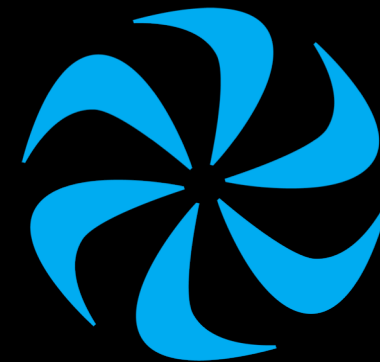




Gravitational probes of Exotic Compact Objects

Djuna Lize Croon (TRIUMF)

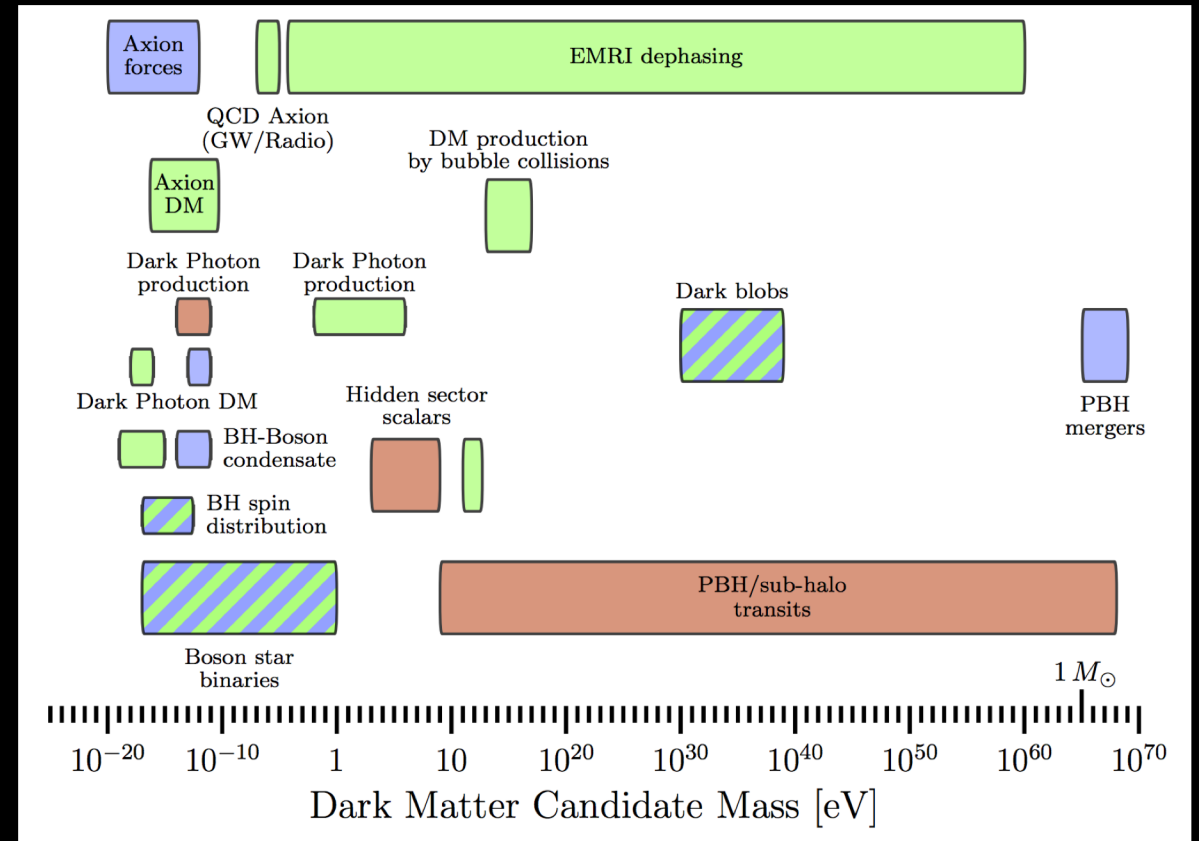
Dark Odyssey 2020 @Seoul, January 2020

dcroon@triumf.ca | djunacroon.com

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  Wei, Sunghoon's talks today
 - Axion (ALP) mini-clusters Ronggen, Chulmoon, Seongchan's talks tomorrow
 - Boson stars / solitons
 - Dark blobs
 - Dark matter inside NSs or BHs/DM atmospheres
 - Mirror stars
- ... And so do some theories of gravity
- *We will have **experimental access** to many such models in the **very near future***

Binary merger events ($M_1 \approx M_2$)

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

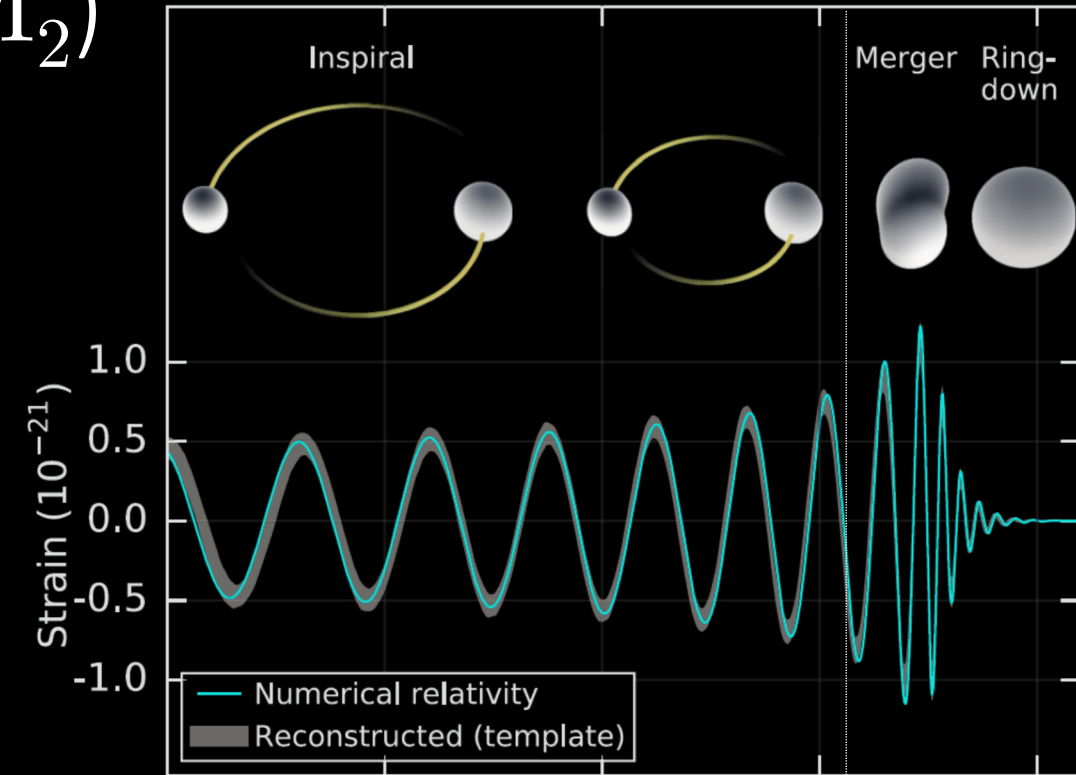
“Chirp” signal

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

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

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

LIGO/Virgo have detected $11+x$
($x > 40$) such merger events



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

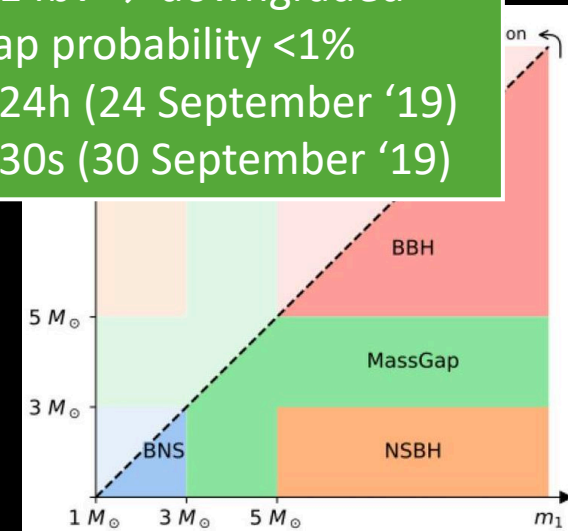
How to distinguish ECO mergers?

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
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]

Hints or mass-gap mergers:

- S190814bv → downgraded mas gap probability <1%
- S190924h (24 September ‘19)
- S190930s (30 September ‘19)



E.g. Raposo, Pani, Emparan [PRD, arXiv:1812.07615]

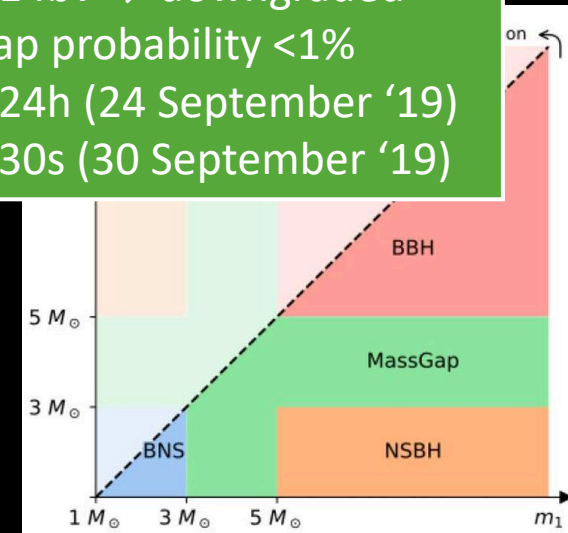
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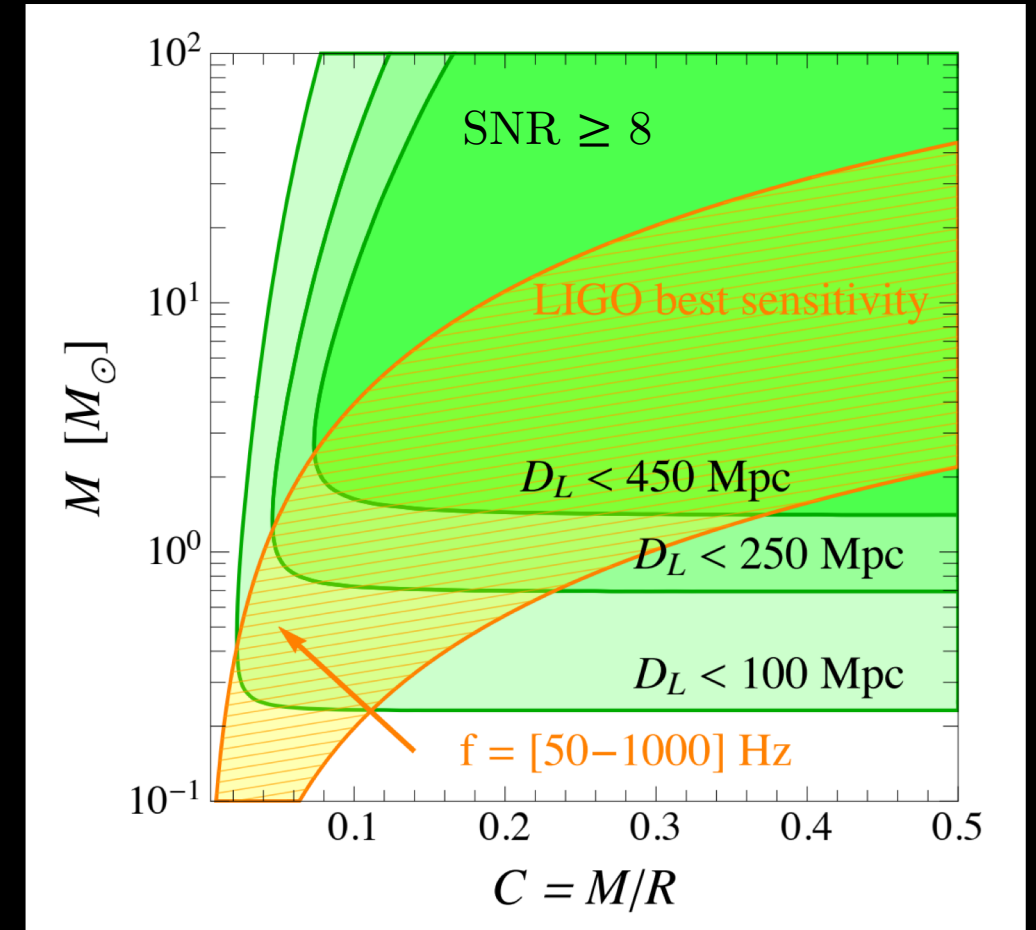
ECO merger sensitivity

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

$$f_{\text{ISCO}} = \frac{C_*^{3/2}}{3^{3/2} \pi G_N (M_1 + M_2)} \quad C_* = \frac{G_N M_*}{R_*}$$

- Sensitivity determined by masses, **compactness** and luminosity distance

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



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:

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

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

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

Einstein equations +
Klein-Gordon equation
for A, B, and Φ

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

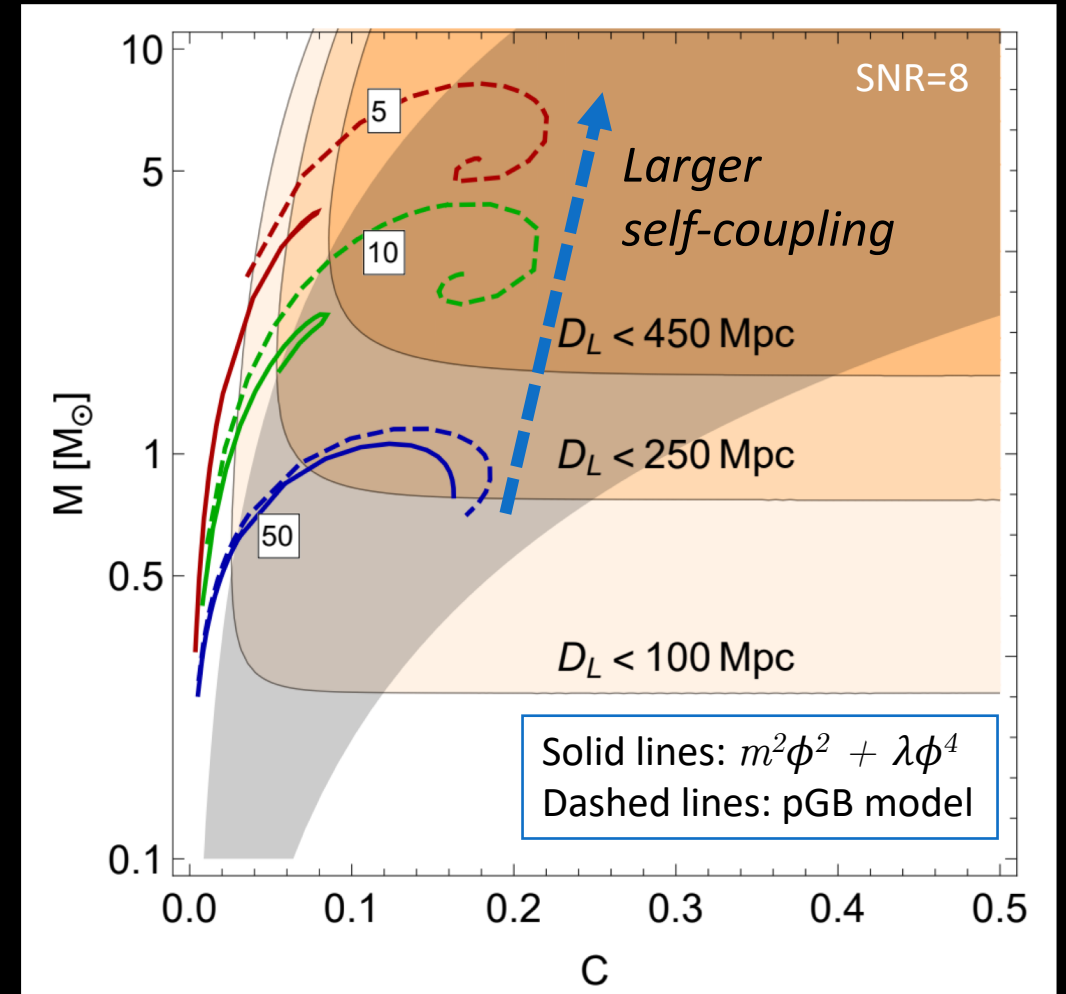
Example: boson stars

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

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, Racanelli, de Putter, Sigurdson [PRD, arXiv:1310.3278]

Tidal effects

- Tidal effects depend on the tidal Love number
- GW phase shift due to tidal deformability

$$\Lambda = \frac{1}{26} \left(\left(1 + \frac{12}{q} \right) \lambda_1 + (1 + 12q\lambda_2) \right)$$

$$q = M_1/M_2 \geq 1$$

quadrupole moment external quadrupolar tidal field

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

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

Correction to the GW phase at 5PN

Flanagan, Hinderer [PRD, arXiv:0709.1915]

- A way to distinguish (for example)

- Neutron star equation of state
- Objects with $C < 0.5$
- Neutron star atmospheres
- Black hole mimickers (ClePhOs)

e.g. Hinderer, Lackey, Lang, Read [PRD, arXiv:0911.3535]

{ e.g. boson stars: Sennet, Hinderer, Steinhoff, Buonanno, Ossokine [PRD, arXiv:1704.08651]; in EMRIs: Guo, Sinha, Sun [JCAP, arXiv:1904.07871]

e.g. Nelson, Reddy, Zhou [JCAP, arXiv:1803.03266]

e.g. Pani, Maselli [IJMPD, arXiv:1905.03947]

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

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

$$\tilde{\alpha}' \equiv \frac{\alpha' q_1 q_2}{Gm_1 m_2}$$

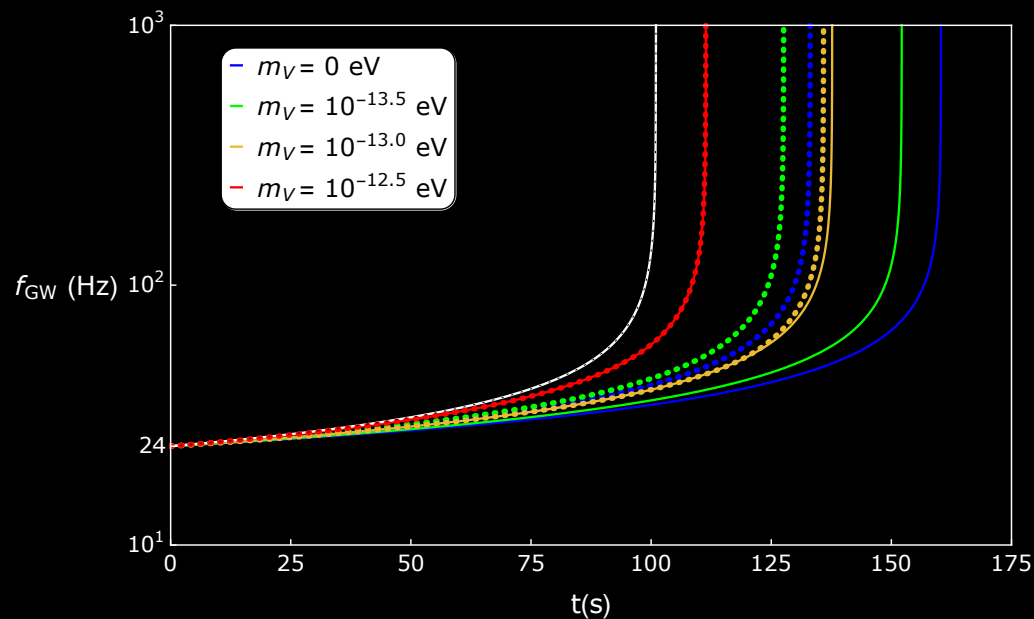
- Extra dipole radiation:

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

$$\dot{E} = - (P_{GW} + P_{dark})$$

quadrupole

Example: dark U(1)



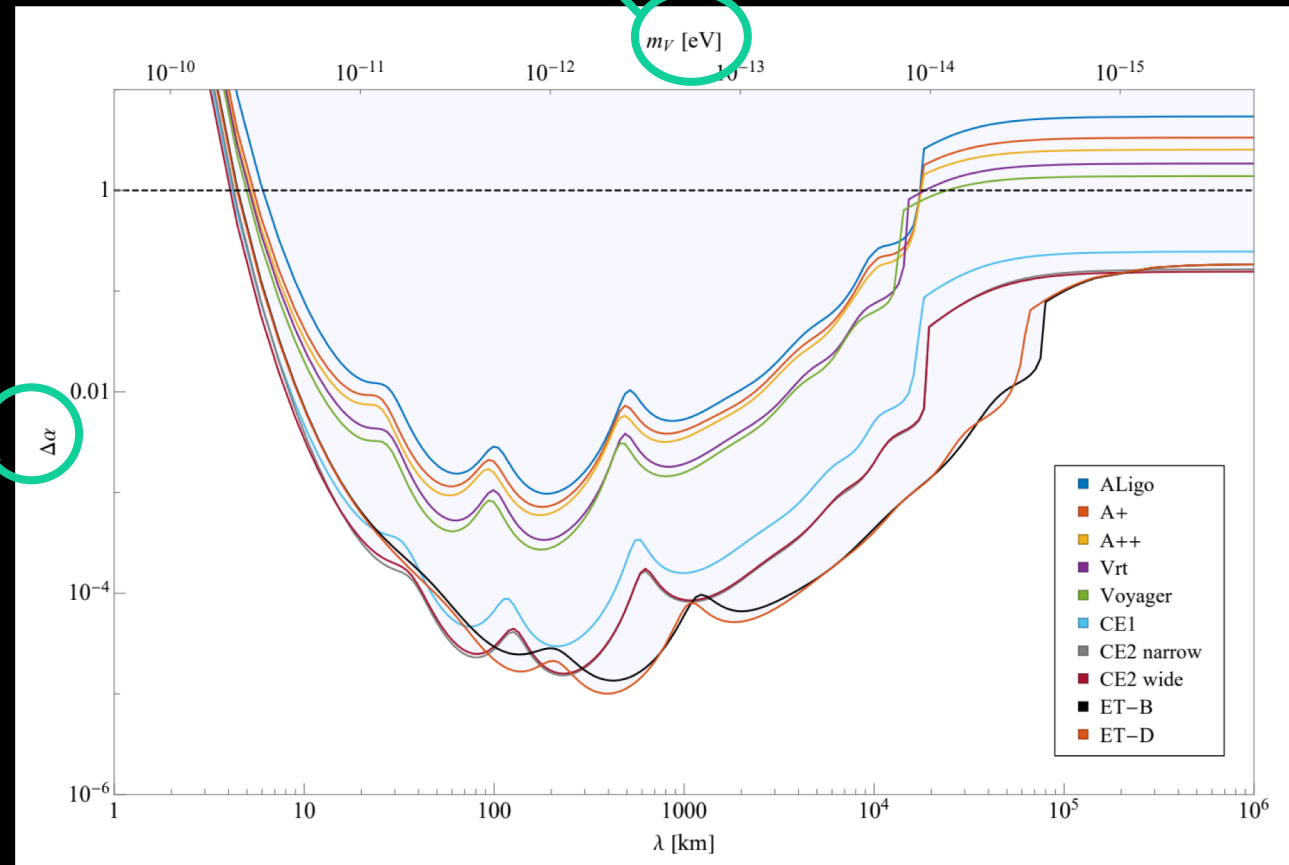
DC, Nelson, Sun, Walker, Xianyu
[ApJ, arXiv:1711.02096]

May also constrain $L_\mu - L_\tau$
See Dror, Laha, Opferkuch
[arXiv:1909.12845]

Effective coupling

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

Mediator mass



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

Binary Merger Rate

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

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.

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

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:

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

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

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

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

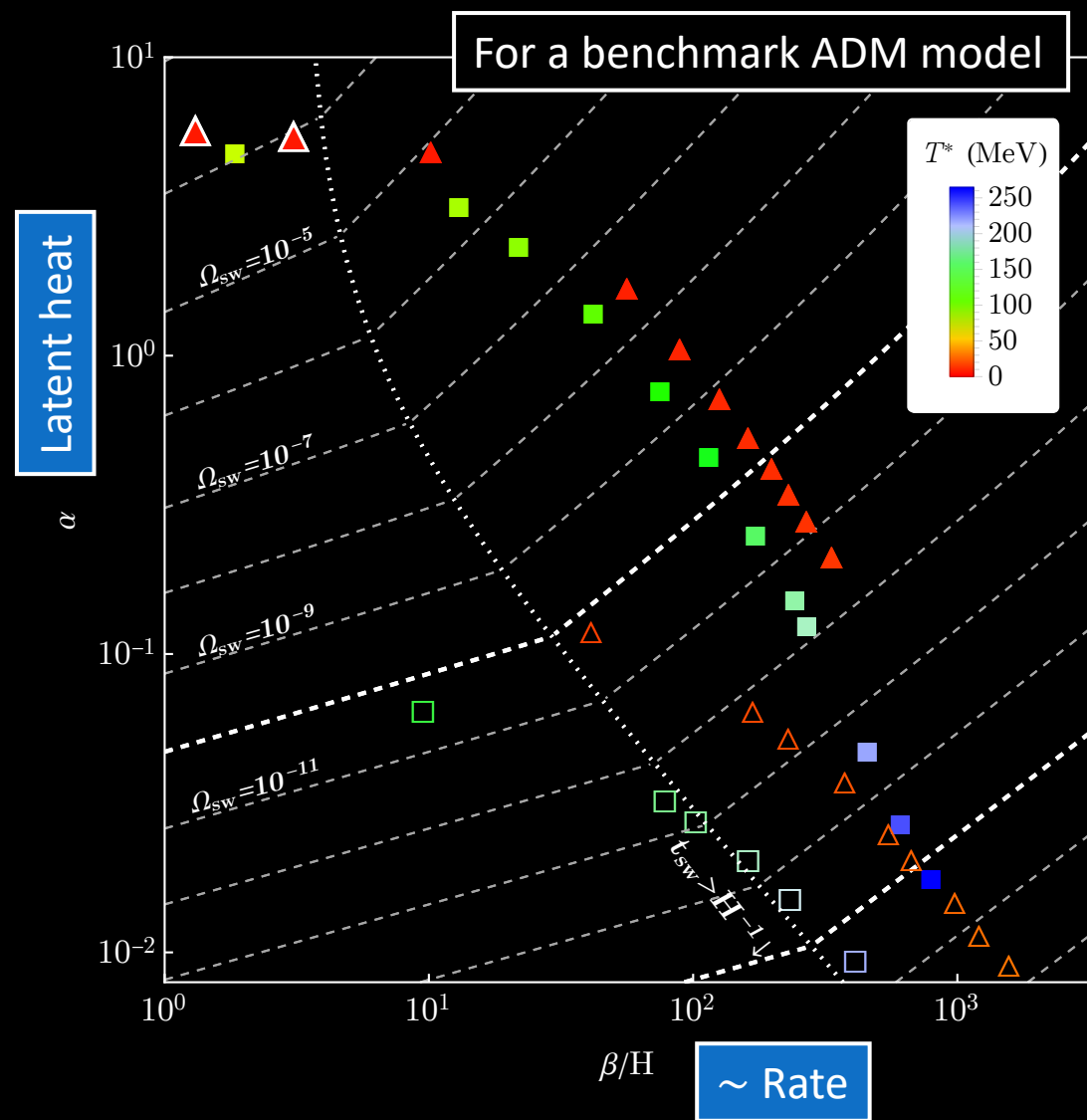
Inspiral phase

Bonus: solitosynthesis

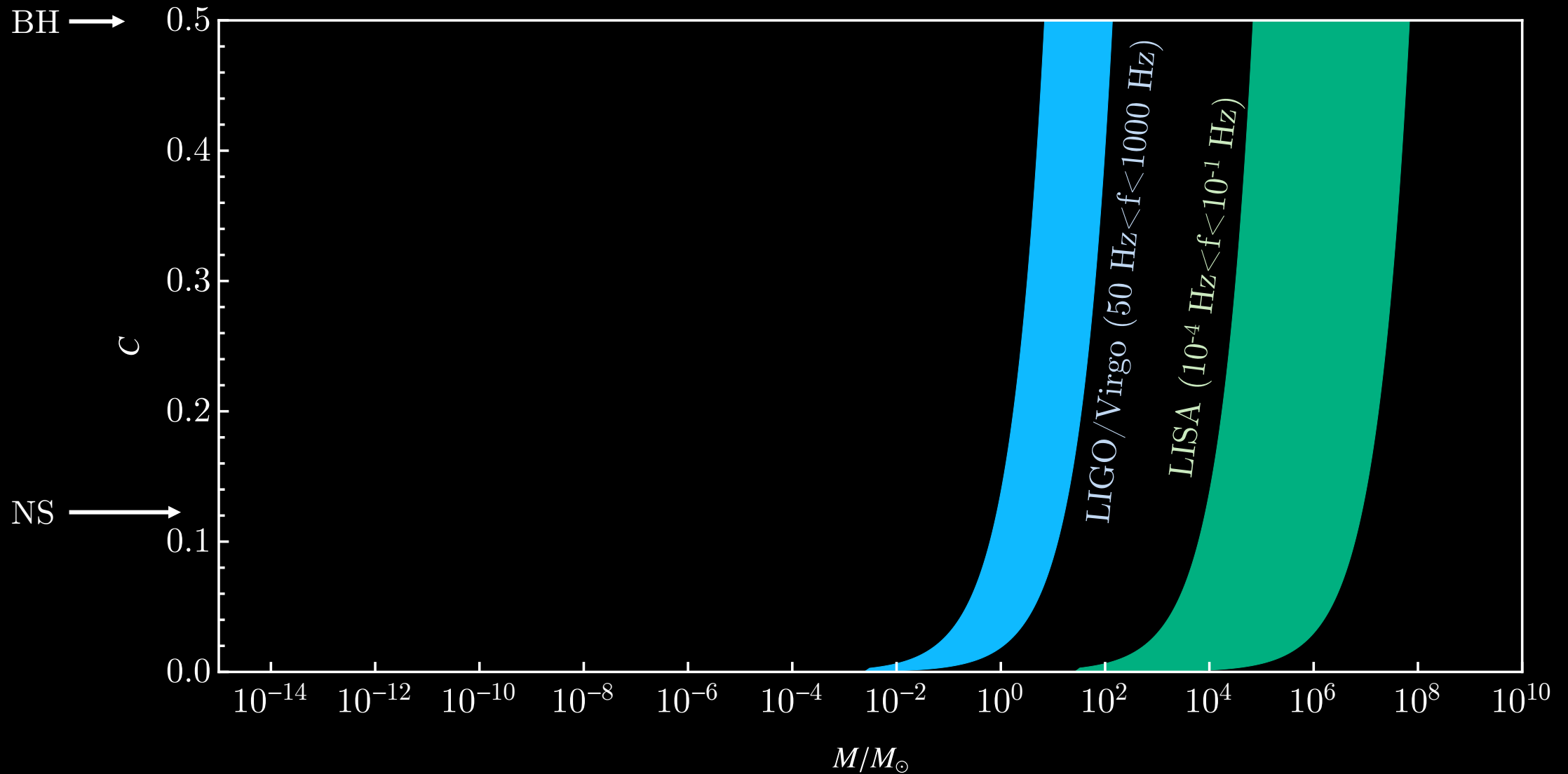
- **Q-balls** may give rise to inhomogeneous phase transitions
 - Q-balls lower their free energy by means of a scalar condensate
 - For a critical charge Q_c it becomes energetically favored to expand

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

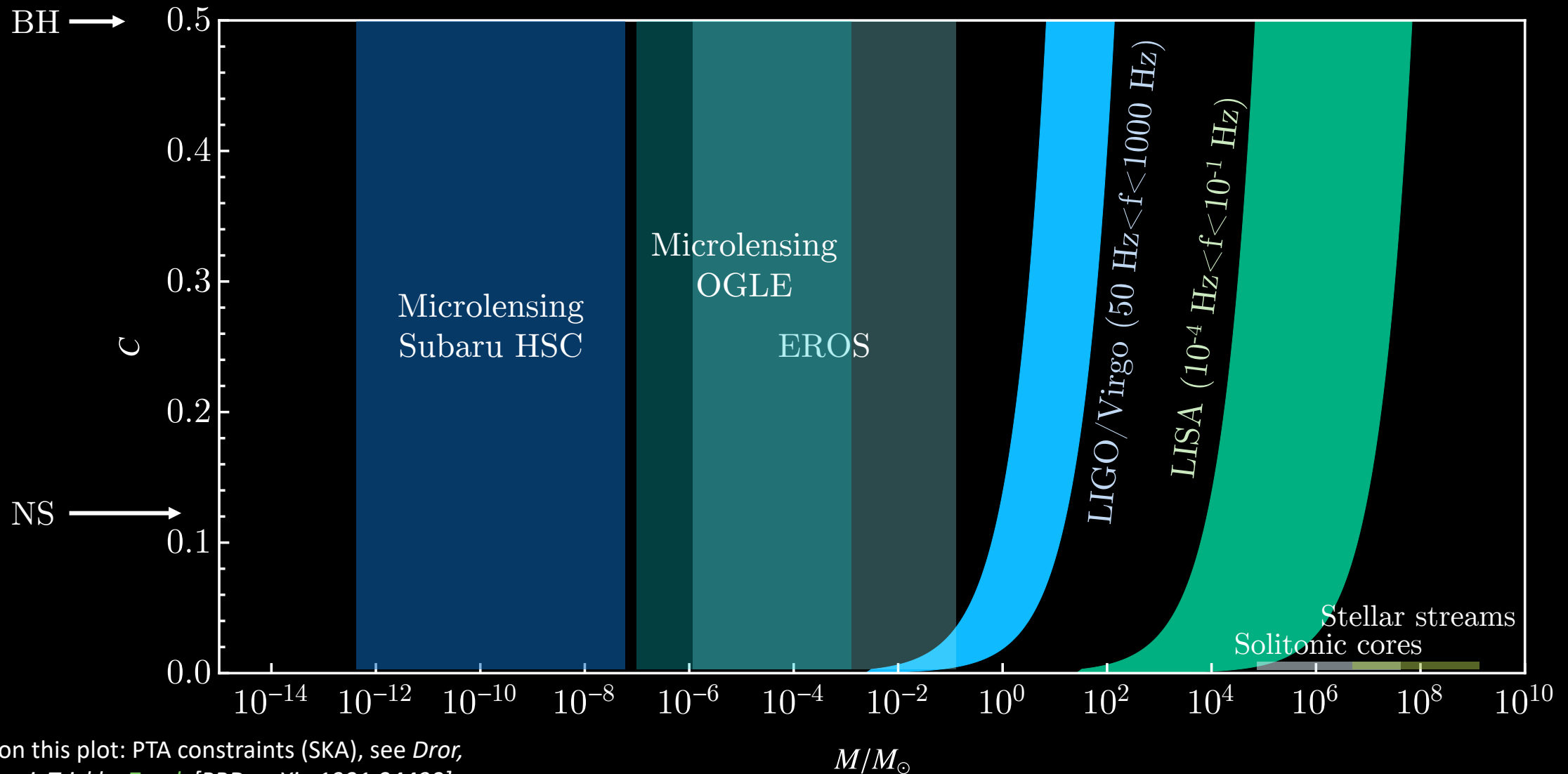
- Solitonic PTs **source GW efficiently**
 - Effective nucleation rate from charge accretion (solitosynthesis) $\rightarrow$ slow
 - Typically, supercooled $\rightarrow$ large latent heat



Gravitational probes of ECO dark matter



Gravitational probes of ECO dark matter



Not on this plot: PTA constraints (SKA), see *Dror, Ramani, Trickle, Zurek* [PRD, arXiv:1901.04490]

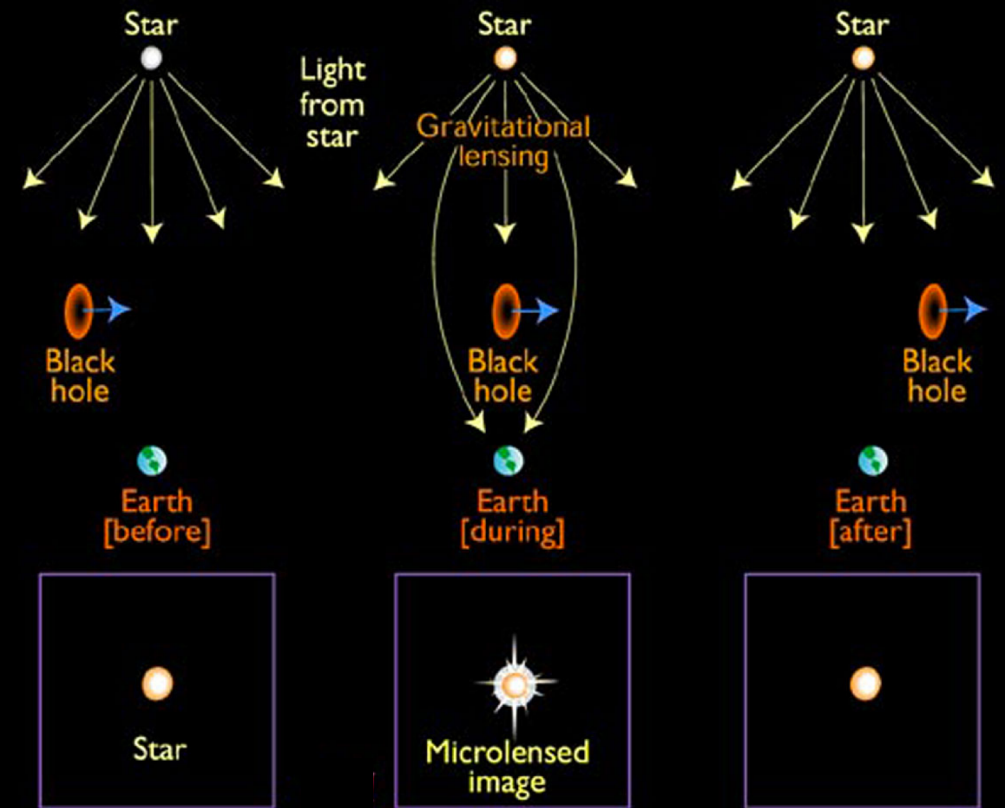
Other gravitational probes: microlensing

- 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 D_L and temporal resolution
 - HSC/Subaru: $\{10^{-12}, 10^{-8}\}^* M_\odot$
 - EROS: $\{10^{-6}, 10^{-1}\} M_\odot$
 - OGLE: $\{10^{-7}, 10^{-3}\} M_\odot$



*Wave-optics and finite source effects weaken constraints at lower masses

Other gravitational probes: microlensing

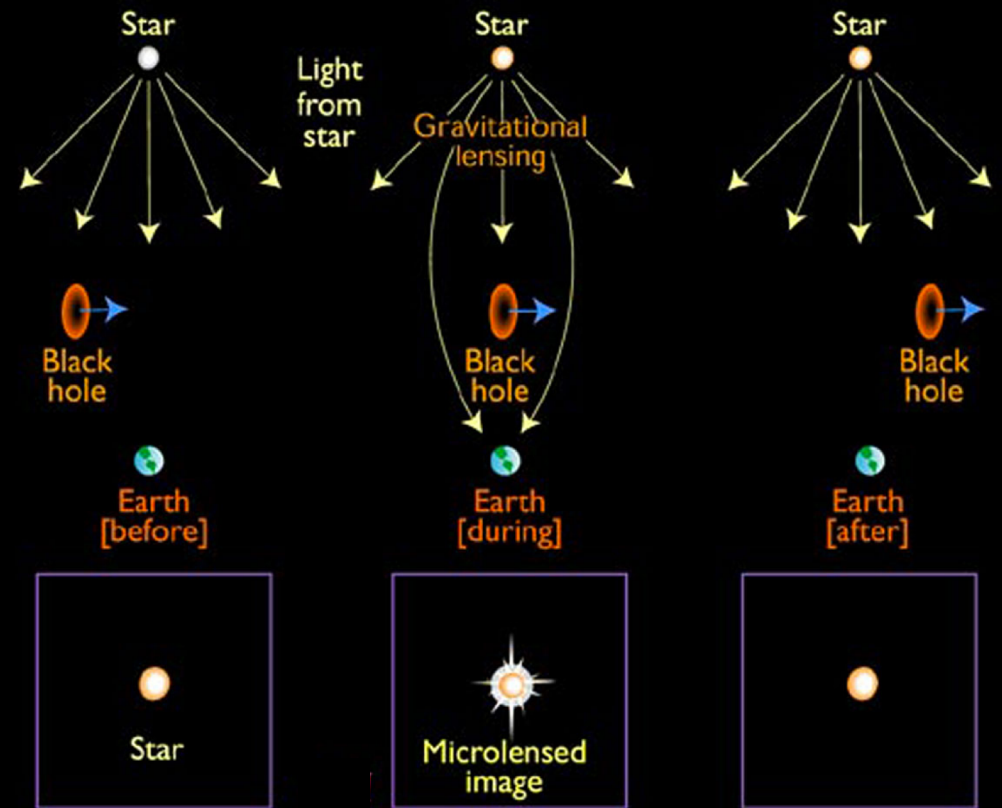
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Generalize this to **finite size** lenses (and sources)

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

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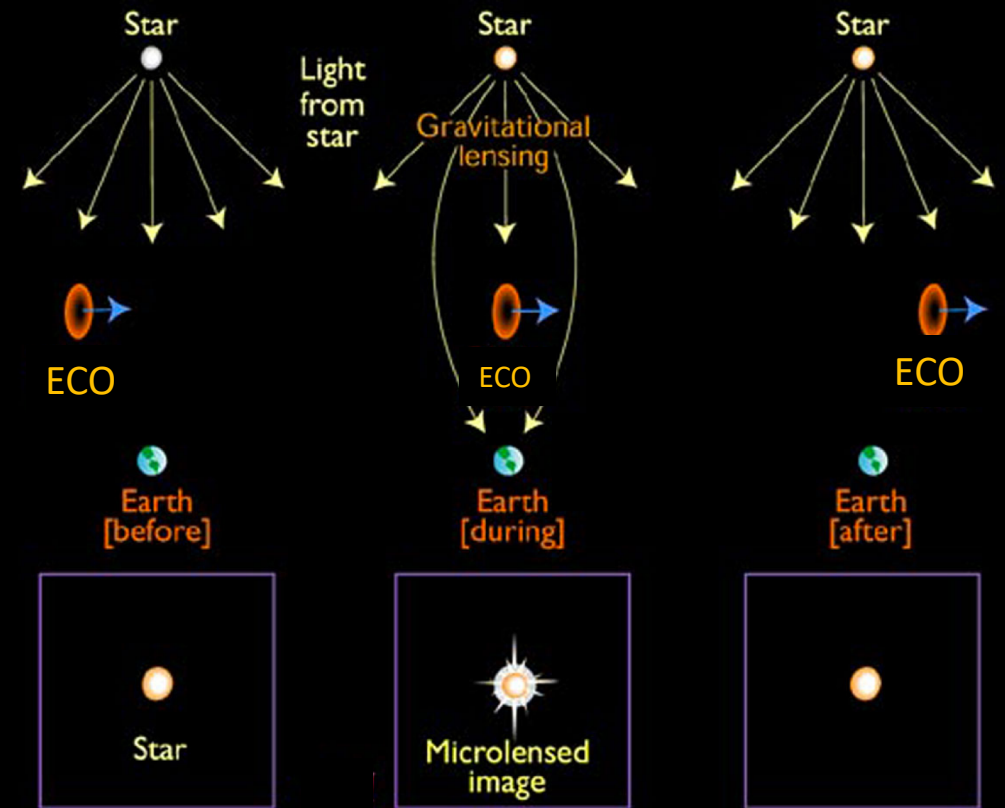
Other gravitational probes: microlensing

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

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

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

- Sensitivity to ECOs depends on D_L and temporal resolution
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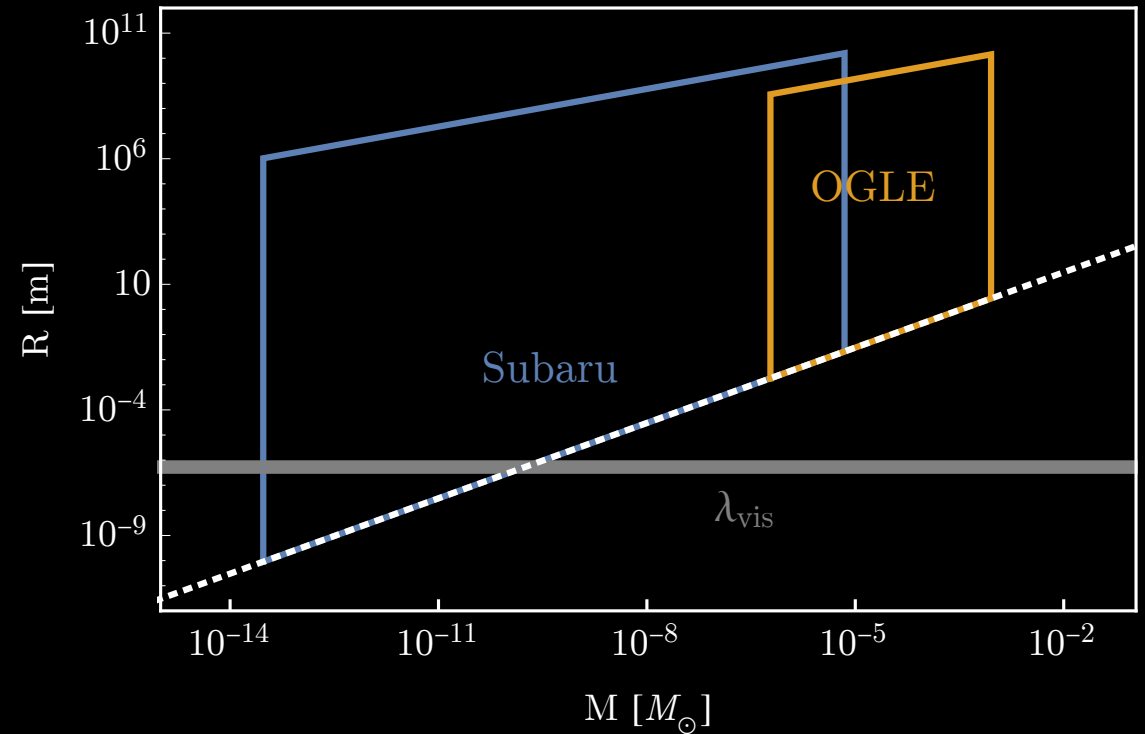
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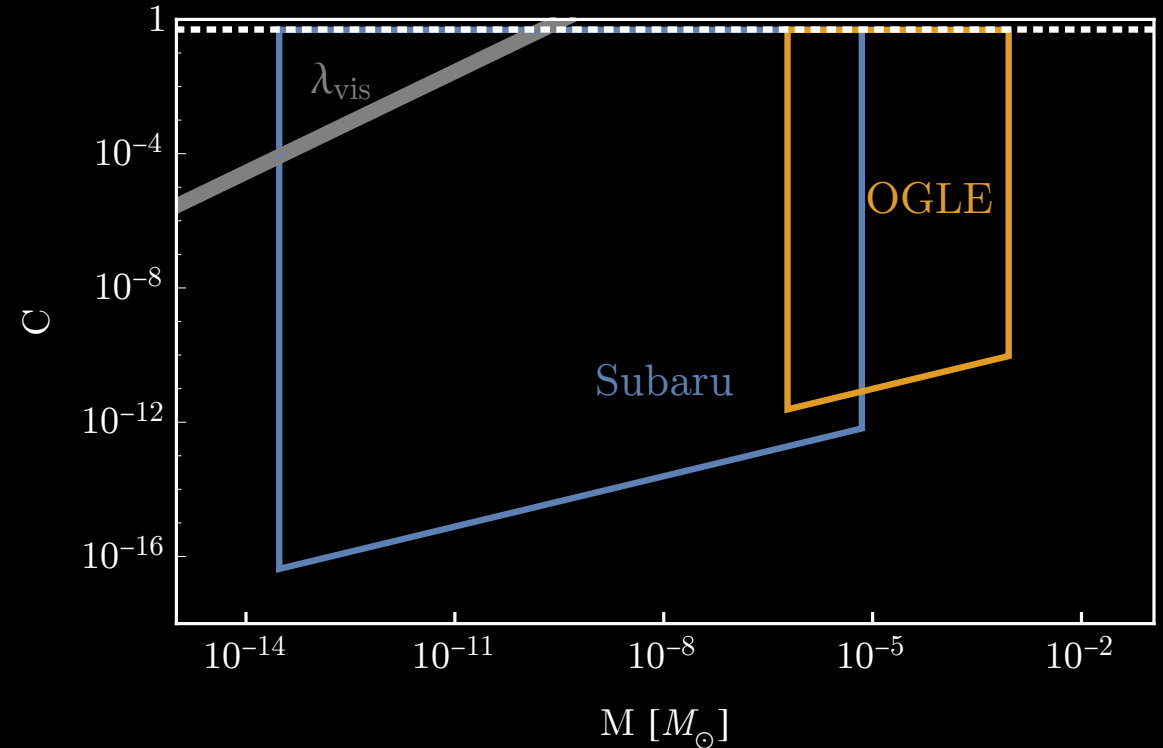
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*Wave-optics and finite source effects weaken constraints at lower masses

Positive detection of ECO-lenses

- Some source profiles lead to **caustics** → two source images are amplified just before they disappear

- For example, for a boson star profile

$$M(r) = \frac{M_p^2}{m} \int_0^r dr' \chi(r') r'^2$$

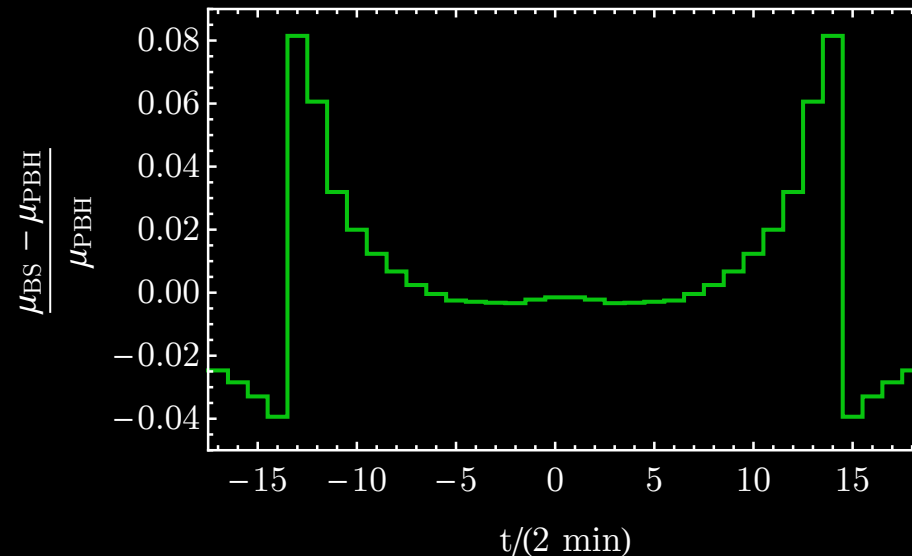
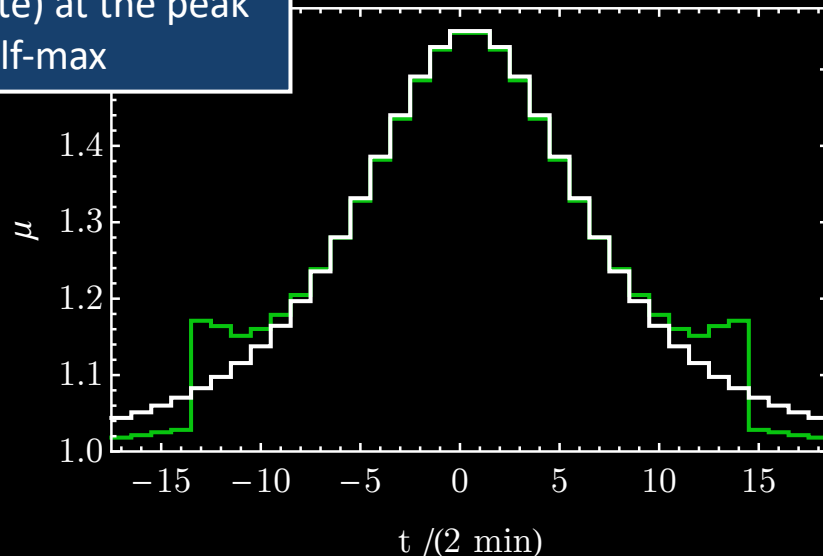
ADM mass

$$\frac{\partial^2(r\chi(r))}{\partial r^2} = 2r\chi(r)(\Phi(r) - \gamma)$$

Schrödinger-Newton system for free boson

$$\frac{\partial^2(r\Phi(r))}{\partial r^2} = r\chi(r)^2$$

Boson star magnification curve (green) fit to a PBH curve (white) at the peak and the half-max



To conclude,

- Many models predict dark matter substructure and exotic compact objects (ECOs)
- We can probe ECOs using their gravitational interactions, using
 - *Gravitational waves*
 - *Gravitational lensing*
 - *Gravitational redshifting*
- Stay tuned: we will learn a lot more about DM substructure in the coming years!

Thank you!

감사합니다

Back up slides

Dark matter spectroscopy in BNS mergers

- A generic model of an interacting asymmetric dark sector,

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

• Can produce observable features at LIGO for ultralight mediators, $\alpha' = g'^2/4\pi$

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

Stochastic Background (from binary mergers)

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

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

Stochastic Background (from binary mergers)

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

Observed frequency

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

Merger rate

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

*Differential energy
emitted by a single source*