# Gravitational probes of Exotic Compact Objects

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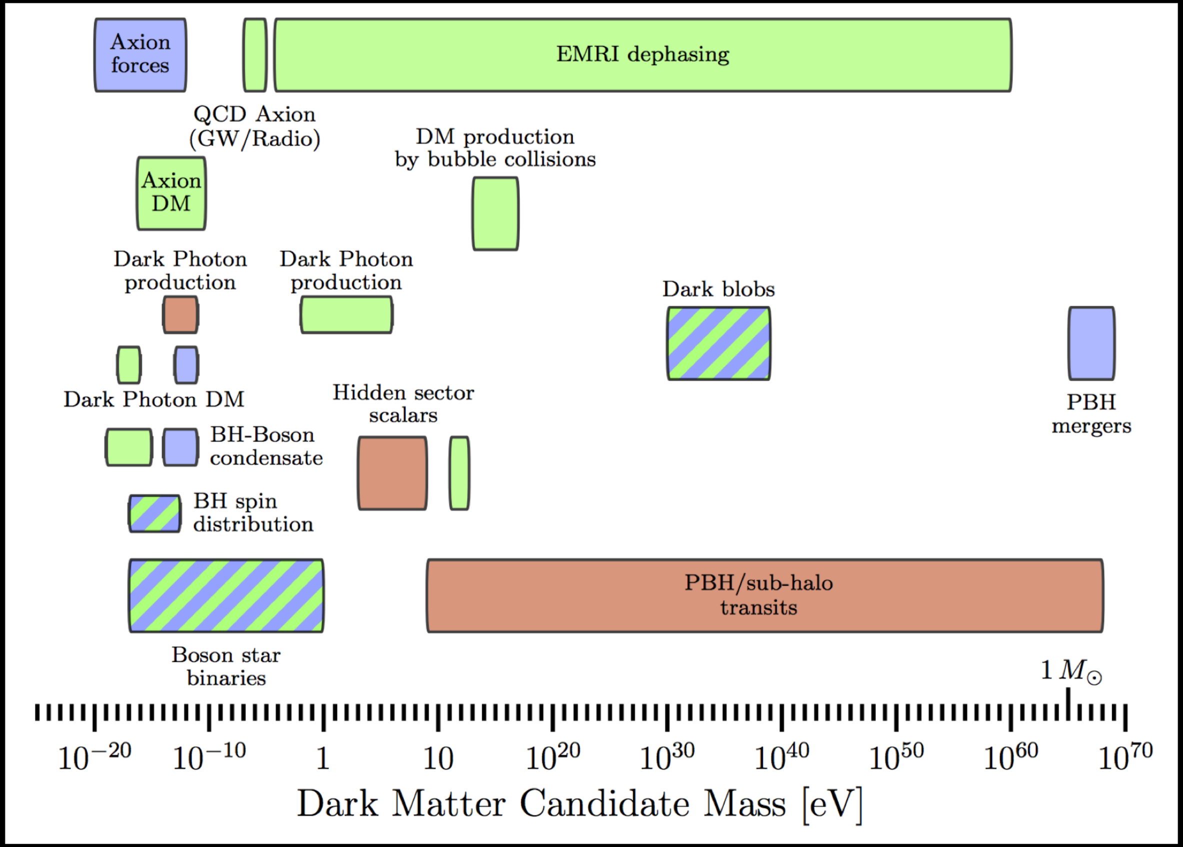
Largely based on
many papers cited explicitly
on the slides ☺

# Gravitational waves shed (no) light on Dark Matter

- *Dark Matter (DM) interacts gravitationally*
- We should fully exploit this interaction!

- GW experiments can probe a wide range of hidden sectors and Dark Matter candidates
- Complementary to other experimental probes: colliders, direct and indirect detection




*Bertone, DC, Amin, Boddy, Kavenagh, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu [arXiv:1907.10610]*

# Exotic compact objects (ECOs)

- Many (DM) models predict small-scale structure. An incomplete list:
  - Primordial black holes ← Bradley Kavenagh's talk
  - Axion (ALP) mini-clusters
  - Boson stars / solitons ← Helvi Witek's, Eugene Lim's talk
  - Dark blobs
  - Dark matter inside NSs or BHs/DM atmospheres
  - Mirror stars
- … And so do some theories of gravity ← Paolo Pani's talk

- *We will have experimental access to many such models in the very near future*

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*Bradley's talk*

- *We will have experimental access to many such models in the very near future*

In the #GW4FP spirit of two-dimensional parameter spaces, I will focus on ECO mass and compactness

# Binary merger events ($M_1 \approx M_2$)

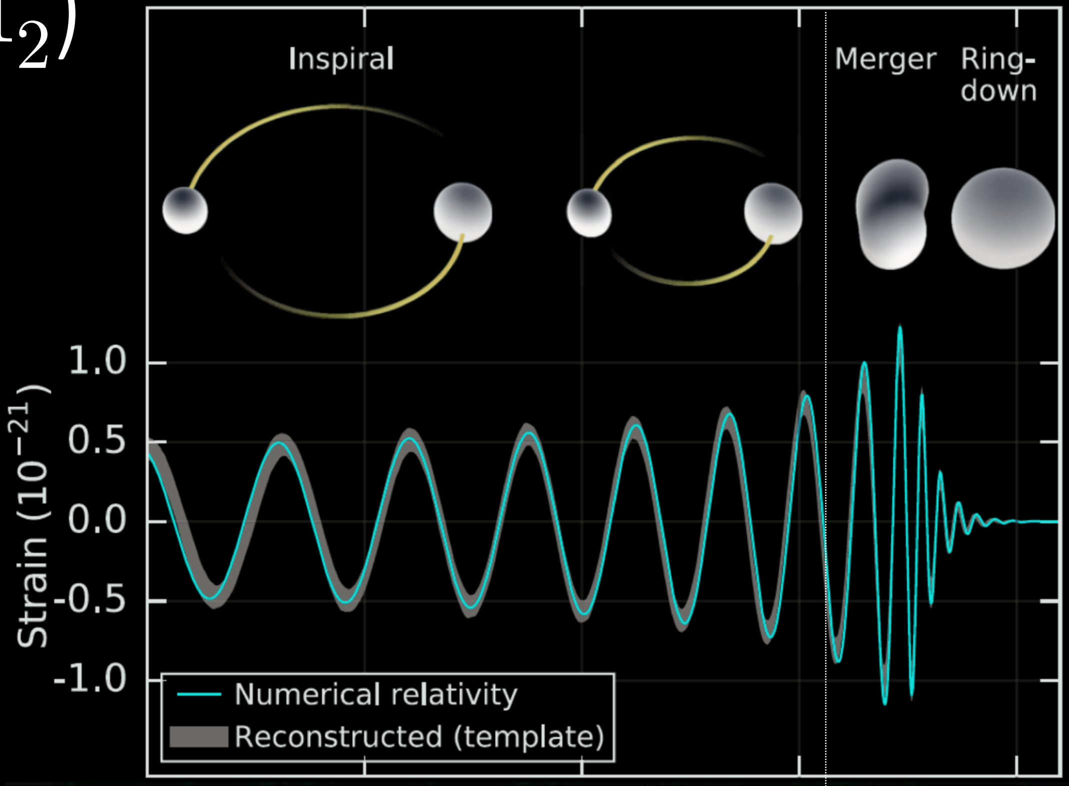
- Most GW radiation from the inspiral phase
  - Ends in $f_{\rm ISCO}$ ~ peak frequency
- Solvable in a PN expansion $(v/c)$
  → Weak gravity, small velocity

"Chirp" signal

$$f(t) = \frac{5^{3/8}}{8\pi}(G_N m_c)^{-5/8} t^{-3/8}$$

$$m_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

$$h_c \sim m_c^{5/3} f^{2/3}/r$$

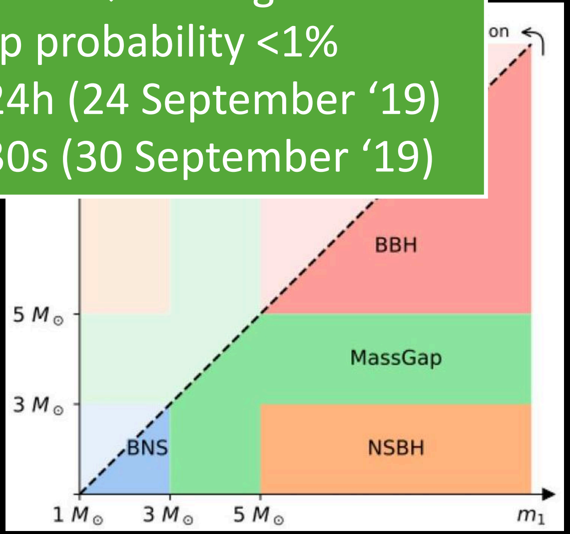



LIGO/Virgo have detected $11+x$ $(x > 30)$ such merger events

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)}$$

# How to distinguish ECO mergers?

Hints or mass-gap mergers:
- S190814bv → downgraded mas gap probability <1%
- S190924h (24 September '19)
- S190930s (30 September '19)




1. Component masses
2. Tidal effects
3. Long-range (dark) forces
4. Extra dissipation channels (dipole radiation)
5. Redshift distribution
6. Multi-messenger signals (or absence thereof)
7. "Hair": multipolar metric deviations + EMRIs *E.g. Raposo, Pani, Emparan [PRD, arXiv:1812.07615]*
8. Post-merger QNM or "echoes"

*e.g. for boson stars: Palenzuela, Pani, Bezares, Cardoso, Lehner, Liebling [PRD, arXiv:1710.09432], Helfer, Lim, Garcia, Amin [PRD, arXiv:1802.06733]*

Paolo Pani's talk on Monday
Eugene Lim's talk today

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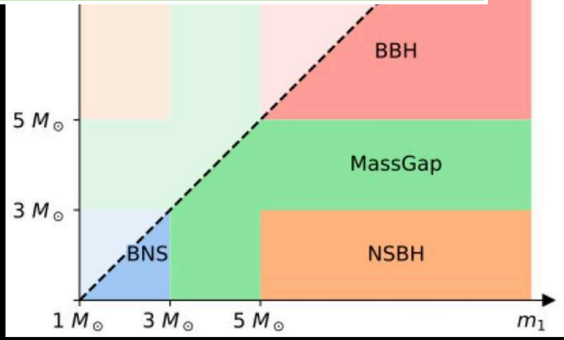


# ECO merger sensitivity

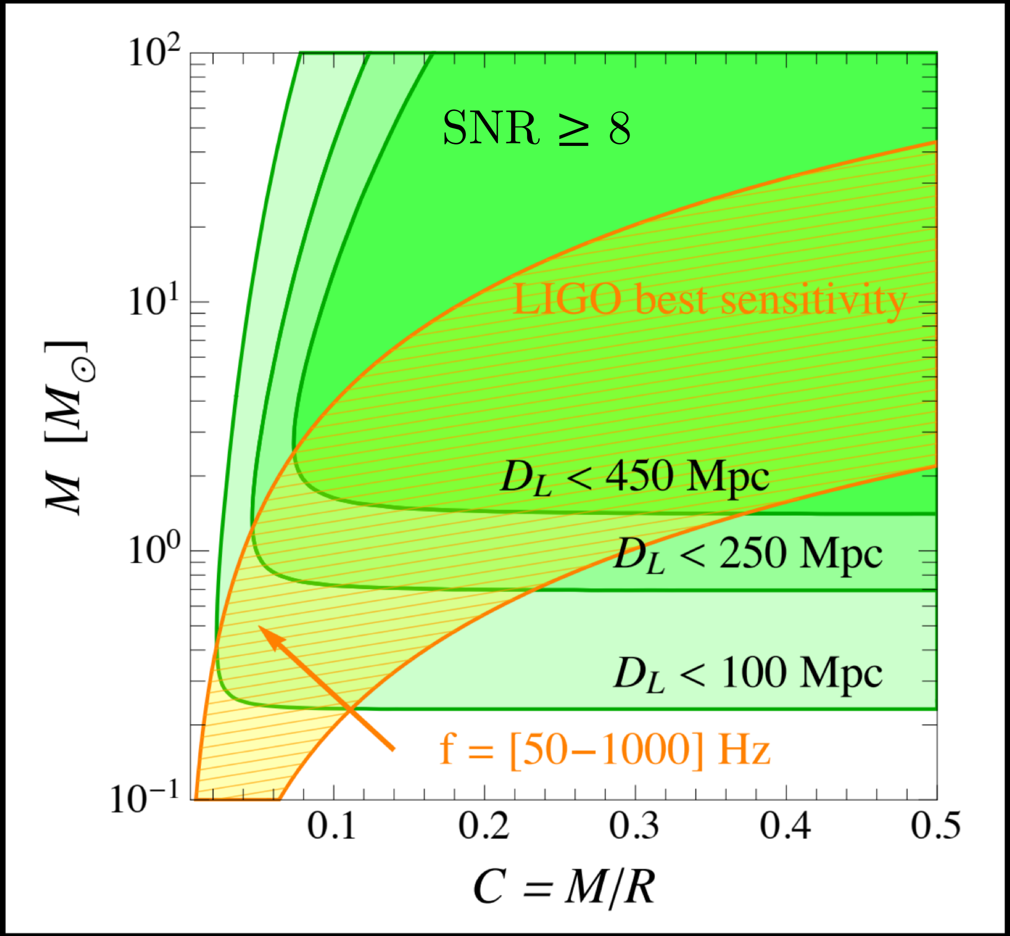
- Best detection prospects for $f_{\rm min} < f_{\rm peak} \sim f_{\rm ISCO} < f_{\rm max}$
- May define an ECO sensitivity band

$$C_* = \frac{G_N M_*}{R_*}$$

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)}$$

- Sensitivity determined by masses, compactness and luminosity distance

$$\boxed{\begin{array}{ll} C_\odot = 2\times 10^{-6} & C_{\rm BH} = 0.5 \\ C_\oplus = 7\times 10^{-10} & C_{\rm NS} \sim 0.1 \end{array}}$$




*Giudice, McCullough, Urbano [JCAP, 1605.01209]*

# Example: boson stars

- Macroscopic Bose-Einstein condensates (BEC)
  - Ultralight NR scalars with overlapping wave functions → many-body system with a single wave function
  - Stabilized against gravitational collapse by kinetic pressure or a repulsive self-interaction
- Solve a simple system of equations to find the mass profile:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi^* \nabla_\nu \phi - \frac{1}{2} m^2 |\phi|^2 - \frac{\lambda}{4} \left( \frac{m^2}{f^2} \right) |\phi|^4$$

$$ds^2 = B(r) dt^2 - A(r) dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

Ansatz: the ground-state is spherically symmetric $\phi(r,t) = \Phi(r) \mathrm{e}^{-i\mu t}$

Einstein equations + Klein-Gordon equation for $\mathrm{A}$, $\mathrm{B}$, and $\Phi$

NR limit: Schroedinger-Newton (but may miss effects, see *DC, J. Fan, C. Sun, [JCAP, 1810.01420]*)

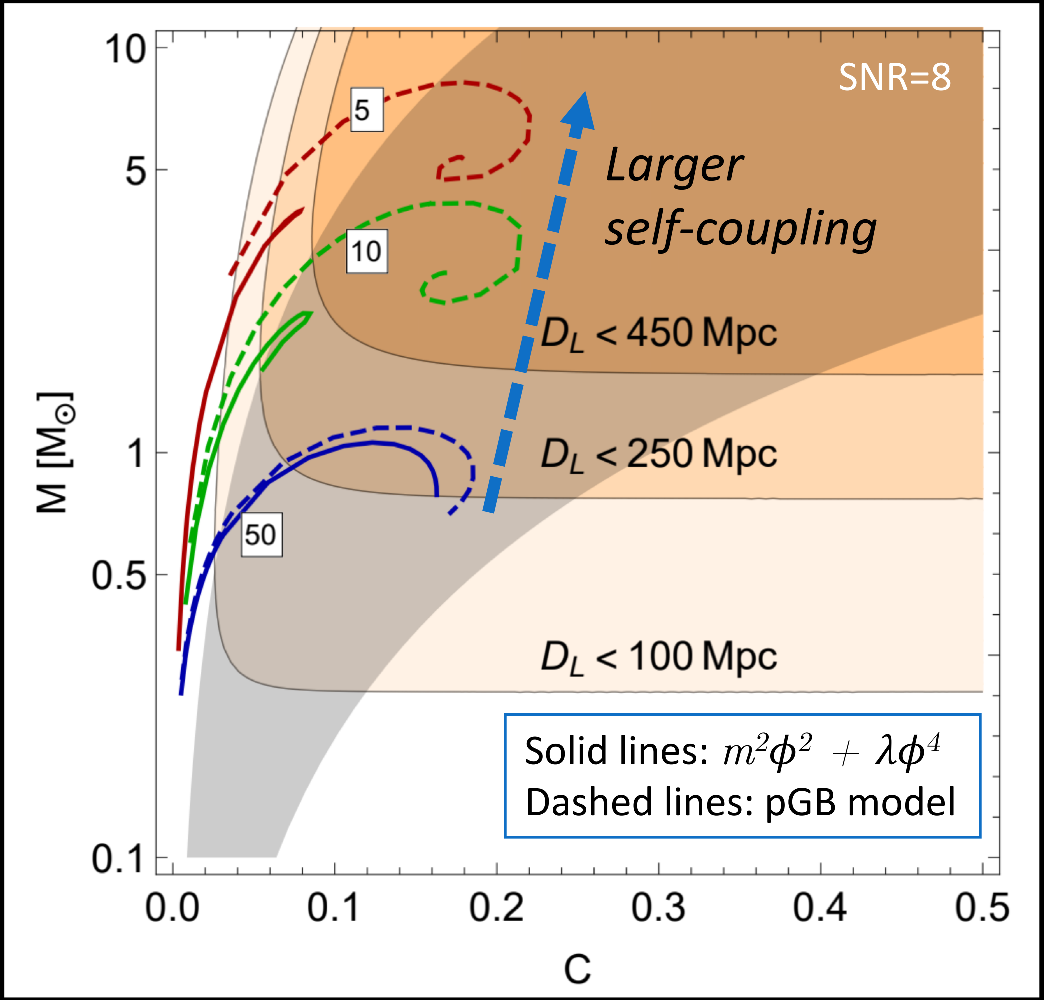
# Example: boson stars

- Numerical stable stable solutions for $(M{=}M_{ADM},\ R{=}R_{90})$ indicate

$$\left.\begin{aligned} R_{\max} &\propto \sqrt{\lambda}\,\frac{M_p}{m^2} \\ M_{\max} &\propto \sqrt{\lambda}\,\frac{M_p^3}{m^2} \end{aligned}\right\} C_{\max} \sim 0.1 - 0.2$$

*See also first study by Colpi, Shapiro, Wasserman [PRL, 1987]*

- Ultralight pGB have effective higher order interactions, resulting in a smaller maximum compactness




*DC, Fan, Sun, [JCAP, 1810.01420]*

*See also Helfer, Marsh, Clough, Fairbain, Lim, Becceril [JCAP, arXiv:1609.04724]; Schiappacasse, Hertzberg [arXiv:1710.04729]*

# Example: fermion stars

- Chandrasekhar mass $\mathrm{M} \lesssim \mathrm{M_p}^3/\mathrm{m}^2$
- Fermion star radius
  - From Landau argument $\mathrm{R}\sim \mathrm{M_p}/\mathrm{m}^2$
  - From Tolman–Oppenheimer–Volkoff (TOV)-equation, $\mathrm{C}\sim 0.1$

Gravitational energy (Newtonian) = Fermi energy of the degenerate Fermi gas (*Landau, 1932*)

*e.g. Narain, Schaffner-Bielich, Mishustin [PRD, arXiv:0605724]*

- May exist in "mirror world" models

*e.g. Berezhiani [IJMP, arXiv:0312335]*
*Curtin, Setford [arXiv:1909.04071]*

- Typically, coupling to dark radiation is needed to allow for enough cooling to collapse into a dark NS

→ Strong constraint on relic abundance of DM interacting with (dark) radiation from dark acoustic oscillations (DAO): $< 5\%$ of total DM

*Cyr-Racine, Raccanelli, de Putter, Sigurdson [PRD, arXiv:1310.3278]*

# Tidal effects

quadrupole moment

external quadrupolar tidal field

- Tidal effects depend on the tidal Love number

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

- GW phase shift due to tidal deformability

$$\left.\begin{aligned}\Lambda &= \frac{1}{26}\left(\left(1+\frac{12}{q}\right)\lambda_1 + (1+12q\lambda_2)\right)\\ q &= M_1/M_2 \geq 1\end{aligned}\right\}$$

$$\delta\Psi = -\frac{117}{8}\frac{(1+q)^2}{q}\frac{\Lambda v^5}{(M_1+M_2)^5}$$

Correction to the GW phase at 5PN

*Flanagan, Hinderer [PRD, arXiv:0709.1915]*

- A way to distinguish (for example)
  - Neutron star equation of state — *e.g. Hinderer, Lackey, Lang, Read [PRD, arXiv:0911.3535]*
  - Objects with $\mathrm{C}<0.5$ — *e.g. boson stars: Sennet, Hinderer, Steinhoff, Buonanno, Ossokine [PRD, arXiv:1704.08651]; in EMRIs: Guo, Sinha, Sun [JCAP, arXiv:1904.07871]*
  - Neutron star atmospheres — *e.g. Nelson, Reddy, Zhou [JCAP, arXiv:1803.03266]*
  - Black hole mimickers (ClePhOs) — *e.g. Pani, Maselli [IJMPD, arXiv:1905.03947]*

DC, Nelson, Sun, Walker, Xianyu
[ApJ, arXiv:1711.02096]

# New forces and extra dissipation

Imagine an asymmetric dark sector with a light mediator. What happens if DM collects inside a NS?

- Long-range interactions:
  - Modified frequency from Yukawa potential
  - Switches on from $r \sim m_V^{-1}$
  - Can be interpreted as a modified chirp mass $m_c$

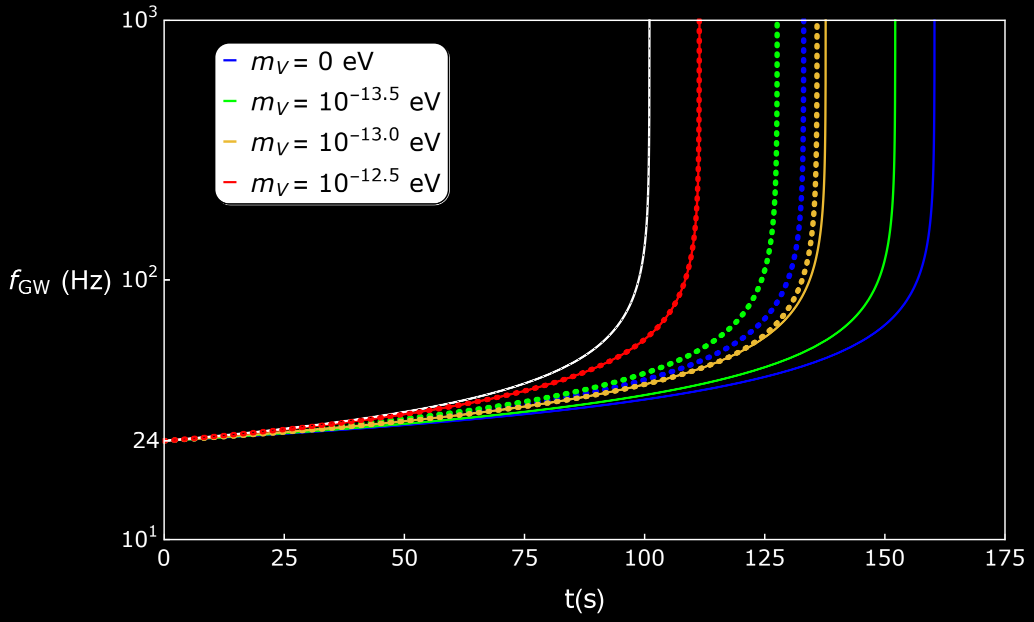
$$\omega^2 = \frac{Gm}{r^3}\left(1 - \tilde{\alpha}' e^{-m_V r}\right),$$

$$\tilde{\alpha}' \equiv \frac{\alpha' q_1 q_2}{G m_1 m_2}$$

- Extra dipole radiation:
  - For unequally charged NS, a dark dipole moment is generated
  - Dark radiation dissipates for light mediator $m_V c/\omega < 1$

$$\dot{E} = -\left(\underbrace{P_{GW}}_{\text{quadrupole}} + \overbrace{P_{dark}}^{\text{dipole}}\right)$$

# Example: dark U(1)

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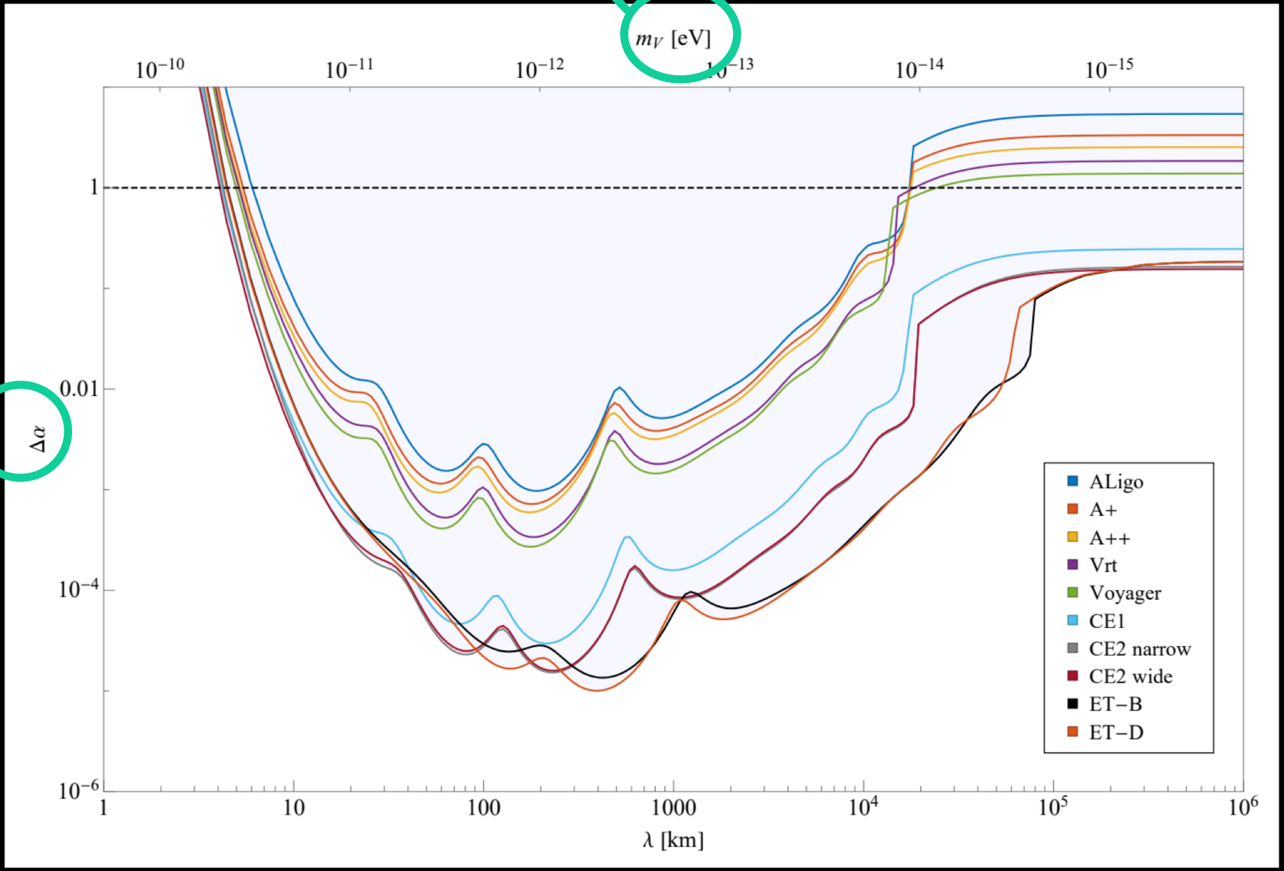
Mediator mass




Effective coupling

$$\tilde{\alpha}' \equiv \frac{\alpha' q_1 q_2}{G m_1 m_2}$$

*See also Ranjan Laha's talk yesterday for constraints on $L_\mu$ - $L_\tau$*

*From Alexander, McDonough, Sims, Yunes, [CQG, arXiv:1808.05286]*
*See also Kopp, Laha, Opferkuch, Shepherd [JHEP, arXiv:1807.02527]*

# Binary Merger Rate

$$R_m(t, M_*, f_{\rm BBS}) = \int_{\Delta t_{min}}^{\Delta t_{max}} R_{\rm BBS}(t - \Delta t, M_*)\, p(\Delta t)\, d\Delta t.$$

Binary formation rate

For example, could assume the ECO formation rate tracks the luminous star formation rate and the binary formation rate tracks the ECO formation rate, i.e.

$$R_{\rm BBS}(z_f, M_*) = f_{\rm BBS} \times {\rm SFR}(z_f, M_*).$$

Strongly depends on formation history (experimental access to higher redshifts with next gen GW detectors) and clustering

Time delay distribution

Probability that two stars initially separated by $a$ are gravitationally bound:

$$p(a) = \binom{N(a)}{2}^{-1} = \frac{2}{N(a)(N(a)-1)} \propto a^{-6}$$

$$N(a) = \rho \pi a^3/6$$

$$\Delta t \sim a^4$$

*Inspiral phase*

*DC, Gleiser, Mohapatra, Sun [PLB, arXiv:1802.08259]*

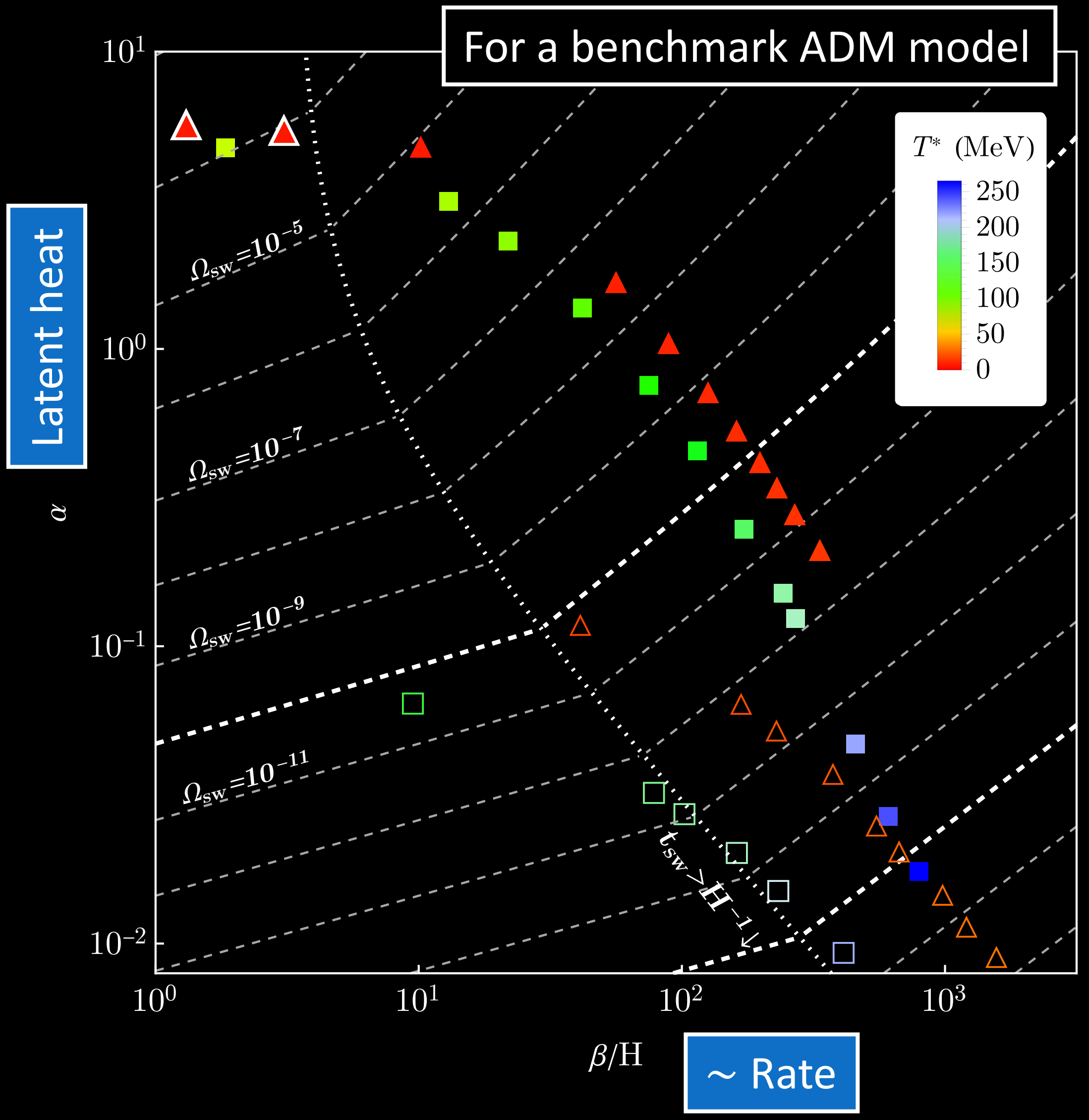
DC, Kusenko, Mazumdar, White
[arXiv:1910.09562]

# Bonus: solitosynthesis

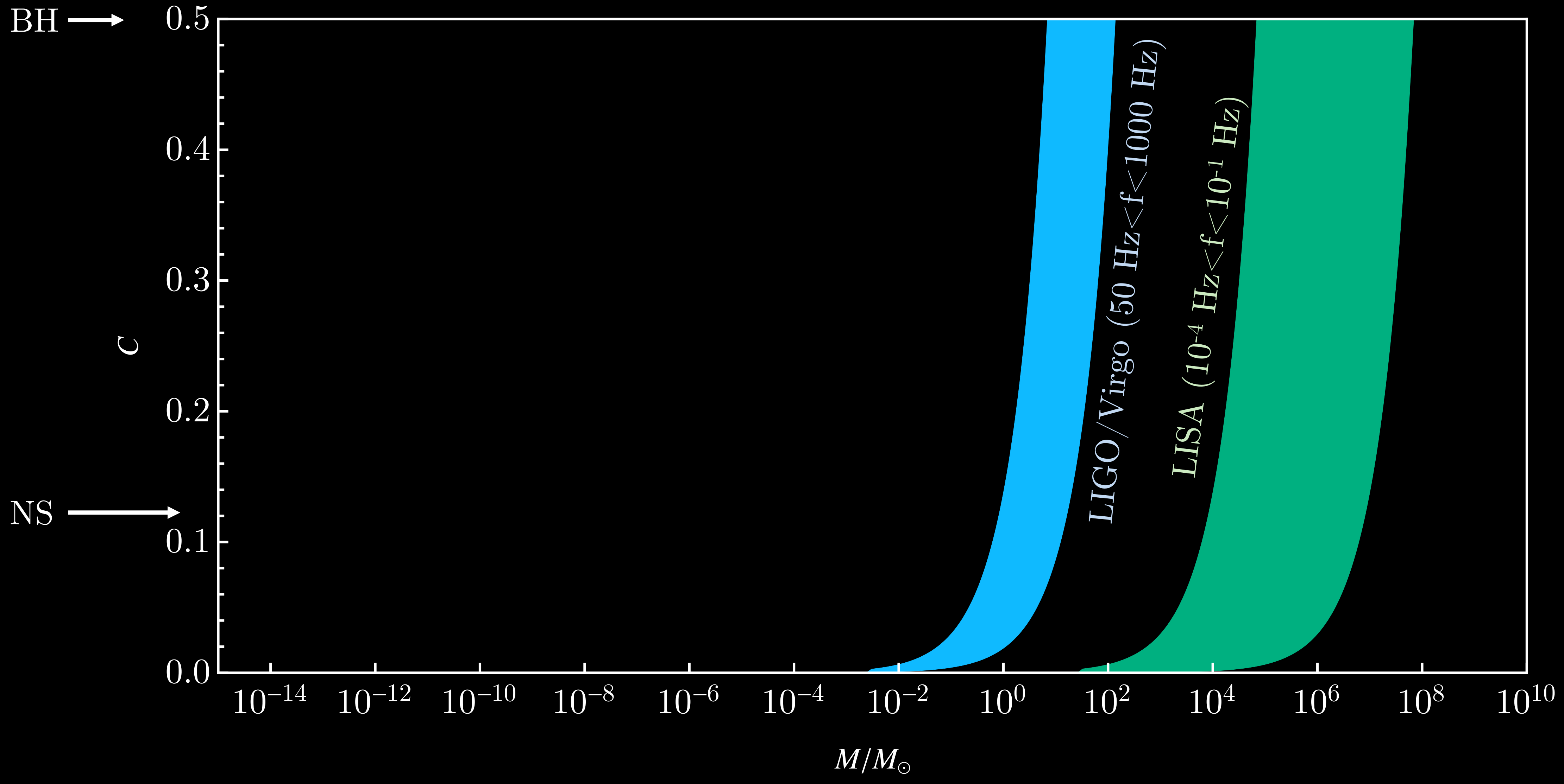
- Q-balls may give rise to inhomogeneous phase transitions
  - Q-balls lower their free energy by means of a scalar condensate
  - For a critical charge $Q_c$ it becomes energetically favored to expand

*e.g. Kusenko [PLB, arXiv:9705361], Postma [PRD, arXiv:0110199]*

- Solitonic PTs source GW efficiently
  - Effective nucleation rate from charge accretion (solitosynthesis) → slow
  - Typically, supercooled → large latent heat



# Gravitational probes of ECO dark matter



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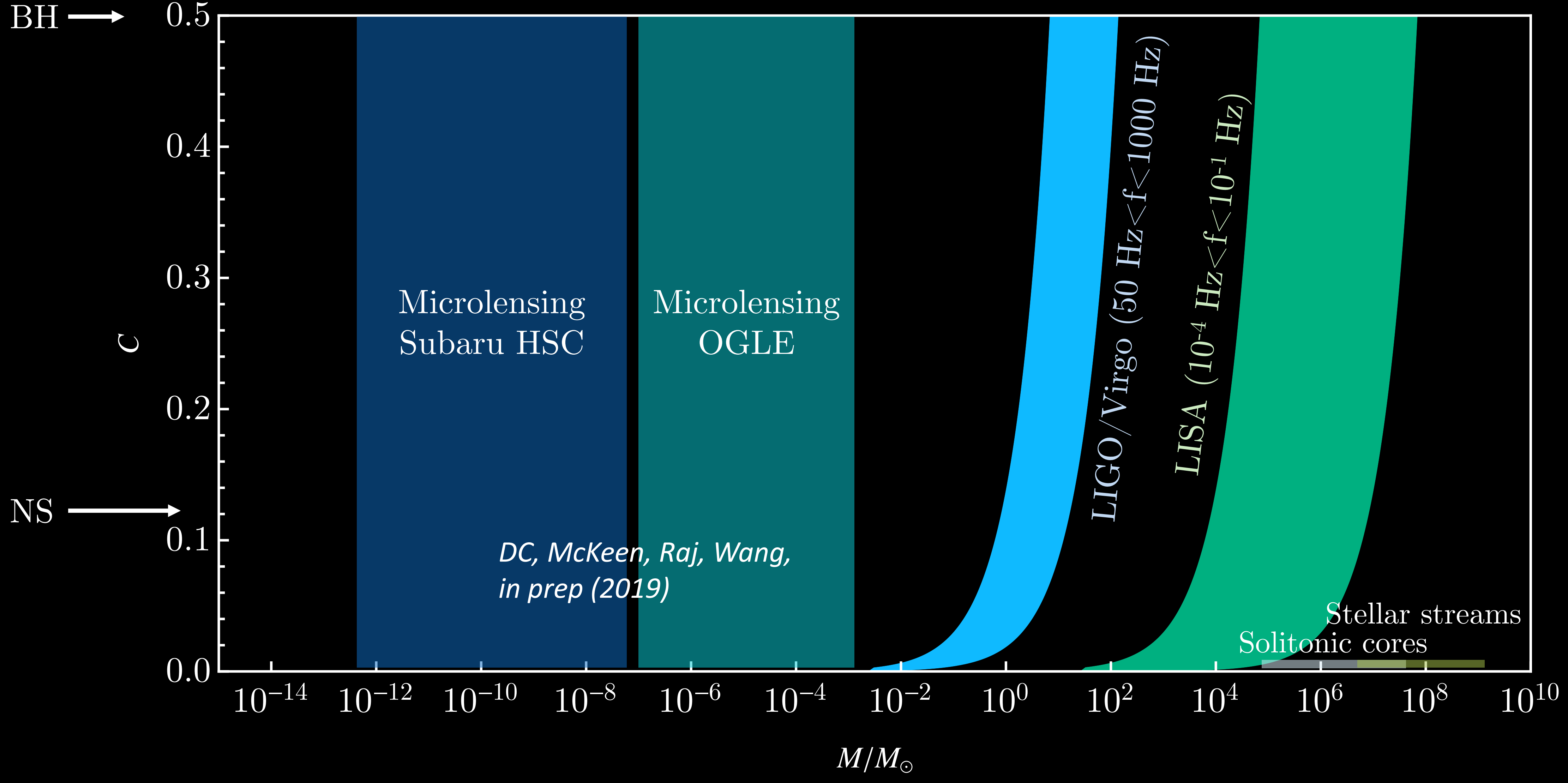


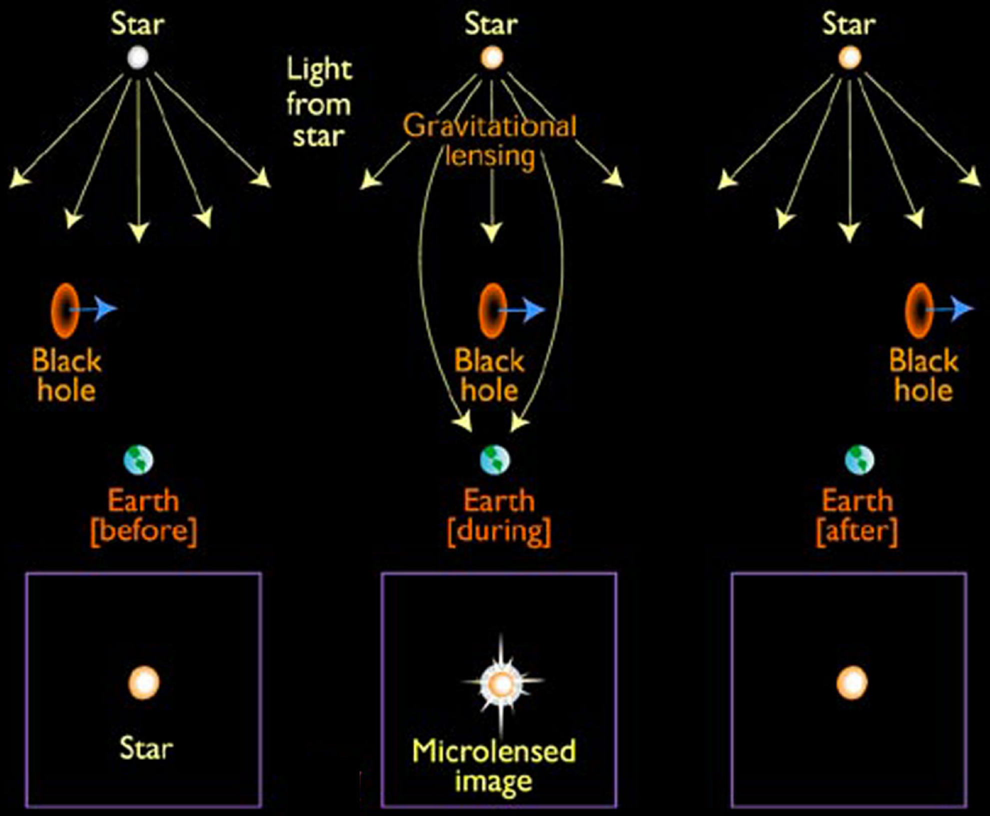
# Other gravitational probes: microlensing

- Temporary increase in brightness due to passing ECO-lens
- Einstein radius:

$$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}}$$

Defines a lensing tube within which $\mu \geq 1.34$ (depends on mass and distances)

- Sensitivity to ECOs depends on $\mathrm{D_L}$ and temporal resolution
  - HSC/Subaru: $\{10^{-12}, 10^{-8}\}\ \mathrm{M}_\odot$
  - EROS: $\{10^{-6}, 10^{-1}\}\ \mathrm{M}_\odot$




*DC, McKeen, Raj, Wang, in prep (2019)*

# Other gravitational probes: microlensing

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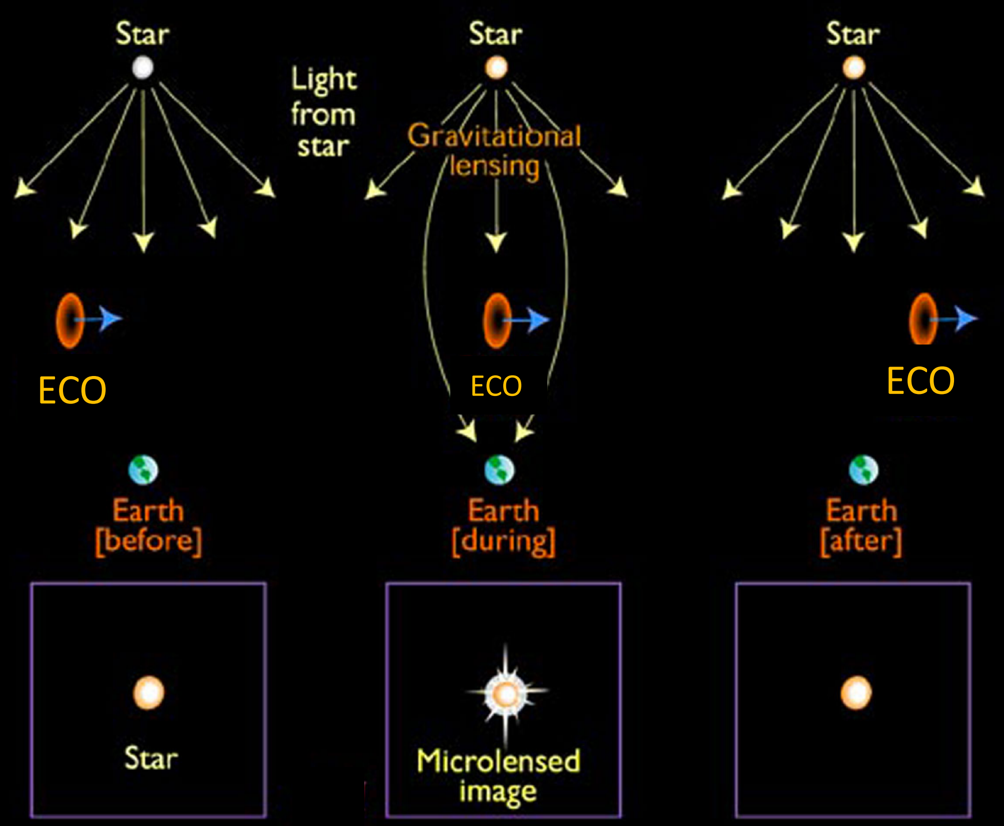
$$R'_E = \mathcal{R}(M, R, \ldots)\sqrt{\frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}}$$

Defined by requiring $\mu \geq 1.34$ as for $R_E$ for a point-like lens

- Sensitivity to ECOs depends on $D_L$ and temporal resolution
  - HSC/Subaru: $\{10^{-12}, 10^{-8}\}\ M_\odot$
  - OGLE: $\{10^{-7}, 10^{-3}\}\ M_\odot$

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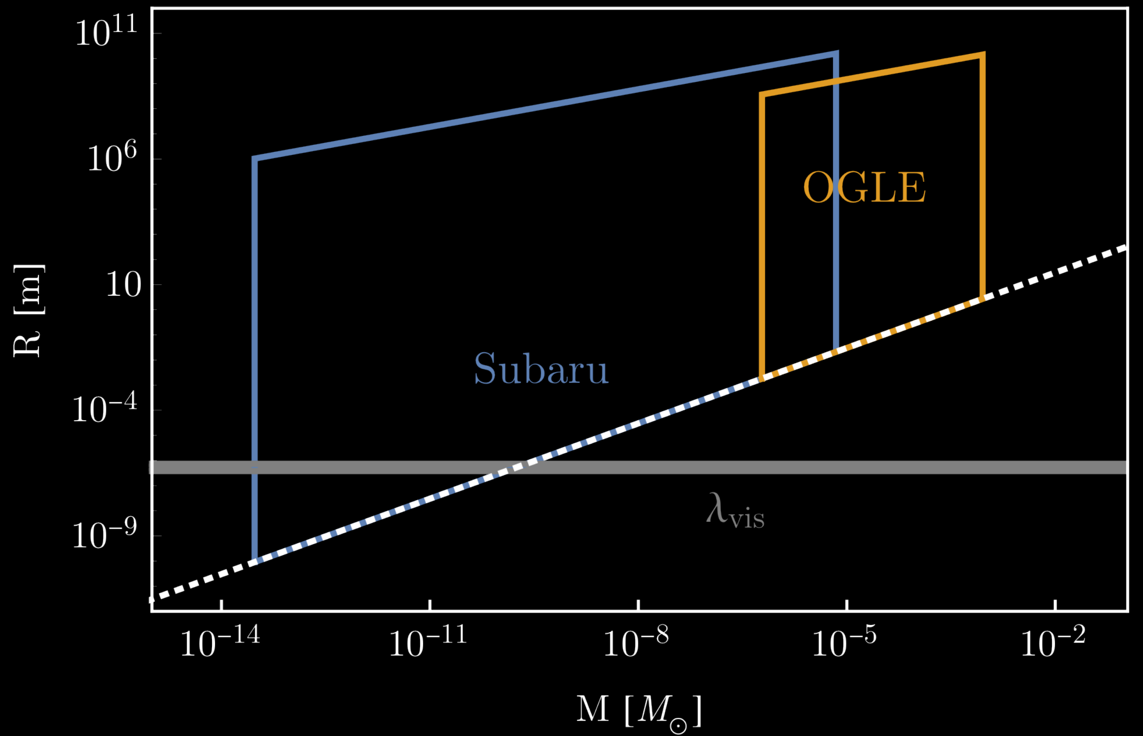


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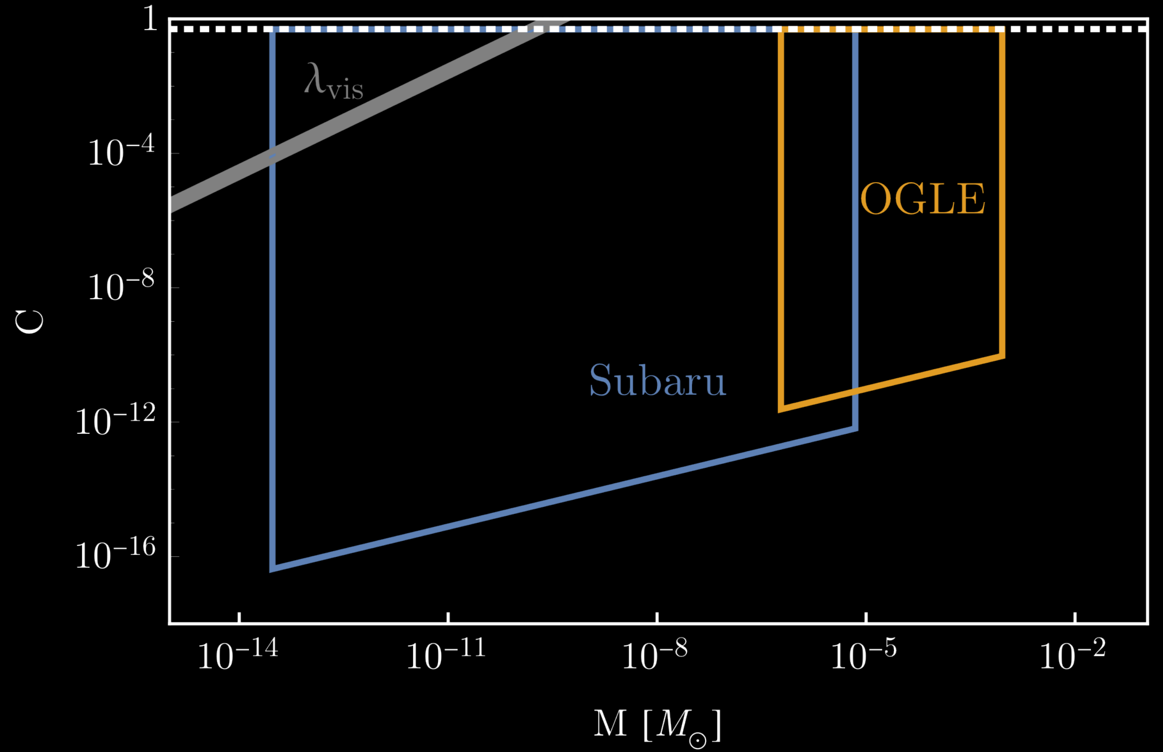


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# To conclude,

- Many models predict dark matter substructure and exotic compact objects (ECOs)

- We can probe ECOs using their gravitational interactions
- *Gravitational waves are exciting new probes of ECOs*

- Stay tuned: we will learn a lot more about DM substructure in the coming years!

Thank you!

# Back up slides

*DC, Nelson, Sun, Walker, Xianyu, ApJ, arXiv:1711.02096 [hep-ph]*

# Dark matter spectroscopy in BNS mergers

- A generic model of an interacting asymmetric dark sector,

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_V + \mathcal{L}_\chi + \mathcal{L}_{mix}, \quad \begin{cases} \mathcal{L}_V = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu \\ \mathcal{L}_\chi = \bar{\chi}\left(\gamma^\mu (i\partial_\mu - g' V_\mu) - m_\chi\right)\chi \,. \end{cases}$$

$$\alpha' = g'^2/4\pi$$

- Can produce observable features at LIGO for ultralight mediators,

$$m_V^{-1} = \{10\text{km}, 1000\text{km}\} \longleftrightarrow m_V = \{10^{-13}\text{eV}, 10^{-11}\text{eV}\}$$

# Stochastic Background (from binary mergers)

$$\boxed{\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}}$$

$$\Omega_{\rm GW}(f, M_*, f_{BBS}) = \frac{f}{\rho_c H_0}\int_0^{z_{max}} \frac{R_m(z, M_*, f_{\rm BBS})}{(1+z)\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\frac{dE}{df_s}\,dz$$

*LIGO, PRL 120, 091101*

# Stochastic Background (from binary mergers)

$$\boxed{\Omega_{\mathrm{GW}}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}}$$

*Observed frequency*

$$f_s = (1+z)f$$

*Merger rate*

$$\Omega_{\mathrm{GW}}(f, M_*, f_{BBS}) = \frac{f}{\rho_c H_0}\int_0^{z_{max}} \frac{R_m(z, M_*, f_{\mathrm{BBS}})}{(1+z)\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} \frac{dE}{df_s} dz$$

*Differential energy emitted by a single source*

*LIGO, PRL 120, 091101*