Gravitational Waves from the Dark Side of the Universe

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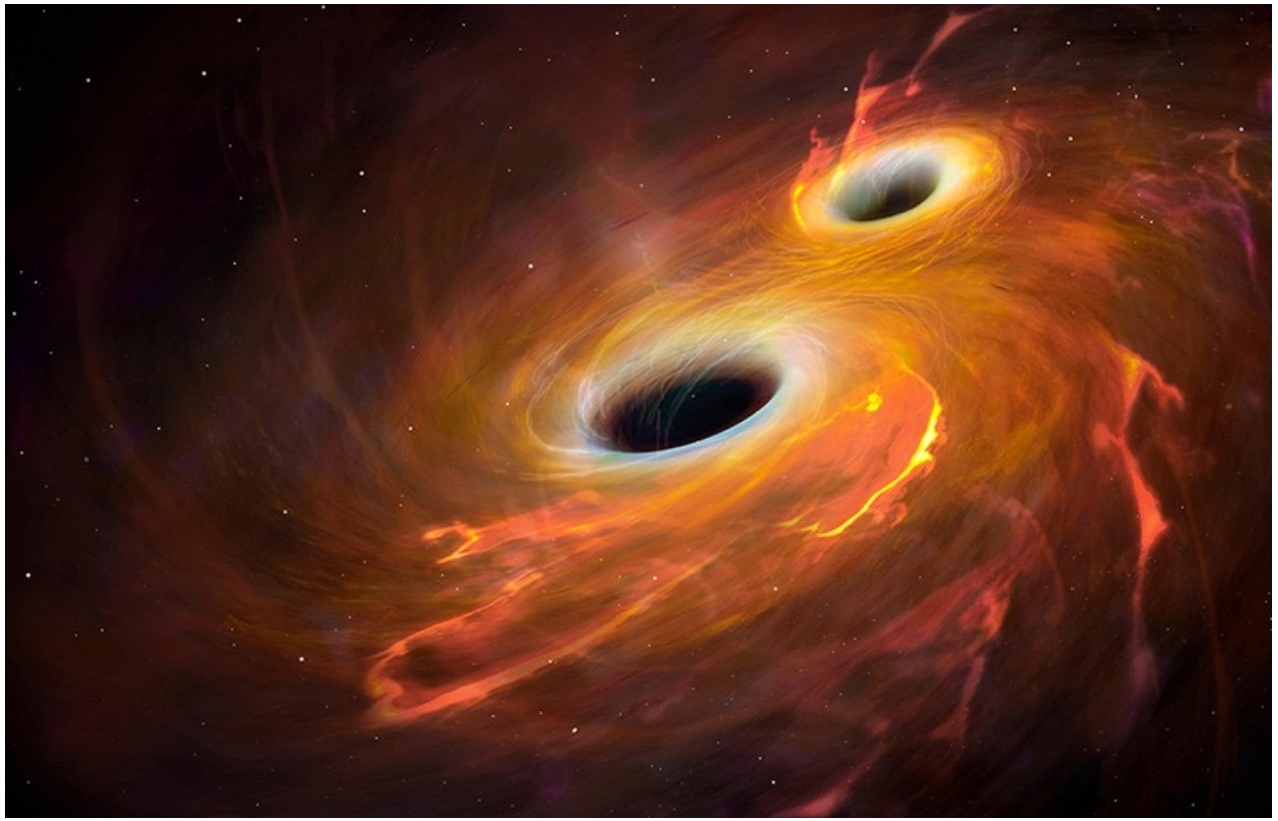
GOETHE UNIVERSITÄT

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

ITP

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

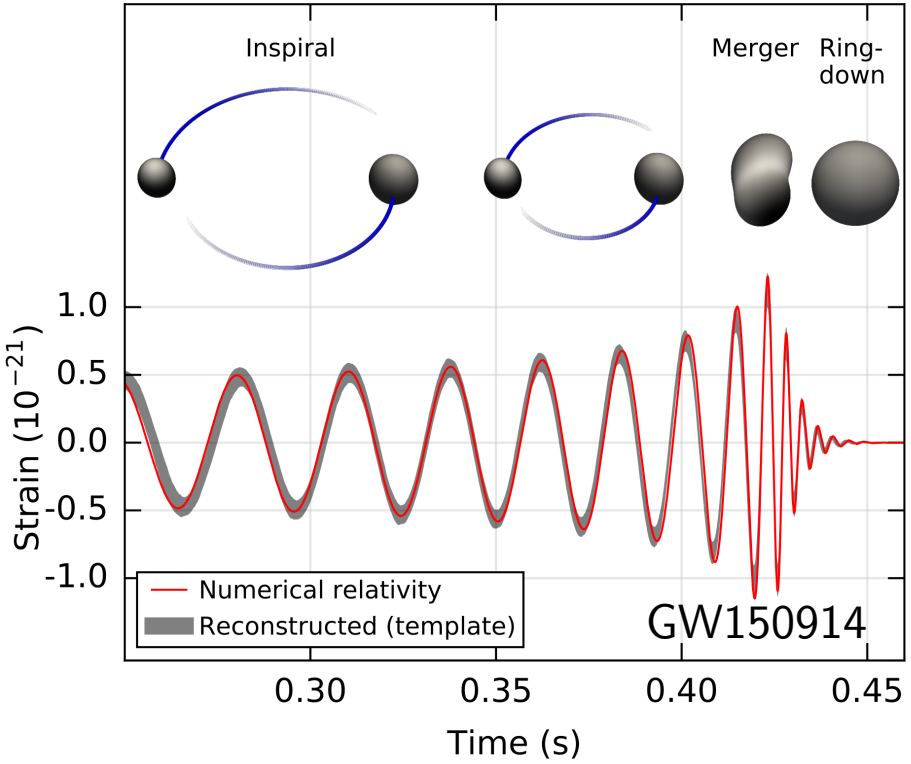


[nature.com/articles/d41586-020-03047-0]

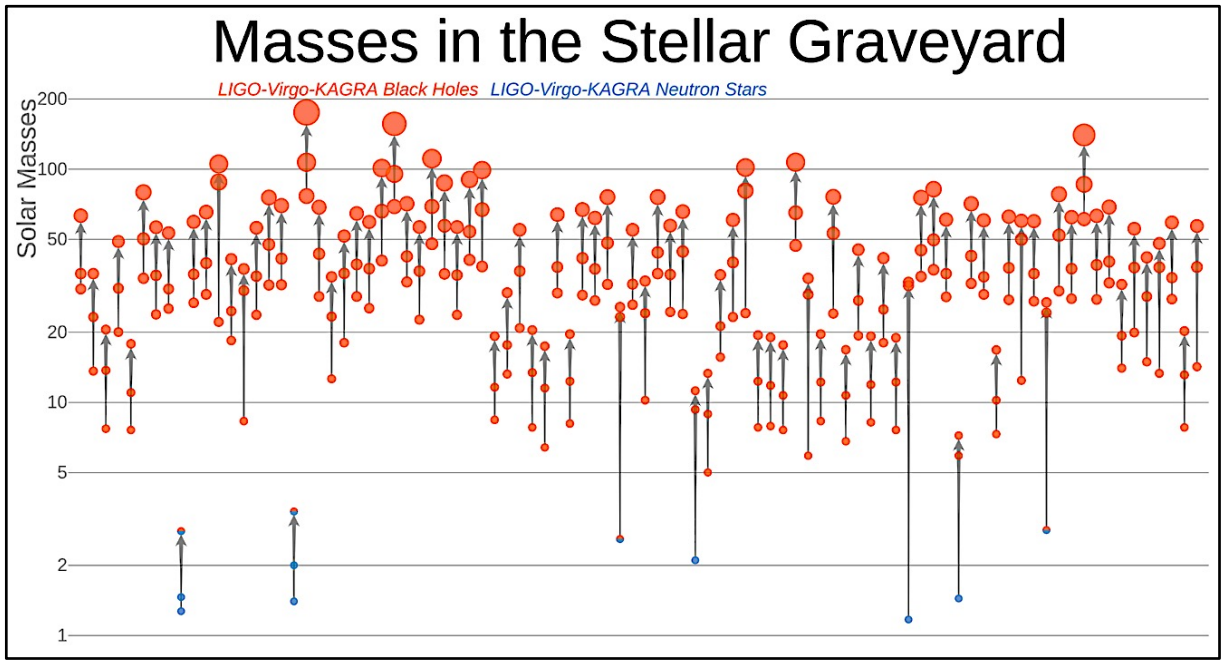
→ GW150914: first ever direct detection of GWs!

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]

GWs from binary mergers

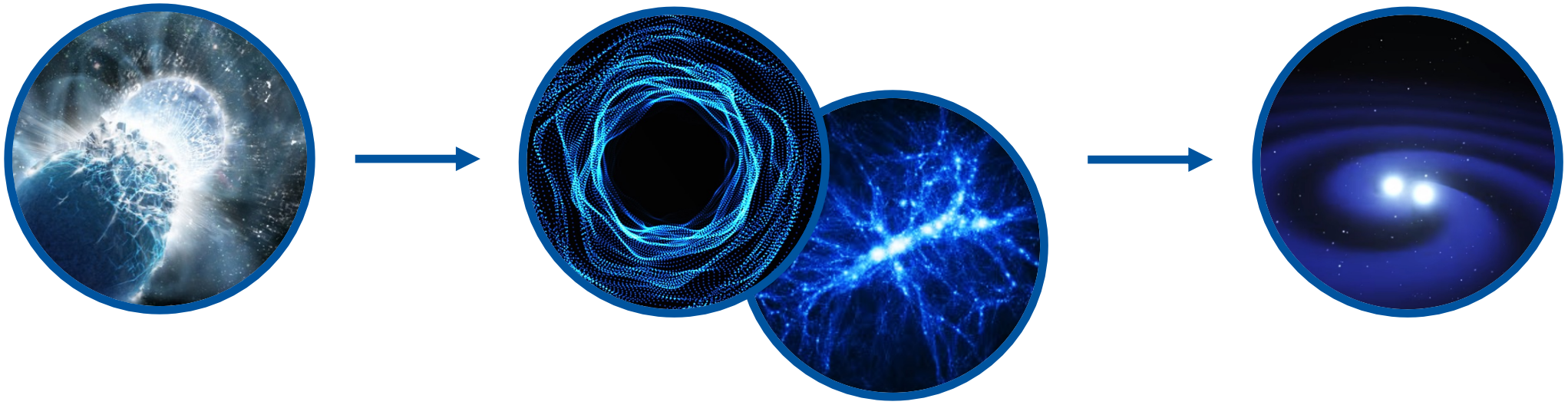
The GW era has just begun...

... 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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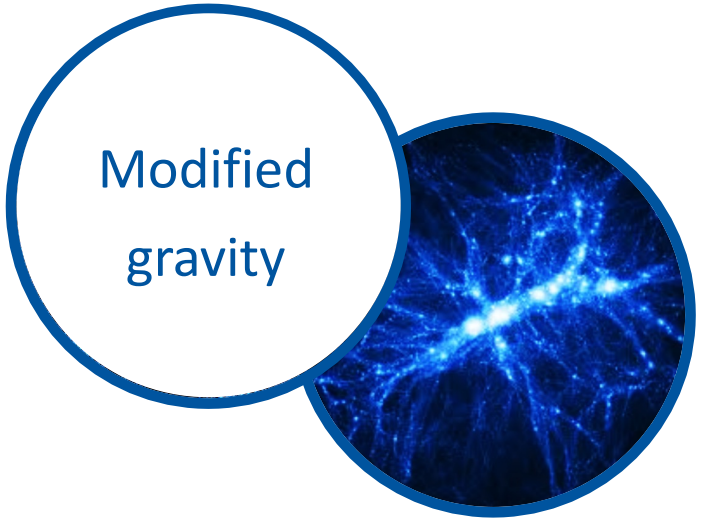

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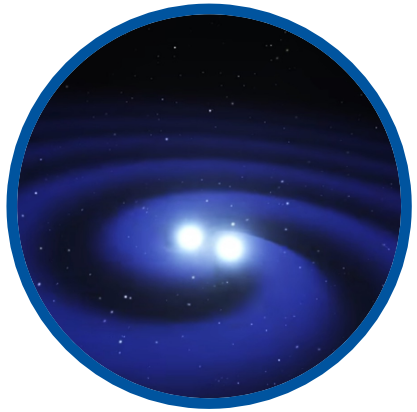

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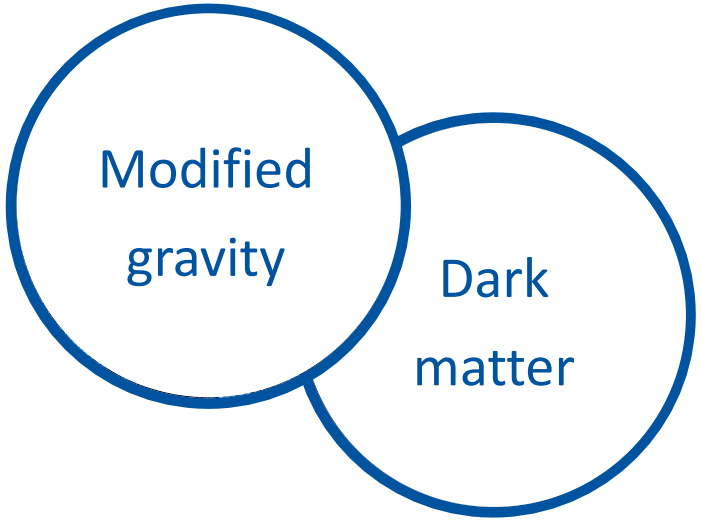

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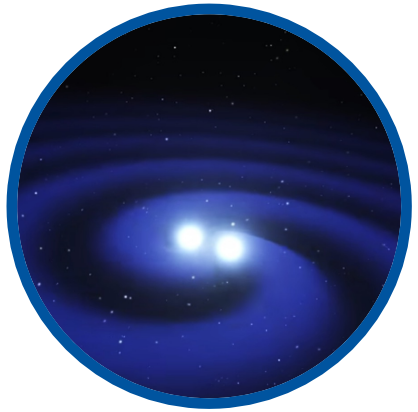


Modified gravity

Why $f(R)$ gravity?

- Important role in cosmology:

  → Scalar field models of inflation e.g., [Starobinsky, '80]

  → Accelerated expansion of the Universe

  [Boisseau et al., '00][Carroll et al., '04][Hu, Sawicki, '07]

  → Viable dark matter candidate e.g., [Cembranos, '08]

- One of the simplest extensions of GR

$f(R)$ gravity

- Generalizes Einstein-Hilbert action of GR: [Sotiriou, Faraoni, '08]

$$S \sim \int d^4x \sqrt{-g}\, f(R) + S^M$$

- Dynamically equivalent to GR + a scalar field φ:

$$\varphi \sim \ln f'(R)$$

$$\to \tilde{S} \sim \int d^4x \sqrt{-\tilde{g}} \left[\tilde{R} - \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi)\right] + \tilde{S}^M[\varphi]$$

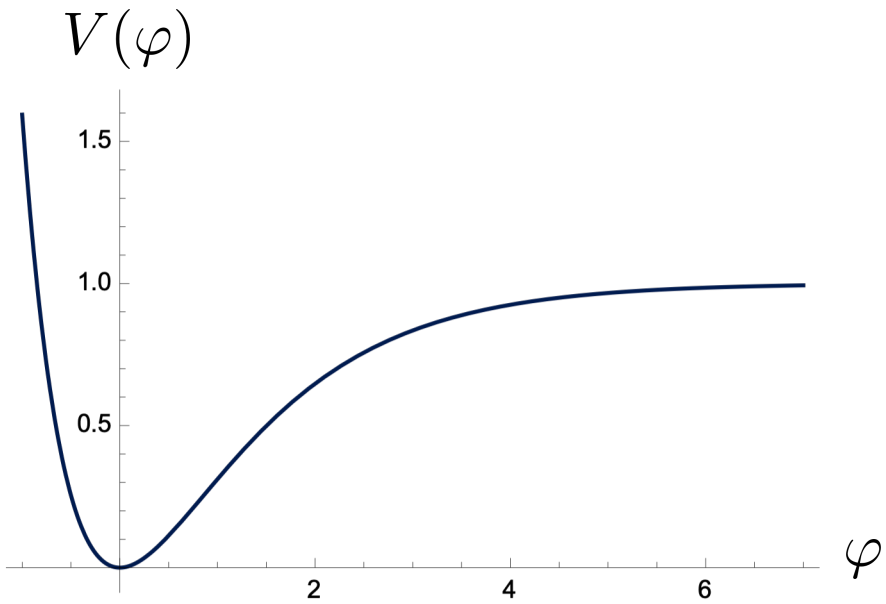
R^2 gravity

Function in the generalized action: [Staykov et al., '14]

$$f(R) = R + a_2 R^2$$

→ Scalar potential:

$$V(\varphi) \sim \frac{1}{a_2}\left(1 - e^{-b\varphi}\right)^2$$



→ Scalar mass:

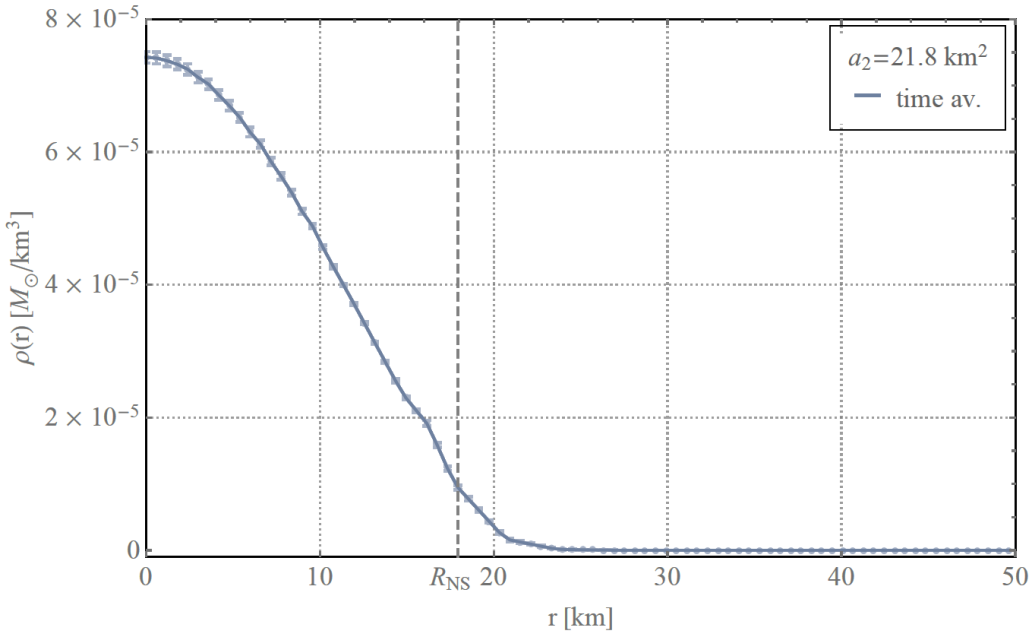
$$m_\varphi = \sqrt{\frac{1}{6a_2}}$$

R^2 gravity

Equation of motion for φ:

Gravity + neutron star ρ, p

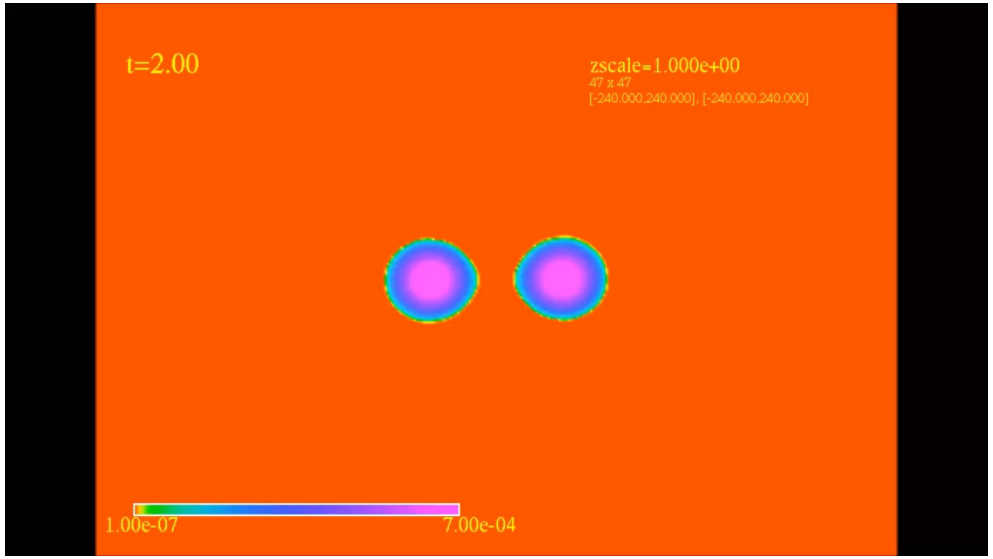
$$\Box\varphi = V'(\varphi) + \frac{1}{2} b \tilde{T}^{\mu}_{\mu}$$



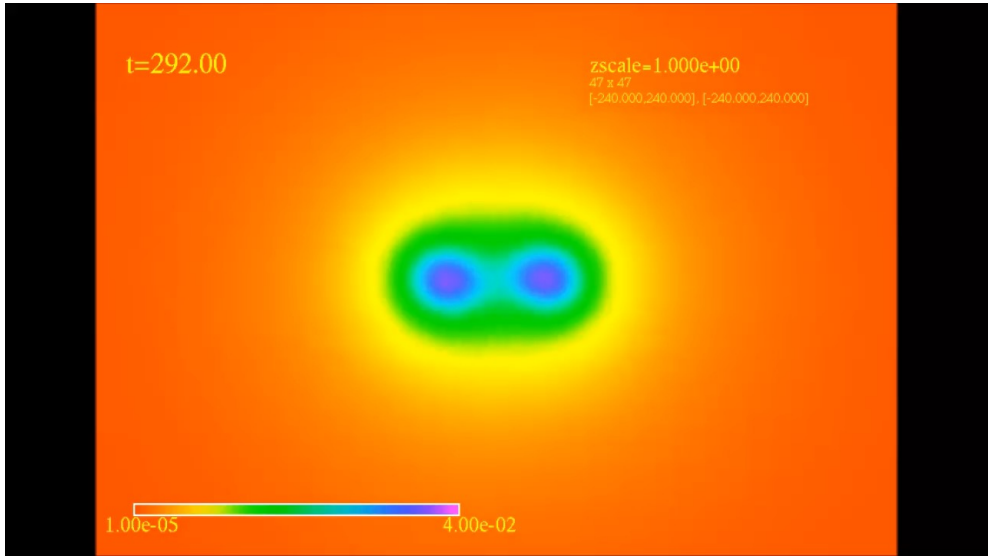
[LS, Zhang, Johnson, Lehner, Sakellariadou, Liebling, Palenzuela, Neilsen, '18]

Numerical simulations

Neutron star density ρ



Scalar field φ



$$M_1 = M_2 \equiv 1.2 M_\odot,\ a_2 = 1.09 \cdot 10^9\,\mathrm{m}^2$$

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

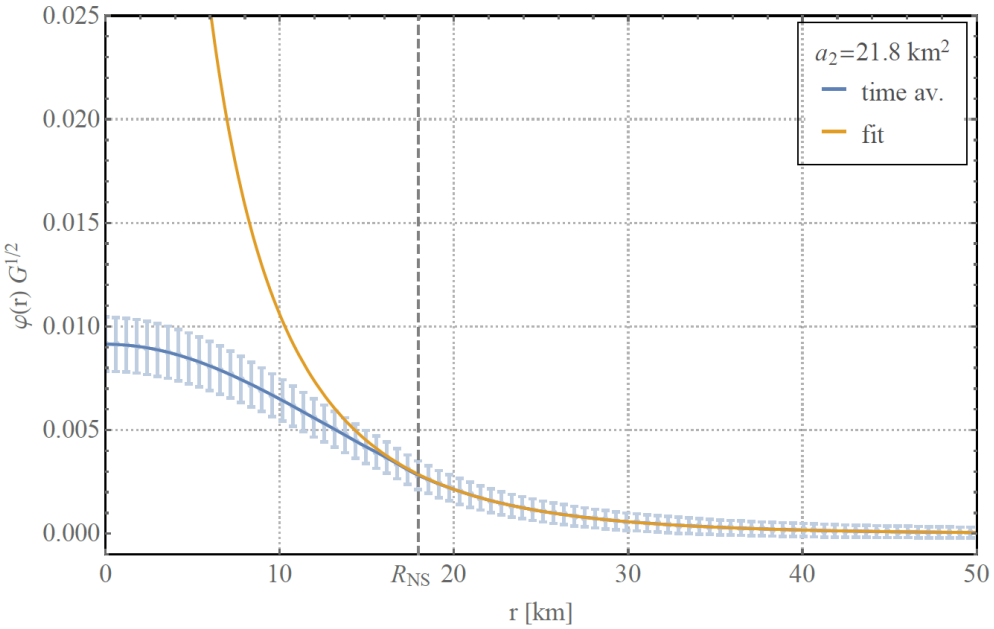
[www.had.liu.edu/][www.lorene.obspm.fr]

R^2 gravity

Scalar field profile:

Scalar charge

$$\varphi \sim \alpha M \frac{e^{-m_\varphi r}}{r}$$



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

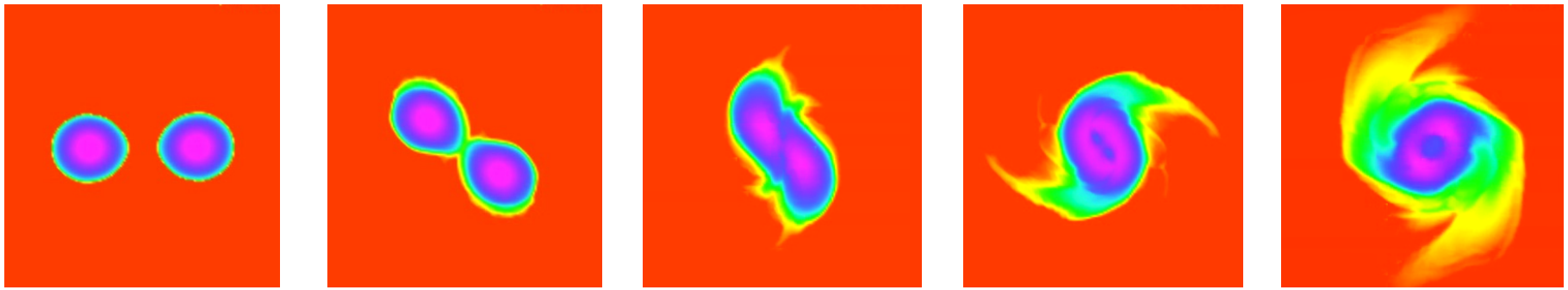
R^2 gravity

Scalar field induces a fifth force:

$$\boldsymbol{F}_\varphi = -\alpha M \nabla \varphi$$

$\longrightarrow$ Scalar force accelerates merger

$\longrightarrow$ Changes GW signal



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

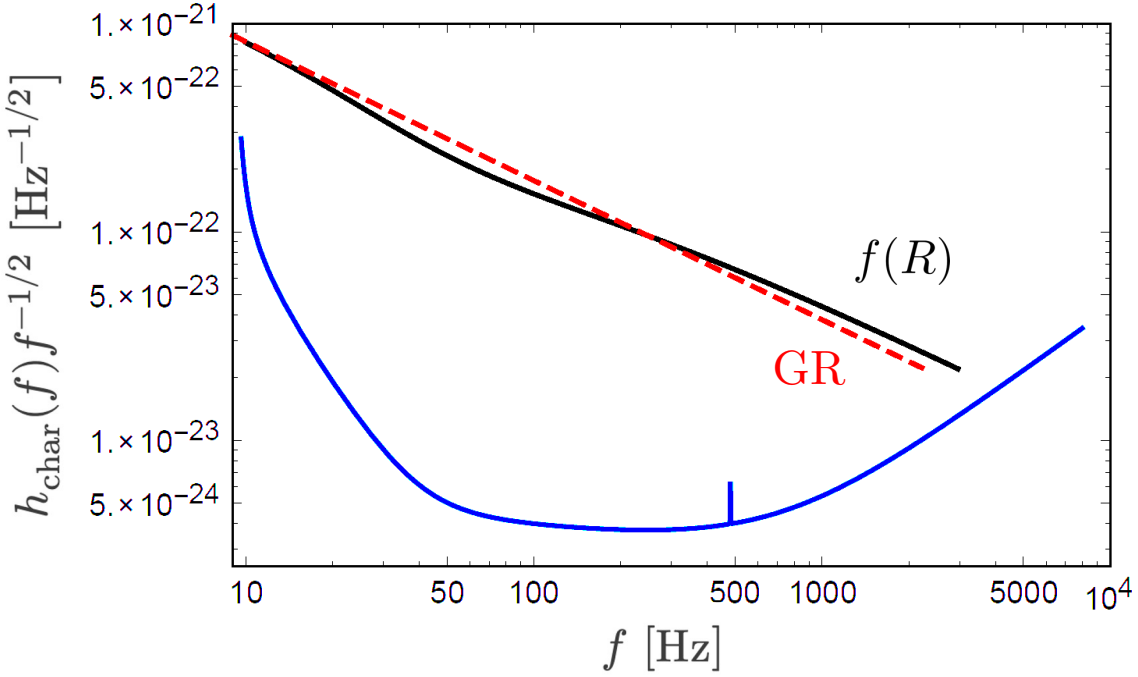
GW signal

Energy emitted in gravitational + scalar radiation:

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

$\longrightarrow$ Characteristic strain:

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



$m_\varphi = 3.98 \cdot 10^{-6}\,{\rm m}^{-1}$,

$\alpha \equiv \alpha_1 = \alpha_2 = 0.89,\ M_1 = M_2 \equiv 1.25 M_\odot$

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

GW signal

Signal-to-noise ratio:

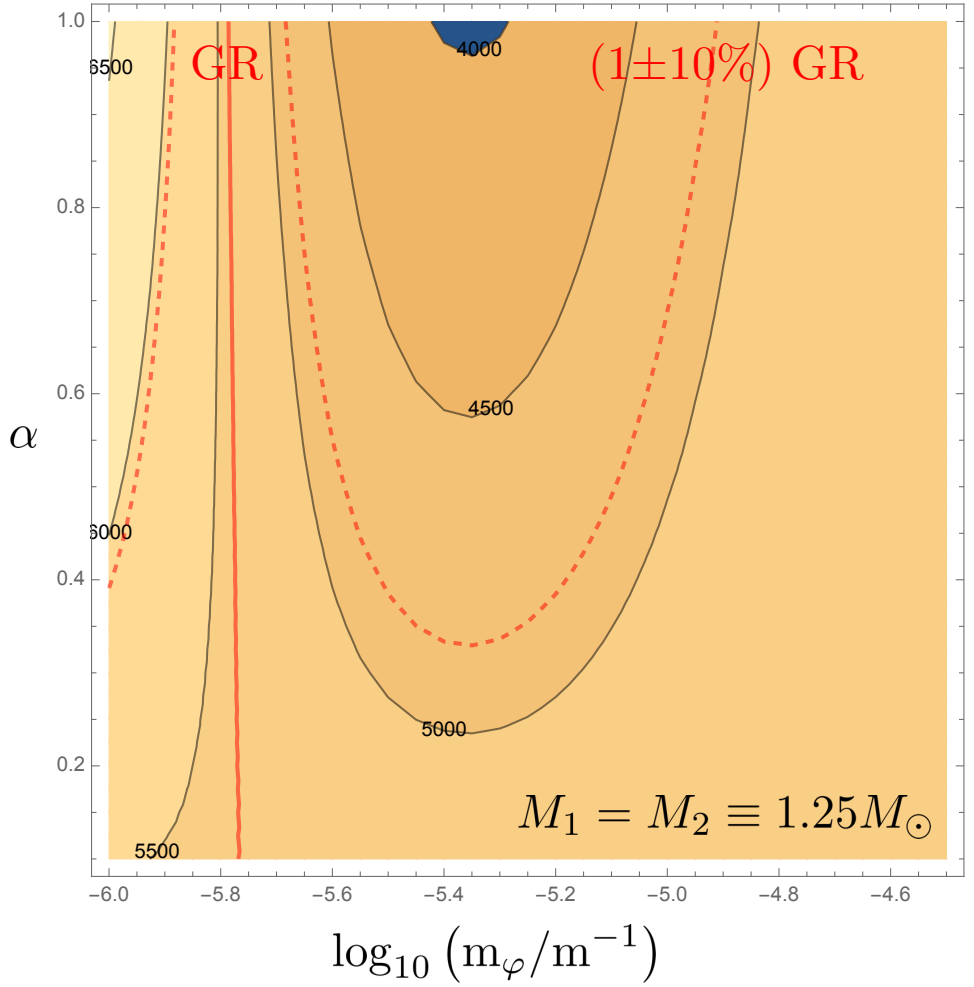
$$\langle \mathrm{SNR}^2 \rangle = 4 \int_0^\infty \frac{|h_{\mathrm{char}}(f)|^2}{S_n(f)}\, df$$

[Allen et al., '14]

→ Clear deviations from GR
in a wide range of parameter space!

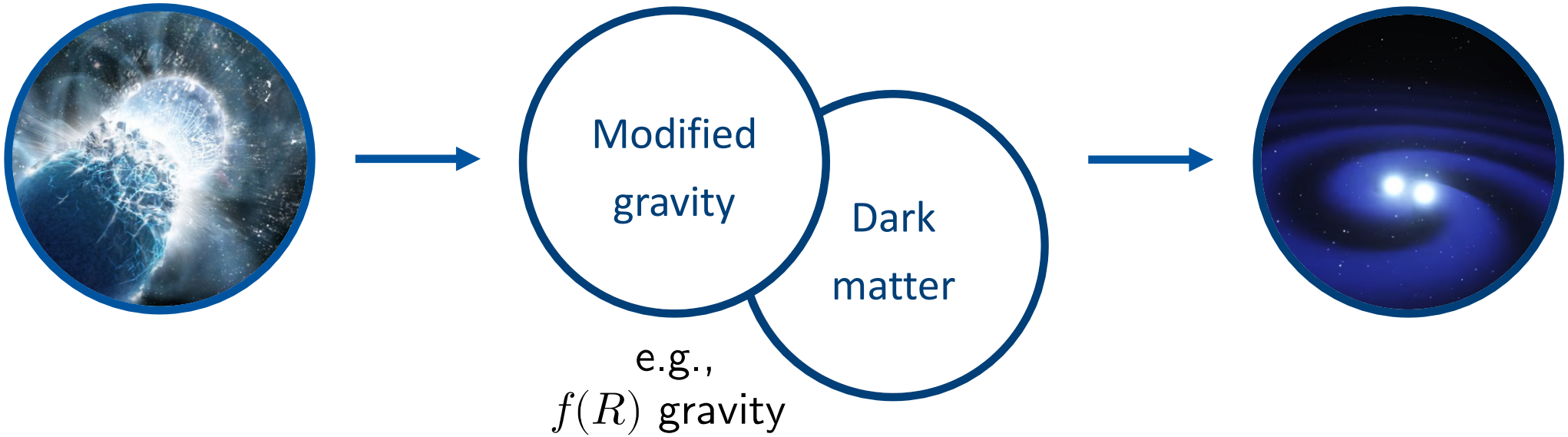
→ Constrain with LIGO/Virgo data!

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



GWs from binary mergers

= Powerful probes of new physics!



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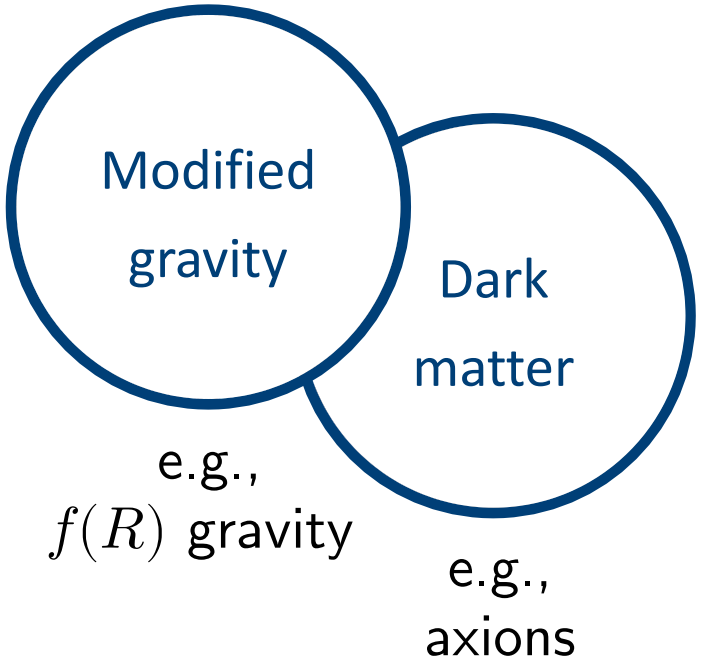
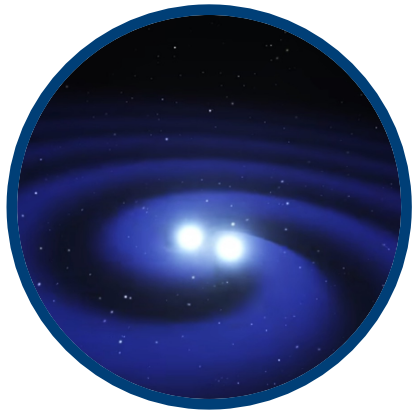




Axions

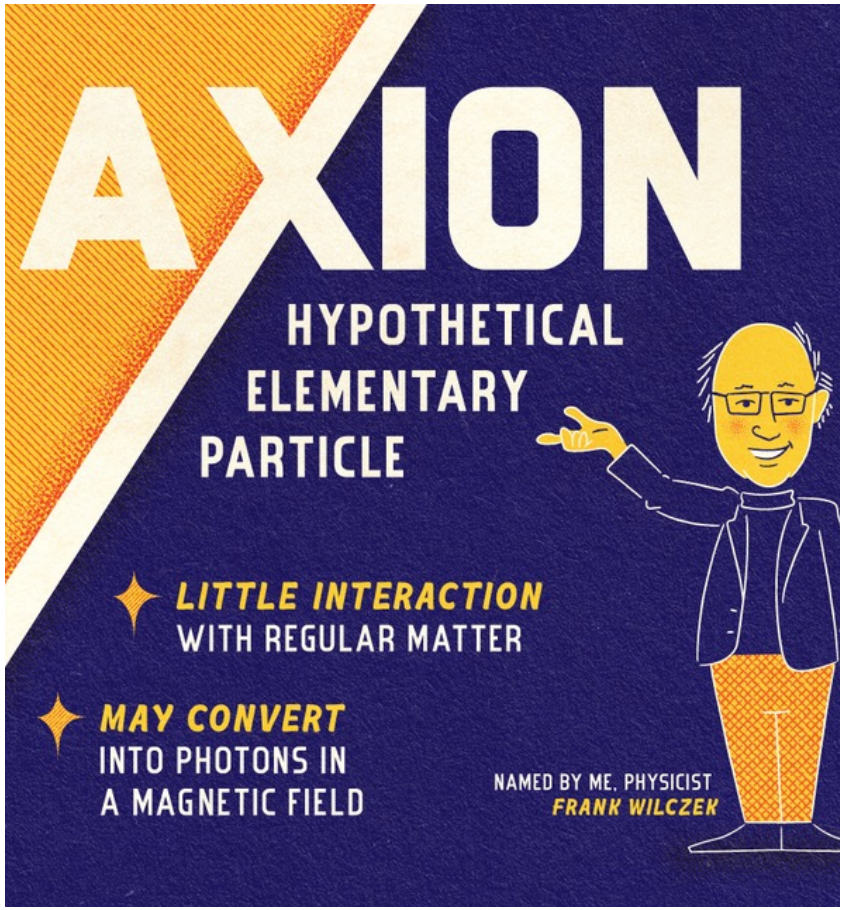
= Hypothetical particles beyond SM

+ promising dark matter candidates

- Scalar potential from axion coupling to gluons
- Axion-mediated dark fifth force

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

[Huang, Johnson, LS, Sakellariadou, Zhang, '21]



[www.symmetrymagazine.org]

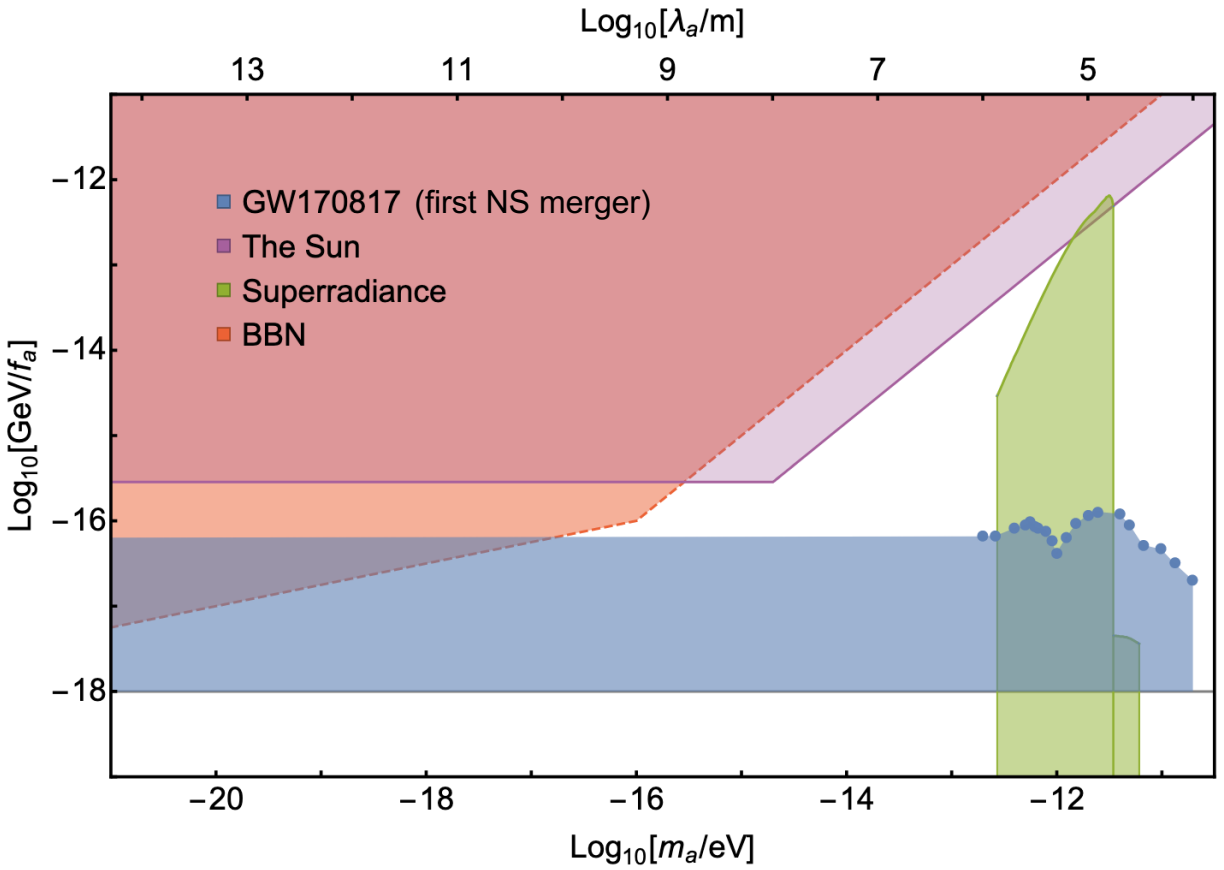
Constraining axions with gravitational waves

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

→ First constraints:

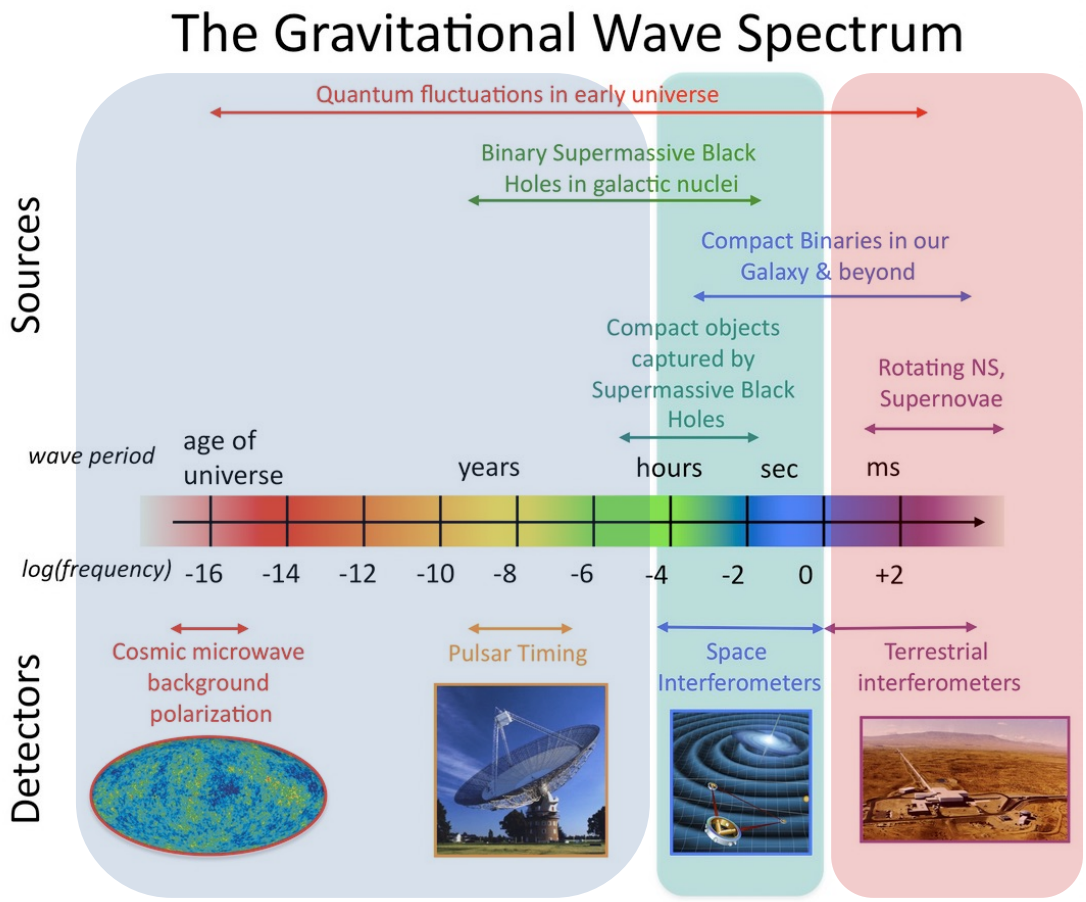
LIGO data excludes axions with:

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



The GW era has just begun!

New GW probes of DM!



[science.gsfc.nasa.gov/663/research/index.html]

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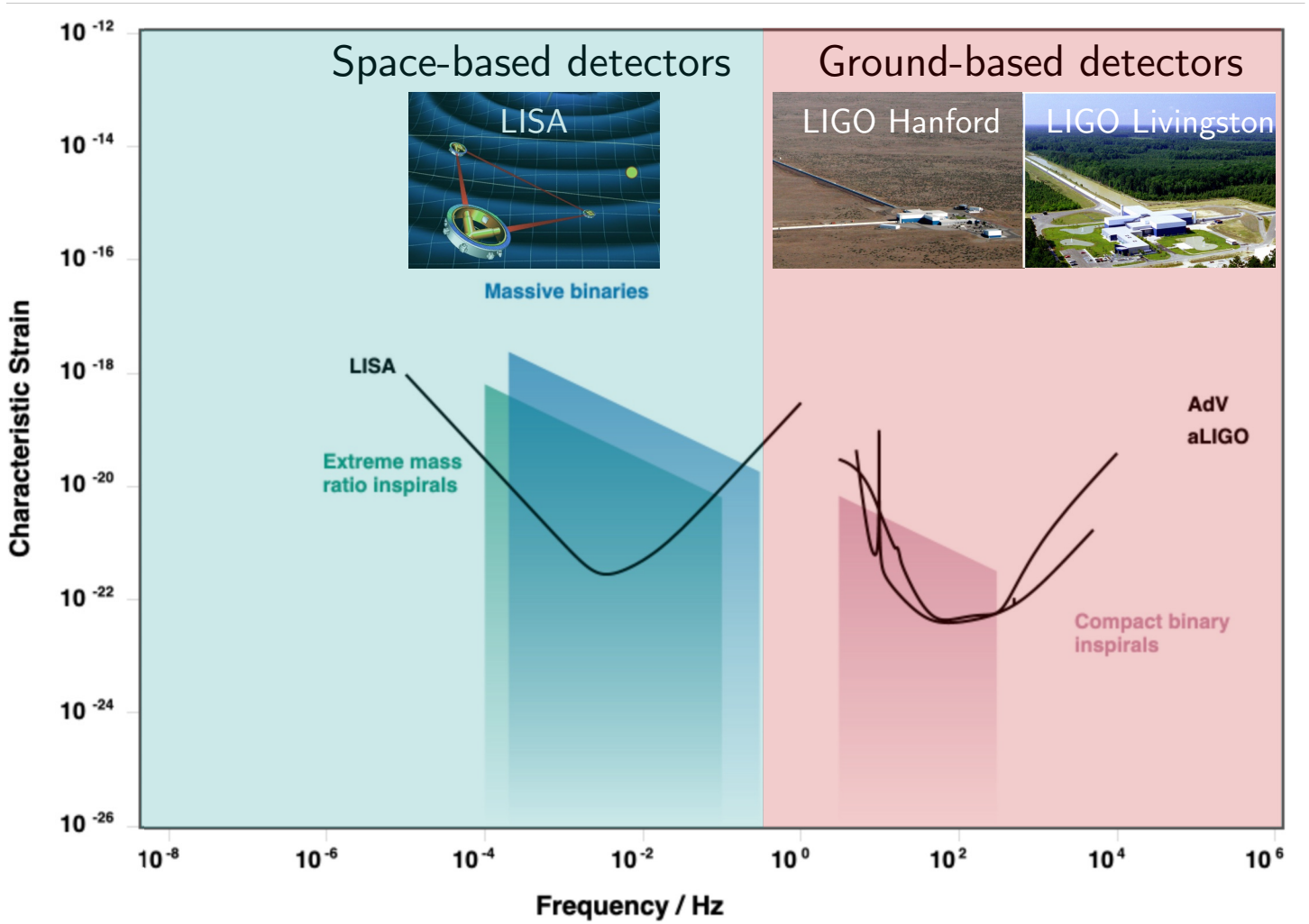
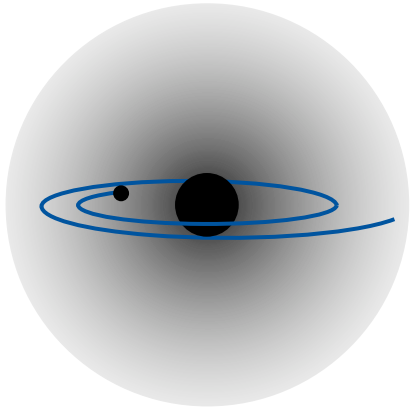


New GW probes of DM

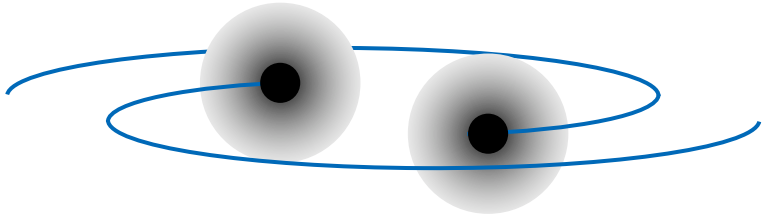
Extreme mass-ratio inspirals (EMRIs)



[Eda et al., '13]

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

Merging black holes + neutron stars

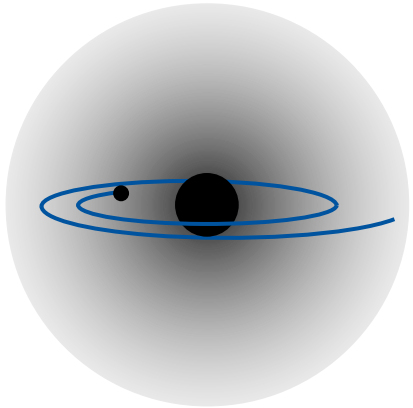


Much to explore:

- Precise dynamics
- Particle nature of DM!

New GW probes of DM

Extreme mass-ratio inspirals (EMRIs)



[Eda et al., '13]
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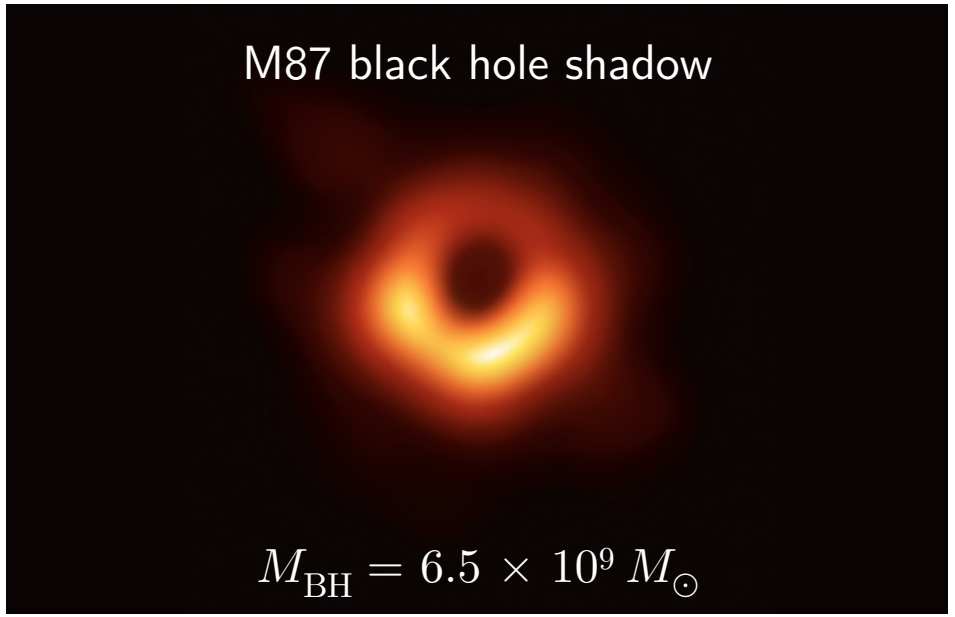


[EHT Collaboration, '19]

Much to explore:

- Precise dynamics
- Particle nature of DM!

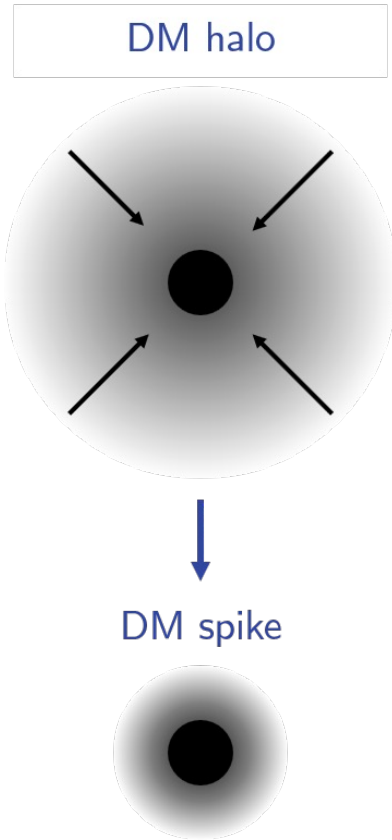
New GW probes of DM

DM density spikes

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

  → Violent environment

  → Binary dynamics drastically affected



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

Extreme mass-ratio inspirals (EMRIs)

- Additional energy loss through dynamical friction:

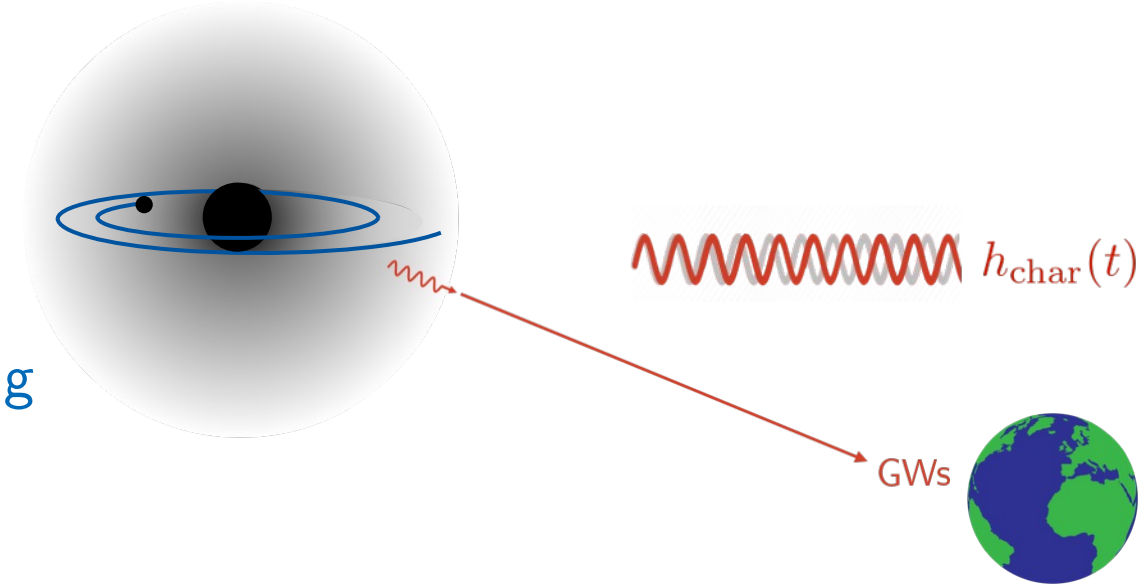
$$-\frac{dE}{dt} = \frac{dE_{\mathrm{GW}}}{dt} + \frac{dE_{\mathrm{friction}}}{dt}$$

- Accelerated dynamics: dephasing of GW signal

  → Depends on DM properties

  → Probe DM with GWs!

  → Much to explore!



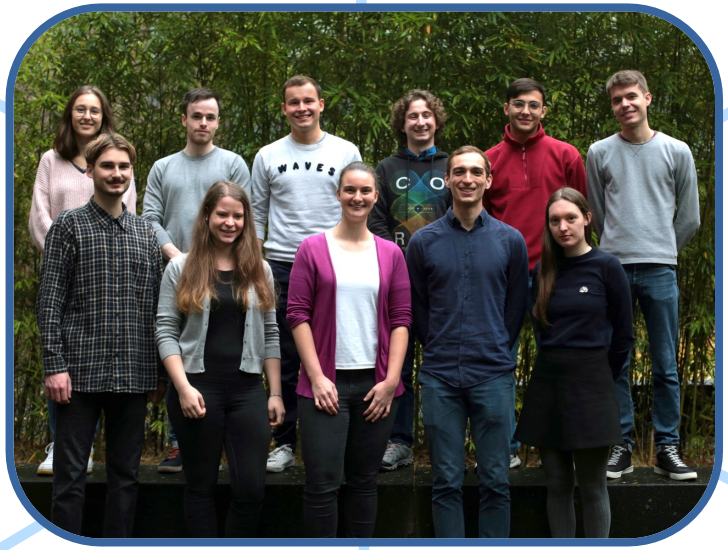
[Becker, LS, Prinz, Rastgoo, '21]

New GW probes of dark matter

Dark fifth forces

- $f(R)$ modified gravity
- Axions
- ...

More ideas!



Dark matter density spikes

- CDM
- Self-interacting dark matter

Exotic objects:

- Boson stars
- NSs with DM cores

Phase transitions:

- Hidden sectors
- Supercooling

Primordial black holes

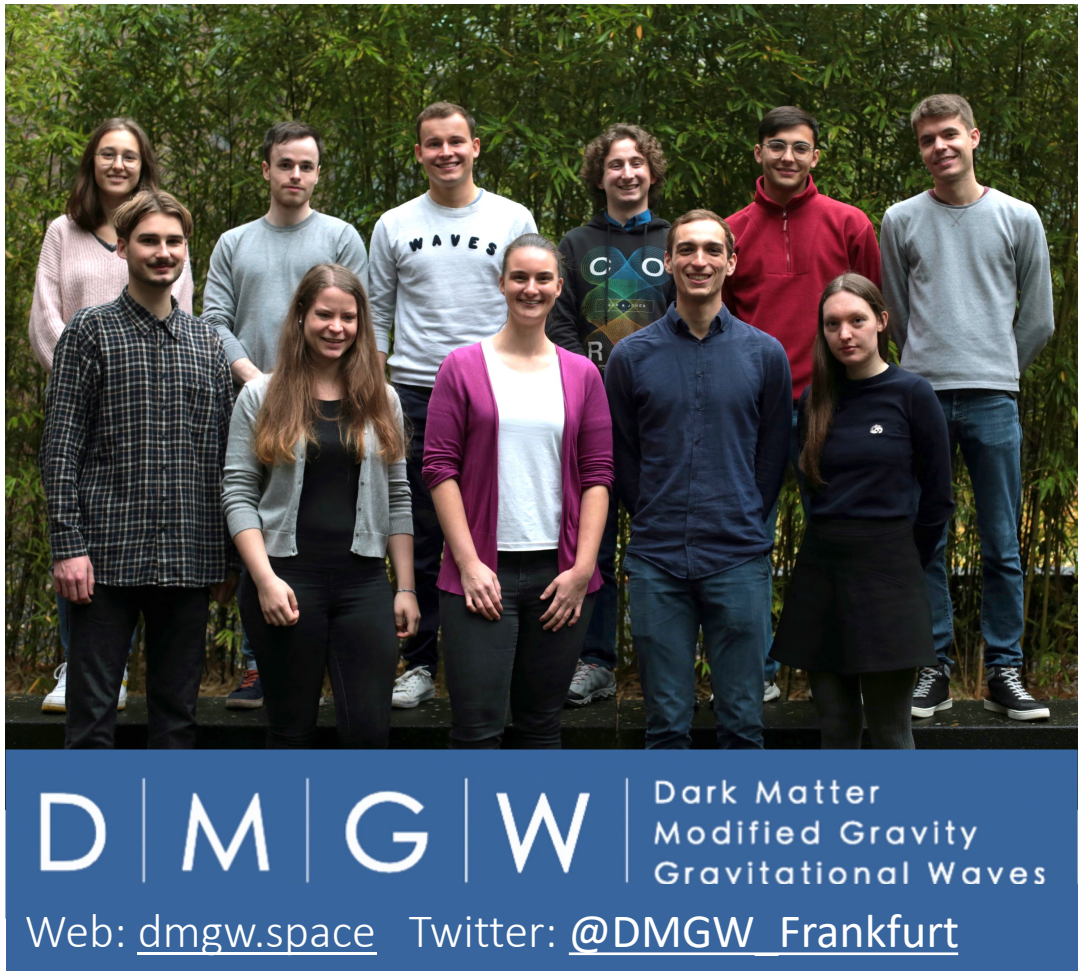
Conclusions

Conclusions

GWs are powerful probes of new physics:

- Extensions of general relativity, e.g., $f(R)$ gravity
- Particle physics beyond SM = dark matter,
  e.g. axions, self-interacting dark matter, ...

→ Much to explore in the future!



Thank you for your attention!