Searching for Solar System Giant Analogs with SIM and GAIA

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Hipparcos(Credit ESA)


SIM/Heavy (Credit JPL)


GAIA (Credit ESA)

Outline

- Astrometric Scales in Astronomy
- Long Period Planets in Solar System & elsewhere
- Observability
- 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]

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$_{\oplus}$ ref.motion 450 km

Long Period Objects (Planets, BDs, Stars)

- **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	5.2	11.9	318
Saturn	9.5	29.4	95
Uranus	19.2	84.0	15
Neptune	30.1	164.0	17

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 %**
  - **HOSAs: (17 +/- 3)%**
- **HOSAs: 8% of Sun-like stars**

Long Period Planets: Where?

- 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?**

Some Scales

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

$1M_{JUPITER}$ @ 20 pc				
Period [yr]	a_0 [μas]	|μ| [μas/yr]	|dμ/dt| [μas/yr²]	**Comment**
5	139	174	219.0	
10	220	138	87.0	
20	350	110	35.0	5 yr; SOF
40	555	87	14.0	10 yr SOF; 3-σ GAIA 5yr
80	881	69	5.4	3-σ; SIM 5yr
160	1,399	55	2.2	3-σ; SIM 10yr
320	2,221	44	0.9	
640	3,525	35	0.3	

Only around Nearby/Bright Stars

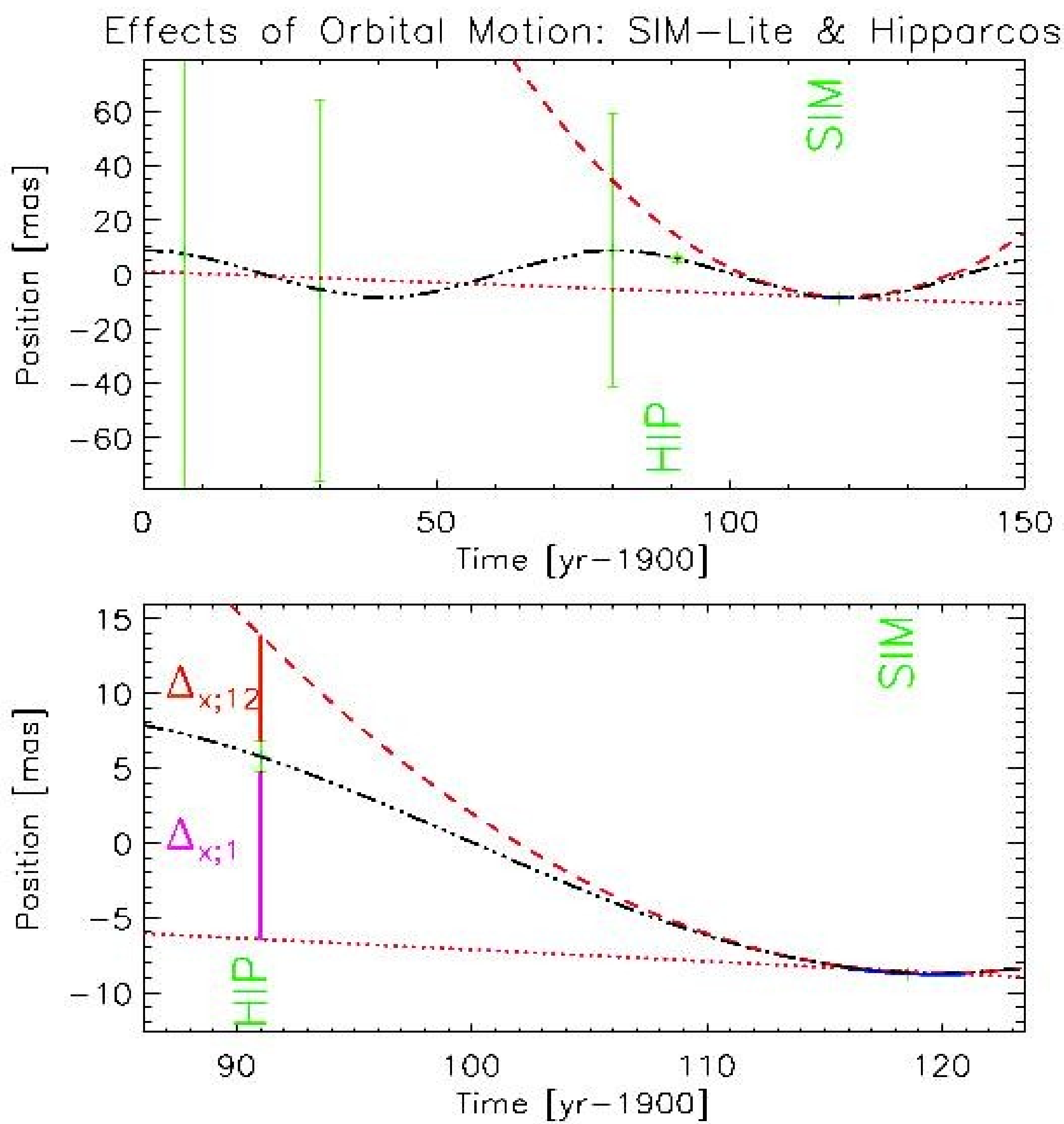
- **Sun-like stars are really bright**
  - **GAIA bright-star capability is very desirable**

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}					
5	2.0	2.9	3.6	4.4	5.9		1	2	3	4	7	
10	3.5	4.4	5.1	5.9	7.4		10	17	25	32	55	
20	5.0	5.9	6.6	7.4	8.9		79	138	198	256	439	
30	5.9	6.8	7.5	8.3	9.8		266	467	667	862	1,482	
40	6.5	7.4	8.1	8.9	10.4		630	1,106	1,582	2,044	3,512	
60	7.4	8.3	9.0	9.8	11.3		2,126	3,732	5,338	6,899	11,853	
80	8.0	8.9	9.6	10.4	11.9		5,040	8,847	12,653	16,353	28,095	
100	8.5	9.4	10.1	10.9	12.4		9,844	17,279	24,714	31,940	54,873	
125	9.0	9.9	10.6	11.4	12.9		19,226	33,748	48,269	62,382	107,174	
150	9.4	10.3	11.0	11.8	13.3		33,222	58,316	83,409	107,796	185,197	
175	9.7	10.6	11.3	12.1	13.6		52,756	92,603	132,451	171,176	294,086	

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 AGK2 (1930 @ 70 mas)
    - USNO's TAC (1980 @ 50 mas)
    - **Hipparcos** (1991 @ 1 mas)
    - ...
- Compare pr.-motions in
  - short-period cat (Hipparcos)
  - W. long-period cat (Tycho-2)

Finding long-period systems w. SIM & Hipparcos

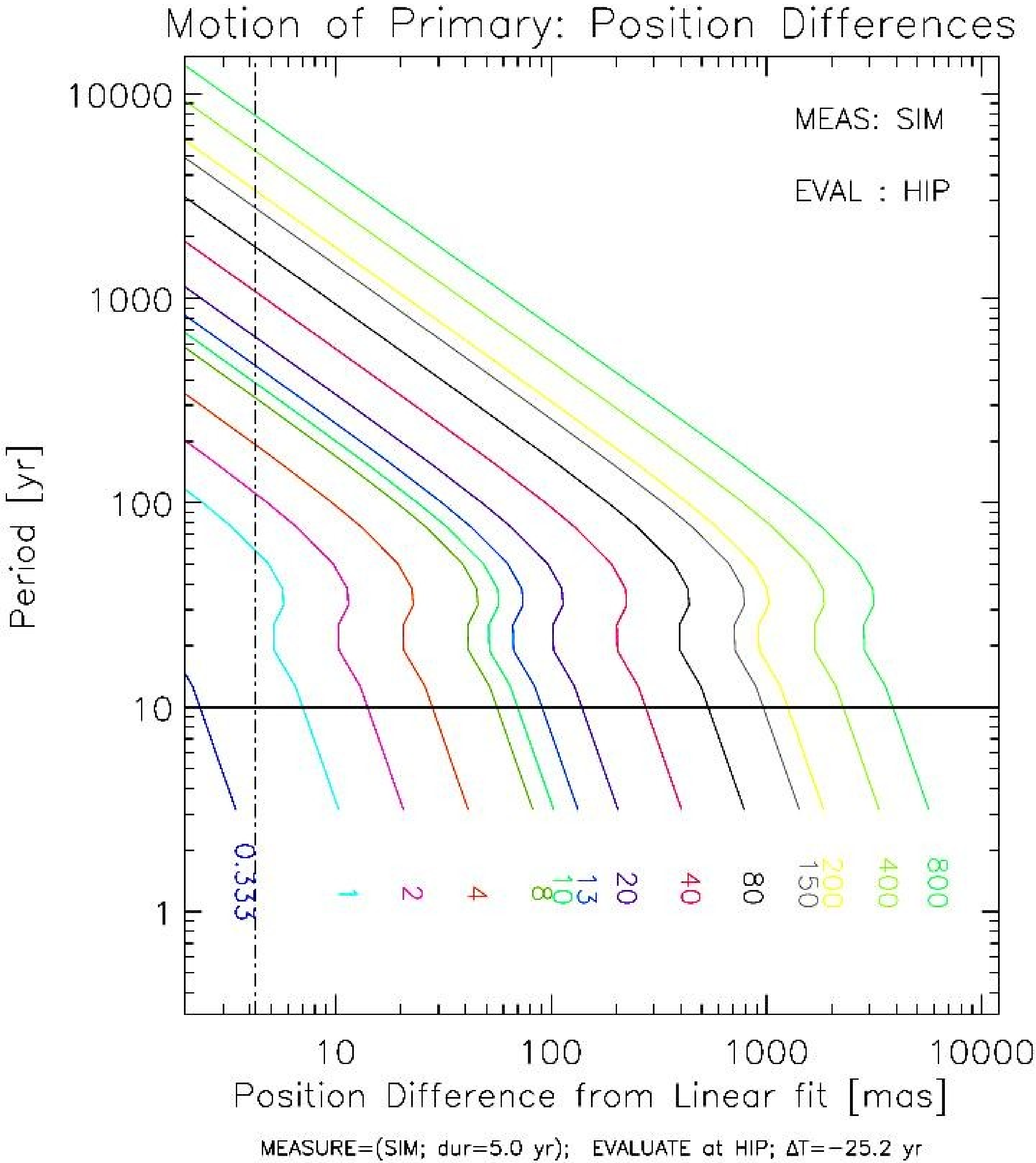


M = 10 M_{JUP}
P = 80 yr
D = 20 pc
a_0 = 8.8 mas
μ_{ORBIT} = 0.69 mas/yr

Difference between: backtrapolations:

Linear: $\Delta_{x;1}$

Quadratic: $\Delta_{x;12}$



MEASURE: SIM
B.TRAPOLATE: HIP

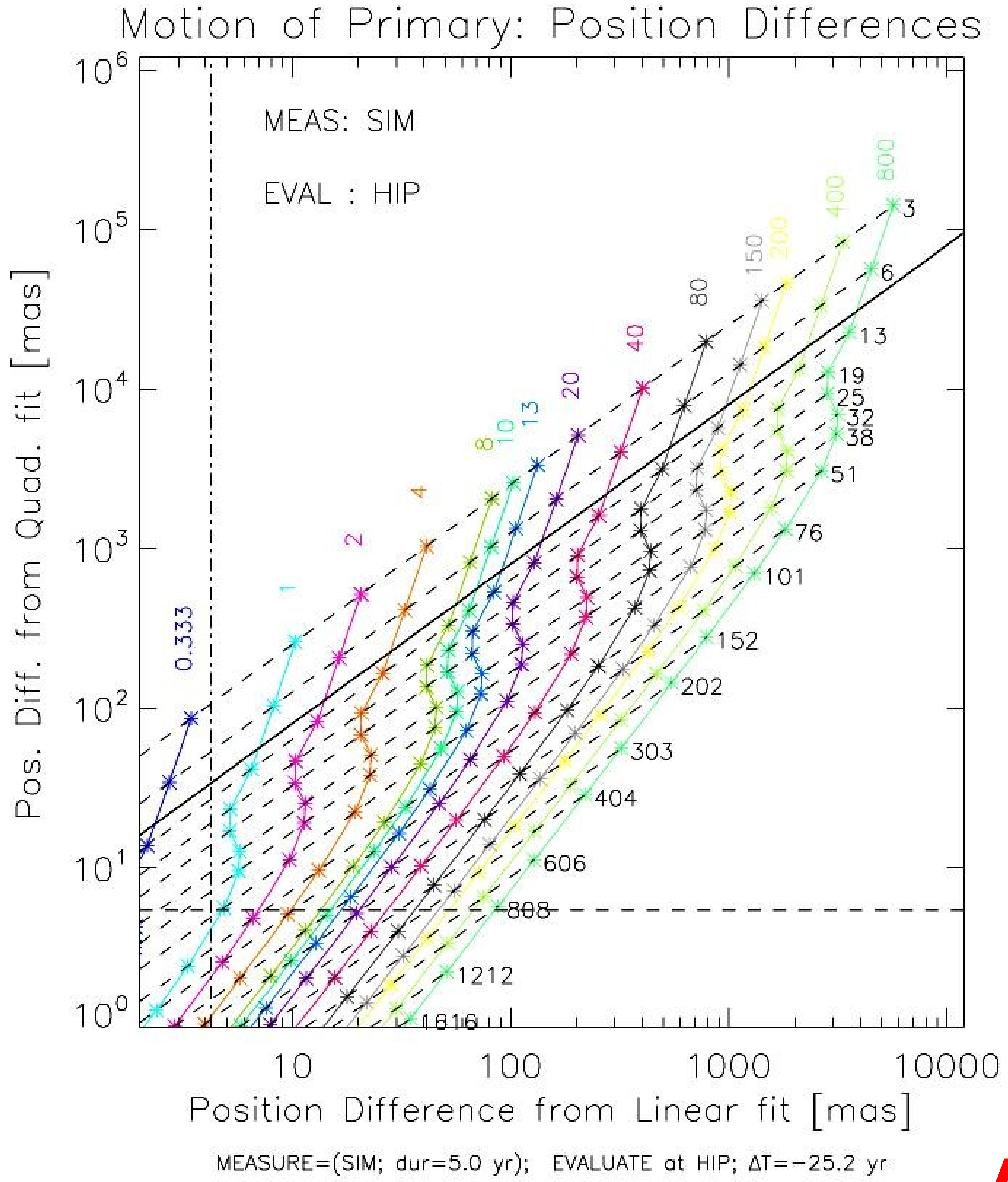
Position Differences from **linear fit** are degenerate:

multiple
Masses & Periods

at given pos.dif

Backtrapolates: Sensitive to Mass & Period

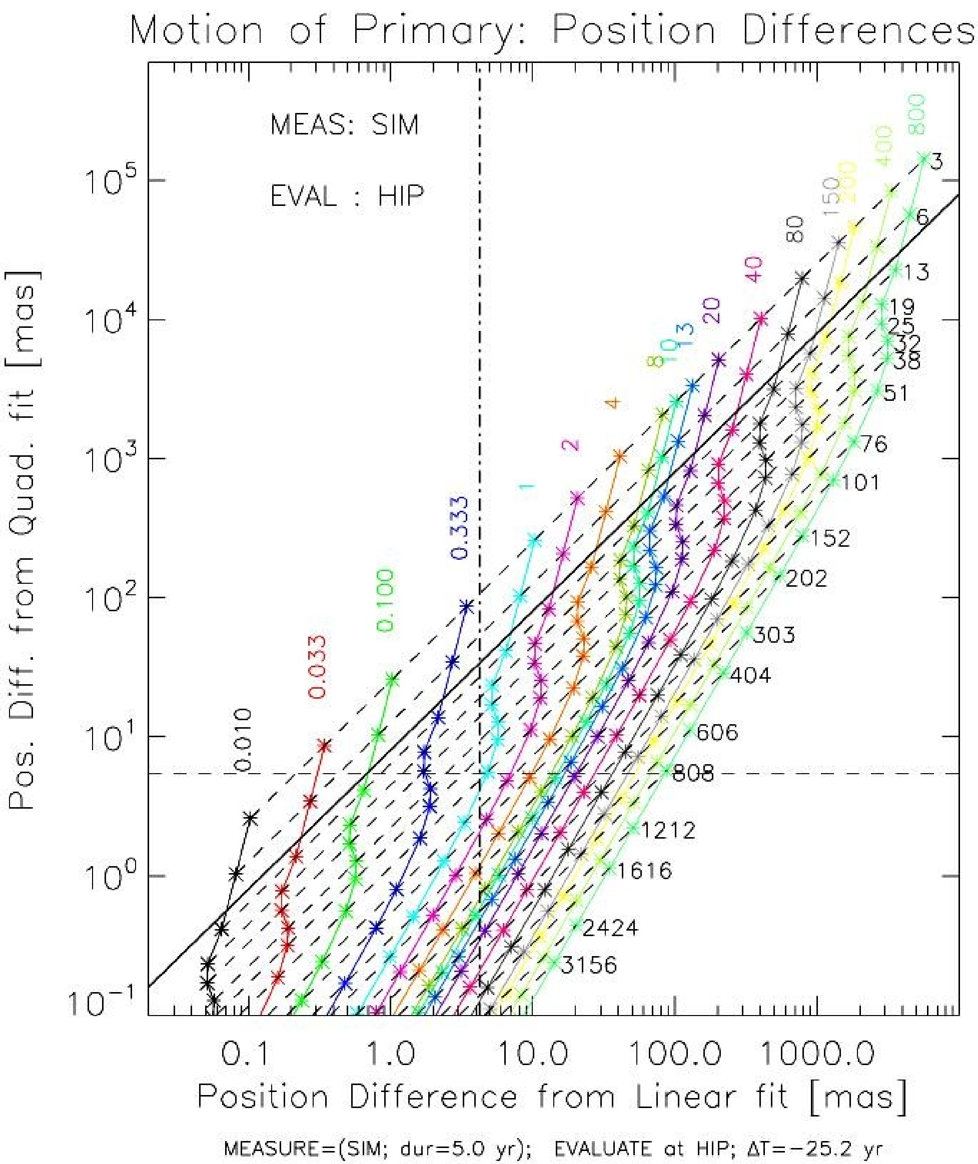
- **Order-dependent Position Difference**
  - **1st order fit yields Δx_1**
  - **2nd order Δx_2**
- **$\Delta x_n(t) \equiv x_{0RBIT} - x_{FIT,n}(t)$**
    - **$x_{FIT,n}(t) = x_0 + \mu_{FIT}\, t + 0.5\, d\mu/dt_{FIT}\, t^2$**
- **NO center-of-mass velocity needed**
  - **$\Delta x_1 - \Delta x_2 \neq 0 = f(P,M)$**
    - Can be calculated analytically
    - Little/No phase dependence for TOTAL position difference
      - Face-on & circular: $\Delta_{XY;n} = (\Delta_{X;n}{}^2 + \Delta_{Y;n}{}^2)^{1/2}$

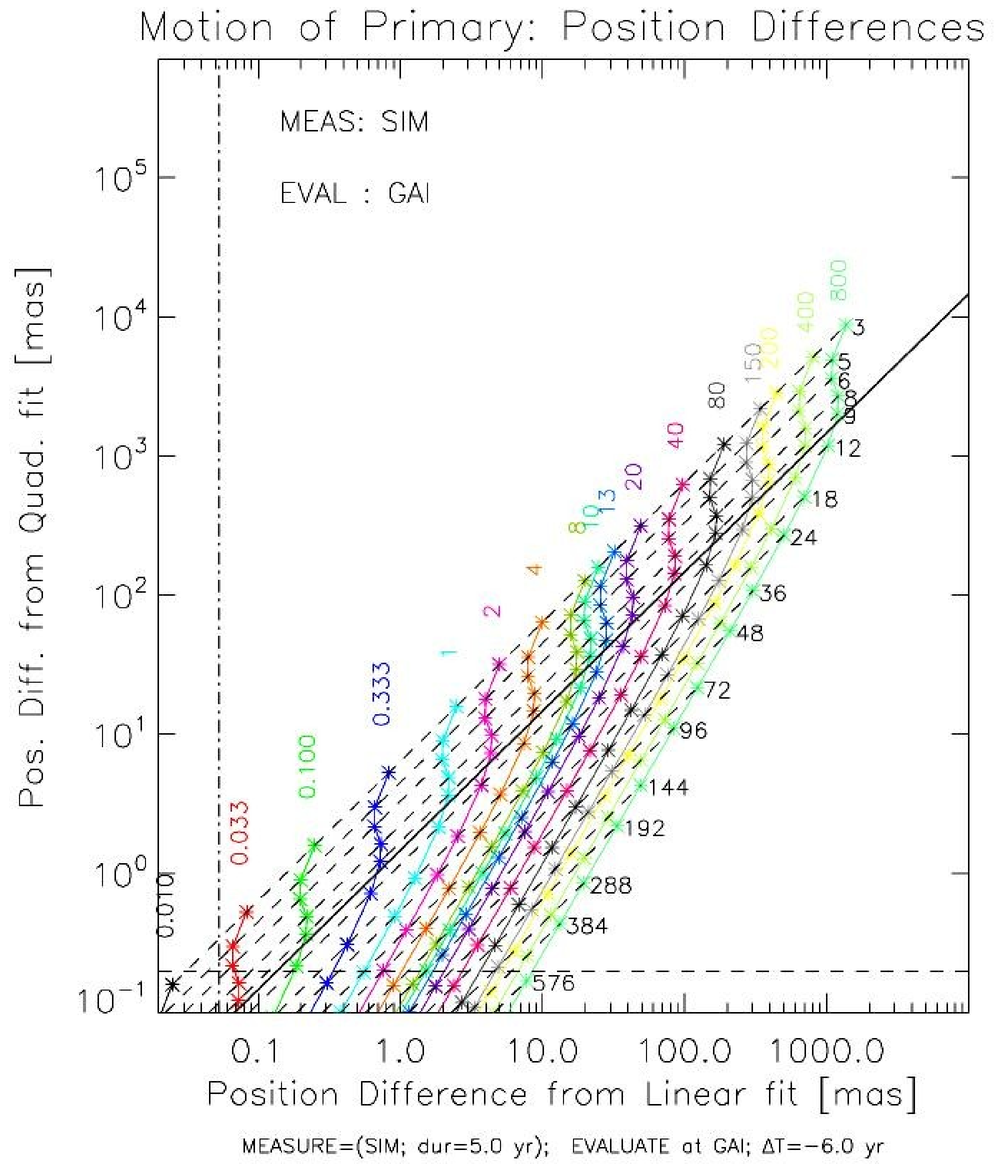


Lift Degeneracy when considering **quadratic fit**

Analytically proven

SIM+GAIA -> HIPPARCOS?





- **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:
      - 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 $M_{JUPITER}$**

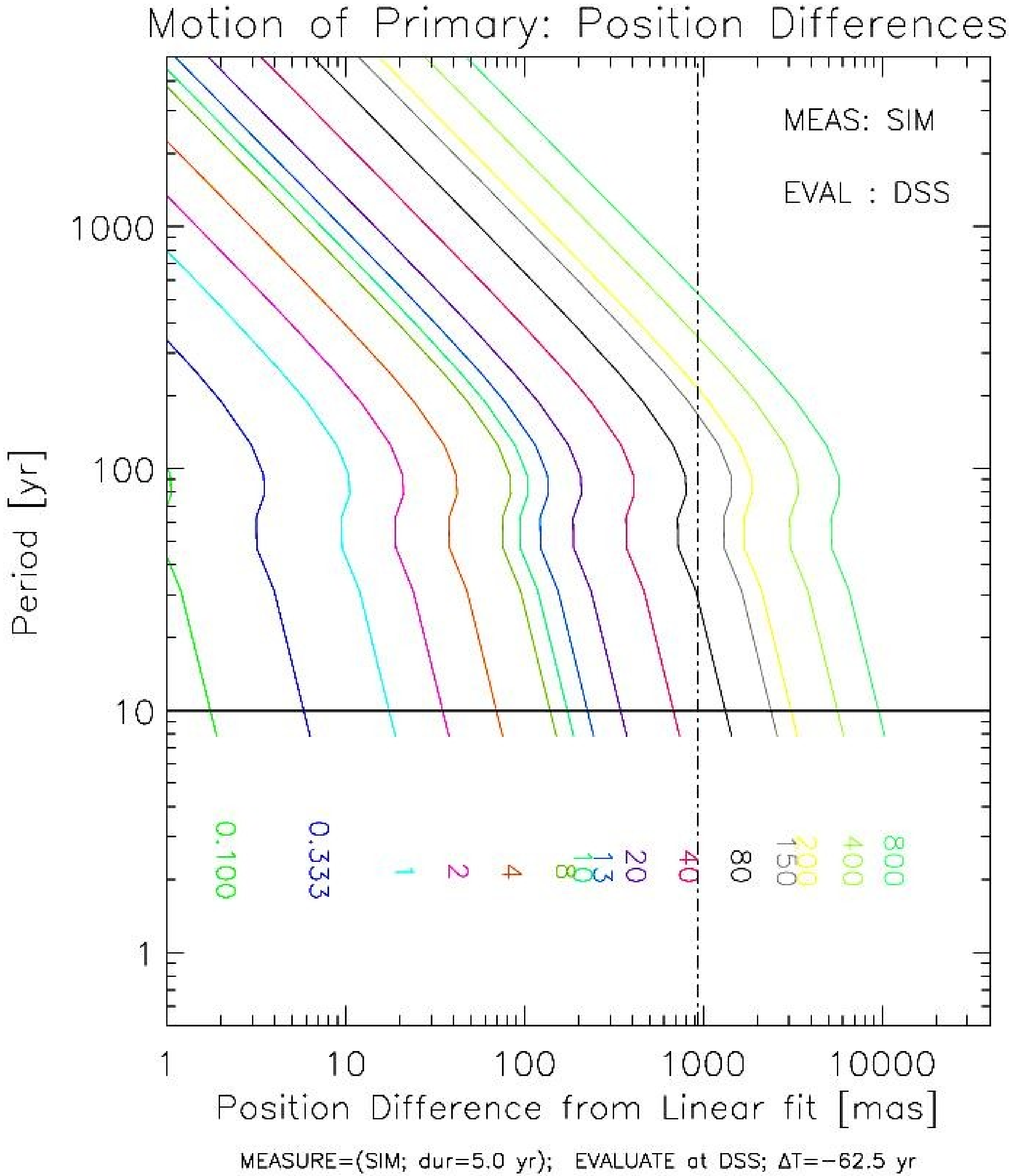
Conclusions & Future Work

- **Position Difference Powerful New Tool**
  - **To find long-period objects**
    - **Samples in 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?**
- **Realistic observing time estimates**
    - **Local reference frames?**

Backup Slides

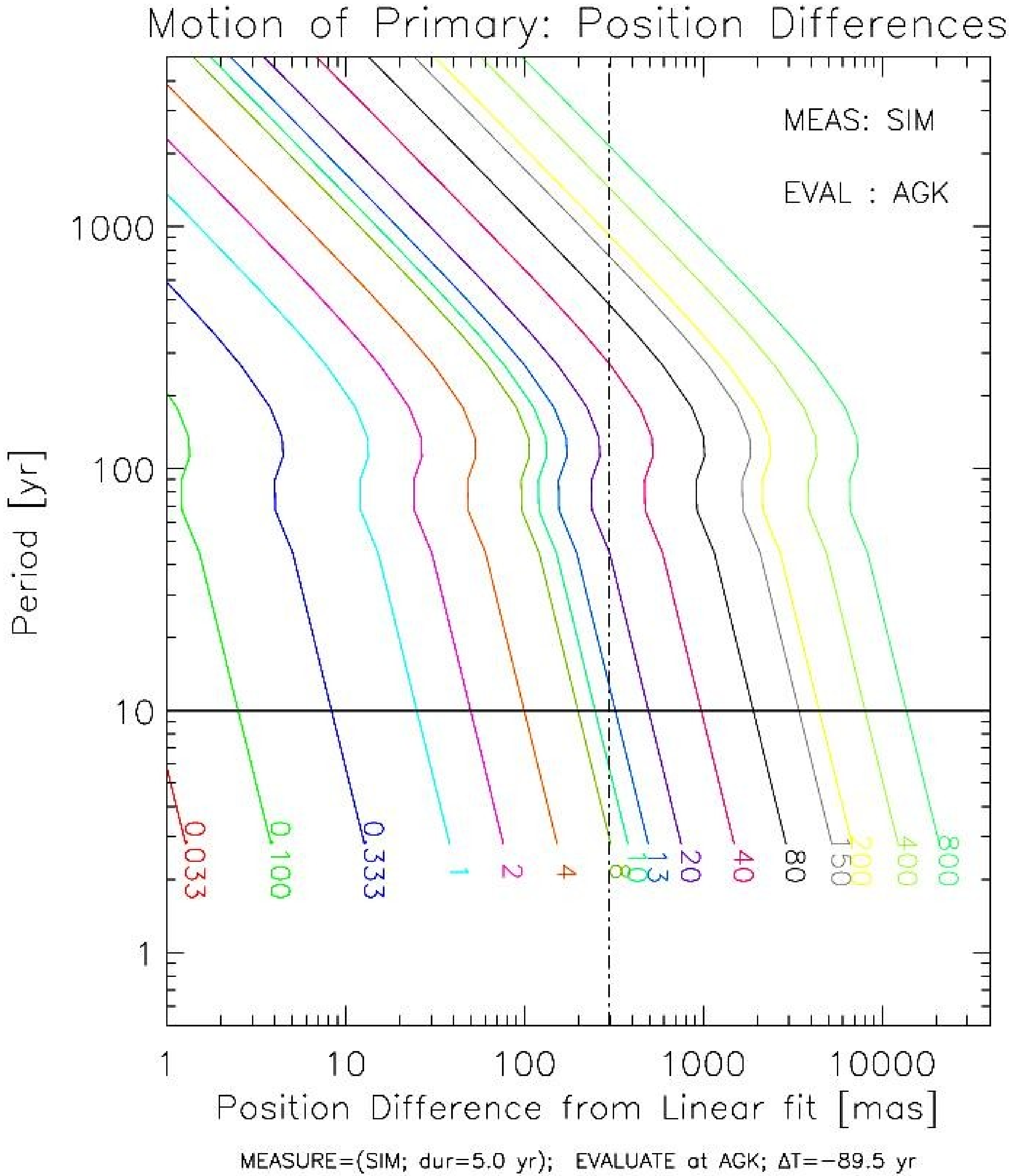
SIM & Ground-based Surveys

DSS (1957)



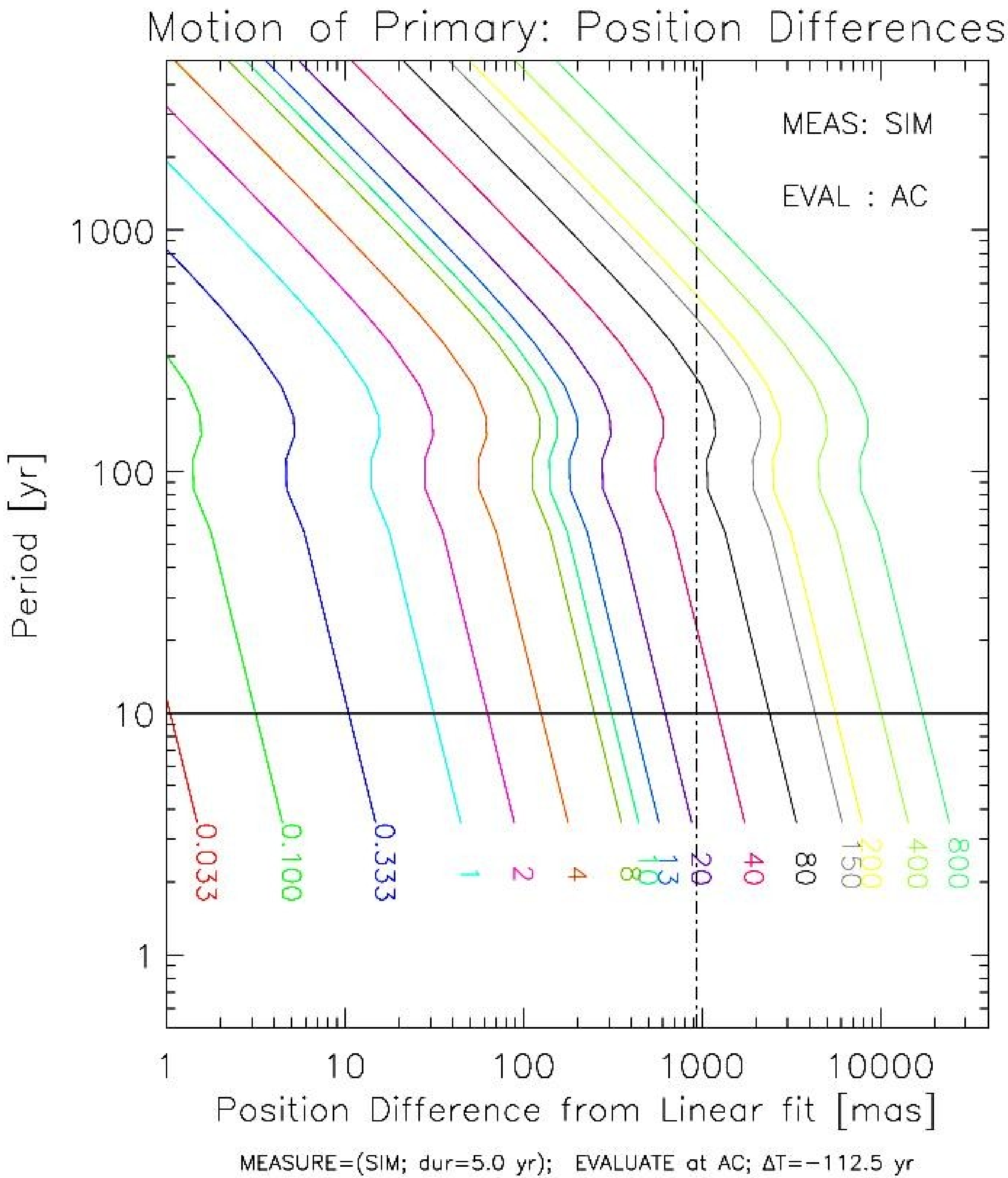
SIM & Ground-based Surveys

AGK (1930)



SIM & Ground-based Surveys

AGC (1907)



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**

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: $\Delta_{XY;n} = (\Delta_{X;n}{}^2 + \Delta_{Y;n}{}^2\,)^{1/2}$
- <u>**Periods**</u> 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 $P \sim [1\;\;, 2] \times \tau$
- <u>**Masses**</u> follow immediately once P is known