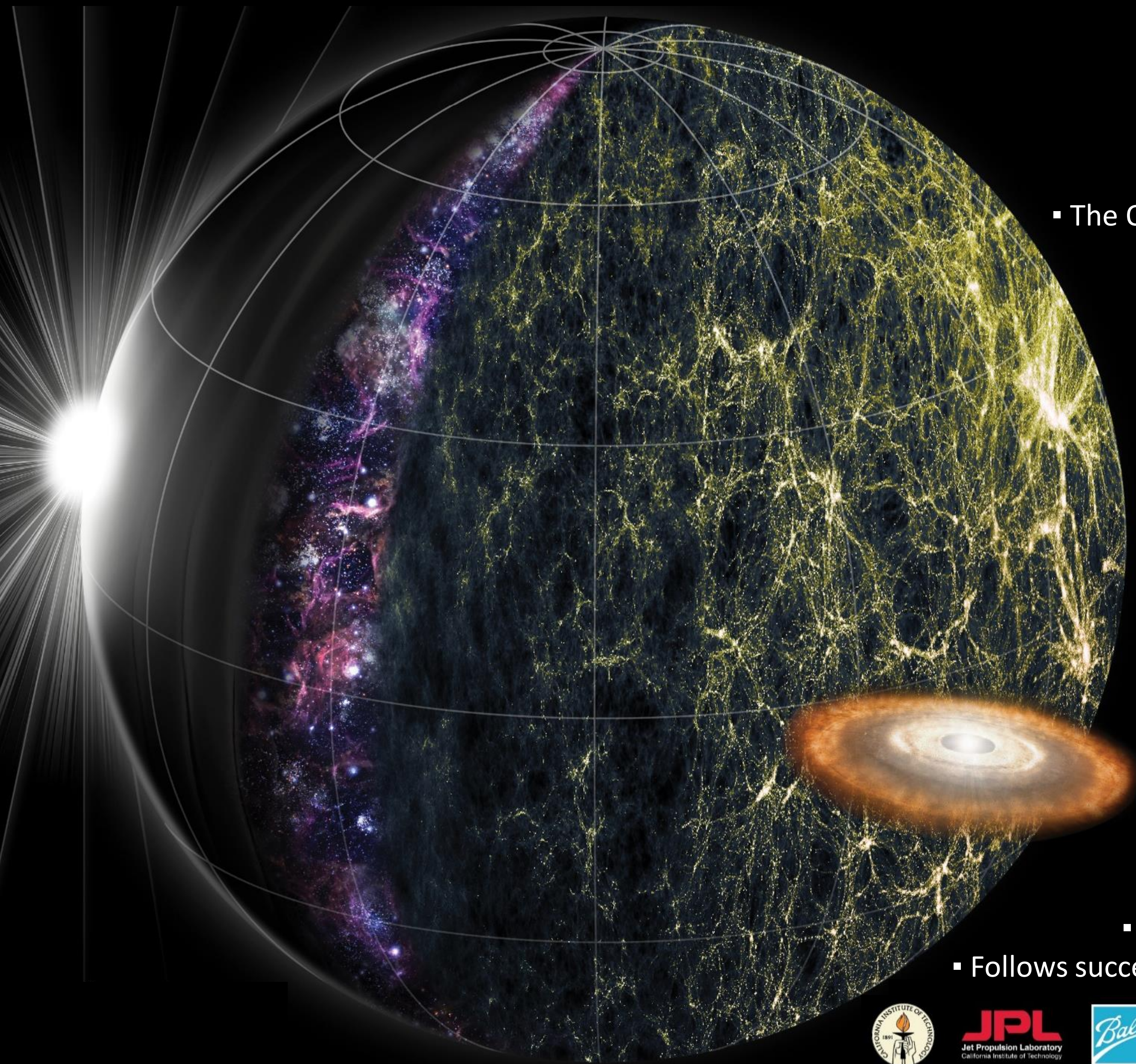
SPHEREx: An All-Sky Spectral Survey



Designed to Explore

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

The First All-Sky Near-IR Spectral Survey

A Rich Legacy Archive for the Astronomy Community with 100s of Millions of Stars and Galaxies

Low-Risk Implementation

- No Moving Parts
- Single Observing Mode
- Large Technical & Scientific Margins
- Follows successful CIT/JPL mgt. model of NuSTAR

What are the Most Important Questions in Astrophysics?

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"

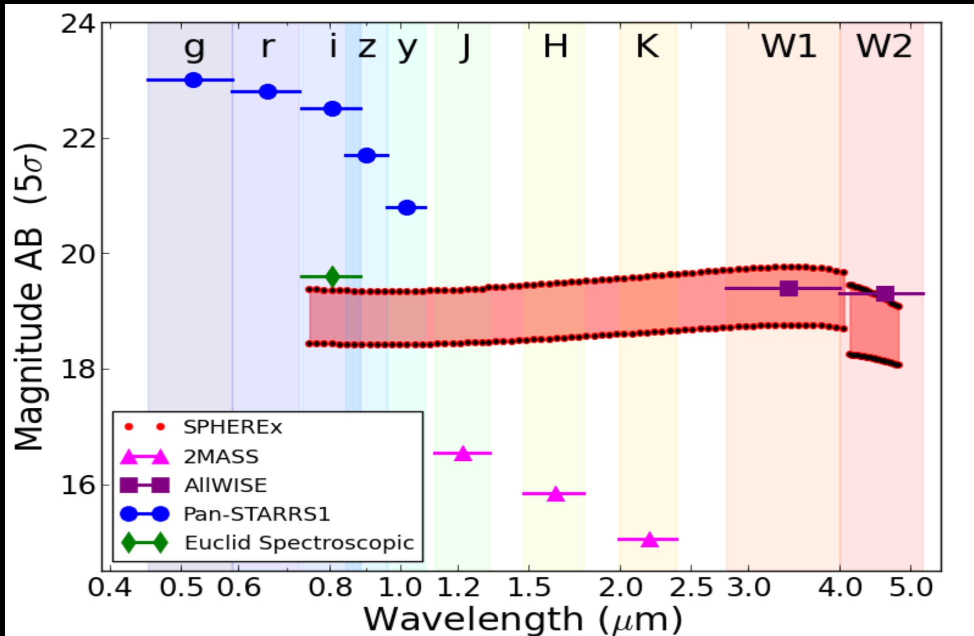
How Did Galaxies Begin?

"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"

SPHEREx Creates an All-Sky Legacy Archive



Legacy Science Opportunities: A Few Examples

Object	# Sources	Legacy Science	Reference
Detected galaxies	1.4 billion	Properties of distant and heavily obscured galaxies	Simulation based on COSMOS and Pan-STARRS
Galaxies σ(z)/(1+z) < 0.03	120 million	Study (H, CO, O, S, H_2O) line and PAH emission by galaxy type. Explore galaxy and AGN life cycle	
Galaxies σ(z)/(1+z) < 0.003	9.8 million	Cross check of Euclid photo-z. Measure dynamics of groups and map filaments.	
QSOs	> 1.5 million	Understand QSO lifecycle, environment, and taxonomy	Ross et al. (2013) plus simulations
QSOs at z > 7	0-300	Determine if early QSOs exist. Follow-up spectro-scopy probes EOR through Lyα forest	
Clusters with ≥ 5 members	25,000	Redshifts for all X-ray clusters. Viral masses and merger dynamics	Geach et al., 2011, SDSS counts
Main sequence stars	>100 million	Test uniformity of stellar mass function within our Galaxy as input to extragalactic studies	2MASS catalogs
Mass-losing, dust forming stars	Over 10,000 of all types	Spectra of M supergiants, OH/IR stars, Carbon stars. Stellar atmospheres, dust return rates, and composition of dust	Astro-physical Quantities, 4th edition [ed. A.Cox] p. 527
Brown dwarfs	>400, incl. >40 of types T and Y	Atmospheric structure and composition; search for hazes. Informs studies of giant exoplanets	dwarfarchives.org and J.D. Kirkpatrick, priv. comm.
Stars with hot dust	>1000	Discover rare dust clouds produced by cataclysmic events like the collision which produced the Earth's moon	Kennedy & Wyatt (2013)
Diffuse ISM	Map of the Galaxy	Study diffuse emission from interstellar clouds and nebulae; (H, CO, S, H_2O and PAH emission)	GLIMPSE survey (Churchwell et al. 2009)

Notable Features of the SPHEREx All-Sky Survey

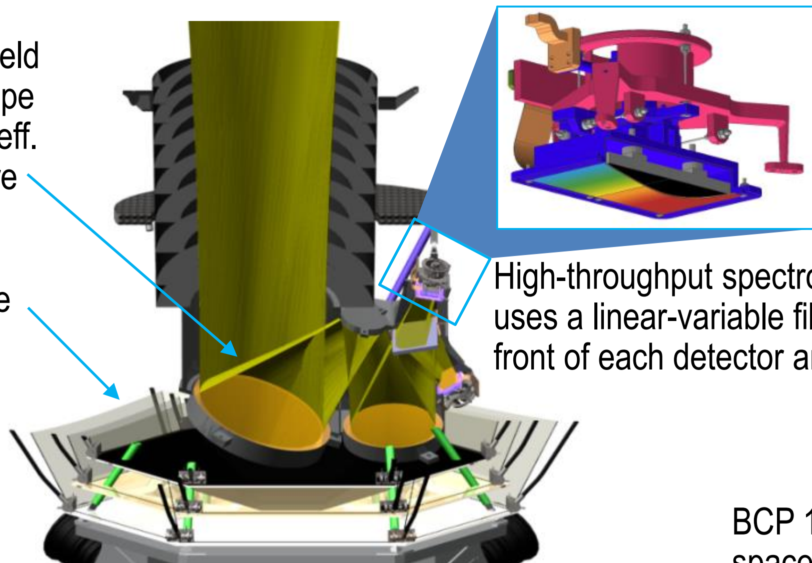
- High S/N spectrum for every 2MASS source
- Solid detection of faintest WISE sources
- Catalogs ideal for JWST observations

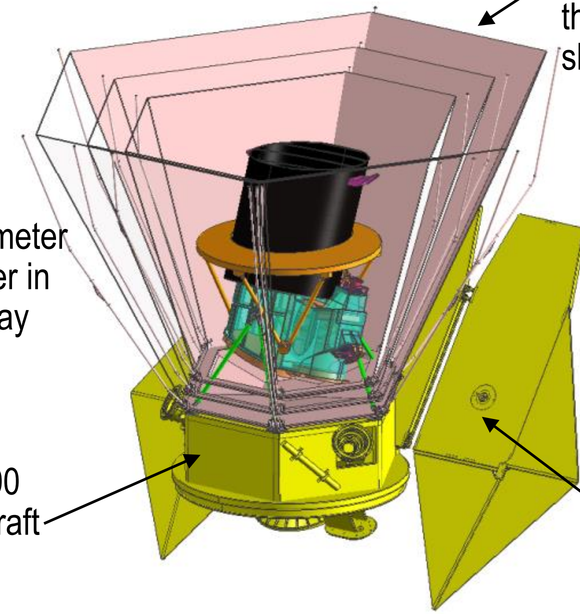
New ideas recently brought to our attention

- Redshifts for the all-sky eRosita X-Ray survey
- Photo baselines for wide-field transient survey
- Mapping 3D distribution of Galactic ices

And there's more!

SPHEREx: Simple Instrument, Large Margins





Instrument Specifications

Parameter	Value
Telescope Effective Aperture	20 cm
Pixel Size	6.2" x 6.2"
Field of View	2 x (3.5° x 7.0°); dichroic
Spectrometer	Linear-Variable Filters
Resolving Power and Wavelength Coverage	R=41.5 λ=0.75 - 4.1 μm R=150 λ=4.1 - 4.8 μm
Arrays	2 x Hawaii-2RG 2.5 μm 2 x Hawaii-2RG 5.3 μm
Point Source Sensitivity (MEV Performance)	18.5 AB mag (5σ) with 300% margin to req't
Cooling	All-Passive

Large Resource Margins

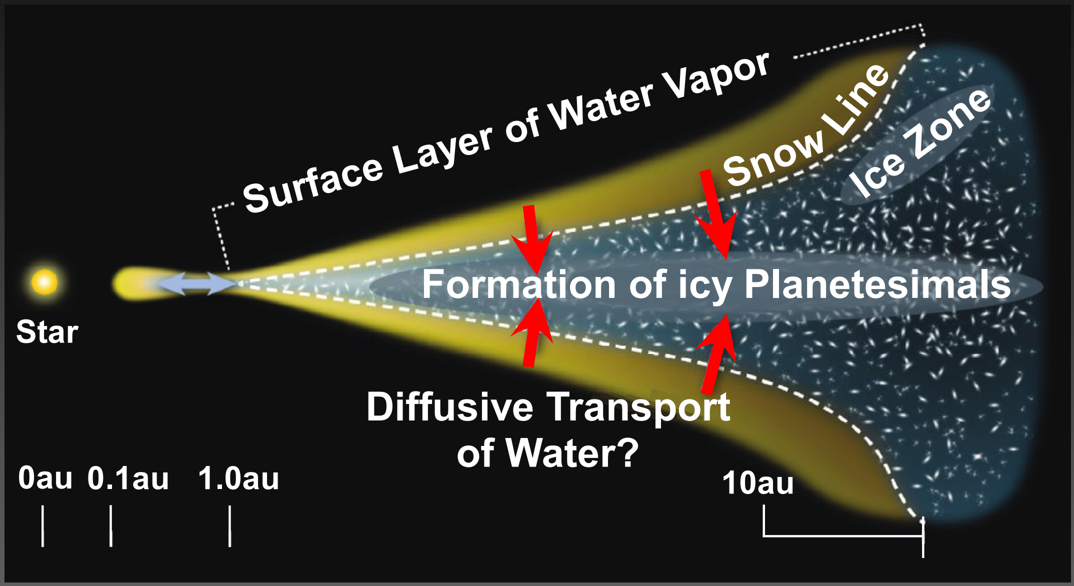
Observatory Mass	53 %
Observatory Power	36 %
Pointing stability	43 %
Cooling power	450 %
Science overall	300 %

Replicates successful Caltech-JPL management structure of NuSTAR

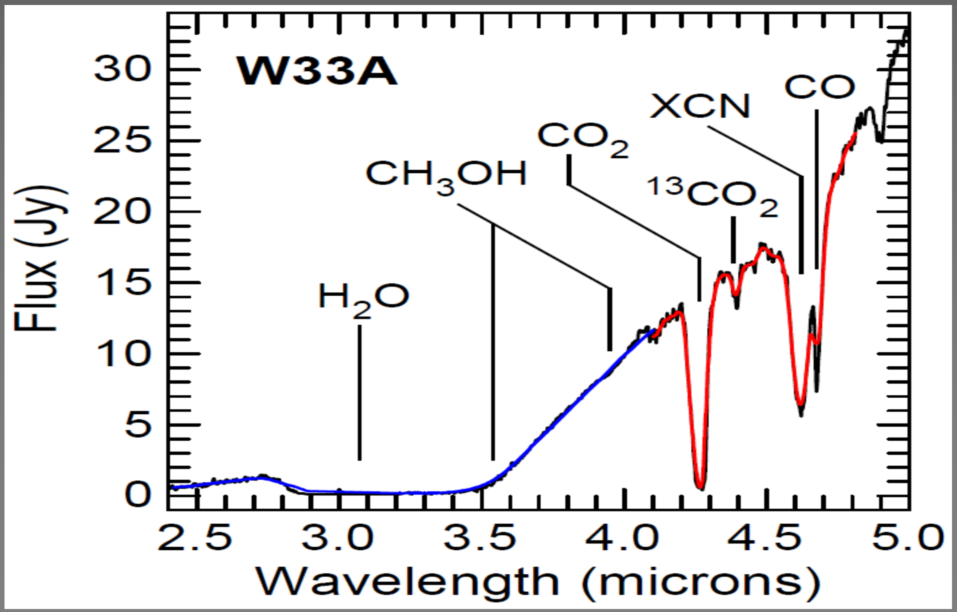
Why Study Ices?

- **Gas and dust in molecular clouds are the reservoirs for new stars and planets**
  - In molecular clouds, water is 100-1000x more abundant in ice than in gas
  - Herschel observations of the TW Hydrae disk imply the presence of 1000s of Earth oceans in ice (Hogerheijde *et al*. 2011)
  - Models suggest water and biogenic molecules reside in ice in the disk mid-plane and beyond the snow line
- **Ideal λs to study ices: 2.5 - 5 μm**
  - Includes spectral features from H_2O, CO and CO_2
  - Plus chemically important minor constituents NH_3, CH_3OH, X-CN, and $^{13}CO_2$

Schematic of a protoplanetary disk



ISO absorption spectrum



SPHEREx Galactic Ice Survey

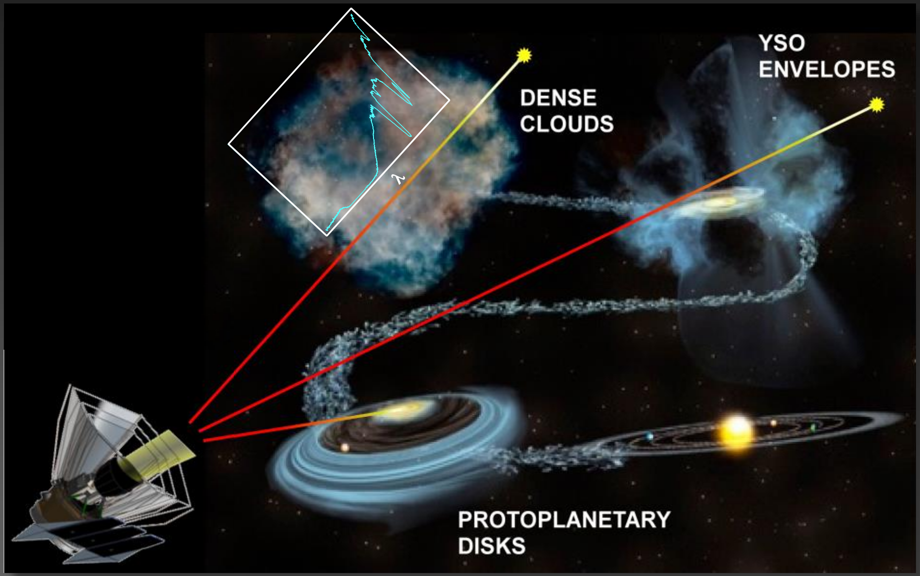
SPHEREx will be a game changer to resolve long-standing questions about the amount and evolution of key biogenic molecules through all phases of star and planet formation

- SPHEREx increases the number of ice spectra from ~200 to >> 20,000
- Band 4 spectral resolving power $\lambda/\Delta\lambda$ = 150 chosen to isolate the absorption from each ice species

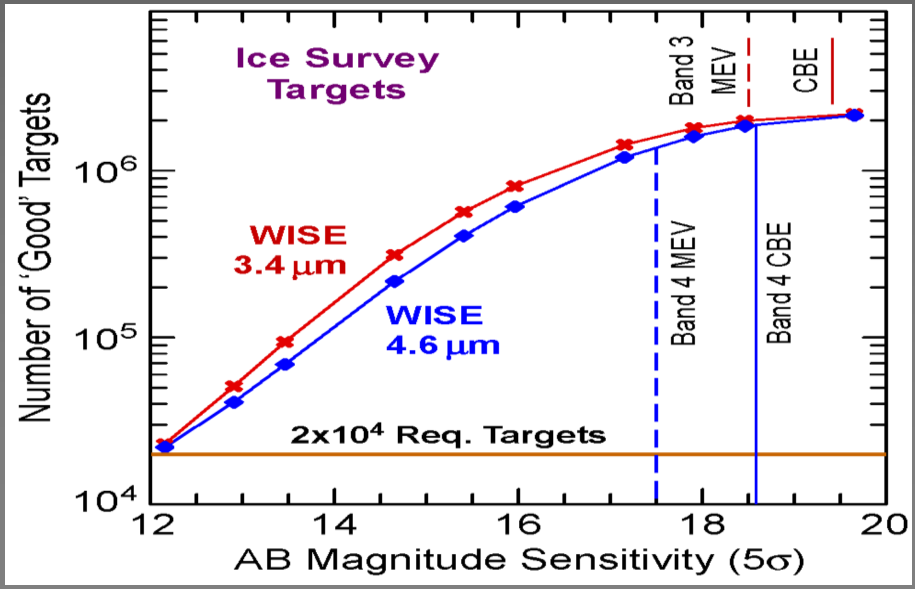
The SPHEREx ice catalog will:

- Contain molecular clouds, YSOs, and 1000s of protoplanetary disks
- Determine the role of environment (T, n, radiation field, cosmic rays) in forming ices
- Determine if ices in disks come from the parent cloud or are reformed
- Measure the abundance of water and biogenic ices in disks that is available to new planets

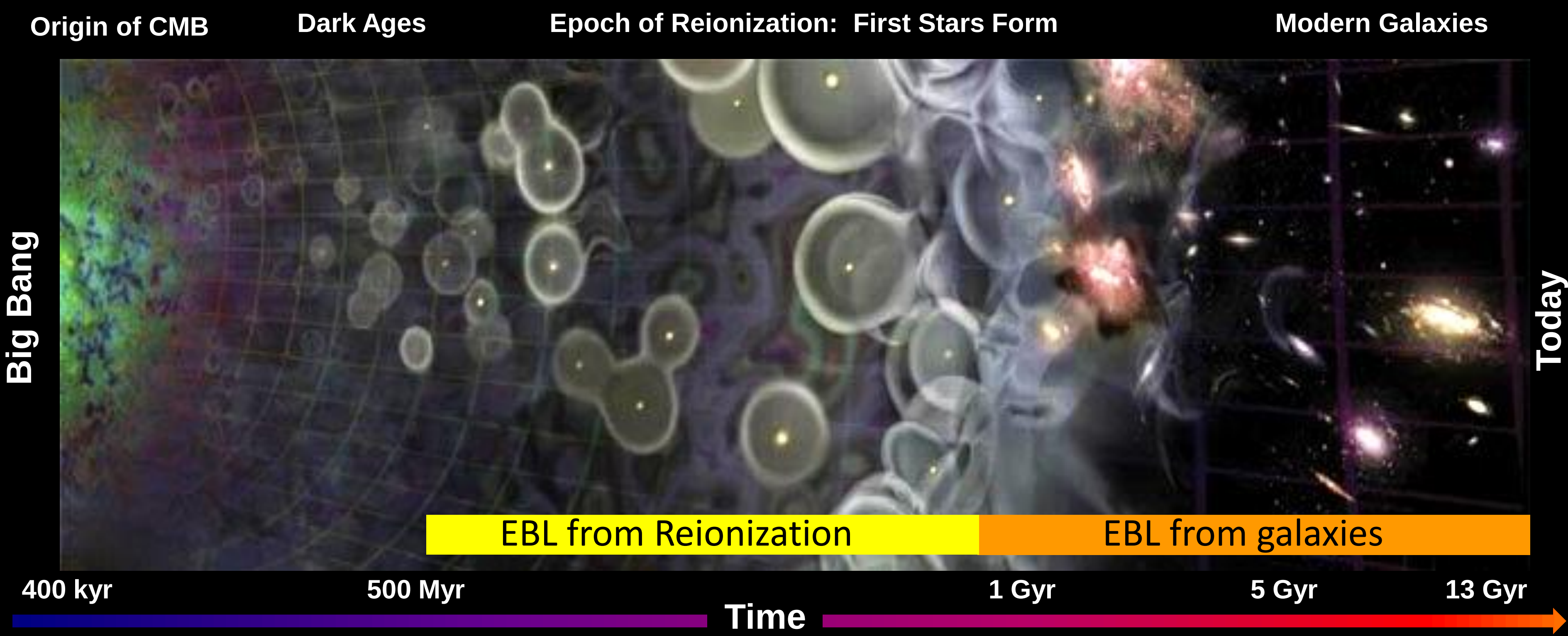
Ices in each Phase of Star Formation



One Million Targets with |b| < 1°



Why Study the Extragalactic Background Light?



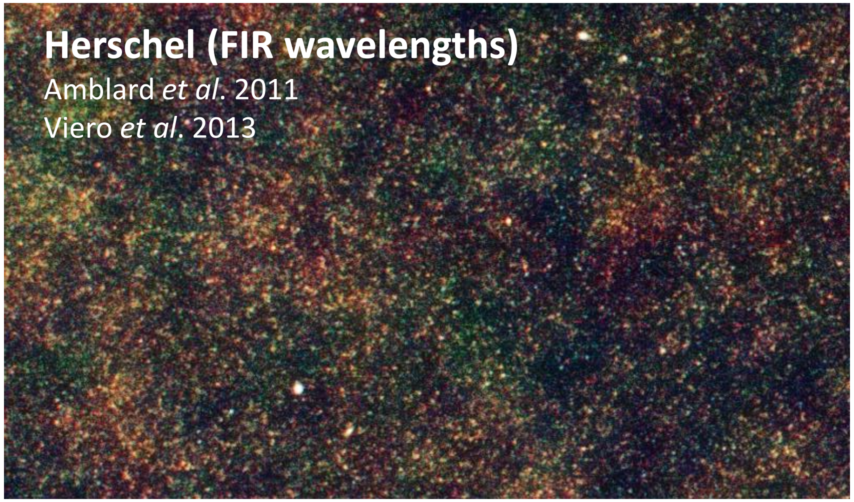
Epoch of Reionization

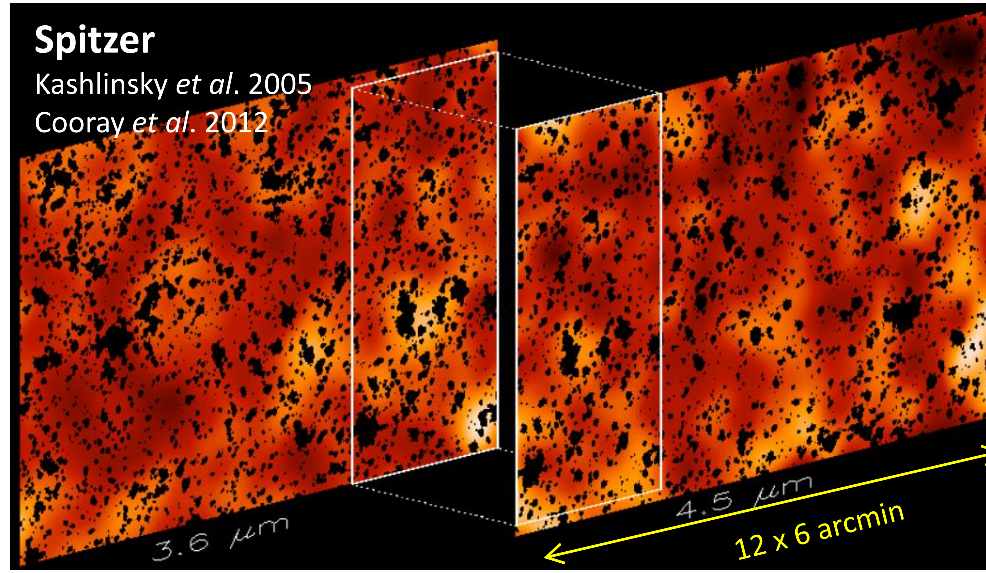
When did it begin?
When did it end?
What were the first sources like?

Observables

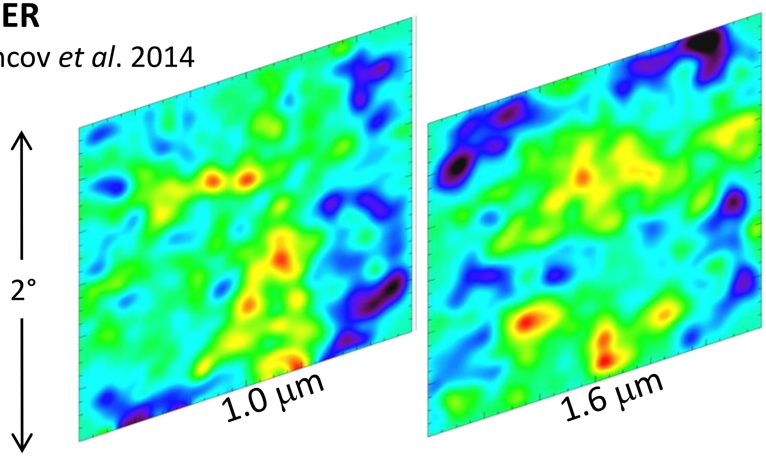
Free Electrons: Scatter CMB photons
Neutral Gas: HI 21 cm, Ly absorption
Galaxies: Stellar light, line emission

Measure Extragalactic Background Via *Spatial Variations*

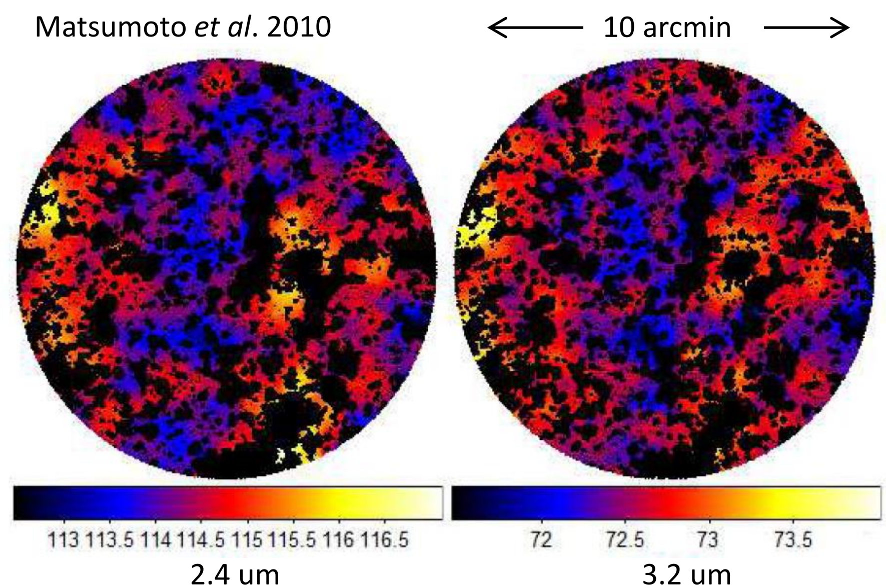




CIBER
Zemcov *et al*. 2014



Akari
Matsumoto *et al*. 2010

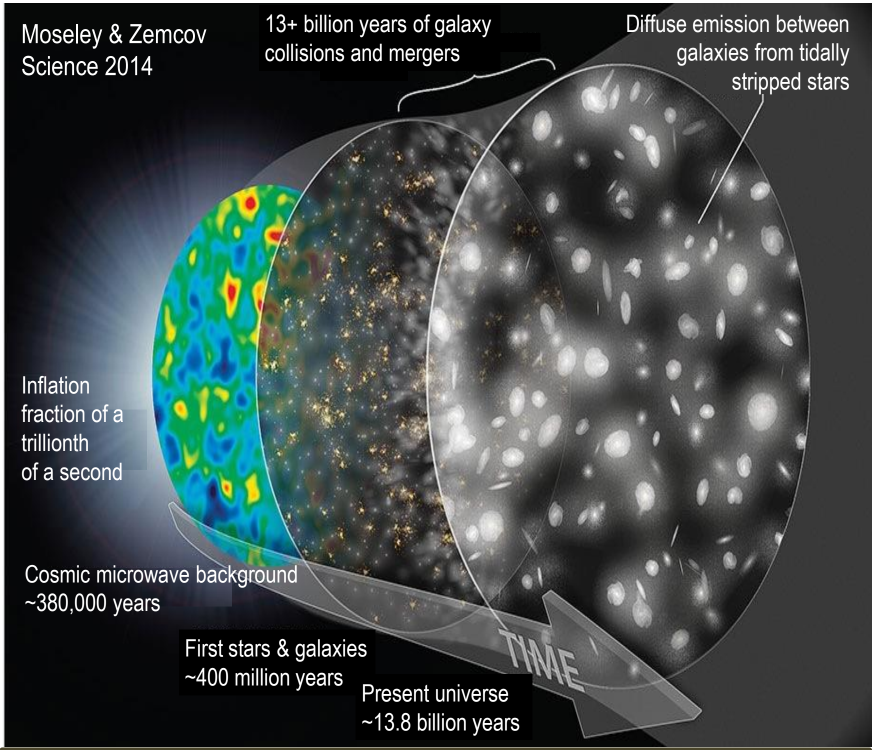


Successful Applications at Longer Wavelengths

Herschel EBL: Viero *et al*. 2013
Planck EBL: Planck C. *et al*. 2013
Planck EBL x CMB Lensing: Planck C. *et al*. 2014
Herschel EBL x CMB Lensing: Many

Measuring Cosmic Light Production

What Constitutes Cosmic Light Production?



1) Photon Production in Galaxies

Nucleosynthesis & black holes, peaks at z ~ 2

2) First Stars and Galaxies

Epoch of Reionization z > 6

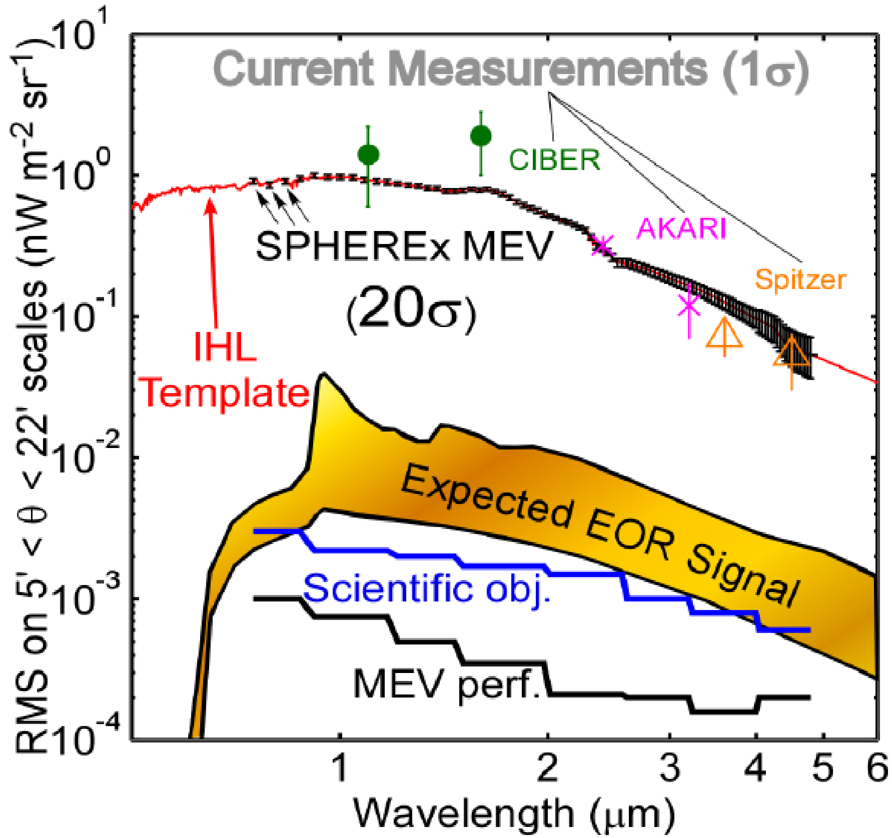
3) Inter Halo Light

Tidally stripped stars at z = 0 - 2

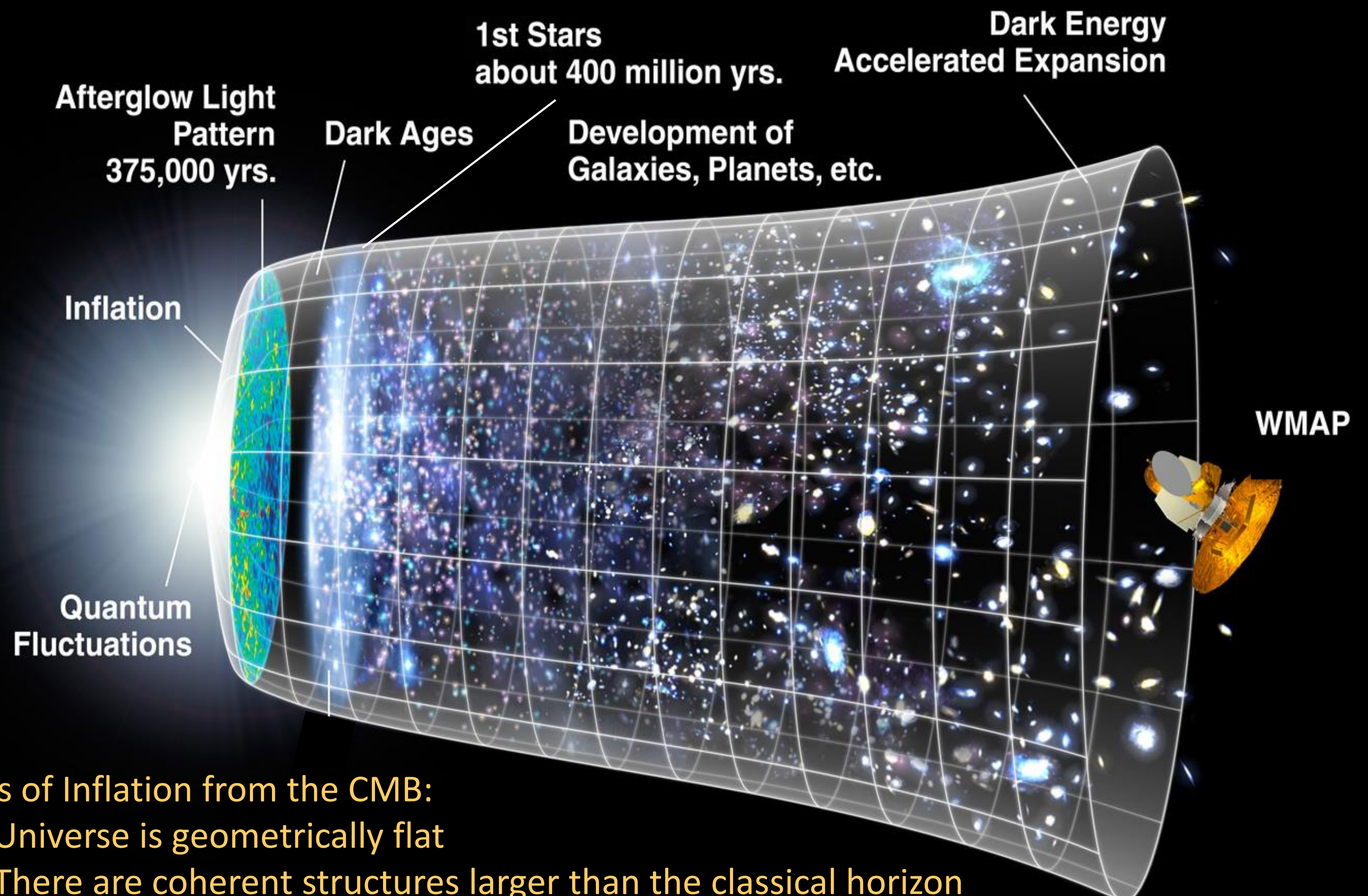
4) Surprises?

E.g. Light from particle decay

Fluctuations in Continuum Bands



- SPHEREx has ideal wavelength coverage and high sensitivity
- Multiple bands enable correlation tests sensitive to redshift history
- Method demonstrated on CIBER, Spitzer, AKARI, Herschel, Planck



Tests of Inflation from the CMB:

- Universe is geometrically flat
- There are coherent structures larger than the classical horizon
- Fluctuations have a nearly “scale invariant” spectrum

  but with a slight departure *as predicted*
- Density and velocity fluctuations are in phase
- Fluctuations have Gaussian statistics

NASA/WMAP Science Team

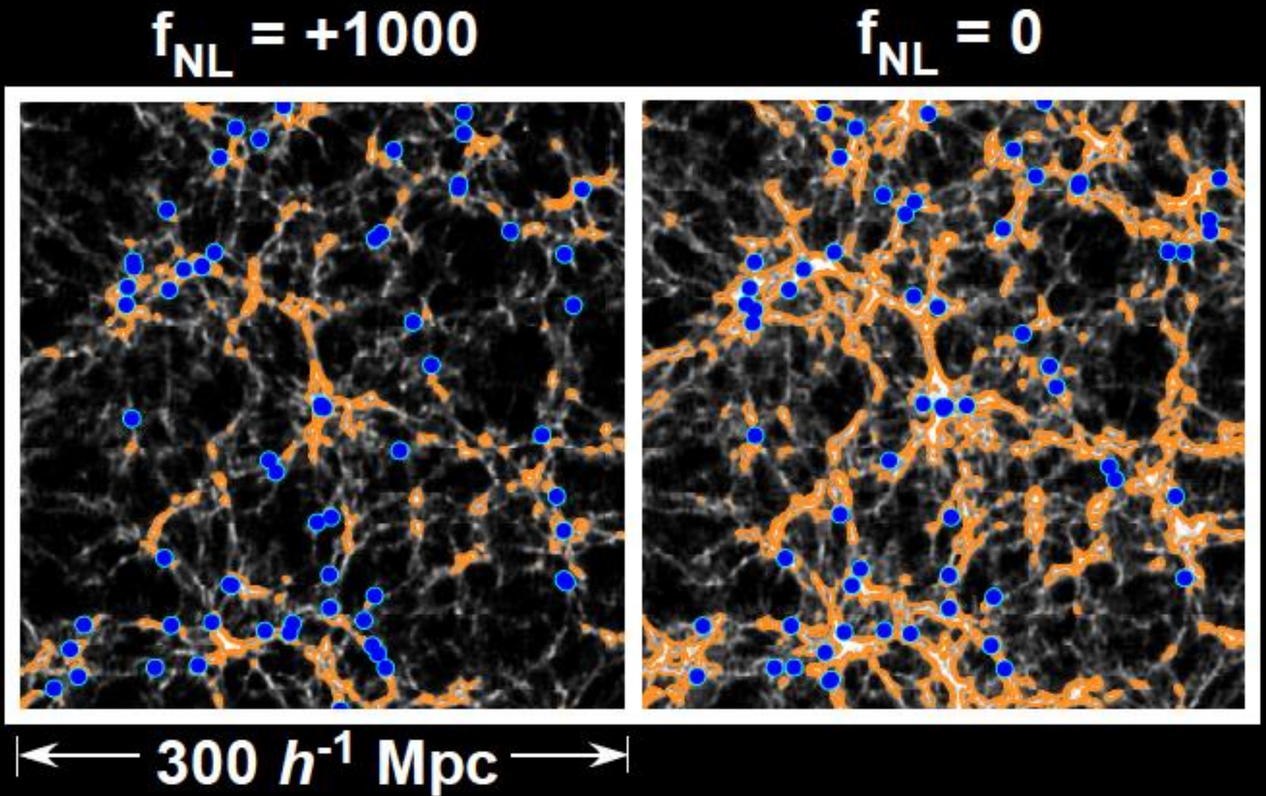
How to Probe the Physics that Caused Inflation?

Observables:

Inflationary gravitational waves – CMB “B-mode” polarization

Spectral index of fluctuations – CMB and large-scale structure

Non-Gaussianity – Sensitive to **Inflaton field** (single-field vs. multi-field)



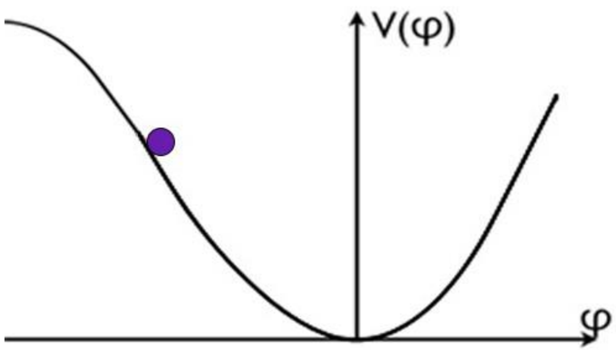
Large-scale structure will give the tightest constraints on non-Gaussianity

Effect is on largest scales: Need large volume survey

Measuring Primordial Non-Gaussianity to $\sigma(f_{NL}) < 1$

A test to distinguish between single- and multi-field Inflation

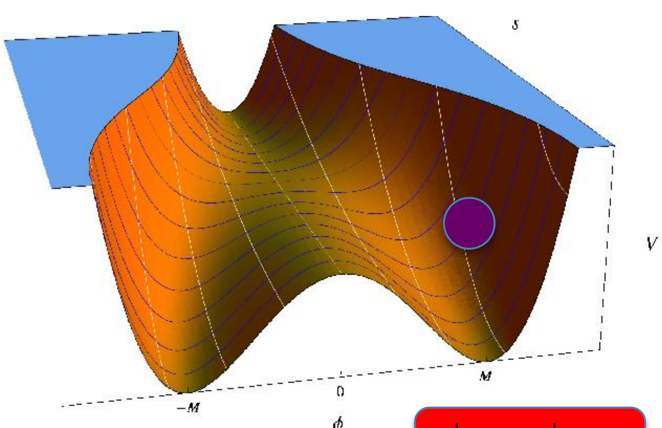
Single-Field Inflation:



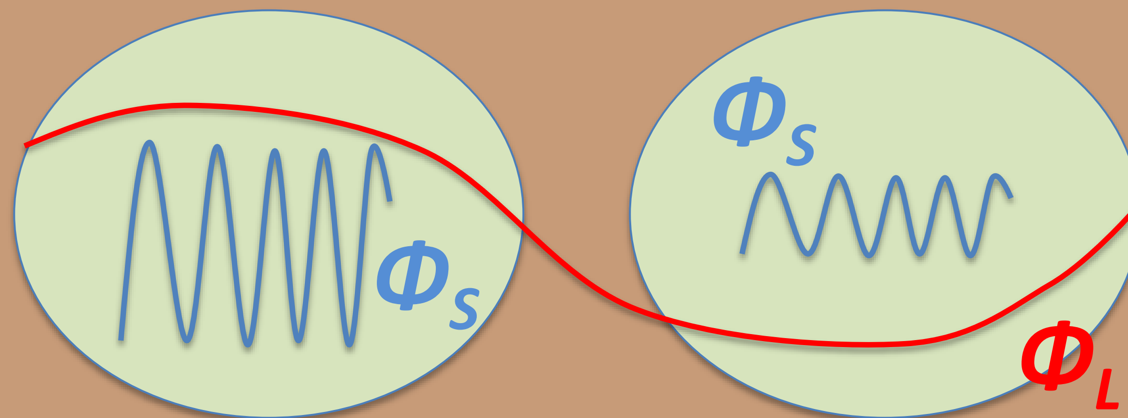
Squeezed limit consistency condition by Maldacena (2003):

$$f_{NL}^{(\mathrm{infl})} \sim (n_s - 1) << 1$$

Multi-Field Inflation:



$$\left| f_{NL}^{(\mathrm{infl})} \right| \geq 1$$



Non-Gaussianity Produces Two Signatures

Modulated small-scale power Φ_S on large scales Φ_L due to non-linear mode coupling

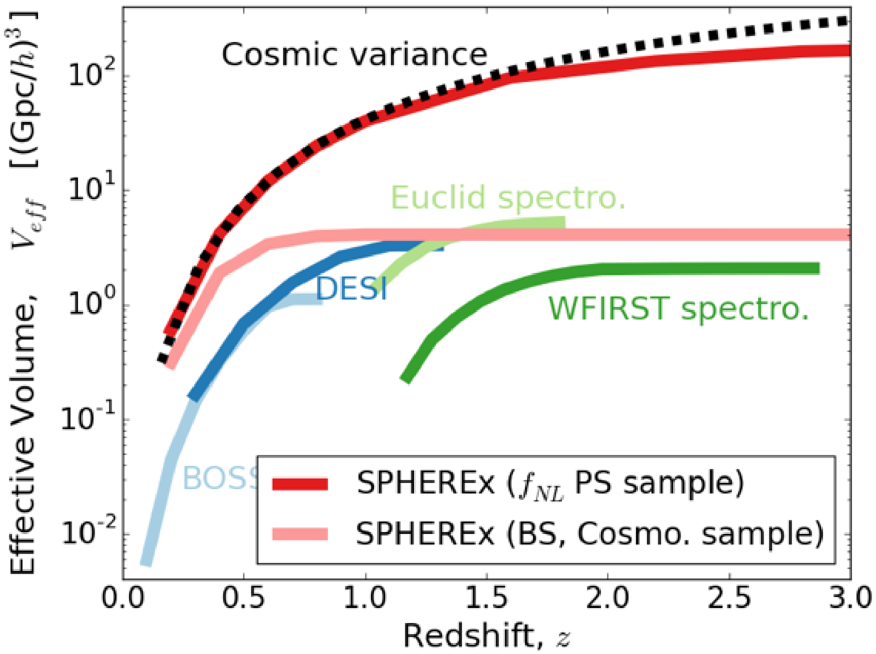
- measured with galaxy bispectrum

Enhanced galaxy clustering on large spatial scales

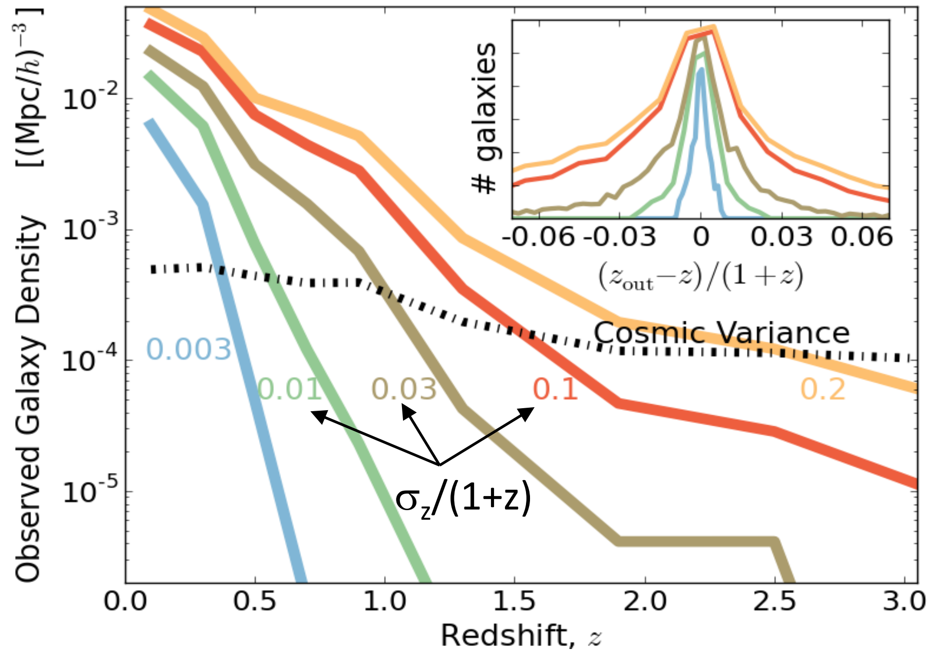
- measured with galaxy power spectrum and bispecttrum

SPHEREx Large Volume Galaxy Survey

SPHEREx Surveys Maximum Cosmic Volume



Catalog Split into Redshift Accuracy Bins



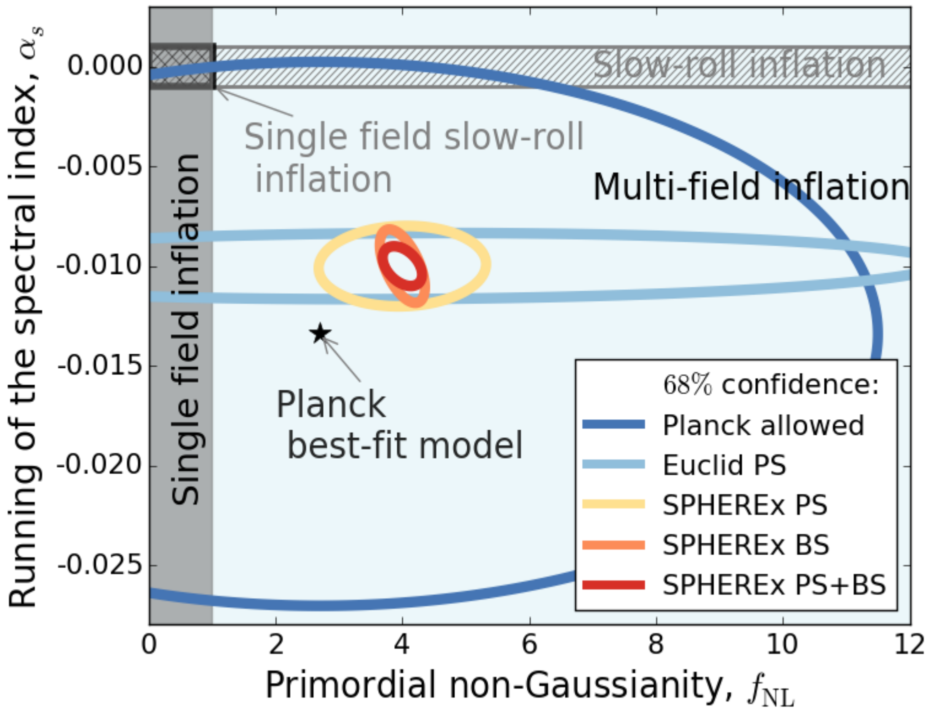
SPHEREx Large-Volume Redshift Catalog

- Largest effective volume of any survey, near cosmic limit
- Excels at z < 1, complements dark energy missions (Euclid, WFIRST) targeting z ~ 2
- SPHEREx + Euclid measures gravitational lensing and helps calibrate Euclid photo-zs

Survey Designed for Two Tests of Non-Gaussianity

- Large scale power from **power spectrum**: large # of low-accuracy redshifts
- Modulation of fine-scale power from **bispectrum**: fewer high-accuracy redshifts

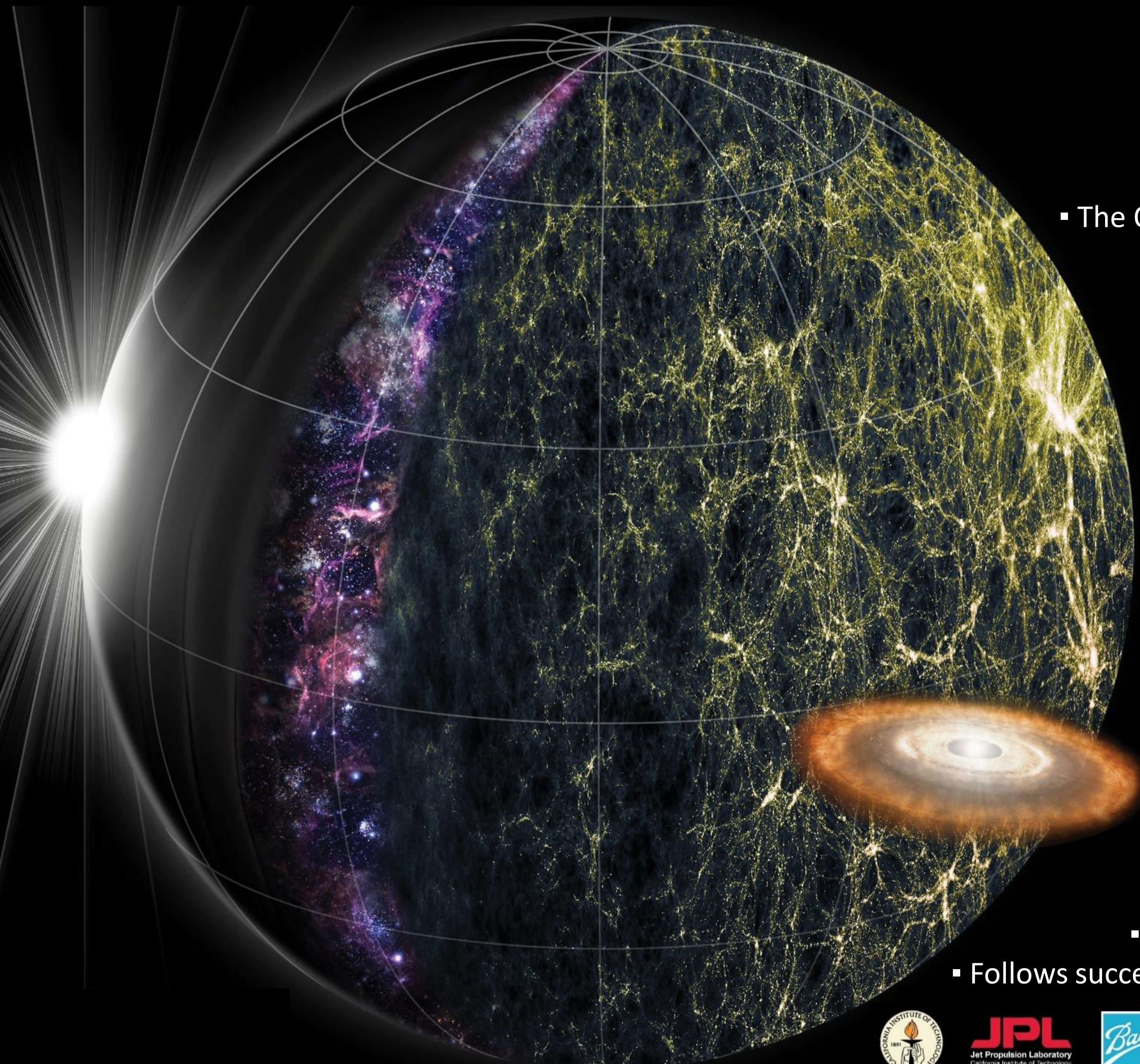
SPHEREx Tests Inflationary Non-Gaussianity



1σ errors	SPHEREx (MEV)			Euclid	Current
	PS	BS	PS+BS		
f_{NL} Req't	1.0	0.5	0.5	N/A	N/A
f_{NL}	0.87	0.23	0.20	5.59	5.8
Spectral Index n_s (x 10^{-3})	2.7	2.3	2.2	2.6	5.4
Running α_s (x10^{-3})	1.3	1.2	0.65	1.1	17
Curvature Ω_k (x10^{-4})	9.8	9.5	6.6	7.0	66
Dark Energy figure of merit	202	NC	NC	309	14

- Non-Gaussianity distinguishes between multi- and single-field models
- Projected SPHEREx sensitivity is $\delta f_{NL} < 1$ (2σ)
  - Two *independent tests* via power spectrum and bispectrum
- Competitively tests running of the spectral index
- SPHEREx low-redshift catalog is complementary for dark energy

Thanks for Listening!



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