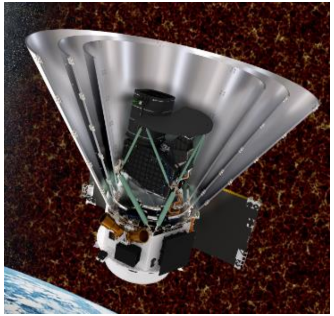
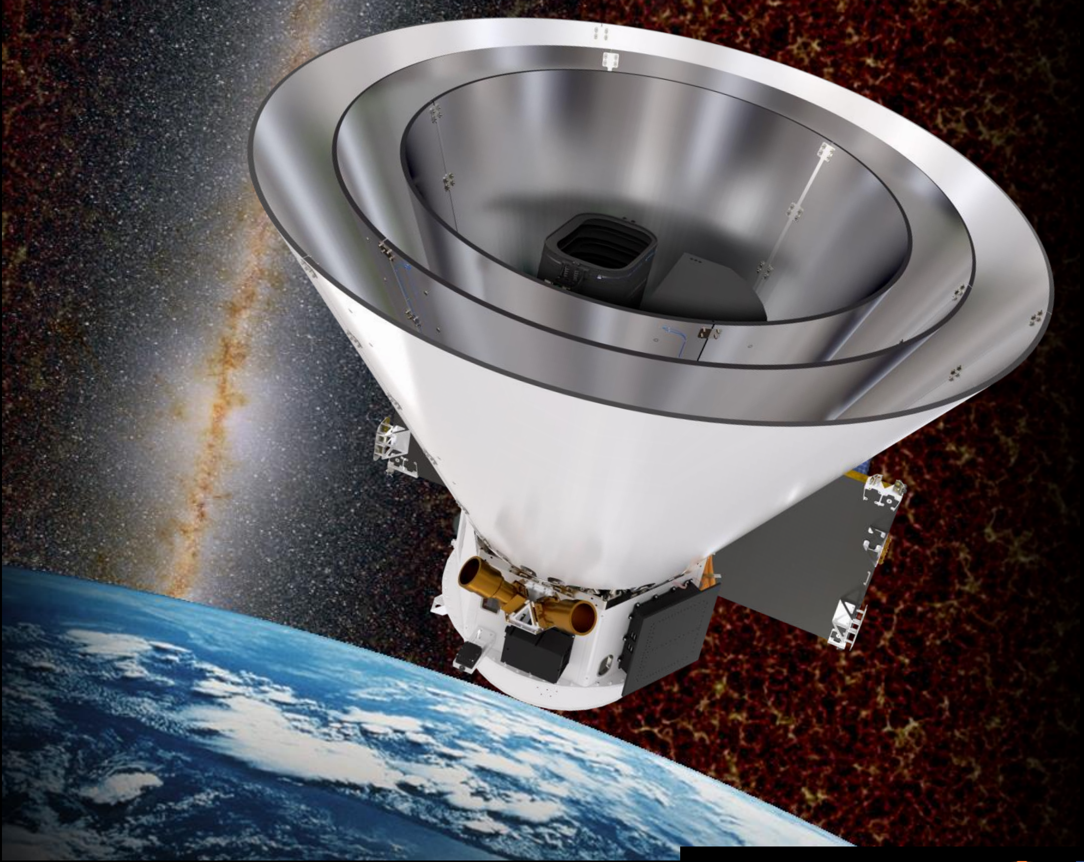


Spherical Fourier-Bessel Power Spectrum for SPHERE^x

Robin Wen, on behalf of Henry Gebhardt
California Institute of Technology

SPHERE^{x}: An All-Sky Infrared Spectral Survey Satellite



Designed to Explore

- Origin of the Universe
- Origin and History of Galaxies
- Origin of Water in Planetary Systems

First All-Sky Near-IR Spectral Survey

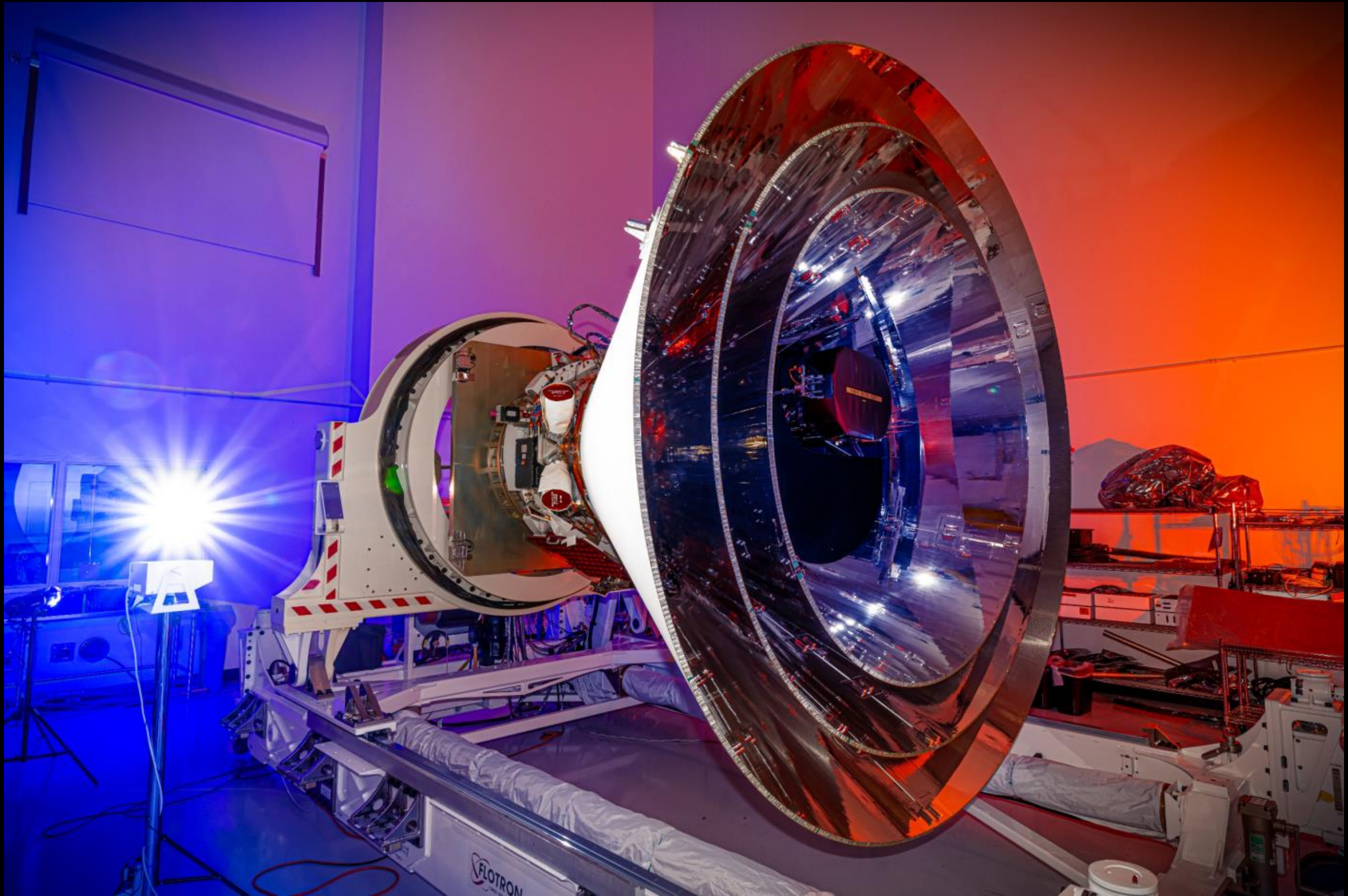
102 bands in 0.75-5 μm
Scan full-sky 4 times in 2 years

Elegantly Simple

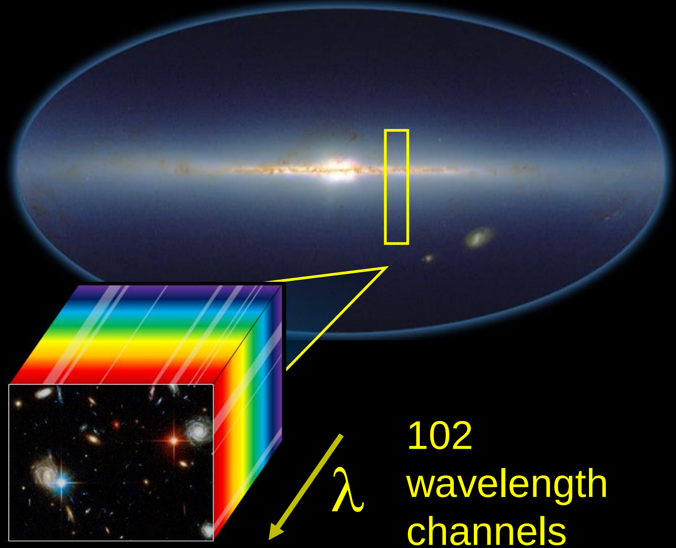
- Single Observing Mode
- No Moving Parts in Instrument

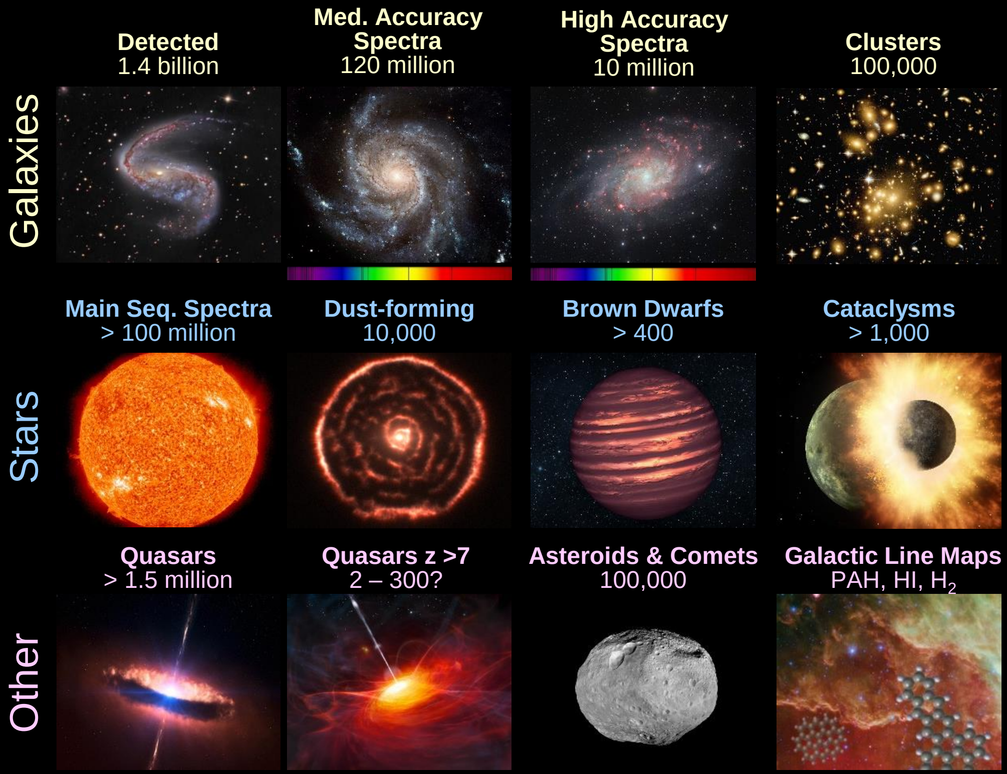
PI: Jamie Bock -- Caltech/JPL
PS: Olivier Doré -- JPL

Launch in early 2025!



SPHERE^{X} PROVIDES A RICH ALL-SKY SPECTRAL CATALOG





SPHEREx provides a new and unique dataset

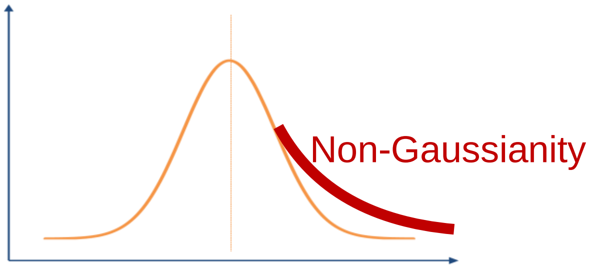
a complete near-infrared spectrum for every 6” pixel on the sky

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

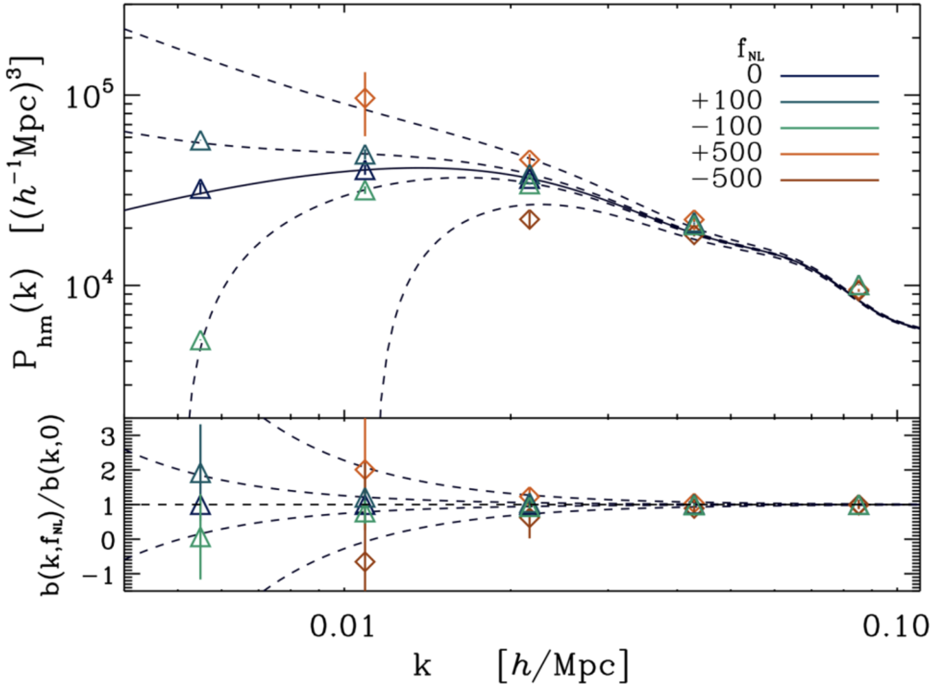
Many exciting discoveries will come from the community

SPHEREx Constrains Local Primordial Non-Gaussianity (PNG)

$$\Phi(\boldsymbol{x}) = \varphi(\boldsymbol{x}) + f_{\rm NL}\left(\varphi^2(\boldsymbol{x}) - \langle\varphi^2\rangle\right)$$



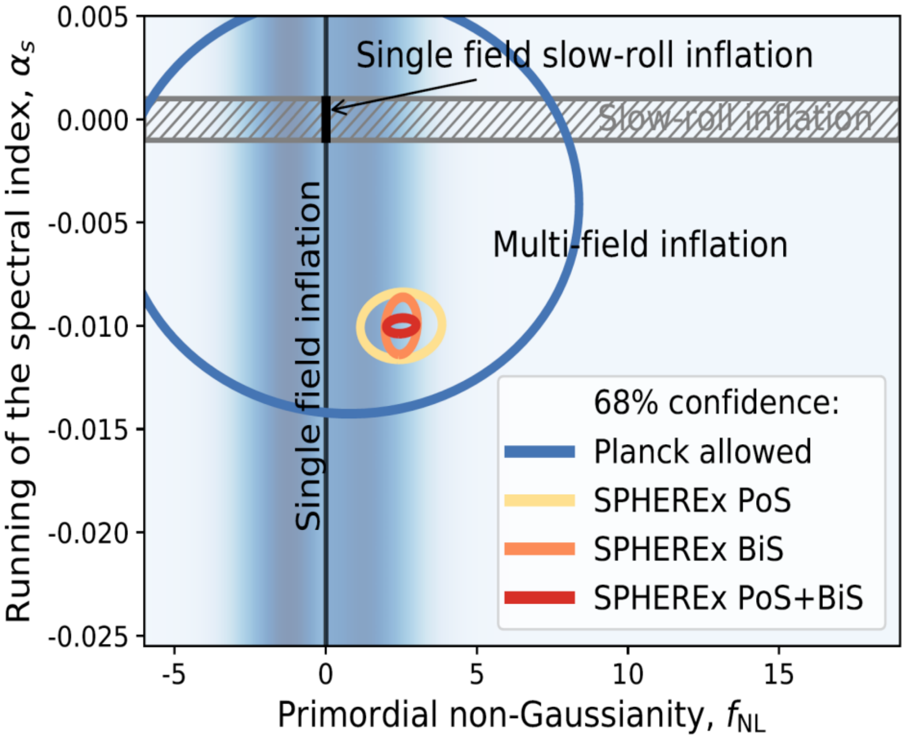
- Single-field inflation generically predicts $f_{\rm NL} < 0.01$
- Multi-field inflation generically predicts $f_{\rm NL} \sim \mathcal{O}(1)$
- Power Spectrum (PS): scale-dependent bias
- Bispectrum (BS): primordial non-Gaussian perturbation



Dalal, Doré et al. 2008

$$\delta_g(k) = \left[b_1 + b_\phi f_{NL}\,\alpha^{-1}(k)\right]\delta_m(k)$$

SPHEREx Tests Inflation through local PNG



PS: $\sigma(f_{\rm NL}) \sim 1$

BS: $\sigma(f_{\rm NL}) \sim 0.7$

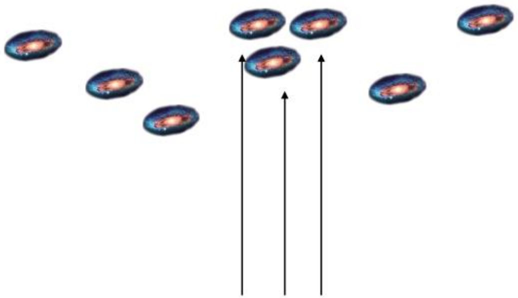
PS+BS: $\sigma(f_{\rm NL}) \sim 0.5$

Doré et al. 2014
Heinrich, Doré, Krause 2024

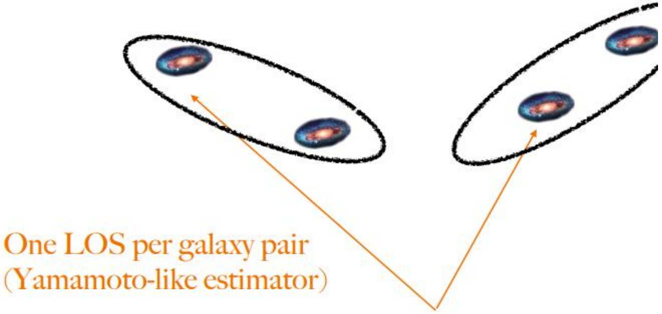
*Multi-tracer analysis exploiting LPNG bias (b_ϕ) may offer further improvement!

Challenges

- Observational Systematics
- Redshift-error modelling (spectro-photometric survey)
- Theoretical Modeling at Large-scale
  - Wide-angle (WA) Effects
  - General Relativistic (GR) Effects
  - Covariance



Plane-parallel approximation



End-point LOS

Spherical Fourier-Bessel (SFB) Transform

Laplacian Eigenfunctions: $\nabla^2 f = -k^2 f$

Cartesian Coordinates:

$$f(\mathbf{k}, \mathbf{r}) = e^{-i\mathbf{k}\cdot\mathbf{r}}$$

Fourier transform:

$$\tilde{\delta}(\mathbf{k}) = \int d^3r \, e^{-i\mathbf{k}\cdot\mathbf{r}} \, \delta(\mathbf{r})$$

Spherical Coordinates:

$$f_{\ell m}(k, \mathbf{r}) = j_\ell(kr) \, Y_{\ell m}(\hat{\mathbf{r}})$$

SFB transform:

$$\tilde{\delta}_{\ell m}(k) = \int d^3r \, j_\ell(kr) \, Y_{\ell m}(\hat{\mathbf{r}}) \, \delta(\mathbf{r})$$

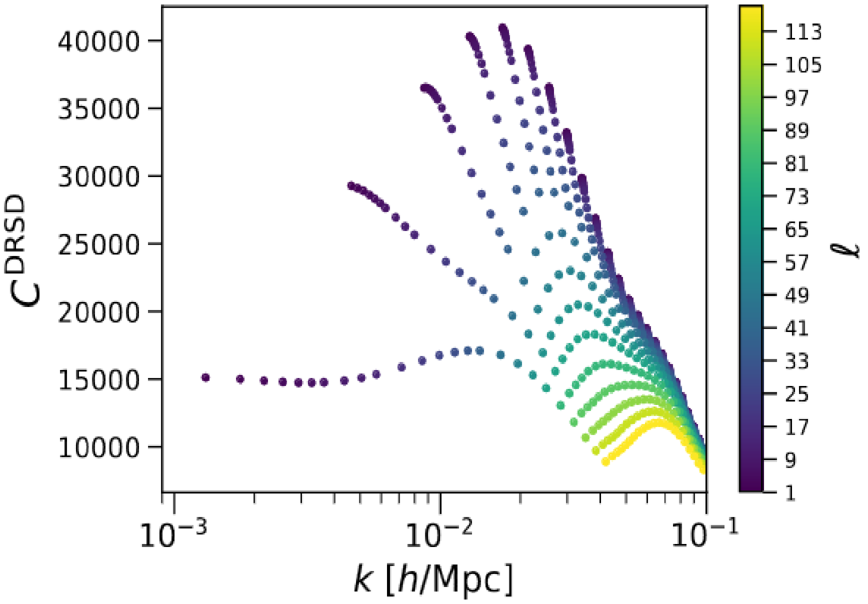
- Obey curved-sky geometry. Retain angular modes
- Naturally include WA effects
- Remain in Fourier space, diagonal covariance
- Easy implementation of line-of-sight (GR) effects

SFB Power Spectrum

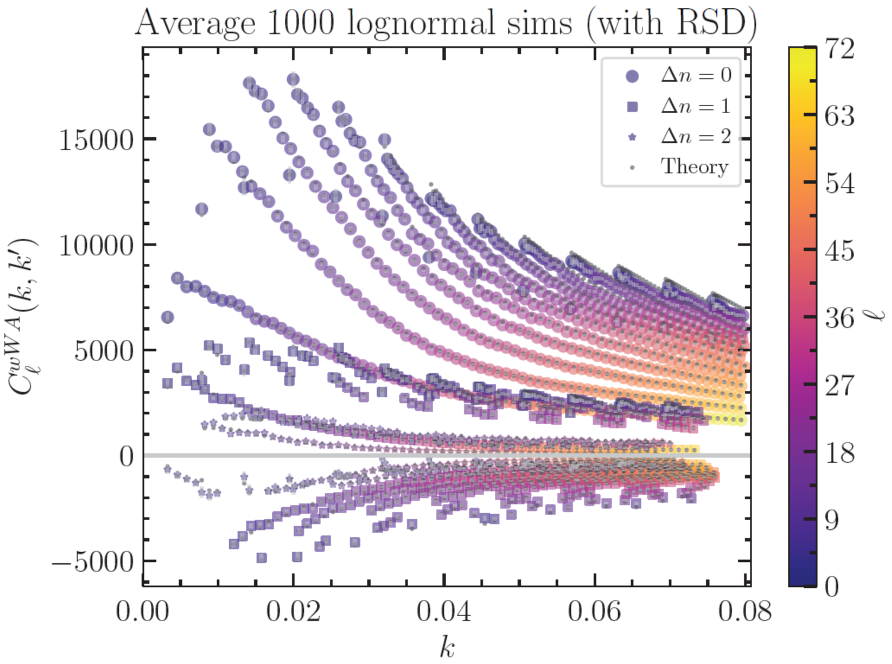
Wen et al. 2024

Grasshorn Gebhardt & Doré 2024

$$\langle \delta_{\ell_1 m_1}(k_1)\delta^*_{\ell_2 m_2}(k_2)\rangle = C_{\ell_1}(k_1,k_2)\delta^K_{\ell_1\ell_2}\delta^K_{m_1 m_2}$$

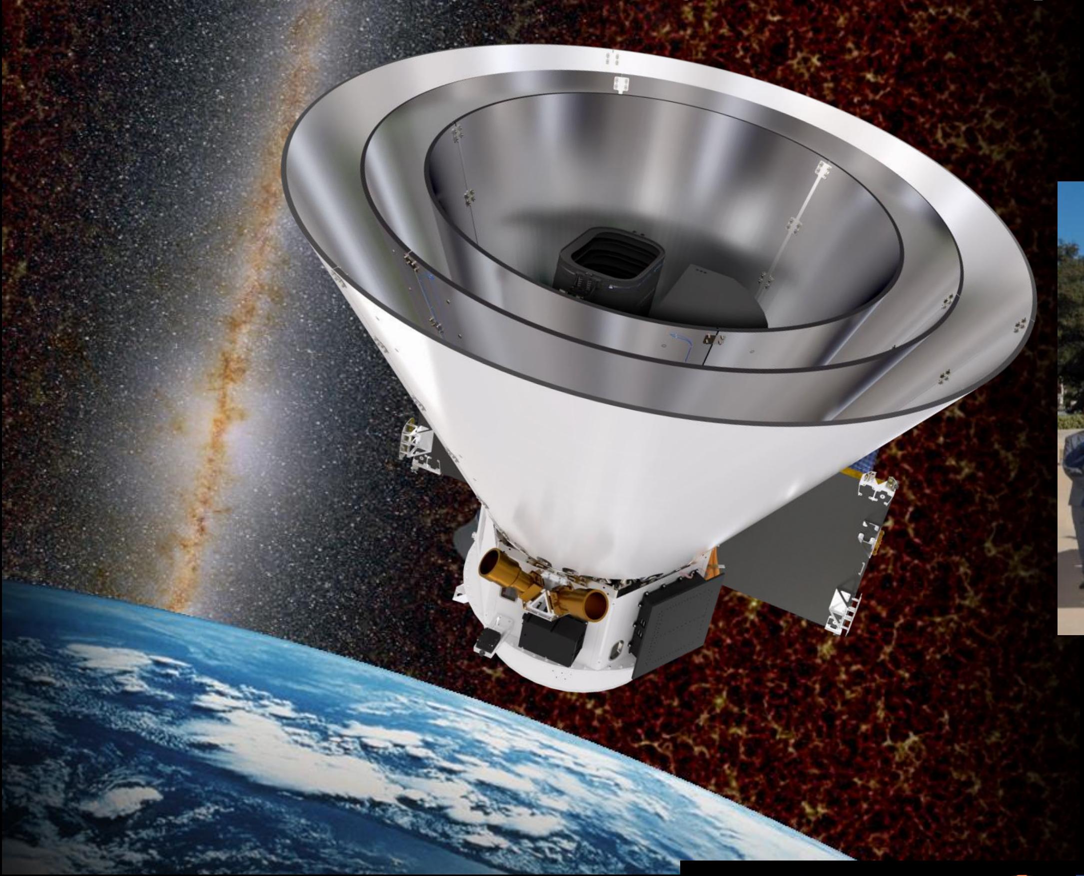


theory



Validation with mock

SPHERE^{x}: An All-Sky Infrared Spectral Survey Satellite



Looking forward to launch in early 2025!

JPL
Jet Propulsion Laboratory
California Institute of Technology
Ball
ipac
UCI
THE OHIO STATE UNIVERSITY
ASU
R·I·T
JOHNS HOPKINS UNIVERSITY
ARIZONA
Argonne

Backup Slides

SFB Power Spectrum

$$\langle \delta_{\ell_1 m_1}(k_1) \delta^*_{\ell_2 m_2}(k_2) \rangle = C_{\ell_1}(k_1, k_2) \delta^K_{\ell_1 \ell_2} \delta^K_{m_1 m_2}$$

$$C^{\mathrm{R}}_\ell(k_1, k_2) = \int_0^\infty dq\, \mathcal{W}^{\mathrm{R}}_\ell(k_1, q) \mathcal{W}^{\mathrm{R}}_\ell(k_2, q) P_{\mathrm{m},0}(q)$$

$$\mathcal{W}^{\mathrm{R}}_\ell(k, q) \equiv \sqrt{\frac{2}{\pi}} q \int_0^\infty dx\, x^2 j_\ell(kx) R(x) \Delta_\ell(x, q)$$

Projection to SFB space

angular kernel

$$\Delta_\ell(x, q)^{\mathrm{DRSD}} = b_1(x) D_{\mathrm{m}}(x, q) j_\ell(qx) + \frac{q}{\mathcal{H}(x)} v(x, q) j''_\ell(qx)$$

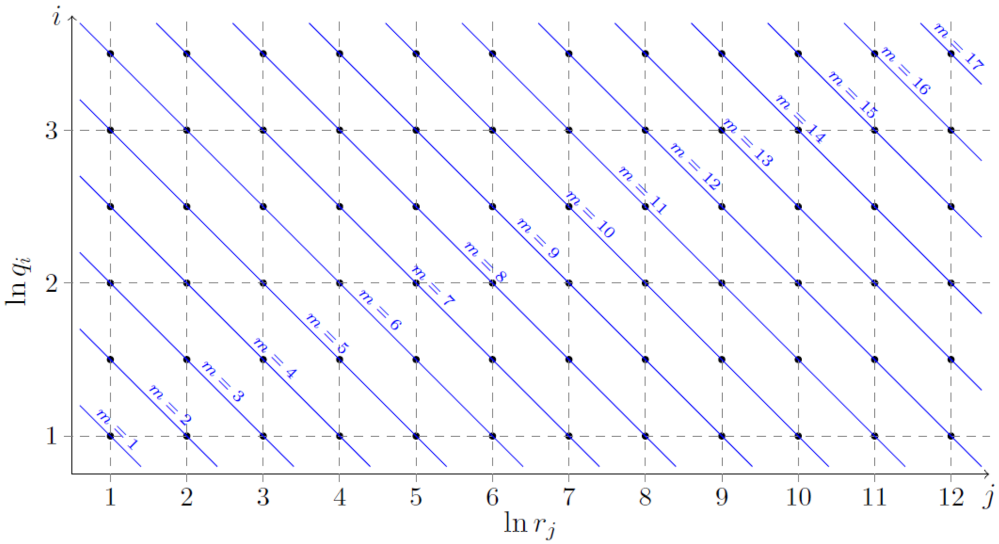
Drawbacks:

- Unfamiliar statistics
- Large Data Vector
- No FFT estimator
- Challenging non-linear modeling

Numerical Technique: Iso-qr Integration

First proposed in [Grasshorn Gebhardt & Doré 2024]

$$\int_{r_{\min}}^{r_{\max}} f(r,q)\, j_\ell(qr)$$



- f(r,q) evaluation is fast, spherical Bessel is slow
- Spherical Bessel only depends on “qr” combination
- Choose q and r on iso-qr lines, efficiently cache spherical Bessel
- Quadrature integration
- A few seconds for Newtonian RSD, Performed MCMC with SFB
- Can be adapted for all GR effects

Continuous versus Discrete SFB

Continuous

$$\delta_{\ell m}(k) = \int_{\mathbf{x}} j_\ell(kx) Y^*_{\ell m}(\hat{\mathbf{n}}) \delta(\mathbf{x}) \qquad \langle \delta_{\ell_1 m_1}(k_1) \delta^*_{\ell_2 m_2}(k_2) \rangle = C_{\ell_1}(k_1, k_2) \delta^K_{\ell_1 \ell_2} \delta^K_{m_1 m_2}$$

Discrete

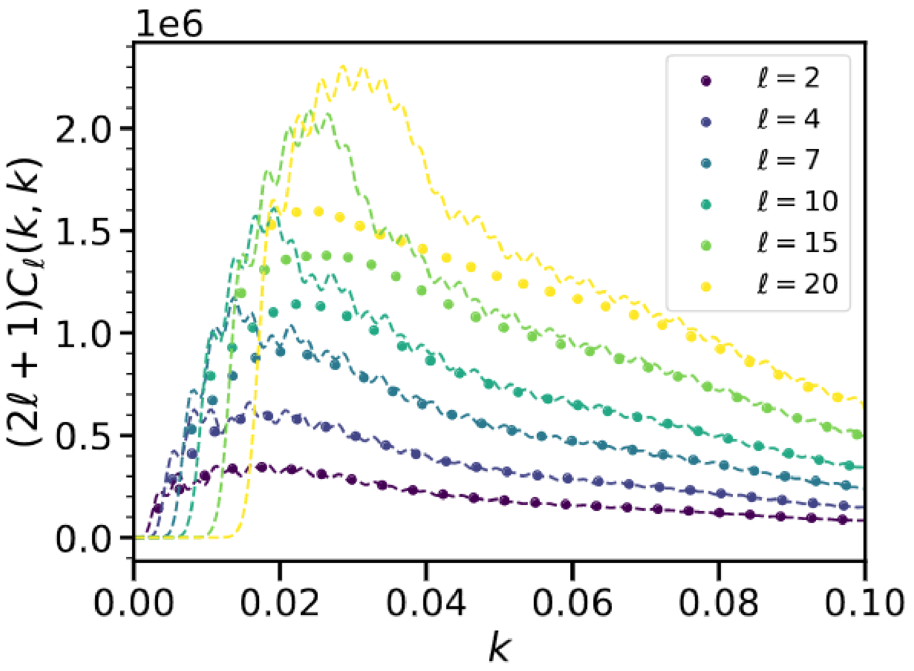
$$\delta_{n\ell m} = \int_{\mathbf{x}} g_{n\ell}(x)\, Y^*_{\ell m}(\hat{\mathbf{n}}) \delta(\mathbf{x}) \qquad \langle \delta_{n_1 \ell_1 m_1} \delta^*_{n_2 \ell_2 m_2} \rangle = C_{\ell_1 n_1 n_2} \delta^K_{\ell_1 \ell_2} \delta^K_{m_1 m_2}$$

$$g_{n\ell}(x) = c_{n\ell}\, j_\ell(k_{n\ell} x) + d_{n\ell}\, y_\ell(k_{n\ell} x)$$

$$\int_{x_{\min}}^{x_{\max}} dx\, x^2\, g_{n\ell}(x)\, g_{n'\ell}(x) = \delta^K_{nn'}$$

Benefit of Discrete SFB

- Numerical Stability
- Complete decomposition of the finite volume
- Efficient for large scale
- Explicit angular-fourier mode dependence
- Matching the estimator



- GR effects only in continuous basis (Yoo & Desjacques 2014, Semenzato et al. 2024)

SPHERE^{X} ADDRESSES 3 CENTRAL QUESTIONS

…as stated in the NASA 2014 Science Plan

How Did the Universe Begin?

"Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity"

How Did Galaxies Begin?

"Explore the origin and evolution of the galaxies, stars and planets that make up our universe"

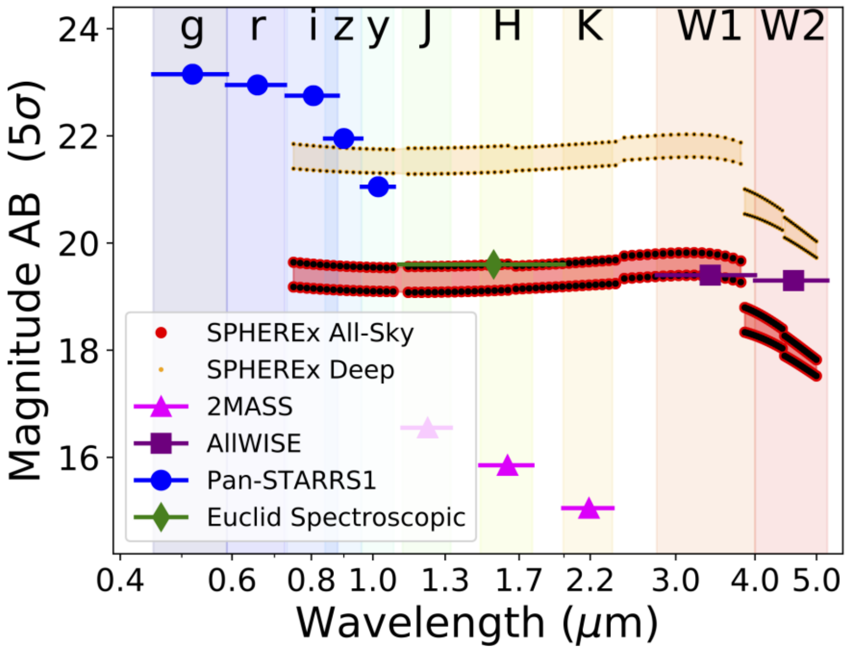
What are the Conditions for Life Outside the Solar System?

"Discover and study planets around other stars, and explore whether they could harbor life"

…While Creating a Unique All-Sky Spectral Survey

What Can YOU Do With the all-sky survey?

SPHEREx Point Source Sensitivity



Data are rapidly released to the public

- Calibrated spectral images within 2 months of observation, updated following 2nd and 4th survey recalibration
- High-reliability catalog after 3rd survey
- Core science products at end of mission

Users have access to data exploration, analysis, and visualization tools

- On-the-Fly Mosaics
- Photometry on Known Position
- Spectral Data Cube Extractor
- Variable Source Extractor
- Source Discovery

REDSHIFTS FROM LOW-RESOLUTION SPECTROSCOPY

We extract the spectra from *known* galaxy positions

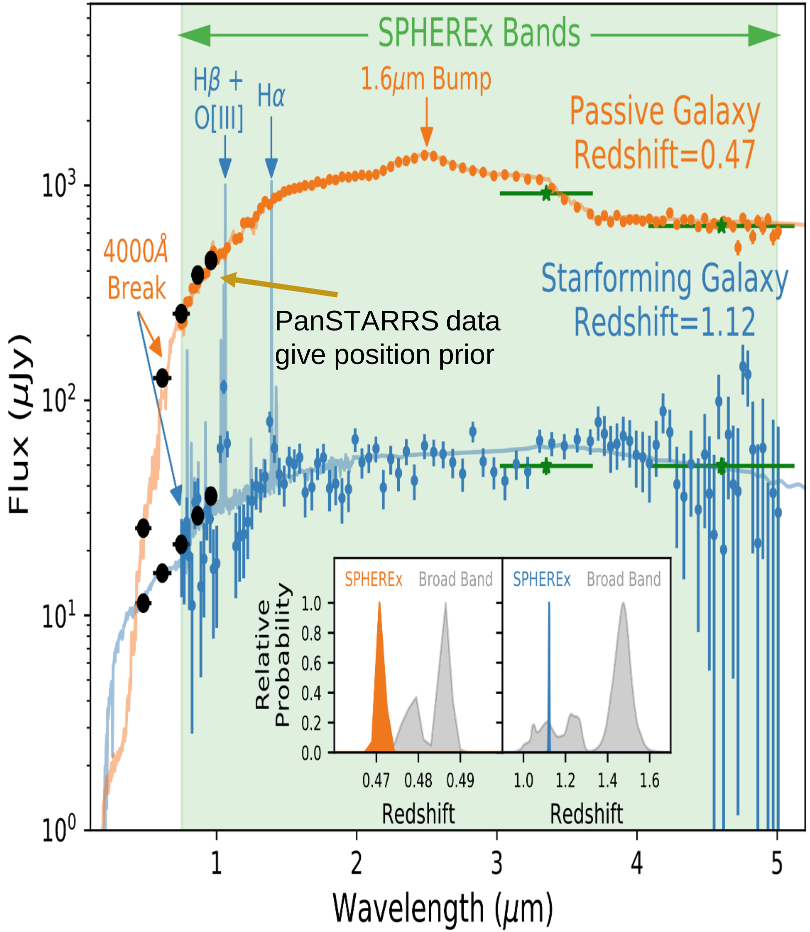
Controls blending and confusion

We compare each spectrum to a template library:

For each galaxy: redshift, type and redshift error

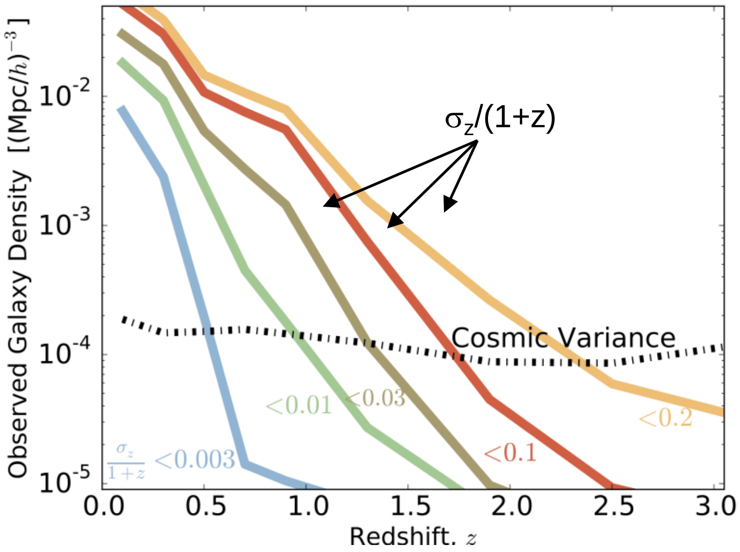
Many self-consistency tests using SPHEREx data, spectral models, and external redshift catalogs

Detected galaxies	**> 1 billion**
Galaxies Δz/1+z < 10 %	**> 450 million**
Galaxies Δz/1+z < 0.3%	**> 10 million**

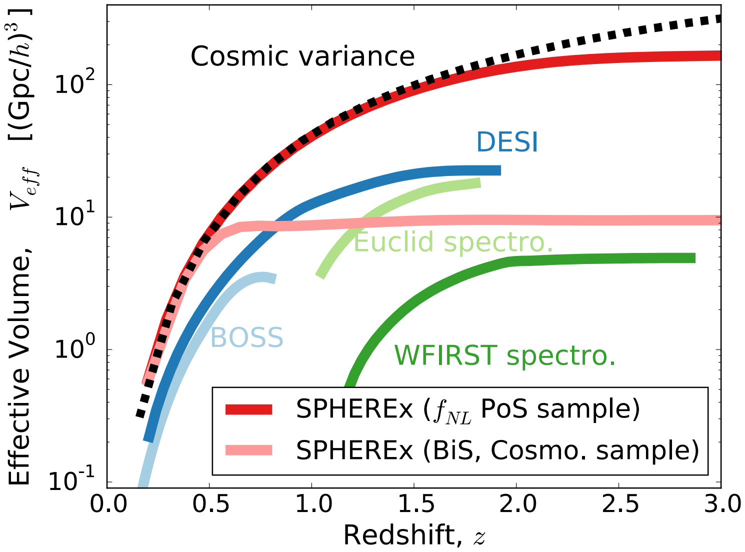


SPHEREx Galaxy Redshift Survey

Catalog Split into Redshift Accuracy Bins



SPHEREx Surveys Maximum Cosmic Volume



Survey Designed for local PNG

- Probe large spatial modes: wide redshift range, full sky, IR wavelengths, stable
- Large scale power from PS: large number of low-accuracy redshifts
- Modulation of fine-scale power from BS: fewer high-accuracy redshifts

Challenges

- Systematics
  - SPHEREx is designed to minimize systematics (in space, stable gain)
  - However, galactic foregrounds (dust, star,…)
  - Crowding
  - Systematics in reference catalogues
  - Unknown systematics