sample up the ramp, adding noise, dark current, crosstalk, saturation, QE map, etc.



7. Fit photocurrent



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Input Astrophysical Sky

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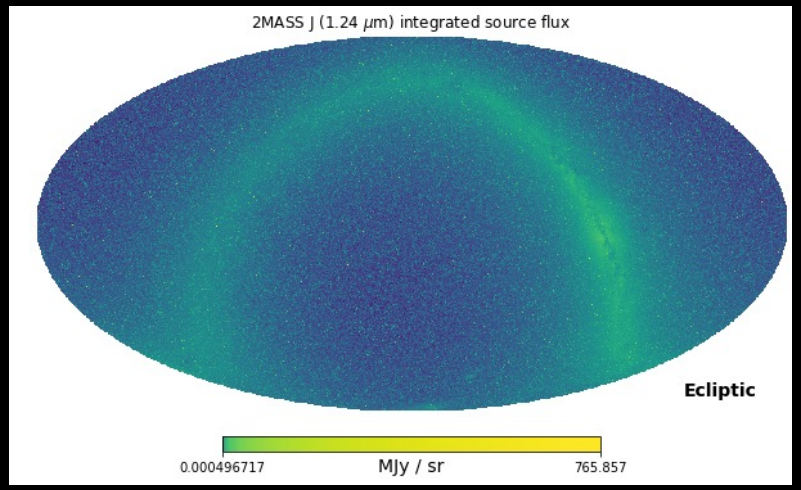
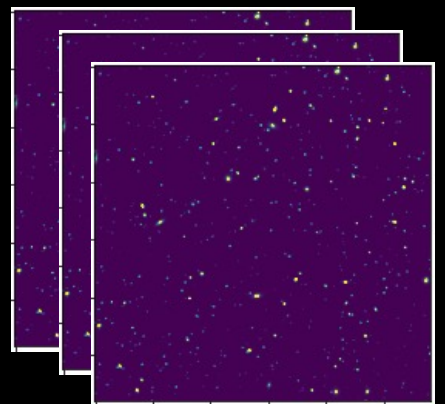
Compact sources

A reference catalog of ~3B sources
Gaia EDR3, 2MASS, CatWISE2020, Pann-STARRS1
(spatial matching enables very rough SEDs)



Simulated Galaxy data cubes

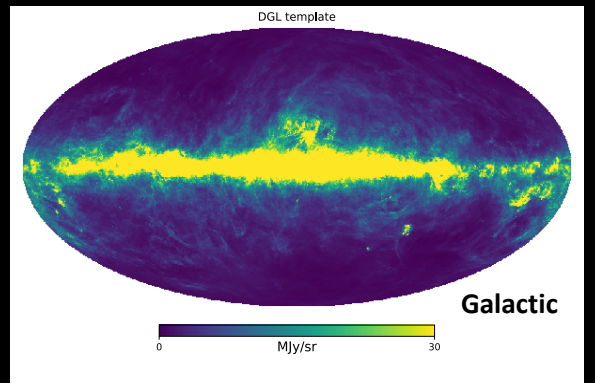


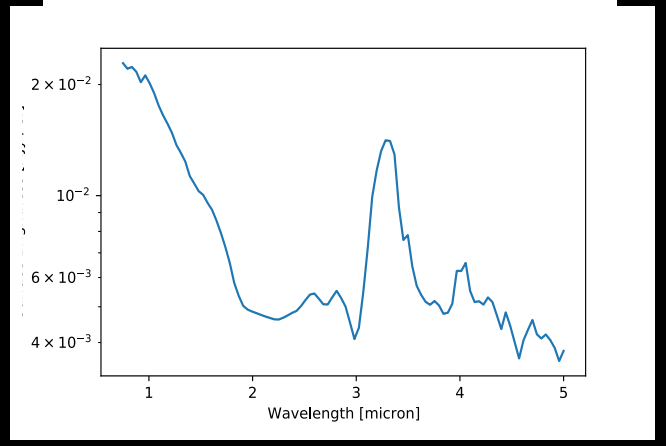
GALSIM (Rowe+2015)

Diffuse Backgrounds

Diffuse Galactic Light

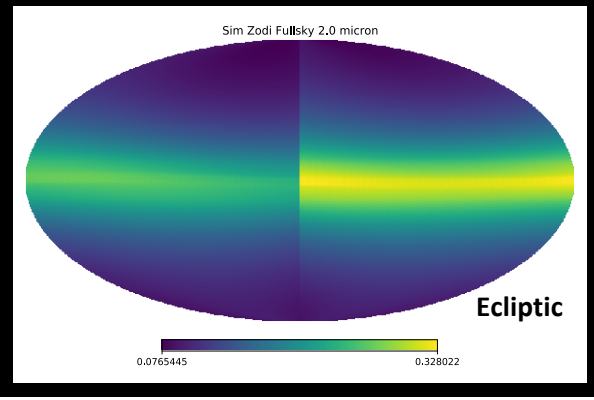
Planck/IRAS (2016) scaled to NIR:
Draine (2003), Lillie+(1976), Tsumura+ (2013), Zubko+ (2004),
Arai+ (2015)

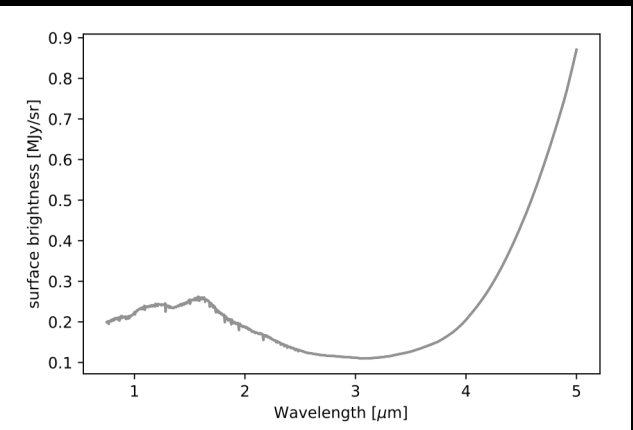




Zodiacal Light

COBE/DIRBE (Kelsall+ 1998)
Also uses Solar spectrum,
updates based on CIBER (Tsumura+ 2010), AKARI (Tsumura+ 2013), IRTS (Matusmoto+ 2015) HST (Kawara+ 2013), Planck (2014)





Instrument Model

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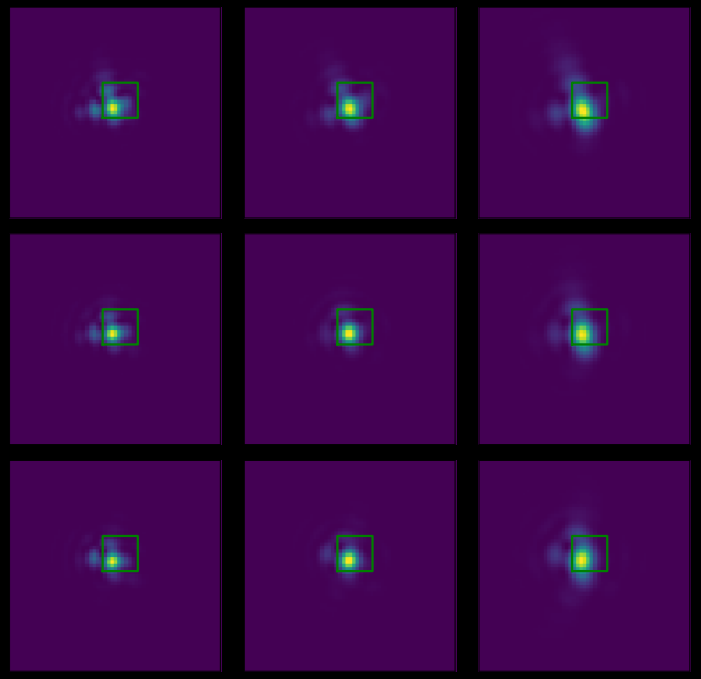
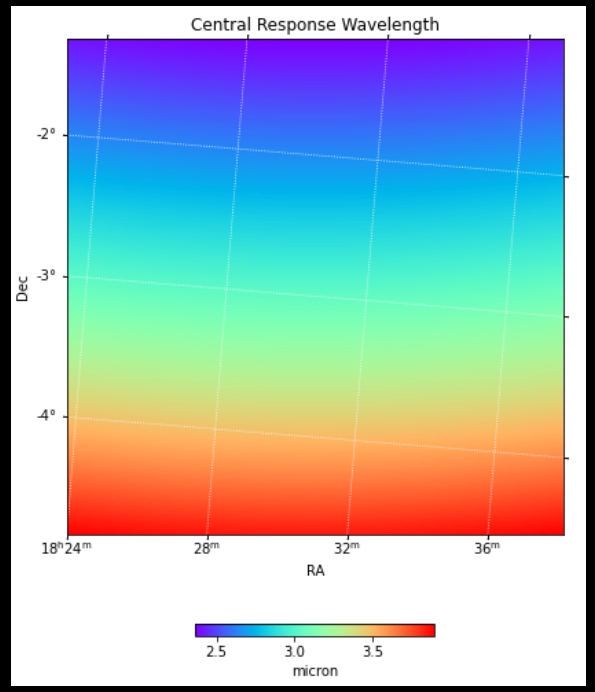
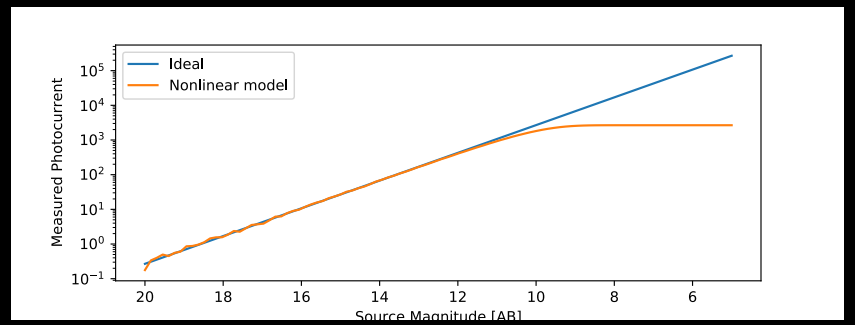
PSF (optionally smear w/jitter)



LVF response model

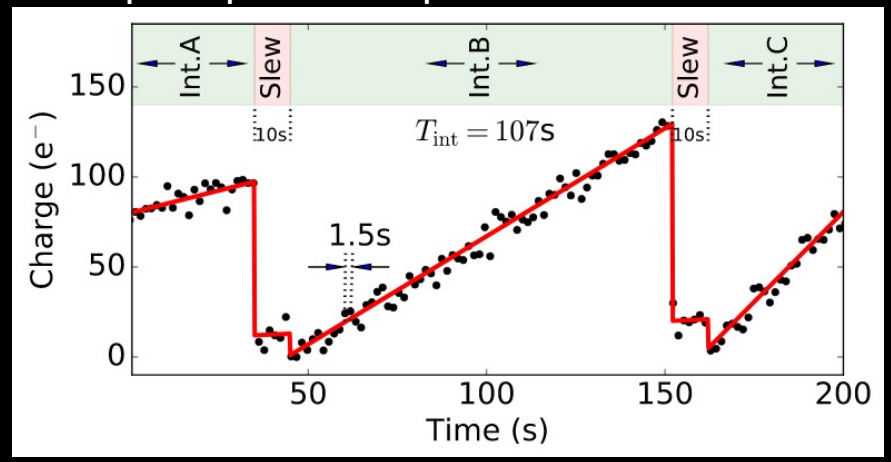


Saturation model



Biesiadzinski+ (2011)

Sample-up-the-ramp readout scheme:



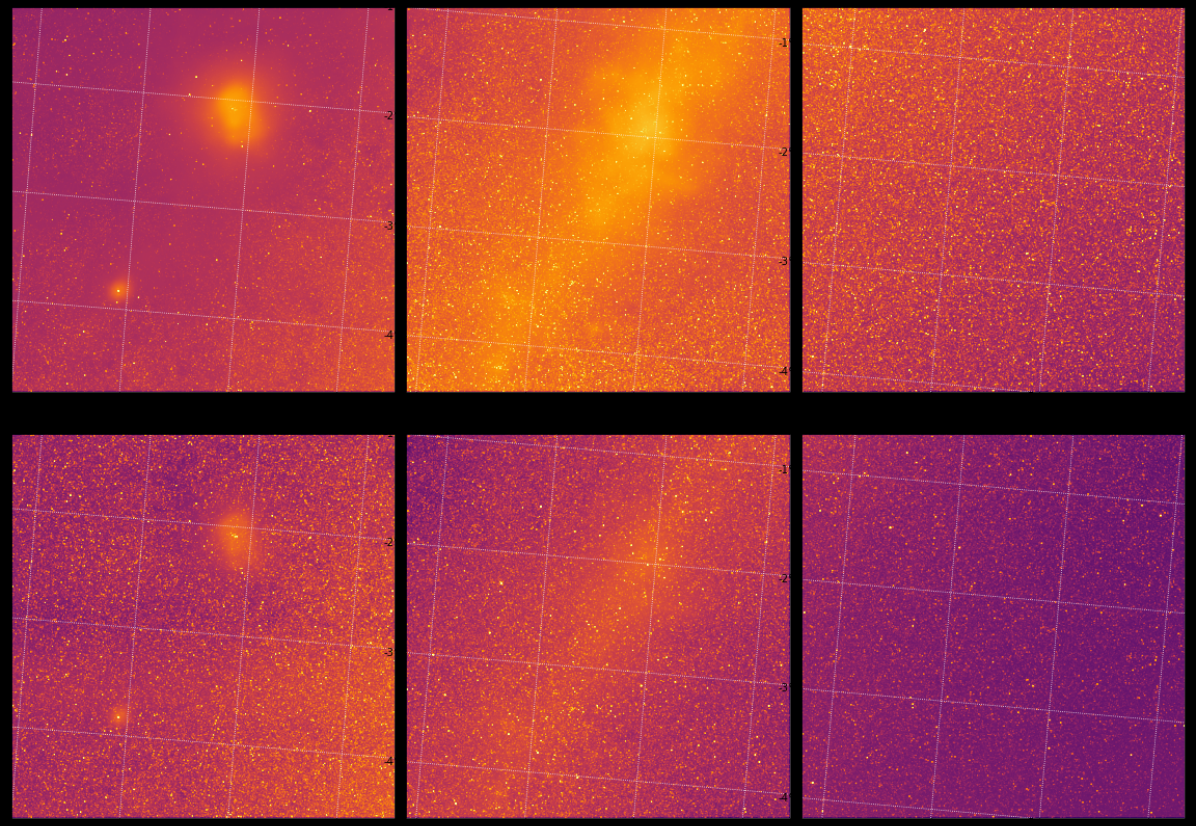
Zemcov et al+ (2016)

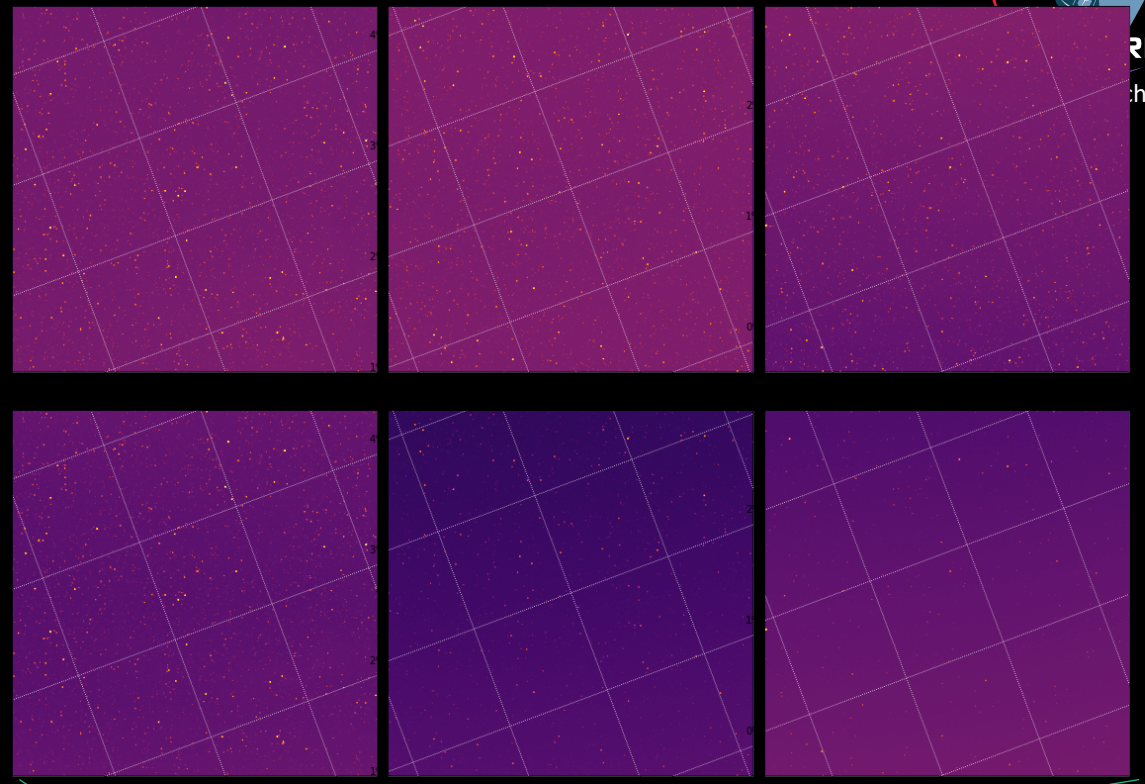
Other options: field distortion, cosmic rays hits, subpixel gain, persistence model (post processing)

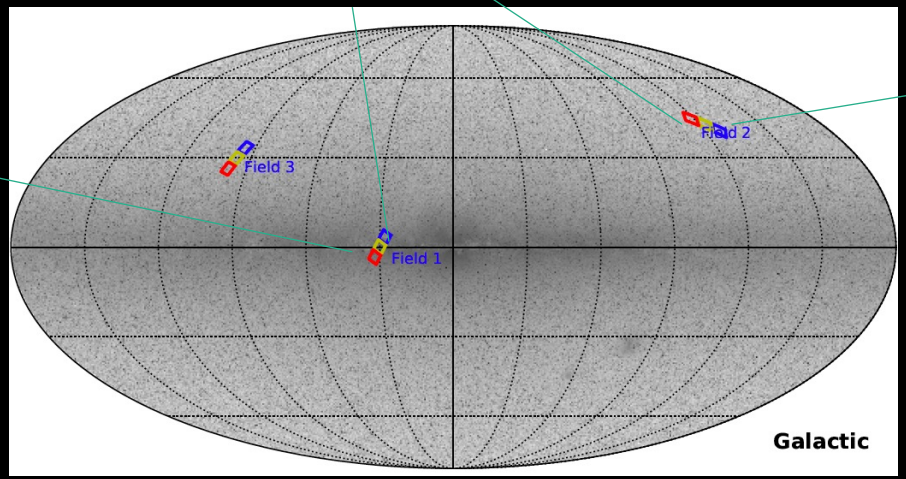
More effects on the list to add: reciprocity failure, charge diffusion, IPC

Crowded field in the Galactic plane

The COSMOS field







The Sky Simulator and the SPHEREx project: use cases so far

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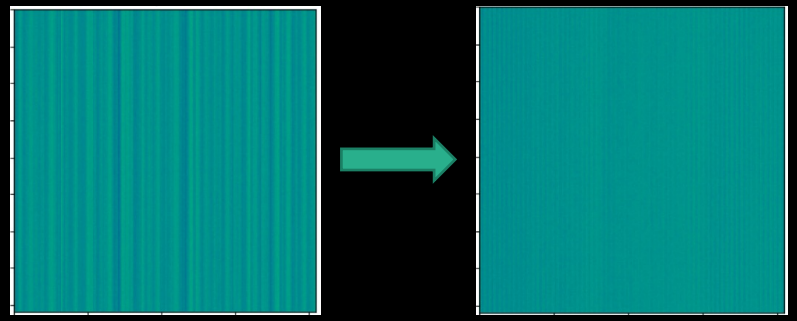
- Impacts on overall instrument design
  - For example:
    - Evaluate interplay of detector readout scheme and 1/f amplifier noise -> “row chopping” scheme
    - Design/parameterize on-board compression (full sky)

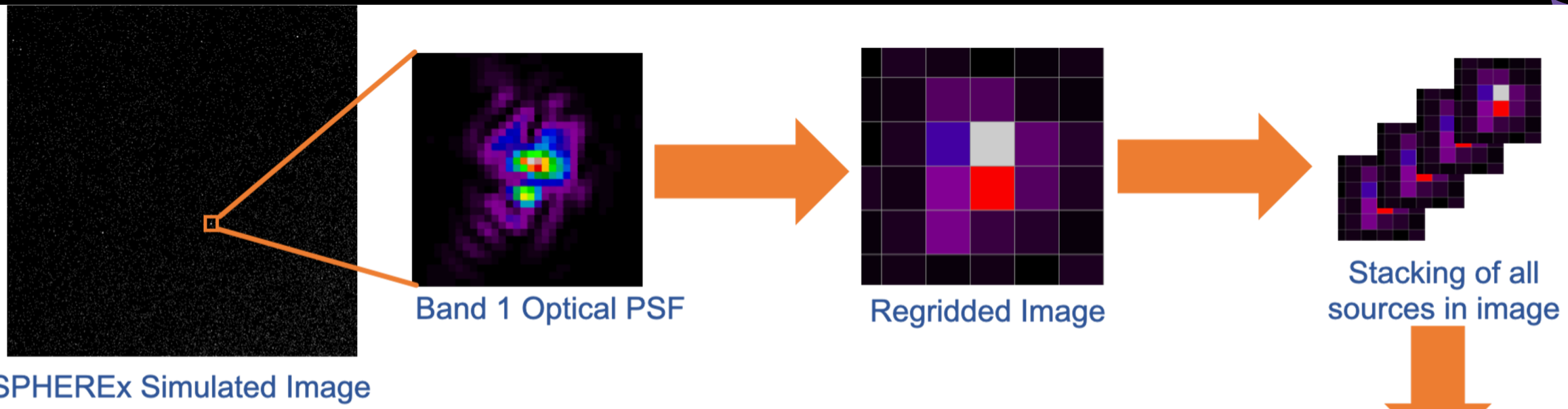


- Helping to set instrument and data pipeline requirements
  - Example: photometry error budgeting

- Address practical data analysis questions / prototype analysis code:
  - Mosaic map-making
  - Photometry in crowded fields, handling backgrounds, etc.
  - Reconstructing the PSF
  - Astrometric solution

- Data pipeline software validation at SPHEREx Science Data Center (IPAC)

PSF reconstruction prototype



- **SPHEREx measures PSF-weighted photometry of already known sources: knowledge of PSF determined by sub-pixel stacking of stars in each exposure**
- **Symons+ (2021) showed less than 0.1% bias in photometry due to PSF knowledge, allocation of 0.5% OK**
- **Sky simulator enabled prototyping of this code with realistic crowding, stellar brightness distributions, backgrounds, variation of PSF across FOV, etc.**

Next Steps

- The simulation software will continue to evolve to match improved knowledge of instrument
  - Instrument I&T: learn as-built instrument properties
  - During in-orbit checkout: learn behavior in operational environment

- During science data analysis: characterizing systematic errors in science results

Stay tuned for SPHEREx data in just a few years: launch planned for 2024

BACKUP

Sensitivity of SPHEREx Survey

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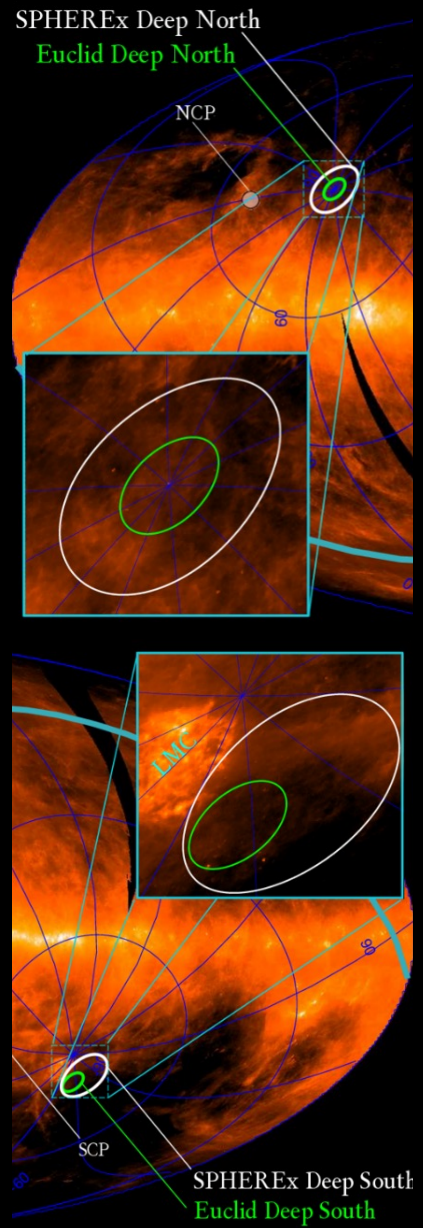
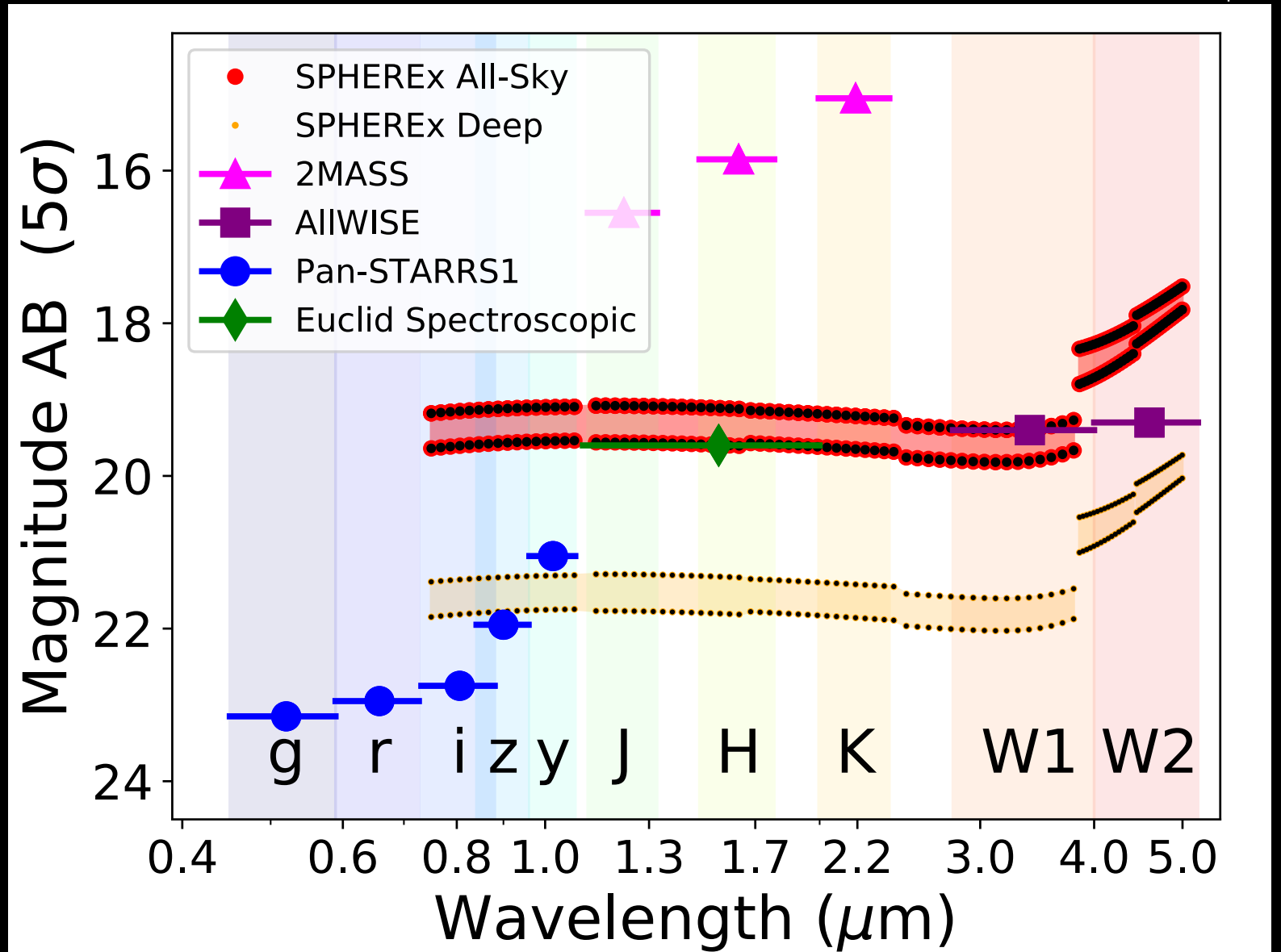
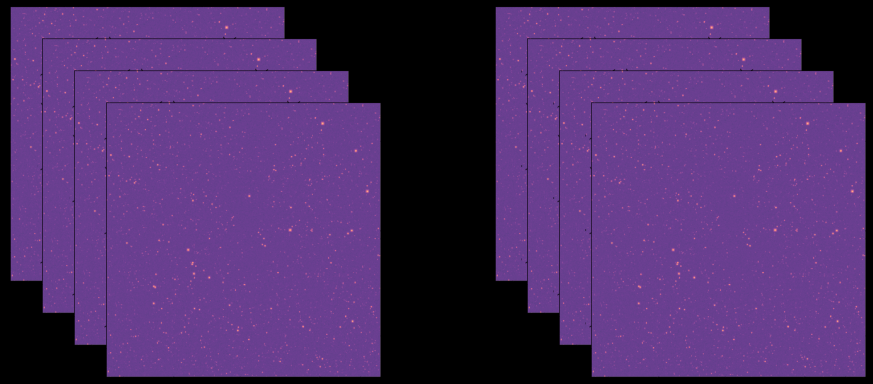
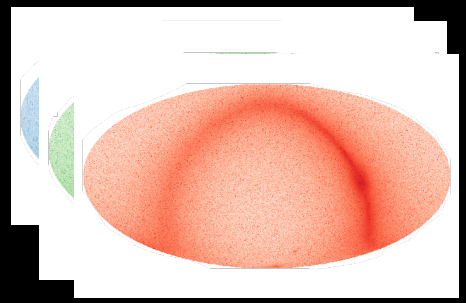


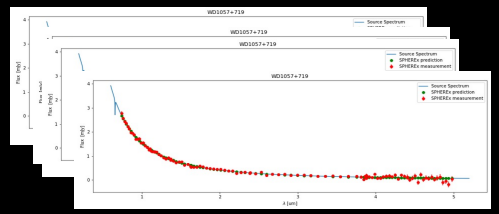


SPHEREx Data Products

- Will be released through IPAC-IRSA
- Quick Release Spectral Images
  - On order 500 exposures/day
  - Released 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
- High Reliability Source Catalog
- Legacy Data Products
  - Deep Field Mosaics
  - Galaxy Redshift Catalog
  - Ice Column Density/Stellar Type catalog







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