Astrophysical and cosmological probes of very light dark matter and dark sector particles

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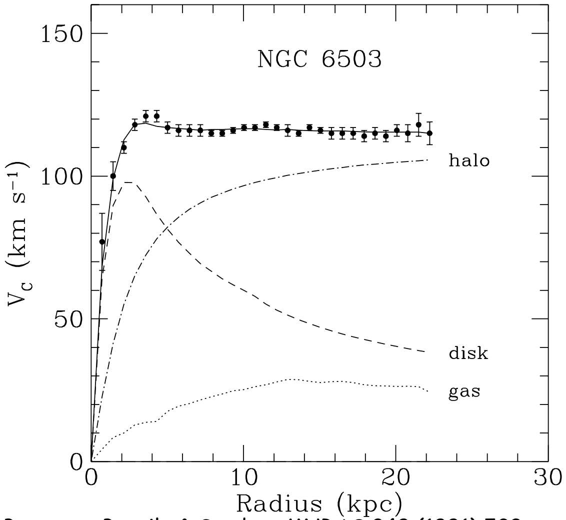
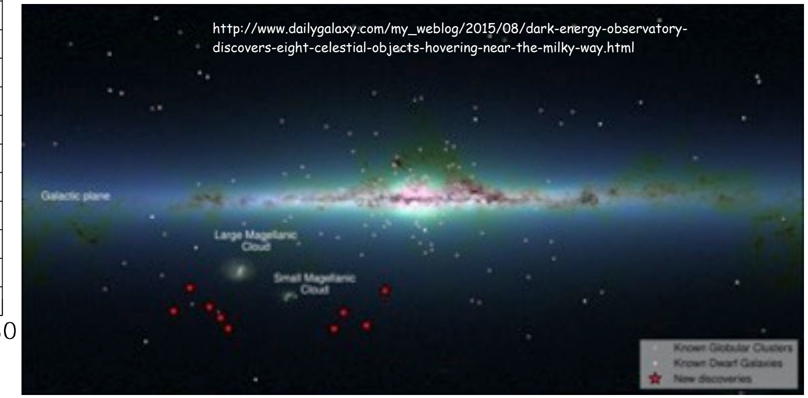
Gravitational detection of dark matter

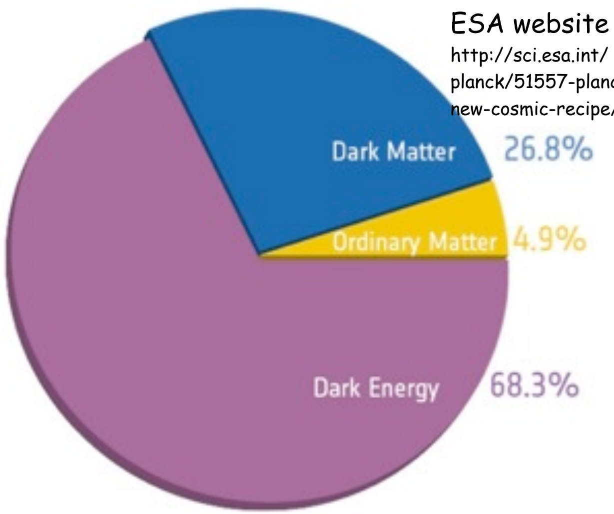


Begeman, Broeils & Sanders MNRAS 249 (1991) 523



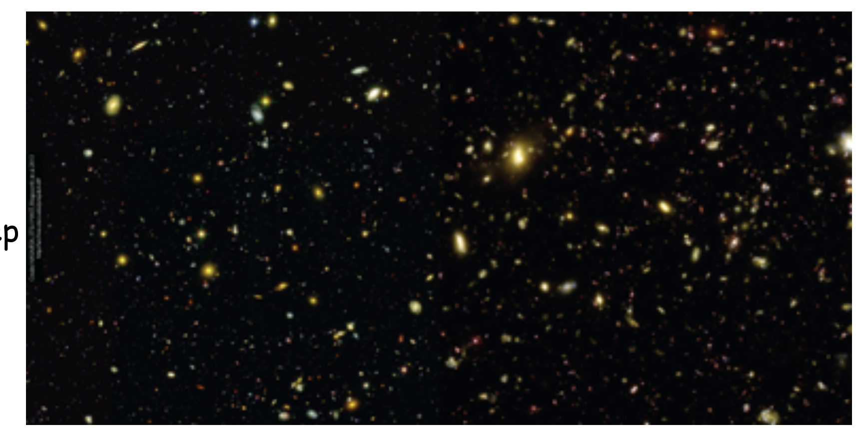
Bullet cluster
https://en.wikipedia.org/wiki/File:1e0657_scale.jpg

ESA website
http://sci.esa.int/planck/51557-planck-new-cosmic-recipe/

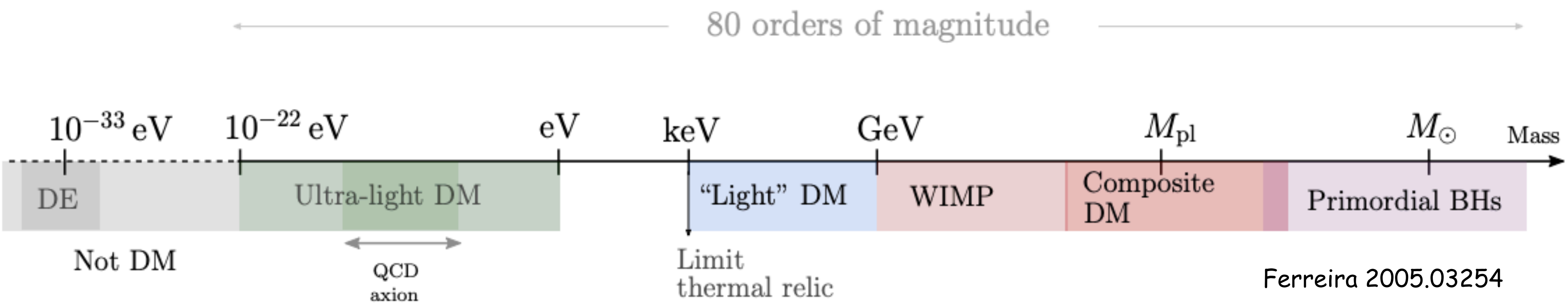


Real observation from Hubble eXtreme Deep Field Observations: left side

Mock observation from Illustris: right side
Illustris website



Range of dark matter mass



Ferreira 2005.03254

We need to thoroughly test all well-motivated candidates

It is important to test all regions of dark matter parameter space, esp. regions where dark matter candidates saturate the cosmic dark matter density

See talks by D. Kaplan, F. Gao, T. Han, F. Bianchi, R. Maselek, T. Nguyen, N. Cao, C. Boehm, A. Long, B. Ivanov, N. V. Tran, F. Scutti, M. Citron, J. T. Acuna, A. Ganguly, K. Hamaguchi, N. Nguyen, and others

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- Very light dark matter particle
- Cosmology of very light dark matter particle
- Sub-halo mass function of very light dark matter
- Pulsar timing array constraints on very-light dark matter
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- Conclusion

Very light dark matter particle

Very light dark matter particle

Assuming a particle of mass m moving with a velocity v, the de Broglie wavelength is

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.55\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{220\,{\rm km\,s^{-1}}}{v}\right)$$

Given the local density of dark matter = $0.4\,{\rm GeV\,cm^{-3}}$, the de Broglie wavelength exceeds the inter-particle separation if $m \lesssim 30\,{\rm eV}$

Average number of particles in a de Broglie volume $\lambda_{\rm dB}^3$ is

$$N_{\rm dB} \approx \left(\frac{30\,{\rm eV}}{m}\right)^4 \left(\frac{250\,{\rm km\,s^{-1}}}{v}\right)^3$$

Hui 2101.11735

Very light dark matter particle

For $m \ll 30\,\mathrm{eV}$, the dynamics can be described by the wave description due to the extremely large occupancy number

Due to the Pauli exclusion principle, such a light dark matter particle is bosonic

In this talk, we concentrate on spin-0 particle, unless mentioned otherwise

Such very light dark matter is well motivated from various theoretical considerations: axions, axion-like particles from various string theory inspired models, and many others

Cosmology of very light dark matter particle

Cosmology of very light dark matter particle

Assume that the scalar particle is denoted by ϕ

$$S_\phi = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

g = determinant of the space-time metric $g_{\mu\nu}$

$V(\phi)$ = potential energy of the scalar field ϕ .

We will only consider mass term $\frac{1}{2}m_\phi^2\phi^2$ where m_ϕ = scalar particle mass

Equation of motion: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$ where H is the Hubble parameter

$\bar{\rho}_a = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m_\phi^2\phi^2$ = background energy density of the scalar particle

$\bar{P}_a = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m_\phi^2\phi^2$ = background pressure of the scalar particle

Marsh 1510.07633; Ferreira 2005.03254

Cosmology of very light dark matter particle

The equation of motion can be solved exactly for radiation dominated and matter dominated era, when the scale factor is represented by $a \propto t^p$

$$\phi(t) = a^{-3/2}(t/t_i)^{1/2}[C_1 J_n(m_\phi t) + C_2 Y_n(m_\phi t)]$$

where $n = \frac{3p-1}{2}$ and $J_n(x),\ Y_n(x)$ = Bessel functions of the first and second kind

t_i = initial time and $C_1,\ C_2$ = dimensional constant depending on the initial conditions

The equation of motion can be solved numerically during other cosmological epochs

The equation of motion resembles a damped harmonic oscillator:

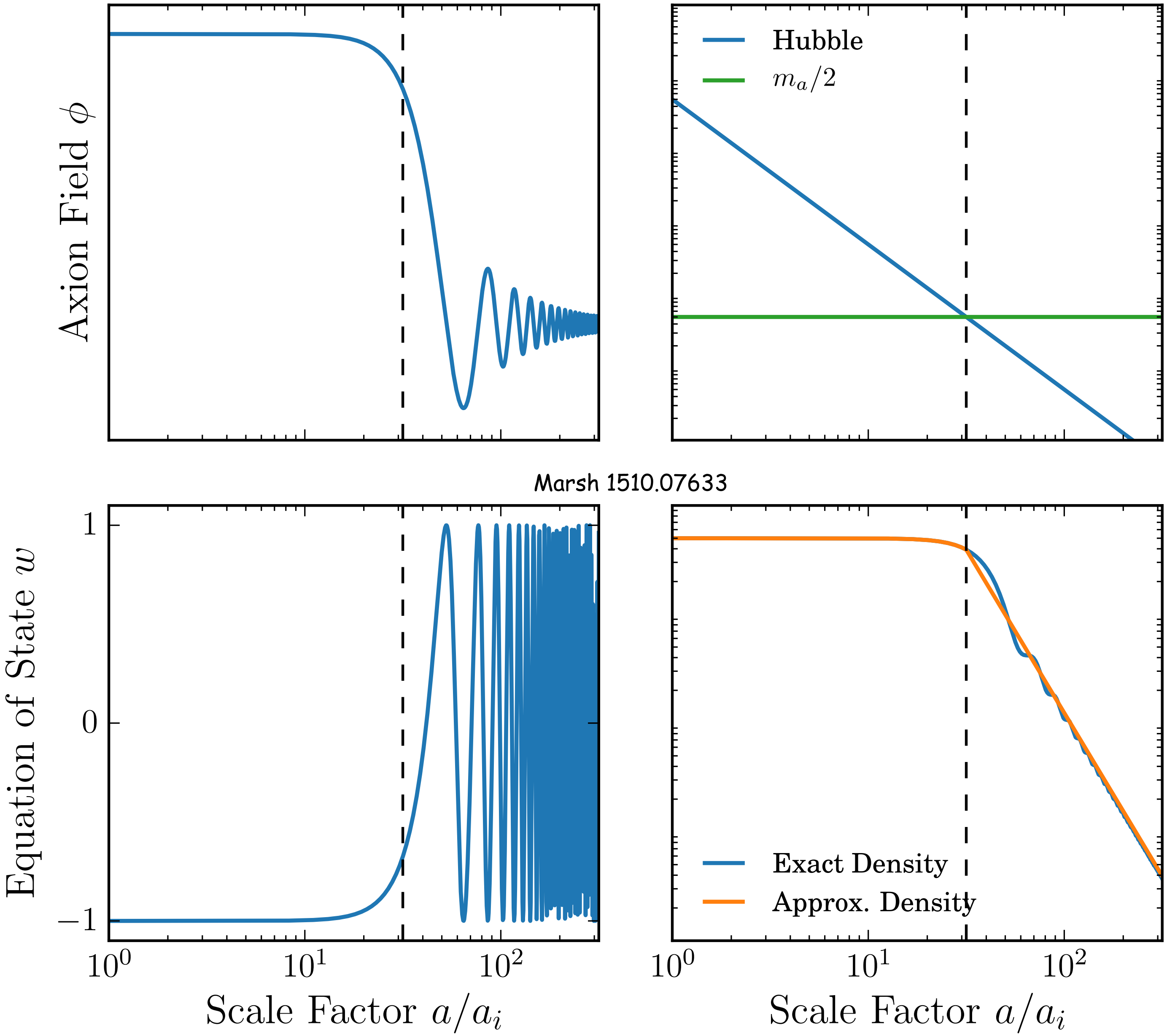
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

The term containing the Hubble parameter resembles the damping term

The term containing the mass term resembles the forcing term

Marsh 1510.07633

Cosmology of very light dark matter particle



Marsh 1510.07633

Redshift dependence of various quantities in the exact solution to the background evolution of an ALP, for a radiation-dominated universe (p = 1/2). Normalisation is arbitrary for dimensionful quantities. Vertical dashed lines show the condition defining $a_{\rm osc}$.

Cosmology of very light dark matter particle

At the earliest times: $H > m_\phi$ and the scalar field is stuck at its initial value due to Hubble friction

At these epochs, the equation of state is $w_\phi = -1$, and the scalar field contributes to vacuum energy

As time goes on, the value of H decreases whereas m_ϕ remains constant

At later times, $H < m_\phi$ and the scalar field undergoes an oscillatory behaviour

At these epochs, the equation of state is $w_\phi = 0$, and the scalar field contributes to matter energy density

The energy density scales as $\rho_\phi \propto a^{-3}$

Marsh 1510.07633

Cosmology of very light dark matter particle

In order to be dark matter, the scalar field needs to act as matter during the matter radiation equality, where $H(a_{\rm eq}) \approx 10^{-28}\,{\rm eV}$, thus the scalar field mass $m_\phi > 10^{-28}\,{\rm eV}$

The scale factor when the scalar field starts oscillating is denoted by $a_{\rm osc}$

The energy density of the scalar field after this period is

$\rho_\phi(a) \approx \rho_\phi(a_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3$ where $a > a_{\rm osc}$

The energy density of the scalar field is determined by the value of the field determined by initial conditions and its mass — does not track the temperature of the Universe — thus, very light dark matter is non-thermal

The value of $a_{\rm osc}$ is determined numerically by solving the evolution equation in the presence of real-Universe epochs

Marsh 1510.07633

Intuitive understanding of the cosmological constraints on very light dark matter

Consider an object on the Hubble flow, i.e., receding from the origin at a velocity $\mathbf{v}_H = Hr\hat{r}$

The de Broglie wavelength $\lambda_H = \frac{1}{m_\phi v} = \frac{1}{m_\phi H r}$ gives the positional uncertainty Δr

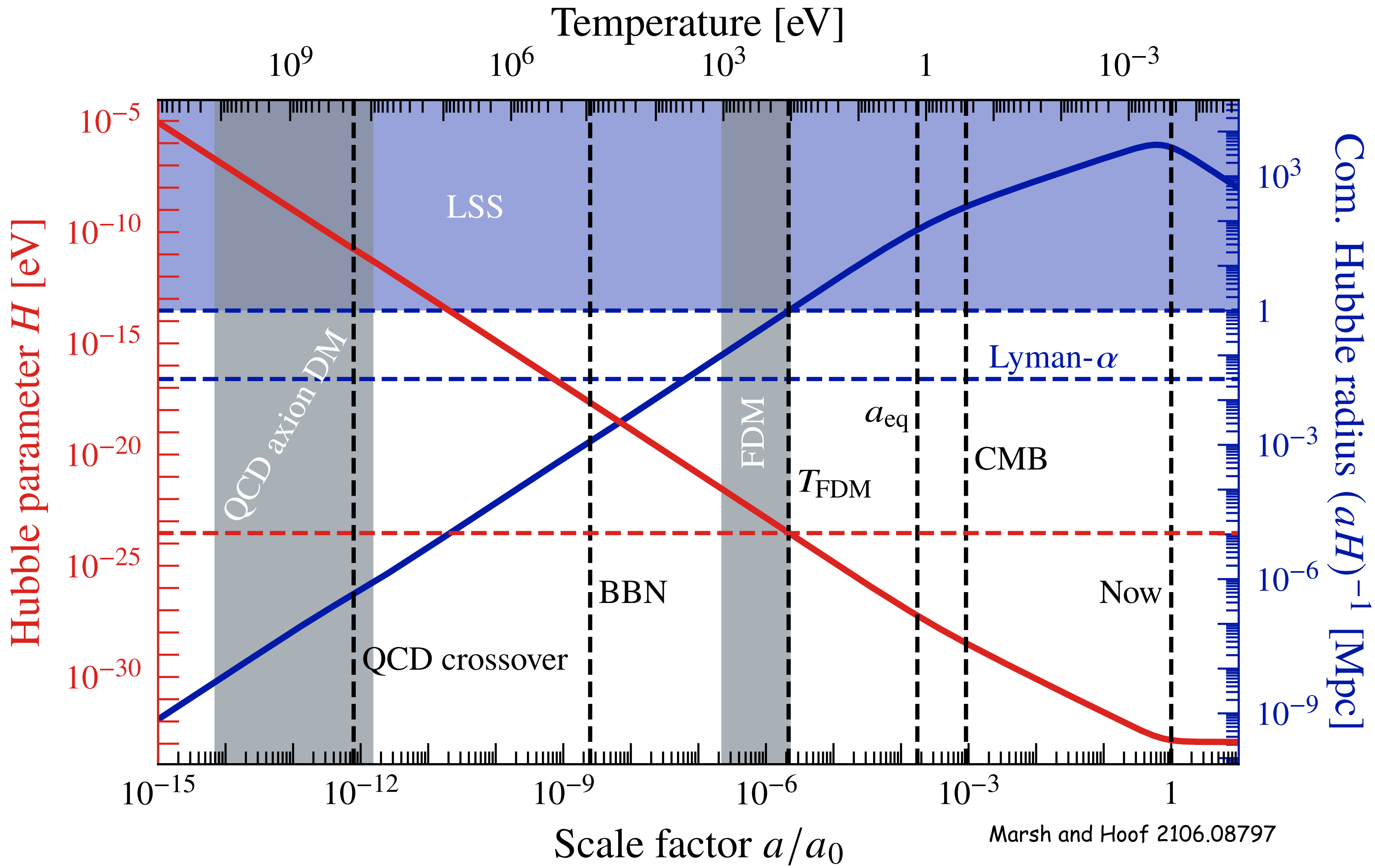
For dark matter to clump, we want the positional uncertainty to be smaller than the radial co-ordinate: $\Delta r \lesssim r$ implying $r \gtrsim (m_\phi H)^{-1/2}$

For distances larger than $r_{\rm crit} \equiv (m_\phi H)^{-1/2}$, clumping happens and thus structure formation can take place at these large scales

Many cosmological constraints can be understood by comparing with the above mentioned length scale

Marsh and Hoof 2106.08797

Cosmological history



Marsh and Hoof 2106.08797

Hubble parameter and co-moving Hubble radius as a function of the scale factor/temperature

Cosmological constraints

Dark matter must cluster within the cosmological horizon $R_H \approx H^{-1}$

Hubble scale today $H_0 = 100h\,\mathrm{km\,s^{-1}}$ where $h \approx 0.7$

$m_\phi \gtrsim 1.5 \times 10^{-33}\,\mathrm{eV} \times \left(\frac{h}{0.7}\right)$ Any dark matter candidate must obey this bound

Dark matter was gravitationally relevant during matter - radiation equality:

$z_{\mathrm{eq}} \approx 3390$

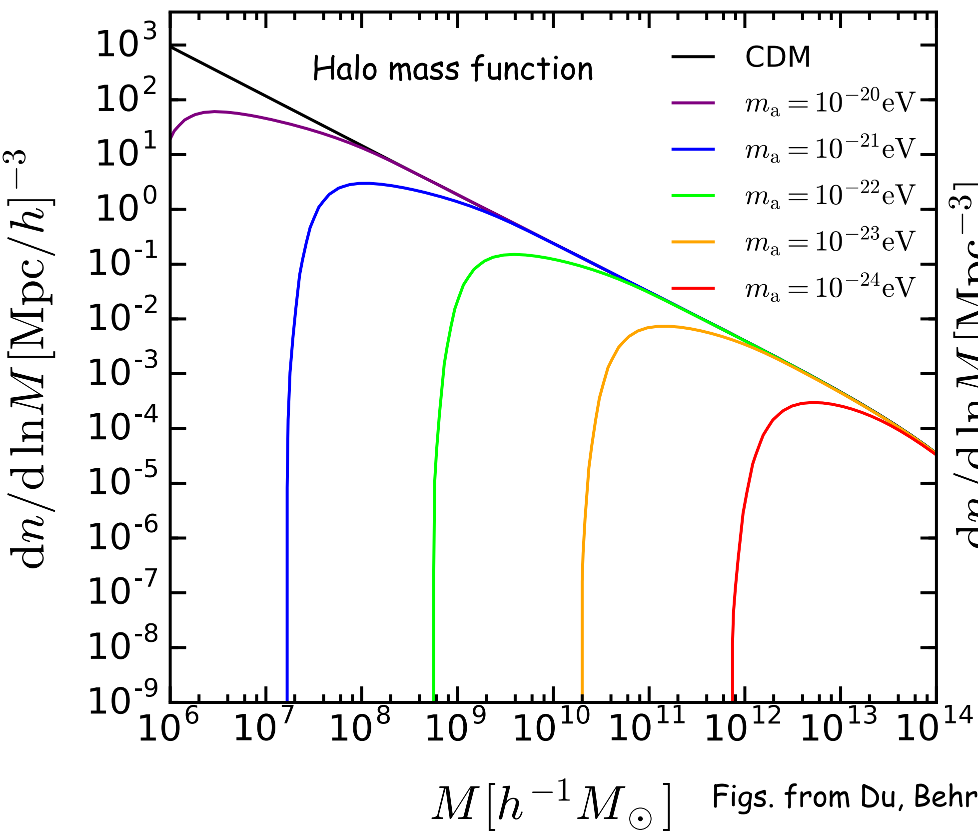
$$m_\phi \gtrsim 1.6 \times 10^{-28}\,\mathrm{eV} \times \left(\frac{h}{0.7}\right)\left(\frac{\Omega_m}{0.311}\right)^{1/2}\left(\frac{1+z_{\mathrm{eq}}}{3390}\right)^{3/2}$$

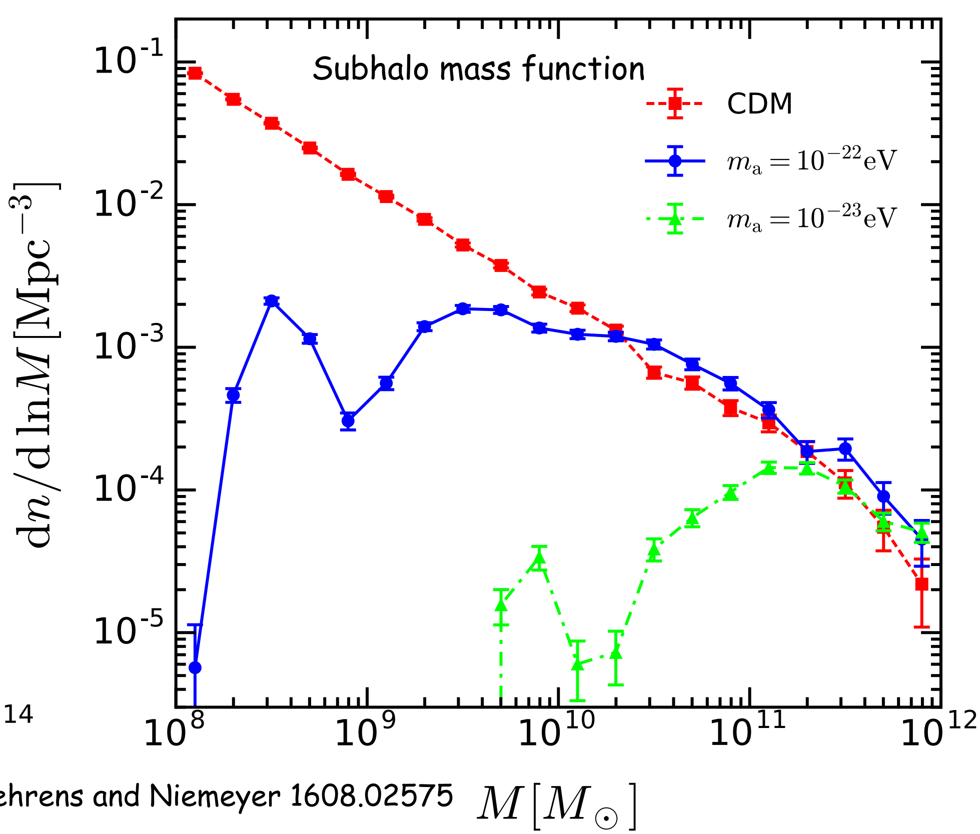
Marsh and Hoof 2106.08797

Sub-halo mass function of very light dark matter

Sub-halo mass function and very light dark matter

The finite de Broglie wavelength causes a suppression in the number of dark matter halos and sub-halos below that particular length scale

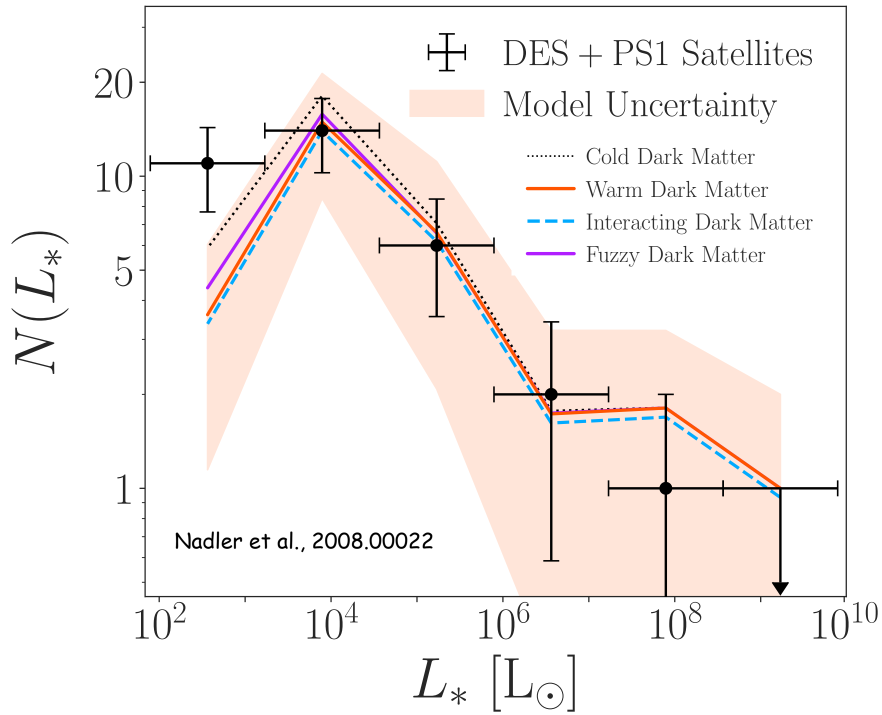


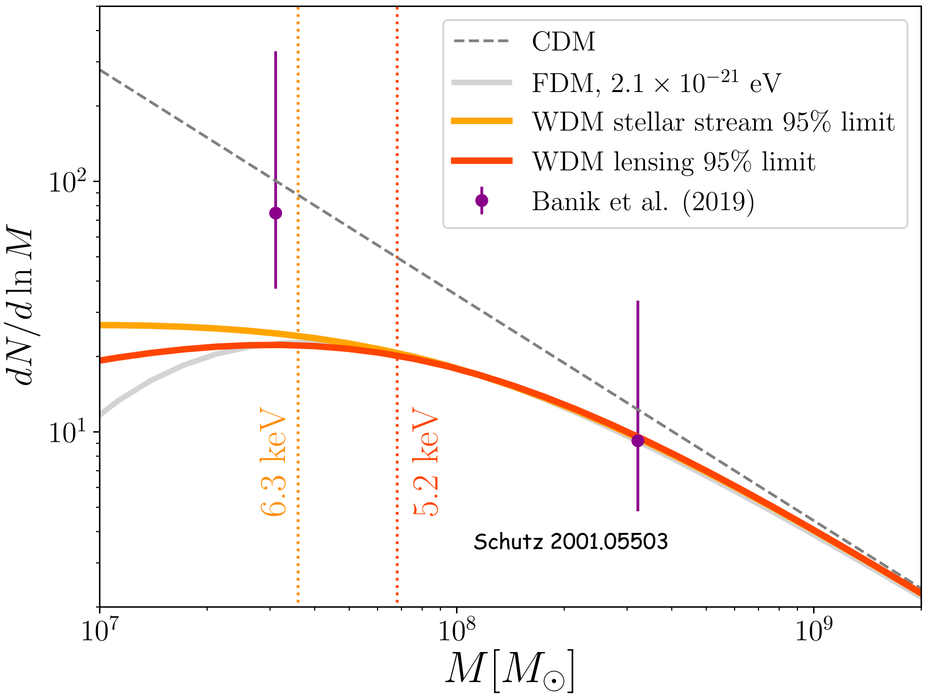


Figs. from Du, Behrens and Niemeyer 1608.02575

Smaller mass of the very light dark matter particle implies a larger cut-off in the halo and sub-halo masses

Subhalo mass function and very light dark matter



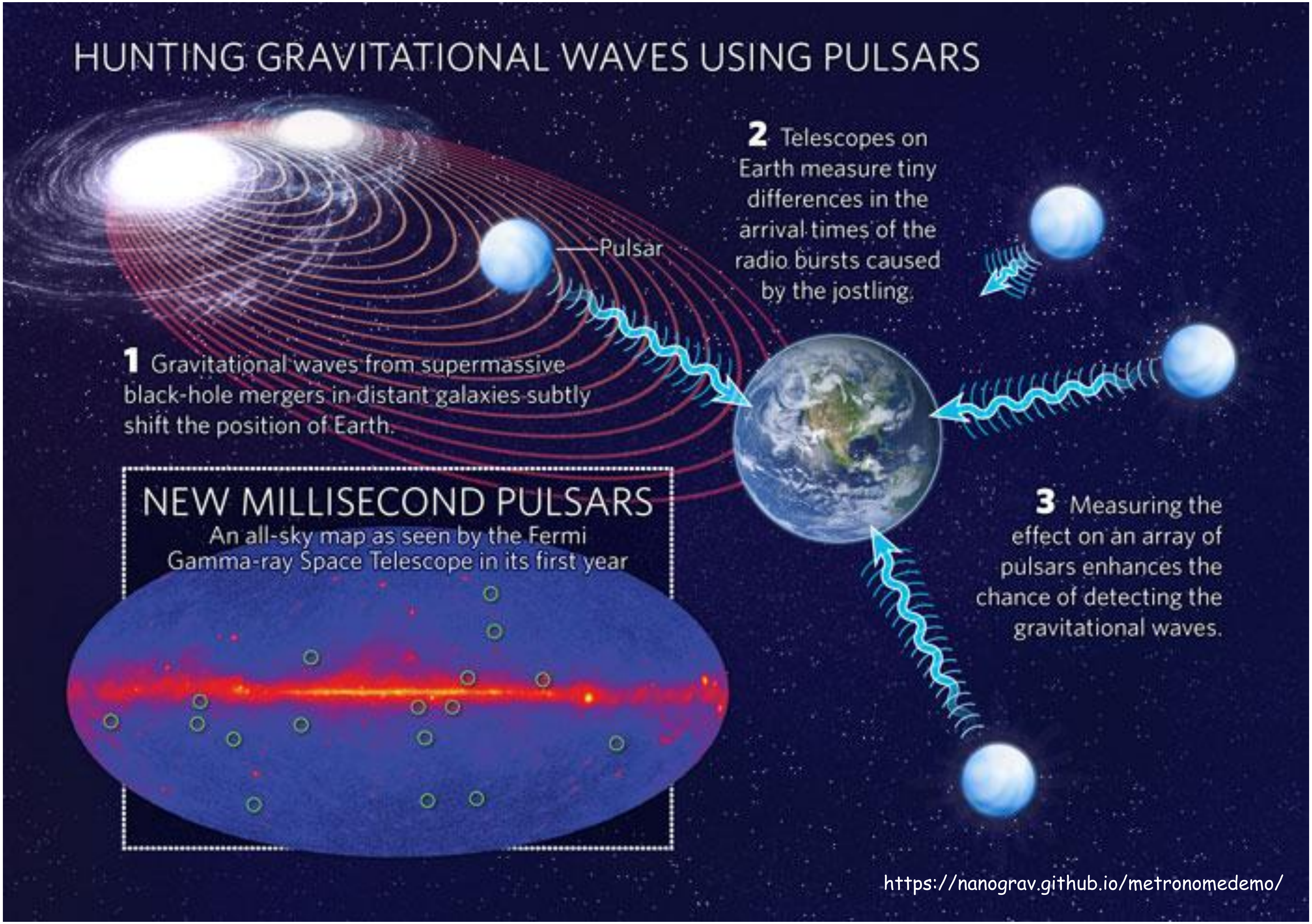


Study of Milky Way satellites can constrain the particle property of dark matter: Nadler et al., found $m_\phi > 2.9 \times 10^{-21}\,\mathrm{eV}$. The constraint depends on the Milky Way satellite modeling

Study of Milky Way stellar streams and strong gravitational lensing of quasars can constrain the particle property of dark matter: Schutz found $m_\phi > 2.1 \times 10^{-21}\,\mathrm{eV}$.

Pulsar timing array constraints on very light dark matter

Pulsar timing array



Pulsar timing array constraints on very light dark matter

The oscillating dark matter field is denoted by $\phi(\mathbf{x},t) = A(\mathbf{x})\cos(m_\phi\, t + \alpha(\mathbf{x}))$

Given this field, one can calculate the energy-momentum tensor

$$T_{\mu\nu} = \partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}((\partial\phi)^2 - m_\phi^2\phi^2)$$

The spatial components T_{ij} oscillates in time with frequency $\omega = 2m_\phi$

$$T_{ij} = -\frac{1}{2}m_\phi^2 A^2\cos(\omega\, t + 2\alpha)\,\delta_{ij} \equiv p(\mathbf{x},t)\,\delta_{ij}$$

The average value of the pressure term is zero implying that the very light scalar particle acts as pressure-less dust

The oscillating pressure term causes oscillations in the gravitational potential, thus, impacting light propagation through them

Khmelnitsky and Rubakov
1309.5888 JCAP

Pulsar timing array constraints on very light dark matter

The gravitational fields, $\Phi(\mathbf{x}, t)$ and $\Psi(\mathbf{x}, t)$ induced by the scalar field can be determined using the metric:

$$ds^2 = \big(1 + 2\Phi(\mathbf{x}, t)\big)dt^2 - \big(1 - 2\Psi(\mathbf{x}, t)\big)\delta_{ij}dx^i dx^j$$

Since the underlying matter distribution oscillates, the potential can be written as

$$\Psi(\mathbf{x}, t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x})\cos\left(\omega t + 2\alpha(\mathbf{x})\right) + \Psi_s(\mathbf{x})\sin\left(\omega t + 2\alpha(\mathbf{x})\right)$$

and a similar equation for $\Phi(\mathbf{x}, t)$ and $\alpha(\mathbf{x})$ is the phase

The potential can be determined from Einstein's equation using the energy-momentum tensor:

$\Psi_0(\mathbf{x}) = \Phi_0(\mathbf{x}) \approx G_N \frac{\rho_{\rm DM}}{k^2}$, $\Psi_s = 0$, and $\Psi_c(\mathbf{x}) = \pi \frac{G\rho_{\rm DM}(\mathbf{x})}{m_\phi^2}$

Khmelnitsky and Rubakov
1309.5888 JCAP

Pulsar timing array constraints on very light dark matter

The time-dependent oscillating metric causes a time-dependent frequency shift and a temporal delay for a propagating signal

$$\Delta t(t) = \frac{2\Psi_c}{\omega} \sin\left(\frac{\omega D}{2} + \alpha(\mathbf{x}) - \alpha(\mathbf{x_p})\right) \cos\left(\omega t + \alpha(\mathbf{x}) - \alpha(\mathbf{x_p}) - \frac{\omega D}{2}\right)$$

The change in arrival time of the pulse at time t is denoted by $\Delta t(t)$

The distance to the pulsar is D and the position of the pulsar is $\mathbf{x_p}$

It can be shown that the scalar field dark matter has the same effect as a monochromatic gravitational wave with strain

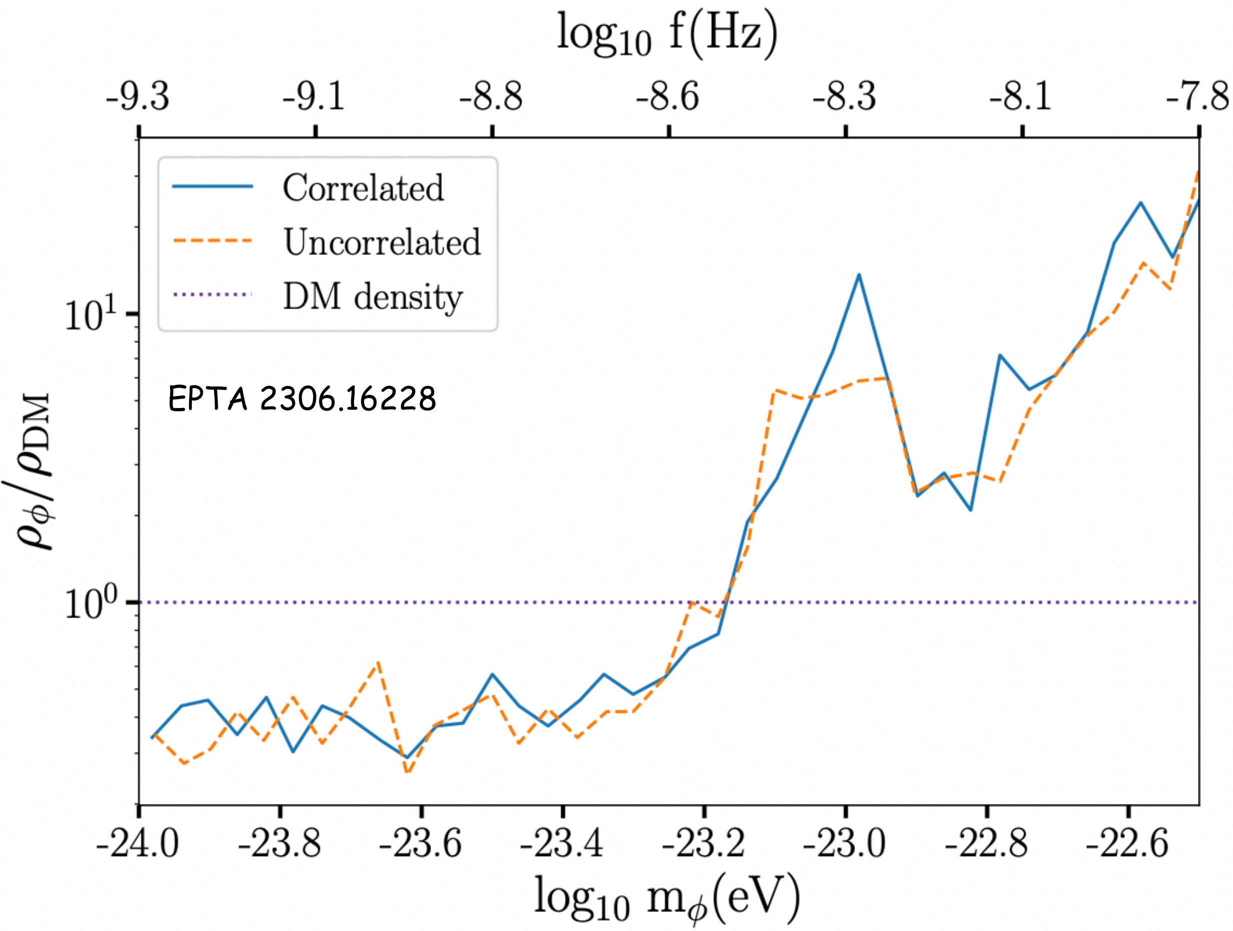
$$h_c = 2\sqrt{3}\,\Psi_c = 2 \times 10^{-15} \left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm^3}}\right) \left(\frac{10^{-23}\,{\rm eV}}{m_\phi}\right)^2$$

with frequency

$$f \equiv 2\pi\omega = 5 \times 10^{-9}\,{\rm Hz} \left(\frac{m_\phi}{10^{-23}\,{\rm eV}}\right)$$

Khmelnitsky and Rubakov
1309.5888 JCAP

Pulsar timing array constraints on very light dark matter



uncorrelated: coherence length of the very-light dark matter is less than the distance between pulsars and distance between pulsar and the Earth

correlated: coherence length of the very-light dark matter is larger than the distance between pulsars and distance between pulsar and the Earth

EPTA observations state that dark matter of mass $10^{-24}\,\mathrm{eV} < m_\phi < 10^{-23.4}\,\mathrm{eV}$ contributes only 30% to 40% of the local dark matter density

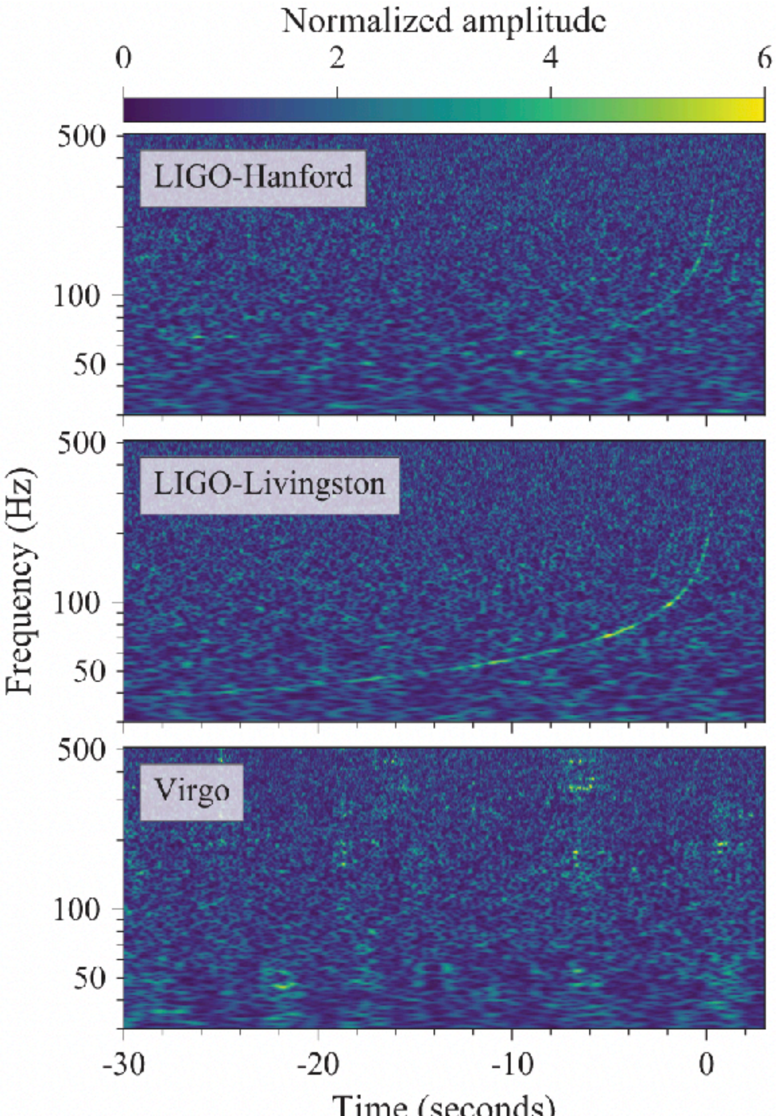
Similar constraints from the NANOGrav collaboration 2306.16219

Probing long-range muonic forces with neutron star systems

Dror, Laha, and Opferkuch
Phys. Rev. D 102 (2020) 2, 023005
1909.12845

related work: Kopp, Laha, Opferkuch, and Shepherd
JHEP 11 (2018) 096
1807.02527

Binary neutron star observation



GW170817

Component masses: 1.17 - 1.60 $M_\odot$

Total mass of the system: $2.74^{+0.04}_{-0.01}\ M_\odot$

Luminosity distance: 40^{+8}_{-14} Mpc

Near co-incident detection of gamma-ray burst

Radiated energy: > 0.025 $M_\odot$

Chirp mass: $\mathcal{M}_c \equiv \mu^{3/5}(M_1 + M_2)^{2/5}$

$= 1.188^{+0.004}_{-0.002} M_\odot$

reduced mass

LIGO-Scientific and Virgo "GW170817: observation of gravitational waves from a binary neutron star inspiral"

Semi-classical understanding of GW170817

$$(1)\quad \omega^2 = \frac{G_N\,(M_1 + M_2)}{\Delta^3}$$

Kepler's law

$$(2)\quad E_{\rm tot} = -\frac{G_N \mu (M_1 + M_2)}{\Delta} + \frac{1}{2}\mu\Delta^2\omega^2$$

Total energy of the system ($E_{\rm tot}$)

Orbital frequency (ω)

$$(3)\quad \frac{dE_{\rm GW}}{dt} = \frac{32}{5} G_N \mu^2 \Delta^4 \omega^6$$

Power radiated via gravitational waves

$$(4)\quad \frac{dE_{\rm tot}}{dt} = -\frac{dE_{\rm GW}}{dt}$$

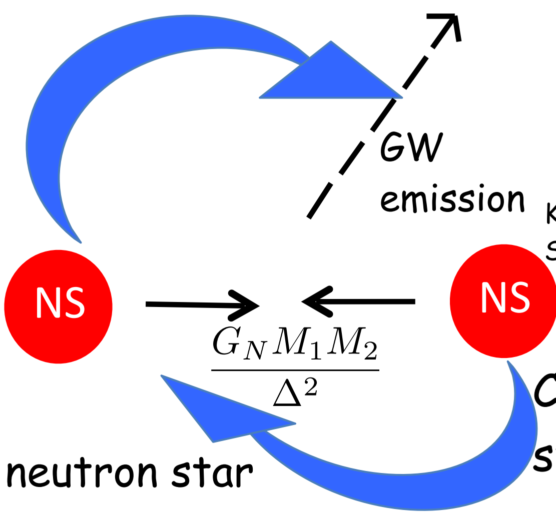
: Energy conservation

$$\Downarrow$$

$$\frac{d\omega}{dt} = \frac{96}{5}(G_N \mathcal{M}_c)^{5/3}\omega^{11/3}$$

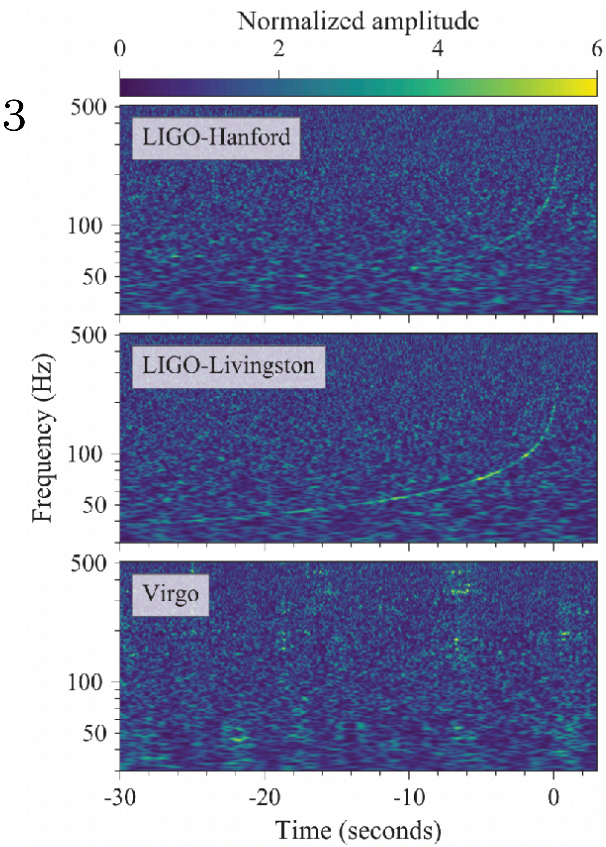
GW frequency

$$f_{\rm GW} = \frac{\omega}{\pi}$$



Cartoon of neutron star inspiral

Kopp, **Laha**, Opferkuch, and Shepherd 1807.02527 JHEP



$M_{1,2}$ = neutron star

Δ = distance between two neutron stars

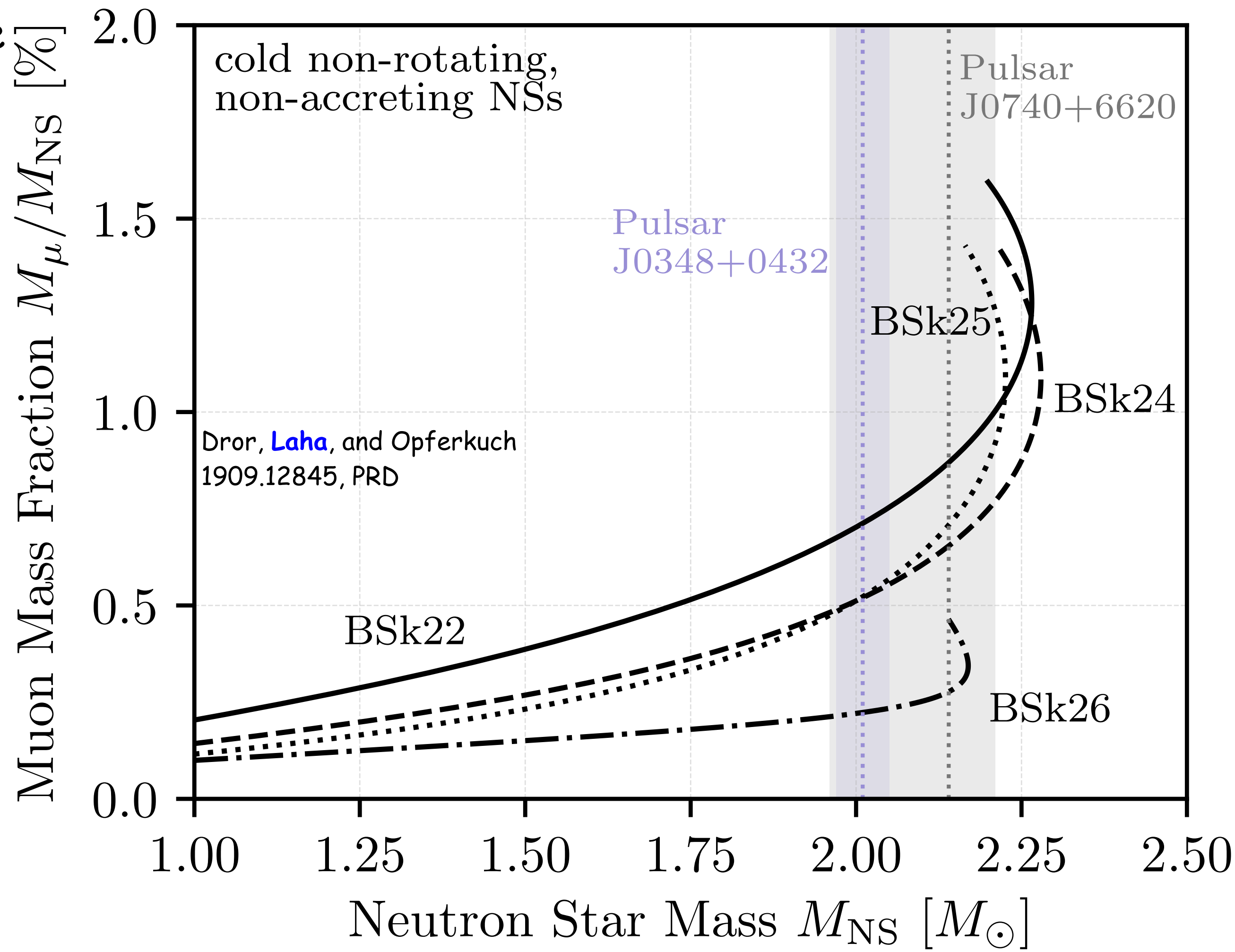
Muons inside neutron stars

Neutron stars host a large population of muons

Muon population arises from chemical equilibrium, charge neutrality, and a typical Fermi energy of ~ 100 MeV

A pure Standard Model phenomenon

Muon fraction depends on the equation of state



Bell etal. 1904.09803, Garani and Heeck 1906.101445, Poddar etal. 1908.09732, Pearson etal. 1903.04981

A new Yukawa force (attractive/ repulsive)

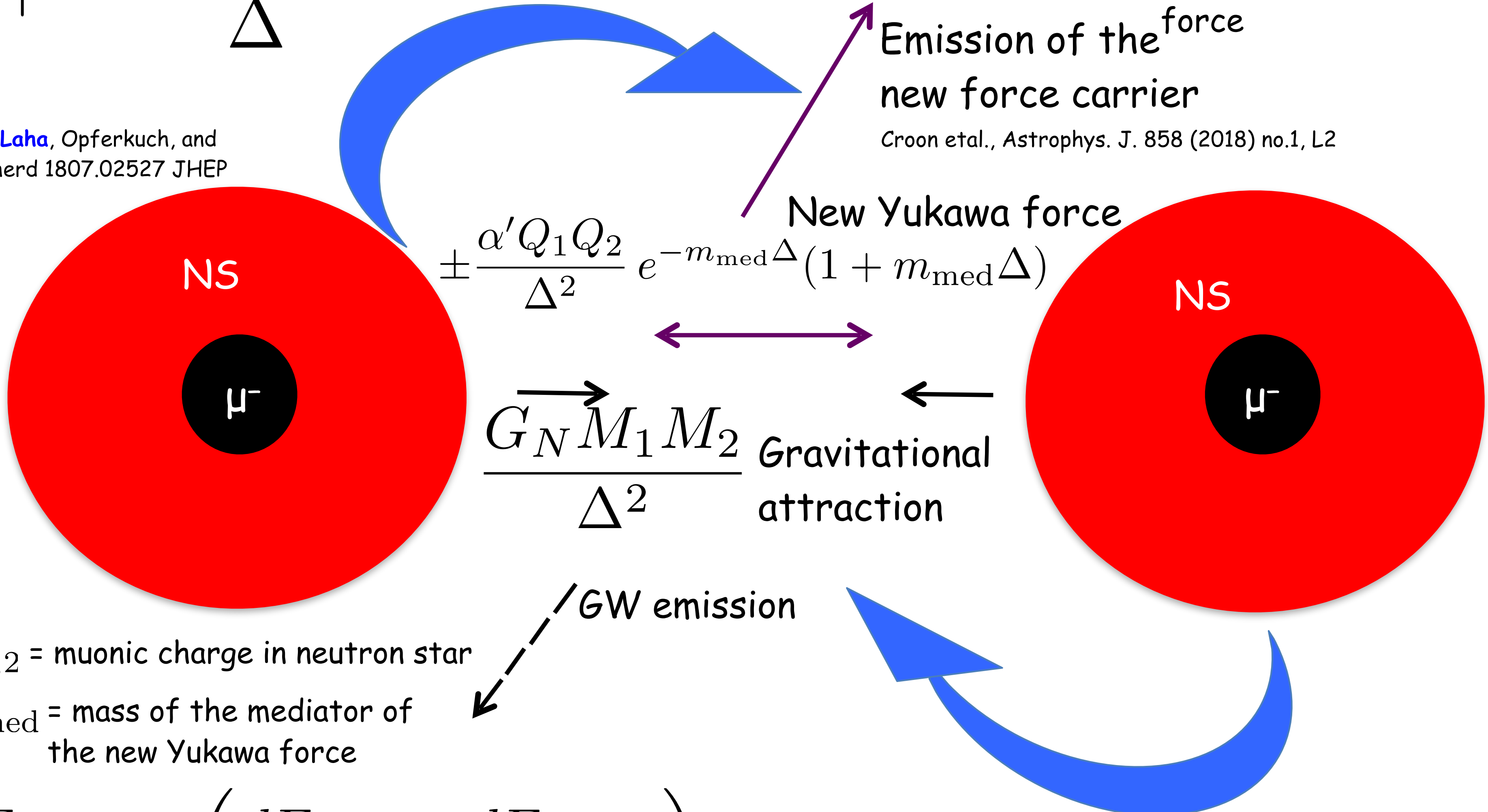
$$|V| = \frac{\alpha' Q_1 Q_2}{\Delta} e^{-m_{\rm med}\Delta}$$

α' = coupling of the new force

Emission of the new force carrier

Croon etal., Astrophys. J. 858 (2018) no.1, L2

Kopp, **Laha**, Opferkuch, and Shepherd 1807.02527 JHEP



New Yukawa force

$$\pm \frac{\alpha' Q_1 Q_2}{\Delta^2} e^{-m_{\rm med}\Delta}(1 + m_{\rm med}\Delta)$$

$$\frac{G_N M_1 M_2}{\Delta^2}$$

Gravitational attraction

GW emission

$Q_{1,2}$ = muonic charge in neutron star

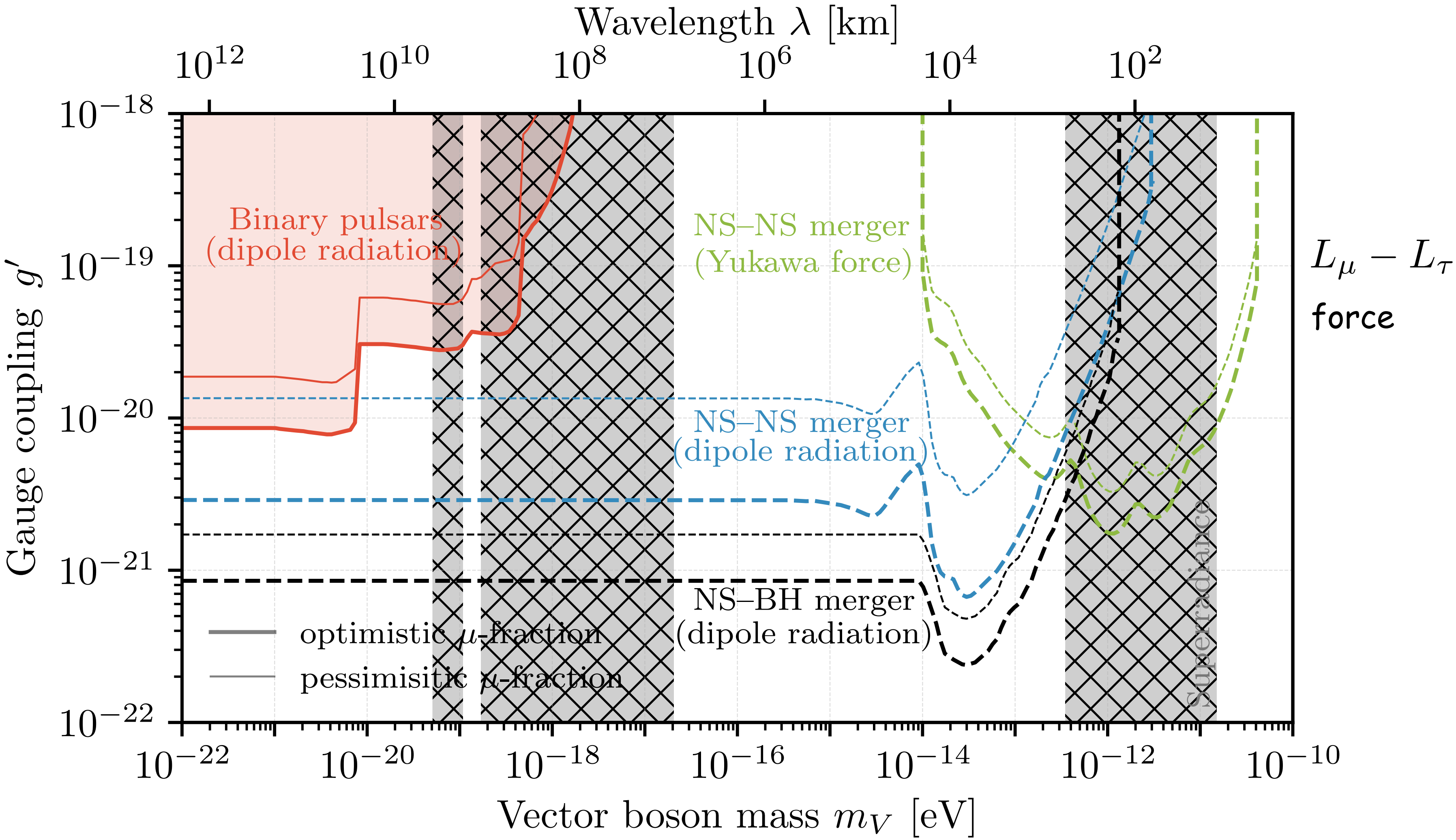
$m_{\rm med}$ = mass of the mediator of the new Yukawa force

$$\frac{dE_{\rm tot}}{dt} = -\left(\frac{dE_{\rm GW}}{dt} + \frac{dE_{\rm dipole}}{dt}\right)$$

Dror, **Laha**, and Opferkuch 1909.12845 PRD

Ranjan Laha

Probing long-range muonic interactions



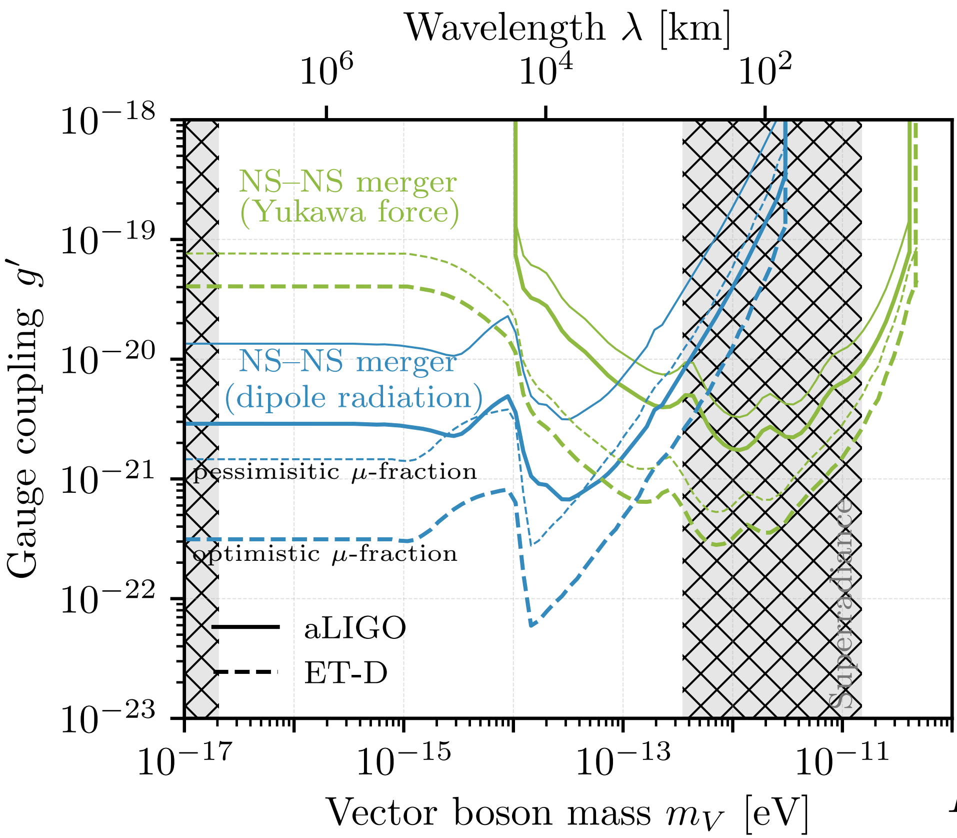
Huge discovery potential on exotic long-range forces due to muons

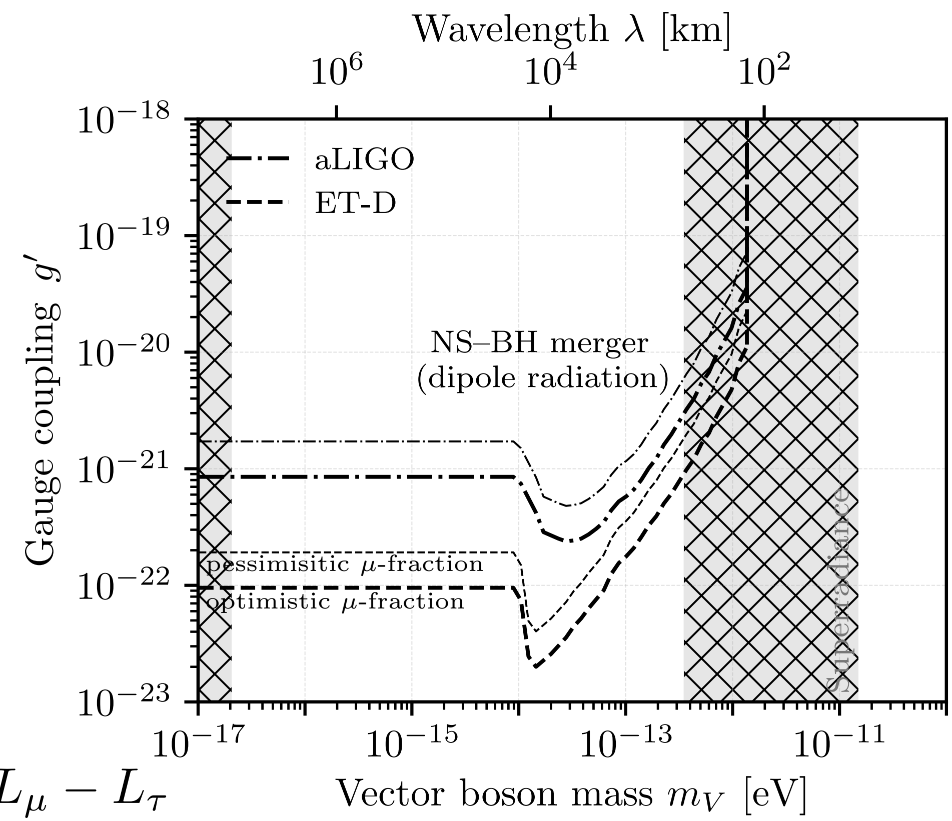
LIGO - VIRGO can probe large parts of the unexplored parameter space

Dror, Laha, and Opferkuch 1909.12845 PRD

See also Poddar etal. 1908.09732

Probing long-range muonic interactions





$L_\mu - L_\tau$

force

Einstein Telescope, Cosmic Explorer, and other near-future gravitational wave observatories have great potential to discover new parts of the parameter space

Neutron star – black hole mergers hold promising avenues for discovery

Dror, Laha, and Opferkuch 1909.12845
PRD

Conclusions

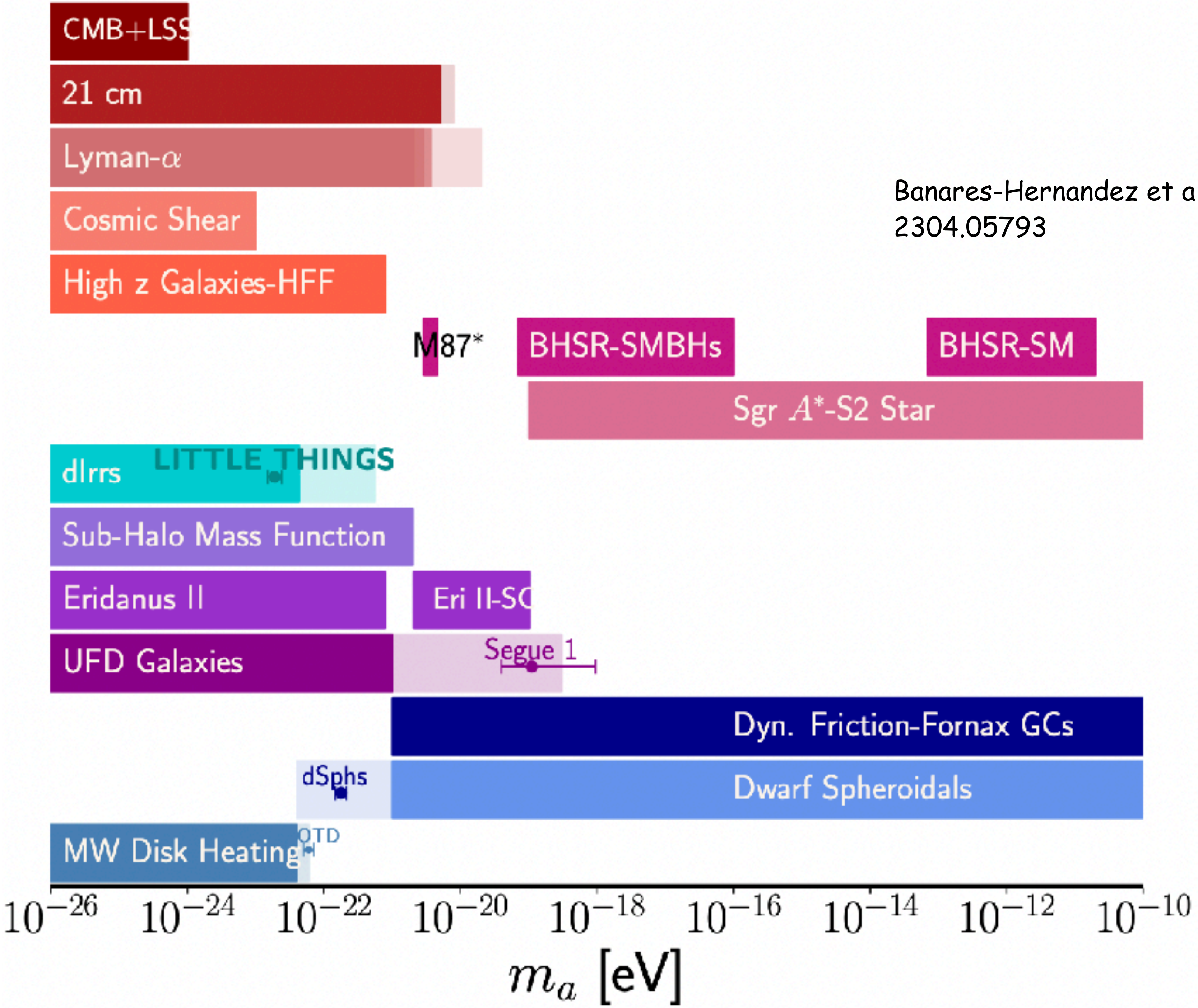
Very light dark matter particle and dark sector particles are one of the most promising candidates of beyond the Standard Model physics

I have talked about the phenomenology of very light dark matter particle/ dark sector particles in four different regimes:
cosmological observations,
sub-halo mass function,
pulsar timing array observations, and
muonic forces in neutron star systems

There are many other probes of these particles:
superradiance,
galaxy rotation curves,
dynamical friction, and
many other others

Promising avenues for discovery

Questions & comments: ranjanlaha@iisc.ac.in



Banares-Hernandez et al.,
2304.05793