Concept for Structurally-Connected Interferometer for the Terrestrial Planet Finder Mission

Ken Johnston

Second TPF/Darwin Conference

July 29, 2004

San Diego, CA

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

USNO

Co-Authors

- Bertrand Mennesson, Gene Serabyn, Oliver Lay (JPL)
  Curt Henry, Serge Dubovitsky, Brent Ware
- Charley Noecker, Dan Miller (Ball)
- Bill Danchi (GSFC)
- Nick Woolf, Jonathan Lunine, Phil Hinz (UofA)
- Dave Miller (MIT)

SCI Basics

Terrestrial Planet Finder Mission

TPF

- Objective
  - Detect Earth like planet
    - Flux $2x10^{-7}$ star at 10 microns
    - Null floor for instrumental imperfections 10^{-6} star at 10 microns
    - Local zodi greatly exceeds detected planet photon rates
- Suppress star by nulling architecture
  - Null order
    - Relative amplitude and phase for nulling & background suppression
  - Modulation Efficiency
- Suppress noise by
  - Synchronous detection
    - Rotate the array
    - Phase chopping

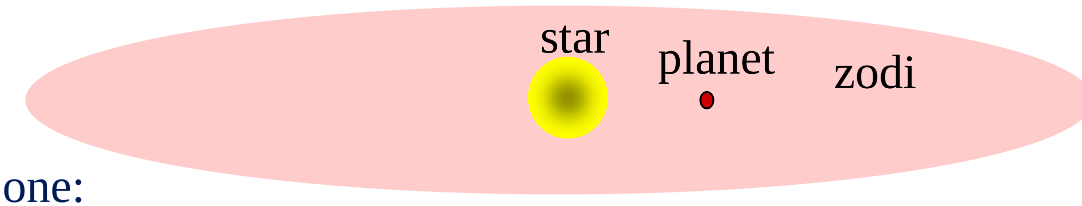
A NASA Origins Mission

TPF Science

- **Detection**: Complete survey within 2 yrs (Late F,G,K dwarf stars)

	Core Science	Full Science
Full Survey	>**35** stars	>**165** stars
Spectra	~1-2 stars	~8-12 stars

- **Full Survey Parameters**:
  - Completeness 95%
  - Continuously Habitable Zone:
    - 0.7 to 1.5 AU (G-dwarf) – Earth area
    - 0.9 to 1.1 AU (G-type) – Half Earth area
  - At least 3 visits
  - Earth albedo



- **Wavelength:**
  - 6.5 - 13μm (17-20 desirable), SR=25
  - 0.5 - 0.8μm (1.05 desirable), SR= 75
- **Field of View** (0.5 to 1 arcsec) to characterize Jovian planets in subset of stars
- **Spectral resolution** of R>100 for brightest sources

Trade Criteria

Science Requirements:

Capability if Detecting 35 (partial) and 165 (full) Earth like Planets

Planet Spectra to Characterize Planet (50% of Detected Planets)

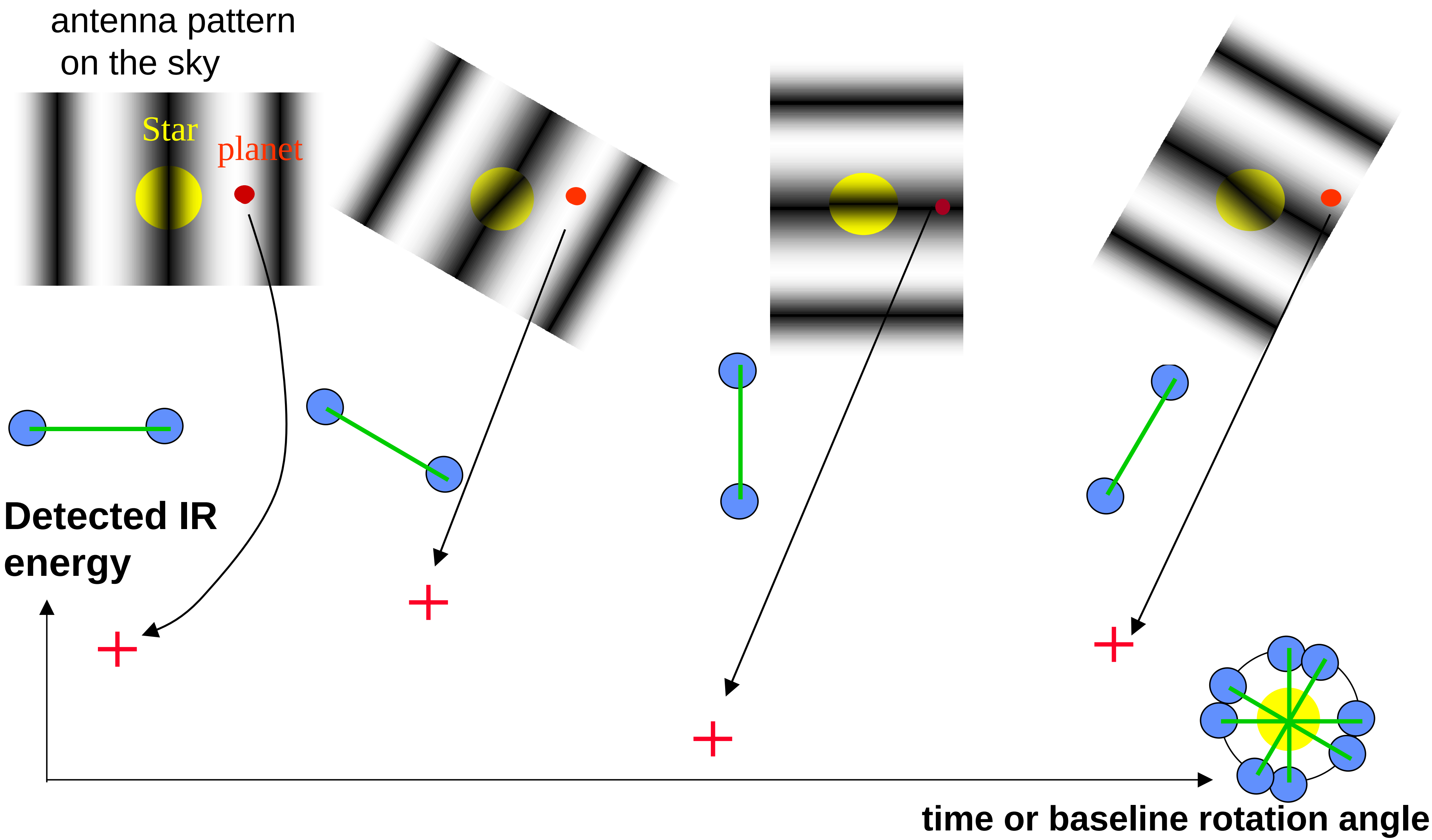
Mandatory Criteria:

1. **Planet signal isolation**
   1. Phase Chopping
2. **Resolution and Sensitivity:**
   1. SNR and PSF
      1. Distinguish Multiple Planets
      2. Observe Orbital Motion

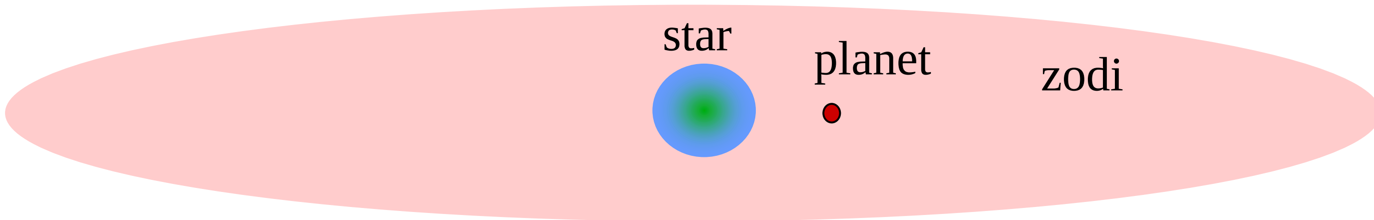
Discriminators:

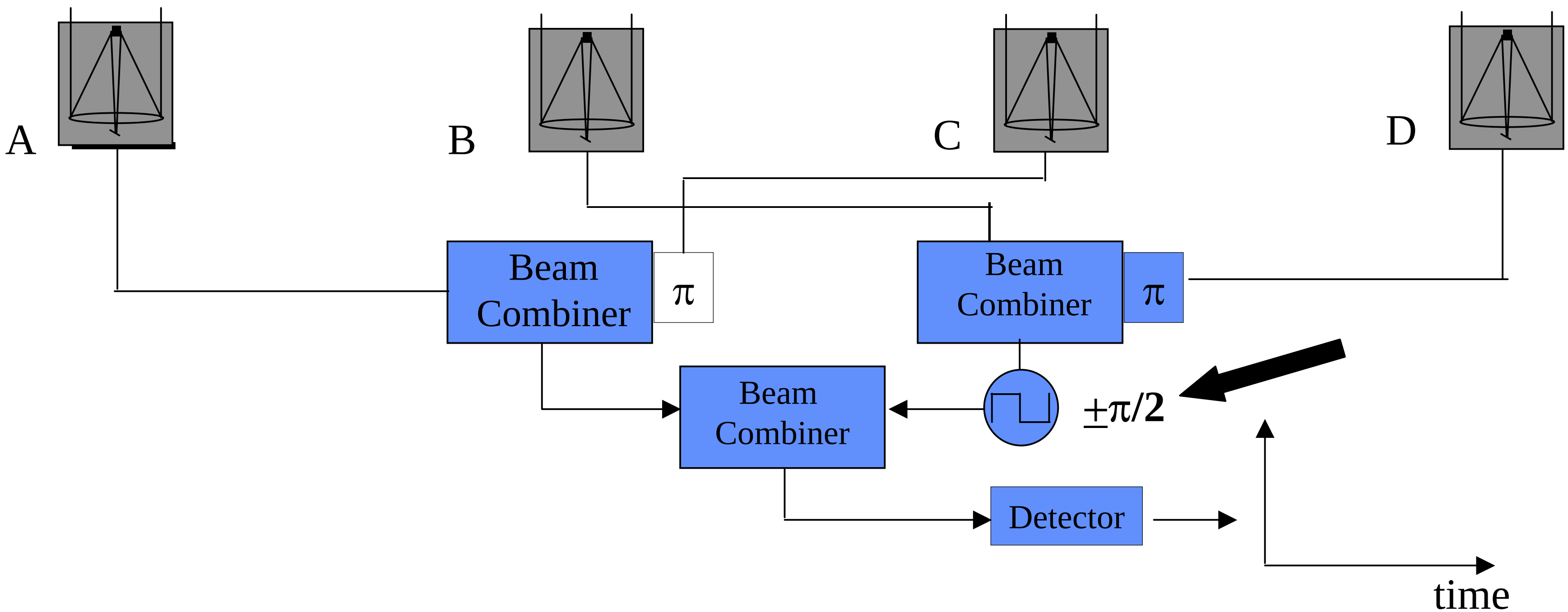
1. **Stars Surveyed:** Total number beyond [35, 165]
2. **Array size efficiency** for survey
3. **Beam combiner simplicity**

Interferometer Exo-Planet Detection

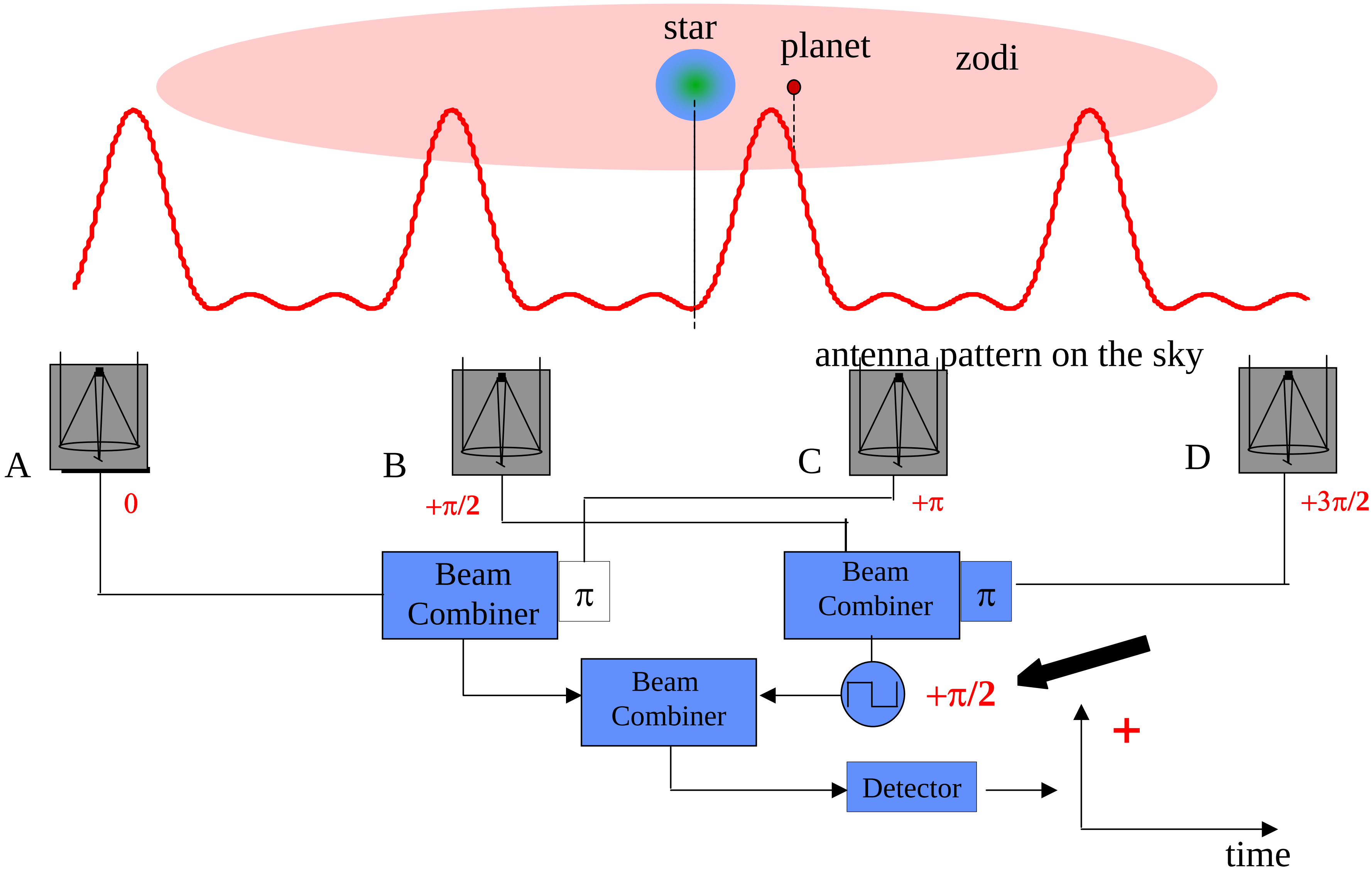


Chopping: a method for background suppression

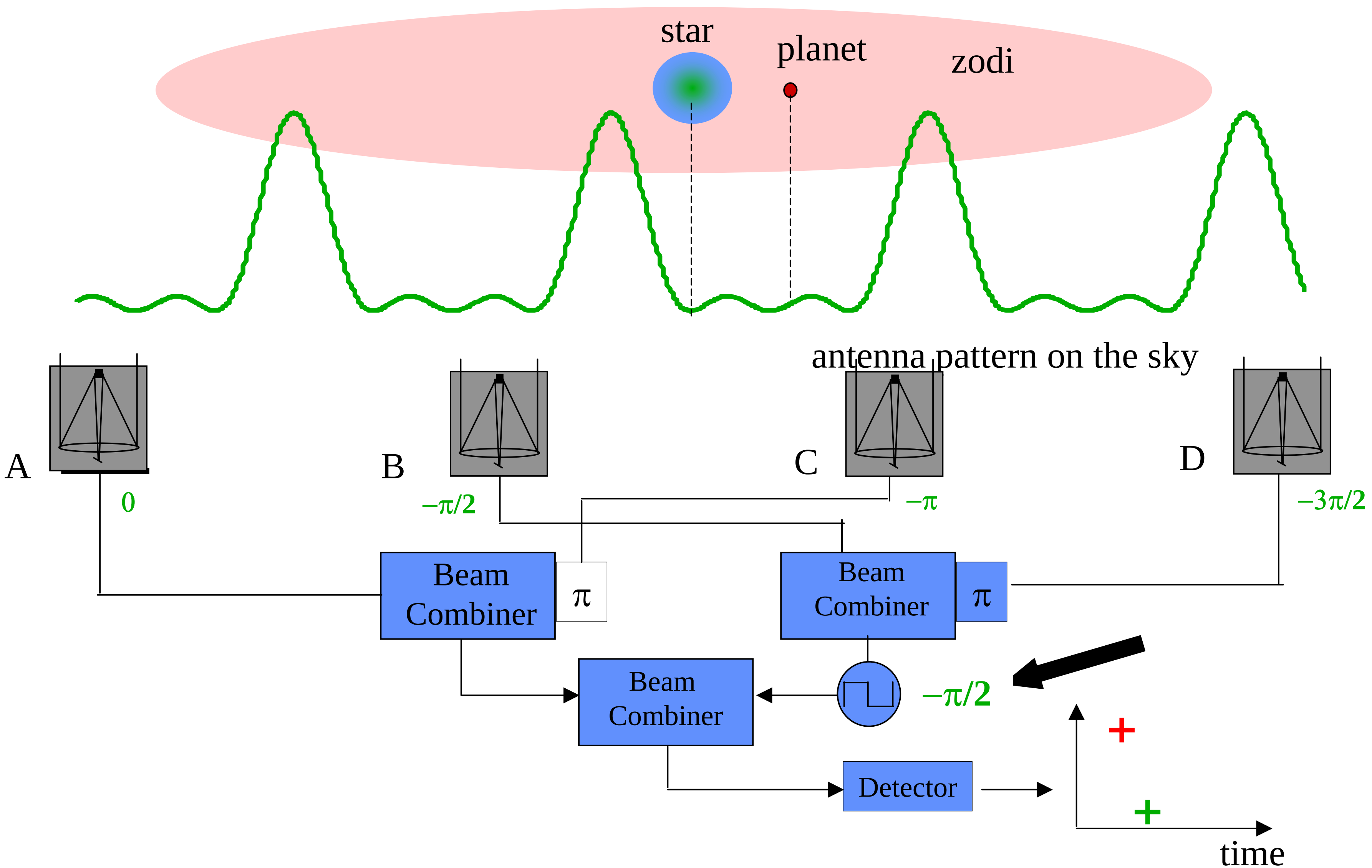




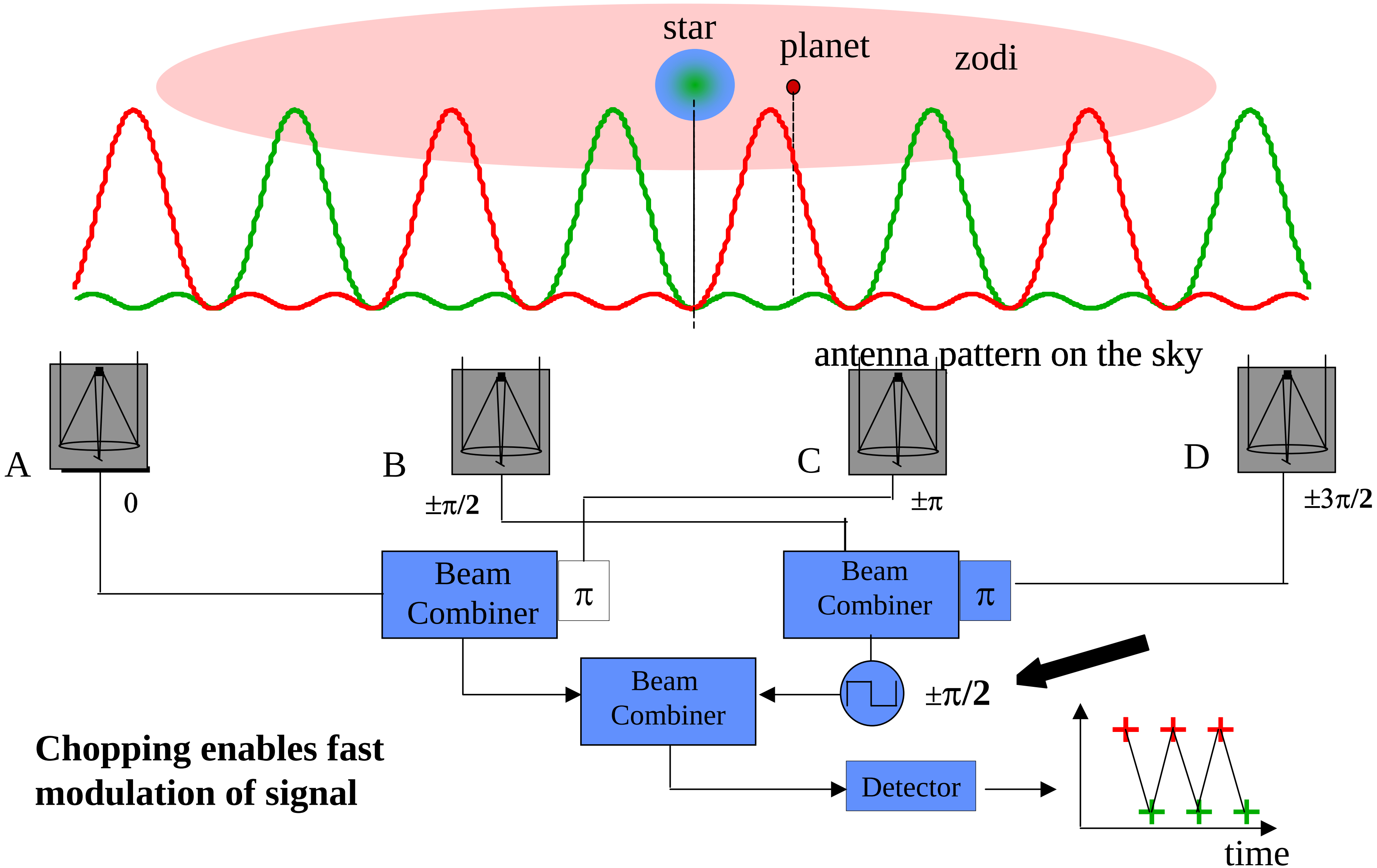
Chopping: a method for background suppression



Chopping: a method for background suppression

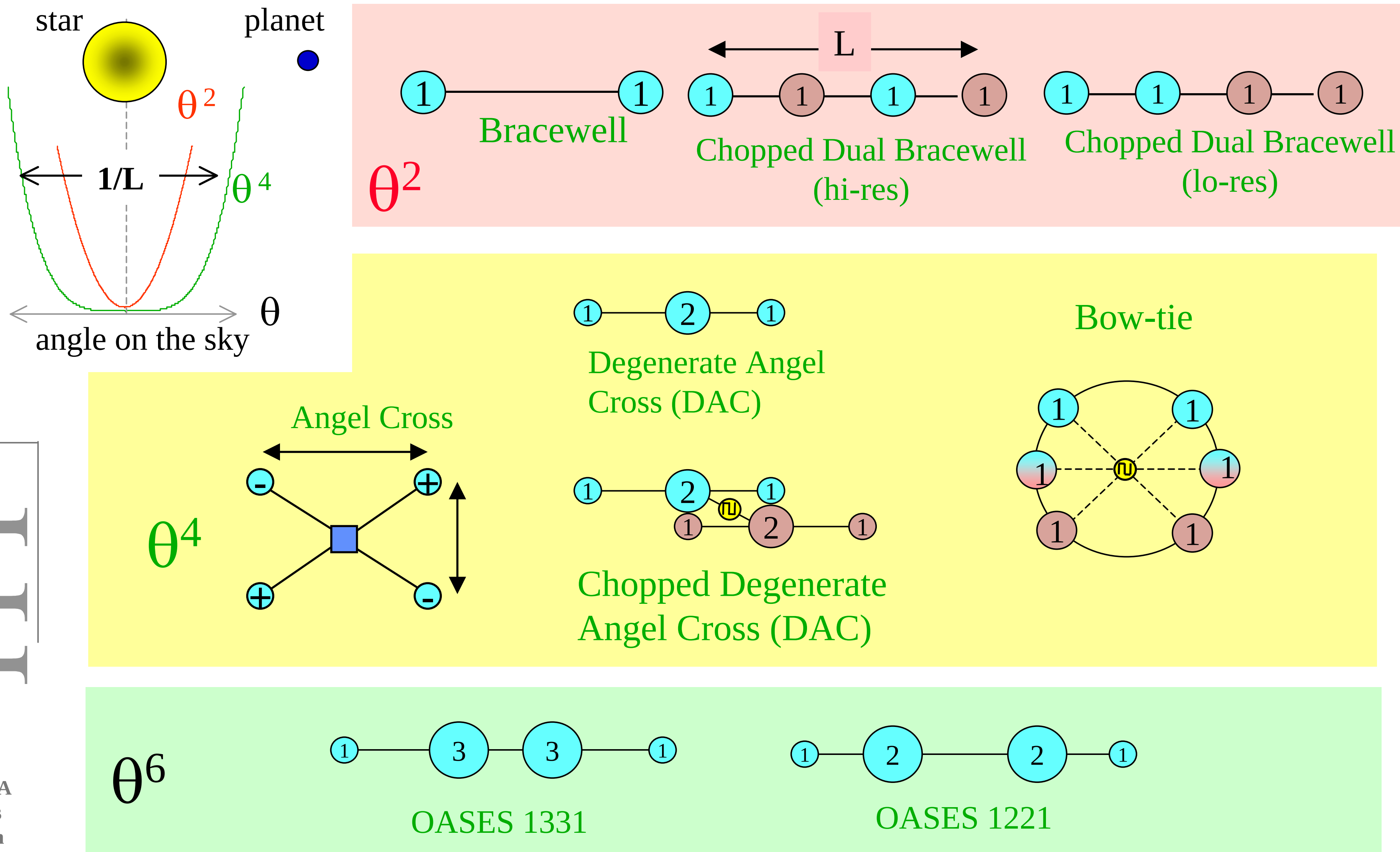


Chopping: a method for background suppression



Chopping enables fast modulation of signal

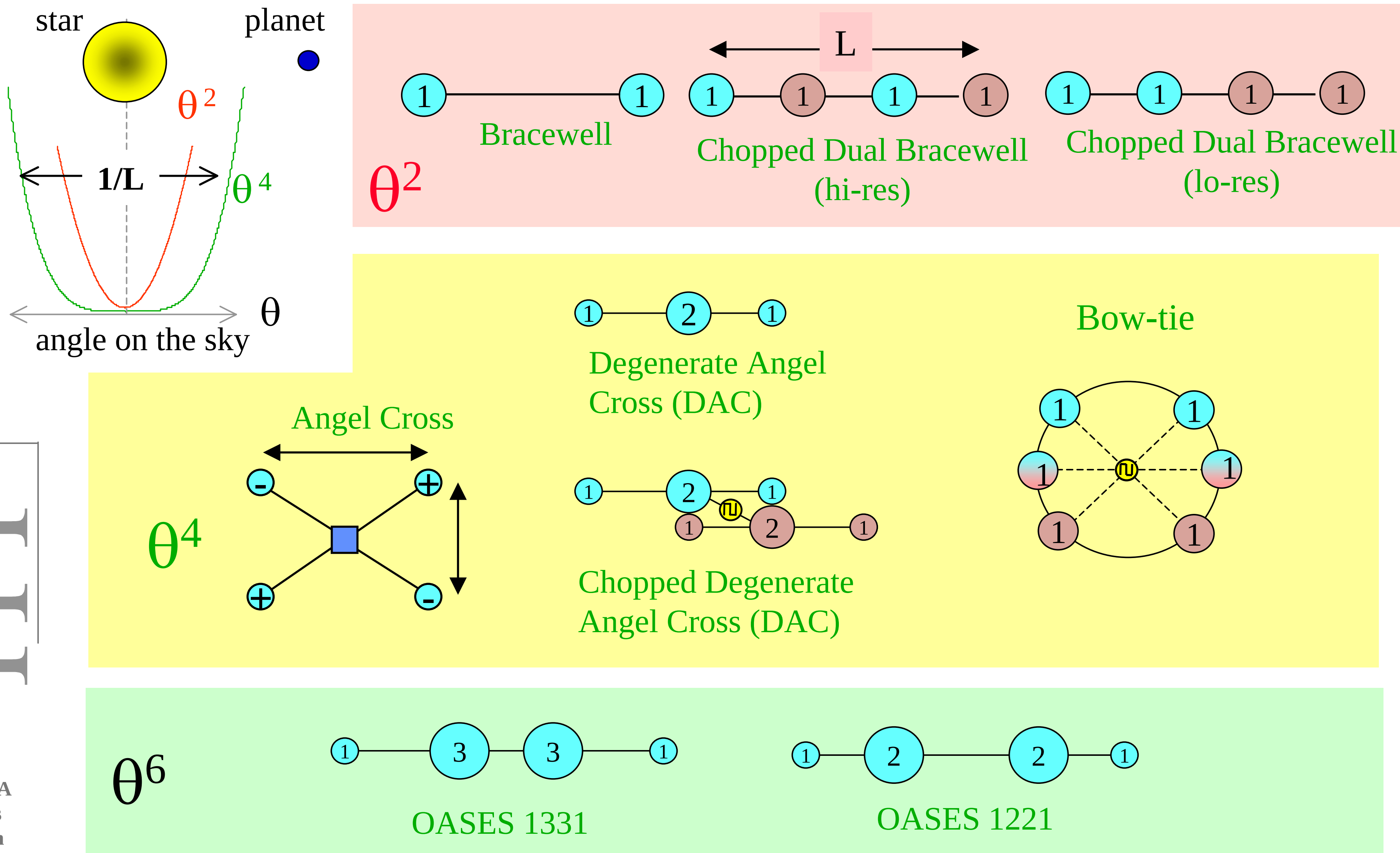
Architecture Trade: Core Science



1. Planet Signal Isolation (chopping)

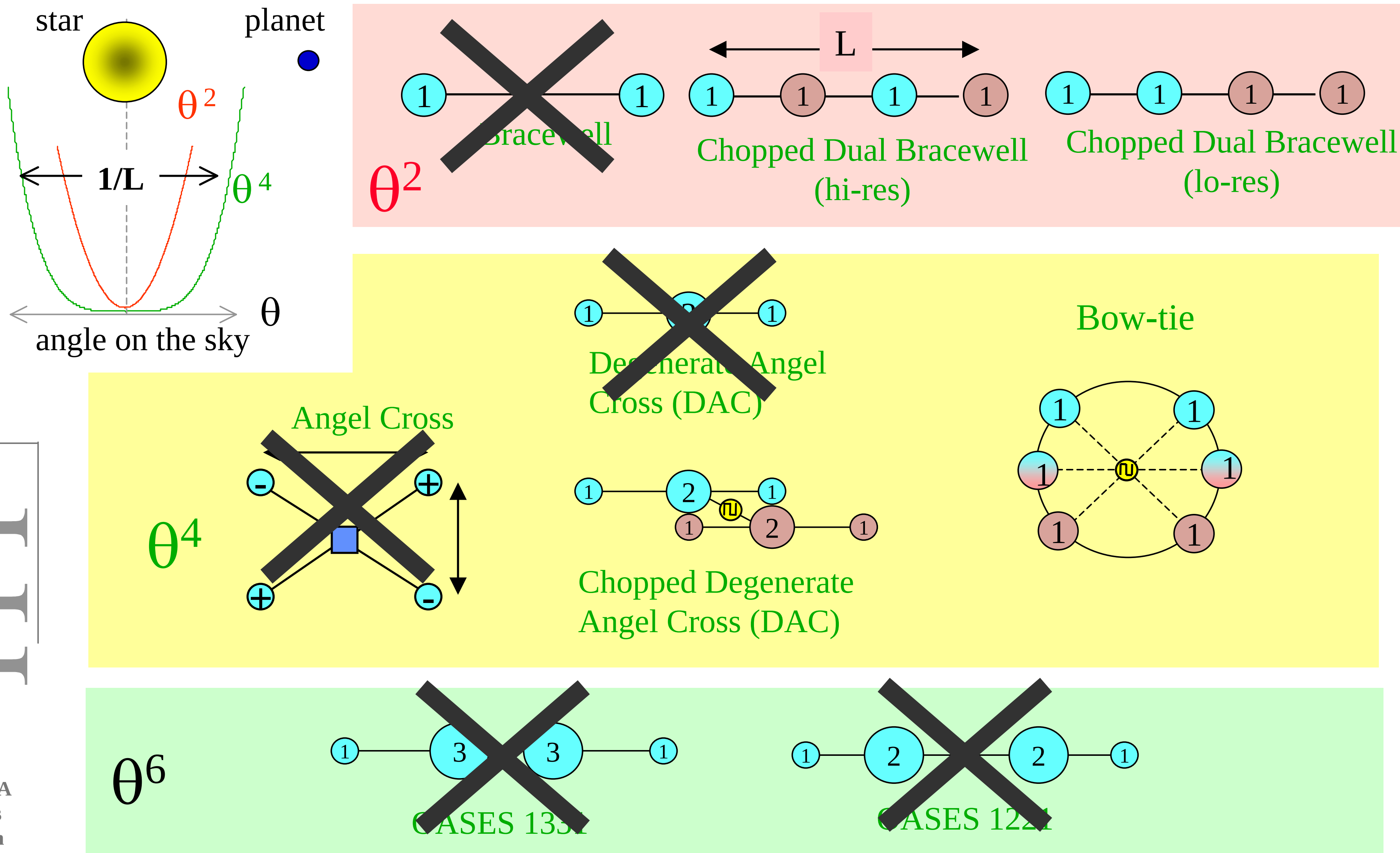
Terrestrial Planet Finder Mission

TPF



A NASA Origins Mission

1. Planet Signal Isolation (chopping)



Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

General Conclusion

Terrestrial Planet Finder Mission

TPF

Under the following assumptions

– Near shot noise limited performance (allowed systematics and shot noise to be equal)

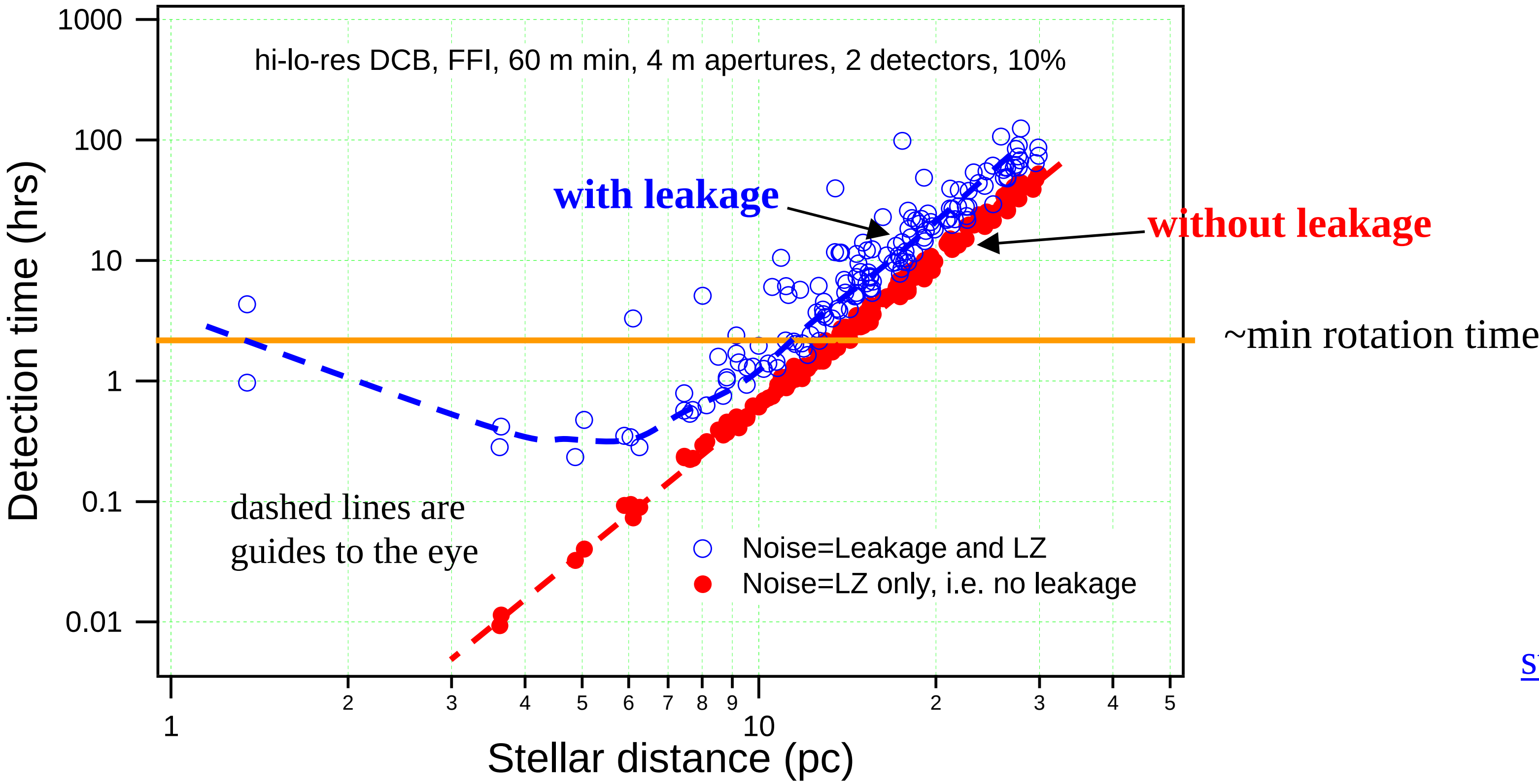
To see more stars (in the order of biggest gains), Increase signal/noise

$$\mathbf{SNR = N^{1/2}_{DET}\ S_P / (\ 2\ (\ S_{LZ} + S_{SL}\ )\ )^{1/2}}$$

- Decreasing only Stellar Leakage at the expense of the planet signal does not help

A NASA Origins Mission

What about Stellar Leakage?



star table

- Although stellar leakage is the dominant noise source for nearby stars, it is NOT a problem for observation of nearby stars.
- More distant stars, which we need to pick up for a full mission, are NOT leakage dominated

θ^2 Configurations preferred

A NASA Origins Mission

Terrestrial Planet Finder Mission

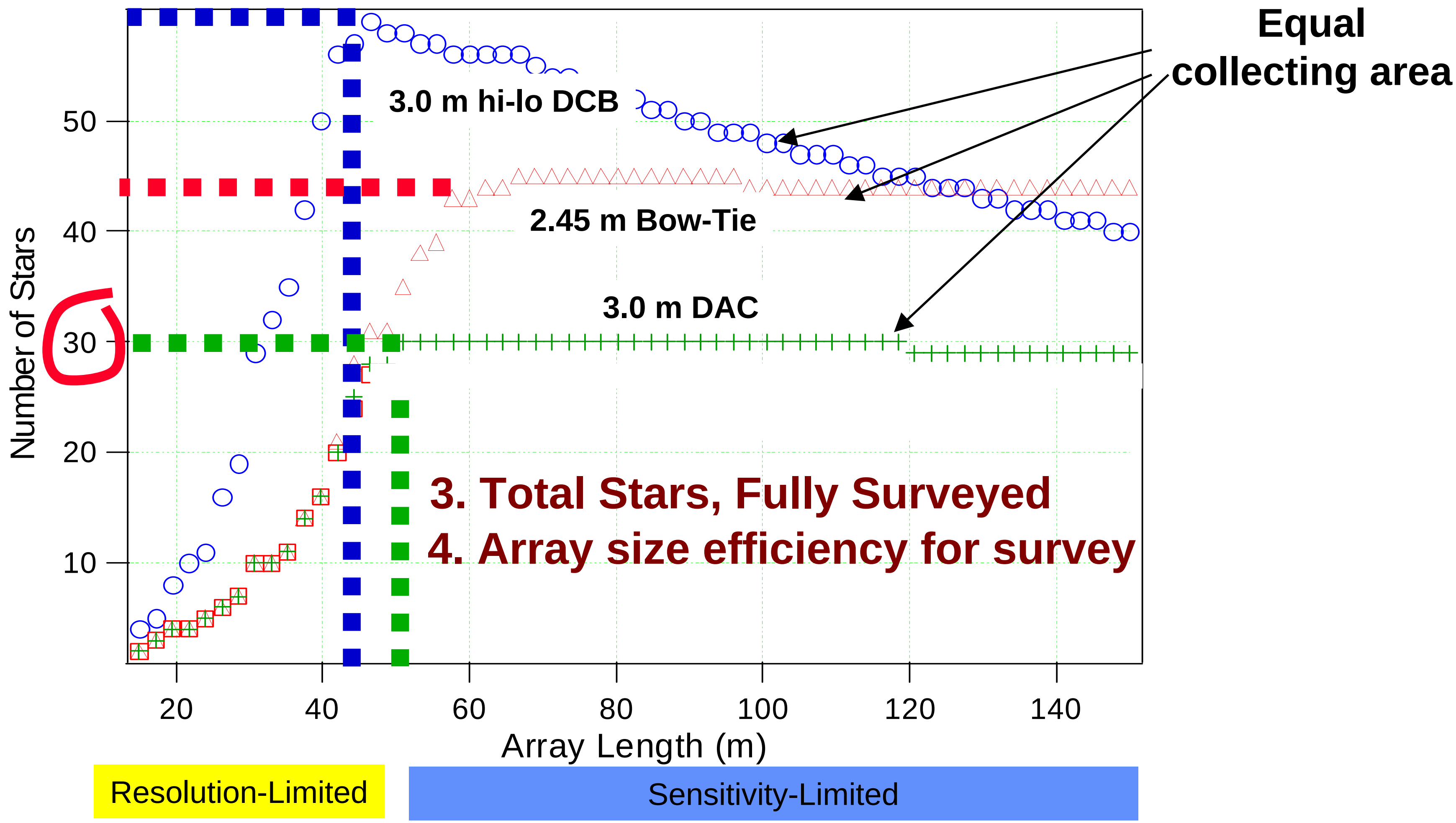
TPF

A NASA Origins Mission

Method

- List of Target Stars (Nearby Stars: F, G, K, M?)
- Planet Model (Science Requirements)
- Interferometer Array
  - Architecture (modulation efficiency)
  - Aperture geometry and size
  - Stellar leakage
  - Local/Exo zodi
  - Assume instrumental noise = photon noise
  - Throughput efficiency
  - Orbital and FOV limitations
- Mission duration
  - 2 years 50% observations; launch vehicle (lift&shroud area)
- Processing Algorithms
- One DIVH Launch vehicle

2. Resolution and Sensitivity: Fully Survey >30 stars



Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

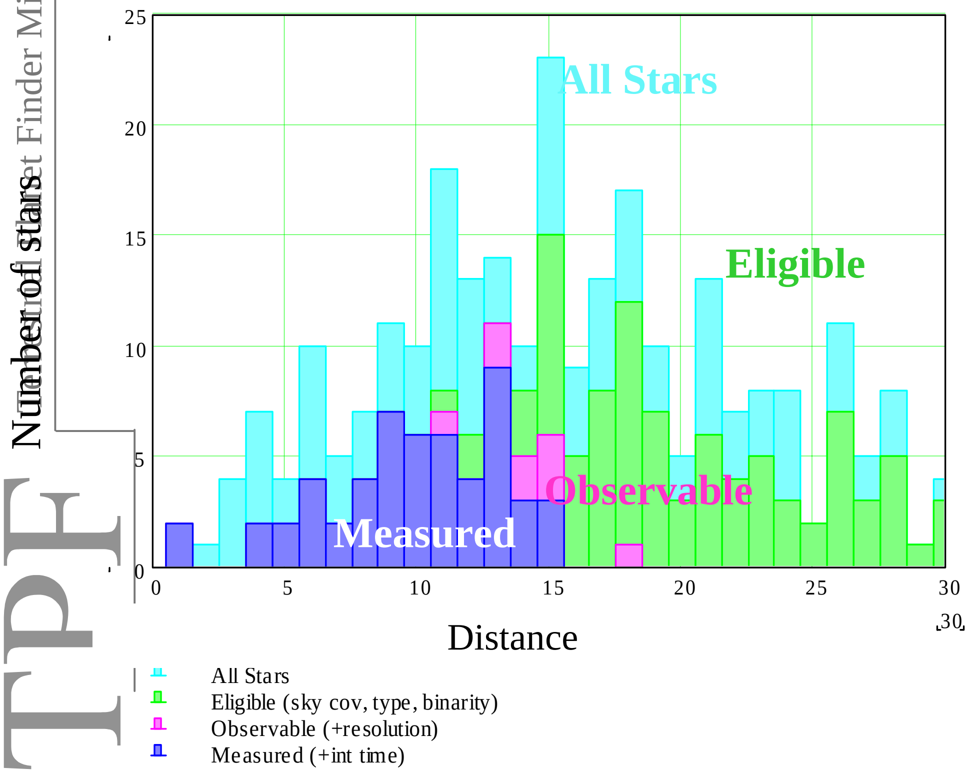
Possible Stars Measured

TPF

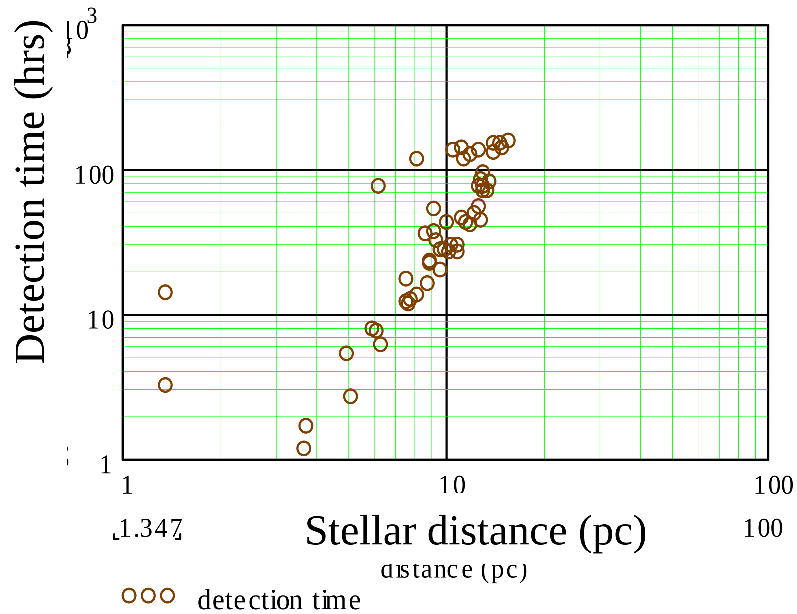
Terrestrial Planet Finder Mission

A NASA Origins Mission

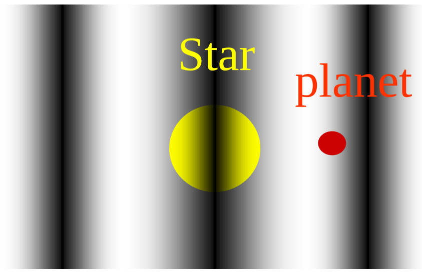
Histograms of star sets



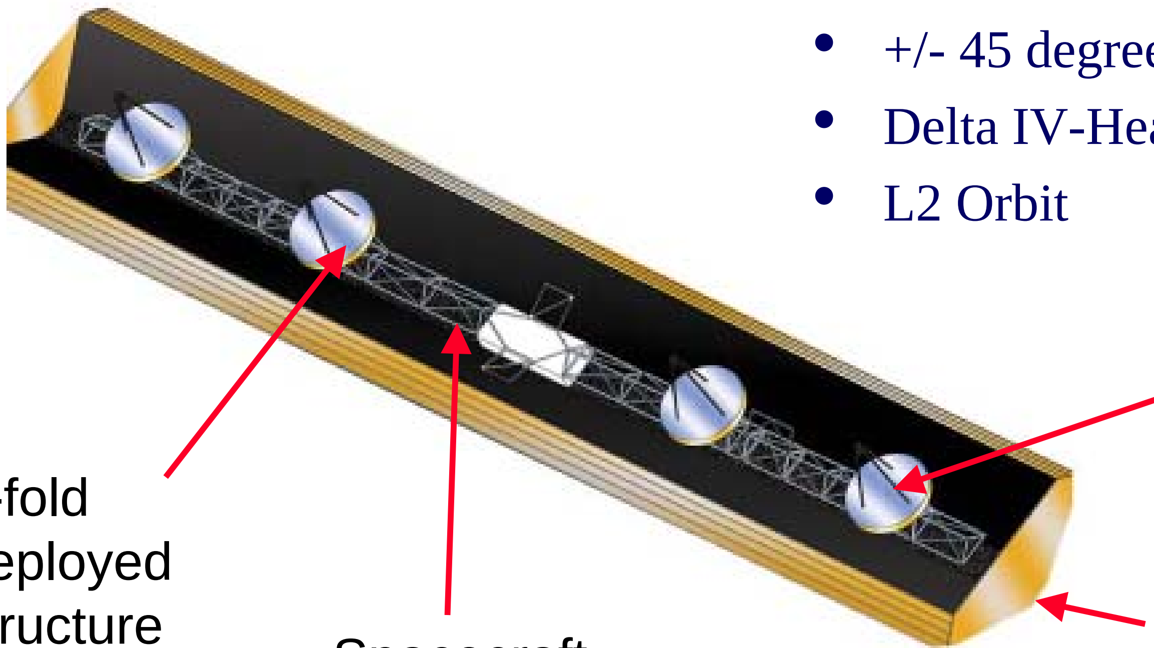
Detection times



Strawman for Structurally-Connected Interferometer



- Dual-chopped Bracewell
- 36 m array
- Four apertures, 3.2 m diameter
  - -18, -9, +9, +18 m positions
- 56 stars surveyed in 2 years
- +/- 45 degrees sky coverage
- Delta IV-Heavy, 22.4 m fairing
- L2 Orbit



Dual Chopped Bracewell Beamcombiner D.2

Assumptions:

- Identical telescopes
- Phase correction (φ) via dispersion correctors
- BC = sym. constructive beamcombiner (MMZ)
- XC = cross-combiner (MMZ or simple BS)

Two levels of phase correction redundant?

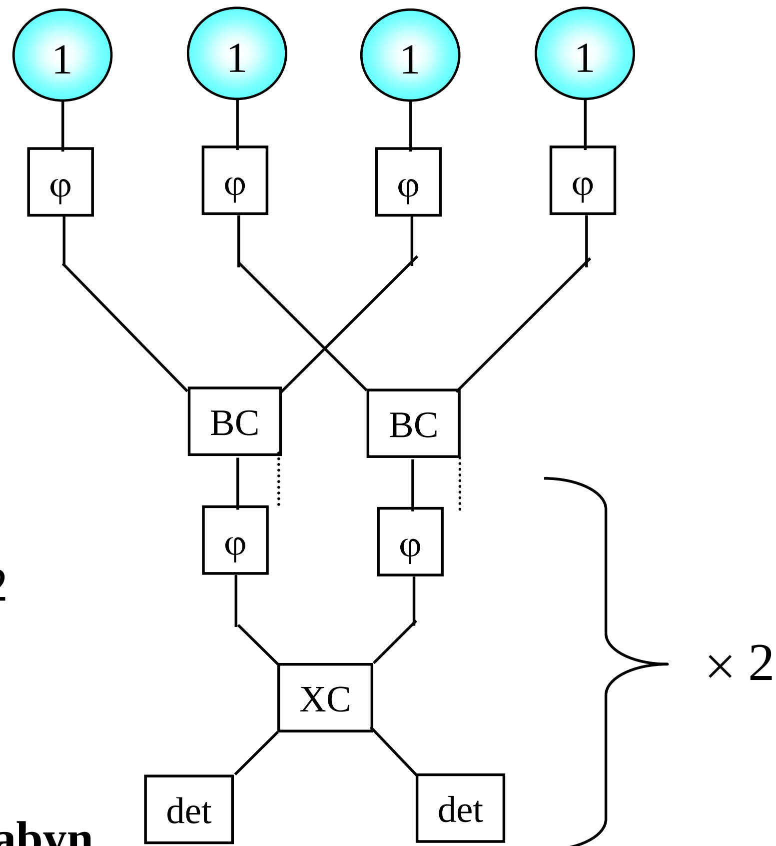
- First level: π, π, 0, 0
- At chop level: 0, -π/2 → 0, π/2
- Gives π, π/2, 0, -π/2 → π, 3π/2, 0, π/2

This is formally equivalent to

- First level: π, π/2, 0, -π/2 → π, 3π/2, 0, π/2

Totals for MMZs:

- 2 BCs
- 2 XCs
- 6-8 beamsplitters
- 4-6 φ shifters
- 4 detectors

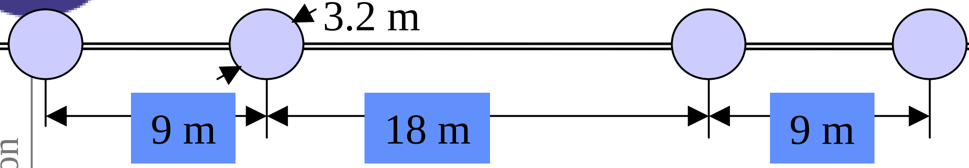


See poster 69 Serabyn

A NASA Origins Mission

SCI

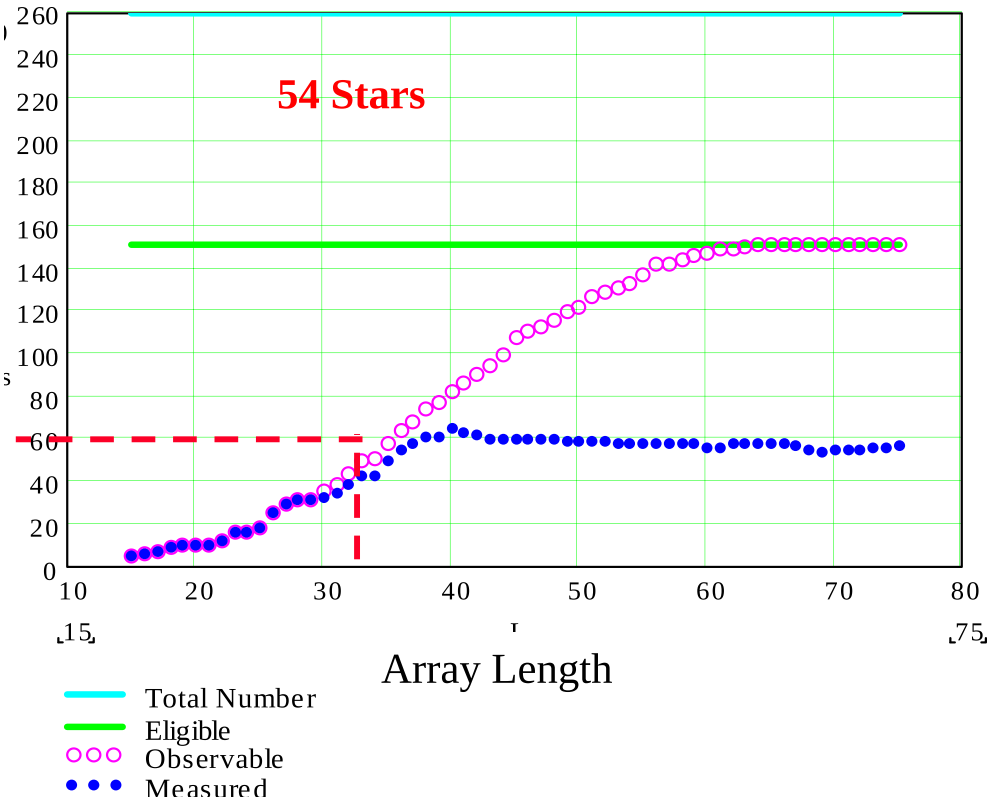
SCI Baseline: Minimum Mission



hi-lo-res Chopped Dual Bracewell, x=0.25

Terrestrial Planet Finder Mission

TPF



- Under current implementation assumptions SCI Baseline achieves the Minimum Mission Requirement (30 stars)

	Baselined Option
CONFIGURATION SPECIFICATIONS	
Array length	**36**
Enrance pupil/nulling architecture	**DCB hi/lo res**
Chop response (right-left)	0.87/0.77
Chop de-modulation efficiency (~Ndet)	0.5
BeamCombiner efficiency (on top of ideal)	1
Apertures Locations Factor (x=bs/s)	**0.25**
Collecting area (m^2)	**32.2**
Number of apertures	4
Apertures diameter (m)	**3.2**
IMPLEMENTATION ASSUMPTIONS	
Inner Working Distance (fraction of 1st peak at 10um)	**1**
Sky coverage (+/- degrees)	**45**
Internal throughput	**0.05**
Optics transmission	0.2
Det Response	0.5
Number of detectors (Ndet)	1
Null floor	**1.E-06**
OBSERVATION PARAMETERS (Constrains)	
planet surface area	0.5 Earth
planet distance from star	0.7 MidHZ
Required SNR (shot noise only)	**7**
Bandwidth (um)	**7-17**
Completeness	**95%**
Number of visits	3
Orbit Inclanation factor	1.29
Time avaliable for integration	**1 year**
Max single observation time	**7 days**
LZ flux density	**13.7 Mjy/sr @ 12um**
PERFORMANCE METRICS	
Number of stars (req=30)	**54**
F	7
G	20
K	27

SCI Planetary Signal Extraction

Terrestrial Planet Finder Mission

TPF

- Blind Test Cases
  - Earth, Earth + Jupiter, etc
- Models
  - Planet, stellar flux, exo and local zodi
  - Interferometer: 36m max baseline, 3.2 m apertures, DCB configuration
  - Integration time (50ks), rotate array 360 degrees
- Algorithms
  - Cross-Correlation + CLEAN (Draper/Elias,Ball)
  - Bayesian Image Reconstruction (Marsh/Velusamy, JPL) **Poster 70**
  - Non-linear optimization (Woolf, Eatchel, U of AZ)

A NASA Origins Mission

SCI Planetary Signal Extraction

Terrestrial Planet Finder Mission

TPF

- Results:
  - Detected Jupiter like planets
  - Detected 14 of 24 planets of mass < 3 Earth
  - Did not use multiple observation information
  - Many of the non-detections conflated two close planets, so we would go back and look anyway.
- Conclusions
  - Refine or Develop New Algorithms
  - Improve Array Architecture (2D)
  - Higher S/N (>5) may be necessary

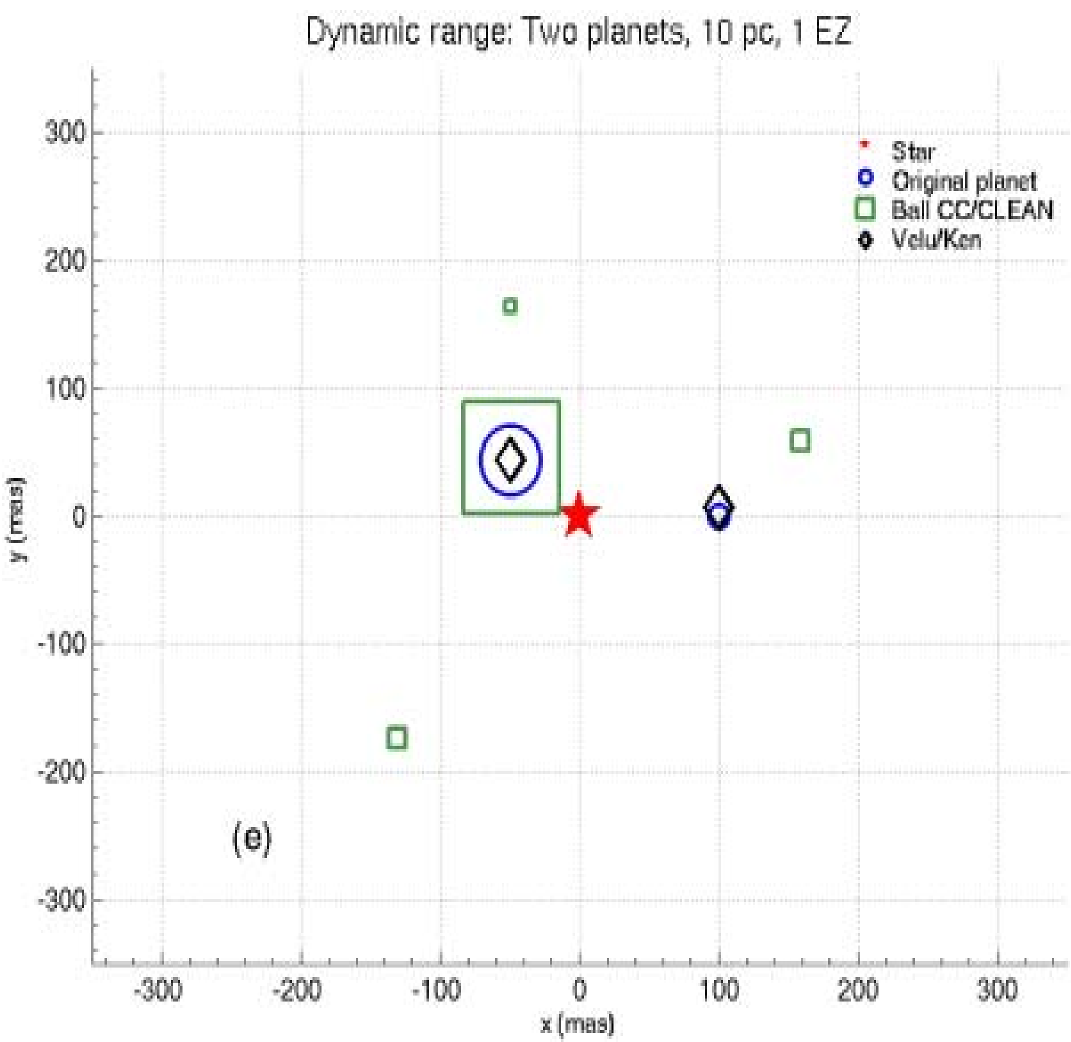
A NASA Origins Mission

SCI Planetary Signal Extraction

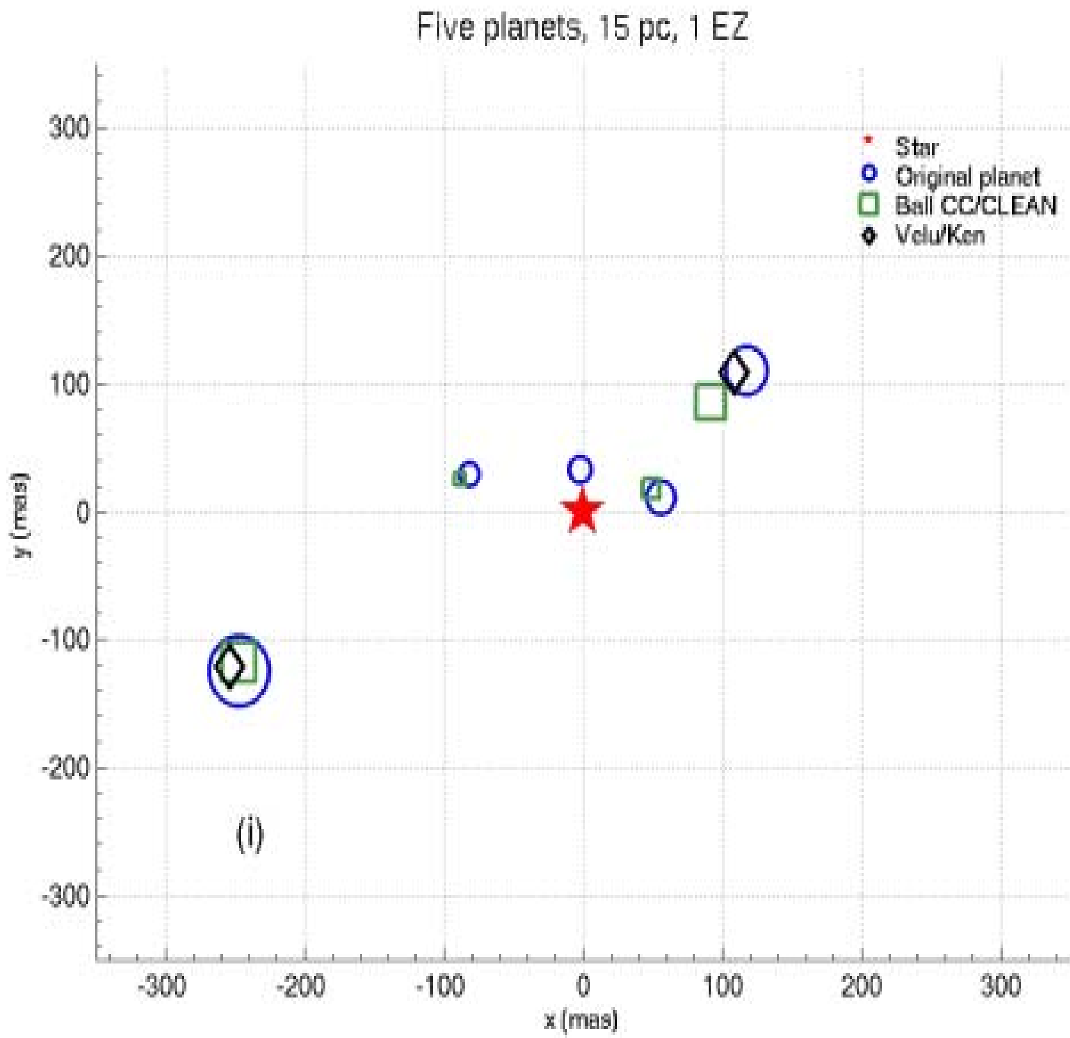
Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission



SCI Planetary Signal Extraction

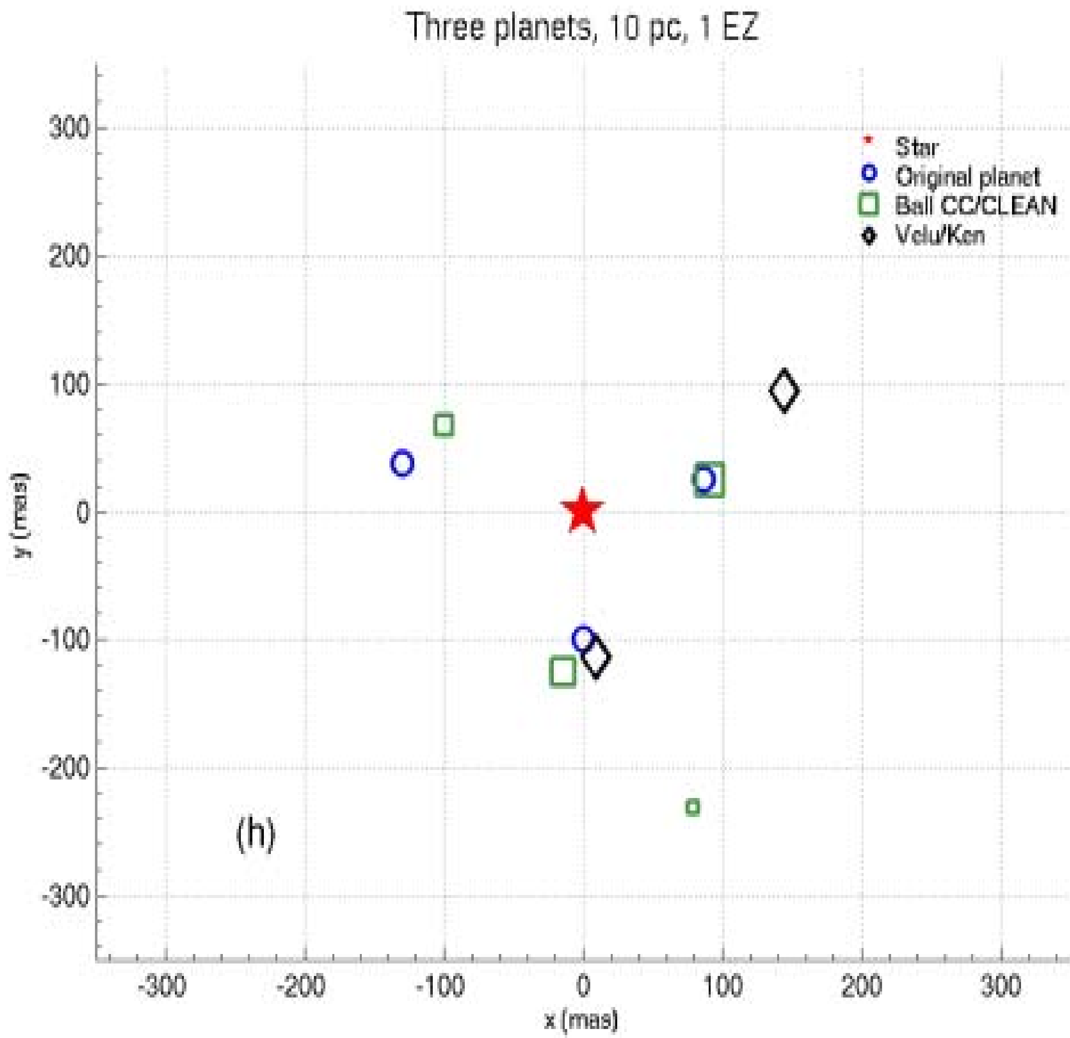


SCI Planetary Signal Extraction

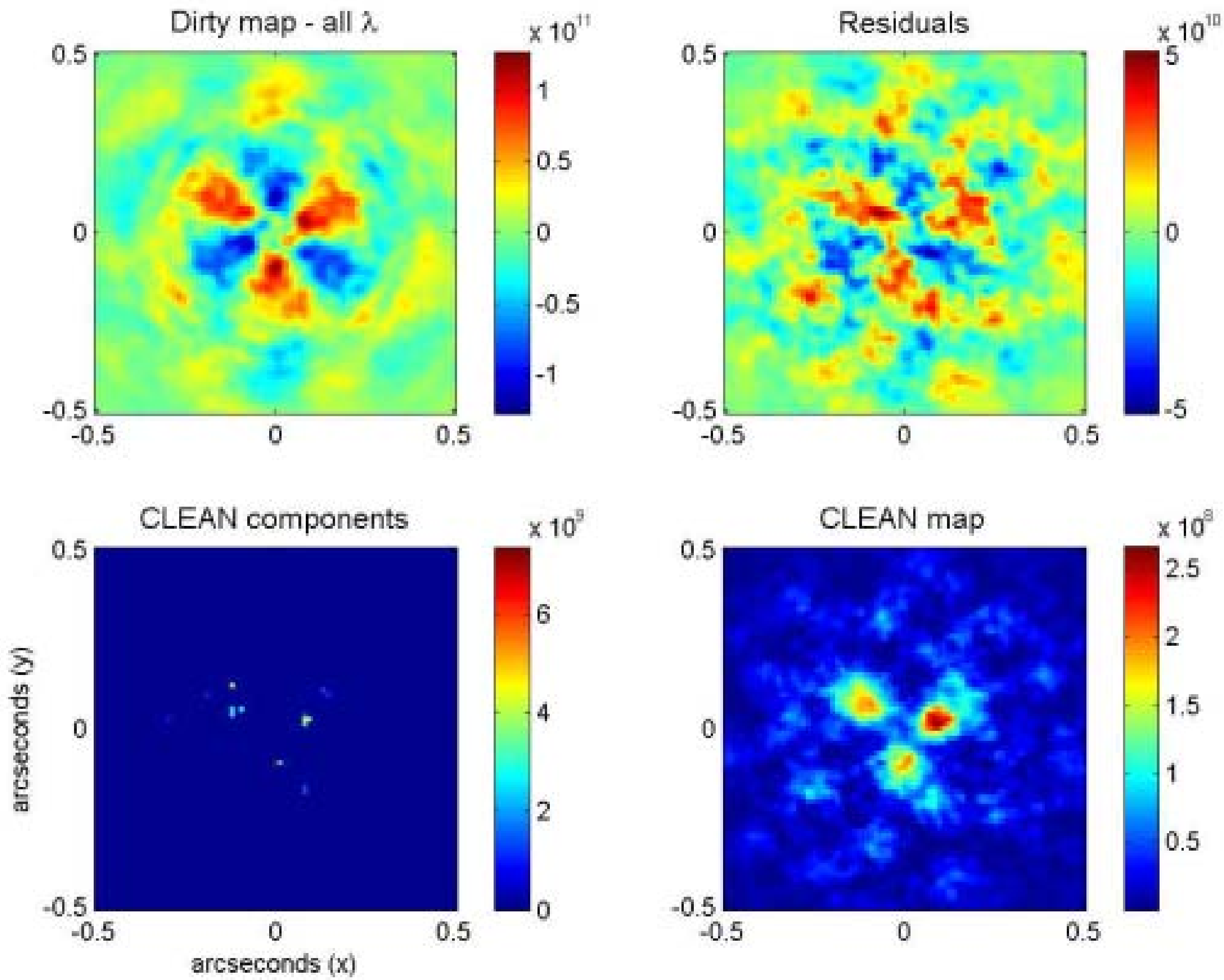
Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission



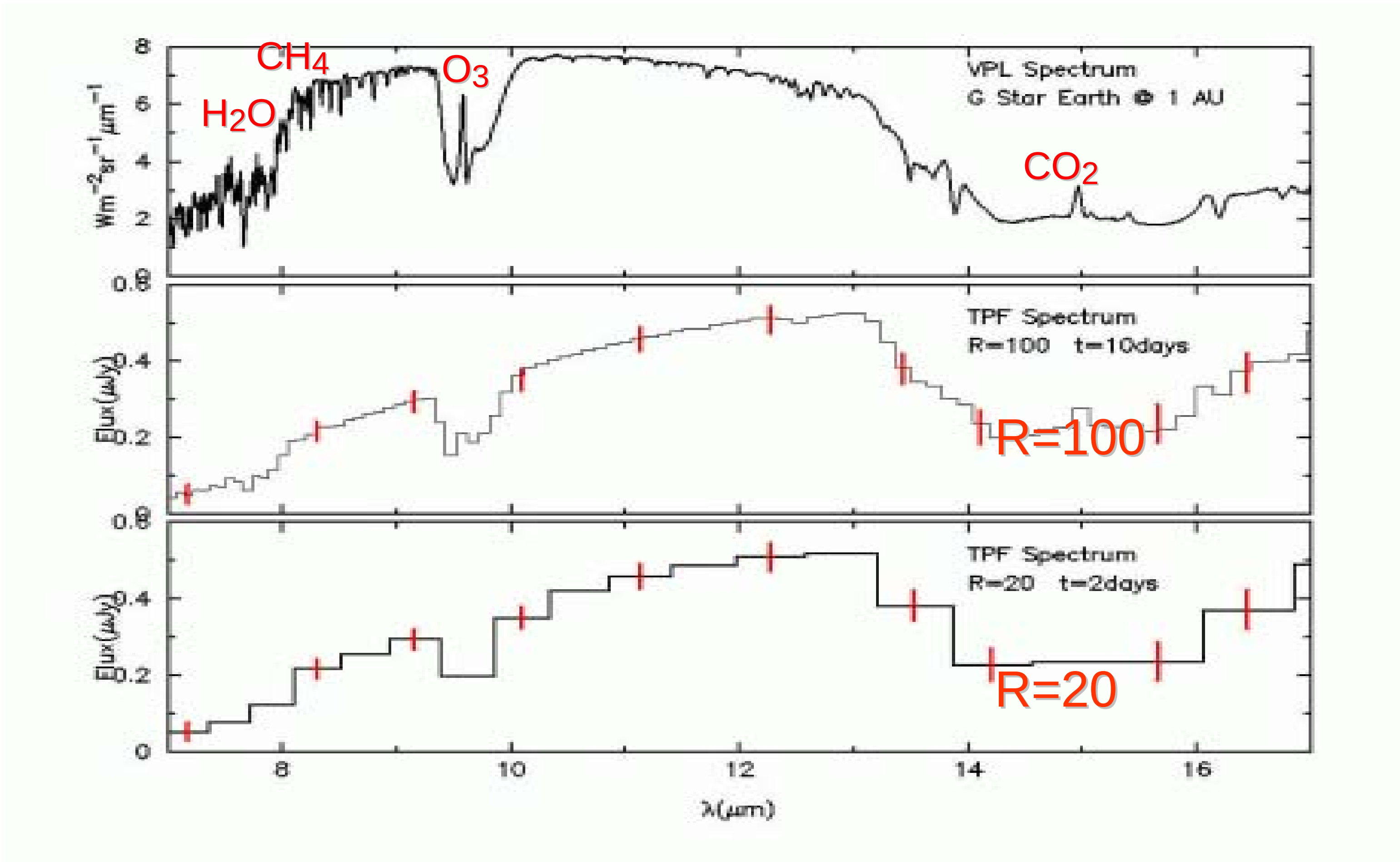
SCI Planetary Signal Extraction



Earth detection by TPF

Poster 63 G. Tinetti et. al.

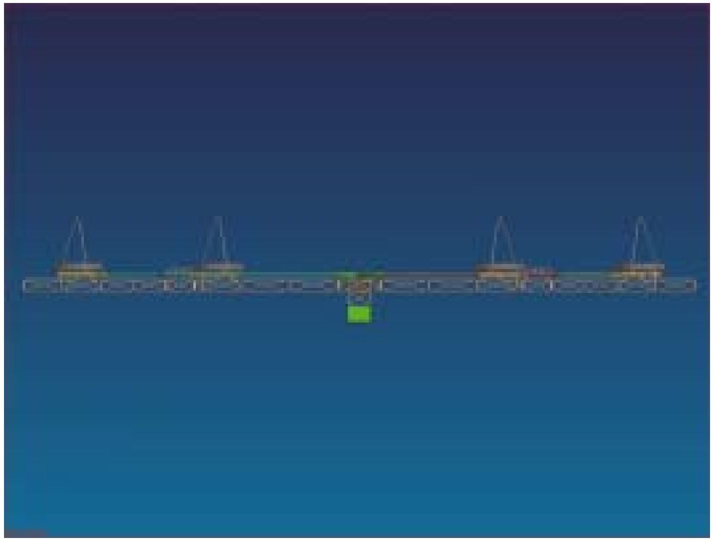
TPF simulation by T. Velusamy

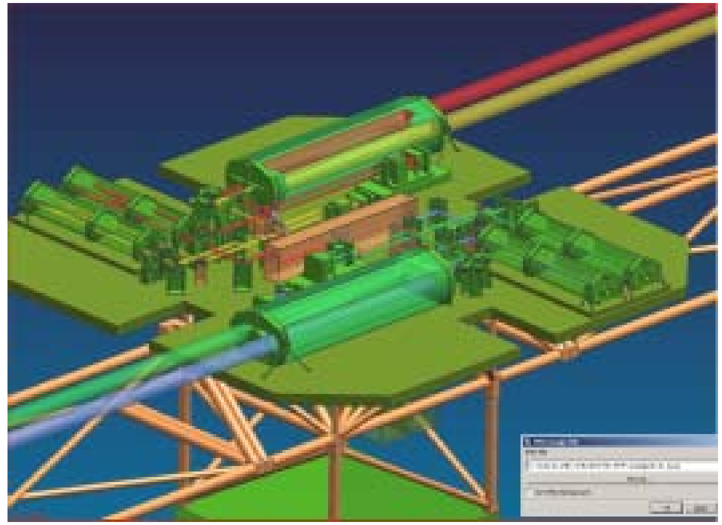


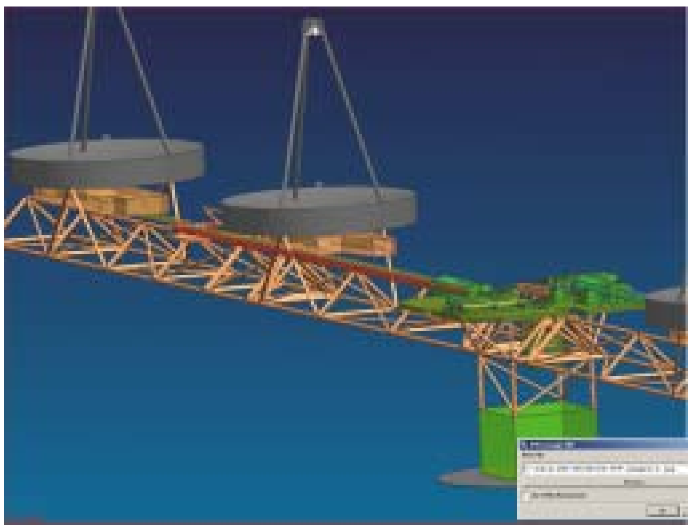
TPF

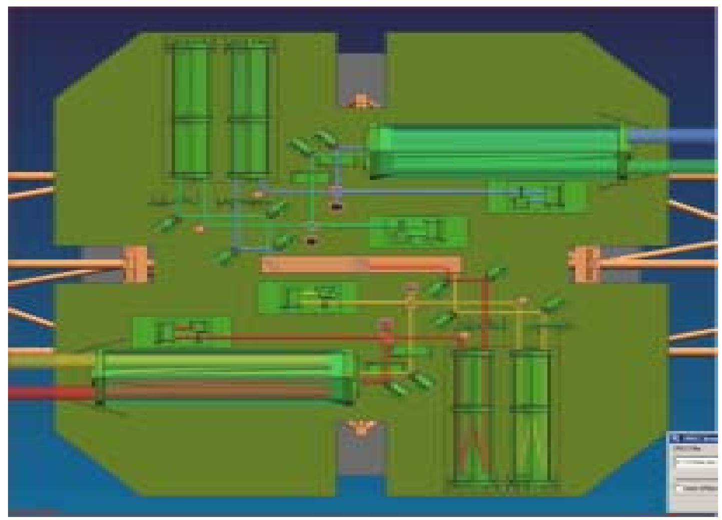
A NASA Origins Mission

SCI Interferometer Configuration

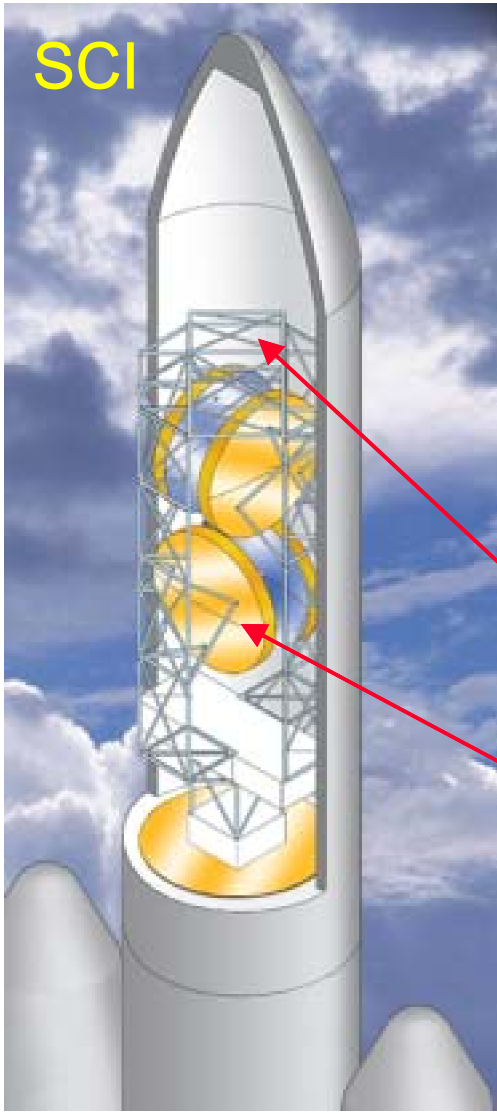






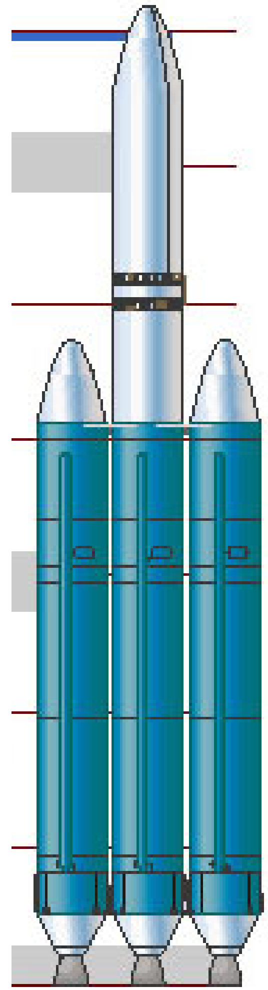


Launch Vehicle Packaging: 5 x 22.4 m fairing, Delta IV-Heavy



6-fold oblique structure

3.2 m telescopes



SCI STATUS

Terrestrial Planet Finder Mission

TPF

- Minimum Mission C
- oncept
  - Interferometer:
    - Nulling Architecture: DCB
    - Geometry: 1D, Baseline: 36m, Apertures 4 @ 3.2 m
    - Beam Combiner
      - Laboratory Work
        - White light null 10^{-4}
  - Number of stars > 30
  - Launch DIVH, orbit L2, etc.

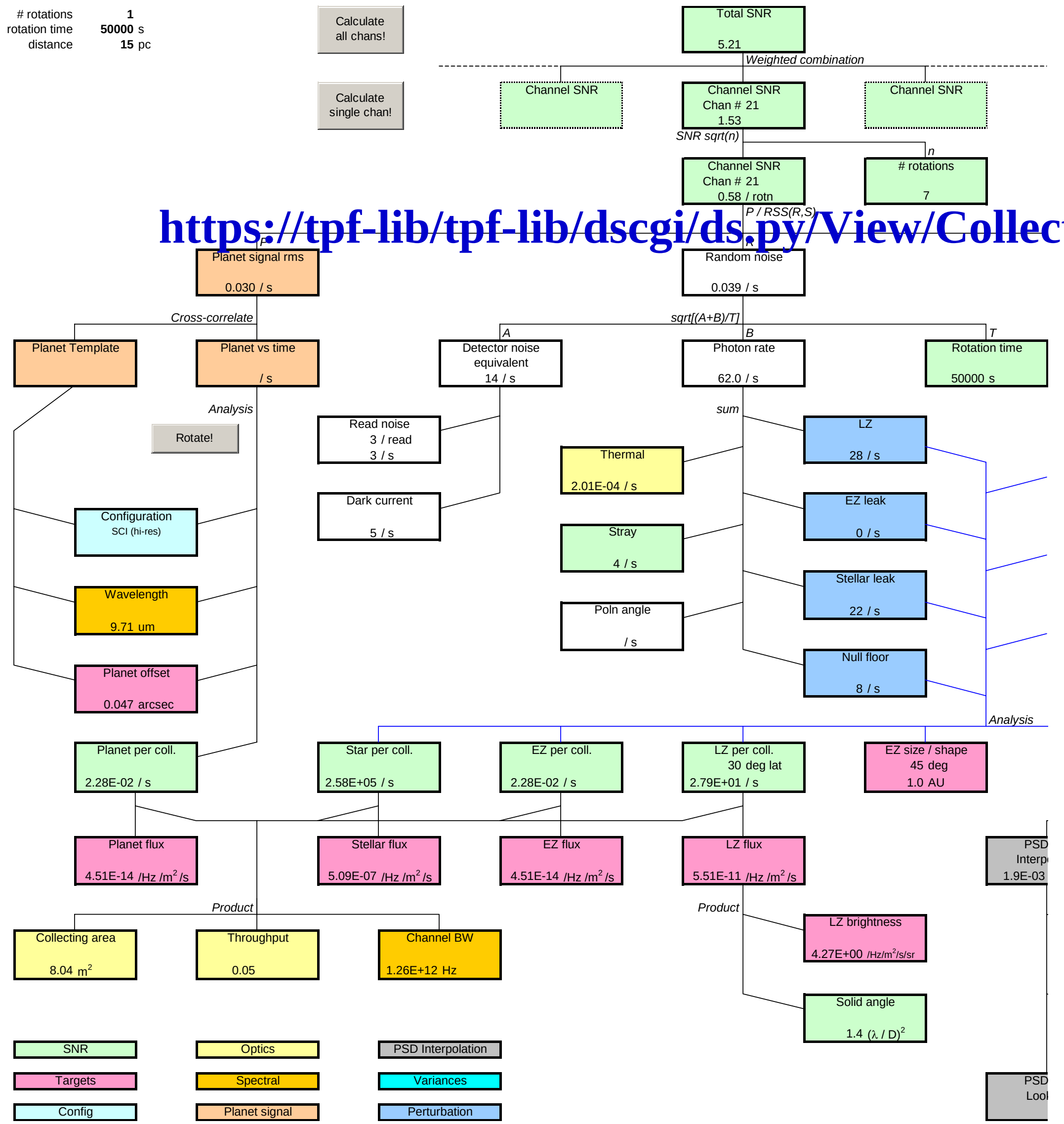
A NASA Origins Mission

Interferometer Peformance Model (IPM)

Terrestrial Planet Finder Mission

TPF

https://tpf-lib/tpf-lib/dscgi/ds.py/View/Collection-1310



A self consistent set of assumptions, constrains and requirements that can be use as a starting reference point by the design teams

A NASA Origins Mission

Next Steps

- Investigate Formation Flying Arrays
  - Variable Baseline
    - Tune length for stars
- Establish baseline for detection confirmation strategy:
  - Basic observation scenario
  - Signal extraction methods
    - Handling multiple planets
- Review/refine error budget / Rqt flowdown
- Continue Laboratory/Industry Studies
- Refine Spectroscopic capability
- Mechanical trades to expand sky coverage
- FFI architecture trade with ESA Darwin:
  - Show mutual science requirements, design assumptions, analysis methods
  - Compare beam combination approaches

Structurally Connected Interferometer Concept