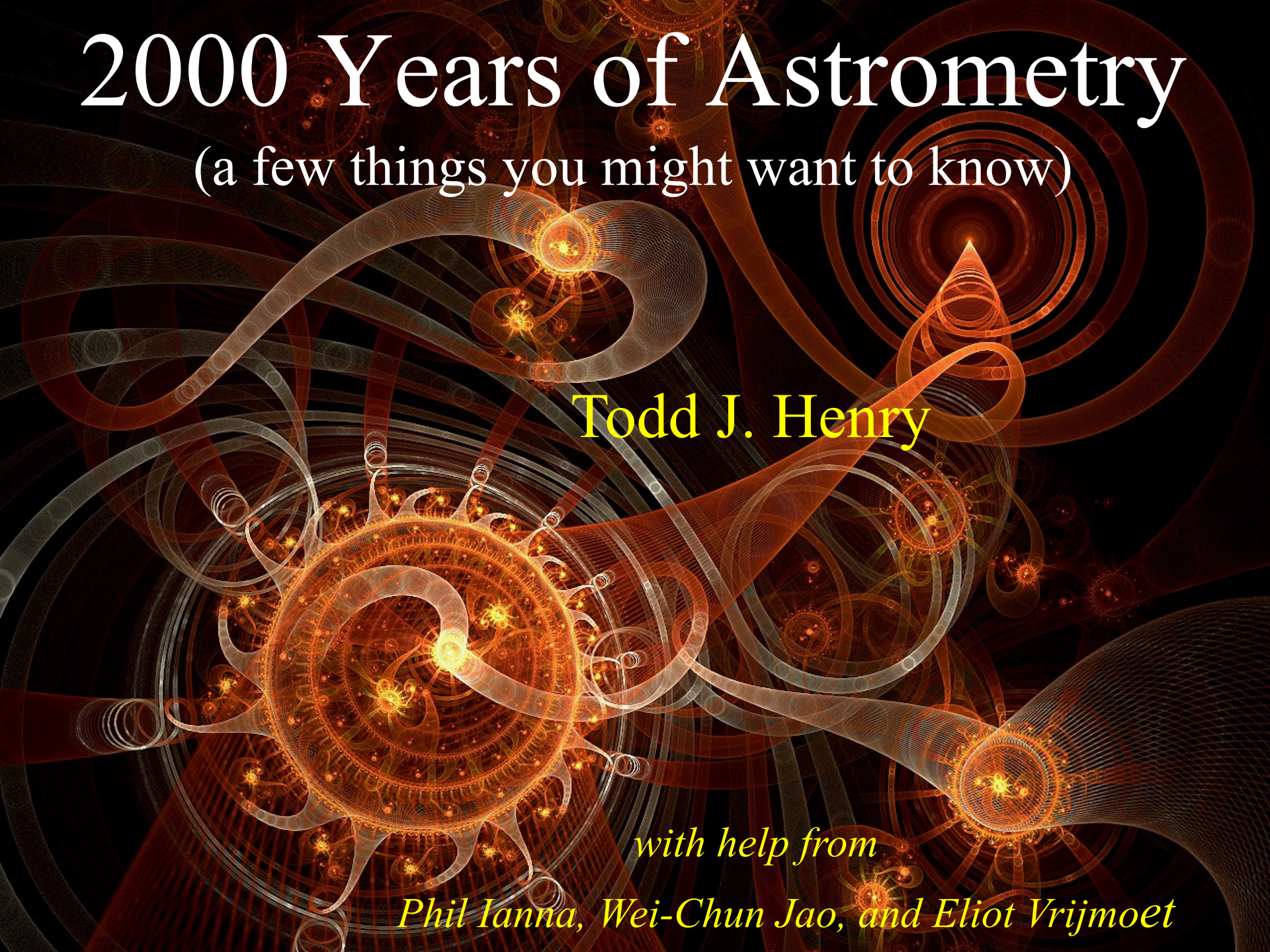
2000 Years of Astrometry

(a few things you might want to know)



Todd J. Henry

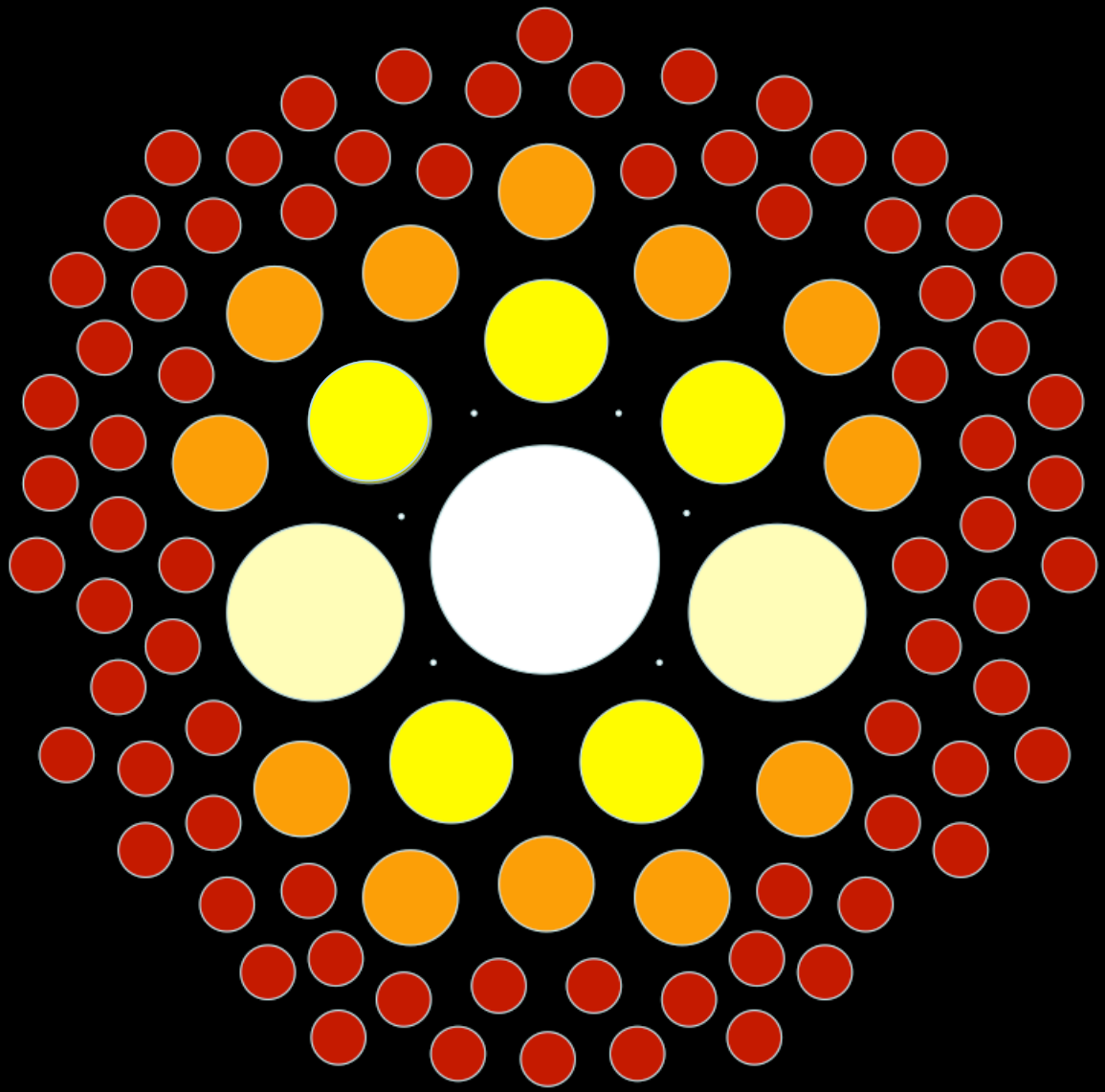
with help from

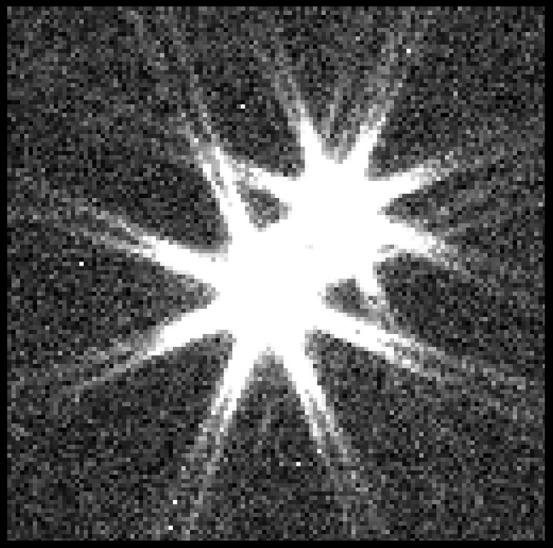
Phil Ianna, Wei-Chun Jao, and Eliot Vrijmoet

What is the Universe made of?

100 dwarfs

6 wd
1 A
2 F
5 G
12 K
74 M





RECONS

Research Consortium on Nearby Stars

recons.org

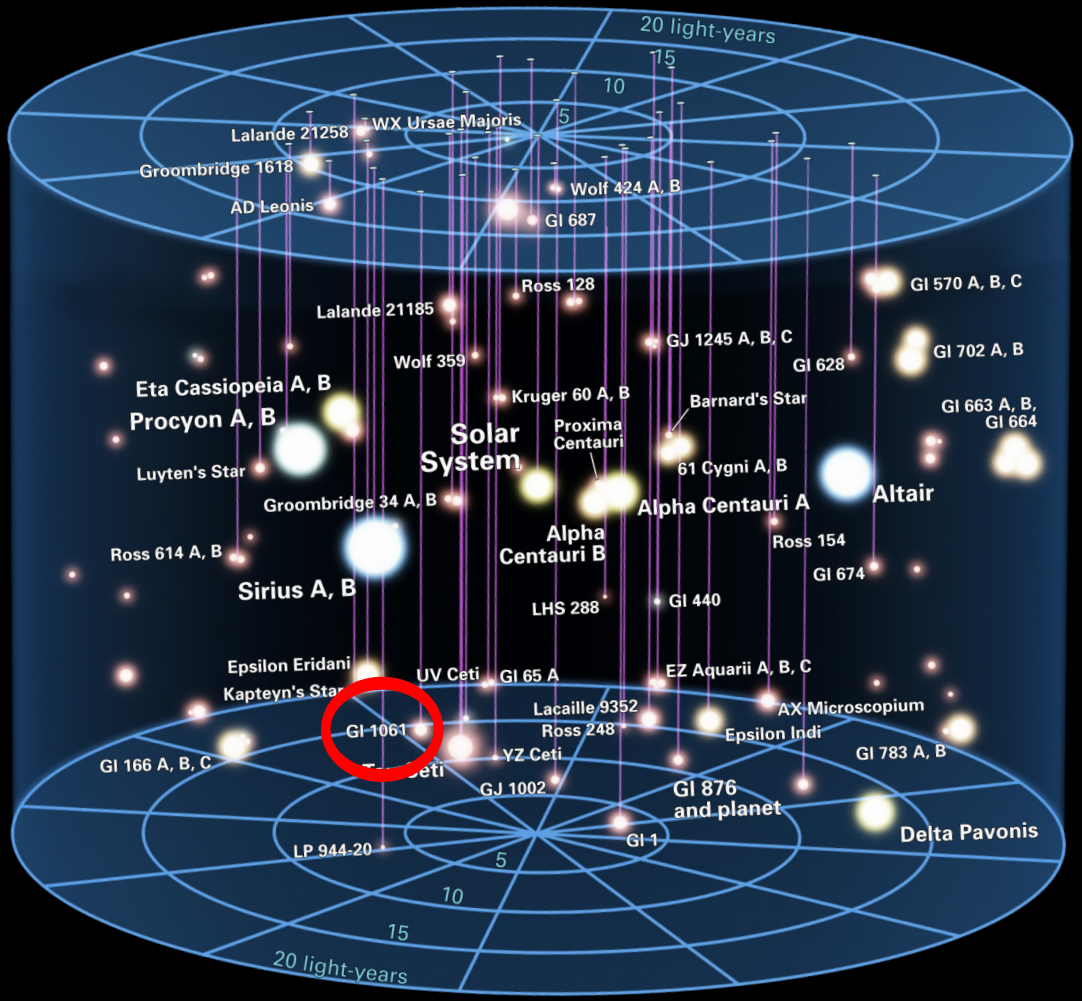
What is the Universe made of?

Where are the planets?

Is there life?

Astrometry helps answer these …

Astrometry = “metering the stars”



location

location

location

Henry/National Geographic (2000)

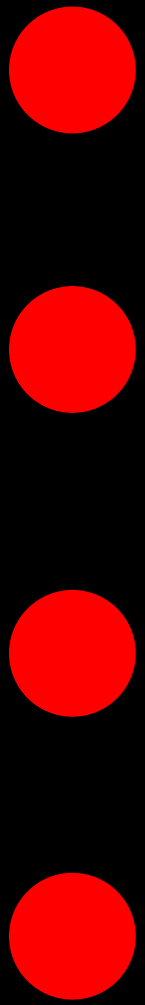
Astrometry = “metering the stars”

Position

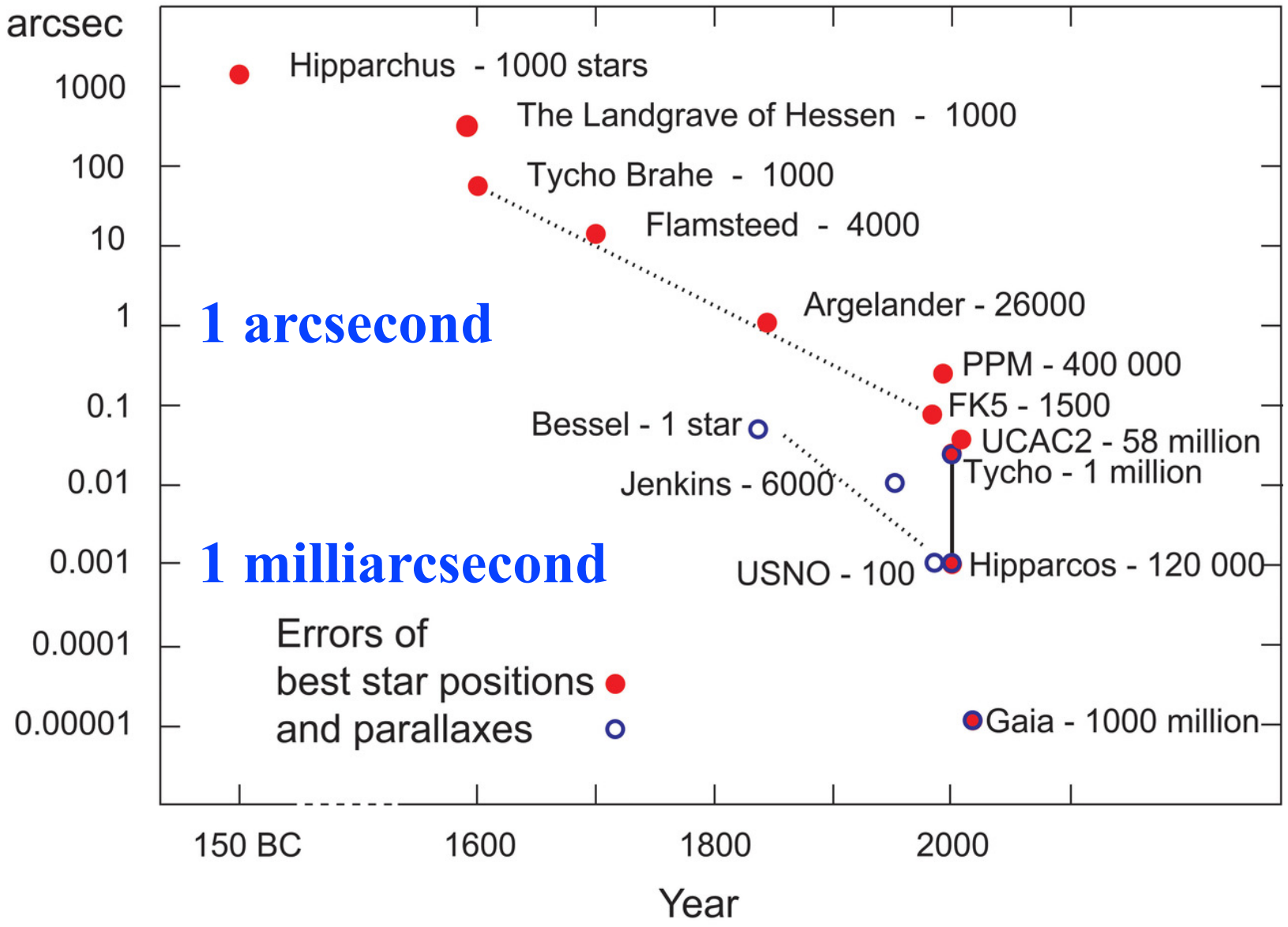
Proper Motion

Parallax

Perturbation



2000 Years of Astrometry

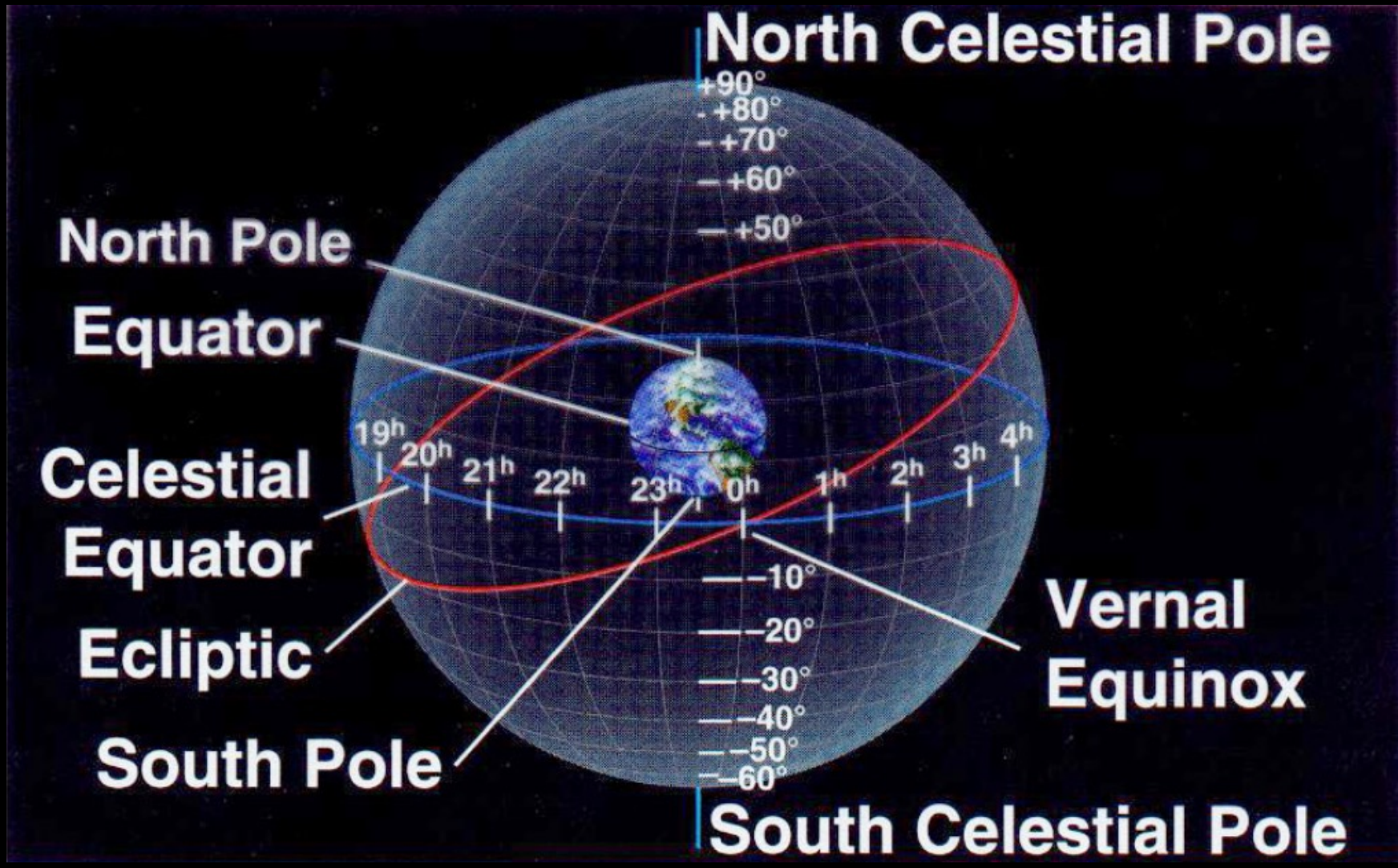


Position

RA α

Dec δ

Orientation



Position: Herschels' Milky Way (1785)

I. Table of Star-Gages.

R.A.	P.D.	Stars.	Fields.	Memorandums.
H. M. S.	D. M.			
0 1 41	78 47	9,9	10	
0 4 55	65 36	20,0	10	
0 7 54	74 13	11,3	10	Moſt of the ſtars extremely ſmall.
0 8 24	49 7	60	1	
0 9 52	113 17	4,1	10	* The gages marked with an aſteriſk
0 12 52	113 17	3,2	10	* are thoſe by which fig. 4. tab.
0 16 48	67 44	11,9	10	VIII. has been delineated.
0 21 52	113 17	3,9	10	*
0 22 21	87 10	5,9	10	
0 28 26	46 54	60	1	
0 31 38	46 54	40	1	
0 33 33	65 32	20,4	10	
0 34 22	56 38	20	1	
0 35 22	55 38	24	1	
0 36 39	76 32	11,3	10	
0 39 56	78 43	8,1	10	
0 40 29	48 43	60	½	
0 44 21	87 10	7,6	10	
0 46 22	69 51	11	10	
0 46 33	65 32	13	10	
0 48 42	58 47	40	1	
0 48 50	58 13	17	1	
0 53 18	67 41	9,8	10	A little hazy.
0 53 40	45 37	73	1	
0 54 10	75 16	13	1	

USED

star count model with "Star-Gages"

stellar number densities in > 600 fields

low density? … several fields averaged

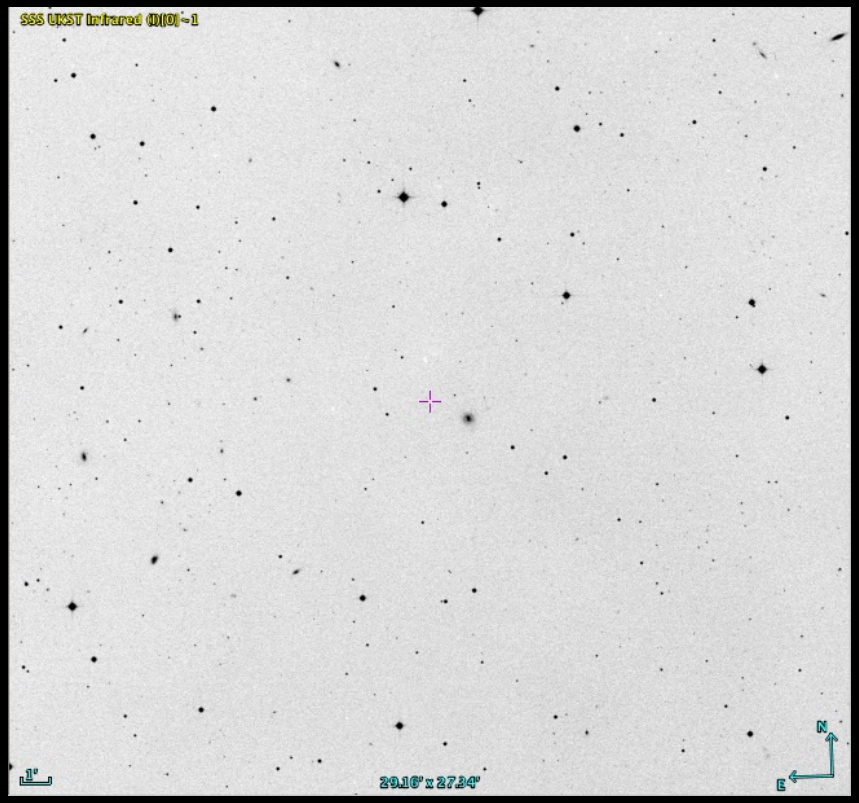
DID NOT HAVE

parallaxes … no luminosities

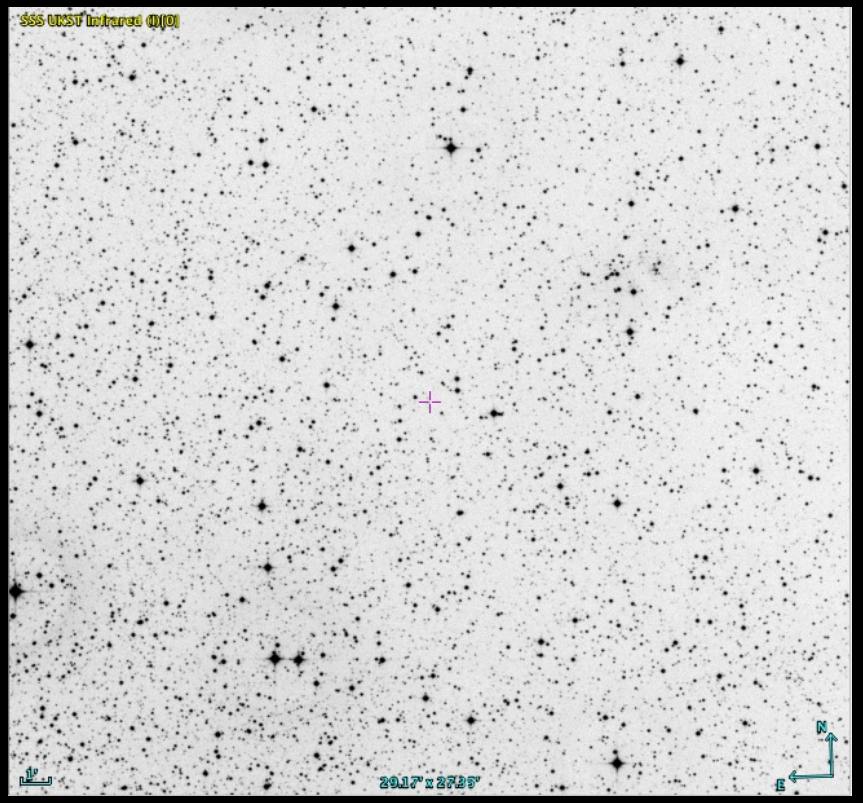
star colors … no temperatures

… no HR diagram

Position: Herschels' Milky Way (1785)



Galactic
North Pole



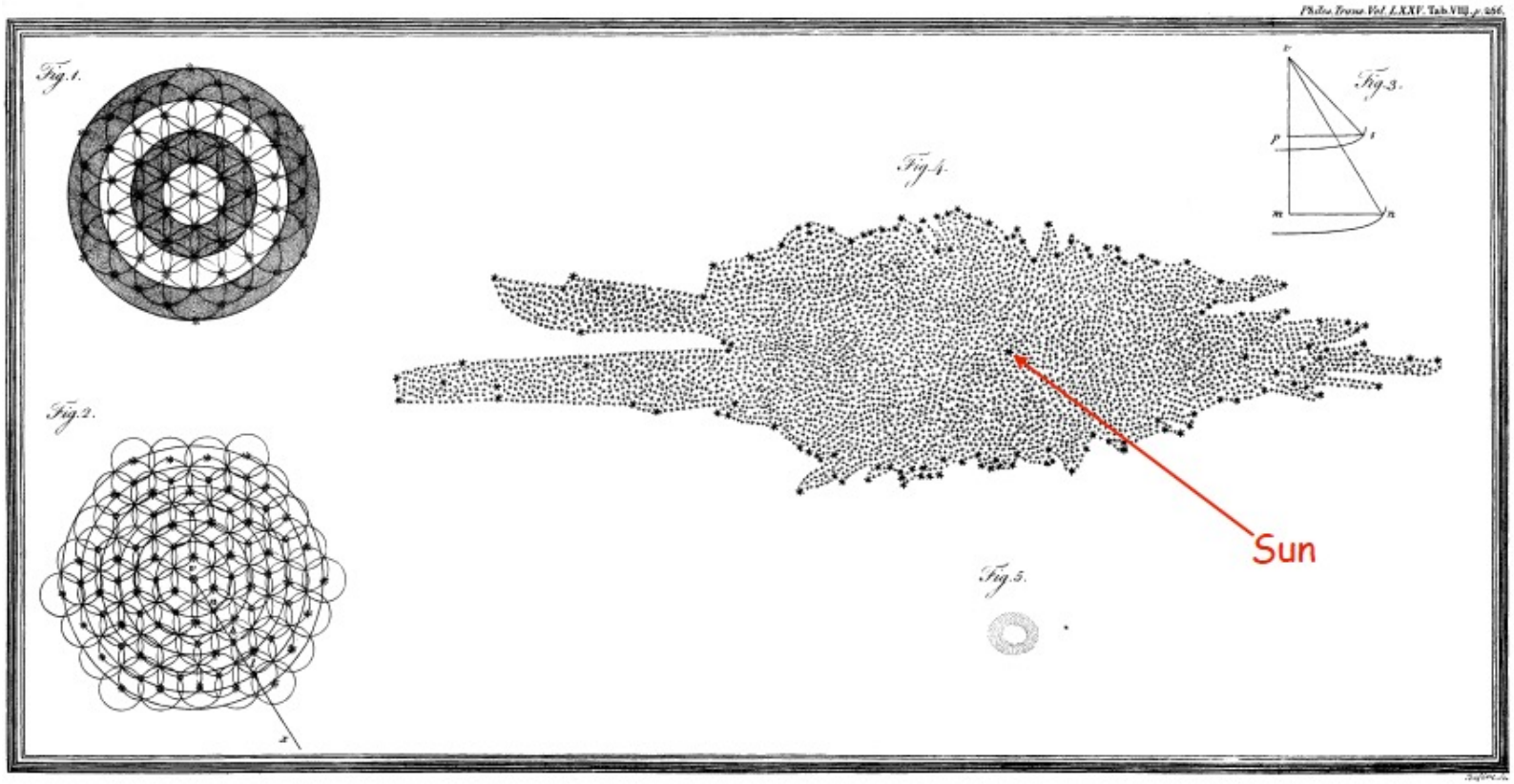
Galactic
Center

SuperCOSMOS
30 arcmin images

Position: Herschels' Milky Way (1785)

ASSUMED

1. all stars identical
2. stellar density uniform
3. no obscuration



RESULTS

disk of stars
thickness 1/10 diameter

Sun near center
MW much too small

Position: Shapleys' Globulars (1920)

Harlow Shapley

Martha Betz Shapley

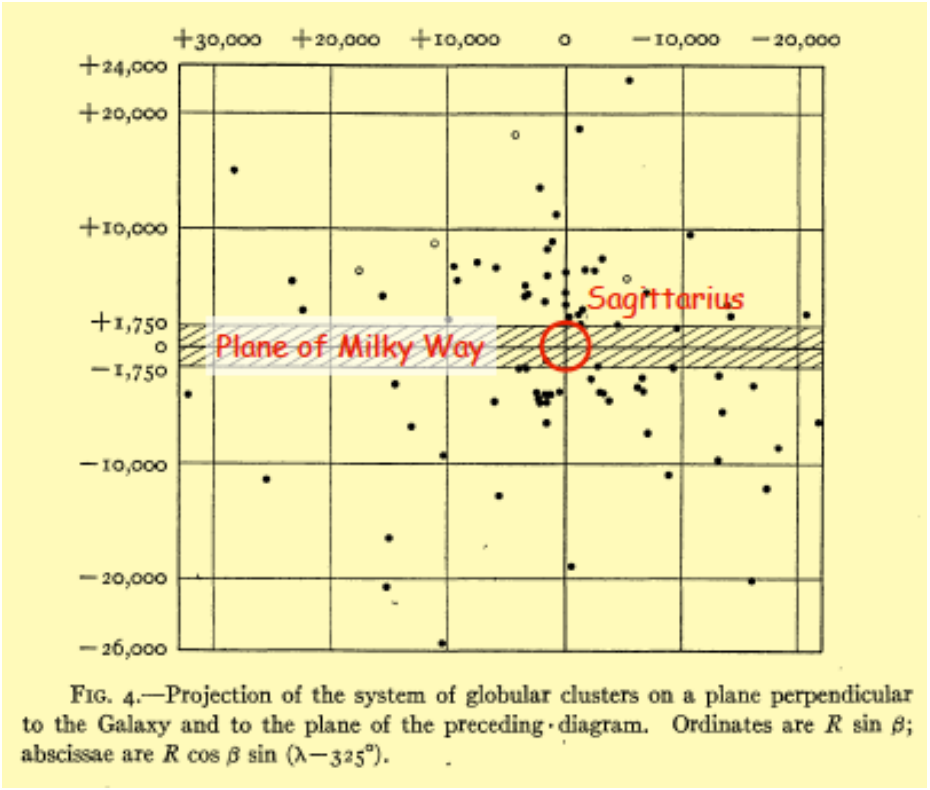
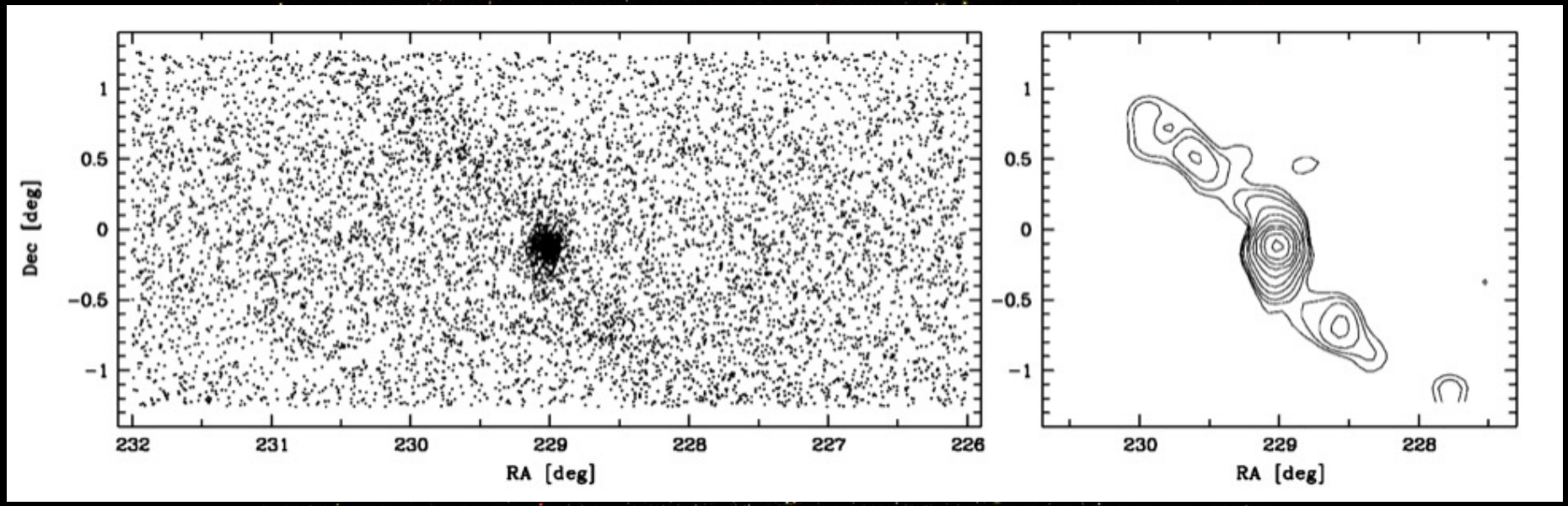


FIG. 4.—Projection of the system of globular clusters on a plane perpendicular to the Galaxy and to the plane of the preceding diagram. Ordinates are $R \sin \beta$; abscissae are $R \cos \beta \sin (\lambda - 325°)$.

1. use apparent sizes + brightest star mags
2. derive distances
3. make a map … distribution of globulars not symmetric

WE ARE NOT AT THE CENTER OF MW

Position: Halo Population (2001)



Odenkirchen+ (2001)

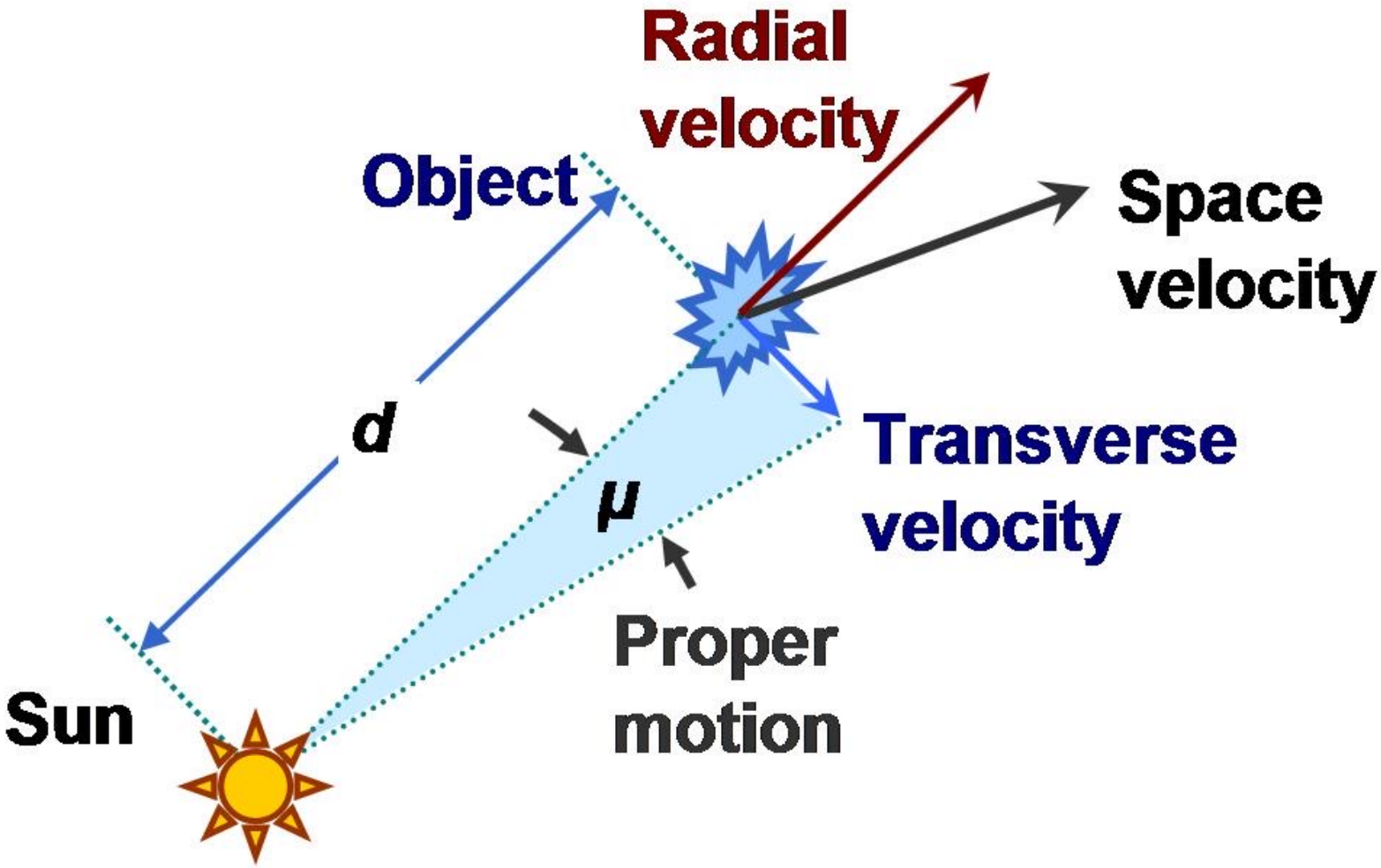
Palomar 5
SDSS commissioning data

tidal tails stretching 2.6^{o} on sky
mass loss … halo members
estimate orbit around MW

Proper Motion

μ

Proper Motion



15
image: Brews O'Hare

WARNING: Equation

$$v_{\text{tan in km/sec}} = 4.74\ \mu_{\text{arcsec/yr}}\ d_{\text{parsecs}}$$

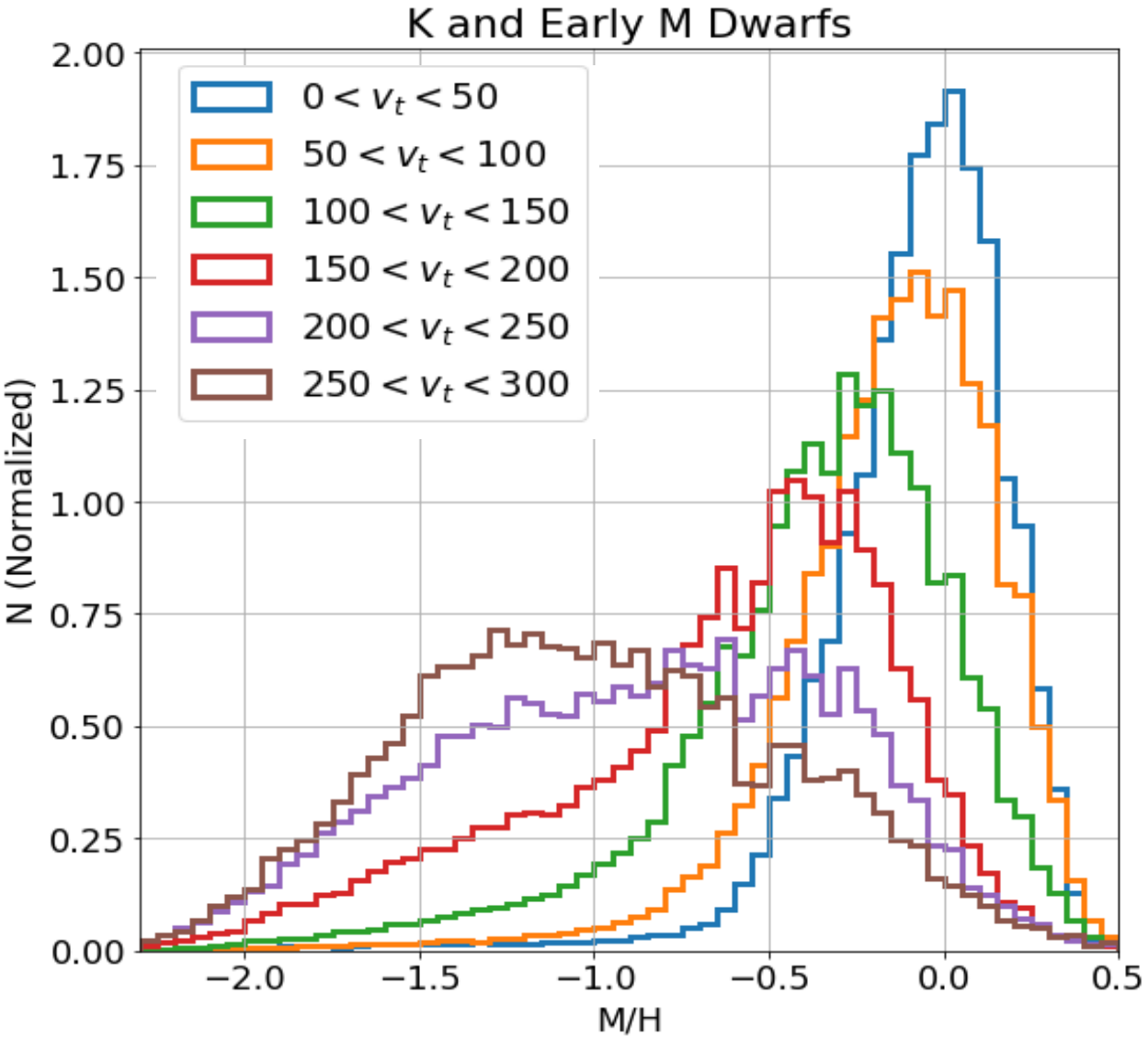
(need a distance)

4.7 km/sec	1 arcsec/yr at 1 parsec
47 km/sec	1 arcsec/yr at 10 parsecs
[474 km/sec	1 arcsec/yr at 100 parsecs]

Gaia DR3 errors ~ 0.04 mas/yr in RA and Dec

add radial velocity and parallax … get total velocity and UVW space motions

Proper Motion



Medan et al. 2021

Cerro Tololo Inter-American Observatory

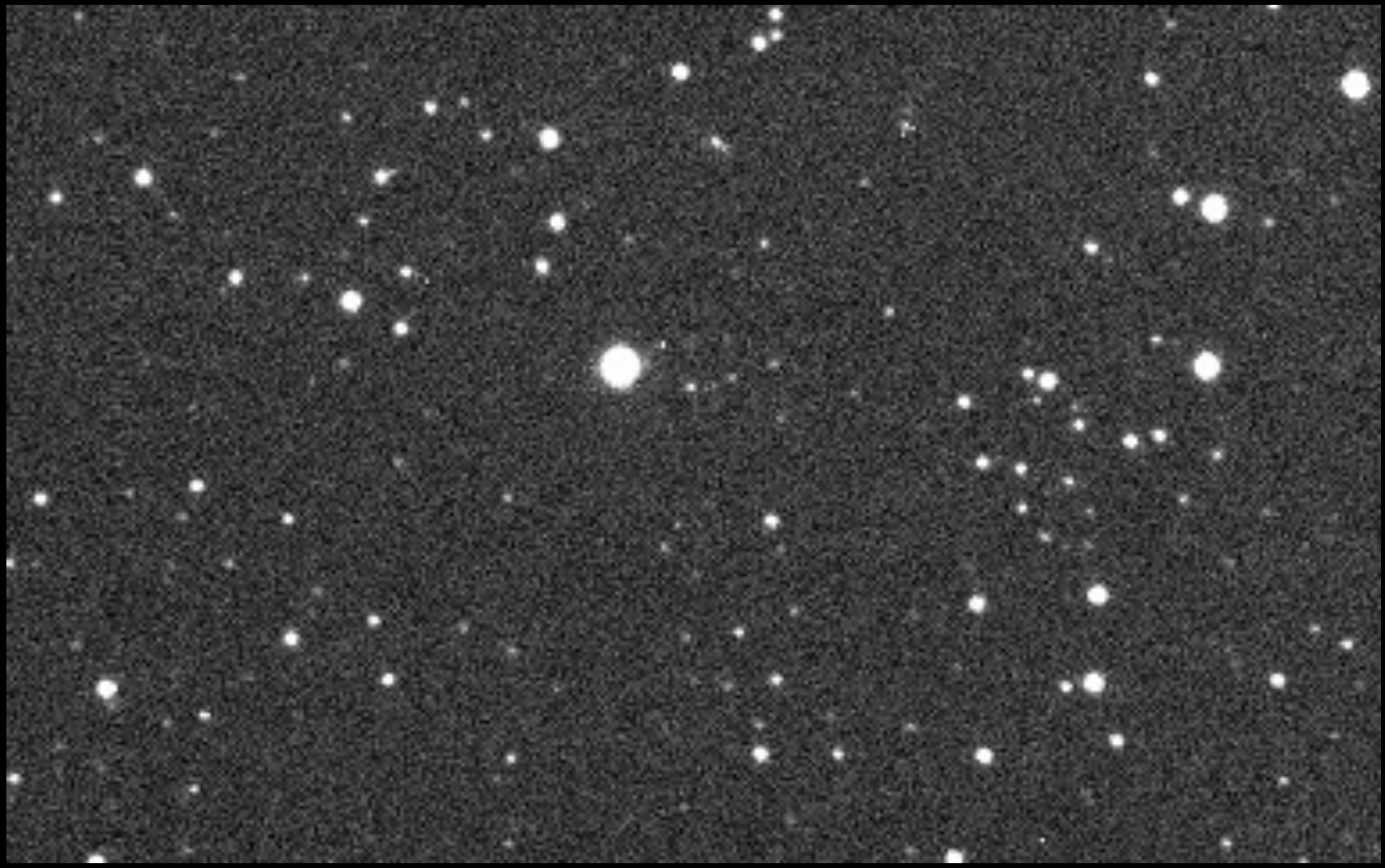
astrometry+
photometry
program

1999+

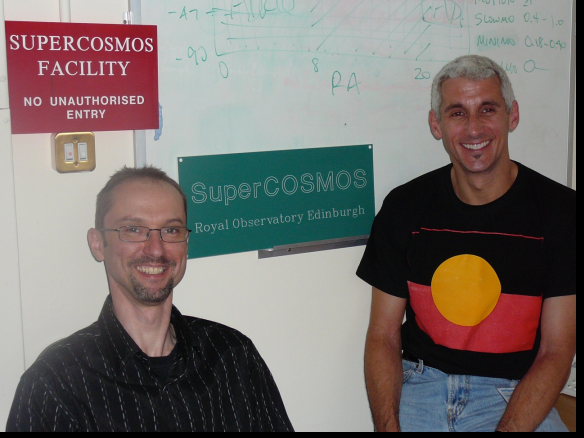
1.0m Schmidt 4.0m 1.5m 0.9m

SMARTS telescopes at CTIO

Proxima Centauri

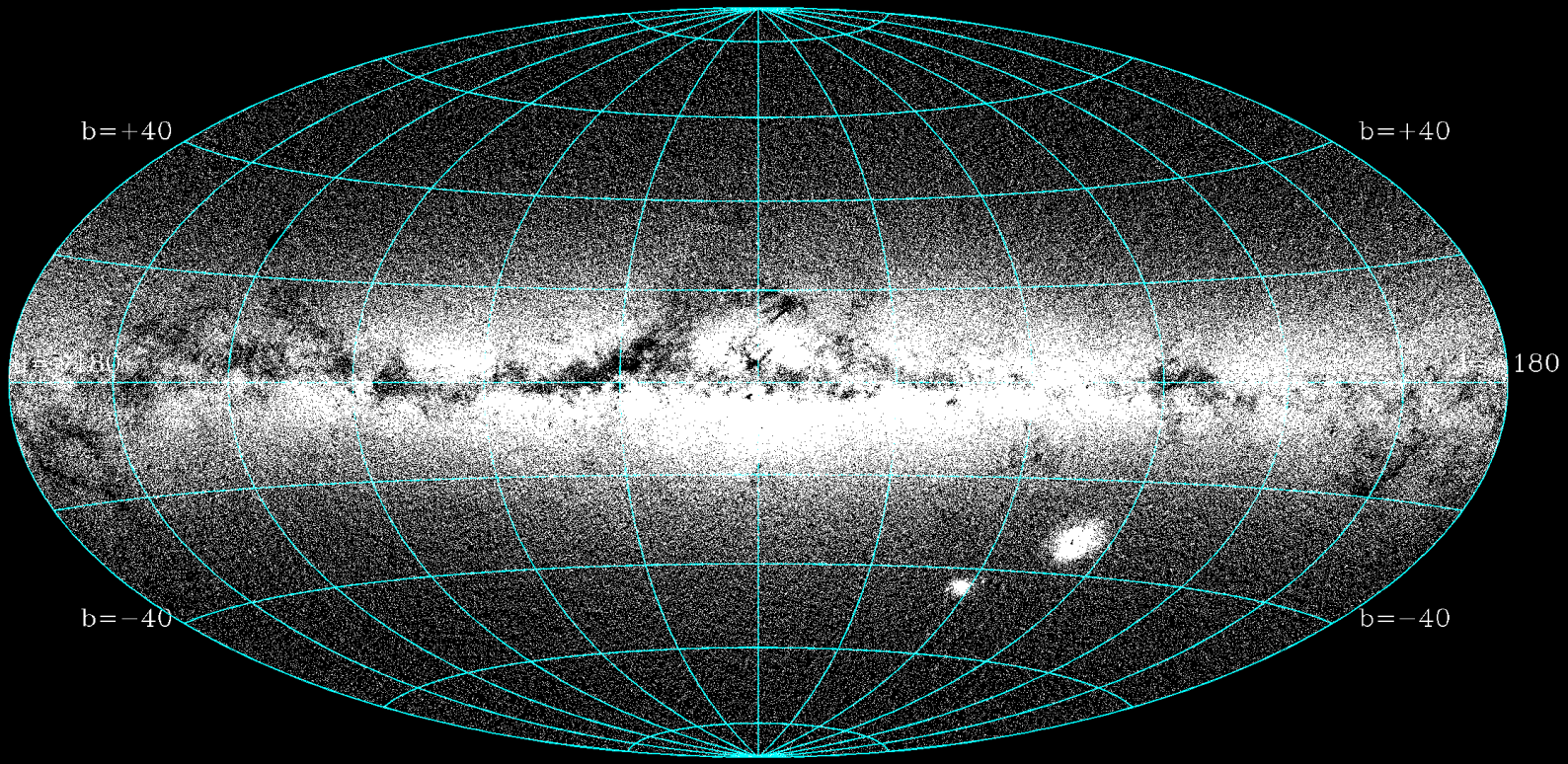


movie by Adric Riedel



SuperCOSMOS-RECONS (SCR) Search

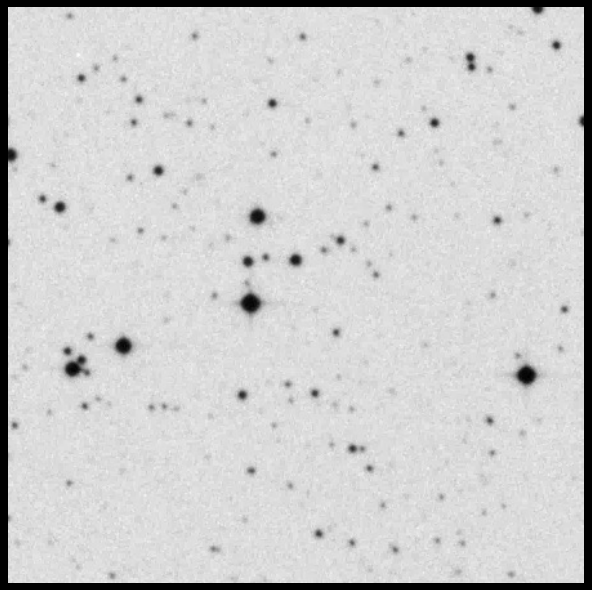
with Nigel Hambly (U. Edinburgh)



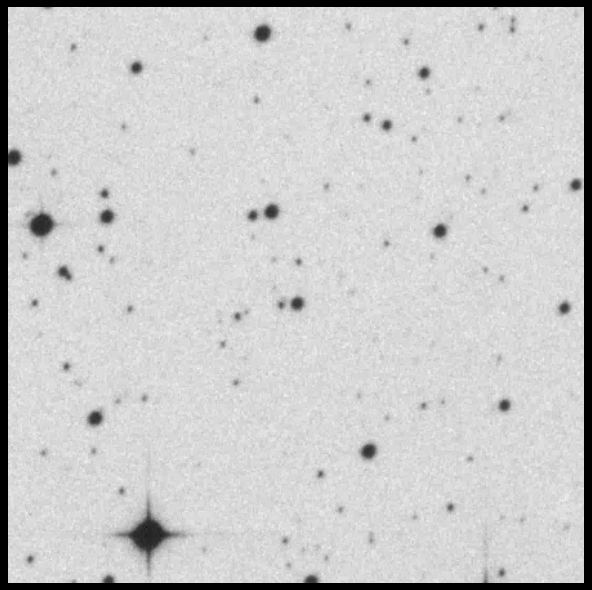
1.9 billion sources

Proper Motion

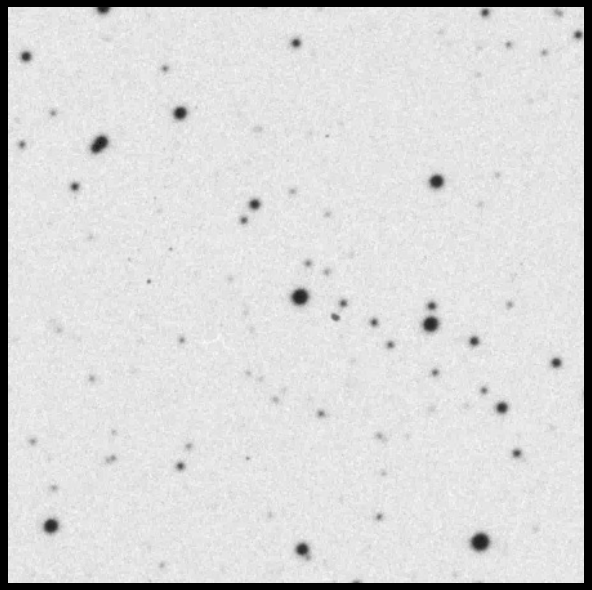
SCR 1138-7721



SCR 1848-6855

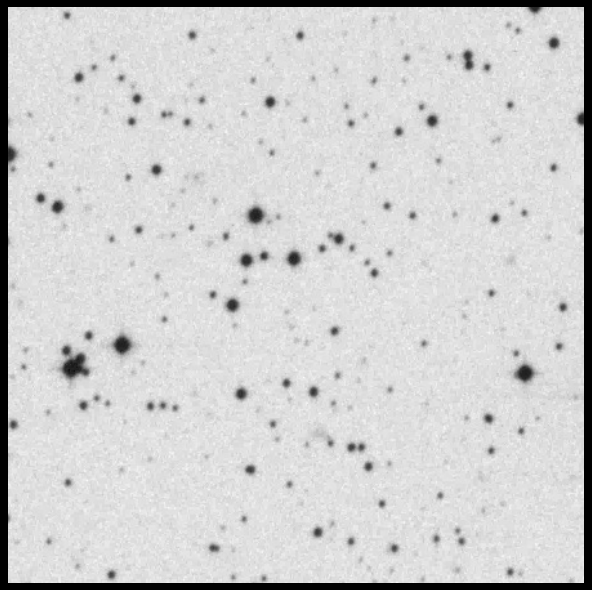


SCR 1845-6357

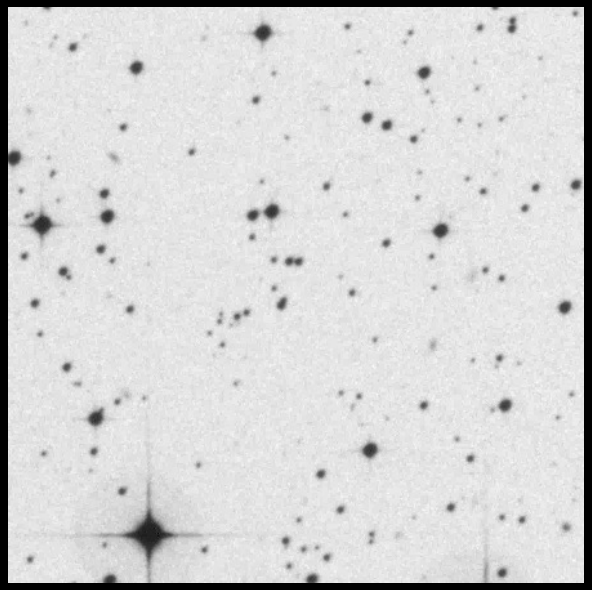


Proper Motion

SCR 1138-7721



SCR 1848-6855



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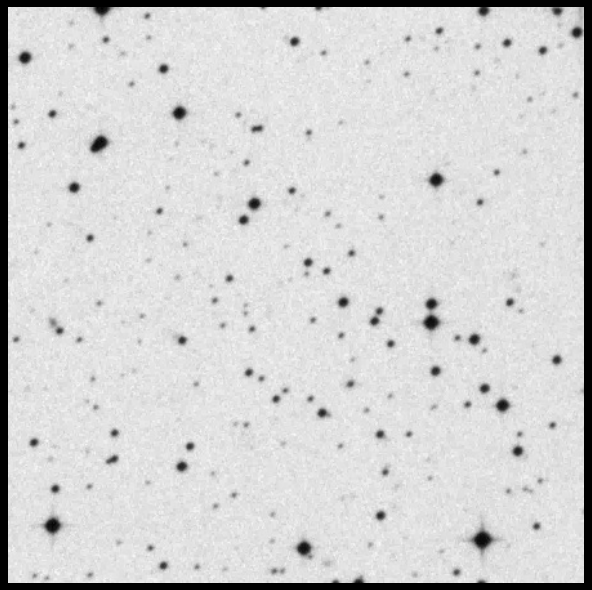
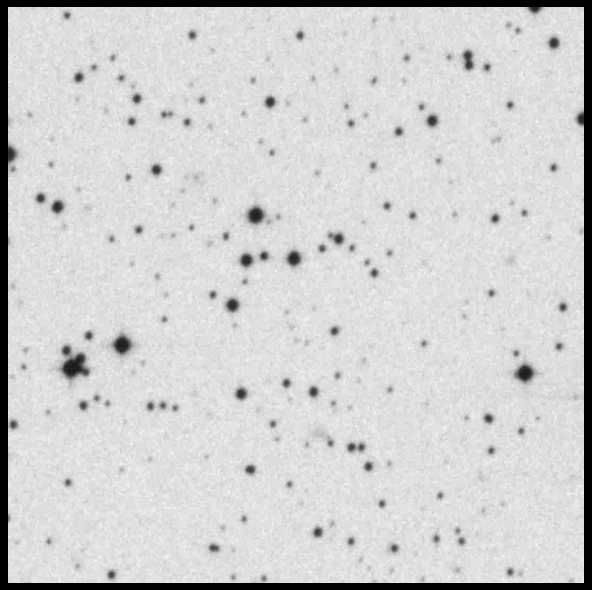


Proper Motion

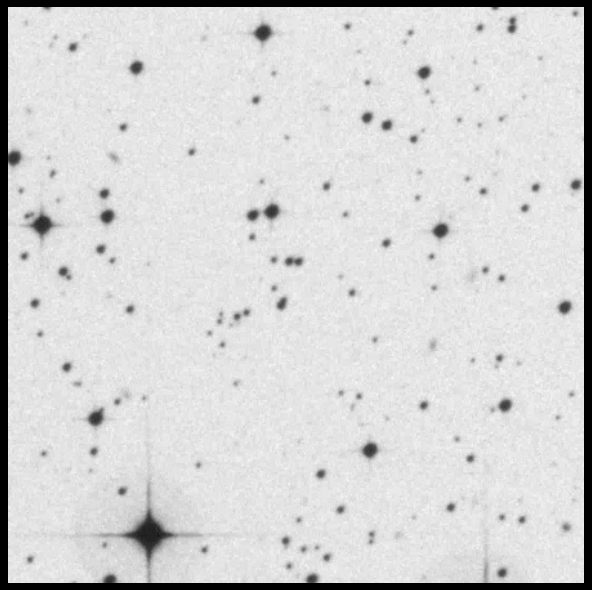
SCR 1138-7721



M dwarf
single

8.4 pc

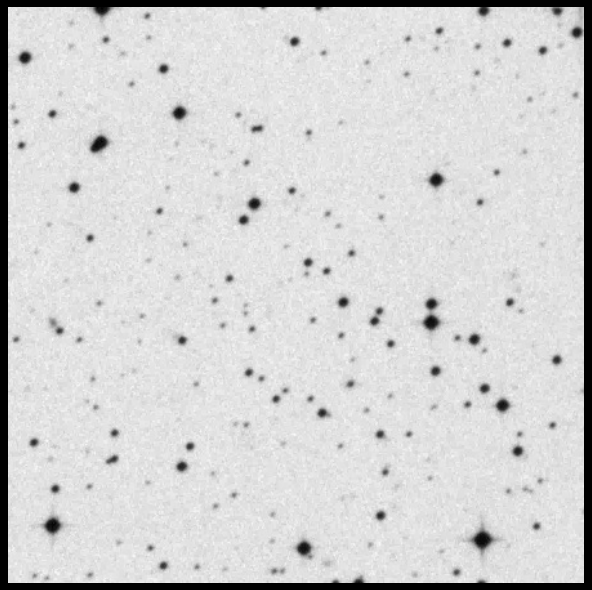
SCR 1848-6855



M dwarf +
white dwarf

26.1 pc

SCR 1845-6357



M dwarf +
brown dwarf

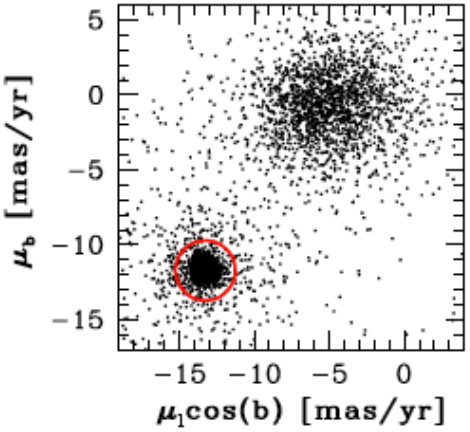
4.0 pc

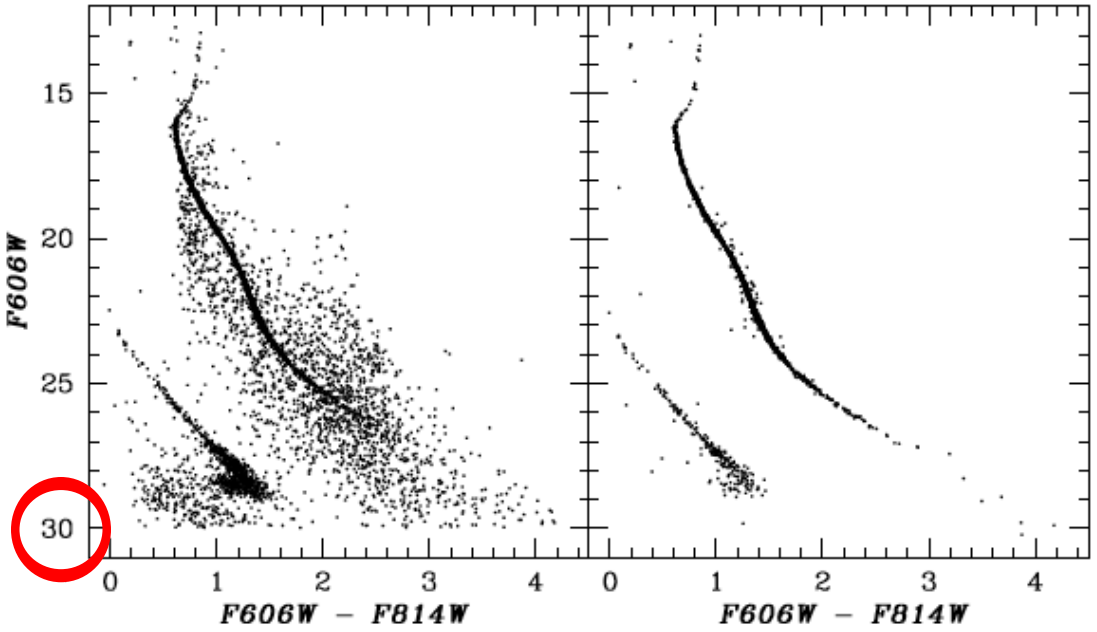
Proper Motion

image: Verschatse

globular cluster NGC 6397

126 orbits
with HST/ACS





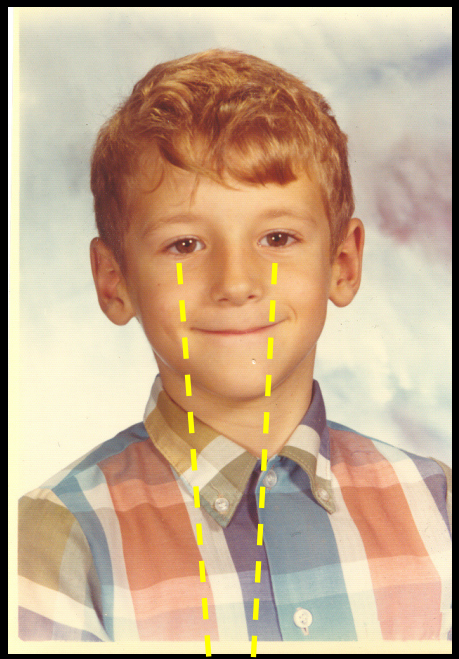
Kalarai & Richer (2010)

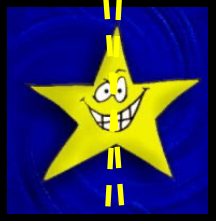
Parallax

π

(ϖ)

Parallax

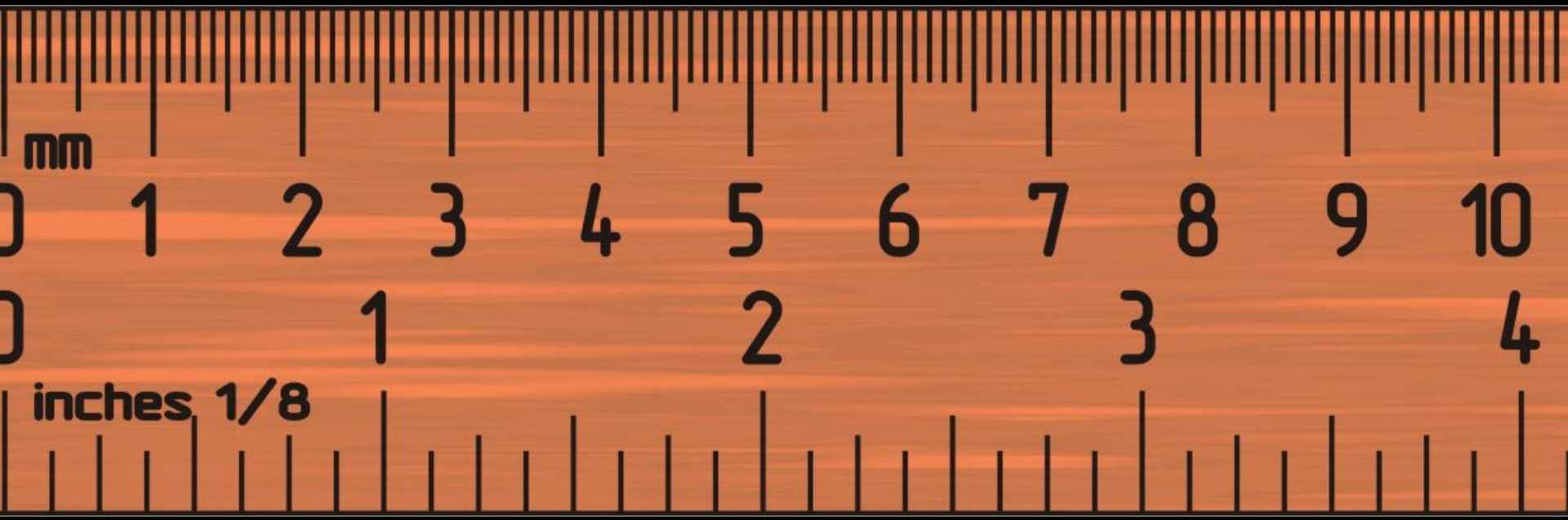




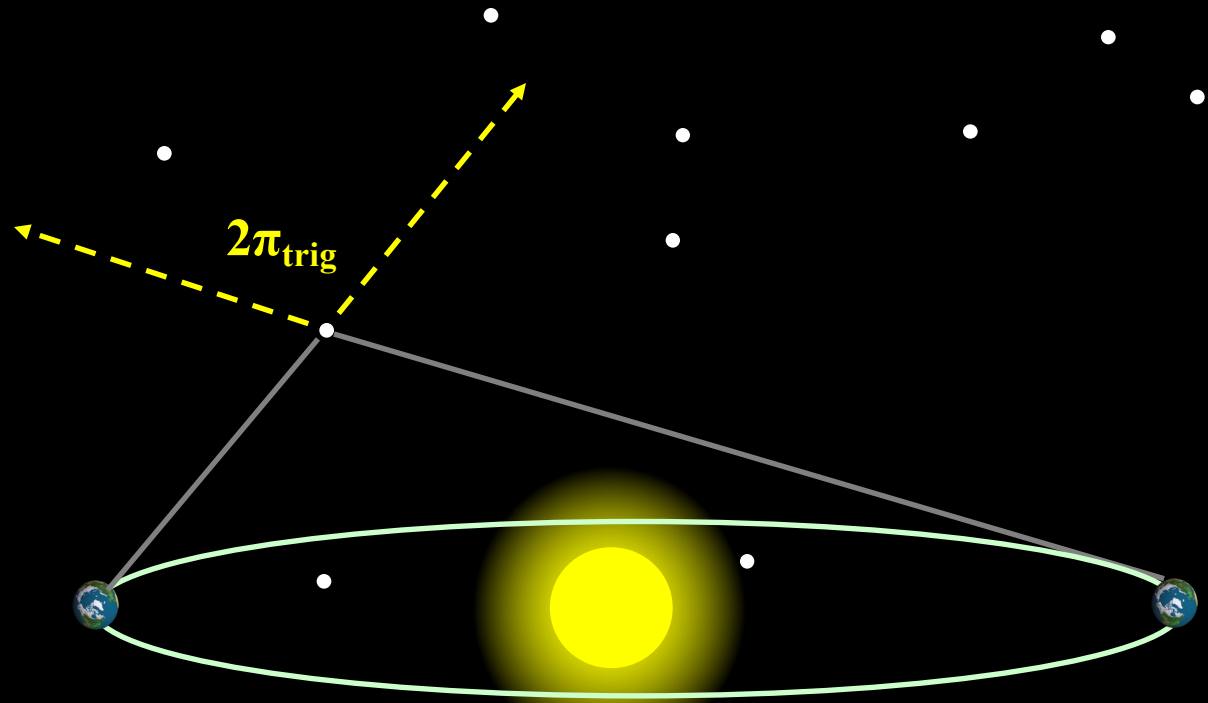
π_{trig}

1 arcsecond at 1 parsec

Parallax



Parallax



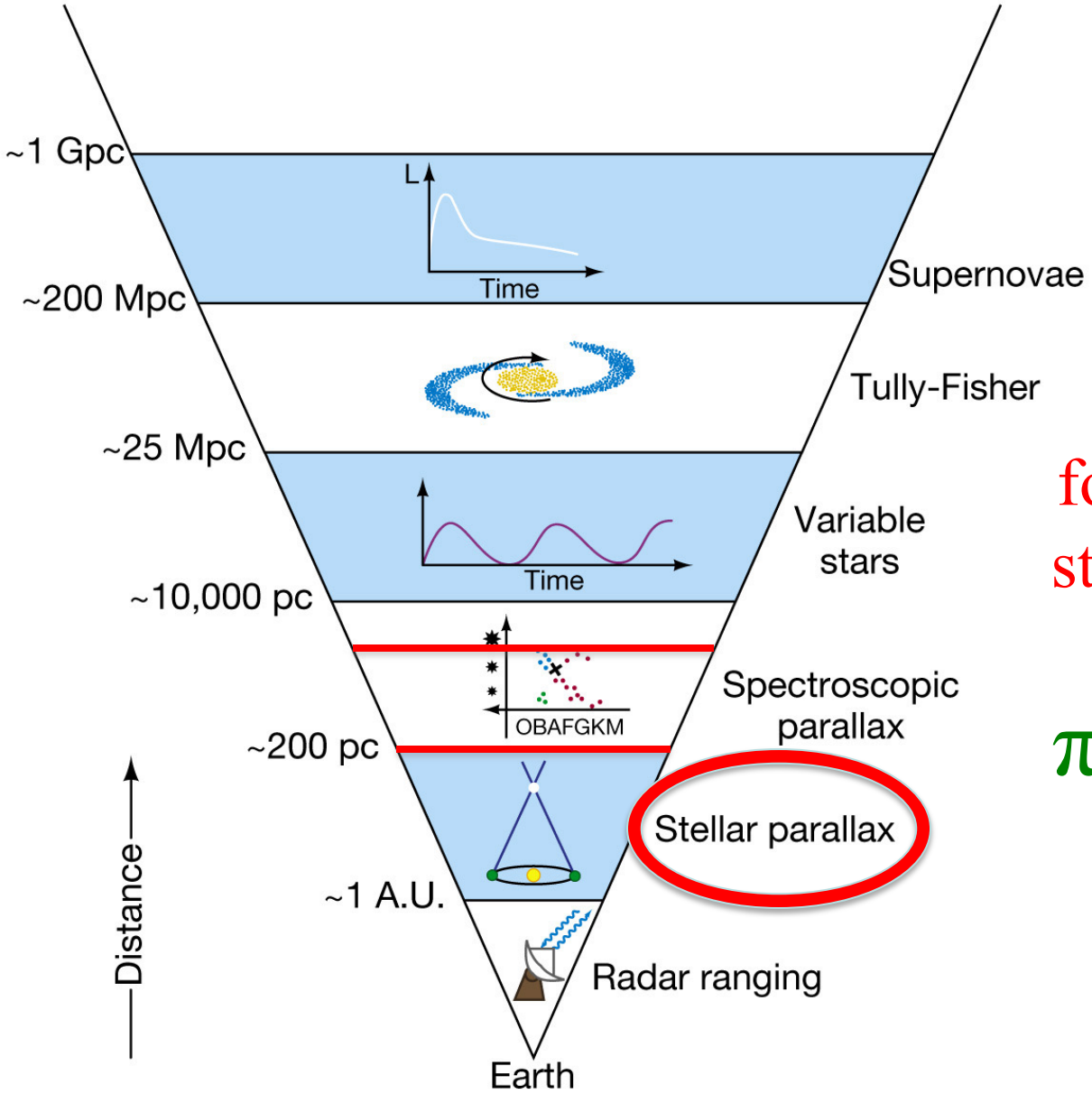
WARNING: Equation

$$d_{parsec} = 1 / \pi_{arcsec}$$

1 parsec	1 arcsec = 1000 millliarcseconds (mas)
10 parsecs	0.1 arcsec = 100 mas
100 parsecs	0.01 arcsec = 10 mas
1000 parsecs	0.001 arcsec = 1 mas

Gaia DR3 errors ~ 0.04 mas

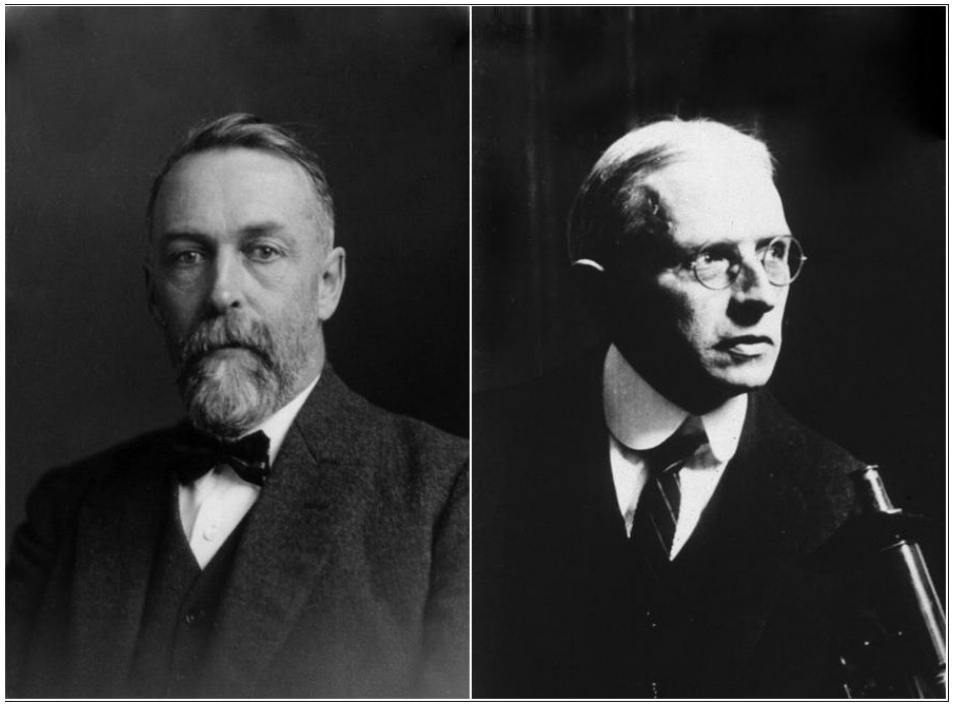
Parallax: Distance Ladder



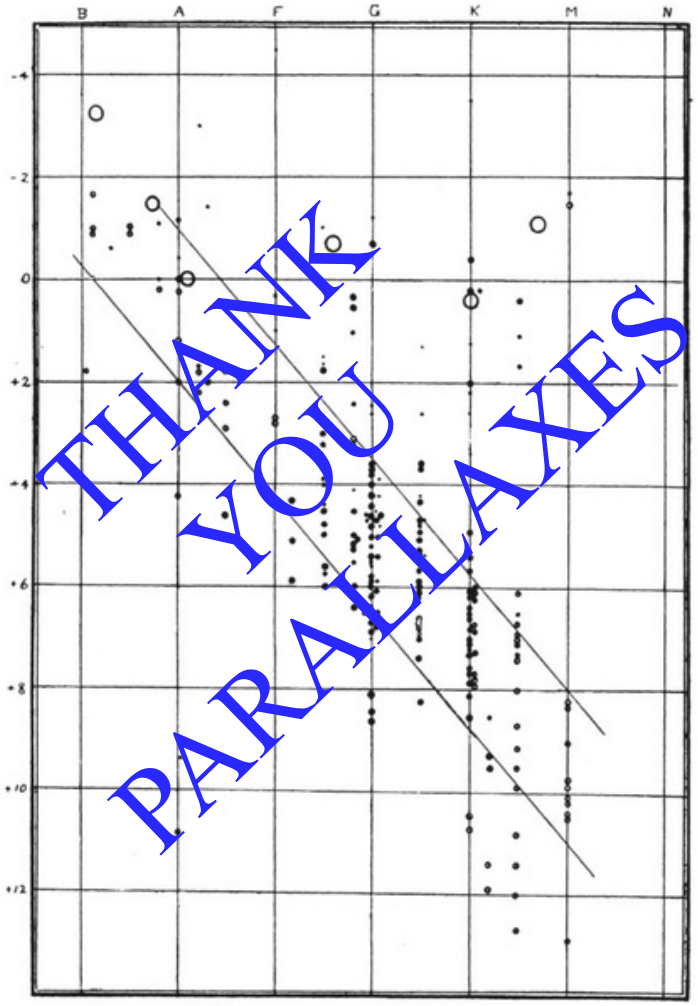
for this Workshop
stay within 100 pc

$\pi \geq 10$ mas

Parallax: H-R Diagram (1914)



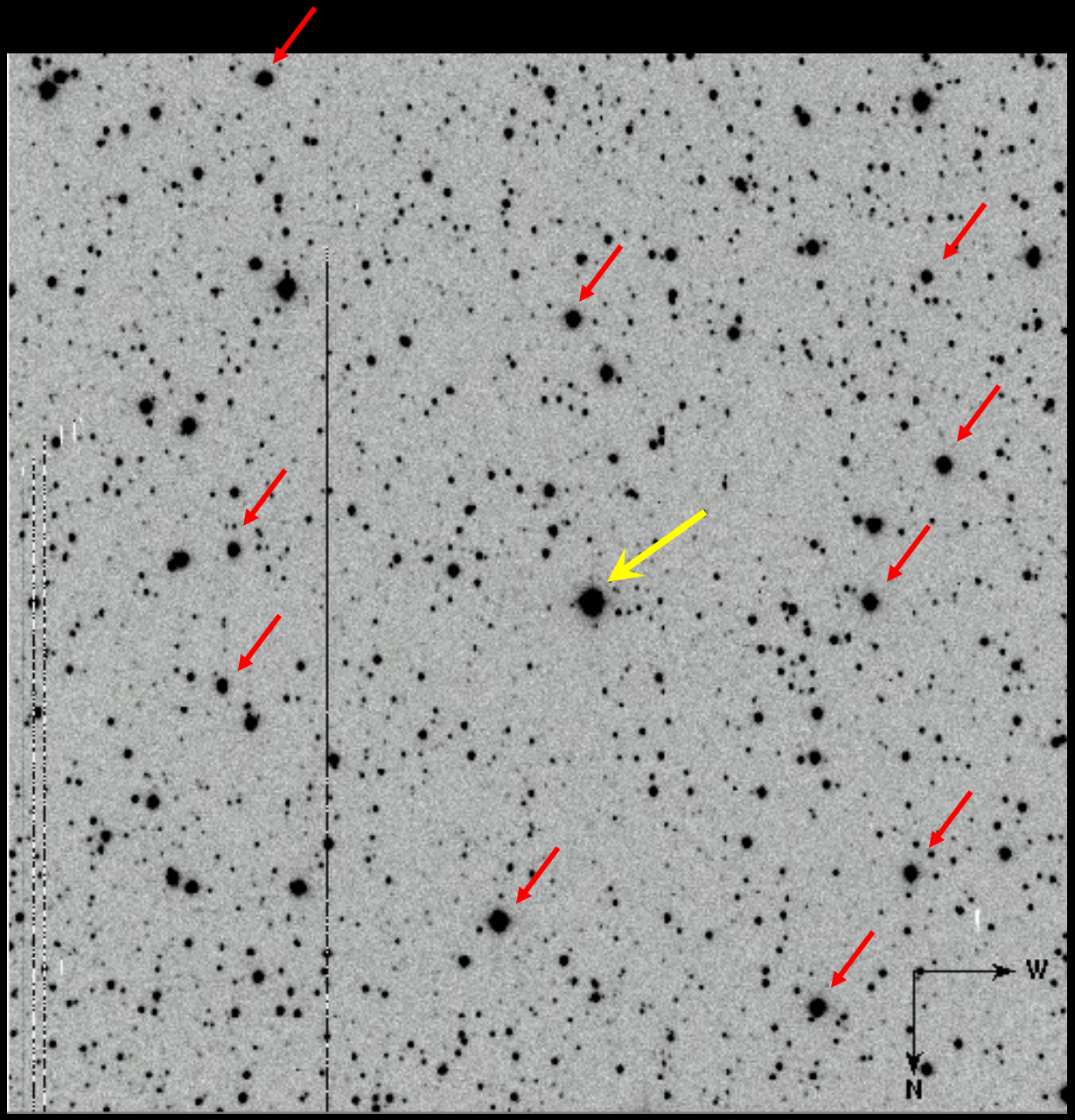
Ejnar Hertzsprung and Henry Norris Russell



many papers with tabular data, but no (?) plots
Hertzsprung (1910s)

Relations Between the Spectra and Other Characteristics of the Stars II
Russell (1914)

Proxima Centauri



parallax factors

evening/morning frames

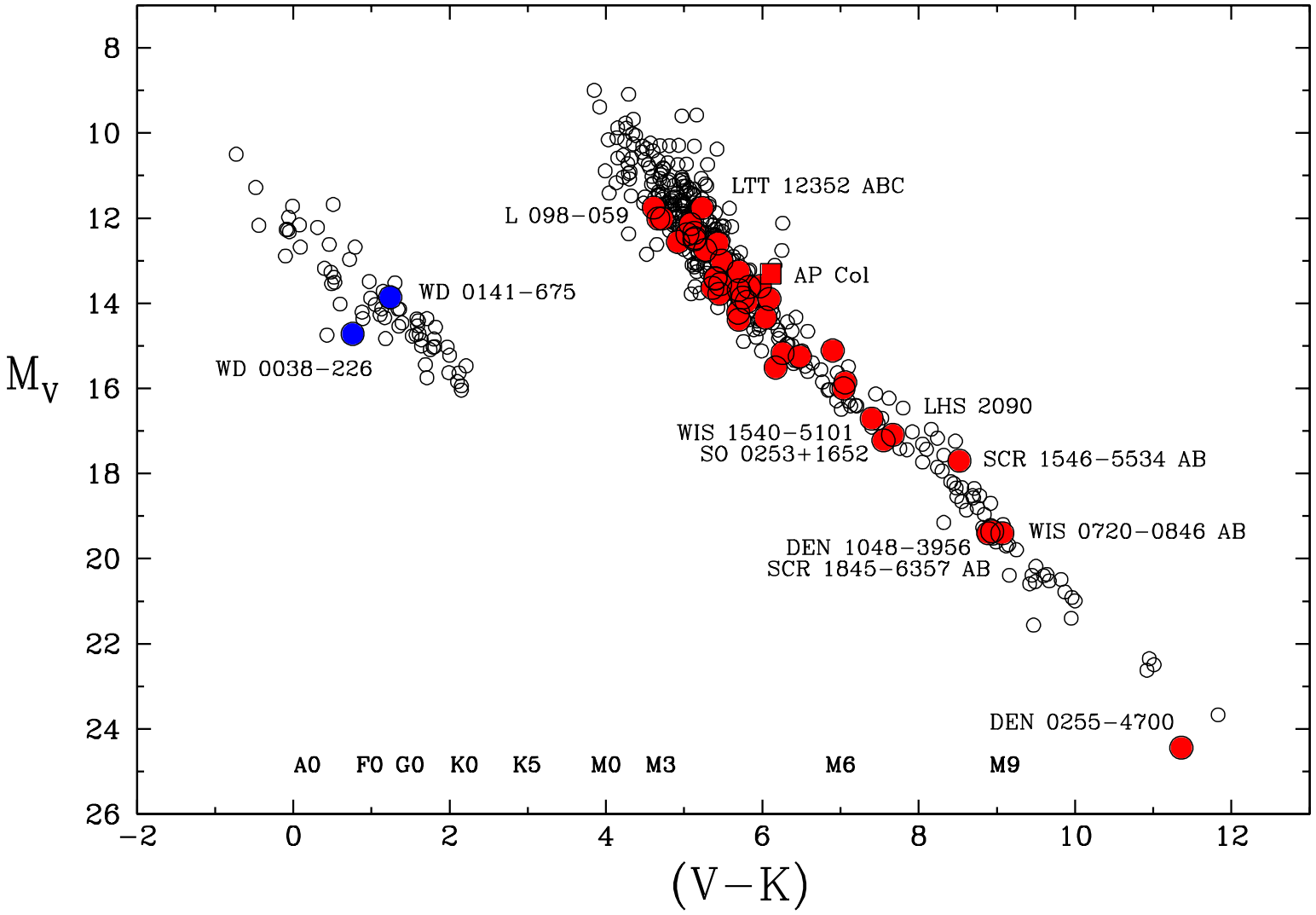
transit observations

differential color refraction

plate constants

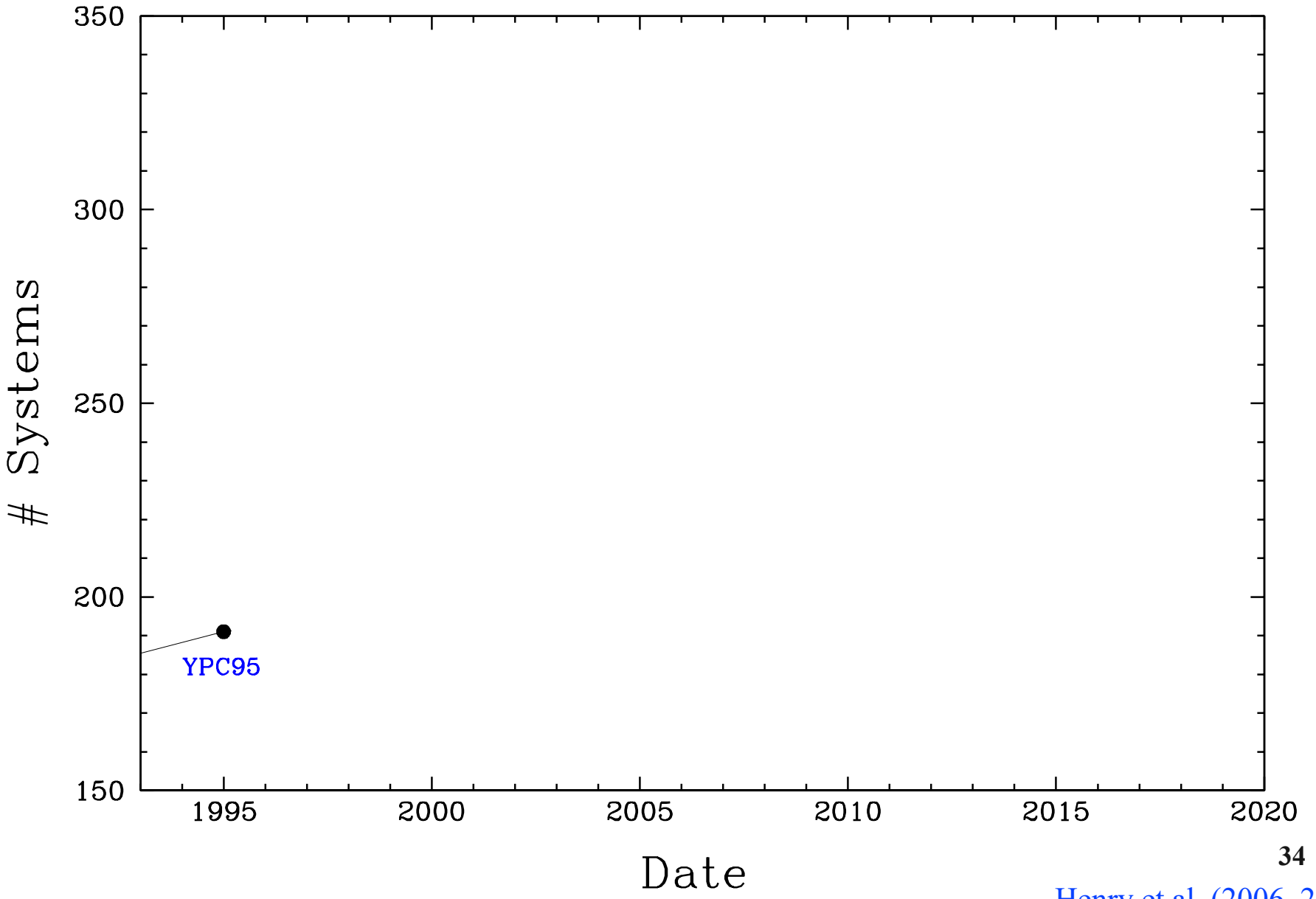
π_{trig} to < 1 mas

Parallax: New 10 pc H-R Diagram



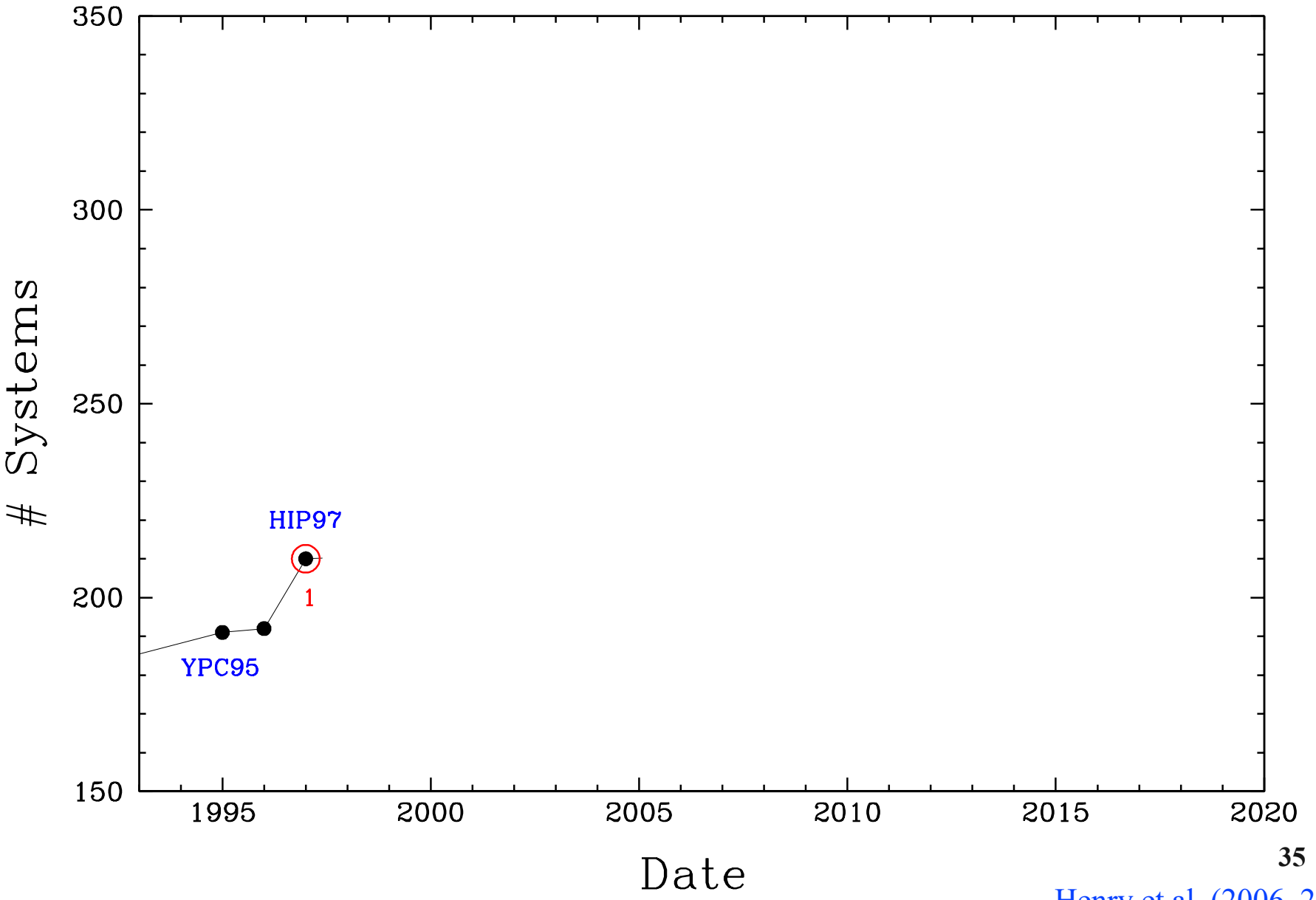
Henry et al. (2018)

Parallax: 10 Parsec Census



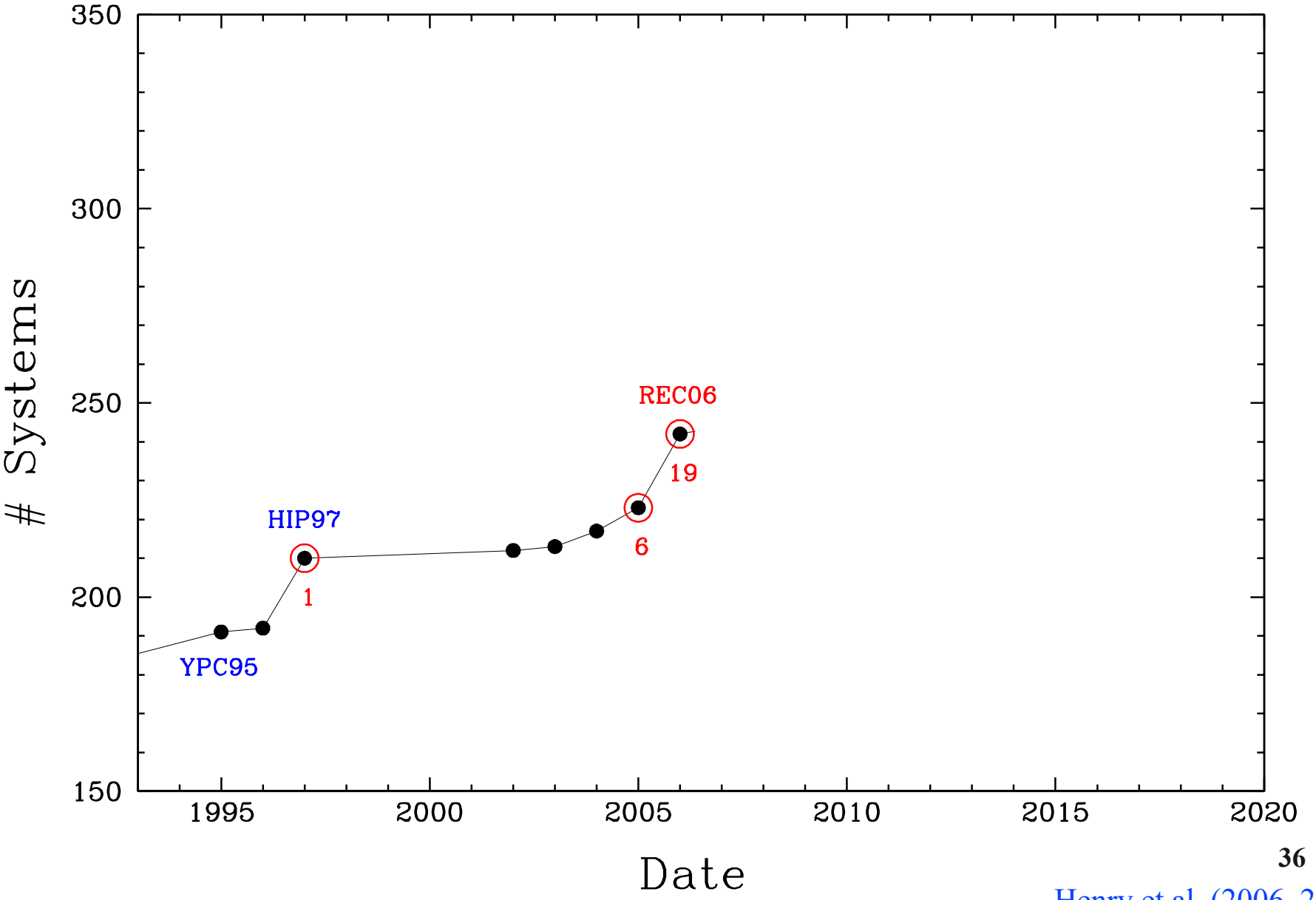
Henry et al. (2006, 2018)

Parallax: 10 Parsec Census



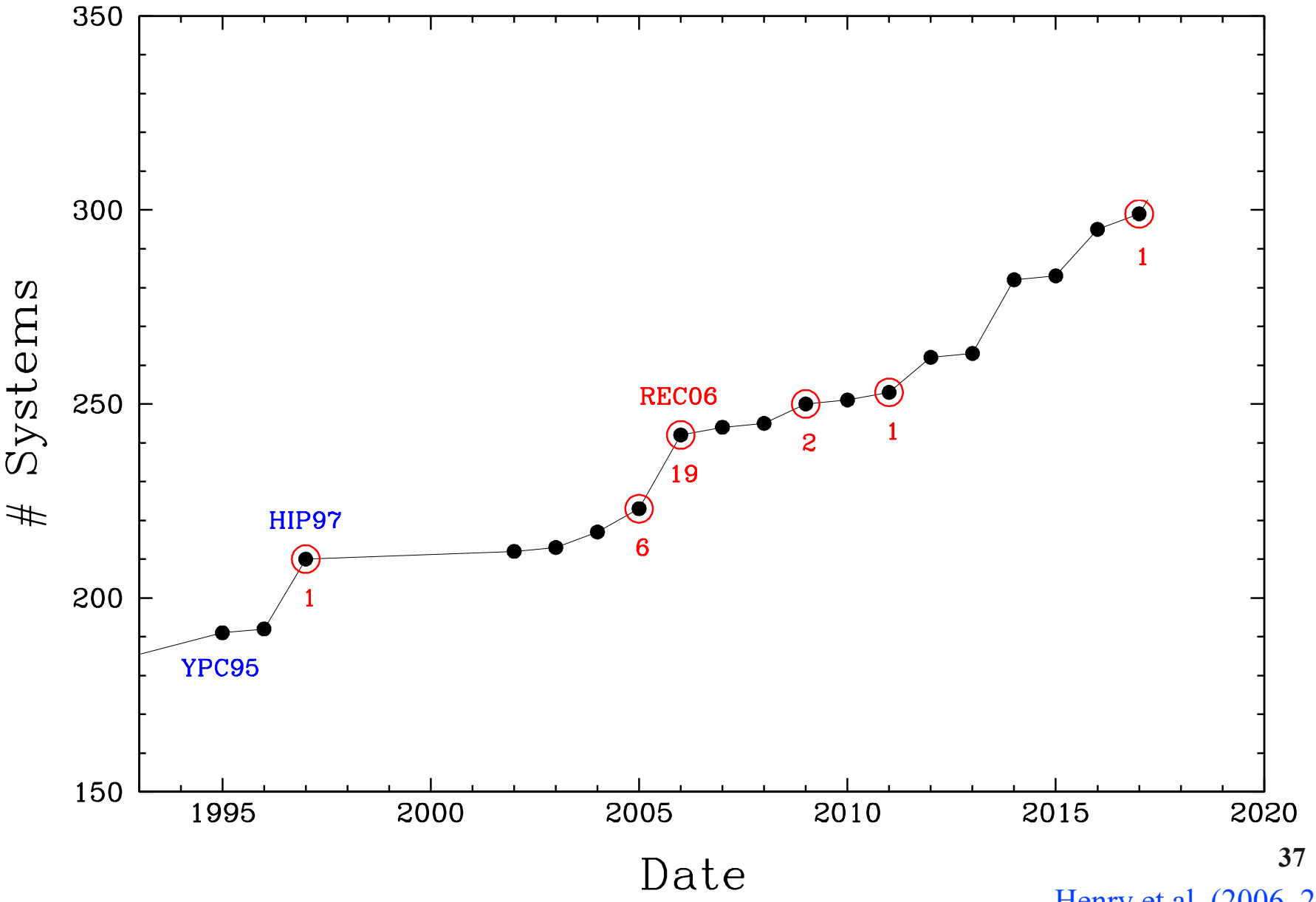
Henry et al. (2006, 2018)

Parallax: 10 Parsec Census



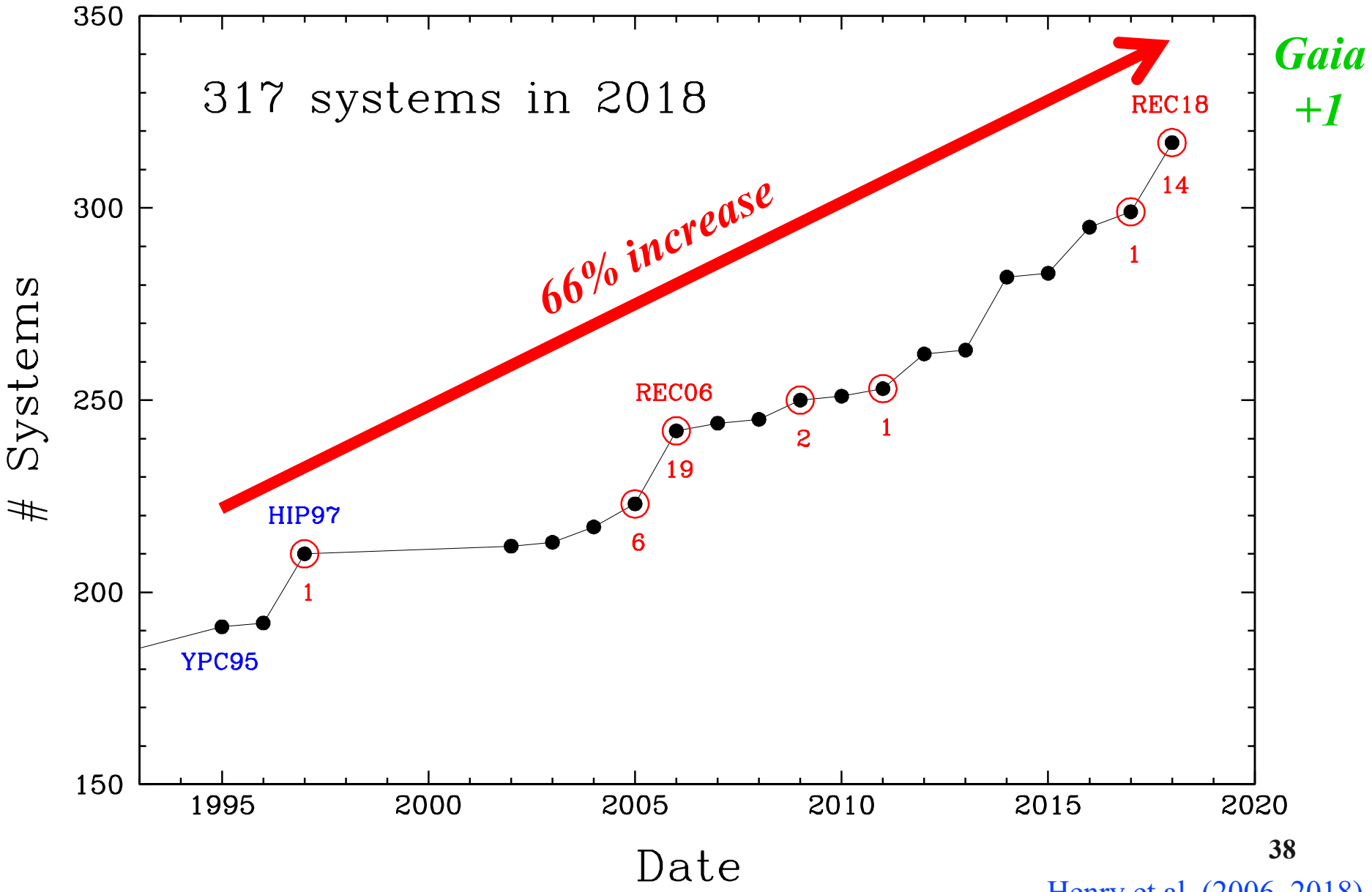
Henry et al. (2006, 2018)

Parallax: 10 Parsec Census



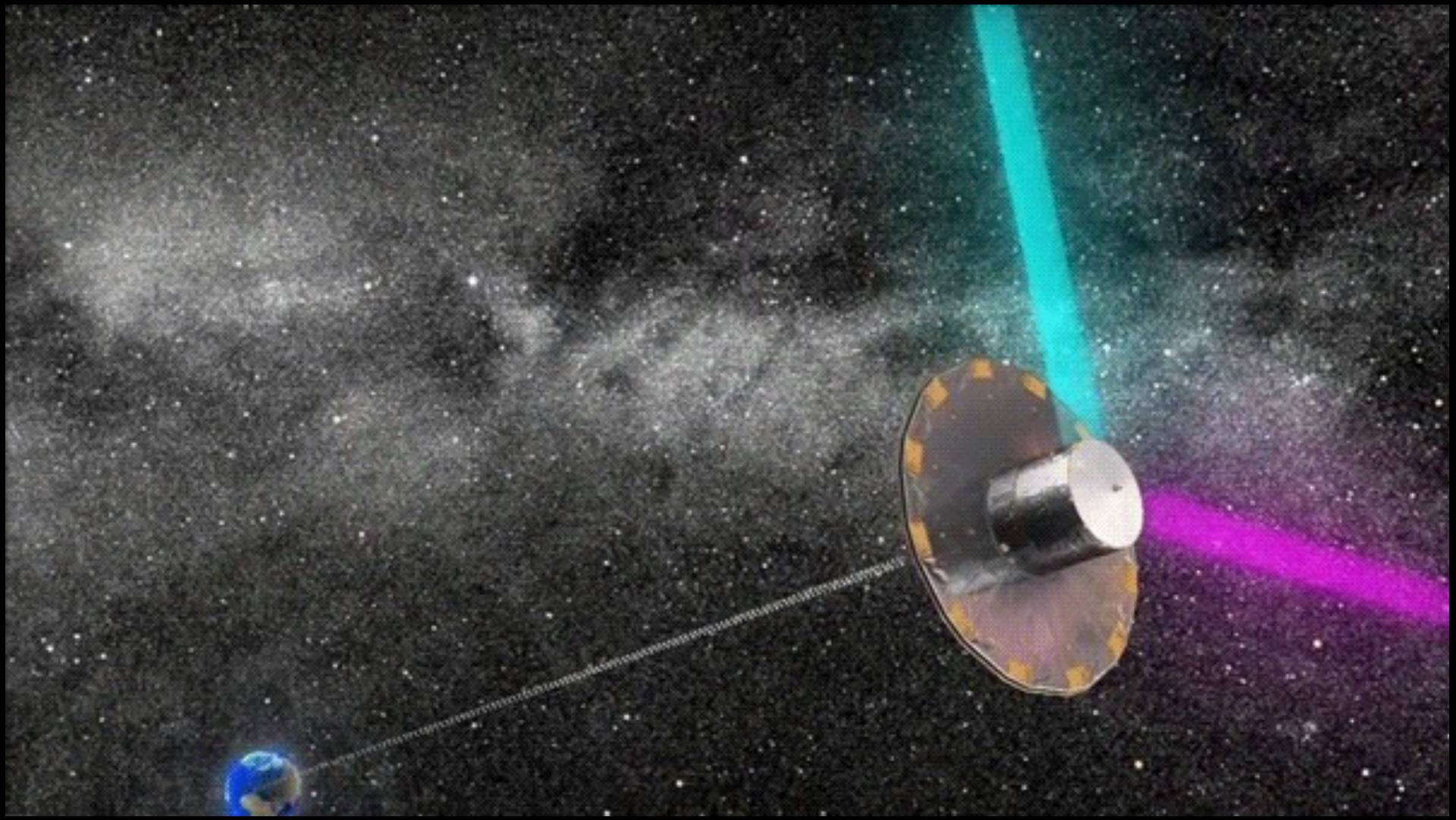
Henry et al. (2006, 2018)

Parallax: 10 Parsec Census



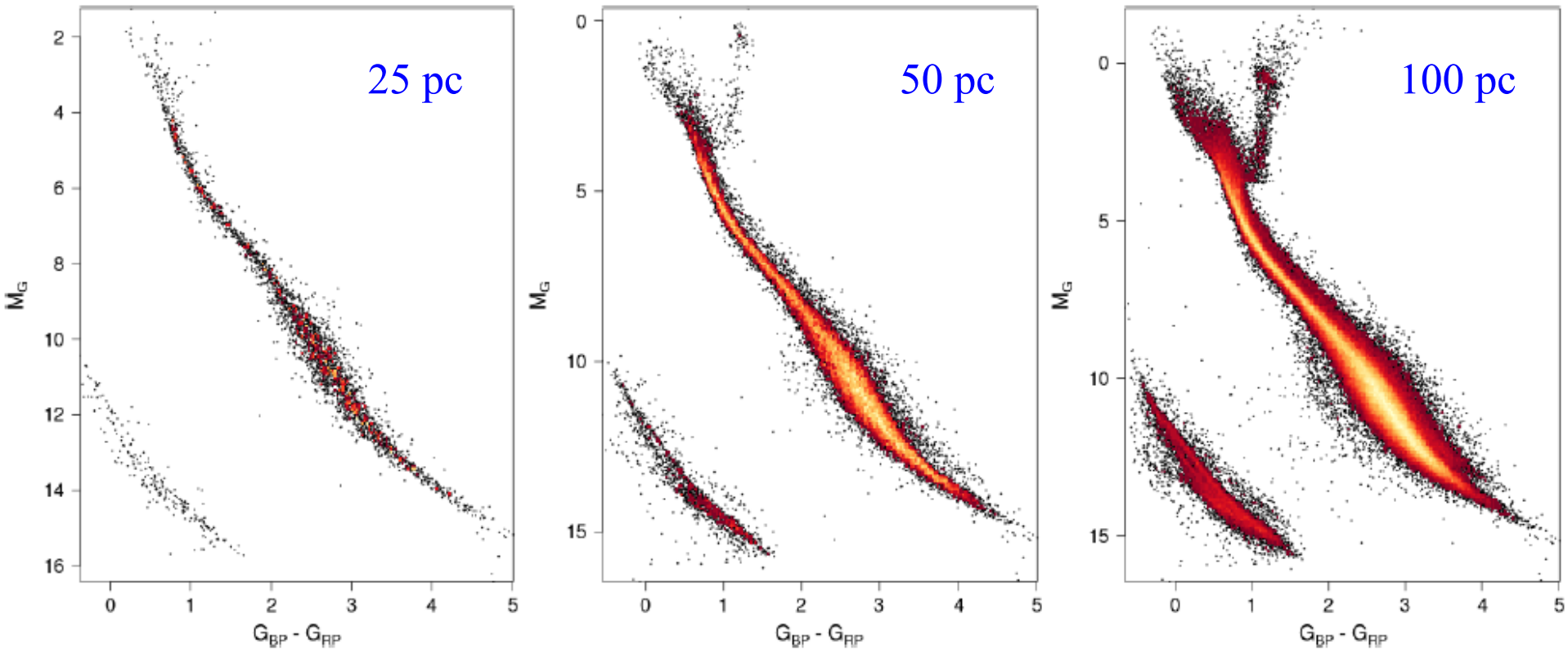
Henry et al. (2006, 2018)

Gaia



June 2022: 1.8 billion sources

Parallax: *Gaia* Reach to 100 pc

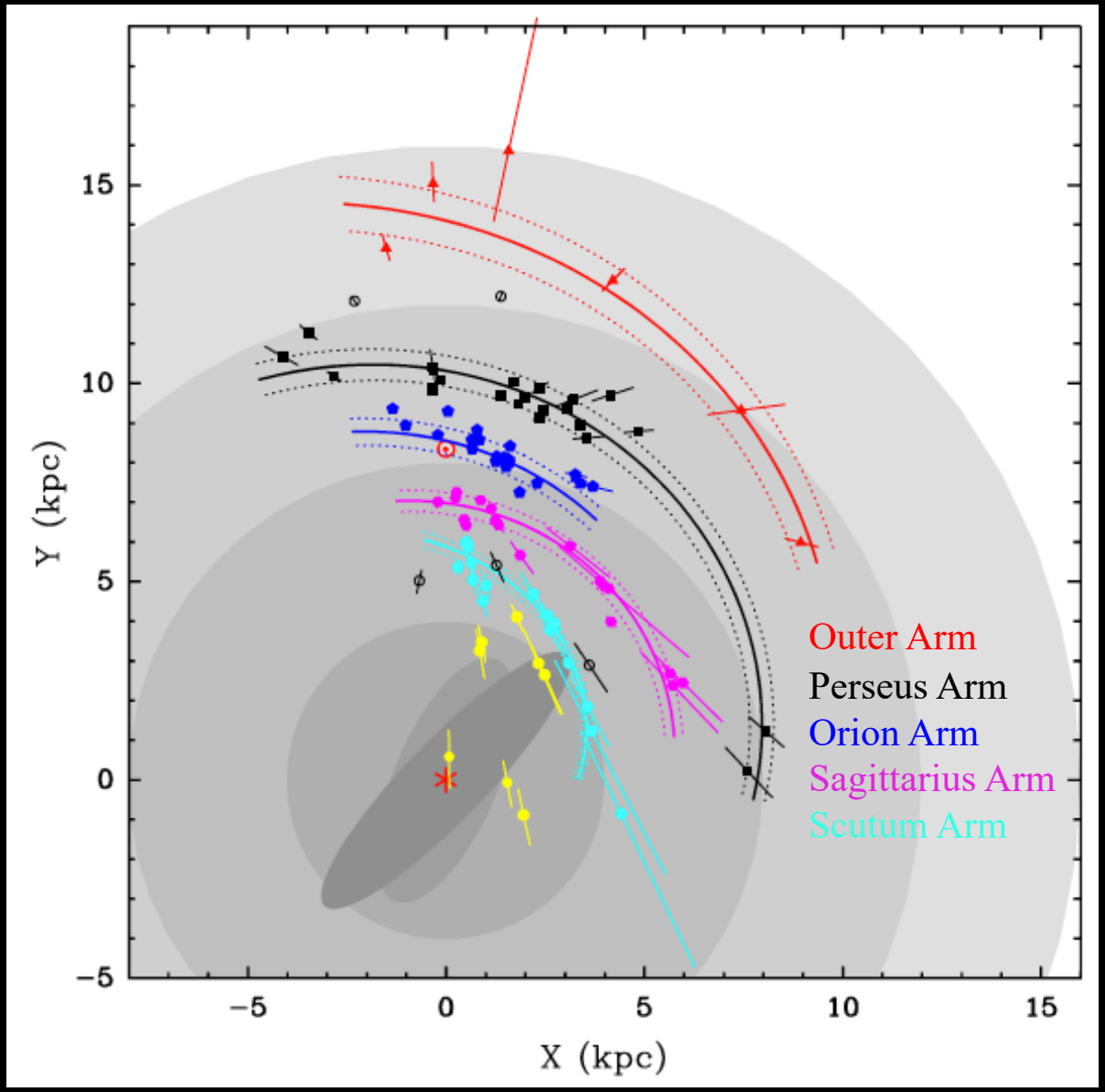


Babusiaux et al. (2018)

What "extra" populations are evident past 25 parsecs?

red giants, red clump stars
cool subdwarfs, binary M dwarfs
WD sequences, WD binaries

Parallax: SFR Masers in the Radio



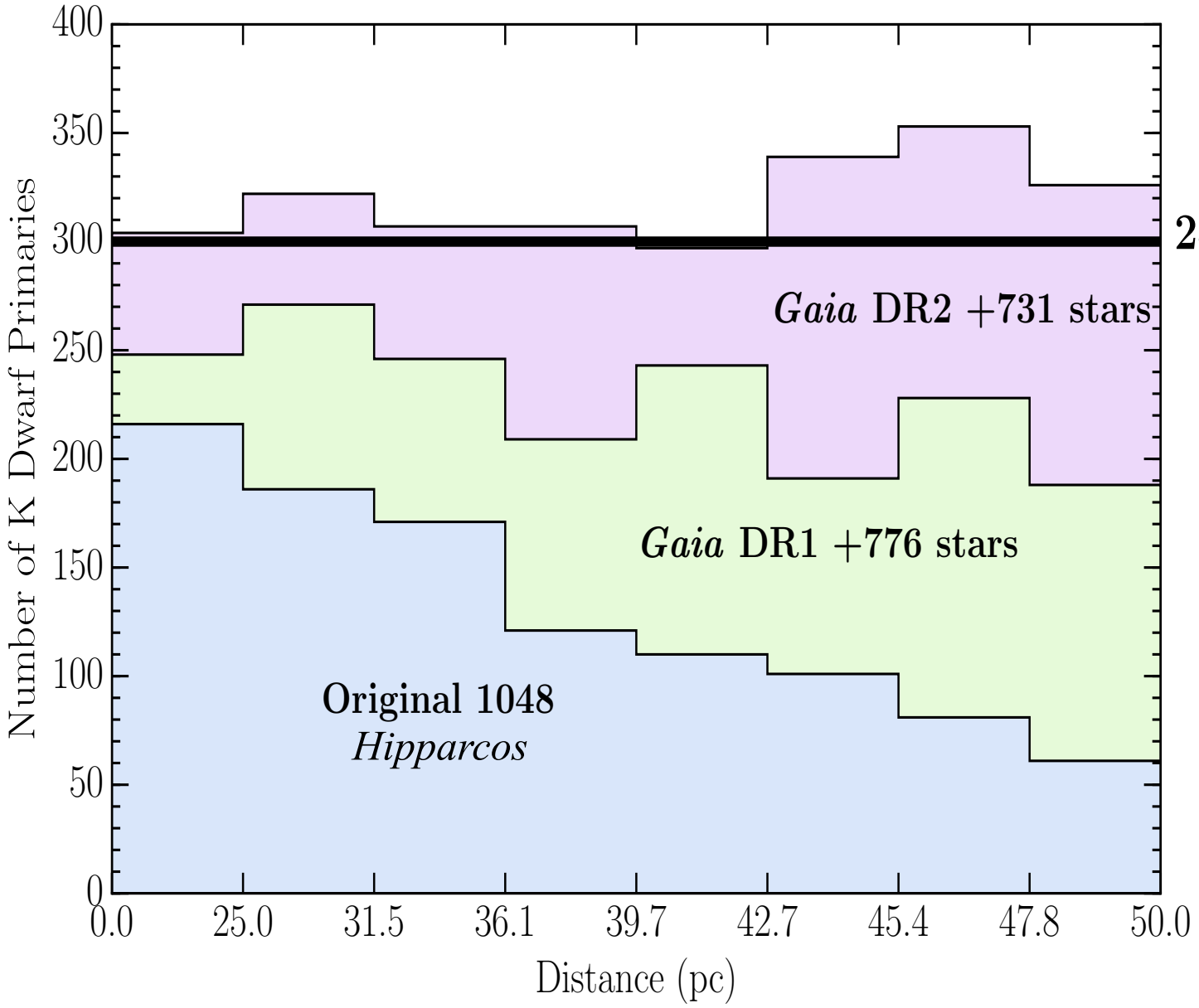
Reid+ (2009) … 18 masers

Reid+ (2014) … 103 masers

π = 0.1–2.4 mas
errors = 0.01–0.08 mas

small portion of spiral arms wrapped

Parallax: RKSTAR Sample



K Dwarfs
< 50 pc

Equatorial
2555

All-Sky
5095

Perturbation

a , α

(ρ)

WARNING: Equation

$$P^2_{\text{years}} = a^3_{\text{AU}} \qquad \text{(Kepler)}$$

$$M_1 + M_2 = \frac{a^3}{P^2} \qquad \text{(Newton)}$$

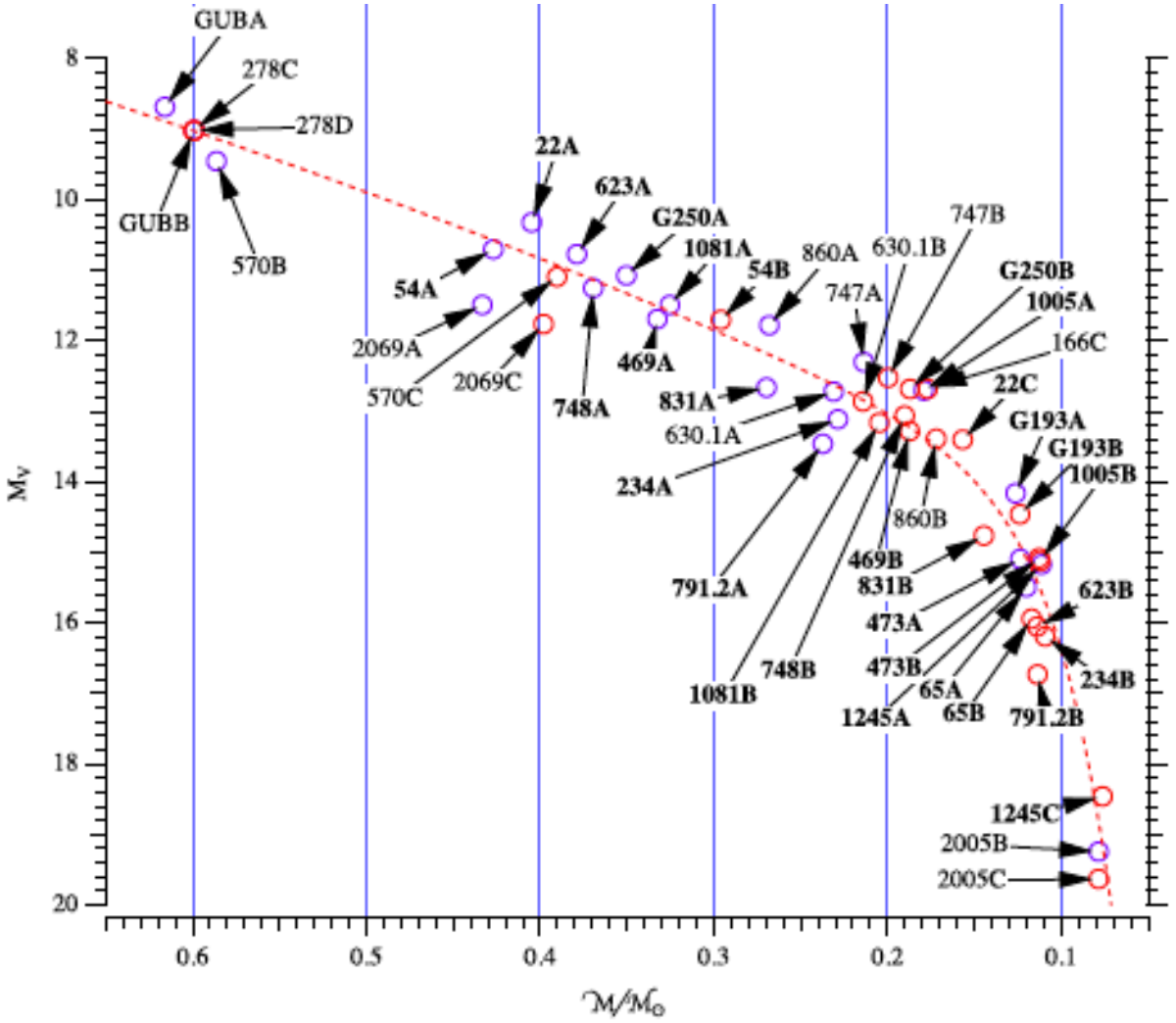
solar masses

Sun + Jupiter .. P = 11.8 years	5.2 AU
2 red dwarfs @ 0.3 $M_\odot$… P = 10 years	3.9 AU
1 red dwarf @ 0.3 $M_\odot$ + planet … P = 10 years	3.1 AU

P and a are comparable for normal stars on Solar System scales.

Dirty secret #1: you only get MASS SUM.
Dirty secret #2: exoplanet masses assume stellar mass.

Mass-Luminosity Relation

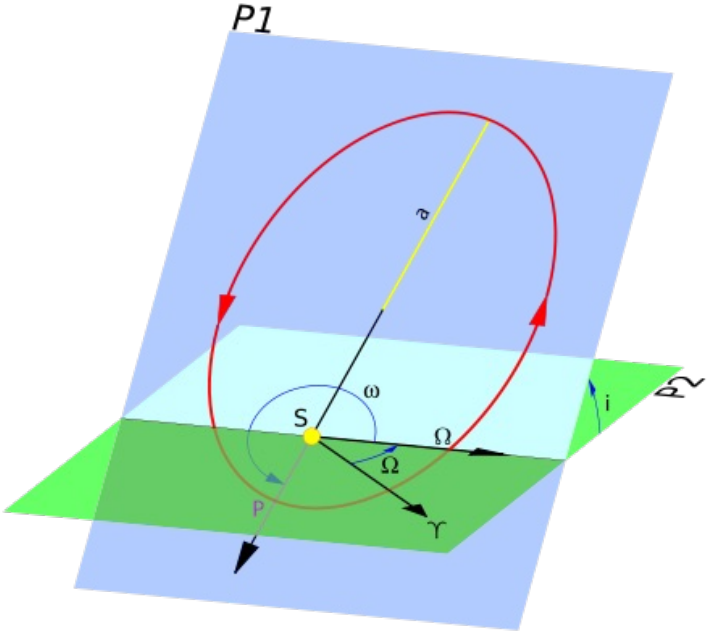


mass errors ~2%

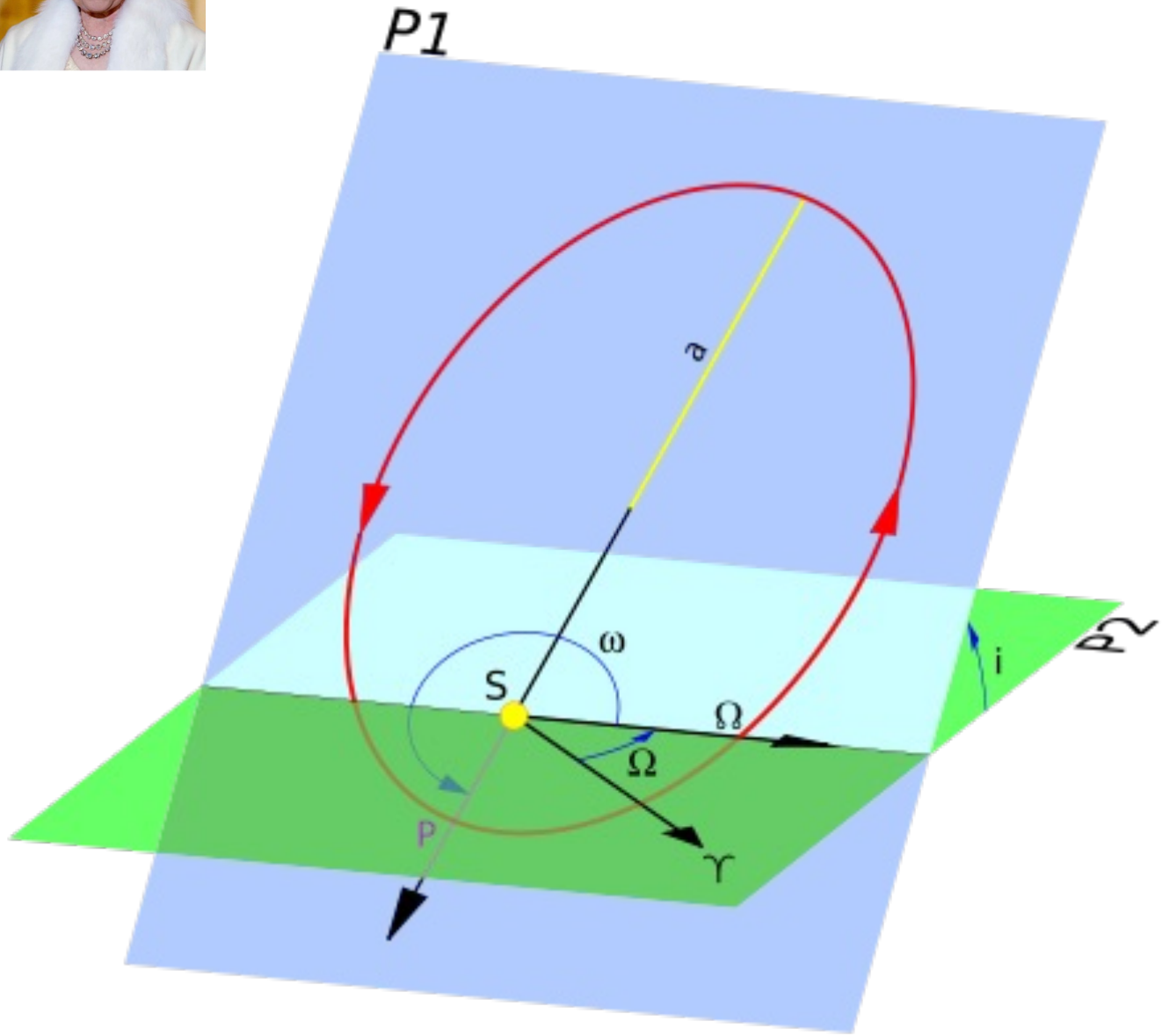
Benedict et al. (2016)

Perturbation: Orbital Elements

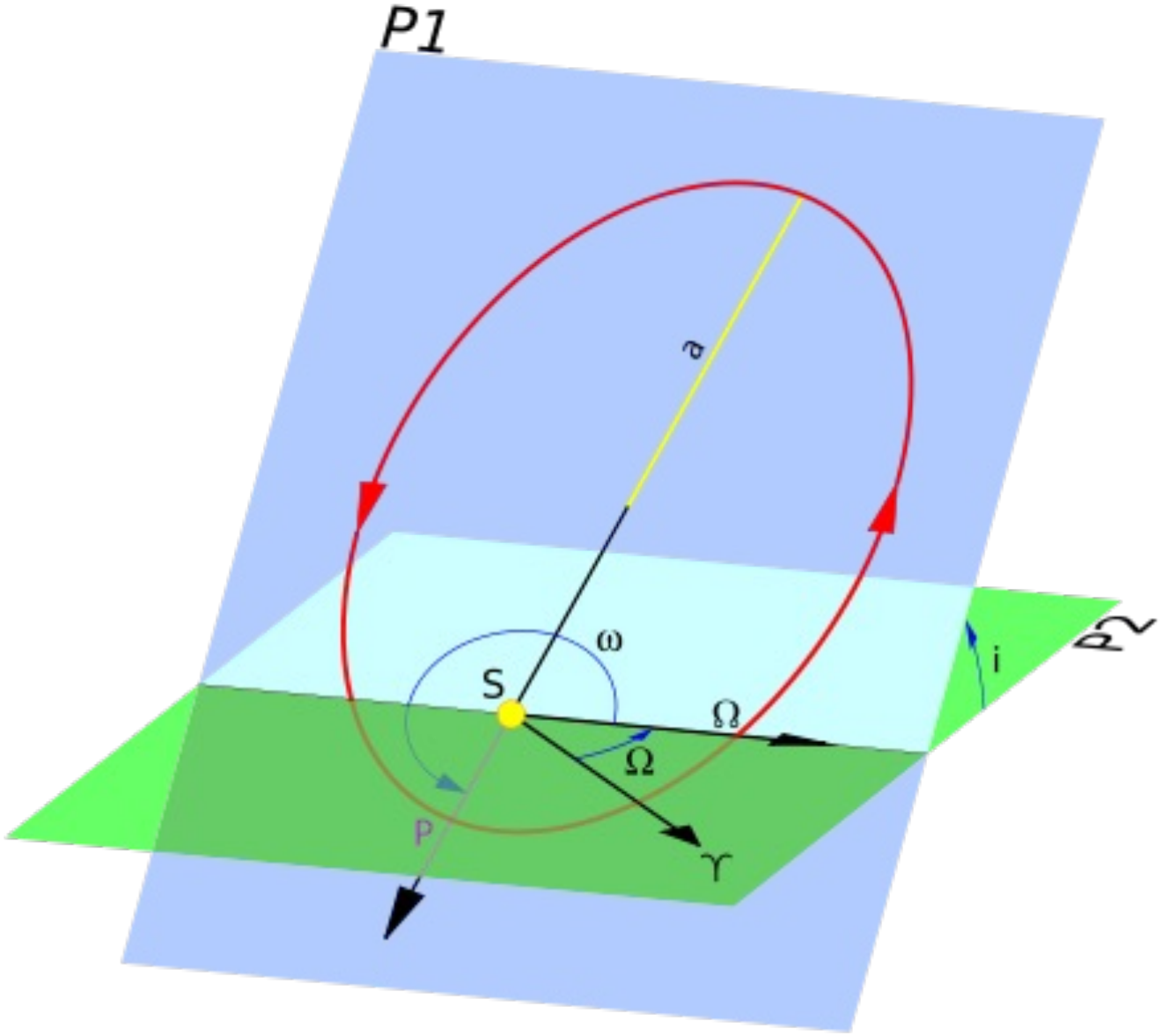
a	semimajor axis	size
e	eccentricity	shape
i	inclination (0 degrees = face-on)	tilt angle
P	orbital period	time
T	epoch of periastron	a date
Ω	longitude of ascending node	spin angle
ω	argument of periastron	tωist angle



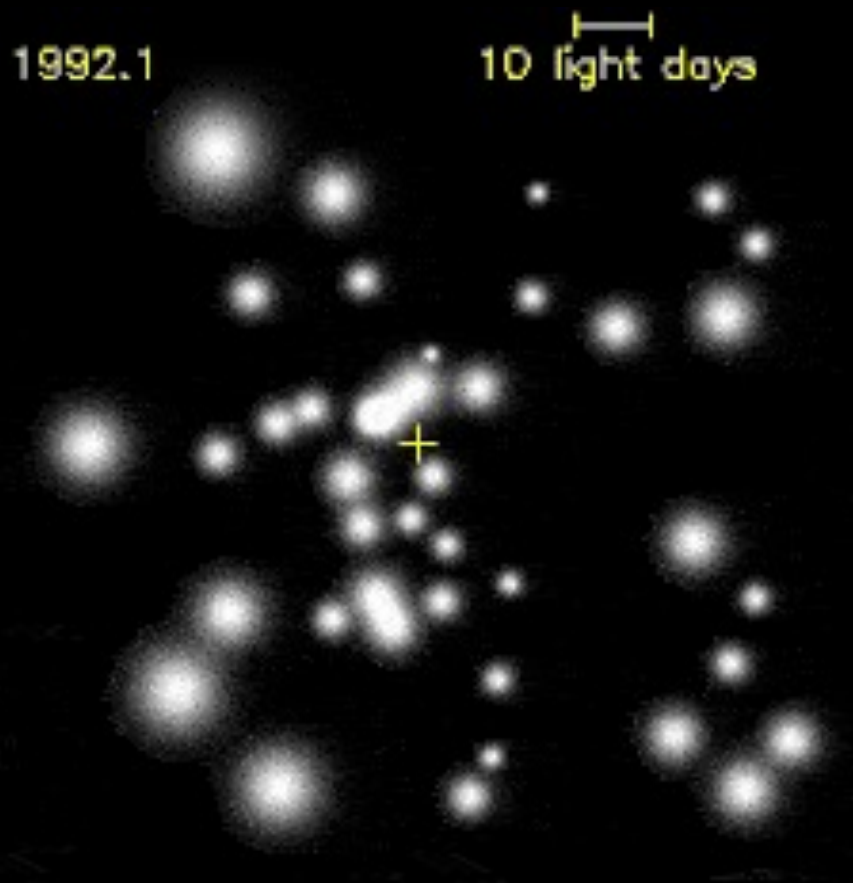
Spin Ω: Longitude of Ascending Node

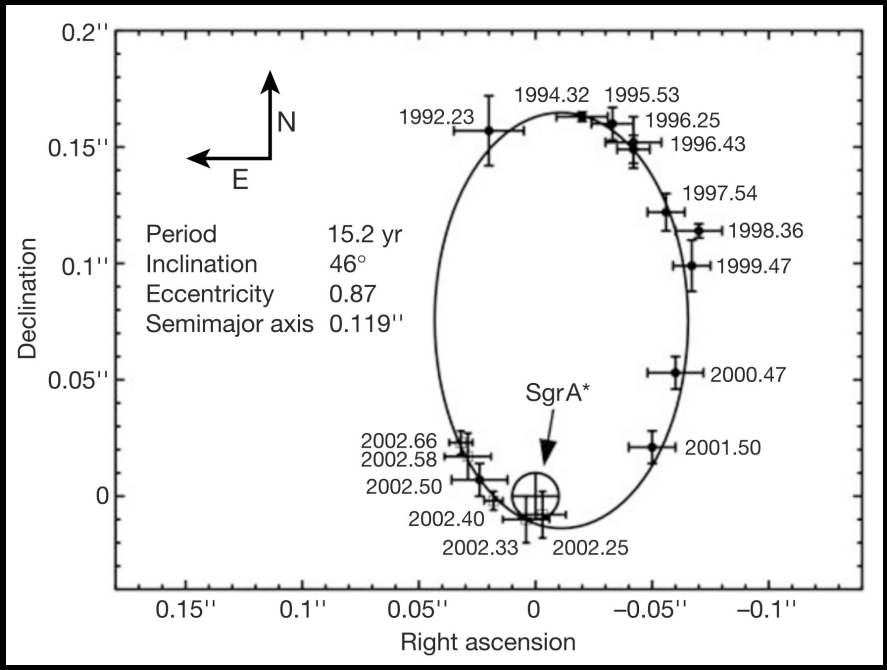


Twist ω: Argument of Periastron



Perturbation: Galactic Center (2002)





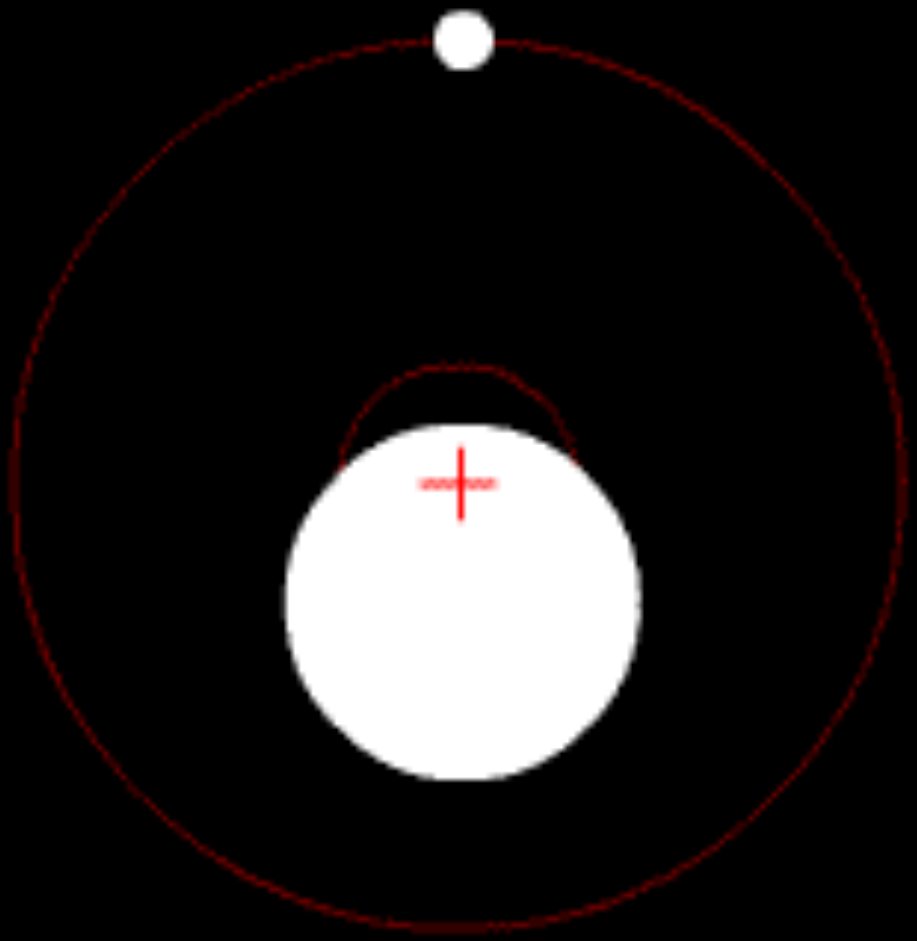
A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way

R. Schödel*, T. Ott*, R. Genzel*†, R. Hofmann*, M. Lehnert*, A. Eckart‡, N. Mouawad‡, T. Alexander§, M. J. Reid‖, R. Lenzen¶, M. Hartung¶, F. Lacombe#, D. Rouan#, E. Gendron#, G. Rousset☆, A.-M. Lagrange**, W. Brandner††, N. Ageorges††, C. Lidman††, A. F. M. Moorwood††, J. Spyromilio††, N. Hubin†† & K. M. Menten‡‡

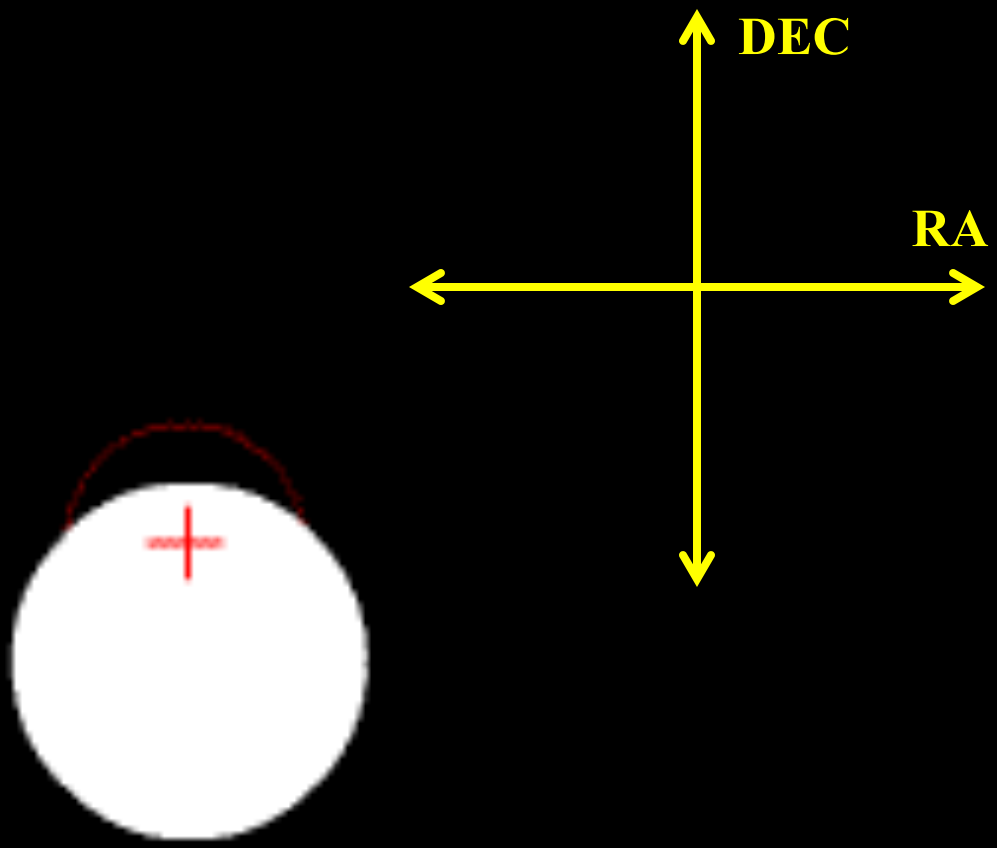
Schodel et al. (2002)

astrometry 1992-2002
SO-2 orbital P = 15.2 yr
$M_{BH} = 3.7 \times 10^6 M_\odot$

Perturbation

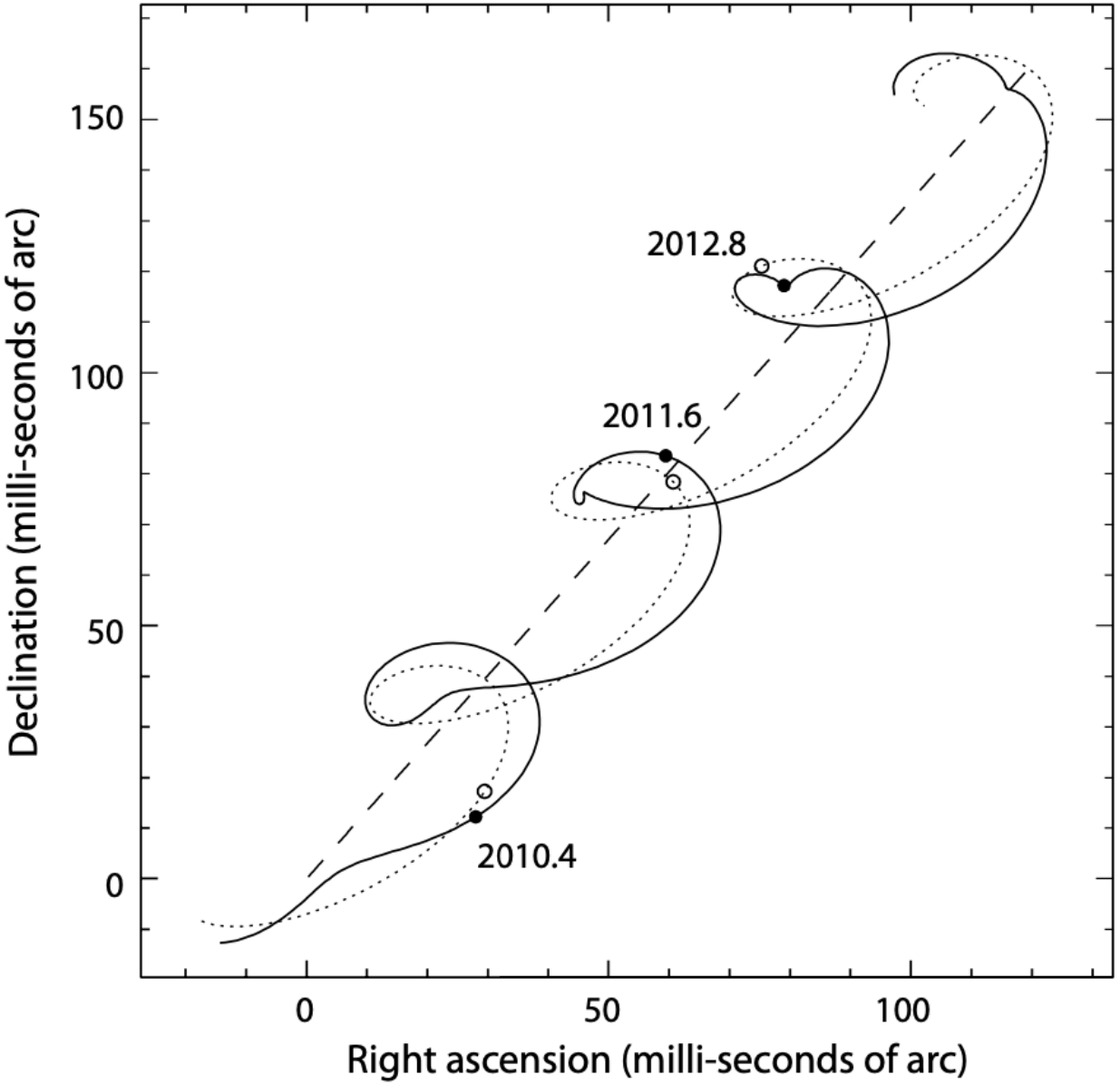


Perturbation



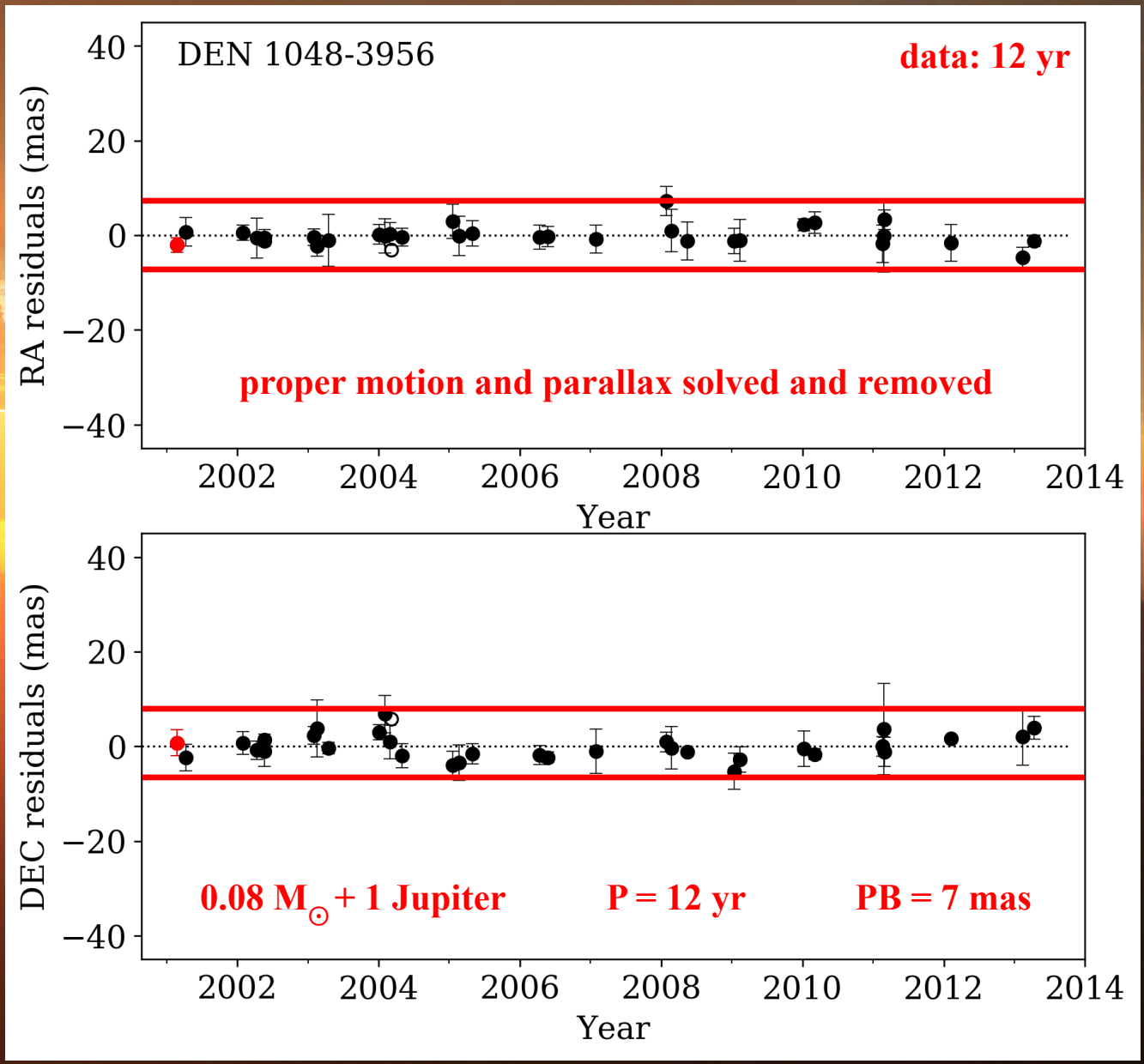

exo
planet dance

Perturbation: All Together Now …

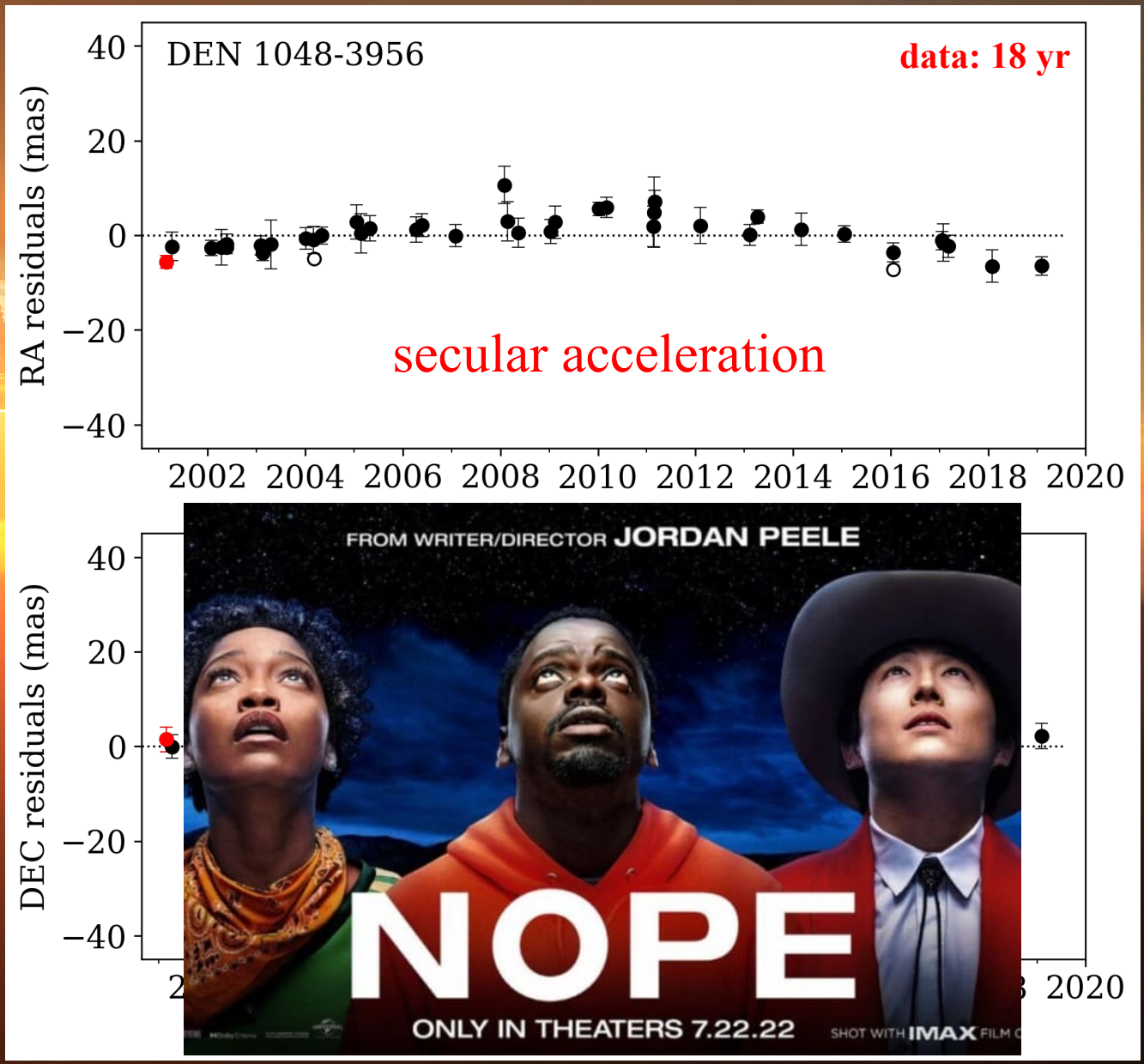


Perryman 2012

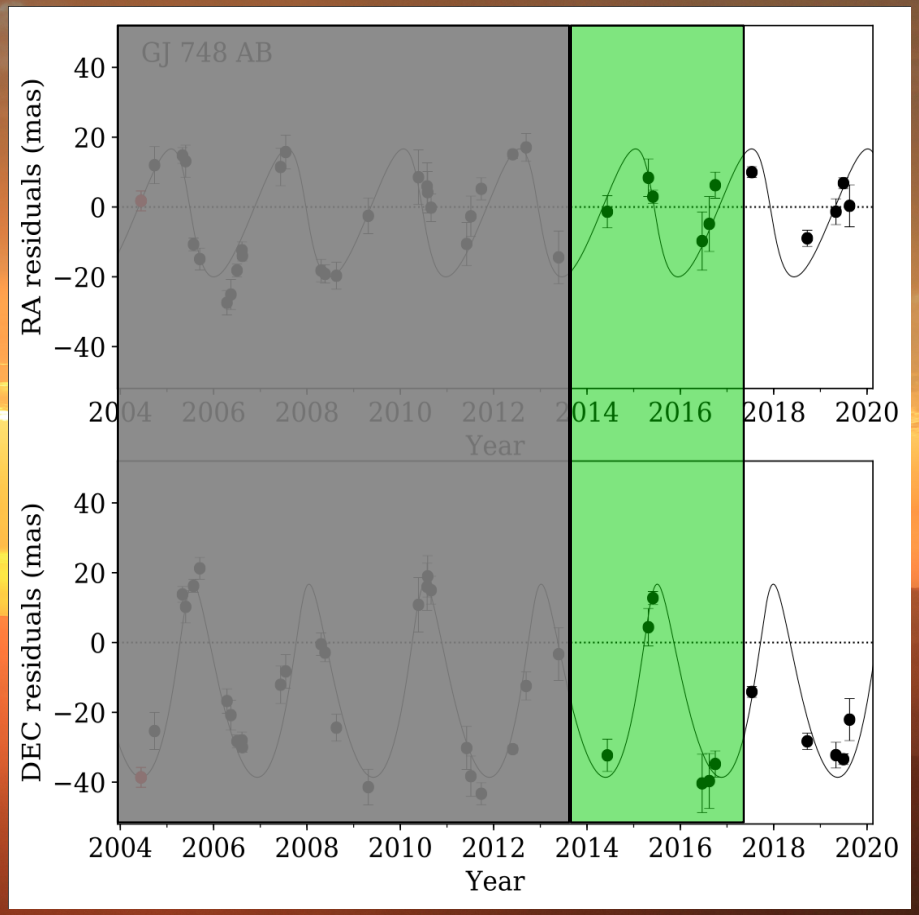
Perturbation: NONE

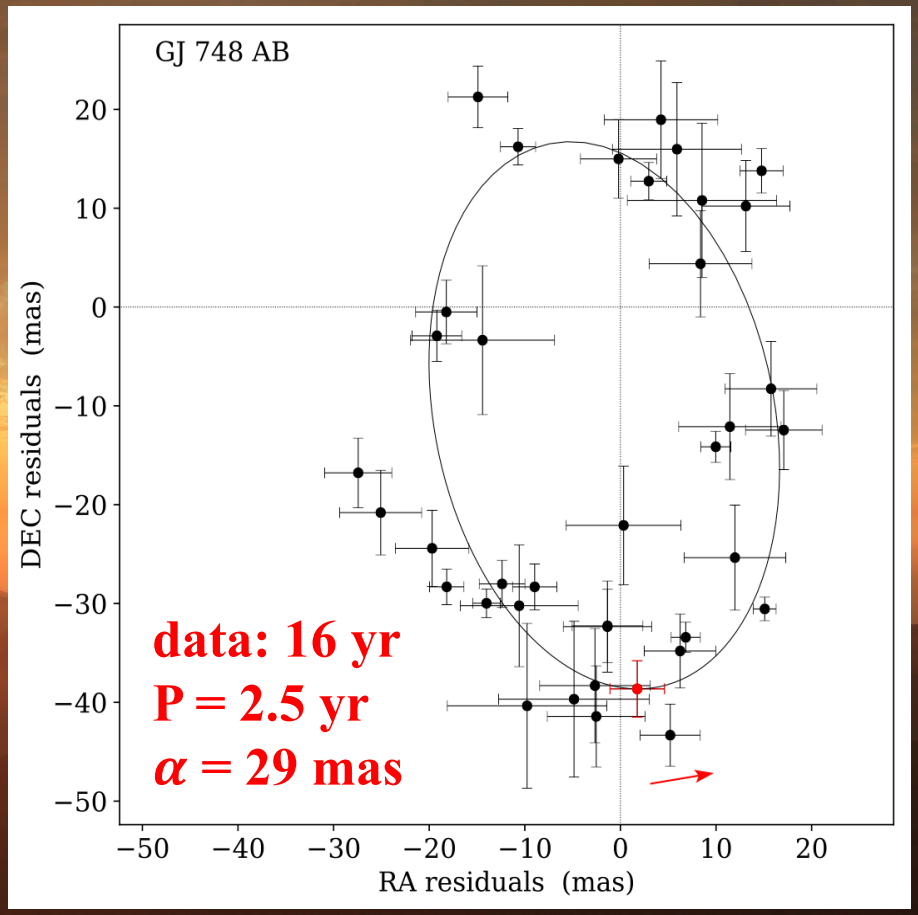


Perturbation: planet?



Perturbation: 6.4 orbits

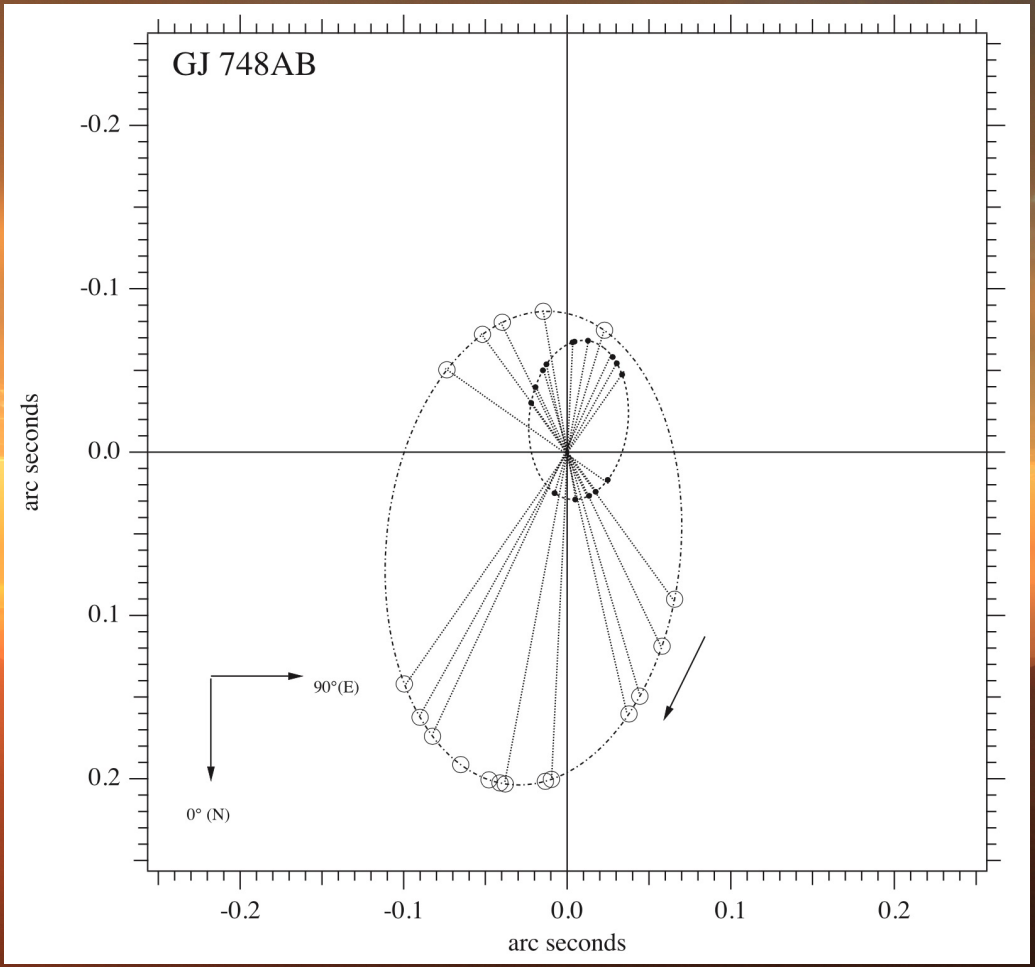




relative photocentric orbit

16 years of data … multiple orbit wraps

Perturbation: Resolved Orbits

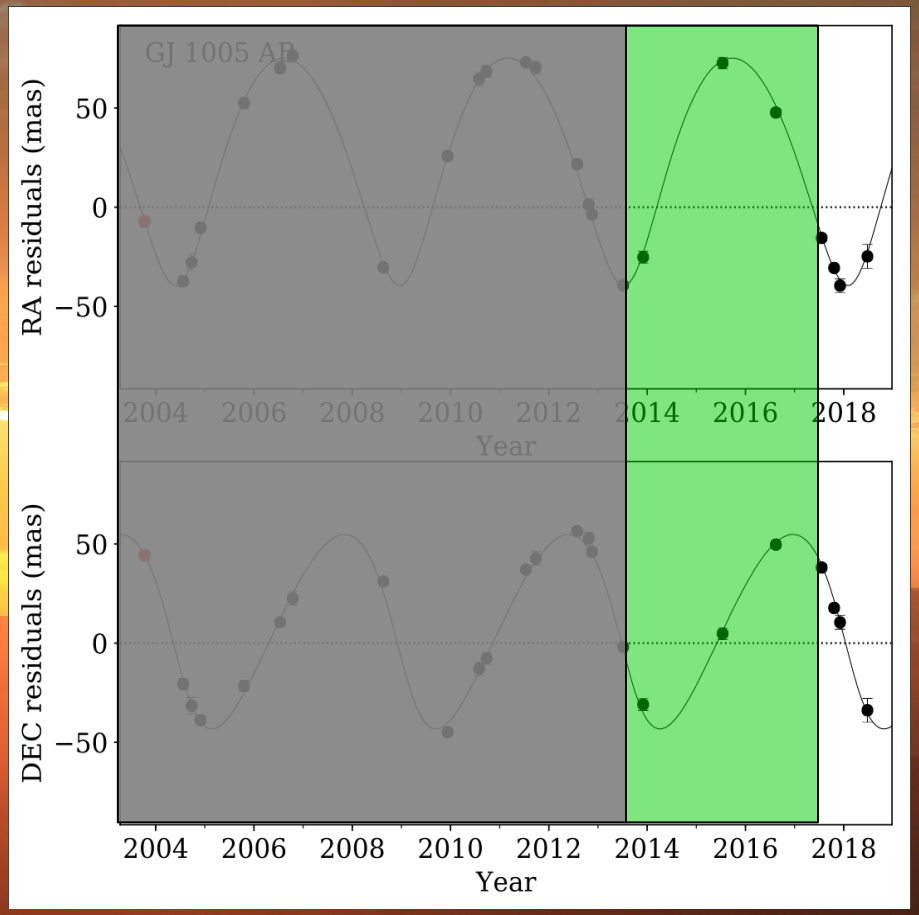


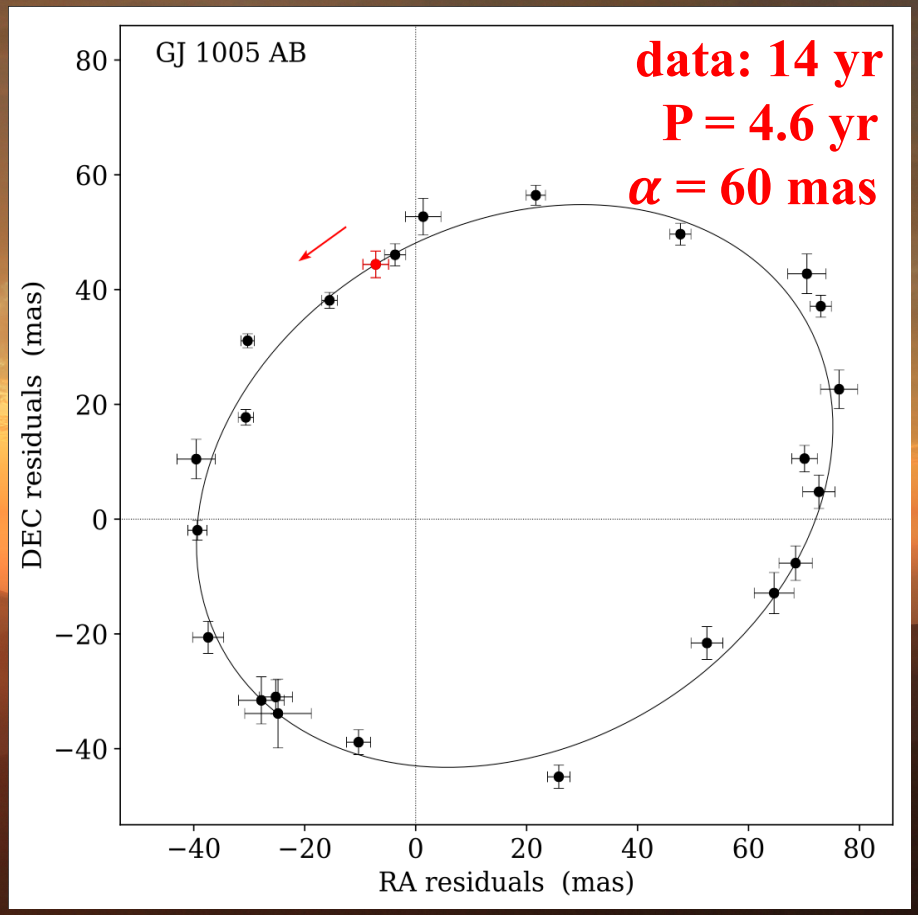
resolved orbits … orbits same shape

HST Fine Guidance Sensors

Benedict et al. (2016)

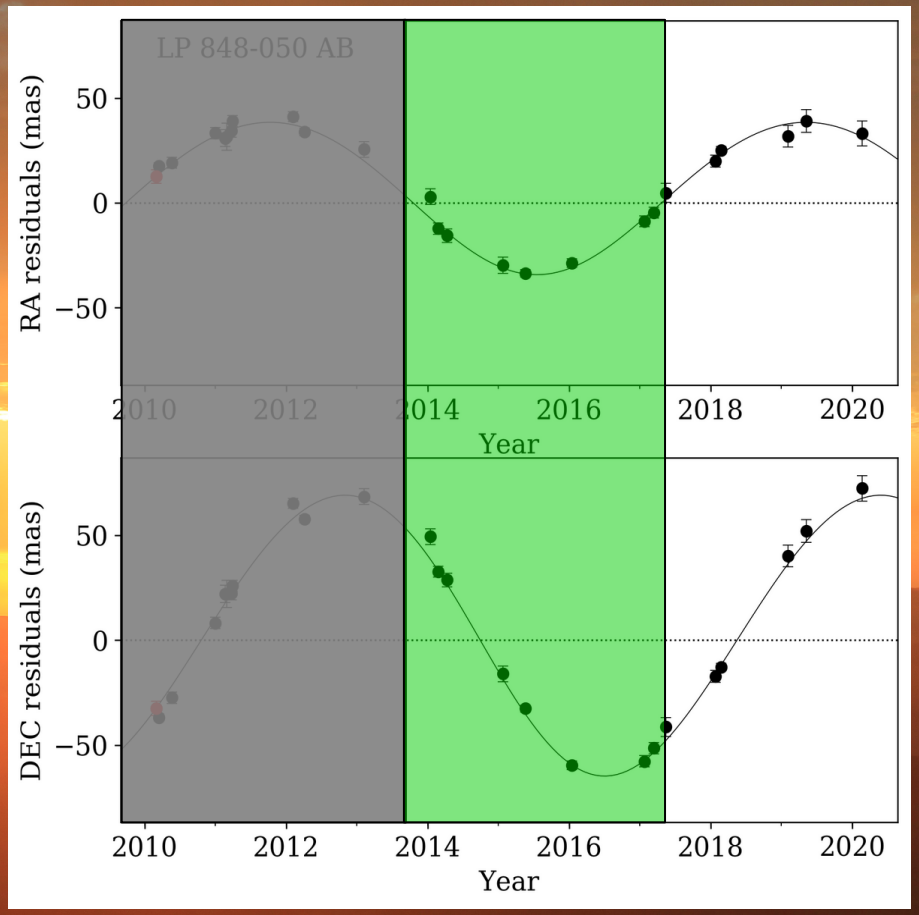
Perturbation: 3.0 orbits

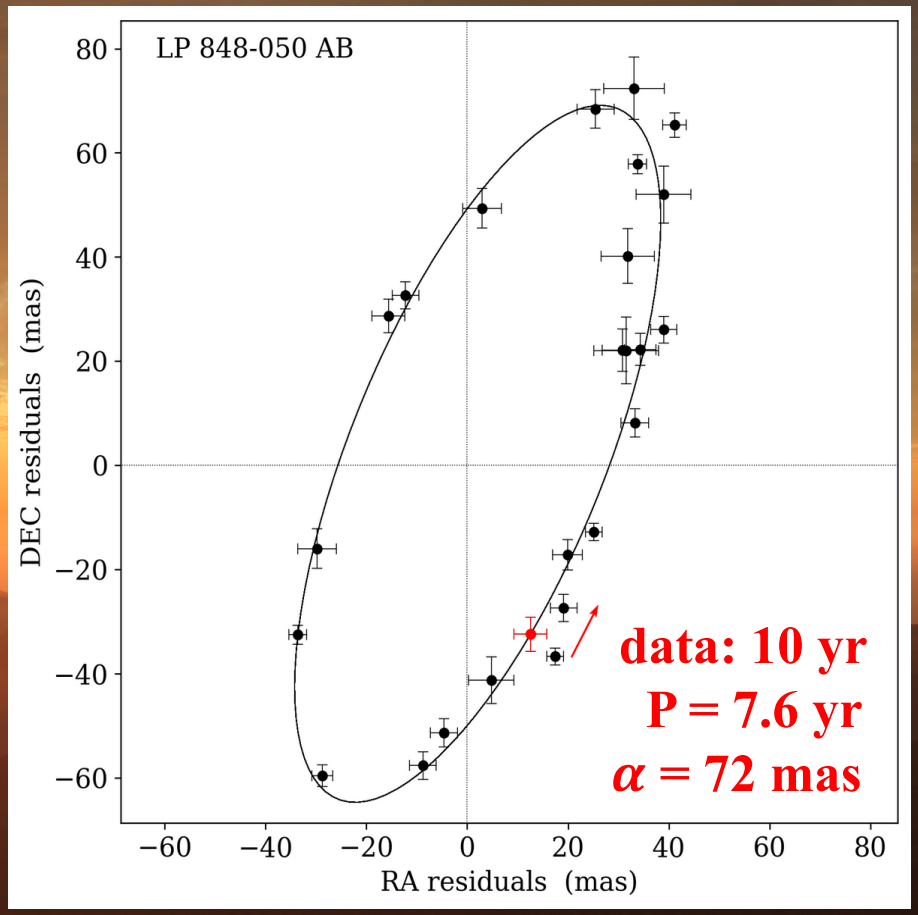




wrapping the orbit is GOOD

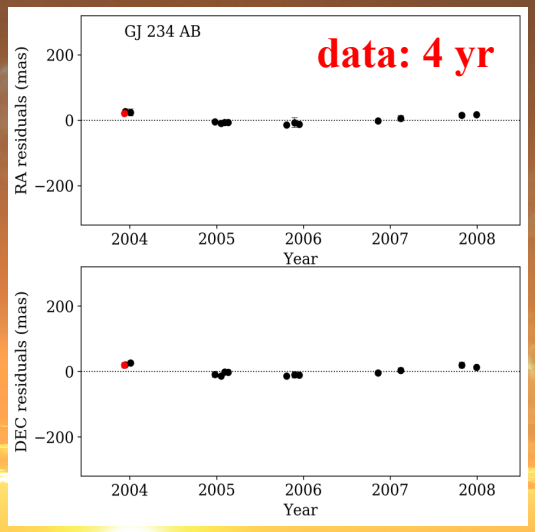
Perturbation: 1.5 orbits

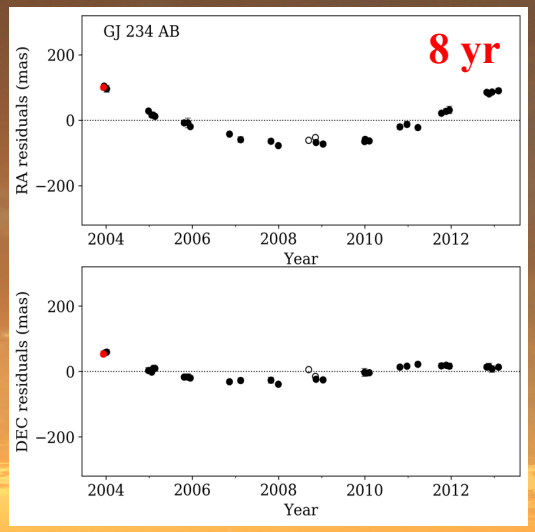


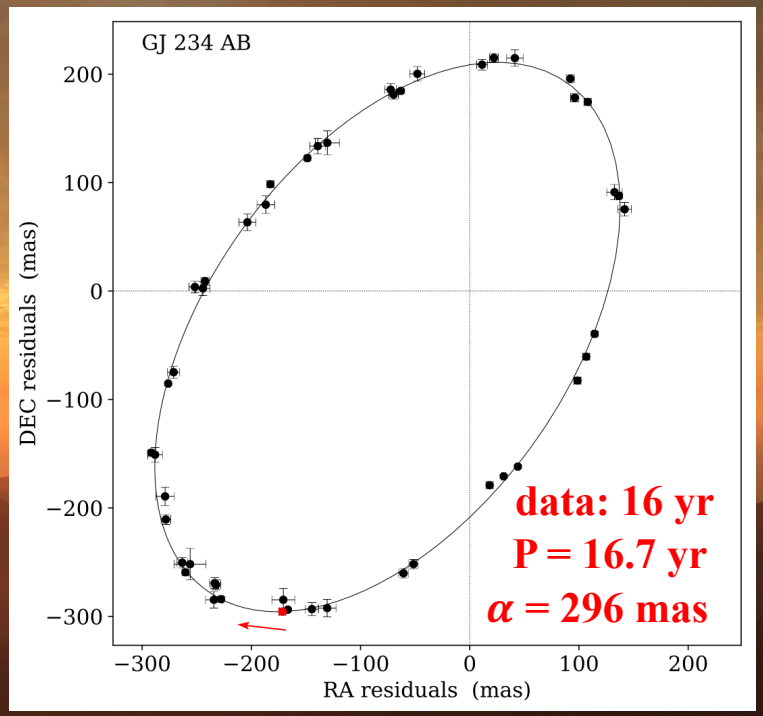


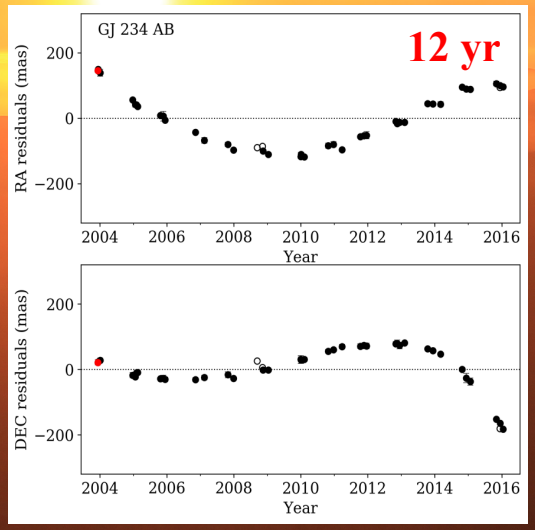
an extra half orbit is plenty

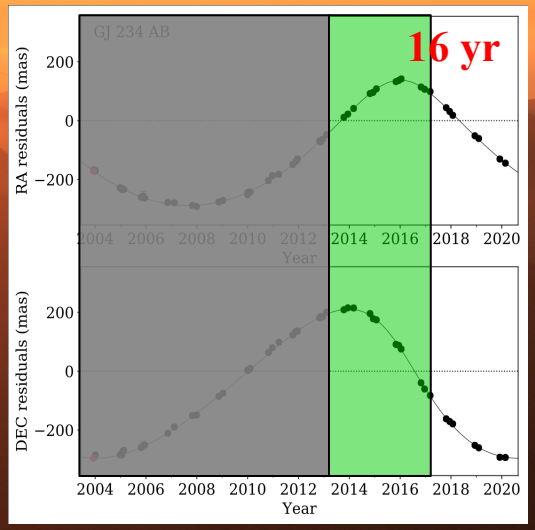
Perturbation: 0.9 orbit





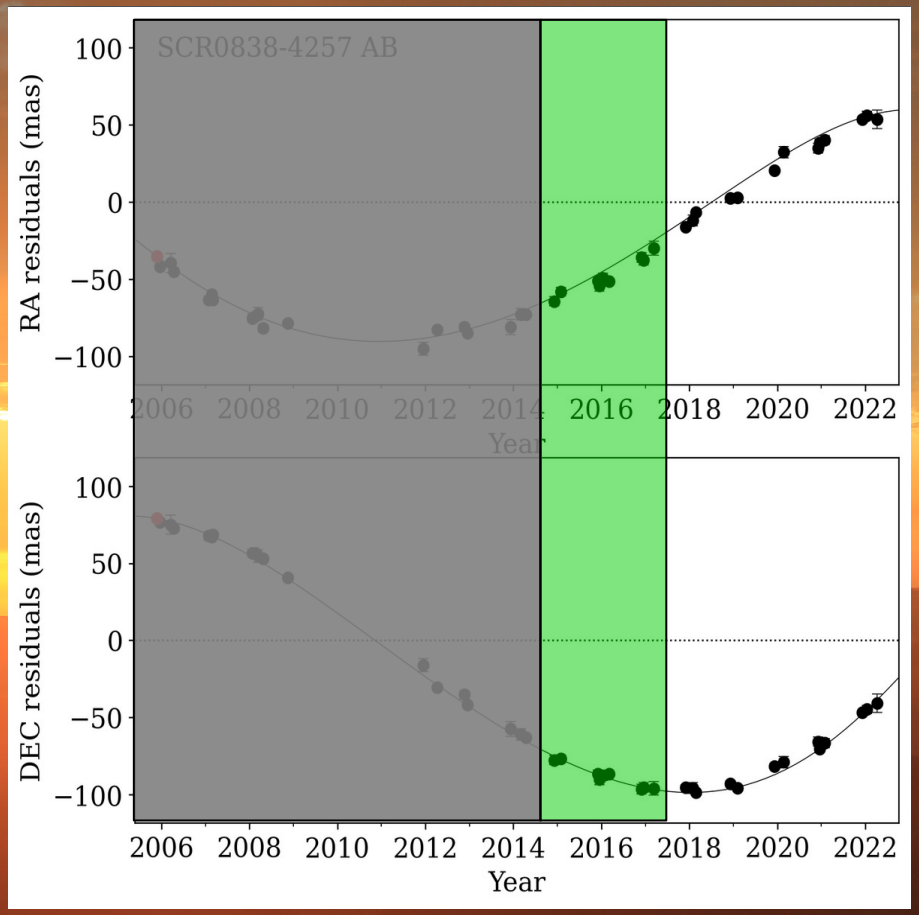


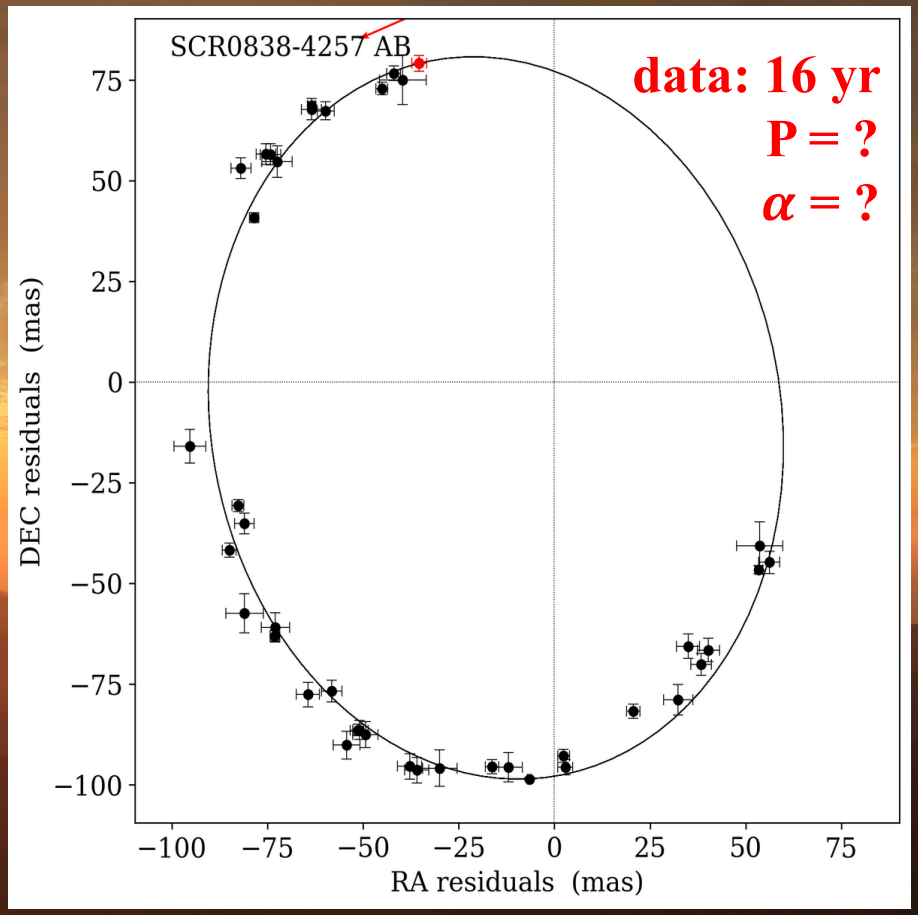




patience is critical

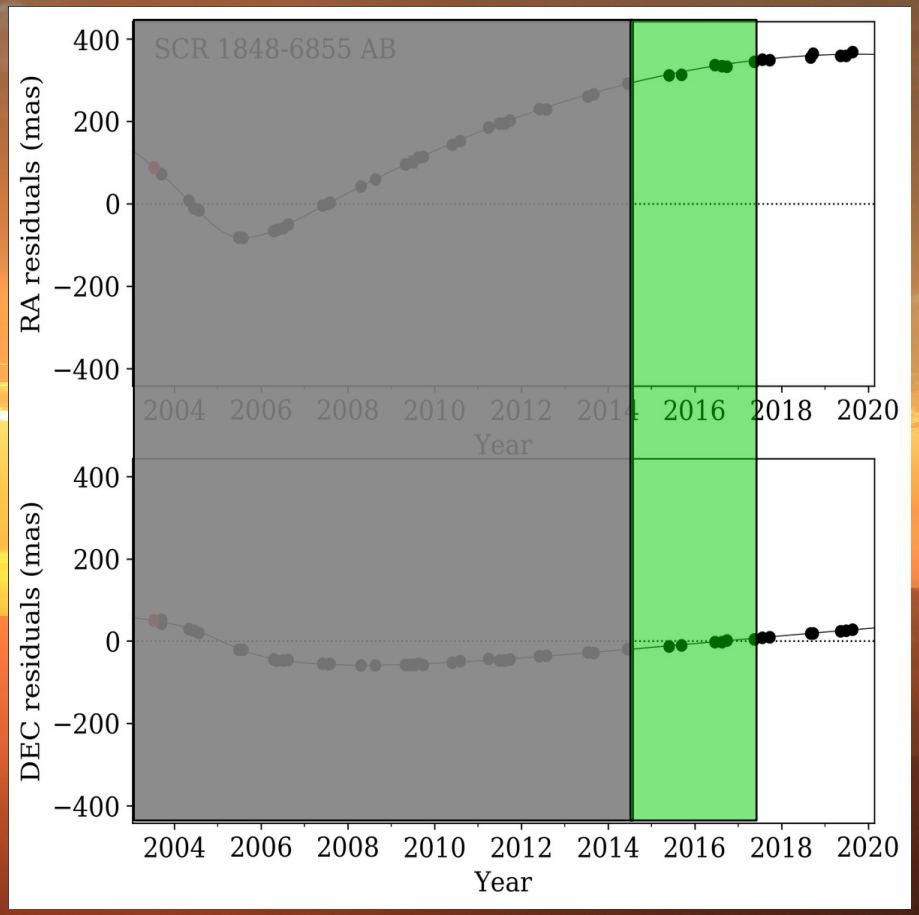
Perturbation: 0.6 orbit

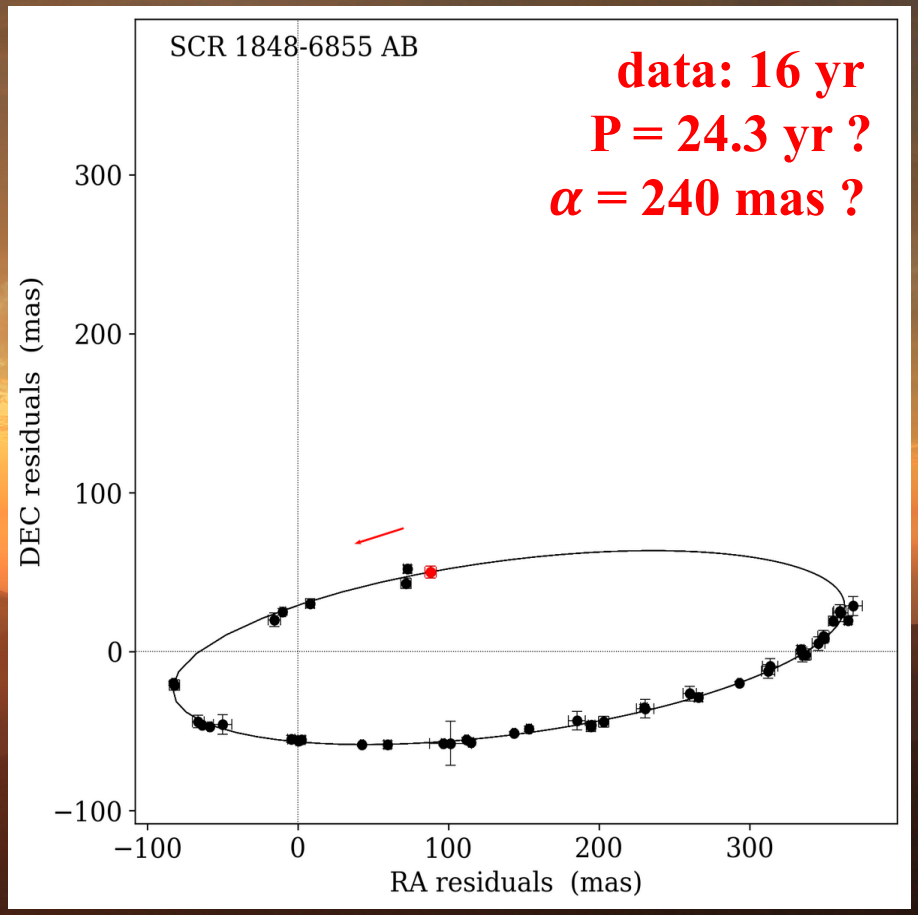




incomplete orbit … BEWARE

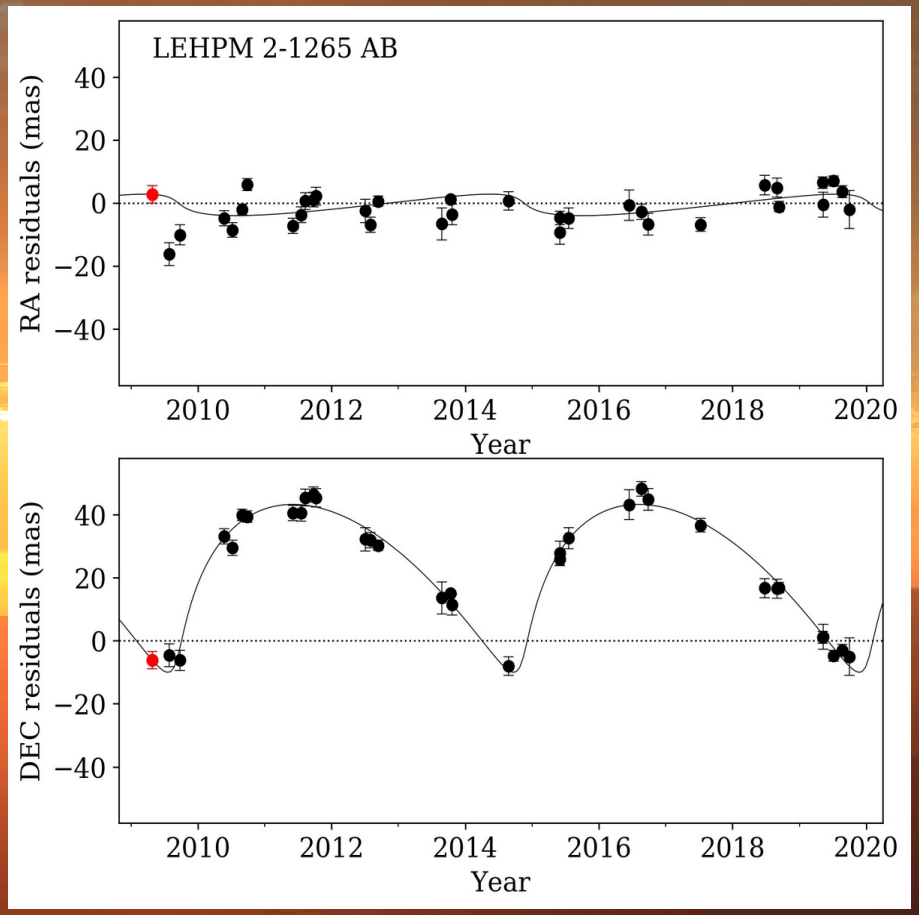
Perturbation: getting there

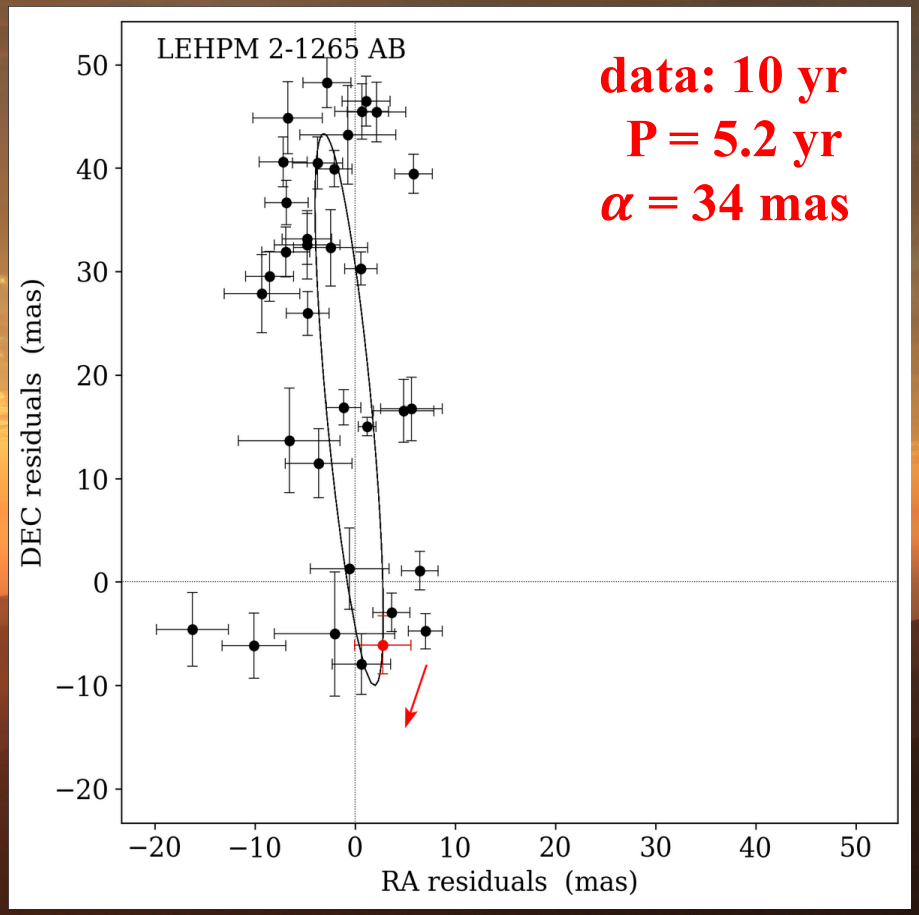




long-term programs yield gold

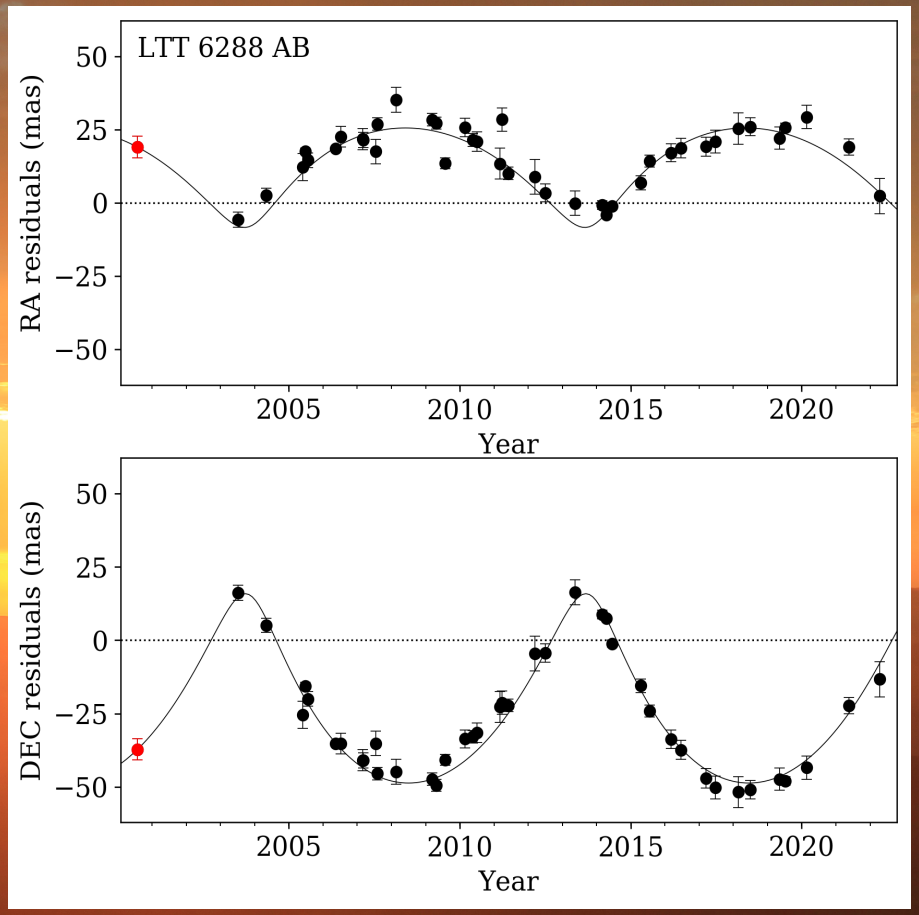
Perturbation: one axis only

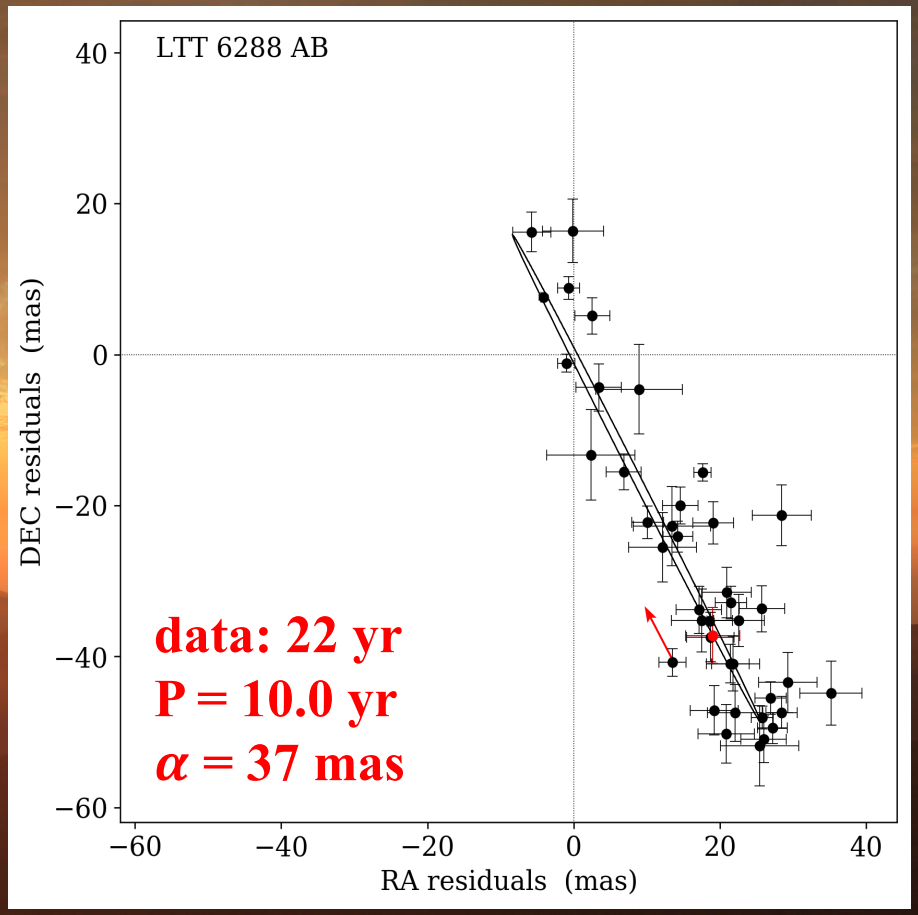




don’t count on clear PB on both axes

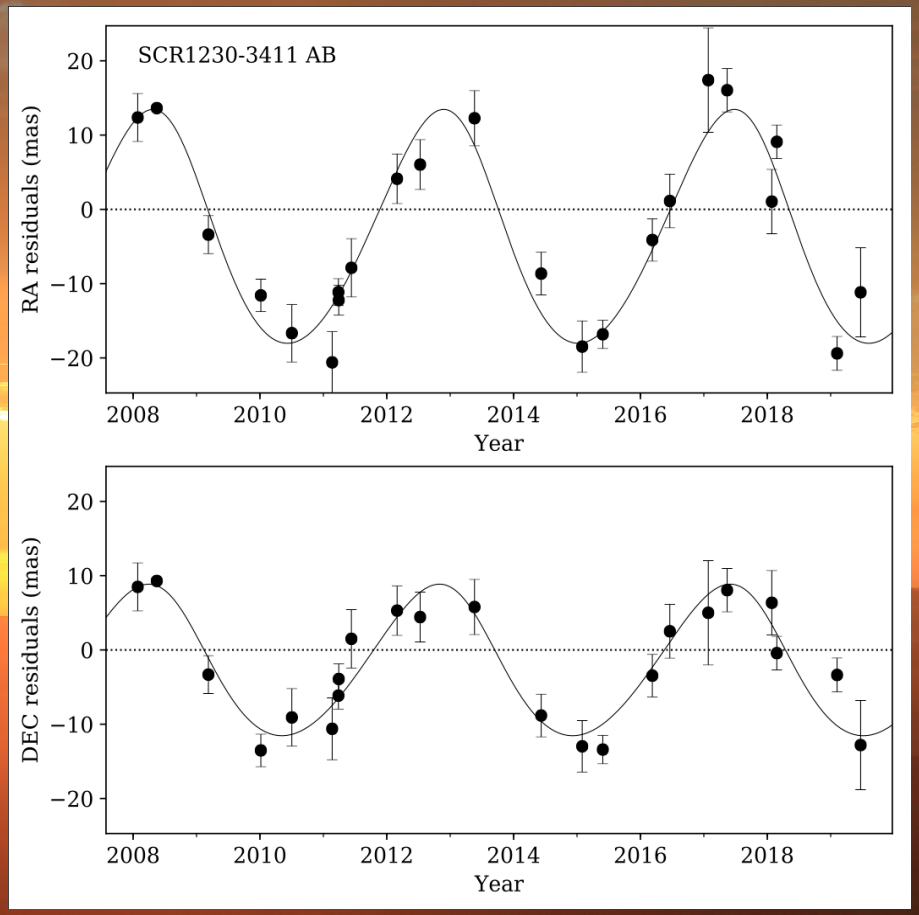
Perturbation: high inclination

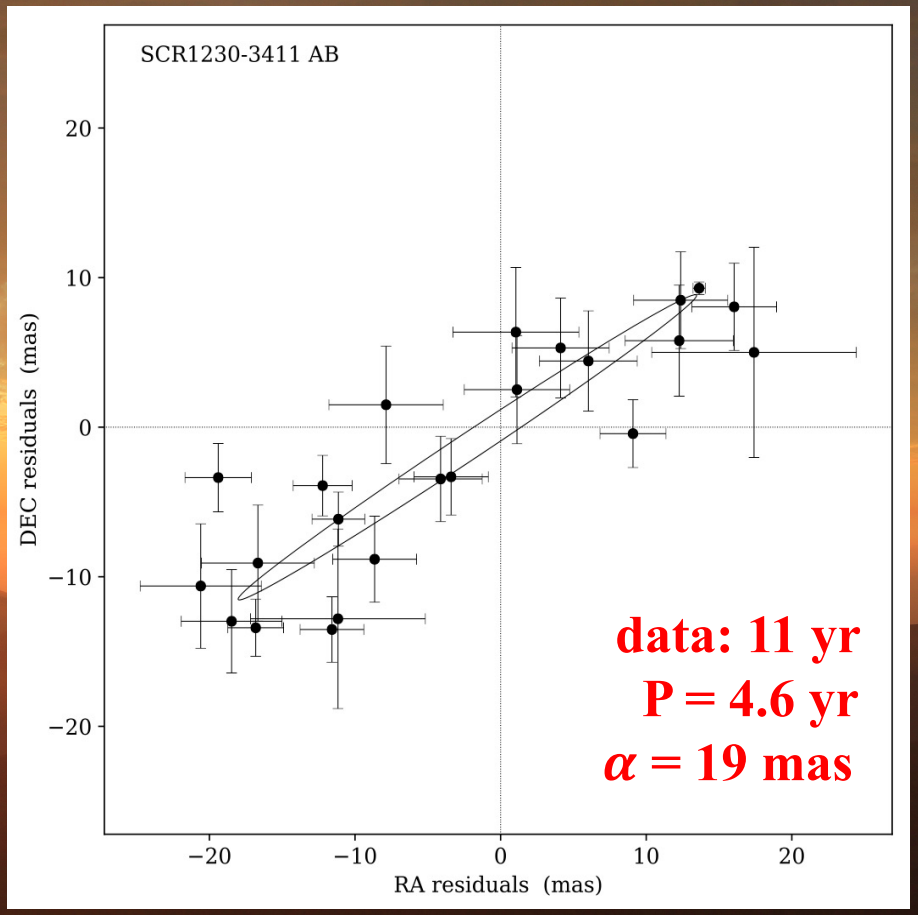




$i = 89^{\circ}$ … BEWARE, but high i orbits happen

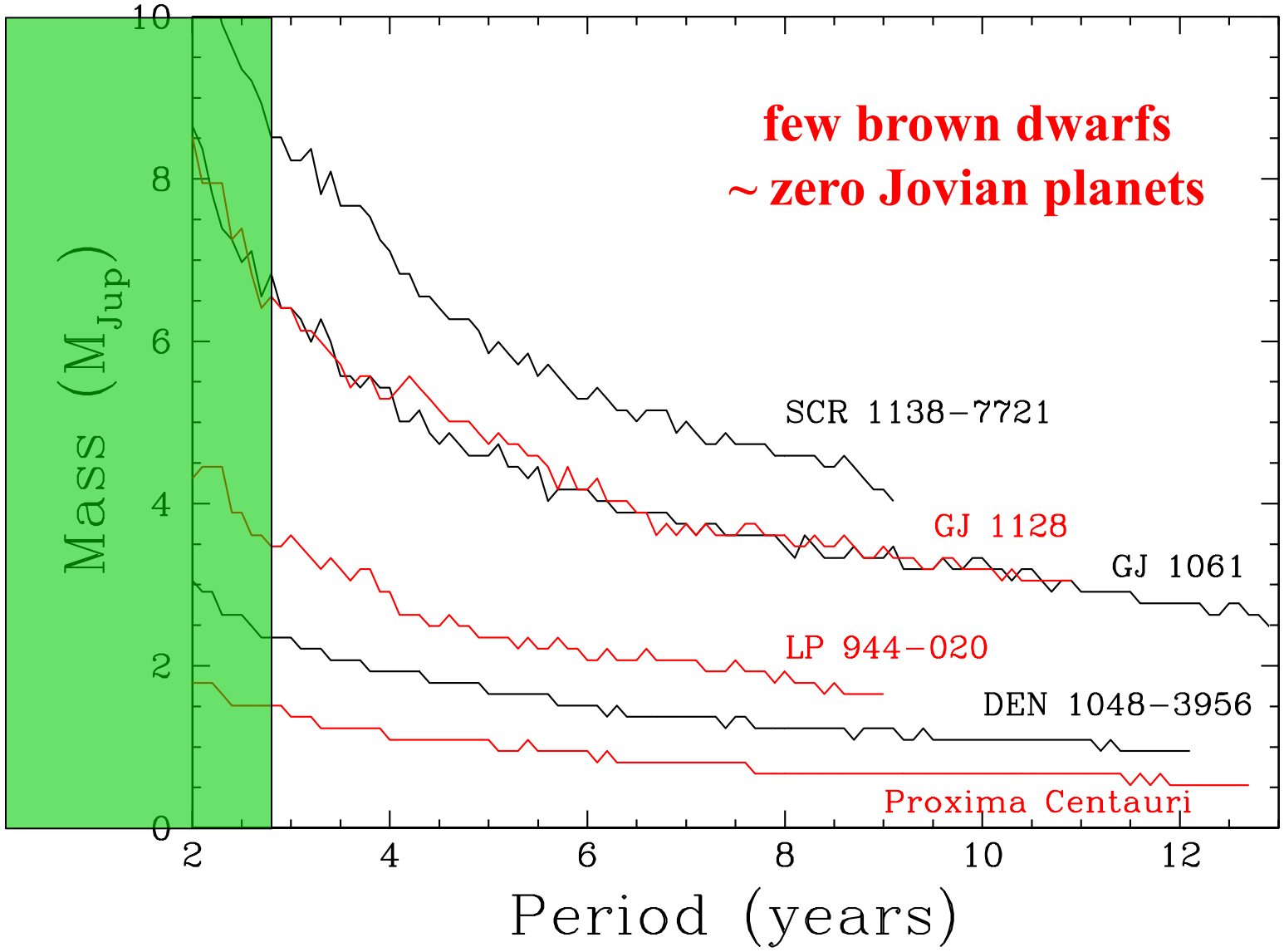
Perturbation: tiny orbit





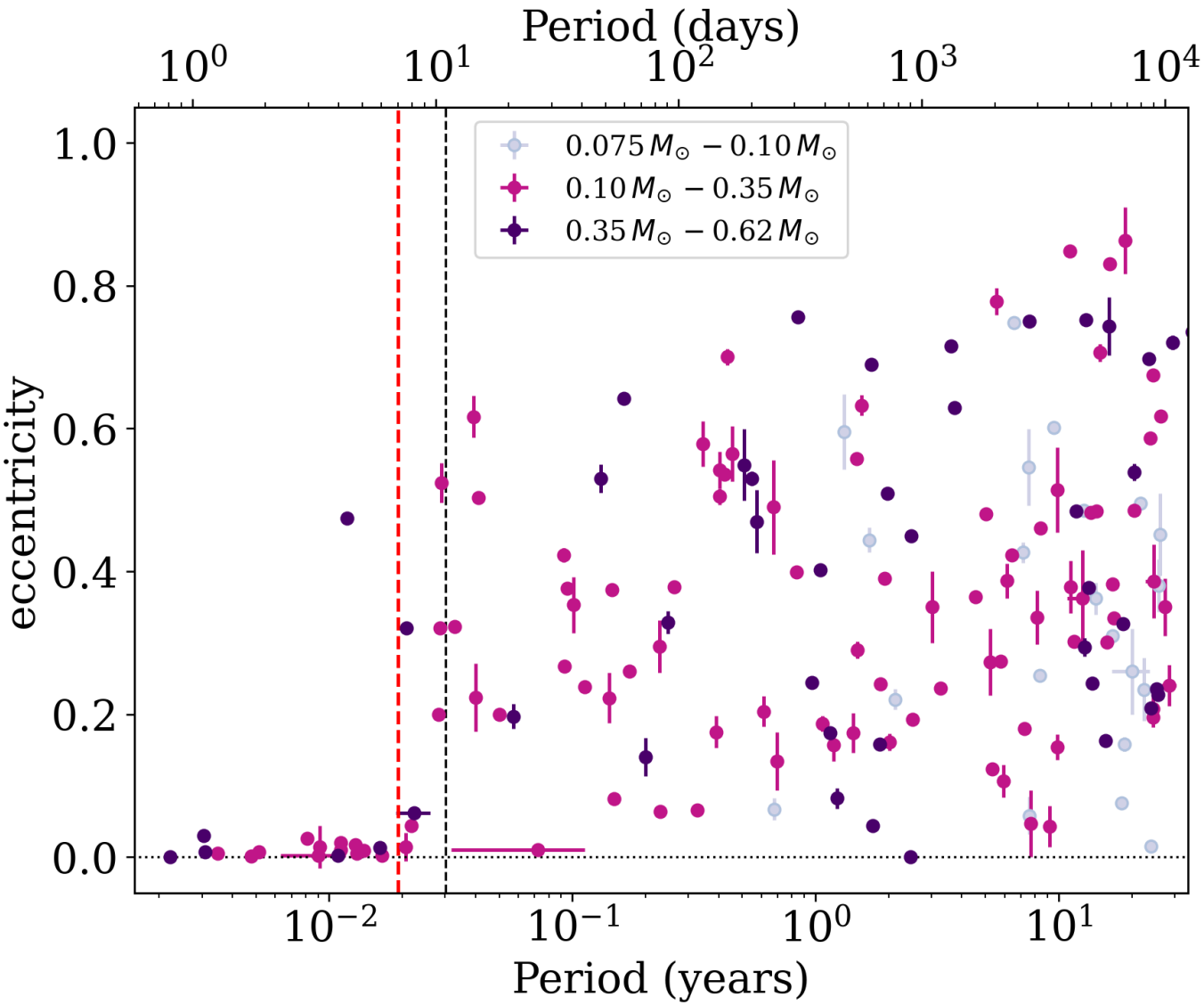
α = 19 mas … a few mas for Jupiter

Perturbation: planet search



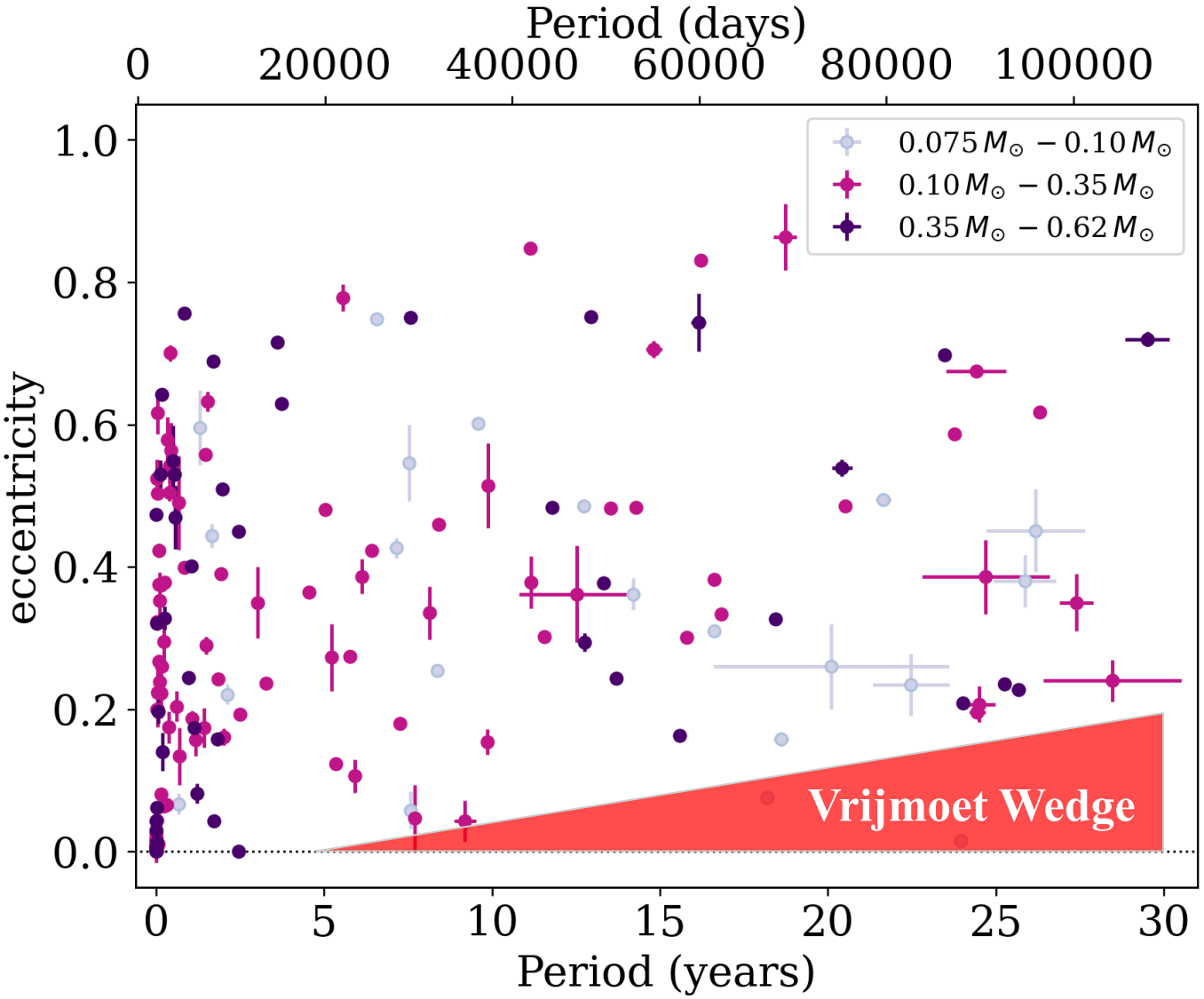
Lurie et al. (2014)

Perturbation: M Dwarf Orbits



Vrijmoet thesis (2023)

Perturbation: M Dwarf Orbits



Vrijmoet thesis (2023)

Astrometry = “metering the stars”

Position

Proper Motion

Parallax

Perturbation

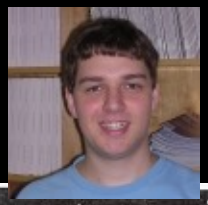
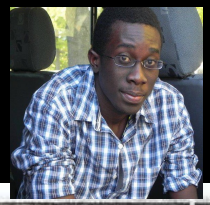
Big Questions

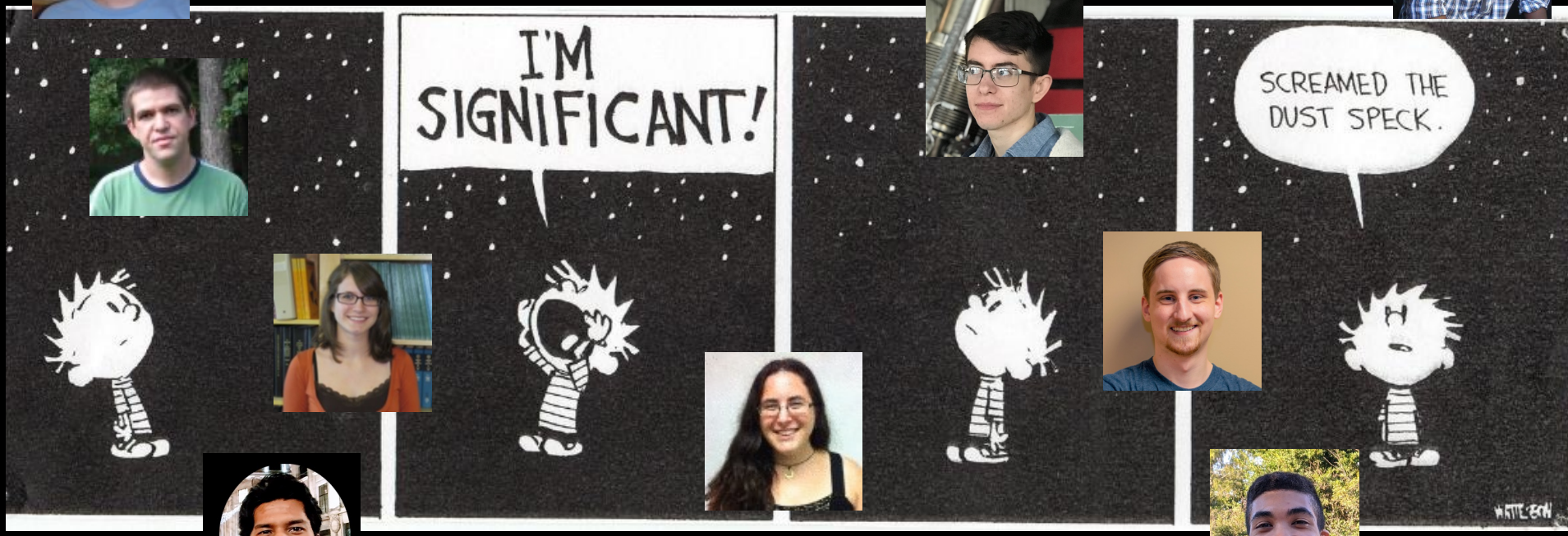
RECONS
Research Consortium on Nearby Stars


What is the Universe made of?

Where are the planets?

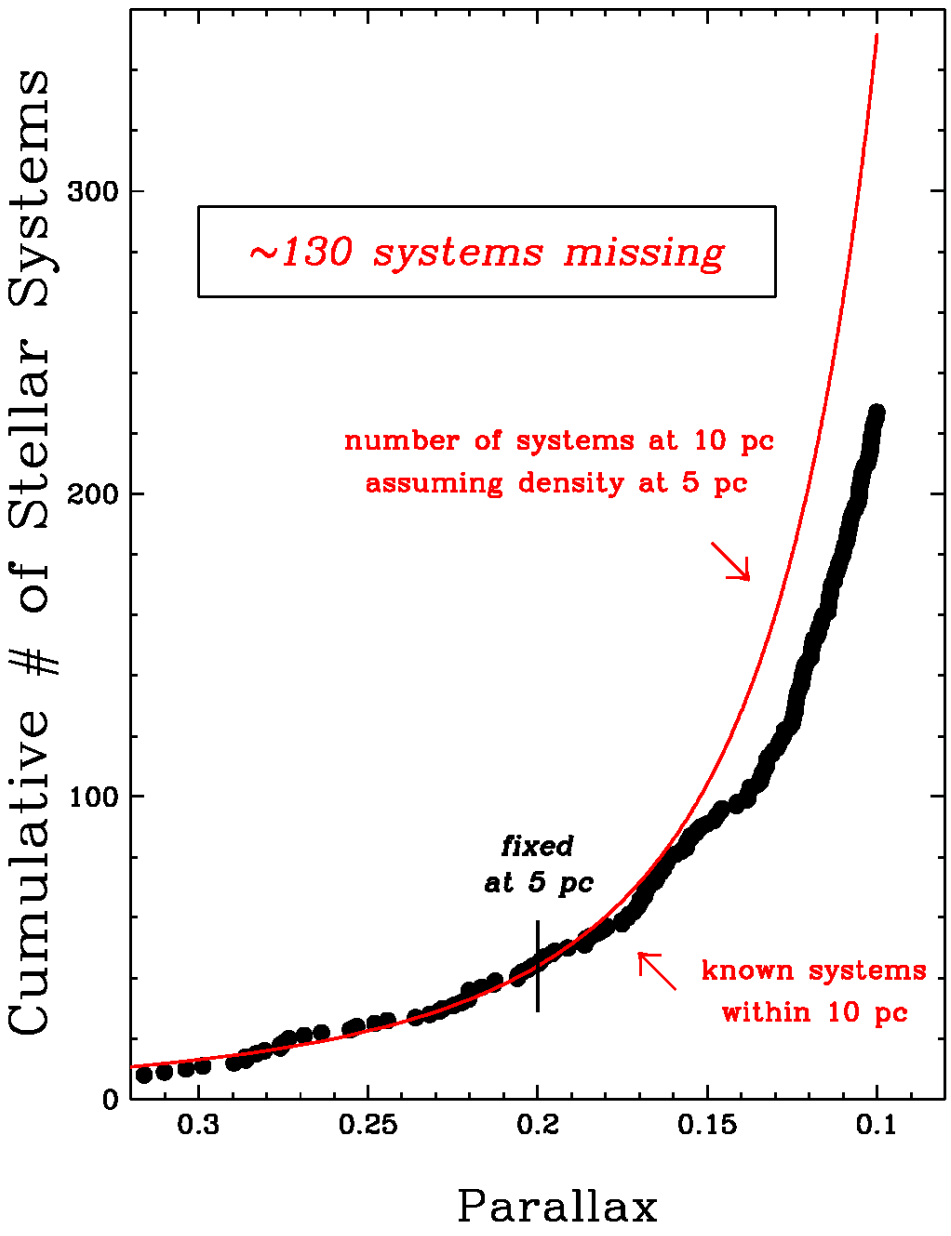
Is there life?



don't forget your map …

END



Henry et al. 1997

RECONS

Research Consortium on Nearby Stars

established 1994

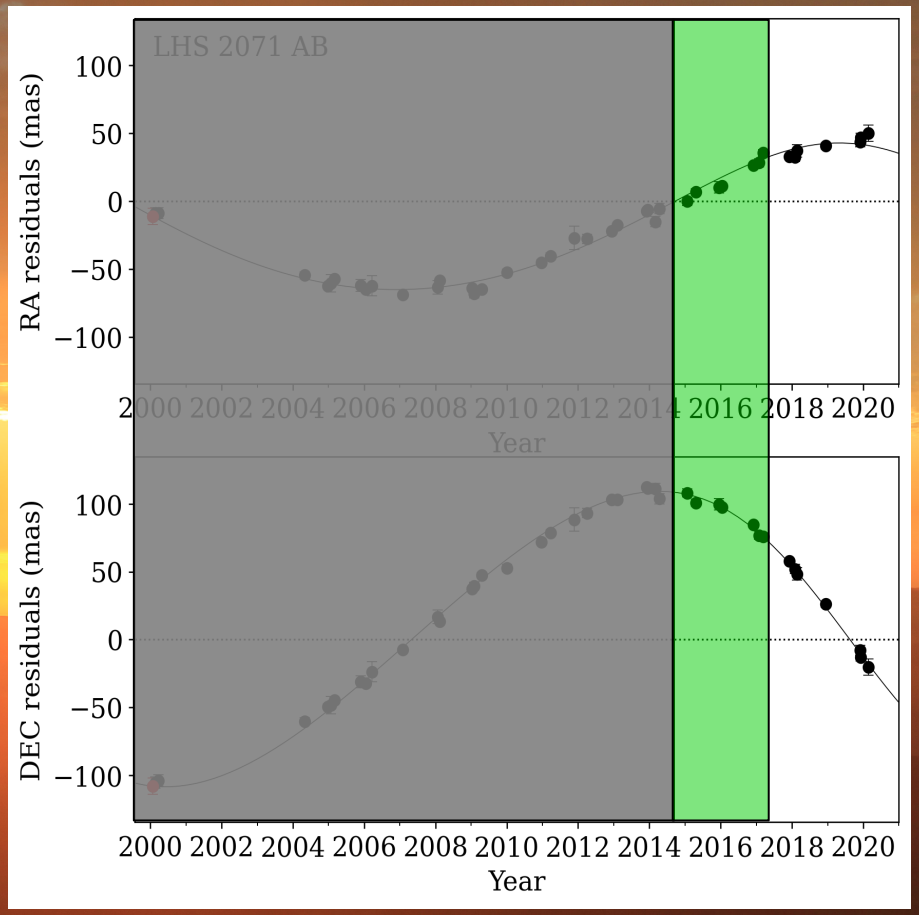
recons.org

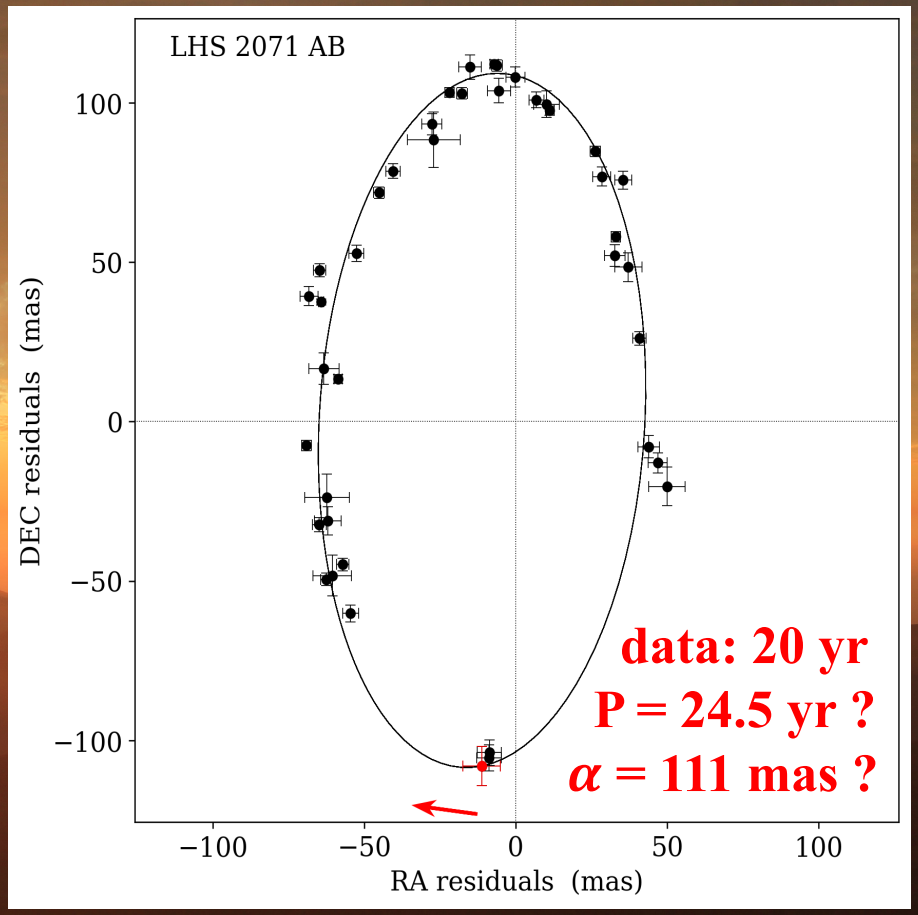
GOAL: explore the solar neighborhood

Perturbation: Orbital Elements

a	semimajor axis	size
e	eccentricity	shape
i	inclination	tilt
P	orbital period	time
T	epoch of periastron	a date
Ω	longitude of ascending node	flip angle
ω	longitude of periastron	twist angle
equinox	equinox of date	sets direction of equinox
f	fractional mass	a number

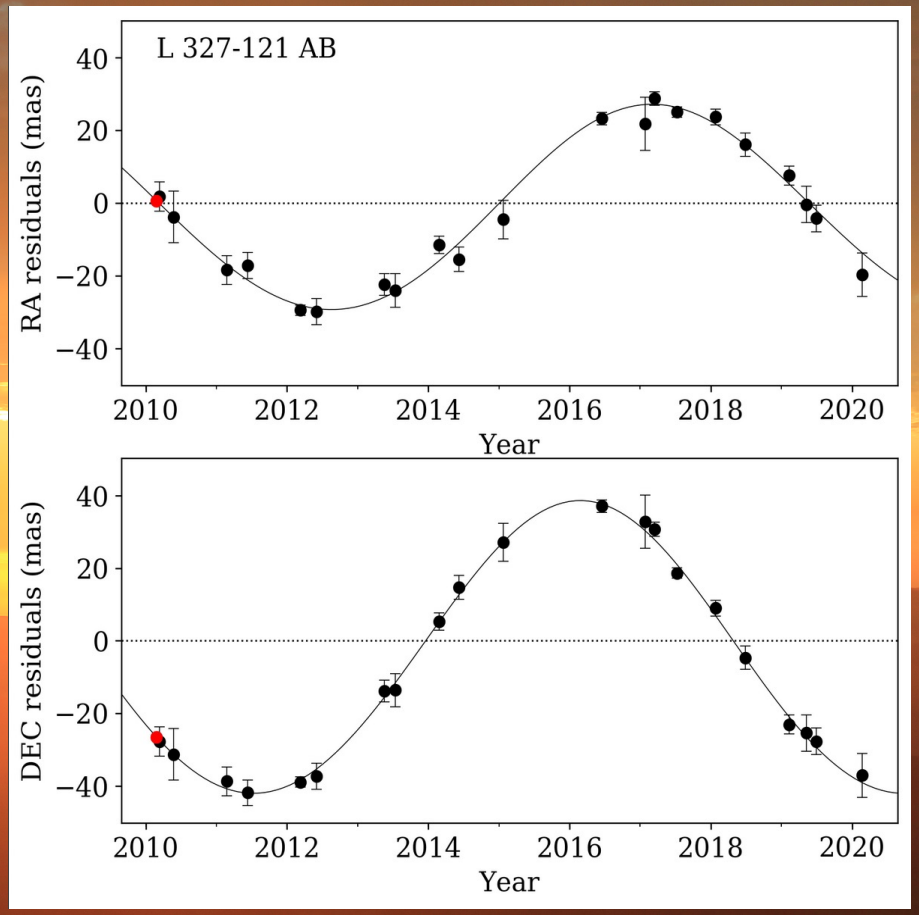
Perturbation: 0.8 orbit

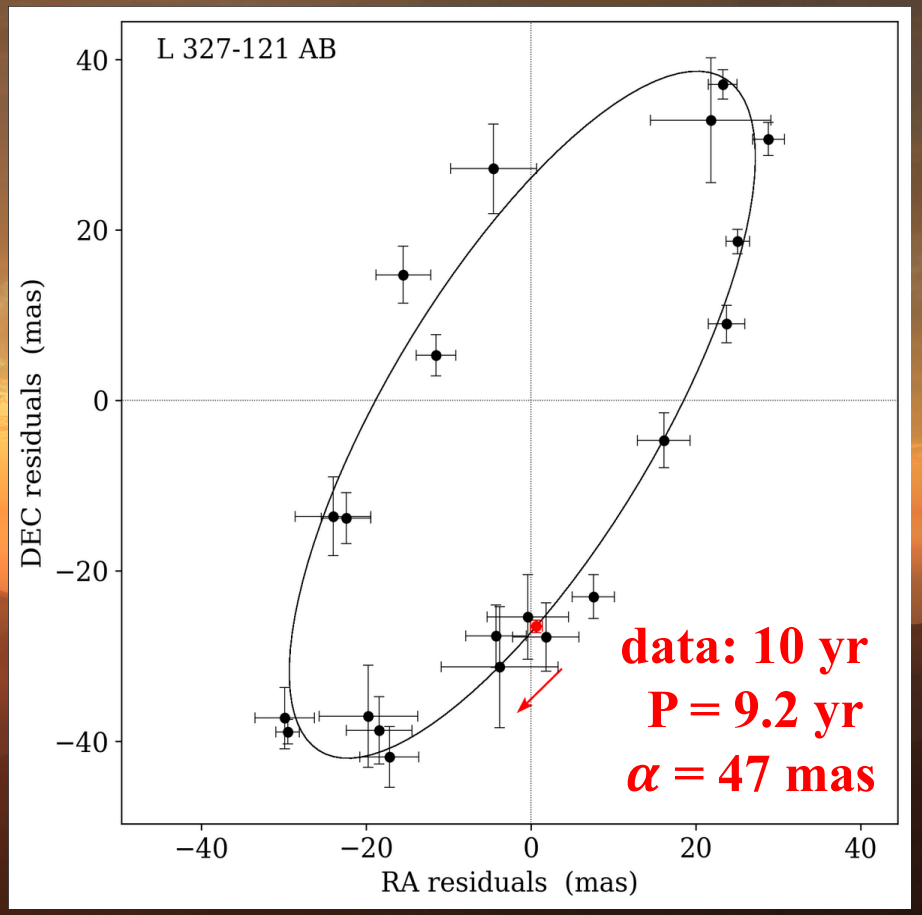




early observation helps, not quite wrapped, BEWARE

Perturbation: 1.1 orbits





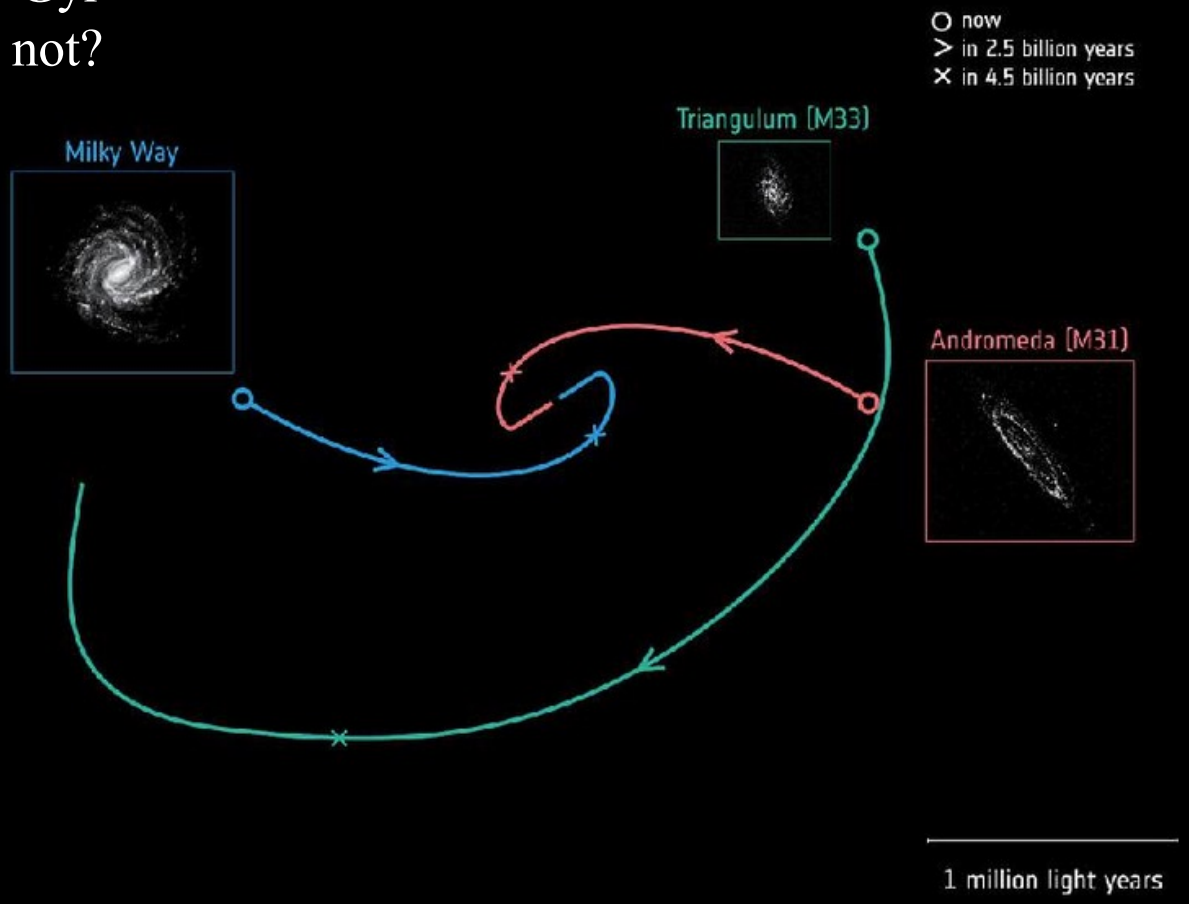
just wrapped … feeling good

Gaia Predicts the Future

previously …
- MW+And head-on in 3.9 Gyr
- Tri+And first infall … or not?

1000s of stars in And+Tri
- proper motions

new
- MW+And
  - 4.5 Gyr first pass
  - near miss at 120 kpc
- Tri on first infall
- also, And+Tri rotations



van der Marel+ (2019)

Milky Way + Andromeda Future

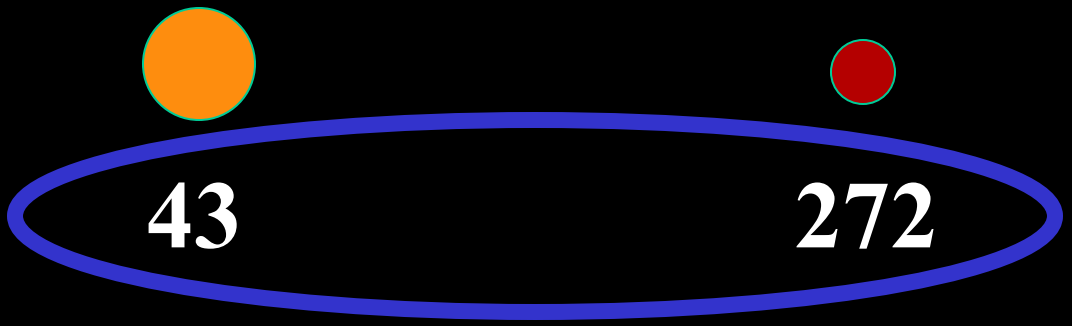
Gaia's Predicts the Future

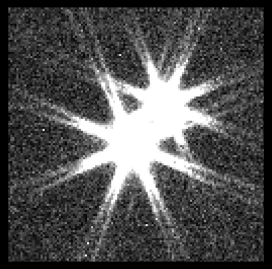
Gaia Additions: OCT 2019

7 total systems

4	**drifters**	**parallaxes near 100 mas**
2	**lurkers**	**parallax errors > 10 mas**
1	**true add**	**a brown dwarf (56 known)**

0 new stars within 10 parsecs





RECONS

Research Consortium on Nearby Stars

Census

10 pc	all	366 stars	265 systems
25 pc	M	~ 4200 stars	~ 3000 systems
50 pc	K	~ 7000 stars	5095 systems

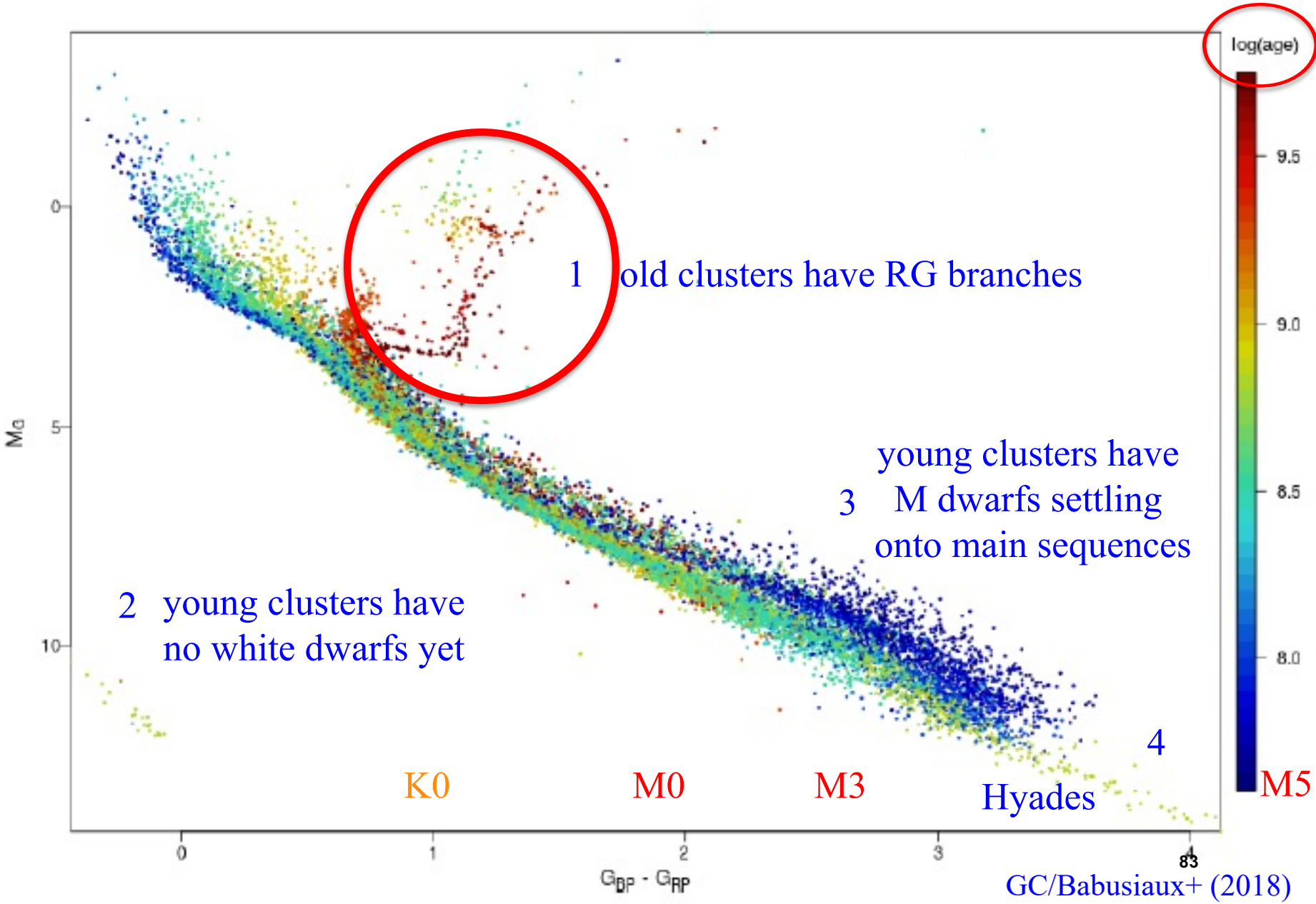
Type	Survey	Sample	Comp Stars	
M	wide	1120	137	12%
M	speckle	(1120)	144	>13%
M	rad vel	~ 300	…..	…..

Winters et al. 2019 and Vrijmoet ongoing

K	wide	5095	…..	…..
K	speckle	1048	154	15%
K	rad vel	300	59	20%

Nusdeo/Paredes et al. ongoing

32 Open Clusters in Gaia



GC/Babusiaux+ (2018)

Hyades by Gaia

https://www.youtube.com/watch?v=Wqqj2T6ox70

Milky Way + Enceladus (the galaxy)

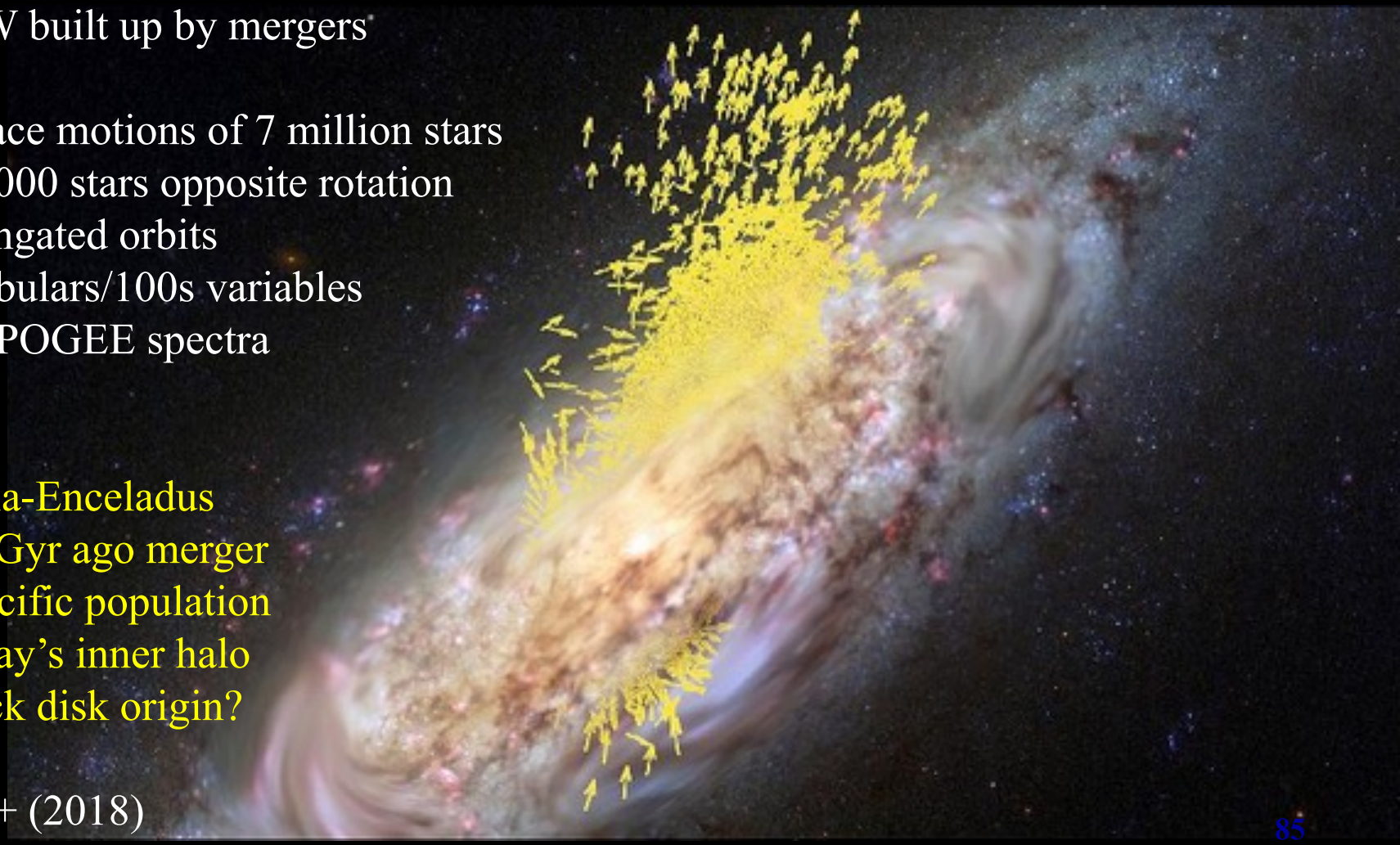
previously …
- MW built up by mergers

3D space motions of 7 million stars
- 30,000 stars opposite rotation
- elongated orbits

13 globulars/100s variables
- +APOGEE spectra

new
- Gaia-Enceladus
- 10 Gyr ago merger
- specific population
- today's inner halo
- thick disk origin?

Helmi+ (2018)



MW Construction

Gaia-Enceladus = Gaia-Sausage
SDSS + *Gaia* DR2

orbits have e ~ 0.9
[Fe/H] > -1.7
merger 8-11 Gyr ago

+ 5 X 10^9 $M_\odot$ in stars
+ at least 8 globulars to MW

puffed up thin disk to thick disk
new gas collapsed to thin disk

Helmi+ (2018)
Deason+ (2018)
Myeong+ (2018)
Belokurov+ (2018)

Milky Way + Enceladus (the galaxy)

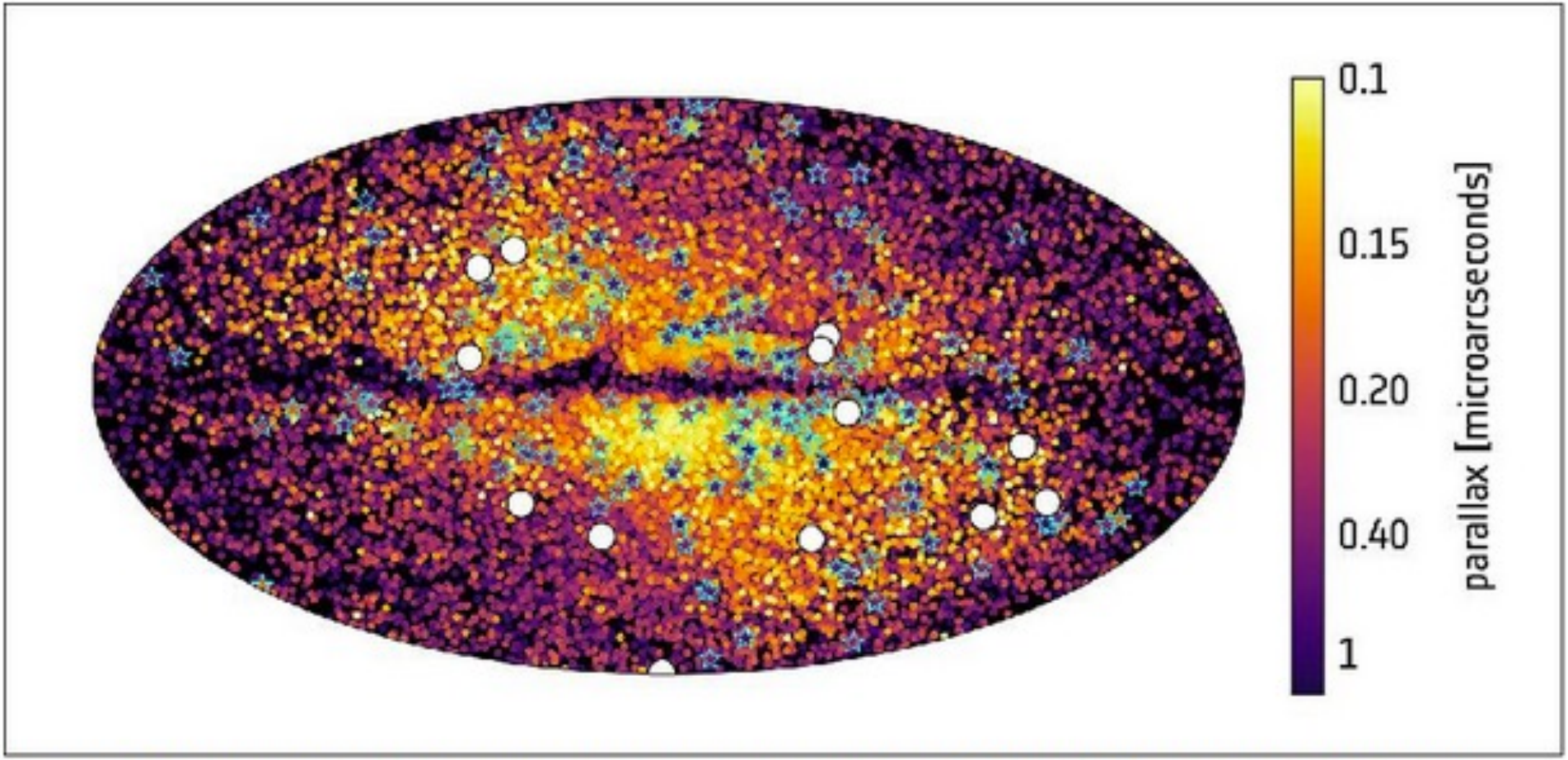
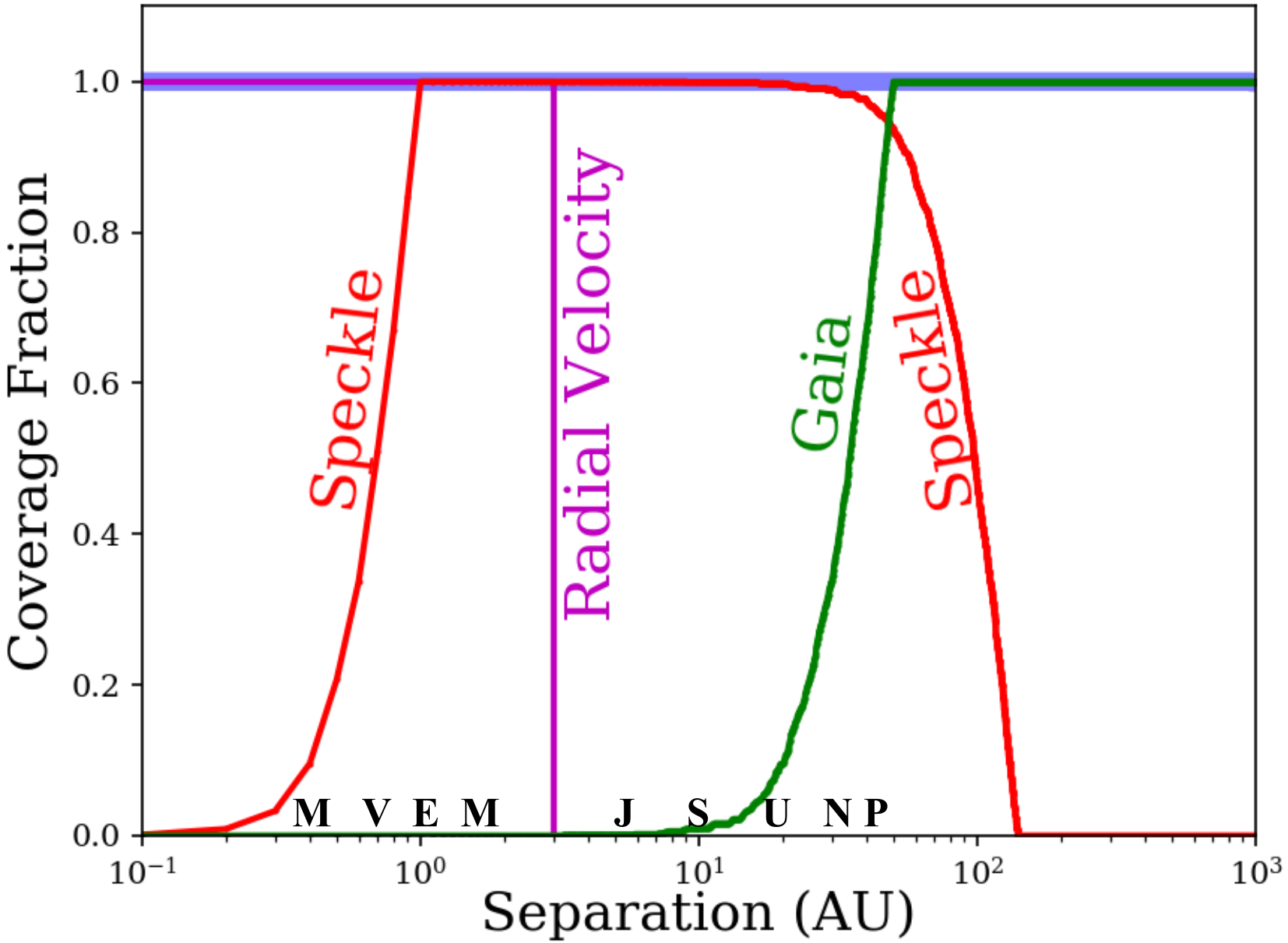


Figure 59: Gaia-Enceladus stars across the sky (image credit: ESA/Gaia/DPAC; A. Helmi et al. 2018)

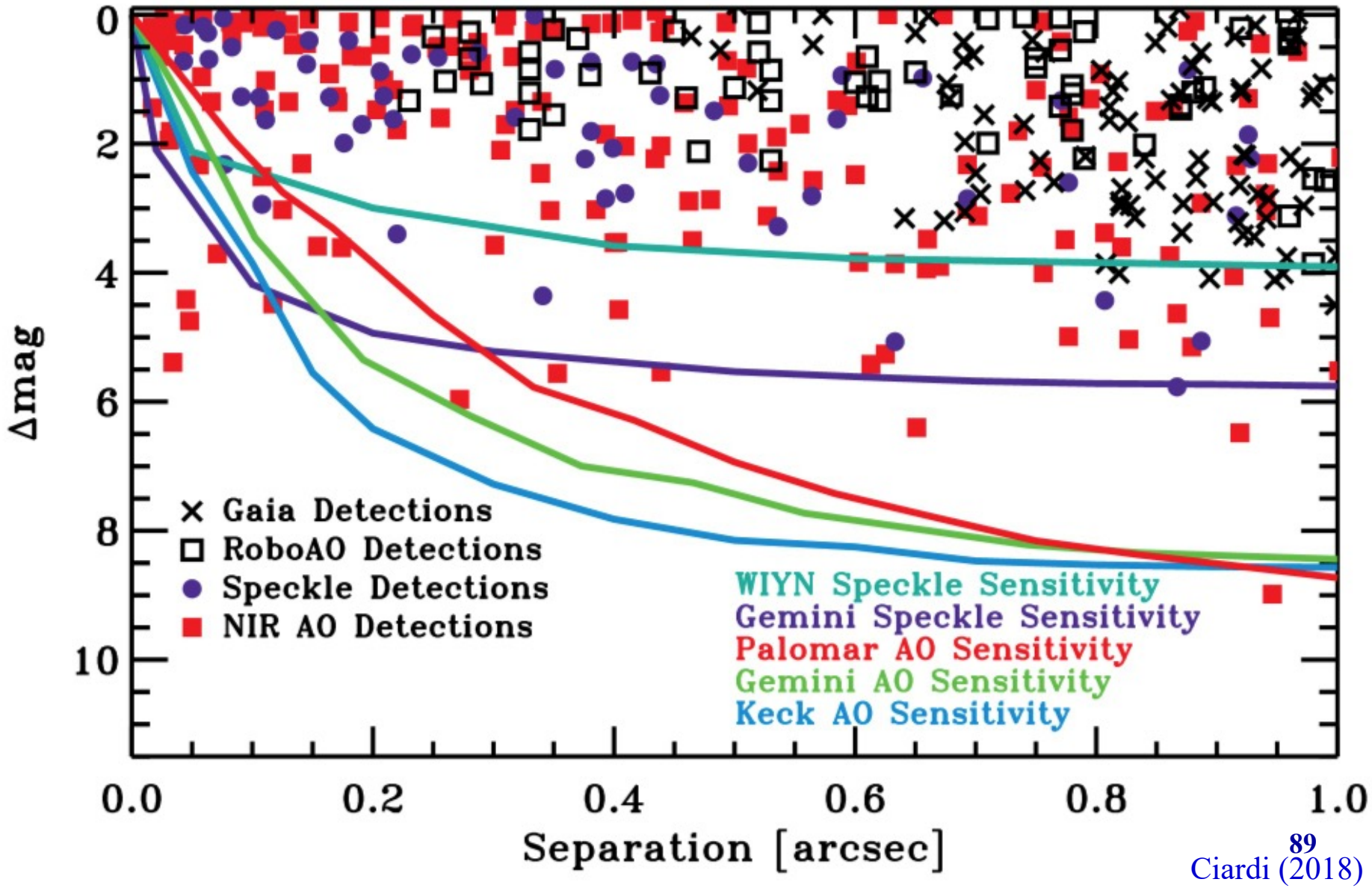
variables starred / globular clusters as dots
Magellanic Cloud sized?
tiny parallaxes …

How far away is an object with parallax 1 microarcsecond?

K Dwarf Surveys



High Resolution Sensitivities



Ciardi (2018)

Speckle Survey

‘Alopeke on Gemini-N

Zorro on Gemini-S

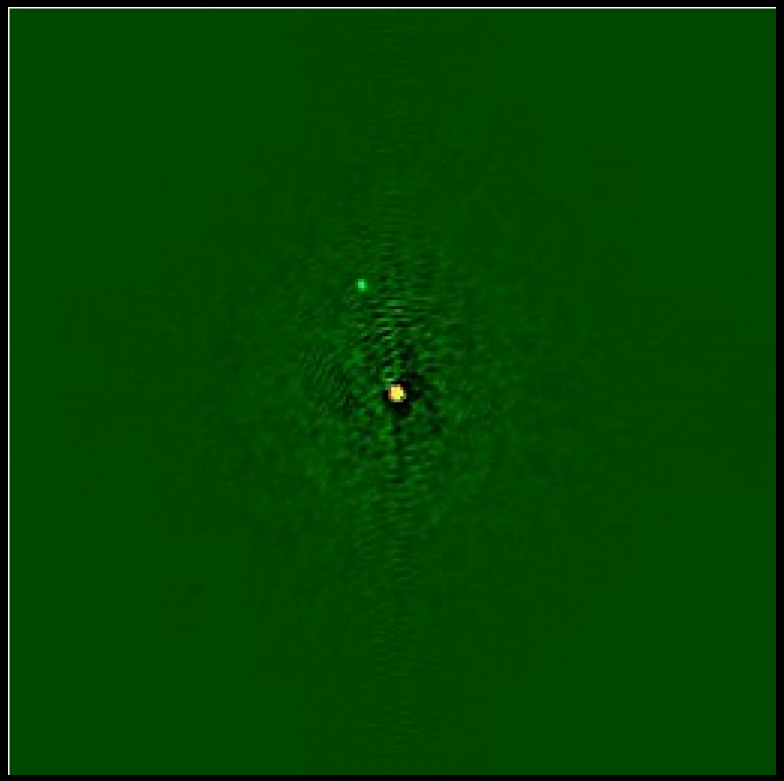
DSSI on DCT

NESSI on WIYN

with Elliott Horch, Steve Howell, et al.

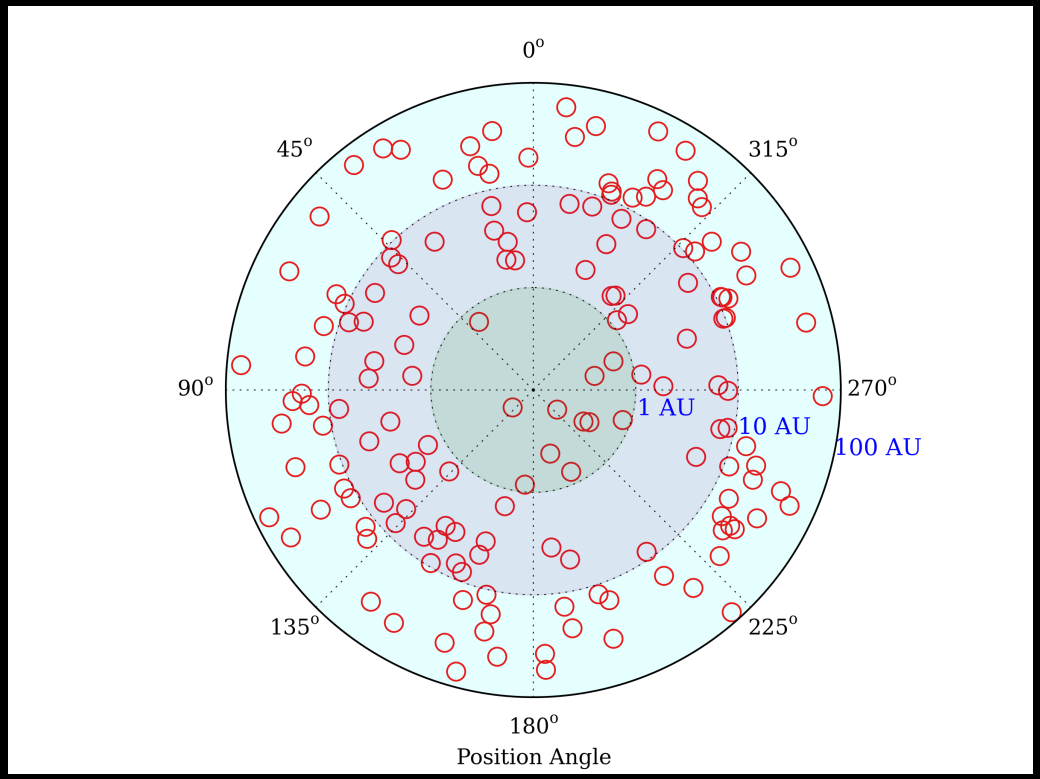
Speckle Survey Results

GJ 538 AB at 17 pc



0.4″ = 7 AU

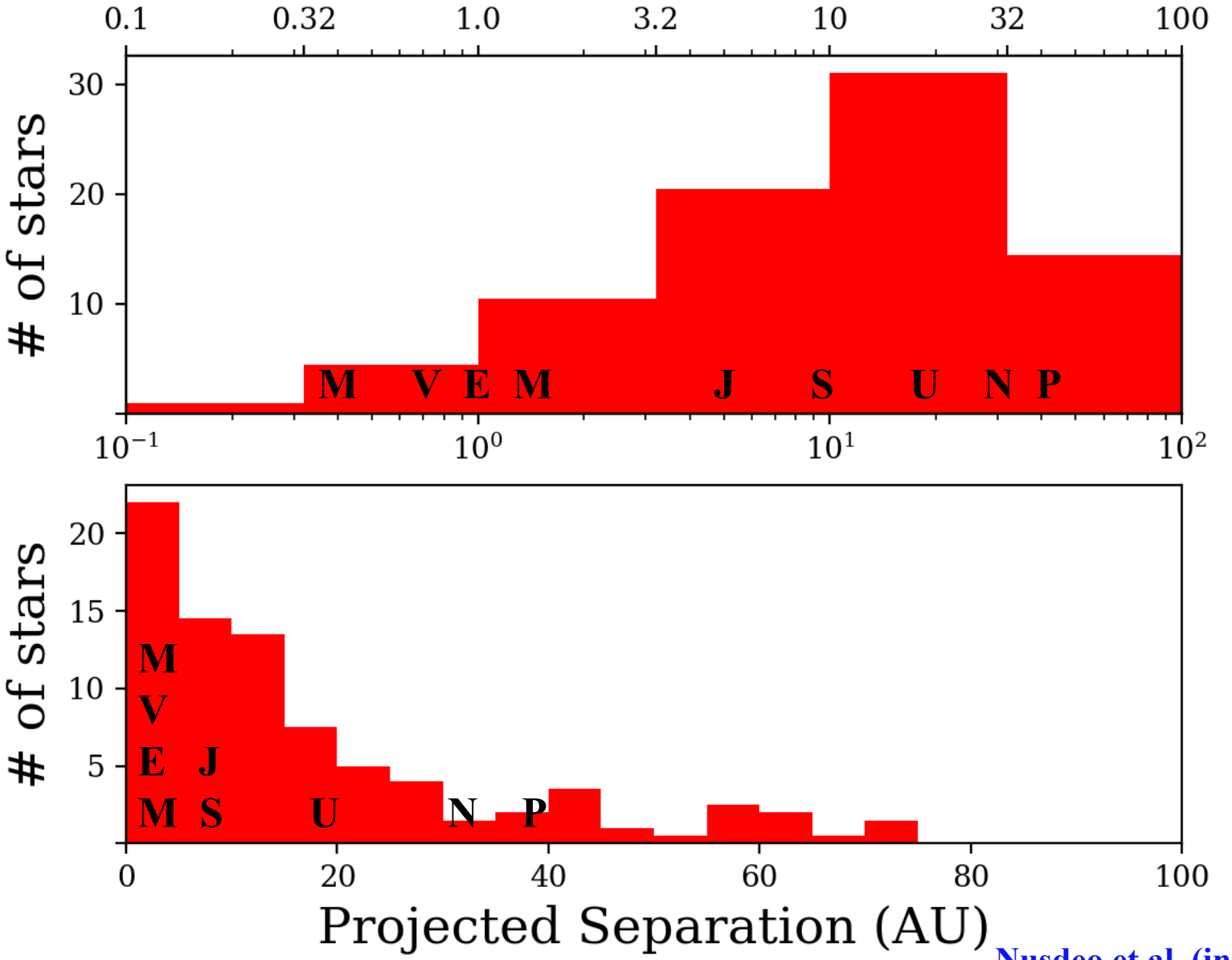
1048 stars imaged



154 companions

Nusdeo et al. (in progress)

Speckle Survey Results



Nusdeo et al. (in progress)