New opportunities to detect gravitational waves and dark matter in orbital dynamics

Overview and meeting Expectations

Diego Blas

ICREA

IFAE

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

bist SCIENTIFIC COMMUNITY

CERCA Centres de Recerca de Catalunya

European Research Council
Established by the European Commission

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

Fundación BBVA

Who we are (in person for workshop)


Luca Teodori (Instituto Astrofísico de Canarias)

Galactic dynamics, Dark matter

Jorge M. Camalich (Instituto Astrofísico de Canarias)

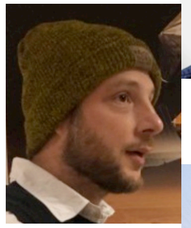
Galactic dynamics, Dark matter, Theoretical Particle Physics

Jorge Peñarrubia (University of Edinburgh)

Galactic dynamics, galactic substructure, Dark matter

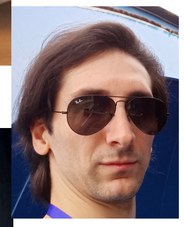
Prasenjit Saha (Zurich U)

Gravitational lensing, gravitational dynamics, Data analysis and observations



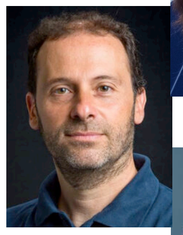
Bruno Bertrand (Royal Observatory of Belgium)

Global Navigation Satellite System (GNSS), Atomic clocks, Dark Matter



Alessandro di Marco (INAF-IAPS)

Satellite Laser Ranging, Satellite Dynamics, Theoretical Physics



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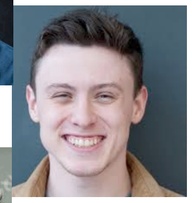

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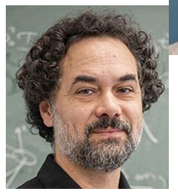
Theoretical Particle Physics, Dark Matter, Data analysis and observations



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Theoretical Physics, Dark Matter, Gravitational waves, Quantum sensors,


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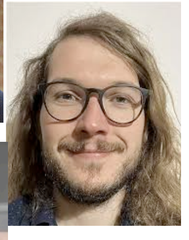

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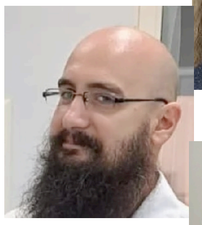

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Gravitational waves, Multimessenger astrophysics, Lensing of GWs, Data Analysis

Florin-Ioan Constantin (I. of Space Science, Romania)

Theoretical and Computational Physics

Laurentiu-Ioan Caramete (Institute of Space Science, Romania)

Gravitational waves, Quantum sensors, Data analysis

Xiao Xue (IFAE, Barcelona) (organizer)

Gravitational waves, Pulsar timing arrays, Astrometry, Dark Matter

Matthew Miles (Vanderbilt University)

Pulsar timing arrays, pulsar dynamics, Data analysis and observations

Paulo Freire (MPI für Radioastronomie)

Pulsar dynamics, Gravitational dynamics, Data analysis and observations

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Leaves on 16th

Arrives on 17th

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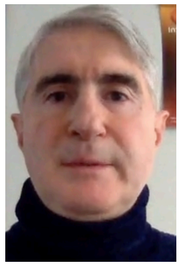
Pulsar dynamics, Gravitational dynamics, Data analysis and observations

Who we are (online or coming for GUEST)

Simone Dell'Agnello (LNF, INFN)

Satellite Laser Ranging, Lunar Laser Ranging
Experimental physics, Space exploration



Soumen Roy (Royal Observatory of Belgium)

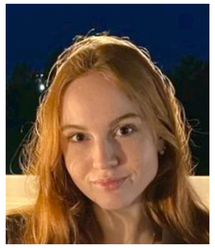
Gravitational waves, Gravitational dynamics,
Theoretical Physics

Alex Jenkins (University of Cambridge)

Gravitational waves, Gravitational dynamics,
Theoretical Physics, Cosmology

Rosa Martínez Rubiella ((GMV Aerospace and Defence, Spain)

Mission analysts, Aerospace Engineer



Javier Atapuerca (GMV Aerospace and Defence, Spain)

Mission analysts, Aerospace Engineer

Carlos Sopuerta (Institute of Space Sciences, Spain)

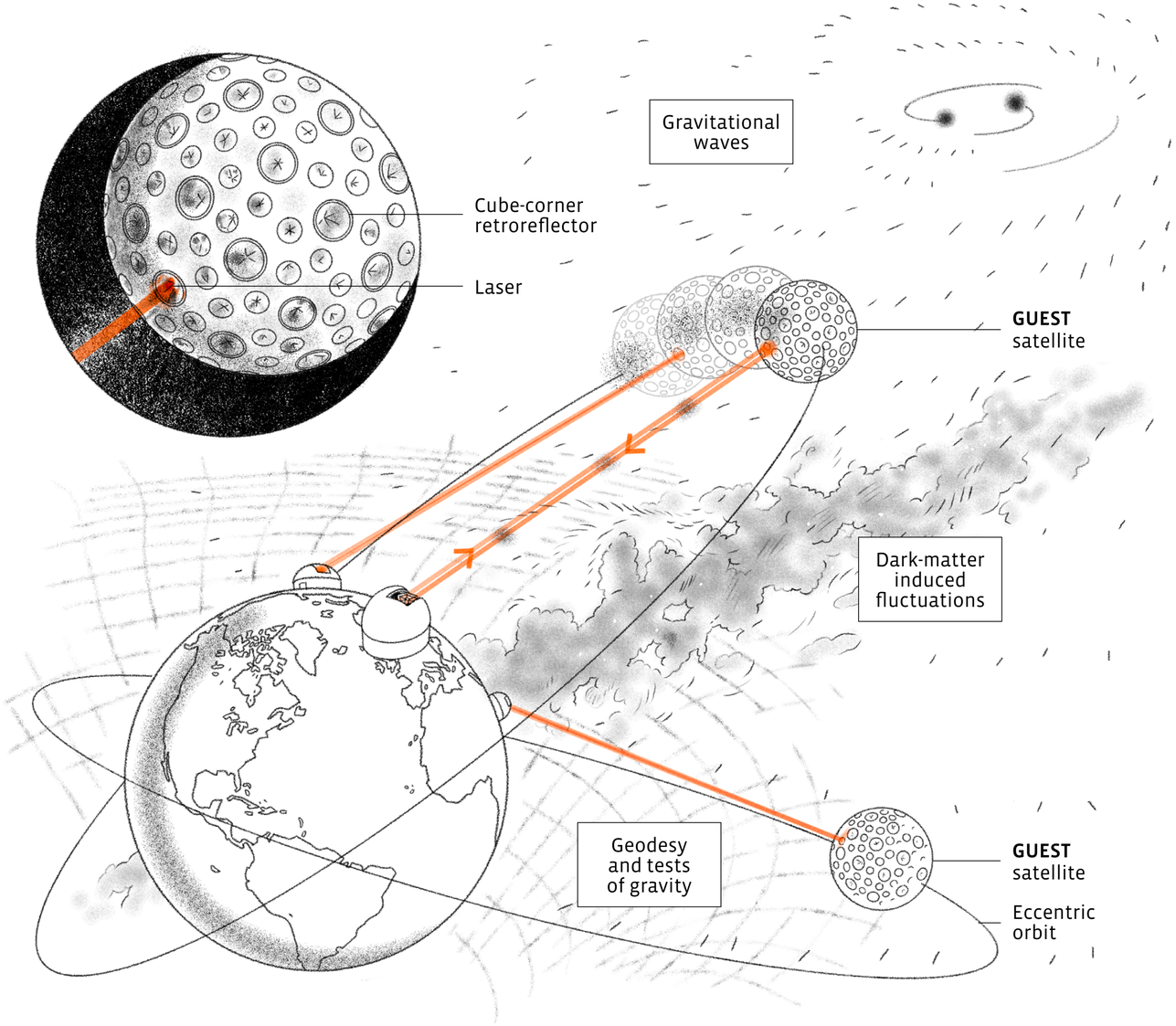
Gravitational waves, LISA ,ET , Gravitational dynamics,
Theoretical Physics, Cosmology

	Monday 15	Tuesday 16	Wednesday 17	Thursday 18	Friday 19
9-10	Registration				
10-11	Diego	Prasenjit	Peñarrubia	WG1 Aurelien	GUEST
11-11:30	COFFEE	COFFEE	COFFEE	COFFEE	COFFEE
11:30-12:30	Alex (online)	Luca	Bruno (pres.) & Soumen (online)	WG2 Bruno	GUEST
12:30-13:30			Soumen (online)		
LUNCH BREAK		GUEST CORE at 14:30			
15-16	Matthew		Xiao	WG3 Tamanini	GUEST
16-17	Paulo	Caramate	Marco/Alessandro	WG4 Simone	
		Monica			
	Reception			Dinner	

Speaker	Talk title
Diego	Overview and meeting expectations
Bruno & Soumen	GNSS orbital data to probe dark matter & GWs
Soumen	Scalar fields around black hole binaries in LVK
Alex	TBC
Prasenjit	TBC
Monica	Multimessenger in different bands
Matthew	PTA and GWs
Paulo	Pulsars and new physics
Peñarrubia	TBC
Prasenjit	TBC
Luca	Dynamical heating in ULDM and GW (informal)
Xiao	Astrometry
Marco/Alessandr	Satellite and lunar laser ranging
Caramete	New data analysis methods in GW

GUEST.

Gravitational **U**niverse **E**xploration with **S**atellite **T**racking



ESA 2025 Call

F-class Proposal

esa

European Space Agency

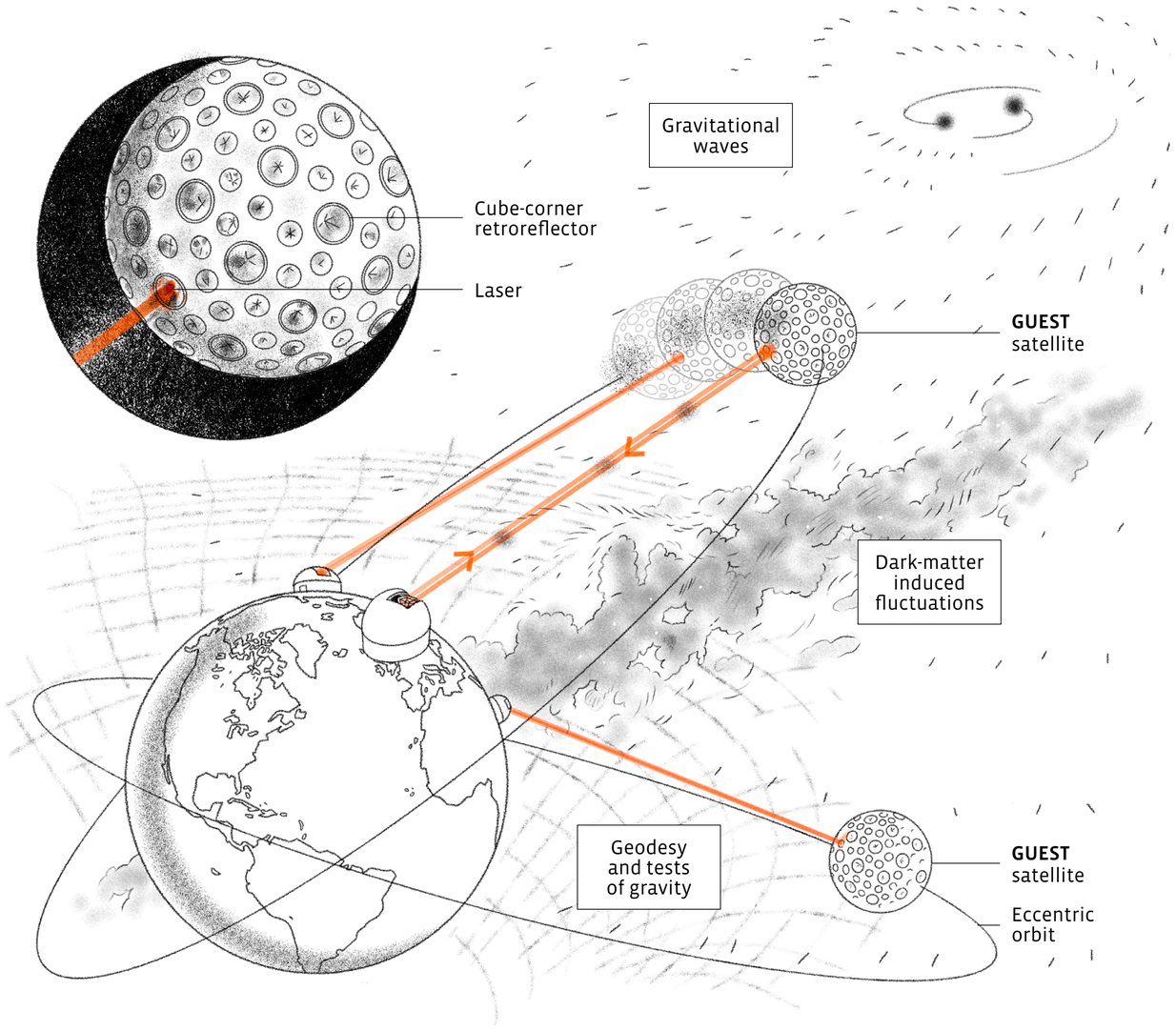
Lead Proposer: Prof. Diego Blas Temiño, Spain

Proposal in 5 seconds

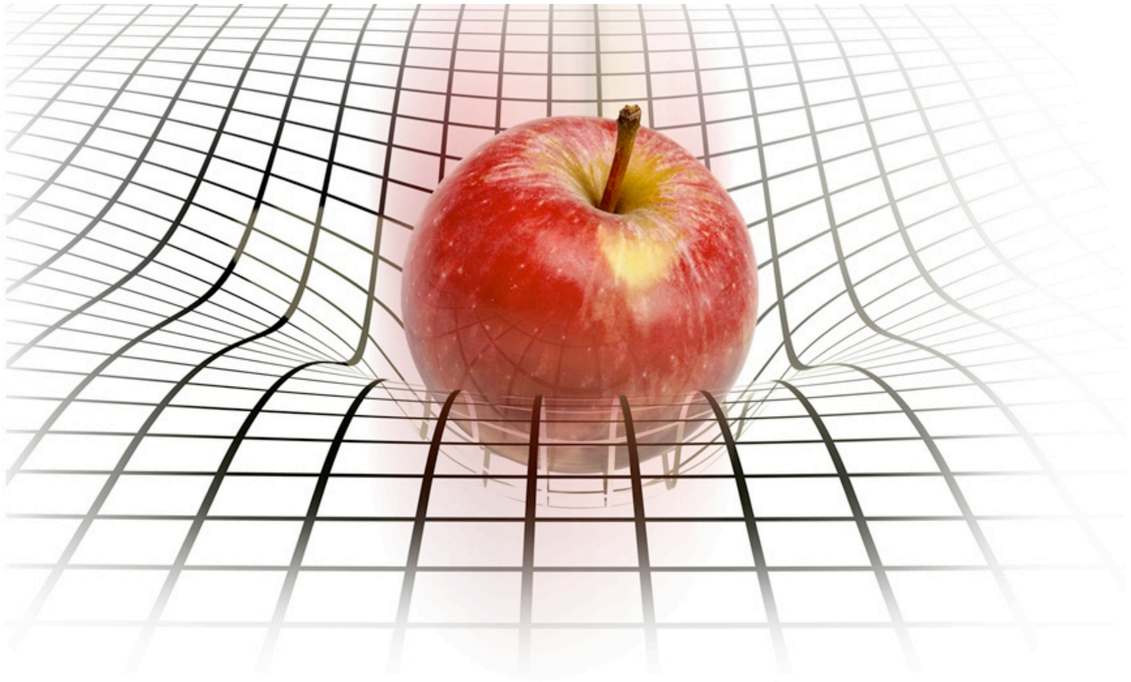
GUEST.

GUEST

Two satellites laser tracked
at cm accuracy
in orbits $e > 0.75$, $P_b > 1$ day
for more than 10 years.



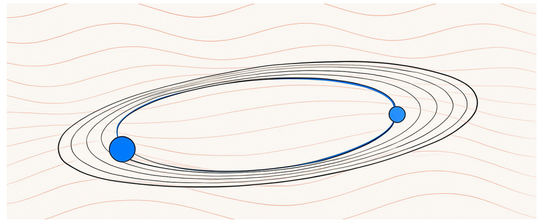
Why are we here?



New opportunities to detect
gravitational waves
and **dark matter** in
orbital dynamics

gravitational **fluctuations** affect gravitational dynamics

Non-relativistic $v_{\max} \ll c$



1. $1 \gg r_{\max}\partial_i\phi$

$$\delta\ddot{r}_i^{\mathrm{CM}} = R_{0i0j}\Big|_{\mathrm{CM}} r_j^{\mathrm{CM}}$$

for bound systems

$$h \sim \cos(2\pi f t)$$
$$r \sim e\cos(2\pi t/P)$$

possible **resonances** at $f=n/P$

2. $1 \lesssim r_{\max}\partial_i\phi$

$$\delta\ddot{r}_i = \frac{1}{2}\eta^{ij}\left[2\partial_0 h_{0j} - \partial_j h_{00}\right]$$

Time and **space** dependent **force**

Relativistic

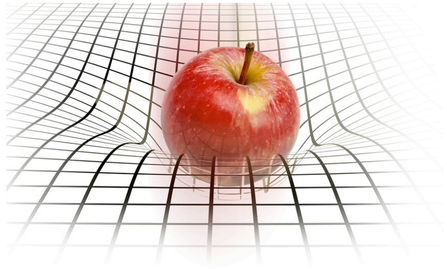
$$(\eta_{\mu\nu} + h_{\mu\nu})P^\mu P^\nu = 0$$

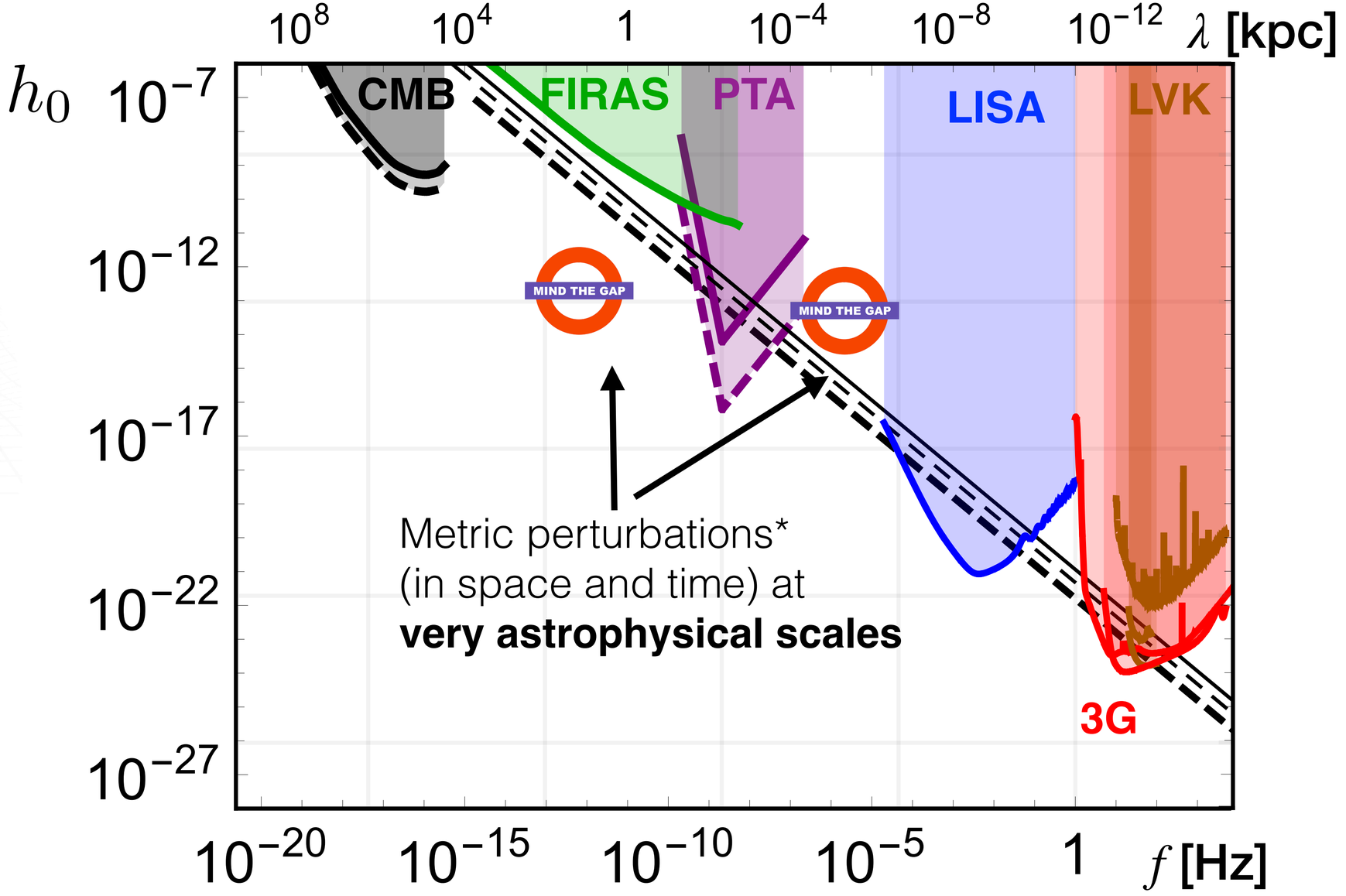
+ geodesic equation

gravitational **fluctuations** affect relative clocks (proper times) $\left((\eta_{\mu\nu} + h_{\mu\nu})P^\mu P^\nu\right)^{1/2}$

Gravitational wave searches ca. 2040

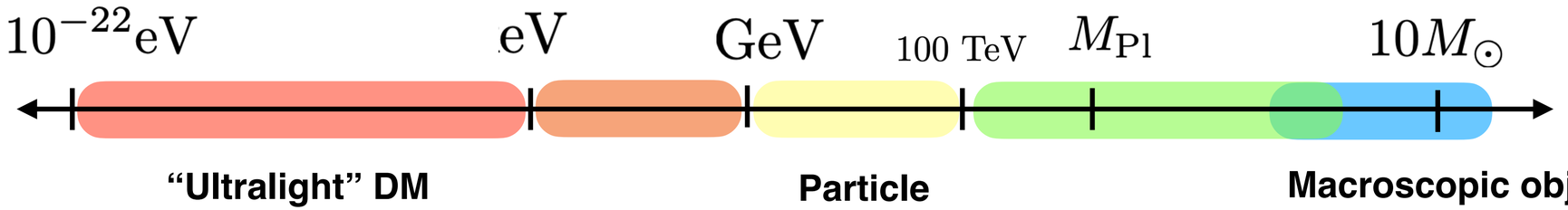
$$R^{\mathrm{TT\,GWs}}_{0i0j}\Big|_{\mathrm{CM}} = \frac{1}{2}\ddot{h}_{ij}$$



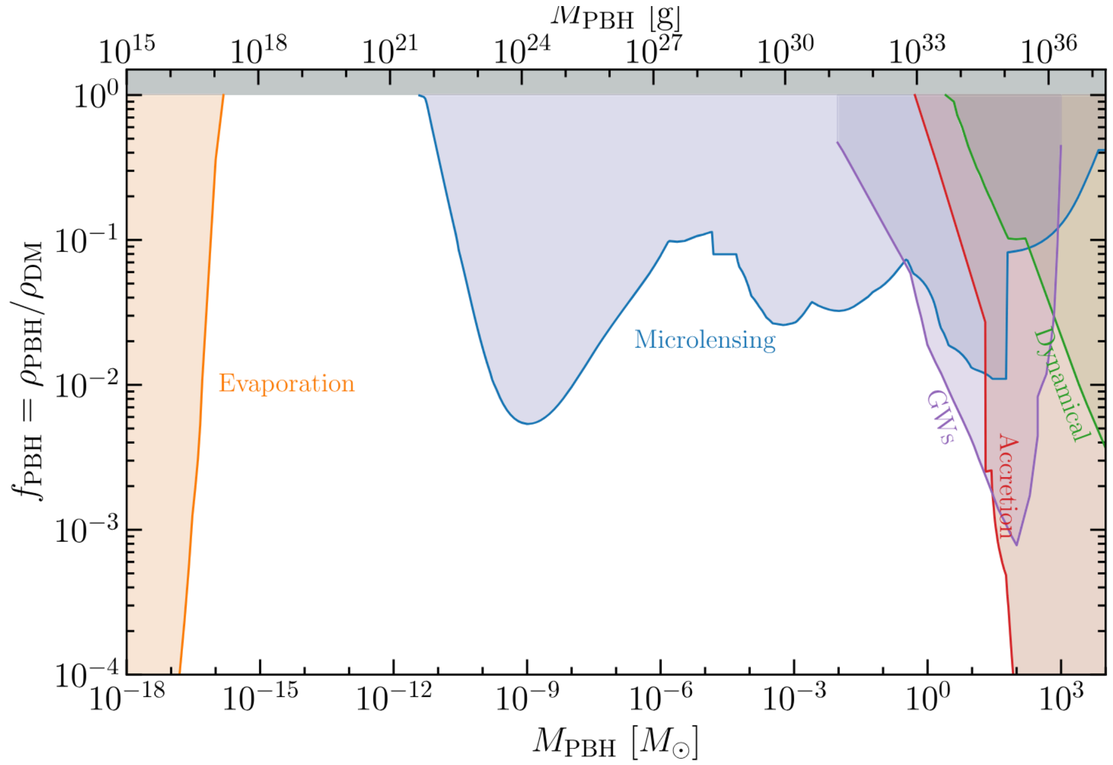


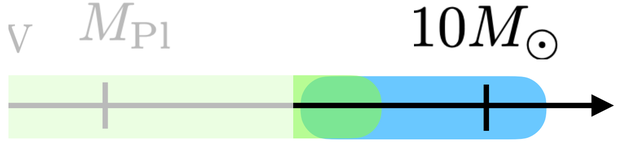
*We can discuss sources in this band later

Dark matter candidates and orbital dynamics



Dark matter candidates and orbital dynamics

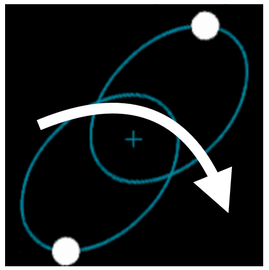




Macroscopic objects

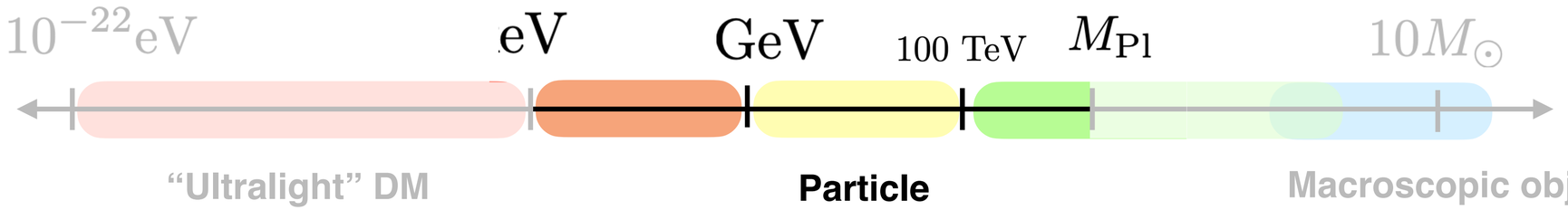
If DM is made of macroscopic objects, $M_{\rm DM}(R) \approx 3.8 \times 10^{-18} \left(\frac{\rho}{0.3\ {\rm GeV\,cm^{-3}}}\right)\left(\frac{R}{\rm AU}\right)^3 M_\odot$

But they can exchange enough momentum ($\delta \dot{r}^i = F^i(t)$) with bound systems to



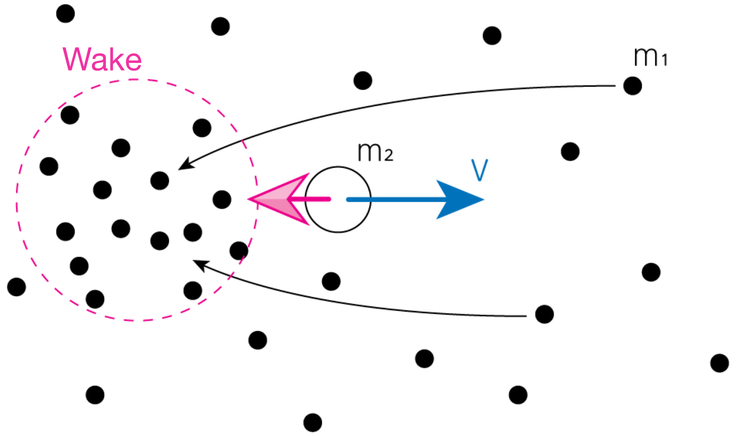
* destroy some of them
* modify their distributions
* heat some systems (if $E_{\rm DM} > E_{\rm system}$)

Dark matter candidates and orbital dynamics



Particle dark matter can generate dynamical friction in orbiting systems

$$\delta\ddot{r}^i = F^i$$



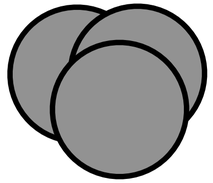
There can also be direct DM - celestial body interactions beyond gravity

this can generate new long range phenomena or friction

Dark matter candidates and orbital dynamics

10^{-15} eV $\sim$ 1 Hz

Ultralight dark matter is characterized by $d \ll L$



As a results, DM behaves as a oscillating very coherent wave

At 'short' times and 'small' distances

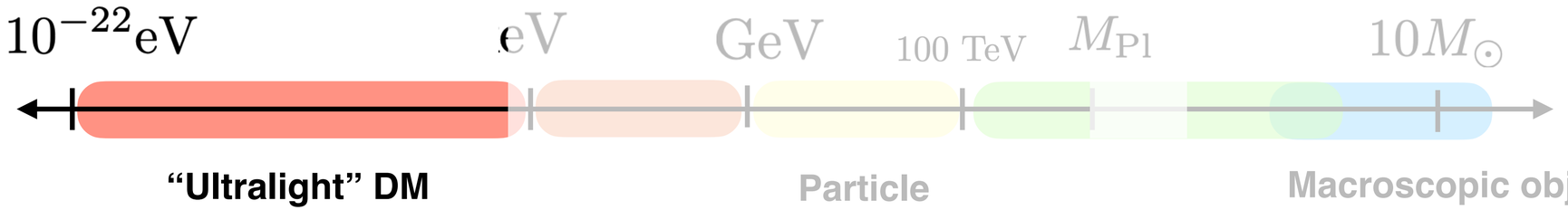
$$\phi = \phi_0 \cos(mt + m\vec{\mathrm{v}} \cdot \vec{x} + \varphi_0)$$

ϕ_0 and $\vec{\mathrm{v}}$ are stochastic variables

This induces **oscillations** in the gravitational potentials $\frac{h_{ii}}{3} \approx \frac{\pi}{m^2}\bar{\rho}_\phi \cos(2mt)$

If there is direct coupling, the mass of stars may oscillate at this frequency, etc

Dark matter candidates and orbital dynamics



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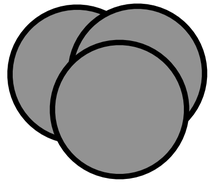
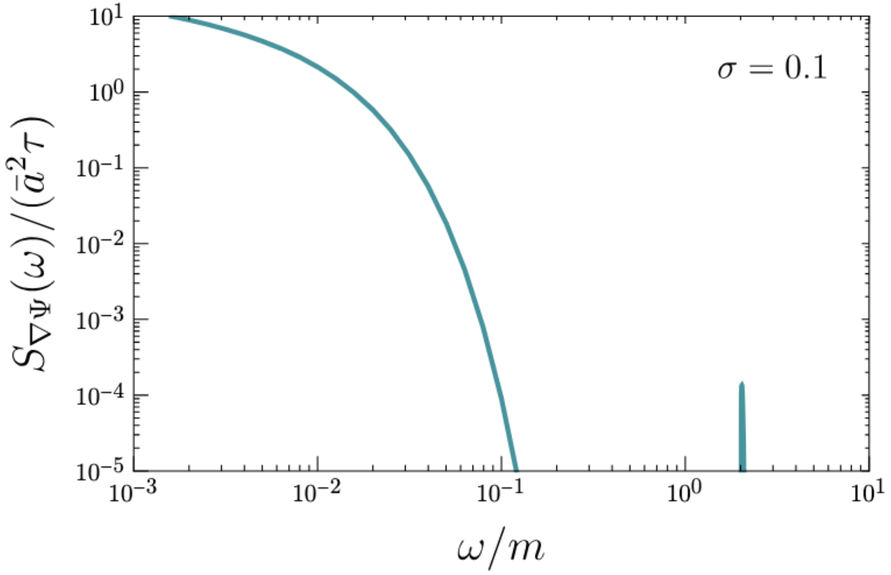


The power spectrum of the fluctuations in gravitational potential is



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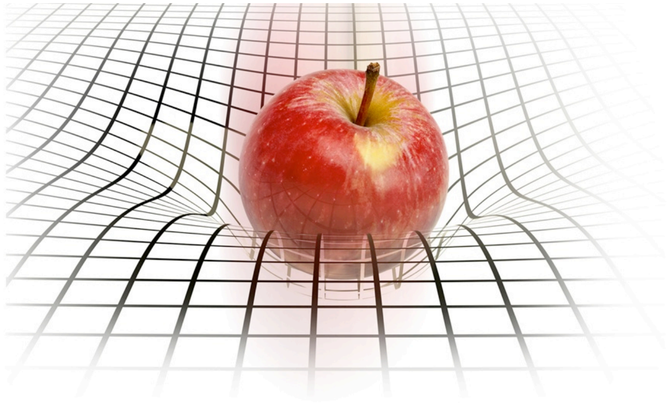

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$\delta\ddot{r}^i = F^i(x,t)$ With $\langle F^i(x,t)F^i(x',t')\rangle$ and $\mathrm{d}\tau(x,t)_s$ with $\langle \mathrm{d}\tau(x,t)_s \mathrm{d}\tau(x',t')\rangle$

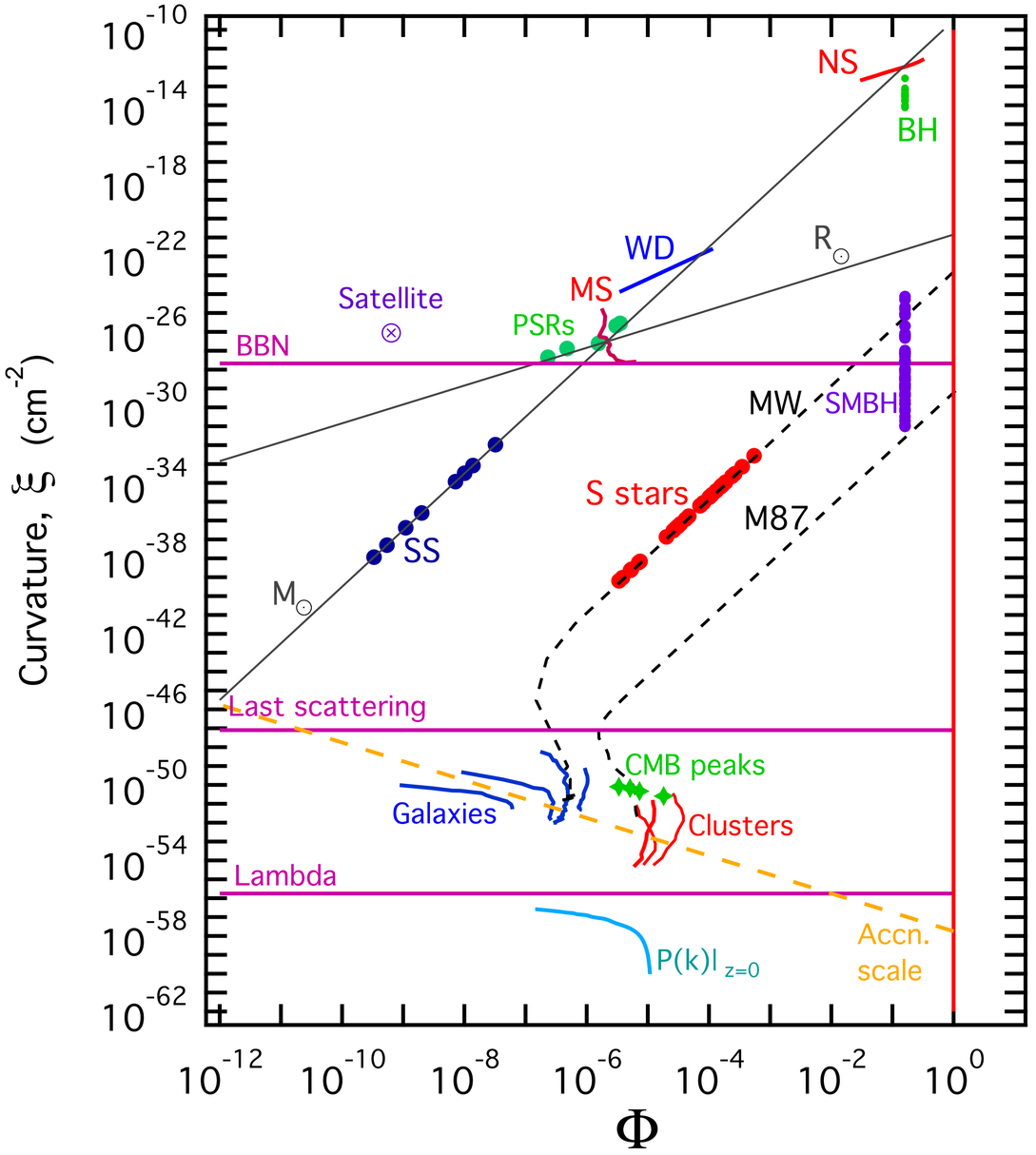
Gravitational waves in poorly covered frequencies ($10^{-15} - 10^{-11}\,\mathrm{Hz}$ and $10^{-7} - 10^{-4}\,\mathrm{Hz}$) may induce **resonances, heating, evaporation, orbital changes…** in orbiting systems with $P \sim 1/f$.

Dark matter in poorly covered masses may induce **resonances, heating, evaporation, orbital changes…** in orbiting systems

We are here **to identify the best systems for different frequencies/masses**

Best systems

If virtualized $v^2 \sim \Phi$



Best systems

Tracked very precisely

The effect are typically enhanced at large periods!

Pulsars

Doppler tracking of satellites

Satellite Laser Ranging, Lunar Laser Ranging, GNSS

Loosely bound

Oort Cloud, Kuiper belt

Wide binaries

Dark matter substructure (streams, disks)

Lots of data

Galactic dynamics

Astrometry

Old

Pulsar populations

Moon libration

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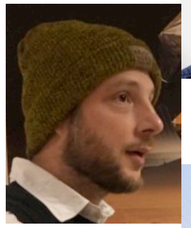

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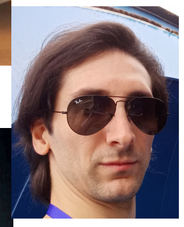

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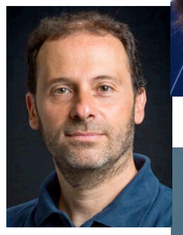

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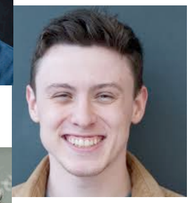

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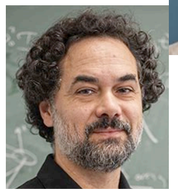

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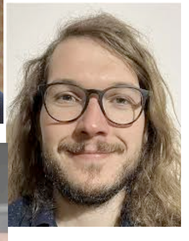

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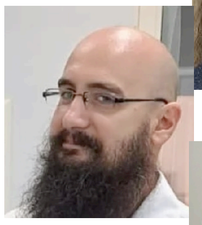


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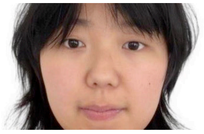
Laurentiu-Ioan Caramete (Institute of Space Science, Romania)

Gravitational waves, Quantum sensors, Data analysis




Xiao Xue (IFAE, Barcelona) (organizer)

Gravitational waves, Pulsar timing arrays, Astrometry, Dark Matter

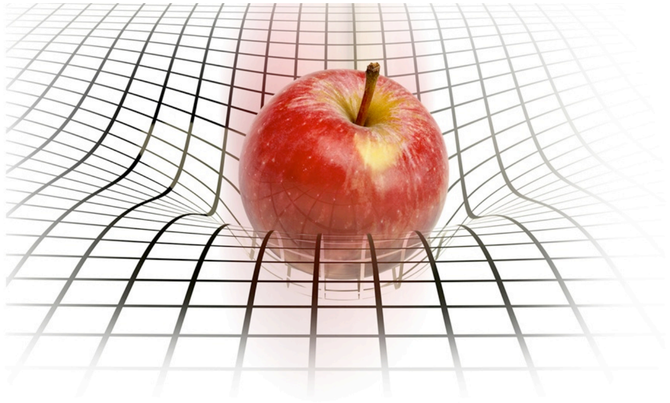
Matthew Miles (Vanderbilt University)

Pulsar timing arrays, pulsar dynamics, Data analysis and observations

Paulo Freire (MPI für Radioastronomie)

Pulsar dynamics, Gravitational dynamics, Data analysis and observations

Why are we here?



New opportunities to detect
gravitational waves
and **dark matter** in
orbital dynamics

$\delta\ddot{r}^i = F^i(x,t)$ with $\langle F^i(x,t)F^i(x',t')\rangle$ and $\mathrm{d}\tau(x,t)_s$ with $\langle \mathrm{d}\tau(x,t)_s \mathrm{d}\tau(x',t')\rangle$

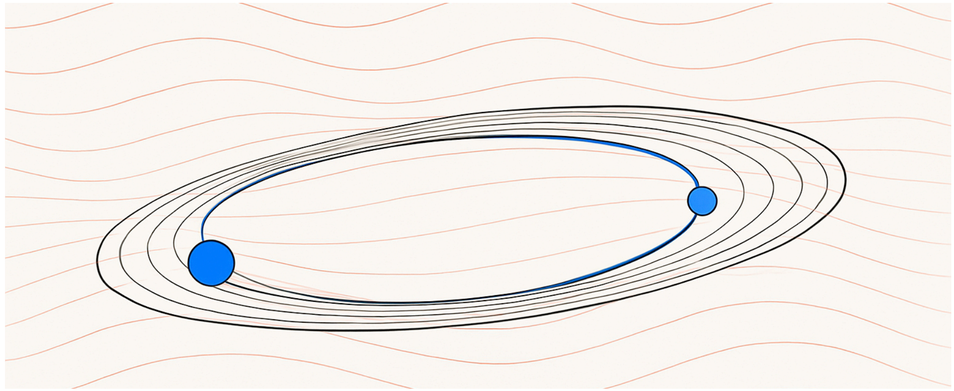
Gravitational waves in poorly covered frequencies ($10^{-15} - 10^{-11}\,\mathrm{Hz}$ and $10^{-7} - 10^{-4}\,\mathrm{Hz}$) may induce **resonances, heating, evaporation, orbital changes…** in orbiting systems with $P \sim 1/f$.

Dark matter in poorly covered masses may induce **resonances, heating, evaporation, orbital changes…** in orbiting systems

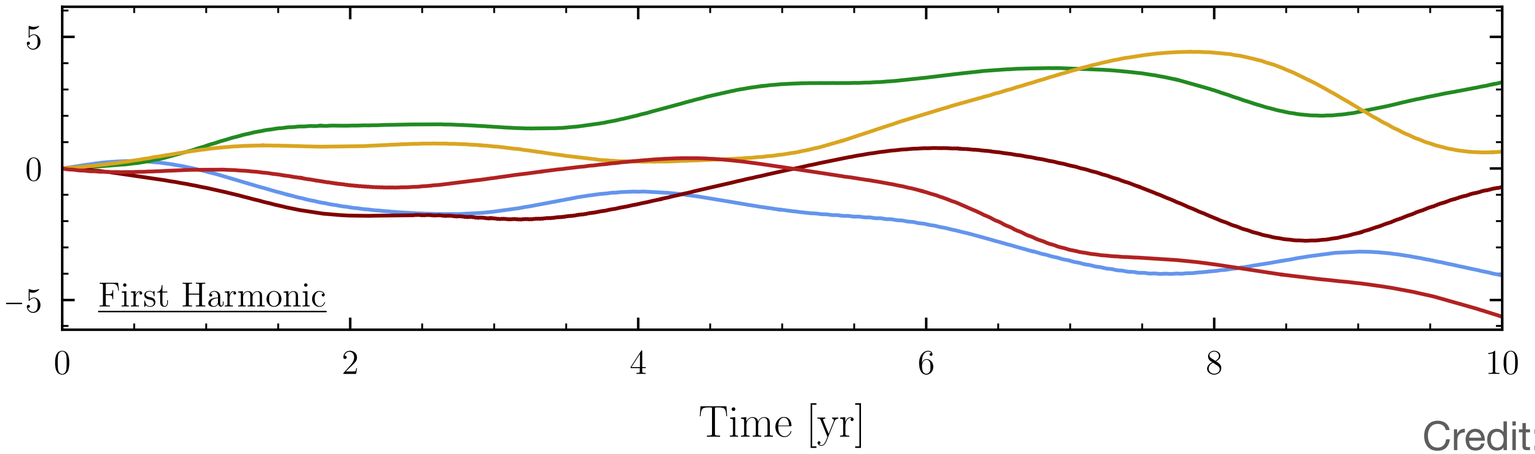
We are here **to identify the best systems for different frequencies/masses**

Few biased examples (more this week)

Binary system embedded in stochastic GWB



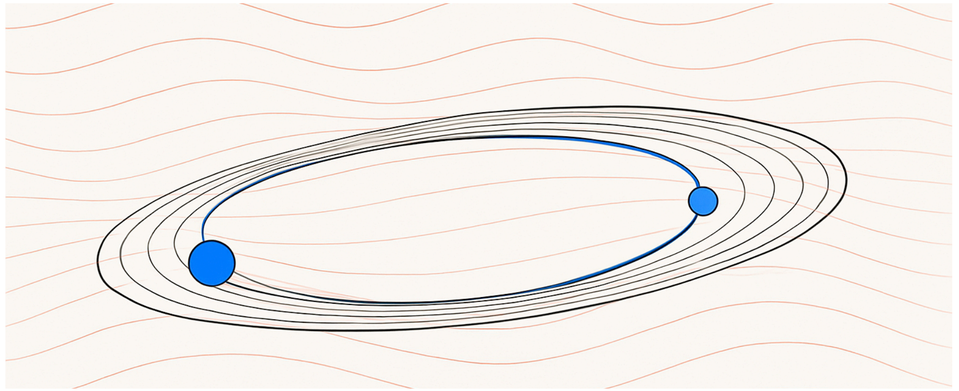
$$\ddot{r}_i + \frac{GM}{r^3} r_i = \frac{1}{2} \frac{\mathrm{d}^2 h_{ij}}{\mathrm{d}^2 t} r^j$$



Credit: J. Foster

Binary resonances: ULDM

fluctuating gravitational potentials of ULDM affect gravitationally bound systems



$$\ddot{r}_i + \frac{GM}{r^3} r_i = -\ddot{\psi}\, r_i$$

$g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu \approx -(1-2\Phi)\mathrm{d}t^2 + (1+2\psi)\delta_{ij}\, \mathrm{d}x^i\, \mathrm{d}x^j$

External Gravitational Potential

Blas, Lopez-Nacir, Sibiryakov, 1612.06789, 1910.08544

Newtonian Potential

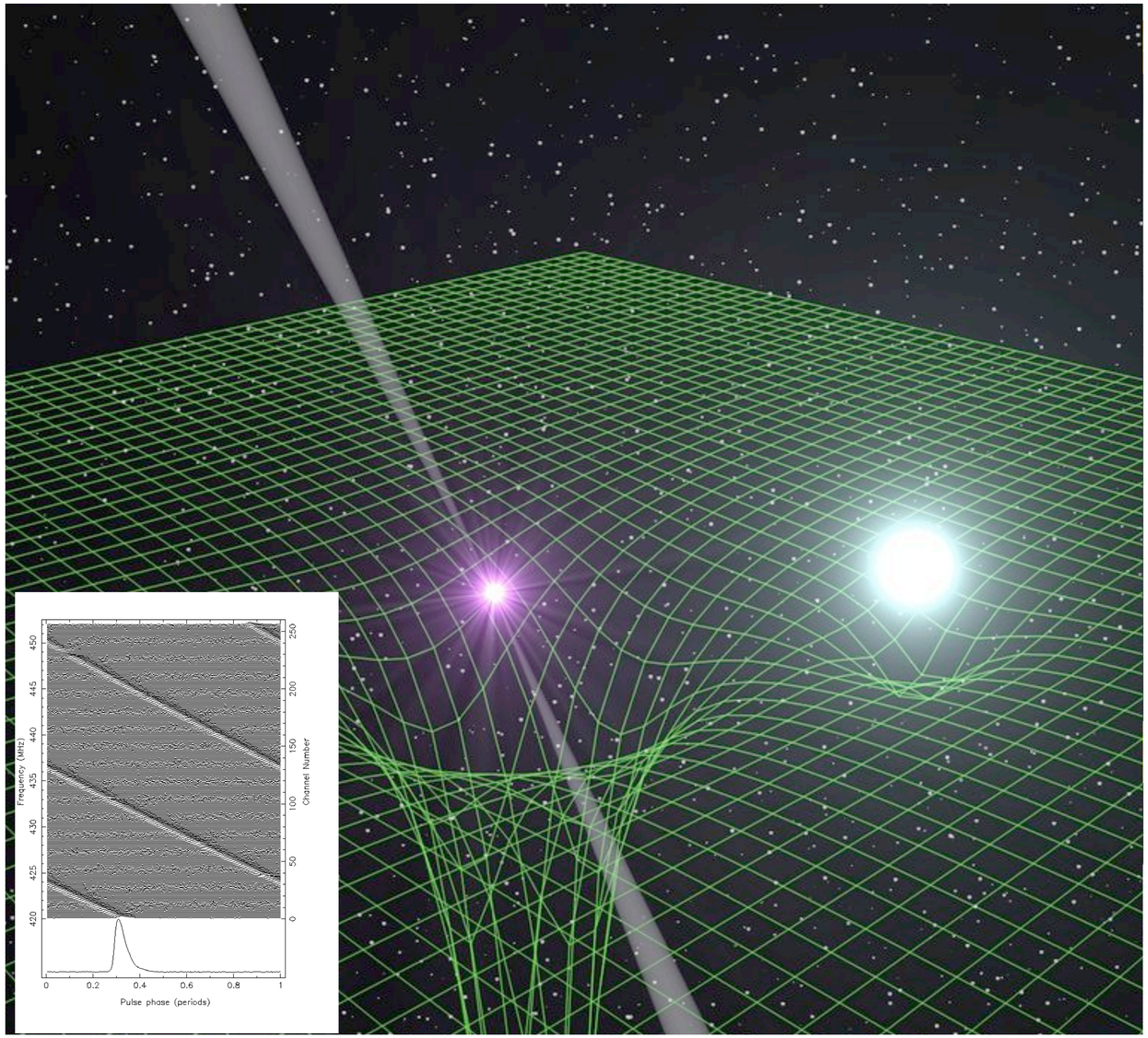
$\psi \sim \cos(2\pi f t)$

$r \sim e\cos(2\pi t/P)$

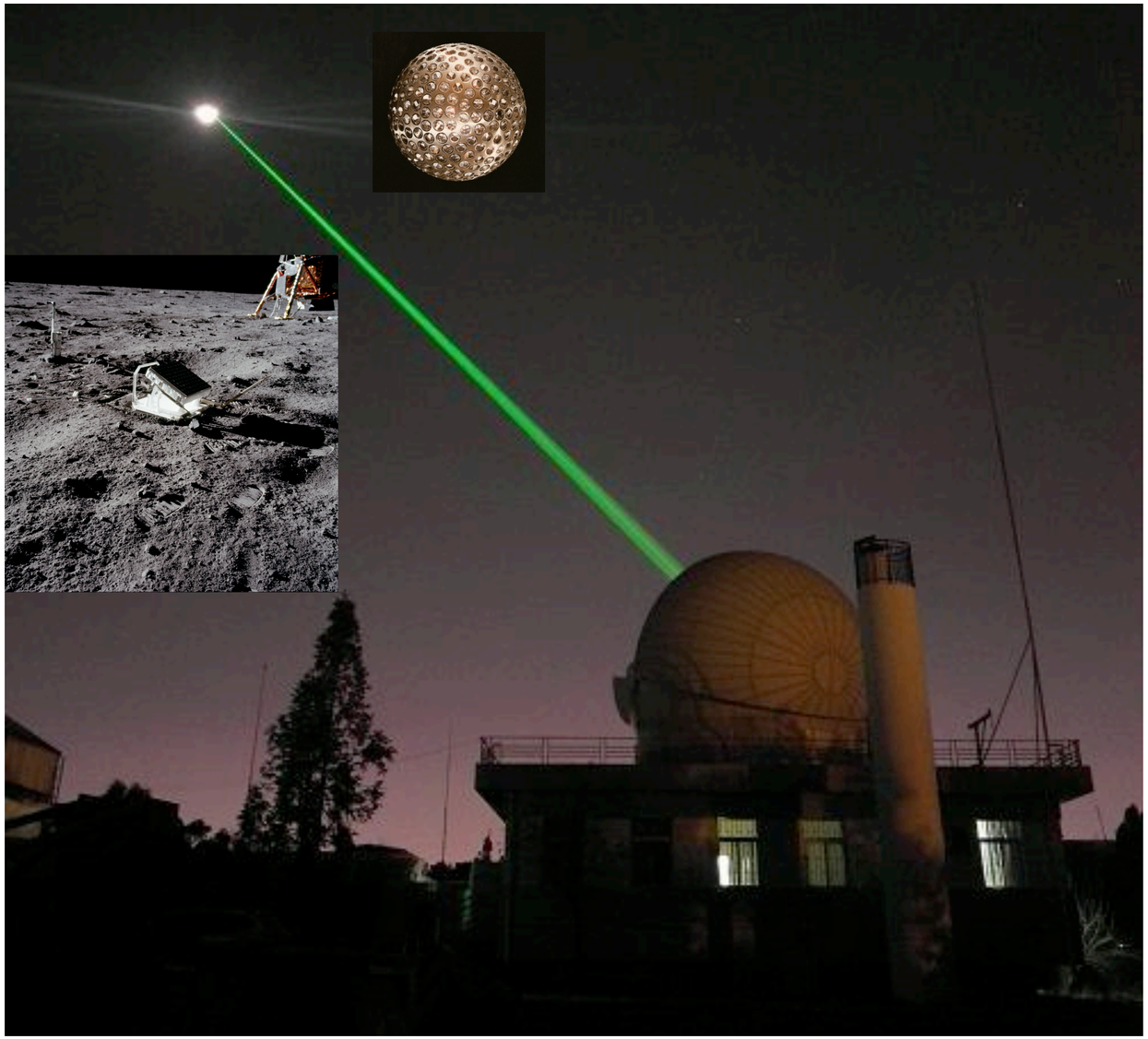
possible resonances at $f=n/P$

Two probes: precise timing of binaries

timing of binary pulsars

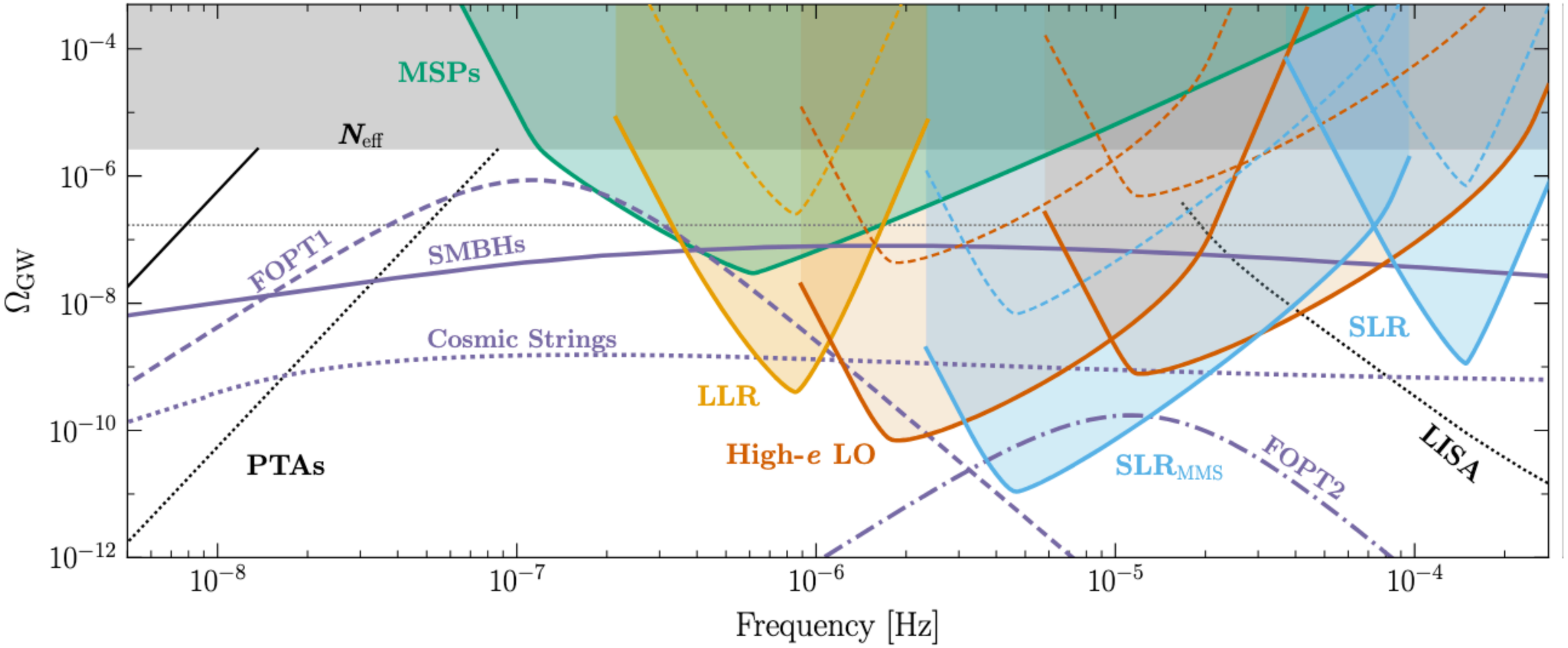


lunar and satellite laser ranging

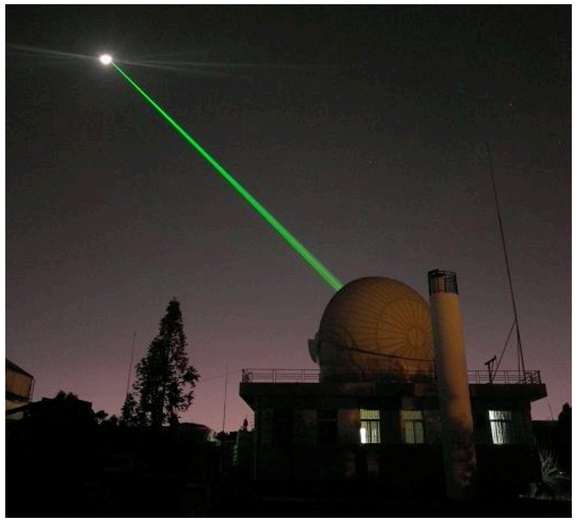


Our estimates from 2025 for 2025

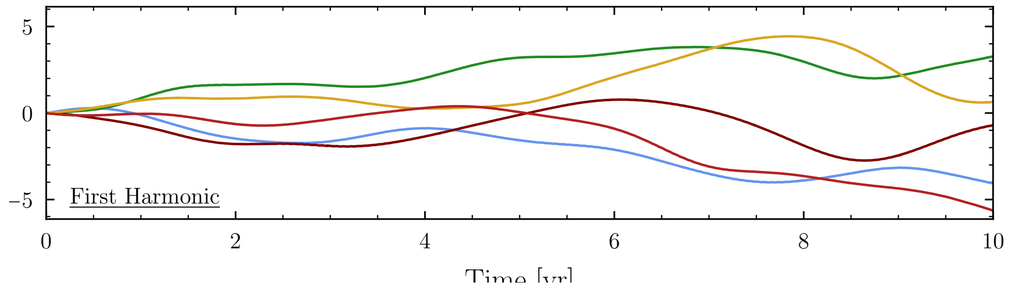
Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et a., arXiv:2504.16988 [gr-qc]



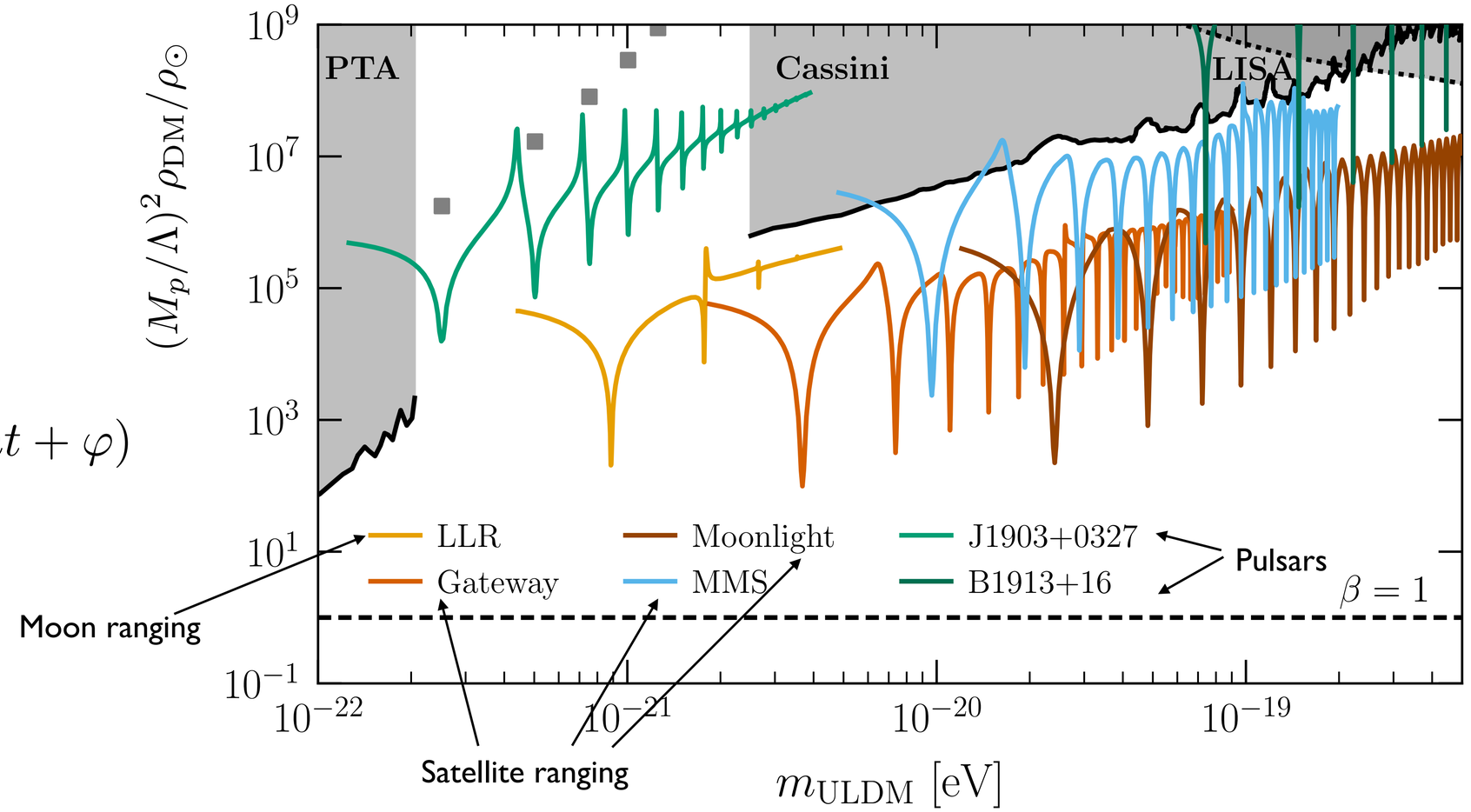
New ULDM handles: resonant absorption



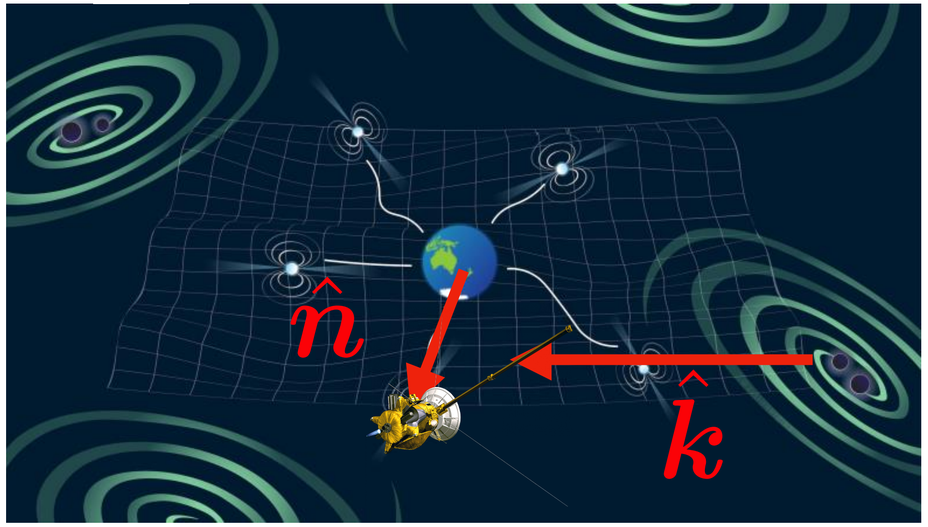
Moon's orbit
Δr (cm)



$$\delta\Phi_N \sim \frac{G\rho_{\rm DM}}{m^2}\cos(2mt+\varphi)$$



Tracked space-craft in weak metric



Armstrong, J.W. , Living Reviews in Relativity, 9, 1, doi: 10.12942/lrr-2006-1

$$\left.\frac{\Delta\nu}{\nu_0}(t)\right|^{\rm GW} = \frac{\mu-1}{2}\bar{\Psi}(t) - \mu\bar{\Psi}\left(t - \frac{\mu+1}{2}T_2\right) + \frac{\mu+1}{2}\bar{\Psi}\left(t - T_2\right)$$

$$\bar{\Psi}(t) = (\hat{\boldsymbol{n}}\cdot\mathbf{h}(t)\cdot\hat{\boldsymbol{n}})/\left(1-\mu^2\right) \qquad \mu = \hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}}$$

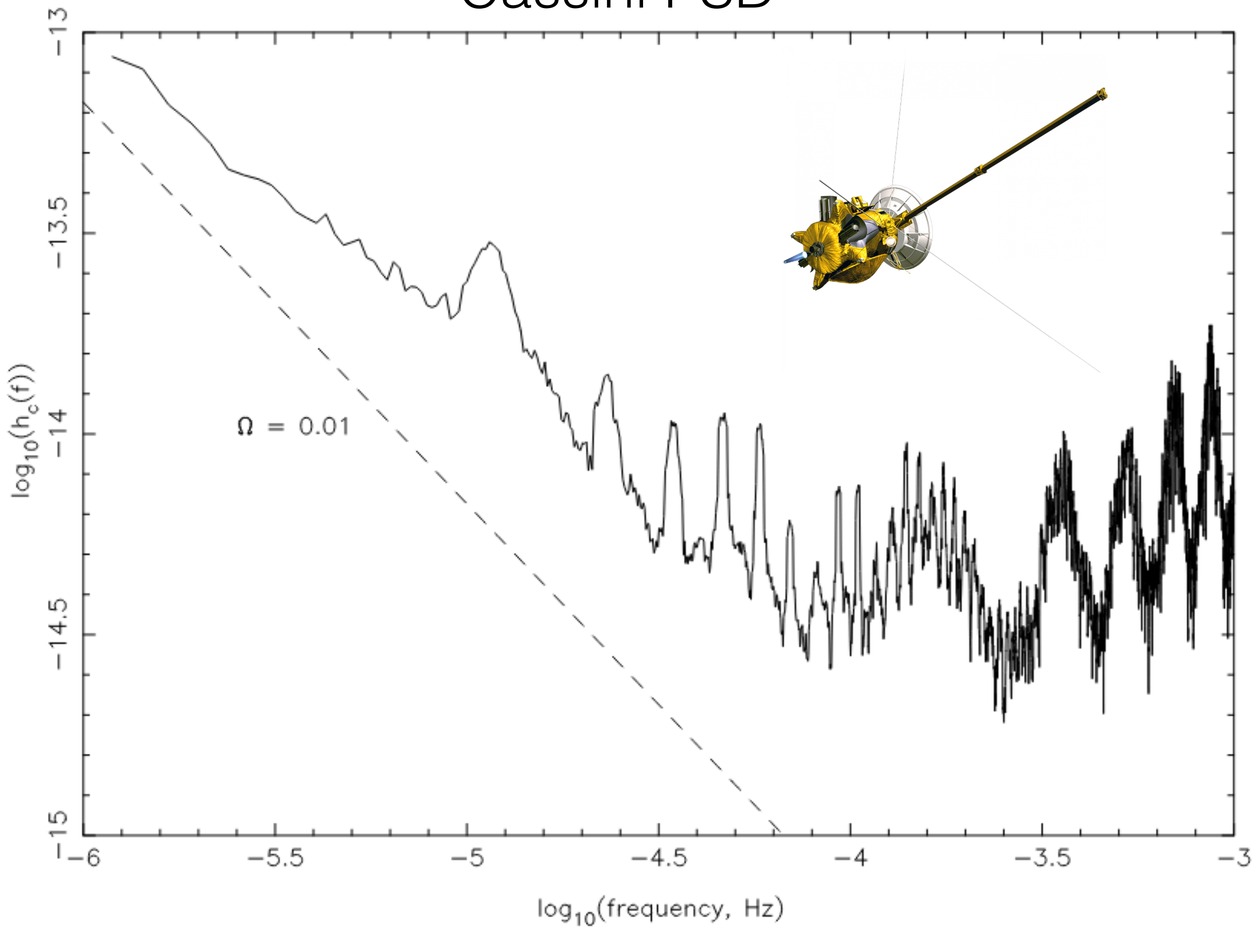
Zwick, DB et al 2406.02306 [astro-ph.HE]
Khmelnitsky, Rubakov 1309.5888 [astro-ph.CO]

$$\left.\frac{\Delta\nu}{\nu_0}(t)\right|^{\rm ULDM} = -\Psi(t) + \Psi\left(t - T_2\right).$$

GWs and ULDM searches w/ Doppler tracking

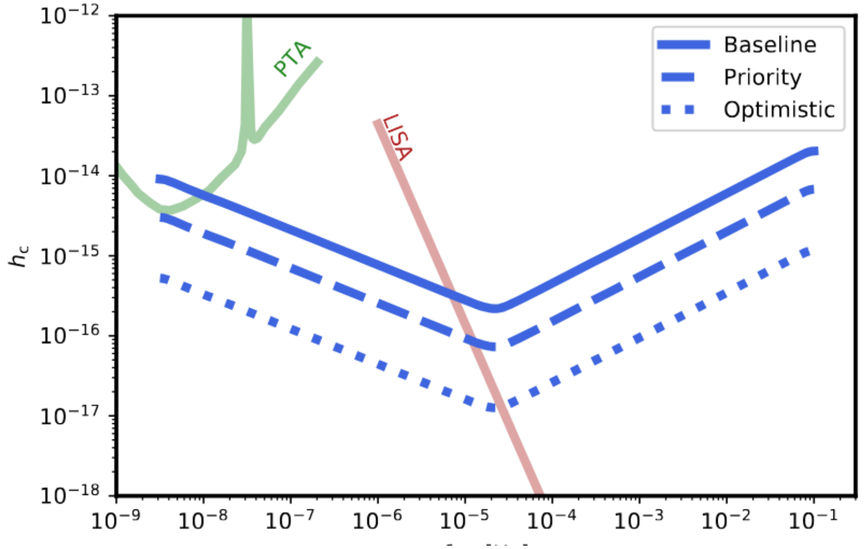
Zwick, DB et al 2406.02306 [astro-ph.HE]

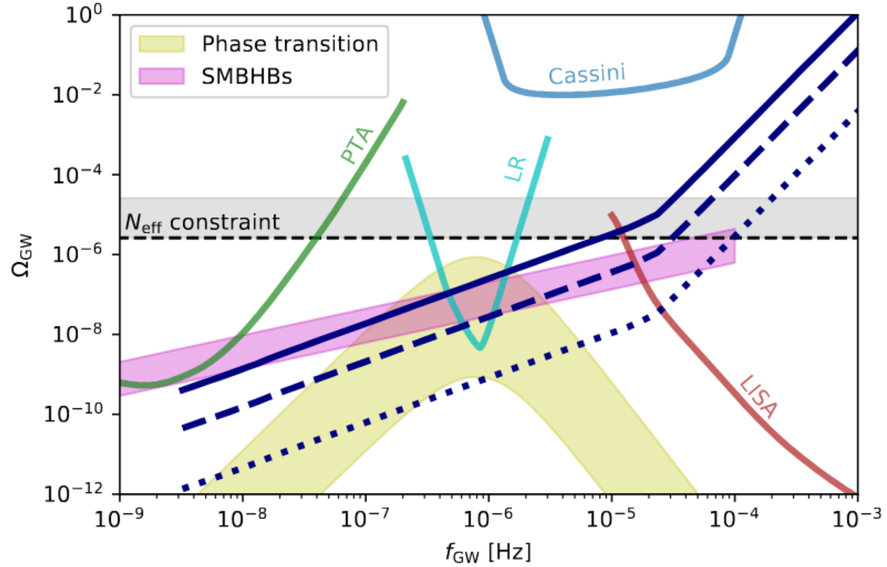
Cassini PSD



Bertotti, B., Vecchio, A., & Iess, L. 1999, Phys. Rev. D, 59, 082001

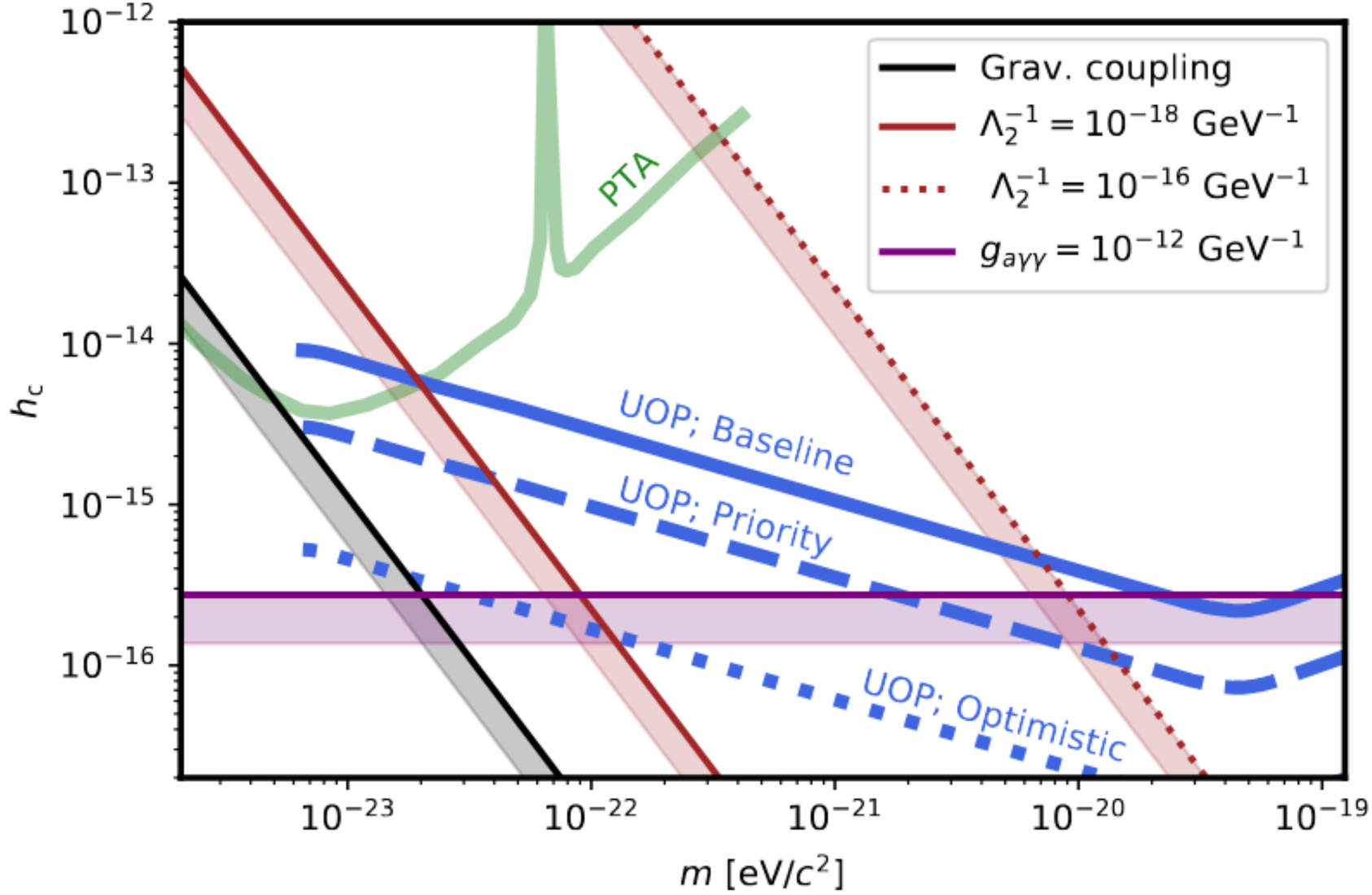
Uranus Orbiter and Probe





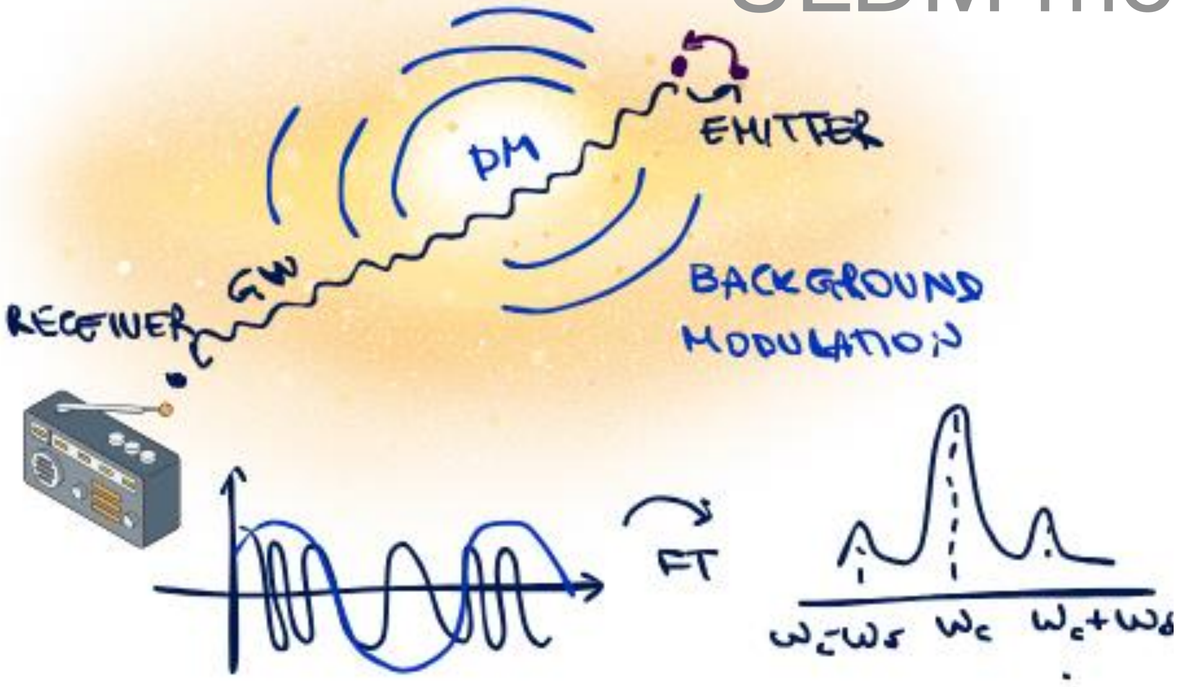
GWs and **ULDM** searches w/ Doppler tracking

Zwick, DB et al 2406.02306 [astro-ph.HE]



ULDM modulates GWs

DB, Gasparotto, Vicente, 2410.07330



$$\Upsilon = \Psi_2 - \frac{2}{\omega_\delta} n^i \partial_i \Phi_2 \Big|_e$$

$$\uparrow$$

$$\frac{\pi}{m^2}\bar{\rho}_\phi$$

primary wave

$$h \approx \mathcal{A}\Big[\cos\left(\omega_e u + \alpha_0'\right) + \pm \frac{\omega_e}{2\omega_\delta}\Upsilon\Big|_{r_e} \cos\left[\left(\omega_e \pm \omega_\delta\right) u + \alpha_0' \pm \varphi_\delta\right]\Big]$$

$$\omega_\delta = 2m$$

$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N}SNR_h$$

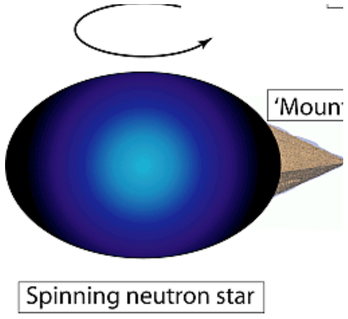
Galactic sources

DB, Gasparotto, Vicente, 2410.07330

$$SNR_\delta = \frac{1}{\sqrt{2}} \frac{\omega_e}{\omega_\delta} \Upsilon \sqrt{N} SNR_h$$

	N	$\langle \mathrm{SNR}_h \rangle$	$\sqrt{N}\langle \mathrm{SNR}_h \rangle \langle f_e \rangle [\mathrm{Hz}]$
	Double White Dwarfs		
LISA	$5.5(1.6) \times 10^3$	37(38)	7.8(4.3)
TianQin	$2.5(0.7) \times 10^3$	37(37)	5.1(2.9)
Taiji	$5.8(1.7) \times 10^3$	59(60)	13(6.8)
μAres	$504(148) \times 10^3$	49(48)	97(52)
	X-MRIs		
LISA	$\mathcal{O}(5)$	$\sim 10^3$	~ 10
	Spinning NSs		
ET/CE	$\mathcal{O}(200)$	~ 30	$\sim 10^5$

$f_e \sim \mathrm{mHz}$

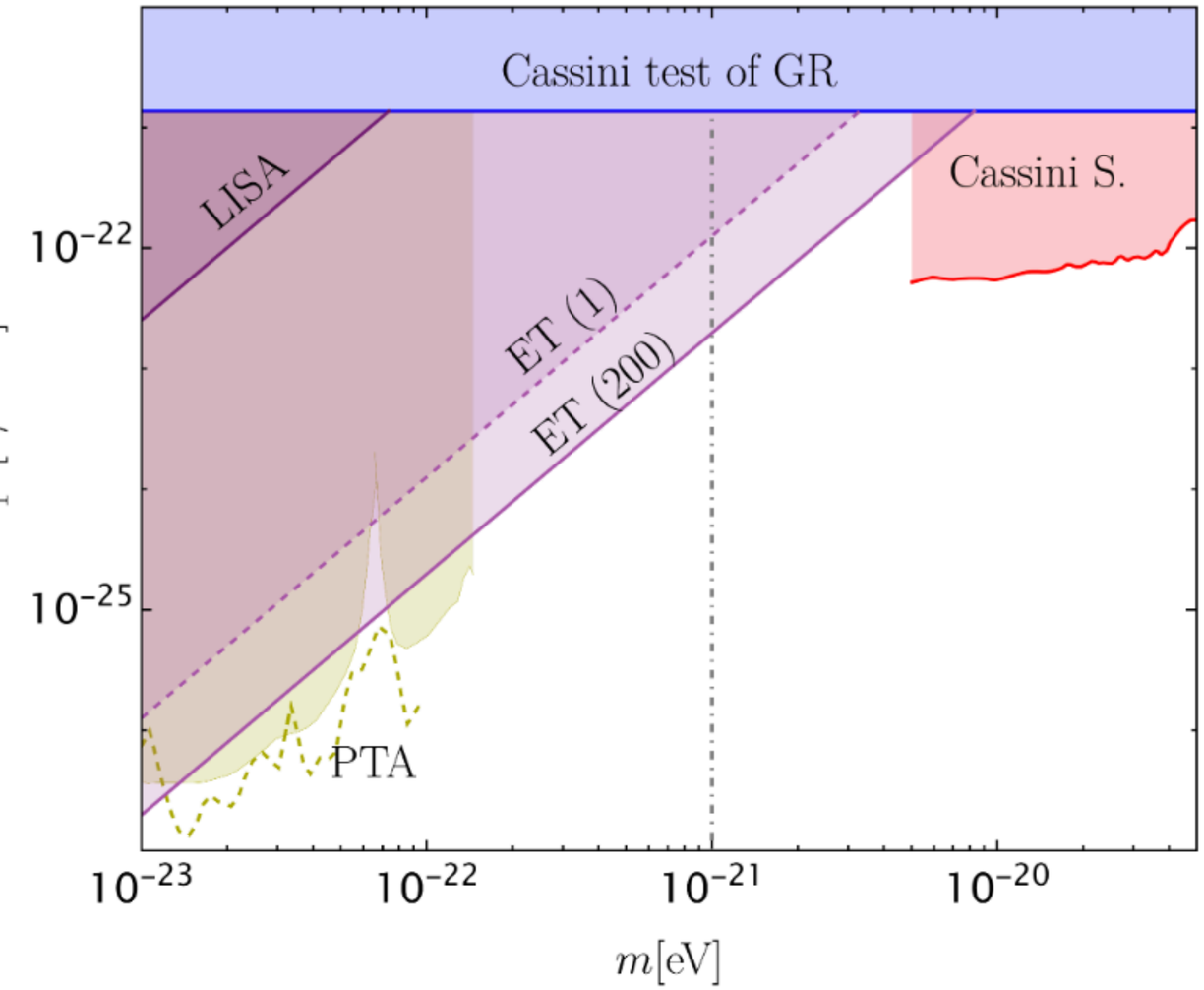


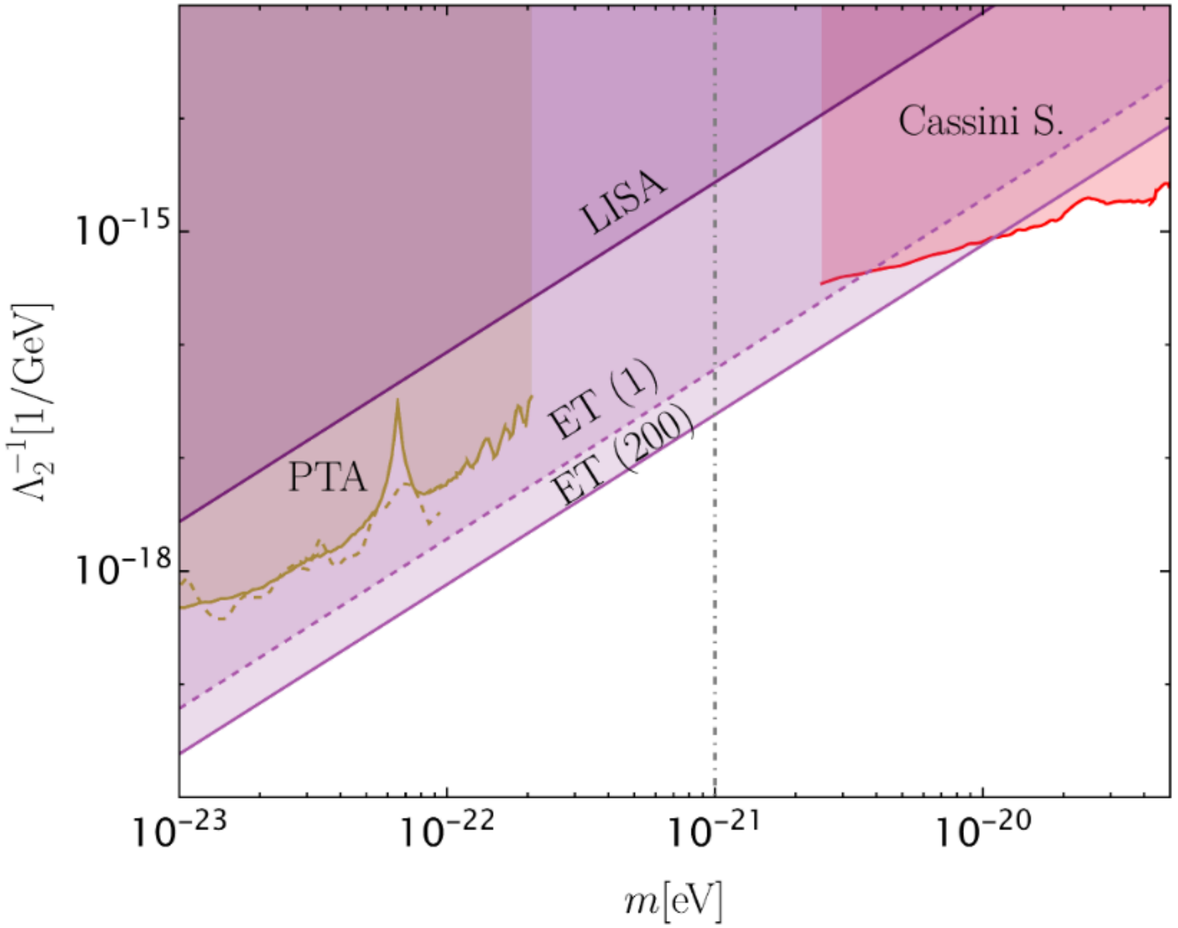
$f_e \sim \mathrm{kHz}$

Sensitivity to ULDM from MW sources

DB, Gasparotto, Vicente, 2410.07330

Case with direct coupling $\widetilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$ with $A \approx 1 + \phi^2/\Lambda_2^2$





Summary and expectations

- Time and/or space dependent phenomena associated to
  - **Dark matter**
  - **Gravitational waves**
    - may have secular effect on dynamics orbiting bodies
    - may have relevant effect on well tracked orbiting bodies
- These may be more relevant for frequencies/masses hard to measure otherwise: **big opportunity**

Expectations

- Dialogue among theorists/astrophysicists towards fun and new ideas
- Move from concepts to realistic analysis
- Craziest idea: is quantum communication with Mars possible?

Summary and expectations

- Feel free to suggest topics to discuss during the breaks

- Use this blackboard + email to announce them

Summary and expectations

- Proposal for highly eccentric and long period satellites
- Focus of Th and Fr