Detection and Measurement of Sub−Stellar Companions: GAIA Scientific Potential (and Limitations)

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Extra−Solar Planets Statistics

- ~3−4% of solar−type stars (spectral classes F−G−K) in the Solar neighborhood, with moderately high metallicity (peaking at [Fe/H] ~ 0.3) harbor Jupiter−mass companions
- ~80% of the discovered giant planets orbit at R < 1 AU, well inside the ice condensation zone
- All multiple systems found so far are very unlike our Solar System
- Some of the planets may not be planets after all: over 1/5 of the candidates have $M \sin i > 5\ M_J$
- Planet and Brown Dwarf candidates, and stellar binaries have very similar orbital elements distributions, but mass distributions in the two cases are strikingly different!

The big picture is still unclear…

Fundamental Questions

(1) Where Are the Earth−Like Planets?
(2) Do Planets Occur in Coplanar Stable Planetary Systems?
(3) Do Planets Form by Core Accretion or Disk Instability?
(4) When, Where, and for How Long does Migration Occur?
(5) When do Gas and Ice Giant Planets Form?
(6) How Long Ago did the First Planets Form?
(7) Do Stars with Circumstellar Dust Disks Shelter Planets?
(8) What Are the Actual Mass and Orbital Elements Distributions of Sub−Stellar Companions?
(9) What Is the Role of Enhanced or Poor Metallicity?
(10) Why do We Observe a Brown Dwarf Desert?

By the Time GAIA Flies...

a) **<u>High−precision ground−based spectroscopy:</u> it should begin providing the signposts for (1), and will improve statistics for (8). It may contrib− ute significantly to (6−9) but should have a marginal role in (3−4−5−10)**

b) **<u>High−precision groud−based astrometric interferometry (Keck, VLTI):</u> it will begin addressing all questions (but (6)), but with limited potential (poor statistics and accuracies a factor 5−10 worse than GAIA)**

c) **<u>Transit photometry (Kepler):</u> will build additional statistics for (8) and may come tantalizingly close to give an actual answer to (1)**

d) **<u>Direct imaging:</u> it should play a role in (6)**

e) **<u>Other high−precision space−borne astrometric missions (SIM) will likely be flying together with GAIA</u>**

How Does GAIA Fit In?

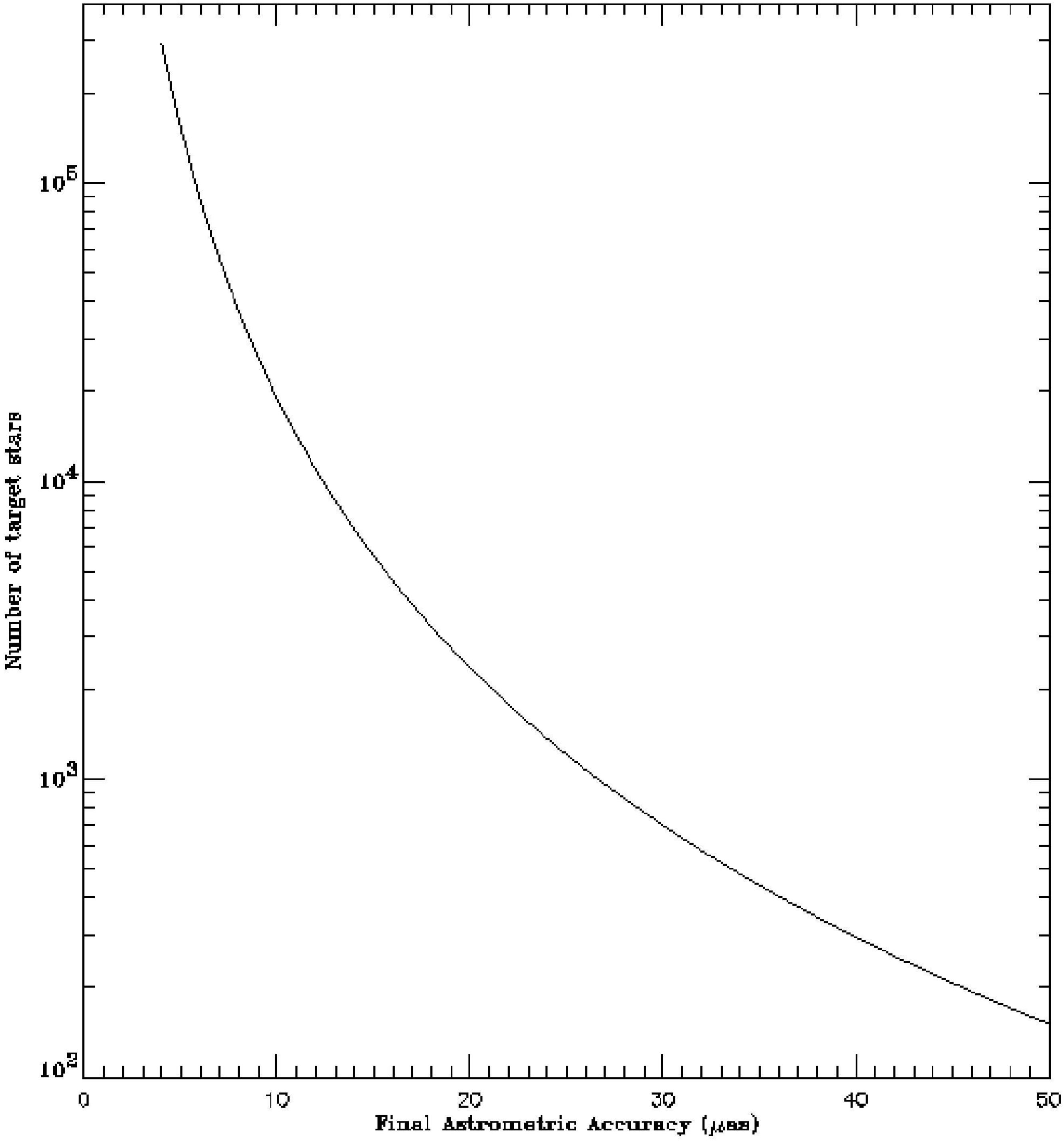
GAIA will provide only *indirect* evidence for (1), and should not be able to answer (6), but will play a key−role in all other fundamental issues of the science of planetary systems, the crucial parameters to be accurately measured being:

MASSES, INCLINATIONS, PERIODS, DISTANCES

NECESSARY REQUIREMENT: σ_{ψ} = 10 μas (V < 13)

OR, END of MISSION ACCURACY = 4 μas (V < 13)

Target Stars as a Function of Astrometric Accuracy



The GAIA Contribution (8)

IN THE FIELD:

- Which stars? Solar−type dwarfs (F−G−K)
- How faint? V < 13
- How far away? 150−200 pc from the Sun
- Which masses? Giant planets (0.1−5 M_J)
- Which periods? Up to twice the mission duration
- The available horizon includes ~3×10^5 stars, and thou− sands of giant planets might be detected and measured

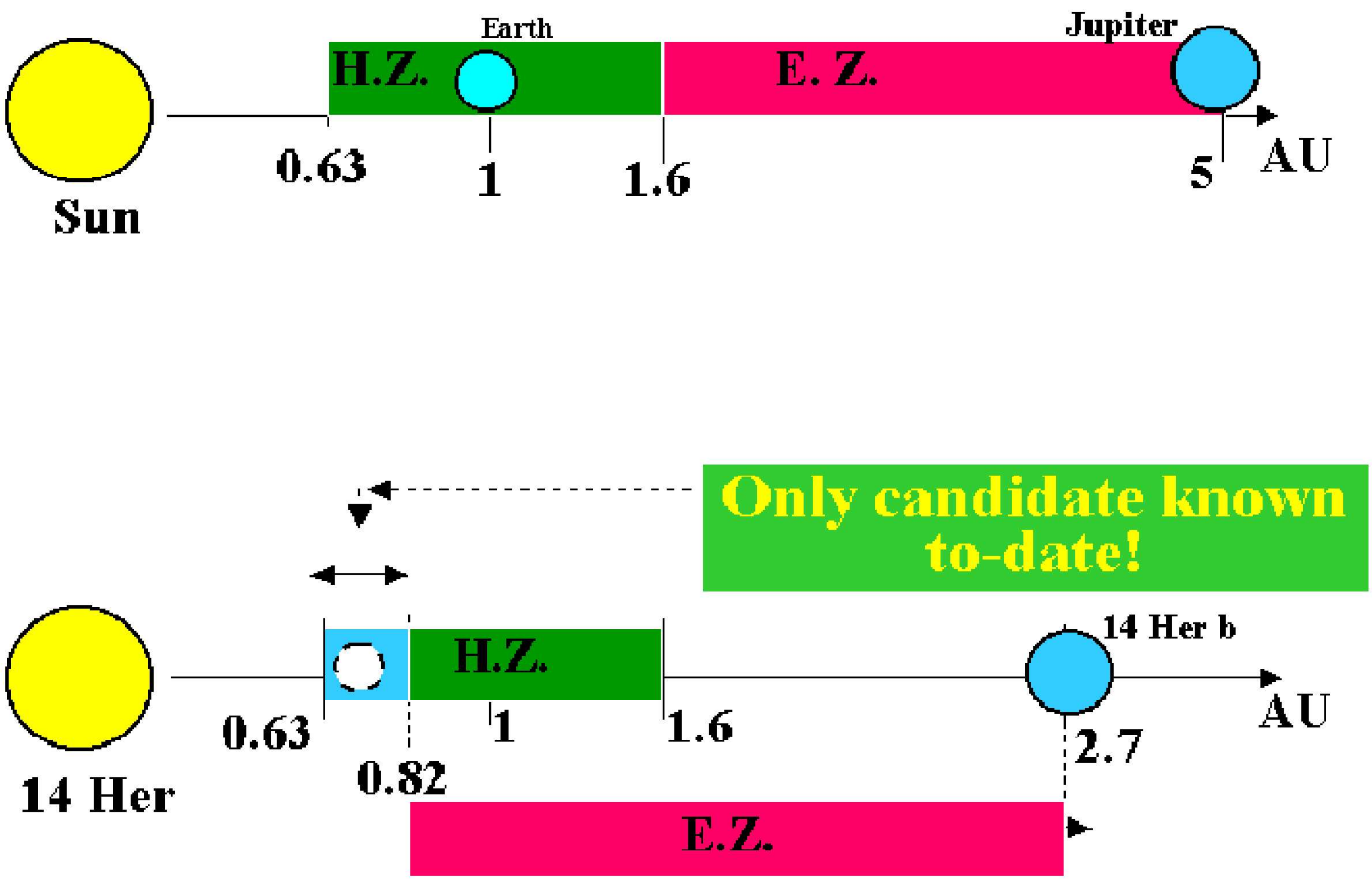
The GAIA Contribution (2)

- **For Planetary SYSTEMS having components producing S/N > 2, and on well−sampled orbits (P < 5 yr), GAIA will measure masses and orbital elements of each com−panion to < 1−10%**
- **In the same period range, GAIA will determine whether orbits are coplanar (or not!) with uncertainties of a few degrees in systems with components producing S/N > 10, providing insights on the long−term stability issue**
- **The available horizon extends out to ~60 pc, or ~15000 solar type stars**

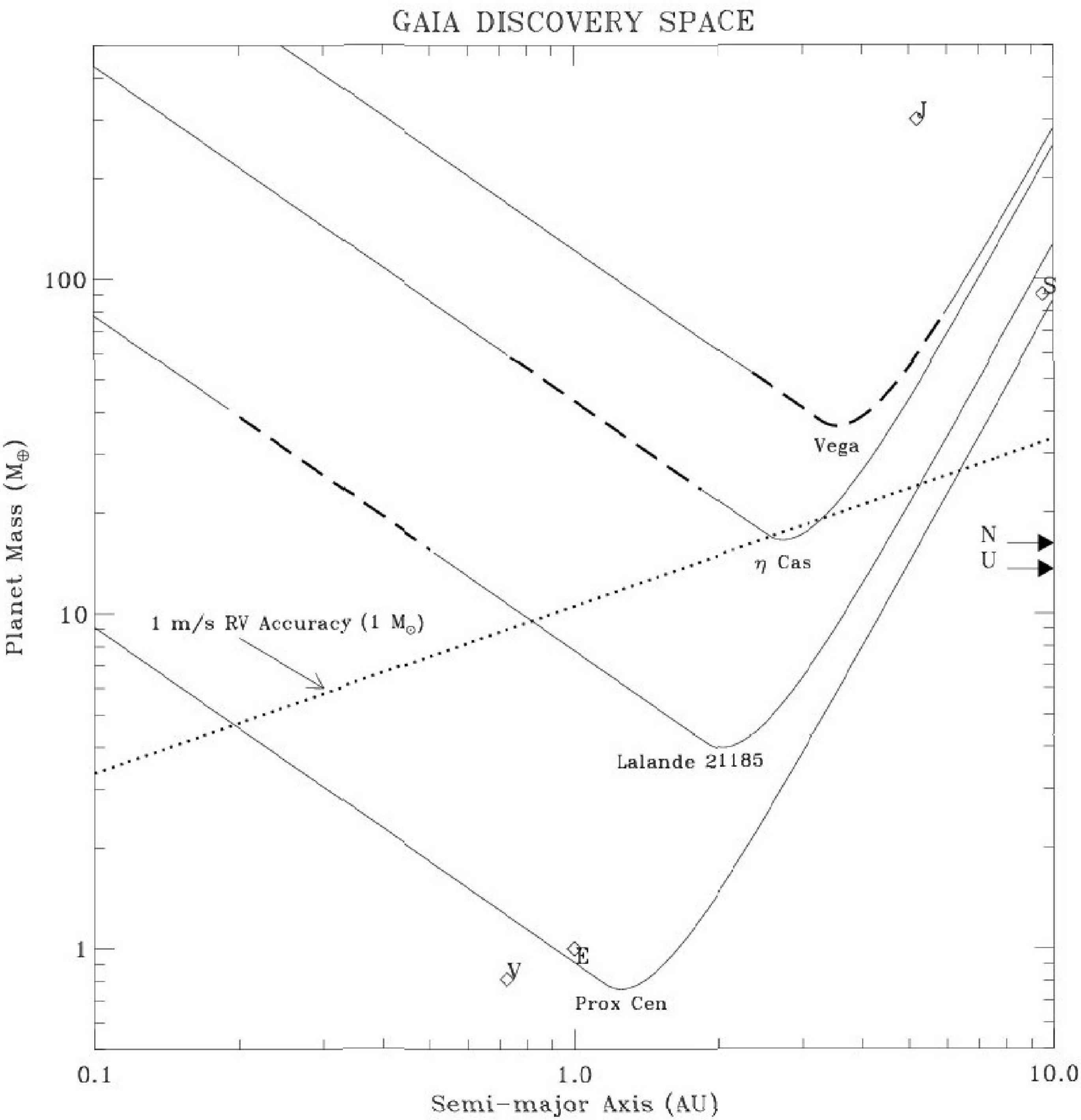
The GAIA Contribution (1)

- ➔ **Today, only 2 candidate planets (14 Her and ε Eri) found by spectroscopy can be considered as actual *Jupiter−signposts***
- ➔ **GAIA has the potential to discover MANY interest− ing systems, depending on actual frequencies, largely unknown to date.**
- ➔ **Every system discovered harboring a giant planet at > 3−4 AU, and *devoid of close−in giants*, will auto− matically become a target for further investigations of the *Habitable Zone***

GAIA and the Habitable Zone



GAIA and the Closest Stars

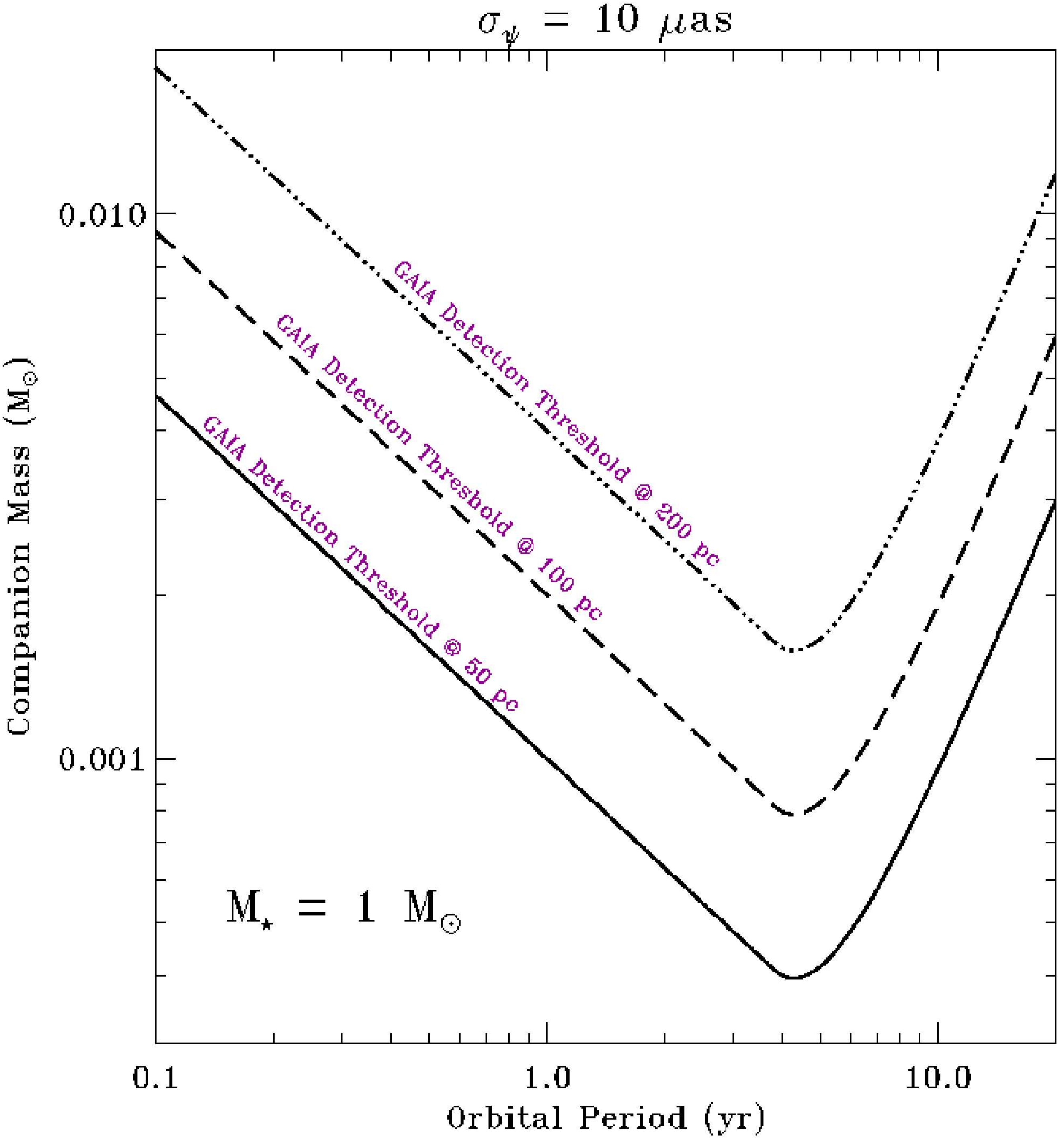


The GAIA Contribution (3−4−5−7−9−10)

IN NEARBY YOUNG ASSOCIATIONS:

- **The closest SFRs (~10 within 200 pc) and OCs (a handful within the same horizon) contain hundreds of optically visible, relatively bright (V < 13) PMS stars with ages in the range 0.5−100 Myr.**
- **These objects are metal poor, fast rotators and chromospherically active, thus astrometry can go deeper than spectroscopy in terms of the smaller detectable mass**
- **Assuming a S/N ~ 2 for detection, GAIA will perform a thorough survey for Jupiters/Brown Dwarfs at 1−5 AU, and will deliver a significant fraction of reliable orbits**

GAIA and the Star−Forming Regions



The GAIA Contribution (6)

IN GALACTIC GLOBULAR CLUSTERS:

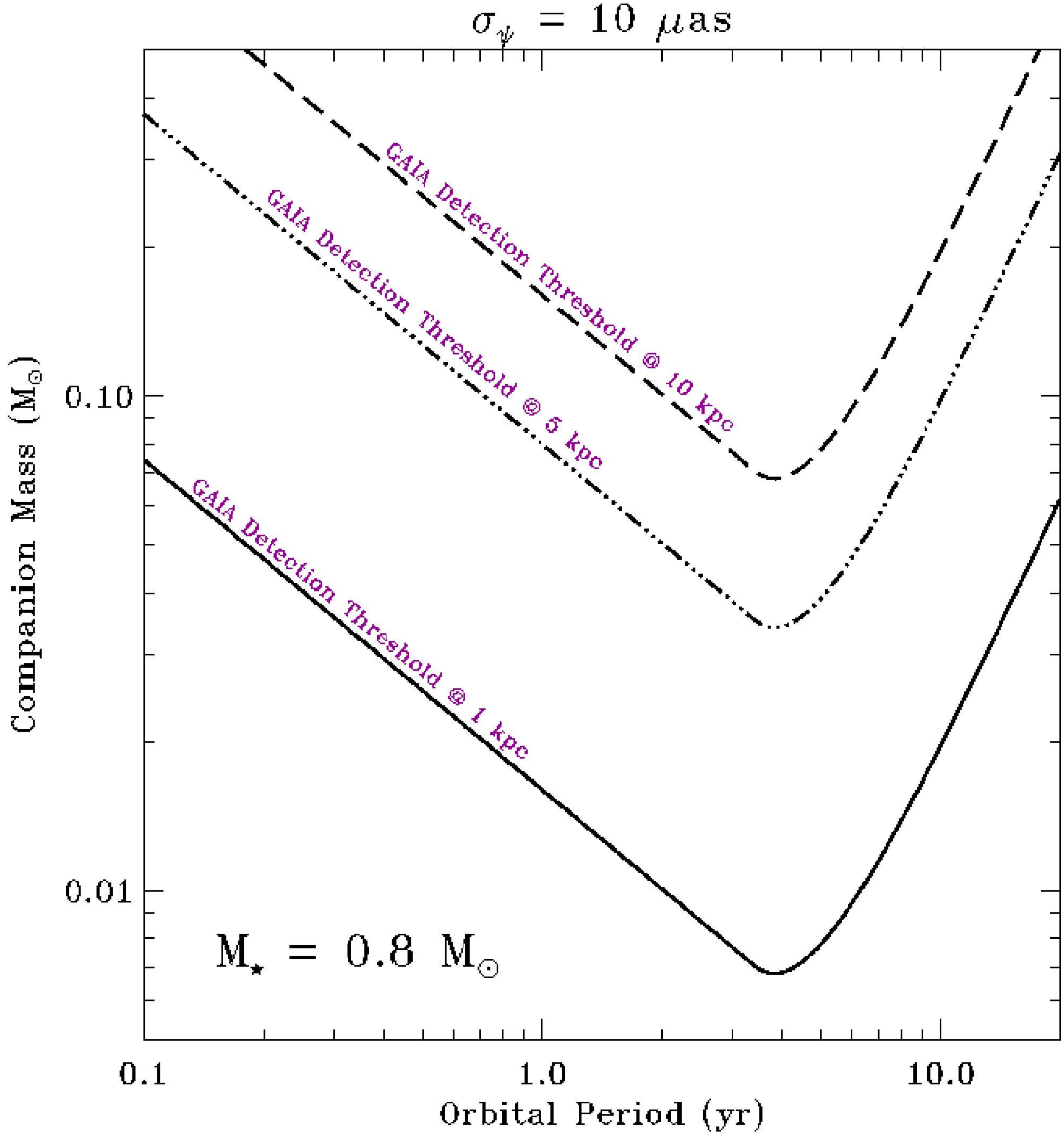
A) Only good targets: Evolved Red Giants (V~13−15)

B) dM/dt can be significant: smaller masses can be detected, but no real advantage because of D (1−10 kpc)

C) GAIA will still measure D precisely, but will only be ca−pable of probing the Brown Dwarf/Binary companion mass range

D) Except for the low−metallicity drawback, these are better targets for high−precision spectroscopy (at short periods)

GAIA and the Globular Clusters



Realistically, there are problems...

- **Astrophysical Noise:** intrinsic to the object, due to the sorrounding environment, due to the local environment of the observer
- **Dynamical Noise:** due to higher order effects in proper motion, parallax, aberration, and companions on very long periods
- **Detection and orbital fitting procedures:** must correctly disentangle contributions coming from different noise sources, cope with low S/N, handle ill−behaved cases, such as quasi−edge−on, or highly eccentric orbits

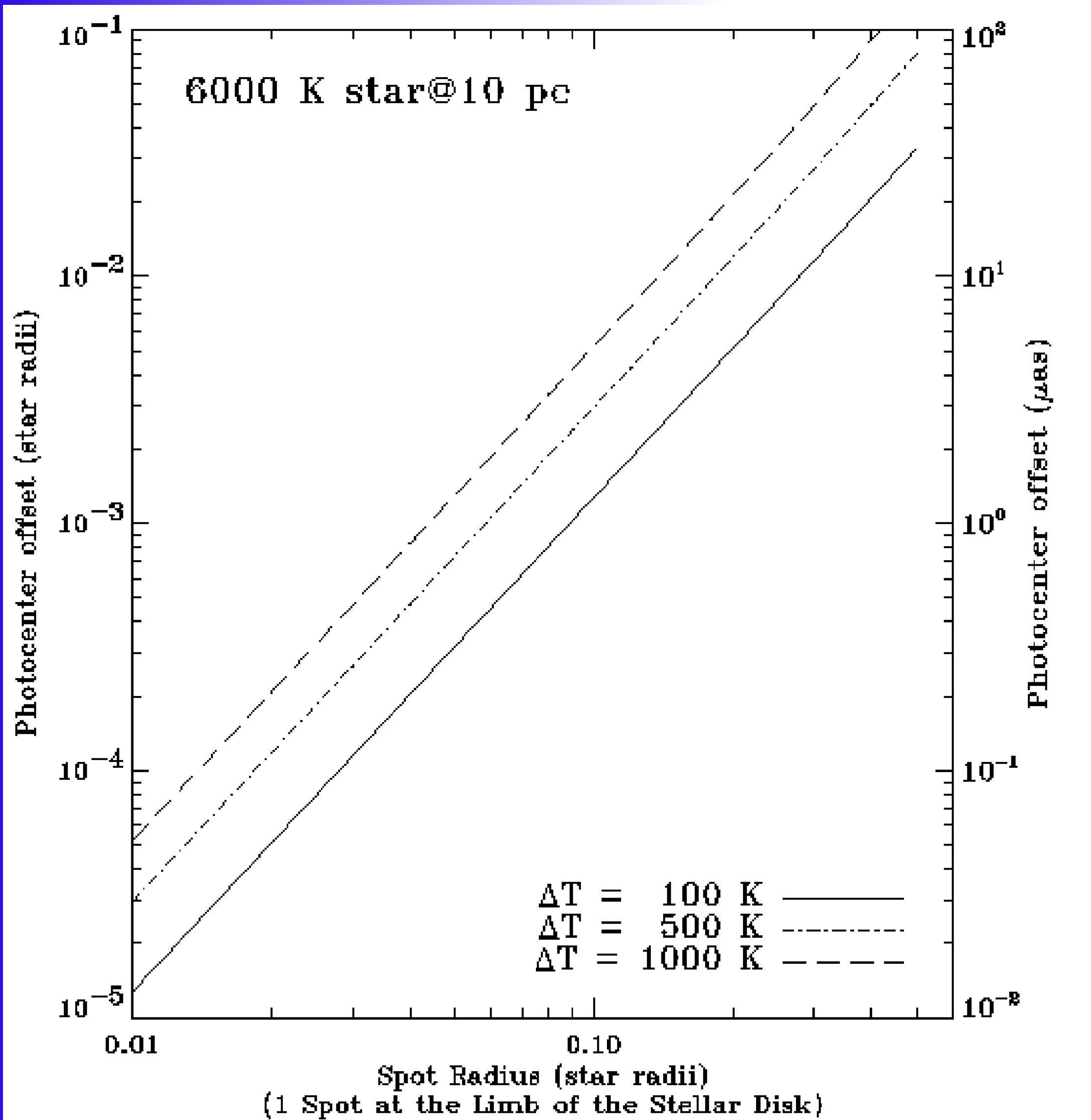
Astrophysical Noise Sources

1) **Stellar atmospheric activity (spots, flares):** characteristic of the youngest PMS stars (< 1 M_s), they can be large (covering up to 10−40% of a projected hemisphere vs. few millionths for the Sun), cool or hot, and long−lived. They should not constitute a severe problem for GAIA in the field, and should also have marginal effects in SFRs, due to D. They are strongly correlated to $\Delta F/F$, so they might be modeled and removed

2) **Circumstellar disks:** time−variable scattered light by a dust disk from a rotating star with hot and cool spots can induce photocenter shifts (following the star rotation period). For a 30 AU disk at D typical of SFRs, the excursion is of order of a few μas (again, not a big obstacle for GAIA)

3) **Light−bending from Solar−system bodies:** not addressed here

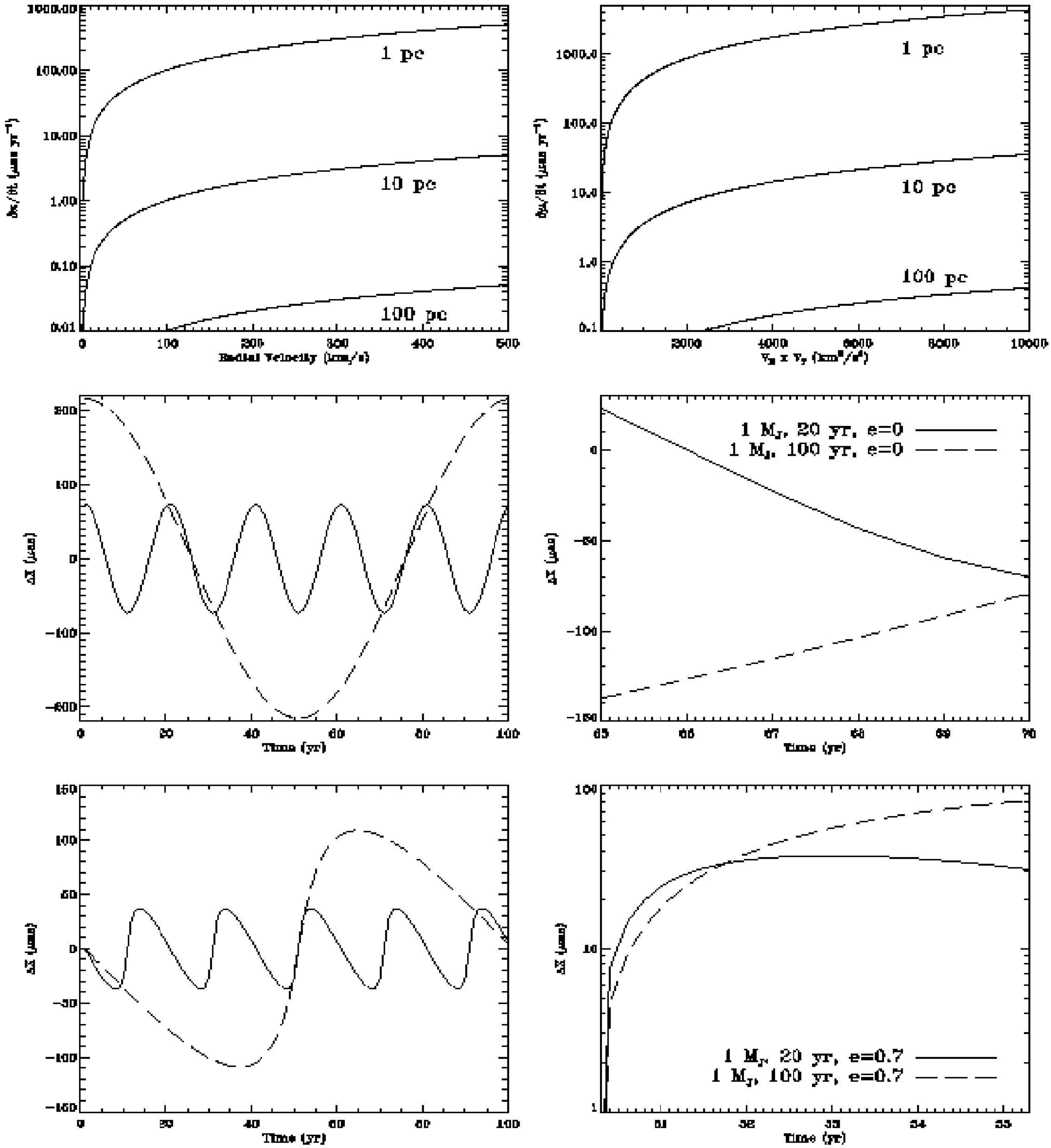
Effects of Astrophysical Noise



Dynamical Noise Sources

- **Perspective Acceleration (dμ/dt):** within reasonable ranges of V_R and V_T, it is an important effect out to a few tens of parsecs (over 5 years of mission)
- **Change in Parallax (dπ/dt):** it should be detectable for D<10 pc
- **Accelerations due to long−period companions:** difficult to distinguish from dμ/dt at small D, difficult to disentangle from μ at larger D. These constitute a serious problem!
- **Relativistic correction to aberration:** not addressed here

Effects of Dynamical Noise



Orbit Reconstruction

- **It will be performed from scratch for a big number of objects. Which is the most effective approach?**
- **Local Search:** needs starting guesses within convergence radii
- **Global Search:** very time consuming, for large parameter spaces
- **Full decomposition in Fourier harmonics:** is (almost) model−inde−pendent, but has drawbacks (multiple planets or an eccentric orbit?)
- **Downhill Simplex:** effective but time consuming, and seems to fail as the parameter space gets larger
- **Simulated Annealing:** very time consuming
- **Genetic Algorithms:** when applied to the pulsar planets, seems a promising tool

PROPOSED ACTION ITEMS:

- **Conduct Double−Blind Tests:** **a necessary step to verify the global performance of the search and analysis methods**
- **Refine Models for the Observable ψ:** **the classical description of moving objects does not hold anymore for astrometry at the μas level**
- **Design a reliable orbital fitting procedure:** **required for a proper assessment of the effectiveness of the search and measurement strategy**