Horndeski and the Sirens

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Pierre Fleury
Instituto de Física Teórica UAM/CSIC

Colloque National Action Dark Energy, 14 October 2020

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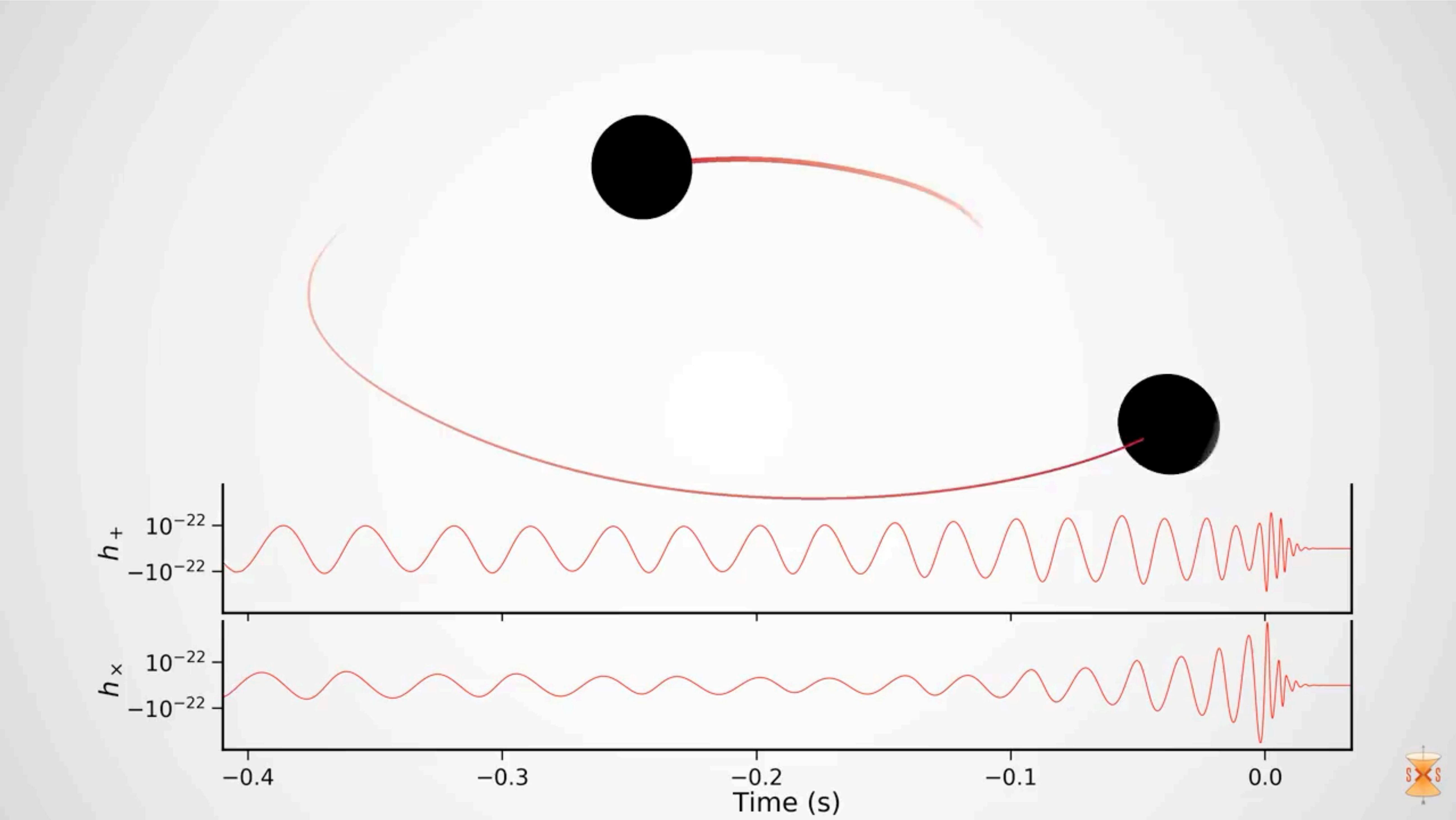
Standard sirens

Schutz (1986)
Holz & Hughes (2005)
"standard siren" suggested by Carroll and Phinney



$$h_{+,\times} \propto \frac{\mathcal{M}_z^{5/3}}{D_\mathrm{G}} \cos w(t) \qquad \frac{\mathrm{d}^2 w}{\mathrm{d}t^2} \propto \mathcal{M}_z^{5/3}$$

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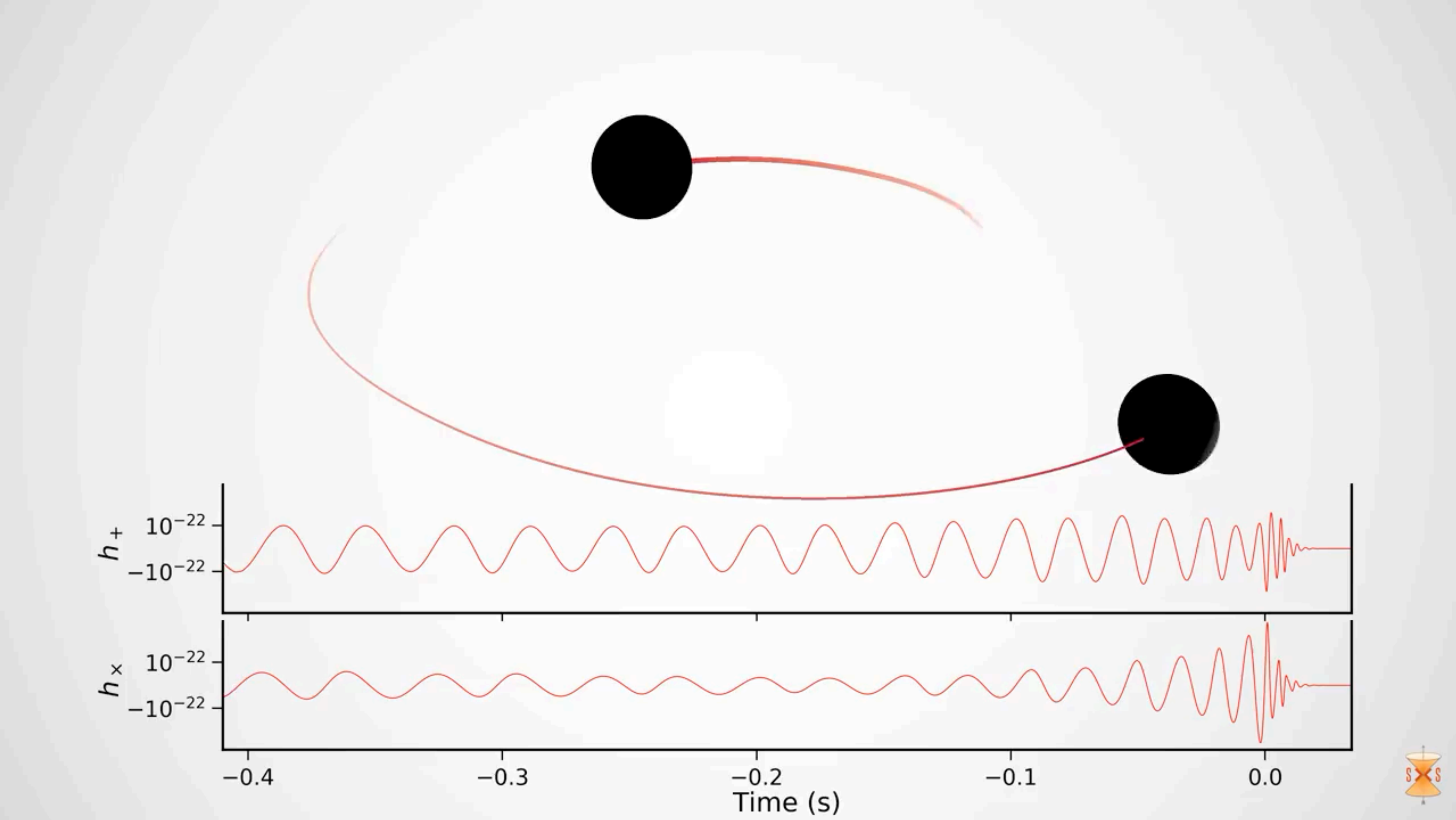

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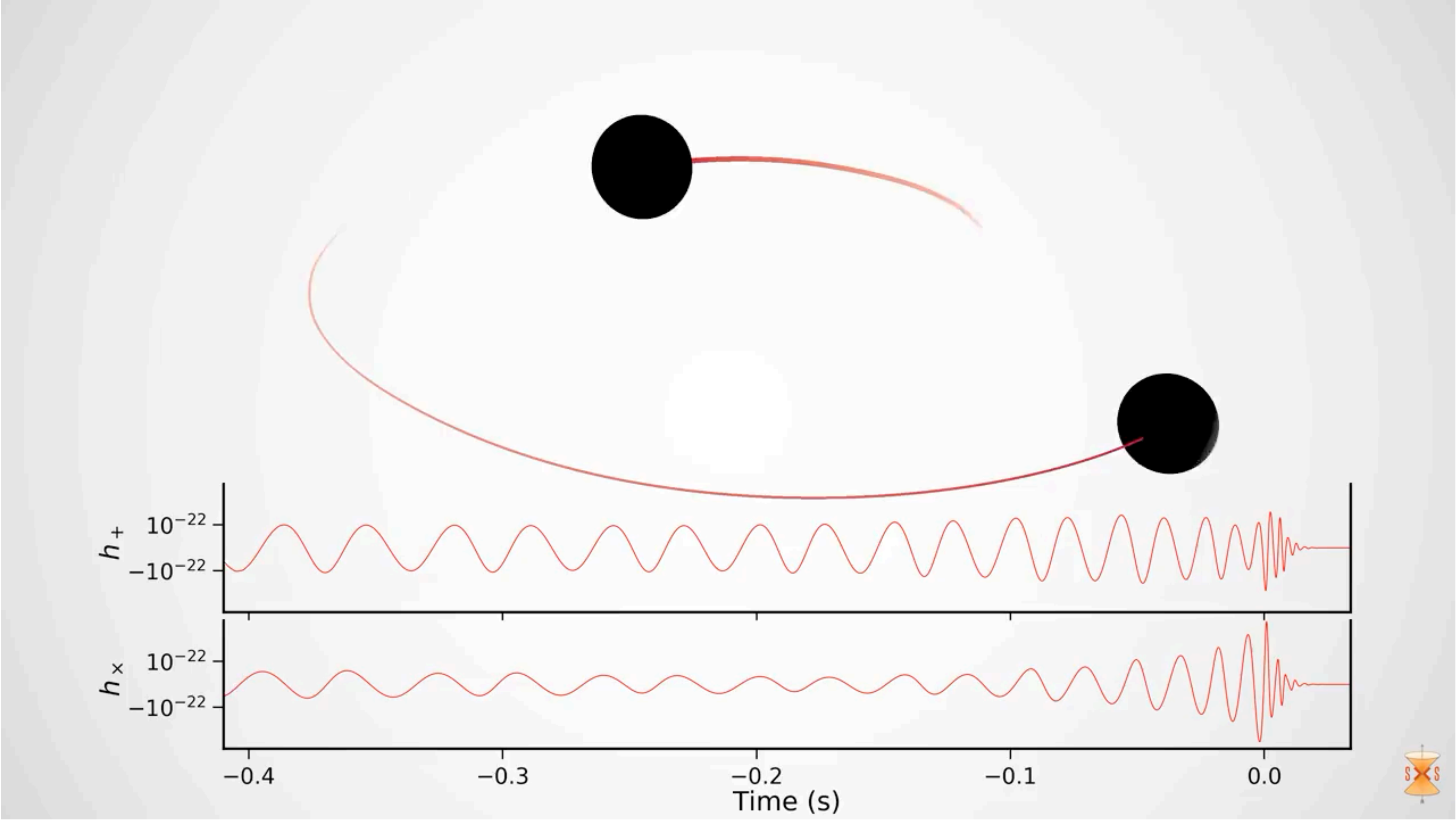
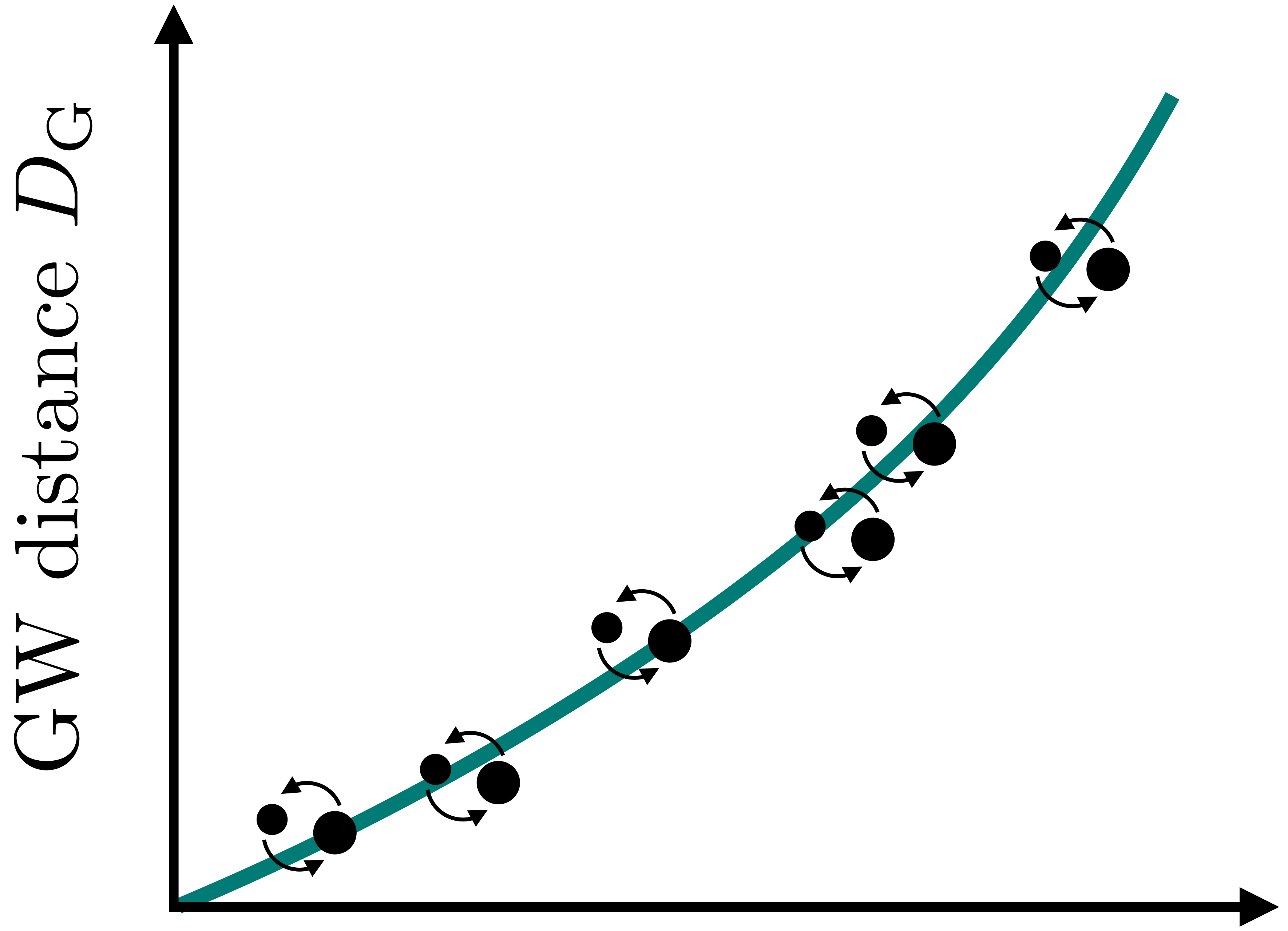


If z is measured: *Hubble diagram*



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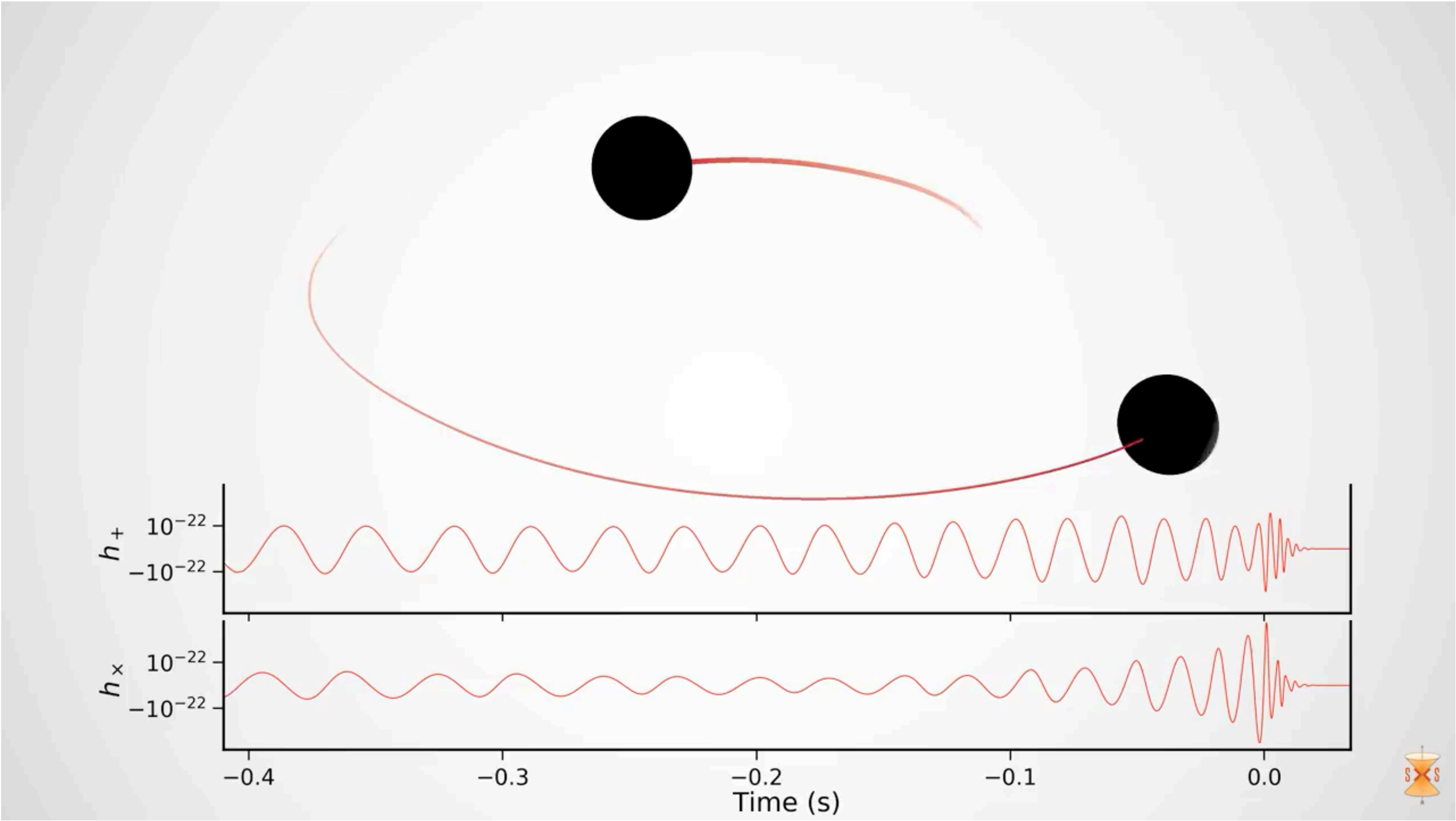

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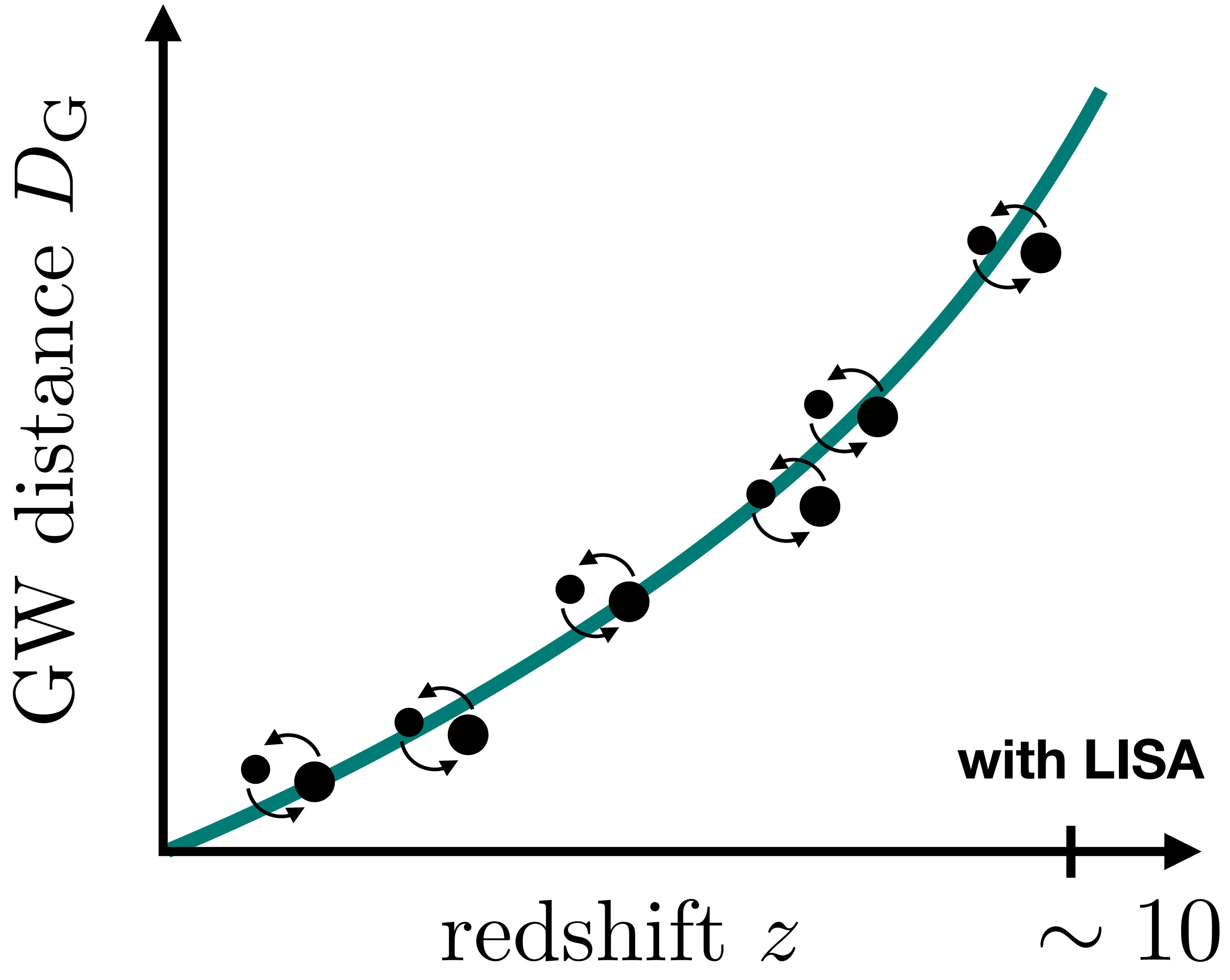

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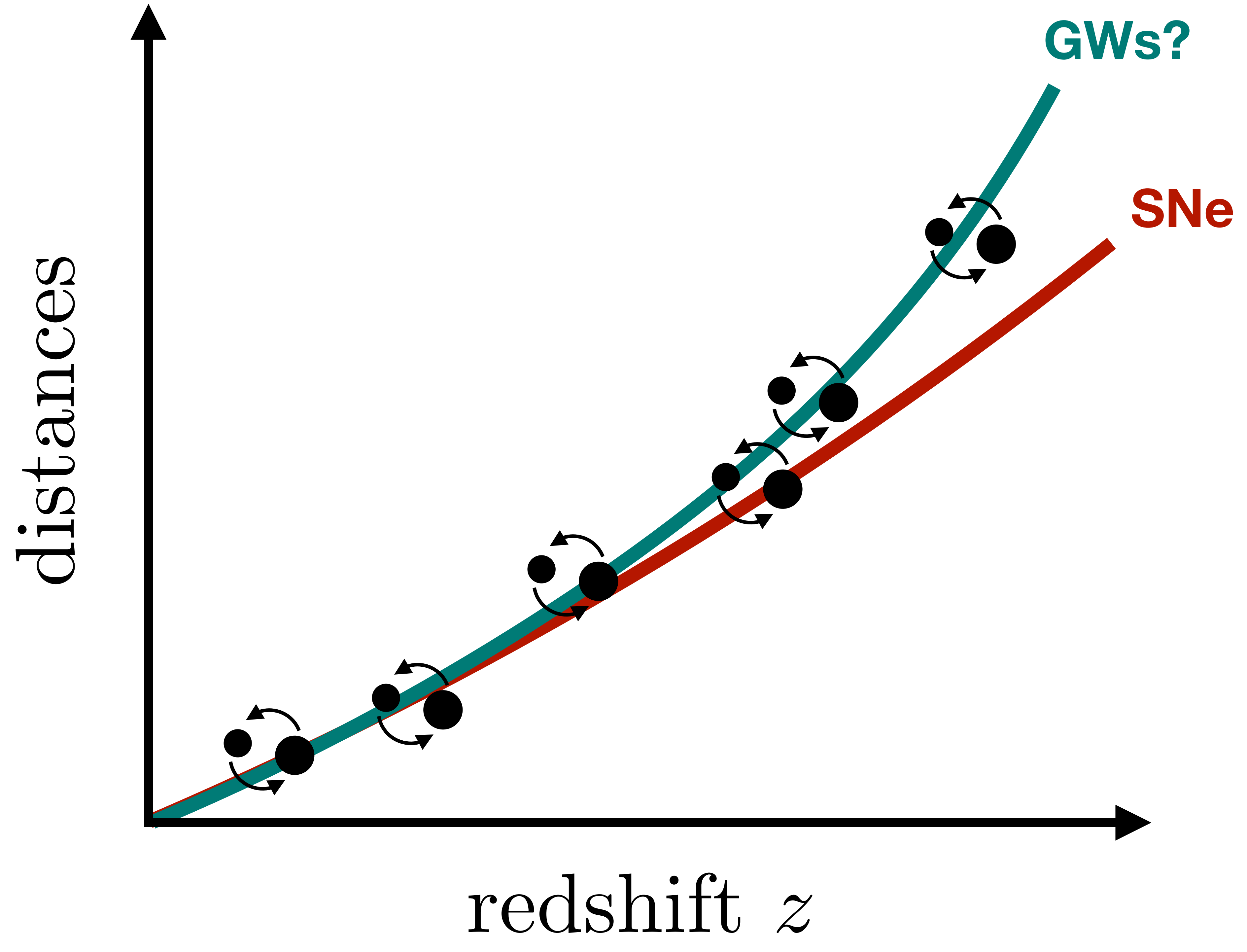
Testing gravity with sirens

Saltas et al. (2014)
Lombriser & Taylor (2016)
Belgacem et al. (2017-2019)

In a wide class of gravity theories, in a homogeneous-isotropic Universe (FLRW)

$$\underbrace{D_{\mathrm{G}}(z)}_{\text{GW distance}} = \underbrace{\frac{M_*(0)}{M_*(z)}}_{\text{effective Planck mass}} \underbrace{D_{\mathrm{L}}(z)}_{\text{(electromagnetic) luminosity distance}}$$



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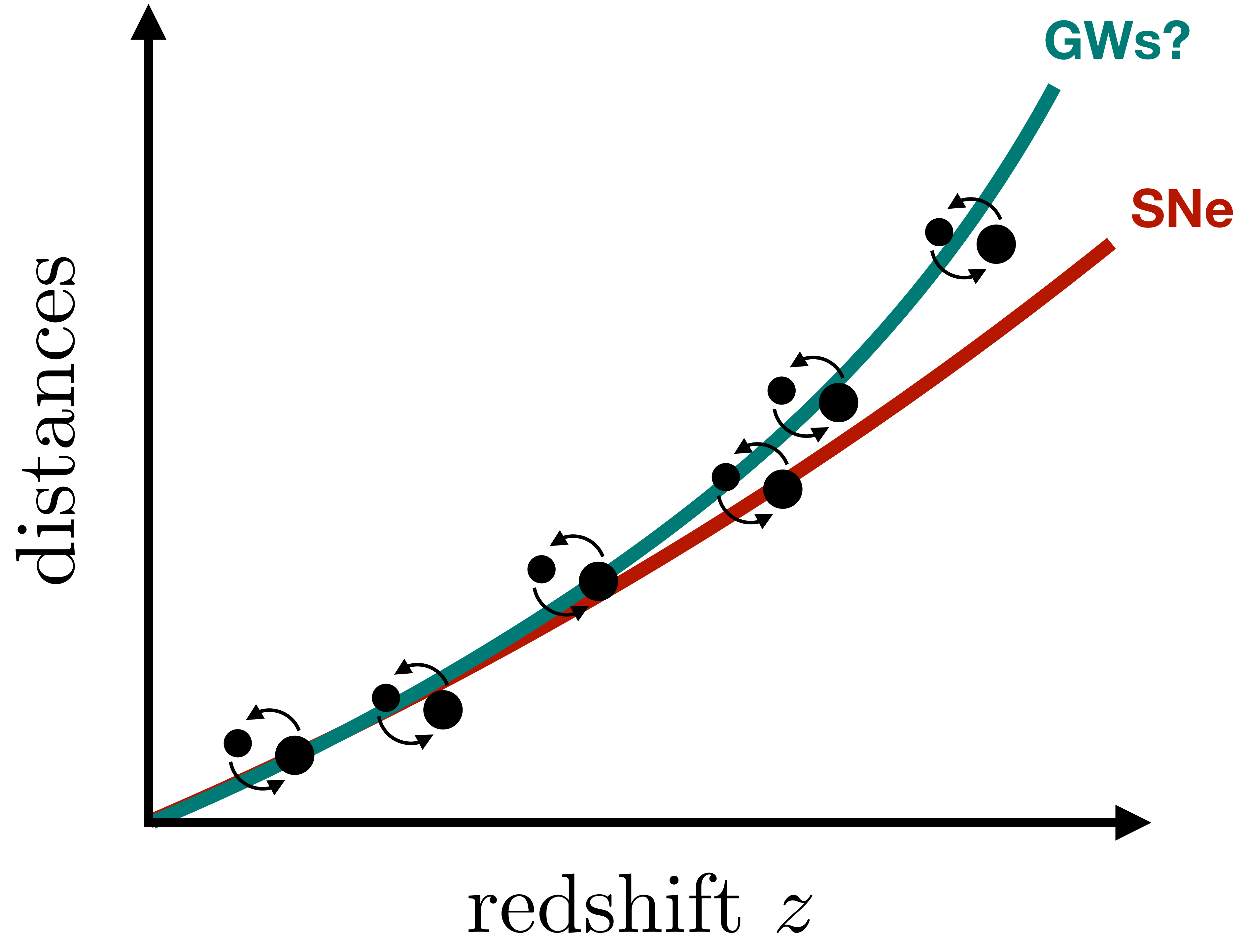
The GW Hubble diagram probes a potential cosmic evolution of the Planck mass



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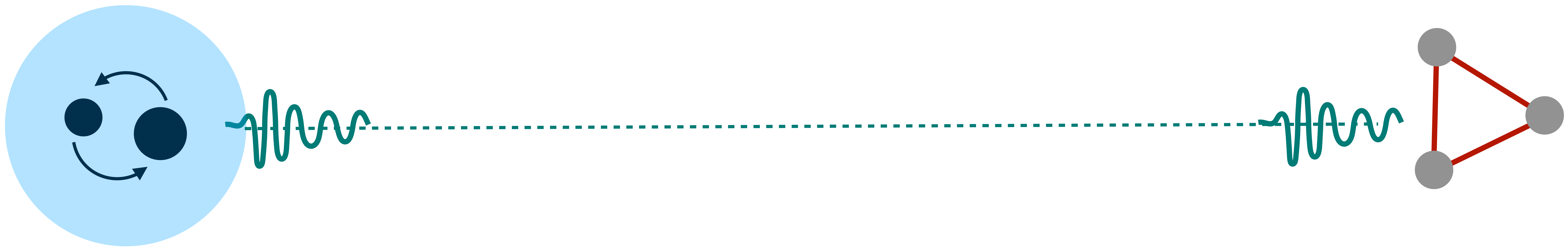

unaltered emission?
need screening

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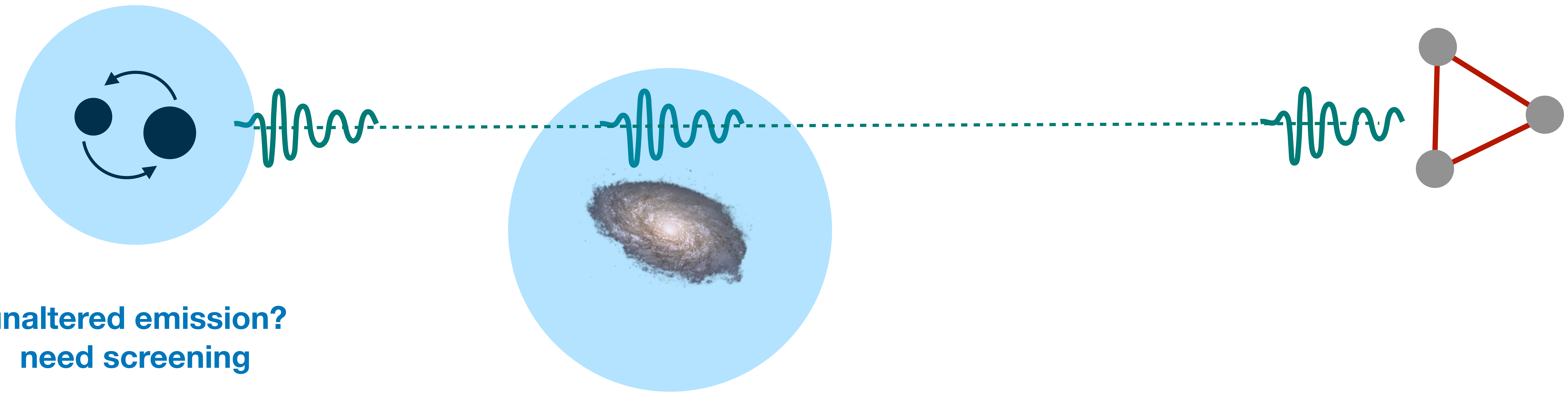

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propagation through
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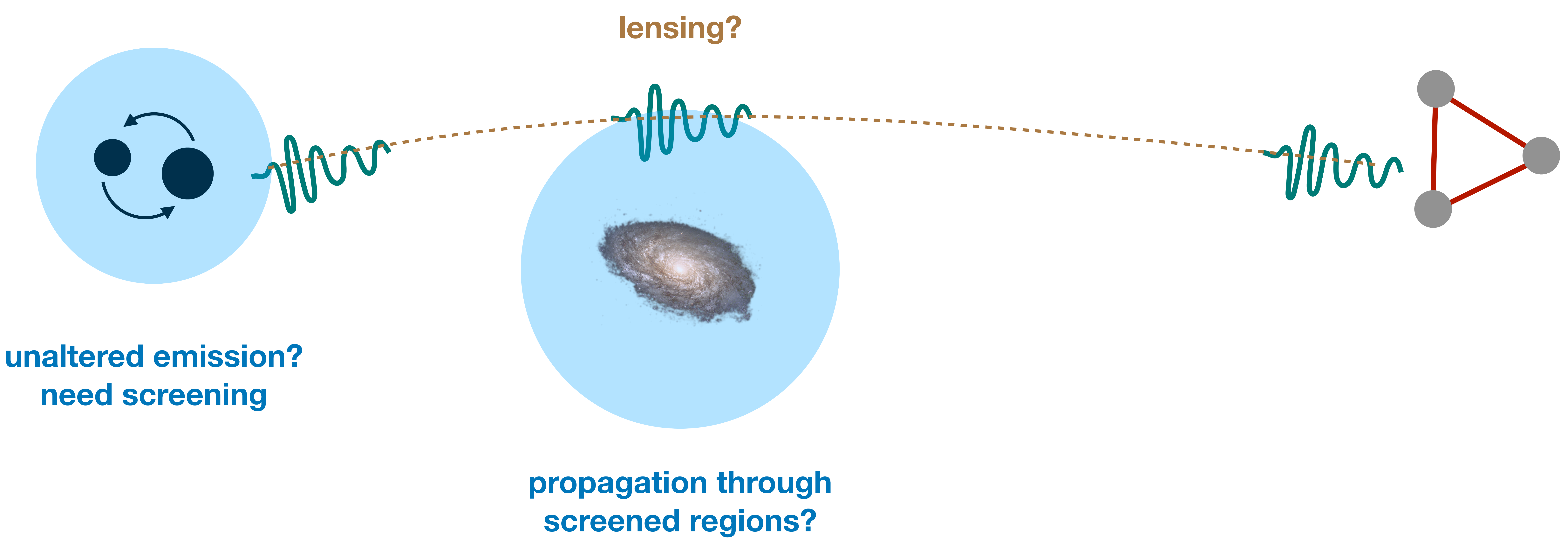

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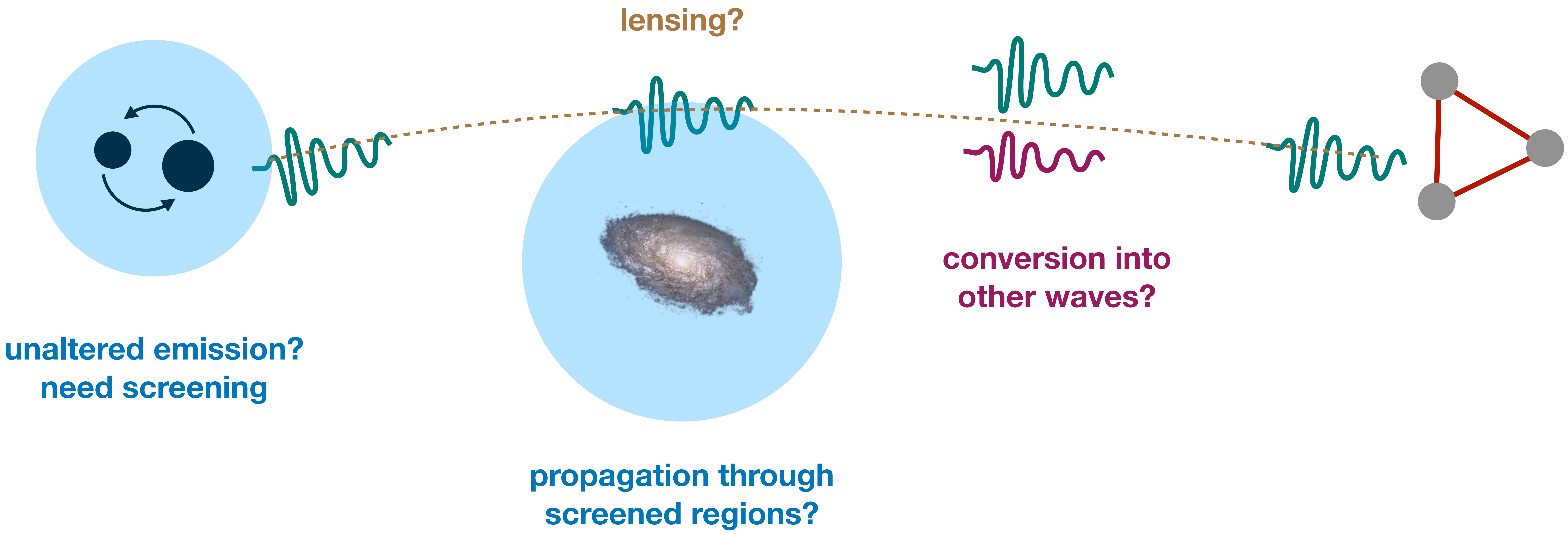

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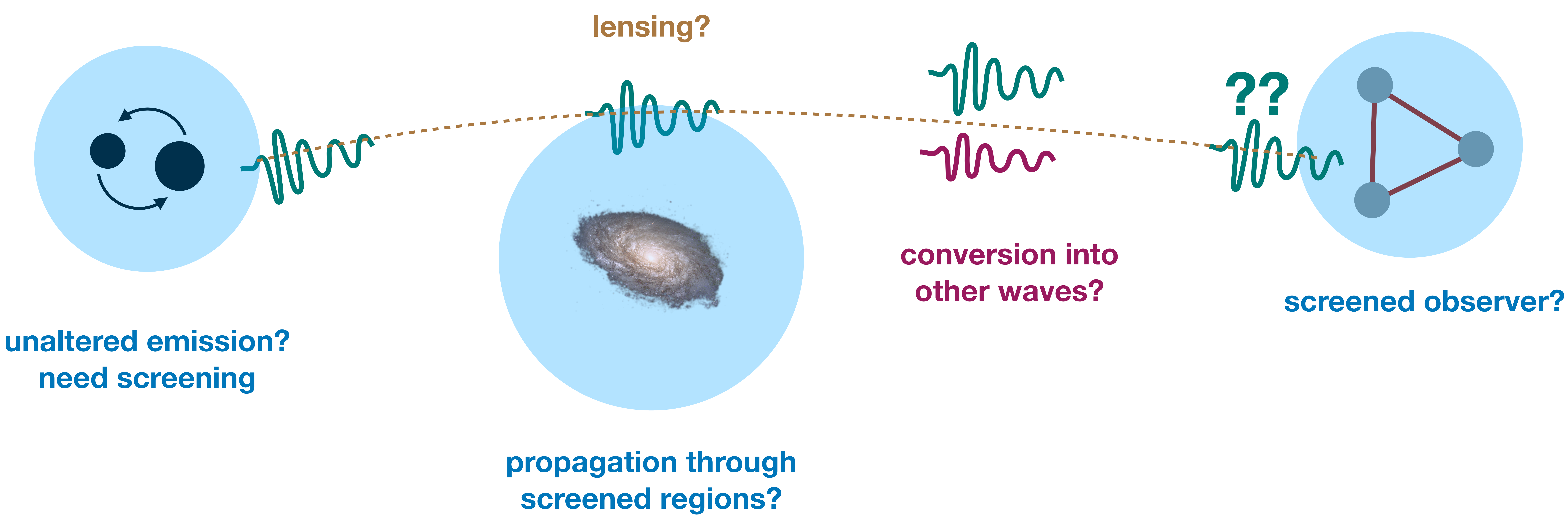

Motivation of this project: what is the GW distance in the real Universe?

Gravity model: reduced Horndeski

Horndeski (1974)
Deffayet et al. (2009)
GW170817/GRB170817

- **Horndeski theories** = GR + an extra scalar field
- Effective behaviour of some **high-energy theories**
- Scalar field could be **dark energy**
- **Reduced** Horndeski: models with *luminal* GWs

$$S_{\mathrm{RH}}[\varphi, g_{\mu\nu}] = K(\varphi, X) + G(\varphi, X)\Box\varphi + M_*^2(\varphi)R$$

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Linearised equations of motion

Dalang, PF, Lombriser (2020)
Ezquiaga & Zumalacárregui (2020)

Perturbations on arbitrary background:

$$\begin{aligned} \varphi &= \bar{\varphi} + \delta\varphi \\ g_{\mu\nu} &= \bar{g}_{\mu\nu} + h_{\mu\nu} \end{aligned}$$

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astro/cosmo background

GW

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negligible

scalar dispersion relation

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negligible

scalar dispersion relation

how scalar waves
“feed” tensor waves

Dispersion relations

Wave ansätze

$$\delta\varphi = \boxed{\Phi}\ \boxed{\mathrm{e}^{\mathrm{i}v}}$$
$$\gamma_{\mu\nu} = \boxed{\Gamma_{\mu\nu}}\ \boxed{\mathrm{e}^{\mathrm{i}w}}$$

amplitude phase

Wave four-vectors

$$q_\mu \equiv \partial_\mu v$$
$$k_\mu \equiv \partial_\mu w$$

Dispersion of tensor waves

$$0 = \mathsf{K}_{\mu\nu}{}^{\rho\sigma\alpha\beta} k_\alpha k_\beta \propto k^\alpha k_\alpha$$

tensor waves propagate along *null geodesics*

Dispersion of scalar waves

$$0 = \mathsf{K}_{\varphi}{}^{\varphi\alpha\beta} q_\alpha q_\beta$$
$$1 - c_{\mathrm{S}} \sim K_{,XX}, G_{,X}, G_{,\varphi X}, G_{,XX}$$

scalar waves can be *luminal or sub-luminal*

Effect of the waves on matter

Observable: **curvature** perturbation

$$\delta R_{\mu\nu\rho\sigma} = -2h_{[\mu[\rho;\sigma]\nu]}$$

Effect of the waves on matter

Observable: **curvature** perturbation

$$\delta R_{\mu\nu\rho\sigma} = -2h_{[\mu[\rho;\sigma]\nu]} = \underbrace{2k_{[\nu}\hat{\Gamma}_{\mu][\rho}k_{\sigma]}\mathrm{e}^{\mathrm{i}w}}_{\text{from tensor wave}} - \underbrace{2\Phi q_{[\nu}C_{\mu][\rho}q_{\sigma]}\mathrm{e}^{\mathrm{i}v}}_{\text{from scalar wave}}$$

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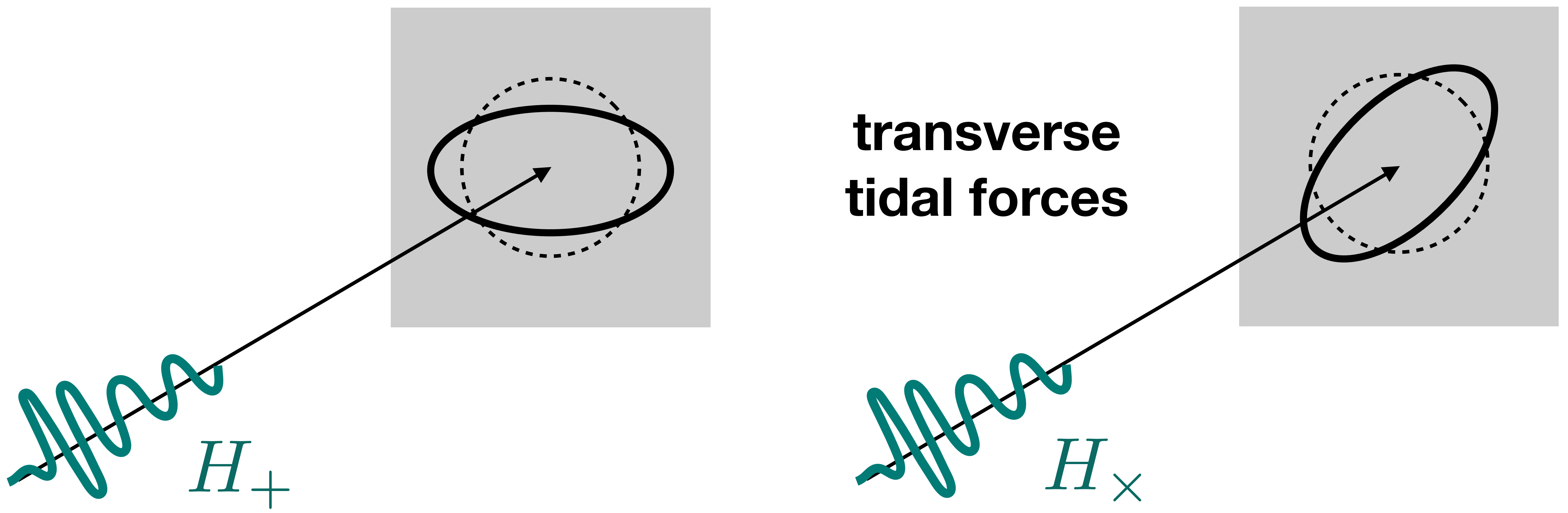

$$(\delta R^{\mathrm{T}}_{0i0j}) = \frac{\omega_{\mathrm{T}}^2}{2}\begin{pmatrix} H_+ & H_\times & 0 \\ H_\times & -H_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}\mathrm{e}^{\mathrm{i}w}$$

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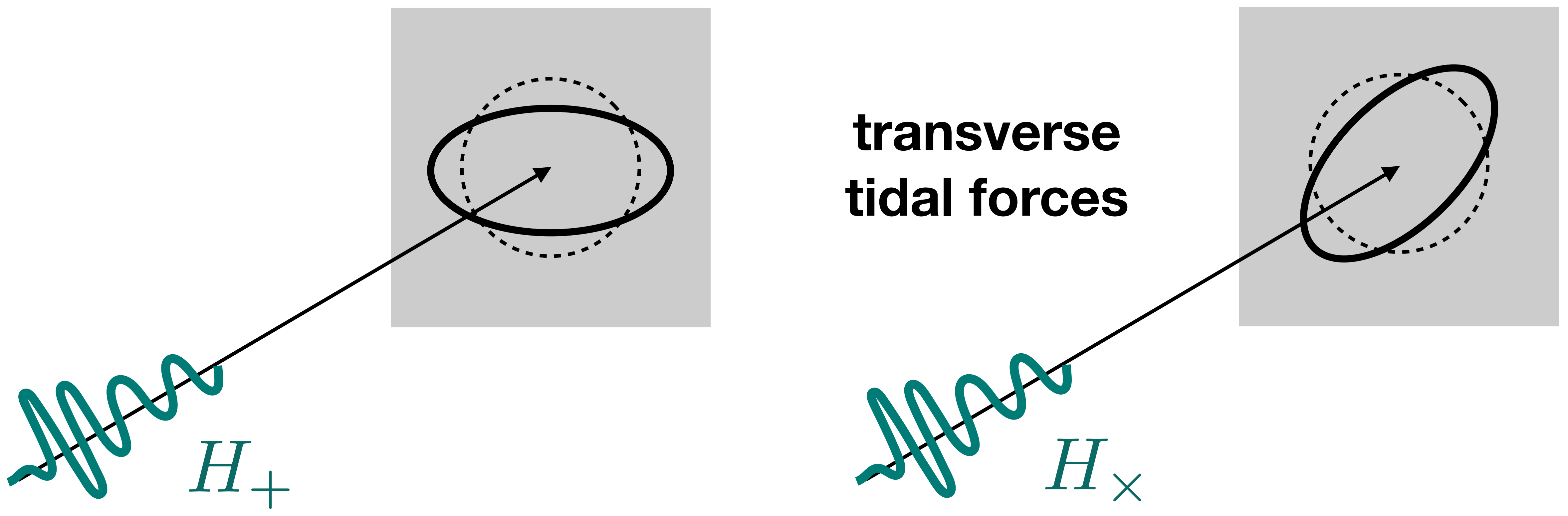

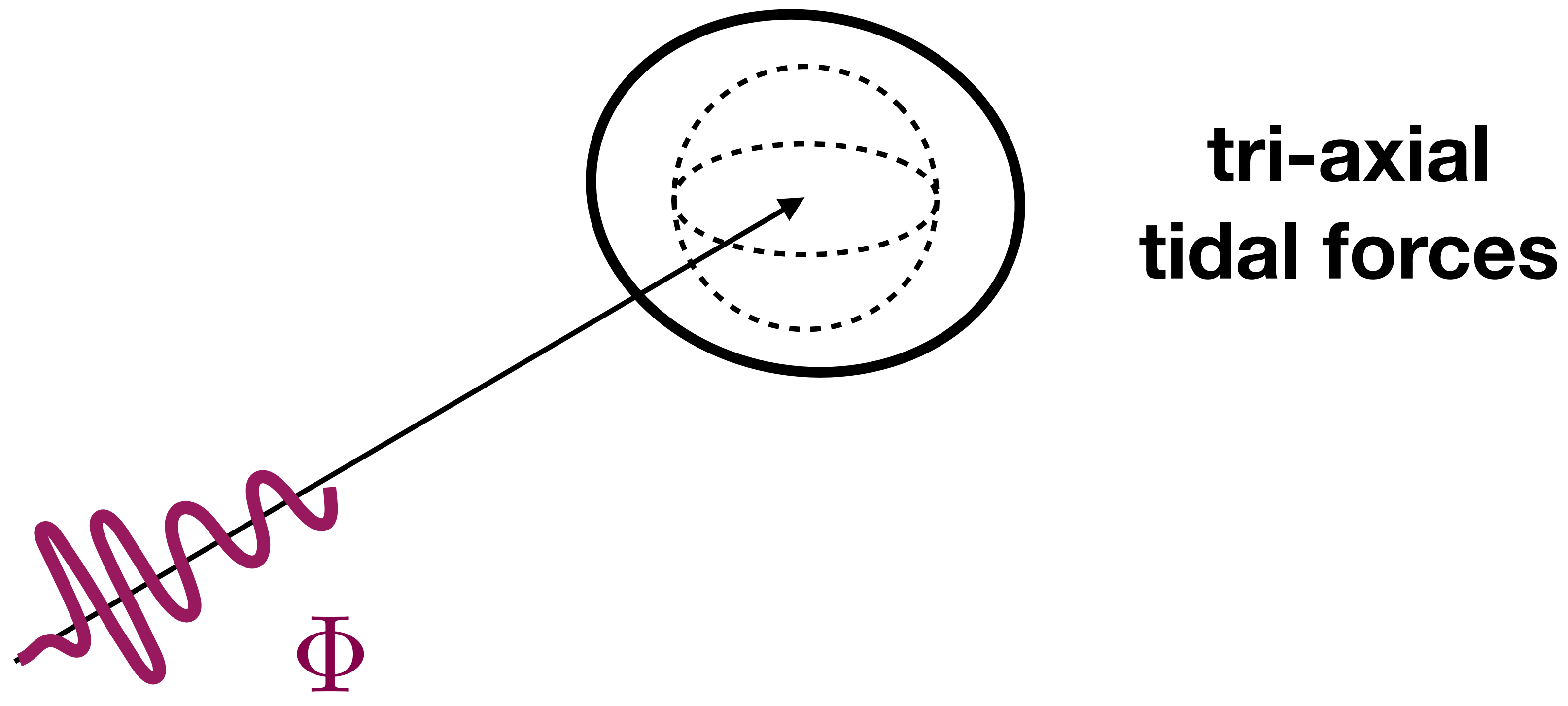

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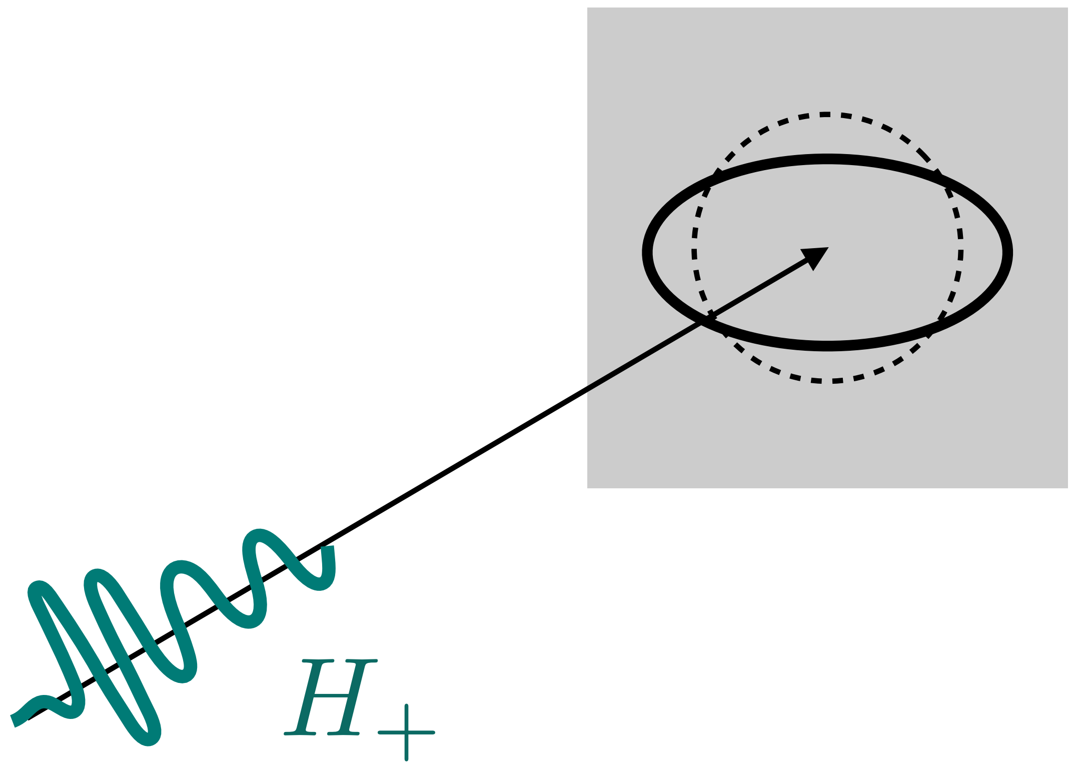
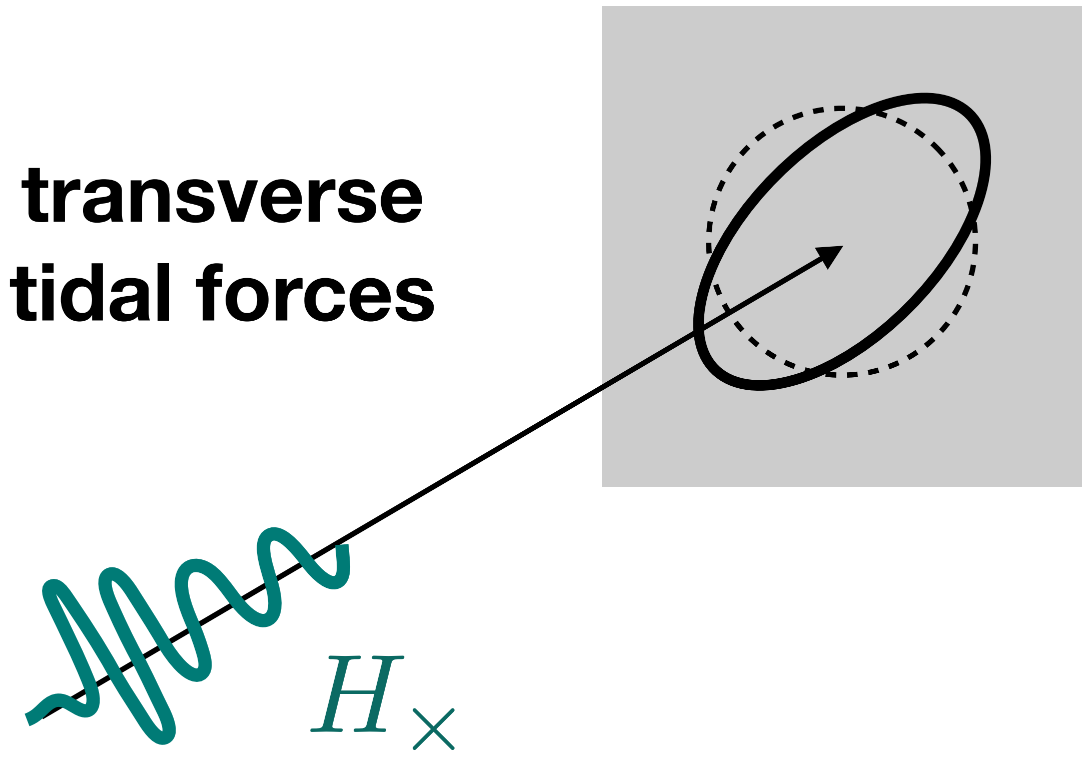


transverse tidal forces



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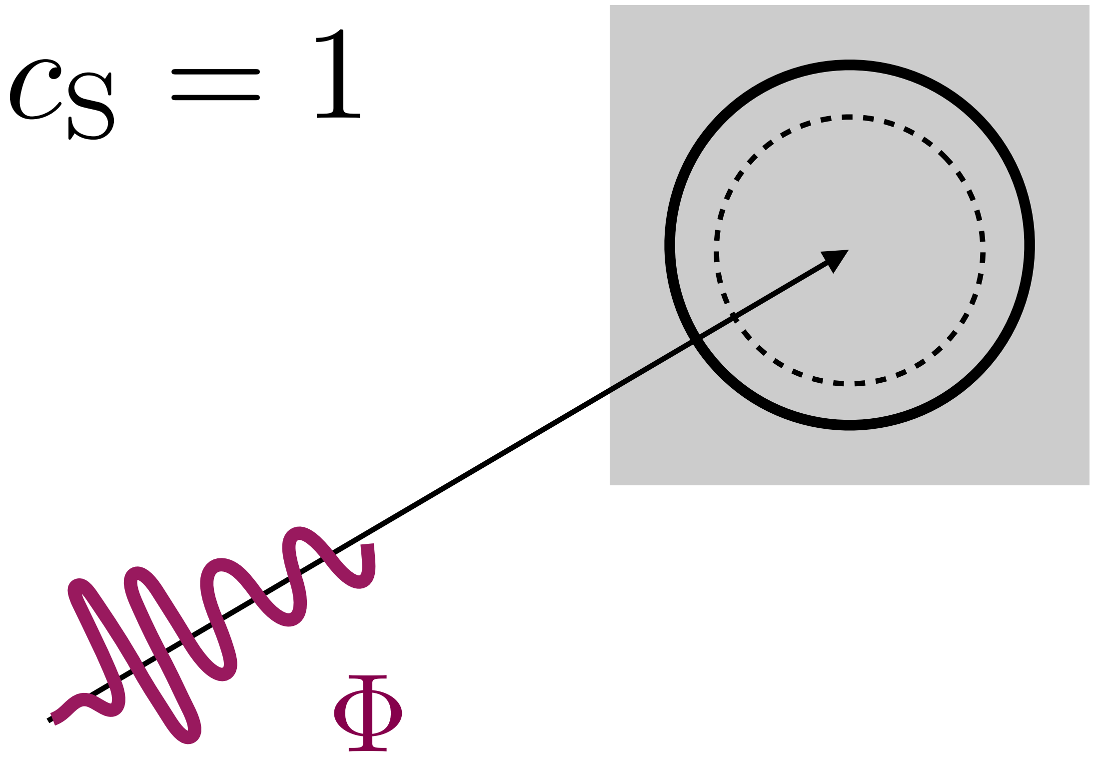
If $c_{\mathrm{S}} = 1$



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Amplitude and polarisation

Dalang, PF, Lombriser (2019)
Dalang, PF, Lombriser (2020)
NB: disagreement with Garoffolo et al. (2019)

Evolution equations for the GW amplitudes:

Scalar wave: $$0 = \mathcal{D}_\mathrm{S}\Phi\,\mathrm{e}^{\mathrm{i}v} + \mathsf{A}_{\varphi}{}^{P\alpha}k_\alpha H_P\,\mathrm{e}^{\mathrm{i}w}$$

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$$P = +, \times$$

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free propagation

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Luminal scalar waves

Sub-luminal scalar waves

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Luminal scalar waves

- No scalar-tensor interactions!
- Tensor-wave polarisation is parallel-transported
- Expression for the GW distance:

$$\frac{D_{\mathrm{G}}}{D_{\mathrm{L}}} = \frac{M_*^{\mathrm{obs}}}{M_*^{\mathrm{em}}}$$

Local effective Planck mass at reception and emission

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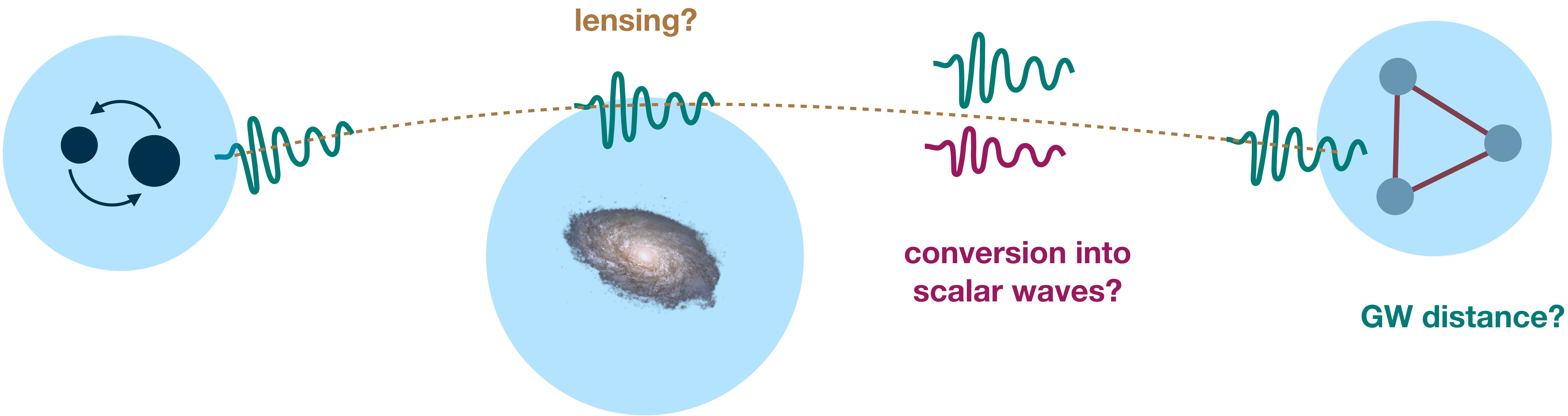
The waves at out of phase…
… eikonal approximation breaks down

Scalar Cherenkov effect?

Conclusion and open questions

See also:
Creminelli et al. (2019bc)
Hogg et al. (2020b)



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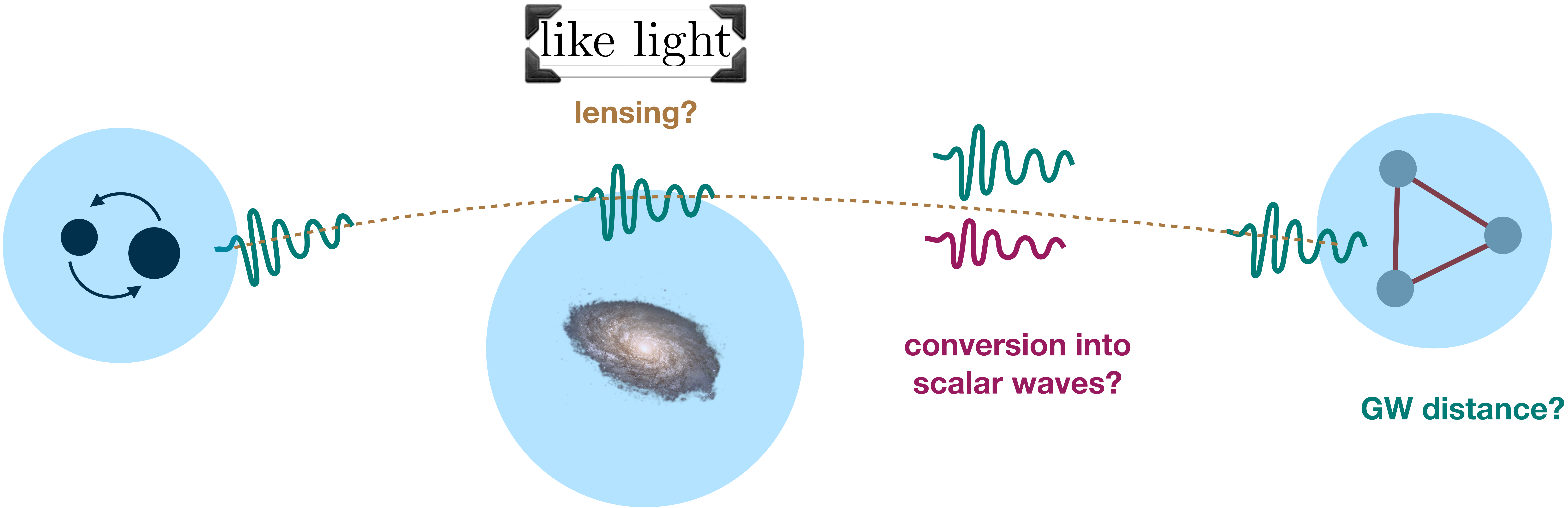

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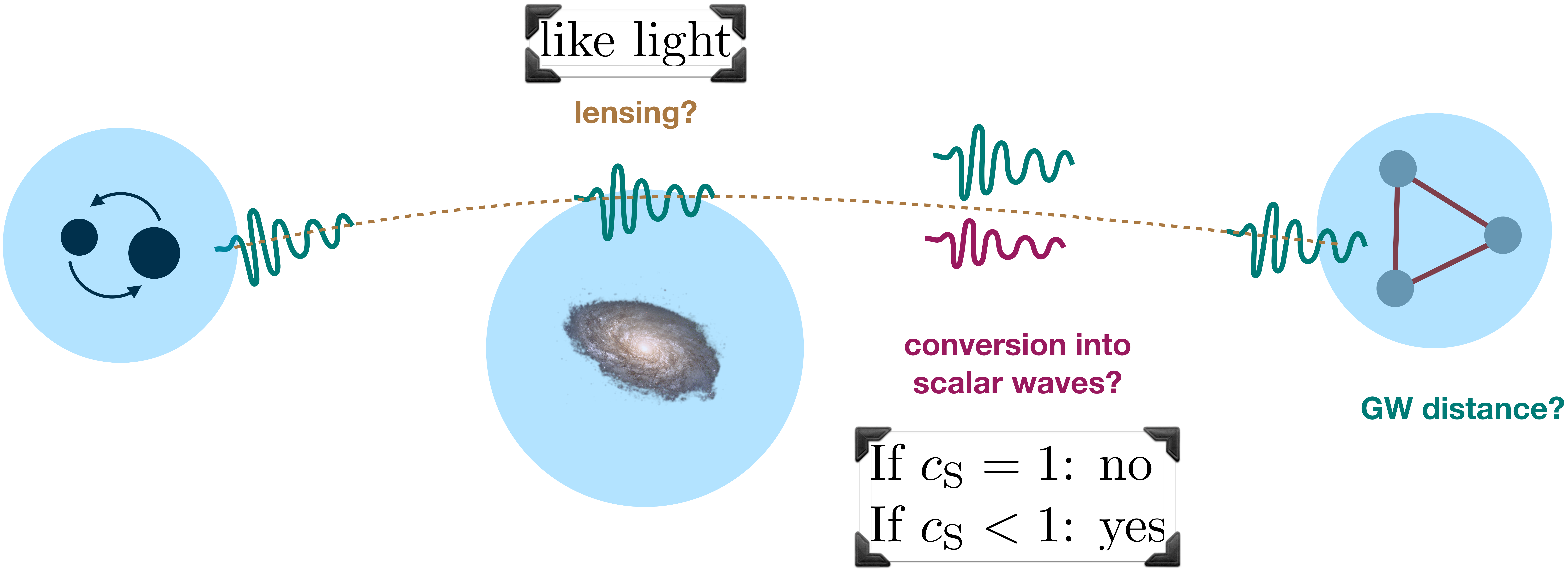

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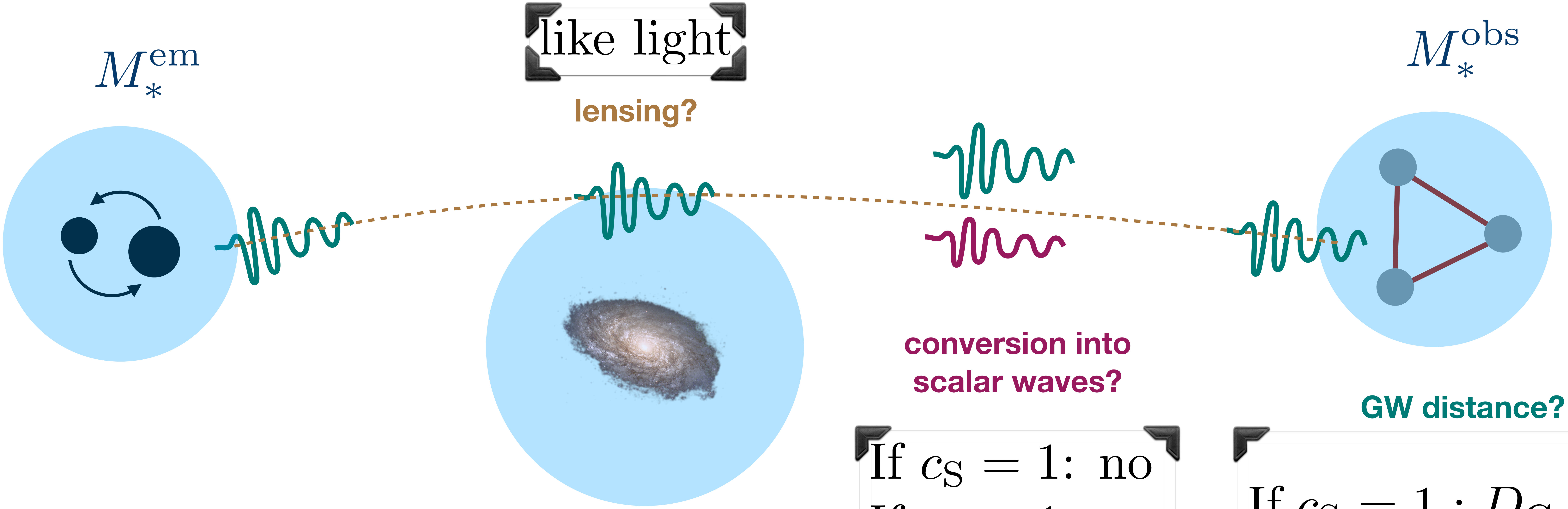

If $c_{\rm S} = 1$: no
If $c_{\rm S} < 1$: yes

GW distance?

$$\text{If } c_{\rm S} = 1 : D_{\rm G} = \frac{M_*^{\rm obs}}{M_*^{\rm em}} D_{\rm L}$$

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Conclusion and open questions

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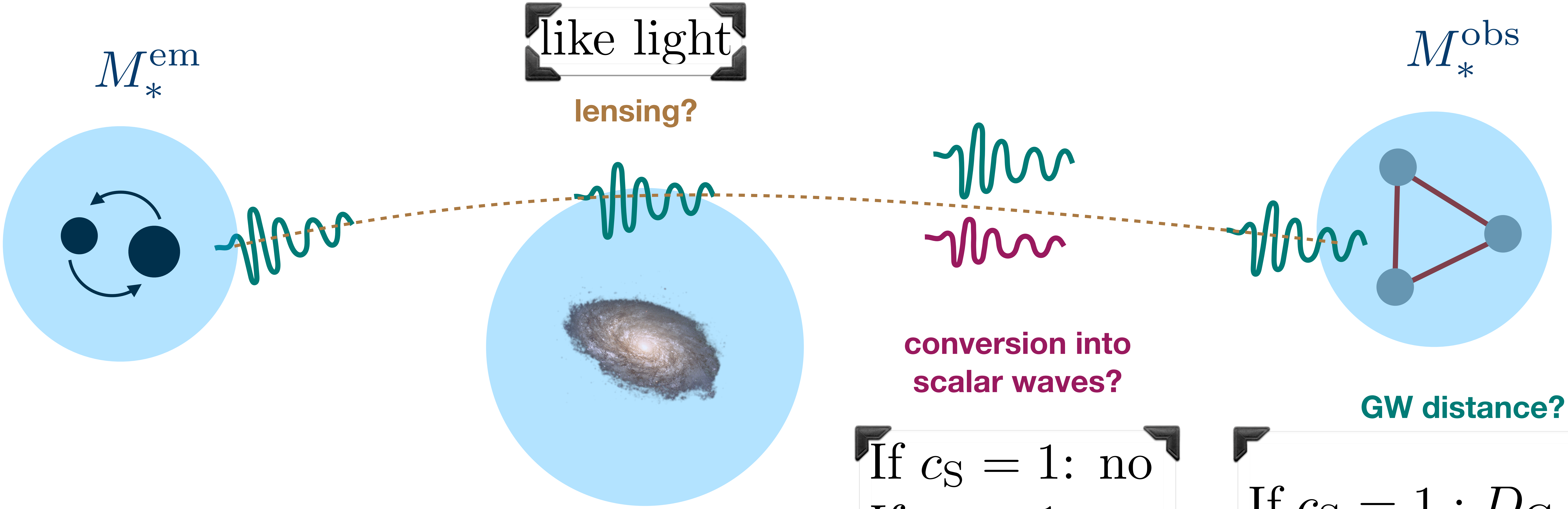

If $c_S = 1$: no
If $c_S < 1$: yes

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To be further explored:

1. effect of screening on the effective Planck mass
2. scalar Cherenkov effect