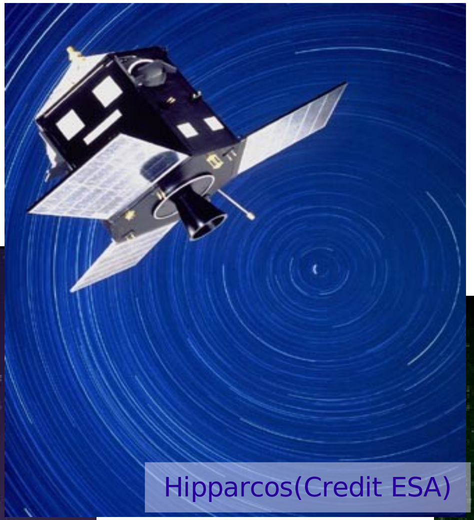
Astrometric & Photometric Detection & Characterization of (massive) Extrasolar Giant Planets

Searching for Solar System Giant Analogs with SIM (and GAIA)

Rob Olling, Ed Shaya (UMd)



Hipparcos(Credit ESA)

Hipparcos: 3 years,
early 1990s: **mas accuracy**

SIM/Heavy (Credit JPL)

GAIA (Credit ESA)

SIM-Lite: 5-10 yrs; 201?+; **1/1000 mas**

GAIA: 5-7 years, 2012+; **1/100 mas**

Outline

- Dabblings (2000-2006.5 @ USNO: FAME/AMEX/OBSS)
  http://www.astro.umd.edu/~olling/index_1.htm#My_Astrometry_USNO
  - Astrometric Scales in Astronomy
  - Astrometric Detections
  - dFTS: Radial Velocities & TPF-C Characterization
  - Transits w. scanning (Astrometric) Missions
    - LEAVITT: 10,000 Transiting planets down to R_{EARTH}*4.6
- Long Period Planets (Solar System Analogs)
  - Observability: Where/Why?
  - Traditional search methods
    - (μ_B problem)
  - Position Differences
    - Hipparcos to the Rescue
    - Period & Mass determination
- Conclusions & Future work
  - Backup slides
    - Part of this talk is based on a contribution to the Extrasolar Planet Task Force [Olling, 2007arXiv0704.3059O & http://www.astro.umd.edu/~olling]

Astrometric Scales in Astronomy

Parallaxes, in μas	
• α Cen:	742,000
• RR Lyra:	4,380
• δ Cep:	3,320
• 1 kpc:	1,000
• Gal. Center:	125
• LMC:	20
• M 31:	1.5

Proper Motions, in μas/yr	
• α Cen:	3,600,000
• RR Lyra:	200,000
• δ Cep:	16,500
• 10 km/s @ 1 kpc:	2,110
• 200 km/s @ 8 kpc	5,275
• 50 km/s @ LMC:	211
• 200 km/s @M 31:	60

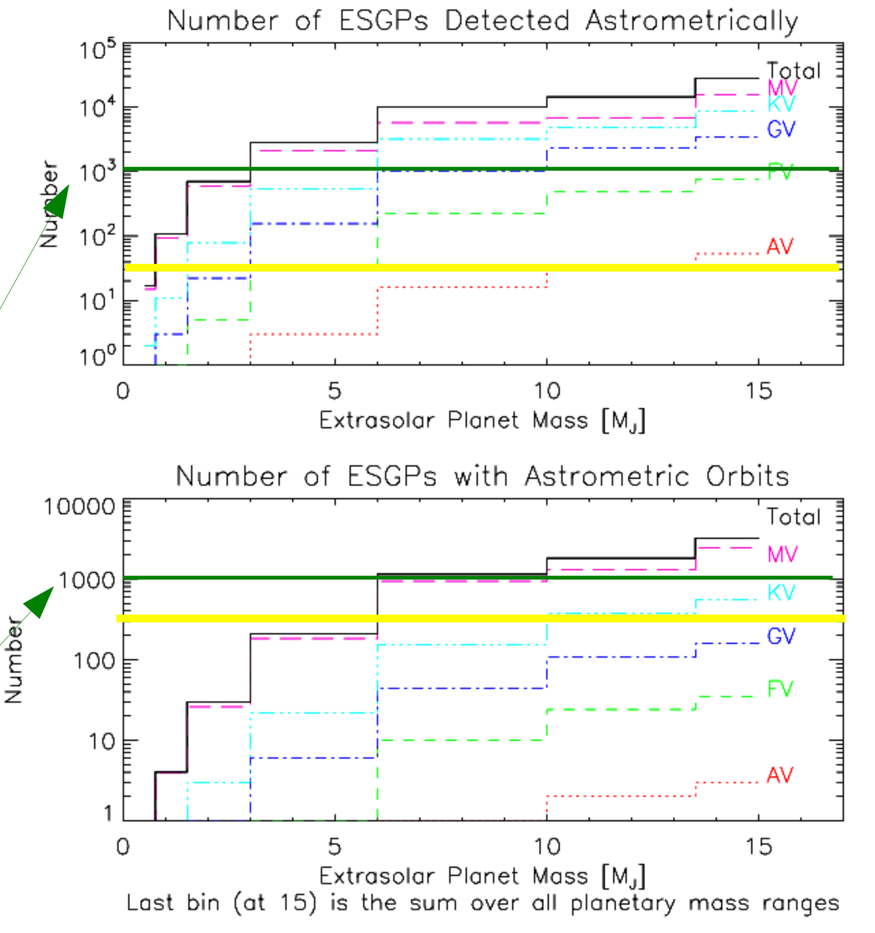
USA @ 10 pc 2.9 ; 2 M_{EARTH} @ 10 pc: 1 μas/yr

Sun's$_{\oplus}$ reflex motion 450 km

Astrometric Detections:

- Advantages of large numbers and/or high accuracy
  - Large numbers:
    - find rare objects (e.g., **old, high [Fe/H] stars**)
    - accurate statistics/general properties of majority
    - Identify ES planetary systems
  - High accuracy: ⇒ characterize individual objects
- Astrometry:
  - OBSS/GAIA
    - 5σ 28,000 =28*Kepler
    - 15σ 3,200 = 3*Kepler

OBSS/GAIA



Dispersed Fourier Transform Spectrometer:

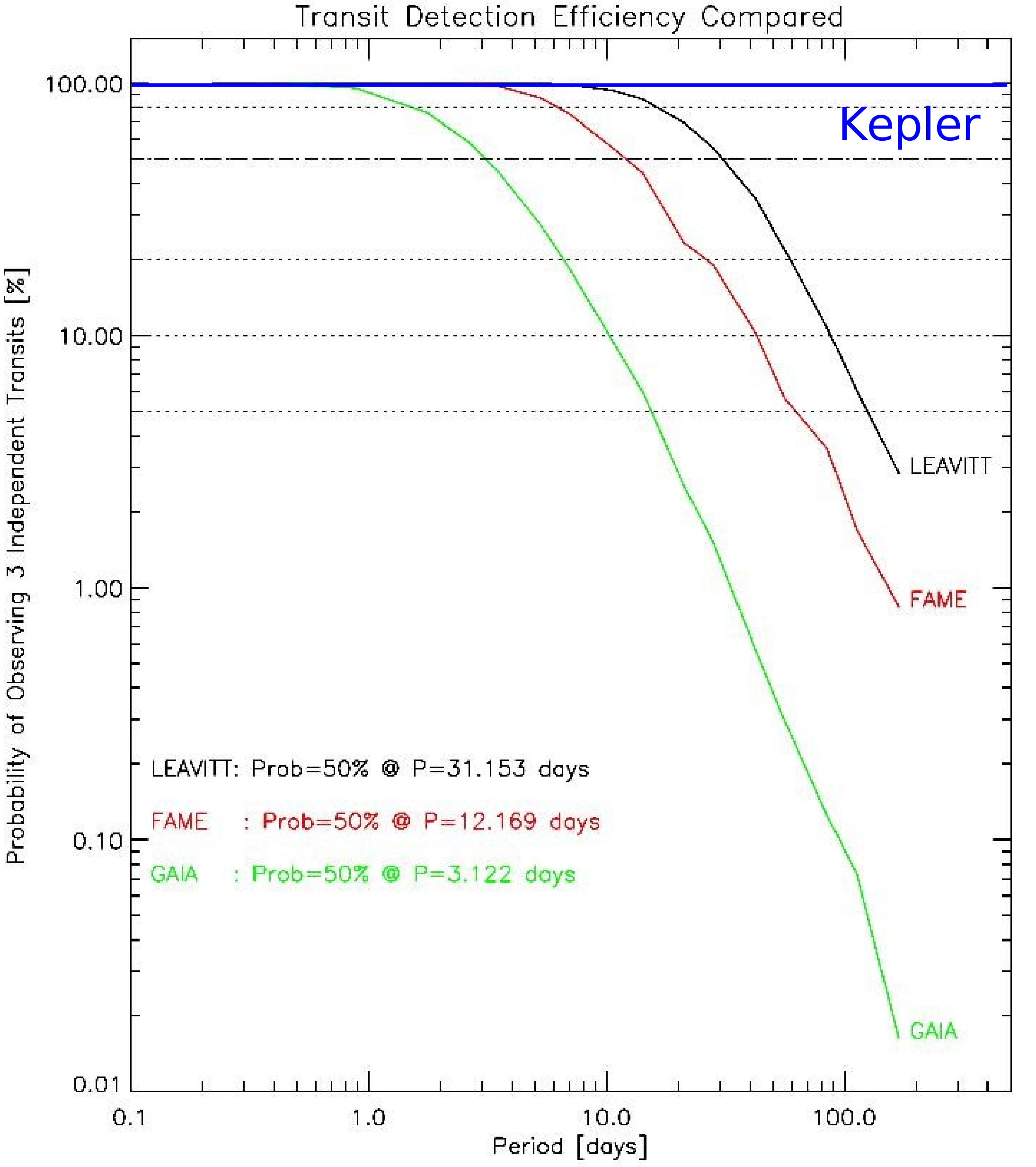
- dFTS @ USNO: PI: Arsen Hajian (now at Waterloo)
  http://adsabs.harvard.edu/abs/2007ApJ...661..616H
  http://www.astro.umd.edu/~olling/Papers/dFTS_white_paper_final.pdf
  - Like conventional FTS, but dispersed by GRATING into many thousands of spectral channels
    - Much, much better sensitivity: $S/N_{dFTS} = S/N_{FTS} * (R_{GRATING})^{½}$
    - Whole (optical) spectrum
      - Configurable spectral resolution (down to **TPF** needs)
    - Small size (~1 m^3)
    - Cheap (shoestring)
  - Full-aperture metrology
    - Extreme wavelength sensitivity (“arbitrary” resolution)
      - ~3 m/s for our shoestring instrument
      - Many known improvements await funding
      - **cm/s** long-term stability expected ==> **Earth-mass planets**

Planetary Transits w. Astrometric Telescopes:

- HIPPARCOS/FAME/LEAVITT-like instruments are "good" for transit detections (GAIA spins too slowly)
  - Large number of (independent) observations
    - Hipparcos 100/3yr = 1 per 7.7 "days"
    - FAME: 129/5yr = 1 per 9.9 "days"
    - GAIA: 60/5yr = 1 per 21.3 "days"
    - LEAVITT: 183/5yr = 1 per 7.0 "days"
  - **SHOW sky coverage**

PTs w. Astrometric Telescopes: Detection Efficiency

- **Resulting detection efficiency depends critically on cadence**
- **Efficiency from:**
  - Cadence
  - Edge-on probability
    from period distribution (PDF_{PLAN})
  - Duration of transit
    $==> T_{TRANS}/P_{ORBIT}=R_{PLAN}/R_{STAR}$
  - Number of Stars surveyed
- **Bottom Line:**
  - **LEAVITT: good**
  - **Kepler: int./good**
  - **FAME: intermediate**
  - **GAIA: poor**



Planetary Transits w. Astrometric Telescopes:

- Many observations (CCD transits) per “epoch” ==> good sensitivity for 2 mmag accuracy per 2.5 hour & not saturated & GV primary
  ”Maximum” possible number of Extrasolar Giant Transiting Planets (1/2000)

  - H: V= [0.0, 9.5] mag => N'_{EGP} = 95 ; R_{PLANET} = [0.9, 1.5] $R_{NEPTUNE}$
  - F: V= [5.2, 10.8] mag => N'_{EGP} = 341 ; R_{PLANET} = [0.5, 2.0] $R_{NEPTUNE}$
  - G: V= [11.0, 15.9] mag => N'_{EGP} = 26,800 ; R_{PLANET} = [0.7, 2.1] $R_{NEPTUNE}$
  - **L: V=[5.8, 14.8] mag => N'_{EGP} = 12,000 ; R_{PLANET}= [0.3, 2.4] $R_{NEPTUNE}$**
  - **K: V=[10.0, 14.0] mag => N'_{EGP} = 1,000 ; R_{PLANET}= [0.3, 2.4] $R_{NEPTUNE}$**
    mostly from reflection effects (phase variations)
  - **T: V=[4.5, 13.5] mag => N'_{EGP} = 1,700 ; R_{PLANET}= [1.0, 2.4] $R_{NEPTUNE}$**

H	=Hipparcos
F	=FAME
G	=GAIA
L	=LEAVITT
K	=Kepler
T	=TESS (NASA/SMEX)

Quantity	unit	Symbol	FAME	GAIA	LEAVITT	TESS
Mission Type			*MIDEX*	*"PROBE"*	*MIDEX*	*SMEX*
Mission Duration	Years	t_{MIS}	5	5	5	2
In-scan Mirror Size	cm	D_I	40	**140**	55	13.3
X-scan Mirror Size	cm	D_X	9	**50**	14	13.3
Photon-collecting power			1	**19.4**	2.1	2.9
Time to cover accessible sky = Median re-visit Time	days	$t_{SKY,70\%}$	28	35	**7.5**	
In-scan Field of View	degrees	FOV_I	1.1	0.74	**3.5**	
Total Number of broad-band observations		N_{BB}	2,684	1,057	**10,253**	
Epoch Duration	hours	t_{EPO}	2.73	3.69	**6.60**	
Average # Broad-Band Observations per Epoch		$N_{BB/EPO}$	22.4	26.8	**61.0**	
# of Independent Epochs		N_{EPO}	120.1	39.4	**168.0**	
# of Photometric Observations per band (R=3; R=2 for FAME)		N_{R5}	*244.0*	*96.1*	***10,253.4***	
Average # Photometric Observations per Epoch		$N_{PHO/EPO}$	2.0	2.4	**61.0**	
Photometric Saturation Level [mag]		V_{SAT}	5.21	10.69	**5.76**	4.5
V magnitude for 2 mmag photometry in 0.83 hr	magnitude	V_{2mmag}	10.81	**15.59**	14.83	13.5
Number of Stars Surveyed	10^6	$N_{S,TR}$	1	**73**	36	2.5
Minimum Planetary Radius (GV)	$R_{NEPTUNE}$	$R_{PL,MIN}$	0.51	0.68	**0.30**	**1.00**
Number of Planetary Transits (AV, FV, GV, KV & MV stars)		$N_{EXOP,BB}$	115	2,279	**10,451**	**1,687**
Number of Planetary Transits (AV, FV, GV, KV & MV stars) & PHOTOMETRIC CHARACTERIZATION		$N_{EXOP,PHOT}$	10	*400*	***5,777***	
Number of Eclipsing Binaries (AV .. MV stars) & PHOTOMETRIC CHARACTERIZATION		$N_{EB,PHOT}$	1,091	9,246	**79,572**	**2,111**
Orbital Period with P_{DET} = 50% for 5 Transits, FROM SCANNING LAW	days	$P_{50\%,D=3,SCAN}$	6.24	1.48	**16.13**	2.5

Mission Parameters & Abilities Compared

(More detailed talk available)

<u>**Long Period Objects** (Planets, BDs, Stars)</u>

- **For astrometry & velocimetry: need: P_{ORBIT} <~ twice observing span to determine P_{ORBIT}**
- **Most of Solar System's angular momentum is in Jupiter & Saturn:**
  - **Solar System Analog**: system that has a “Jupiter” and/or “Saturn” and/or Uranus/Neptune
- All outer planets have $P_{ORB} > 2\ T_{MISSION}$

Planet	AU	Period	Mass
Jupiter	[illegible]	[illegible]	[illegible]
Saturn	[illegible]	[illegible]	[illegible]
Uranus	[illegible]	[illegible]	[illegible]
Neptune	[illegible]	[illegible]	[illegible]

How Many Long-Period Planets?

- **Which long-period planets:**
  - **S**OSAs: $P \in [11.9, 165]$ yr
    $M \in [0.05, 1]$ M_{JUP}
  - **H**OSAs: $P \in [11.9, 165]$ yr
    $M \in [1, 13]$ M_{JUP}
- Fraction of Planetary Systems:
  [Tabachnik & Tremaine (2002) or Cumming et al (2008)]
  - **SOSAs: 13 %** of planetary systems
  - **HOSAs: (17 +/- 3)%** of planetary systems
- **HOSAs: 8 % of Sun-like stars**

Long Period Planets: Where/Why?

- Some Planetary Migration Theories predict
  - Inward migration (known “RV” planets)
  - Outward migration (Uranus & Neptune)
    - Outer edge: 50-100 AU (350 – 1,000 yr) [Ida & Lin, 2004]
  - Predict massive long-period planets
  - Would require more massive disk
- Without migration: 30-40 AU (165-250 yr)
- MUCH, MUCH, MUCH, MUCH longer than $2T_{MISSION}$
  - **How to measure this?**

Only around Nearby/Bright Stars

- **Sun-like stars are really bright**
  - **GAIA saturates at V~12, but usable to V~6**

MS Star	F5	G0	G5	K0	K5	F5	G0	G5	K0	K5		
MV(abs)	**3.5**	**4.4**	**5.1**	**5.9**	**7.4**	**2.35**	**4.13**	**5.9**	**7.63**	**13.1**	**[*/pc^3] / 1000**	
Distance [pc]	apparent magnitude					Number of Stars out to D_{pc}					Total # Stars	Total # OSAs
5	2.0	2.9	3.6	4.4	5.9	1	2	3	4	7	17	1.4
10	3.5	4.4	5.1	5.9	7.4	10	17	25	32	55	139	11.1
20	5.0	5.9	6.6	7.4	8.9	79	138	198	256	439	1,109	88.7
30	**5.9**	**6.8**	**7.5**	**8.3**	**9.8**	**266**	**467**	**667**	**862**	**1,482**	**3,744**	**299.5**
40	6.5	7.4	8.1	8.9	10.4	630	1,106	1,582	2,044	3,512	8,874	709.9
60	7.4	8.3	9.0	9.8	11.3	2,126	3,732	5,338	6,899	11,853	29,948	2,395.9
80	8.0	8.9	9.6	10.4	11.9	5,040	8,847	12,653	16,353	28,095	70,988	5,679.1
100	8.5	9.4	10.1	10.9	12.4	9,844	17,279	24,714	31,940	54,873	138,649	11,091.9

Out to 30 pc,
must survey ~3,700 stars
expect to find ~ 300 HOSAs

Some Scales

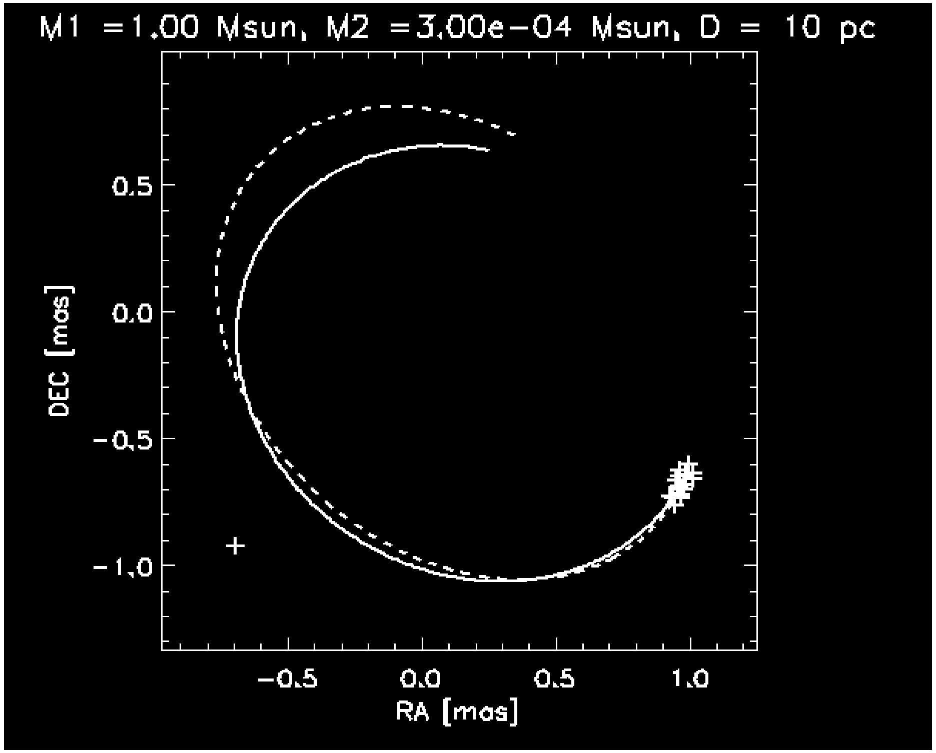
$$a_0 = 95/d_{10pc}\ (P^{+2}\ M_{TOT}^{-2})^{1/3}\ M_{C;J} \quad [\mu as\ ]$$
$$|\mu| = 600/d_{10pc}\ (P^{-1}\ M_{TOT}^{-2})^{1/3}\ M_{C;J} \quad [\mu as/yr\ ]$$
$$|d\mu/dt| = 3800/d_{10pc}\ (P^{-4}\ M_{TOT}^{-2})^{1/3}\ M_{C;J} \quad [\mu as/yr^2]$$

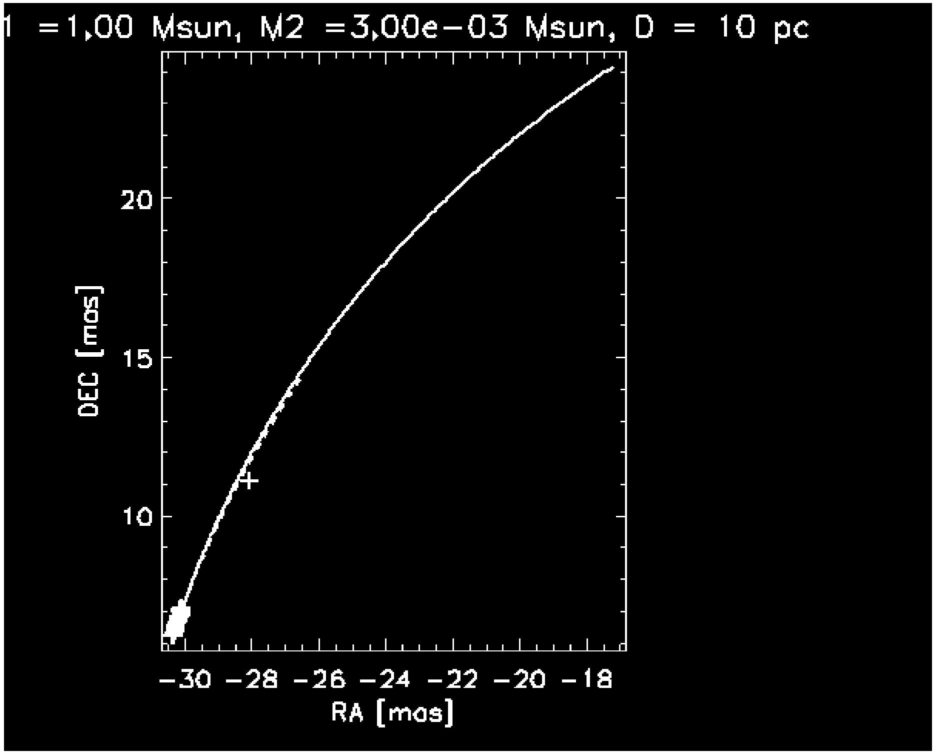
5	$M_{JUPITER}$ @	20 pc		
Period	a_0	$\|\mu\|$	$\|d\mu/dt\|$	**Acceleration accuracies**
[yr]	[μas]	[μas/yr]	[μas/yr^2]	
10	1,099	690	433.8	
20	1,744	548	172.2	
40	2,769	435	68.3	3-σ; Tycho-2
80	4,396	345	27.1	
160	6,977	274	10.8	3-σ; GAIA 5yr
320	11,076	217	4.3	3-σ; SIM 5yr
640	17,582	173	1.7	3-σ; GAIA+SIM

GAIA+SIM accuracy ~ 2 x smaller than SIM
~10 x smaller than GAIA

Long Period Planets have HUGE orbits

Reflex Motion from 10 pc due to 1/3rd Jupiter:





160 year orbit

1,700 year orbit

Simulated SIM-Lite Data (2017) + Hipparcos (1991)

- - - - - True Orbit

--------- Fitted Orbit

Old-Fashioned Way of finding long-period systems: w. Hipparcos & Tycho-2

- Use information from other astrometric catalogs
  - e.g., **Tycho-2** catalog comprises data from 144 catalogs going back to ~1907
    - Astrographic catalog (1907 @ 220 mas)
    - USNO's AGK3 (1930 @ 70 mas)
    - USNO's TAC (1980 @ 50 mas)
    - **Hipparcos** (1991 @ 1 mas)
    - ...
- **Compare proper motions:**
  - long-period cat (e.g., Tycho-2)
    - "mostly" center of mass motion if P <~ 40 years
  - short-period cat (e.g., Hipparcos)
    - Binary + center of mass motion if P <~ 12 years
  - **Difference is due to binary motion**
    - **FAILS if P >~ 4 x $T_{MISSION}$**

Eliminating μ_B: Backtrapolates

- Total motion (face-on; circular):

  $z_{TOT}(t) = z_0 + \mu_B\, t + z_{ORBIT}(t)$

  $z_{ORBIT}(t) = a_0 \cos(2\pi t/P+\varphi)$

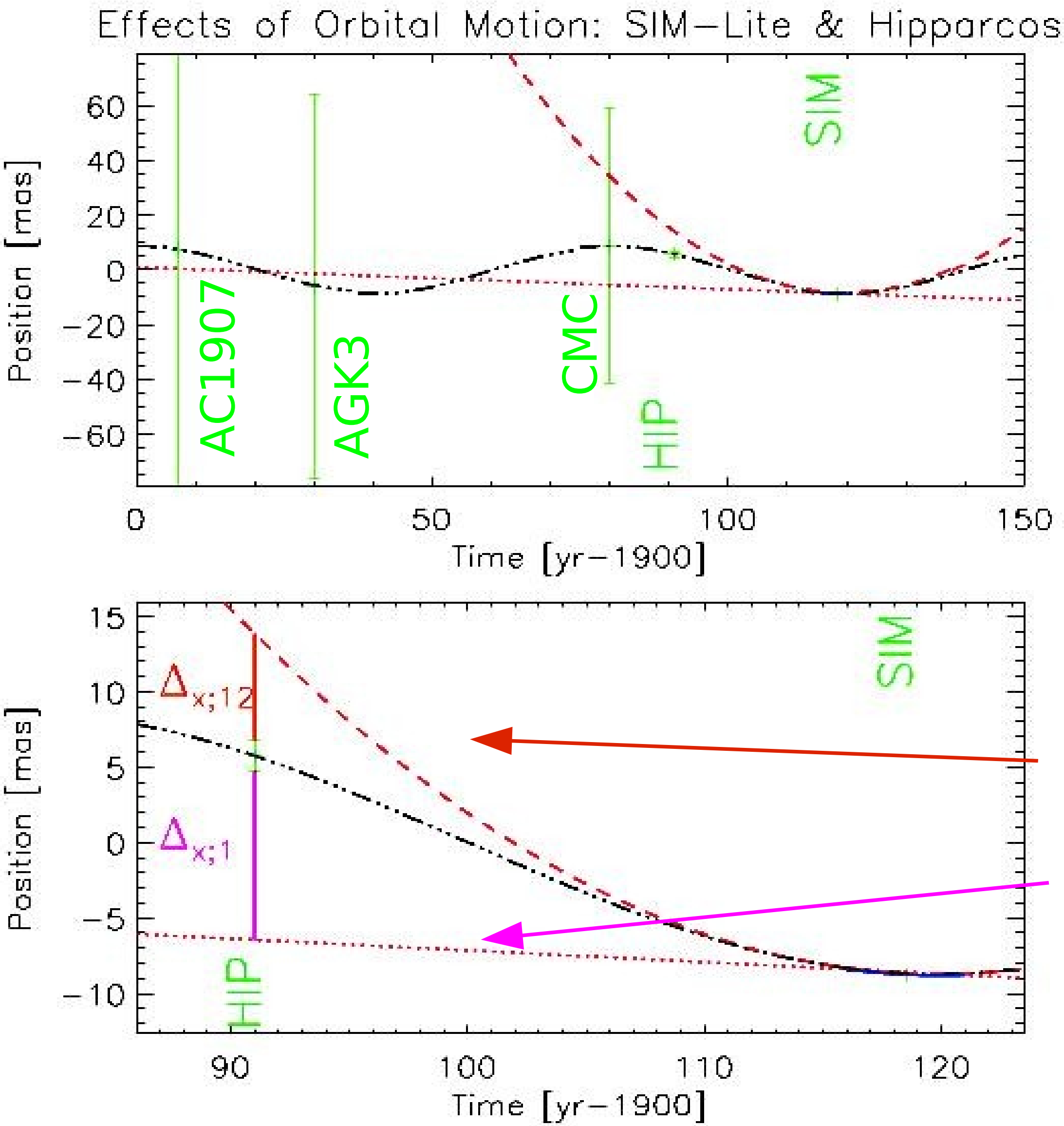
- Expand $Z_{ORBIT}(t)$
  - $\zeta(t)/a_0 = \cos(\varphi) - (2\pi/P)\sin(2\pi t/P+\varphi)t - ½\,(2\pi/P)^2 \cos(2\pi t/P+\varphi)t^2 + \ldots$
  - $Z_{TOT}'(t) = Z_0 + \mu_B\, t + \zeta(t)$

    = n^{th} order polynomial fit to SIM data

- Position Difference at Hipparcos epoch (τ)
  - $\Delta_z(\tau) = z_{TOT}(\tau) - z_{TOT}'(\tau) = z_{0RBIT}(t) - \zeta(\tau)$

- **INDEPENDANT of Barycentric motion**
  - **Only depends on orbit & its expansion**

Future Method of Finding long-period systems w. SIM & Hipparcos



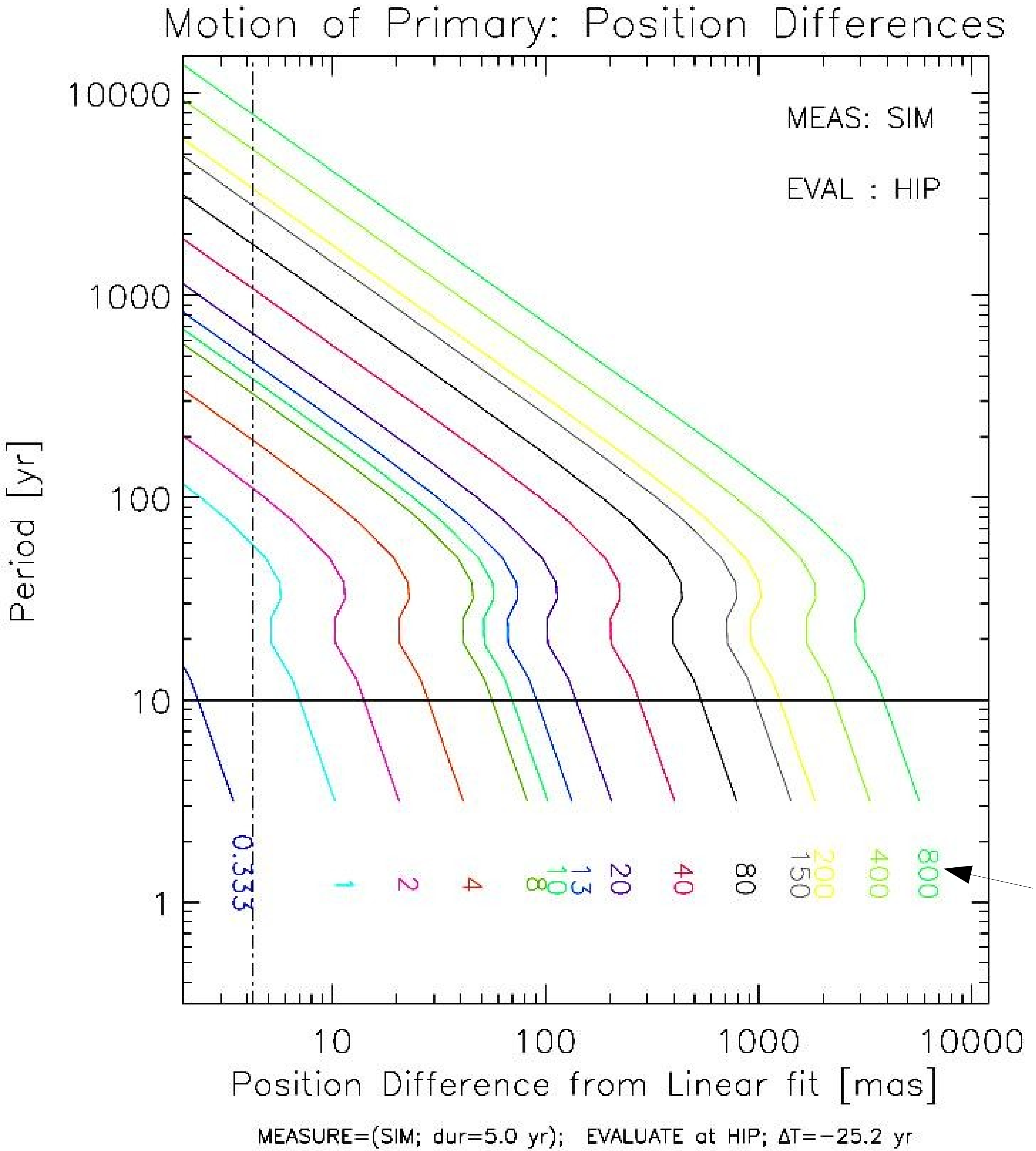
M = 10 M_{JUP}
P = 80 yr
D = 20 pc
a_0 = 8.8 mas
μ_{ORBIT} = 0.69 mas/yr

Difference between: backtrapolations:

Quadratic: $\Delta_{x;12}$

Linear: $\Delta_{x;1}$

Period/Mass dependent?



YES !

MEASURE: SIM
B.TRAPOLATE: HIP

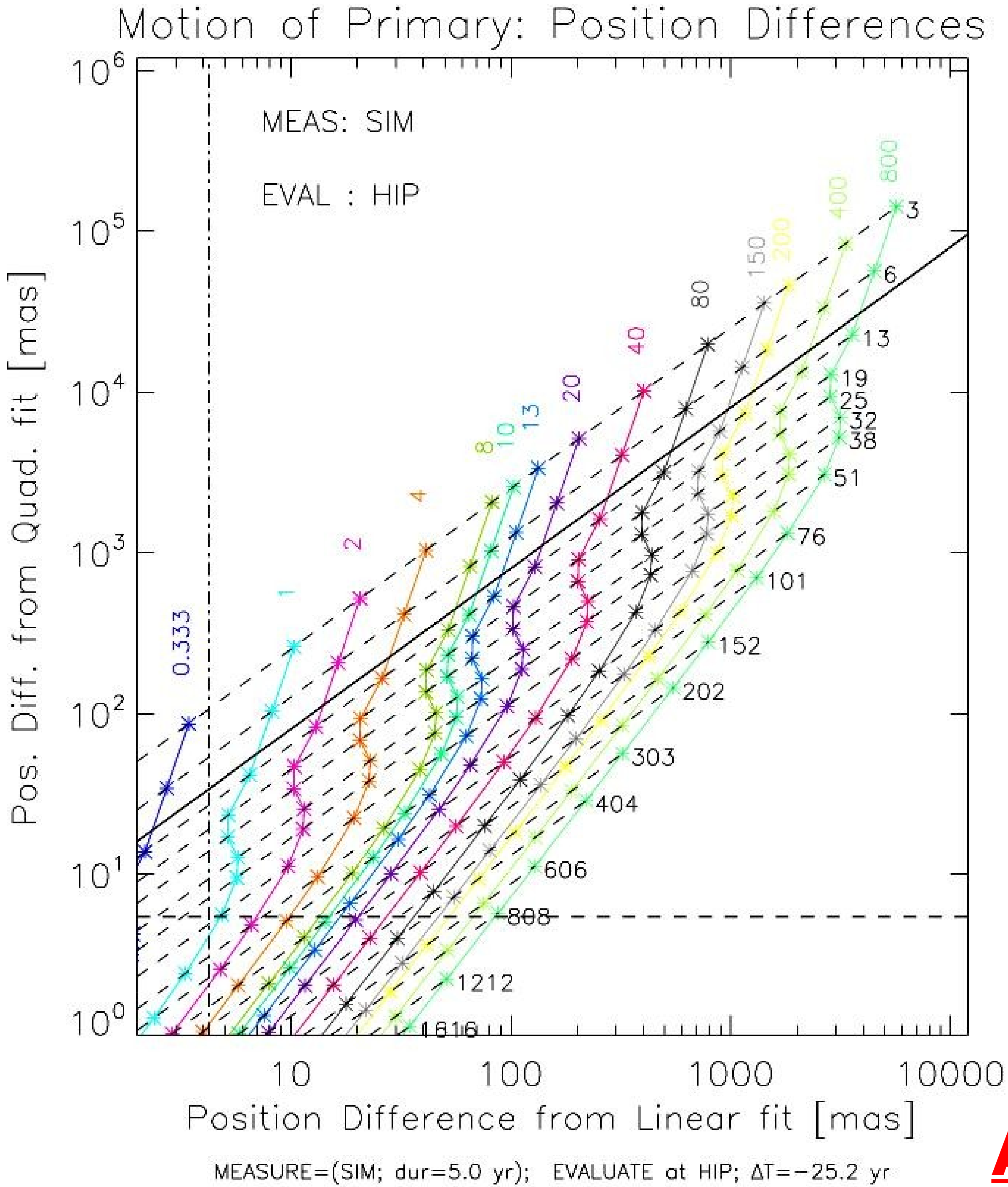
Position Differences from **linear fit** are degenerate:

Multiple Masses & Periods

at given pos.dif

Backtrapolates: Sensitive to Mass & Period

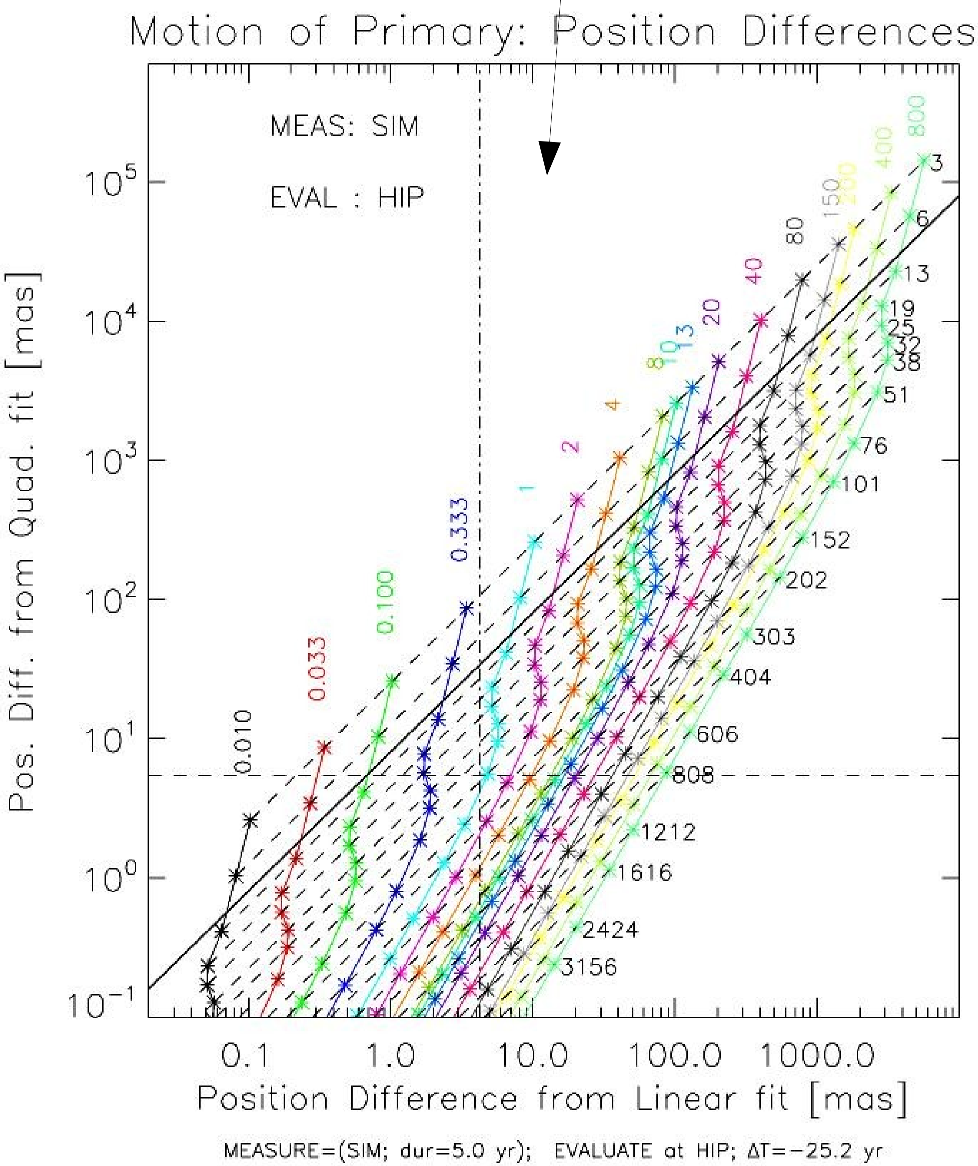
- **Order-dependent:** $\Delta_{z;n}(\tau) = z_{0RBIT} - \zeta^{n}(\tau)$
  - Can be calculated analytically
- No phase dependence for TOTAL pos. dif.
  - Face-on & circular: $\Delta_{XY;n} = (\Delta_{X;n}^{2} + \Delta_{Y;n}^{2})^{½}$
- **Periods** can be estimated from $\Delta_{XY;n}$ values
  - $\mathcal{P}_{1,2} = 2/3\ \ \pi\tau\ \Delta_{XY;1} / \Delta_{XY;2}\quad \sim\ P$ for $P \geq 2\tau$
  - $\mathcal{P}_{2,3} = 1/2\ \ \pi\tau\ \Delta_{XY;2} / \Delta_{XY;3}\quad \sim\ P$ for $P \geq 2\tau$
    - $\mathcal{P} \sim P$ for $P \ll \tau$
    - $\mathcal{P}$ oscillates strongly for $P \sim [0.5, 1] \times \tau$
    - $\mathcal{P}$ decays (exponentially) towards P for $P \sim [1\ \ , 2] \times \tau$
- **Masses** follow immediately once P is known

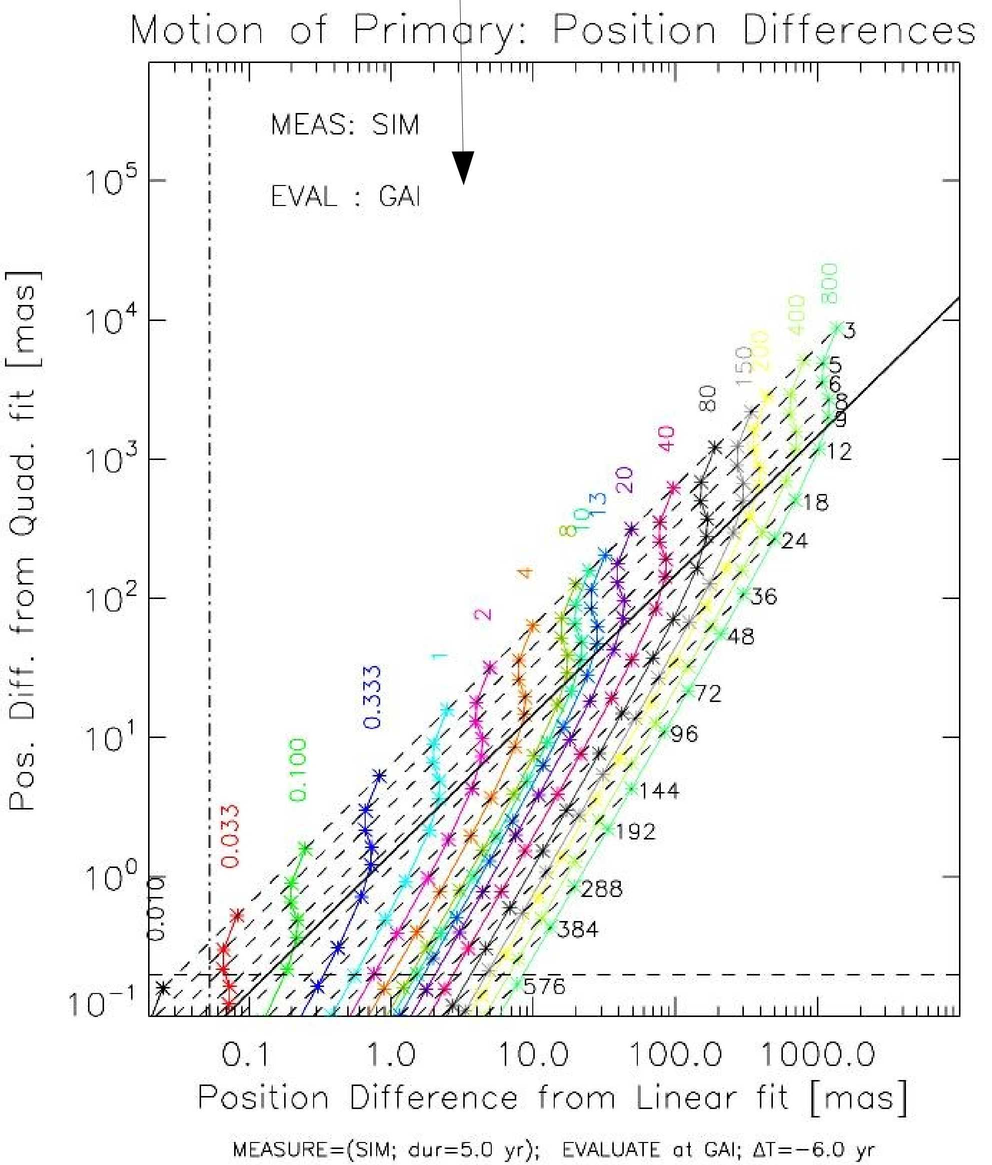


Lift Degeneracy
when considering
quadratic fit

Analytically proven

SIM --> HIP vs. SIM --> GAIA





- **SIM & HIPPARCOS**
  - 1 M_J and up; P <~ 80 yr
  - 13 M_J and up; P <~ 160 yr
    - **Improved 2nd generation Hipparcos @ 1/3 mas**
    - **GAIA data can be used to re-reduce Hipparcos to eliminate any residual systematic errors**
    - twice better Period Limits
      - **“Detection”** w. $\Delta_{XY;1}(13M_J)$: P <~ 800 yr
- **SIM & GAIA**
  - Characterization: ½ period range
  - Detection: 50% larger period range
  - **SIGNIFICANCE: x5 – x15 better**
    - **Lower-mass range extended by x5 to 0.2 $M_{JUPITER}$**

Conclusions & Future Work
(SIM Science Studies grant)

- **Position Difference Powerful New Tool**
  - **To find long-period objects**
    - **(initial estimates: Period, Mass & center-of-mass motion)**
    - **Samples the migration-cutoff regime (100s of years)**
- **Need to develop method for generalized orbits**
  - **Expectations are:**
    - **Inclination not too important**
    - **Eccentric orbits: manageable** [MK2005]
    - **Orbit fitting employing historical data?**
      - **Just starting to realize the power of SIM-only**
- **Realistic observing time estimates**
    - **Local reference frames?**

Backup Slides

Dabblings

- I've been working on:
  - Astrometric detections (**FAME, AMEX, OBSS**)
  - Transit detections (**FAME**, **AMEX**, **OBSS**)
    - **FAME**: now-cancelled astrometric MIDEX (USNO-led)
    - **AMEX**: proposed Germany/NASA/USNO SMEX
    - **OBSS**: proposed "Origins Probe" mission
      - Capable of duplicating GAIA, if necessary
  - Radial velocity work & TPF-C characterizations
    - **Dispersed Fourier Transform Spectrometer**
      - P.I., Arsen Hajian (USNO; now U. Waterloo)
  - **LEAVITT:** my MIDEX-class planetary-transit finder
- **Solar System Analogs (SOSAs; 2008-present)**

http://www.astro.umd.edu/~olling/index_1.htm#My_Astrometry_Latest

Astrometry: Number Estimates

http://www.astro.umd.edu/~olling/FAME/otm_plas_rpo_2004_01.pdf

Procedure:

Semi-major axis:

$a = 95/d_{10pc}\ (P_{YR}/M_{TOT,SUN})^{2/3}\ \ M_{PLANET,JUP}$ [μas]

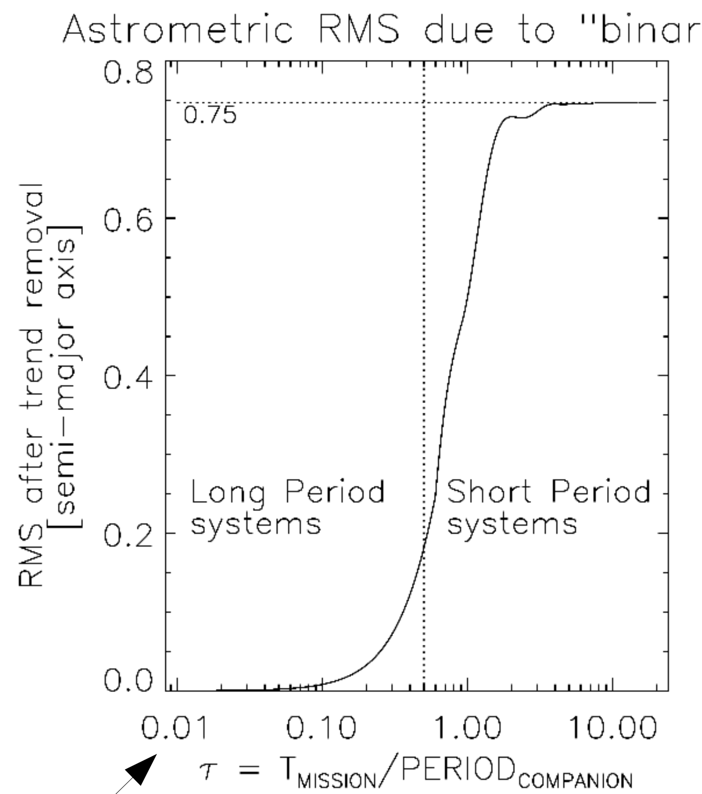
x/y coordinates for face-on orbit

$x = a \cos(2\pi t_{YR}/P_{YR} + \phi)$ [μas]

$y = a \sin (2\pi t_{YR}/P_{YR} + \phi) \cos(i)$ [μas]

$dx/dt = -2\pi/P_{YR}\ \ a \sin (2\pi t_{YR}/P_{YR} + \phi)$ [μas/yr]

$dy/dt = +2\pi/P_{YR}\ \ a \cos(2\pi t_{YR}/P_{YR} + \phi) \cos(i)$ [μas/yr]



- For each model, compute x,y and fit linear proper m. model
- Compute RMS w.r.t. best fit
  - Depends **only** on $= T_{MISSION}$ / $Period_{COMPANION}$
  - Turns out: "RMS"/a = Function(τ)

Astrometry: Number Estimates

http://www.astro.umd.edu/~olling/FAME/otm_plas_rpo_2004_01.pdf

Procedure, cntd:

For a given astrometric error (δ_{AE}) per observation

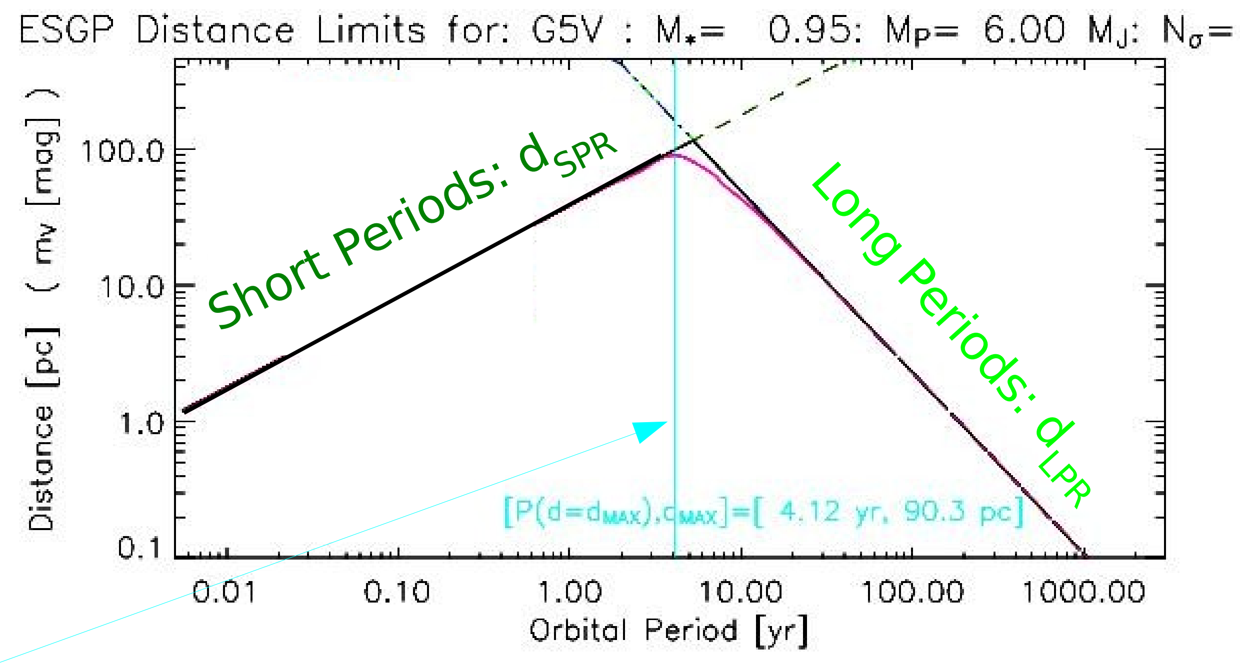
- In Short Period Regime: "RMS_{SPR}" ~ 0.75 * a
  - Detection: "RMS_{SPR}" = ¾ *a >= N_σ * $\boldsymbol{\delta_{AE}}$
  - $d'_{MAX;SPR} \sim 7.5 \quad (P_{YR}/M_{TOT})^{2/3} \; M_{PL,JUP} \; (10/N_\sigma) * (10\ \mu as/\delta_{AE})$ [pc]
- **In Long Period Regime: "RMS_{LPR}" >~ N_σ * δ_{AE}**
  - $d'_{MAX;LPR} \sim 8.3 \; \tau^2 \, (P_{YR}/M_{TOT})^{2/3} \; M_{PL,JUP} \; (10/N_\sigma) * (10\ \mu as/\delta_{AE})$ [pc]
- Photometric distance & magnitude-dependent δ_{AE} introduces $d_{MV} = 10^{(V_F+5-M_V)/5}$ and:
  - $d_{MAX;SPR;MV} = \mathrm{sqrt}(\, d'_{MAX;SPR} * d_{MV} \,)$
  - $d_{MAX;LPR;MV} = \mathrm{sqrt}(\, d'_{MAX;LPR} * d_{MV} \,)$

d_{SPR} INcreased with P

d_{LPR} DEcreased with P

Primary HAS to be closer

than d_{SPR} & d_{LPR}



Maximum distance @

$P(d_{MAX}) \sim 0.82\ T_{MISSION}$

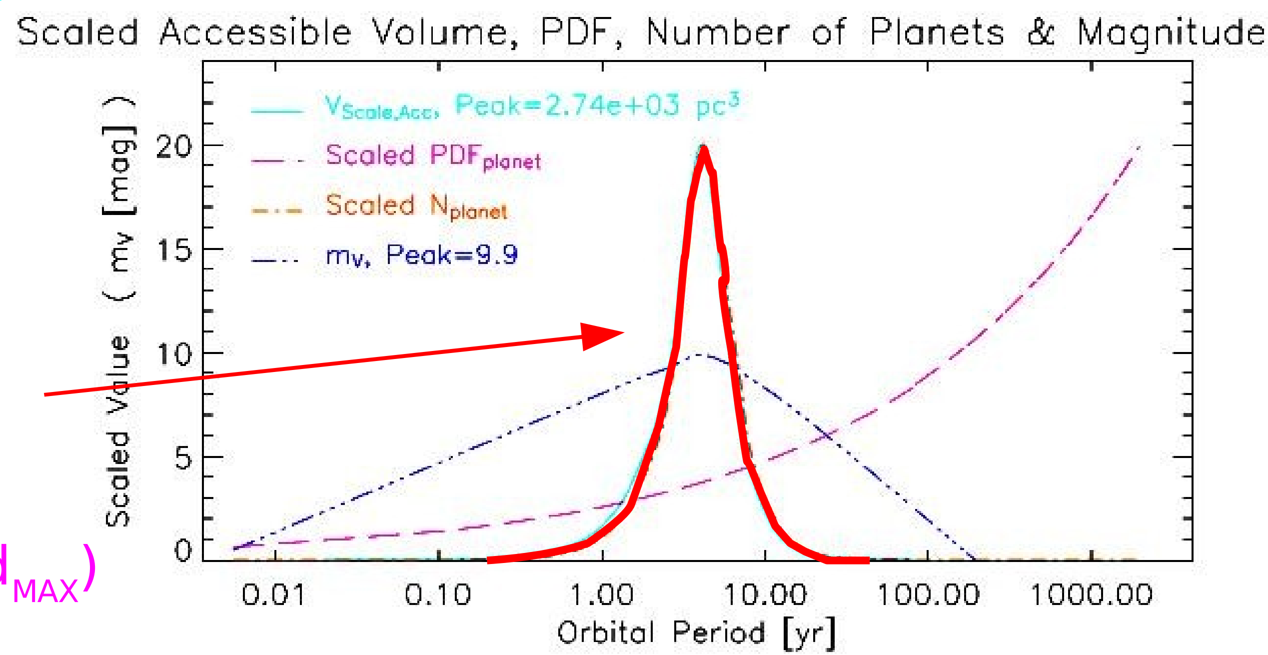
$\text{Volume}(P) \sim 4/3\ \pi\ d(P)^3$

drops of quickly

either side of $P(d_{MAX})$

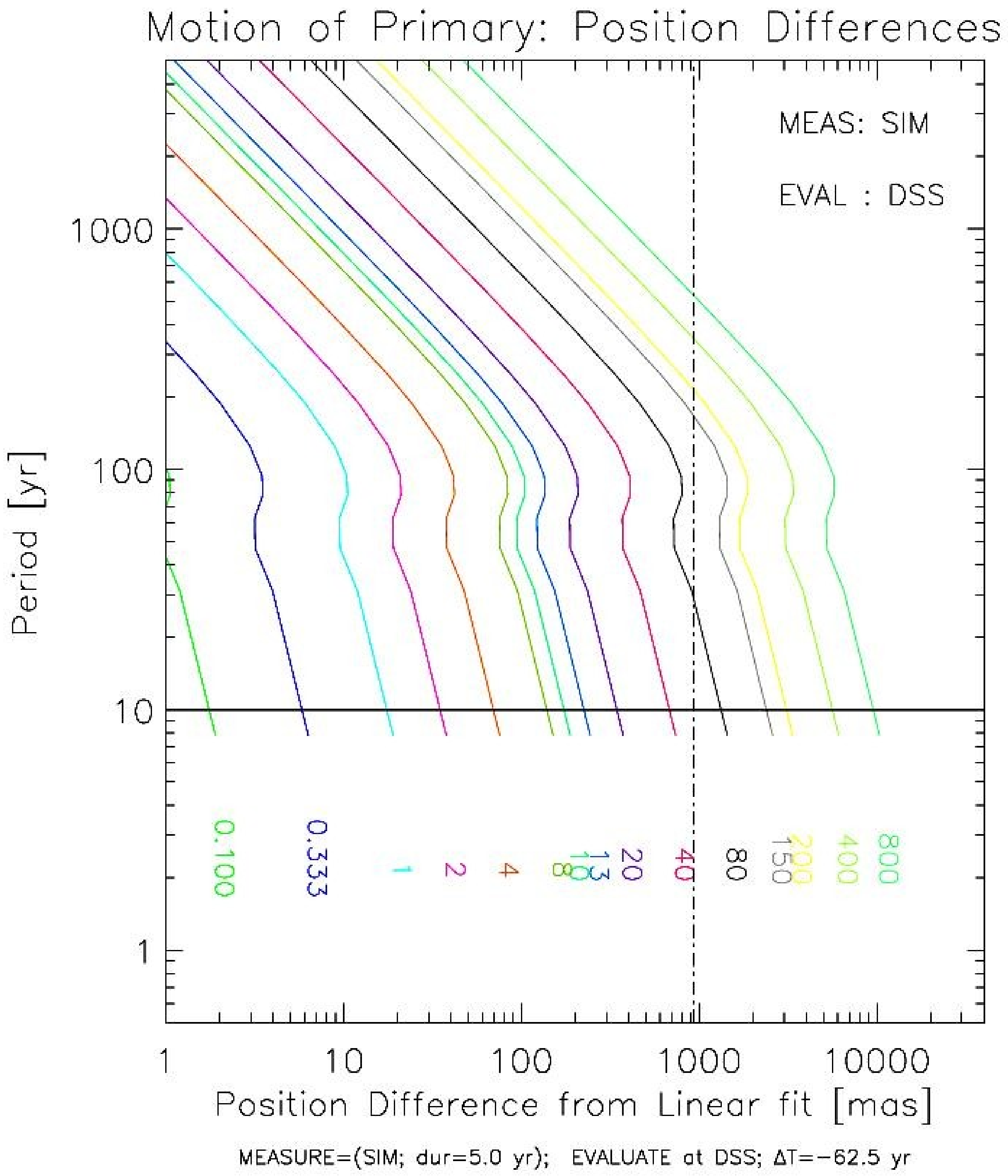
=> Most companions @ $P(d_{MAX})$

=> ... @ small range in m_V



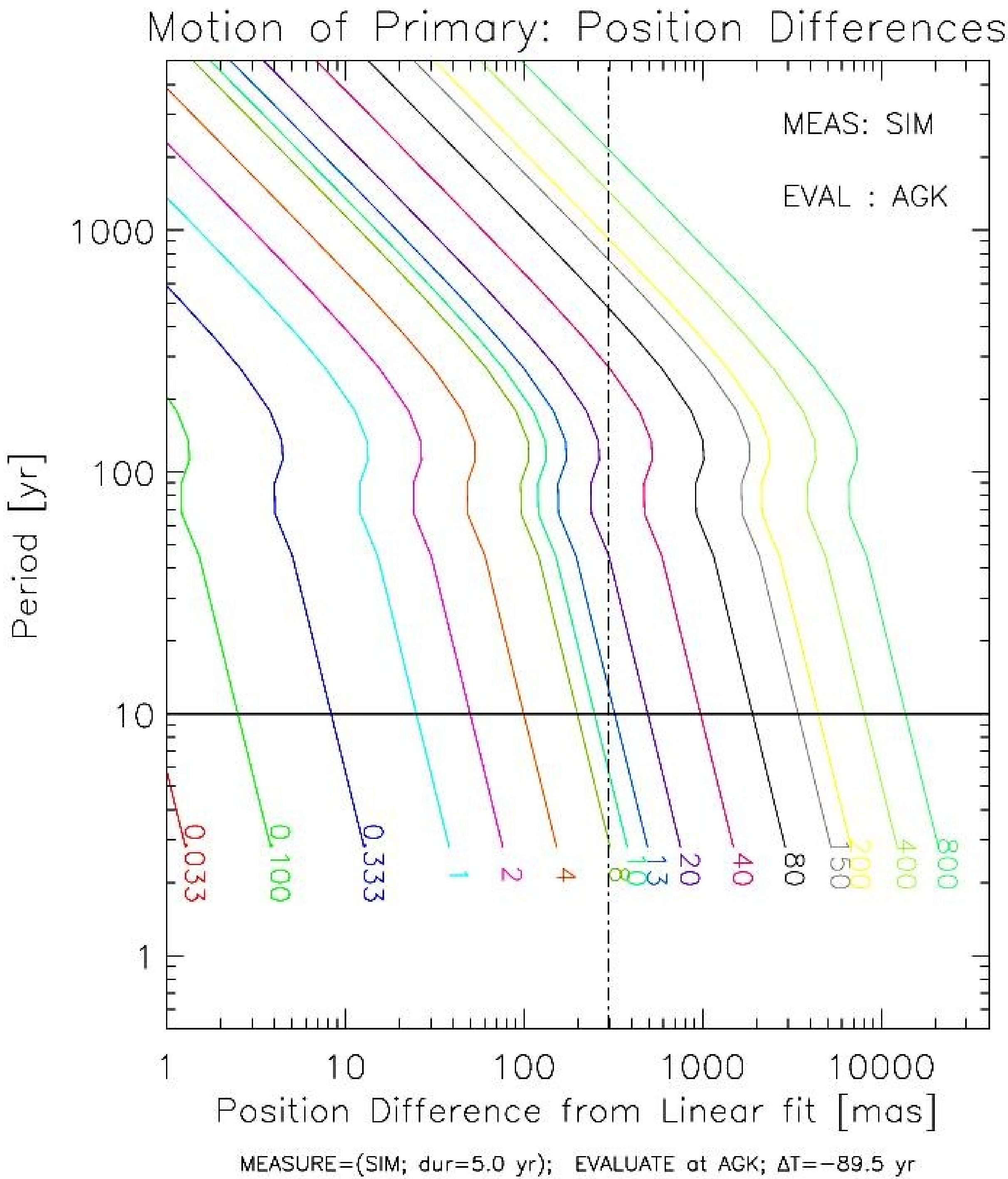
SIM & Ground-based Surveys

DSS (1957)



SIM & Ground-based Surveys

AGK (1930)



SIM & Ground-based Surveys

AGC (1907)