Probing Dark Matter with Gravitational Waves

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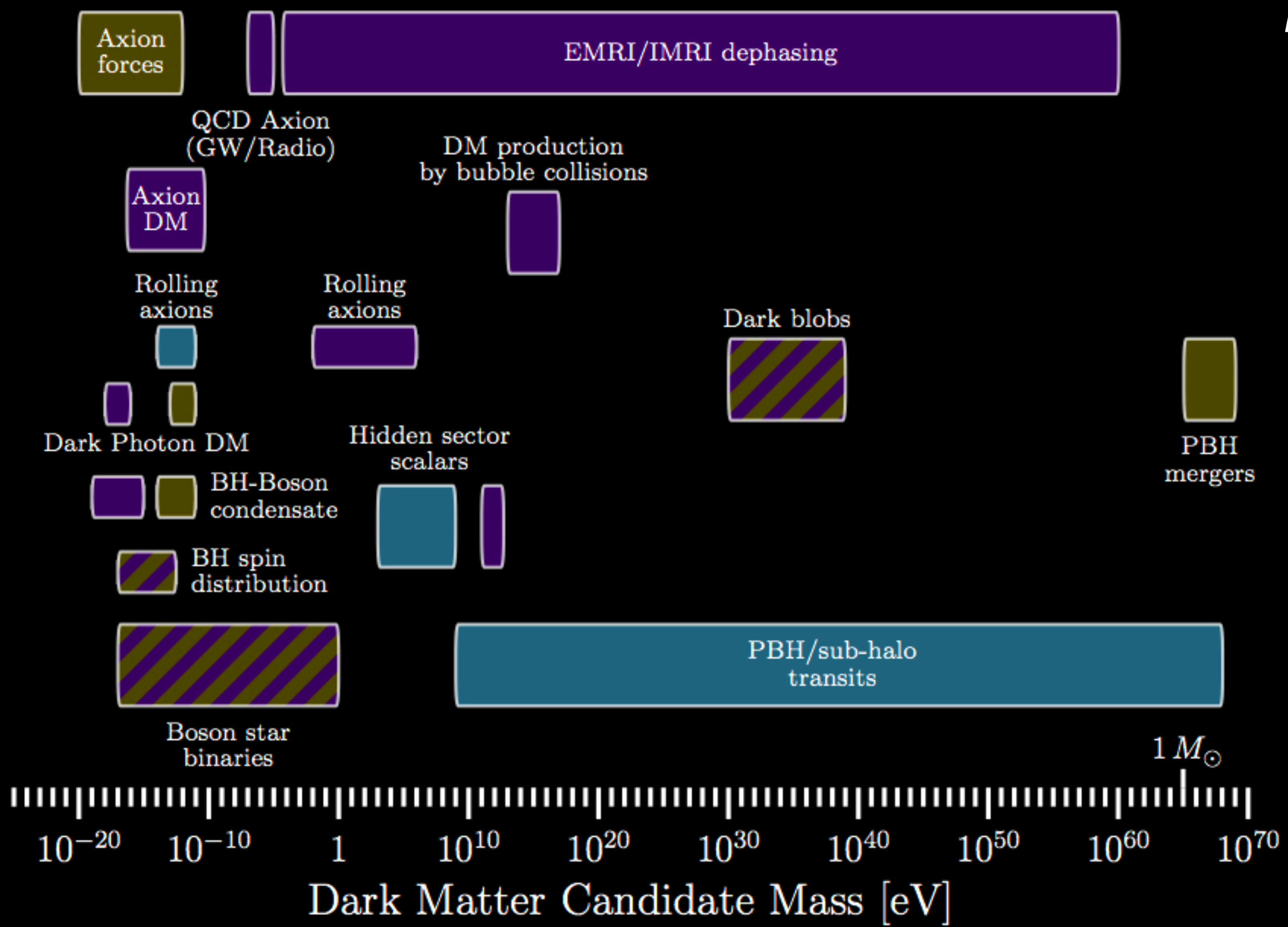
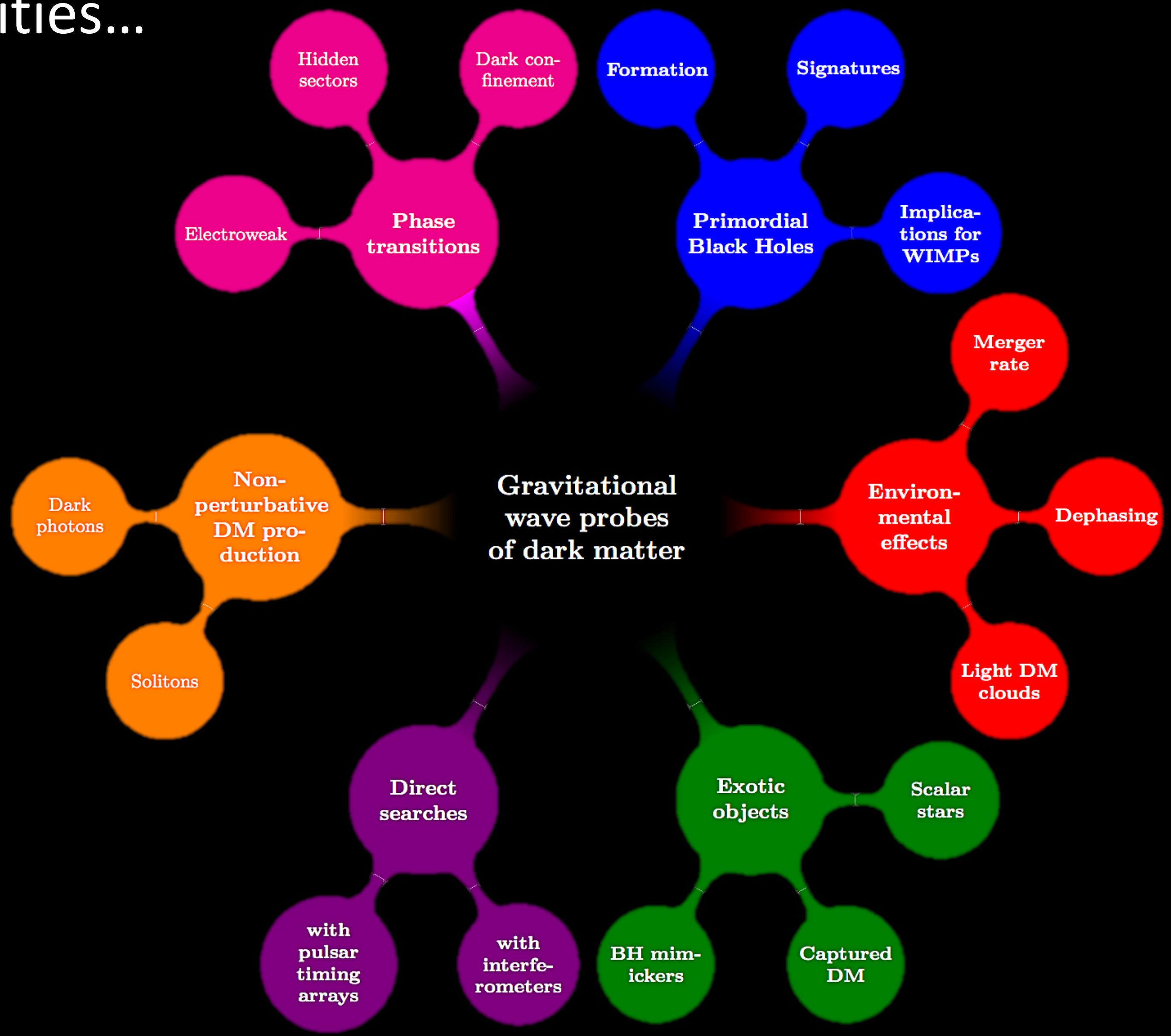
Gravitational waves may shed light on dark matter

DC + Bertone (coordinators), et al. [arXiv:1907.10610]



Many opportunities…



G. Bertone, DC, et al. arXiv:1907.10610

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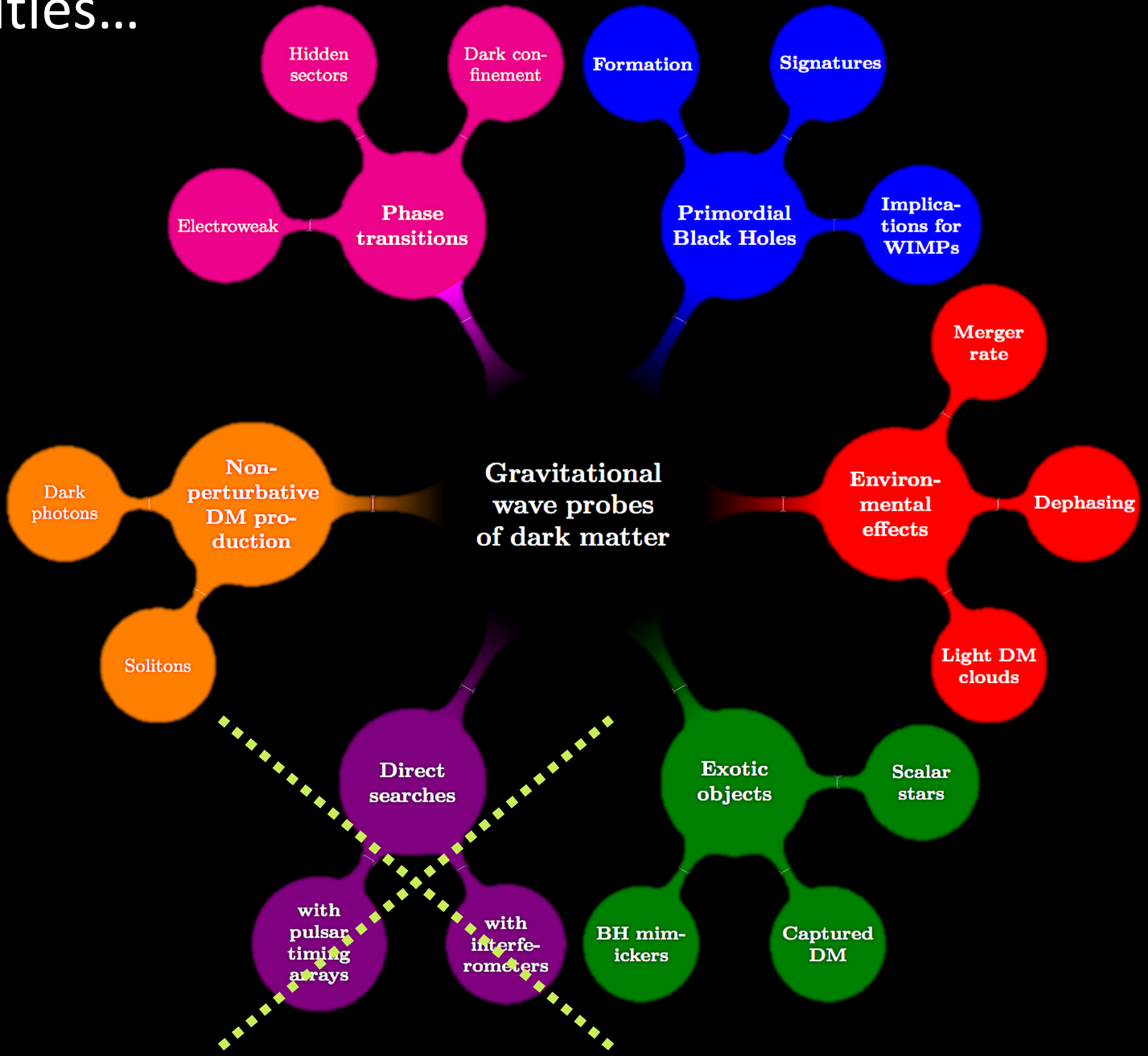

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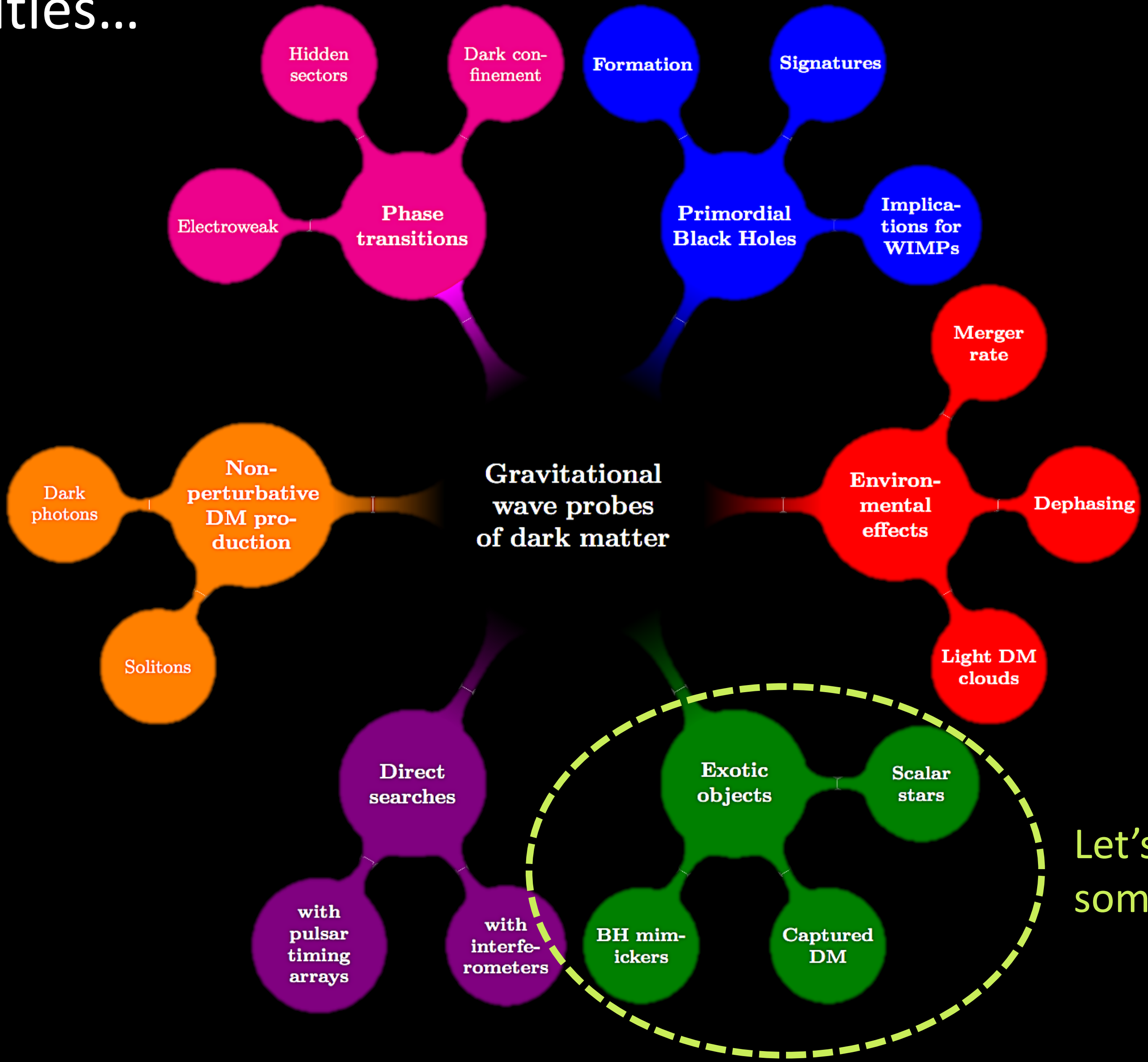


Let’s look at some examples

G. Bertone, DC, et al. arXiv:1907.10610

Binary merger events ($M_1 \approx M_2$)

- >50 LIGO/Virgo observations
  - 2017 Nobel Prize in Physics

- *Can be used to learn about dark matter in various ways*

- Most GW radiation from the inspiral phase, ending in $f_{\rm ISCO}$

- Solvable in a (v/c) expansion

  → Weak gravity, small velocity

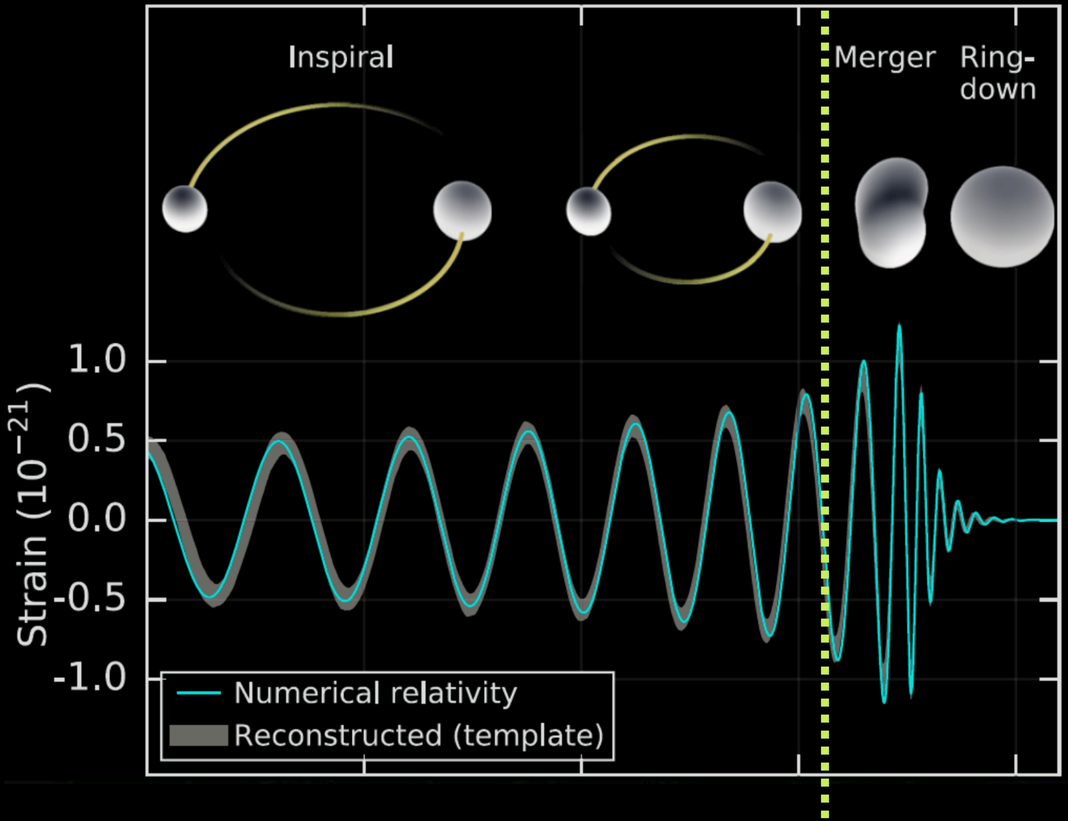


Image credit: LIGO collaboration

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

What can we learn from the inspiral waveform?*

A lot, for example,

1. Component masses
2. Tidal effects → equation of state
3. Dynamical friction → environmental effects
4. Long-range (dark) forces → BSM effects
5. Extra dissipation channels → BSM effects
6. Redshift distribution of events → age of objects
7. "Hair": multipolar metric deviations (EMRIs) → tests of GR

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

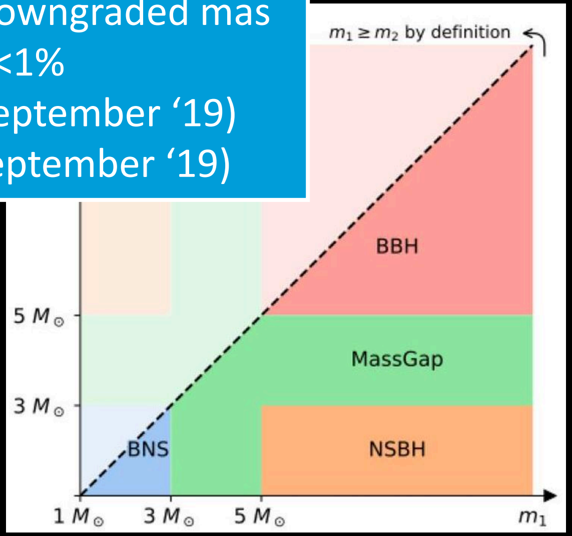


Image credit: LIGO collaboration

So what about Dark Matter? Let's look at two examples: exotic compact objects and neutron star mergers.

**Further information could come from (for example) from multi-messenger signals (or absence thereof), or post-merger quasi-normal modes or "echoes"*

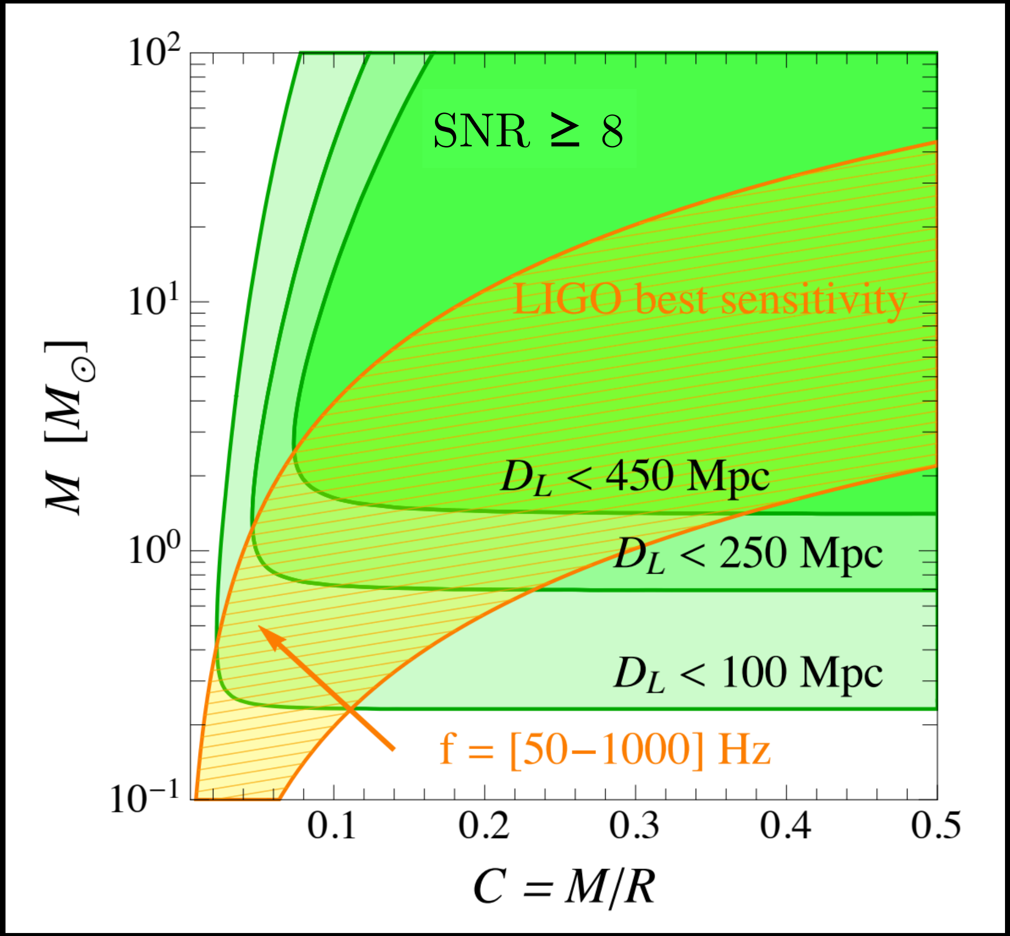
Exotic compact object merger sensitivity

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

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

$$C_\odot = 2\times 10^{-6} \qquad C_{\text{BH}} = 0.5$$
$$C_\oplus = 7\times 10^{-10} \qquad C_{\text{NS}} \sim 0.1$$

- Sensitivity determined by masses, compactness and luminosity distance

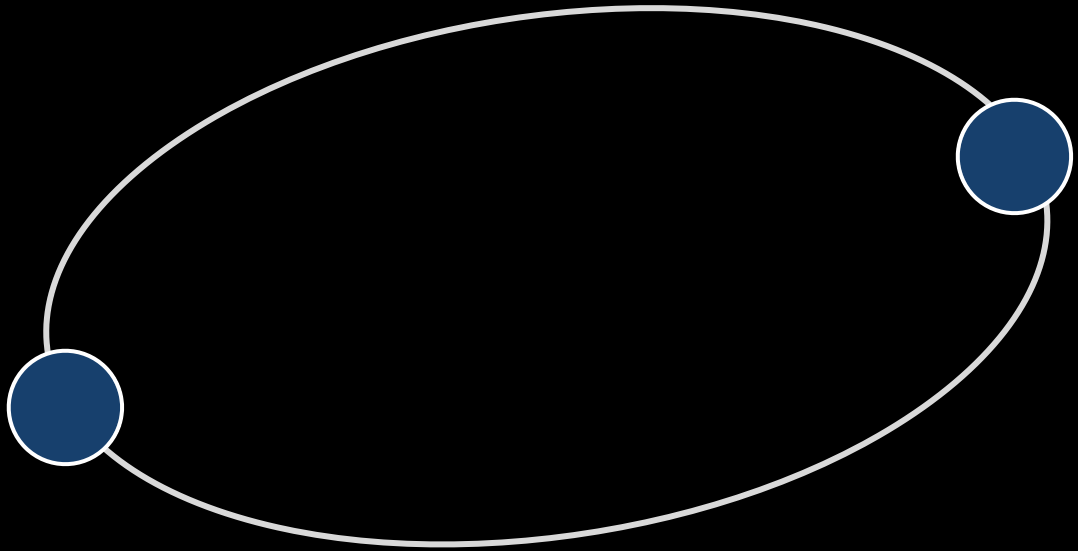


Giudice, McCullough, Urbano [JCAP, 1605.01209]

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

Dark Matter inside Neutron Stars

Asymmetric dark matter with a light mediator may collect inside a neutron star. What does that mean for the BNS inspiral phase?



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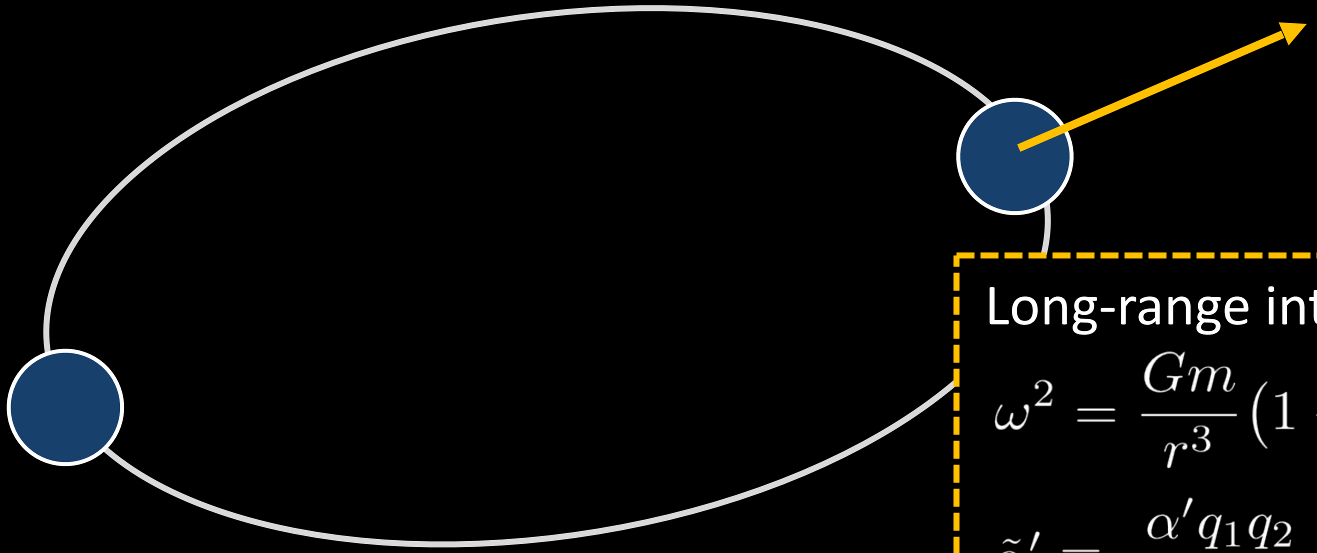

Long-range interactions

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

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

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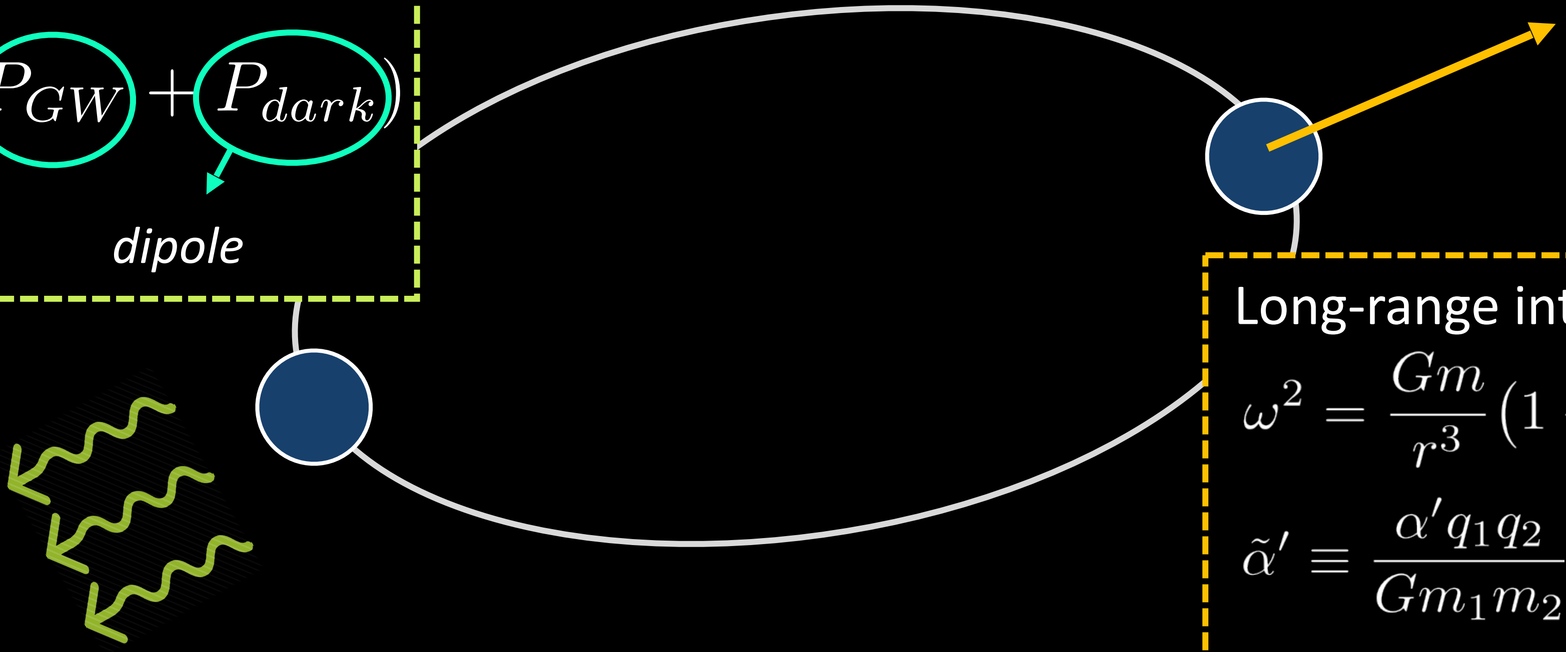
Dark radiation

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

quadrupole *dipole*



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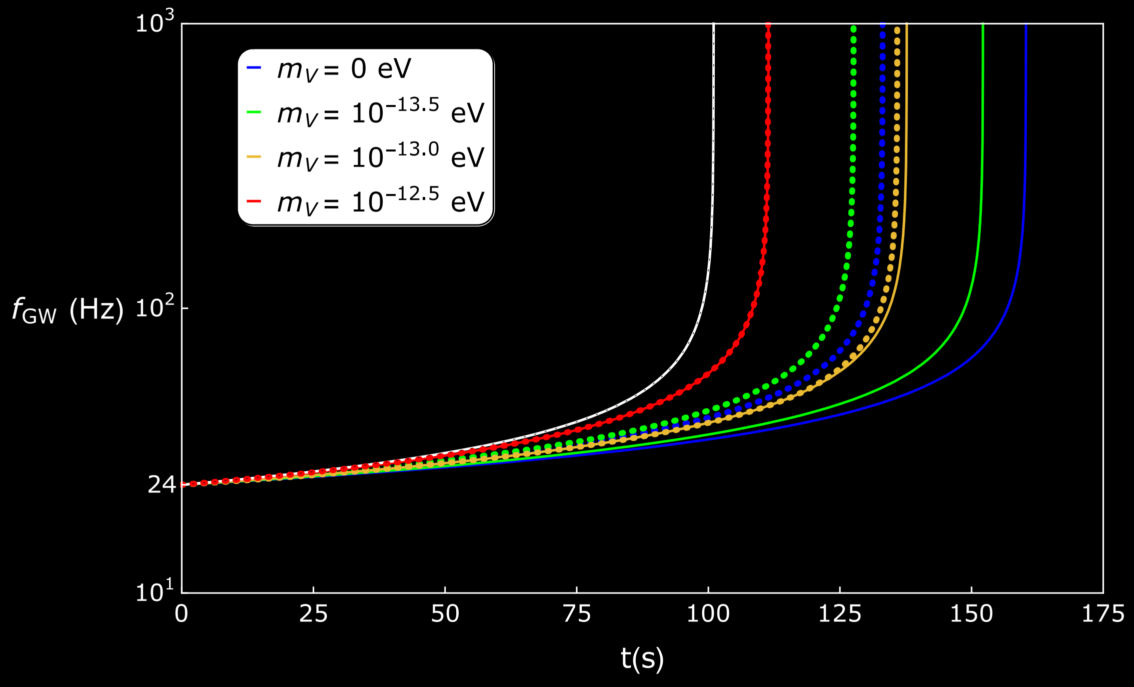
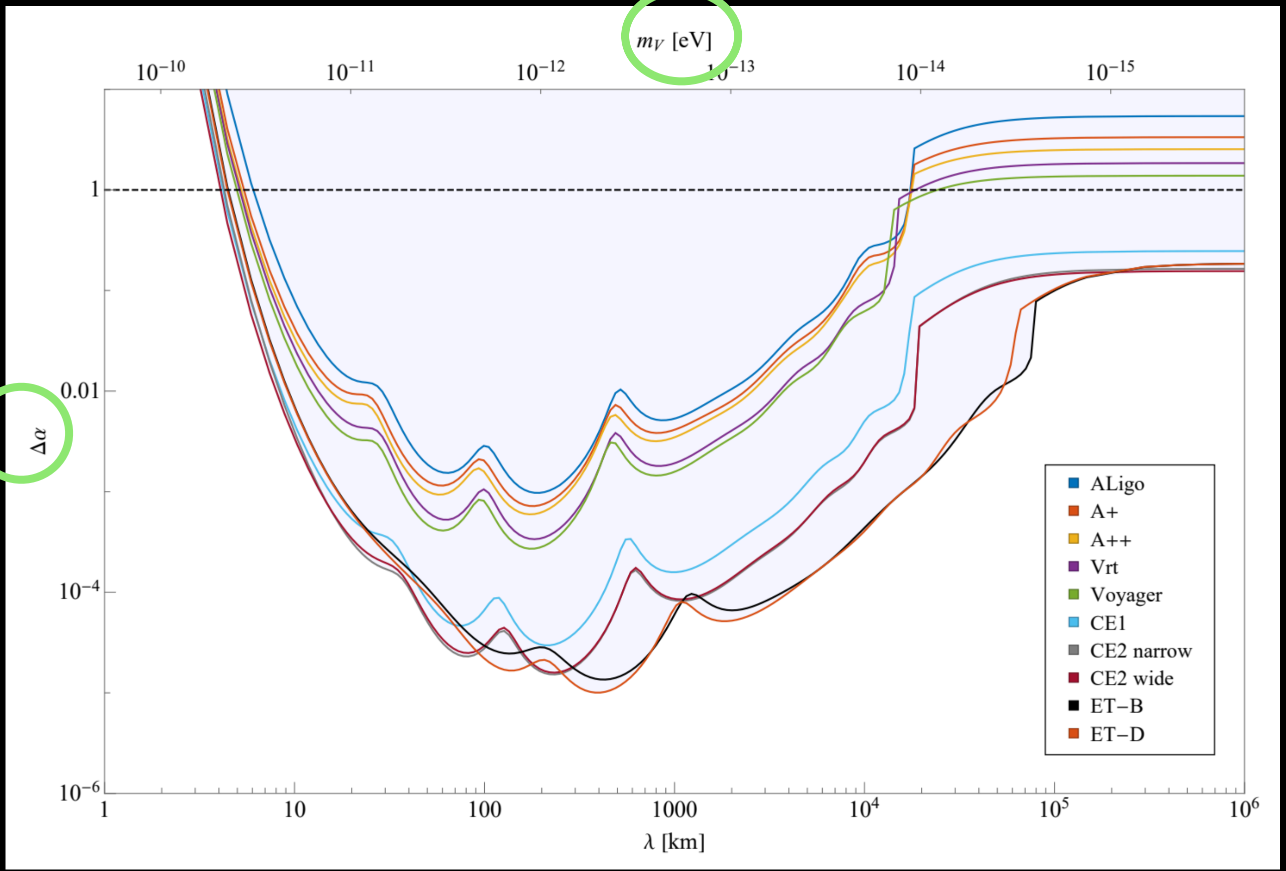


White line: GW170817
Continuous lines: repulsion
Dashed: + dipole radiation

Mediator mass



Effective coupling

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

From Alexander, McDonough, Sims, Yunes, [CQG, arXiv:1808.05286]
More follow-ups: Kopp, Laha, Opferkuch, Shepherd [JHEP, arXiv:1807.02527]
Dror, Laha, Opferkuch [arXiv:1909.12845]

Many opportunities…

G. Bertone, DC, et al. arXiv:1907.10610

Primordial black hole mergers

- Direct evidence
  - Stellar evolution: no BHs $< 1.4\ \mathrm{M}_\odot$ (Chandrasekhar mass)
  - No astrophysical BH mergers with $z > 40$ (which will be probed by ET and CE)

Koushiappas, Loeb [PRL, 1708.07380]

- Statistical evidence (population studies)

E.g. Sasaki, Suyama, Tanaka, Yokoyama [CQG, 1801.05235]

  - PBH binaries could form abundantly before matter-radiation equality
  - PBHs are expected to have different spin distributions than astrophysical BHs
  - Recently: interesting discussions about the merger rate

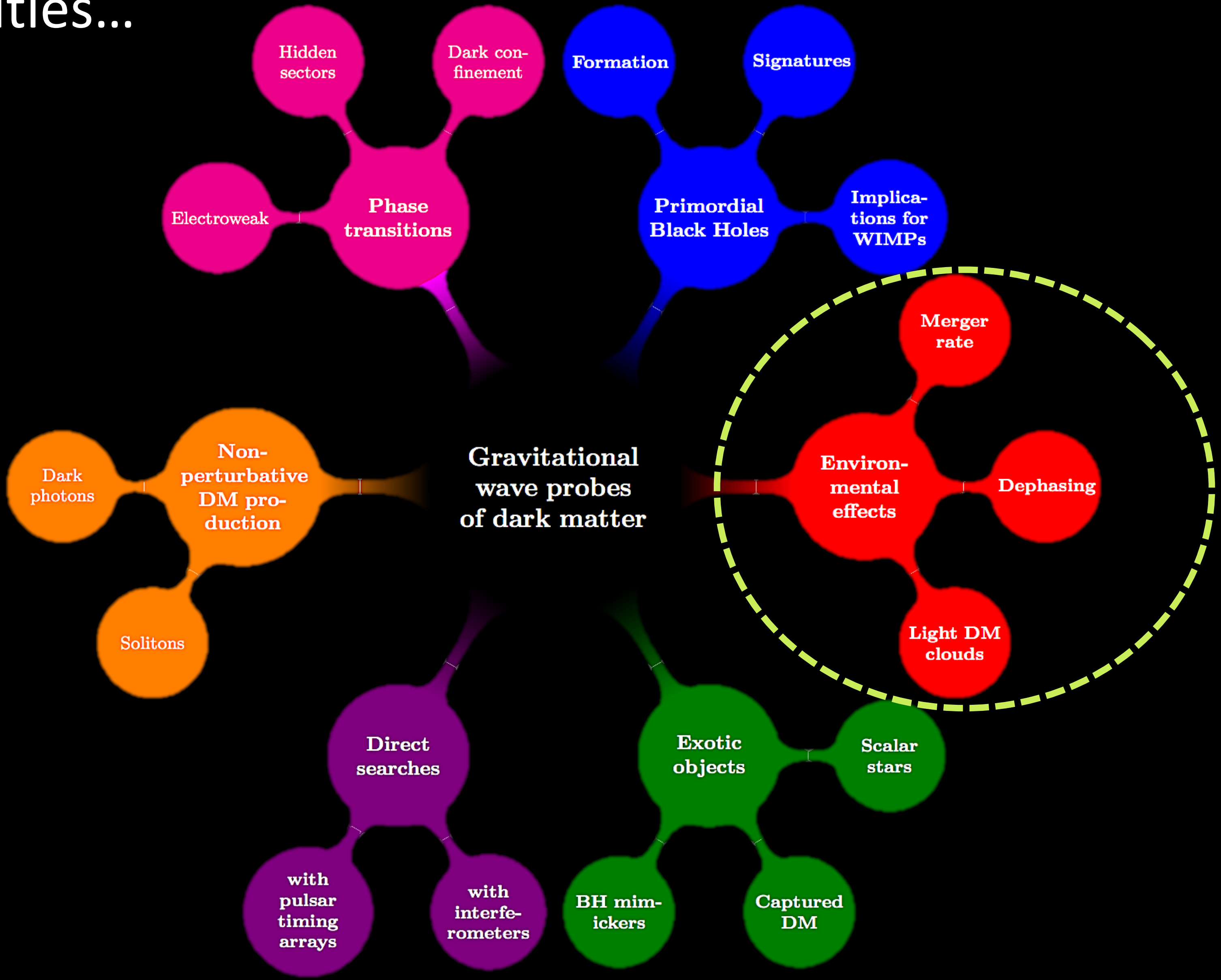
E.g. Fernandez, Profumo [1905.13019]

E.g. Boehm, Kobakhidze, O'Hare, Picker, Sakellariadou, [2008.10743]

- (Maybe) incompatible with WIMPs

E.g. Adamek, Byrnes, Gosenca, Hotchkiss [PRD, 1901.08528]

Many opportunities…



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Environmental effects and EMRIs/IMRIs

- Merger of a $\sim \mathrm{M}_\odot$ object and a SMBH ($\sim 10^6\ \mathrm{M}_\odot$) or MBH ($\sim 10^4\ \mathrm{M}_\odot$)
  - LISA will detect EMRIs up to $\mathrm{z}=4$
  - Inspirals are slow: LISA typically probes 10^4-10^5 cycles

- Potential to probe black hole spacetime
  - Nonzero Love numbers imply tidal forces
  - For black holes these effects are absent, while for mimickers they are present

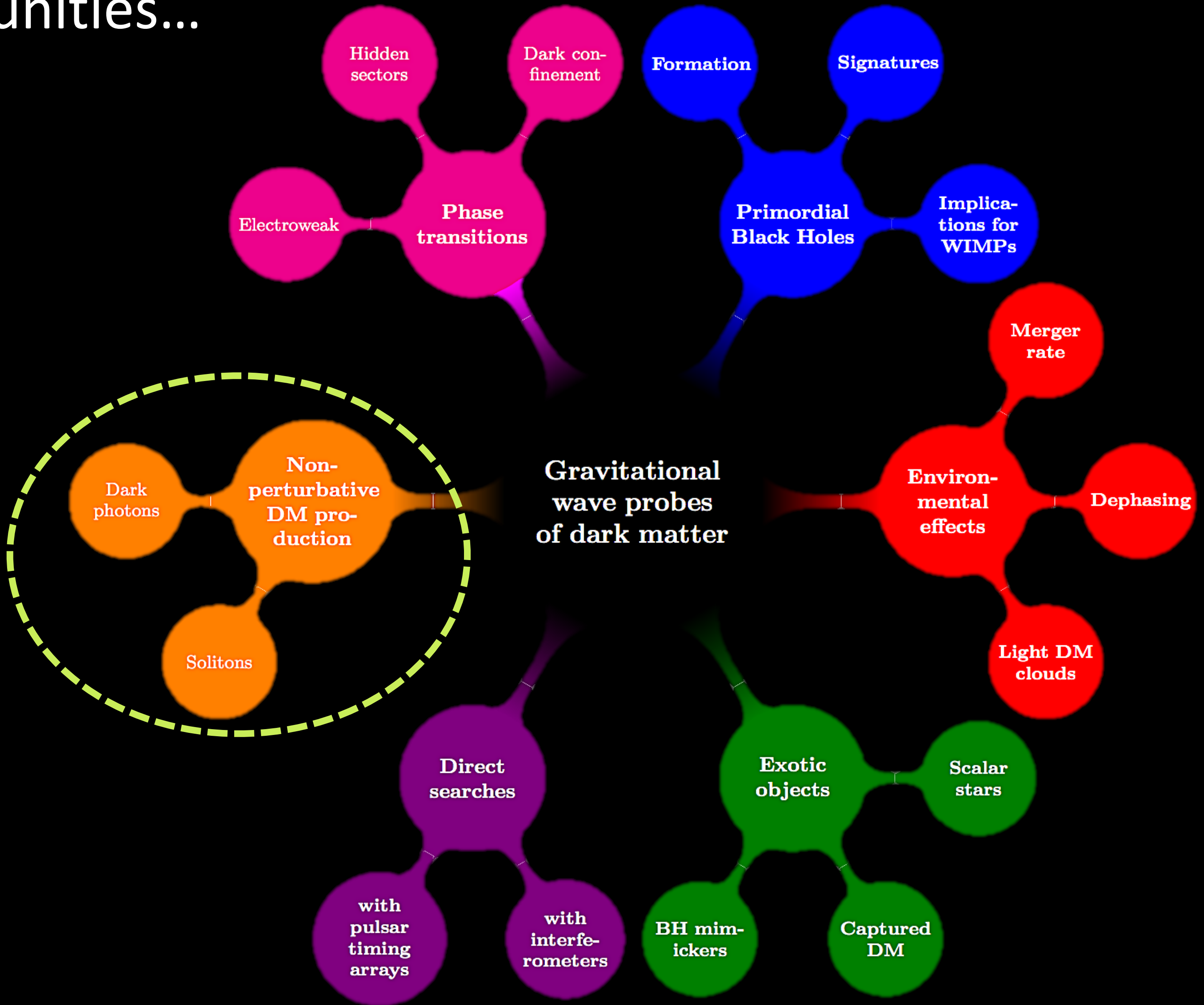
E.g. Pani, Maselli [IJMPD, 1905.03947]

- Potential to probe matter distribution around a MBH
  - Dark matter mini-spikes modify the waveform
  - Axion cloud implies an EM signal for an inspiraling pulsar

E.g. Eda, Itoh, Kuroyanagi, Silk [PRD, 1408.3534]

Hannuksela, Wong, Brito, Richard, Berti, Li [Nat.Astron 1804.09659]

Many opportunities…



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Non-perturbative particle production

- Chern—Simons coupling $(\phi/f)A_{\mu\nu}\tilde{A}_{\mu\nu}$ between the inflaton and a dark photon leads to a tachyonic instability in a photon helicity
  → Exponential particle production and *chiral* GW

E.g. Turner and Widrow, [PRD, 1988]
Anber and Sorbo, [JCAP, arXiv:0606534]

- Oscillating bosonic condensate is in general unstable to spatial perturbations, leading to,
  - Self-resonance (parametric and tachyonic)
  - Rapid fragmentation
  - Spatial clustering in the condensate → Sources a stochastic GW background

E.g. *Kusenko and Mazumdar, [PRL, arXiv:0807.4554]*

Many opportunities…

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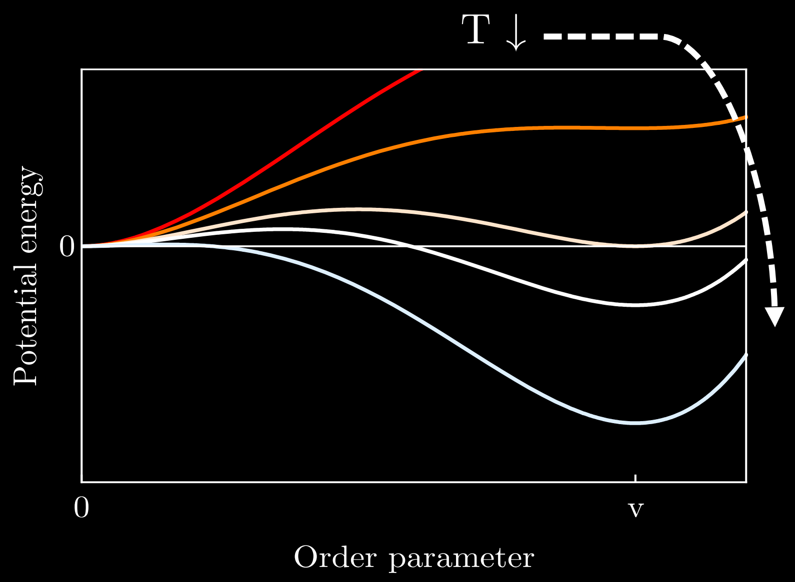
Dark matter in the Early Universe

First order phase transitions imply a stochastic GW background

First order phase transitions are described by tunneling through a potential barrier



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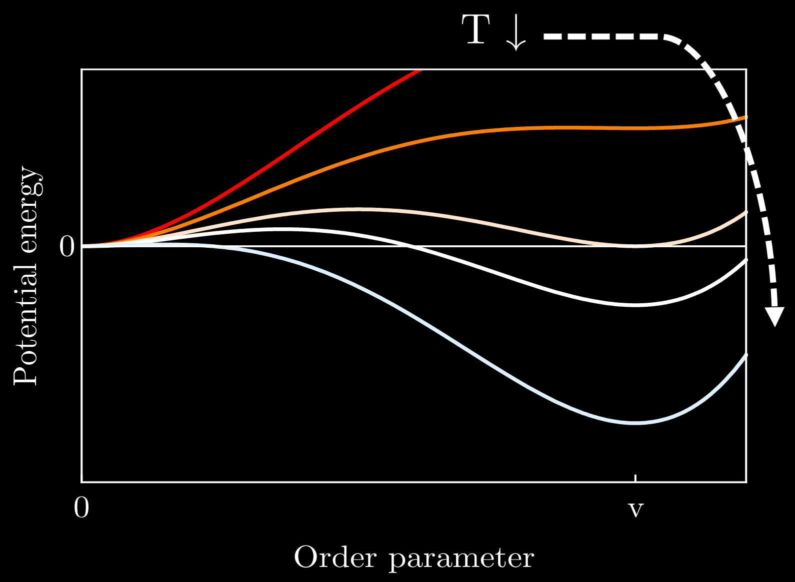
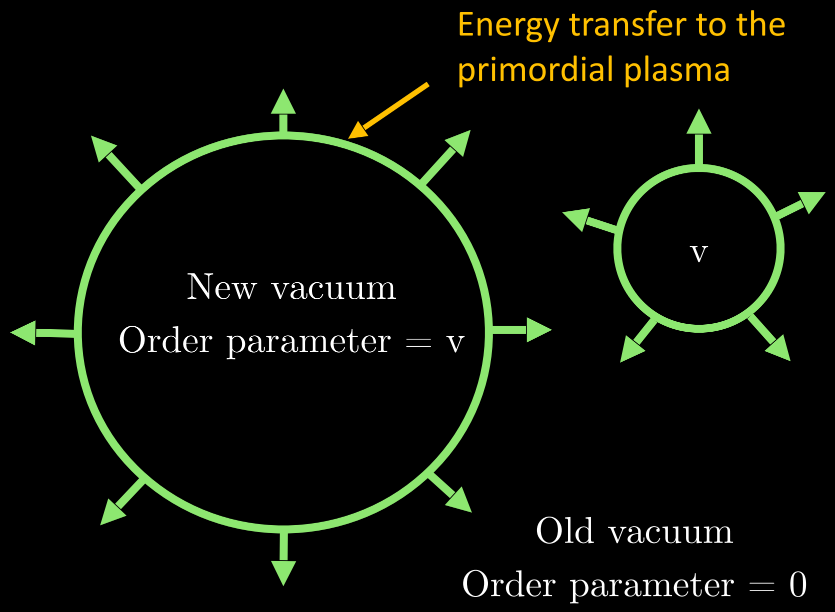


Bubbles nucleate, expand, and interact with the plasma; Bubble and plasma shell collisions source GWs



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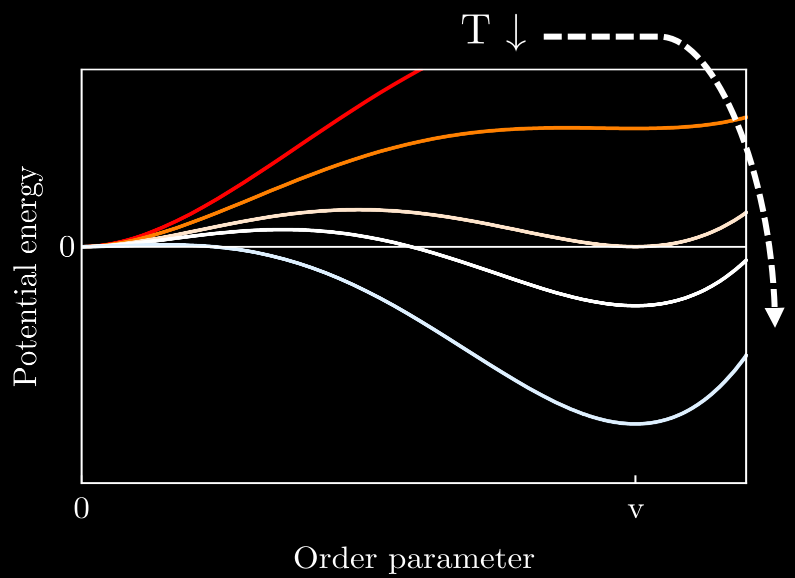

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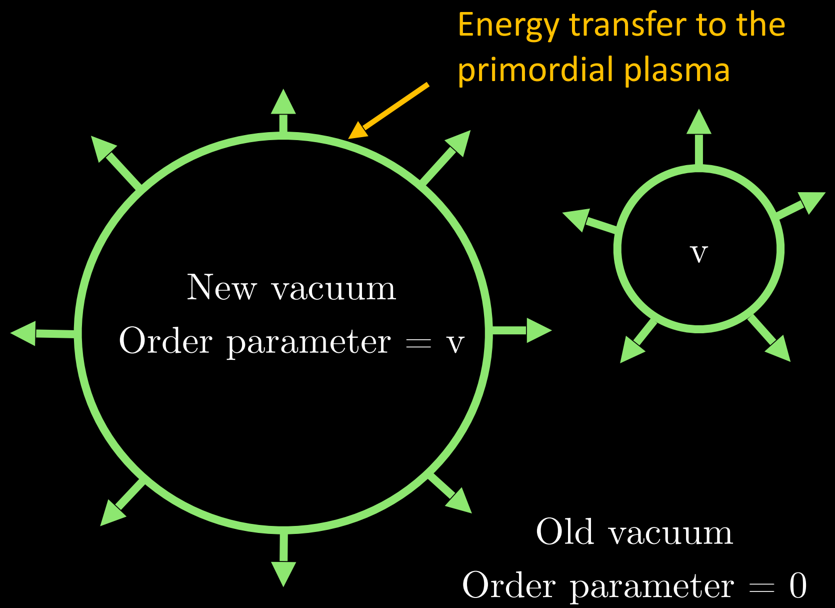
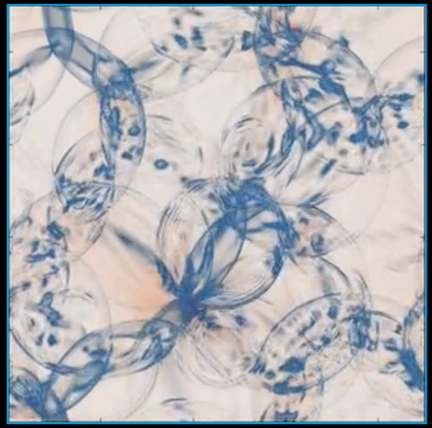


Simulations relate thermal parameters to GW spectra



Snapshot from simulation: Daniel Cutting, private communication

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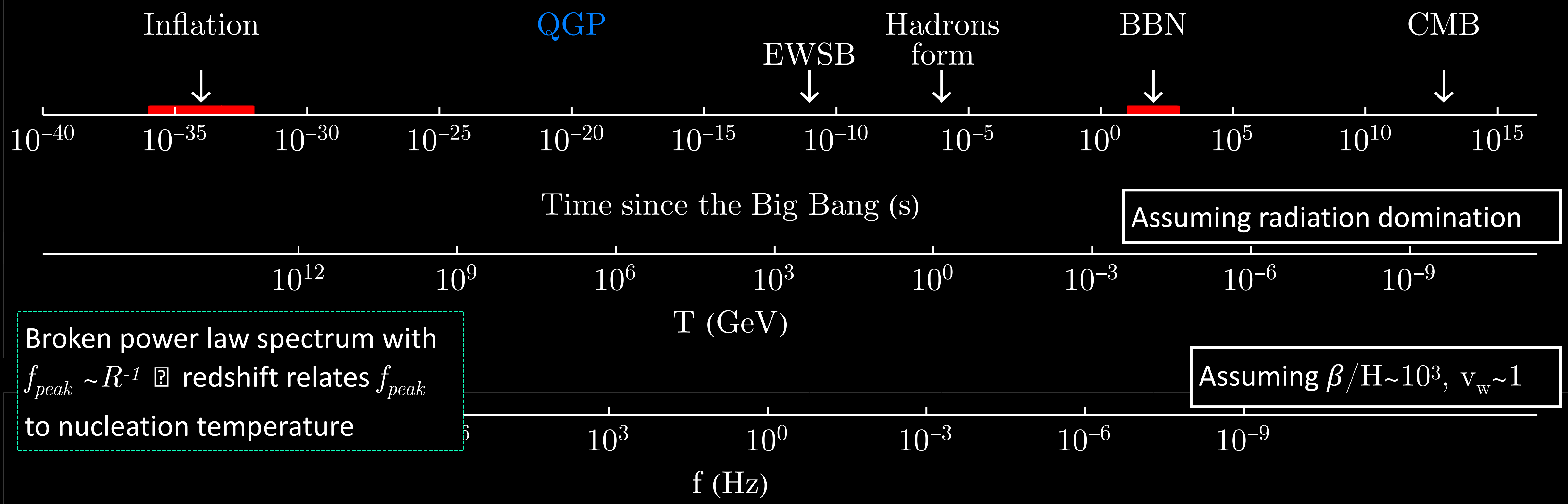

Assuming radiation domination

Broken power law spectrum with $f_{peak} \sim R^{-1}$? redshift relates f_{peak} to nucleation temperature

Assuming $\beta/H \sim 10^3$, $v_w \sim 1$

Gravitational waves released in the Early Universe travel unimpeded until today

Dark matter in the Early Universe

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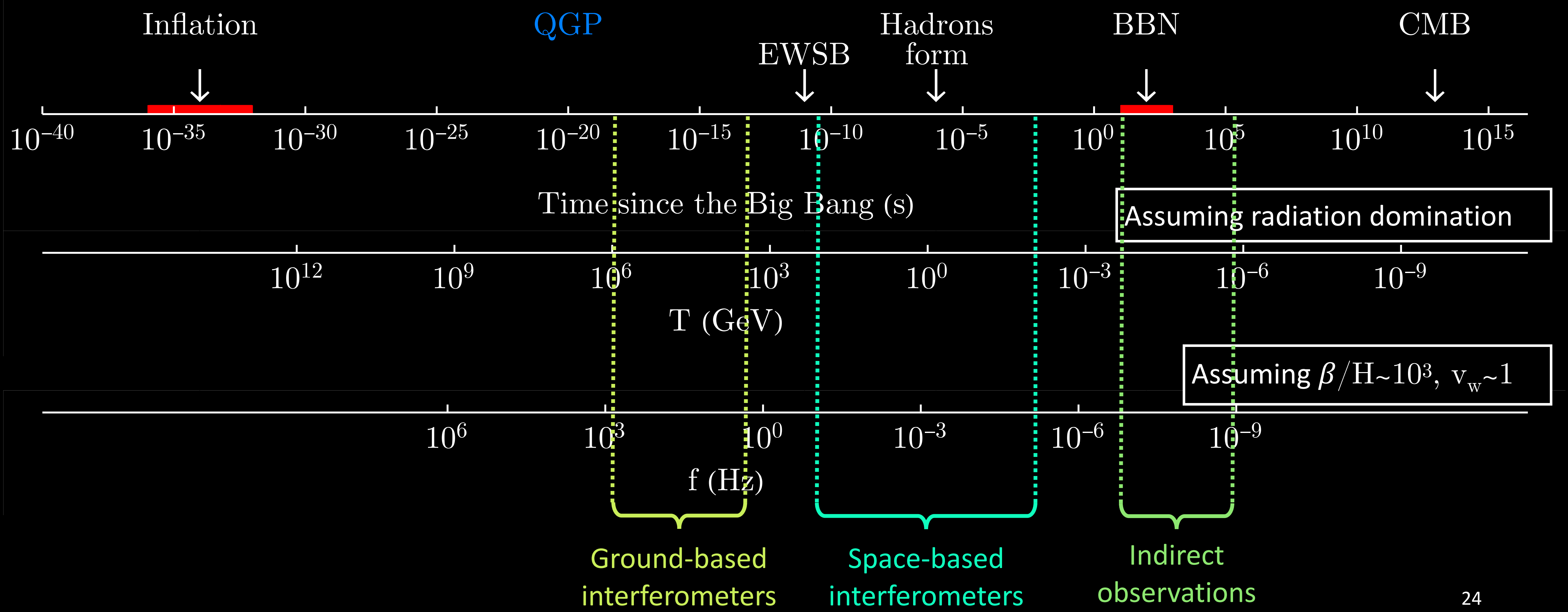
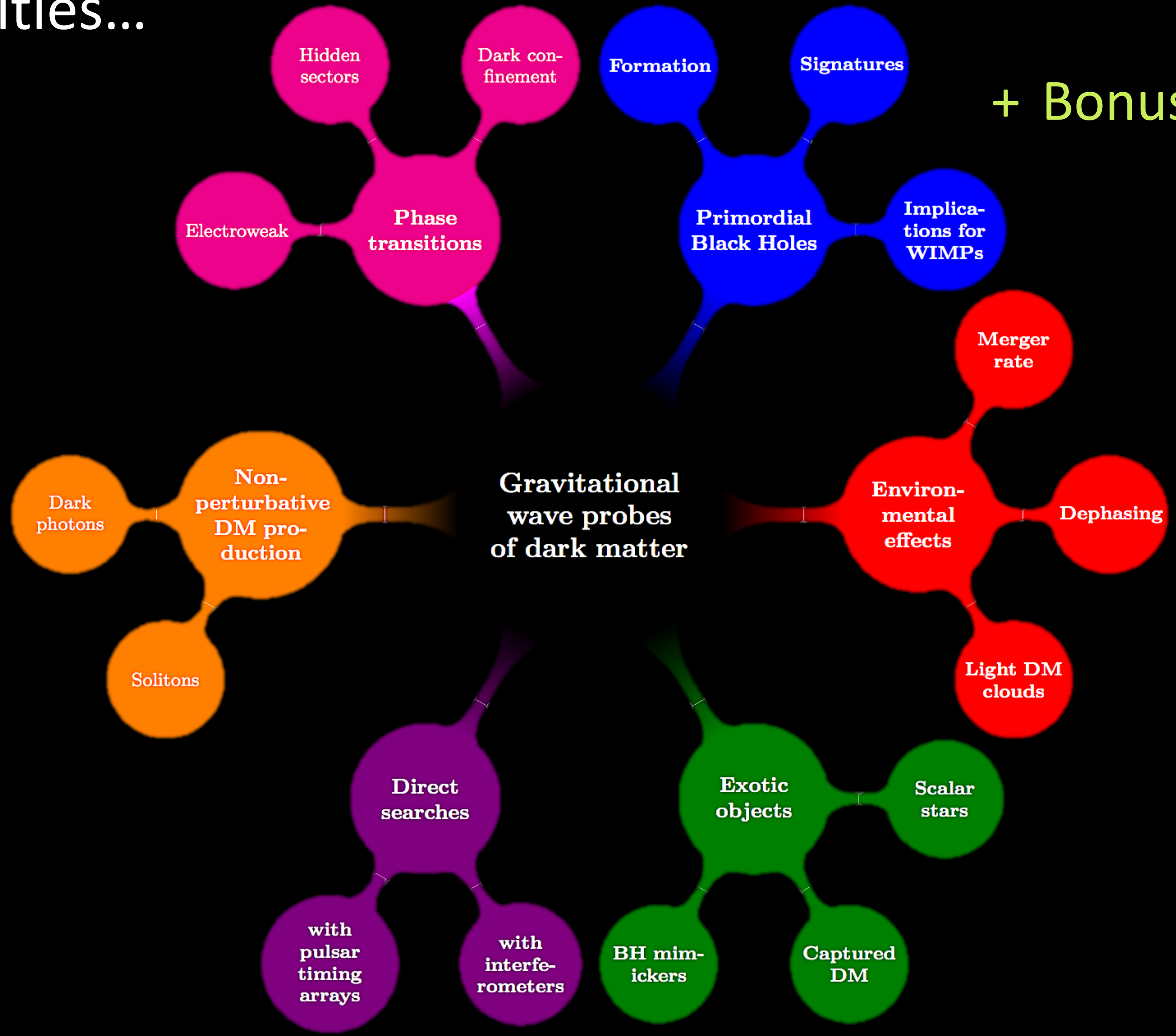


Many opportunities…

+ Bonus: population studies



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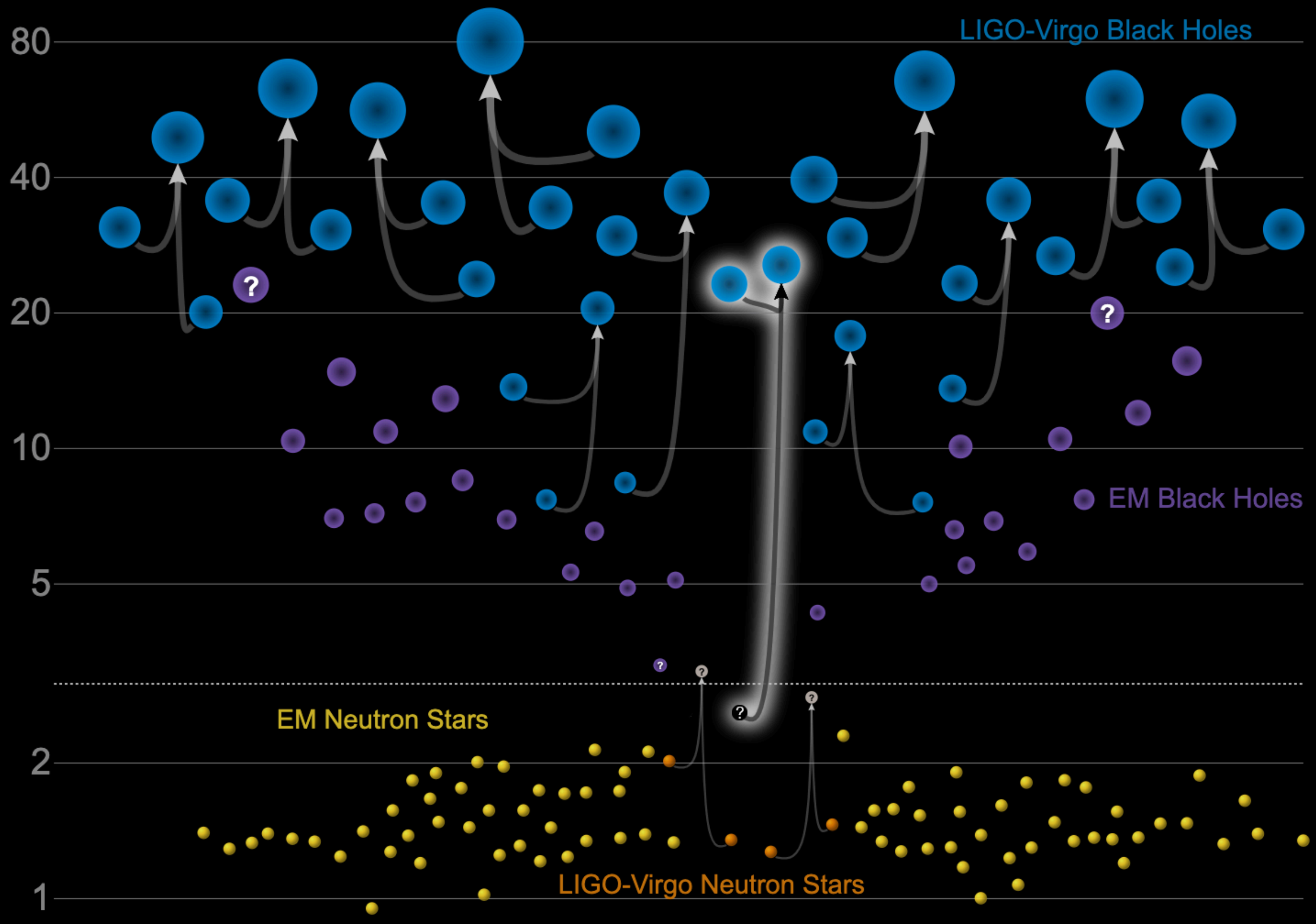
Population studies (LIGO/Virgo O1+O2)

"The Stellar Graveyard"



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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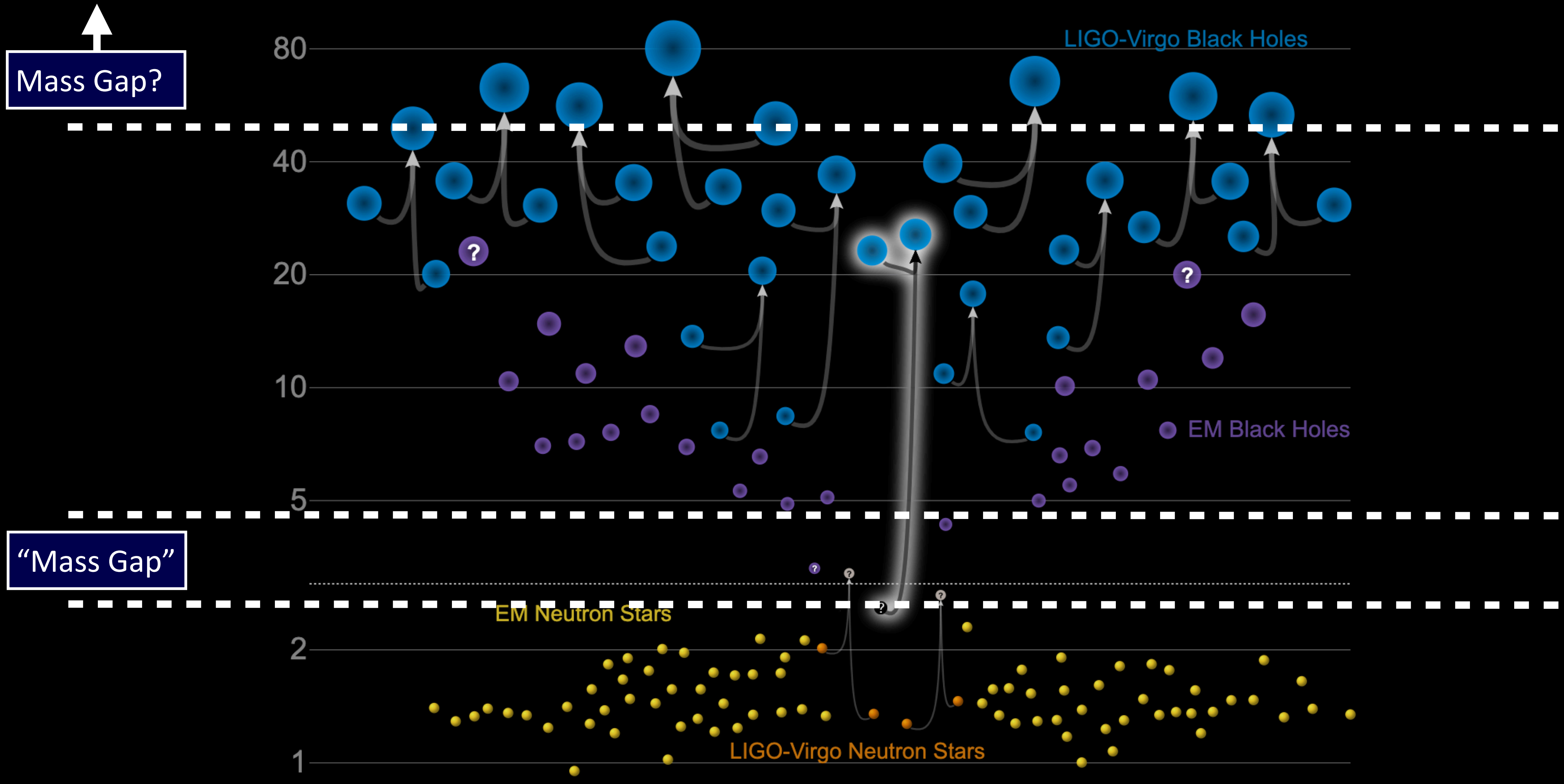

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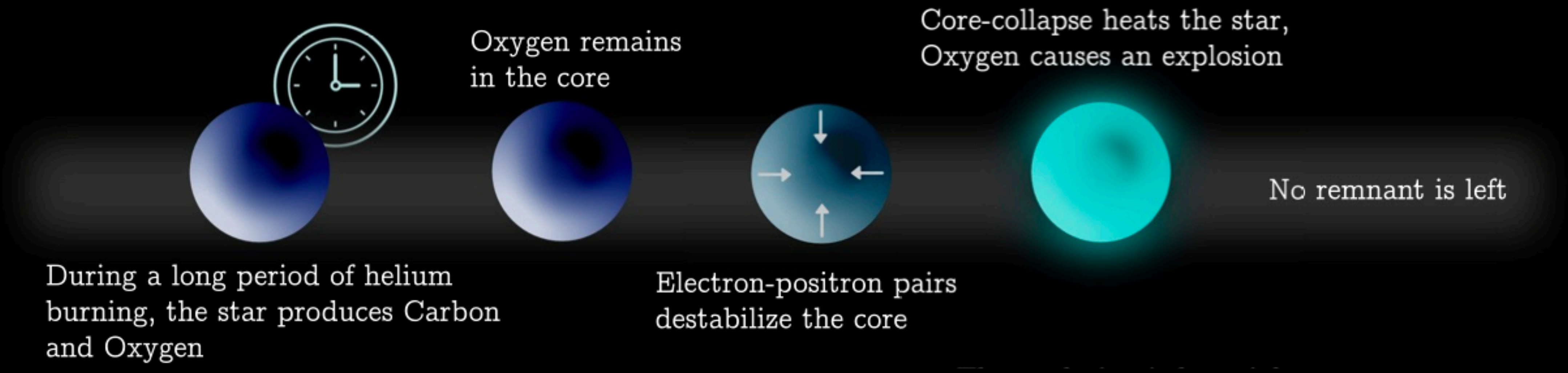
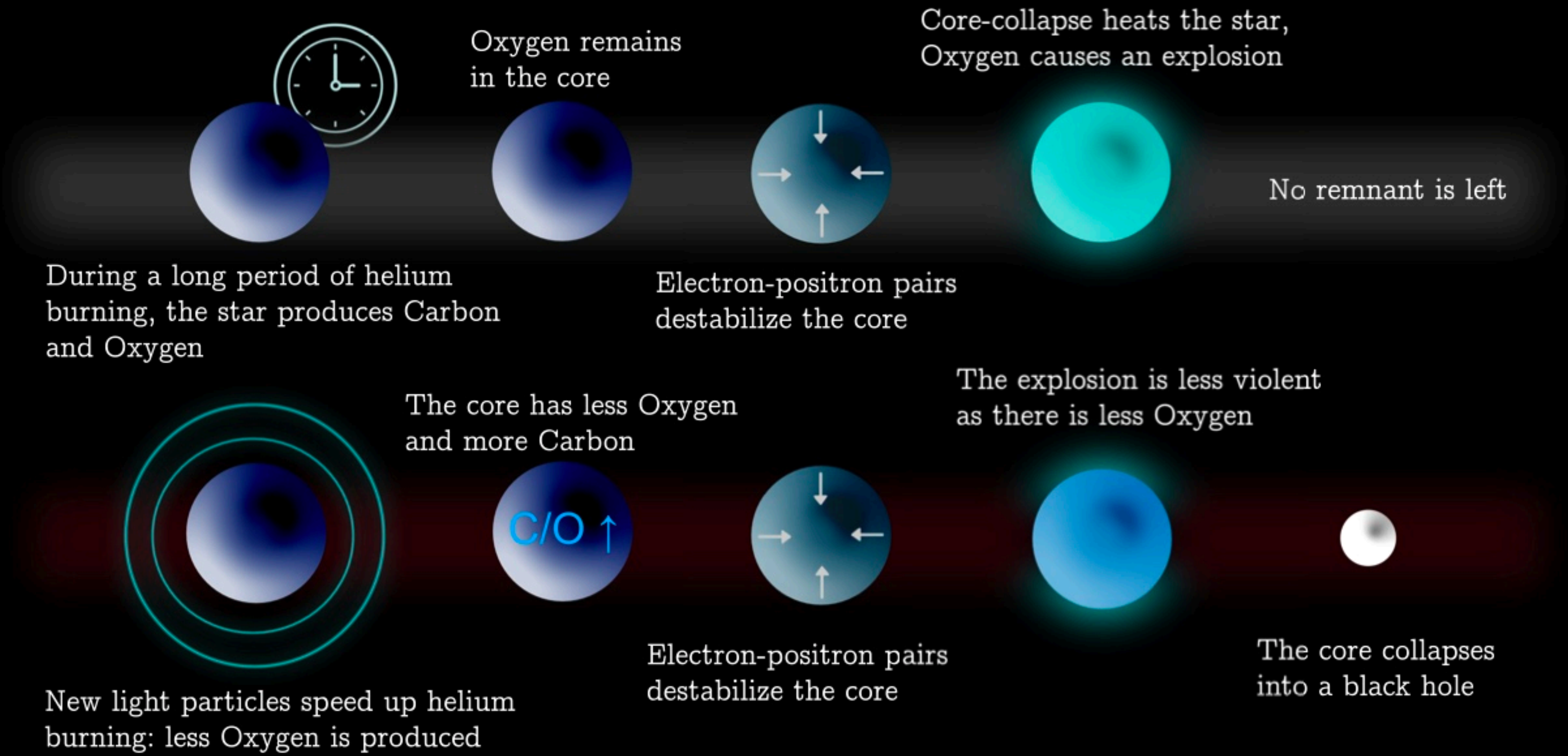
The black hole mass gap



The mass gap is a robust prediction from stellar structure theory

The black hole mass gap and BSM physics



New physics changes the location of the mass gap

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]; DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]; Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

To conclude,

- Gravitational waves offer an exciting new opportunity to study open questions in particle astrophysics and cosmology
- Uniquely, gravitational waves may offer a probe of the dark. We discussed a few examples, but there are others! *G. Bertone, DC, et al. arXiv:1907.10610*
- Ground, space and atom interferometers, as well as PTAs and astrometry give information across many decades in frequency
- We *will* learn more about dark matter through gravity!

Thank you!

…ask me anything you like!

dcroon@triumf.ca | djunacroon.com

Example ECO: boson stars

- Non-relativistic, ultralight scalars appear in many theories of particle physics → may condense into boson stars
- Many-body system with a single wave function → solve a simple set of equations to find the properties of the star

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

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

→ Einstein-Klein-Gordon equations for A, B, and Φ (NR limit: Schrödinger-Newton, but may miss effects, see *DC, J. Fan, C. Sun, [JCAP, arXiv:1810.01420]*)

- Stabilized against gravitational collapse by kinetic pressure or a repulsive self-interaction

Example ECO: boson stars

- Solutions for $M = M_{\rm ADM}$, $R = R_{90}$

$$R_{\rm max} \propto \sqrt{\lambda}\,\frac{M_p}{m^2}$$

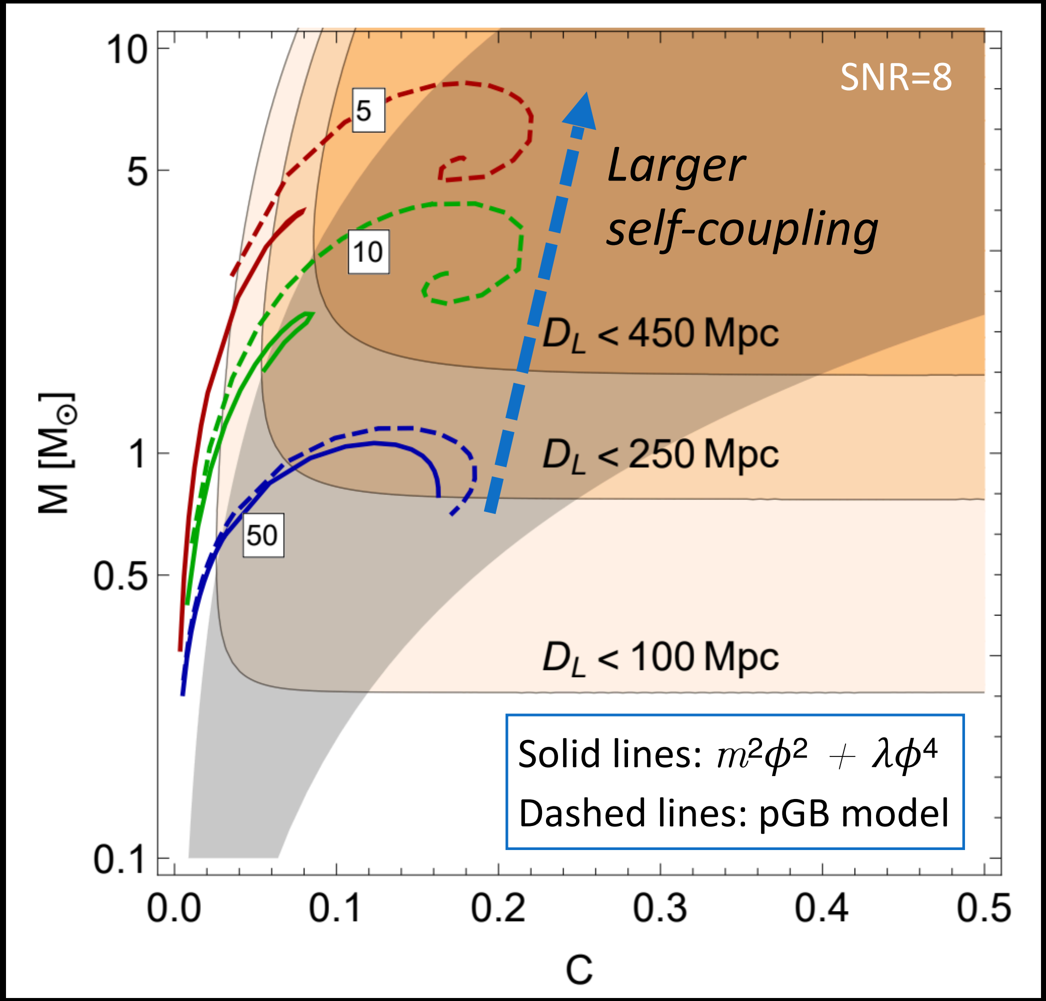
$$M_{\rm max} \propto \sqrt{\lambda}\,\frac{M_p^3}{m^2}$$

$\Bigg\}$ $C_{\rm max} \sim 0.1 - 0.2$

→ Similar to a neutron star

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

- Ultralight pGB have effective higher order interactions, resulting in a smaller compactness
- Tidal forces my distinguish boson stars



DC, Fan, Sun, [JCAP, 1810.01420]