National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

Mid-Scale and Small-Scale Mission Completeness Modeling

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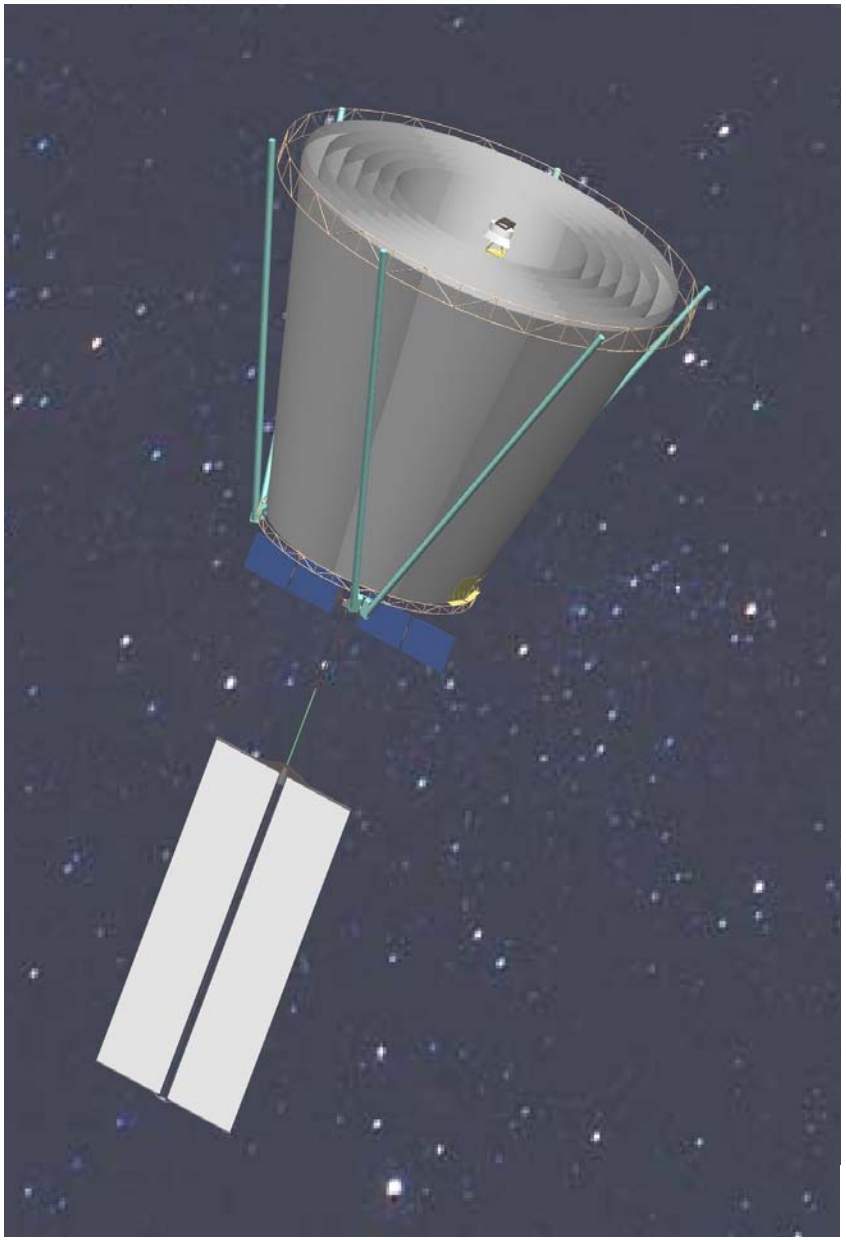
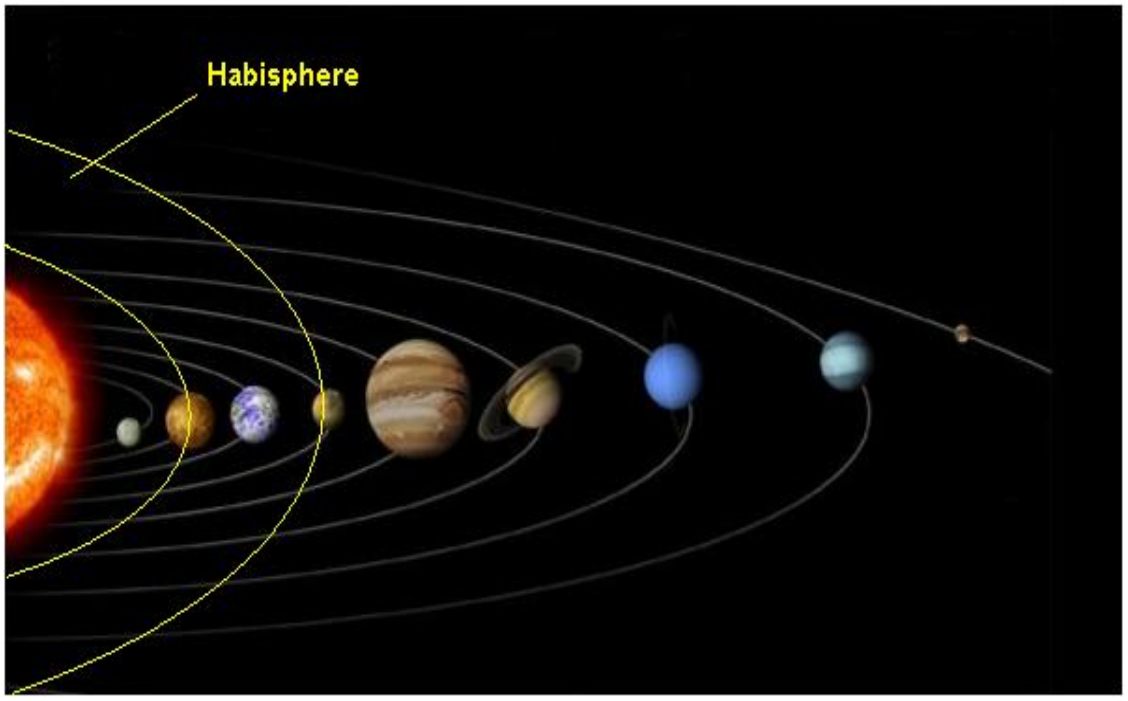


Overview

- Brief overview of completeness
- Overview of program completeness
- Parameters and assumptions
- Definition of terms
- Description of optimization
- Results for TPF-C, TPF-O and TPF-I completeness modeling
- Conclusions

Completeness

- Each star has a habitable zone which is determined by the stellar luminosity and mass
- In order to define this habisphere we populate the habitable zone of the given star with 1,000-10,000 planets in random orbits with eccentricities from 0 to 0.1
- Completeness is the fraction of planets that we are able to observe in a single stellar visit.
- Total accumulated completeness is the sum of all the completeness values for all the stars over the mission duration.
- For η_{earth}=1, the total accumulated completeness is equal to the expected number of detections.



Stellar Availability

- Solar avoidance restricts S/C view different to regions of the stellar sphere.

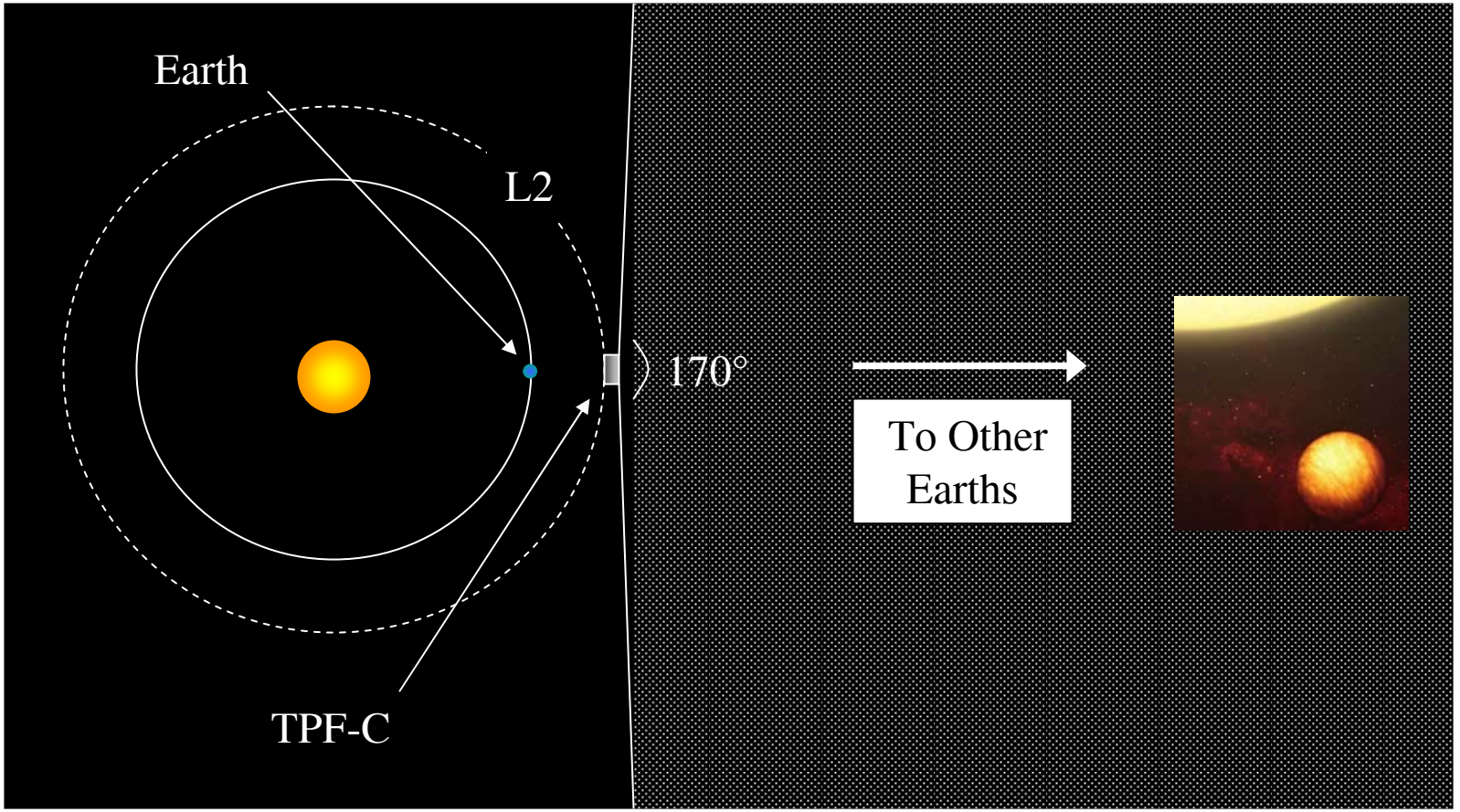


Image Credit: NASA/JPL-Caltech

Program Completeness - Coronagraph

Terrestrial Planet Finder

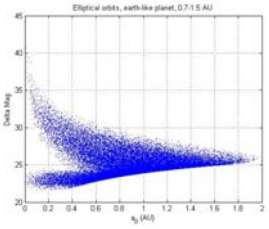
TPF

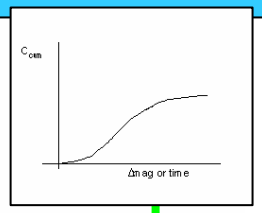
Start

Determine if star is available for observation

Generate orrery of planets

Compute completeness based on observable planets that have not yet been observed





Determine stellar visits and observation time by implementing optimization.

Eliminate planets that are observed with visit

next week

repeat up to 3 years

eccentricity

phase

inclination

argument

stars in list

1=available

0=observed

planets

End

Program Completeness

Assumptions

TPF-C (EO, Mid and Small Scale)

- Three year mission
- One year of planet finding time
  - One year includes slew time overheads with current reaction wheels.
  - Integration time = 1 year - number of visits * overhead

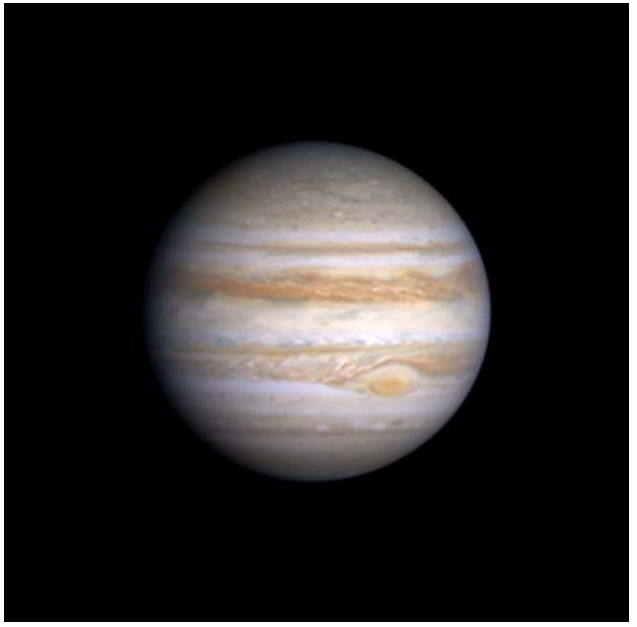
TPF-I

- Two year mission
- Optimized over 10 wavelengths and 10 baseline lengths
- 70 % Efficiency of observation time
  - Includes slew time overheads
  - Integration time = Efficiency*2 years - number of visits * overhead

Earth and Jupiter Search Parameters

- $R_p = 1$
- IHZ = 0.75
- OHZ = 1.8

- $R_p = 11$
- HZ = 5 AU



- All planets were uniformly distributed in semi-major axis.

Program Completeness Parameters

Symbol	Baseline	Quantity
IWA	65.5 mas	(4λ/D) inner working angle with dither effect
$\Delta mag_{0,MAX}$	25.5	limiting delta magnitude sensitivity
λ	550 nm	central wavelength
$\Delta\lambda$	110 nm	bandpass
t_o	0.553 - 0.8	optical throughput
t_m	varies	mask throughput
t_{Ly}	0.34 - 1	Lyot throughput
CCD QE	0.8	CCD quantum efficiency
t_h	2hrs-20days	overhead for telescope slew maneuvers
n_x	28.6	noise pixels
Ω_x	2.70E-15 steradans	solid angle of critically sampling pixels at central wavelength
μ	0.001 $sec^{-1}pixel^{-1}$	dark count rate
ζ	5.00E-11	uniform contrast level in detection zone
R	2 $pixel^{-1}$	read noise
$\Delta mag_{speckle}$	25.75	magnitude of the speckle noise
Δmag_{zodi}	23	magnitude of the uniform zodi noise
z	1	density of exozodi relative to Earth zodi
r_e	4.26E-5R_p AU	radius of the earth/planets
A_p	0.2R_p Earth areas	effective area of the planet
e	[0, 0.1]	range of eccentricities of planetary orbits

TPF-C revisit = 3 weeks

TPF-O revisit = 2 – 3 weeks

TPF-I revisit = 2 weeks

TPF-I zodi is modeled with *z*=3 in a Kelsall distribution

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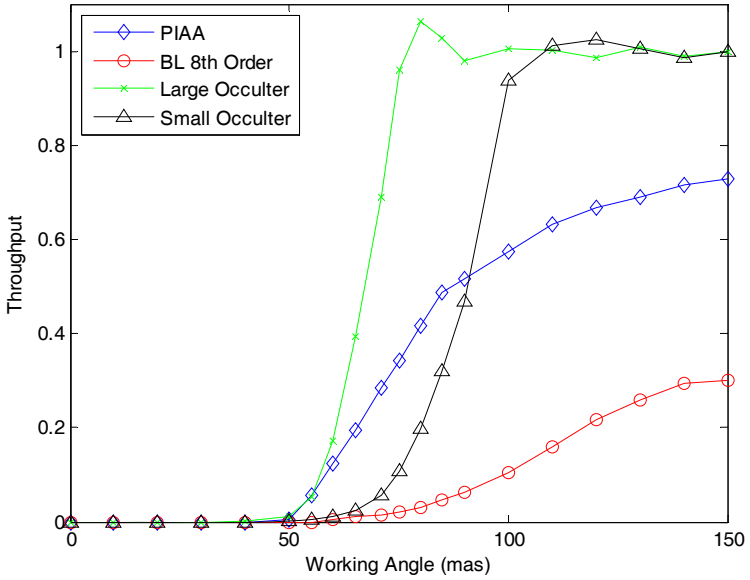
Throughput



- Optical throughput varies for different masks.
  - TPF-C throughput = 0.578 (based on FB-1 design w/o BS)
  - PIAA requires two more optics (throughput = 0.553)
  - TPF-EO requires far fewer optics (throughput = 0.8)
- Mask throughput varies as a function of working angle
- Lyot throughput also is different for different masks
  - TPF-C BL8 Lyot throughput = 0.34
  - PIAA Lyot throughput = 0.8
  - TPF-EO does not require a Lyot stop

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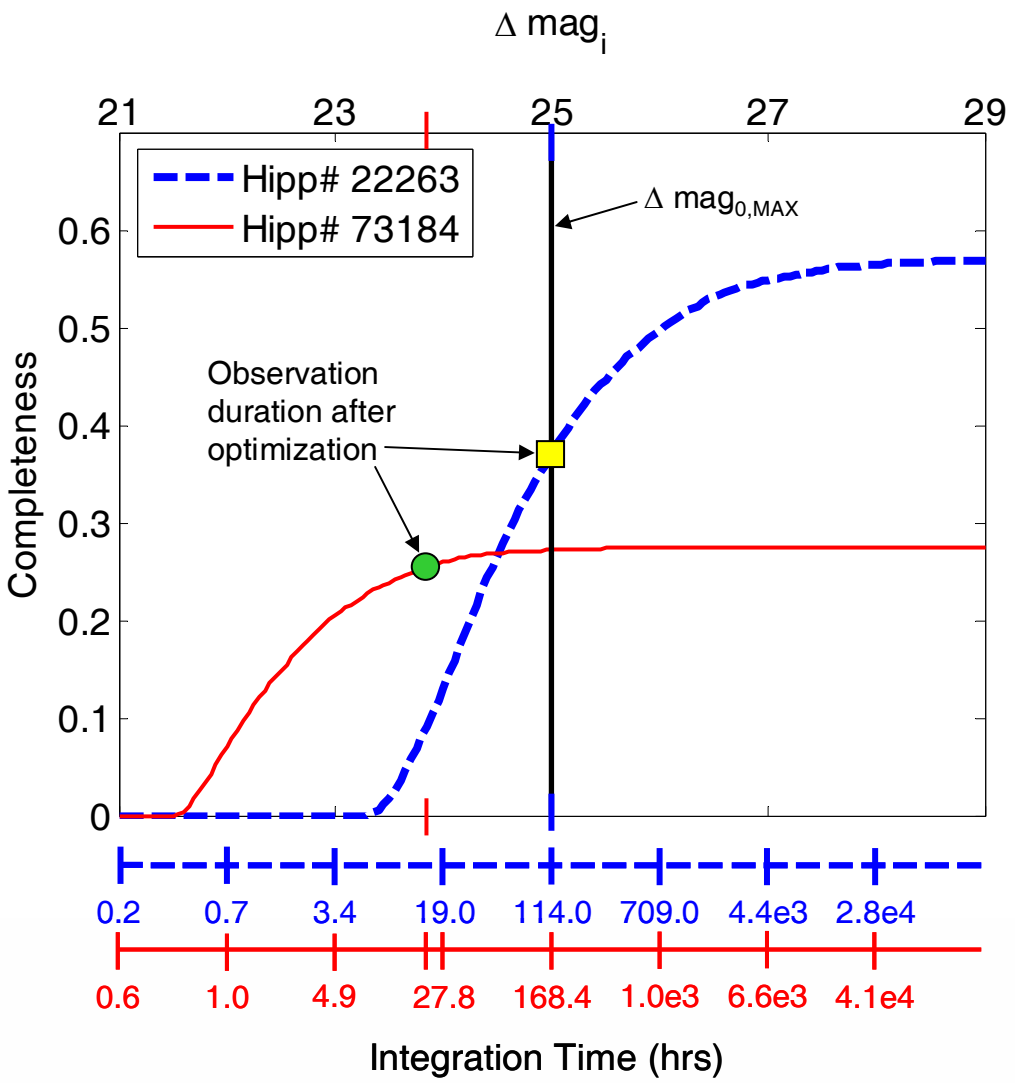
Optimization



- Total completeness is given by:

$$C = \sum_{i=1}^{N} C_i(\tau_i)$$

- Total integration time is constrained by:

$$\tau_m \geq \sum_{i=1}^{N} \tau_i$$

- We wish to maximize completeness by eliminating unproductive time and giving it to another star.

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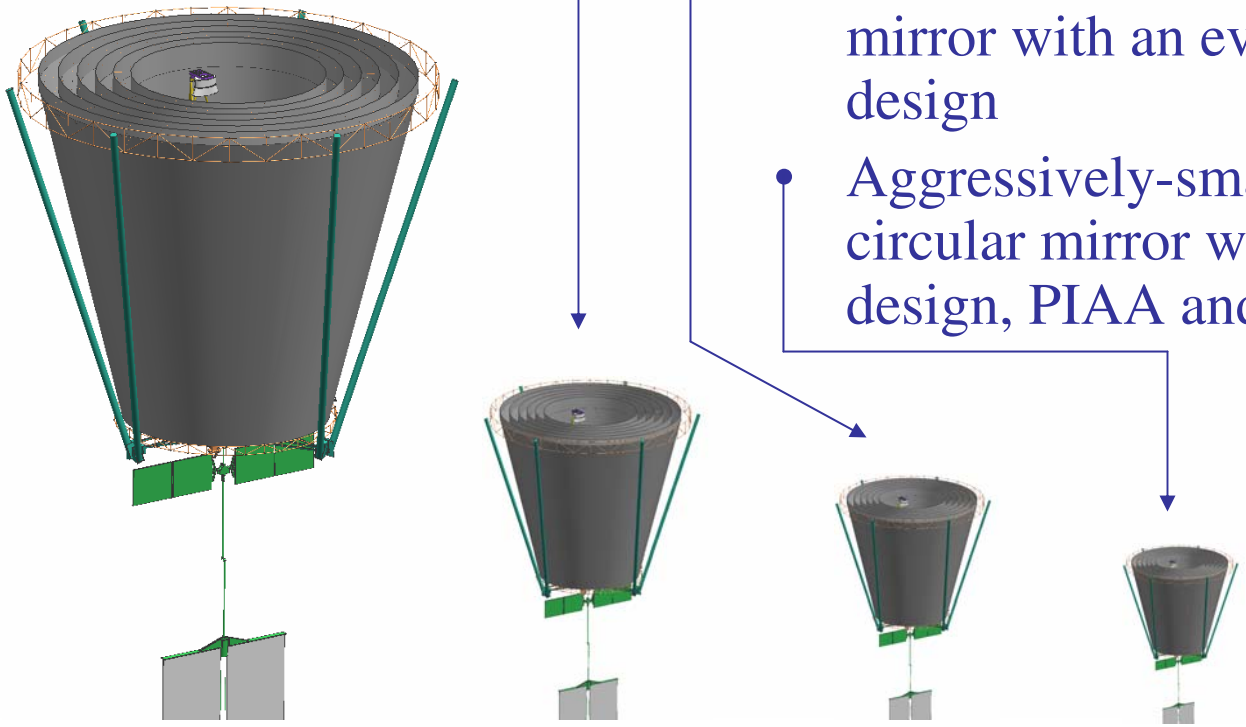
Terminology

- Large-scale mission = 8m x 3.5 m elliptical FB-1 TPF-C telescope design
  - Mid-scale mission = 3.6m circular mirror with a reduced size TPF-C design
  - Small-scale mission = 2.5m circular mirror with an even smaller TPF-C design
  - Aggressively-small scale= 1.5m circular mirror with a smaller TPF-C design, PIAA and an IWA=2.5 λ/D



Smaller-Scale Missions

- With circular mirrors, the telescope rolls can be eliminated (but not the dither). This reduces integration time by a factor of 3.
- Stability requirements and surface requirements are not as stringent, allowing a smaller IWA (i.e. $4\lambda/D \rightarrow 3.5\lambda/D$).
- Lower completeness with smaller mirror is partially offset by a more aggressive IWA.
- Significant numbers of Jupiter size planets can be observed and characterized with the smallest missions.

Mission Scale Comparisons

	Type	IWA* (l/Dmax)	Primary Mirror	# Earths, # Targets	# Jupiters, # Targets
Large-class Mission (> $2B)					
TPF-I	Classic-X Array	2.5	4 @ 4 m plus beam combiner spacecraft	190, 380	440, 460
TPF-C	Flight Baseline - 1	4	8 m x 3.5 m	41, 85	390, 680
TPF-C	Flight Baseline - 1 with Pupil Mapping (PIAA)	4	8 m x 3.5 m	73, 140	580, 800
Mid-class Mission (< $2B)					
TPF-I	Emma-X Array	2.5	4 @ 2 m plus beam combiner spacecraft	70,150	160, 190
TPF-C	Band Limited Mask, Shaped Pupil or Visible Nuller	3.5	4 m	19, 36	320, 540
TPF-C	Pupil Mapping (PIAA)	3.5	4 m	25, 56	460, 580
TPF-C	Pupil Mapping (PIAA)	2.5	4 m, aggressive IWA	48, 99	550, 710
TFF-O	External Occultor	~2.5	4 m telescope + 50 m occulter @ 72000 km	28, 64	70, 78
Probe-class Mission (< $1B)					
TPF-C	Band Limited Mask, Shaped Pupil or Visible Nuller	3.5	2.5 m	6, 13	130, 240
TPF-C	Pupil Mapping (PIAA)	3.5	2.5 m	7, 15	230, 380
TPF-C	Pupil Mapping (PIAA)	2.5	2.5 m, aggressive IWA	16, 29	290,470

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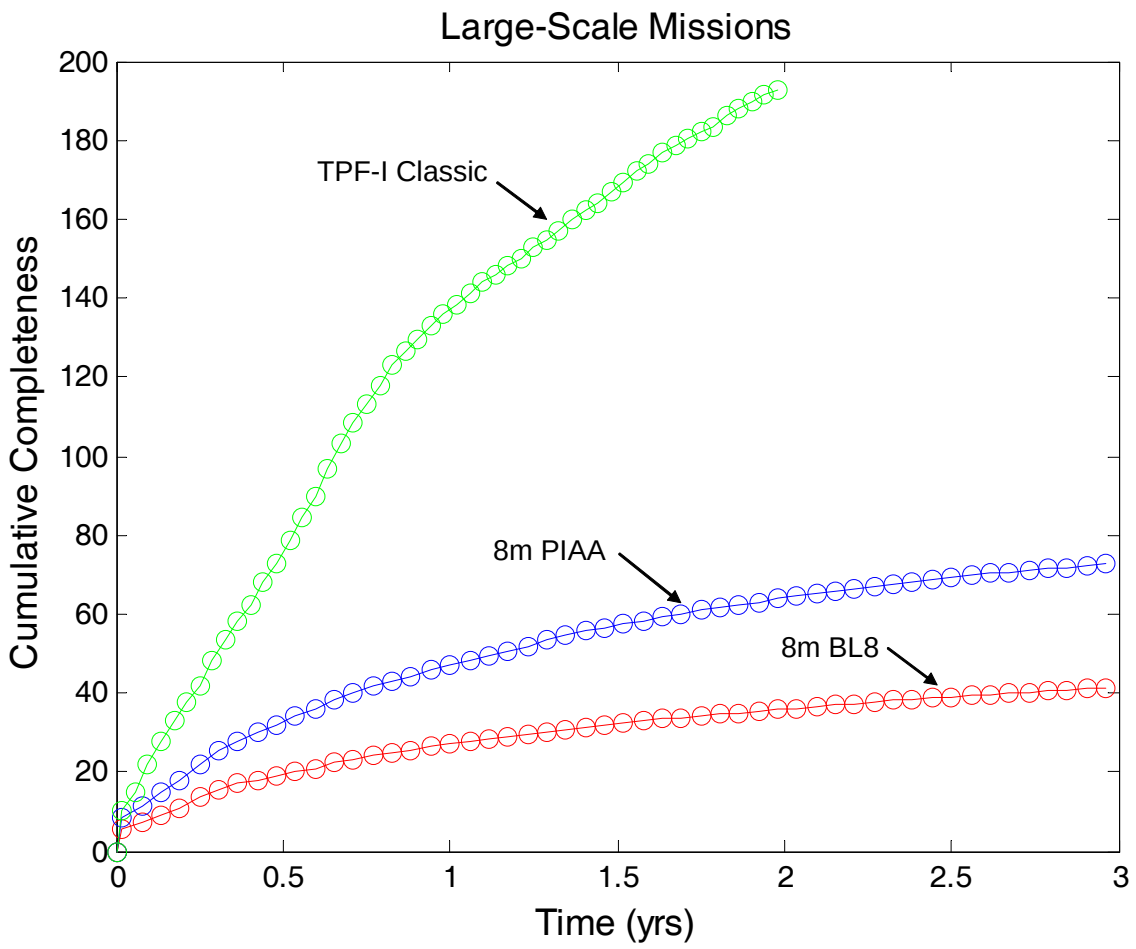
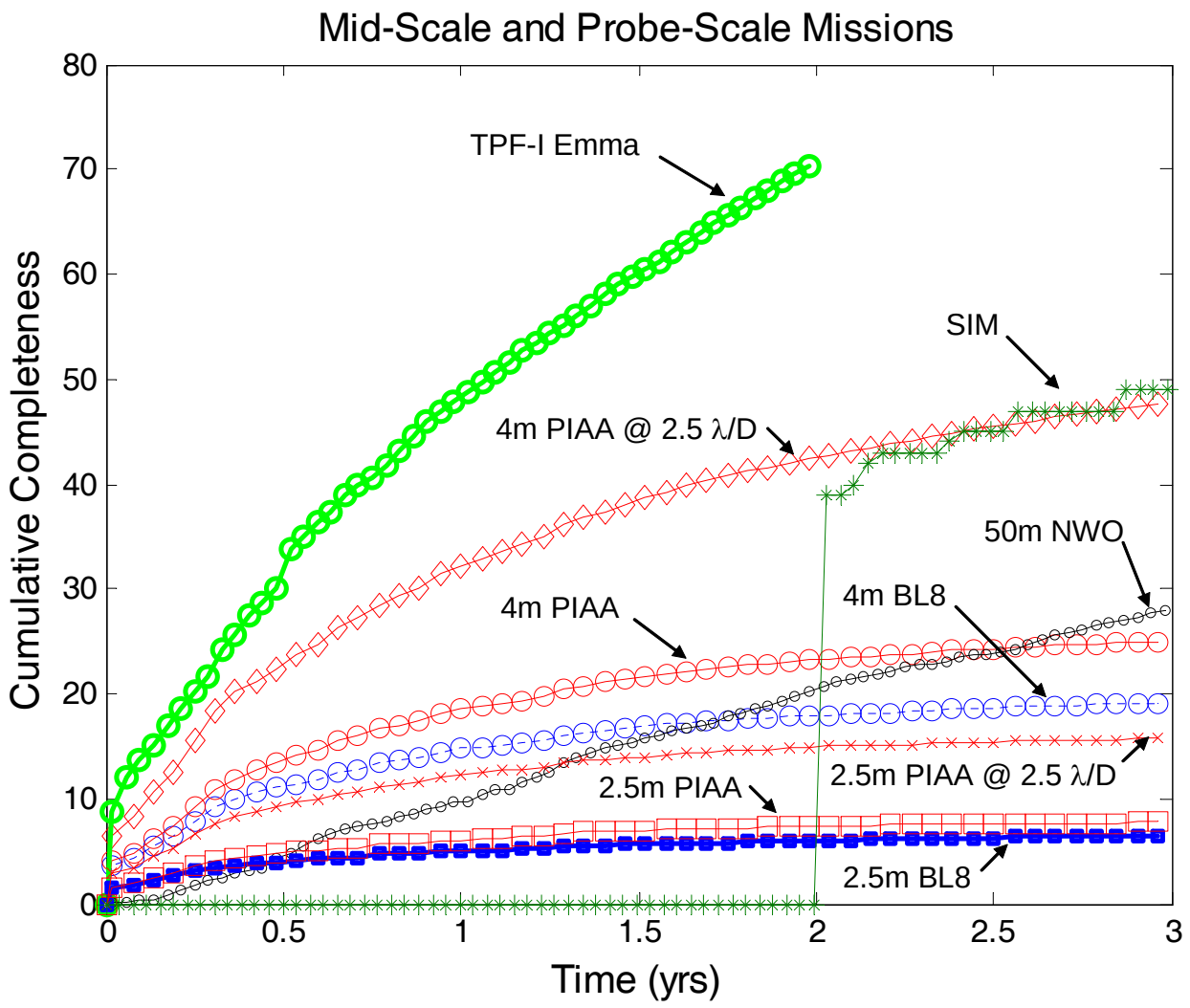
Large-Scale Mission Completeness



- TPF-C IWA = 4 λ/D for the FB-1 configuration modeled for the large-scale mission concept.

Mid-Scale and Small-Scale Mission Completeness



IWA = 3.5 λ/D where not otherwise noted for TPF-C completeness curves.

Aggressively Small Scale Mission

- 1.5m telescope + PIAA

λ/D	Completeness	Targets
3.5	2.25	5
2.5	4.45	9
2.0	6.01	11

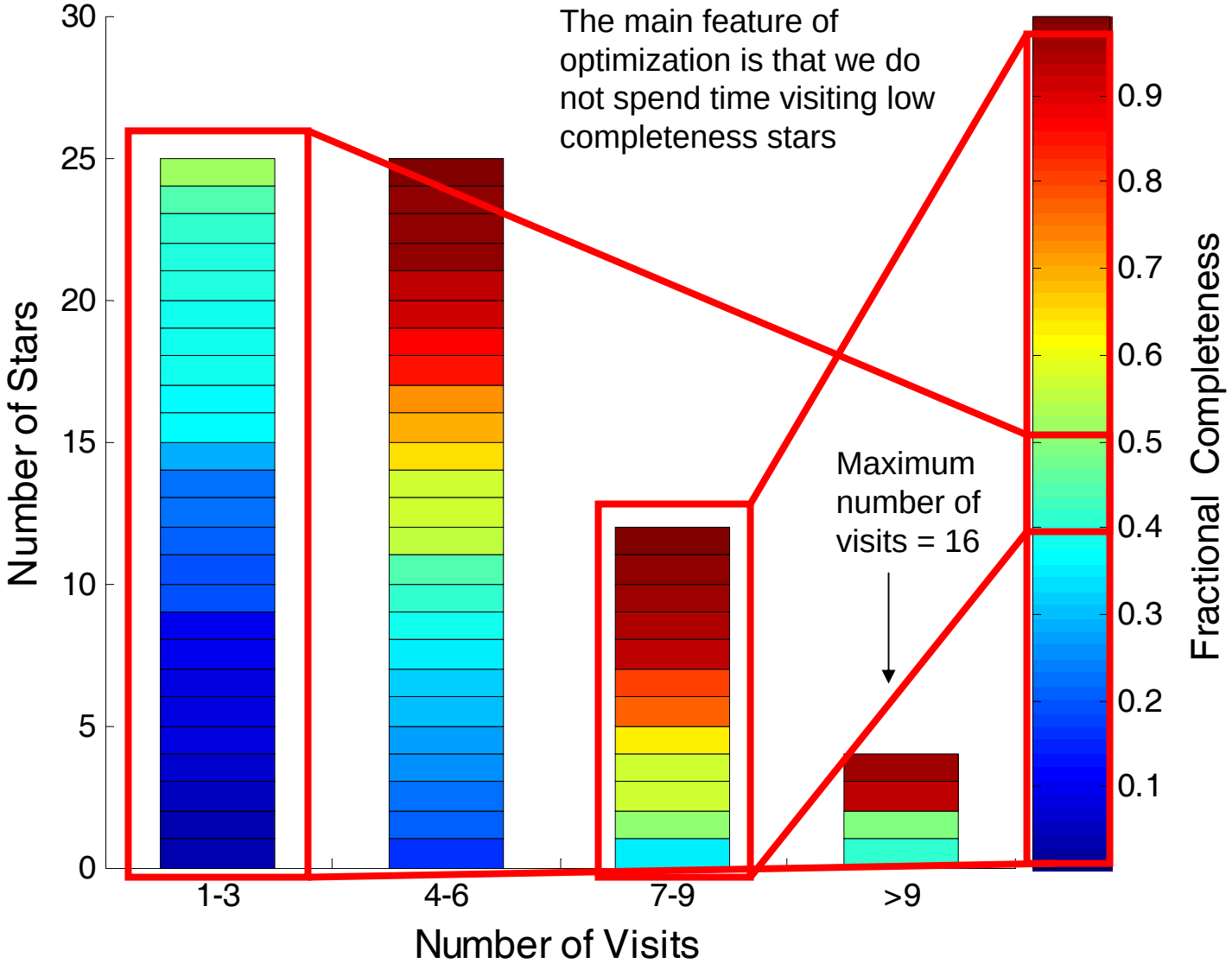
λ/D	Completeness	Targets
3.5	81.59	154
2.5	105.23	186
2.0	114.57	195

- JWST + Occulter
  - 13 day slew and 1 day integration time
  - 6.5m telescope
  - IWA = TPF-O Large occulter shifted outward by 40mas

Earth
Completeness = 24.6
Targets = 62

Jupiter
Completeness = 71.2
Targets = 78

Visit Number

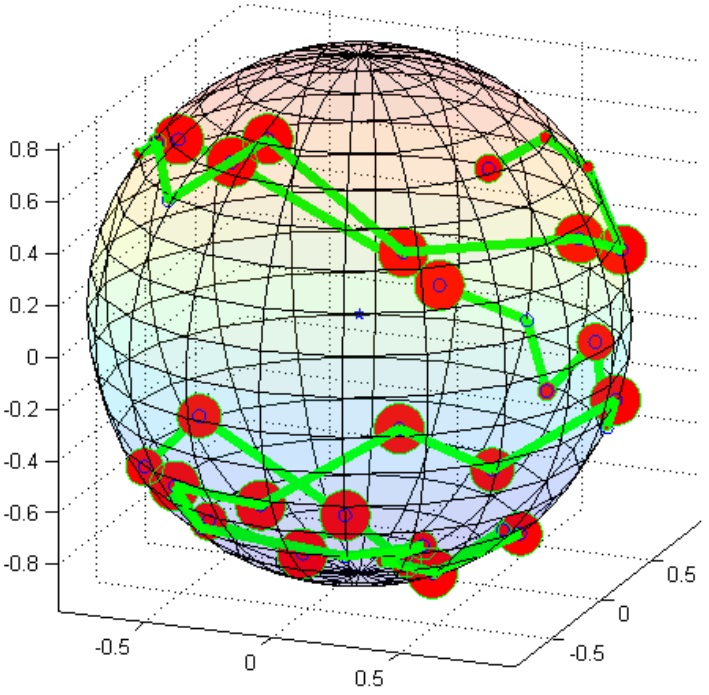


TPF-O Simulation Results

Type	Completeness	Targets	No. 1x Revisit	No. 2x Revisit	No. Skipped Weeks
Large	18.22	41	6	0	3
Small	25.54	56	25	3	66

Maximum Total Accumulated Completeness

With the 6 day slew scenario some stars are visited 3 times. These visits occur in back to back to back years and not in consecutive viewing periods.

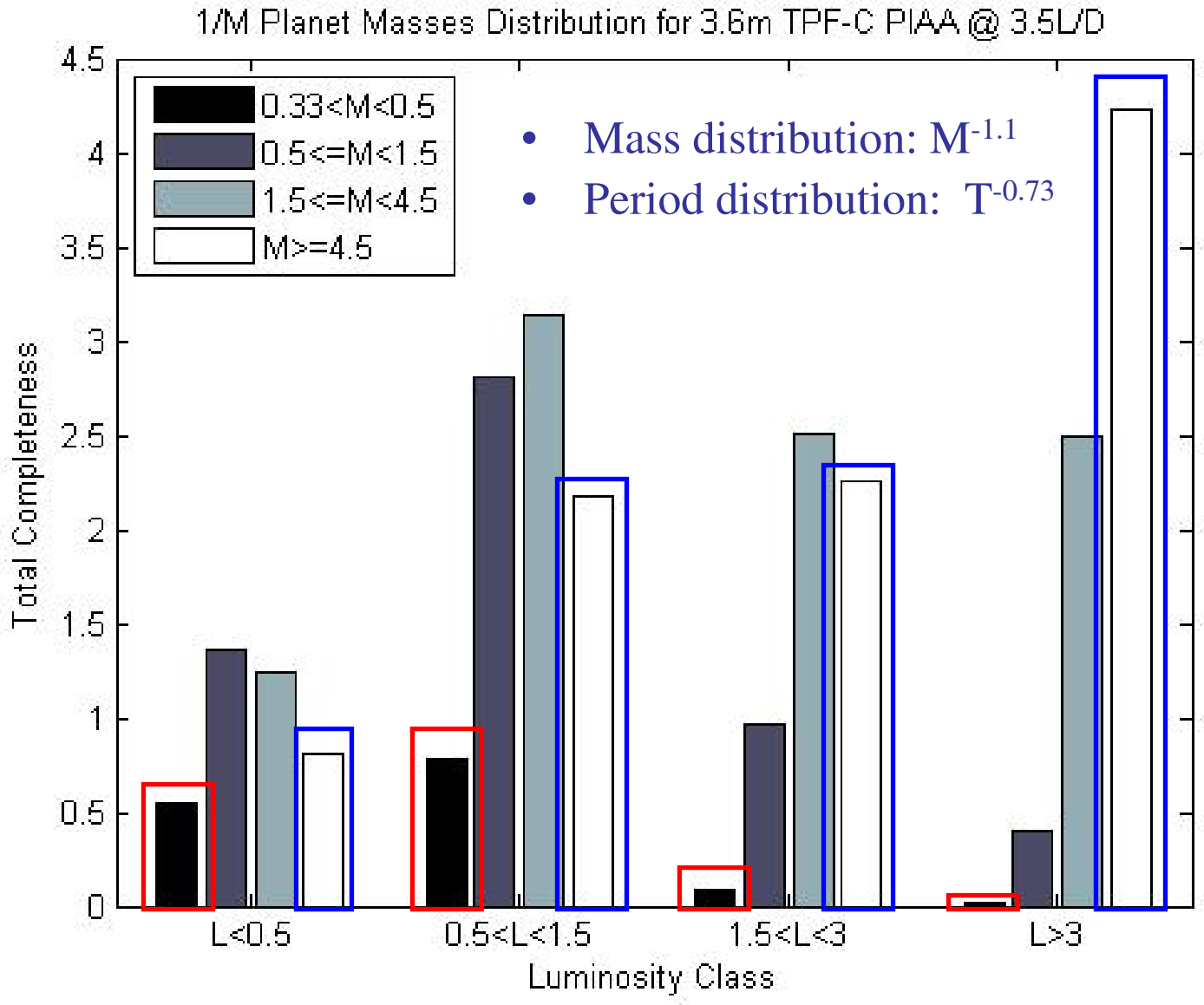


Note: Completeness numbers above are from a simulation with different overhead parameters and do not match the chart earlier.

1/M Results

- Previous results were preformed with a model that simulated Earth-size planets uniformly distributed over the habisphere.
- The following simulation utilized a mass and period distribution according to the following laws (Tabachnik, S., & Tremaine, S. 2002):
  - Mass goes as $M^{-1.1}$
  - Period goes as $T^{-0.73}$

1/M Results



- Mass distribution: $M^{-1.1}$
- Period distribution: $T^{-0.73}$

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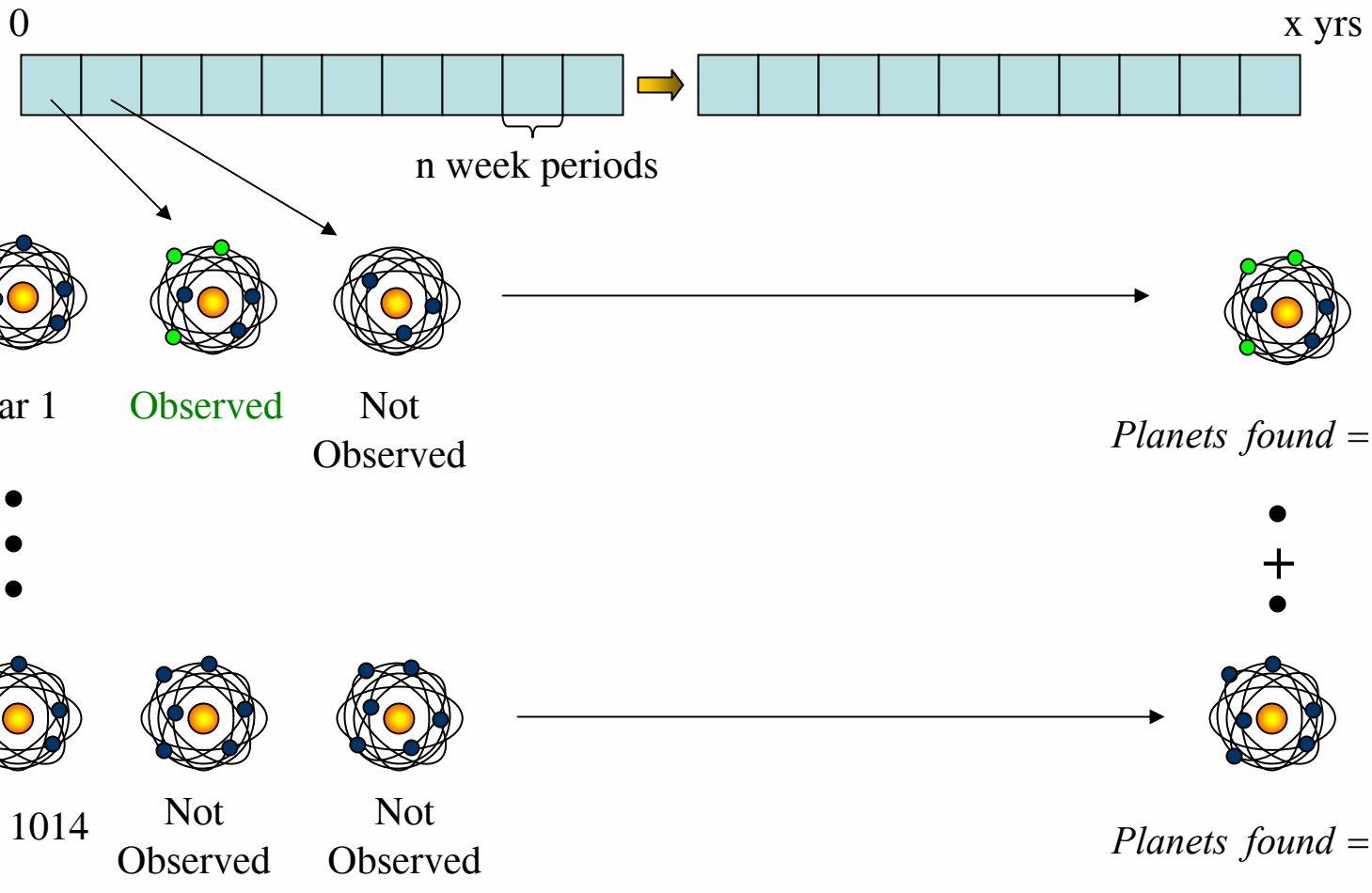
Conclusions

- A significant planet discover program is possible with a 4m class telescope utilizing existing technology.
- A 50m occultor plus a 4m telescope yields the same completeness ass a 4m telescope with PIAA with an IWA = 3.5 λ/D.
- New technology (aggressive IWA PIAA coronagraph) doubles the number of planets detected.
- A small number of Earths and a large number of Jupiter-like planets can be detected with a 1.5m class telescope.
- We continue to perform analyses in terms of orbit determination and characterization.

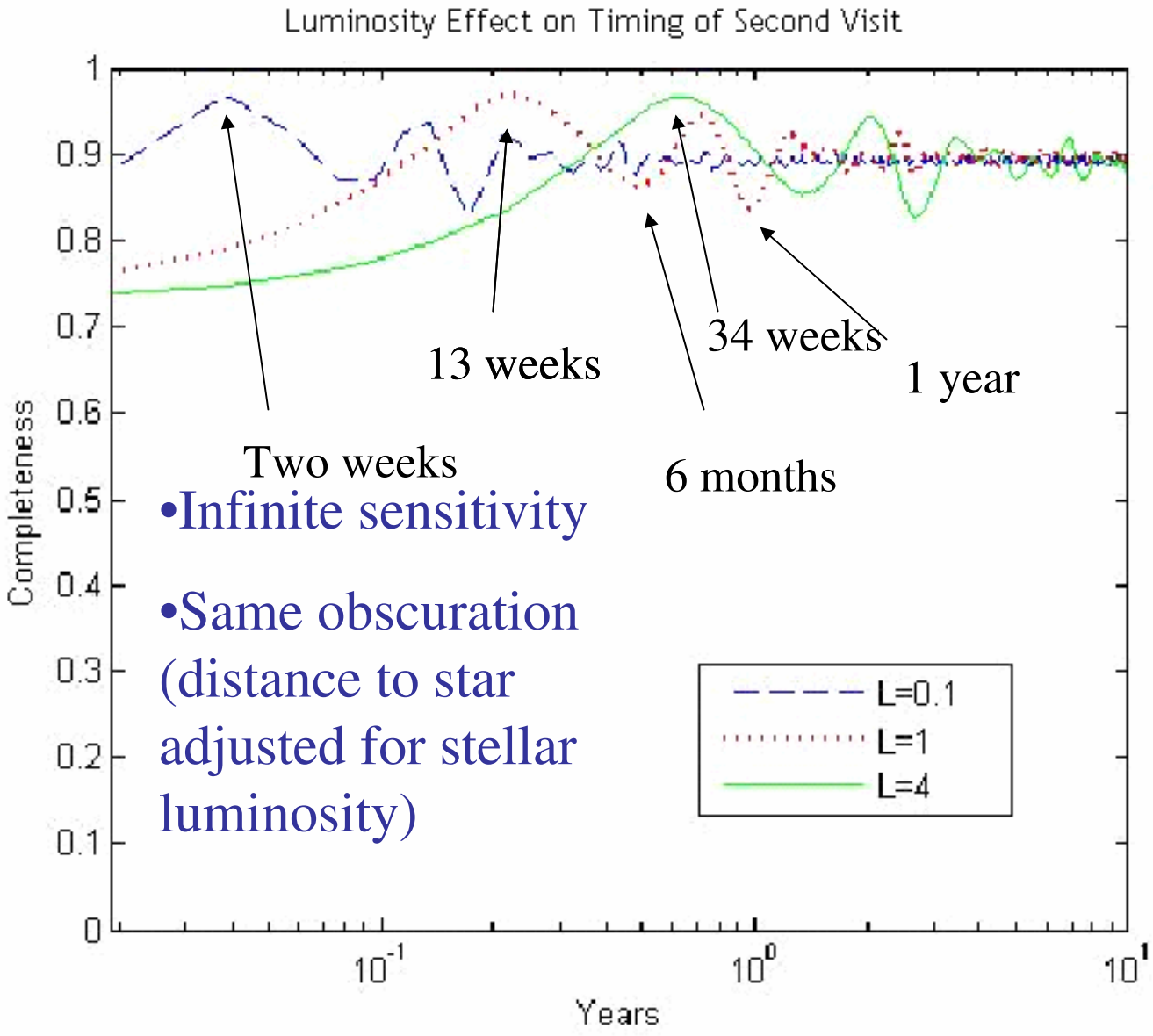
Questions?

Back-up Slides

Program Completeness Overview

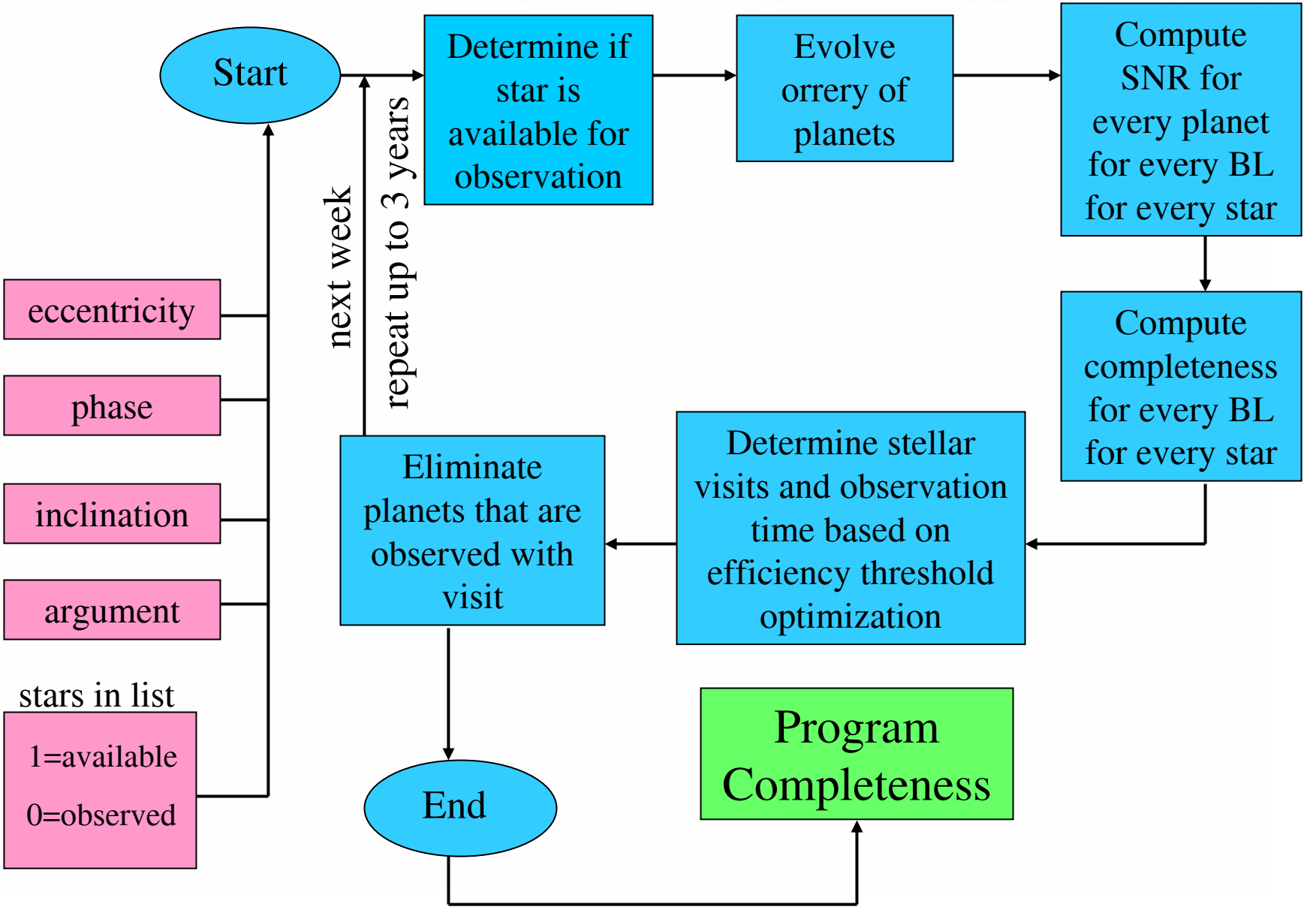


Timing of Second Visit



- Infinite sensitivity
- Same obscuration (distance to star adjusted for stellar luminosity)

Program Completeness - Interferometer



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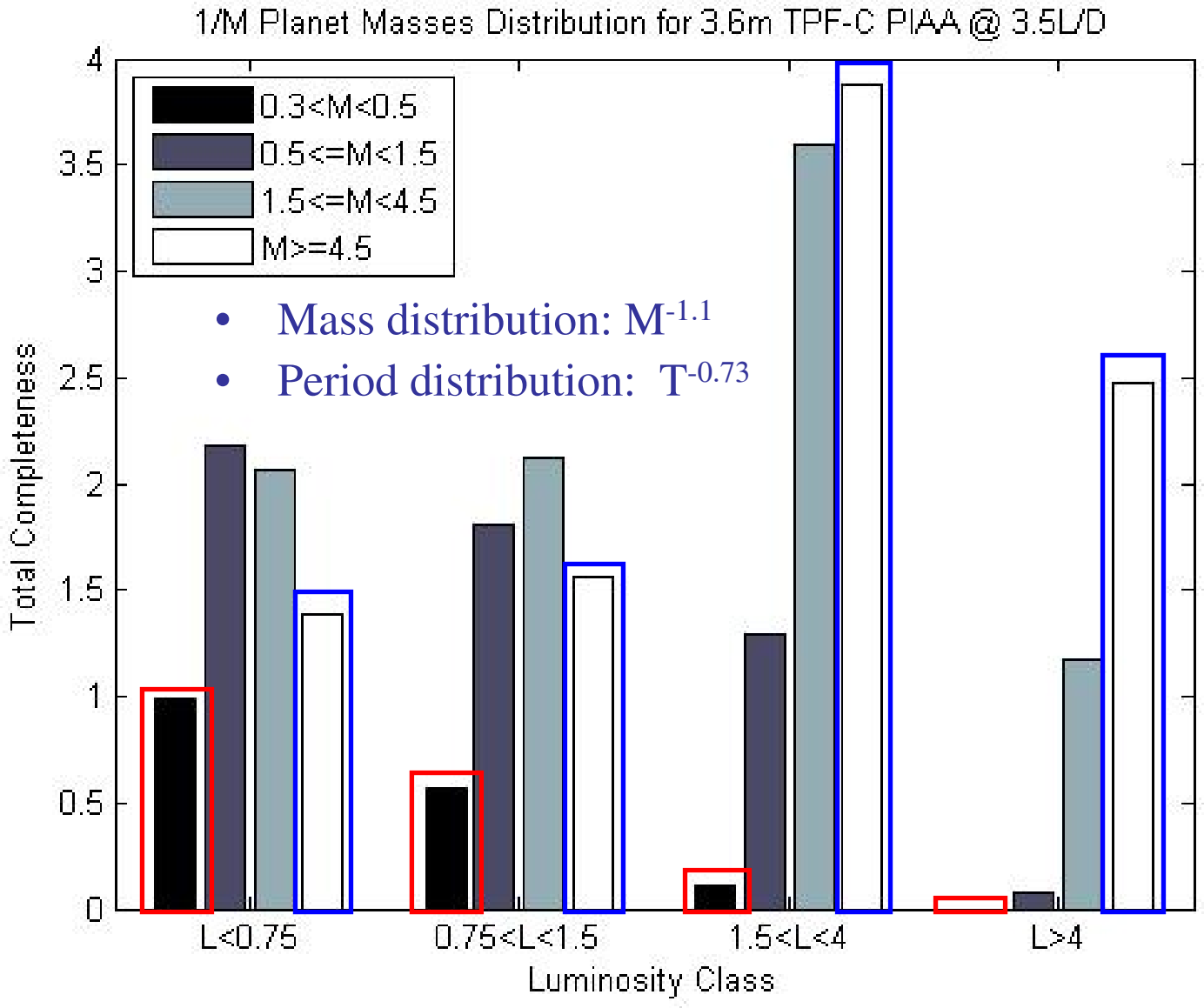
1/M Results (Different Luminosity Sorting)



- Mass distribution: $M^{-1.1}$
- Period distribution: $T^{-0.73}$