Searching for large dark matter clumps using the Galileo Satnav clock variations

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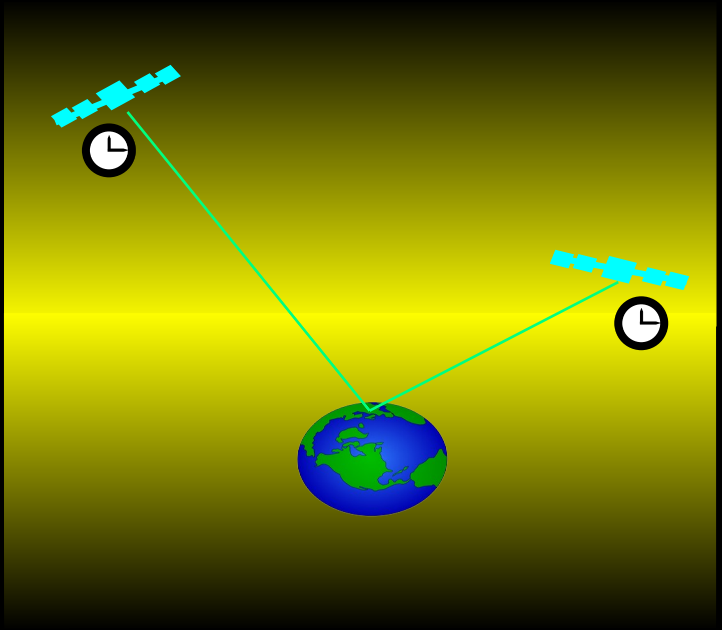

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The work reported in this paper has been performed and fully funded under a contract of the European Space Agency in the frame of the EU Horizon 2020 Framework Programme for Research and Innovation in Satellite Navigation. The views presented in the paper represent solely the opinion of the authors and should be considered as R&D results not necessarily impacting the present and future EGNOS and Galileo system designs.

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Geo Azur

Our goal

Use atomic clocks onboard Galileo satellites to test transient variations of fundamental constants

The fine structure constant

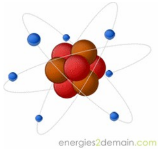
α

Strength of the electromagnetic interaction

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar\, c} \approx \frac{1}{137}$$

Proton-to-electron mass ratio

μ



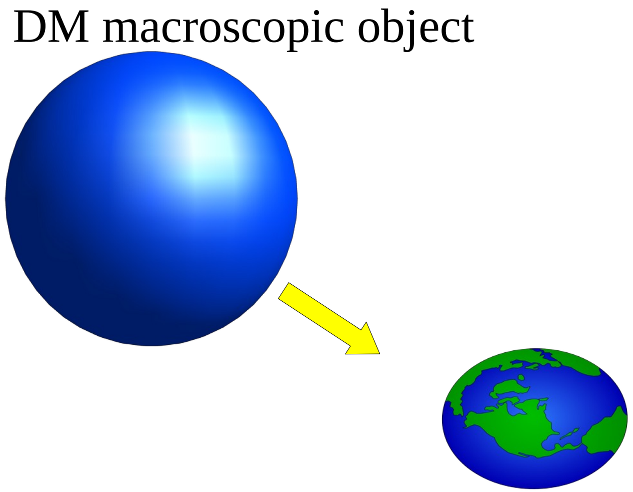
$$\mu = \frac{m_{\rm p}}{m_{\rm e}} \approx 2000$$

Dark matter

Dark matter (DM) models as a test bench of our method

- Recent investigation: DM could be on the form of clusters or macroscopic structures.

- Such structures could cross regularly the Earth!
  => DM transients



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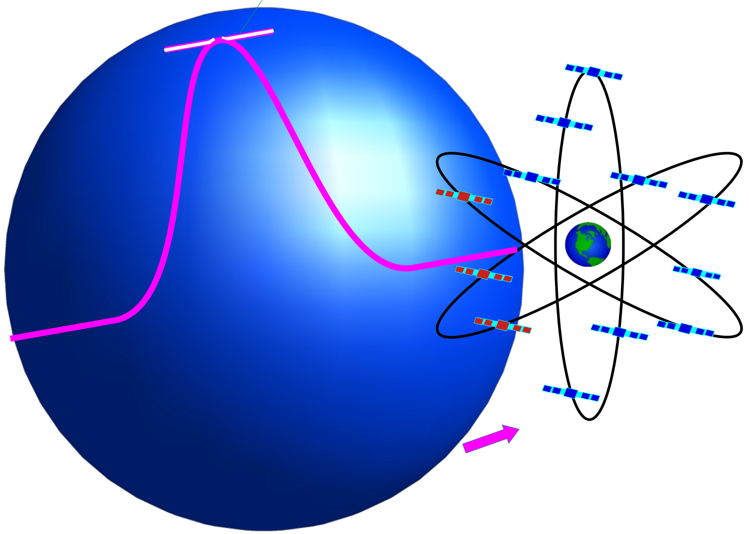
Phenomenological approach

Apparent spacetime variation of fundamental constants



Effective fermion mass $m_f^{eff}(x) = m_f^0 \left(1 + \Gamma_f \varphi^2(x)\right)$

Effective fine structure constant $\alpha_{eff}(x) = \alpha_0 \left(1 + \Gamma_\alpha \varphi^2(x)\right)$

Γ_x characterises the strength of the coupling between the DM field and electromagnetism/fermions $\Gamma_x \equiv \Gamma_\alpha$ or Γ_f

$\varphi(x)$ dark matter scalar field

Observable from Galileo clocks

A. Derevianko & M. Pospelov, Nature Phys., vol.10, 2014
M. Pospelov et al., Phys. Rev. Lett. 110, 2013
L. Visinelli & J. Redondo, arXiv:1808.01879,2018
A. Banerjee et al., arXiv:1902.08212, 2019

Galileo: a giant detector for new physics

Shift in energy levels inside the transient

⬇

Transient shift in H-maser clock frequencies

$$\frac{\omega(t)-\omega_0}{\omega_0} = \kappa_\alpha \frac{\Delta\alpha(t)}{\alpha_0} + \sum_{\mathrm{f}} \kappa_{\mathrm{f}} \frac{\Delta m_{\mathrm{f}}(t)}{m_0}$$

Sensitivity coefficients

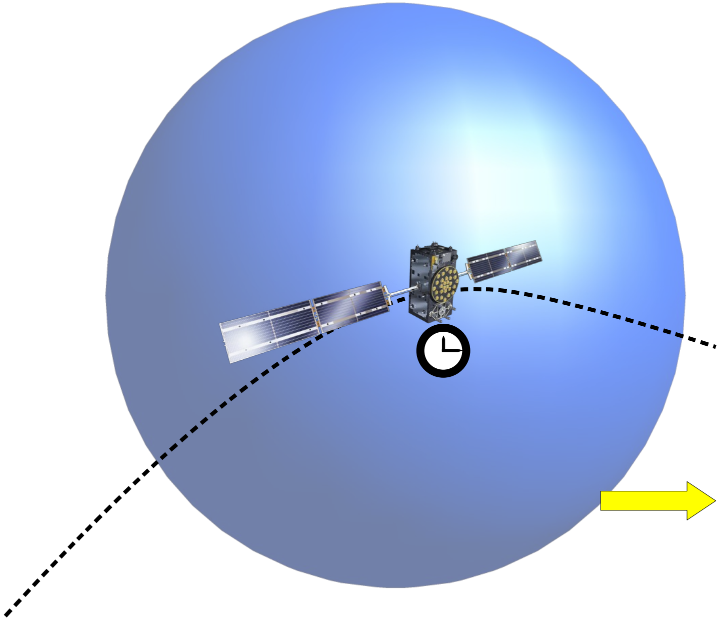


Image Galileo sat.: Nicky Appelgryn

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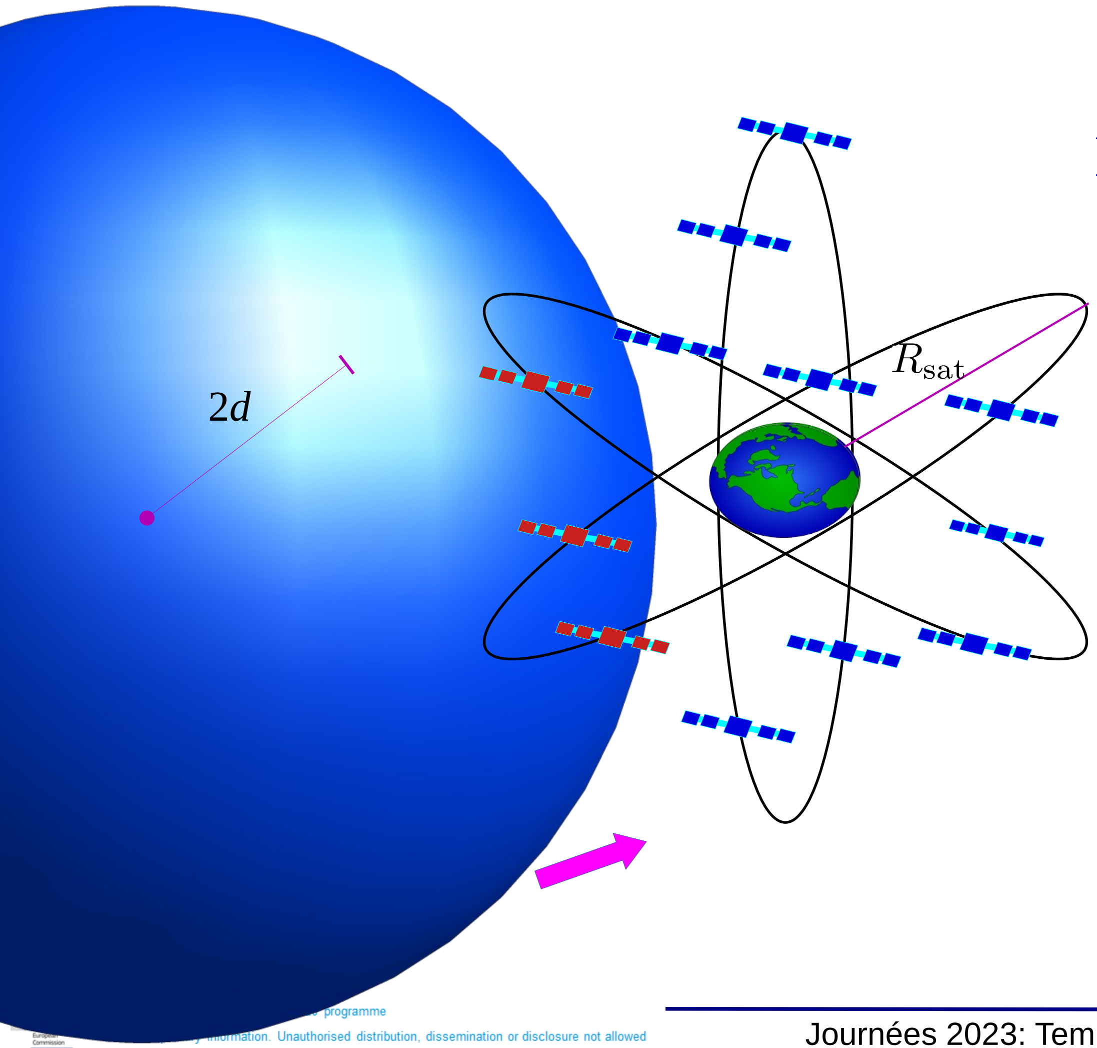
Large transients of size 4d

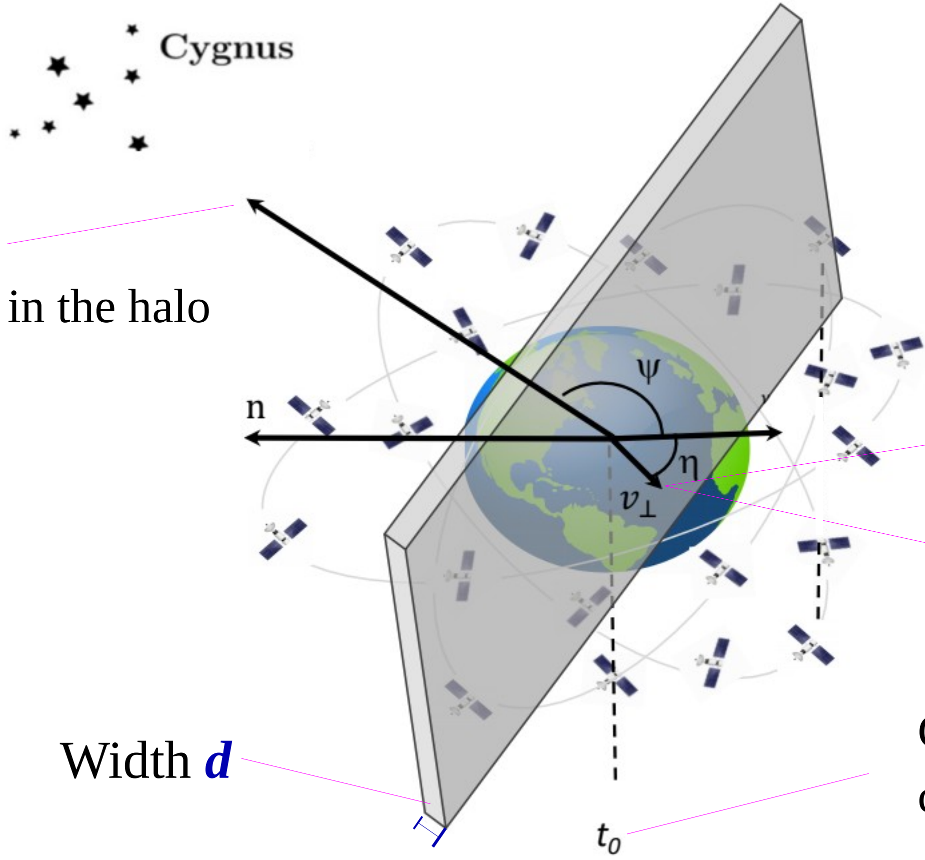


Large transient: $2d >> 30\,000$ km (R_{sat})

Approximate the transient variation of fundamental constant with a planar symmetry

Geometry of a transient encounter

Our modeling depends on a set ξ of 5 parameters: $\xi \equiv (d, v_\perp, \theta, \phi, t_0)$



v_c=220 km/s
Sun velocity in the halo frame

Transient relative incident velocity
$\vec{v} = v\,\vec{n}$

Velocity component normal to the transient surface
$v_\perp = v\cos(\eta)$

2 incident angles ***θ***, ***ϕ***

Width ***d***

Crossing time t_0 of the Earth center by the transient core

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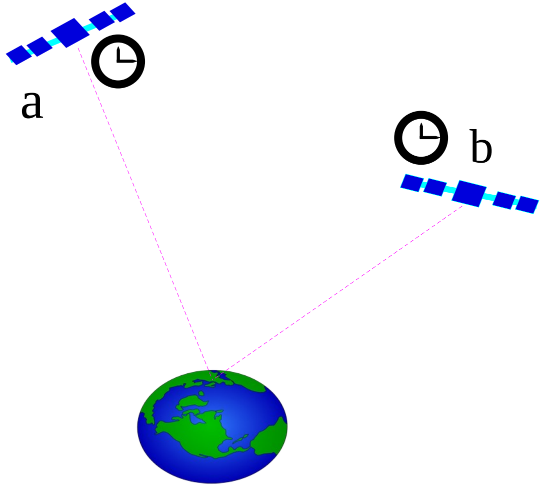
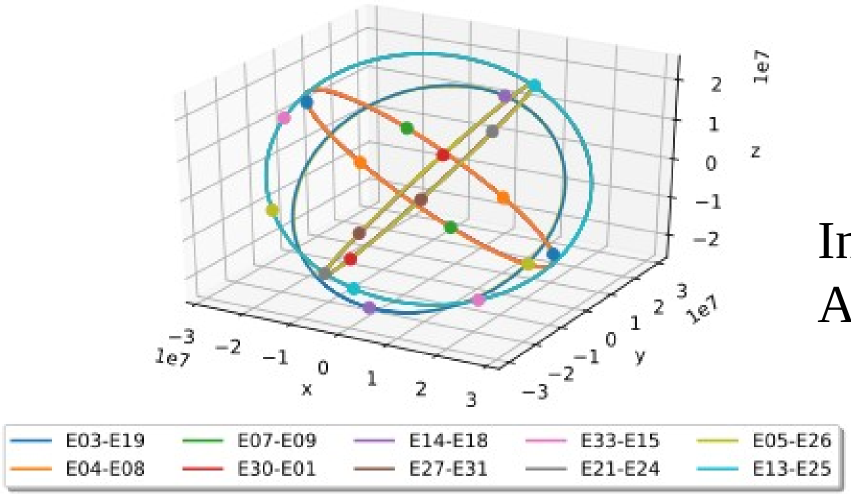
Clock data series over 1 year

$s_{\mathrm{ab}}(t)$ Clock bias between two clocks ‘a’ and ‘b’



With a time sample ΔT = 30s

‘Frequency bias’: $s^{(1)}_{\mathrm{ab}}(t) = \dfrac{s_{\mathrm{ab}}(t) - s_{\mathrm{ab}}(t-\Delta T)}{\Delta T}$



Independent pairs of clocks a,b
As far apart as possible

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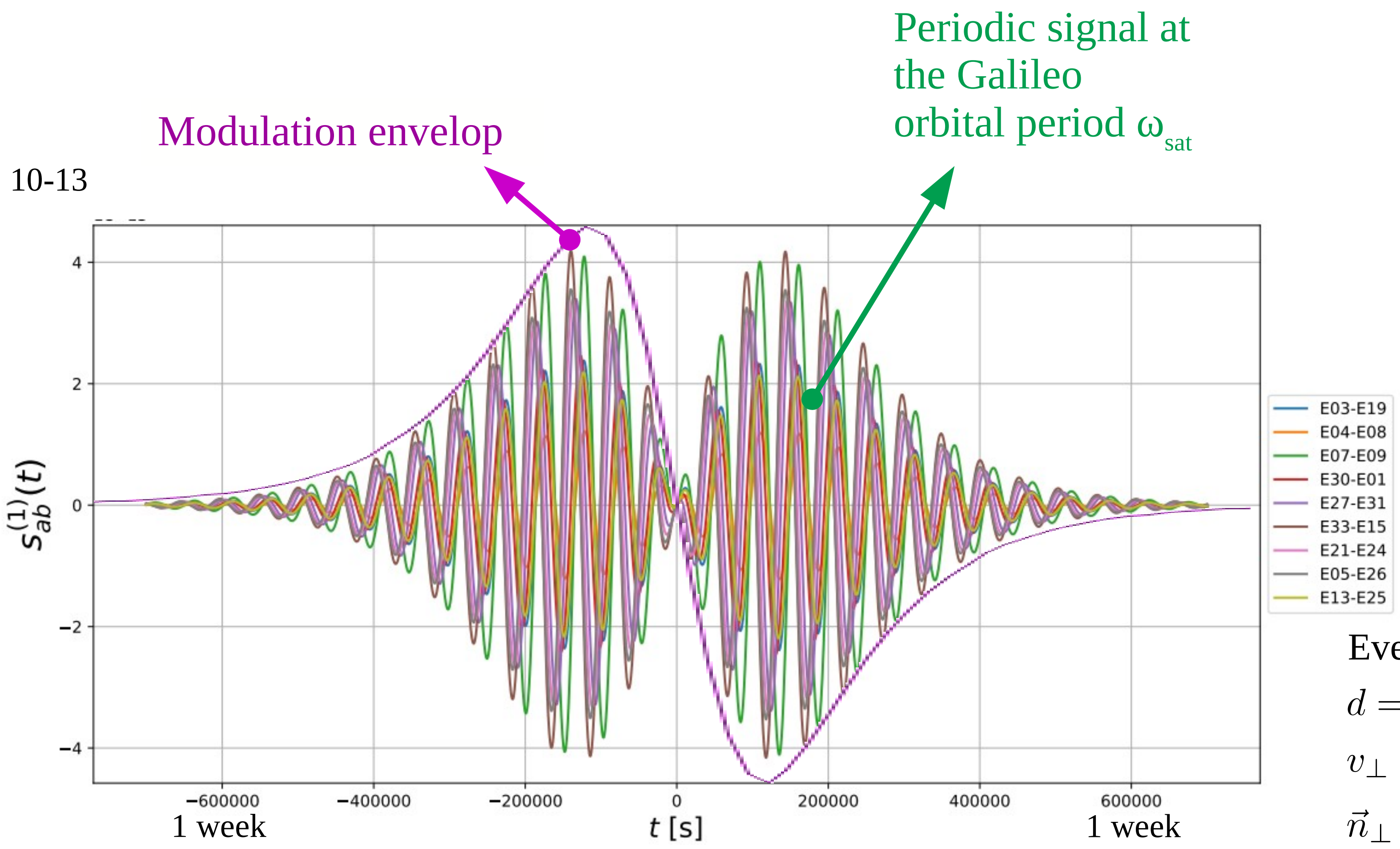
Modeling the expected signature



Event simulation

$d = 10^7\,\mathrm{km}$

$v_\perp = 220\,\mathrm{km/s}$

$\vec{n}_\perp = 0.5(\sqrt{2}, 1, 1)$

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Template bank

Modeled signal

$$s^{(1)}_{\mathrm{ab}} = h\,\boxed{\bar{s}_{\mathrm{ab}}(t,\xi)}$$

A large bank of N_t signal templates $\bar{s}_{ab}$ was created by N_t combinations of the ξ event parameters

$$s^{(1)}_{\mathrm{ab}} = h\,\bar{s}_{ab}(t; d, v_\perp, \theta, \phi, t_0; \vec{r}_{\mathrm{a}}(t), \vec{r}_{\mathrm{b}}(t))$$

Event parameters

$$\xi \equiv (d, v_\perp, \theta, \phi, t_0)$$

Galileo satellite orbital data

Signal strength $h(\Gamma_x, \rho_{DM})$

Parameter to constrain

Local dark matter energy density: upper limit for the energy density

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Detection threshold

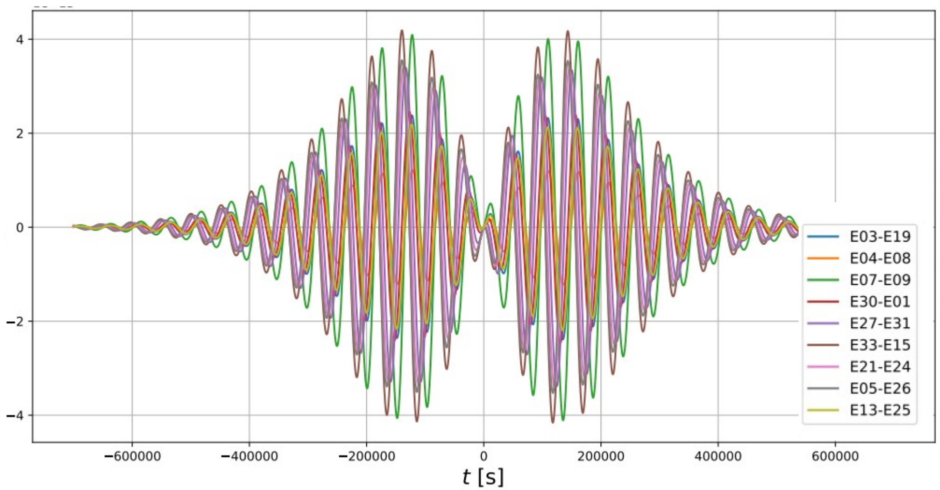
Covariance Matrix $\mathbf{C}^{-1}$

Modeled signal $s_{\mathrm{ab}}^{(1)} = h\,\bar{s}_{\xi}$

Data series d

Template-dependent signal-to-noise ratio (SNR) ρ_ξ

$$\rho_\xi = \frac{h_\xi}{\sigma_{h_\xi}} = \frac{d^T \cdot C^{-1} \cdot \bar{s}_\xi}{\sqrt{s_\xi^T \cdot C^{-1} \cdot \bar{s}_\xi}}$$



$d = 10^7$ km

$t_0 = 720$ h

$v_\perp = 300$ km/s

$\theta = 45°$ $\phi = 45°$

Detection threshold ρ_{thres} with N_t templates $\bar{s}(\xi_{\mathrm{i}})$ from max-SNR distribution

ρ_{thres}

- Candidate events $\rho[\bar{s}(\xi_{\mathrm{i}})] > \rho_{\mathrm{thres}}$
- No event in the data stream $\rho[\bar{s}(\xi_{\mathrm{i}})] < \rho_{\mathrm{thres}} \quad \forall \mathrm{i} \in [1, N_{\mathrm{t}}]$

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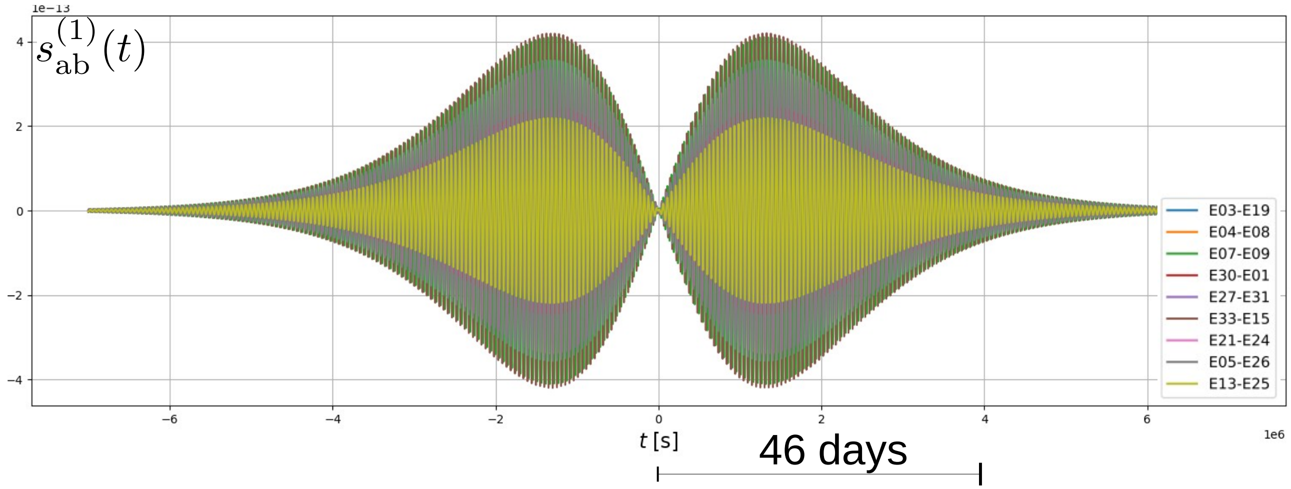
Observed candidate events

Over 1 year of observation, up to 6% of events with $\rho[\overline{s}(\xi_{\rm i})] > \rho_{\rm thres}$ according to the observation epoch

The SNR increases for large transients ($d \sim 10^8$ km) and low velocities ($v_\perp < 100$ km/s)



Simulation of typical observed events

$d = 10^8$ km

$v_\perp = 50$ km/s

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Origin of observed signatures

Least likely origin

Known systematic effects not correctly taken into account

Interstellar or extra-galactic known source

New unknown physics like DM interaction

Picture: Nasa

Image: Nasa

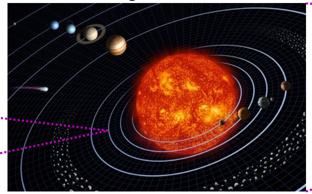
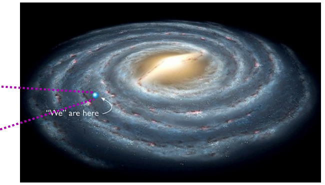


Image:
Jet Propulsion Laboratory



Earth albedo,
⊕ magnetic field variations
…

Solar radiation pressure (SRP)
…

Transient variation of fundamental constants

Unknown systematic effect for GNSS clocks

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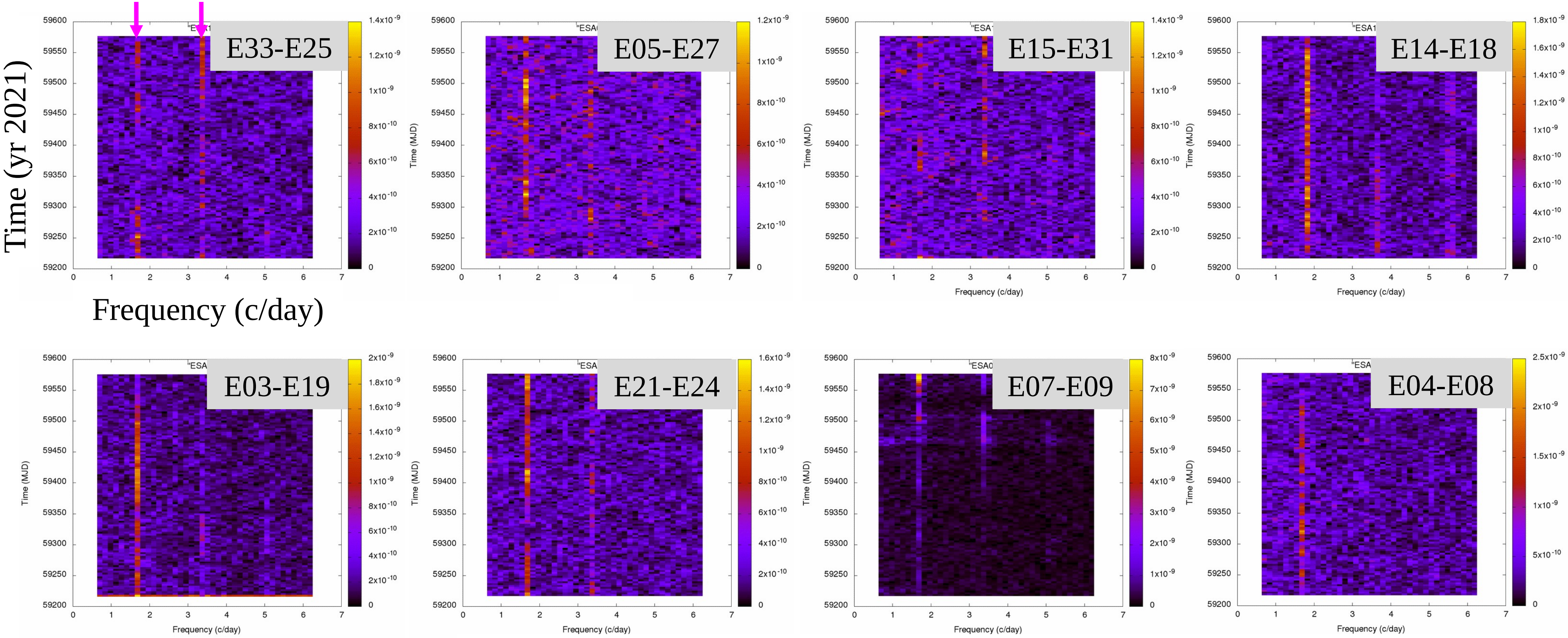
Systematic effects at the orbital period

Sliding window Fourier Transform of satellite clock frequency data

Orbital period Semi-Orbital period



Orbital period present in the clock frequency data, with variable amplitude

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Disentangle systematics

Transients DM objects

Full time correlation over the 21 satellites

Statistical SNR threshold ρ_{thres}

Candidate events

~~No event~~

Intensive SLR campaign over 3 months

Finer analysis of systematic effects

Exclusion of some models

Discovery of an unknown effect

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