Basics of Long-Baseline Optical Interferometry

A Gentle Introduction

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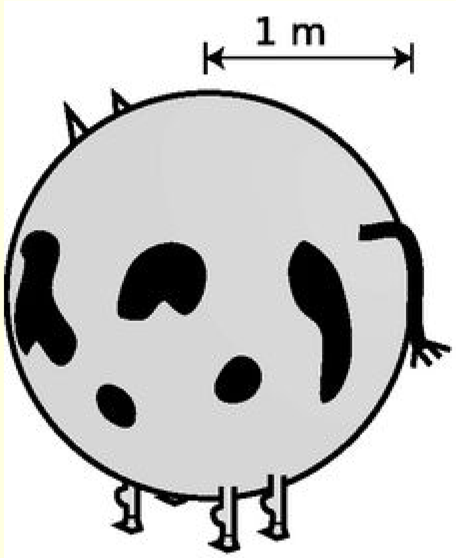
Caveat Emptor

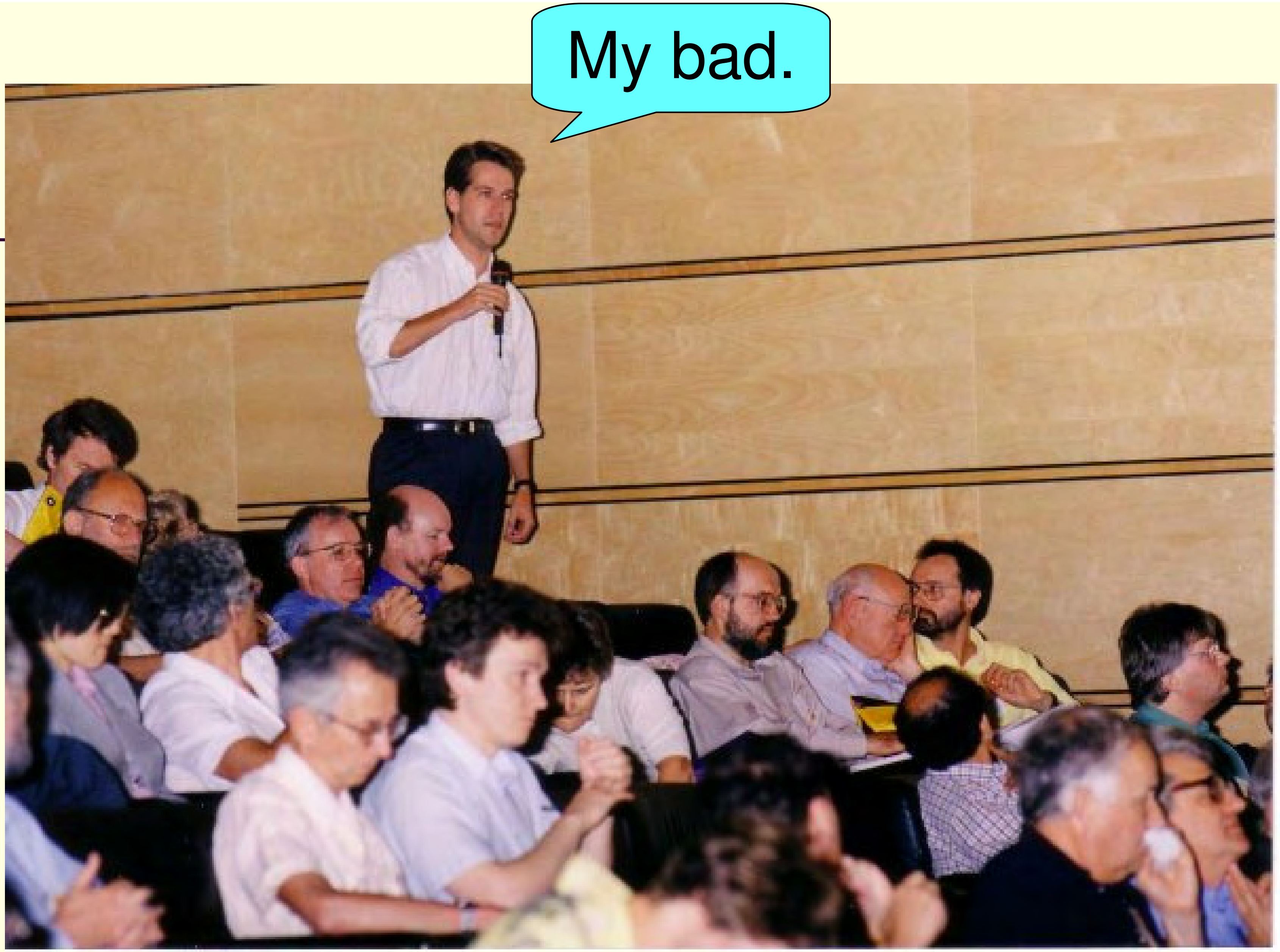
- A number of ***assumptions*** will be made herein
- A number of ***simplifications*** will be made herein
- And I'll probably make a few outright errors, which I will attempt to cover up with an aura of smug self-confidence
  - Feel free to poke at that during Q&A

Example Astronomer Simplification:



Cows are, to zeroth order, spherical in shape.

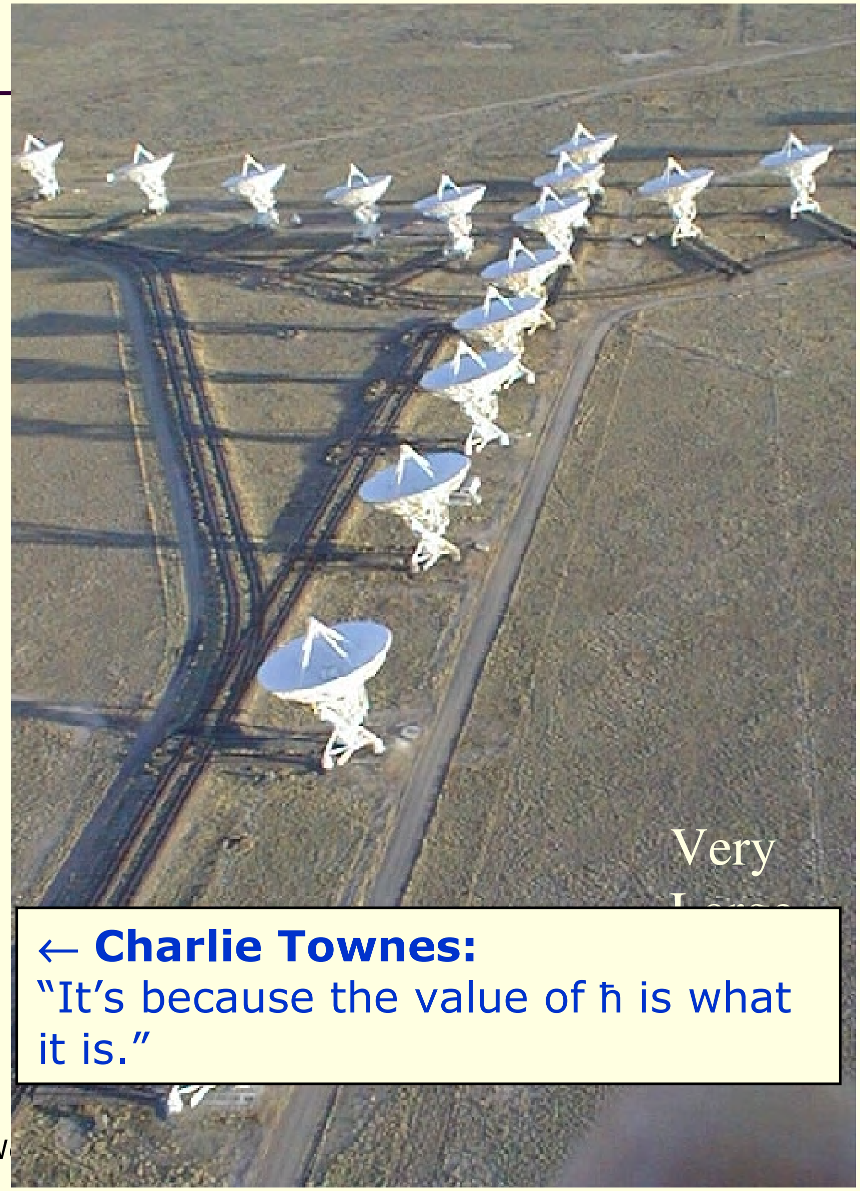
[We will see, shortly, how patently false this is]



IAU 191, Montpellier France, 27 Aug – 1 Sep 1998

Interferometric Arrays

- Use multiple telescopes as a single telescope
- Break the resolution limit without breaking the bank
- This is *not* a talk about radio interferometry
  - Things are much more difficult in the visible
  - Radio: **Detect-and-mix**
  - Optical: **Mix-and-detect**



← **Charlie Townes:**
"It's because the value of ħ is what it is."

Don’t Panic

- I only have a brief time slot here
- For more in-depth reviews, see summer school proceedings
  - If you have a burning desire to hear the phrase ‘van Cittert-Zernike theorem’
- Emphasis on practical knowledge
  - What do I need to know to critically read a paper?

IAU Commission 54:
http://iau-c54.wikispaces.com/

After all, it's not like we're doing particle physics

The Standard Model Lagrangian

(Please memorize for later)

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \\
& \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \\
& \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
& \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - \\
& A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + \\
& H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + \\
& 2(\phi^0)^2 H^2] - g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \\
& \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \\
& \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
& \tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \\
& \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - \\
& W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \\
& \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \\
& \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - \\
& 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
& \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1+\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \\
& \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \\
& \gamma^5) d^\kappa_j) + m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
& \gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + \\
& i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

http://www.math.fsu.edu/~marcolli/SMtalkVU.pdf

Thought #1: Why Do I Care?

Interferometry is Inevitable

Stars are Small

(Back of the envelope)

- Use the sun as our prototype
- Solar vs. bright star apparent brightness:

$$V_\Theta - V_* = -2.5\log\left(I_\Theta / I_*\right)$$

$\rightarrow$ 2.5 × 10^{10} change in apparent brightness

- Since brightness scales with disk area:

$$\frac{I_\Theta}{I_*} = \frac{A_\Theta}{A_*} = \frac{\omega_\Theta}{\omega_*} = \left(\frac{\theta_\Theta}{\theta_*}\right)^2 \rightarrow \theta_* = \theta_\Theta \times \sqrt{I_*/I_\Theta}$$

Since the sun is ~30' $\rightarrow$ θ_* = 12 mas

- Realized by Newton

Really High Resolution Stellar Observations

- Best example: observations of the sun
  - Roughly 1,000,000× closer than any other star
  - SOHO observations of the Sun
- Interesting structure
  - Sun spots
  - Phlages
  - Prominences
  - Mass ejections
- Interactions with the surrounding environment
- Wish to extend these observations to other stars
  - Conversely, other stars will inform us about the sun

Exoplanet Angular Sizes
(Back of the envelope)

- Use the earth as our prototype
  - ~12,700km diameter
- Distance?
  - Kepler – *"All stars have planets"*
  - So, for a reasonable sample, say 10pc
- Thus, roughly 10μas in size
- So for 10×10 pixels, need 1μas resolution
  - Keck (J-band): $1.22^{\lambda}/_{d} \approx$ 30mas
  - Need to increase *d* by 30,000× → ~30km!

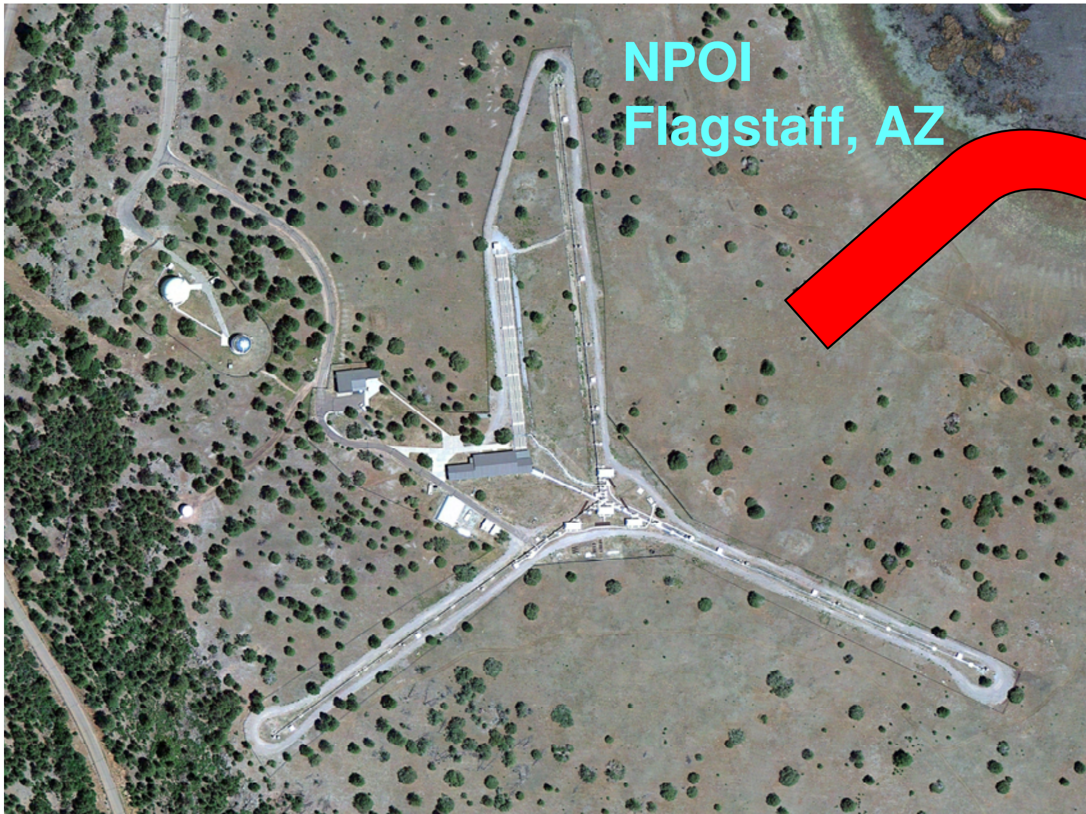
Interferometry: 'Silver Bullet Science'

- A very good analogy
  - Very expensive
  - Very hard to get to work
  - But, it gets results that are otherwise impossible
- And it's kind of magical

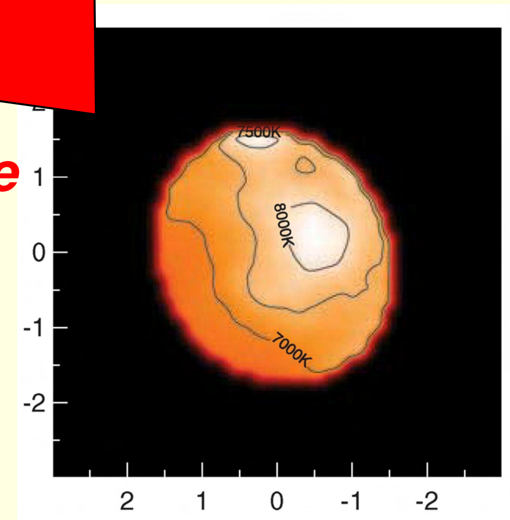
Interferometry: ‘Silver Bullet Science’

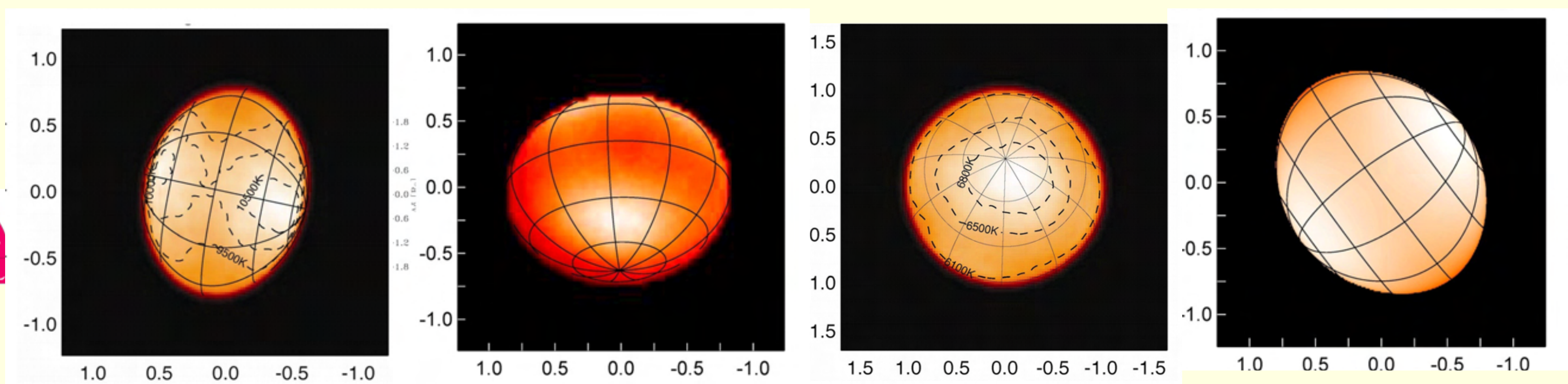
- Not something for everyone – sacrifices are made
  - Interferometers aren’t very sensitive
  - Interferometers don’t make ‘pretty pictures’
- But occasionally you have a werewolf to deal with
  - What’s an example?

The Short Version



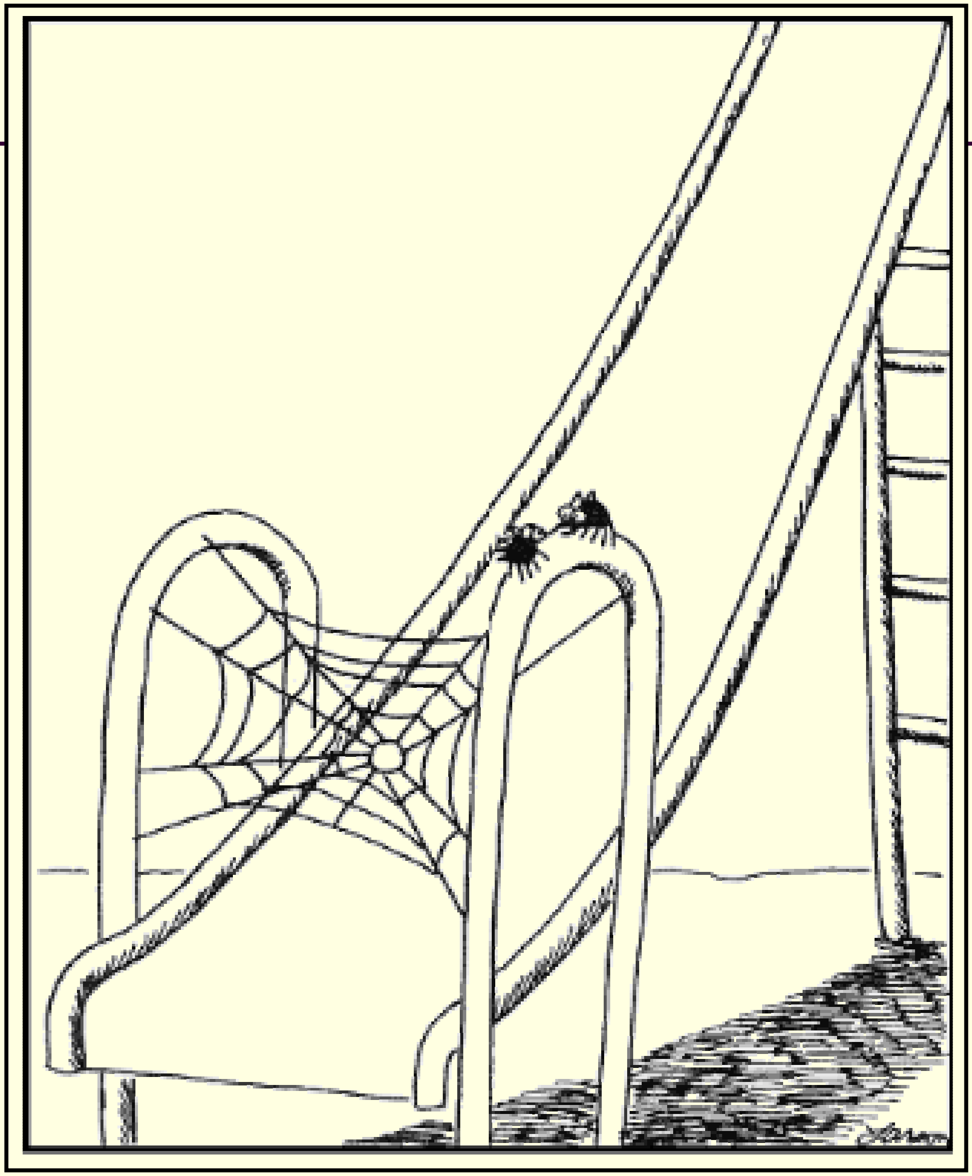
A Miracle Occurs





CHARA-MIRC Images of Rapid Rotators

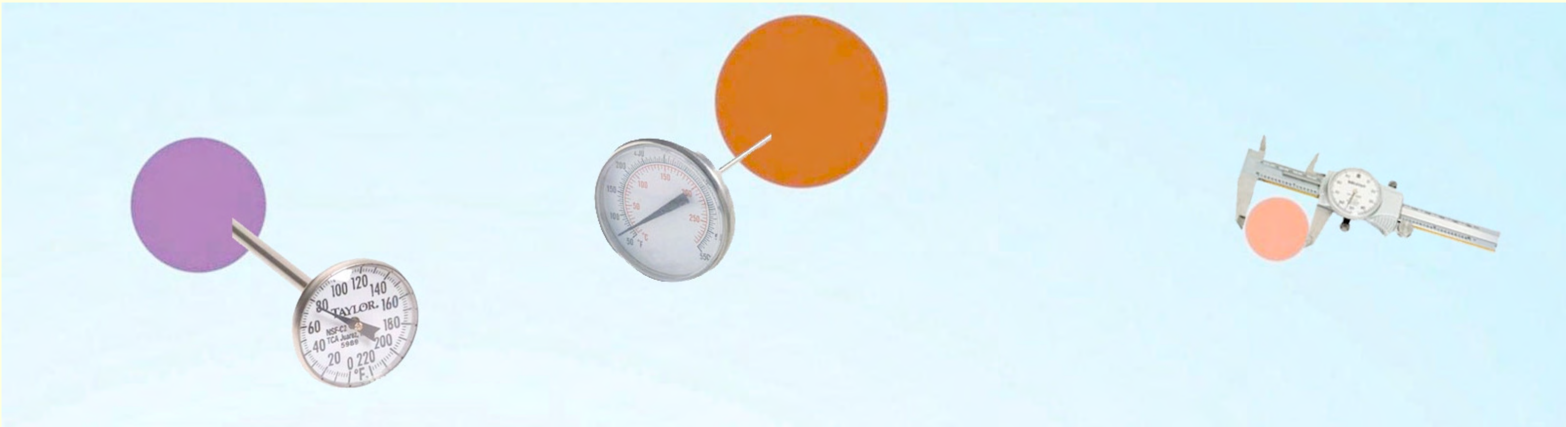
What Interferometers *Really* Look Like



"If we pull this off, we'll eat like kings."

Angular Sizes: How are they Useful?

- By measuring the contrast of fringes, we *directly* measure the angular size of a star
  - If we know the distance to a star, we get its **linear size** (*R*)
  - If we know the brightness of a star, we get its **temperature** (*T*)
- Interestingly enough, these fundamental parameters are often very hard to directly measure
- The key here is ‘directly’
  - Astronomers often guess their way to *R* and *T*
  - But the guesses needed to be tested



Fundamental Parameters from Angular Sizes

- **Linear Size**

$$R = \pi\theta$$

(the real trick here is determination of π)

- **Effective Temperature** – from *definition* of luminosity

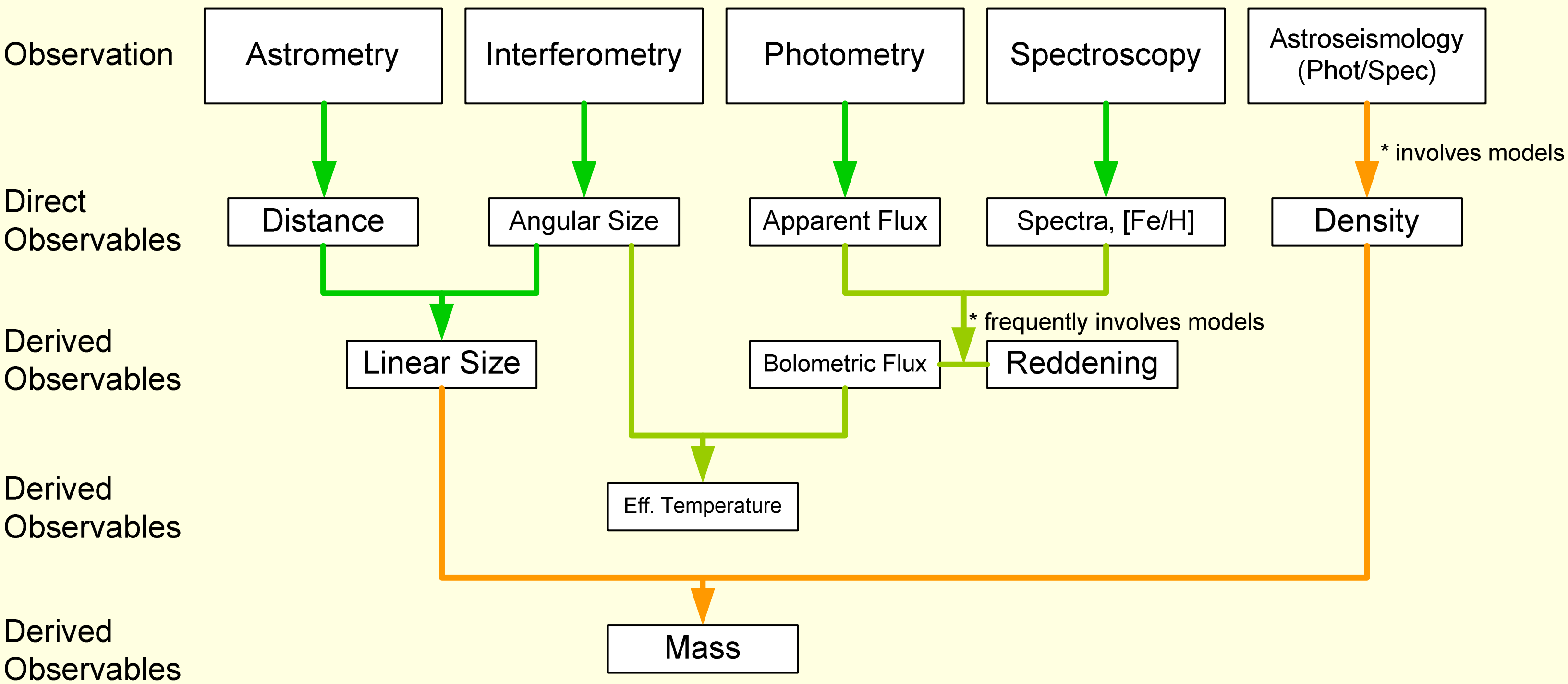
$$L = 4\pi\sigma R^2 T_{\mathrm{EFF}}^2$$

we can divide out distance and get

$$T_{\mathrm{EFF}} \propto \left(\frac{F_{\mathrm{BOL}}}{\theta^2} \right)^{1/4}$$

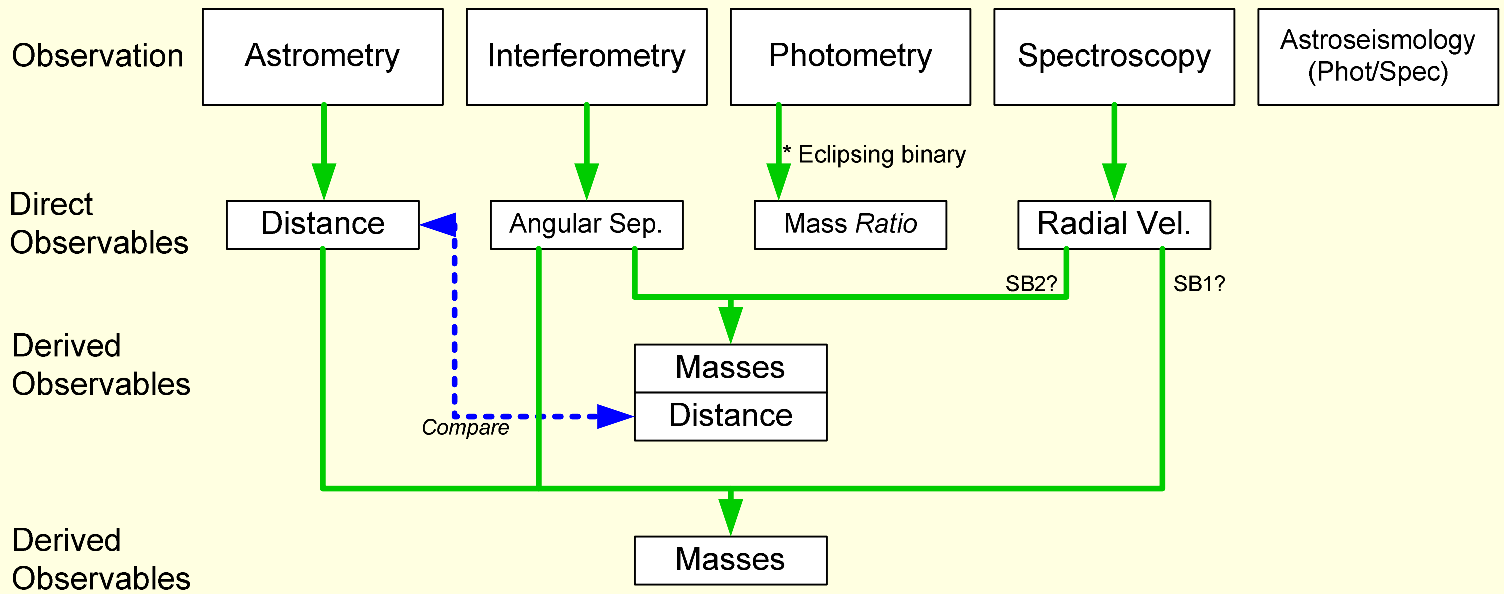
(the real trick here is determination of F_{BOL})

Tree of Fundamental Parameters: Single Stars



Green = Empirical
Red = Contaminated by models

Tree of Fundamental Parameters: Binary Stars



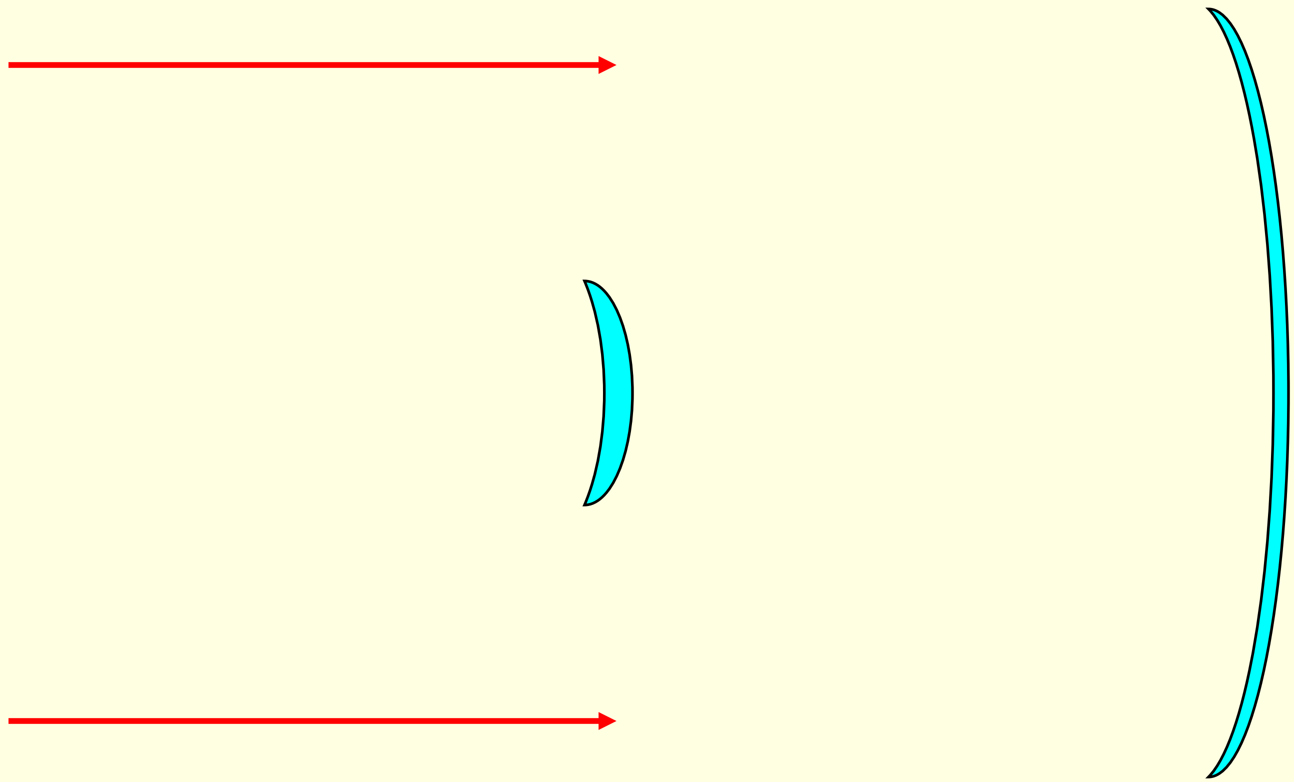
Green = Empirical
Red = Contaminated by models

Thought #2:
All Telescopes are Interferometers

This is meant to make you feel better

The Telescope: What's Happening Inside?

- Our parallel rays enter and bounce around – **in a very special way**



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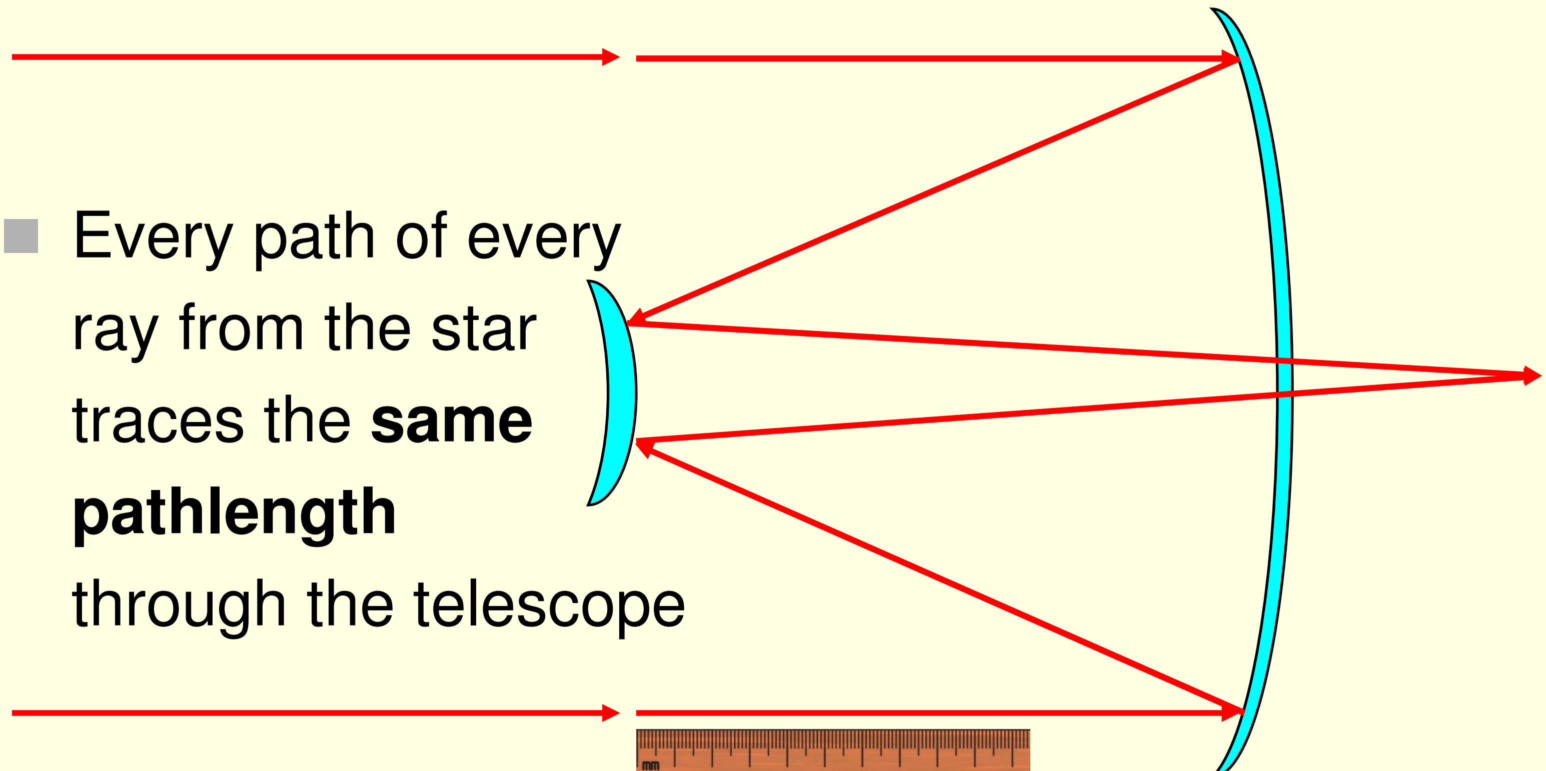
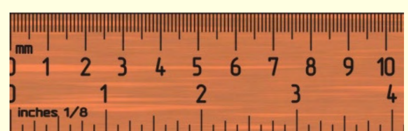


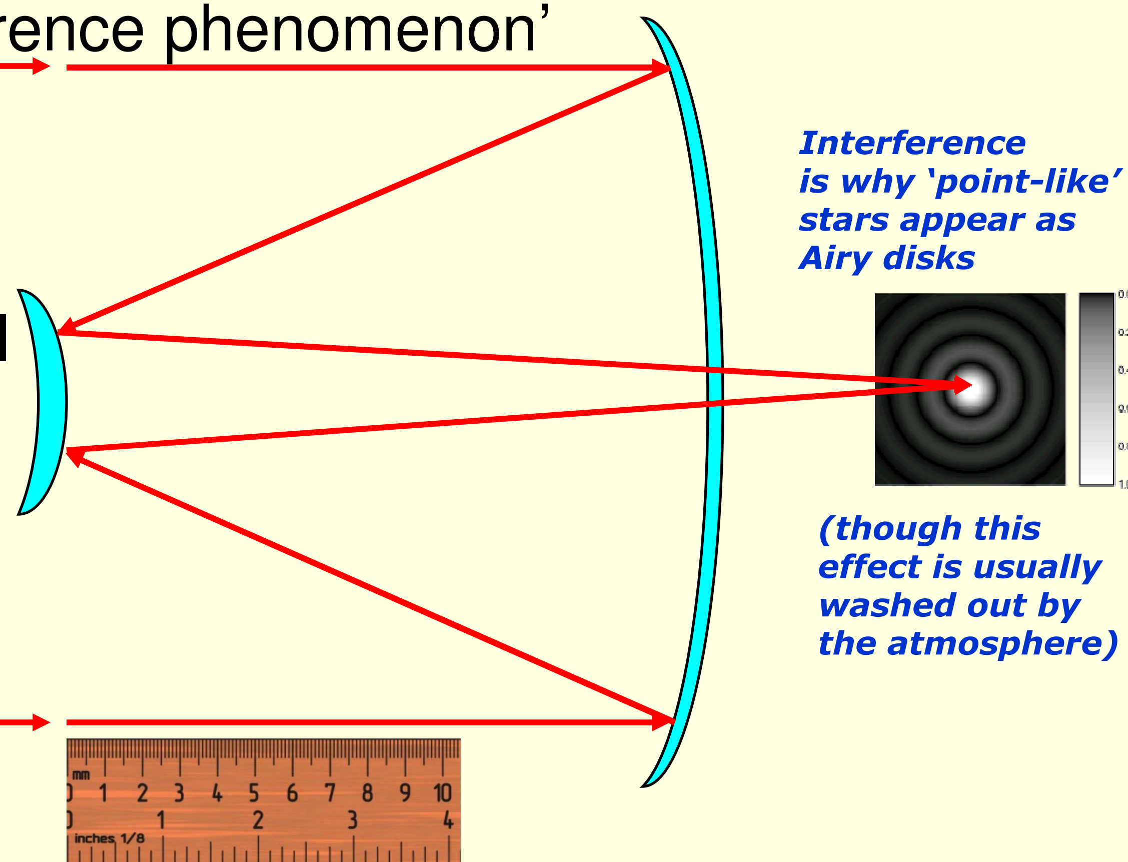
- Every path of every ray from the star traces the **same pathlength** through the telescope



The Telescope: What's Happening Inside?

- When light rays from a source satisfy this pathlength condition, the can form an image
- This is an 'interference phenomenon'

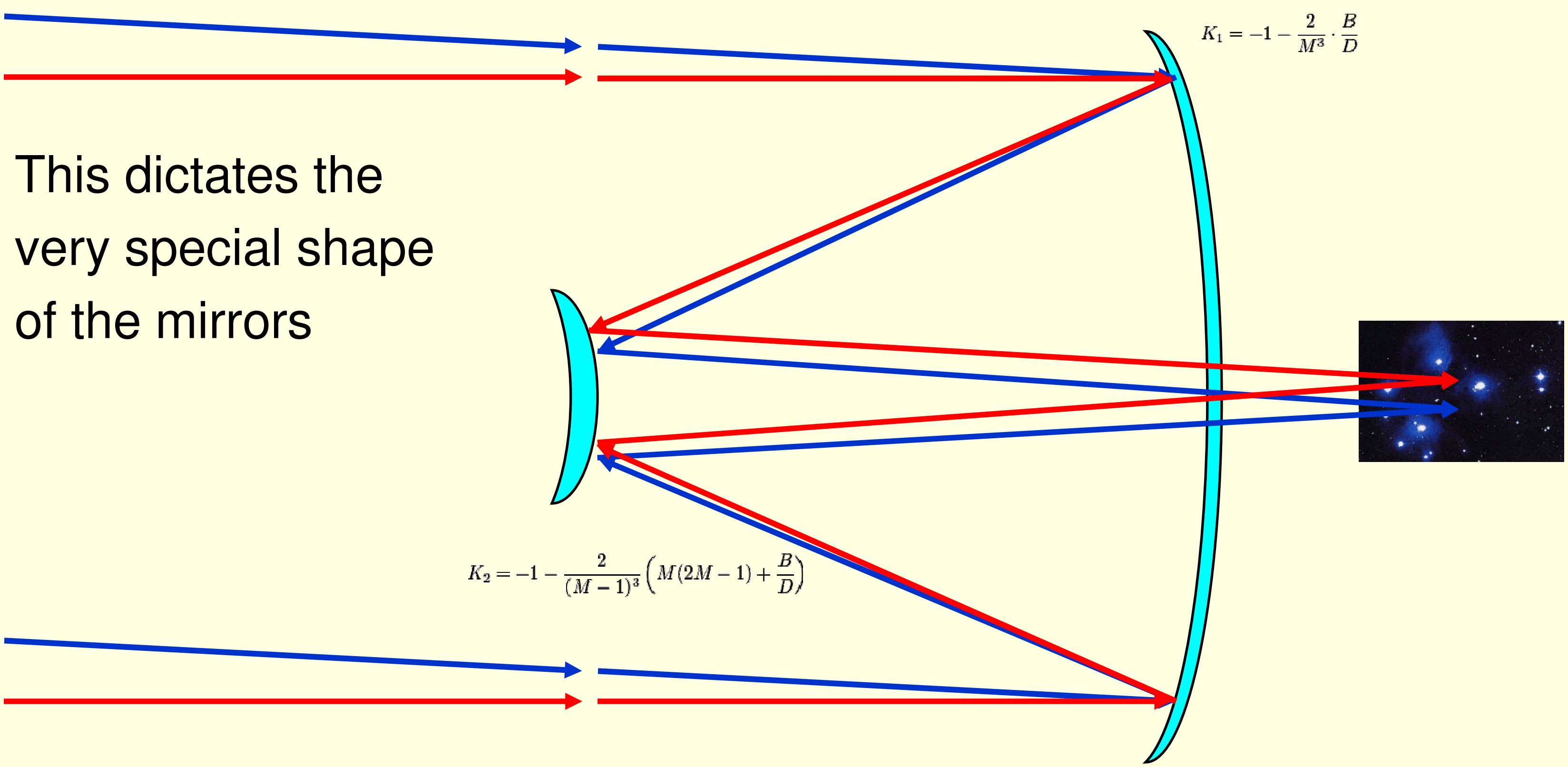
  (more on this later)
- Special secret: **all telescopes are interferometers**



The Telescope: What's Happening Inside?

- This **pathlength condition** is true for other nearby stars in the field of view of the telescope, at slightly different angles

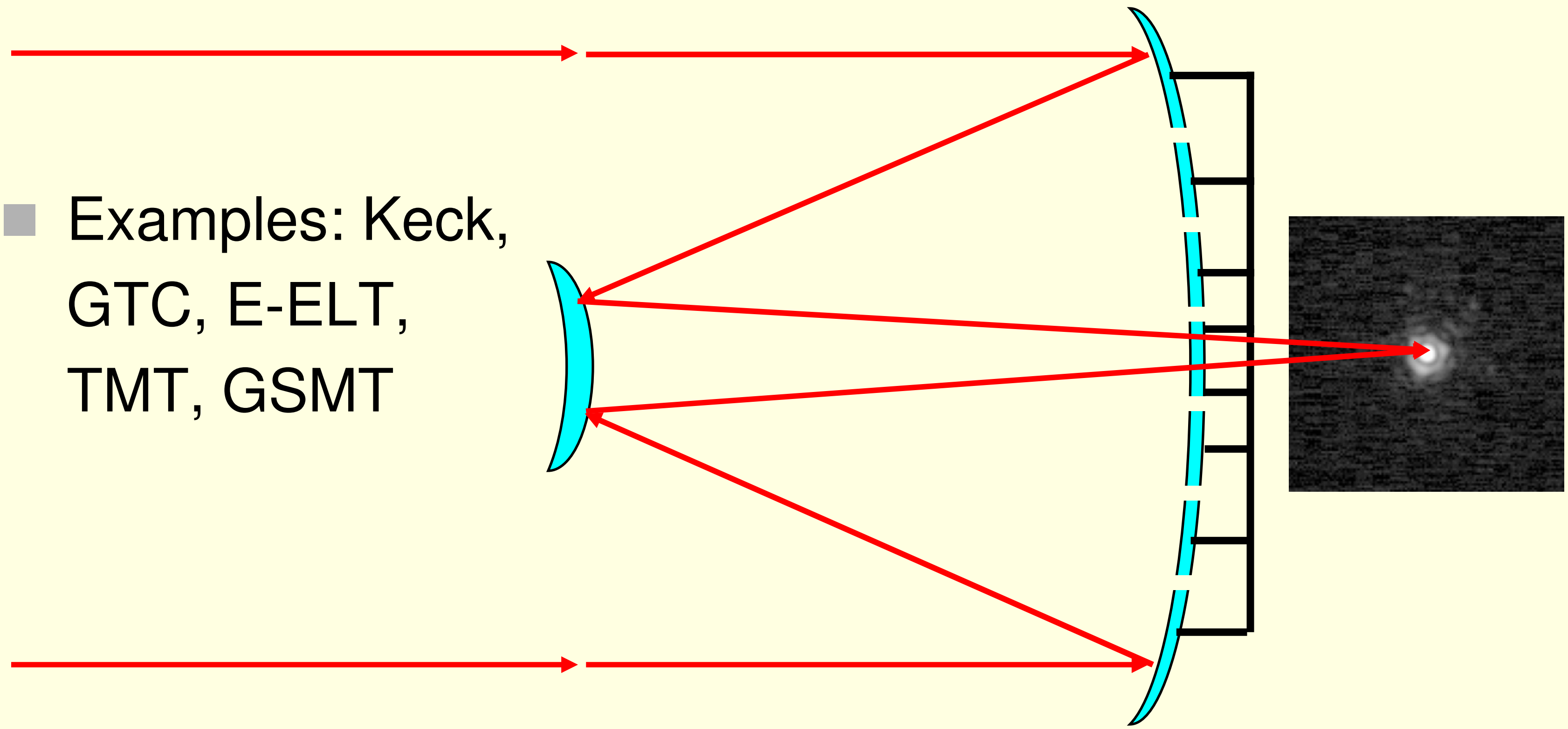
- This dictates the very special shape of the mirrors



In the Pursuit of Clever (at the risk of Stupid)

- Here’s a neat trick: satisfy the pathlength condition with separate pieces of glass for your primary mirror

- Examples: Keck, GTC, E-ELT, TMT, GSMT

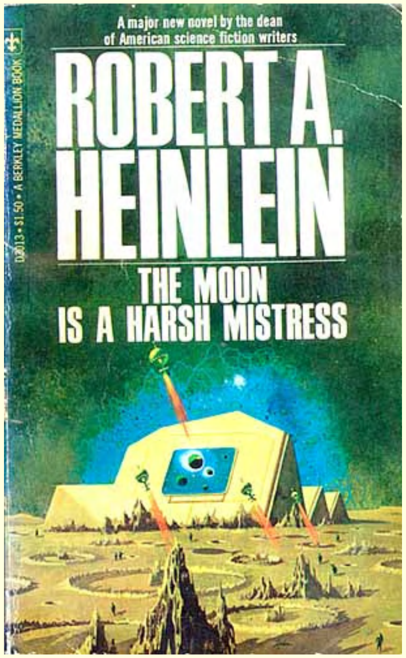


Thought #3: Interferometers Have Unbelievable Amounts of Resolution

This comes at a price

Food for Thought

"There ain't no such thing as a free lunch"[1] – R. A. Heinlein



[1]Often abbreviated as TANSTAAFL, from *The Moon is a Harsh Mistress*, 1966

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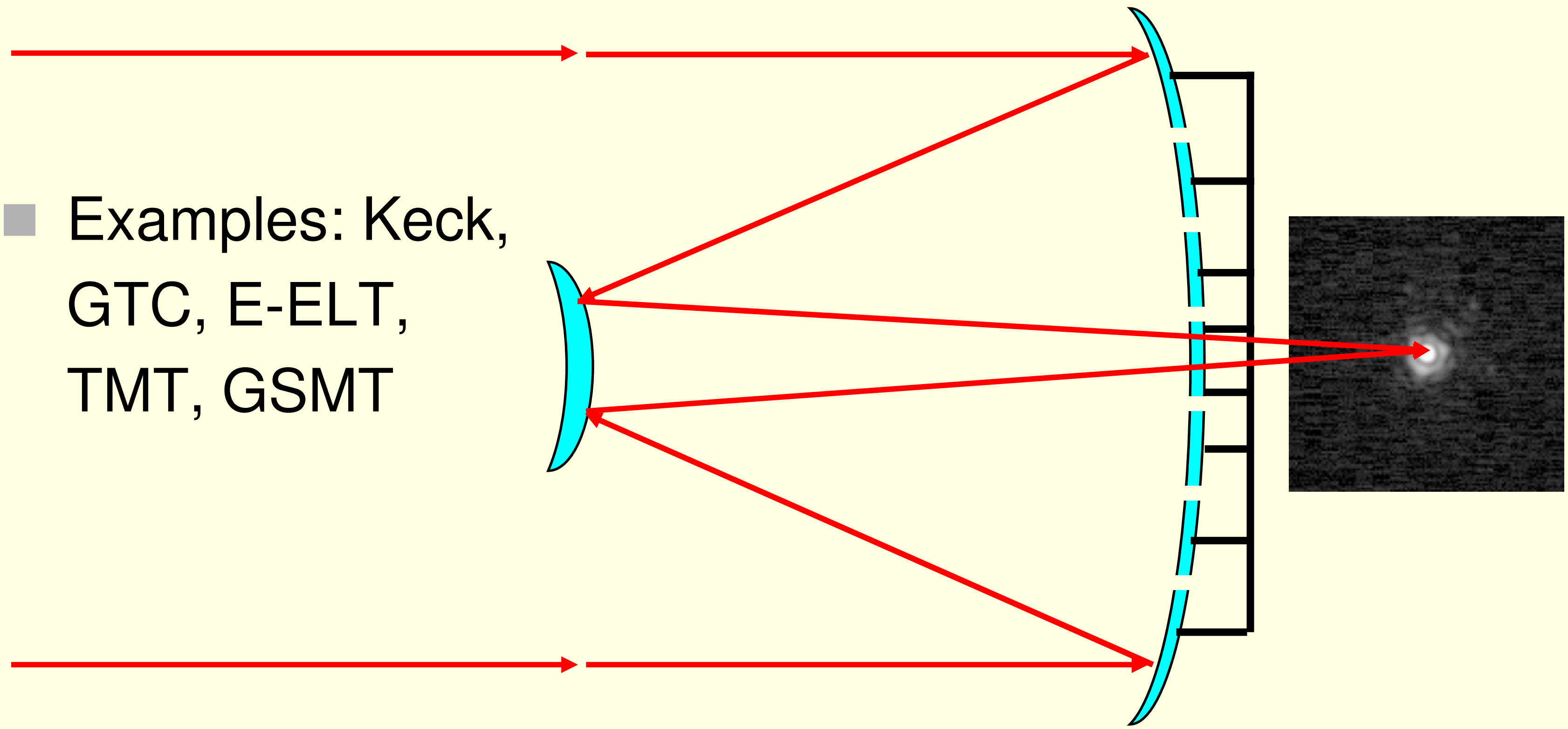
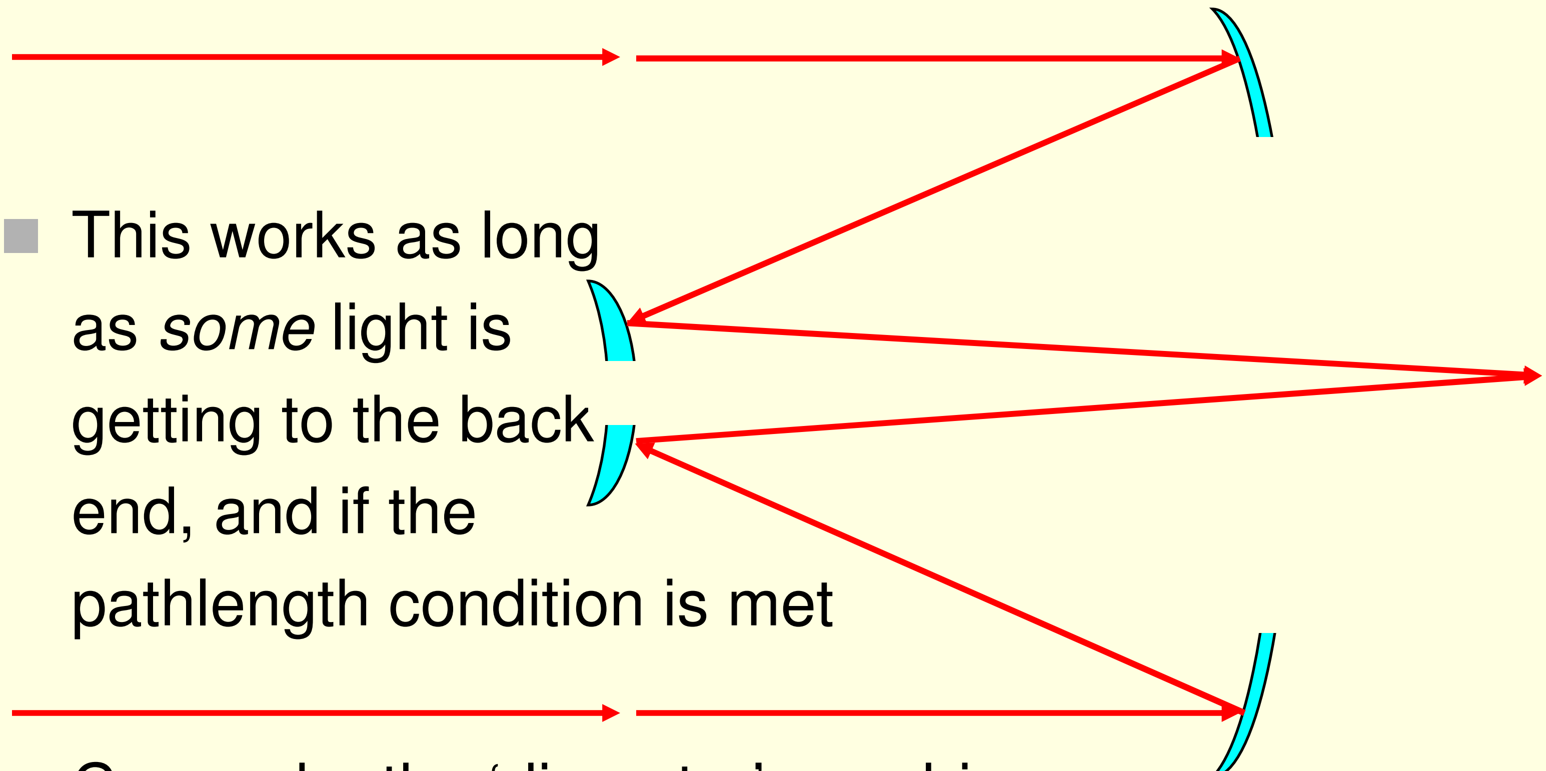


Cracking the Resolution Problem

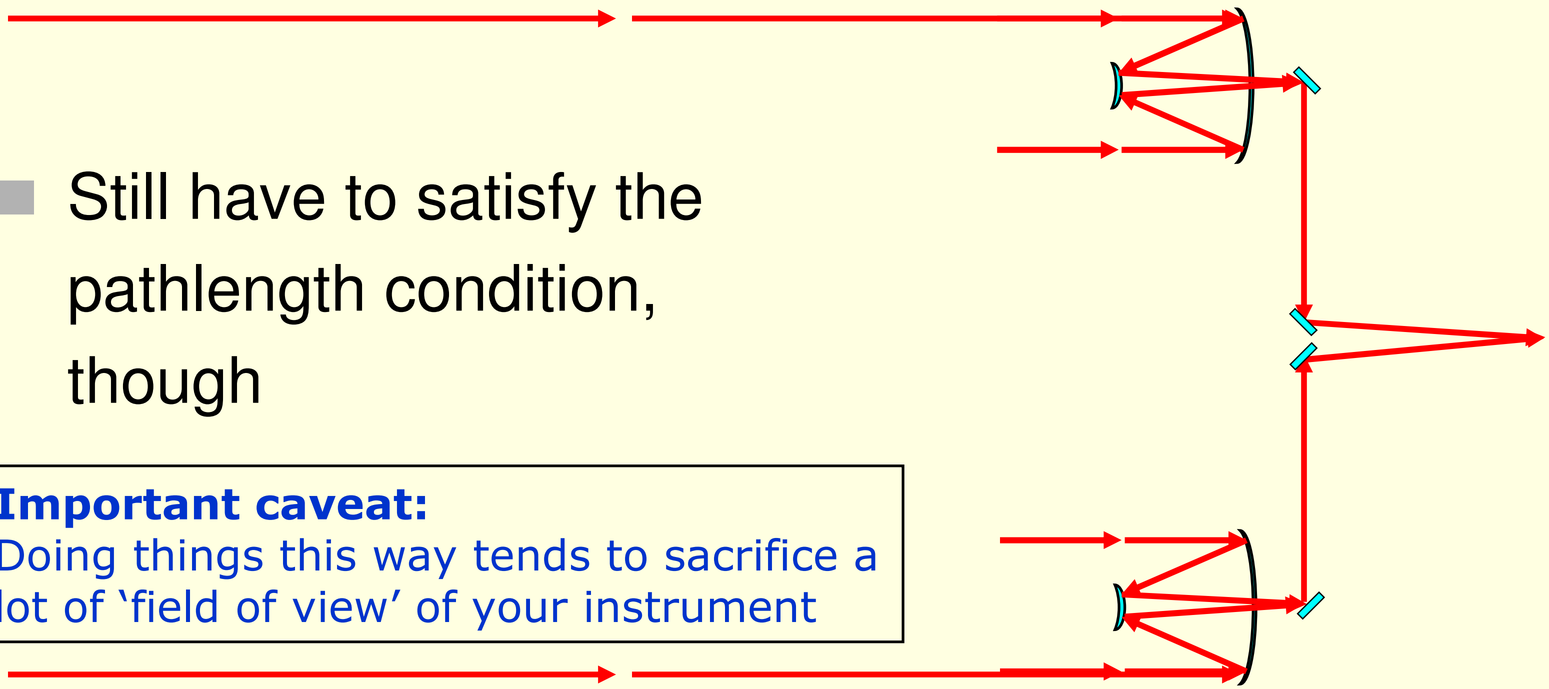
- Taking the neat trick even further: really chop up your telescope into a **long baseline interferometer**



- This works as long as *some* light is getting to the back end, and if the pathlength condition is met
- Can make the 'diameter' very big

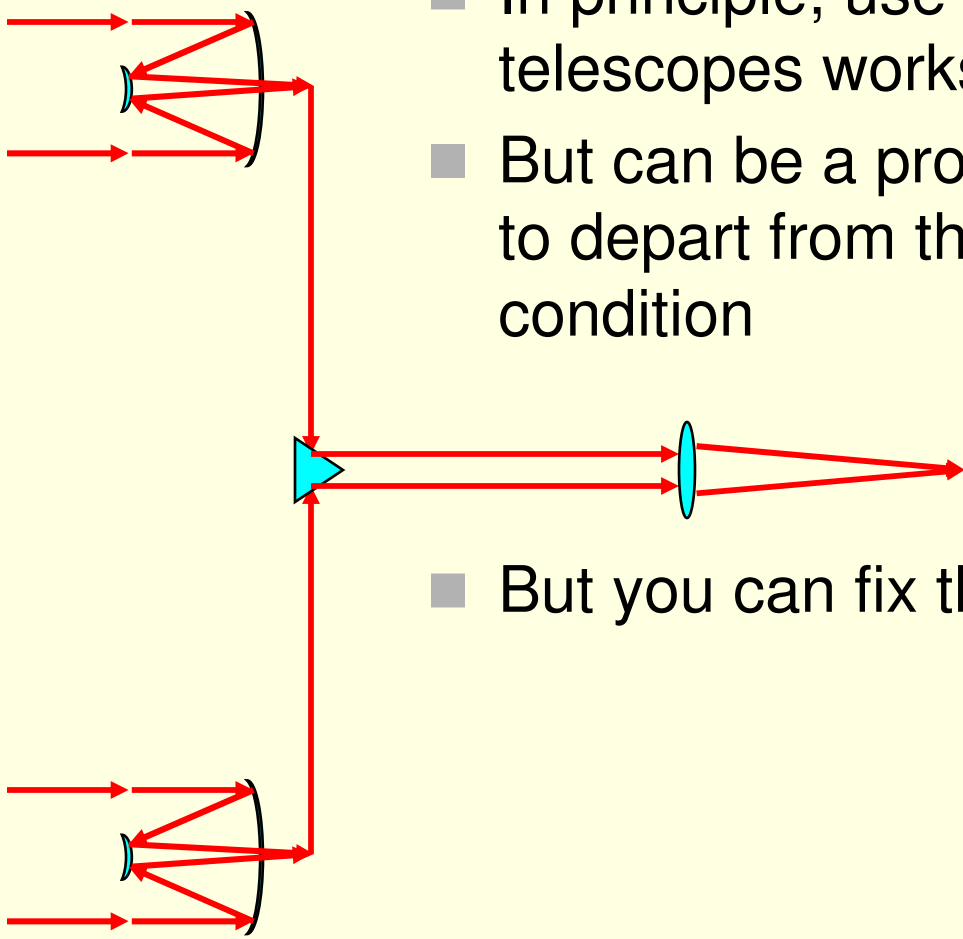
Cracking the Resolution Problem

- Taking the neat trick even further: really chop up your telescope by making it **many telescopes**
- Still have to satisfy the pathlength condition, though



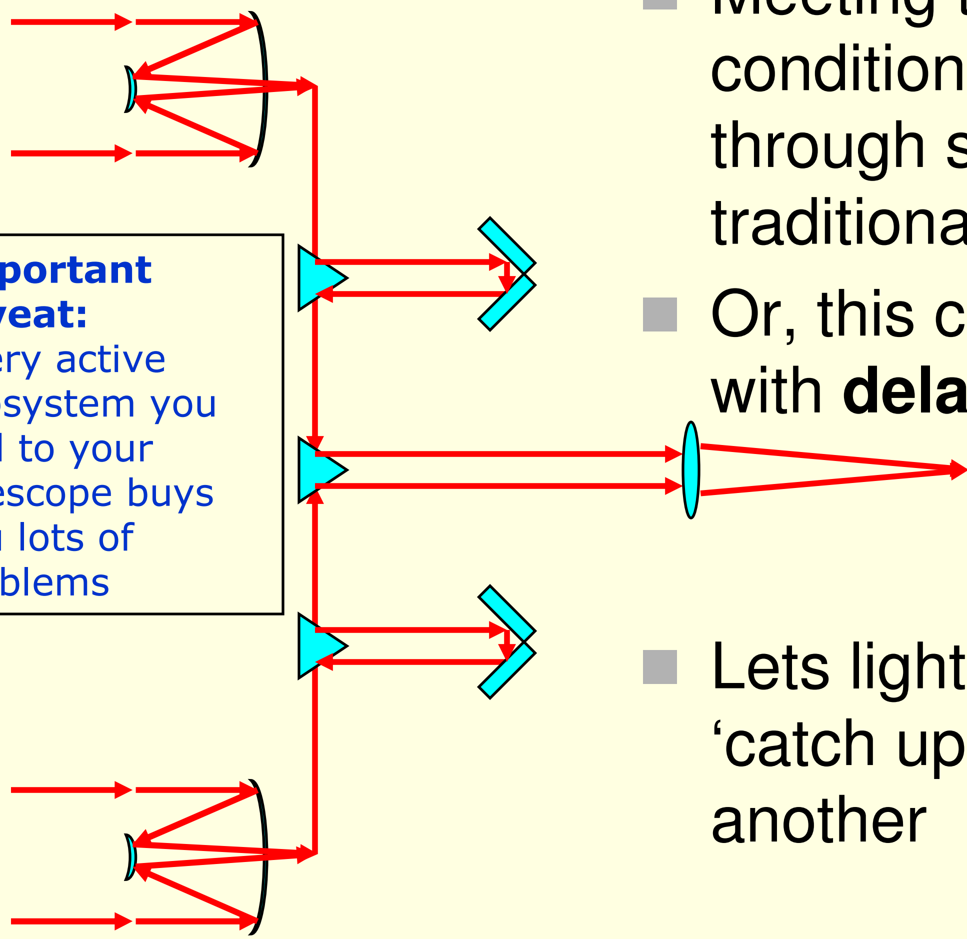
Important caveat:
Doing things this way tends to sacrifice a lot of 'field of view' of your instrument

Cracking the Resolution Problem



- In principle, use of multiple telescopes works
- But can be a problem when you start to depart from the pathlength condition
- But you can fix this problem

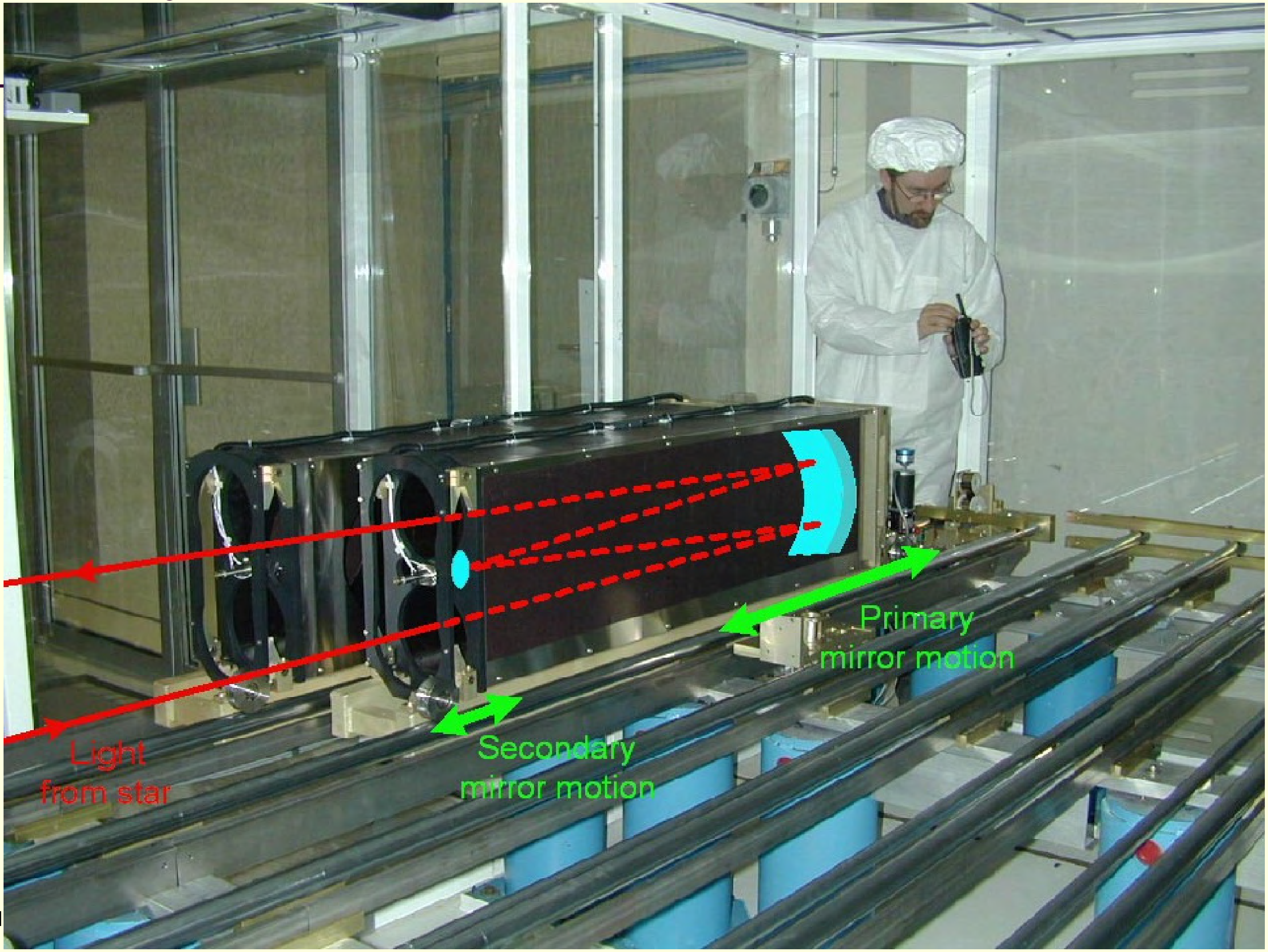
Cracking the Resolution Problem



Important caveat:
Every active subsystem you add to your telescope buys you lots of problems

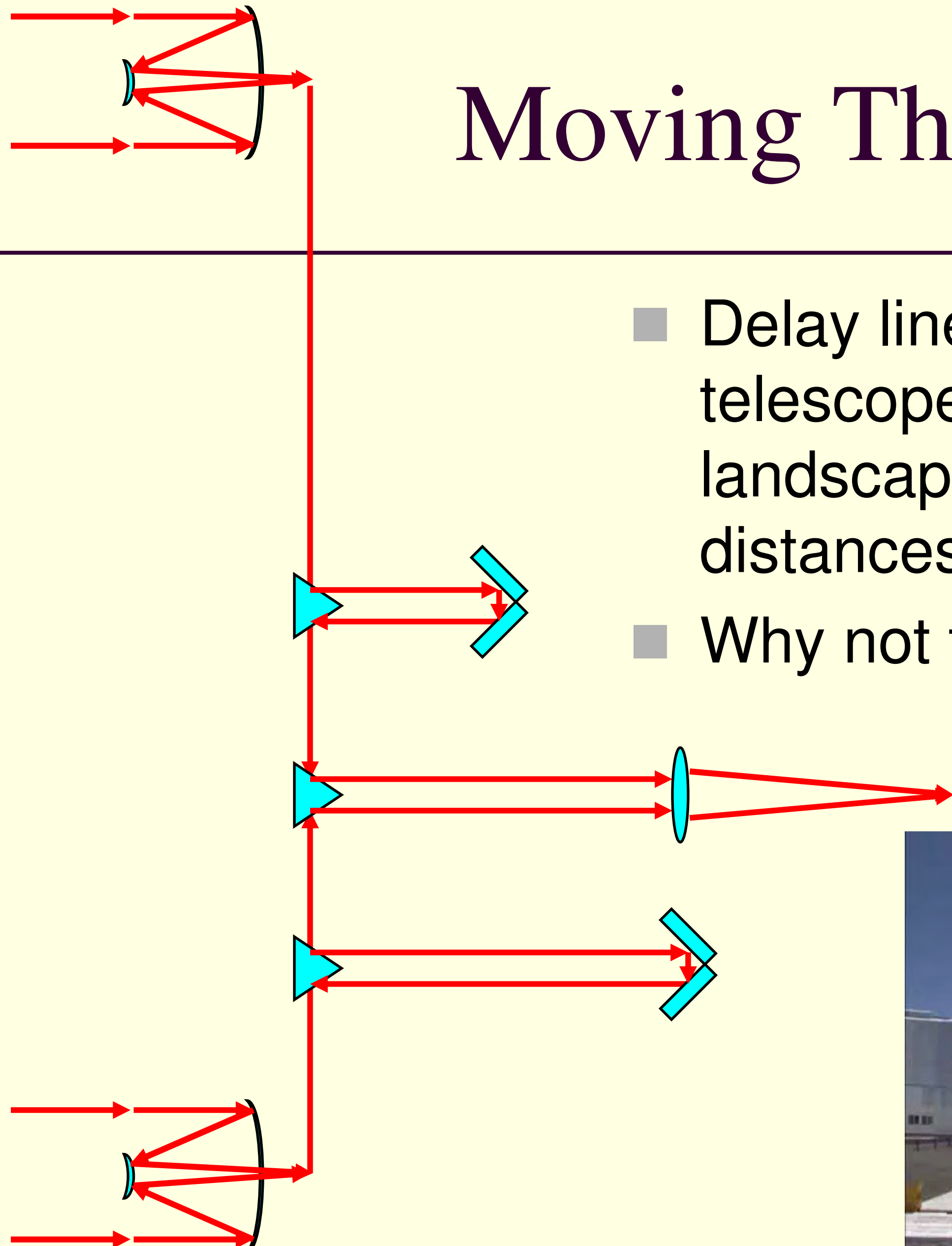
- Meeting the pathlength condition can be done through static means (the traditional approach)
- Or, this can be done actively with **delay lines**
- Lets light from one telescope 'catch up' with light from another

Delay Lines at Keck



gvb4

Moving Things Around



- Delay lines let you have telescopes scatter across the landscape at unequal distances
- Why not fix things in place?

Slide 33

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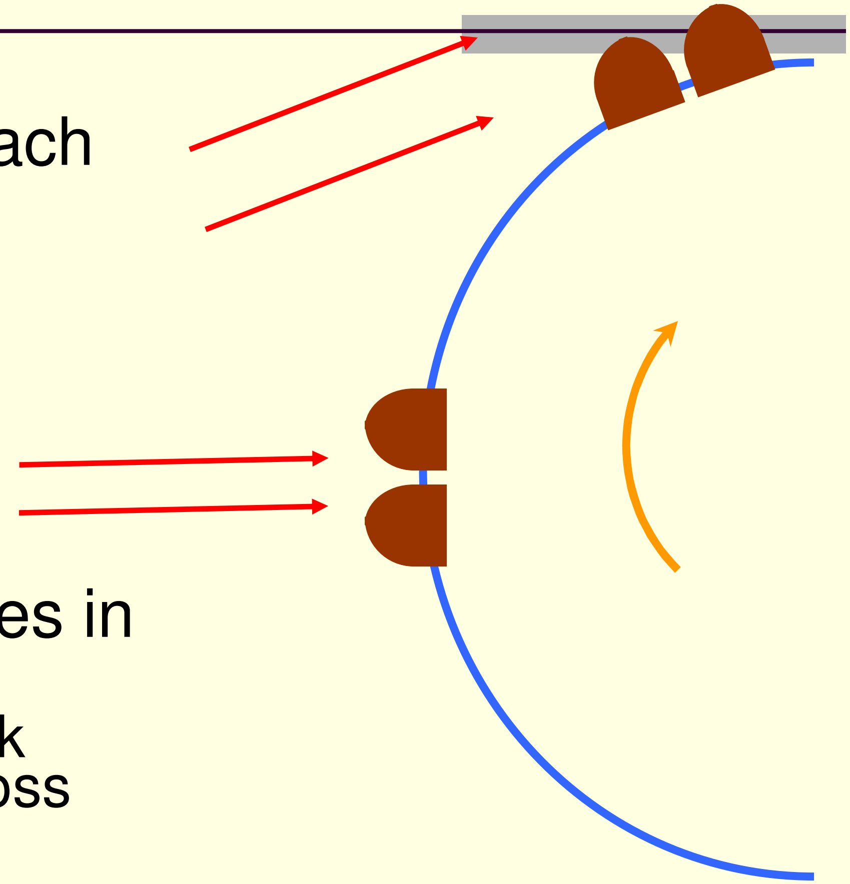
gvb4 gerard, 10/13/2011

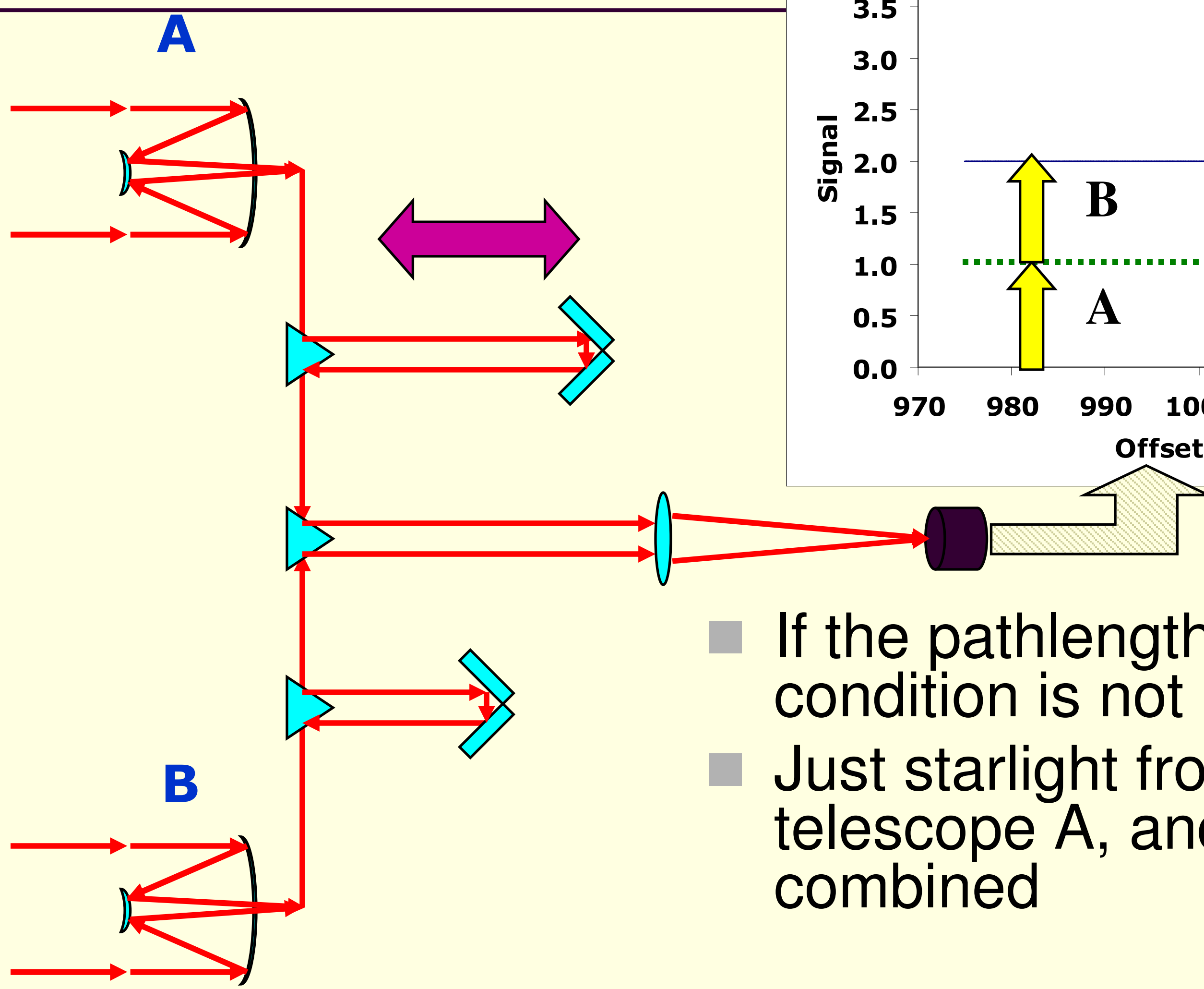
Things Move Around On Their Own

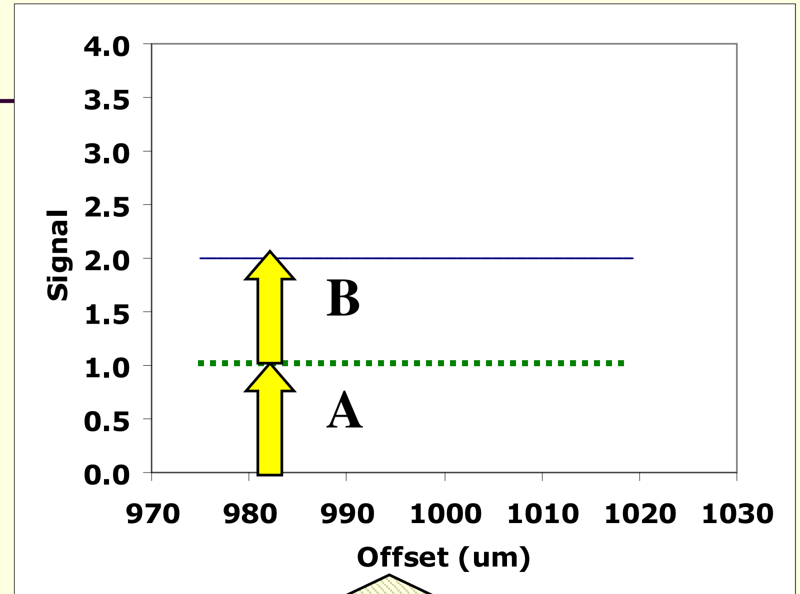
- Earth's rotation move telescopes relative to each other
- Delay lines are needed to account for diurnal motion



- Delay lines track changes in pathlength
  - just like telescopes track stars as they move across the sky

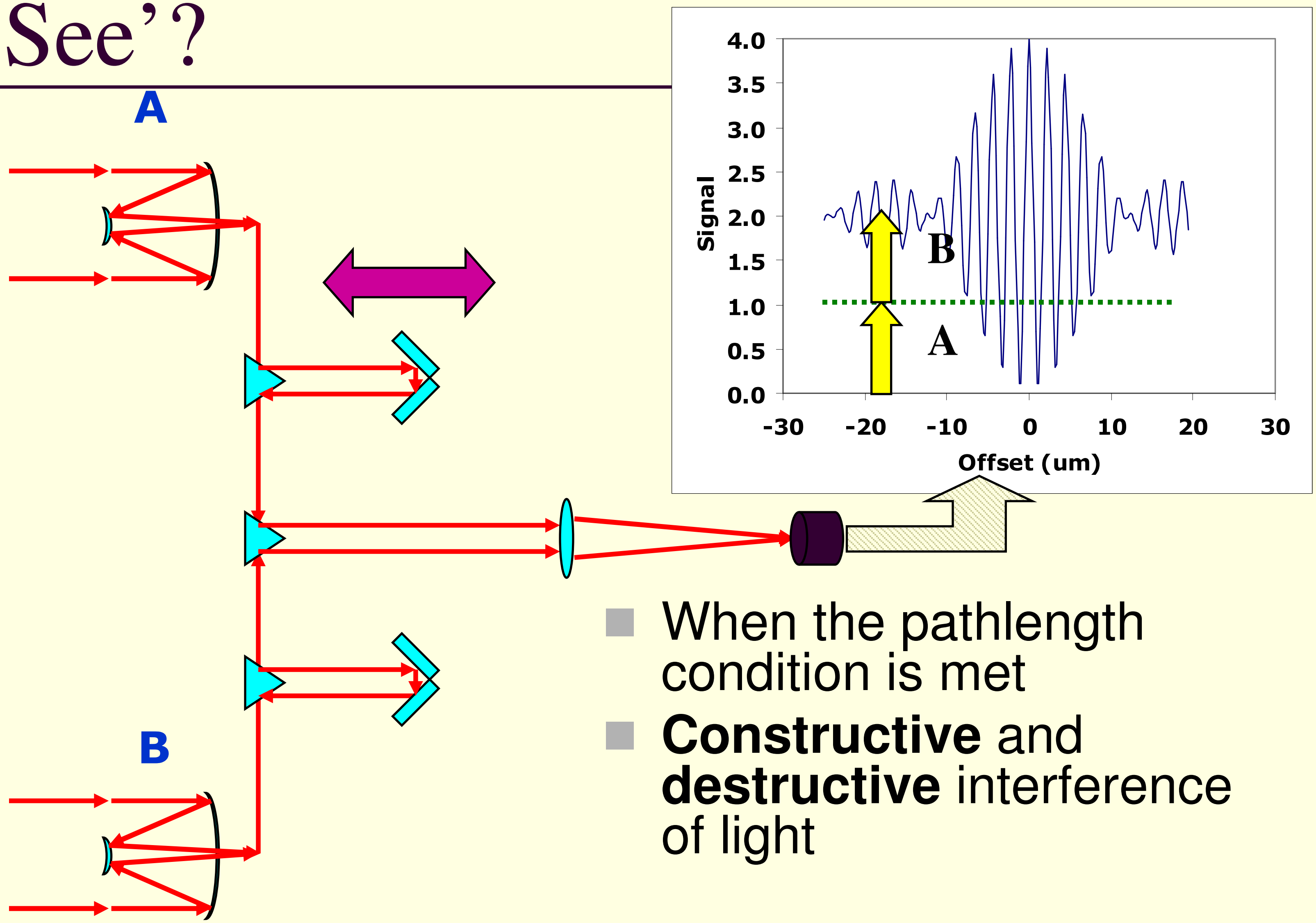
What Does an Interferometer 'See'?





- If the pathlength condition is not met
- Just starlight from telescope A, and B, combined

What Does an Interferometer 'See'?

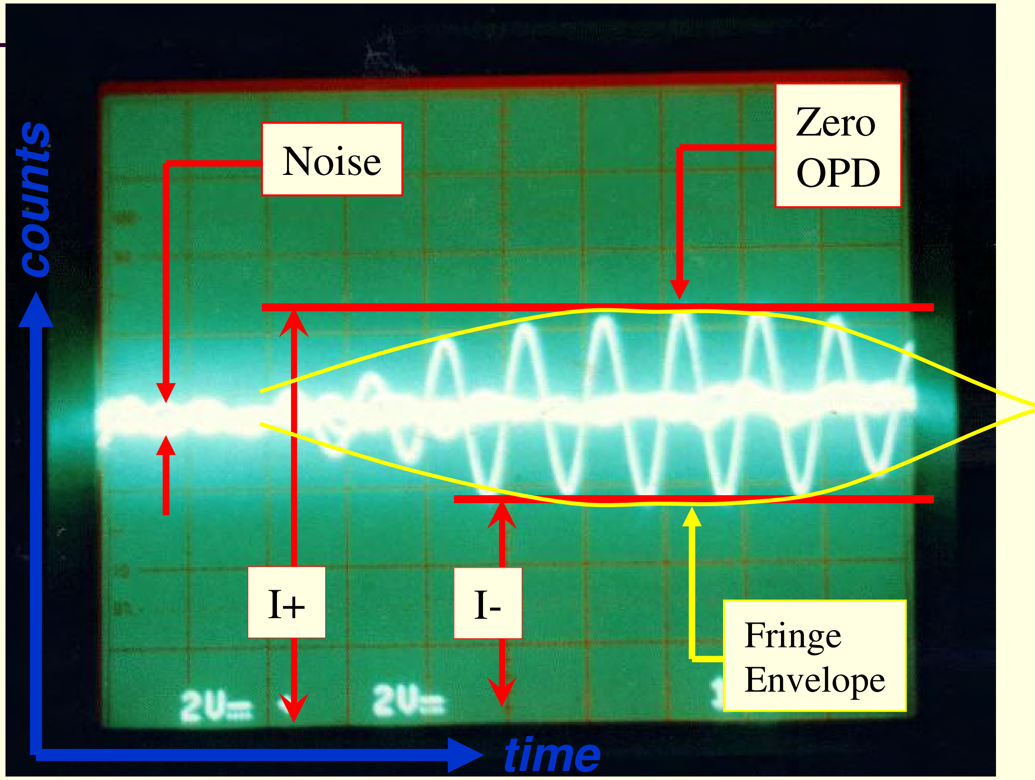


- When the pathlength condition is met
- **Constructive** and **destructive** interference of light

What does a Fringe *Actually* Look Like?

- With a moving delay line: **a time-varying photometric signal**
- Constructive & destructive interference of light
- Fringe **contrast** or **visibility**:

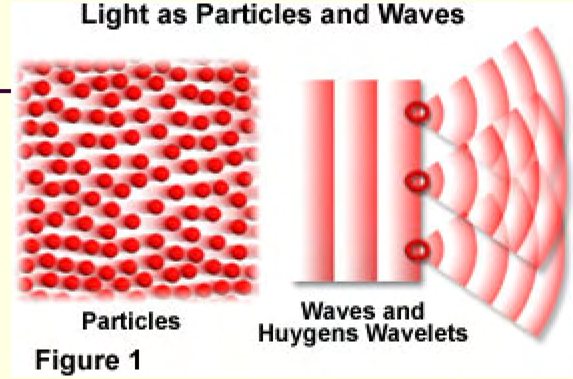
$$V = \frac{I^+ - I^-}{I^+ + I^-}$$

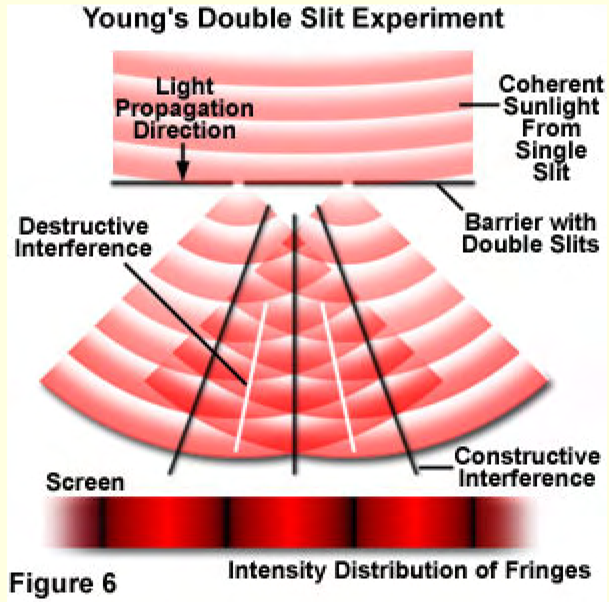


Actual starlight fringes from IOTA - β And
Photo credit: R.R. Thompson

What’s Going on Here?

- Wave-particle duality of light
- Manifestation of quantum mechanical nature of light
- Sampling the fringes is ‘riding the crest of the waves’

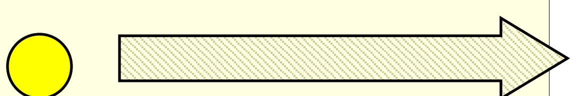


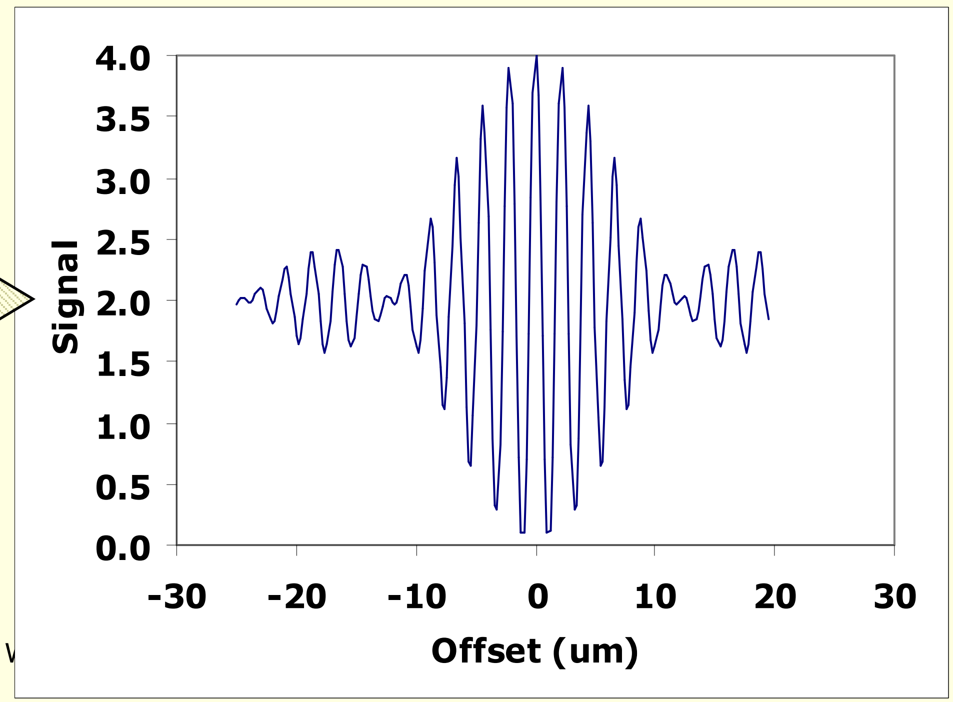


Brain teaser: *Which telescope does the photon enter?*

Observing Small Stars

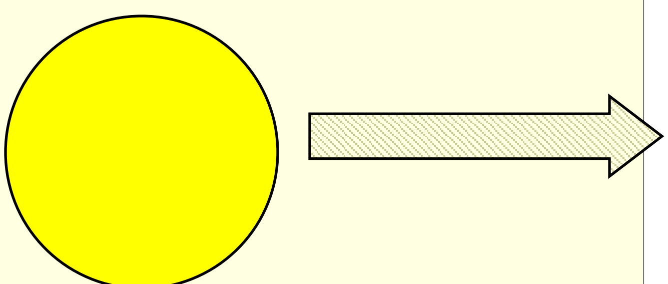
- For a very small – **point-like** – star, fringes will be high contrast
- By ‘very small’, I mean $\theta < 0.25$mas

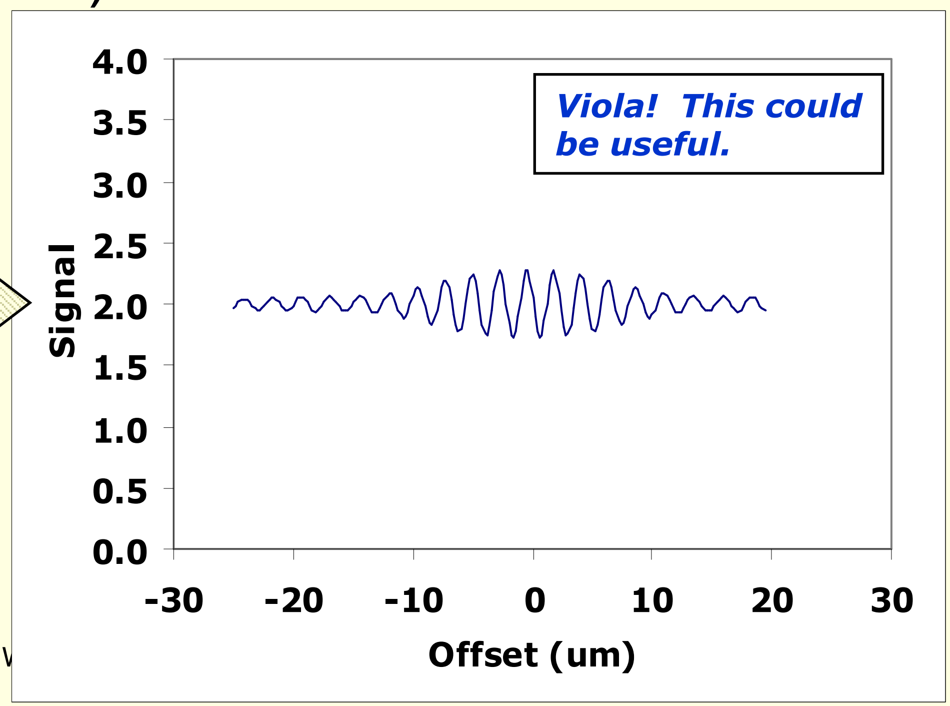




Observing Large Stars

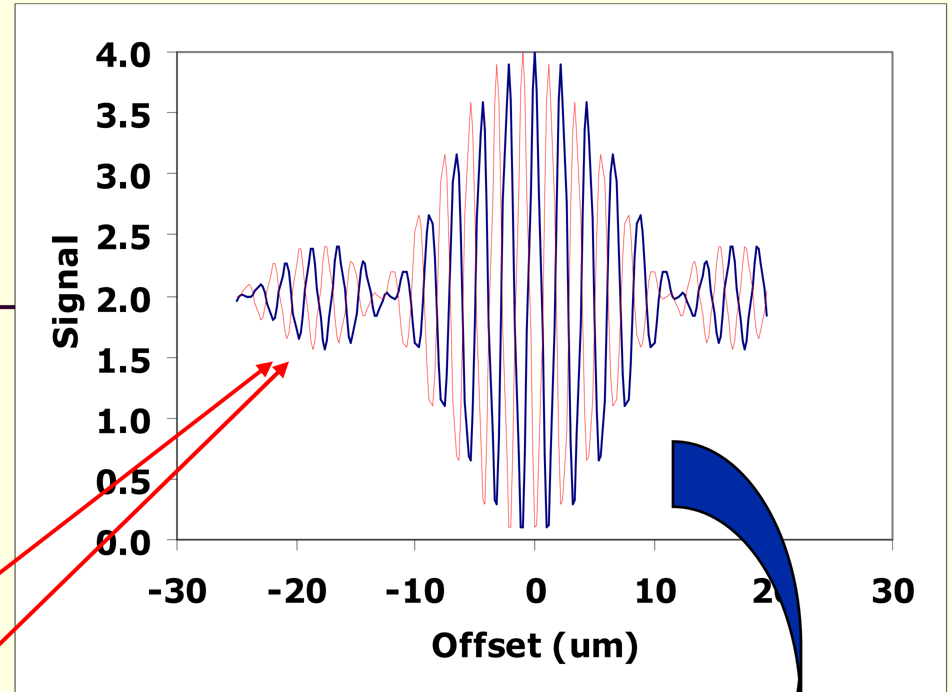
- For a large – **resolved** – star, fringes will be high contrast
- By 'large', I mean $\theta \approx$ 0.5-3 mas (in the case of NPOI, VLTI, CHARA)

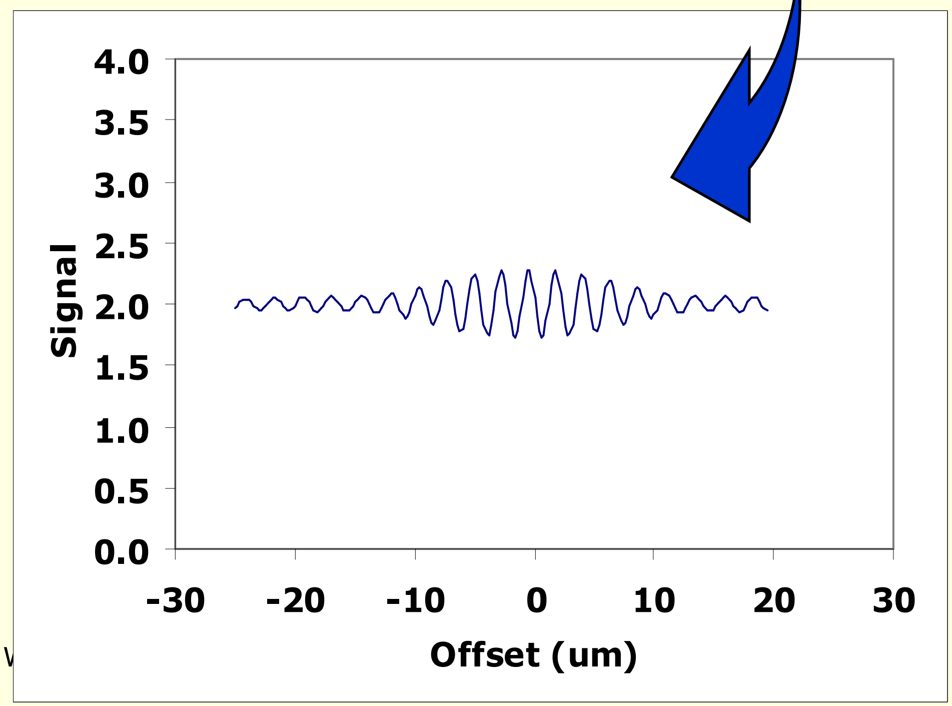


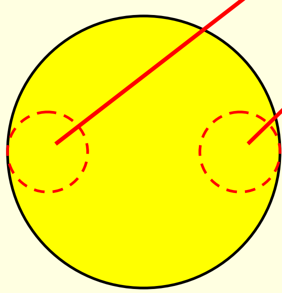


Why is This?

- Light from different sides of the star correspond to different ZPDs
- Optical path = interferometer pointing



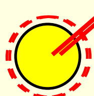


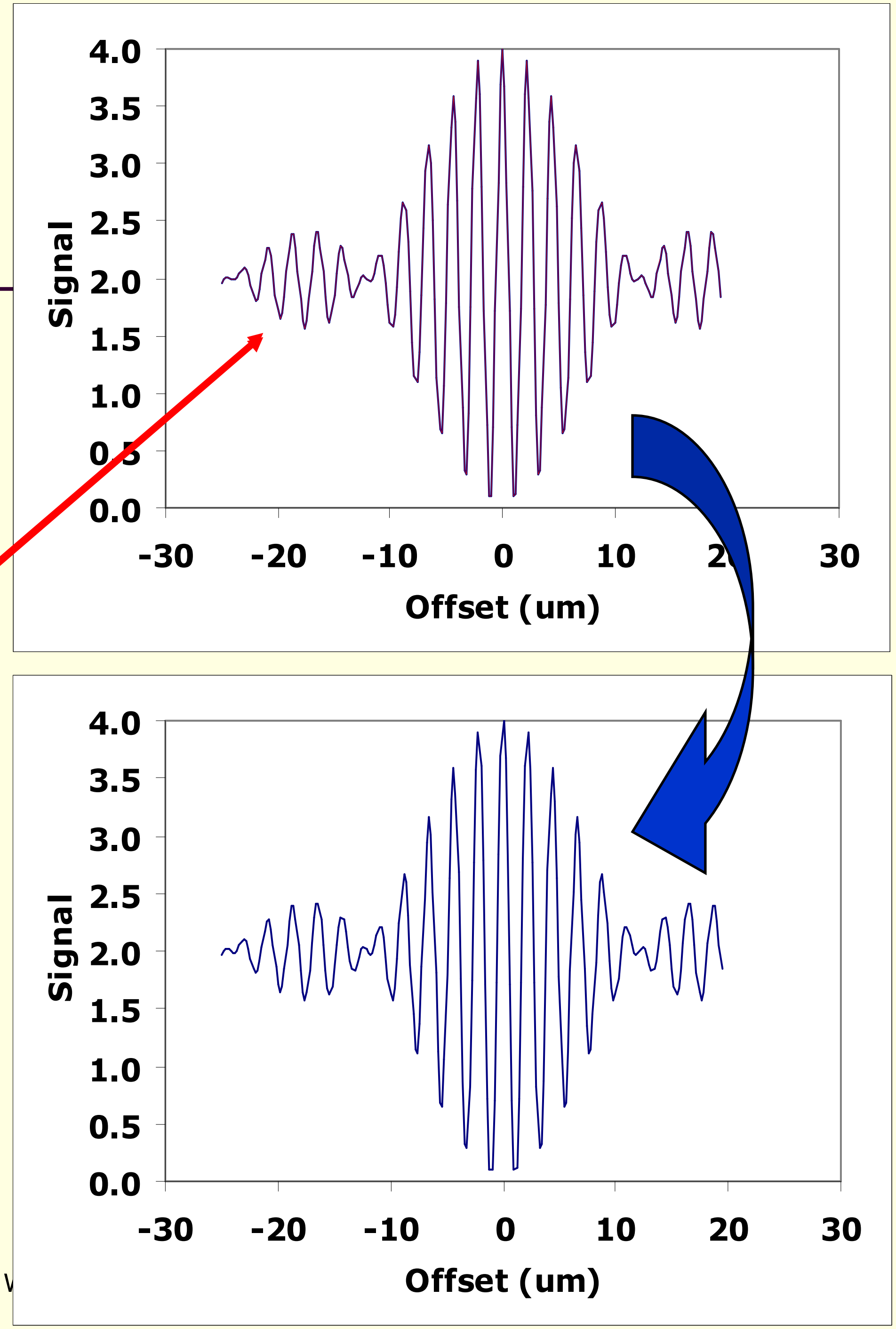


- The interferometer sees both fringe packets simultaneously

Why is This?

- For a small star, there is only one ZPD
- The interferometer still sees both fringe packets simultaneous-ly, but they don't smear each other out





Visibility Function

- For a 'uniform disk', visibility matches:

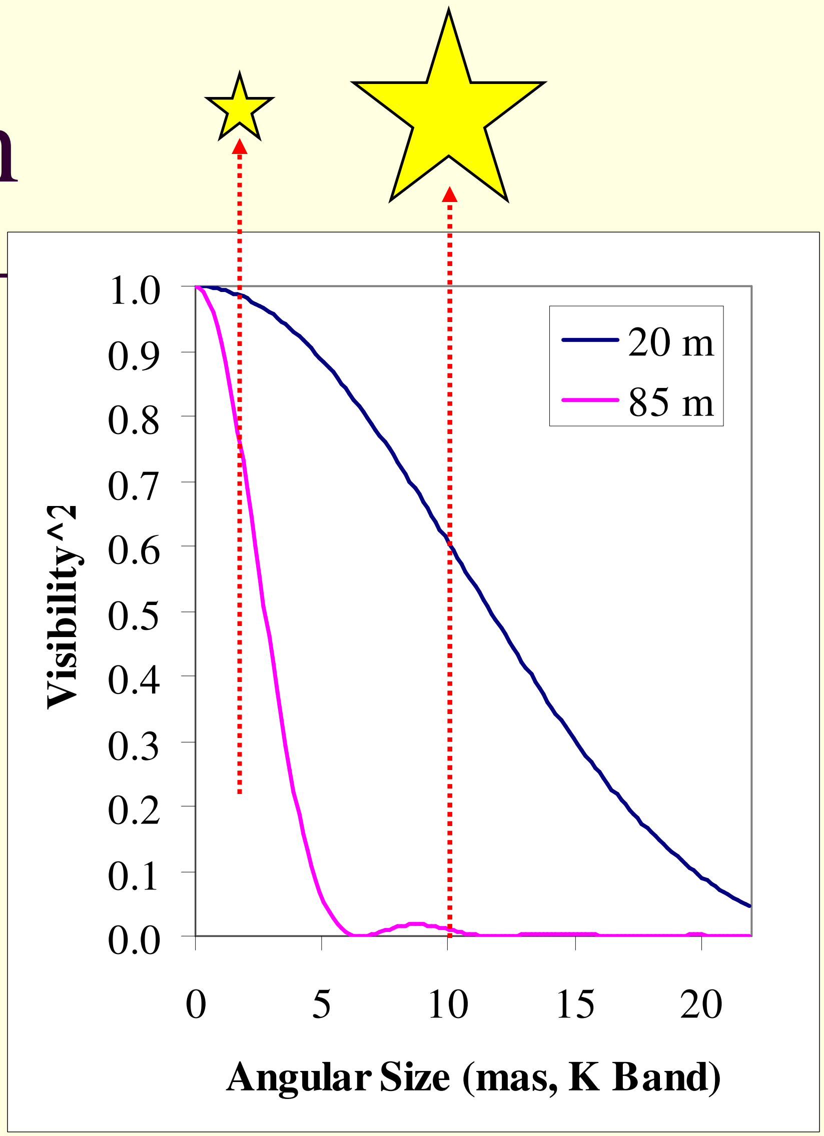
$$V = \frac{2J_1(x)}{x} \quad \text{where} \quad x = \frac{\pi\theta B}{\lambda}$$

  B is the projected baseline

  θ is the stellar disk size

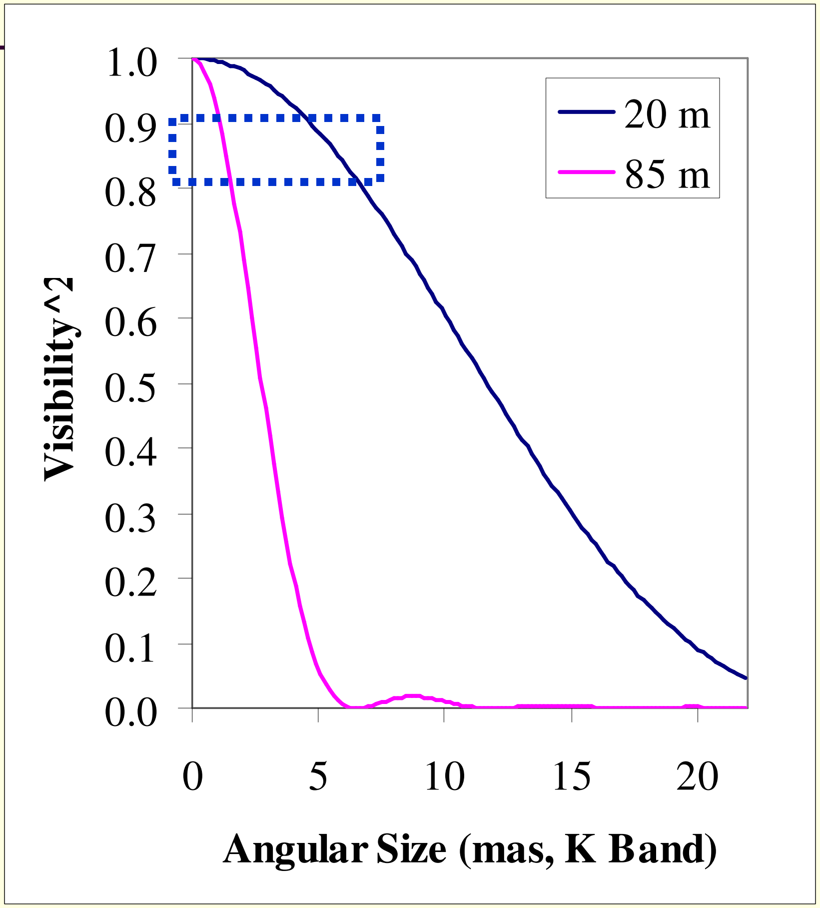
  λ is the instrumental wavelength

- Baseline, wavelength known
  - Can solve for θ
- Use V^2 instead of V
  - Unbiased estimator of visibility
  - See Colavita (1999)

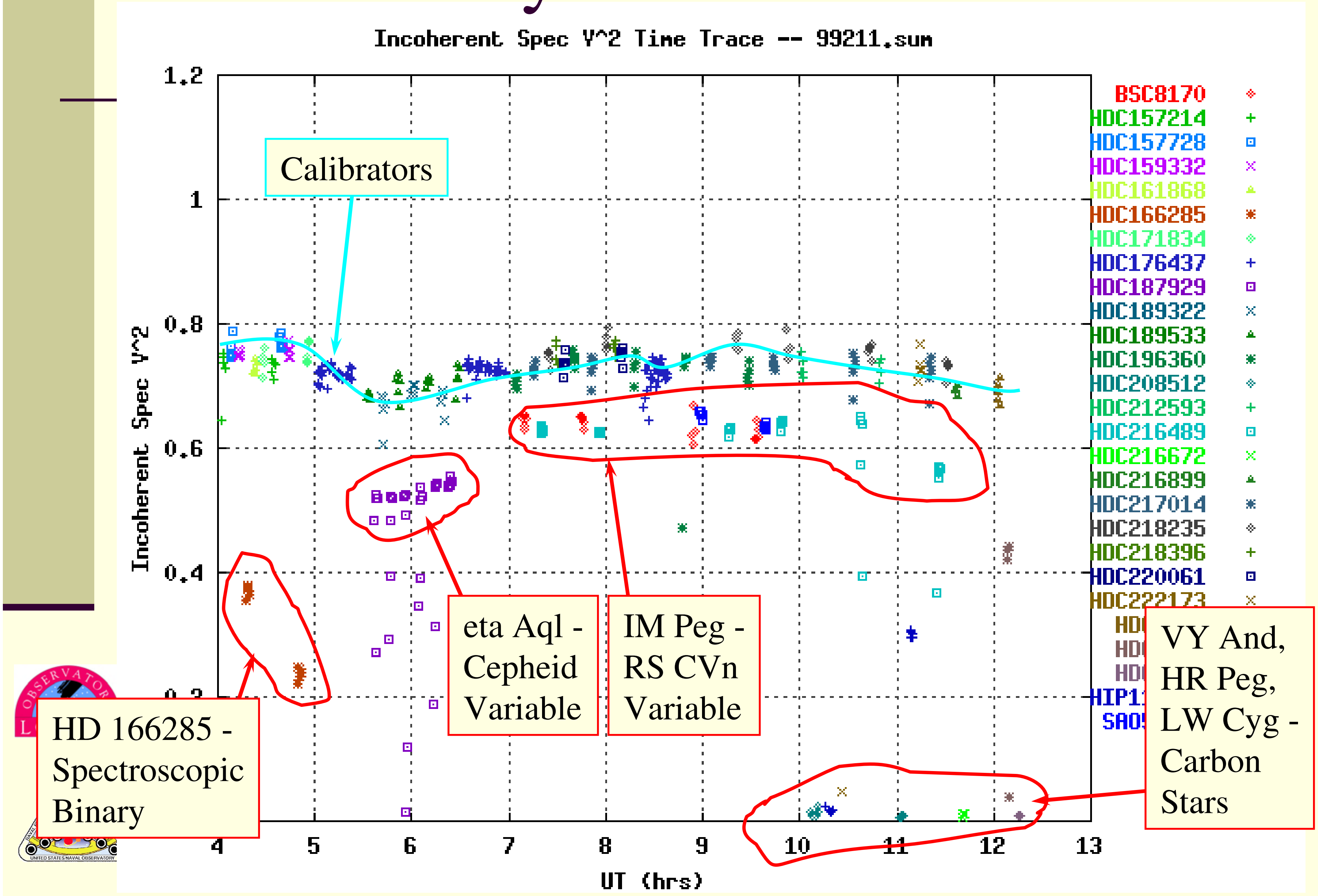


An Aside: True Resolution of Optical Interferometry

- Single aperture resolution limit usually quoted as 1.22 × λ/D
  - This is the somewhat arbitrary Airy limit
- Optical interferometry resolution limit often quoted as the corresponding ~λ/B
- But, for optical interferometer, we can work much higher up on visibility curve
  - **If** sufficient measurement precision is provided
- Example: for a 110m baseline at K-band
  - Can get down to ~1.00mas size measurements with σ_{V2}=0.015
    - NB. This is hard to do
  - Corresponds to ~ 0.24 × λ/B

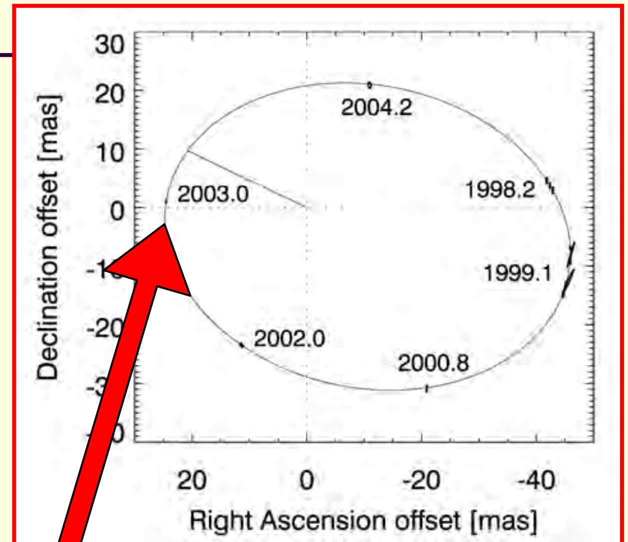


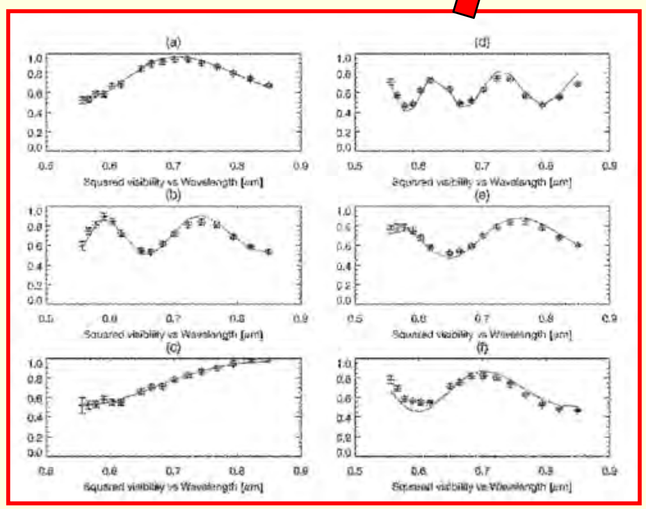
PTI Visibility Data



Stellar Binaries and Interferometry

- For a pair of point sources, visibility has a sinusoidal variation
- Can easily decompose into separation, position angle
- With RV information, can get masses, distance





zeta Ori A: Hummel+ 2013

2002 Dec 20:
ρ = 24.6mas
PA: 87.7°

Thought #4: Interferometers are Getting More Complicated

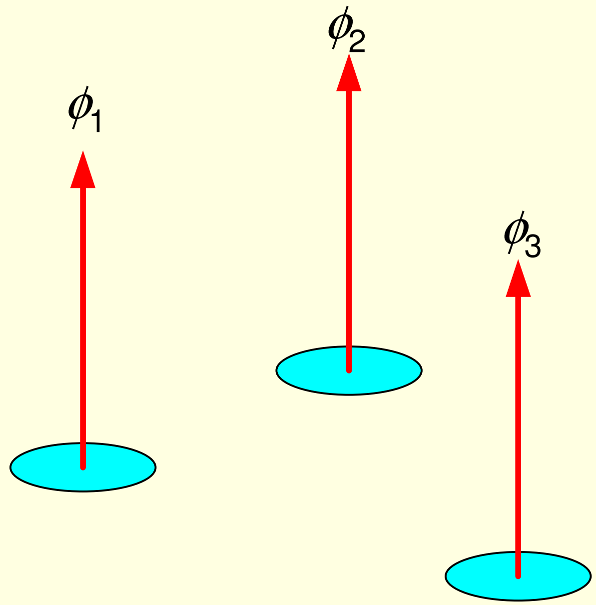
Remember, don't panic

Multi-Element Arrays

- Higher order observables are possible with N>2 arrays
- Specifically, the **closure phase**
- What is that, and how do we get it?

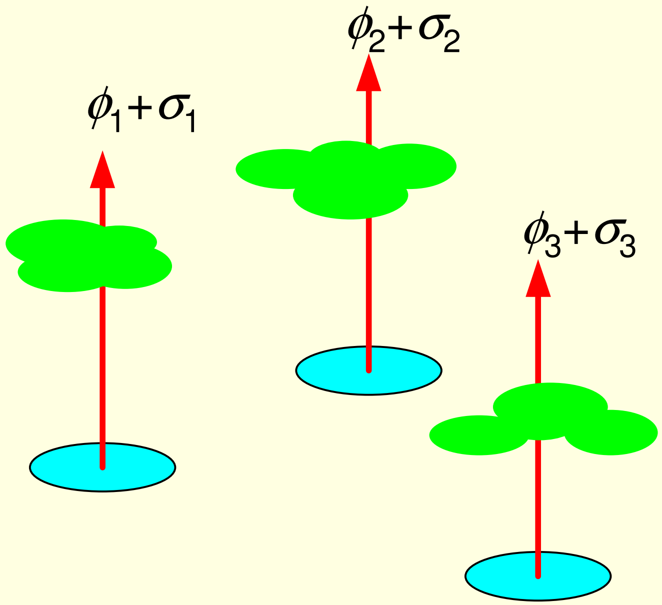
Closure Phase

- Going from 2 telescopes to 3
- This actually provides a significant new lever arm – how?
- Each individual telescope has an individual *phase* – essentially a light travel time or pathlength from the source object



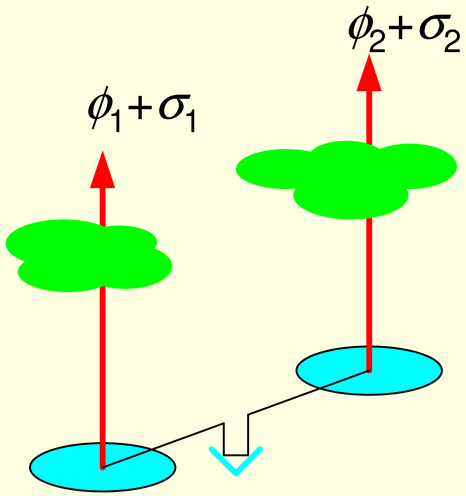
Closure Phase

- But individual telescopes phases are corrupted by the atmosphere (and are unrecoverable)
- In the optical, this is time-variant on ~millisecond, micron scales
  - *Fringe tracking* (FTK) is necessary



Closure Phase

- Recall how we combine two telescopes
- It's no surprise FTK is frequently referred to as 'phasing' two apertures
- Can adjust delay line position to obtain fringes
- But absolute fringe phase still unknown, since errors (σ_1, σ_2) unknown



Closure Phase

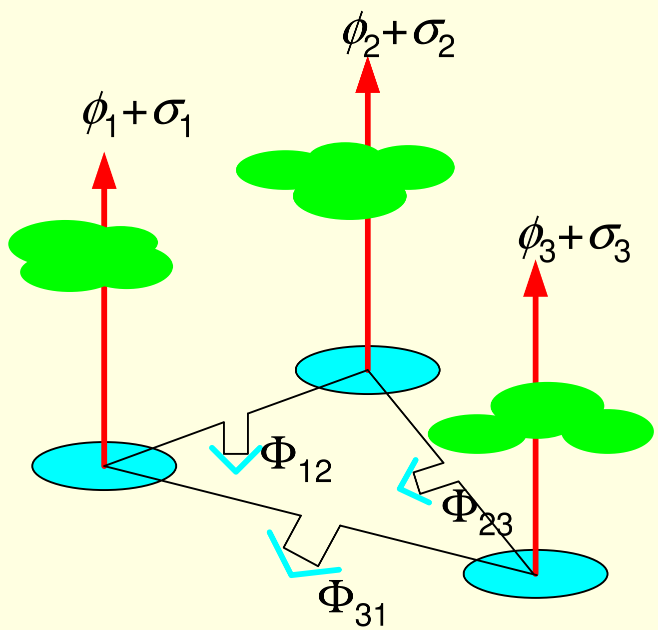
- But with three telescopes a neat thing happens: the atmospheric errors cancel

What We Want

What We Measure

$$\Phi_{12} = \phi_1 + \sigma_1 - \phi_2 - \sigma_2$$
$$\Phi_{23} = \phi_2 + \sigma_2 - \phi_3 - \sigma_3$$
$$\Phi_{31} = \phi_3 + \sigma_3 - \phi_1 - \sigma_1$$

What We Don't Know



$$\Phi_{123} = \Phi_{12} + \Phi_{23} + \Phi_{31} = \phi_1 + \phi_2 + \phi_3$$

Winning with Closure Phase

- Additional important point: CP information grows rapidly with number of telescopes *N*
- Phases:

  $N(N-1)/2$
- Observed phases:

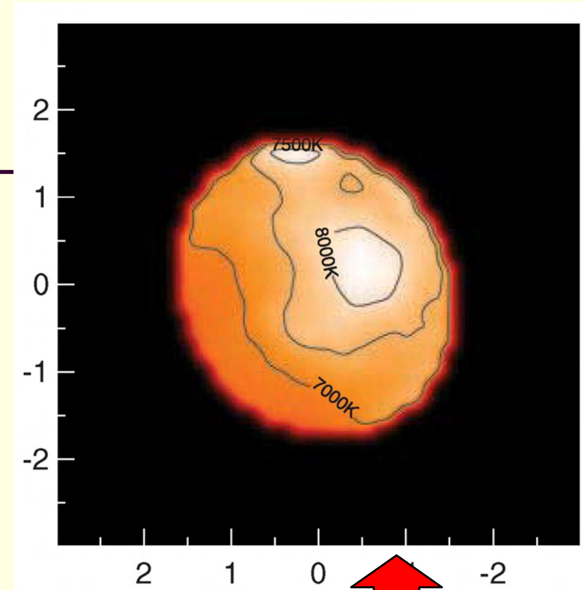
  $(N-1)(N-2)/2$
- Fraction from observations:

  $(N-2)/N$

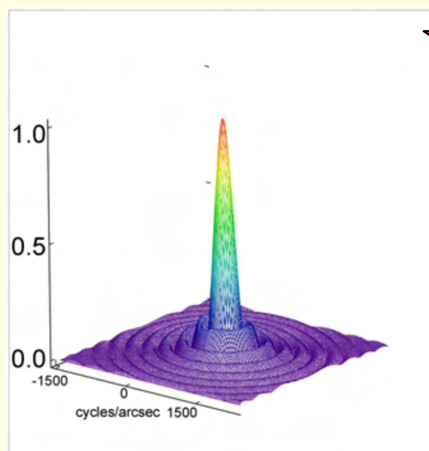
Number of Telescopes	Phases	Observed Phases	Fraction from Observation
3	3	1	33%
4	6	3	50%
6	15	10	67%
8	28	21	75%

Putting It Back Together

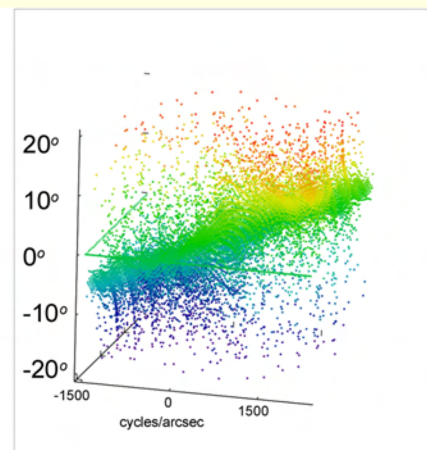
- Fourier transform of image upon the sky
  - Amplitude ↔ Visibility
  - Phase ↔ Closure phase
- Sparsely sampled data
  - Direct inversion not possible
  - Clever reconstruction necessary



Altair – Monnier+ 2007



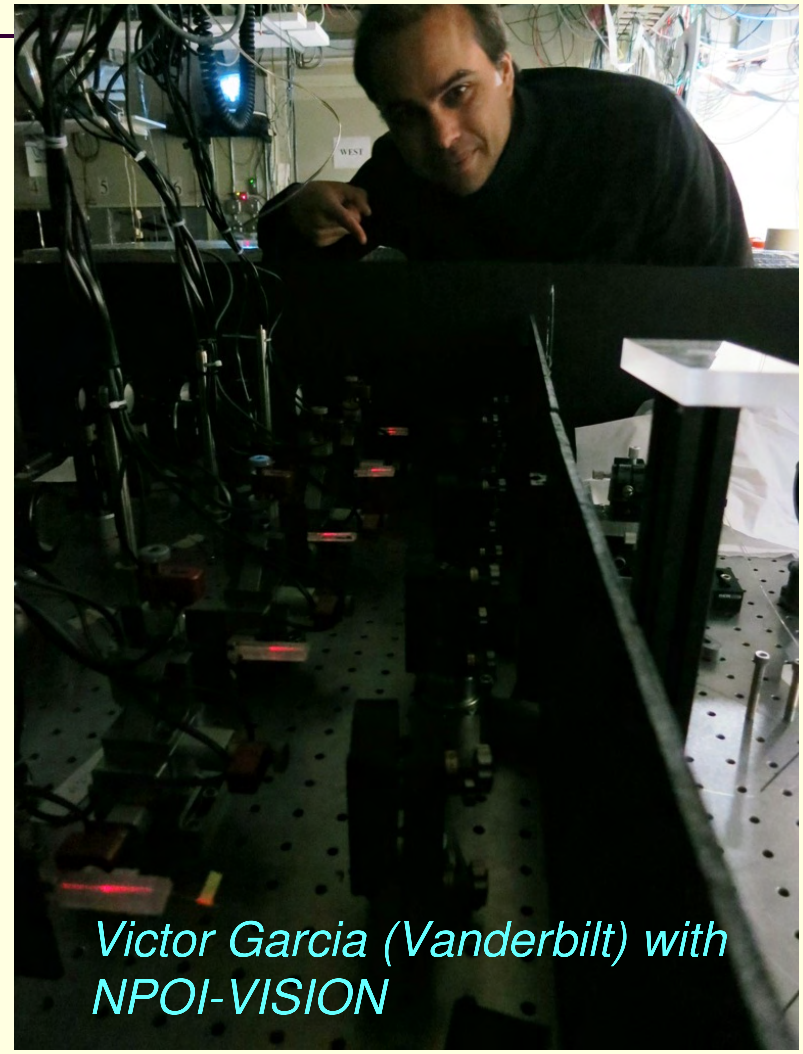
Visibility



Phase

New Closure Phase Engines

- New tools (# beams)
  - CHARA: MIRC (4→6), Vega (3), PAVO (3)
  - NPOI: VISION (5→6)
  - VLTI: PIONIER (4), MATISSE (4), Gravity (4)
- No 8-way combiners (yet)
  - Diminishing returns after 8

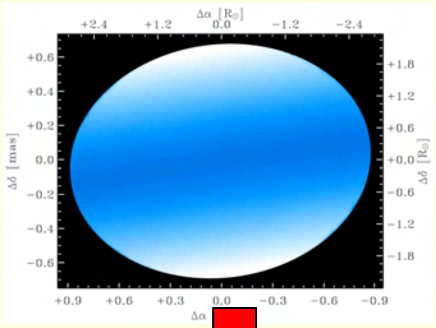


Victor Garcia (Vanderbilt) with NPOI-VISION

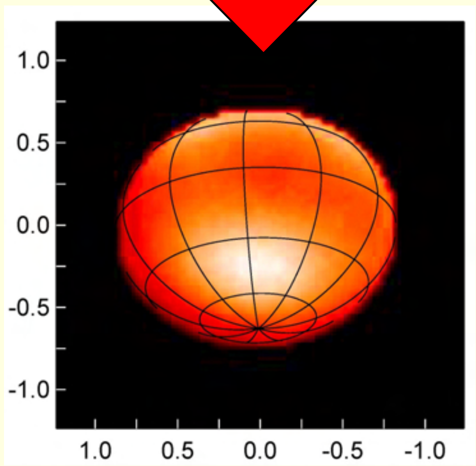
Importance of Closure Phase

- Closure phase is very sensitive to **image asymmetries**
- *Not* having closure phase can make for key errors with interpretation
- Direct characterization of gravity darkening → evidence for convection, meridonial circulation

Alpha Cep

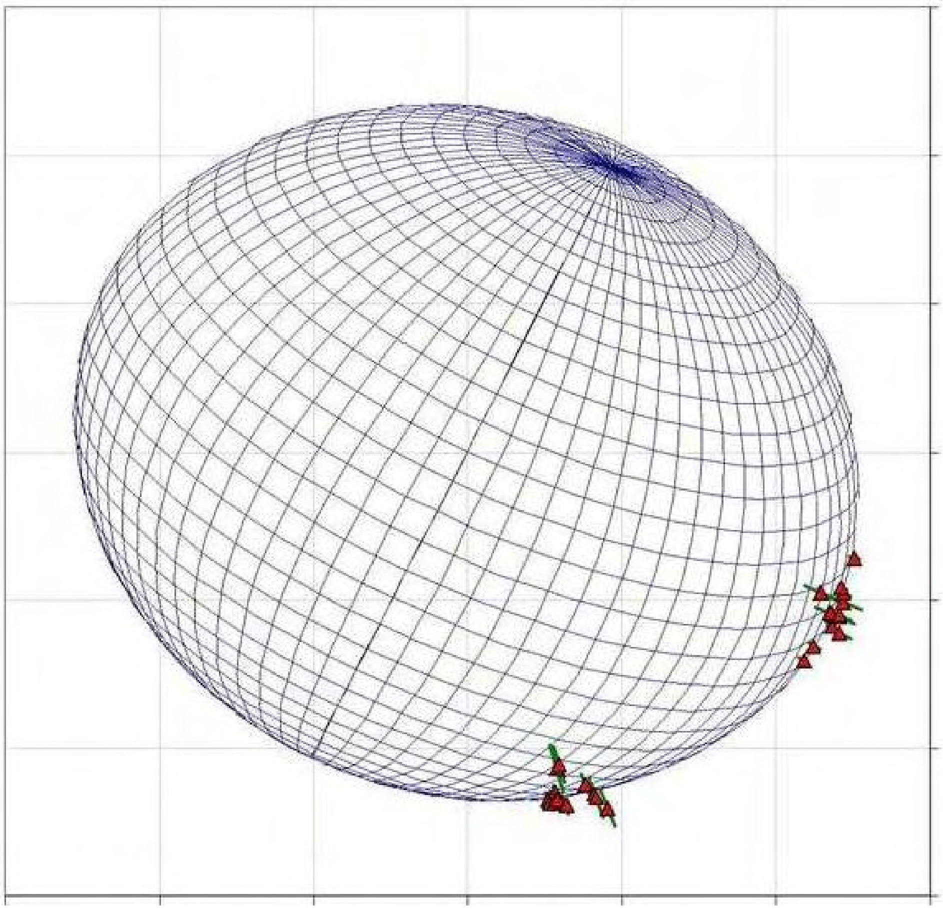


van Belle+ 2006



Zhao+ 2009

Stellar Surface Imaging



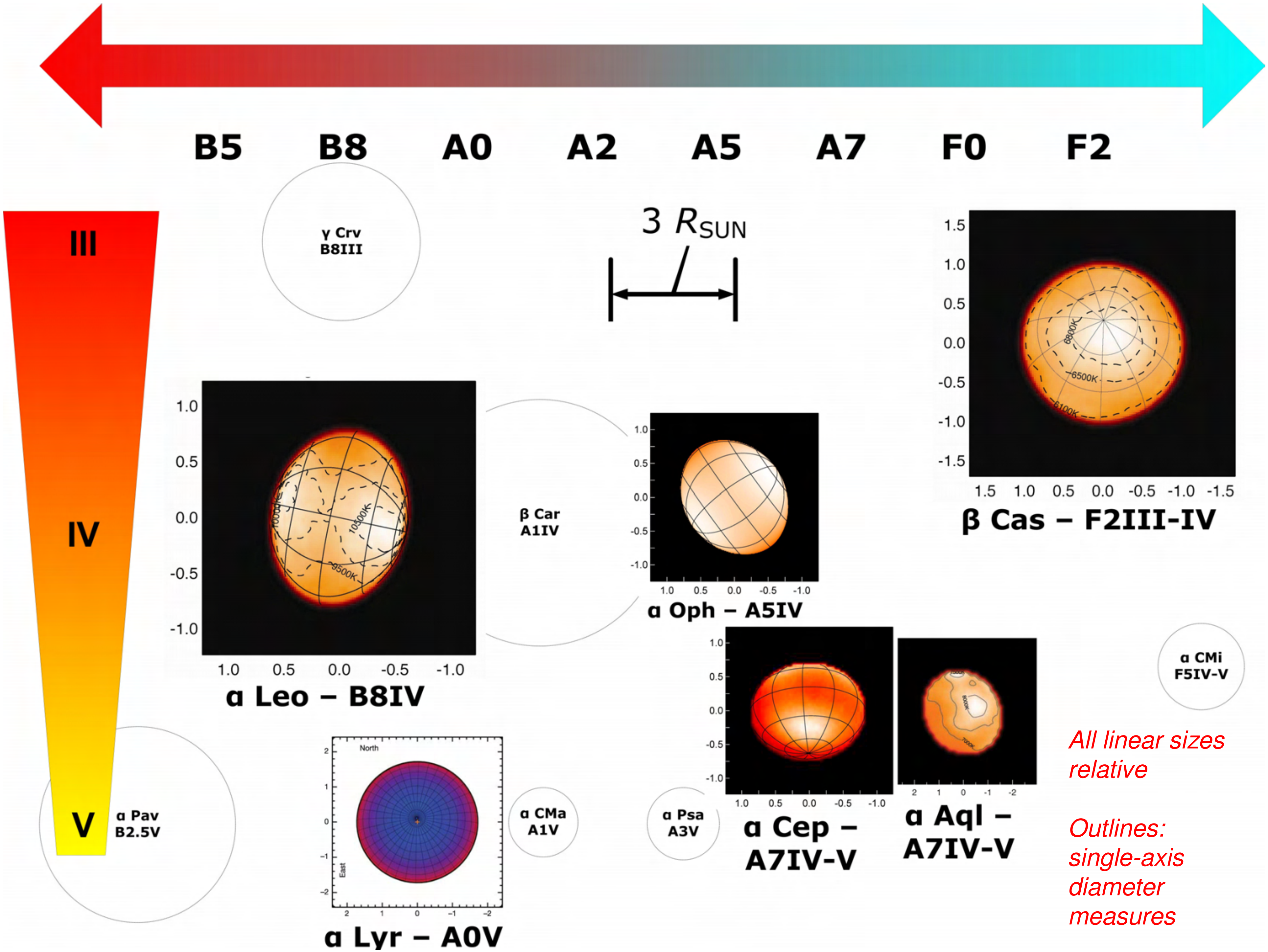
Toy model of Altair:
v sin i = 210km/s
oblateness ≈ 14%
NB. solar ≈ 10^{-5}

(see van Belle+ 2001)

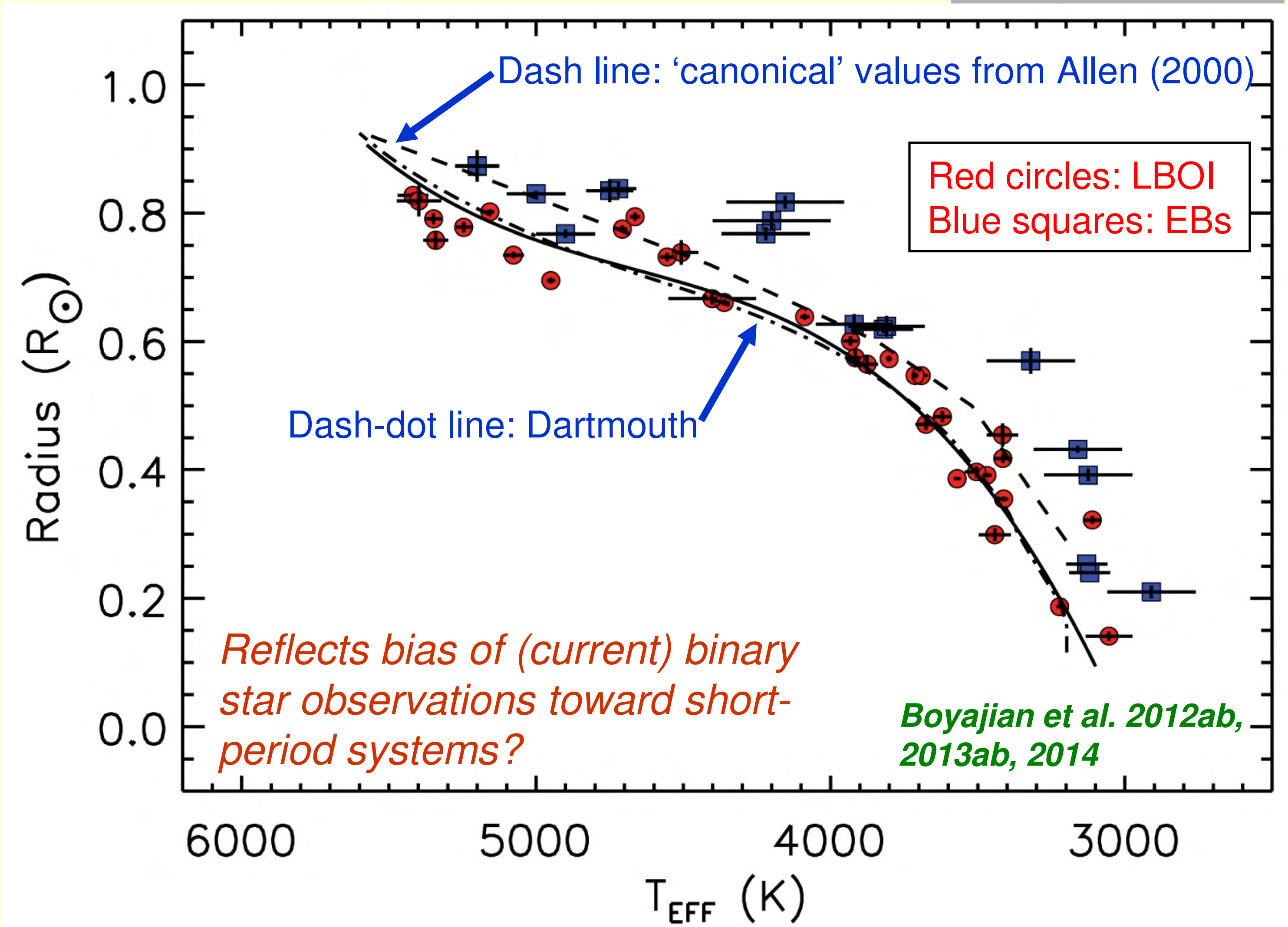
- Rapid rotators an interesting case example
- Large (M>2$M_{\odot}$) star spinning rapidly (P<12^{hr})
- First-order modeling of photosphere with Roche surface
- Latitude-dependent gravity darkening first predicted by von Zeipel (1924)
  - Rotation rate, inclination, temperature vs. latitude, energy transport
- Initial foray in 2001, rapid progress since then

Thought #5: Everything You Know About Stars Might be Horribly Wrong

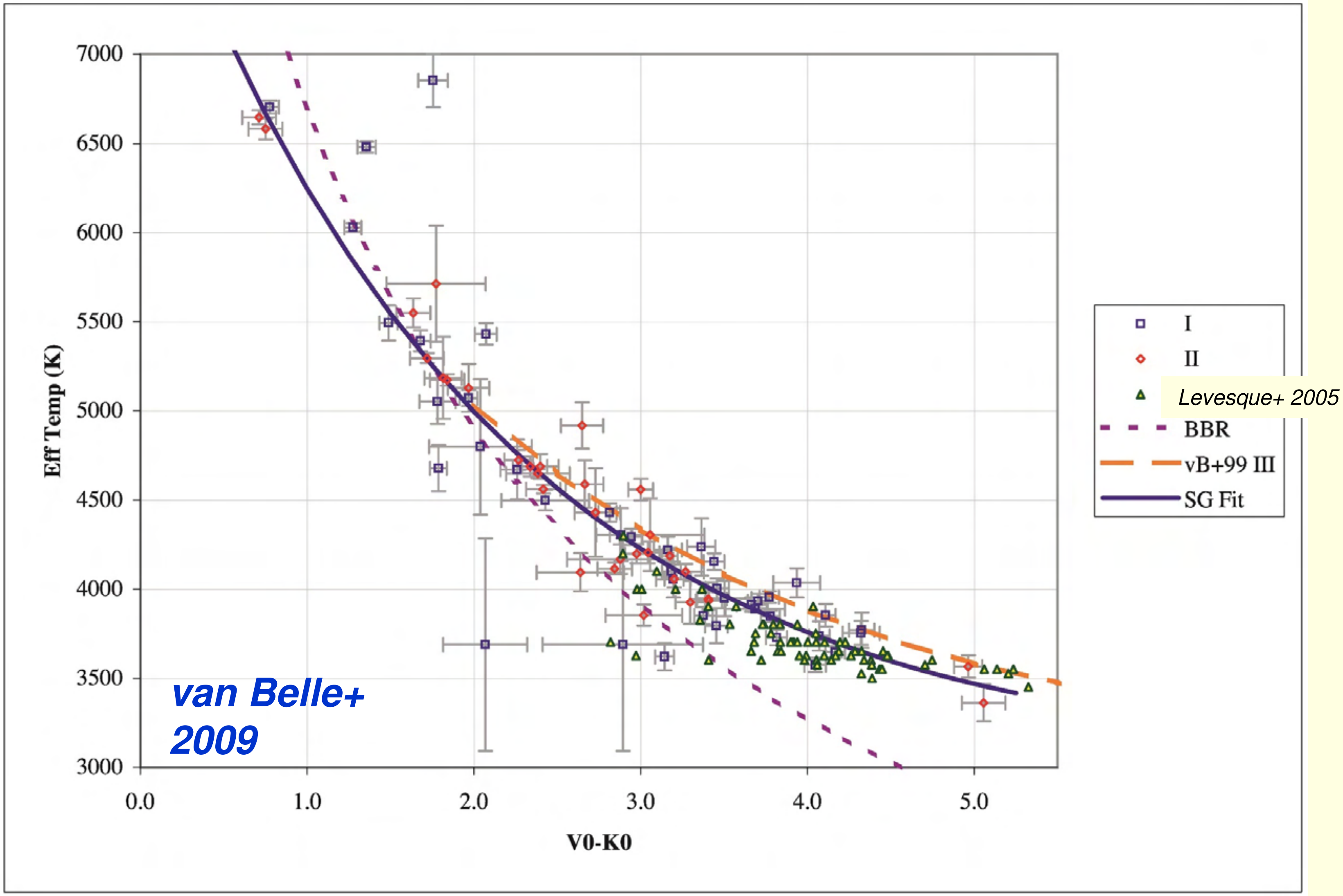
Getting back to the 'Why Do I Care'?


B5
B8
A0
A2
A5
A7
F0
F2
III
IV
V
γ Crv
B8III
3 R_{SUN}
β Cas – F2III-IV
6800K
6500K
6100K
α Leo – B8IV
10500K
9500K
β Car
A1IV
α Oph – A5IV
α Cep –
A7IV-V
α Aql –
A7IV-V
α CMi
F5IV-V
α Pav
B2.5V
North
East
α Lyr – A0V
α CMa
A1V
α Psa
A3V
All linear sizes relative
Outlines: single-axis diameter measures

Radius vs. T_{EFF}: Single vs. Binary



T_{EFF} versus V_0-K_0 for Supergiants

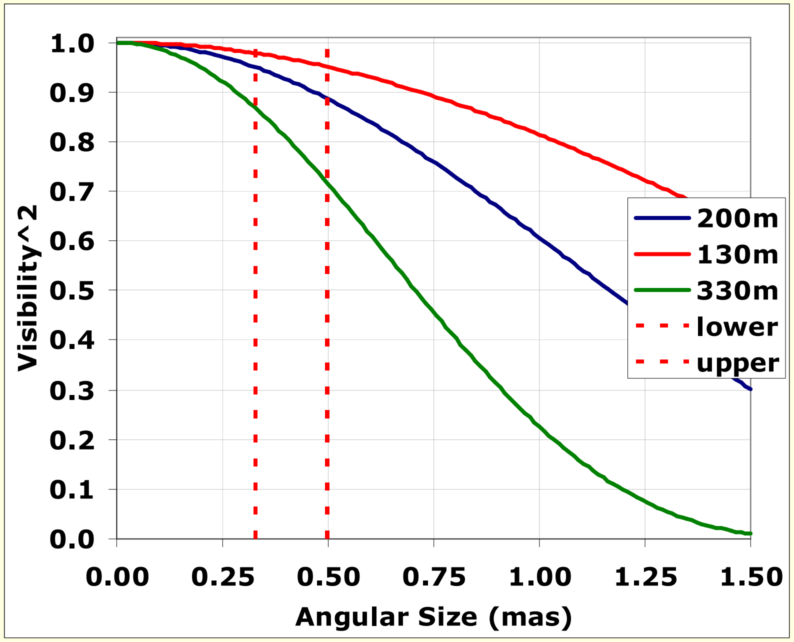


Thought #6: You Should Be Skeptical of Everything I Just Said

It’s OK to be mildly alarmed here

Key Limitations

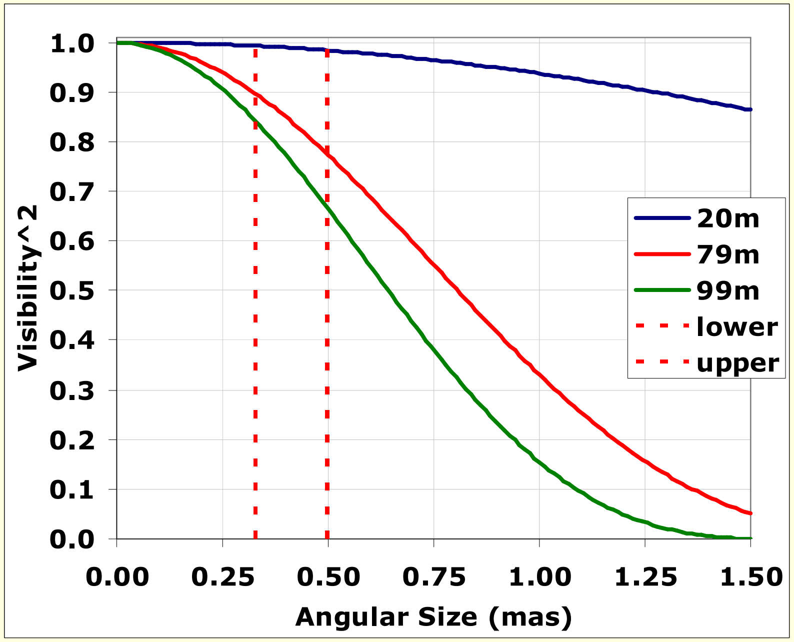
- Sensitivity
  - V<≈7 (CHARA), 5 (NPOI)
  - K<≈6
- Angular Resolution
  - For a V~4.5 B-type star, θ≈0.30 mas
  - *The more significant limitation*



CHARA, K-band operation, 330-m

Key Limitations

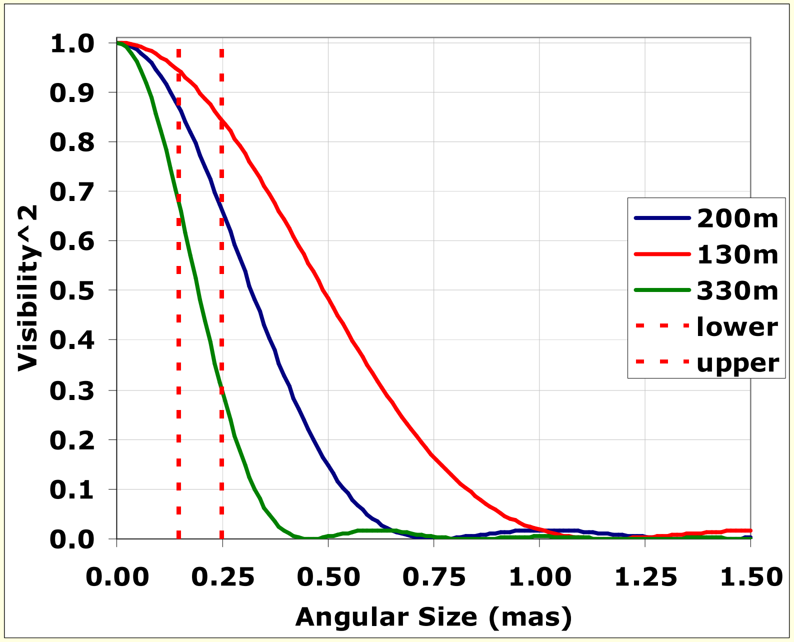
- Sensitivity
  - V<≈7 (CHARA), 5 (NPOI)
  - K<≈6
- Angular Resolution
  - For a V~4.5 B-type star, θ≈0.30 mas
  - *The more significant limitation*



NPOI, V-band operation, 99-m

Key Limitations: Improvements

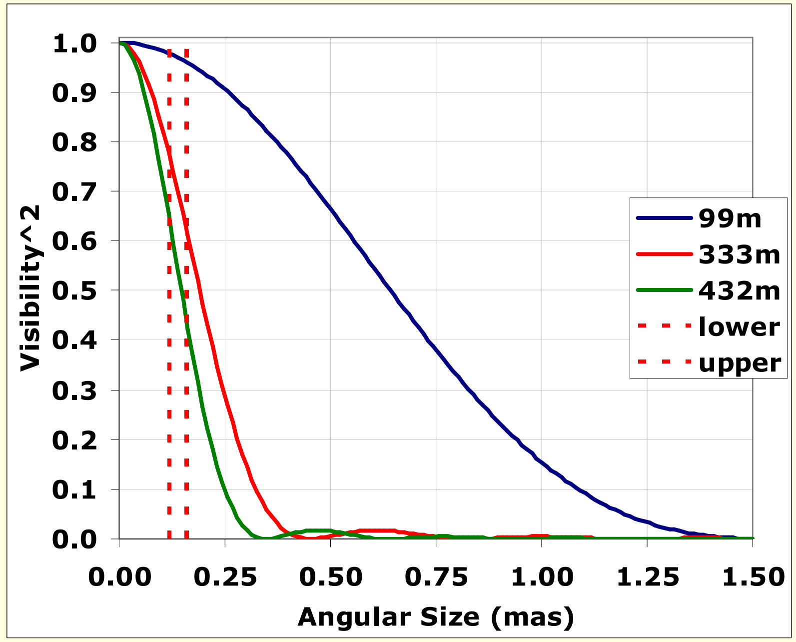
- Sensitivity
  - V<≈7 (CHARA), 5 (NPOI)
  - K<≈6
- Angular Resolution
  - For a V~4.5 B-type star, θ≈0.30 mas



CHARA, V-band operation, 330-m

Key Limitations: Improvements

- Sensitivity
  - V<≈7 (CHARA), 5 (NPOI)
  - K<≈6
- Angular Resolution
  - For a V~4.5 B-type star, θ≈0.30 mas
- Excellent overlap with asteroseismology targets (Cunha & Aerts et al. 2007)



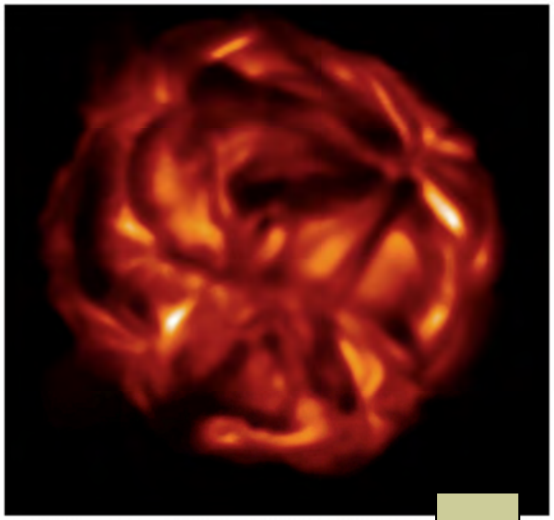
NPOI, V-band operation, 432-m

Thought #7: Many Exciting Things on the Horizon

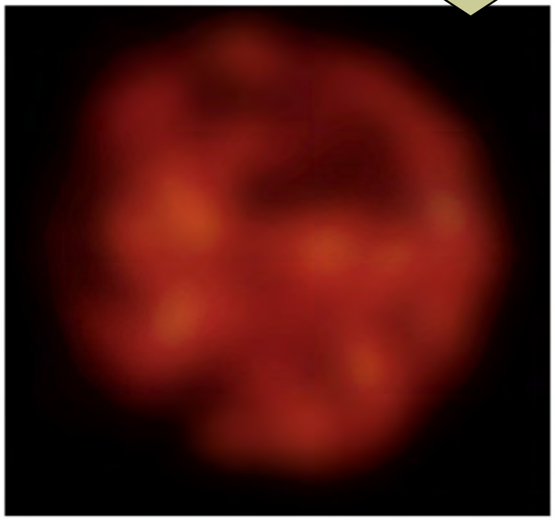
Just to whet your appetite

Stellar Surface Mapping

- RSG surfaces are thought to be dominated by large convection cells (Schwarzschild 1975)
- Direct imaging of these features should be possible with NPOI, CHARA, VLTI
  - Time-evolution → *movies*



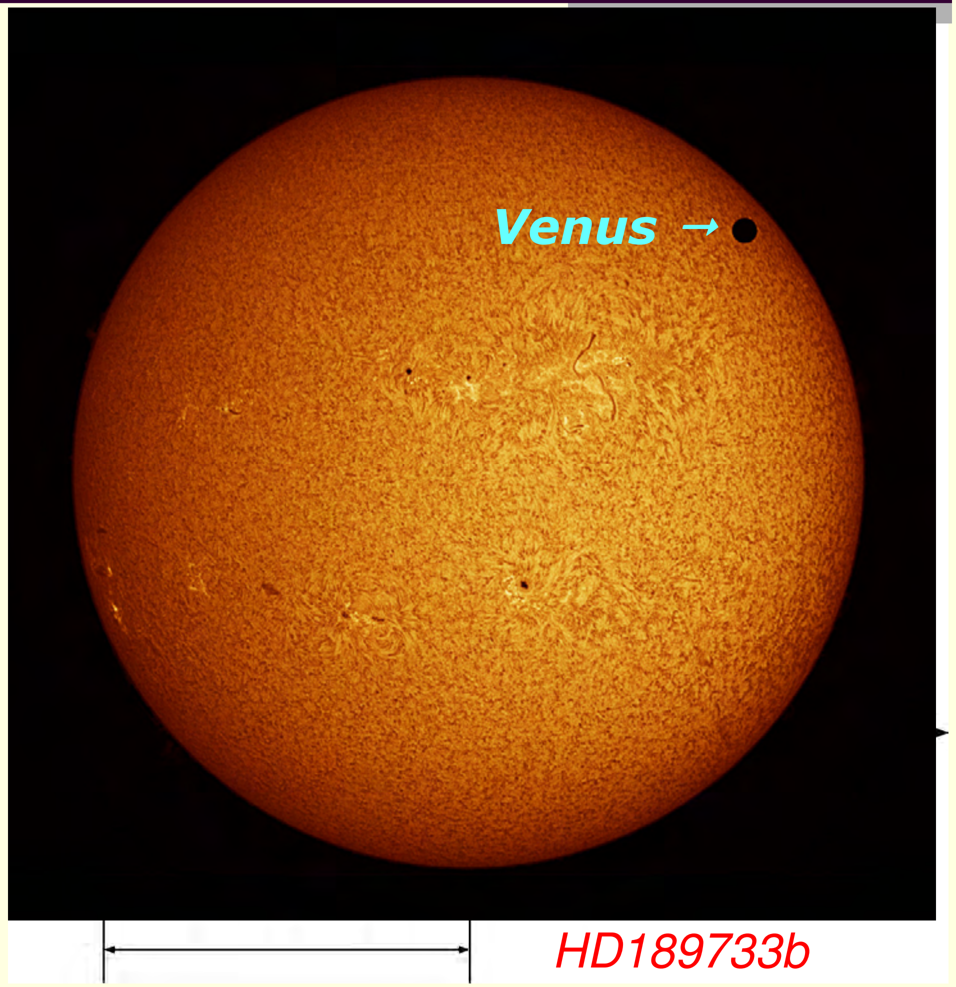
Freytag simulation (Chiavassa+ 2010)



6×6 pixel imaging (NPOI 2014?)

Next Big Thing: Imaging Exoplanet Transits

- CHARA, NPOI, VLTI can observe exoplanet transits
- Planet's shadow is 'perfect' star spot
- λ-specific observations → atmospheric composition
- Extreme challenge: ΔCP~0.1-0.01 °



HD189733b Theory paper: van Belle 2008

Summary

- Interferometry is Inevitable
- All Telescopes are Interferometers
- Long-baseline Interferometers Have Loads of Resolution
- Key Observables
  - Visibility – Fringe amplitude → Spatial scales
  - Closure Phase – Fringe(s) position → Asymmetries
  - Fourier transform of the image on sky matches these observables
- Spatially resolving stellar surfaces key to tests of theory, new discoveries


Haben Sie
Fragen?
WELCOME TO
OKTOBERFEST
FAT TIRE
HOPTOBER