Mit dem **Preis der Mathematisch-Naturwissenschaftlichen Klasse für Physik 2020** wurde TRIFON TRIFONOV, Heidelberg, in Anerkennung seiner Arbeiten zu extrasolaren Planeten ausgezeichnet.

Trifon Trifonov

Exoplanetary architectures and stability: Understanding complex transit and extreme precision radial velocity data.

Trifon Trifonov, Träger des Nachwuchspreises für Physik 2020

Extrasolar multiple-planet systems are common in our galaxy. To date, the extrasolar systems with more than one detected planet are about 800 and this number is continuously growing. The observed statistical and physical characteristics of these multi-planet systems are vitally important for understanding the formation history of the Solar System and planetary formation and evolution in general. For instance, discoveries such as pairs of planets in mean-motion resonances have led to major developments in the theory of the formation and dynamical evolution of planets and of the importance of planet-disk interactions (e.g., Kley & Nelson 2012). The orbital architecture and dynamical state of multiple-planet systems are records of the past planet formation and evolution mechanisms.

Despite the remarkable advances in the field of exoplanets, the parameter distribution of known planetary systems is still profoundly affected by the typical (and unavoidable) observational biases imposed by different detection techniques. Fig. 1 shows the distribution of exoplanets for the three most successful detection techniques, namely; the radial velocity (RV, or Doppler), the transit, and the direct imaging method compared to the five most massive planets in the Solar system. From Fig. 1 it is clear that we tend to find more massive and short-period exoplanets, whereas Solar system analogs are still far from our reach, due to insufficient temporal baseline of observations and precision. Therefore, we must rely on the current observational data to fine-tune the applicable planet formation theories in an attempt to understand the formation of the Solar system, and the planet formation mechanisms in general.

However, I am convinced that there are even more biases induced by planetary characterization techniques and data. For example, in the past, strong planetary signals in Doppler data were published based on sparse RV data samples, assuming only one, often eccentric planet in the system. Such discoveries have been around in the literature for years, but follow-up surveys of such planetary systems have only recently shown that collecting more precise RV data often reveals the existence of a second, and in some cases even third, planetary candidate (Kuerster et al. 2015, Trifonov et al. 2017, Wittenmyer et al. 2019, etc.,). Further, biases in characterization techniques, such as multi-Keplerian models that do not account for the planetary dynamics, or inconsistent stability criteria applied to these systems, are hampering the theoretical advance in the field. Important for probing the planet formation are the dynamical properties of the systems, such as the osculating orbital parameters over time, not the Keplerian best-fit parameters for a given epoch, which circulate in the literature. It seems that it has often been neglected that the secular and resonant, osculating orbital parameters of the planets are important for probing planet formation, not their formal best-fit parameters, which are valid only for a given epoch (see e.g., Trifonov et al. 2014, 2019b, 2021a). On top of that, some RV planets have been published without stellar activity analysis. Thus, some planets may not be real at all but are an artifact due to stellar activity, which can mimic a gravitationally induced Doppler signal (e.g., Queloz et al. 2001). In this context, given the increasing significance of the multi-planet systems as a link between theory and observations, it is clear that a comprehensive and homogeneous dynamical characterization of the known (and newly discovered) multi-planet systems is urgently needed.

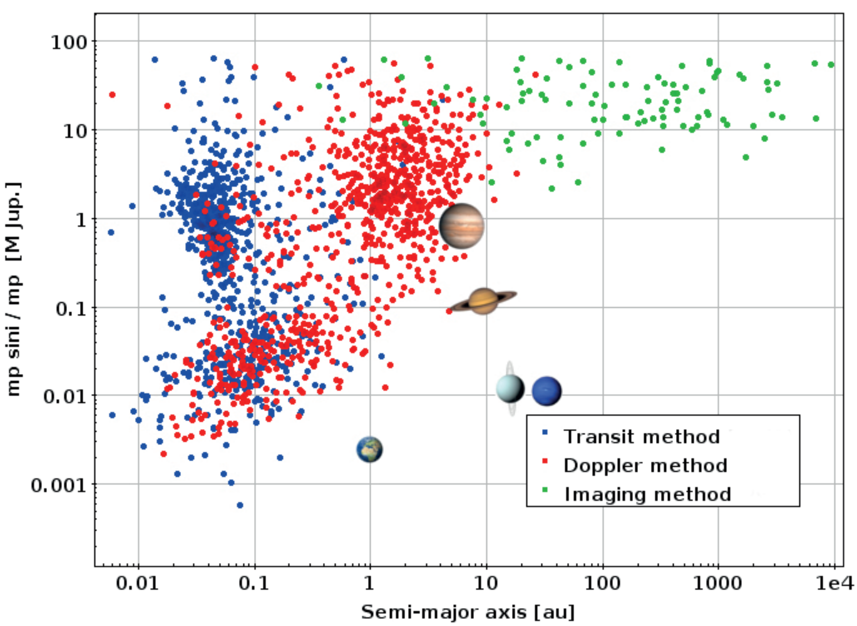

Fig. 1. Mass and semi-major axis distribution of exoplanets as of 2021. Observational biases lead to systems, over-population of massive planets and planets close to their host. A sufficient number of these exoplanet discoveries are likely multiple-planet systems, but so far we do not have the needed precision and temporal baseline to detect Solar-system analogs.

My work focuses to overcome these biases and study planetary formation and evolution by applying *state-of-the-art* numerical techniques. My immediate goal is to perform dynamical modeling of high-precision Doppler and transit photometry data consistent with multiple-planet systems and apply extensive long-term stability analysis in order to reveal the current dynamical architecture. My research aims to reveal the orbital configurations of exoplanet systems, purely by dynamical and stability constraints. Further, I conduct planet migration and planet-planet scattering simulations to probe the formation mechanisms of high-order mean motion resonance (MMR) eccentric multiple-planet systems, and circumprimary planets in close binary systems, which are currently poorly studied. These analyses will reveal the primordial planet-disk conditions needed to assemble the observed planetary architectures.

I led the discovery of many multiple planet systems discovered by precise Doppler survey and transit data. I am part of large survey collaborations which obtain precise RV data with CARMENES, HARPS, and FEROS (Trifonov et al. 2014, 2017, 2020, etc.). The *Transiting Exoplanet Survey Satellite* (*TESS*, Ricker et al. 2015) is another great source of excellent exoplanet data I have worked, and successfully test my multi-planet modeling tools. *TESS* uncovered hundreds of transiting exoplanet candidates around nearby stars, many of them members of multiple-planet systems. I have already gained experience with *TESS*, with the Doppler validation of the transiting planetary systems GJ 143, HD23472, and TOI-2202 (Trifonov et al. 2019, 2021), among many others. For the *TESS* multiple-planet systems, I apply transit timing variation (TTVs) models, and in some cases more sophisticated photo-dynamical models, which take into account the gravitational interaction between the planets directly in the light curves. These superior dynamical models are being applied jointly with the acquired RVs data when possible. The achieved orbital configurations are used a base for more detailed dynamical and long-term stability analyses of resonant and near-resonant chains of transiting planets.

The data modeling and long-term dynamical analyses are performed using the *Exo-Striker* exoplanet toolbox (Trifonov 2019). I am developing this code with the ultimate goal to provide complete and publicly available data modeling software as a service to the exoplanet community. At present, the *Exo-Striker* is the most sophisticated *all-in-one*, open-source software for exoplanet orbital analysis and N-body dynamical stability. Fig. 2 shows a typical view of the Graphical User Interface (GUI) of the tool, yet, only a small part of the fitting and N-body capabilities of the tool. The tool combines *FORTRAN* efficiency and *Python* flexibility, and it can be used either through its user-friendly GUI or as an importable *Python* library useful for automated analysis and data mining. The *Exo-Striker* offers a wide range of numerical tools for RV, transit, and stellar activity data analysis, including power-spectrum period-search analysis, Keplerian and dynamical modeling of multiple-planet systems, MCMC and nested sampling, Gaussian Processes modeling, MMR analysis, and many more.

Fig. 2. GUI screenshot of the Exo-Striker exoplanet toolbox, which provides easy access to orbital analysis, interactive plotting, parameter overview, and statistics. The top panel shows a view of the transit+RV fitting results of the Super-earth discovery of Gl486 b (Trifonov et al. 2021a). The bottom panel shows a view of the N-body part, particularly an eccentricity evolution analysis of a 2:1 MMR two-planet system.

The investigation of the origins of the observed exoplanet systems using well-suited N-body and hydrodynamical simulations is vital. An accurate determination of the dynamical architectures of the multiple-planet systems will allow for reverse-engineering the initial conditions needed for their formation.

For example, systems with planets in mean-motion resonances are an important fossil relic of the planet migration mechanisms. While MMR capture is a probabilistic phenomenon by nature, the type of the resonance and the amplitude of the resonance angles do have a „memory“ of the eccentricity, orbital phase, and migration rate at capture. This helps to reveal the disk-planet interactions during planetary migration, which could shed light on the primordial circumstellar disk properties and disk-planet interactions during planetary migration. Similar, analyses can also be performed also in non-resonant systems, although the initial parameter space is much larger due to the relaxed dynamical constraints.