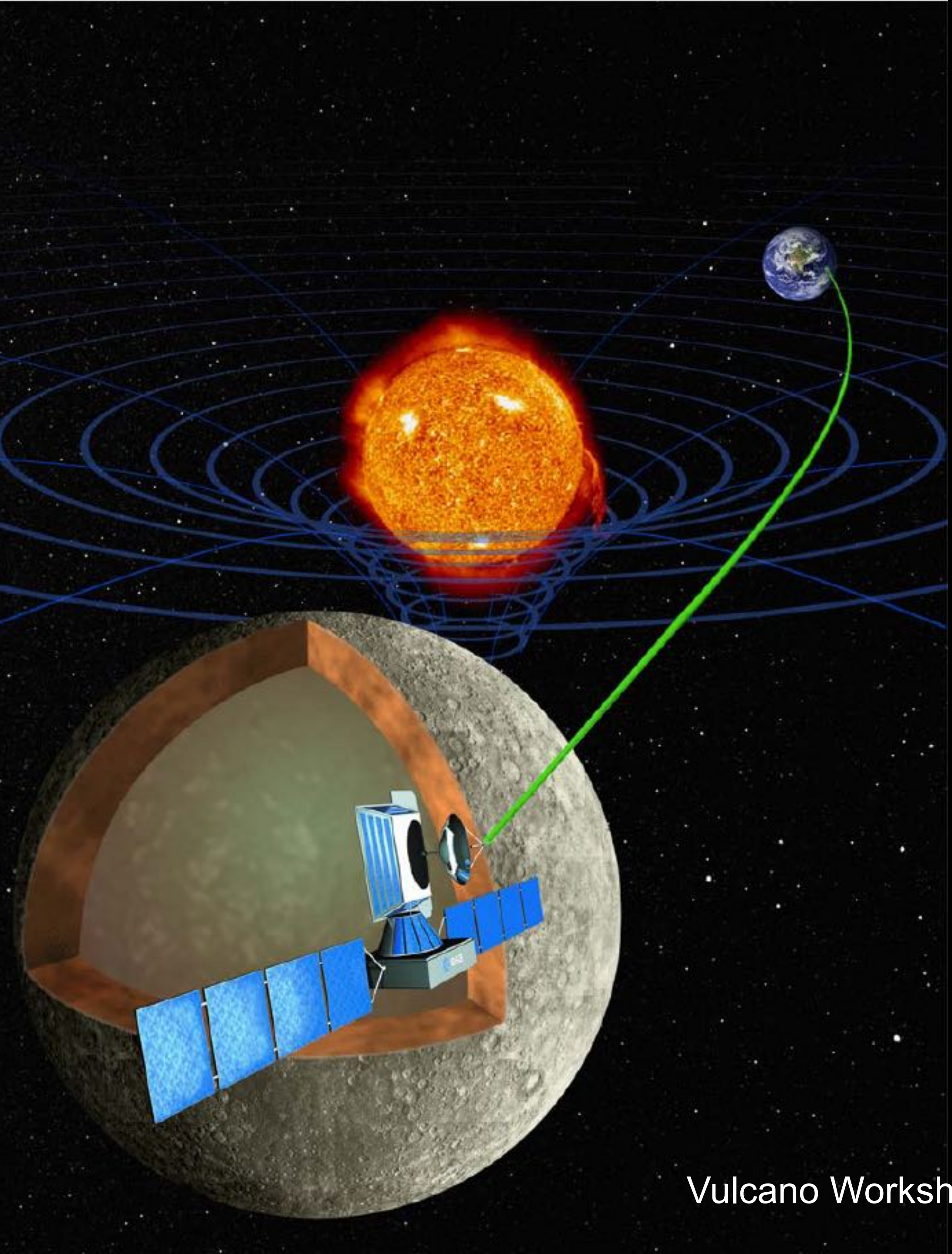

Probing Laws of Gravity in the Solar System: from Cassini to BepiColombo

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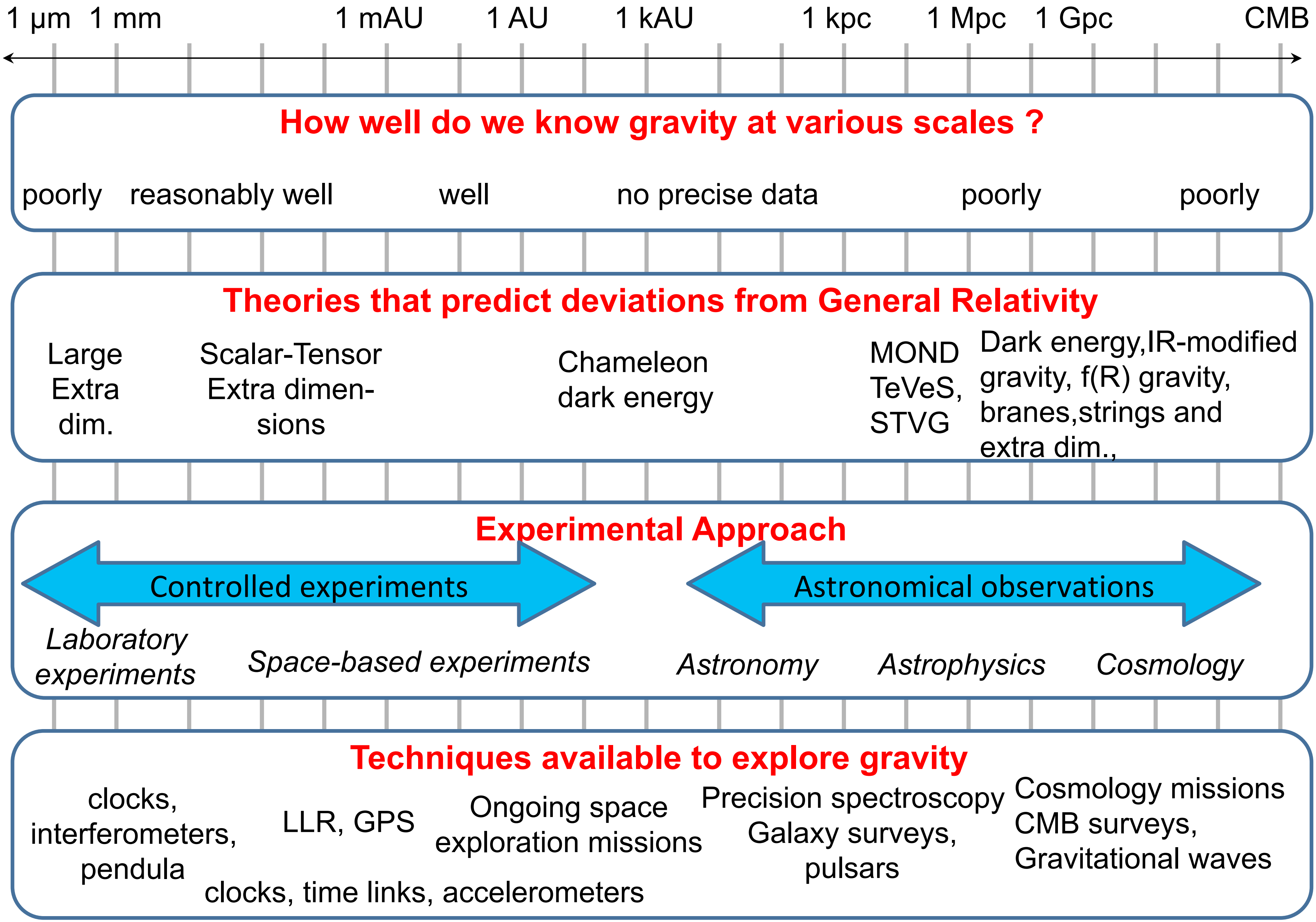
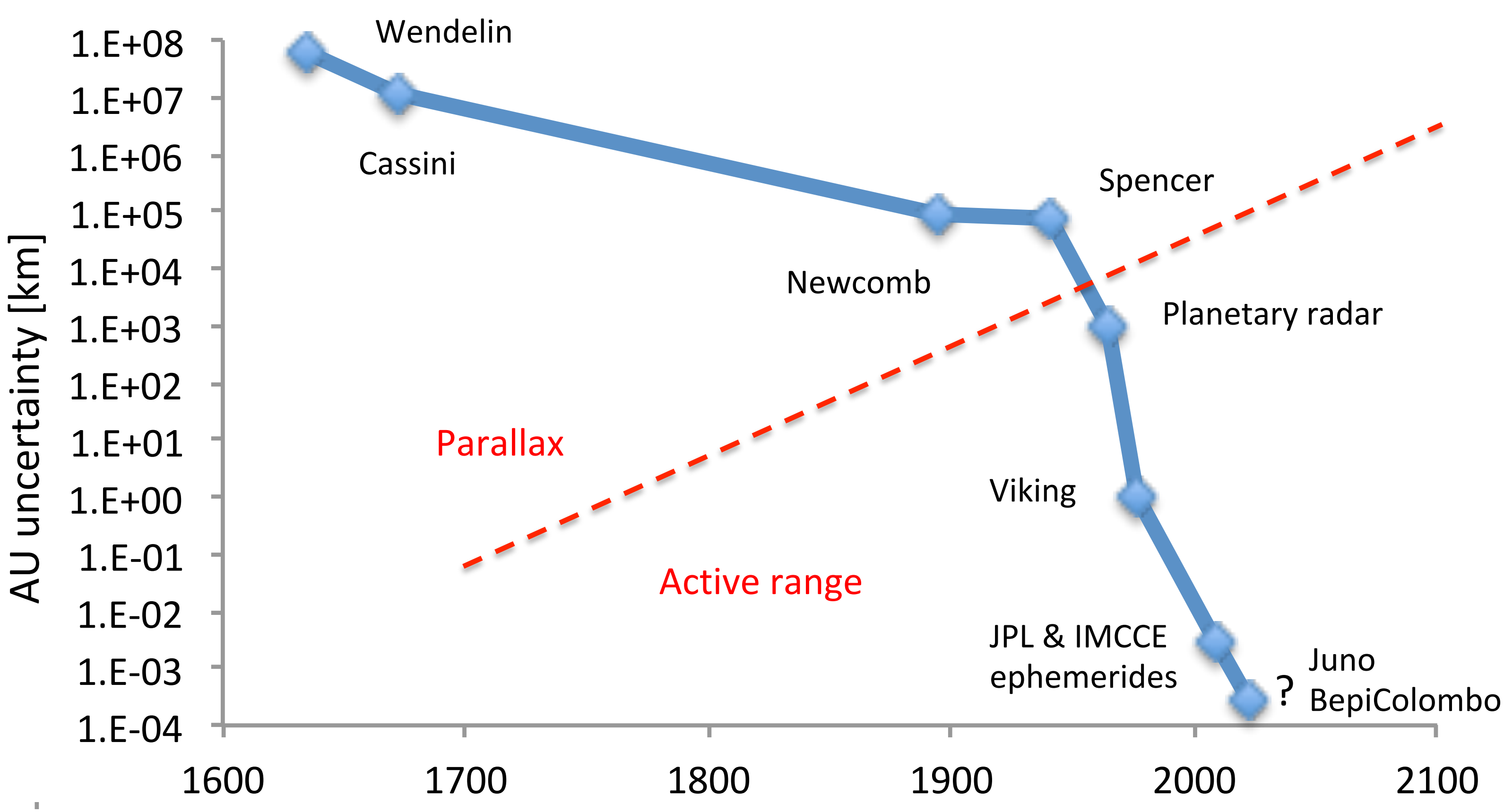
Vulcano Workshop 2018

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



The yardstick of the solar system



Which tools are available?

- Geodesic motion of test masses (deep space probes, solar system bodies)
- Propagation of photons in a gravity field
- Measurements of angles, distances and velocities

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

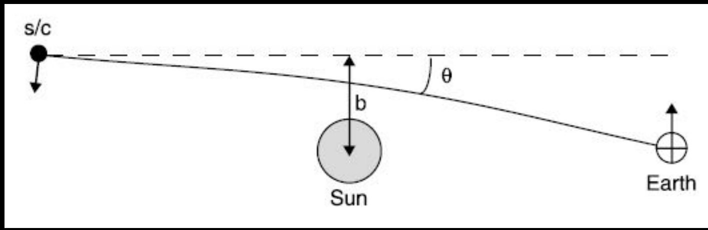
Best accuracy attained (2-way, Cassini):
$1.5\ 10^{-6}$ m/s @1000 s (Ka-band /multilink radio systems)

Tests based on propagation of photons

Deflection of light (GAIA)

$$\theta_{gr} = 2(1+\gamma)\frac{M_{sun}}{b} = 4\times10^{-6}(1+\gamma)\frac{R_{sun}}{b}\,\mathrm{rad}$$

Main advantage:
short time scale !
[7-10 days]



Solar Gravity

Time delay (BepiColombo)

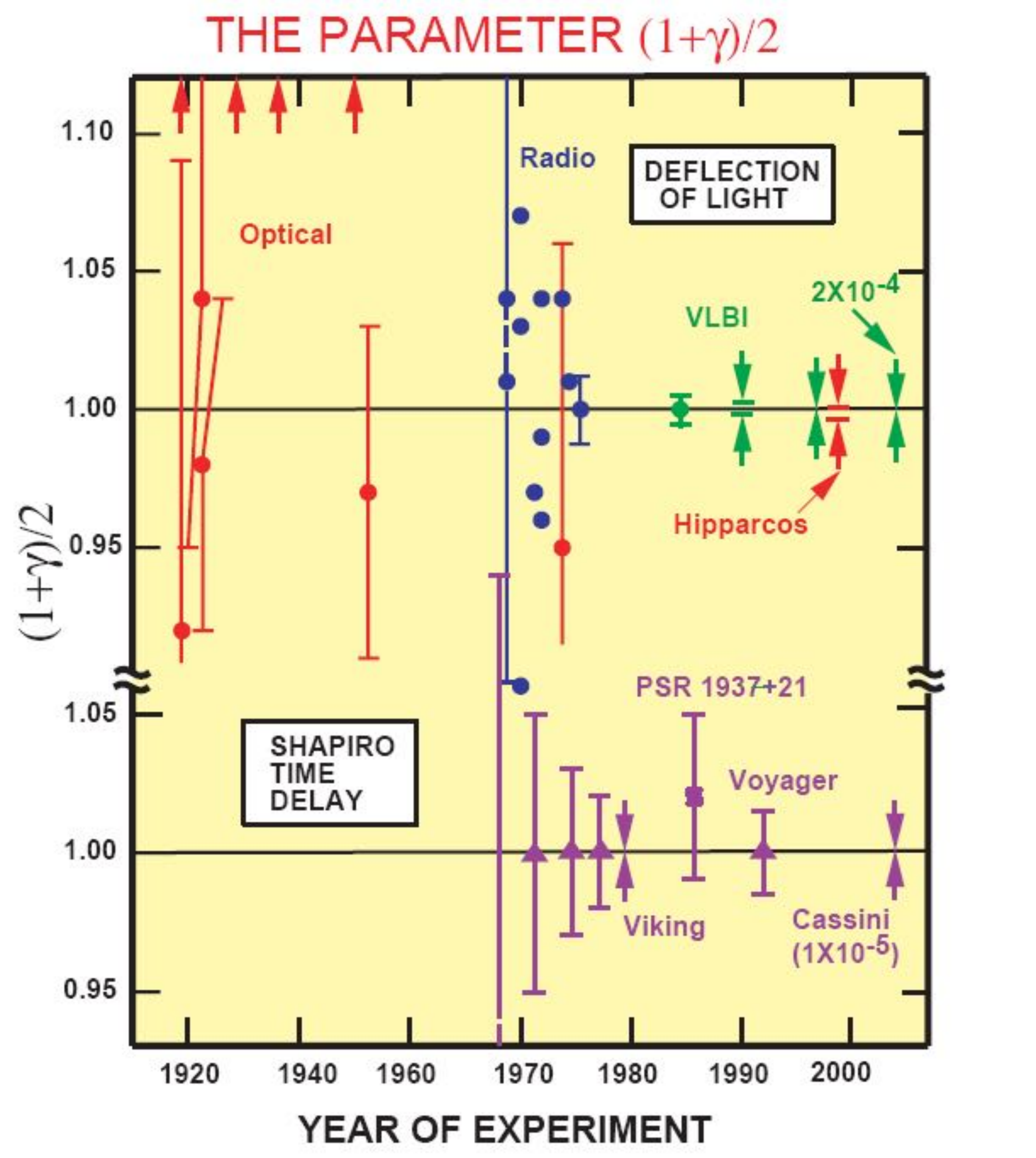
$$\Delta t = (1+\gamma)M_{sun}\ln\frac{l_0+l_1+l_{01}}{l_0+l_1-l_{01}}$$

≈ 70 km for a grazing beam

Frequency shift (Cassini&BepiColombo)

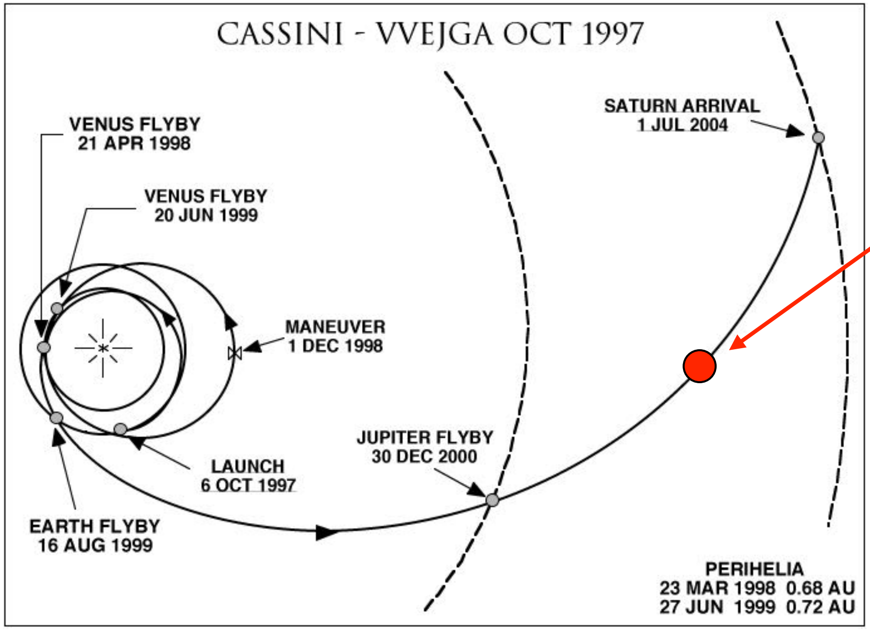
$$\frac{\Delta\nu}{\nu} = \frac{\mathrm{d}}{dt}\Delta t \cong 4(1+\gamma)\frac{M_{sun}}{b}\frac{db}{dt}$$

≈ 8×10^{-10} for a grazing beam



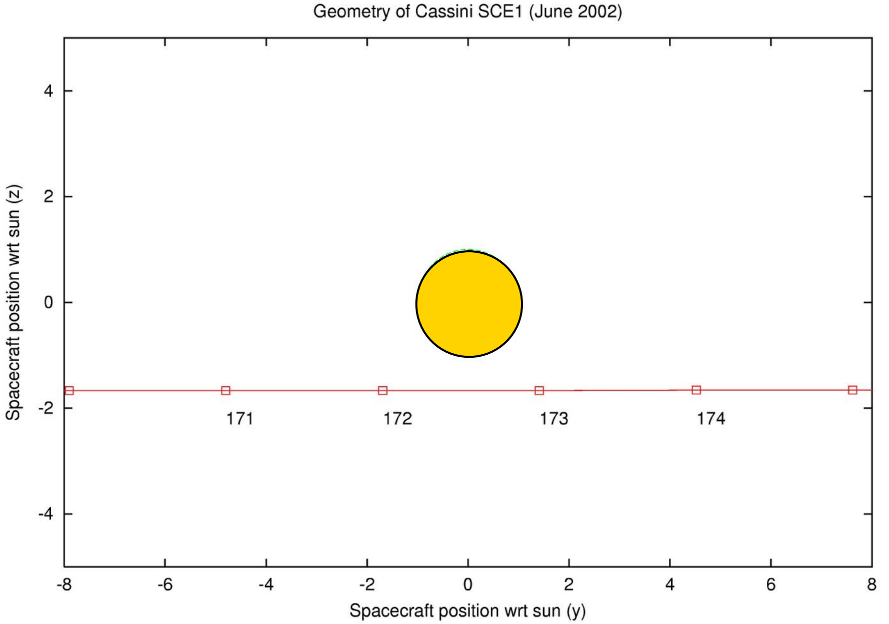
From:

Clifford M. Will,
"The Confrontation between General Relativity and Experiment",
Living Rev. Relativity, 9, (2006), 3.
http://www.livingreviews.org/lrr-2006-3

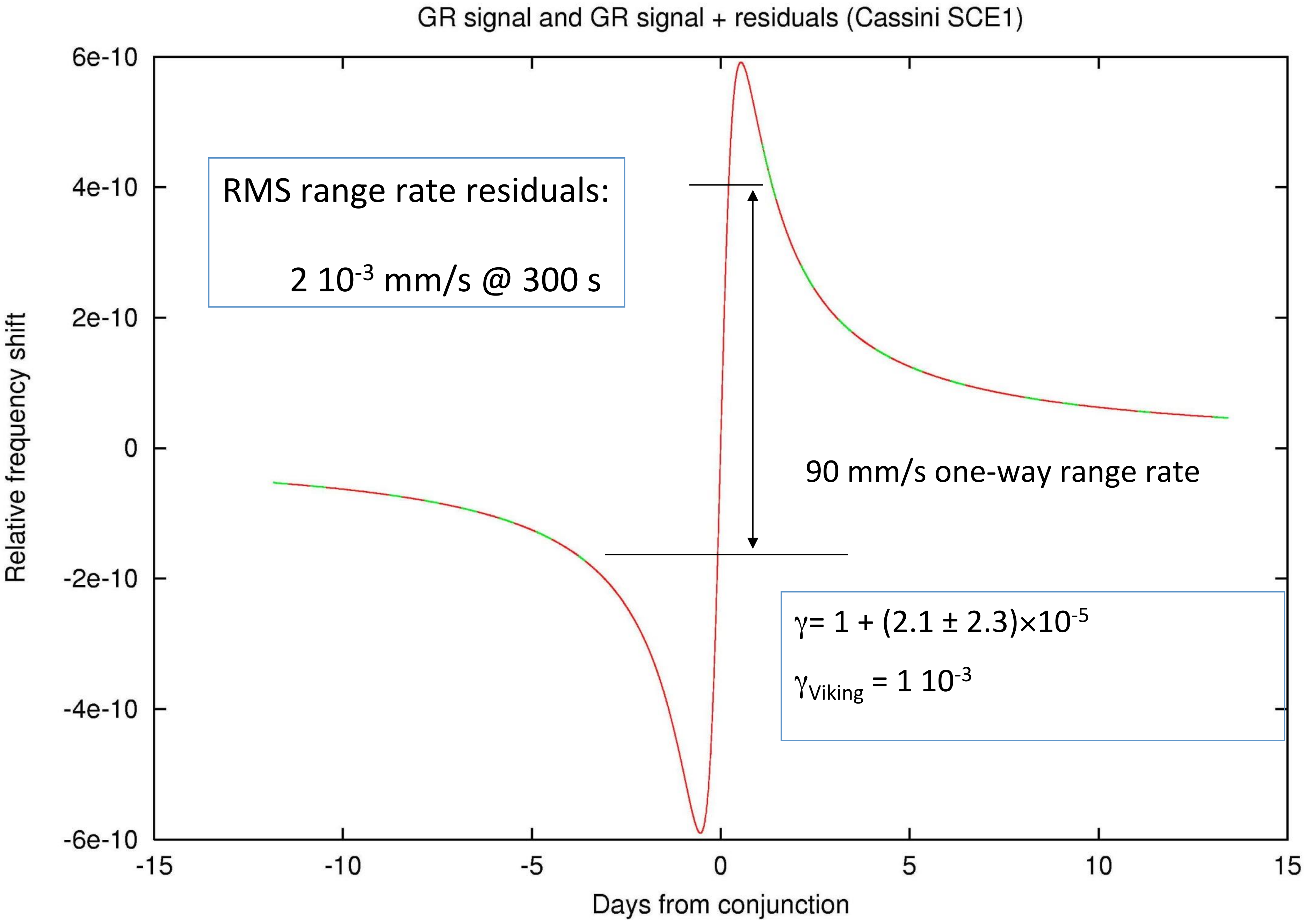


30 days coverage from DSN

June 6 to July 5, 2002

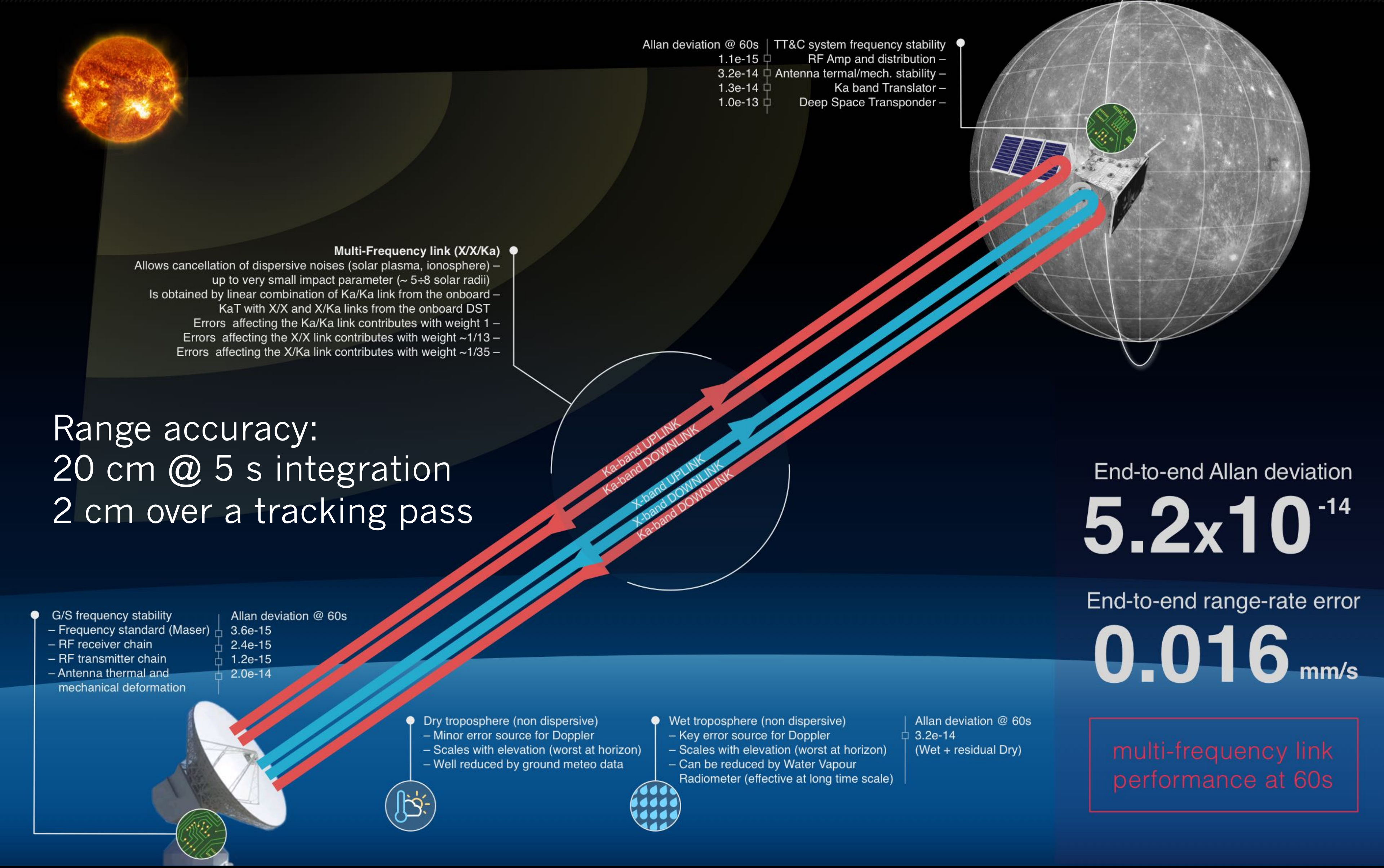


Heliocentric distance: 7.2 AU



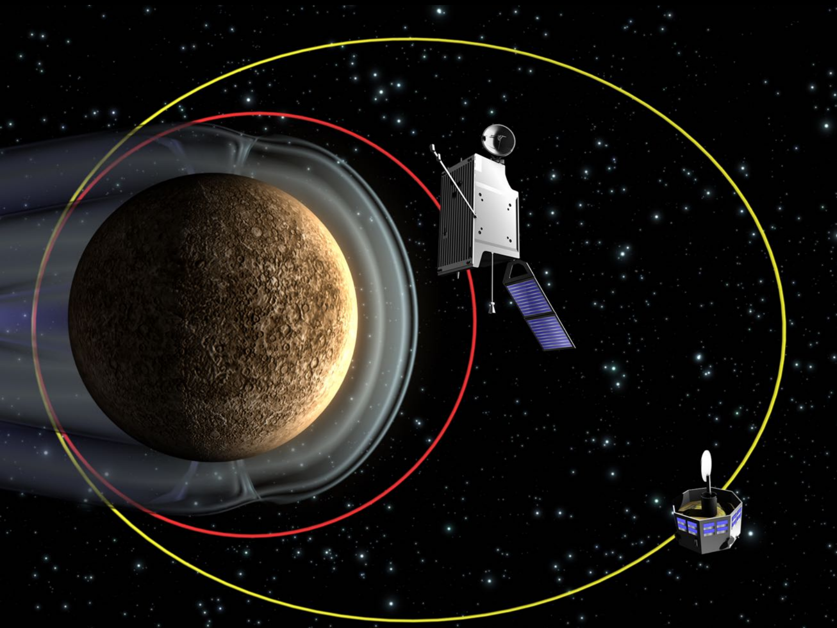
GR signal and GR signal + residuals (Cassini SCE1)
RMS range rate residuals:
2 10-3 mm/s @ 300 s
90 mm/s one-way range rate
γ= 1 + (2.1 ± 2.3)×10-5
γViking = 1 10-3
Relative frequency shift
Days from conjunction
6e-10
4e-10
2e-10
0
-2e-10
-4e-10
-6e-10
-15
-10
-5
0
5
10
15

BepiColombo - range rate error budget

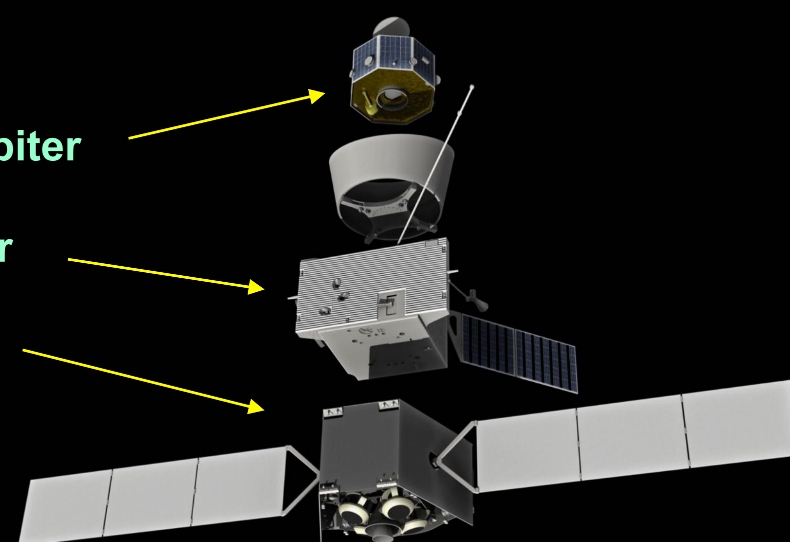


Range accuracy:
20 cm @ 5 s integration
2 cm over a tracking pass

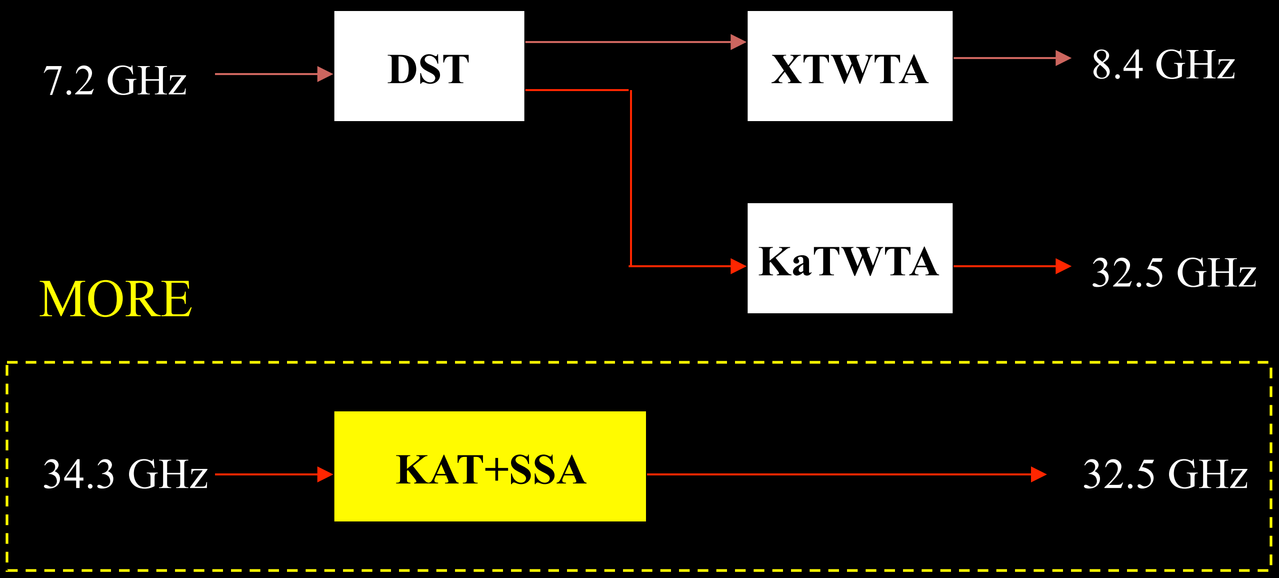
BepiColombo: ESA's mission to Mercury

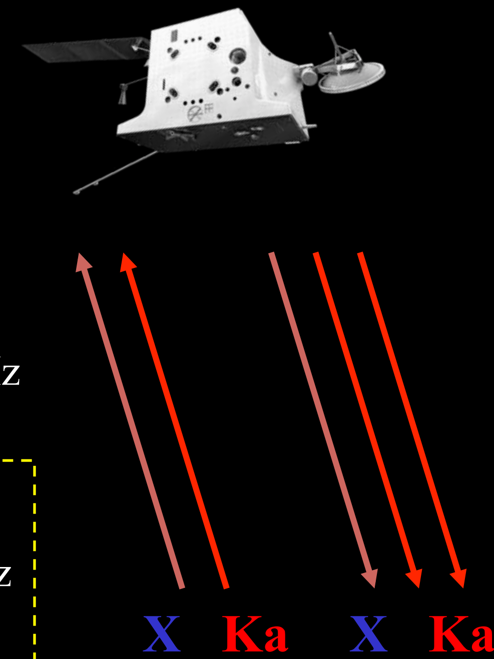


Launch: Ariane 5 (Oct. 2018)
Solar Electric Propulsion
Arrival at Mercury: 2025
MPO orbit altitude: 400x1500 km



Multifrequency link - BepiColombo



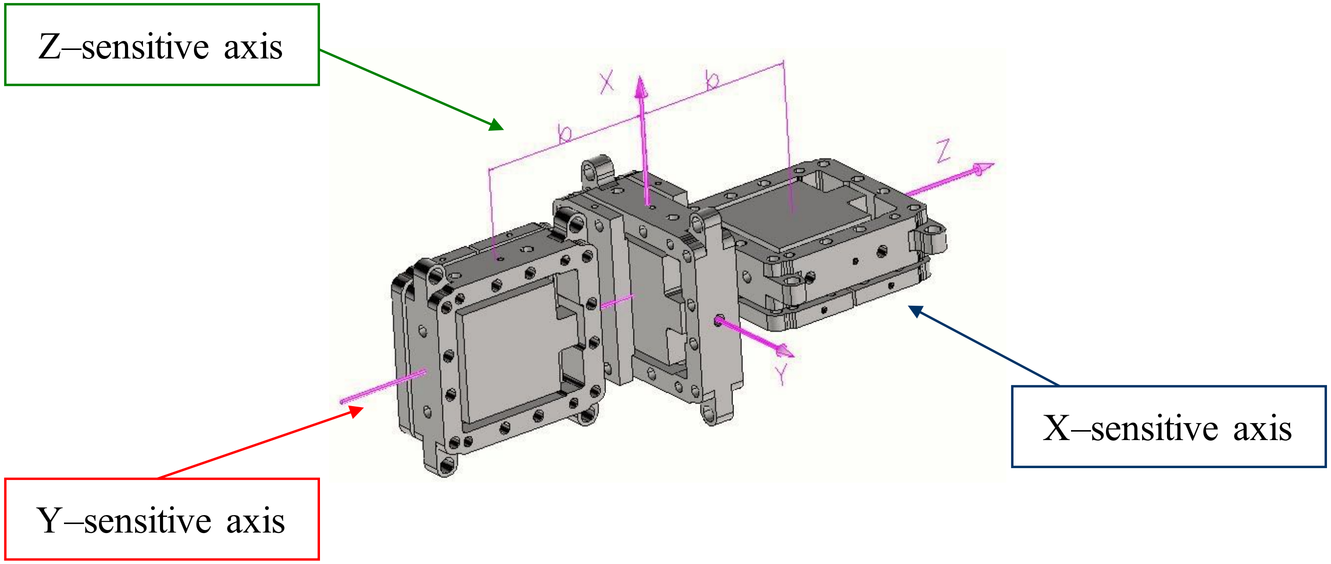


- Multilink needed for plasma noise cancellation
- 24 Mcps PN range modulation on Ka/Ka link
- Onboard range delay calibration
- End-to-end range accuracy (post-cal): 2-3 cm
- End-to-end 2-way range rate accuracy: 3 μm/s @ 1000 s ($\sigma_y=10^{-14}$)

The Italian Spring Accelerometer

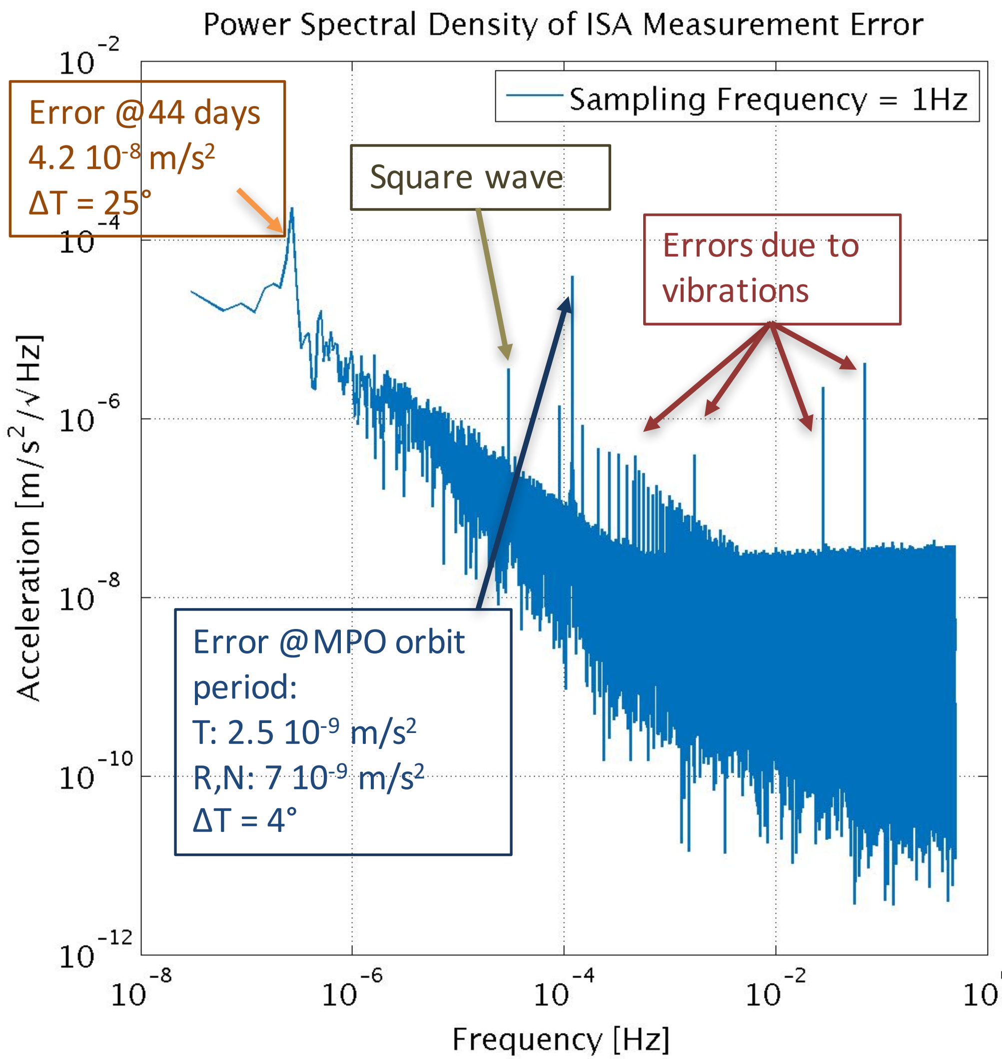
Italian Spring Accelerometer (PI V. Iafolla, IAPS-INAF)

- 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.

The PPN parameters of interest are:

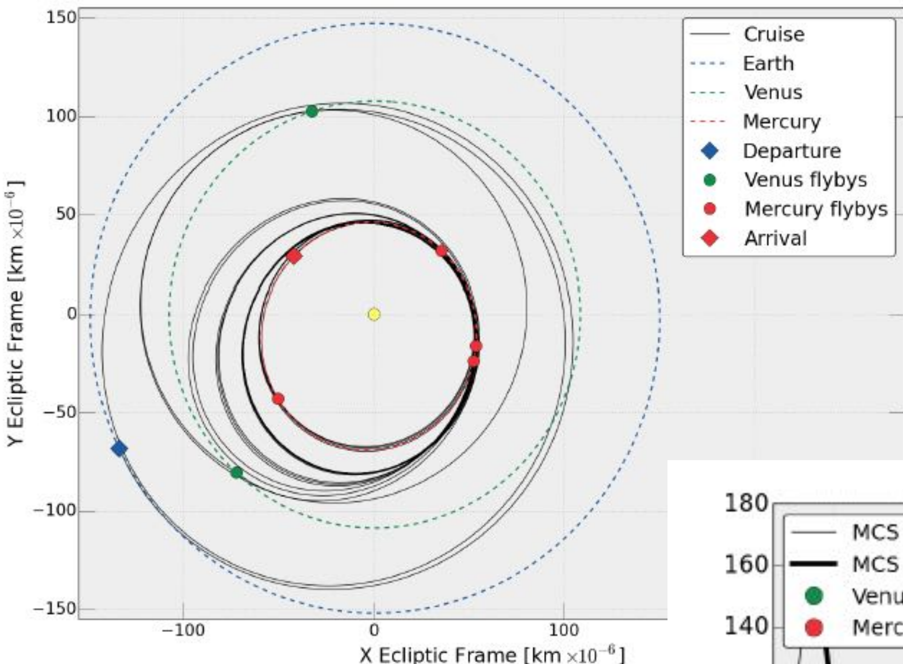
- **β**: related to non-linear 3-body general relativistic interaction (β=1 in GR).
- **γ**: parameterizes the velocity-dependent modification of the 2-body interaction and measures the space curvature produced by a unit mass (γ=1 in GR).
- **η**: measures the contribution of the gravitational self-energy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

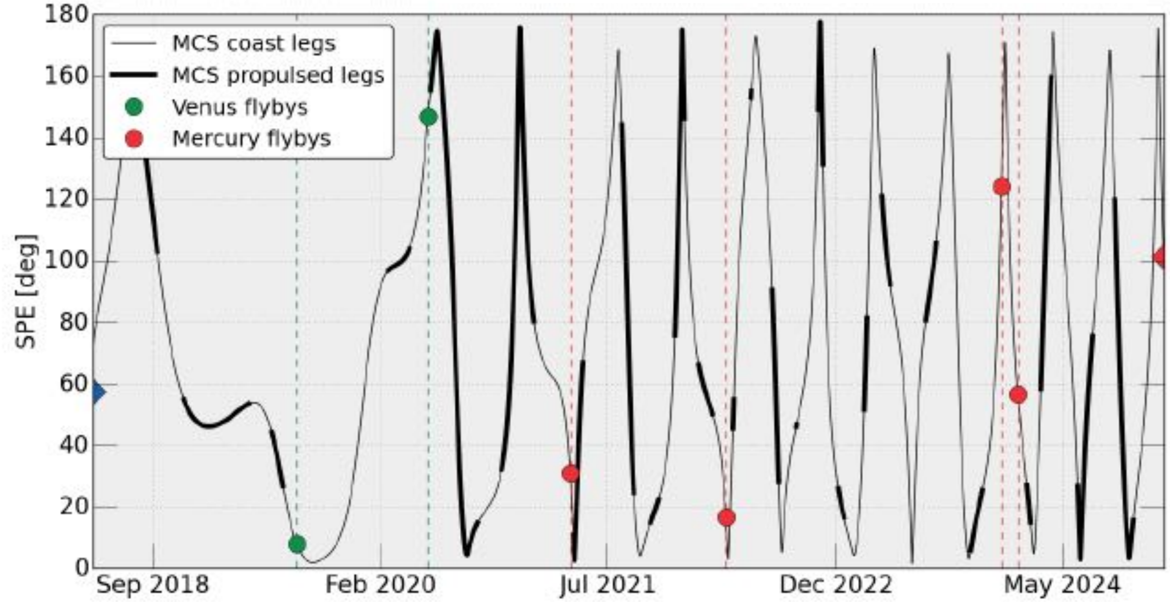
The addition parameters affecting the planetary orbits are:

- **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.

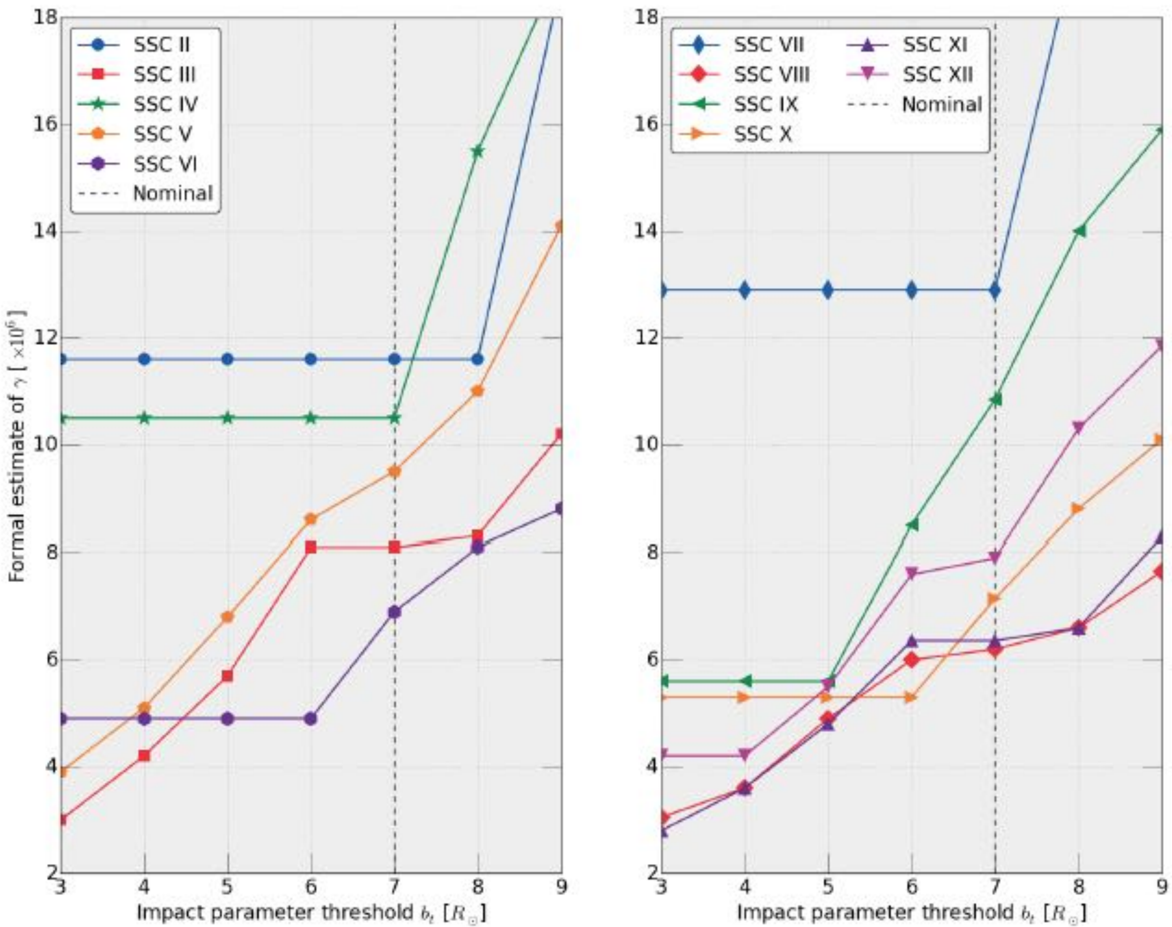
Measuring γ in cruise

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)

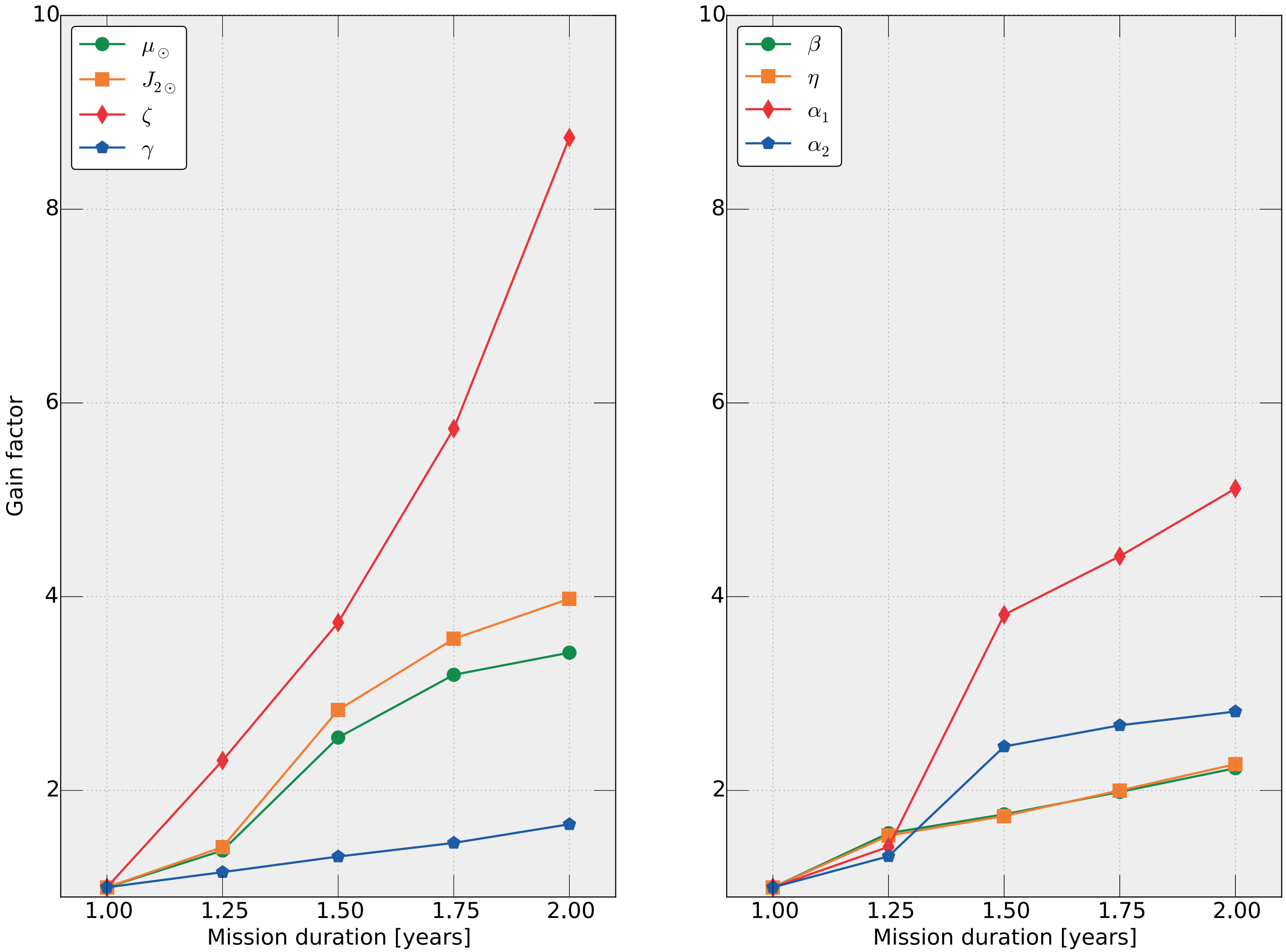
PPN parameters

Parameter	Current limit	Method	MORE
β-1	$7x10^{-5}$ 3.9×10^{-5}	IMPOP global planetary fit MESSENGER range data	10^{-6}
γ-1	$2.3x\ 10^{-5}$	Cassini SCE	$1.1x10^{-6}$
η	$4.5x10^{-4}$	LLR	$3.0x10^{-6}$
α_1	$6x10^{-6}$ $4x10^{-5}$	Solar system precession Pulser-white dwarf	$6.1x10^{-7}$
α_2	$3.5x10^{-5}$ $1.6x10^{-9}$	Solar system precession Milliseconds pulsar	$1.3x10^{-7}$
μ_{Sun}	10	EPM global planetary fit	$5.3x10^{-2}$ km^3/s^2
J_{2Sun}	10^{-8} $1.2x10^{-8}$ $9x10^{-9}$	Helioseismology IMPOP global planetary fit MESSENGER range data	$5.5x10^{-10}$
ς	$4.3x10^{-14}$ $1.6x10^{-13}$	EPM global planetary fit MRO range data	$2.8x10^{-14}$ y^{-1}

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

(Imperi, Iess & Mariani, 2017)

PPN parameters



Conclusions and Outlook

- The quest for violations of GR continues ... but the theoretical framework is uncertain.
- In this context, space agencies are reluctant to fund expensive dedicated missions.
- BepiColombo may push 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.
- An interplanetry network of orbiters and landers (Mars, Moon, ...) could immensely strengthen the geometry of the observations, improve the dynamical model of the solar system and put GR to much more challenging tests.