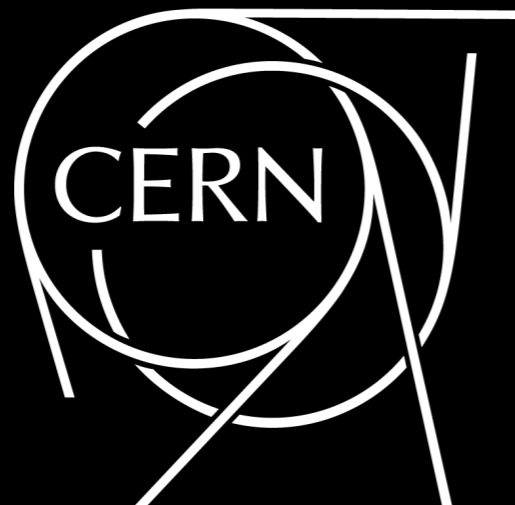


# Gravitational Waves and Dark Matter

Toby Opferkuch

CERN Theory Department

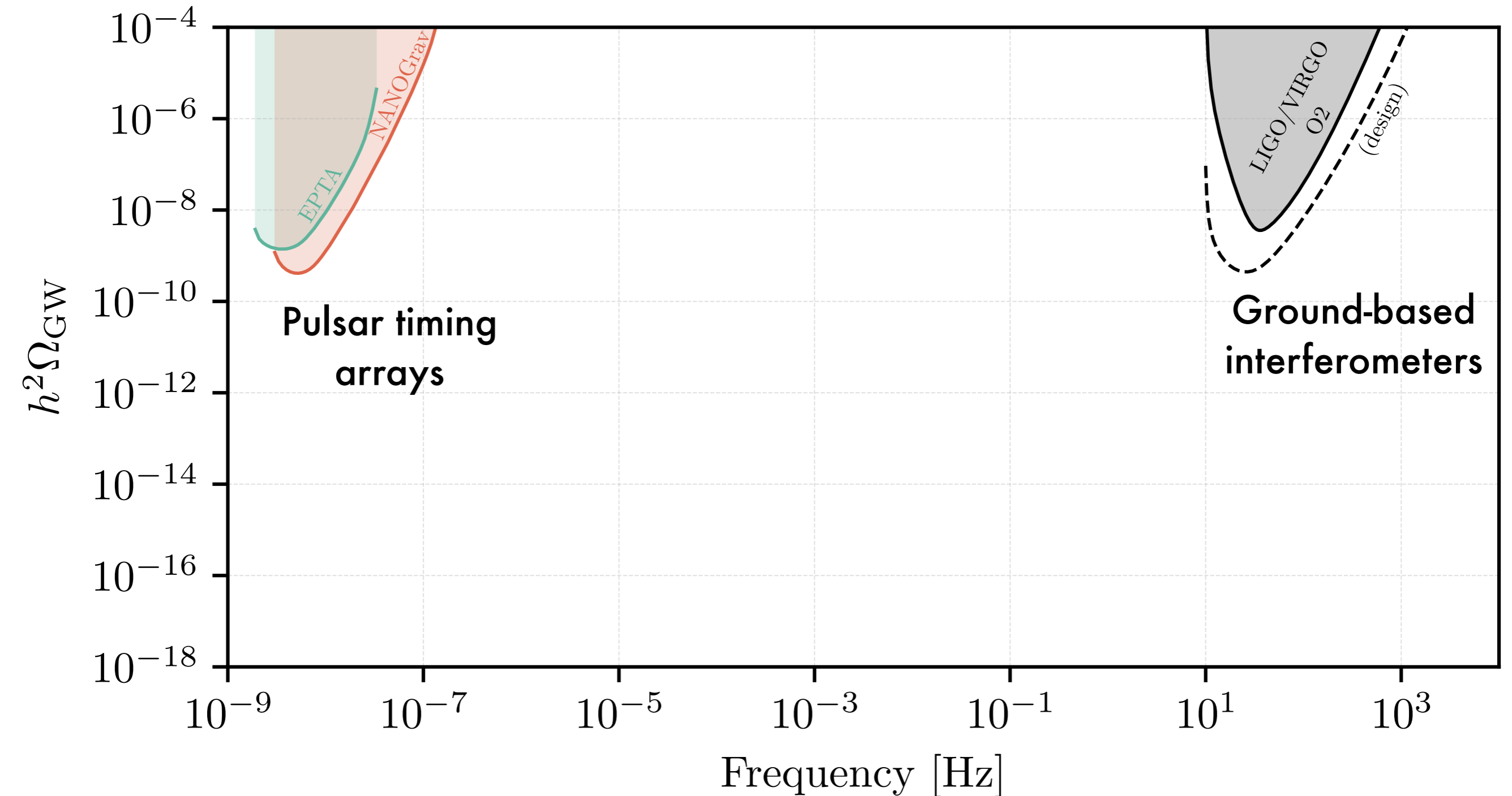
DM@LHC – DESY 4<sup>th</sup> June 2020



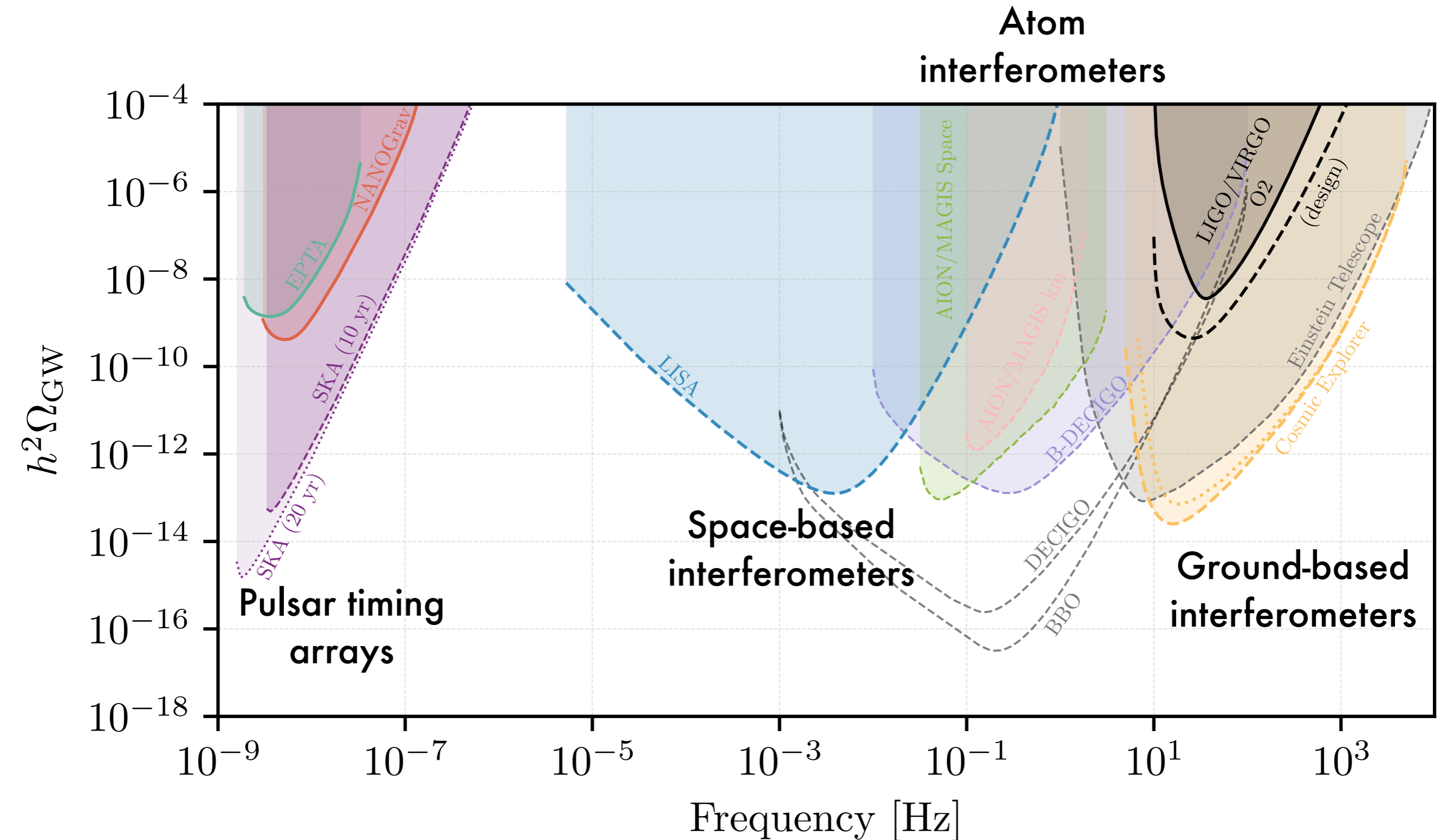
European Research Council

Established by the European Commission

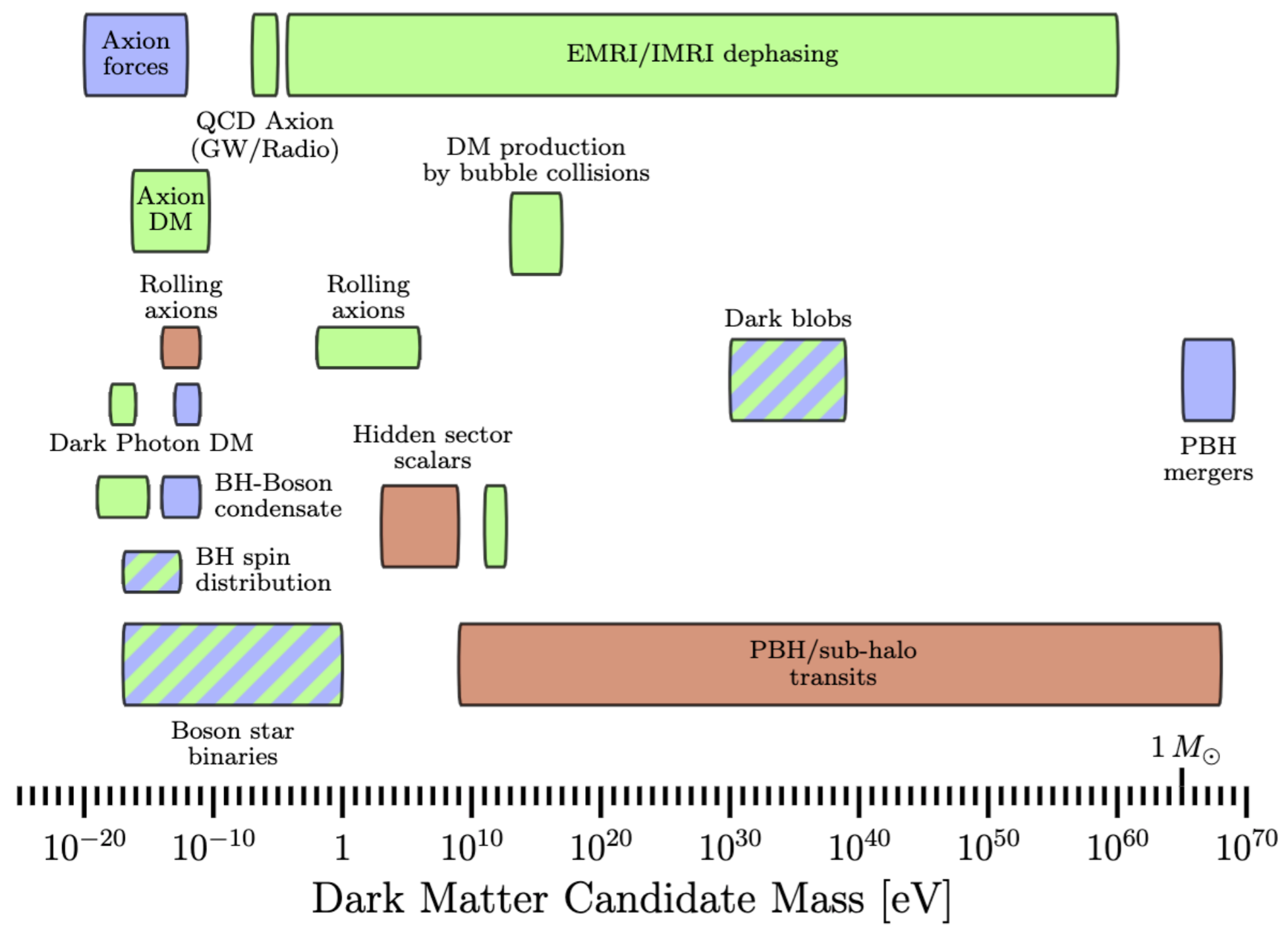
# Landscape of GW Experiments



# Landscape of GW Experiments



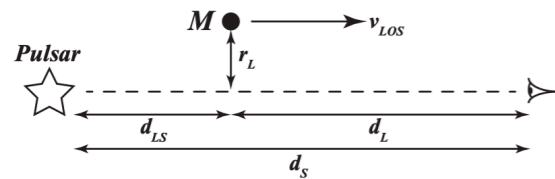
# Overview: GWs and Dark Matter



- Current Interferometers**
- Future Interferometers**
- Pulsar Timing Arrays**
- 
- Constraints**
- Axion forces [178]
  - QCD Axion (GW/Radio) [133]
  - EMRI dephasing [112, 113]
  - Axion DM [204]
  - Bubble collision DM [289]
  - Rolling axions [246]
  - Dark Photon DM [202]
  - Dark blobs [195]
  - PBH mergers [56, 62]
  - BH-boson condensate [122, 123]
  - Hidden-sector scalars [279, 280]
  - BH spin distribution [122, 123]
  - Boson stars [157, 158, 163, 166]
  - PBH/sub-halo transits [228, 229]

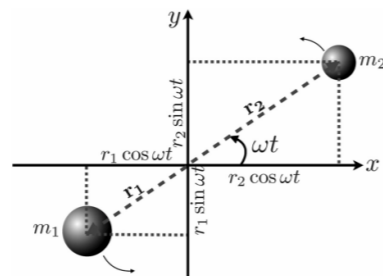
[Bertone, Croon, Amin, Boddy, Kavanagh, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, and Yu 1907.10610]

# Overview: GWs and Dark Matter



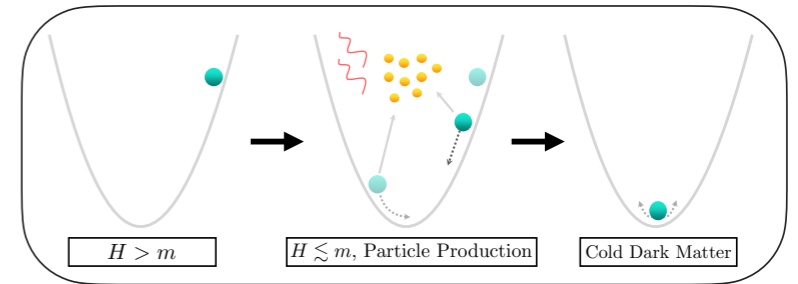
### PBH/sub-halo transits

See for example:  
 Schutz, Liu 1610.04234  
 Dror et. al. 1901.04490



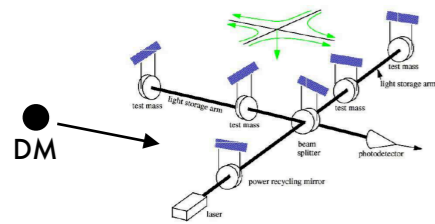
### PBH mergers & exotic compact objects

See for example:  
 De Luca et. al. 2005.05641  
 Koushiappas, Loeb 1708.07380  
 Ali-Haïmoud et. al. 1709.06576  
 Kavanagh et. al. 1805.09034  
 Croon et. al. 1810.01420  
 Giudice et. al. 1605.01209



### Early universe particle production

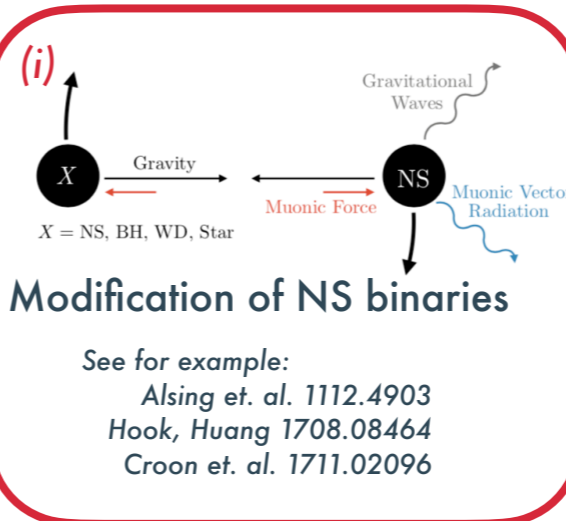
See for example:  
 Machado et. al. 1912.01007  
 Dufaux et. al. 0707.0875  
 Amin et. al. 1802.00444



### Additional forces on interferometer test masses

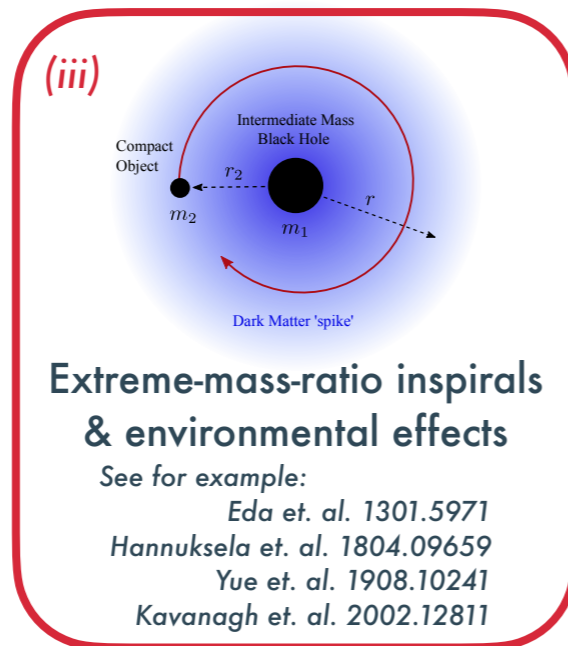
- axions
- dark photons
- macroscopic DM

See for example:  
 Pierce et. al. 1801.10161  
 Grabowska et. al. 1807.03788  
 Nagano et. al. 1903.02017



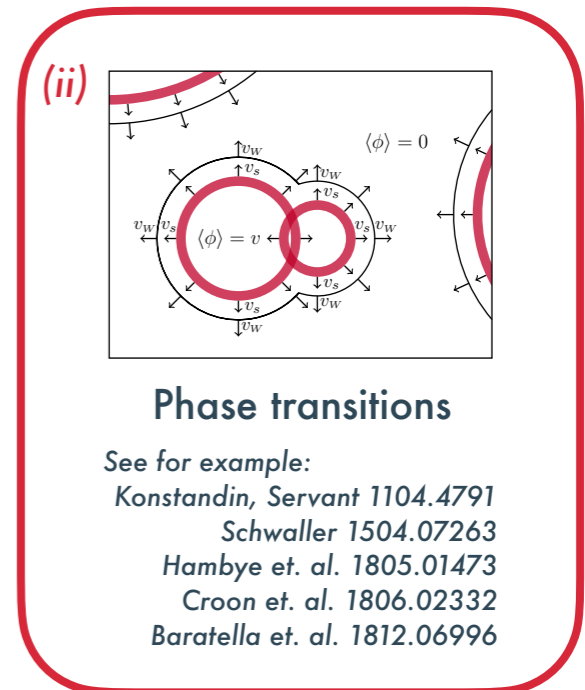
### Modification of NS binaries

See for example:  
 Alsing et. al. 1112.4903  
 Hook, Huang 1708.08464  
 Croon et. al. 1711.02096



### Extreme-mass-ratio inspirals & environmental effects

See for example:  
 Eda et. al. 1301.5971  
 Hannuksela et. al. 1804.09659  
 Yue et. al. 1908.10241  
 Kavanagh et. al. 2002.12811



### Phase transitions

See for example:  
 Konstandin, Servant 1104.4791  
 Schwaller 1504.07263  
 Hambye et. al. 1805.01473  
 Croon et. al. 1806.02332  
 Baratella et. al. 1812.06996

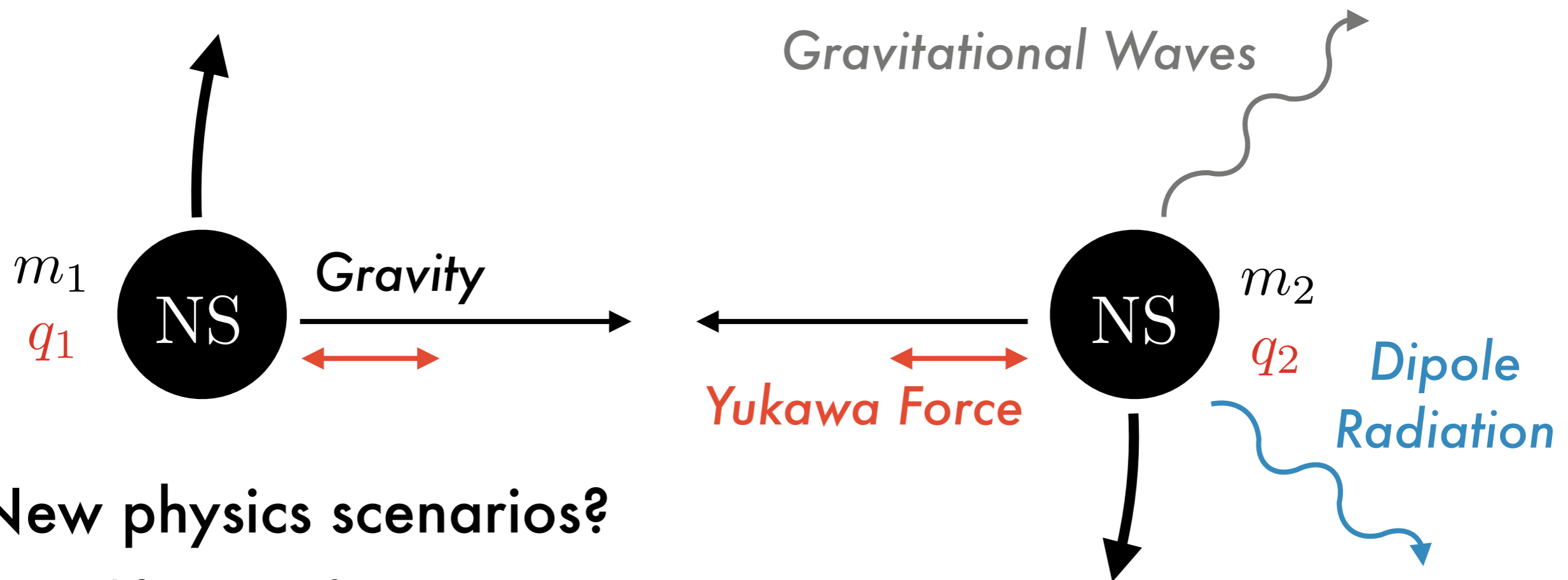
Astro-/cosmological abundance

GW production mechanism

Production/other dynamics

# Modification of NS Binaries

- Observable:



- New physics scenarios?

- Modifications of gravity

[Alsing et. al. 1112.4903; Sagunski et. al. 1709.06634]

- Fifth forces (e.g. axionic forces)

[Hook, Huang 1708.08464]

- Forces coupled only to DM

[Croon et. al. 1711.02096; Kopp, Laha, Opferkuch, Shepherd 1807.02527]

[Alexander et. al. 1808.05286; Fabbrichesi & Urbano 1902.07914]

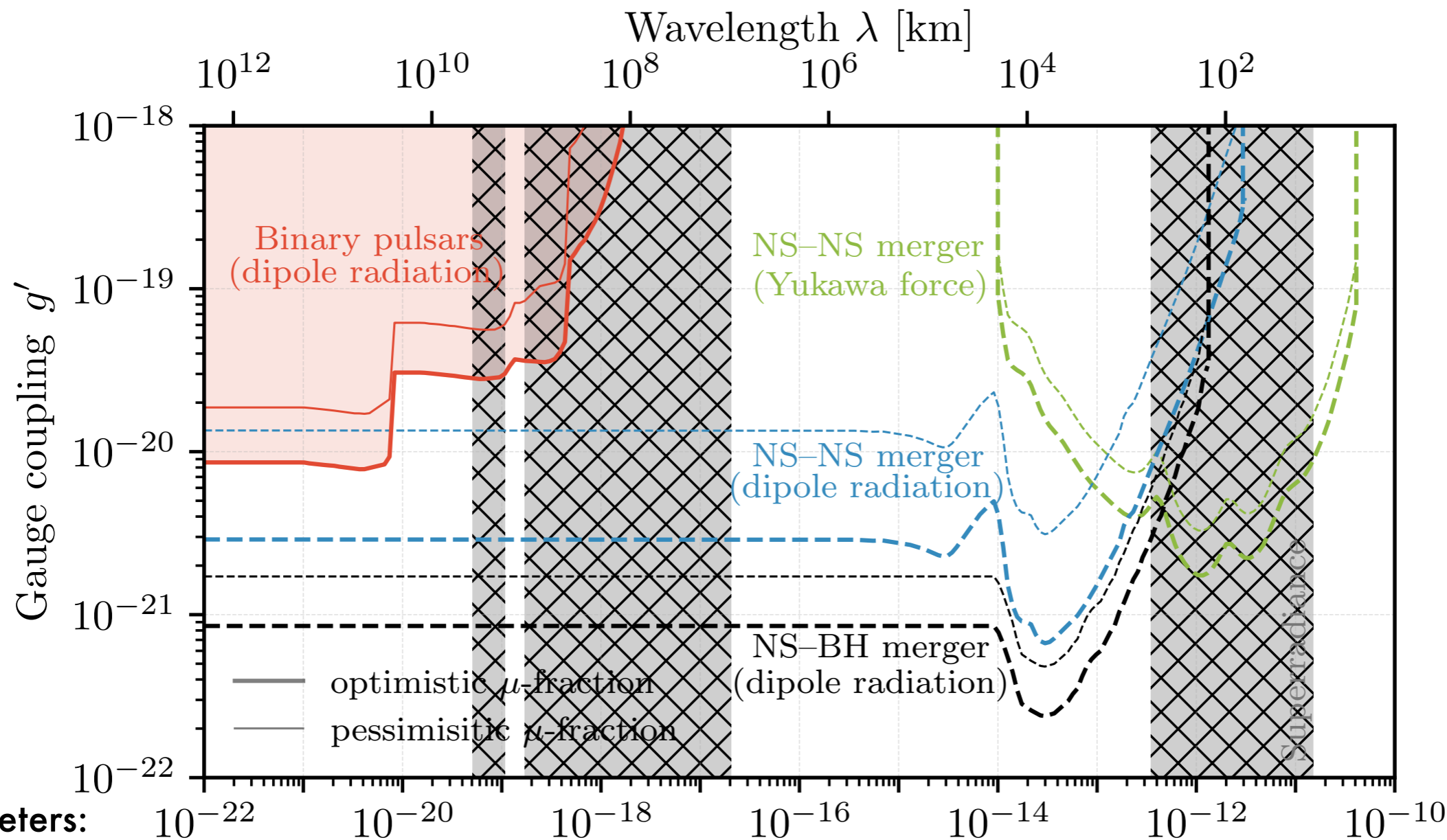
- Muonic Forces

[Dror, Laha, Opferkuch 1909.12845]

**sensitivity to**  
 $m \lesssim \mathcal{O}(10^{-10} \text{ eV})$

# Modification of NS Binaries

Large NS muon abundance  $\implies$  Constraints on ultra-light gauged  $L_\mu - L_\tau$  bosons



Parameters:  $10^{-22}$   $10^{-20}$   $10^{-18}$   $10^{-16}$   $10^{-14}$   $10^{-12}$   $10^{-10}$

low spin  $m_1 = 1.46M_\odot$

Vector boson mass  $m_V$  [eV]

[Dror, Laha, Opferkuch 1909.12845]

$D_{\text{eff}} = 40$  Mpc  $m_2 = 1.27M_\odot$

# Phase Transitions

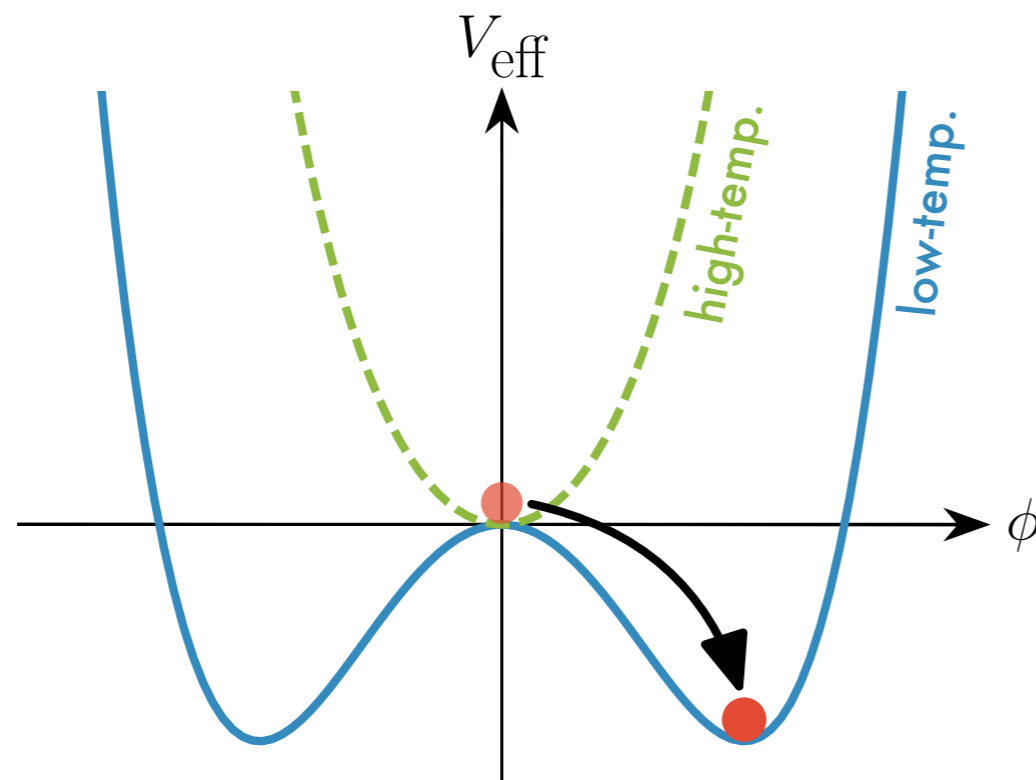
Particle physics:

**(i) Spontaneous Symmetry Breaking**

**(ii) Confinement**

Type:

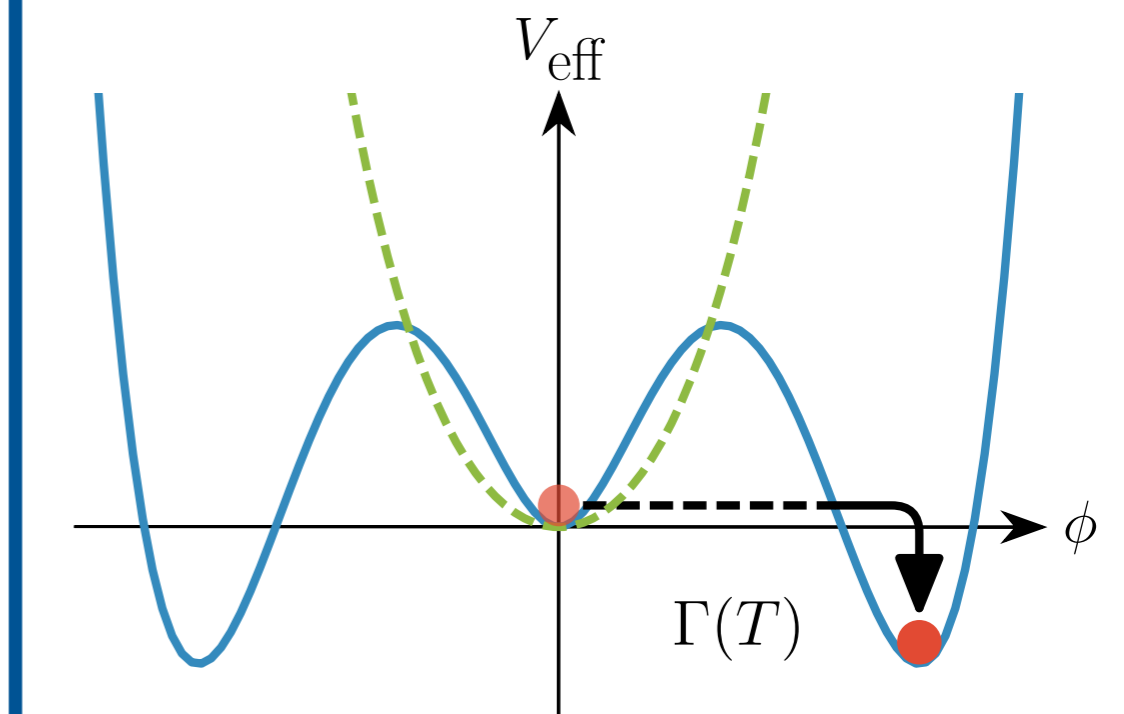
**Cross-over**



Example:

*EW symmetry breaking in SM*  
*QCD confinement (3 massless flavours)*

**1<sup>st</sup>-order**

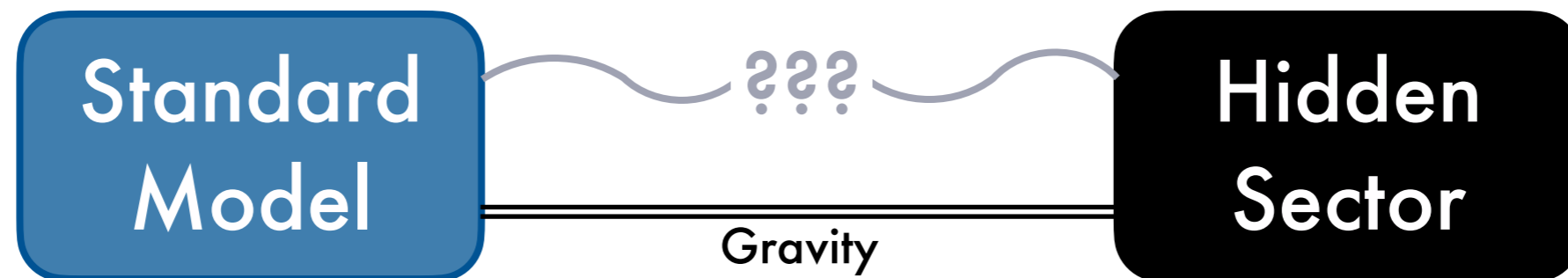


**Stochastic GW background!**

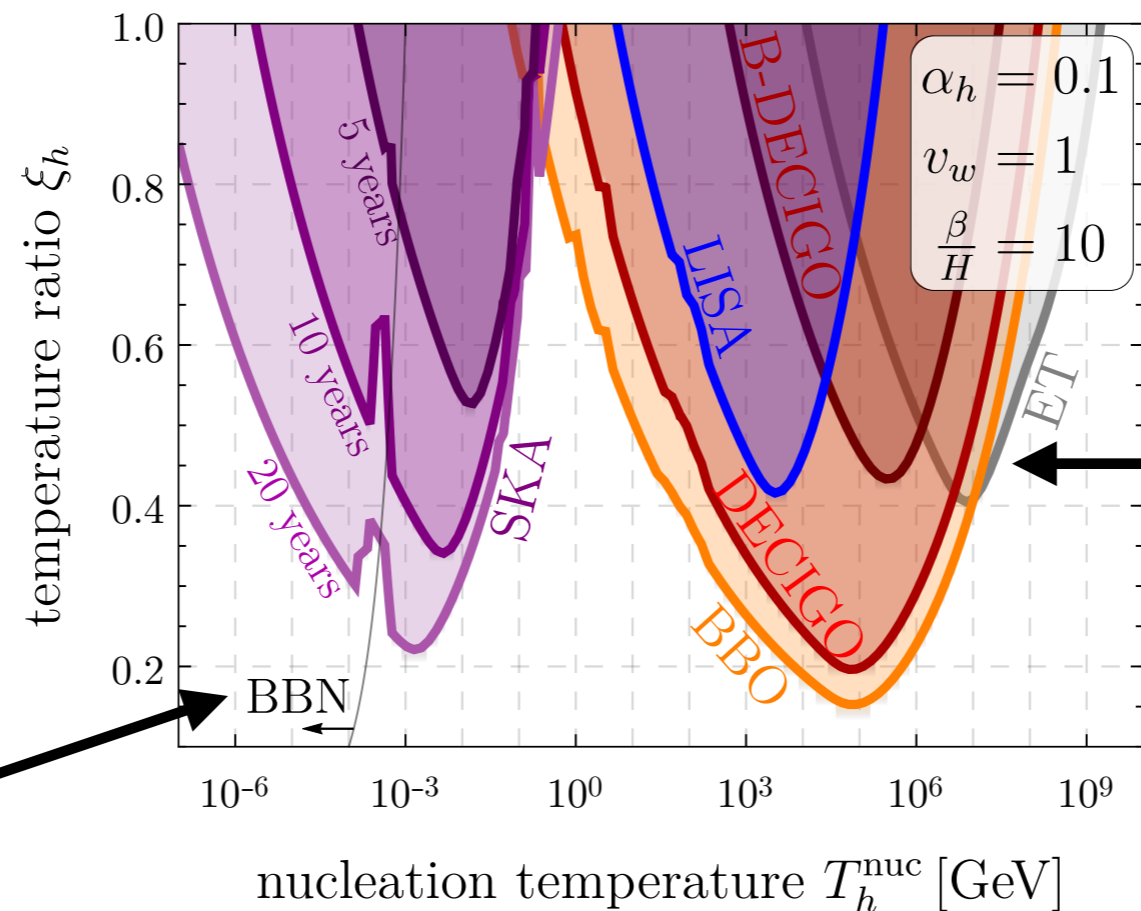


# Phase Transitions

- Sensitivity to hidden sector transitions:



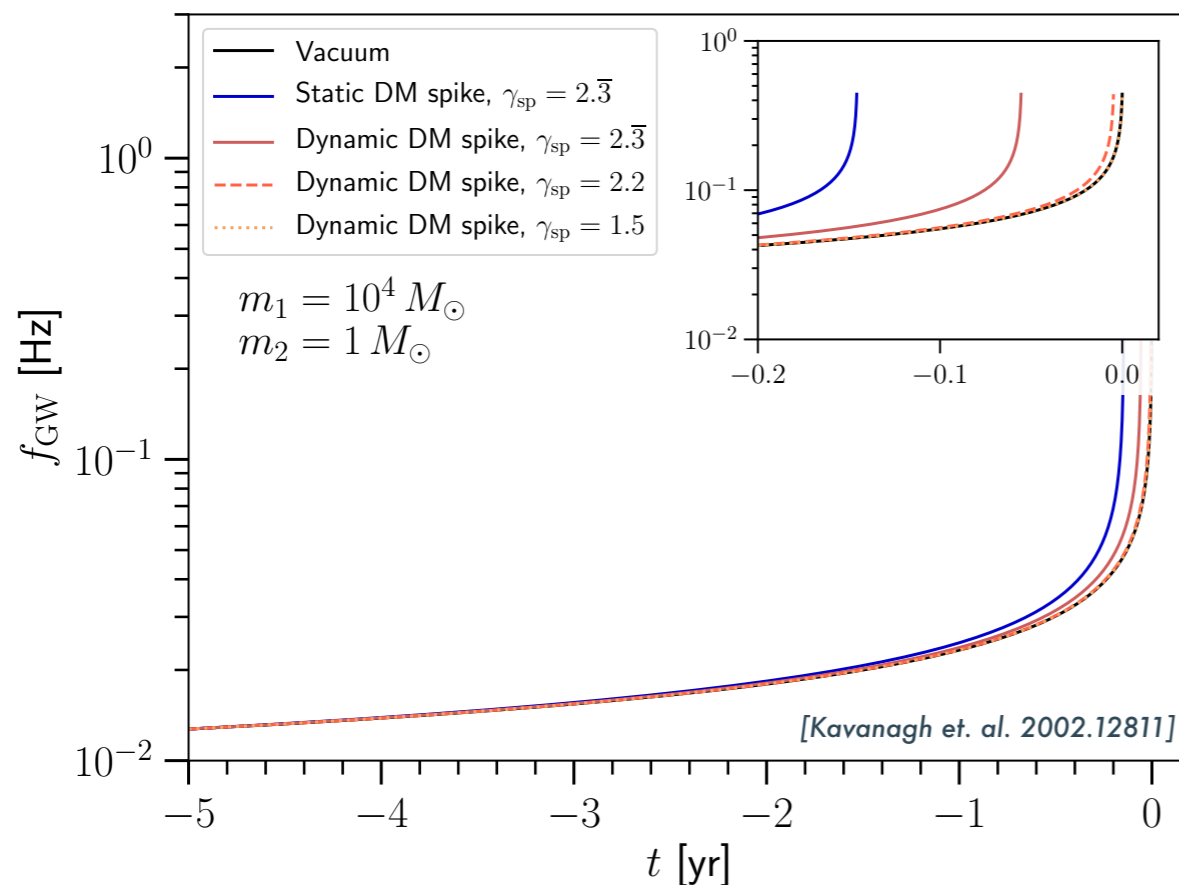
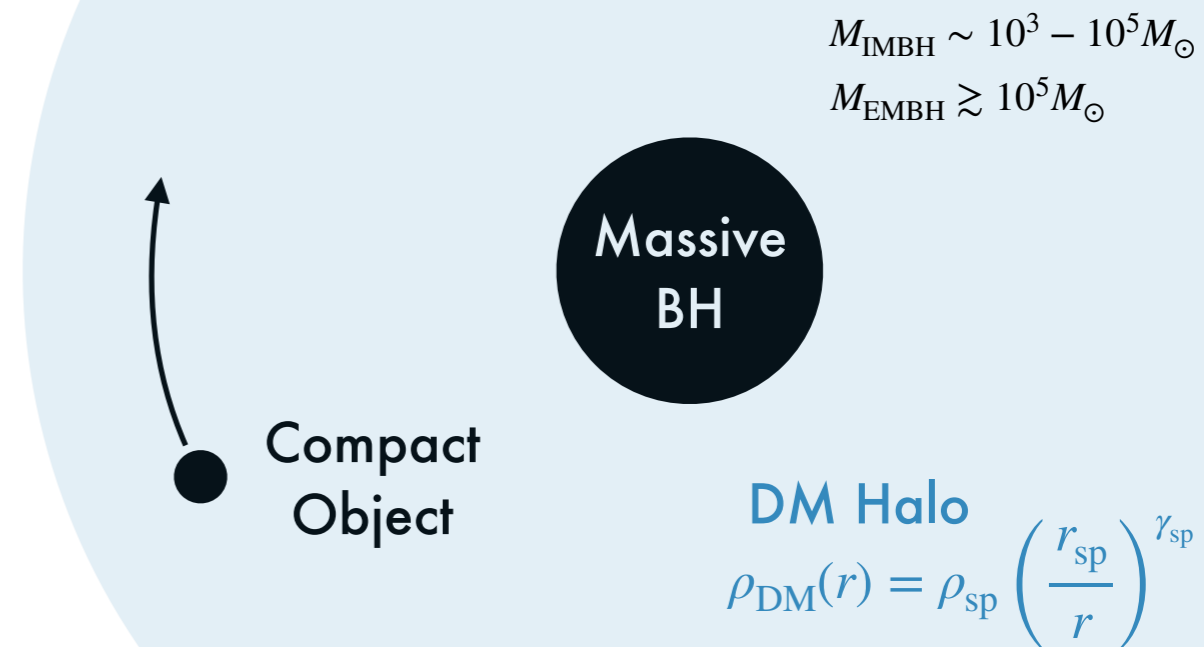
Stringent  
cosmological  
constraints



Reach far beyond  
foreseeable  
collider program

# Extreme-Mass-Ratio Inspirals

- LISA will observe at least  $\mathcal{O}(10)$  EMRIs per year
- Sensitivity arises from long duration of waveform obs.



- Gravitational interactions of DM impart dynamical friction

[see Lancaster et. al. 1909.06381 and references therein]

- Sensitivity to DM spikes via:
  - de-phasing of GW waveform
  - increased eccentricity

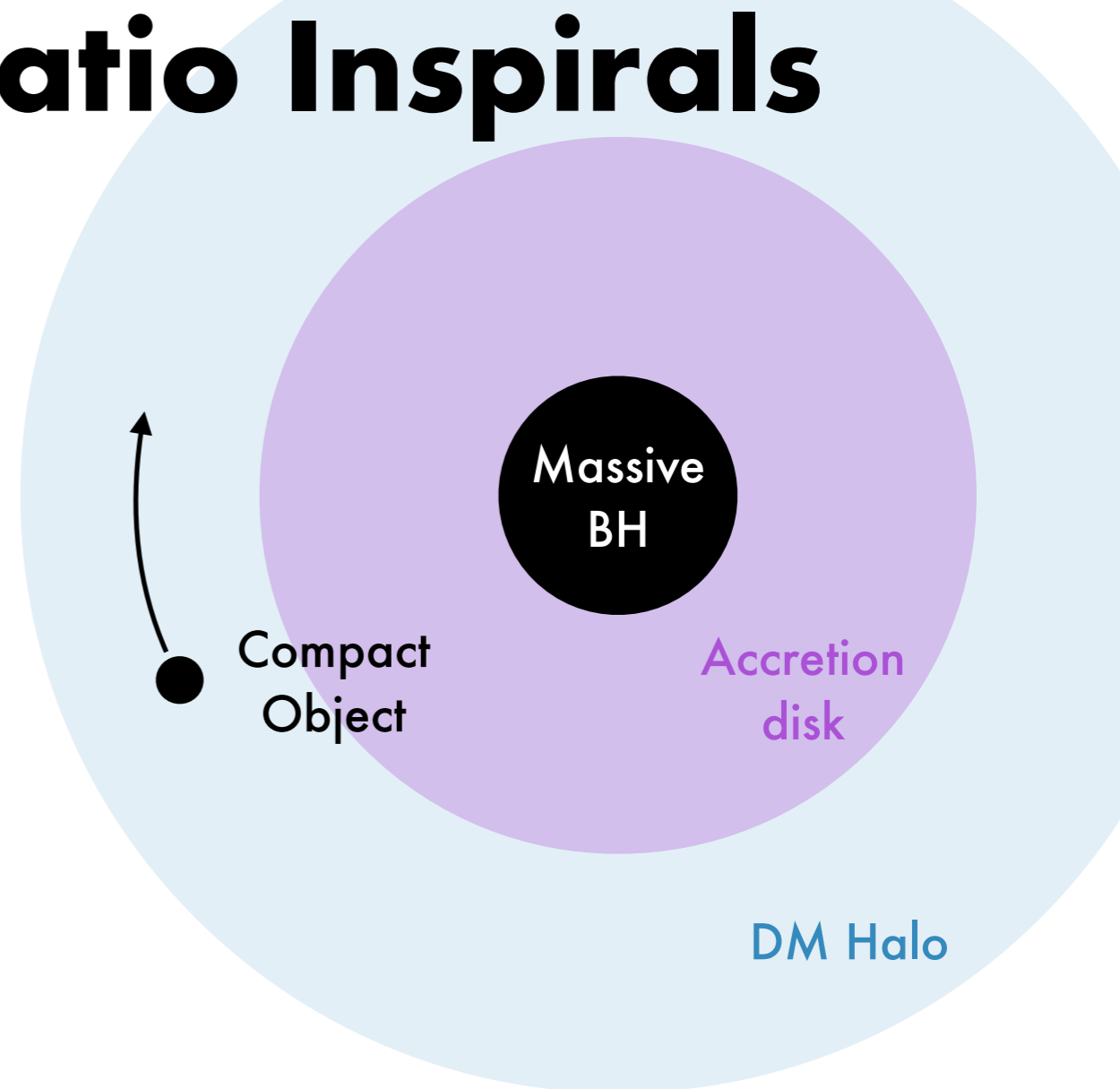
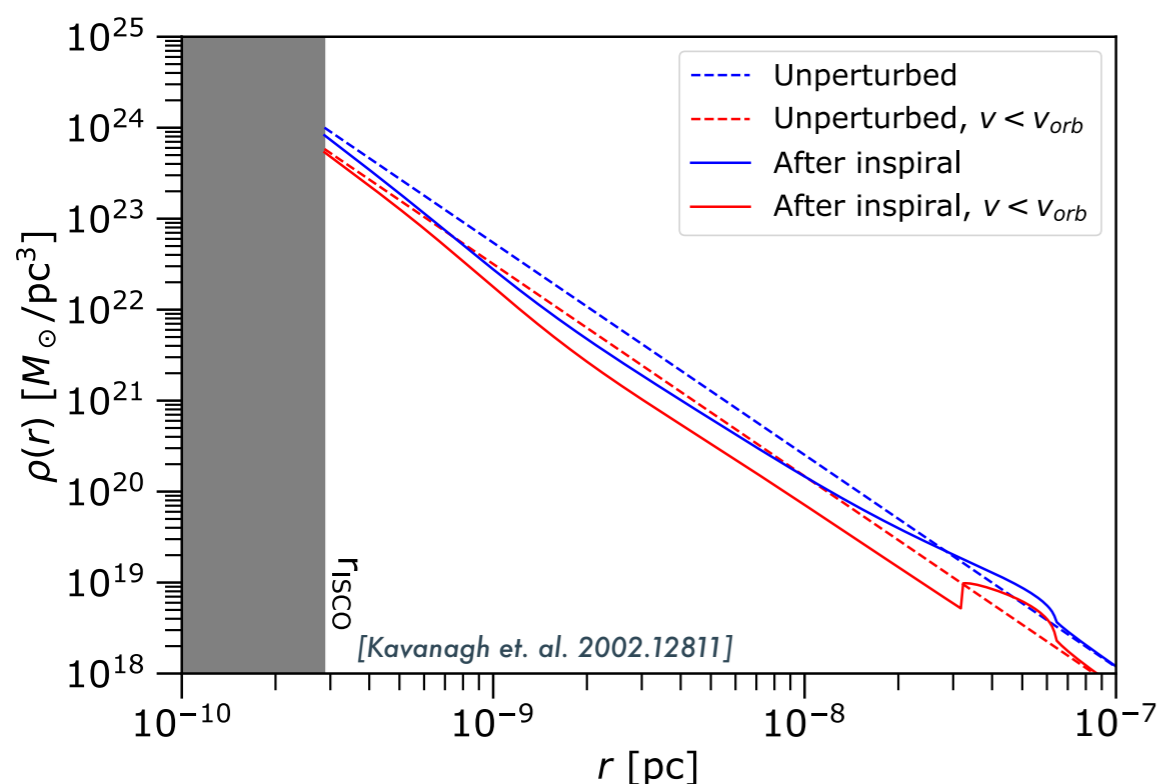
[Eda et. al. 1301.5971, 1408.3534]

[Yue et. al. 1908.10241]

# Extreme-Mass-Ratio Inspirals

## ● Challenging systems:

- Waveform difficult to calculate
- Accretion disk and other astrophysical nuisances
- DM stripping from mergers



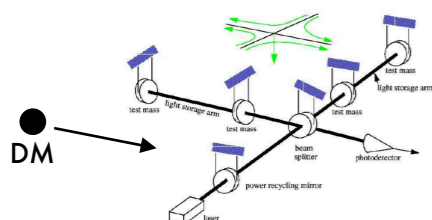
## ● Current on-going work:

[Croon, Kopp, Laha, Opferkuch]

- Simulating accretion disks and merging accurate GW calculations
- Beyond DM spikes

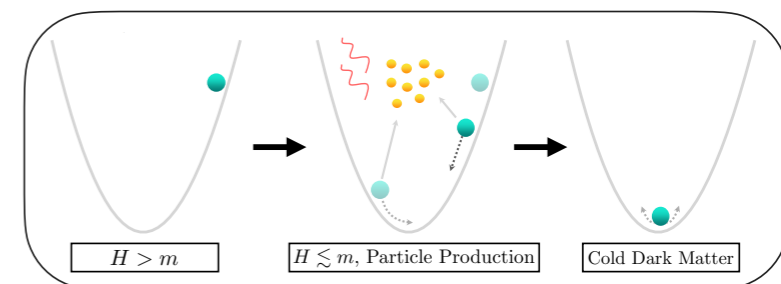
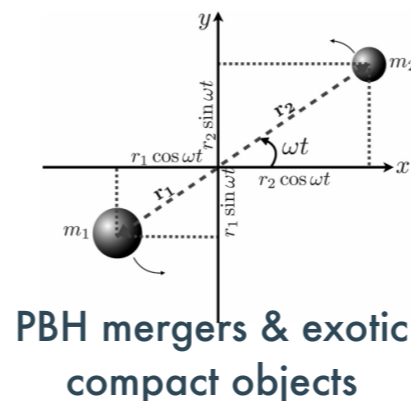
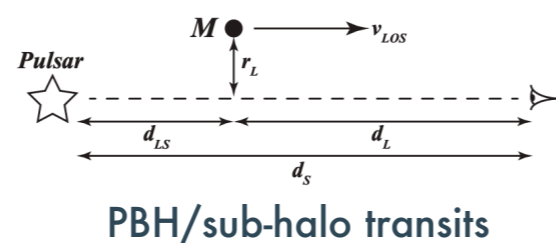
# Take Home Message

- GWs provide a complementary probe of DM scenarios neigh impossible to see with traditional collider probes
- This talk was just a small taste – many more exciting phenomena not discussed here!



Additional forces on interferometer test masses

- axions
- dark photons
- macroscopic DM



Early universe particle production