Compact objects in and beyond the Standard Model

Loris Del Grosso

Gravity theory group

https://web.uniroma1.it/gmunu

in collaboration with G. Franciolini, P. Pani and A. Urbano

2015: a discovery that shook the world

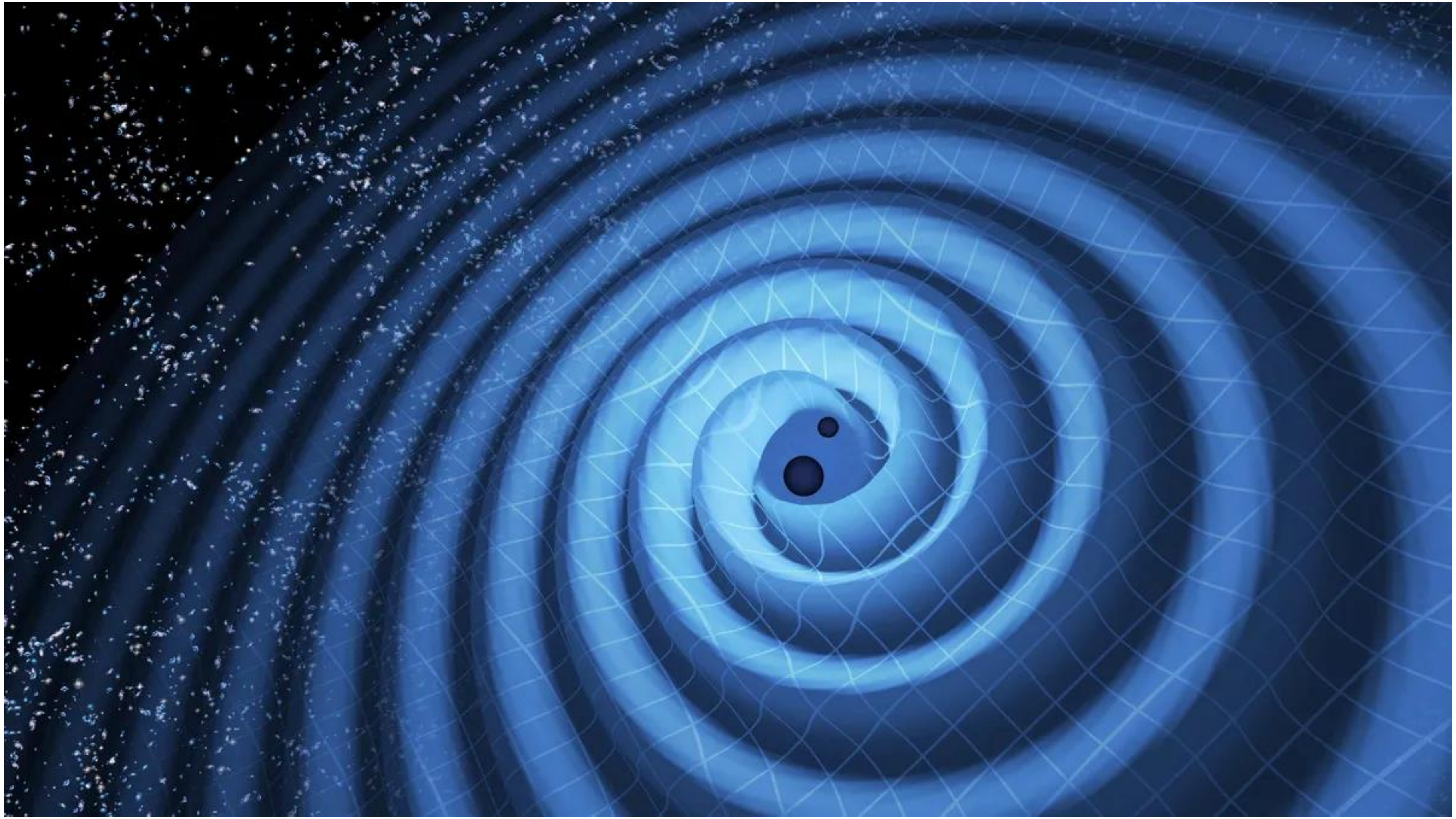


Image credit: LIGO/T. Pyle

Introduction

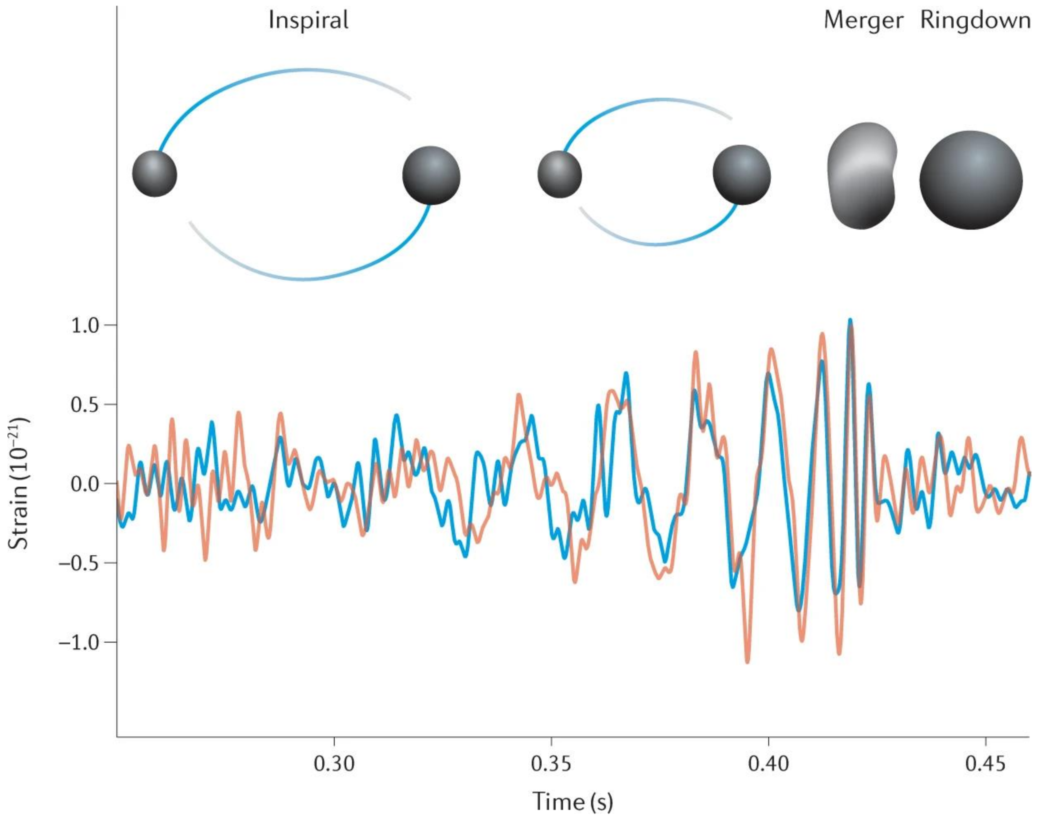
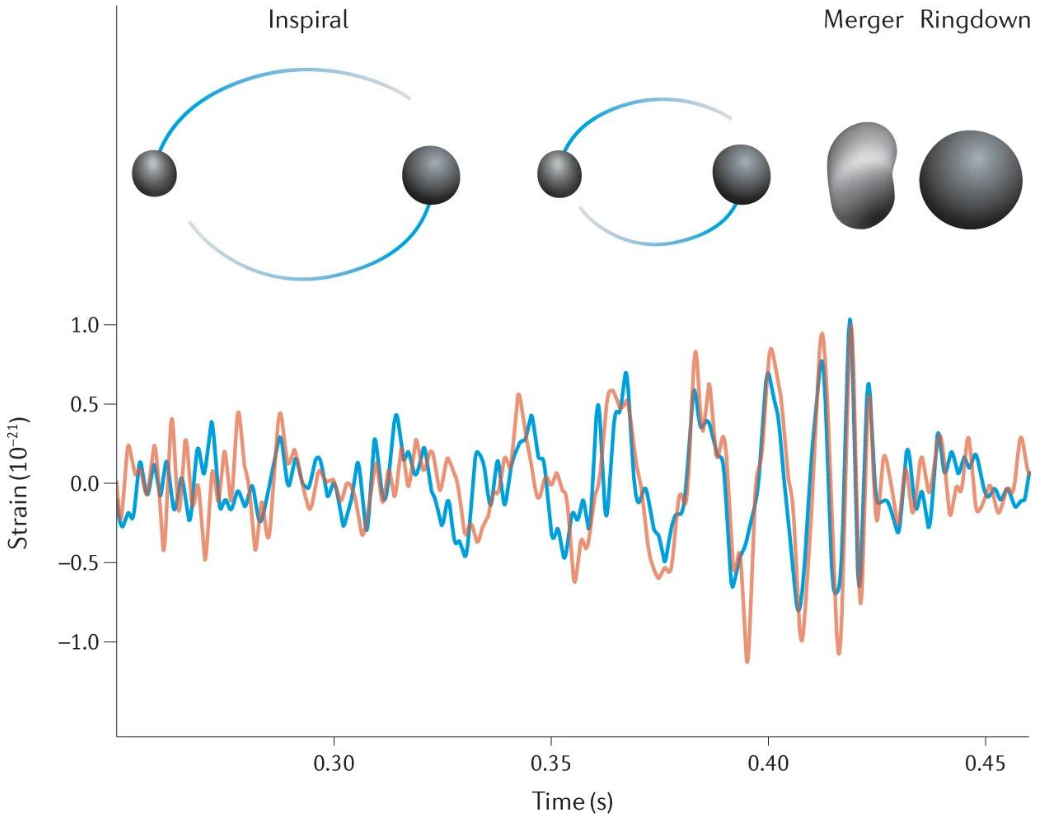


Image credit: M. Bailes et al., “Gravitational-wave physics and astronomy in the 2020s and 2030s,” Nature Rev. Phys., 2021.

Introduction

The simplest source are binaries



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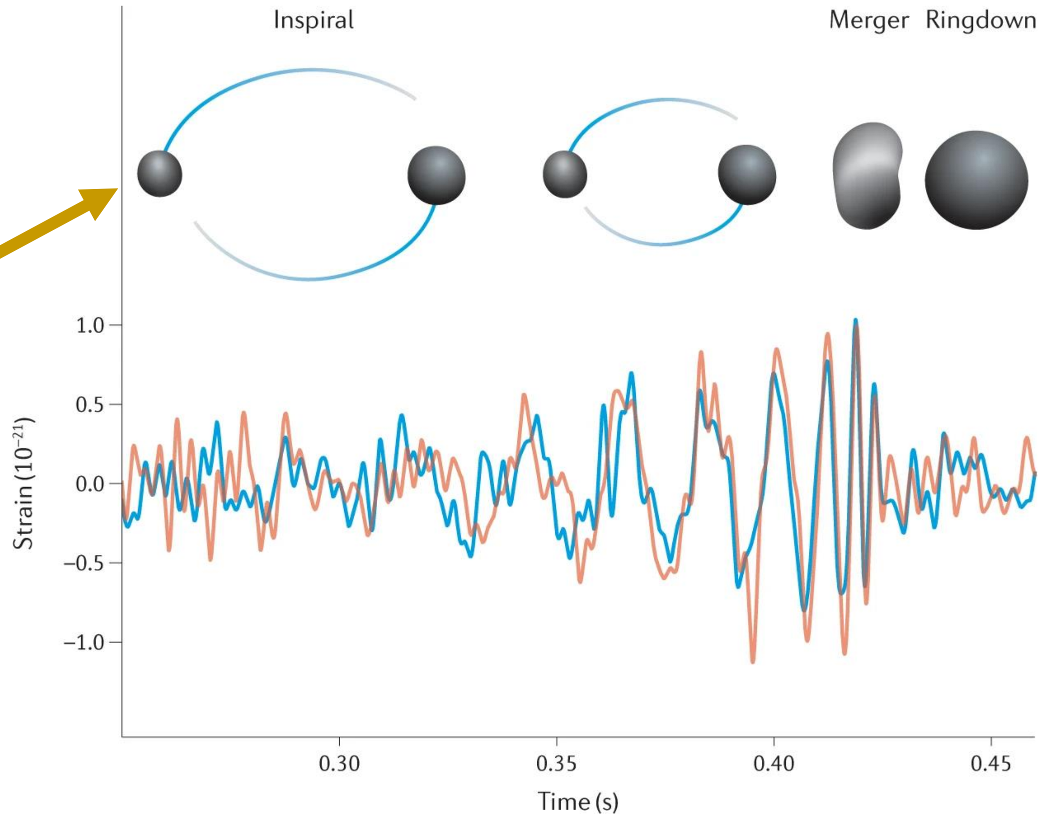
Introduction

The simplest source are binaries

?



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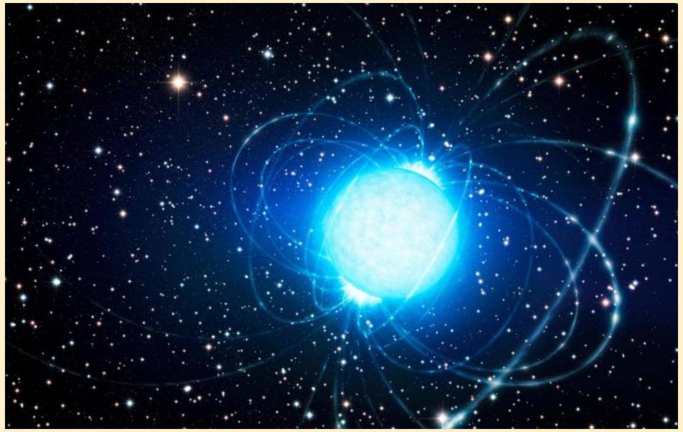
Introduction

Neutron stars



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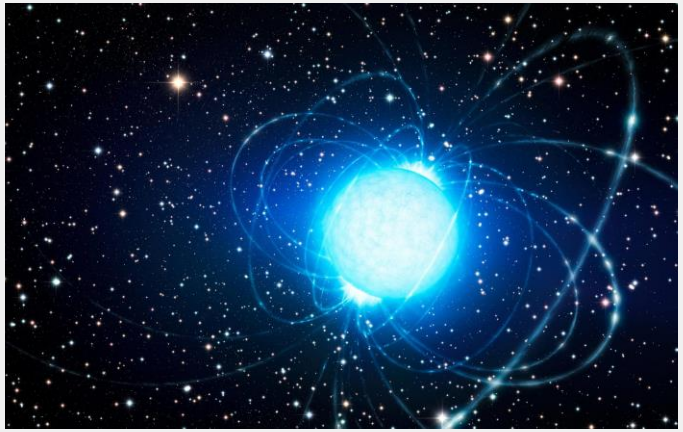
Neutron stars



$$\sim (0.1 - 3)\, M_\odot$$

Colpi, Shapiro, Teukolsky, "A Hydrodynamical Model for the Explosion of a Neutron Star Just below the Minimum Mass", *Astrophysical Journal v.414, p.717*, 1993.

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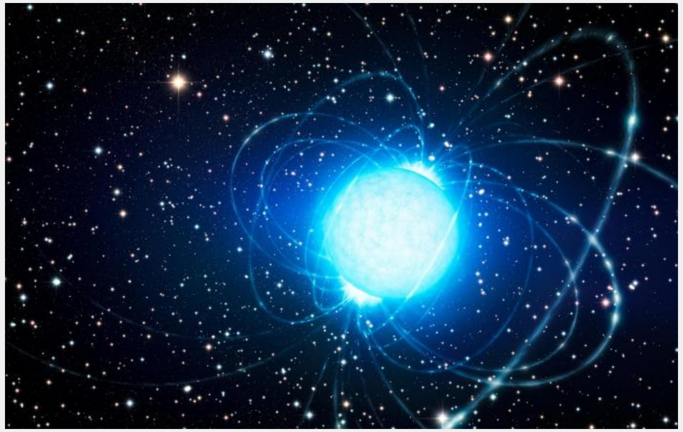
Neutron stars



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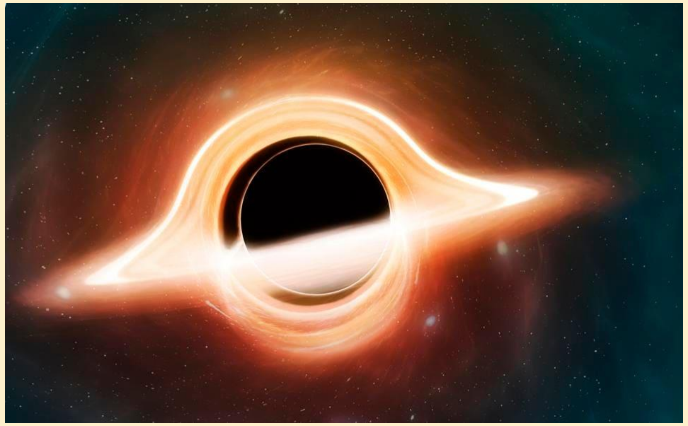
Black holes



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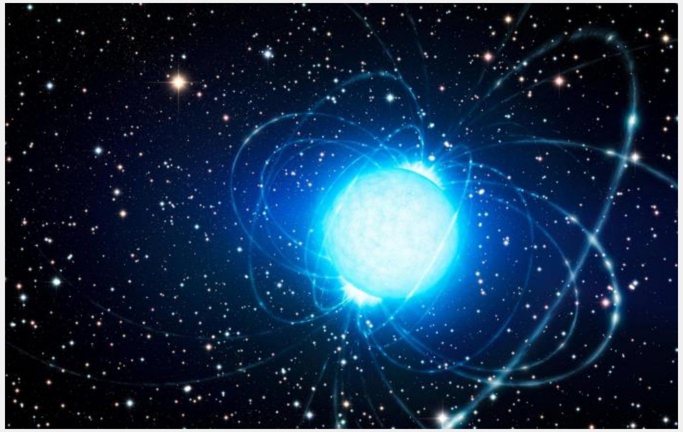

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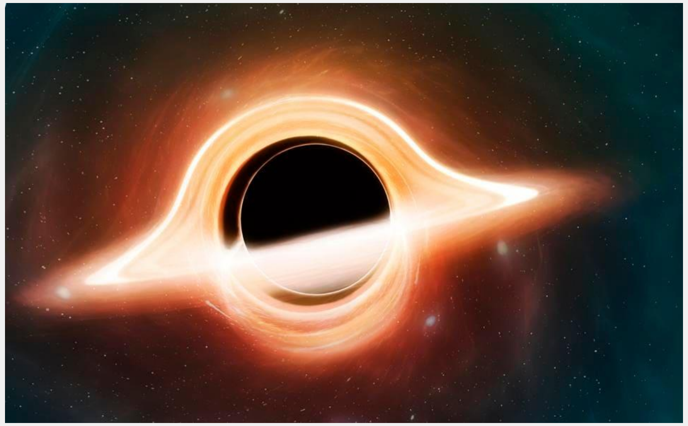


$\sim (5 - 10^{10})\, M_\odot$

Exotic compact objects?

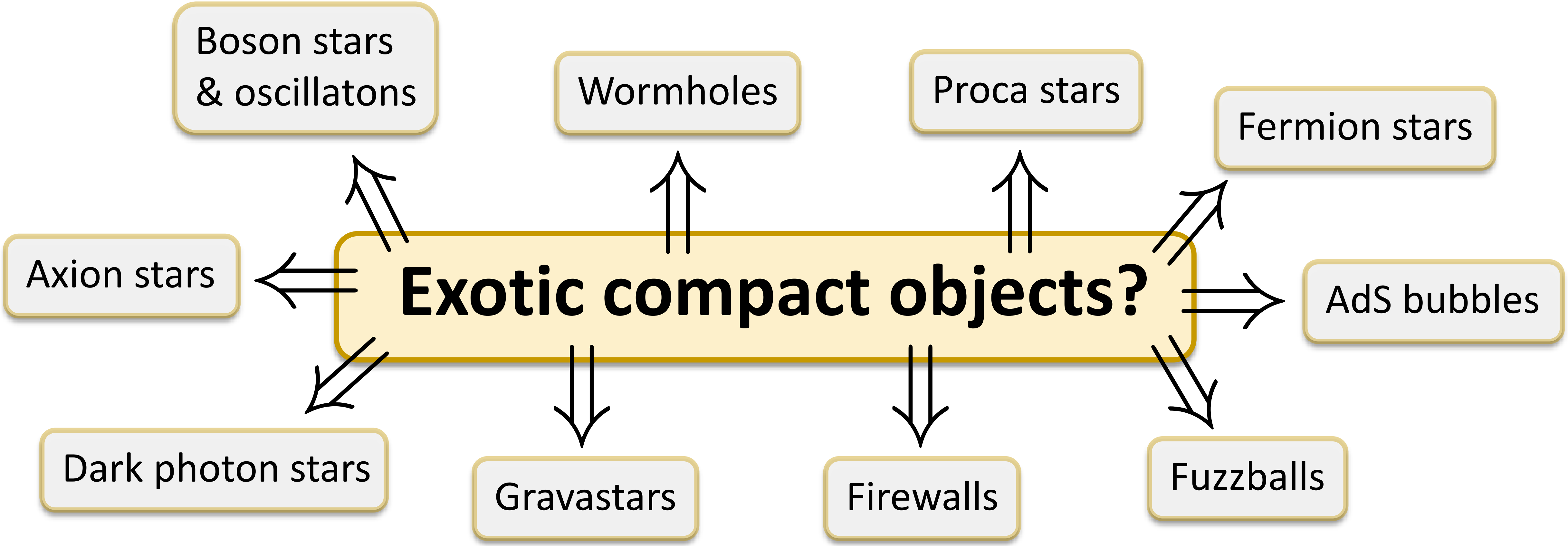
- Dark matter $\Rightarrow$ new stable particles?

Exotic compact objects?

- Dark matter $\Rightarrow$ new stable particles?

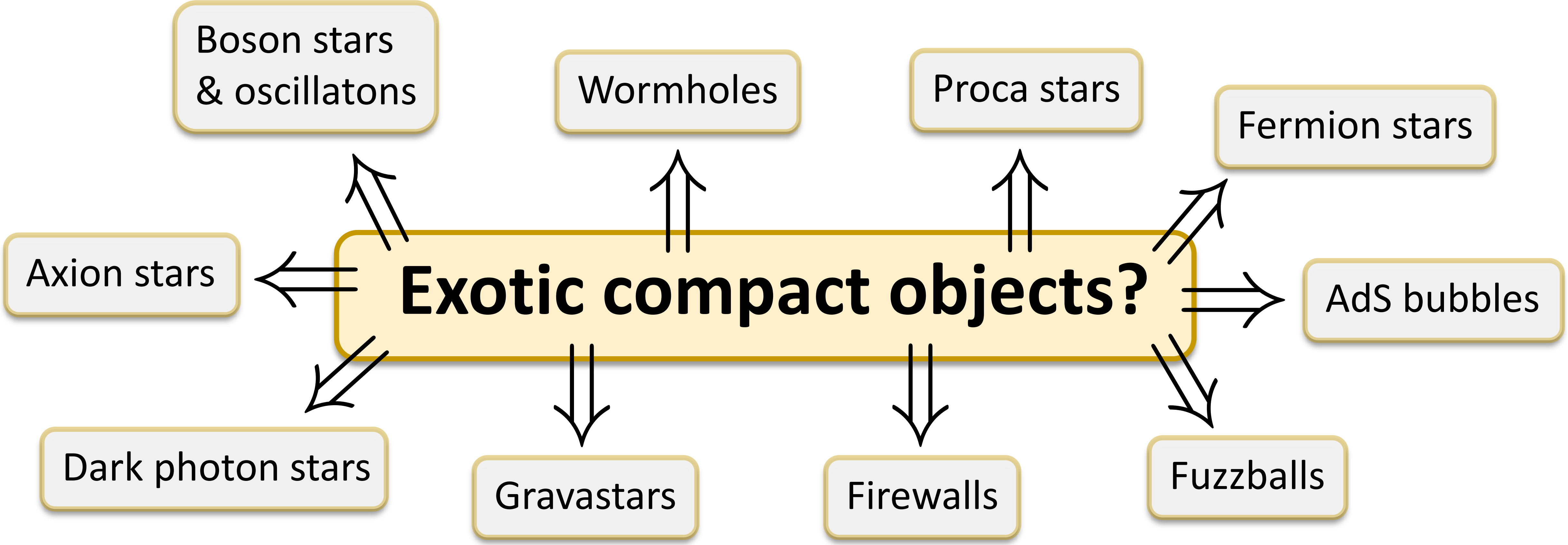
- New fields $\Rightarrow$ ECOs arise

The ECO atlas

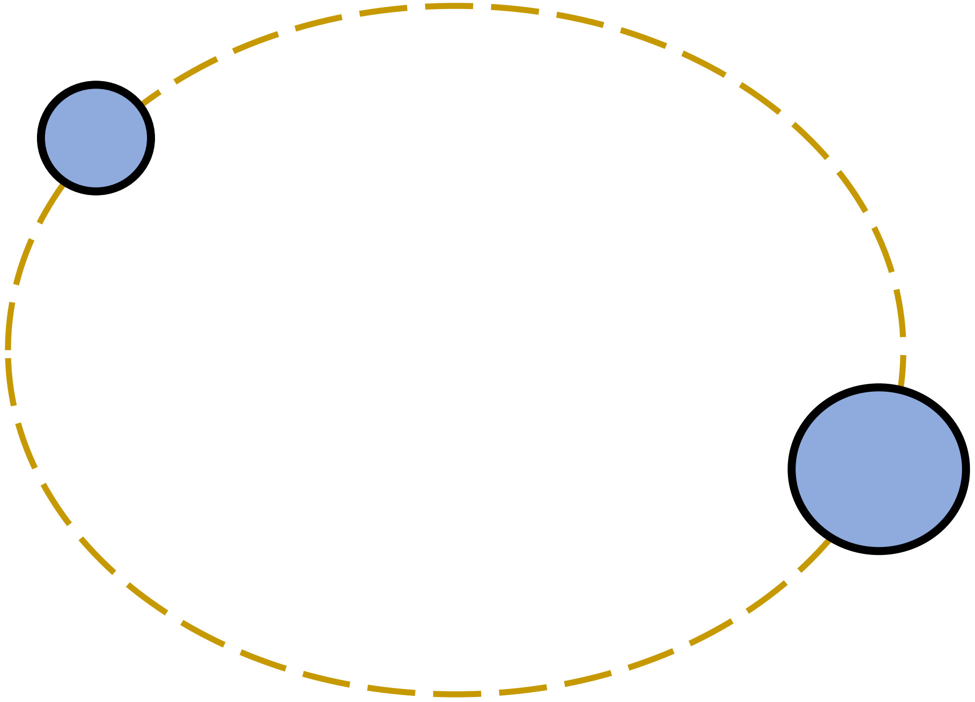


The ECO atlas

[Kaup, 1968; Ruffini, Bonazzola, 1969; Colpi, et. al., 1986]

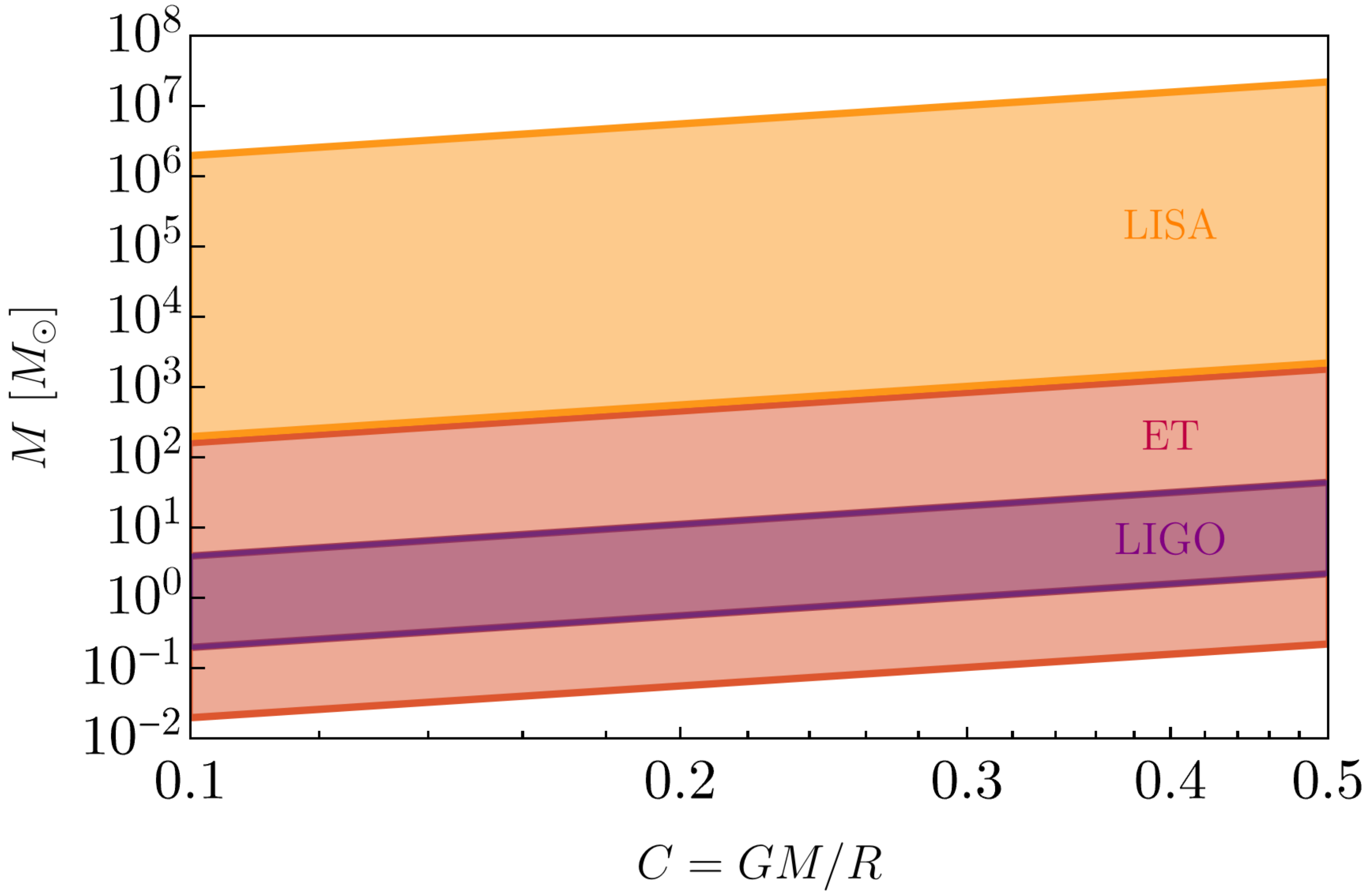


Testing ECOs with gravitational waves



$$f_{\mathrm{ISCO}}^{ECO} = \frac{C^{3/2}}{3^{3/2}\pi\, G M_{\mathrm{tot}}}$$

Testing ECOs with gravitational waves



Setup

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}\partial^\mu h \partial_\mu h - \frac{\lambda}{16}(h^2 - v^2)^2 - \bar{\psi}\gamma^\mu D_\mu \psi - \frac{f}{\sqrt{2}} h \bar{\psi}\psi$$

[Lee, Pang, 1987]

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[Lee, Pang, 1987]

- It is renormalizable (cf. solitonic boson stars)

[R. Friedberg, T. D. Lee, and Y. Pang, 1987]

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- It is local $\Longrightarrow$ causality respected

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- It is local $\Longrightarrow$ causality respected

- Arises in several BSM extensions

Setup

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}\partial^\mu h \partial_\mu h - \frac{\lambda}{16}(h^2 - v^2)^2 - \bar{\psi}\gamma^\mu D_\mu \psi - \underbrace{\frac{f}{\sqrt{2}} h}\, \bar{\psi}\psi$$

$$m_{\text{eff}} = \frac{f}{\sqrt{2}} h$$

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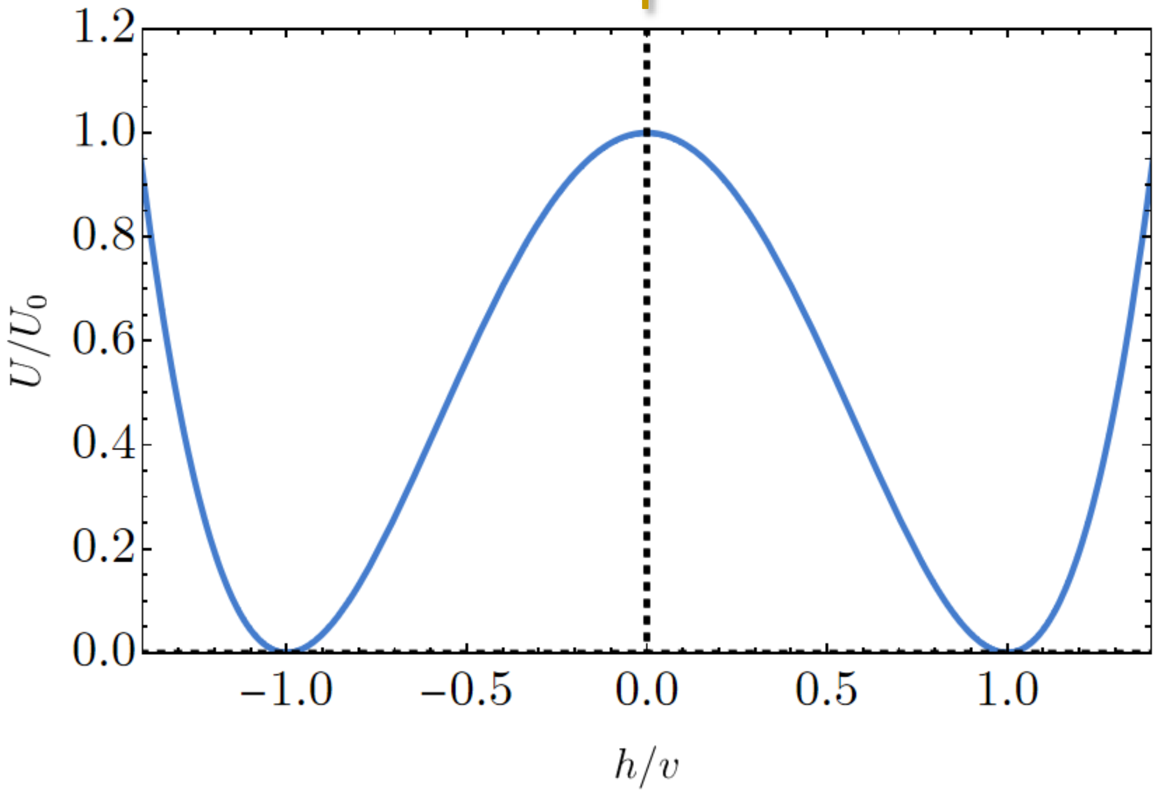
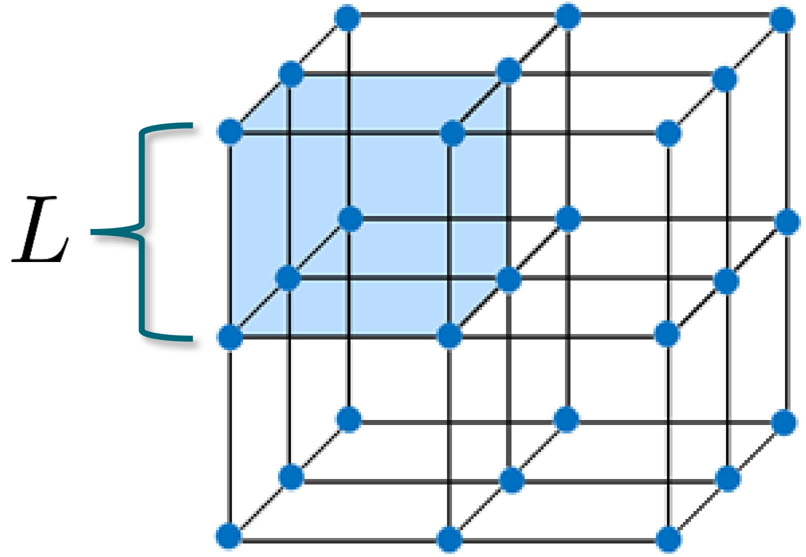


$$m_{\text{eff}} = \frac{f}{\sqrt{2}} h$$

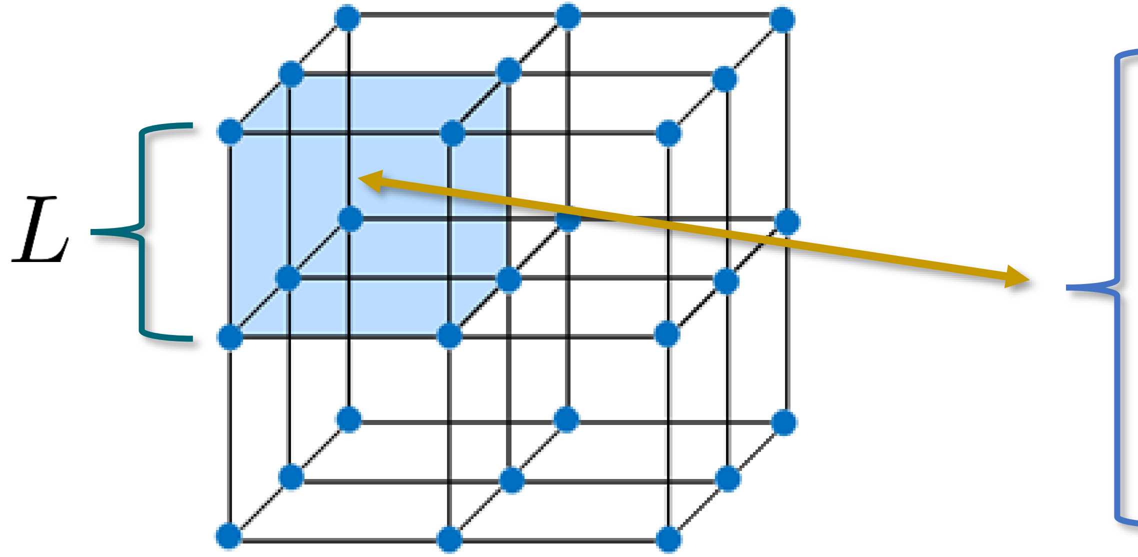
Thomas-Fermi approximation

- Devide the three-space into small cubes $L_{g_{\mu\nu},h} \gg L \gg \lambda_B$



Thomas-Fermi approximation

- Devide the three-space into small cubes $L_{g_{\mu\nu},h} \gg L \gg \lambda_B$
- Fill each cube with a degenerate Fermi gas of Fermi momentum



- $W[k_F]$ (Energy density)
- $P[k_F]$ (Pressure)
- $S[k_F] = < \bar{\psi}\psi >$ (Scalar density)

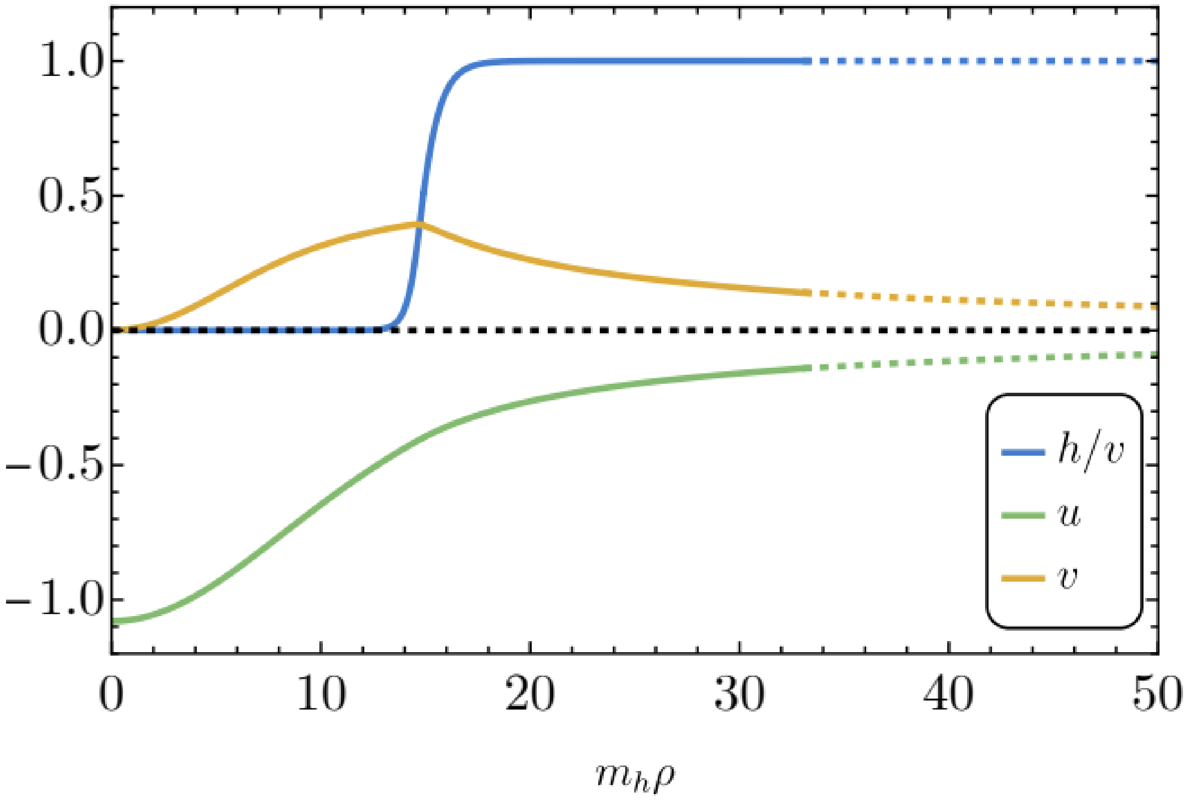
Equations of motion

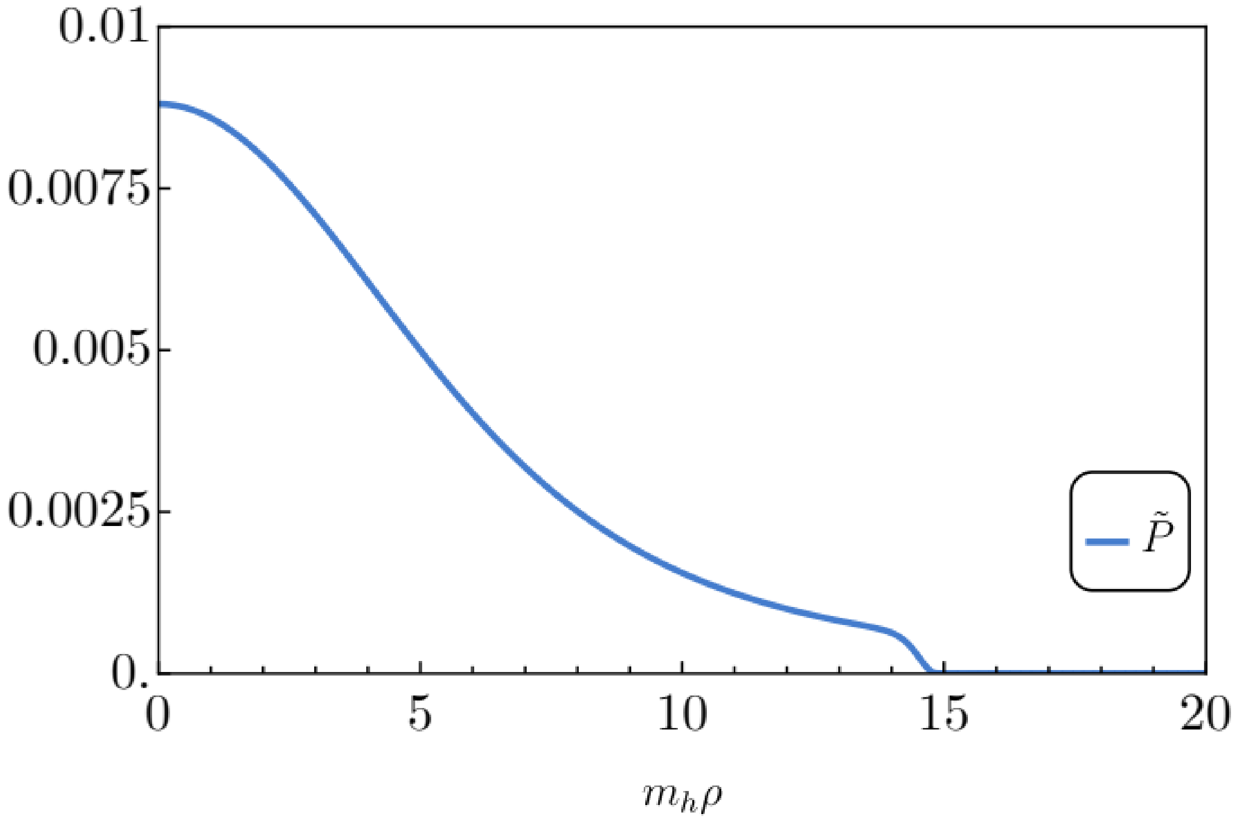
1. $$G_{\mu\nu} = 8\pi G \left(\underbrace{\partial_\mu h \, \partial_\nu h - \frac{1}{2} g_{\mu\nu} (\partial^\alpha h \, \partial_\alpha h + 2U)}_{= T^{[h]}_{\mu\nu}} + \underbrace{(W + P) u_\mu u_\nu + P g_{\mu\nu}}_{= T^{[f]}_{\mu\nu}} \right)$$

2. $$\Box h - \frac{\partial U}{\partial h} - \frac{f}{\sqrt{2}} \underbrace{S}_{\propto (T^{[f]})^\mu_\mu = -W + 3P} = 0$$

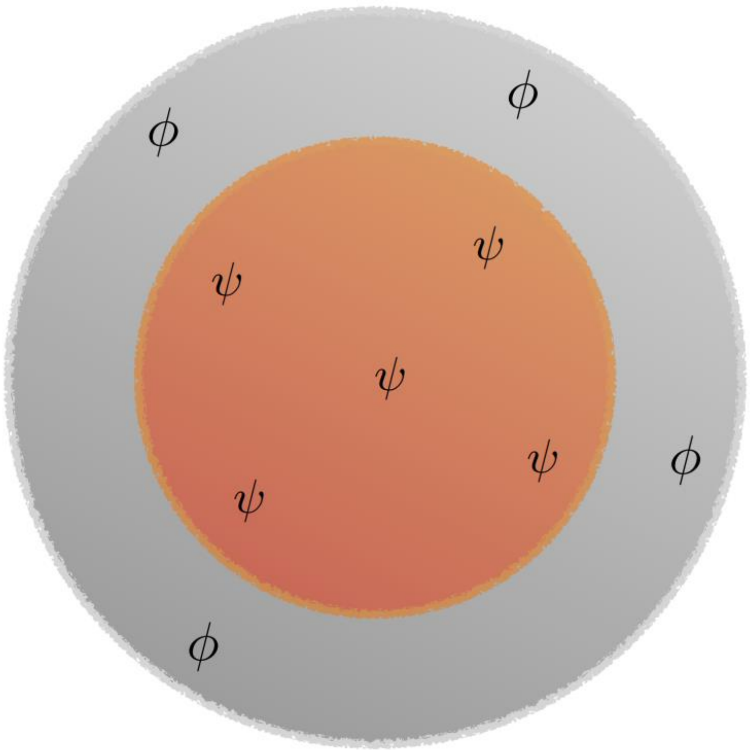
3. $$F(\underline{k_F}, g_{\mu\nu}, h) = 0$$

Example of solution

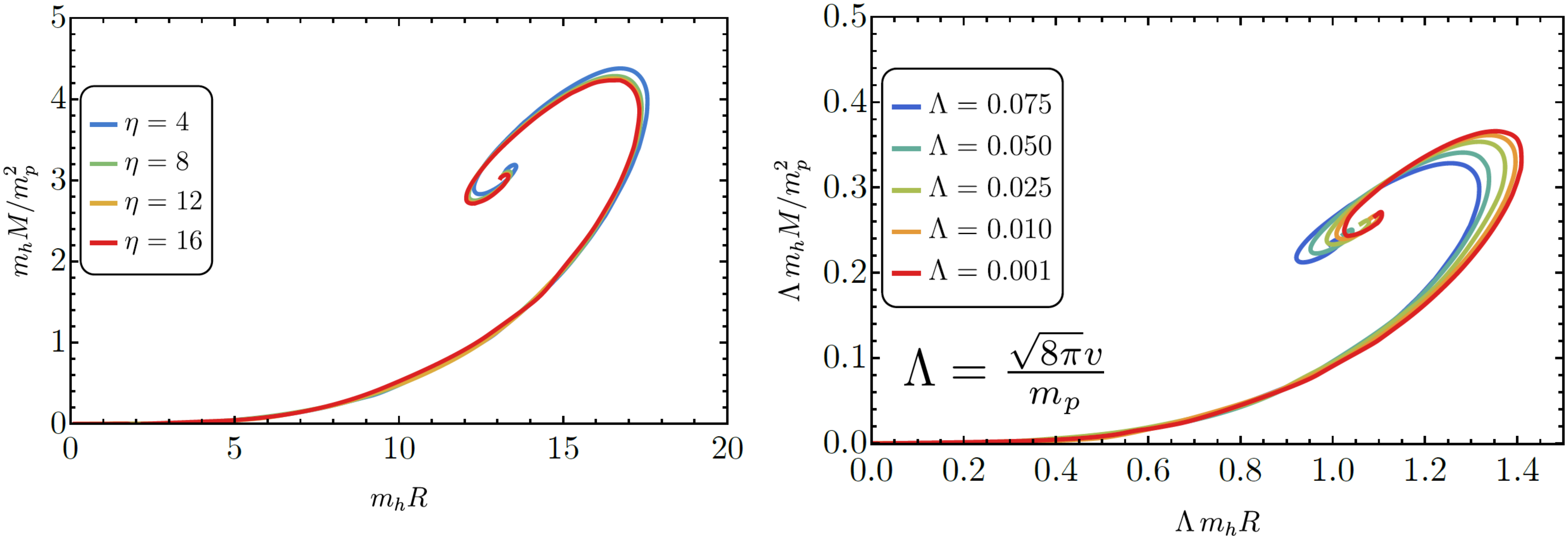




Pictorial illustration of a fermion soliton star



Mass-radius diagrams



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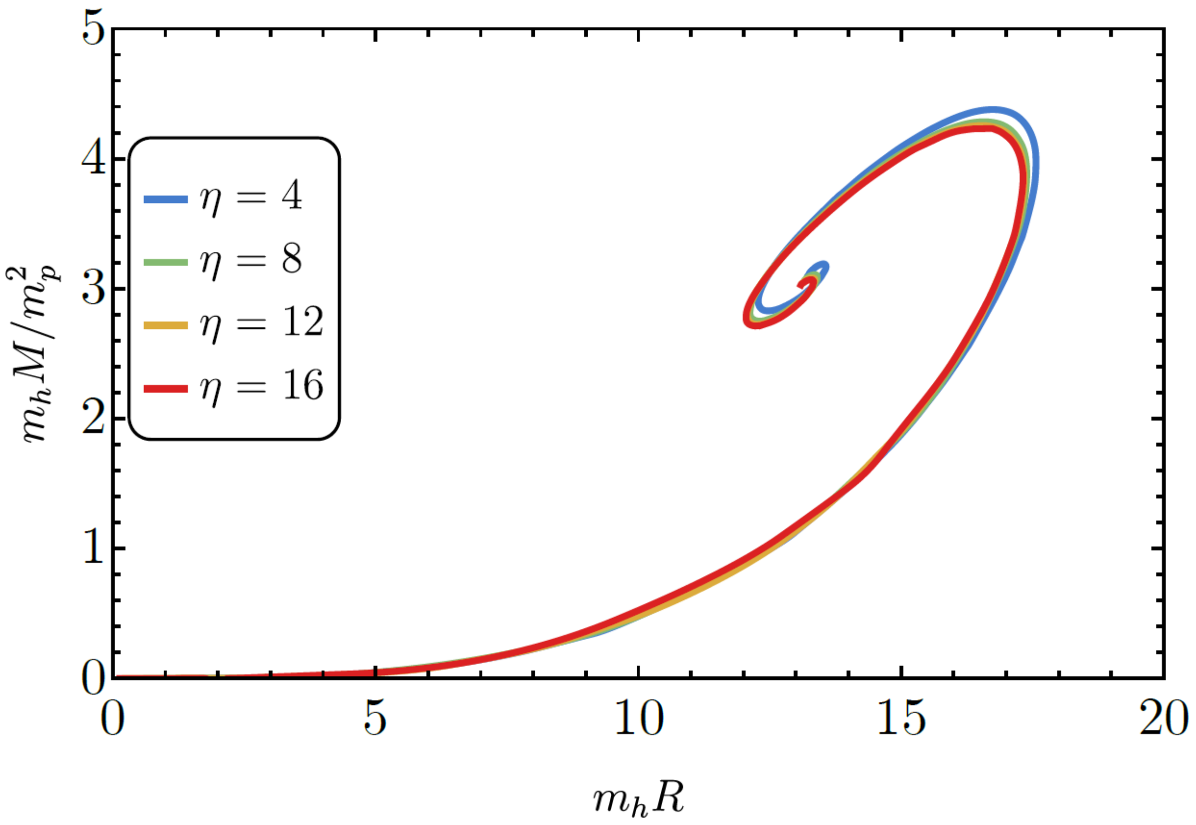
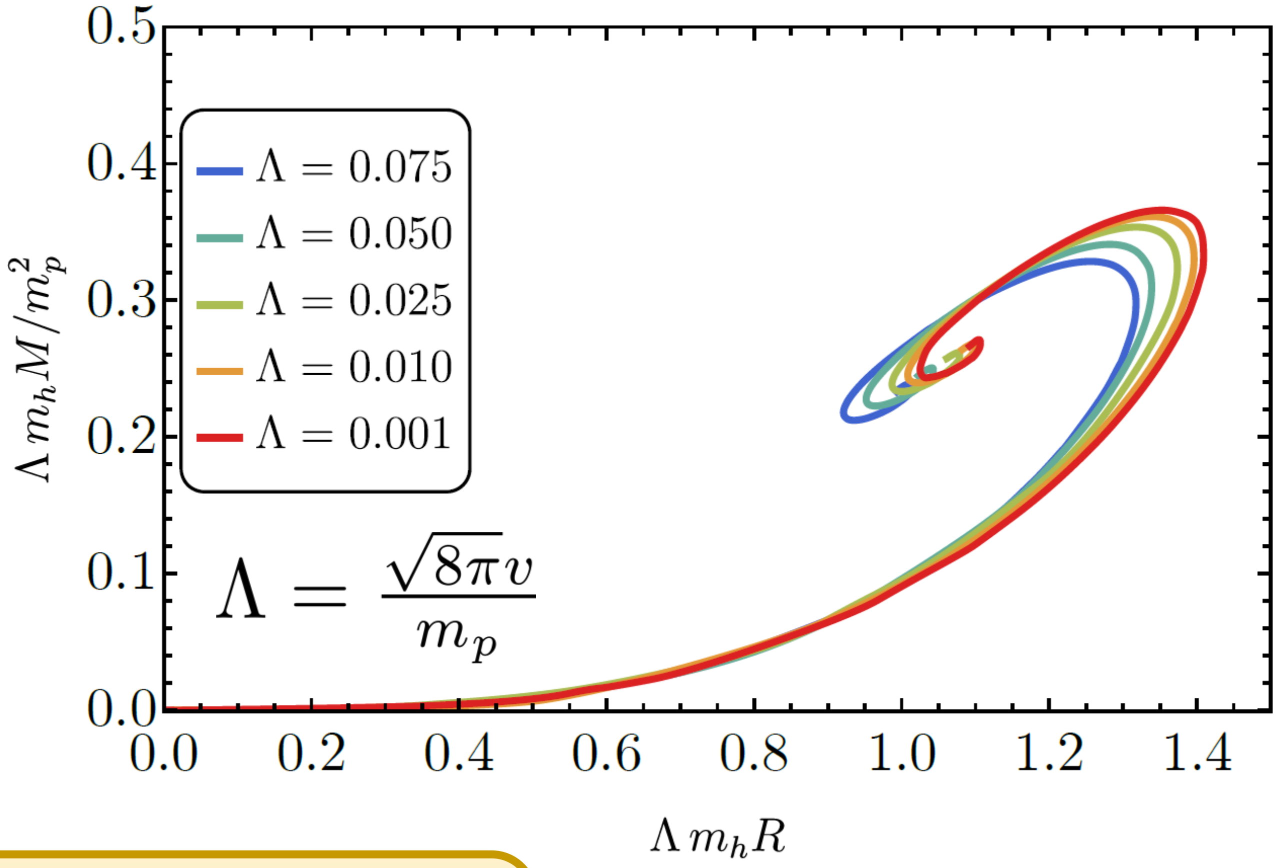
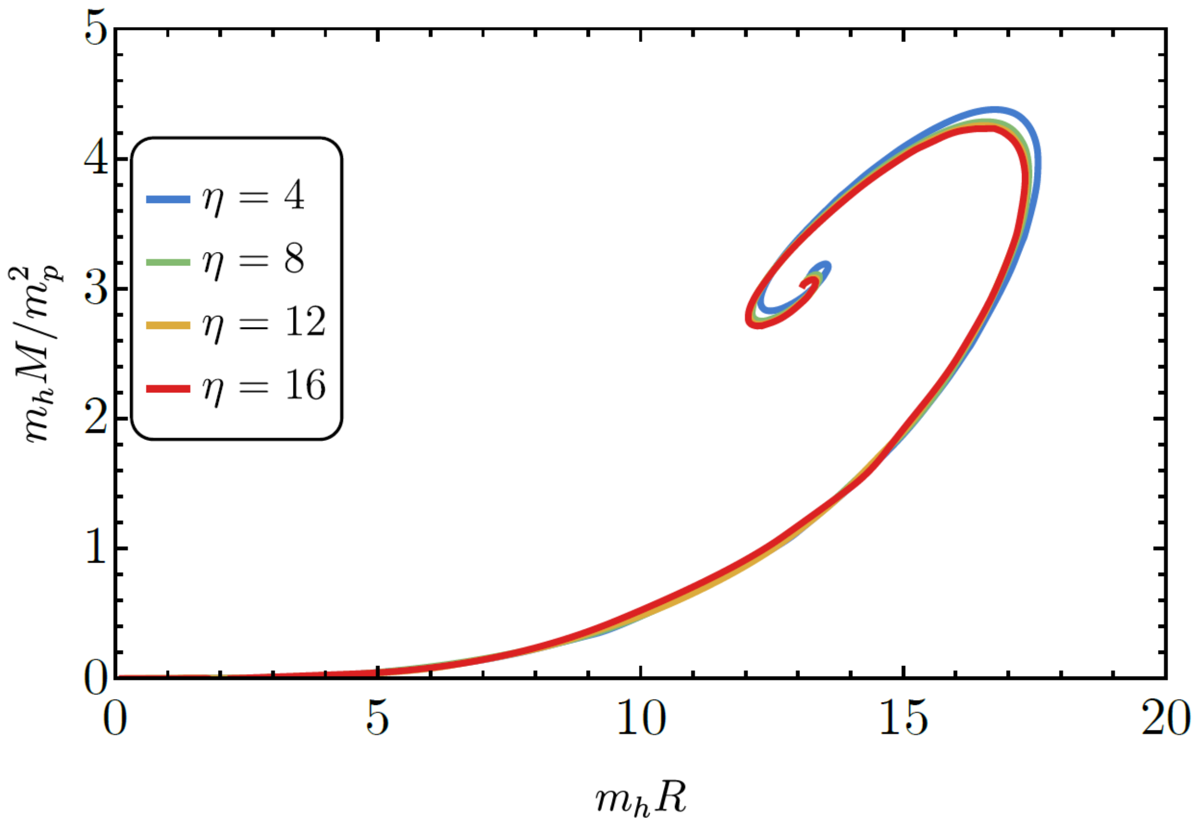


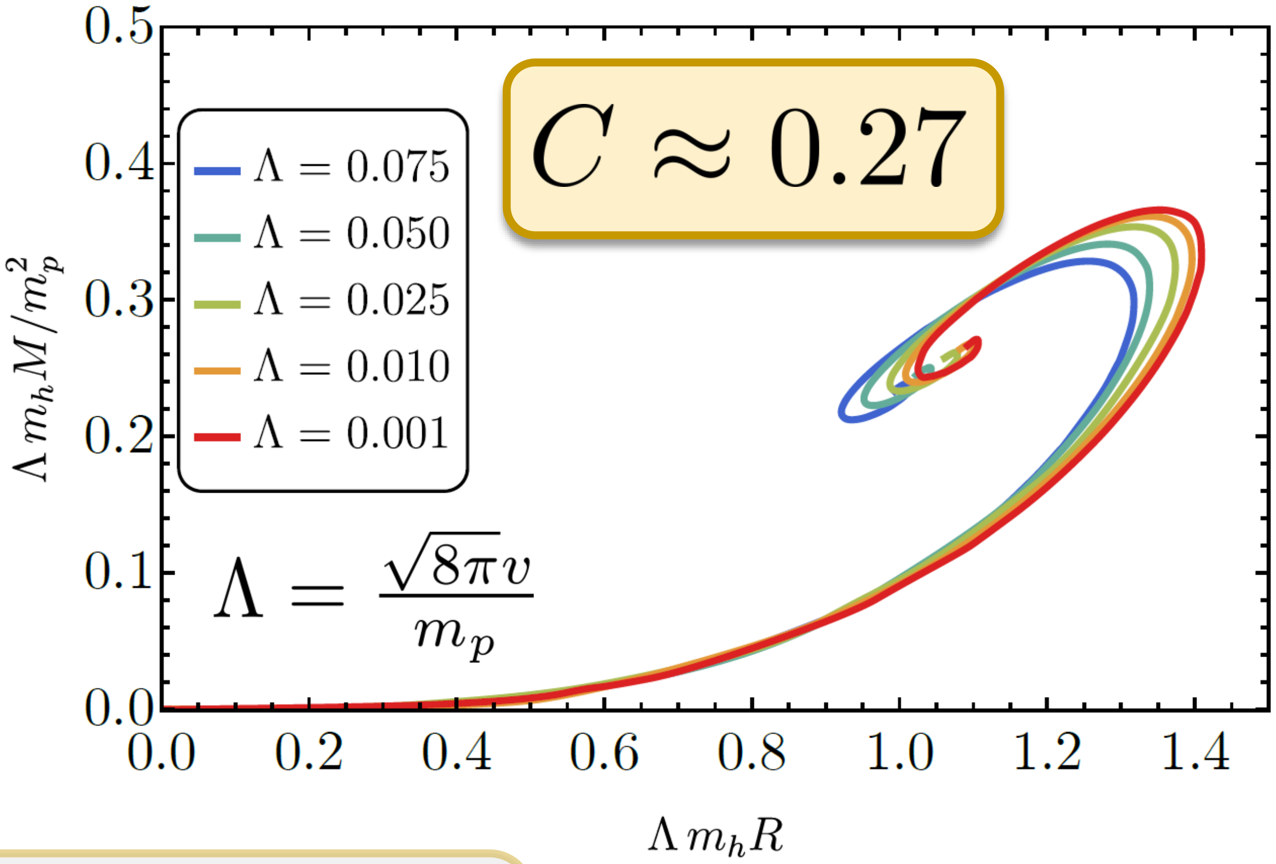


$$M_c \sim M_\odot \left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2 \qquad R_c \sim 5.5\,\mathrm{km} \left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2$$

$$q \equiv (m_h v)^{1/2}$$

Mass-radius diagrams





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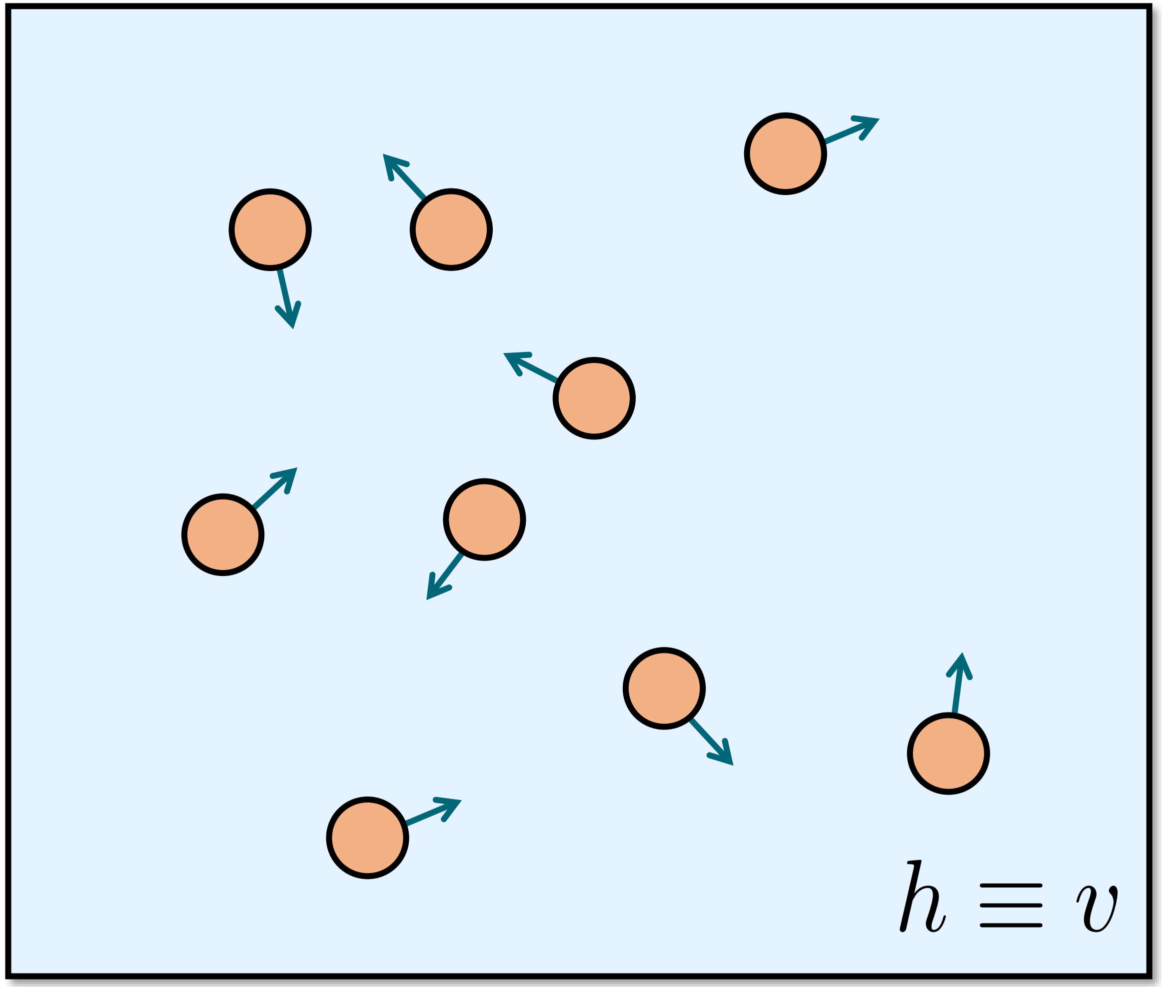
What is the actual ground state?



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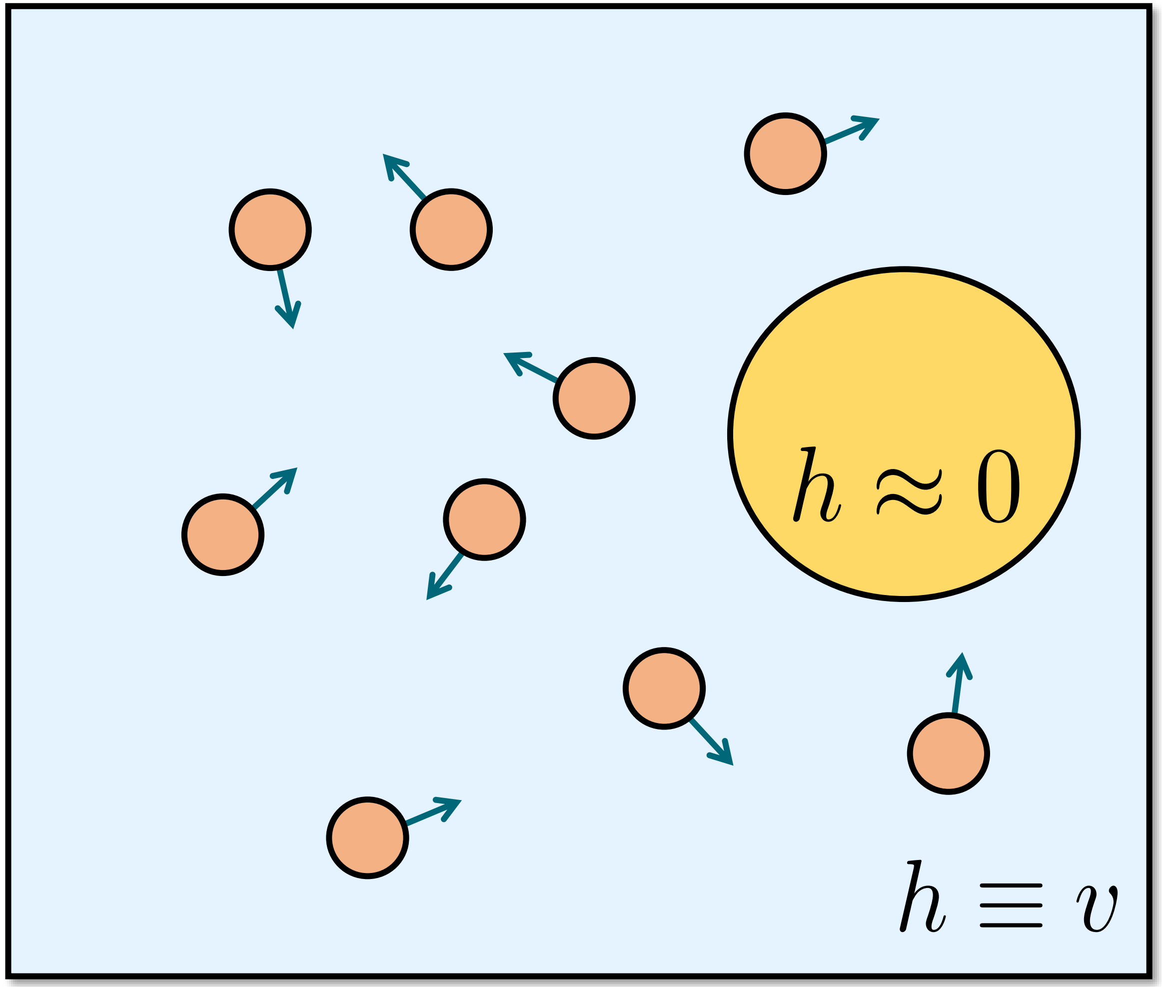

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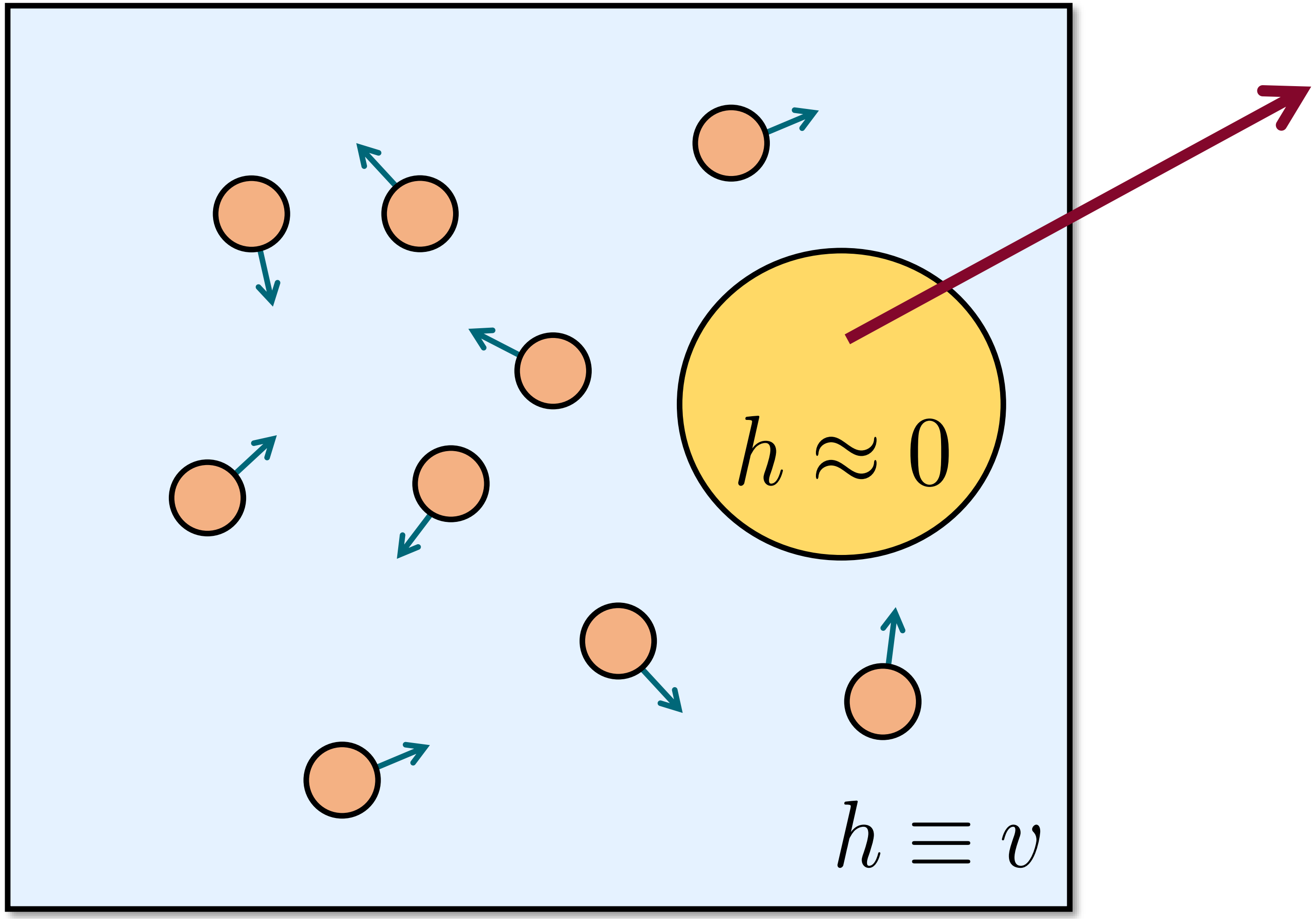

$$E_{\text{cost}} \sim m_h^2 v^2 R^3$$

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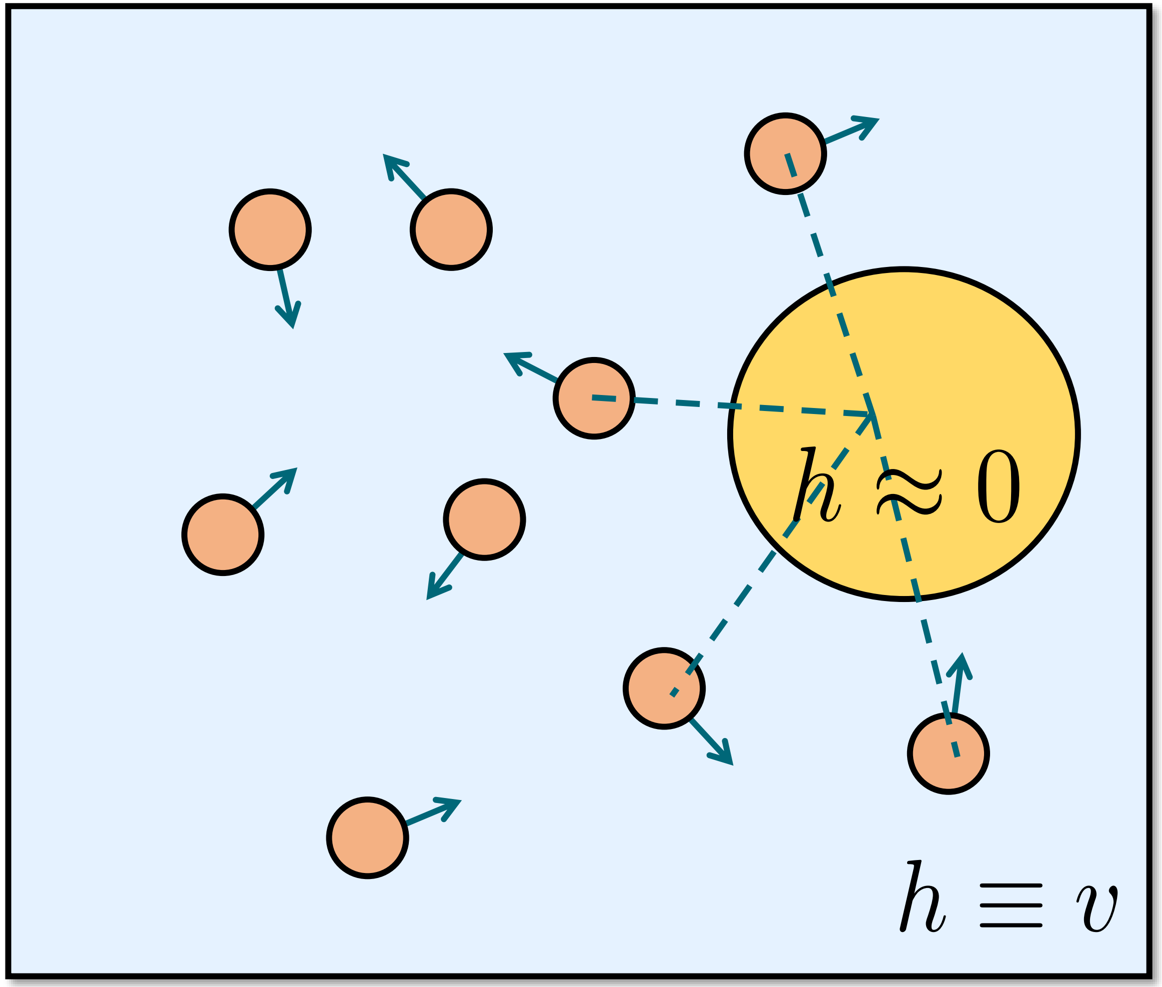

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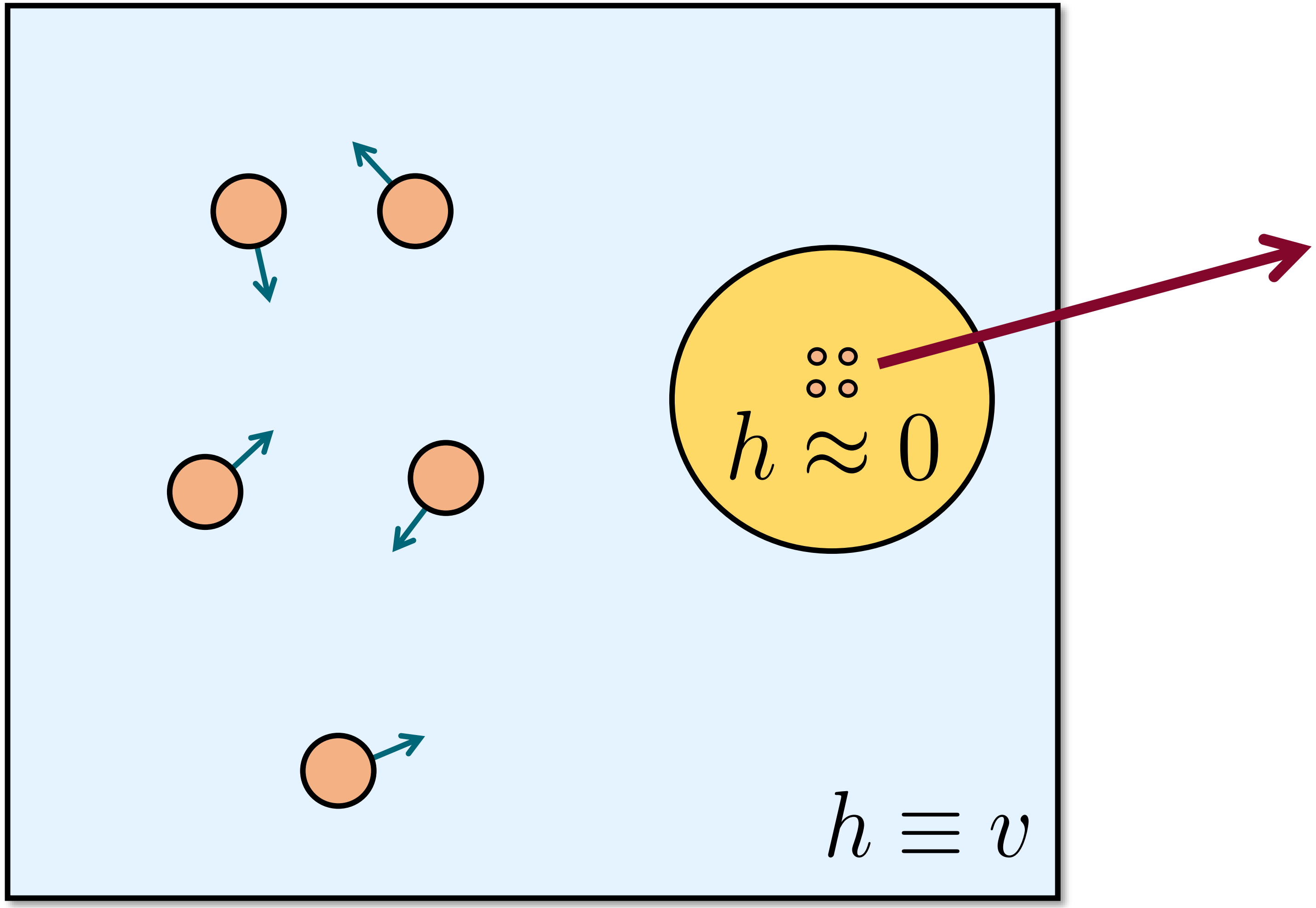

$$E_{\text{cost}} \sim m_h^2 v^2 R^3$$

$$E_{\text{gain}} \sim N m_f$$

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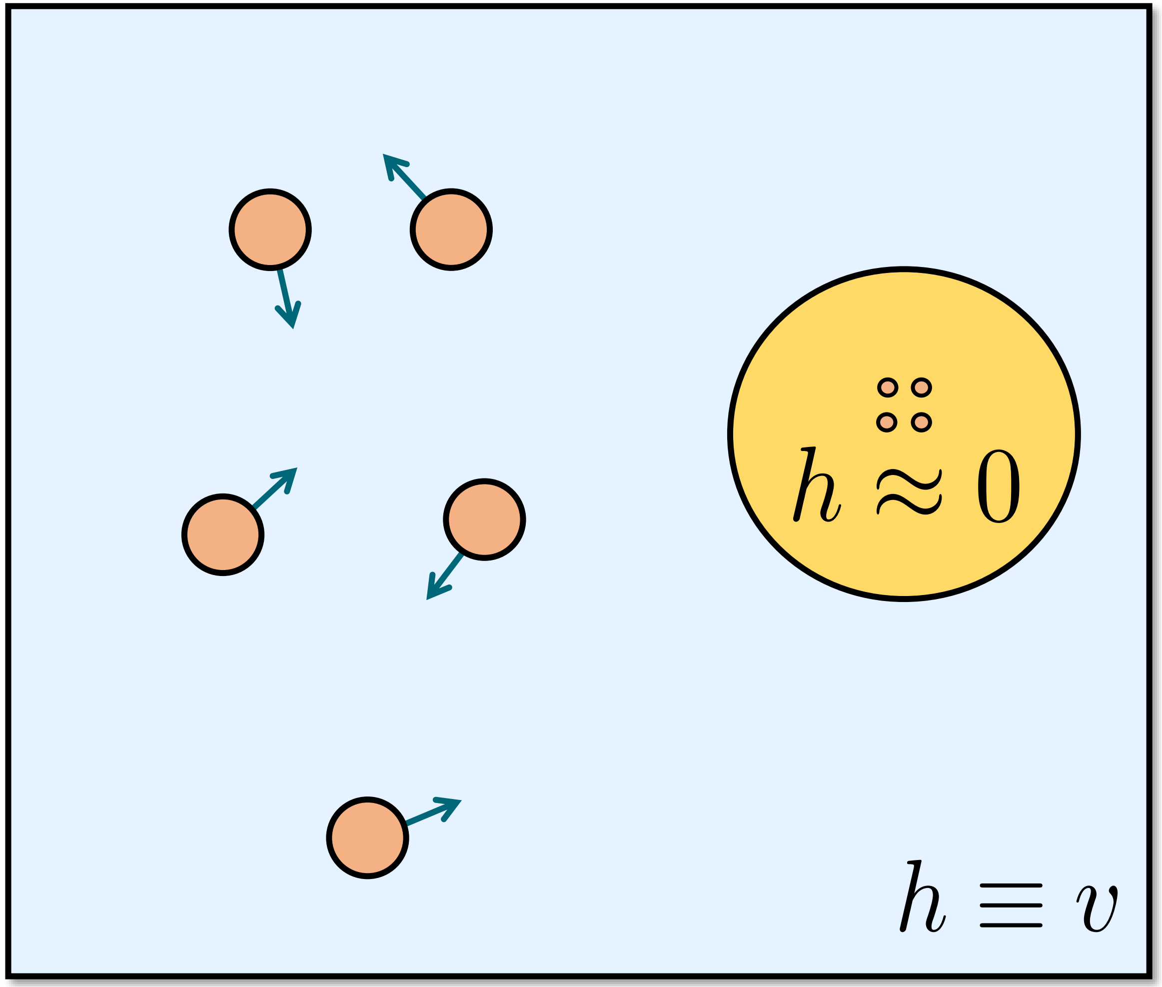


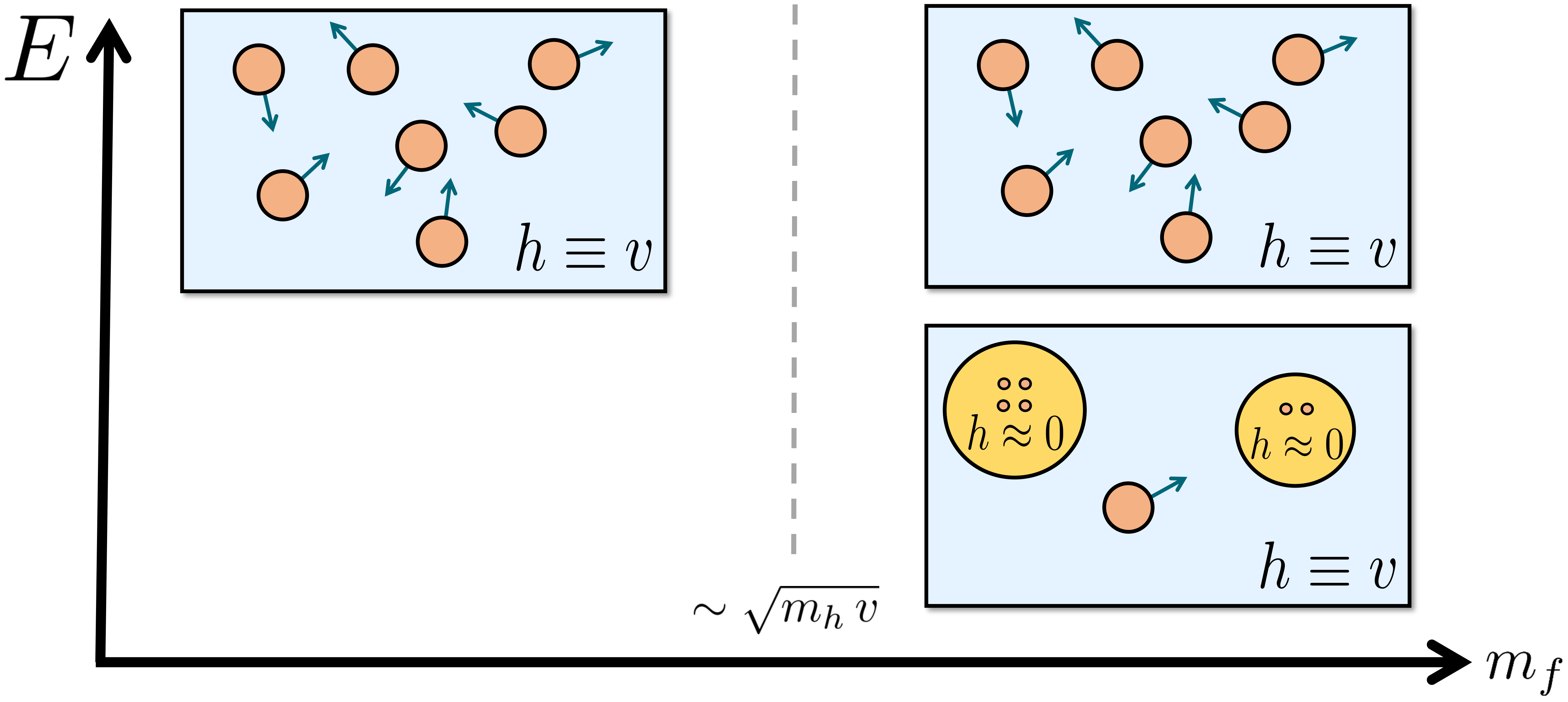
$$E_{\text{cost}} \sim m_h^2 v^2 R^3$$

$$E_{\text{gain}} \sim N m_f$$

$$E_{\text{gain}} > E_{\text{cost}}$$

$$m_f \gtrsim \sqrt{m_h v}$$

Non-perturbative vacuum scalarization



Neutron soliton stars

Linear sigma model → Chiral symmetry breaking

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$$m_h \sim 500\,\text{MeV}$$

$$v \sim f_\pi \sim 130\,\text{MeV}$$

$$m_f \sim 1\,\text{GeV}$$

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$$m_f > \sqrt{m_h v} \sim 255\,\text{MeV}$$

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Linear sigma model → Chiral symmetry breaking

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$$m_f > \sqrt{m_h v} \sim 255\,\mathrm{MeV}$$

$$M_c \approx 2\,M_\odot$$

$$R_c \approx 10\,\mathrm{km}$$

[R. Balkin, J. Serra, K. Springmann, S. Stelzl, and A. Weiler, 2023]

Other applications

Standard Model Higgs

Other applications

Standard Model Higgs →

$$M_c \approx (4 \times 10^{-6})\, M_\odot$$
$$R_c \approx 2\,\mathrm{cm}$$

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Dark soliton stars

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Standard Model Higgs → $M_c \approx (4 \times 10^{-6})\, M_\odot$

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Dark soliton stars → $m_h \gtrsim m_{h_{\rm SM}} \quad \lambda \sim \mathcal{O}(1)$

Other applications

Standard Model Higgs →

$$M_c \approx (4 \times 10^{-6})\, M_\odot$$
$$R_c \approx 2\,\mathrm{cm}$$

Dark soliton stars → $m_h \gtrsim m_{h_{\rm SM}} \quad \lambda \sim \mathcal{O}(1)$

↓

sub-solar regime

Thank you

Fermionic quantities

$$W = \frac{2}{(2\pi)^3} \int_0^{k_{\mathrm{F}}(\rho)} d^3k \sqrt{k^2 + (m_f - f\phi(\rho))^2} \tag{1}$$

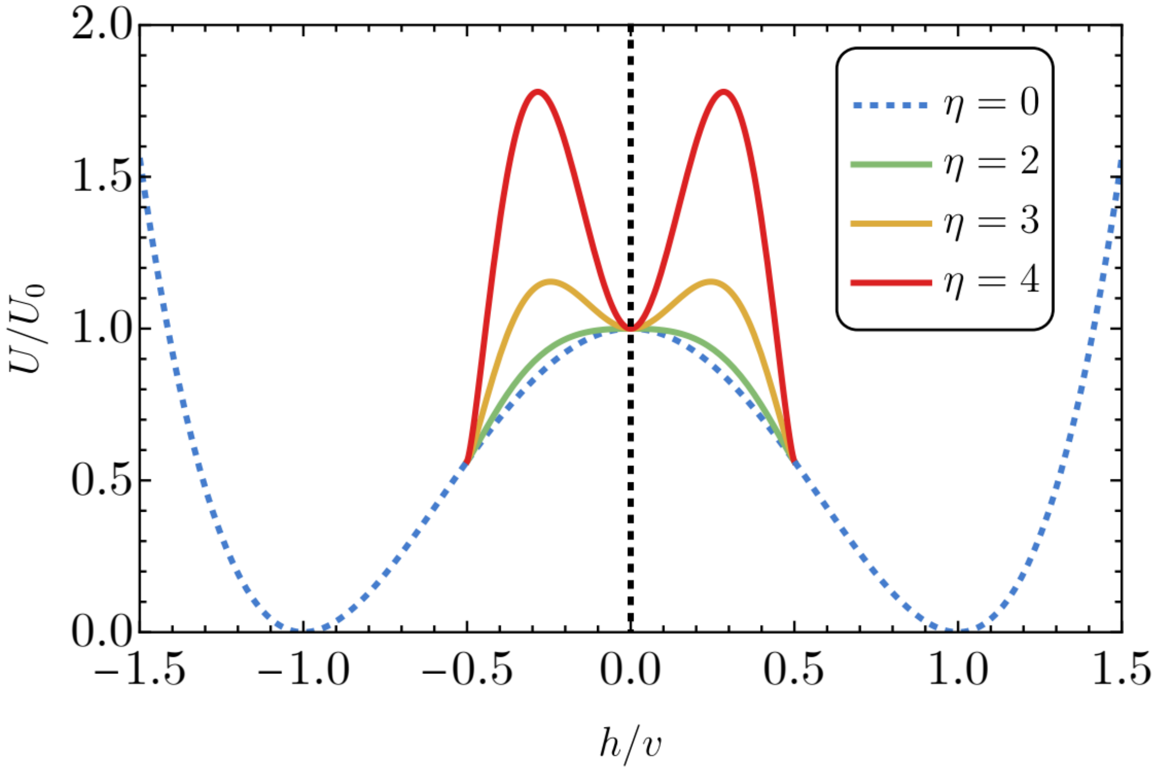
$$P = \frac{2}{(2\pi)^3} \int_0^{k_{\mathrm{F}}(\rho)} \frac{d^3k\, k^2}{3\sqrt{k^2 + (m_f - f\phi(\rho))^2}} \tag{2}$$

$$S = \frac{2}{(2\pi)^3} \int_0^{k_{\mathrm{F}}(\rho)} d^3k \frac{m_f - f\phi(\rho)}{\sqrt{k^2 + (m_f - f\phi(\rho))^2}} \tag{3}$$

Effective potential

$$U_{\text{eff}} = \frac{\lambda}{16}(h^2 - v^2)^2 + \frac{f}{\sqrt{2}} h < \bar{\psi}\psi >$$

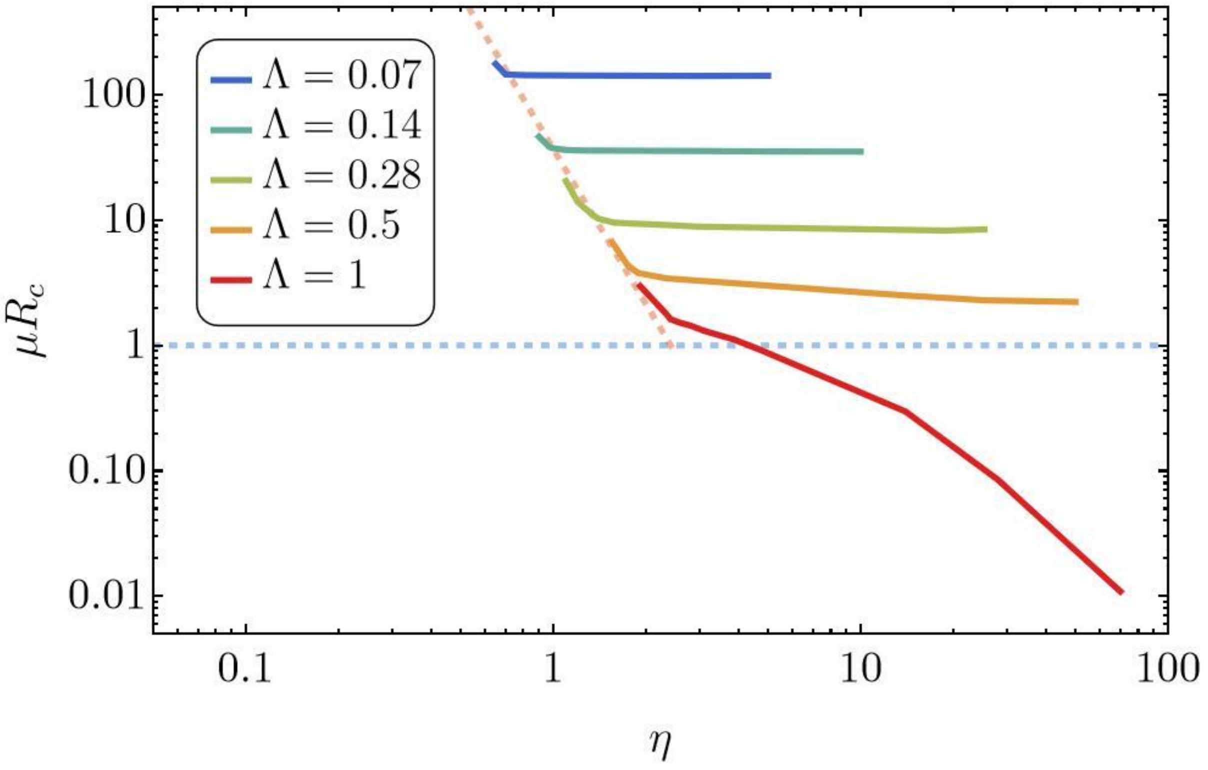
$$\eta = \frac{m_f}{m_h^{1/2} v^{1/2}}$$

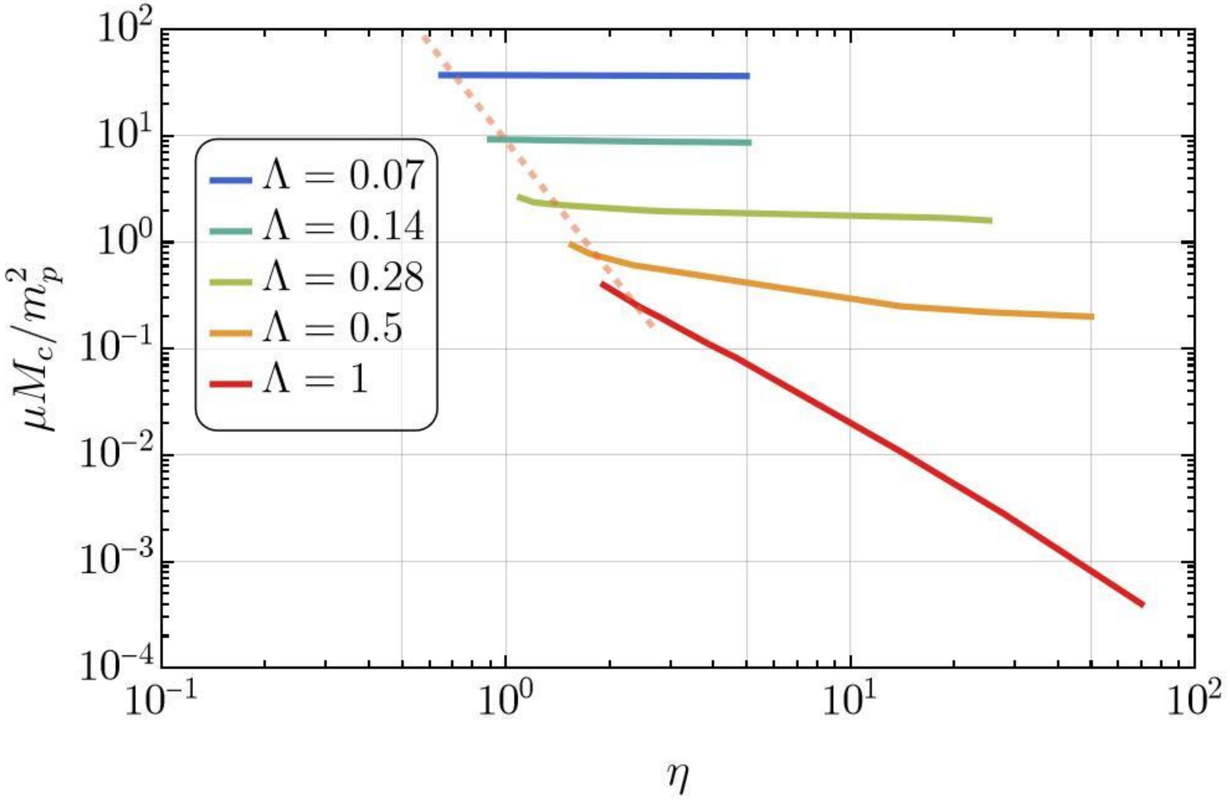


False vacuum pockets if

$$m_f \gtrsim \sqrt{m_h v}$$

Confining regime



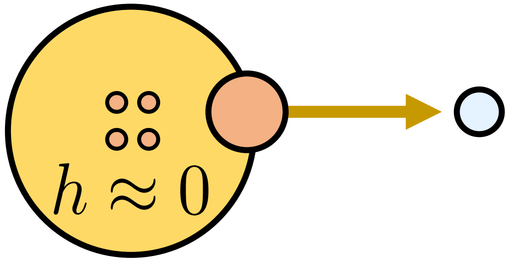


Issues

Numerical computations gives the actual condition

$$m_f > 2\sqrt{m_h v} \sim 350\,\mathrm{GeV}$$

If the fermion is a weakly interacting particle coupled to the SM $t_{decay} \sim \left(\frac{m_h v}{m_f^2}\right) \times 10^{-11}\,\mathrm{sec}$



Exotic phase?

Number density inside the pocket

$$n \sim (m_h v)^{3/2} \sim 7 \times 10^{47}\,\mathrm{cm}^{-3}$$

Nuclear matter density

$$n \sim 10^{38}\,\mathrm{cm}^{-3}$$

Colored superconductor?

PBH?

Higgs balls are produced in the radiation domination era with an initial mass M_i

$$GM = \frac{t}{1 + \frac{t}{t_i}\left(\frac{t_i}{GM_i} - 1\right)}$$

$$M_i \gtrsim 3 \times 10^{-6} M_\odot$$

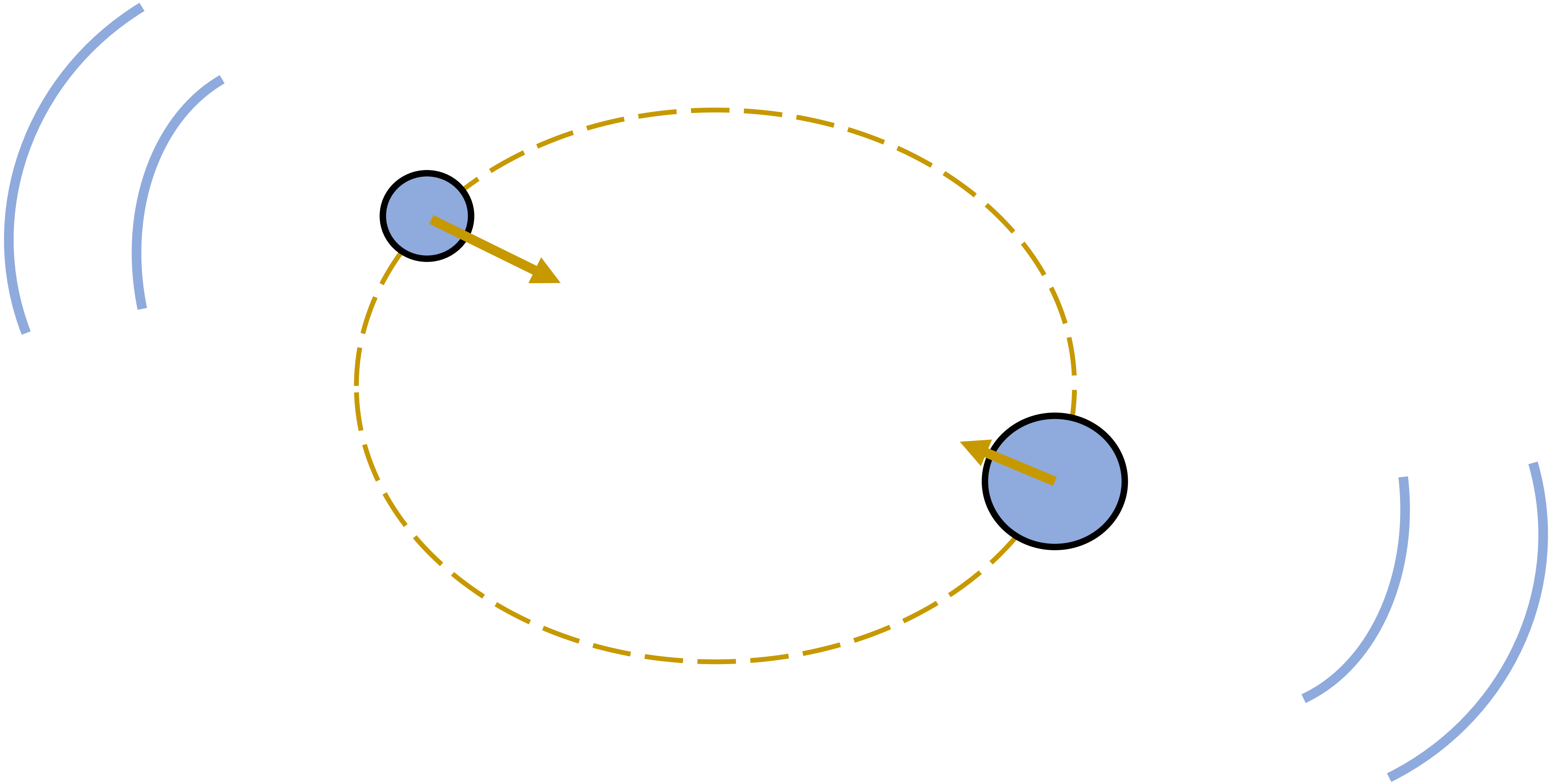
How to discriminate among compact objects?

Tidal deformability is encoded in the Love numbers

$$Q_{ij} = \lambda_2 E_{ij}$$

The spherical symmetry allows us to decompose the perturbation into polar and magnetic sectors

How to discriminate among compact objects?



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