Einstein Equivalence Principle test with RadioAstron: preliminary results

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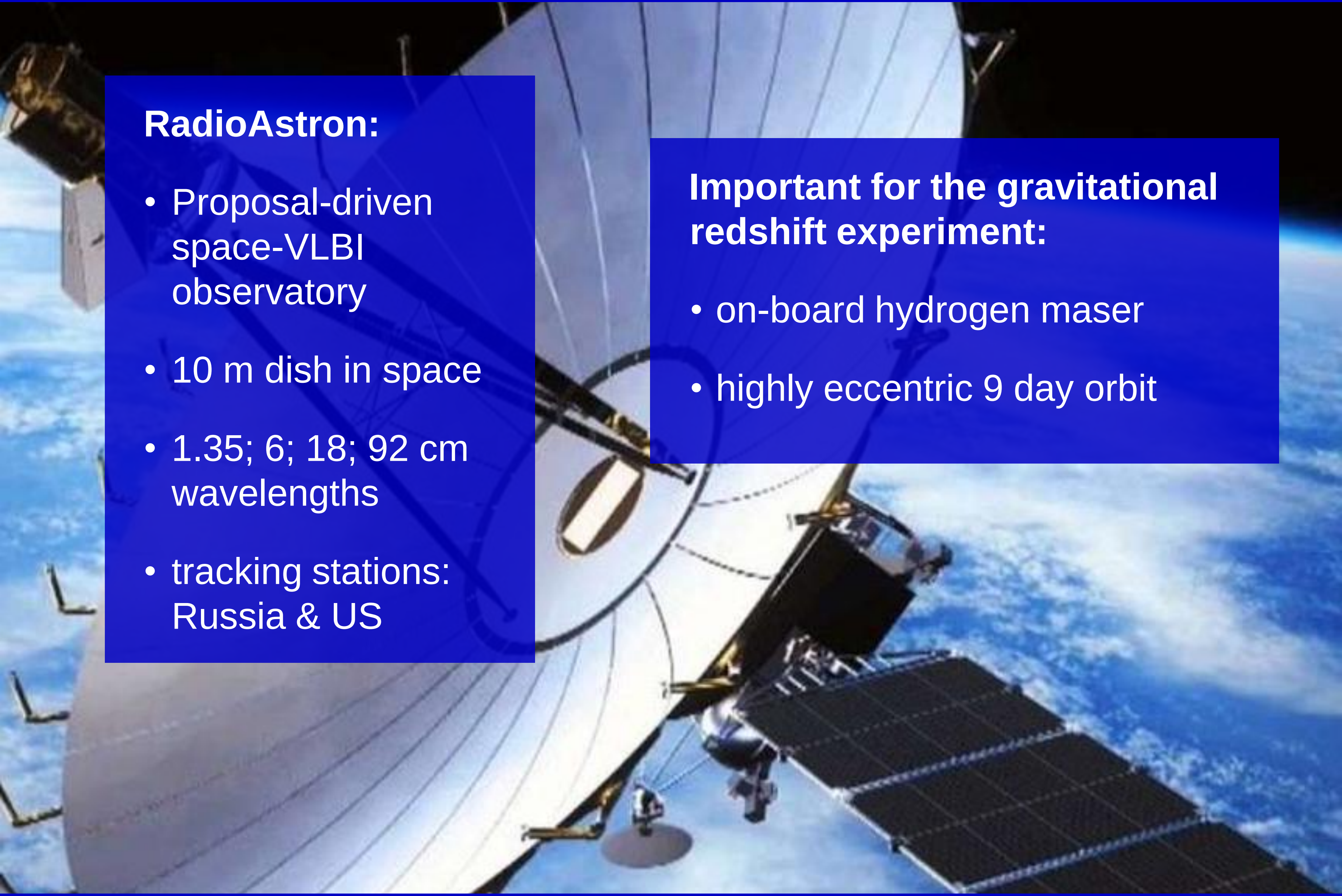
RadioAstron:

- Proposal-driven space-VLBI observatory
- 10 m dish in space
- 1.35; 6; 18; 92 cm wavelengths
- tracking stations: Russia & US



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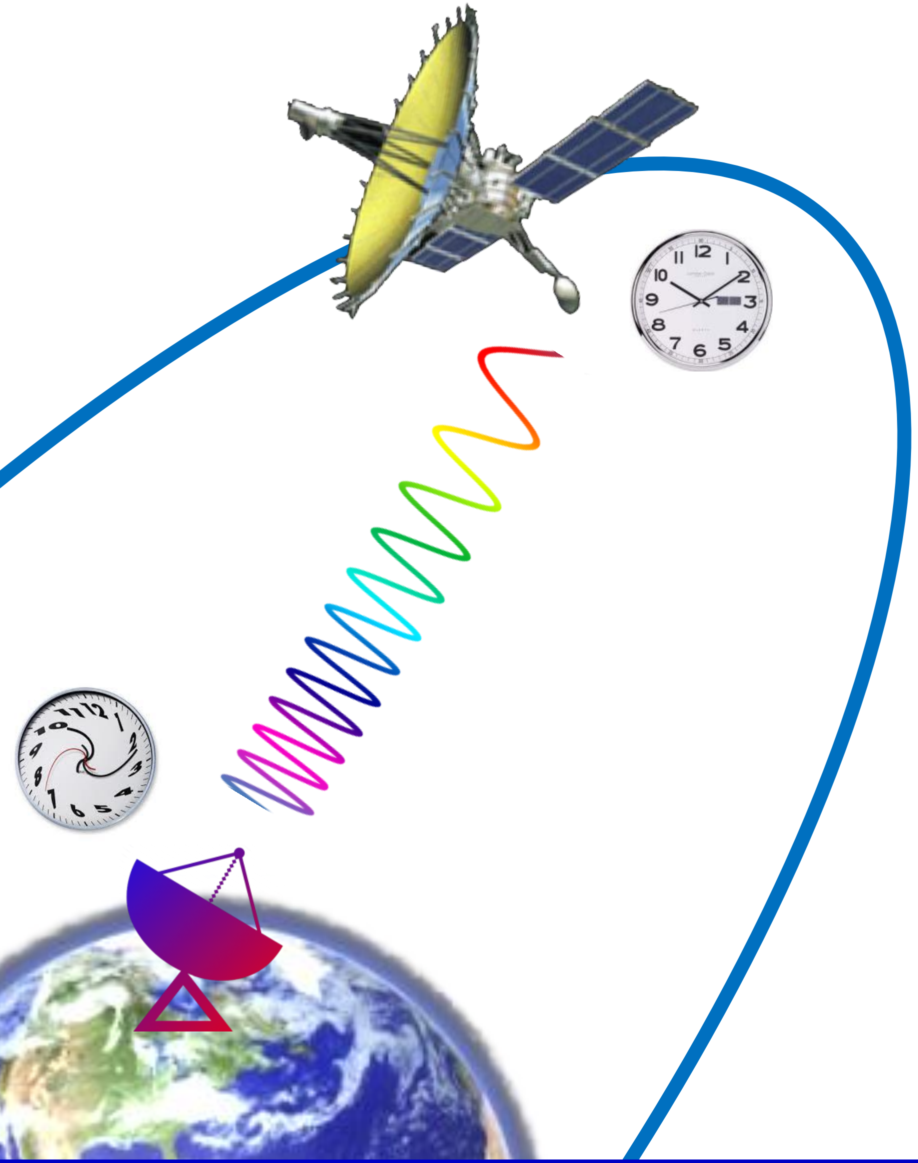
Important for the gravitational redshift experiment:

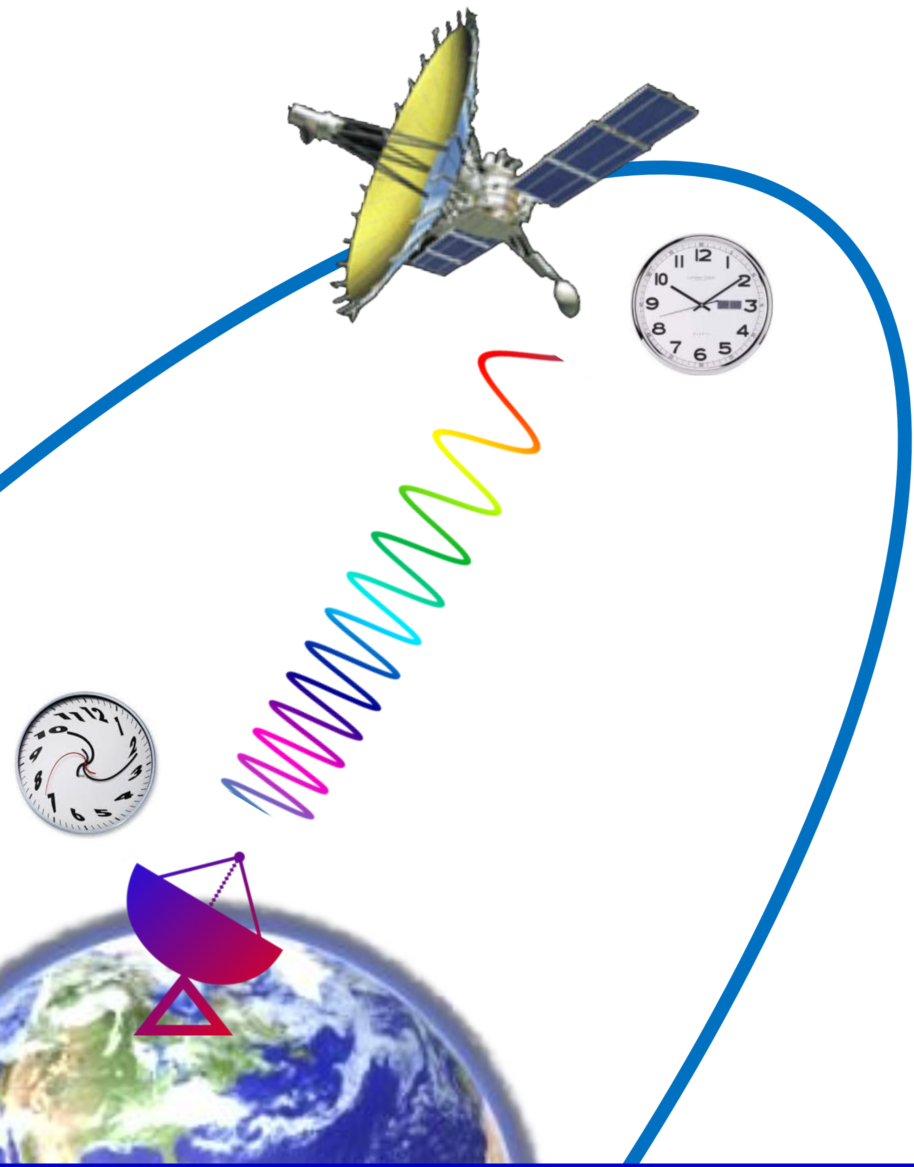
- on-board hydrogen maser
- highly eccentric 9 day orbit



- frequency-based approach
- downlink at 8.4 and 15 GHz
- uplink at 7.2 GHz

Einstein Equivalence Principle:

$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}$$



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Einstein Equivalence Principle:

$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}$$

or

$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}(1+\varepsilon) \quad ?$$

Grand Unification: $$\frac{\Delta f_{\rm grav}}{f} = \frac{\Delta U}{c^2}(1+\varepsilon)$$

violation parameter

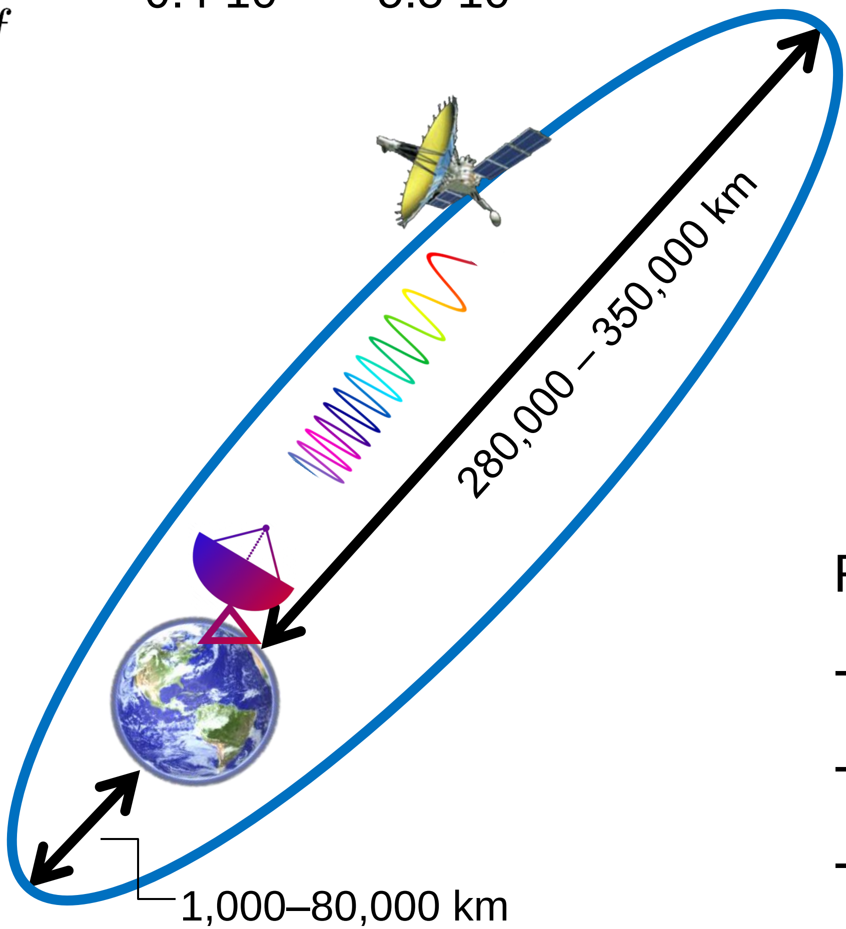
Possible mechanisms: Local Position Invariance broken (dark matter halo, etc.)

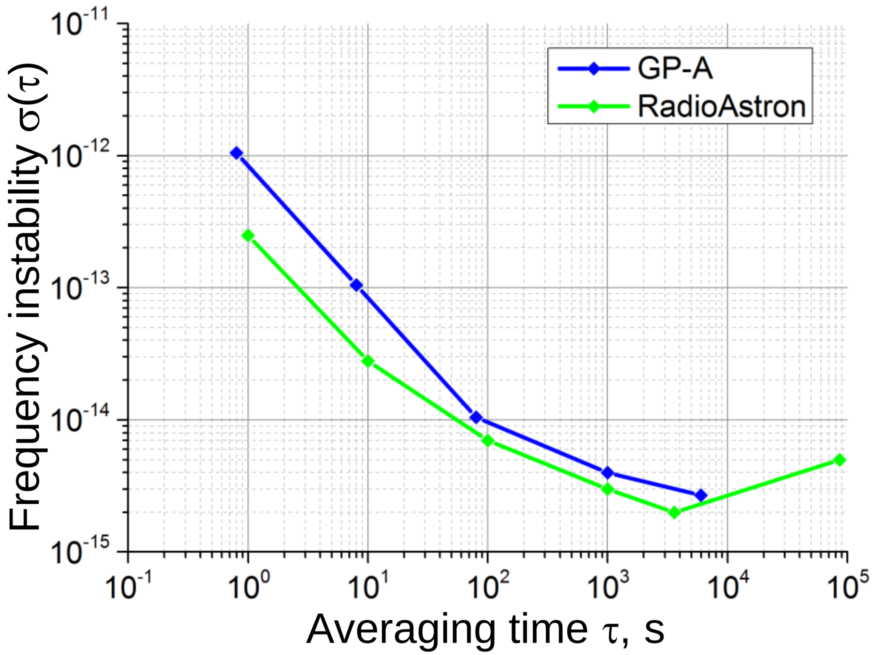
Violation magnitude: difficult to predict

Consequences: new physics, satellite navigation

Grav. redshift modulation:

$$\frac{\Delta f_{\rm grav}}{f} = 0.4\cdot10^{-10} - 5.8\cdot10^{-10}$$





RadioAstron vs. Gravity Probe A:

- more stable H-maser
- greater modulation of the effect
- multiple measurements

Estimated accuracy: $\delta\varepsilon = (1–2)\times10^{-5}$

One-way approach to measuring redshift

Fractional frequency shift of the spacecraft downlink:

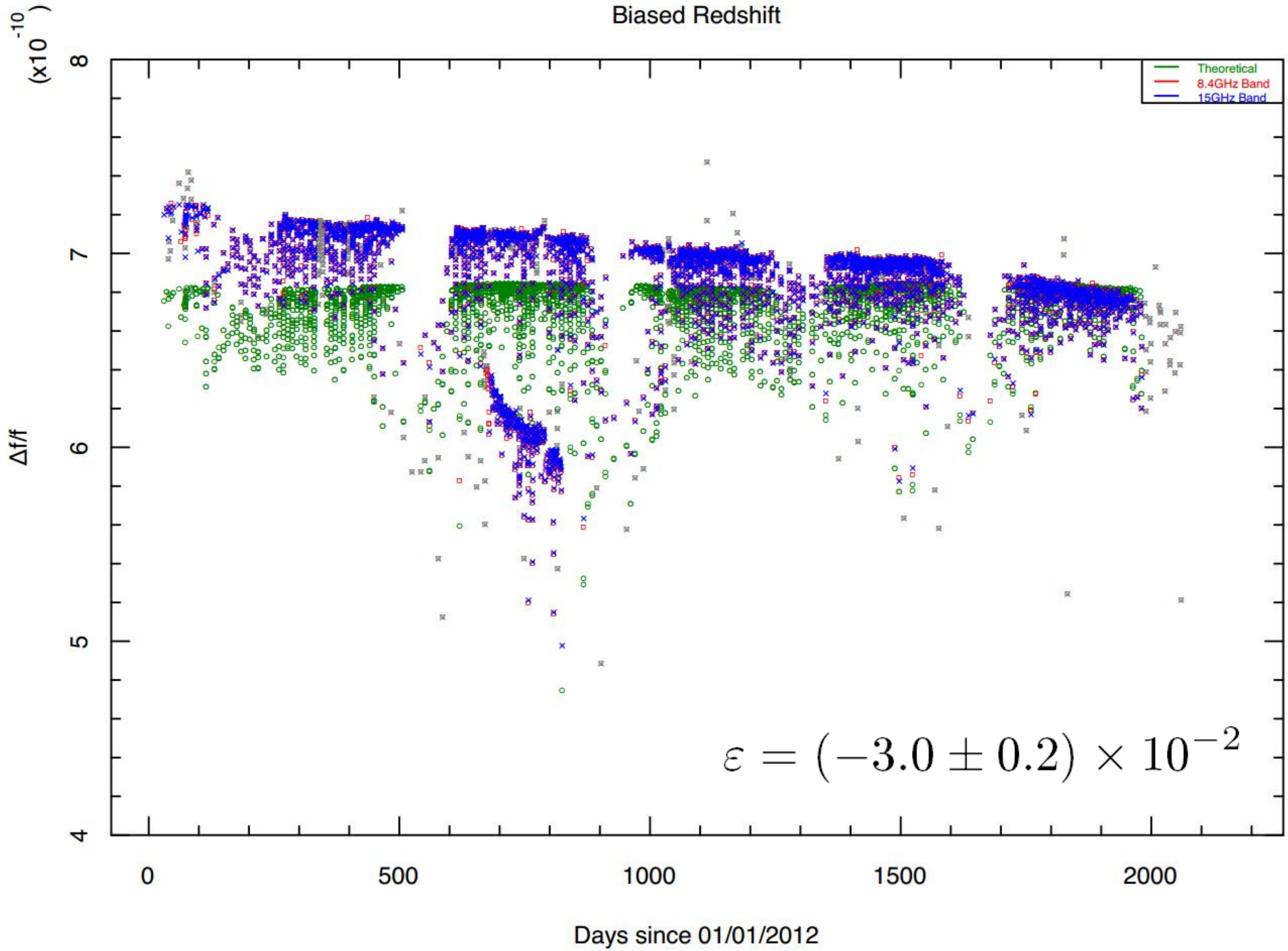
$$\frac{\Delta f}{f} = -\frac{\dot{D}}{c} - \frac{v_s^2 - v_e^2}{2c^2} + \frac{(\vec{v}_s \cdot \vec{n})^2 - (\vec{v}_e \cdot \vec{n}) \cdot (\vec{v}_s \cdot \vec{n})}{c^2} + \frac{\Delta U}{c^2} + \frac{\Delta f_{\mathrm{trop}}}{f} + \frac{\Delta f_{\mathrm{ion}}}{f} + \frac{\Delta f_{\mathrm{instr}}}{f} + O\left(\frac{v}{c}\right)^3$$

Pro: 6 years of radio science data

Con: orbit reconstruction accuracy

$\dot{D} \sim 0.5$ mm/s $\rightarrow$ $\delta\varepsilon \sim 2\times10^{-3}$

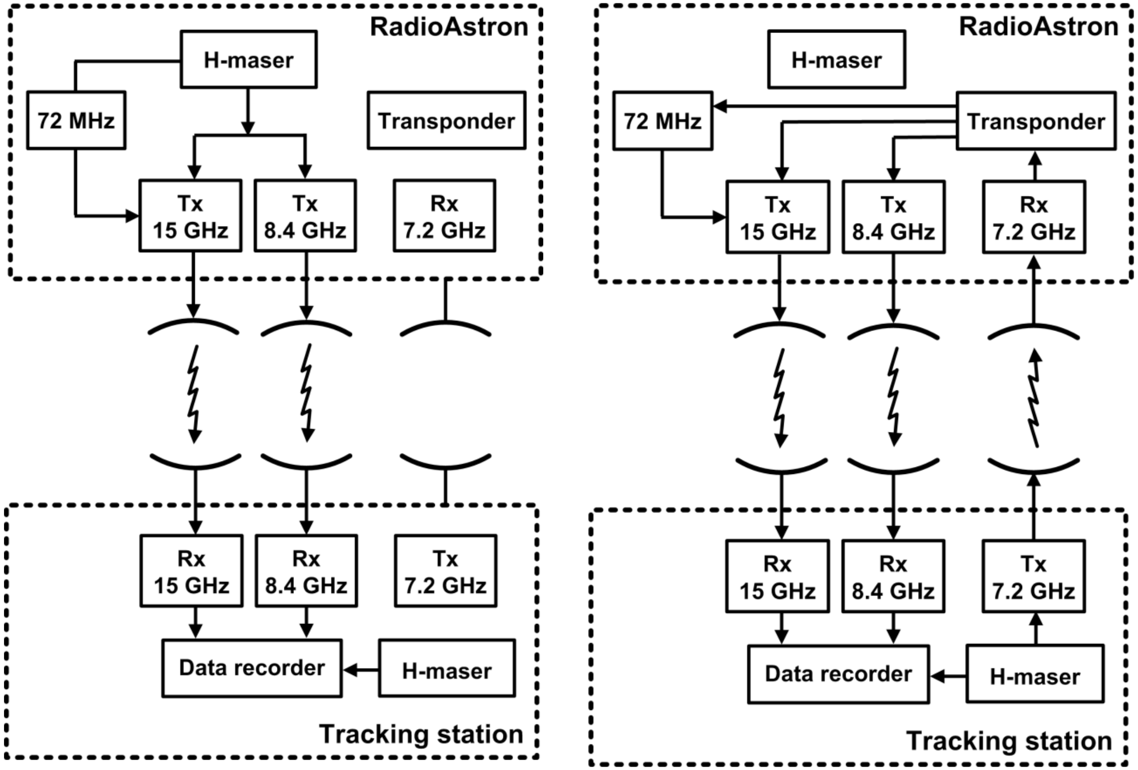
One-way data analysis results



Solution: 1-way downlink – from the on-board H-maser
2-way phase-locked loop – from the ground H-maser

1-way "H-maser" **2-way "Coherent"**

$$\frac{\Delta f_{1\mathrm{w}}}{f} = -\frac{\dot{D}}{c} + \ldots$$



$$\frac{\Delta f_{2\mathrm{w}}}{f} = -\frac{2\dot{D}}{c} + \ldots$$

Biriukov+14

$$\Delta f_{1\mathrm{w}} - \frac{1}{2}\Delta f_{2\mathrm{w}} = \Delta f_{\mathrm{grav}} + \Delta f_0 + f_0\left(-\frac{|\mathbf{v}_{\mathrm{s}}^2 - \mathbf{v}_{\mathrm{e}}^2|}{2c^2} + \frac{\mathbf{a}_{\mathrm{e}}\cdot\mathbf{n}}{c}\Delta t\right) + \Delta f_{\mathrm{ion}}^{(\mathrm{res})} + \Delta f_{\mathrm{fine}} + O(v/c)^4$$

measured

to be determined

computed from orbit, models, aux. data

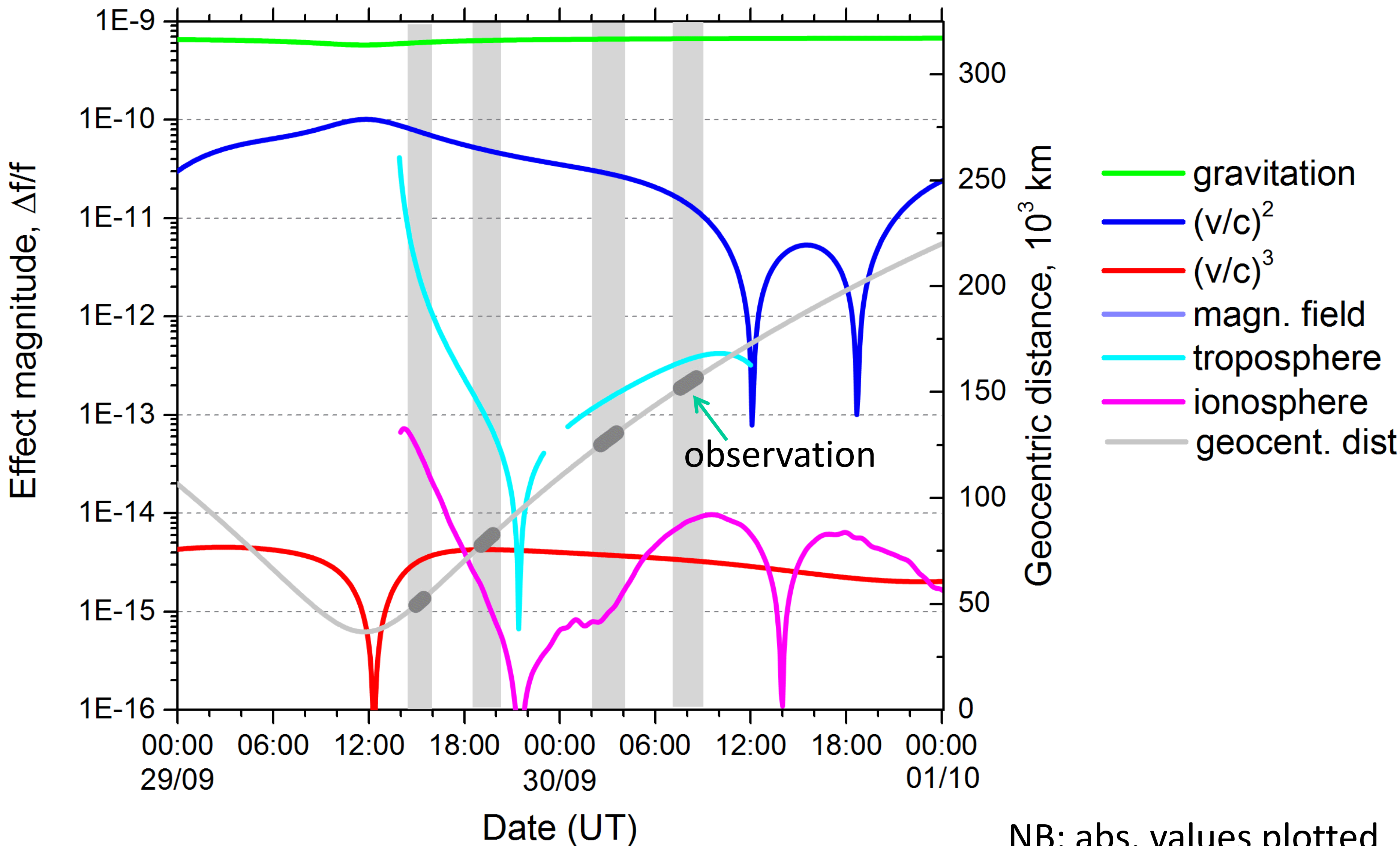
measured

NB: nonrelativistic Doppler and tropospheric shifts are compensated, ionospheric shift is reduced by a factor of 6

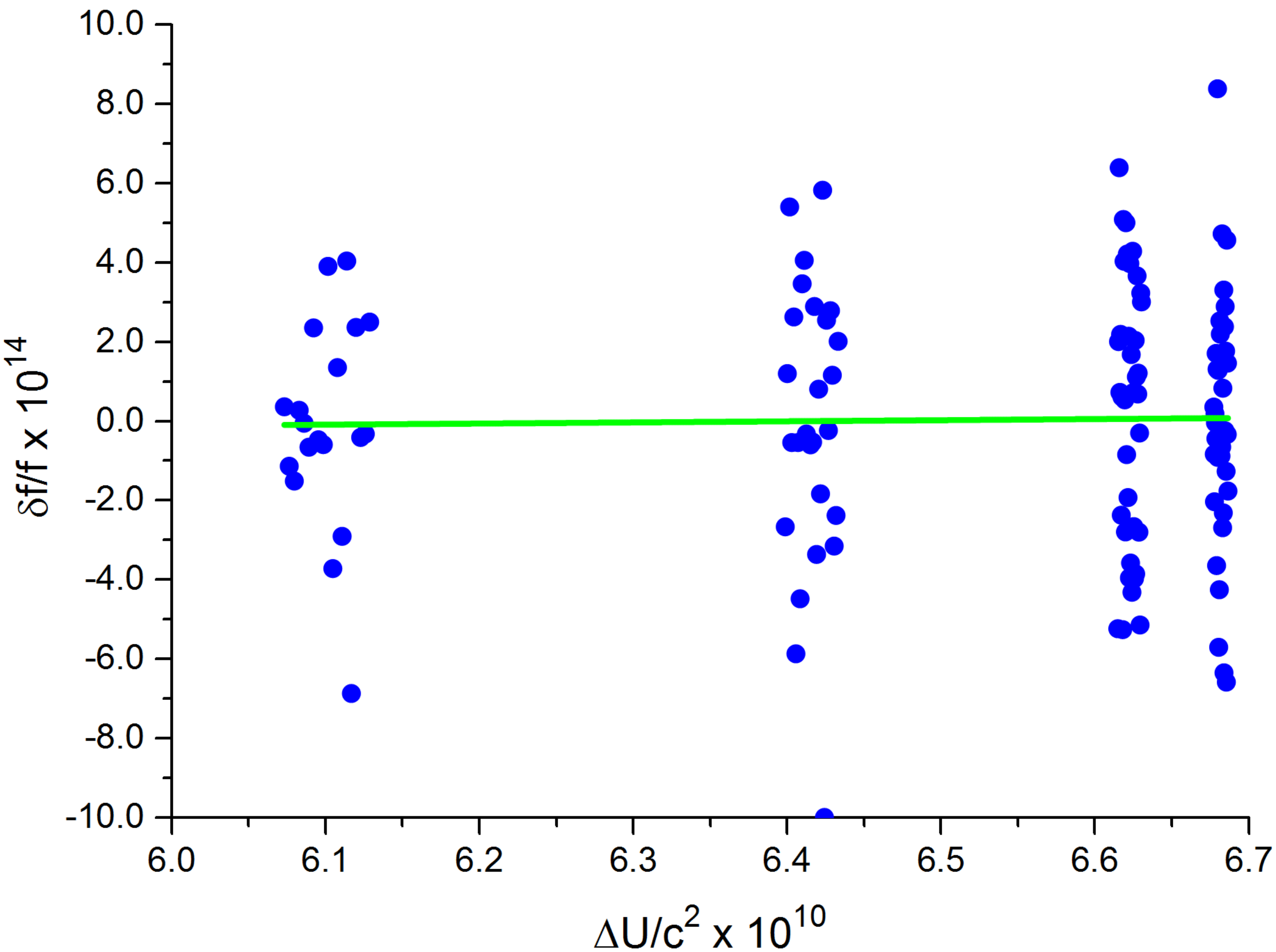
Fine effects: $(v/c)^3$ kinematics, phase center motion, temperature and magnetic sensitivity of the H-masers

Final step – regression analysis: $\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}(1+\varepsilon)$

Data: Gb, Ef, Hh, On, Sv, VLBA, Wn, Wz, Yg, Ys, Zc + tracking stations



NB: abs. values plotted



Litvinov+18

$$\frac{\delta f}{f} = \frac{\Delta f_{\rm grav}}{f} - \frac{\Delta U}{c^2} = \varepsilon \frac{\Delta U}{c^2}$$

Gravity Probe A: $\varepsilon = (0.05 \pm 1.4) \times 10^{-4}$

RadioAstron: $\varepsilon = (0.3 \pm 1.7) \times 10^{-4}$

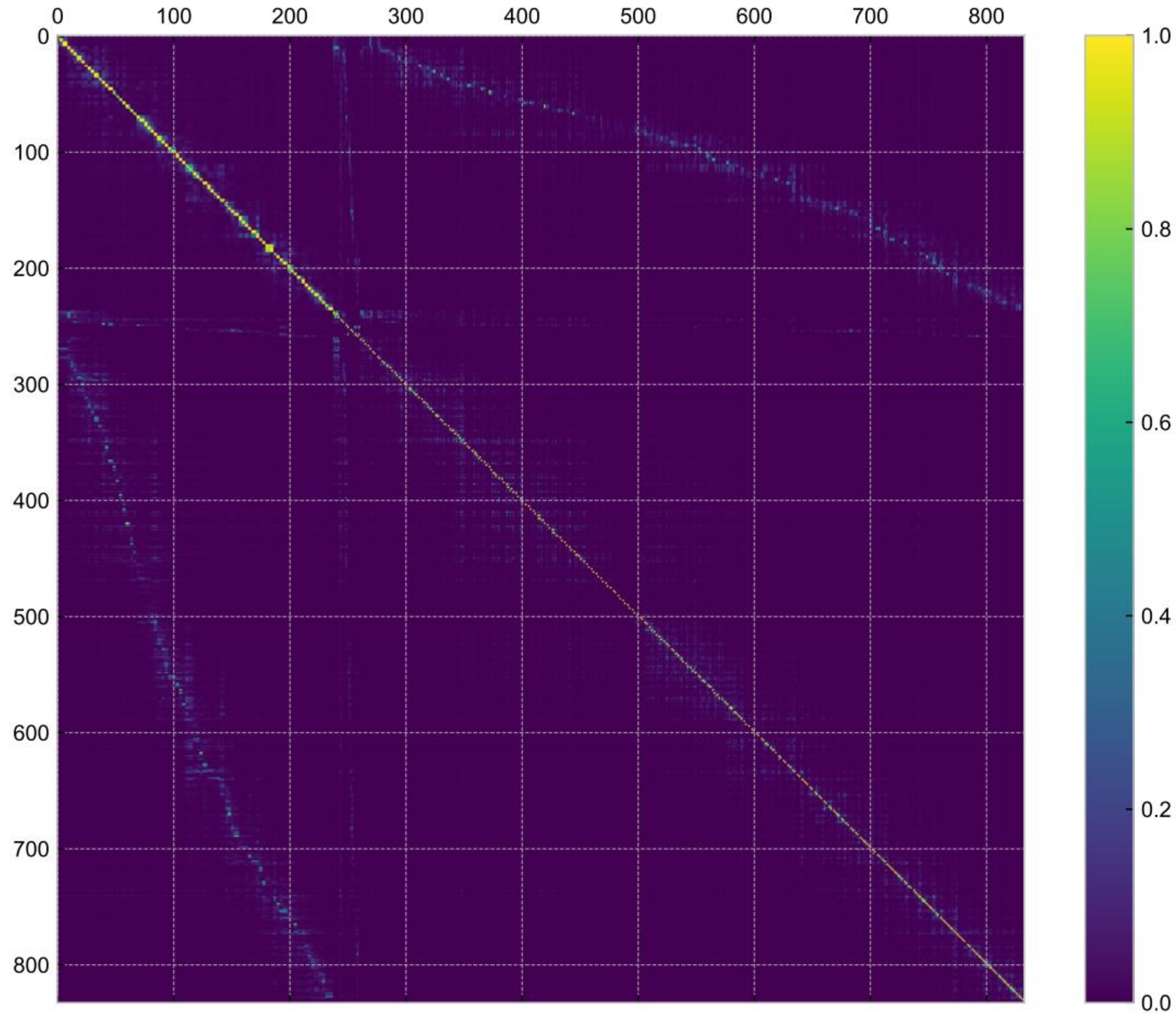
How large are systematic errors?

How much does ε depend on tracking station position, our knowledge of solar radiation pressure, etc.?

Over 800 parameters solved for, including the EEP violation parameter

(Others: spacecraft state vector, SRP coefficients, reaction wheel unloading, etc.)

Covariance matrix based on analysis of March 2017 data



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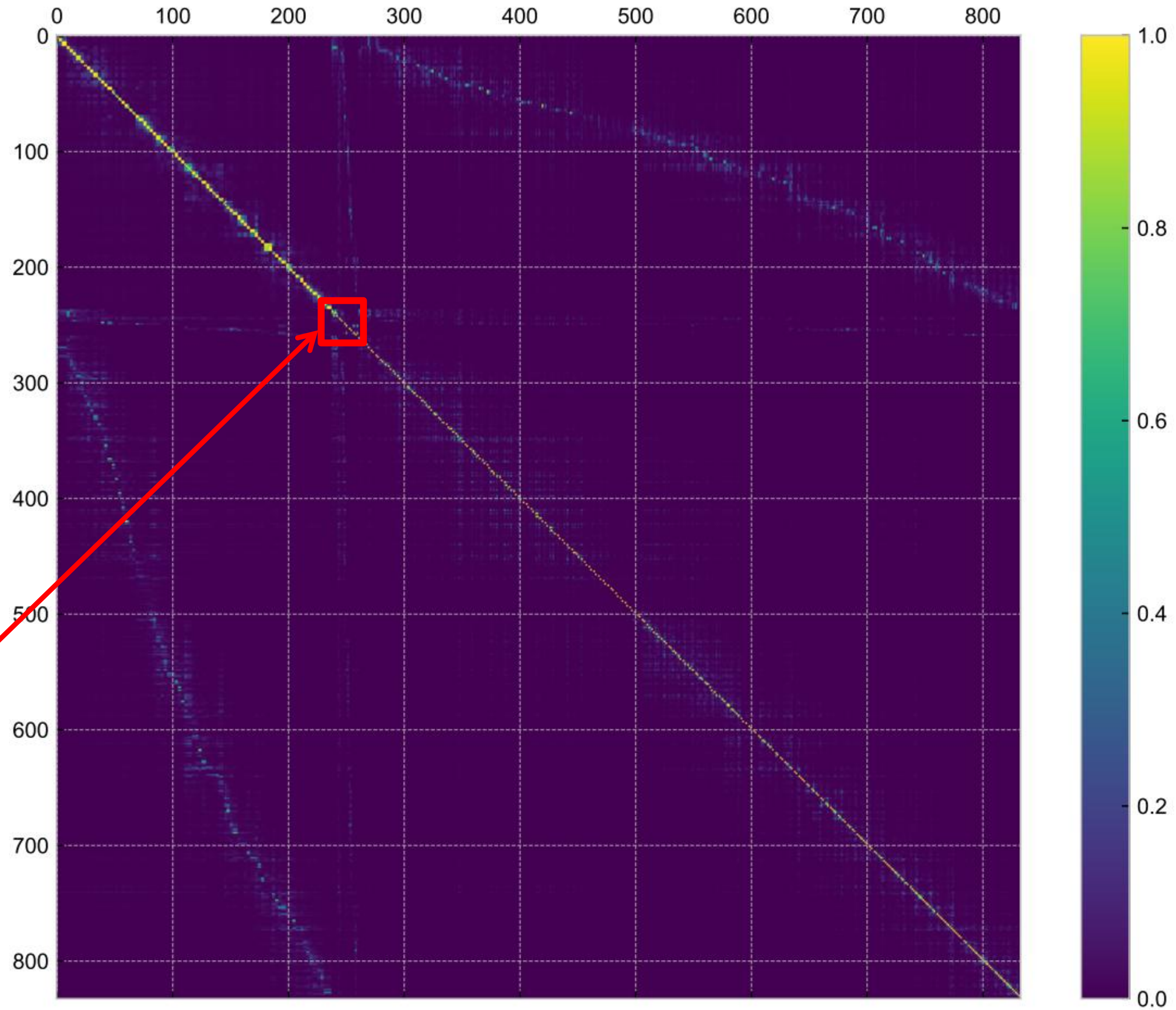
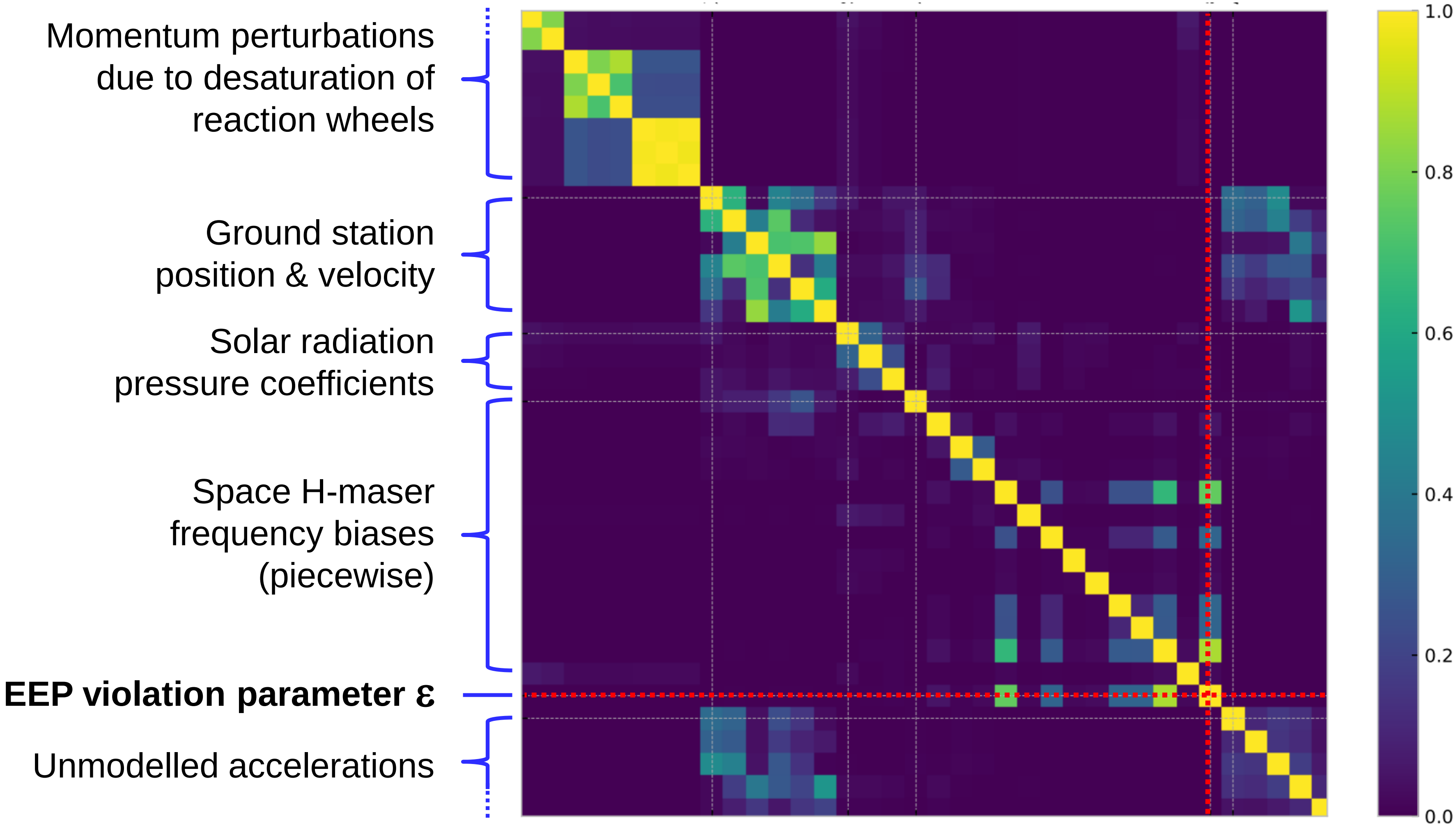
(Others: spacecraft state vector, SRP coefficients, reaction wheel unloading, etc.)

Let's zoom into this area

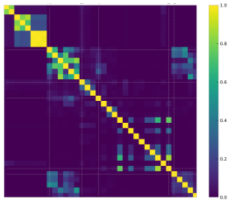
Covariance matrix based on analysis of March 2017 data



Systematic errors: covariance analysis

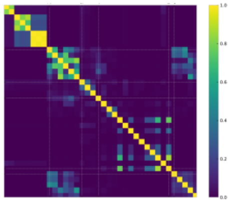


ε is correlated only with the space H-maser frequency biases



Lessons from the covariance analysis:

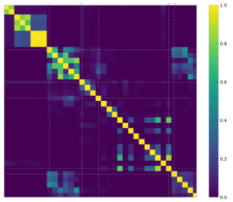
1. EEP violation parameter ε is correlated only with the space H-maser frequency biases.



Lessons from the covariance analysis:

1. EEP violation parameter ε is correlated only with the space H-maser frequency biases.

2. Independent measurement of these biases is required – done in calibration observations.



Lessons from the covariance analysis:

1. EEP violation parameter ε is correlated only with the space H-maser frequency biases.

2. Independent measurement of these biases is required – done in calibration observations.

3. Other parameters are harmless, e.g. tracking station position uncertainty up to 1 meter is ok.

Well-known fact:

Redshift violation parameter ε may depend on clock type and element composition of the gravitational field source, e.g. its ratio of neutrons to protons. Possible clock dependence is exploited in null-redshift tests.

New (Wolf & Blanchet, 2016):

EEP violation due to other bodies is at first order in respective Δ*U*'s.

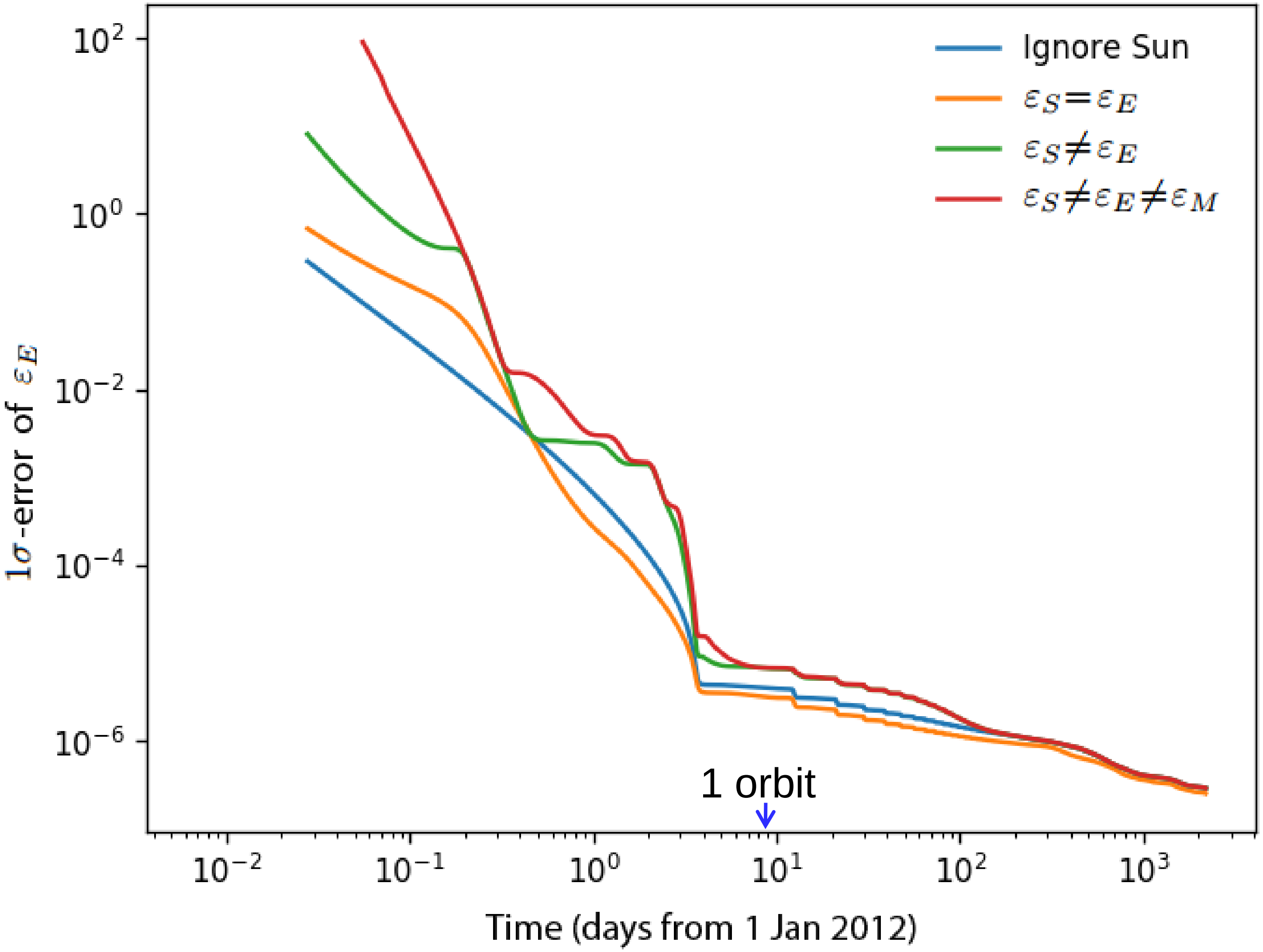
$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U_E}{c^2}(1+\varepsilon_E)$$

⇓

$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U_E}{c^2} + \frac{\varepsilon_E \Delta U_E + \varepsilon_S \Delta U_S + \varepsilon_M \Delta U_M + \ldots}{c^2}$$

E – Earth
S – Sun
M – Moon

Accuracy of measuring ε_E with RadioAstron – simulations



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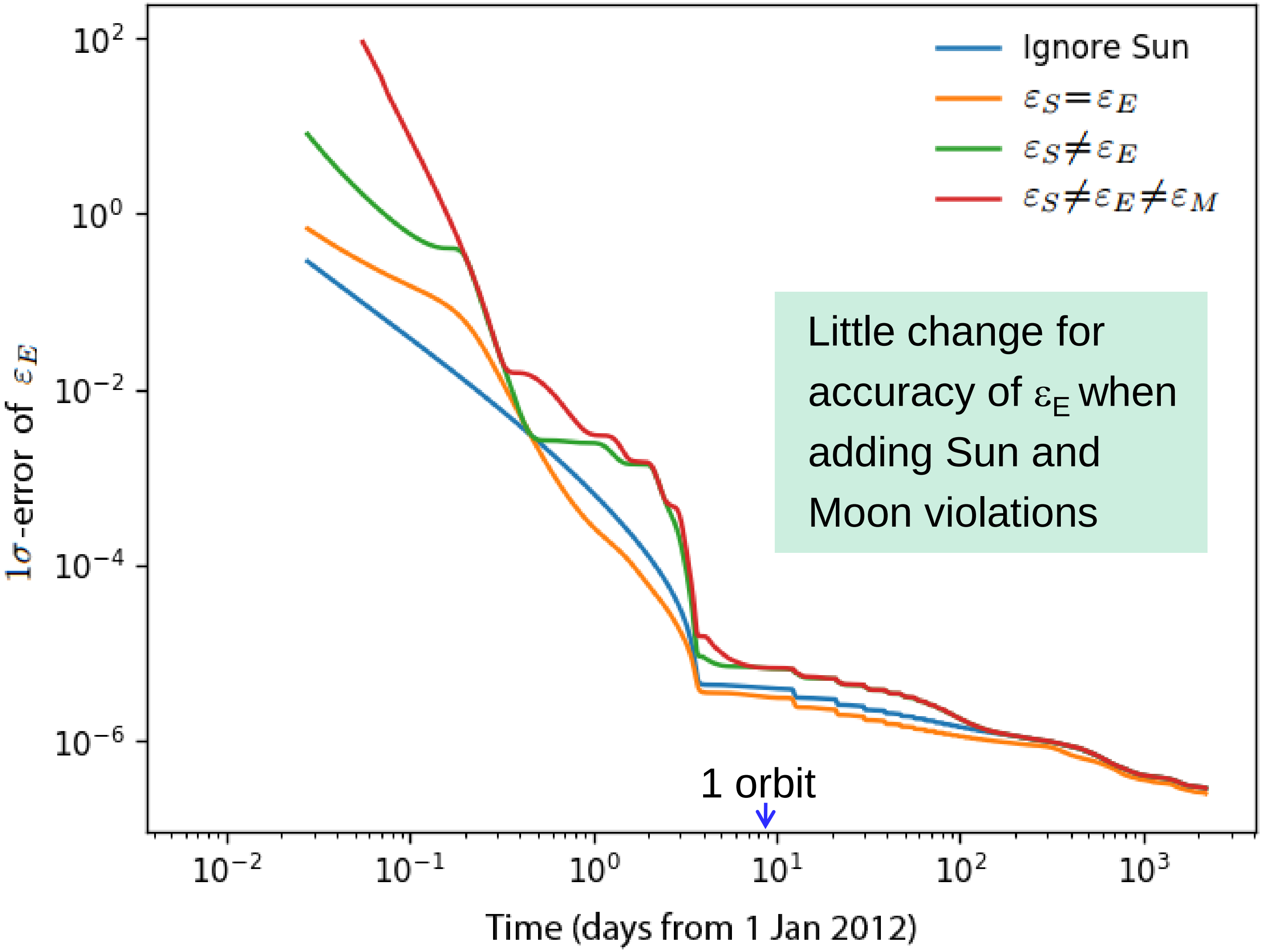

Gravitational redshift experiments

Experiment	Launch/ Status	Frequency standard	Achieved/ expected $\delta\varepsilon$
Gravity Probe A	1976 completed	H-maser	1.4×10^{-4}
RadioAstron	2011 data processing	H-maser	$(1–2)\times10^{-5}$
Galileo 5 & 6	2014 data processing	H-maser	$(3–4)\times10^{-5}$
ACES	2020 to be launched	Cs-fountain + H-maser	$(2–3)\times10^{-6}$

Summary

1. Observations finished: 62 measurements + 79 calibrations. Data analysis in progress.

2. Accuracy of 2×10^{-4} achieved in a single experiment (GP-A: 1.4×10^{-4})

3. Final accuracy of $\sim 10^{-5}$ seems realistic after full data analysis

4. One-way data analysis results: $\sim 10^{-3}$ as expected, systematics

5. Good news from the covariance analysis

6. Now taking into account the violation of Sun and Moon redshifts

Thank you!