ICTS | INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Searches for dark matter and dark sector particles using gravitational waves

Ranjan Laha

Centre for High Energy Physics

Indian Institute of Science, Bengaluru, India

Centre for
High Energy Physics

The need for beyond the Standard Model physics

- Why do we need new physics?

- Standard Model of particle physics and ΛCDM cosmology explains many observations about our Universe

- However, there are many open questions:

(i) what is dark matter?

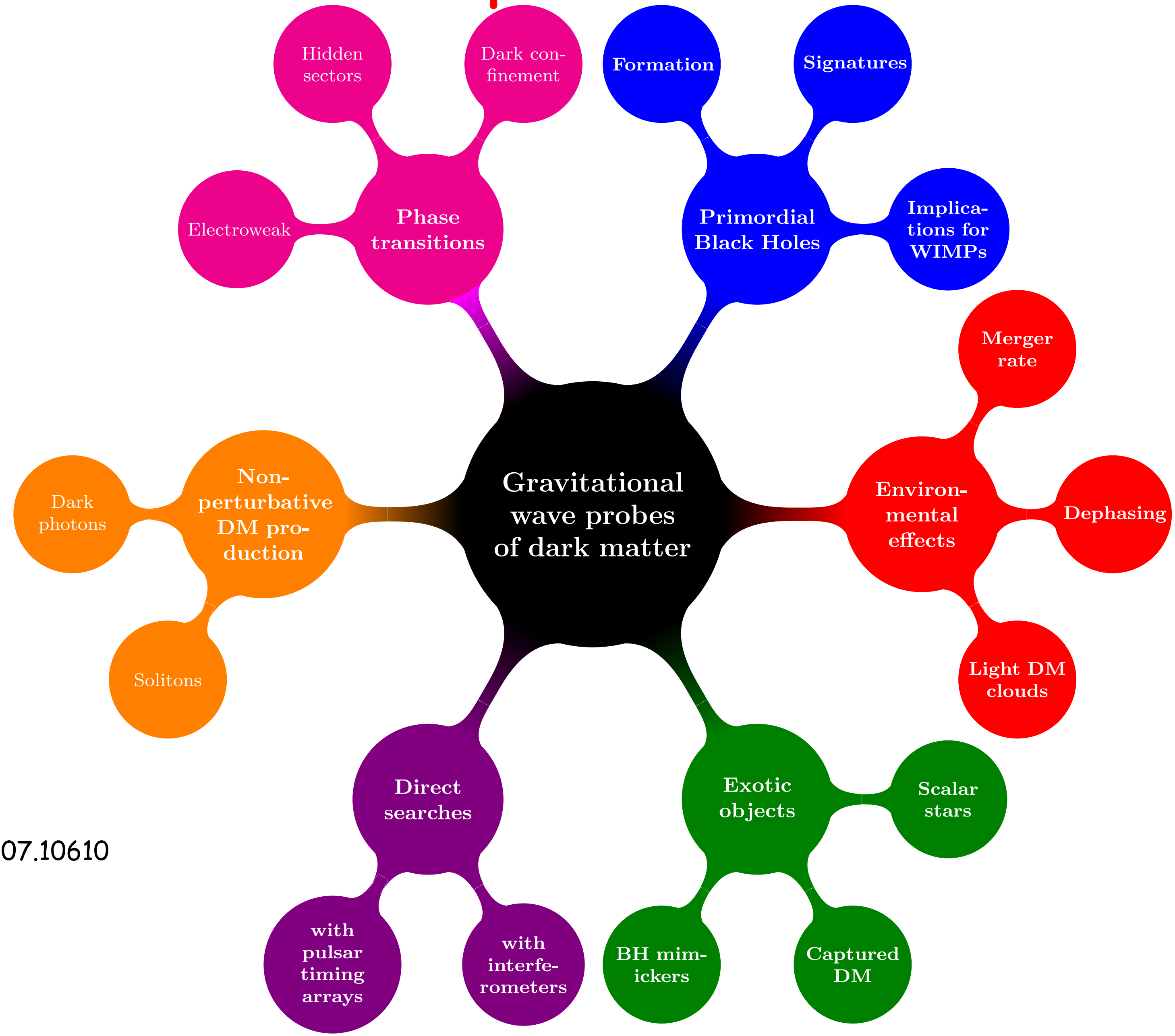
(ii) what is dark energy?

(iii) are there new forces in the Universe?

(iv) can we understand the phase transitions of the Universe?
and many others

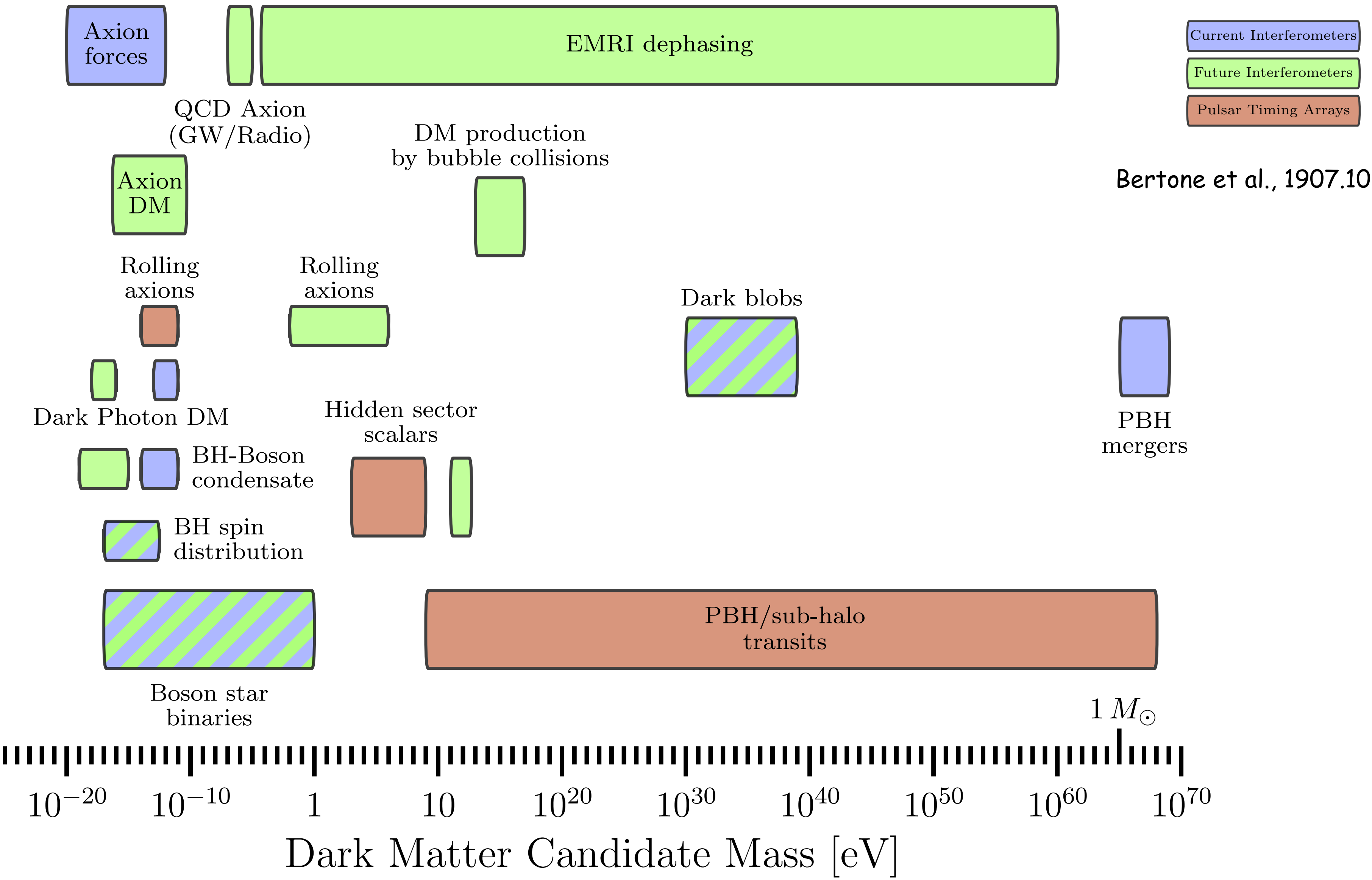
- Gravitational wave observatories may provide an answer

Gravitational wave probes of dark matter



Bertone et al., 1907.10610

Gravitational detection of dark matter



Bertone et al., 1907.10610

Contents

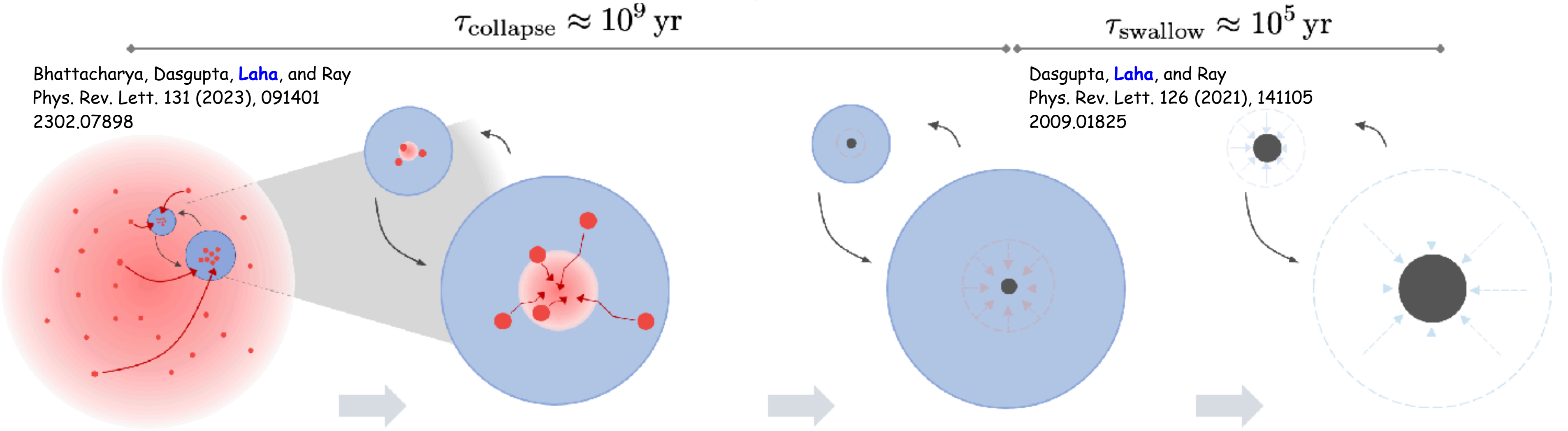
- Probing dark matter - nucleon cross-section via transmuted black holes
- Probing long-range muonic forces with neutron star systems
- Dark photon dark matter search at gravitational wave detectors
- Conclusion

Probing dark matter - nucleon cross-section via transmuted black holes

Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 126 (2021), 141105
2009.01825

Bhattacharya, Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 131 (2023), 091401
2302.07898

Dark matter accretion in compact astrophysical objects



Bhattacharya, Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 131 (2023), 091401
2302.07898

Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 126 (2021), 141105
2009.01825

Dark matter accumulates from the galactic halo into binary neutron stars

Dark matter scatters and thermalizes as a dark core with $T_\chi = T_{\rm core}$

Dark core collapses to a tiny seed black hole if core-mass $> m_\chi \times \max[N_\chi^{\rm self}, N_\chi^{\rm Cha}]$

Transmuted black holes form when the seed black holes swallow their host stars

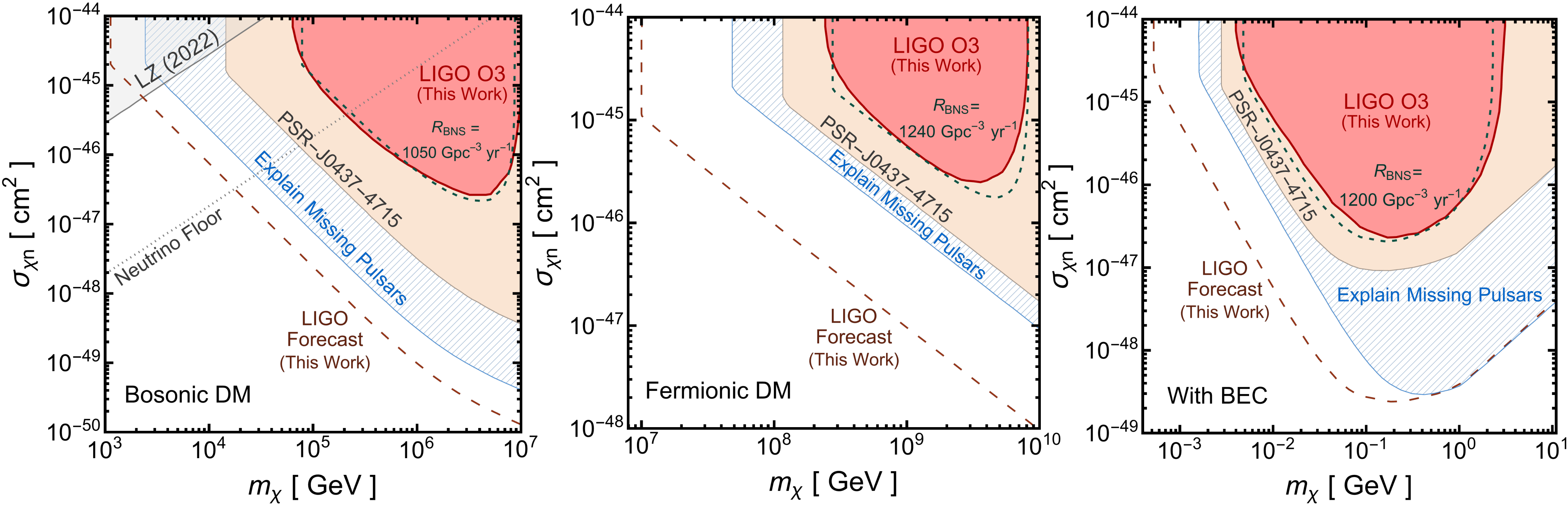
Formation of transmuted black holes

- Dark matter can accrete inside compact astrophysical objects due to non-zero dark matter - nucleon interaction

- For certain allowed dark matter - nucleon cross-sections, the accumulated dark matter can convert into a black hole; which will subsequently eat up the star: formation of transmuted black holes of the same mass as that of the star

- Mergers of transmuted black holes can give rise to gravitational waves: thus probing dark matter - nucleon cross-sections

Transmuted black holes as probe of particle dark matter



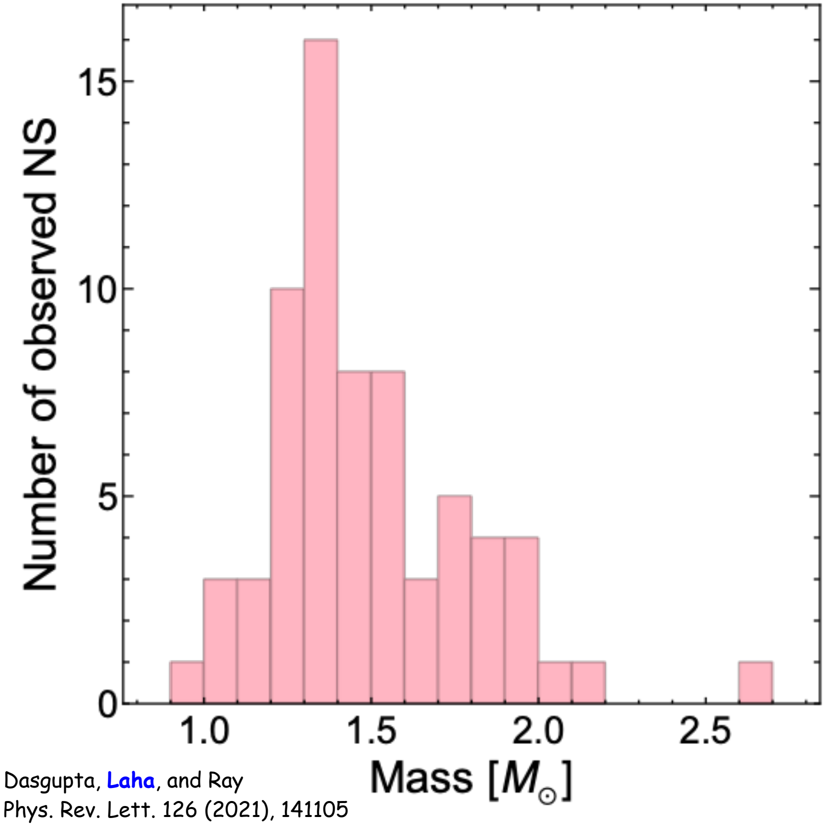
- A new probe of dark matter - nucleon cross-section
- Near future observations of gravitational waves from sub-Solar or Solar mass black holes can discover dark matter - nucleon cross-section beyond the reach of underground detectors
- New science case for gravitational wave detectors

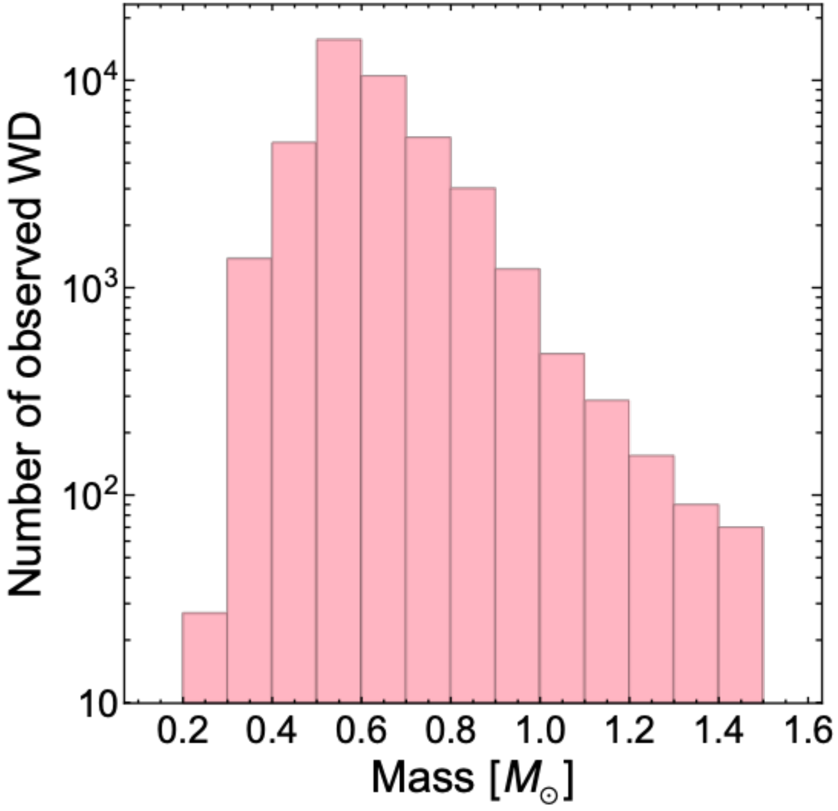
Bhattacharya, Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 131 (2023), 091401
2302.07898

Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 126 (2021), 141105
2009.01825

Mass function of transmuted black holes

- Two classes of astrophysics targets: neutron stars (NS) and white dwarfs (WD)
- These transmuted black holes can be detected
- Sub-Solar mass black holes need not be primordial in origin

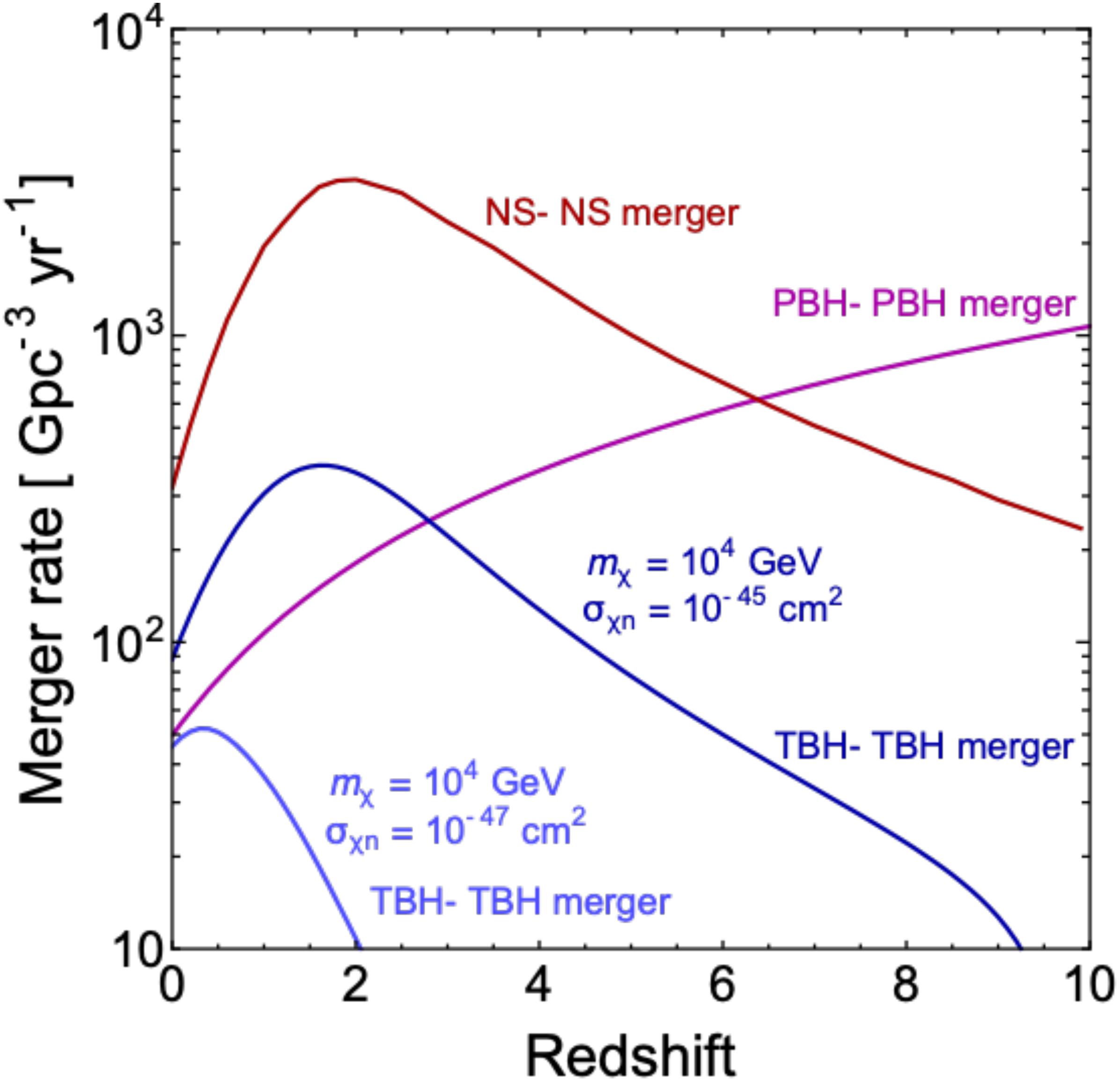




Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 126 (2021), 141105
2009.01825

See also Takhistov et al 2008. 12780

Red-shift distribution of transmuted black holes



Redshift dependence of the binary NS, PBH and transmuted BH (TBH) merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments (DECIGO, EINSTEIN, Cosmic Explorer telescope)

Dasgupta, **Laha**, and Ray
Phys. Rev. Lett. 126 (2021), 141105
2009.01825

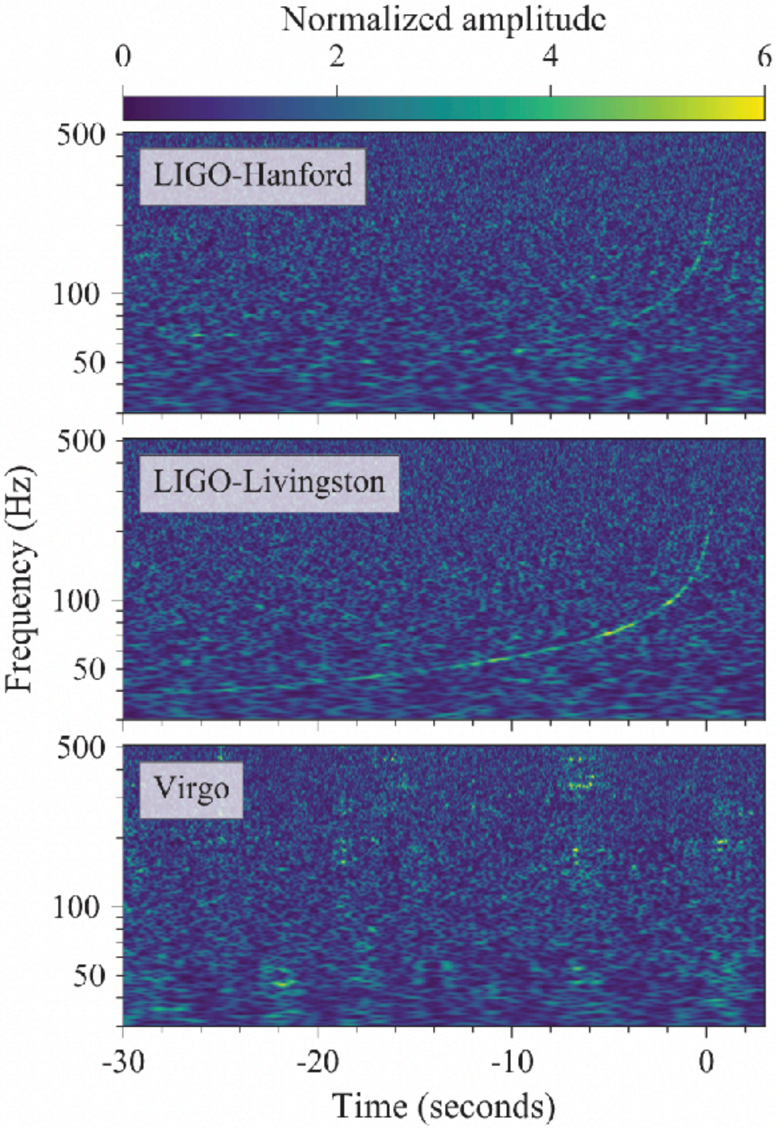
Probing long-range muonic forces with neutron star systems

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

$$(1)\quad \omega^2 = \frac{G_N\,(M_1 + M_2)}{\Delta^3} \qquad (2)\quad E_{\rm tot} = -\frac{G_N \mu (M_1 + M_2)}{\Delta} + \frac{1}{2}\mu\Delta^2\omega^2$$

Kepler's law

Total energy of the system

Orbital frequency

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

: Energy conservation

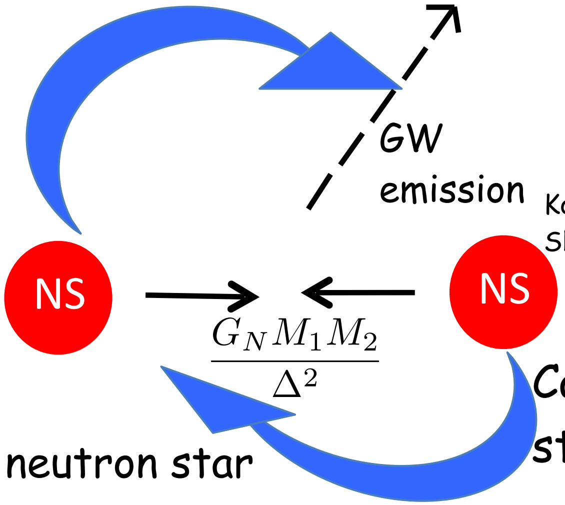
Power radiated via gravitational waves

$$\Downarrow$$

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

GW frequency

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

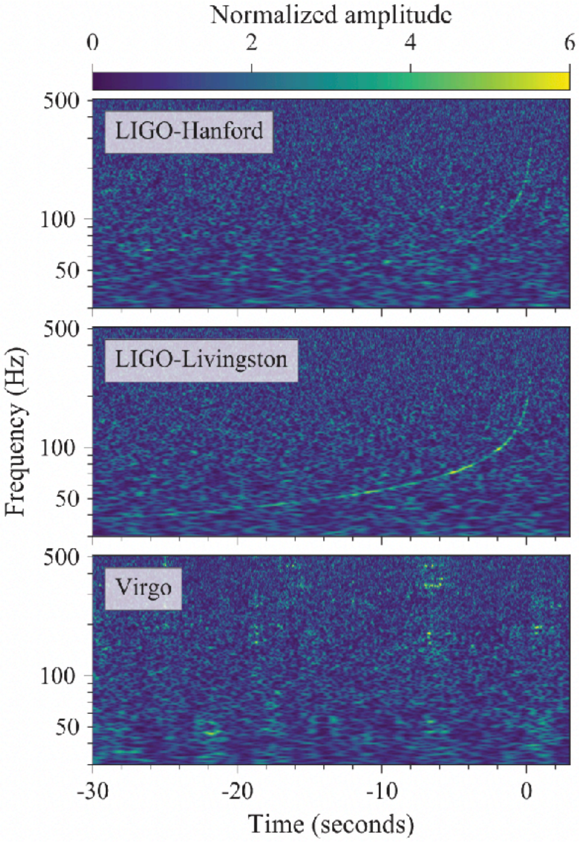


Kopp, **Laha**, Opferkuch, and Shepherd 1807.02527 JHEP

Cartoon of neutron star inspiral

$M_{1,2}$ = neutron star

Δ = distance between two neutron stars



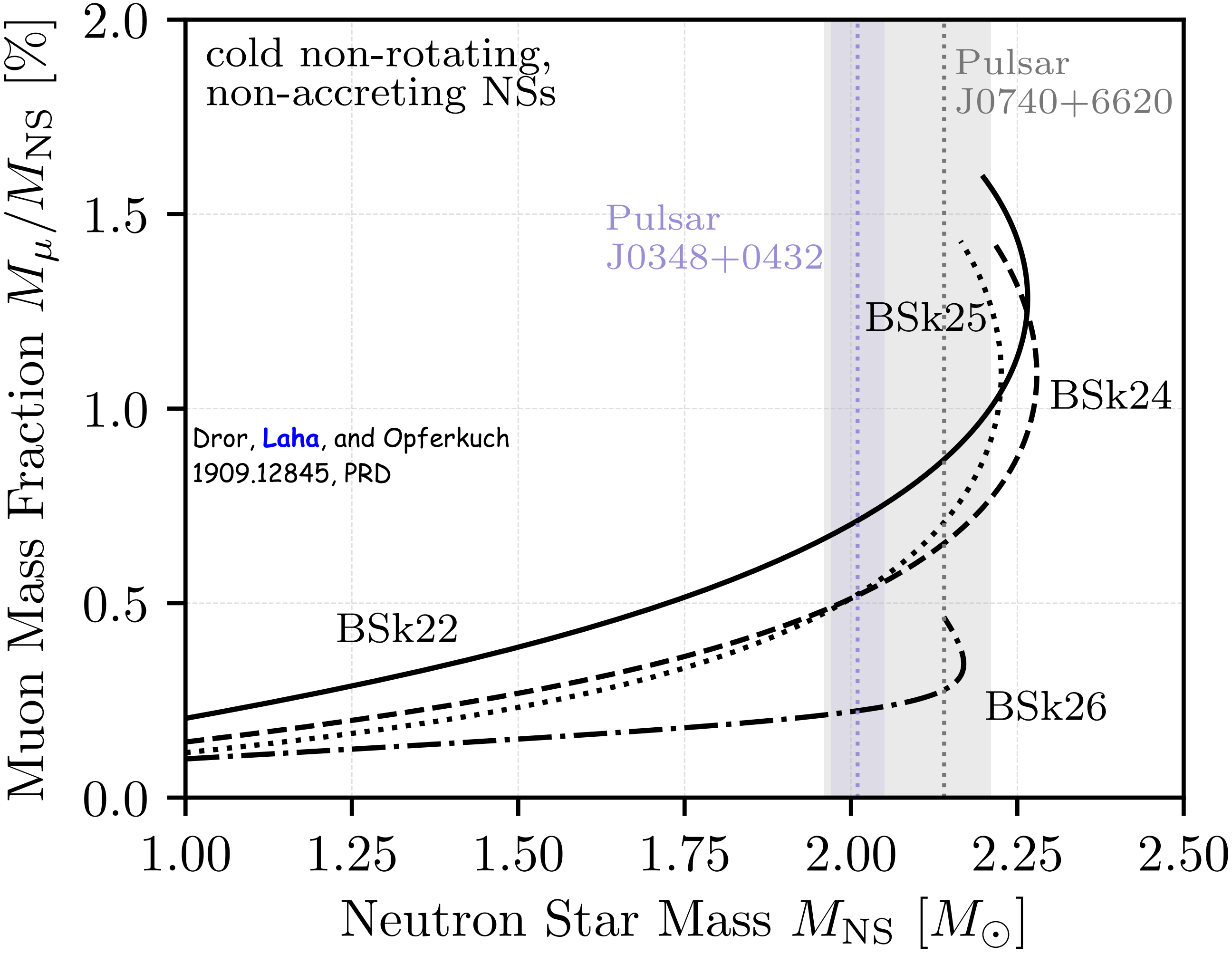
Muons inside neutron stars

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



Dror, Laha, and Opferkuch 1909.12845, PRD

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

A new Yukawa force (attractive/ repulsive)

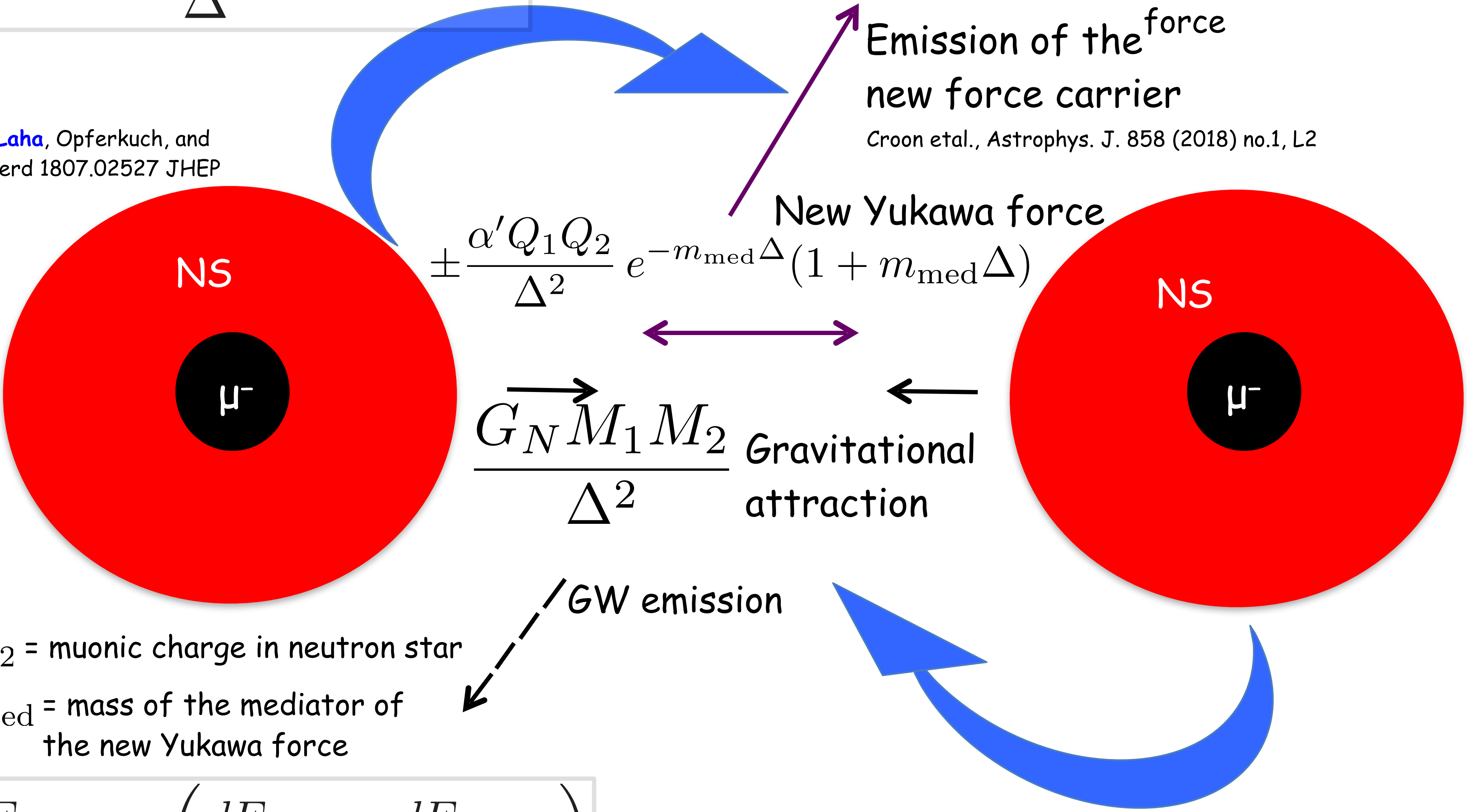
$$|V| = \frac{\alpha' Q_1 Q_2}{\Delta} e^{-m_{\rm med}\Delta}$$

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

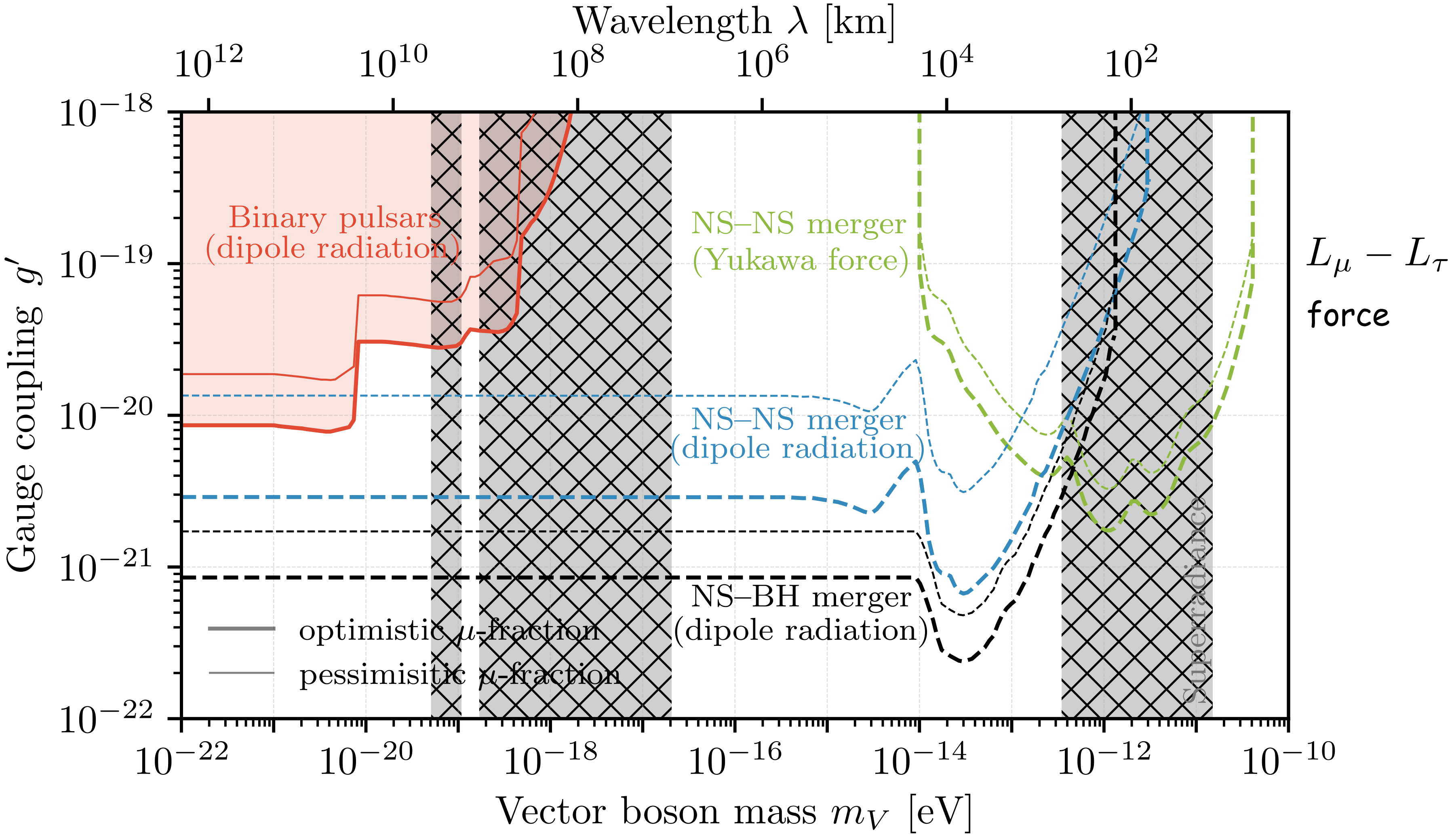
$Q_{1,2}$ = muonic charge in neutron star

$m_{\rm med}$ = 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
Phys. Rev. D 102 (2020), 023005

Probing long-range muonic interactions



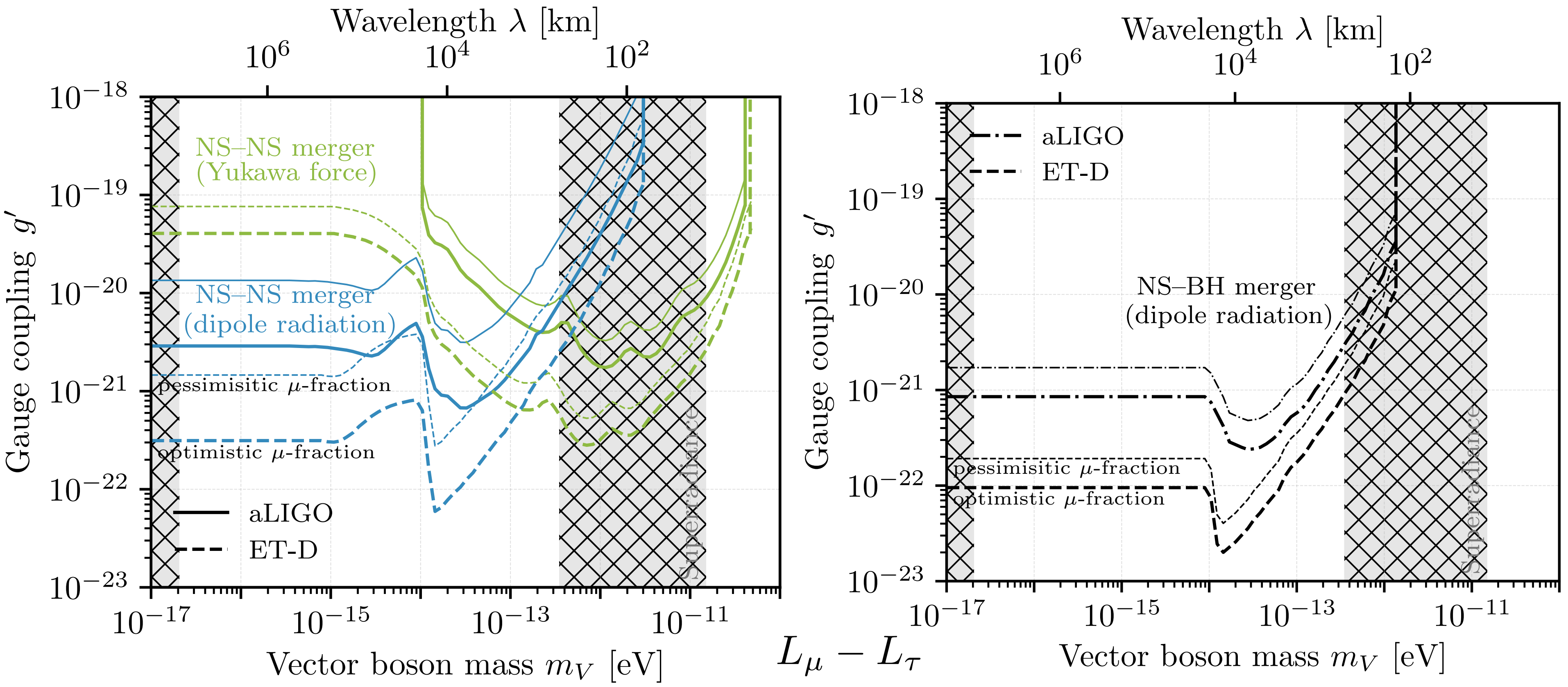
Huge discovery potential on exotic long-range forces due to muons

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

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

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
Phys. Rev. D 102 (2020), 023005

Dark photon dark matter search at gravitational wave detectors

Pierce, Riles, and Zhao
Phys. Rev. Lett. 121 (2018), 061102
1801.10161

Guo, Riles, Wang, and Zhao
Commun.Phys. 2 (2019) 155
1905.04316

LVK collaboration
Phys. Rev. D 105 (2022), 063030
2105.13085

Dark photon dark matter search at gravitational wave detectors

- A dark photon is a massive spin-1 vector boson which can be a good dark matter candidate

- Addition of such a particle to the dark sector implies that there is a dark charge under which some Standard Model particles will be charged

- Let us denote the dark photon by A^{d}_{μ} : it either couples to baryons $U(1)_{\mathrm{B}}$ or baryon minus lepton number $U(1)_{B-L}$

$$\mathcal{L} = -\frac{1}{4} F^{\mathrm{d}\,\mu\nu} F^{\mathrm{d}}_{\mu\nu} + \frac{1}{2} m_A^2 A^{\mathrm{d}\,\mu} A^{\mathrm{d}}_{\mu} - \epsilon e J^{\mu} A^{\mathrm{d}}_{\mu}$$

LVK collaboration
Phys. Rev. D 105 (2022), 063030
2105.13085

$F^{\mathrm{d}}_{\mu\nu} = \partial_\mu A^{\mathrm{d}}_\nu - \partial_\nu A^{\mathrm{d}}_\mu$

m_A = dark photon mass

ϵ = strength of the particle/ dark photon coupling

J^μ = number current density of baryons or baryons minus leptons

coherence length $\ell_{\mathrm{coherence}} = \dfrac{2\pi}{m_A v_0} \approx 3 \times 10^6\,\mathrm{km} \left(\dfrac{4 \times 10^{-13}\,\mathrm{eV}}{m_A}\right) \left(\dfrac{10^{-3}}{v_0}\right)$

Dark photon dark matter search at gravitational wave detectors

- Within a coherence length $A_\mu(t,\,\mathbf{x}) \approx A_{\mu,0}\sin(m_A t - \mathbf{k}\cdot\mathbf{x})$

- This dark photon will source a dark electric field that will produce an acceleration of the LIGO-Virgo Kagra mirrors; resulting in a displacement of these objects

$$\mathbf{a}_i(t,\,\mathbf{x}_i) = \frac{\mathbf{F}_i(t,\mathbf{x}_i)}{M_i} \approx \epsilon e \frac{q_{\mathrm{D},i}}{M_i}\partial_t \mathbf{A}(t,\mathbf{x}_i) = \epsilon e \frac{q_{\mathrm{D},i}}{M_i} m_A \mathbf{A}_0 \cos(m_A t - \mathbf{k}\cdot\mathbf{x}_i)$$

$\mathbf{x}_i$ = position of the test mass

M_i = total mass of the test object

$q_{D,i}$ = dark charge of the test object

For $U(1)_{\mathrm{B}}$, dark charge is the total baryon number

For $U(1)_{B-L}$, dark charge is the number of neutrons in the material

Pierce, Riles, and Zhao
Phys. Rev. Lett. 121 (2018), 061102
1801.10161

LVK collaboration
Phys. Rev. D 105 (2022), 063030
2105.13085

Dark photon dark matter search at gravitational wave detectors

- The different accelerations experienced by the mirrors (due to different phases) cause an effective strain $\sqrt{\langle h_D^2 \rangle} \approx 6.5 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}} \right) \left(\frac{100\,\mathrm{Hz}}{f_0} \right)$

- Common motion of the interferometer mirrors due to the dark matter background can lead to an apparent differential strain $\sqrt{\langle h_C^2 \rangle} \approx 6.5 \times 10^{-26} \left(\frac{\epsilon}{10^{-23}} \right)$

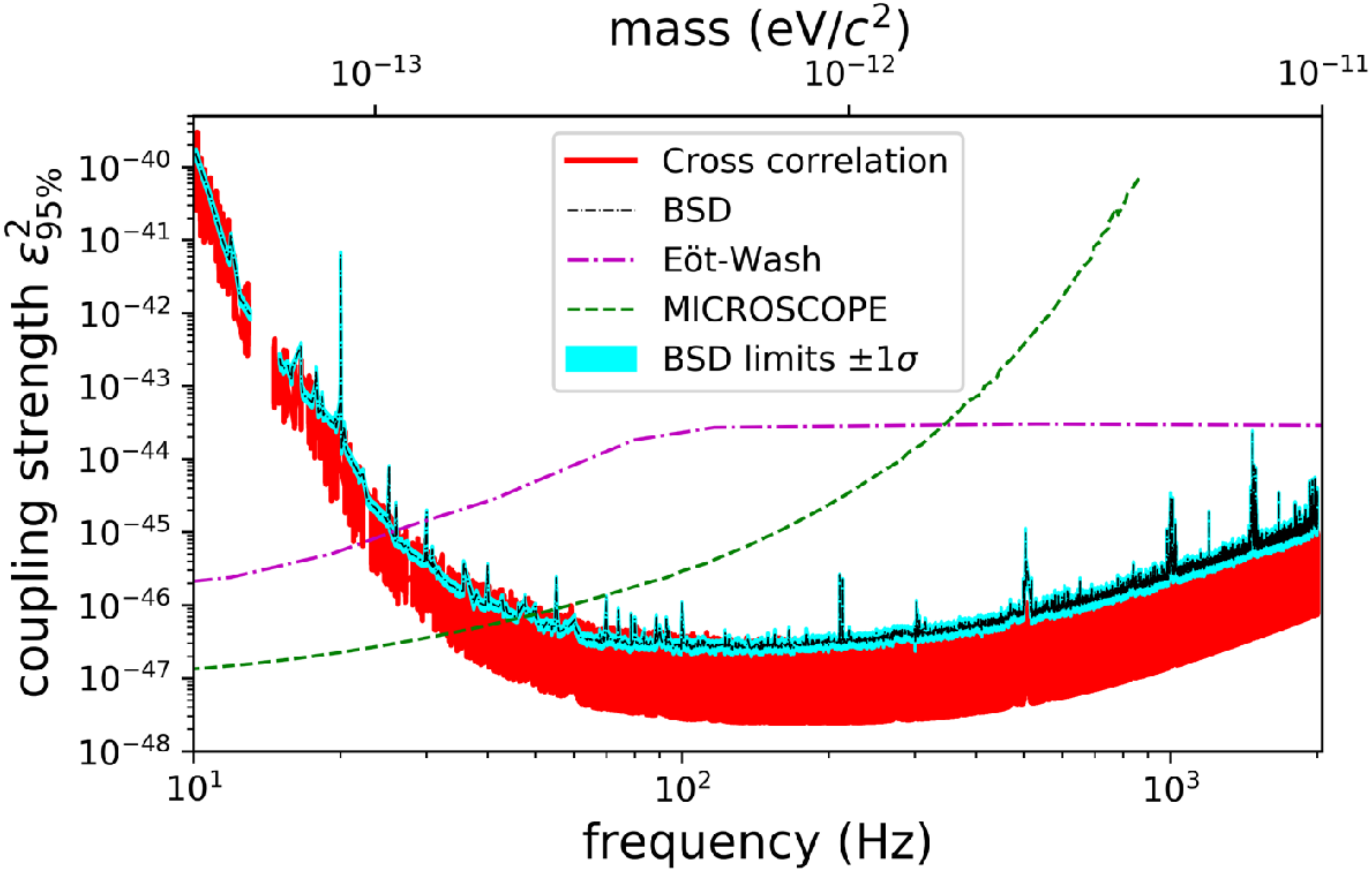
- Total effective strain $\langle h_{\mathrm{total}}^2 \rangle = \langle h_D^2 \rangle + \langle h_C^2 \rangle$

- Two different analyses are performed by the LIGO Virgo Kagra collaboration to probe this dark matter candidate: direct detection of dark matter

Pierce, Riles, and Zhao
Phys. Rev. Lett. 121 (2018), 061102
1801.10161

LVK collaboration
Phys. Rev. D 105 (2022), 063030
2105.13085

Dark photon dark matter search at gravitational wave detectors



Upper limits on dark photon - baryon $U(1)_{\mathrm{B}}$ coupling

LVK collaboration
Phys. Rev. D 105 (2022), 063030
2105.13085

Conclusions

- Gravitational wave observatories can probe beyond the Standard Model physics
- A large number of science cases
- I discussed three science cases: (i) probe of dark matter - nucleon cross-section, (ii) probe of new muon - coupled force, and

  (iii) probe of dark photon dark matter
- Many other sciences cases exist which can probe beyond the Standard Model scenarios
- Promising cases for ground-breaking discovery

Questions & comments: ranjanlaha@iisc.ac.in