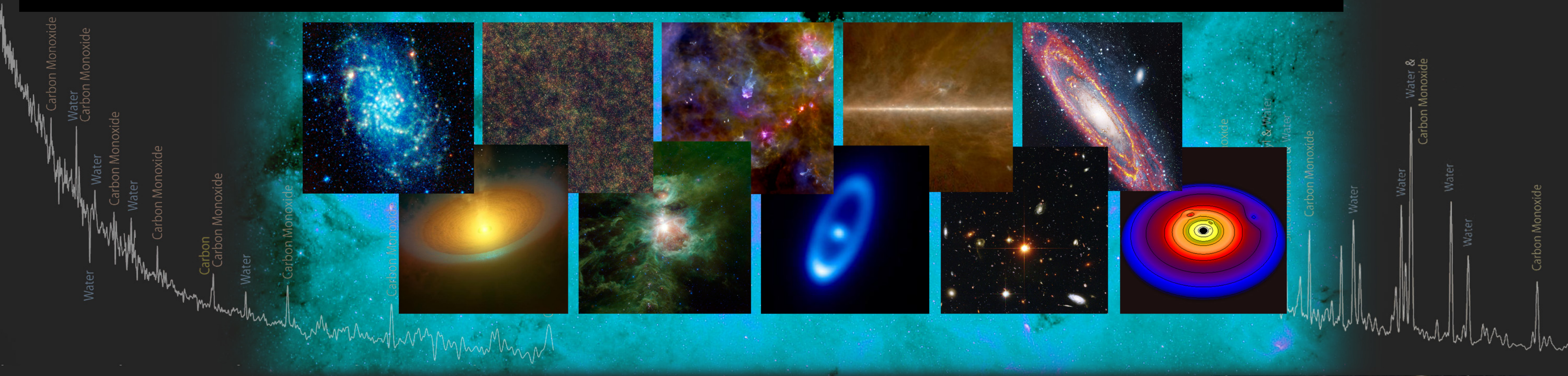
Interferometry Concept for the Far-IR Surveyor: Bringing Fundamental Astrophysical Processes Into Focus

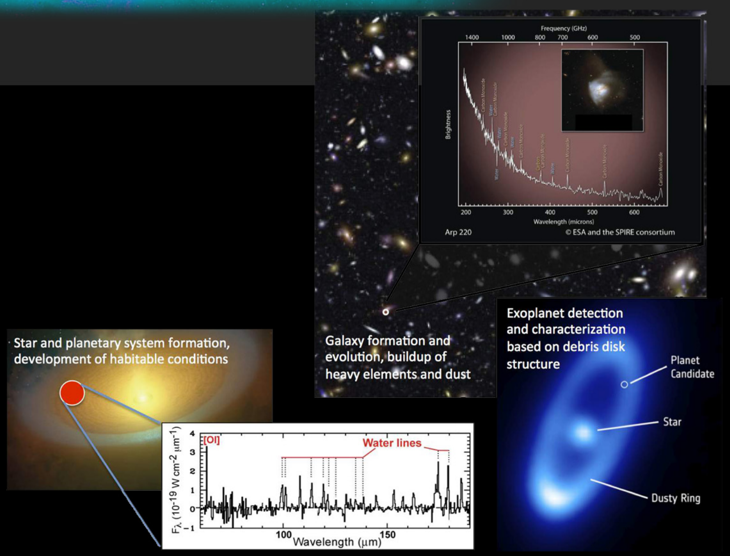


Dave Leisawitz

NASA/GSFC

Far-IR Surveyor Workshop

3 – 5 June 2015



Outline

- Killer apps for an interferometry mission
- Why interferometry?
- Twelve things you should know about a far-IR interferometer
- A quick look at the SPIRIT "C" mission concept

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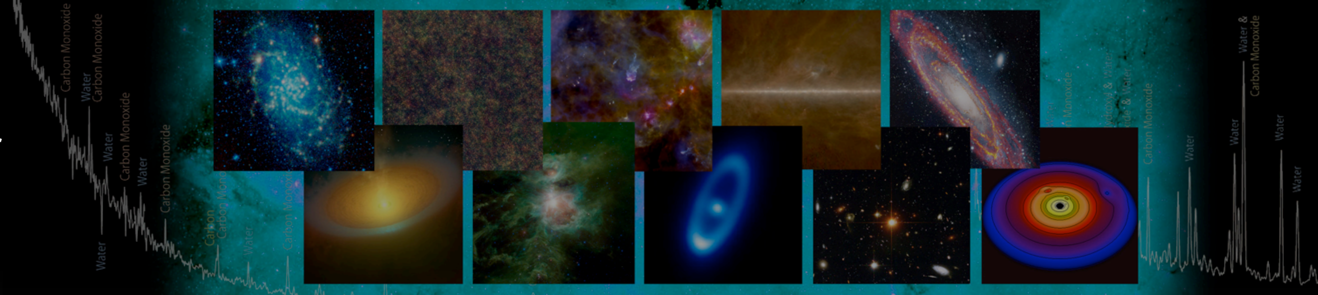

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Killer Apps

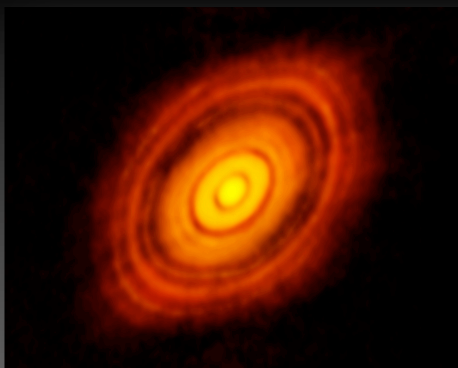
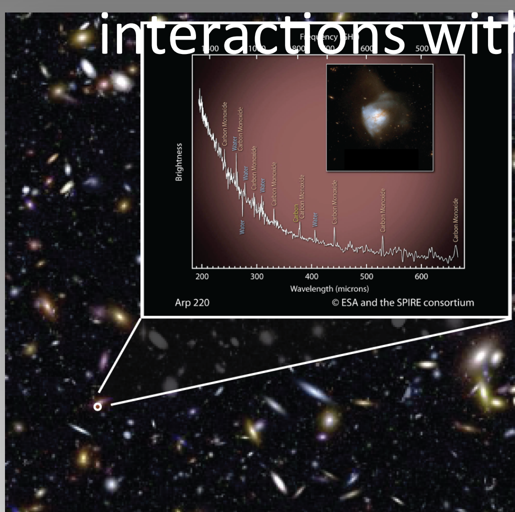


Image protoplanetary disks and measure the distributions of H_2, HD, water vapor and ice, and dust to learn how the conditions for habitability arise during the planet formation process;

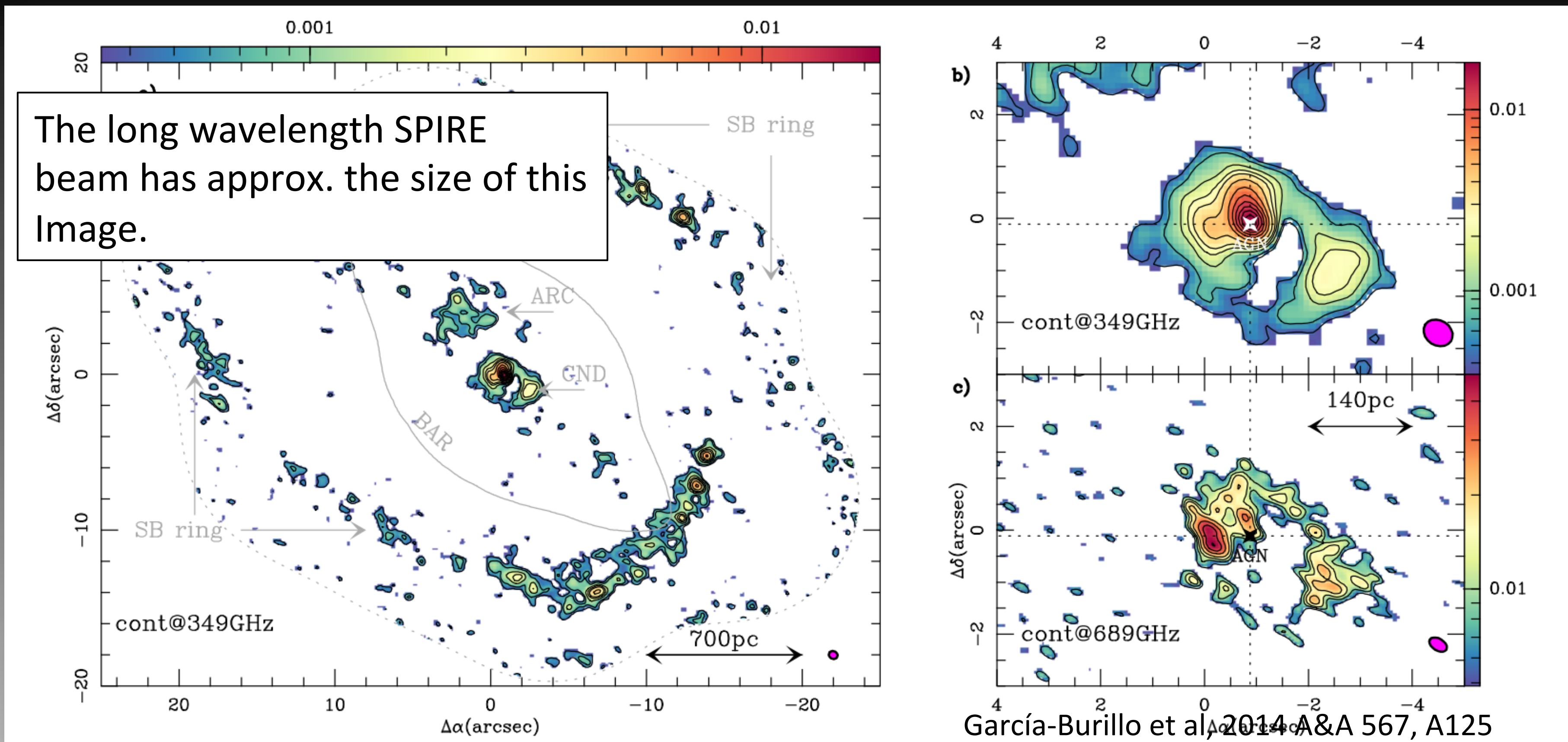
- Image structures in a large number of debris disks to find and characterize exoplanets through their interactions with the disks; and



- Understand the formation, merger history, and star formation history of galaxies, and the role of AGN in galaxy evolution.

… and much more

ALMA continuum observations of NGC 1068



The long wavelength SPIRE beam has approx. the size of this Image.

García-Burillo et al. 2014 A&A 567, A125

A FIR interferometer will enable detailed water and ionization line studies of the nuclei and starburst rings of of nearby active galaxies, complementing submm observations with ALMA.

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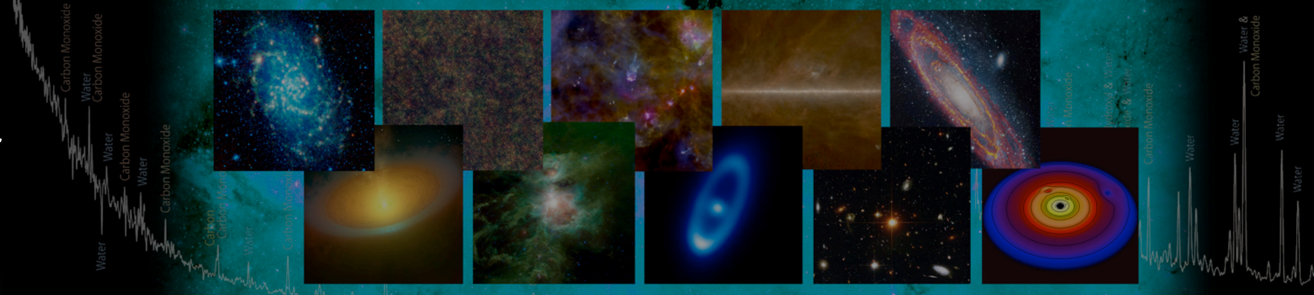


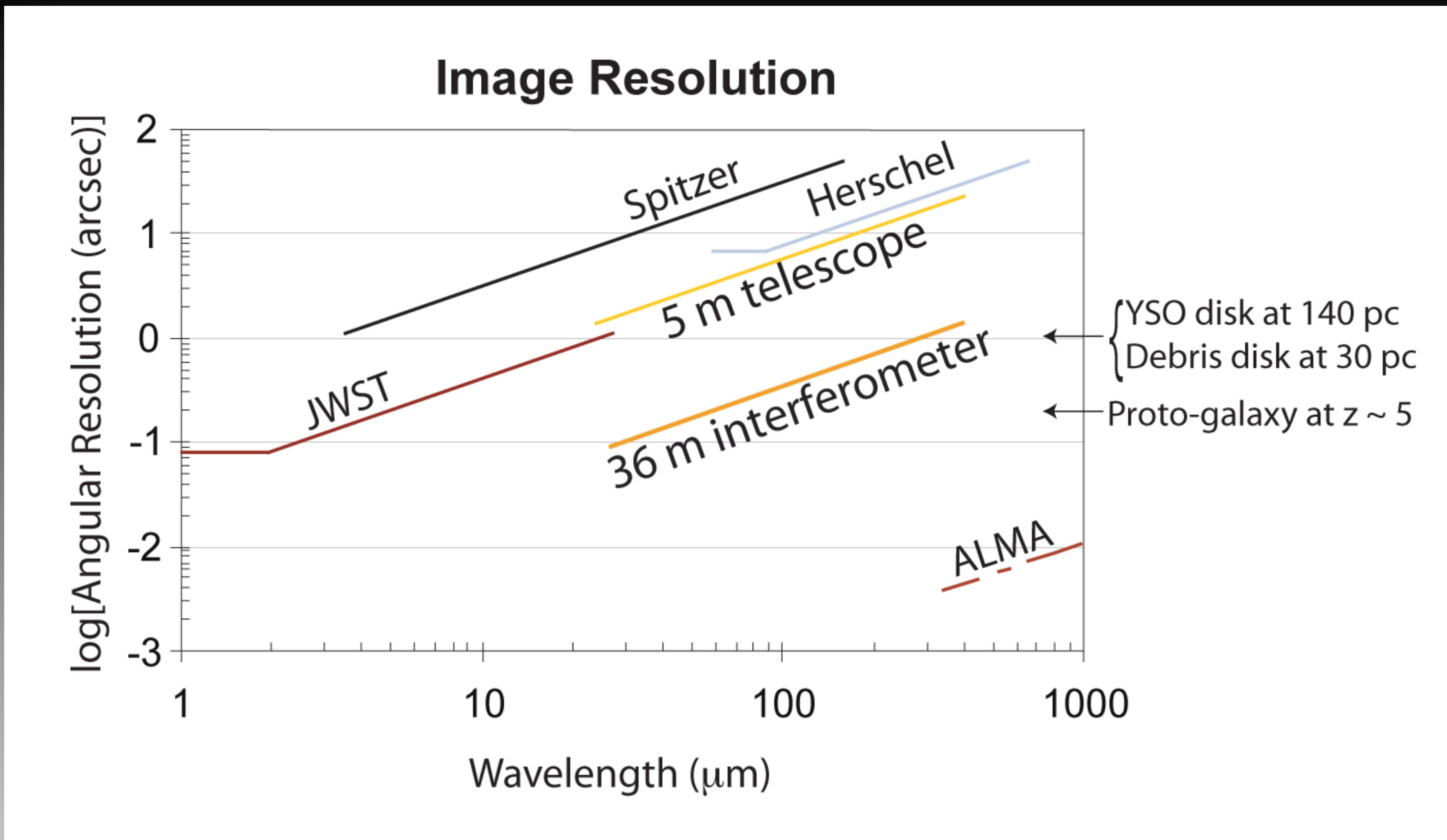
Galileo did a bit better

The sky at 200 μm convolved with the diffraction-limited beam of a 5 m telescope, assuming an unobstructed aperture (θ_{FWHM} = 8.5”)

So, is that..

- An outflow or a rotating protoplanetary disk?
- A cirrus bright spot, or a debris disk?
- Which spectral line from which galaxy at what redshift?

Resolution: the key to breaking degeneracy

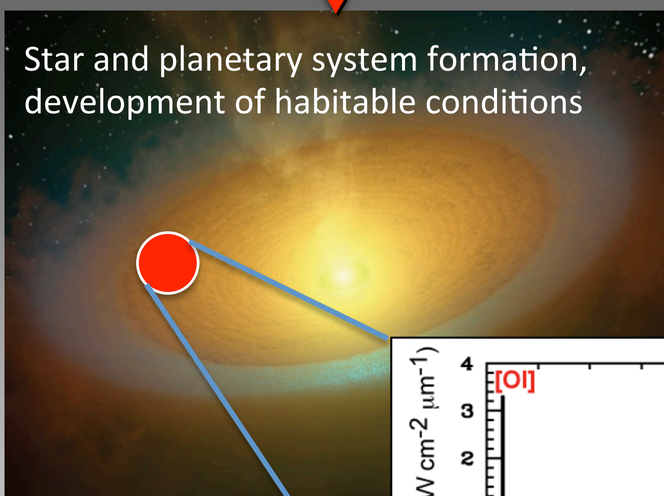


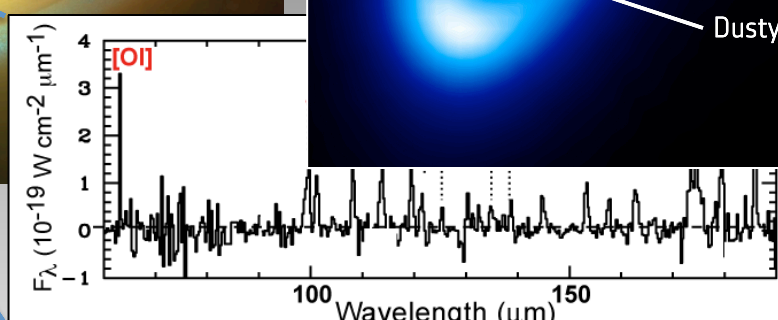
Measurement requirements

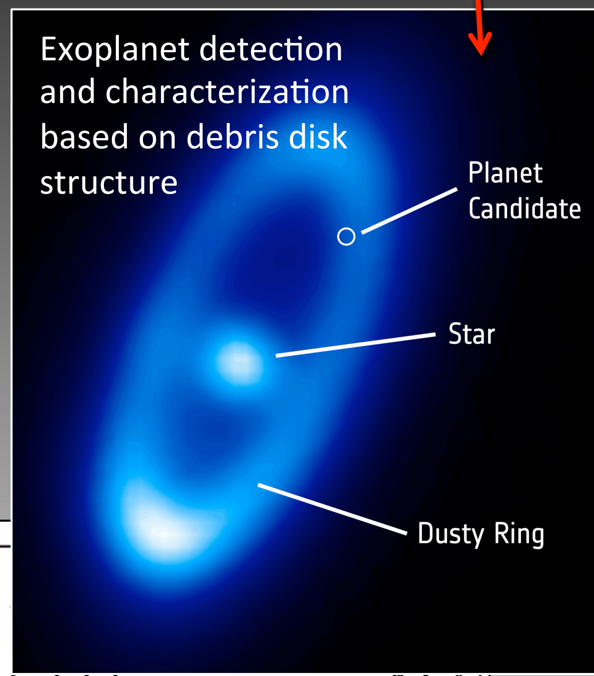
Parameter	Units	Value or Range
Wavelength range	μm	25 - 400
Angular resolution	arcsec	< 1
Spectral resolution, (λ/Δλ)	dimensionless	
Continuum sensitivity	μJy	
Spectral line sensitivity	10^{-19} W m^{-2}	
Instantaneous FoV	arcmin	
Number of target fields	dimensionless	
Field of Regard	sr	

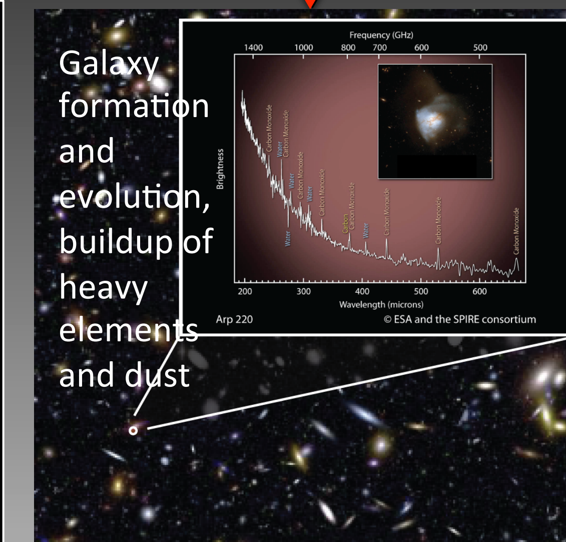
Measurement requirements

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









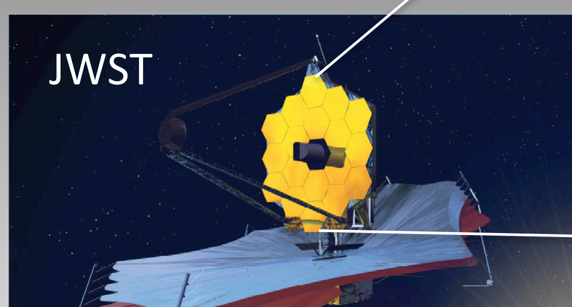
Diffraction is our enemy

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

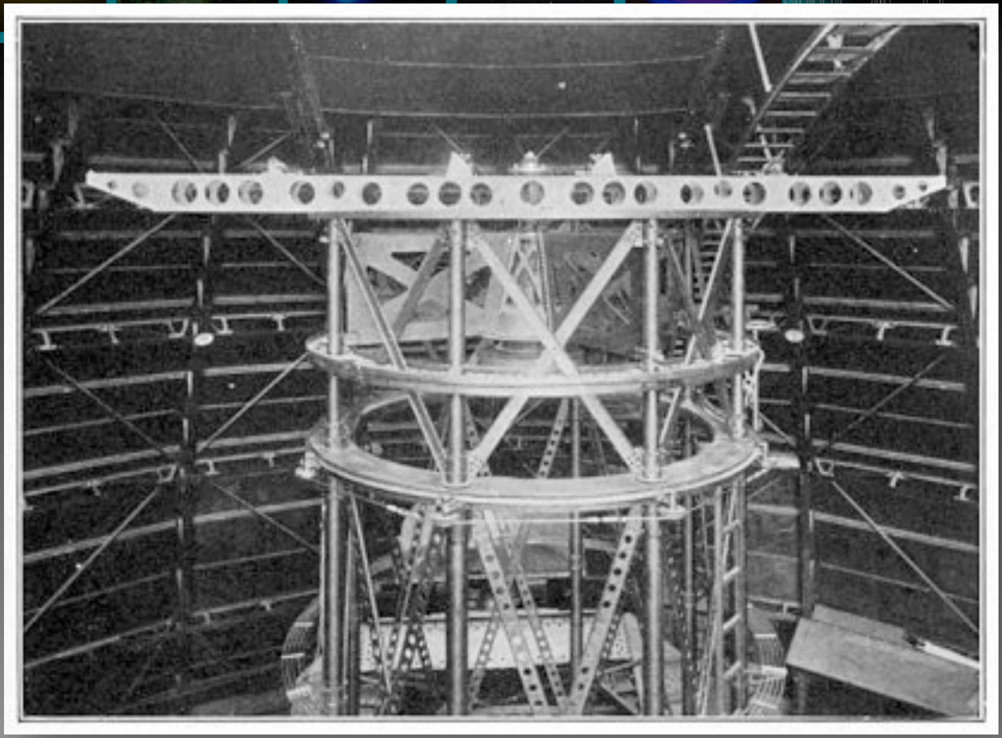
$$\theta = 1.22\lambda/D$$

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

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



Michelson is our friend



Stellar Interferometer with 6 m baseline , c. 1919

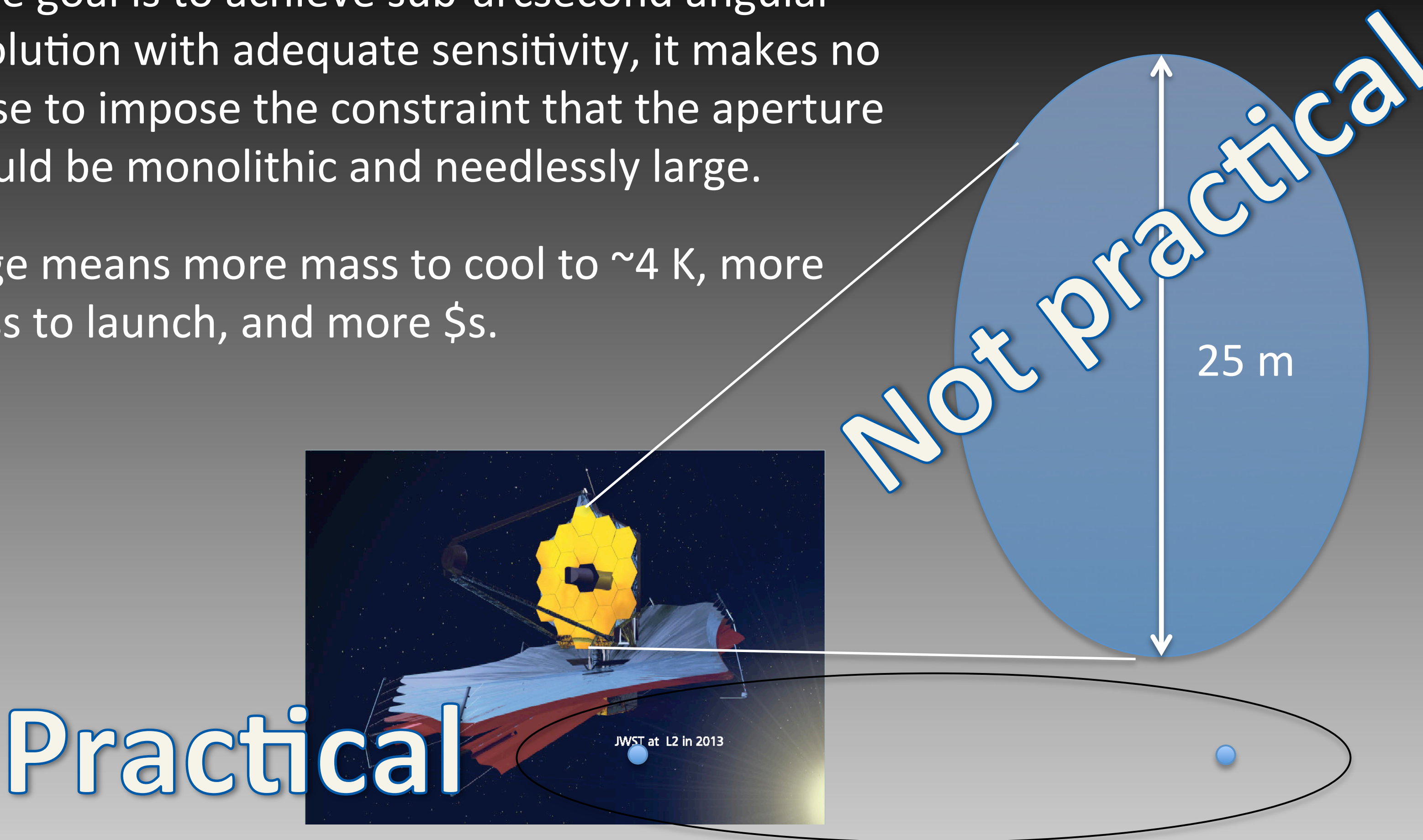
$$\theta = \lambda/2b$$

$$b = \lambda/2\theta$$
$$= 10.3\ (\lambda/100\ \mu m)(\theta/1\ \text{arcsec})^{-1}\ \text{meters}$$

Single aperture telescope: an unnecessary 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.



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Interferometry: flexibility to meet measurement requirements

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
- Dispersive element or filter
- 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.

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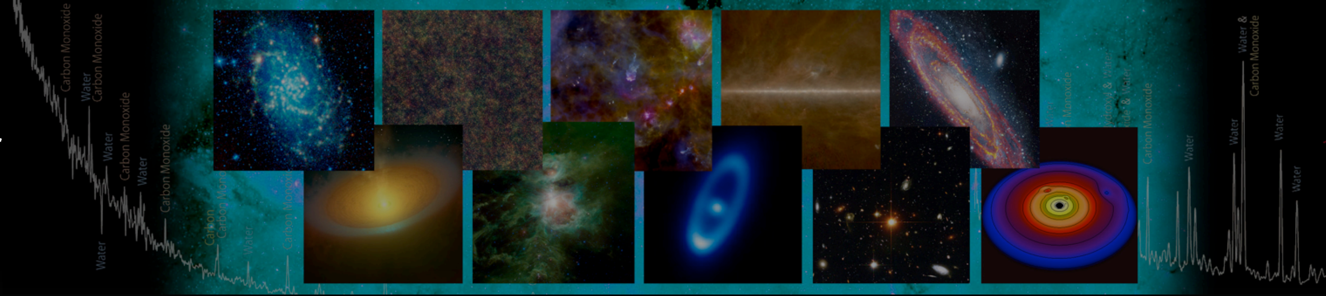
Why interferometry?

Interferometry provides the flexibility needed to satisfy science-driven measurement requirements …

… without paying a penalty for the self-imposed constraint that telescope size determines both resolution and sensitivity.



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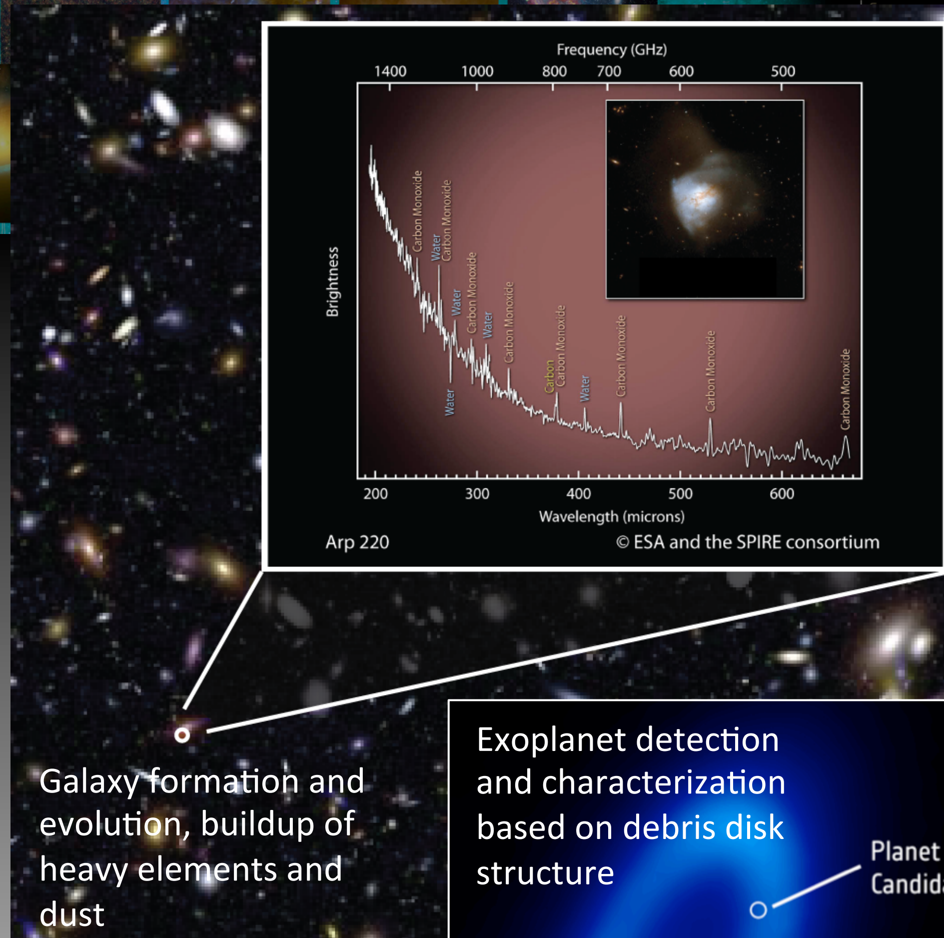
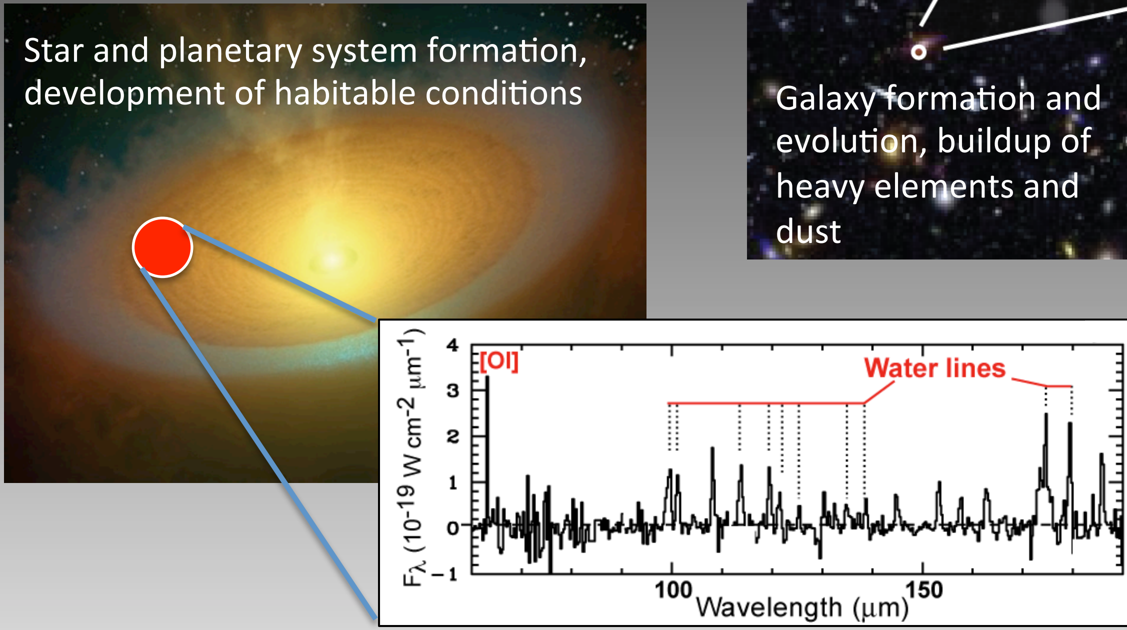
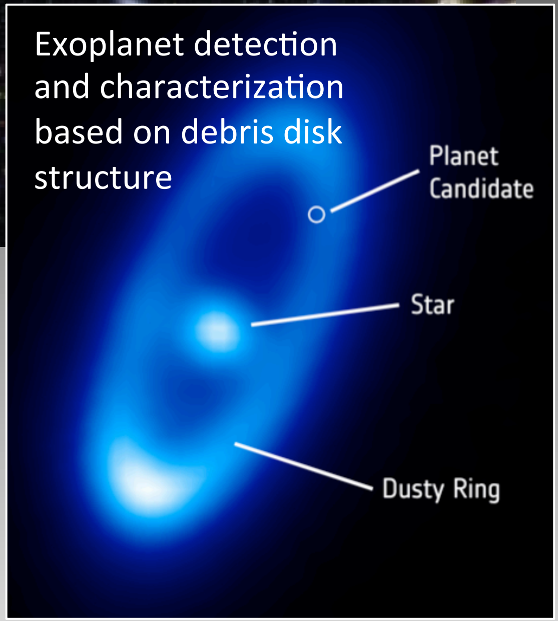
1. Compelling science



Galaxy formation and evolution, buildup of heavy elements and dust



Star and planetary system formation, development of habitable conditions



Exoplanet detection and characterization based on debris disk structure

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2. Compelling theme

Leverage NASA's "follow the water" theme …

The pubic will understand and invest in our effort to learn **"Why are there habitable planets?"**

- How do planets form?
- How does the planet formation process sometimes lead to the development of habitable conditions?

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3. Astrophysics roadmap

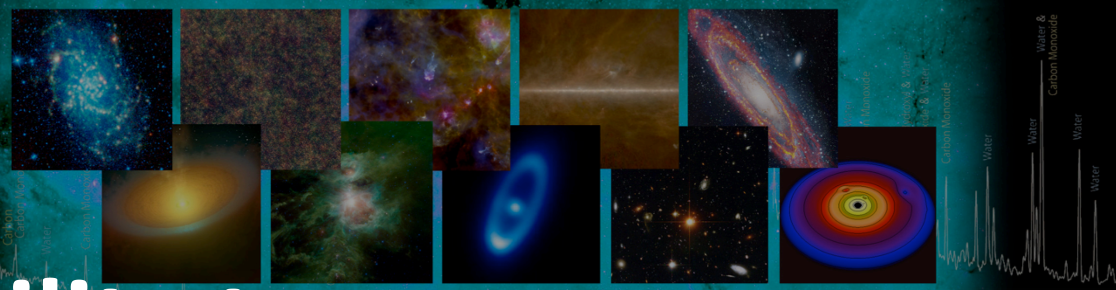
The community-generated roadmap, "Enduring Quests – Daring Visions," describes the Far-IR Surveyor:

- New start in the 2020s
- "Pioneer space interferometry to resolve protoplanetary disks"
- "Directly measure water emission lines from young stellar systems identified by ALMA and JWST" and "detect the distribution and flow of water"
- "Provide critical information on the chemical and dynamical evolution of [the first stars and protogalaxies]"
- Relative to Herschel, it will:
  - be cooled to ~4 K to gain 3 orders of magnitude in sensitivity;
  - have enhanced spectroscopic capability;
  - use interferometry to attain sub-arcsecond angular resolution.

4. Innovation & training

The "Enduring Quests – Daring Visions" roadmap

- Sees interferometry as the way of the future, across the electromagnetic spectrum
- Recommends starting down this path in the far-IR, where interferometry is easier than it is at shorter wavelengths
- NASA investment in interferometry in the 2020s will
    - demonstrate a willingness to innovate
    - train people in skills they'll need to design, develop, and operate many future astrophysics (and other space science) missions.



5. Traceability to long-standing far-IR community plans

Consensus developed through a series of workshops, starting in 1998

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

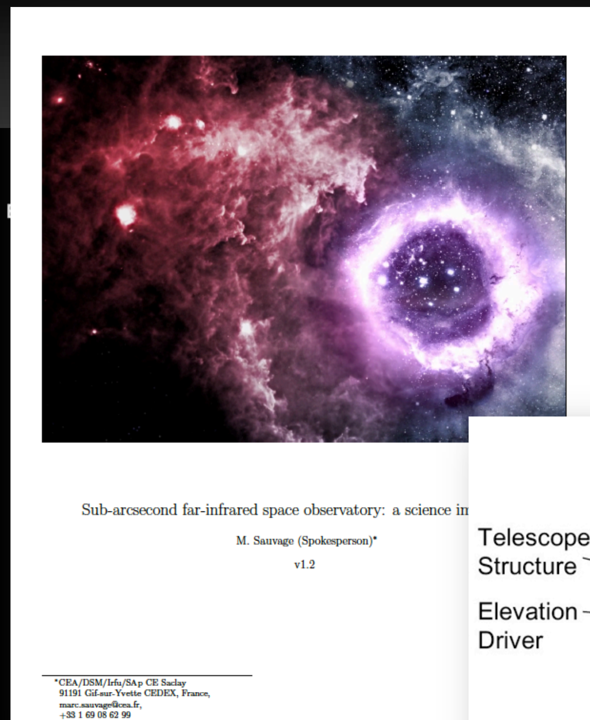
While it has evolved over time, the Plan has consistently called for high resolution

6. Affordability, with confidence

- In 2004, NASA sponsored "Origins Probe" studies.
- SPIRIT was studied according to methodology described by Mission Systems Engineer D. DiPietro (2014).
- The SPIRIT "C" design – the most advanced of three concepts studied – will serve as an excellent starting point for future far-IR interferometry mission studies.
- The study yielded a DRM, a mature pre-Phase A design concept, and an **independently validated grass roots cost estimate** (Leisawitz et al. 2007, Adv. Sp. Res., 40, 689).
- The estimated lifecycle cost, including technology development, I&T, launch, and operation, is $1.3B in FY09 $s.

Publications based on the study results, and the SPIRIT white paper submitted to the 2010 Decadal Survey, are available online at http://asd.gsfc.nasa.gov/cosmology/spirit.

7. International partners



Sub-arcsecond far-infrared space observatory: a science im

M. Sauvage (Spokesperson)*

v1.2

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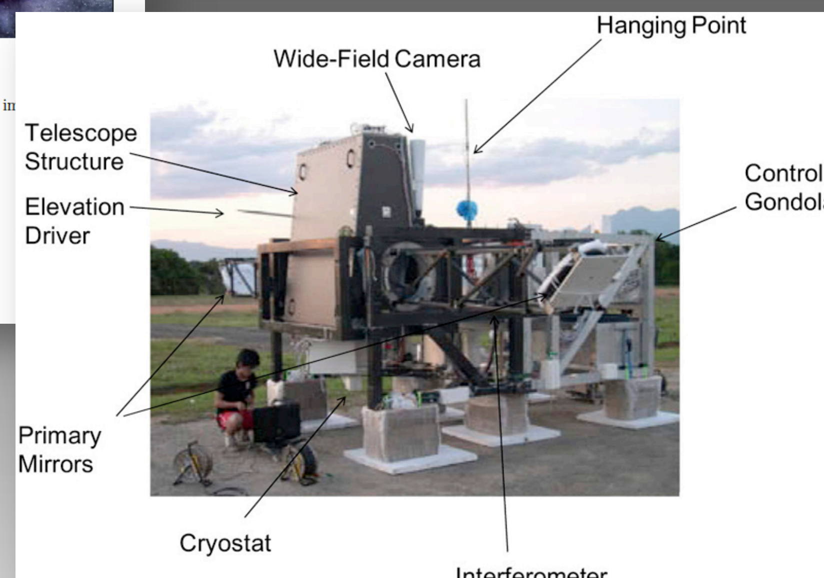
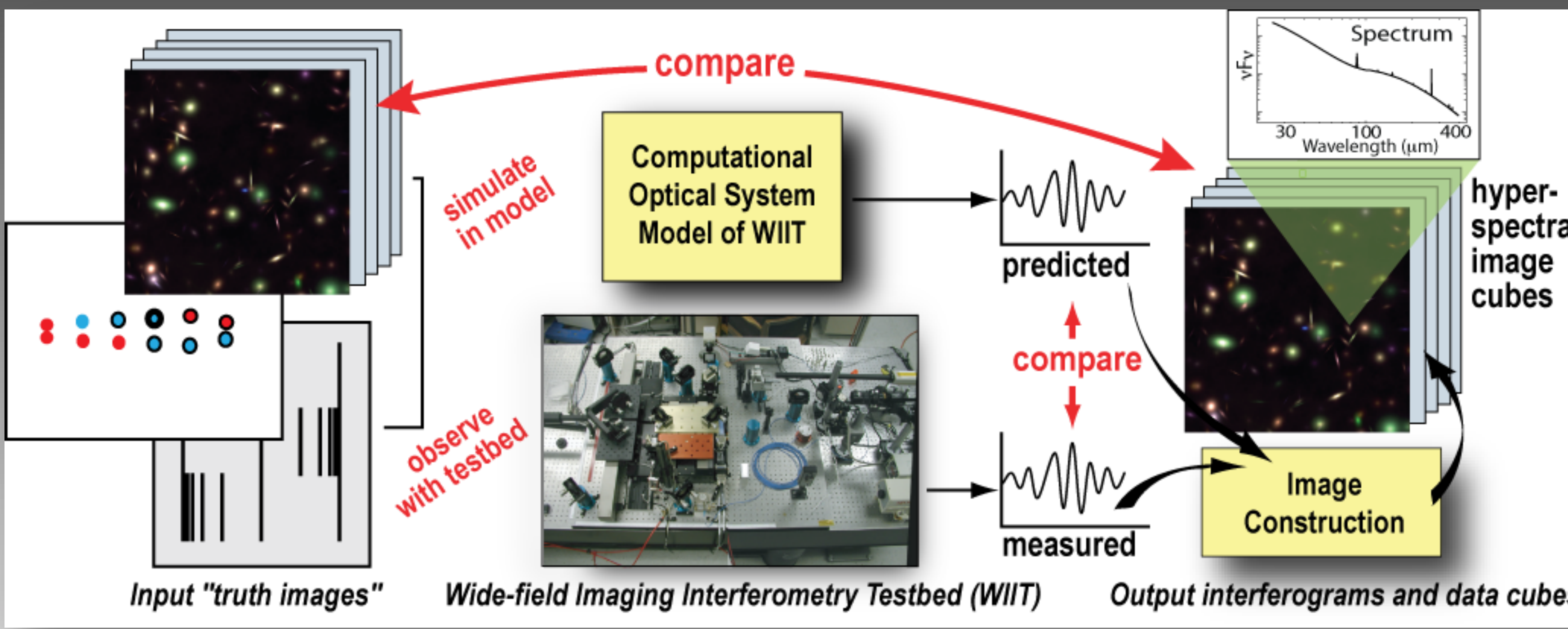
The international far-infrared astrophysics community is preparing for far-IR interferometry.



8. A single instrument

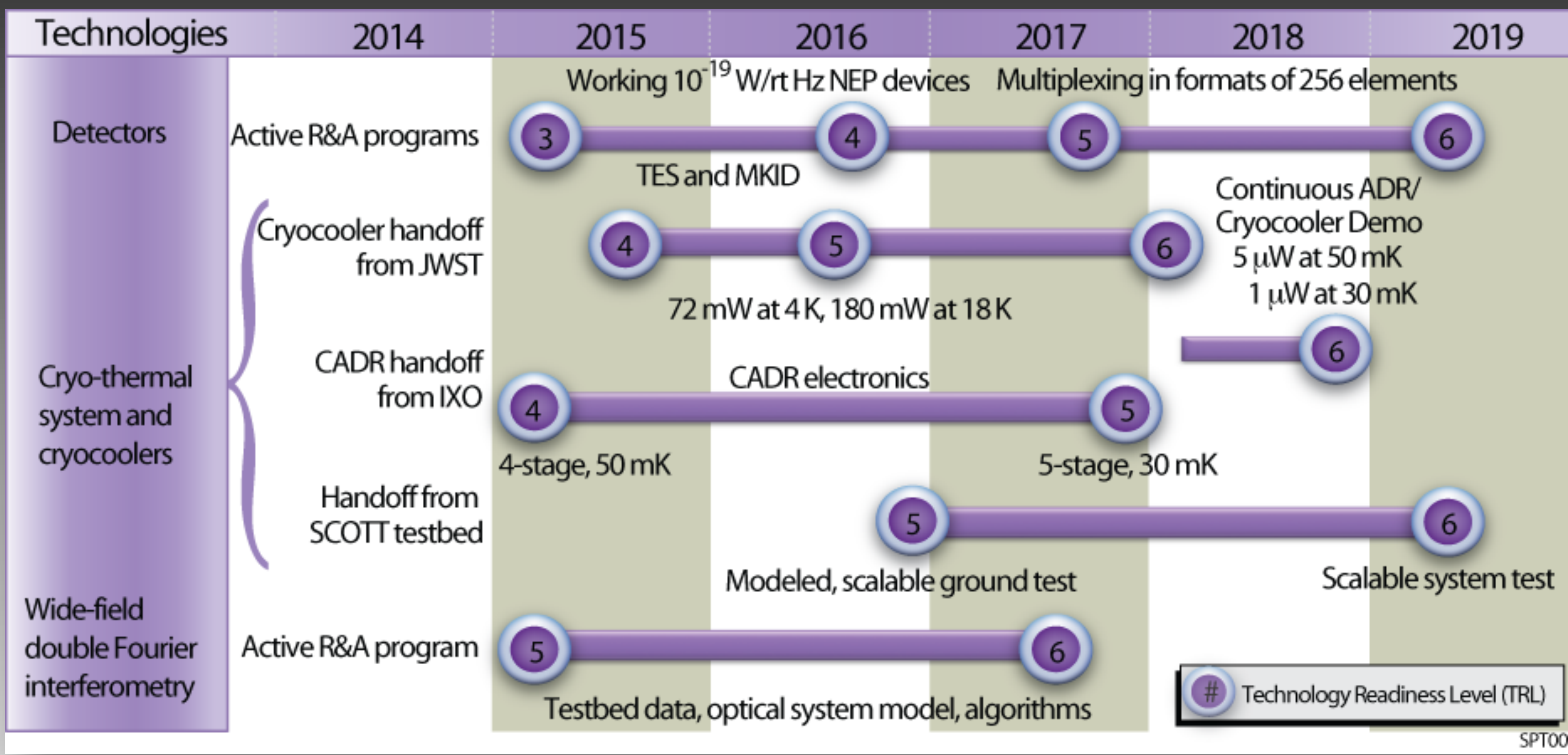
- A single instrument – a "double Fourier" beam combiner – will provide sub-arcsecond imaging and spectral line mapping.
- Space-qualified instruments typically cost >$100M



9. Technology readiness

Enabling technology:

- 10^{-19} W $Hz^{-1/2}$, 200 μs detectors in sub-kilopixel arrays
- Cryocoolers for 4 K telescopes, 30 mK focal planes
- Wide-field spatio-spectral interferometry



10. Design flexibility

Design parameters can be adjusted to satisfy the community's current measurement requirements.

- Aiming to optimize science return at a price point <$1B, the SPIRIT science and engineering study team methodically examined three distinct point designs, called A, B, and C.
- SPIRIT "C" was studied in greatest detail, benefiting from earlier experience with "A" and "B."
- SPIRIT "C" (1 m telescopes, 36 m structure) is valuable as a benchmark for capability at a calculated cost.
- Many knobs to turn, enabling re-optimization to satisfy new science requirements with a mission whose cost is <$2B, giving the STDT a good starting point and a rich array of topics to explore as it looks at re-optimization.

11. Flexible operation

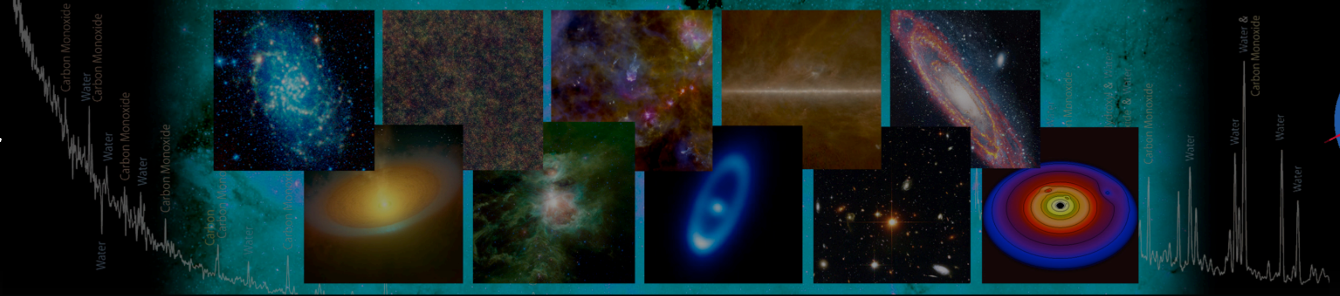
Workshop white paper describes four basic modes of operation:

- **Clustered survey modes** for quick reconnaissance of closely spaced fields (e.g., YSOs in a molecular cloud)
  - Broadband or spectral line
  - One or more baselines per target field
- **Spectral line mapping** – e.g., H_2O lines in a protoplanetary disk; fine structure lines in galaxies
- **Broadband imaging** – e.g., debris disk imaging

Dense u-v plane coverage

12. Complementarity to JWST and ALMA

- **H_2 28 μm**: JWST will observe this important line in YSOs and nearby galaxies. The far-IR interferometer will follow up interesting sources in the same line, but at 10x higher angular resolution, and will make complementary measurements of the 112 μm line of HD.
- **H_2O**: ALMA will image protoplanetary disks, but it won't be able to observe water through the Earth's atmosphere. The far-IR interferometer will map water line emission, as well as the 45 μm water ice feature.
- **Debris disks**: ALMA will observe dust thermal emission far out in the Rayleigh-Jeans tail, where many disks will be undetectable. The far-IR interferometer will image the disks at the wavelengths where they're brightest.



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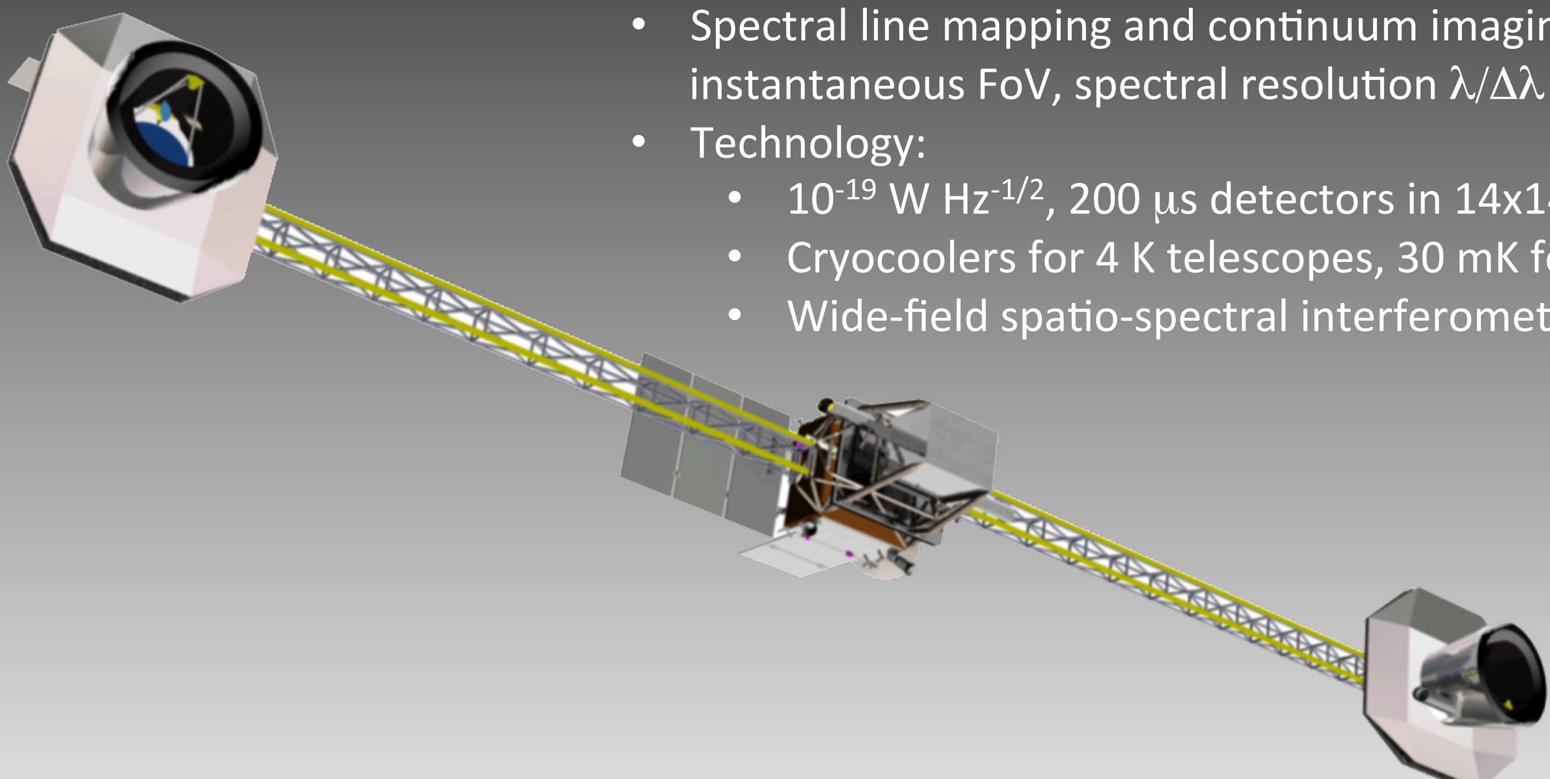
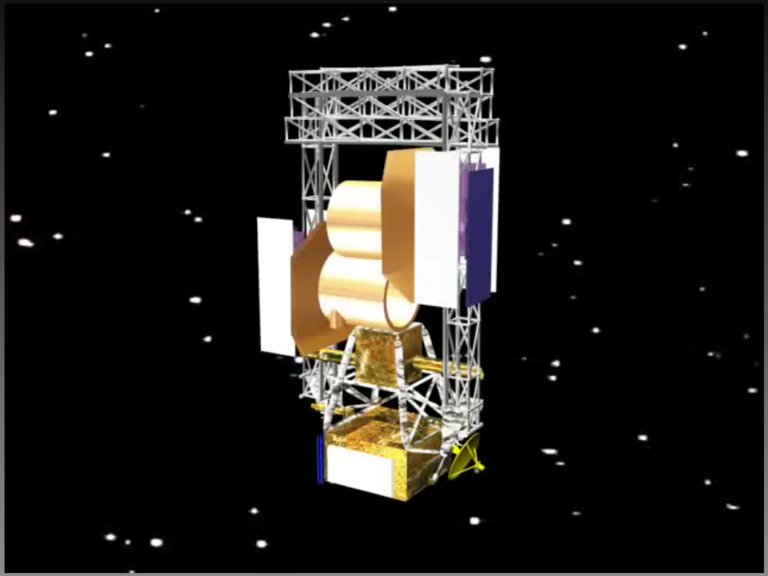
SPIRIT "C" mission concept

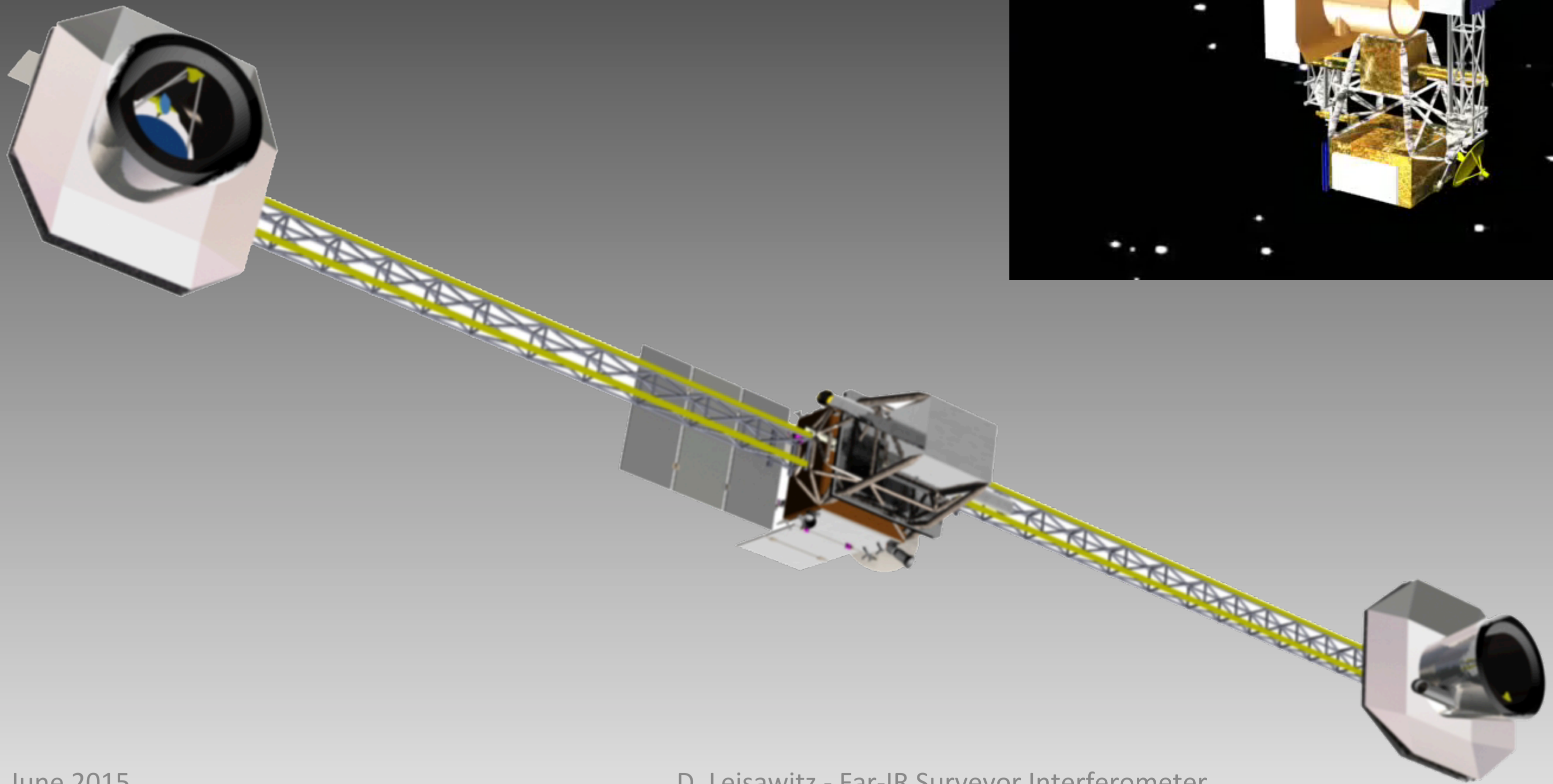
Space Infrared Interferometric Telescope

- Structurally-connected λ25 – 400 μm 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
- Spectral line mapping and continuum imaging 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

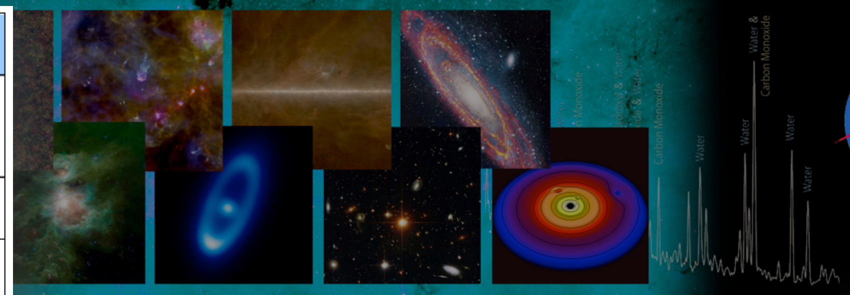


Deployment sequence (SPIRIT "C" concept)





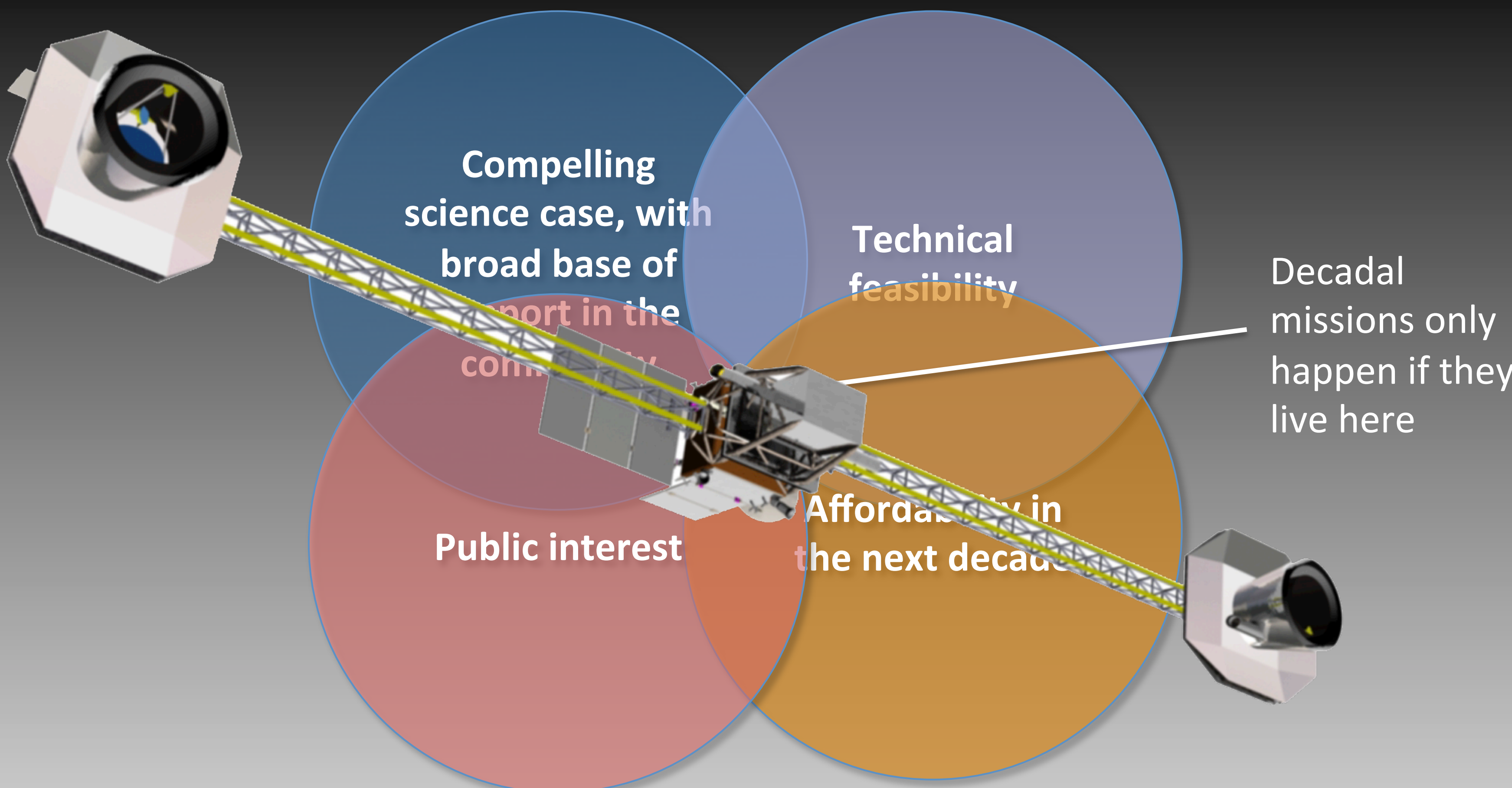
Operation (SPIRIT "C" concept)



Notional Interferometric Far-IR Surveyor

Parameter	Value
Spectral Bands	25-50 µm, 50-100 µm, 100-200 µm, 200-400 µm
Telescopes	2 off-axis, afocal
Telescope Diameter	1.5 m
Baseline Range	2.5 to 36 meter
Angular Resolution	0.3 (λ/100 µm) arcsec
Field of View	1 arcmin
Detector Array	21 x 21 pixel (max)
Short slew/settle time	5 minutes for < 10 arcminutes
Broadband Clustered Survey Mode (5σ, 1 hour per pointing, 1 arcmin FoV)	R = 10 Point Source Sensitivity = 4, 3, 4, 4 mJy in Bands 1, 2, 3, 4
Line Clustered Survey Mode (5σ, 1 hour per pointing, 1 arcmin FoV)	R = 3000 Point Source Sensitivity = 5, 3, 2, 2 x 10^{-19} W m^{-2} in bands 1, 2, 3, 4
Line Full Imaging Mode, line sensitivity (R = 3000, 5σ, 24 hrs, 1 arcmin FoV)	Band — Sensitivity (10^{-20} W m^{-2}) 1 — 9.4 2 — 5.6 3 — 4.7 4 — 3.7
Broadband Full Imaging Mode Sensitivity (5σ, 24 hrs, 6" FoV)	Band — R — Sensitivity (µJy) 1 — 15 — 280 2 — 7.5 — 190 3 — 3.8 — 130 4 — 1.9 — 94

The STDT will look for a mission in the sweet spot

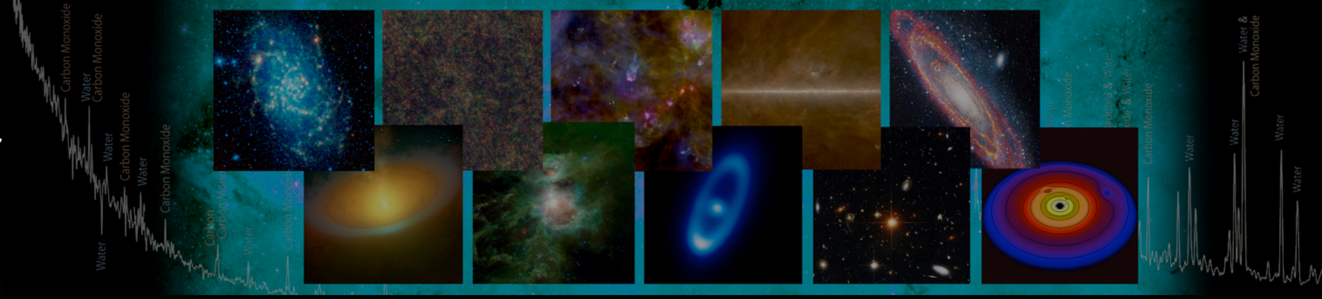


A far-IR interferometer could be that mission

Summary

- **Space-based far-infrared interferometry is scientifically compelling and technically feasible.**
- The enabling technologies can be matured to TRL 6 by 2019
- 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.

Thank you



Backup

External constraints

Launch vehicle

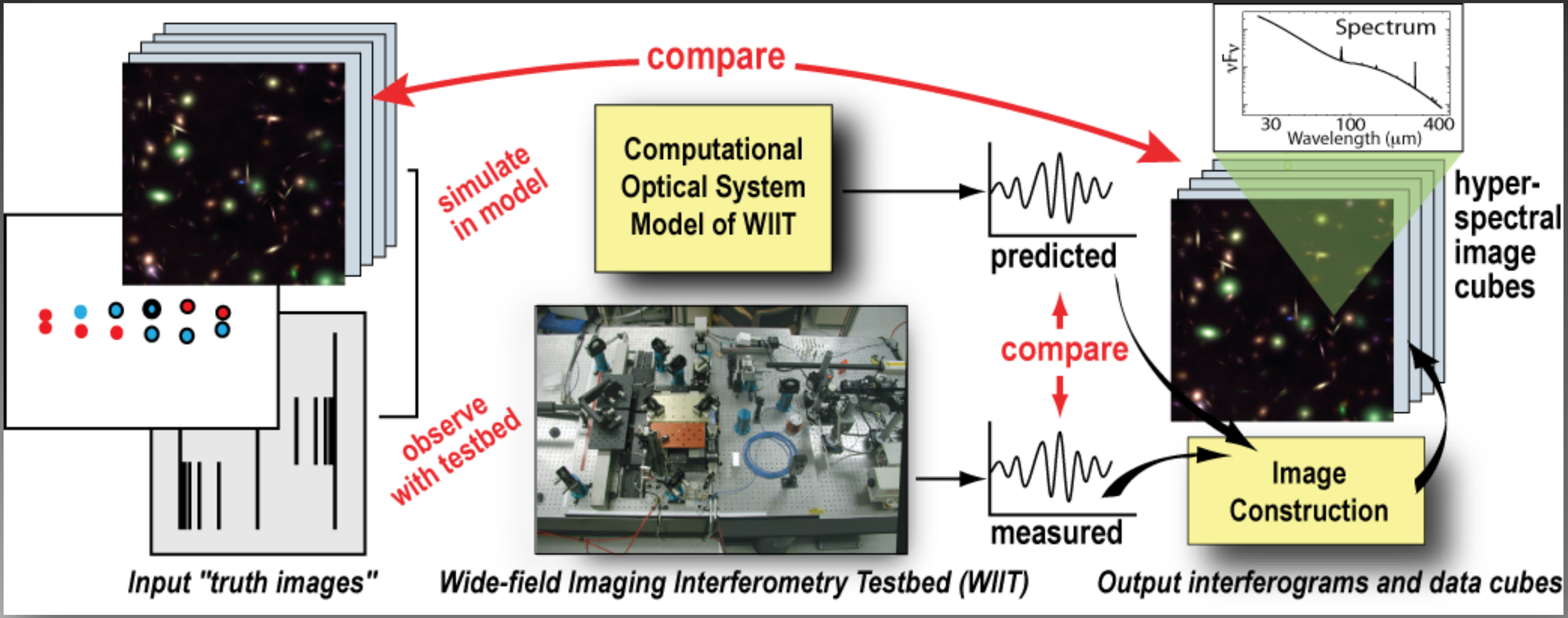
- Lift capacity to desired orbit (e.g., Sun-Earth L2)
- Fairing dimensions
- Interferometers tend to be volume-limited, not mass-limited (e.g., trade collecting area for baseline length)

Technology must be ready – TRL 6 or above

Affordability

- Cost estimates become increasingly accurate as design concepts mature
- Aiming for ~$1 – 2B "Far-IR Surveyor" mission

Interferometry in the lab



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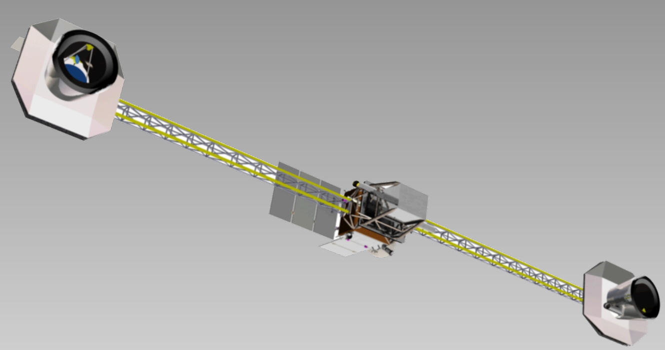
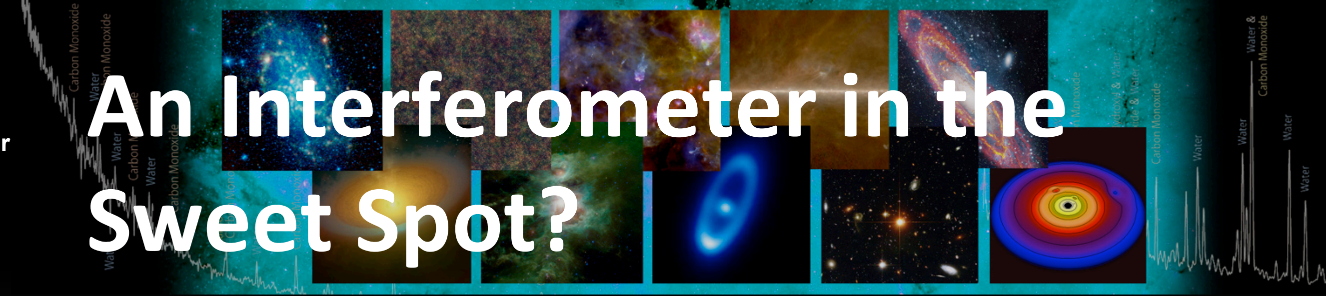
An Interferometer in the Sweet Spot?

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



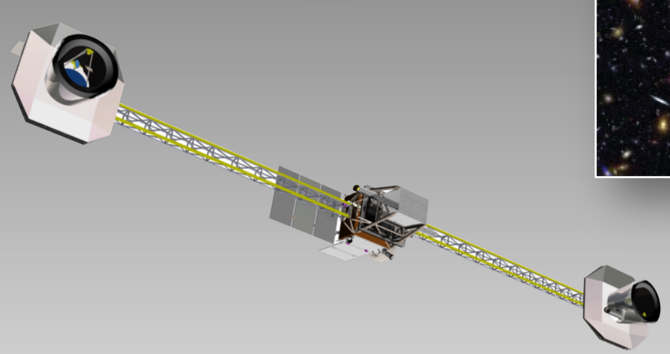
- Image protoplanetary disks and measure the distributions of water vapor and ice to learn how the conditions for habitability arise during the planet formation process;
- Image structures in a large number of debris disks to find and characterize unseen exoplanets;
- Probe the atmospheres of extrasolar 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?

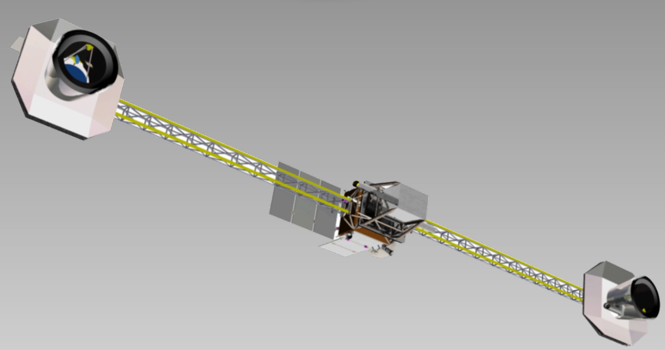
Public interest?

- 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”



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

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 $<10^4$