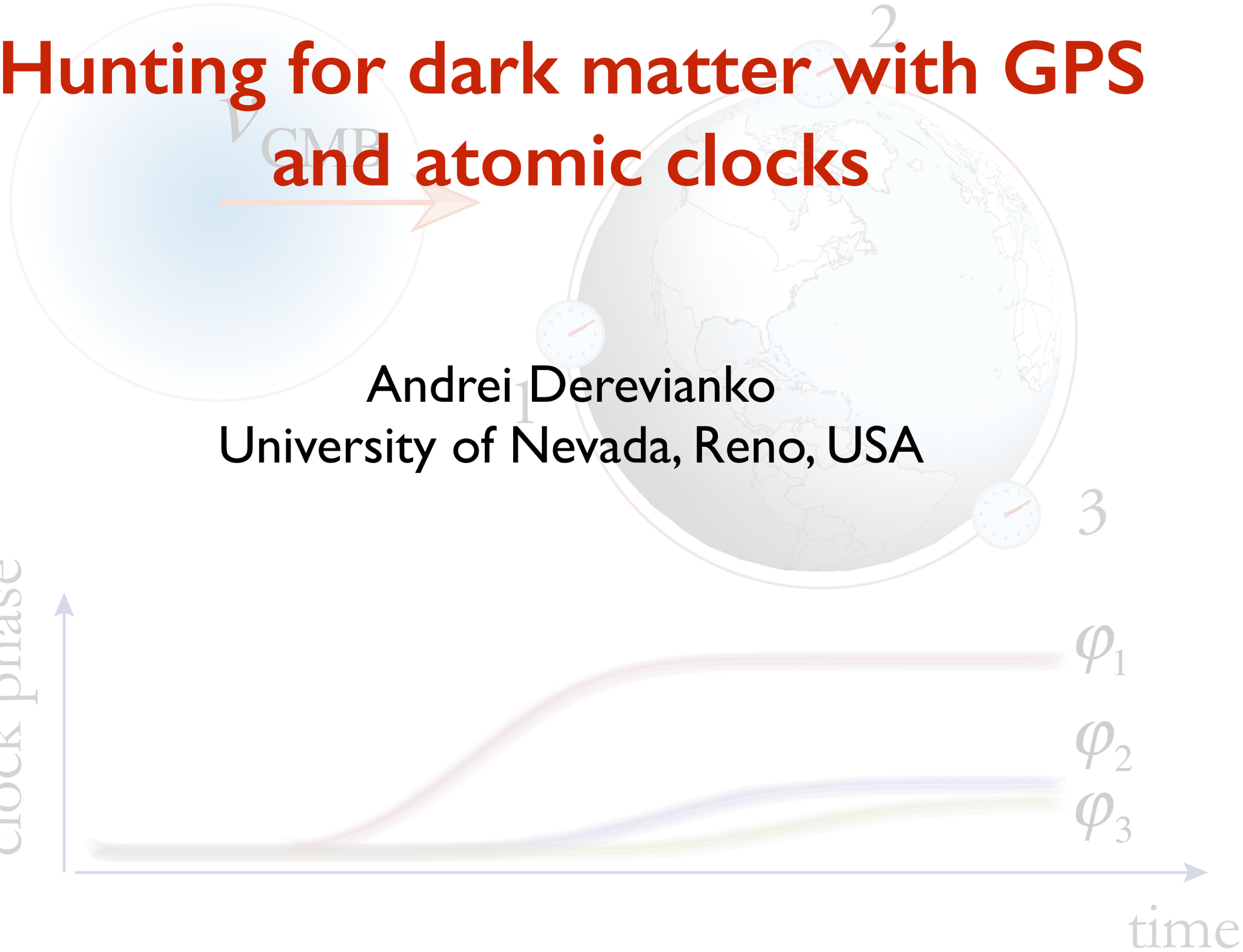
Hunting for dark matter with GPS and atomic clocks

Andrei Derevianko
University of Nevada, Reno, USA

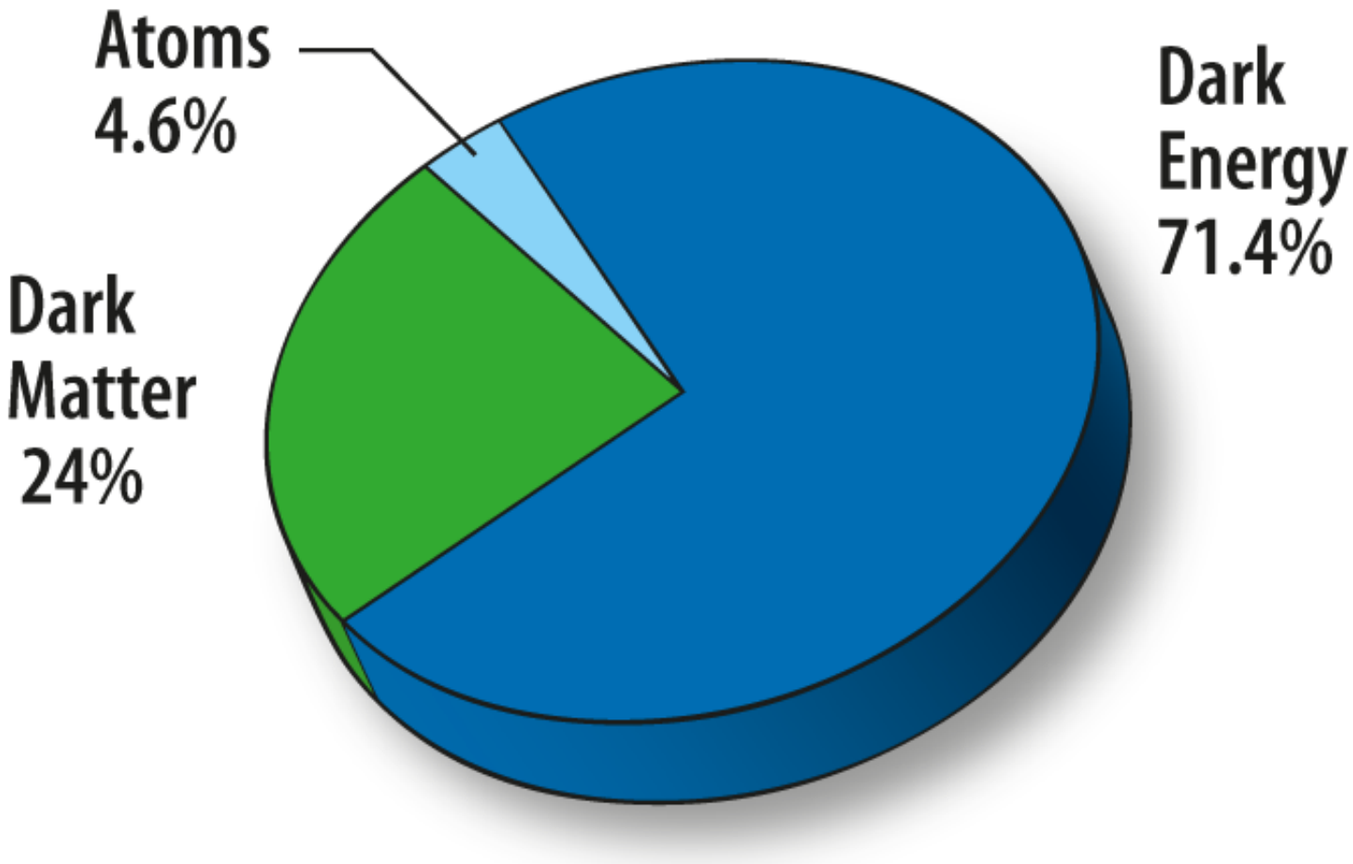


Outline

- Dark-matter (DM) problem
- Topological DM/ “Lumpy” DM
- Transient variation of fundamental constants
  - Scalar fields -> oscillating fundamental consts
  - Clocks and GPS as DM detectors

A. Derevianko and M. Pospelov, Nature Phys. 10, 933 (2014)

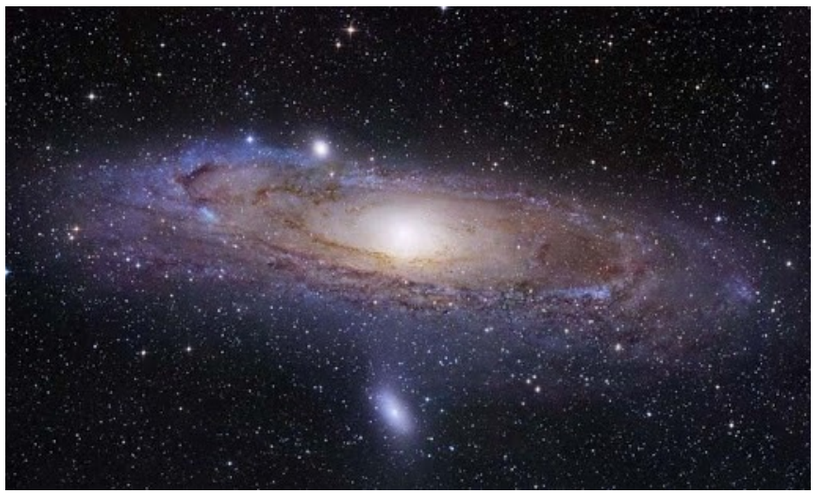
Problem of dark matter/dark energy



Excellent textbook: S. Weinberg "Cosmology"

Dark matter puzzle

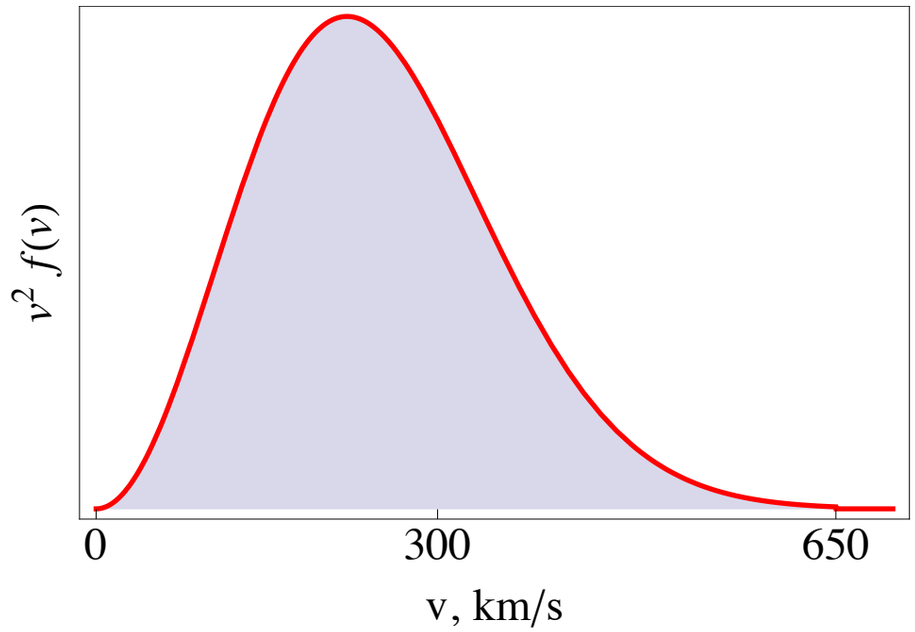
- Only 5% of the Universe is made up of ordinary (baryonic) matter
- Does not emit/absorb radiation: can not be seen with telescopes
- Multiple observational evidences: galactic rotation curves, gravitational lensing, cosmic microwave background,…
- Inferred from **gravitational interactions** with luminous matter on **galactic scales**
- What is it?
  Does it interact with baryonic matter non-gravitationally?



What do we know about DM?

Dark Matter halo

Velocity distribution



Galactic orbital motion

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

Energy density

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

Candidates: from WIMPs to MACHOs

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

$M < 10^{-24}\, M_\odot$?

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

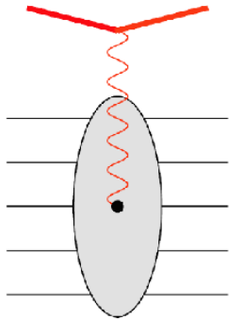
WIMPs

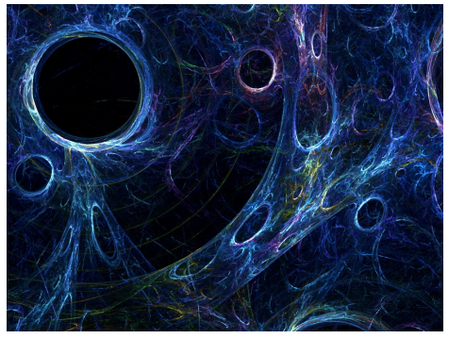
Weakly interacting massive particles

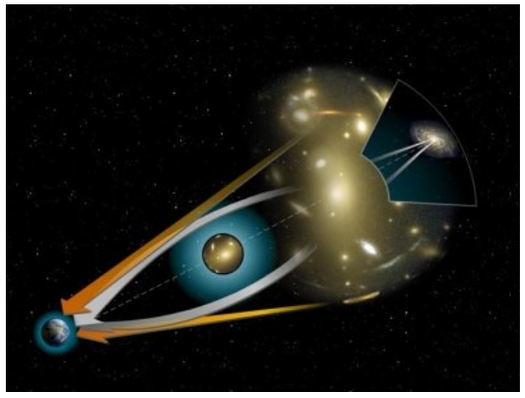
Quantum fields

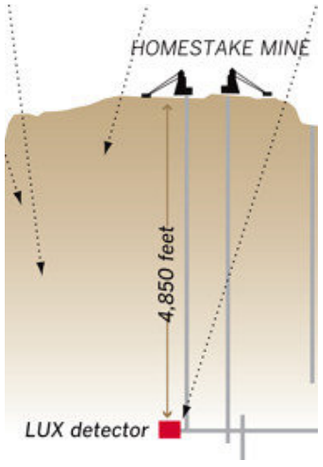
MACHOs

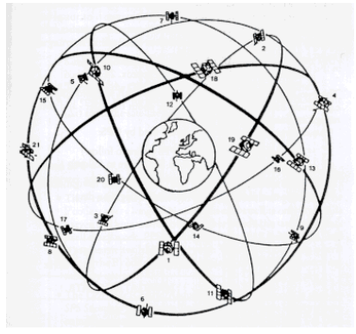
Massive compact halo objects



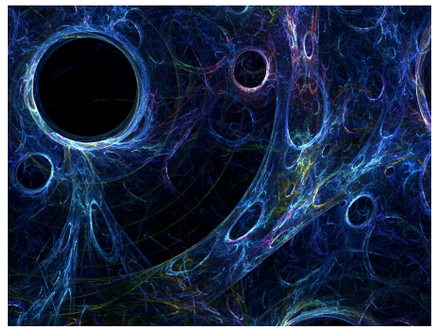








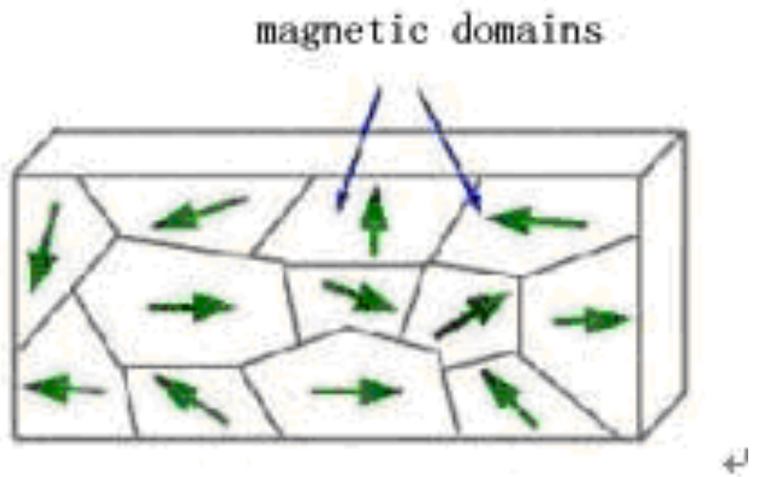
Topological Dark Matter = TDM



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 (lumpy DM)

Illustration: ferromagnets

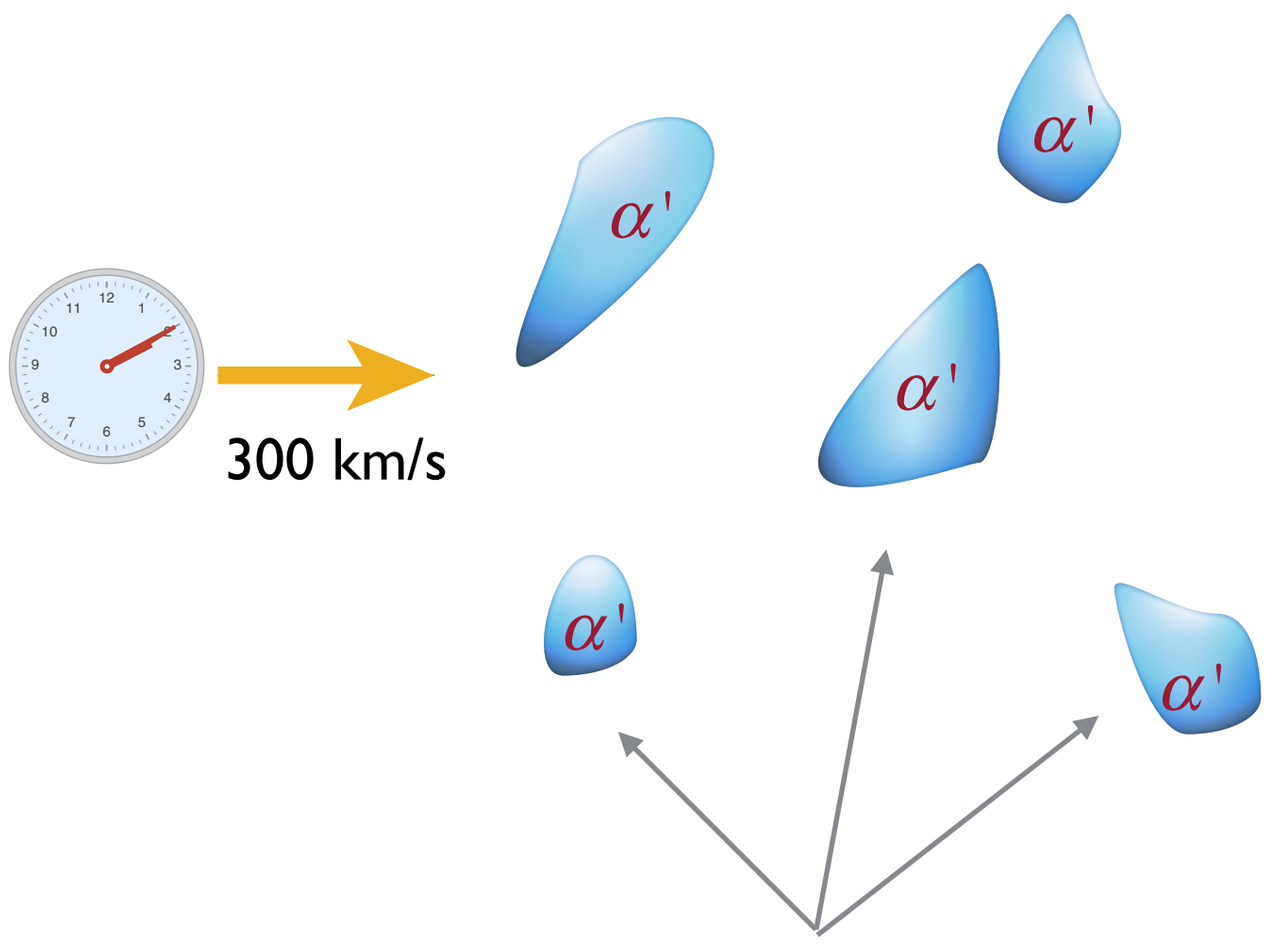


Curie point in ferromagnetic phase transitions

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

DM halo="preferred" reference frame



Macroscopic DM objects

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

Clocks

quantum oscillator:

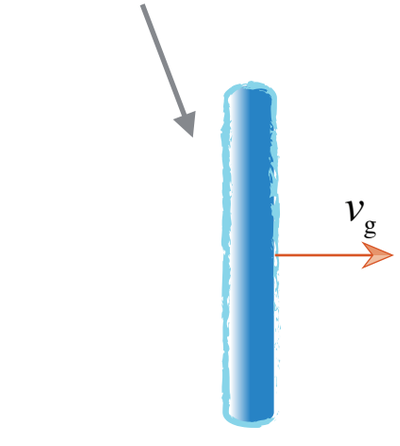
phase = $\phi_0(t) = \int_0^t \omega_0 dt'$ ⇒ time = $\phi_0(t)/\omega_0$

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

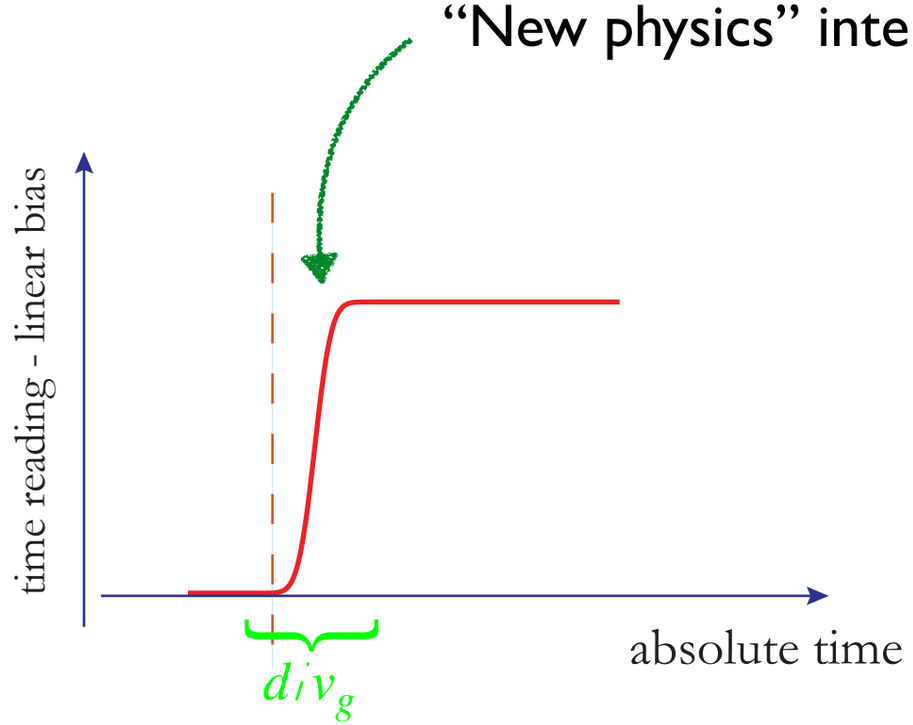
$$\Delta\phi_{\mathrm{TDM}}(t) = \int_{-\infty}^{t} \delta\omega(t')dt' \Rightarrow \Delta t_{\mathrm{TDM}}(t) = \frac{\Delta\phi_{\mathrm{TDM}}(t)}{\omega_0}$$

Basic idea

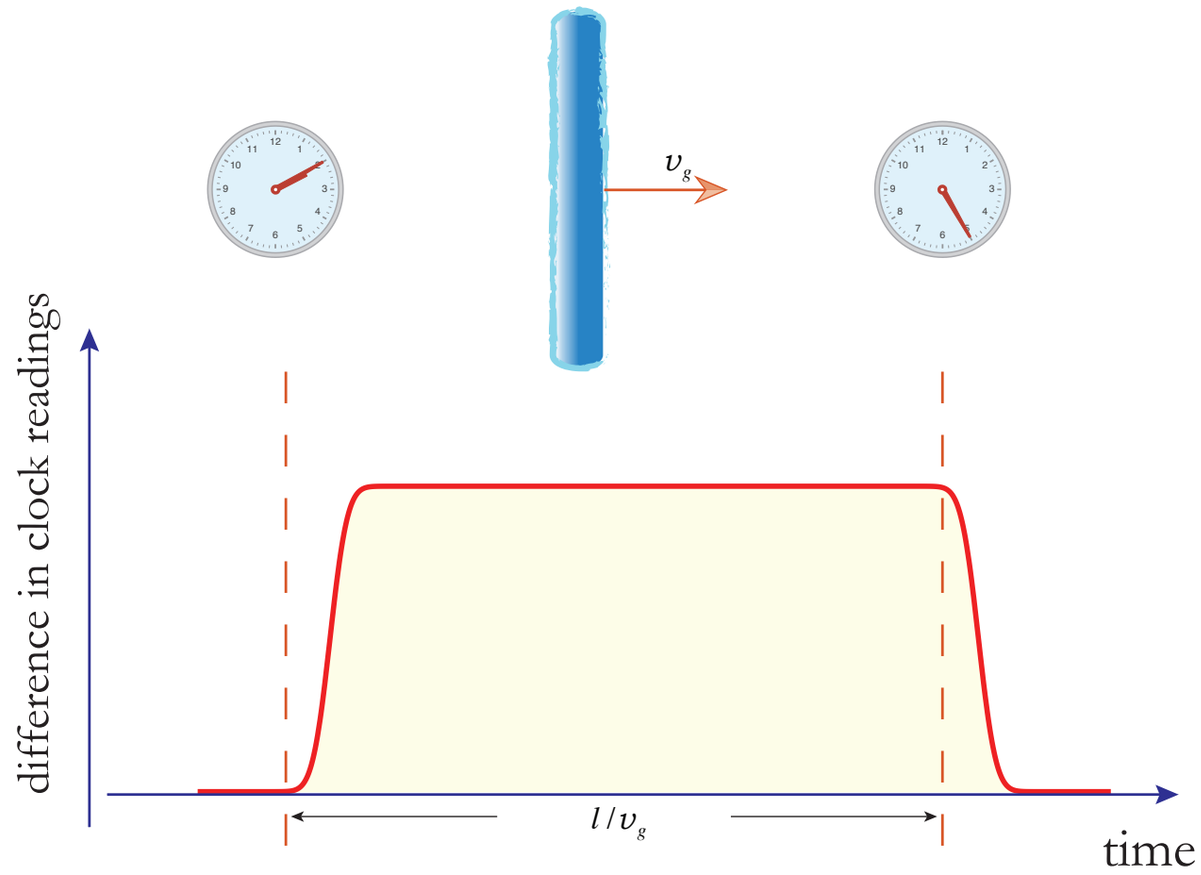
Lump of dark matter ~300 km/s



atomic frequencies are shifted by the lump



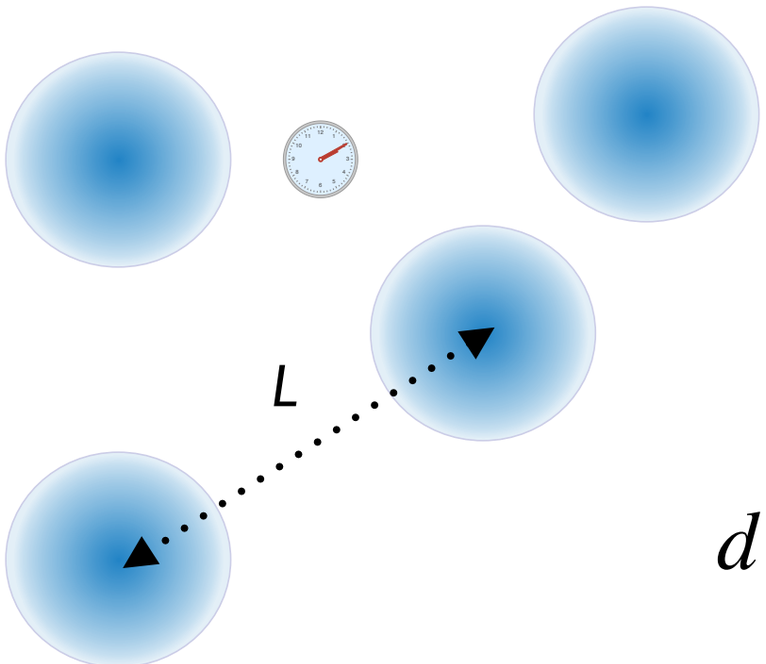
Dark matter signature

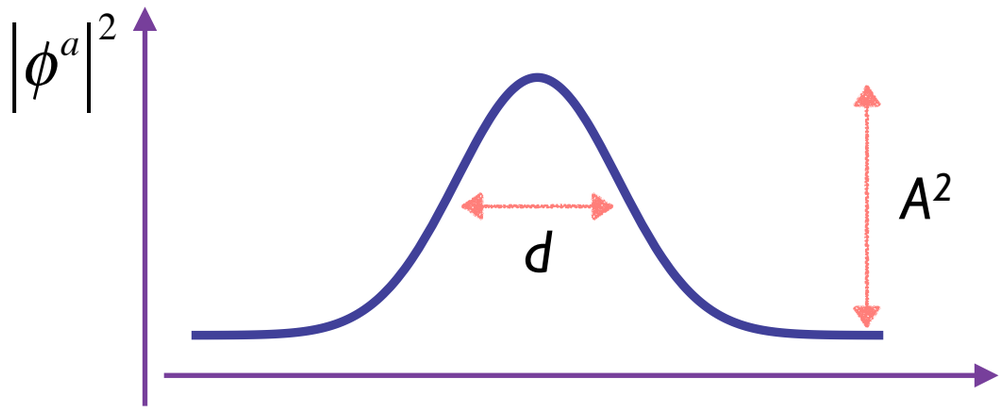


Monitor time difference b/w two spatially-separated clocks
⇒ persistent clock discrepancy for over time l/v_g

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

“Gas of topological defects” DM model





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

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

M. Pospelov

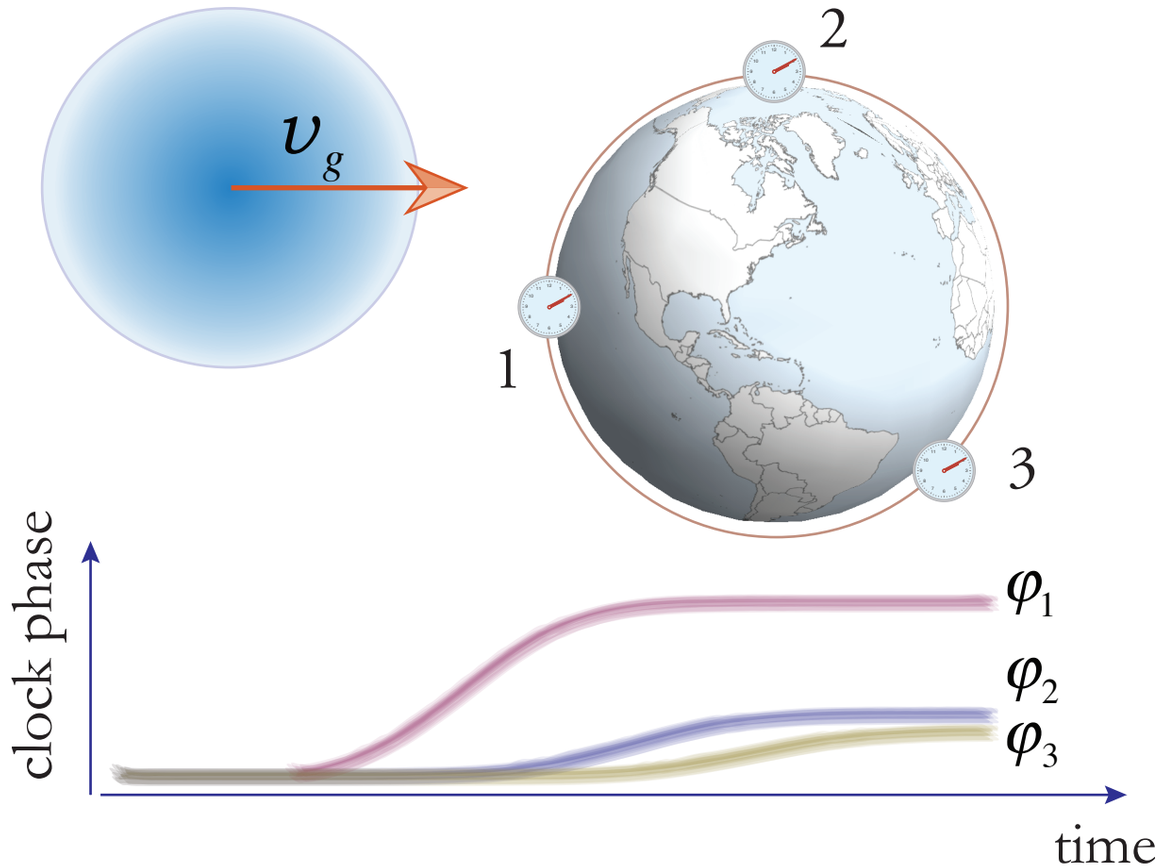
$$T_{coll} \sim \frac{1}{n\sigma v} \sim \frac{1}{1/L^3 \times d^2 \times v_g}$$

Time b/w “collisions”

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

Interaction time

Tomography of monopoles



Dark-matter portals

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

DM field — electrons — protons — EM field

Compare to the QED Lagrangian

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

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

$$\alpha \to \alpha / (1 - a^2(\mathbf{r},t)/\Lambda_\gamma^2)$$

DM lumps pull on the rest masses of electrons, quarks and EM coupling

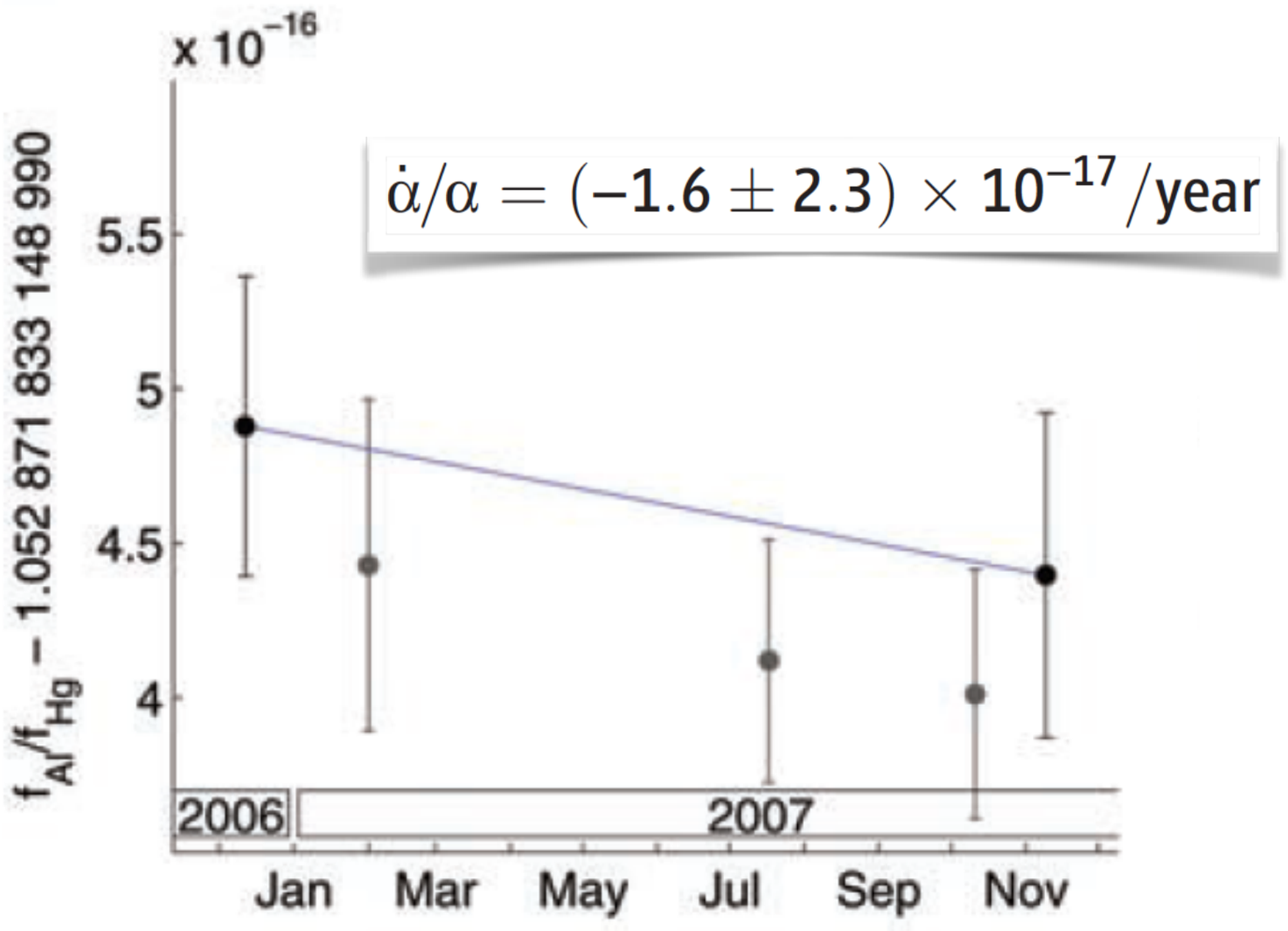
Energies and frequencies are modulated as TD sweeps through

Variation of fundamental constants

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

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

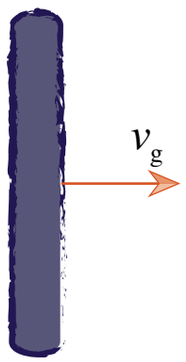
Compare ratio of frequencies of two clocks with different sensitivities



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

Variation of fundamental constants

Drift vs transients



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

Transient

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

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

Variations of fundamental constants (circa 2015)

Slow drifts

Transients

Oscillations

Stochastic background

Topological DM
Microstructure

Dilaton DM
Axion-like particles

Dark Energy?

This talk

Arvanitaki et al PRD (2015)

Oscillating fundamental constants

scalar ultralight fields: e.g., dilatons

$$\phi(\mathbf{r},t) = \phi_0 \cos\left(\omega_\phi t - k_\phi \cdot \mathbf{r} + \cdots\right)$$

Compton frequency

$$\omega_\phi = m_\phi c^2 / \hbar$$

$$\rho_\phi = \frac{1}{2}\left(\frac{m_\phi c}{\hbar}\right)^2 \phi_0^2 .$$

Energy density = local DM energy
=> field amplitude

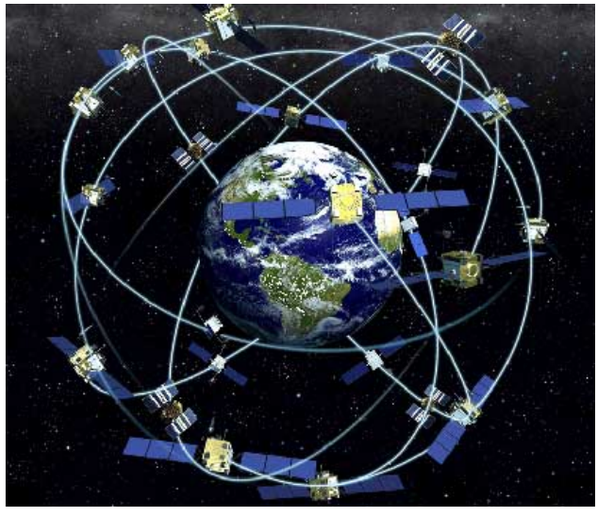
Portal

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

How to detect variation of fundamental constants?

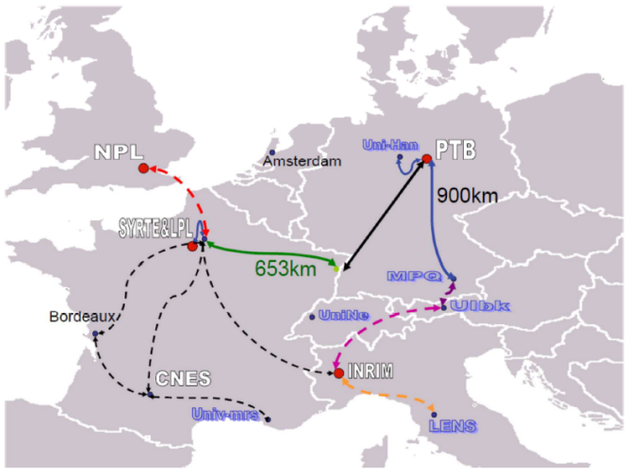
- Clocks (frequency)
- Cavities (length -> frequency)
- EPV tests (atom interferometry)
- Portal induced gravity (sat orbits?, gravimeters, AI)
- Gravitational wave detectors

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

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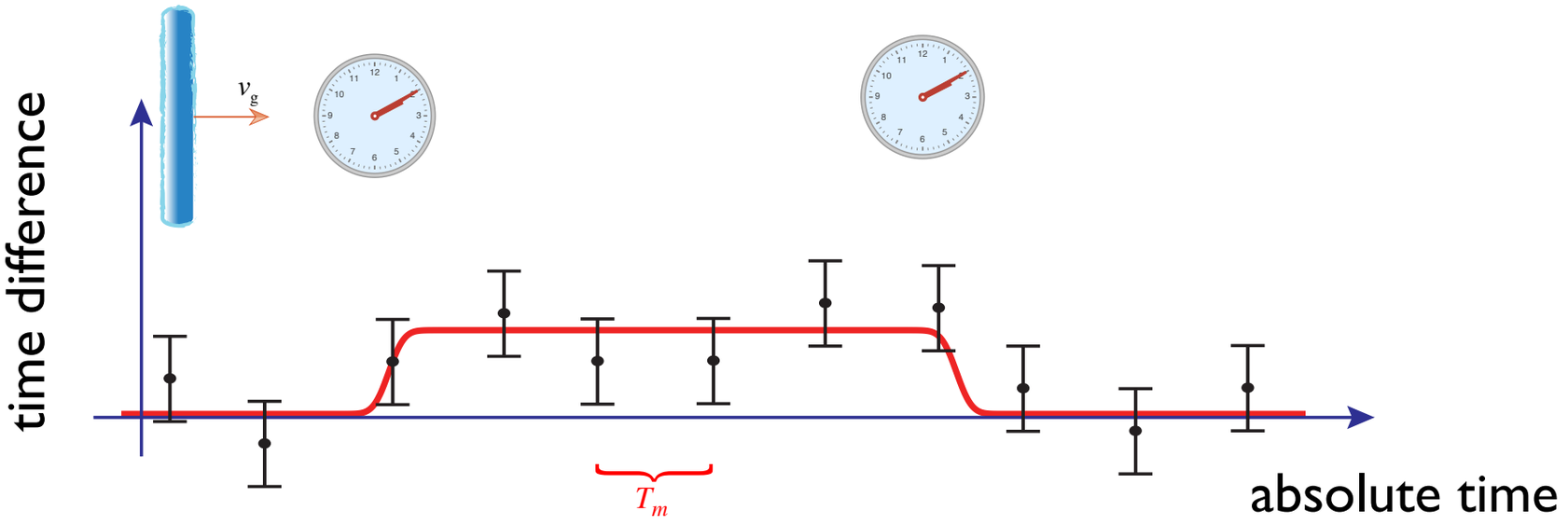
Signal-to-noise ratio



Time b/w events

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

Allan variance

Dark matter energy density

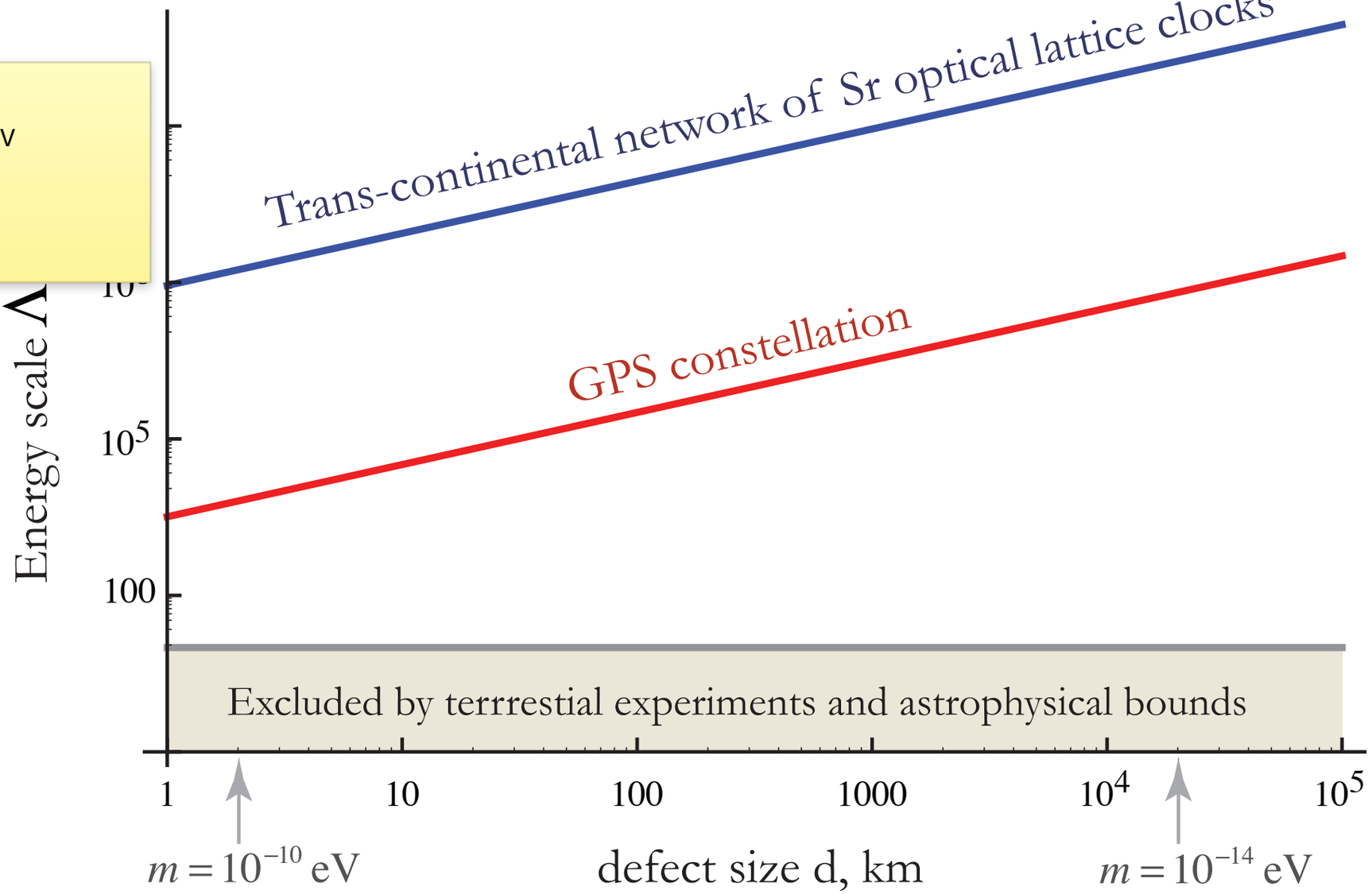
defect size

Projected limits (thin domain walls)

(if the TDM signature is not observed)

Total monitoring time = 1 year

Plank energy scale 10^16 TeV



+ Link noise: D. Calonico, M. Inguscio, and F. Levi, EPL 110, (2015).

GPS as a dark matter detector

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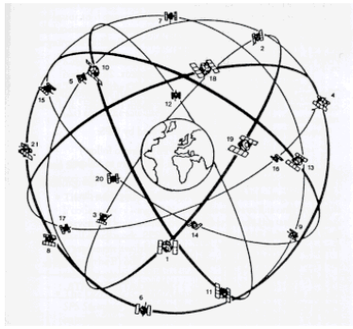
GPS as a dark matter detector (GPS.DM observatory)



- GPS = 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
- About 10 years of 30 second solutions are available
- Fit clock solutions to box-car functions/x-correlate clocks

GPS.DM Observatory

G. Blewitt (GPS, Nevada-Reno)
A. Derevianko (Theory/data analysis, Nevada-Reno)
M. Pospelov (QFT/Cosmology, Perimeter)
J. Sherman (Clocks, NIST-Boulder)

Postdoc: B. Robberts

Students (all Nevada-Reno)
M. Murphy(graduated), N. Lundholm, A. Rowling

Cooling with combs (cold atoms +precision spectroscopy)

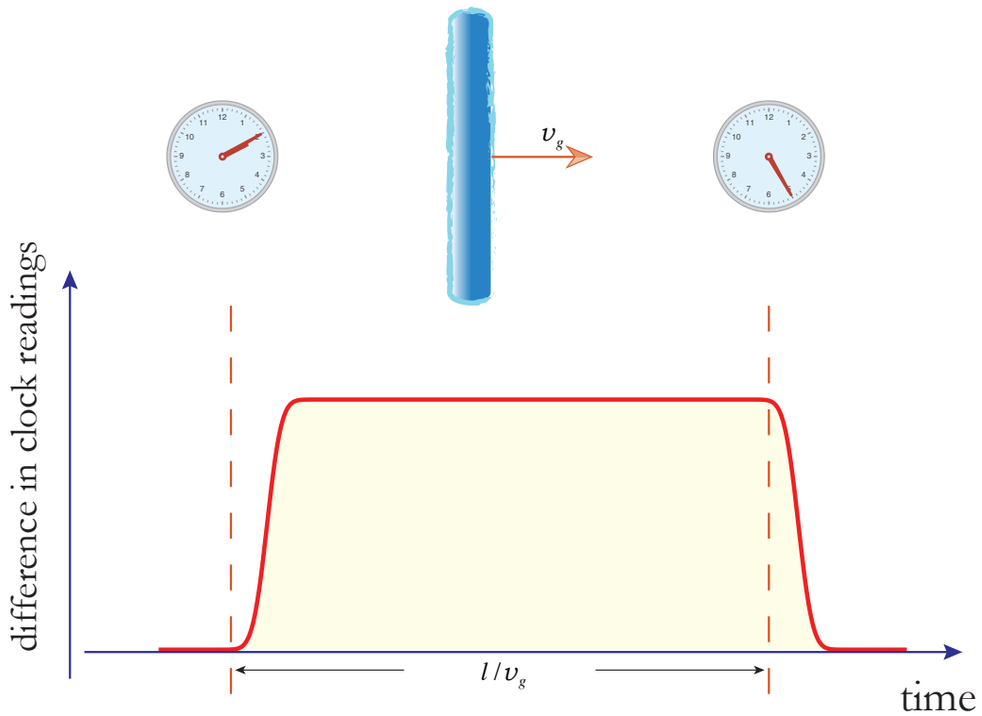
1 **Stimulated cooling of molecules on multiple rovibrational transitions with coherent pulse trains**, E. Ilinova, J. Weinstein, and A. Derevianko, *New J. Phys. 17, 055003 (2015), arXiv:1201.1015*

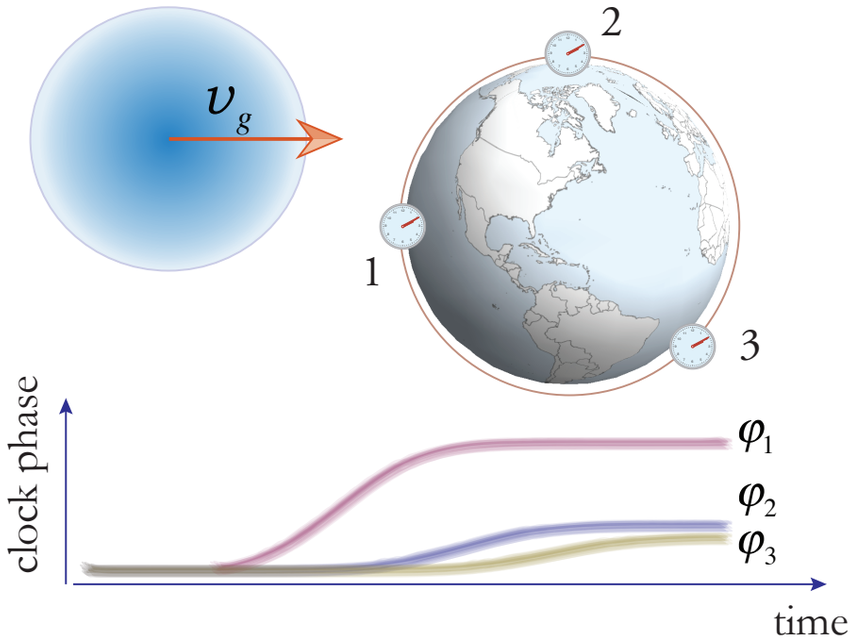
2 **See-saw protocol for Doppler cooling of multilevel systems with coherent pulse trains**, M. Ahmad, E. Ilinova, and A. Derevianko, *arXiv:1206.2393*

3 **Doppler cooling of three-level Λ-systems by coherent pulse trains**, E. Ilinova, A. Derevianko, *Phys. Rev. A 86, 023417 (2012), arXiv: 1203.1963*

4 **Dynamics of three-level Λ-type system driven by the trains of ultrashort laser pulses**, E. Ilinova and A. Derevianko, *Phys. Rev. A 86, 013423 (2012)*, *arXiv:1203.0034*

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,…
- Ultra-stable clocks are beneficial => Heisenberg-limited spectroscopy

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