GPS as a dark matter detector

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GPS.DM (?) collaboration

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A. Derevianko (Theory/Clocks/Data analysis, Nevada-Reno)
M. Pospelov (Theory, Perimeter/UBC)
J. Sherman (Clocks, NIST-Boulder)

Students (all Nevada-Reno)
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* = graduated

+ GNOME connections

Postdoctoral position available

supported by the US NSF

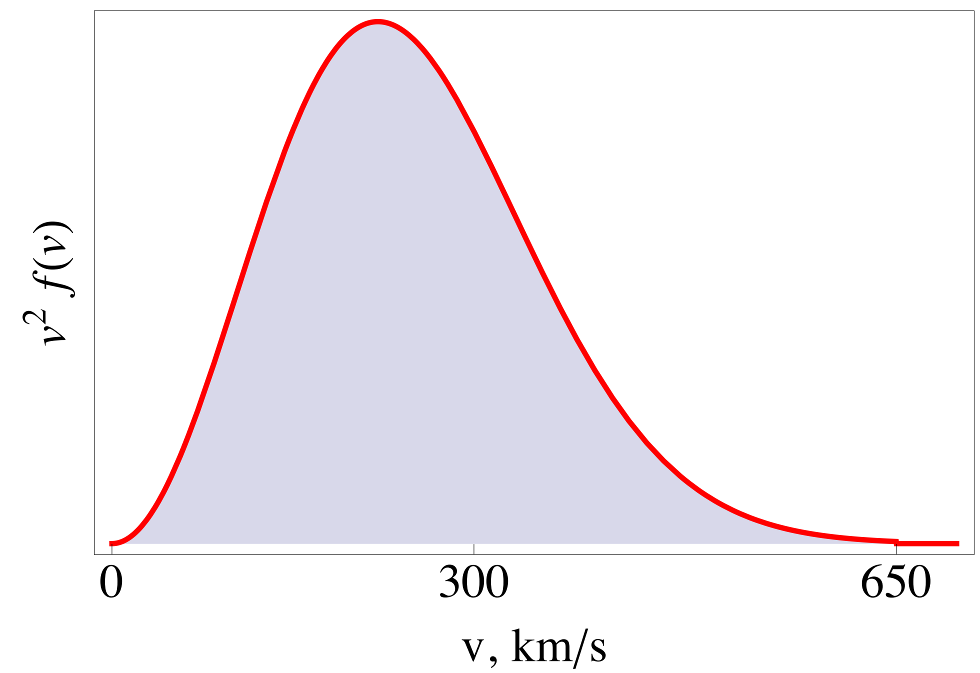
Outline

- What do we know about DM?
- “Lumpy” dark matter
- Atomic clocks
- GPS as a dark matter detector

What do we know about DM?

Dark Matter halo

Velocity distribution



Energy density

$$\rho_{DM} \sim 0.3\,\text{GeV/cm}^3$$

Galactic orbital motion

$$v_g \sim 300\,\text{km/s}$$

Candidates: from WIMPs to MACHOs

$M \sim 10^{-56} - 10^{-54} M_\odot$

$M > 10^{-24} M_\odot$

$M \sim 10^{-7} - 10^{2} M_\odot$

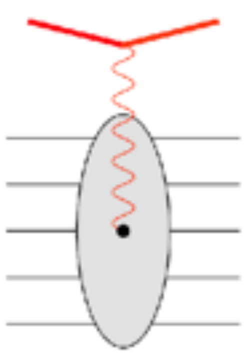
WIMPs

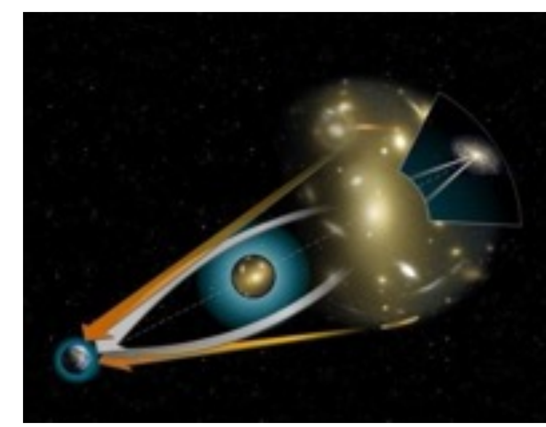
Weakly interacting massive particles

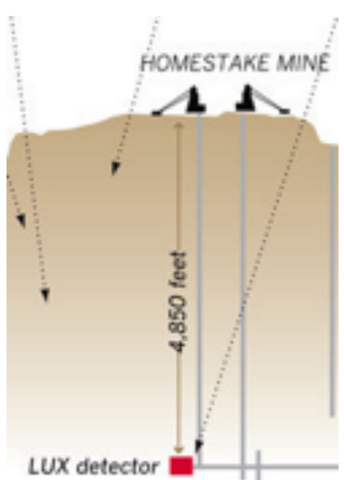
Quantum fields

MACHOs

Massive compact halo objects



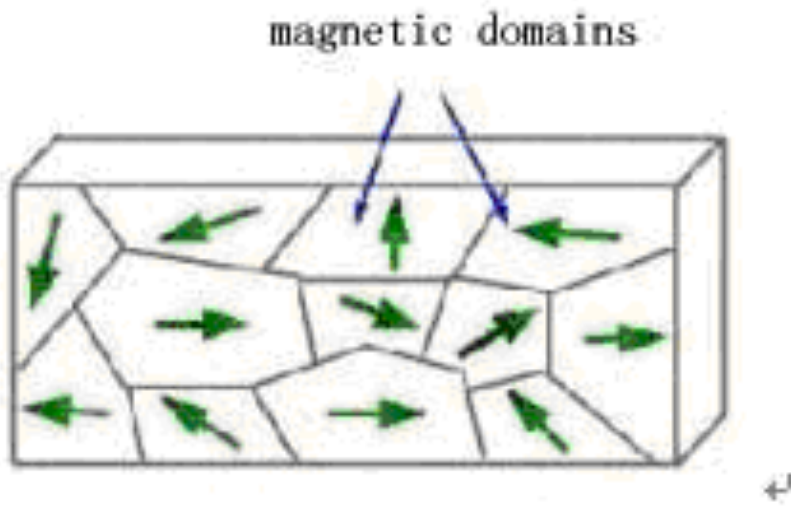




DM as a gas of stable extended objects

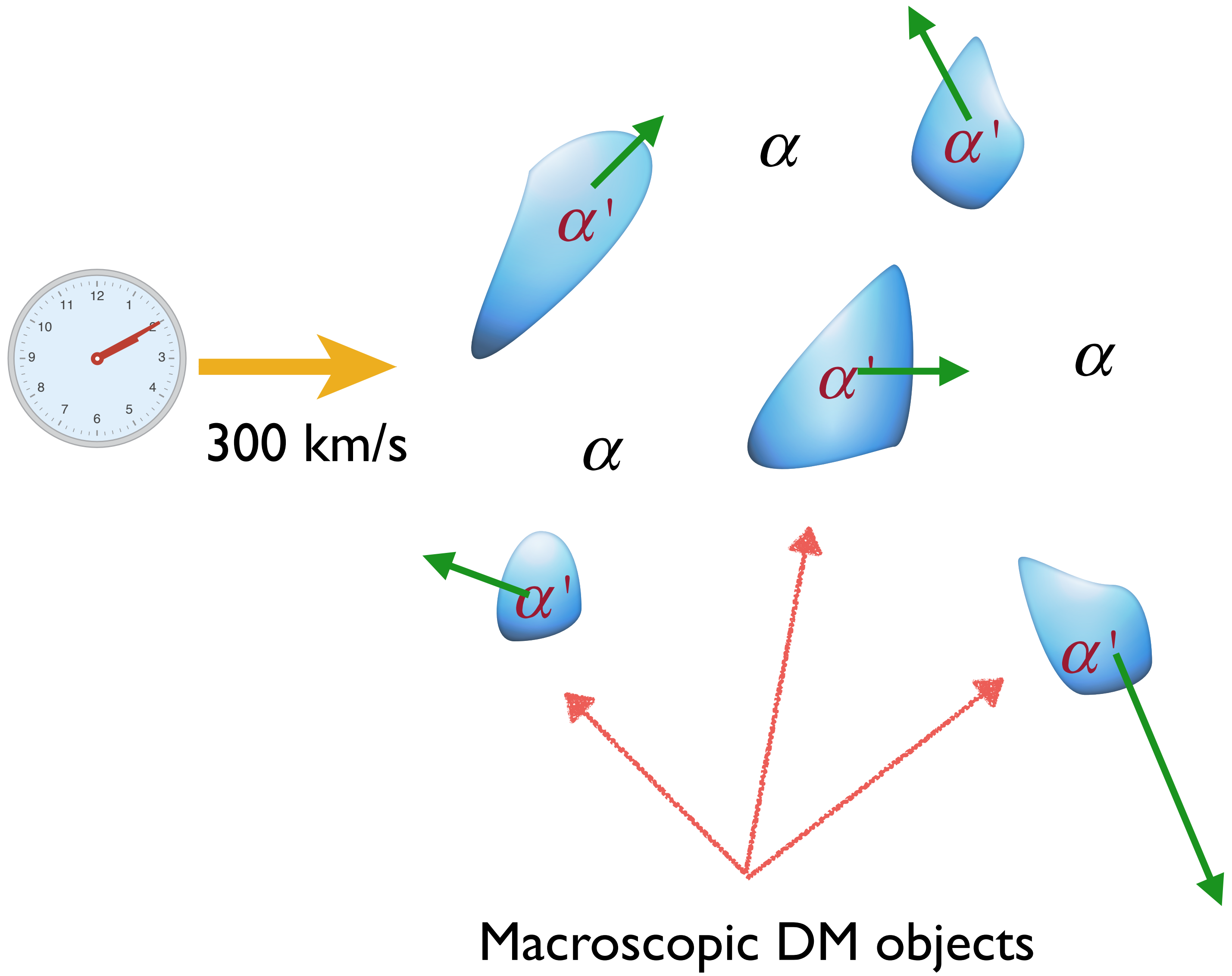
- Self-interacting quantum fields
- Networks of topological defects (light quantum fields = monopoles, vortices, domain walls), solitons, Q-balls
- Non-gravitational (dissipative) interactions in the dark sector

Illustration: ferromagnets



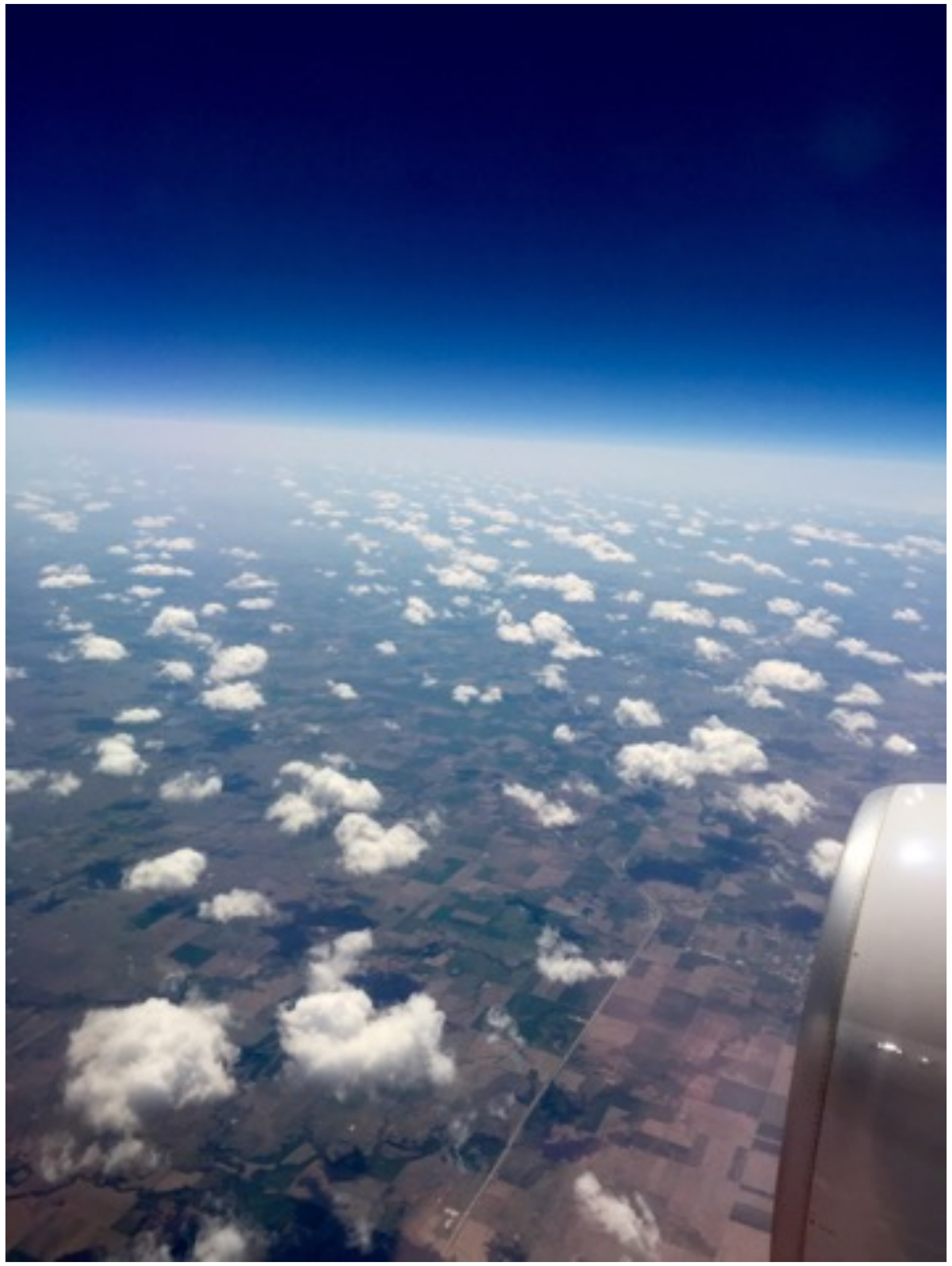
Curie point in ferromagnetic phase transitions

DM halo="preferred" reference frame

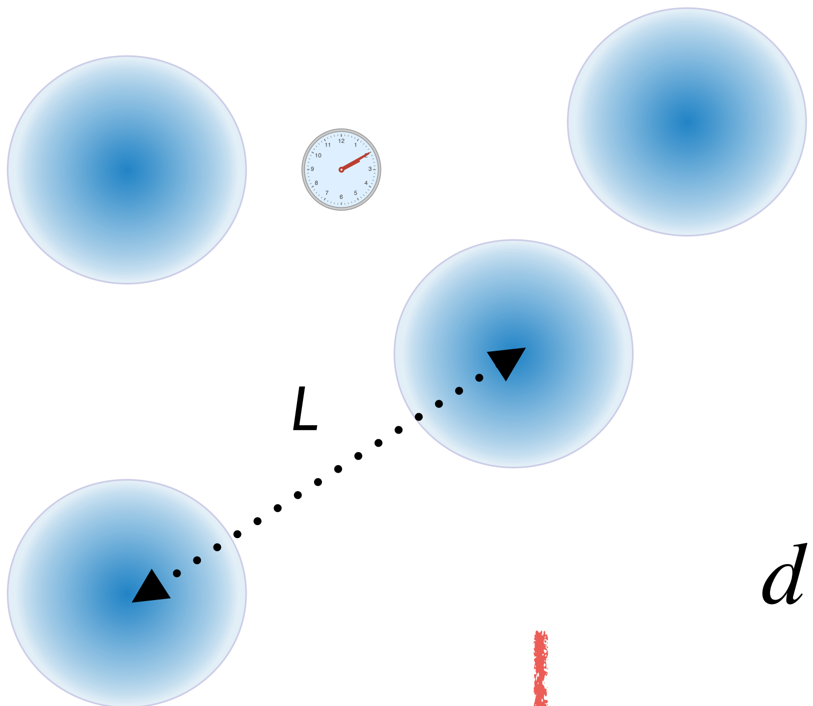


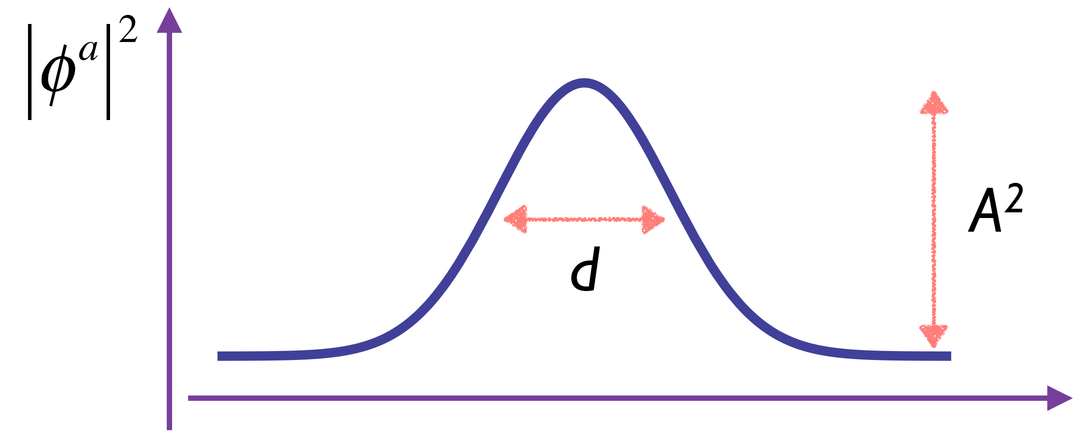
Are there correlations with galactic velocity of moving through DM halo?

Are the clouds "natural"?



"Gas of topological defects" DM model





M. Pospelov

$$d \sim \frac{\hbar}{m_\phi c}$$

Defect size and particle mass

$$\rho_{TDM} \sim \frac{1}{L^3} \times \left(\frac{1}{\hbar c} \frac{A^2}{d^2} d^3 \right)$$

Energy density

$$T_{coll} \sim \frac{1}{n\sigma v} \sim \frac{1}{1/L^3 \times d^2 \times v_g}$$

Time b/w "collisions"

$$\tau \sim \frac{d}{v_g}$$

Interaction time

Atomic clocks - amazing listening devices

- Most precise instruments ever built
- Modern nuclear/atomic clocks aim at 19 significant figures of accuracy
- Fraction of a second over the age of the Universe
- Best limits on modern-epoch drift of fundamental constants

Clocks

quantum oscillator:

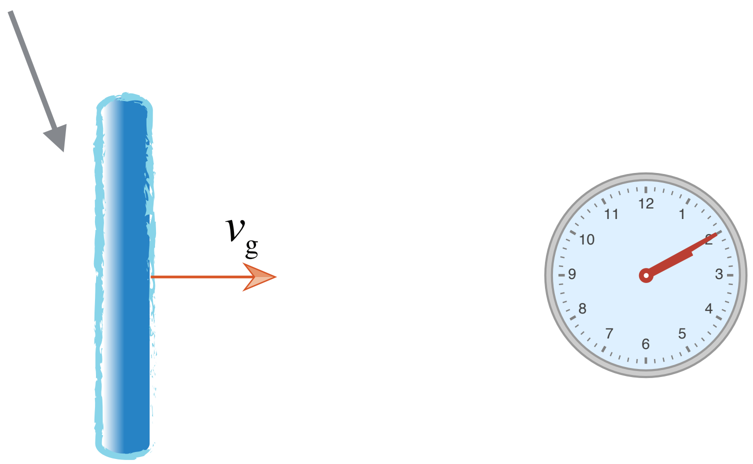
phase = $\phi_0(t) = \int_0^t \omega_0 dt'$ ⇒ time = $\phi_0(t)/\omega_0$

with TDM $\phi(t) = \int_0^t (\omega_0 + \delta\omega(t'))\, dt'$ ⇒ clock speeds up/slows down

$\Delta\phi_{\mathrm{TDM}}(t) = \int_{-\infty}^{t} \delta\omega(t')\, dt'$ ⇒ $\Delta t_{\mathrm{TDM}}(t) = \dfrac{\Delta\phi_{\mathrm{TDM}}(t)}{\omega_0}$

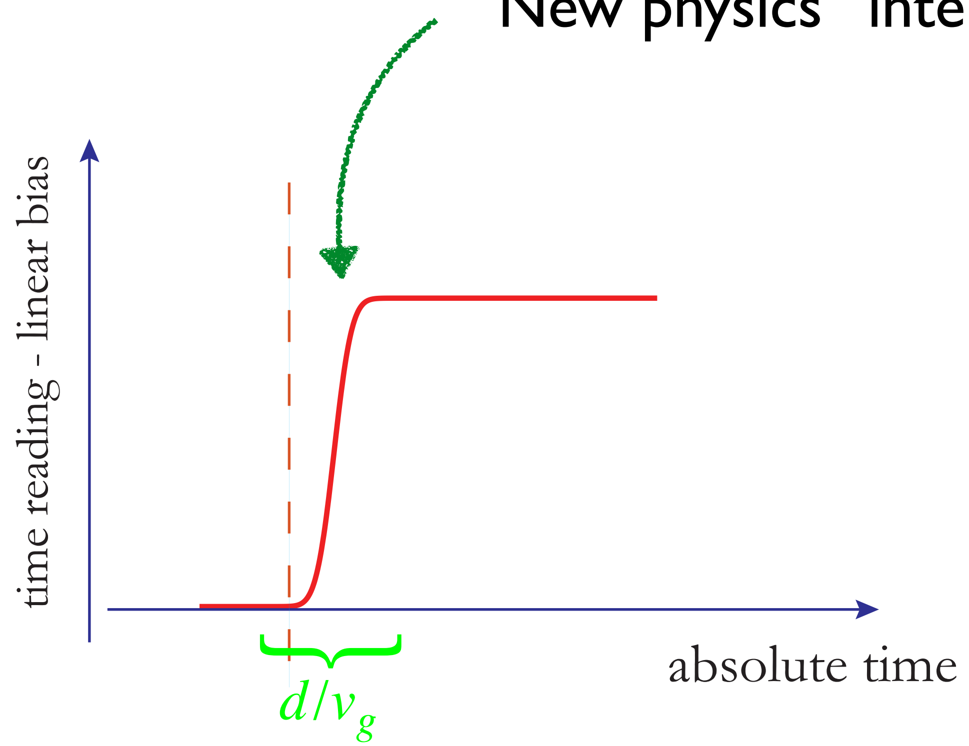
Basic idea

Lump of dark matter ~300 km/s

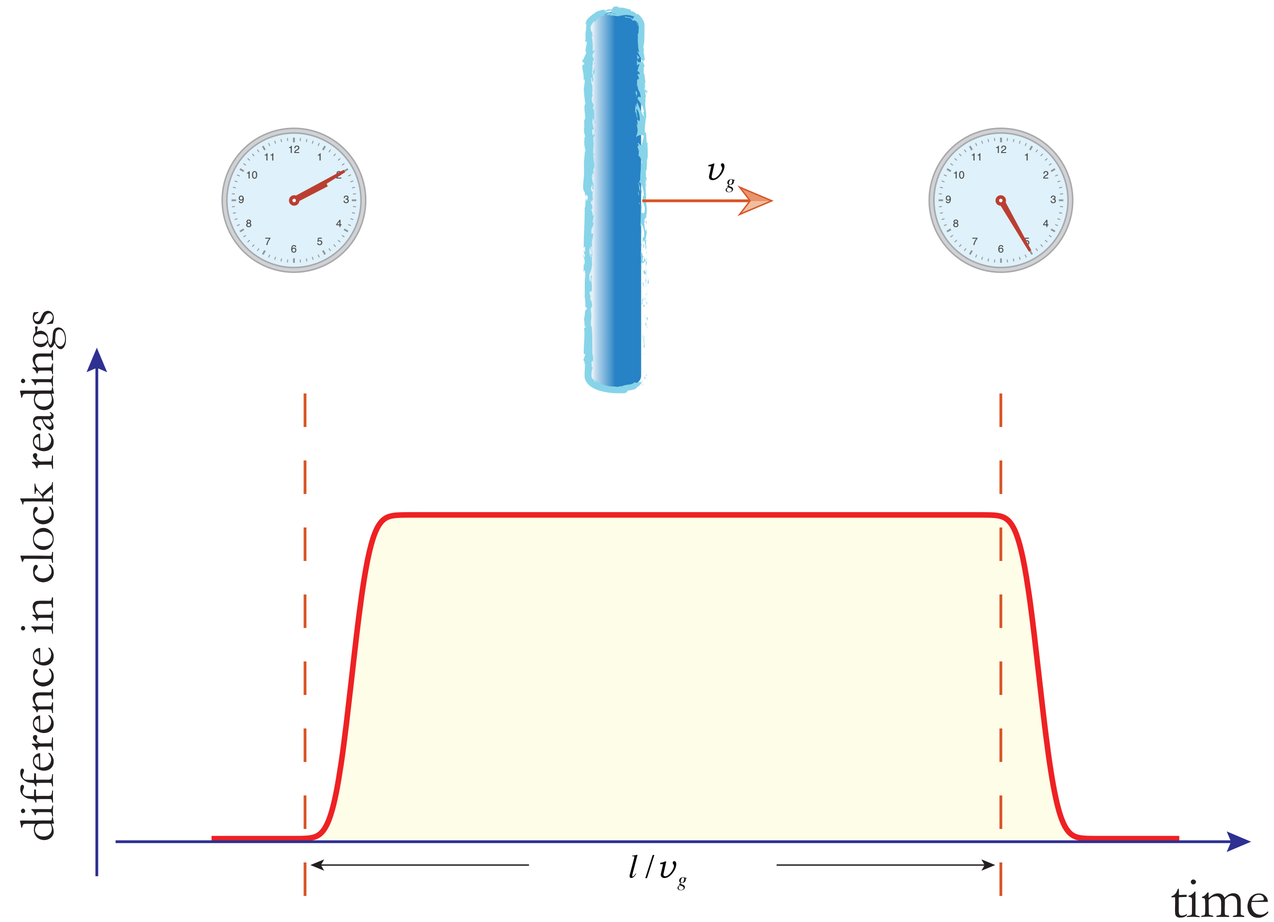


atomic frequencies are shifted by the lump

"New physics" interaction



Dark matter signature

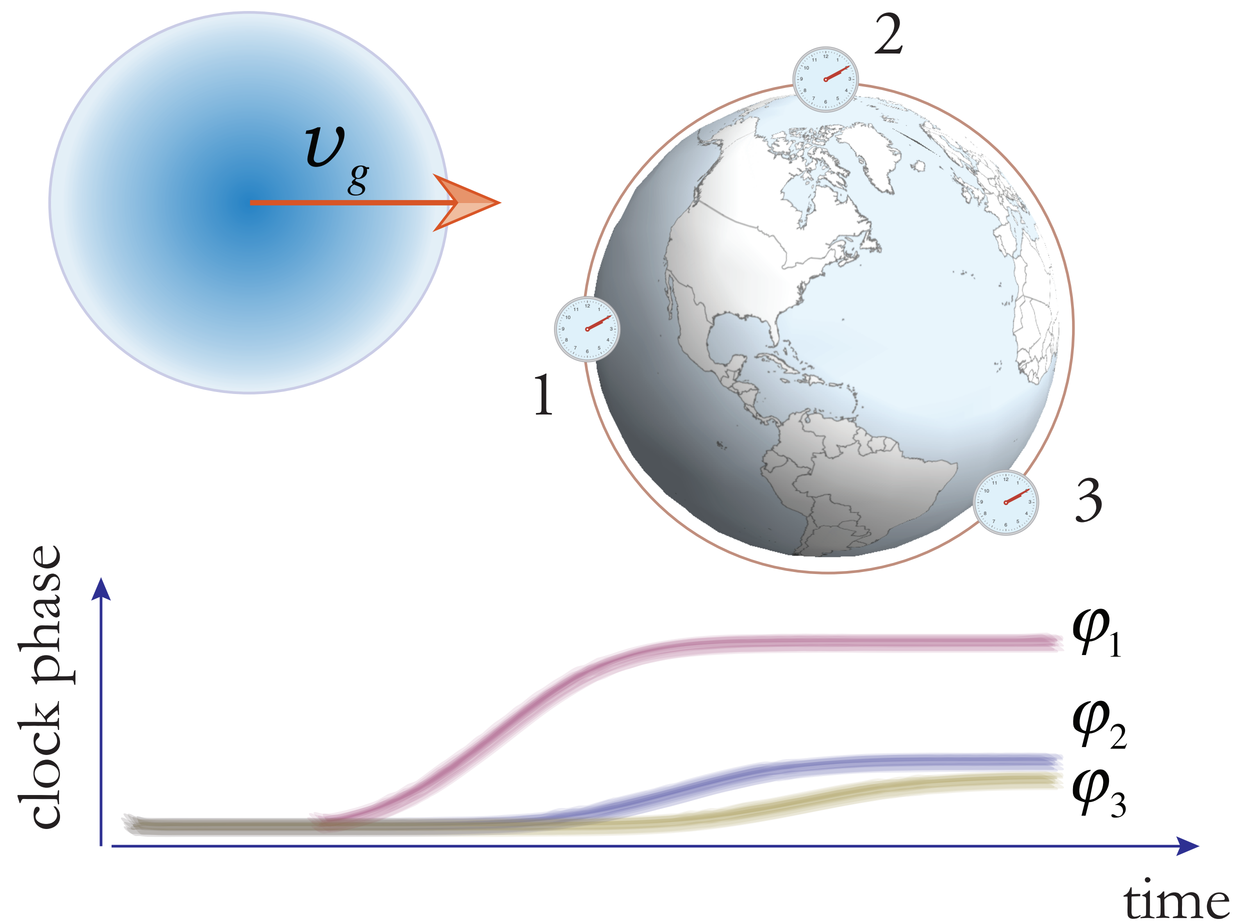


Monitor time difference b/w two spatially-separated clocks
⇒ persistent clock discrepancy for over time l/v_g

GPS aperture =50,000 km => l/v_g~ 150 sec

Details in Derevianko and Pospelov, Nature Phys. 10, 933 (2014)

Tomography of a monopole



Dark-matter portal

$$-L_{\text{int}} = a^2(\mathbf{r},t)\left(\frac{m_e \bar{e}e}{\Lambda_e^2} + \frac{m_p \bar{p}p}{\Lambda_p^2} + \frac{1}{4\Lambda_\gamma^2}F_{\mu\nu}^2 + \dots\right)$$

DM field — electrons — protons — EM field

Compare to the QED Lagrangian

$$L_{\text{QED}} = i\hbar c\bar{e}De - m_e c^2 \bar{e}e - \frac{1}{4\mu_0}F_{\mu\nu}^2$$

$$m_e c^2 \to m_e c^2\left(1 + \frac{a^2(\mathbf{r},t)}{\Lambda_e^2}\right)$$

TD lump pulls on the rest masses of electrons, quarks and EM coupling

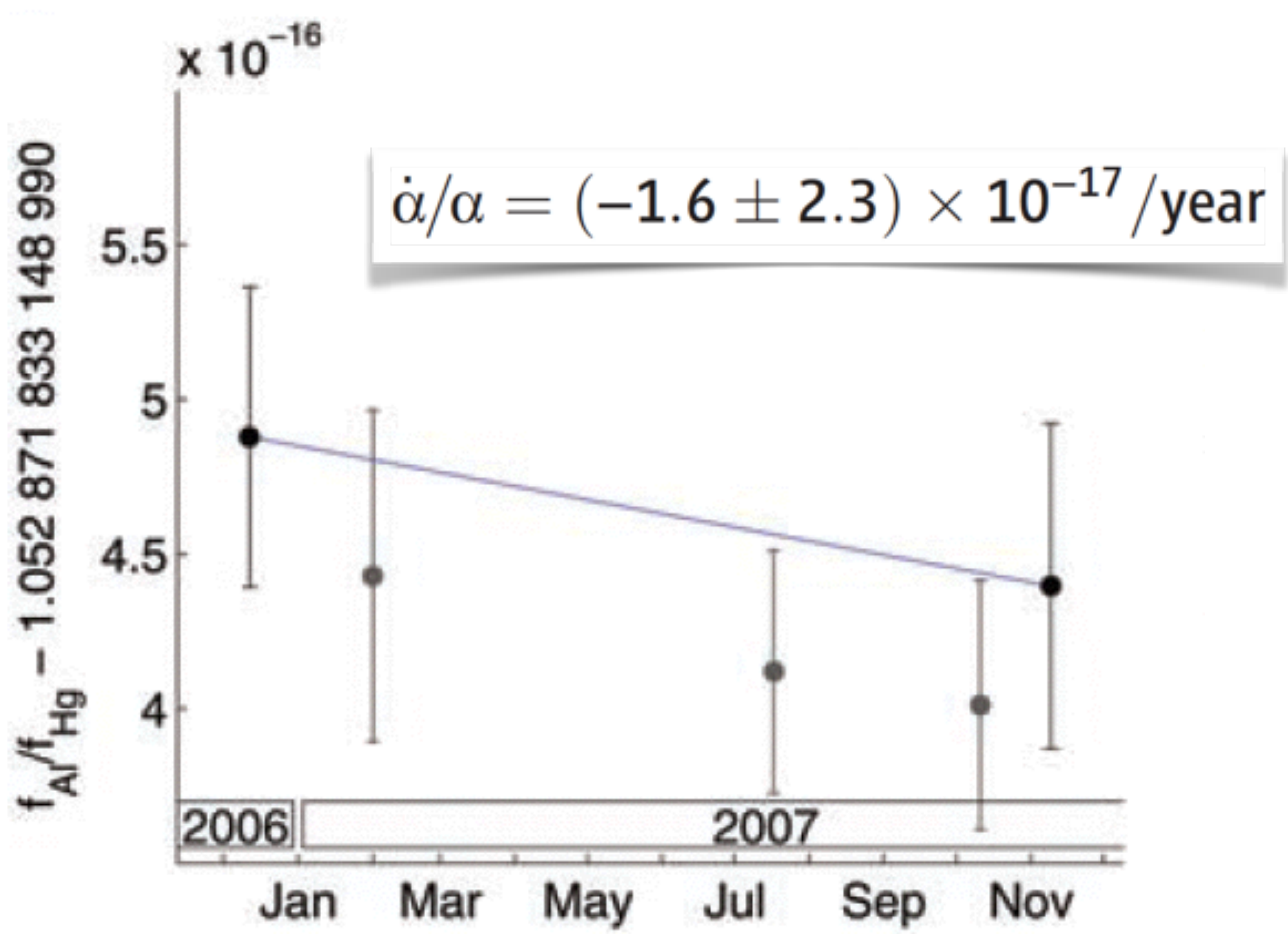
Energies and frequencies are modulated as TD sweeps through

Variation of fundamental constants

$$\omega_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right)$$

$$\frac{\delta\omega(t)}{\omega_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

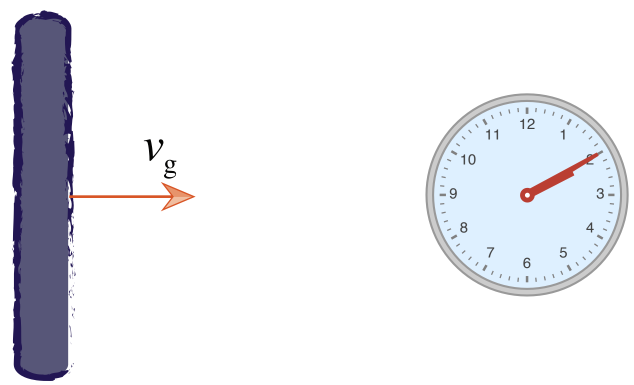
Compare ratio of frequencies of two clocks with different sensitivities



T. Rosenband, et al. Science 319, 1808 (2008)

Variation of fundamental constants

Drift vs transients



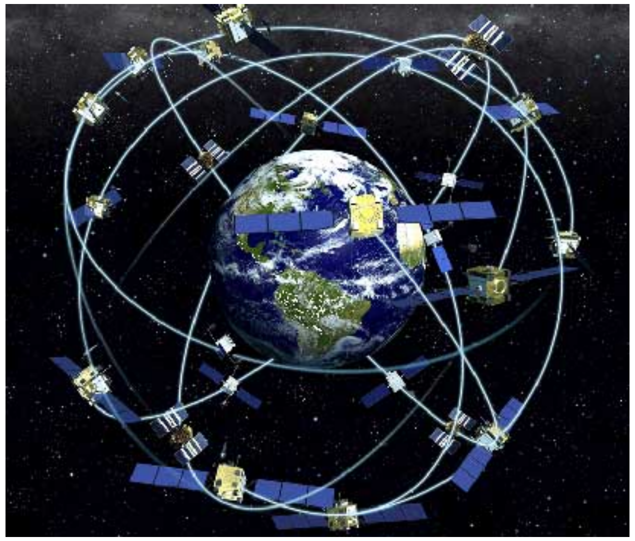
$d \sim 100\,\text{km}$

Transient

Slow drift (e.g., NIST Al/Hg ion clocks)

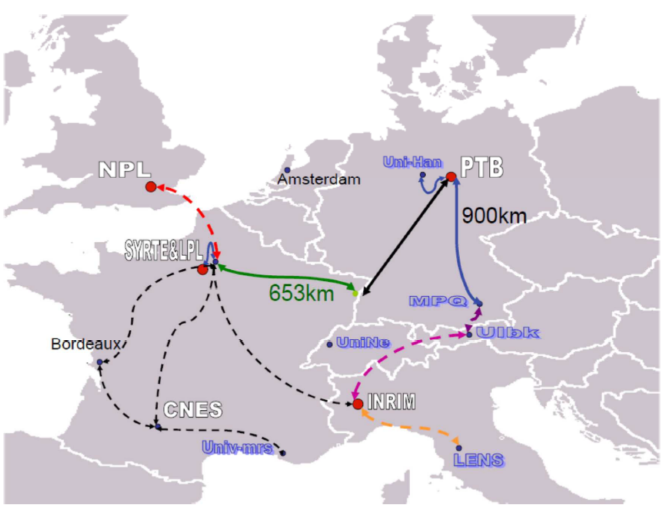
$$d > 300\,\text{km/s} \times 1\,\text{year} = 10^{10}\,\text{km}$$

Networks of clocks



Global Positioning System

- ❖Each GPS satellite has four clocks (32 satellites)
- ❖Data are sampled every second
- ❖Vast terrestrial network of monitoring stations (H masers)

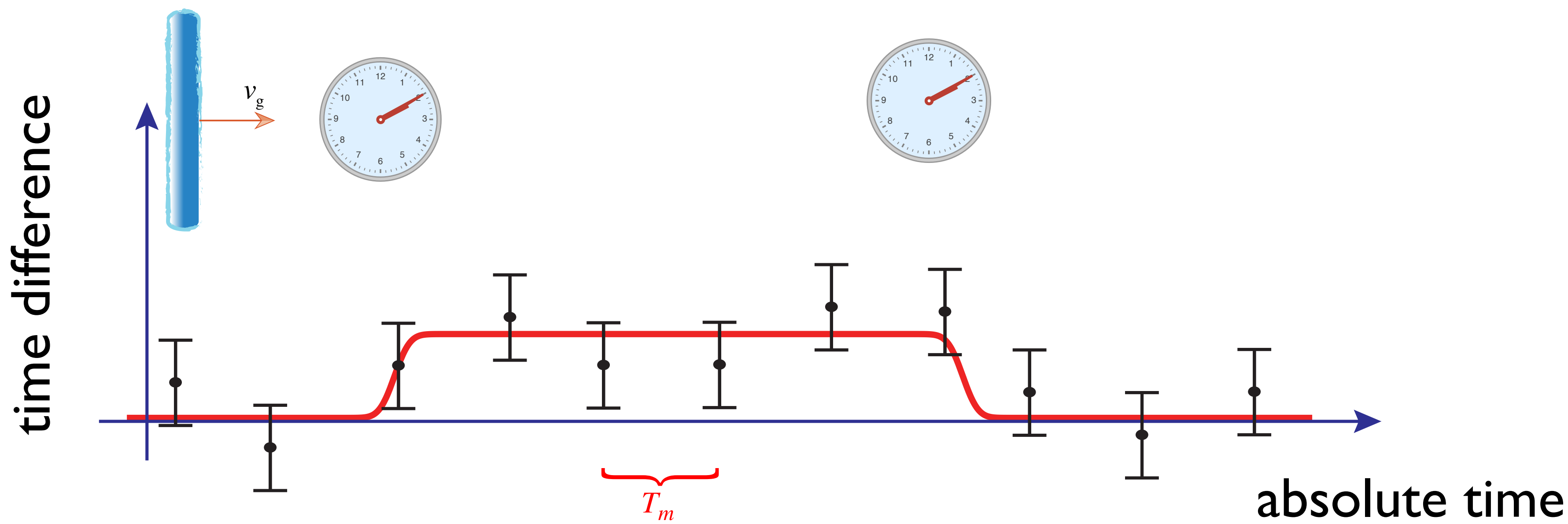


Trans-european clock network

- ❖Optical fiber connects state-of-the art clocks
- ❖Elements were demonstrated (PTB-MPI Munich 920 km link) *(Predehl et al., Science (2012))*

TAI dissemination network between national labs

Signal-to-noise ratio (thin wall)



Time b/w events

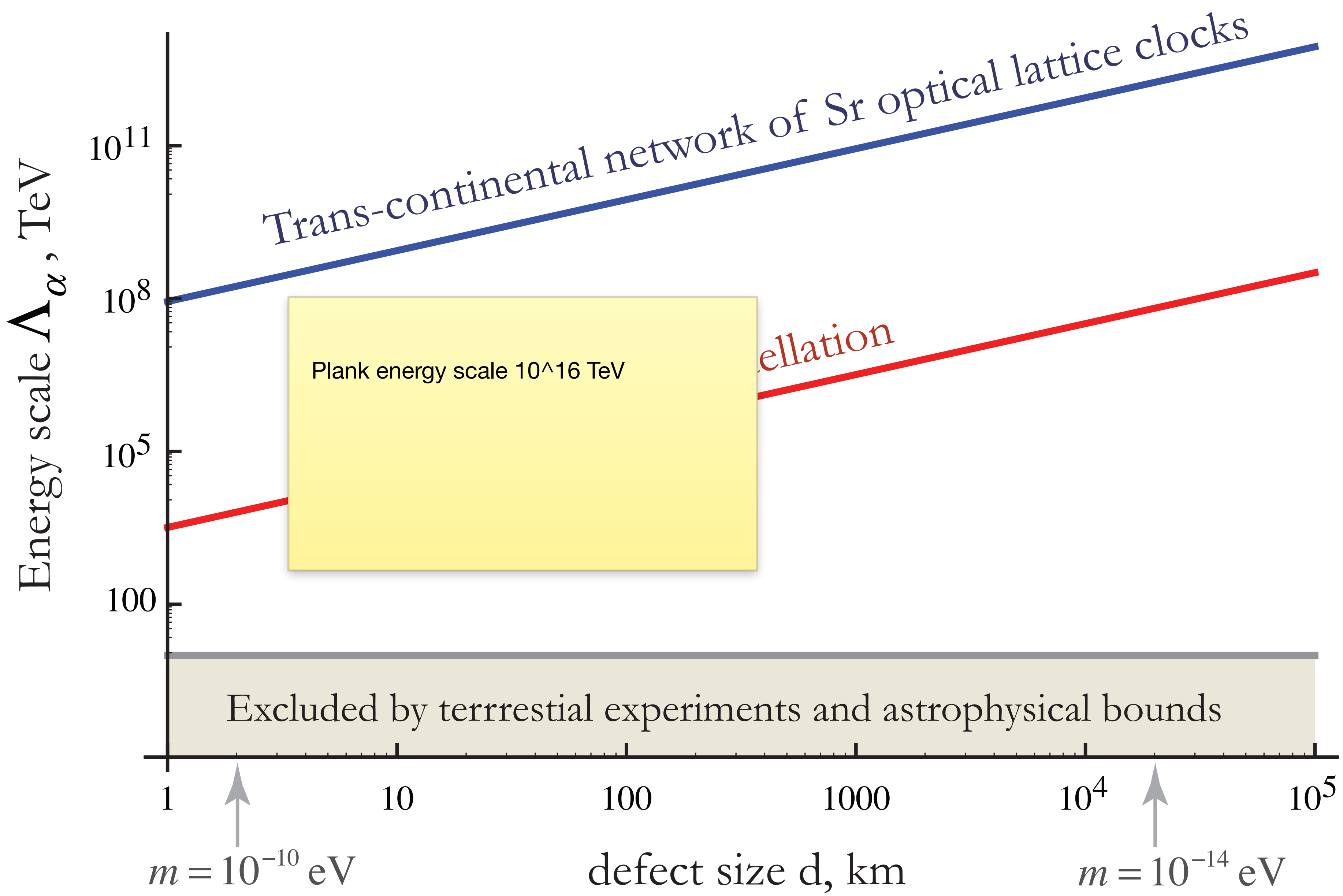
$$S/N = \frac{c\hbar}{T_m \sigma_y(T_m)\sqrt{2T_m v_g / l}}\, \rho_{\text{DM}}\, d^2\, \mathcal{T}_{\text{coll}} \sum_{\substack{\text{fundametal}\\ \text{constants X}}} \frac{K_X}{\Lambda_X^2}$$

Allan variance

Dark matter energy density

defect size

Projected limits (thin domain walls)
(if the TDM signature is not observed)

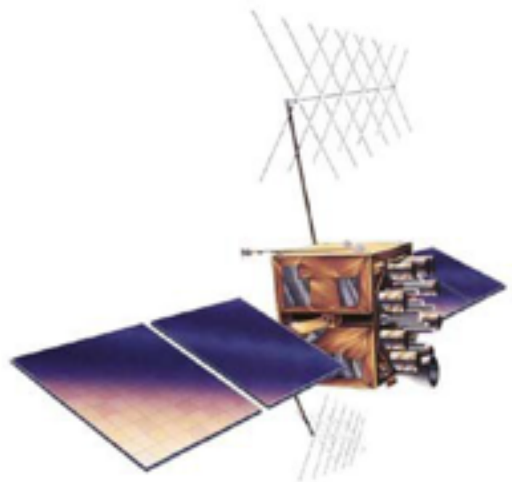


Total monitoring time =1 year

Andrei Derevianko - U. Nevada-Reno

GPS as a dark matter detector

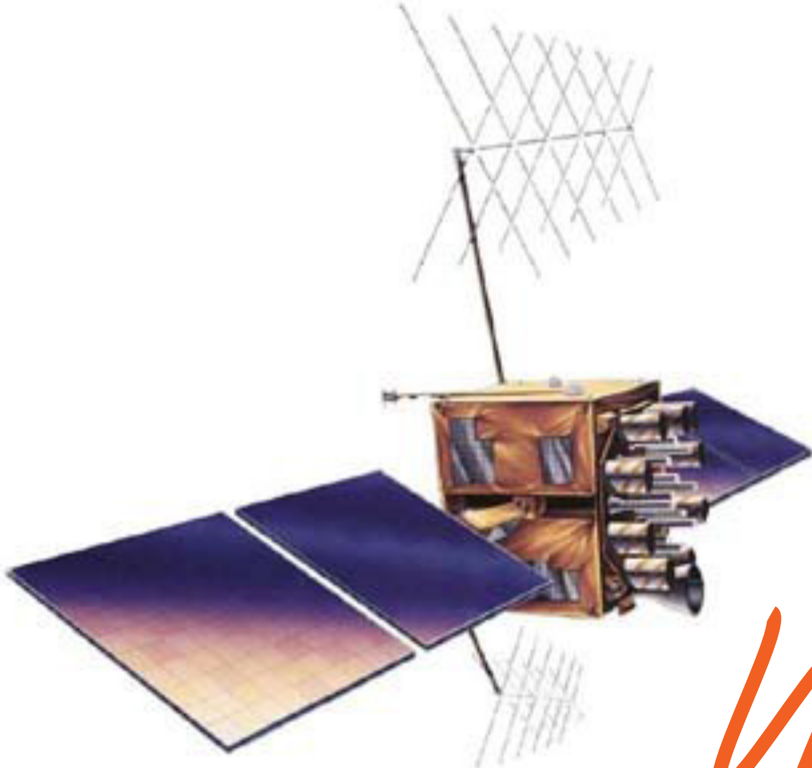
- GPS = max 32 satellites with Rb/Cs clocks
- 50,000 km aperture - largest human-built DM detector - no extra $$$
- None of conventional effects would sweep at 300 km/s (except for solar flares)
- Other navigation systems: Glonass/Galileo/BeiDou
- Extensive terrestrial clock network on receiving stations



GPS clocks

- Presently a mix of II-generation block sats (IIA,IIR,IIRM,IIF)
- 12 hr orbits
- Each satellite has 4 clocks (depends on individual satellite)
- Only a single clock is operational at a time on a single satellite (misbehaving clocks are swapped, swaps are documented)
- Rb and Cs clocks (20+ Rb, 5 Cs)
- The broadcast microwave signals are tied to the clock output

Data acquisition



Downlink microwave signals:
L1 = 1572.42 MHz
L2 = 1227.6 MHz
L5 = 1176.45 MHz

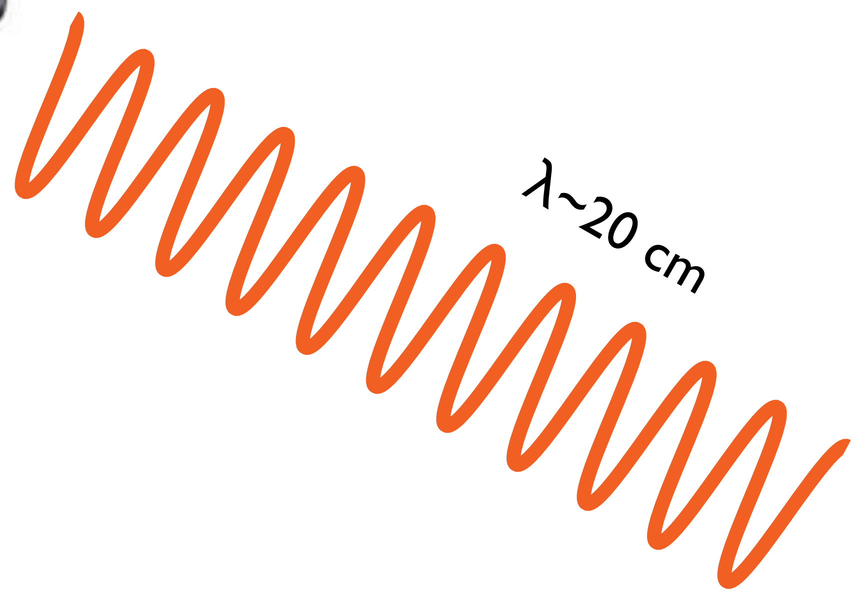


Figure 1 Permanent IGS station at Slide Mountain, Nevada, USA.

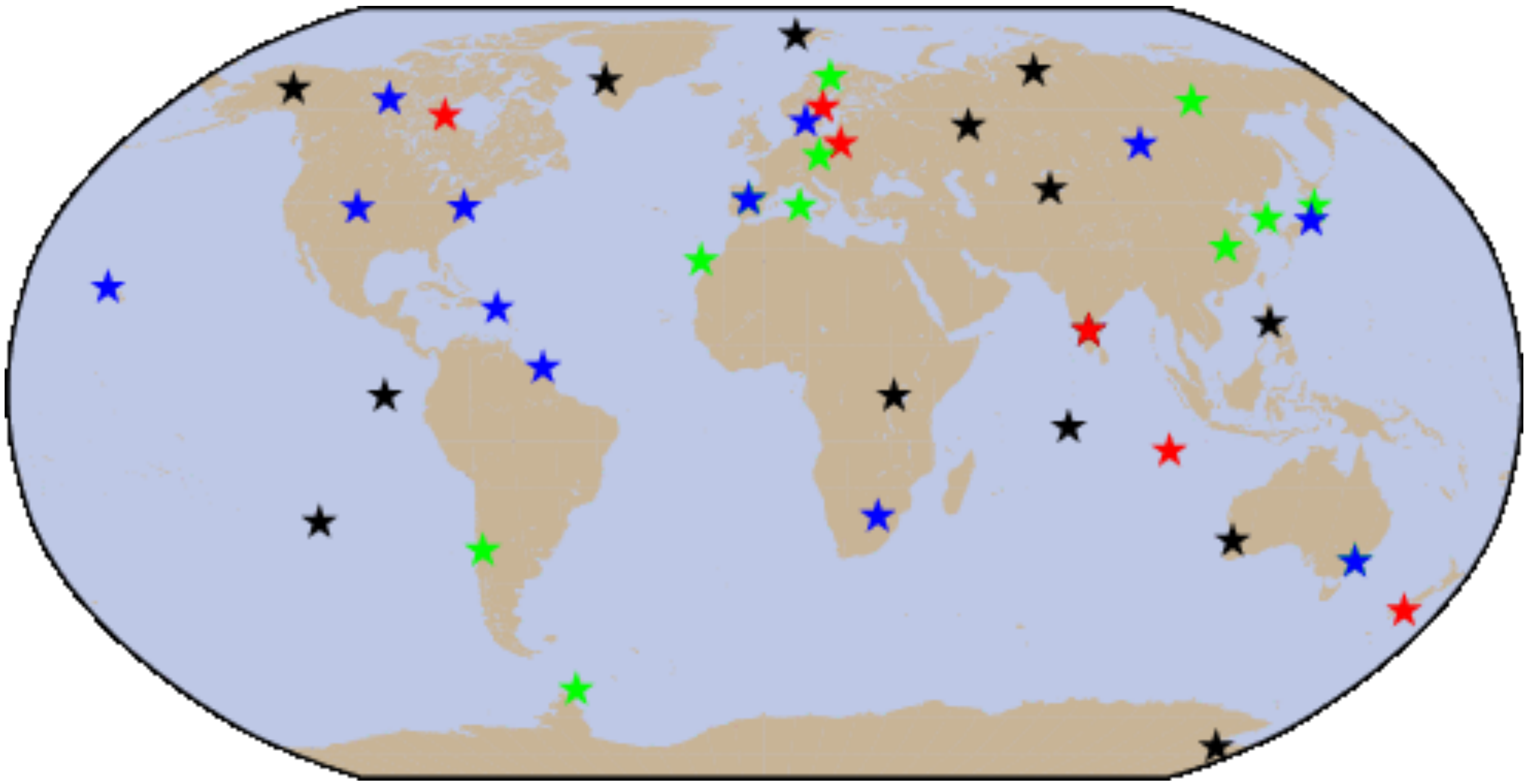
Measure the carrier phase of the broadcast signal
(much more precise than the navigational message)

Collect data from many receivers around the world

Phases are combined => clock,orbit, position solutions

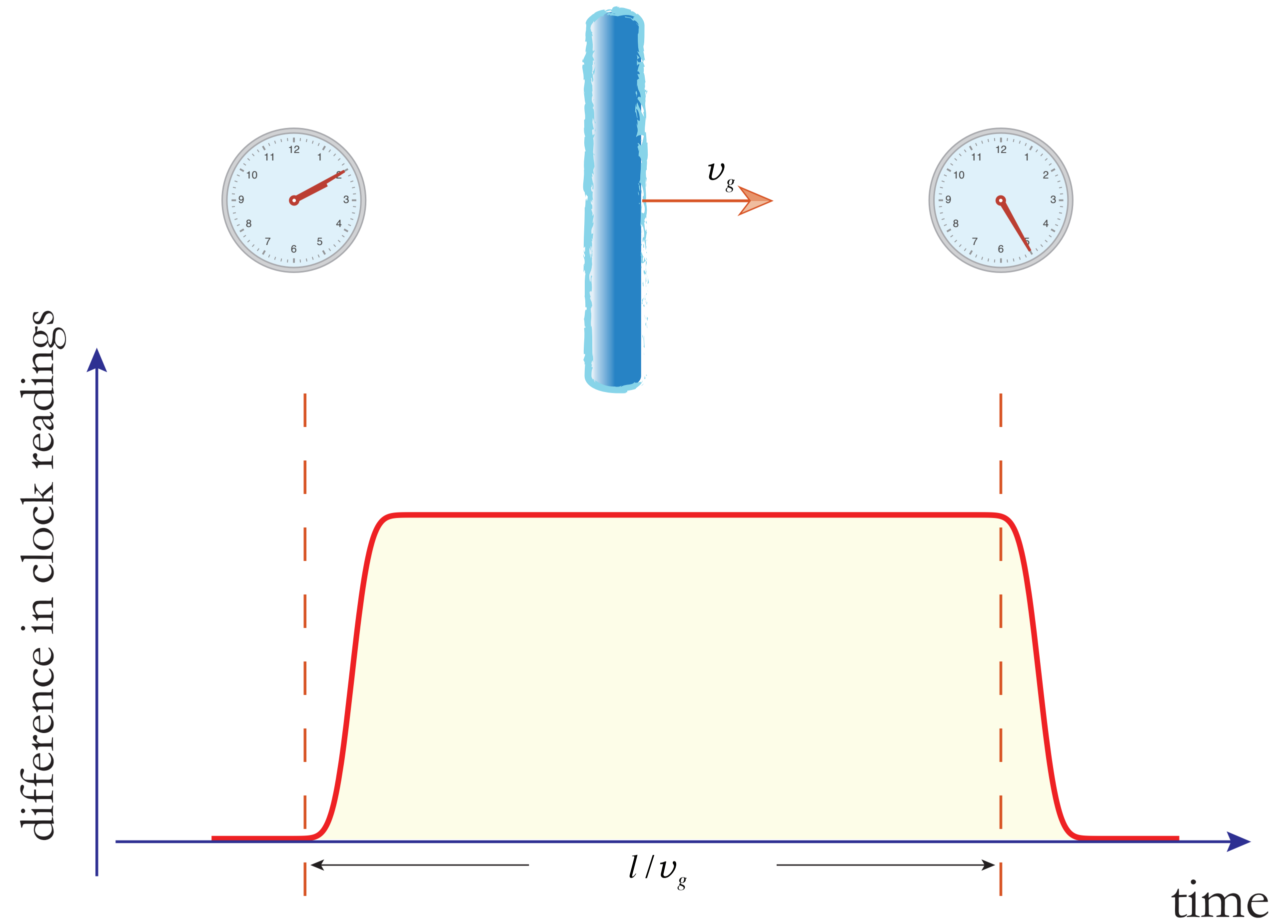
Errors: time ~ 0.1ns and positions ~ 1 mm

Representative GNSS ground stations
(with 10 years of 1-sec carrier phase data)



Quartz oscillators (black)
Atomic clocks: Hydrogen Rubidium Cesium

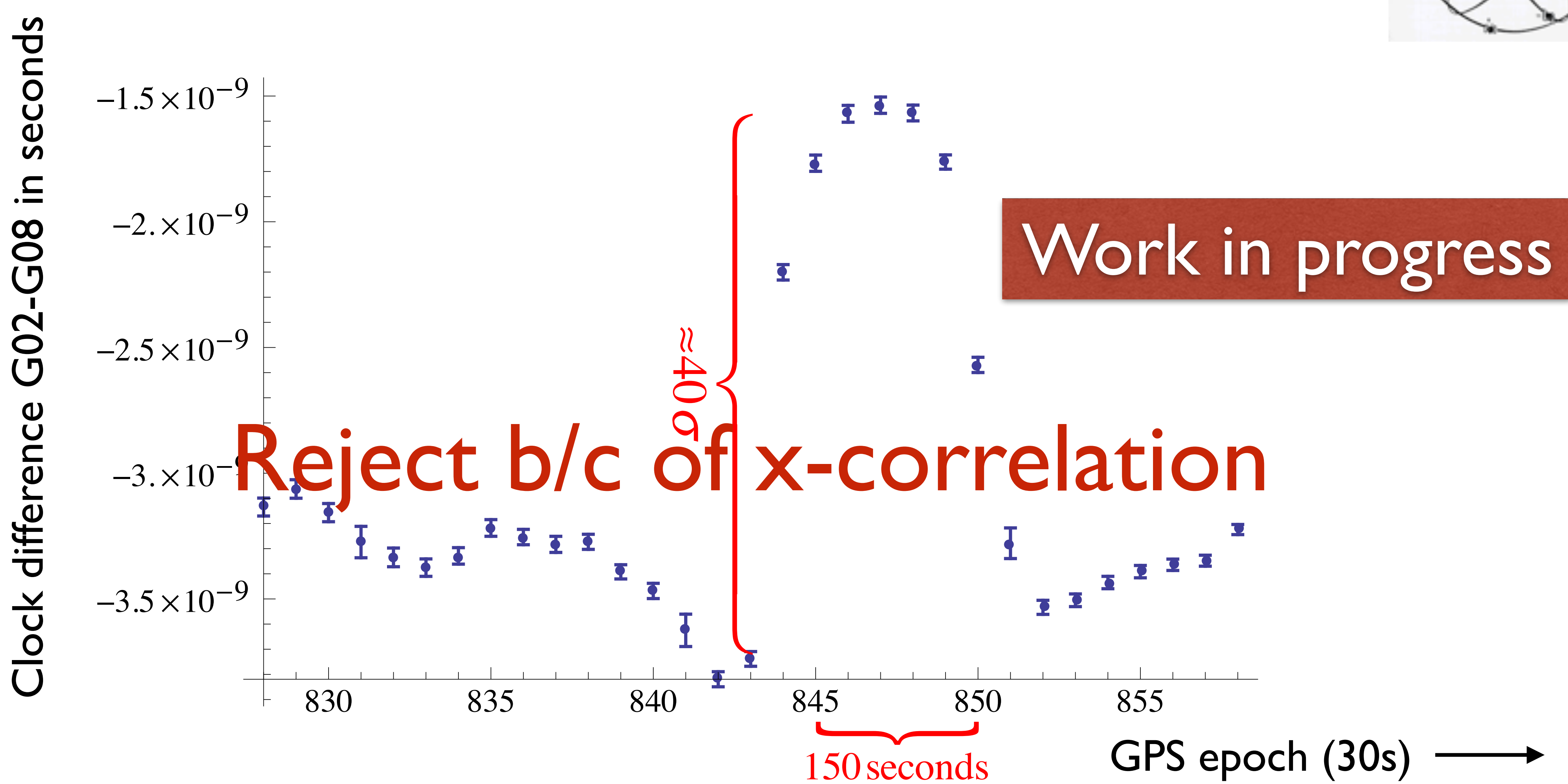
Signature



Monitor time difference b/w two spatially-separated clocks
⇒ persistent clock discrepancy for over time l/v_g

GPS aperture =50,000 km => l/v_g~ 150 sec

GPS data (Oct 16, 2007, 7AM EST)



40σ signal - but this occurs for all pairs with G02 satellite -
=> technical glitch with the clock on the G02 satellite ?

Data analysis

At the end of the day I would like to be able to say:
a certain signature fits the data with such-and-such probability.
Also we need to estimate parameters for a given signature

Bayesian data analysis

$$P(M_i \mid D, I) = \frac{P(M_i \mid I) \times P(D \mid M_i, I)}{P(D, I)}$$

Hypoteses:

- M_0 = "No DM signal"
- M_1 = "Thin domain wall"
- M_2 = "Monopole"
- …
- M_X="…."

Relative odds (assuming equal priors):

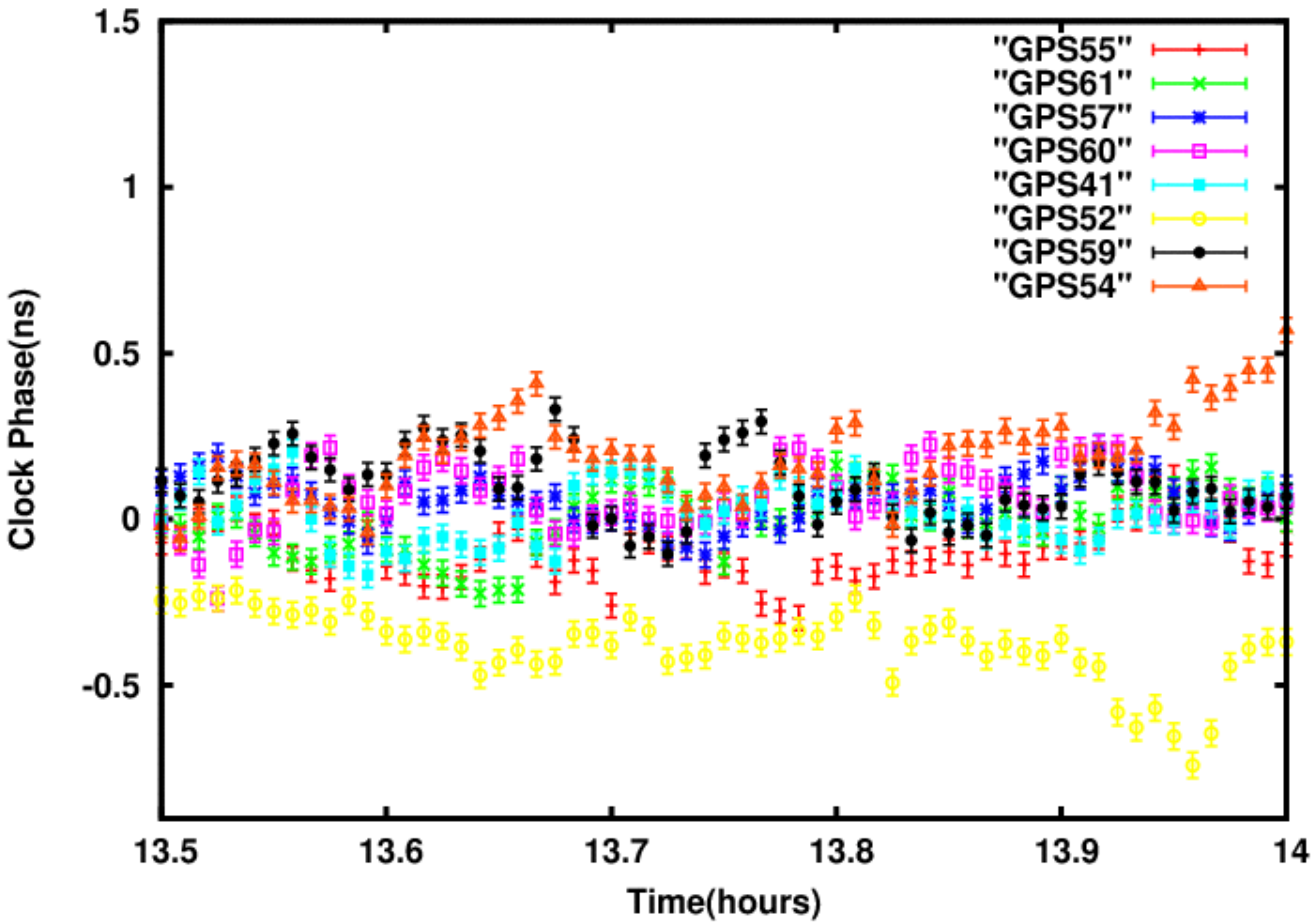
$$O_{i,0} = \frac{P(D \mid M_i, I)}{P(D \mid M_0, I)}$$

Complex multi-parameter models are "punished" automatically: built-in Occam's razor

$$O_{i,0} = \frac{P(D \mid M_i, I)}{P(D \mid M_0, I)}$$

How to assign likelihoods?

Clocks are noisy and non-stationary



Deterministic:

Time offset

Frequency offset

Frequency drift

Stochastic:

White noise PM

Flicker noise PM

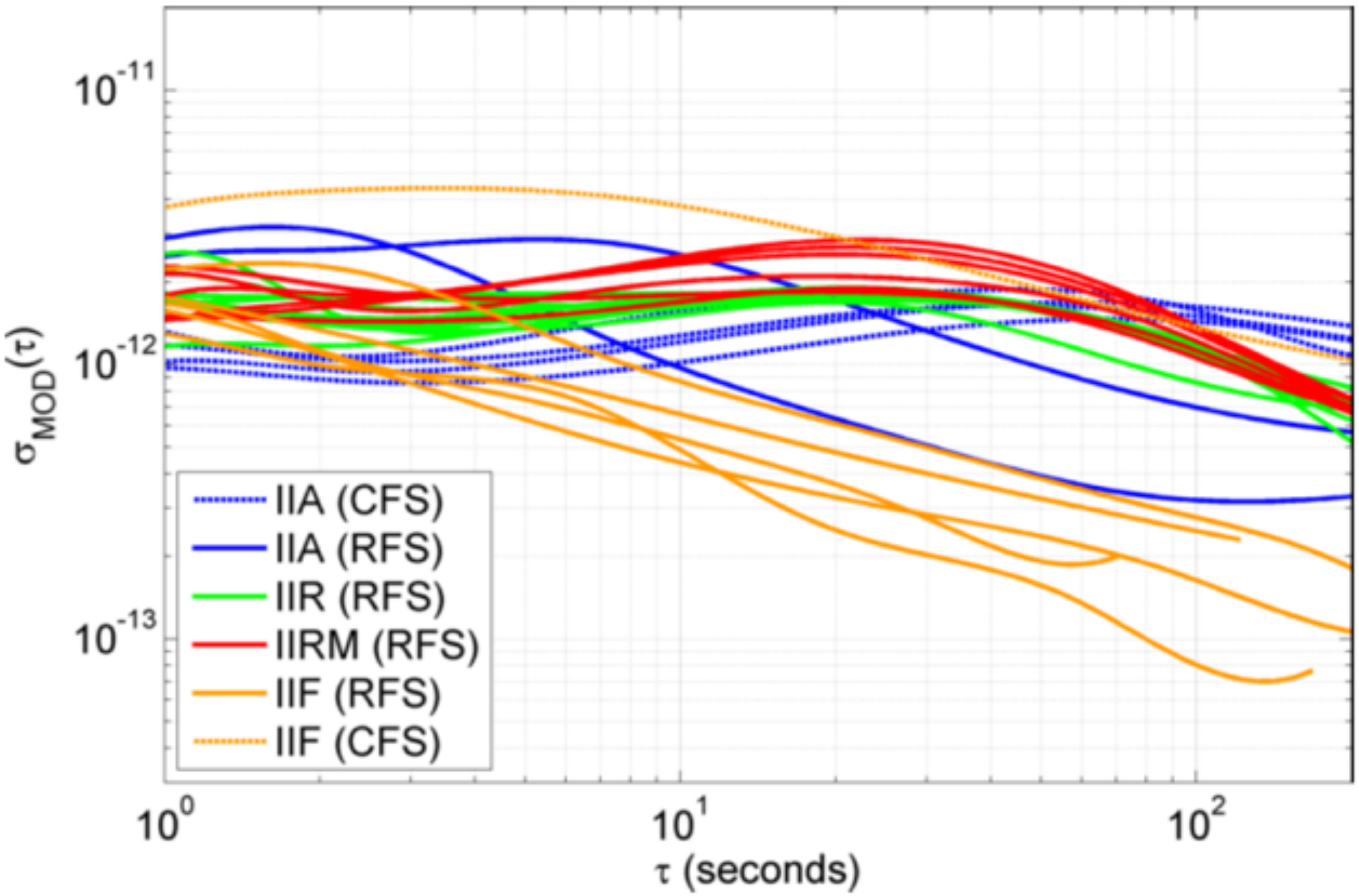
White noise FM

Flicker noise FM

Random walk FM

Allan variances as noise characteristics

E.R. Griggs, E.R. Kursinski, D.M.Alkos (Radio Science, in press)



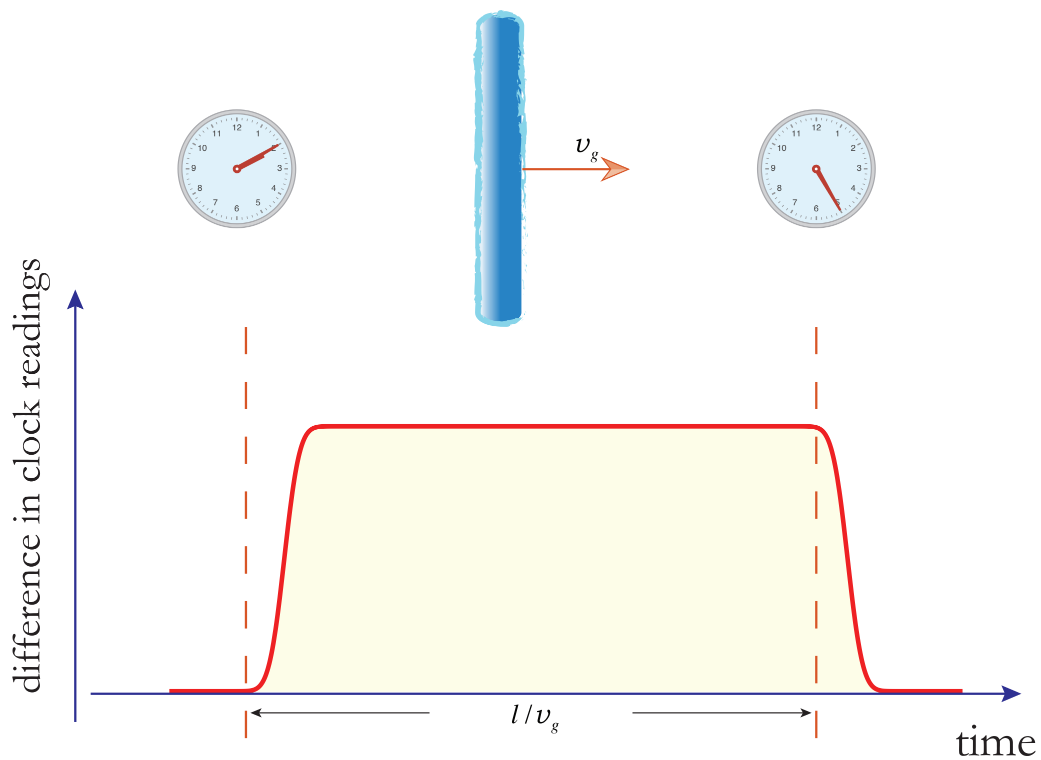
Time projection error $$\sigma_x(\tau) = \frac{\tau}{\sqrt{3}} \mathrm{Mod}\ \sigma_y(\tau)$$

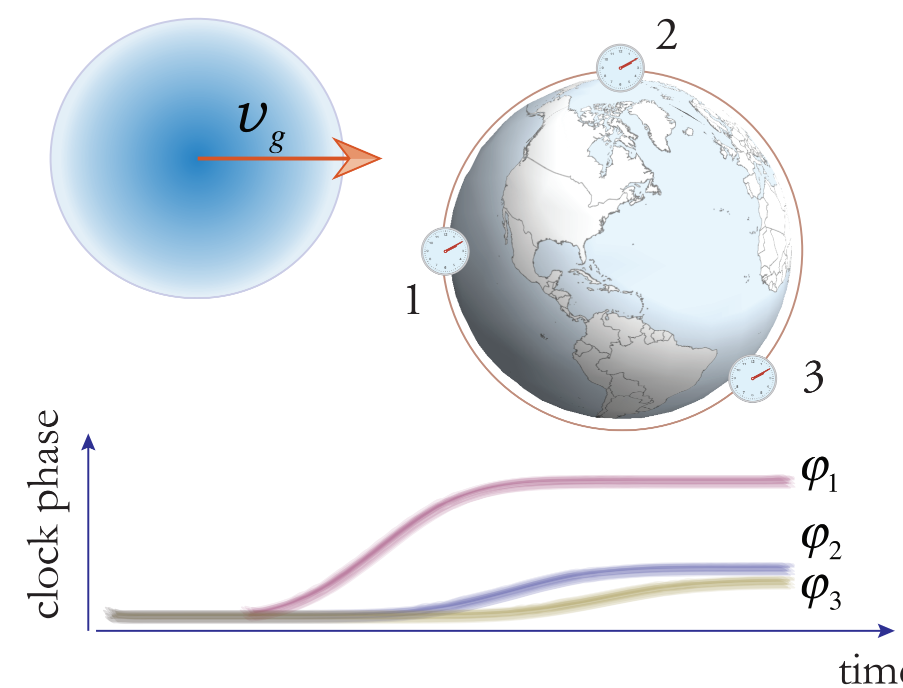
$$\sigma_x(30\,\mathrm{s}) \sim 3.5\times10^{-3}(\text{Cs-IIF}) - 5.2\times10^{-2}(\text{Rb-IIRM})\ \text{ns}$$

Plan

- About 10 years of 30 second solutions are publicly available (too bad they use "compound" reference clock (US/EU))
- Regenerate GPS clock solutions with a single reference clock (massive computational task but doable: "free" computer time)
- Characterize likelihoods for clocks (non-stationarity/ covariances)
- X-correlate clocks
- Stage I: 30s IGS satellite clock solutions
- Stage II: high-rate 1s data from ground station/satellite clocks

Listening to dark matter with a network of atomic clocks





- Differential signals last for ~30 s for transcontinental networks, ~200 s for GPS
- X-correlations between clocks are important as once a year short-duration events can be dismissed as outliers
- Other possibilities: networks of magnetometers (Budker et al), LIGO, EPV,…

Details in Derevianko and Pospelov, Nature Phys. 10, 933 (2014)