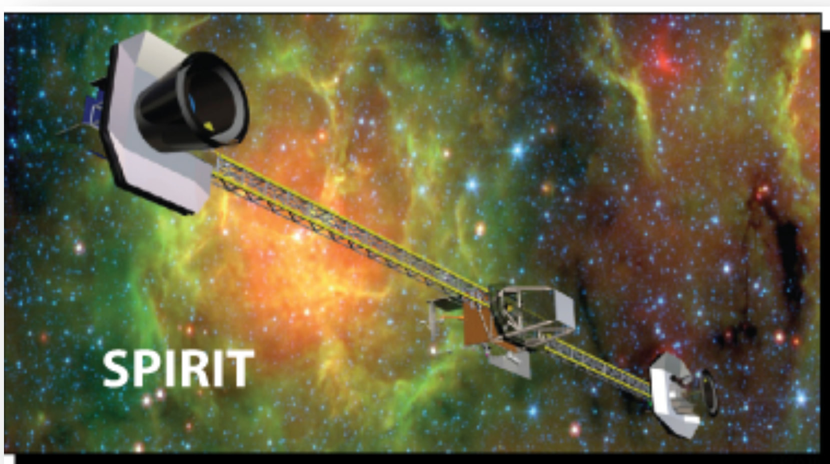
The Space Infrared Interferometric Telescope (SPIRIT)



Dave Leisawitz
Goddard Space Flight Center

1st FISICA Workshop
18 February 2014

SPIRIT Origins Probe Mission Concept Study Team

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Outline

- Far-infrared interferometry as a community priority
- Scientific motivation for high angular resolution and spectroscopy in the far-infrared (~25 to 400 μm)
- SPIRIT mission concept: turning the community's vision into reality
- A tutorial on wide field-of-view spatio-spectral interferometry

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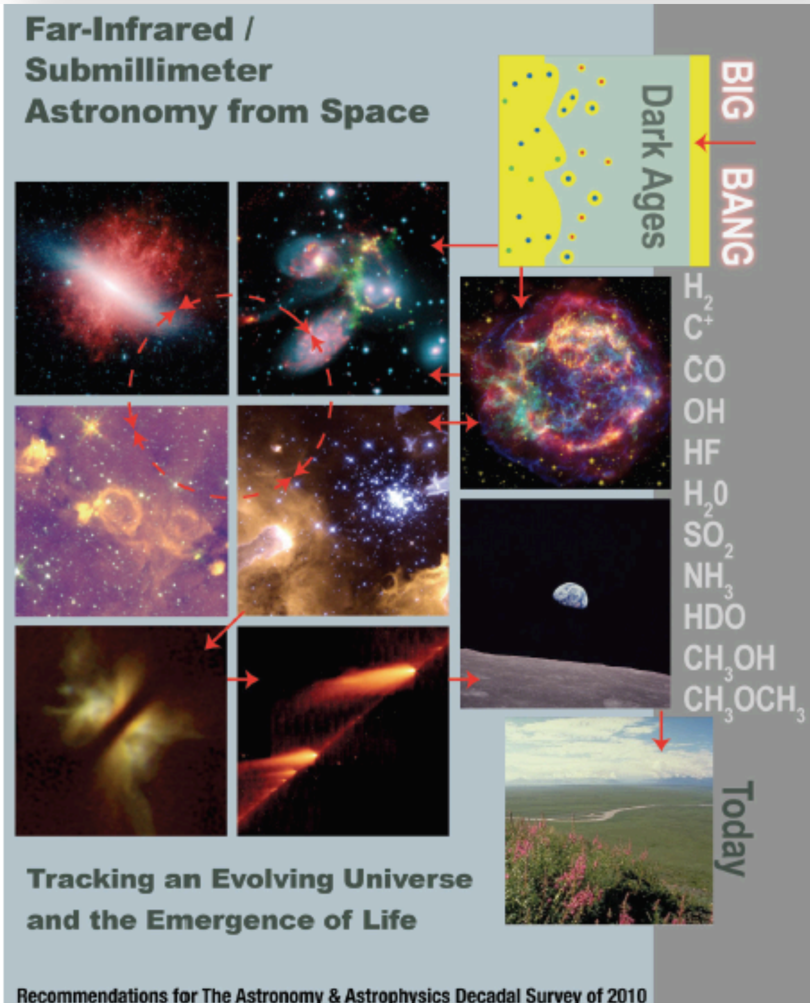
The Far-IR community plan

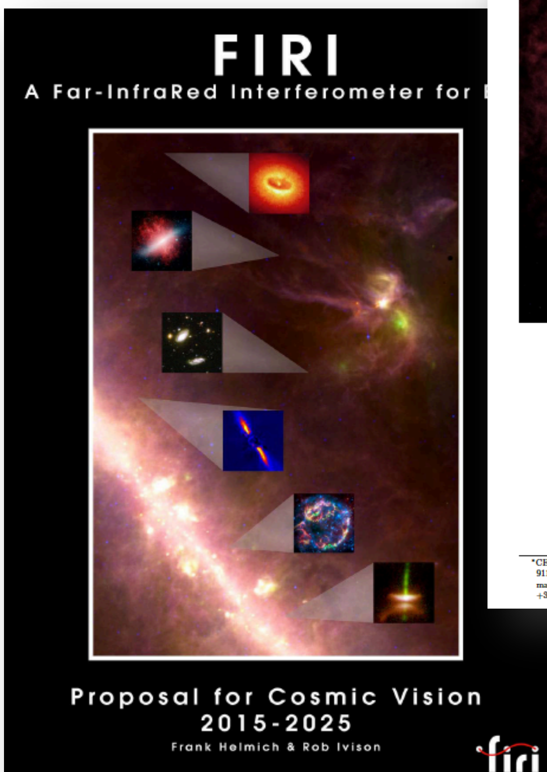


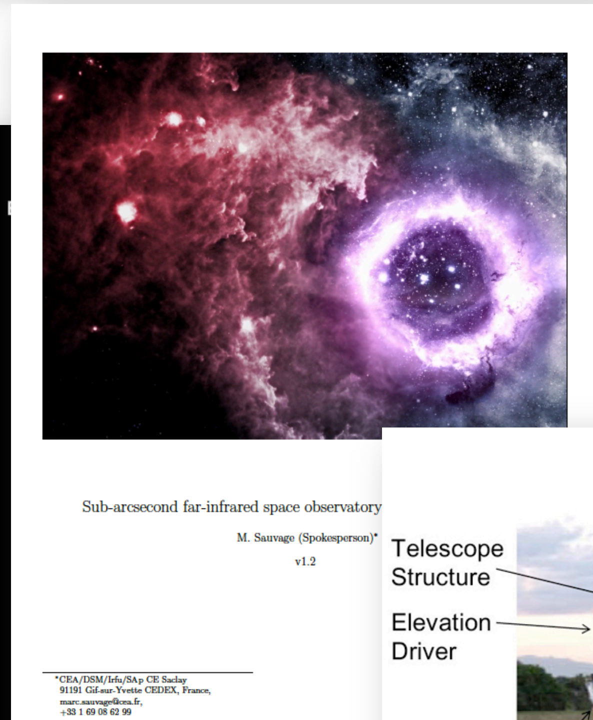
Consensus developed through a series of workshops, starting in 1998

Compelling science case for high angular resolution imaging and spectroscopy, mission concepts, enabling technologies

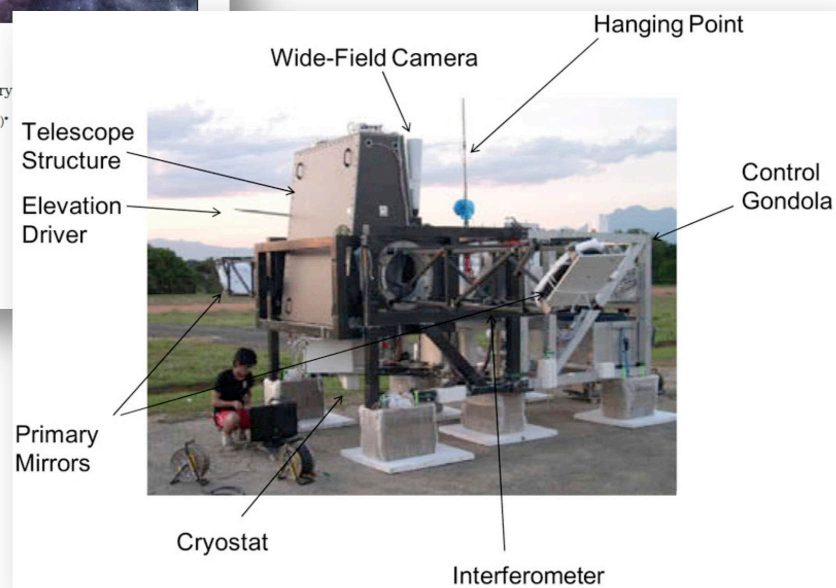
While it has evolved over time, the Plan has consistently called for high resolution

A vision without borders





The international far-infrared astrophysics community shares this vision



NASA Astrophysics Roadmap

A recent community-generated multi-decade Roadmap – "Enduring Quests – Daring Visions" – foresees interferometry at the heart of nearly all of NASA's astrophysics missions in the 2030+ "Visionary Era."

The Roadmap Committee envisages a far-infrared interferometer as the first such mission, on a 15 to 30 year timescale.

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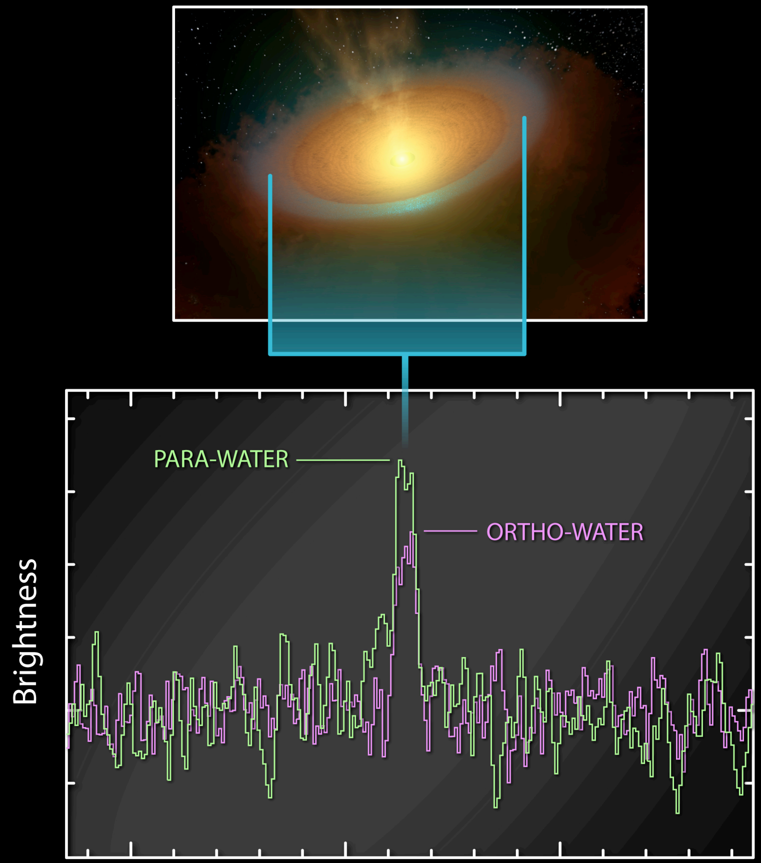
Forming habitable planets



HIFI Spectroscopic Signatures of Water Vapor in TW Hydrae Disk
ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory)

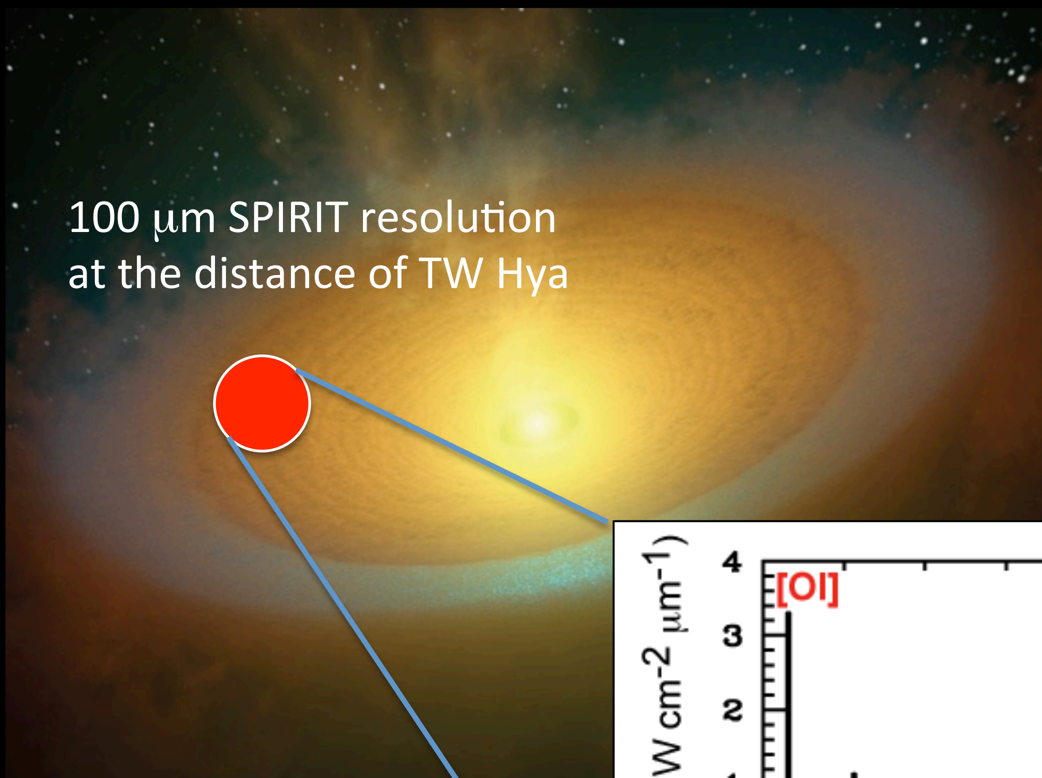
How did the Earth acquire its water? How do habitable planets form?

Herschel observed developing planetary systems and measured water, but it couldn't resolve these objects spatially.

Theorists have models, but lack unique solutions.

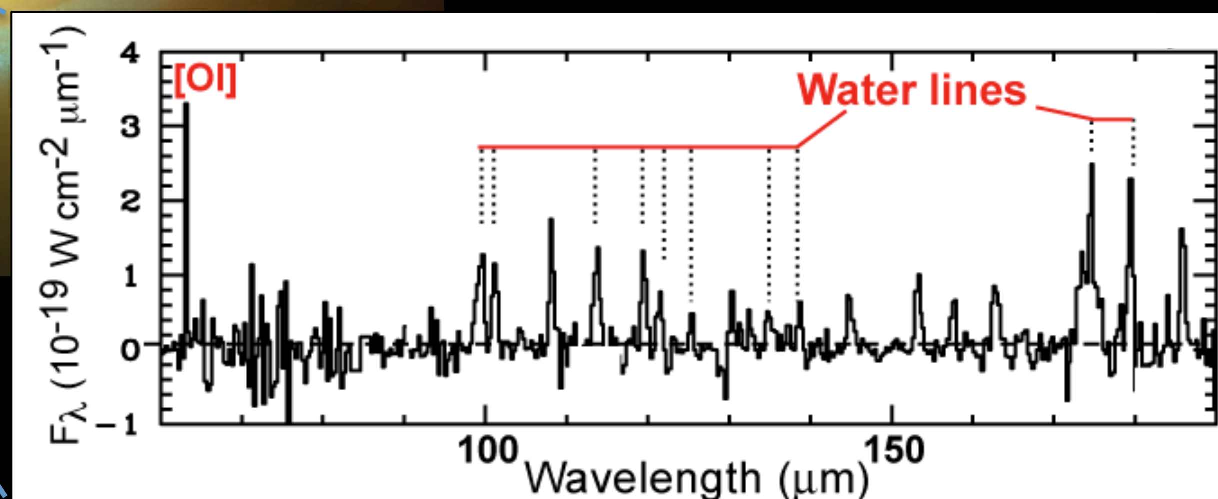
Spatially resolved spectroscopy will break model degeneracy.

Forming habitable planets

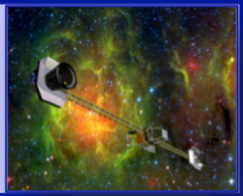


How did the Earth acquire its water? How do habitable planets form?

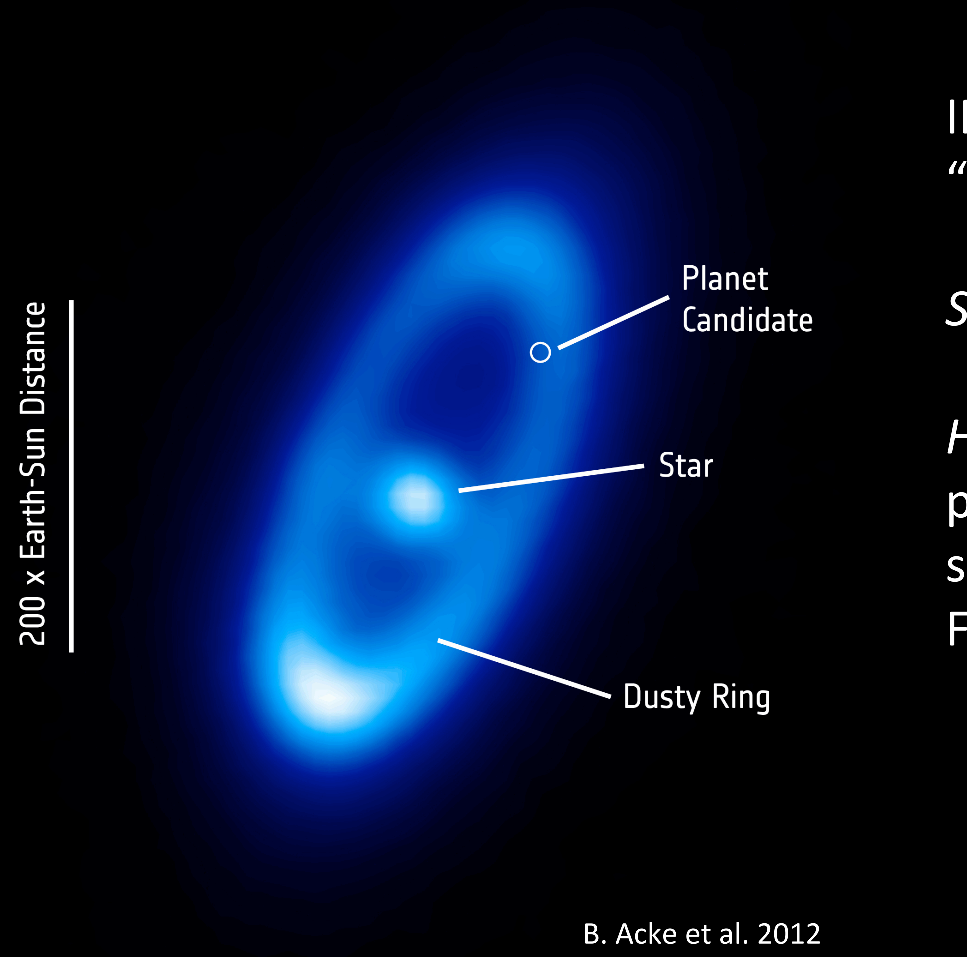
SPIRIT will provide the missing information.



Debris disks: from the Fab 4 …



Fomalhaut



B. Acke et al. 2012

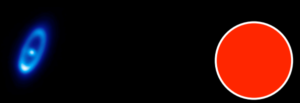
IRAS discovered the "fabulous 4" debris disks

Spitzer imaged them

Herschel vastly improved the picture and captured this stunning image of the Fomalhaut disk

… to hundreds

At 100 pc



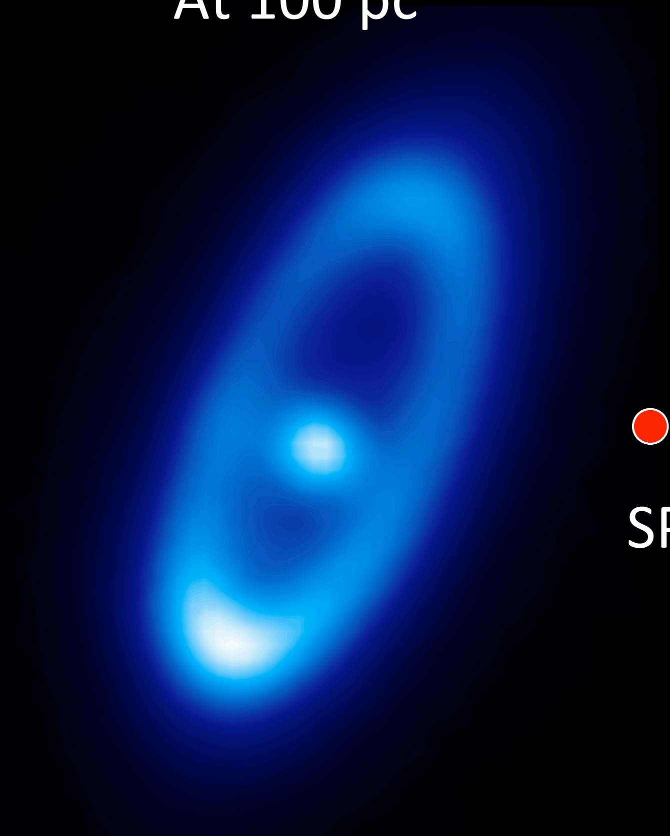
Herschel at 70 μm

To image <u>hundreds</u> of debris disks and tap them for information about planetary systems, we'll have to image disks out to 100 pc.

A 3.5 m telescope isn't big enough.

… to study planetary systems

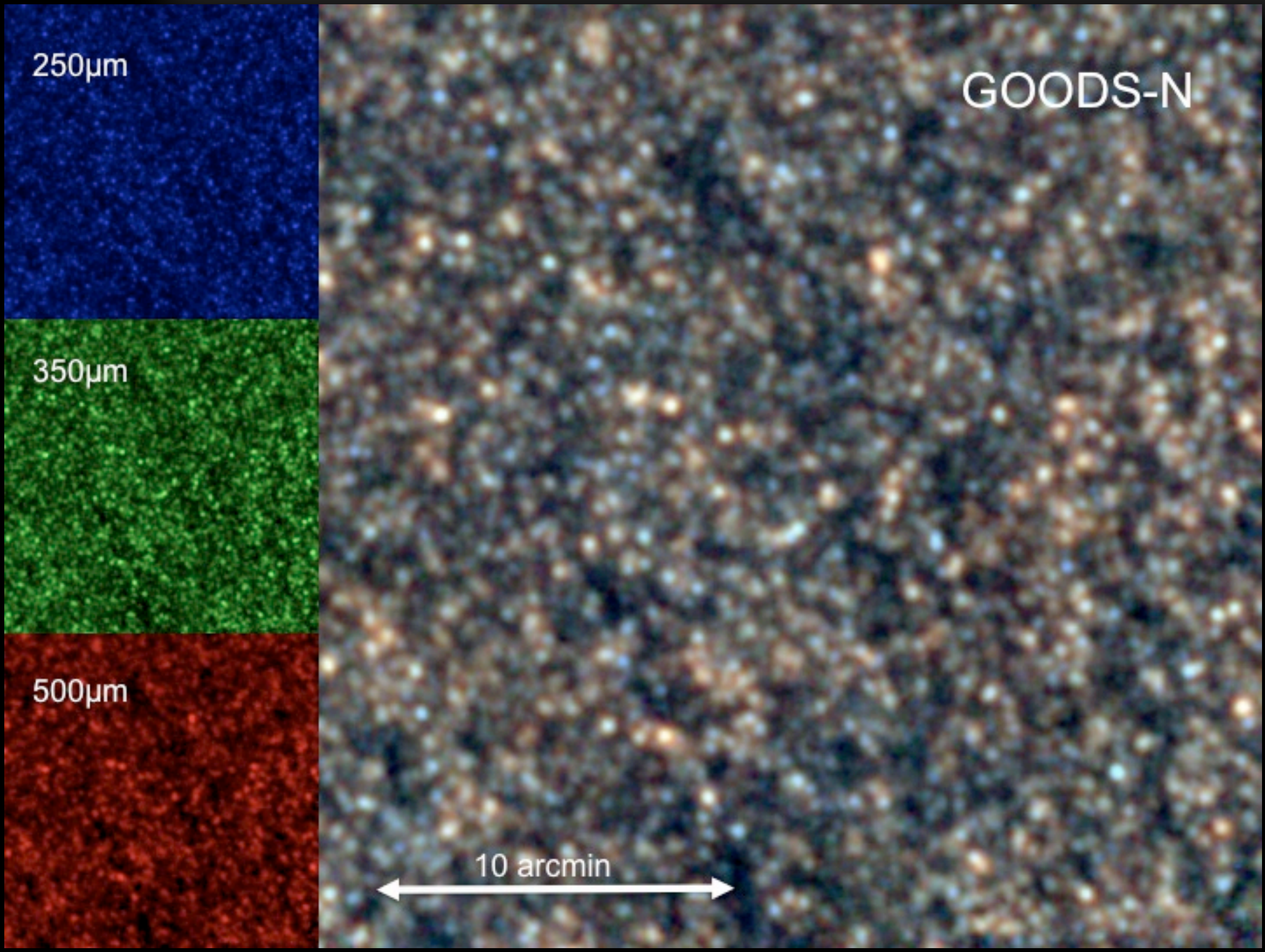
At 100 pc



SPIRIT at 70 μm

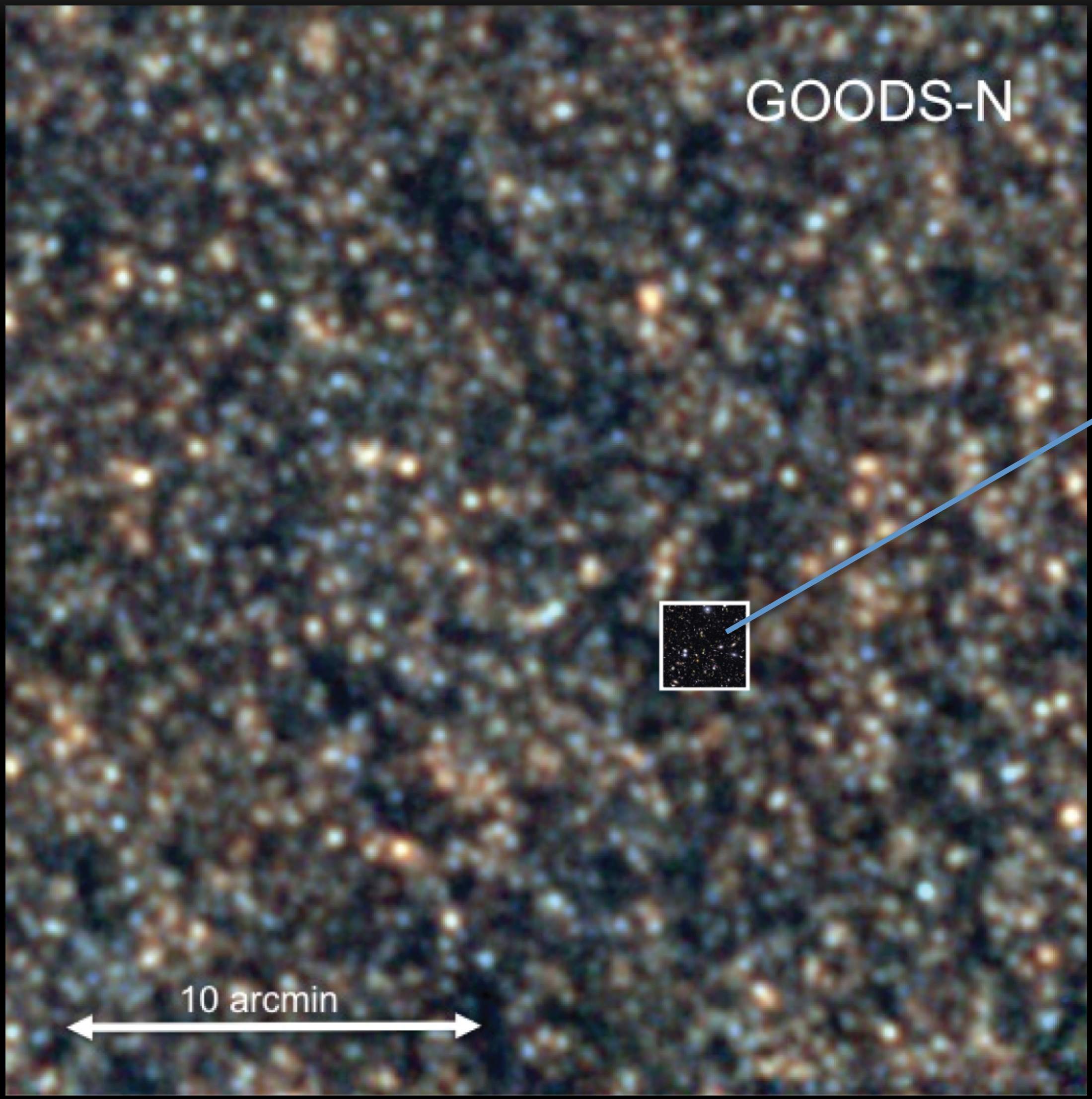
SPIRIT will image <u>hundreds</u> of debris disks

Probing the universe deeply



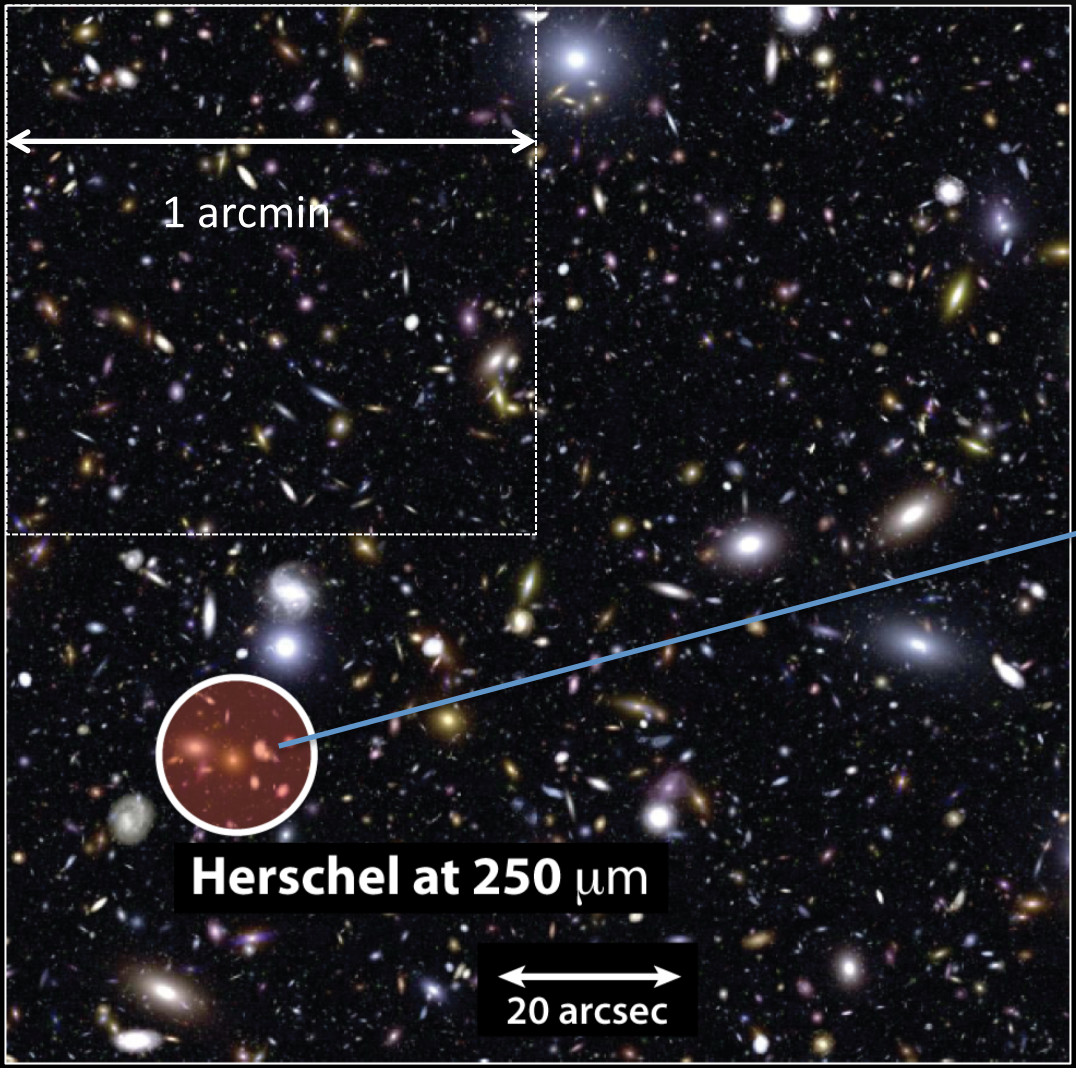
Herschel deep field

Probing the universe deeply



JWST deep field

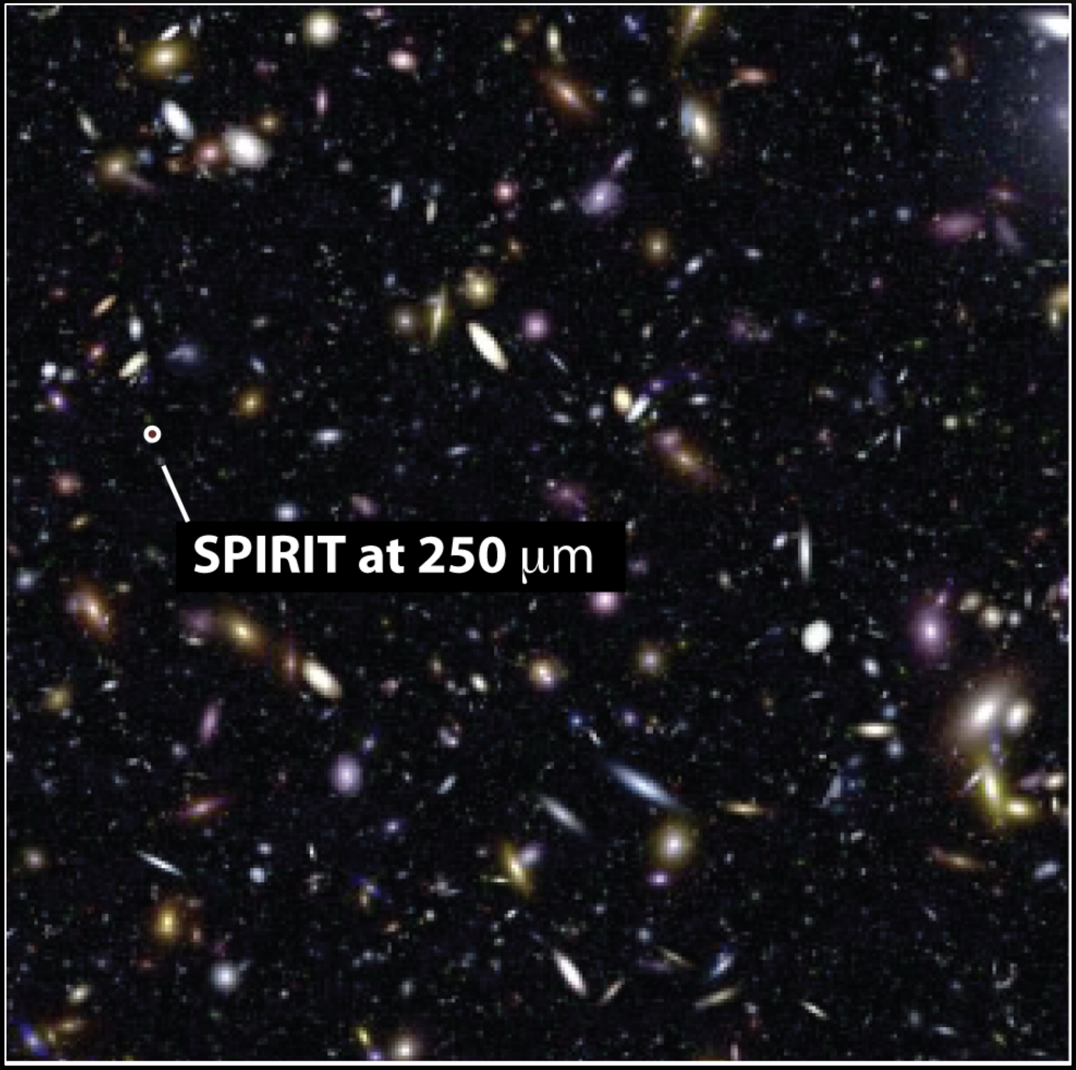
Probing the universe deeply



JWST deep field

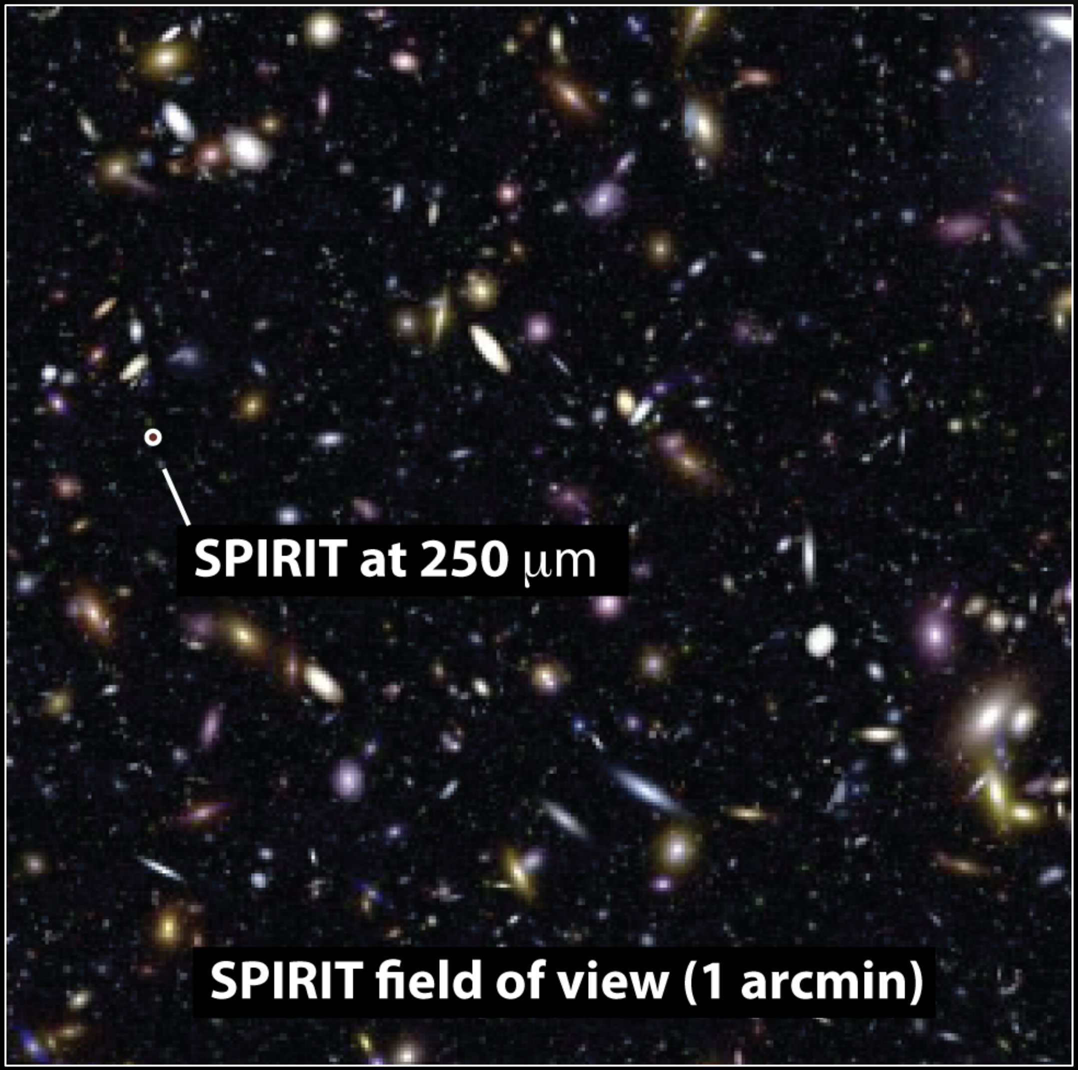
many galaxies per *Herschel* beam

Probing the universe deeply

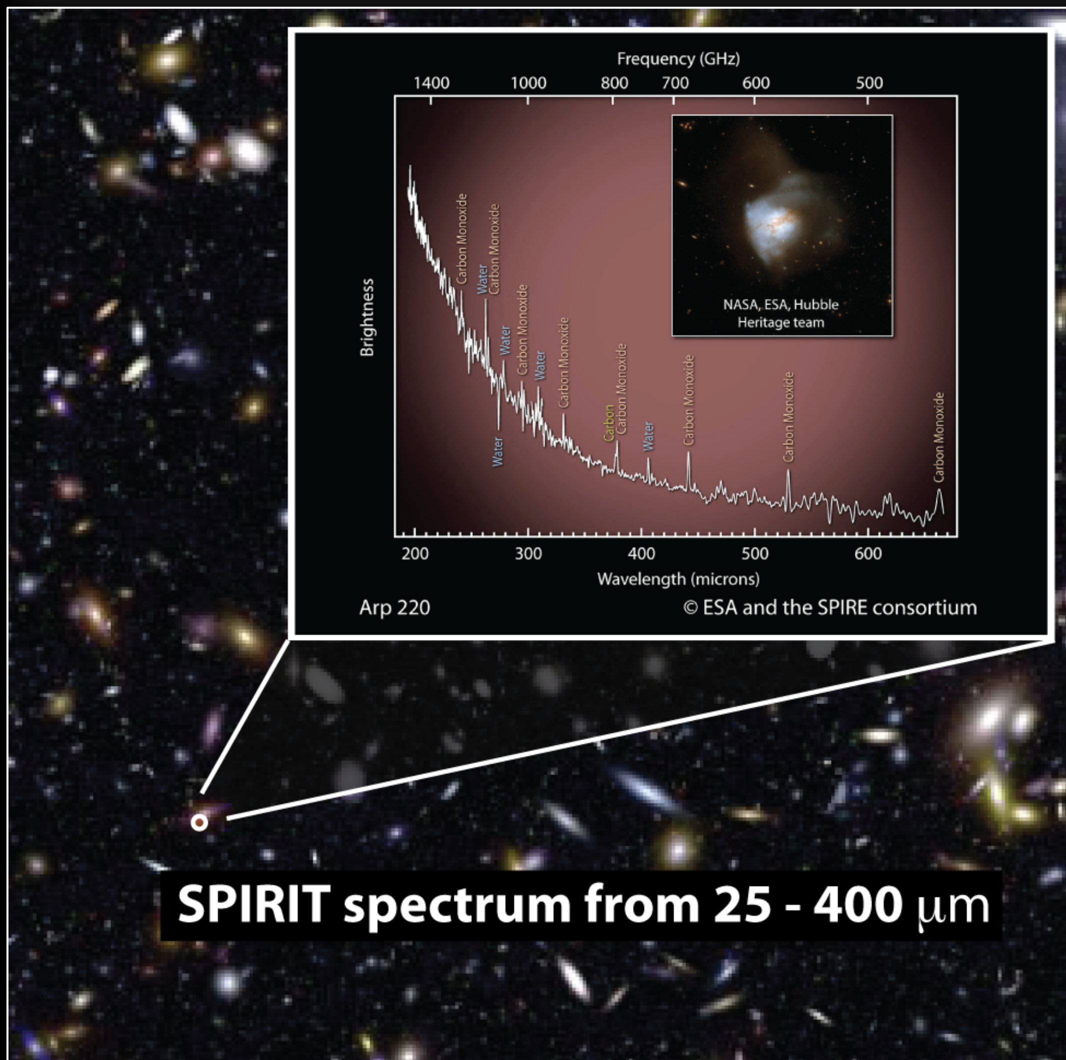


JWST deep field
(1 arcmin cutout)

Probing the universe deeply



Probing the universe deeply



SPIRIT will measure the dominant interstellar gas cooling lines and diagnostic lines in the spectra of individual high-redshift galaxies.

Derived requirements

- Sub-arcsecond angular resolution over the wavelength range 25 – 400 μm (between JWST and ALMA)
  - Image protostellar and debris disks
  - Beat extragalactic source confusion
- Spectral resolution, R ~ 3000 (integral field spectroscopy)
- ~10 μJy continuum, 10^{-19} W/m^2 line sensitivity
  - Detect low surface brightness debris disks
  - Measure SEDs and spectral lines of high-z galaxies
- >1 arcmin instantaneous FOV

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The challenge

- Diffraction imposes a fundamental limit to image resolution

  $\theta = 1.2\lambda/D$ at wavelength λ for a telescope of diameter D

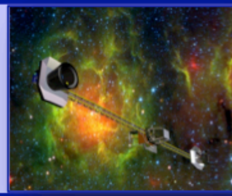
- At far-infrared wavelengths, one needs a very large telescope to view the sky with the resolution of JWST (about 1 km to achieve Hubble-class resolution)
- But, there is another way …

Imaging interferometry

Interferometry is the natural choice when the need for angular resolution surpasses the need for sensitivity as the driver for aperture size.

The 85 cm diameter *Spitzer* telescope demonstrates the extraordinary power of a space-based cryogenic telescope equipped with low-noise detectors. The sky is teeming with far-IR photons!

It's feasible … with a bonus

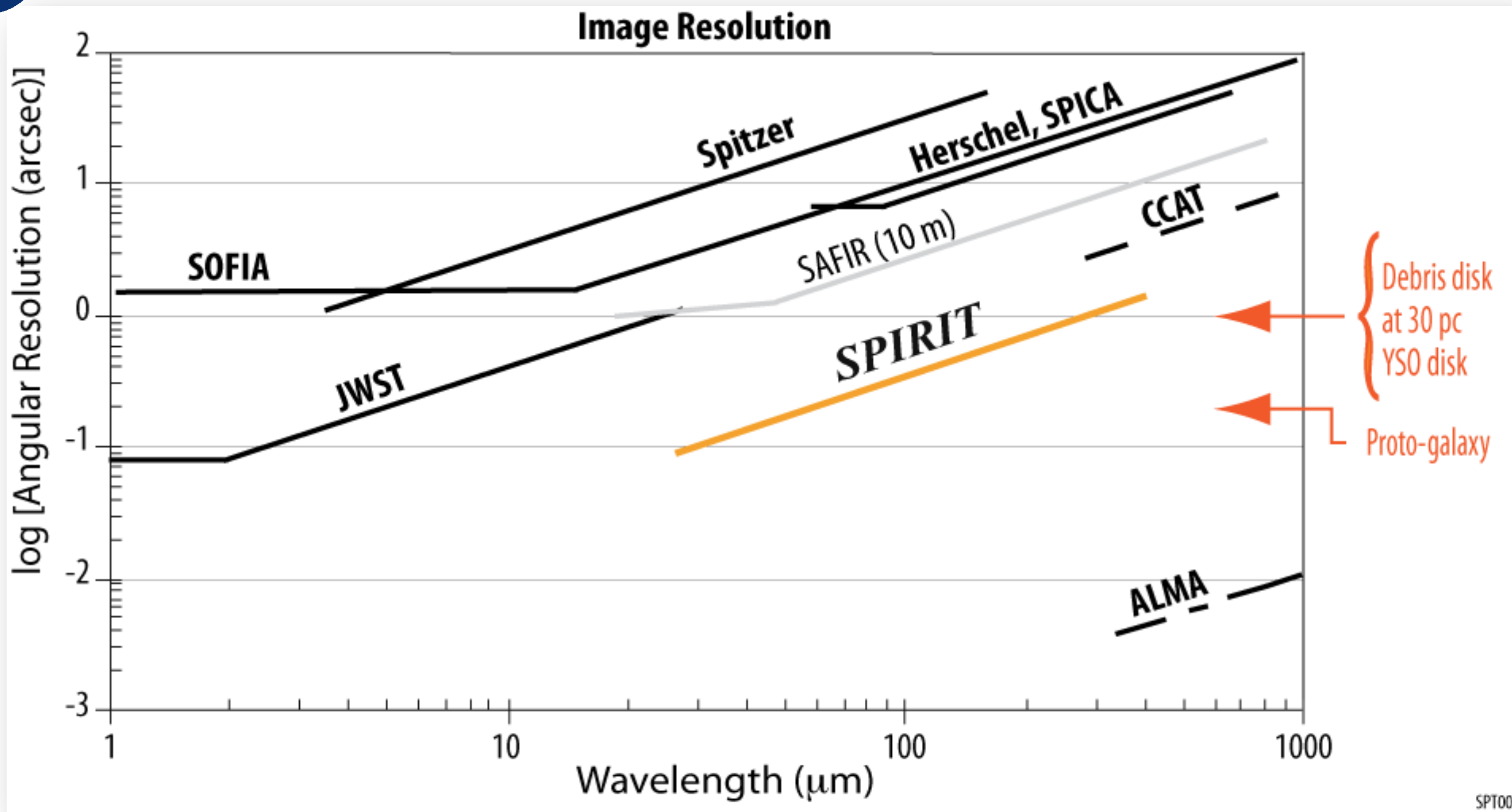


In the far-IR, interferometry (wavefront control, mirror surface accuracy) is not difficult; the technical challenges are those to which IR astronomers are accustomed: detectors and cryogenic temperatures.

An interferometer decouples the design parameters that affect angular resolution from those that impact sensitivity and spectral resolution.

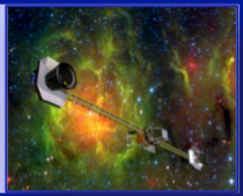
"The human quest to understand our place in the cosmos – How did we get here? – depends on our probing sensitively and in fine detail developing planetary systems and distant galaxies in the far-infrared, and no alternative method is as technically feasible and affordable."

– from the Far-IR Community Plan



Sub-arcsecond angular resolution is sorely lacking in the far-IR, where protoplanetary and debris disks, and even high-z galaxies, are bright and their information content is great.

Outline



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The Space Infrared Interferometric Telescope (SPIRIT)

A Probe-class far-infrared mission to:

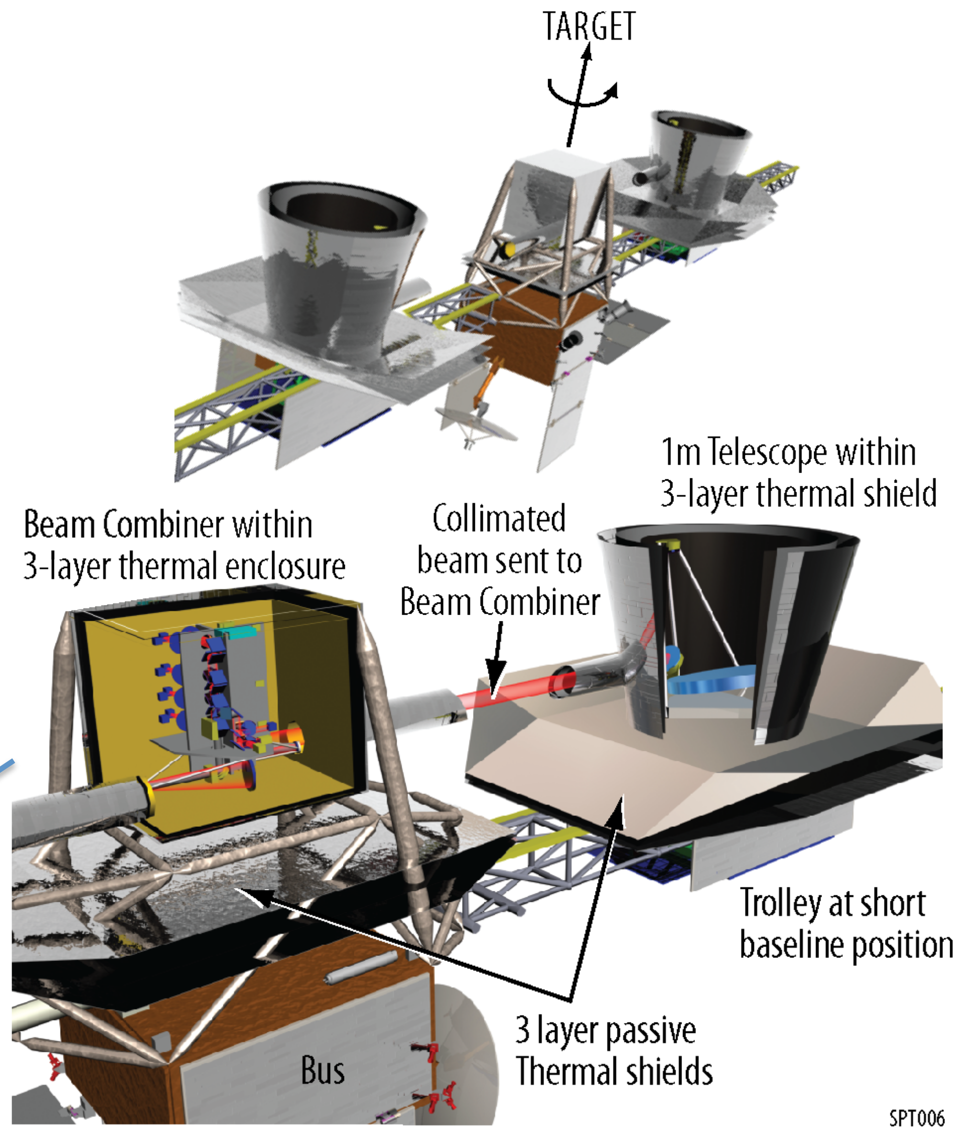
- image protoplanetary disks and measure the distributions of water vapor and ice to learn how the conditions for habitability arise during the planet formation process;
- image structures in a large number of debris disks to find and characterize unseen exoplanets;
- probe the atmospheres of extrasolar giant planets; and
- make profound contributions to our understanding of the formation, merger history, and star formation history of galaxies.

http://astrophysics.gsfc.nasa.gov/cosmology/spirit/

Questions? David.T.Leisawitz@nasa.gov

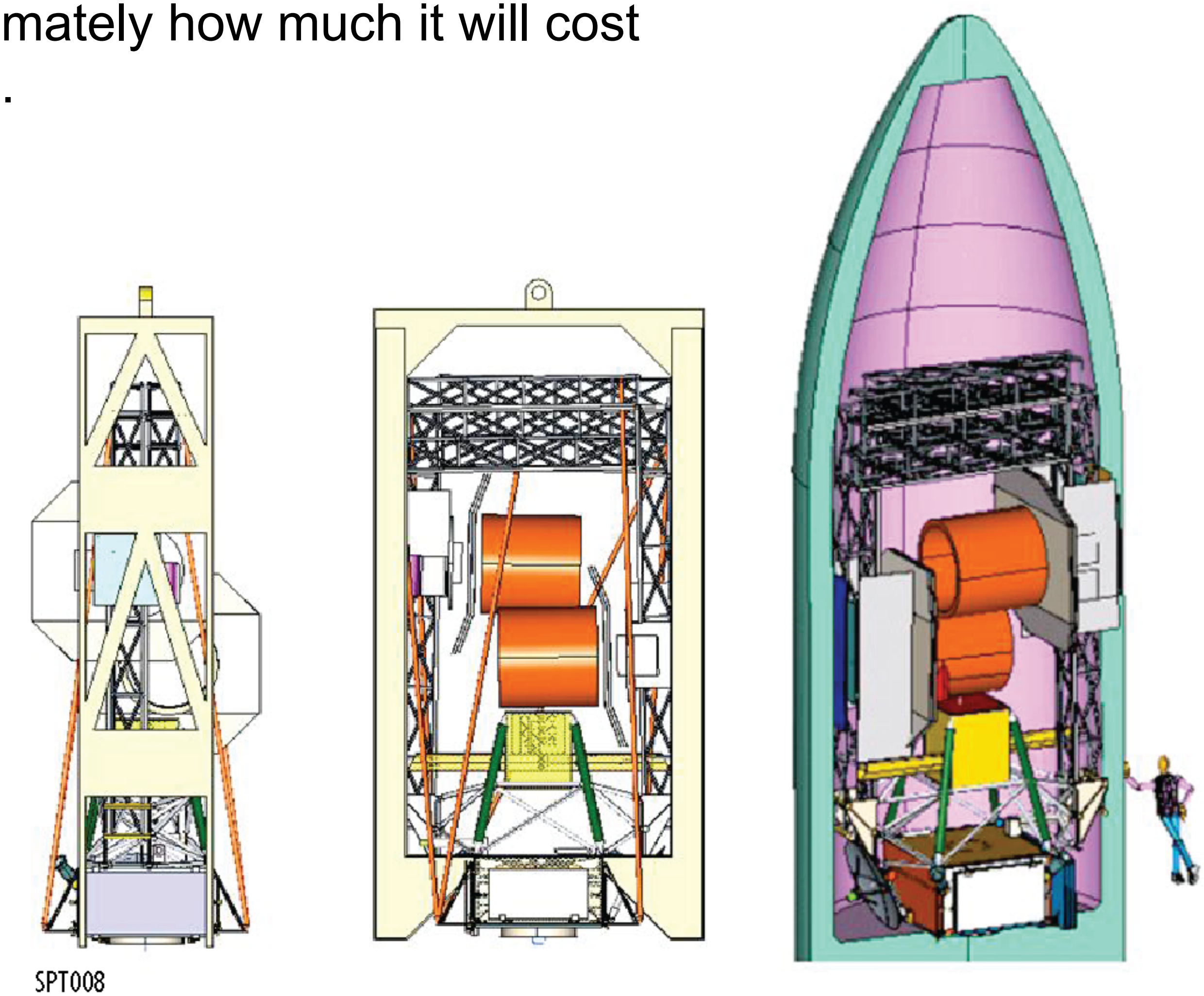
- Wavelength range 25 – 400 μm
- Angular resolution 0.3 (λ/100 μm) arcsec
- Dense u-v plane coverage for high quality imaging
- Integral field spectroscopy over a 1 arcmin FOV
- Spectral resolution $\lambda/\Delta\lambda$ > 3000 in each spatial resolution element
- Sensitivity 10 μJy continuum; 10^{-19} W m^{-2} spectral lines
- Single scientific instrument (“double Fourier” beam combiner)
- Mature technology in time for 2020 Decadal Survey
- Could develop and launch in the next decade with international collaboration

- SPIRIT was studied as a candidate Origins Probe mission
- The concept has matured to Phase A level

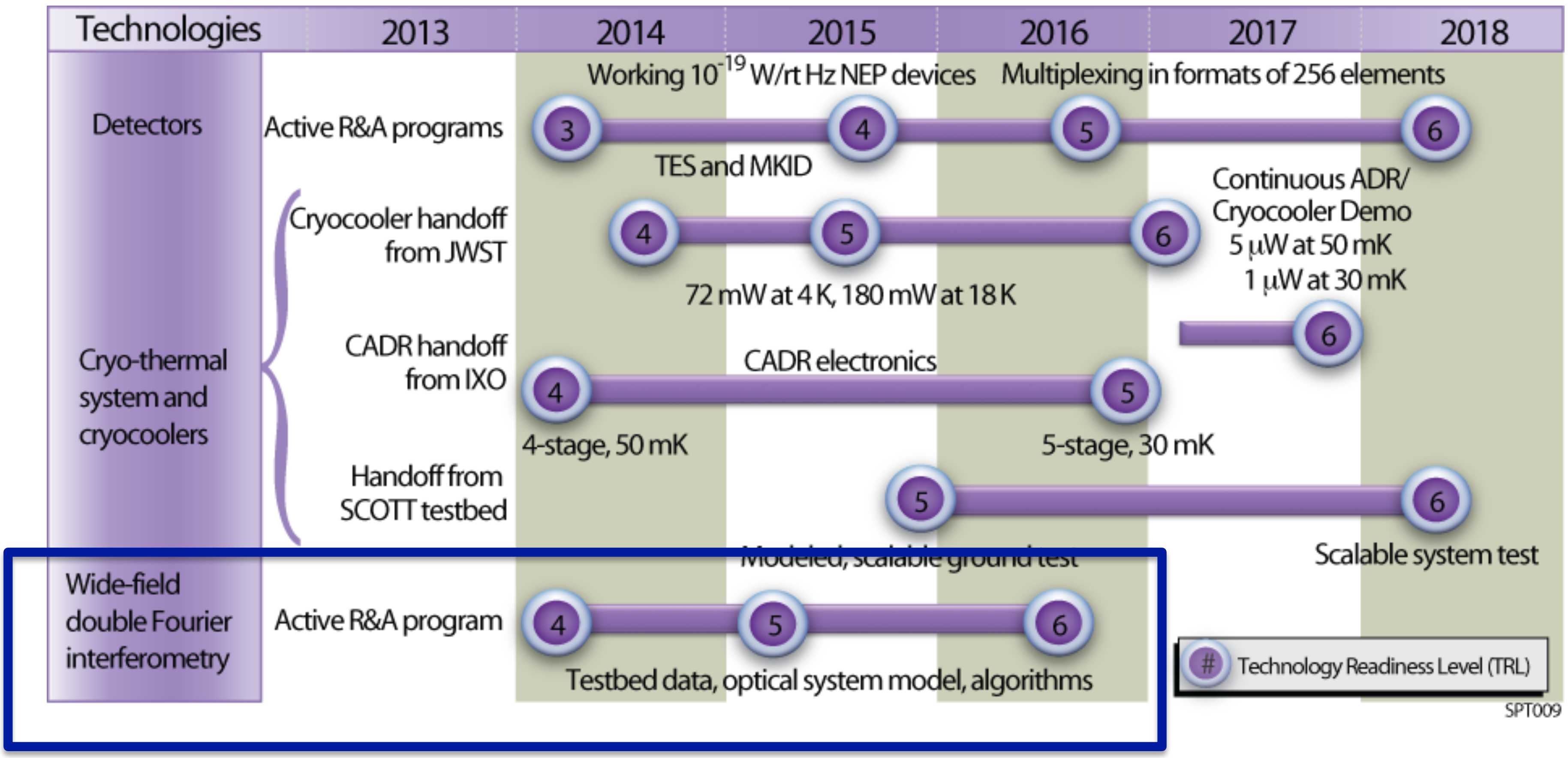


A single instrument

We know how to build, test, launch, and operate SPIRIT, and we know approximately how much it will cost ($1.3B).



SPIRIT technology roadmap



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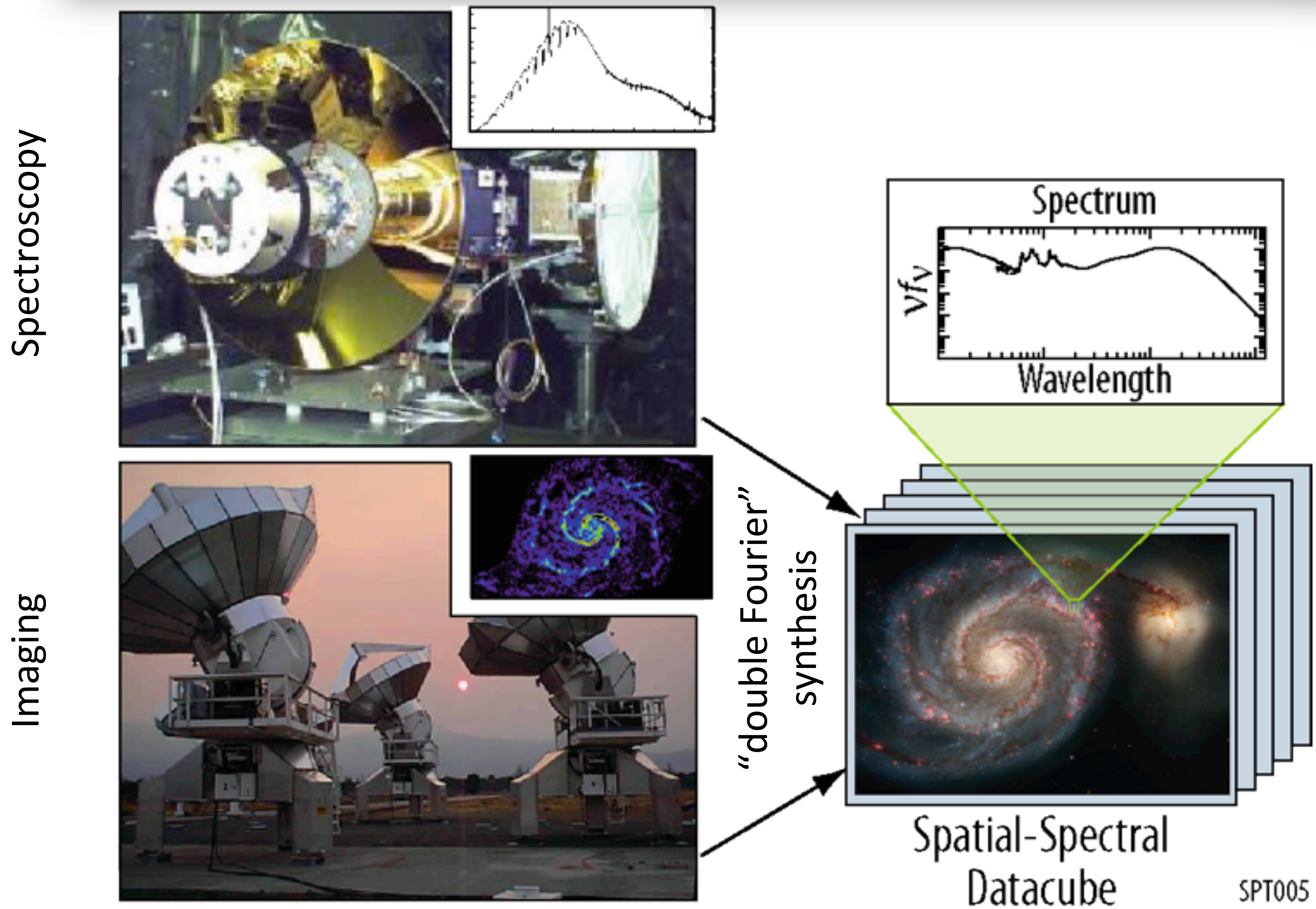
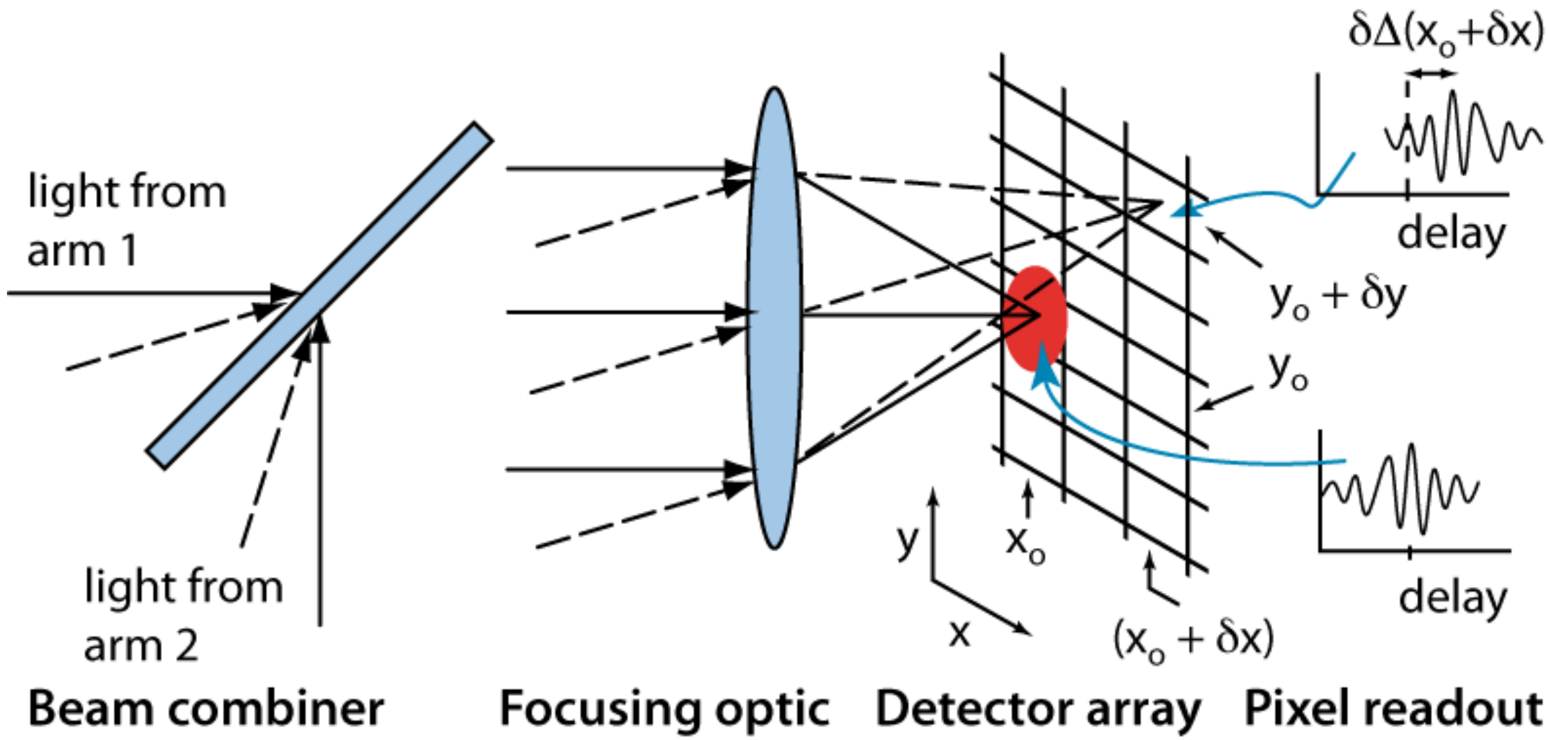
Spatio-spectral Interferometry

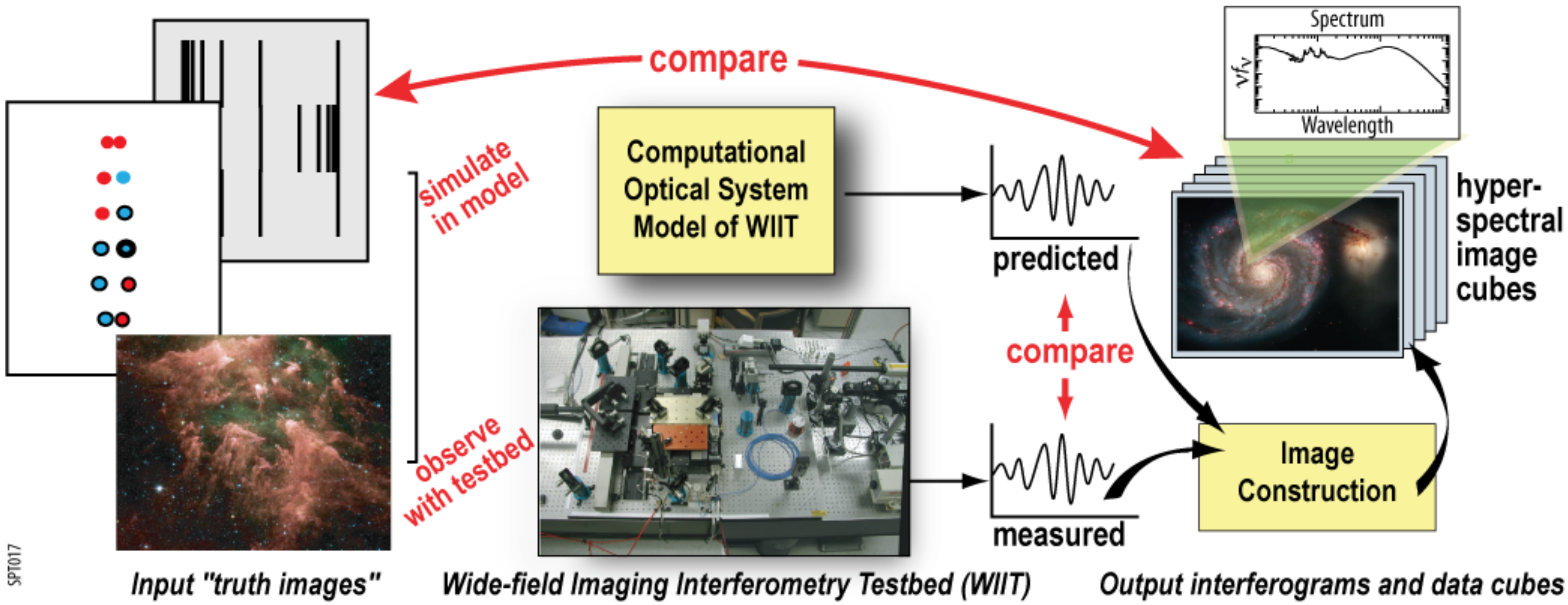


Wide field-of-view interferometry



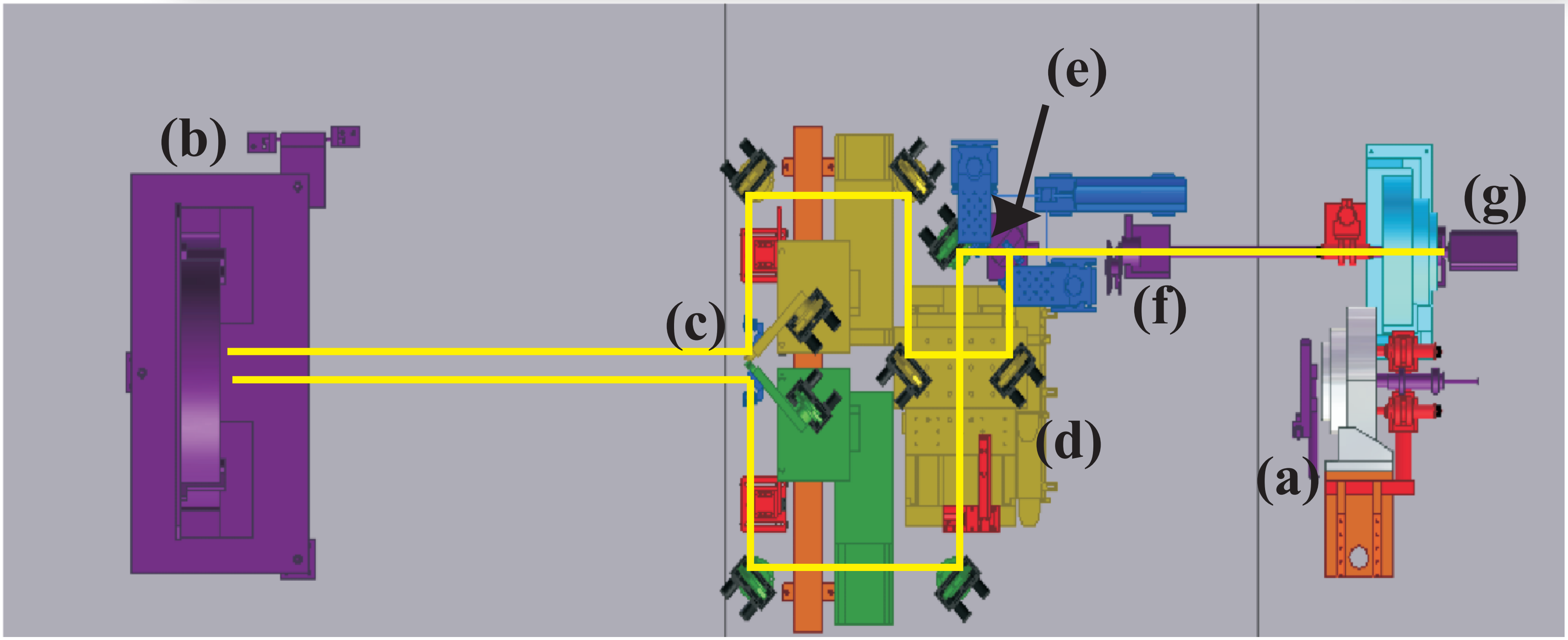
Take advantage of the optical delay scan used to obtain spectroscopic data to compensate for the ZPD shift in external optical delay, δΔ, associated with off-axis field angles.

Experimental approach



Goal: Demonstrate the viability of spatio-spectral interferometry in realistic circumstances, recognizing that far-IR astronomical sources are spatially and spectrally complex.

Wide-field Imaging Interferometry Testbed

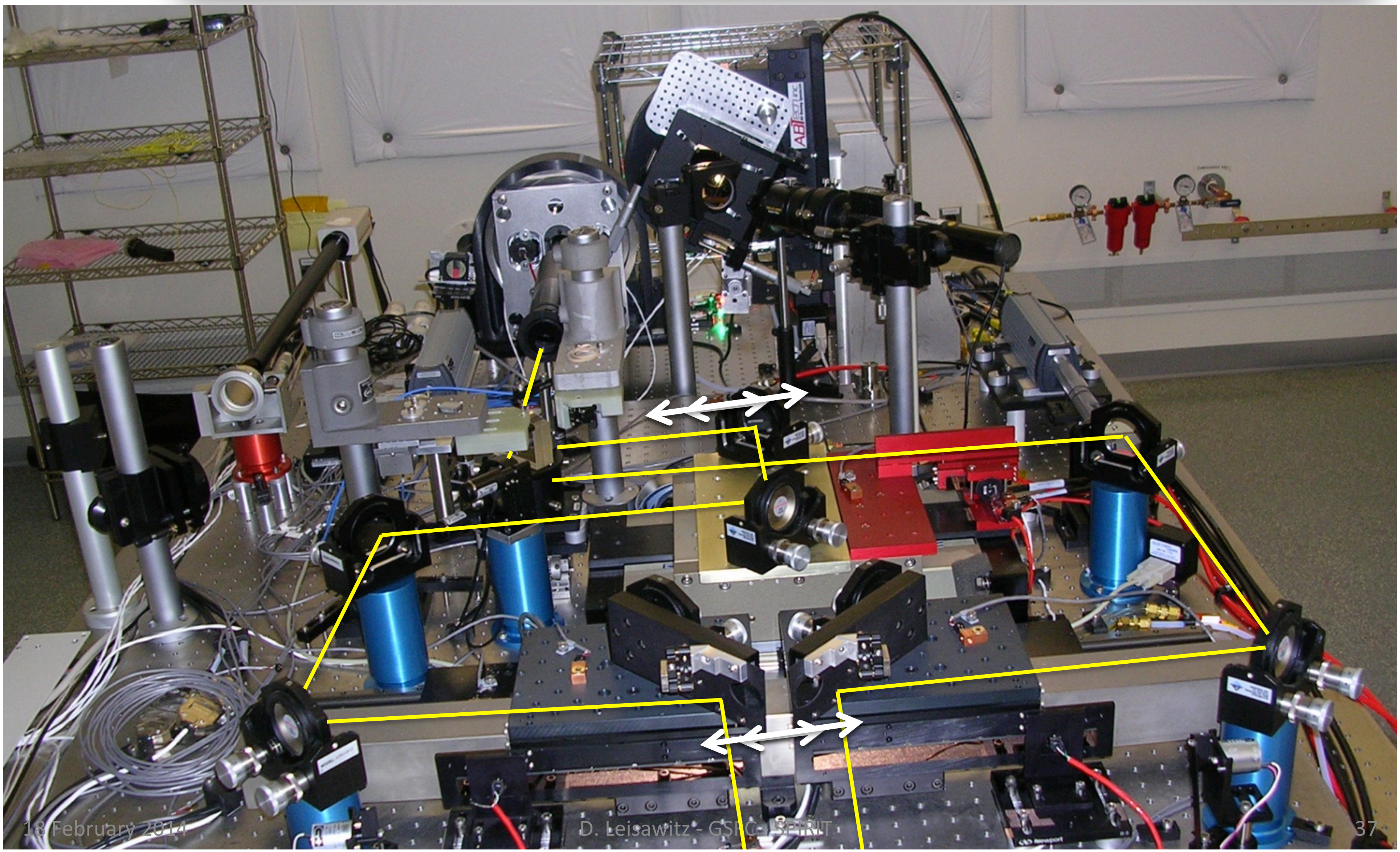


(a) Light source *
(b) Parabolic mirror
(c) Baseline mirrors (2)
(d) Optical delay stage

(e) Beamsplitter (combiner)
(f) Lens system
(g) Camera

* Calibrated Hyperspectral Image Projector

Wide-field Imaging Interferometry Testbed



When operated in Goddard's Advanced Interferometry and Metrology (AIM) Lab, WIIT is functionally and operationally equivalent to SPIRIT: its performance is limited by instrumental factors rather than environmental conditions.

The testbed has been thoroughly characterized and its performance is well understood.

Understanding instrumental visibility loss

Table 1a: Sources of Visibility Loss in WIIT

Source	Parameter ID	Parameter Value	Visibility Formula	Visibility Value
Alignment				
Coalignment at pupil	$1-\eta$	0.975	$1-\eta$	0.975
Tip/tilt at exit pupil	α	0.5"	$2J_1(\pi D\alpha/\lambda)/(\pi D\alpha/\lambda)$	0.995
Optics (RMS wavefront error)				
Collimating mirror	δ	15.75 nm	$\exp[-2\pi\delta/\lambda]^2$	0.97
Beamsplitter	δ	15 nm	$\exp[-2\pi\delta/\lambda]^2$	0.98
Interferometer mirrors	δ, N	10 nm, 9 mirrors	$\exp[-2N\pi\delta/\lambda]^2$	0.92
Intensity Mismatch	ρ	92%	$2/(\rho^{1/2} + \rho^{-1/2})$	0.999
Positional Knowledge	δx	9.89 nm	$\mathrm{sinc}(2\pi\delta x/\lambda)$	0.999
Frame Exposure Time	t_{obs}	100 ms	$\mathrm{sinc}(2\pi v_{stage} t_{obs}/\lambda)$	0.9995
Total Visibility Loss				0.84

The greatest single source of fringe visibility loss is imperfect mirrors. The visibility we measure in the lab on an unresolved point source is 0.84, matching our theoretical expectation.

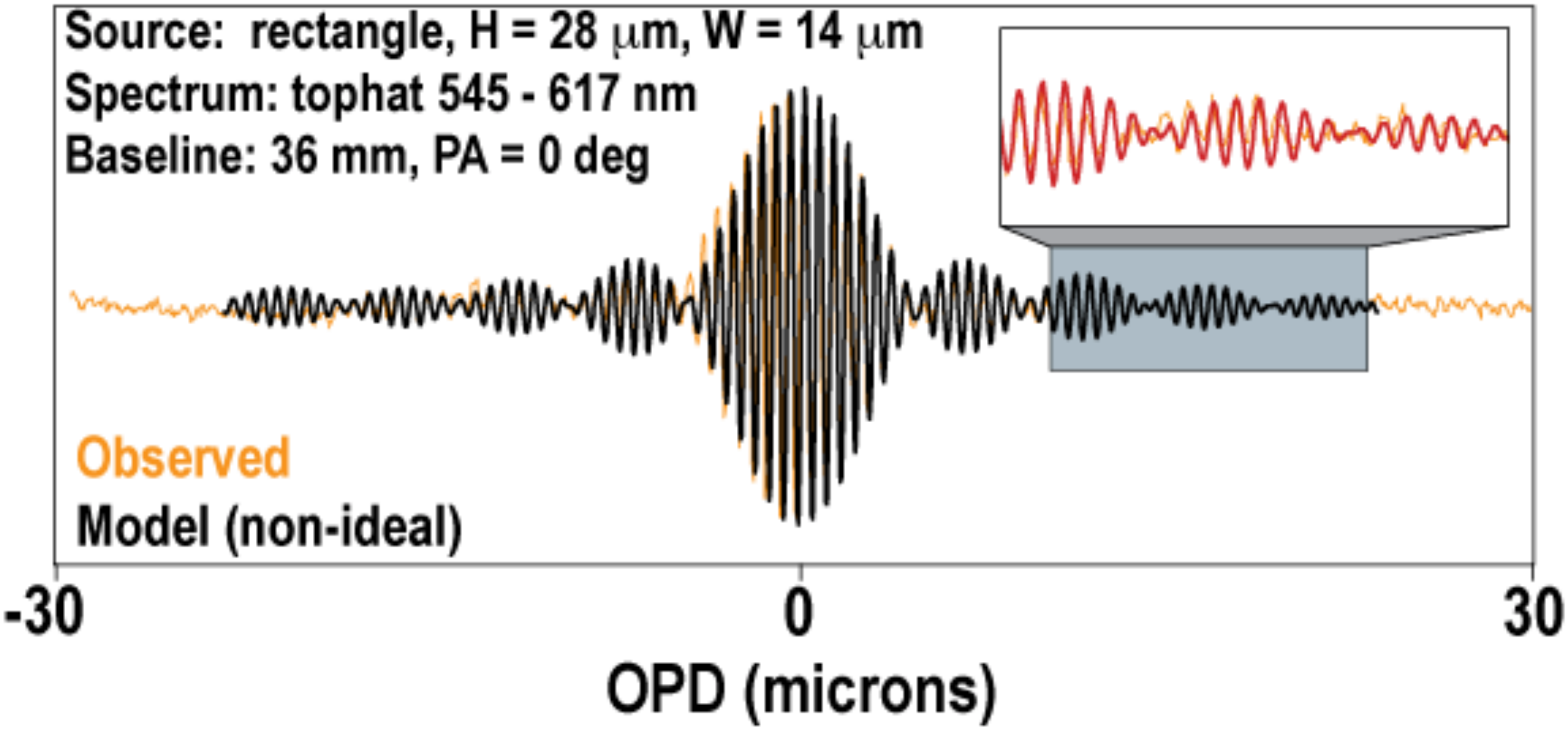
Understanding visibility uncertainty

Table 1b: Sources of Visibility Uncertainty in WIIT

Source	Parameter ID	Parameter Value	Visibility Uncertainty Formula	Visibility Uncertainty Value
Light Source				
Tip/tilt at exit pupil	$\delta I/I$	<0.5%	$\delta I/I$	<0.71%
Camera				
Bit Noise	σ_{bit}	0.5 counts	σ_{bit}/N_{cnts}	0.011%
Photon Counting	N_{elec}	2×10^5 e^-	$[(2/N_{elec})(2^{16}/N_{cnts})]^{1/2}$	1.40%
Camera noise (read noise, dark current)	σ_{det}	15 e^-	$(2\sigma_{det}/N_{elec})(2^{16}/N_{cnts})$	0.22%
Total Visibility Uncertainty				1.59%

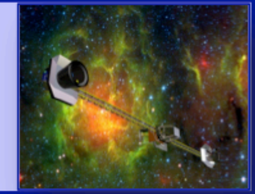
The typical visibility uncertainty is ~2%, dominated by photon noise.

Observed and model interferograms



Our computational optical system model predicts interferograms that closely match those seen in the lab.

An experiment



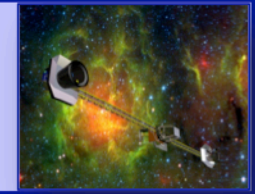
Nominal source configuration

Each source is a "binary star"	6	5	4	3	2	1
	A	A	A	C	D	D
	A	B	C	D	E	E

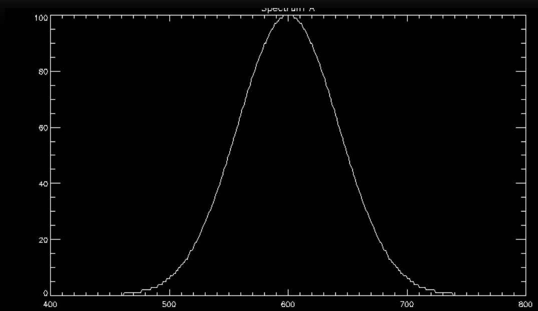
Letters indicate the spectrum of each "star"

- A = broadband (red)
- B = broadband (blue)
- C = broadband (blue) with narrow line (λ_1)
- D = broadband (blue) with weak narrow line (λ_2)
- E = broadband (red) with broad feature

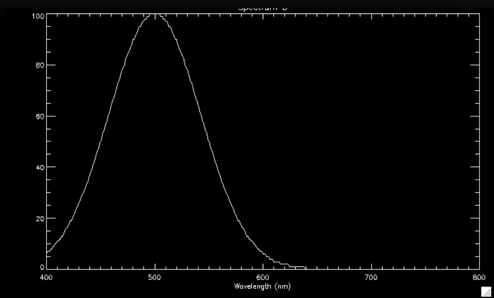
Nominal spectra



A



B



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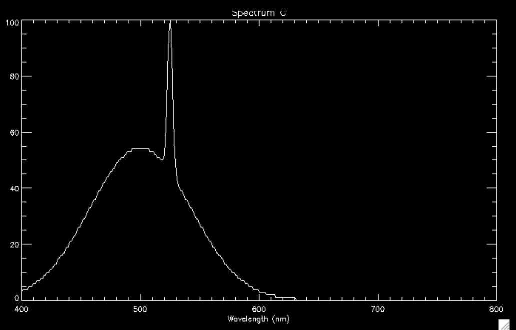
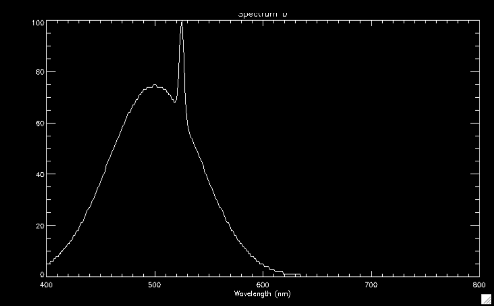
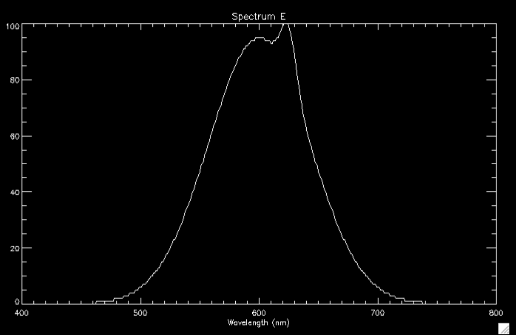


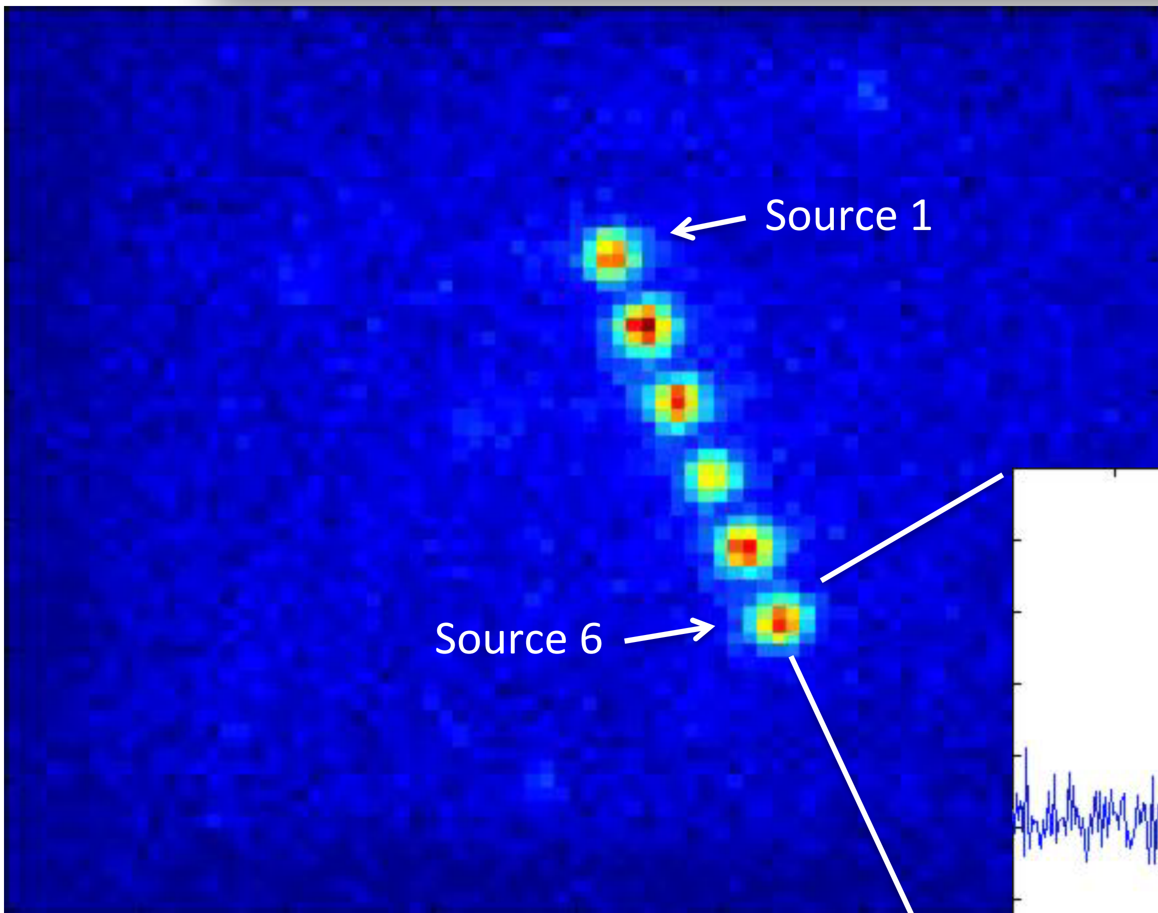
D

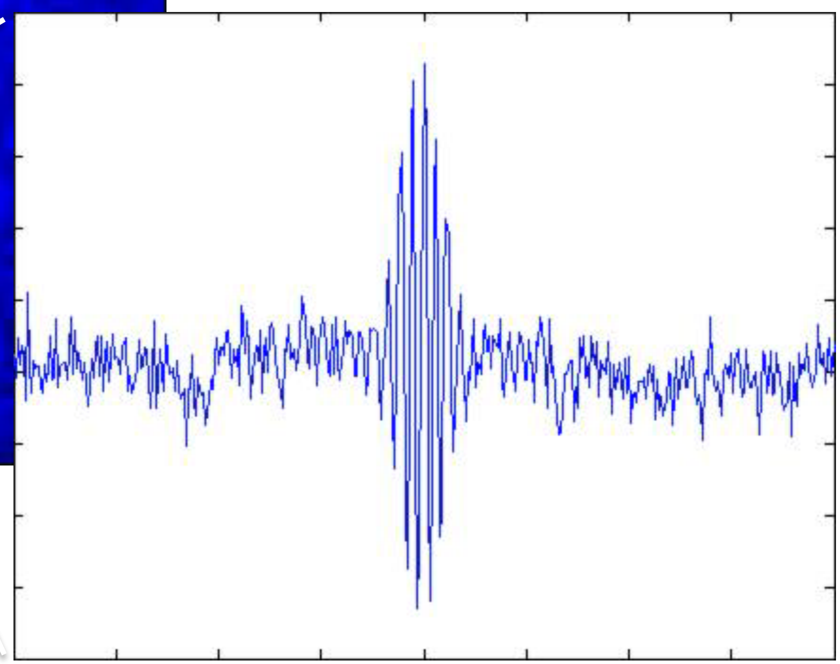


E



Representative testbed data



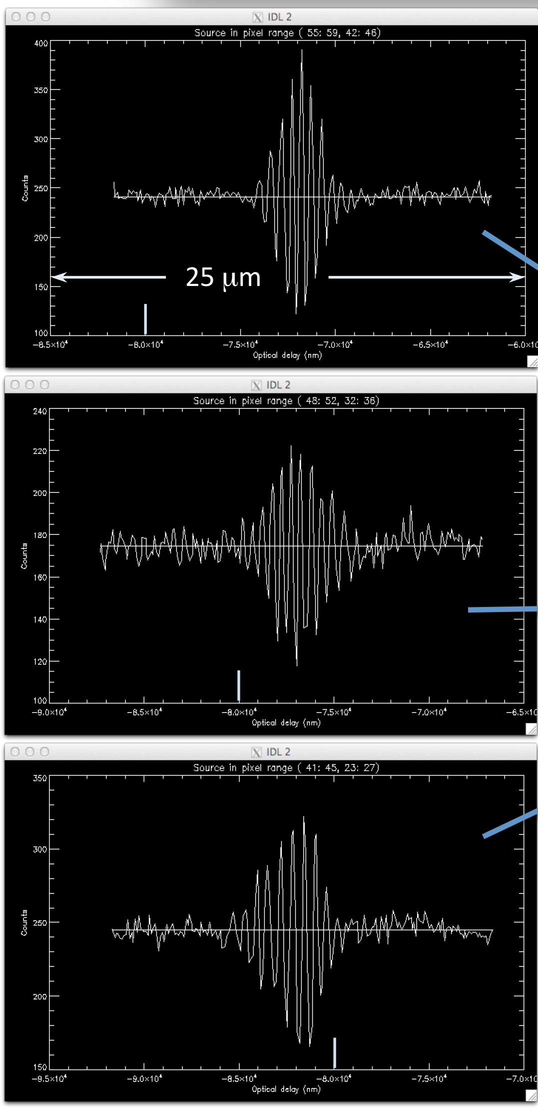


WIIT data from 2013-05-02:

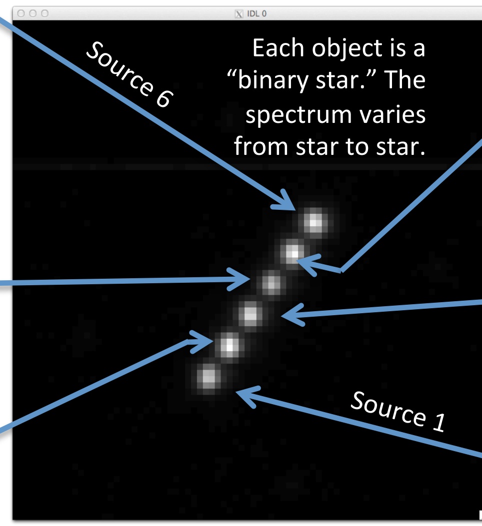
- Baseline: 56 mm
- PA = -67.5 deg

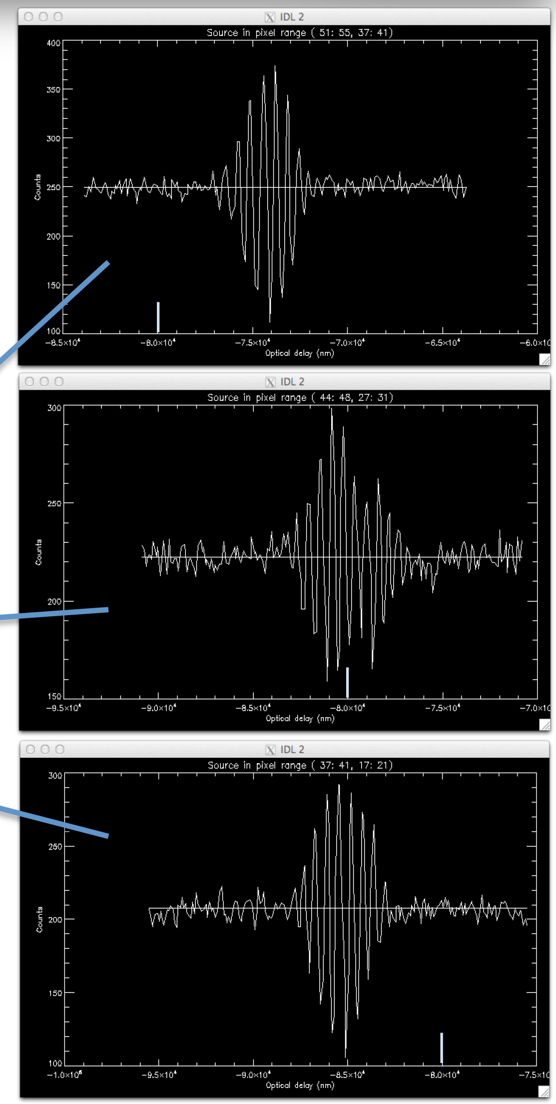
421 baselines like this; dense *u*-*v* plane coverage.

Representative testbed data



Spatial and spectral information is encoded in the interferograms.

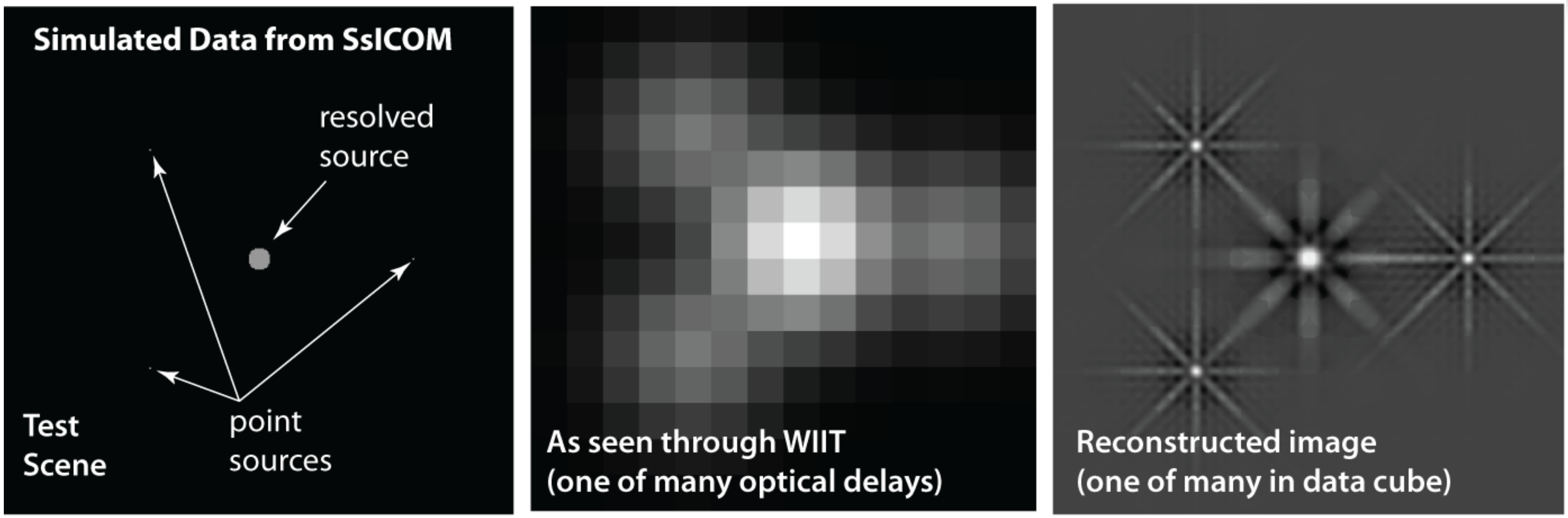




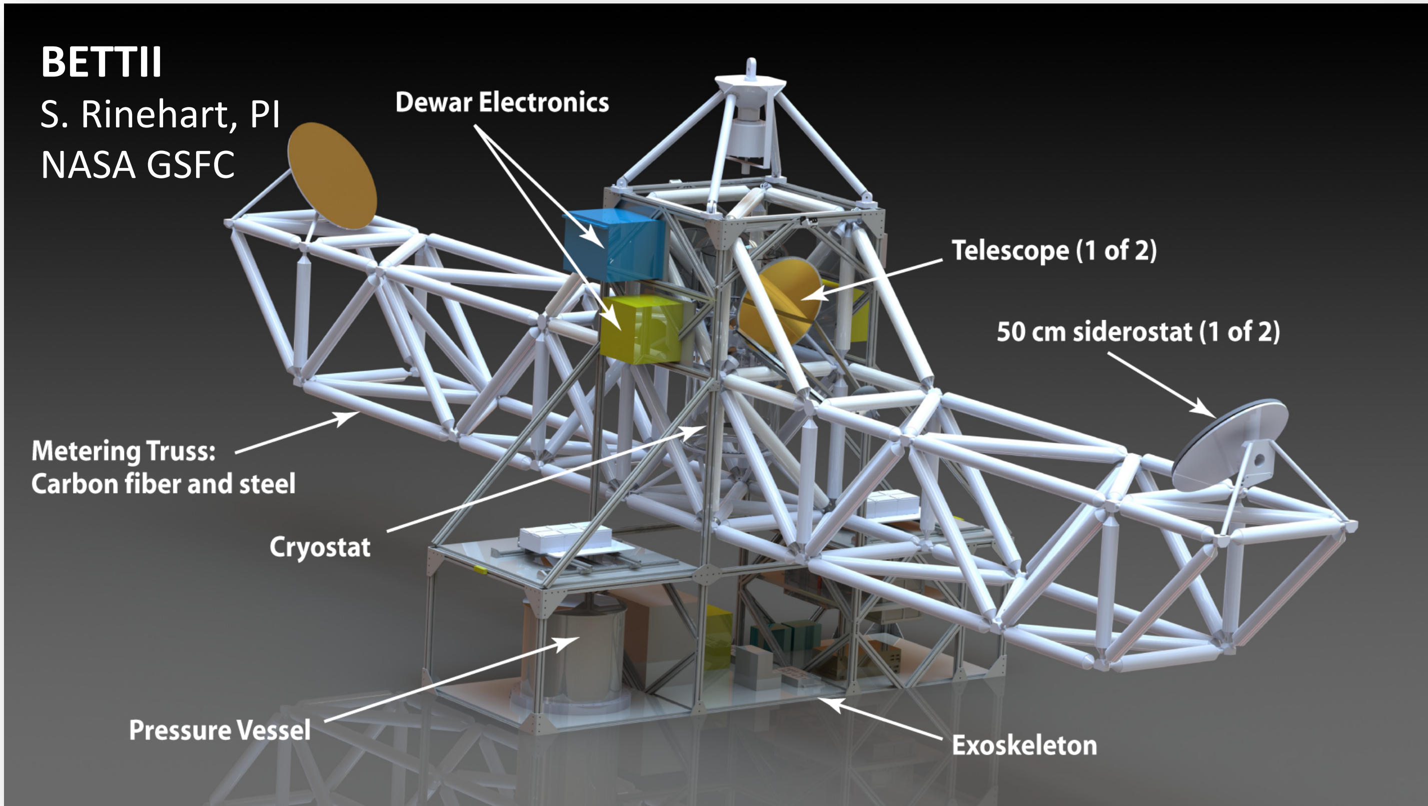
WIIT data from 2013-05-02:

- Baseline: 66 mm
- PA = -54.0 deg

“Double Fourier” synthesis

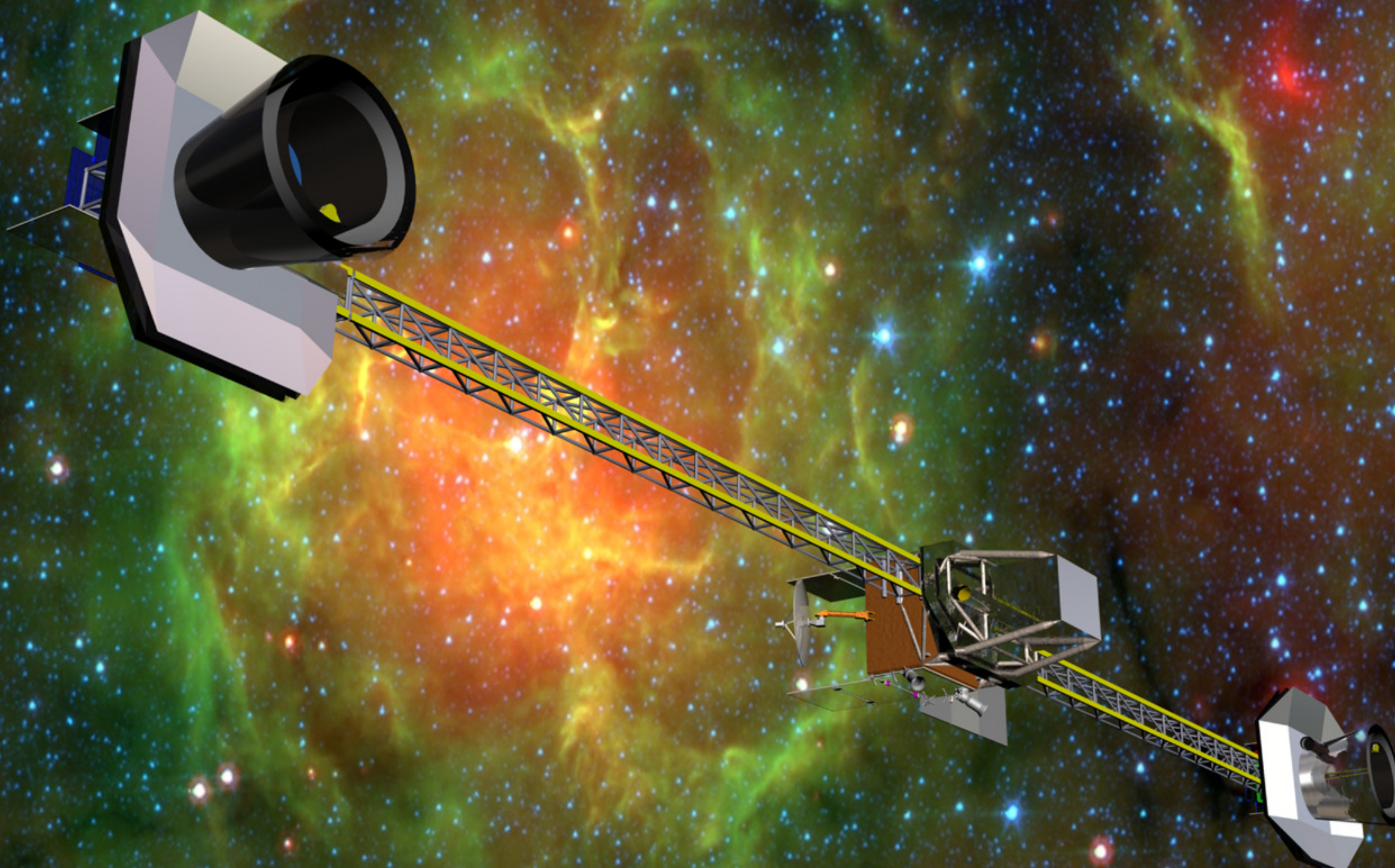


Balloons will come first



The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is under development and will fly in ~2015. Japan's Far-IR Interferometric Telescope Experiment (FITE; H. Shibai, PI) will soon have its maiden flight.

Maybe next decade, SPIRIT …



Summary

- Science questions of Decadal importance drive the need for high-resolution imaging and spectroscopy at far-IR wavelengths
  - Formation and habitability of planets
  - Evolution and star formation history of galaxies
- Spatio-spectral interferometry is the natural solution
  - plenty of photons, so we don't need enormous light-collecting area, but
  - we do need much better angular resolution and integral field spectroscopy
- We're developing this technique in the lab
- Some day, maybe in the next decade, you'll be able to propose to make observations with SPIRIT

BACKUP