

Stochastic fluctuations of bosonic dark matter

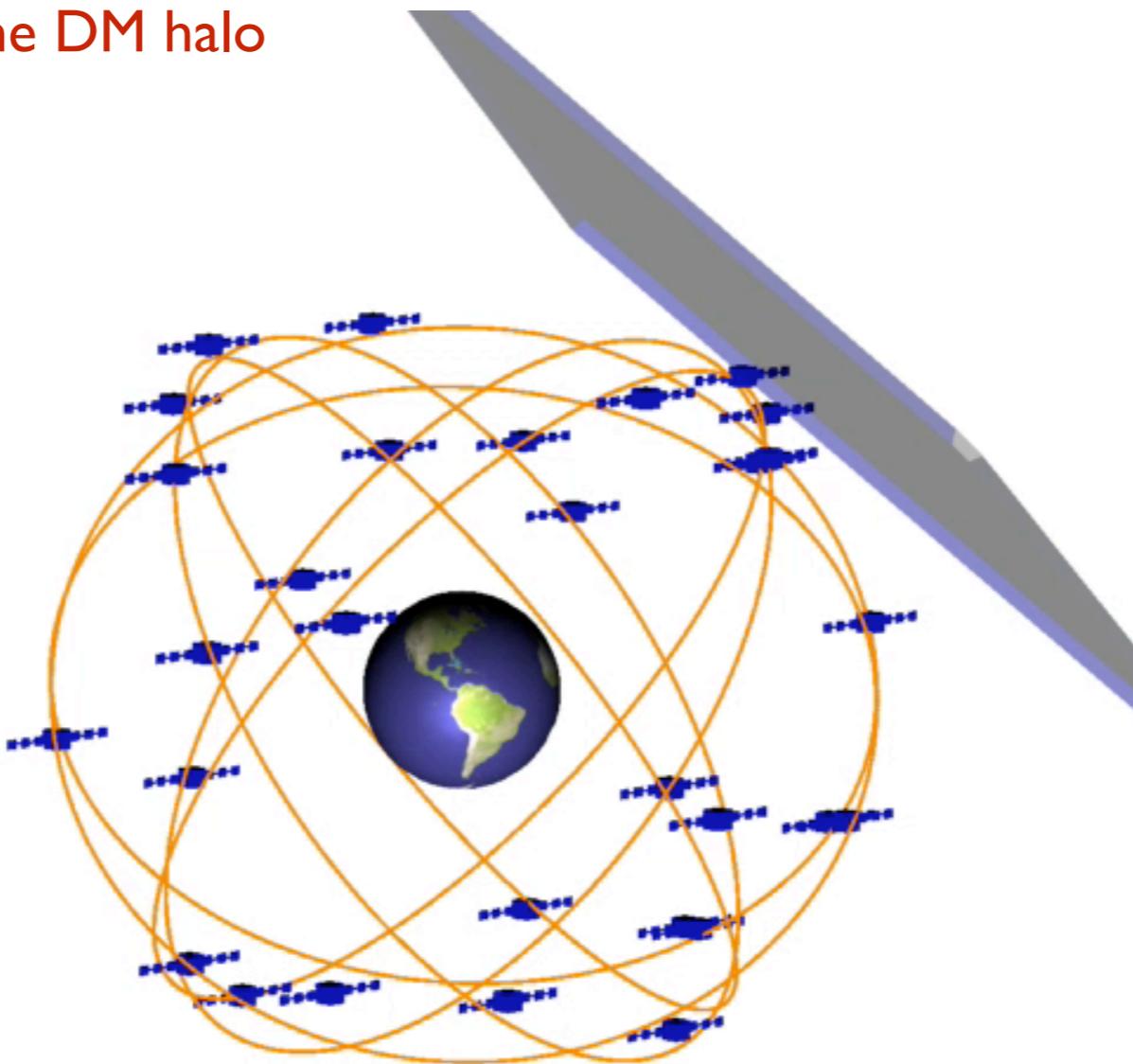
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arXiv:1605.09717
arXiv:1905.13650

DM search with GPS (not today)

Search for GPS glitches correlated with
the Earth's motion through the DM halo



Credit: Conner Dailey

GPS.DM collaboration: data mining ~20 years of atomic clock data aboard GPS satellites

Editors' Suggestion**Detecting dark-matter waves with a network of precision-measurement tools**

Andrei Derevianko

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Astro-local vs Lab-local DM energy density

Astro
local

$\bar{\rho}_{\text{DM}}$ = average over a “small” volume $(100 \text{ pc})^3$

N.B.: $100 \text{ pc} = 2 \times 10^7 \text{ AU} = 3 \times 10^{18} \text{ m}$

$$\bar{\rho}_{\text{DM}} \approx 0.4 \text{ GeV/cm}^3$$

Lab
local

ρ_{DM} @ sensor => $\sim(1 \text{ nm})^3$ for an atom

In general, $\rho_{\text{DM}} \neq \bar{\rho}_{\text{DM}}$

ρ_{DM} depends on a specific DM model

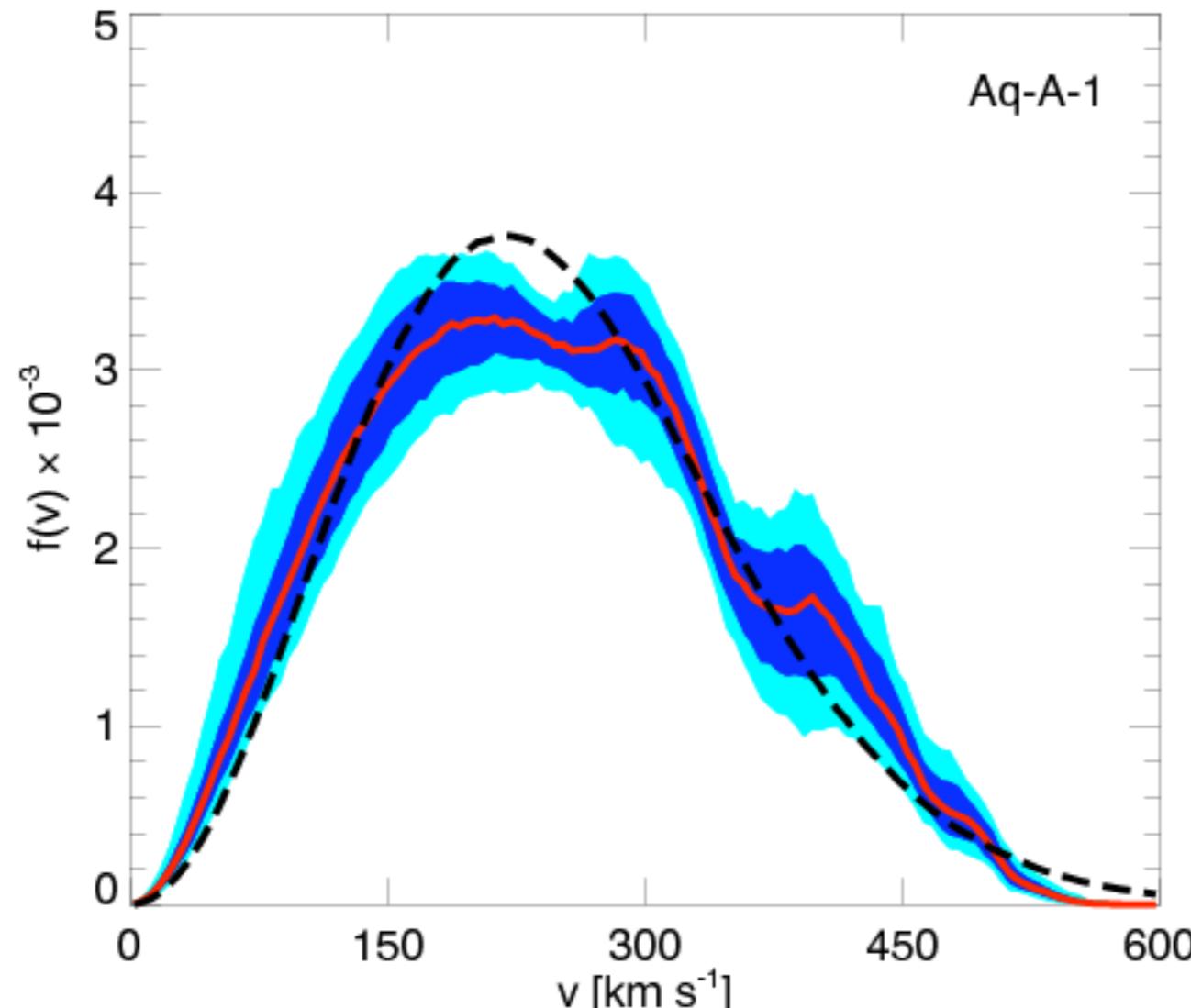
Model-dependence of lab-local ρ_{DM}

- ▶ Clumpy DM
 - Streams/clusters/solitons/Q-balls/topological defects ...
- ▶ Environmental screening/amplification (e.g., Earth)
 - Gravitational or due to hypothesized coupling to baryons

▶ Less obvious: non-self interacting but virialized fields (axions, dilatons,...)

- Lab-local ρ_{DM} fluctuates around astro-local $\bar{\rho}_{\text{DM}}$
- Reason: DM velocity distribution => stochastic field
- Revision of exclusion plots for at least 7 published experiments
- Substantial - order of magnitude - effect

DM velocity distro



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

I will use the Standard Halo Model (SHM) velocity distro

Virialized ultra-light fields (VULFs)

Virialized ultra-lite fields (VULFs)

Example: S=0 fields, no self-interaction

- ▶ True scalars: dilatons/moduli
- ▶ Pseudo scalars: axions/ALPs

Single mode (fixed velocity)

$$\phi(t, \mathbf{r}) = \Phi_0 \cos(\omega_\phi t - \mathbf{k} \cdot \mathbf{r} + \theta)$$

$$\hbar\omega_\phi \approx mc^2 + \frac{1}{2}mv^2$$

Compton
frequency

$$\rho_{\text{DM}} = \frac{1}{2} \left(\frac{mc}{\hbar} \right)^2 \Phi_0^2$$

average over many oscillations

Many modes \Rightarrow Stochastic field

$$\frac{\text{# of particles}}{\text{mode}} \sim \left(\frac{\rho_{\text{DM}}}{mc^2} \right) \times (\lambda_{\text{de Broglie}})^3 \gg 1$$

$m \ll 10 \text{ eV} \Rightarrow$ ultra-lite DM

$\phi(t, \mathbf{r}) = \sum_{\text{modes}}$ many waves with random phases

\Rightarrow **Gaussian random fields** (radiophysics, CMB, stochastic GW background,...)

- ▶ Correlation time and length
- ▶ Statistics is fully determined by 2-point correlation function

Stochastic approach: 2-point correlation function

$$\hbar\omega_\phi = \sqrt{(mc^2)^2 + \left(\frac{kc}{\hbar}\right)^2} \approx mc^2 + \frac{mv^2}{2}$$

← Dephasing

⇒ coherence time & length

$$\phi(t', \mathbf{r}')$$



$$\phi(t, \mathbf{r})$$

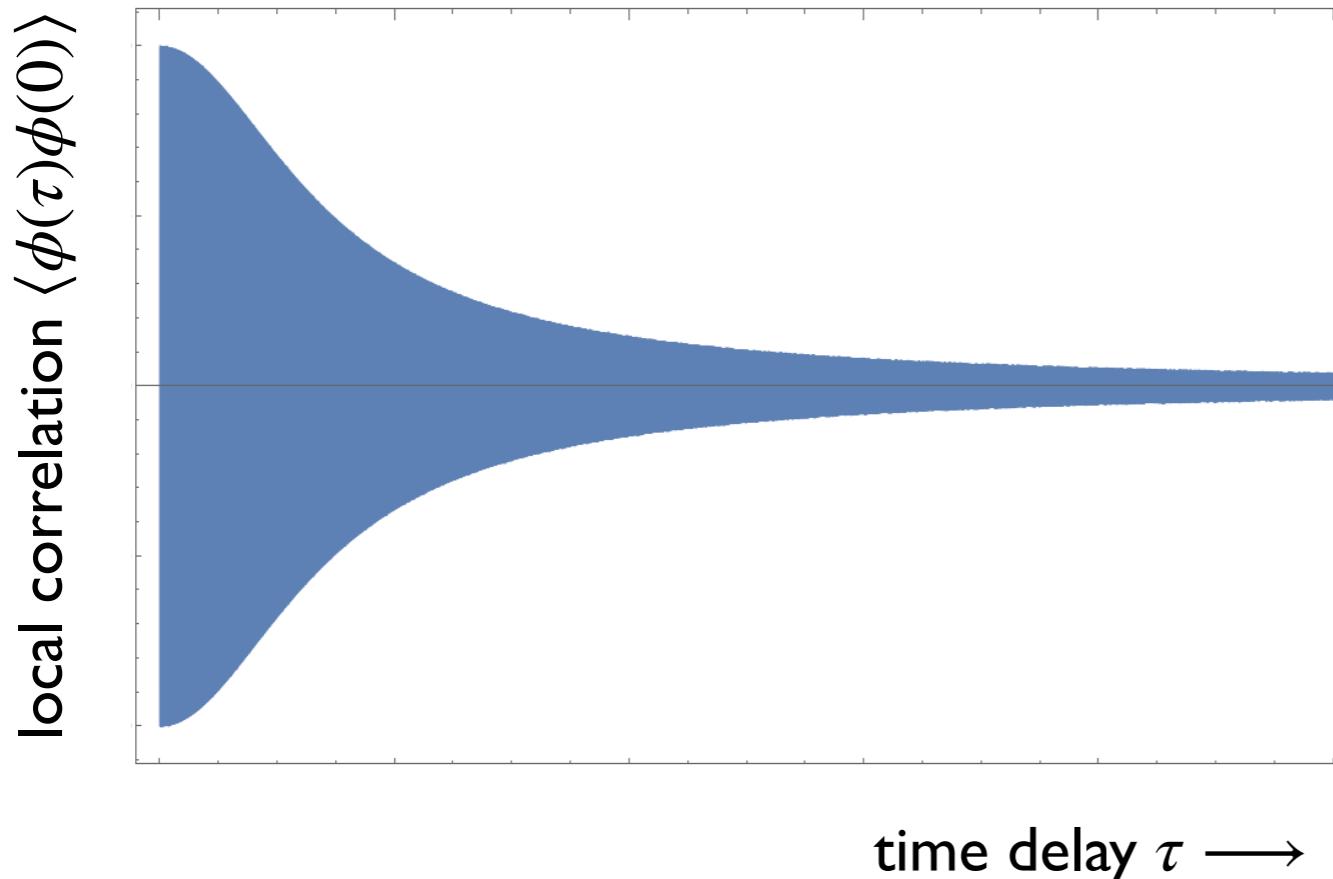


$$g(\tau, \mathbf{d}) = \langle \phi(t' = t + \tau, \mathbf{r} = \mathbf{r}' + \mathbf{d}) \phi(t, \mathbf{r}) \rangle$$

2-point correlation function

Analytical result in PRA **97**, 042506 (2018)

$$\langle \phi(t + \tau, \mathbf{r} + \mathbf{d}) \phi(t, \mathbf{r}) \rangle = \frac{1}{2} \bar{\Phi}_{\text{DM}}^2 A(\tau, \mathbf{d}) \cos(\omega_c' \tau - \mathbf{k}_g \cdot \mathbf{d} + \Psi(\tau, \mathbf{d}))$$



Correlation time and length

$$\tau_{\text{corr}} \approx 10^6 / m$$

$$\lambda_{\text{corr}} \approx 10^3 / m$$

The amplitude

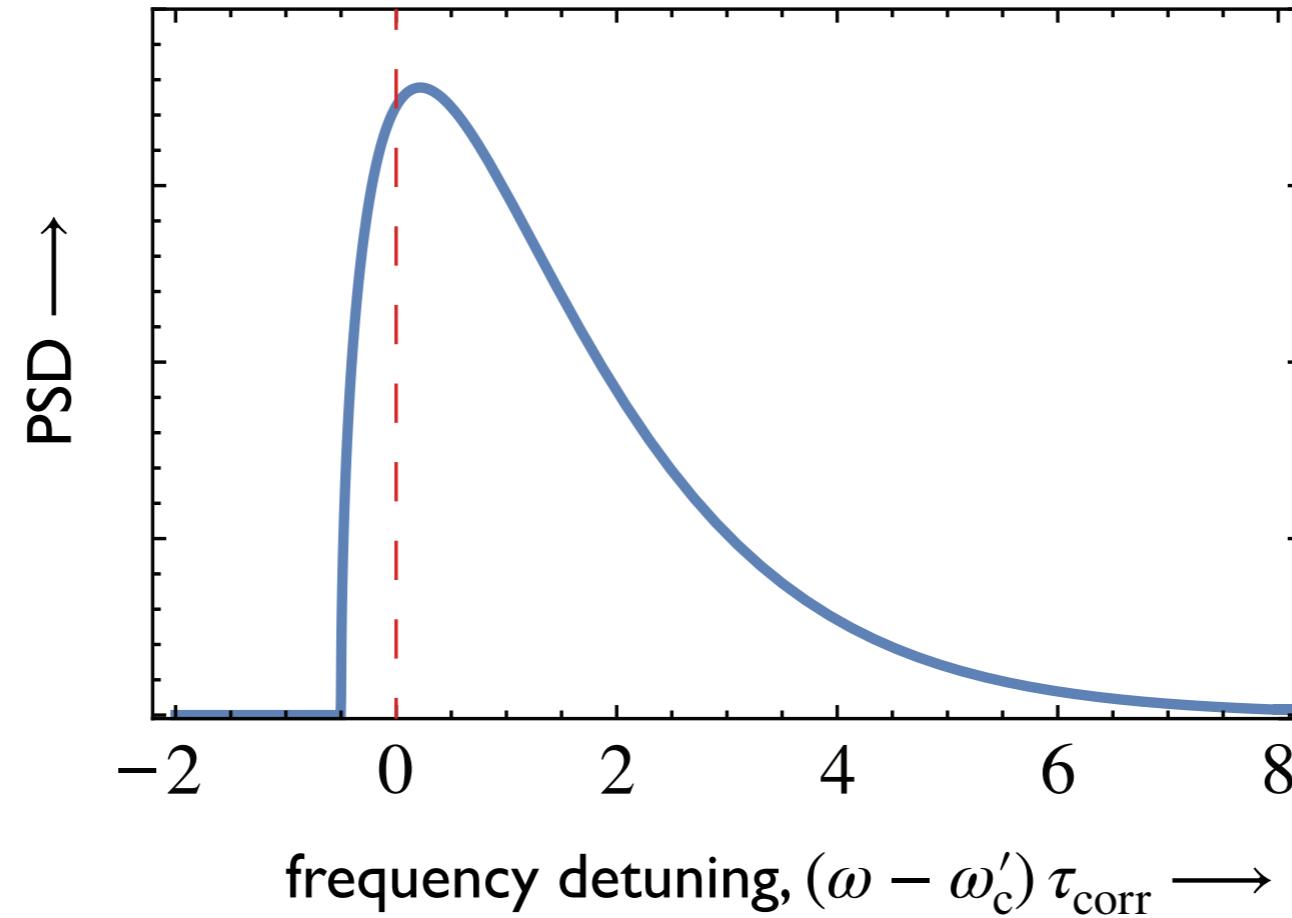
$$\bar{\Phi}_{\text{DM}}^2 = \frac{2}{m^2} \bar{\rho}_{\text{DM}}$$

Astro-local

Line-shape

Wiener–Хинчин theorem

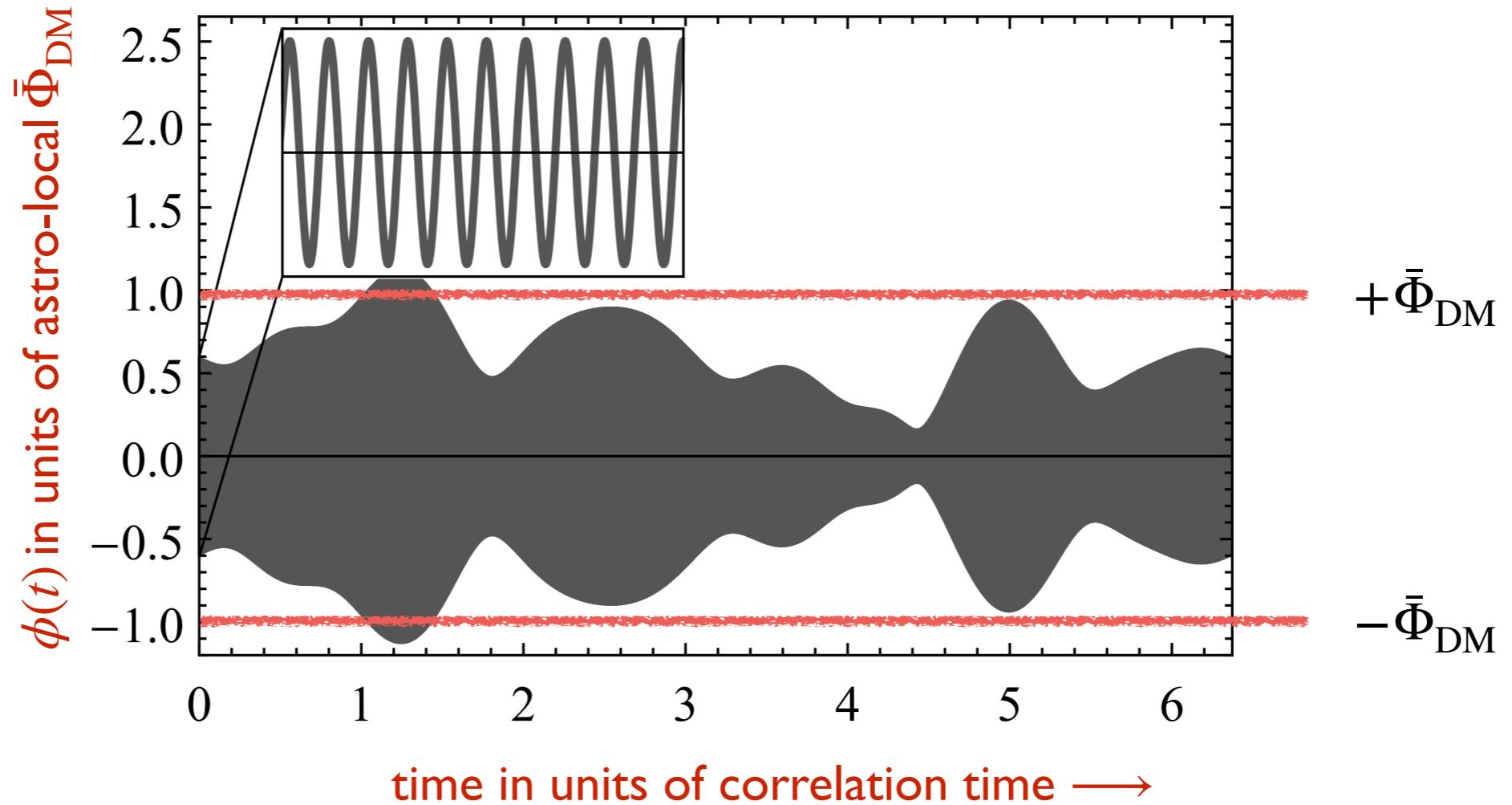
Power spectral density (PSD) = Fourier transform[2-point correlation function]



Strongly asymmetric due to relativistic dispersion for massive particles

Earlier result: [Turner, PRD 42, 3572 \(1990\)](#)

VULF simulation



If the observation time \ll correlation time

$$\phi(t, \mathbf{r}) \approx \Phi_0 \cos(\omega_\phi t + \theta)$$

Lab-local $\rho_{\text{DM}} \neq$ astro-local $\bar{\rho}_{\text{DM}}$

Unlucky experimentalist may encounter near-zero amplitudes

Time scales

mass	oscillation period	correlation time
10^{-15} eV	~ 5 seconds	~10 days
10^{-20} eV	~ 6 days	~ 2000 years

Uncertainty in the amplitude/lab-local ρ_{DM} is an issue for $m \ll 10^{-14}$ eV

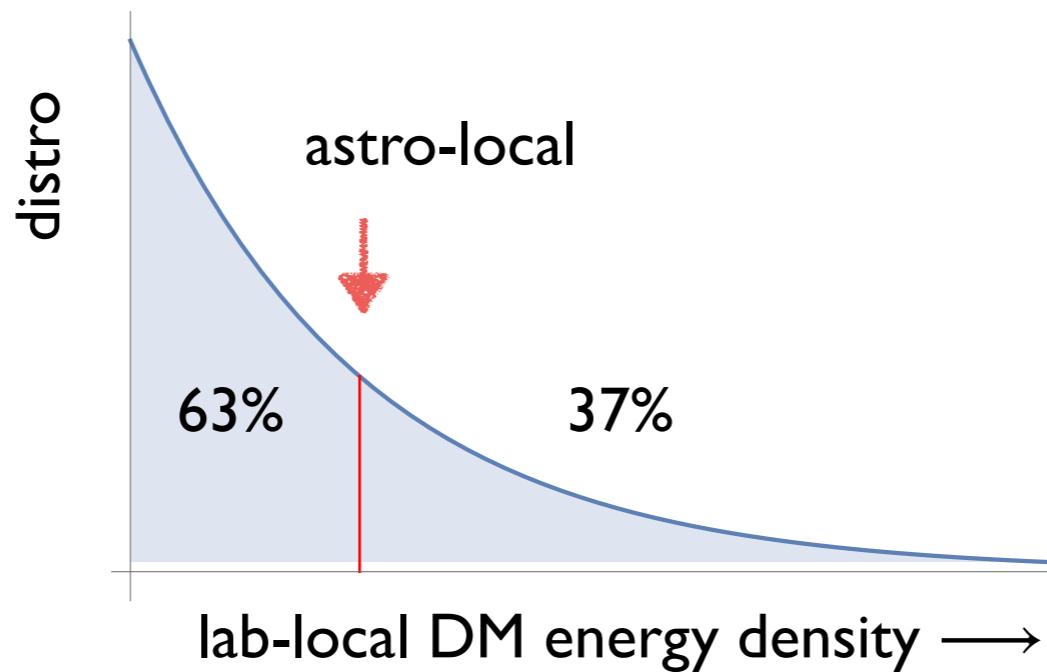
Statistics for the amplitude and ρ_{DM}

For observation time $\ll \tau_{\text{corr}}$, Rayleigh distro

$$p(\Phi_0 | \bar{\Phi}_{\text{DM}}) d\Phi_0 = \frac{2\Phi_0}{\bar{\Phi}_{\text{DM}}^2} \exp\left(-\frac{\Phi_0^2}{\bar{\Phi}_{\text{DM}}^2}\right) d\Phi_0$$

or for lab-local ρ_{DM}

$$p(\rho | \bar{\rho}_{\text{DM}}) d\rho = \frac{1}{\bar{\rho}_{\text{DM}}} \exp\left(-\frac{\rho}{\bar{\rho}_{\text{DM}}}\right) d\rho$$



Experimental VULF search template

Axion/ALP searches in the $m < 10^{-14}$ eV regime = magnetometry (Budker's talk)

Dilaton - // - = atomic clocks/spectroscopy

$$\text{signal}(t) \approx \gamma \Phi_0 \cos(\omega_\phi t + \theta)$$


coupling strength

DFT(signal) → search for spike in power spectrum @ ω_ϕ

No DM signal found so far \Rightarrow constraints on γ

Previous literature: ρ_{DM} or Φ_0 are fixed at the “astro-local” values

What is the effect of not knowing Φ_0 ?

Bayesian approach

Posterior distro for coupling strength γ

$$p(\gamma | m, \bar{\rho}_{\text{DM}}, \text{data}, I) = \mathcal{C} \int p(\Phi_0 | \bar{\rho}_{\text{DM}}, I) d\Phi_0 \int p(\theta | I) d\theta \mathcal{L}(\text{data} | \text{sought signal})$$

Constraints on γ at 95% C.L.

$$2 \int_0^{\gamma_{95\%}} p(\gamma | m, \bar{\rho}_{\text{DM}}, \text{data}, I) d\gamma = 0.95$$

- ▶ Deterministic: $\rho_{\text{DM}} \text{ lab-local} \equiv \rho_{\text{DM}} \text{ astro-local}$
- ▶ Stochastic: $\rho_{\text{DM}} \text{ lab-local is exponentially distributed}$

Posteriors for coupling strength γ

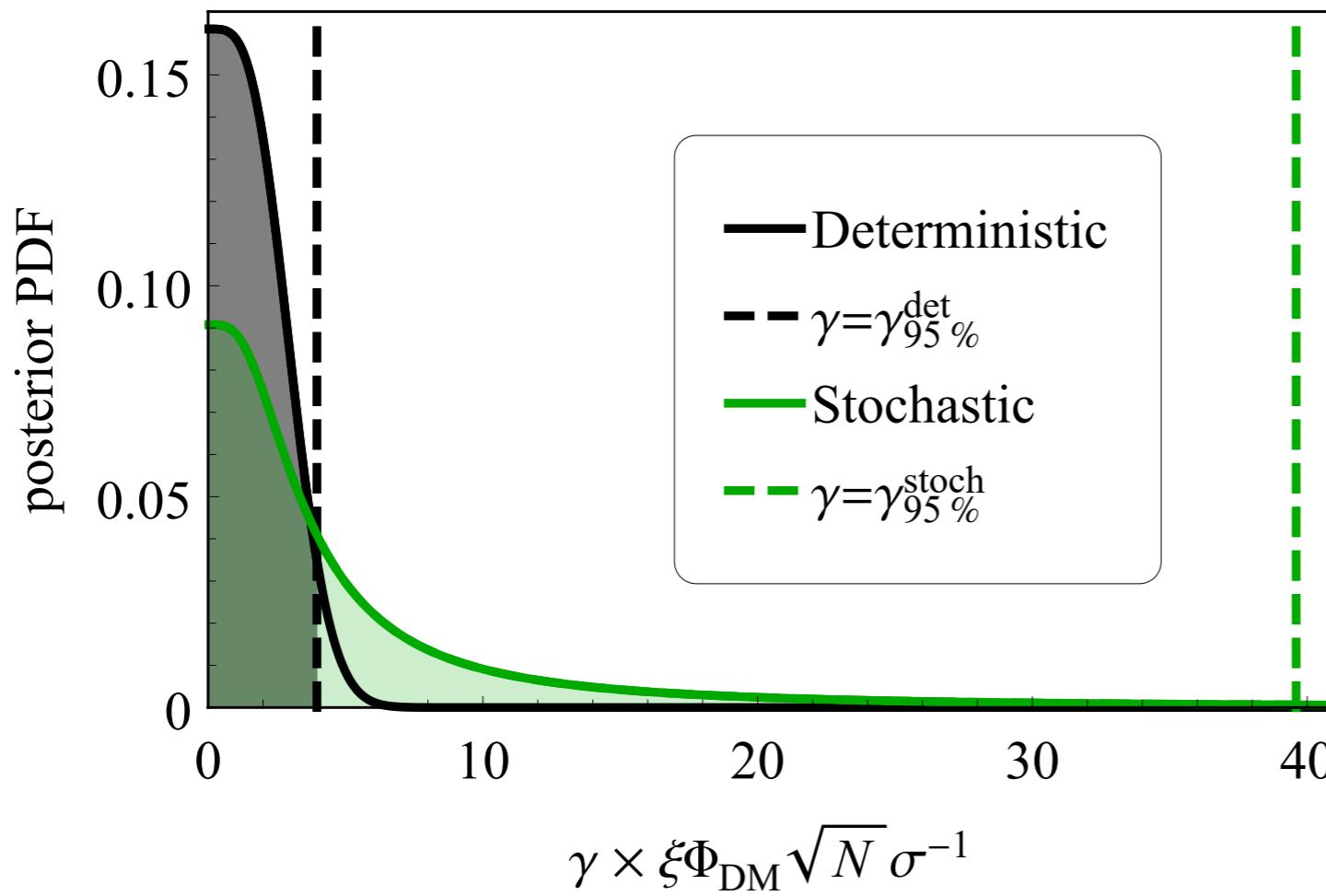
$$p_{\text{det}}(x) = \mathcal{A} \exp(-x^2/4) I_0(x)$$

$$p_{\text{stoch}}(x) = \frac{\mathcal{B}}{1+x^2/4} \exp\left(-\frac{1}{1+x^2/4}\right)$$

Gaussian-like

Lorentzian-like

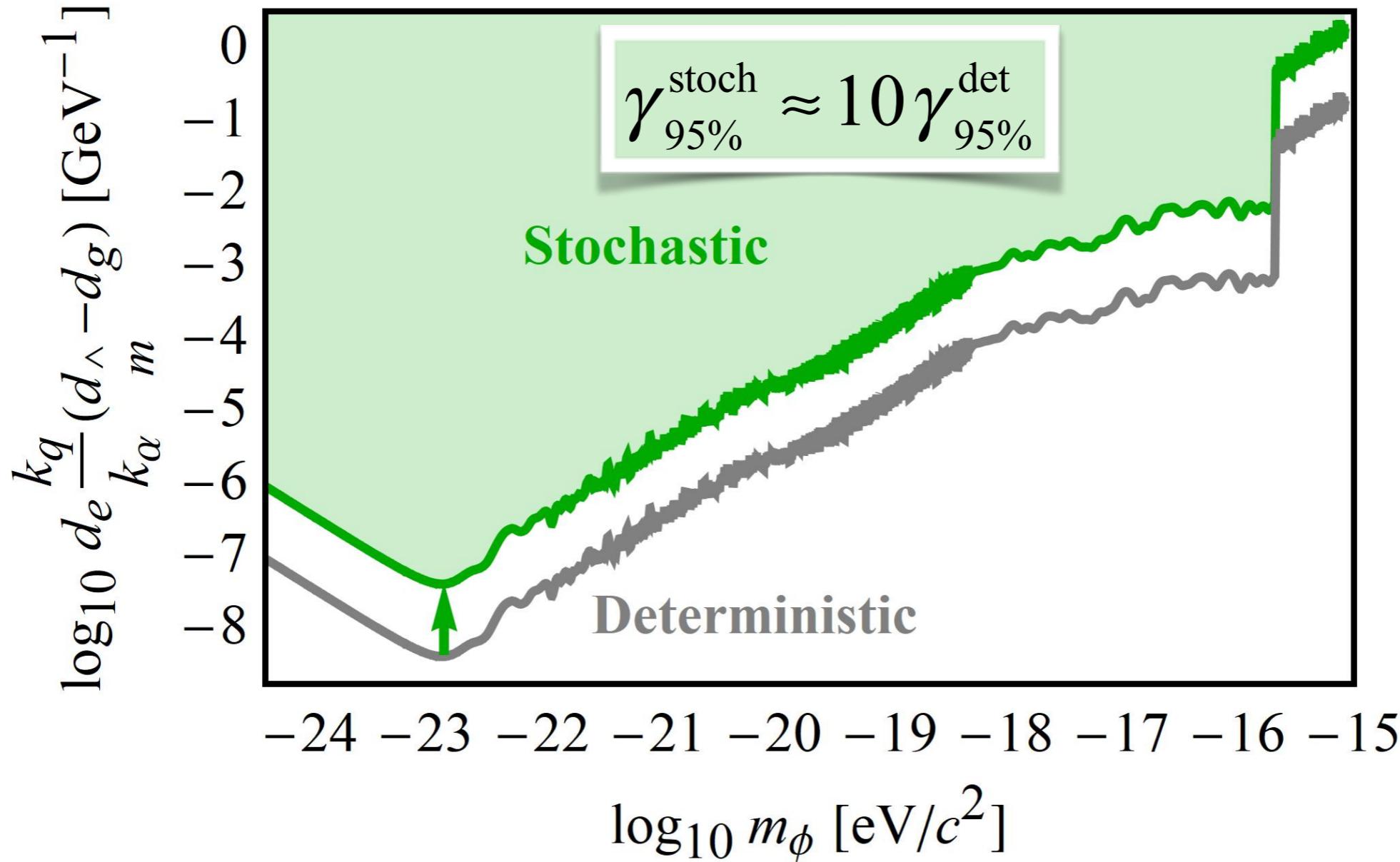
$$x \equiv \gamma \times \bar{\Phi}_{\text{DM}} \sqrt{N} \sigma^{-1}$$



$$2 \int_0^{\gamma_{95\%}} p(\gamma) d\gamma = 0.95$$

$$\gamma_{95\%}^{\text{stoch}} \approx 10 \gamma_{95\%}^{\text{det}}$$

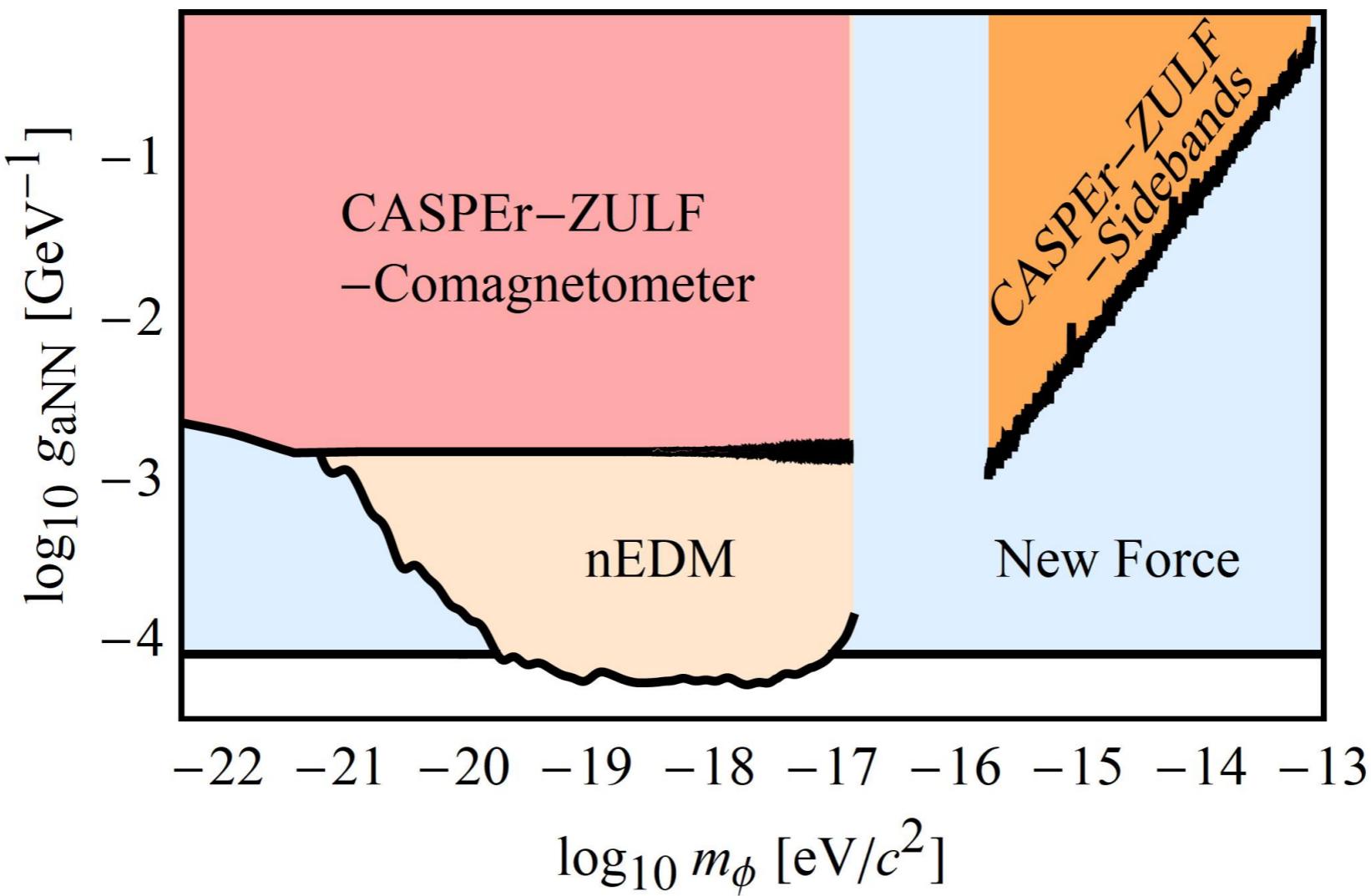
Effect on exclusion plots



Previous bounds from (microwave clocks)

A. Hees, J. Guena, M. Abgrall, S. Bize, and P. Wolf, PRL 117, 061301 (2016)

Revised axion-nucleon coupling



Previous bounds from:

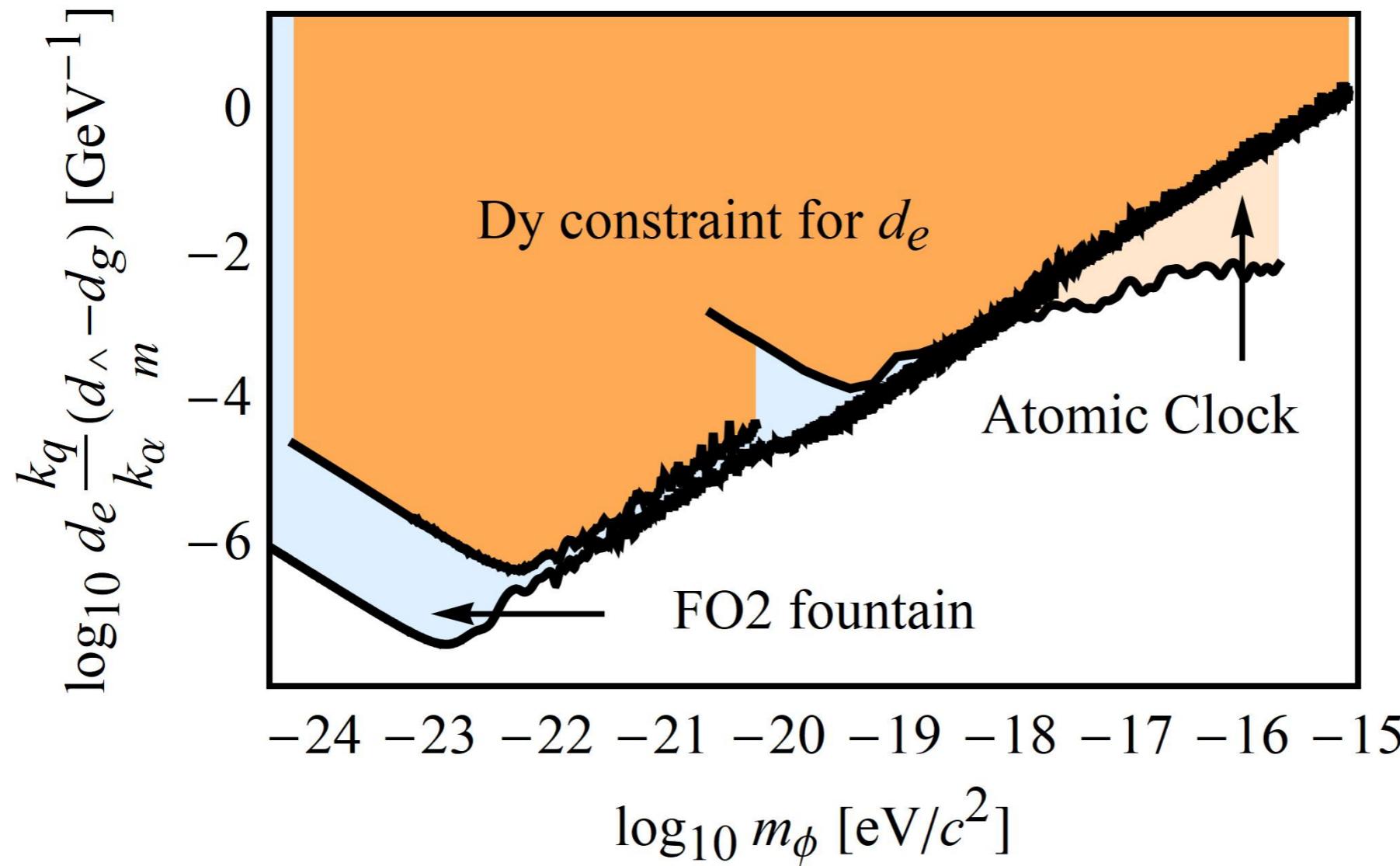
[Abel .. Zsigmond PRX 7, 041034 \(2017\)](#)

[Garcon...Budker 1902.04644](#)

[Wu...Budker, PRL 122, 191302 \(2019\)](#)

[Terrano ... Heckel 1902.04246](#)

Revised dilaton coupling



Previous bounds from:

Van Tilburg ... Budker, PRL 115, 011802 (2015)

Hees...Wolf, PRL 117, 061301 (2016)

Wcislo...Zawada, Science Advances 4, eaau4869 (2018)

Summary

- ▶ Astro-local vs lab local

$$\text{lab } \rho_{\text{DM}} \neq \text{astro } \rho_{\text{DM}}$$

Astro is recovered only when lab values are averaged over (very) long times

- ▶ Uncertainty in lab ρ_{DM} can have a substantial effect on sensitivity
- ▶ For observation time $\ll \tau_{\text{corr}}$ ($m \lesssim 10^{-15} \text{ eV}$), all the published VULF constraints are weakened by an order of magnitude.

$$\gamma_{95\%}^{\text{stoch}} \approx 10 \gamma_{95\%}^{\text{det}}$$