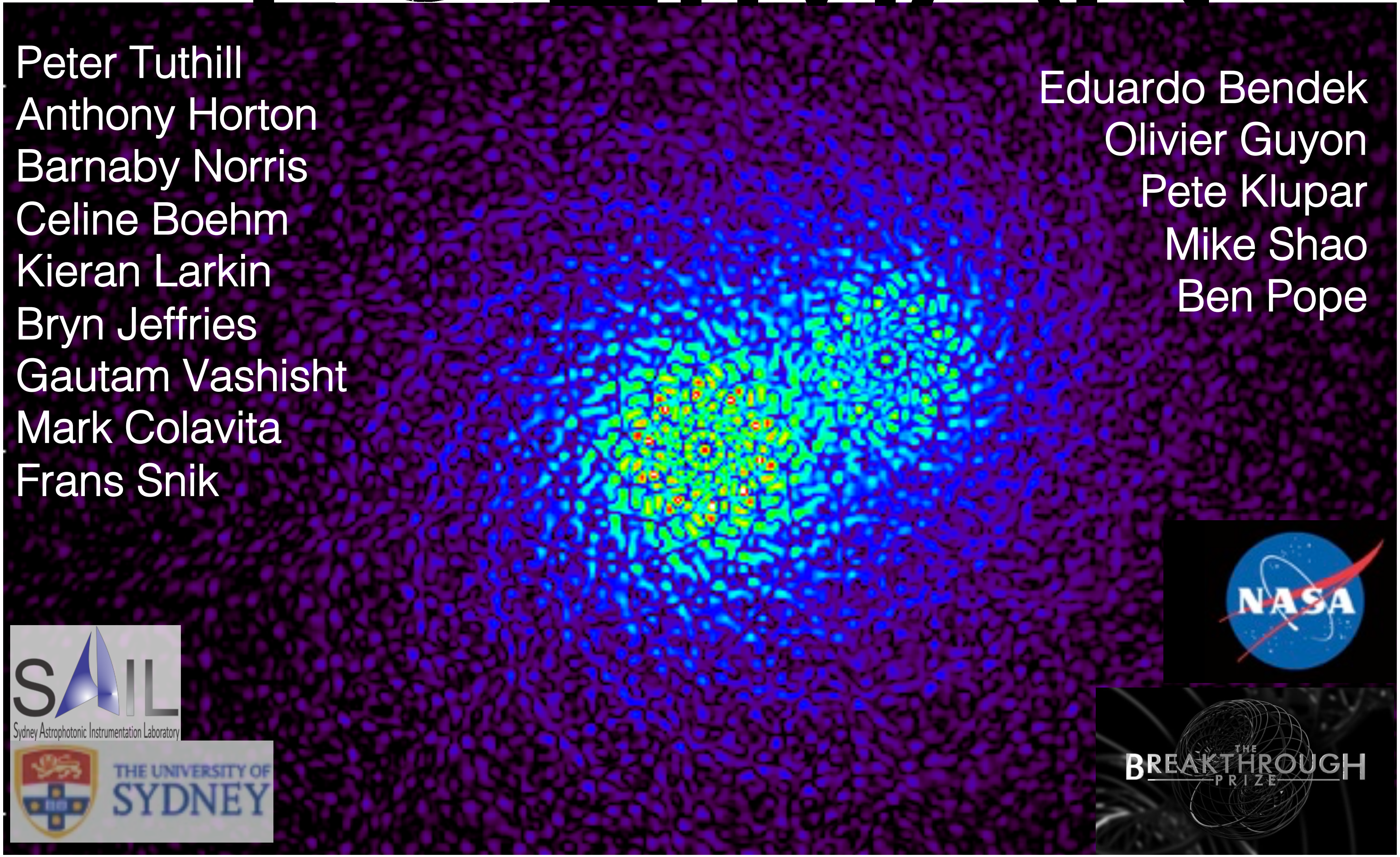
TOLIMAN



Peter Tuthill
Anthony Horton
Barnaby Norris
Celine Boehm
Kieran Larkin
Bryn Jeffries
Gautam Vashisht
Mark Colavita
Frans Snik

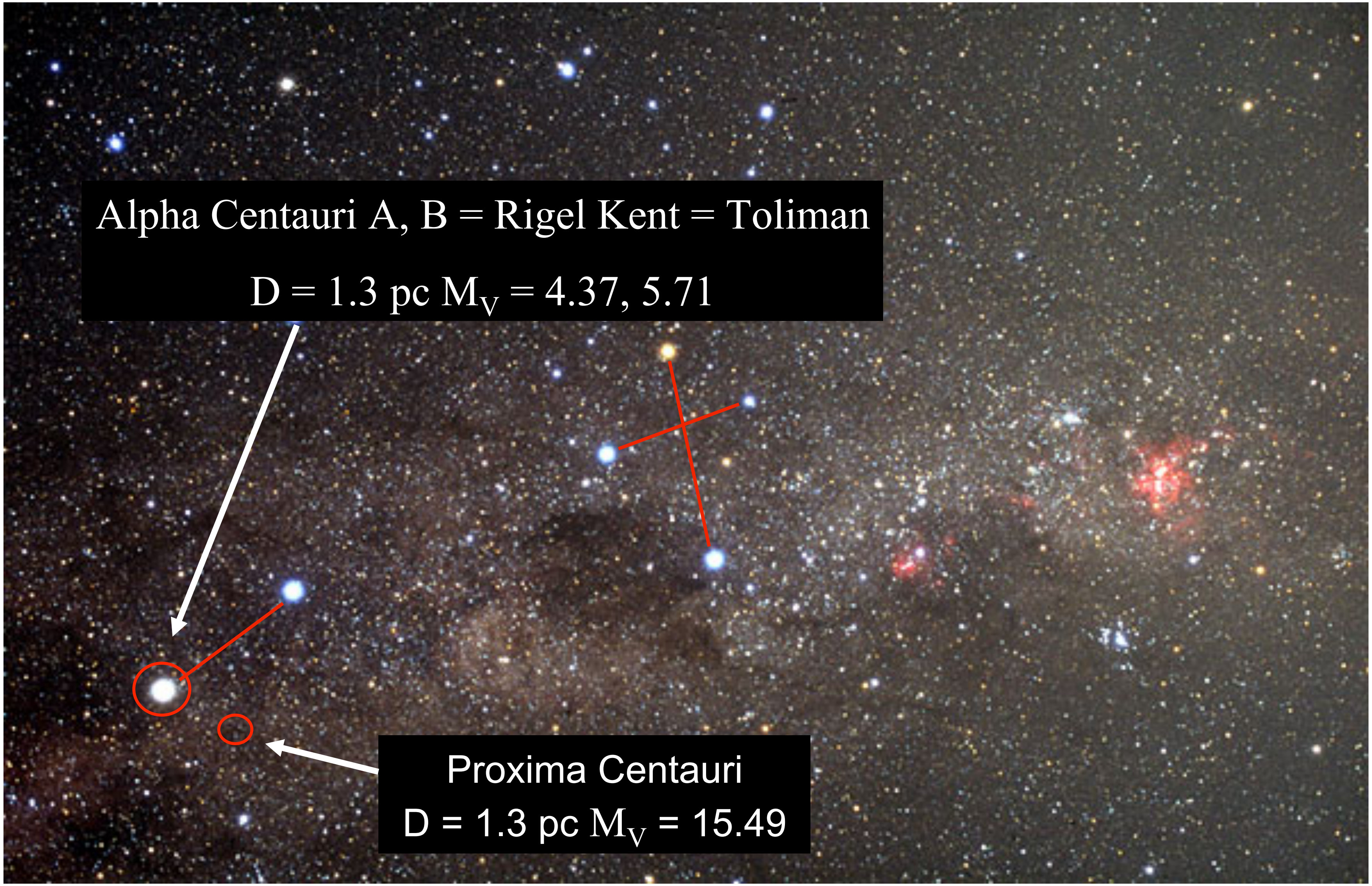
Eduardo Bendek
Olivier Guyon
Pete Klupar
Mike Shao
Ben Pope

SAIL Sydney Astrophotonic Instrumentation Laboratory
THE UNIVERSITY OF SYDNEY
NASA
THE BREAKTHROUGH PRIZE

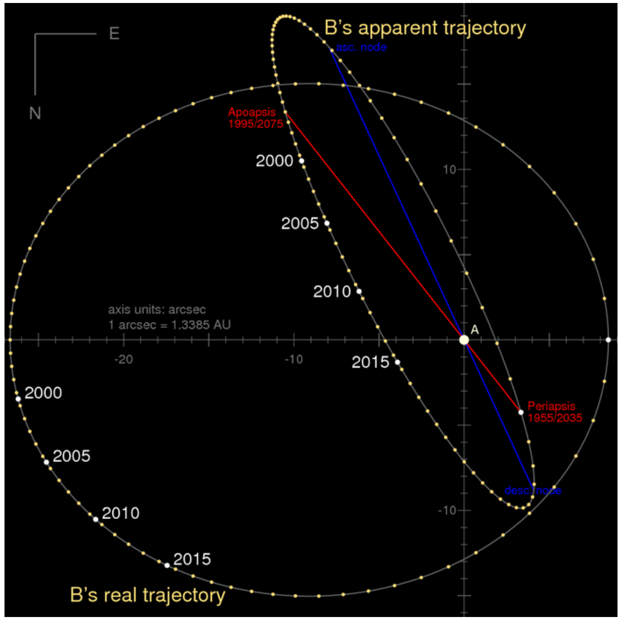
TOLIMAN

- Recap: Astrometry and Alpha Cen
- Motivating TOLIMAN
- Fundamentals: Design for micro-arcsecond astrometry
- Milestones: algorithms and simulations
- Milestones: optical testbed
- Milestones: the TOLIMAN collaboration

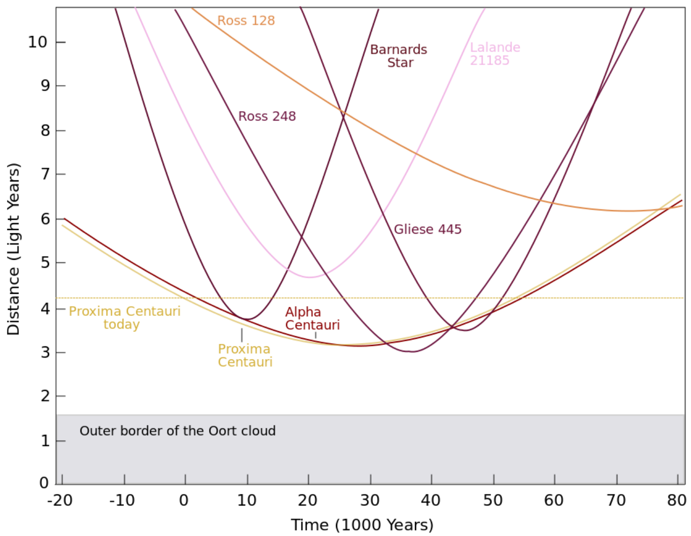
Alpha Cen System: our nearest neighbor



Alpha Cen (= Rigel Kent = Toliman)



Stars within 10 pc of the Sun



- Componets A, B (+ distant Proxima)
- Bright: 0 Mag + 1.3 Mag
- Nearest sun-like stars (more than factor 2!)
- Apparent 4” close approach: RV problematic
- 1 Earth Mass – 2.4 μAs for A; 1.2 μAs for B
- With .3m area needs ~hours of integration (compared to ~months for 12th mag ref star)
- Binary is near-equal (no contrast problem!)
- Unusual and Unique to have this system so close!

How do we find rocky temperate zone planets around stars within 5 (or 10) Parsec?

✗ Transits? - Sample too small to get lucky

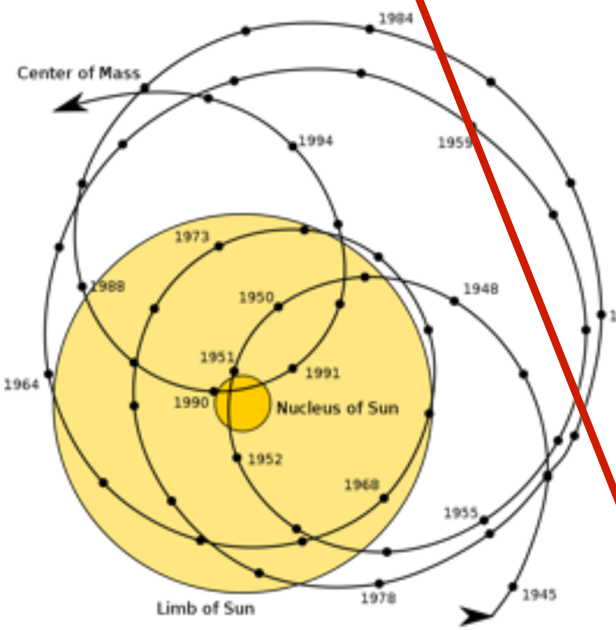
✗ Doppler RV? - Signals very small FGK stars

Pale Red Dots

✔ Astrometry ? - *“Astr … ique*

True Earth Analogs

plane … habitable zone (HZ) around solar-type stars within 20 pc.” Shao et al 2010

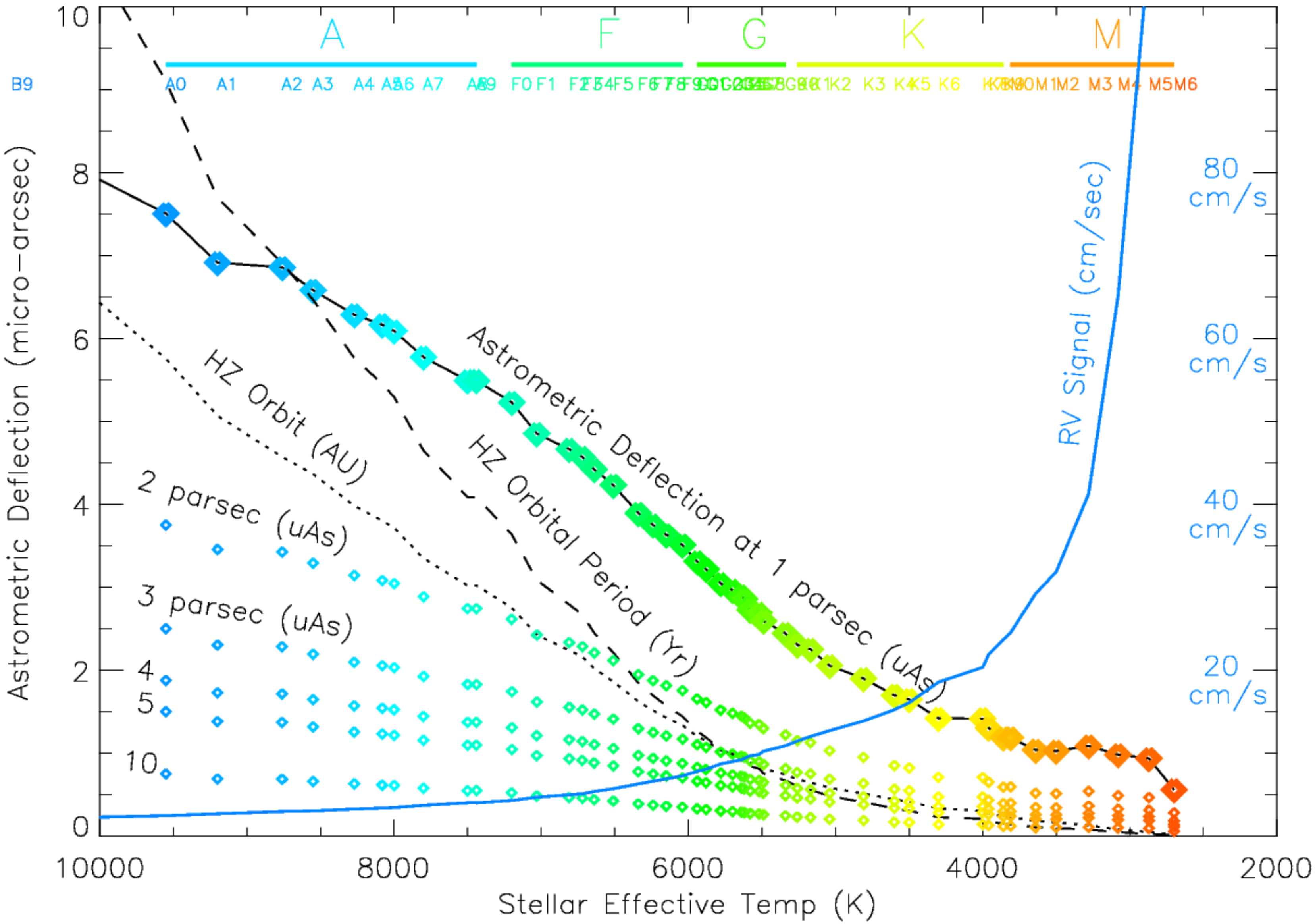


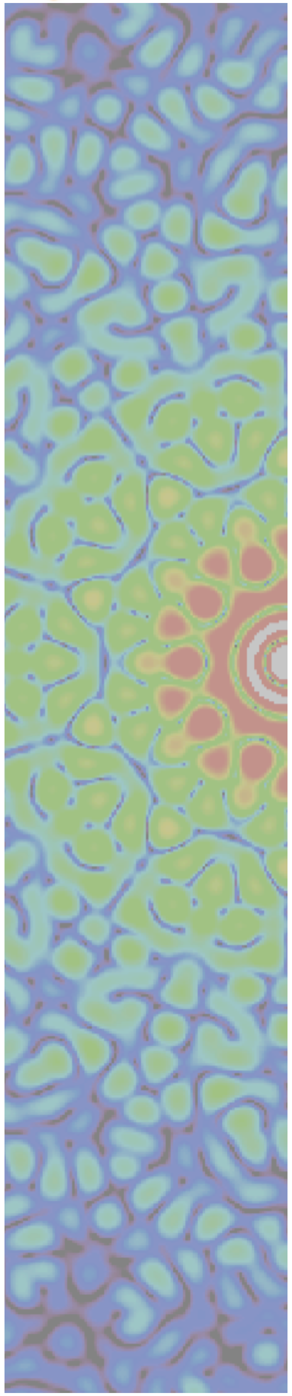
Locus of the Sun’s motion due to planets (mainly Jupiter)

What is the stellar (and projected HZ rocky planet) population within 10 PC?

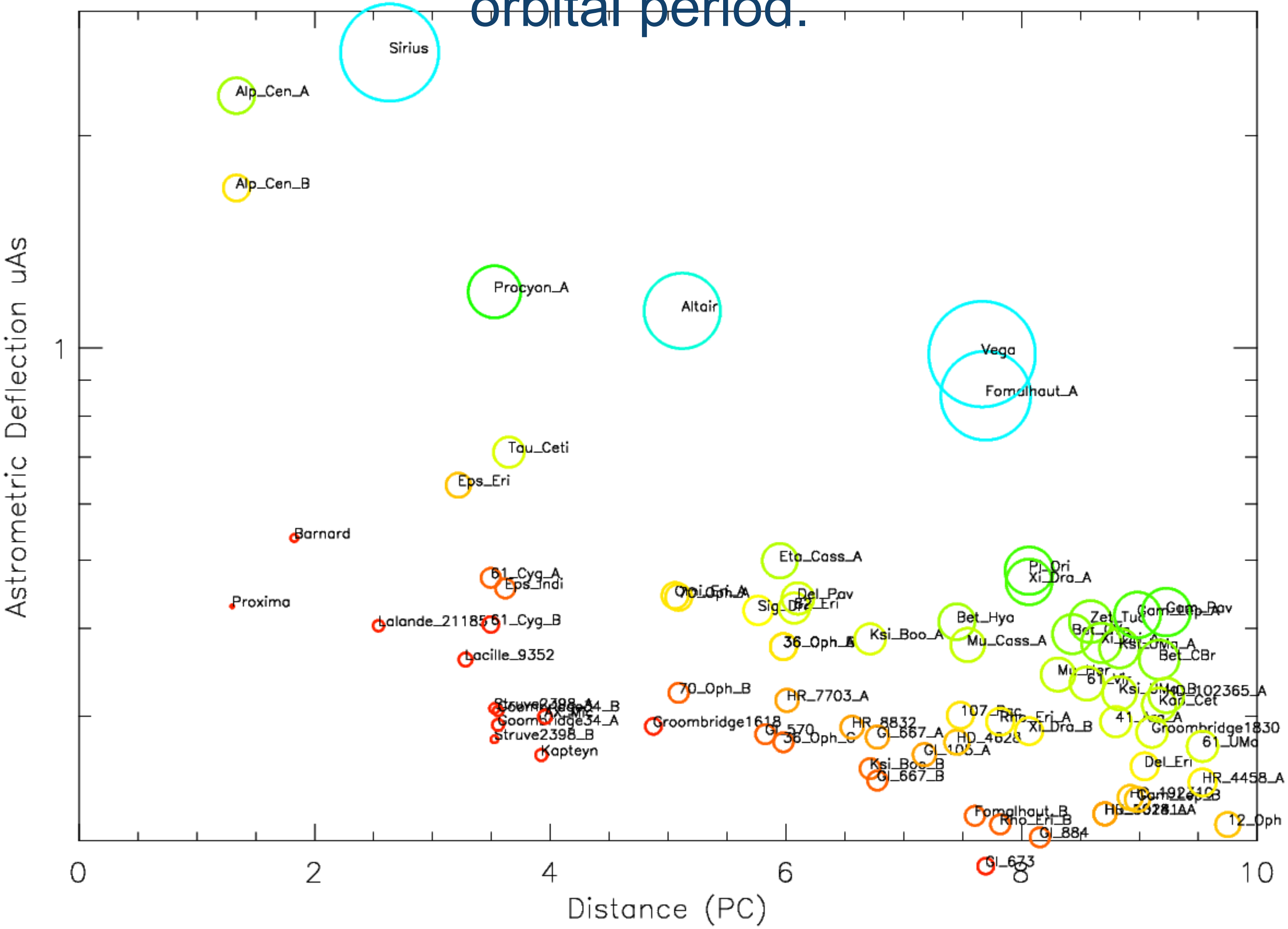
- 5 A-type Stars. Likely 0 (or 1) HZ rocky planet
- 69 FGK-type Stars. Likely about a dozen HZ rocky planets
- 273 (+) M-type stars. Likely 140 HZ rocky planets

Astrometric signal of a 1 M_earth planet in the HZ assuming 1PC distant from star of given Sp. type.

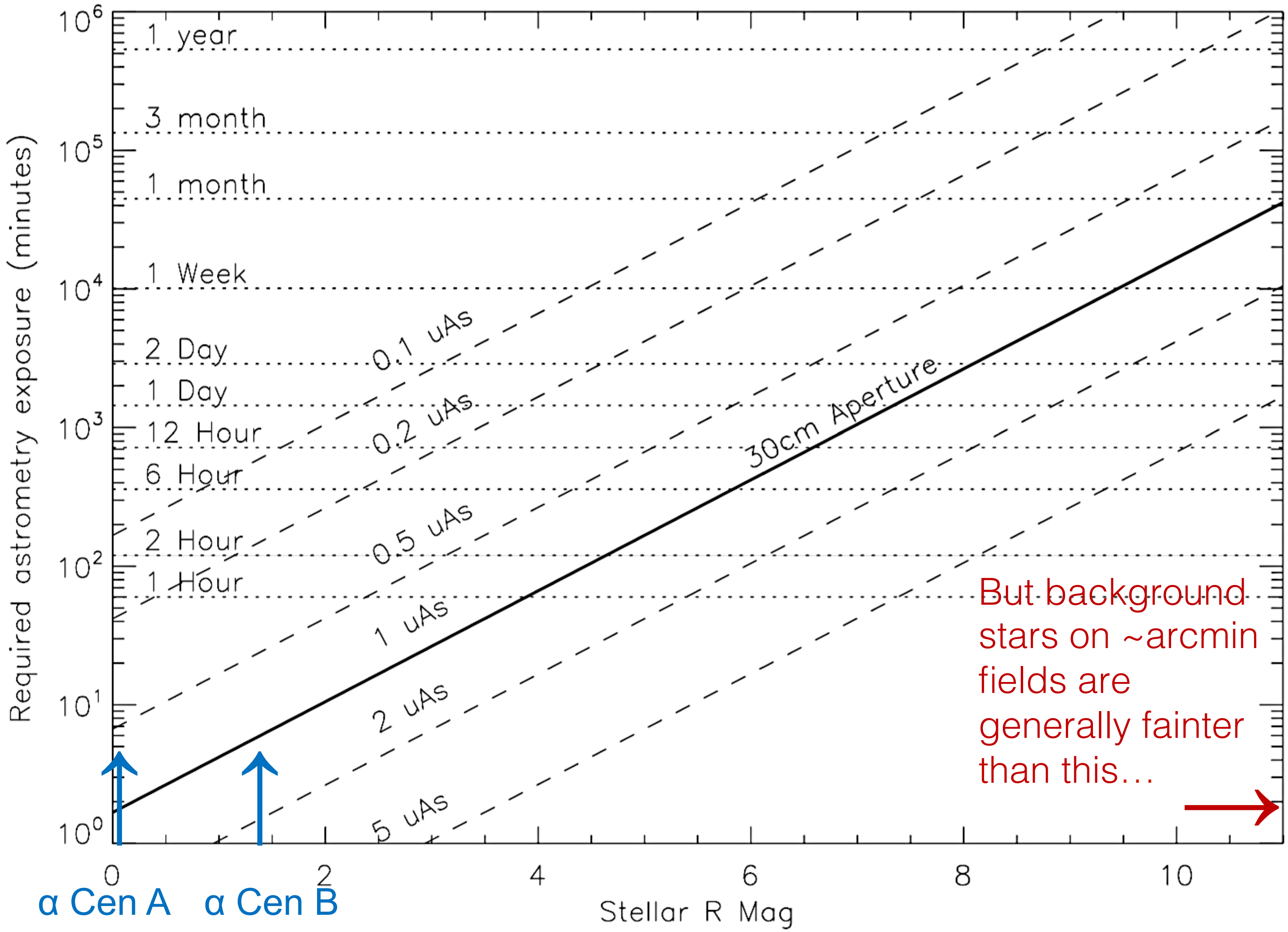




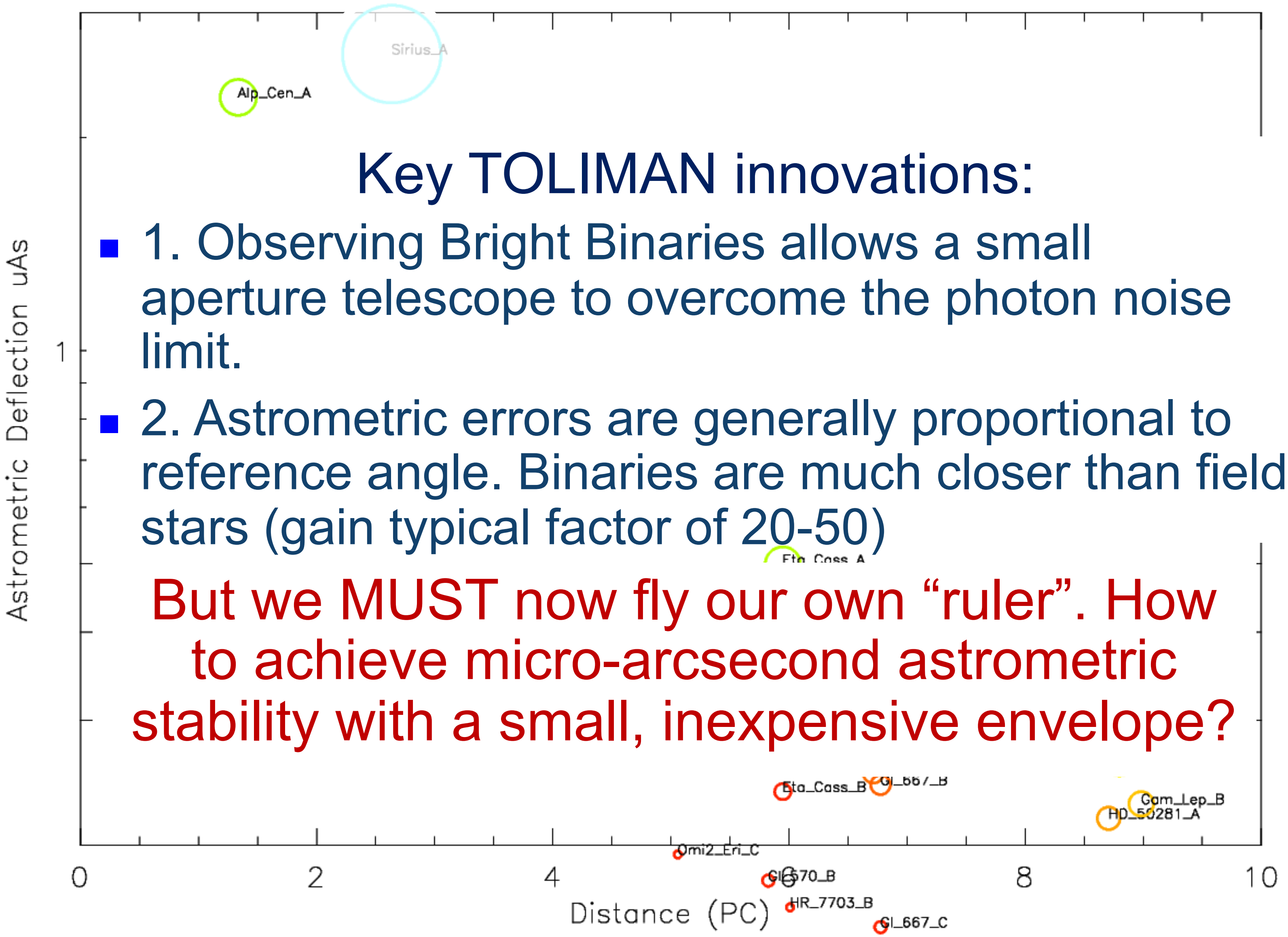
Astrometric signal for HZ Earth mass for all FGK stars to 10PC together with some M stars (<5PC). Symbol color indicates host spectrum, size indicates orbital period.



30cm Telescope fundamental (photon noise) limit: integration time required to obtain a given astrometric noise



Same as previous plot, but now restricted to binaries – many suited for study by TOLIMAN.

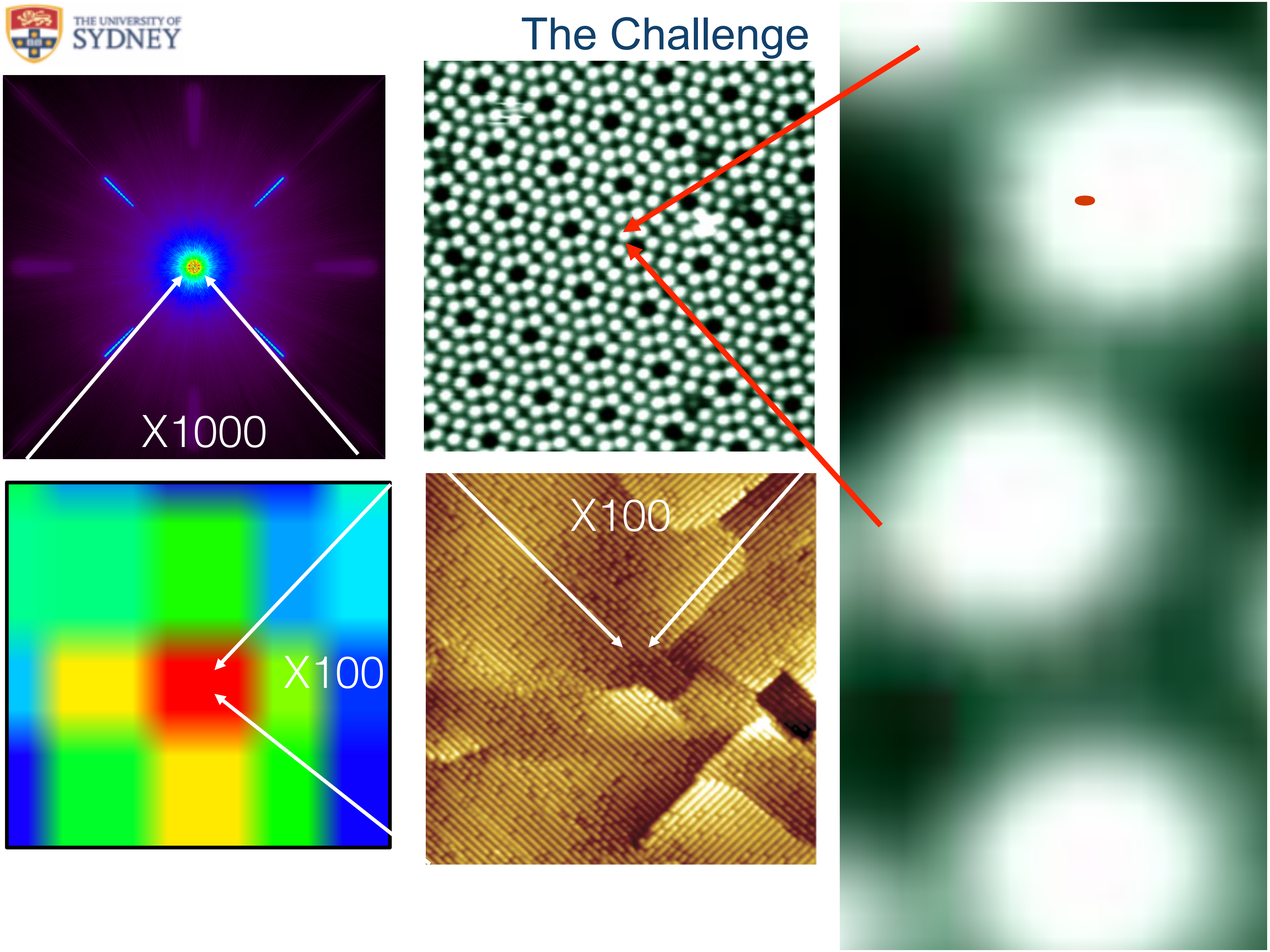


Key TOLIMAN innovations:

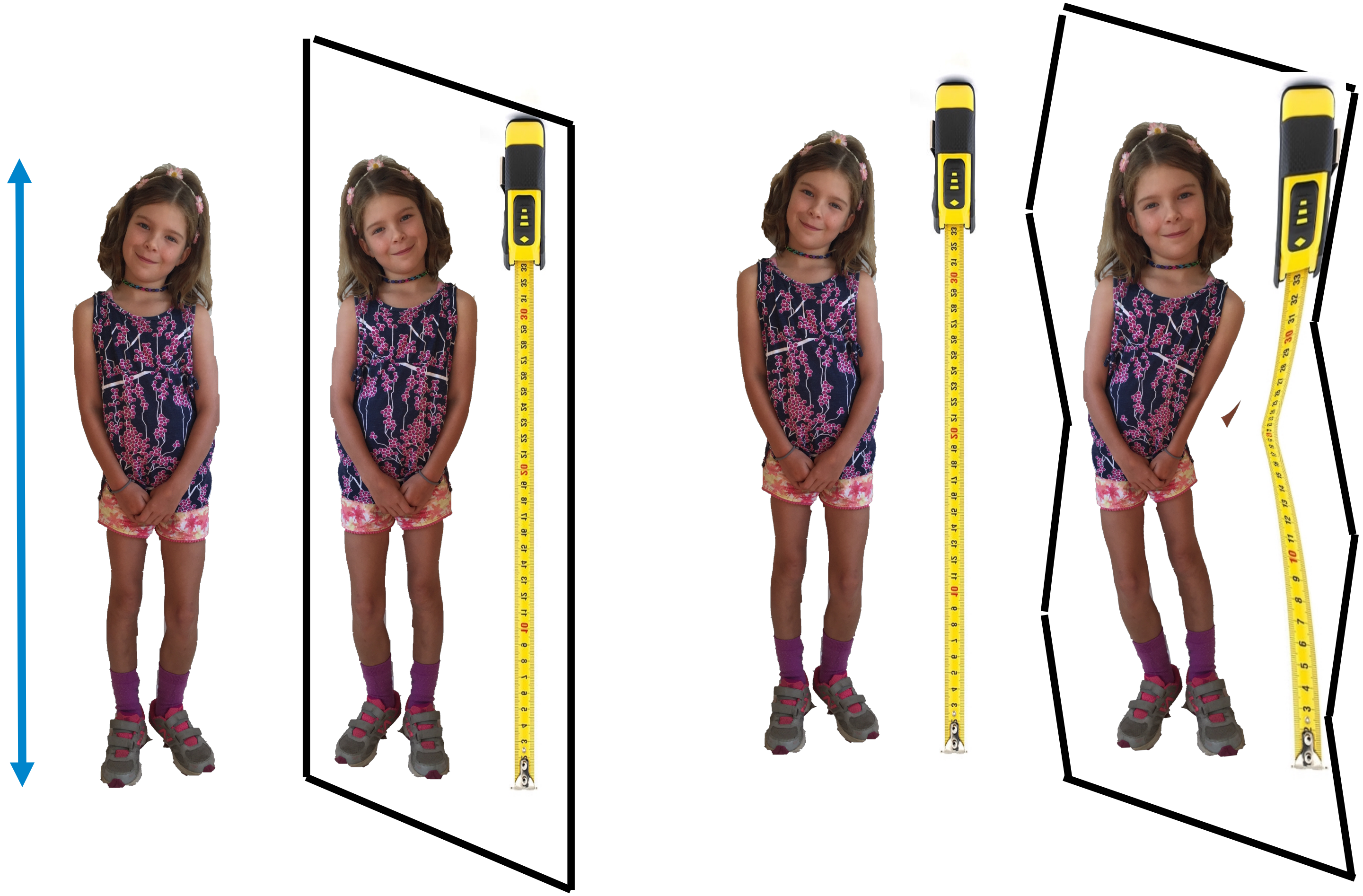
- 1. Observing Bright Binaries allows a small aperture telescope to overcome the photon noise limit.
- 2. Astrometric errors are generally proportional to reference angle. Binaries are much closer than field stars (gain typical factor of 20-50)

But we MUST now fly our own “ruler”. How to achieve micro-arcsecond astrometric stability with a small, inexpensive envelope?

The Challenge

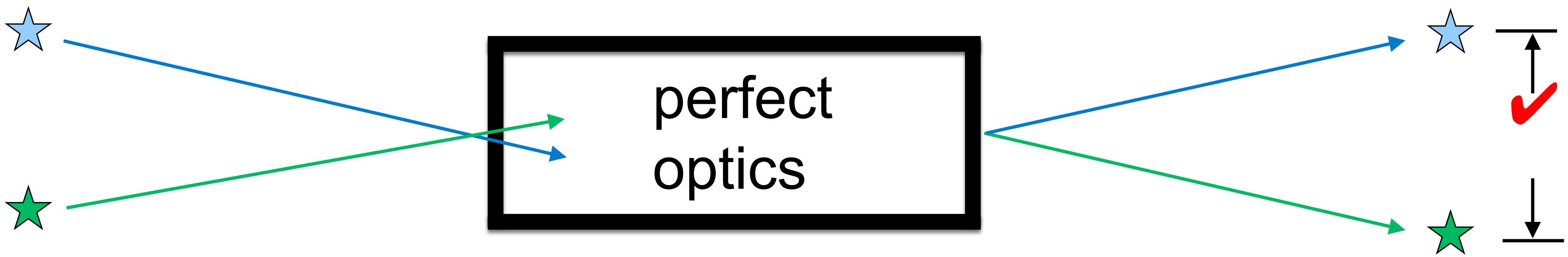


Optical distortions don't matter if they bend both your ruler and your object…

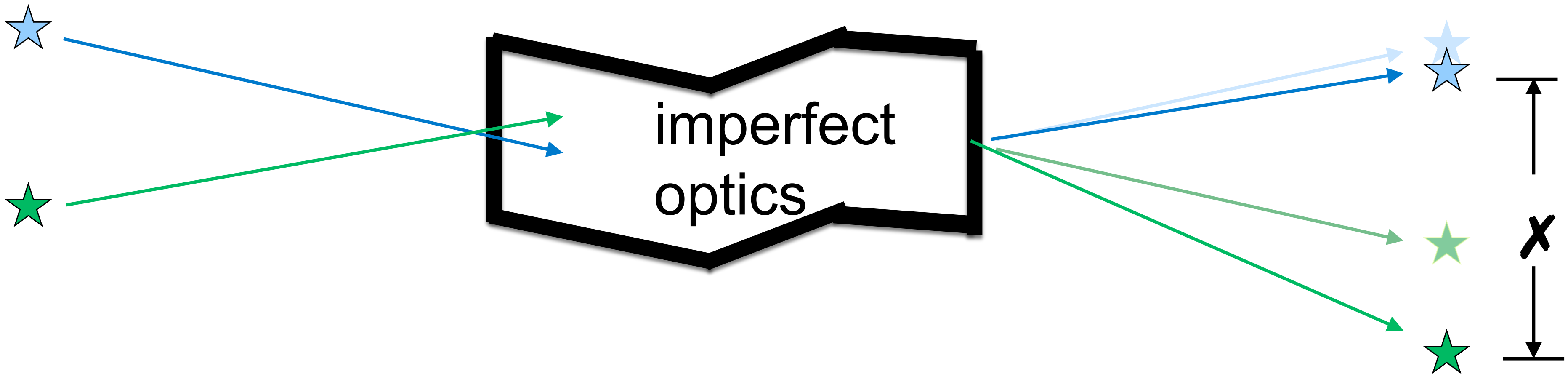


Fundamental principle: Diffractive Pupils

1. The basic problem

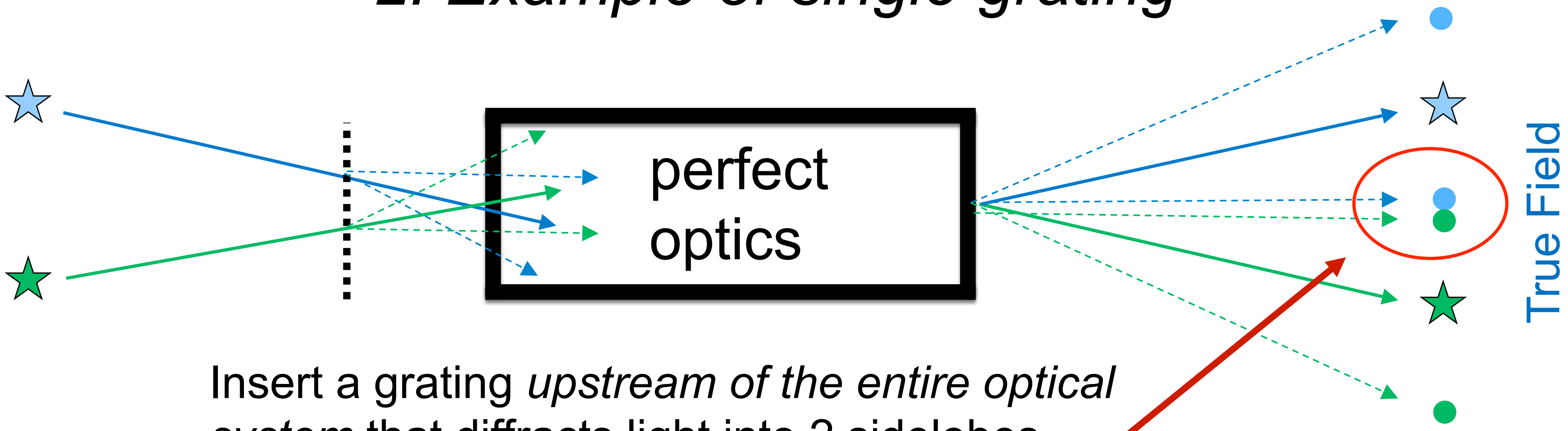


Distortion in the image field caused by unstable optical errors causes us to register the wrong apparent separation for the binary



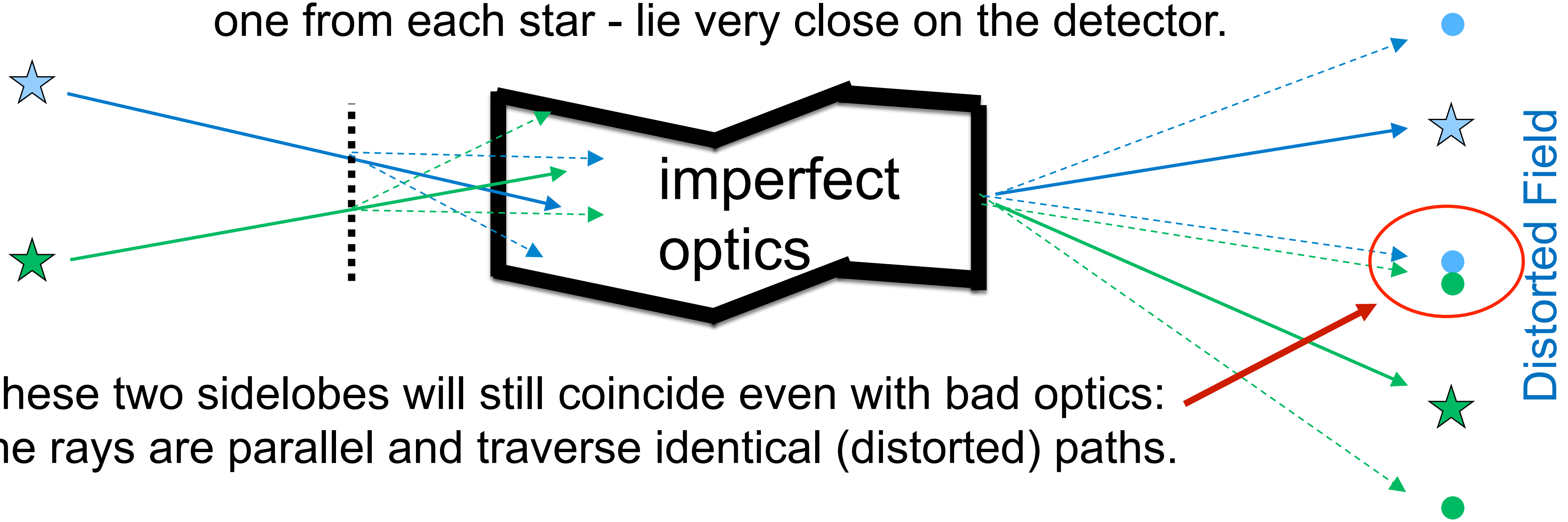
Fundamental principle: Diffractive Pupils

2. Example of single grating



Insert a grating *upstream of the entire optical system* that diffracts light into 2 sidelobes.

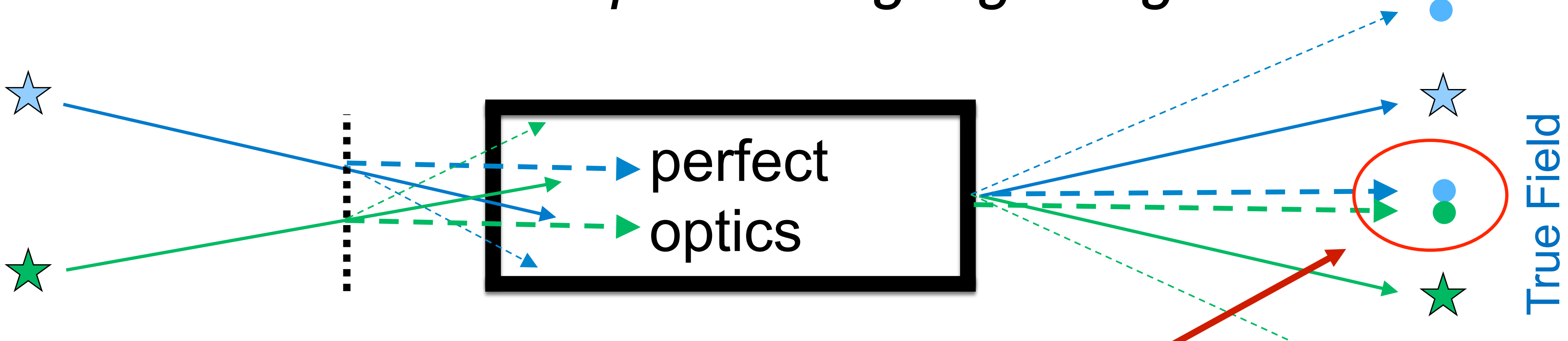
The grating spacing is chosen so that two sidelobes – one from each star - lie very close on the detector.



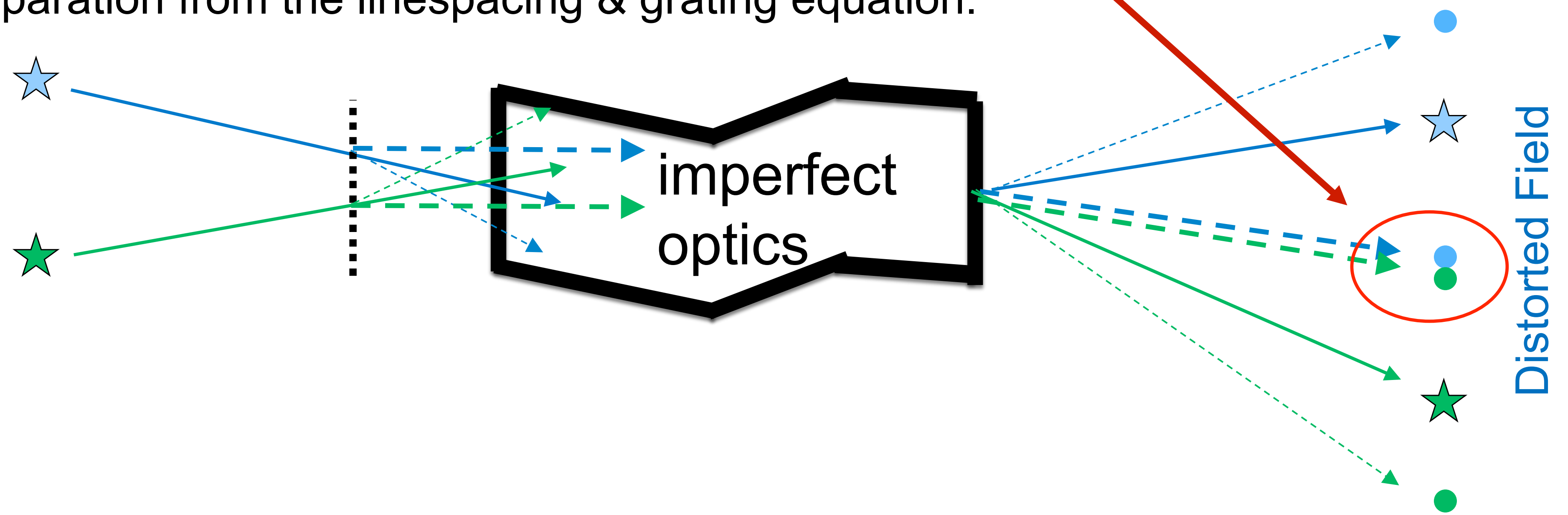
These two sidelobes will still coincide even with bad optics: the rays are parallel and traverse identical (distorted) paths.

Fundamental principle: Diffractive Pupils

2. Example of single grating

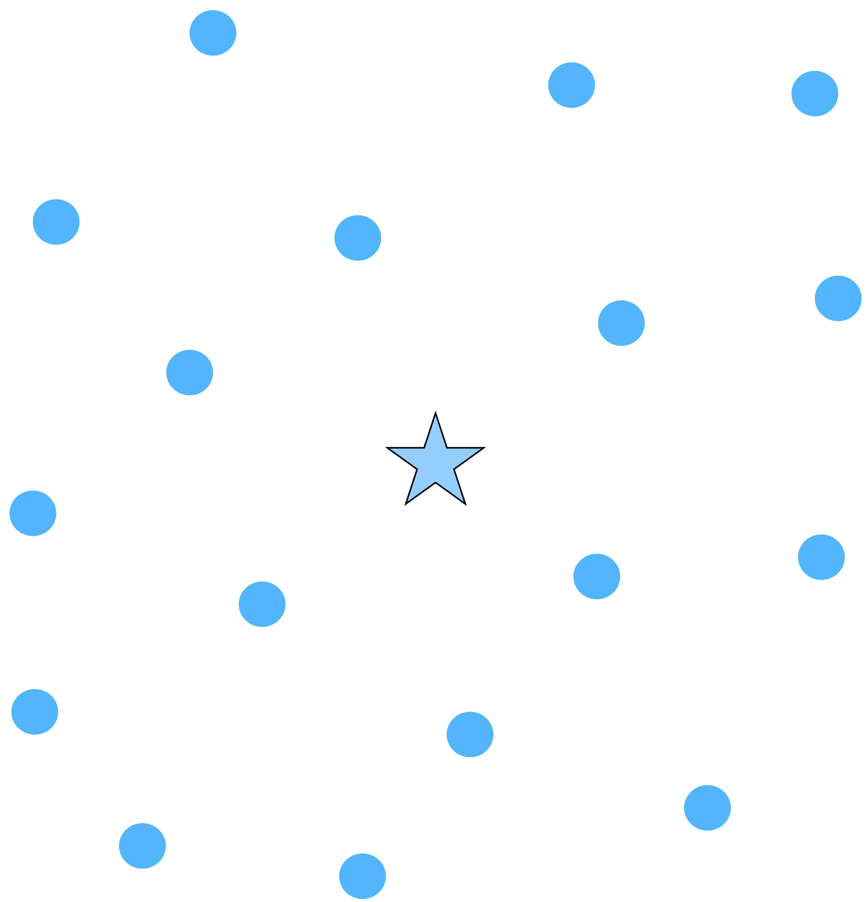


We can measure the separaton of a binary through a distorted optical system by simply observing that the 2 sidelobes coincide. We can then calculate this separation from the linespacing & grating equation.



How do Diffractive Pupils work?

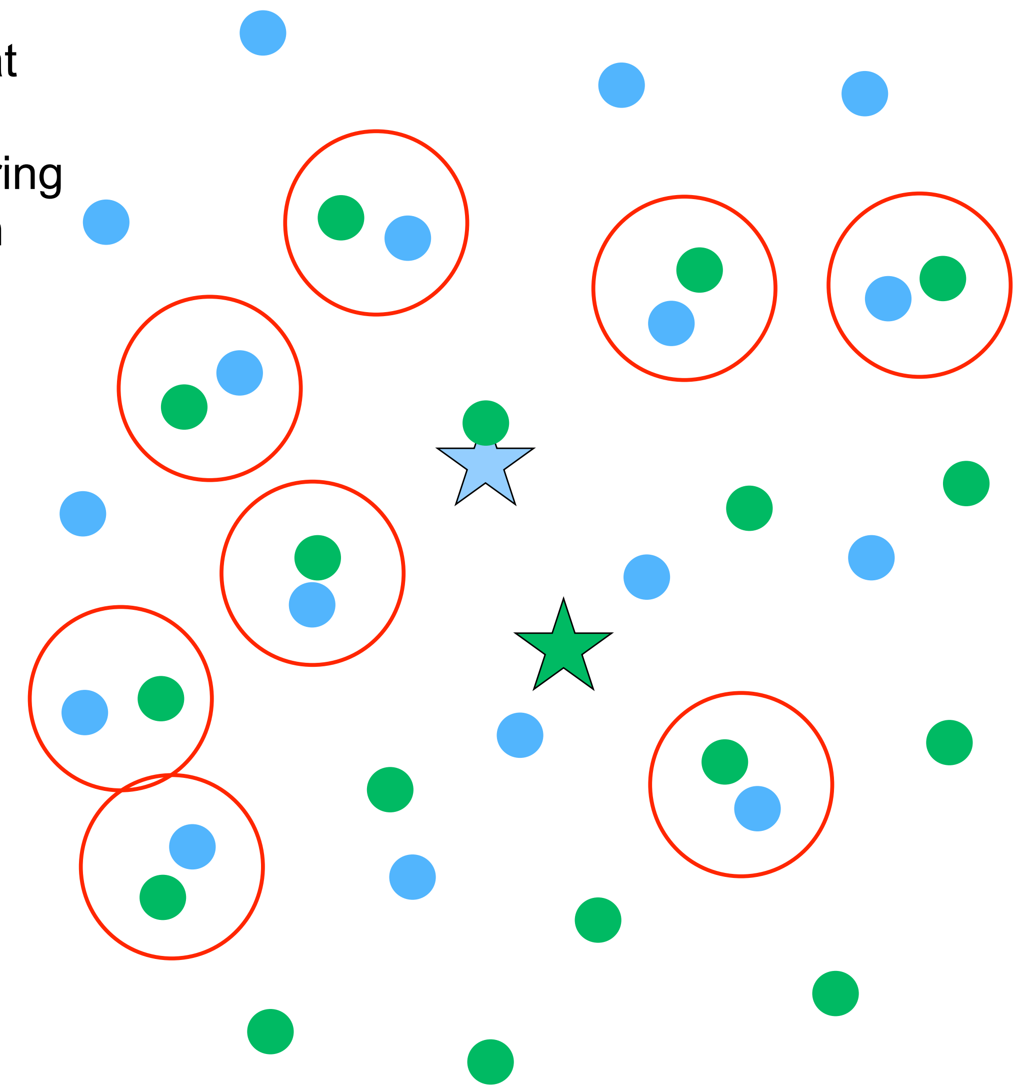
Simple picture: a binary star surrounded by bright speckles from a diffractive pupil



How do Diffractive Pupils work?

Simple picture: a binary star surrounded by bright speckles from a diffractive pupil

For the moment, only consider speckles that (by chance) are in a close pair of neighboring peaks, one from each star



How do Diffractive Pupils work?

THIS is what optical errors/instabilities that result in geometric distortions over the field looks like.

The distortion term causing errors in position measurement accumulates: it is worse when finding the distance of objects that are more separated in the image plane.

THE UNIVERSITY OF SYDNEY

How do Diffractive Pupils work?

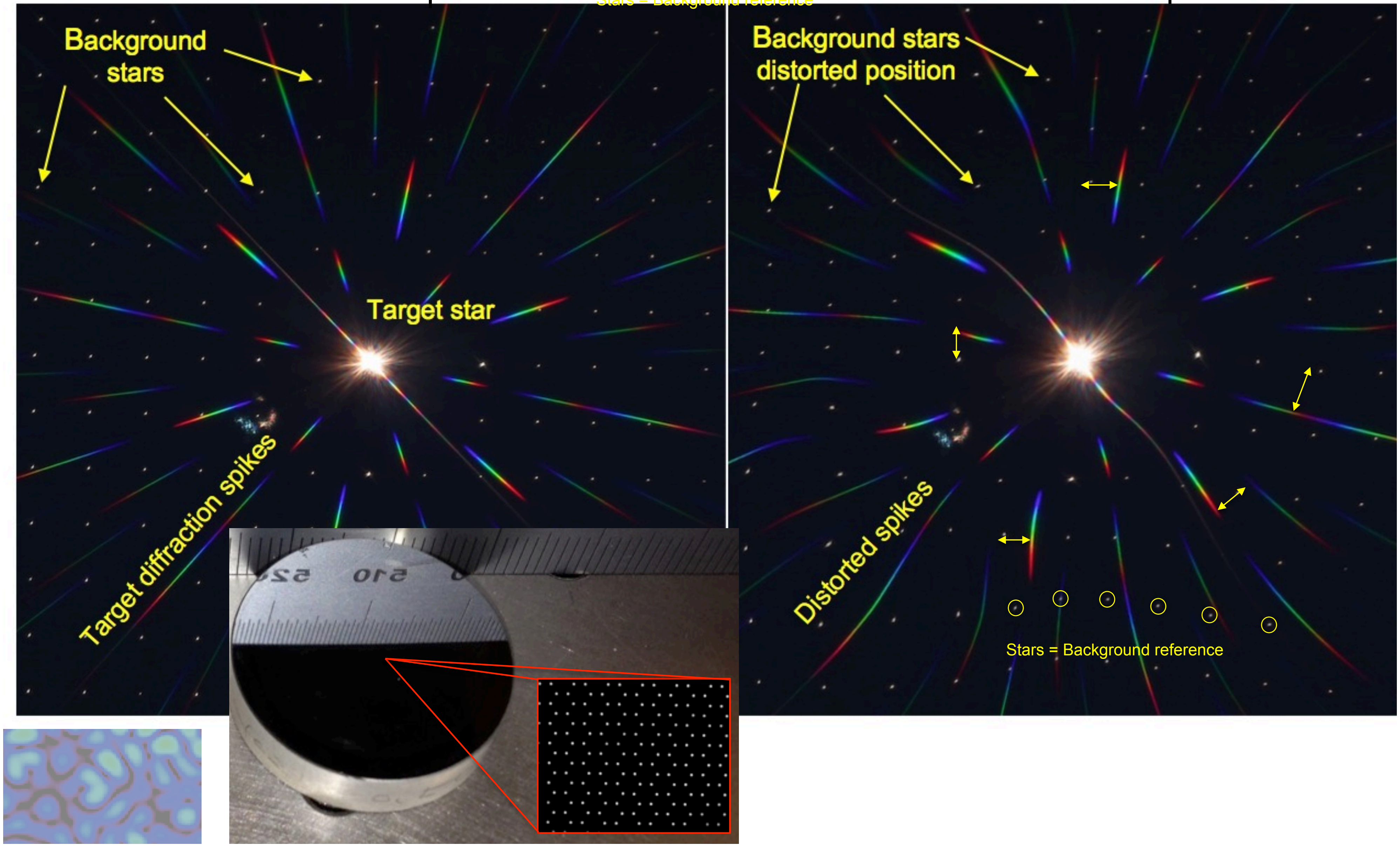
And THIS is what a real astrophysical signal where the stellar positions are gravitationally perturbed should look like.

Conclusion: If we are able to make a measurement of the separation of the binary star by only registering local displacements (between adjacent diffractive speckles – in the limit structures that overlap on the same few detector pixels), then the effects of distortion of the field due to optical errors and drifts will be largely removed. Such a measurement is self-calibrating and the only element requiring absolute stability is the diffractive ruler, not the imaging system.

Optical distortions don't matter if they bend both your ruler and your object…

Perfect Optics

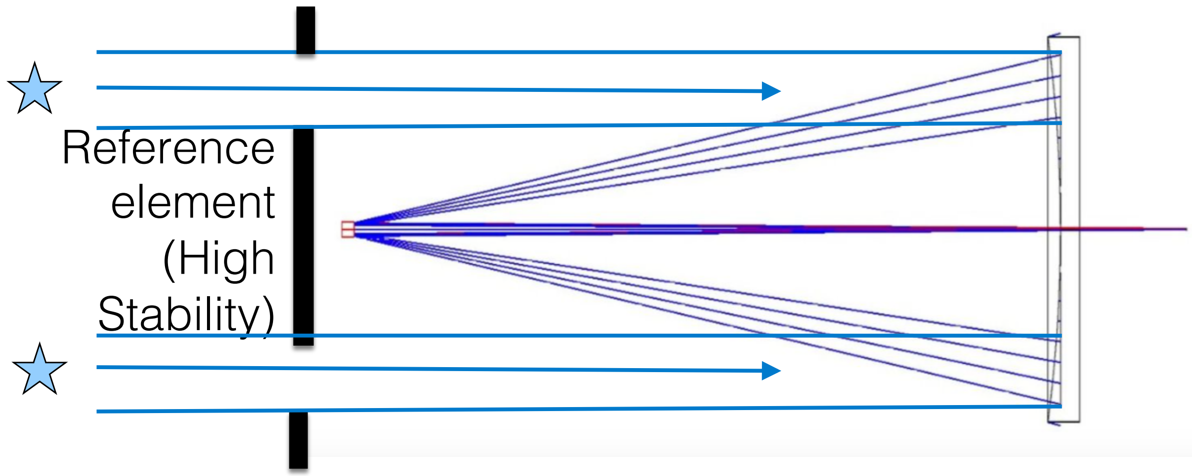
Distorted Optics

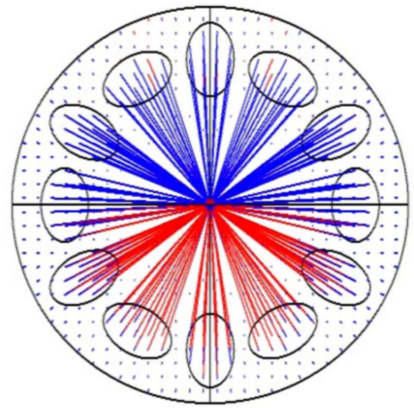


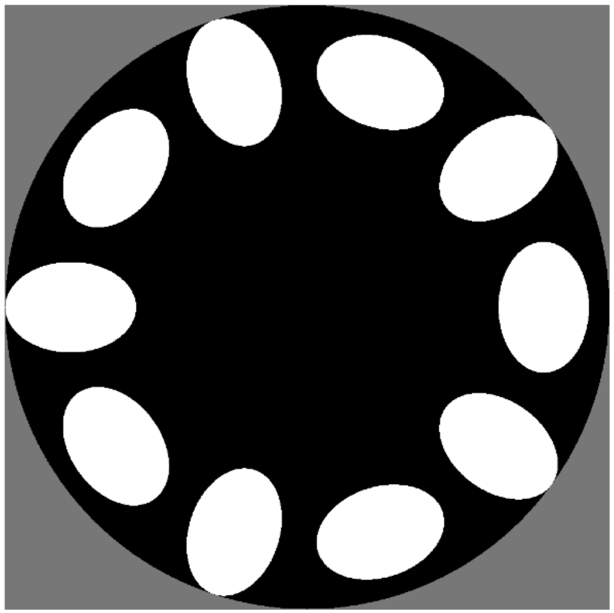
Original concept empowering TOLIMAN

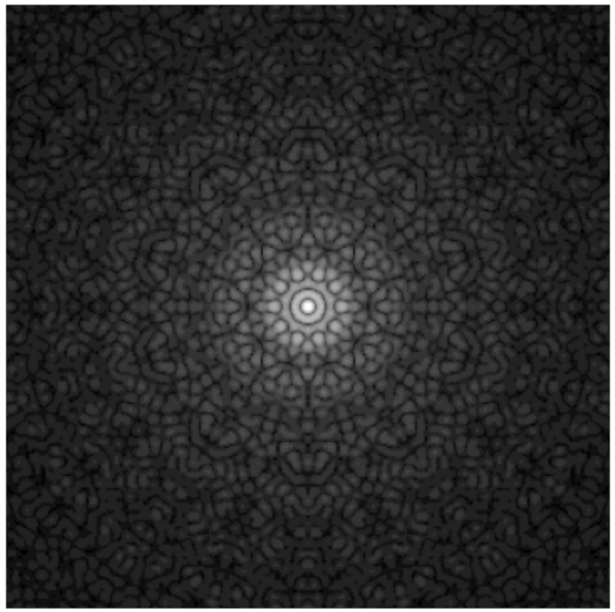
Diffractive-pupil pupil mask

Monitor the binary with a diffractive ruler made of starlight!



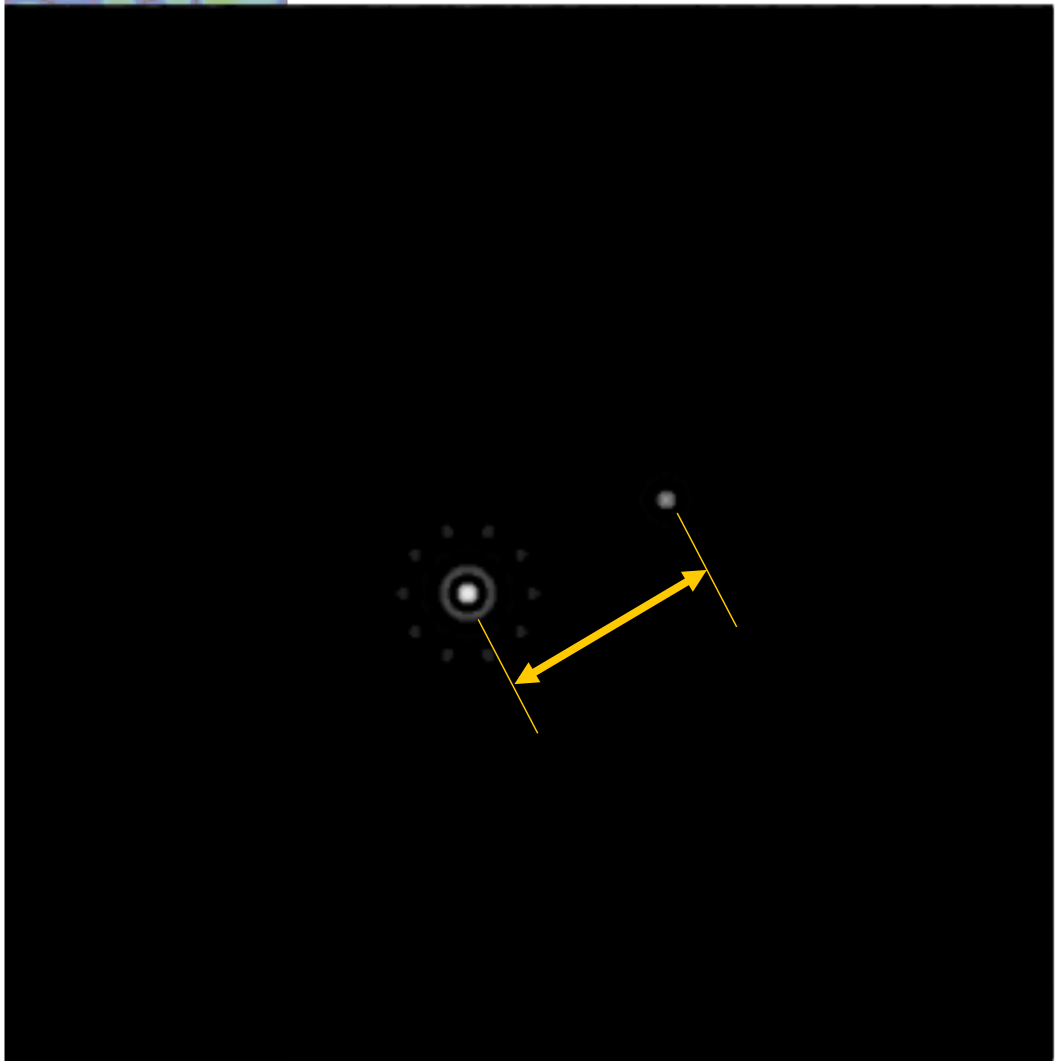






TOLIMAN

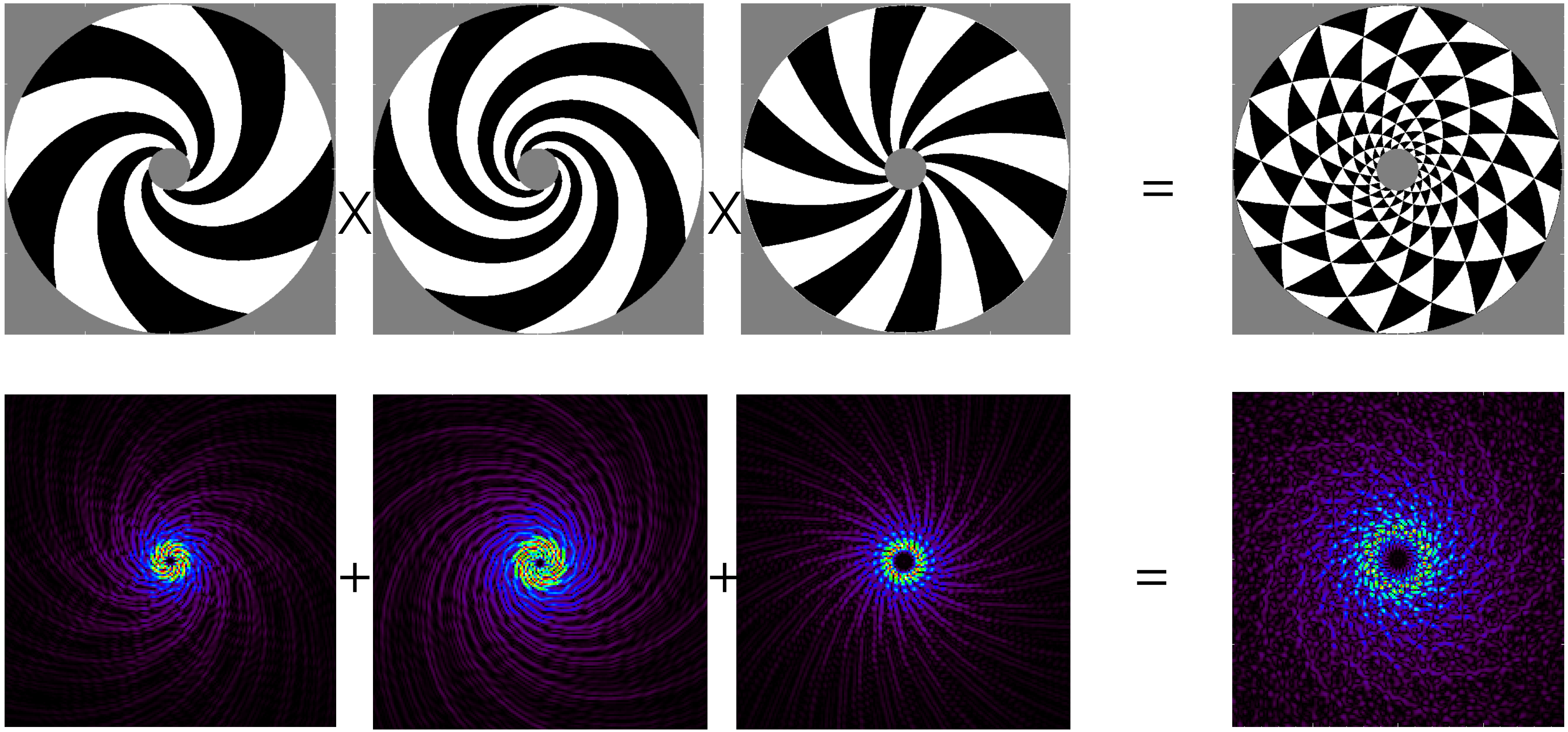
Telescope for Orbital Locus Interferometric Monitoring of our Astronomical Neighborhood



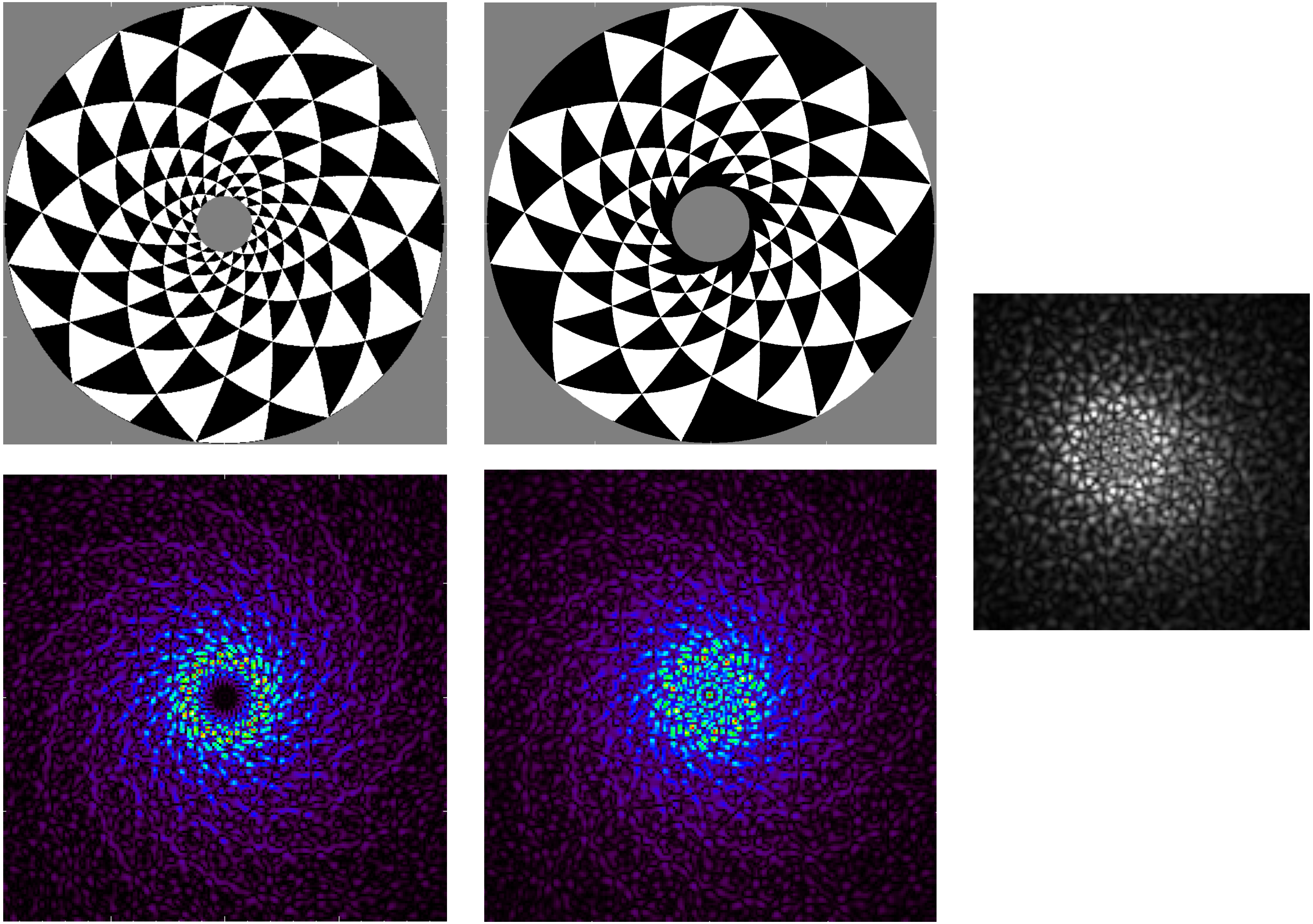
- Binary Star: Only 1-D measurement of separation (azimuthal information cannot be calibrated without background stars)
- Exact converse of Guyon Diffractive Pupil (dots)
- Want strong diffractive spread of starlight to several arcseconds (binary separation)
- Bandwidth will blur fringes away from PSF core. Optical bandwidth must be limited (~ 10%)
- 5-fold symmetry gives non-repeating Penrose pattern fringes
- However on a linear scale, 10-hole mask does not deliver enough spread of starlight!
- Need a way to form strongly speckled diffractive ruler several arcsec across

Jedi Fourier Mind Tricks 1: Log Harmonic Pupils

Pupil has half-wave phase shift between black/white regions
Extremely effective at spreading energy over a large PSF region
Product of 3 log-harmonic spirals gives a speckled disk with a central hole



Jedi Fourier Mind Tricks 1: Log Harmonic Pupils



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- 3. The Diffractive Pupil removes most error terms arising from distortion in the optical train. The fundamental ruler element can be made monolithic, thermally stable, and precisely monitored.
- 4. Naturally spreads the starlight over many pixels, preventing detector saturation and at the same time giving major statistical benefits in beating down noise

But there is a flaw! Our ruler (fringes) depends on the effective wavelength of the starlight – which varies with star Teff!

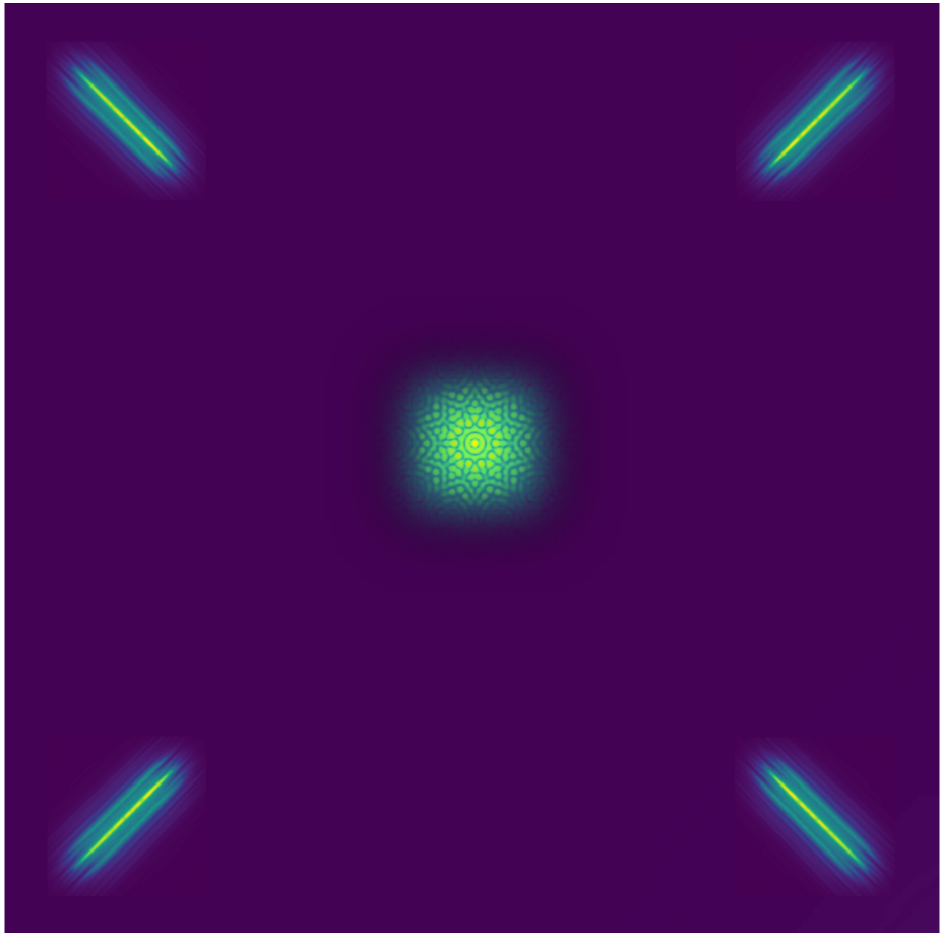
The Problem: Tiny changes in starlight effective wavelength will register as changes in the plate scale. Tiny drifts in opto-mechanical stability (e.g. focal length) also change plate scale.

How can we disentangle and calibrate these effects?

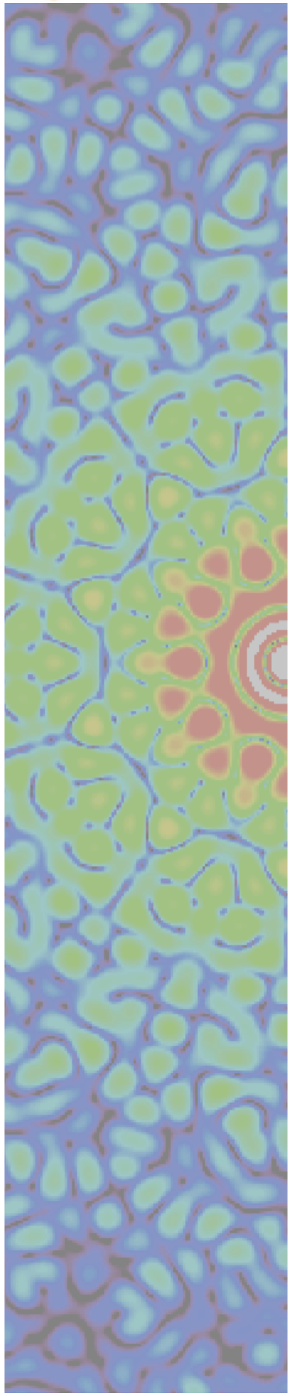
Answer: A *Doubly Diffractive Pupil* architecture

How does it work?

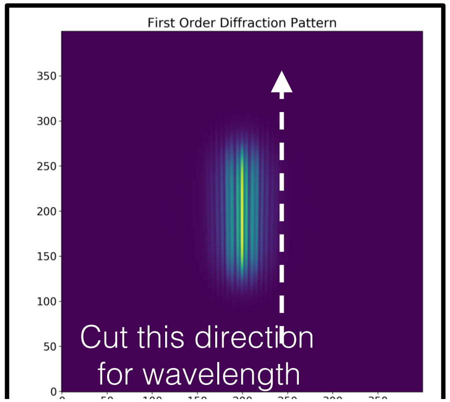
- Engrave sinusoidal phase ripple across the primary mirror
- About 1 cycle per mm; 1/10th of a wave depth
- Two different phase gratings running in orthogonal directions
- This is in addition to the original diffractive pupil (hence *Doubly-Diffractive*)
- This creates satellite copies of the PSF at the periphery of the chip.
- Wavelength diversity causes bandwidth smearing
- We have created a spectrograph!



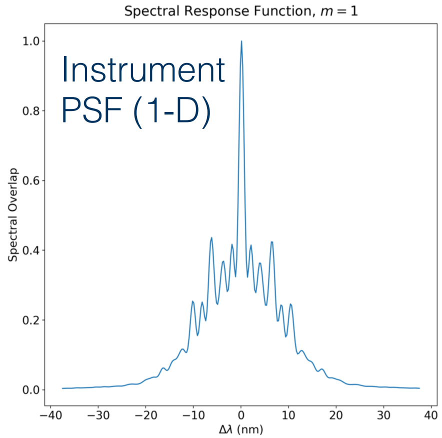
Doubly-Diffractive pupil yields both the effective wavelength and the plate scale in absolute units!



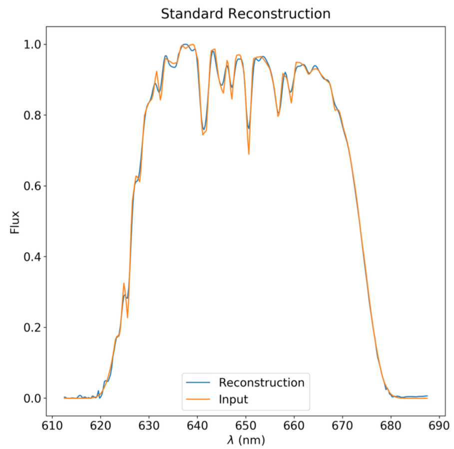
(1) Extract the satellite PSFs. These will yield the spectrum of the star along the radial direction. The stellar spectrum contains embedded atomic lines that give an absolute reference



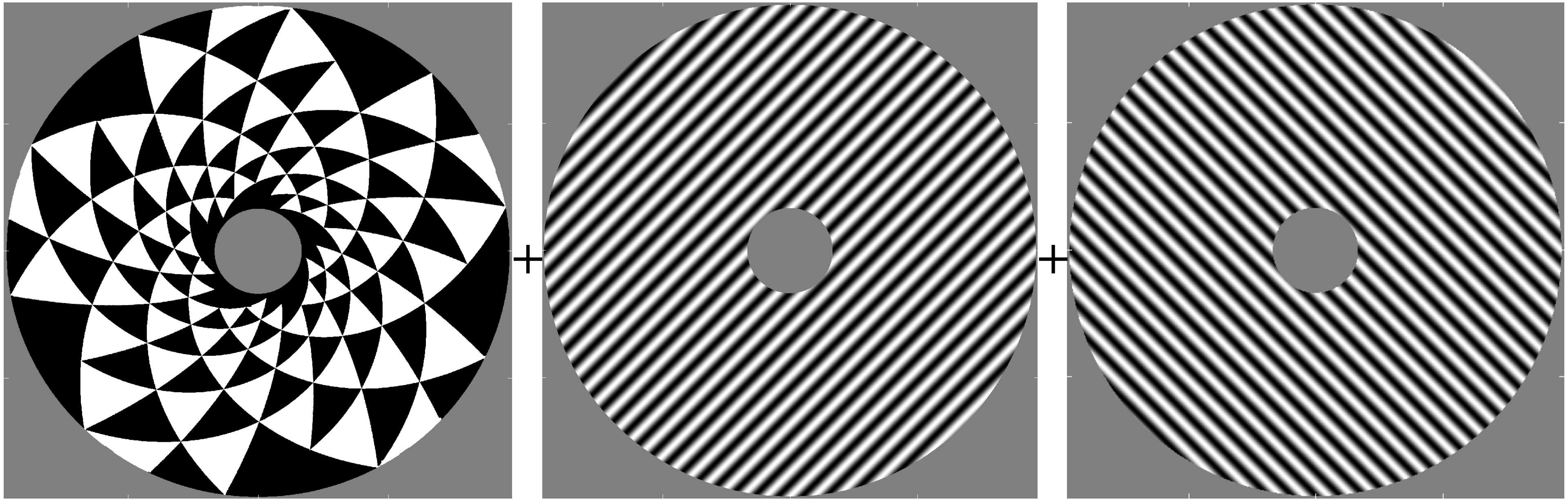
(2) Deconvolve the instrument point spread function to obtain a clean stellar spectrum



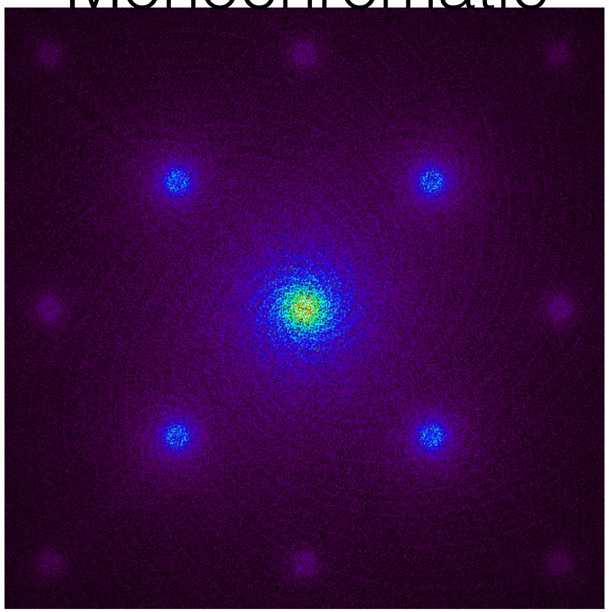
(3) Fit of the stellar spectrum to the data immediately yields the exact plate scale and wavelength scale. Orange is input spectrum, Blue is recovered spectrum. Recovery stable at required levels of precision.



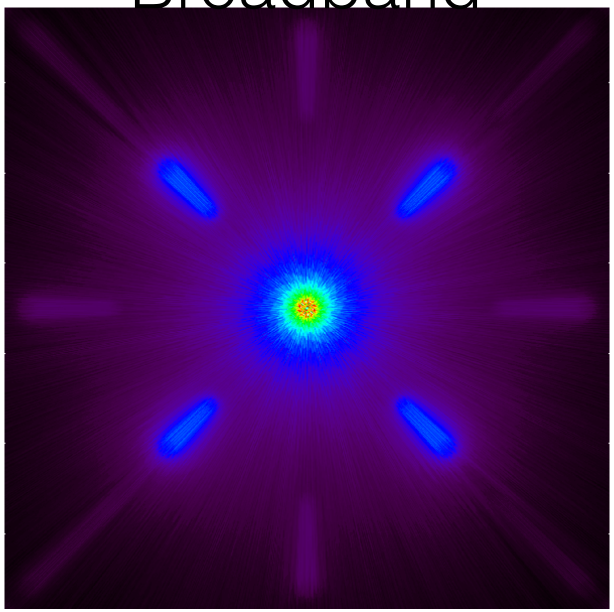
Jedi Fourier Mind Tricks 2: Sidelobe PSF engineering



Monochromatic



Broadband



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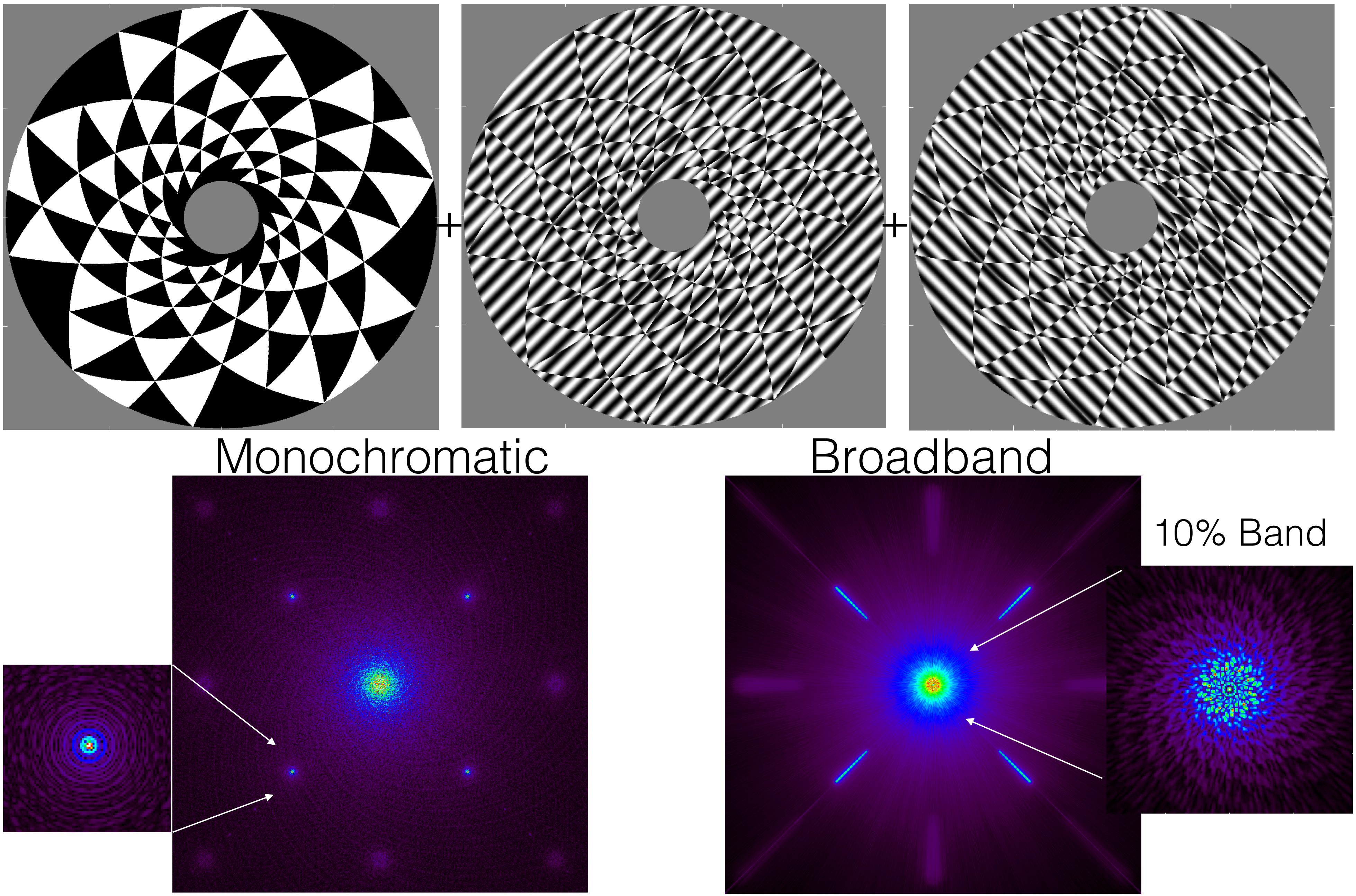
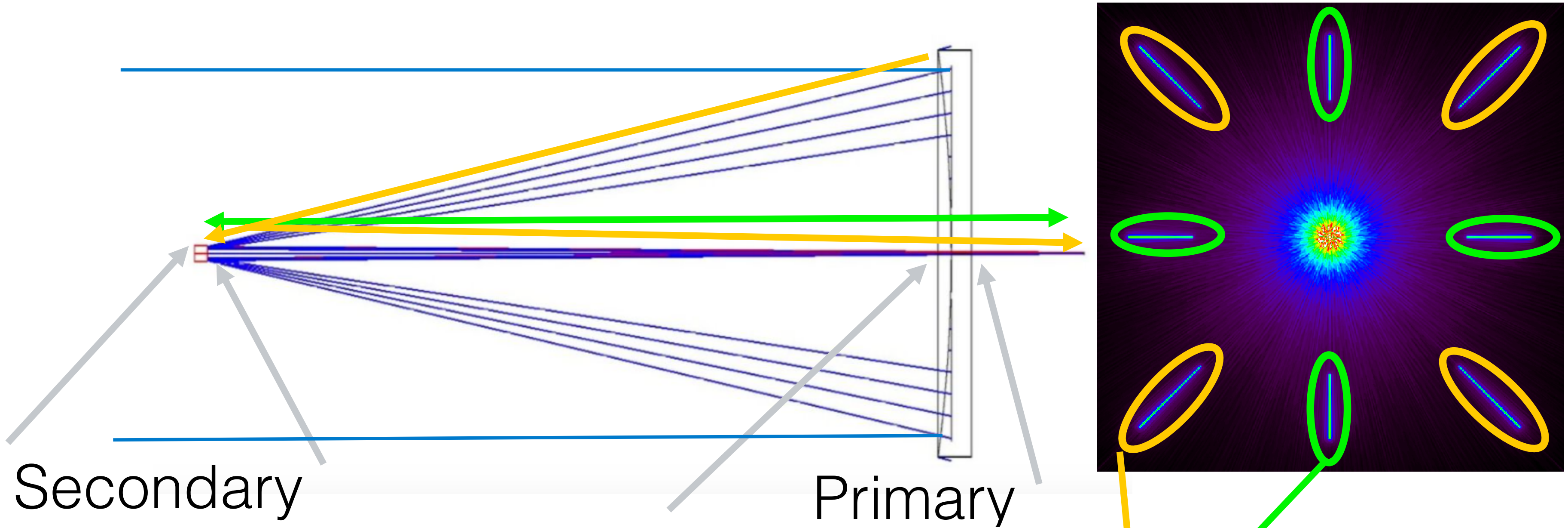
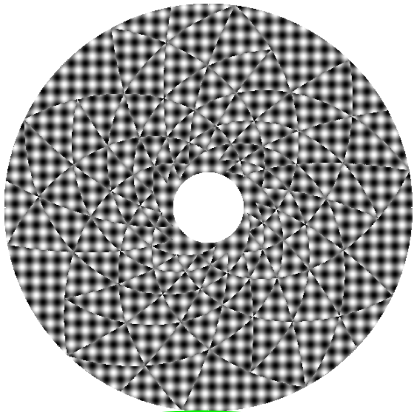


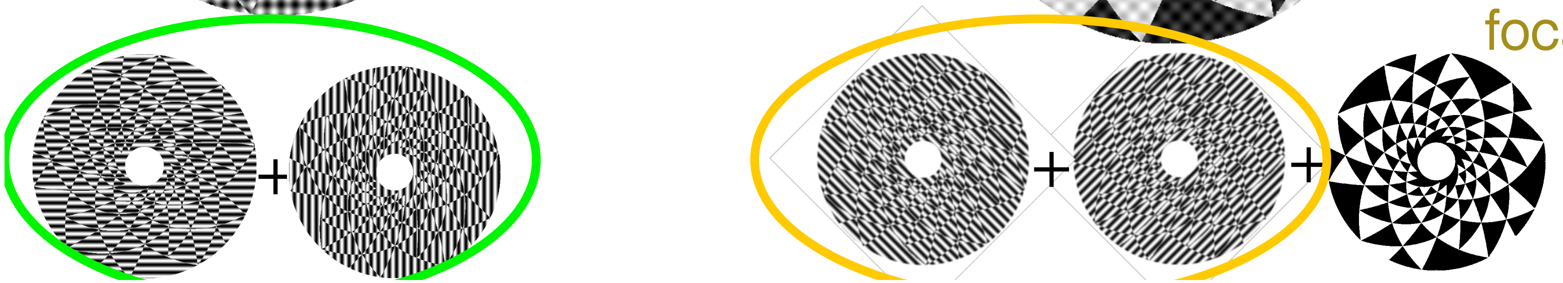
Jedi Fourier Mind Tricks 3:
Full system metrology by distributed diffractive pupils





Secondary grating.
Gives separation
Secondary-Detector

Primary grating.
Gives overall system
focal length



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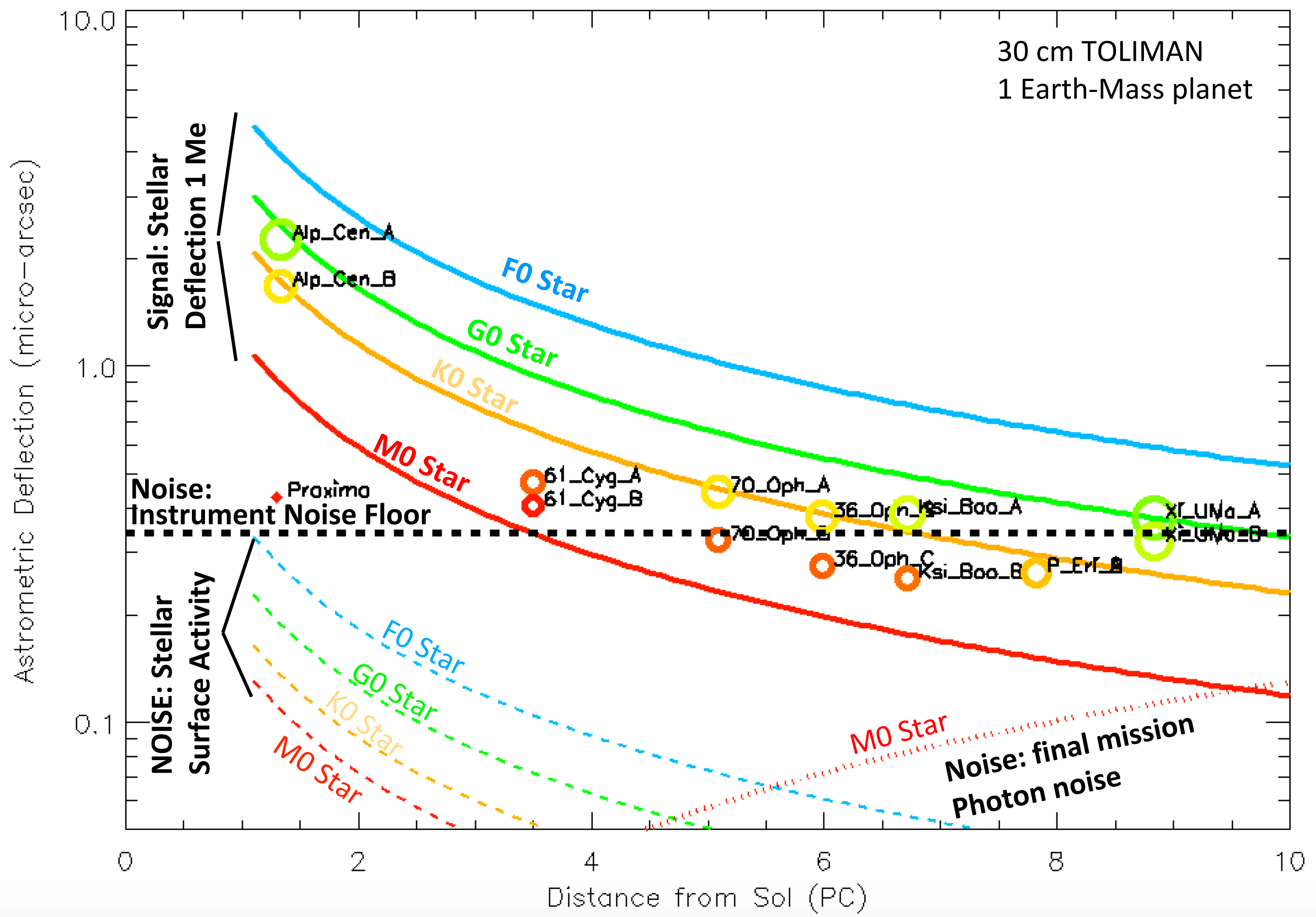
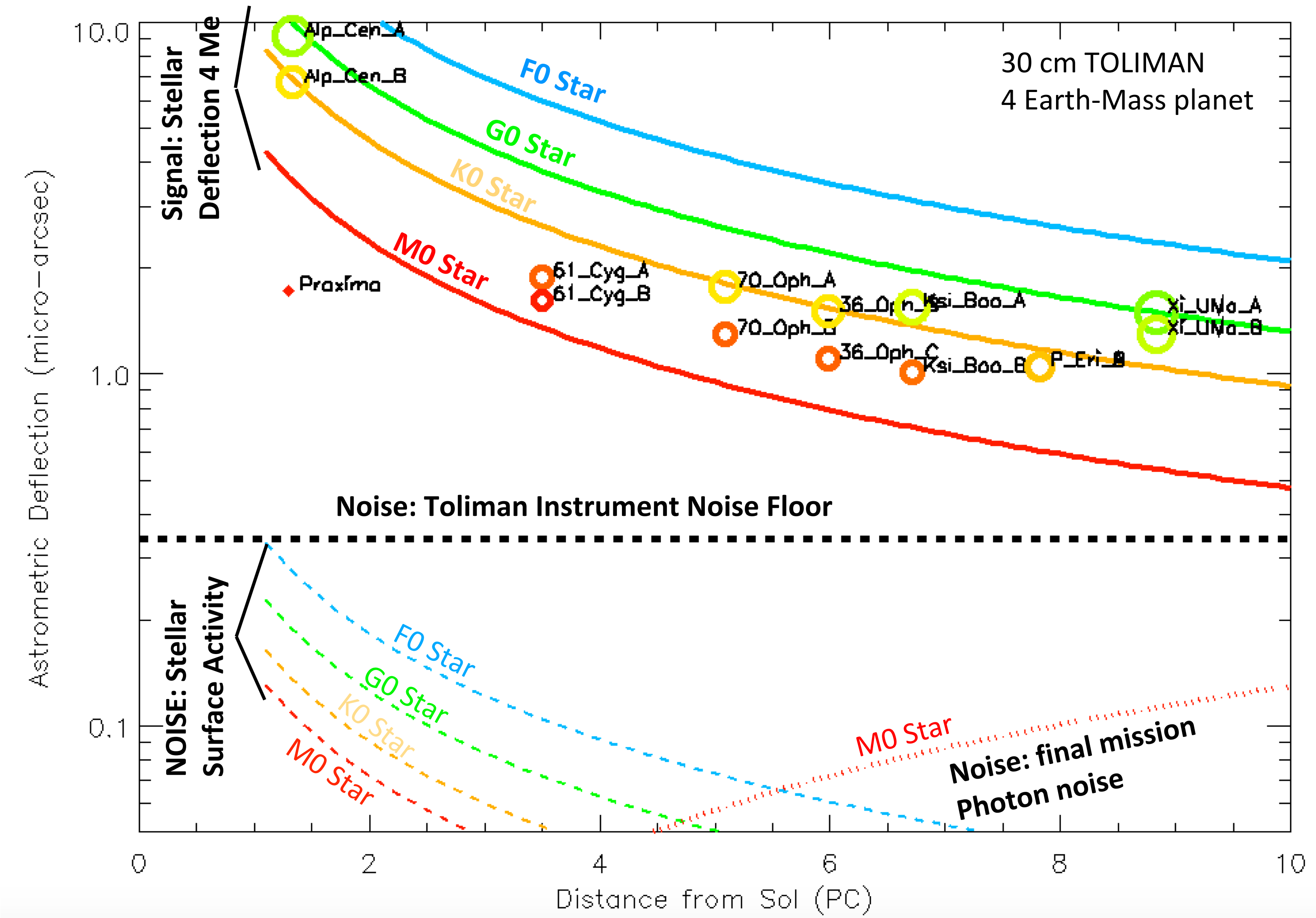
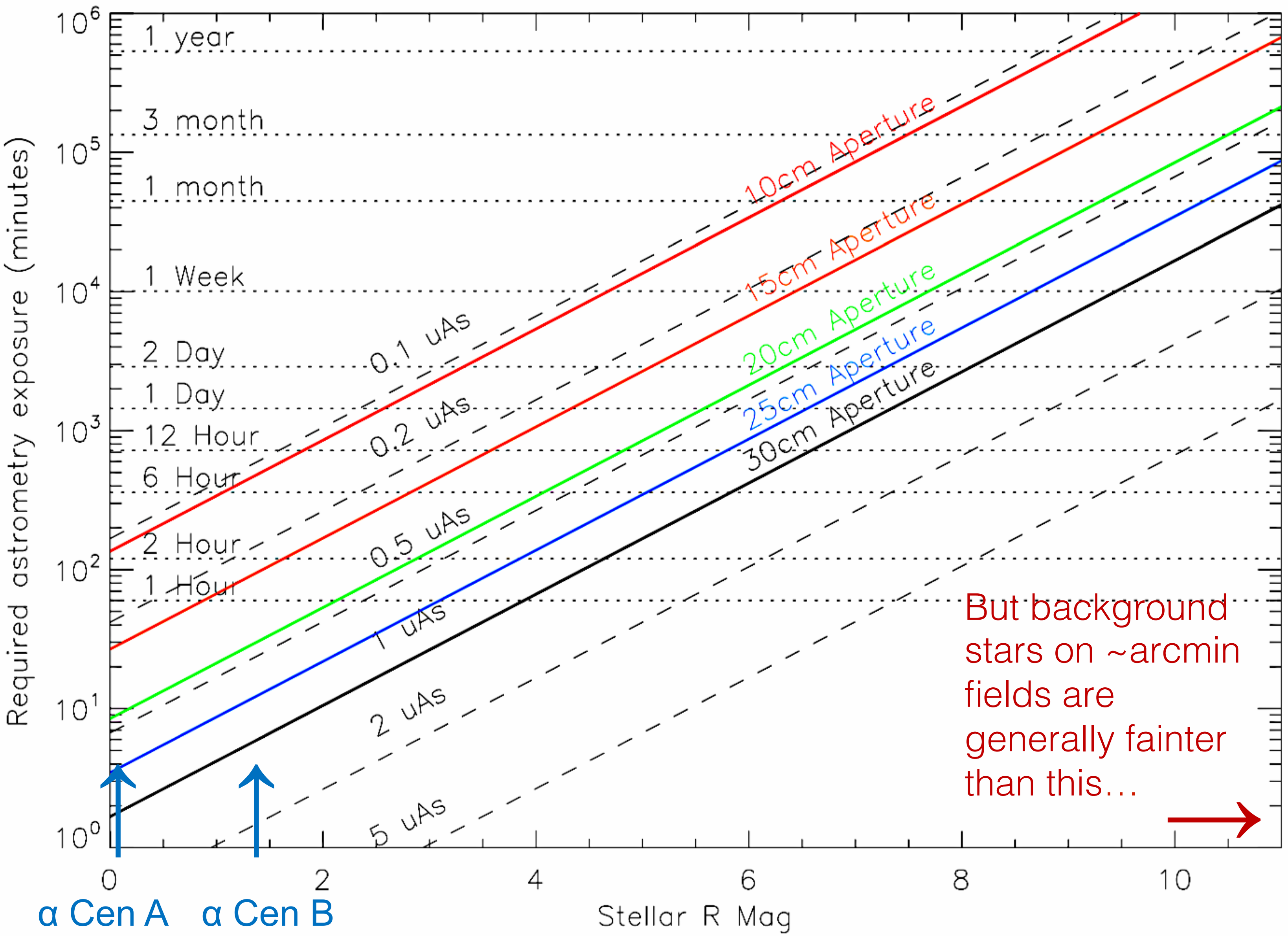
- 4. Naturally spreads the starlight over many pixels, preventing detector saturation and at the same time giving major statistical benefits in beating down noise
- 5. Doubly-Diffractive pupil locks down plate scale and absolute wavelength reference (from atomic physics)
- 6. D-D pupil also delivers spectral monitoring – potential for compensating stellar noise processes
- 7. Achieve required end-of-mission precision for Earth-analogs with inexpensive design.

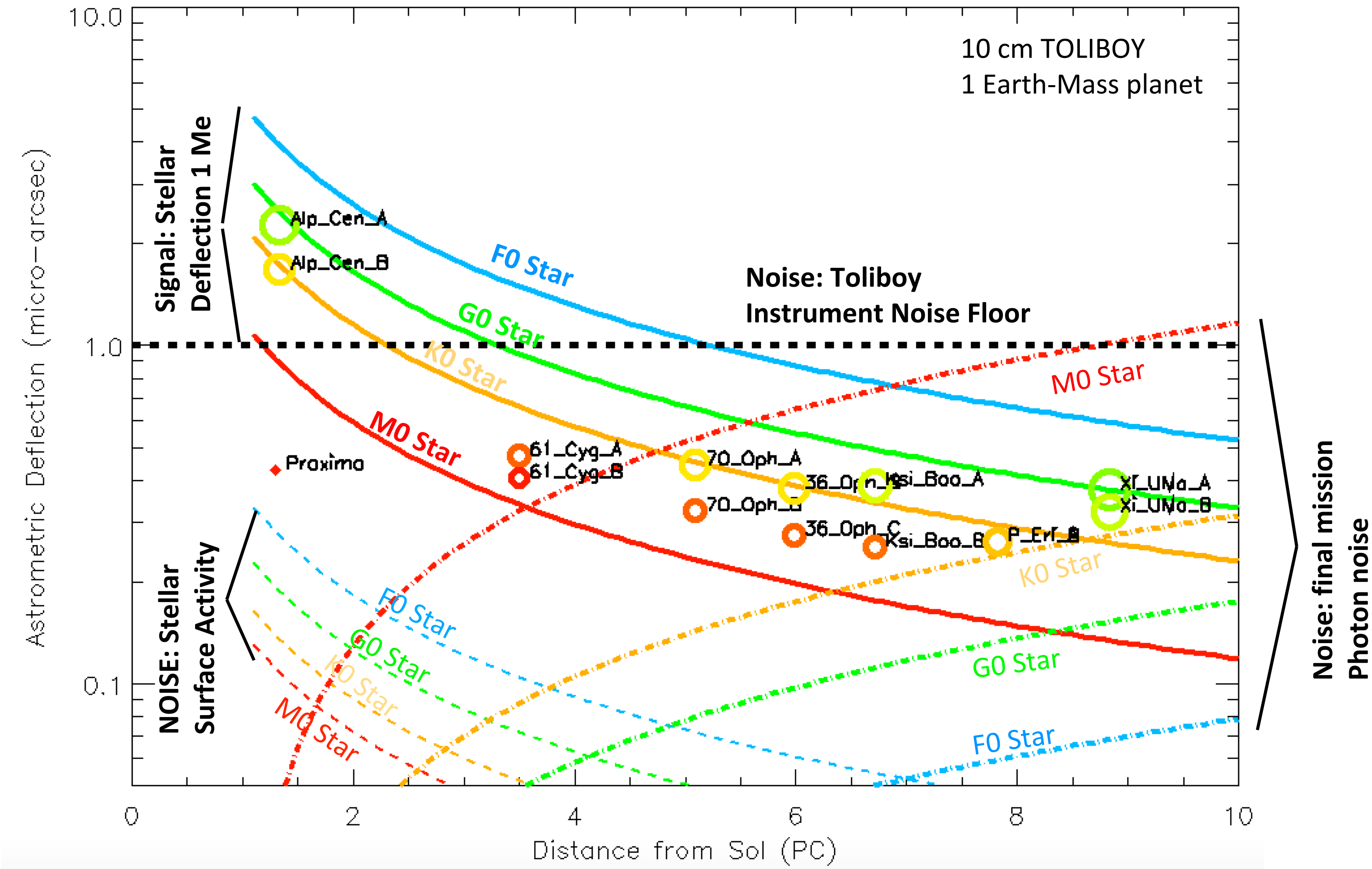

30 cm TOLIMAN
1 Earth-Mass planet
Signal: Stellar Deflection 1 Me
Noise: Instrument Noise Floor
NOISE: Stellar Surface Activity
Noise: final mission Photon noise
F0 Star
G0 Star
K0 Star
M0 Star
Alp_Cen_A
Alp_Cen_B
Proxima
61_Cyg_A
61_Cyg_B
70_Oph_A
70_Oph_B
36_Oph_C
Ksi_Boo_A
Ksi_Boo_B
Xi_UMa_A
Astrometric Deflection (micro-arcsec)
Distance from Sol (PC)
10.0
1.0
0.1
0
2
4
6
8
10



30 cm TOLIMAN
4 Earth-Mass planet
Signal: Stellar Deflection 4 Me
F0 Star
G0 Star
K0 Star
M0 Star
Alp_Cen_A
Alp_Cen_B
Proxima
61_Cyg_A
61_Cyg_B
70_Oph_A
70_Oph_B
36_Oph_C
Ksi_Boo_A
Ksi_Boo_B
Xi_UMa_A
Xi_UMa_B
Noise: Toliman Instrument Noise Floor
NOISE: Stellar Surface Activity
Noise: final mission Photon noise
Astrometric Deflection (micro-arcsec)
Distance from Sol (PC)
10.0
1.0
0.1
0
2
4
6
8
10

Telescope integration times for 1uas as a function of aperture size




10 cm TOLIBOY
1 Earth-Mass planet
Signal: Stellar Deflection 1 Me
Noise: Toliboy Instrument Noise Floor
NOISE: Stellar Surface Activity
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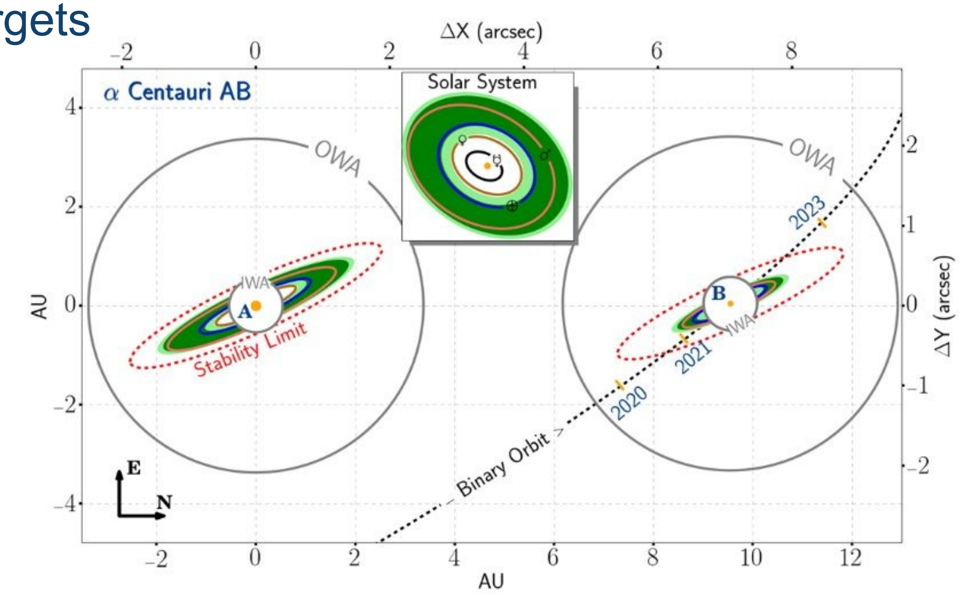
F0 Star
G0 Star
K0 Star
M0 Star
Alp_Cen_A
Alp_Cen_B
Proxima
61_Cyg_A
61_Cyg_B
70_Oph_A
70_Oph_B
36_Oph_B
36_Oph_C
Ksi_Boo_A
Ksi_Boo_B
P_Eri_B
Xi_UMa_A
Xi_UMa_B
Astrometric Deflection (micro-arcsec)
Distance from Sol (PC)
10.0
1.0
0.1
0
2
4
6
8
10

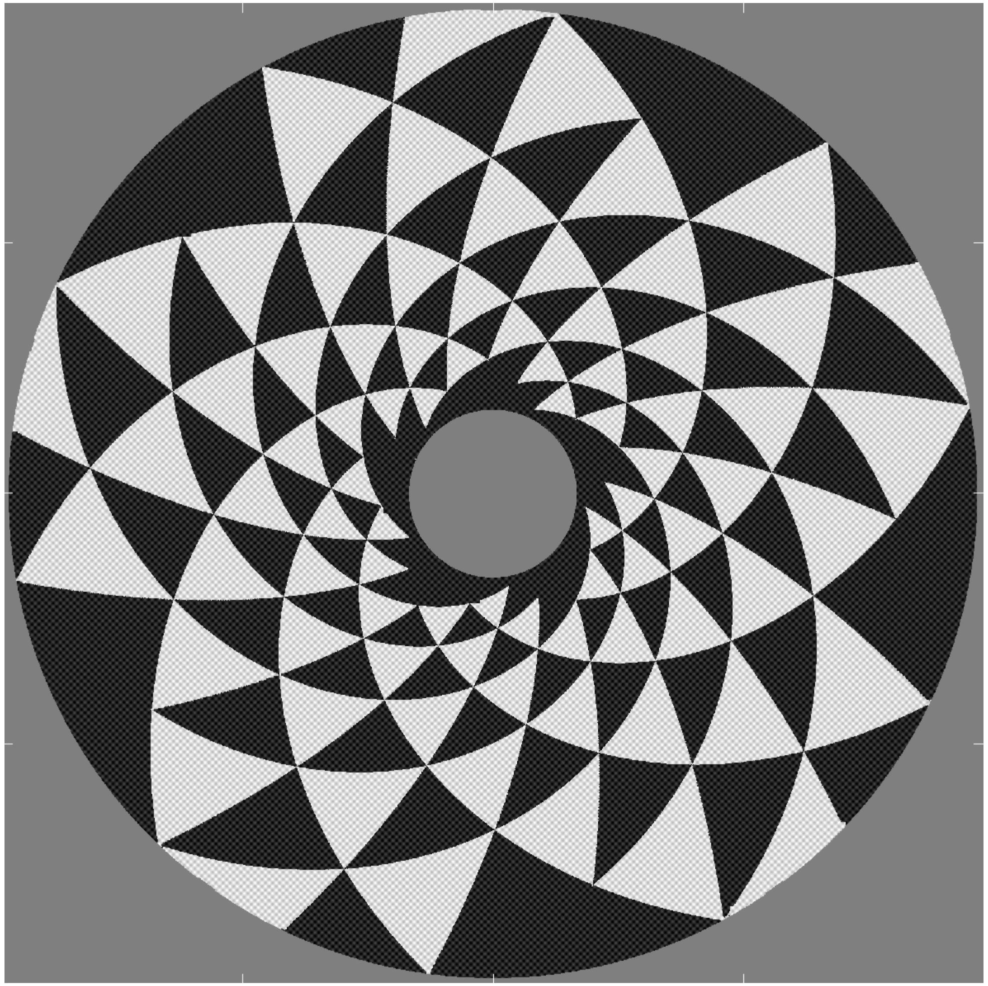
TOLIMAN: Performance

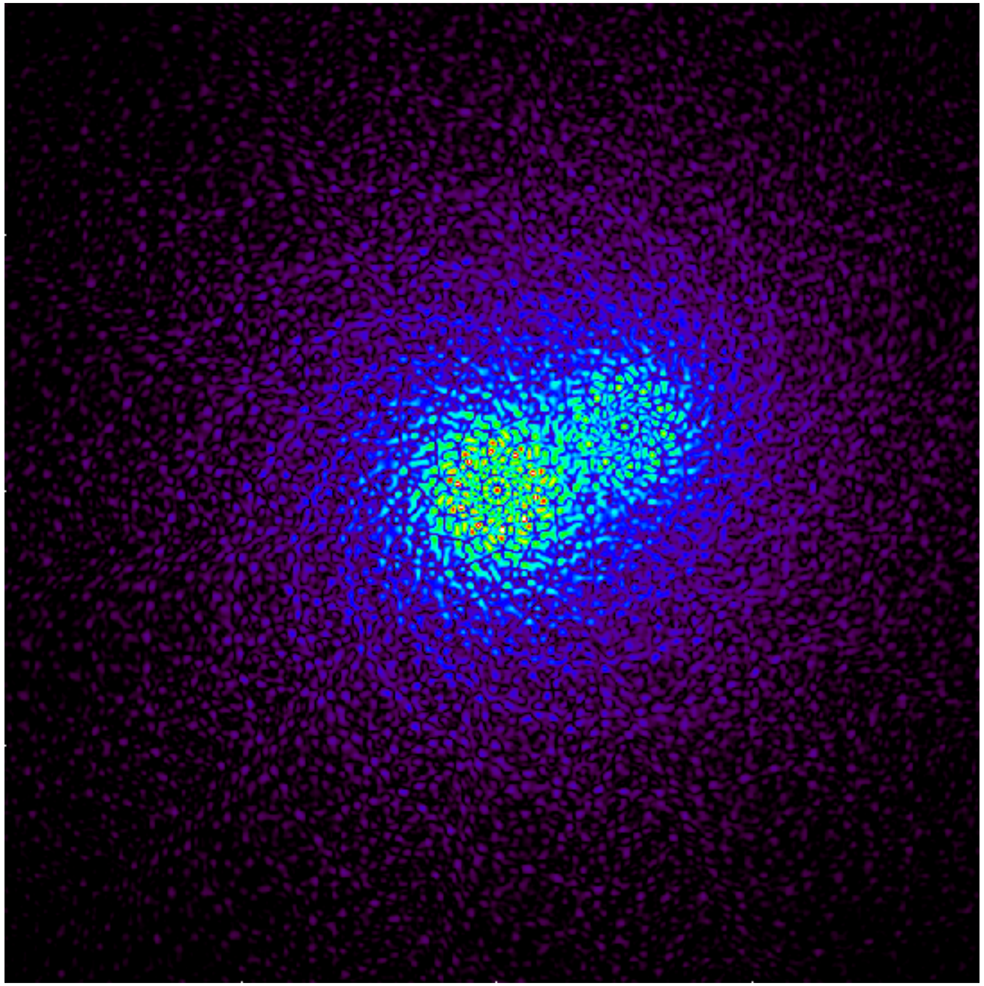
- GOALS
  - Primary Target Alpha Cen A/B system: final mission astrometric precision of 0.2 micro-arcseconds
  - Also perform an astrometric survey of 6 additional suitable binary systems within 10 PC.
  - Astrometric precision for secondary targets of 0.5 micro-arcseconds
  - Provide simultaneous photometric/spectral monitoring
  - 3 year mission.
  - < Earth-mass planets Alpha Cen
  - 2-3 Earth mass for secondary targets
- Caveats …
  - Note we only get 1-D data
  - Planets in orbital plane of binary
  - Orthogonal planets invisible
  - Ambiguity: which star is host?



Habitable zones of Alpha Cen A (left) and B (right) in green, along with dynamical stability boundary (red dashed line)

TOLIMAN





Thank You

Stars within 10 pc of the Sun

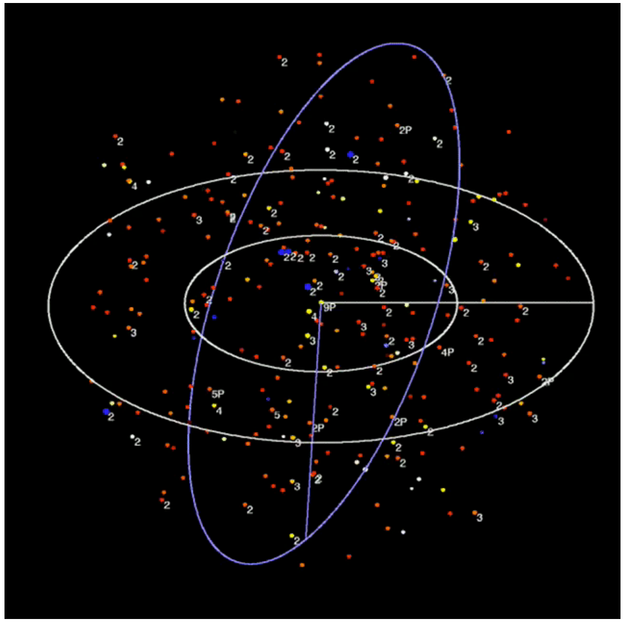
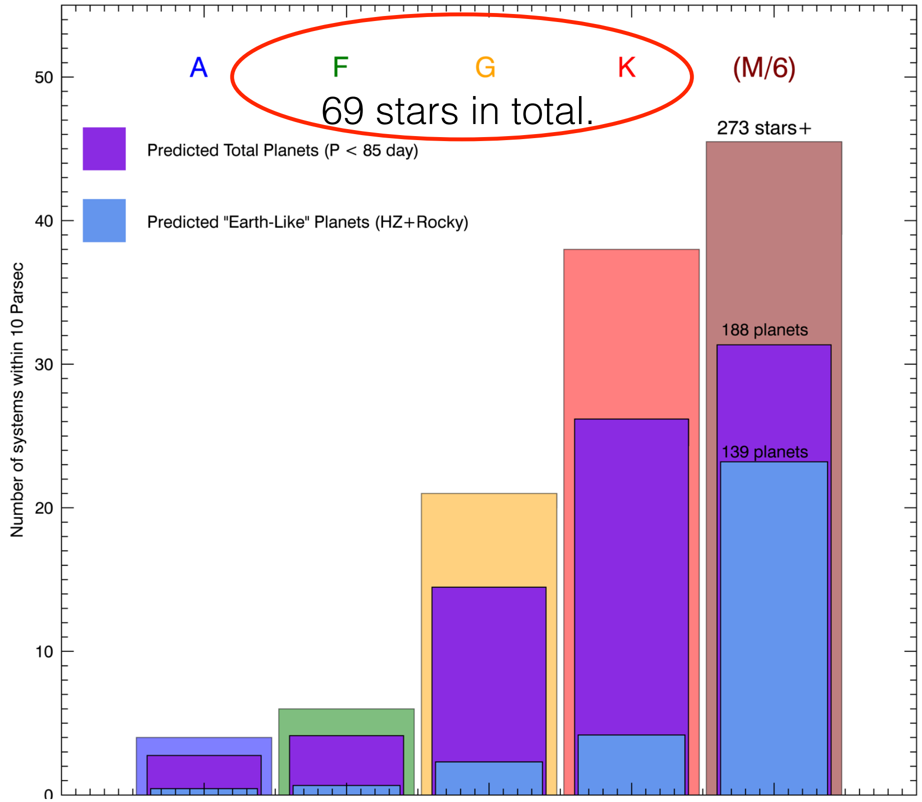


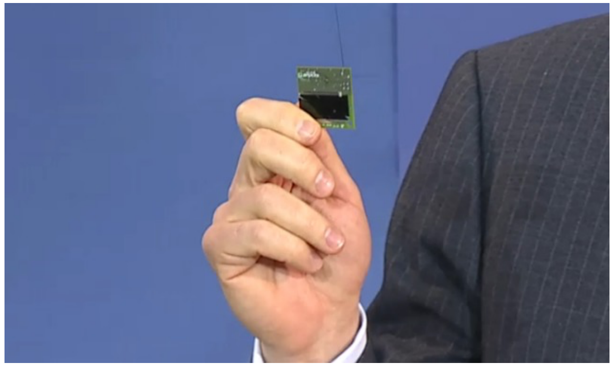
Image Credit: A. Riedel, T. Henry, and RECONS .



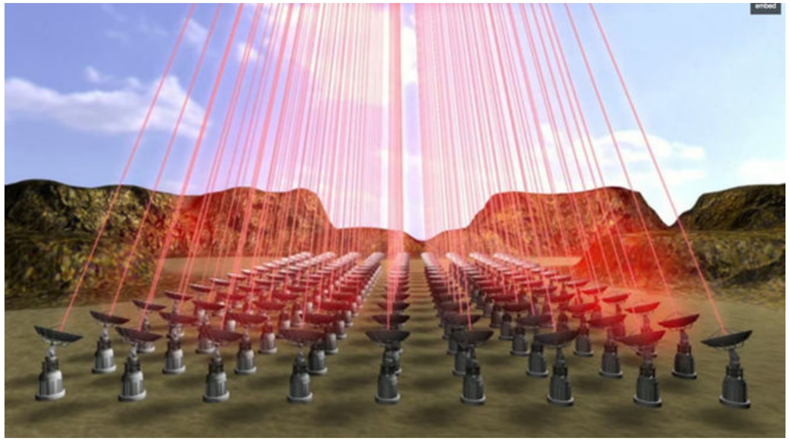
Breakthrough Starshot

Visionary goals drive immediate innovative technologies

Where are the planets within 5 Parsec? → Breakthrough Watch



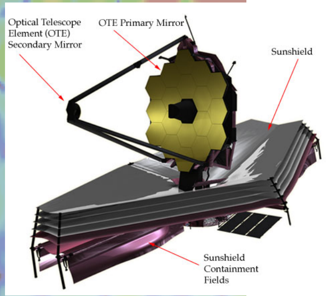


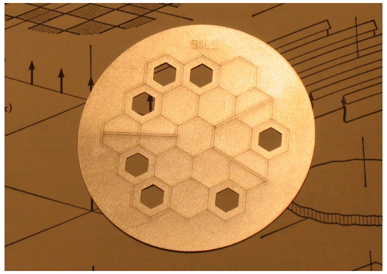


TOLIMAN: Status Summary

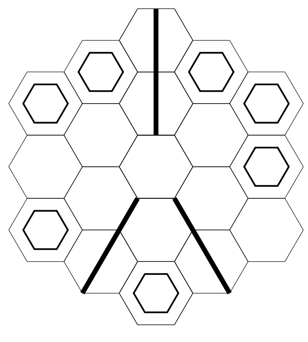
- $300K Foundational Mission Study (USyd/Breakthrough) underway
- Sydney: data/concept (full sims ongoing; paper in prep)
- Sydney: Astrophysical Noise Modeling (started)
- NASA AMES: Optical Testbed (ongoing)
- NASA JPL: detector characterization, possible flight metrology (TBD)
- Japan/JASMINE: Strong collaborative links and technology transfer
- Japan/AstroBiology Center: Established scientific partnership
- Italian Space Agency: strong interest in bus/launch.
- Actively seeking more partners

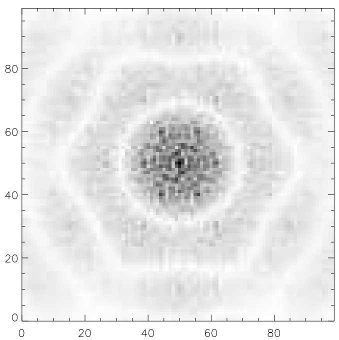
A modest precursor diffractive pupil mission 2020(ish...)

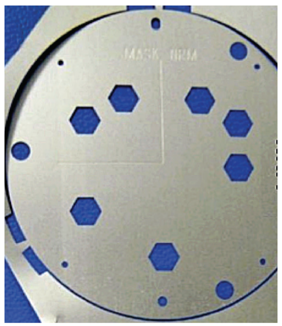


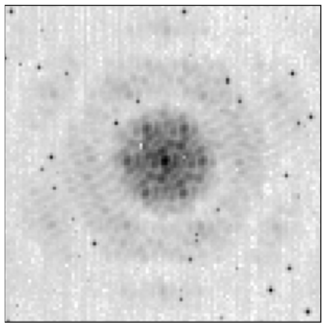


7-hole aperture masking mode NIRISS camera JWST-AMI mode.

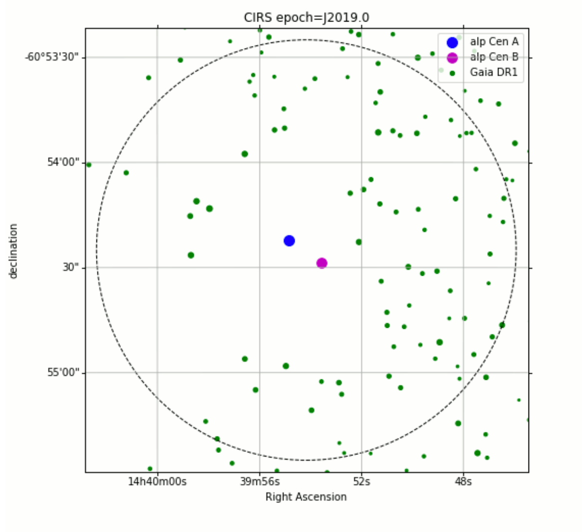




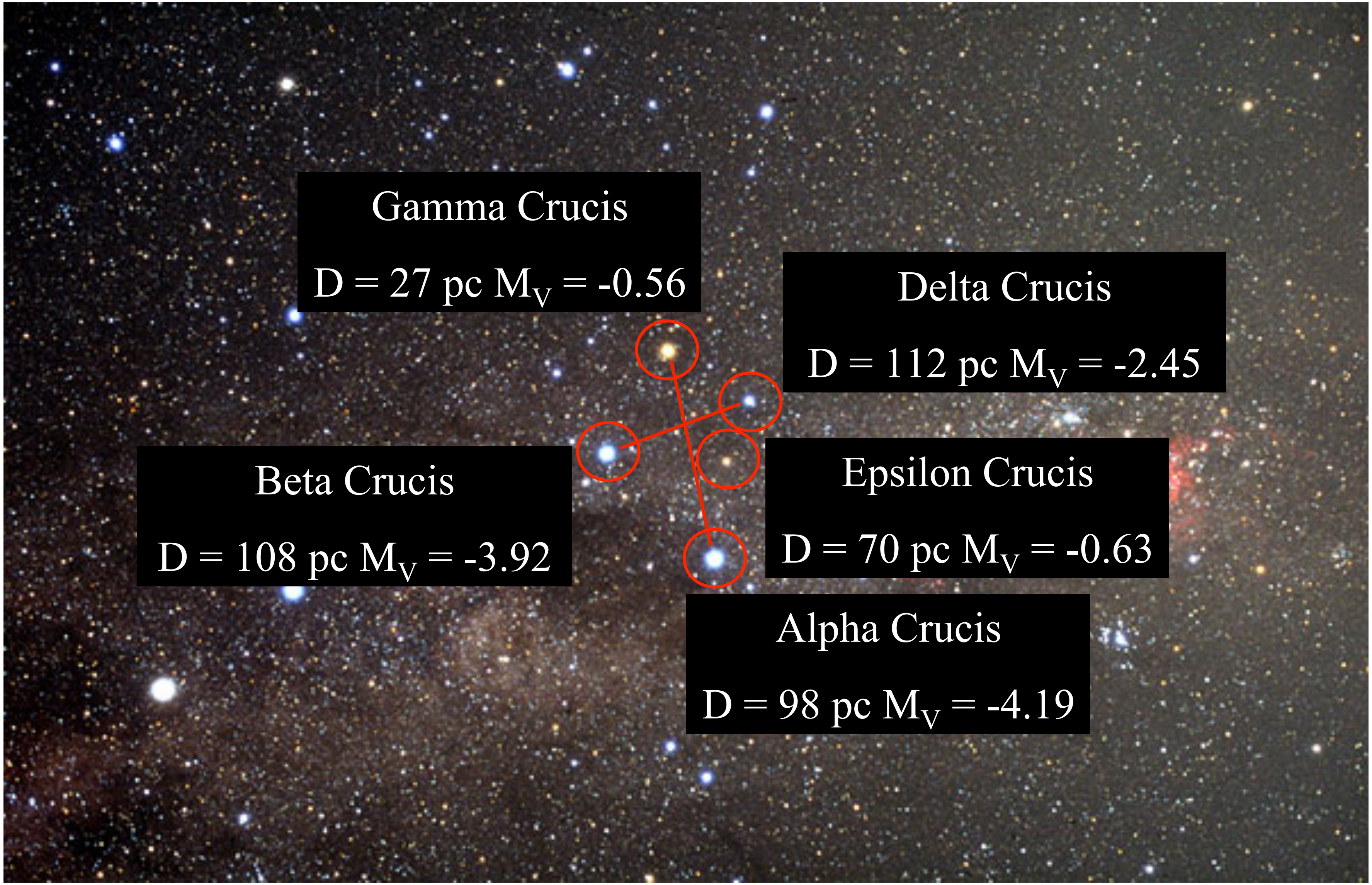




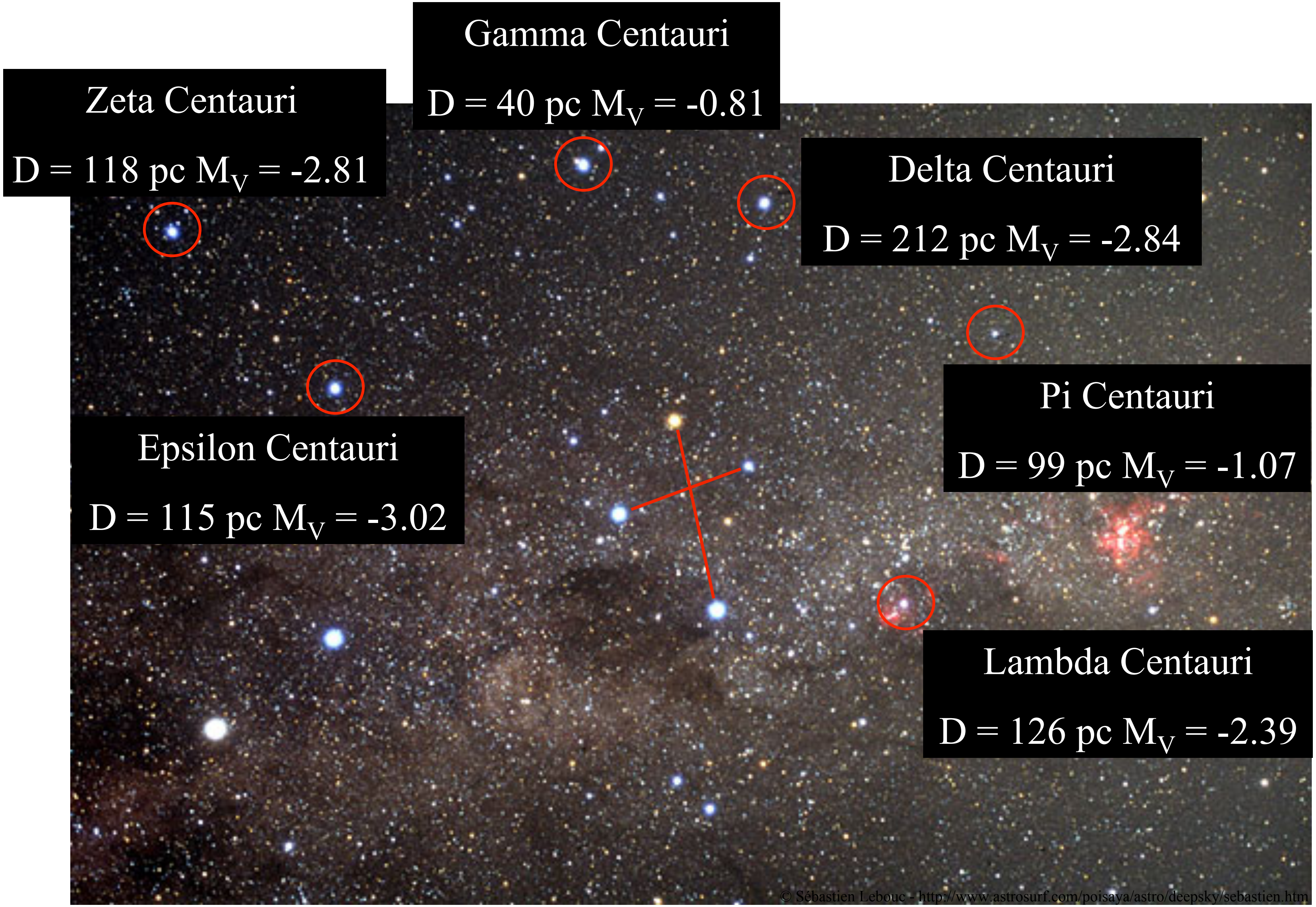
10-year movie of Alpha Cen (high proper motion) against the background field stars



Crux: The Southern Cross

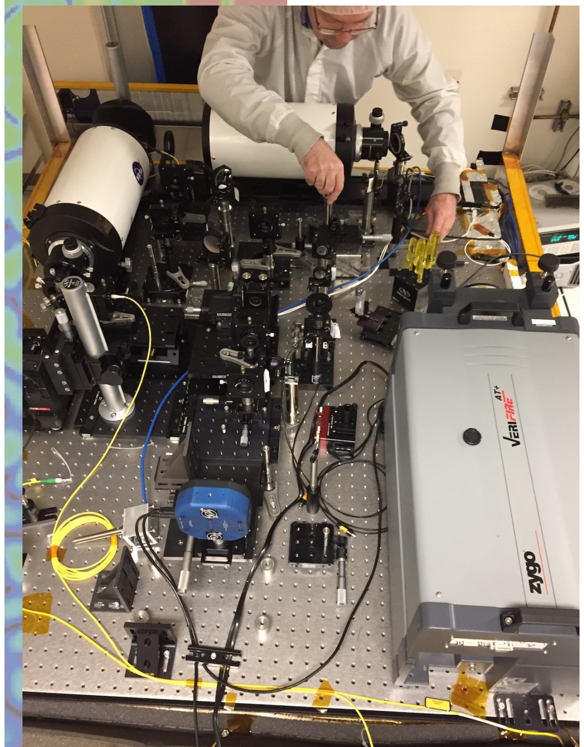


Centurus

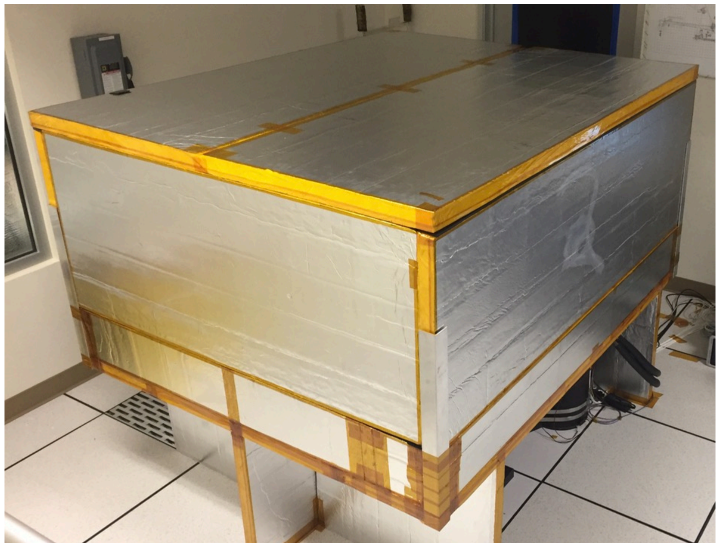

Gamma Centauri
D = 40 pc M$_V$ = -0.81
Zeta Centauri
D = 118 pc M$_V$ = -2.81
Delta Centauri
D = 212 pc M$_V$ = -2.84
Pi Centauri
D = 99 pc M$_V$ = -1.07
Epsilon Centauri
D = 115 pc M$_V$ = -3.02
Lambda Centauri
D = 126 pc M$_V$ = -2.39
© Sébastien Lebouc - http://www.astrosurf.com/poisaya/astro/deepsky/sebastien.htm

Next Steps: Optical Testbed (AMES)

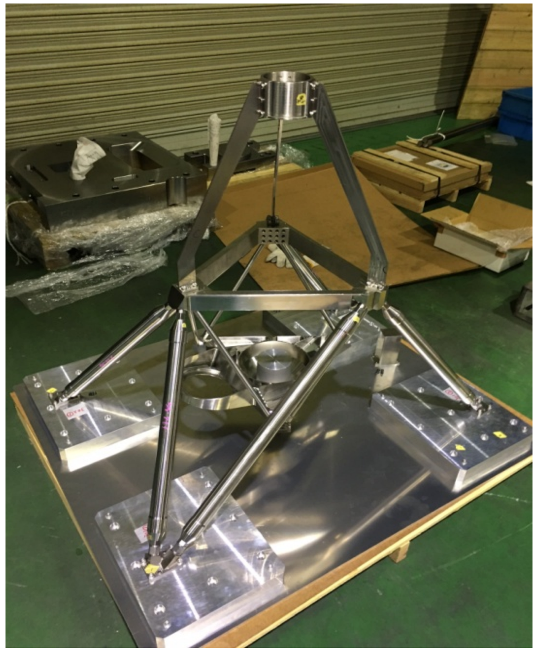
- Construct 10cm diffractive pupil testbed
- Validate algorithms and SNR of extracted astrometry with real lab data
- Impose optical errors and confirm that the Sydney code is able to recover precise system metrology from the diffractive fitting
- Confirm mechanical and thermal tolerancing
- Perform diffractive pupil stability tests on small-JASMINE testbed BBM (special Invar alloy with CTE less than 5×10^{-8})



Thermally stabilized optical testbed at AMES (1mK RMS drift over 24hrs)



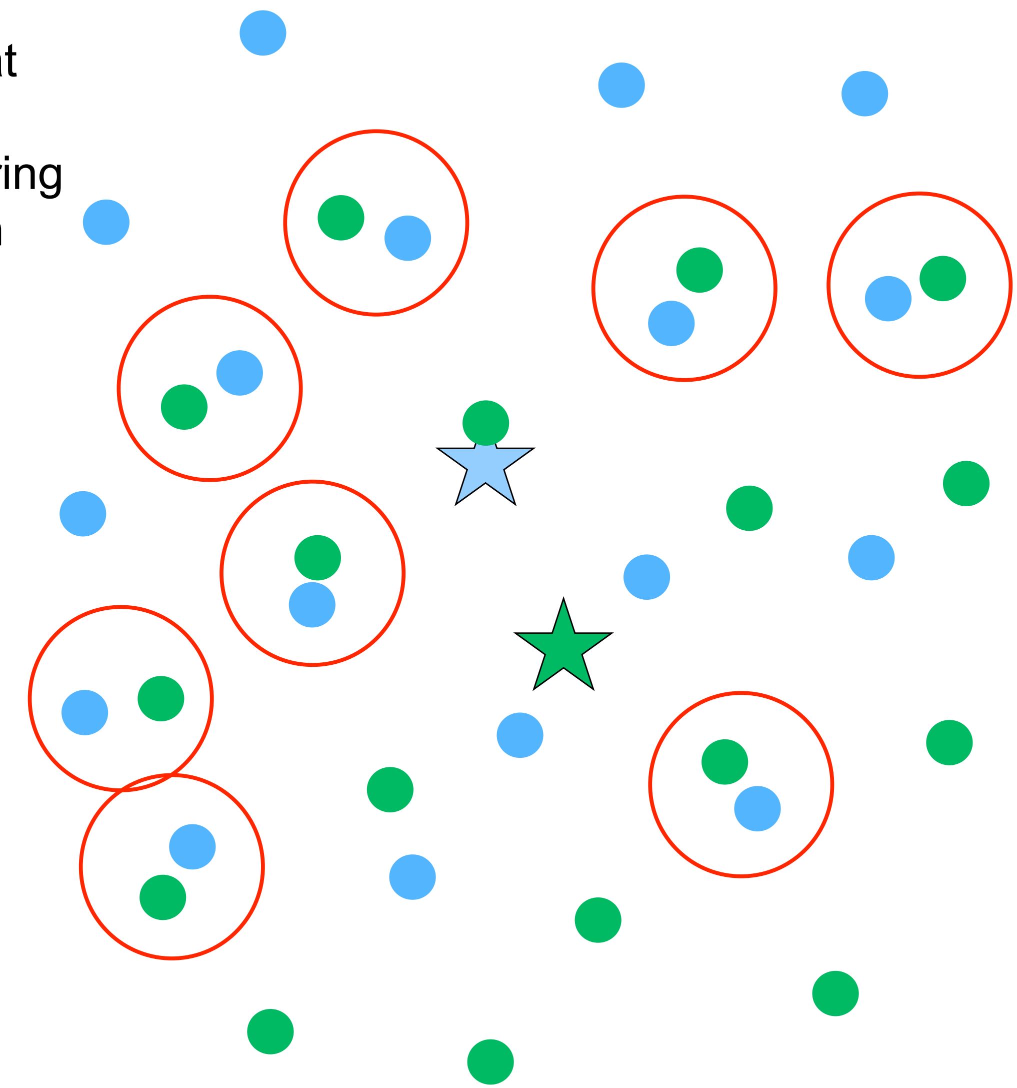
Small-JASMINE super-super-Invar BBM (photo courtesy Prof Gouda and JASMINE team)



How do Diffractive Pupils work?

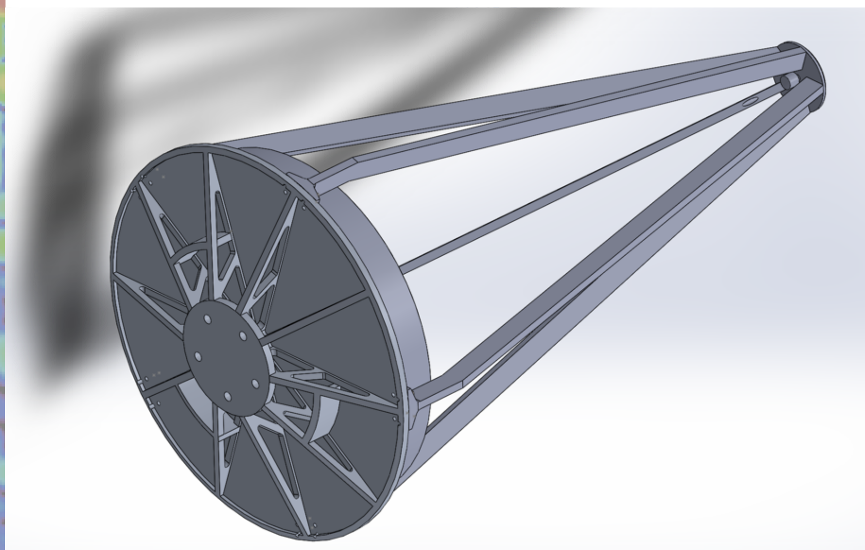
Simple picture: a binary star surrounded by bright speckles from a diffractive pupil

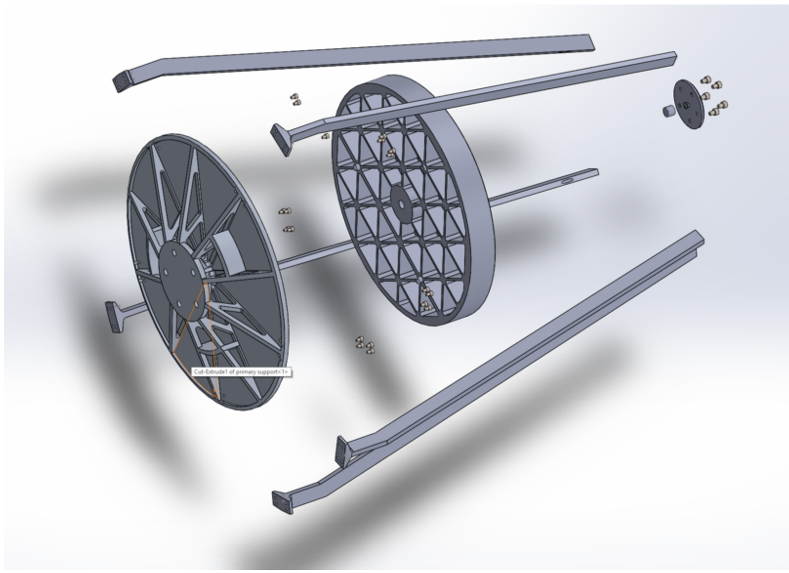
For the moment, only consider speckles that (by chance) are in a close pair of neighboring peaks, one from each star

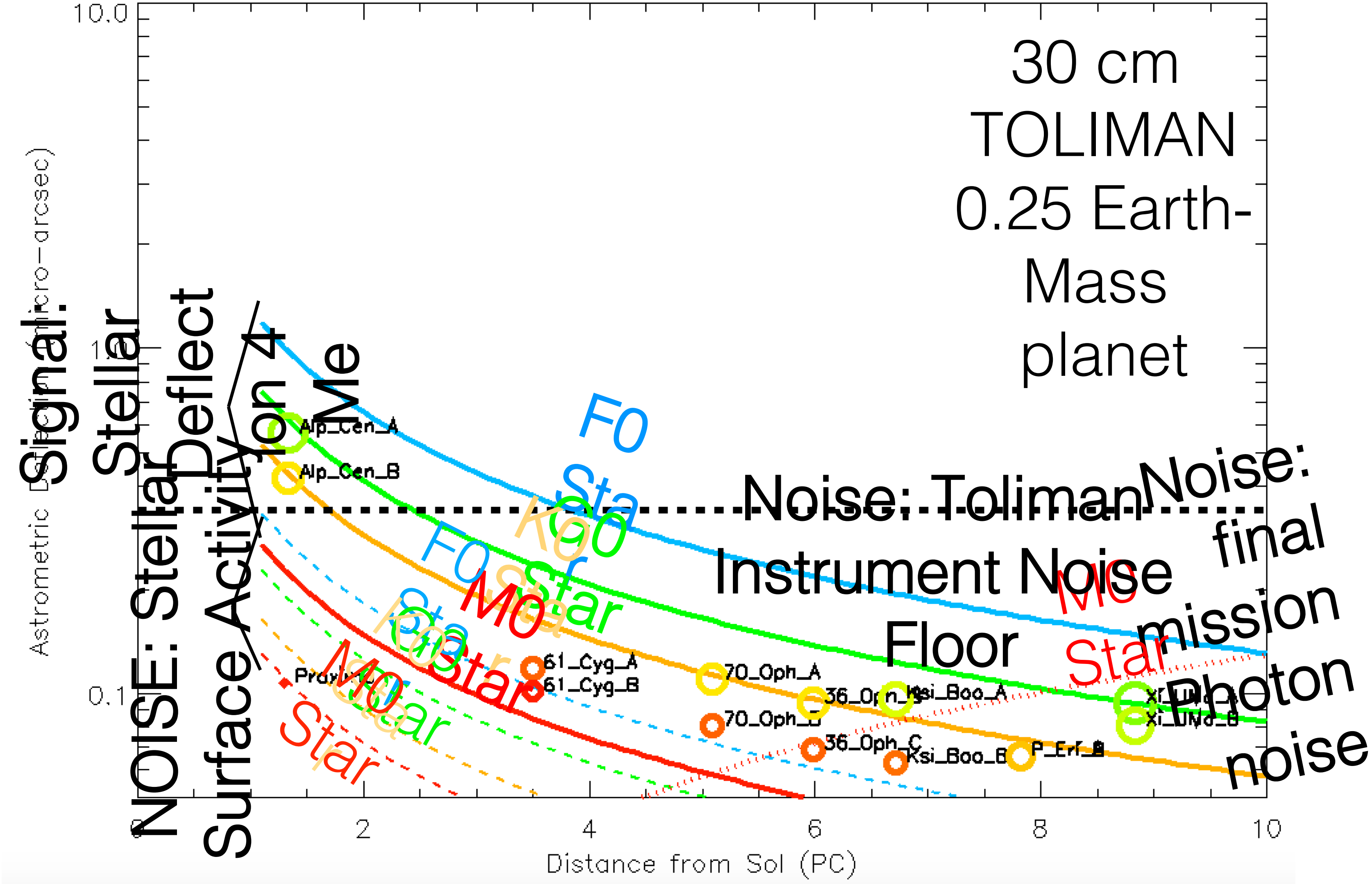


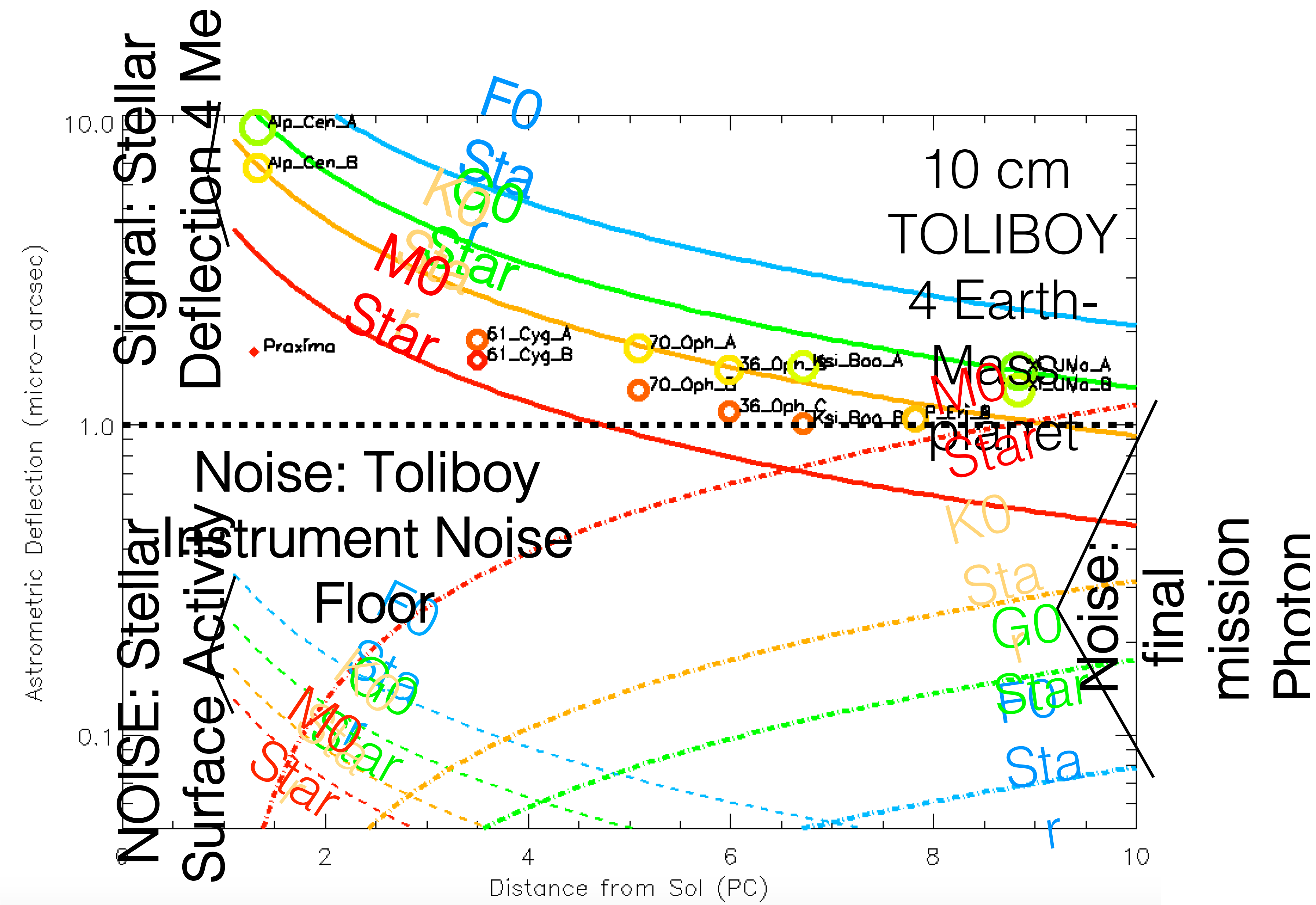
TOLIMAN: Straw-man outline

- Basic Specs
  - 5% fractional bandwidth in V band (Blue susceptible to starspots)
  - 30 cm telescope
  - Diffraction limit = 0.4 arcsec (astrometric signal is factor of 10^{-6})
  - Thermally stable telescope
  - D-D pupil etched on 30cm SiC primary, 2-mirror R-C 2 at about f50
  - 3 year+ mission
  - Orbit: Ideal is GEO, but cost trades may drive LEO if thermally stable





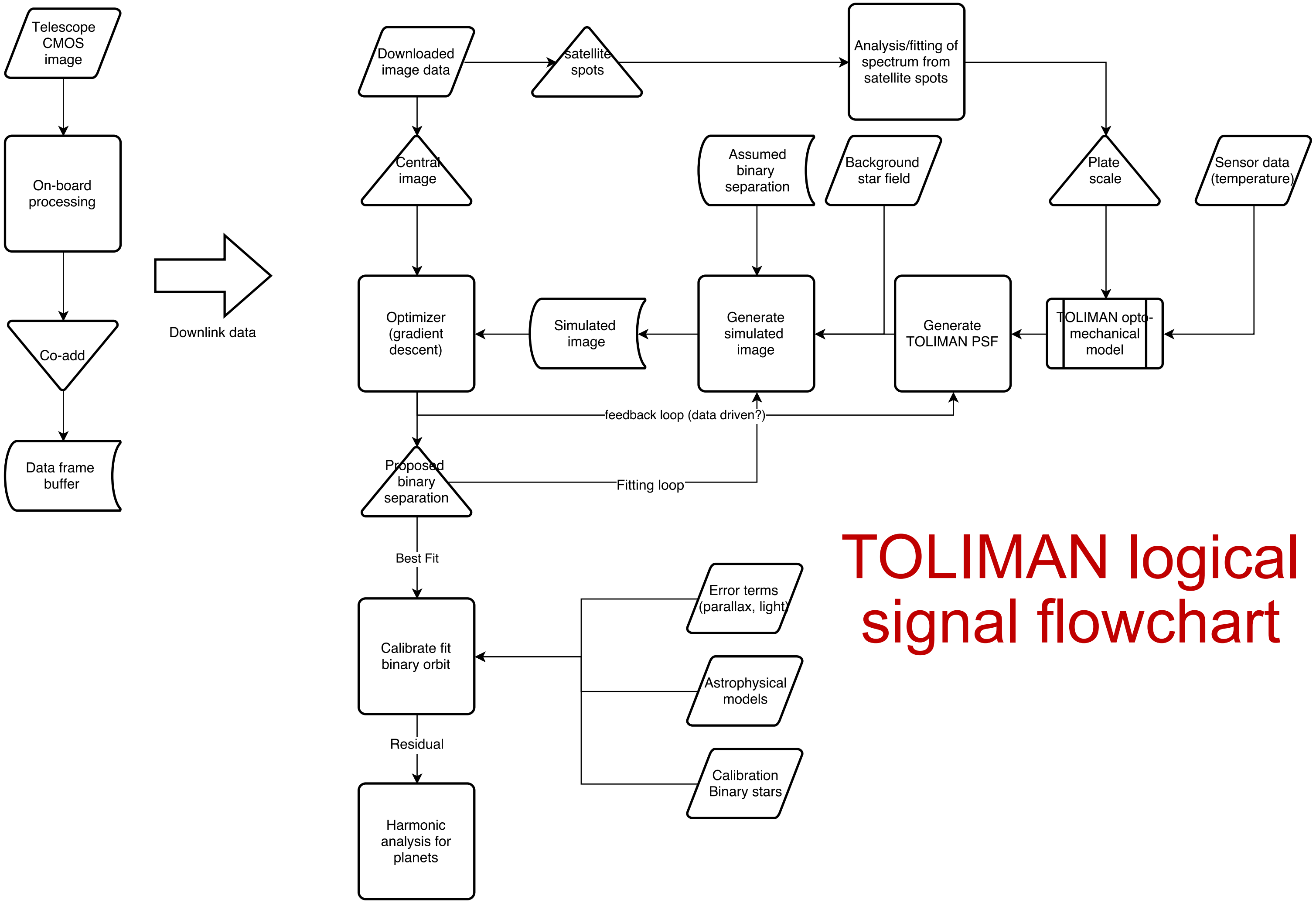

30 cm
TOLIMAN
0.25 Earth-
Mass
planet
Noise: Toliman
Instrument Noise
Floor
Noise:
final
mission
Photon
noise
Signal:
Stellar
Deflect
ion 4
Me
NOISE: Stellar
Surface Activity
F0
Sta
G0
M0
Star
Alp_Cen_A
Alp_Cen_B
61_Cyg_A
61_Cyg_B
70_Oph_A
70_Oph_B
36_Oph_C
Ksi_Boo_A
Ksi_Boo_B
10.0
1.0
0.1
2
4
6
8
10
Distance from Sol (PC)
Astrometric



10 cm
TOLIBOY
4 Earth-Mass planet
Signal: Stellar Deflection 4 Me
Noise: Toliboy Instrument Noise Floor
NOISE: Stellar Surface Activity
Noise: final mission Photon
F0 Star
G0 Star
K0 Star
M0 Star
Alp_Cen_A
Alp_Cen_B
Proxima
61_Cyg_A
61_Cyg_B
70_Oph_A
70_Oph_B
36_Oph_A
36_Oph_C
Ksi_Boo_A
Ksi_Boo_B
Eps_Eri_B
Xi_UMa_A
Xi_UMa_B
Astrometric Deflection (micro-arcsec)
Distance from Sol (PC)
10.0
1.0
0.1
0
2
4
6
8
10

Next Steps: Algorithms (Sydney)

- Complete fitting loop to verify recovery of astrometric signals
- Generate full error budget
- Trade studies for varying design terms
- Assessment of impact of astrophysical noise terms



TOLIMAN logical signal flowchart

The Challenge