TEST OF GENERAL RELATIVITY USING LLR DATA AND THE PLANETARY EPHEMERIS PROGRAM (PEP)

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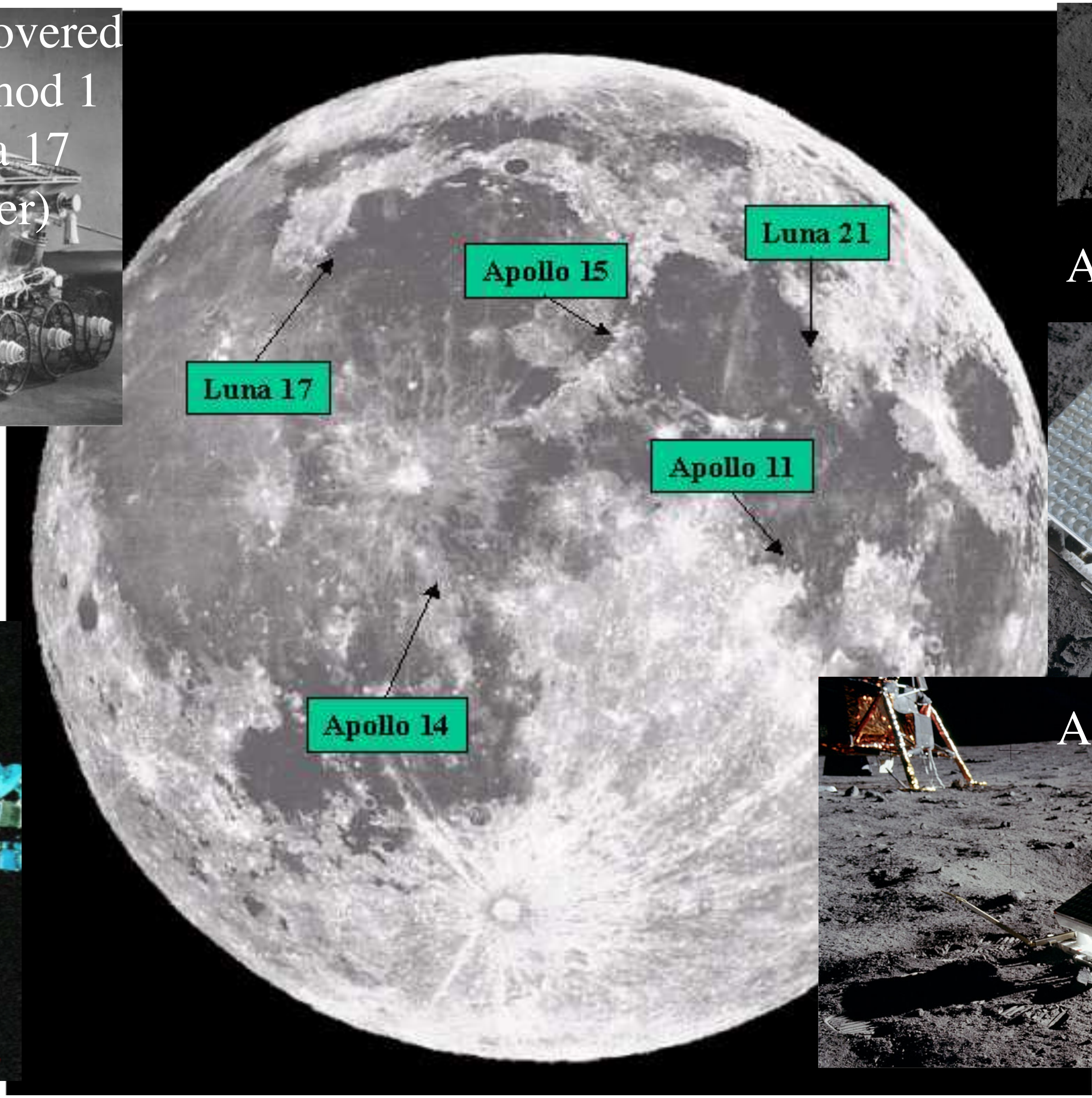
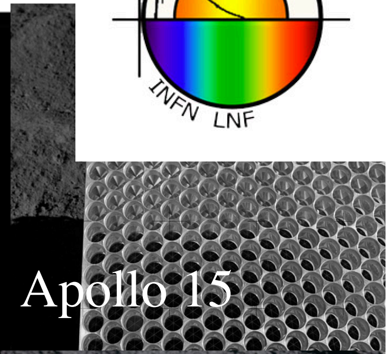
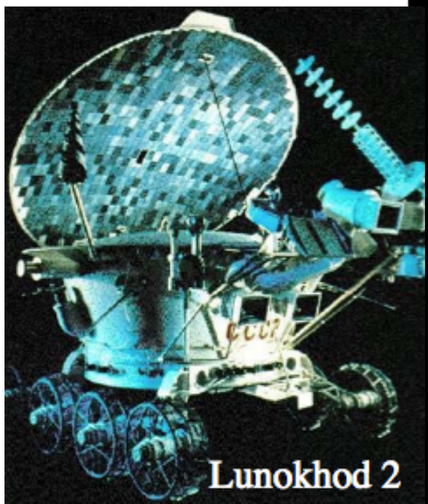
Outline

- Introduction
- Test of General Relativity
- Software package
- Data analysis

CCRs Arrays on the Moon







Current LLR tests of General Relativity

* J. G. Williams, S. G. Turyshev,and D. H. Boggs, PRL 93, 261101 (2004)

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod few cm accuracy*
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert<1.1\times10^{-4}$
Weak Equivalence Principle (WEP)	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$
Strong Equivalence Principle (SEP)	$\lvert\eta\rvert<4.4\times10^{-4}$
Time Variation of the Gravitational Constant	$\lvert\dot{G}/G\rvert<9\times10^{-13}\mathrm{yr}^{-1}$
Inverse Square Law (ISL)	$\lvert\alpha\rvert<3\times10^{-11}$
Geodetic Precession	$\lvert k_{gp}\rvert<6.4\times10^{-3}$

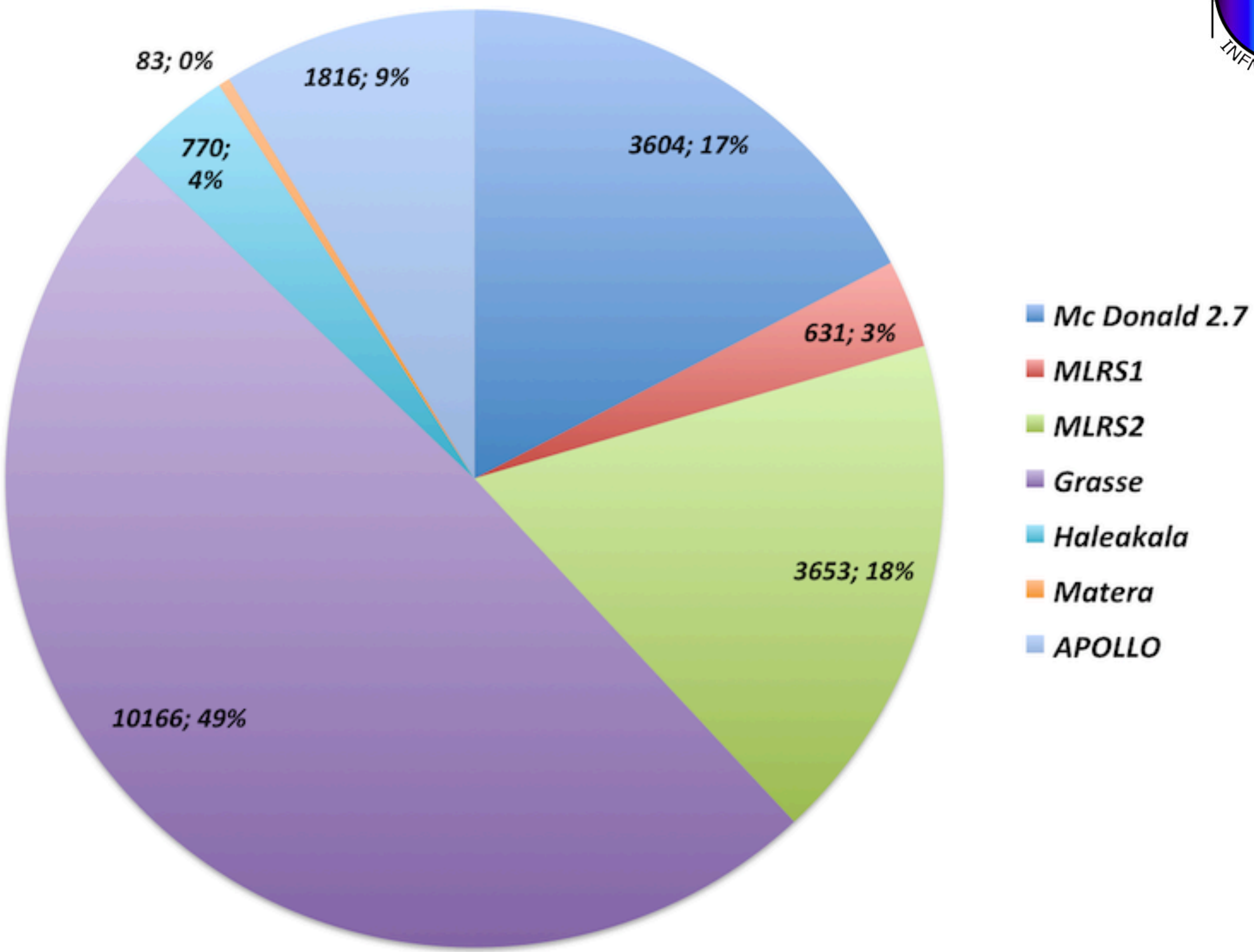
Planetary Ephemeris Program

In order to analyze LLR data we used the PEP software, developed by the CfA, by I. Shapiro et al. starting from 1970s.

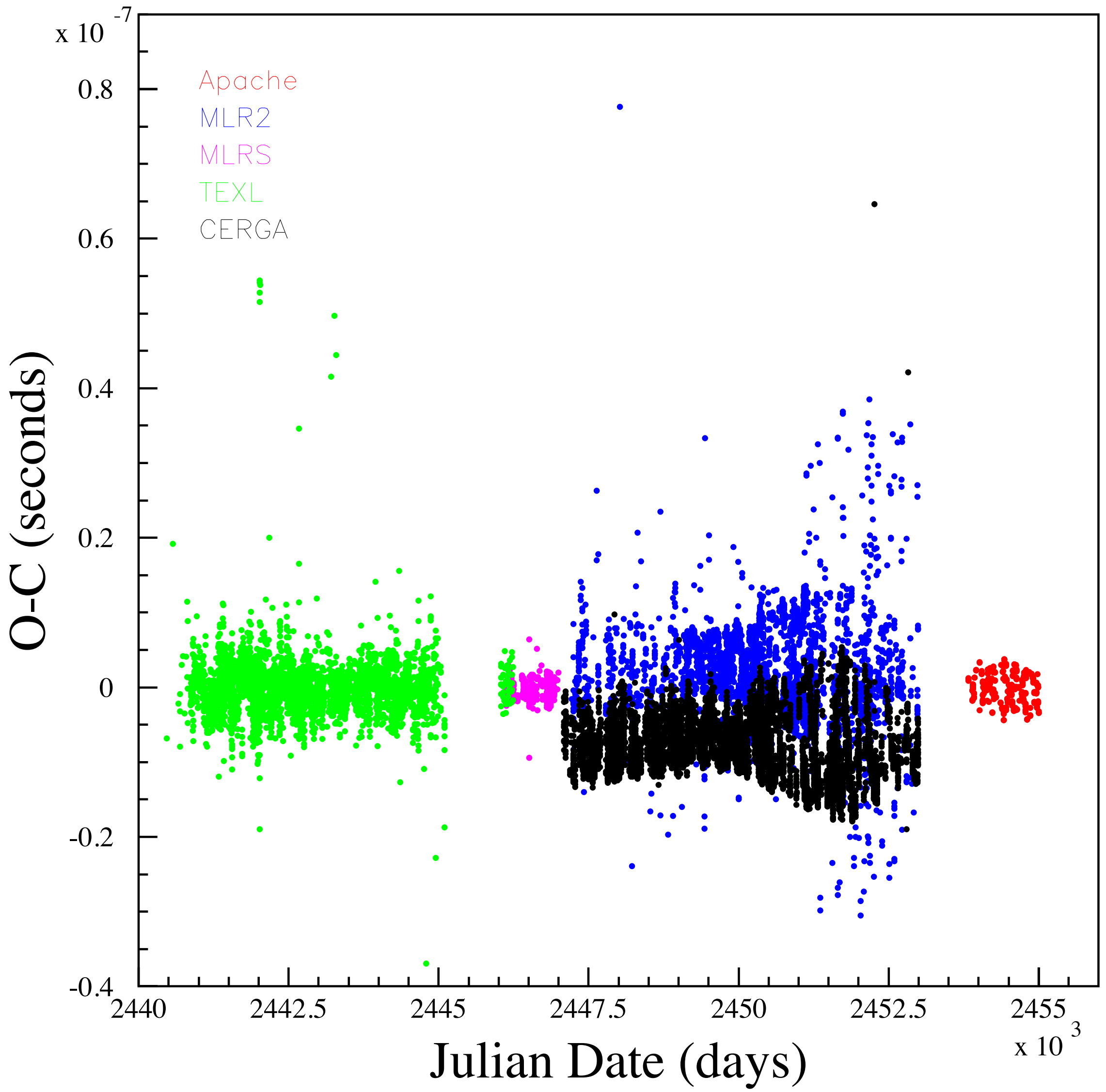
The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for "Computation"), O-C.

"Observed" is round-trip time of flight. "Computed" is modeled by the PEP software.

Data Analysis LLR Normal Points



O-C residual analysis with PEP



Determination of K_{GP}

K_{GP} is the relative deviation from the value of geodetic precession expected in GR

$$K_{GP} = (4.3 \pm 8.6) \times 10^{-3}$$

In this analysis β=γ=1, dG/dt=0. Nominal errors returned by the fit are significantly smaller than the above estimated values of K_{GP}.

Determination of K_{GP}

This preliminary measurement must be compared with the best result published by JPL obtained using a completely different software package

$$K_{GP} = (-1.9 \pm 6.4) \times 10^{-3}$$

Our Goals: accuracy on K_{GP} of few ‰ with current LLR data

≥ x10 improvement possible only with MoonLIGHTs

PEP simulation of physics reach of new CCRs at lunar poles/ limbs/equator

Simulated observations

PEP can make simulated “dummy” observations.

We are simulating new arrays on lunar surface.

We are simulating arrays at the pole of the Moon and we want to see how the PPN parameters change.

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Simulated observations

	2013	2016	2018	2020	2022	2025	2030
Gdot	1,59E-14	7,73E-15	5,43E-15	3,78E-15	2,74E-15	1,72E-15	1,10E-15
KGP	3,38E-04	2,10E-04	1,55E-04	1,15E-04	1,01E-04	7,83E-05	6,27E-05
beta	6,43E-04	4,16E-04	2,73E-04	2,11E-04	1,88E-04	1,49E-04	1,22E-04

ARRAYS:

AP11-AP14-AP15-LN1-LN2
Moon Express 65N 40W
Astrobotic 50S 35E
Israel 45N 27.2E

STATIONS:

APOLLO 3-16 ps
CERGA 7-33 ps
MLRS 7-33 ps
MLRO 7-33 ps

Cadence: 30 days for APOLLO, 20 days for MLRS, 14 days for CERGA, 8 days for MLRO

Simulated observations

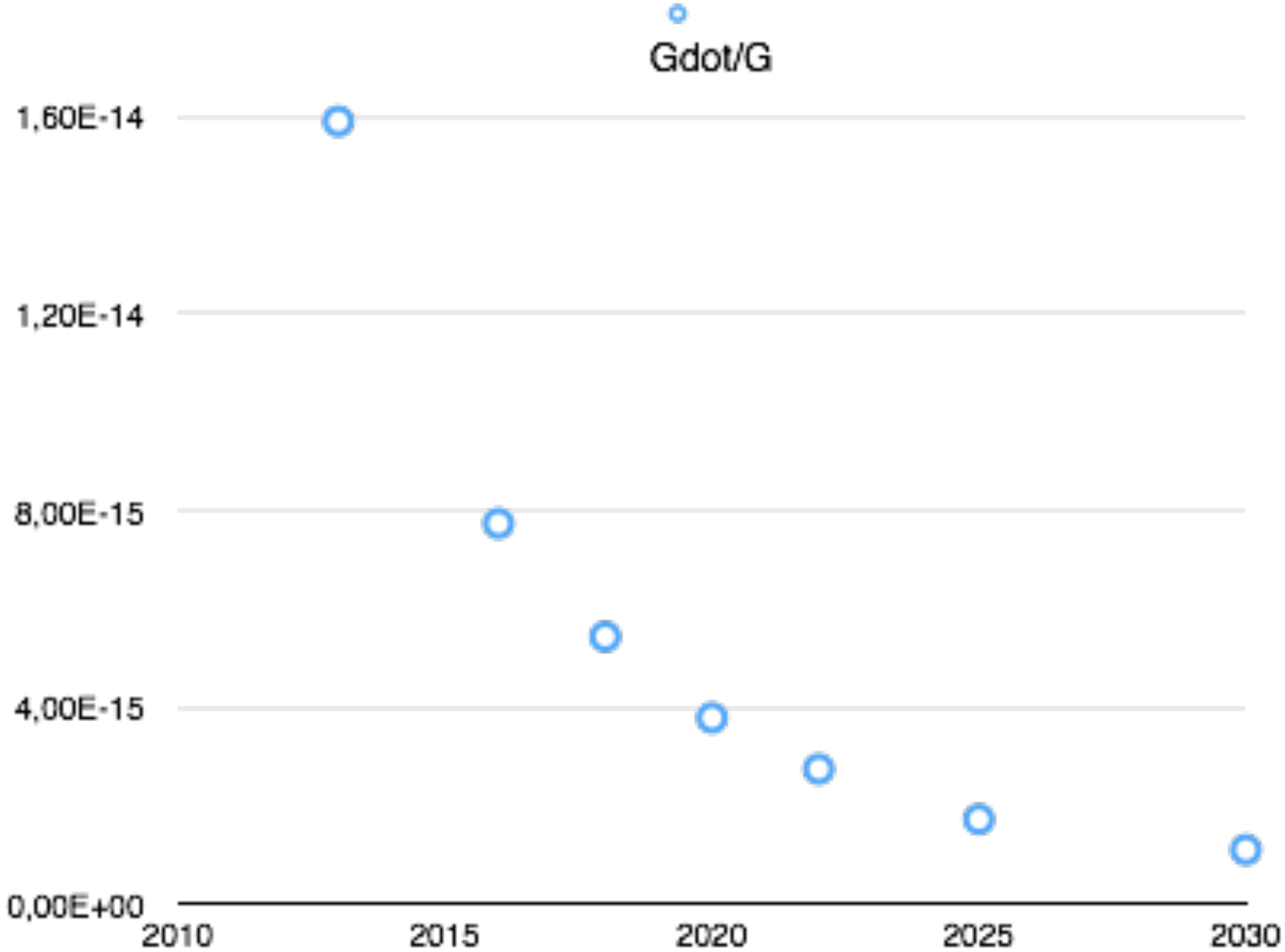
MNEX 65N:

	2013	2016	2018	2020	2022	2025	2030
Gdot/G	1.586E-14	7.731E-15	5.432E-15	3.779E-15	2.744E-15	1.722E-15	1.100E-15
		7.663E-15	5.246E-15	3.593E-15	2.554E-15	1.582E-15	9.927E-16
eta	2.550e-03	1.648e-03	1.093e-03	8.216e-04	7.364e-04	5.882e-04	4.900e-04
		1.536e-03	9.707e-04	7.184e-04	6.264e-04	4.930e-04	4.157e-04
beta	6.425E-04	4.156E-04	2.729E-04	2.113E-04	1.881E-04	1.490E-04	1.223E-04
		3.861E-04	2.417E-04	1.854E-04	1.606E-04	1.255E-04	1.044E-04

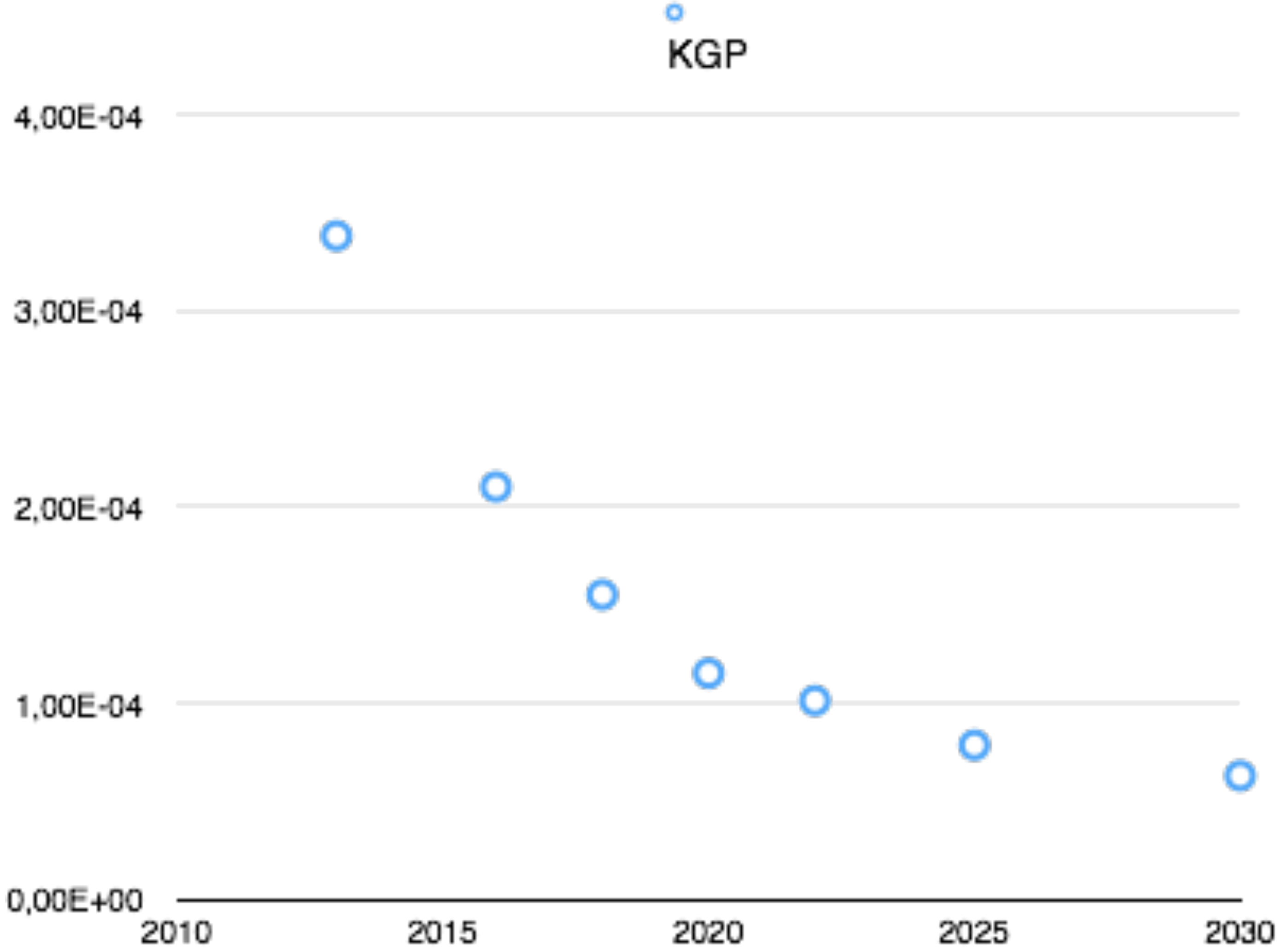
MNEX 87N:

	2013	2016	2018	2020	2022	2025	2030
Gdot/G	1.586E-14	7.813E-15	5.663E-15	4.157E-15	3.283E-15	2.126E-15	1.432E-15
		7.703E-15	5.384E-15	3.711E-15	2.721E-15	1.688E-15	1.061E-15
eta	2.550e-03	1.788e-03	1.269e-03	1.003e-03	9.075e-04	7.211e-04	6.098e-04
		1.561e-03	1.007e-03	7.577e-04	6.655e-04	5.286e-04	4.536e-04
beta	6.425E-04	4.515E-04	3.160E-04	2.572E-04	2.317E-04	1.834E-04	1.532E-04
		3.916E-04	2.495E-04	1.949E-04	1.705E-04	1.349E-04	1.141E-04

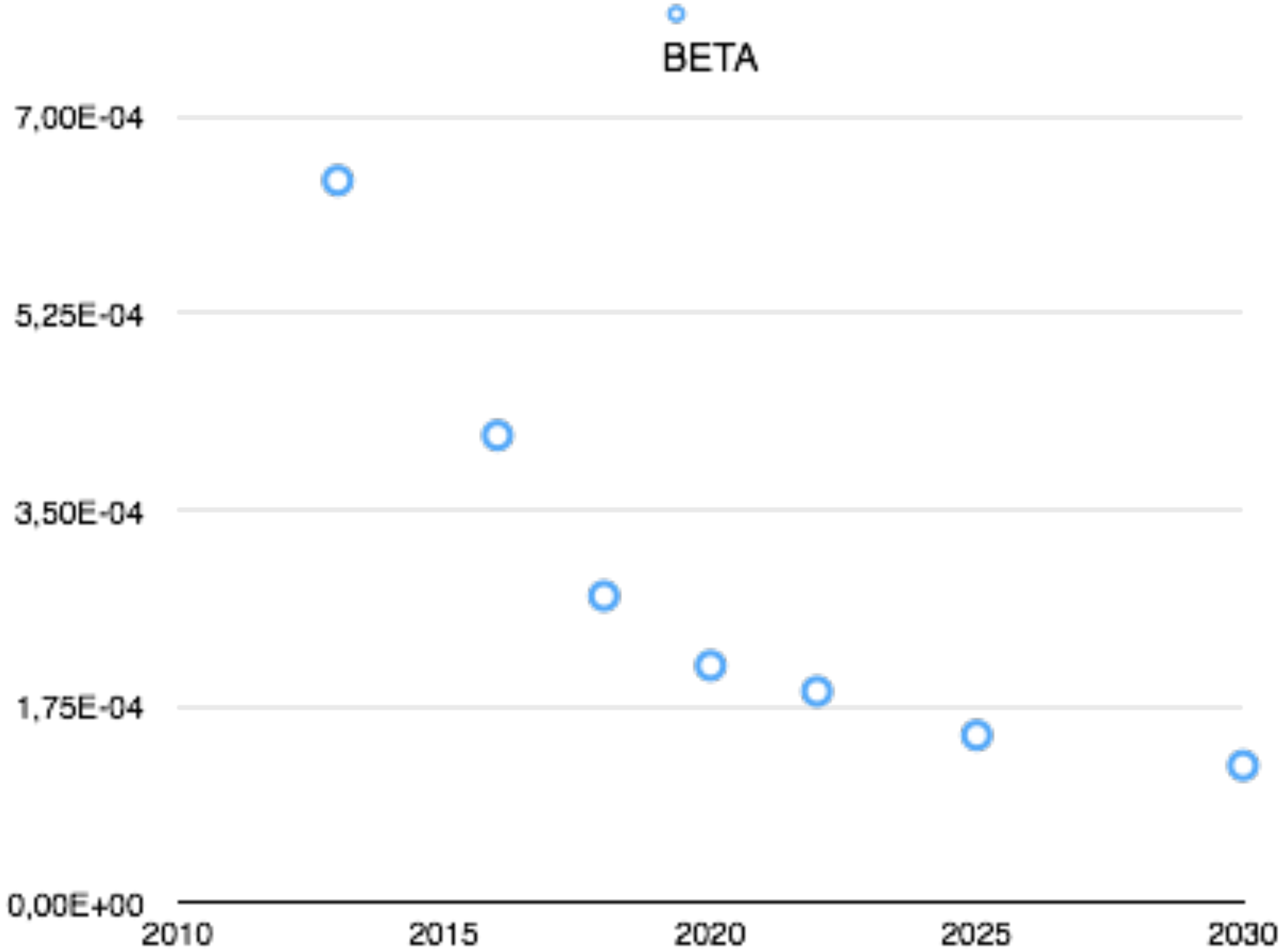
Simulated observations



Simulated observations

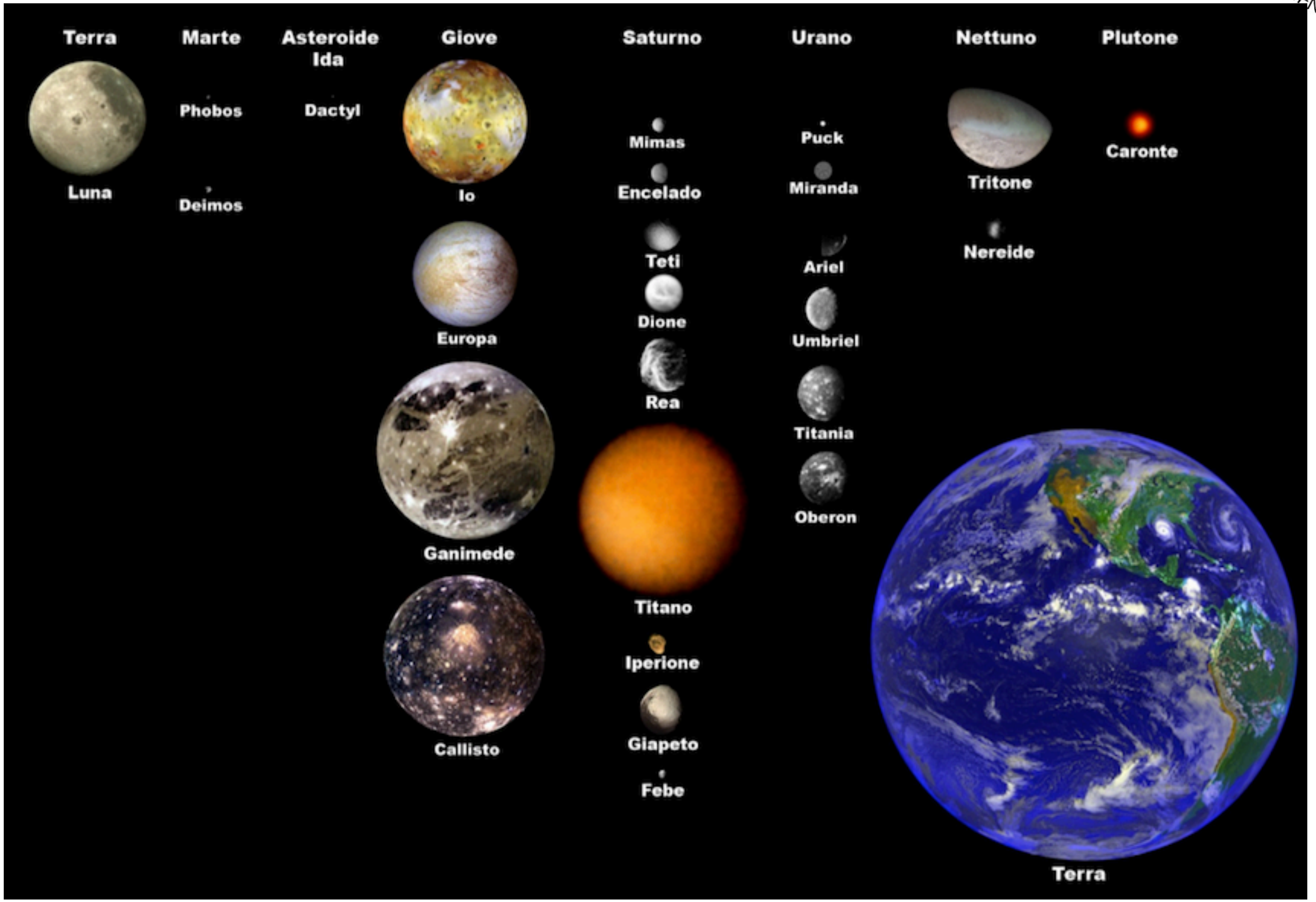


Simulated observations



Other Solar System applications

See talk by S. Dell'Agnello



Conclusion

- Deepen our knowledge about data and software in order to better estimate (and reduce) the measurement uncertainty on K_{GP} and on other GR parameters.
- Improve the precision of these kind of General Relativity measurements by using not only LLR data, but also SLR data to Earth satellites and primarily to LAGEOS.
- We have the option to implement the equations of motion of new gravity theories (like SPACE-TIME TORSION and NON-MINIMALLY COUPLED GRAVITY – see talk by S. Dell'Agnello) inside PEP and study not only the secular variation of the geodetic precession , but also periodic signatures of NEW PHYSICS on the geodetic precession and on other PPN parameters

THANK YOU
FOR YOUR ATTENTION

ANY COMMENTS/QUESTIONS?