Near-Infrared Imaging Spectroscopic Survey in Space

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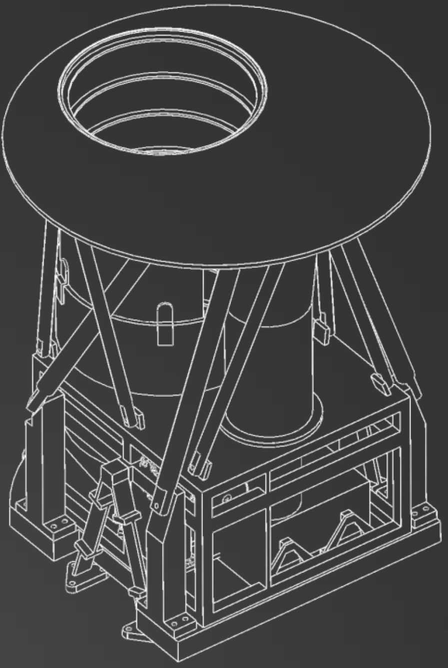
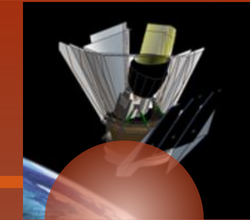
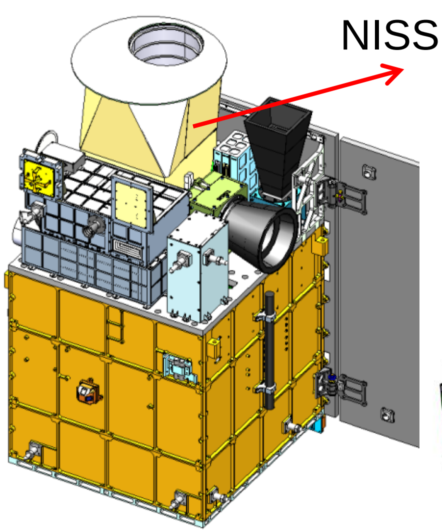


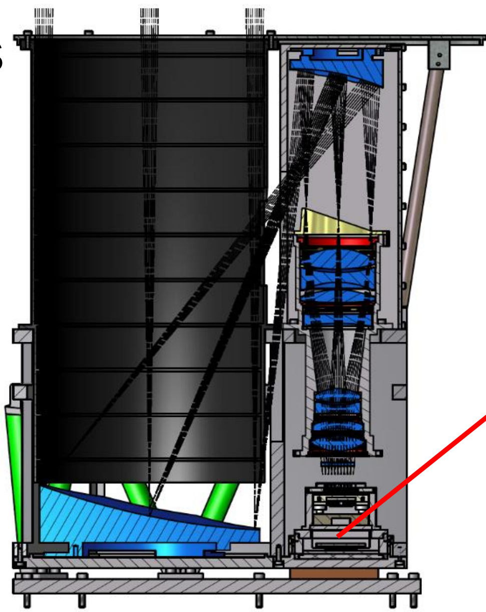
Survey Science Group Workshop, High1 Resort, 25~27 Jan.

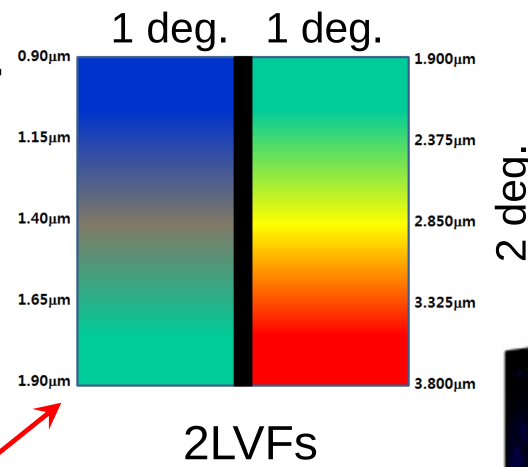
NISS: Near-IR Imaging Spectrometer

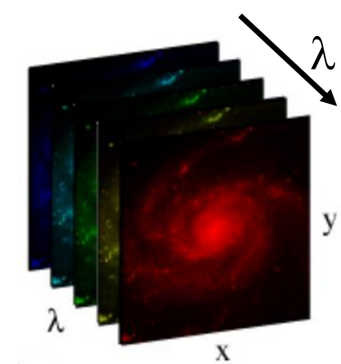


- Technical heritage from MIRIS
- Wavelength range: 0.9 ~ 3.8μm (continuous)
- Array format: 1024 x 1024, FoV: ~2 deg. X 2 deg. (15″ resol.)
- 15cm aperture, Imaging & Low-Resolution Spectroscopy (R~20), Sensitivity ~17 AB mag.

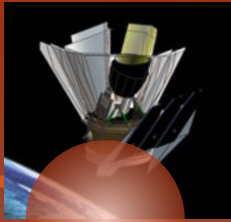




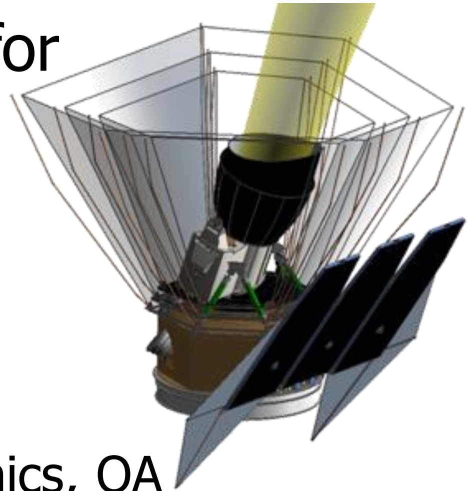




Collaboration in SPHEREx



- **S**pectro-**PH**otometer for the **E**xtragalactic structure, **R**eionization and ices **Ex**plorer
- Science Objectives: All-Sky Spectral Survey for
  - Inflationary Cosmology
  - History of Galaxy Formation
  - Galactic Ices



- Participating Institutes (PI: Jamie Bock)
  - JPL: management, thermal system, readout electronics, QA
  - Caltech: Instrument Development, I&T, Data Pipeline
  - Ball Aerospace & Technologies Corporation: spacecraft
  - ASU, Caltech, Harvard, IfA, JPL, OSU, UC Irvine: Science
  - **KASI: H/W, data pipeline, science**
- SPHEREx is the extended mission of the NISS.

SPHEREx Baseline Mission Parameters

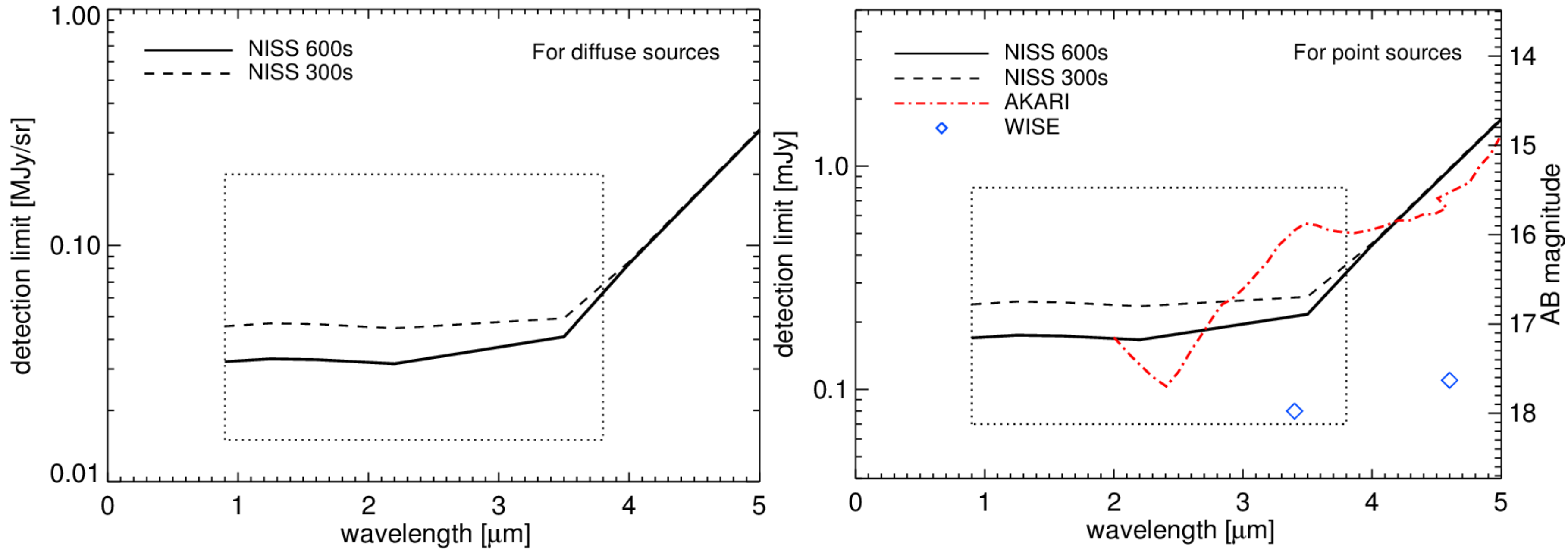
cf. **NISS: 2 bands**
Band1: 0.95 ~ 1.9um
Band2: 1.90 ~ 3.8um

Parameter	Required Value	Capability Value
Telescope aperture	20 cm	
Focal ratio	3	
Band 1	0.75 – 1.25 um; $\lambda/\Delta\lambda$ = 40; H2RG-2.5 um	
Band 2	1.25 – 2.10 um; $\lambda/\Delta\lambda$ = 40; H2RG-2.5 um	
Band 3	2.10 – 3.50 um; $\lambda/\Delta\lambda$ = 40; H2RG-5 um	
Band 4	2.60 – 5.00 um; $\lambda/\Delta\lambda$ = 150; H2RG-5 um	
Total FOV	3.5 deg x 7 deg	
Pixel size	6” x 6”	
Optics temperature	80 K	
5um array temperature	50 K	
Total efficiency	30 %	50 %
Pointing jitter (1σ, 200 s)	3”	1.5”
Large (70°) slew time	150 s	90 s
Small (10′) slew time	20 s	10 s
Read noise CDS	18/15 e^-	10.5 e^-

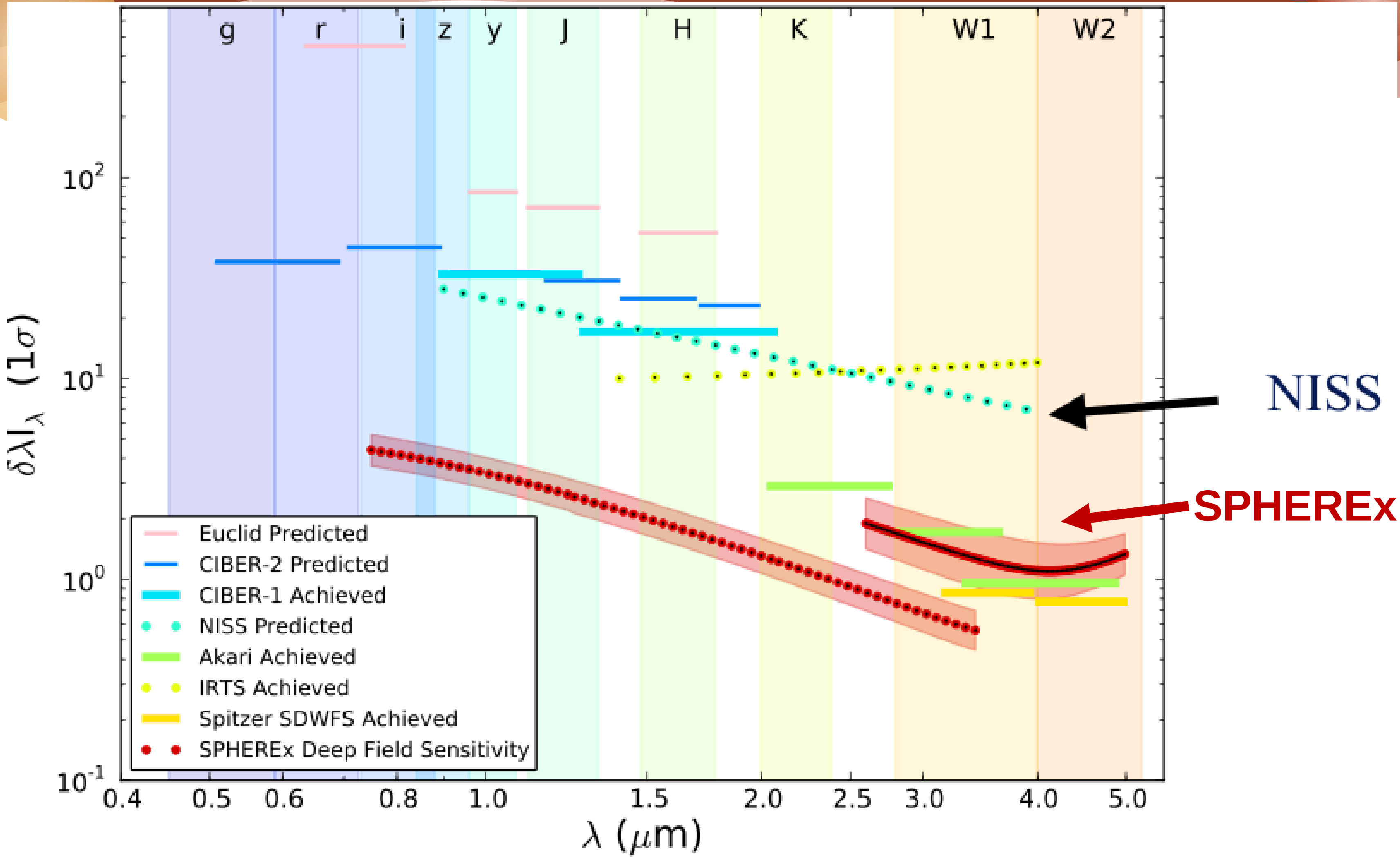
Required assumes not-to-exceed value for all components
Capability assumes estimated performance for all components
Nominal performance is intermediate

NISS Expected Sensitivity

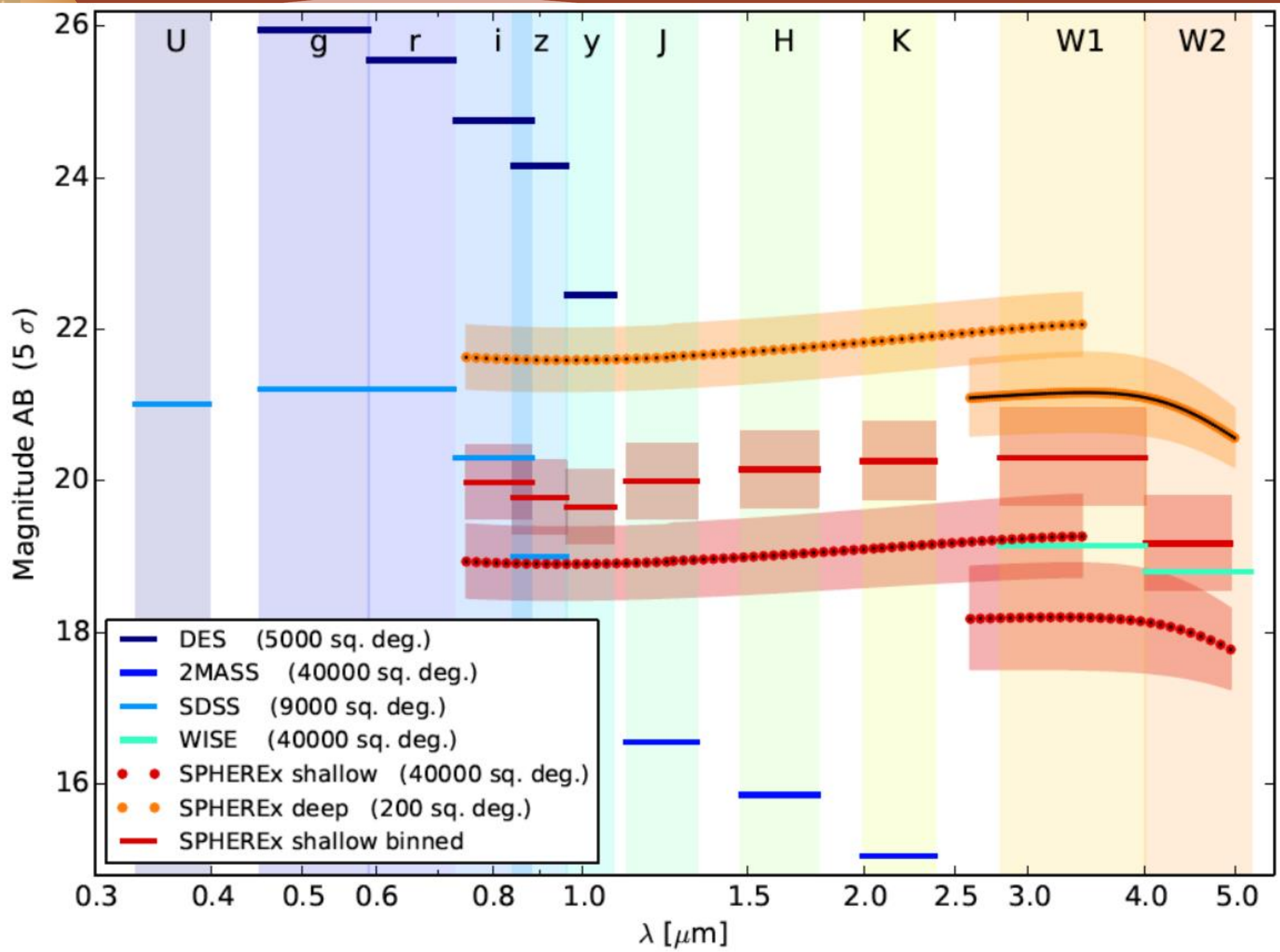
- 10-second interval readout : 600-second integration
- Degradation of sensitivity for point sources
- Sensitivity (15-arcsec resolution)
  - diffuse source (5σ) : 0.03~0.06 MJy/sr
  - Point source (5σ) : 16.9 ~ 17.2 AB mag.



SPHEREx Sensitivity (1/2)



SPHREx Sensitivity (2/2)



NISS Science Mission

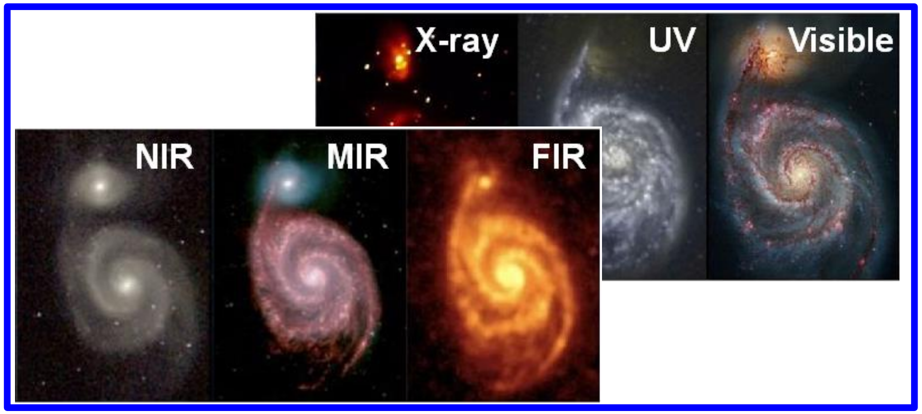
Near-IR Imaging Spectroscopy

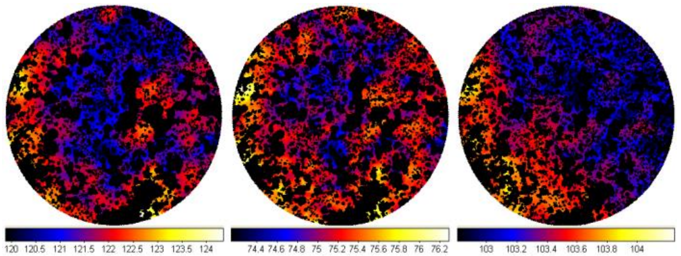
- Large Nearby galaxies / Clusters of galaxies
- Star-forming regions
- Cosmic Near-Infrared Background

λ (μm)	line	Type
1.26, 1.64	[Fe II]	Emission
1.875	**Paα**	**Emission**
1.96	[Si IV]	Emission
2.212	H_2 1-0 S(1)	Emission
3.05	**H_2O Ice**	**Absorption**
3.3	**PAH**	**Emission**

Near-Infrared Emission Lines

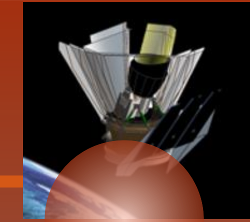
Multiwavelength observation for M55





Detection of Cosmic Near-Infrared Background (2~4μm)

Science Objective I



Star Formation in Local Universe

- Nearby Galaxies
- Star forming regions
- Clusters of galaxies
- Supernova Remnants
- …

Tracer of SFR

- UV continuum: longward of Lyα forest
- Recombination lines: Hα, Hβ, Pα, Pβ, Brα, Brγ, **…**

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 7.9 \times 10^{-42}\ L(\mathrm{H}\alpha)\ (\mathrm{ergs\ s}^{-1})$$

- Forbidden lines: OII

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[\mathrm{OII}]\ (\mathrm{ergs\ s}^{-1})$$

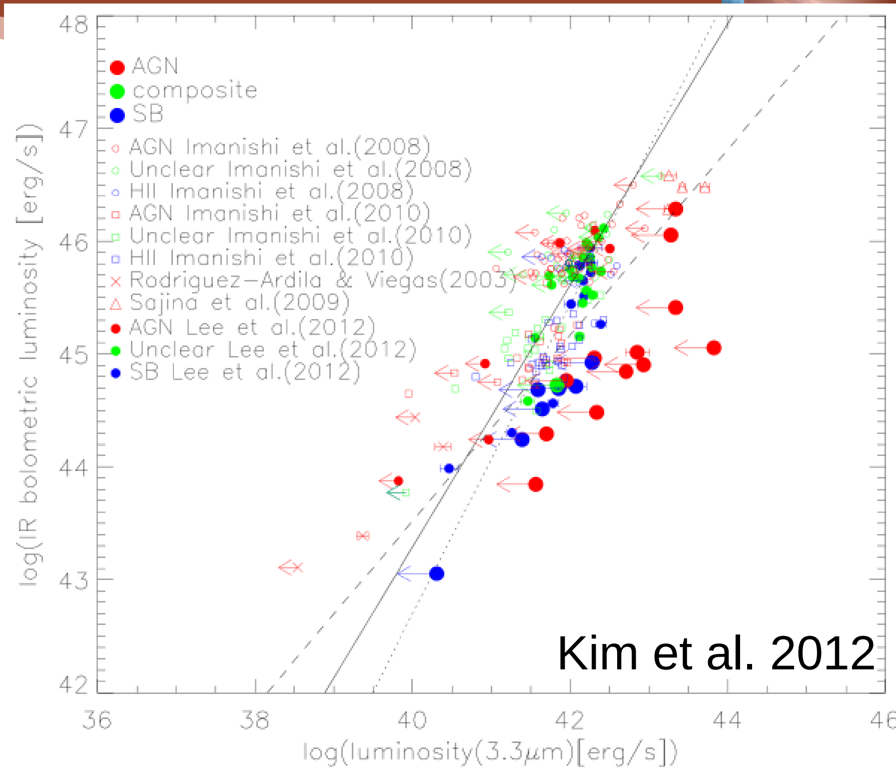
- Far-IR Continuum

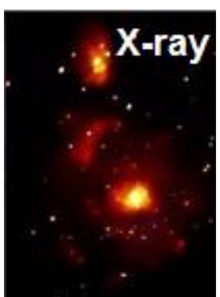
$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s}^{-1})\ (\mathrm{starbursts})$$

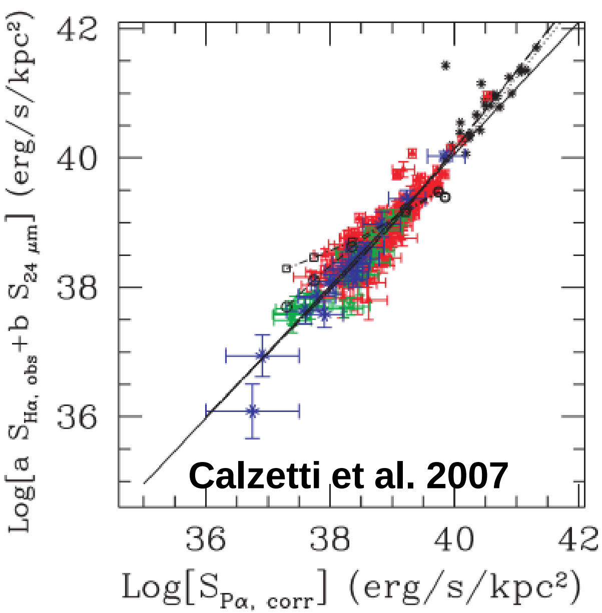
- New Tracers: P$a\alpha$, PAH, … ? $\rightarrow$ supply complementary data

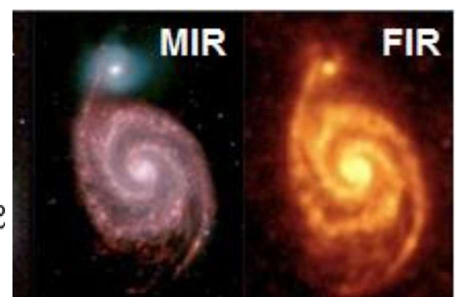
Star Formation in Nearby Galaxies

- Nearby Galaxies
  - Large size: up to ~1 sq. deg.
  - Complementary data: SINGS (Spitzer), KINGFISH (Herschel), HI Survey, Hα survey
  - Star formation relation





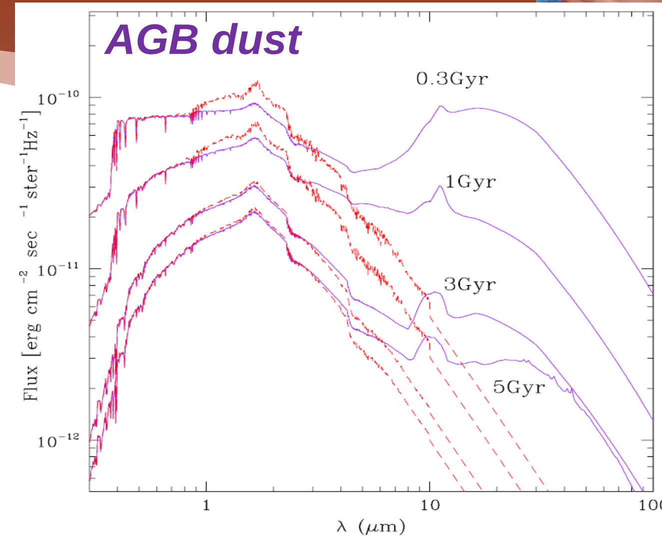




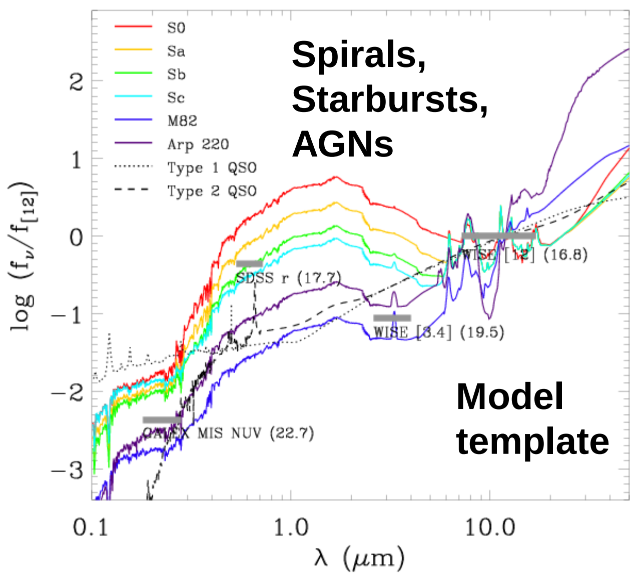
Kennicutt & Evans 2012

Excess Emission in Mid-Infrared

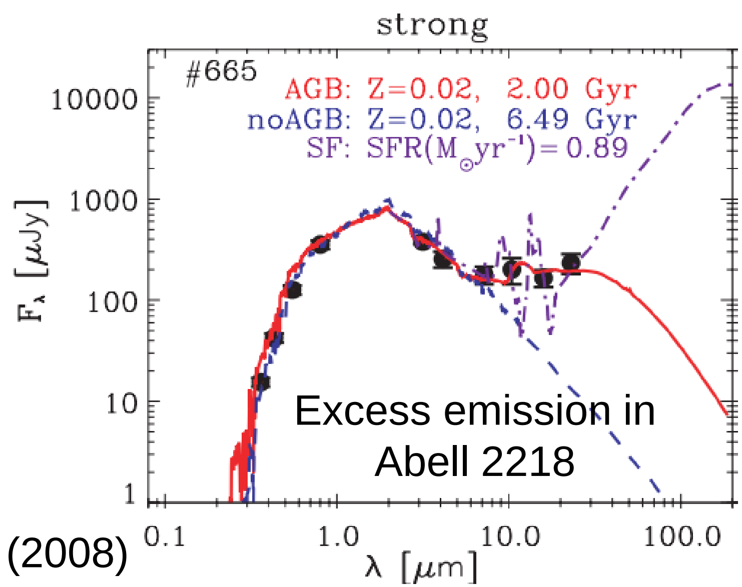
- Observation of ETG & Clusters of Galaxies in MIR
  - Piovan AGB dust model (2003)
  - Excess emission
    → past SF activity in ETG



WISE-SDSS-GALEX
12 μm-selected galaxies

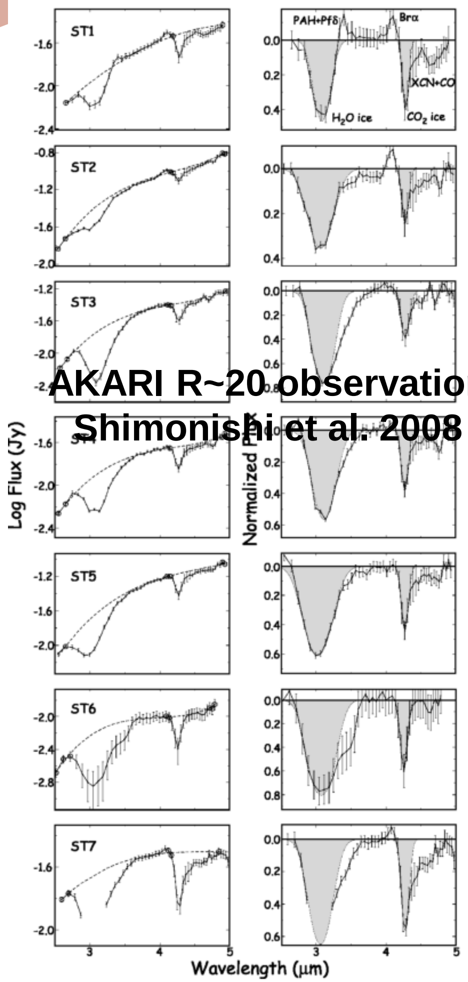


Ko et al. (2008)

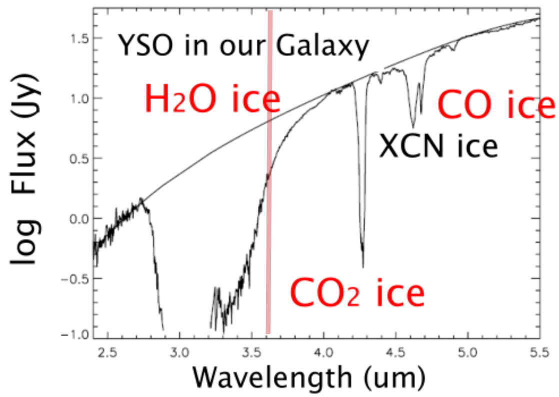


Star Formation in Star forming Regions

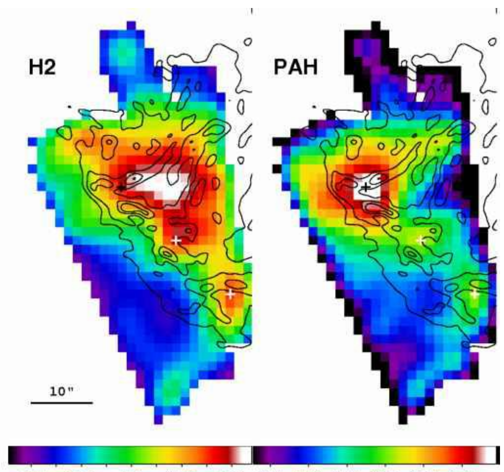
- YSOs in LMC: H_2O ice feature



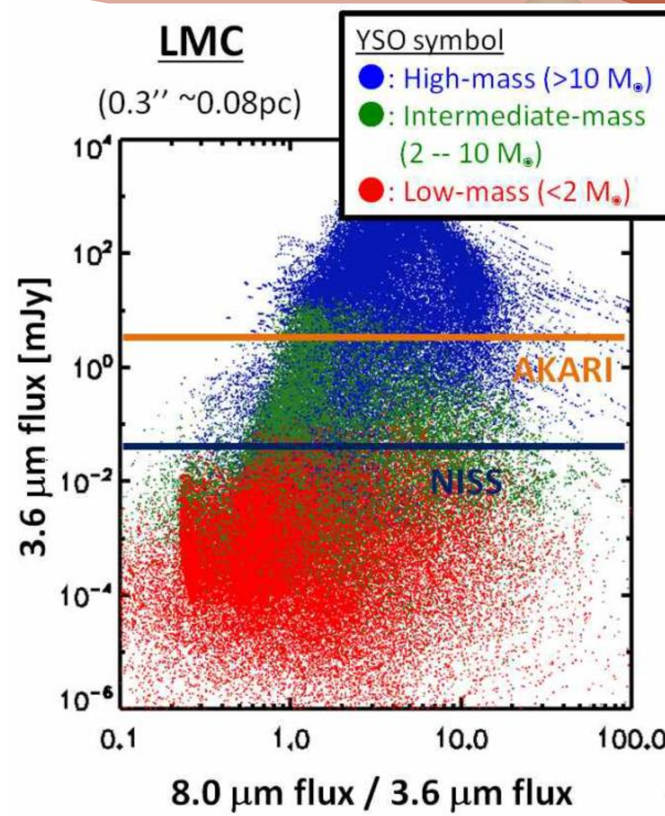
AKARI R~20 observation
Shimonishi et al. 2008



Absorption feature



PAH in SNR (Seok et al. 2013)



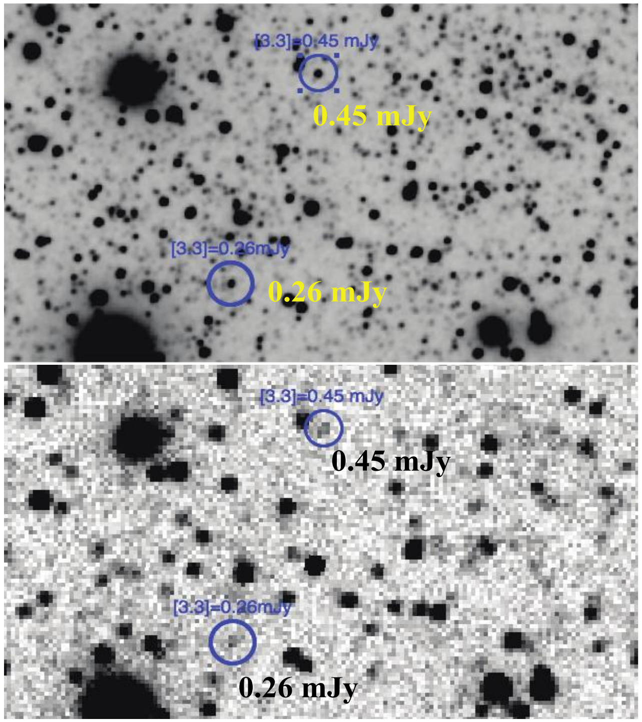
Candidates of observable YSOs

Science Objective II

Star Formation History in High-z Universe

- Cosmic Near-Infrared Background Observation
  → Contribution from resolved or unresolved sources:
  Near-infrared excess emission

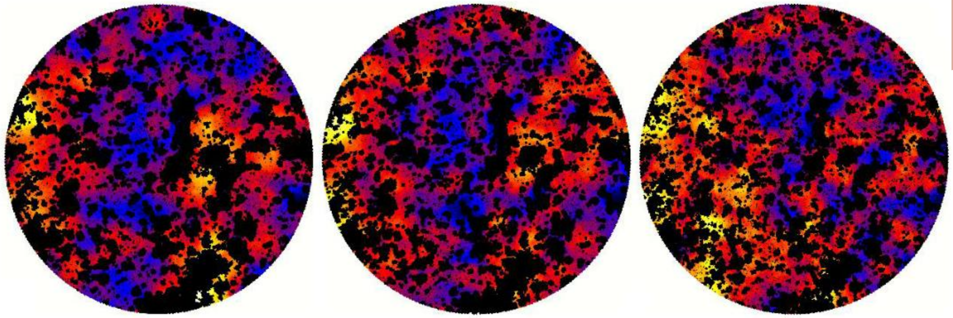
- Serendipitous Discovery of Bright Objects at High Redshift
  → Optional



Detected WISE galaxies

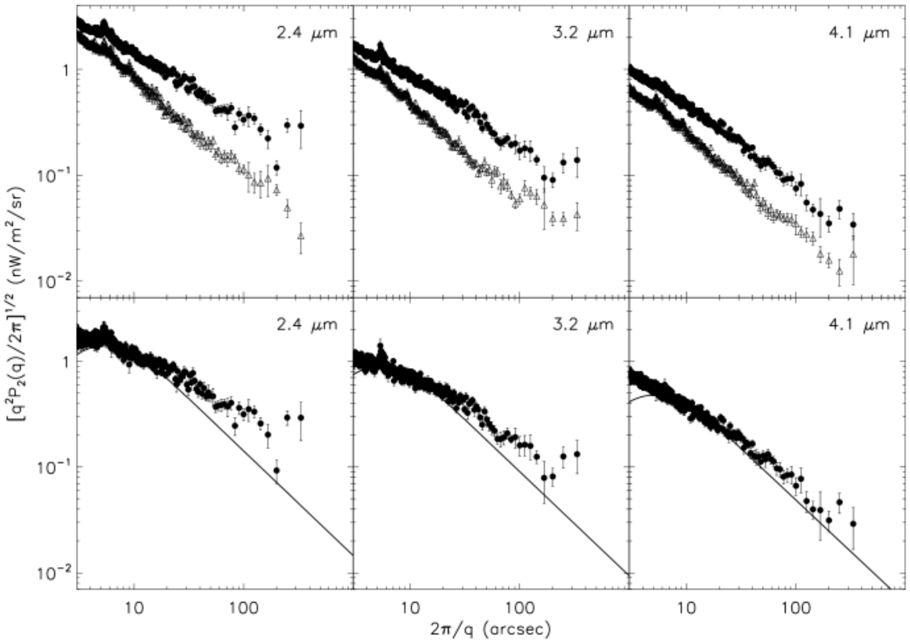
Detection of CIB Fluctuation

- Smoothed image
- Correlation & fluctuation
- Fluctuation strength: ~2% of sky brightness



Matsumoto, Seo, Jeong et al. 2011

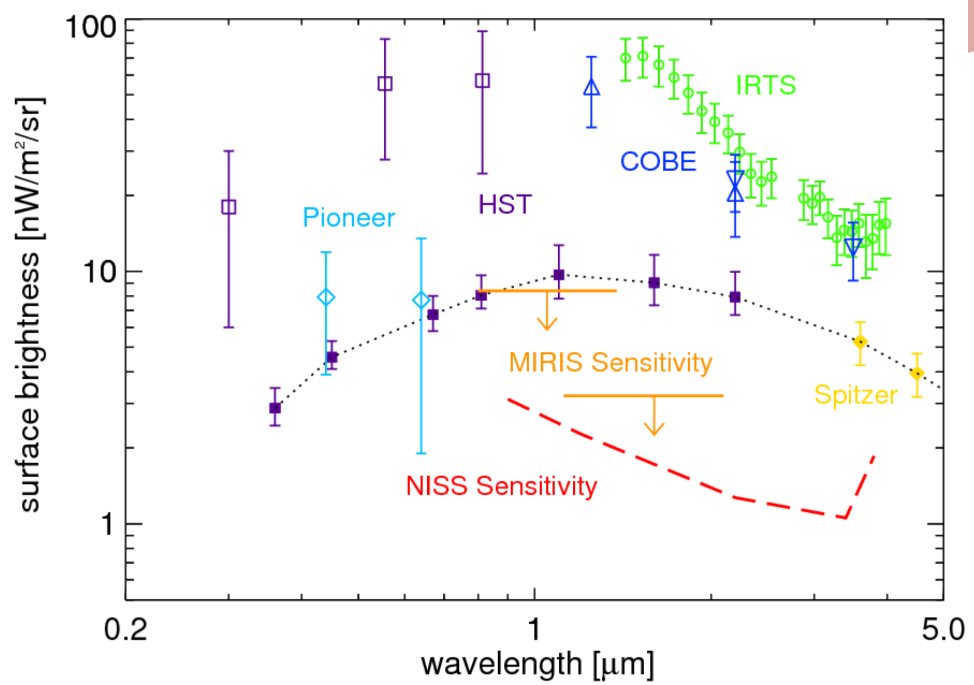
- Fluctuation
  at >100 arcsec



- Smooth fluctuation from ZL (Pyo et al. 2012)
- Upper limit of fluctuation: ~0.02% of sky rightness

Absolute Brightness of CIB

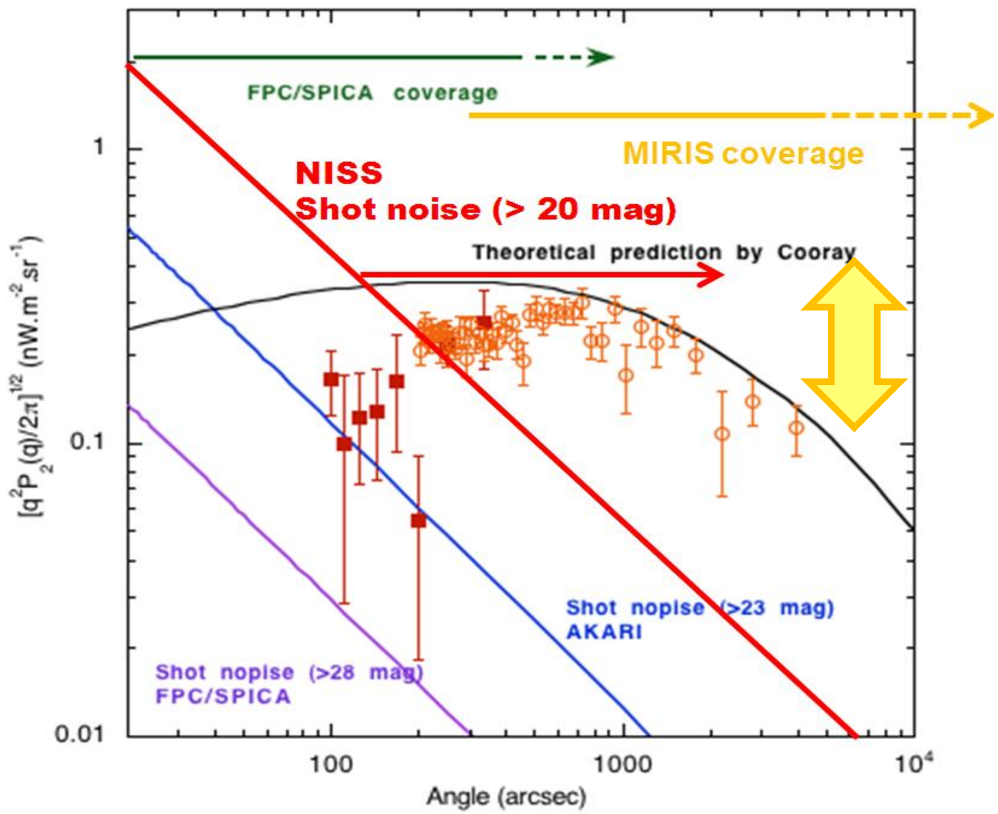
- Absolute brightness
  - Resolution & sensitivity
  - Removal of foreground sources
  - Stacking pixels



- Origin?
  - Zodiacal light
  - Lyman α or Lyman break: drop at $\lambda \sim 1\mu m$ POPIII or first stars or first galaxies
  - TeV Gamma-ray photons from blazars
  - Intra-Halo Light …

Fluctuation of CIB

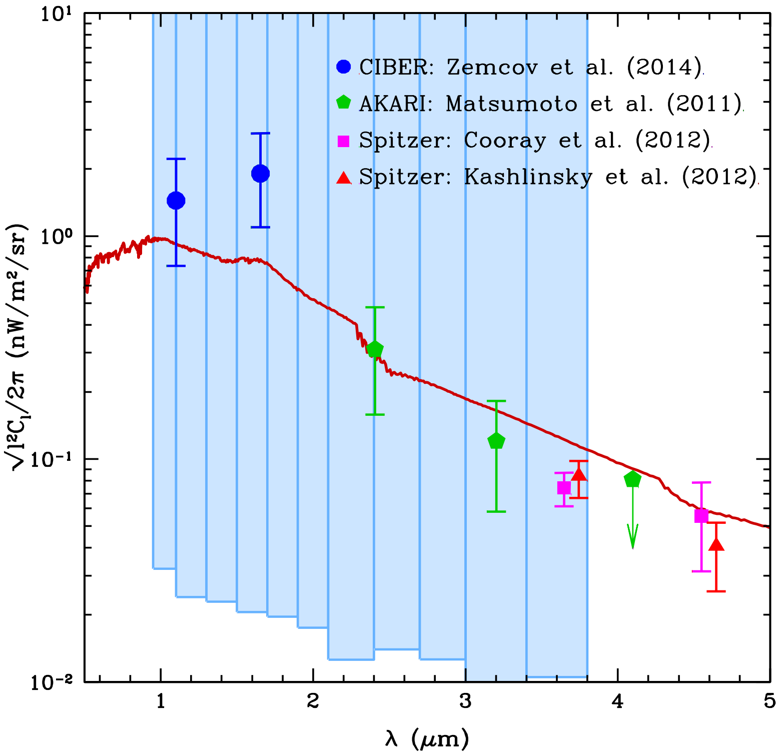
- Detection of fluctuation
  - AKARI observation
  - MIRIS: large scales > 3 deg.
  - NISS: medium scales
    but, continuous
- Spectral resolution ~20
  - Δz ~ 0.5 at z=10
  - Δt ~ 0.03 Gyr



Intra-Halo Lights

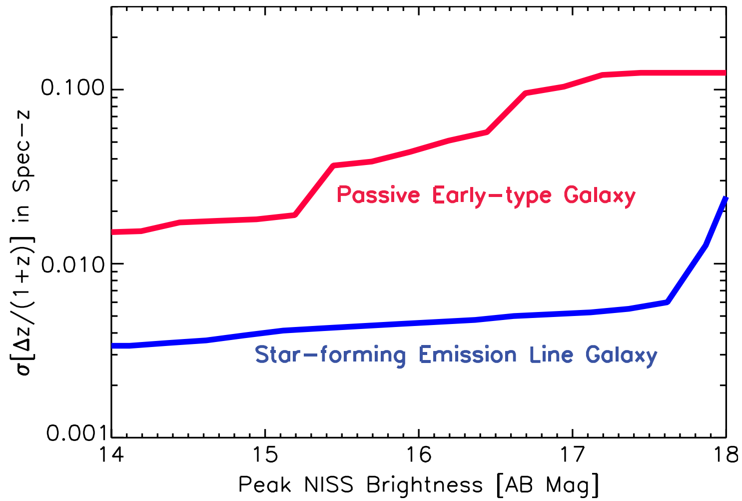
- IHL (NISS-NASA Prop.)
- Stripped stars from galaxy mergers

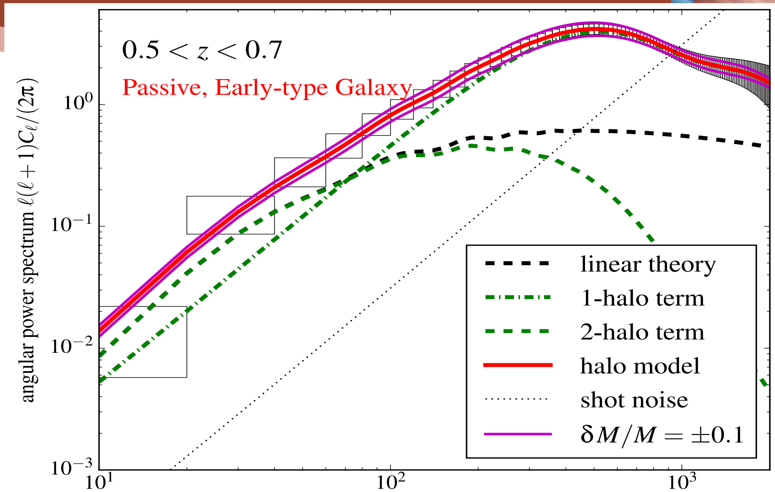
- Spectrum & fluctuation?
  - Flat near 1μm
  - < 1μm spectrum

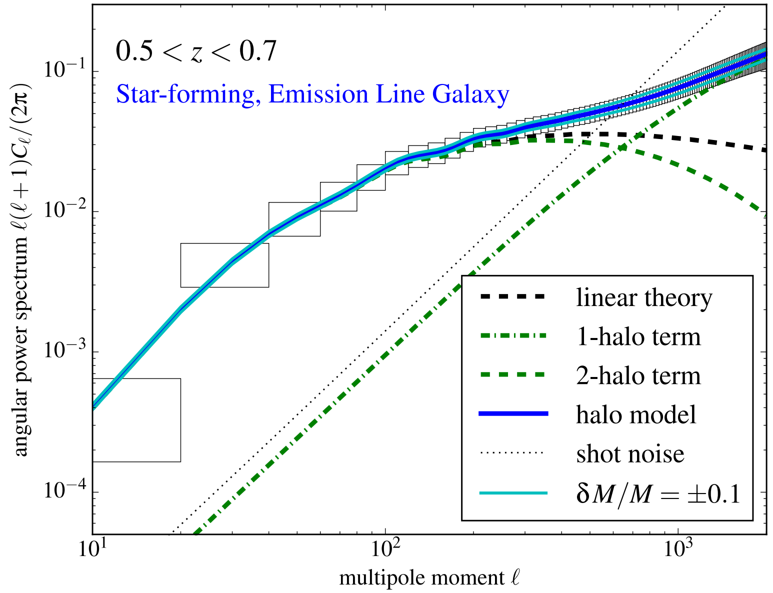


Extragalactic sources

- Expected angular power spectrum
- Halo model + semi-analytical galaxy formation model





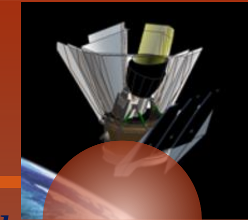


Scientific Targets

- Nearby & Distant Universe
  - Nearby galaxies, clusters of galaxies, star-forming regions …
  - CIB observations in low-background regions
    - Detection of degree-scale fluctuation
    - e.g., 6 deg. x 4 deg. ~ 24 sq. deg. → 2~3 months
  - Number of imaging spectroscopy: > 20 targets

Objects	Targets
Nearby galaxies	M31, NGC628, ··· ; 15 galaxies
Local clusters of galaxies	Abell 2199, ··· ; 1~2 clusters
Star-forming regions	LMC, SMC, ··· ; ~6 regions
CIB observations	NEP, SGP ··· ; 1~2 regions

SPHEREx Science Overview



SPHEREx: An engineered all-sky spectral survey with 3 science goals

Surveys are a natural synergy enabled by by the spacecraft orbit and observing scenario

Inflationary Cosmology and DE (all-sky survey)

- Probes properties of inflation by measuring non-Gaussianity (f_{NL}), running of the spectral index (α_s), departure from flatness (Ω_k)
- Cosmology derived from 3-D clustering of galaxies
- Unique large volume survey at z < 1 measures universe to fundamental limits and complements Euclid and WFIRST surveys at higher redshift

⇒Deliver Euclid like cosmological power ~3-4 years before.

Galactic Ice Survey (Galactic plane survey)

- Surveys the role of ices in all phases of star formation from ambient molecular clouds to circumstellar and protoplanetary systems
- Unique near-infrared spectral survey, provides a catalog for JWST and ALMA

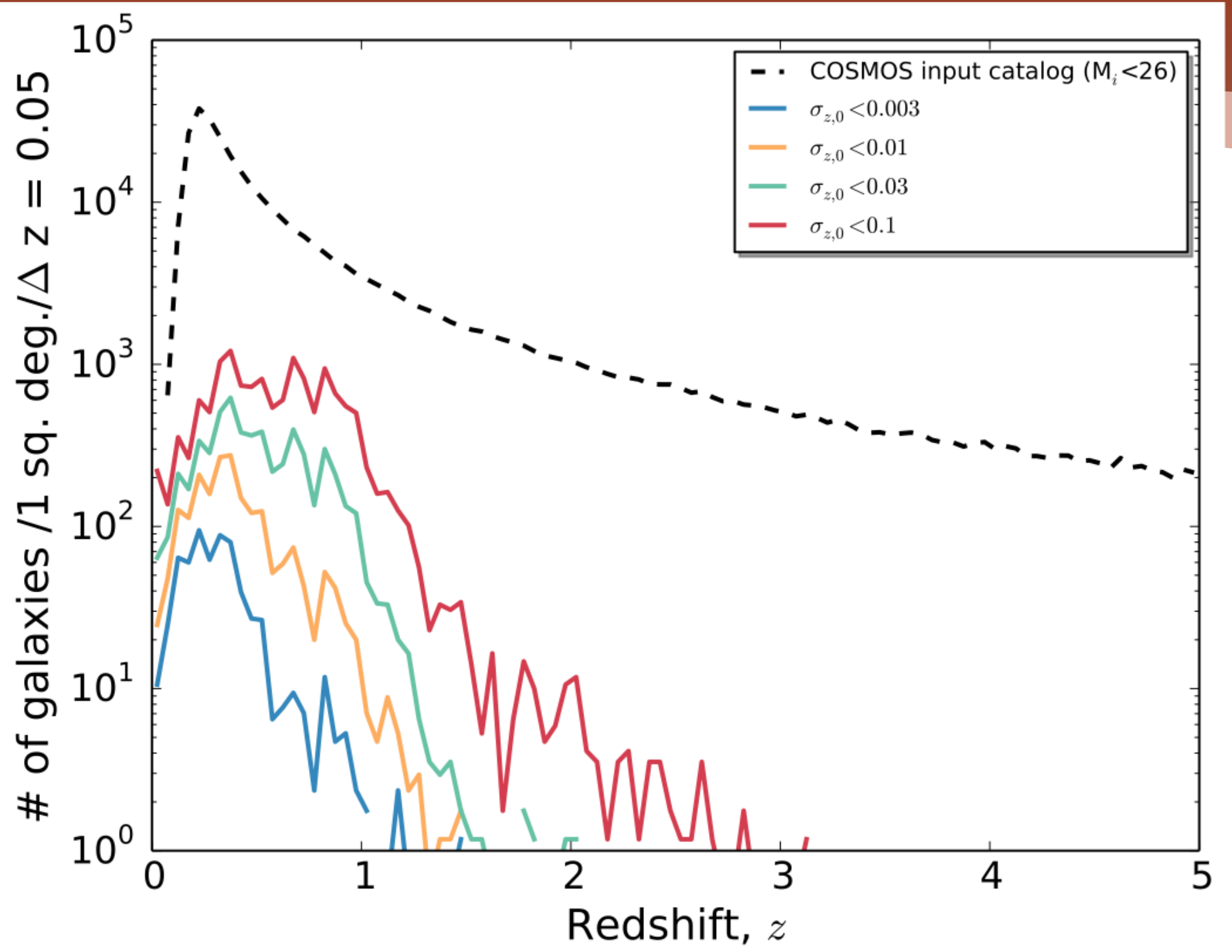
History of Galaxy Formation Survey (deep 200 sq. deg. survey)

- Measures total galaxy star formation for 0 < z < 6
- Probes epoch of reionization for 6 < z < 10
- Ensemble galactic star formation derived from deep 3-D intensity mapping survey
- Unique line-mapping capability complements current and future continuum measurements with Herschel, Planck, Spitzer and Euclid

Ancillary Science

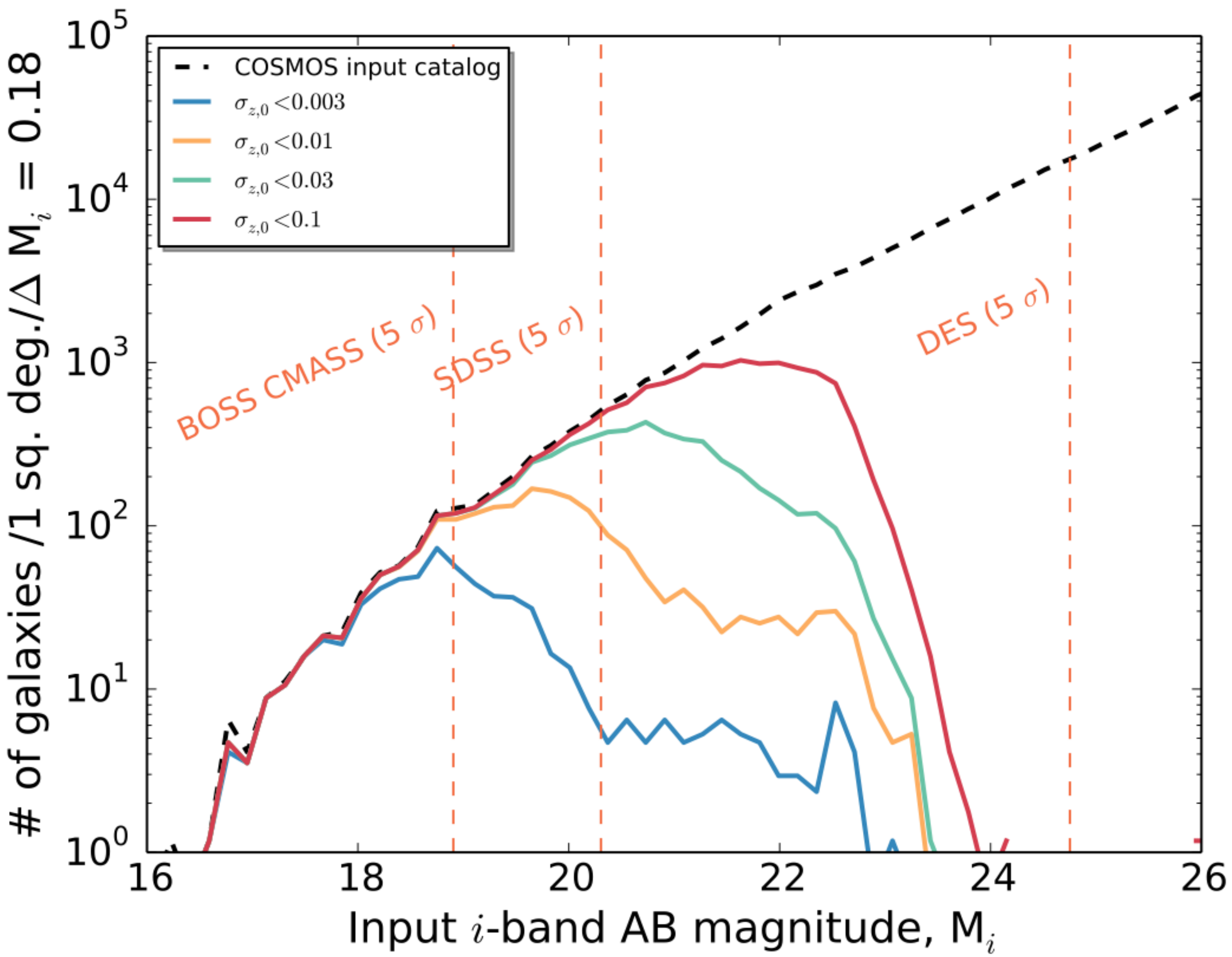
- All-sky spectral survey for rich and diverse astronomy applications with discovery potential for unusual objects
- E.g. clusters and brown dwarfs will be detected in abundance
- High-z QSOs will be detected, if they exist

SPHEREx Full Sky Source Density



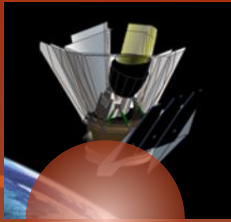
- Number of identified sources is unprecedented for z < 1.2
- Assumes nominal sensitivity between required and capability cases
- Counts based on a full simulation from COSMOS catalog

SPHEREx Full Sky Source Completeness



- Recovered galaxy density as a function of redshift accuracy.
- Important point: SPHEREx provides a redshift for all detected galaxies, not only ELGs.

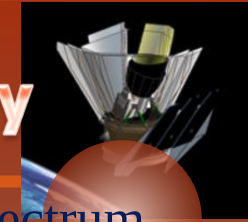
Spectral Database POP



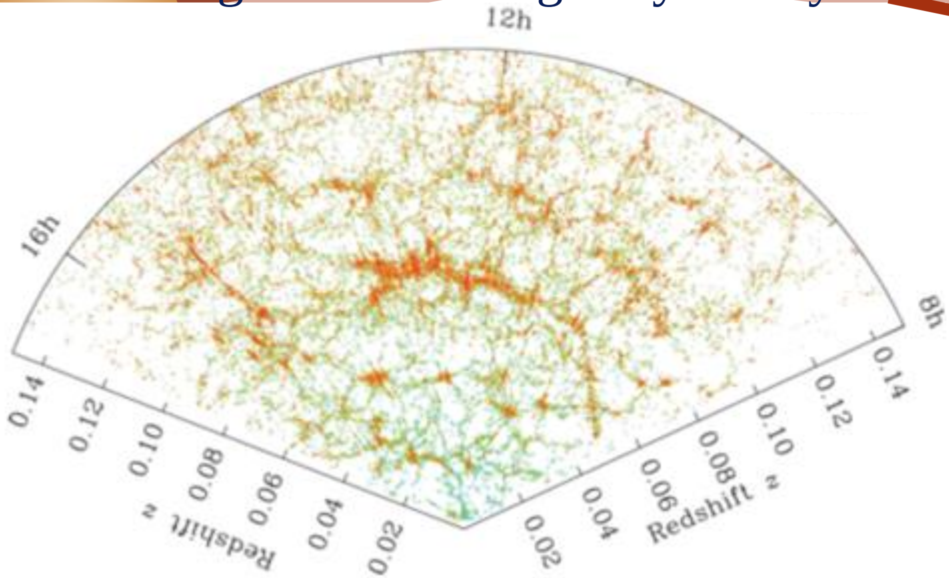
Object	# Sources	Legacy Science	Reference
Detected galaxies	1.4 billion	Properties of distant and heavily obscured galaxies	Simulation based on COSMOS and Pan-STARRS
Galaxies $\sigma(z)/(1+z) < 0.03$	120 million	Study (H, CO, O, S, H_2O) line and PAH emission by galaxy type. Explore galaxy and AGN life cycle	
Galaxies $\sigma(z)/(1+z) < 0.003$	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 spectroscopy probes EOR through Lyα forest	
Clusters with ≥ 5 members	25,000	Redshifts for all eRosita clusters. Viral masses and merger dynamics	Geach et al., 2011, SDSS cnts
Main sequence stars	>100 million	Test uniformity of stellar mass function within our Galaxy as input to extragalactic studies	2MASS catalogs

Object	# Sources	Legacy Science	Reference
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	*Astrophysical 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 Galactic plane	Study diffuse emission from interstellar clouds and nebulae; hydrocarbon emission in the 3μm region	GLIMPSE survey (Churchwell et al. 2009)

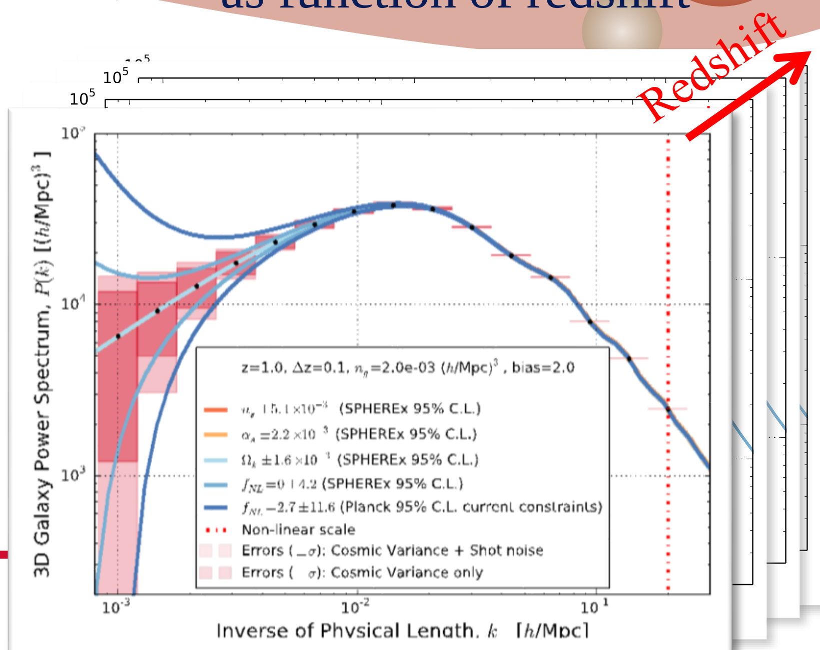
Inflationary Cosmology from a Galaxy Survey



Large-volume 3D galaxy survey



3D galaxy power spectrum
as function of redshift



Goal: Probe the properties of Inflation

- SPHEREx measures non-Gaussianity (f_{NL}), running of the spectral index (α_s), and departure from flatness (Ω_k) to unprecedented precision.
- SPHEREx uniquely surveys the large volume (full sky) required to measure non-Gaussianity.
- SPHEREx will extract all cosmological information to z<1 and thus perfectly complement the higher redshift regime of Euclid and WFIRST.

⇒ Precise measurements of inflationary observables (f_{NL}, n_s, α_s, Ω_k, and r) are used to determine the physical process that caused inflation.

Fit to cosmological parameters
f_{NL}, α_s, Ω_k, …

KASI 한국천문연구원 Korea Astronomy & Space Science Institute

SPHEREx Inflation Summary

- SPHEREx has a very strong galaxy clustering scientific case:
  - It will constrain inflation theories to unprecedented accuracies.
  - It will measure f_{NL} with a precision of $\pm$ 1.1 at 1σ.

- Measuring f_{NL} requires large scales $\Rightarrow$ Full sky survey.
- Measuring f_{NL} and other parameters require many galaxies $\Rightarrow$ Point source sensitivity requirement.
- Measuring α_s and Ω_k require accurate redshifts $\Rightarrow$ Spectral resolution requirements.
- Cosmological parameter forecasts:

1σ errors	SPHEREx	Current (Planck + BOSS)
Spectral index n_s	2.7E-03	5.0E-03
Running α_s	1.0E-03	8.0E-03
Non-Gaussianity f_{nl}	1.1	5.8
Flatness Ω_k	8.0E-04	3.2E-3
Sum neutrino mass [eV]	0.024	0.47

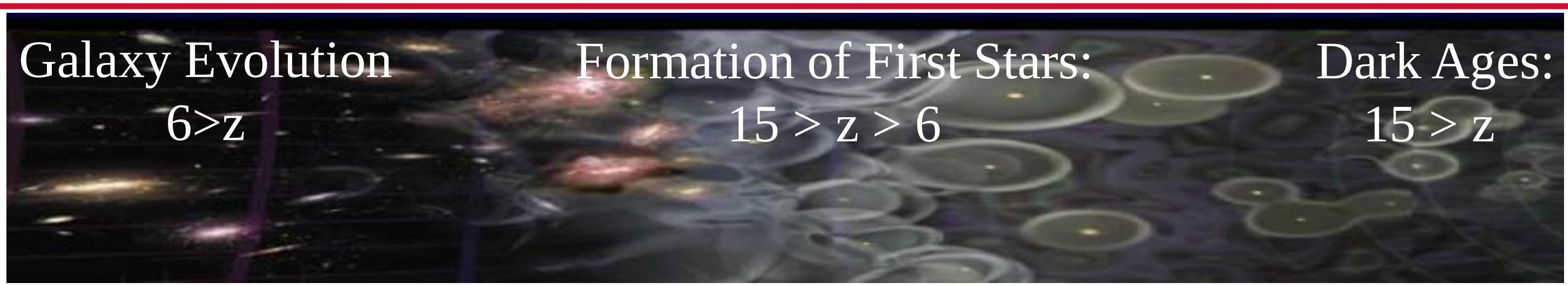
- SPHEREx should be sensitive enough to detect for the first time the running of the spectral index α_s if the Inflation model currently favors by BICEP2 holds.
- A joint Planck & BICEP2 effort will comprehensively test this picture in November

An Encompassing View of Galaxy Formation

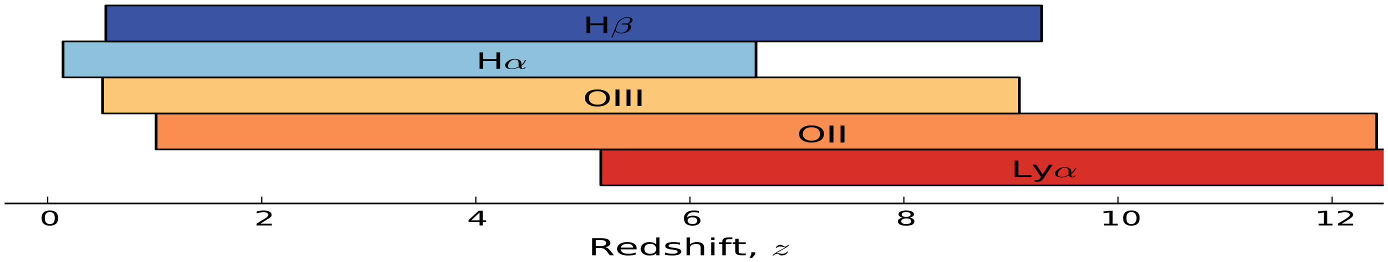
Goal: Chart the full history of galaxy formation with emission line clustering tomography

-SPHEREx will measure the clustering of galaxies with *multiple* emission lines from z=0 to z=6.
-SPHEREx will measure the clustering of the first galaxies at z > 5 using Lyα.
-SPHEREx will potentially detect the direct Lyα emission from the first stars.
-SPHEREx will determine the origin of the *Spitzer-CIBER* fluctuations.

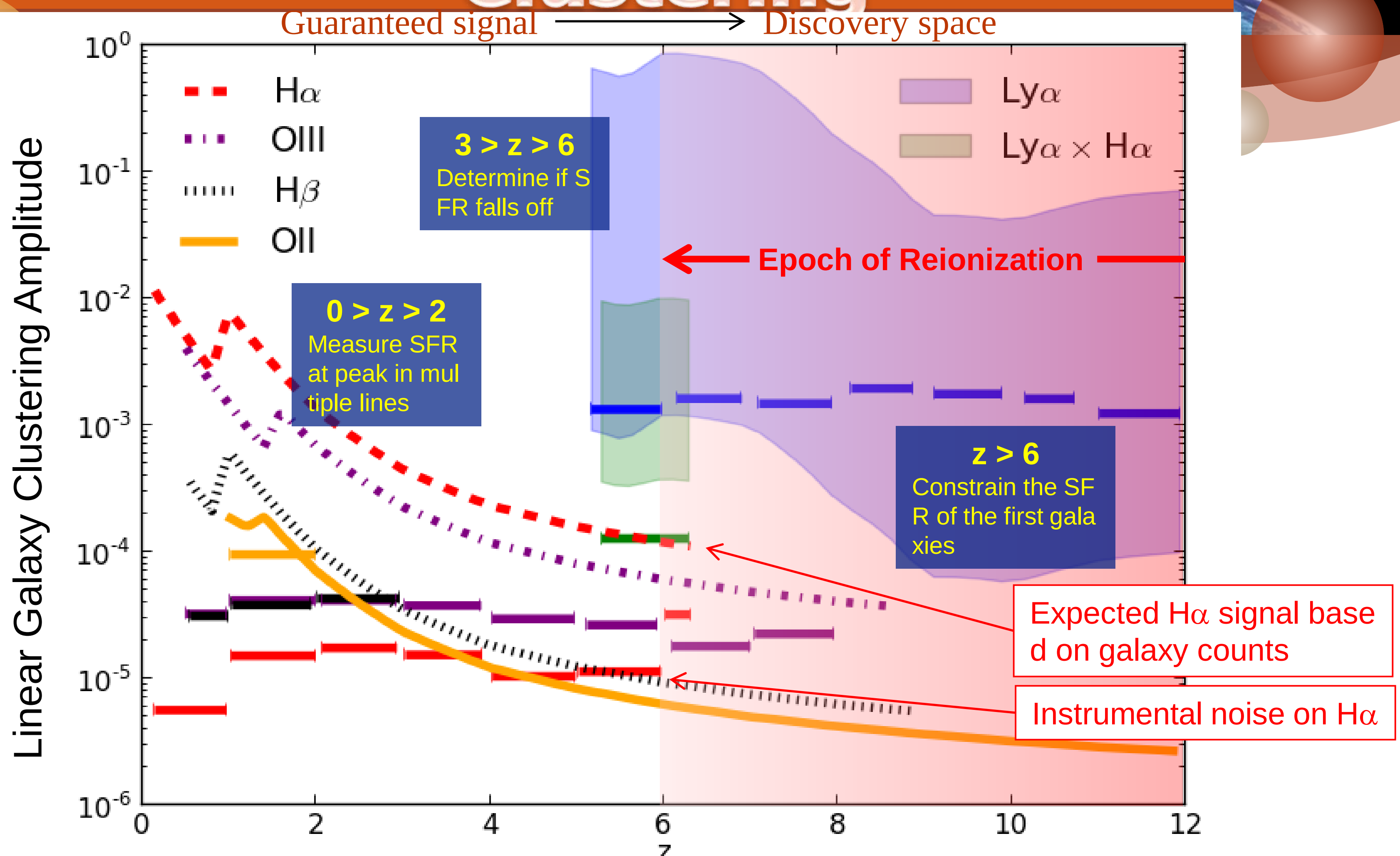
⇒SPHEREx will *uniquely map the spatial distribution* of star formation throughout cosmic times: from the on-set of star formation, to its peak formation rate and its current decline. The large scale (linear) spatial distribution is not measurable with deep small field observations (HST, JWST) and gives us unique insight on the relation between luminous and dark matter.
⇒SPHEREx will measure diffuse intensity fluctuations just like Planck and Herschel mapped the Cosmic Infrared Background (analysis co-led by Bock and Doré)



Redshift coverage of SPHEREx measured emission lines:



Measurements of Galaxy Clustering

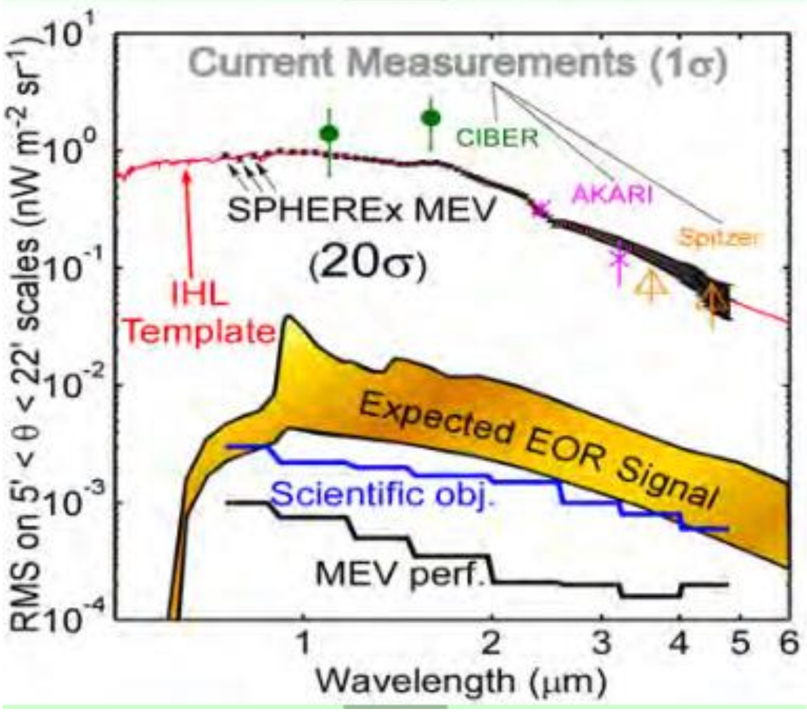


High S/N at low-z on multiple lines: SPHEREx measures galaxy clustering signal at z < 6.
Robust cross-correlation between Lyα and Hα at 5 < z < 6
Probes epoch of reionization models at z > 6 in Lyα

Intra-Halo Lights

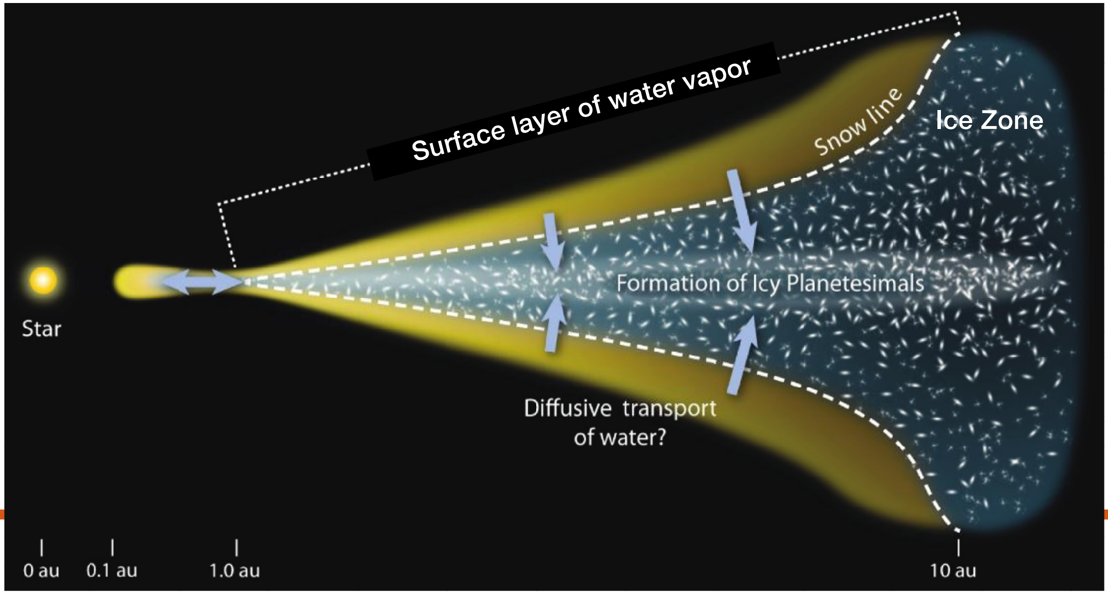
- IHL
- Stripped stars from galaxy mergers

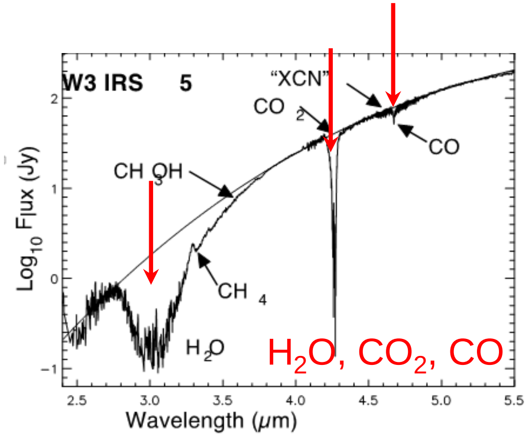
- Spectrum & fluctuation?
  - Flat near 1μm
  - < 1μm spectrum



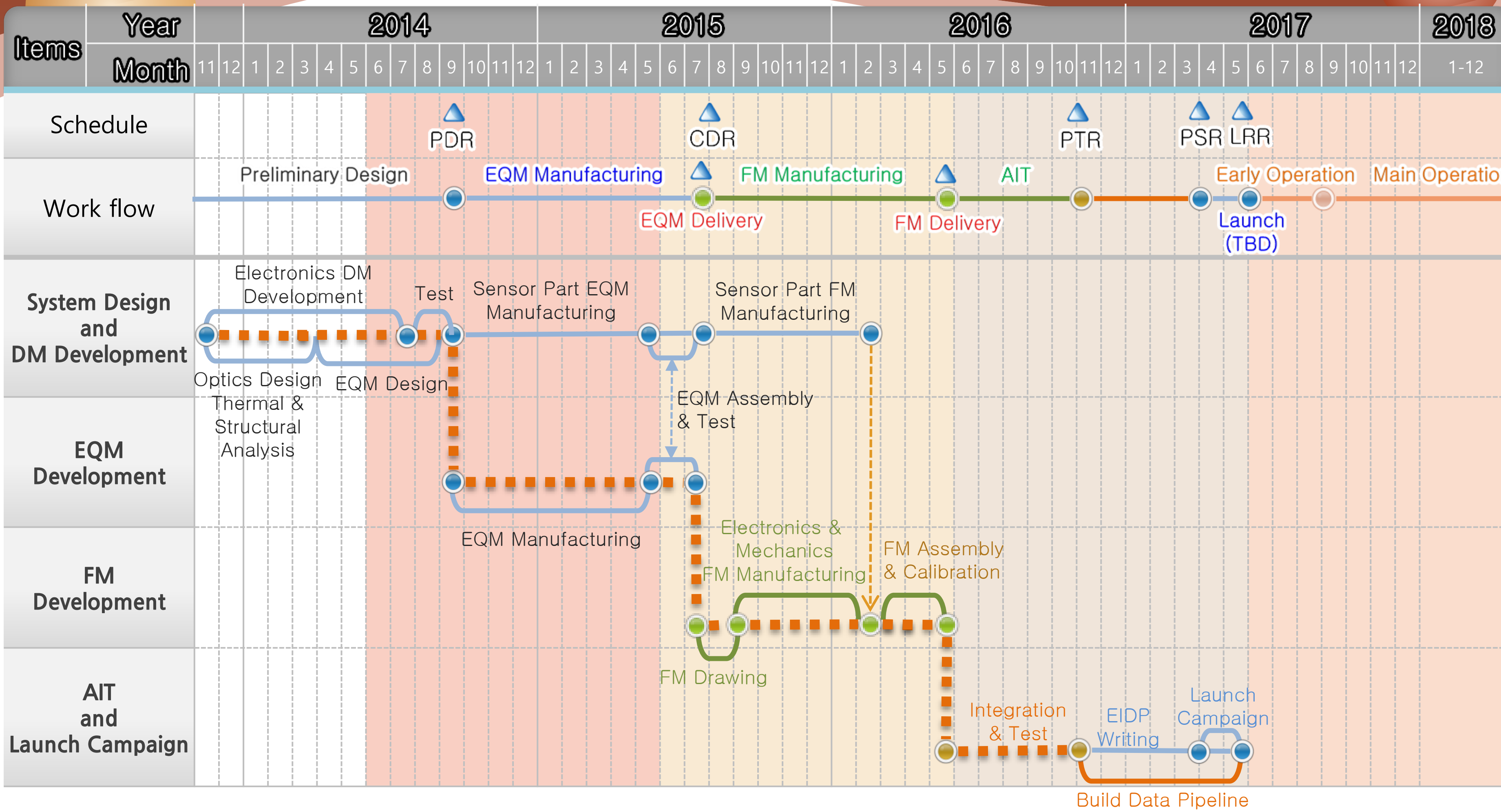
Galactic Ices: Reservoirs of Water and Organics

- Substantial quantities of water and organic material are locked in ices in interstellar space and in the environs of forming stars and planets
- Within molecular clouds, abundance of H_2O_{ice} $10^2 – 10^3$ x greater than H_2O_{gas}
- Within protoplanetary disks abundance of H_2O_{ice} is poorly constrained, but is predicted to be substantial based on:
  - Ice in our solar system (asteroids, Kuiper Belt, Oort Cloud)
  - Models of disk evolution that predict most water in ice in mid-plane
  - Herschel observations of disk around TW Hydrae that imply several thousands of Earth's oceans in ice (Hogerheijde et al. 2011, Science)





NISS Schedule

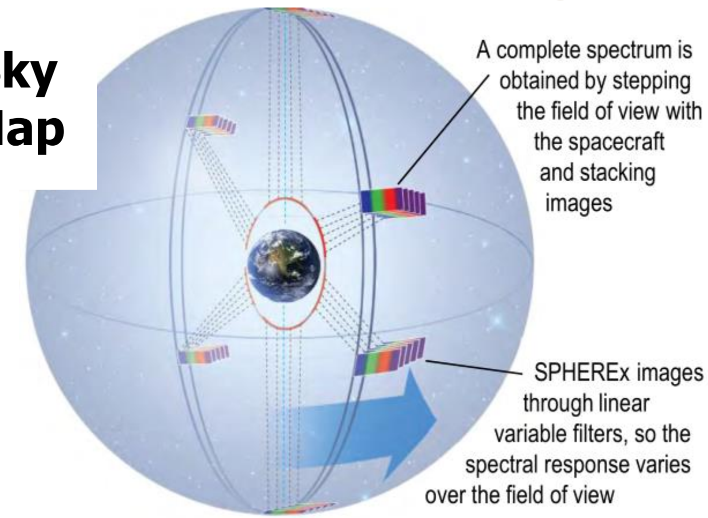


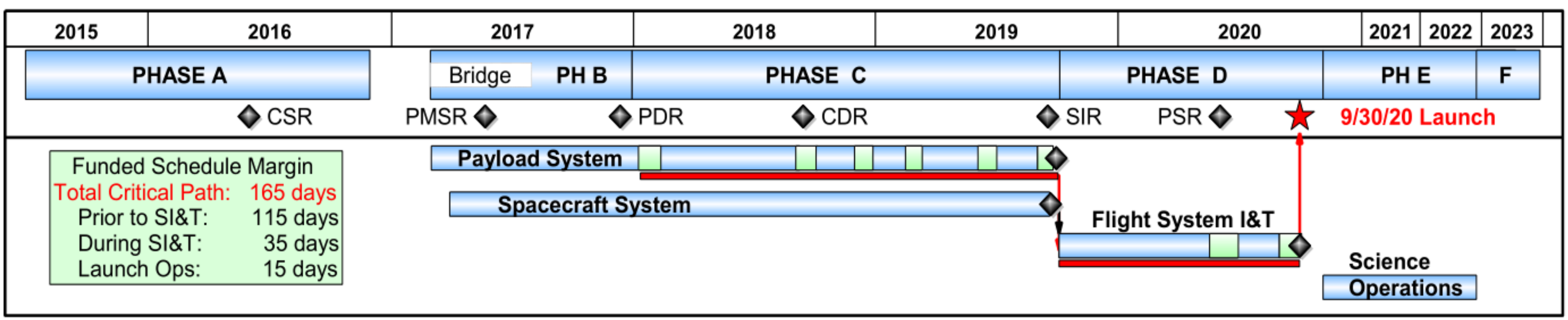
KASI 한국천문연구원 Korea Astronomy & Space Science Institute

SPHEREx Schedule

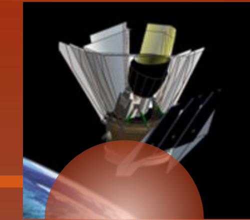
- 2014/12: submission of proposal
- 2015/07: Phase A start
- 2016/06: Phase B start
- 2020/07: Launch

Sky Map





Summary



- NISS
  - Technical demonstration: imaging spectroscopy
  - Imaging spectroscopic survey
  - Nearby galaxies, star-forming regions, low-background regions …
  - Operation in 2017?

- SPHEREx
  - Extended mission of NISS
  - All-sky mission in 2020?