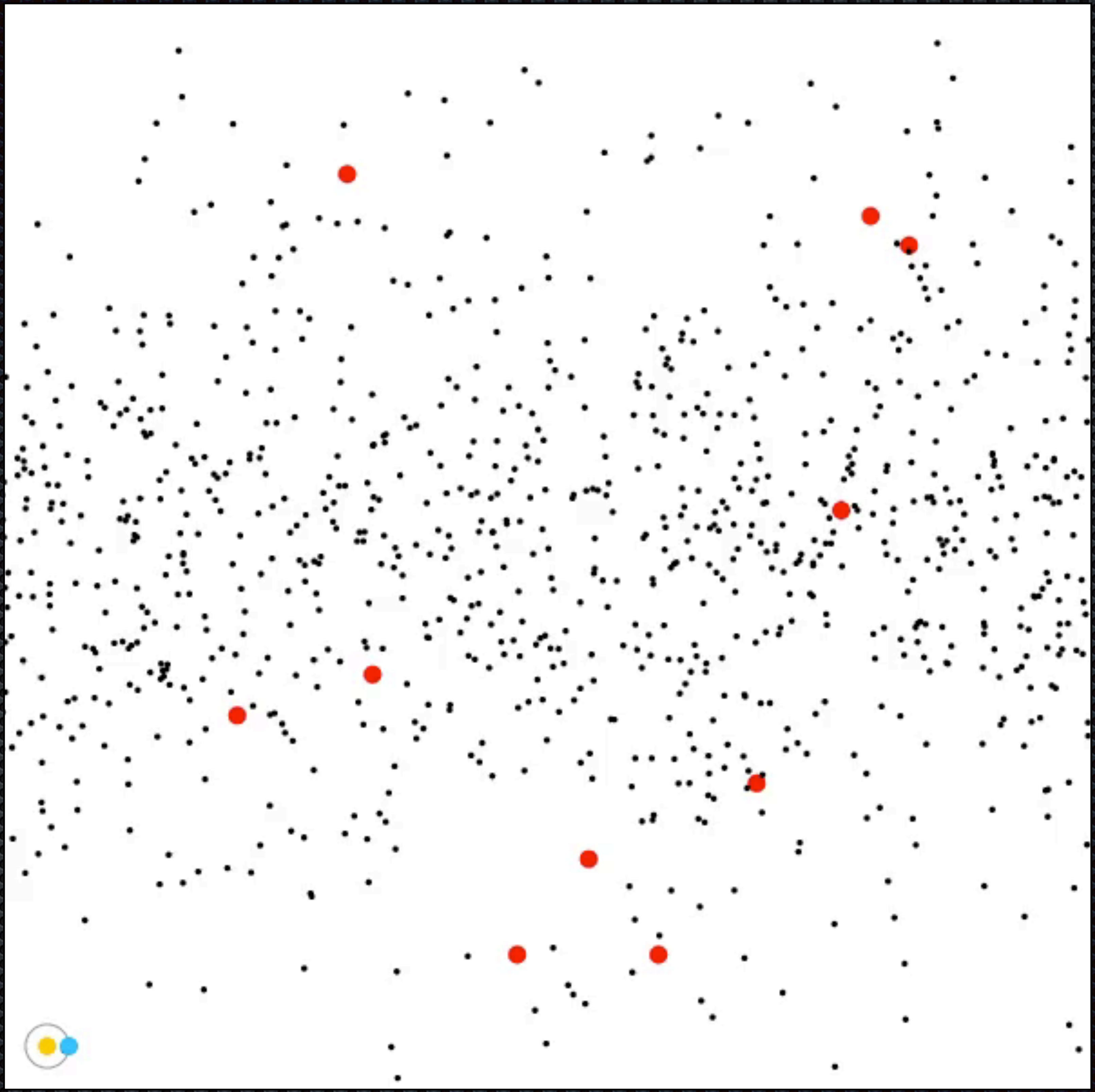
Cooler than *Gaia*: Parallaxes of Ultracool Objects with *WISE*

Christopher A. Theissen
UC San Diego
May 23, 2018

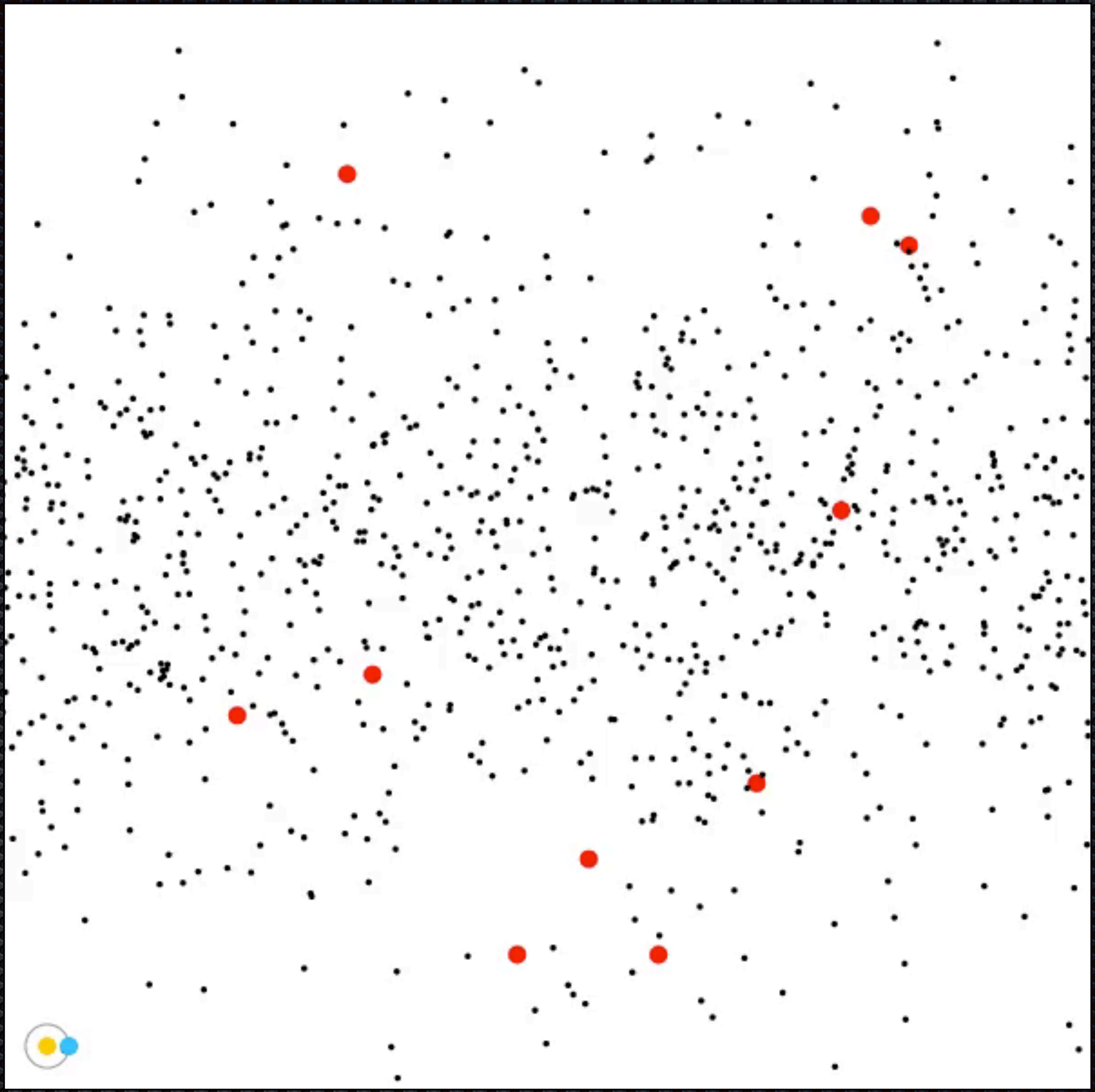
Cooler than *Gaia*: Parallaxes [redacted]cool C[redacted]*E*

Now with Gaia DR2!

[redacted]3, 2018

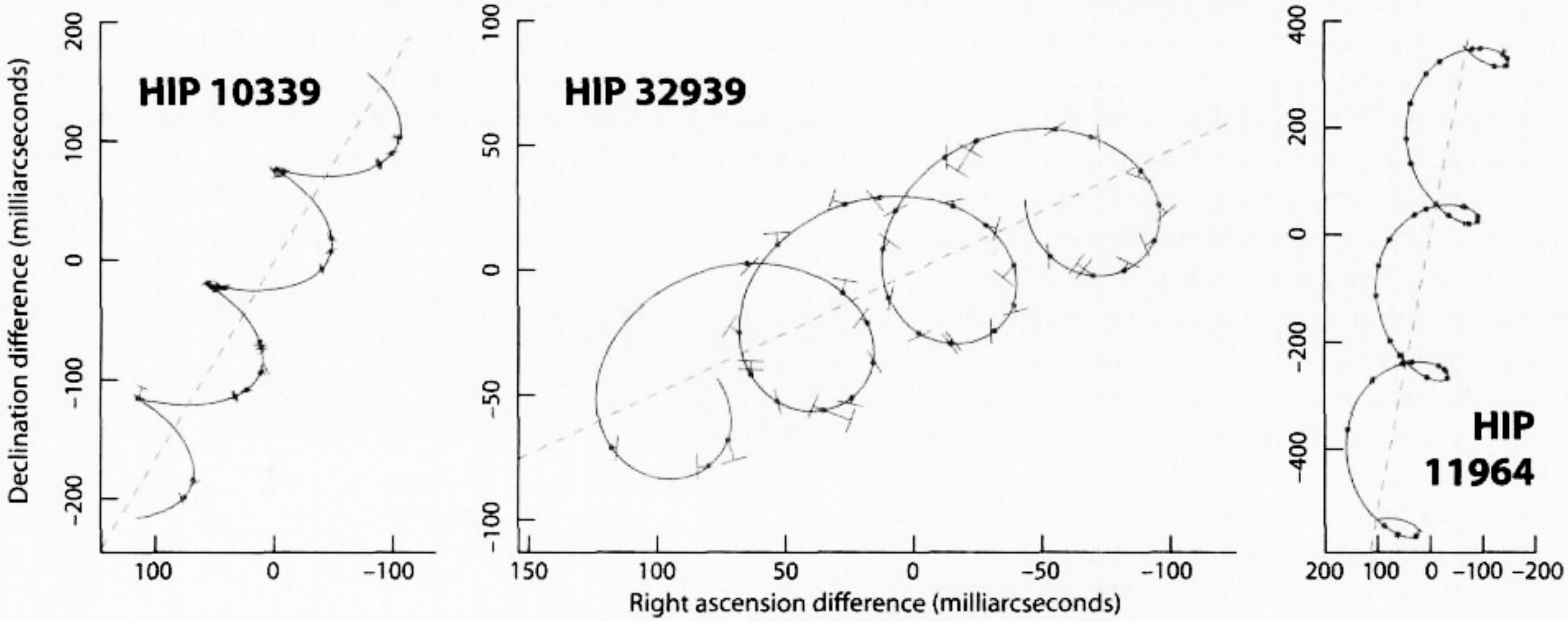


@jrdavenport



@jrdavenport

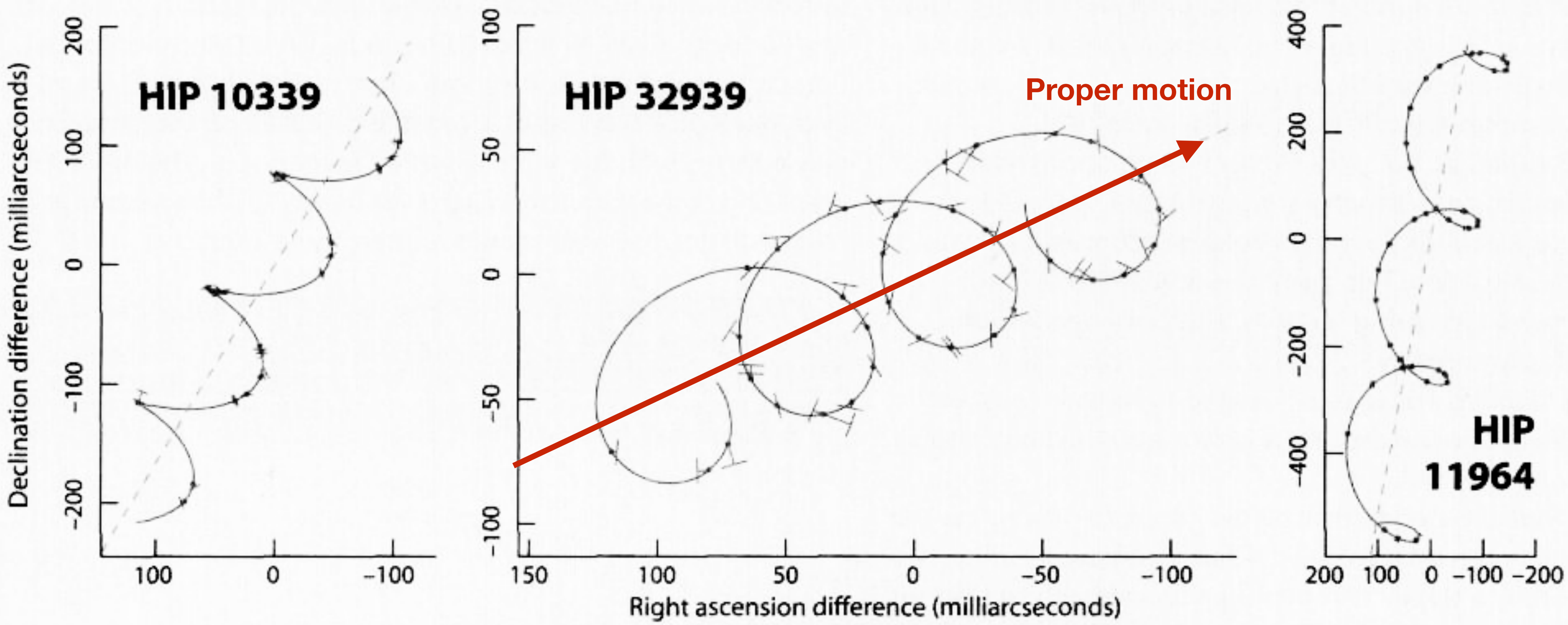
Parallaxes



The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star's measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.

ESA/Hipparcos

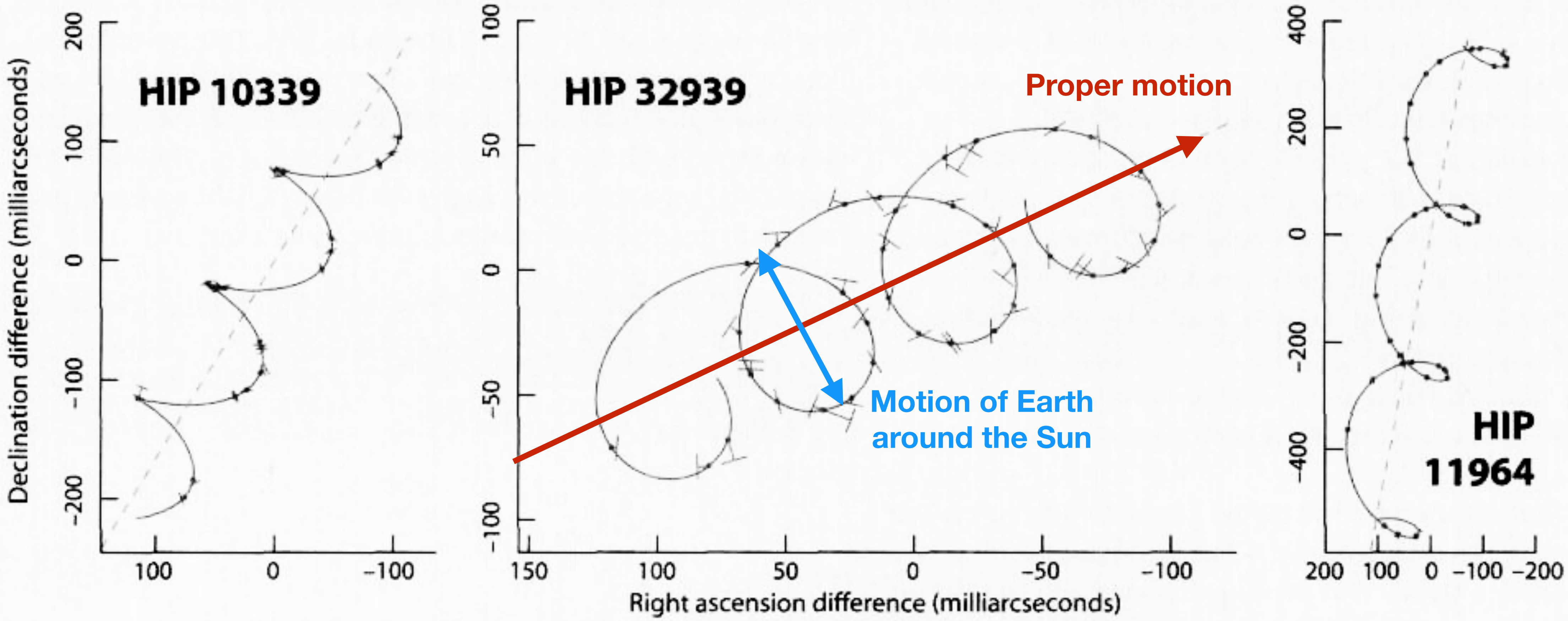
Parallaxes



The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star's measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.

ESA/Hipparcos

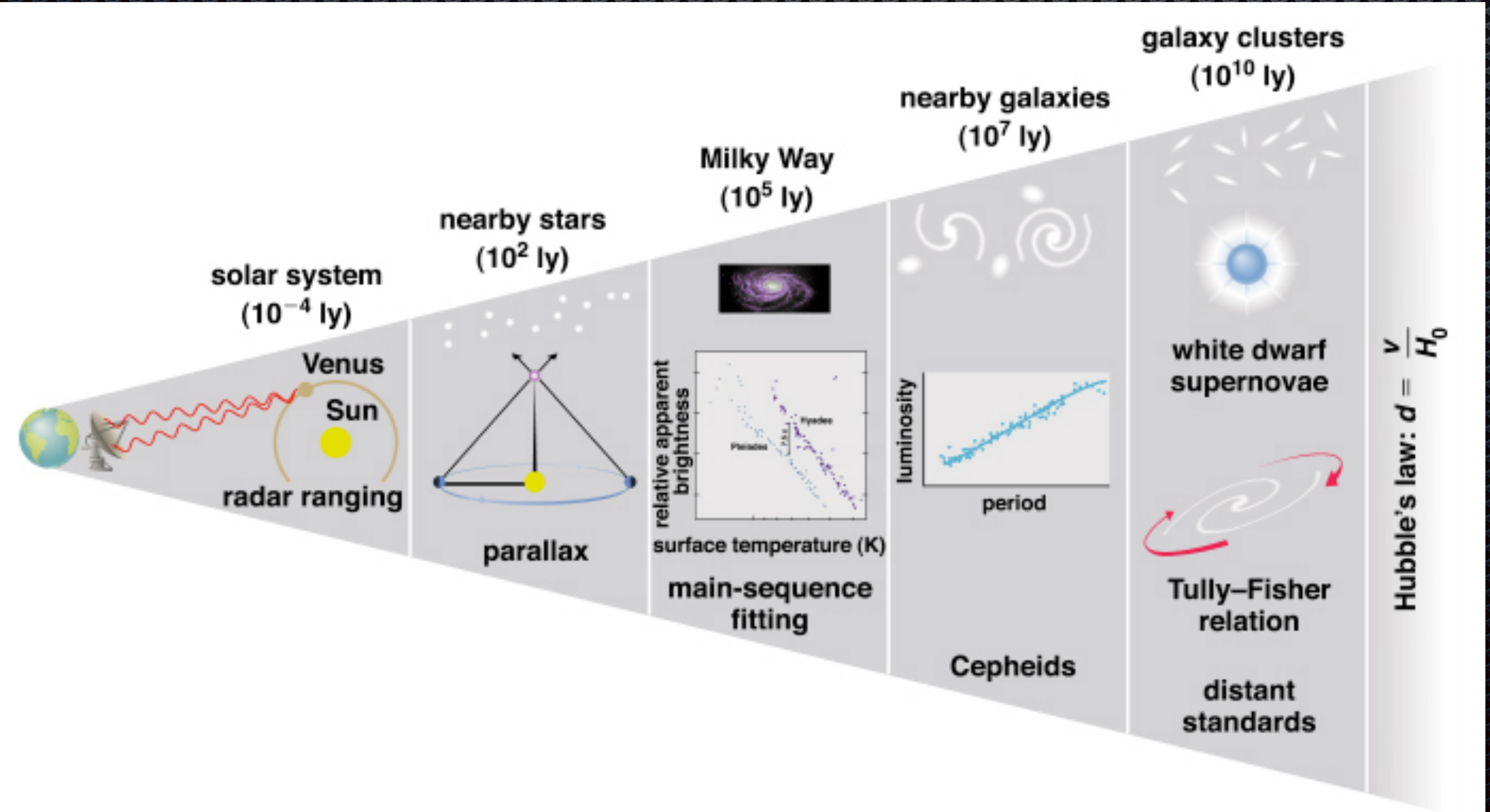
Parallaxes



The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star's measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.

ESA/Hipparcos

Parallaxes - Distance Ladder

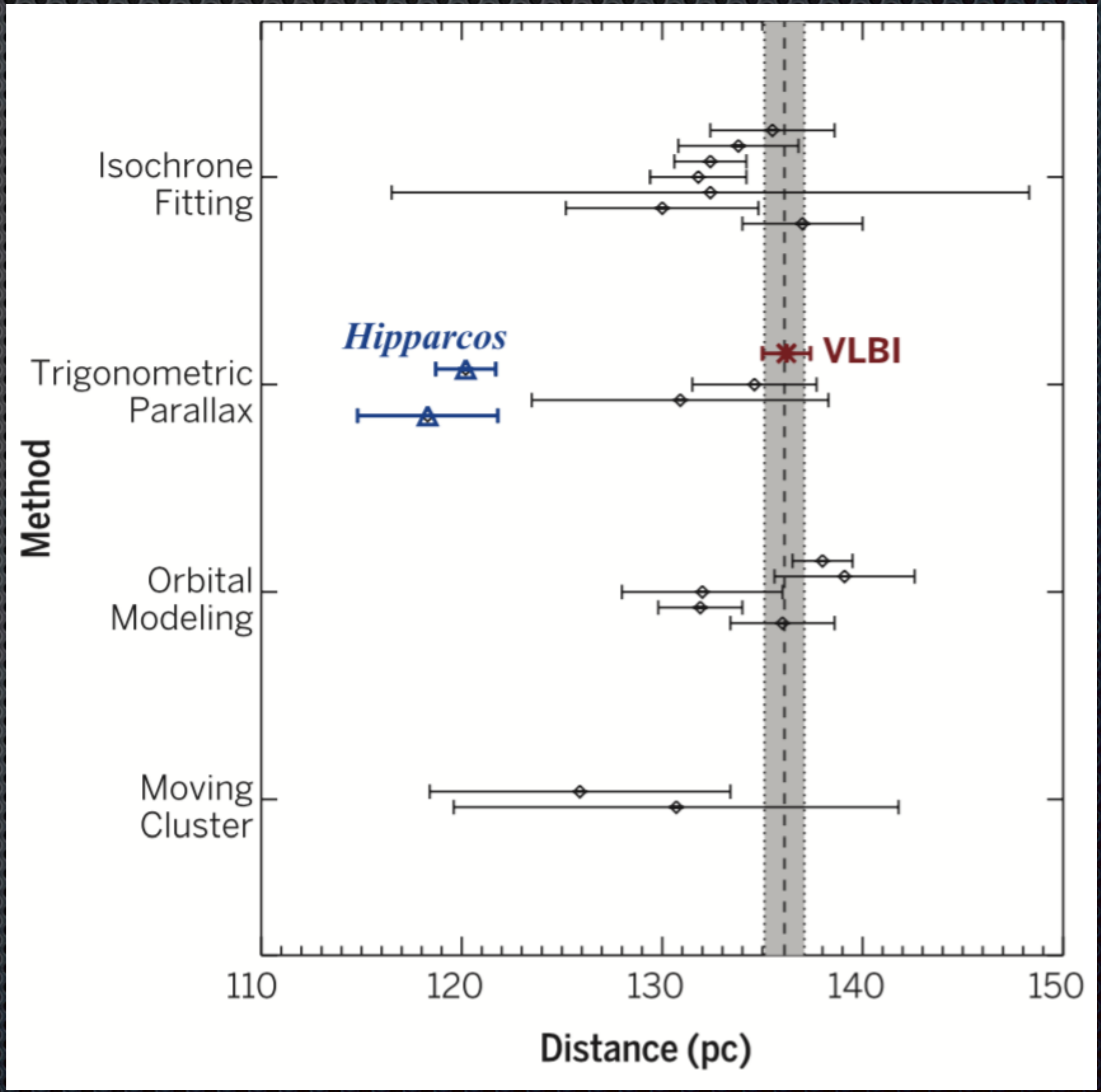


Copyright © Addison Wesley

Parallaxes - Distance Ladder

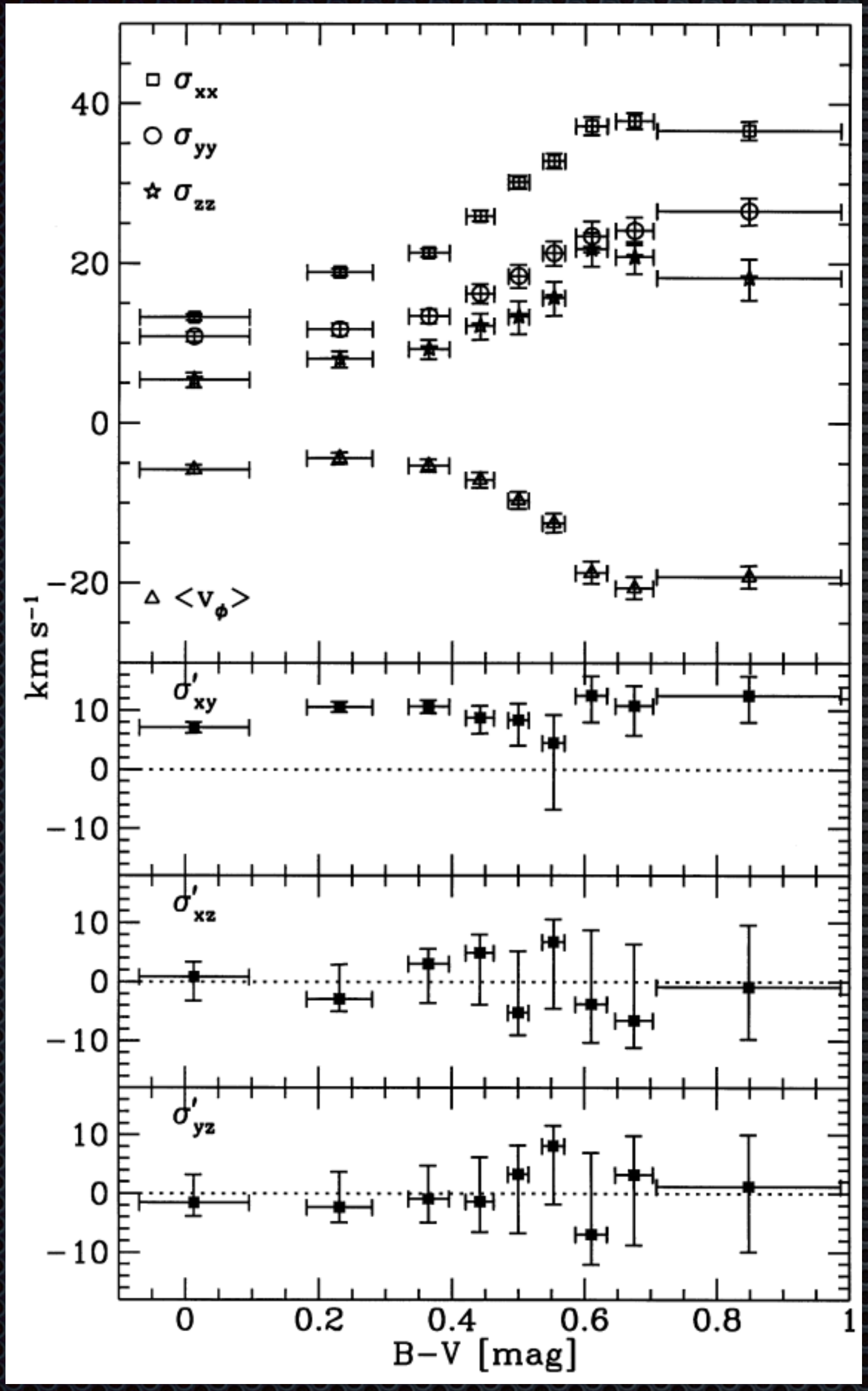
- Accurate distance to an important calibrator

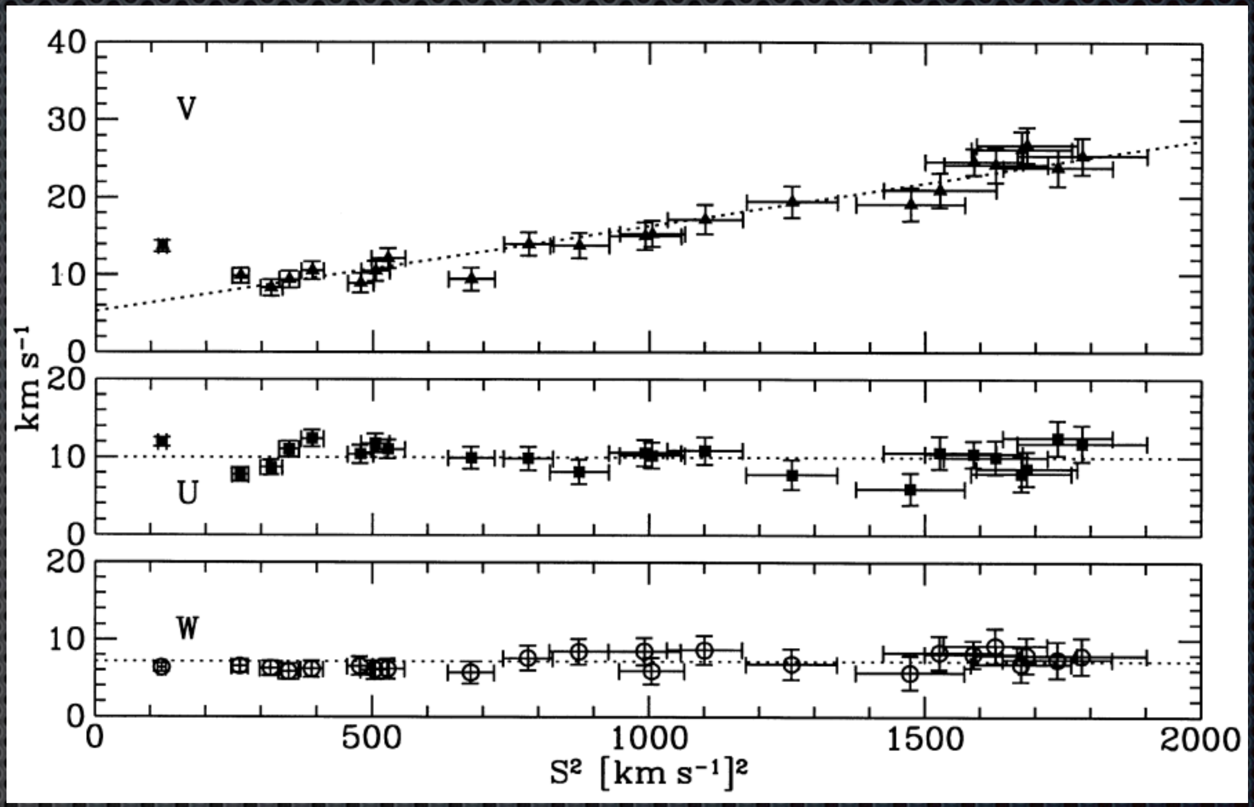
Pleiades

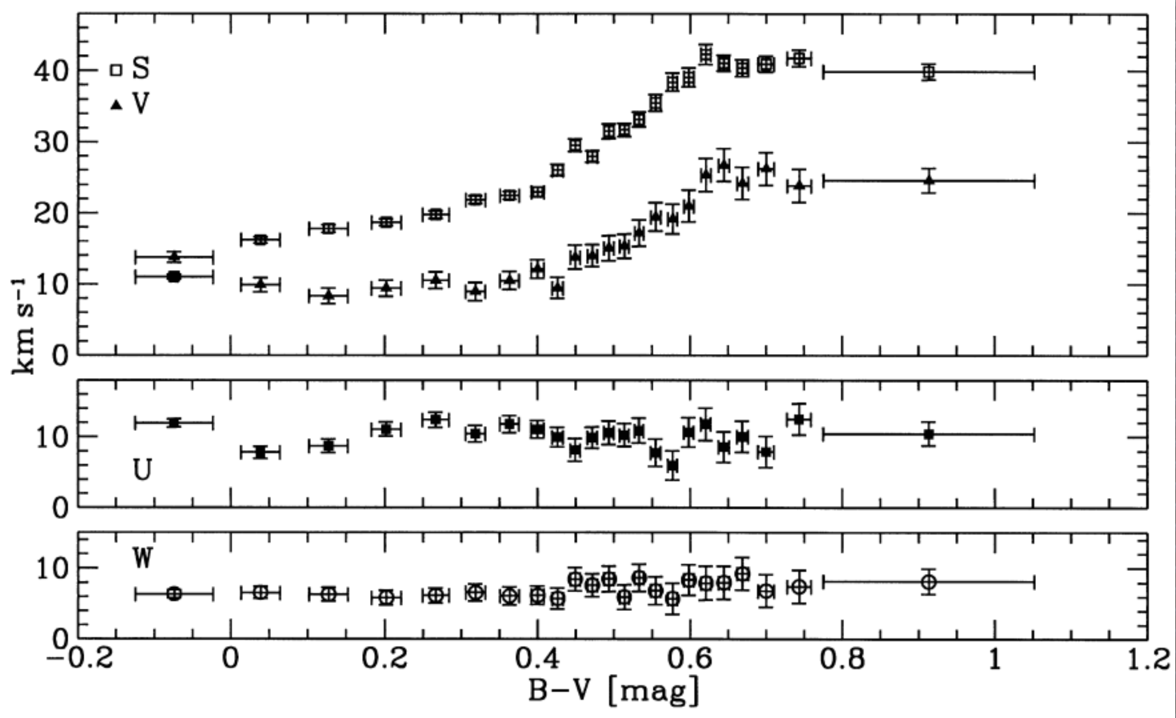


Melis et al. (2014)

Parallaxes - Local Stellar Kinematics



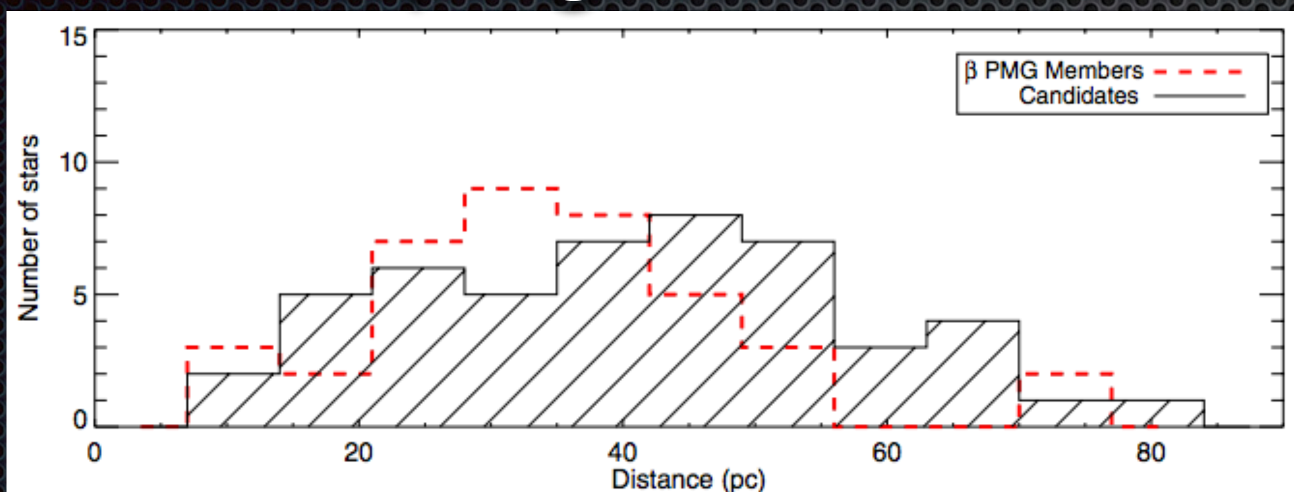


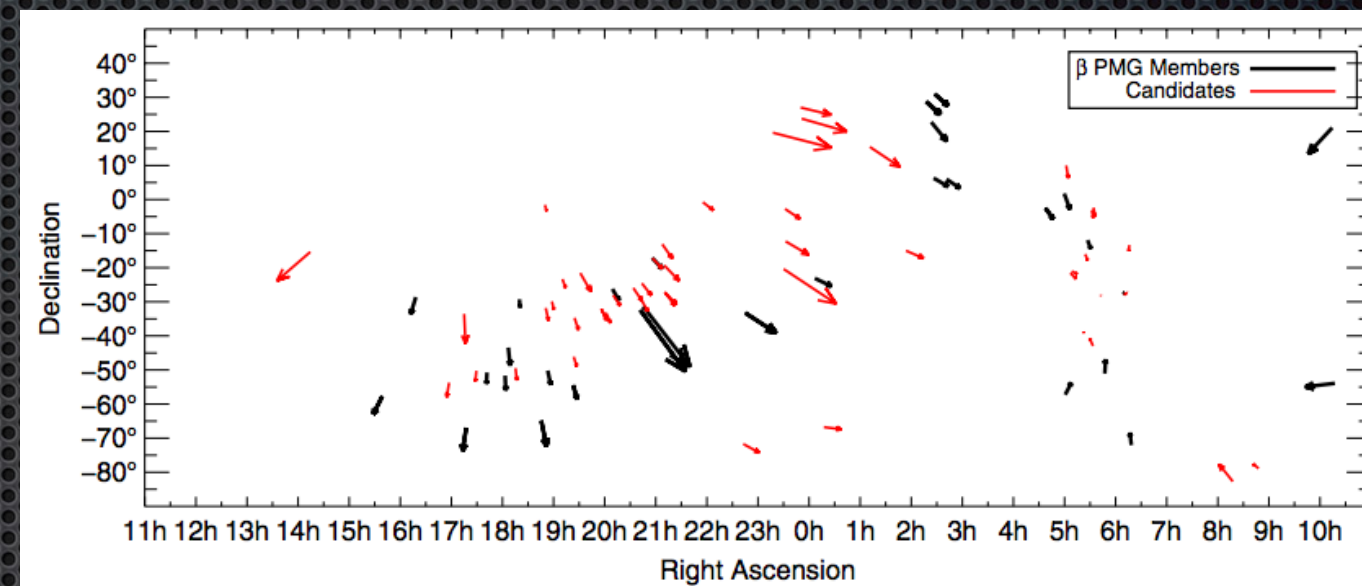


Dehnen & Binnen (1998)

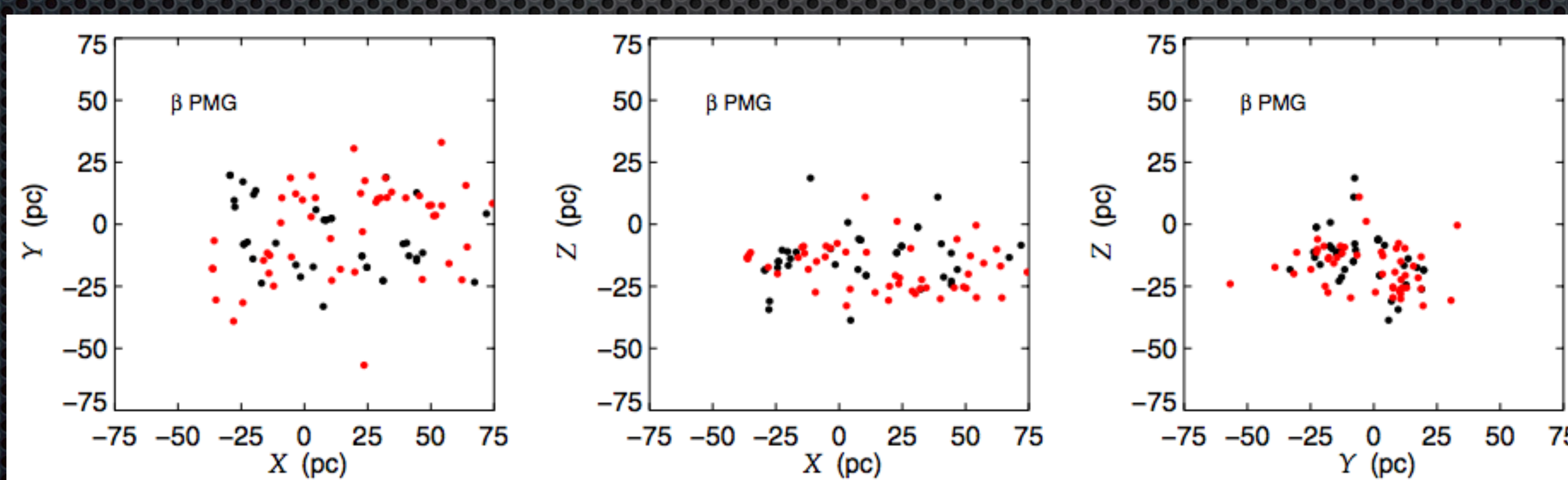
Parallaxes - Kinematic Associations

Grouping in distance





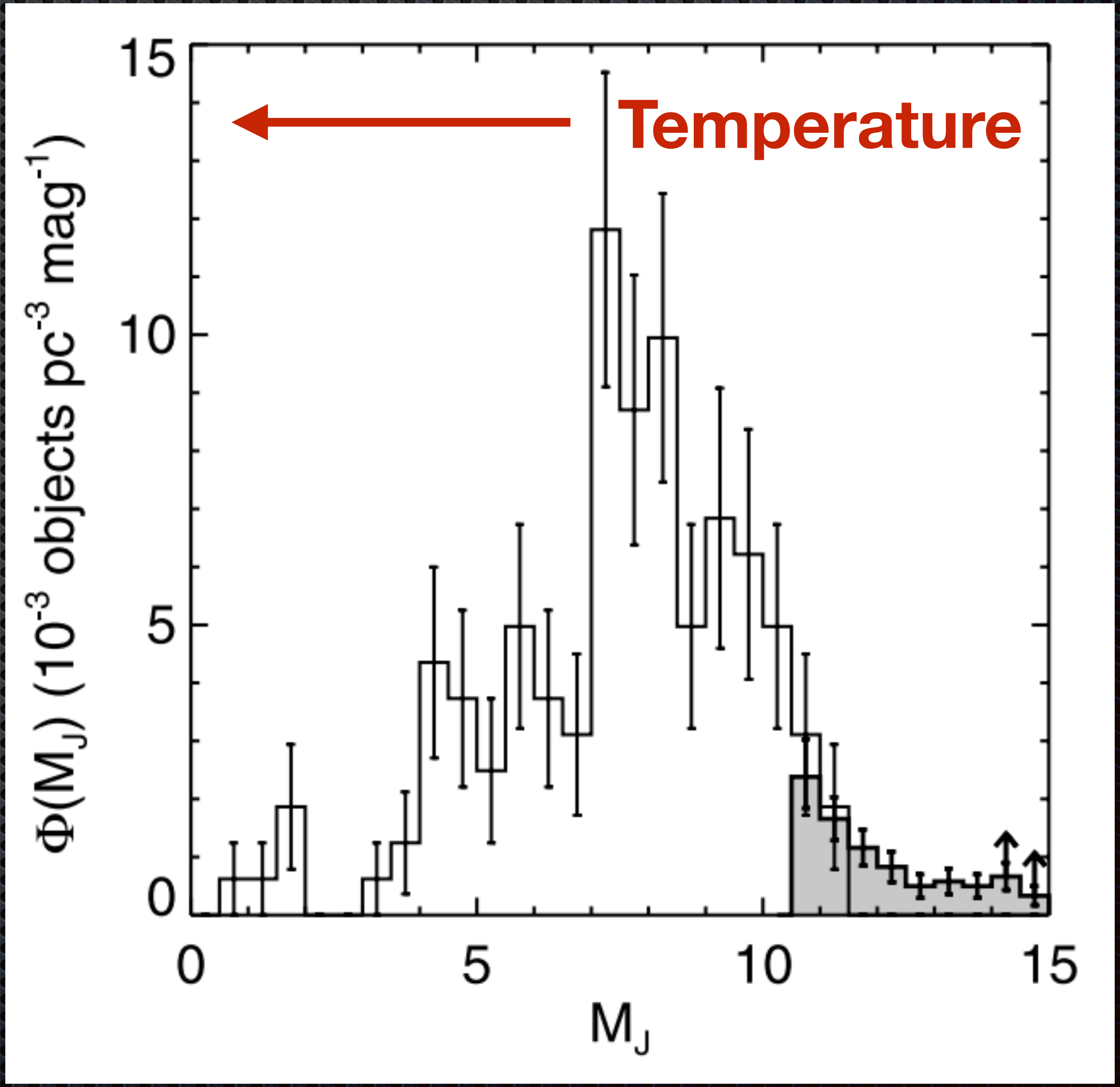
Convergent point kinematics



Grouping in 3D space

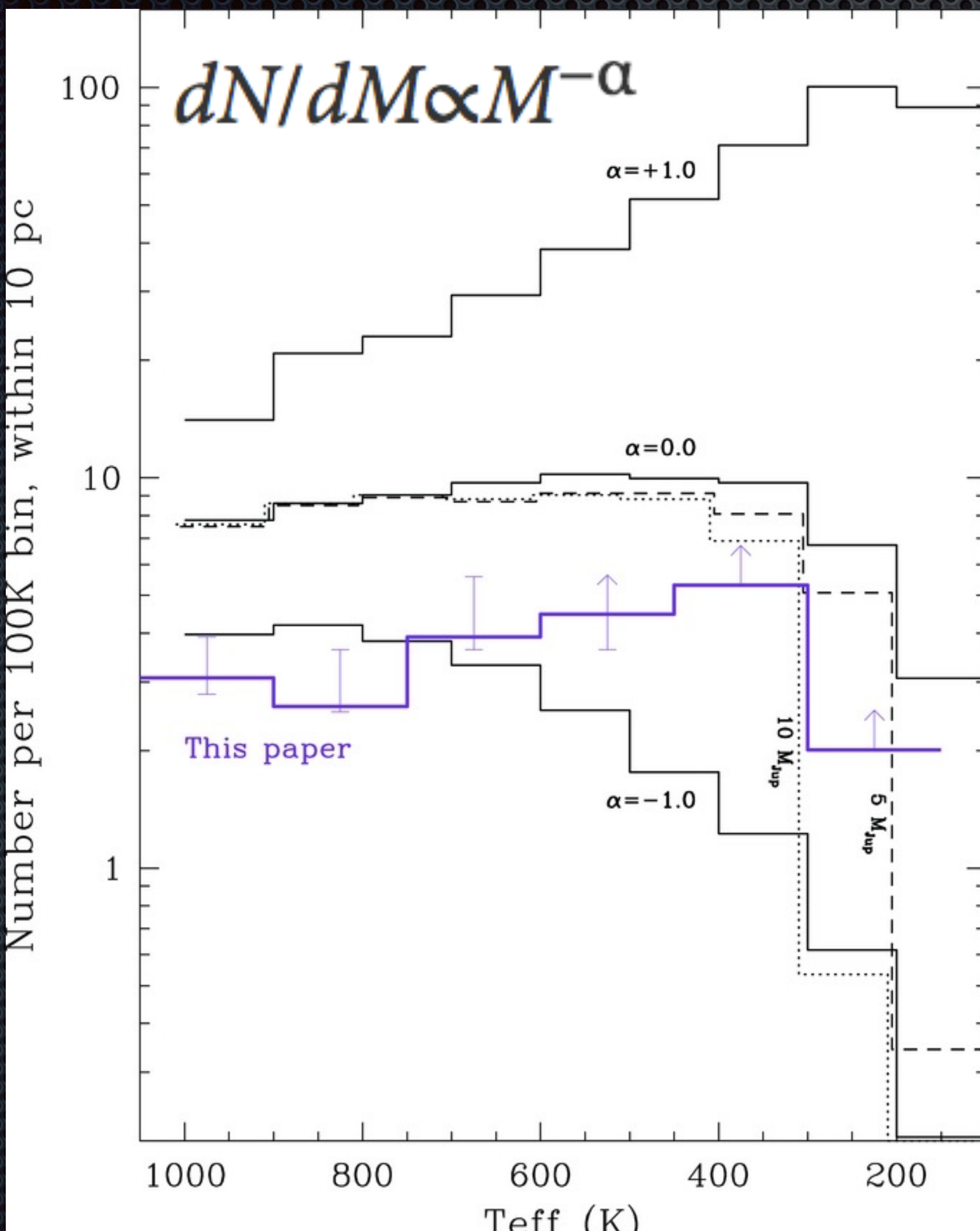
Malo et al. (2013)

Parallaxes - Luminosity/ Mass Function

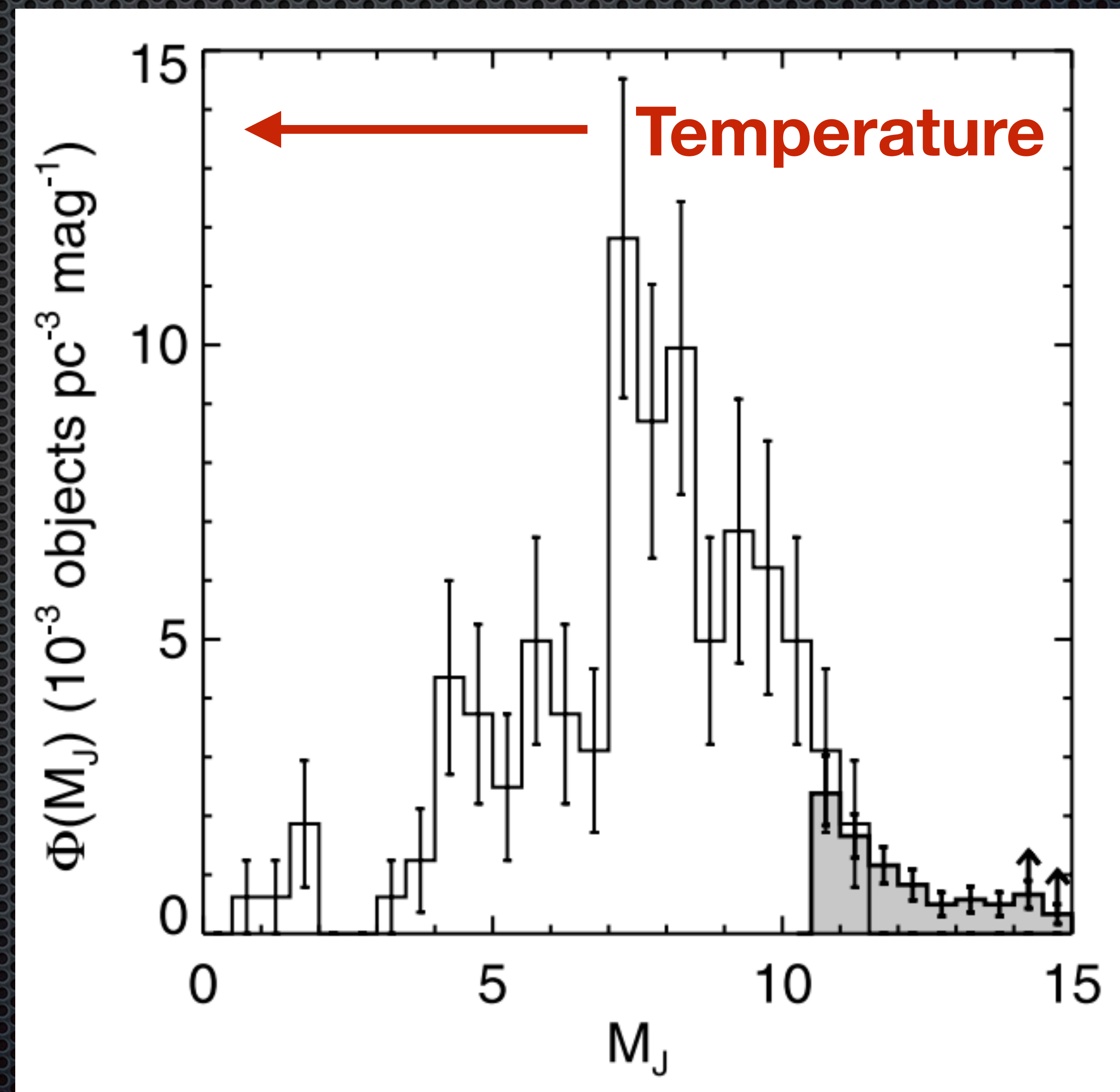


Cruz et al. (2007)

Parallaxes - Luminosity/ Mass Function

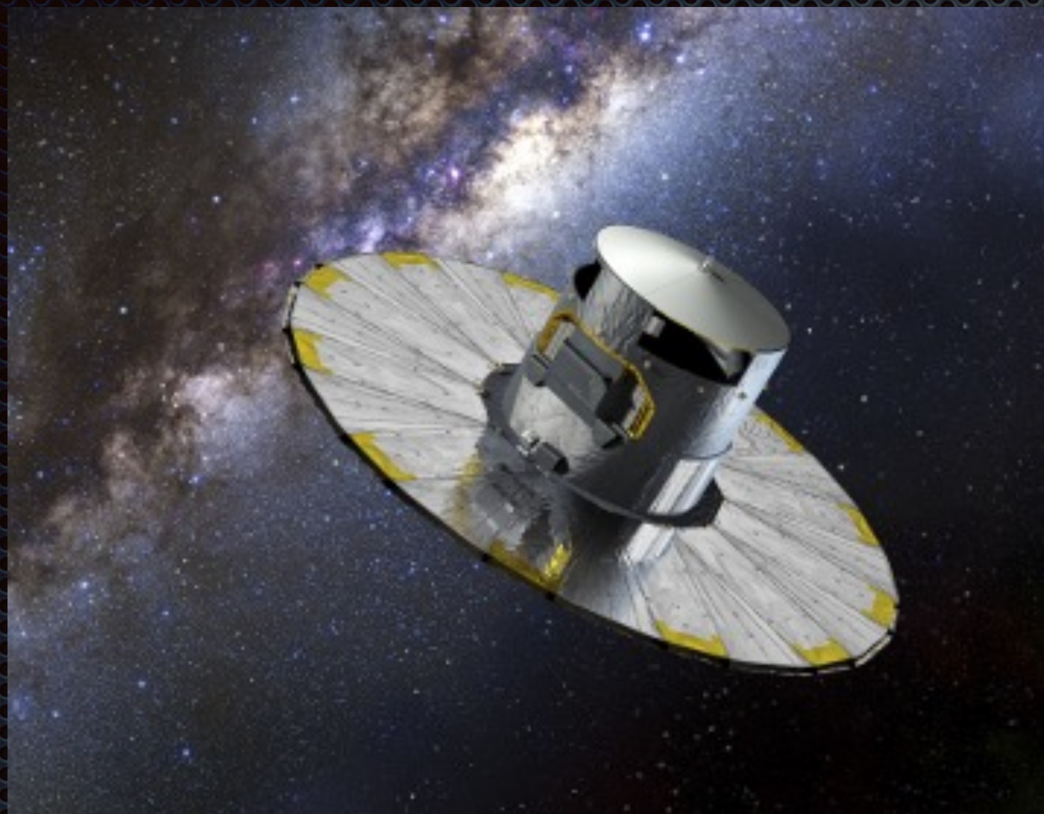


Kirkpatrick et al. (2012)



Cruz et al. (2007)

Gaia will save us all!



ESA/Gaia

Jackie Faherty @jfaherty · 23h

This is me waiting for the Gaia data release of over a billion parallaxes (distances to stars).... @ESAGaia **#GaiaDR2** #gaiaday

Adrian Price-Whelan @adrianprw · Mar 18

during a great Sunday phone chat with @davidwhogg, we noted that after >5 years of "preparing" for @ESAGaia DR2, we're not even emotionally prepared for the fact that we're still not prepared for DR2 -- omg April is going to be fun

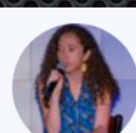
David W. Hogg @davidwhogg · Jan 25

This table is breaking my brain #GaiaSprint #GaiaDR2 cosmos.esa.int/web/gaia/dr2

	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**> 1,500,000,000**	**1,142,679,769**
Number of 5-parameter sources	> 1,300,000,000	2,057,050
Number of 2-parameter sources	> 200,000,000	1,140,622,719
Sources with mean G magnitude	> 1,500,000,000	1,142,679,769
Sources with three-band photometry (G, G_{BP}, G_{RP})	> 1,100,000,000	-
Sources with radial velocities	> 6,000,000	-
Lightcurves for variable sources	> 500,000	3,194
Known asteroids with epoch data	> 13,000	-
Additional astrophysical parameters:	> 150,000,000	-

David W. Hogg @davidwhogg · Mar 23

I am so zen about @ESAGaia #GaiaMission **#GaiaDR2** on April 25. We have a lifetime to figure it out!



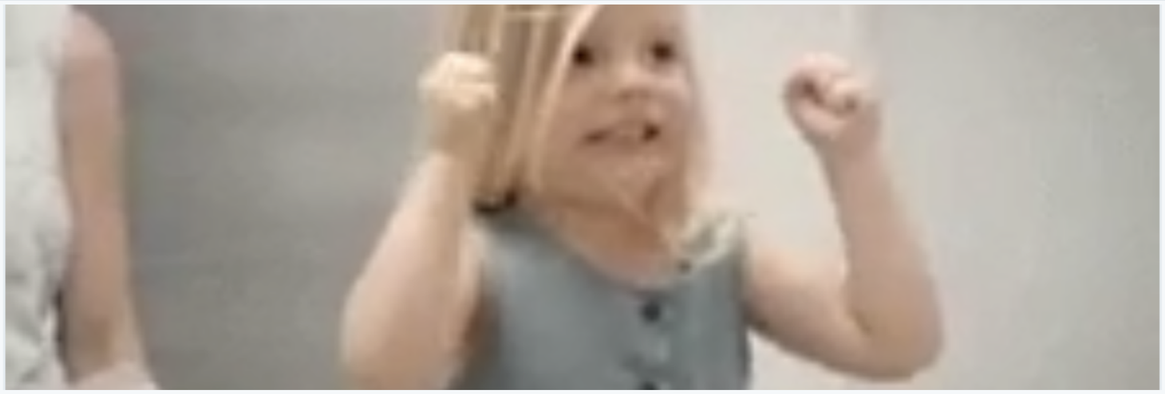
Jackie Faherty @jfaherty · Apr 4

It is exactly three weeks until everything we know about the Milky Way will change and all we understand about stars will be updated. Are you ready for Gaia???? **#GaiaDR2** @ESAGaia #gaiaday

Gaia will save us all!

David W. Hogg @davidwhogg · 12h
I'm going to want way more booze to CELEBRATE this week! #GaiaDR2

Jackie Faherty @jfaherty · Apr 18
Is the time of the Gaia DR2 data drop public yet????? Inquiring minds want to know! #waitingforGaia @ESAGaia

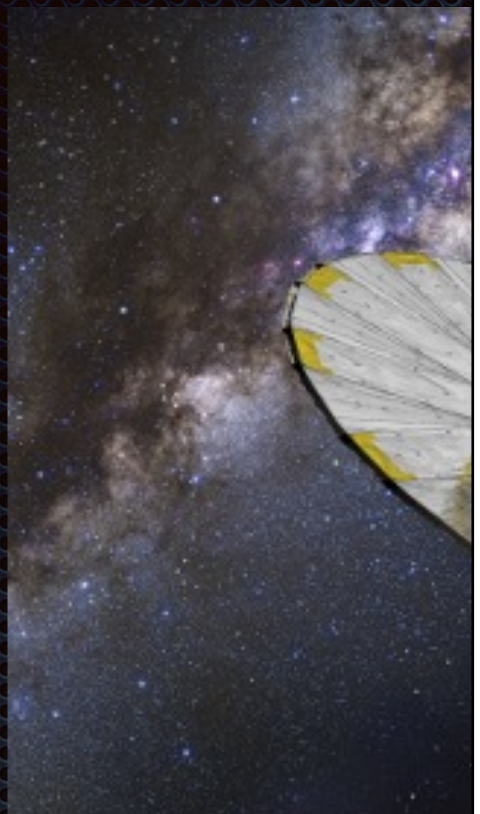


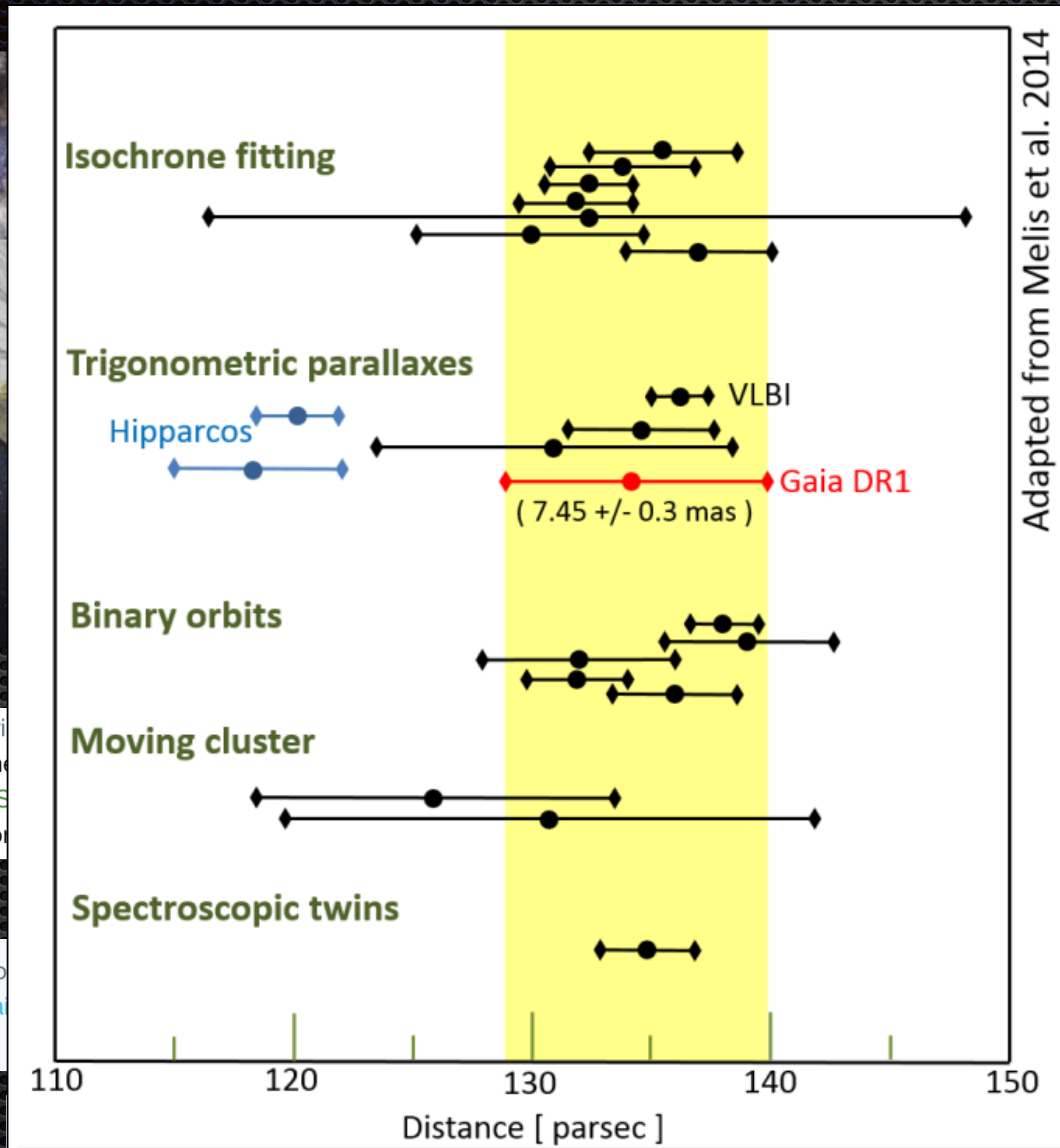
Jackie Faherty @jfaherty · 34m
People of twitter, there are two days left until all of stellar astrophysics, galactic kinematics and all things in between gets turned on its head by @ESAGaia #WaitingForGaia #yearofthemilkyway Get excited!!!!!!

David W. Hogg @davidwhogg · Mar 23
I am so zen about @ESAGaia #GaiaMission #GaiaDR2 on April 2
lifetime to figure it out!

Jackie Faherty @jfahe
It is exactly three week
change and all we unde
Gaia???? #GaiaDR2 @ESAGaia #gaiaday

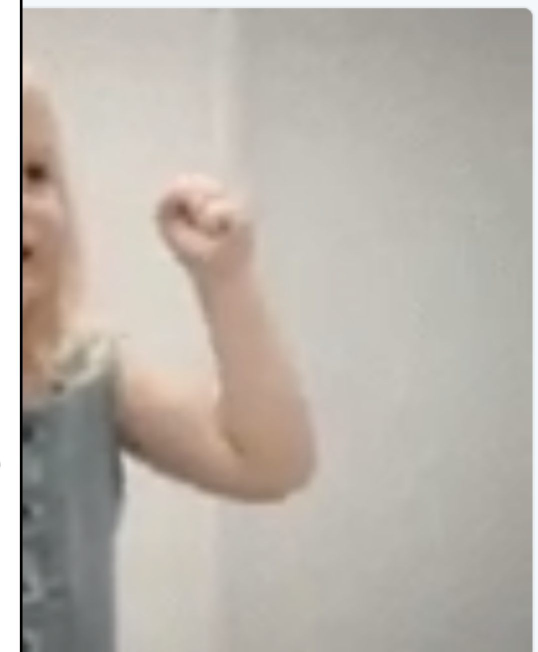
Gaia will save us all!





Gaia Collaboration (2016)

f over a billion parallaxes (distances

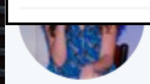


Adrian Price-Whelan @adri
during a great Sunday phon
years of "preparing" for @ES
the fact that we're still not p

David W. Hogg @davidwho
I am so zen about @ESAGa
lifetime to figure it out!

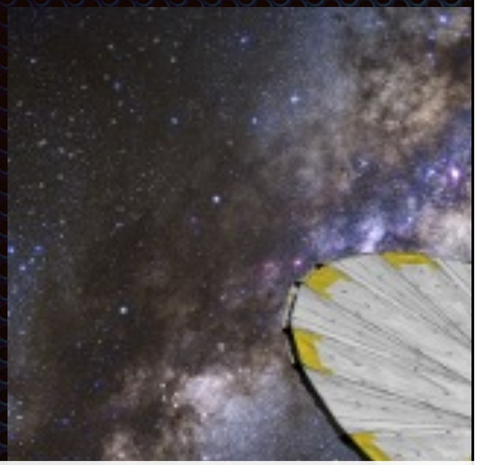
25
Sprint #GaiaDR2

# sources in Gaia DR2	# sources in Gaia DR1
> 1,500,000,000	**1,142,679,769**
> 1,300,000,000	2,057,050
> 200,000,000	1,140,622,719
> 1,500,000,000	1,142,679,769
> 1,100,000,000	-
> 6,000,000	-
> 500,000	3,194
> 13,000	-
> 150,000,000	-

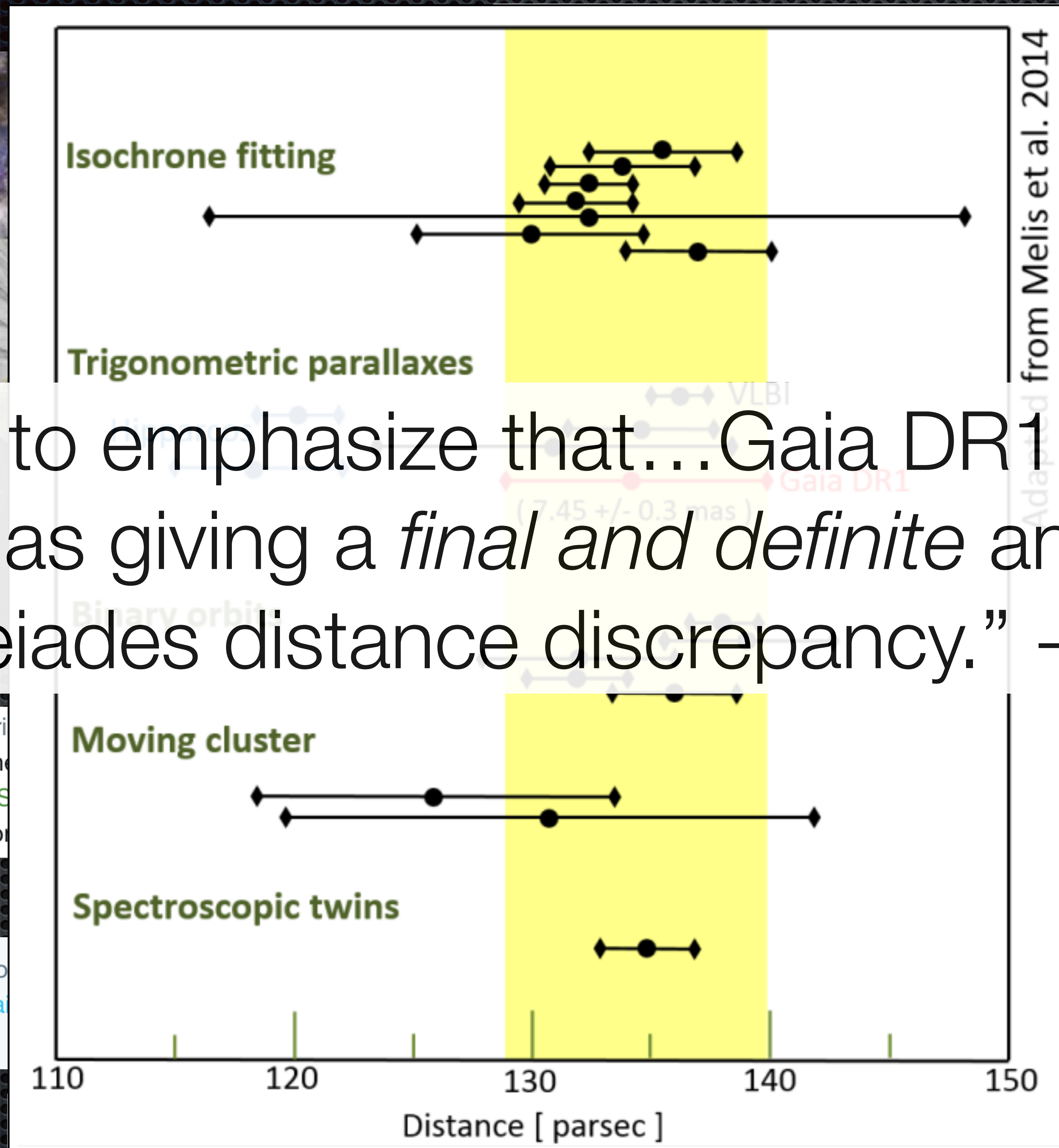


It is exactly three weeks until everything w
change and all we understand about stars
Gaia???? #GaiaDR2 @ESAGaia #gaiaday

Gaia will save us all!



f over a billion parallaxes (distances



“We want to emphasize that…Gaia DR1 cannot be considered as giving a *final and definite* answer on the so-called Pleiades distance discrepancy.” - Gaia Collab.

Gaia Collaboration (2016)

Adrian Price-Whelan @adri
during a great Sunday phon
years of "preparing" for @ES
the fact that we're still not p

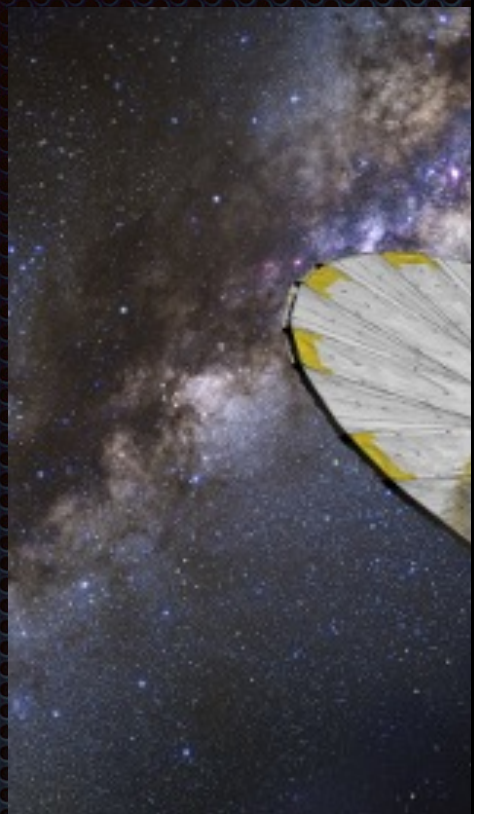
David W. Hogg @davidwho
I am so zen about @ESAGa
lifetime to figure it out!

it is exactly three weeks until everything w
change and all we understand about stars
Gaia???? #GaiaDR2 @ESAGaia #gaiaday

Sprint #GaiaDR2

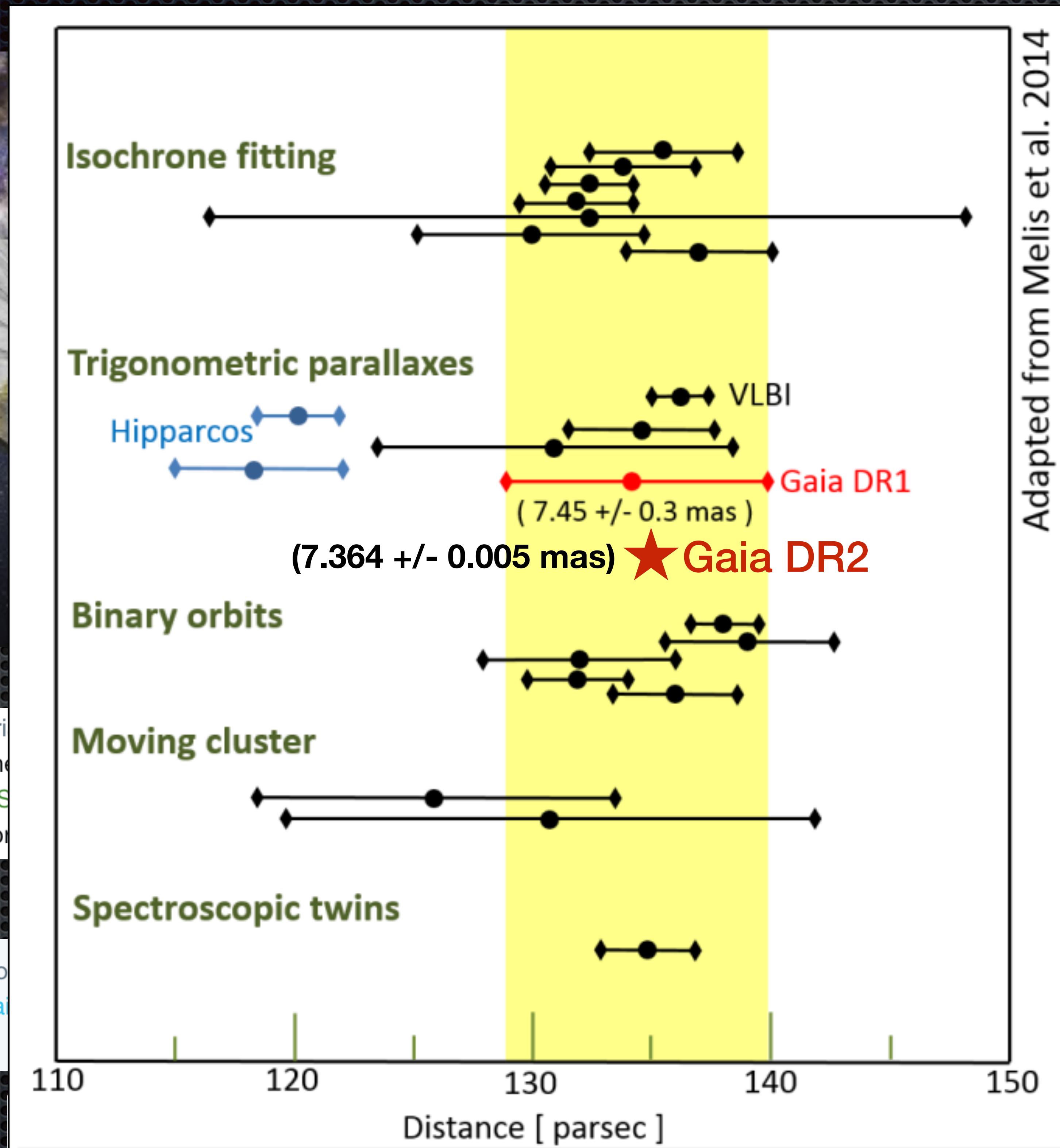
# sources in Gaia DR2	# sources in Gaia DR1
> 1,500,000,000	**1,142,679,769**
> 1,300,000,000	2,057,050
> 200,000,000	1,140,622,719
> 1,500,000,000	1,142,679,769
> 1,100,000,000	-
> 6,000,000	-
> 500,000	3,194
> 13,000	-
> 150,000,000	-

Gaia will save us all!



Adrian Price-Whelan @adri
during a great Sunday phon
years of "preparing" for @ES
the fact that we're still not pr

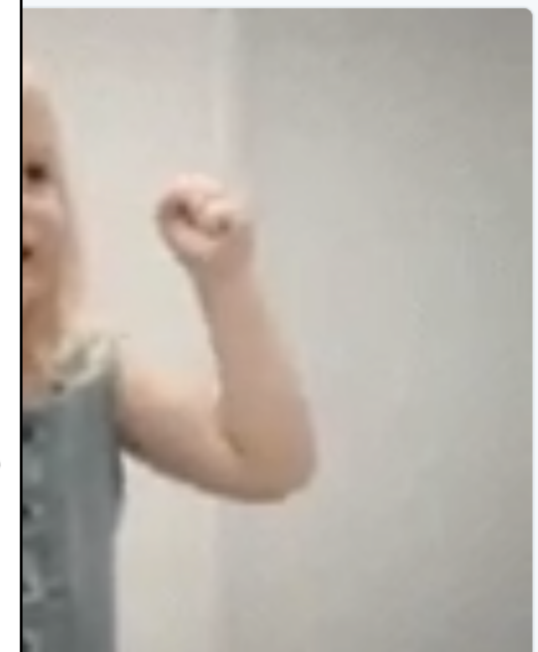
David W. Hogg @davidwho
I am so zen about @ESAGa
lifetime to figure it out!



Gaia Collaboration (2016)

It is exactly three weeks until everything w
change and all we understand about stars
Gaia???? #GaiaDR2 @ESAGaia #gaiaday

f over a billion parallaxes (distances

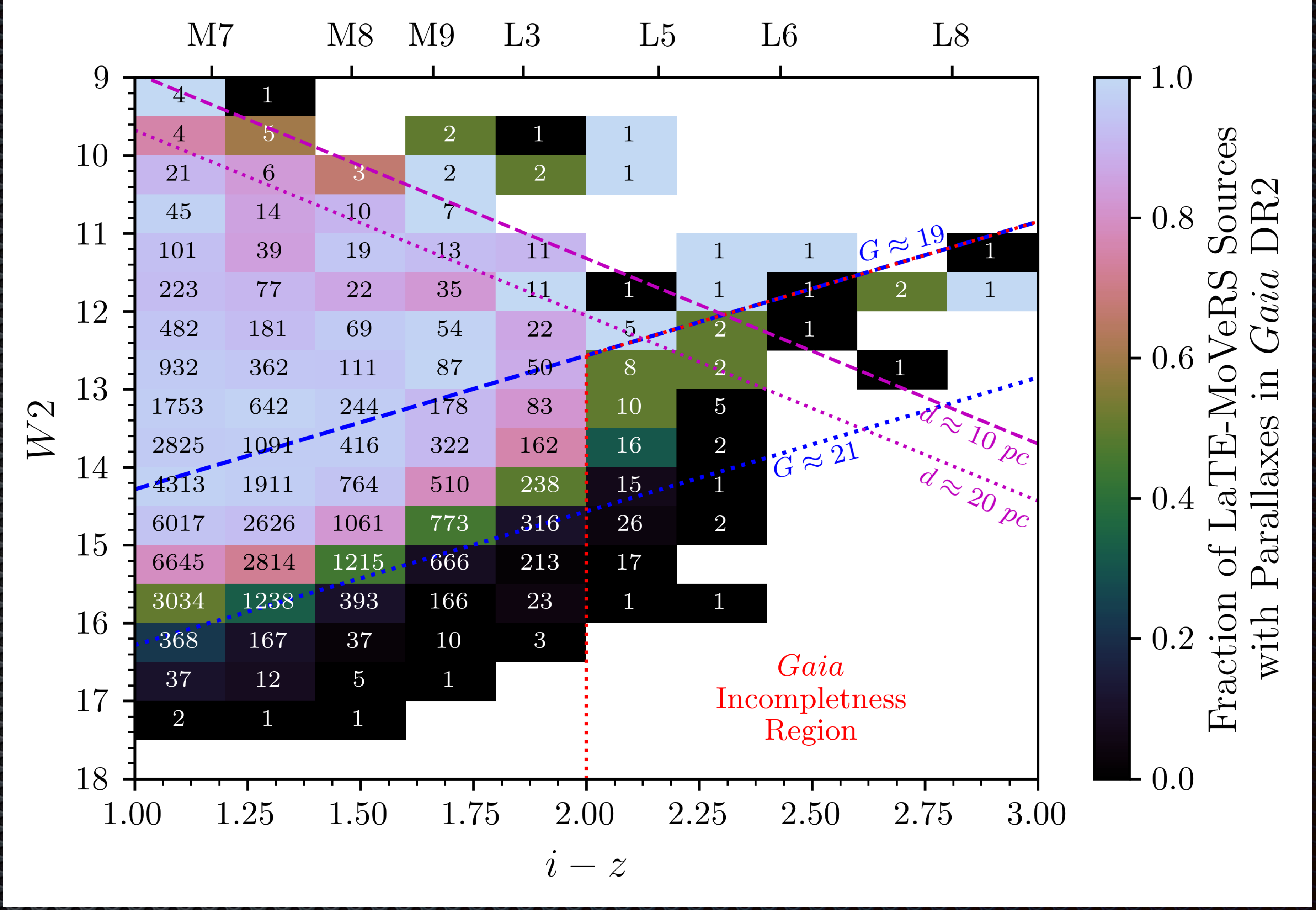


25
Sprint #GaiaDR2

	# sources in Gaia DR2	# sources in Gaia DR1
	> 1,500,000,000	**1,142,679,769**
	> 1,300,000,000	2,057,050
	> 200,000,000	1,140,622,719
	> 1,500,000,000	1,142,679,769
	> 1,100,000,000	-
	> 6,000,000	-
	> 500,000	3,194
	> 13,000	-
	> 150,000,000	-

Gaia will save us all!... maybe

Gaia will be incomplete for nearby, ultracool objects



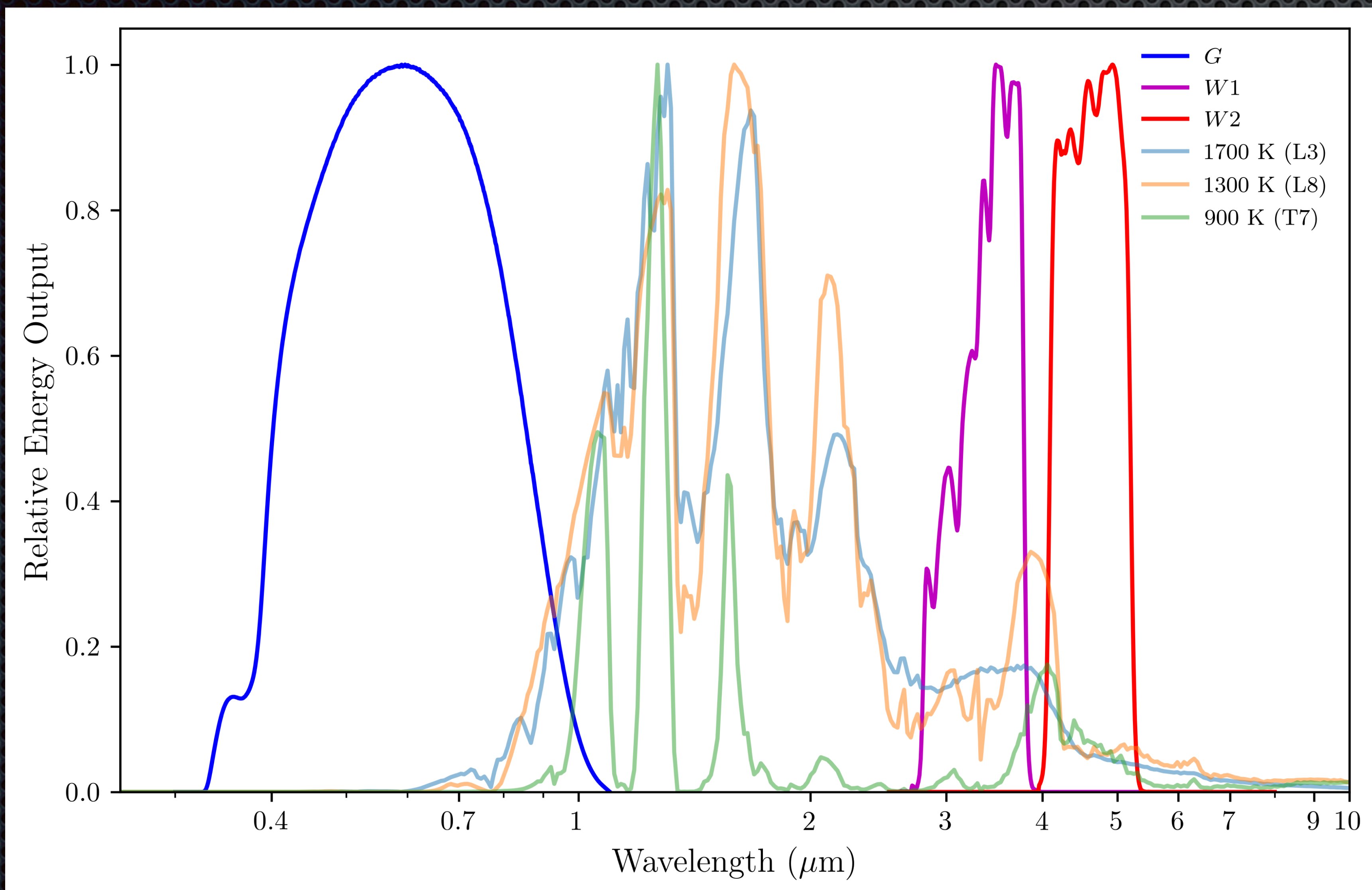
Theissen (2018)

The *Wide-field Infrared Survey Explorer (WISE)*

All-sky survey in 4 mid-infrared (MIR) bands (3.4, 4.6, 12, and 22 microns)

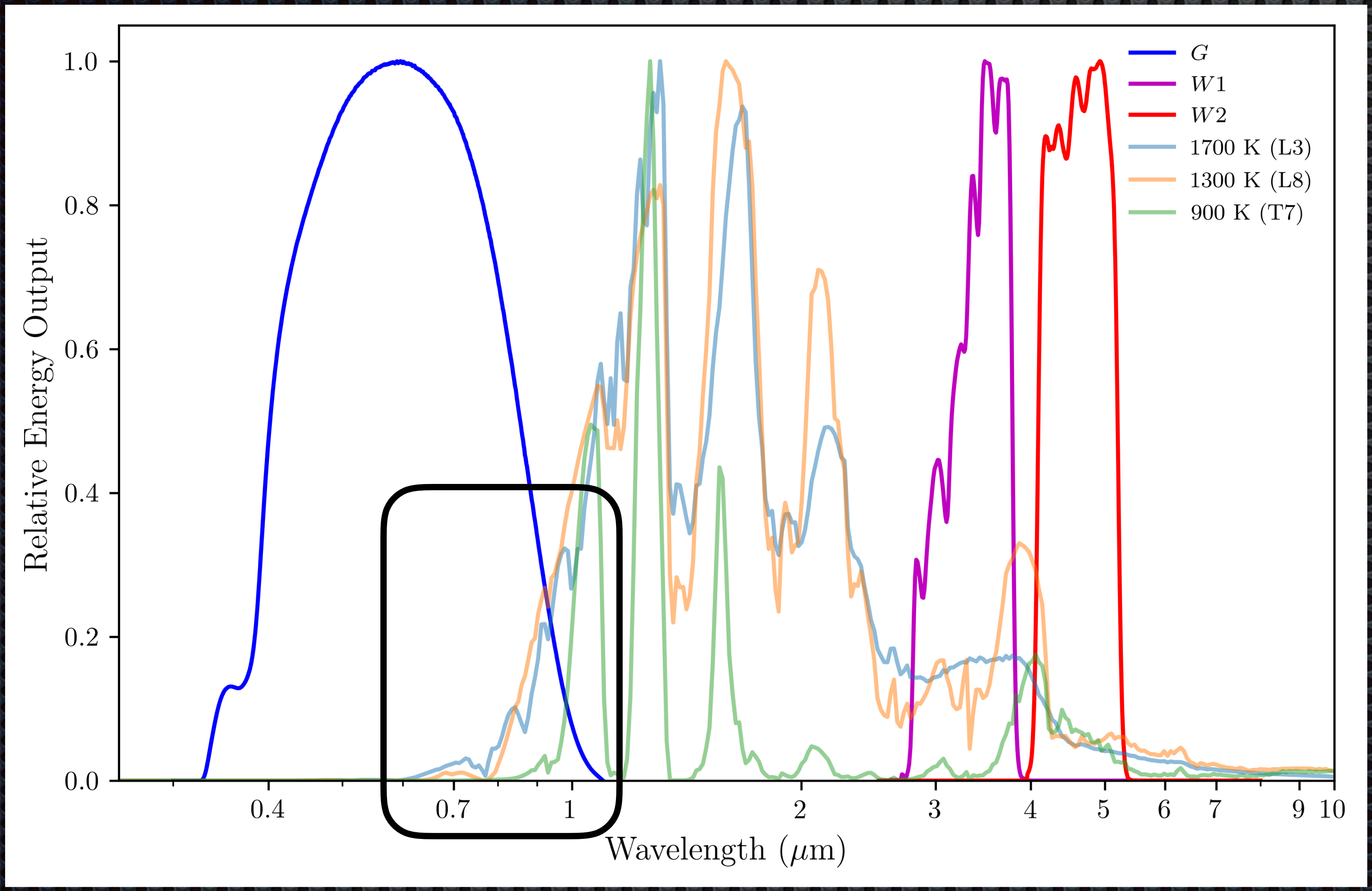
NASA/JPL

Is *WISE* better (than *Gaia*)?



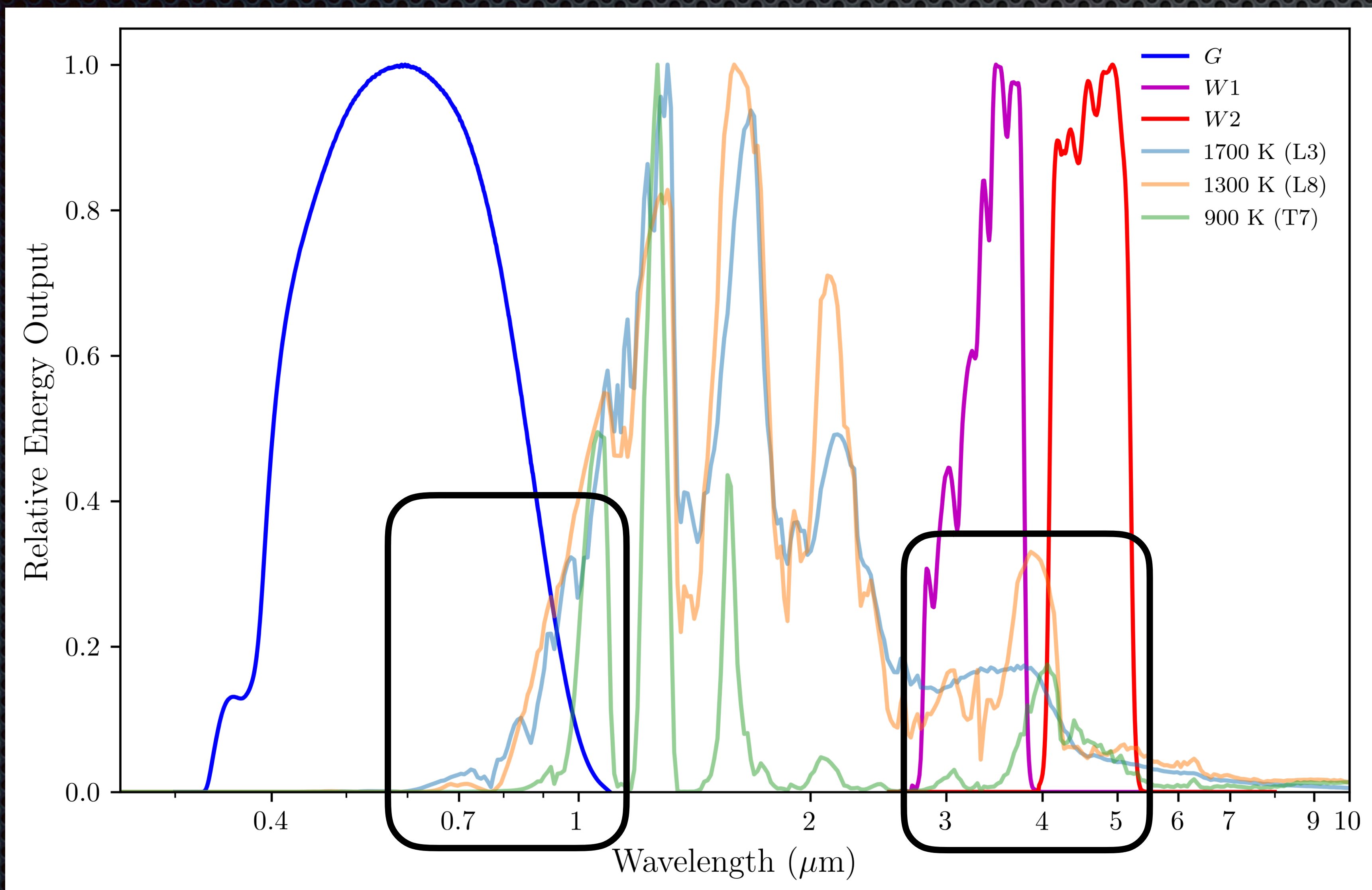
- Ultracool objects produce very little flux at optical (*Gaia*) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.

Is *WISE* better (than *Gaia*)?



- Ultracool objects produce very little flux at optical (Gaia) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.

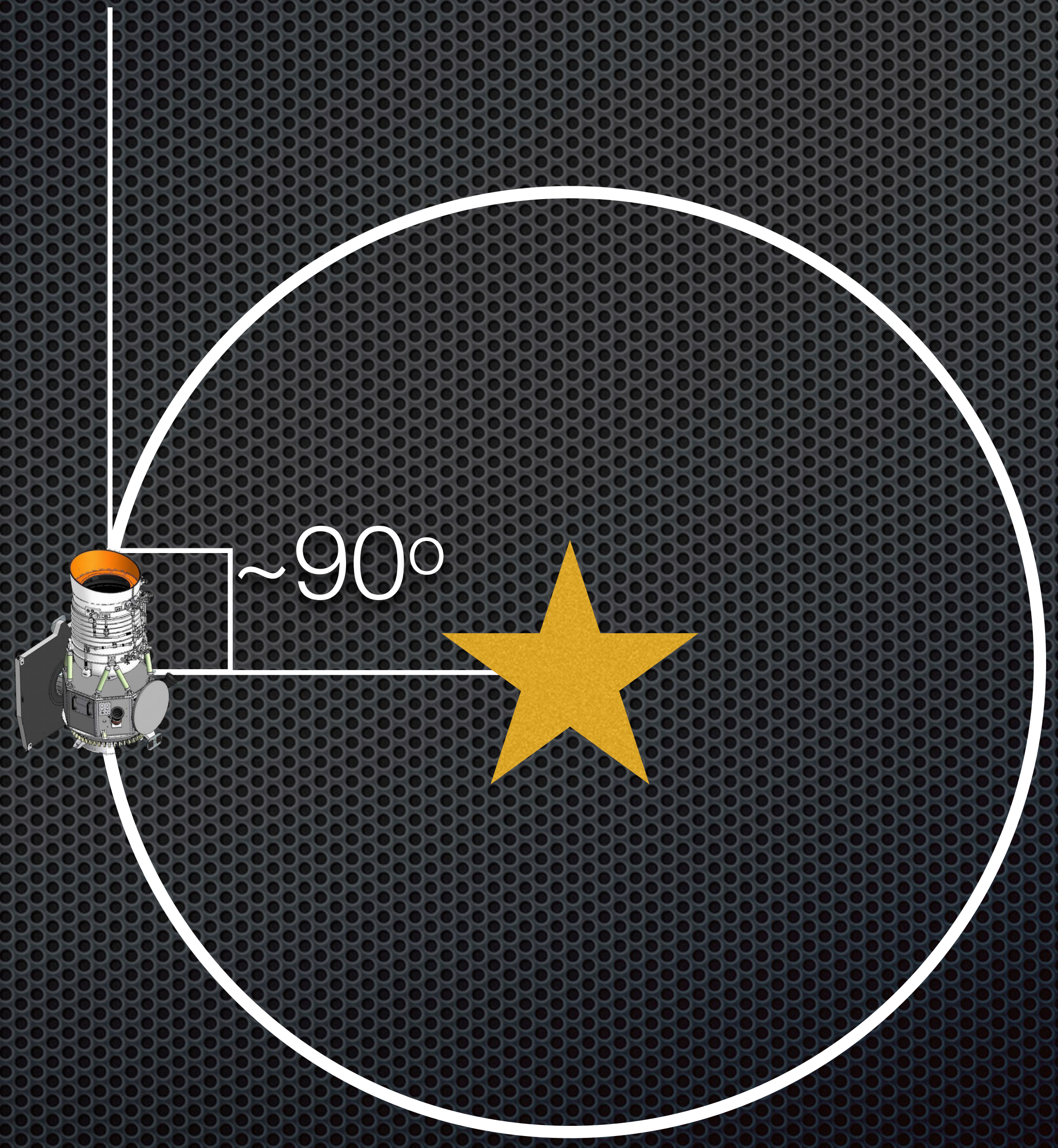
Is *WISE* better (than *Gaia*)?



- Ultracool objects produce very little flux at optical (Gaia) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.

WISE Survey Strategy

WISE Survey Strategy



WISE Survey Strategy

Roughly every 6 months for 7 years

Measuring Parallaxes with *WISE*

The Astrophysical Journal Letters, 767:L1 (6pp), 2013 April 10 doi:10.1088/2041-8205/767/1/L1
© 2013. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

DISCOVERY OF A BINARY BROWN DWARF AT 2 pc FROM THE SUN*

K. L. Luhman
Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA; kluhman@astro.psu.edu
and
Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA

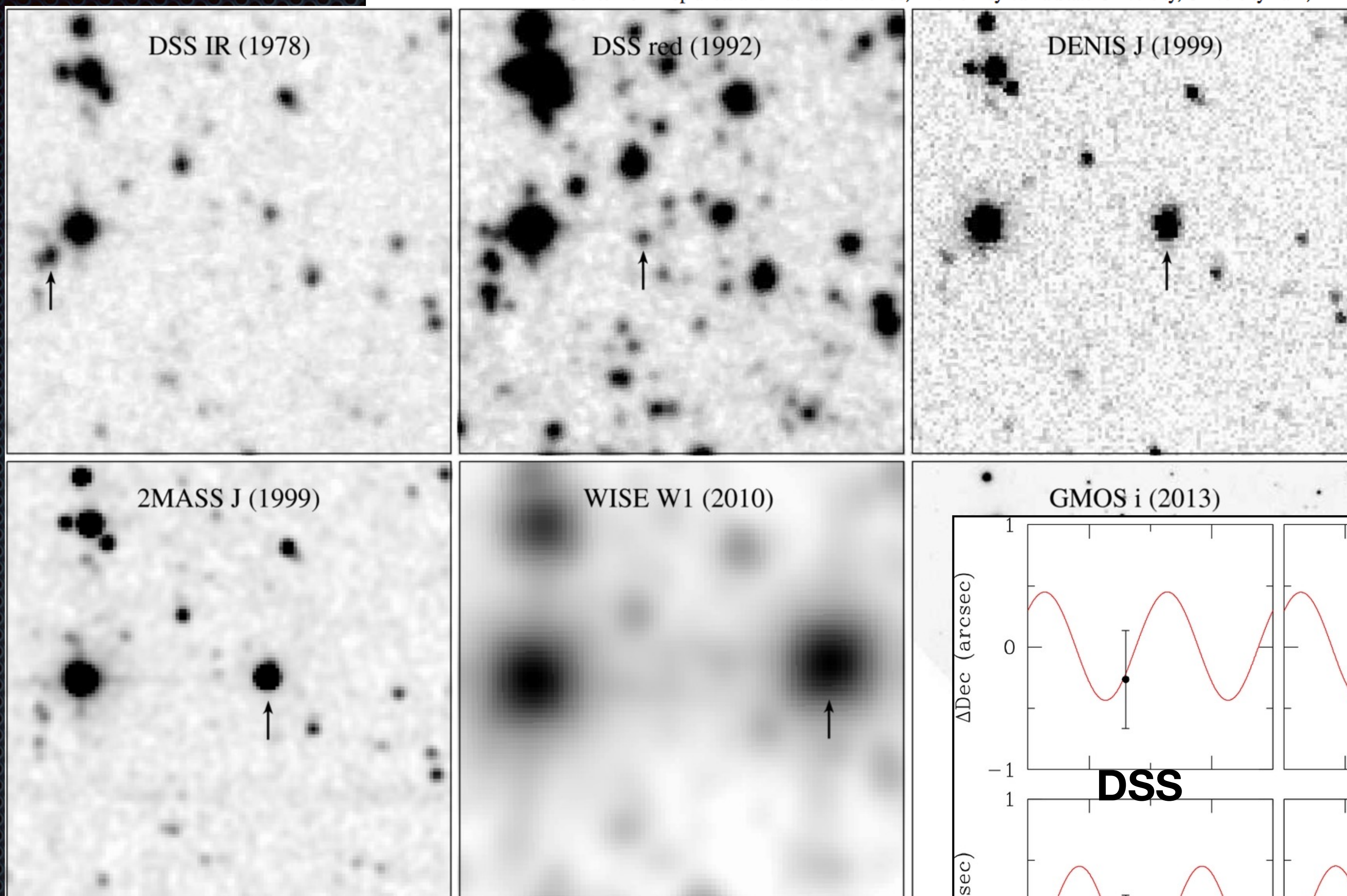
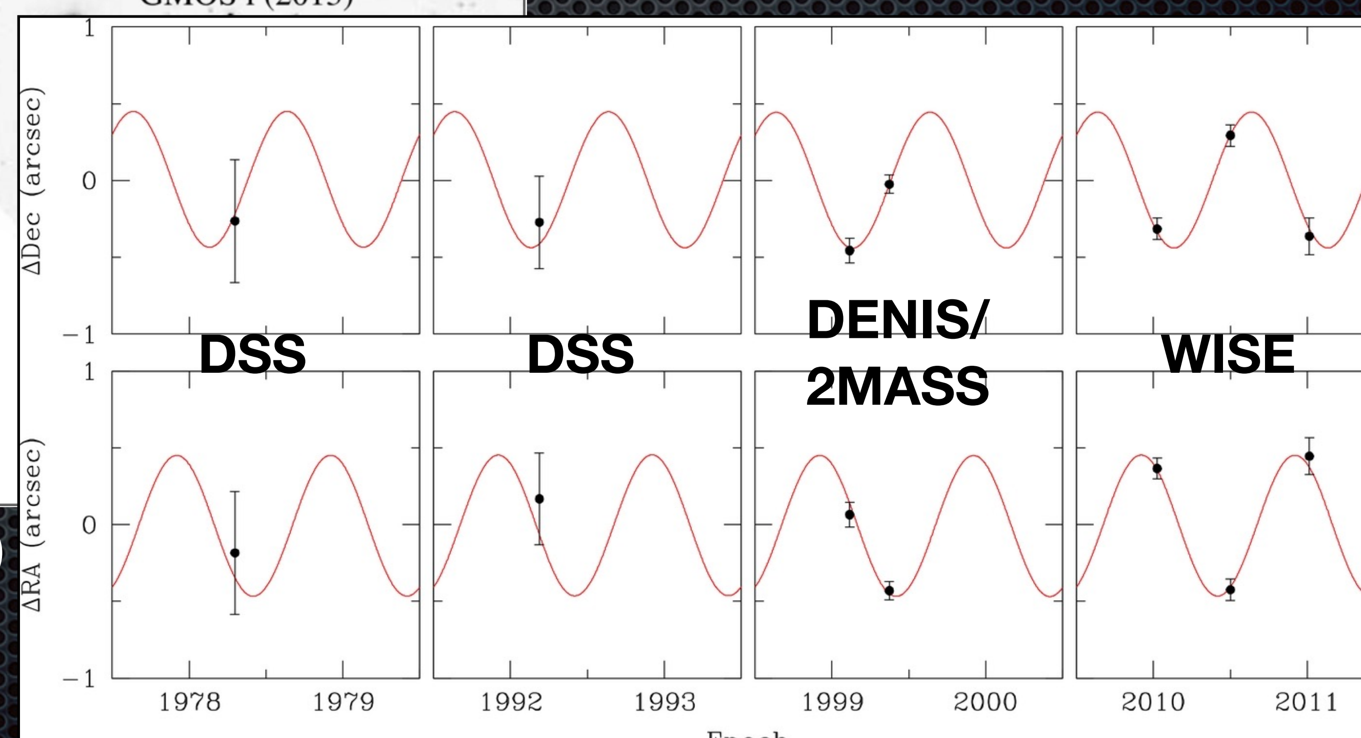


Table 2
Parallax, Proper Motion, and Photometry for WISE J104915.57−531906.1

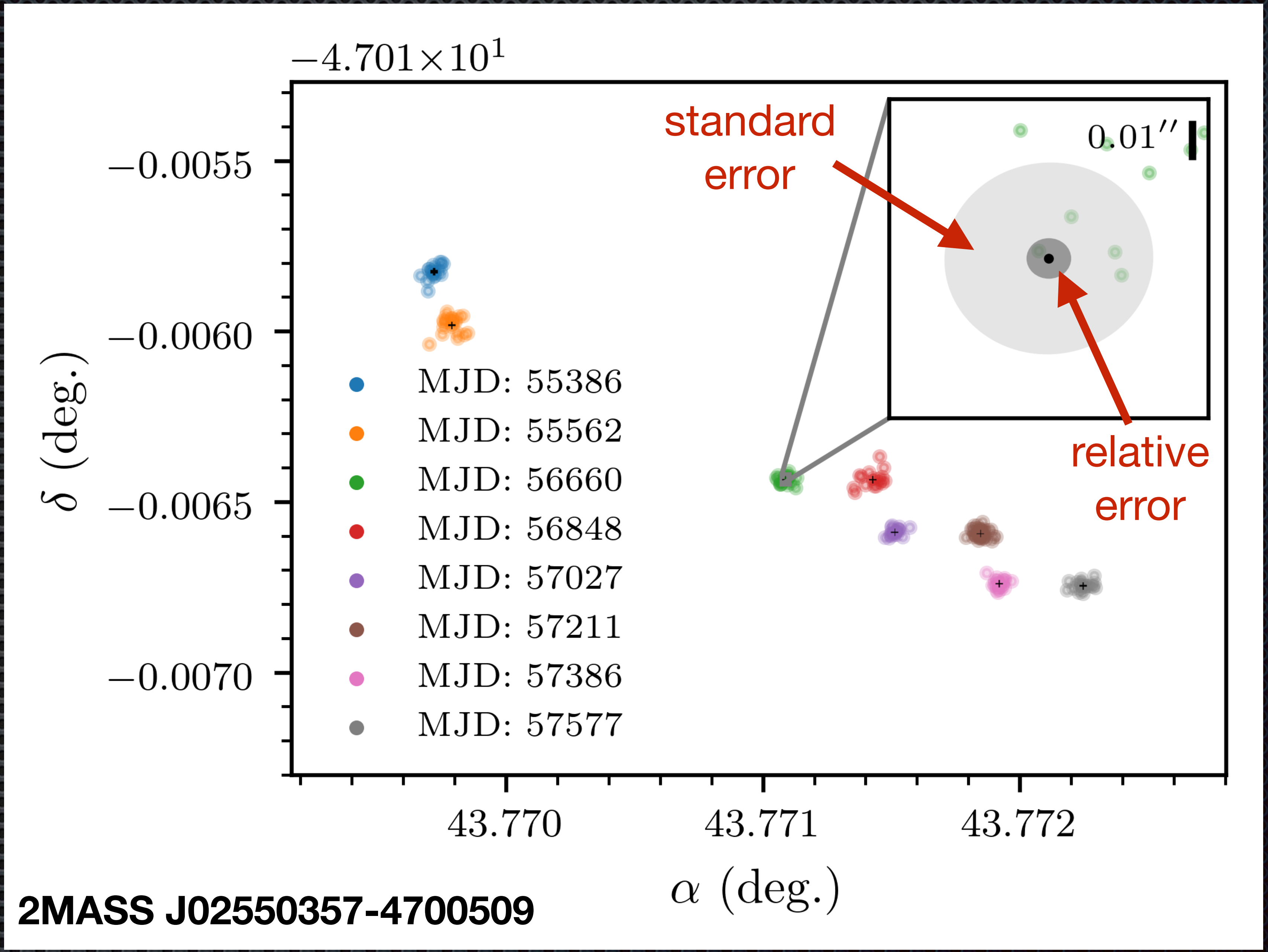
Parameter	Value
π	$0.496 \pm 0.037''$
$\mu_\alpha \cos\delta$	$-2.759 \pm 0.006''$ yr^{-1}
μ_δ	$+0.354 \pm 0.006''$ yr^{-1}



Luhman (2013)

Can we do better with just *WISE*?

- One *WISE* pixel is 2750 mas (2.75")
- We can get a *relative* uncertainty of ~10 mas (for bright sources)



Theissen (2018)

Can we do better with just *WISE*?

Equations of Motion

$$(\alpha_i - \alpha_0)\cos\delta_0 = \Delta\alpha + \mu_\alpha(t_i - t_0) + \pi(P_{\alpha,i} - P_{\alpha,0}),$$

$$\delta_i - \delta_0 = \Delta\delta + \mu_\delta(t_i - t_0) + \pi(P_{\delta,i} - P_{\delta,0}),$$

Can we do better with just *WISE*?

Dan Foreman-Mackey (YouTube)

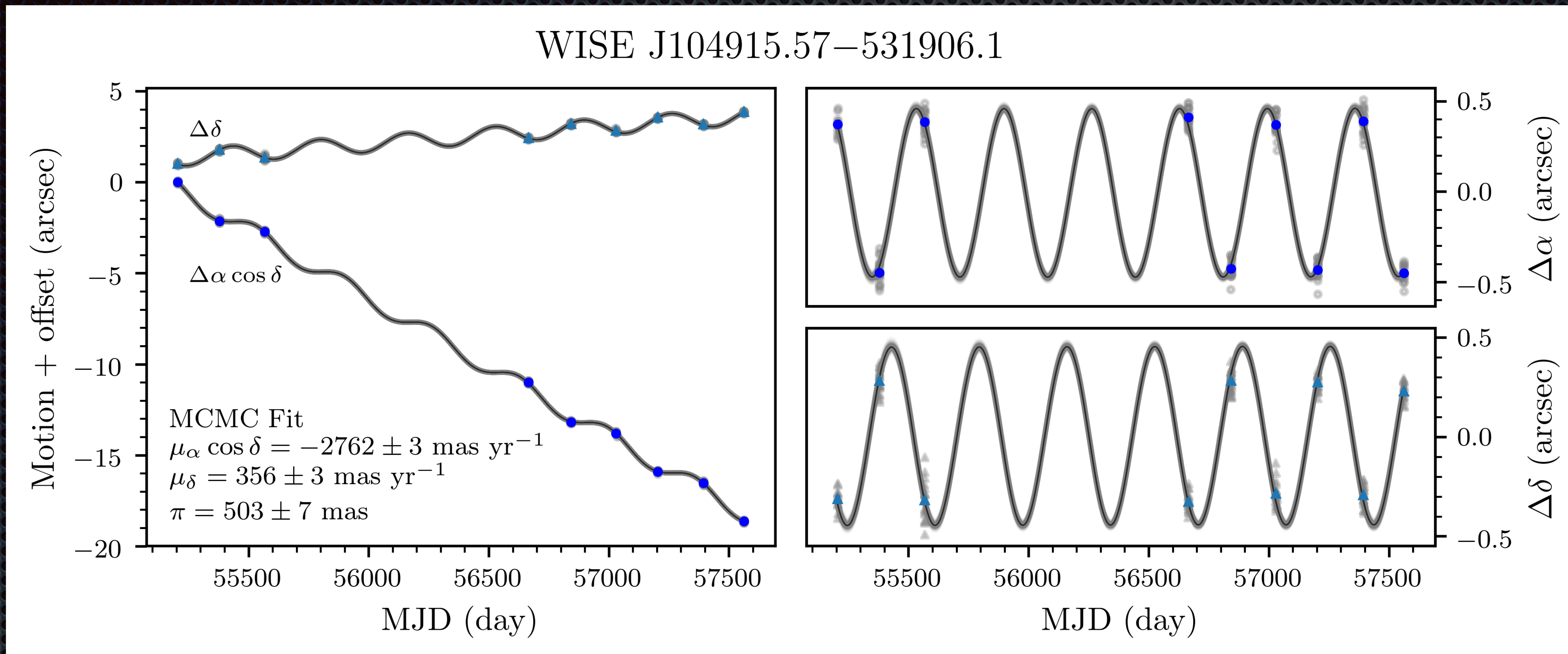
Plug into your favorite solver
(I prefer the *emcee*; Foreman-Mackey+ 2013)

Can we do better with just *WISE*?

Dan Foreman-Mackey (YouTube)

Plug into your favorite solver
(I prefer the *emcee*; Foreman-Mackey+ 2013)

Yes we can!



Theissen (2018)

Table 2
Parallax, Proper Motion, and Photometry for WISE J104915.57−531906.1

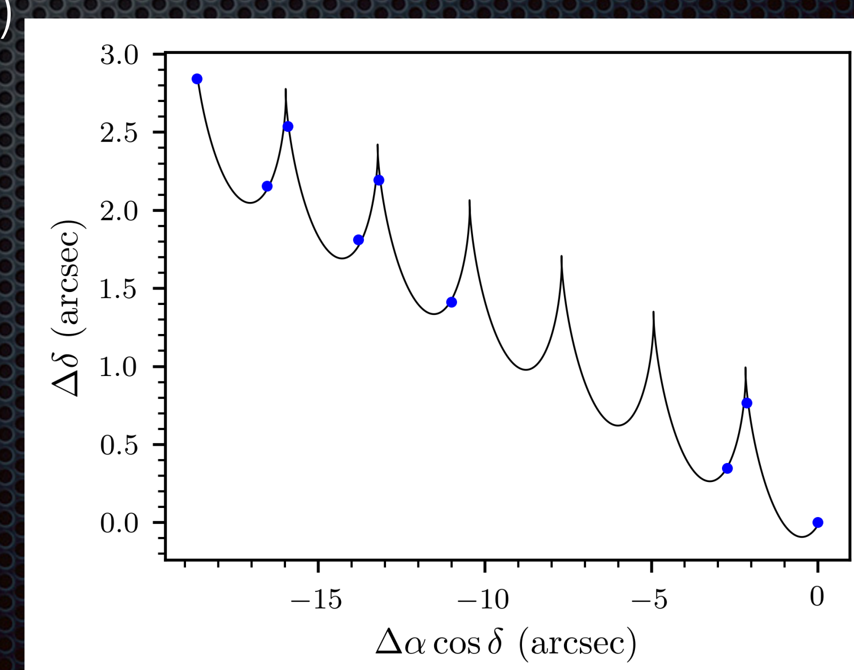
Parameter	Value
π	$0.496 \pm 0.037''$
$\mu_\alpha \cos\delta$	$-2.759 \pm 0.006''\ \mathrm{yr}^{-1}$
μ_δ	$+0.354 \pm 0.006''\ \mathrm{yr}^{-1}$

Luhman (2013)

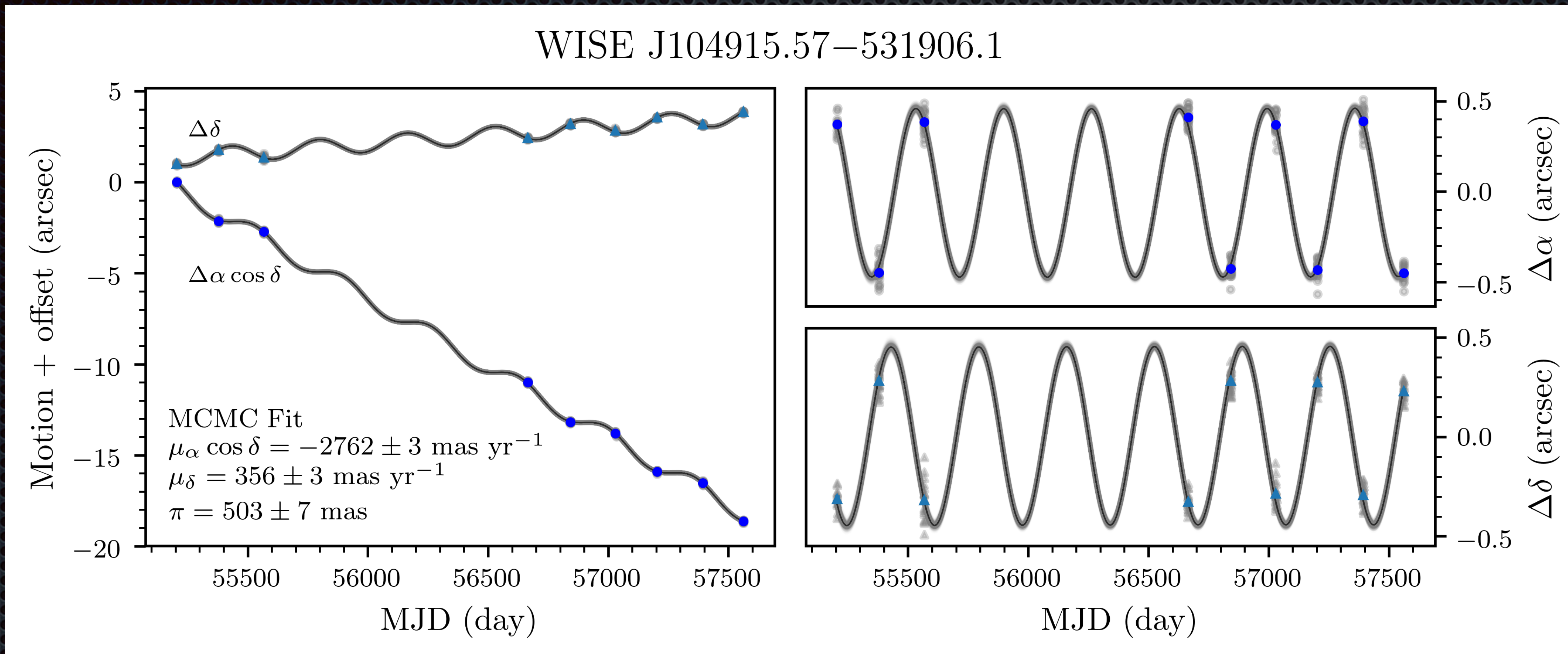
$\mu_{\alpha\cos\delta_{J2000.0}}$ (mas yr^{-1})	−2762.2	±2.3
$\mu_{\delta_{J2000.0}}$ (mas yr^{-1})	354.5	±2.8
π (mas)	501.118	±0.093

HST!

Bedin et al. (2017)



Yes we can!



Theissen (2018)

Table 2
Parallax, Proper Motion, and Photometry for WISE J104915.57−531906.1

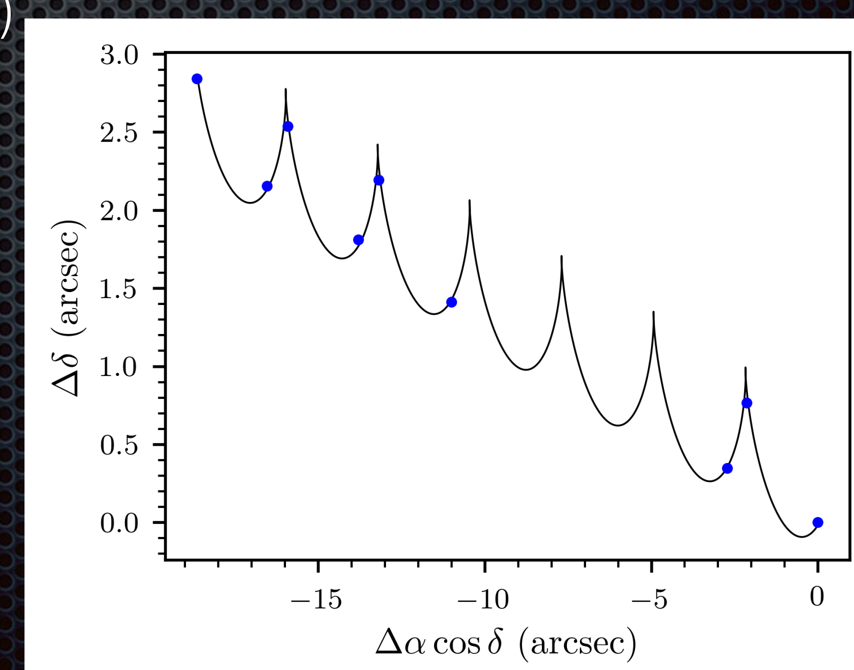
Parameter	Value
π	$0.496 \pm 0.037''$
$\mu_\alpha \cos\delta$	$-2.759 \pm 0.006''\ \mathrm{yr}^{-1}$
μ_δ	$+0.354 \pm 0.006''\ \mathrm{yr}^{-1}$

Luhman (2013)

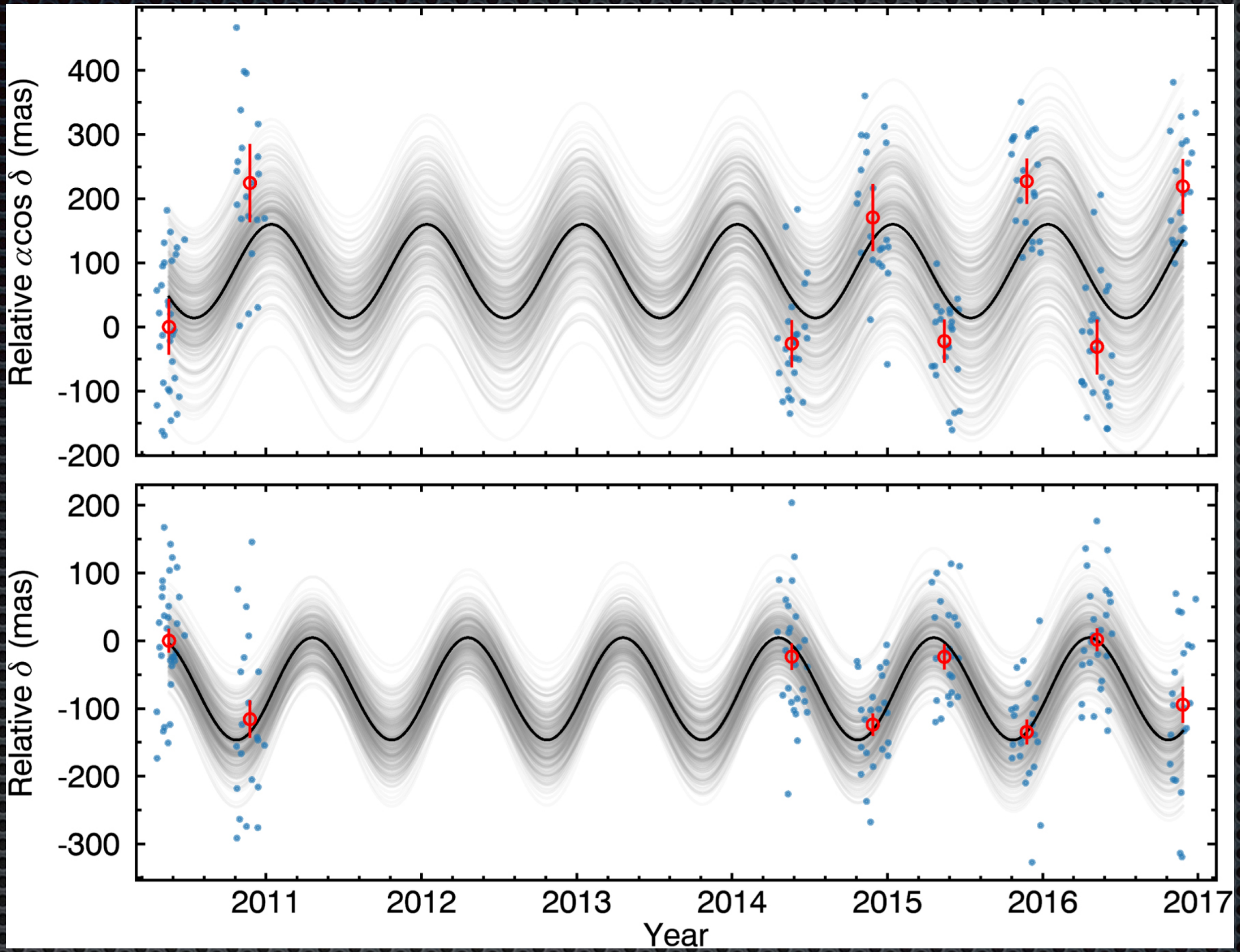
$\mu_{\alpha\cos\delta_{J2000.0}}$ (mas yr^{-1})	−2762.2	±2.3
$\mu_{\delta_{J2000.0}}$ (mas yr^{-1})	354.5	±2.8
π (mas)	501.118	±0.093

Bedin et al. (2017)

HST!



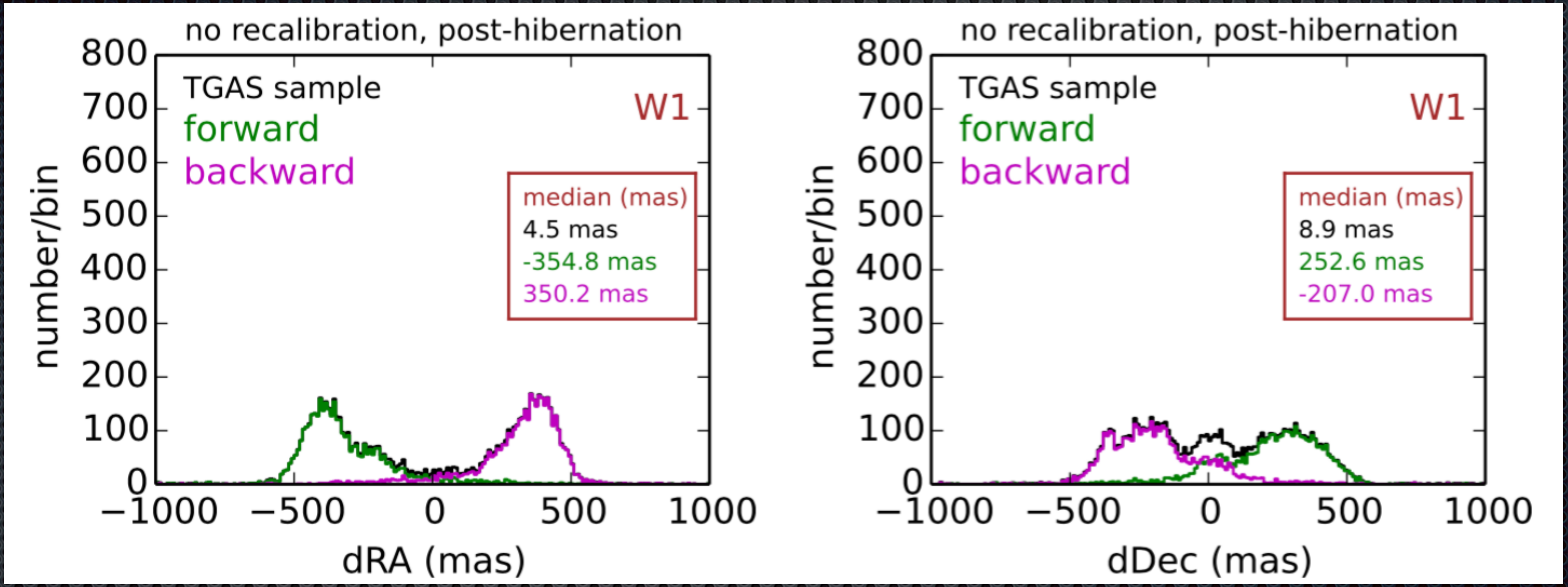
2MASS J1324+6358 (~11 M_{jup})



Gagné et al. (2018)

known high-likelihood members of the ABDMG. The effective temperature of 2MASS J13243553+6358281 provides the first precise constraint on the L/T transition at a known young age and indicates that it happens at a temperature of ~1150 K at ~150 Myr, compared to ~1250 K for field brown dwarfs.

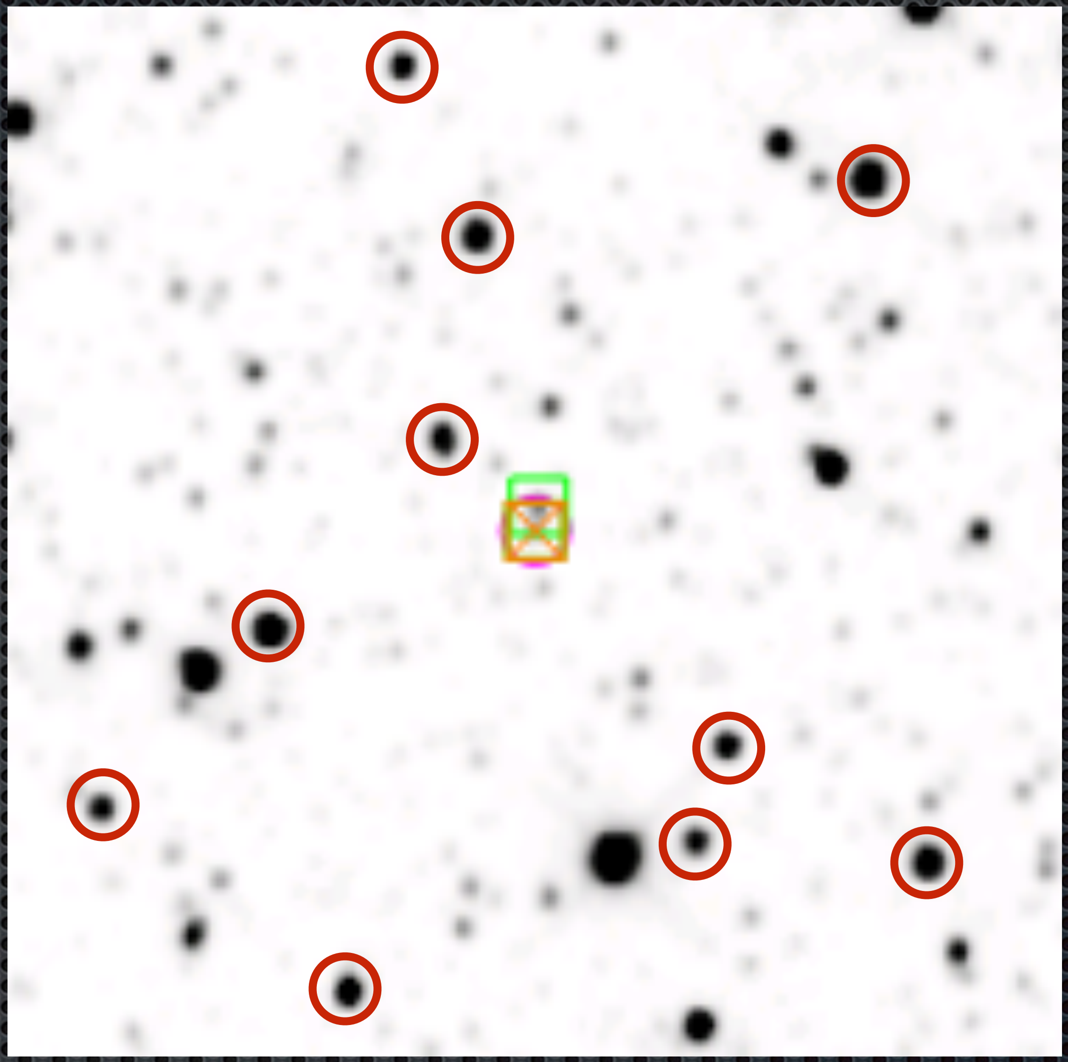
Some caveats - PSF dipole residuals



Meisner, Lang, & Schlegel (2018)

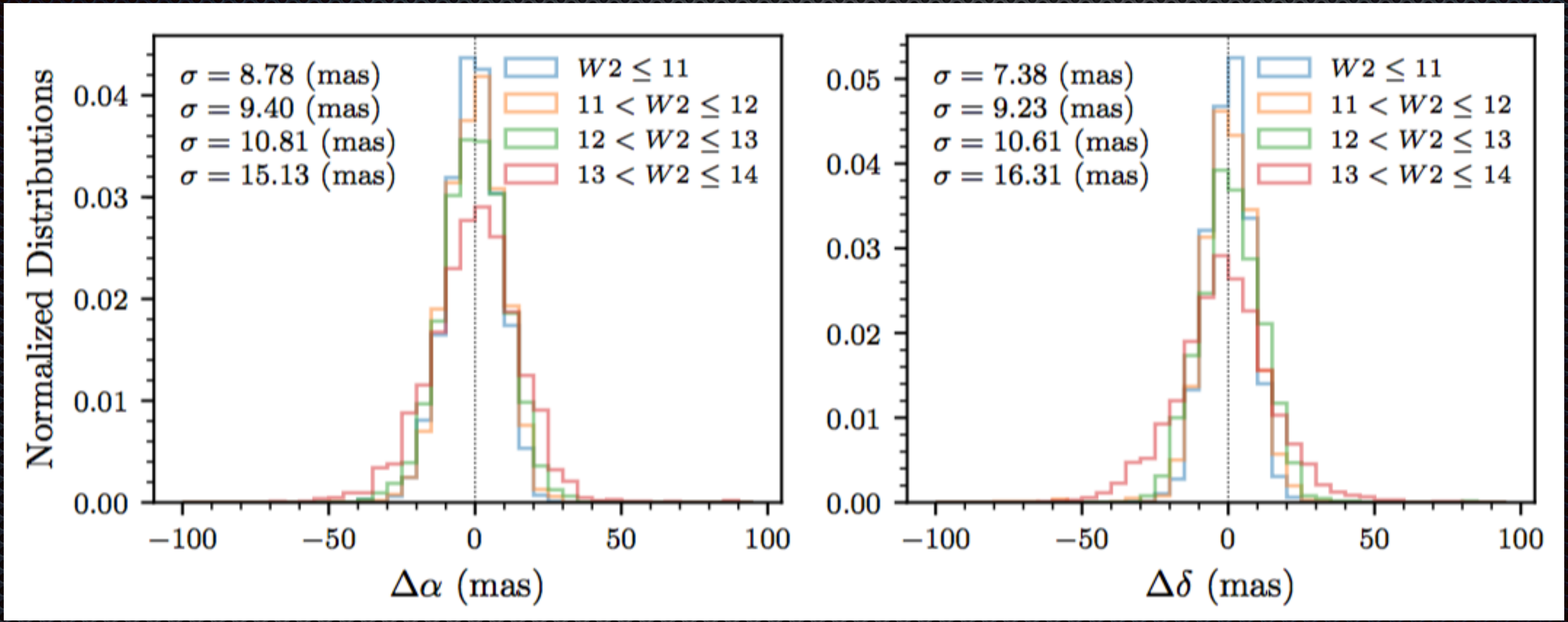
Presumably due to “PSF models adopted by the *WISE* team are not symmetric with respect to swapping the scan direction"

Correction for the PSF dipole residuals



Use reference objects close to the target object to correct for this shift (10’ x 10’ image)

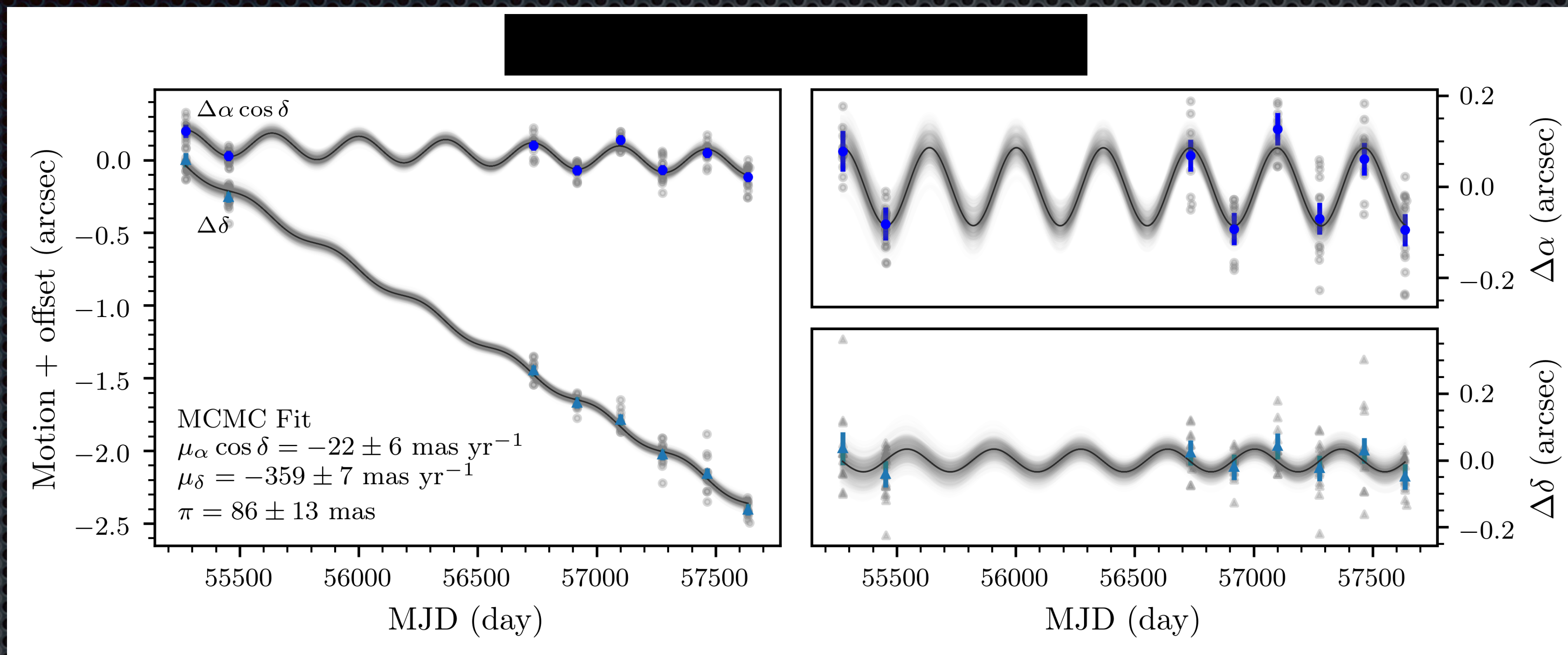
Correction for the PSF dipole residuals

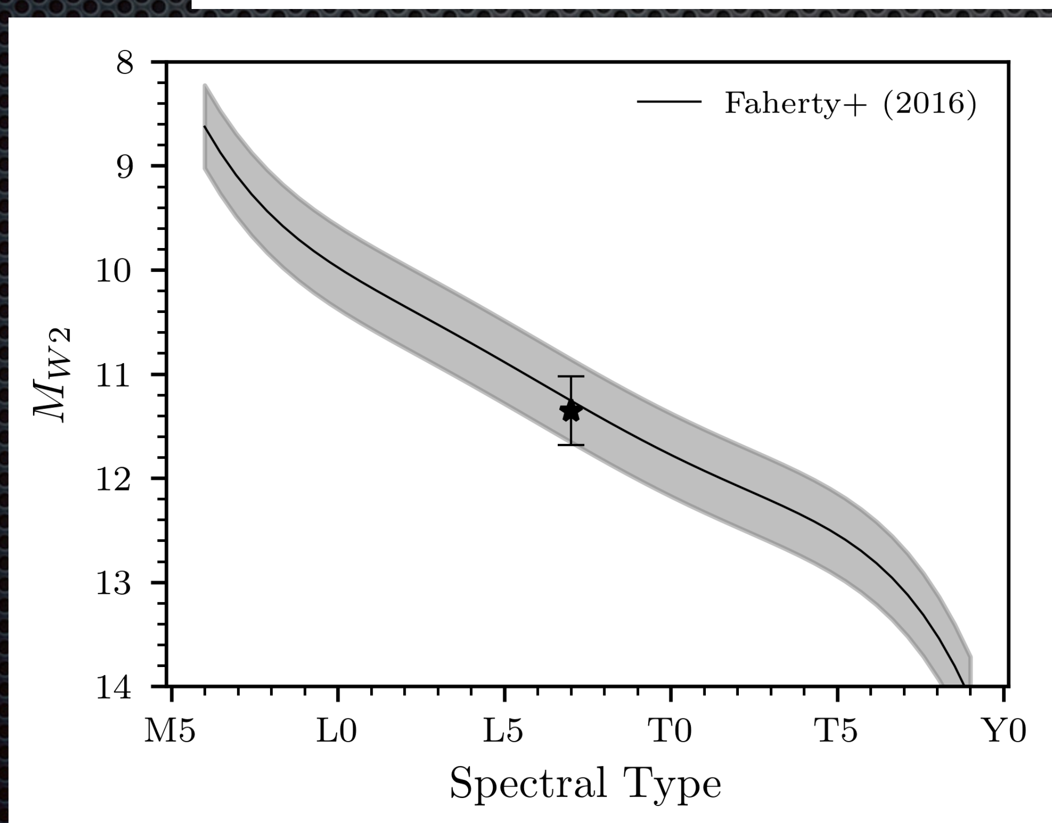


Theissen (2018)

Correction applied to QSOs (bright, non-moving)

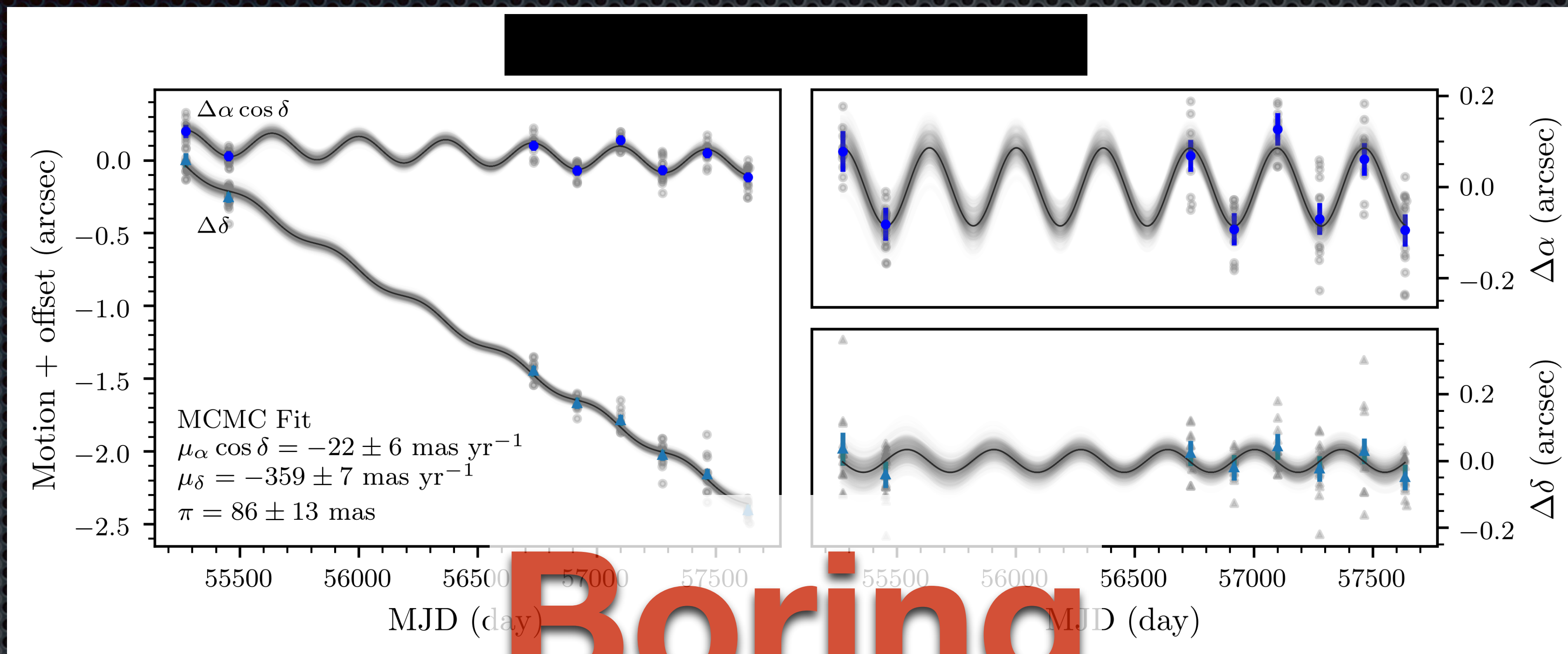
Very important correction



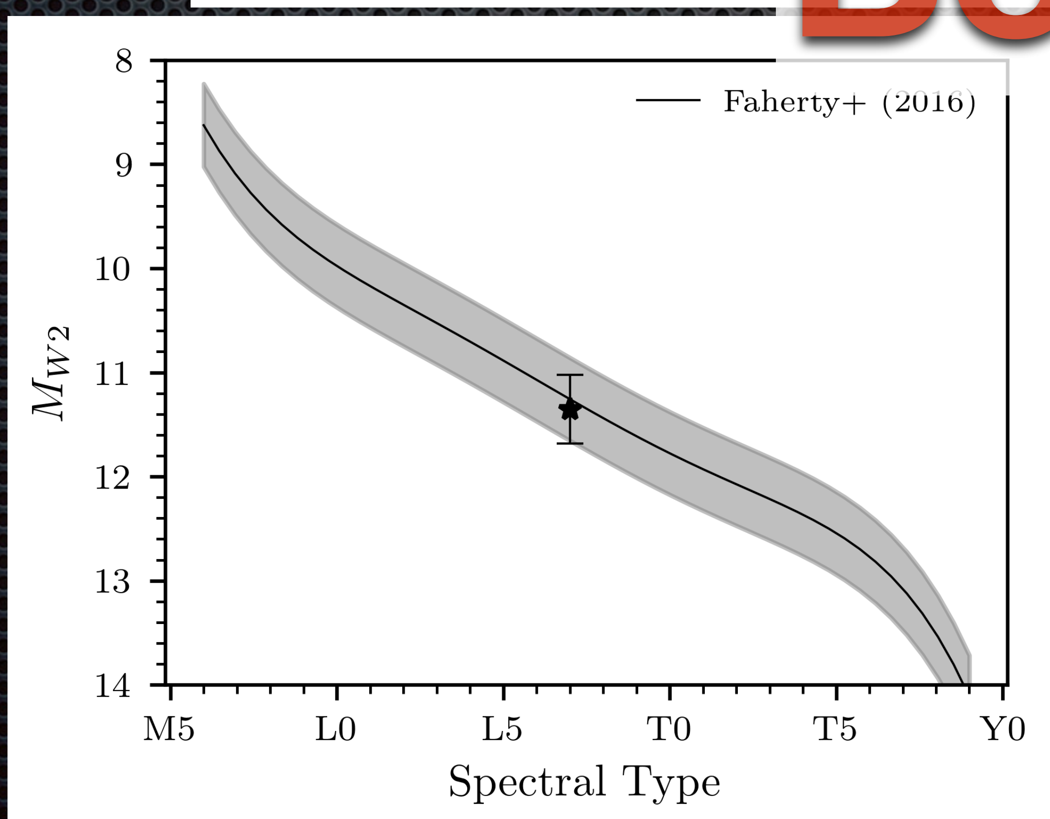


Typical L7 field dwarf

Very important correction

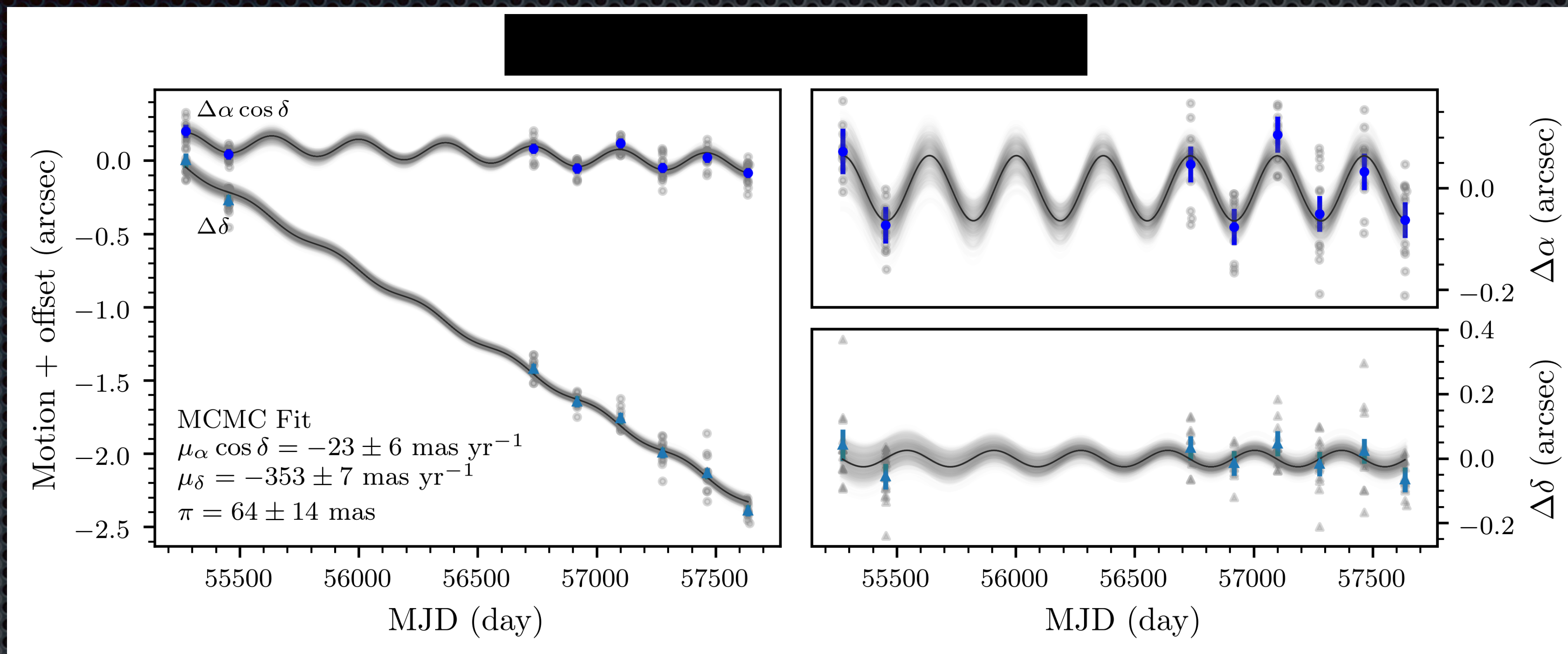


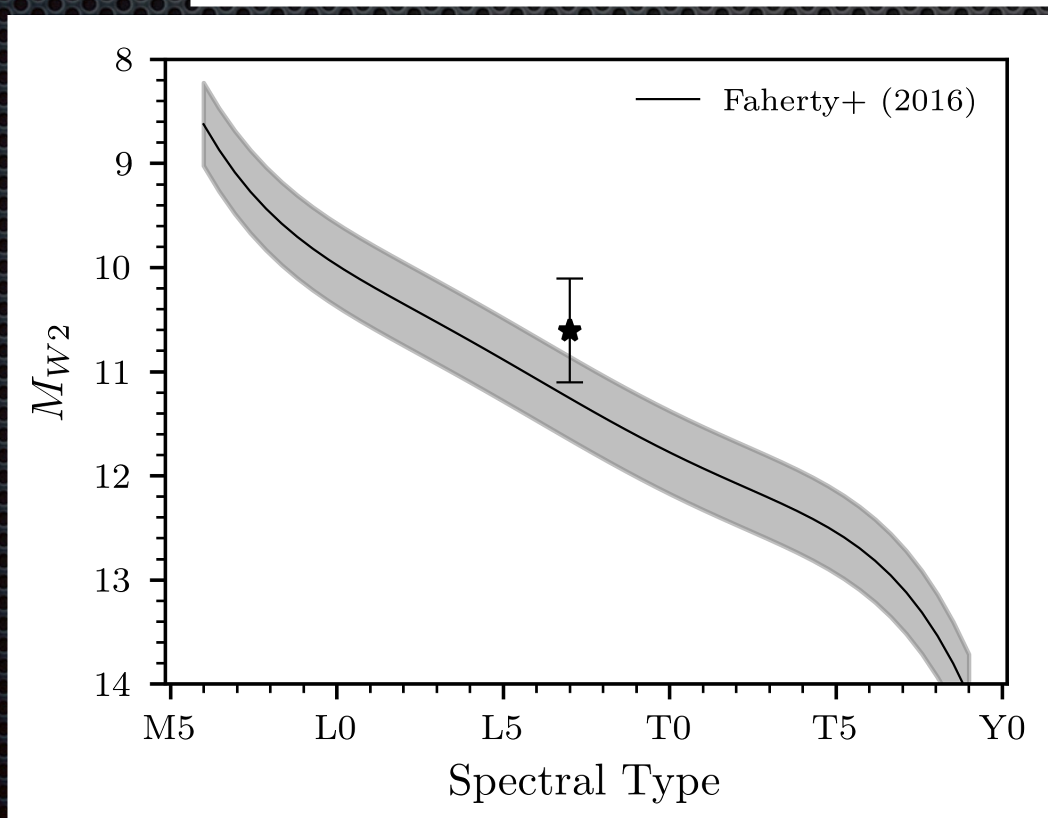
Boring



Typical L7 field dwarf

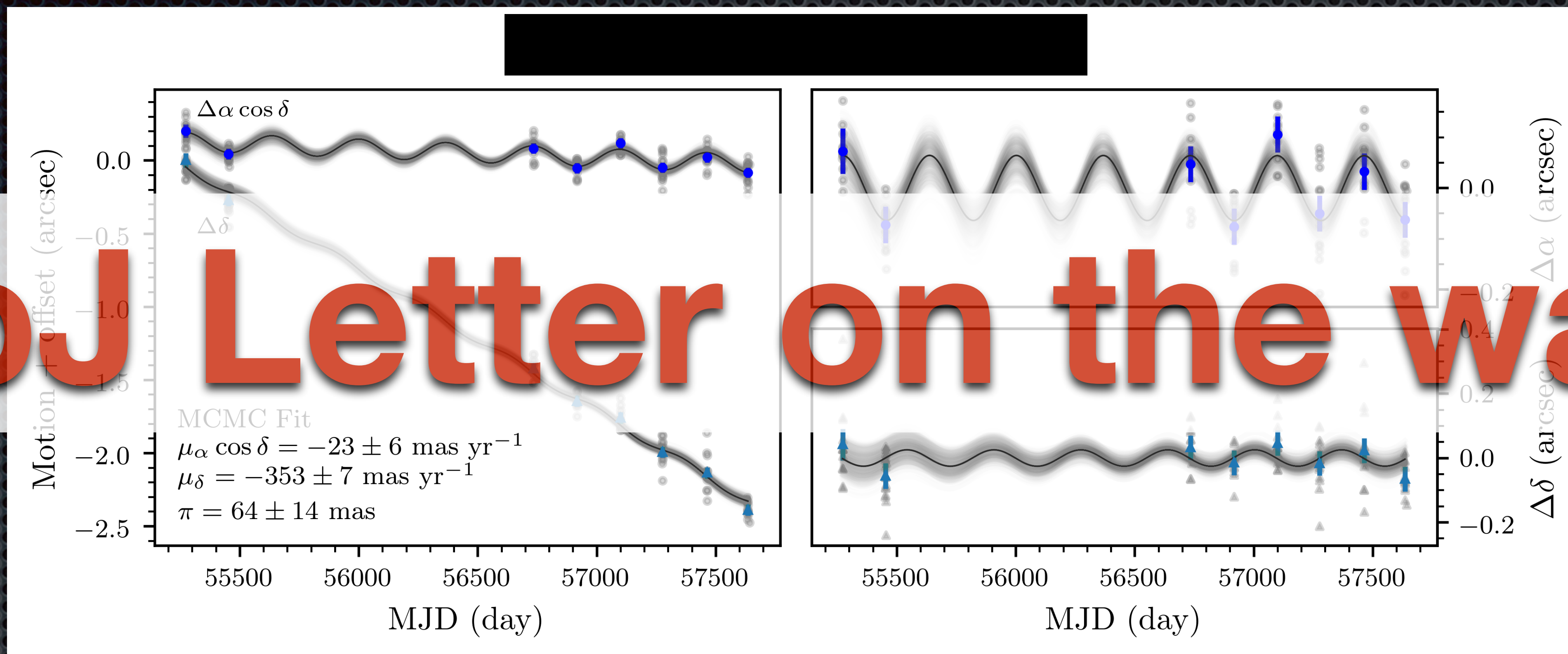
Wait one second



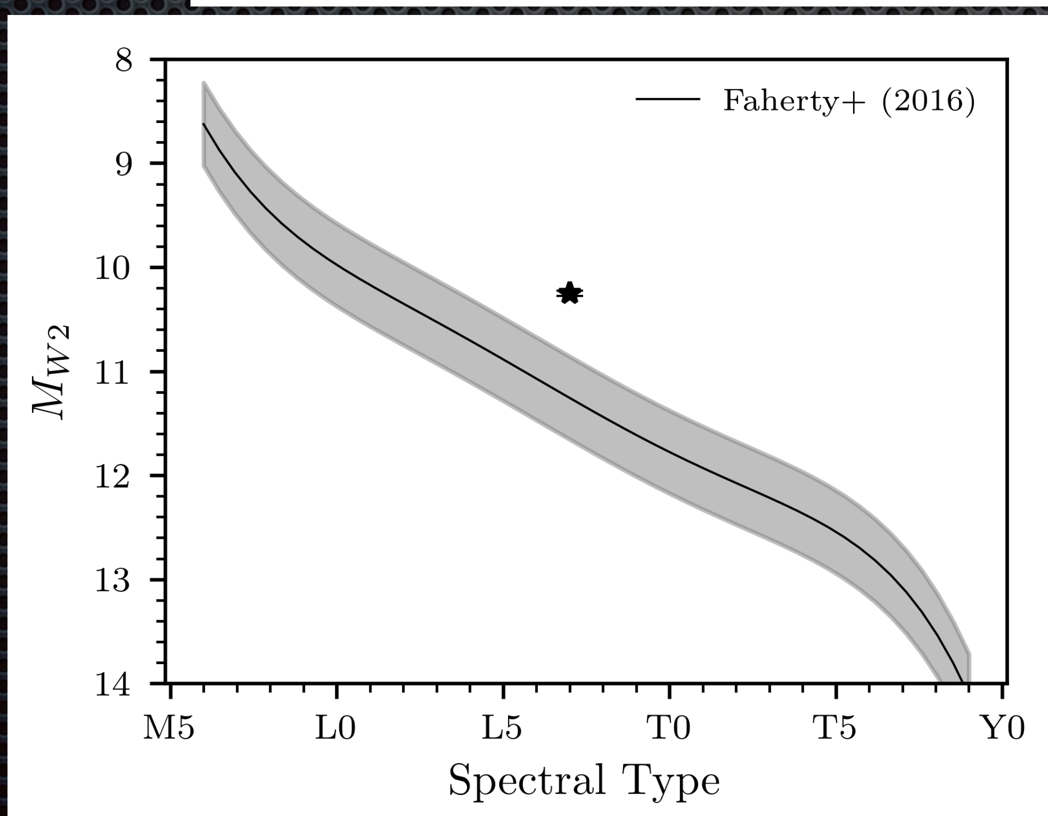


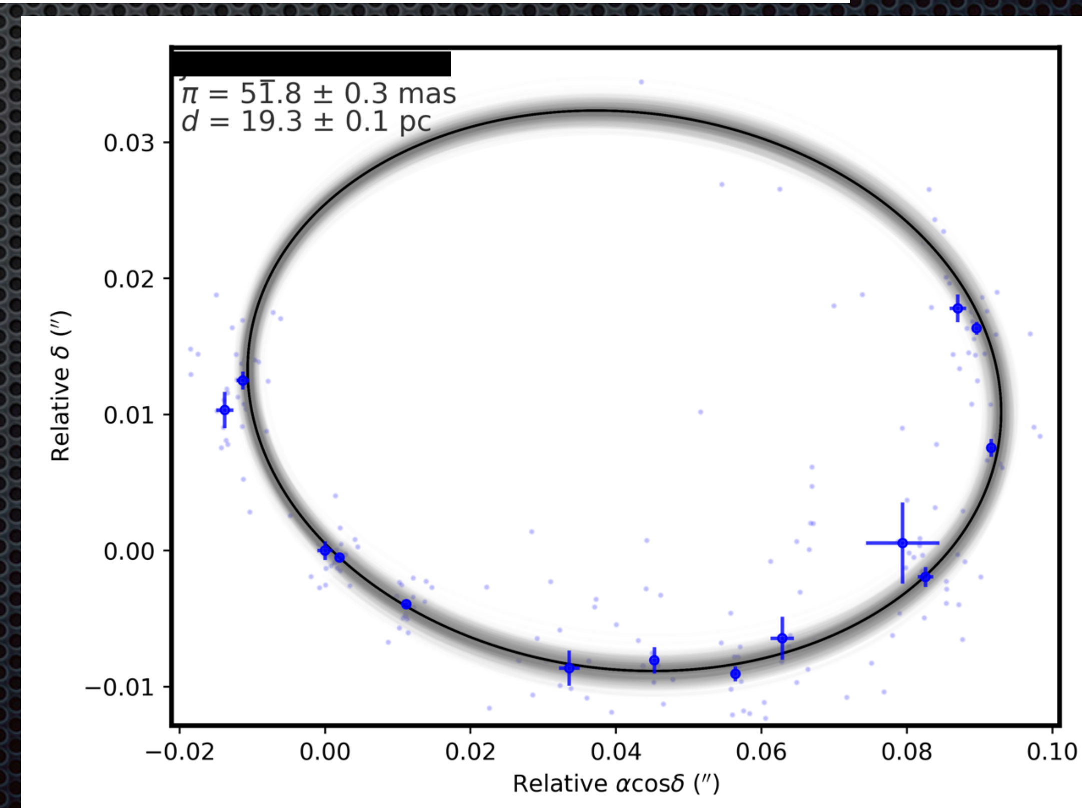
- Possible low-gravity (young, overluminous) object
- Likely member of a young moving group.

Wait one second

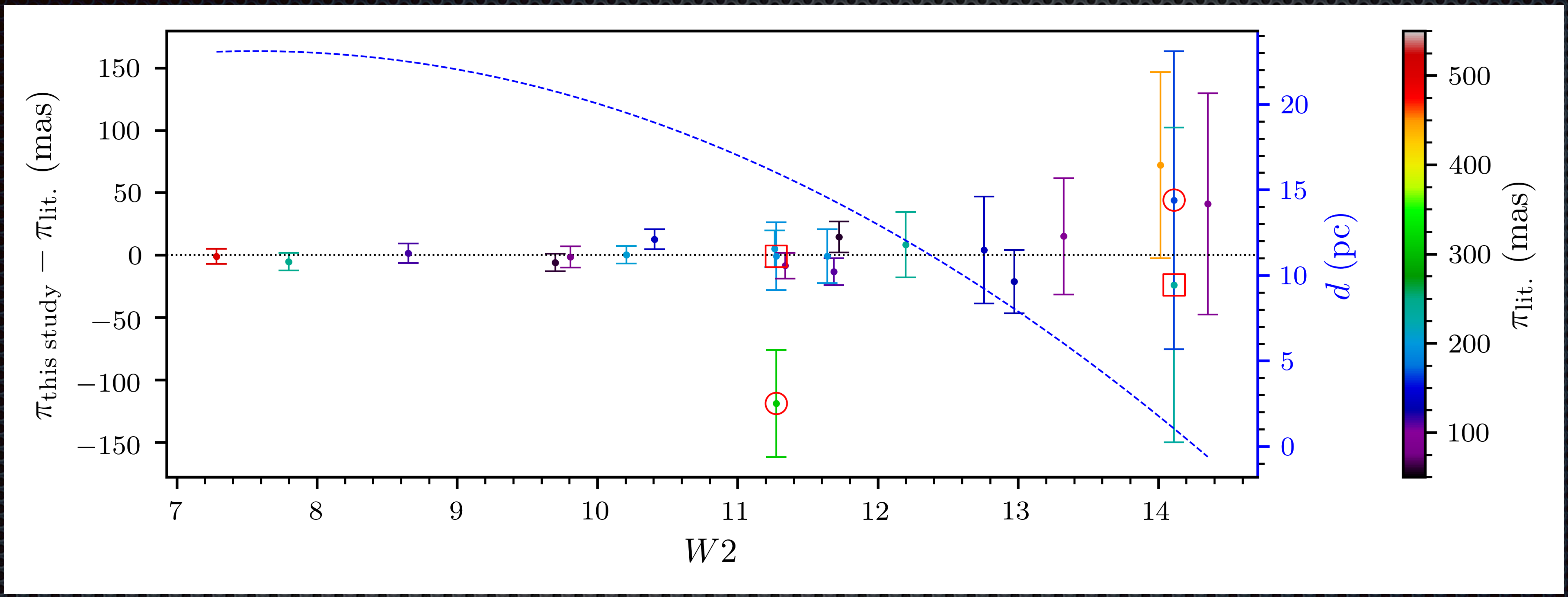


ApJ Letter on the way!





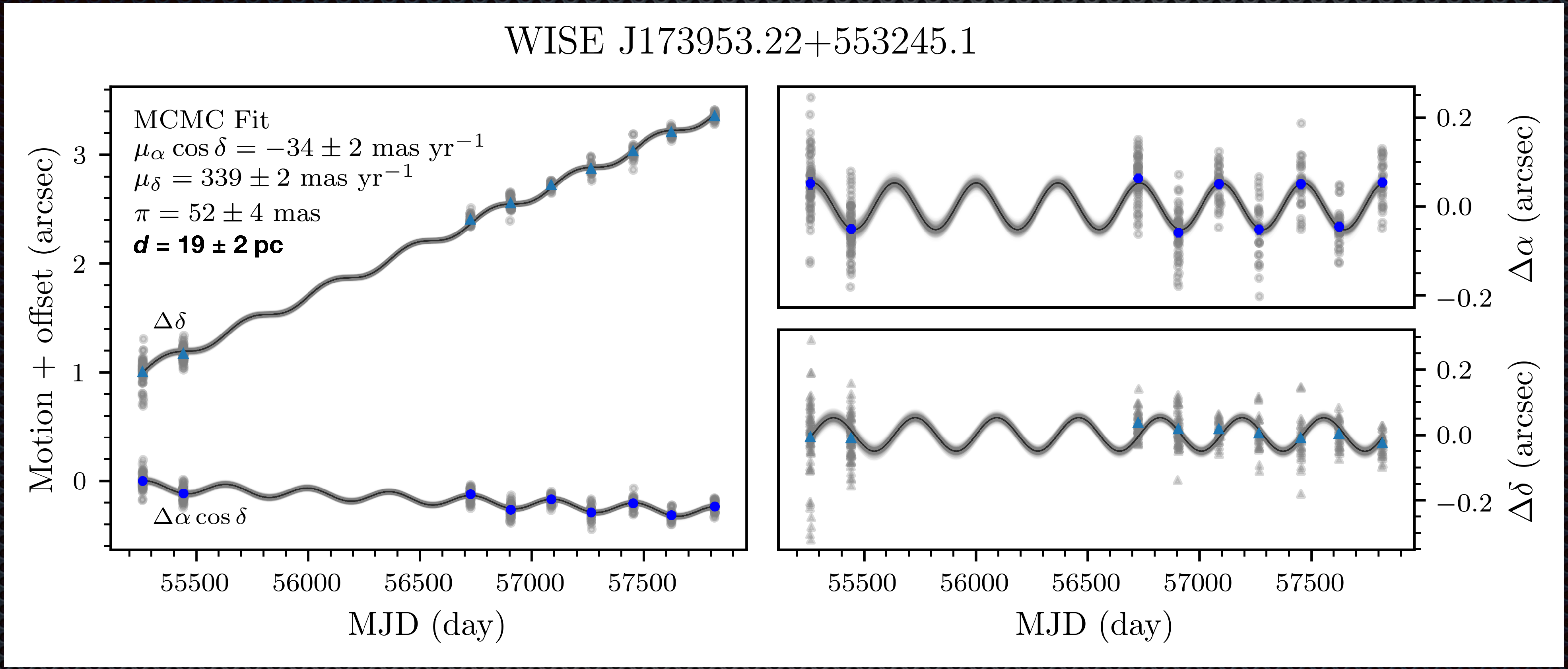
What are the limits?



Theissen (2018)

This method can, in principle, be used for objects out to ~25 pc.

What are the limits?

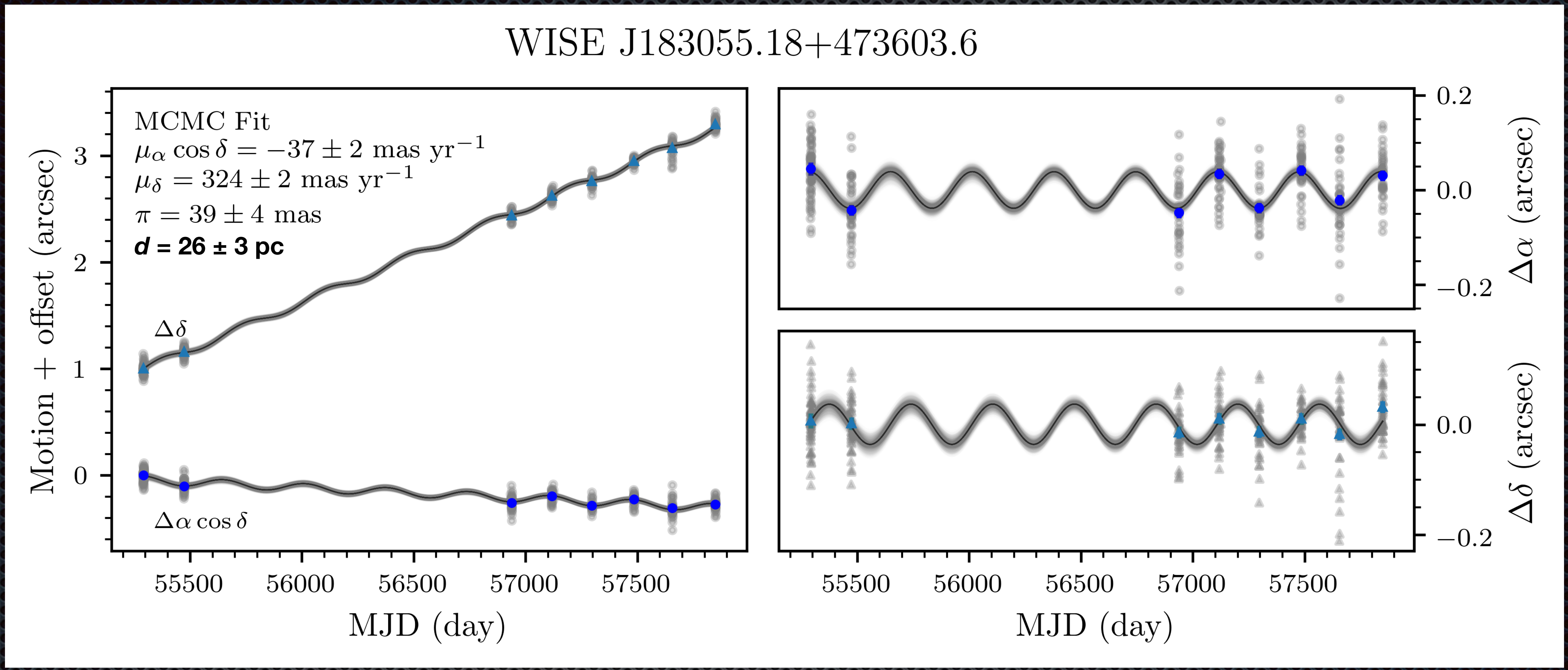


W2 = 10.86

Spectrophotometric distance = 15—24 pc

Gaia DR2 = 19.53 ± 0.55 pc (goodness of fit is baaaad)

What are the limits?



W2 = 9.98

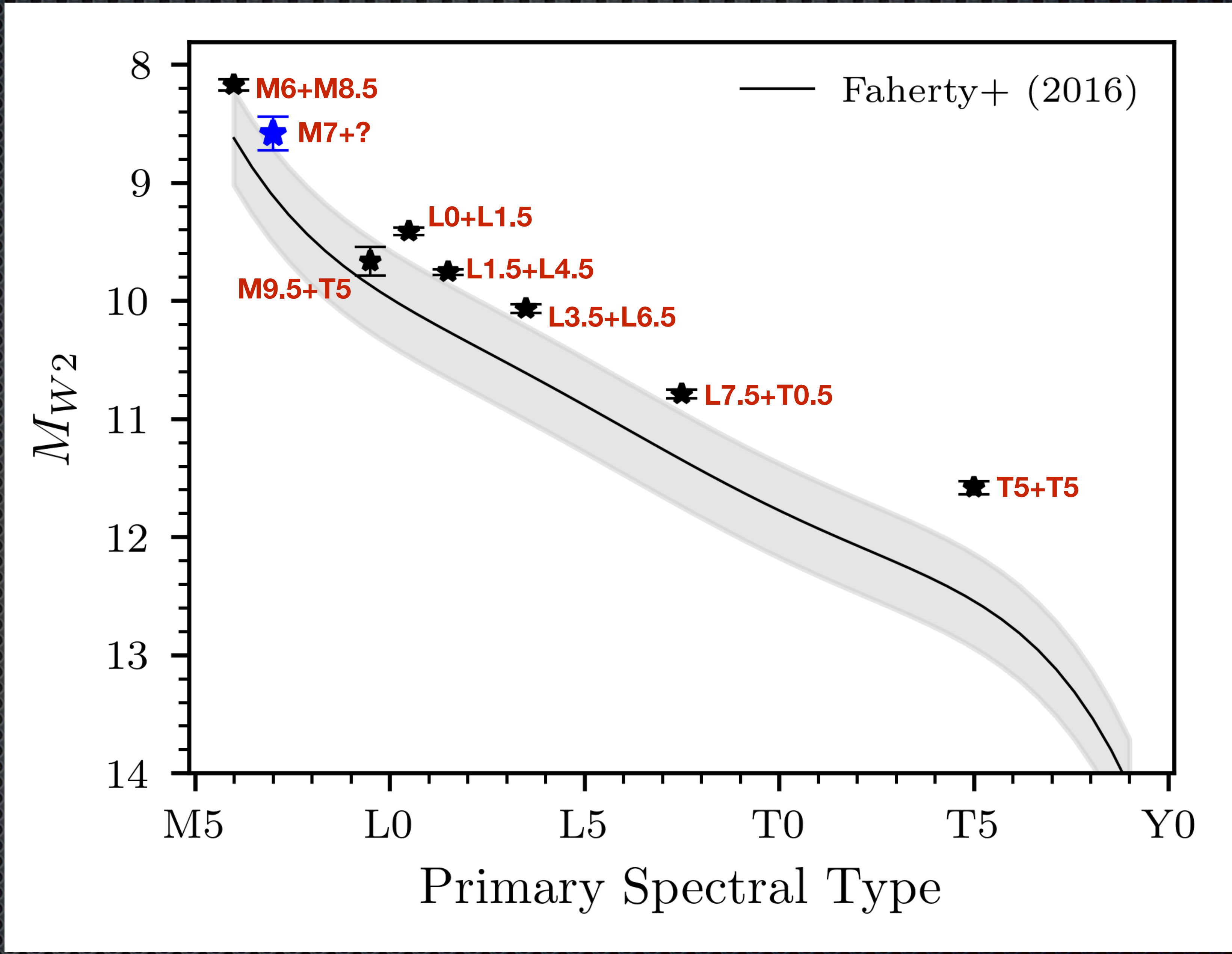
Other trigonometric distances:

URAT = 22.0 ± 2.8 pc

Gaia DR2 = 27.62 ± 0.41 pc (goodness of fit is baaaad)

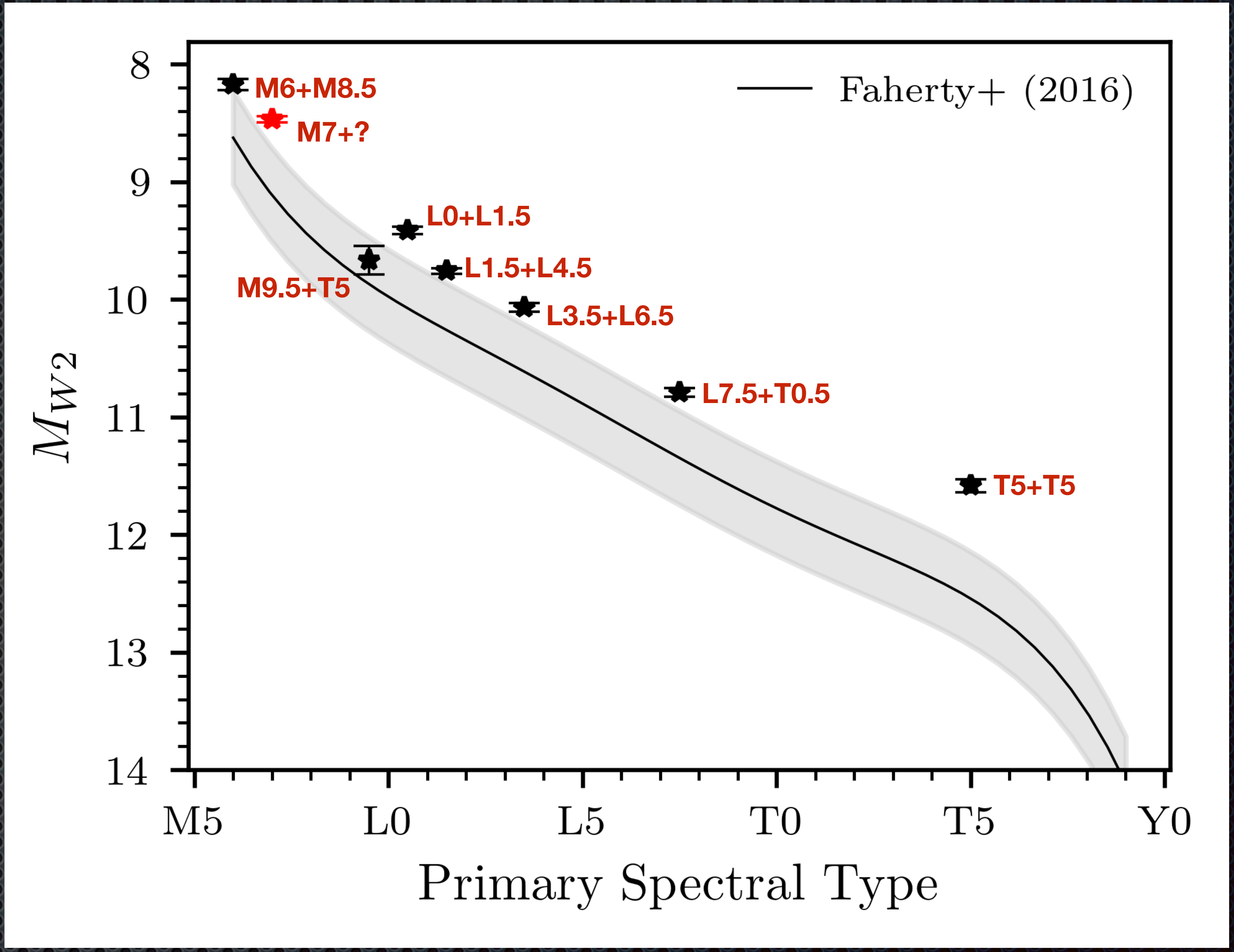
Overluminous Binaries

Unresolved binaries appear overluminous (highly dependent on flux ratio)



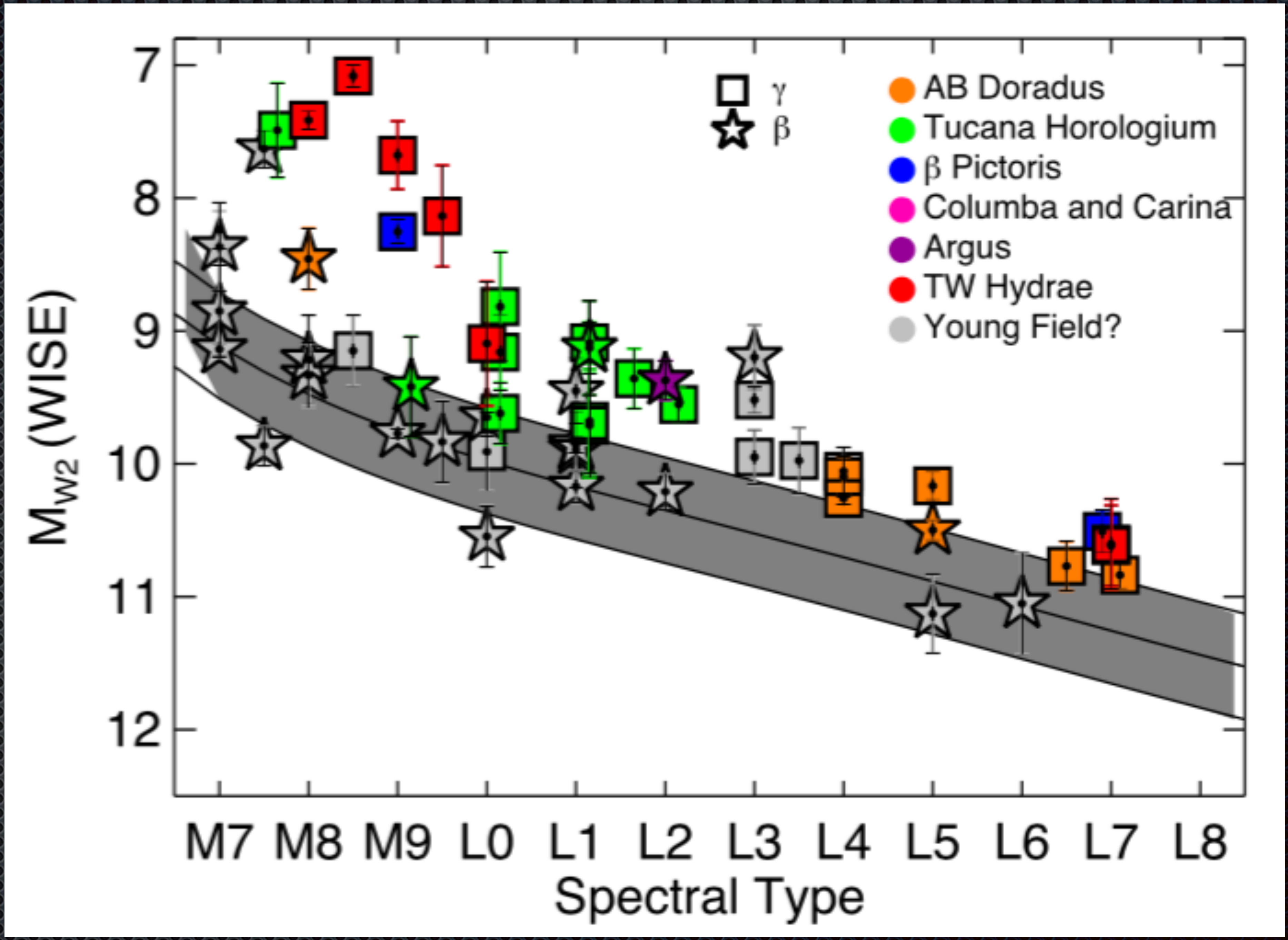
Overluminous Binaries

Unresolved binaries appear overluminous (highly dependent on flux ratio)



Or…low surface gravity

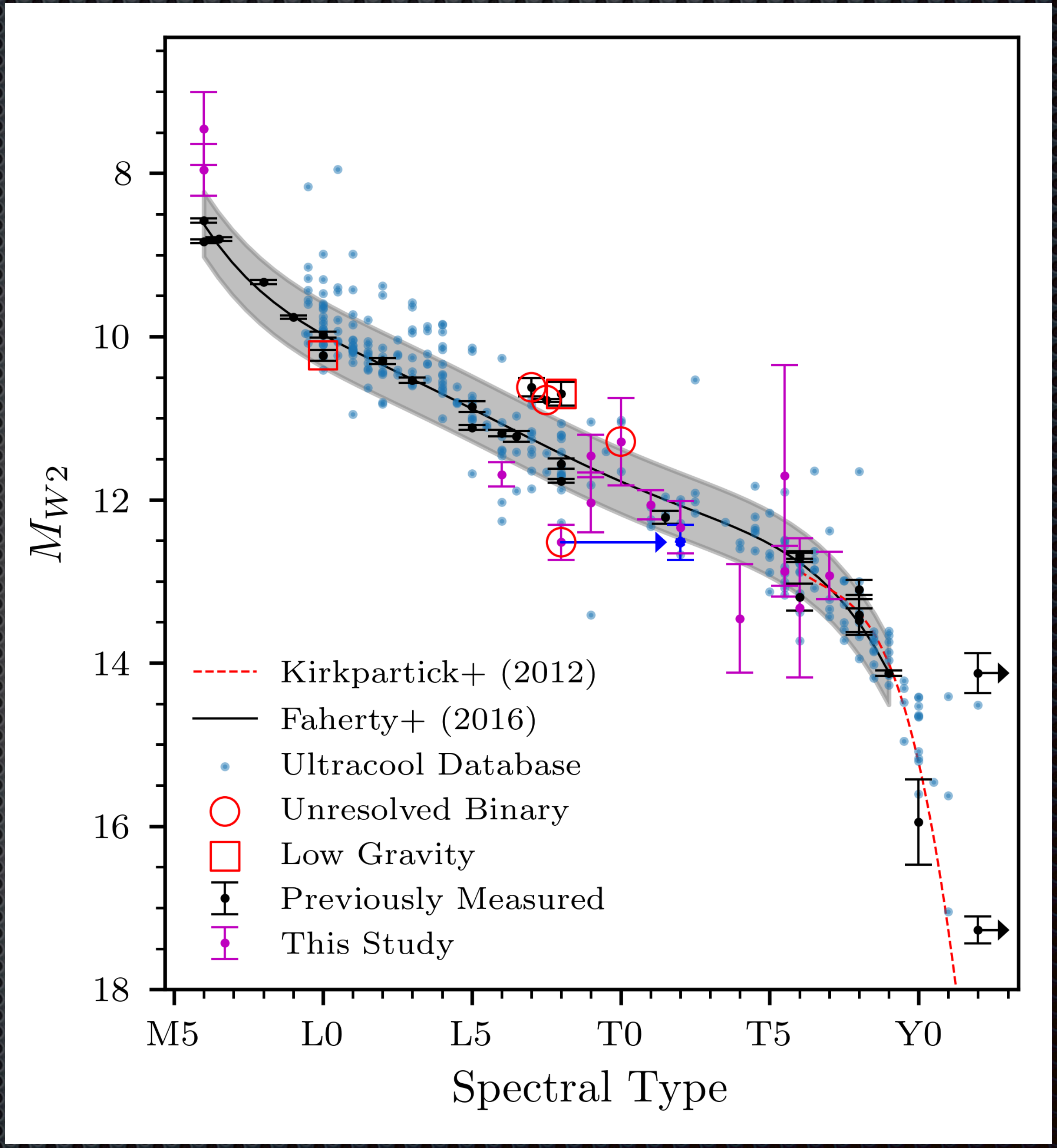
Young, low-gravity objects are also overluminous



Faherty+ (2016)

Controversy?

Spectral type - Absolute magnitude diagram

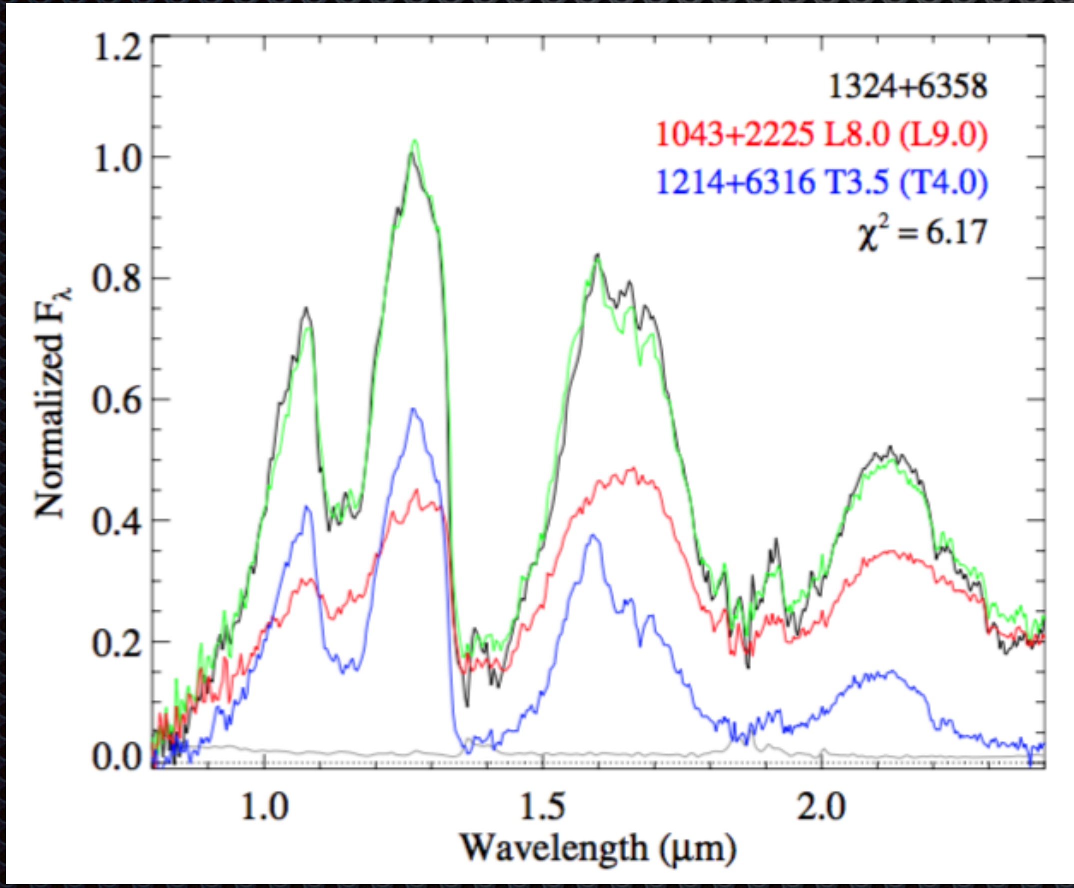


Theissen (2018)

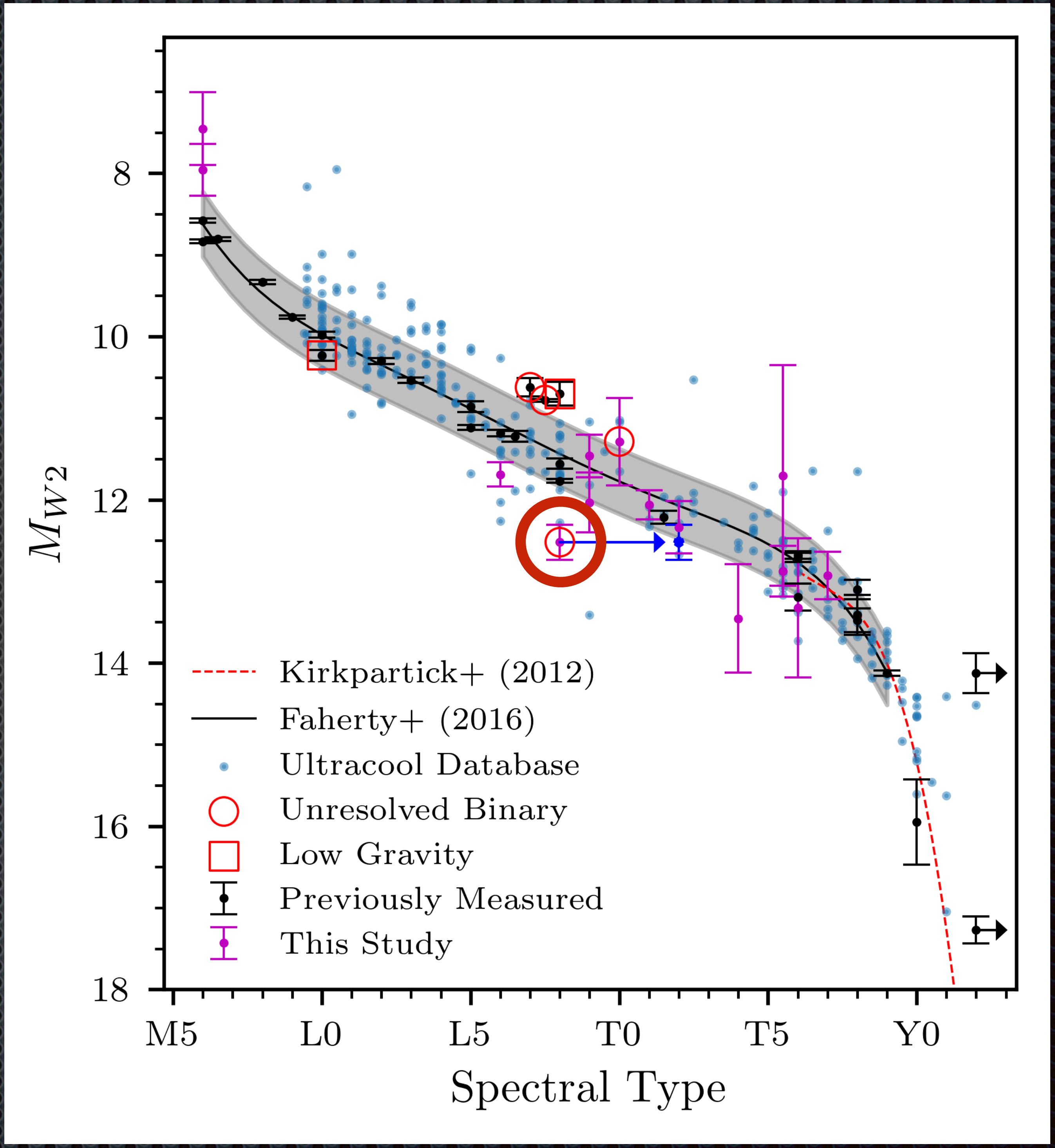
Controversy?

Spectral type - Absolute magnitude diagram

Spectral binary: L8+T3.5 (Burgasser+ 2010)



Burgasser+ (2010)



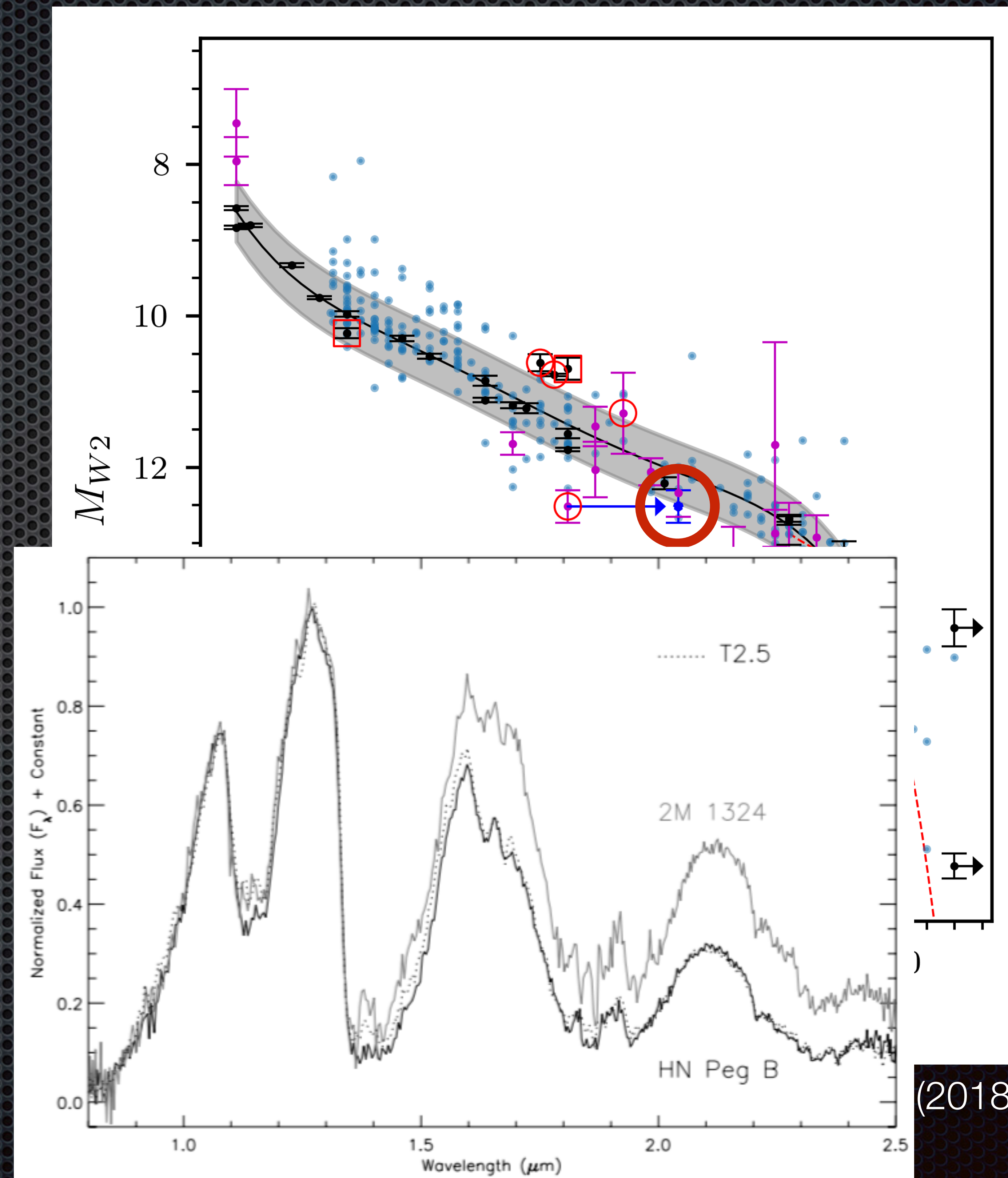
Theissen (2018)

Controversy?

Spectral type - Absolute magnitude diagram

Spectral binary: L8+T3.5 (Burgasser+ 2010)

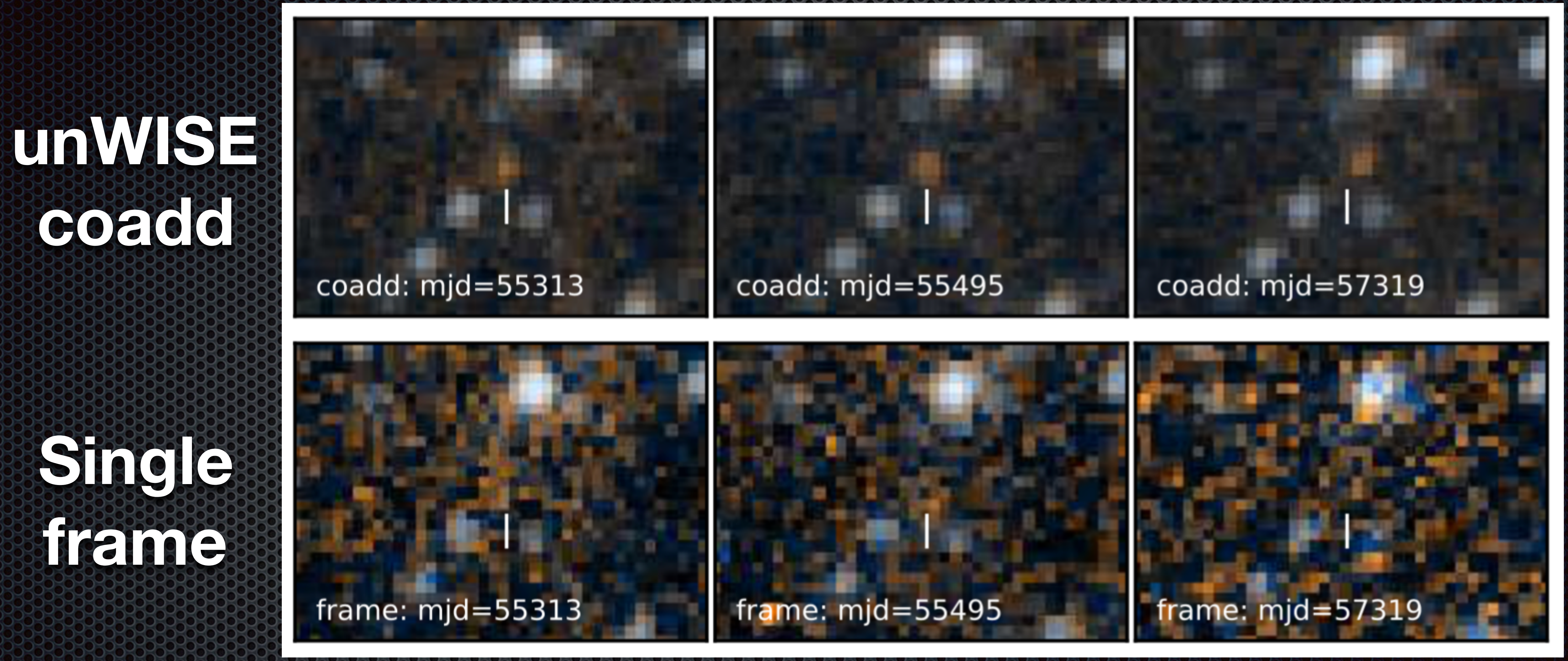
Object appears to be more consistent with a single object (T2; Looper+ 2007)



(2018)

Looper+ (2007)

Future directions: unWISE for deeper photometry



WISE J201404.13+042408.5

Meisner, Lang, & Schlegel (2018)

Thanks for listening

Gaia by the numbers

	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**1,692,919,135**	**1,142,679,769**
Number of 5-parameter sources	1,331,909,727	2,057,050
Number of 2-parameter sources	361,009,408	1,140,622,719
Sources with mean G magnitude	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	1,381,964,755	-
Sources with mean G_{RP}-band photometry	1,383,551,713	-
Sources with radial velocities	7,224,631	-
Variable sources	550,737	3,194
Known asteroids with epoch data	14,099	-
Gaia-CRF sources	556,869	2,191
Effective temperatures (T_{eff})	161,497,595	-
Extinction (A_G) and reddening ($E(G_{BP}-G_{RP})$)	87,733,672	-
Sources with radius and luminosity	76,956,778	-