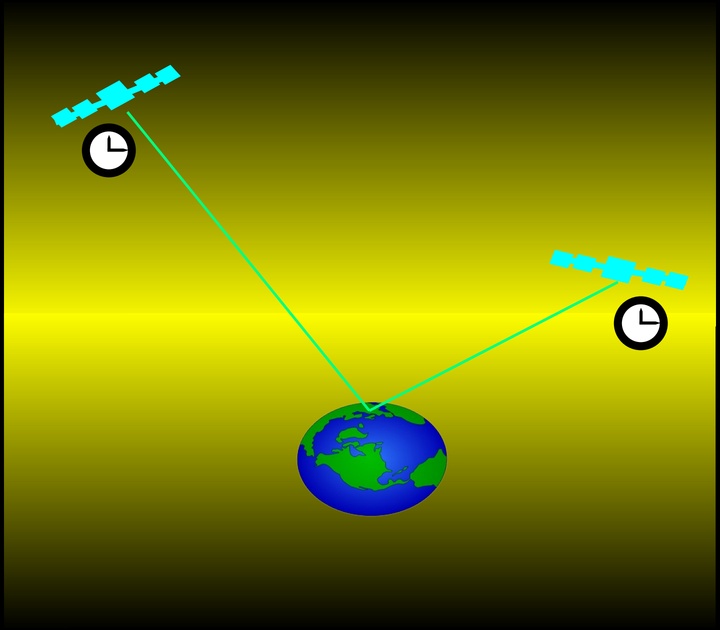
GAlileo Survey of Transient Objects Network (GASTON) project

Searching for dark matter using the Galileo satellites



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8th International Colloquium on Scientific and Fundamental Aspects of GNSS
September, 15th

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.

Fundamental constants

Fundamental constants are free parameters inherent to the theory that introduces them.

Why a constant could vary ?
Signature of new physics beyond the Standard Model

=> Dimensionless combinations of constants are measured: fundamental parameters

Standard Model:
22 constants

Rest mass of particles
Proton, electron, quarks…
m_p m_e m_q

Planck constant $\hbar$

Elementary charge e

Speed of light c
…

Damour T., J. Donoghue, 2010, Phys. Rev. D 82
Stadnik Y., V. Flambaum, 2015, Phys. Rev. Let. 115
Arvanitaki A., et al, 2015, Phys. Rev. D 91
Hees A. et al, 2018, Phys.Rev.D 98

Our goal

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

The fine structure constant

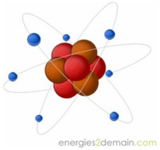
α

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

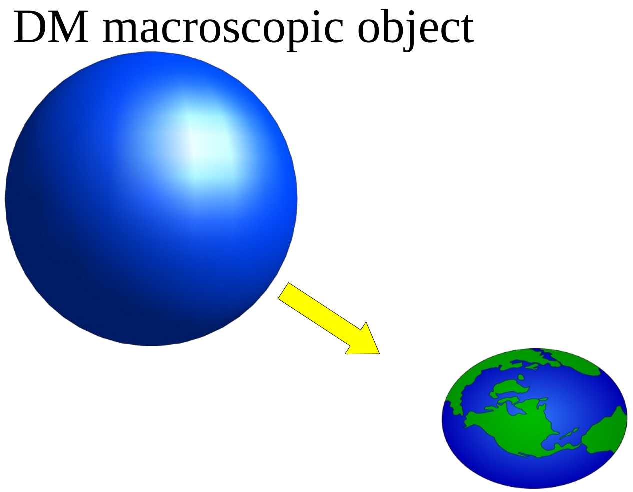


$$\mu = \frac{m_{\mathrm{p}}}{m_{\mathrm{e}}} \approx 2000$$

Dark matter

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

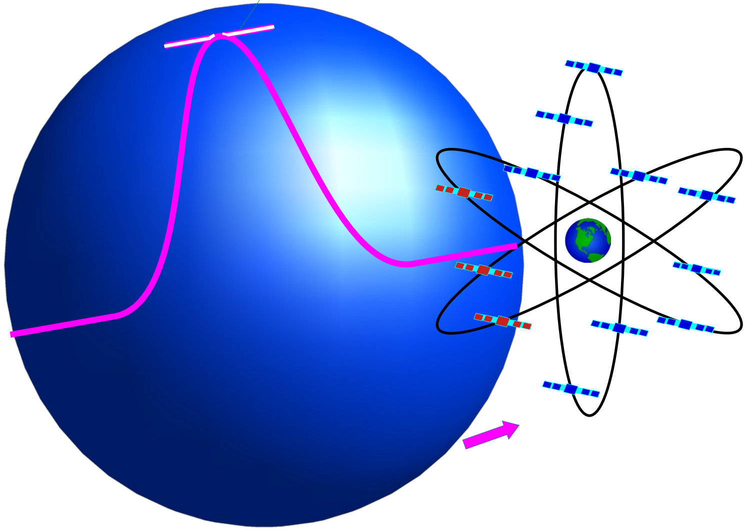
- Recent investigation: DM could be on the form of clusters or macroscopic structures.
- Such structures could cross regularly the Earth!
  => DM transients



Phenomenological approach

$\Gamma_{\mathrm{x}}\,\varphi^2(x)$ interaction

Apparent spacetime variation of fundamental constants



Effective fermion mass $m_{\mathrm{f}}^{\mathrm{eff}}(x) = m_{\mathrm{f}}^{0}\left(1 + \Gamma_{\mathrm{f}}\,\varphi^2(x)\right)$

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

Γ_{x} characterises the strength of the coupling between the DM field and electromagnetism/fermions

$\Gamma_{\mathrm{x}} \equiv \Gamma_{\alpha}$ or Γ_{f}

$\varphi(x)$ dark matter 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 atomic 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

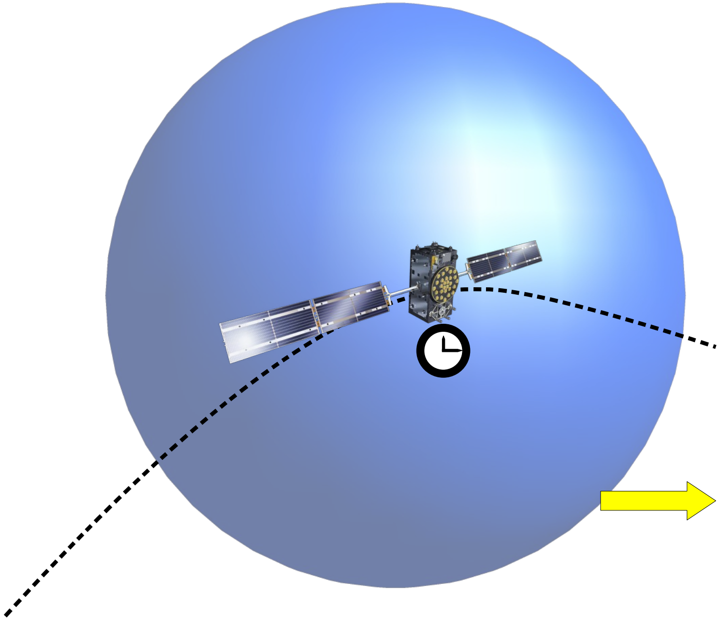


Image Galileo sat : Nicky Appelgryn

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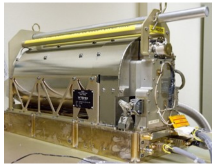
The Gaston project

Gaston project: large extension of B. M. Roberts et al., Nature Com., vol.8, 2017

More stable clocks
↓
Passive H-maser clocks onboard Galileo satellites



Finer analysis of systematic effects
↓
Intensive SLR campaign over 3 months

More complex theoretical model
↓
Extension to *large* transient objects: well beyond 10^3 km

Image maser: ESA

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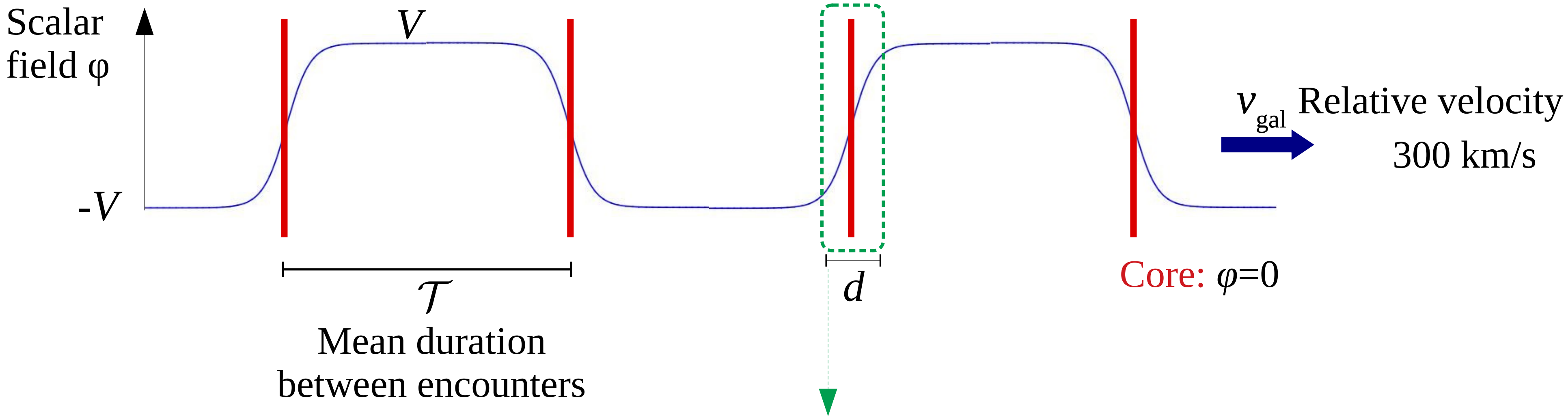
Transient network

Gaston model of energy density for a network of transient objects



Domain wall solution

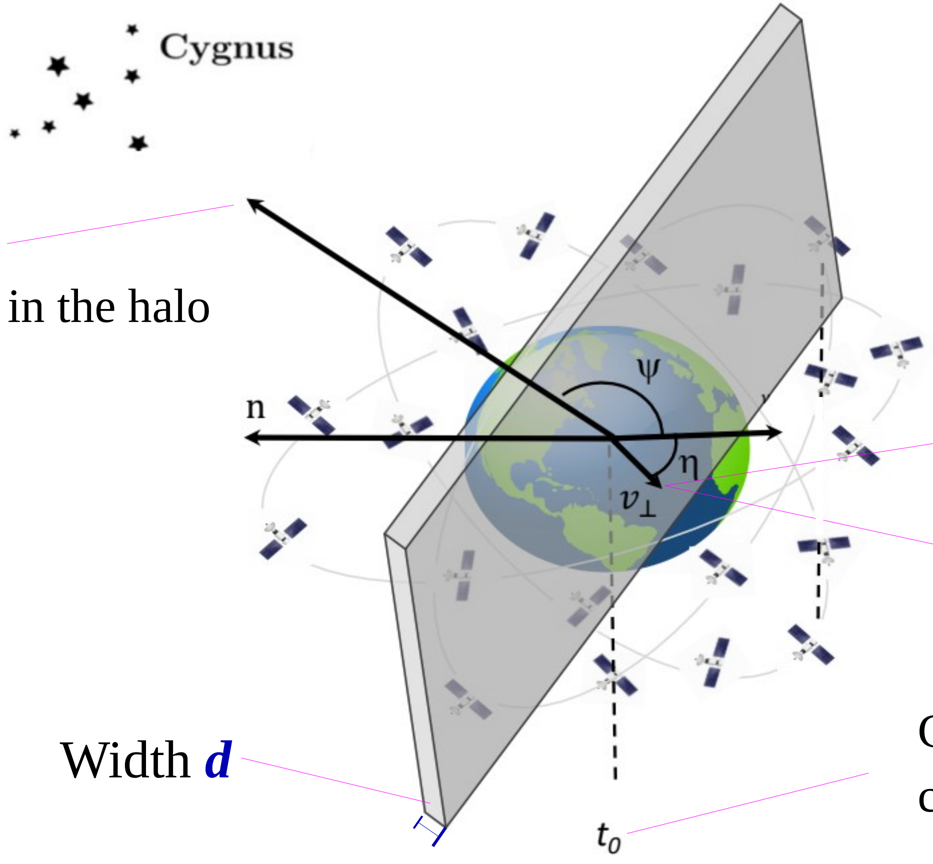
$$\varphi(z) = V\ \tanh\left(\frac{z}{d}\right)$$

Local dark matter energy density ρ_{DM}:
upper limit for the energy density

$$\frac{V^2}{d} \leq \frac{3}{4} v_{\rm gal}\, \mathcal{T}\, \rho_{\rm DM}$$

Geometry of a transient encounter

Our modelling 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 $\boldsymbol{\theta}$, $\boldsymbol{\phi}$

Width ***d***

Crossing time t_0 of the Earth center by the transient core

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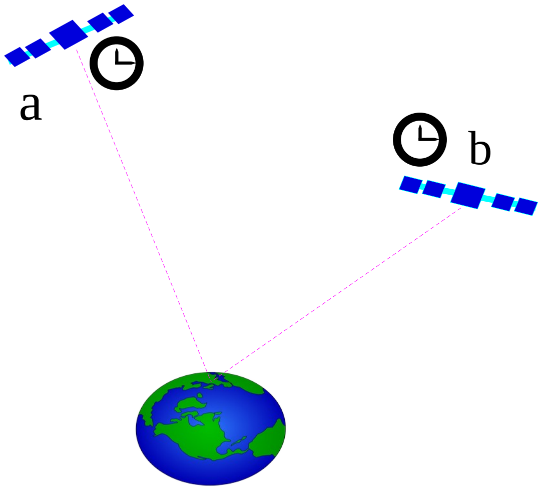
Clock data series

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



With a time sample $\Delta T = 30$s

$$s_{\mathrm{ab}}^{(1)}(t) = \frac{s_{\mathrm{ab}}(t) - s_{\mathrm{ab}}(t - \Delta T)}{\Delta T}$$

For each pair of Galileo clocks

- Moving windows of 14h in the $s_{\mathrm{ab}}^{(1)}(t)$ series
- Remove a linear regression in each window

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Template bank

A bank of signal templates $\bar{s}_{ab}(\xi,t)$ was modeled

Modeled signal

$$s^{(1)}_{\rm ab} = h \frac{\bar{s}_{\rm ab}(t,\xi)}{\Delta T}$$

Model dependent amplitude *h*

$$h = \underbrace{\Gamma_{\rm x}}_{} \frac{3}{2}\frac{R_{\rm sat}}{\omega_{\rm sat}} \underbrace{\rho_{\rm DM}\, v_{\rm gal}\, \mathcal{T}}_{}$$

$\Gamma_{\rm x}$ → Parameter to constrain

$\rho_{\rm DM}\, v_{\rm gal}\, \mathcal{T}$ → DM model

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

$d, v_\perp, \theta, \phi, t_0$ → Event parameters

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

$\vec{r}_{\rm a}(t), \vec{r}_{\rm b}(t)$ → Galileo satellite orbital data

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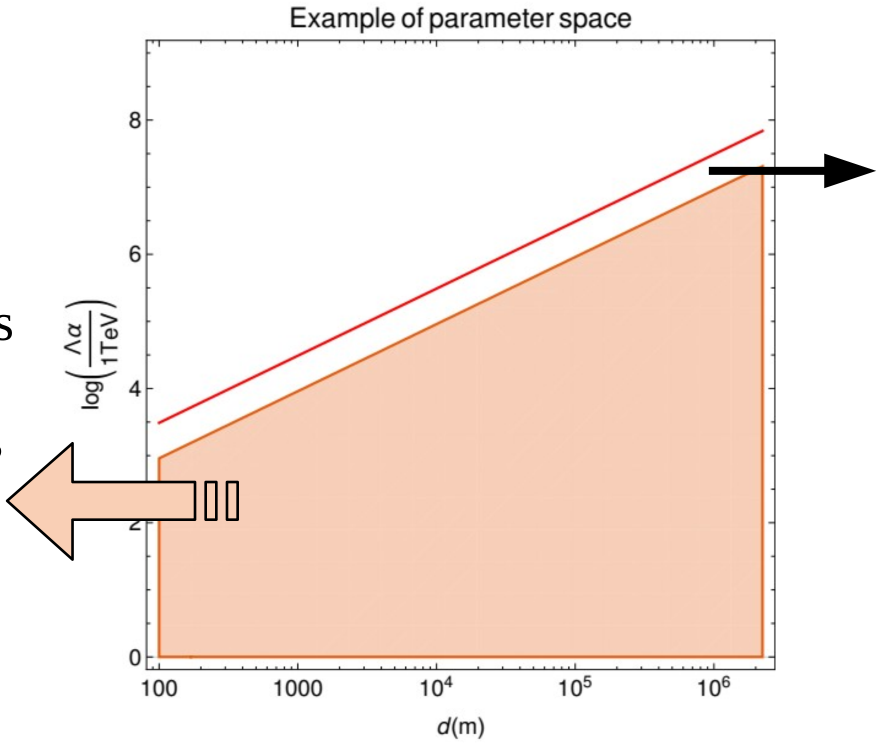
First step: excluding regions

Level 1 :
Maximum reach analysis

Look for frequency spikes in clock differences between pairs of satellites

Goal : Excluding regions of the parameter space



Level 2:
Frequentist approach

Correlation analysis over the whole set of available Galileo satellites

Goal : Detection of possible events

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Theoretical lower reach

Physical model for transient events

$$h(\Gamma_x)\,\bar{s}_{ab}(t; d, v_\perp, \theta, \phi, t_0; \vec{r}_a(t), \vec{r}_b(t))$$

Parameter to constrain

Physical pattern

Experimental data series

$$s^{(1)}_{ab}(t)$$

Theoretical lower reach for event configuration

$$s_*(d) \leq \bar{s}_{ab}(t; d; v_\perp, \theta, \phi, t_0; \vec{r}_a(t), \vec{r}_b(t))$$

Choosing the *worst* transient and satellite configuration at 95% level

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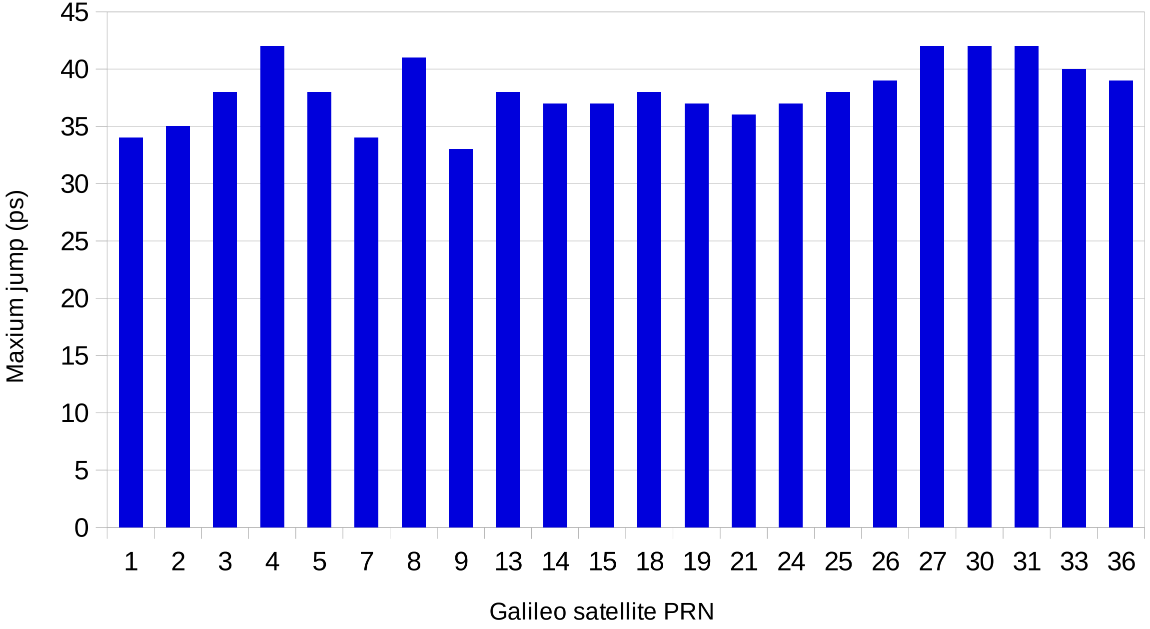
Maximum frequency spike

Experimental data series

$$s^{(1)}_{\mathrm{ab}}(t)$$

Considering for each satellite the maximum frequency spike with respect to all other satellite clocks



Largest Observed effect

$$s^{(1)}_{a,\max} = \max_{b \neq a} \quad \max_{t_i} \; s^{(1)}_{\mathrm{ab}}(t_i)$$

Considering the statistical clock noise:

$$\Delta T \min_a \; s^{(1)}_{a,\max} = 42\mathrm{ps}$$

Constraint on Γ_x

Physical model for transient events

$$s^{(1)}_{\mathrm{ab}} = h\,\frac{\overline{s}_{\mathrm{ab}}(t,\xi)}{\Delta T}$$

Experimental data series

Largest Observed effect

$$s^{(1)}_{a,\max} = \max_{b\neq a} \quad \max_{t_i}\; s^{(1)}_{\mathrm{ab}}(t_i)$$

Theoretical lower reach for event configuration

$$s_*(d) \leq \overline{s}_{\mathrm{ab}}(t;d;v_\perp,\theta,\phi,t_0;\vec{r}_{\mathrm{a}}(t),\vec{r}_{\mathrm{b}}(t))$$

Constraint

$$h(\Gamma_{\mathrm{x}})\, s_*(d) \leq 42\mathrm{ps}$$

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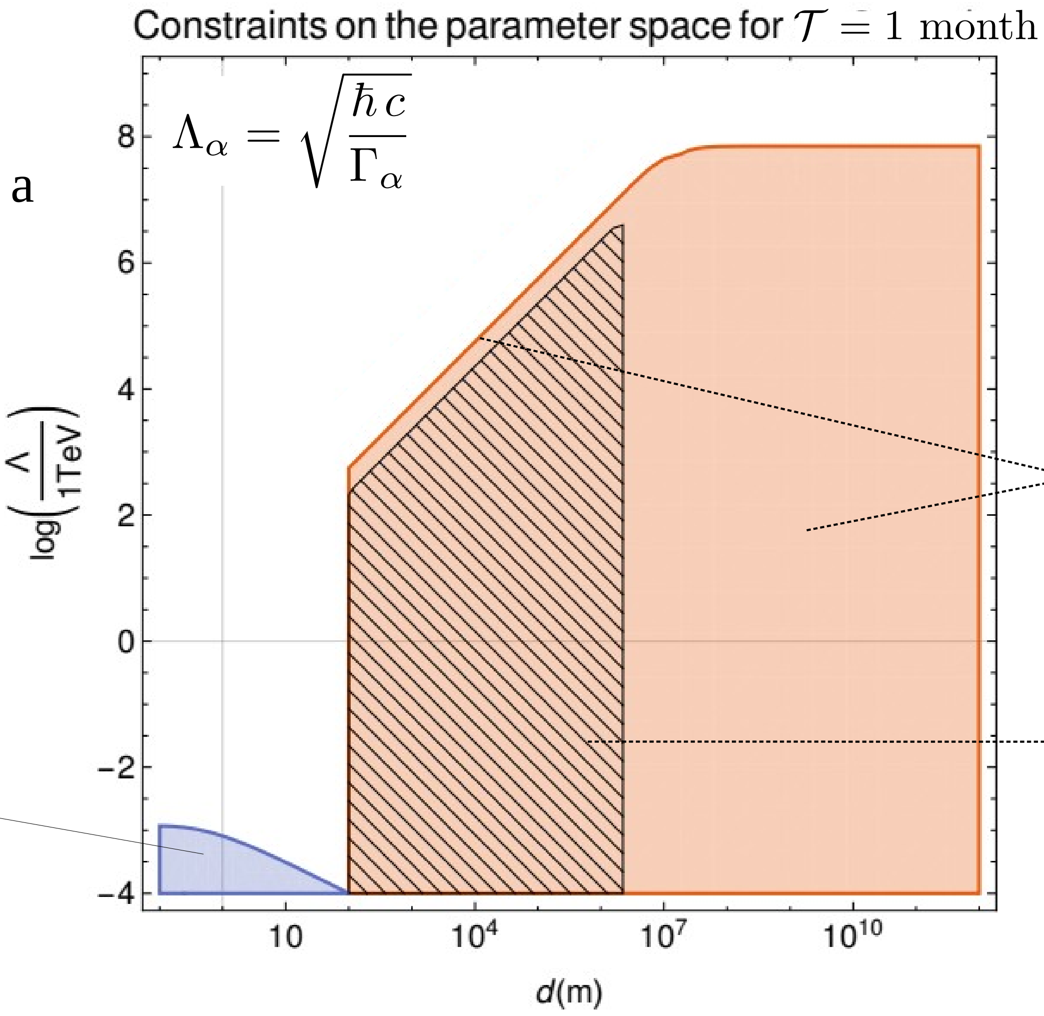
Parameter space exclusion

Size d of the transient restricted to 10^{12} m for a value of $\mathcal{T}$= 1 months



$$h(\Gamma_x)\, s_*(d) \leq 42\text{ps}$$

Gaston constraints by maximum reach analysis

Signal propagation

B. Bertrand and P. Defraigne, Adv. in Space Res.,Vol. 66, Issue 12, 2020

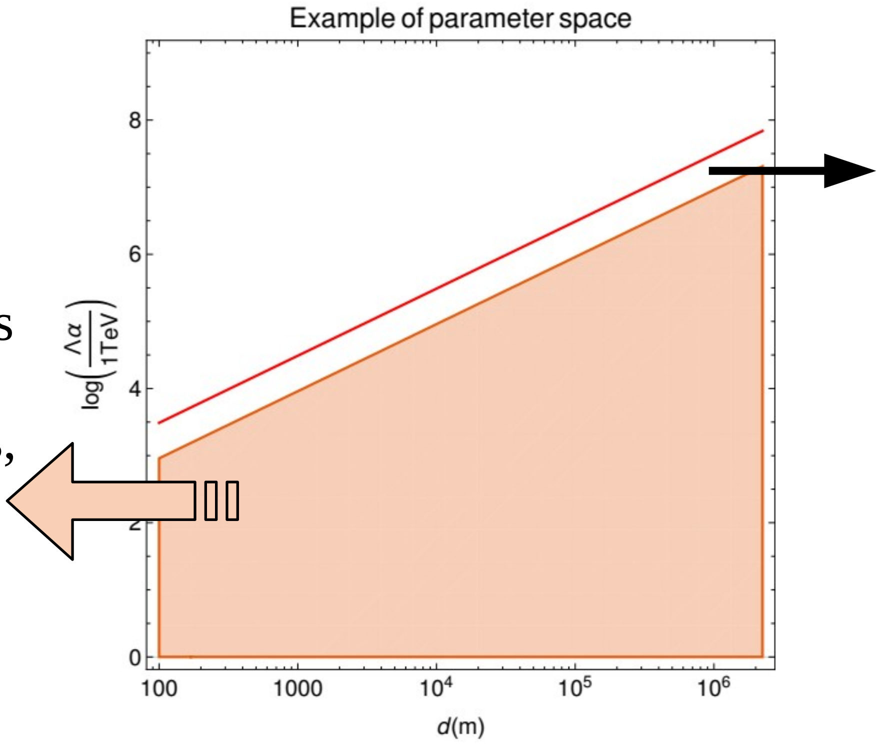
Hatched region:

B. M. Roberts et al., Nature Com., vol.8, 2017

Second step: frequentist approach

Level 1 :
Maximum reach analysis

Look for frequency spikes in clock differences between pairs of satellites, over the 3 months campaign



Level 2:
Frequentist approach

Correlation analysis over the whole set of available Galileo satellites

Goal : Detection of possible events

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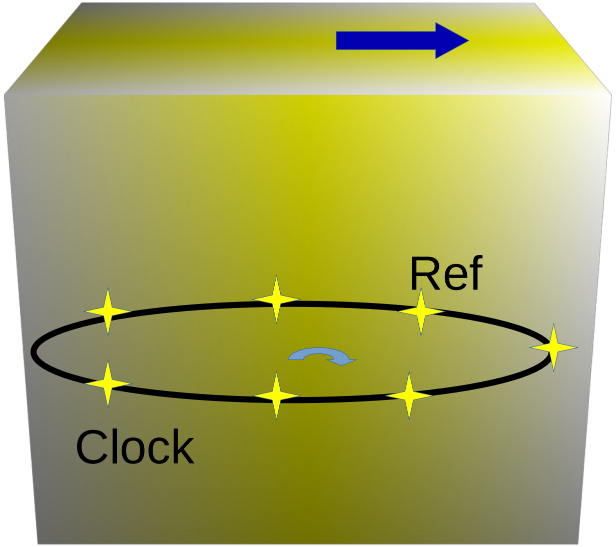
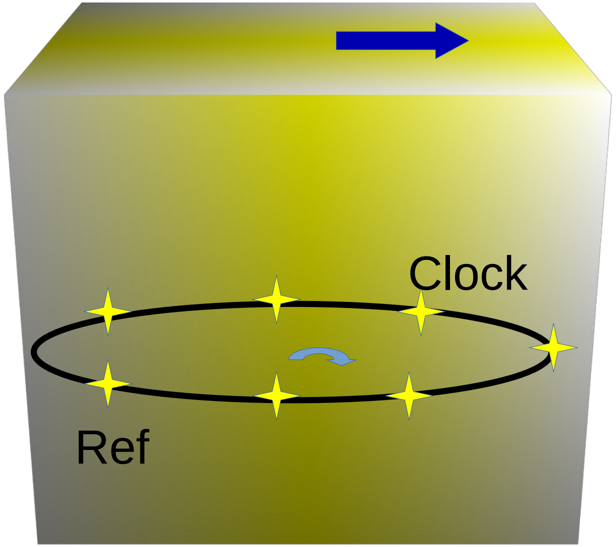
Periodic effect of large transients

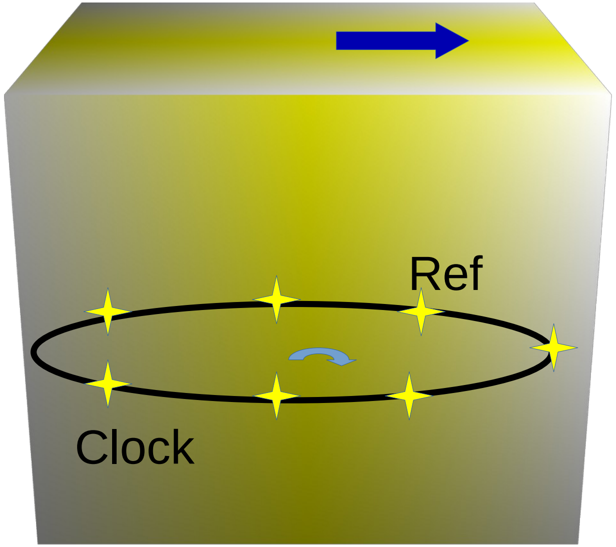
Gradient of the scalar field → Phase difference w.r.t. the reference clock



1) $t = t_0$



2) $t = t_0 + 7\text{h}$



3) $t = t_0 + 14\text{h}$

Periodic signature (orbital period) in the comparison between the clock and the reference clock

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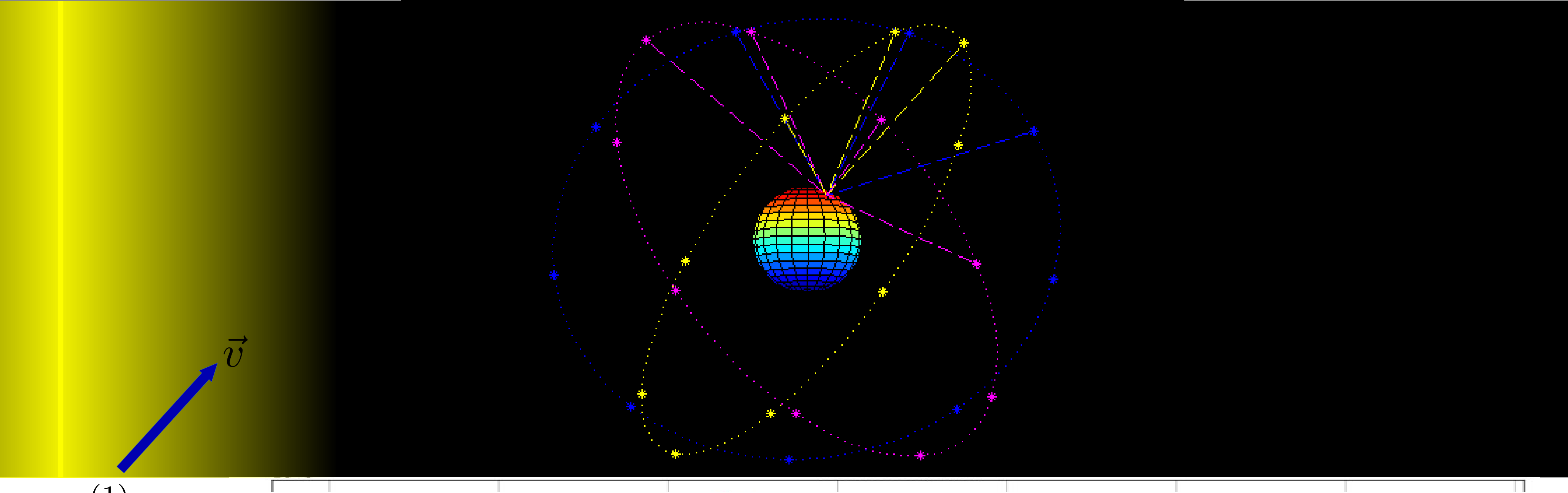


$s^{(1)}_{\mathrm{ab}}(t)$ 10^{-8}

Relative frequency

E03-E19	E07-E09
E04-E08	E30-E01
E14-E18	E33-E15
E27-E31	E21-E24
E05-E26	
E13-E25	

Time [h]

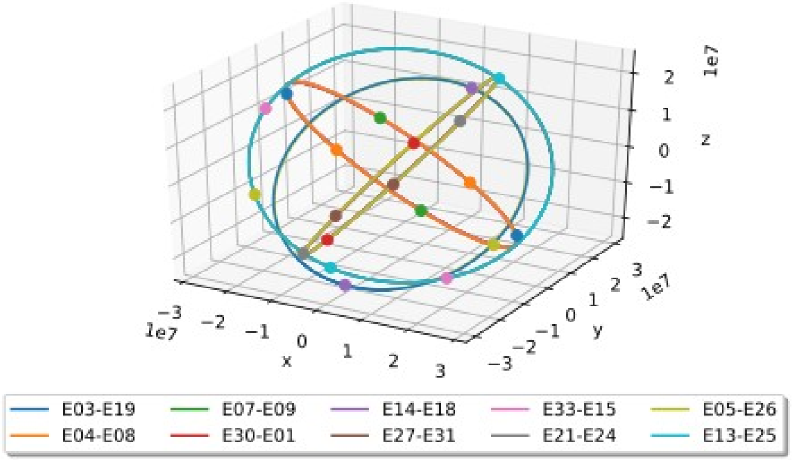
Global animation:
Bruno Bertrand

Gaussian likelihood

$$\mathscr{L}(D|S) \propto \exp\left(-\frac{1}{2}\left[d - h\bar{s}(\xi)\right]^T \boldsymbol{C}^{-1}\left[d - h\bar{s}(\xi)\right]\right)$$

Data series — Covariance matrix

Independent pairs of clocks a,b:
diagonalises **C**



Detection threshold

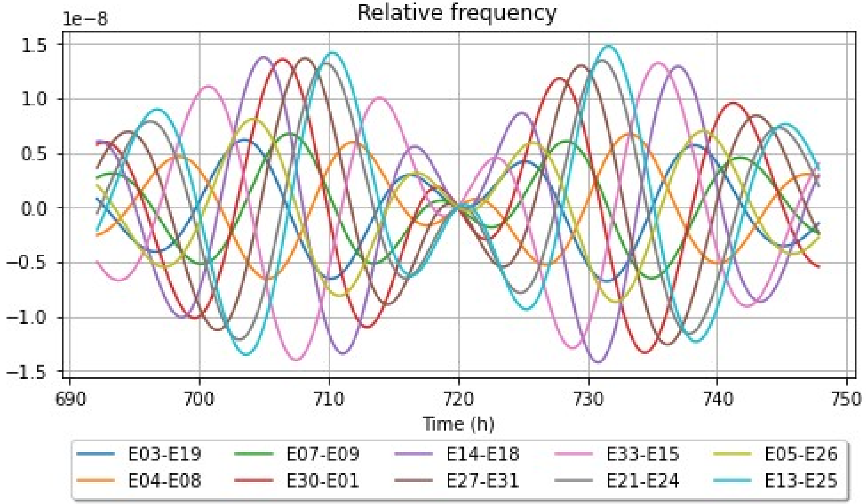
Gaussian likelihood

$$\mathscr{L}(\boldsymbol{D}|\boldsymbol{S}) \propto \exp\left(-\frac{1}{2}[\boldsymbol{d}-h\bar{\boldsymbol{s}}(\xi)]^T \boldsymbol{C}^{-1}[\boldsymbol{d}-h\bar{\boldsymbol{s}}(\xi)]\right)$$

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

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

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



Detection threshold ρ_{thres} with N_{t} templates from max-SNR distribution

$$\rho_{\mathrm{thres}} = \sqrt{2}\,\mathrm{erf}^{-1}\left(0.95^{\frac{1}{N_{\mathrm{t}}}}\right)$$

► Candidate events

► No event in the data stream

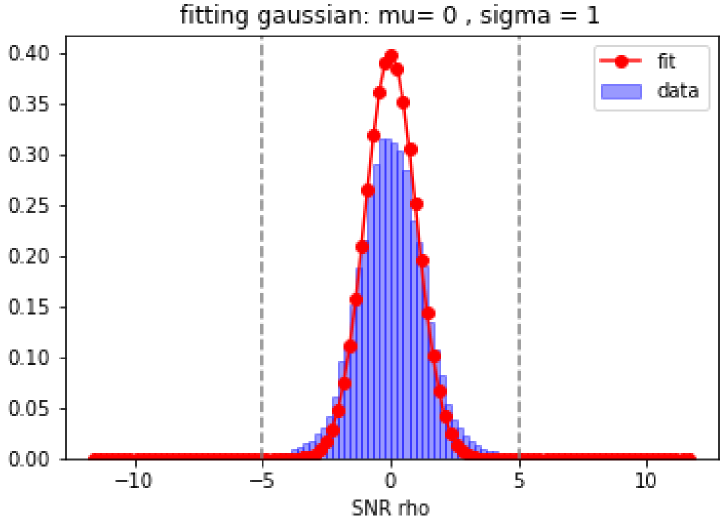
$d = 10^7$ km

$t_0 = 720$ h

$v_\perp = 300$ km/s

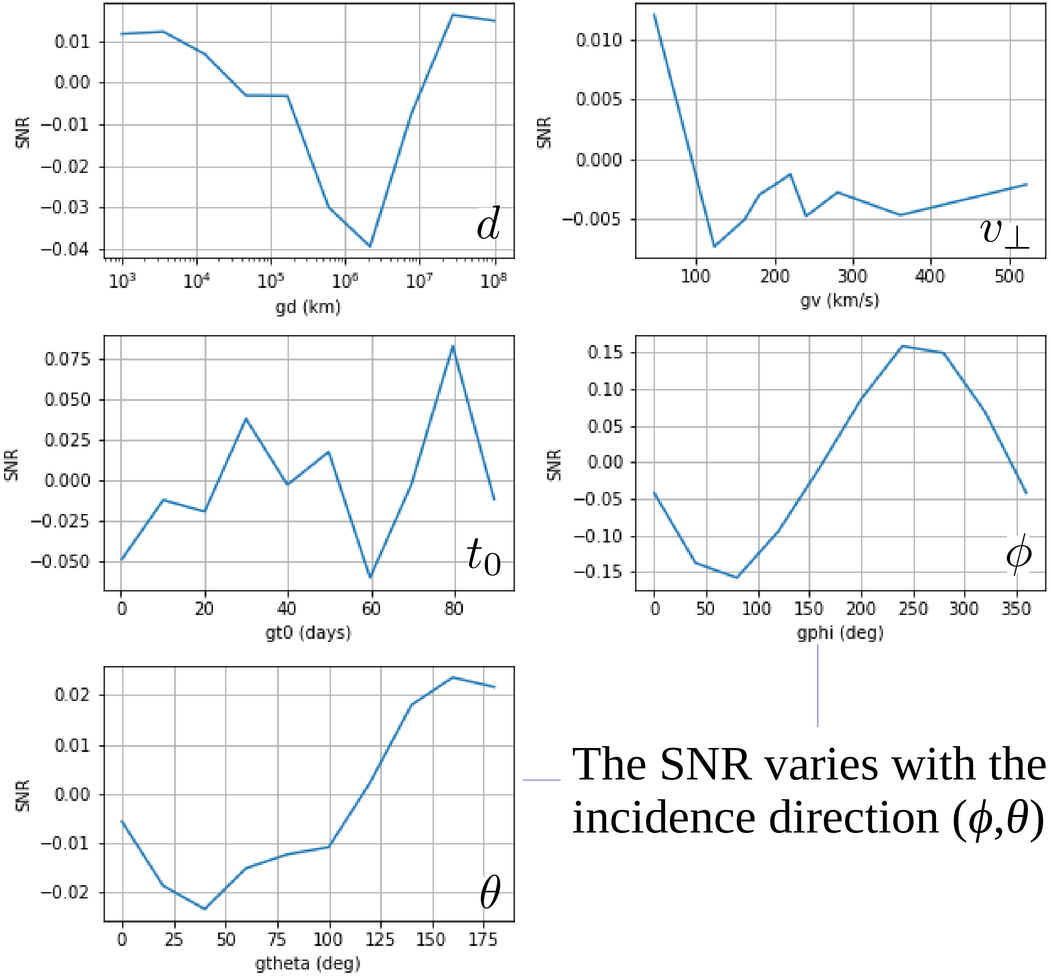
$\theta = 45°$ $\phi = 45°$

Observed candidate events



$$\rho_{\text{thres}} = 5.02$$

Over 1 year of observation, up to 6% of the events with SNR > ρ_{thres} according to the observation epoch.



The SNR varies with the incidence direction (ϕ,θ)

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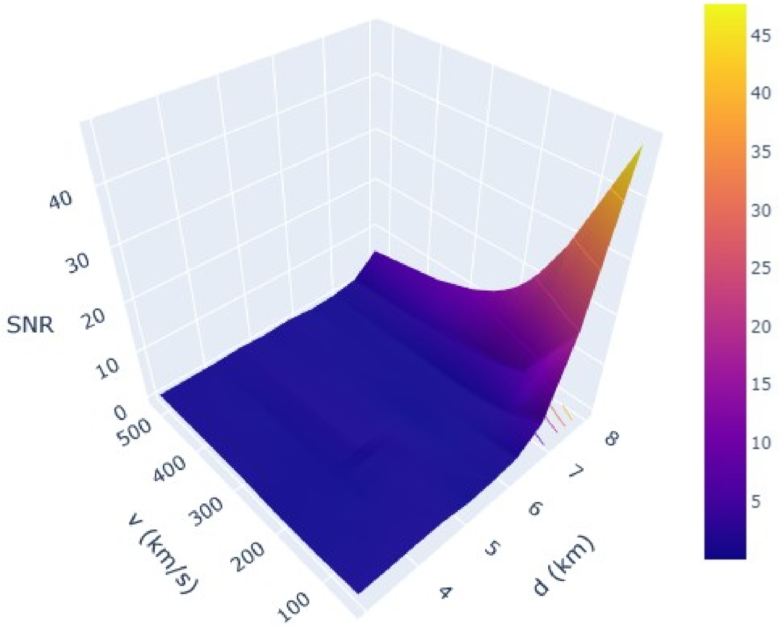
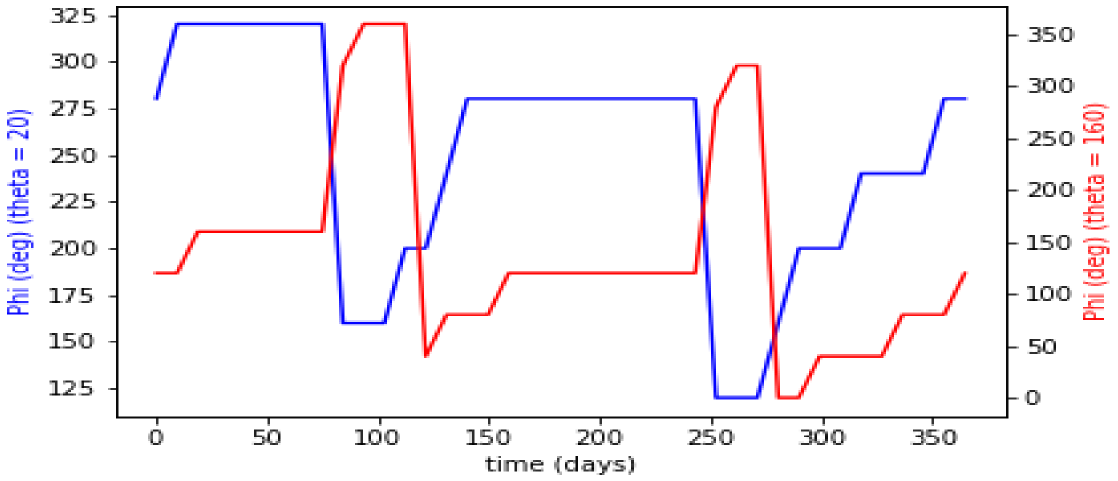
Analysis over 1 year (preliminary)

The SNR increases for large transients (d ~ 10^8 km) and low velocities ($v_\perp$ < 200 km/s)



- Possible correlations with orbital errors (SRP mismodelling?)
- Maxima of SNR: The incident direction of the transient changes with its time of arrival (~ 150 days period)

ϕ_{max} for θ = 20° and θ = 160°



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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

Strong exclusion area in the parameter space

Discovery of an unknown effect

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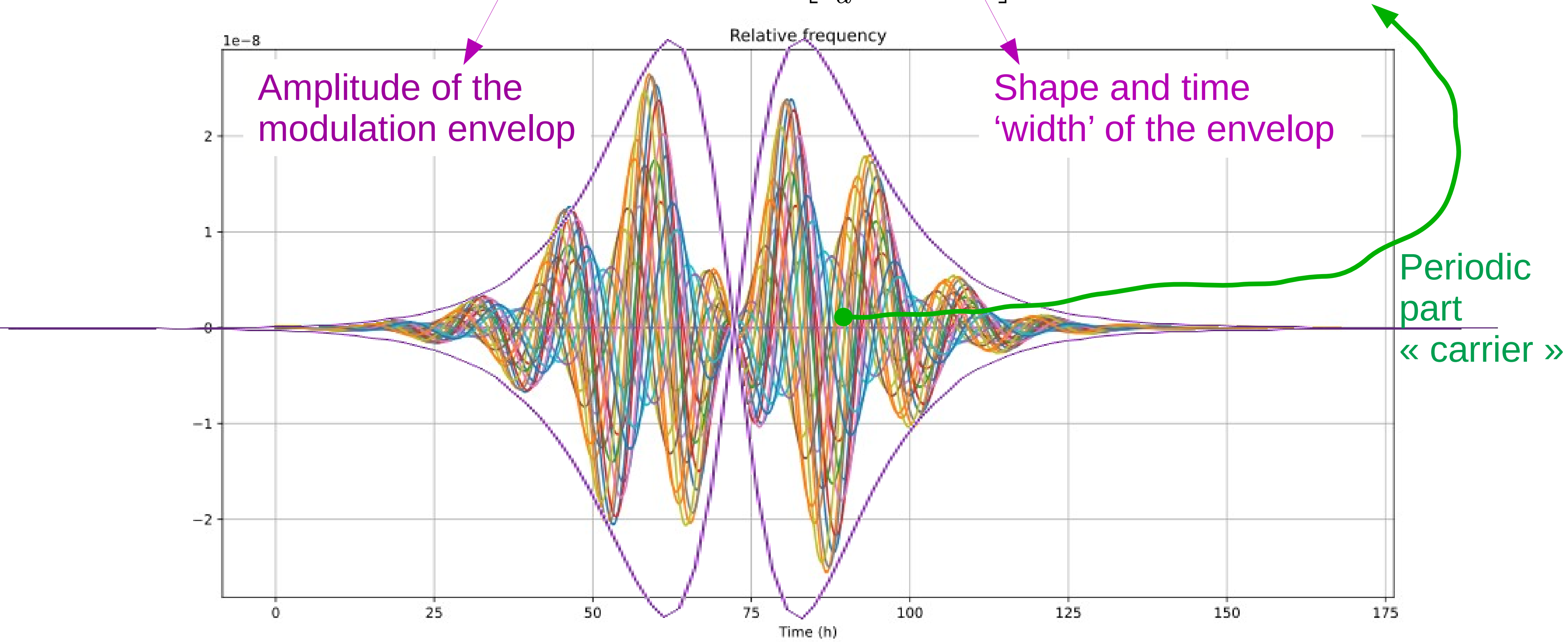
Theoretical modelisation for large transients

$$\Delta s^{ab}(t) = \tilde{A}\left[\frac{\Lambda\, v_{\rm gal}}{\mathcal{T}}, \theta, \phi\right] \frac{\tanh\left[\frac{v_\perp}{d}(t-t_0)\right]}{\cosh^2\left[\frac{v_\perp}{d}(t-t_0)\right]} \cos\left[\omega_{sat}\, t' + \tilde{\Phi}(\theta,\phi)\right]_{t_{\rm i}}^{t}$$



$$\Delta s^{ab}(t) = \frac{3}{2}\frac{R_{\rm sat}}{\omega_{\rm sat}}\,\Gamma_{\rm eff}\,\rho_{\rm DM}\,v_{\rm gal}\,\mathcal{T}\,\sqrt{C^2(\theta,\phi)+D^2(\theta,\phi)}\,\frac{\tanh\left[\frac{v_\perp}{d}(t-t_0)\right]}{\cosh^2\left[\frac{v_\perp}{d}(t-t_0)\right]}\,\cos\left[\omega_{sat}\,t' + \arctan\left(-\frac{C(\theta,\phi)}{D(\theta,\phi)}\right)\right]_{t_i}^{t}$$

Amplitude of the envelope (model part)

$\Gamma_{\rm eff} \times \mathcal{T}$

Degeneracy

Amplitude of the envelope (event & satellite configuration part)

θ, ϕ

Ω_a u_a, i_a

Shape & time width of the envelope

$\frac{v_\perp}{d}$ t

Degeneracy

For large transient, the amplitude of the signal is independent of the size *d* of the transient

Identifying a given event to parameters space only imply two variables : the amplitude of the envelop and its width

How to construct the envelop in a statistically viable way from the stacking of satellites pairs ?