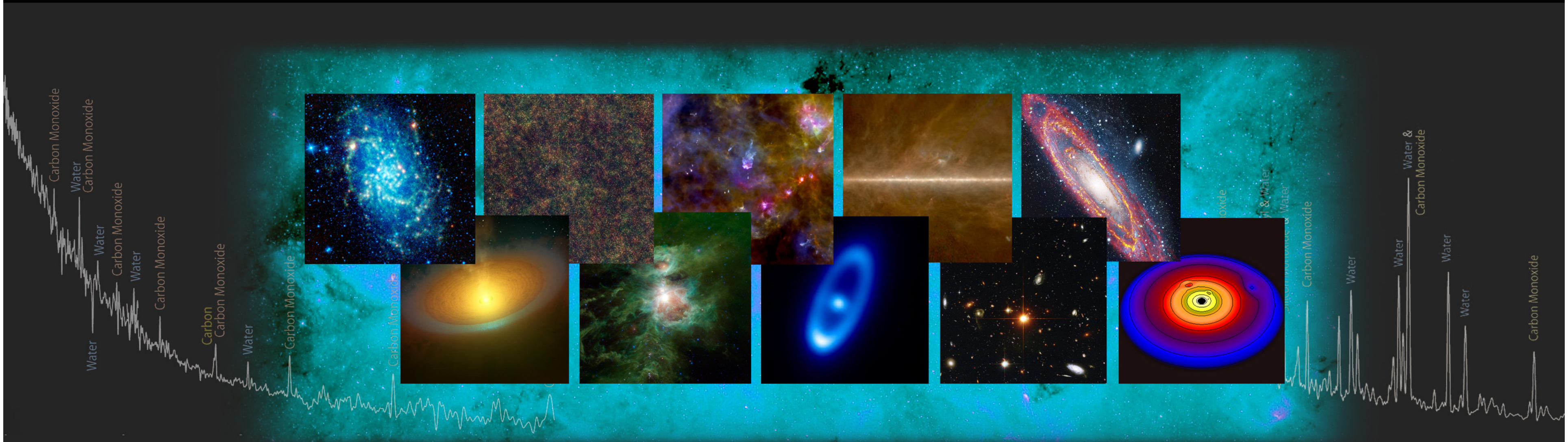
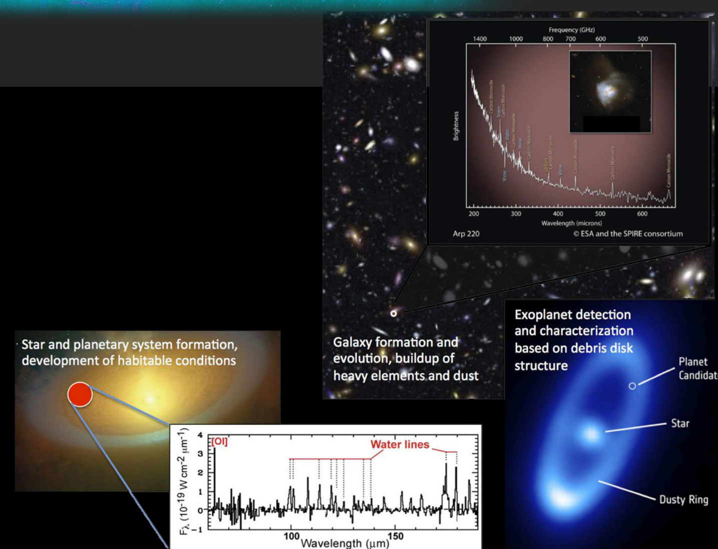
Far-IR Interferometers: Measurement Capabilities and Trade Space



Dave Leisawitz

NASA/GSFC



Why Interferometry?

Interferometry provides the flexibility needed to satisfy science-driven measurement requirements within externally-imposed constraints, and without paying a penalty for a self-imposed constraint.

Space mission design is systems engineering; it's an optimization problem.

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Measurement Requirements

Parameter	Units	Value or Range
Wavelength range	μm	25 - 400
Angular resolution	arcsec	< 1
Spectral resolution, $(\lambda/\Delta\lambda)$	dimensionless	
Continuum sensitivity	μJy	
Spectral line sensitivity	10^{-19} W m^{-2}	
Instantaneous FoV	arcmin	
Number of target fields	dimensionless	
Field of Regard	sr	

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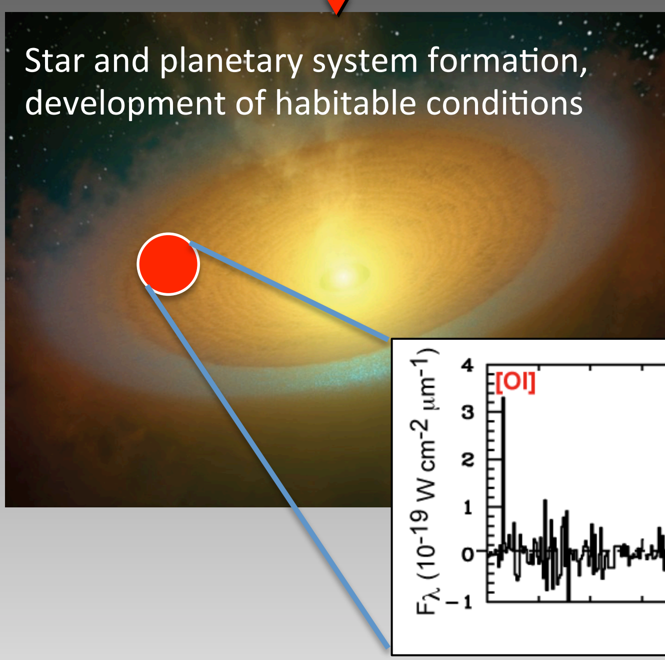
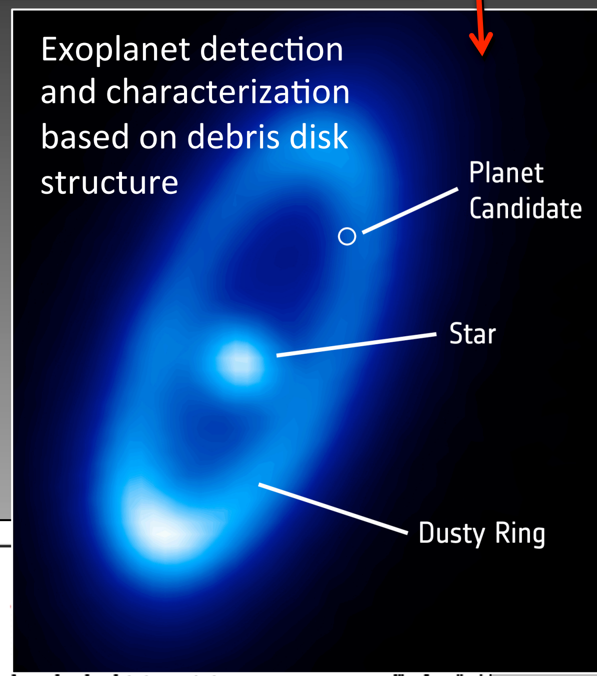
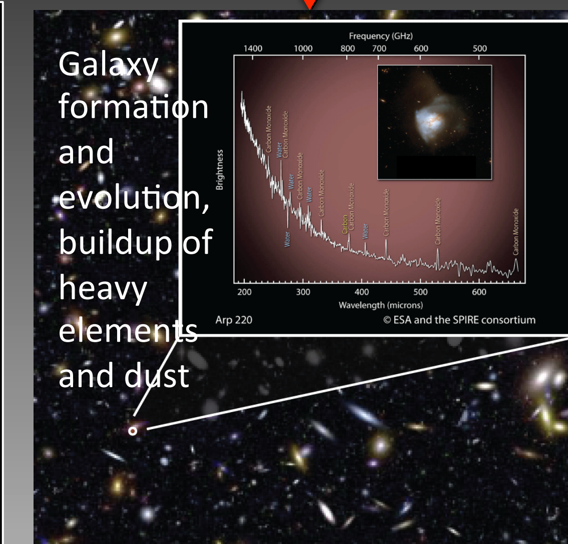
Wavelength range	µm	25 - 400
Angular resolution	arcsec	**< 1**







Diffraction is our Enemy

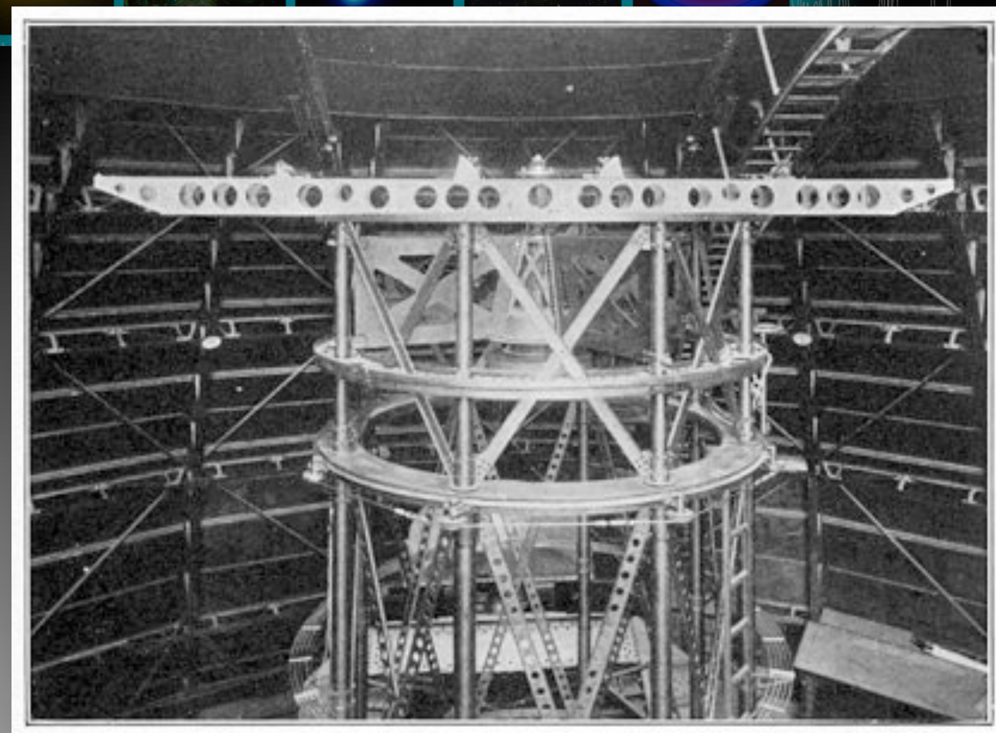
Parameter	Units	Value or Range
Wavelength range	μm	25 - 400
Angular resolution	arcsec	**< 1**

$$\theta = 1.22\lambda/D$$

$$\mathbf{D = 1.22\lambda/\theta}$$

$$\mathbf{= 25\ (\lambda/100\ \mu m)(\theta/1\ arcsec)^{-1}\ meters}$$

Michelson is our Friend



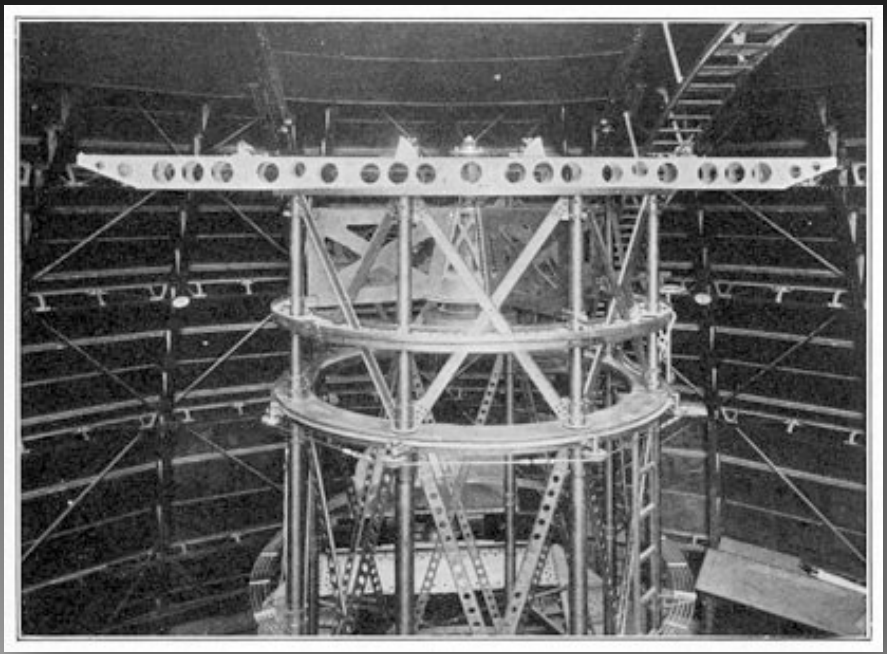
Stellar Interferometer with 6 m baseline , c. 1919

$$\theta = \lambda/2b$$

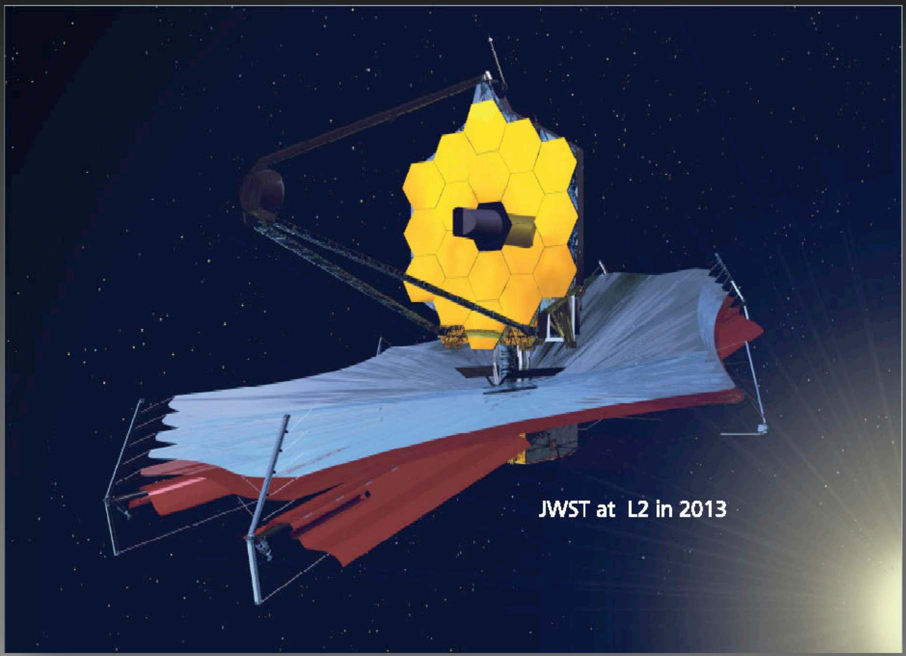
$$b = \lambda/2\theta$$

$$= 10.3\ (\lambda/100\ \mu m)(\theta/1\ arcsec)^{-1}\ meters$$

A Century of Interferometry



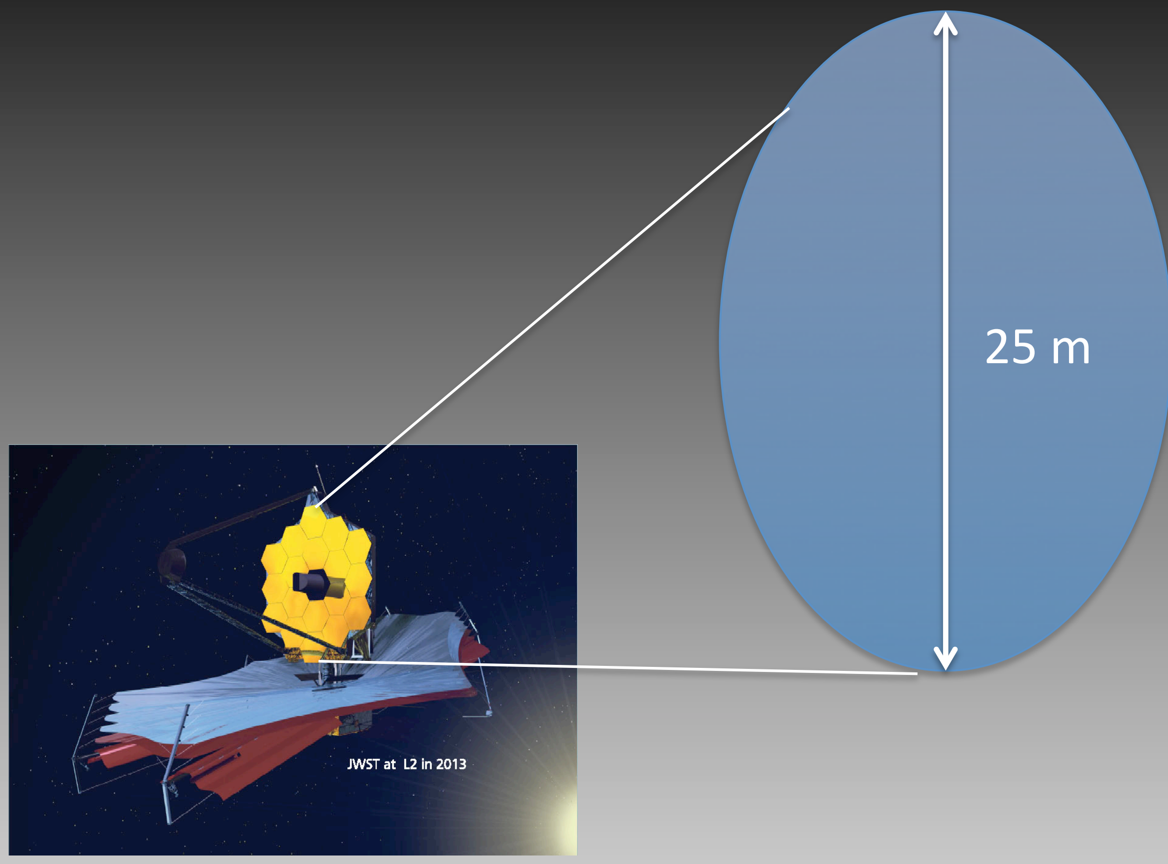
Michelson's Stellar Interferometer, c. 1919



James Webb Space Telescope, c. 2018

These are both Fizeau interferometers.

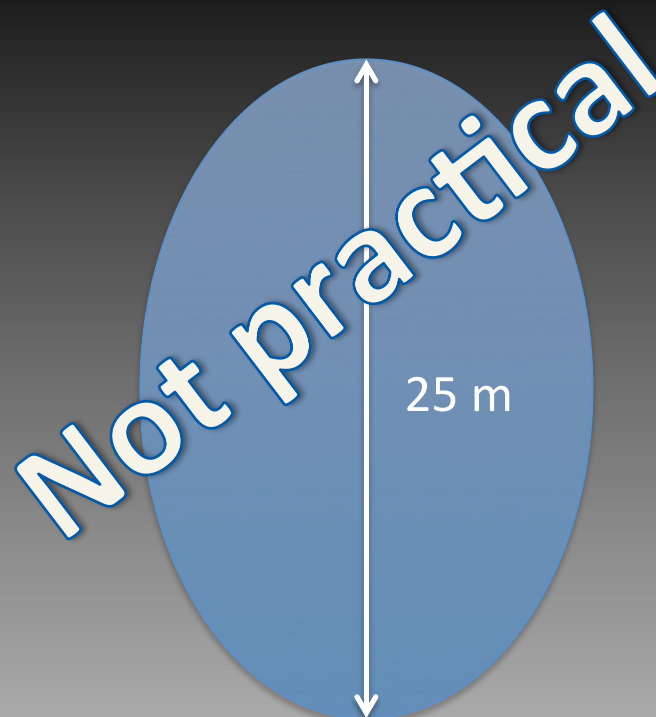
Single Aperture: A Self-imposed Constraint



Single Aperture: A Self-imposed Constraint

As discussed by Wright (1999; see www.astro.ucla.edu/~wright/Jun99AAS/):

- a background-limited, diffraction-limited telescope this size would reach the confusion noise floor (~100 μJy) in about 5 milliseconds!
- The integration time needed to reach a given flux with an interferometer goes as $(b/D)^4$, a steep function, but the integration times for b = D are so short that "working with b/D as large as 30 is very practical."



Practical

Single Aperture: A Self-imposed Constraint

If the goal is to achieve sub-arcsecond angular resolution with adequate sensitivity, it makes no sense to impose the constraint that the aperture should be monolithic and needlessly large.

Large means more mass to cool to ~4 K, more mass to launch, and more $s.

Flexibility to Meet Measurement Requirements

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Measurement Requirements
Wavelength range
Angular resolution
Spectral resolution, ($\lambda/\Delta\lambda$)
Continuum sensitivity
Spectral line sensitivity
Instantaneous FoV
Number of target fields
Field of Regard

Design parameters

- Maximum baseline
- *u-v* plane coverage

- Optical delay scan range (FTS) for $\lambda/\Delta\lambda$ up to ~10^4
- Heterodyne for $\lambda/\Delta\lambda >> 10^3$

- Aperture size
- Number of telescopes

- Number of detector pixels
- Optical delay scan range to equalize path length

- Sun shield size and configuration

Many knobs to turn in design and operation. Nothing is wasted or over-constrained.

First Look at the Trade Space: Heterodyne vs. Direct Detection

Heterodyne detection

Pros:

- Spectral resolution >10^5

Cons:

- Quantum noise-limited sensitivity
- Small FoV
- Limited *u-v* coverage if apertures are free-flying

Direct detection

Pros:

- Astrophysical background photon noise-limited sensitivity
- Imaging and spectroscopy in 1 instrument

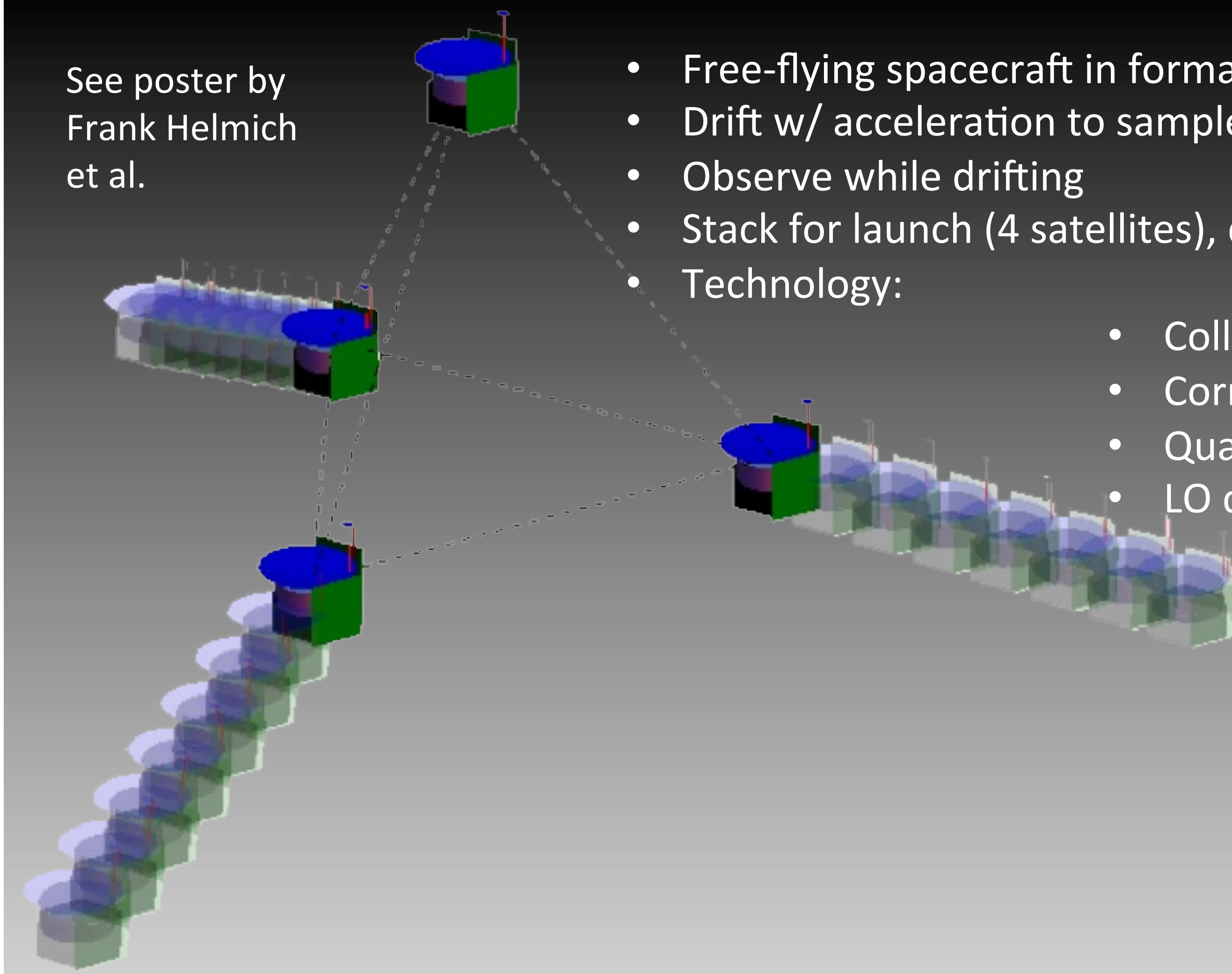
Cons:

- Spectral resolution <10^4

ESPRIT Concept: Heterodyne

Exploratory Submillimeter Space Radio-Interferometric Telescope

See poster by Frank Helmich et al.



- Free-flying spacecraft in formation
- Drift w/ acceleration to sample baselines up to ~50 m
- Observe while drifting
- Stack for launch (4 satellites), deployable secondary mirrors
- Technology:
  - Collision avoidance
  - Correlator (in space)
  - Quantum Cascade Laser
  - LO distribution

ESPRIT Concept: Heterodyne

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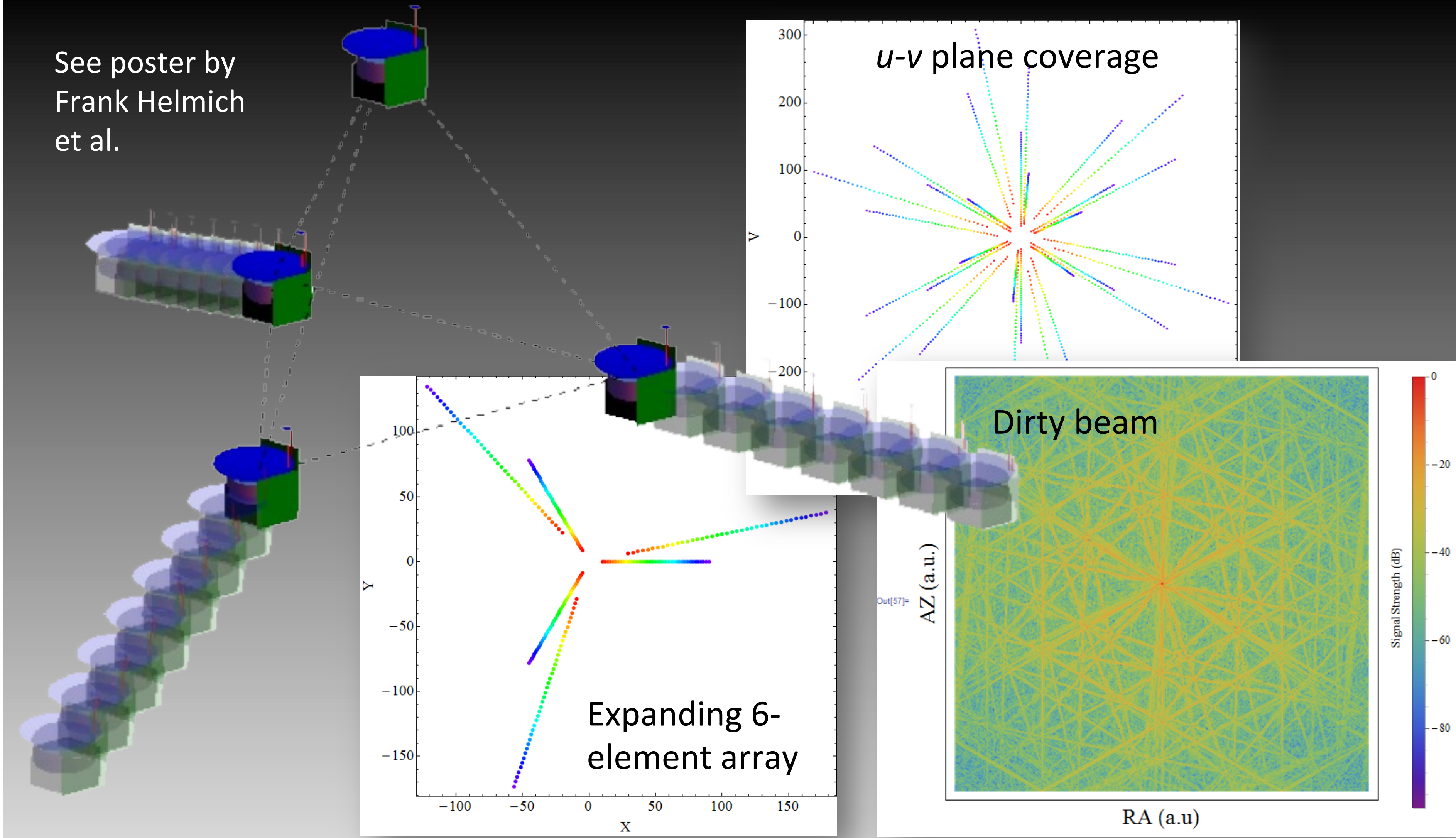

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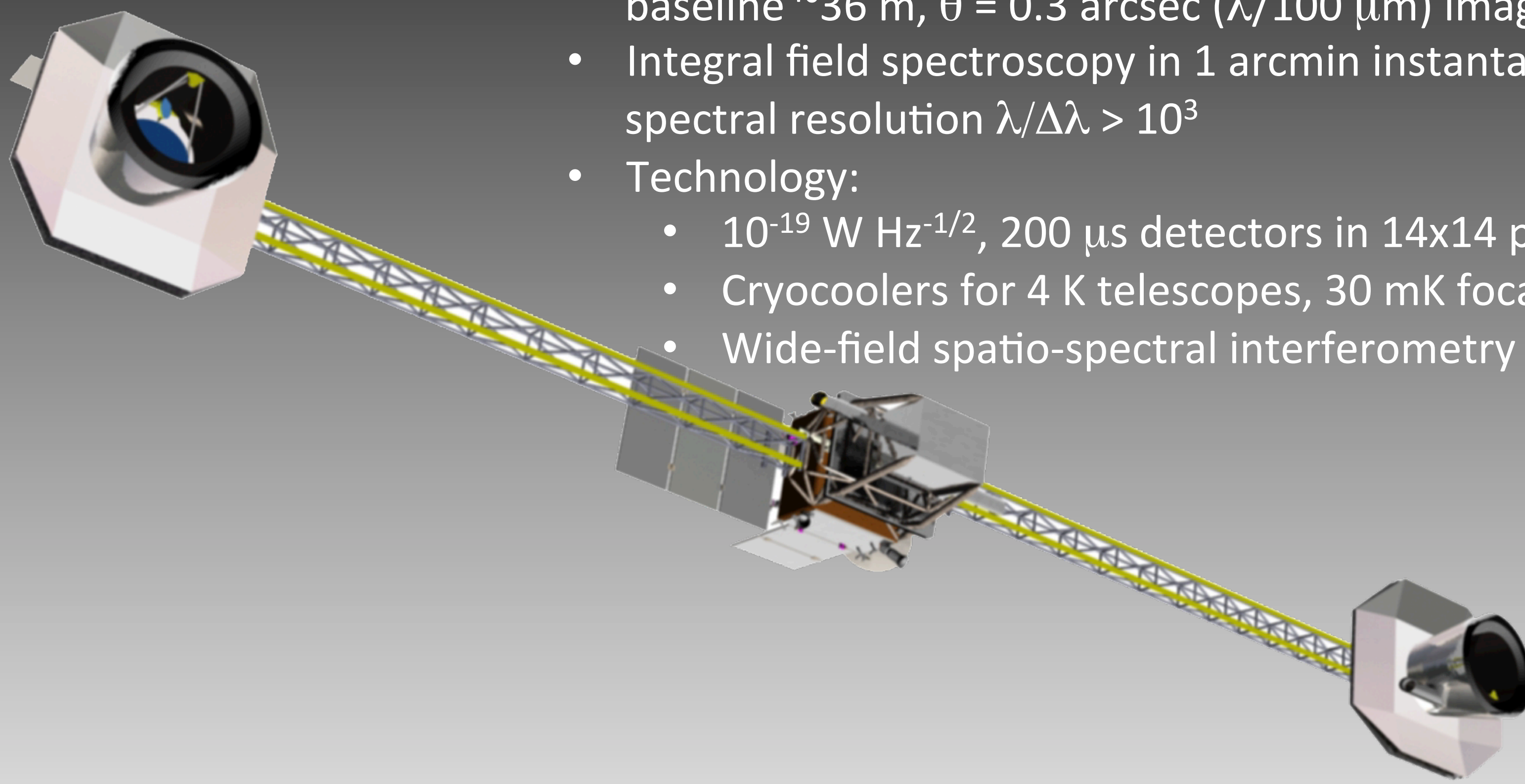
SPIRIT Concept: Direct Detection

Space Infrared Interferometric Telescope

See poster by Dave Leisawitz et al.

- Structurally-connected interferometer
- Two 1-m afocal off-axis telescopes
- Telescopes move radially, and structure rotates to provide dense *u-v* plane coverage with maximum baseline ~36 m, θ = 0.3 arcsec (λ/100 μm) imaging
- Integral field spectroscopy in 1 arcmin instantaneous FoV, spectral resolution $\lambda/\Delta\lambda > 10^3$
- Technology:
  - 10^{-19} W $Hz^{-1/2}$, 200 μs detectors in 14x14 pixel arrays
  - Cryocoolers for 4 K telescopes, 30 mK focal planes
  - Wide-field spatio-spectral interferometry



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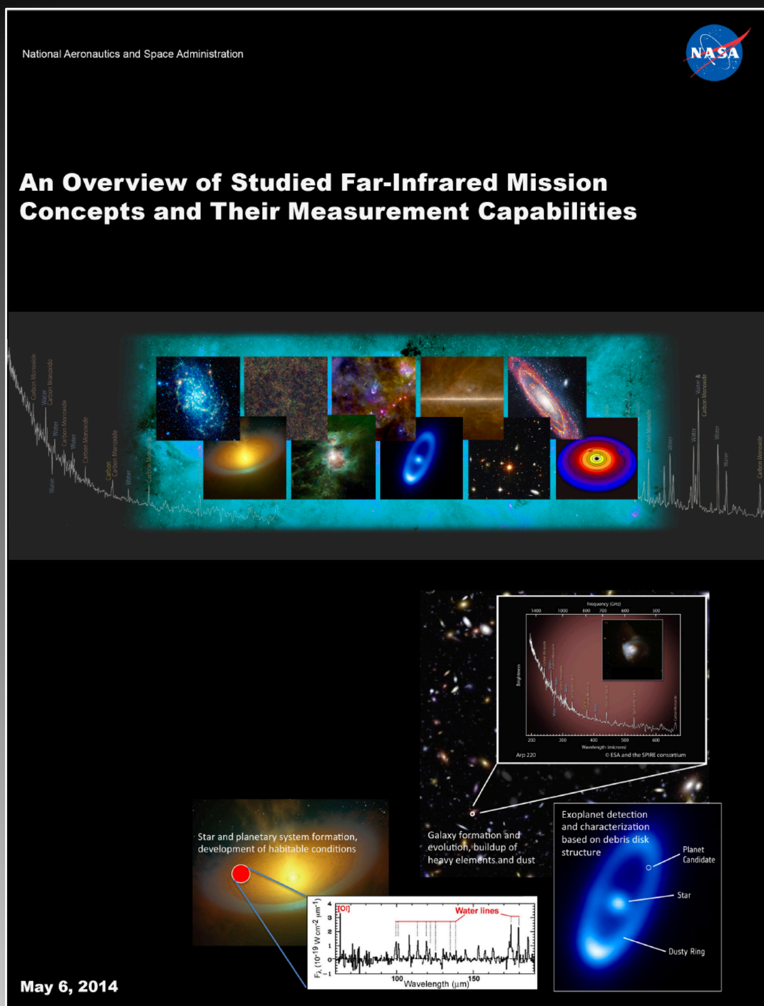
For more details, see …


National Aeronautics and Space Administration

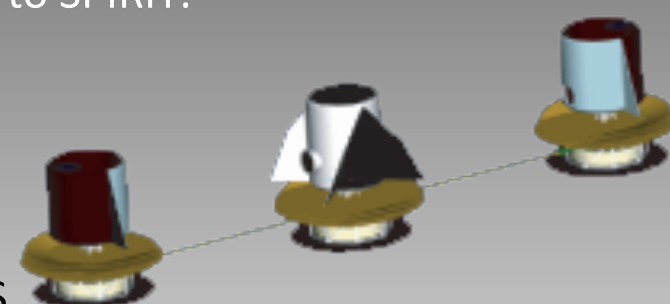
NASA

An Overview of Studied Far-Infrared Mission Concepts and Their Measurement Capabilities

May 6, 2014

Available in hardcopy, and linked to the workshop web site.

Includes concise descriptions of ESPRIT, SPIRIT, and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), a 1 km maximum baseline direct detection interferometer considered to be a successor to SPIRIT.



SPECS
Harwit et al. "vision mission" study (2005)

External Constraints

Launch vehicle

- Lift capacity to desired orbit (e.g., Sun-Earth L2)
- Fairing dimensions
- Interferometers tend to be volume-limited, not mass-limited (e.g., trade collecting area for baseline length)

Technology must be ready – TRL 6 or above

Affordability

- Cost estimates become increasingly accurate as design concepts mature

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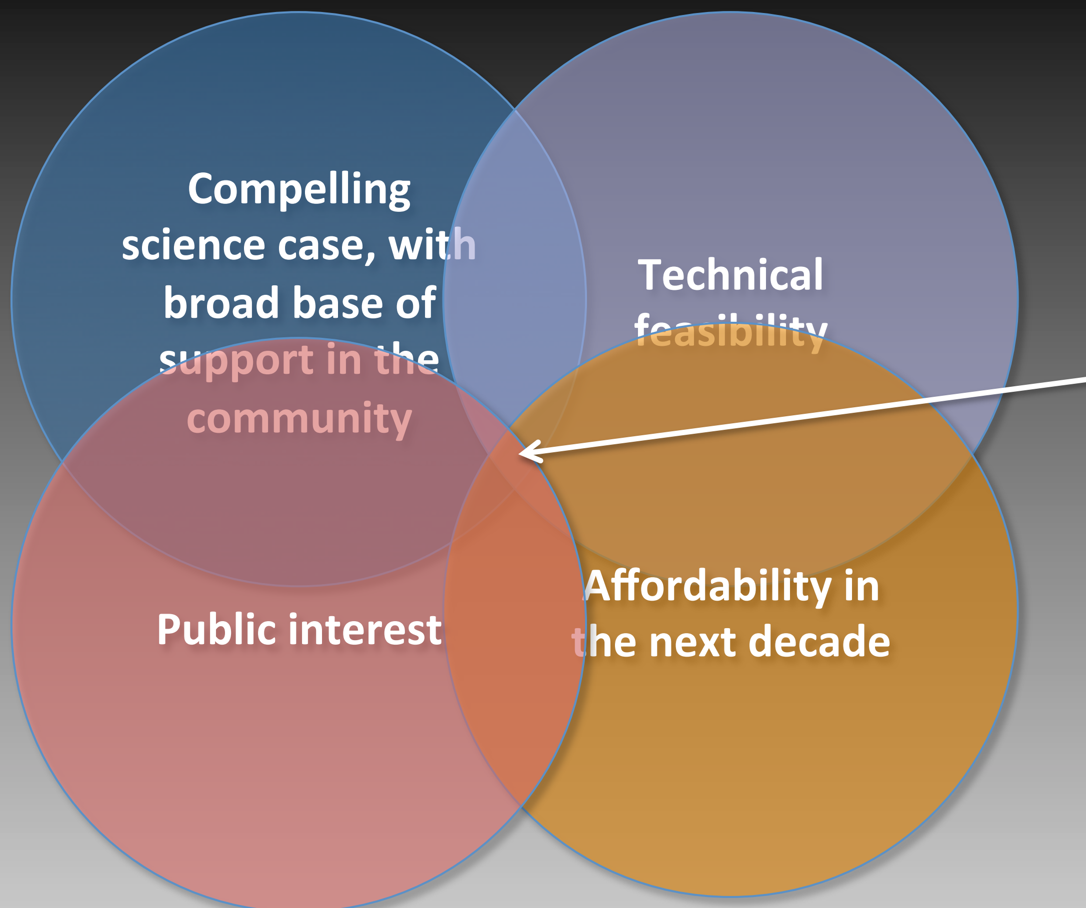
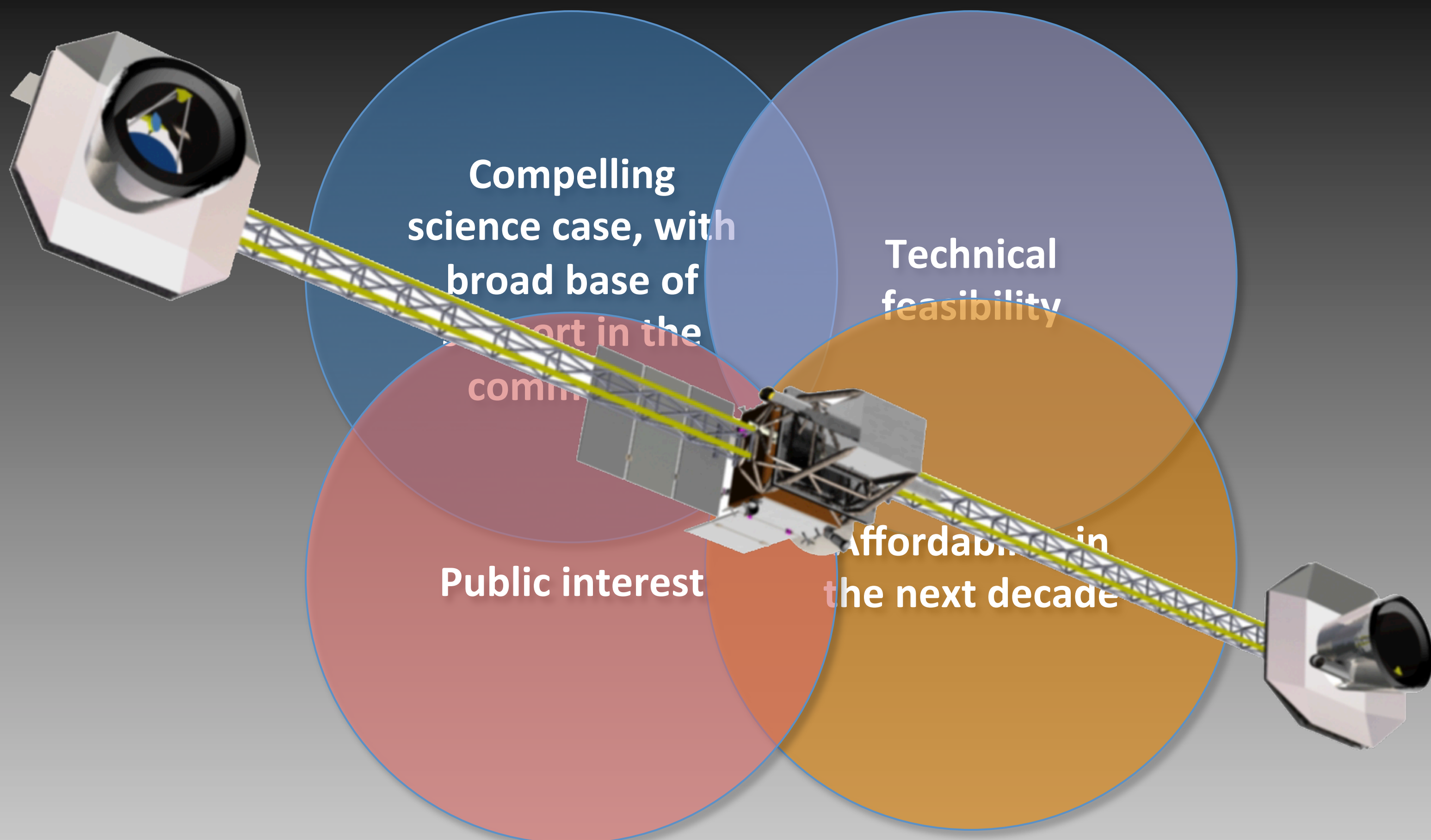
An Interferometer in the Sweet Spot?



Expensive (Decadal) missions only happen if they live here

An Interferometer in the Sweet Spot?



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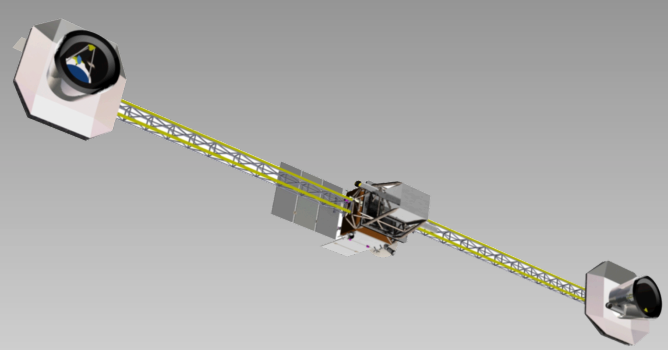
An Interferometer in the Sweet Spot?

Compelling science case, with broad base of support in the community?

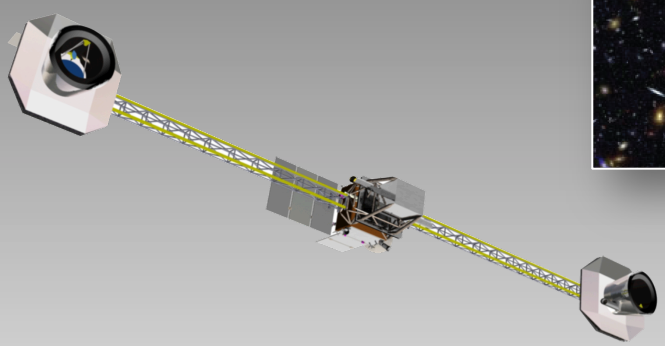


- Image protoplanetary disks and measure the distributions of water vapor and ice to learn how the conditions for habitability arise during the planet formation process;
- Image structures in a large number of debris disks to find and characterize unseen exoplanets;
- Probe the atmospheres of extrasolar gas giant planets; and
- Make profound contributions to our understanding of the formation, merger history, and star formation history of galaxies, including the role of AGN in galaxy evolution.

An Interferometer in the Sweet Spot?

Public interest?

- Iconic images fit for the front page of the *NY Times*
- A profound and easy-to-understand goal: "Tracing our origins from 'stardust' to the formation of habitable planets"



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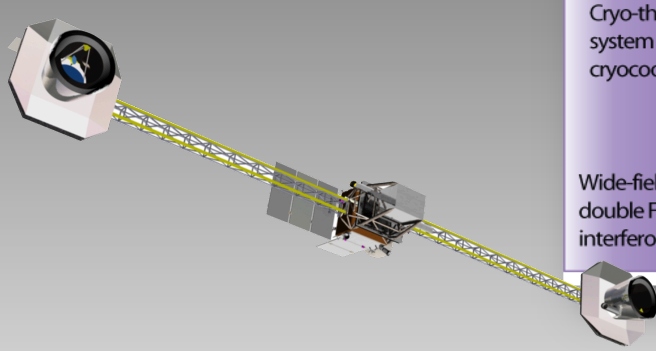
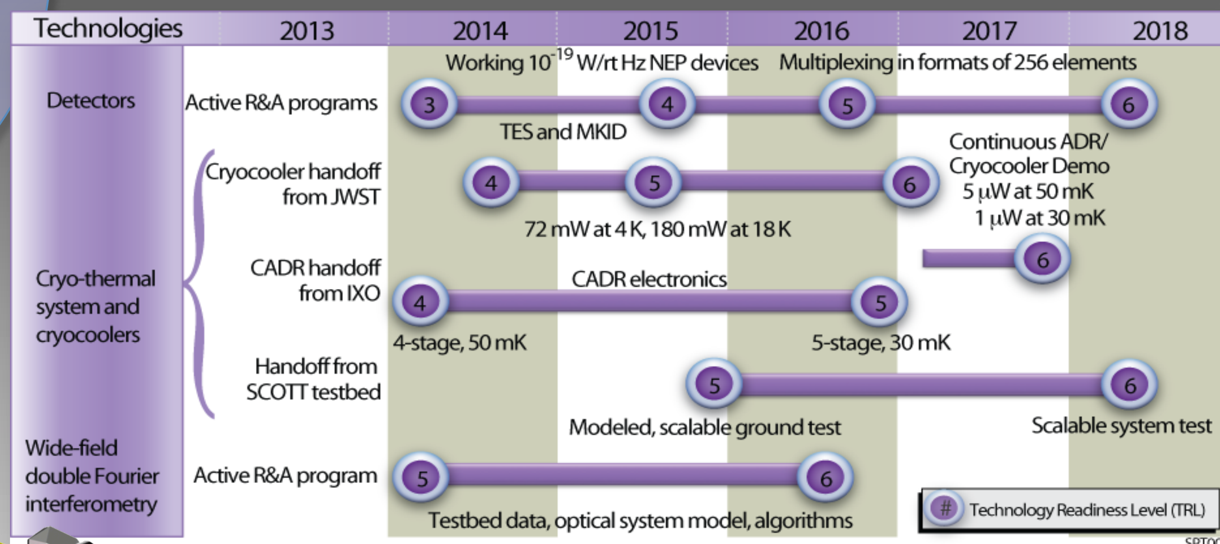
An Interferometer in the Sweet Spot?

Technical feasibility?

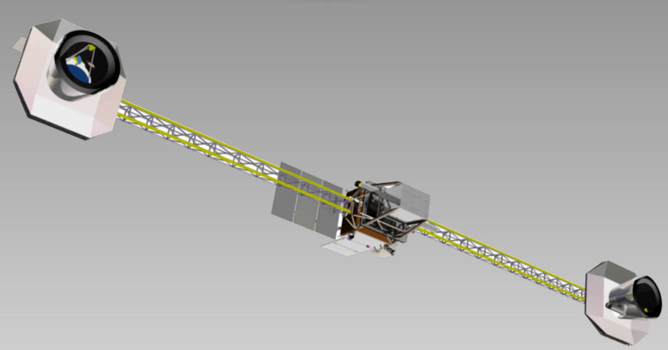
- With coordinated effort, all mission-enabling technologies can be matured to TRL 6 by 2018.
- ROSES SAT and APRA programs provide funding opportunities.





An Interferometer in the Sweet Spot?

Affordability in the next decade?



- SPIRIT was the subject of a robust Pre-Phase A study in 2004-5.
- Grass roots and independent parametric cost estimates agree to within 20%.
- Single instrument, small (1 m) telescopes
- Total lifecycle cost ~$1.25B (FY09); estimate provided to the Decadal Survey (white paper http://astrophysics.gsfc.nasa.gov/cosmology/spirit/)
- International interest is strong, naturally leading to partnership
  - Reduced cost to NASA
  - Sustainable support

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Conclusions

- Interferometry provides the flexibility needed to satisfy science-driven measurement requirements subject only to externally-imposed constraints.
- The SPIRIT study indicates that an affordable interferometer capable of making groundbreaking scientific discoveries can be developed for launch during the next decade.
- The SPIRIT design concept is flexible and can be adapted to meet new scientific goals.
- NASA's Astrophysics Roadmap recognizes the importance of multi-aperture interferometry and suggests we start in the far-IR.