Probing Dark Matter with Gravitational Waves in the LIGO, LISA and PTA Range

Laura Sagunski

GOETHE UNIVERSITÄT

D | M | G | W Dark Matter Modified Gravity Gravitational Waves

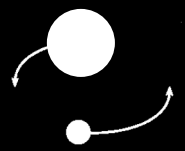
ITP

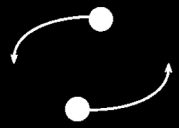
Probing DM with GWs

Cosmological phase transitions in models with DM candidates

DM halos around merging supermassive black holes

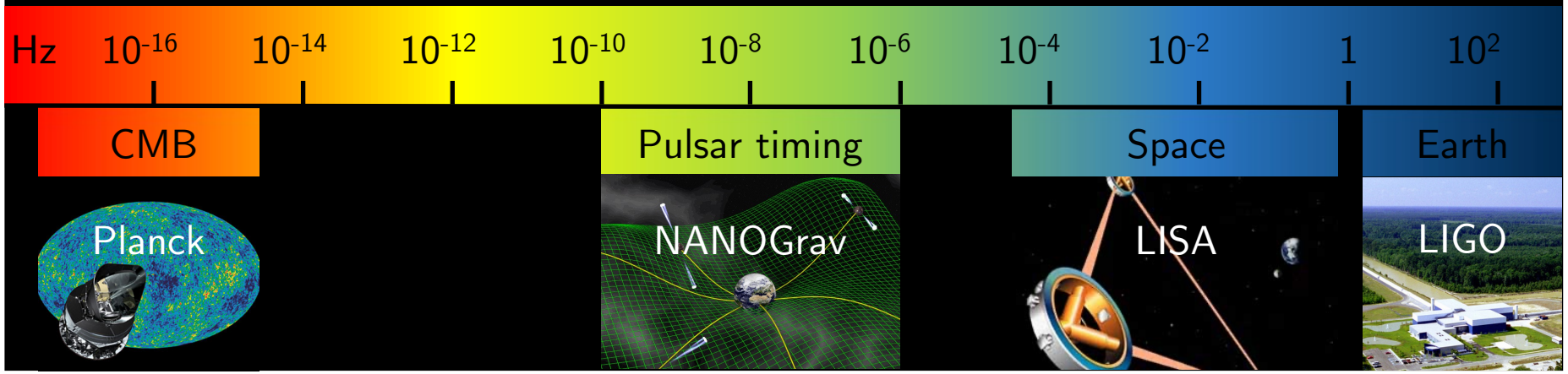
DM spikes in intermediate mass ratio inspirals



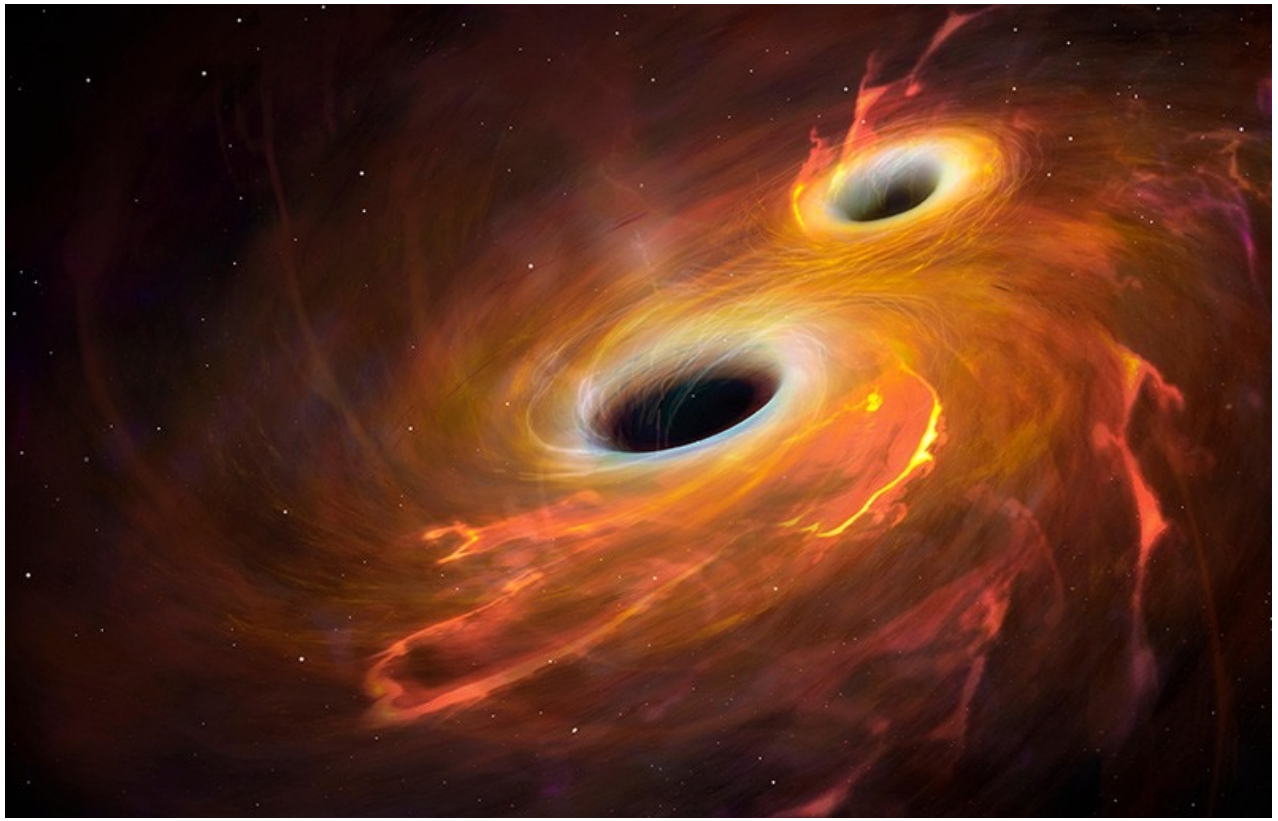


Neutron stars with DM halos/cores

DM effects in rotating neutron stars



On Sep 14, 2015, a dramatic event has taken place...

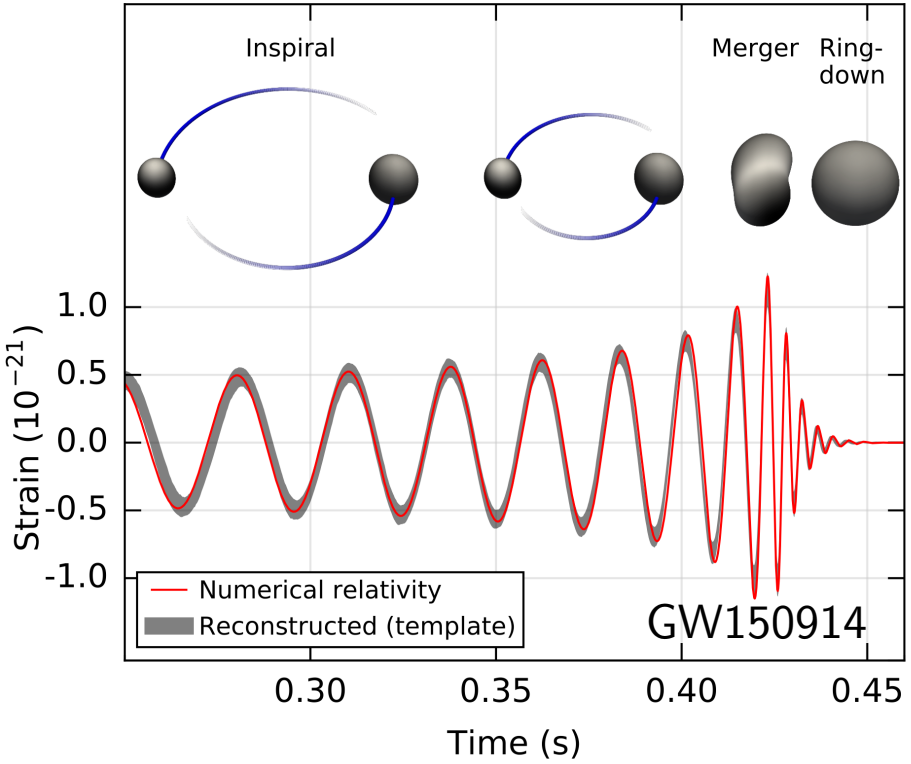


[nature.com/articles/d41586-020-03047-0]

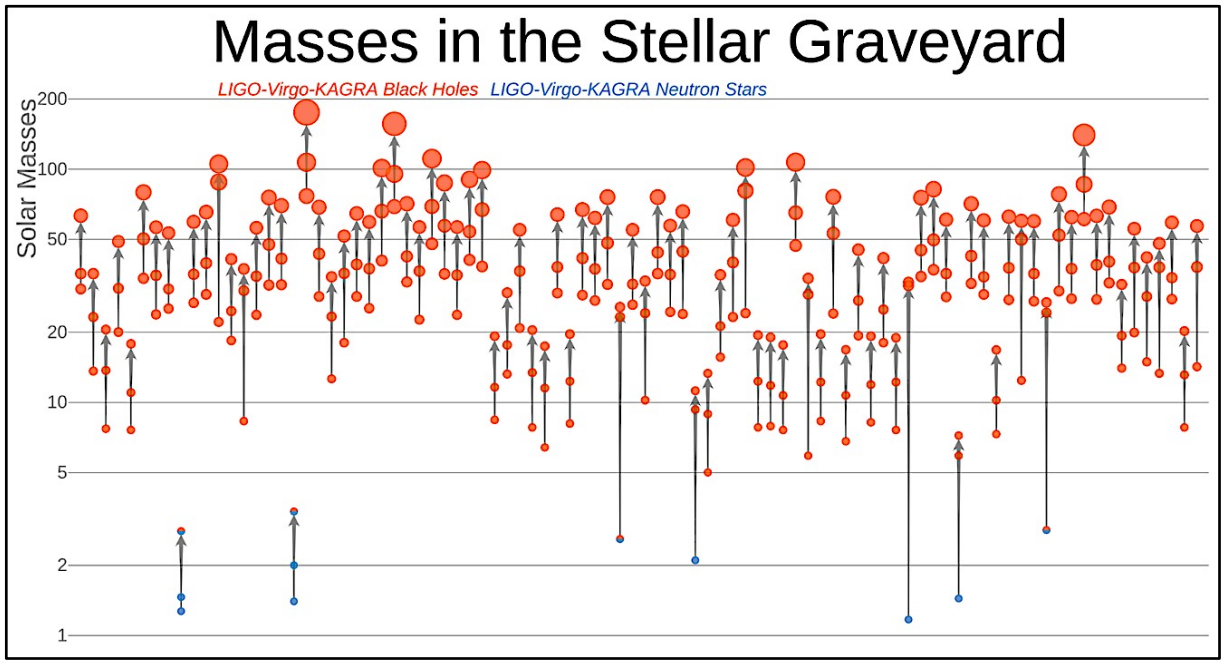
→ GW150914: first ever direct detection of GWs!

GWs from binary mergers

= Target of GW detectors such as LIGO and Virgo



[www.ligo.org/science/faq.php]



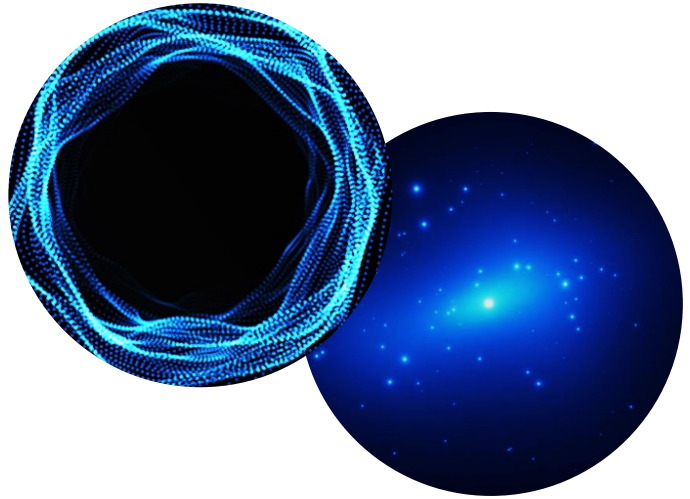
Adapted from: [LIGO-Virgo-KAGRA, Aaron Geller]

The GW era has just begun...

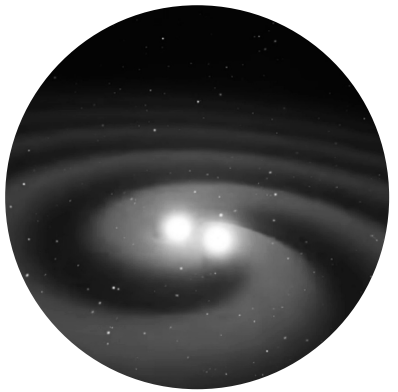
... and a whole new incredible Universe is waiting out there to be explored!

Binary mergers
= cosmic labs

New physics!



GWs
= smoking-gun signals



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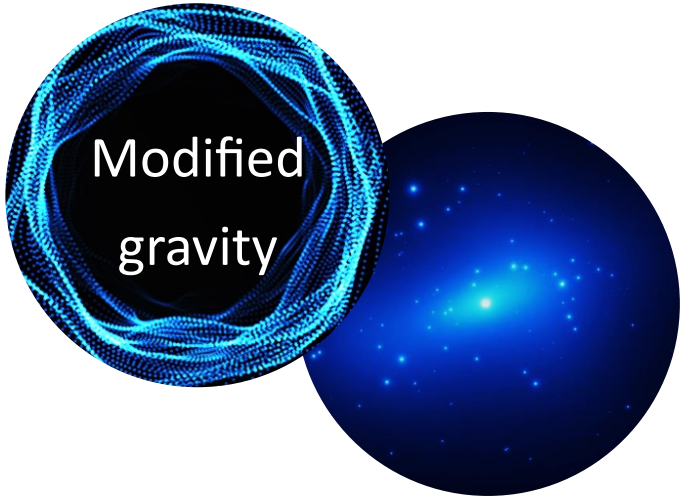

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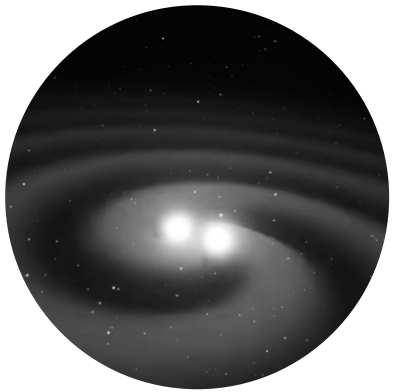

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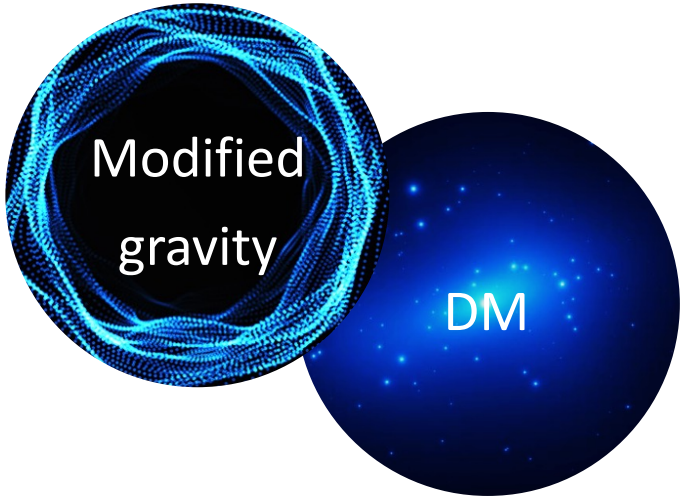

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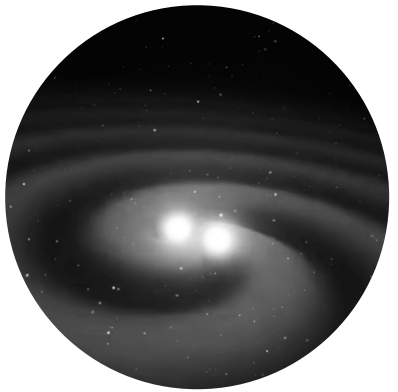
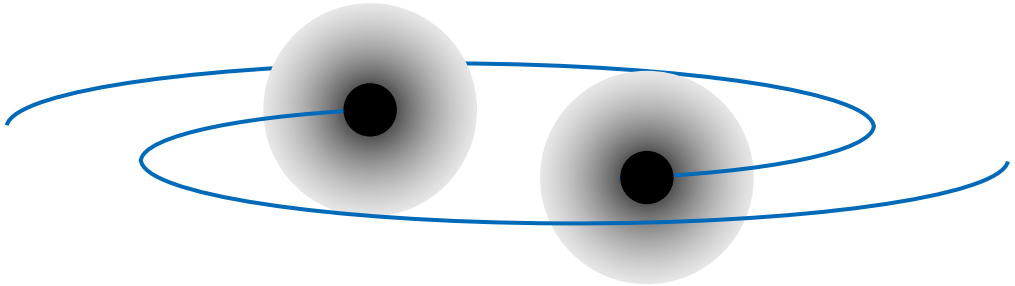


Probing DM with GWs

[NASA/Swift, Dana Berry]

Example:

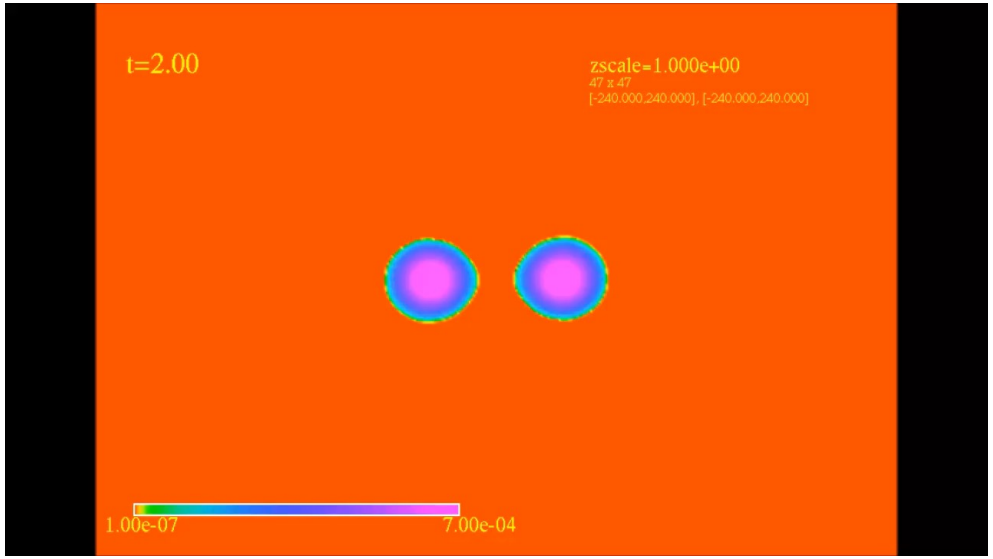
DM halos around neutron stars:



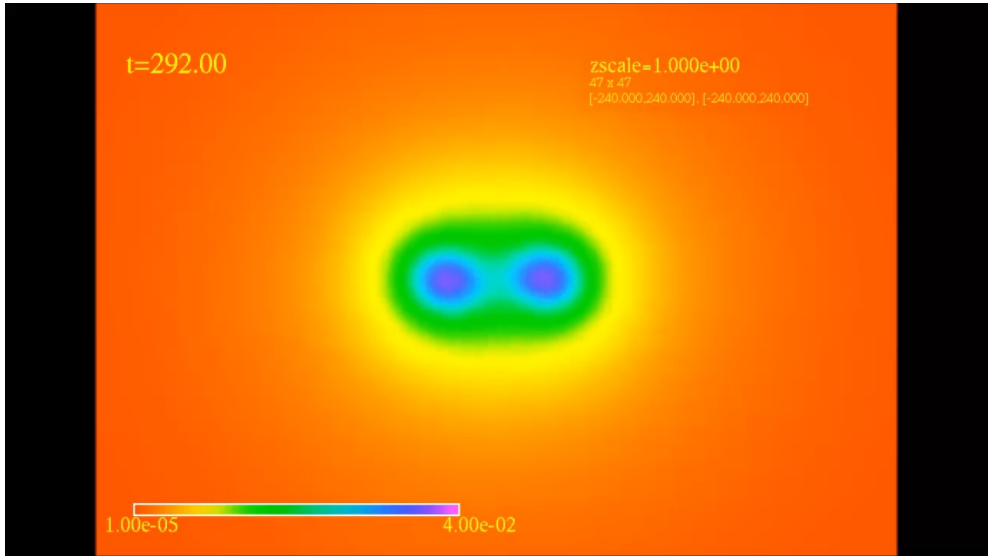
→ What happens?

DM halos around neutron stars

Neutron star density ρ



Scalar field φ



$$M_1 = M_2 \equiv 1.2 M_\odot$$

[LS, Zhang, Johnson, Lehner, Sakellariadou, Liebling, Palenzuela, Neilsen, '18]

[www.had.liu.edu/][www.lorene.obspm.fr]

DM halos around neutron stars

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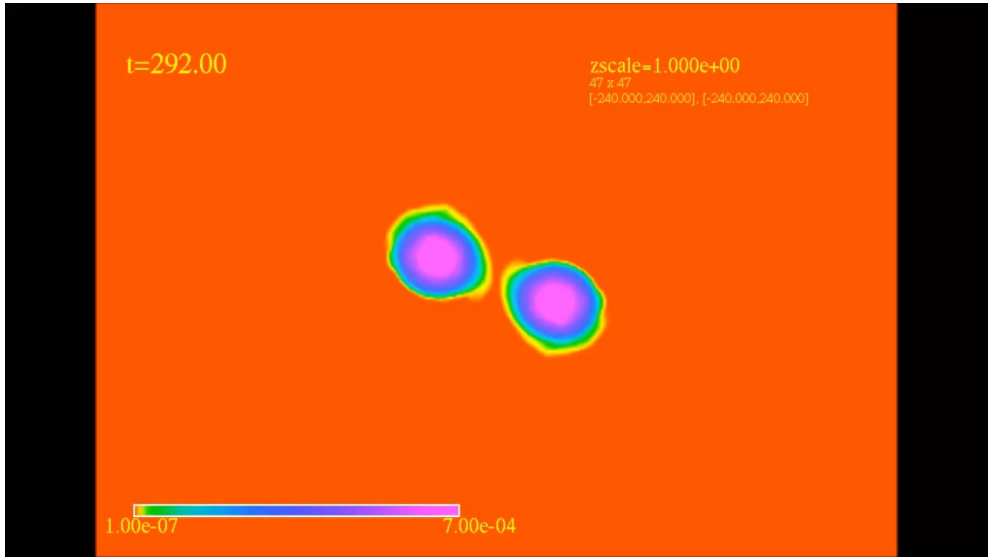

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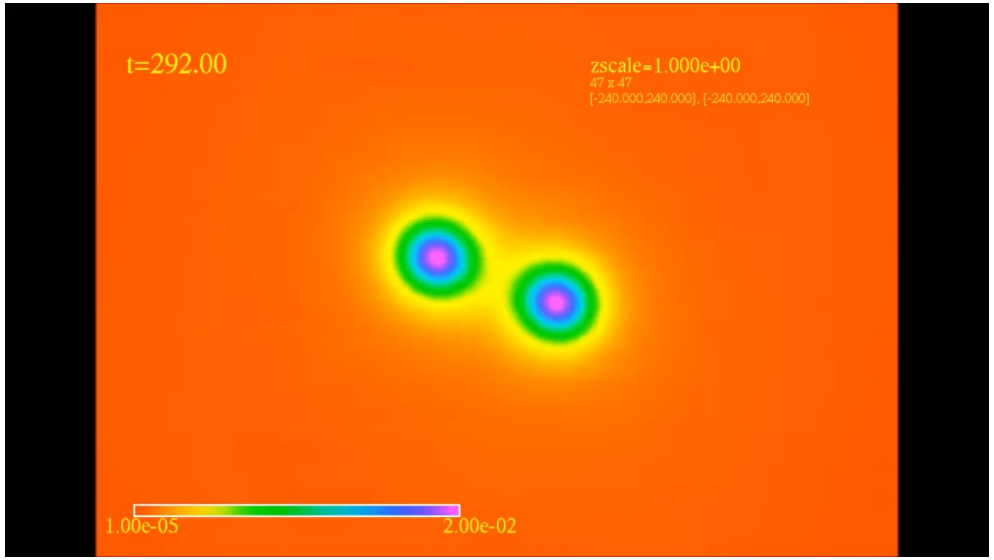

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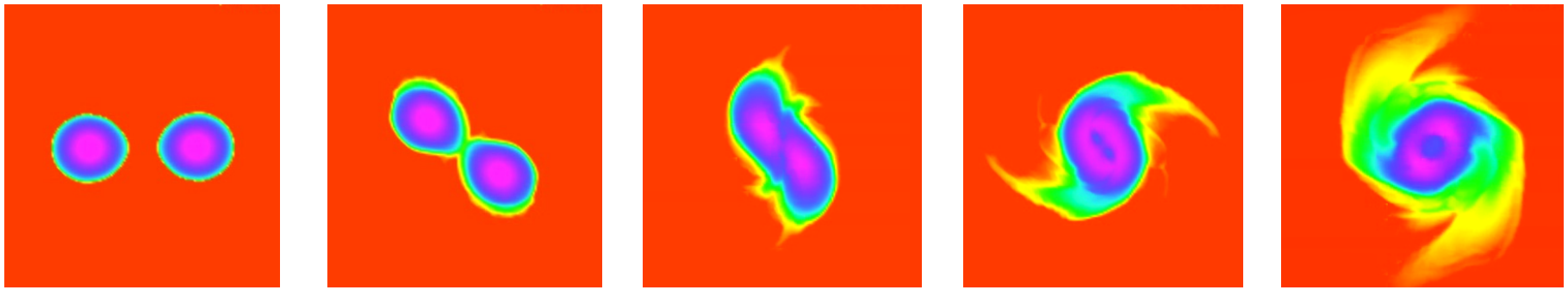
DM halos around neutron stars

Presence of DM halos:

→ Dark fifth force

→ Drastically affects merger dynamics

→ Changes GW signal!



[LS, Zhang, Johnson, Lehner, Sakellariadou, Liebling, Palenzuela, Neilsen, '18]

GW signal

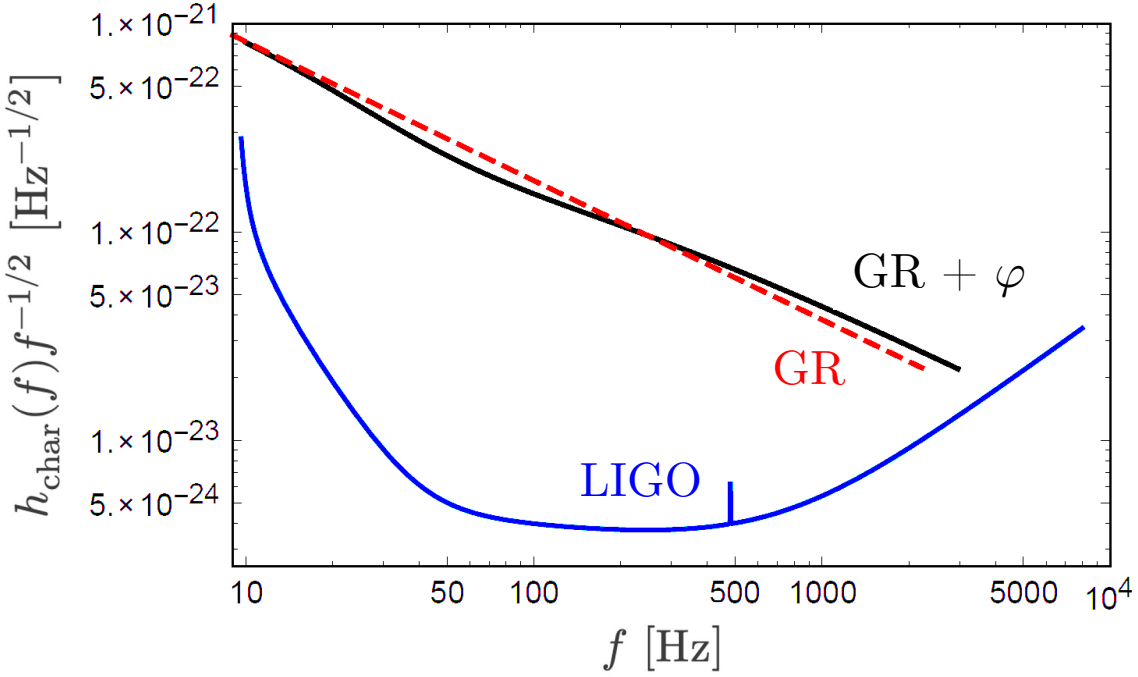
Energy emitted in gravitational + scalar radiation:

$$-\frac{dE}{dt} = \frac{dE_{\rm GW}}{dt} + \frac{dE_{\varphi}}{dt}$$

$\longrightarrow$ Characteristic strain:

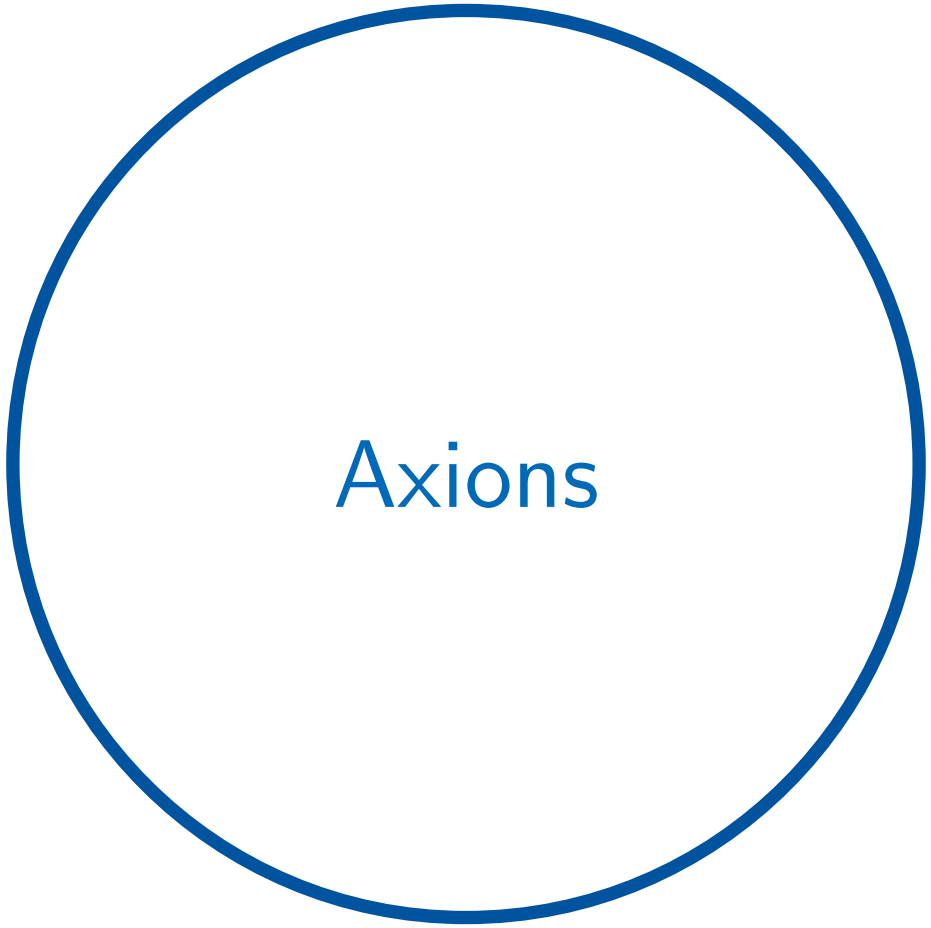
$$h^2_{\rm char} \sim \frac{1}{f^2}\left|\frac{dE}{df}\right|$$

$\longrightarrow$ Constrain with LIGO data!



$M_1 = M_2 \equiv 1.25 M_\odot$

[dcc.ligo.org/LIGO-T0900288/public]


Axions

Axions

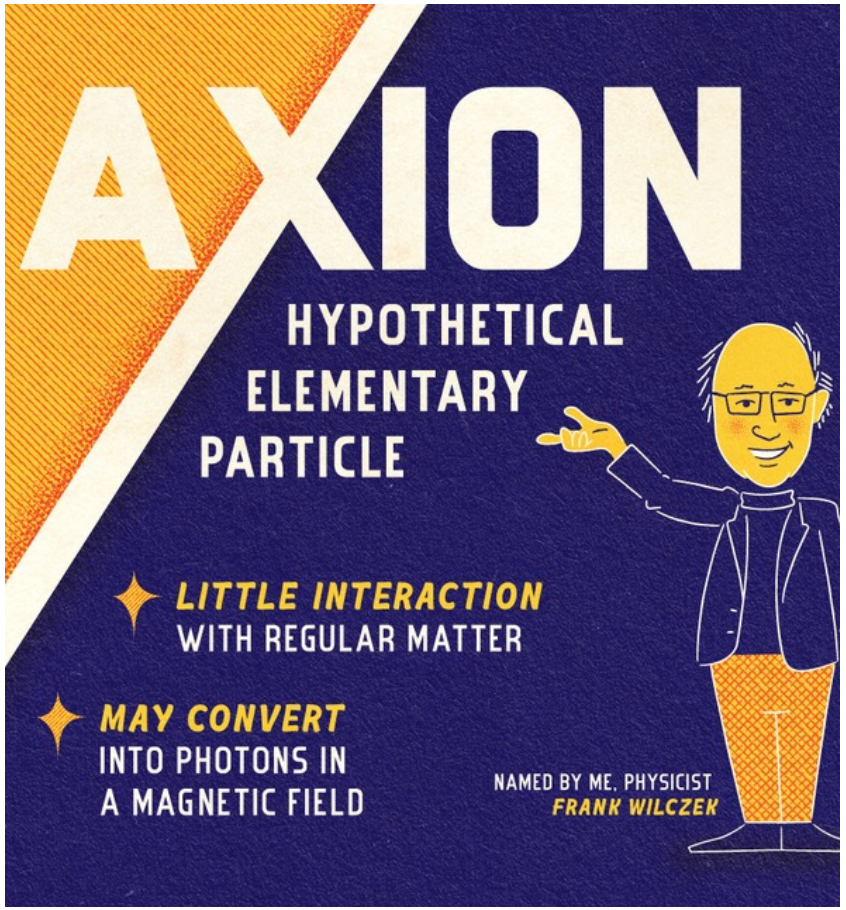
= Hypothetical particles beyond SM

+ promising DM candidates

→ Talks by Géraldine Servant + Tao Liu!

- Axion-mediated dark fifth force

→ Constrain axion parameters (mass m_a + decay constant f_a) with GWs!



[www.symmetrymagazine.org]

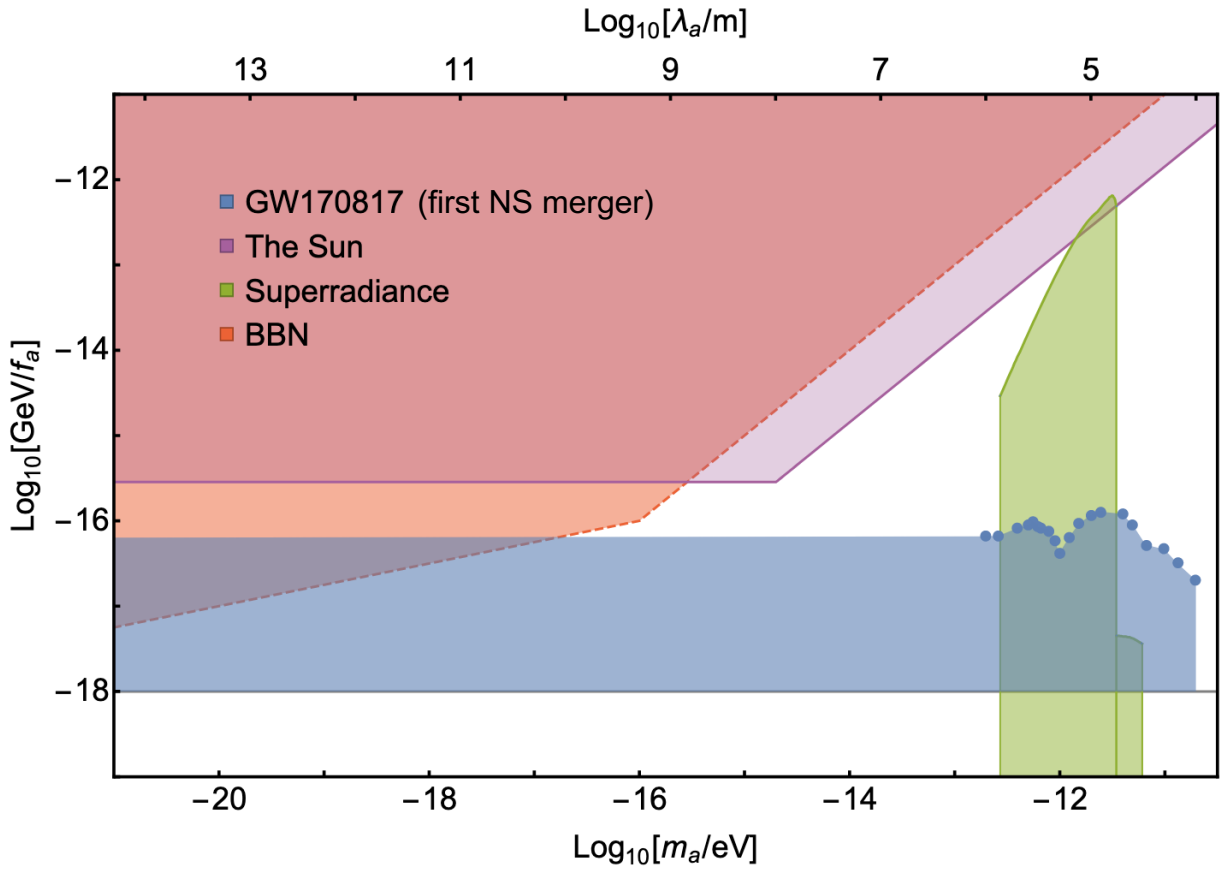
Constraining axions with GWs

[Zhang, Lyu, Huang, Johnson, LS, et al., '21]

→ First constraints:

LIGO data excludes axions with:

$$m_a \lesssim 10^{-11}\,\mathrm{eV}\,,$$
$$f_a \sim (10^{16} - 10^{18})\ \mathrm{GeV}$$

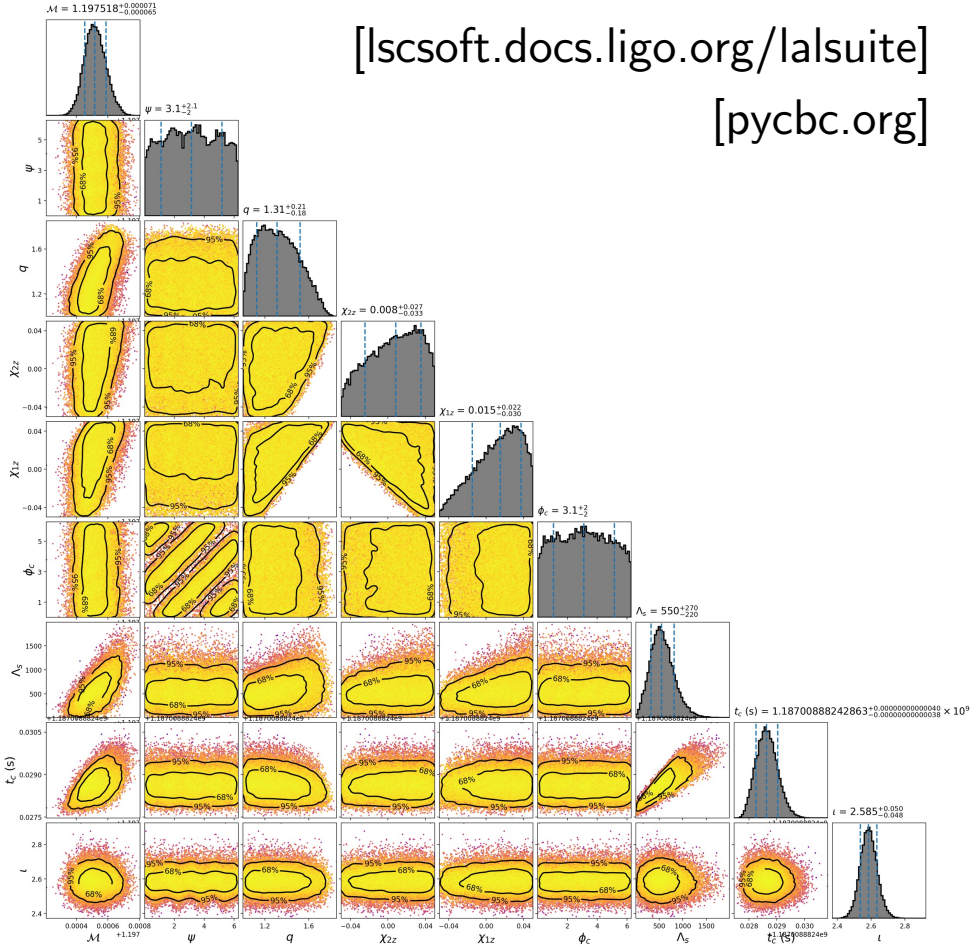


GW signal

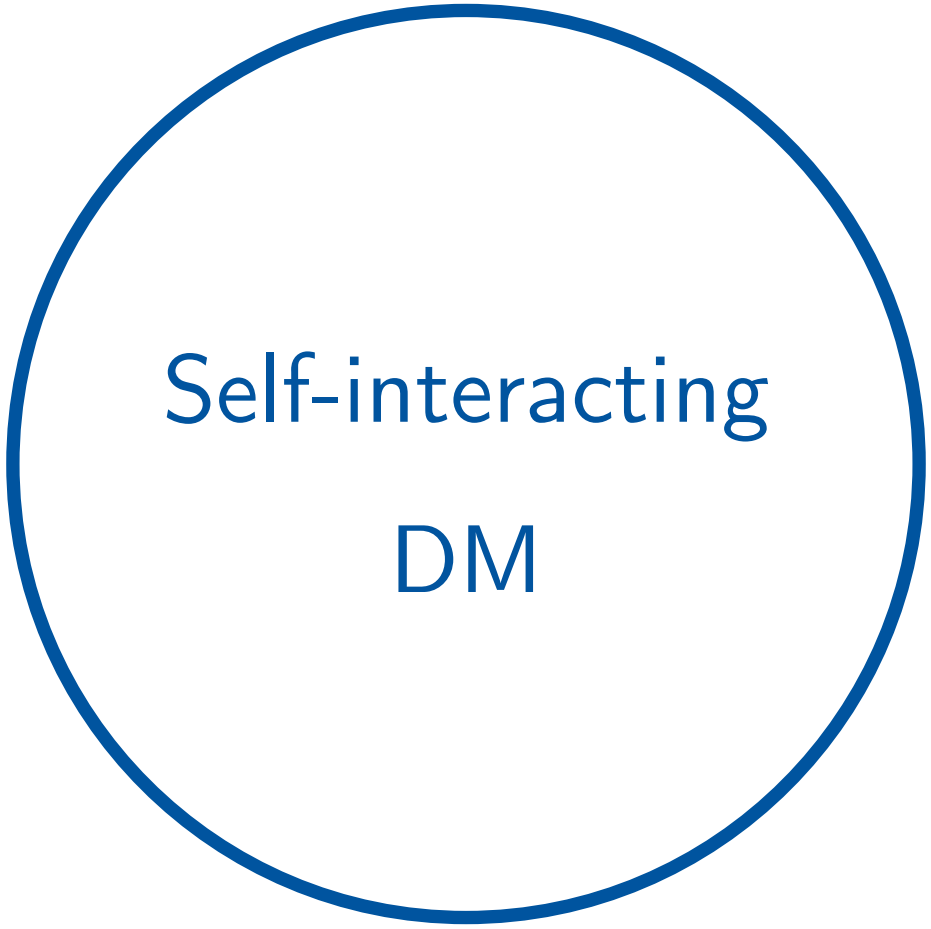
⟶ Stringent constraints from LIGO/Virgo data!

⟶ 4th LIGO observing run since May 2023: New data!

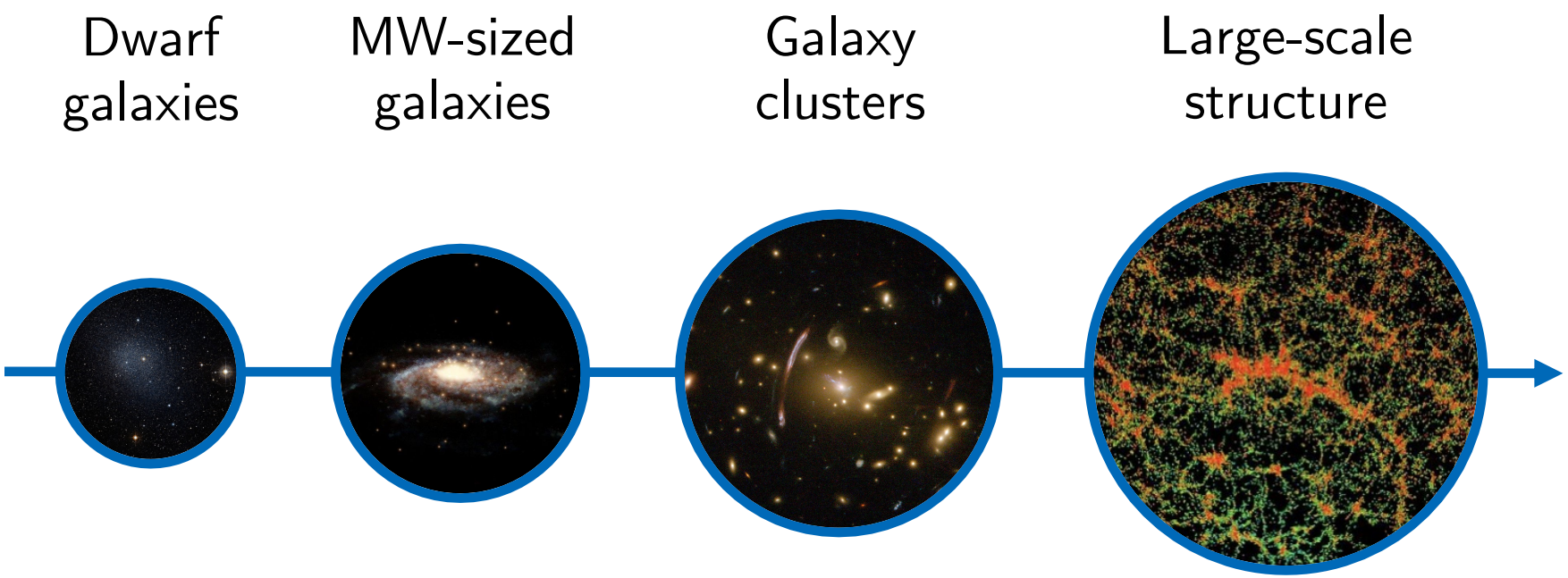
[Becker, Diedrichs, Genoud-Prachex, LS, Schaper, Schmitt, Zhang, in prep.]



[lscsoft.docs.ligo.org/lalsuite]
[pycbc.org]


Self-interacting
DM

Self-interacting DM (SIDM)



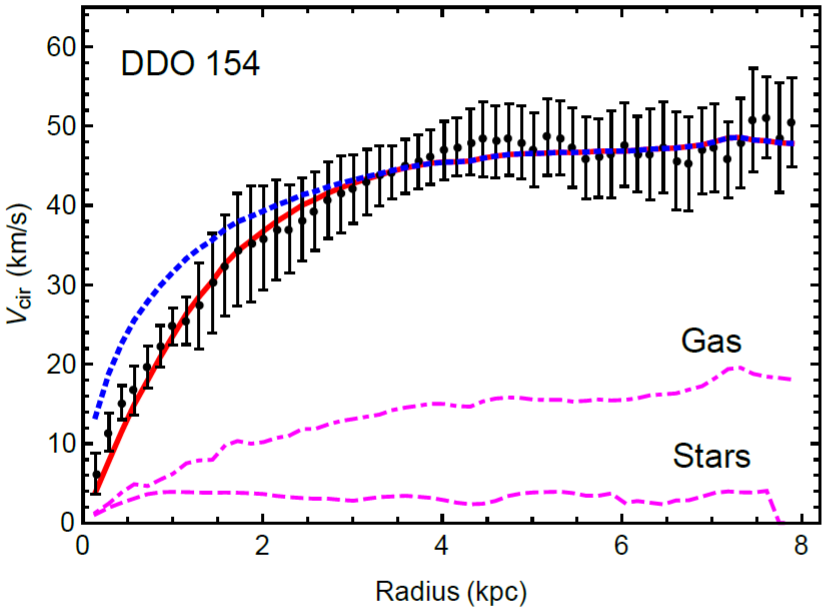
Images: [ESO/Digitized Sky Survey 2][Daley; smithsonian.com]
[NASA, ESA; Richard, Kneib][sdss.org/science/]

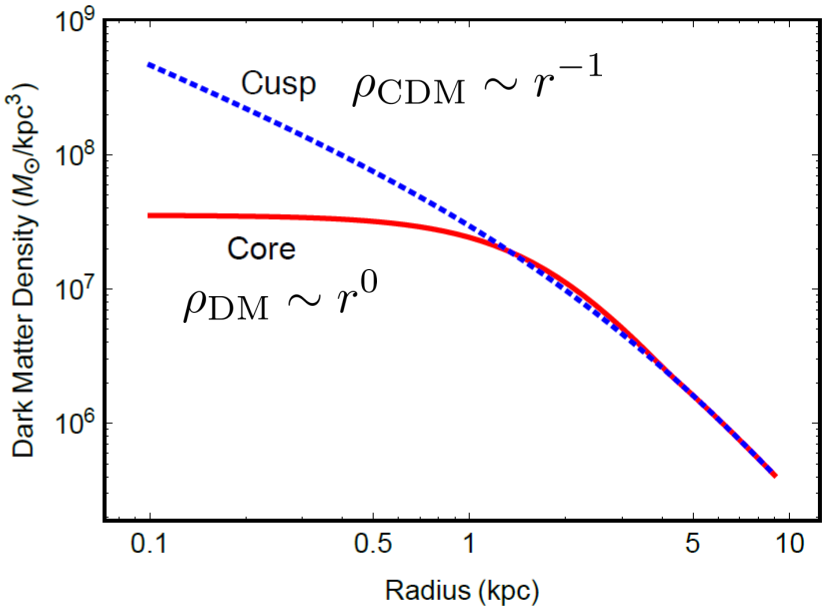
Dwarf galaxies

Core-cusp problem: → Talk by Tao Liu [Moore, '94][Flores, Primack, '94]

DM density profile: core ↔ cusp (cold, collisionless dark matter)

→ Small-scale crisis





Adapted from: [Tulin, Yu, '17]

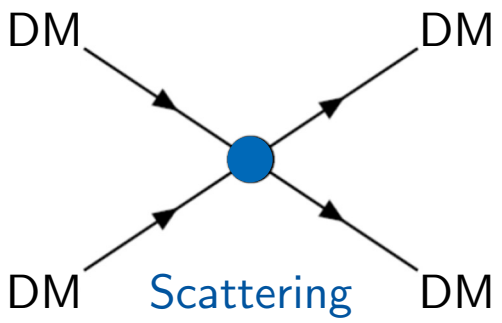
Self-interacting dark matter (SIDM)

CDM = cold, collisionless dark matter

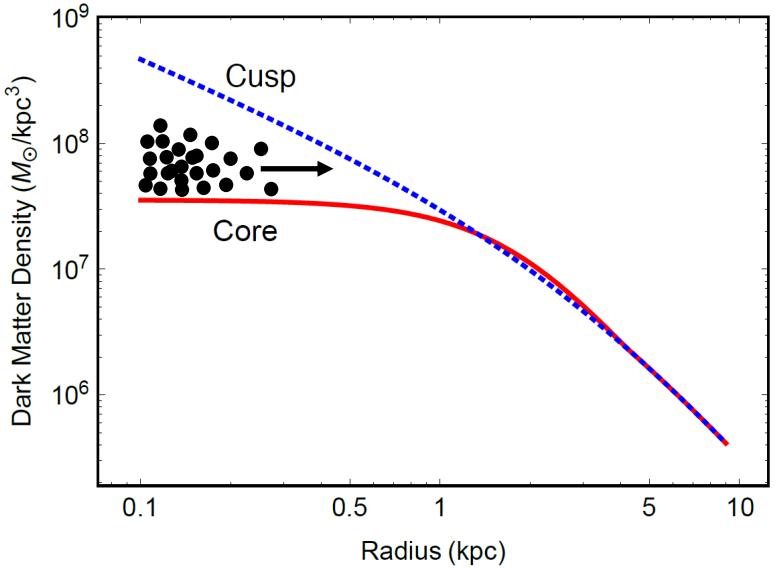
SIDM = cold, collisional dark matter

[Spergel, Steinhardt, '99]

→ DM particles self-interact:



$$\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns/GeV}$$



[Tulin, Yu, '17]
[LS et al., '20]

Self-interacting dark matter (SIDM)

SIDM can explain:

- Core-cusp problem
- Diversity of galactic rotation curves

[Kamada, Kaplinghat, Pace, and Yu, '17]

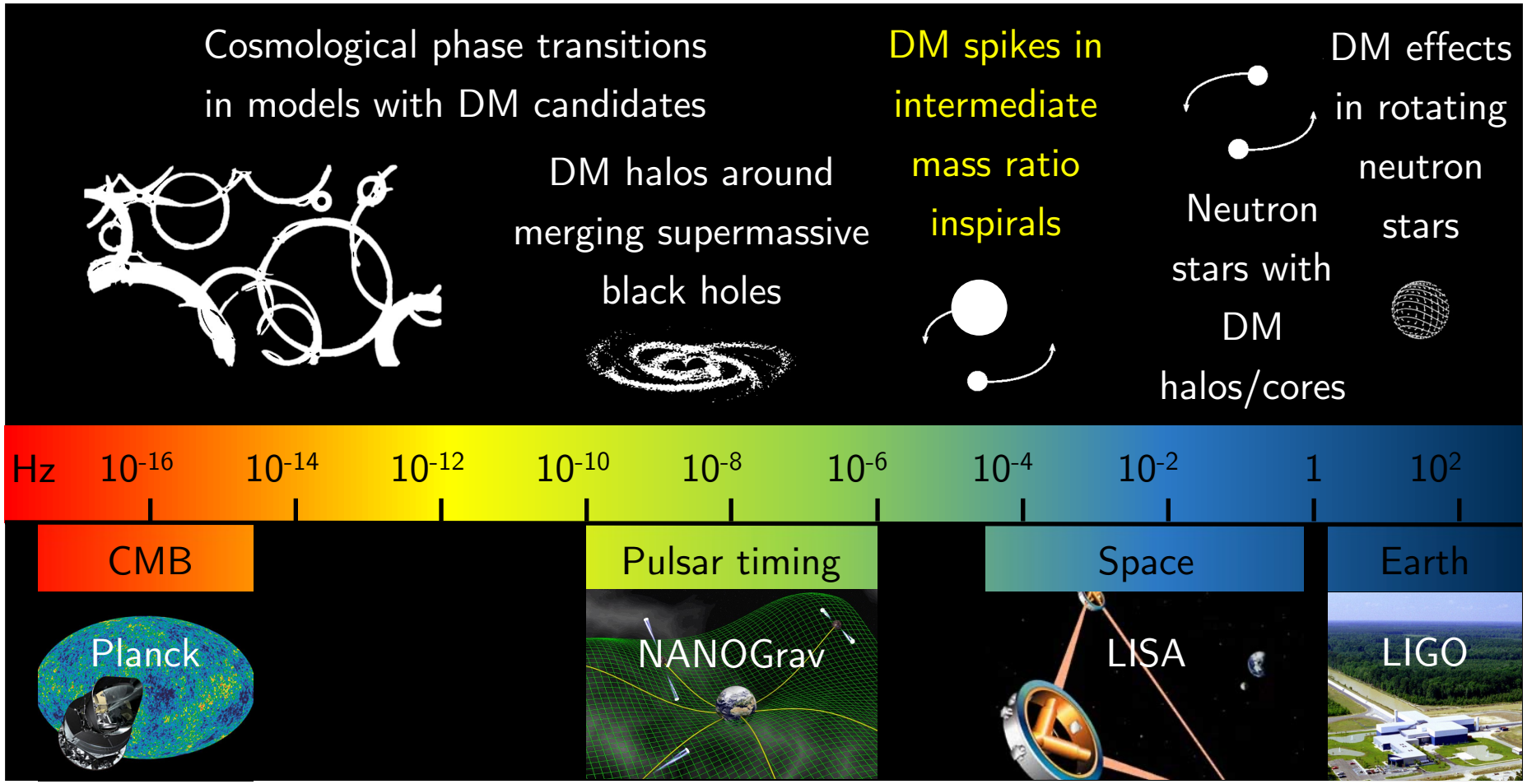
- Origin of supermassive black holes at redshifts $z \sim 6{-}7$

[Feng, Yu, Zhong, '20]
[Outmezguine, Gad-Nasr, Boddy, Kaplinghat, LS, '22]

$\longrightarrow$ Very promising DM candidate!

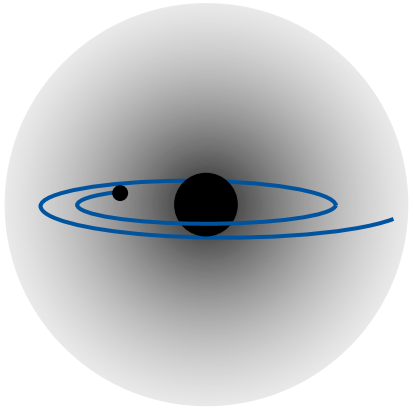
$\longrightarrow$ Constrain self-interaction cross section σ/m!

Probing DM with GWs



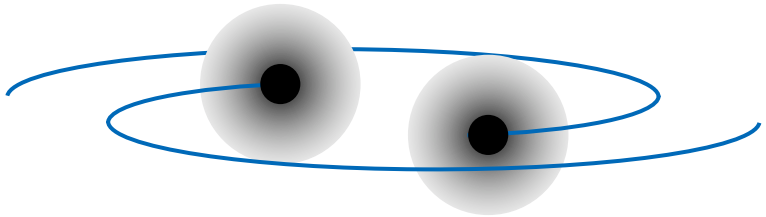
Probing DM with GWs

Intermediate mass-ratio inspirals (IMRIs)



$$M_{\mathrm{BH}} = 10^3 \ldots 10^6 \, M_\odot$$

Merging black holes + neutron stars



$$M_{\mathrm{NS/BH}} = 1 \ldots 100 \, M_\odot$$

→ Probe particle nature of DM!

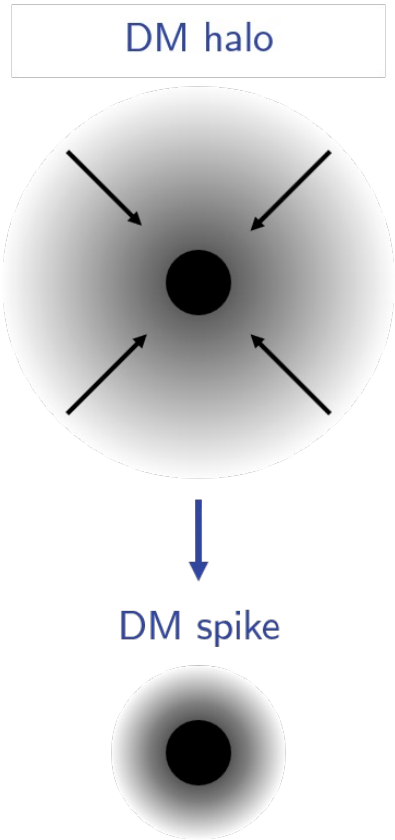
DM spikes in IMRIs

DM spikes

- "Dressed" black hole in DM halo
- Creates DM spike with extremely high density

  → Violent environment

  → Binary dynamics drastically affected



[Gondolo, Silk, '99][Eda et al., '13]

DM spikes in IMRIs

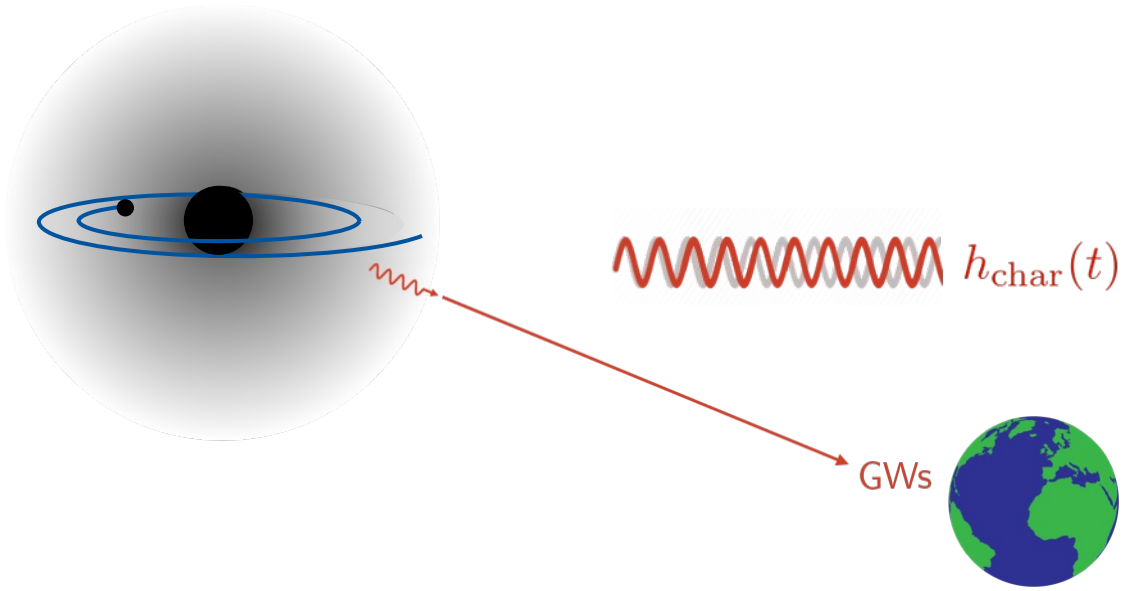
Additional energy loss through dynamical friction:

$$-\frac{dE}{dt} = \frac{dE_{\mathrm{GW}}}{dt} + \frac{dE_{\mathrm{friction}}}{dt}$$

$\sim$ DM density $\rho_{\mathrm{DM}}(r)$

$\rightarrow$ Depends on DM particle properties

$\rightarrow$ Probe DM with GWs: CDM vs. SIDM!



Astrophysical effects → Talk by Luke Kelley

Astrophysical effects:

- ✓ Elliptical orbits
- ✓ Accretion disks
- ✓ Halo feedback
- ✓ Post-Newtonian corrections to the waveform

DM effects:

- ✓ Dynamical friction effects of different DM models (CDM, SIDM, ...)
- ✓ Relativistic corrections to the DM density

➡ SOON Spinning black holes



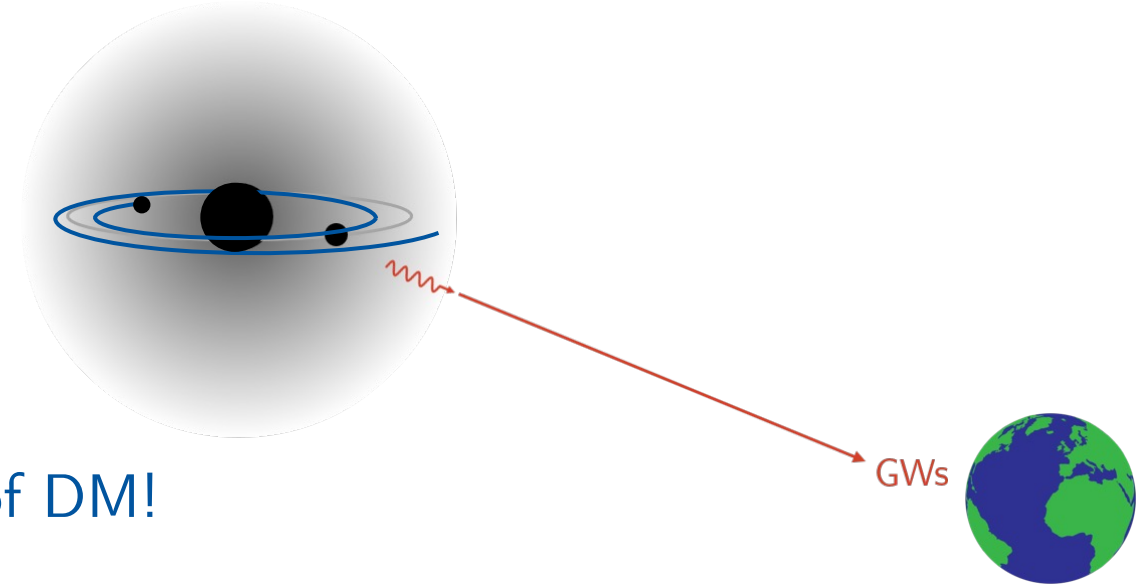
[Becker, LS, Prinz, Rastgoo, '21]
[Becker, LS, '22]
[Becker, Dreichner, Montalvo, LS, Smith, Rastgoo, in prep.]

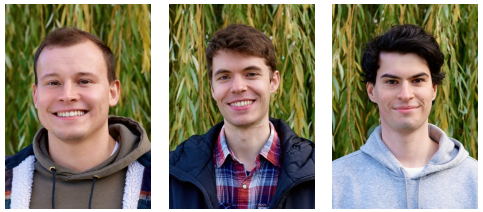
Astrophysical and DM effects

Can be disentangled by looking at different observables:

- Characteristic strain
- Difference in the number of cycles
- Eccentricity evolution
- Braking index

→ Constrain the particle properties of DM!





[Becker, LS, Prinz, Rastgoo, '21]
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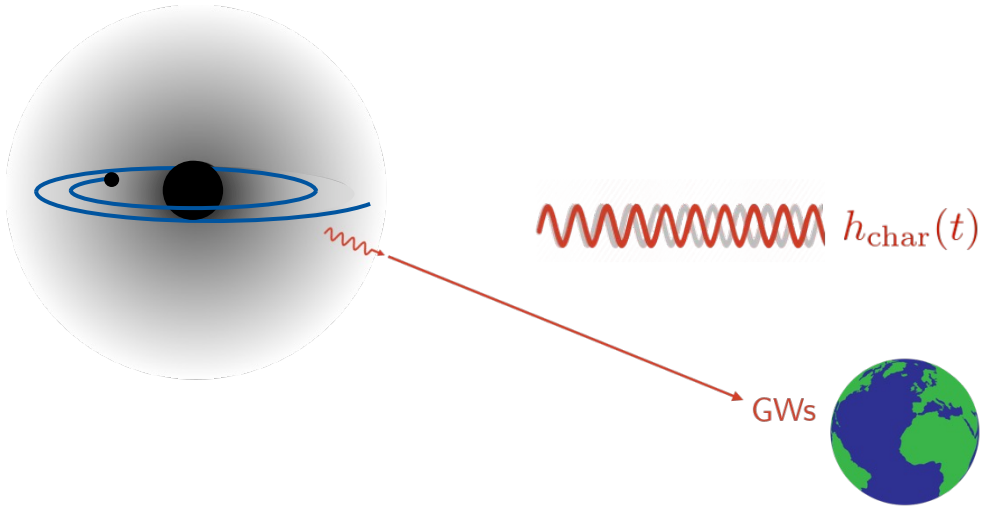
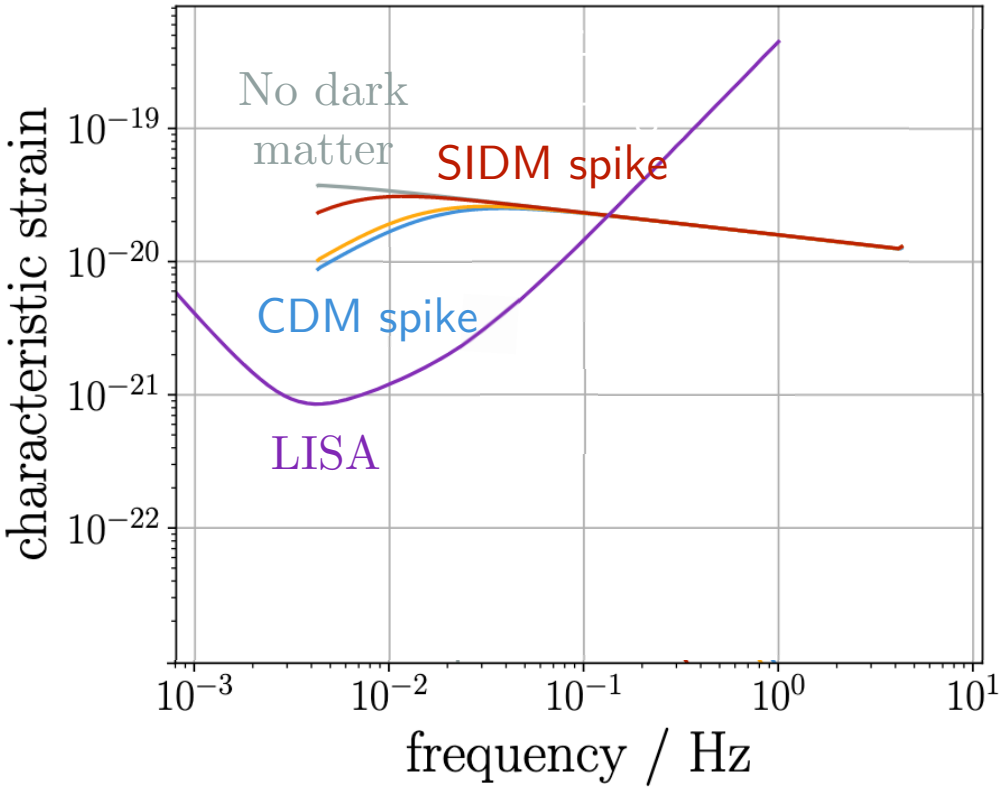


Additional energy loss through dynamical friction:

$$-\frac{dE}{dt} = \frac{dE_{\rm GW}}{dt} + \frac{dE_{\rm friction}}{dt}$$

$\sim$ DM density $\rho_{\rm DM}(r)$



[Becker, Dreichner, Montalvo, LS, Smith, Rastgoo, in prep.]

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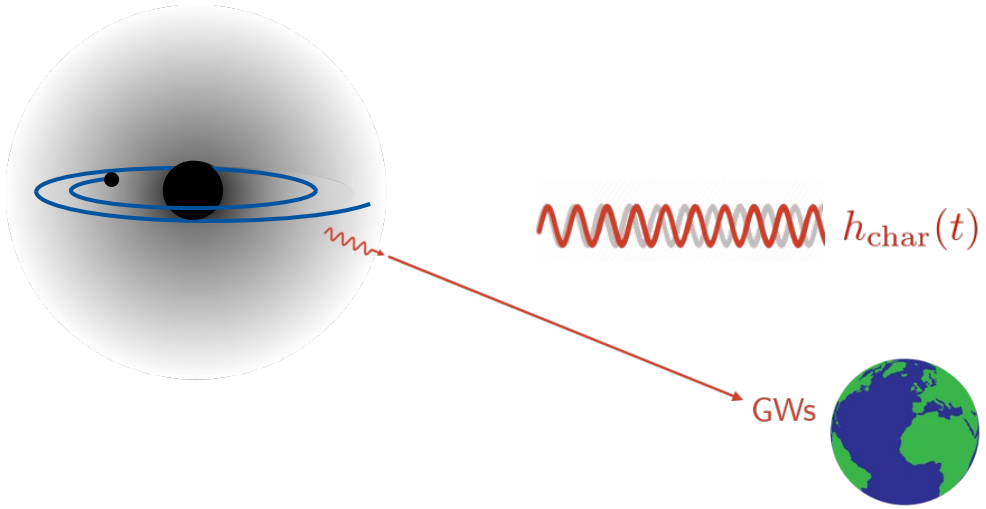

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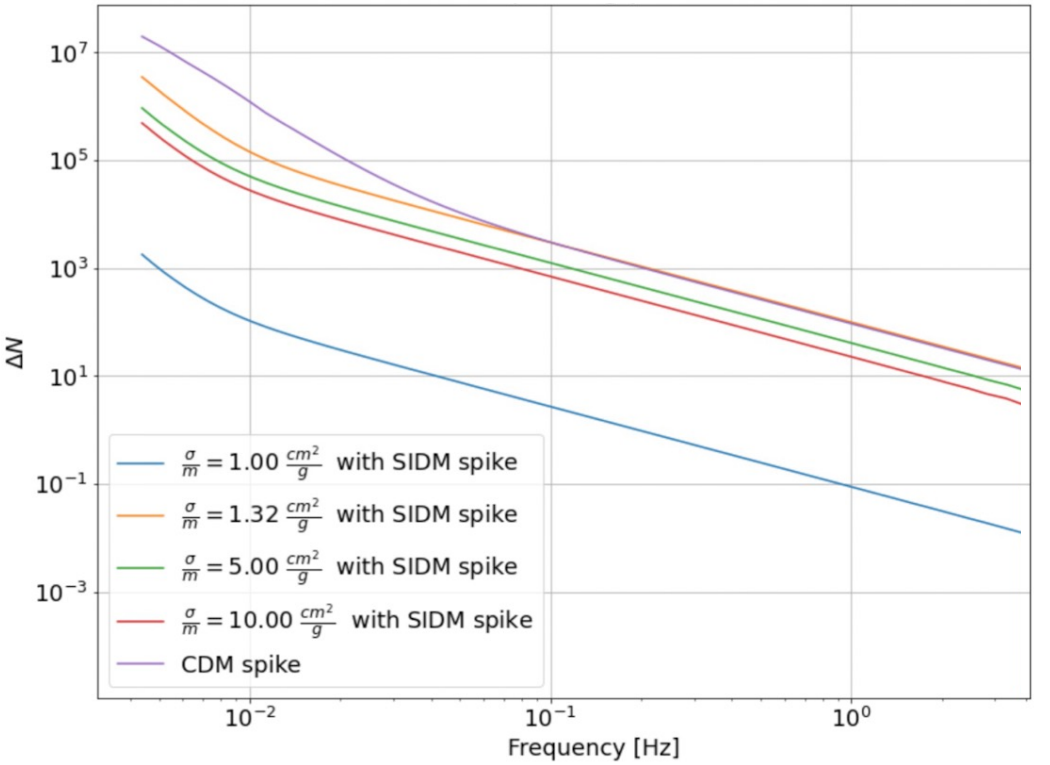

[Becker, Dreichner, Montalvo, LS, Smith, Rastgoo, in prep.]

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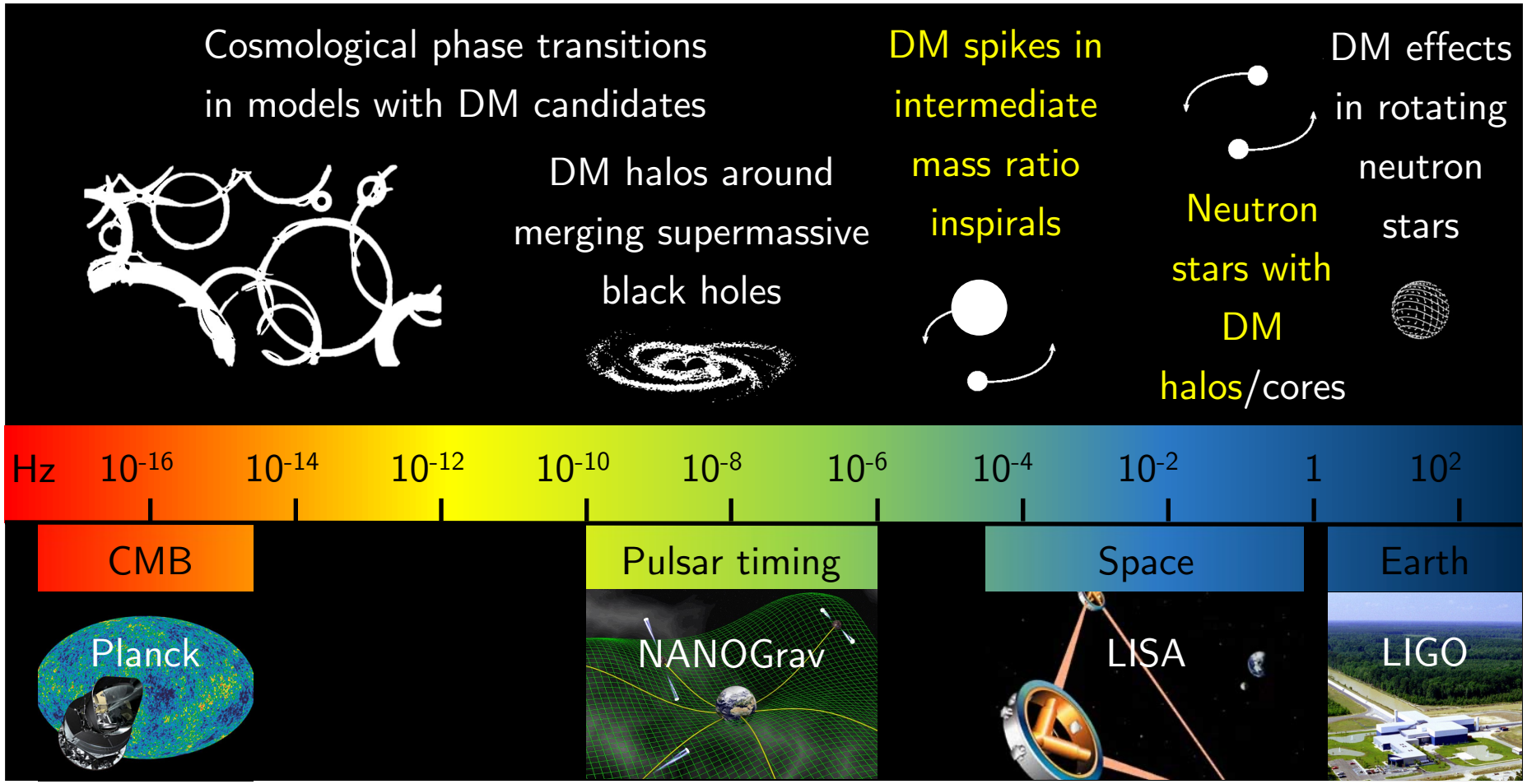

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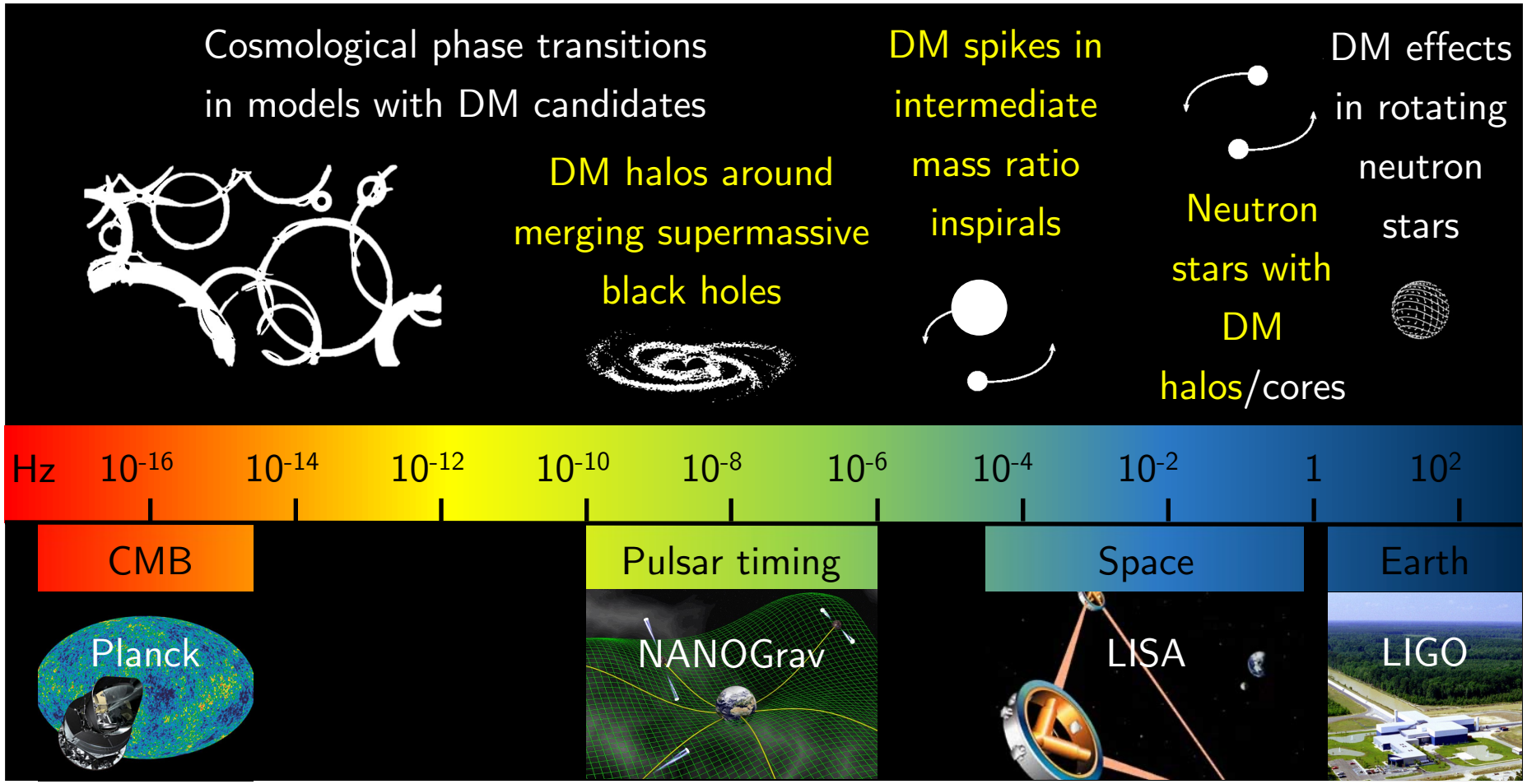
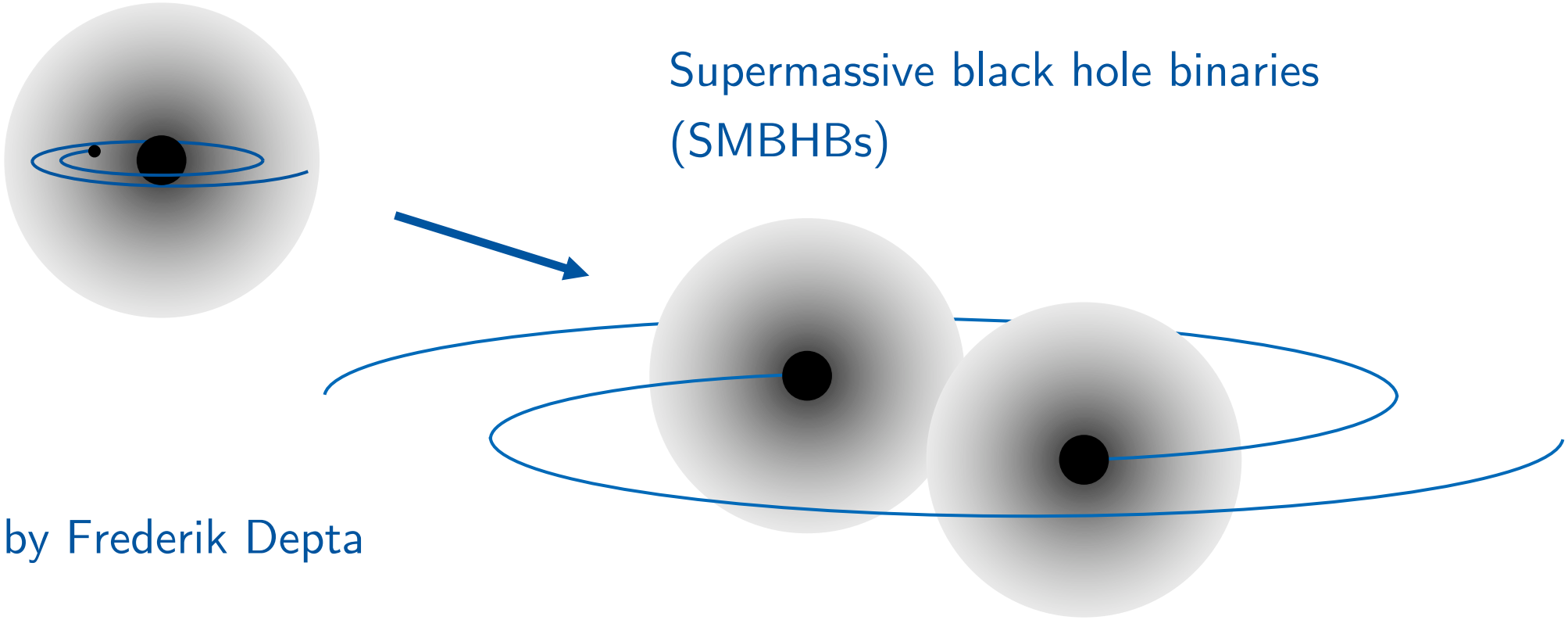


Probing DM with GWs

Intermediate mass-ratio inspirals (IMRIs)

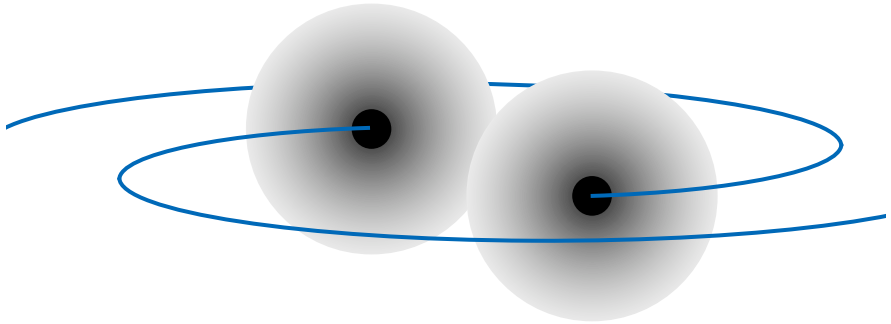
[Daniel, Huhn, Pardo, LS, in prep.]

Supermassive black hole binaries (SMBHBs)

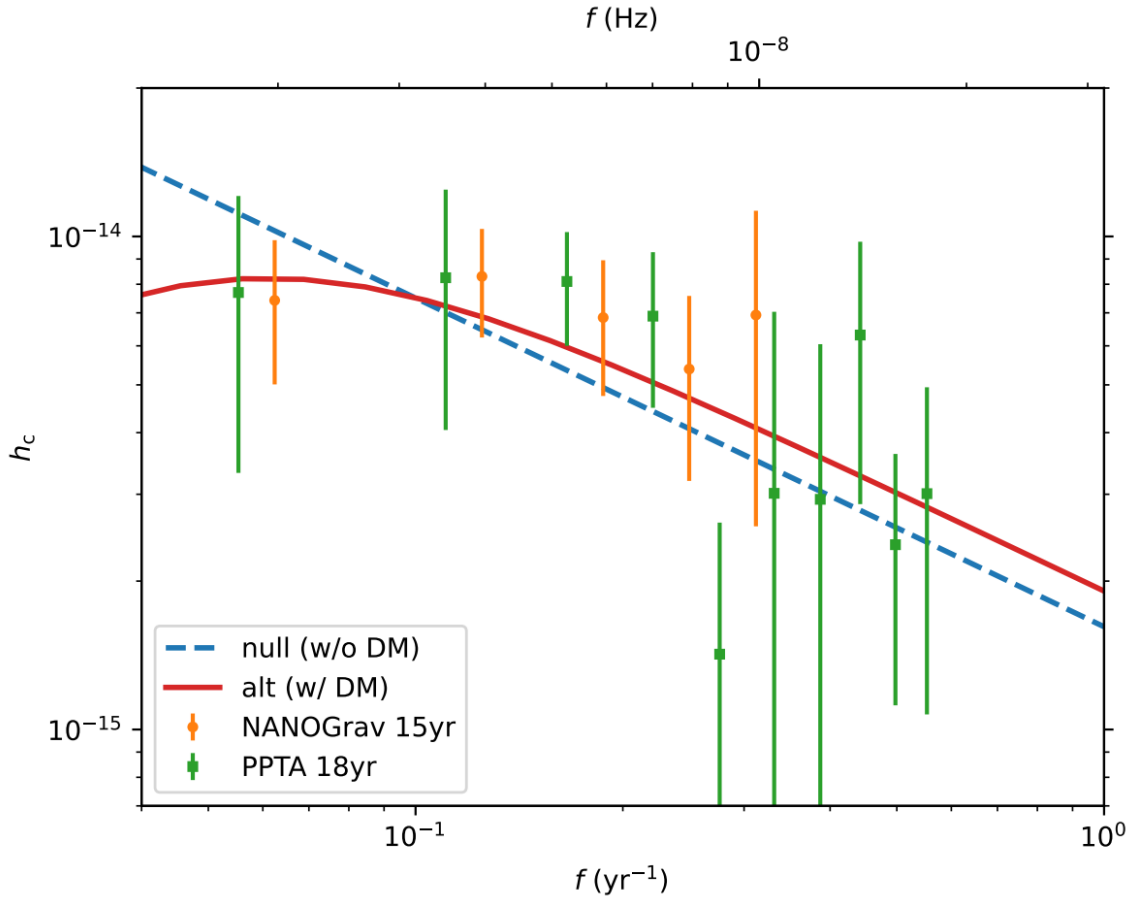


→ Talk by Frederik Depta

SMBHBs with DM halos



- Fit to PTA data
- Promising first estimates!
- New GW probe of DM, much left to explore!



[Shen et al., '23[

Summary and outlook

Summary and outlook

Gravitational waves
= powerful probes of new physics:

- Extensions of general relativity
- Particle physics beyond SM
  = dark matter,
  e.g., axions, self-interacting dark matter, ...

→ The GW era has just begun!

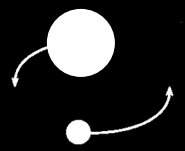
[NASA/Swift, Dana Berry]

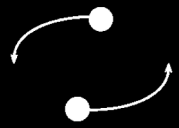
There is a bright future to explore DM with GWs!

Cosmological phase transitions in models with DM candidates

DM halos around merging supermassive black holes

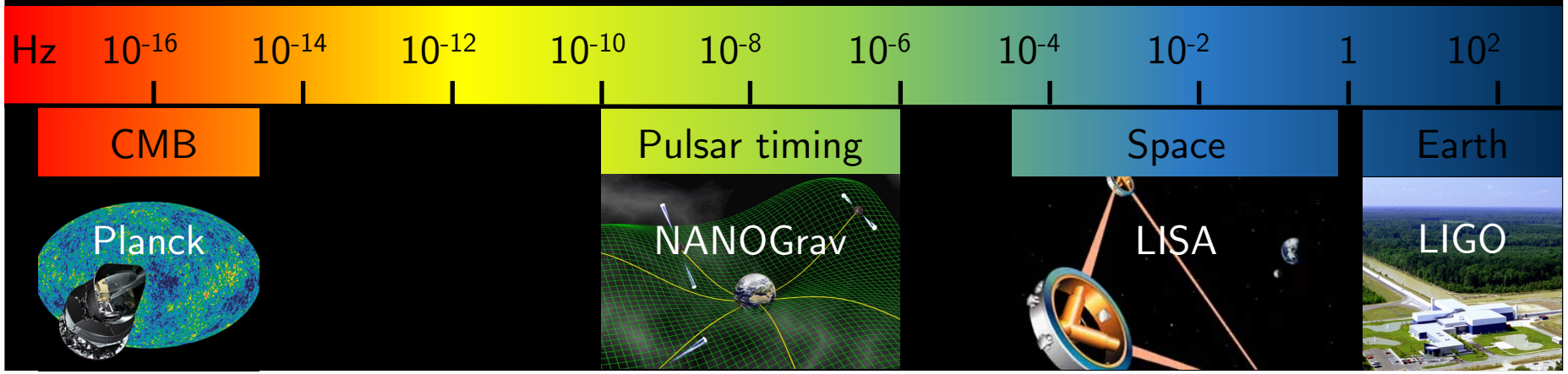
DM spikes in intermediate mass ratio inspirals





Neutron stars with DM halos/cores

DM effects in rotating neutron stars



Thank you for your attention!