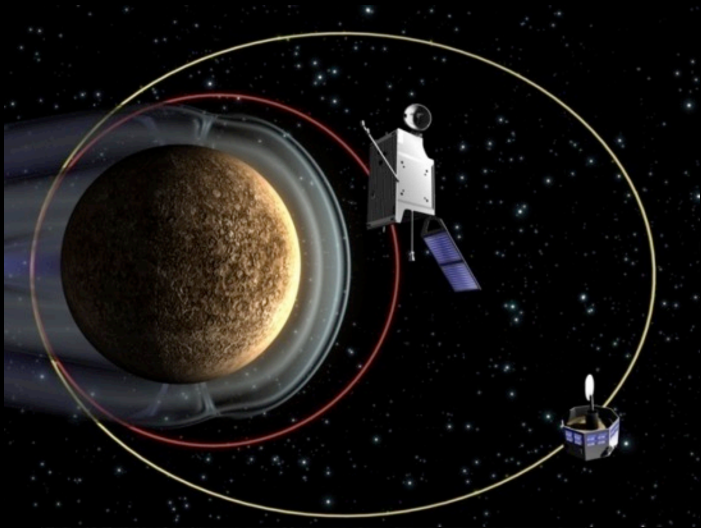

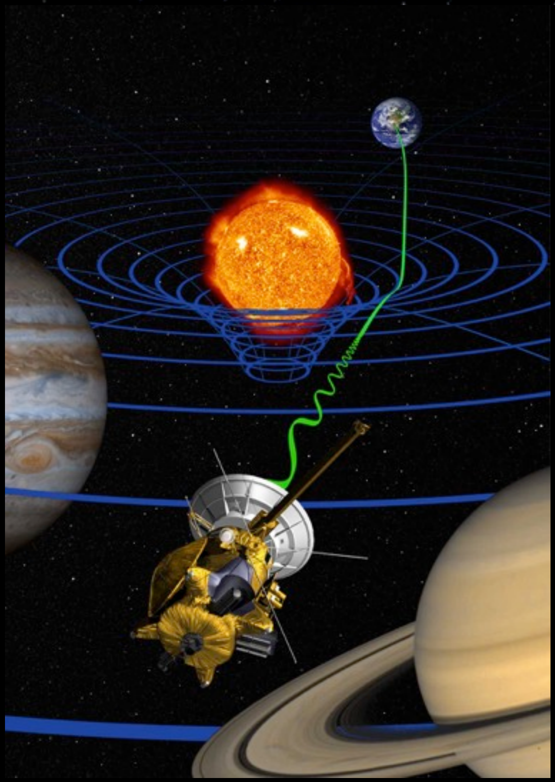

Measuring PPN parameters with space radio links

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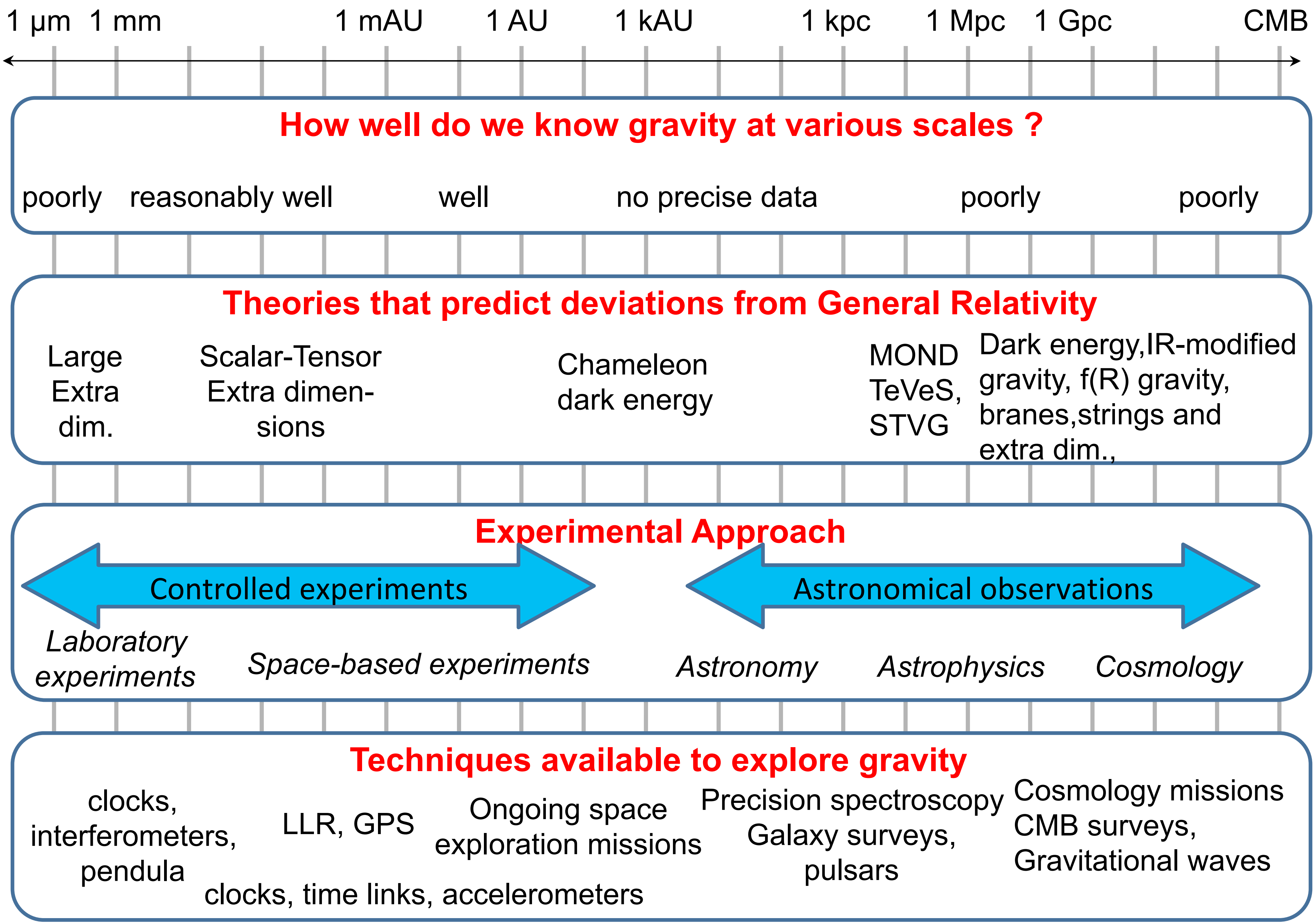
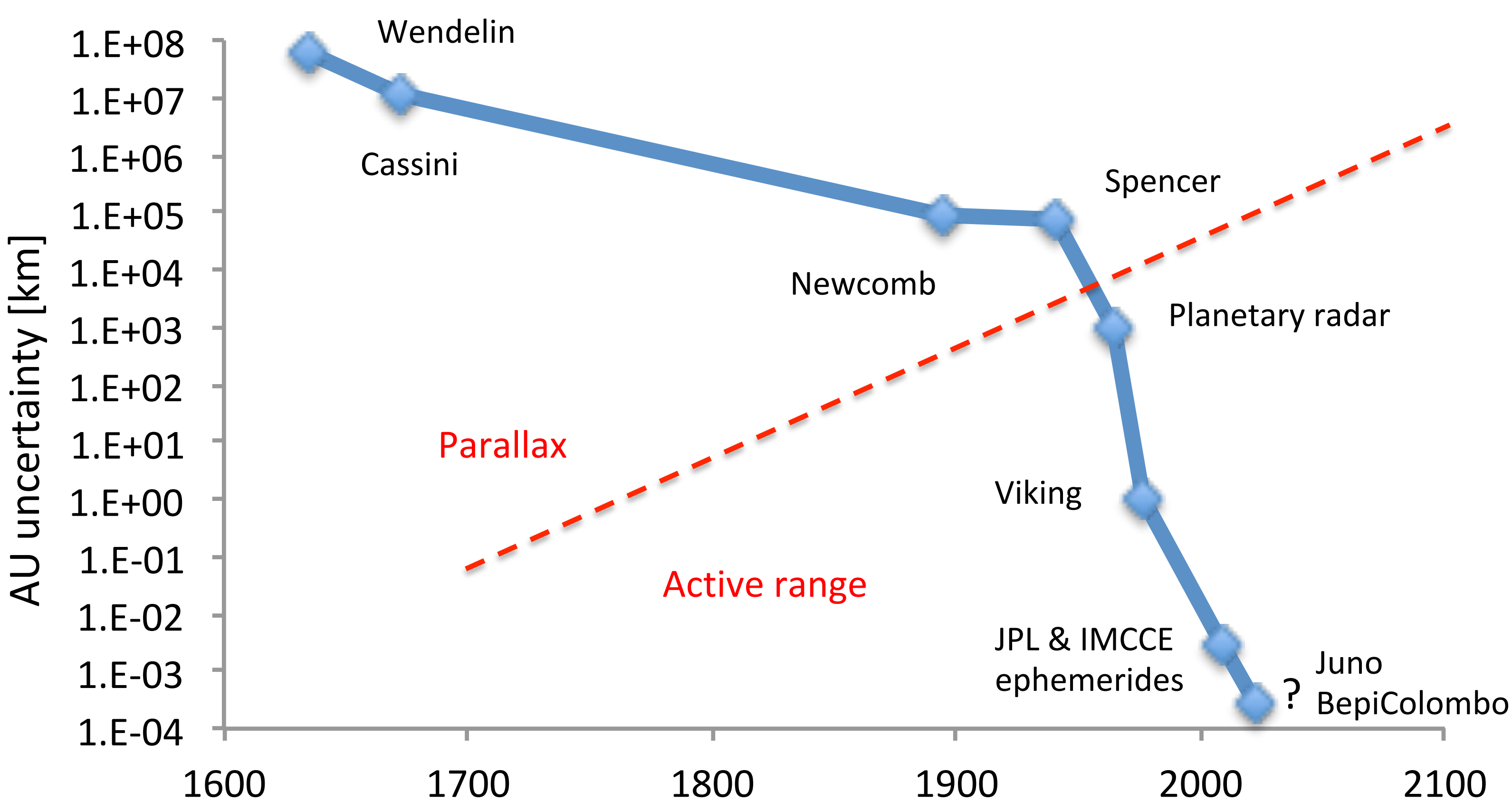
EPS Conference on Gravitation - 2019

ESA Fundamental Physics Roadmap – http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=44552



The yardstick of the solar system (149597870700 m since 2012)



Observables used in deep space navigation and solar system tests of GR

Range (light travel time)

Phase comparison of modulation tones or codes in coherent radio links

Current accuracies (2-way):
0.5-2 m (incl. station bias)
0.02 m (BepiColombo Ka-band / multilink radio systems with wideband code modulation and delay calibration)

VLBI (angles)

Time delay at two widely separated ground antennas

Current accuracies:
≈0.5-1 nrad (ΔDOR)

(0.2-0.4 ns – further improvements limited by quasar position error)

Range rate (velocity)

Phase comparison (carrier) in coherent radio links

Best accuracy attained (2-way, Cassini):
$1.5\ 10^{-6}$ m/s @1000 s (Ka-band /multilink radio systems)

Measurement of γ

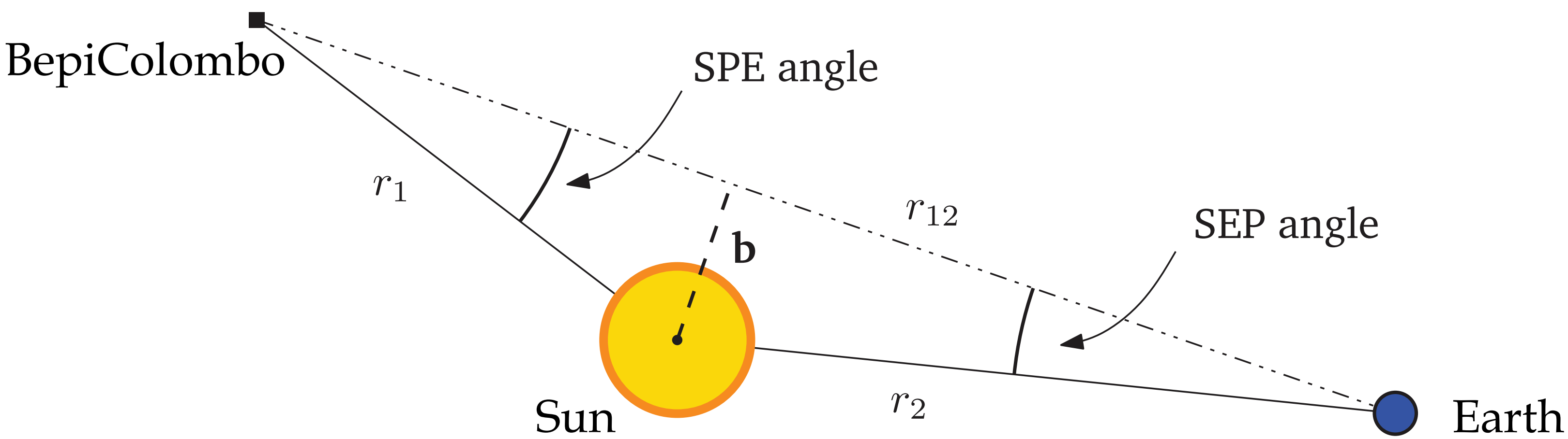
- In GR, $\gamma = 1$
- Shapiro time delay

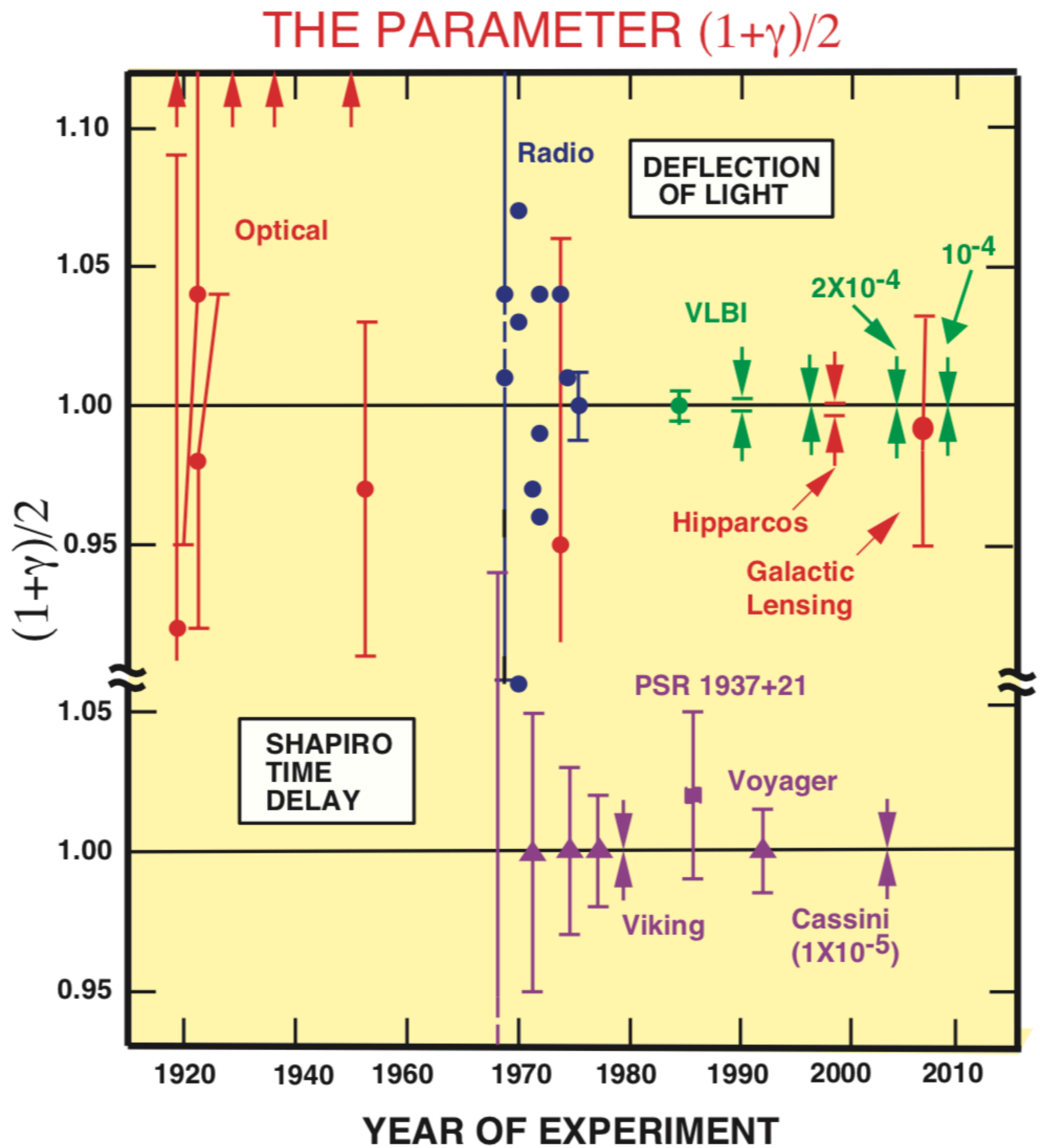
$$\Delta t = (1+\gamma)\frac{GM_{Sun}}{c^3}\ln\left(\frac{r_1+r_2+r_{12}}{r_1+r_2-r_{12}}\right) \approx (1+\gamma)\frac{GM_{Sun}}{c^3}\ln\left(\frac{4r_1r_2}{b^2}\right)$$

- Doppler shift

$$\frac{\Delta\nu}{\nu} = \frac{d\Delta t}{dt} \cong -2(1+\gamma)\frac{GM_{Sun}}{c^3}\frac{1}{b}\frac{db}{dt}$$

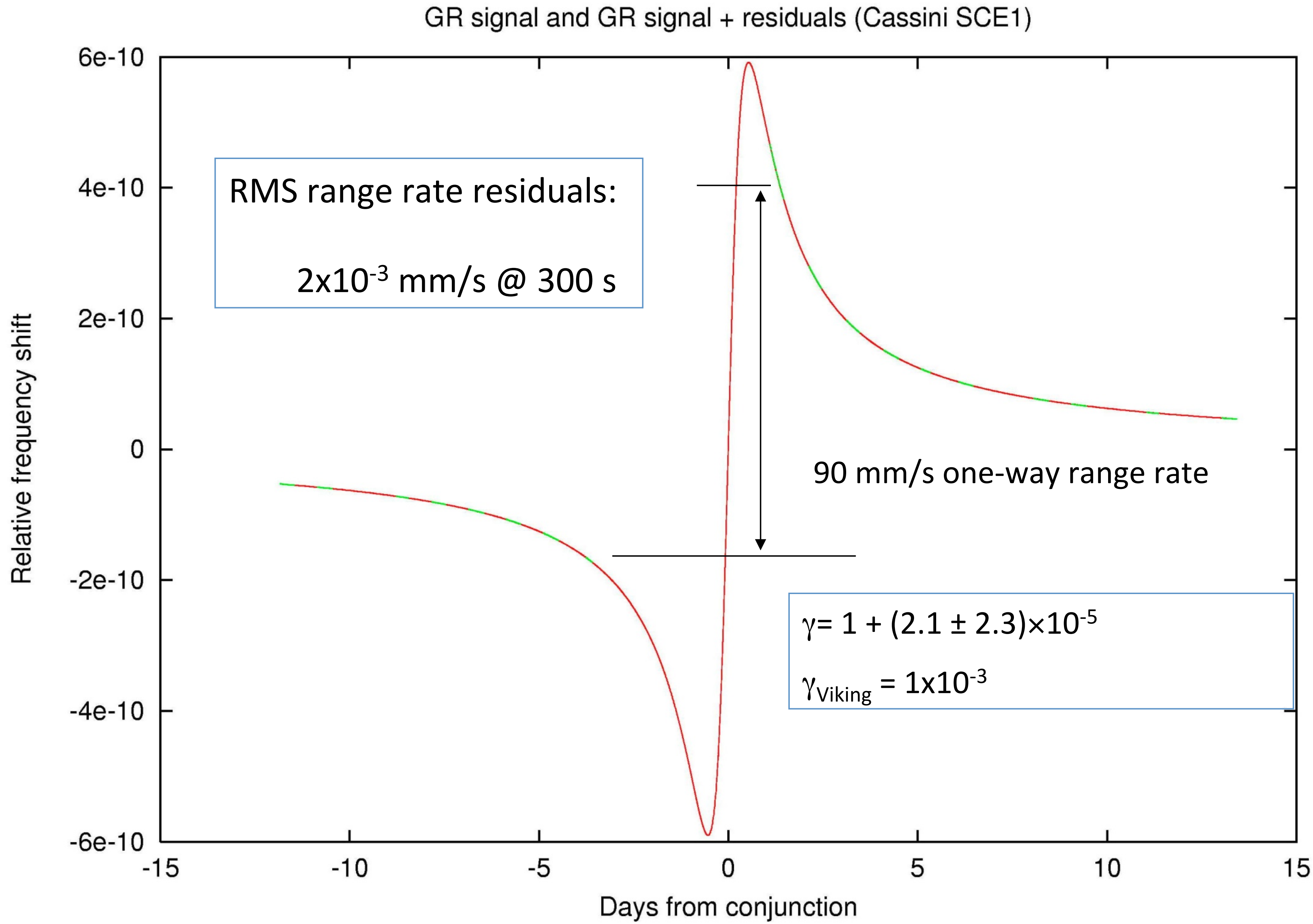
Ideal SSC:
- Large *db/dt*
- Small *b*

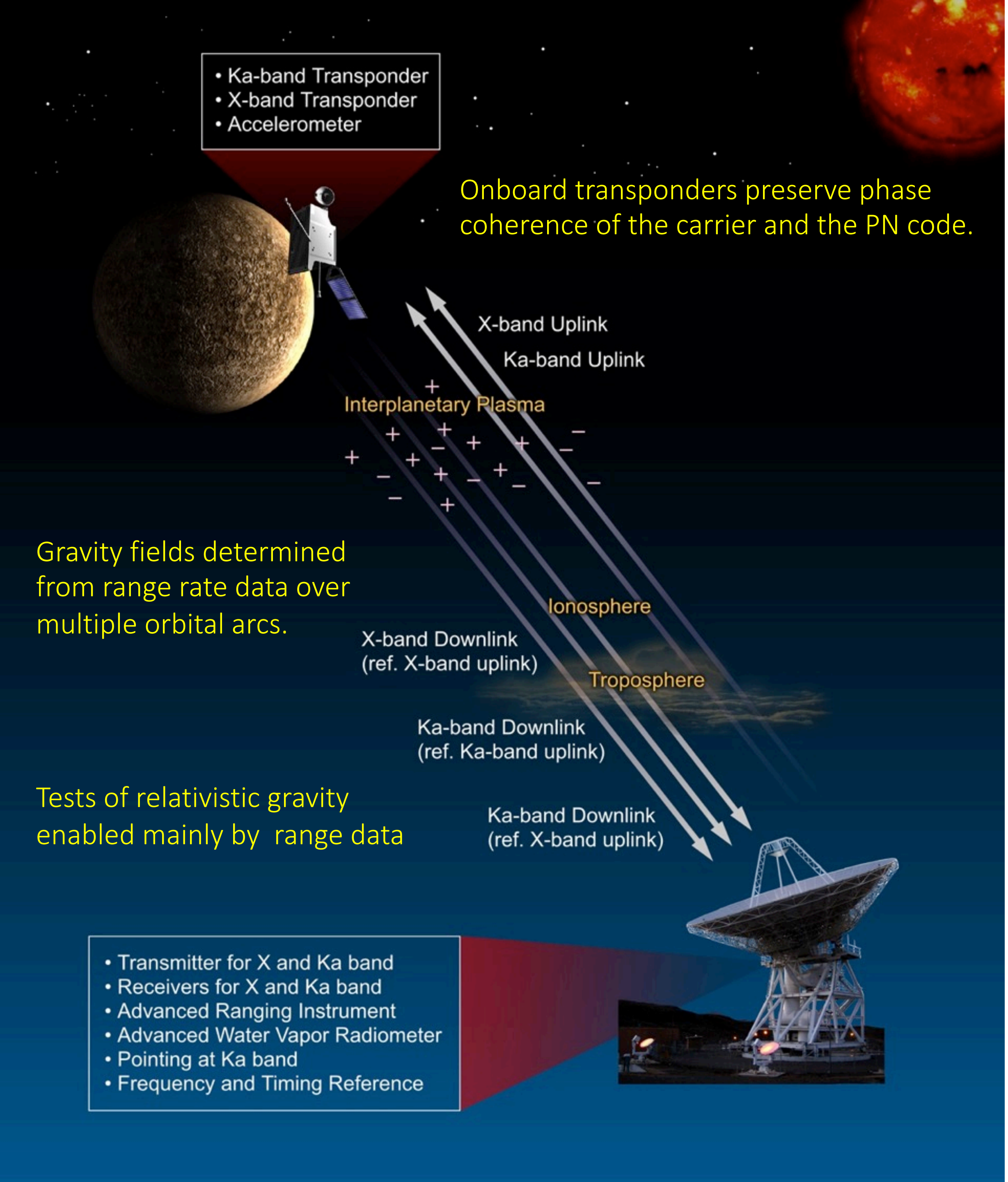




From:

Clifford M. Will,
“The Confrontation between General Relativity and Experiment”,
Living Rev. Relativity, 17, (2014), 4.
http://www.livingreviews.org/lrr-2014-4


GR signal and GR signal + residuals (Cassini SCE1)
RMS range rate residuals:
2x10^-3 mm/s @ 300 s
90 mm/s one-way range rate
γ= 1 + (2.1 ± 2.3)×10^-5
γViking = 1x10^-3
Relative frequency shift
Days from conjunction
6e-10
4e-10
2e-10
0
-2e-10
-4e-10
-6e-10
-15
-10
-5
0
5
10
15



MORE: Mercury Orbiter Radioscience Experiment

- Multifrequency link for plasma noise suppression
- Advanced water vapor radiometer for wet tropo calibrations
- Pseudo-noise, wideband ranging (24 Mcps)

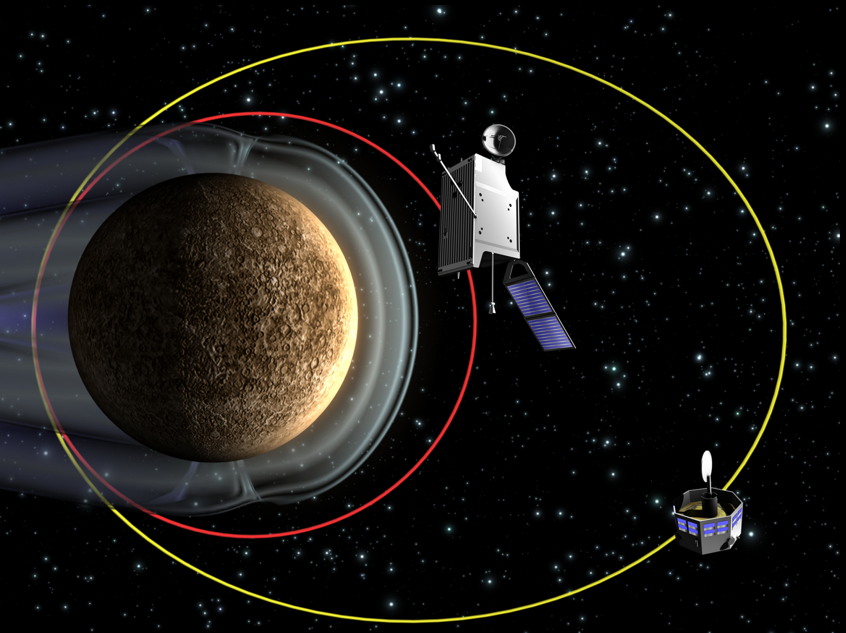
End-to-end accuracy (2-way):

$\Delta f/f$ **= < 10^{-14} @ 10^3-10^4 s**

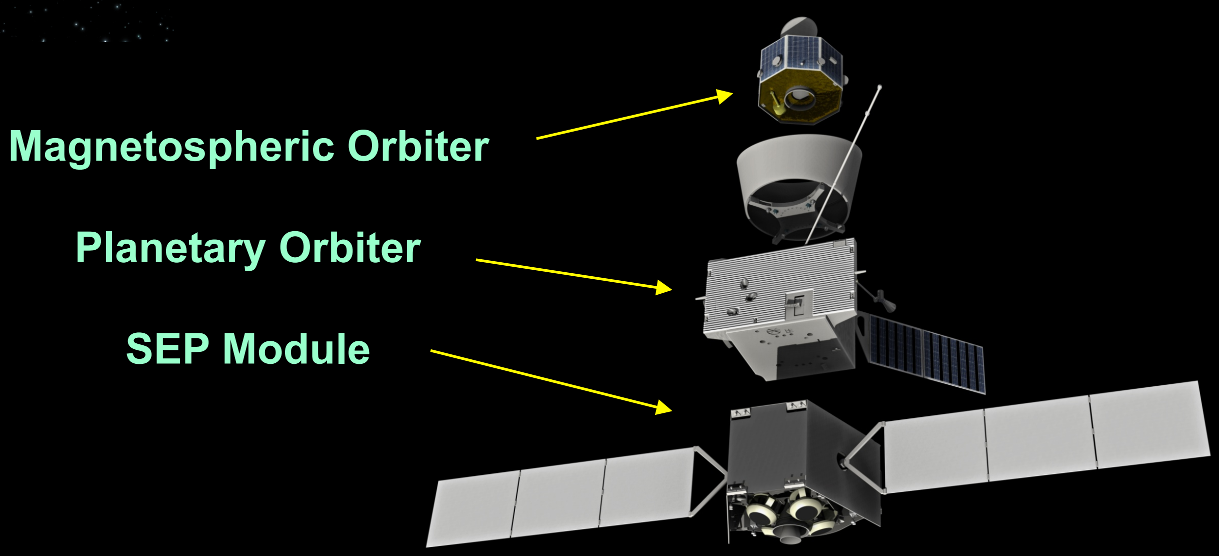
$d\rho/dt$ **= < 3 $\mu m/s$ @ 10^3-10^4 s**

$\delta\rho$ **= 20 cm @ 5-10 s**
2-3 cm over 8 h

BepiColombo: ESA's mission to Mercury



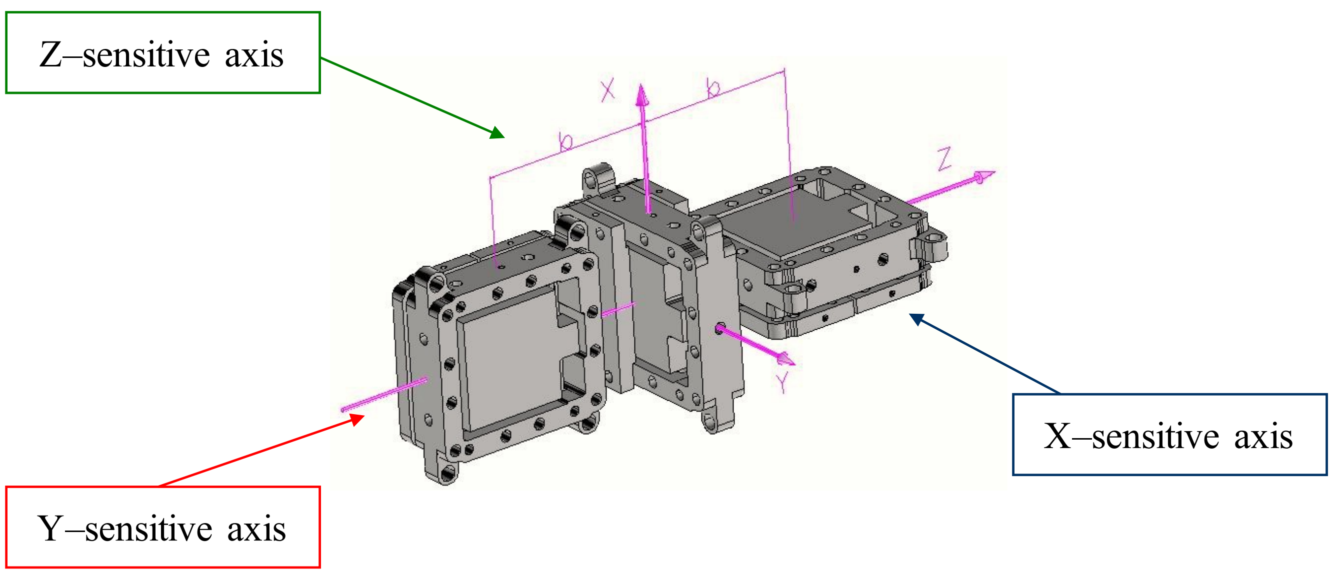
Launch: Ariane 5 (20 Oct. 2018)
Solar Electric Propulsion
Arrival at Mercury: Dec. 2025
MPO orbit altitude: 400x1500 km



The Italian Spring Accelerometer

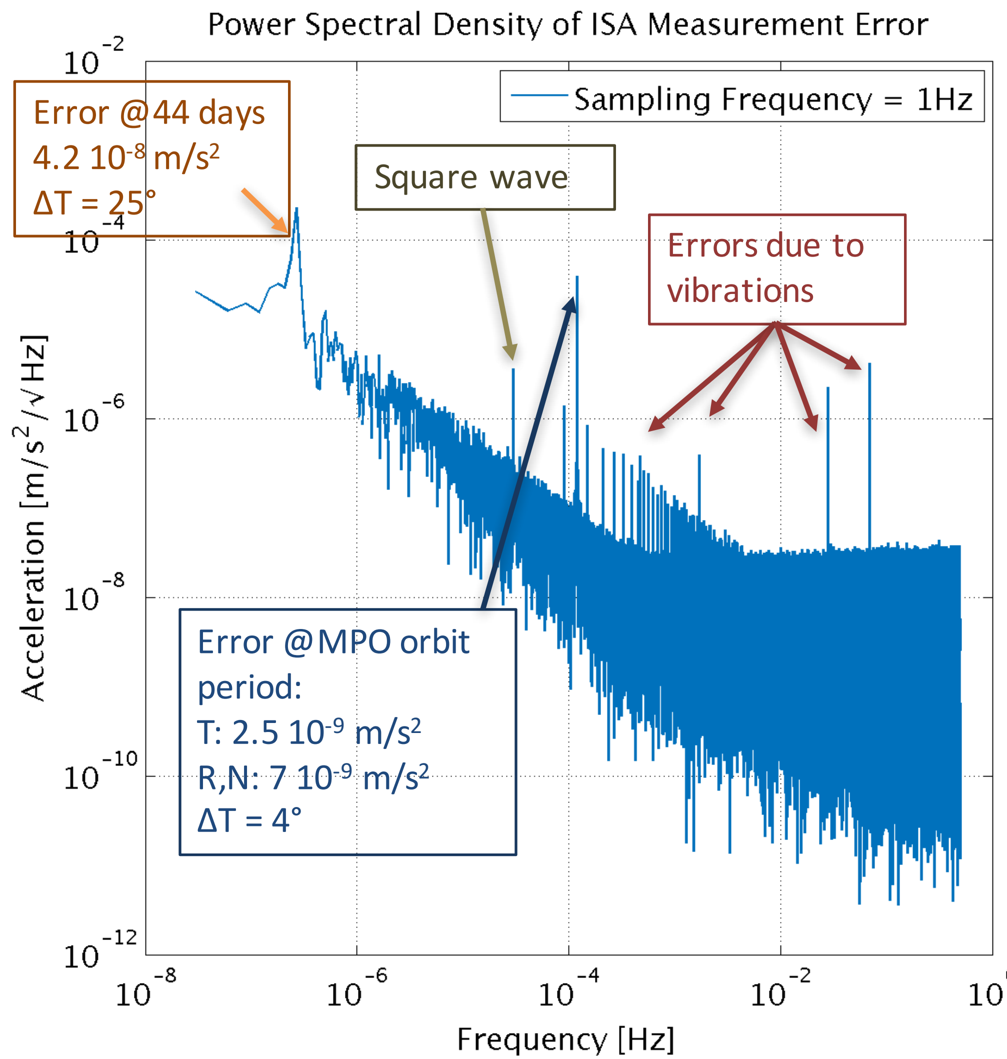
Italian Spring Accelerometer (PI V. Iafolla, IAPS-INAF)

- Non-gravitational perturbations: direct solar radiation pressure, albedo radiation pressure, Mercury IR emission, thermal thrusts due to anisotropic IR spacecraft emission, gas leaks, etc.)
- NGA are large in the Hermean environment. Modelling errors lead to incorrect parameter estimation.
- Acceleration due to solar radiation pressure ≈ 10^{-6} m/s^2.



The Italian Spring Accelerometer

- Scale (transduction) factor error $\pm 10^{-2}$
- ISA random error: 10^{-8} m/s^2/Hz$^{1/2}$
- ISA systematic error:
  - Square Wave due to thermal disturbance from adjacent units
  - 4 sinusoids due to S/C vibrations in the measurement bandwidth (wheels, appendages, etc)
  - Error at MPO period
  - Error at half of Mercury period (flip-over maneuver)
- FIR filtering to reduce the high frequency noise
- Measurement bandwidth:
  - 10^{-4} – 10^{-1} Hz



Relativity experiment

MORE can determine the orbit of Mercury and Earth, using a fully relativistic dynamical model.

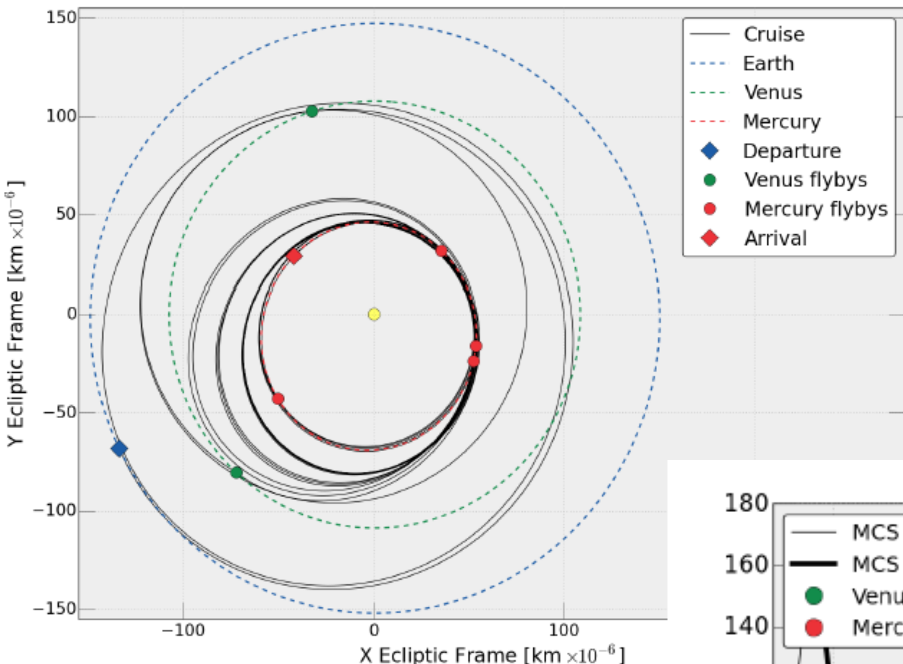
PPN parameters currently considered:

- **β**: related to non-linear 3-body general relativistic interaction (β=1 in GR).
- **γ**: parameterizes the velocity-dependent modification of the 2-body interaction and measures the space curvature produced by a unit mass (γ=1 in GR).
- **η**: measures the contribution of the gravitational self-energy to the violation of SEP (η=0 in GR).
- **α_1, α_2**: describe the preferred frame effects ($\alpha_1=\alpha_2=0$ in GR).

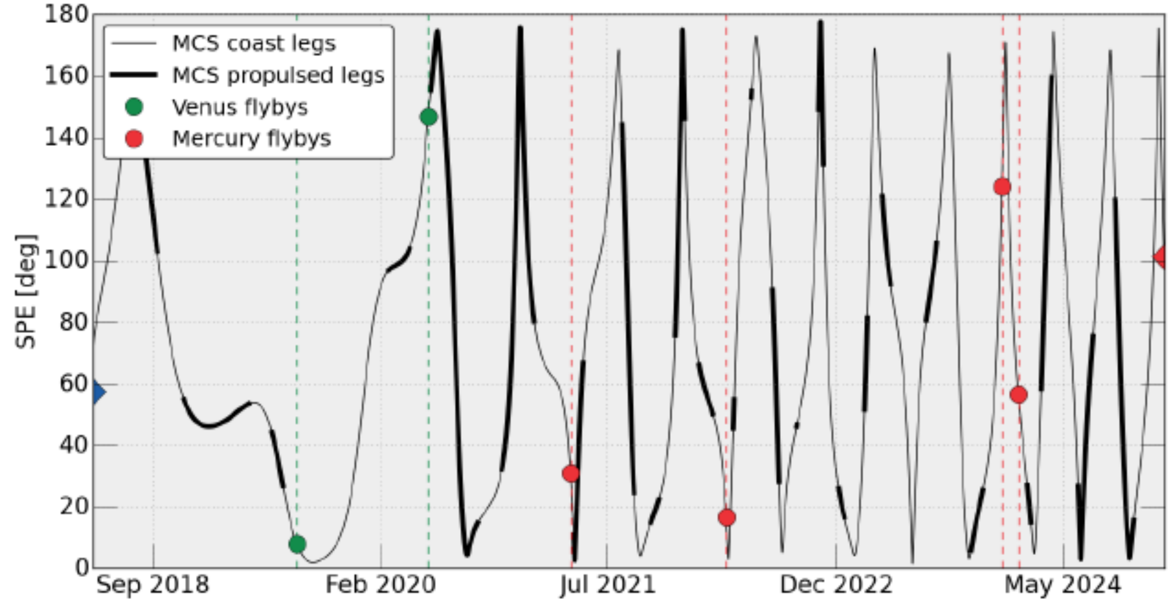
The addition parameters affecting the planetary orbits are:

- **μ_{Sun}**: gravitational parameter of the Sun.
- ς: time derivative of μ_{Sun}, from variations in M_{Sun} and G.
- **J_{2Sun}**: solar quadrupole coefficient.
- Test of $1/r^2$ - Graviton mass upper limits

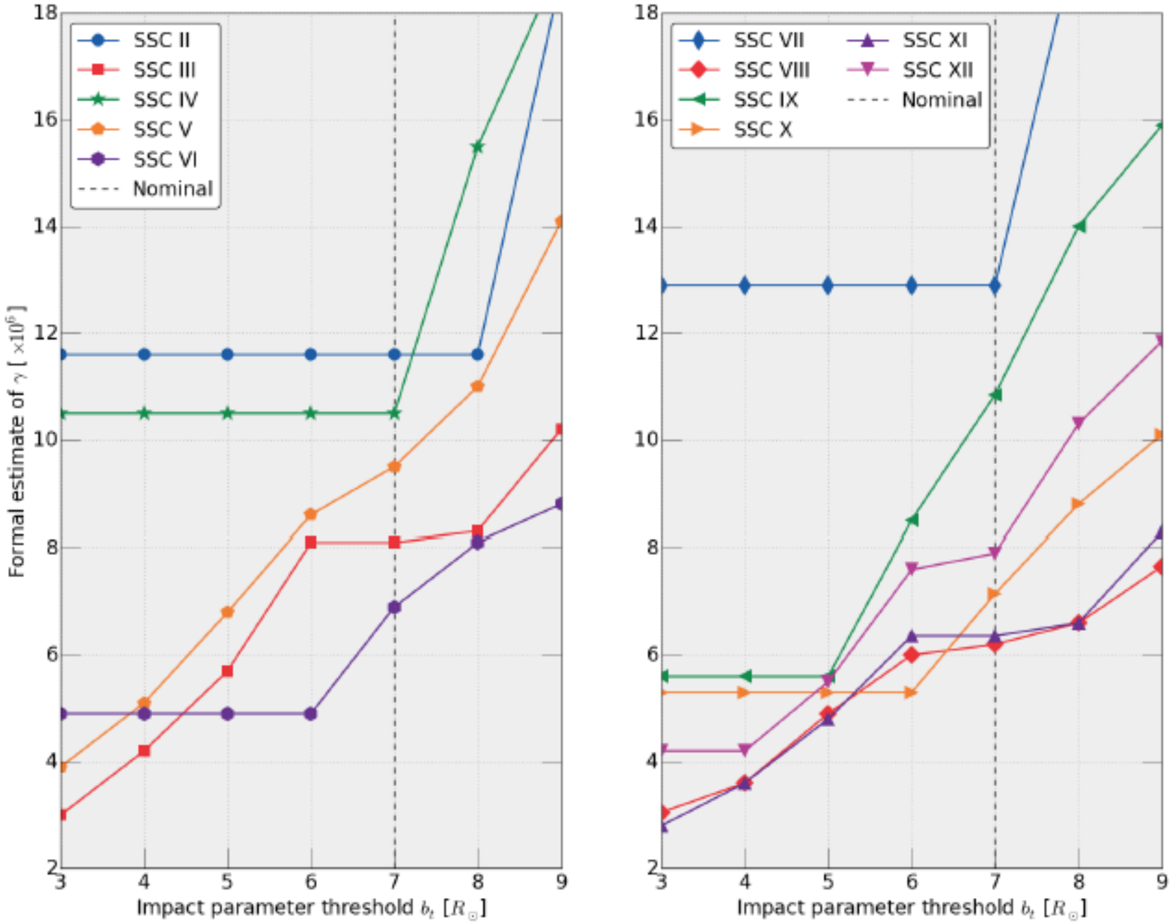
Measuring γ in cruise



SSC	Date	b_{min} [$R_\odot$]	db/dt_{max} [$R_\odot$/day]
#1	31 Aug 2019	5.72	0.01
#2	15 Aug 2020	8.31	1.70
#3	17 Apr 2021	3.04	3.84
#4	14 Sep 2021	7.71	1.36
#5	02 Apr 2022	3.78	3.45
#6	01 Aug 2022	6.65	3.32
#7	13 Jan 2023	7.91	1.09
#8	25 May 2023	1.71	3.99
#9	01 Oct 2023	5.52	1.55
#10	26 Feb 2024	6.75	2.37
#11	11 Jun 2024	3.38	3.57
#12	30 Sep 2024	4.99	1.97



(Imperi & Iess, 2017)



Accuracy as a function of minimum impact parameter

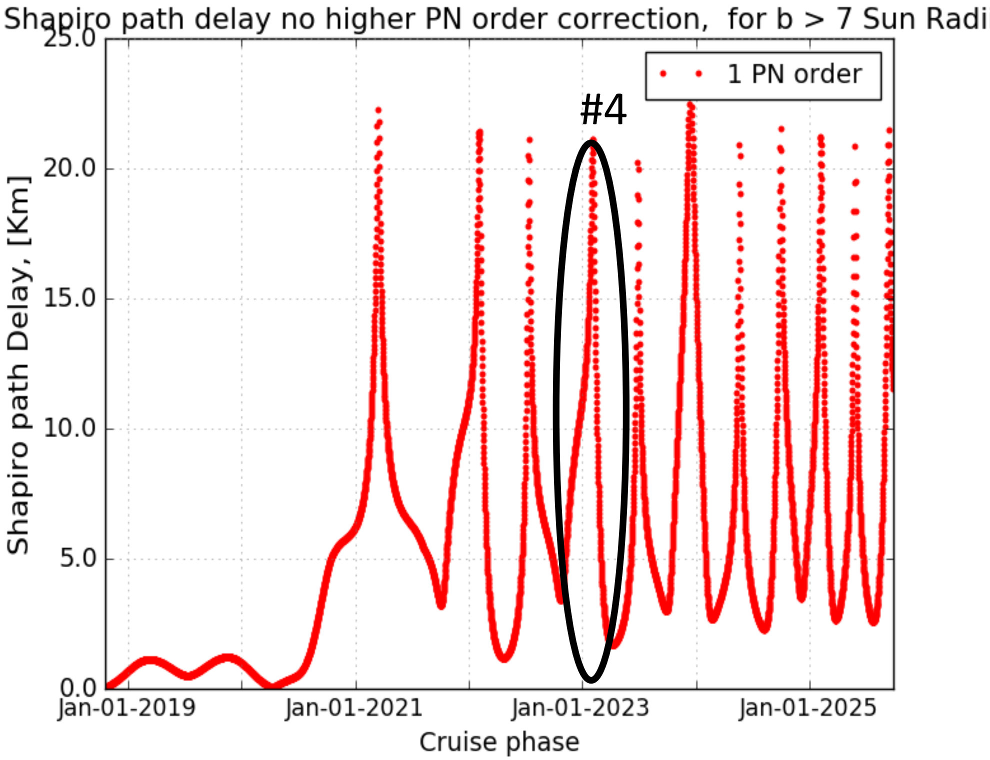
	#8 + #11	Thrust-free	All
Nominal tracking + $b_t = 7R_\odot$	4.4	3.3	2.5
h24 tracking + $b_t = 7R_\odot$	3.2	2.4	1.8
h24 tracking + $b_t = 5R_\odot$	2.4	1.8	1.3

Expected accuracies for different combinations of conjunctions and observation scenarios.

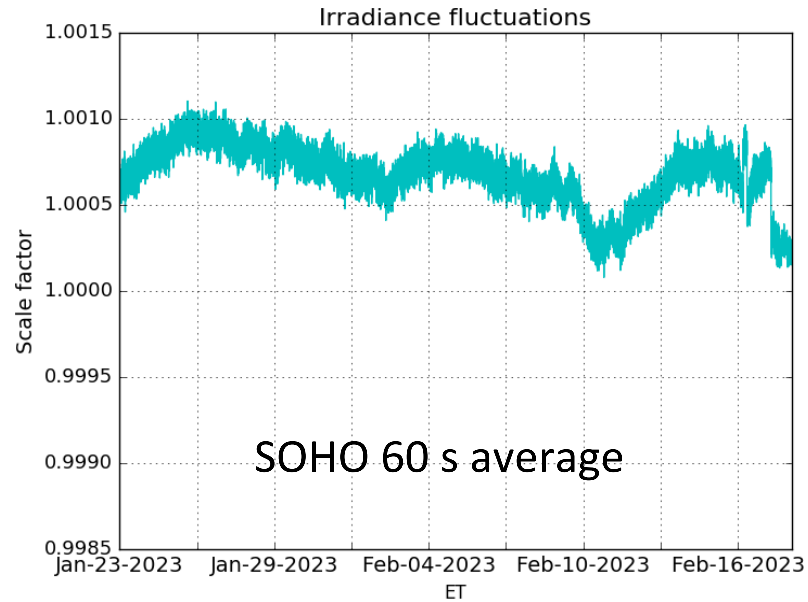
(Imperi & Iess, 2016)

Variations of solar irradiance during cruise tests

Solar Conjunction #4 – σ_γ=8.1x10^{-6}

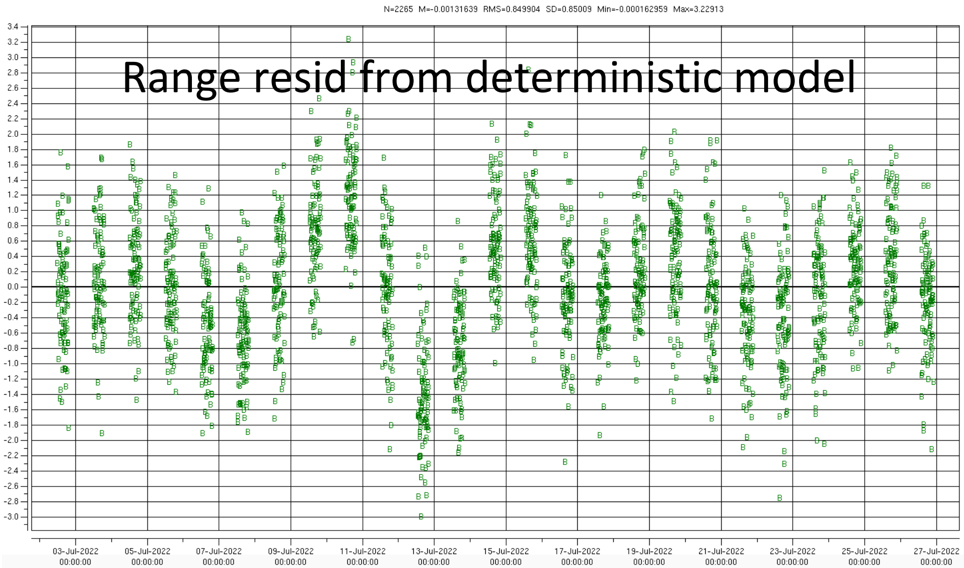


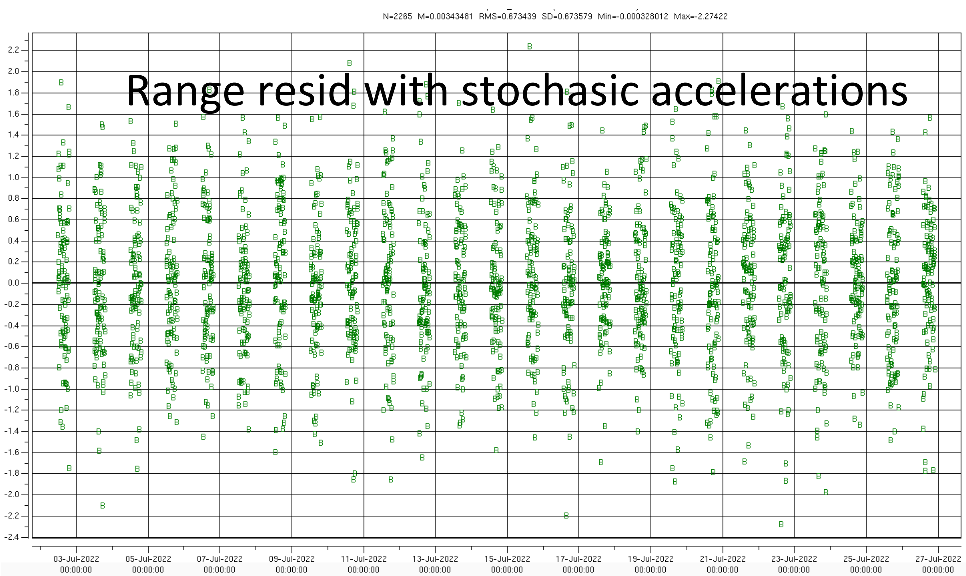
Acceleration due to SRP = 1.8x10^{-7} m/s^2
Fluctuations → 9x10^{-11} m/s^2

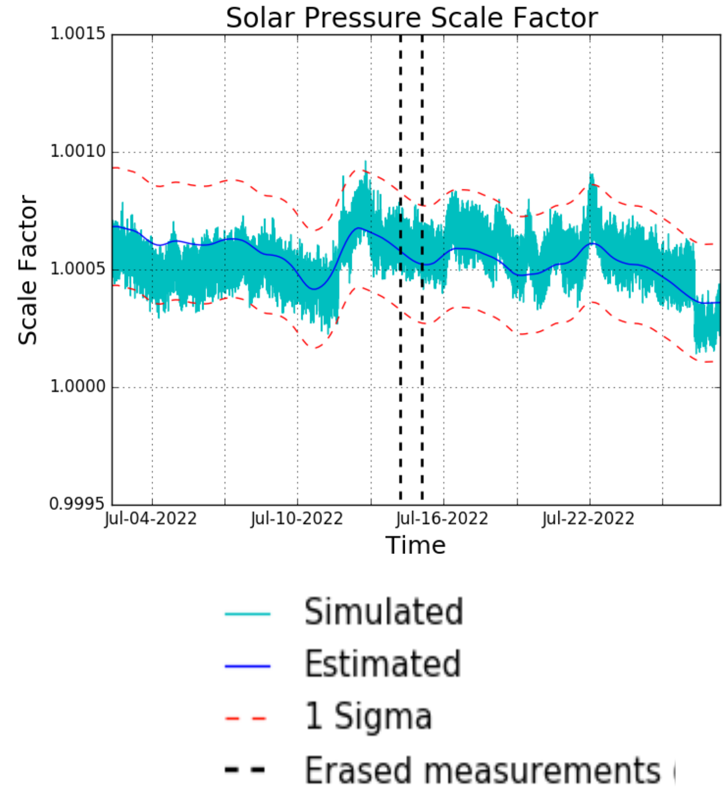


- Solar irradiance fluctuates by 0.01-0.1% over time scales of hours
- Mitigate the adverse effect by using stochastic dynamical model

Stochastic models







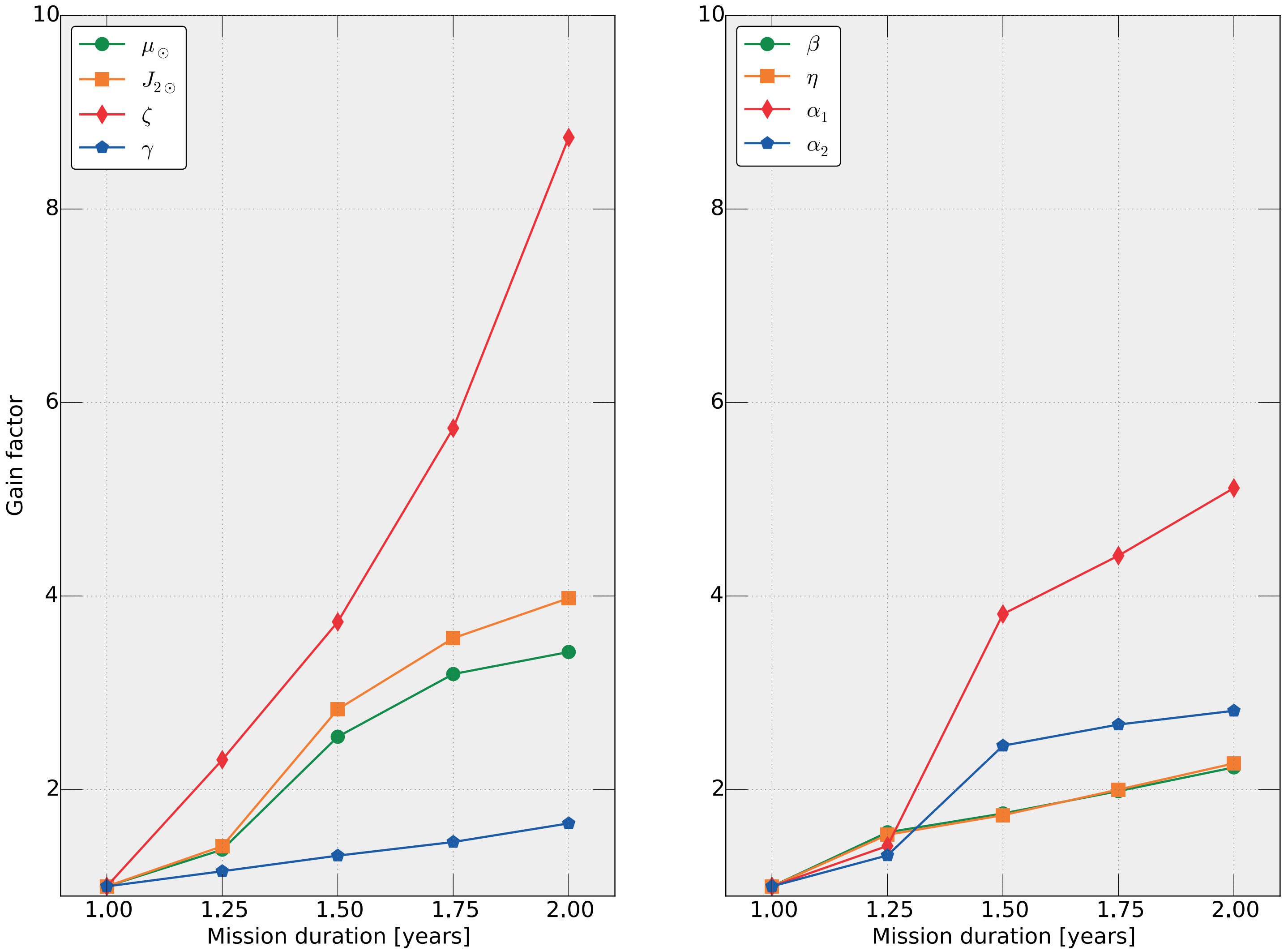
PPN parameters

Parameter	Current limit	Method	MORE
β-1	$7\text{x}10^{-5}$ $3.9 \text{ x } 10^{-5}$	INPOP global planetary fit MESSENGER range data	10^{-6} (Nordvedt + rescaling) (2.8×10^{-5} non-metric)
γ-1	$2.3\text{x } 10^{-5}$	Cassini SCE	$1.1\text{x}10^{-6}$
η	$4.5\text{x}10^{-4}$ - $7.2\text{x}10^{-5}$ $2.6\text{x}10^{-6}$	LLR – MESSENGER Pulsar in triple system	$3.0\text{x}10^{-6}$ (with rescaling) 10^{-5}-10^{-4} (no rescaling)
α_1	$6\text{x}10^{-6}$ $4\text{x}10^{-5}$	Solar system precession Pulsar-white dwarf	$6.1\text{x}10^{-7}$
α_2	$3.5\text{x}10^{-5}$ $1.6\text{x}10^{-9}$	Solar system precession Milliseconds pulsar	$1.3\text{x}10^{-7}$
μ_{Sun}	10	EPM global planetary fit	$5.3\text{x}10^{-2}$ km^3/s^2
J_{2Sun}	10^{-8} $1.2\text{x}10^{-8}$ $9\text{x}10^{-9}$	Helioseismology INPOP global planetary fit MESSENGER range data	$5.5\text{x}10^{-10}$
ς	$4.3\text{x}10^{-14}$ $1.6\text{x}10^{-13}$	EPM global planetary fit MRO range data	$2.8\text{x}10^{-14}$ y^{-1}

- Combining MESSENGER and BepiColombo data looks very promising, especially for some PPN parameters.

(Imperi, Iess & Mariani, 2017)

Uncertainties vs mission duration



ISL and graviton mass (Will, 2018)

$$U = -G\sum_{i\neq j}\frac{M_i M_j}{r_{ij}}\,e^{-r_{ij}/\lambda_g}$$ Yukawa potential

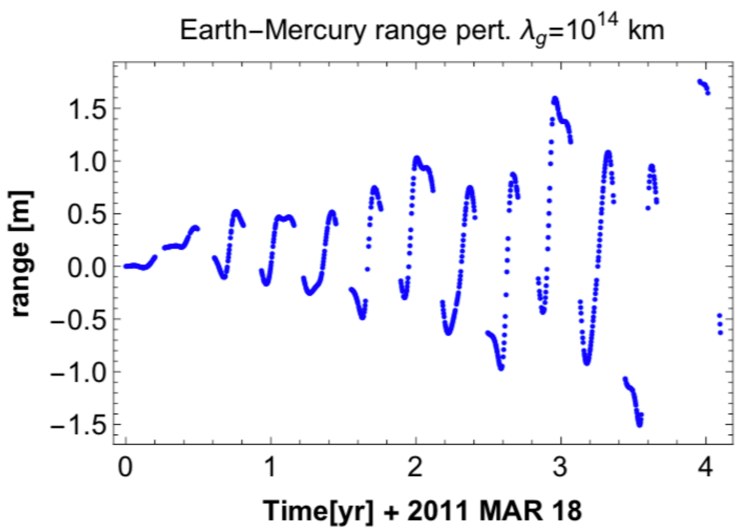
$$\lambda_g = \frac{h}{m_g c}$$ Compton wavelength

$$\mathbf{a}_i \cong -\frac{GM_0}{r_{0i}^3}\left(1-\frac{r_{0i}^2}{\lambda_g^2}\right)\mathbf{r}_{01}$$

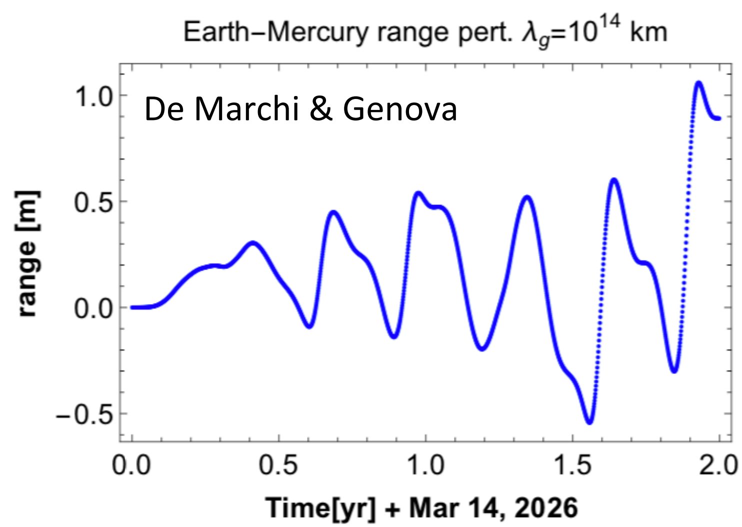
Modified acceleration due to the sun
Constant repulsive force

- $\lambda g > 2.8 \times 10^{12}$ km, inferred from solar-system dynamics (Talmadge et al. 1988)
- Three events GW150914, GW151226 and GW170104 $\lambda g > 1.6 \times 10^{13}$ km.
- Combined MESSENGER-BepiColombo data set: $\lambda g > 1.0 \times 10^{14}$ km

MESSENGER



BepiColombo (2 years)



Conclusions and Outlook

- The quest for violations of GR continues ... but the theoretical framework is still uncertain.
- BepiColombo may go beyond current limits by a significant factor, testing several aspects of GR. Further improvement is expected for some parameters by combining the MESSENGER and BepiColombo data set.
- GAIA is expected to attain similar improvements on γ. The two missions will strenghen each other.
- Astronomical observations of PSR J0337+1715 pulsar in triple stellar system (Archibald et al. 2018) are already providing an excellent test of SEP in the strong regime. More tests will come soon. Are we allowed to combine estimates in the weak and strong regimes?