Finding an Earth via Astrometry and Radial Velocity: Numerical Simulations

KITP
9 February 2010

Wesley A. Traub, JPL

SIM Lite Does Unique Exoplanet Science

- SIM Lite finds nearby ***Earth analogs*** (i.e., with Earth-like mass, orbit, & host star).
  - Astrometry is the only way to get Earth-analog mass and orbit info around stars that are close enough to us for follow up with spectroscopy.

- SIM Lite measures ***mass***, essential for physics, chemistry, & follow-up observations.
  - Real measurements are science; estimates are speculation.

- SIM Lite provides a ***full inventory*** of planets around nearby stars.
  - Existence proof provides sound basis for follow-up characterization mission.
  - Existence proof & mass/orbit reduces science risk for characterization mission.

Charge from HQ

“ I'd be interested in seeing a simulated set of astrometric measurements of our Solar System if it were at 10 pc to see the detectability of Earth as a function of time.

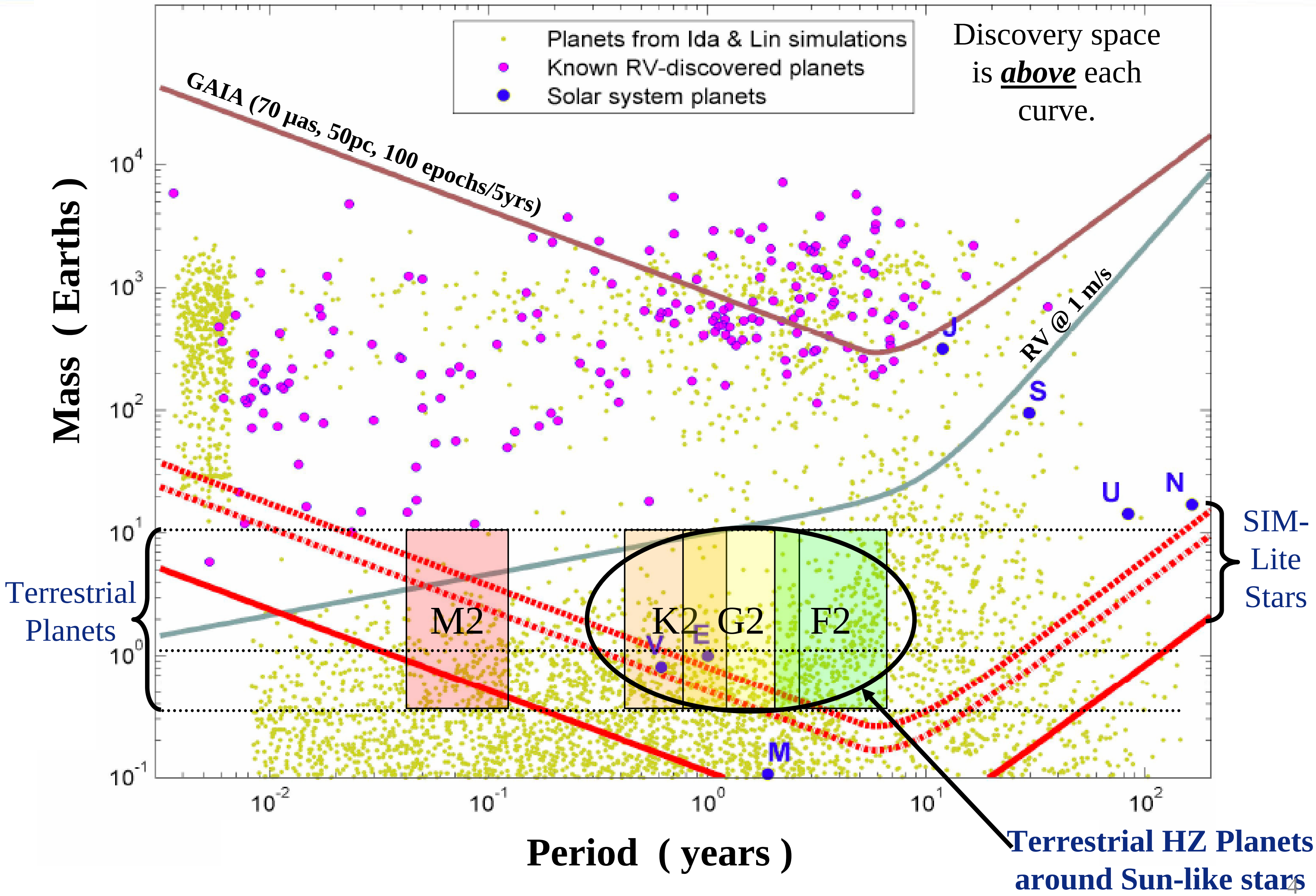
Has the SIM team done this exercise for SIM and SIM-lite with real performance-based error bars?   If not, I'd like to ask them to run this.”

Jon Morse, 10 Jan. 2008

With followup clarification:

L. LaPiana, S. Ridgway, & Z. Tsvetanov,   16 Jan 2008

Astrometric & RV Sensitivities



Timeline and Reports

Preparation

Feb. 2008: 5 modeling teams engaged

Feb. Announcement of competition for analysis teams

Apr. Selection of analysis teams

Apr.-May: White paper drafted, on assumptions and procedures

Phase I

May: Practice analysis runs.

June-July: Phase I simulated data & competitive analysis

August: Report results to HQ & at multi-planet mtg in Poland

Sept.: Preliminary paper, PASP (to appear)

Phase II

Sept-Dec: Phase II simulated data & competitive/cooperative analysis

Jan. 2009: Report results to AAS and to HQ

Feb-Dec: Summarize results of Phase I & II, write ApJ paper.

Feb. 2010: Final paper, ApJ (in prep.)

Methodology

5 years of SIM data, σ = 1 micro-arcsec, 250 visits, Sun exclusion 50°, 40% dedicated
15 years of RV data, σ = 1 m/s, 1 obs./month, Sun exclusion 45°

5 model teams, 1 data simulation team, 5 analysis teams (AO-selected), 1 summary team.
Oversight by External Independent Readiness Board & HQ.

719 model systems, compatible with current knowledge, theorist's best guess.
Selected random systems, random angles, double-blind.

Phase I, competitive:
48 cases, single star, 10 pc, M(sun), random & SS-like planets.
Phase II, competitive/cooperative:
60 cases, random SIM stars, d(star), M(star), random planets.

Solutions based on chi-square. Uncertainties include all correlations.
Require < 1% false alarm probability.

Scored on basis of Cramer-Rao variance estimates of mass & period,
Andy Gould formalism (~Fischer matrix method)

Astrometric-RV Participants

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Andrew F. Boden, NExScI
Alan P. Boss, Carnegie Inst. Wash.
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Joseph Catanzarite, JPL
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Philip C. Gregory, U. British Columbia
Sam Halverson, UC Berkeley
Andrew Howard, UC Berkeley
Shigeru Ida, U. Tokyo
N. Jeremy Kasdin, Princeton U.
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Gregory P. Laughlin, UC Santa Cruz
Harold F. Levison, SWRI
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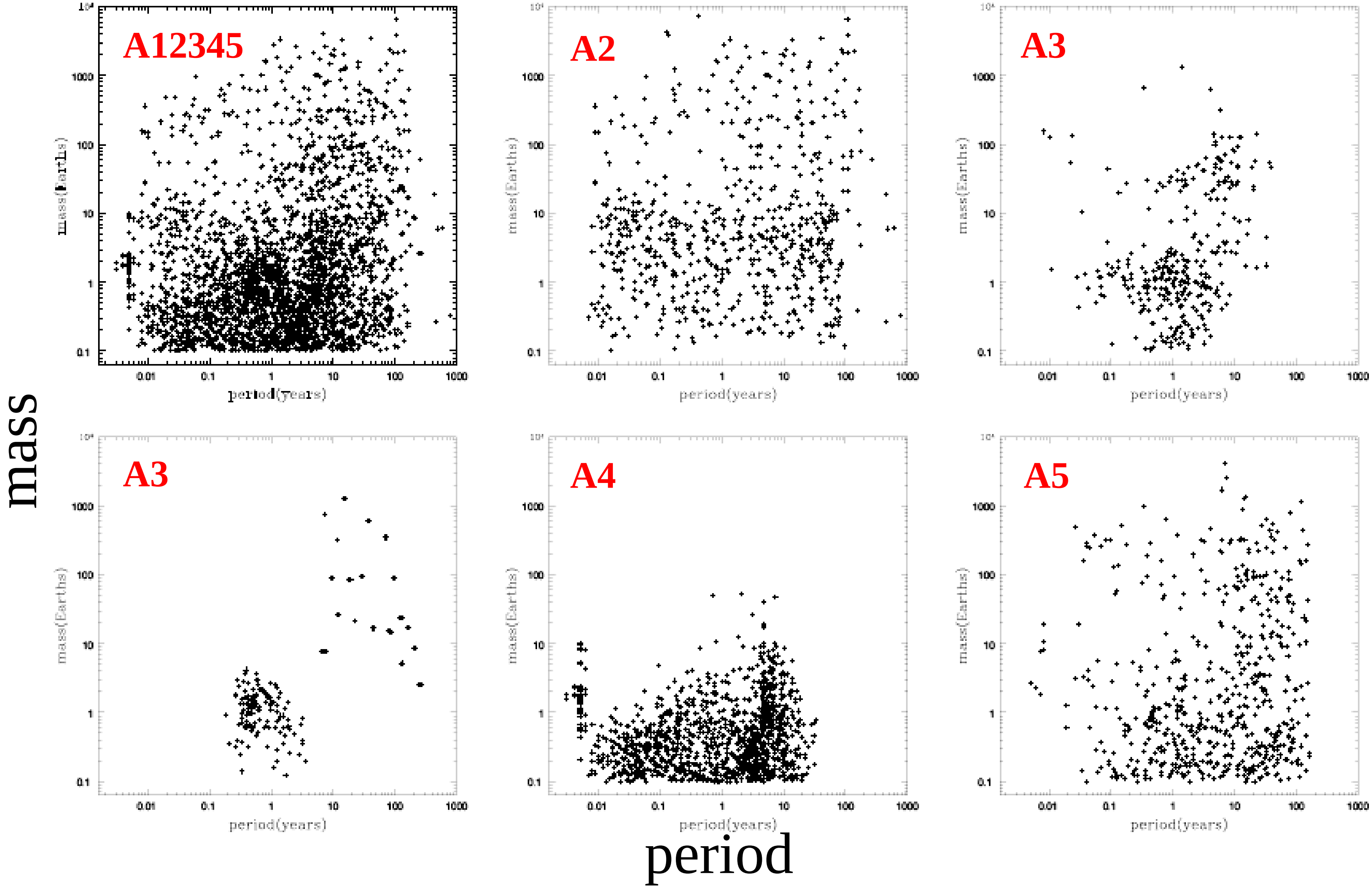
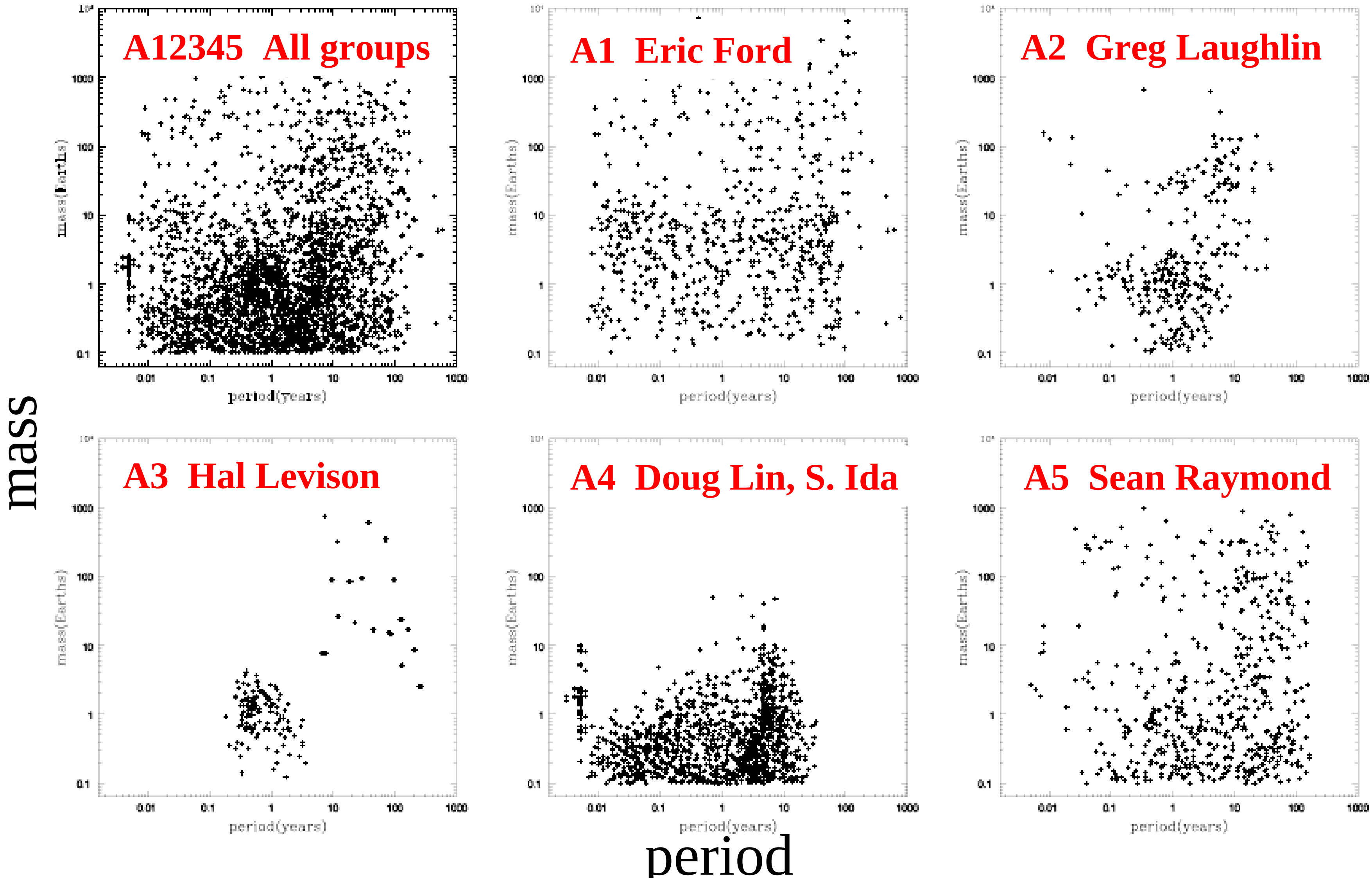
Alessandro Sozzetti, INAF, Torino
Genya Takeda, Japan
Stephen C. Unwin, JPL
Jason Wright, Penn State
Cengxing Zhai, JPL

Bold: Team Leads

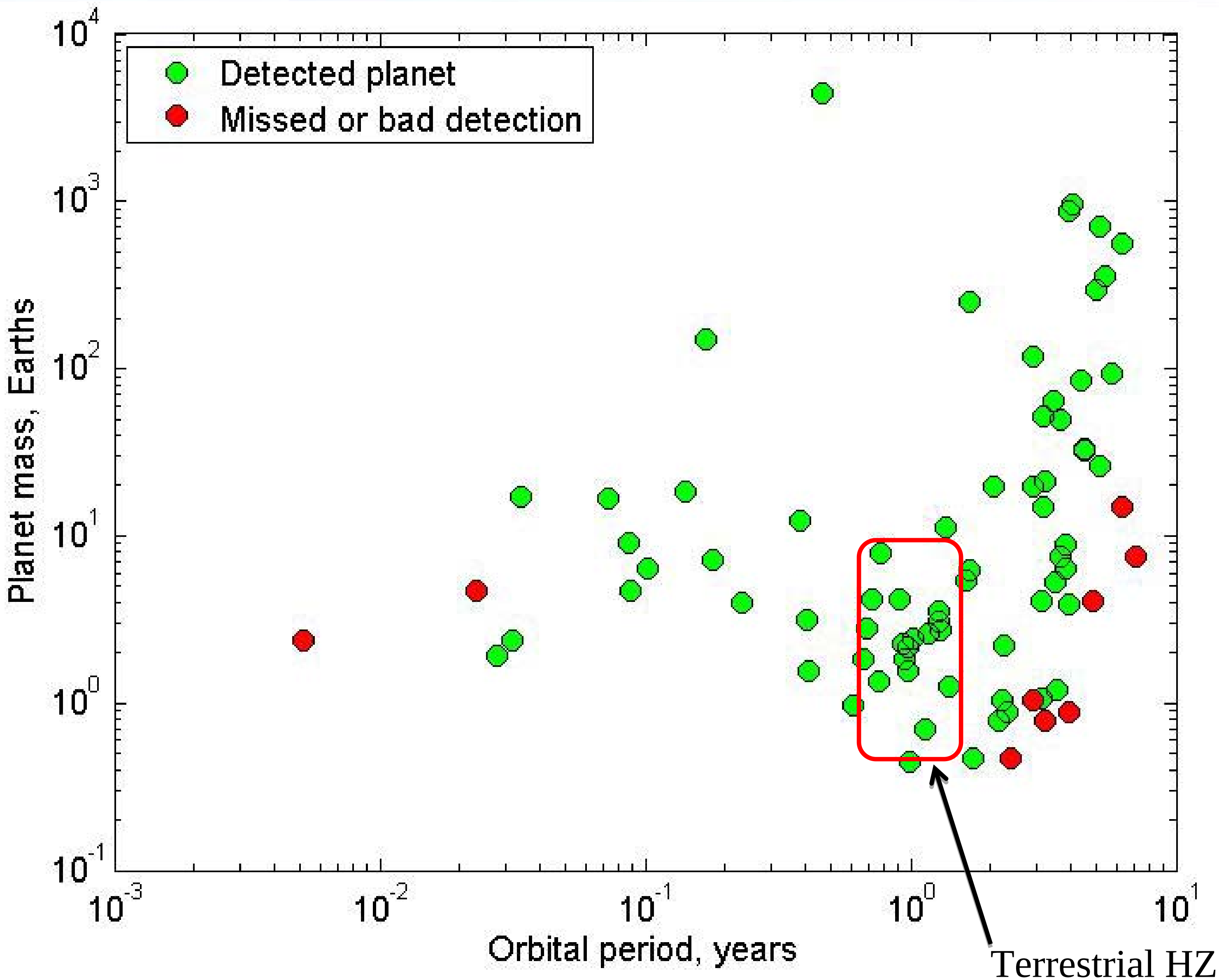
Planets from 5 Modeler Teams



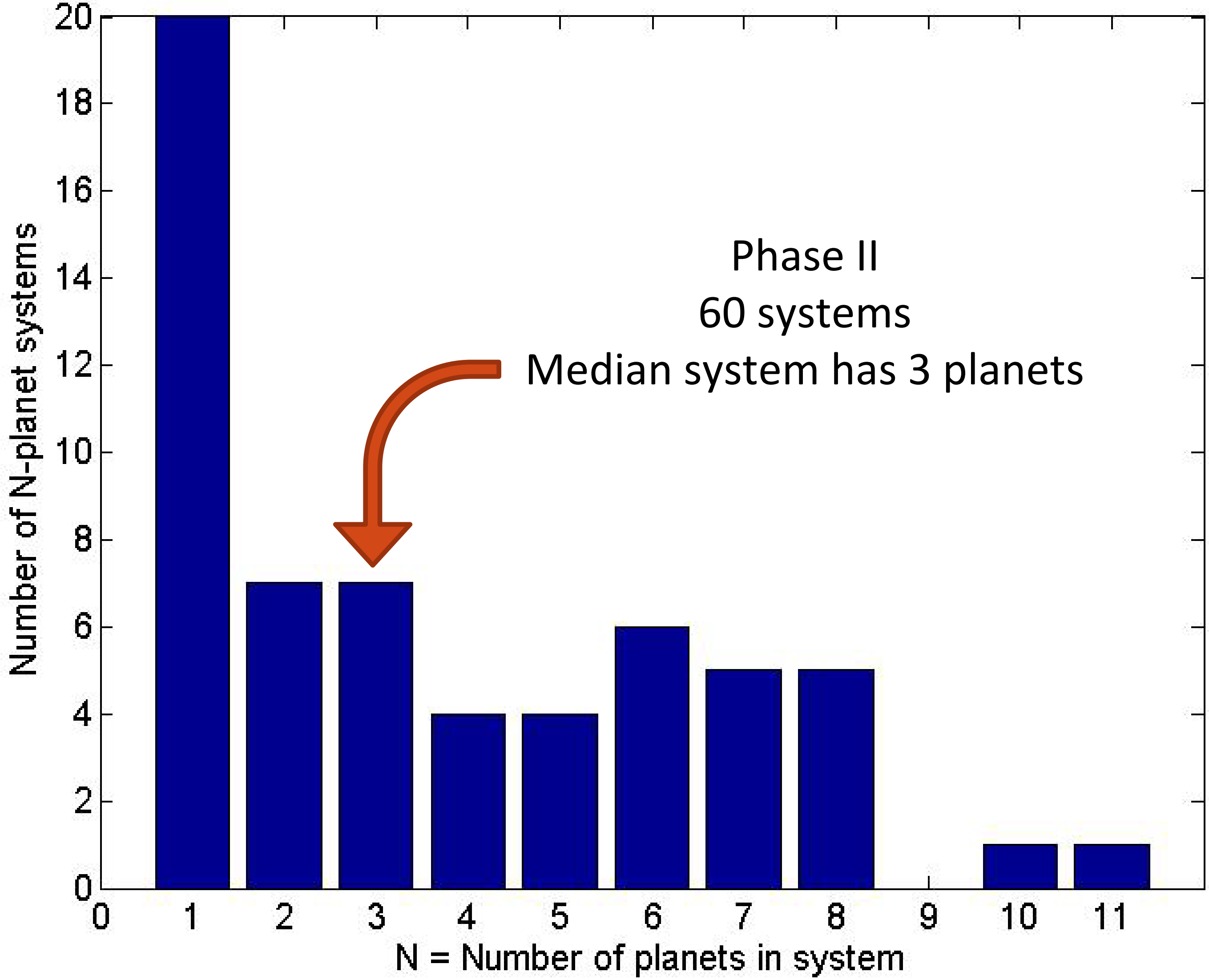
Planets from 5 Modeler Teams



Discovery Space



Planet Multiplicity



Cramer-Rao (Fischer matrix) estimates of parameter uncertainties

QuickTime™ and a
decompressor
are needed to see this picture.

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A. Gould, astroph (2008)

Criteria for correct solution

Main rule

- Period & Mass: |true – fitted | < 3 σ (Cramer-Rao)

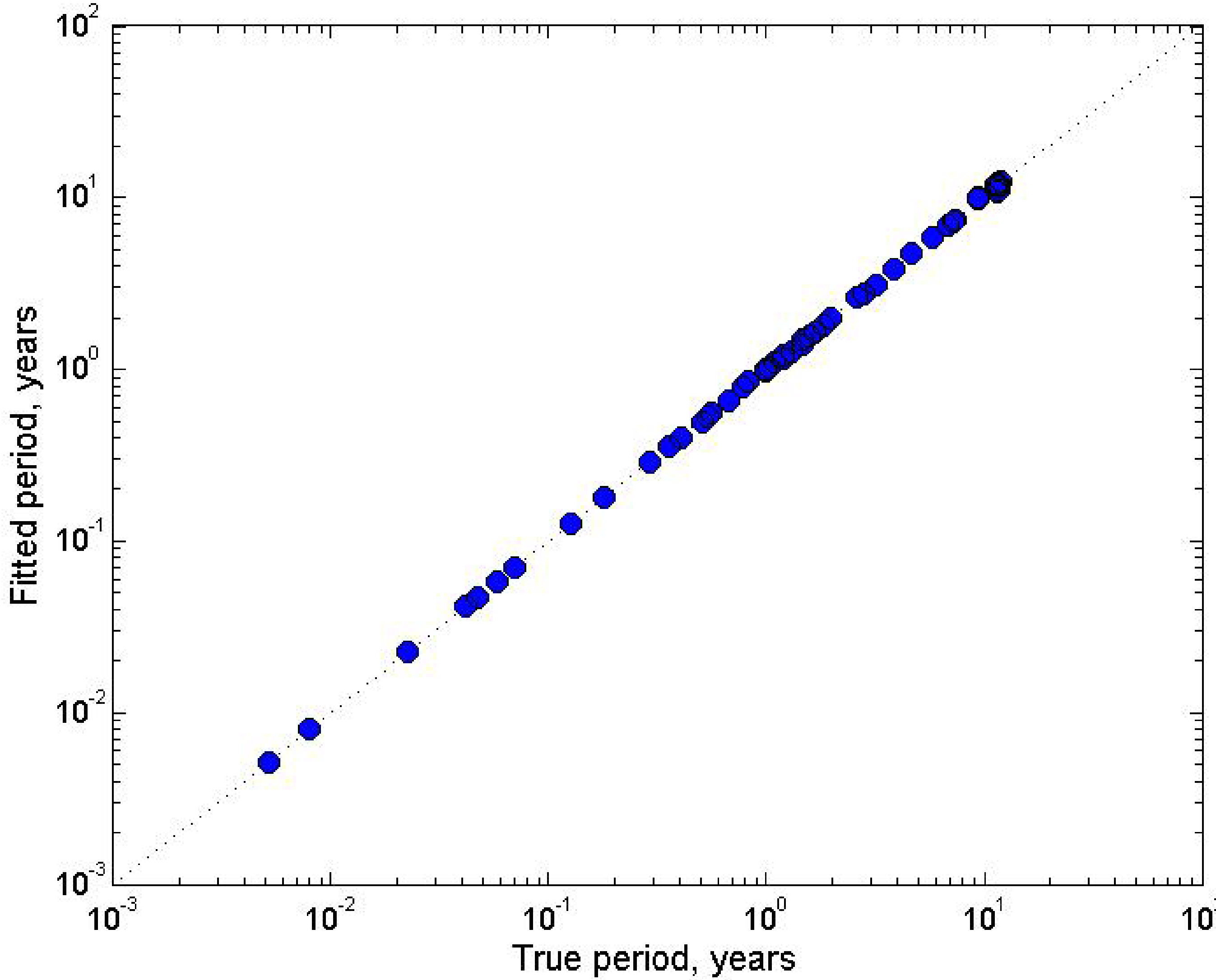
Special cases

- If SNR < 5.8: |true – fitted | < 3*SNR/5.8 σ (Cramer-Rao)
- If SNR >> 5.8: | true – fitted | < 0.5% period
- If SNR >> 5.8: | true – fitted | < 1.0% mass

Note

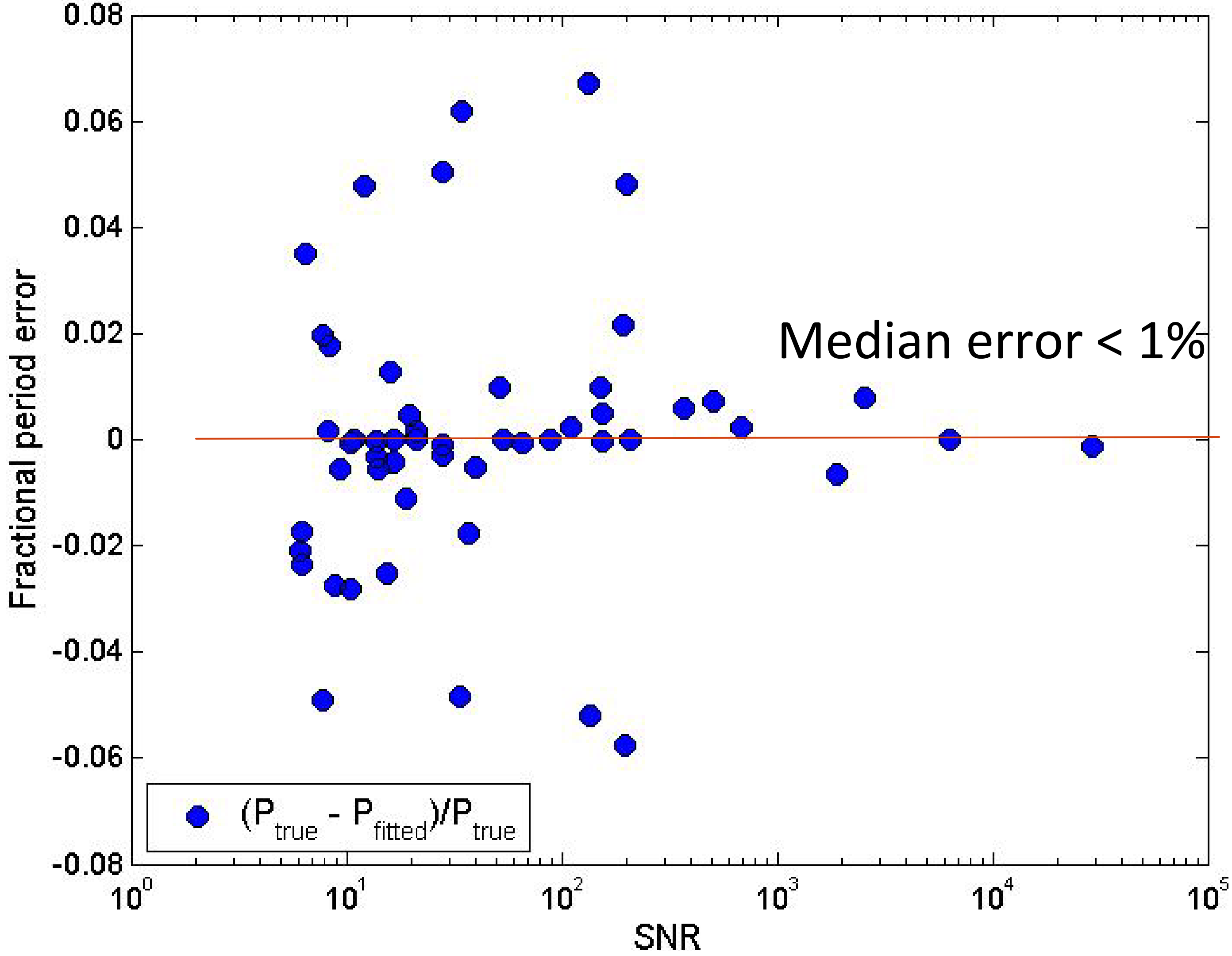
- The synthetic data team calculated σ (Cramer-Rao) for all obit parameters & all planets, for the actual observing conditions, including effects such as proper motion and partial orbits.

Period: fitted vs. true



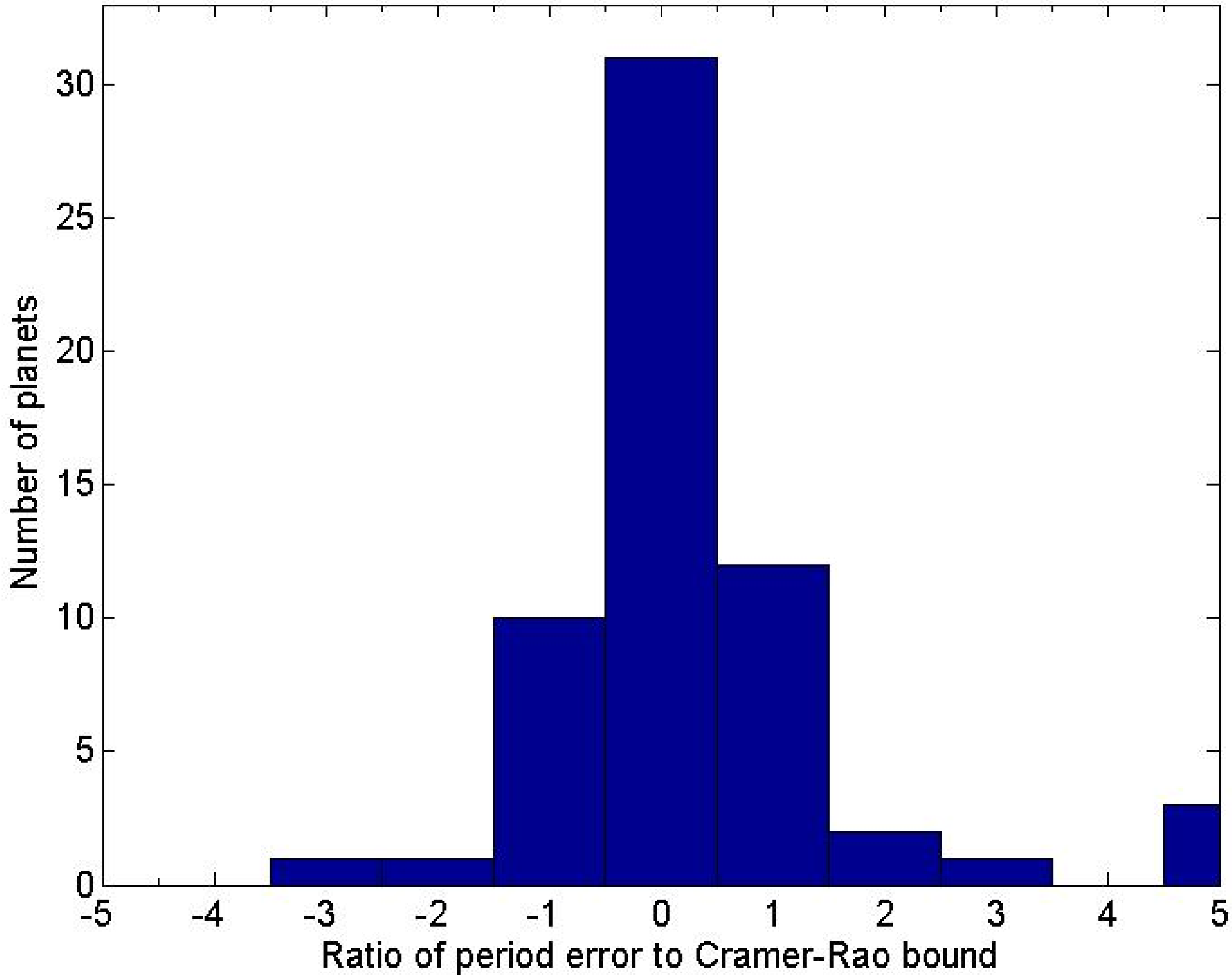
53 SIM-RVplanets with P<4, SNR(SIM)>5.8, or P<12 , SNR(RV)>5.8, all Phase II.

Period: fractional error vs. SNR



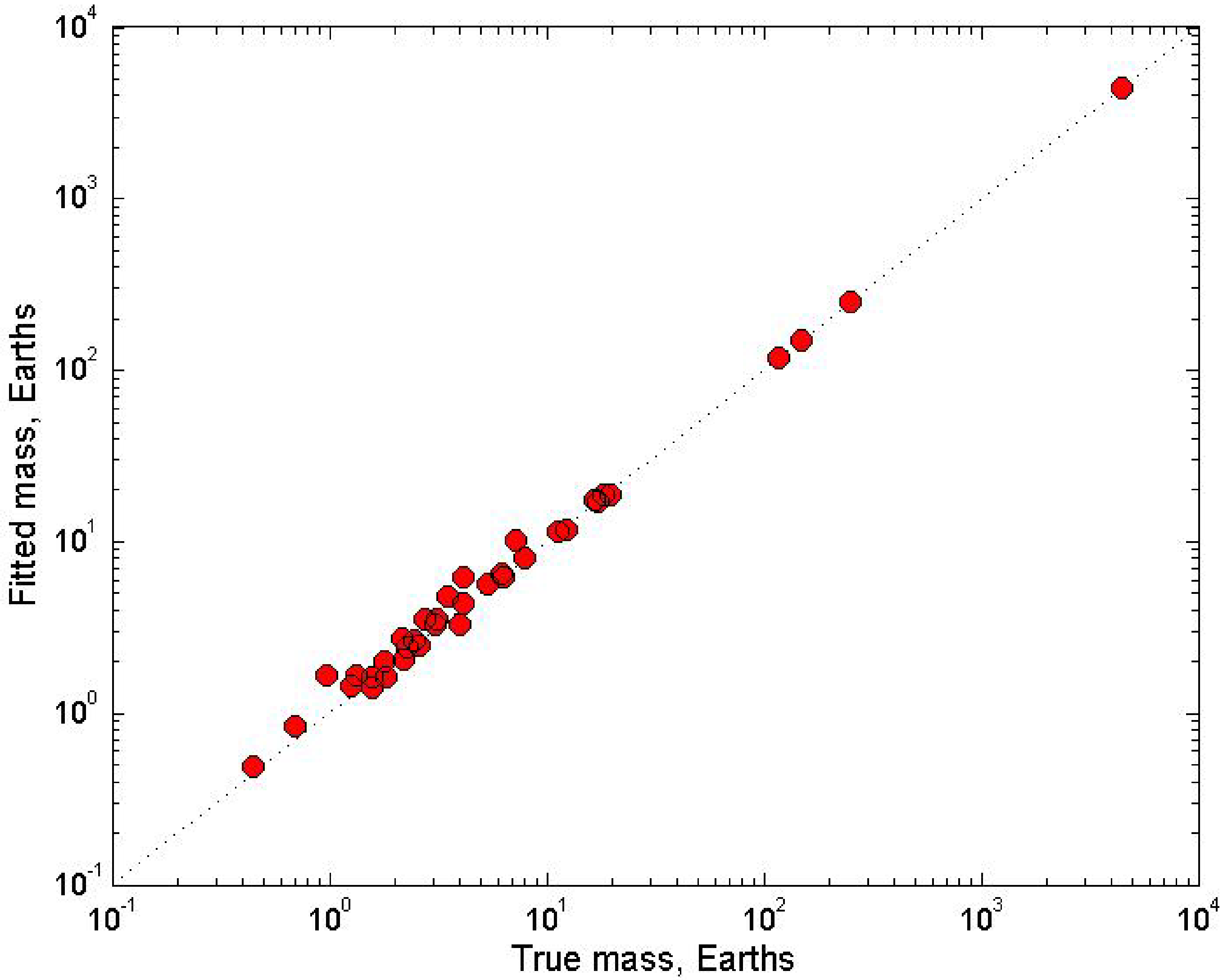
53 SIM-RVplanets, Phase II, as above.

Period: actual error / CR bound



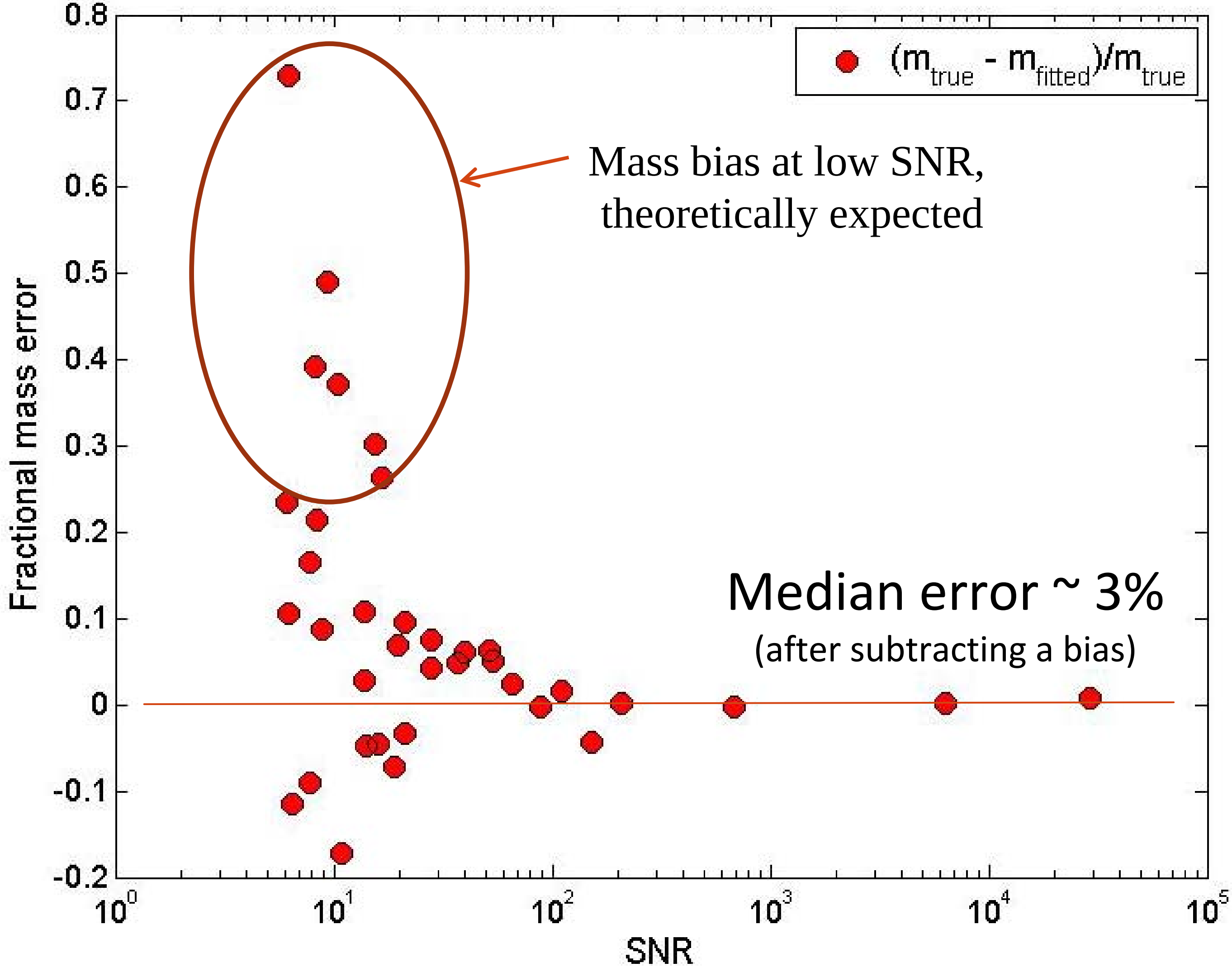
61 planets detected with SNR>5.8 and P<15 yr.

Mass: fitted vs. true mass



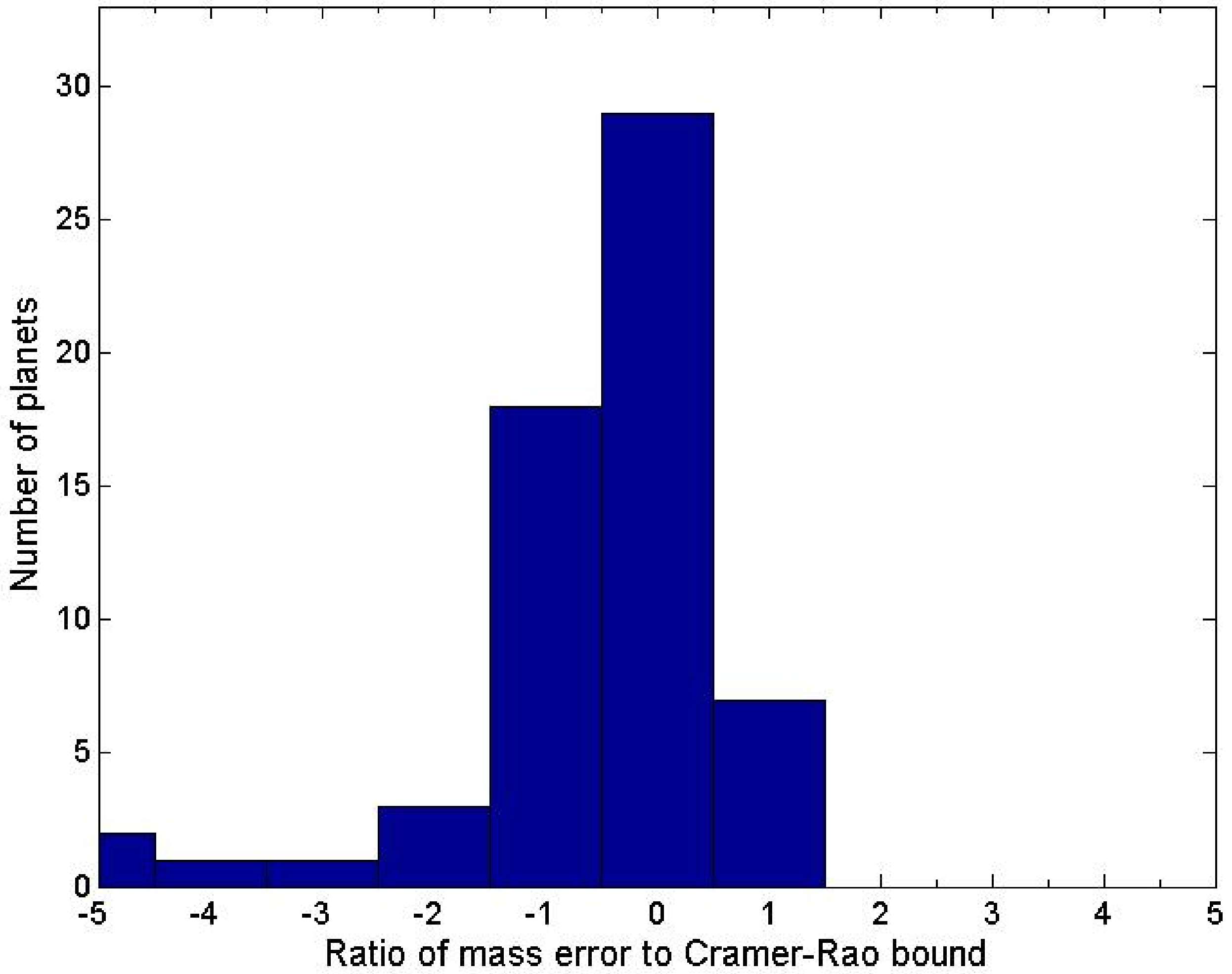
36 SIM planets with P<4, SNR(total)>5.8, Phase II.

Mass: fractional error vs. SNR



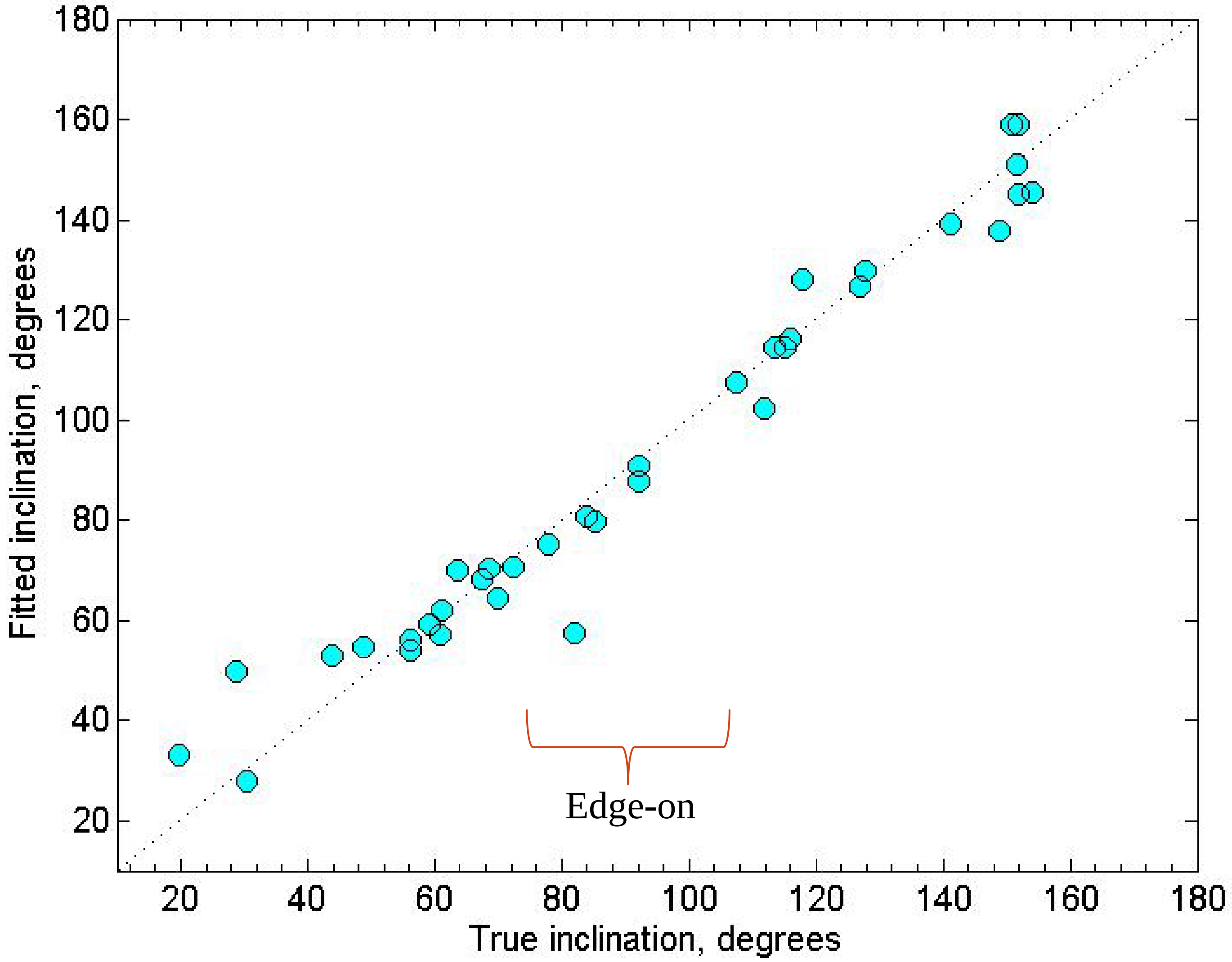
36 SIM-detected planets, as above.

Mass: actual error / CR bound



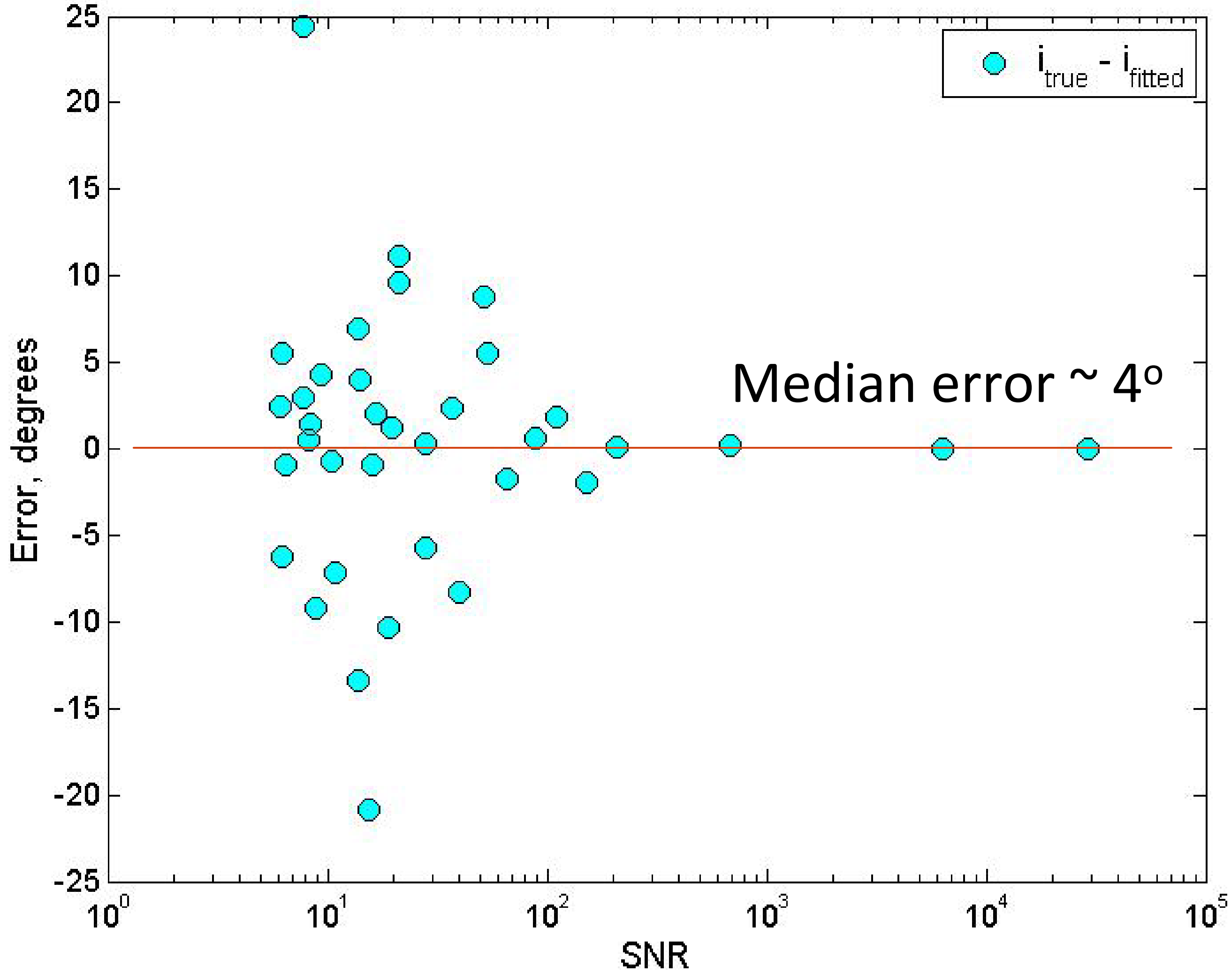
61 planets detected with SNR>5.8 and P<15 yr.

Inclination: fitted vs . true



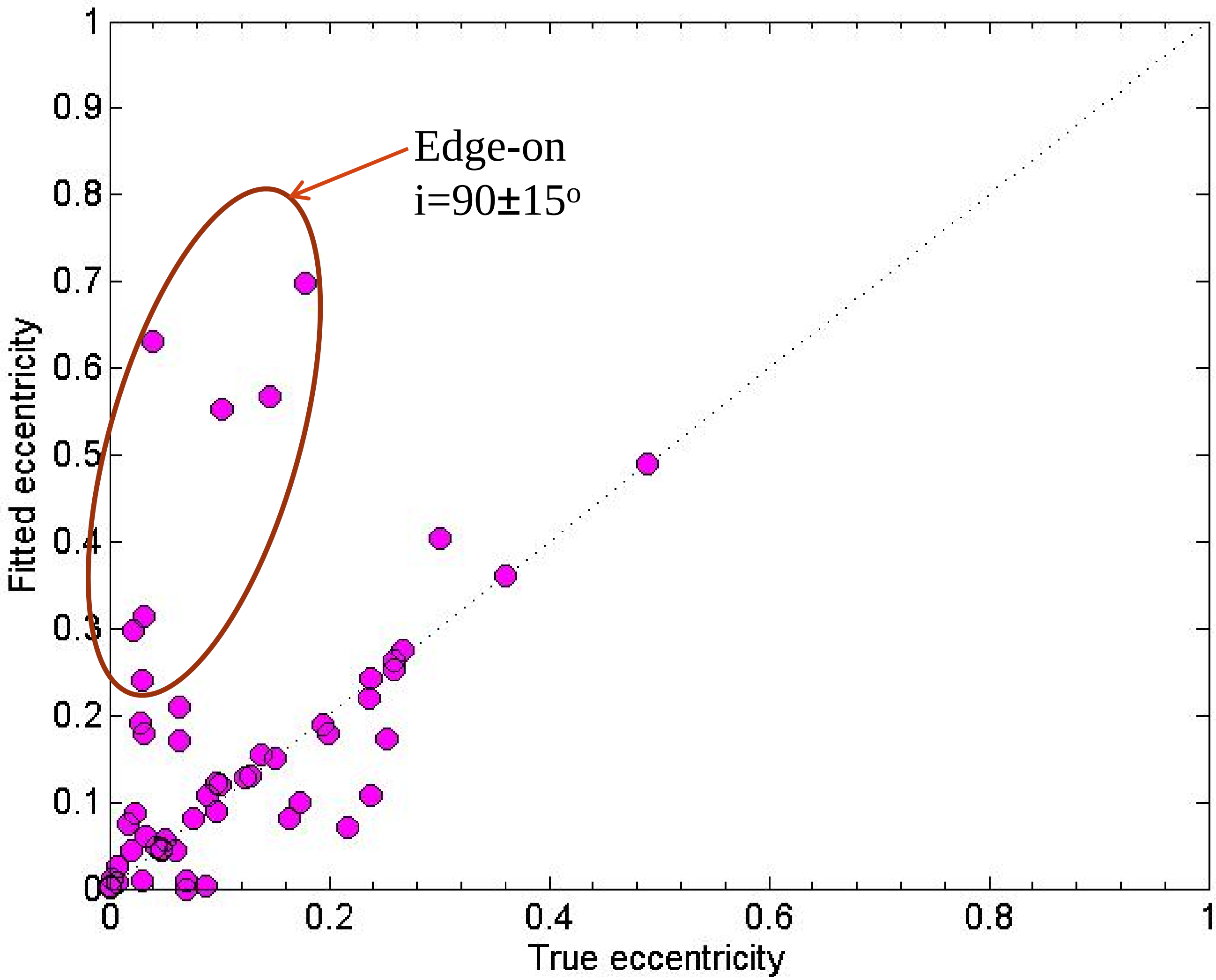
36 SIM planets with P<4, SNR(total)>5.8, Phase II.

Inclination: actual error vs. SNR



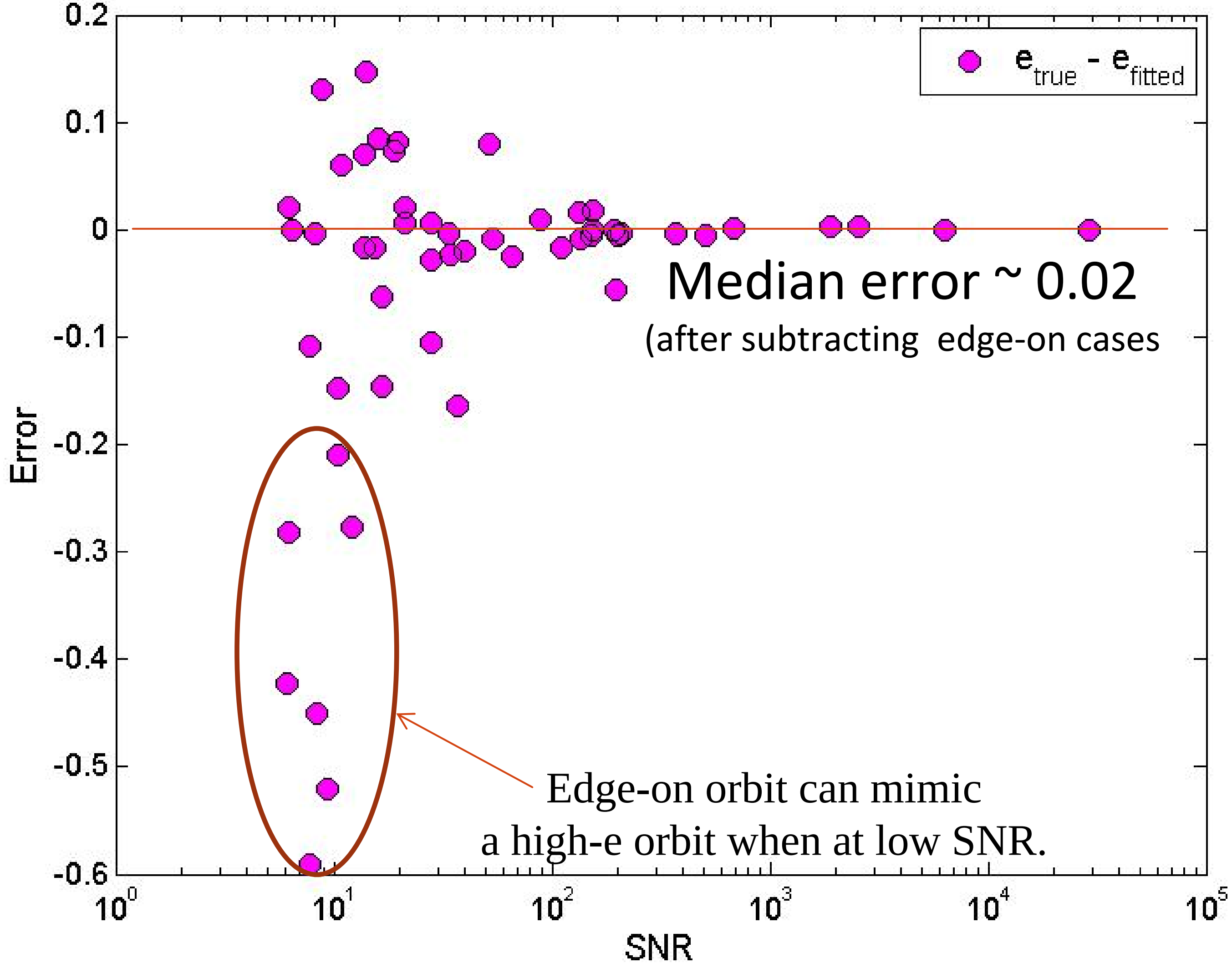
36 SIM planets with P<4, SNR(total)>5.8, Phase II.

Eccentricity: fitted vs. true



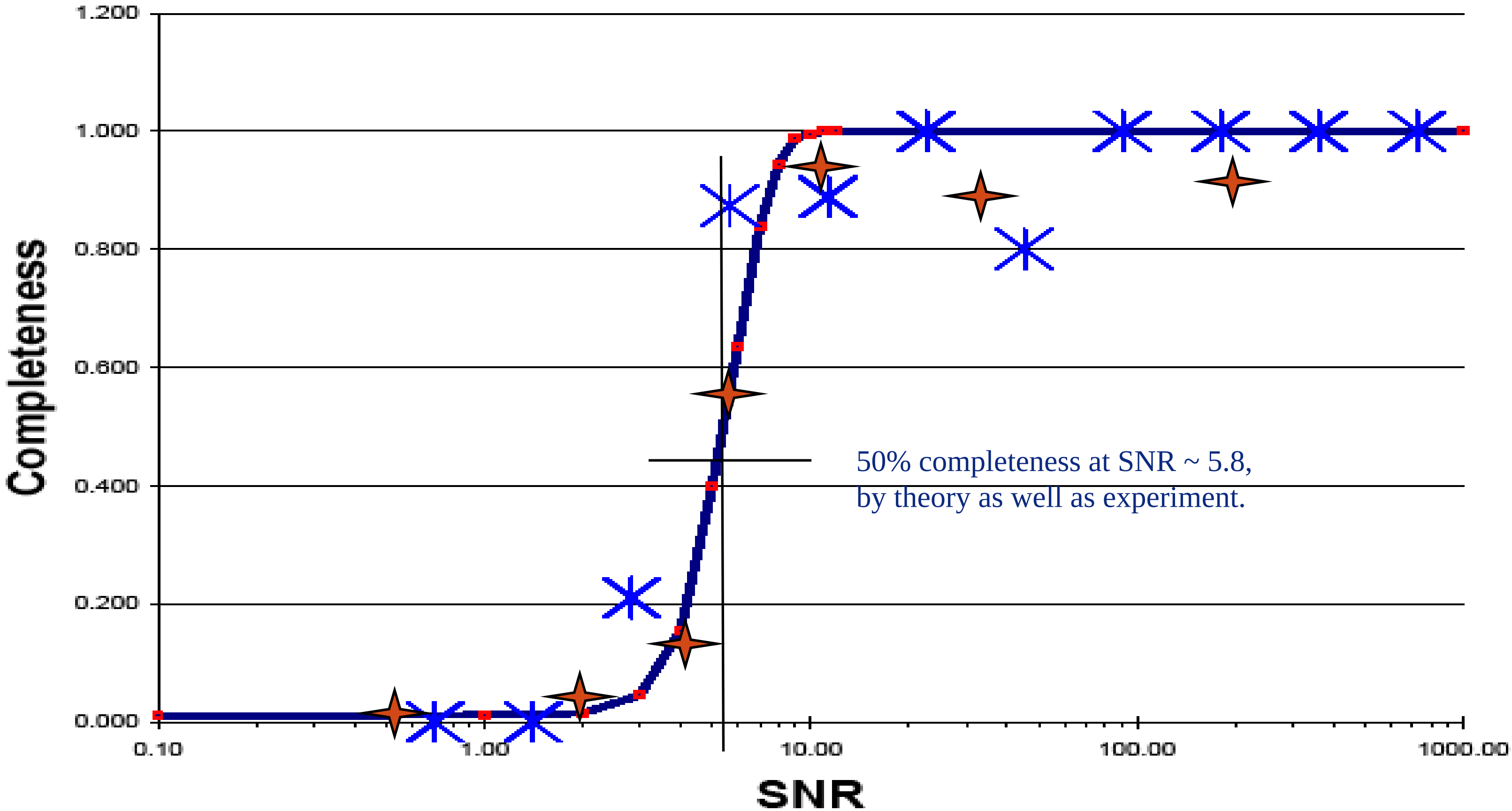
53 SIM-RVplanets with P<4, SNR(SIM)>5.8, or P<12 , SNR(RV)>5.8, all Phase II.

Eccentricity: actual error vs. SNR



53 SIM-RVplanets with P<4, SNR(SIM)>5.8, or P<12 , SNR(RV)>5.8, all Phase II.

Completeness vs SNR



- Completeness = detected / detectable planets.
- Curve is theoretical for 1% FAP (Catanzarite et al. 2006).
- At SNR > 5.8, measured completeness is excellent, as predicted.
- SNR is the RSS of RV & Astro SNRs.

Trend planets

- Trend planets are distant gas giants with long periods.
- Cramer-Rao predicts that planets with long periods, compared to length of observations (~ $P \geq 0.7\ T$), will have increased errors.
- We found 11 real trend planets, & 1 false one.
- RV data was valuable here.

Summary Statistics

Scoring Category	Part I	Part II
Completeness: Terrestrial	18/20 = 90%	35/43 = 81%
Completeness: HZ	13/13 = 100%	21/22 = 95%
Completeness: Terrestrial HZ	9*/9 = 100%	17**/18 = 94%
Completeness: All planets	51/54 = 94%	61/70 = 87%
Reliability: Terrestrial	25/27 = 93%	38/39 = 97%
Reliability: HZ	16/16 = 100%	20/20 = 100%
Reliability: Terrestrial HZ	12/12 = 100%	16/16 = 100%
Reliability: All planets	64/67 = 96%	63/69 = 91%

Completeness = # detected / # detectable (using CR criteria).
Reliability = # detected (incl. low SNR ones) / # all detections (goal is 99%).

- Analysts were told to be aggressive in Part I and conservative in Part II.

* 9/9 T-HZ planets are in multiple-planet systems.
** 10/17 T-HZ planets are in multiple-planet systems.

Empirical lessons

- High-eccentricity planets are hard to detect.
- Solutions showing high-eccentricity are often erroneous.
  - Can also be valid detections of low SNR edge-on systems.
- A period that is a multiple of another is difficult to extract.
- A long set of RV data is very helpful in solving for orbits with a short set of SIM-Lite data.
- Median errors are very good & astrophysically useful:
  - period 1%
  - mass 3%
  - inclination 4 deg.
  - eccentricity 0.02

Conclusions

- ***Charge:*** Can Earths be detected in multi-planet systems?

- ***Findings:***
  – Yes, with excellent average completeness: 112/124 = 90%
  – Yes, with excellent average reliability: 127/136 = 93%
    - Reliability ~100% for Habitable Zone planets, including terrestrial.
  – Yes, a planet in a multi-planet system is about as detectable as one in a single-planet system.
  – Also: RV data is crucial for identifying long-period planets in a multi-planet system.
  – Also: Cramer-Rao (Fischer-Matrix) error estimates are validated, and should be valuable for mission planning

Related Items of KITP Relevance

- What is the measured RV noise for SIM-Lite target stars?
- Knowing the RV noise, we could study the balance needed between astro & RV observations for an Earth around each nearby star, using the C-R method.
- Larger question: do we want masses and spectroscopic characterization of nearby planets, or will the community be happy with the ~1% of transits, hot Jupiters, and young self-luminous planets?
- Assuming that we will need masses and spectroscopy of nearby planets, what can we say about the zodi brightness, by observation and theory?

Thank you!