

2>1: Using Binaries to Learn about Exoplanets

A person is seen from behind, standing on a beach and looking out at the ocean. The sky is a deep purple and blue, suggesting twilight. Two large, bright celestial bodies are visible in the sky: a white one on the left and a red one on the right. The overall scene is serene and contemplative.

Timothy J. Rodigas

Hubble Fellow

Carnegie DTM

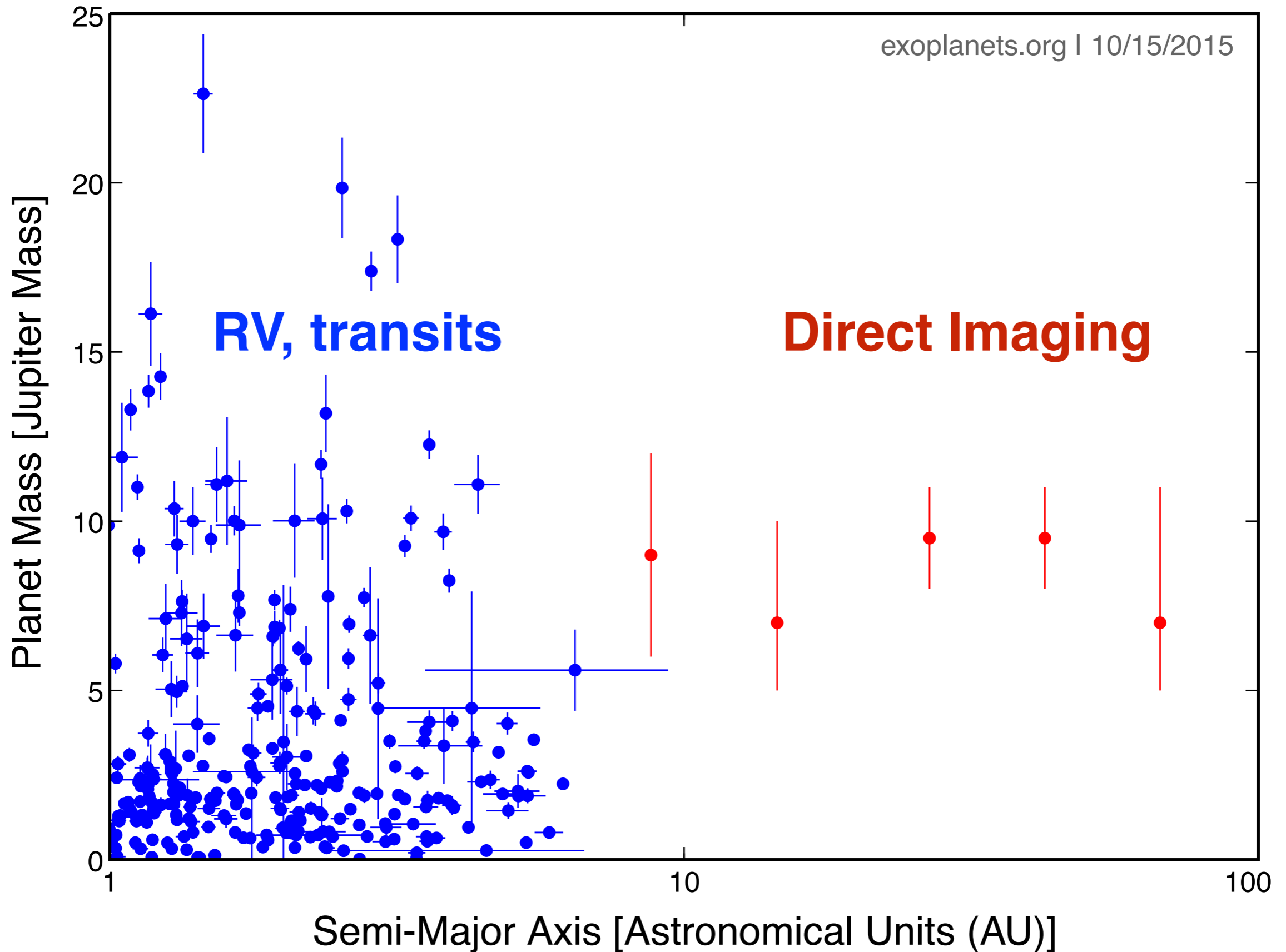
LUVOIR Seminar

September 21, 2016

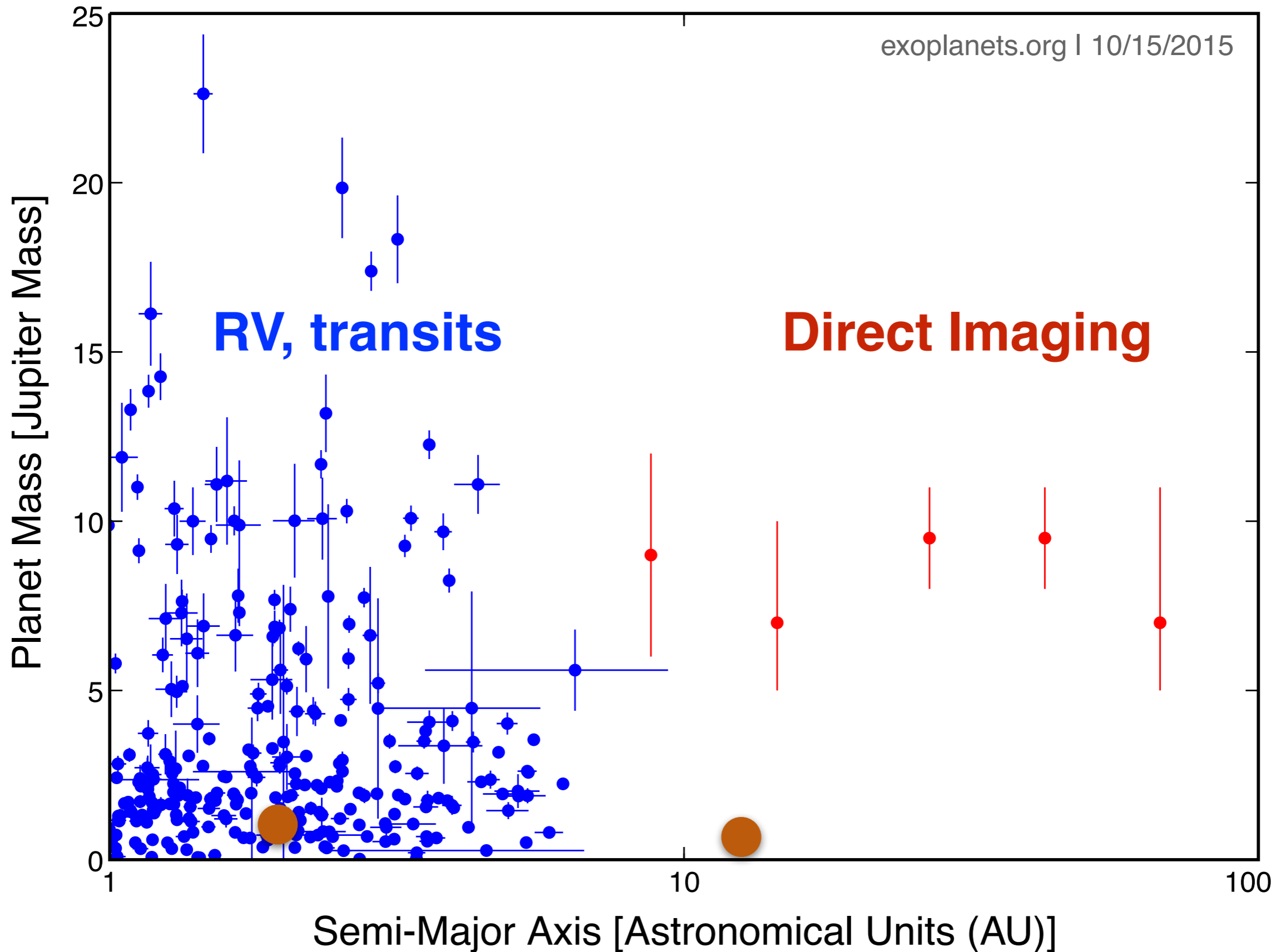
Binary power #1:

Can use binaries to image planets

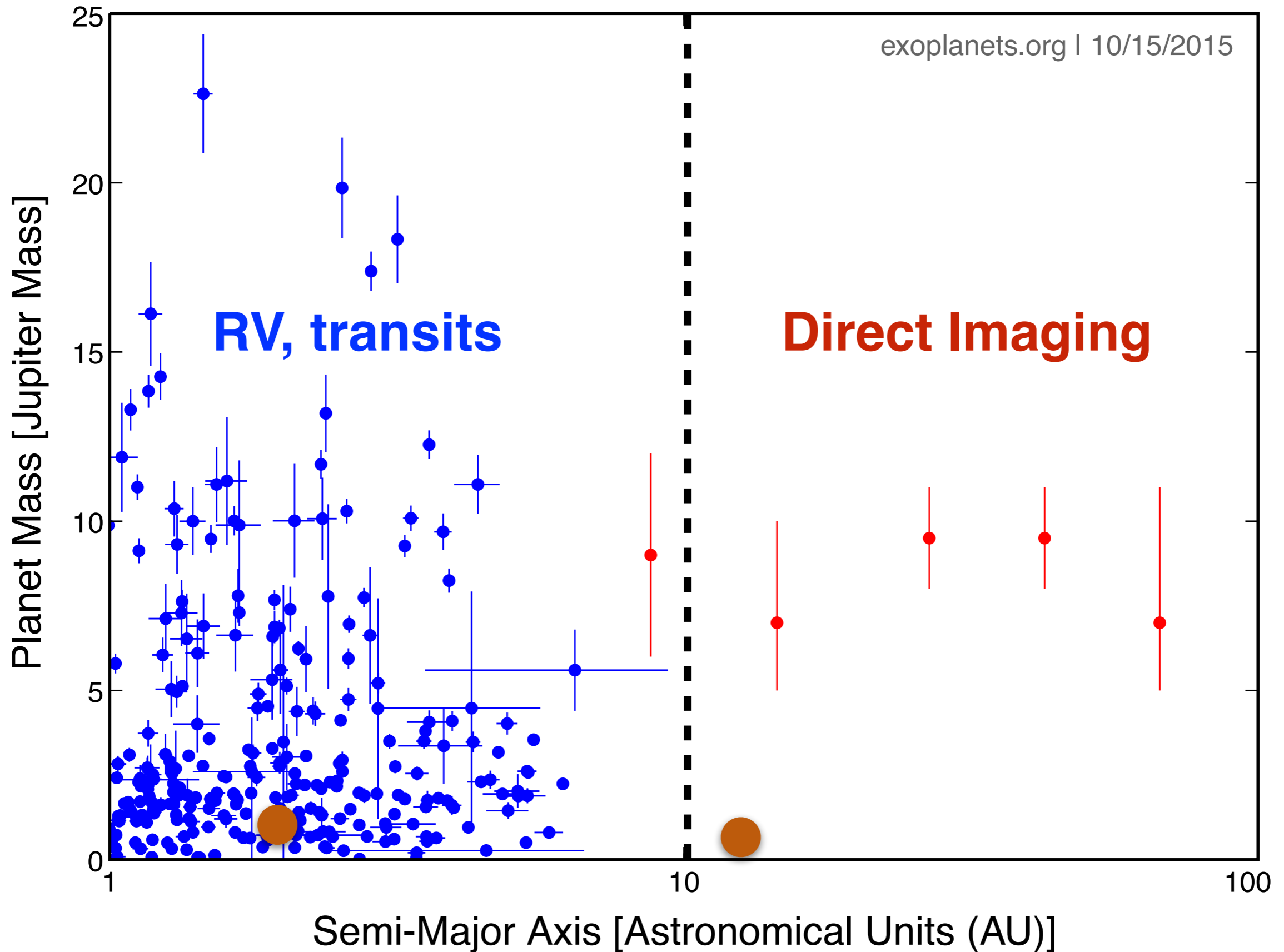
Where do planets live?



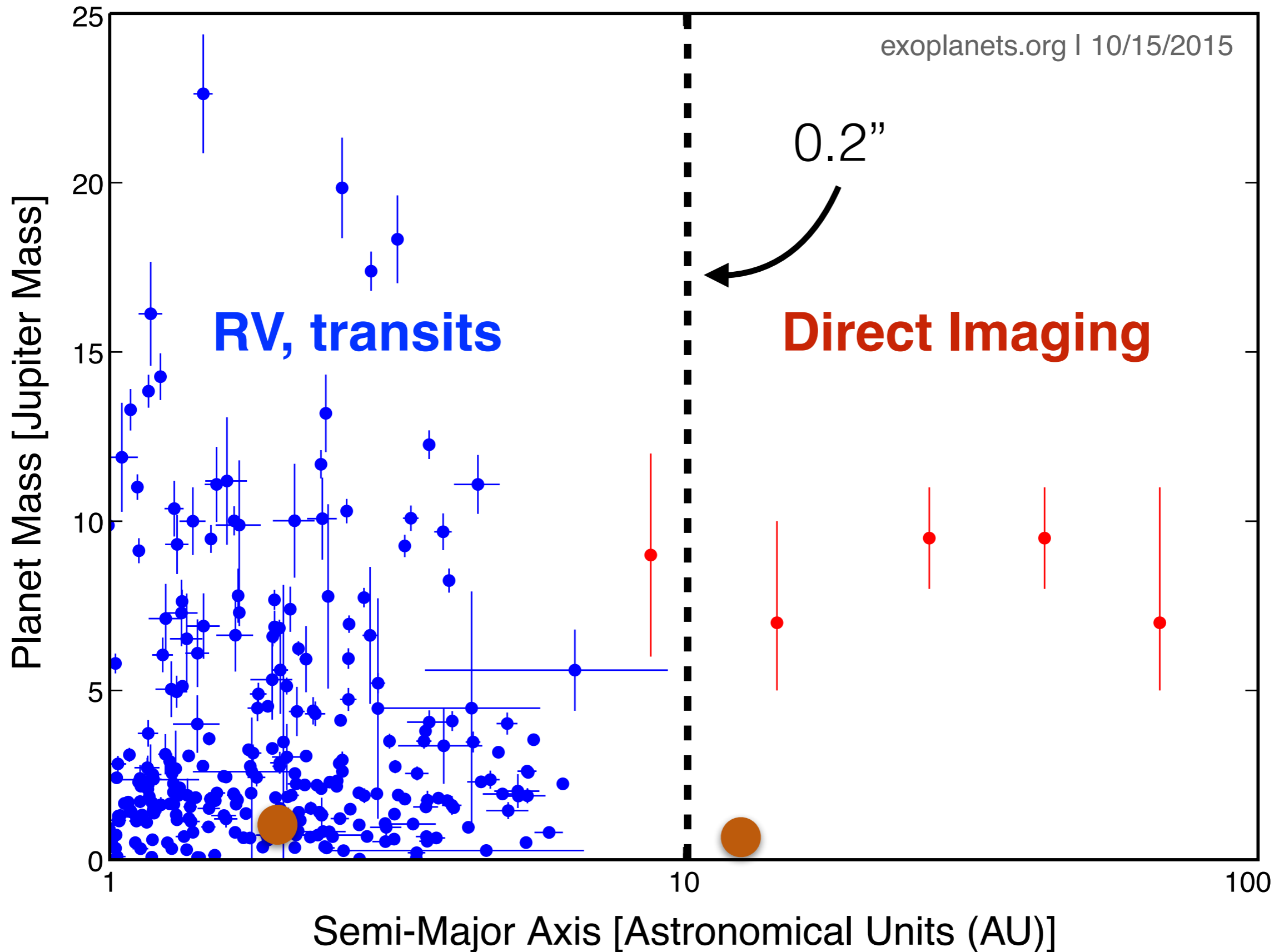
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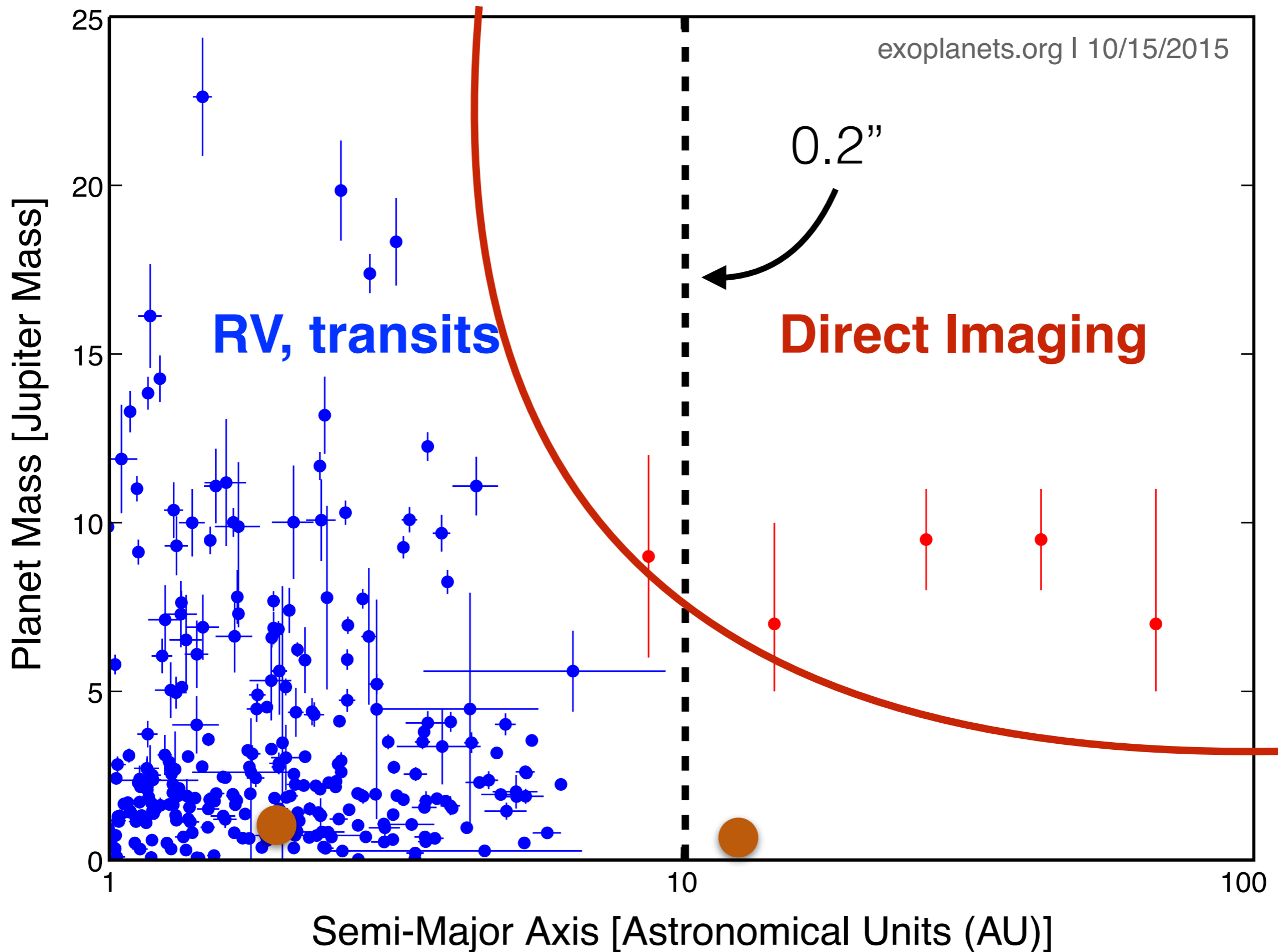
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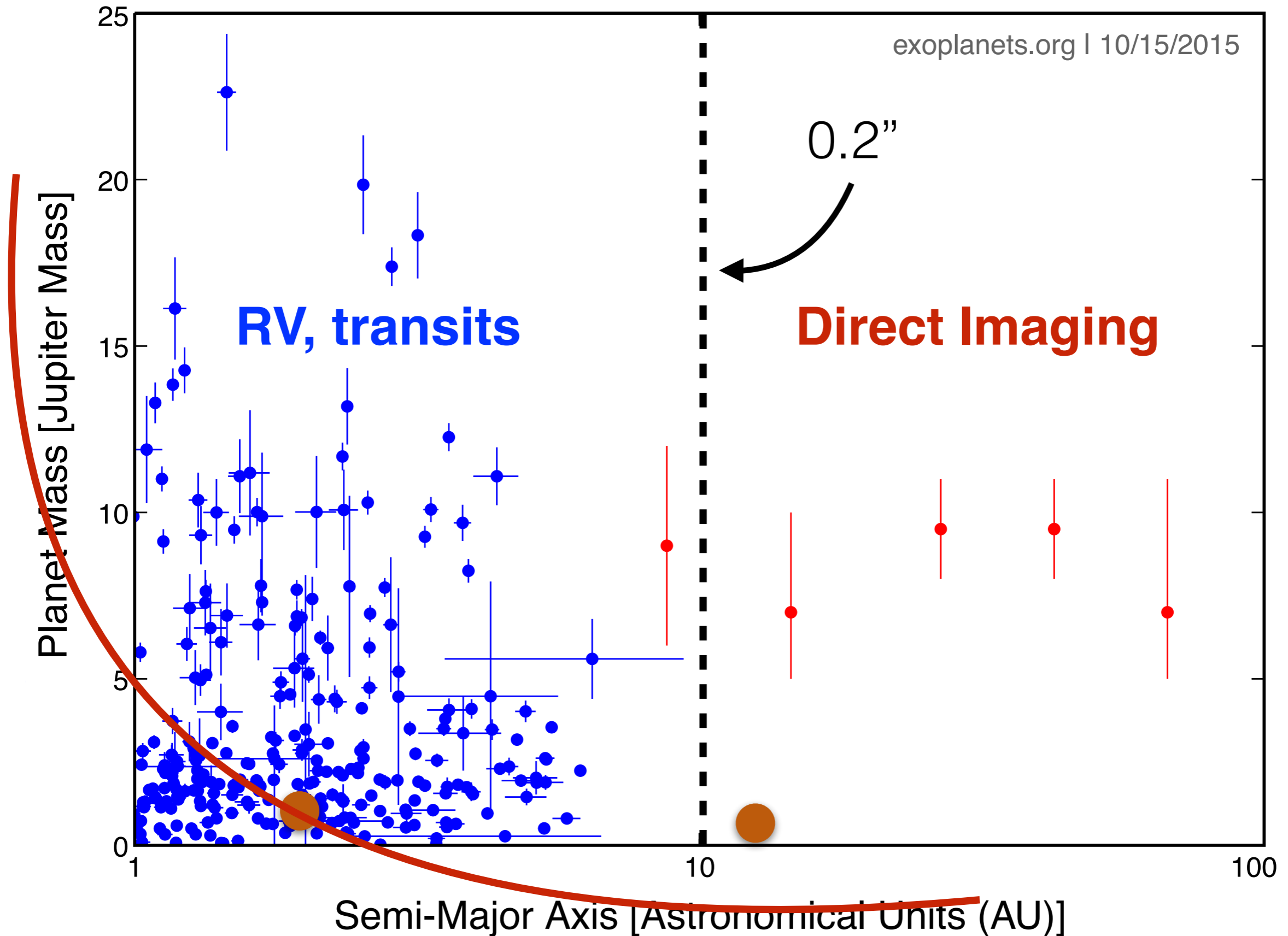
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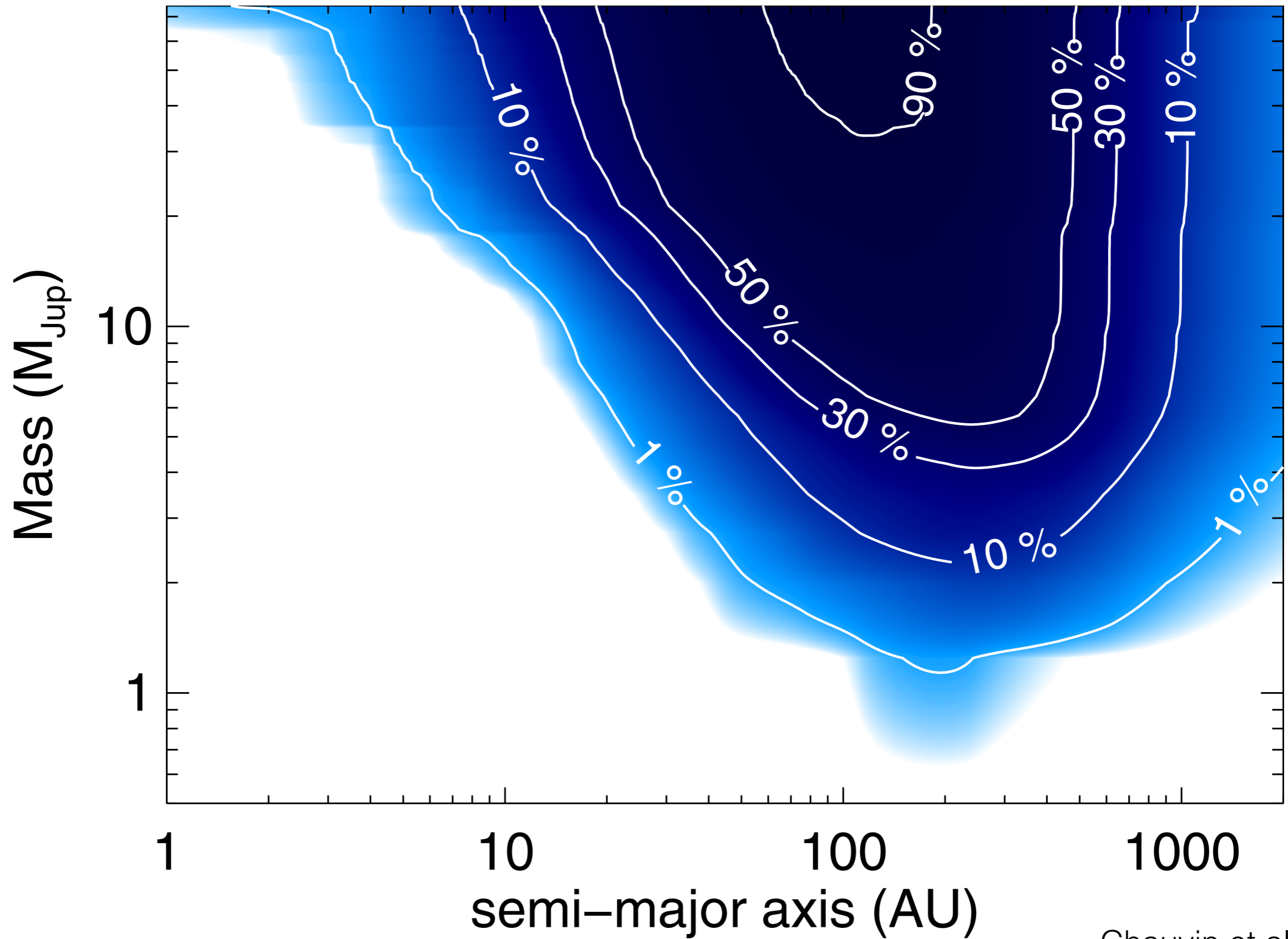
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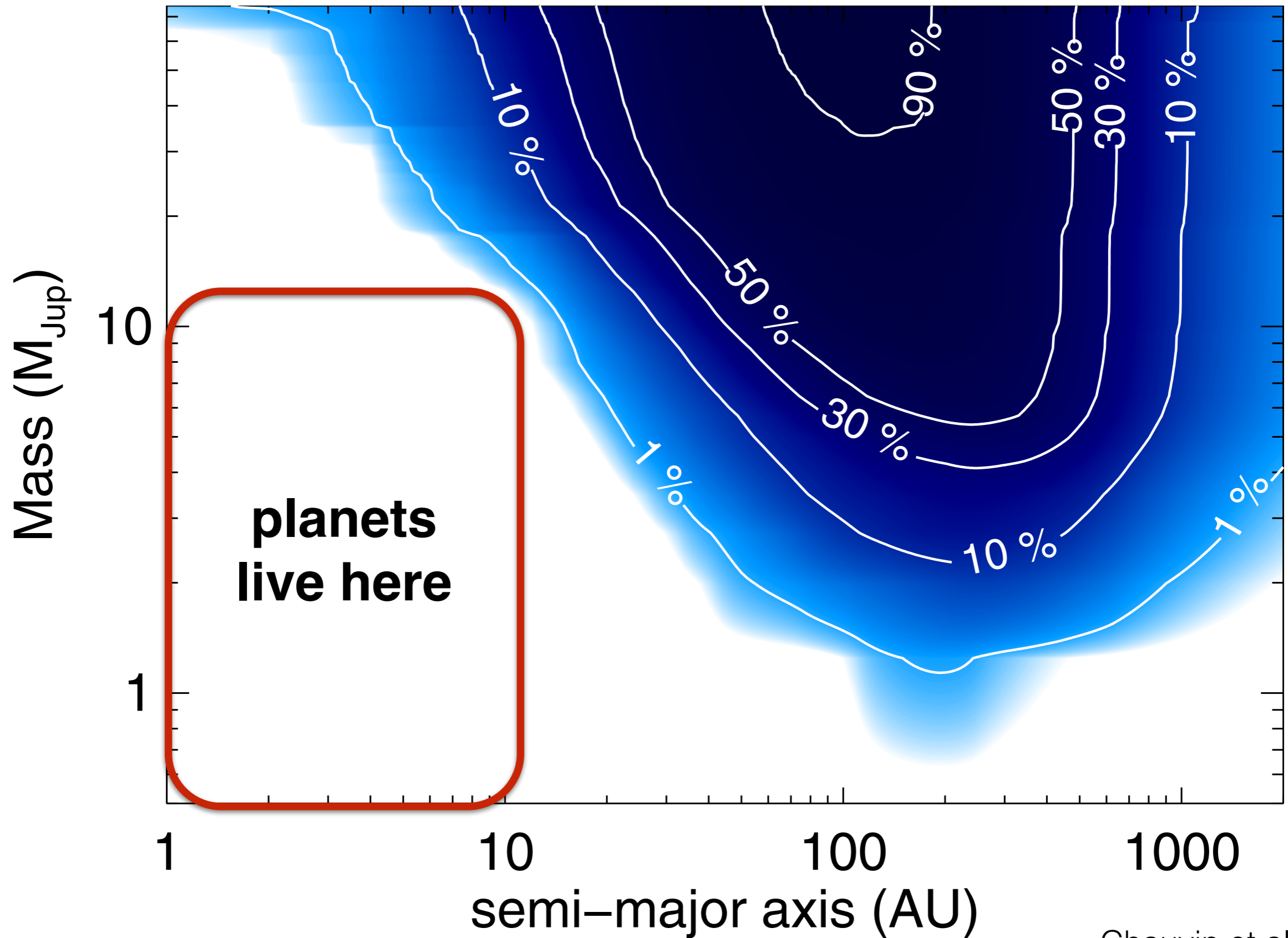
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Status Quo

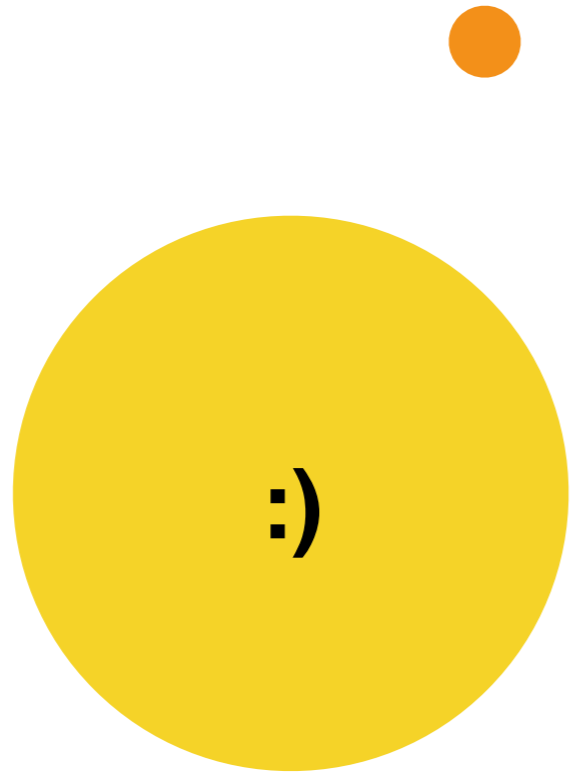


Status Quo

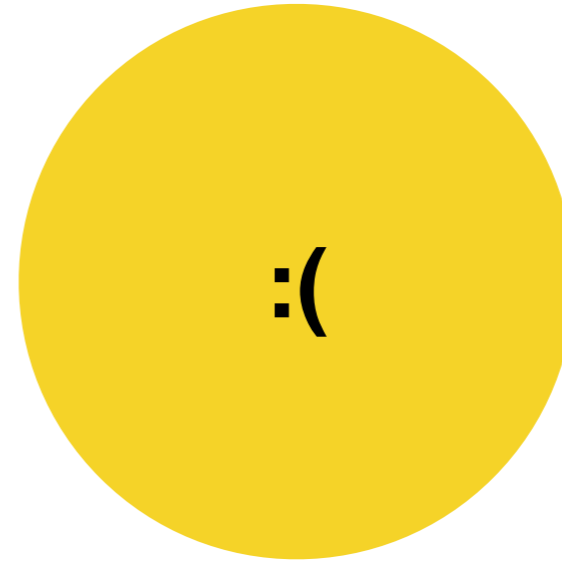
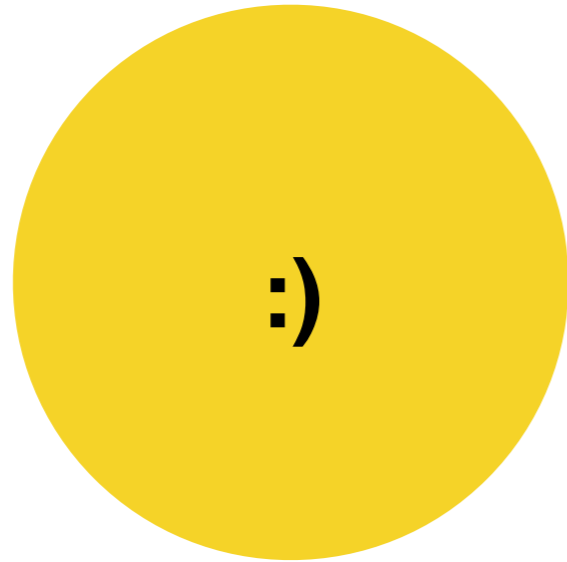


How to Image Planets

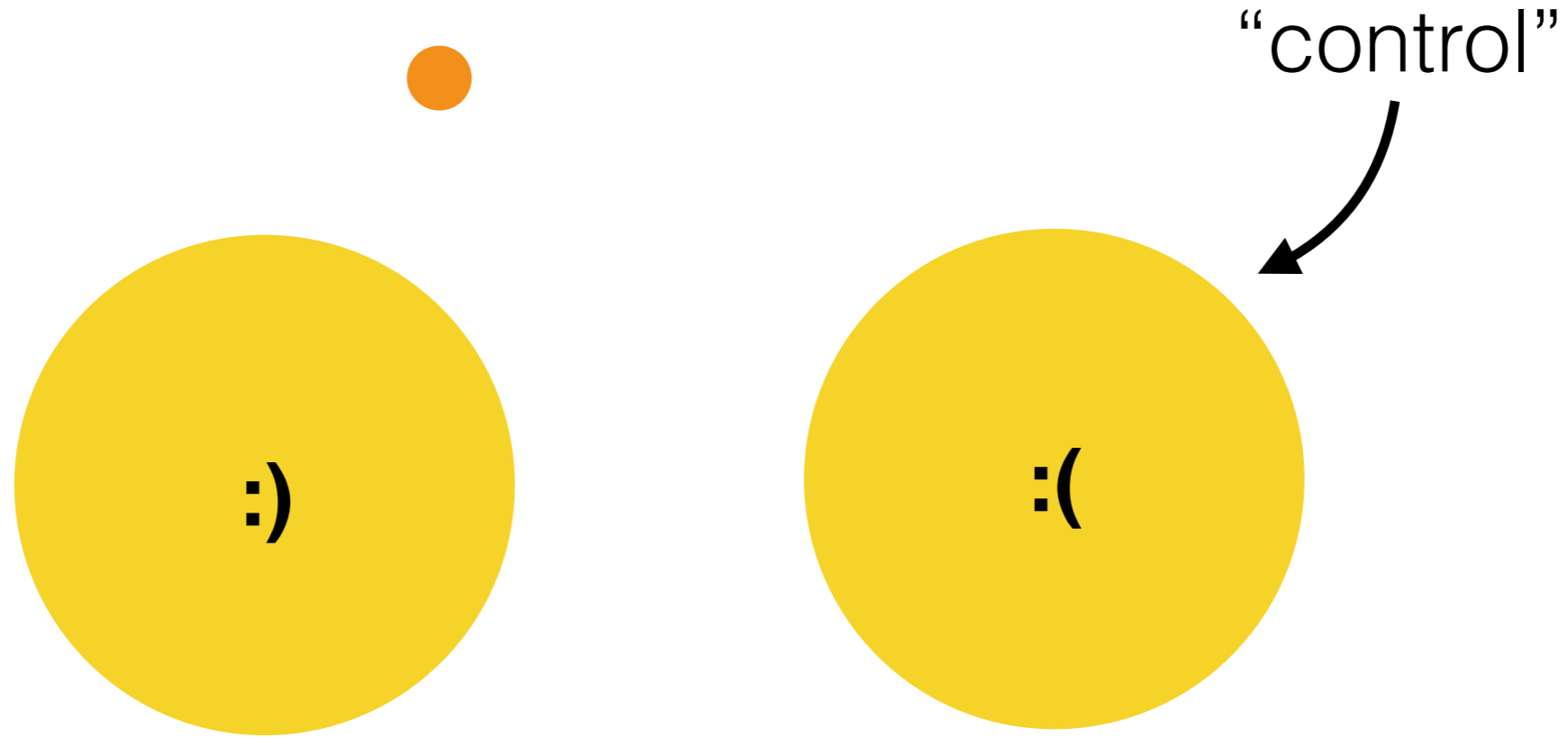
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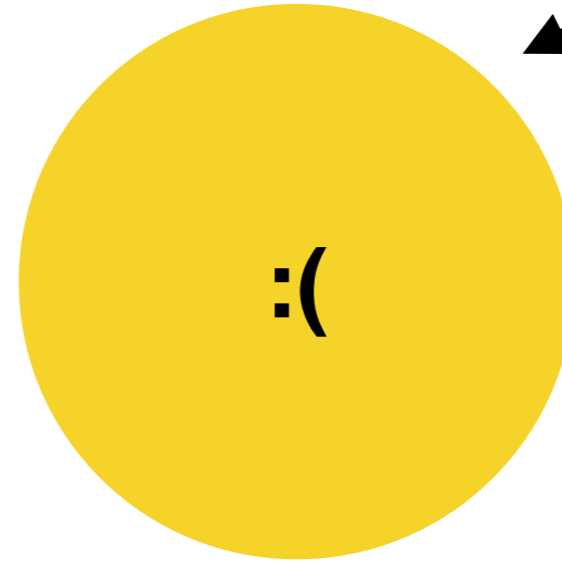
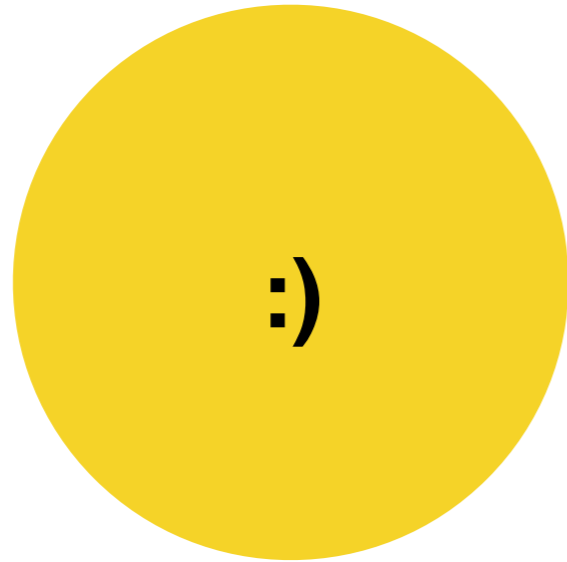
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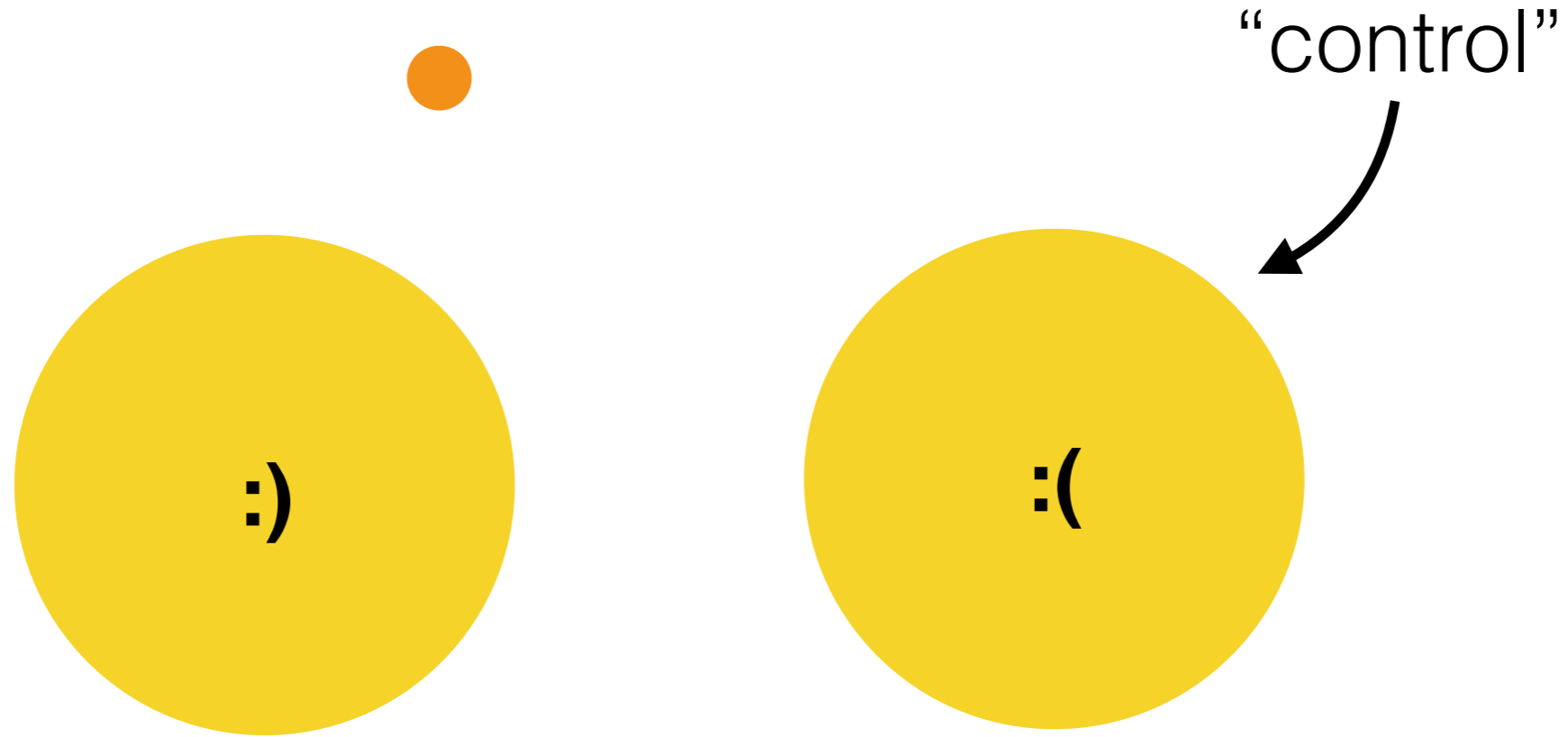
How to Image Planets



“control”

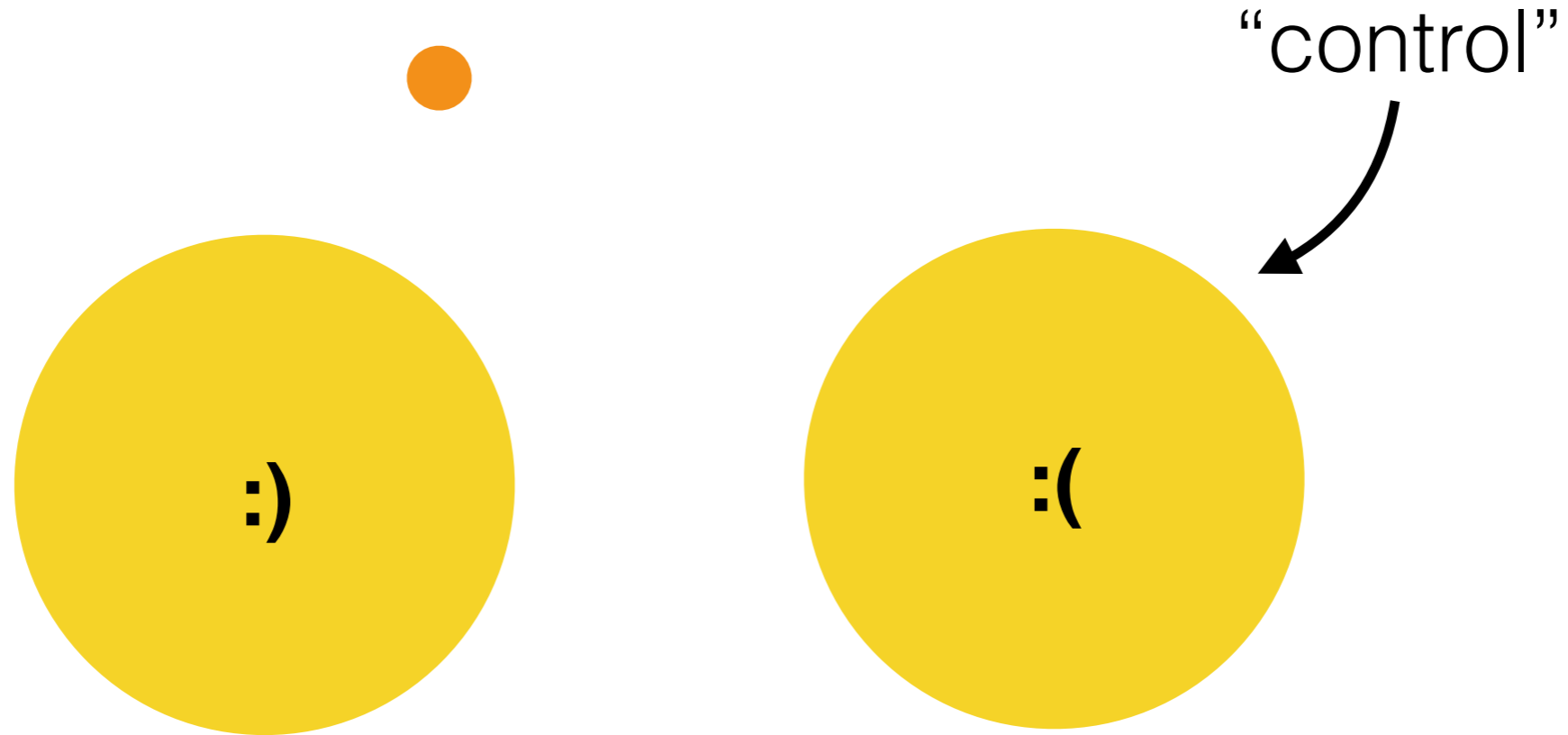


How to Image Planets



↓
A

How to Image Planets

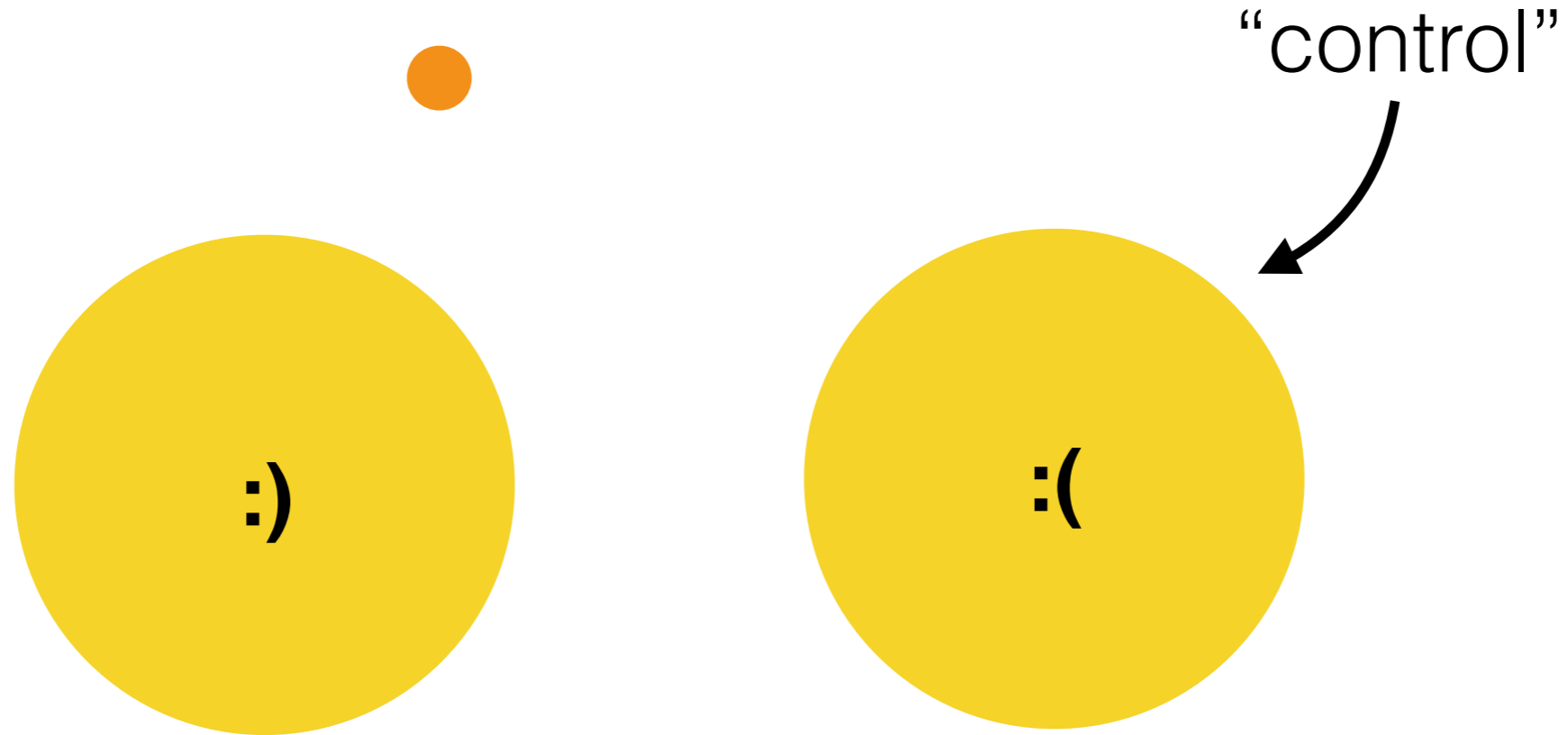


↓
A



↓
B

How to Image Planets



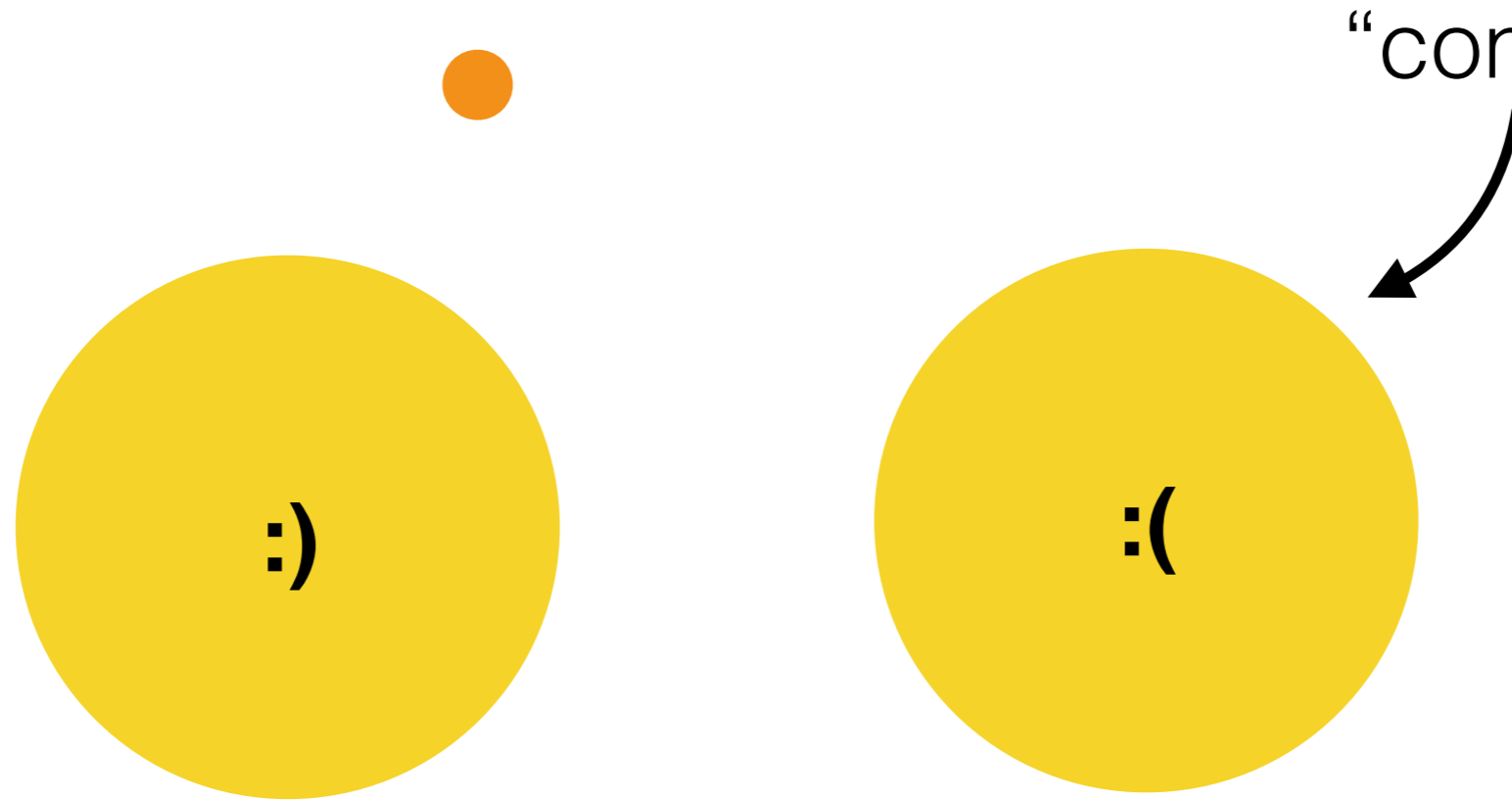
A



B

-

How to Image Planets



A

-

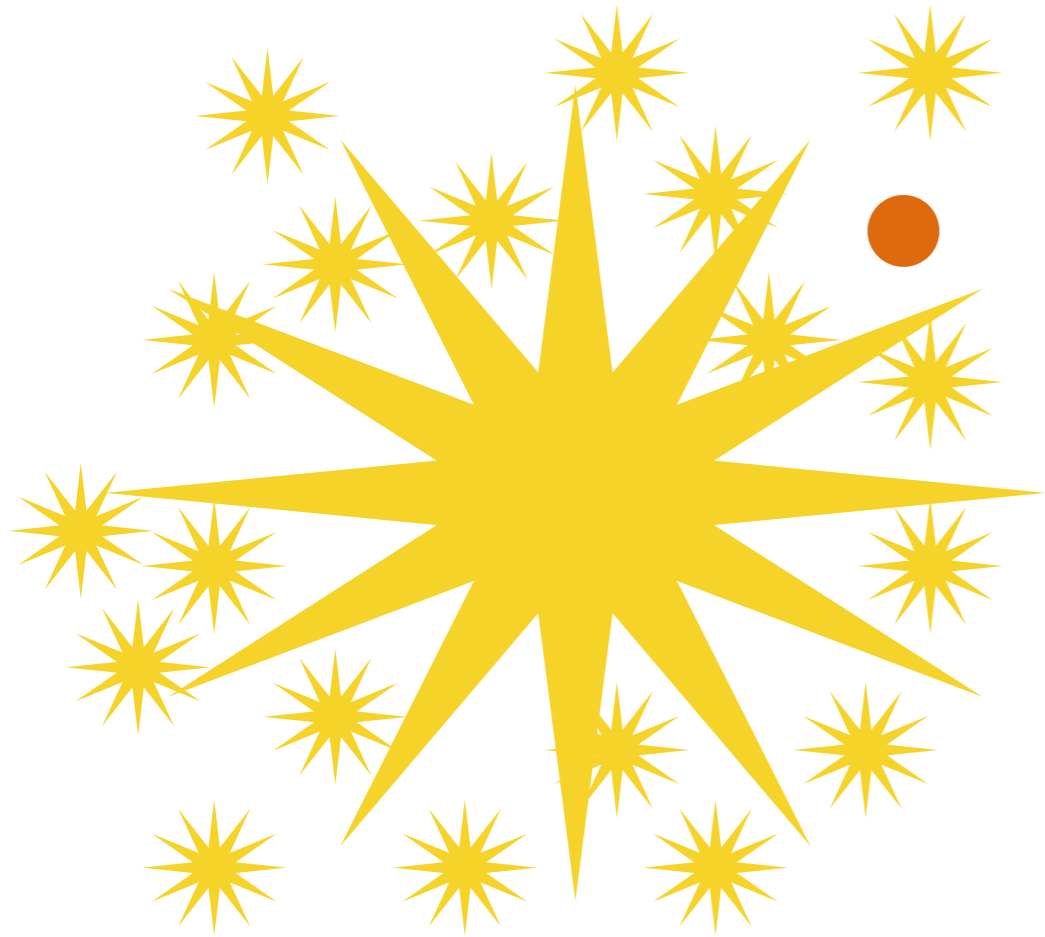


B

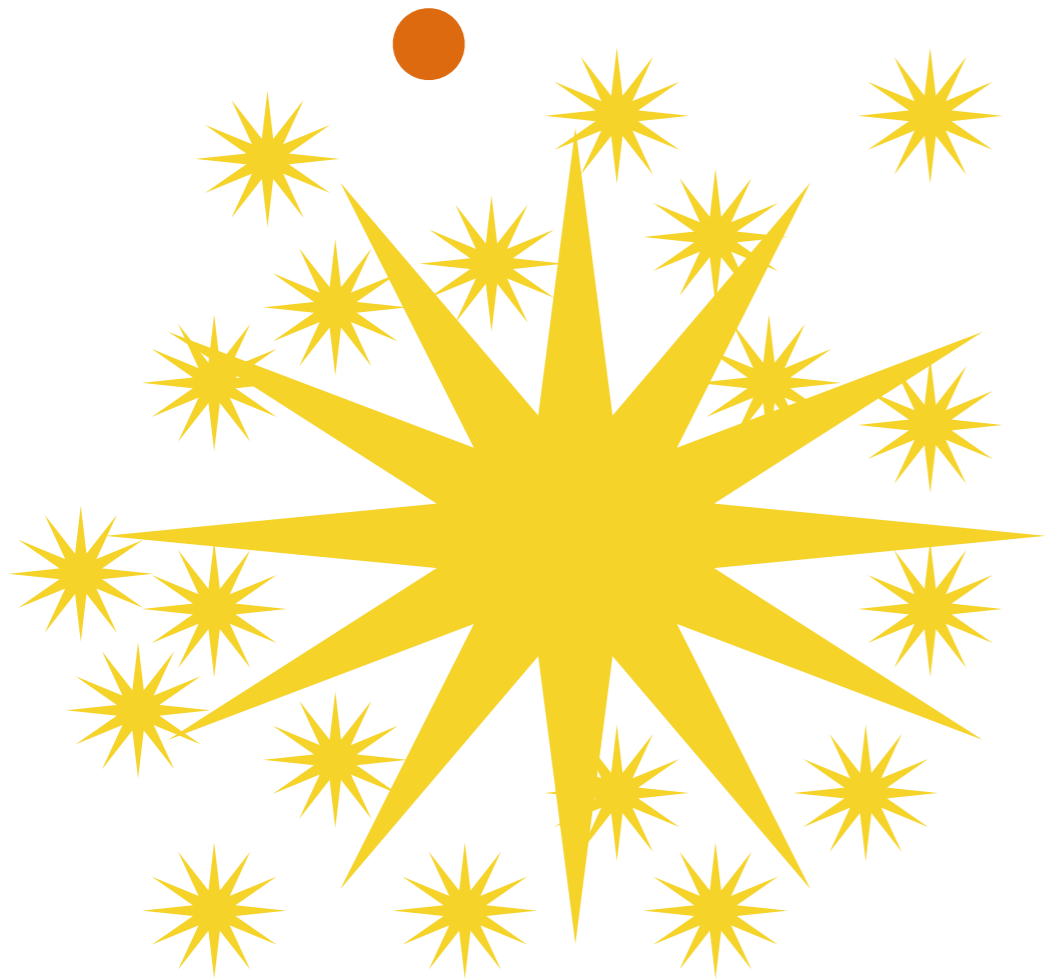
=

planet

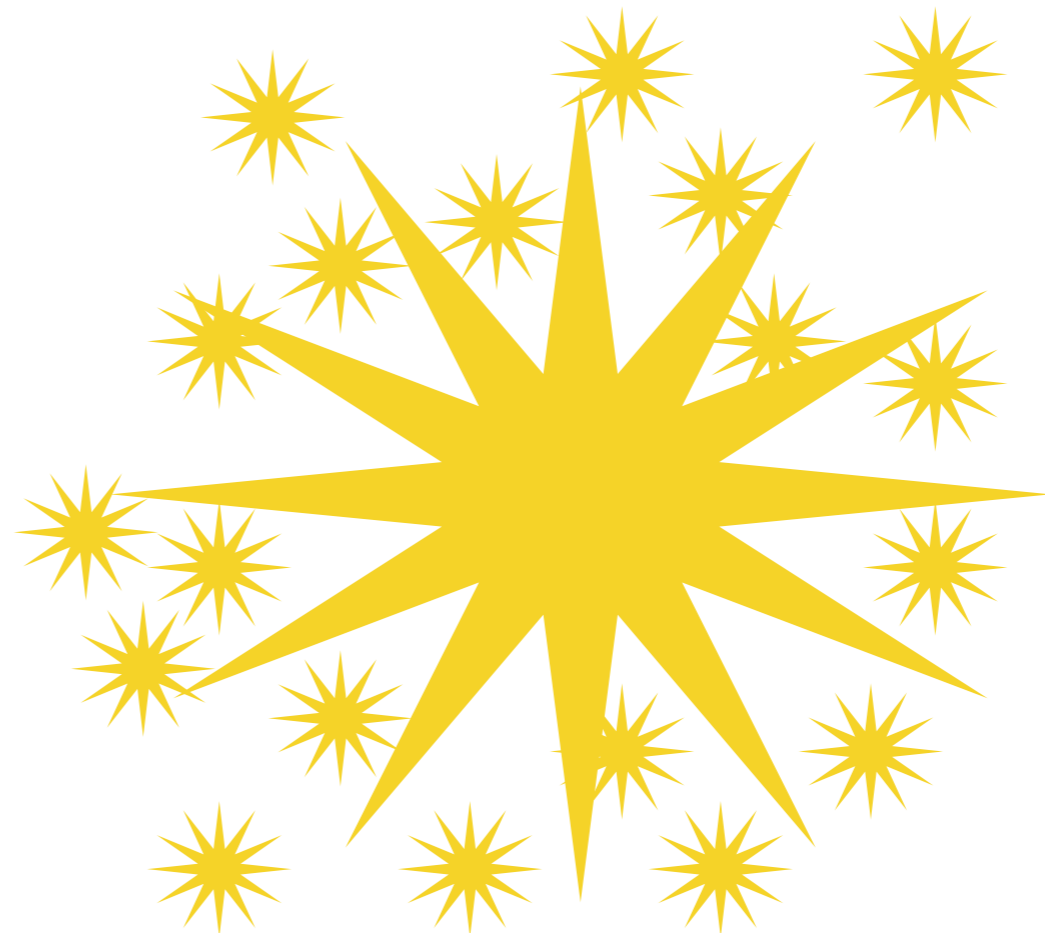
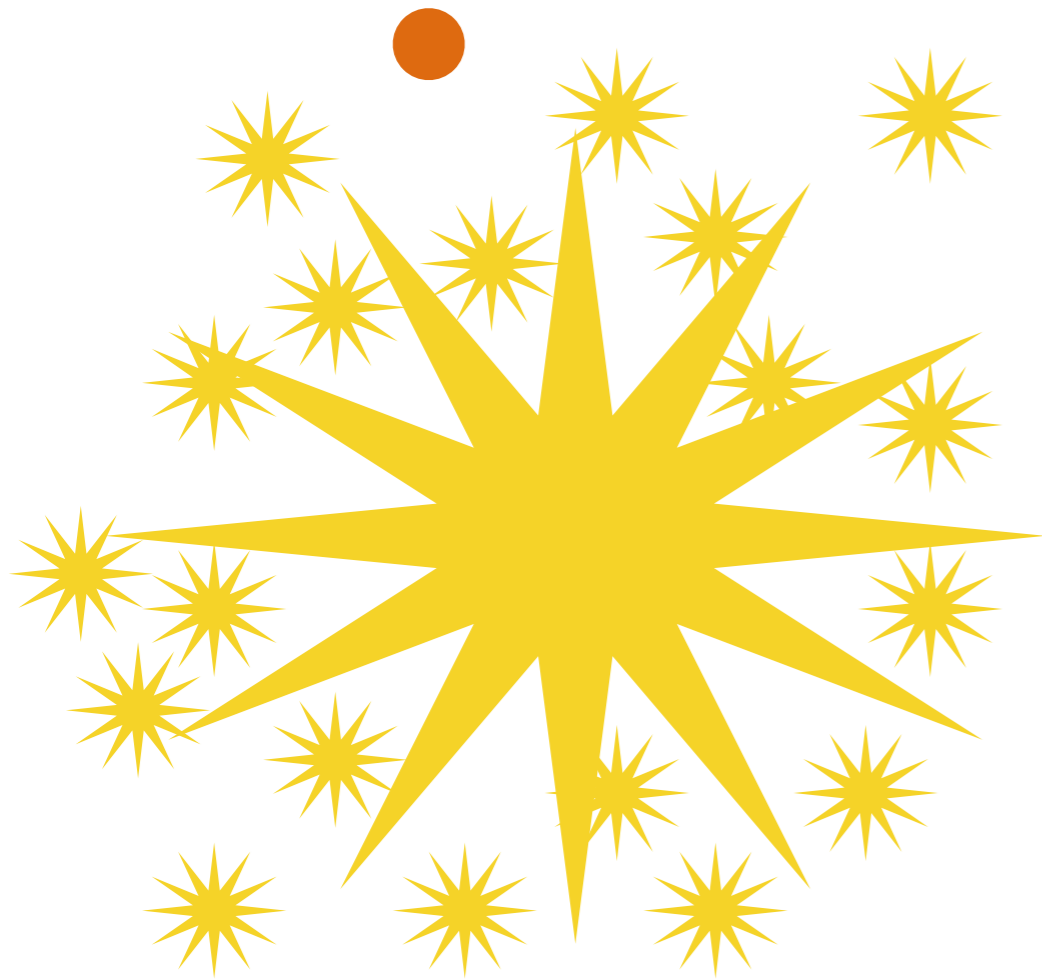
How to Image Planets: “Angular Differential Imaging” = ADI



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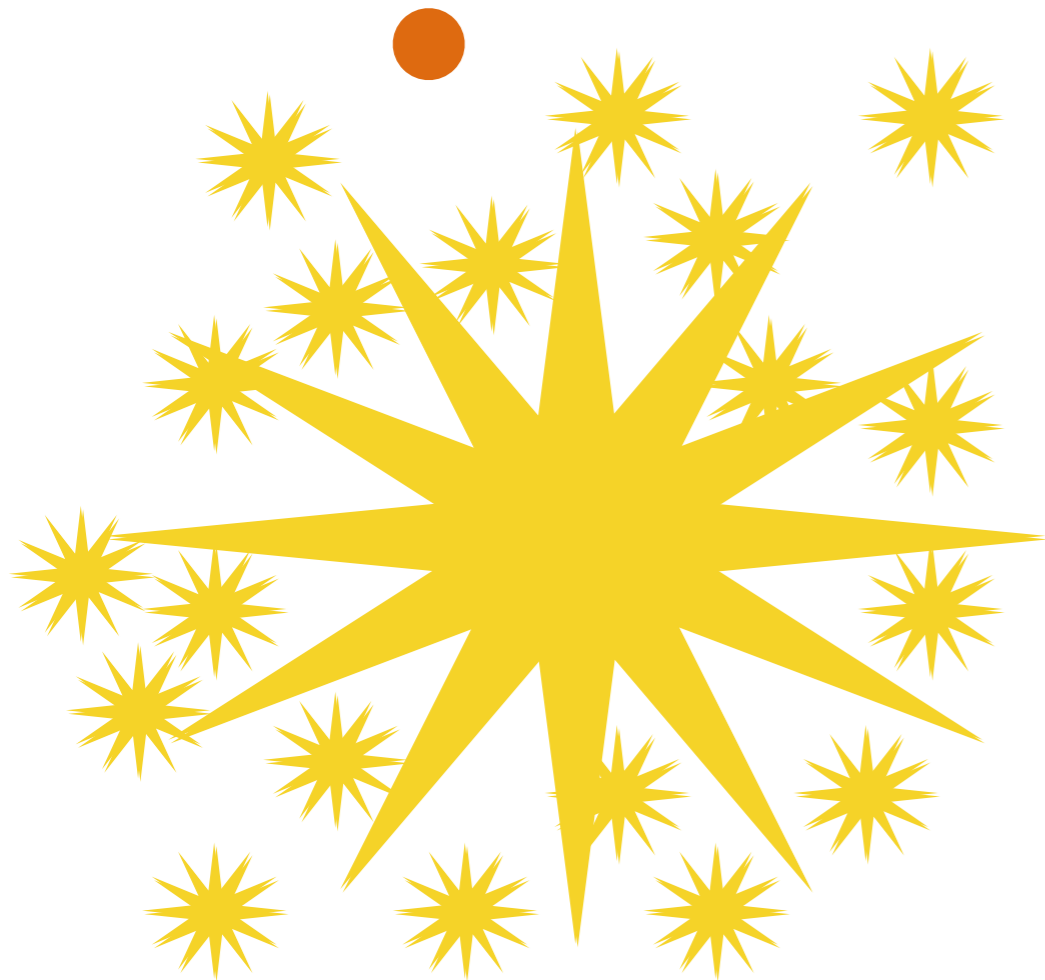


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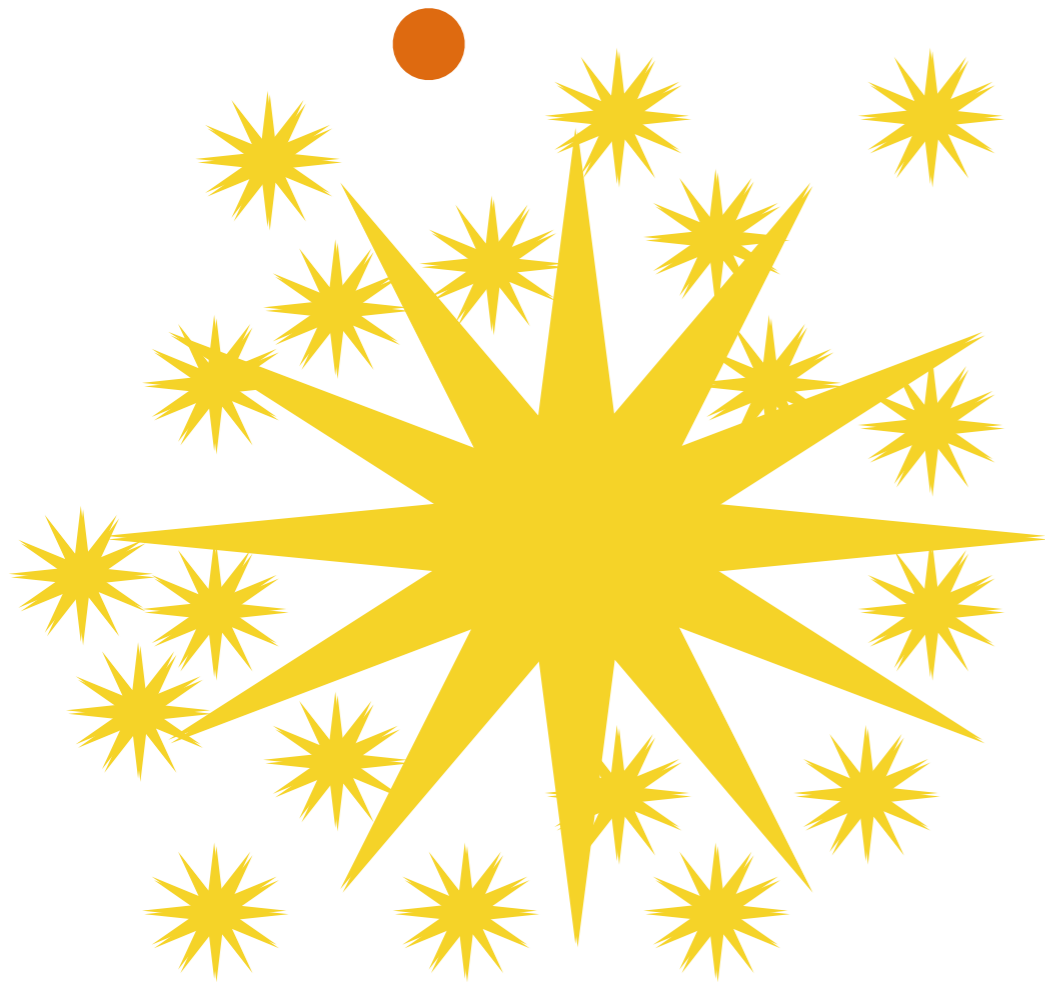
median

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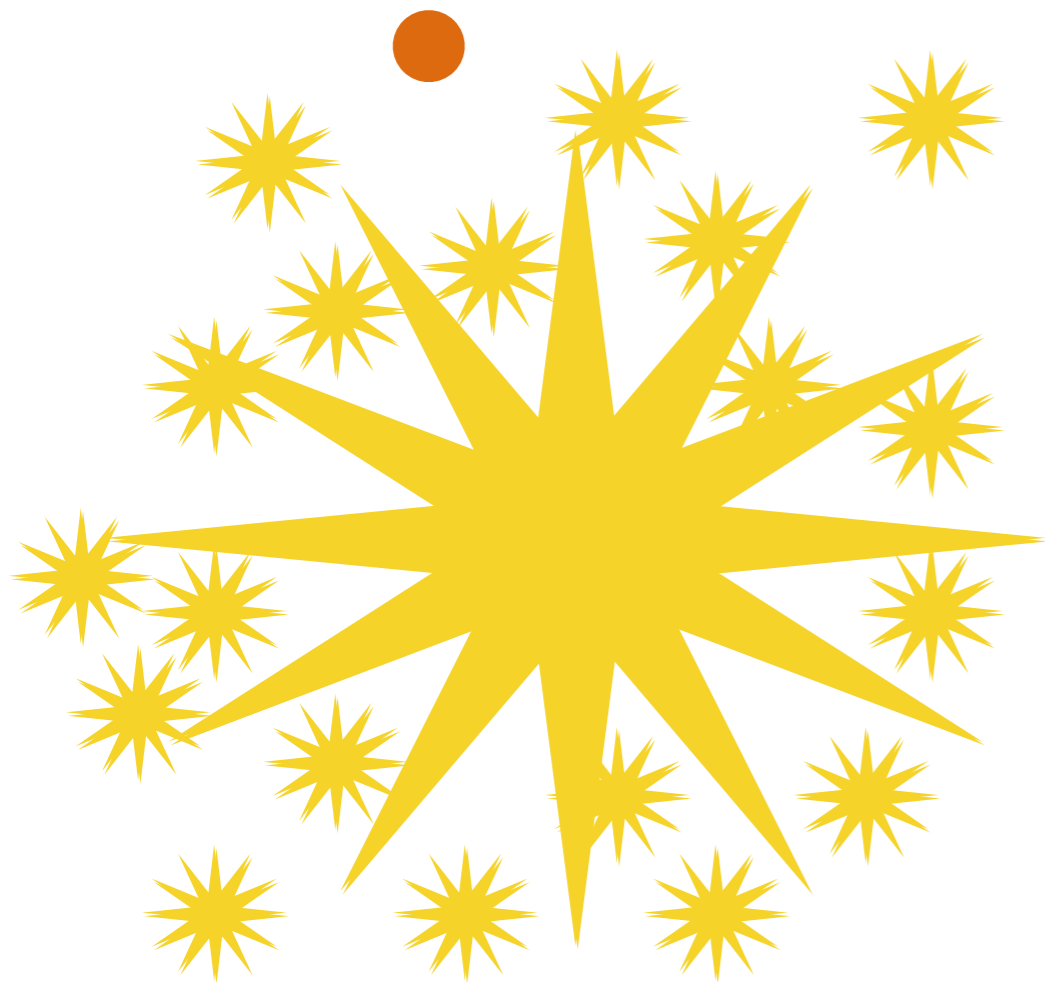
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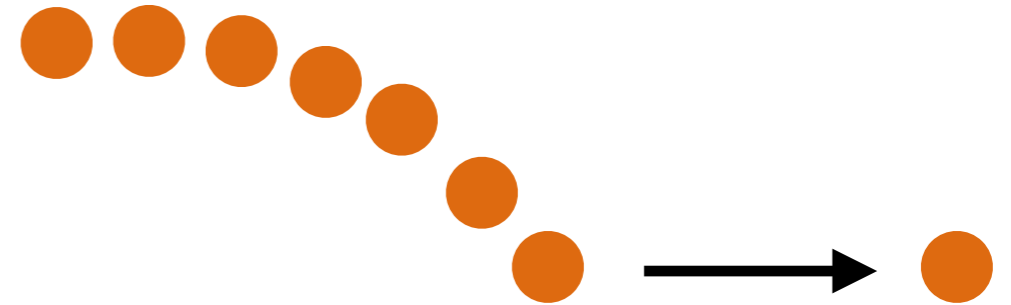
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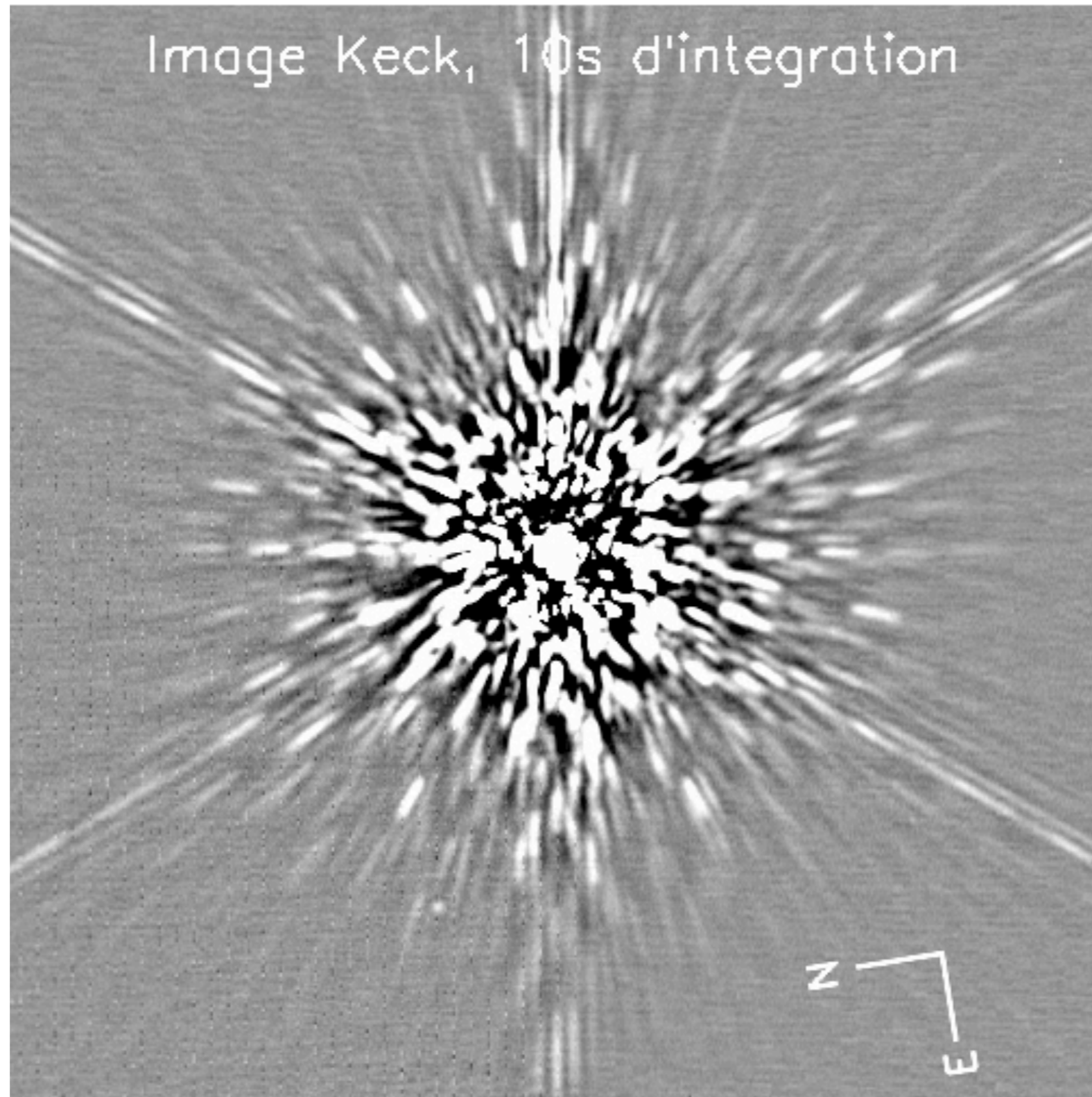
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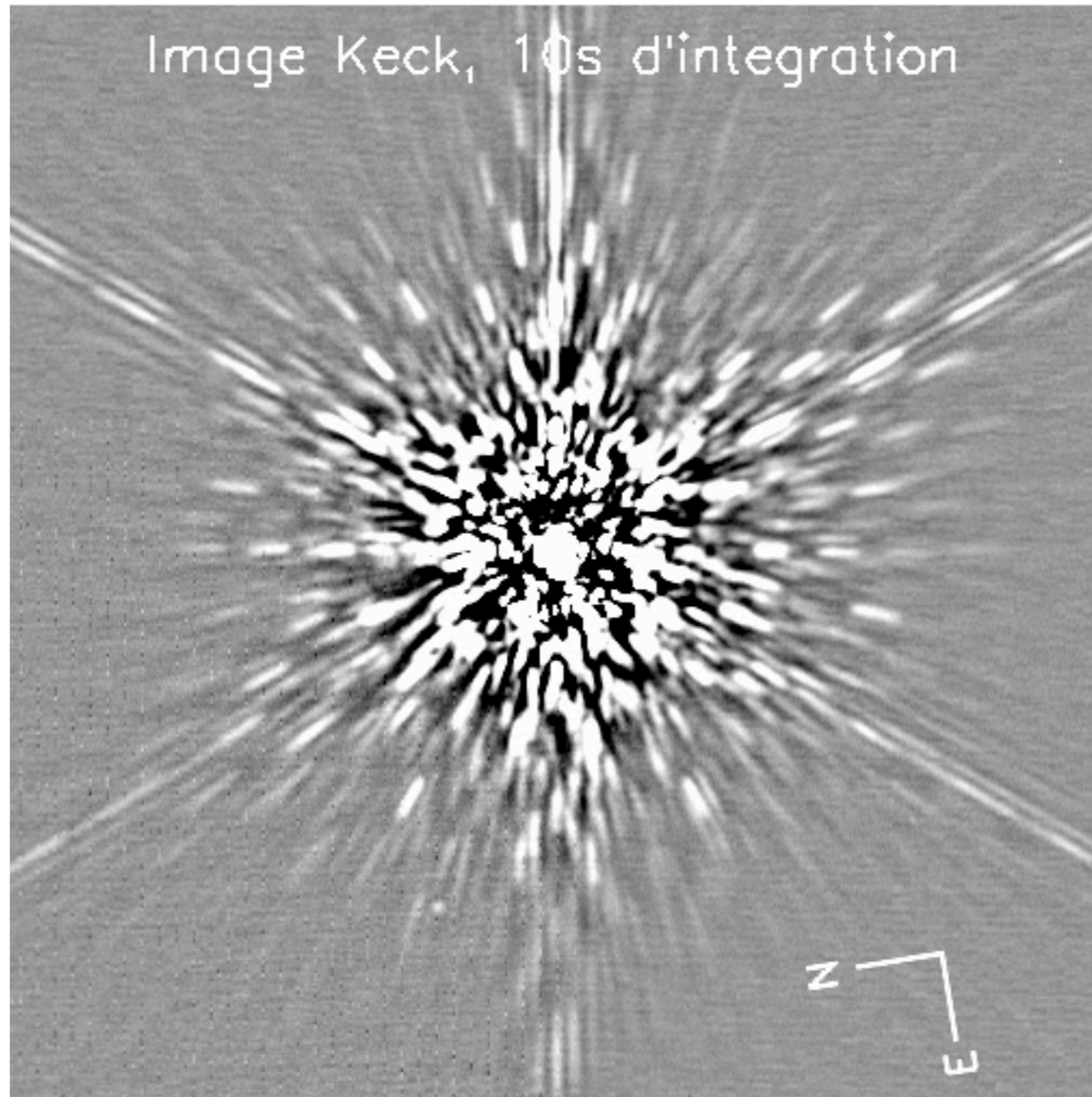
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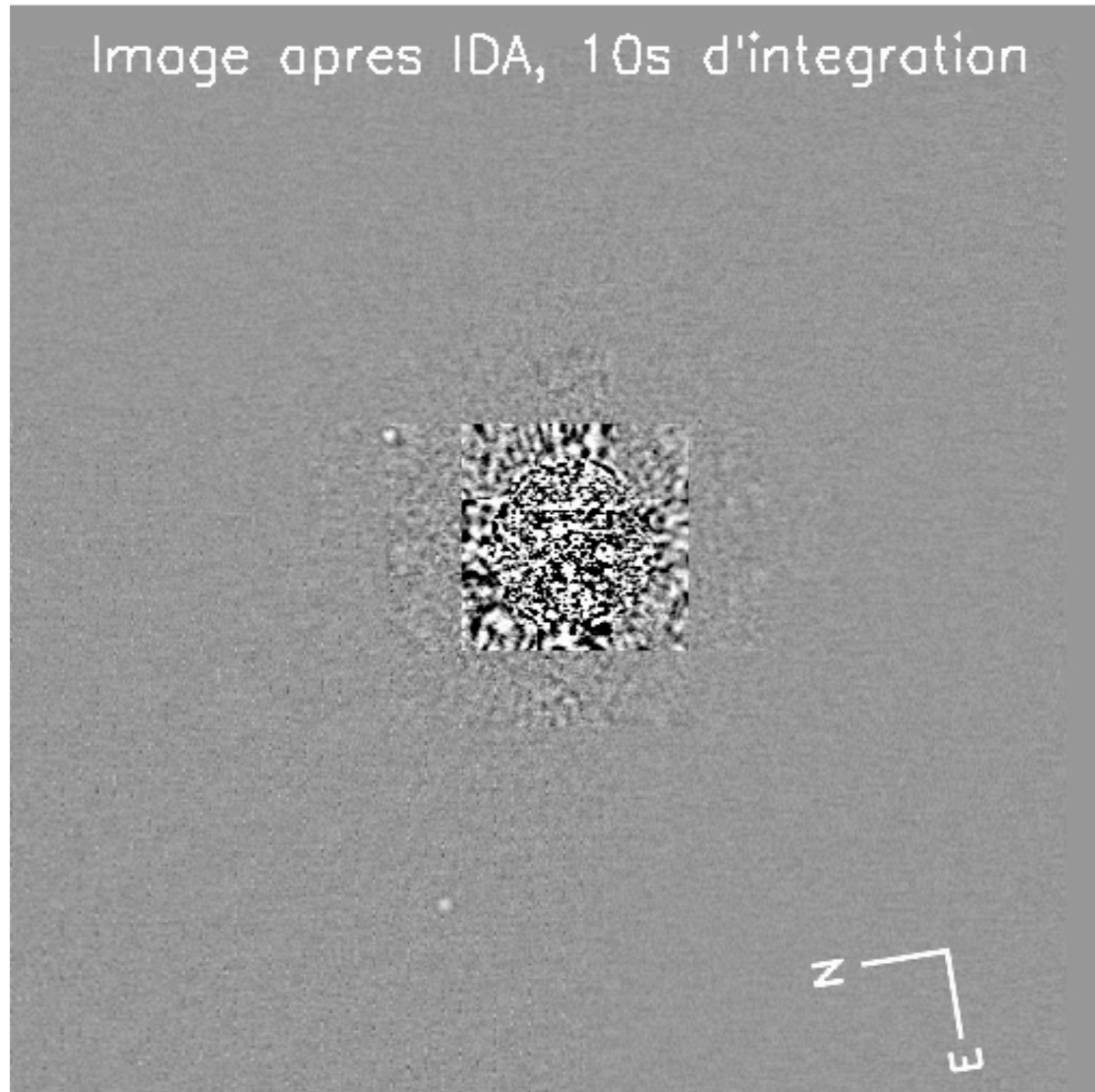
Angular Differential Imaging



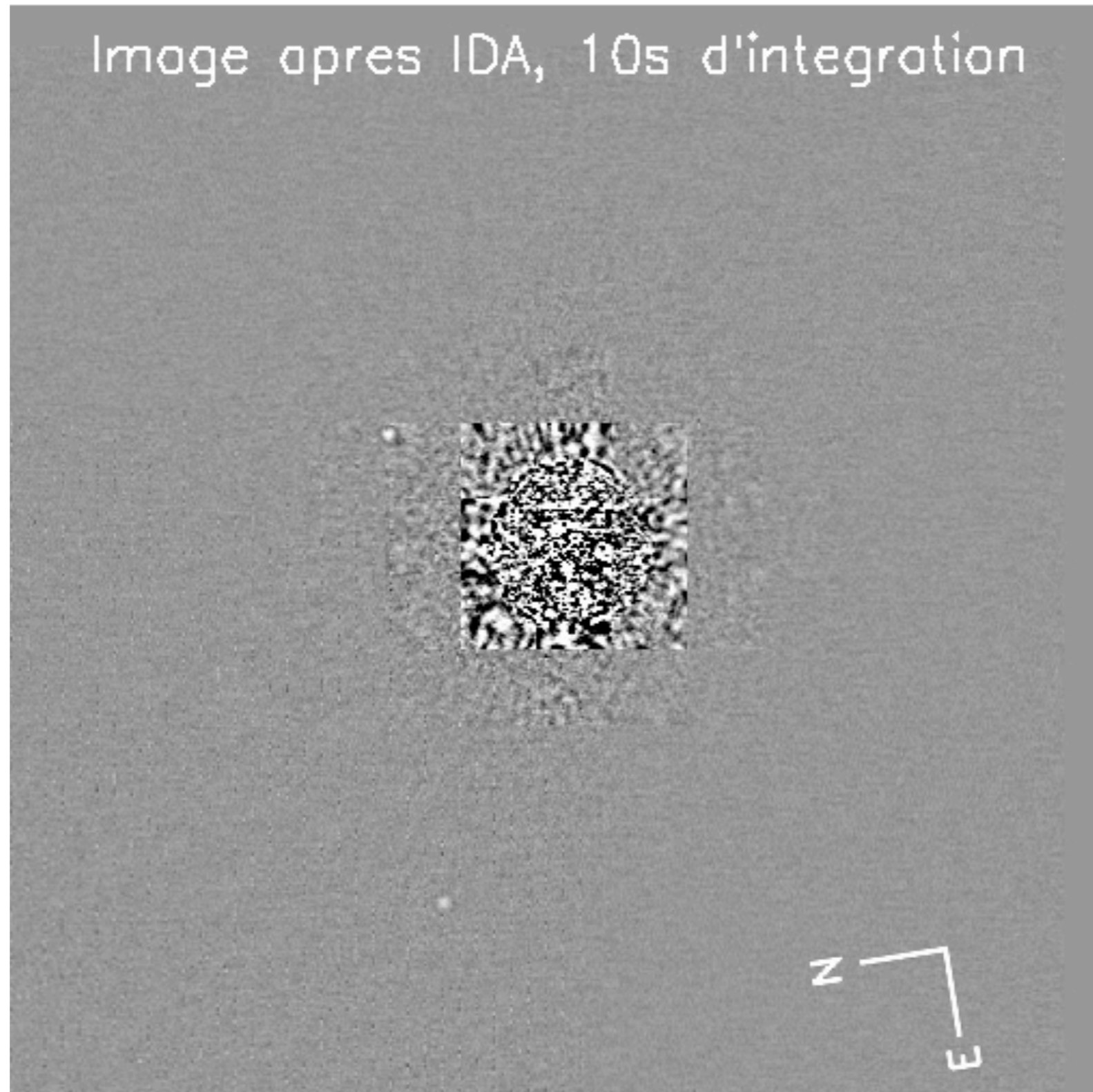
Angular Differential Imaging



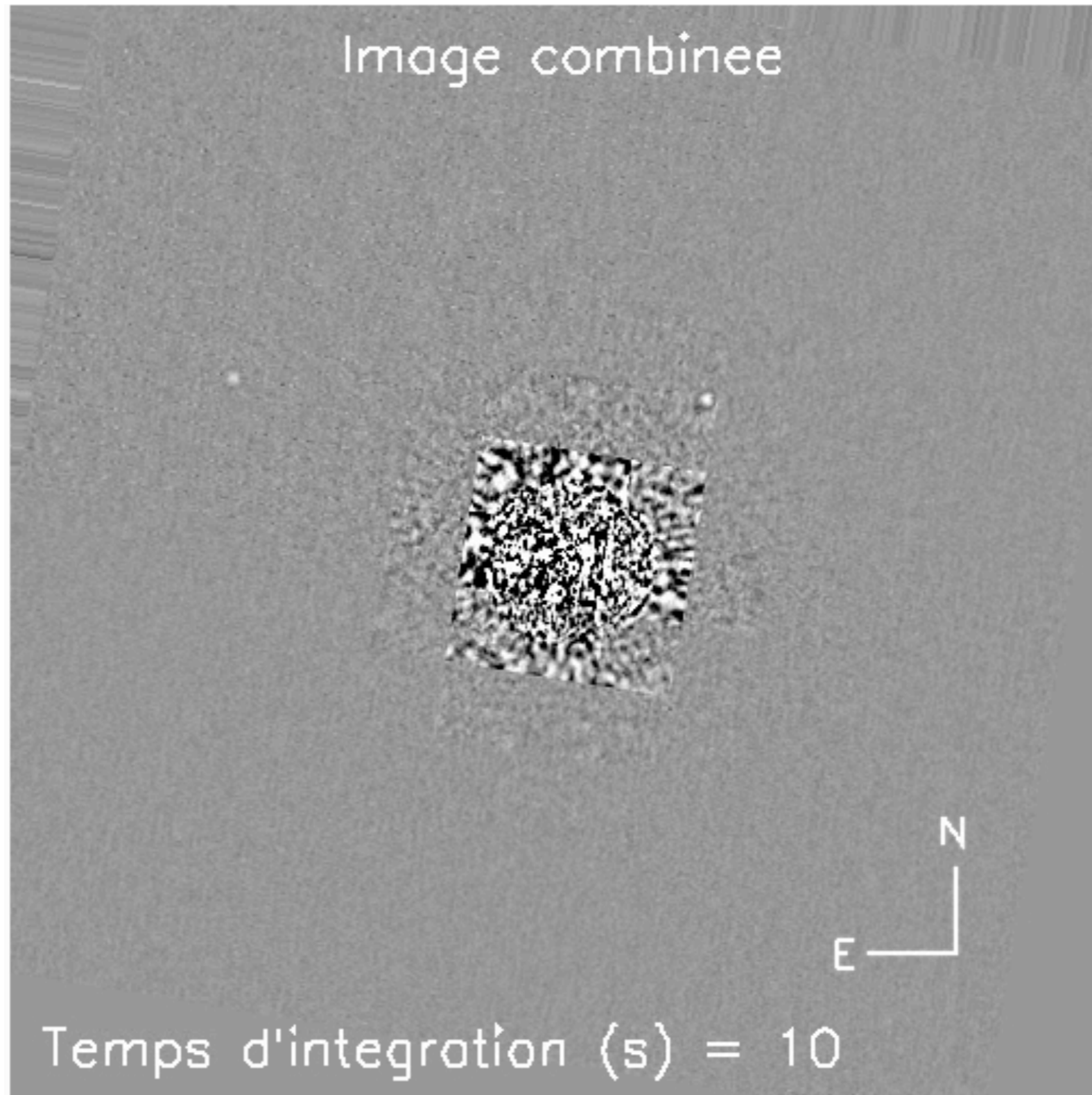
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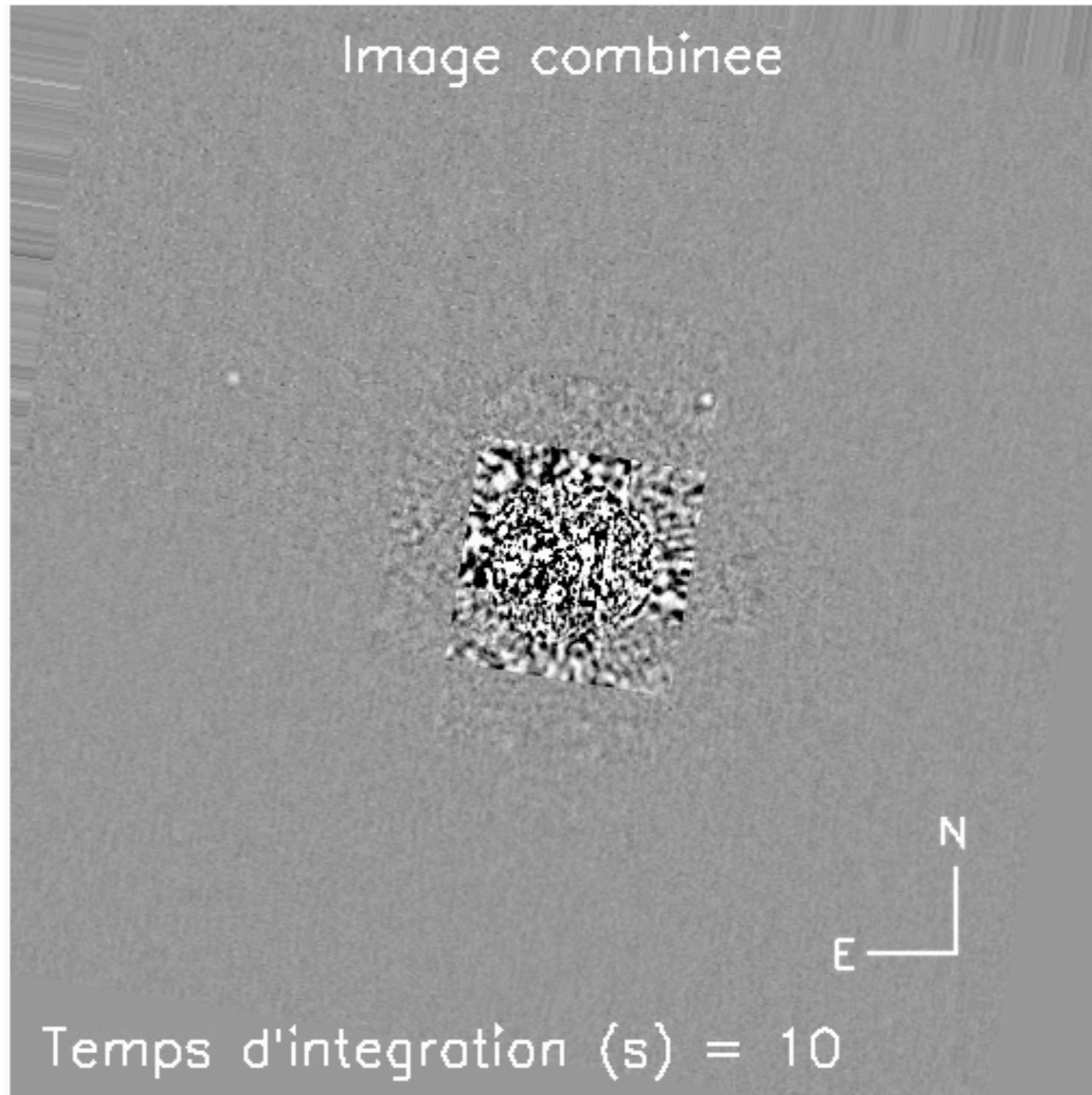
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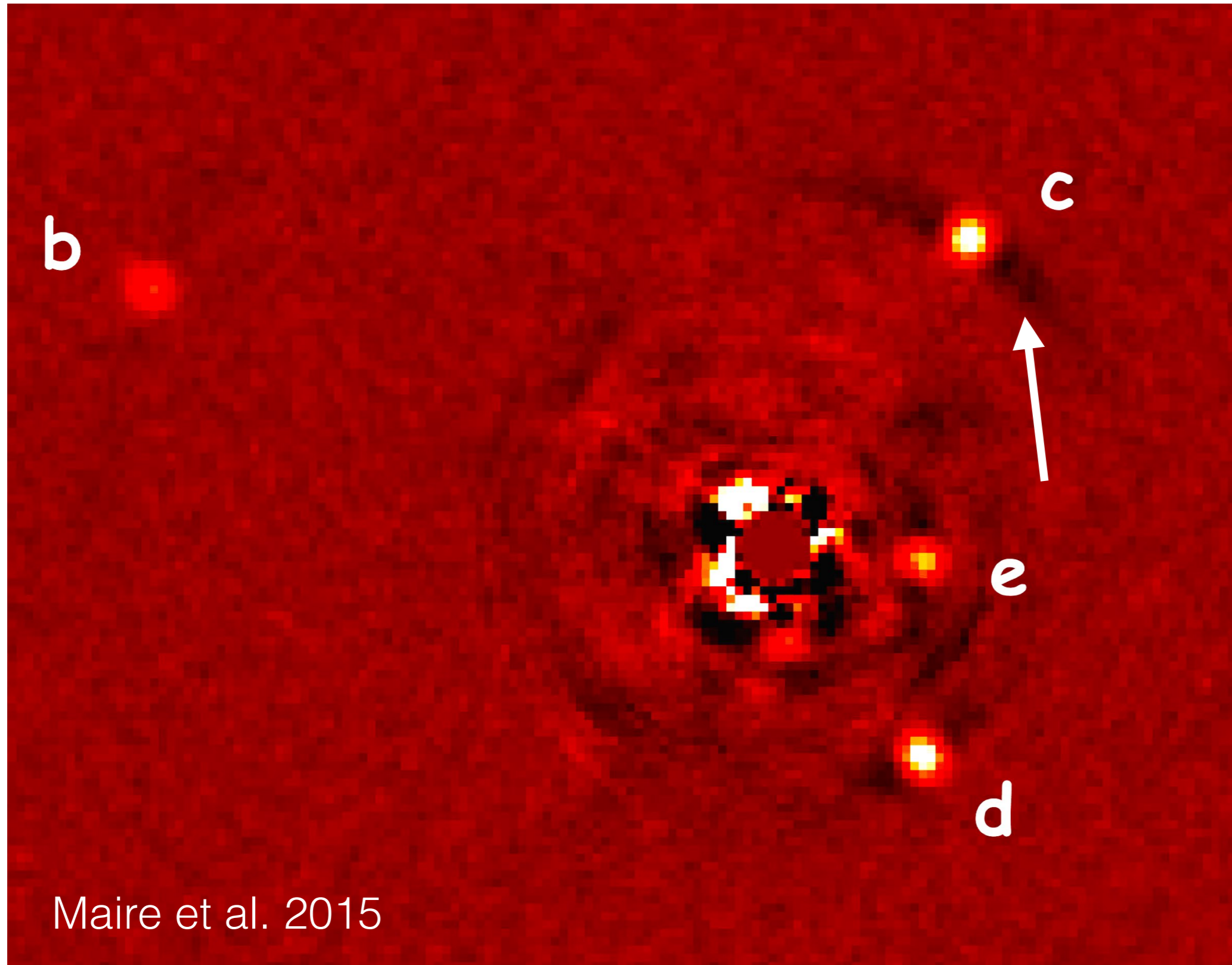
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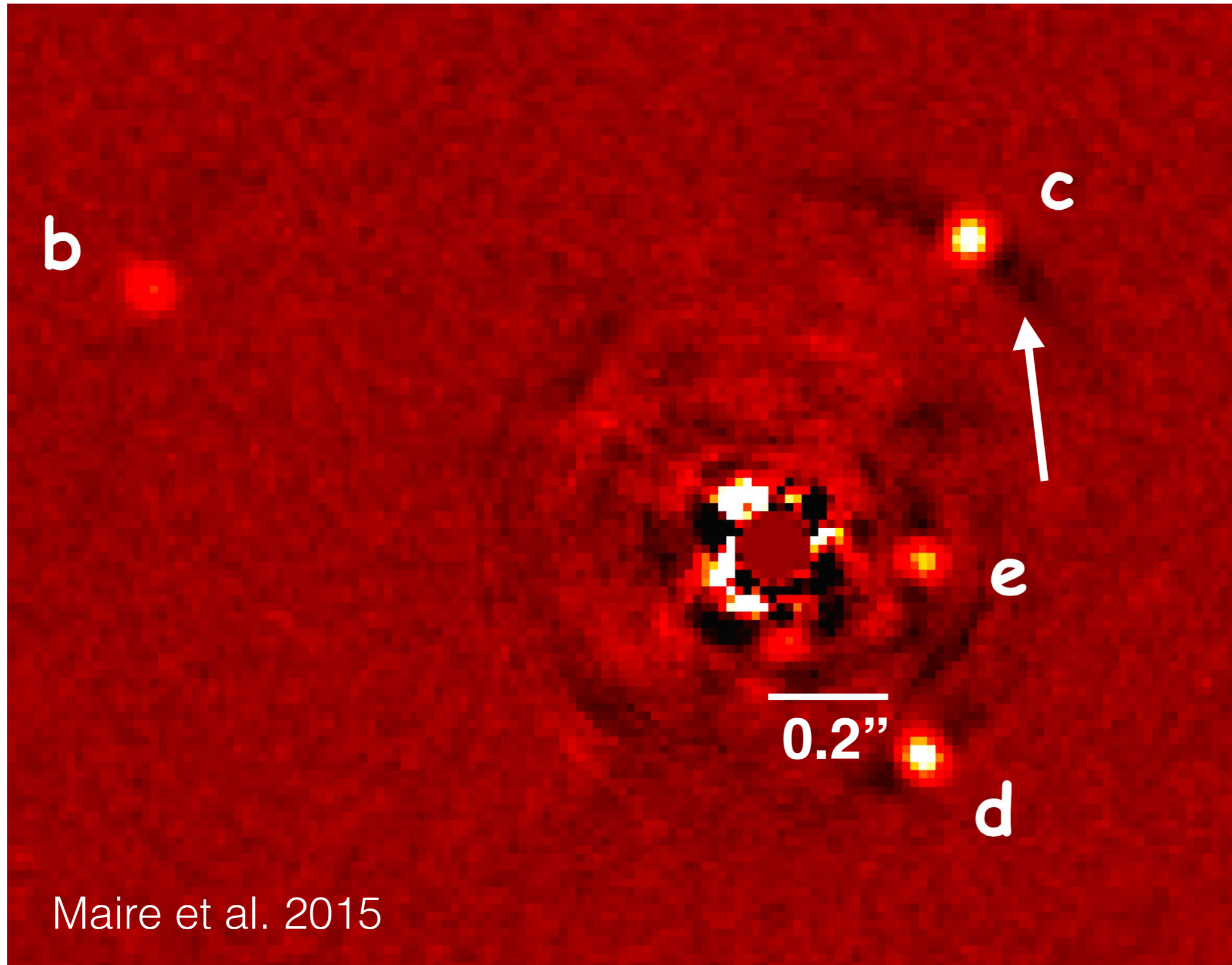


Great! What's the catch?

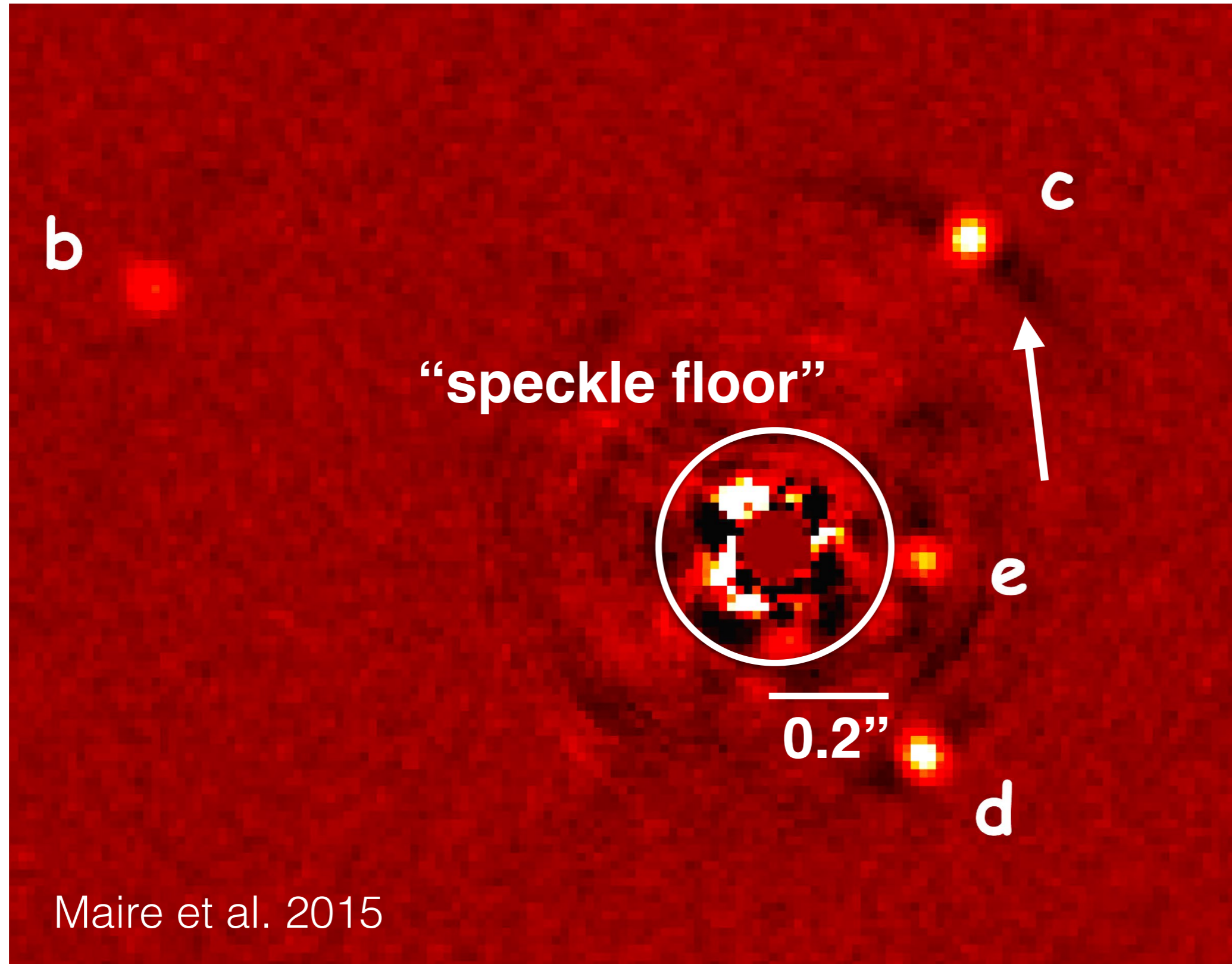


Maire et al. 2015

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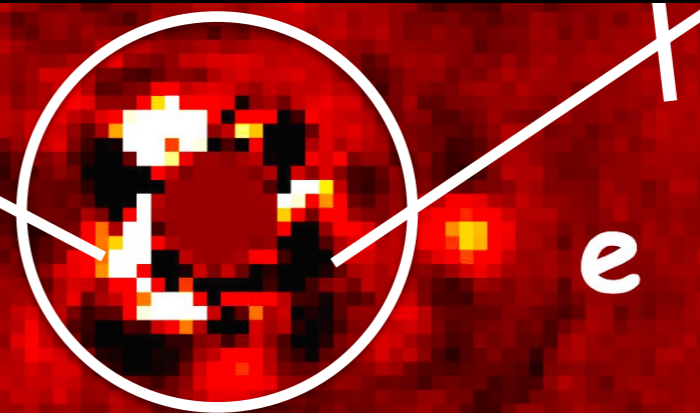
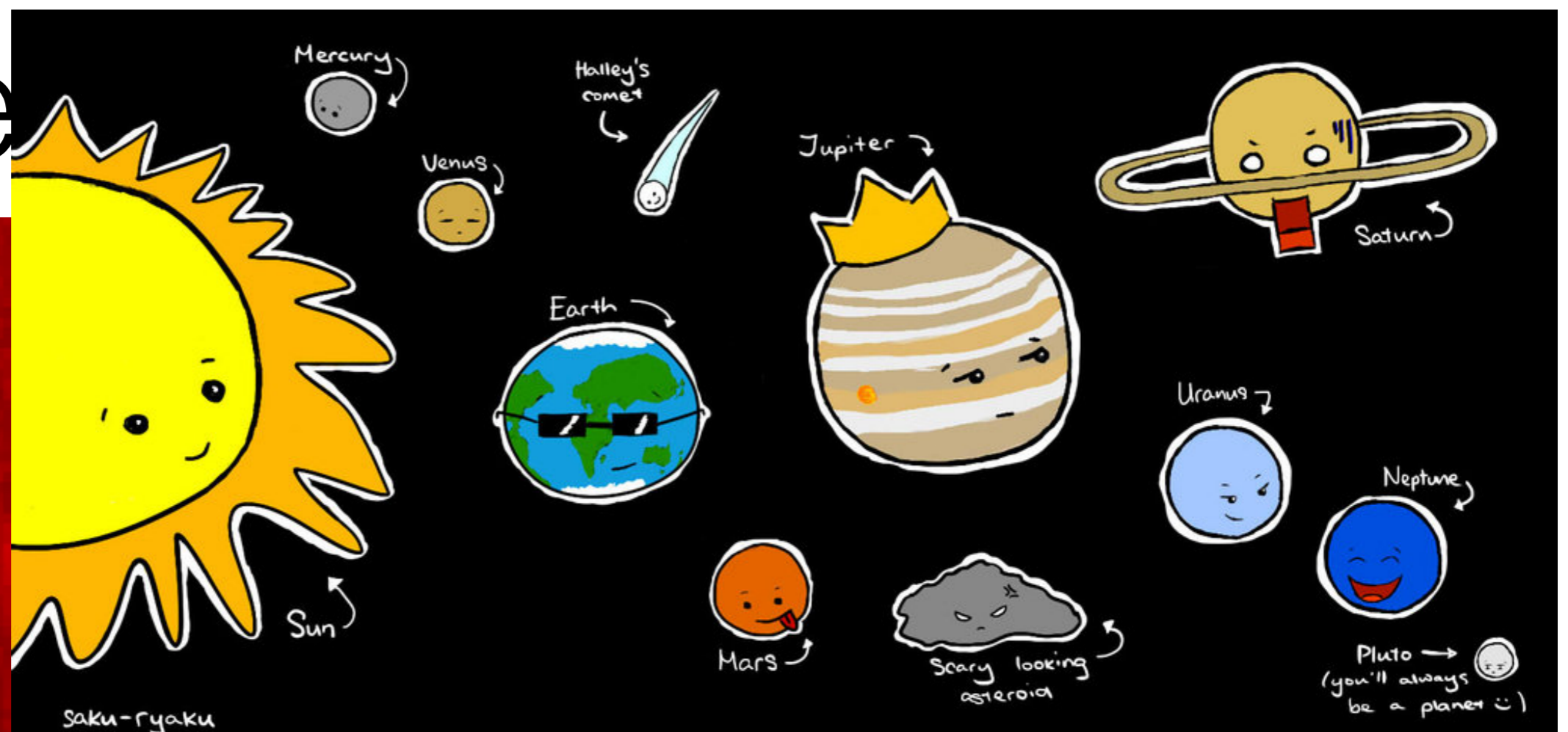


Great! What's the catch?



Gre

b



e

d

Maire et al. 2015

The Problems

The Problems

1. Time is the enemy
2. Self-subtraction
3. Self-subtraction gets worse closer to star (where planets live)

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Hmm.....

Space



Space



Earth's
atmosphere



Space

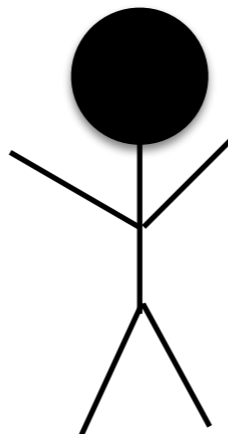


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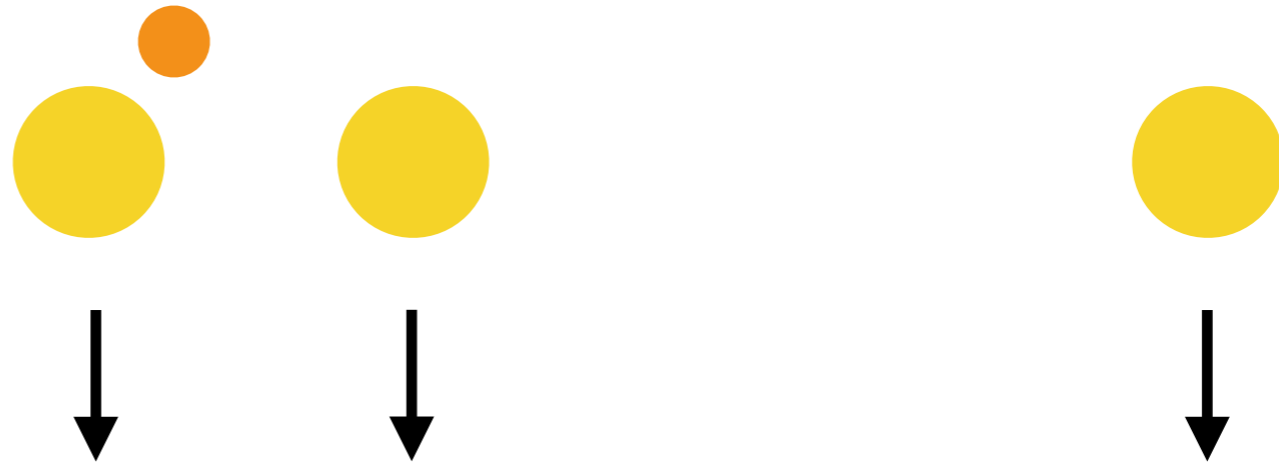
Space



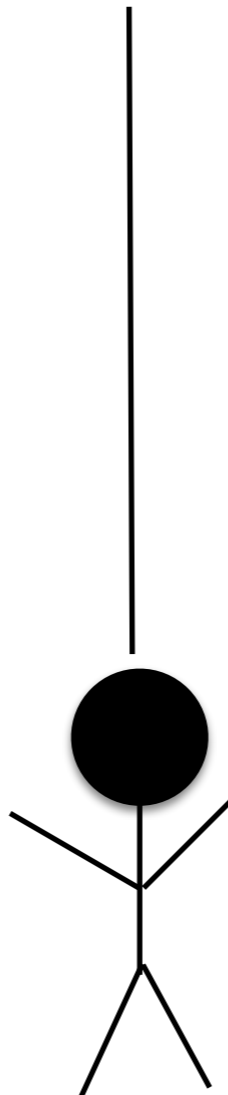
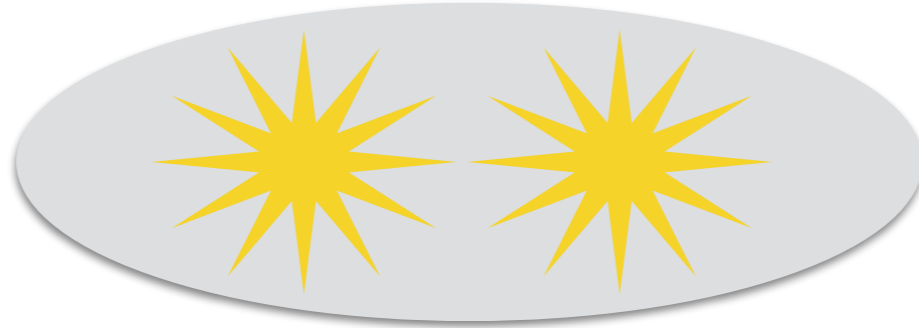
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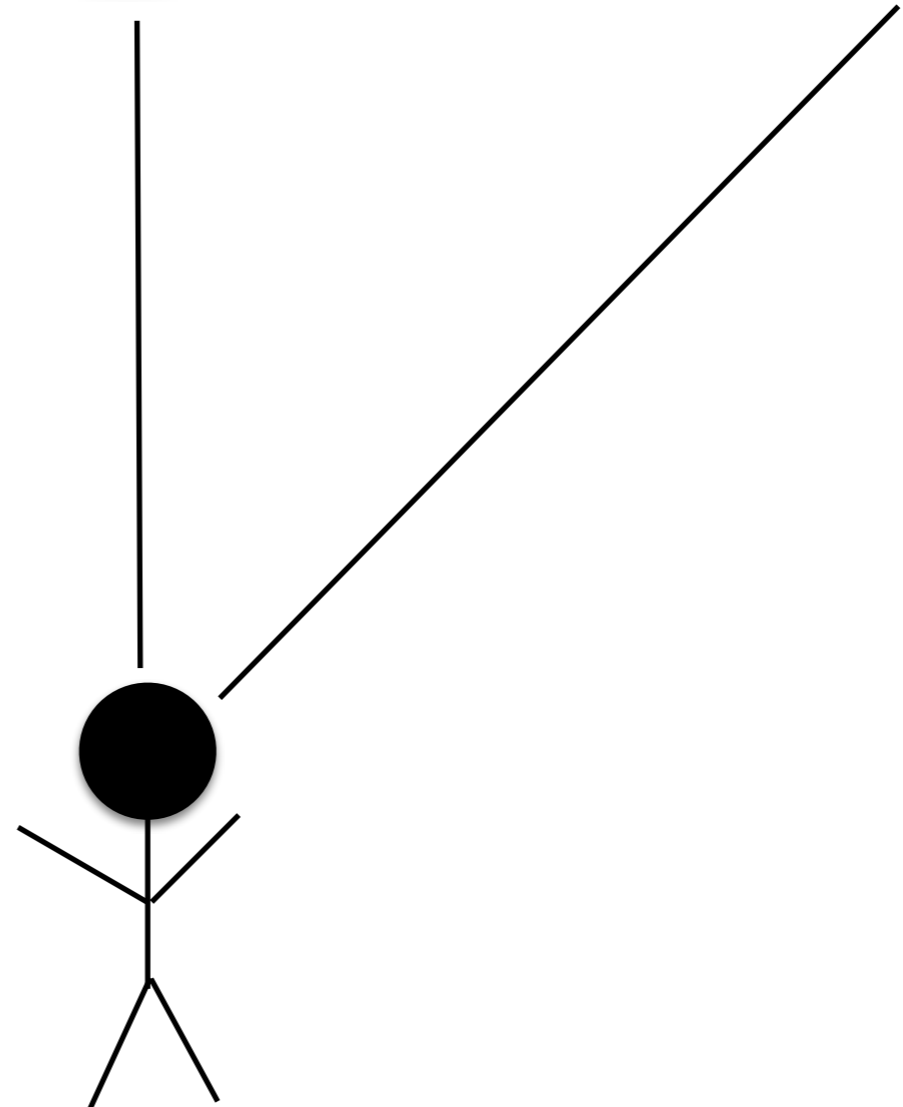
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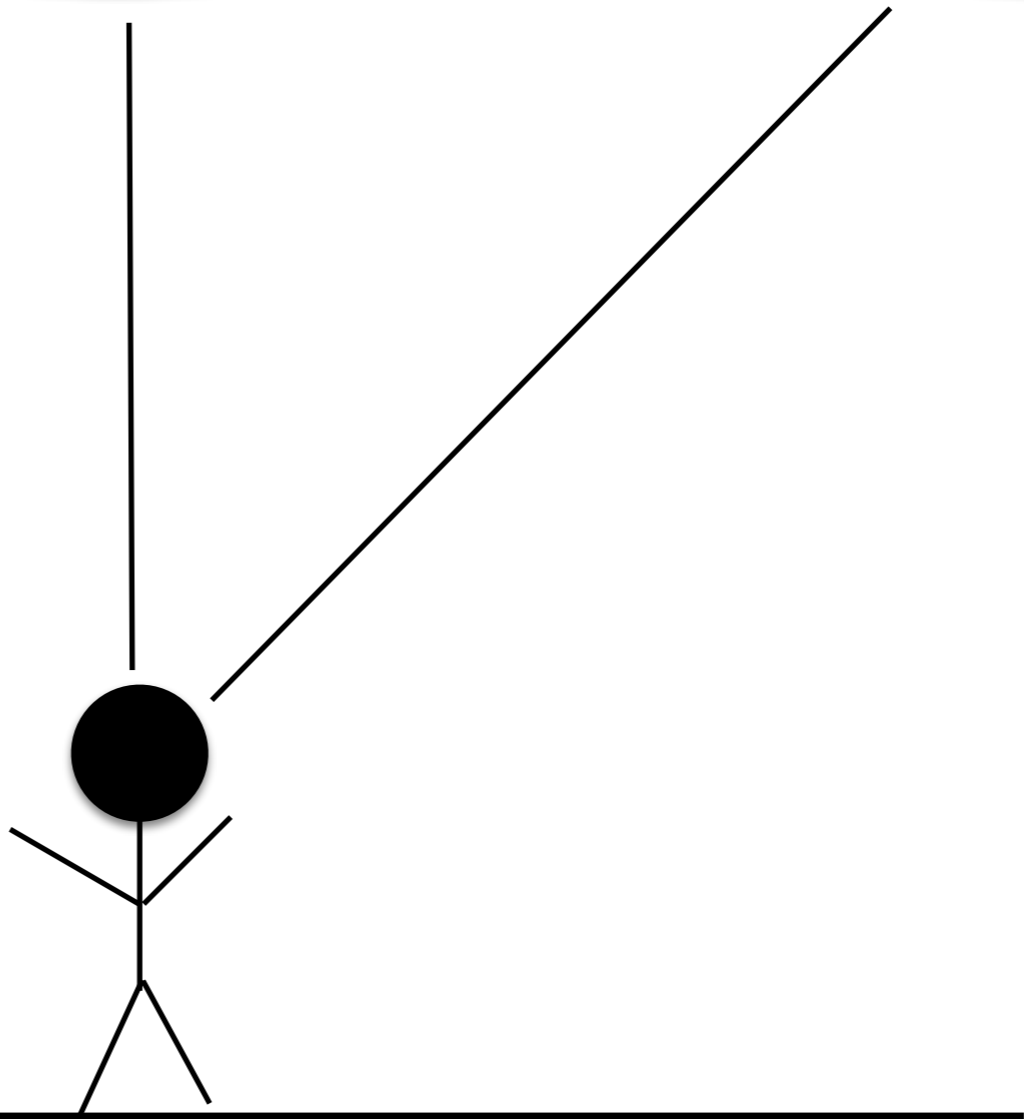
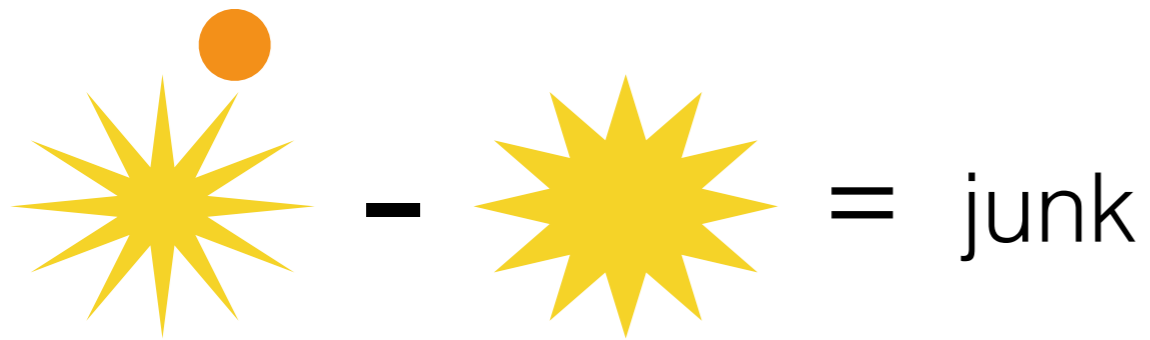
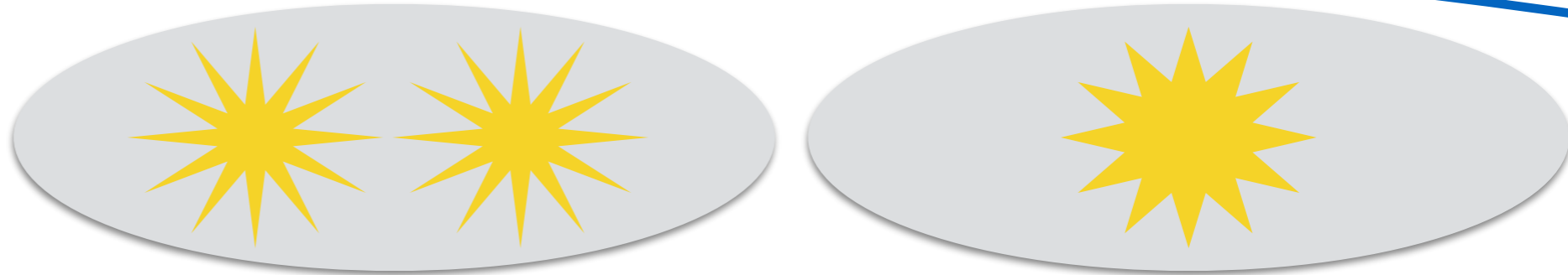
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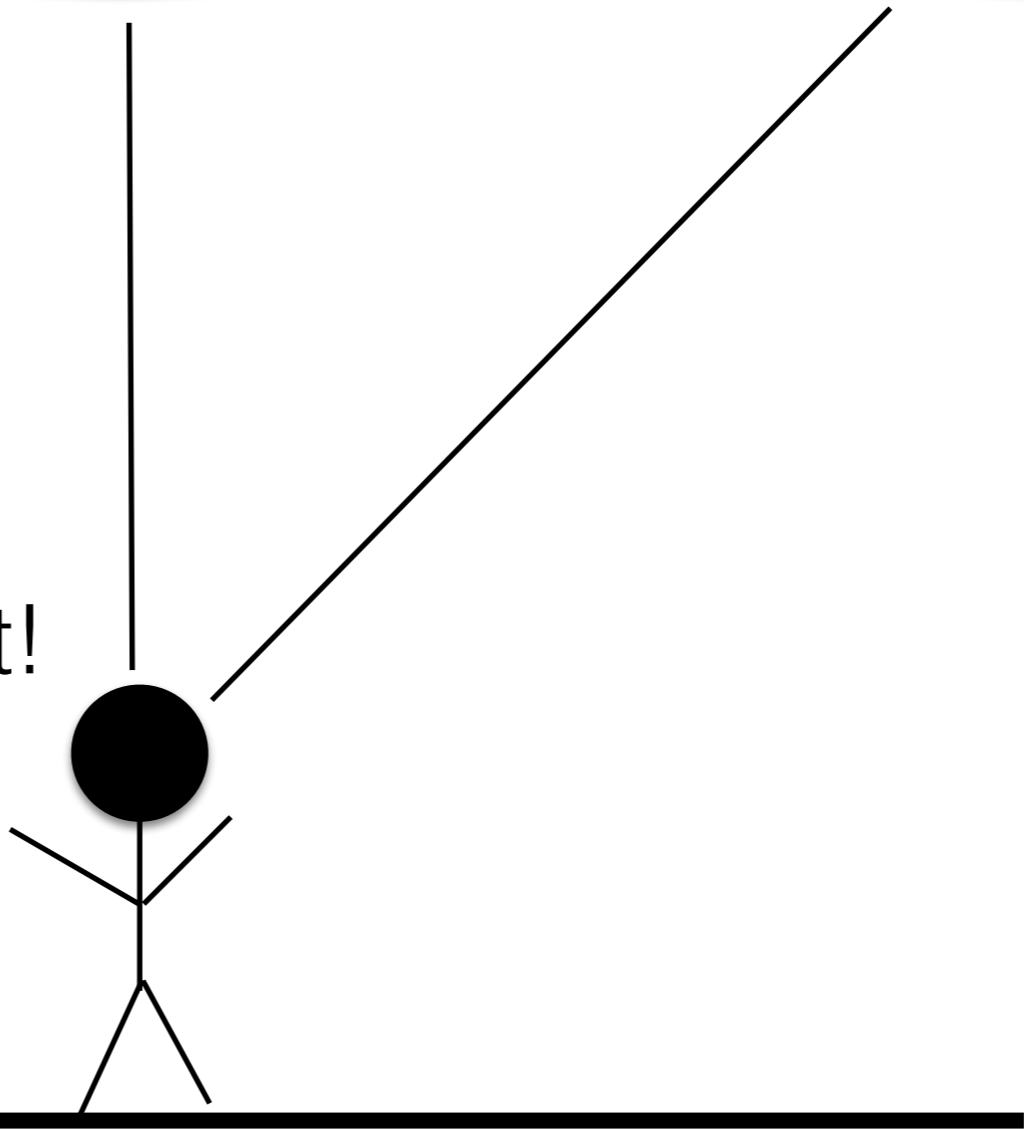
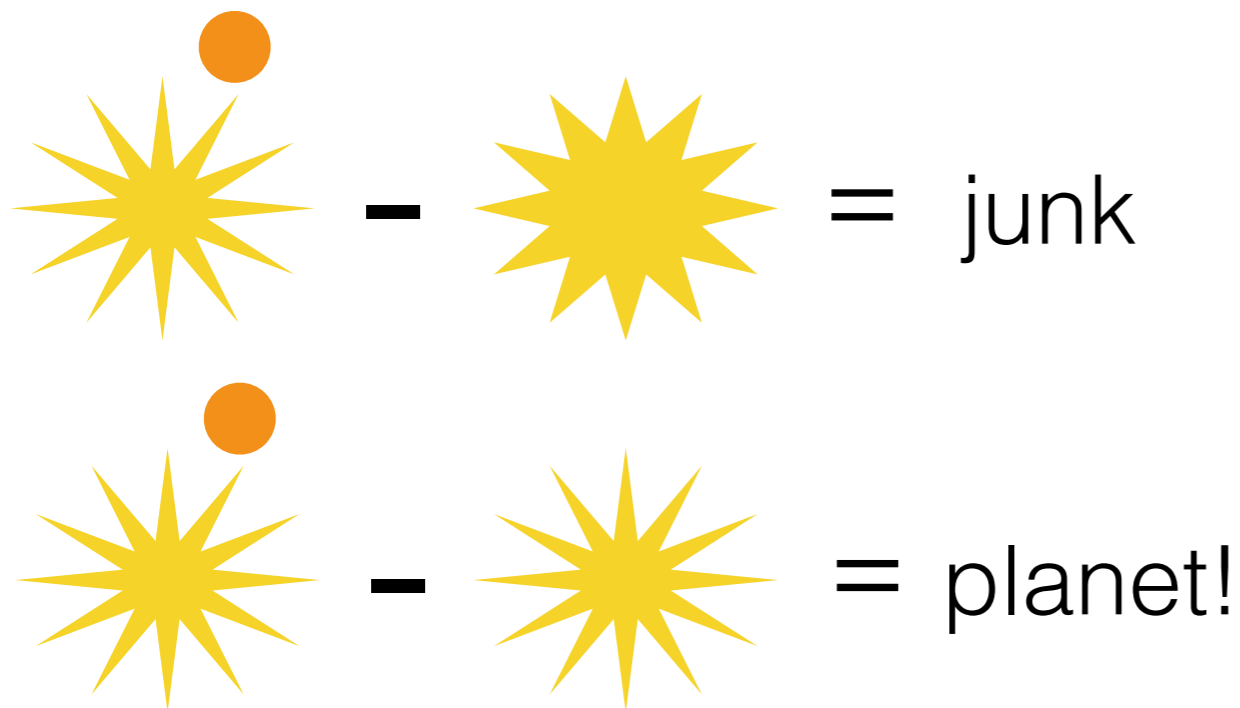
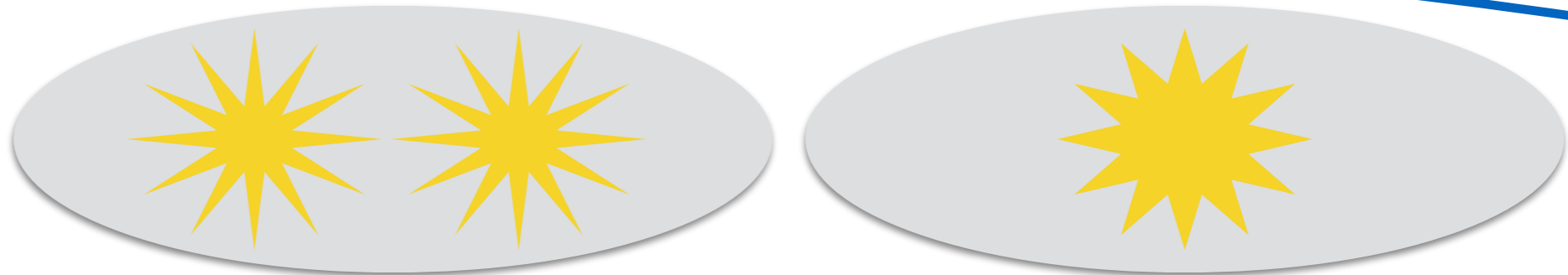
Earth's
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Space



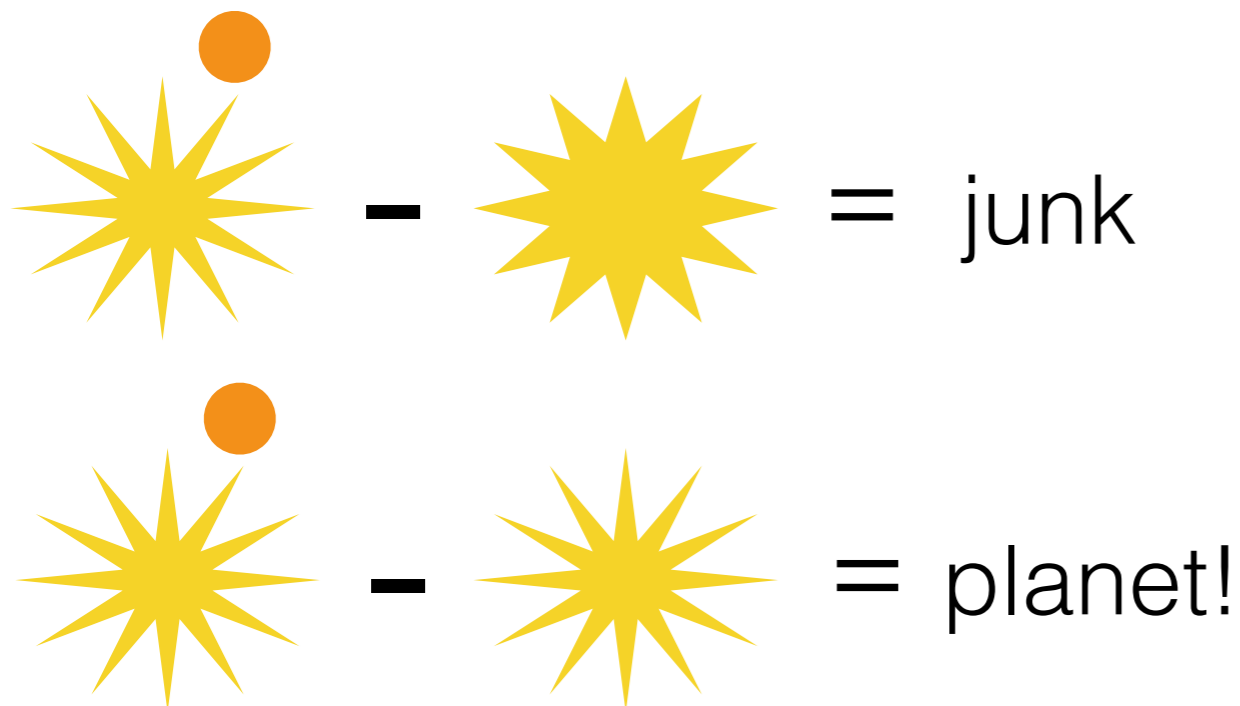
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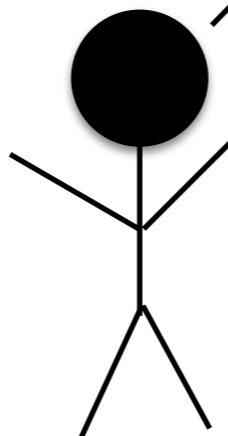
Space



Earth's atmosphere



2 stars look **identical** if they are within the "isoplanatic patch"





MagAO happens here



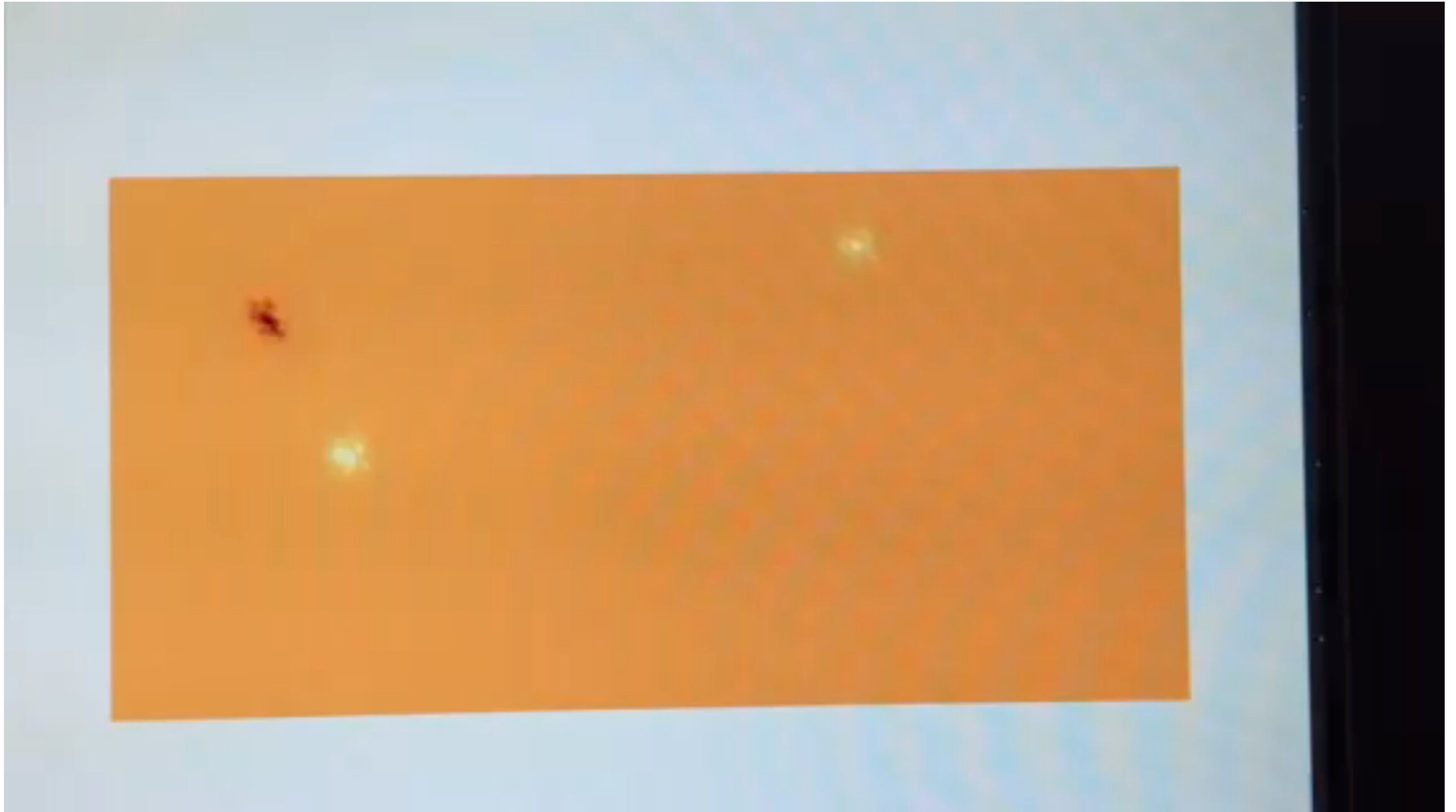
VisAO: diffraction-limited,
0.5-1 μm

Clio-2: diffraction-limited, 1-5 μm ,
low-res spectroscopy

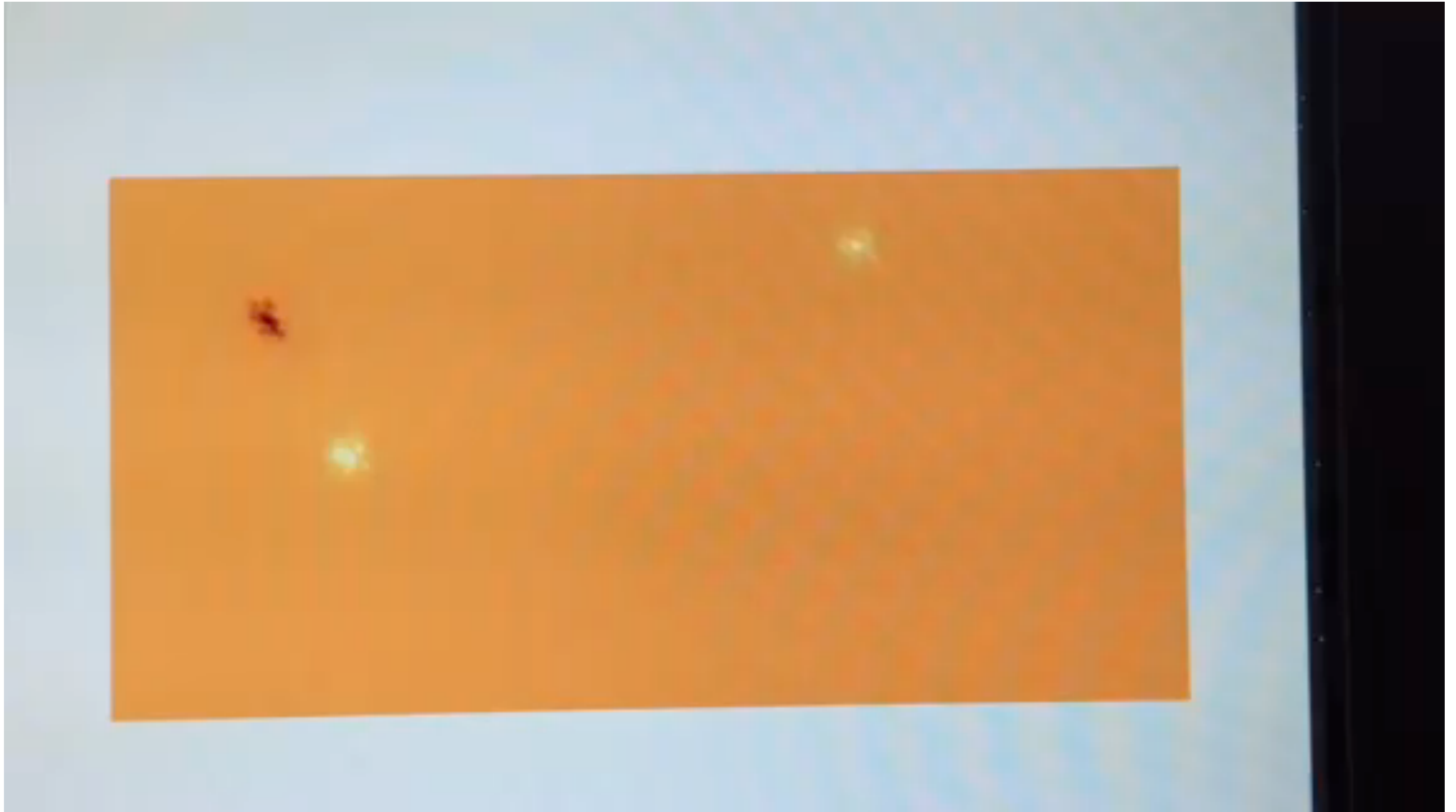
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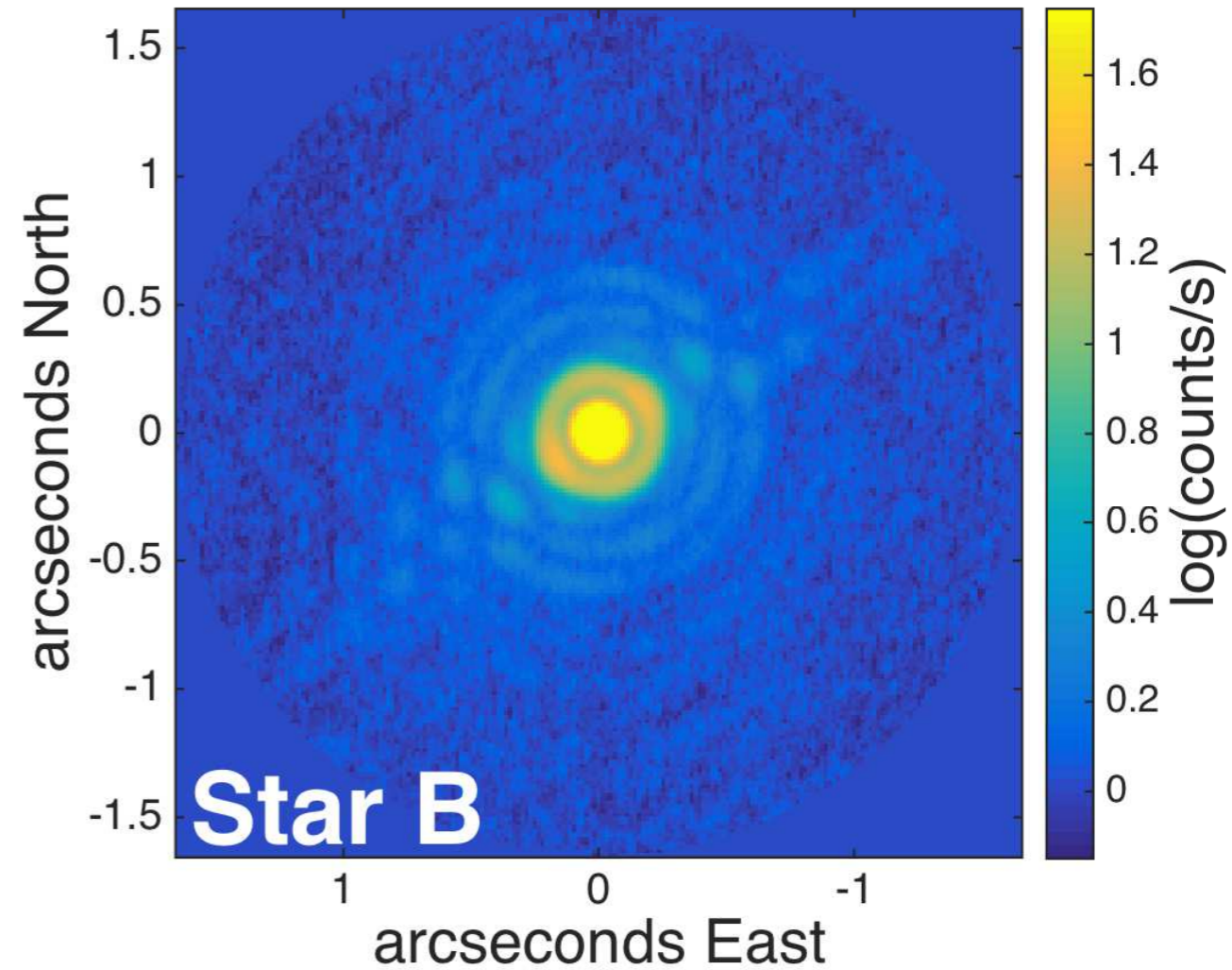
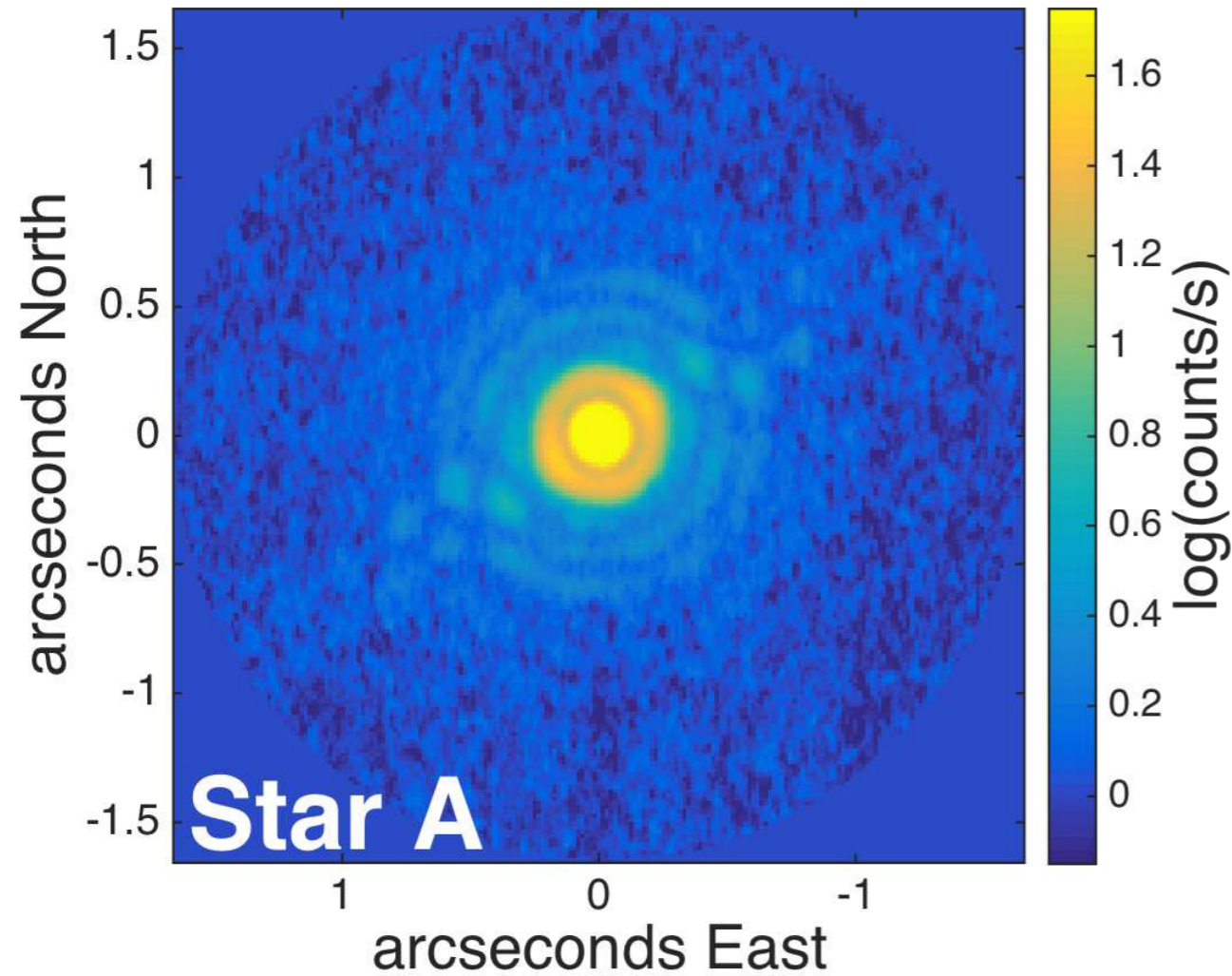
Identical stars in action



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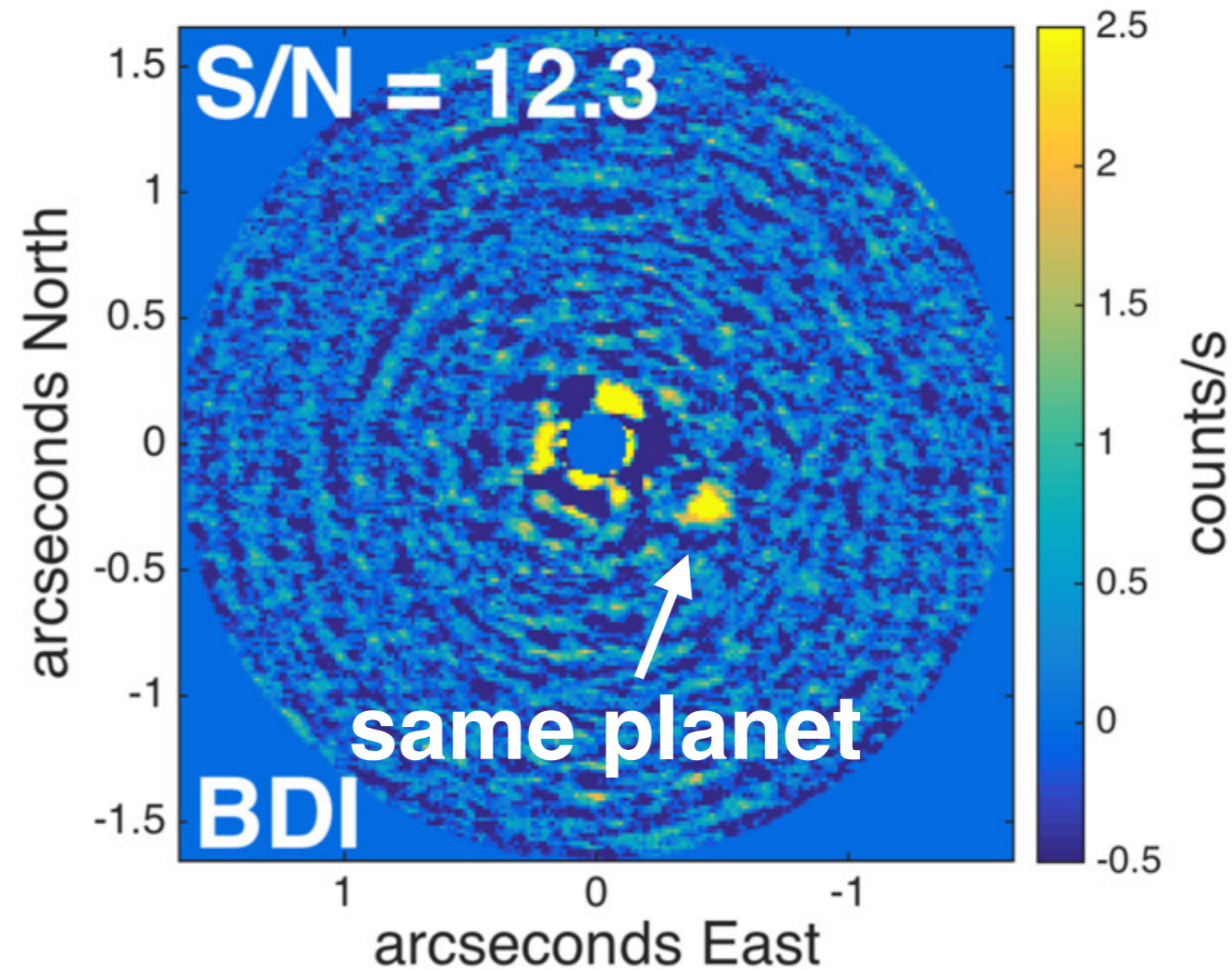
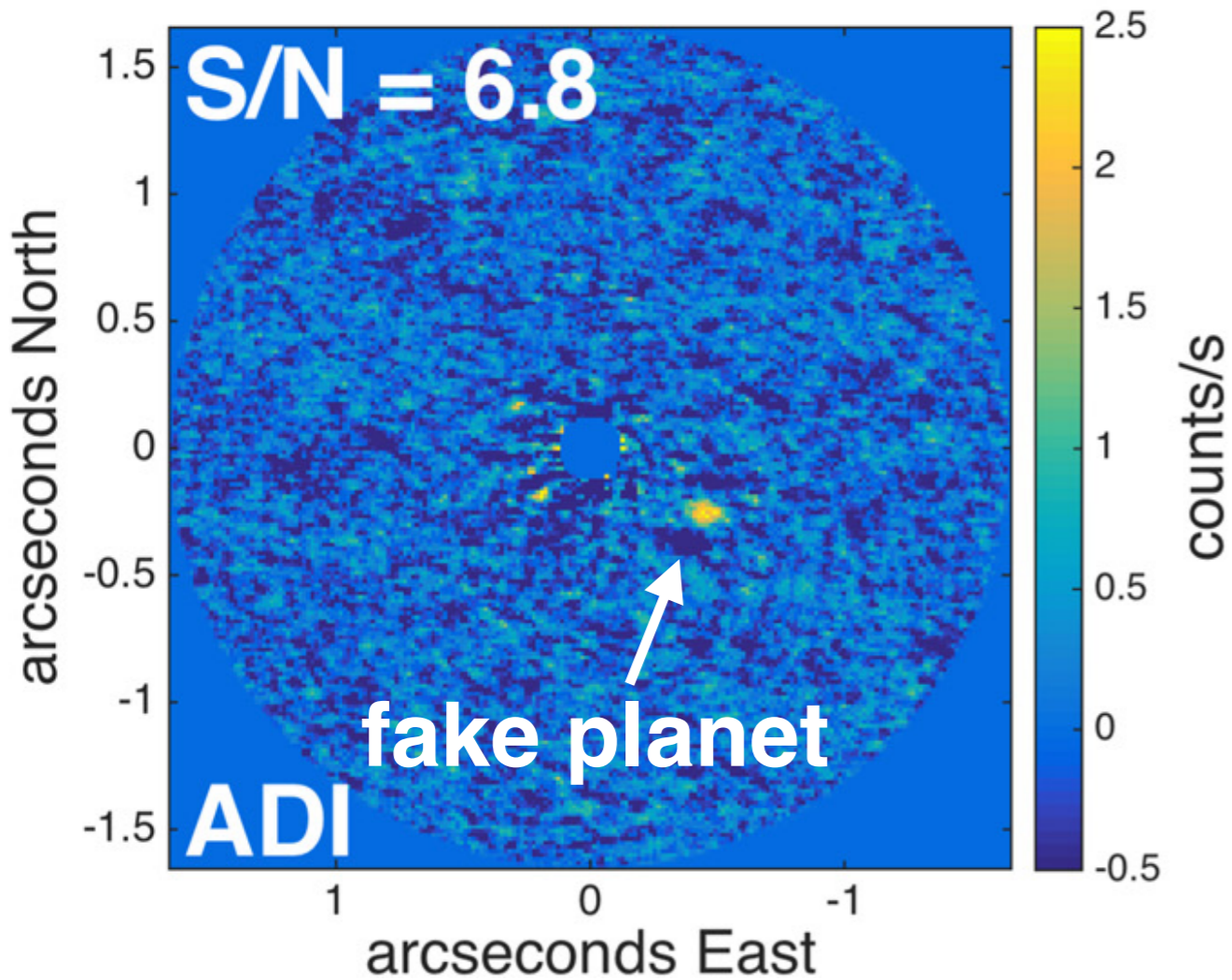
New way to image planets: “Binary Differential Imaging” = BDI



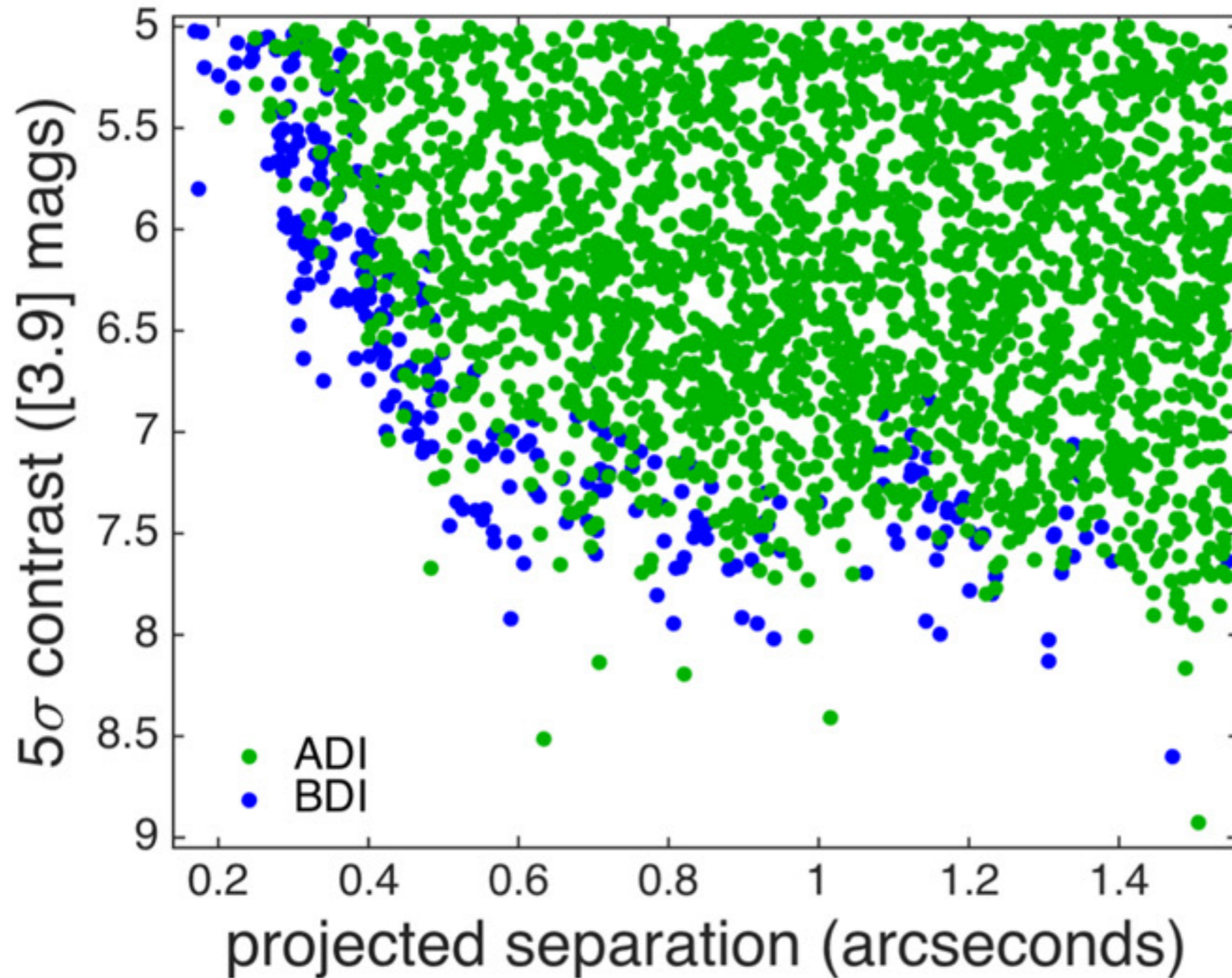
Visual binaries are nature's home-grown solution

Is BDI actually better?

Testing 1 fake planet

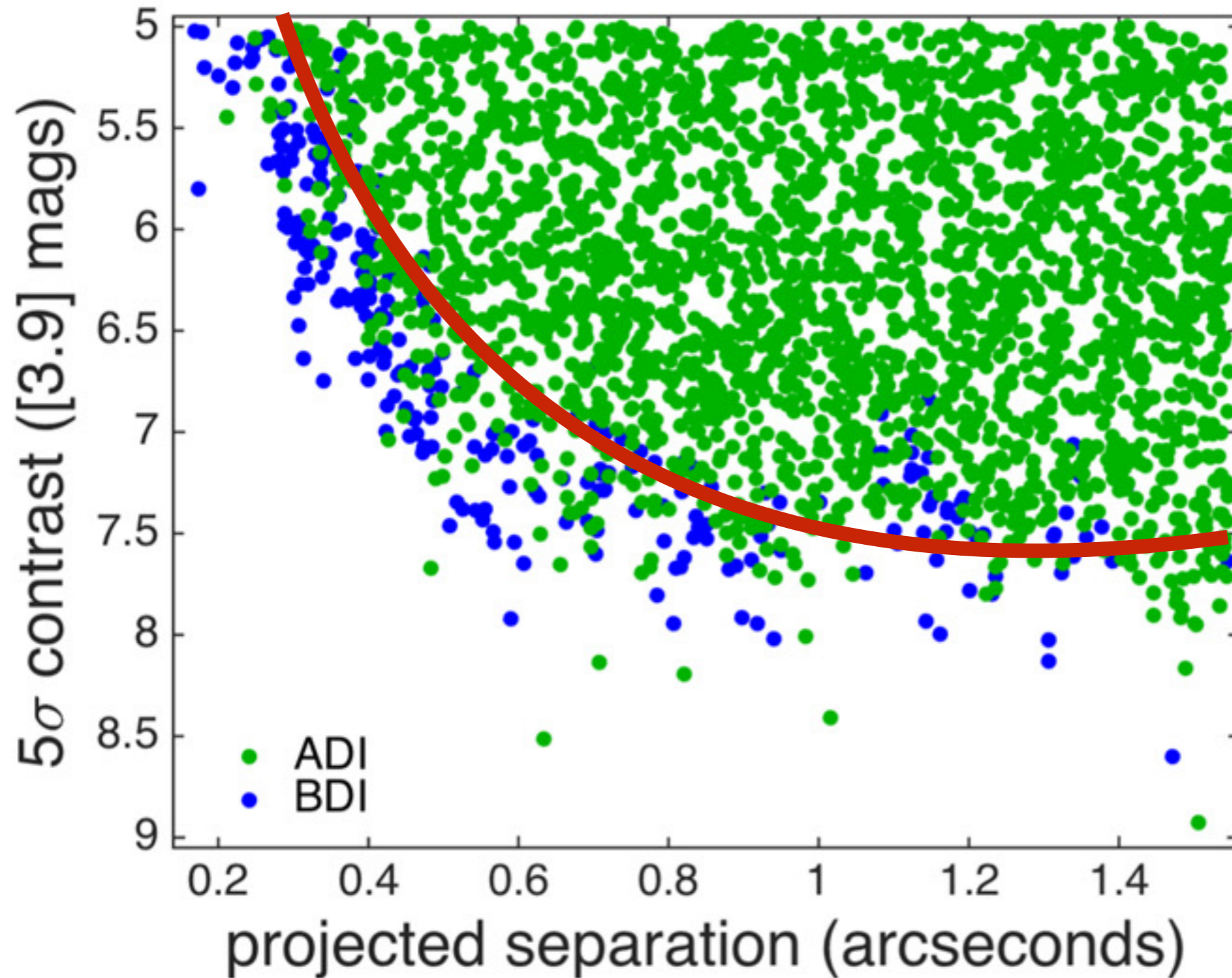


10,000 fake (random) planets



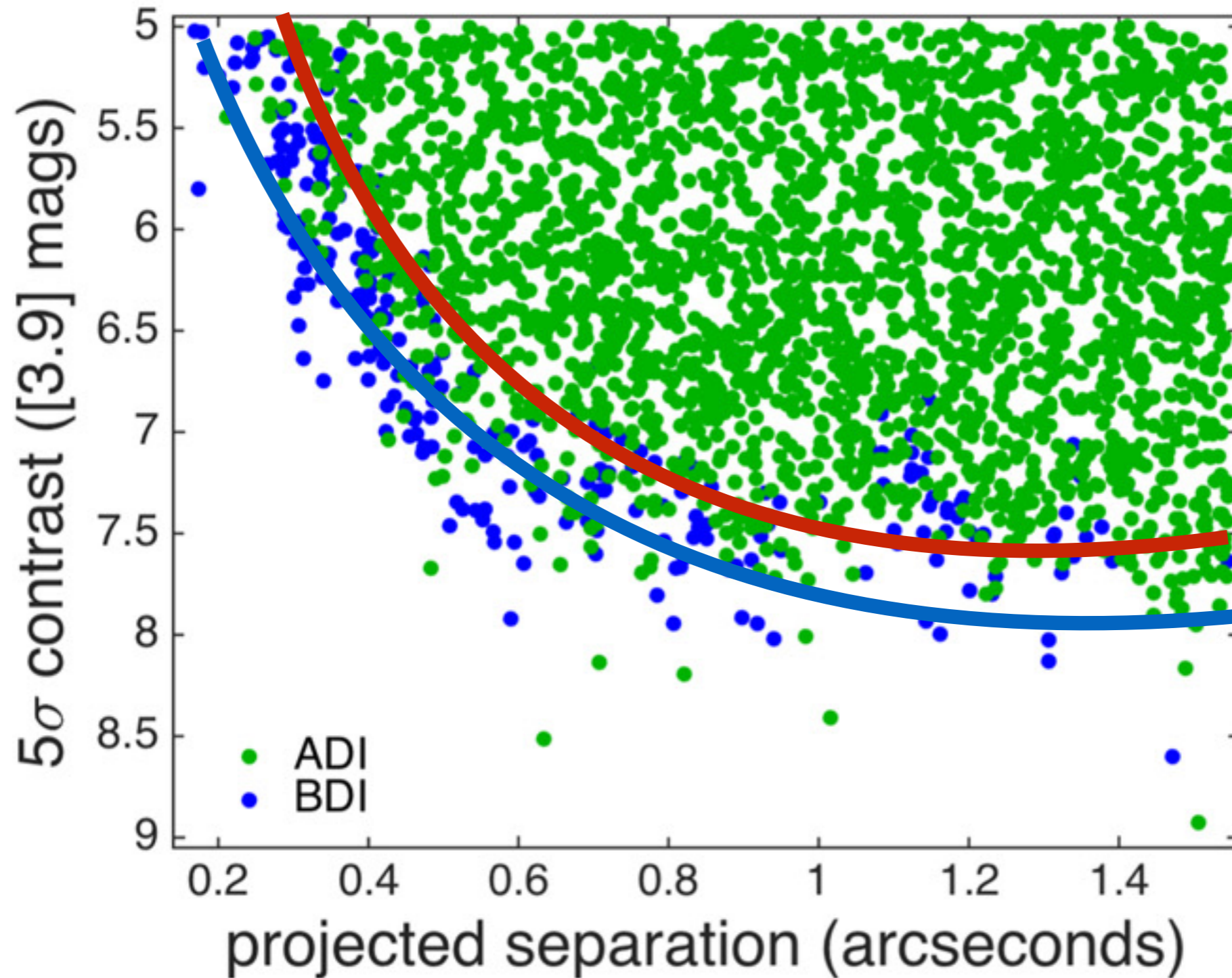
BDI detects **fainter** planets **closer** to the star

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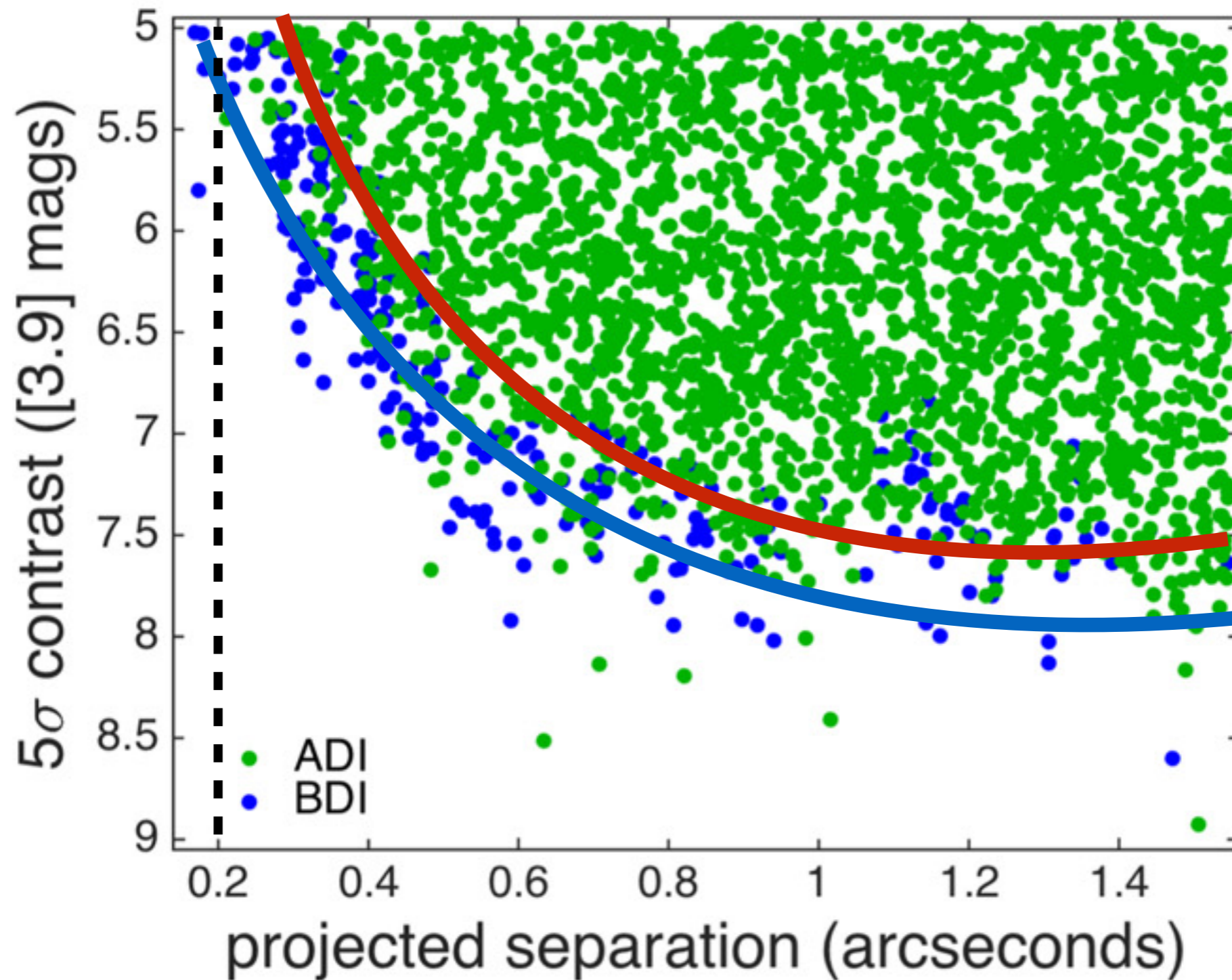
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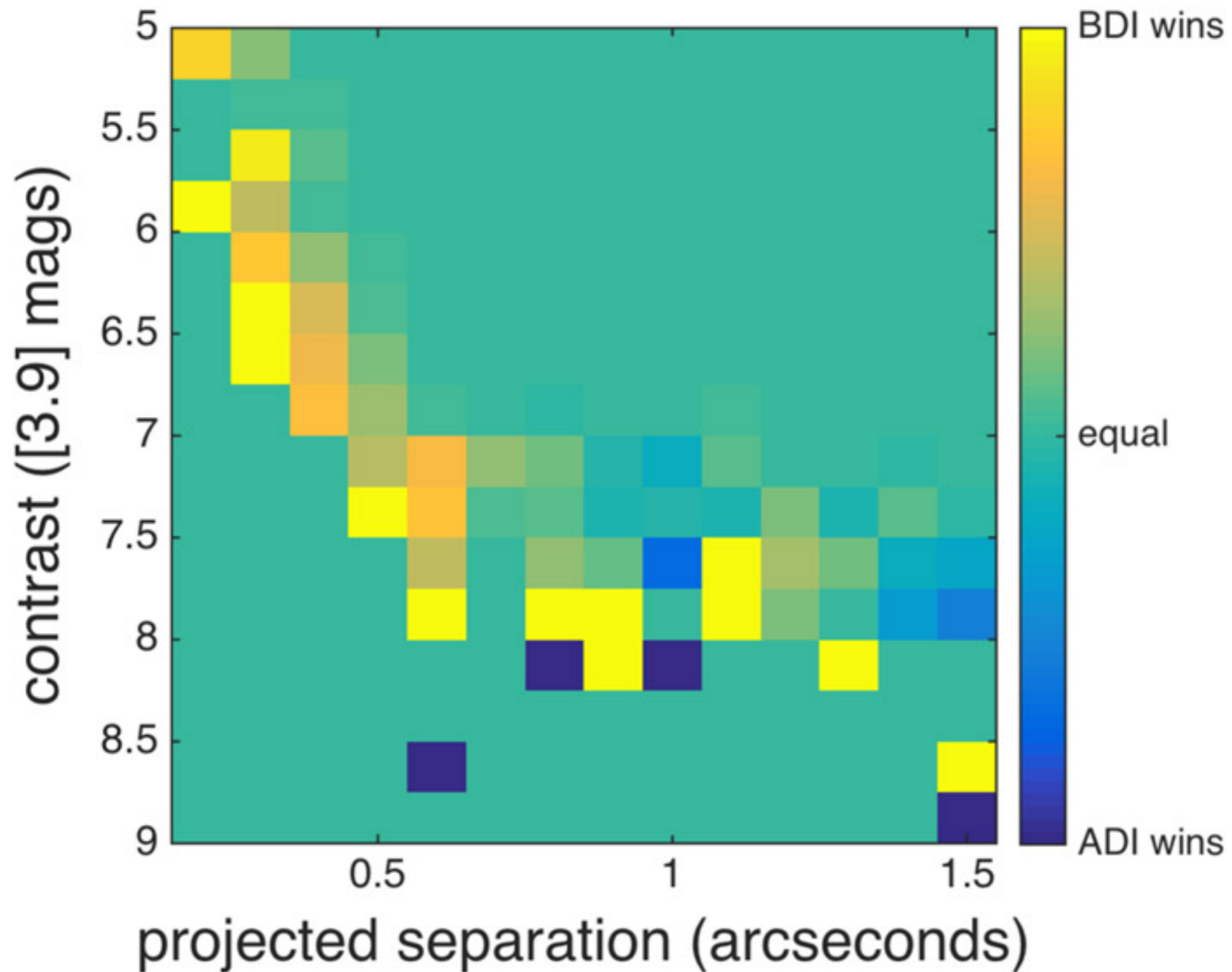
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 - NIRCcam
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- Ground-based? Definitely
 - right now: MagAO (current survey), LBT
 - future: GMT, TMT, E-ELT

My dream for LUVOIR...

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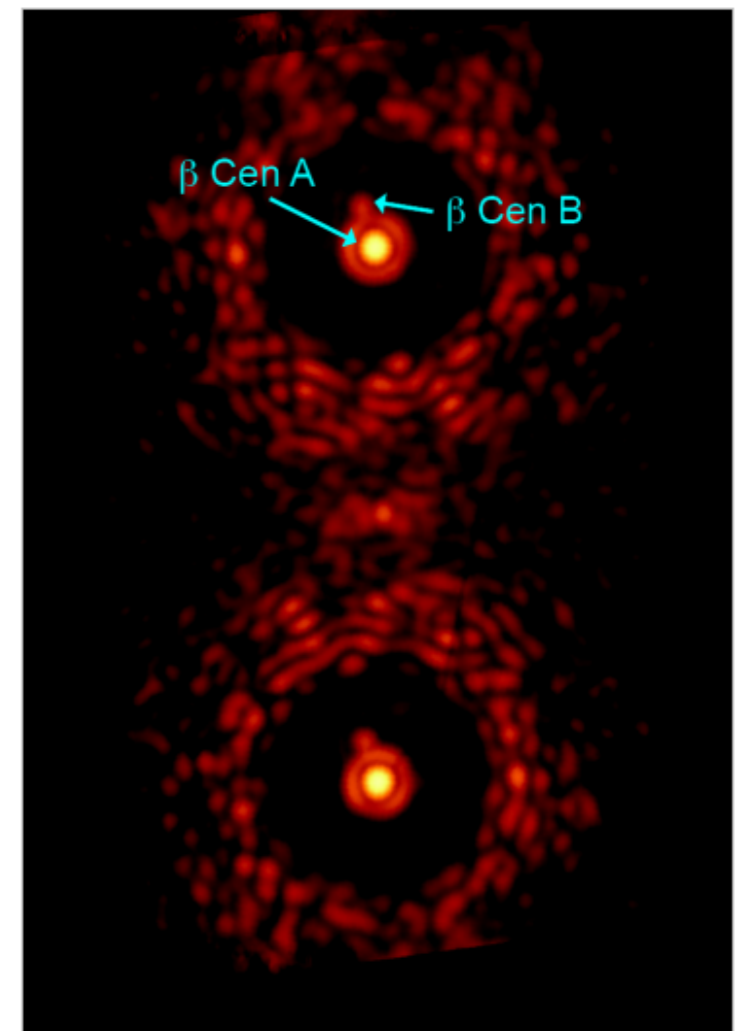
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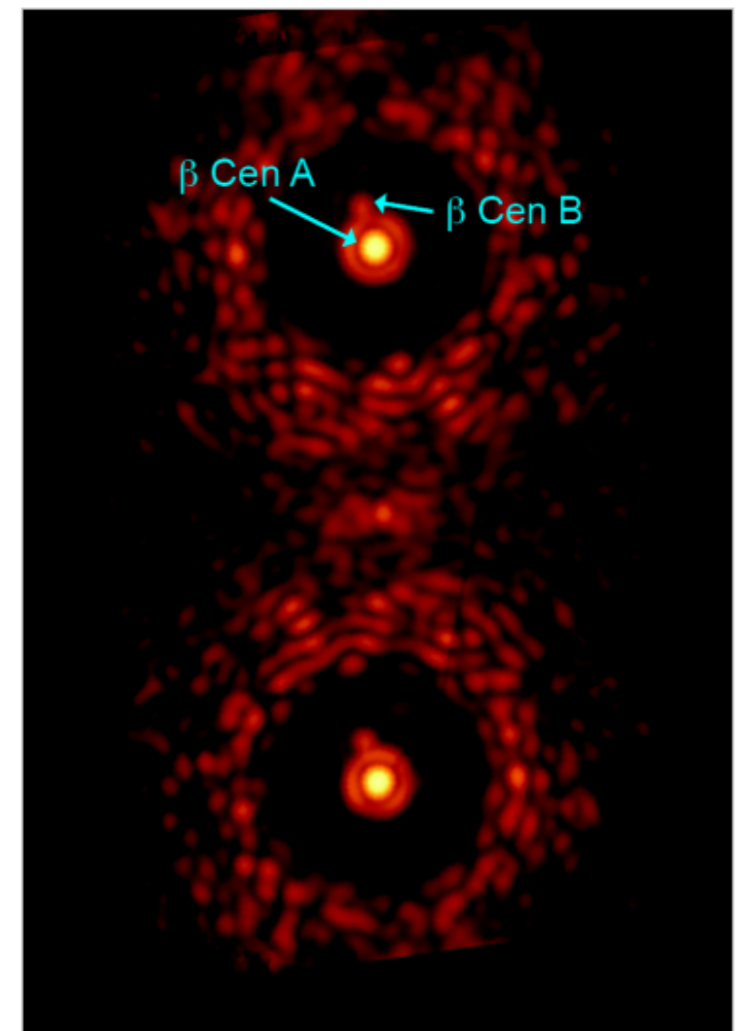
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See papers by Snik and Kenworthy

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- Or...even better:
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- With vAPP, can achieve true *simultaneous differential imaging* and *improve contrast* close to star...+ no need for rotation, no need for reference PSF!



See papers by Snik and Kenworthy

Binary power #2:

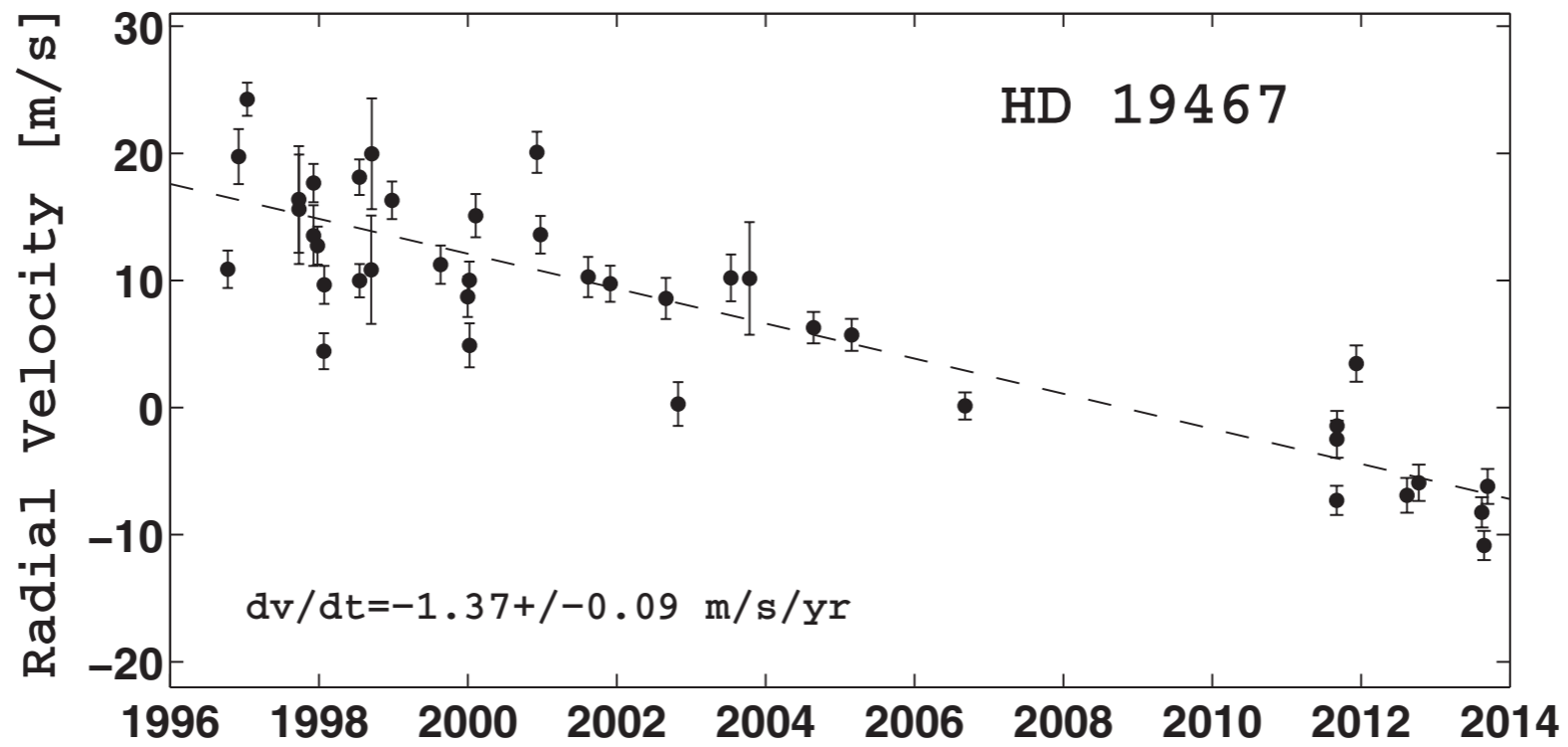
Can use binaries to learn about hidden planets

RV | Direct Imaging

- close-in planets ($a < 5$ AU)
- old, quiet stars
- minimum planet mass
- period and eccentricity
- long-period planets ($a > 5$ AU)
- young, active stars
- model-dependent true mass
- all orbital elements over time

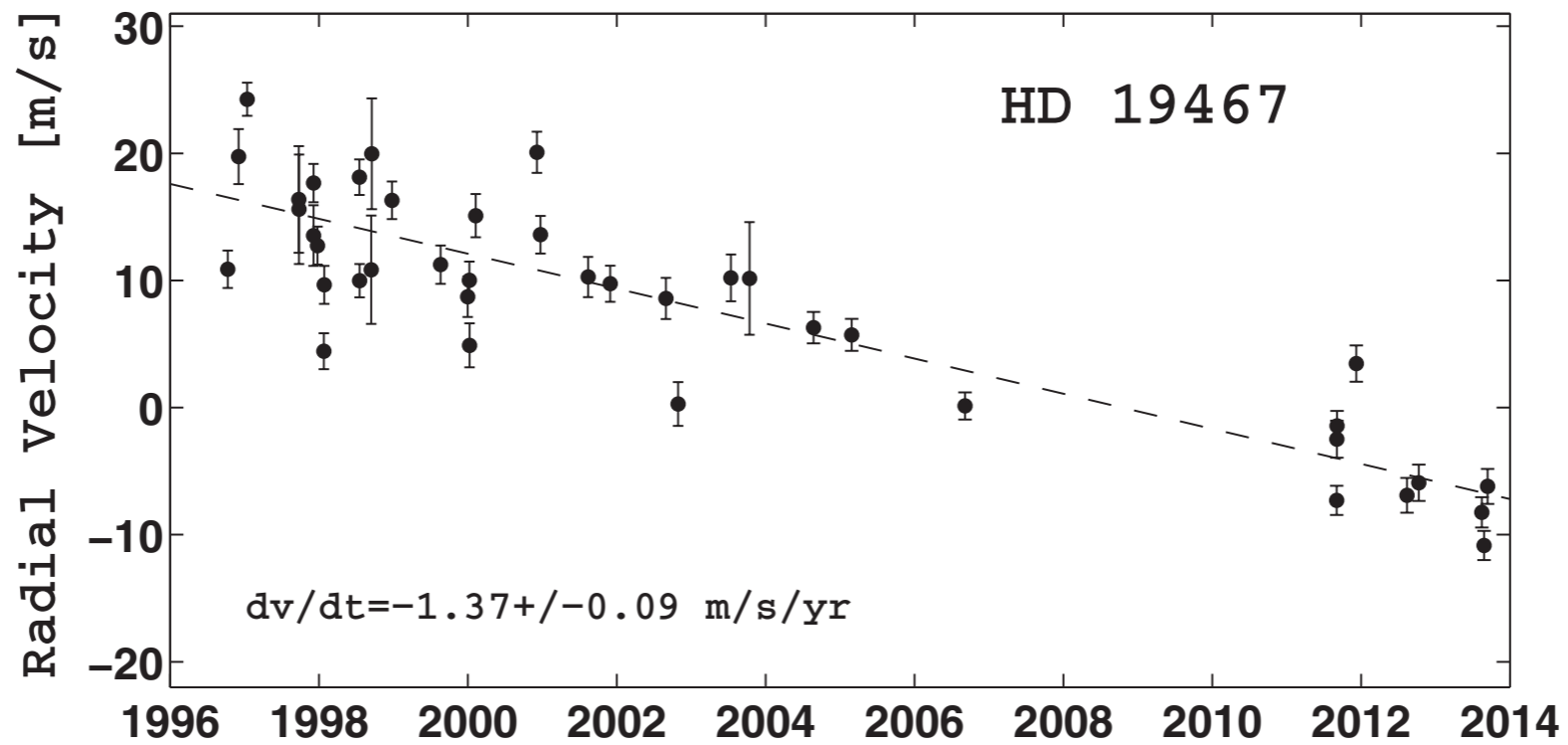
RV & direct imaging are complimentary!

Directly detecting long-term trends

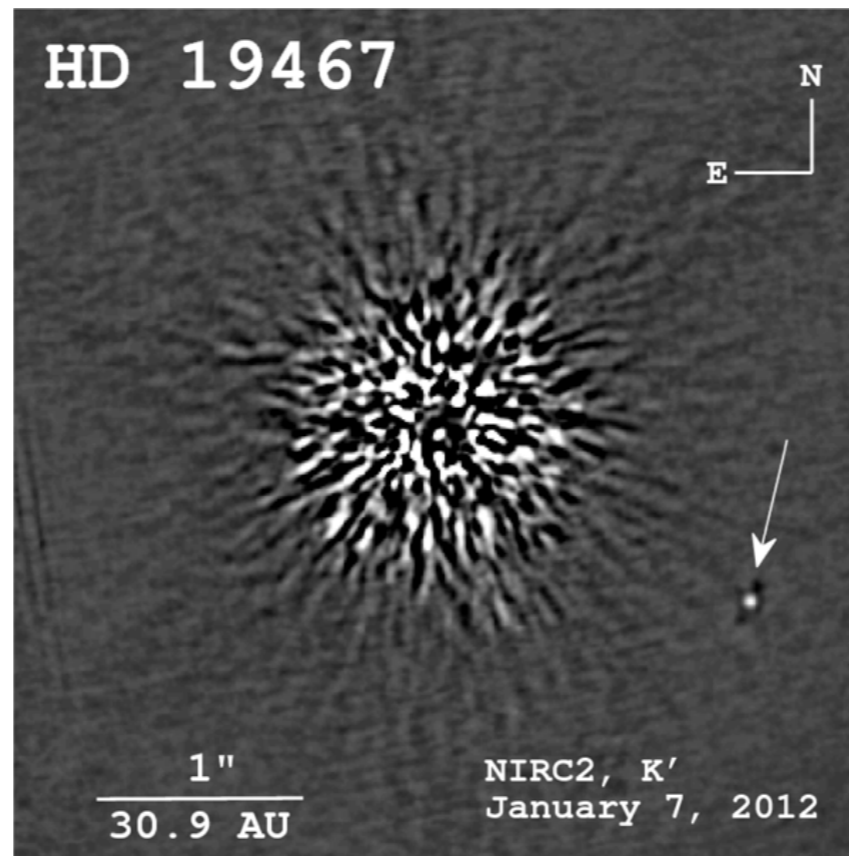


Crepp et al. 2014

Directly detecting long-term trends



Crepp et al. 2014

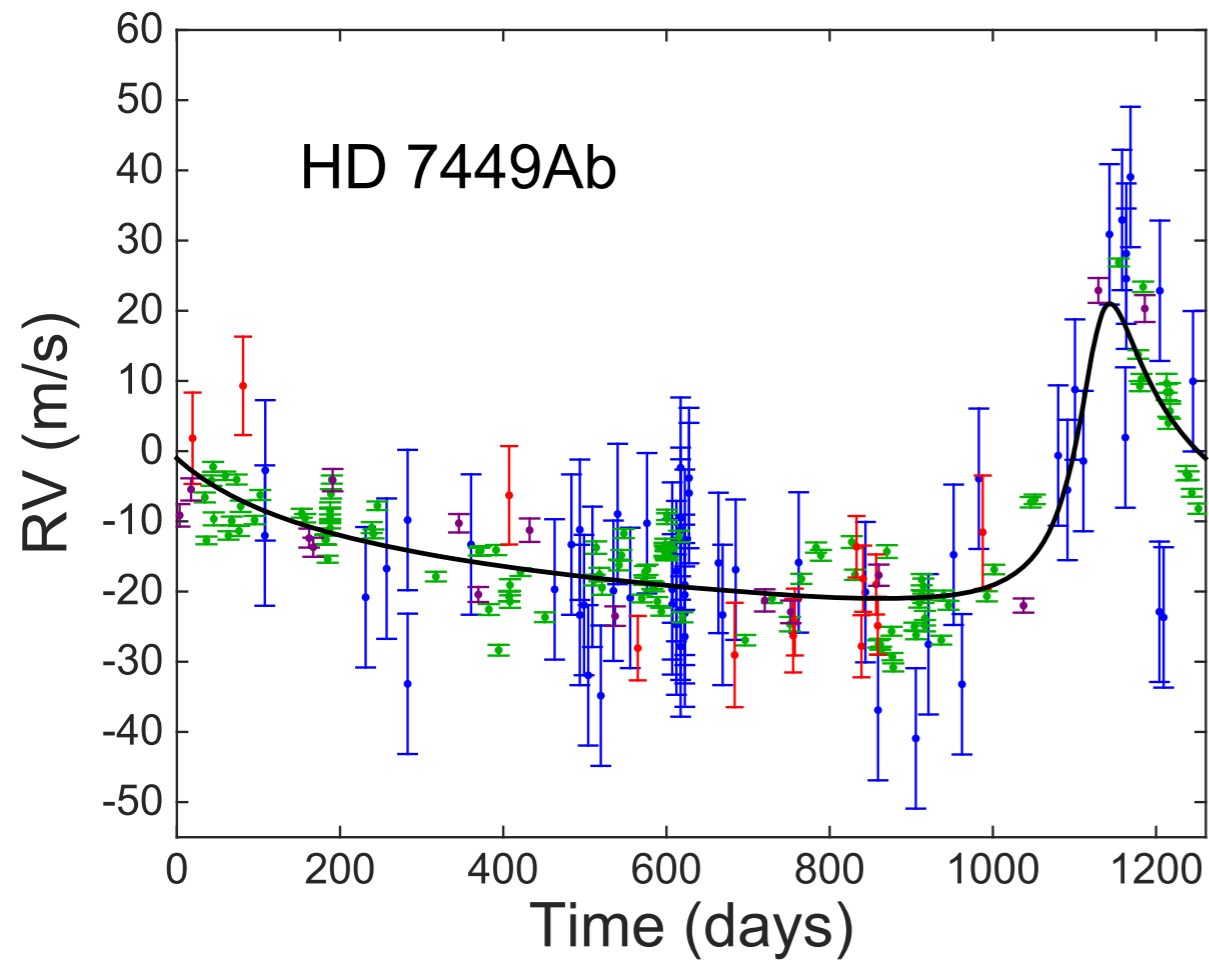


MagAO Imaging of Long-period Objects (MILO)

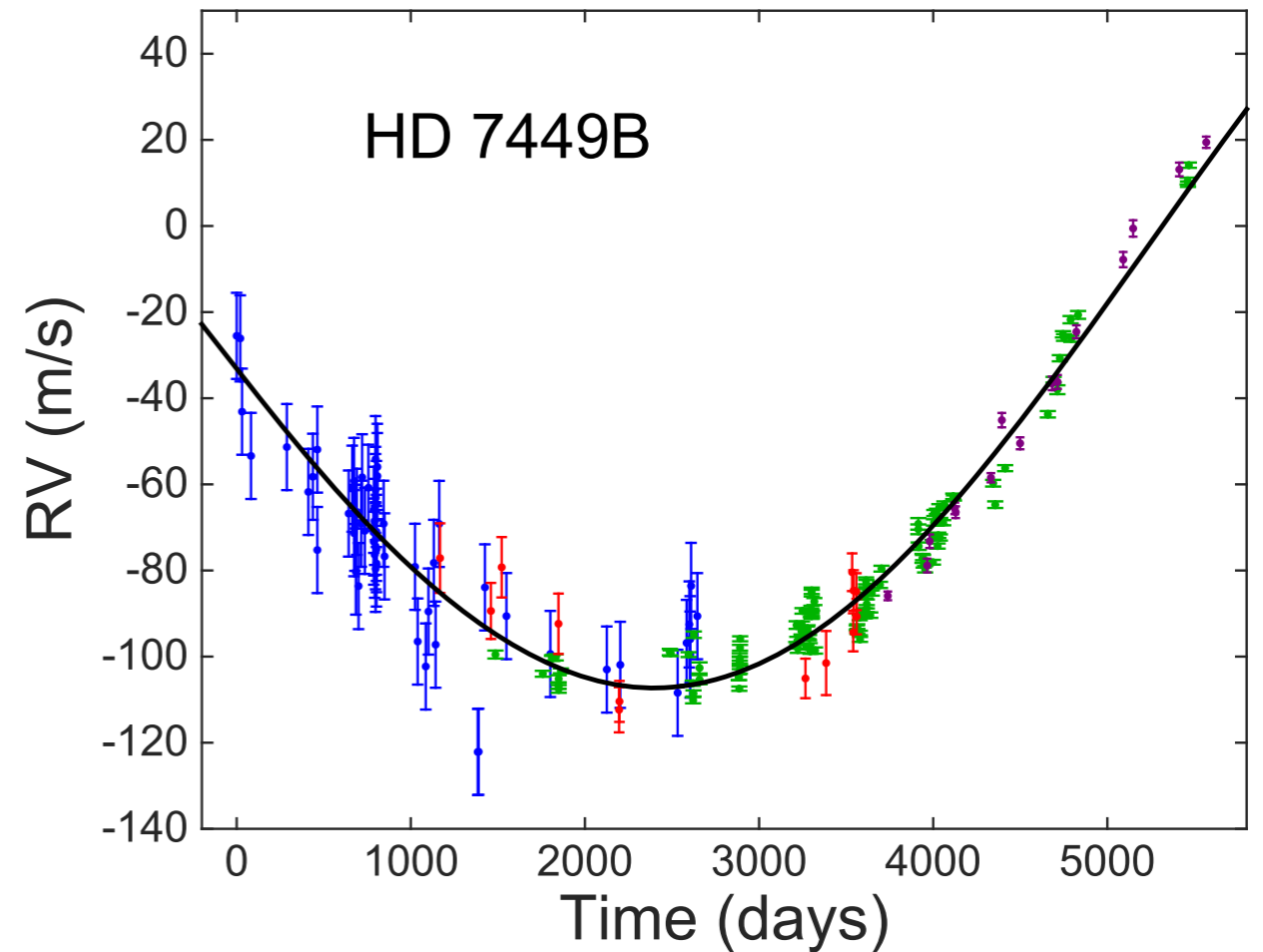
- Collaboration with Paul Butler; Magellan PFS, MIKE, & AAT RV data, imaging with MagAO; now merging with Justin Crepp's TRENDS program
- 30-40 targets with long-term trends
- Imaged 10 stars so far, dozens of new imaged companions

First Result:

A binary with a super-eccentric planet sandwiched in between

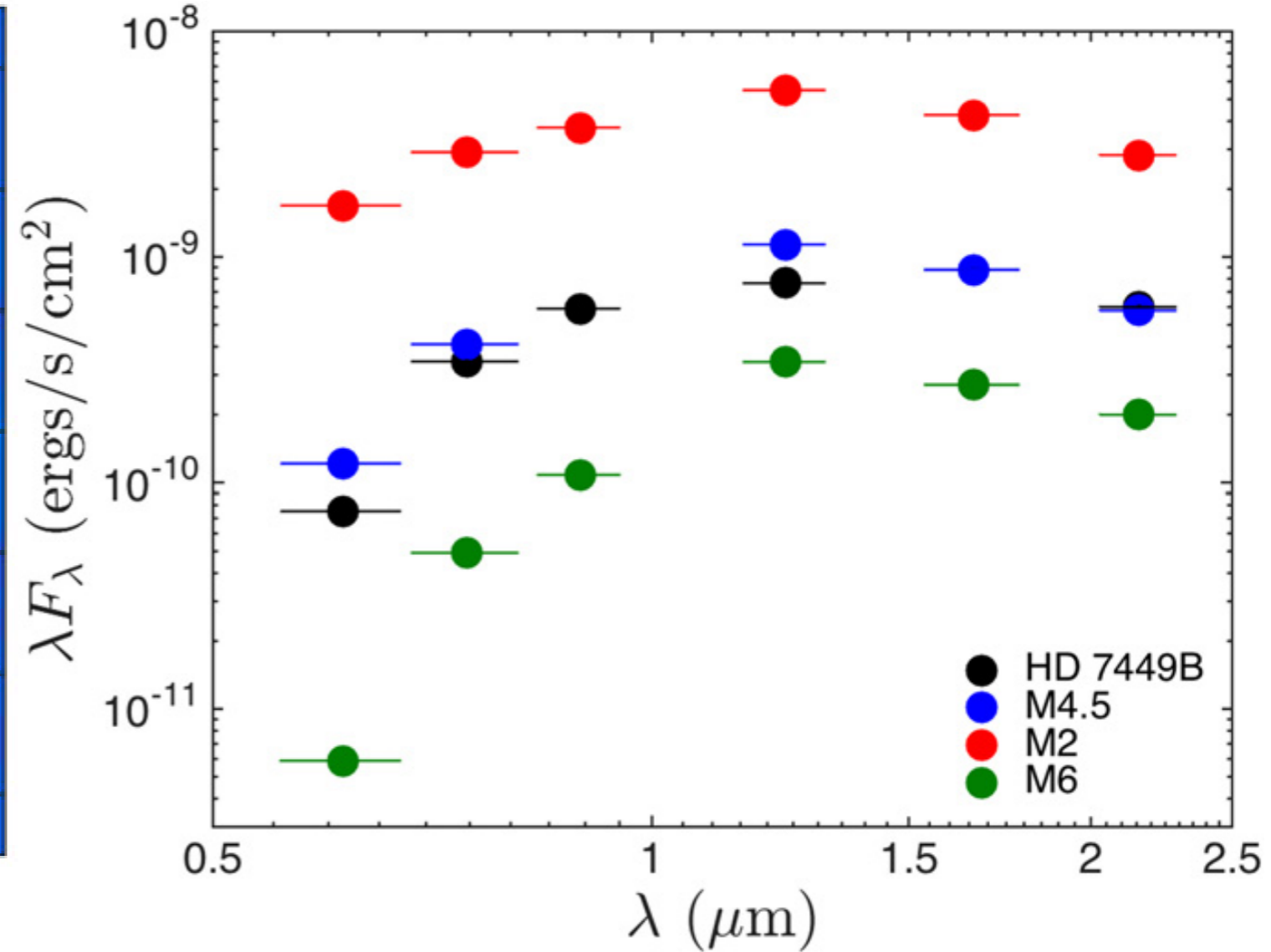
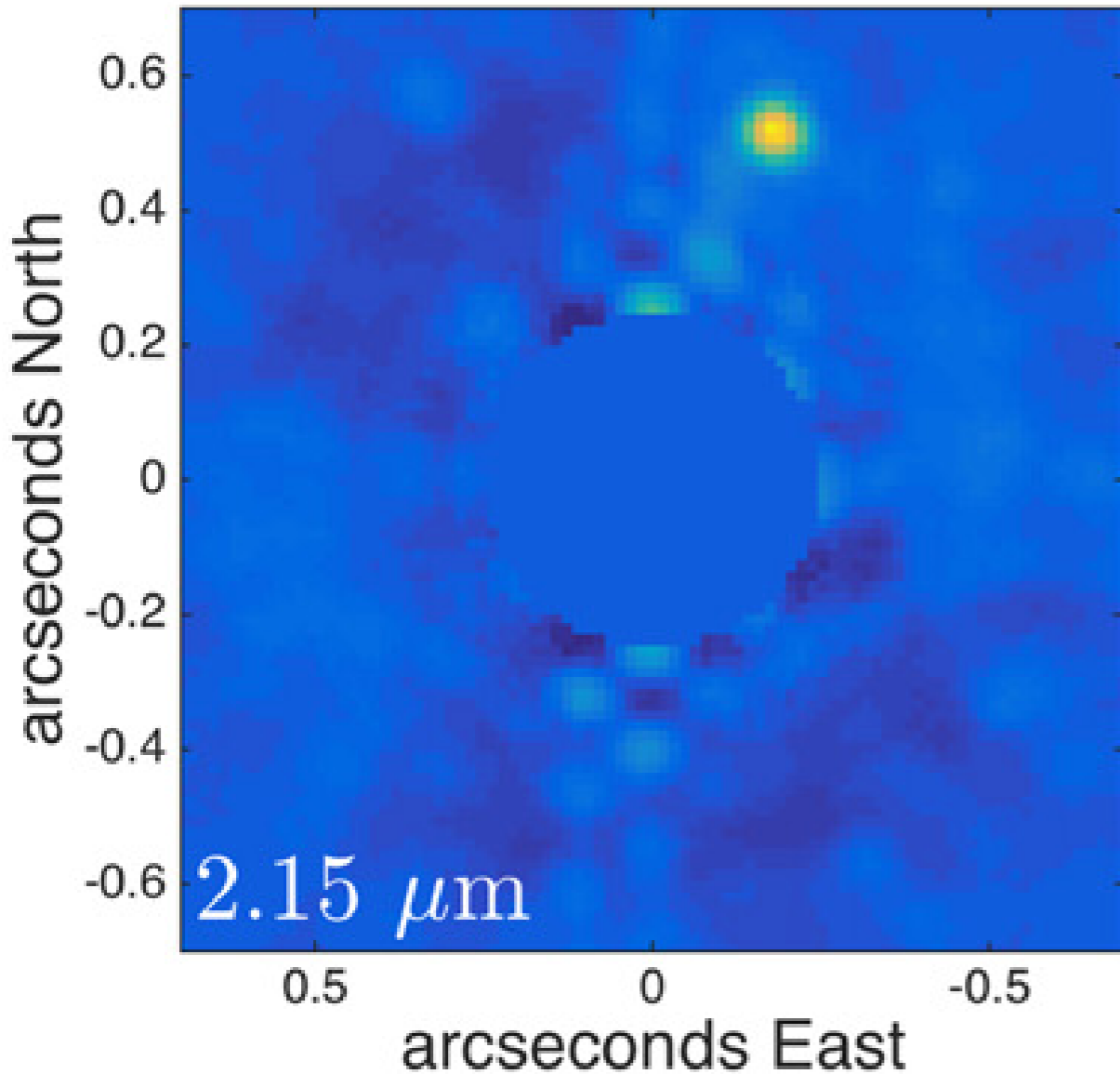


Known (inner) planet



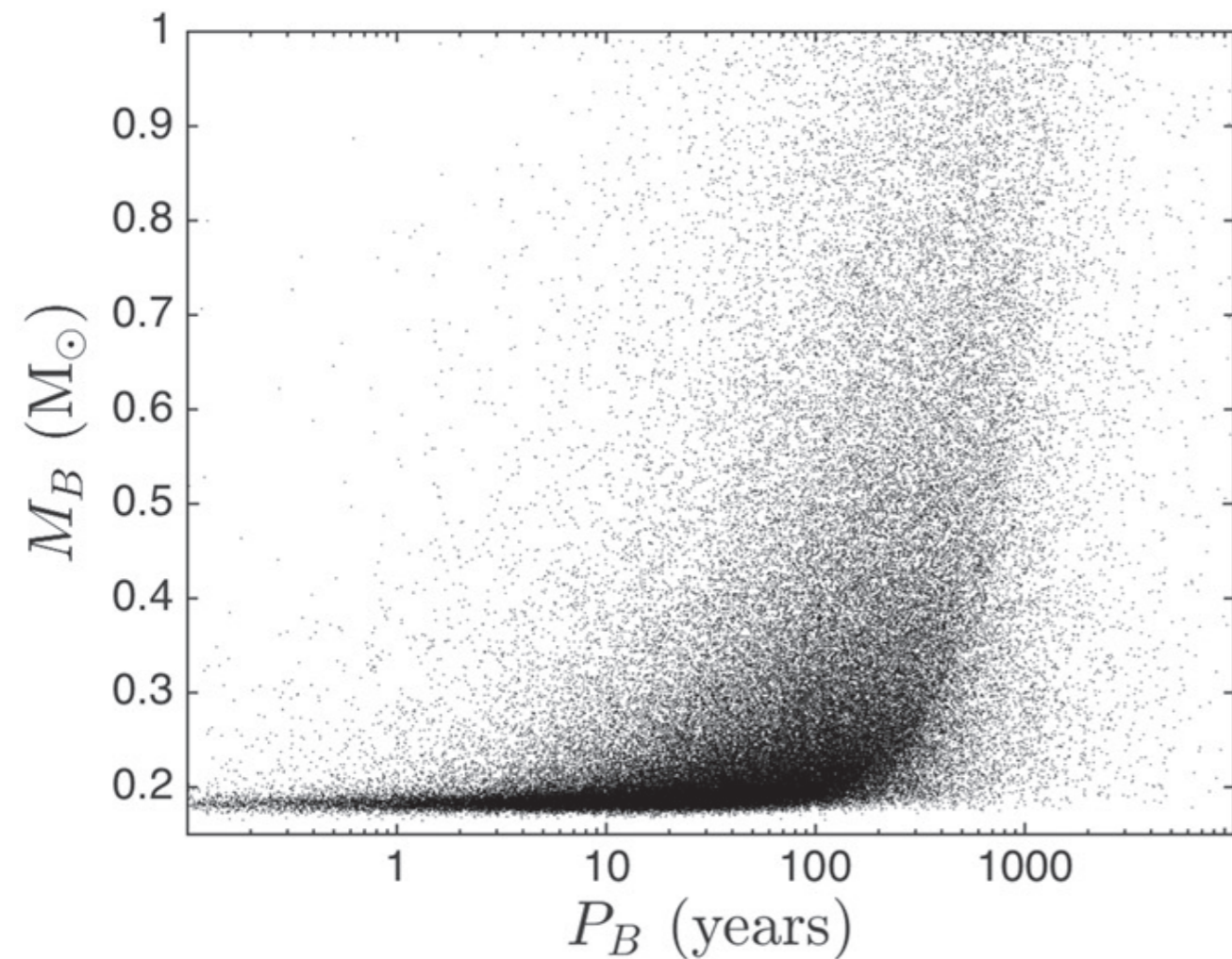
long-period companion

Companion is an M4-M5

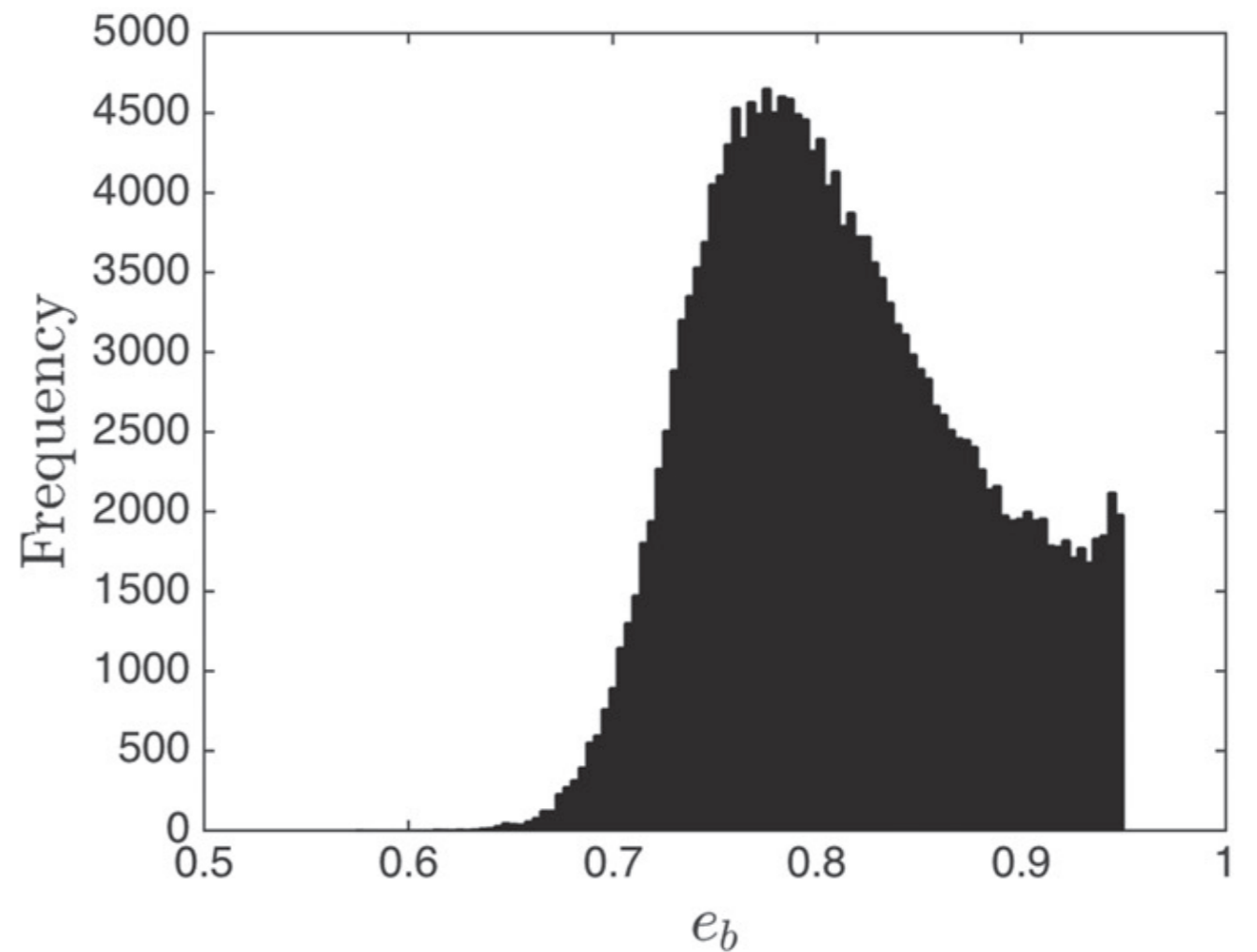


M dwarf at $\sim 15\text{-}20$ AU

Gas giant at 2 AU, super eccentric

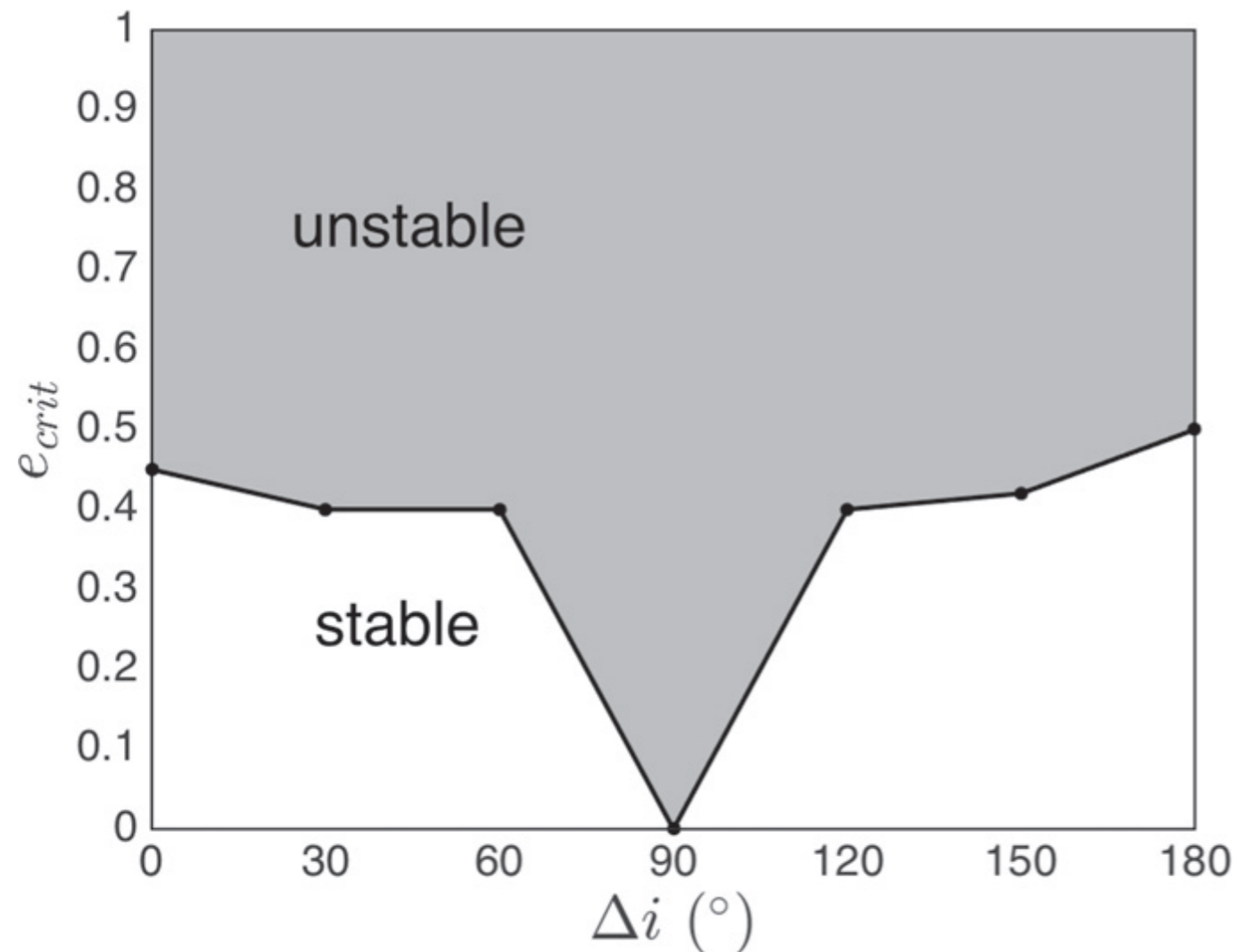


M dwarf



Planet

Constraints from dynamics



Assuming Kozai interactions:

-planet's mass $< 1.5 M_{Jup}$

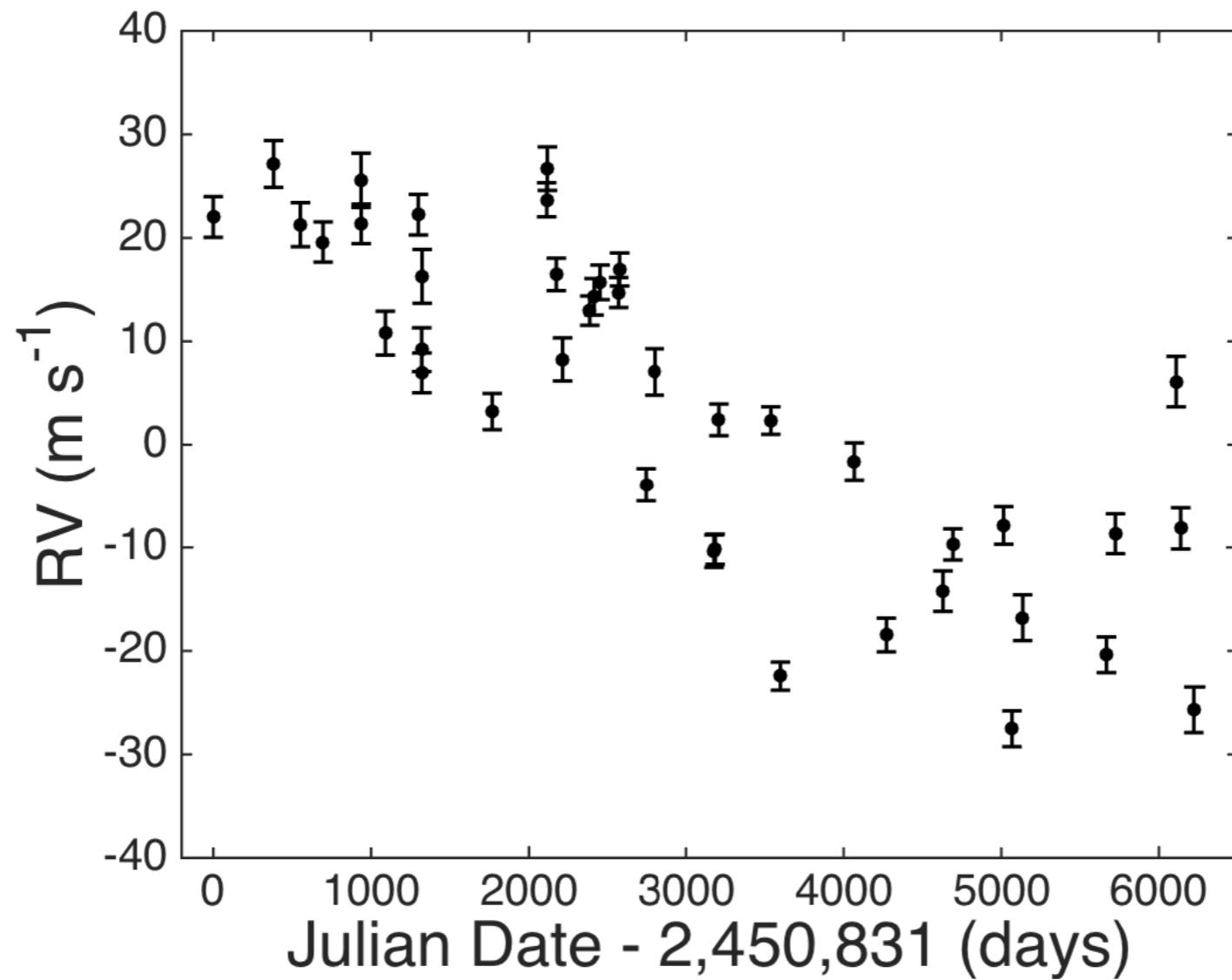
-mutual inclination > 38 deg

-*initial* mutual inclination > 62 deg

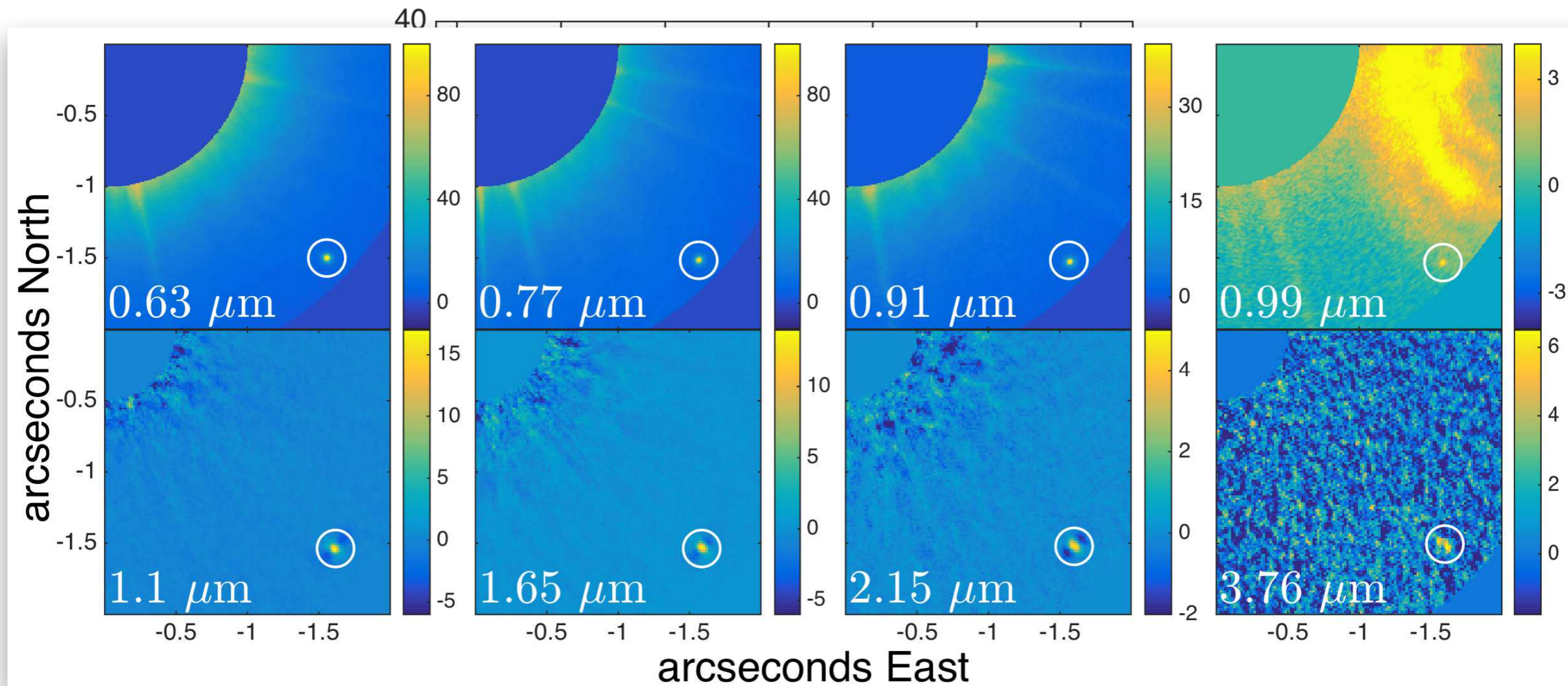
-M dwarf as close as 13 AU!

-How did this planet form?!?!?

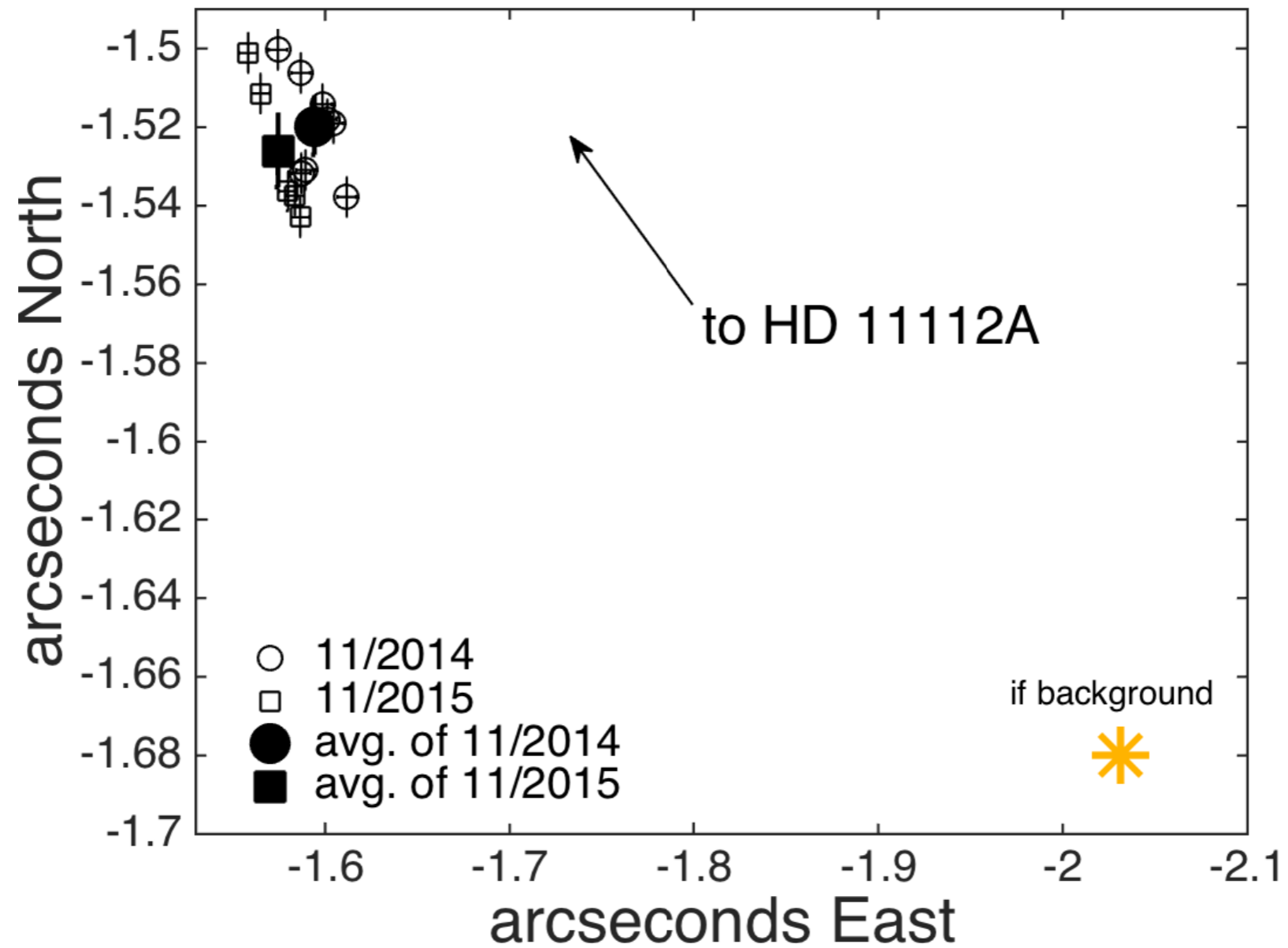
Second MILO Discovery



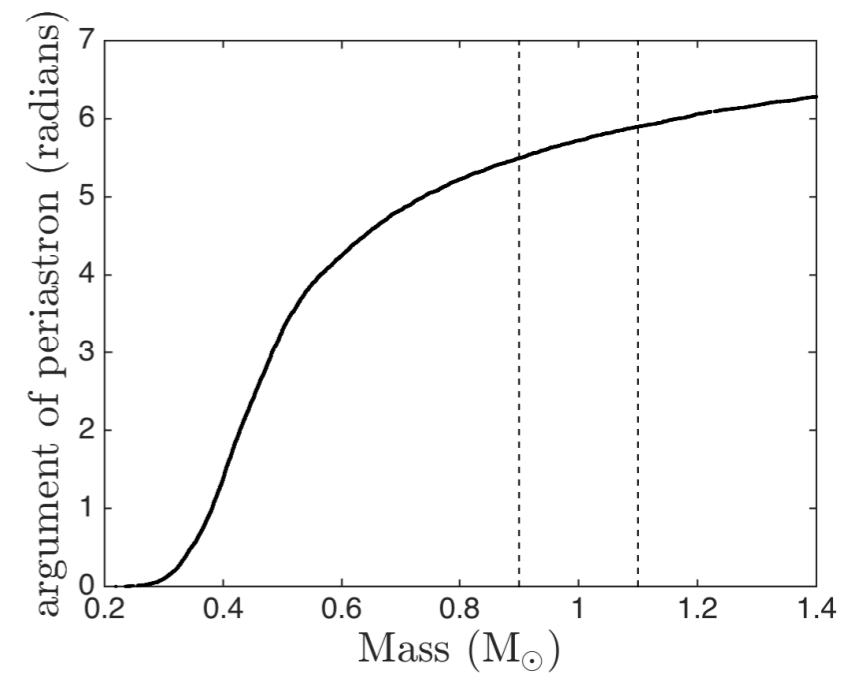
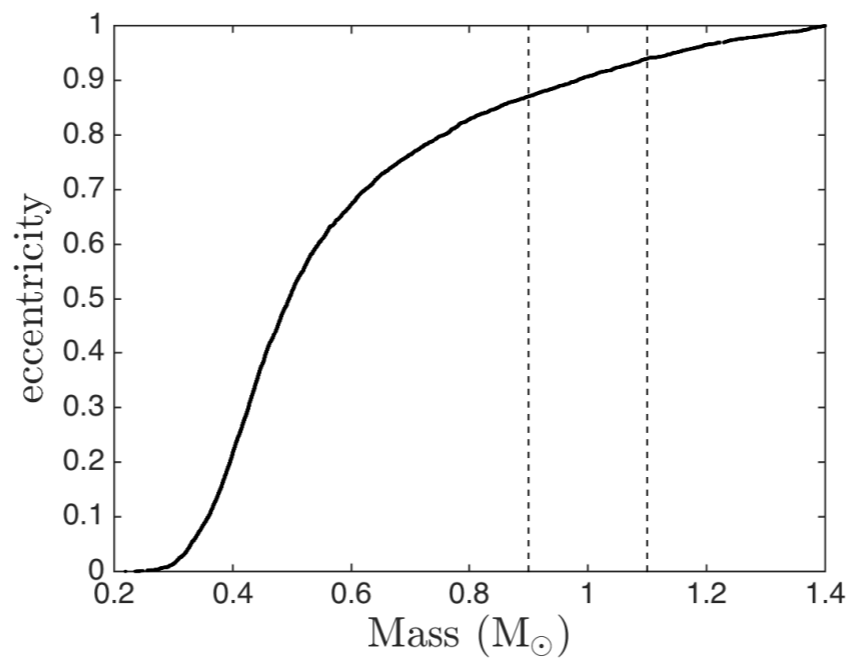
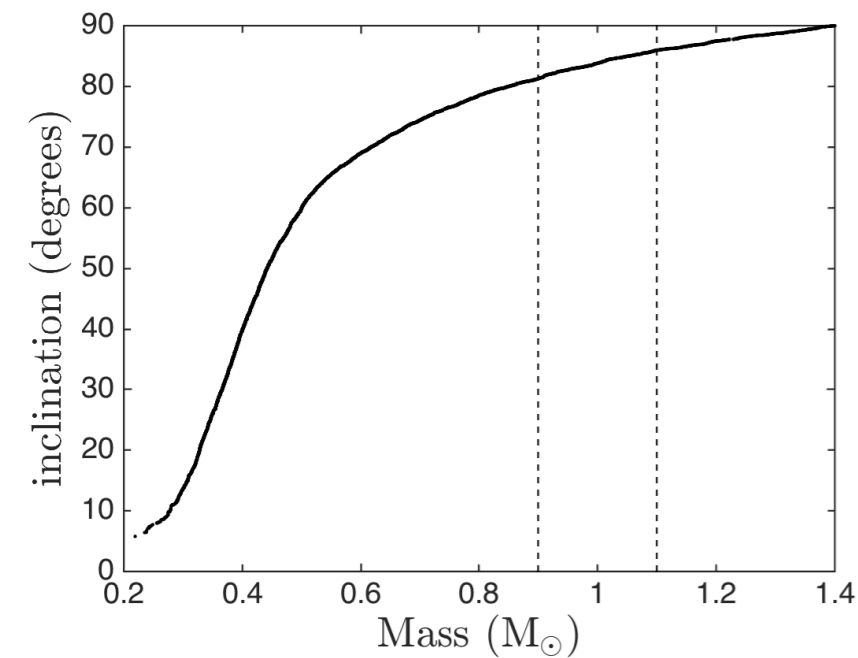
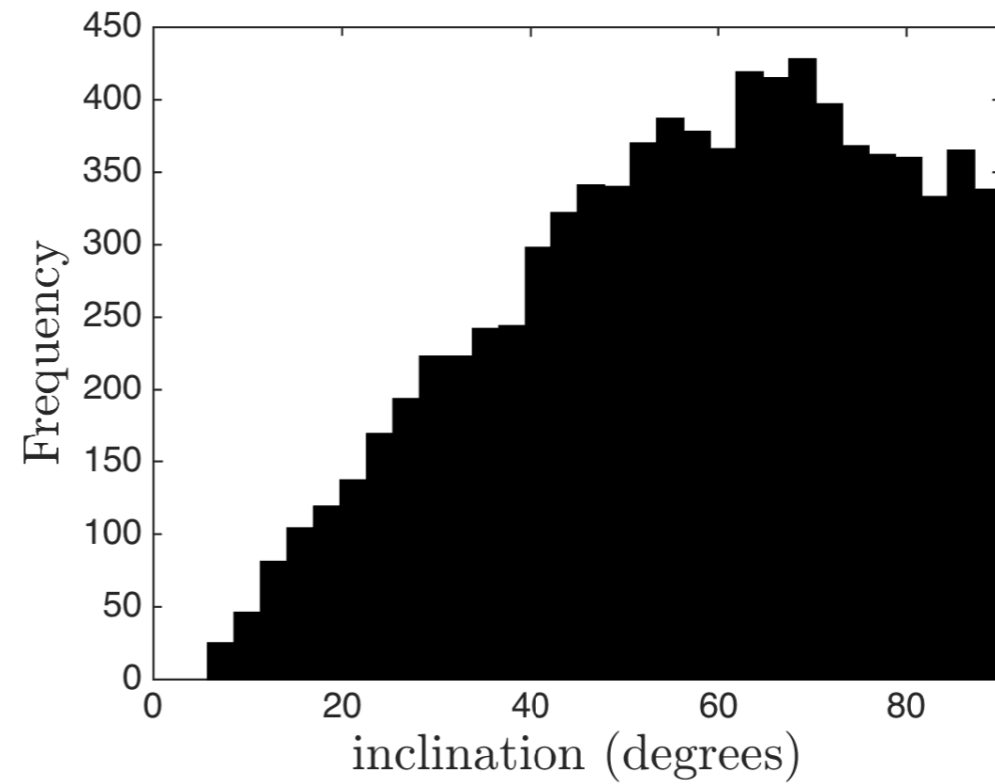
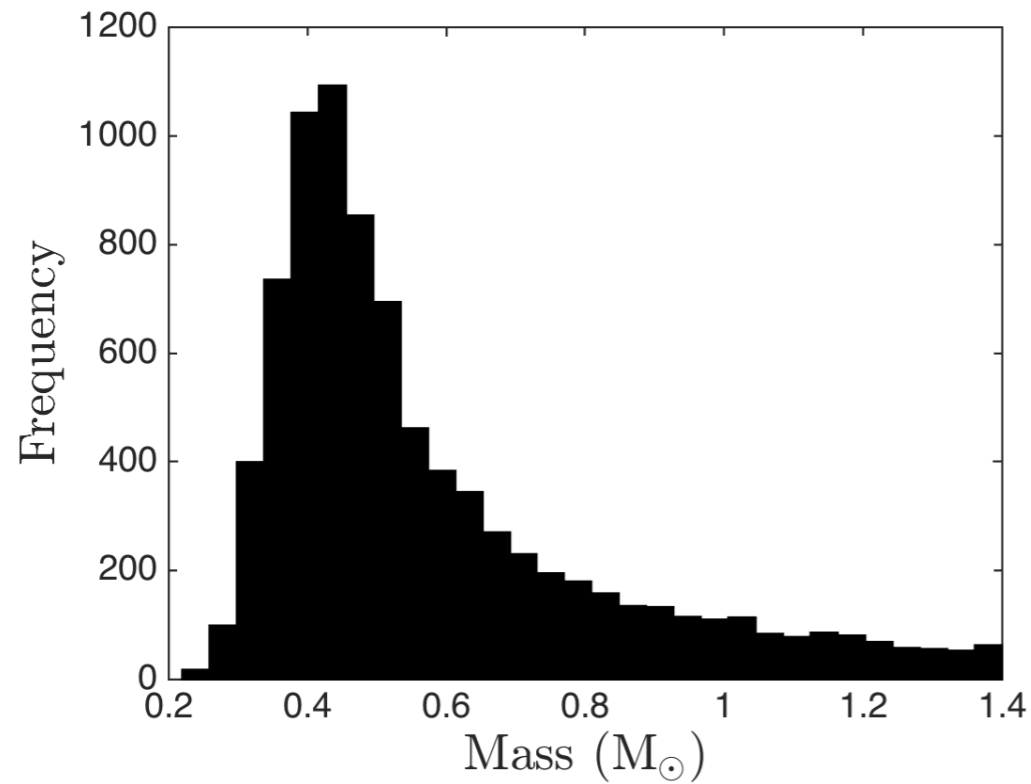
Second MILO Discovery



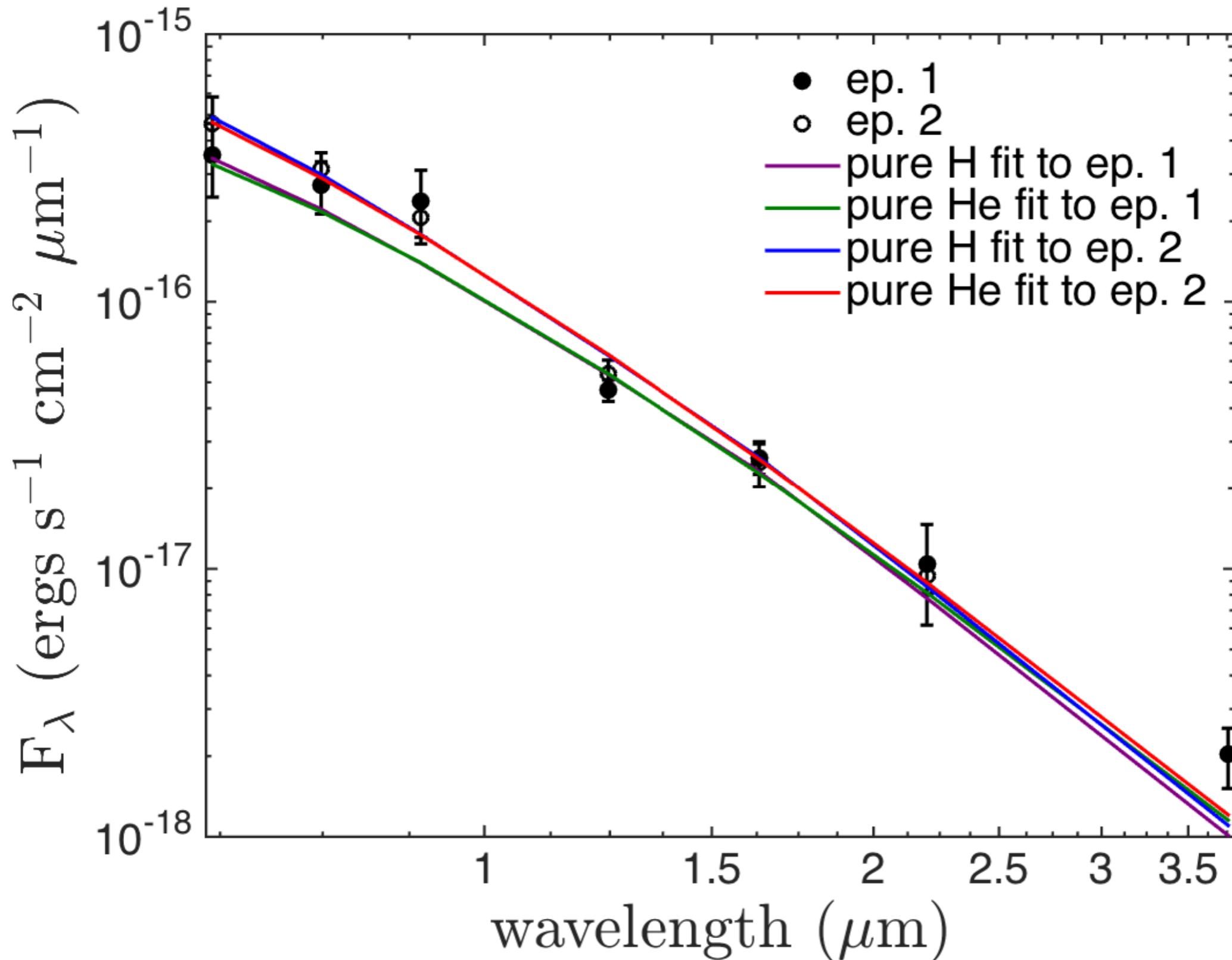
Not a background object...



Combine RV + Imaging...



What is it? A white dwarf!



Problem: ages don't agree

- Primary's age is 7 ± 1 Gyr
- White dwarf cooling age is < 4 Gyr
- WD progenitor main sequence lifetime < 200 Myr
- So...what's going on?
 - WD evolution must have been delayed—by 3 Gyr
 - Merger of some sort \rightarrow most plausible is two 0.5 Msun white dwarfs!

My dream for LUVOIR...

My dream for LUVVOIR...

- Big enough aperture to *directly image RV planets* (either in reflected light or thermal imaging?)

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- Put RV+imaging information together to fully constrain planet mass and orbit

My dream for LUVVOIR...

- Big enough aperture to *directly image RV planets* (either in reflected light or thermal imaging?)
- Put RV+imaging information together to fully constrain planet mass and orbit
- → constrain formation and evolution theories

Binary power #3:

Can use binaries to directly measure $v \sin i$

The need for $v \sin i$

-Stellar evolution

-rotation changes as star evolves

e.g., $v = 4/\pi * \langle v \sin i \rangle = 15.6 - 4.2 * \text{Sp.Type}$ (Gray 1989a)

-Stellar ages

-main sequence stars spin down over time; measure $v \sin i$, infer age

e.g., $v \sin i \text{ (km/s)} \sim 5 * (\text{age/Gyr})^{-1/2}$ (Barry et al. 1987)

-Exoplanets

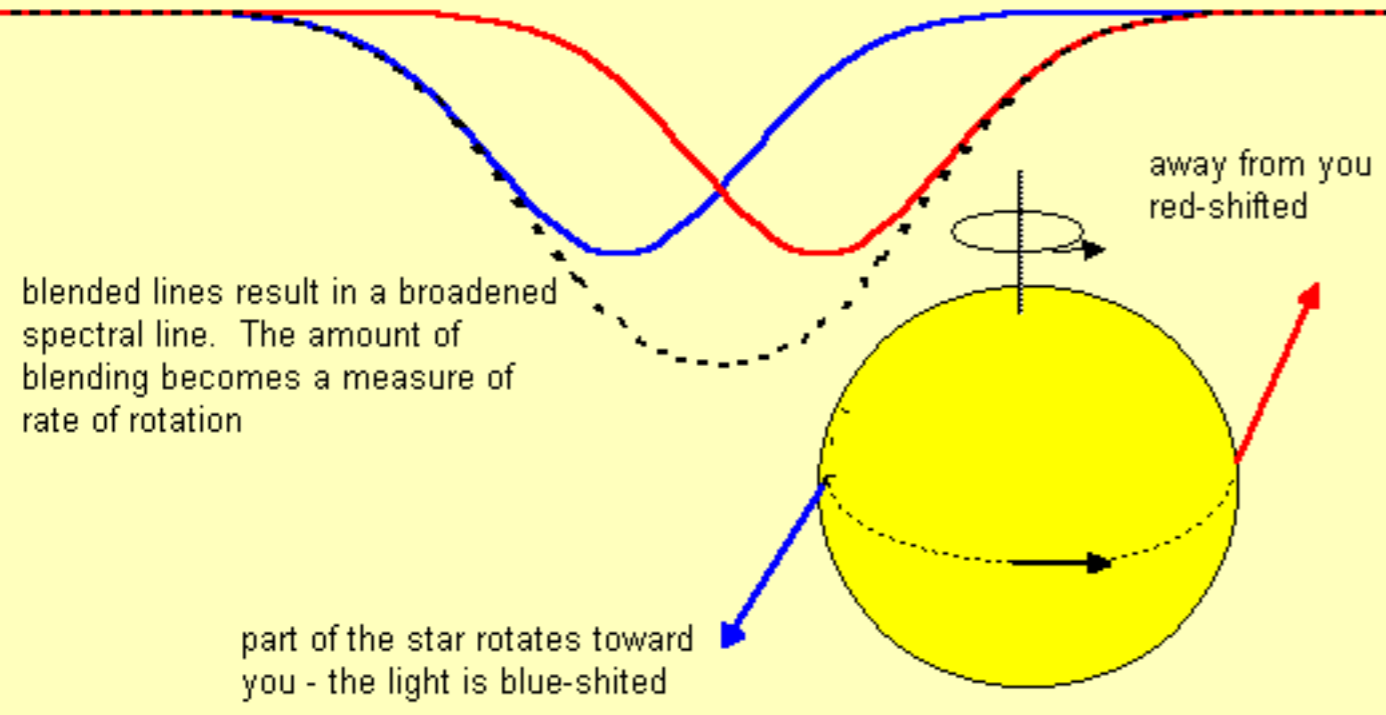
-obliquities of transiting planets [$\sin i = v \sin i / v = v \sin i / (2\pi R/P)$]

-true masses of radial velocity (RV) planets (if $\sin i = \sin i_p$)

Current method for measuring v_{Sini}

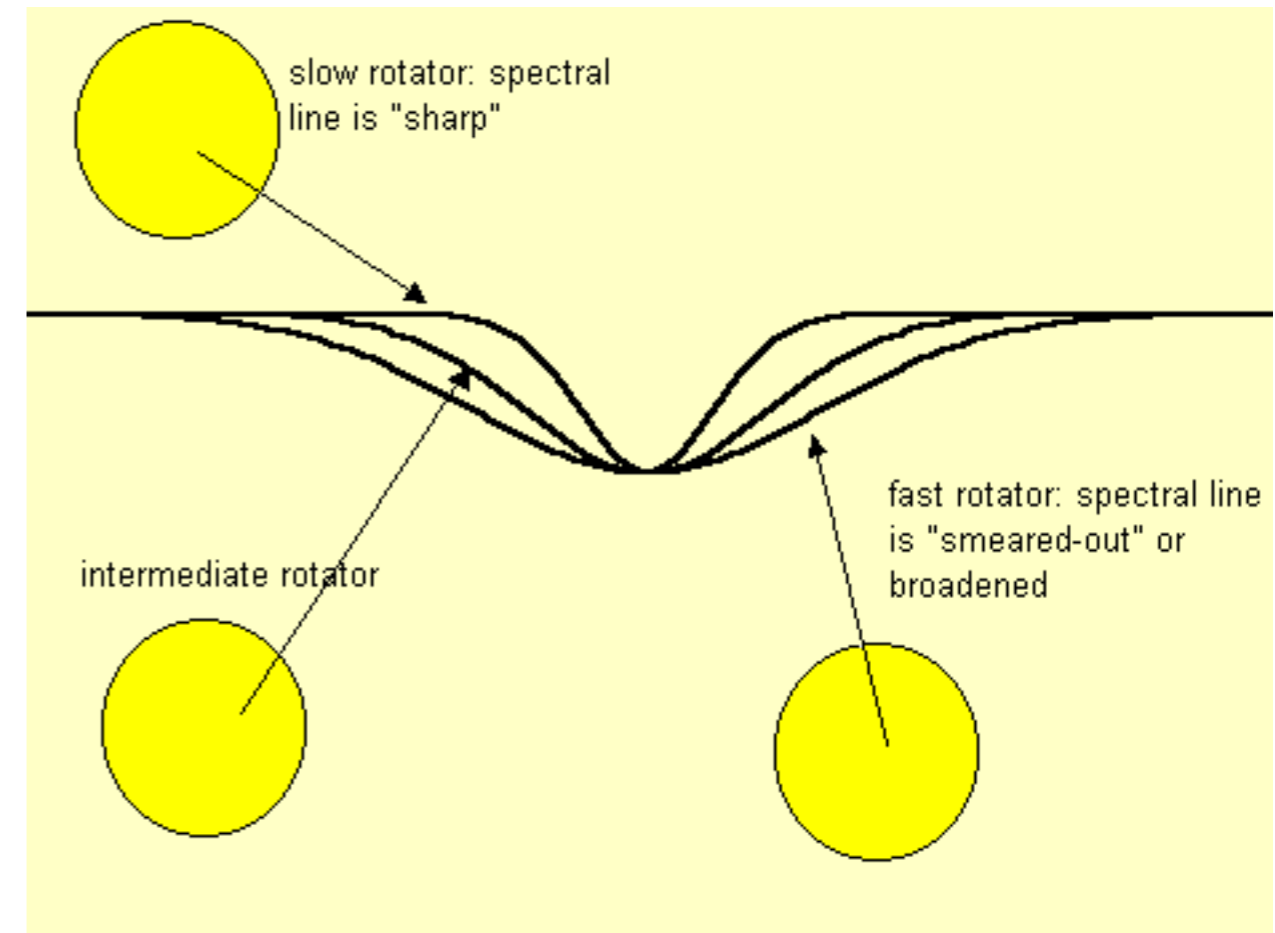
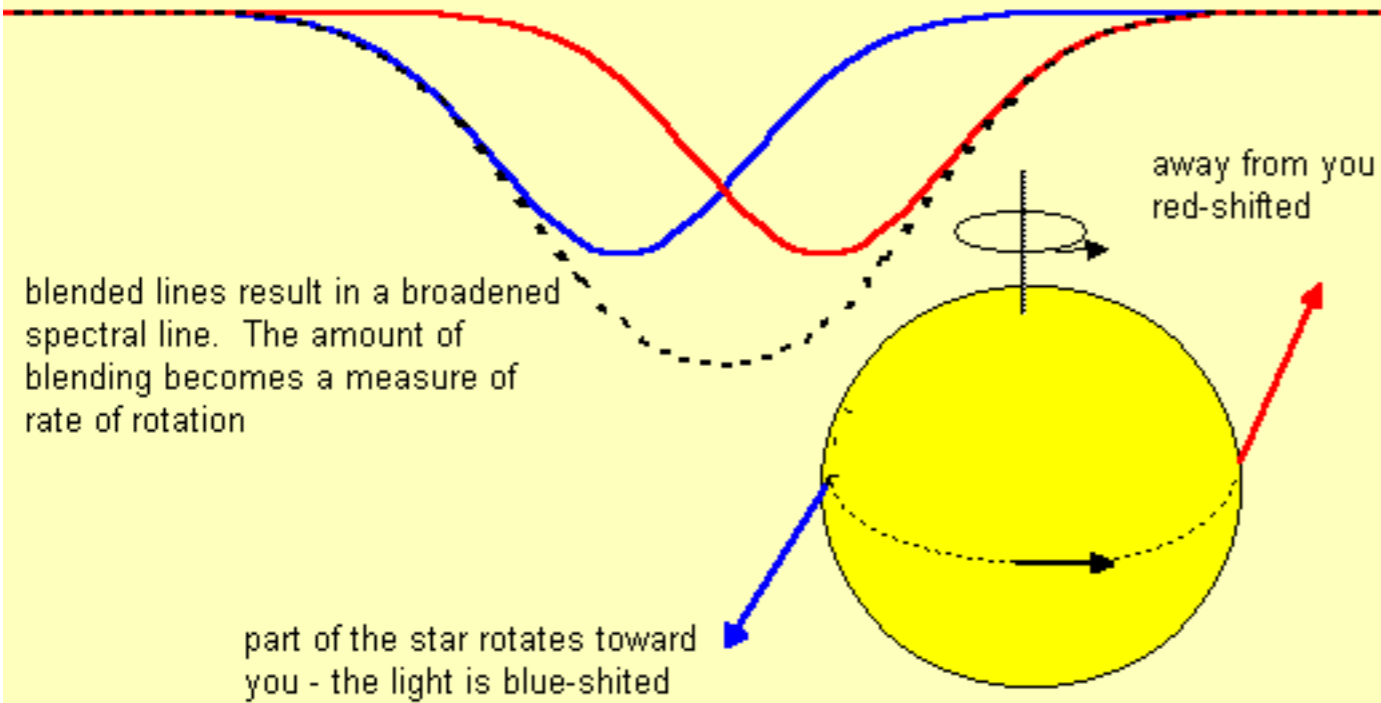
Current method for measuring $v \sin i$

Rotational Broadening: a way of measuring stellar rotation



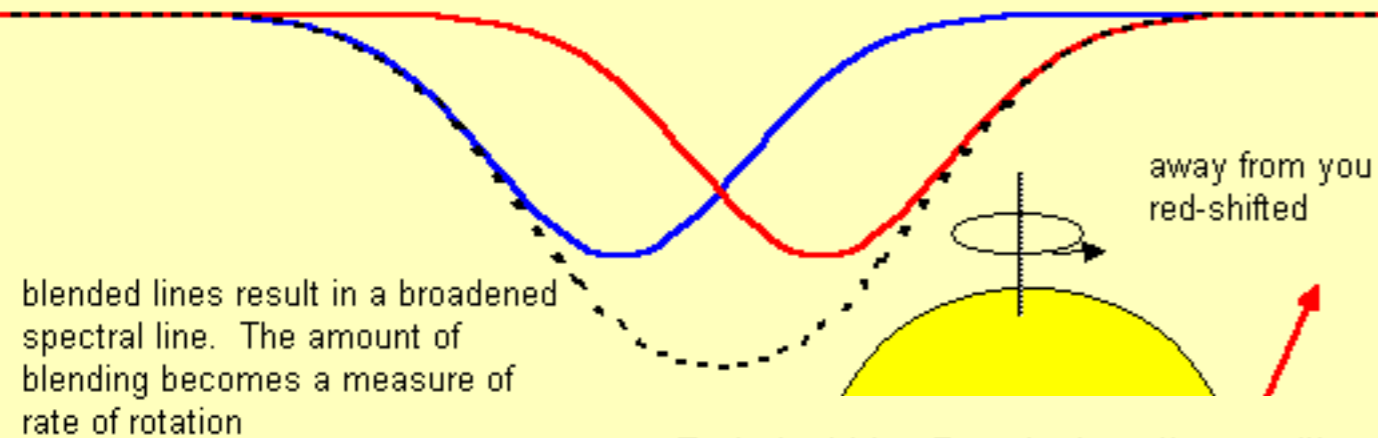
Current method for measuring $v \sin i$

Rotational Broadening: a way of measuring stellar rotation



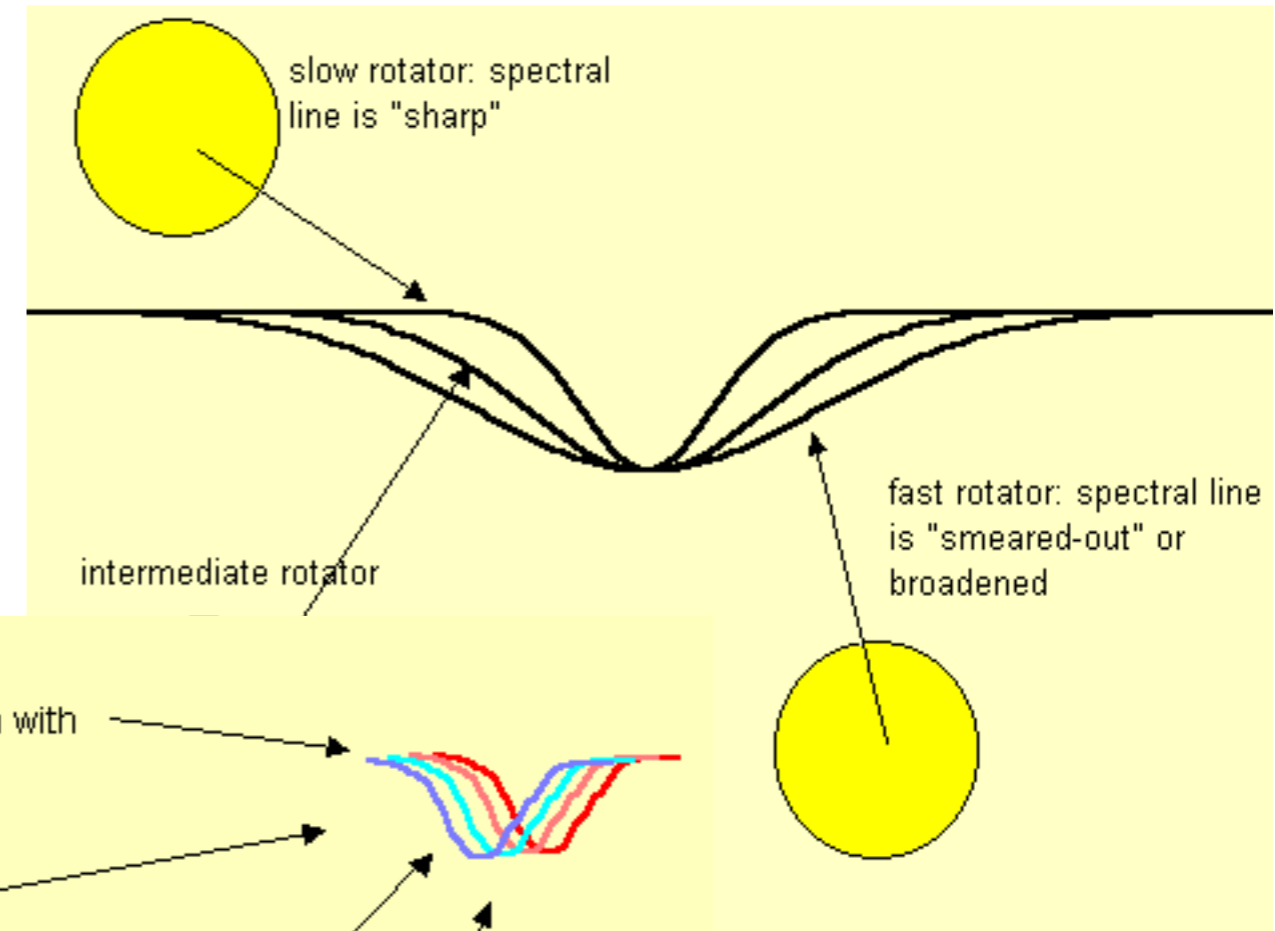
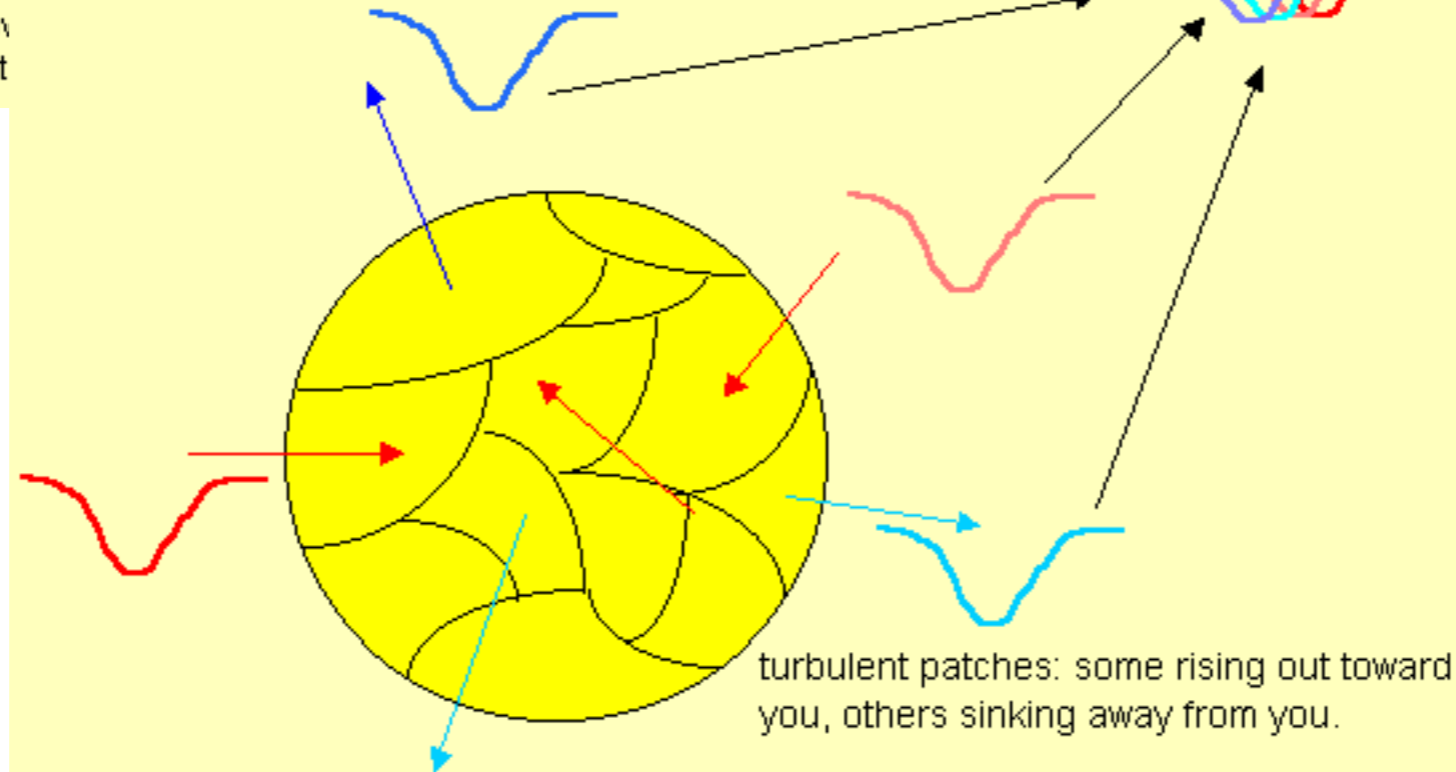
Current method for measuring $v \sin i$

Rotational Broadening: a way of measuring stellar rotation



Turbulent Line Broadening: the resulting spectral line is the sum of many lines, each with its own doppler displacement

part of the star rotates toward you - the light is blue-shifted



Limited to $v \sin i > 2 \pm 0.5$ km/s

Nearby stars
(most with
planets)

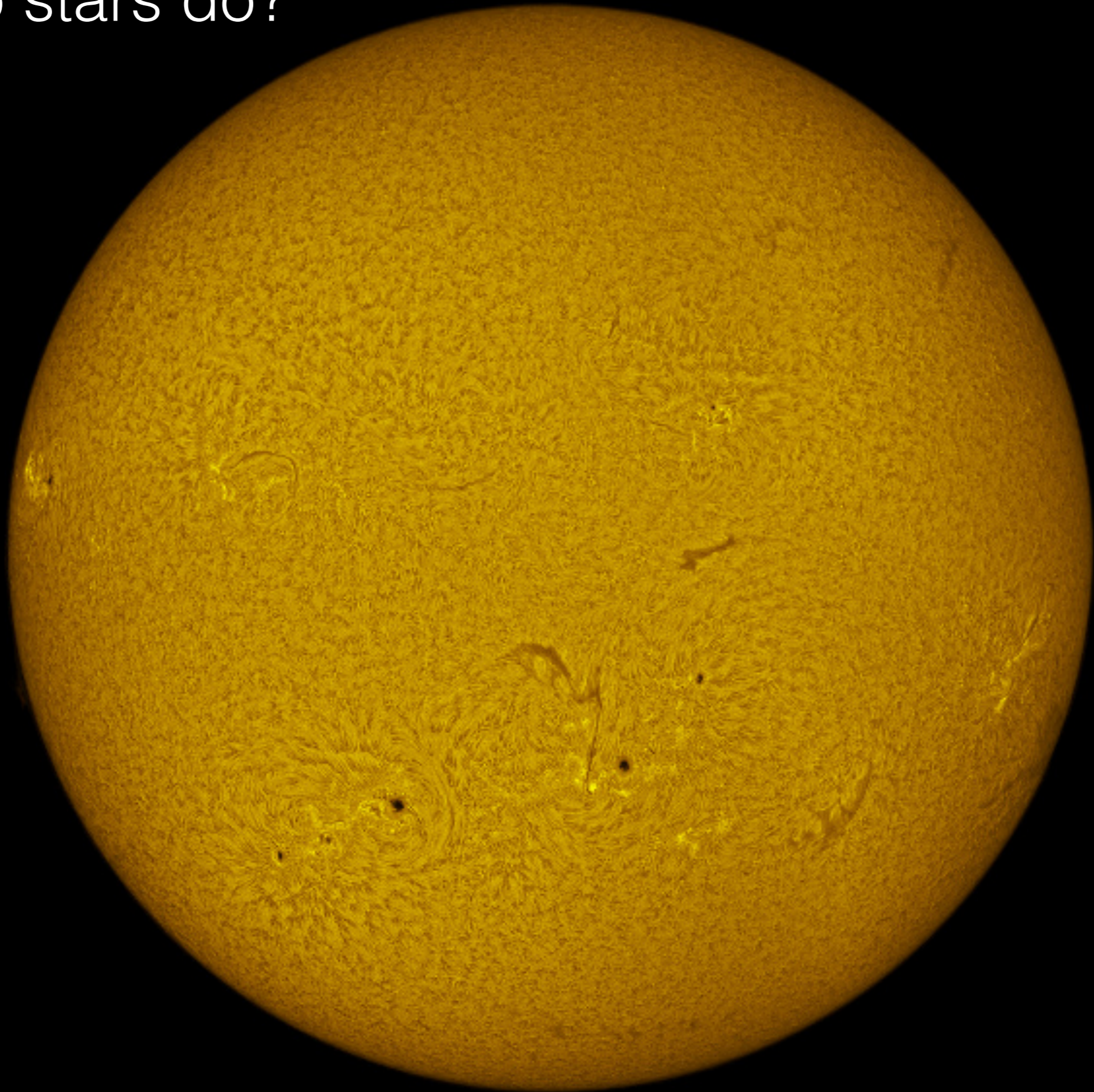
Star	$V \sin i$ (km/s)
ν And ⁺	$9.62^{+0.50}_{-0.50}$
α Cen B	$1.00^{+0.60}_{-0.60}$
ϵ Eri	$2.45^{+0.50}_{-0.50}$
HD 19994	$8.57^{+0.50}_{-0.50}$
ι Hor	$6.47^{+0.50}_{-0.50}$
HD 10647	$5.61^{+0.50}_{-0.50}$
HD 179949	$7.02^{+0.50}_{-0.50}$
HD 20794 ⁺	$1.50^{+1.50}_{-1.50}$
HD 196885	$7.80^{+0.50}_{-0.50}$
HD 40979	$7.43^{+0.50}_{-0.50}$
HD 136118	$7.33^{+0.50}_{-0.50}$
τ Gru	$5.78^{+0.50}_{-0.50}$
HD 113337	$6.30^{+1.00}_{-1.00}$
61 Vir ⁺	$2.20^{+0.30}_{-0.30}$
μ Ara ⁺	$3.12^{+0.50}_{-0.50}$
HD 114613	$2.70^{+0.90}_{-0.90}$
70 Vir	$2.68^{+0.50}_{-0.50}$
HD 30562	$4.32^{+0.50}_{-0.50}$
47 UMa ⁺	$2.80^{+0.50}_{-0.50}$
HD 52265	$4.67^{+0.50}_{-0.50}$

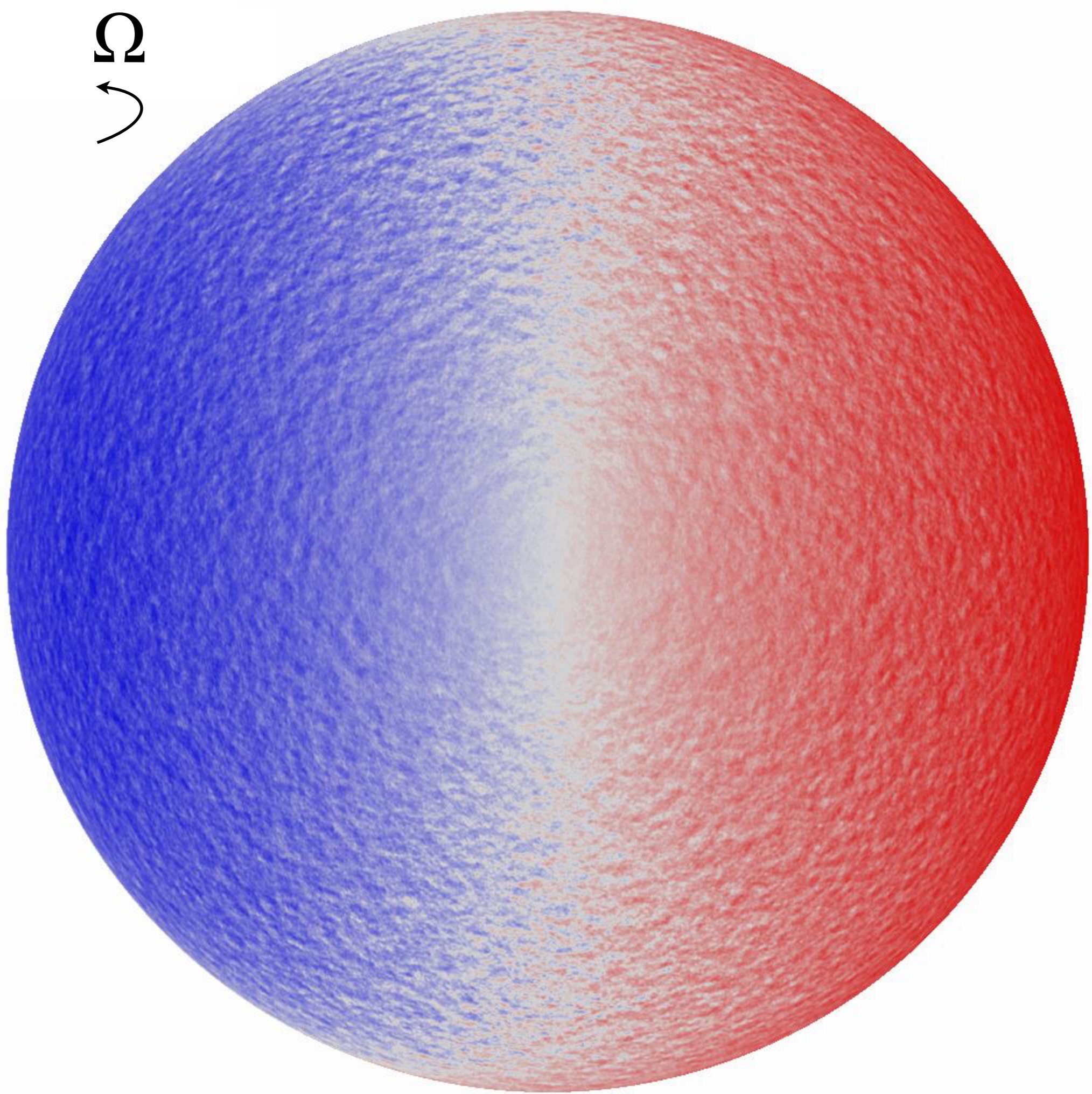
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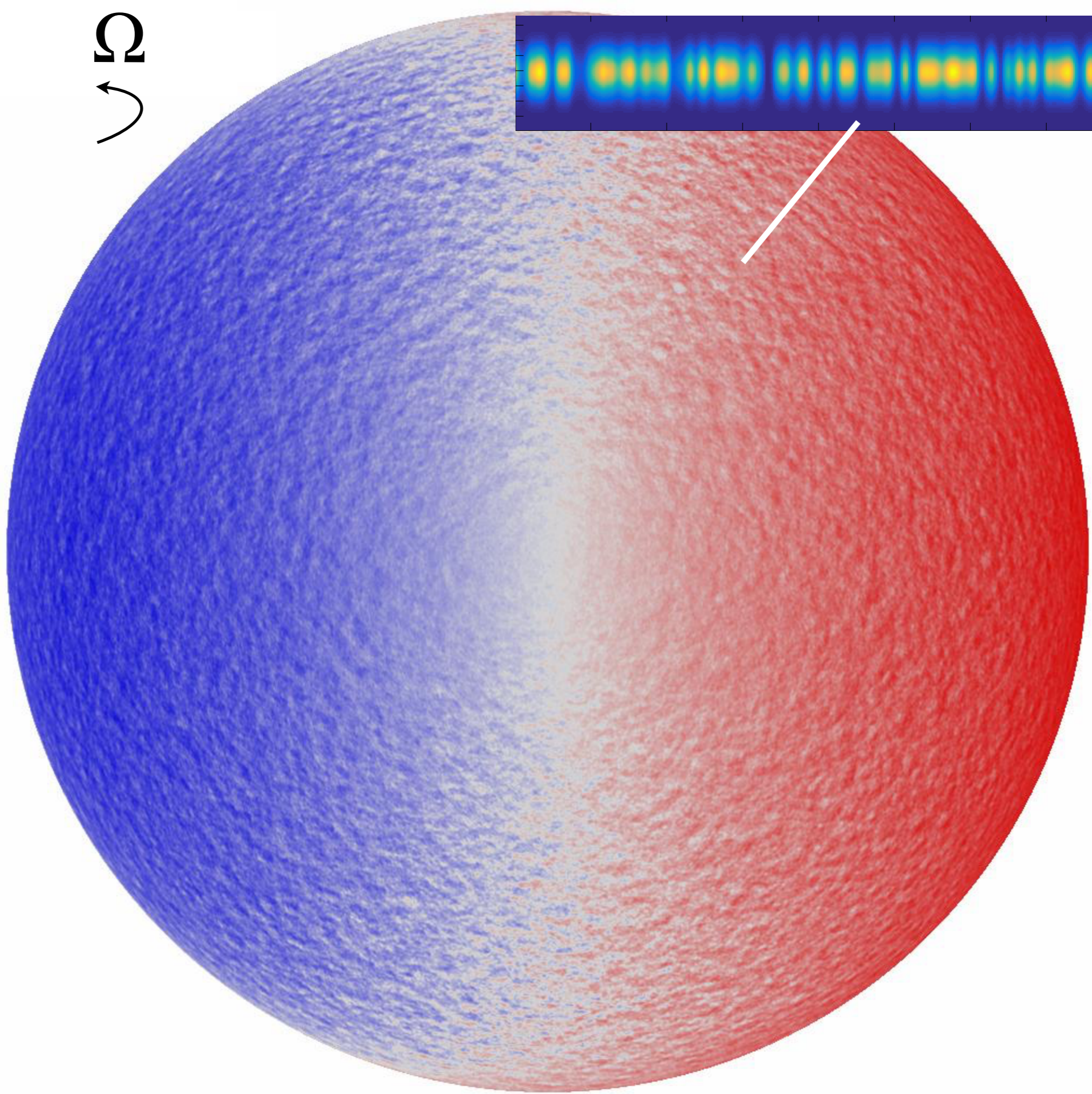
Star	$V \sin i$ (km/s)
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What do stars do?

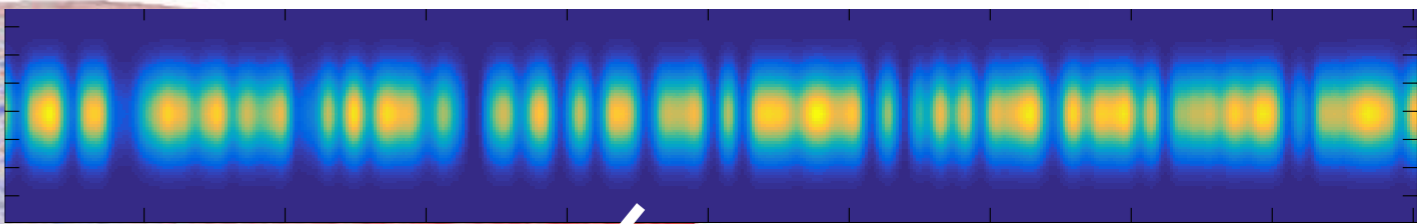


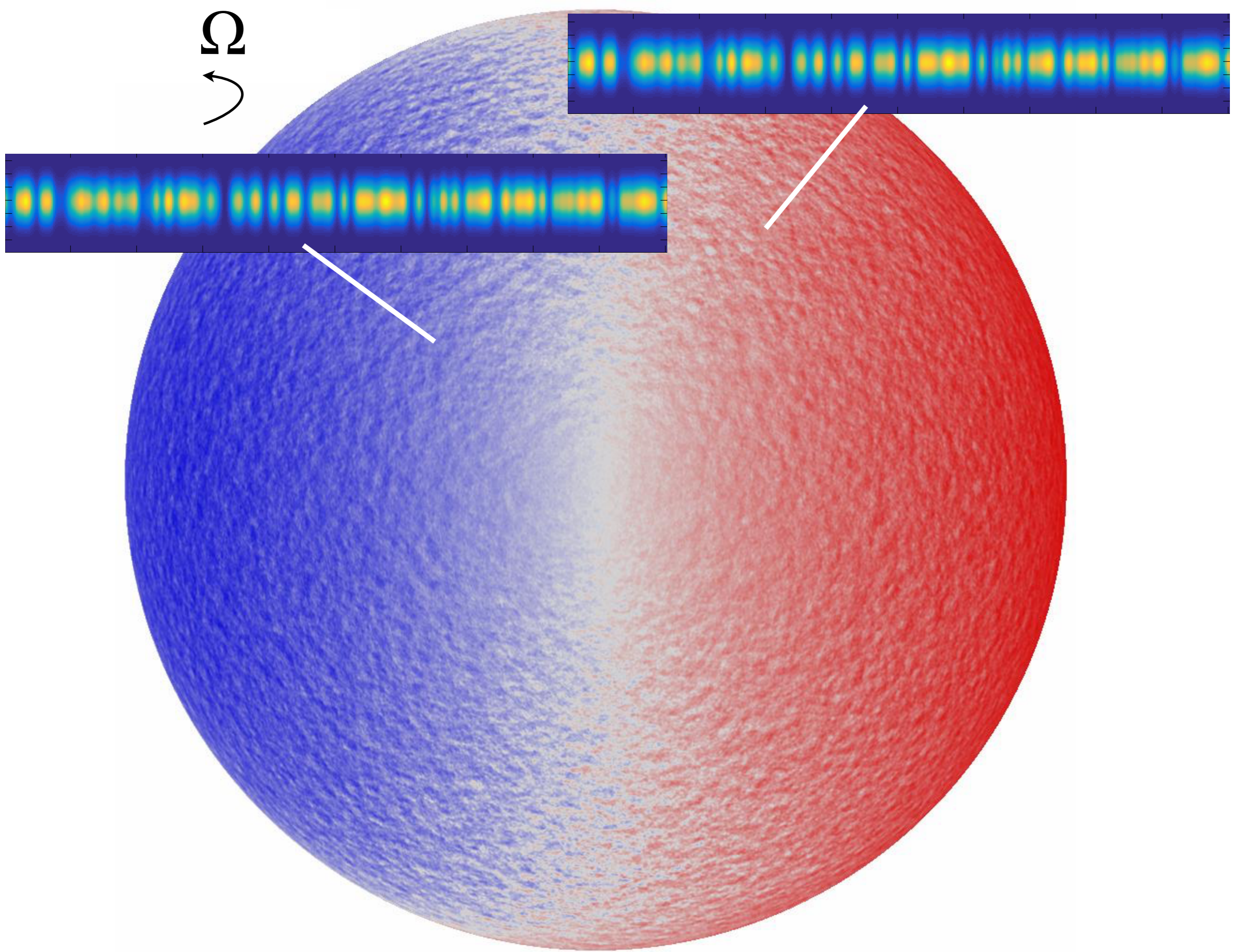


Q

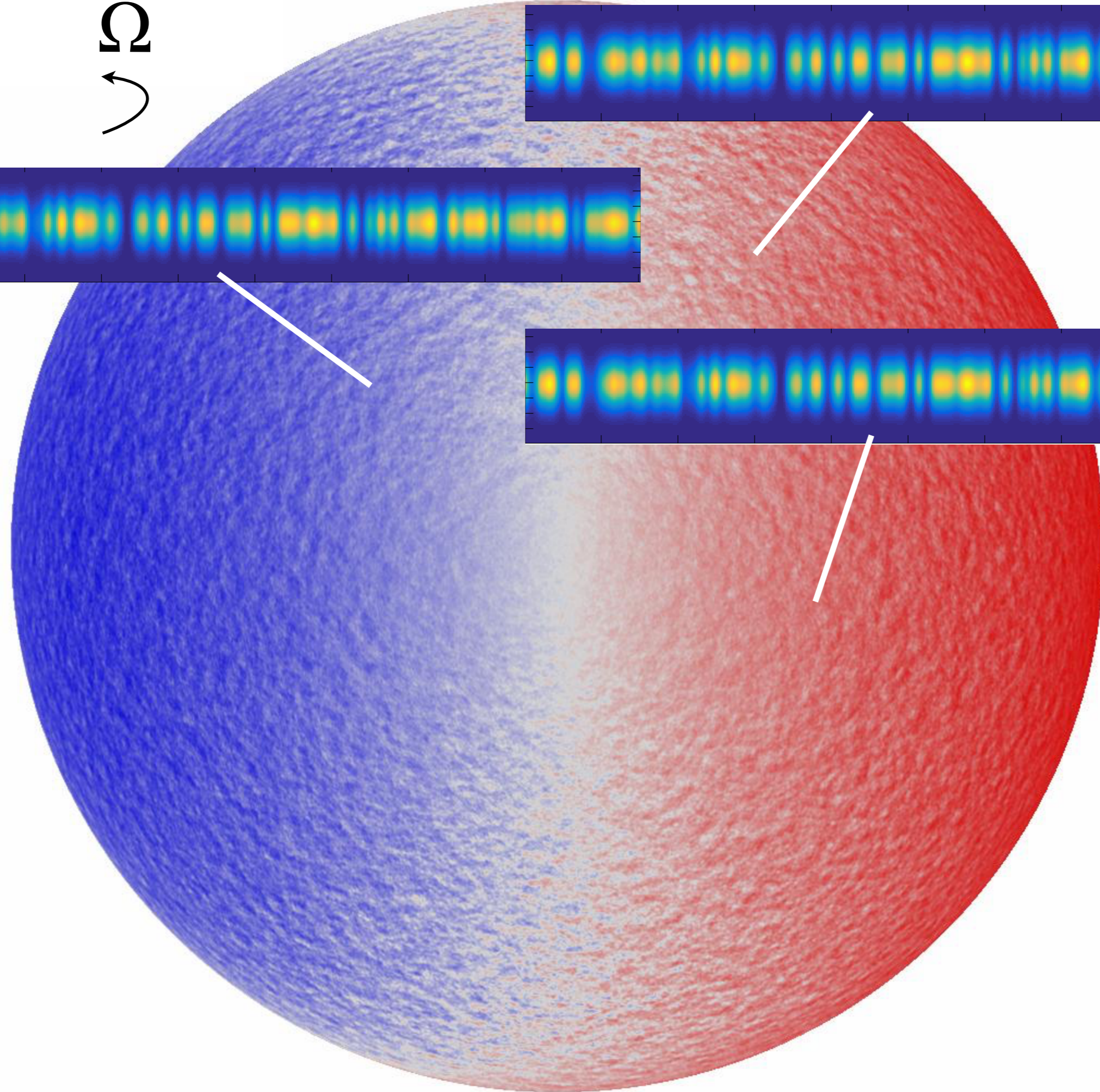
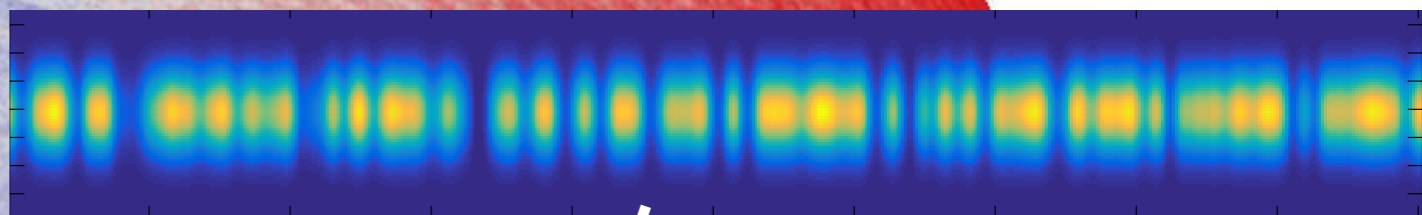
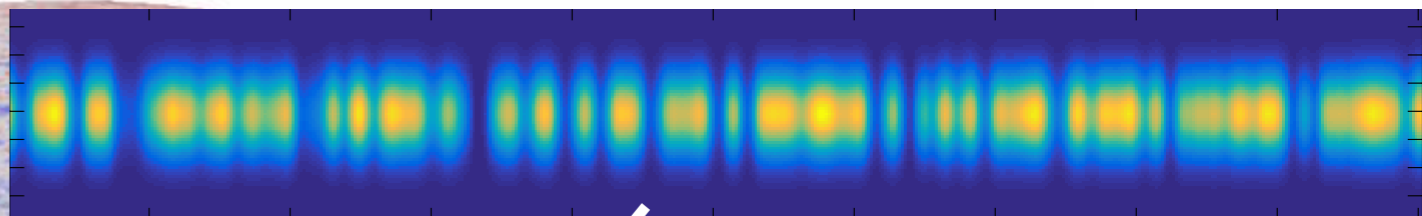
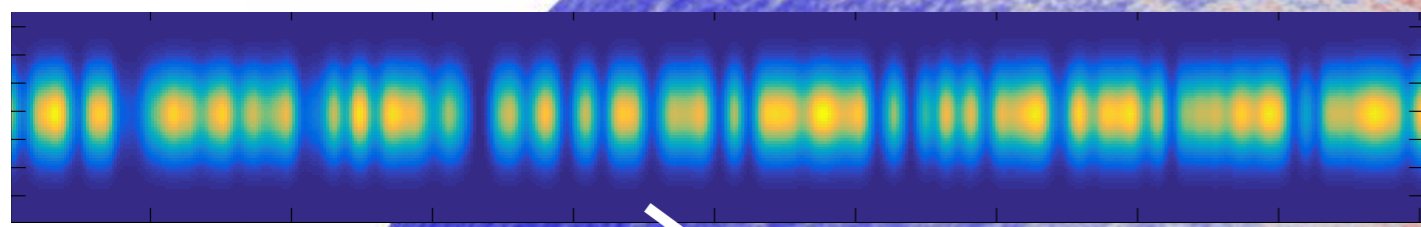


Ω

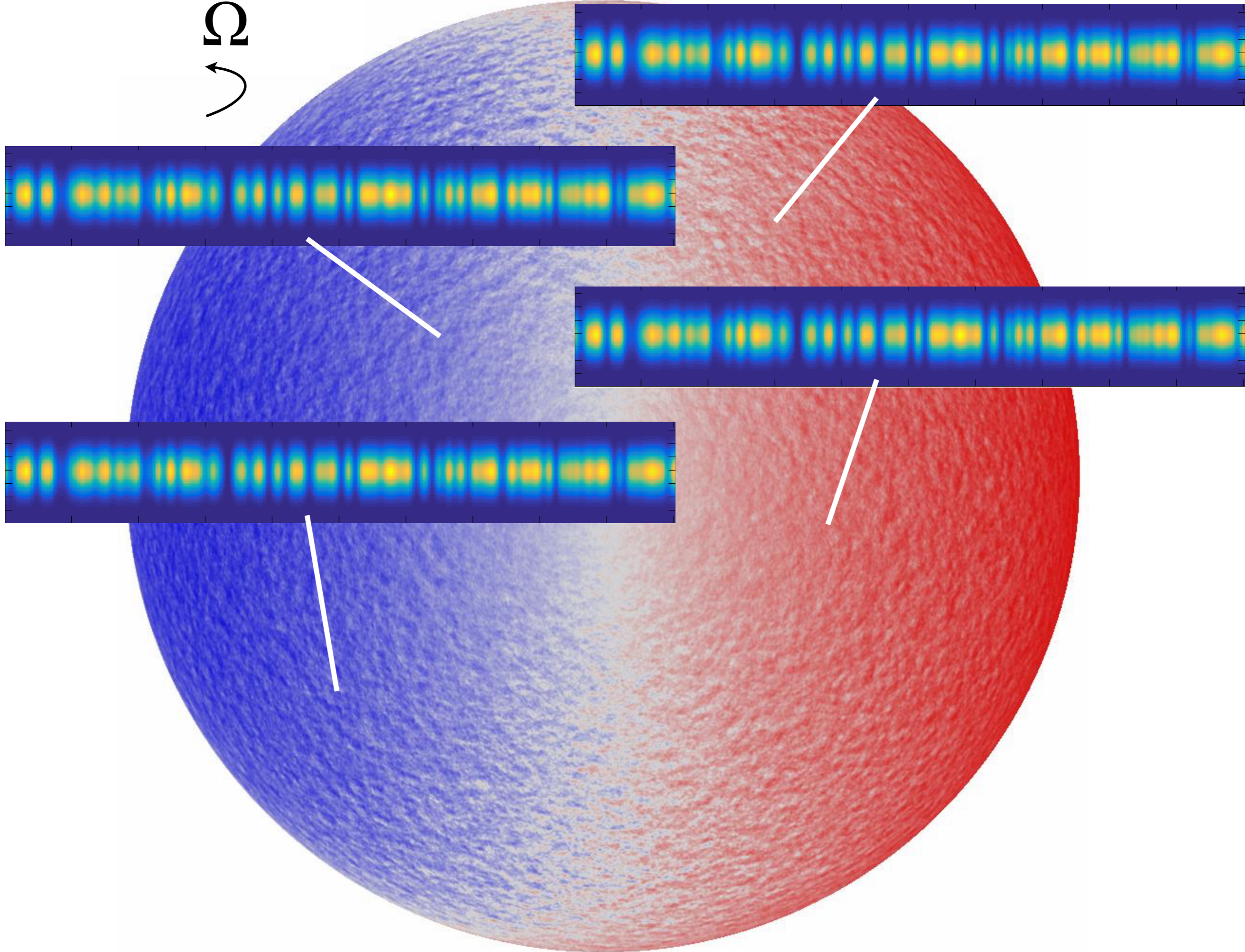




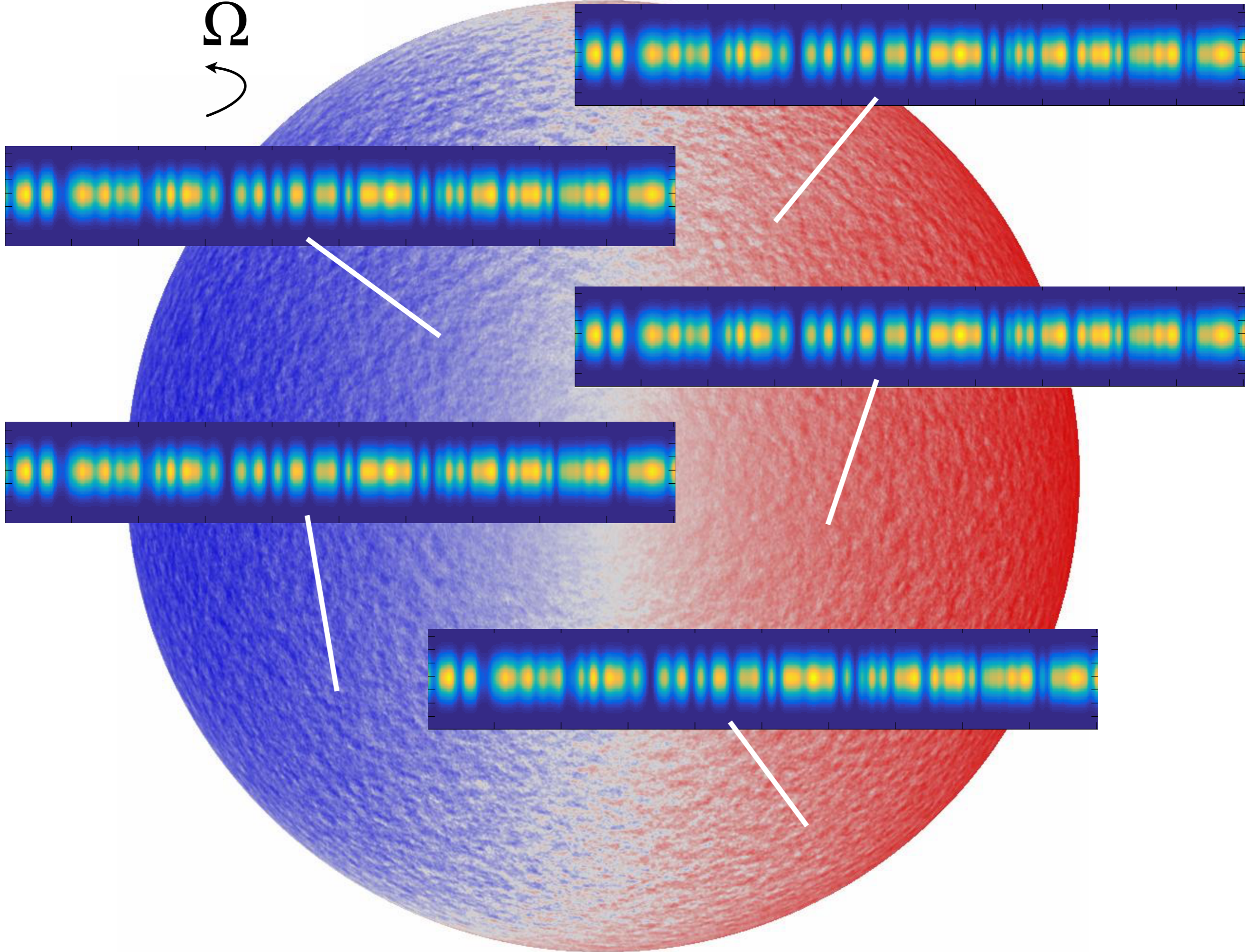
Ω

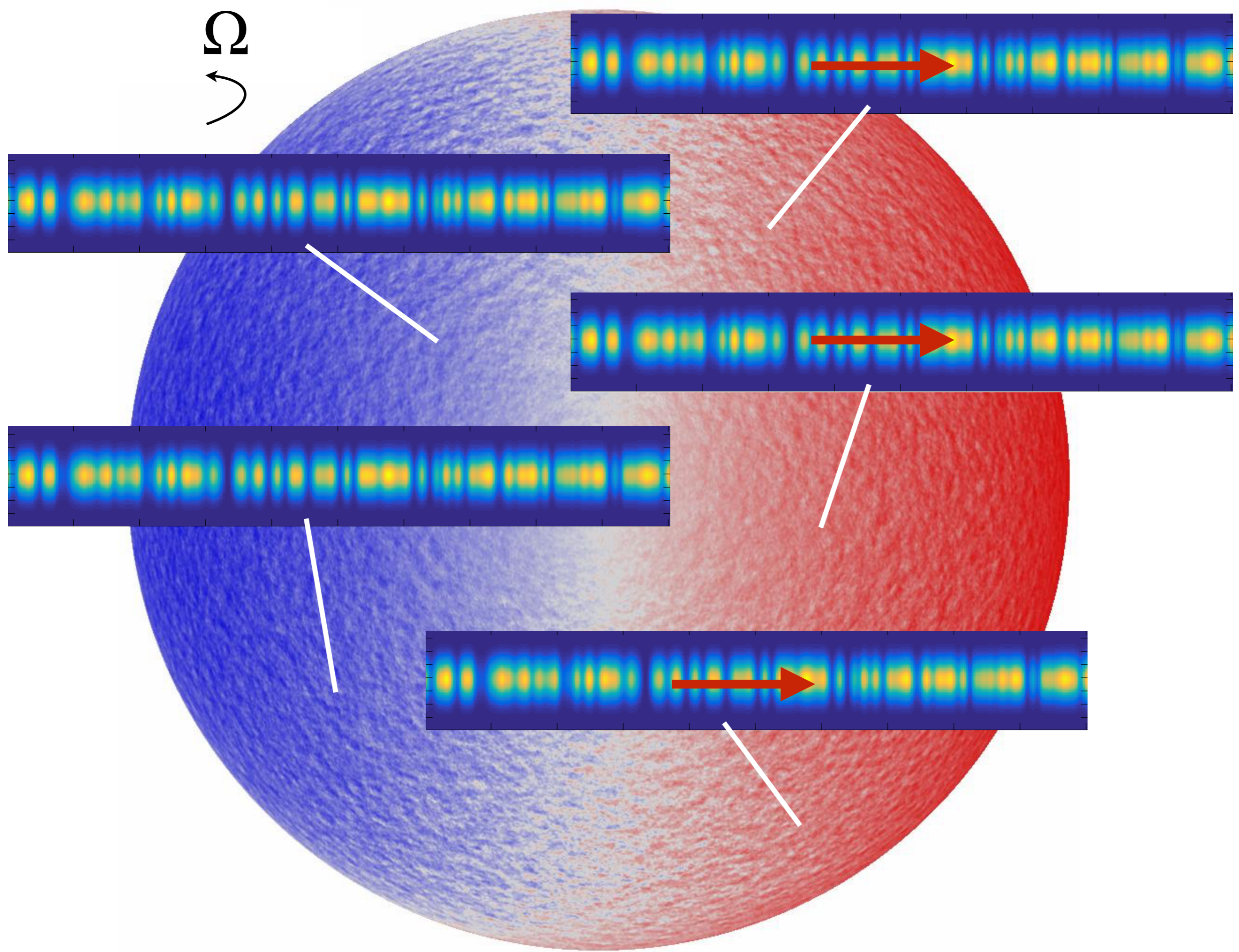


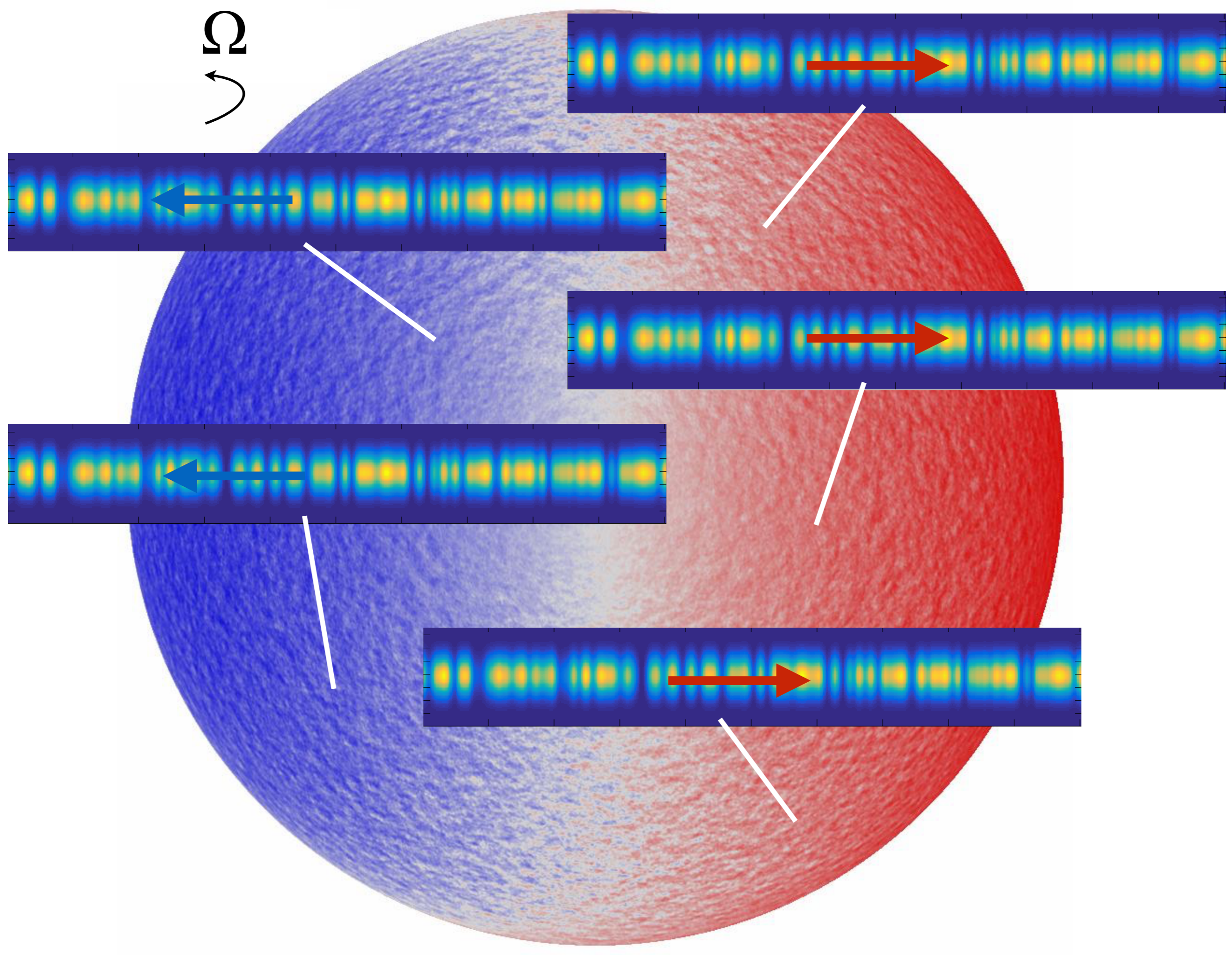
Ω

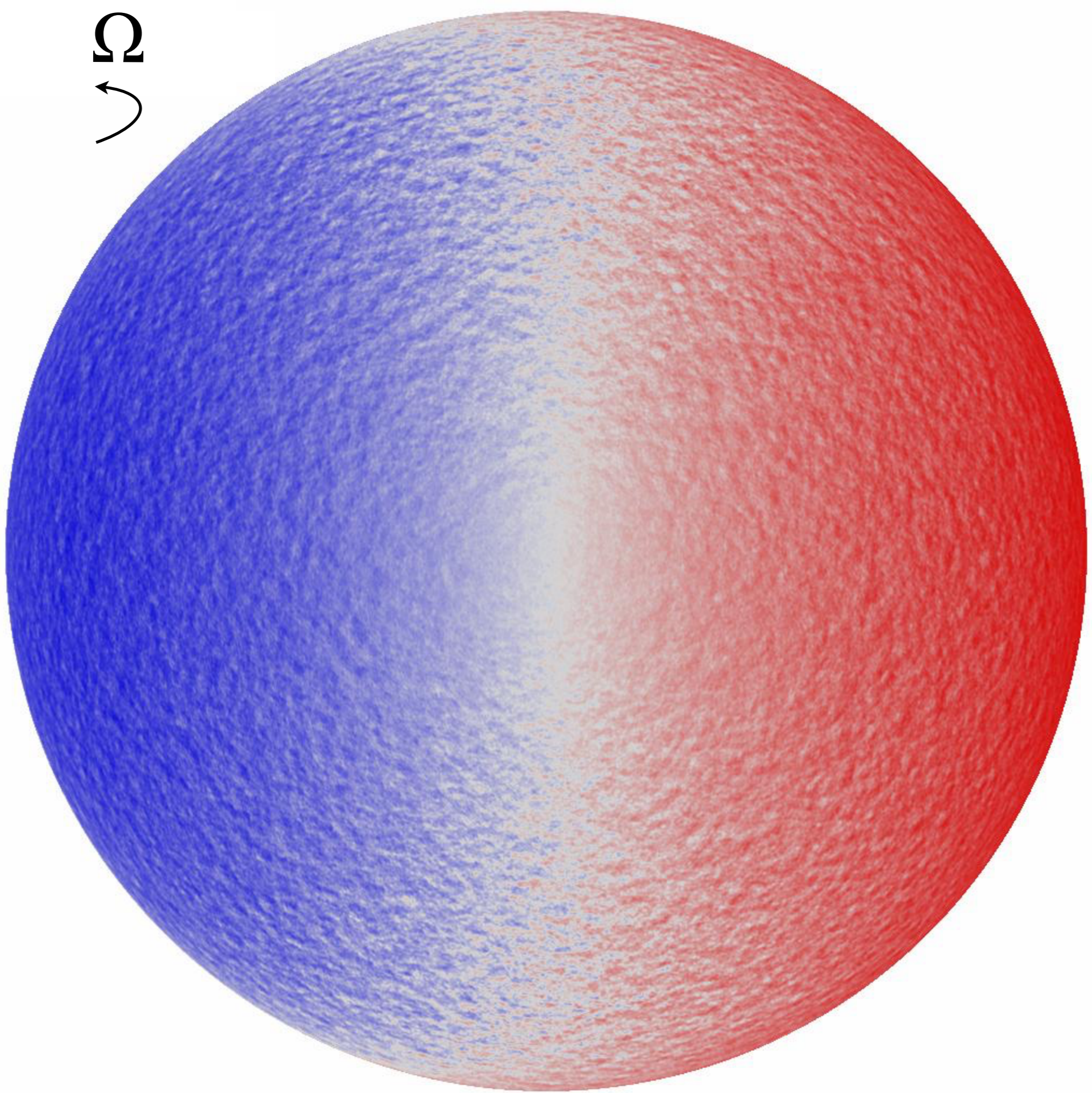


Ω









Ω
↪



Start with a single, stationary star

Start with a single, stationary star



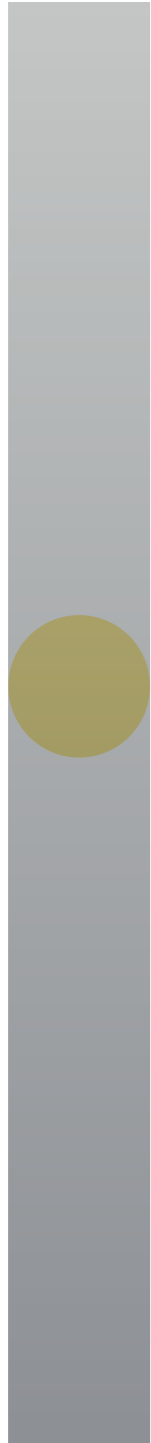
Start with a single, stationary star

$V_{\text{orb}} = 0 \text{ km/s} = V_{\text{rad}}$



Start with a single, stationary star

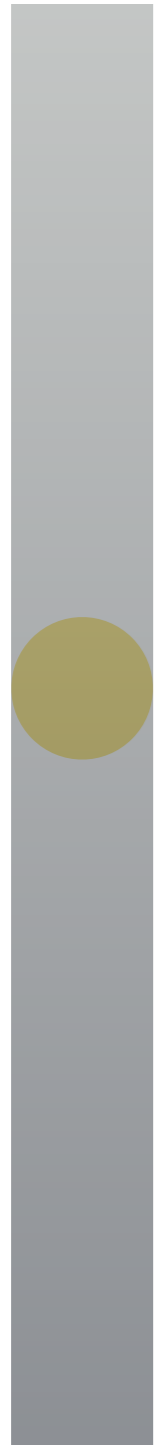
Vorb = 0 km/s = Vrad



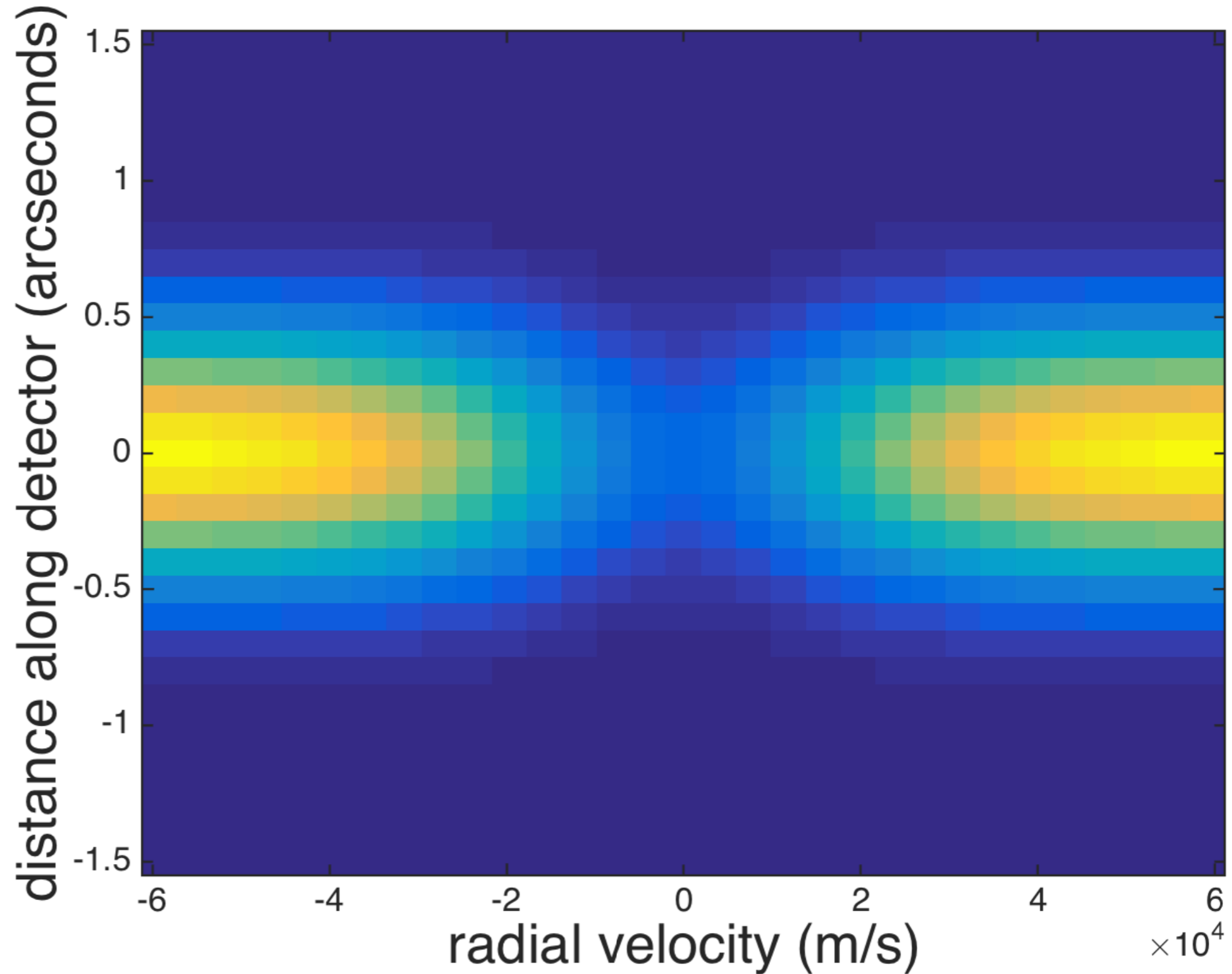
slit

Start with a single, stationary star

Vorb = 0 km/s = Vrad



slit

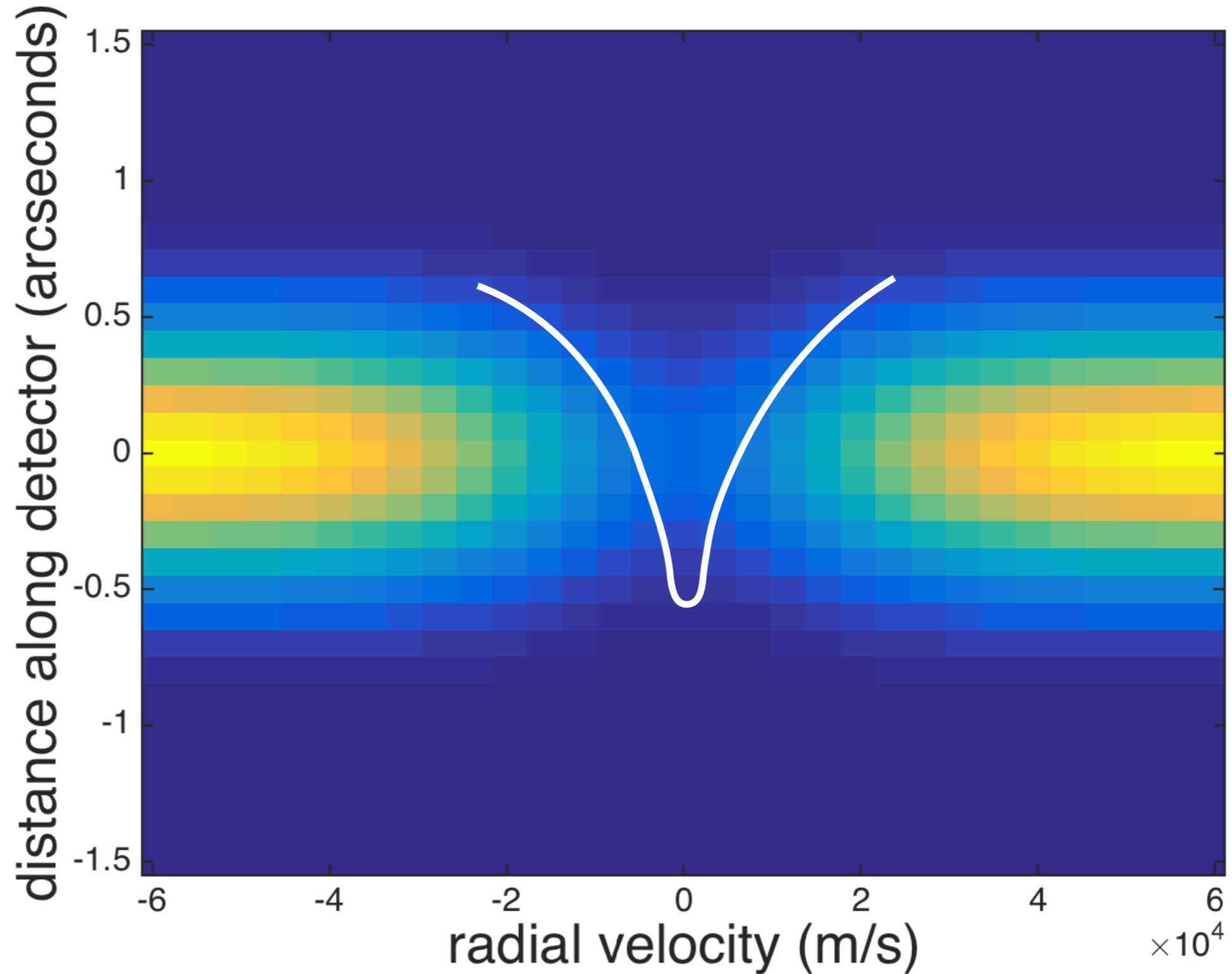


Start with a single, stationary star

Vorb = 0 km/s = Vrad



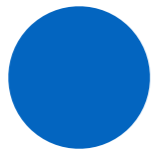
slit



Resolved binary

Vorb = 10 km/s = Vrad

sep = 1.4"



Resolved binary

Vorb = 10 km/s = Vrad

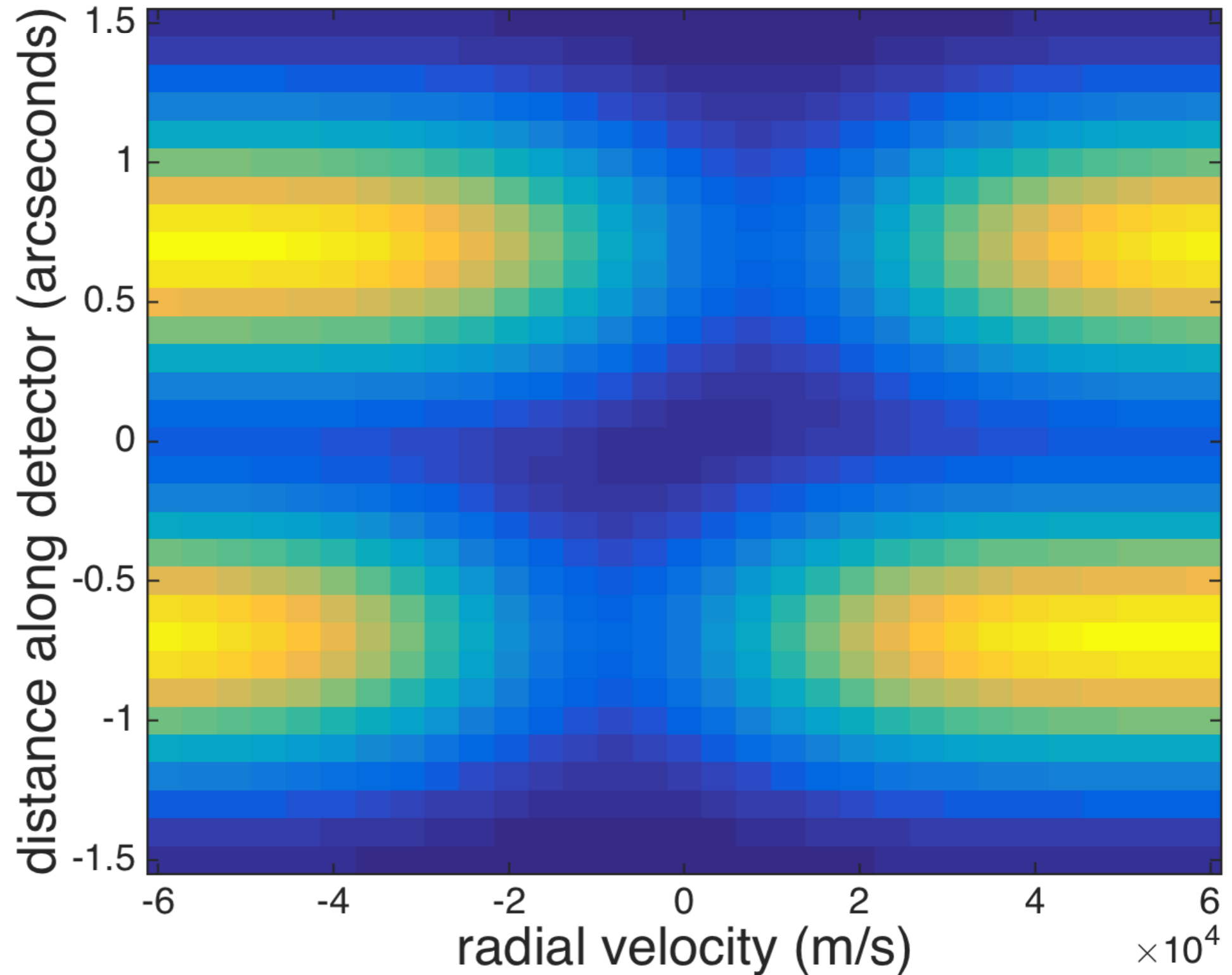
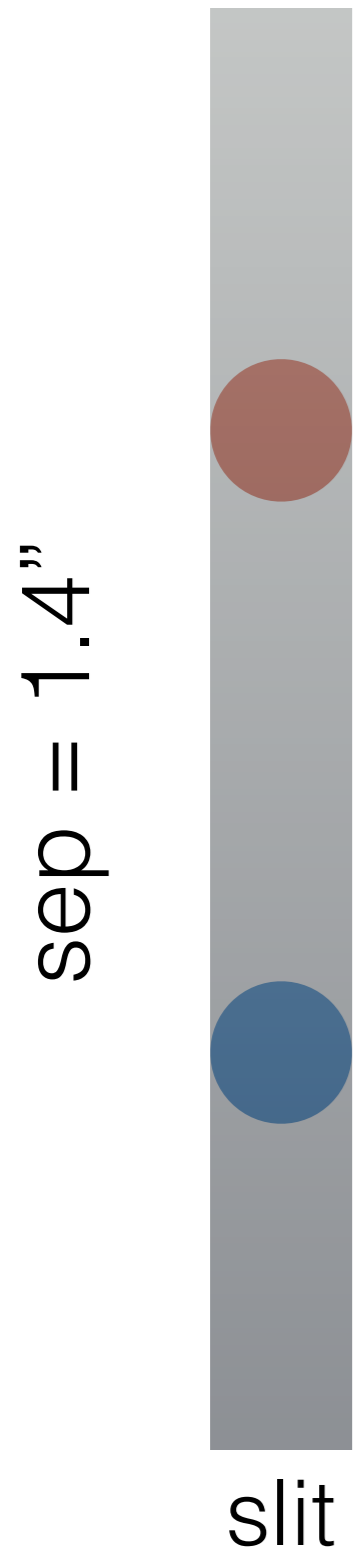
sep = 1.4"



slit

Resolved binary

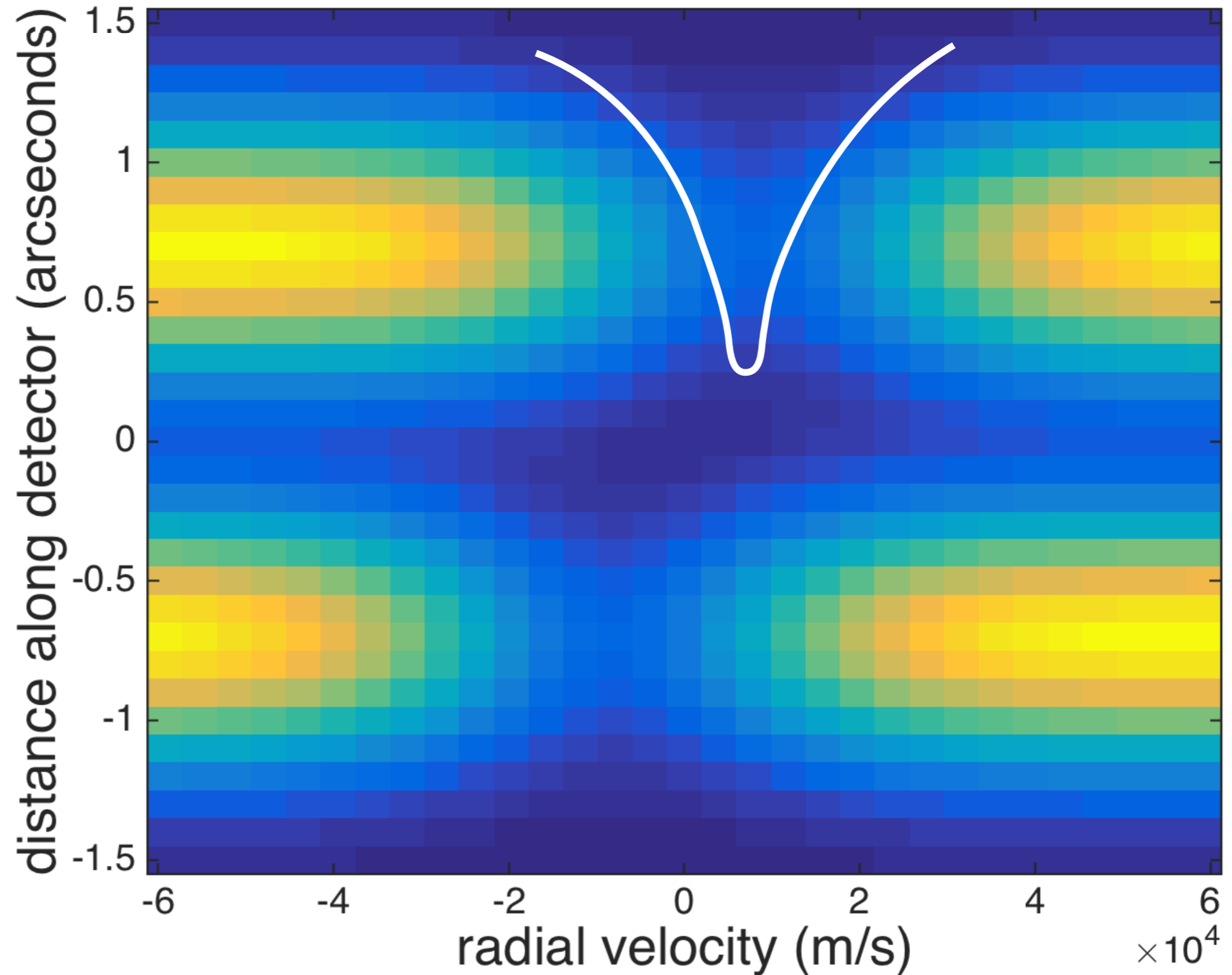
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Resolved binary

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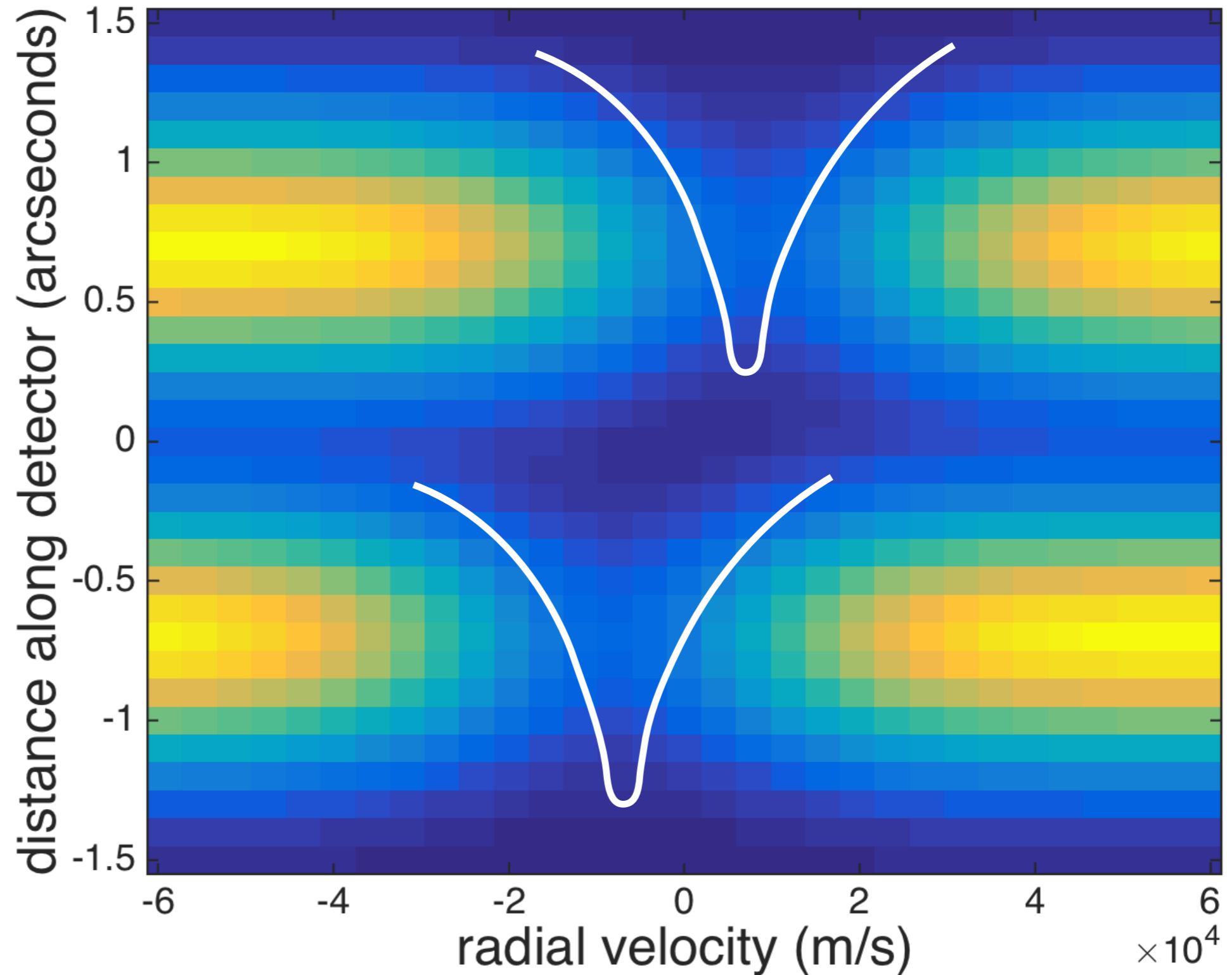
Resolved binary

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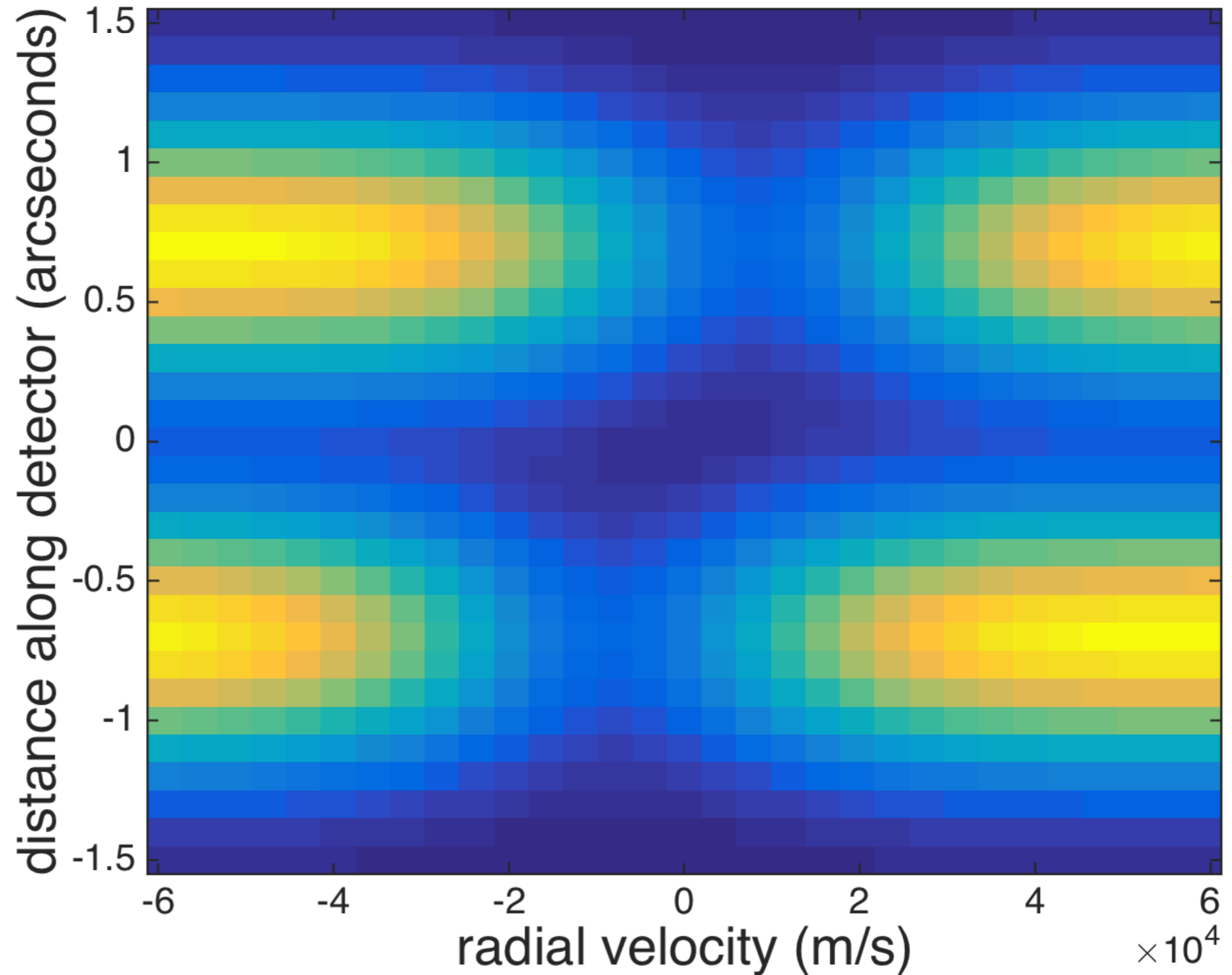
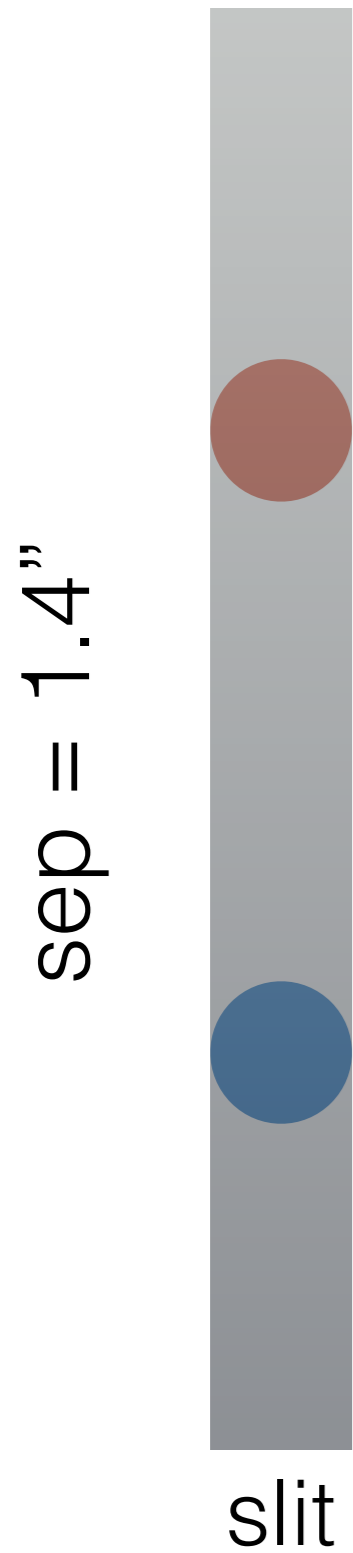


slit



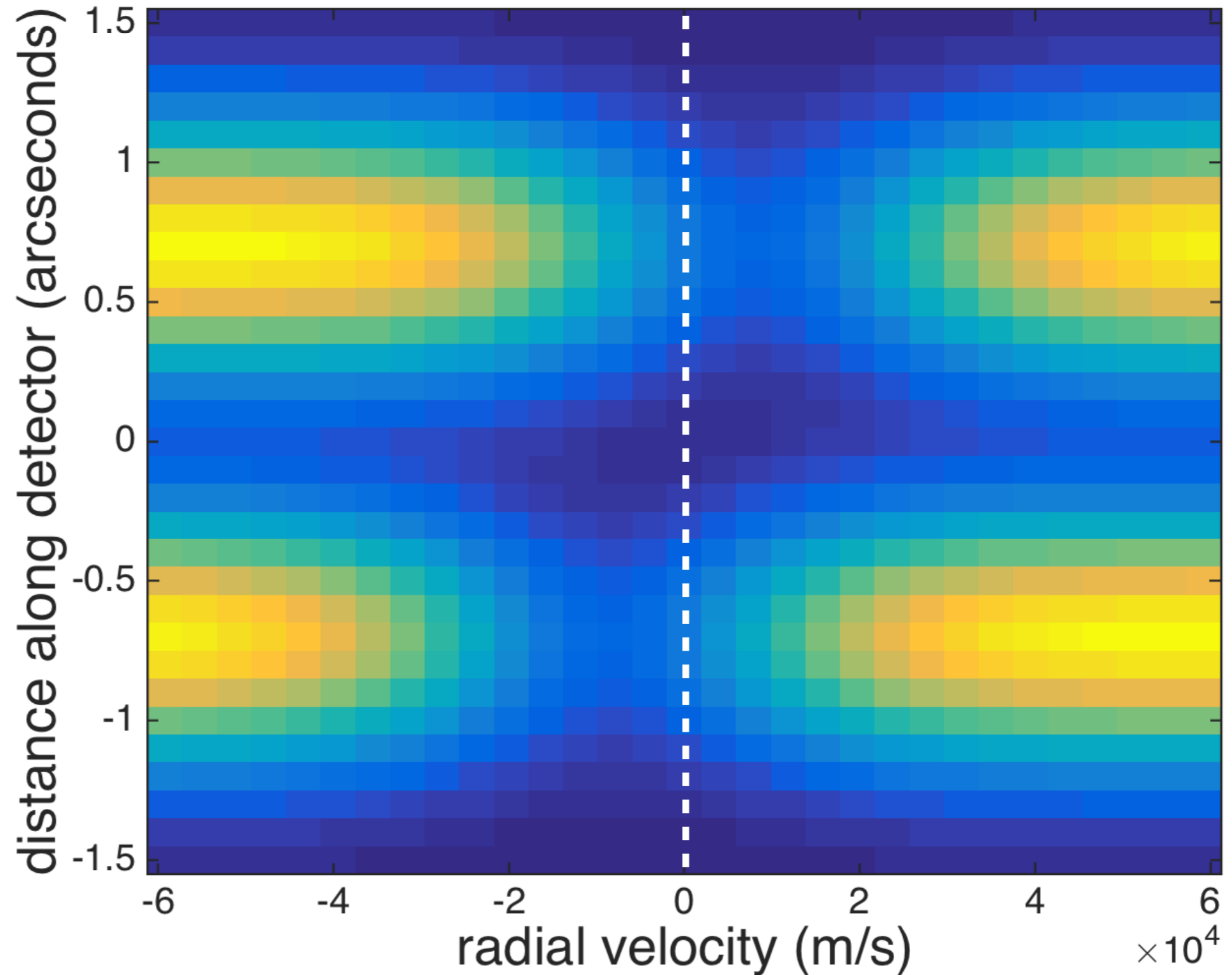
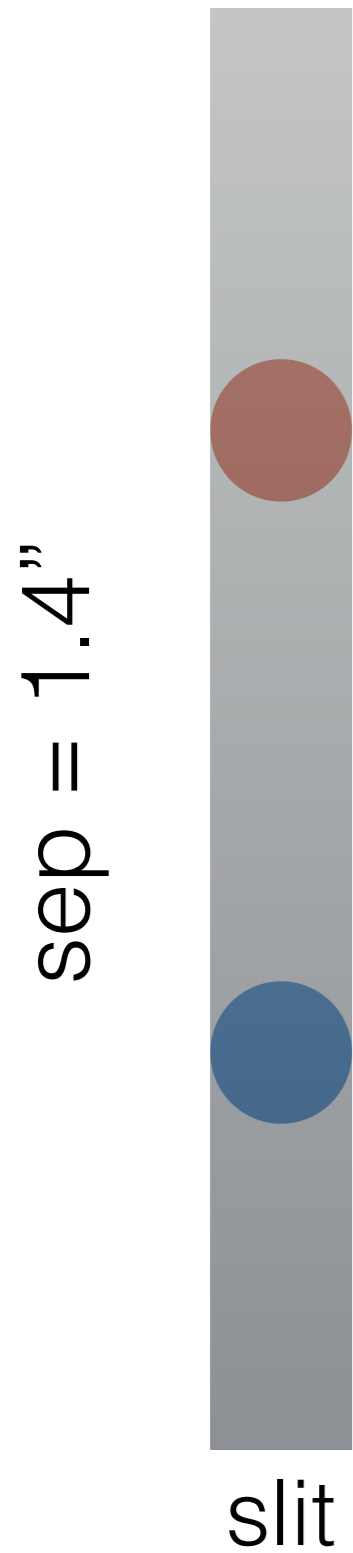
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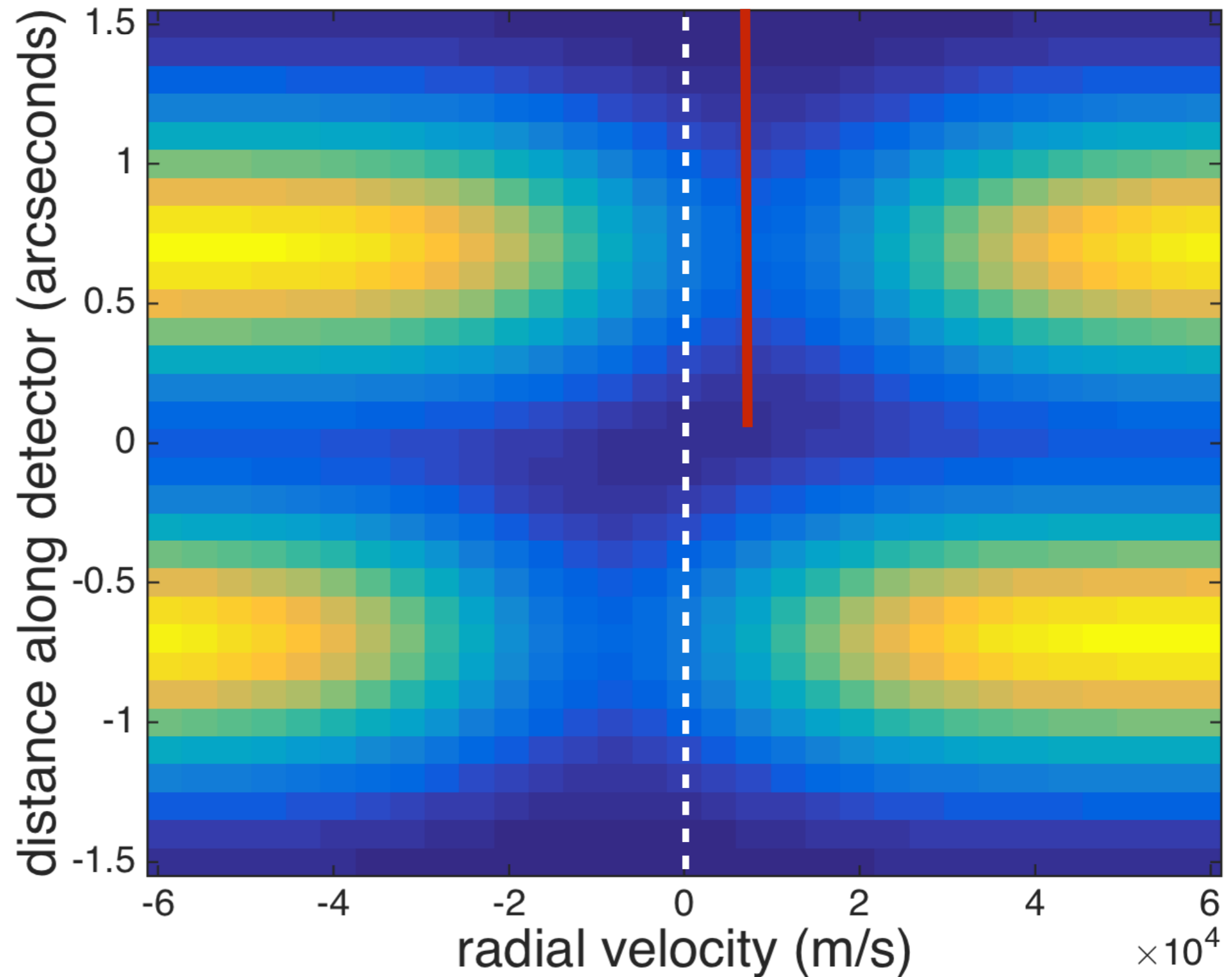
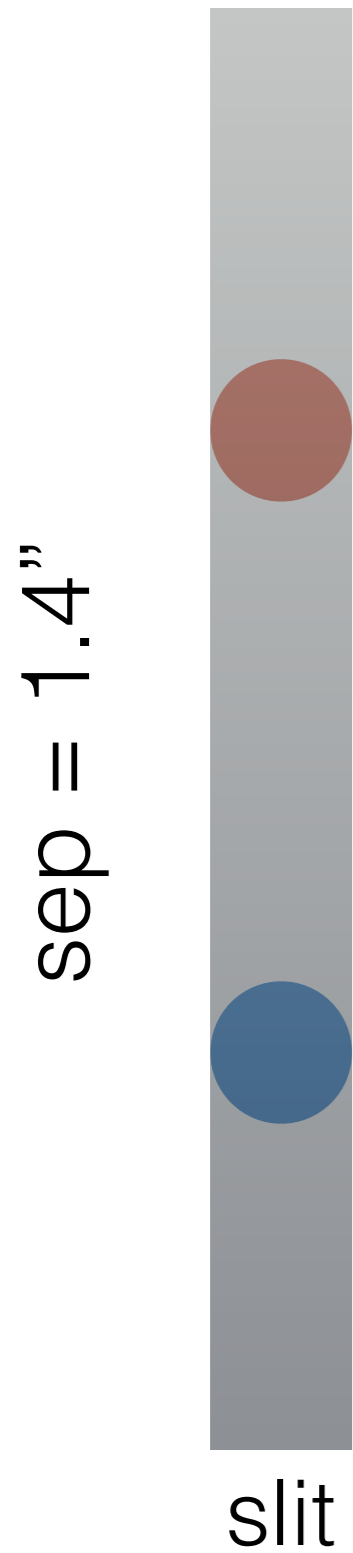
Resolved binary

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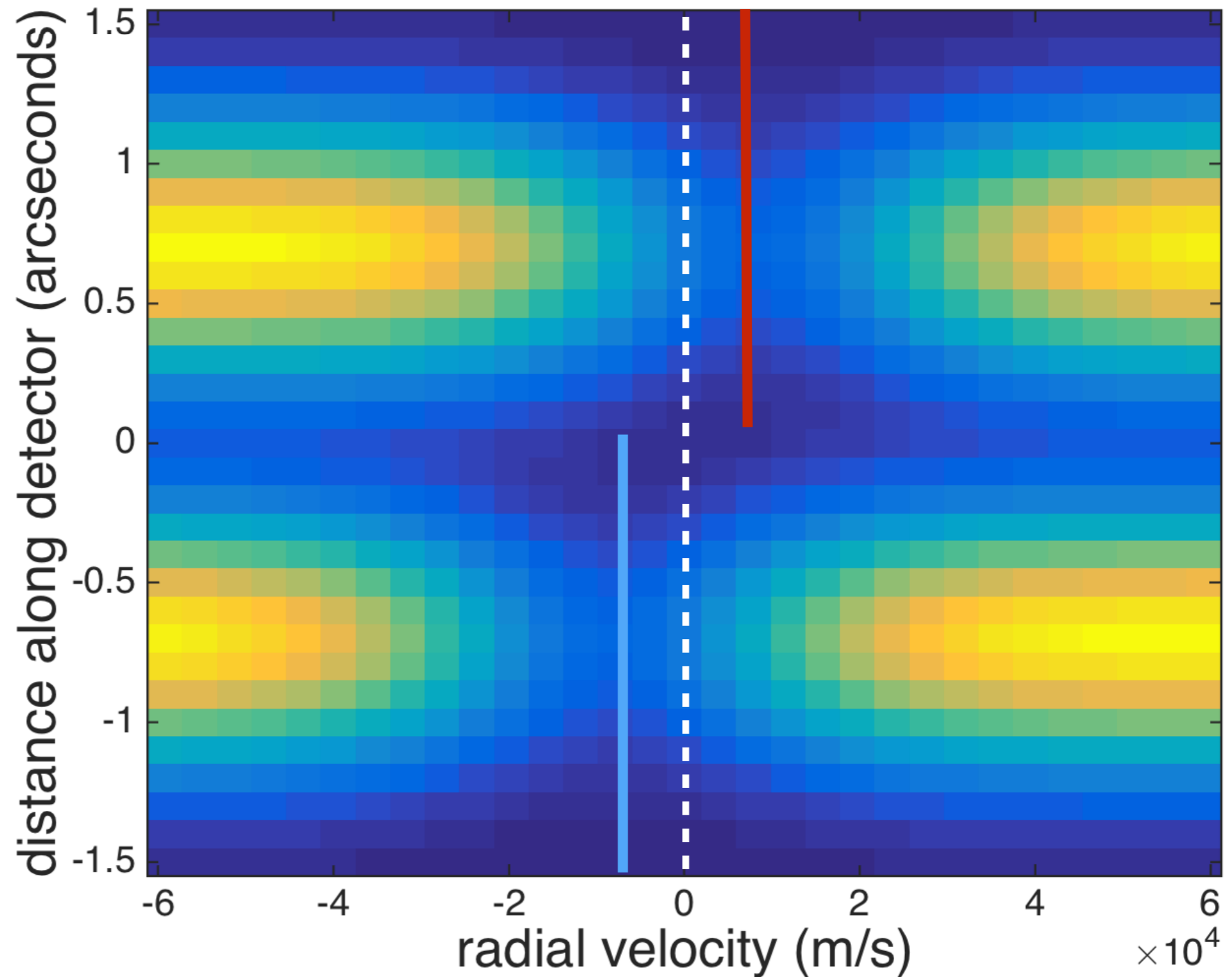
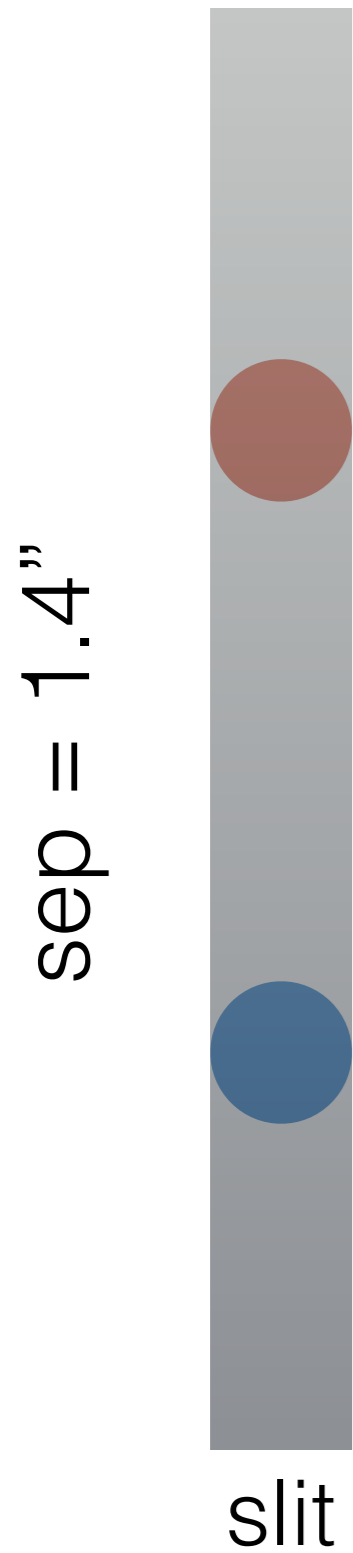
Resolved binary

Vorb = 10 km/s = Vrad



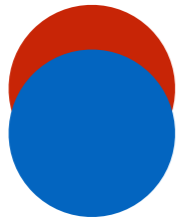
Resolved binary

Vorb = 10 km/s = V_{rad}



Unresolved binary

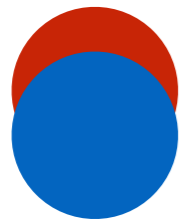
Vorb = 10 km/s = Vrad



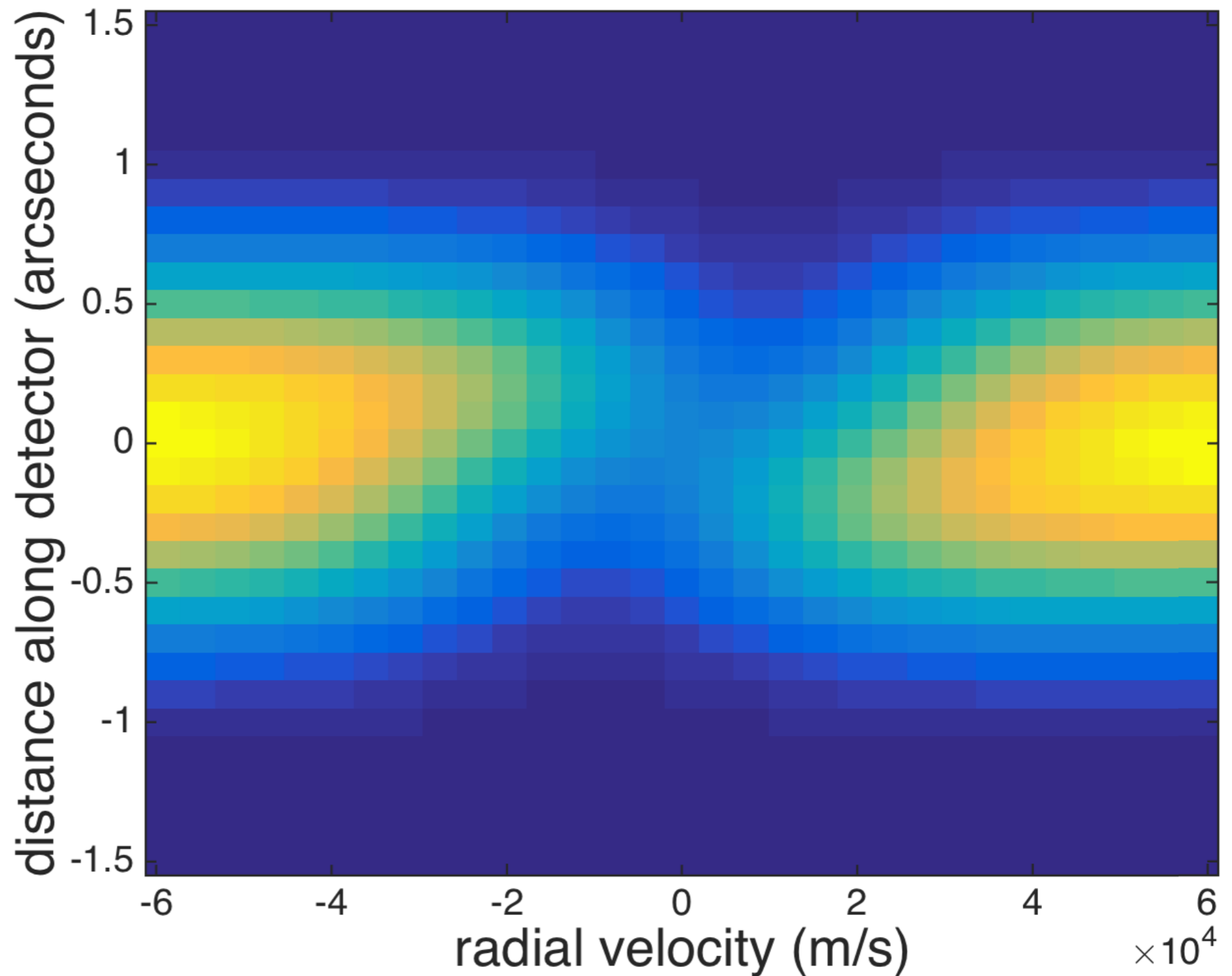
sep = 0.2''

Unresolved binary

Vorb = 10 km/s = V_{rad}

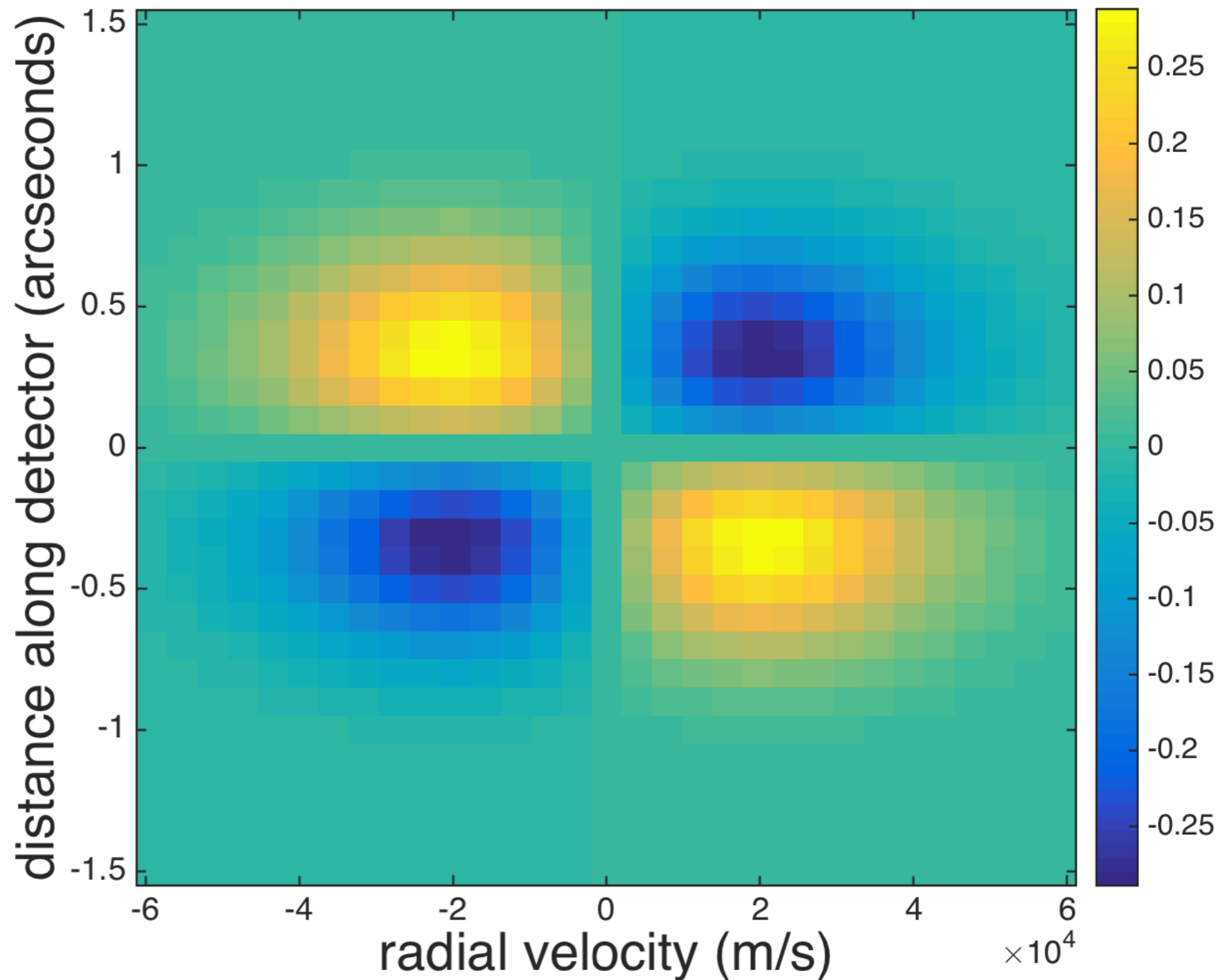
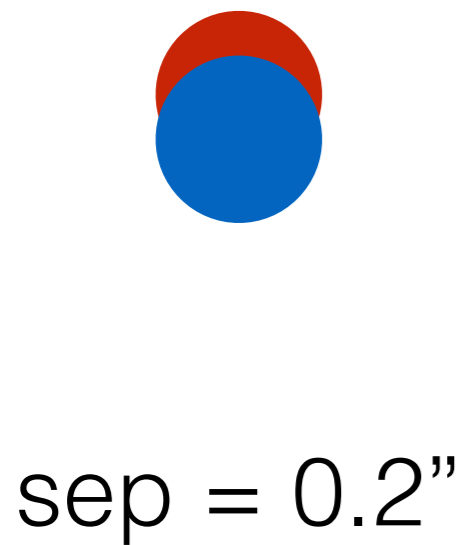


sep = 0.2''

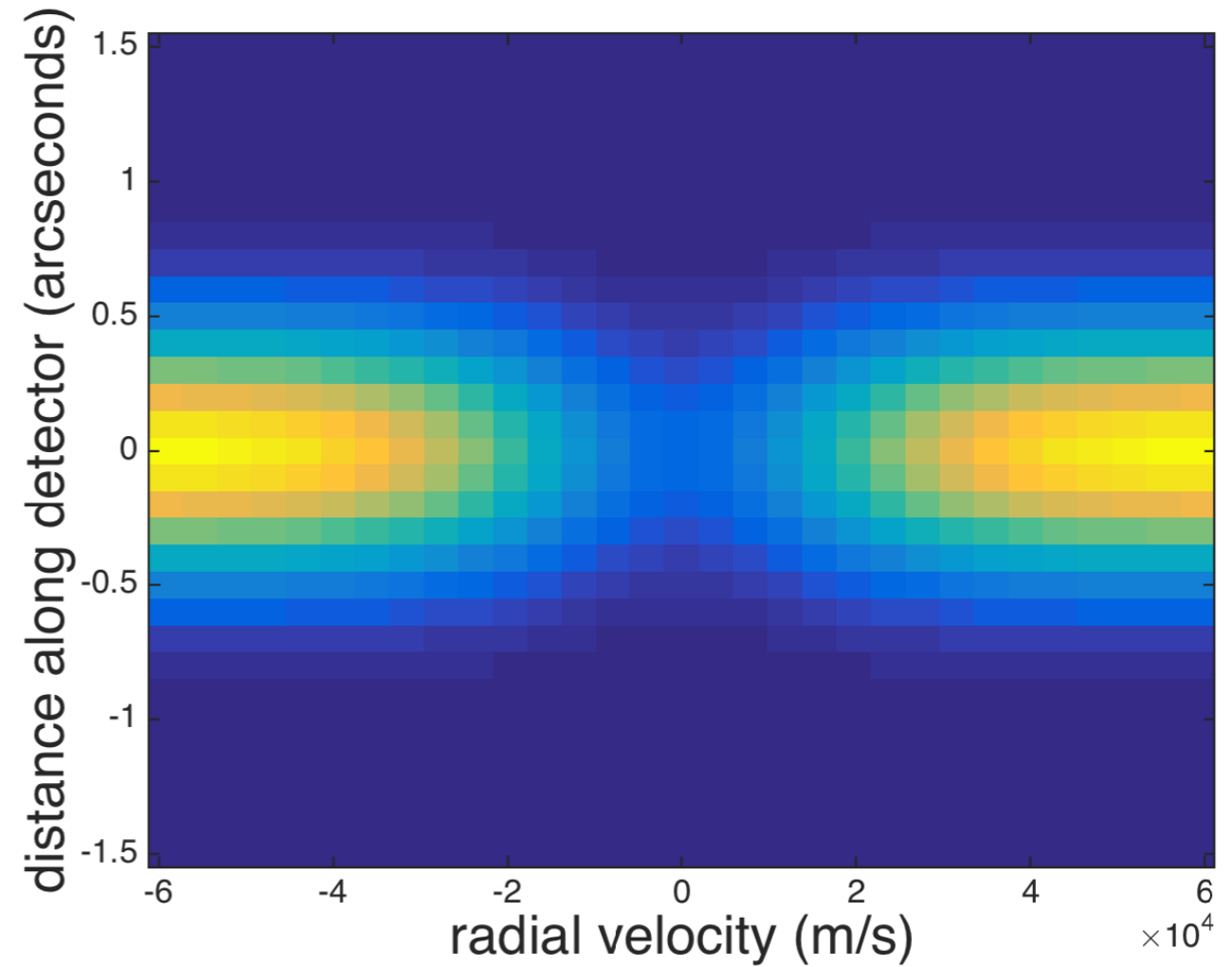
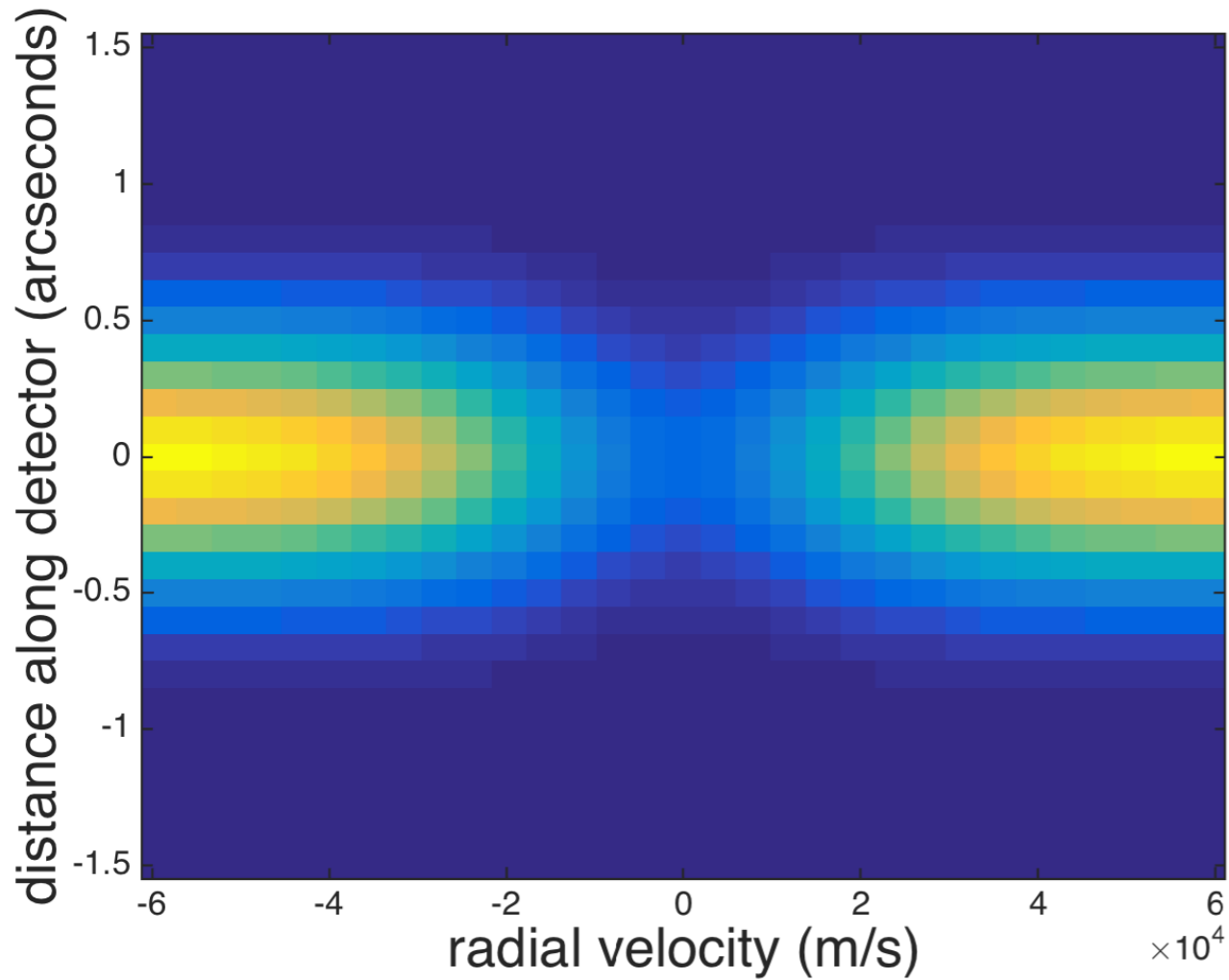


Unresolved binary

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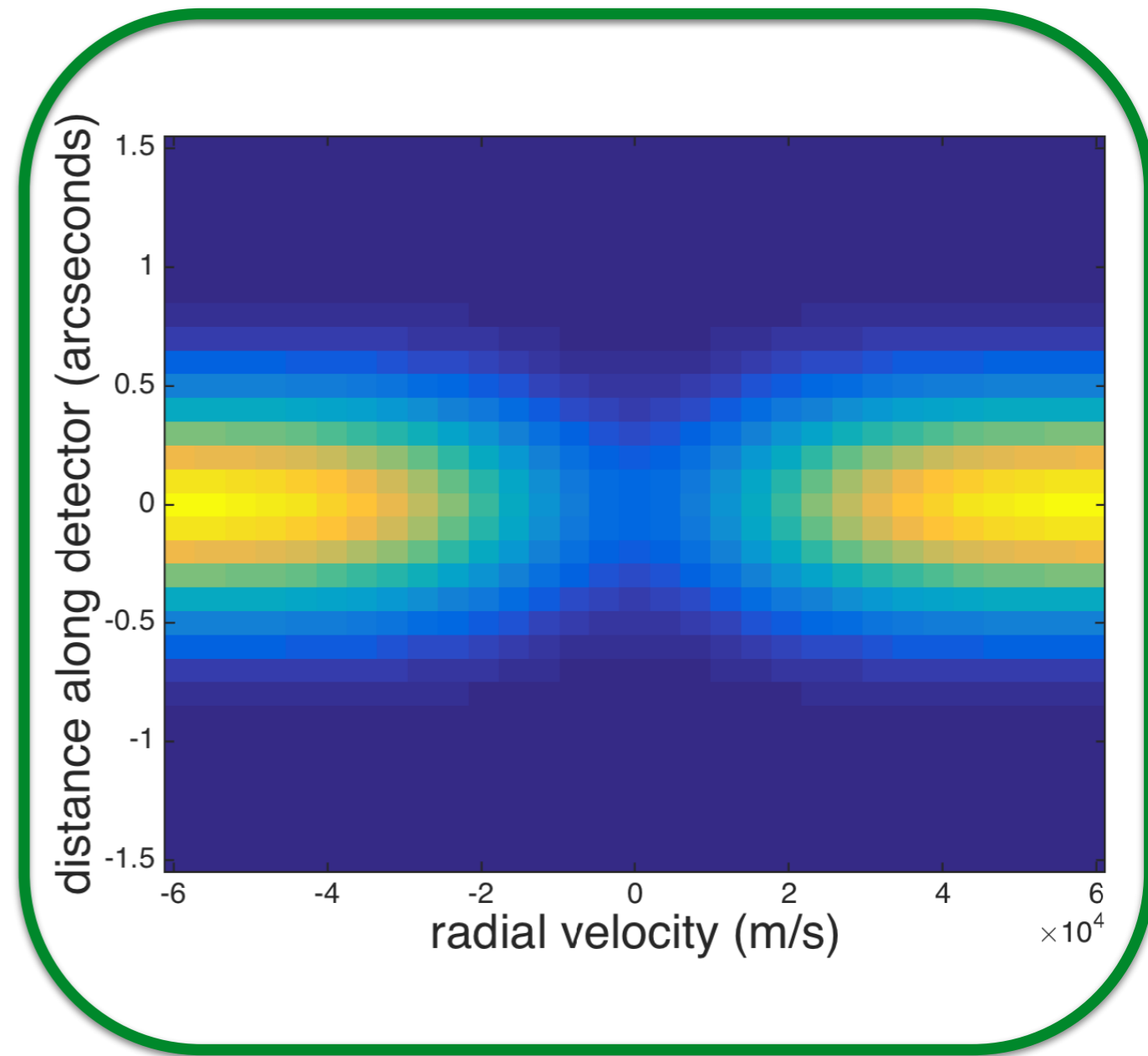
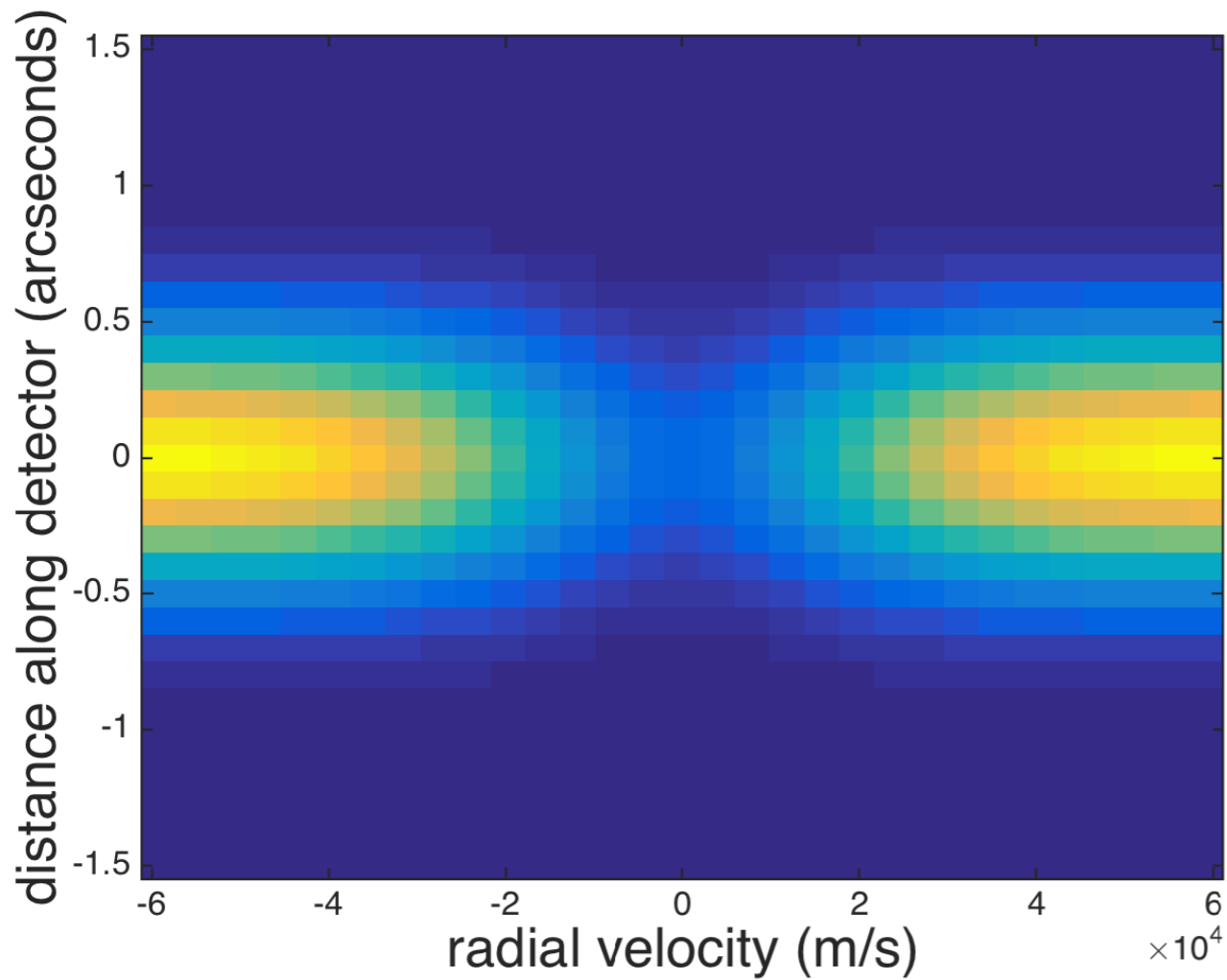


Vote: which one's tilted?



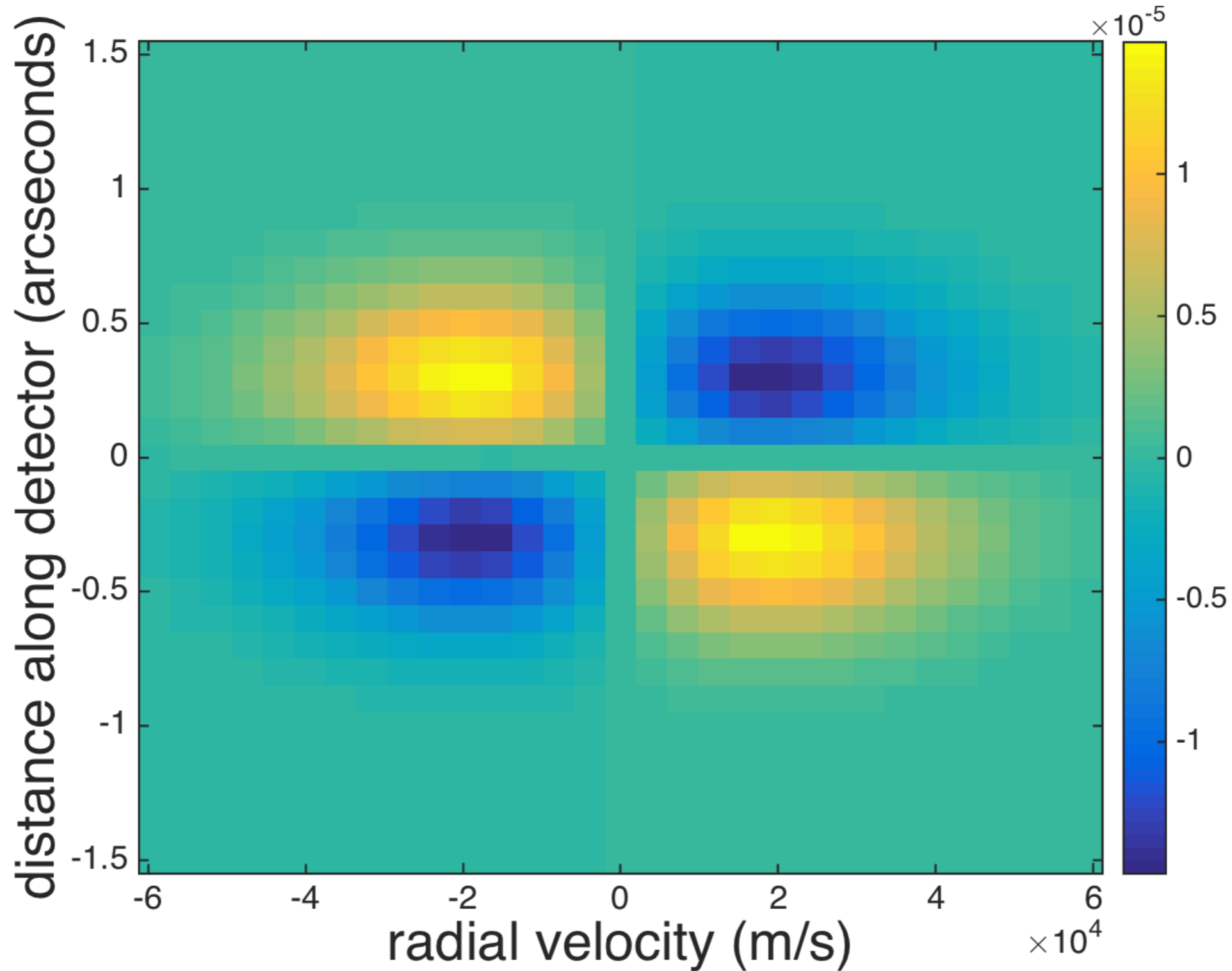
- A: left
- B: right
- C: neither

Vote: which one's tilted?

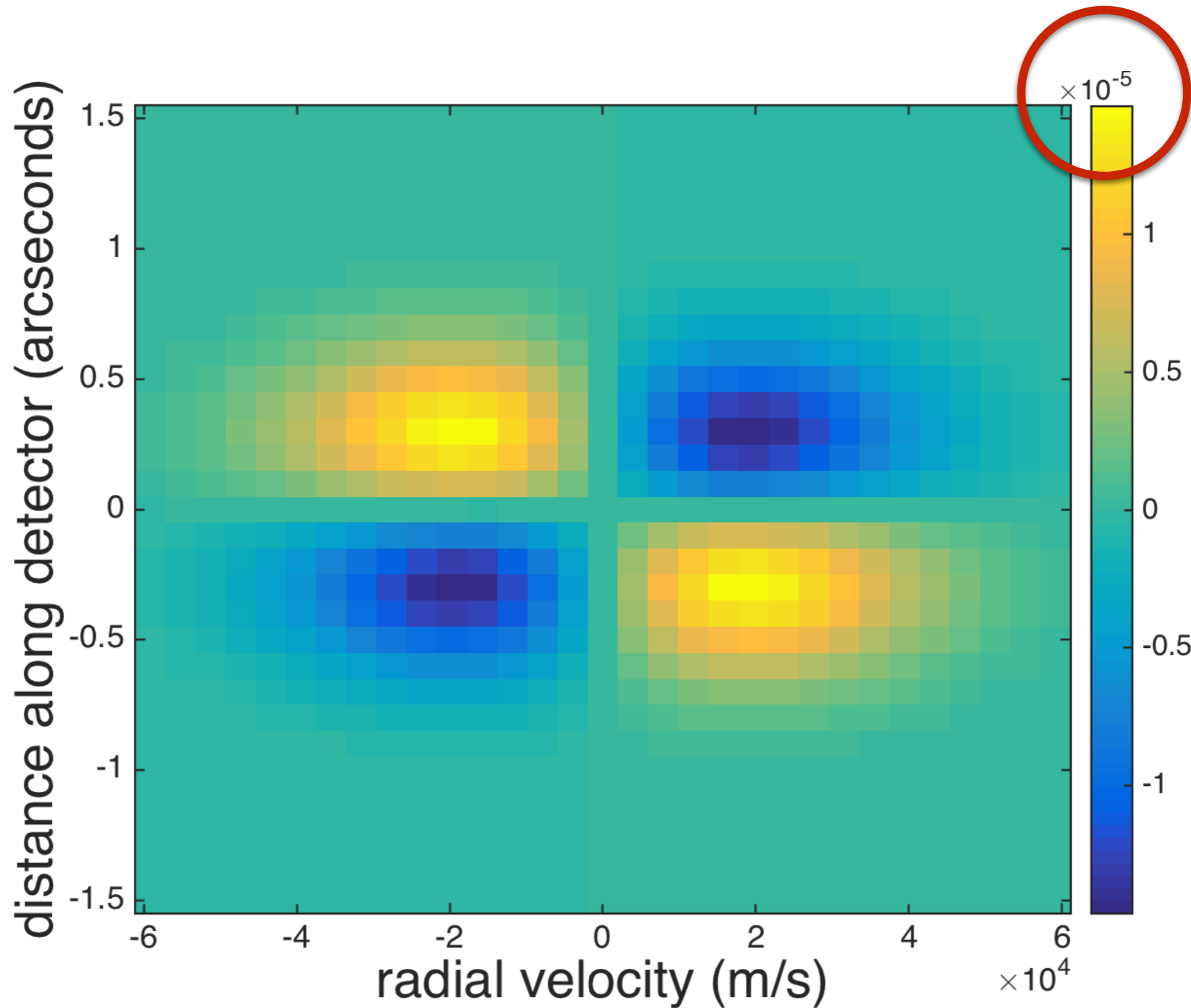


- A: left
- B: right
- C: neither

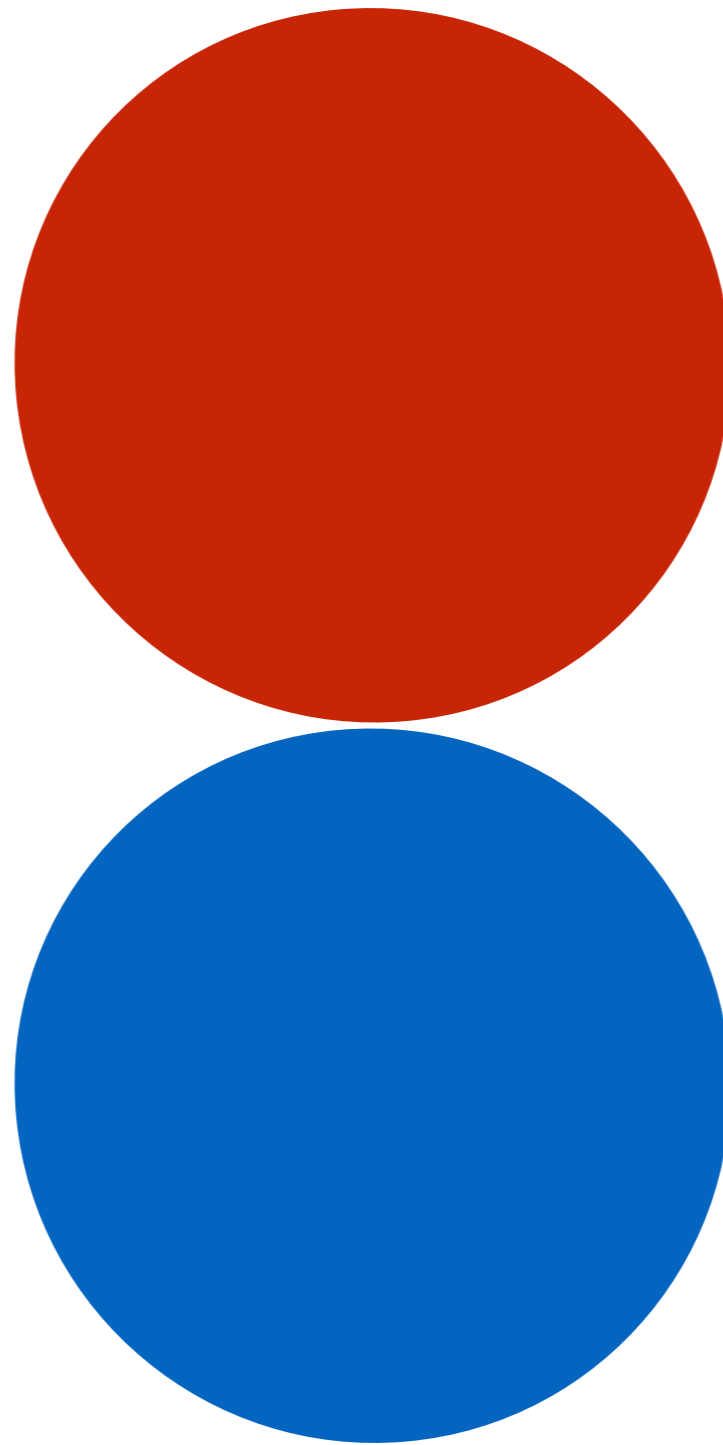
Seeing the (small!) excess



Seeing the (small!) excess



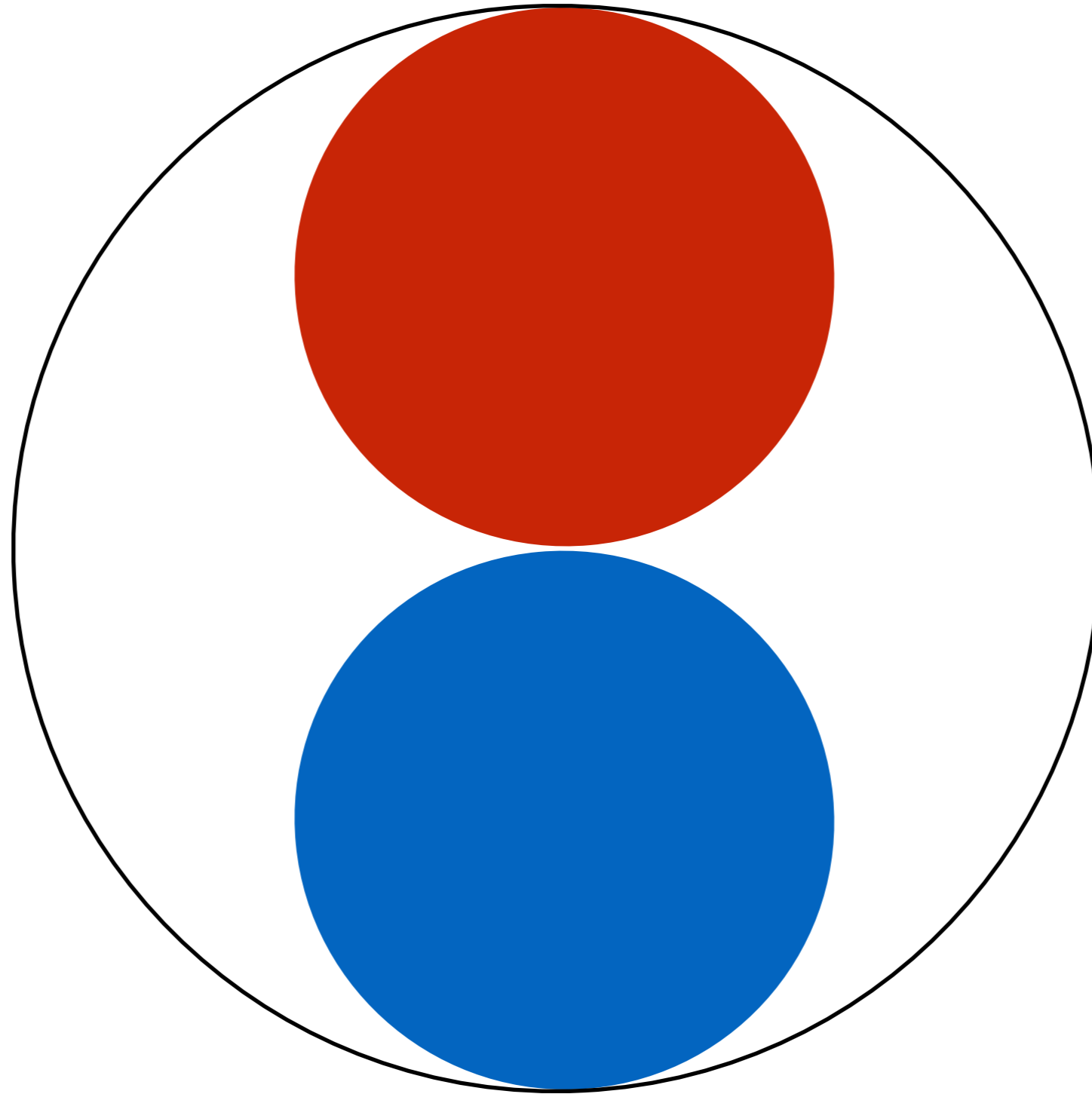
$$V_{\text{orb}} = 2 \text{ km/s} = V_{\text{rad}}$$



0.00093''



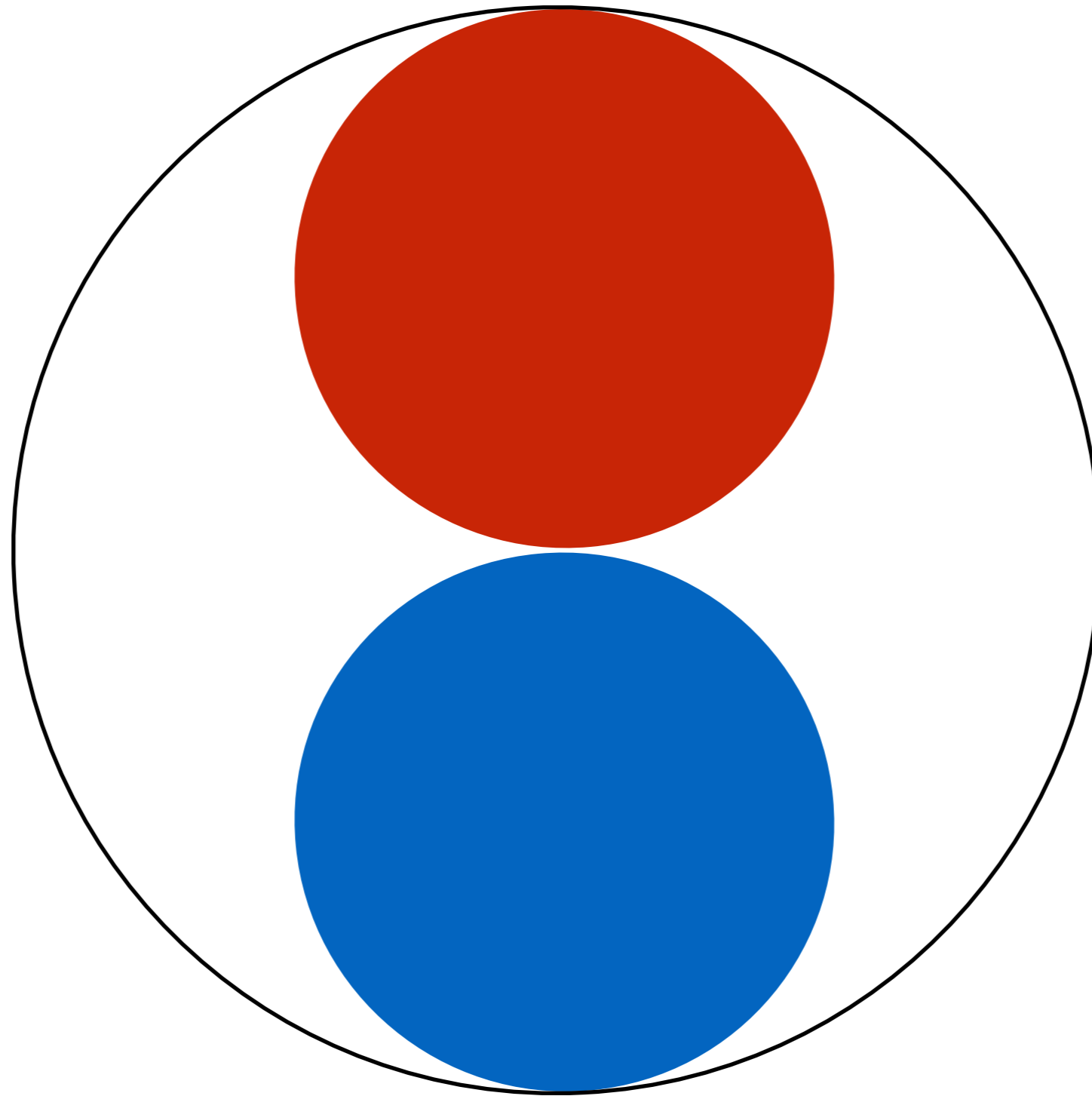
Vorb = 2 km/s = V_{rad}



0.00093''



Vorb = 2 km/s = Vrad

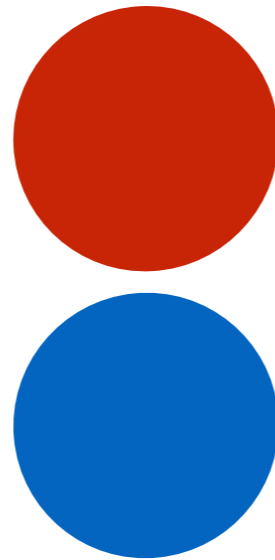


0.00093''

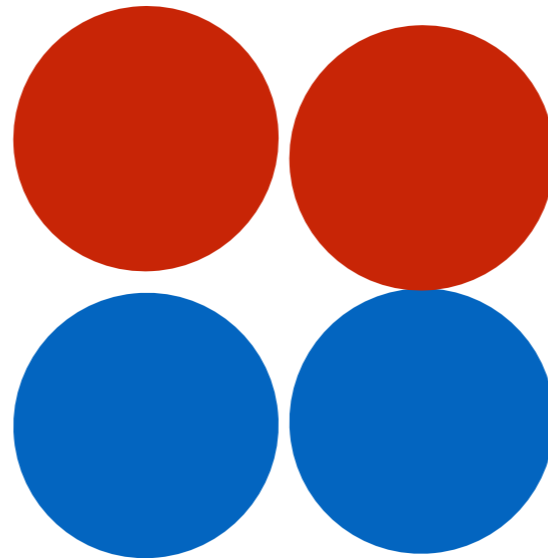


This spectroscopic binary is ~ equivalent to the Sun at 10 pc

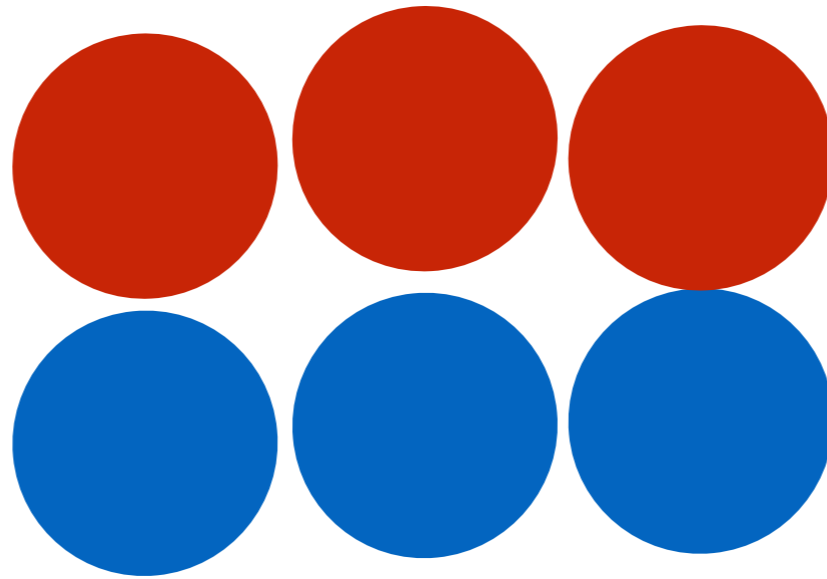
Using binaries to build a simple model



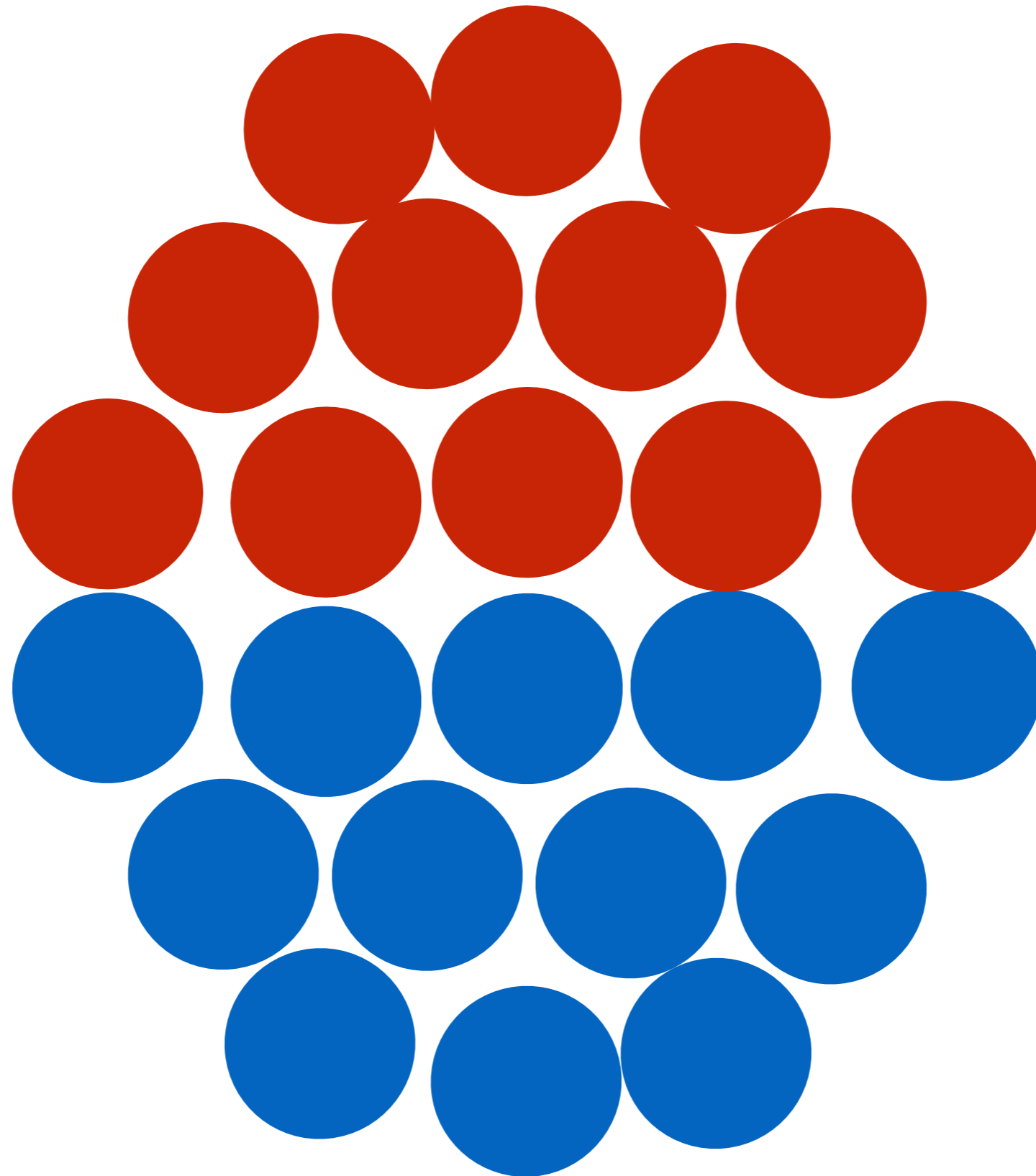
Using binaries to build a simple model



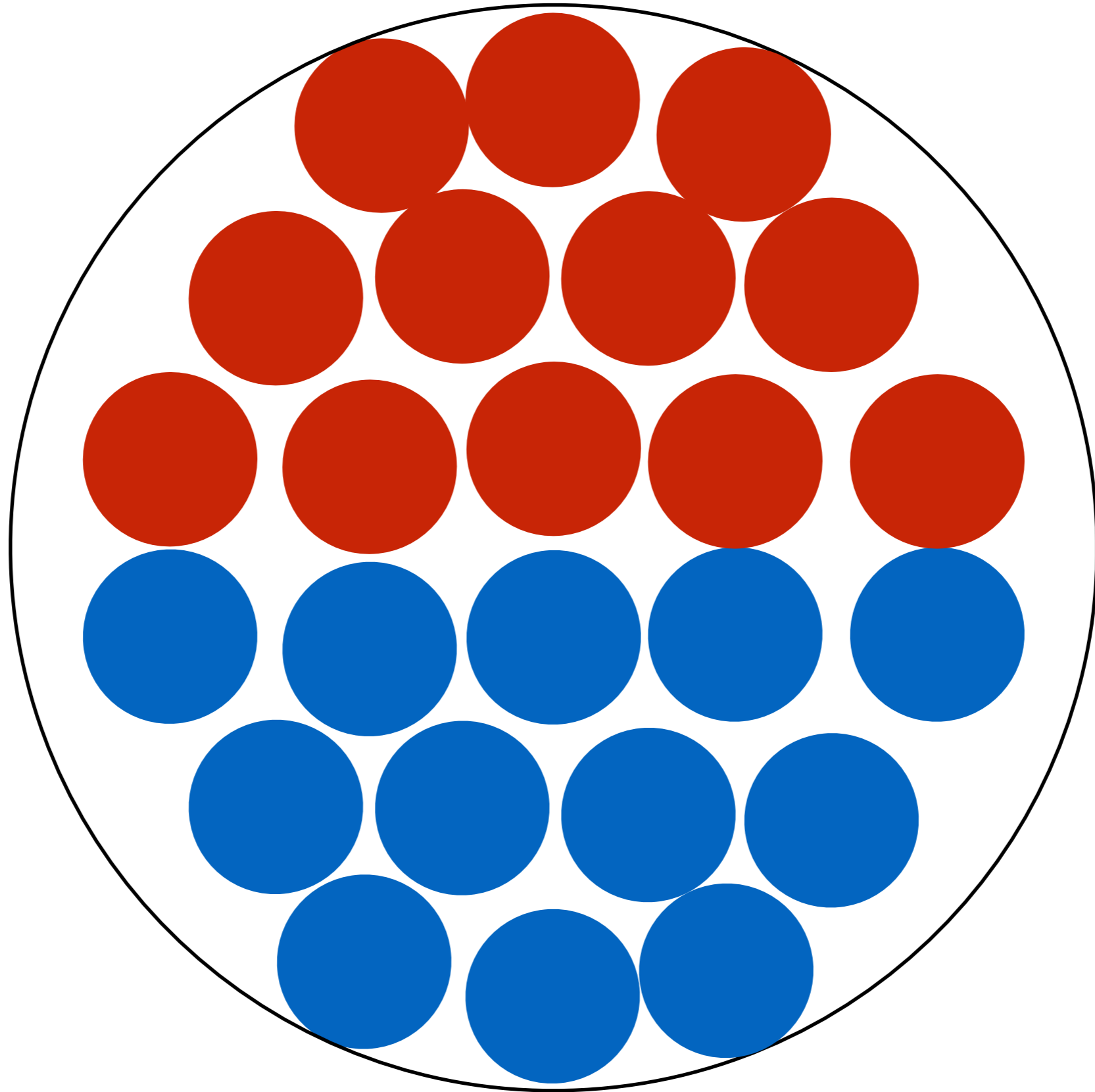
Using binaries to build a simple model



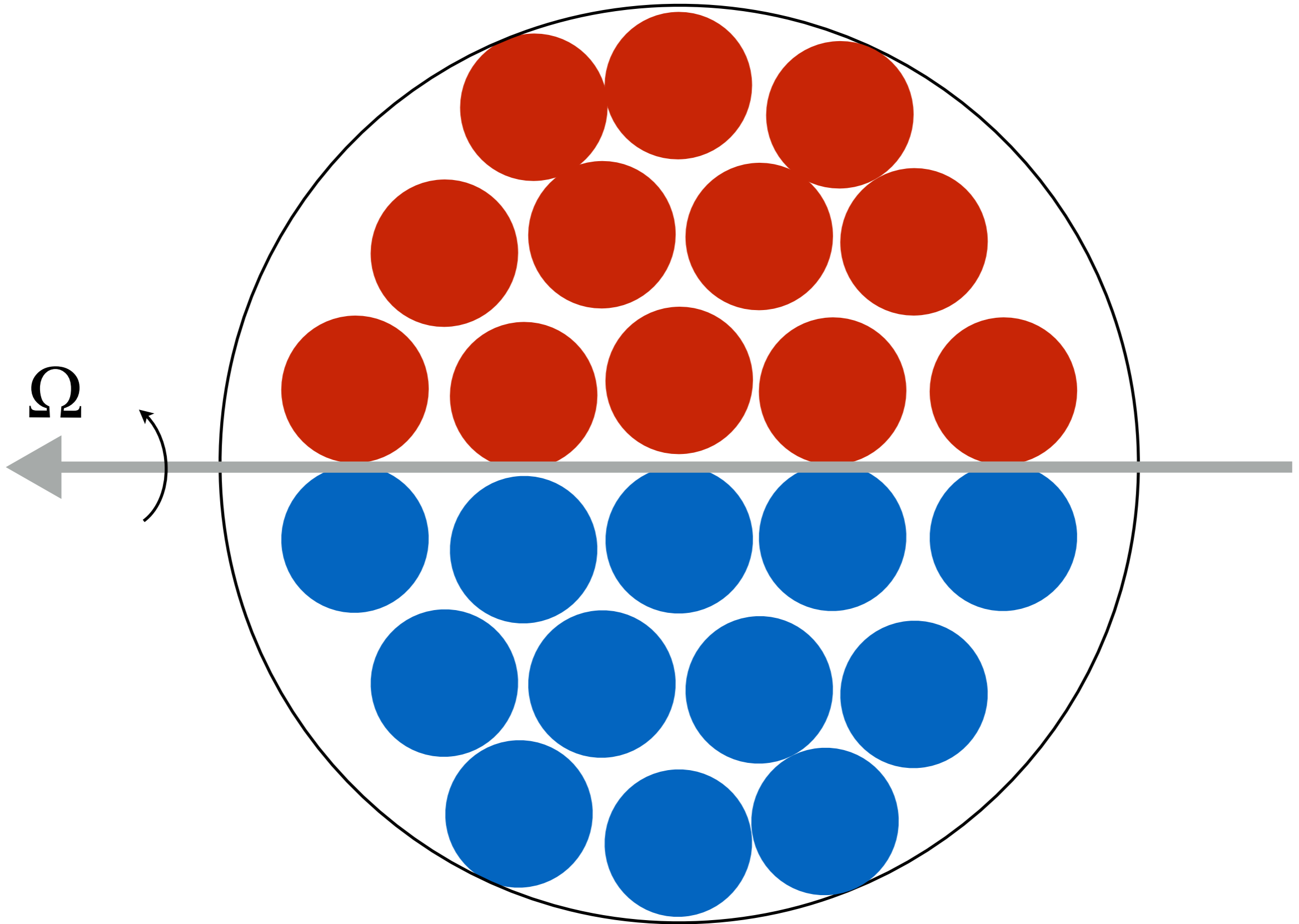
Using binaries to build a simple model



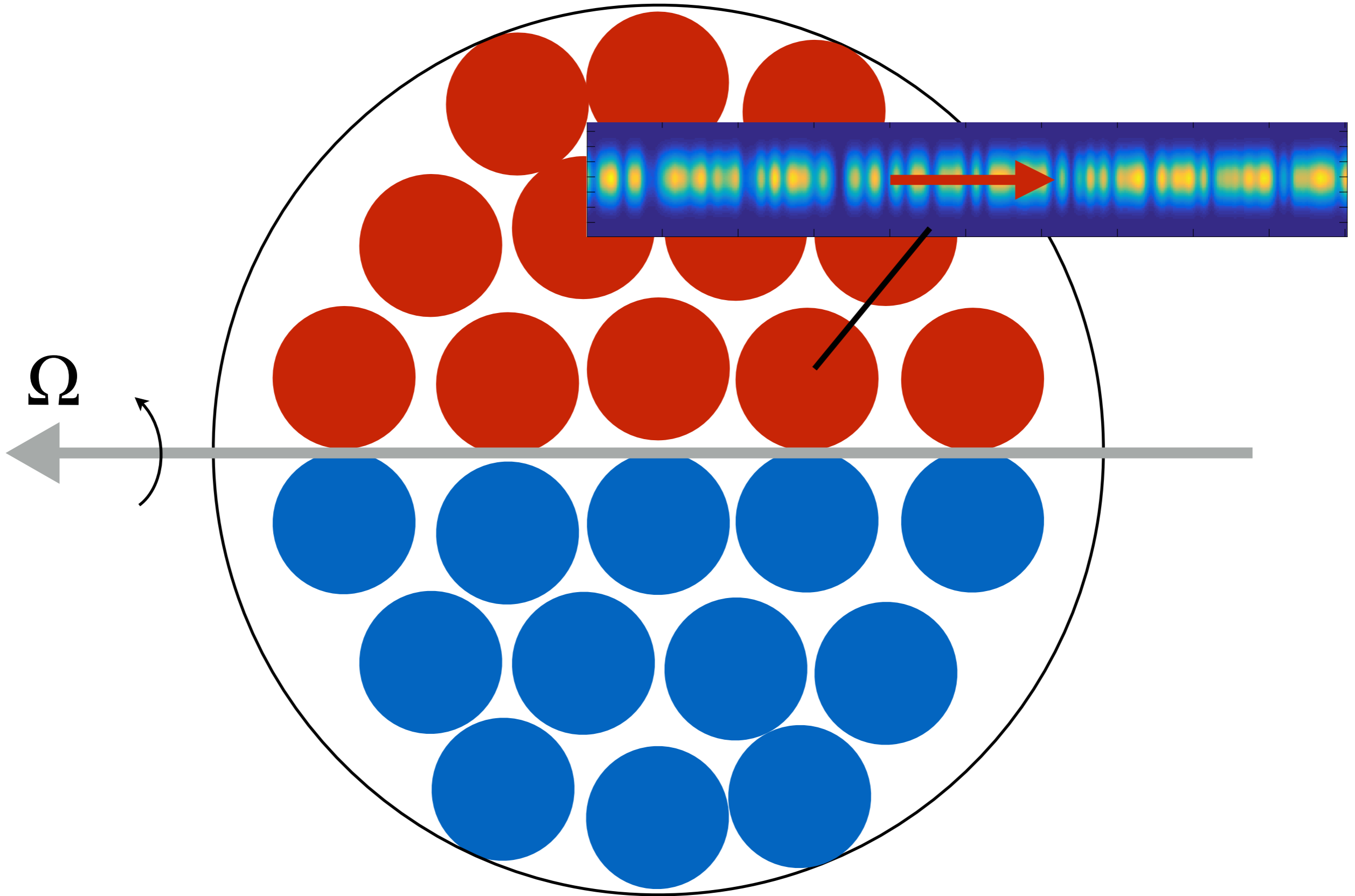
Using binaries to build a simple model



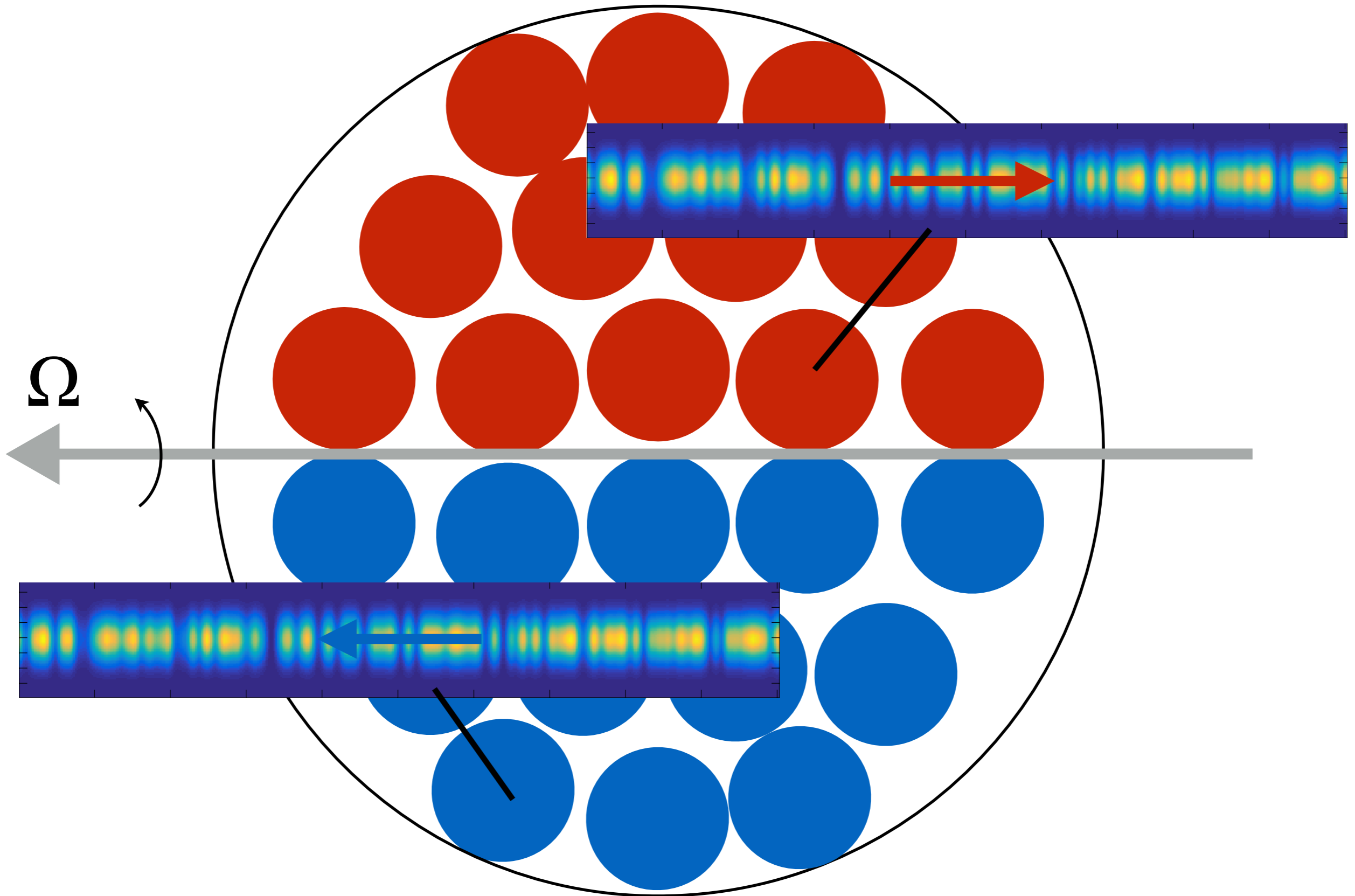
Using binaries to build a simple model



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Using binaries to build a simple model

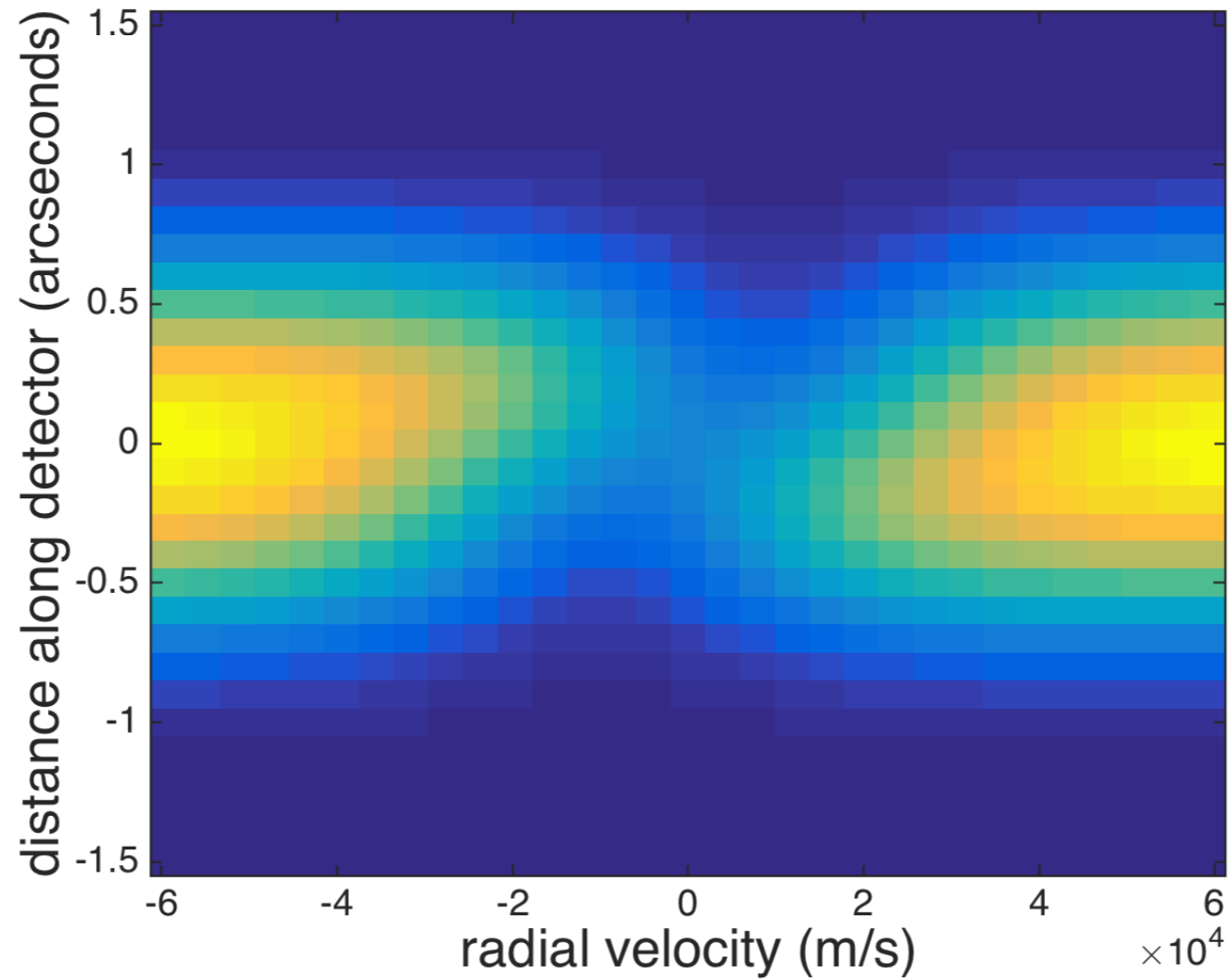


*Fact: A (non pole-on) rotating star
can be treated as the
superposition of an infinite
number of spectroscopic binaries.*

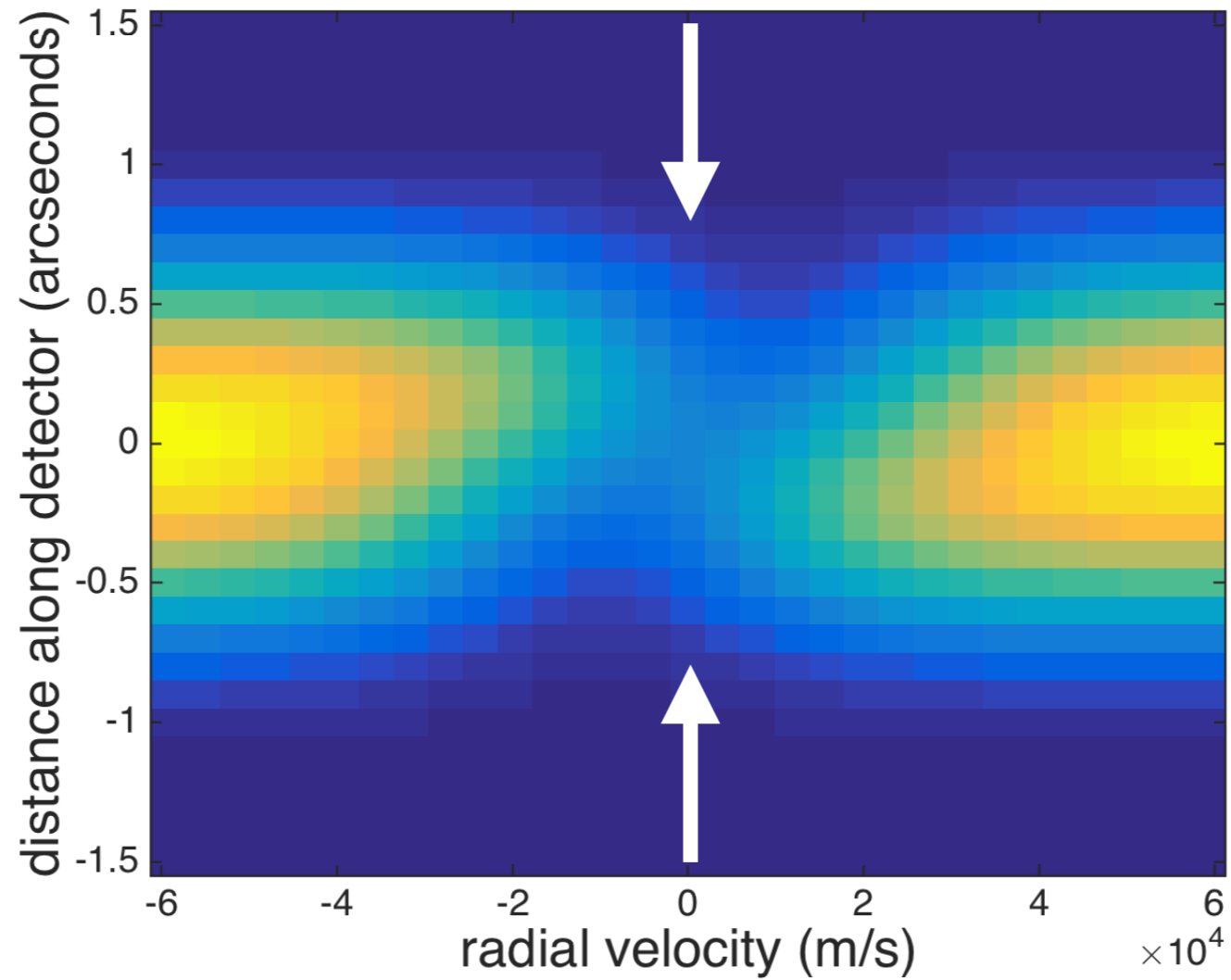
*Fact: A (non pole-on) rotating star
can be treated as the
superposition of an infinite
number of spectroscopic binaries.*

The resulting spectrum will be
tilted. How do we measure the tilt?

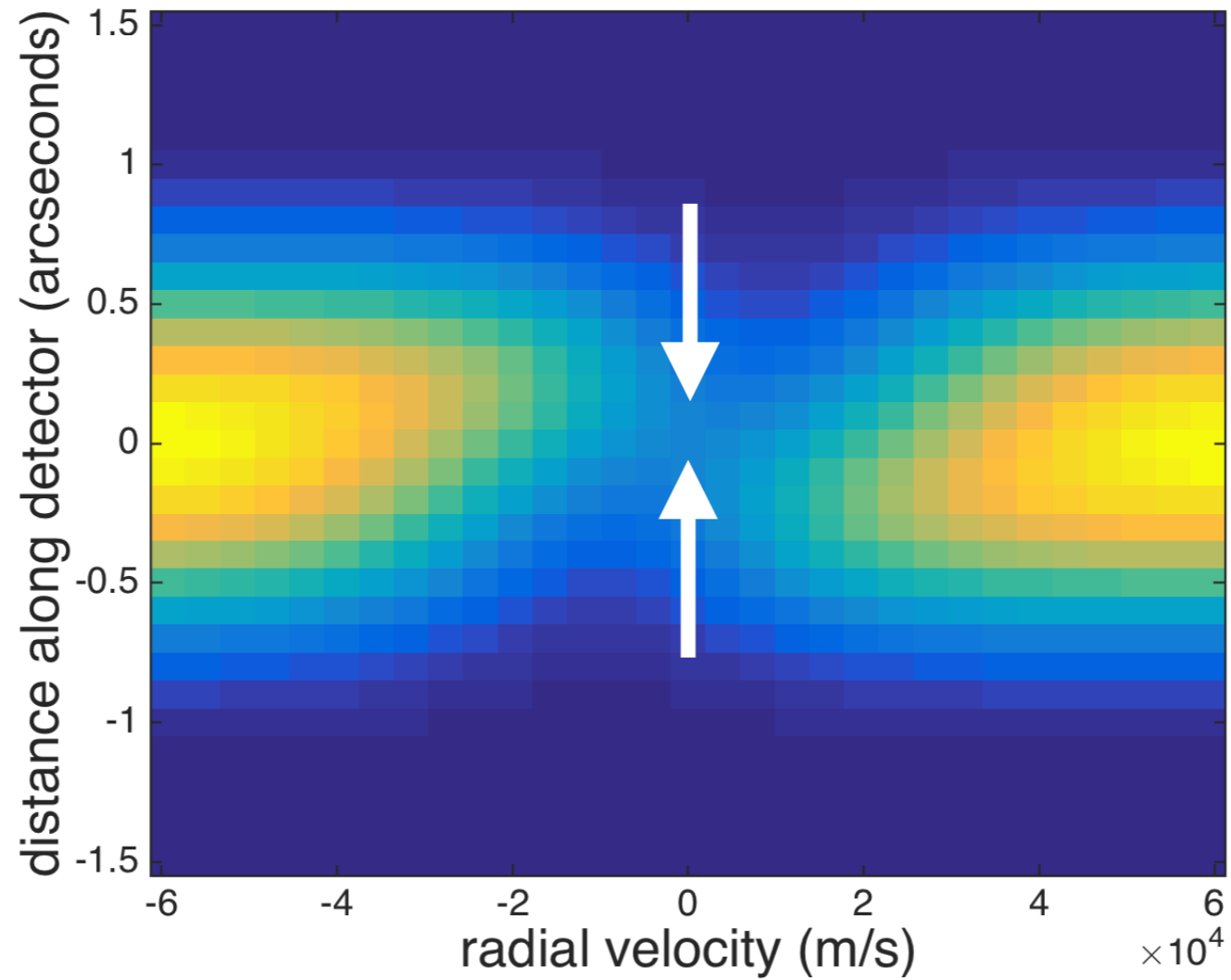
How to measure the tilt



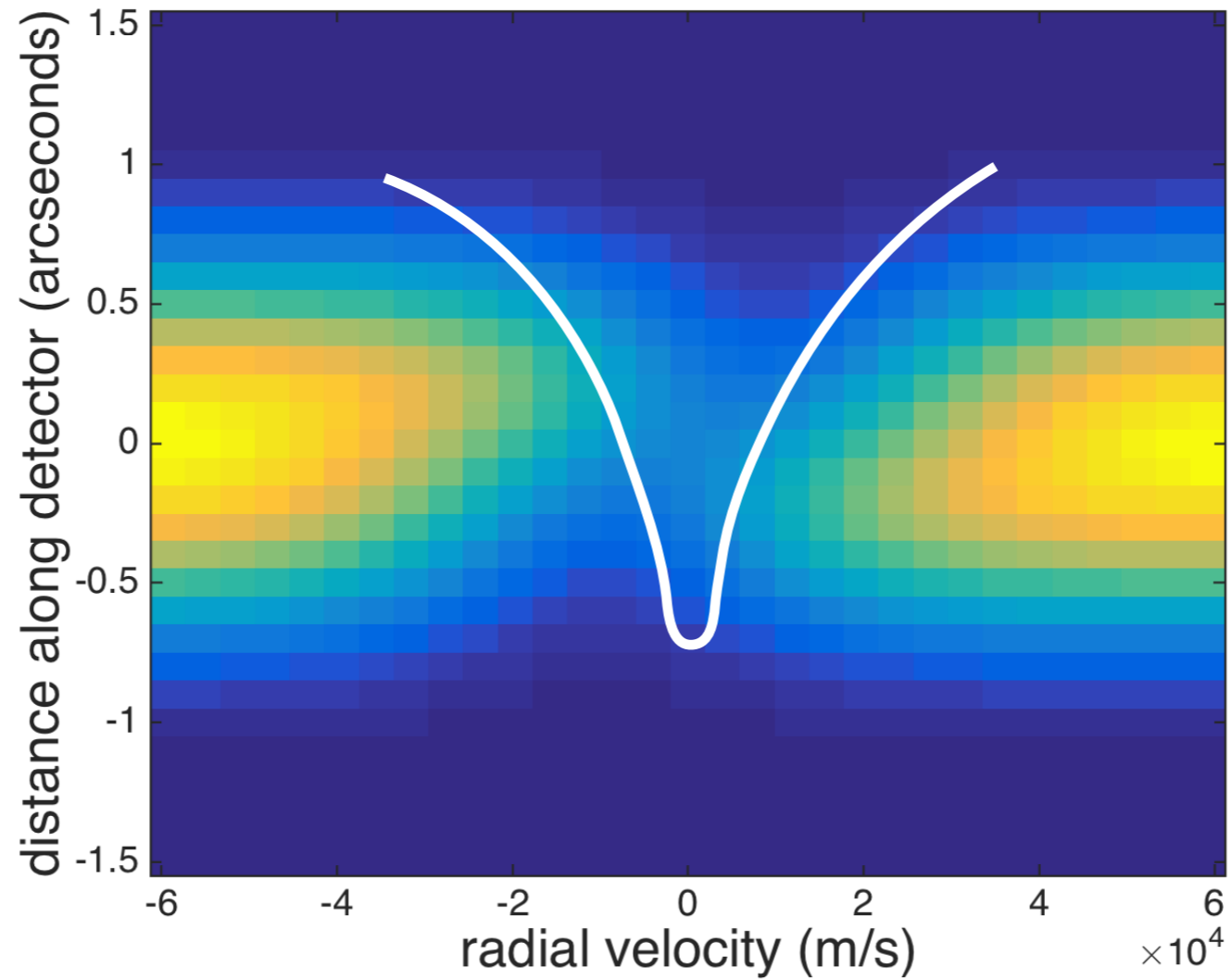
How to measure the tilt



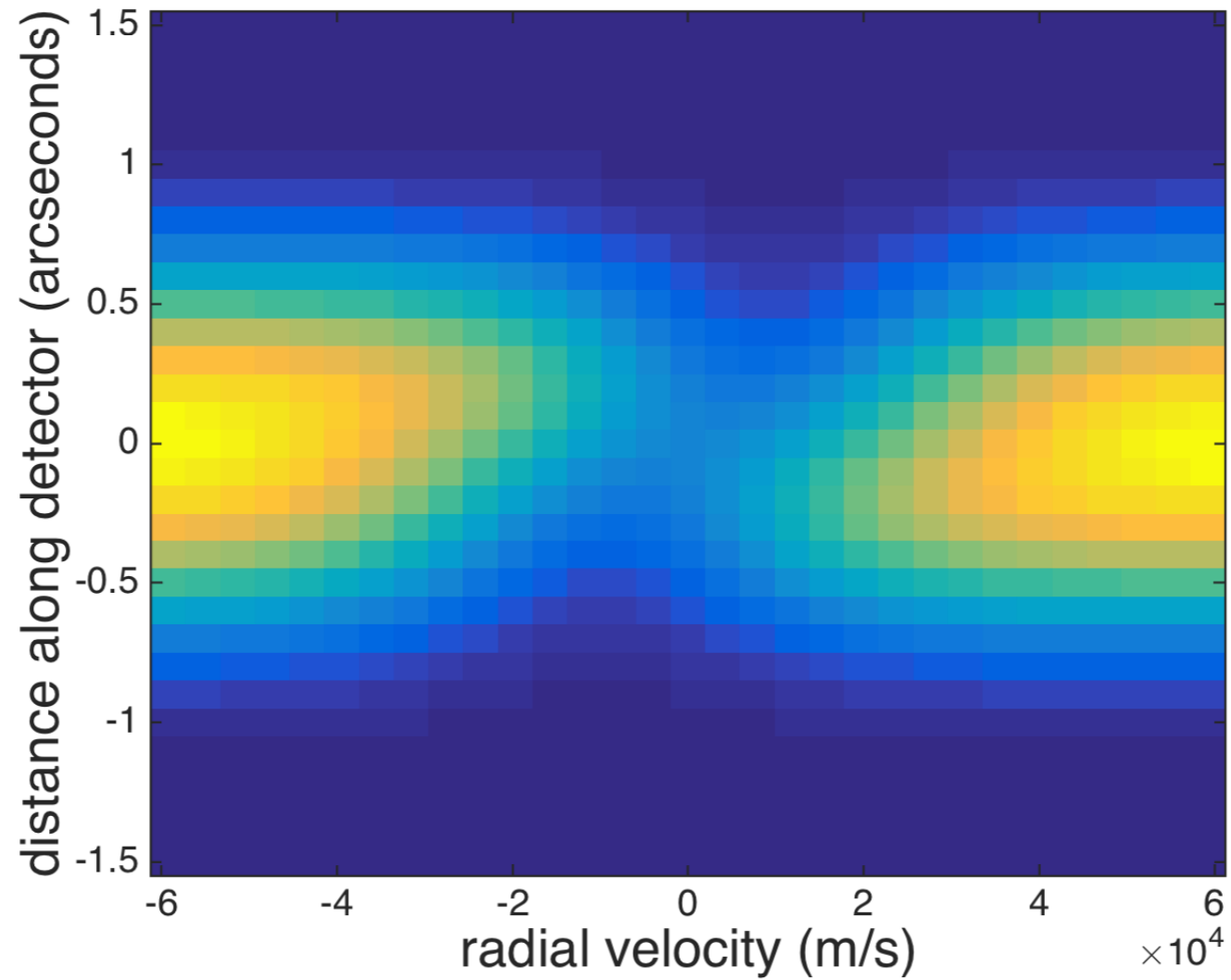
How to measure the tilt



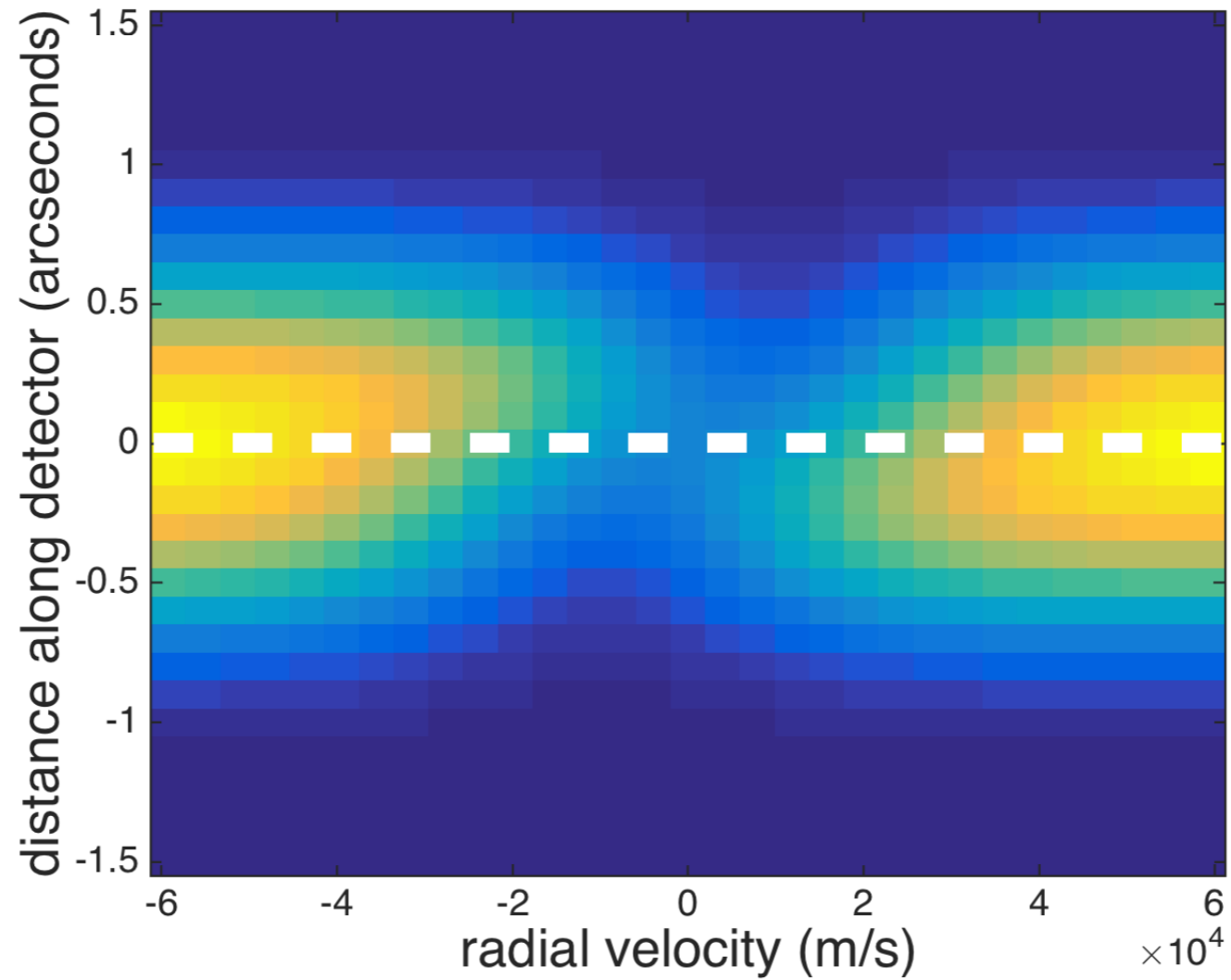
How to measure the tilt



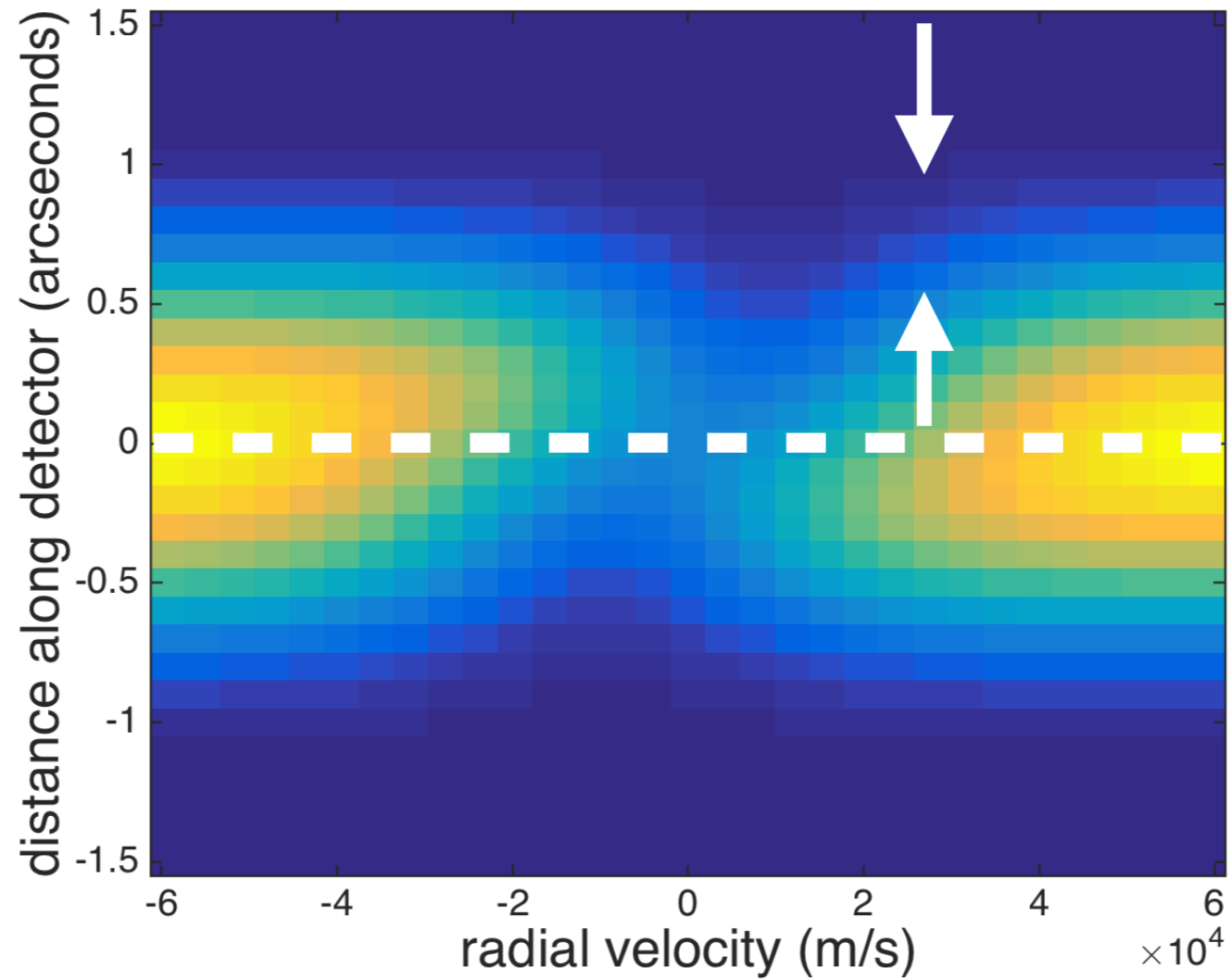
How to measure the tilt



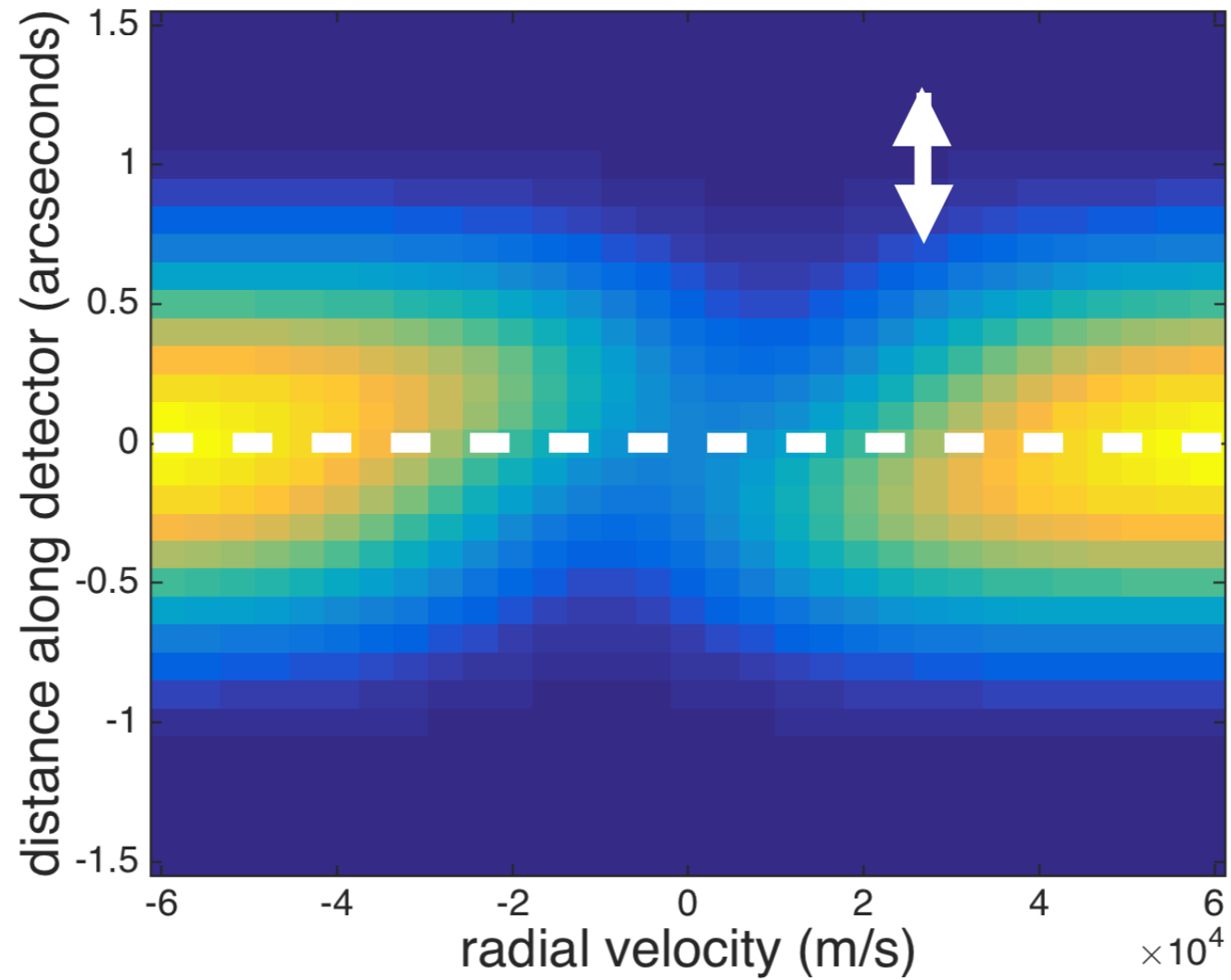
How to measure the tilt



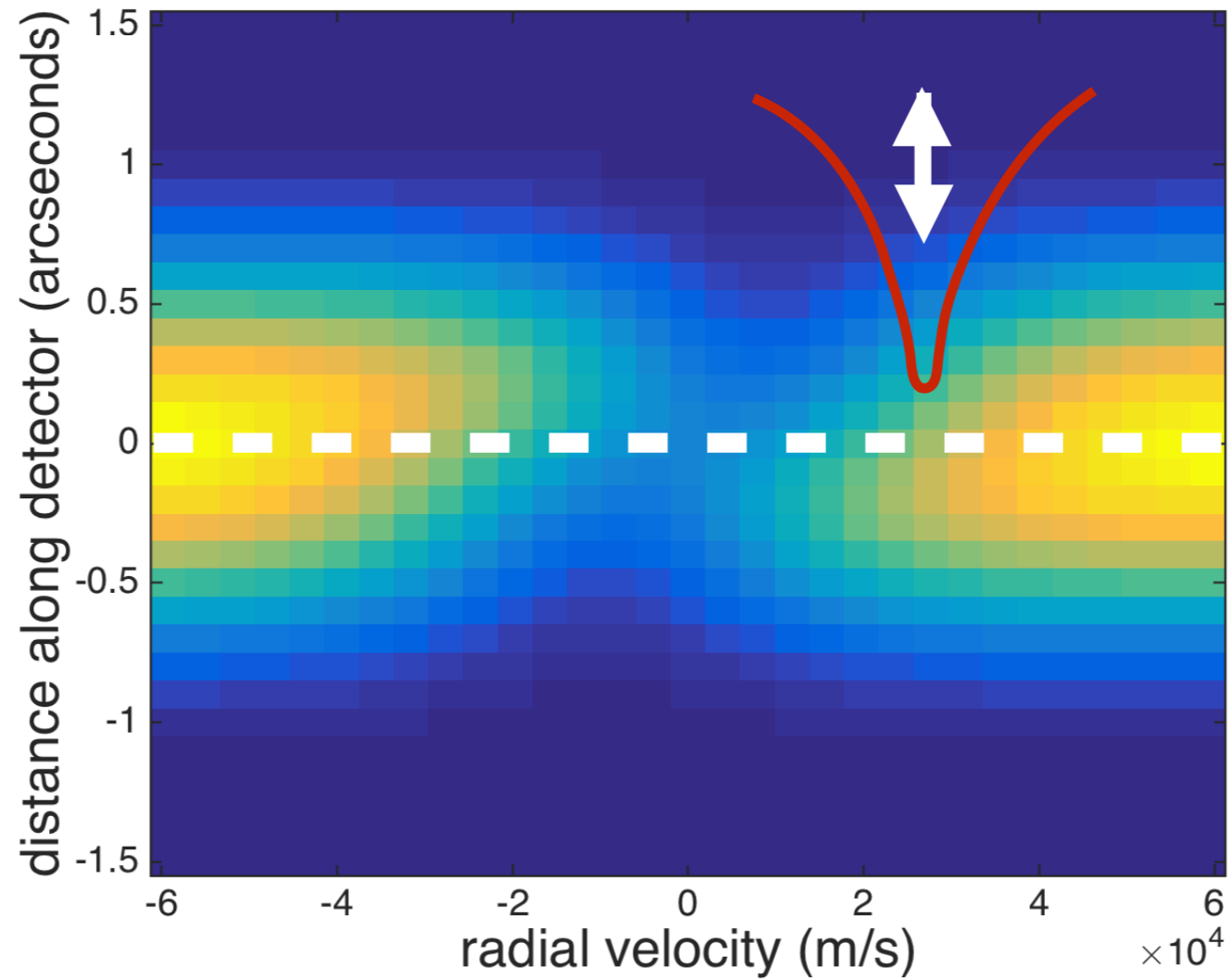
How to measure the tilt



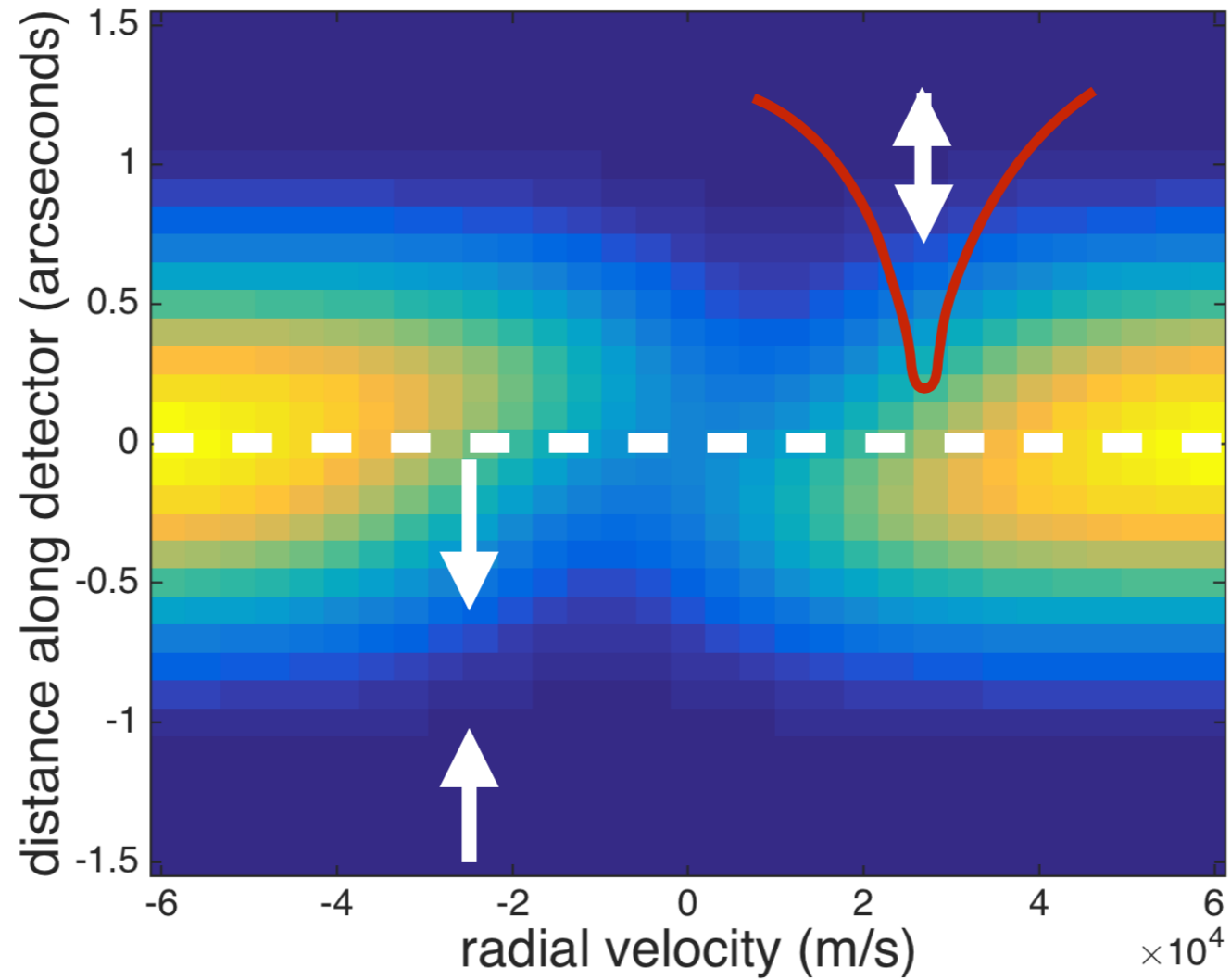
How to measure the tilt



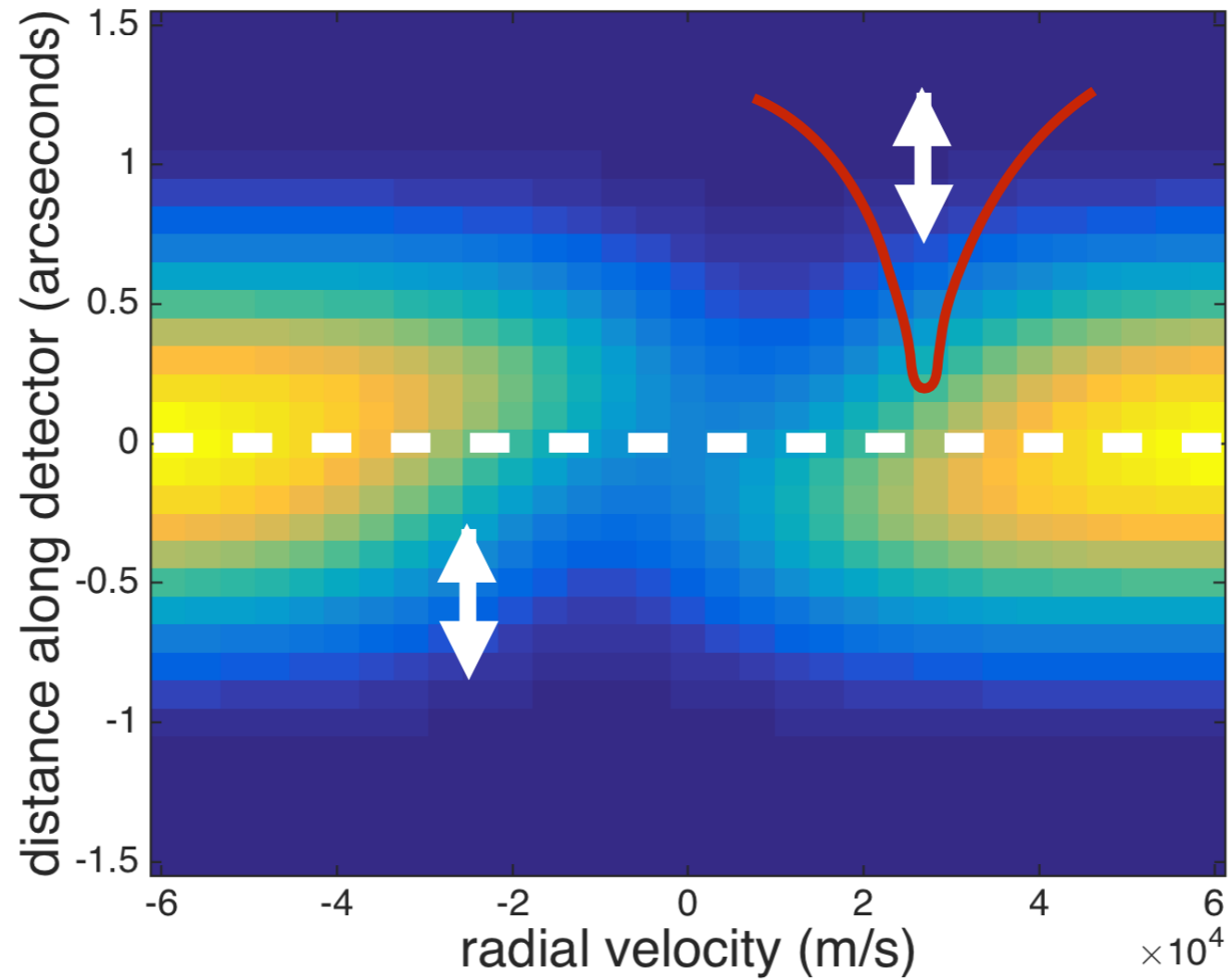
How to measure the tilt



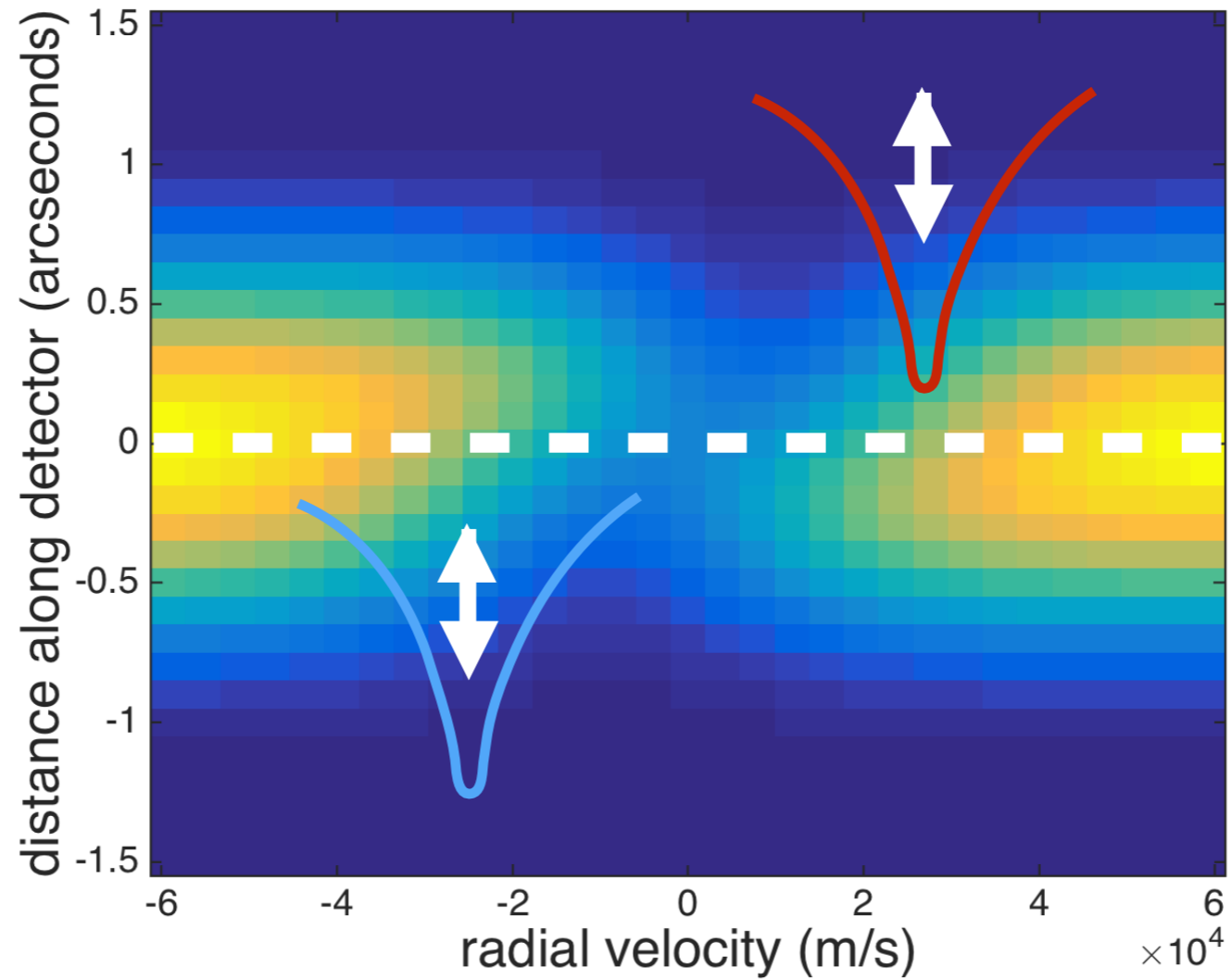
How to measure the tilt



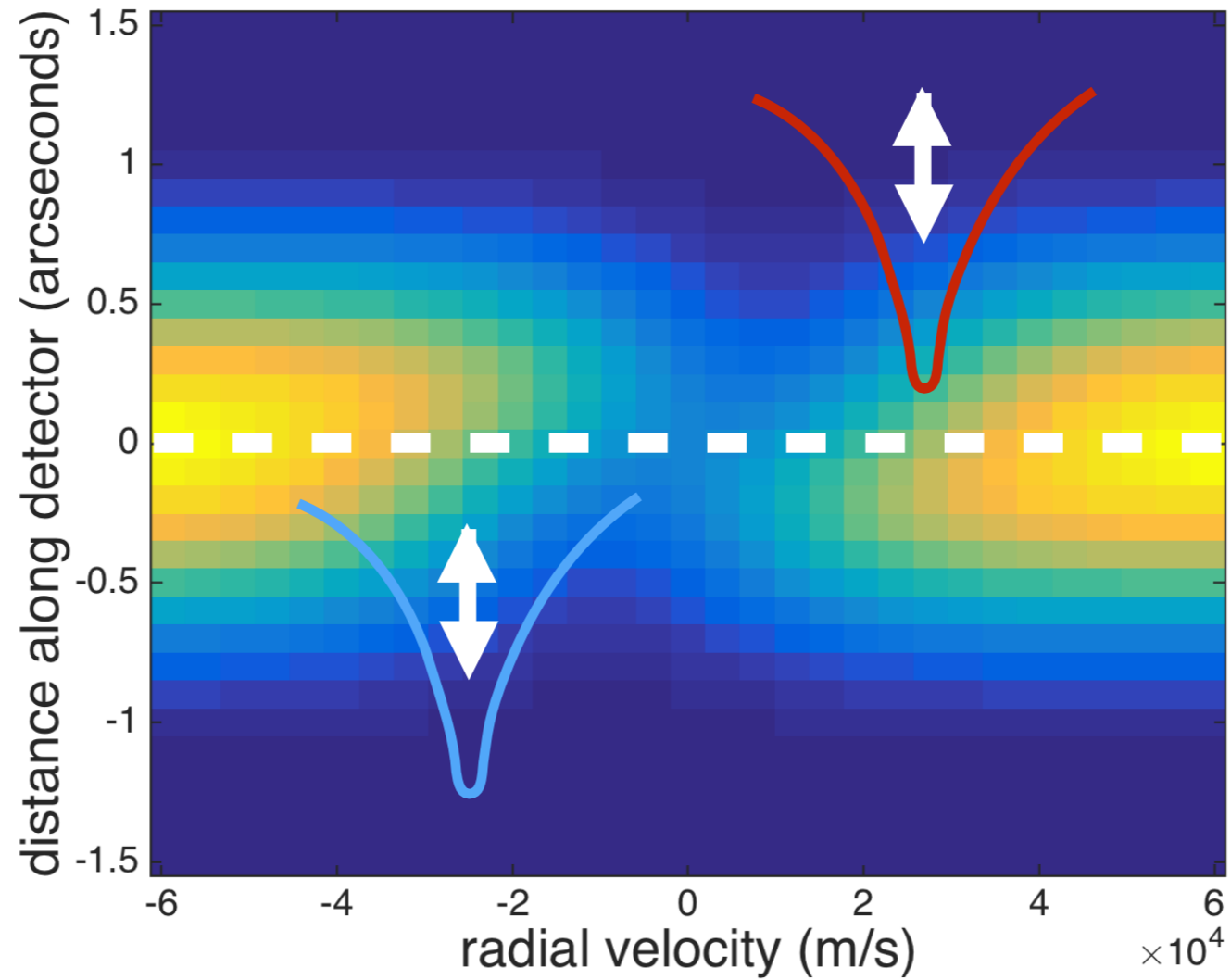
How to measure the tilt



How to measure the tilt



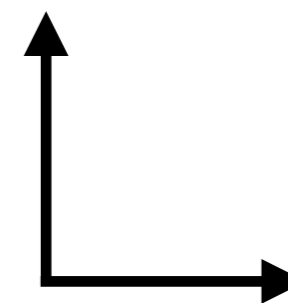
How to measure the tilt



$$\Delta RV_{vsini} = 1/2 * (\text{Red} - \text{Blue})$$

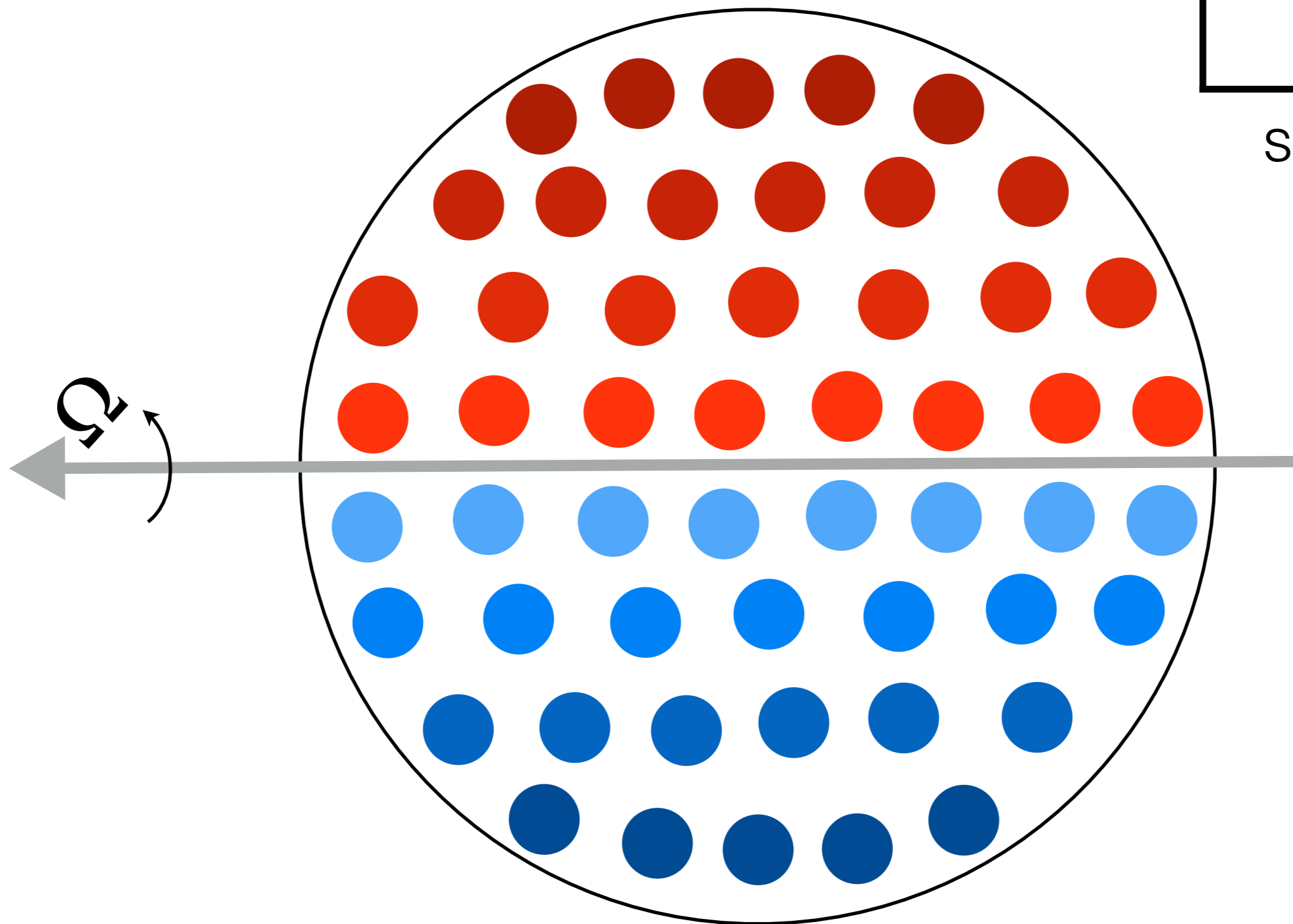
Max measured RV

spatial



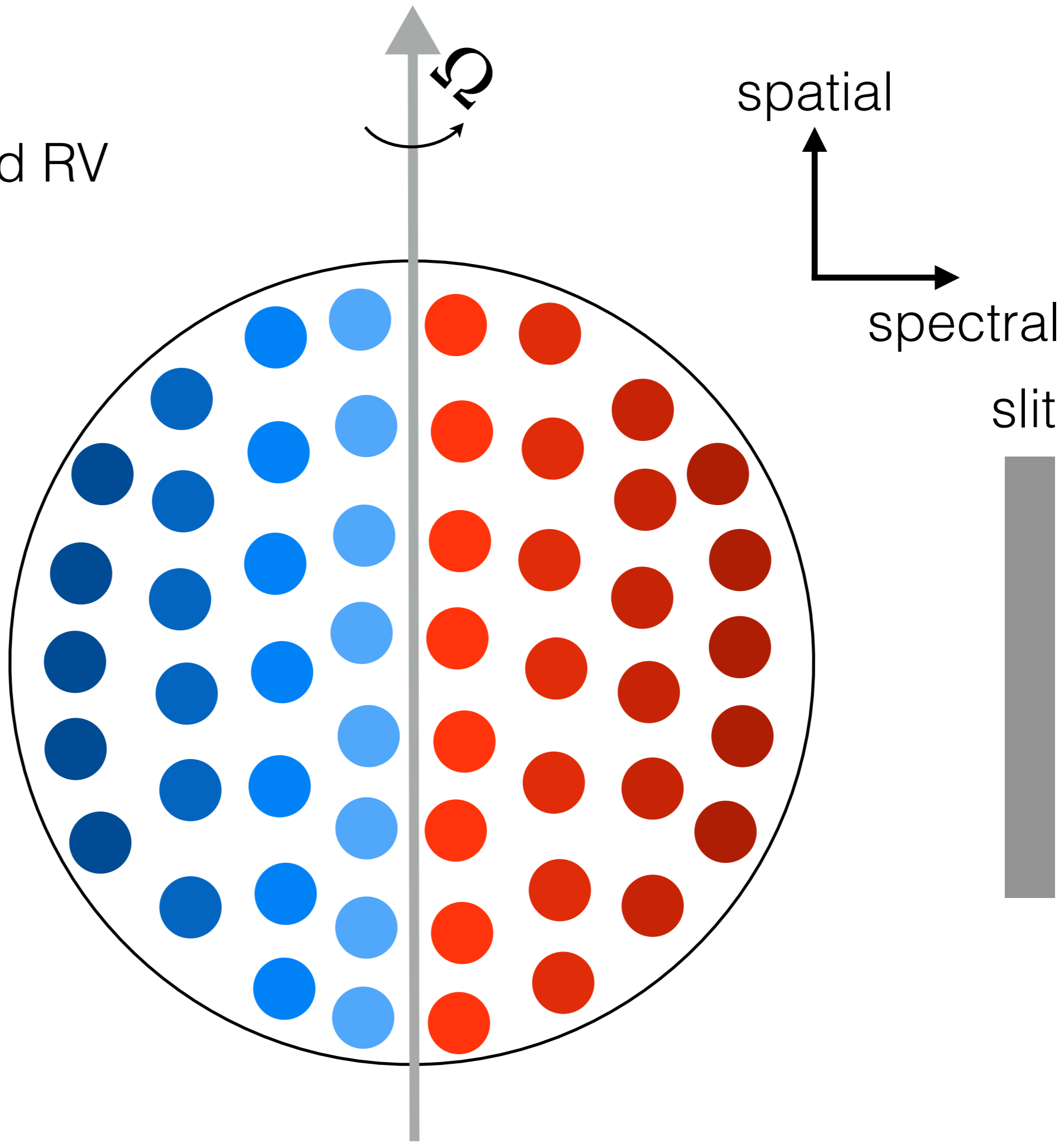
spectral

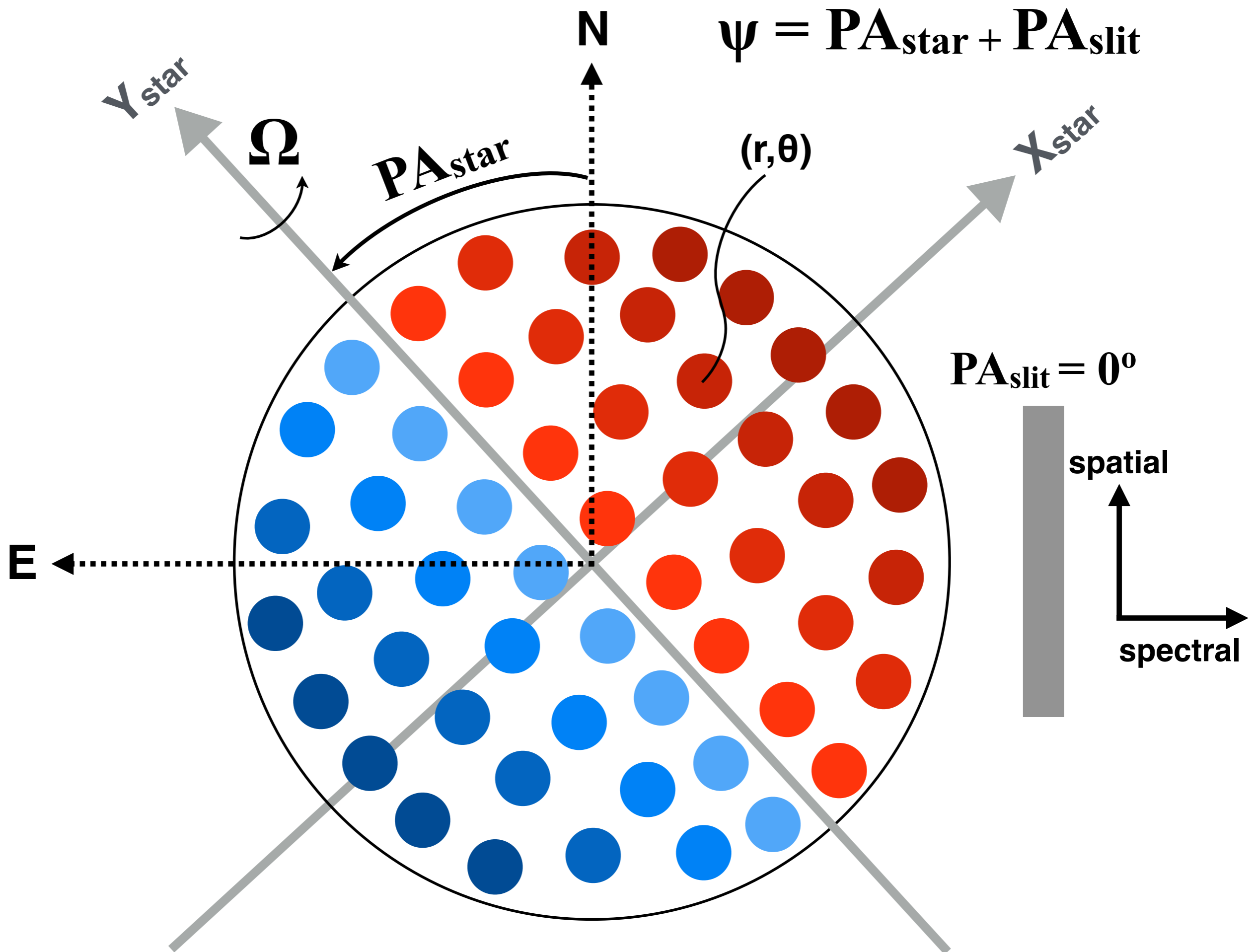
slit



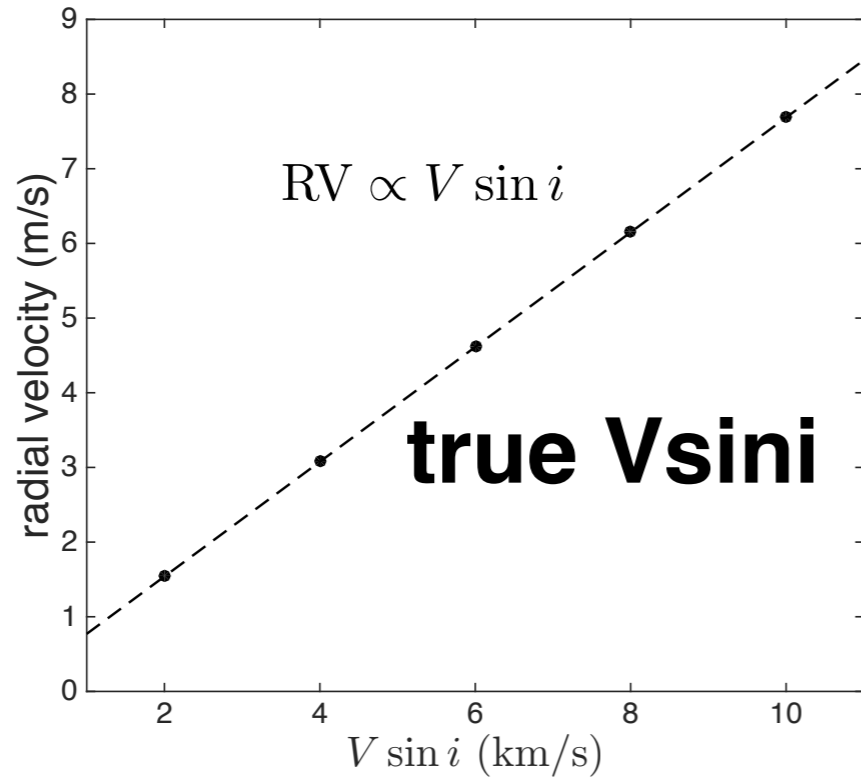
Ω

No measured RV

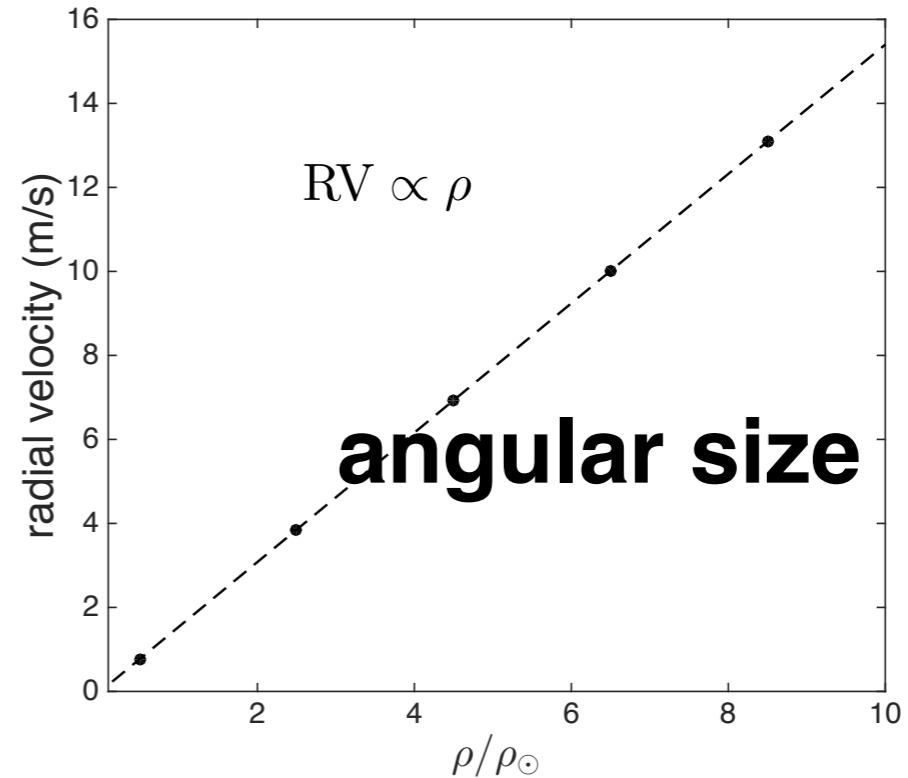




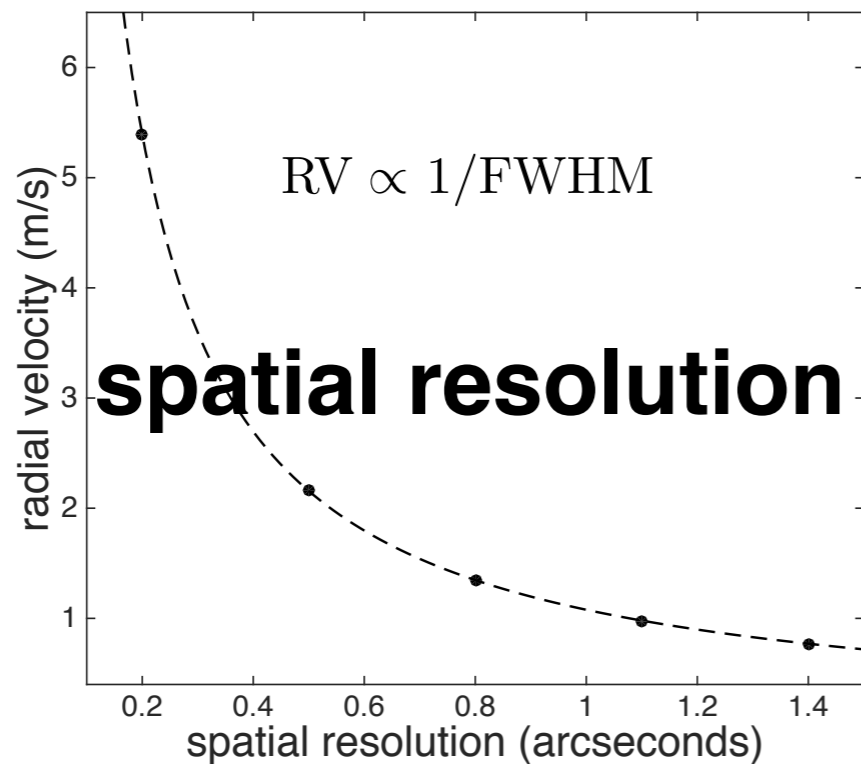
RV depends on just 4 parameters



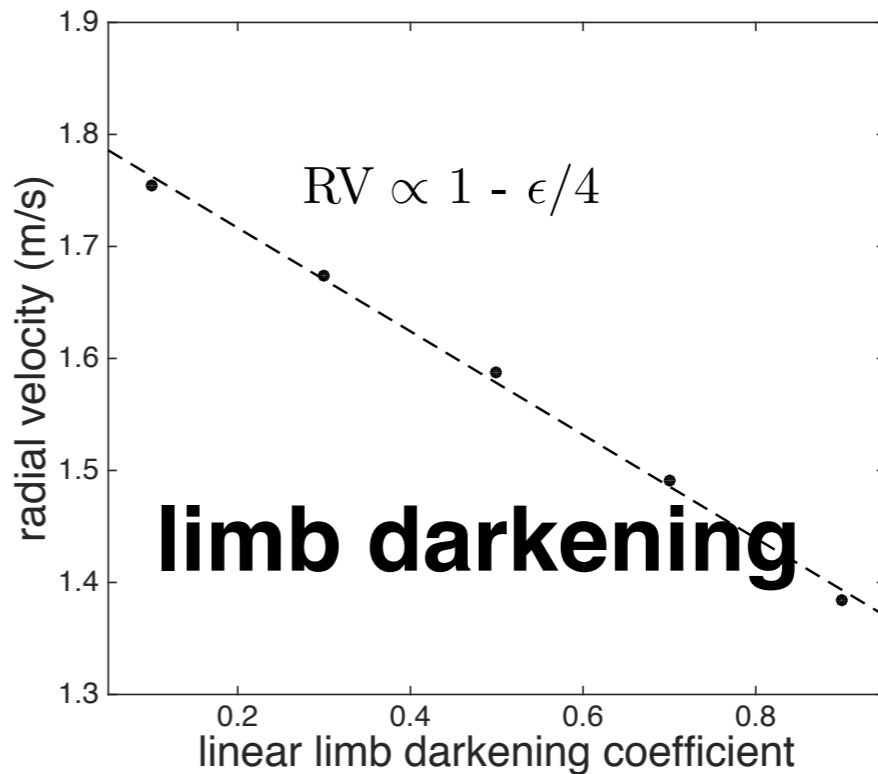
(a)



(b)

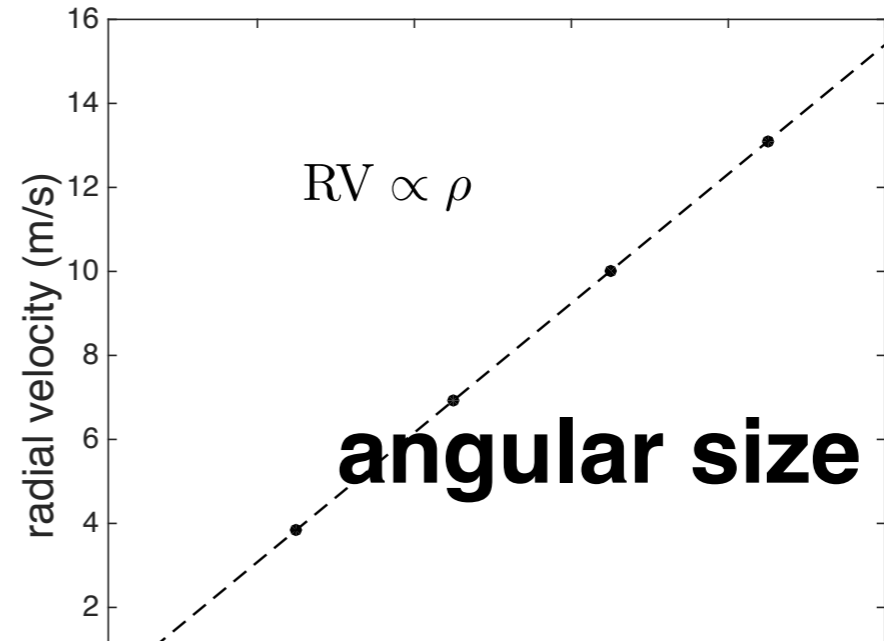
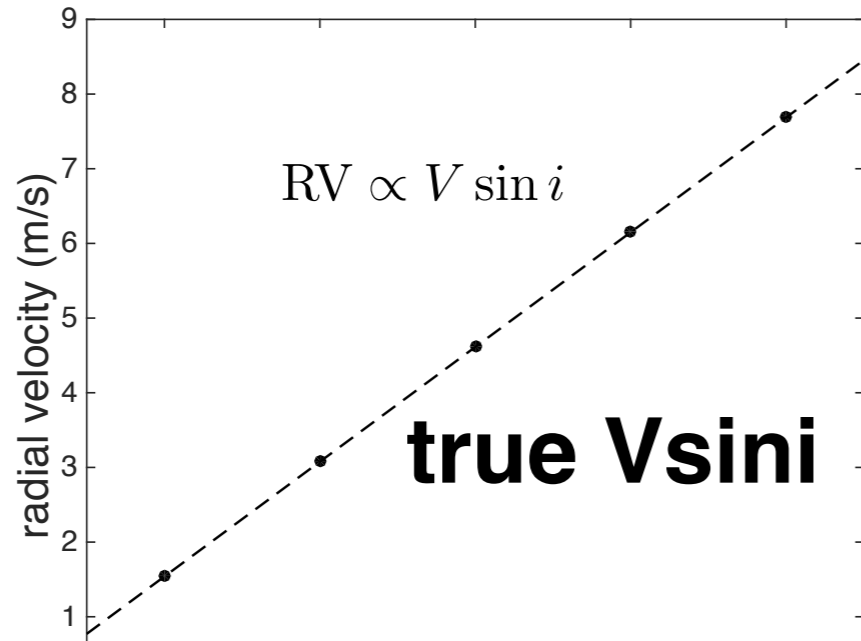


(c)

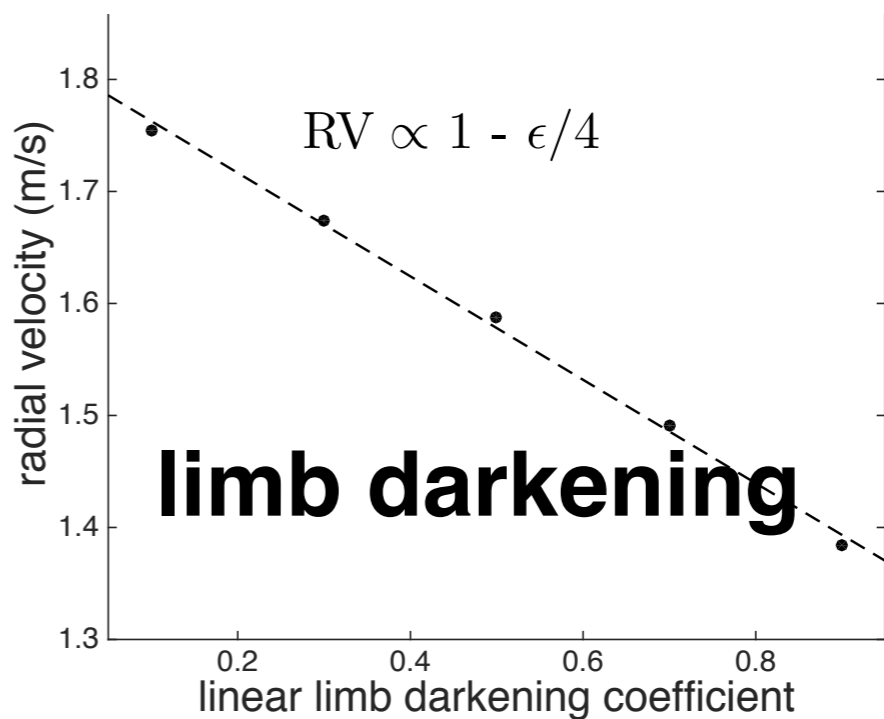
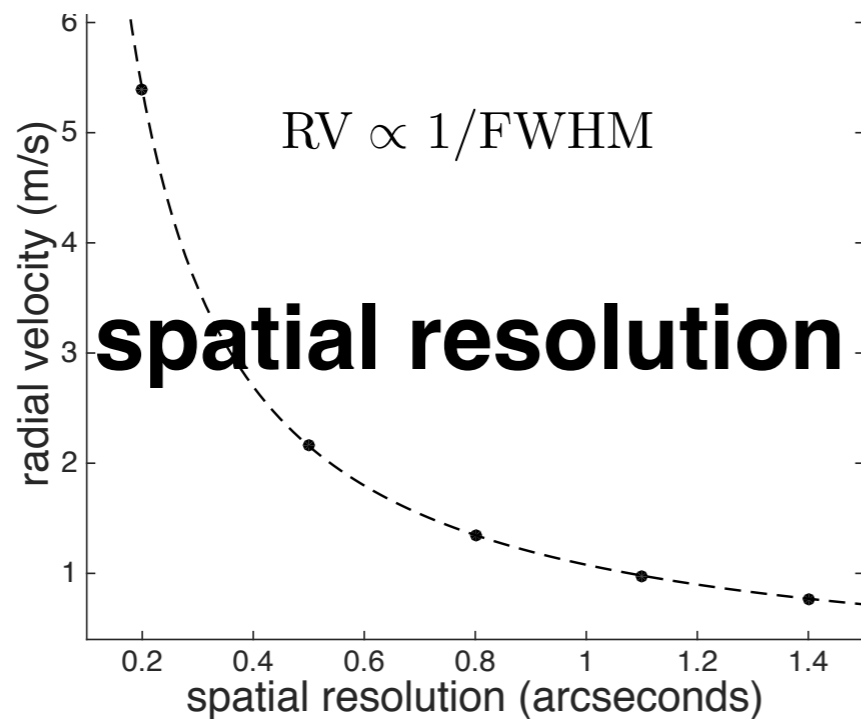


(d)

RV depends on just 4 parameters



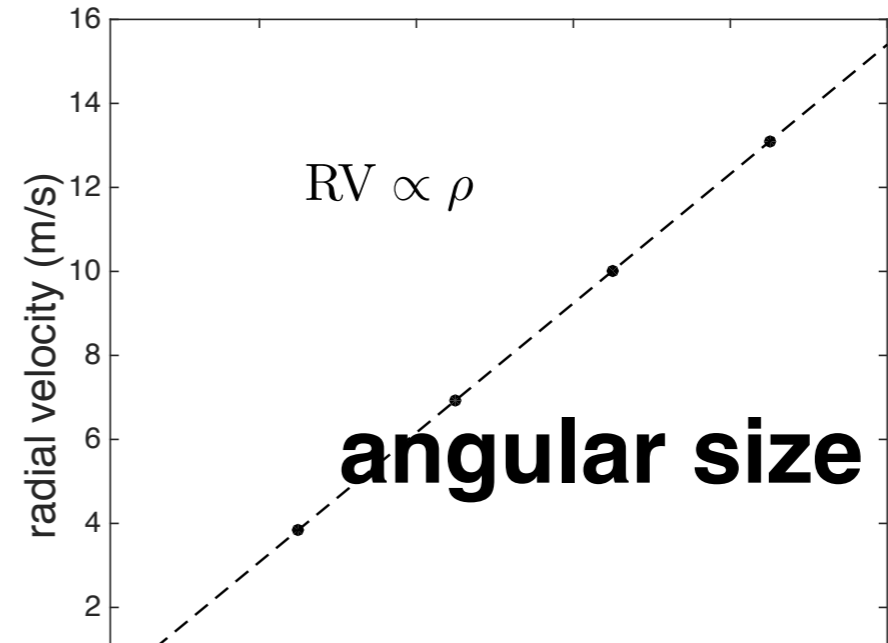
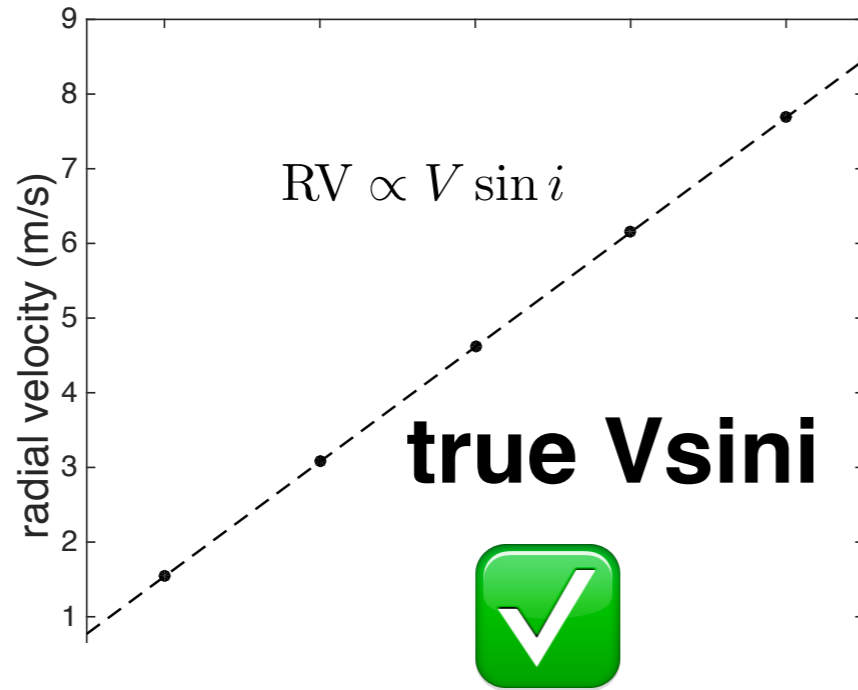
$$V \sin i \approx 2 \text{ km/s} \left(\frac{RV_{V \sin i}}{1.82 \text{ m/s}} \right) \left(\frac{\rho}{0.465 \text{ mas}} \right)^{-1} \left(\frac{\text{FWHM}}{0.''7} \right) \left(1 - \frac{\epsilon}{4} \right)^{-1}$$



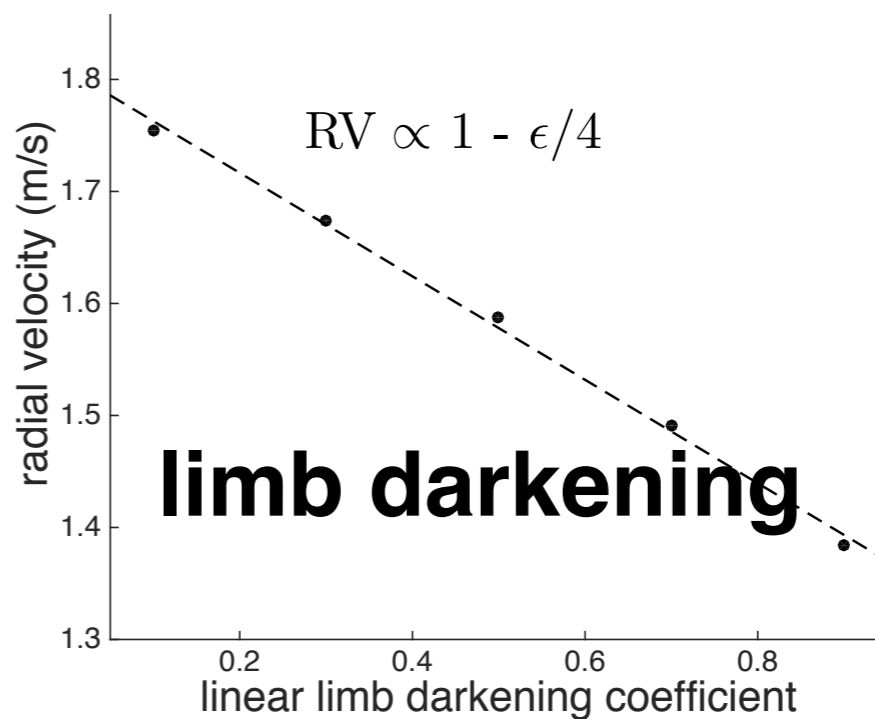
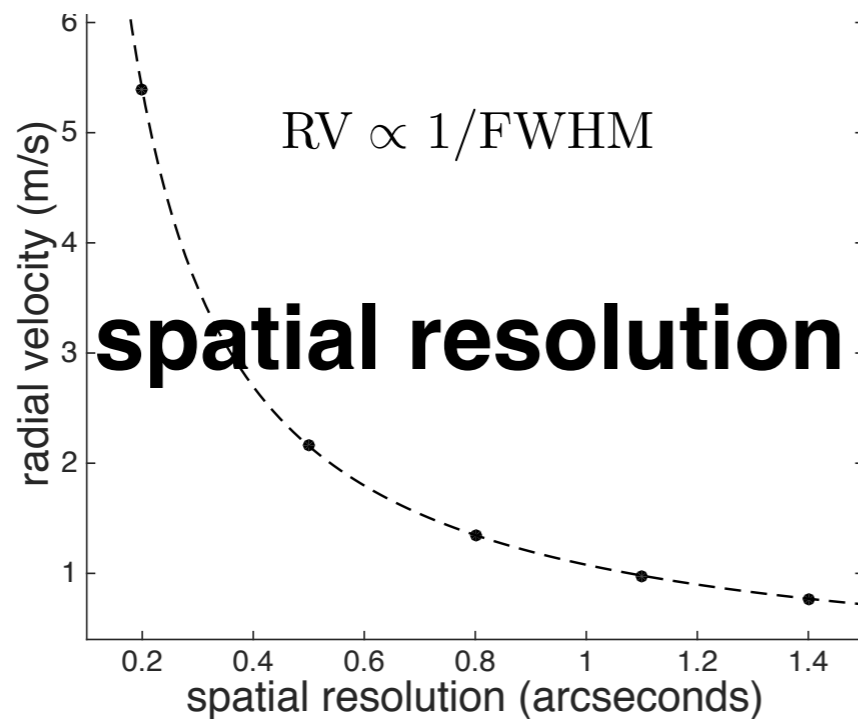
(c)

(d)

RV depends on just 4 parameters



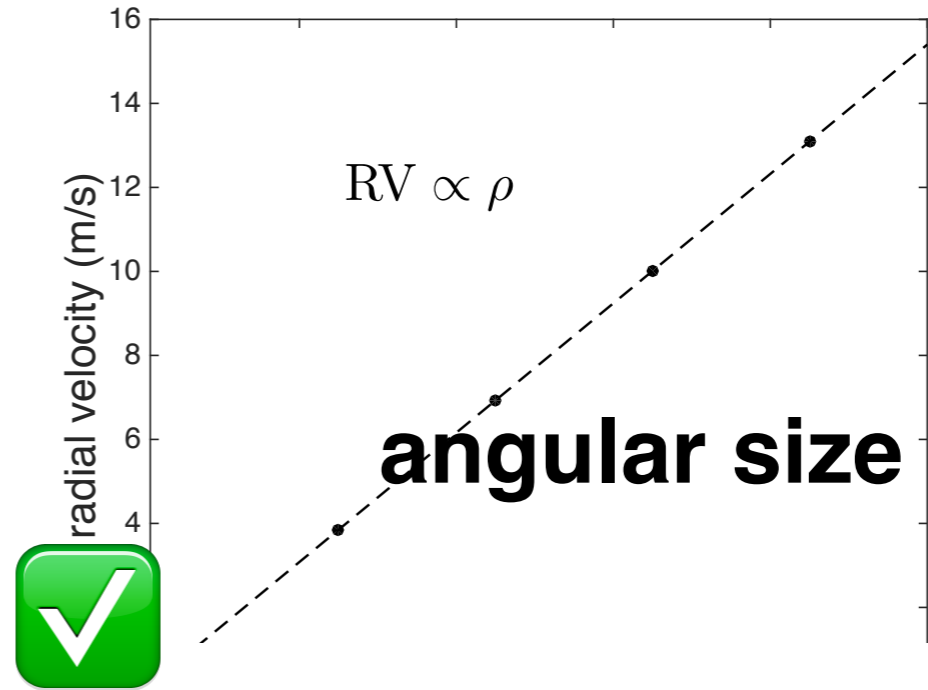
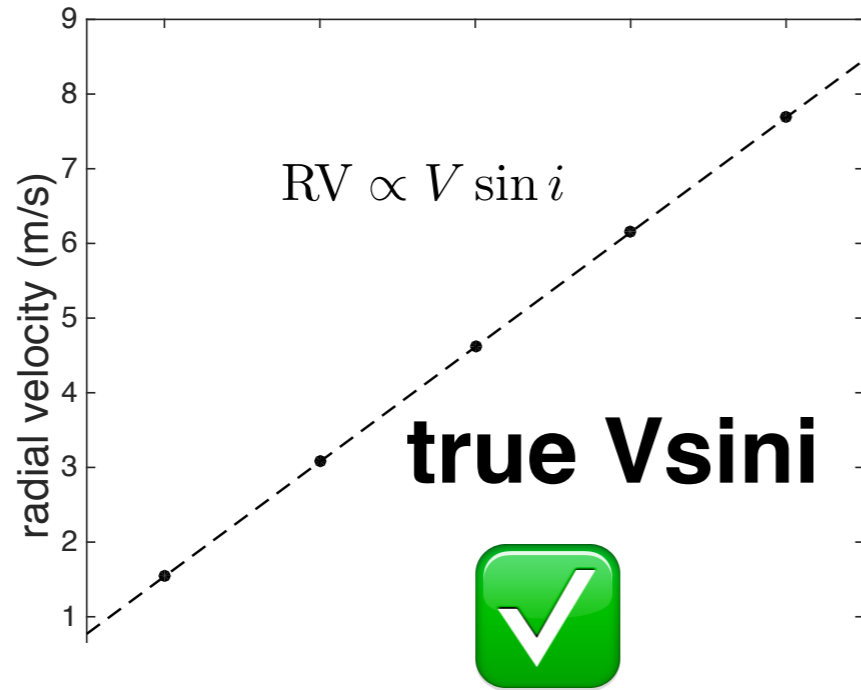
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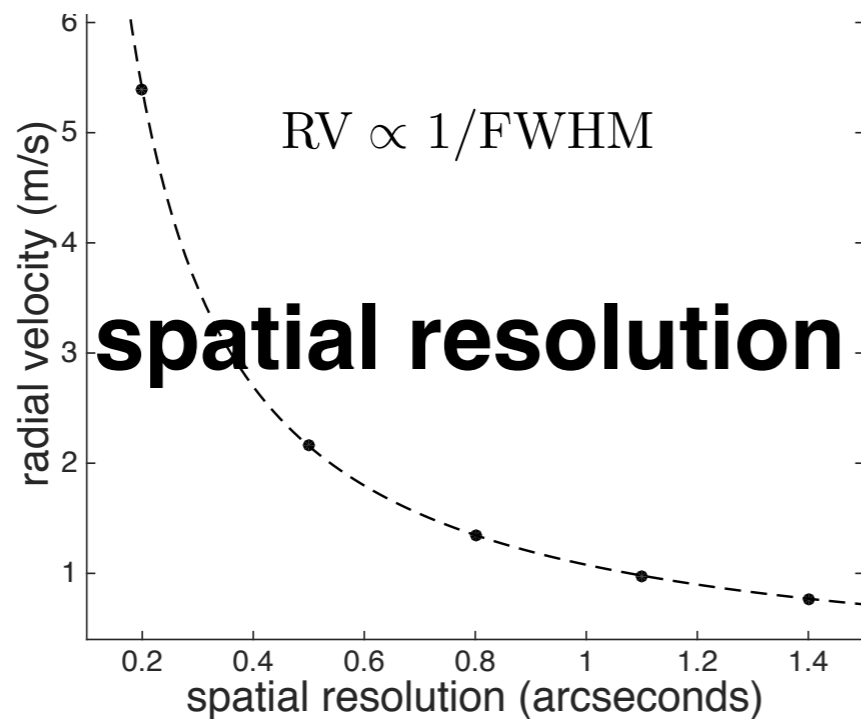
(c)

(d)

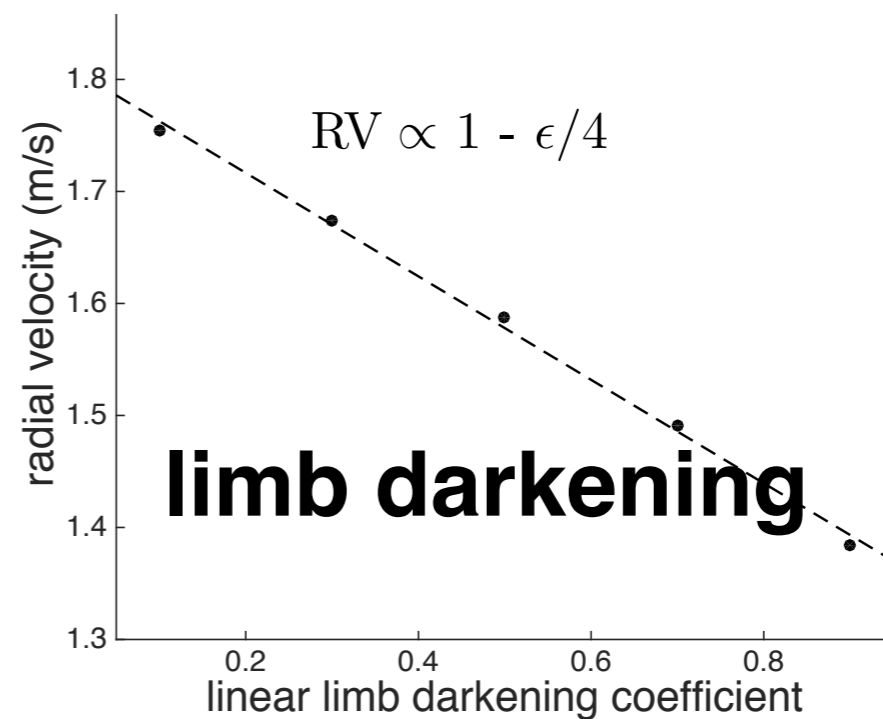
RV depends on just 4 parameters



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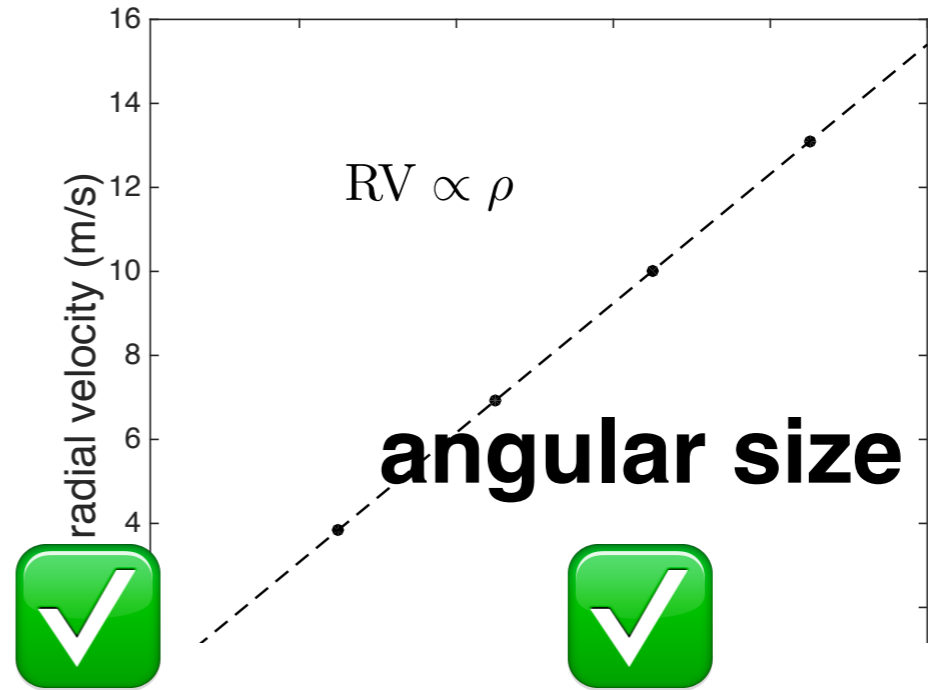
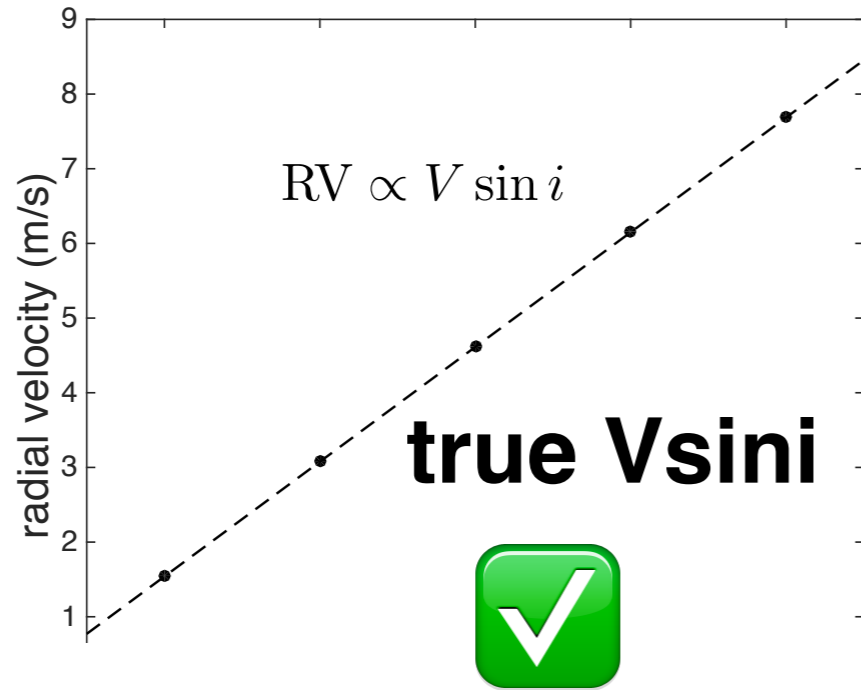


(c)

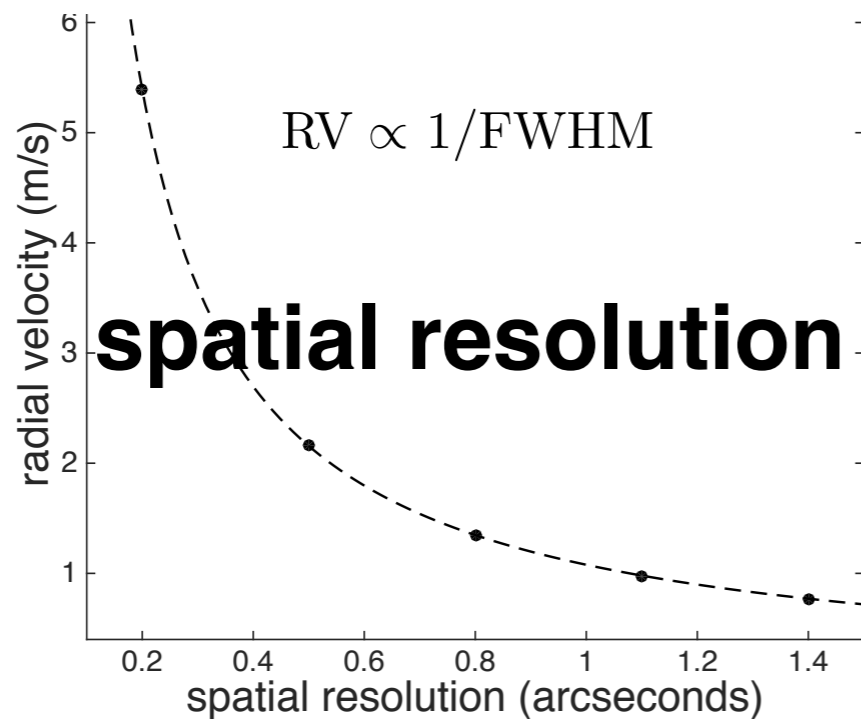


(d)

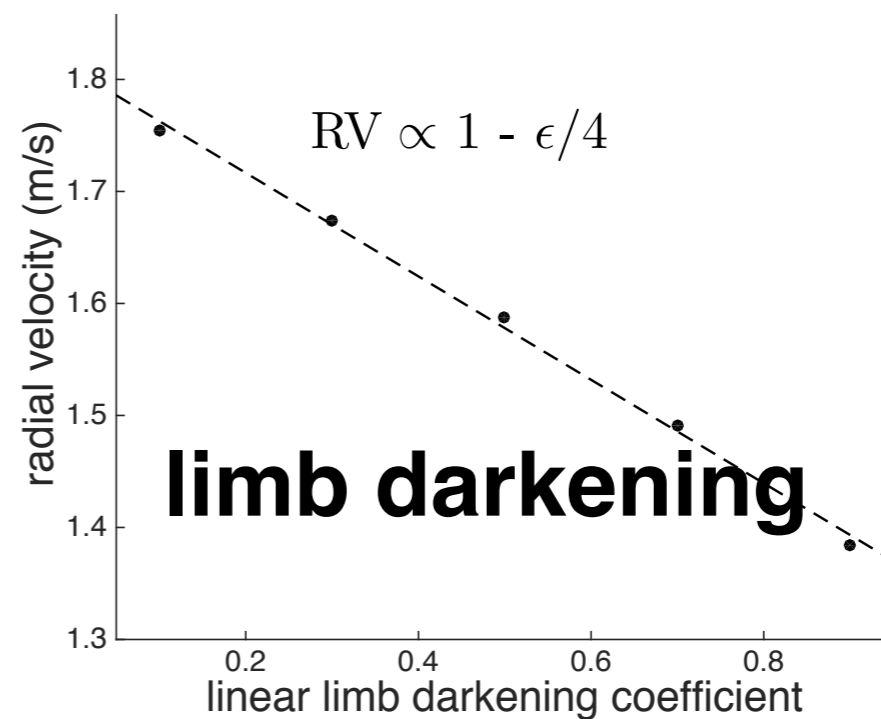
RV depends on just 4 parameters



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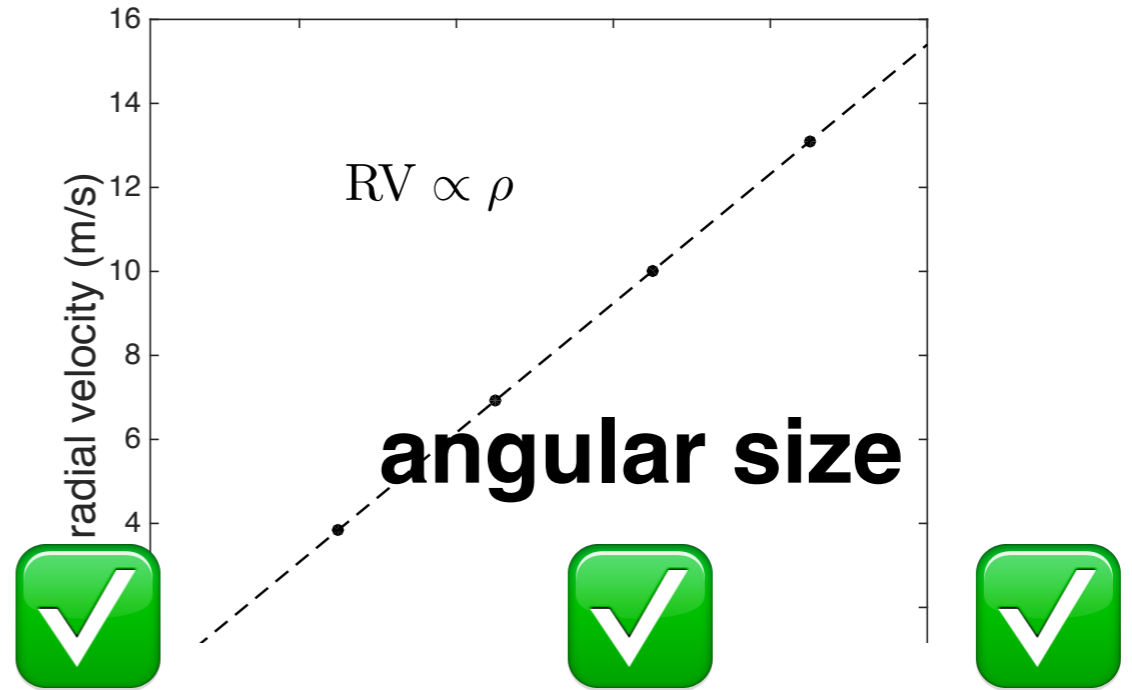
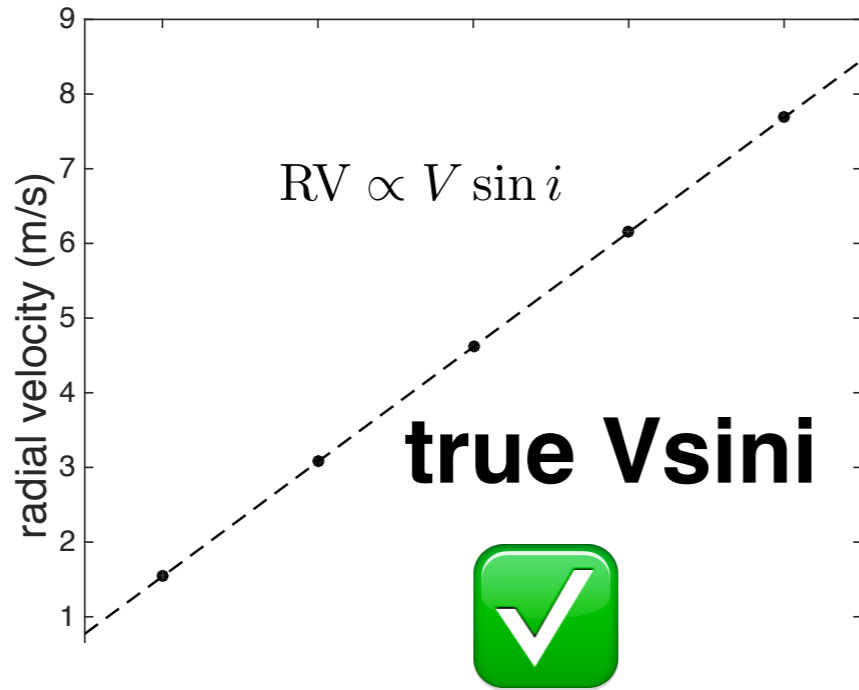


(c)

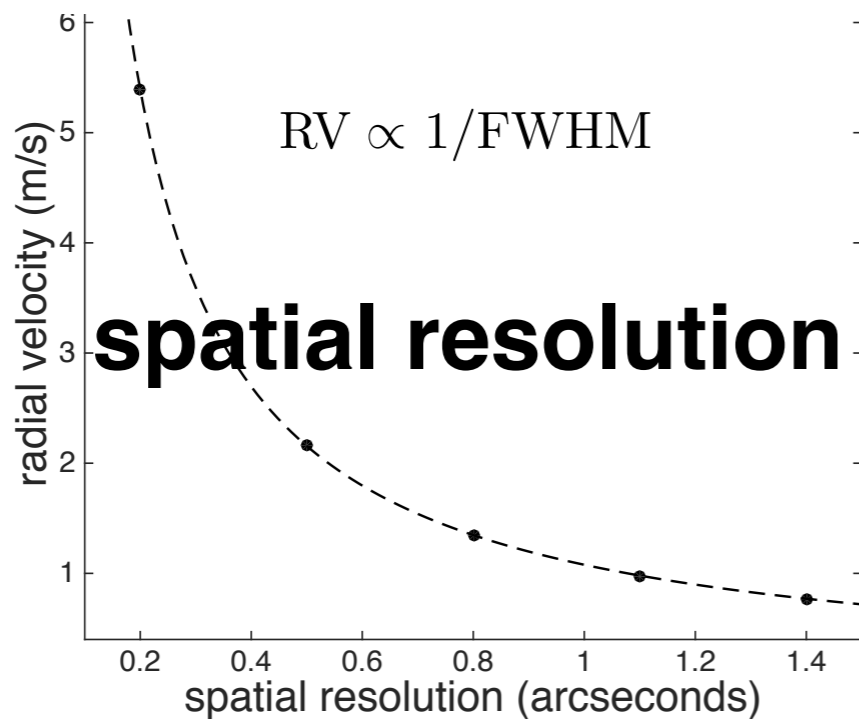


(d)

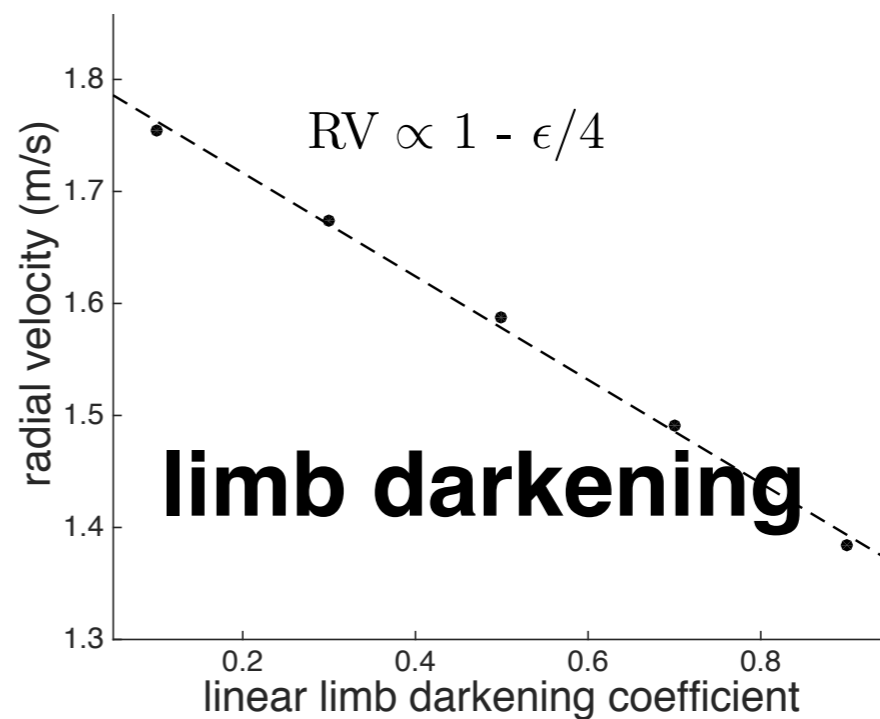
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(c)



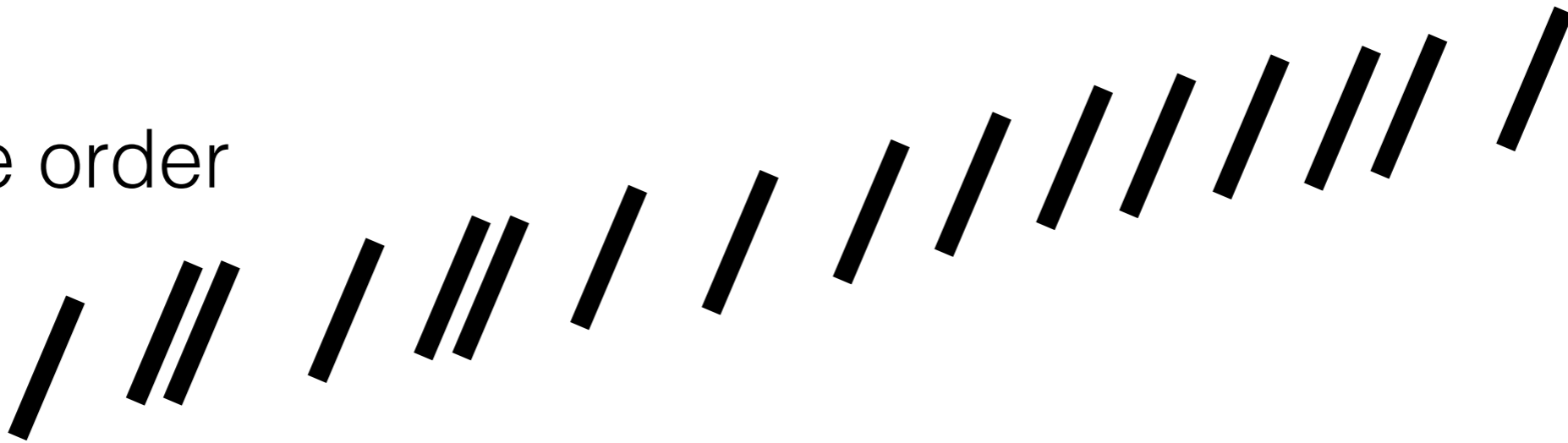
(d)

Proof of concept: a nearby K3III giant

- Interferometrically-measured radius (57 R_{sun})
- Hipparcos parallax (18.09 mas \rightarrow 55 pc)
- Several previously-measured $v_{\text{ sini}}$ values (latest = 2.6 km/s)
- Time awarded with VLT/UVES: 32 (1 second!) exposures at 8 slit angles
- Data reduction: split 2D spectra, feed into planet-hunting pipeline (already written), compute ΔRVs

Reducing Echelle spectra is hard!

echelle order



1. de-bend order

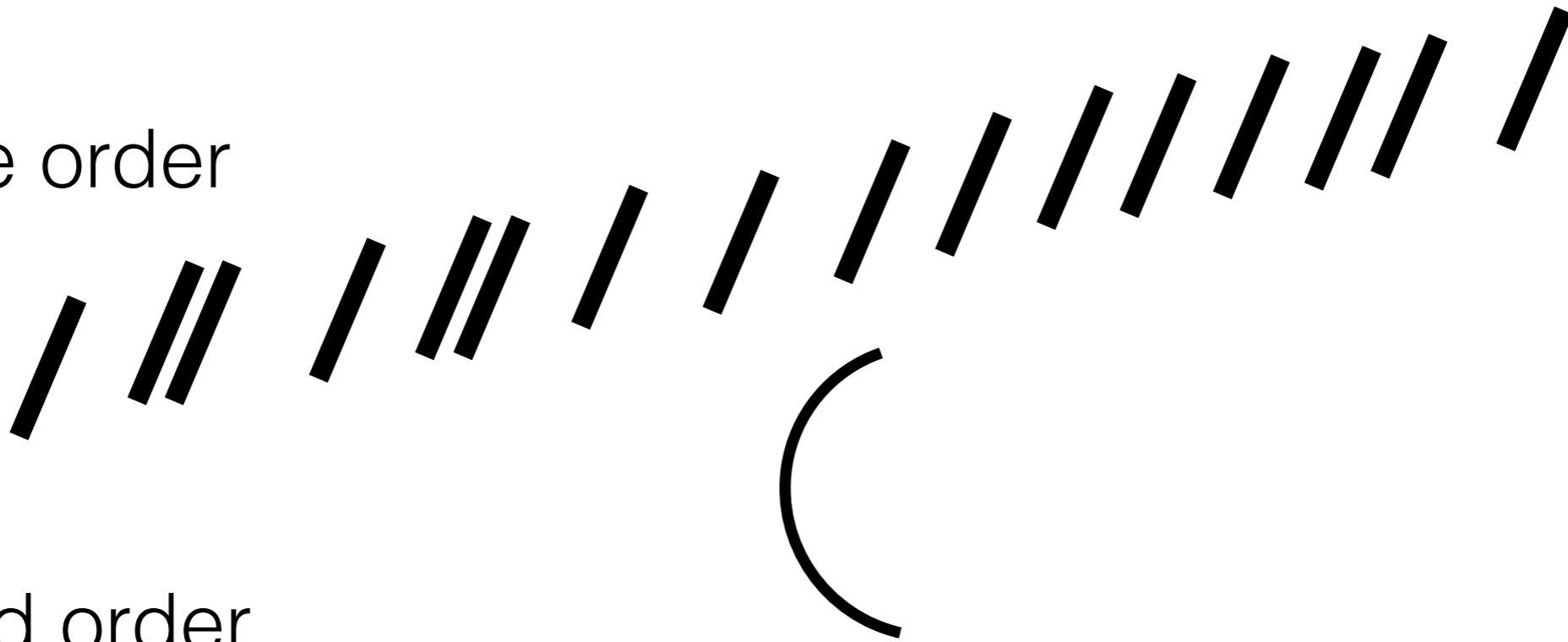


2. straighten lines



Reducing Echelle spectra is hard!

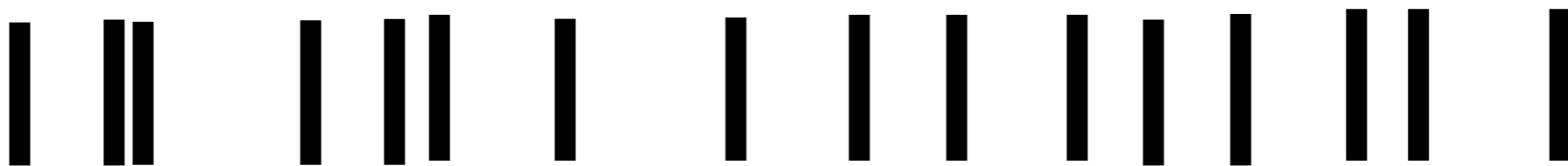
echelle order



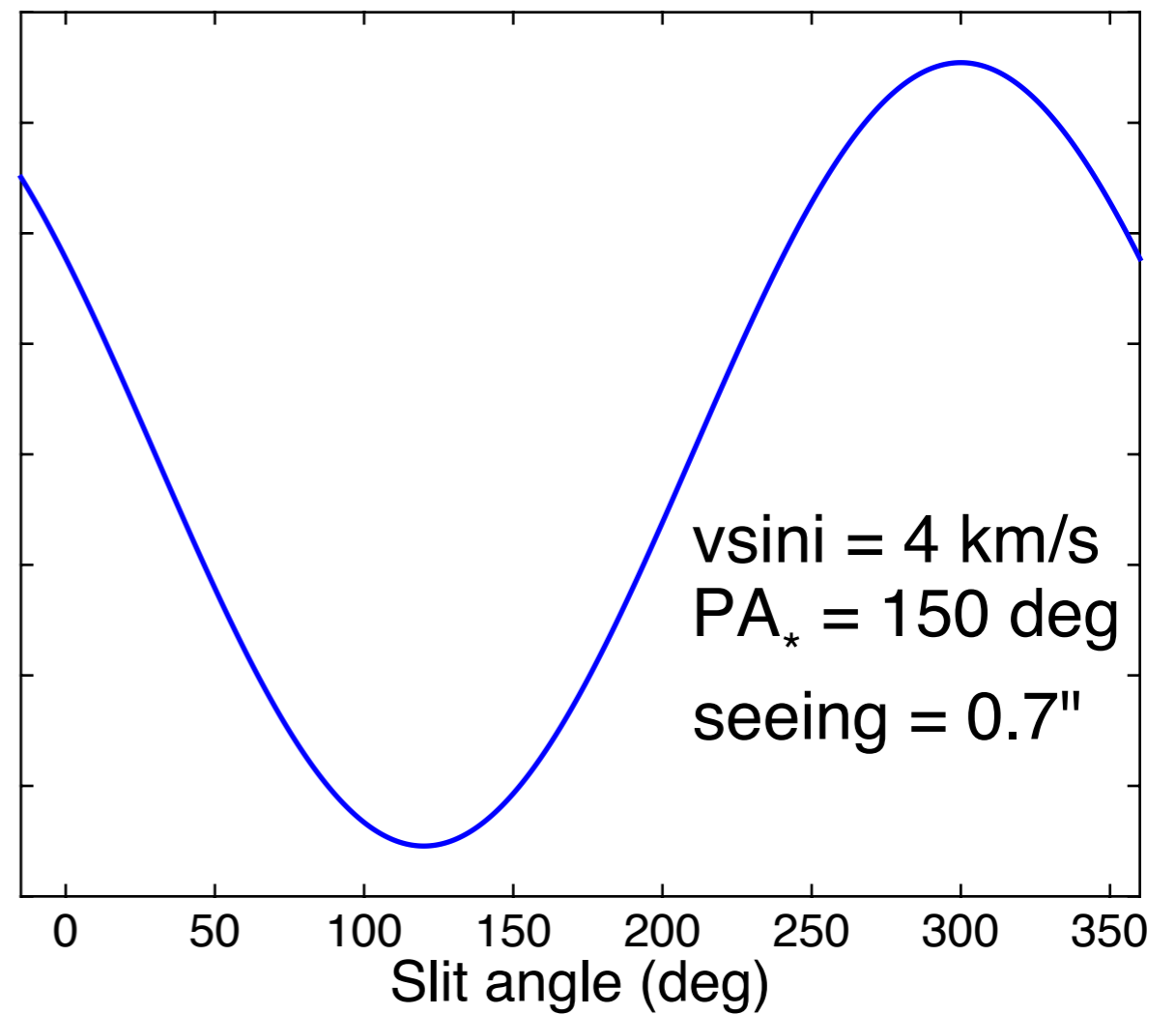
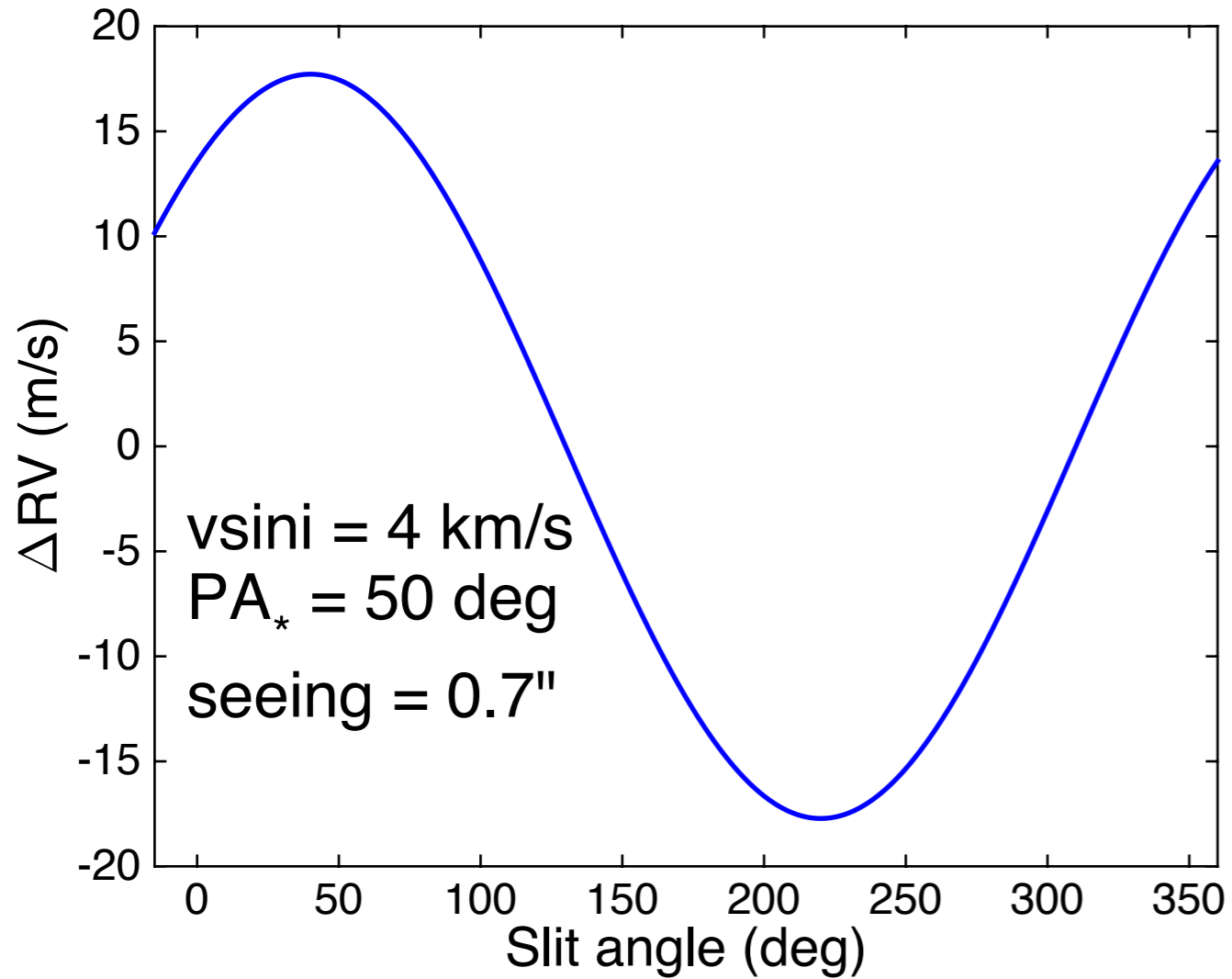
1. de-bend order



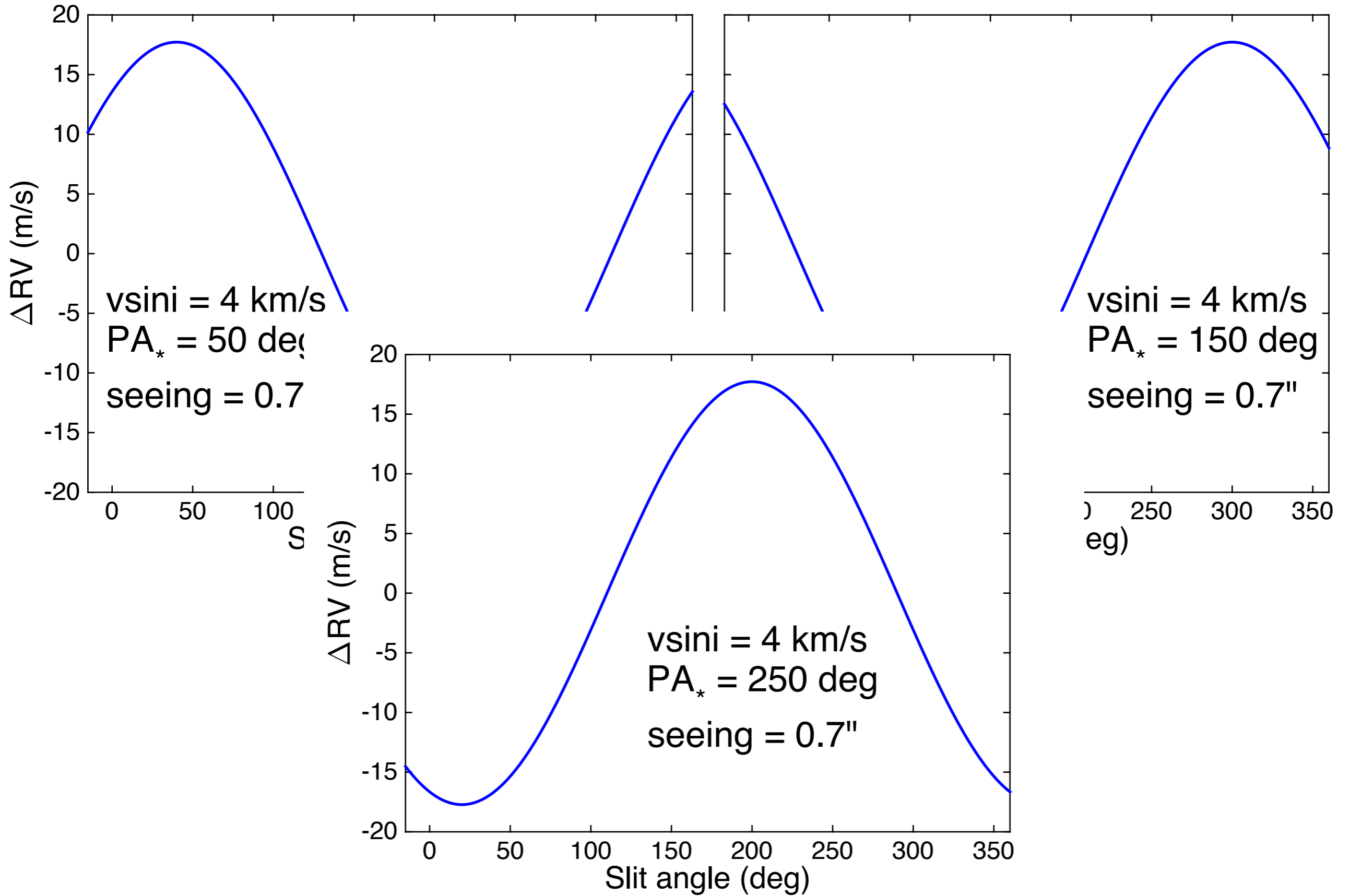
2. straighten lines



Predictions for this star

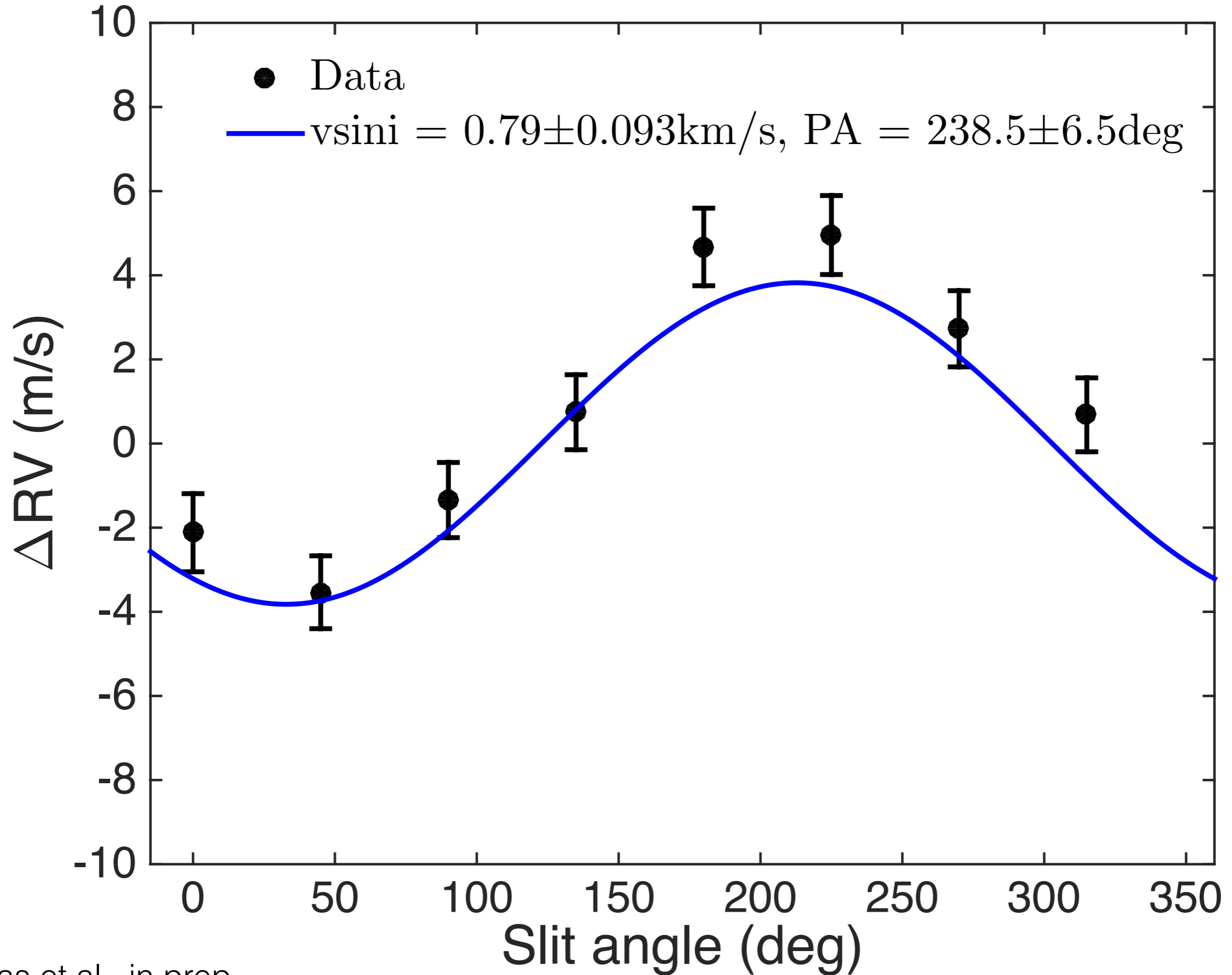


Predictions for this star

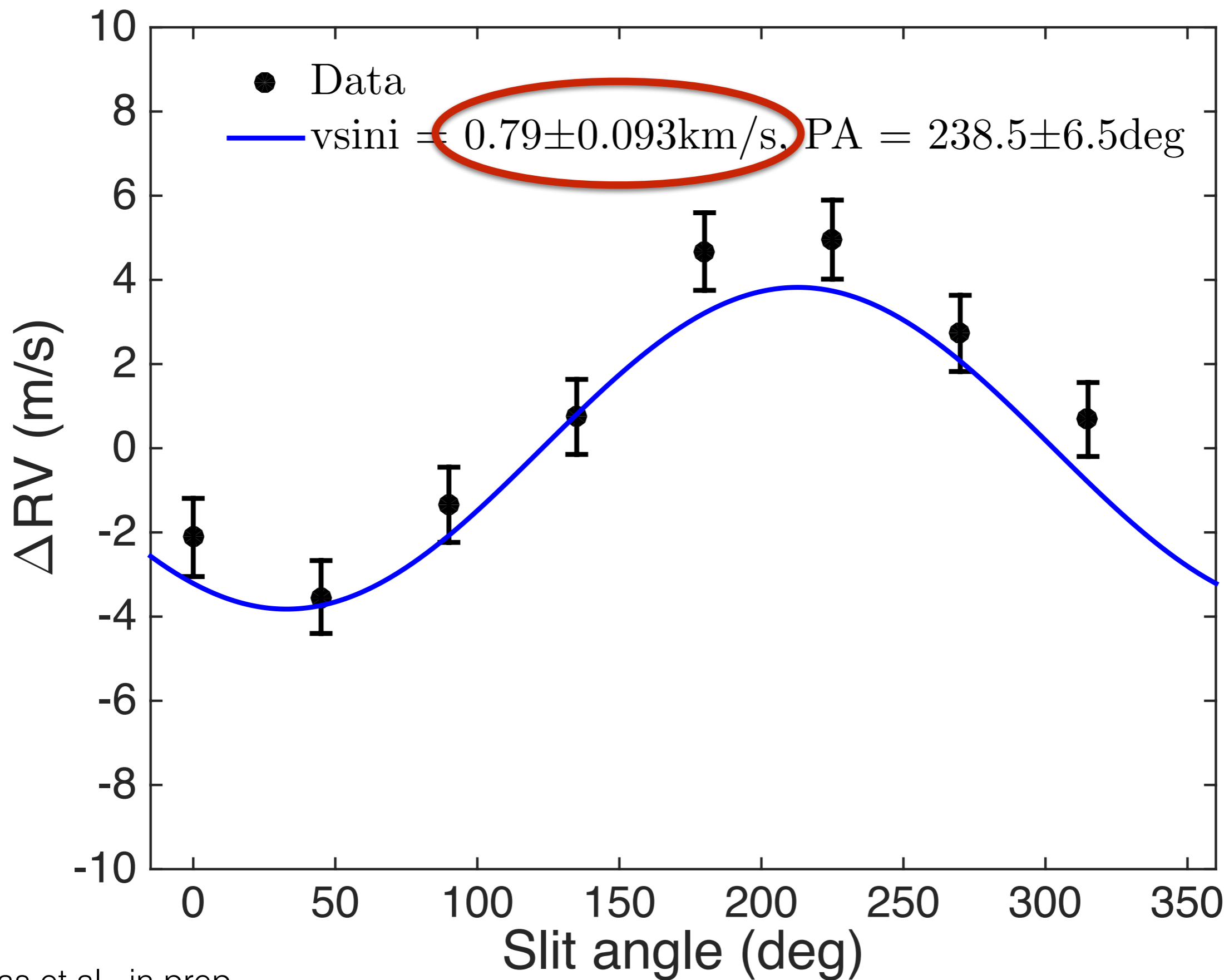


Results: the first direct measurement of v_{Sini}

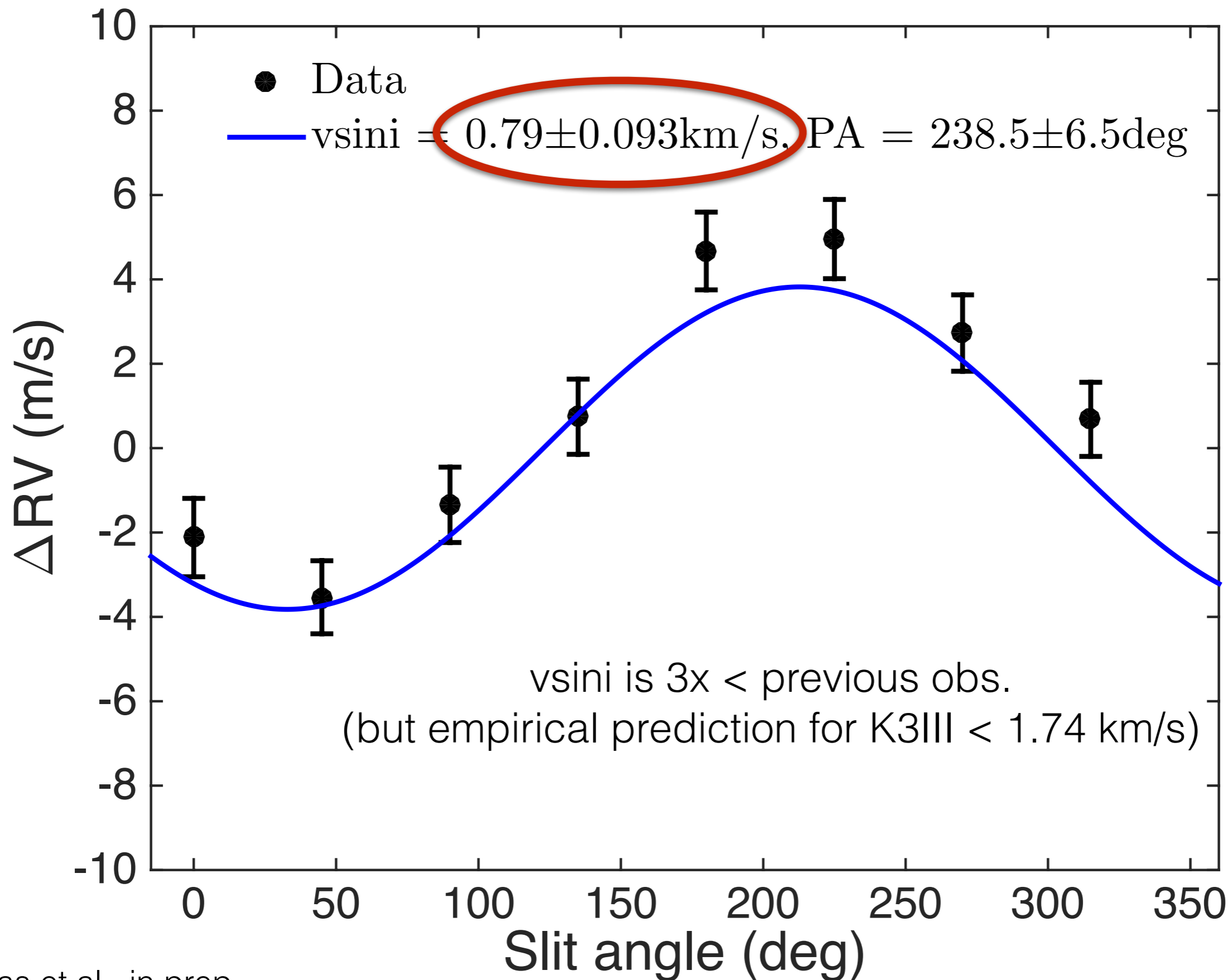
Results: the first direct measurement of $v \sin i$



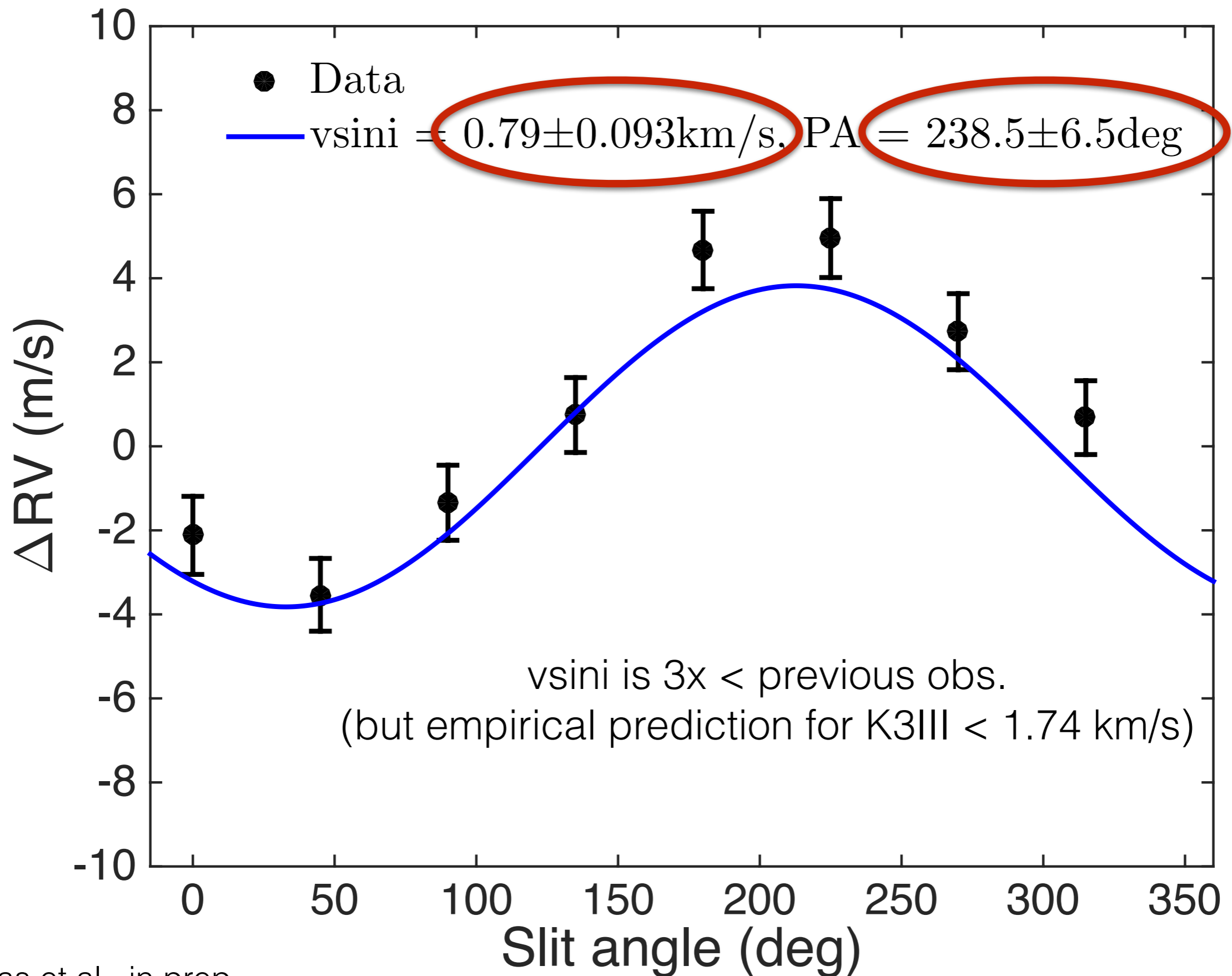
Results: the first direct measurement of $v \sin i$



Results: the first direct measurement of vsini

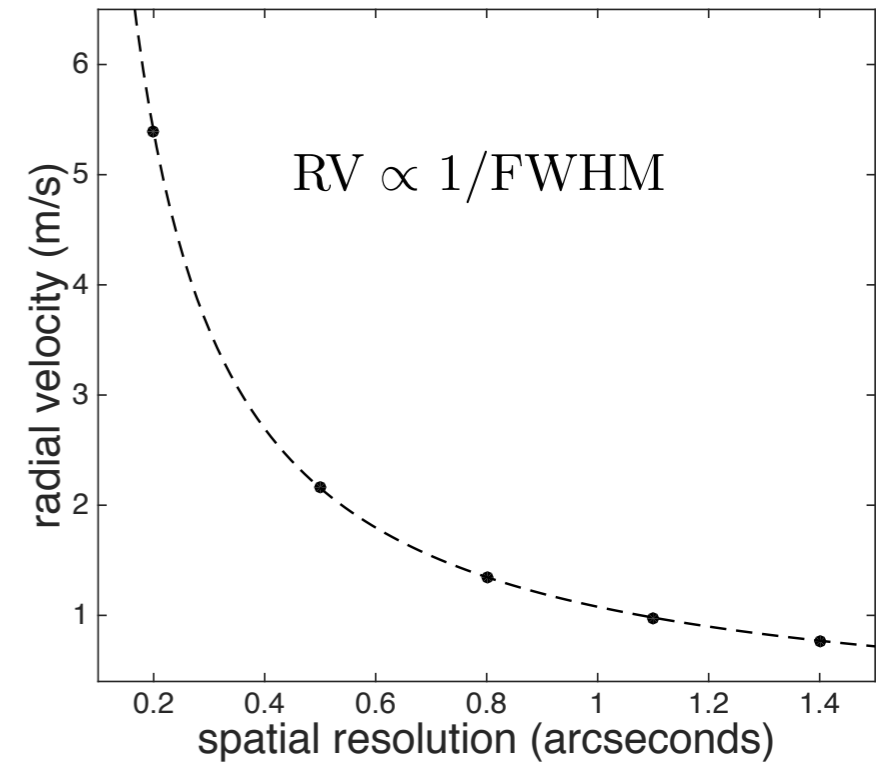


Results: the first direct measurement of vsini



My dream for LUVOIR...

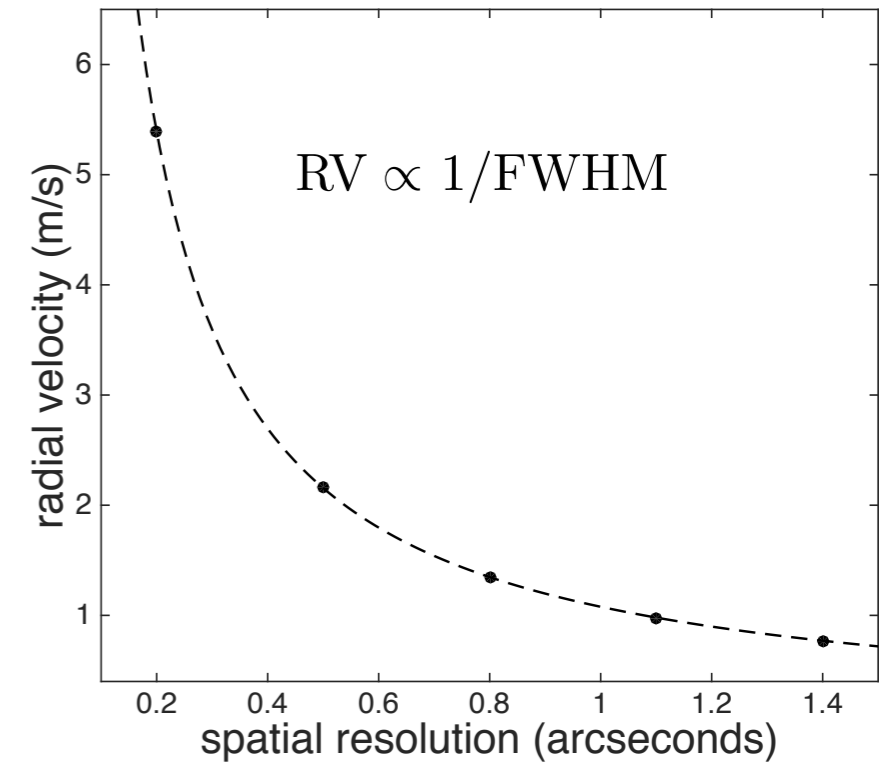
Because signal depends so strongly on resolution...



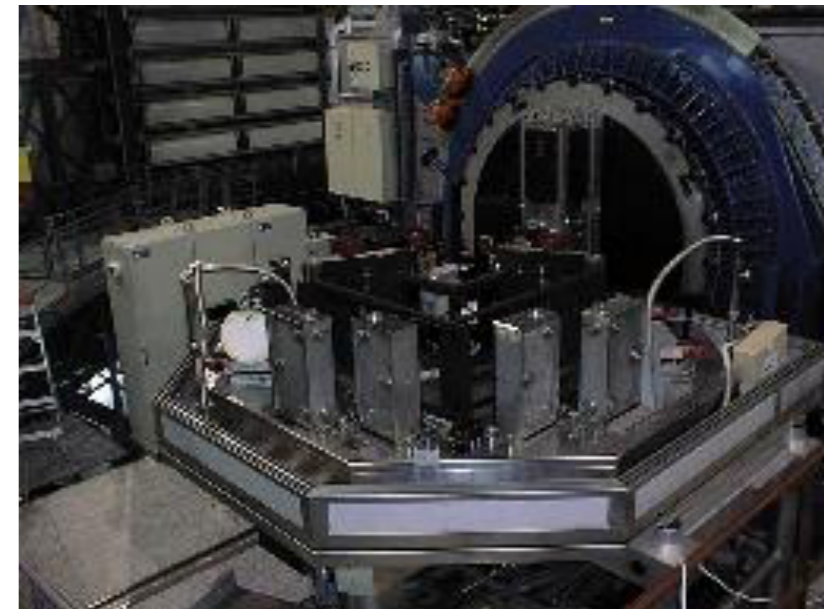
(c)

My dream for LUVOIR...

Because signal depends so strongly on resolution...

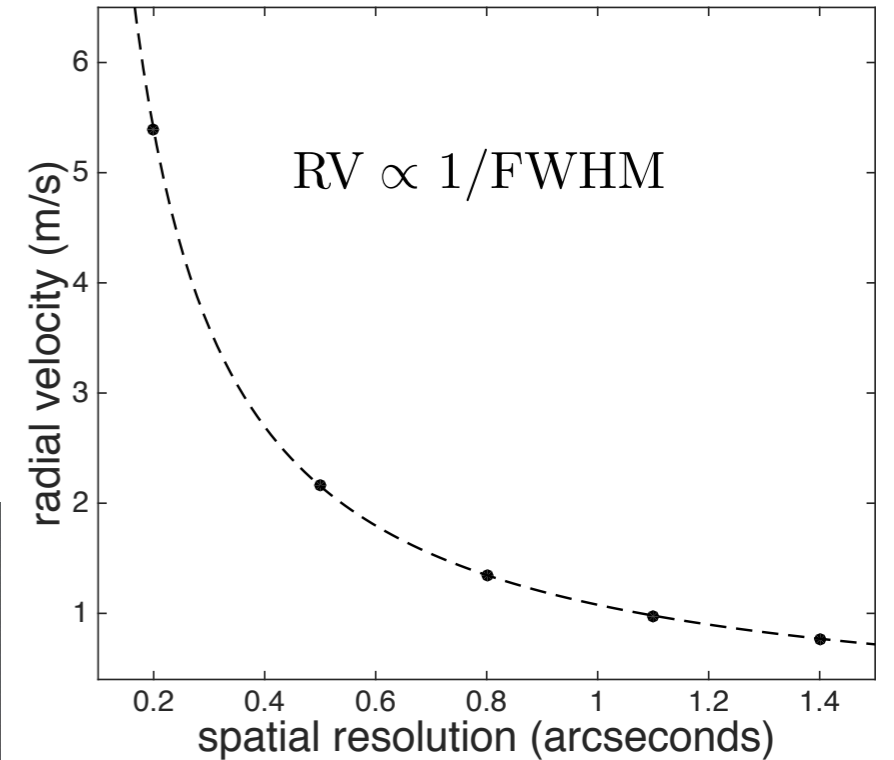


(c)

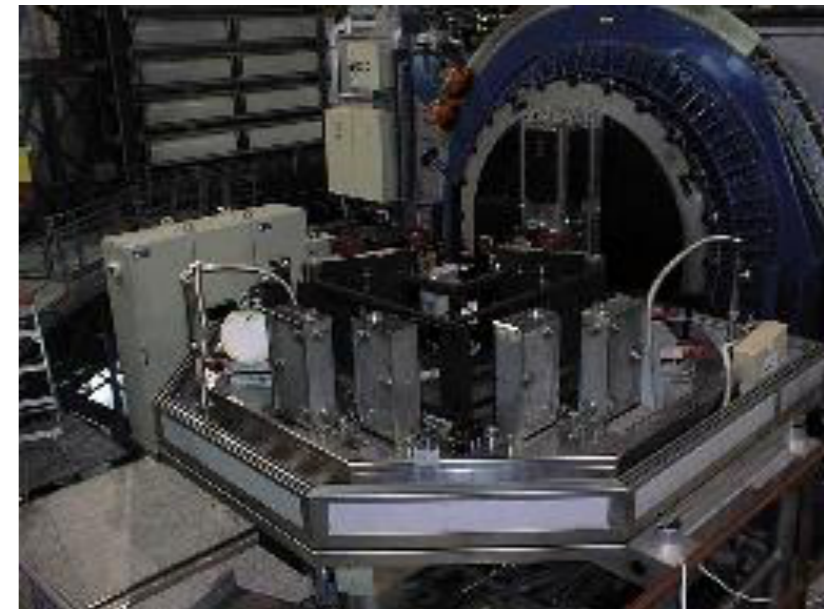


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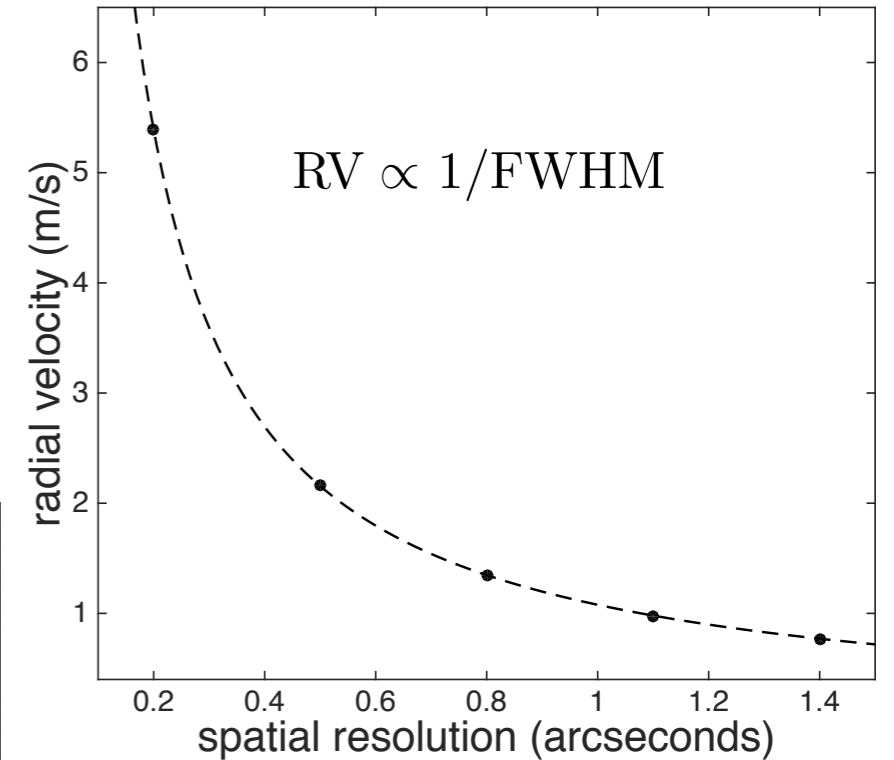


(c)

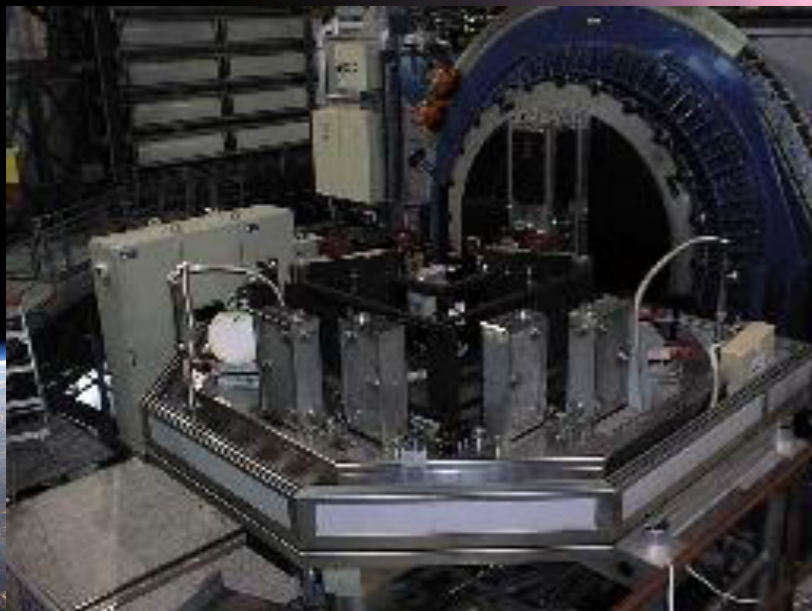


My dream for LUVOIR...

Because signal depends so strongly on resolution...



(c)



Summary

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Binaries can be used to **directly image planets** (Binary Differential Imaging)

-Space-based will be even better for this!

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Binaries can be used to **directly image planets** (Binary Differential Imaging)

- Space-based will be even better for this!

Binaries can be used to **infer properties of hidden planets** (MagAO Imaging of Long-period Objects [MILO])

- Imaging RV exoplanets is the future

Concept of spectroscopic binaries can be used to **directly measure stellar $v \sin i$**

- Signal depends strongly on spatial resolution → AO or space?