Compact objects in and beyond the Standard Model

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Gravity theory group

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Introduction

What is a compact object?

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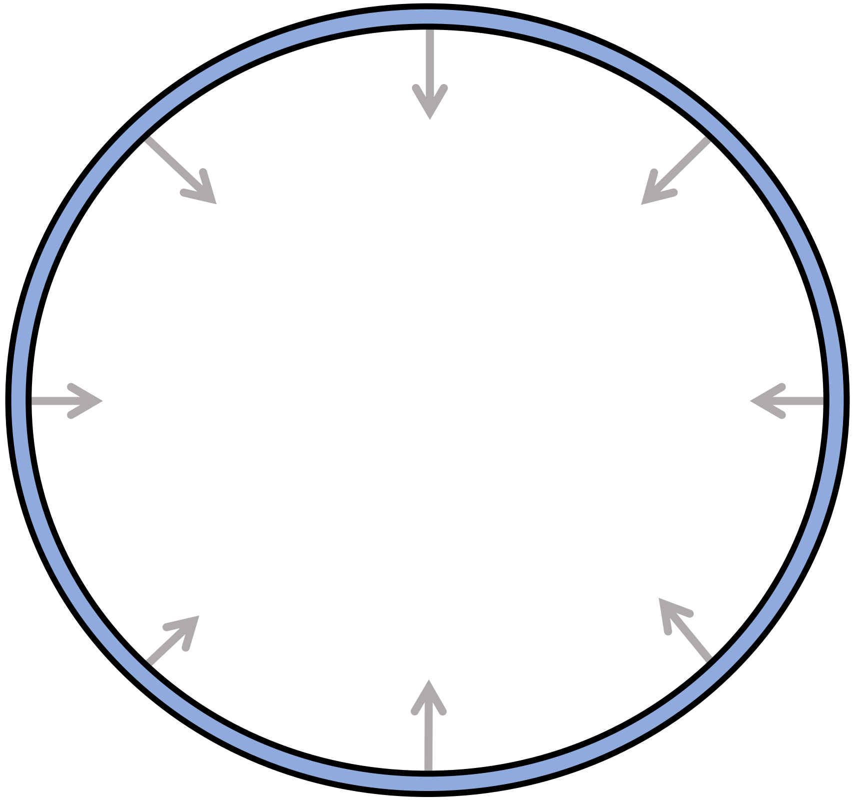

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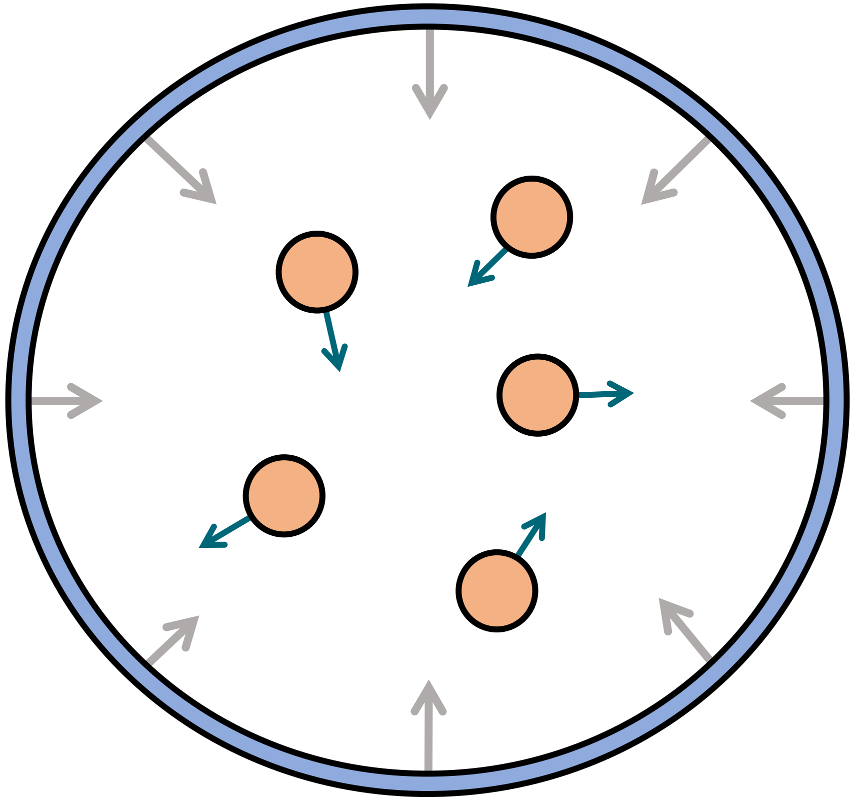

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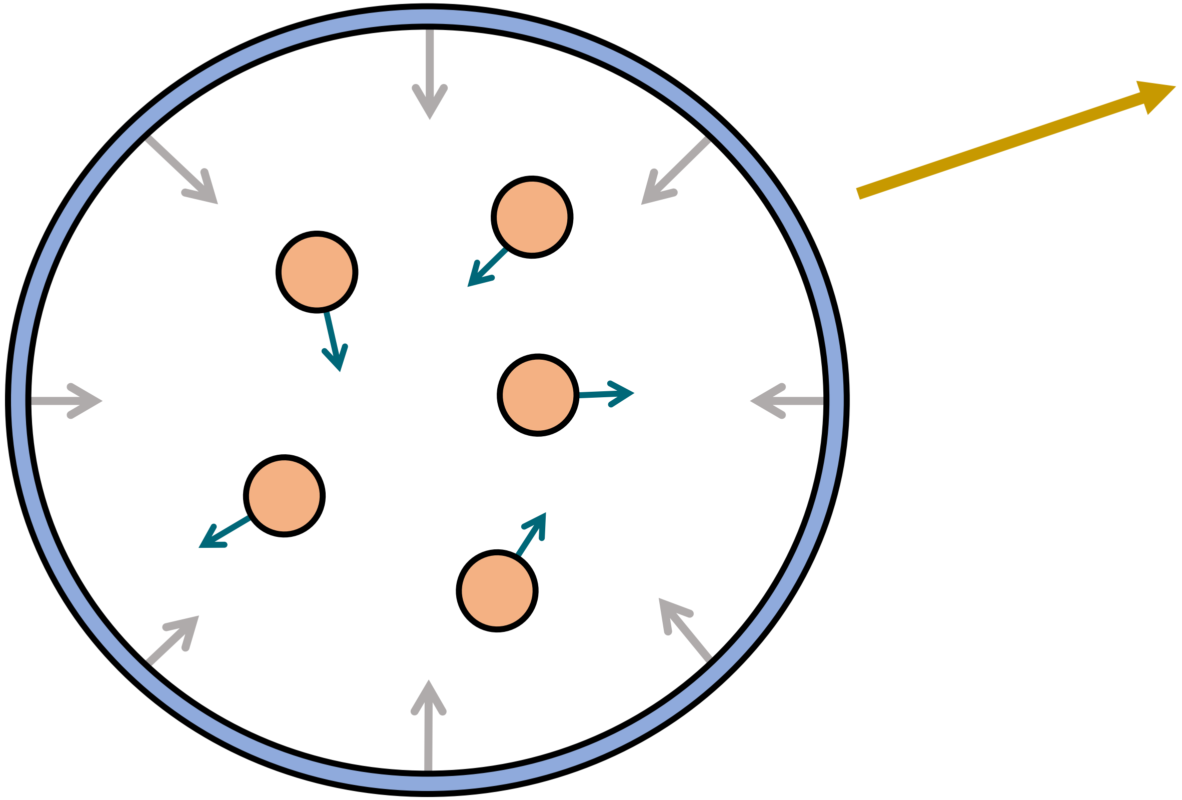

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

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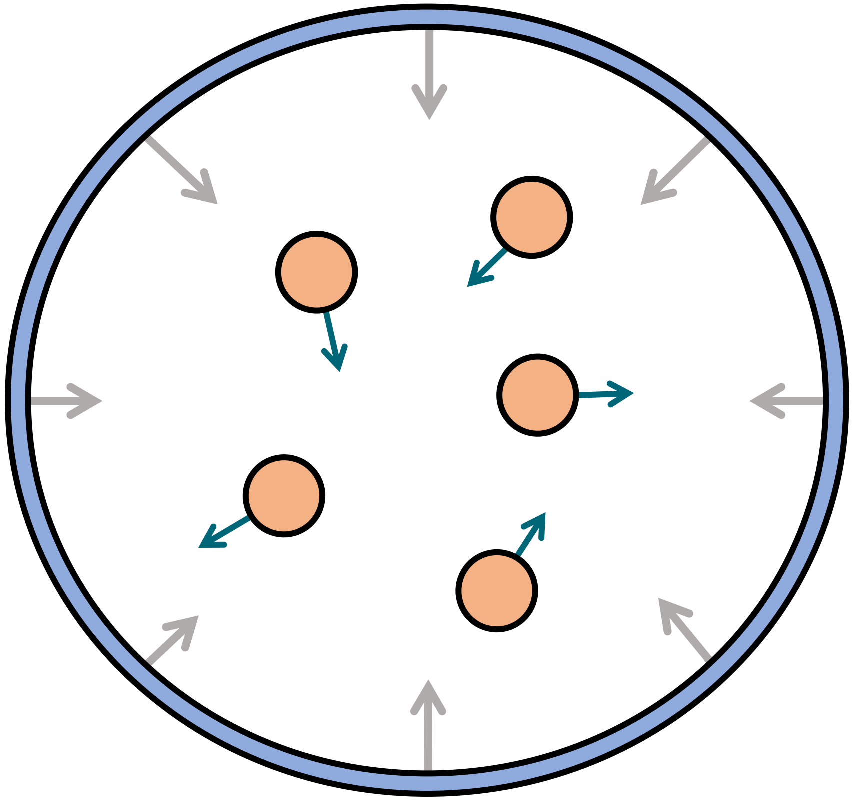

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Spherically symmetric and static

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$$\frac{GM}{R} \sim \mathcal{O}(1)$$

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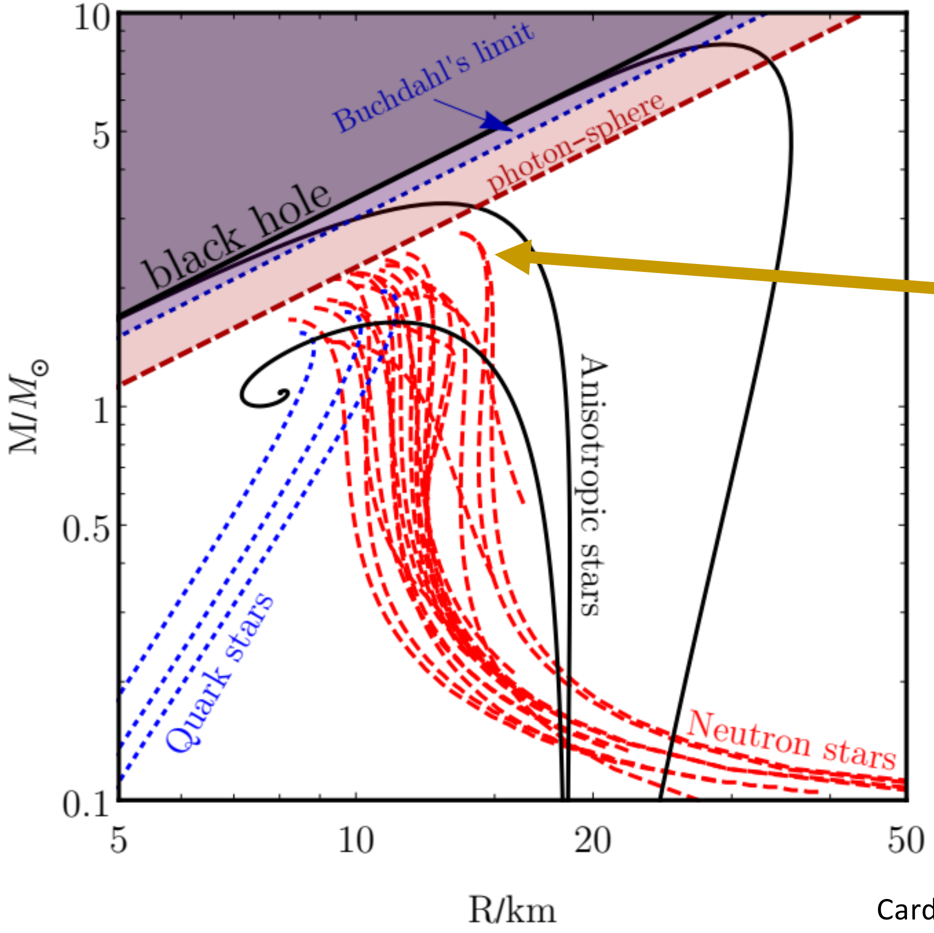
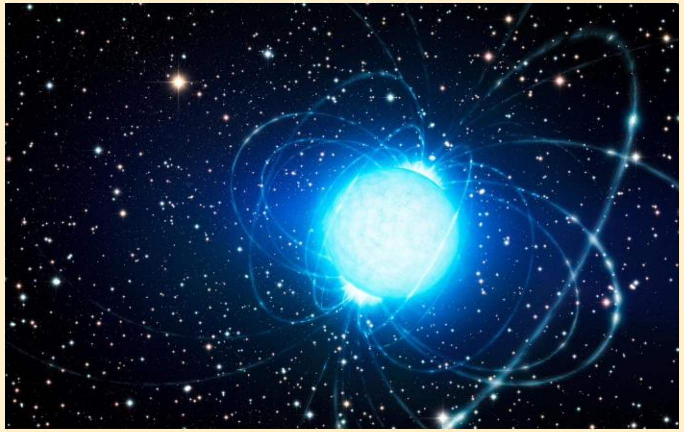


$$\frac{GM}{R} \sim \mathcal{O}(1)$$

Cardoso, Vitor and Pani, Paolo , “Testing the nature of dark compact objects: a status report,” *Living Rev. Rel.*, 2019.

Introduction

Neutron stars



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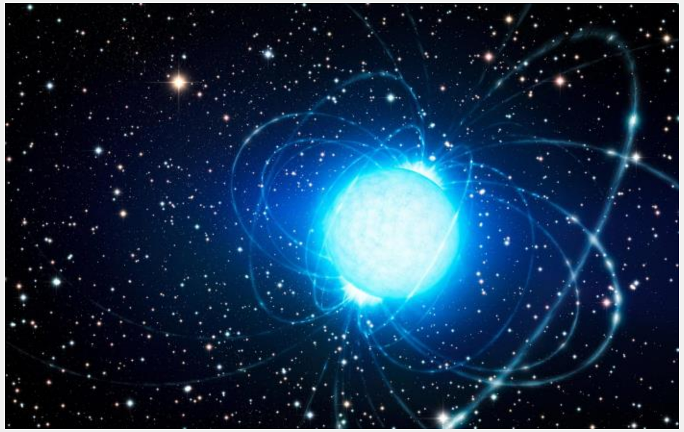

$$\sim (0.1 - 3)\, M_\odot$$

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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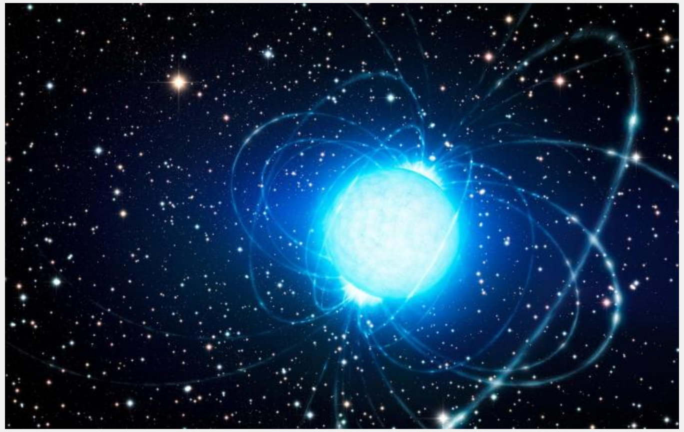

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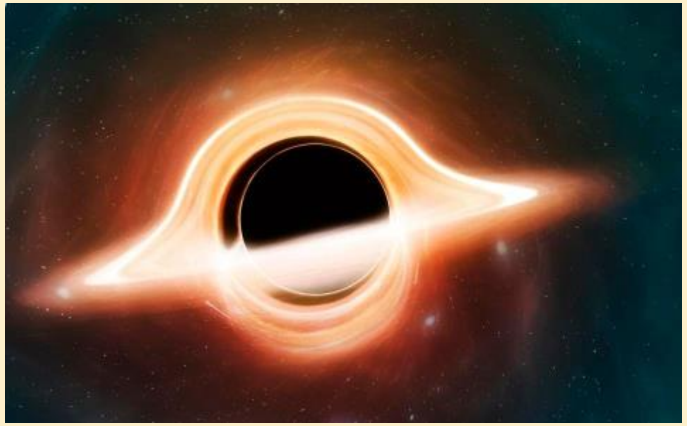
Black holes



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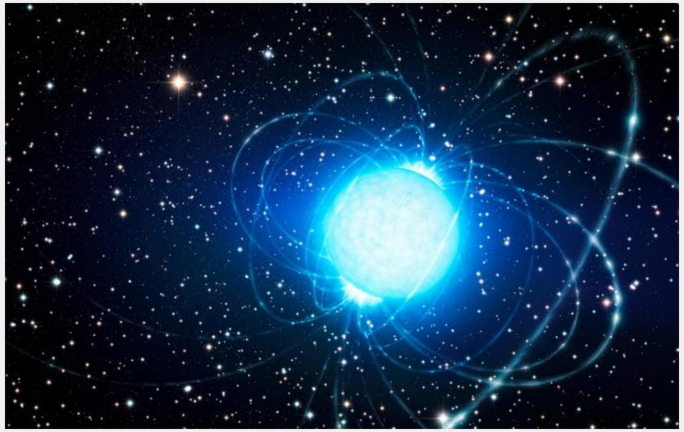

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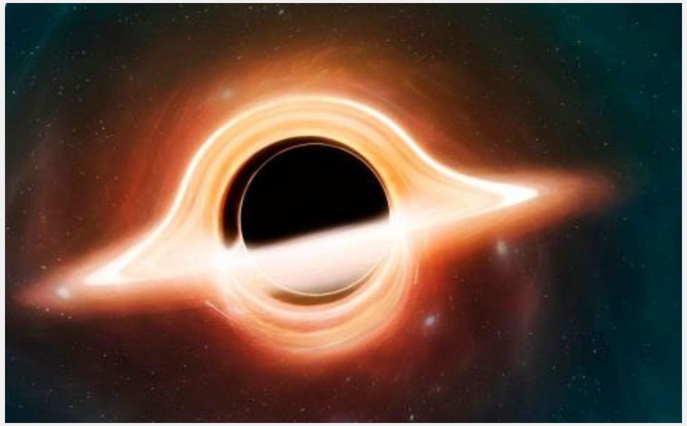
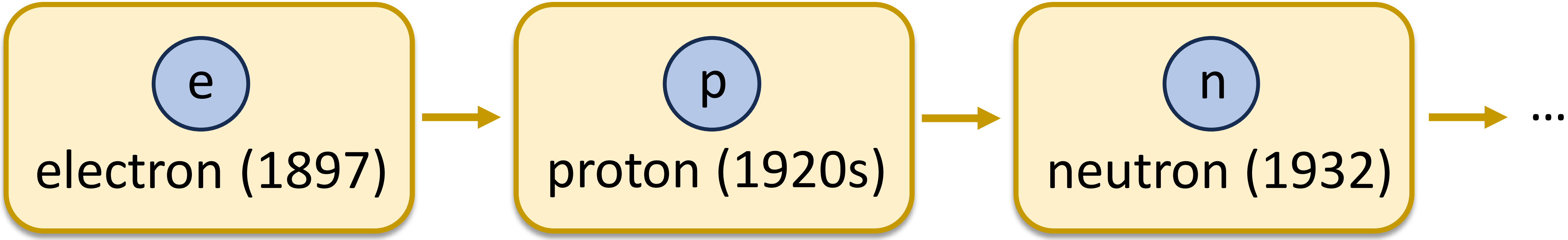


$\sim (4 - 10^{10})\, M_\odot$

Exotic compact objects?



Exotic compact objects?

e
electron (1897) → p
proton (1920s) → n
neutron (1932) → …

NS
Neutron stars (1960s) → BH
Black holes (1970s) → ?

Exotic compact objects?

e — electron (1897) → p — proton (1920s) → n — neutron (1932) → …

NS — Neutron stars (1960s) → BH — Black holes (1970s) → ?

Subsolar objects ($\lesssim 0.1\ M_\odot$)?

Exotic compact objects?

$$\mathcal{L}_{SM}$$

Exotic compact objects?

$\mathcal{L}_{SM}$ → $\mathcal{L}_{BSM}$

Exotic compact objects?

$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{BSM}$$

$$S = \int d^4x \sqrt{-g}\left(\frac{R}{16\pi G} - \frac{1}{2}\partial^\mu \phi^* \partial_\mu \phi - m_S^2\, \phi^* \phi\right)$$

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Boson stars $M \sim M_\odot \left(\frac{10^{-19}\,\mathrm{eV}}{m_S}\right)$

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

Compact objects in the SM?

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

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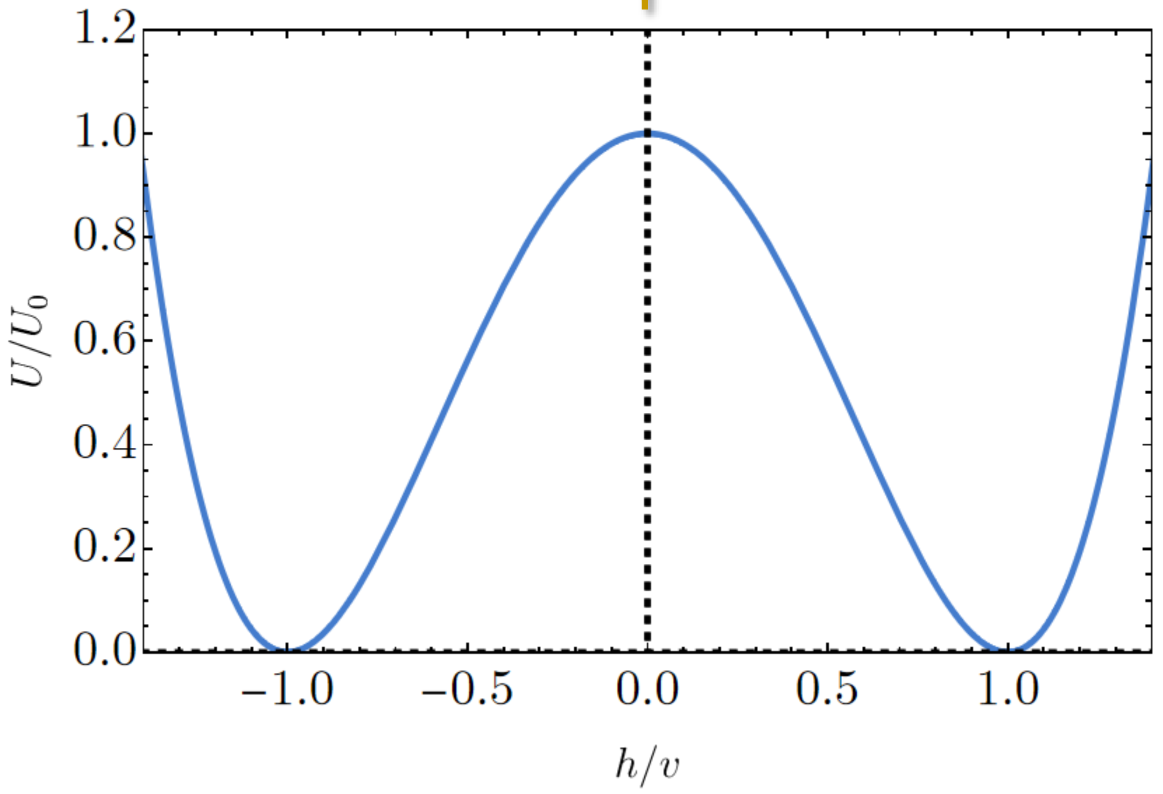
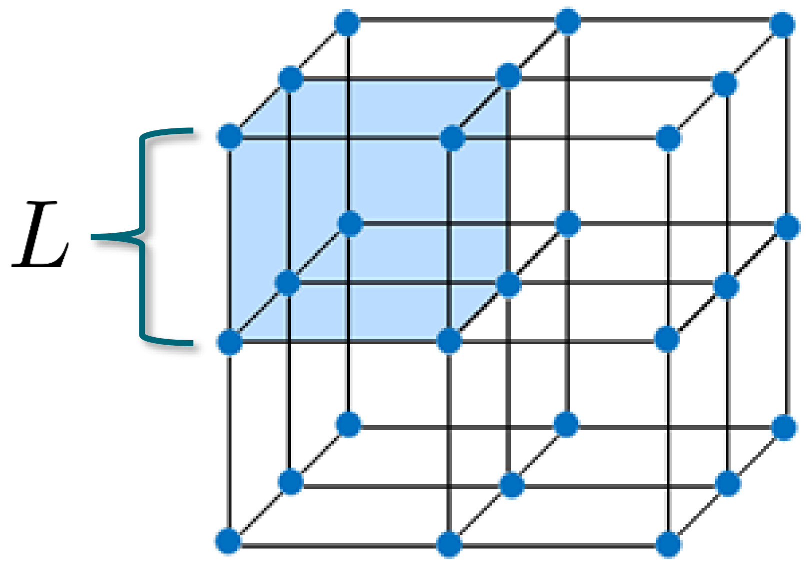


$$m_{\rm eff} = \frac{f}{\sqrt{2}} h$$

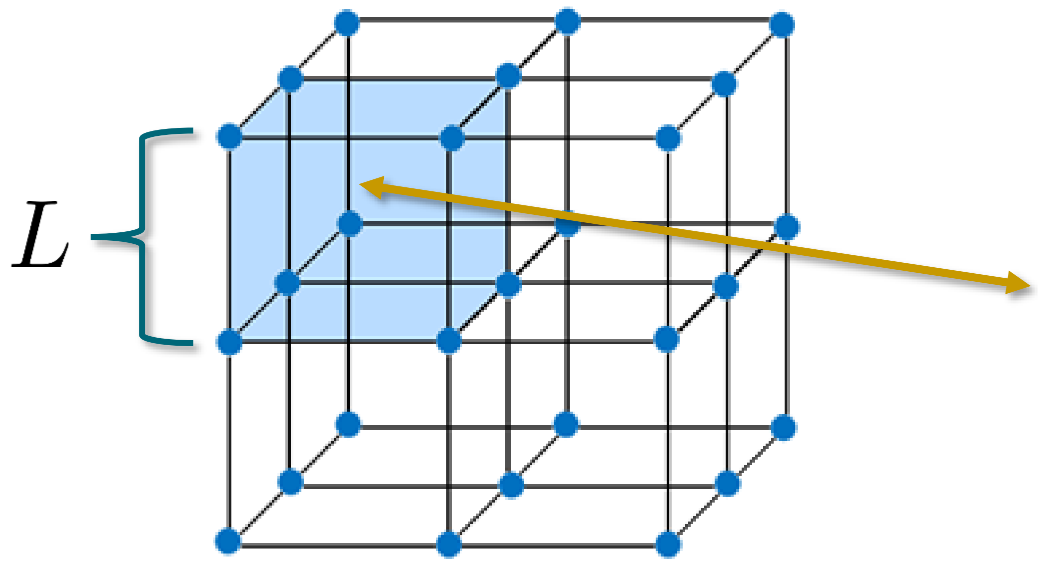
Thomas-Fermi approximation

- 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)

Effective potential

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

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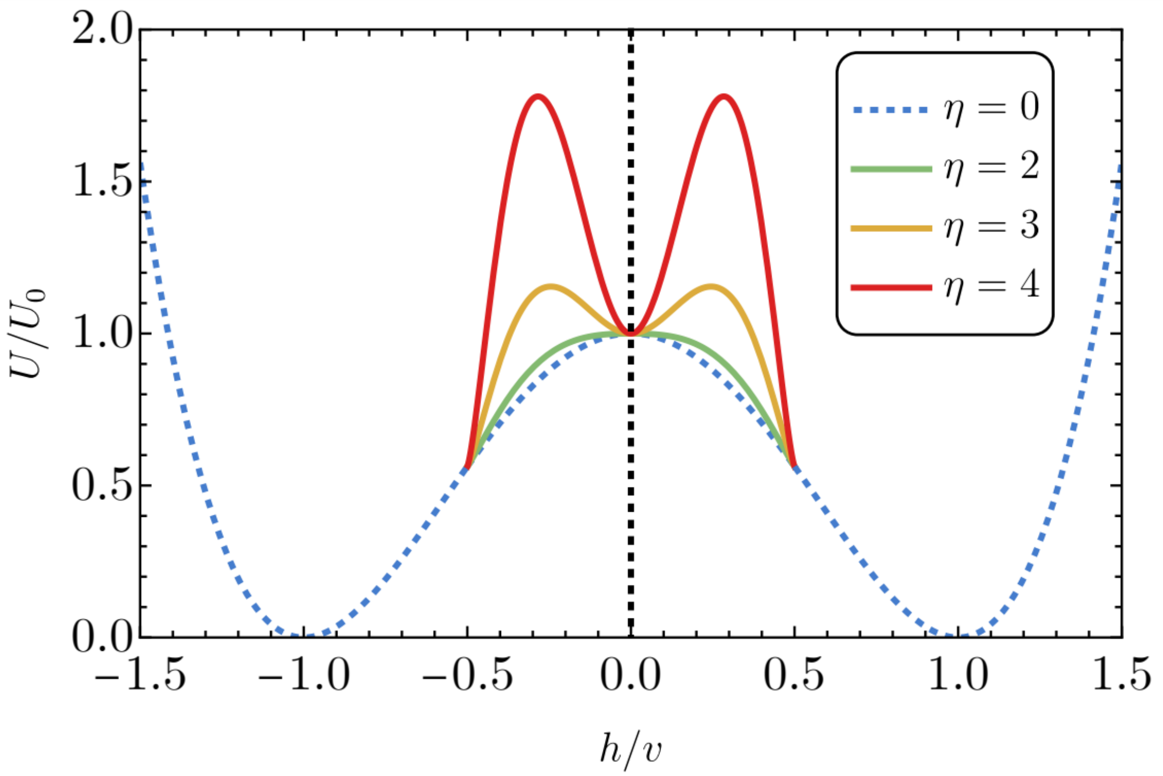

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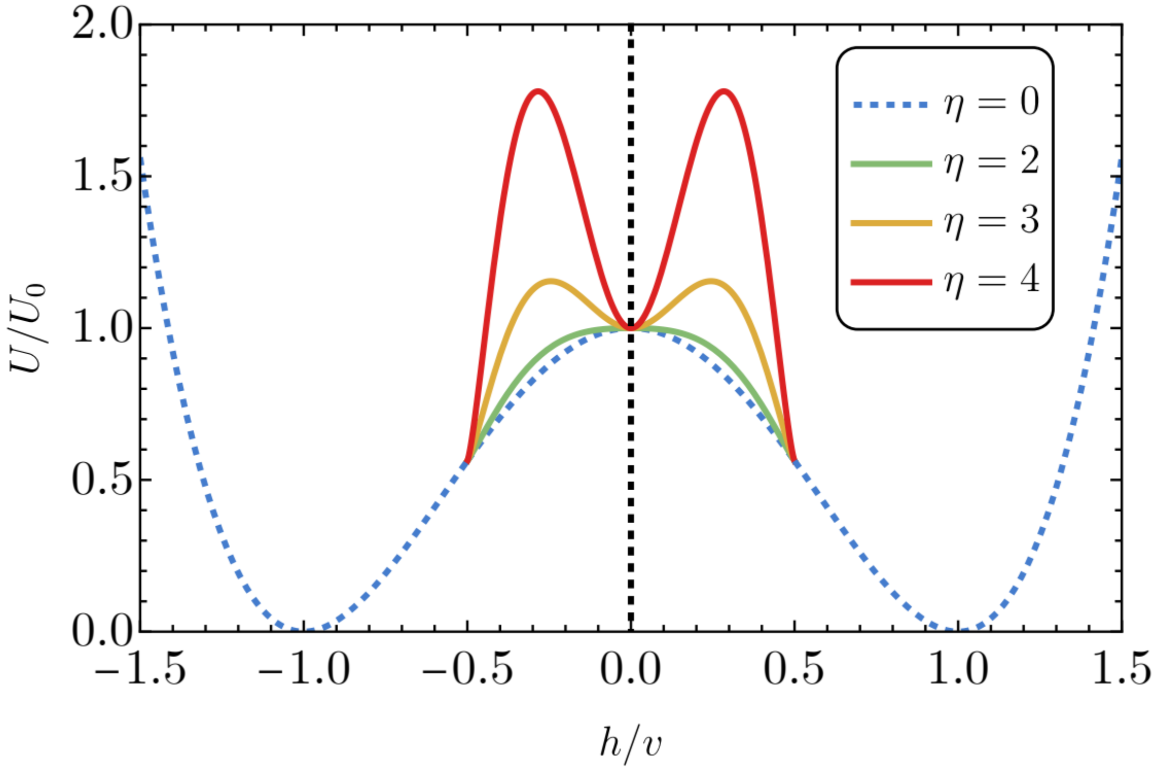

False vacuum pockets if

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

Equations of motion

1. $G_{\mu\nu} = 8\pi G \left(\quad \right)$

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$$= T^{[h]}_{\mu\nu}$$

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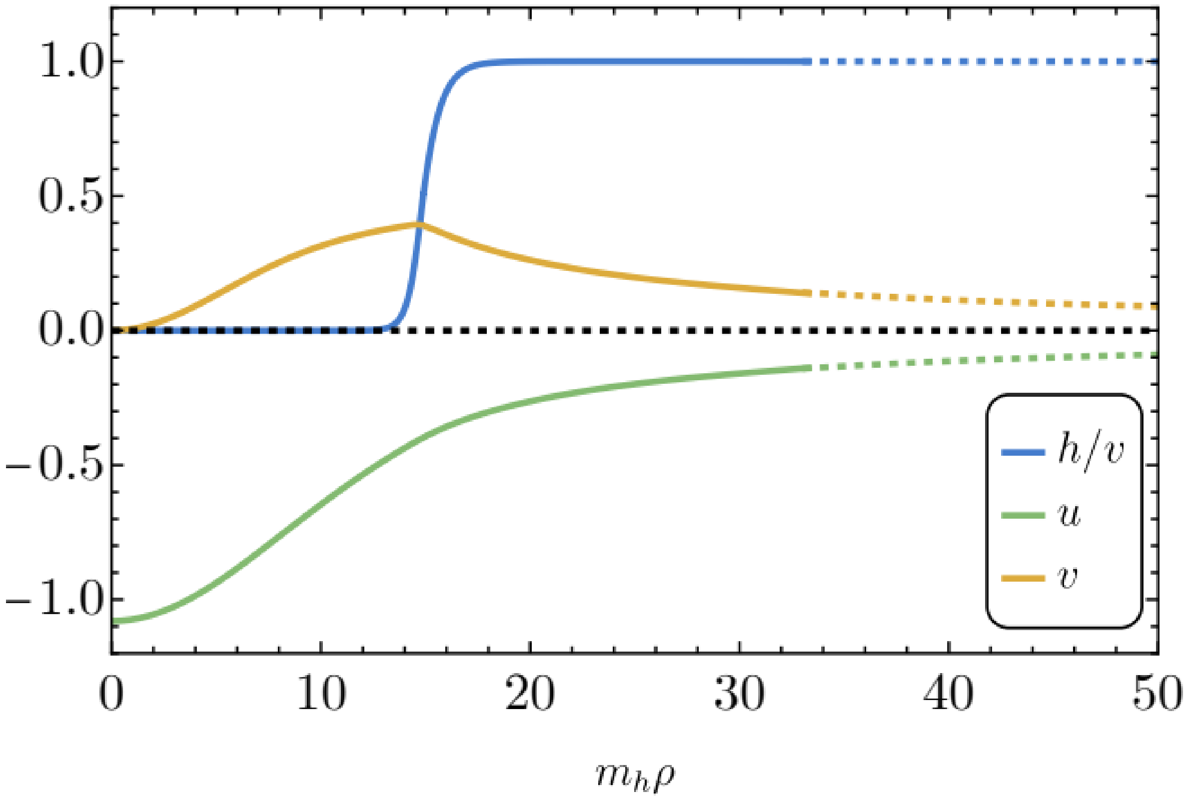
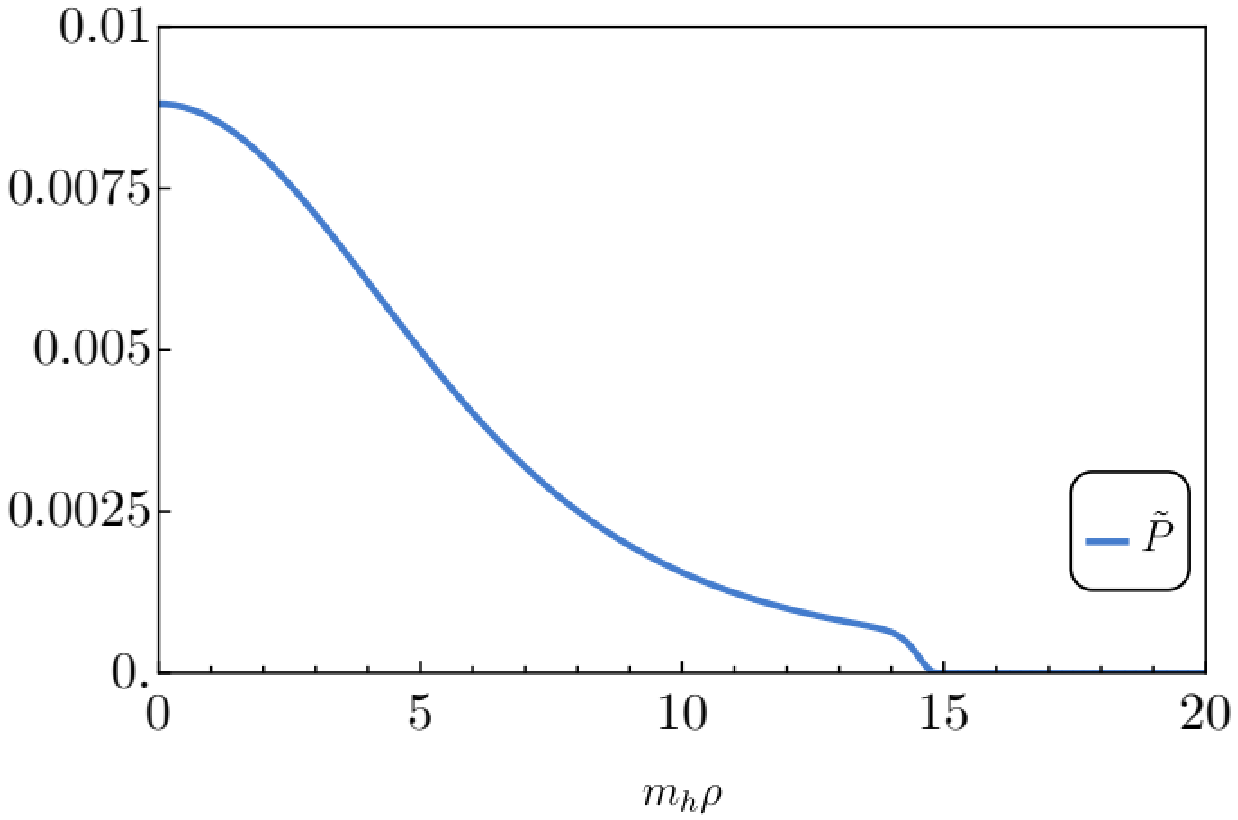
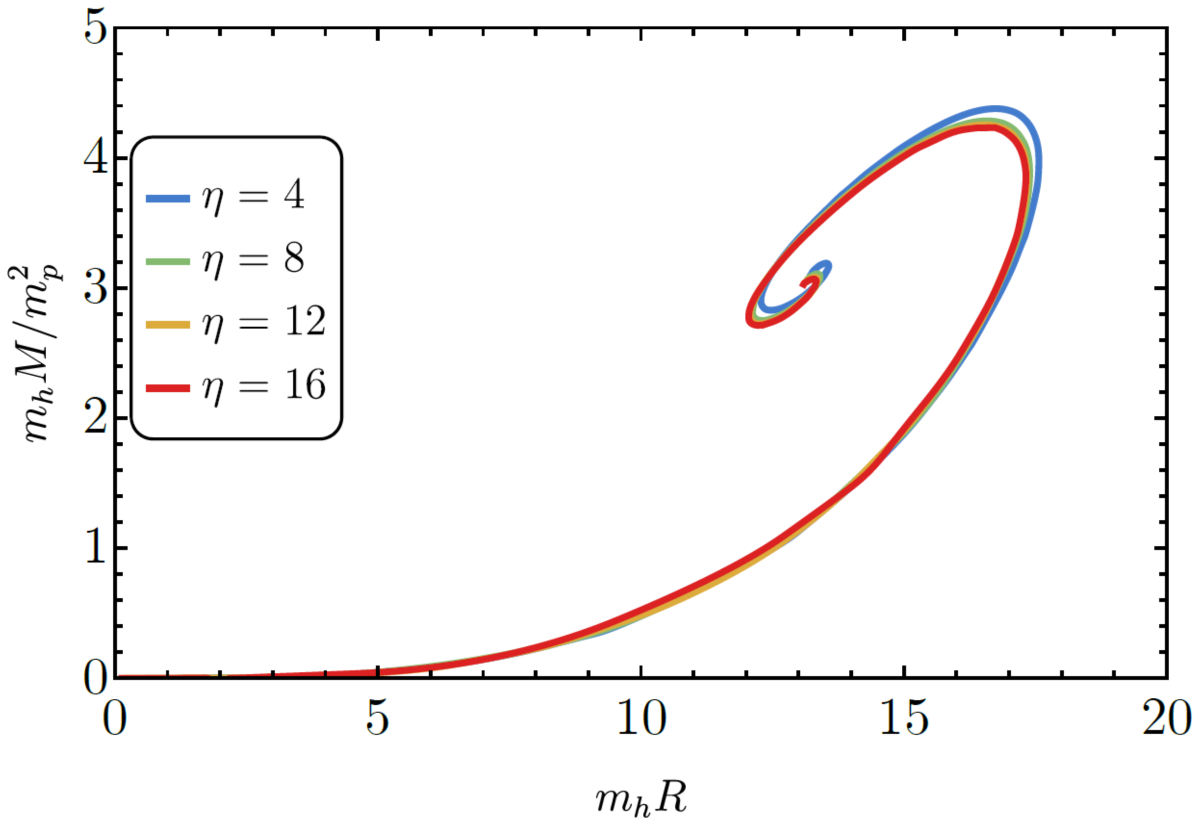
3. $$F(\underline{k_F}, g_{\mu\nu}, h) = 0$$

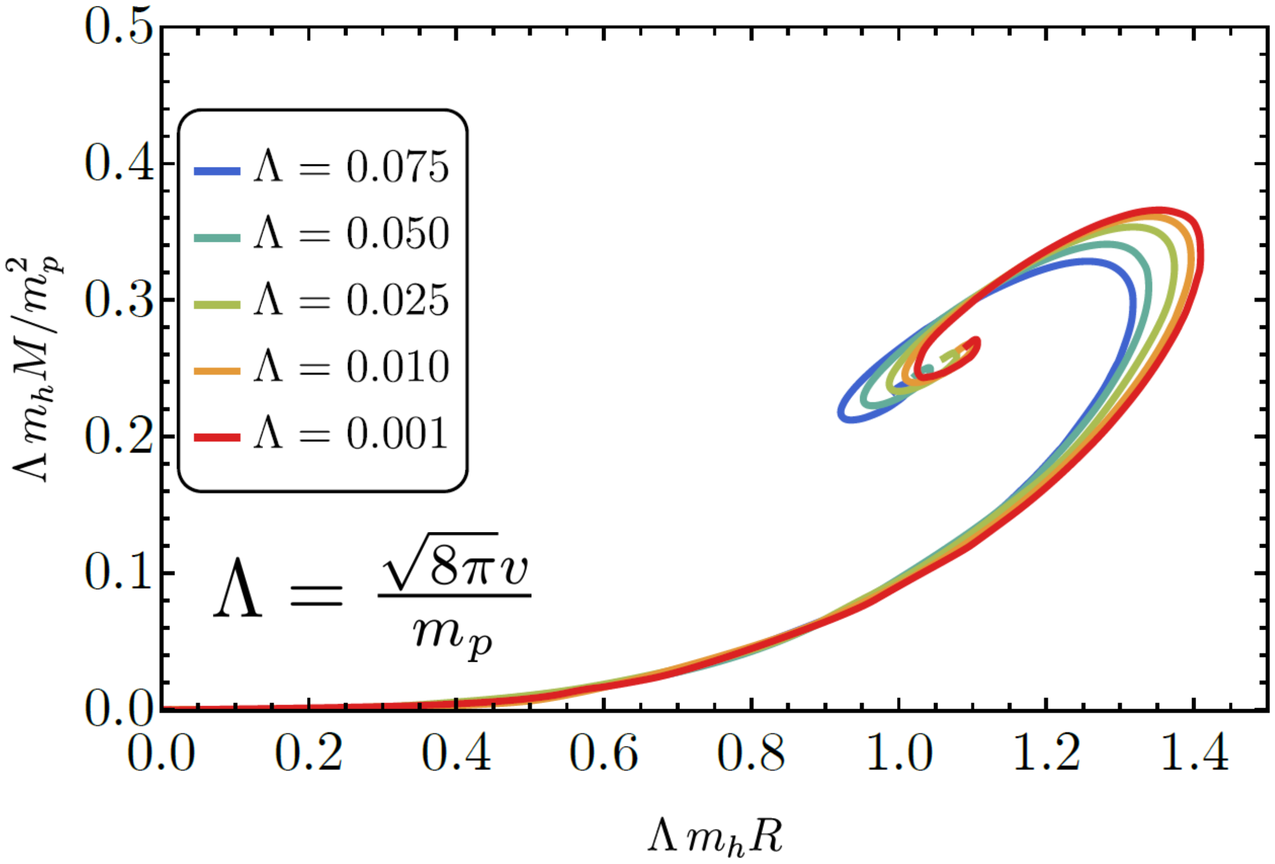
Example of solution





Mass-radius diagrams





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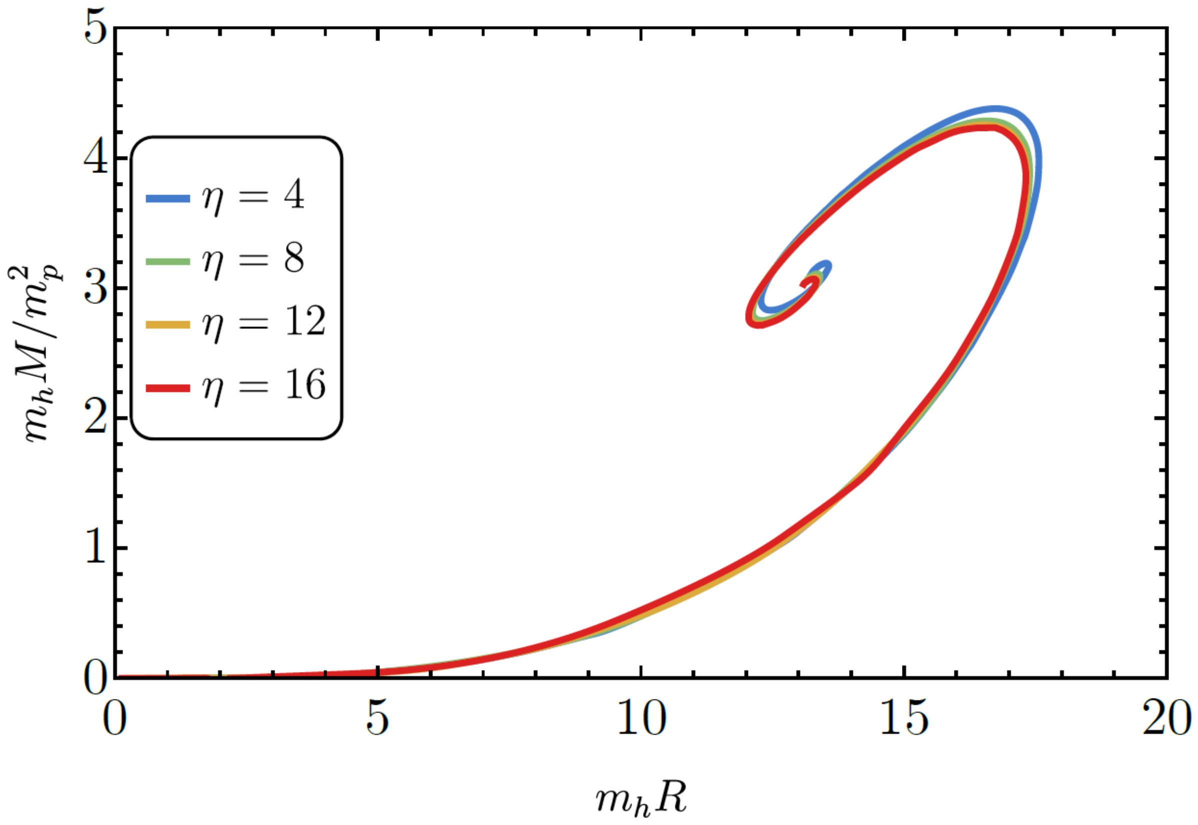
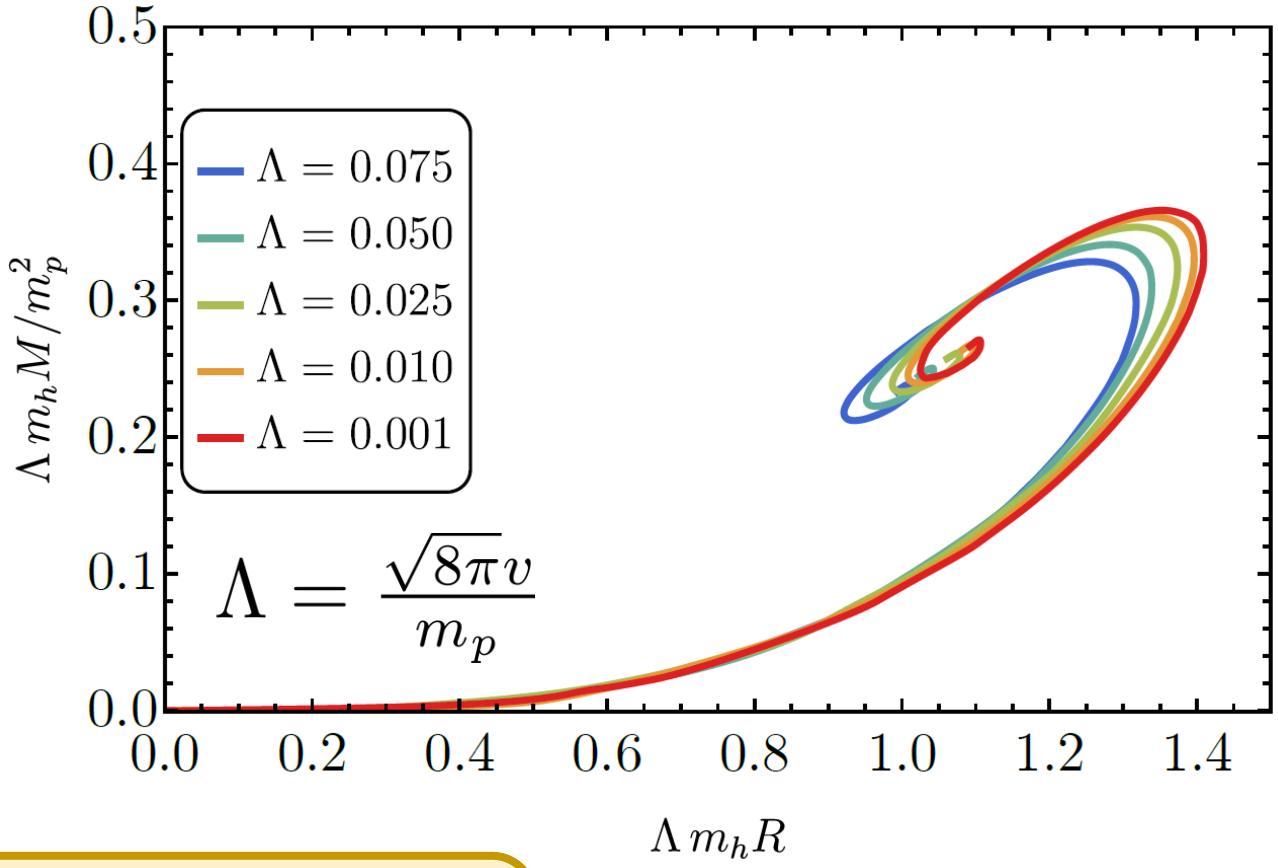
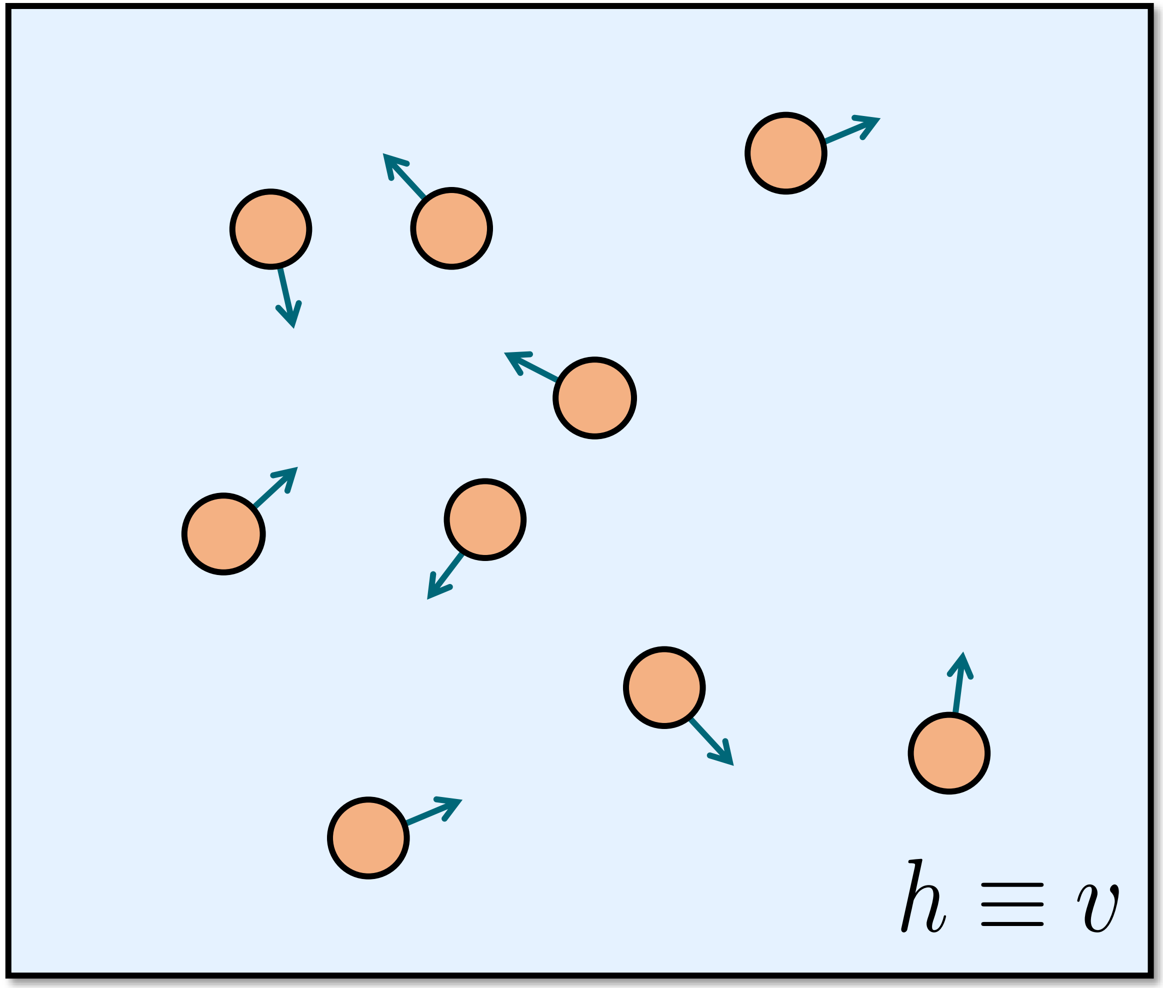




$$M_c \sim M_\odot \left(\frac{0.34\,\text{GeV}}{q}\right)^2 \qquad R_c \sim 5.5\,\text{km}\left(\frac{0.34\,\text{GeV}}{q}\right)^2$$

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

What is the actual ground state?



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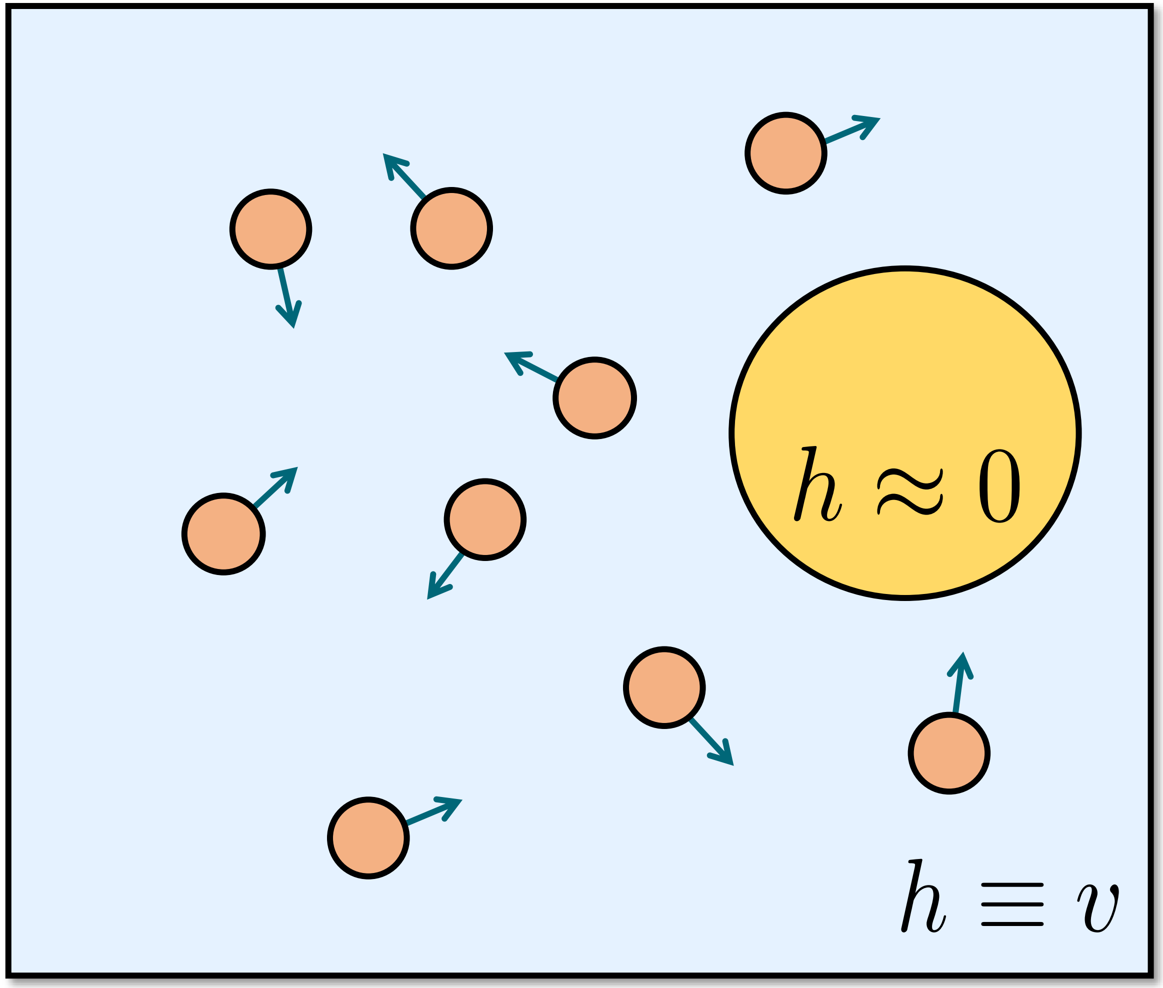

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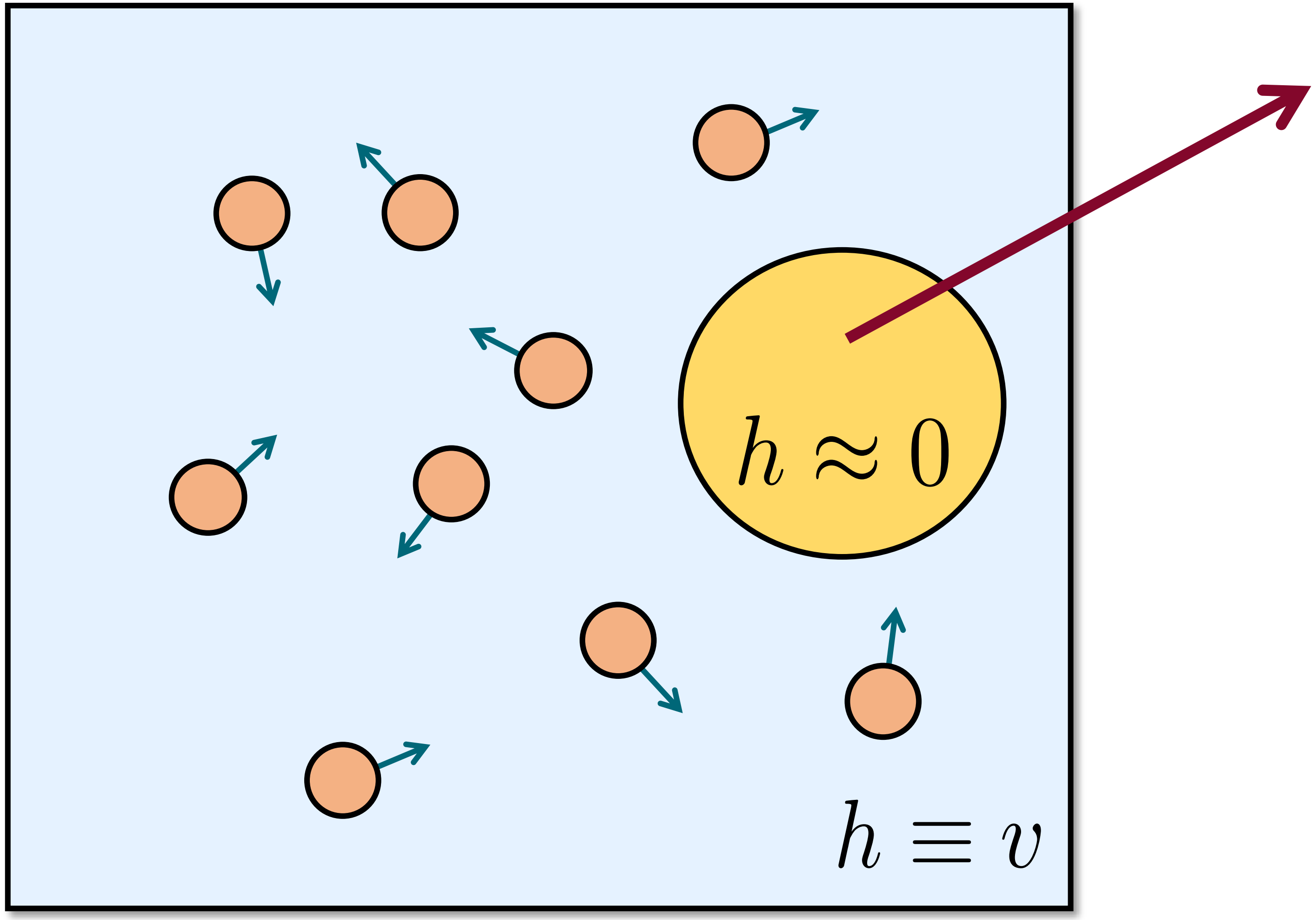

$$E_{\text{cost}} \sim m_h^2 v^2 R^3$$

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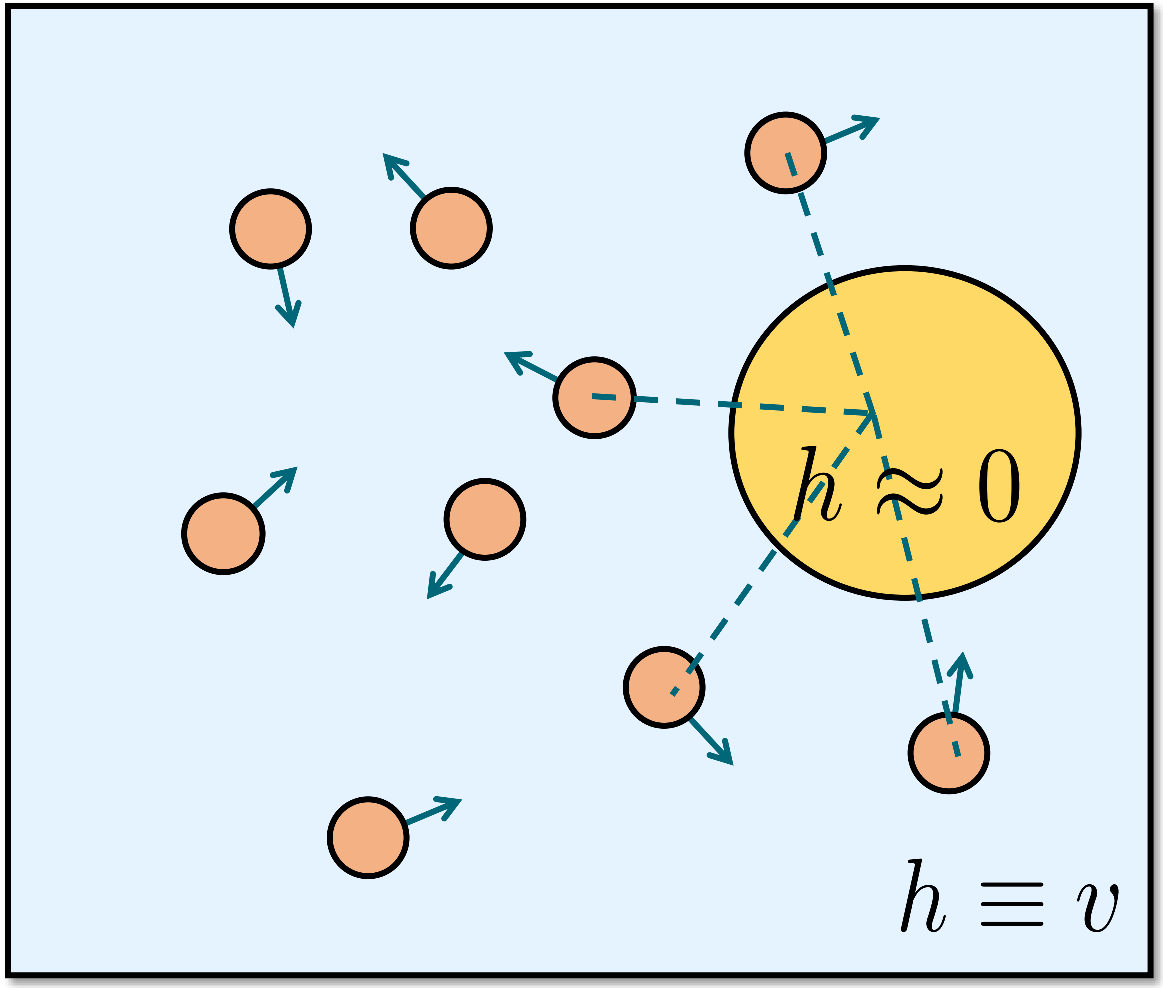

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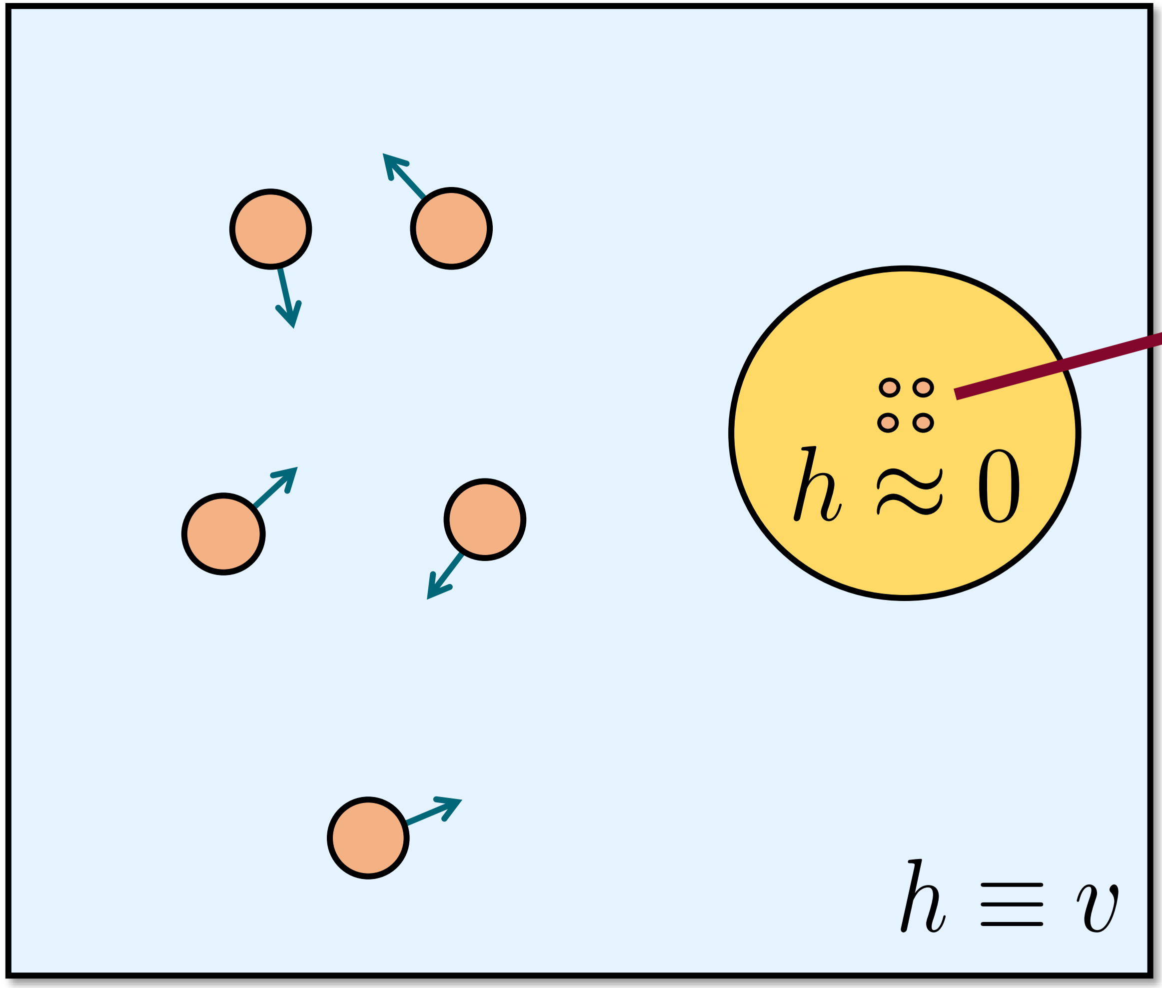

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$$E_{\text{gain}} \sim N m_f$$

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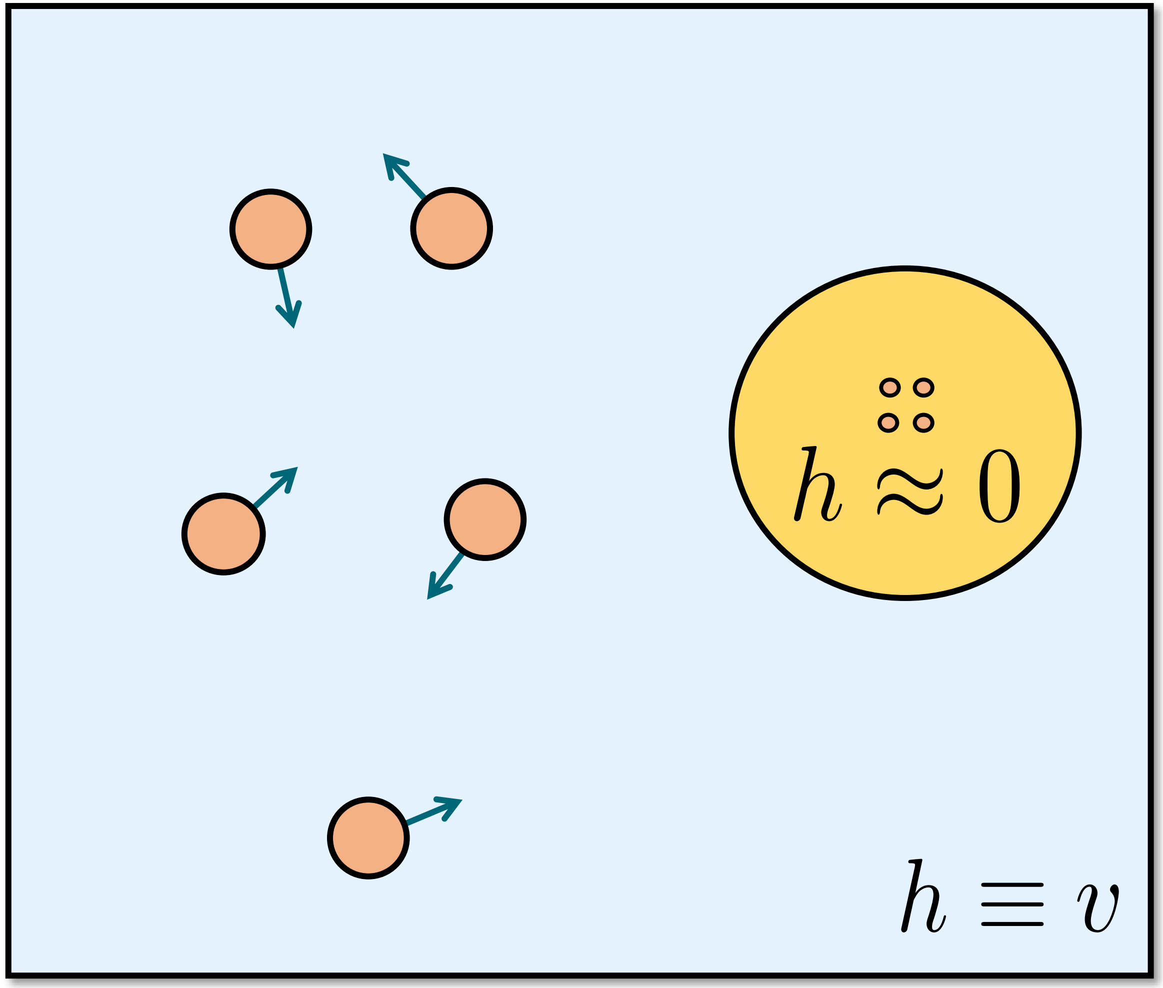


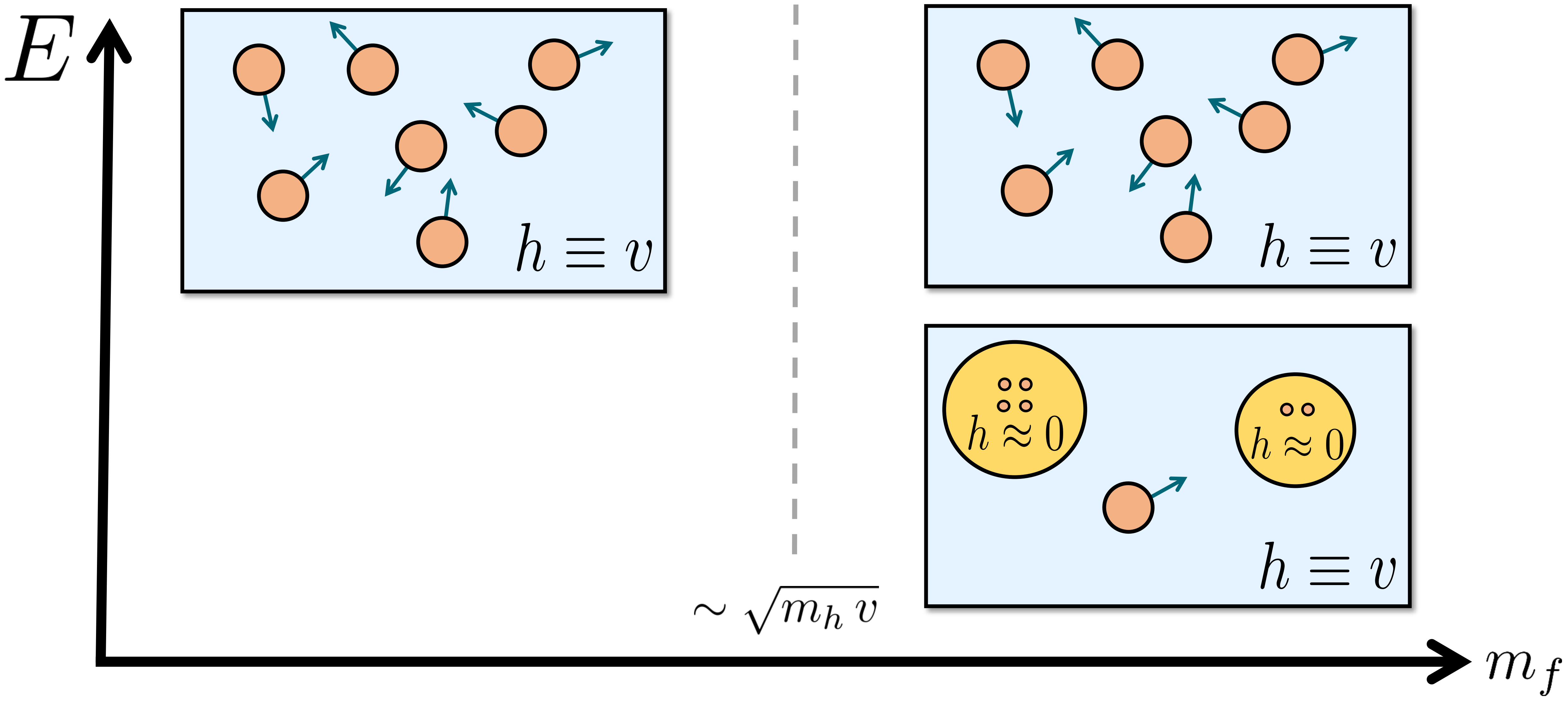
$$E_{\rm cost} \sim m_h^2 v^2 R^3$$

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

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

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

Non-perturbative vacuum scalarization



Neutron soliton stars

Linear sigma model → Chiral symmetry breaking

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

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

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$$M_c \approx 2\,M_\odot$$
$$R_c \approx 10\,\mathrm{km}$$

Higgs false vacuum pockets?

Standard Model Higgs

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$$m_h \sim 125\,\mathrm{GeV}$$

$$v \sim 246\,\mathrm{GeV}$$

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$$m_f > \sqrt{m_h v} \sim 175\,\mathrm{GeV}$$

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

$$R_c \approx 2\,\mathrm{cm}$$

Issues

Numerical computations gives the actual condition

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

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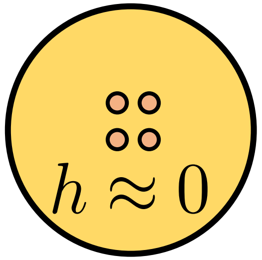
If the fermion is a <u>weakly interacting</u> particle coupled to the SM $t_{decay} \sim \left(\frac{m_h v}{m_f^2}\right) \times 10^{-11}\,\mathrm{sec}$



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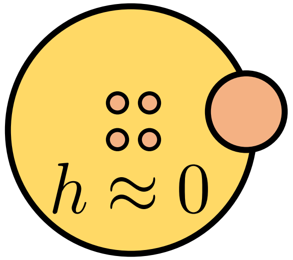

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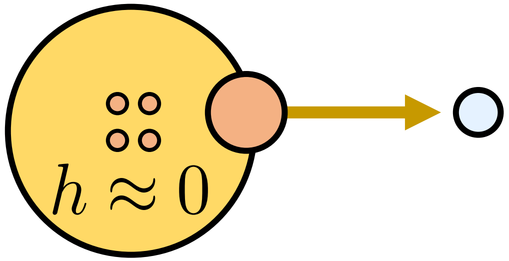

Exotic phase?

Number density inside the pocket

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Colored superconductor?

PBH?

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

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

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

How to discriminate among compact objects?

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Tidal deformability

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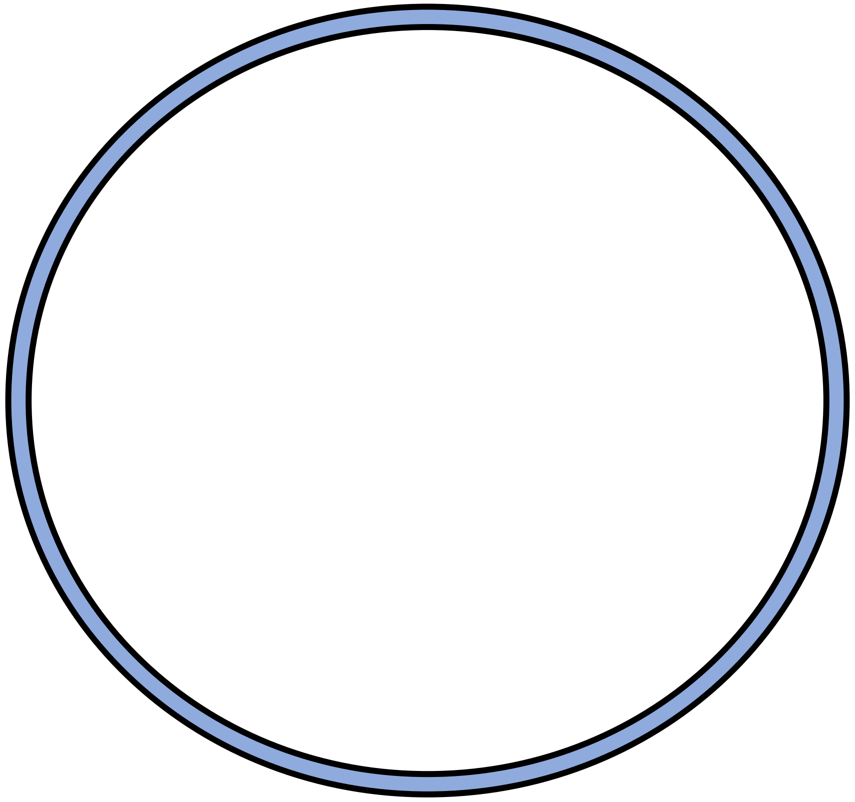

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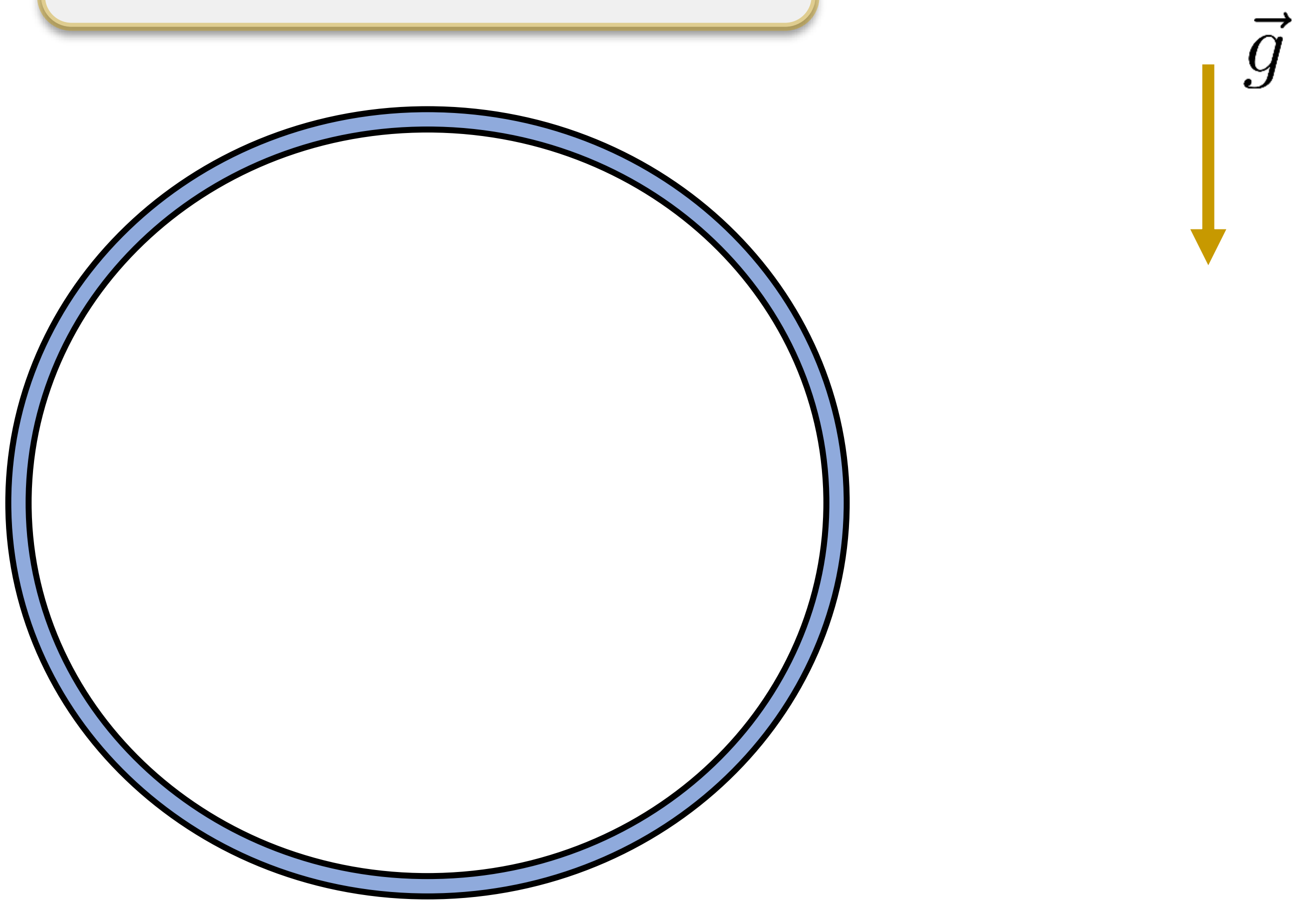

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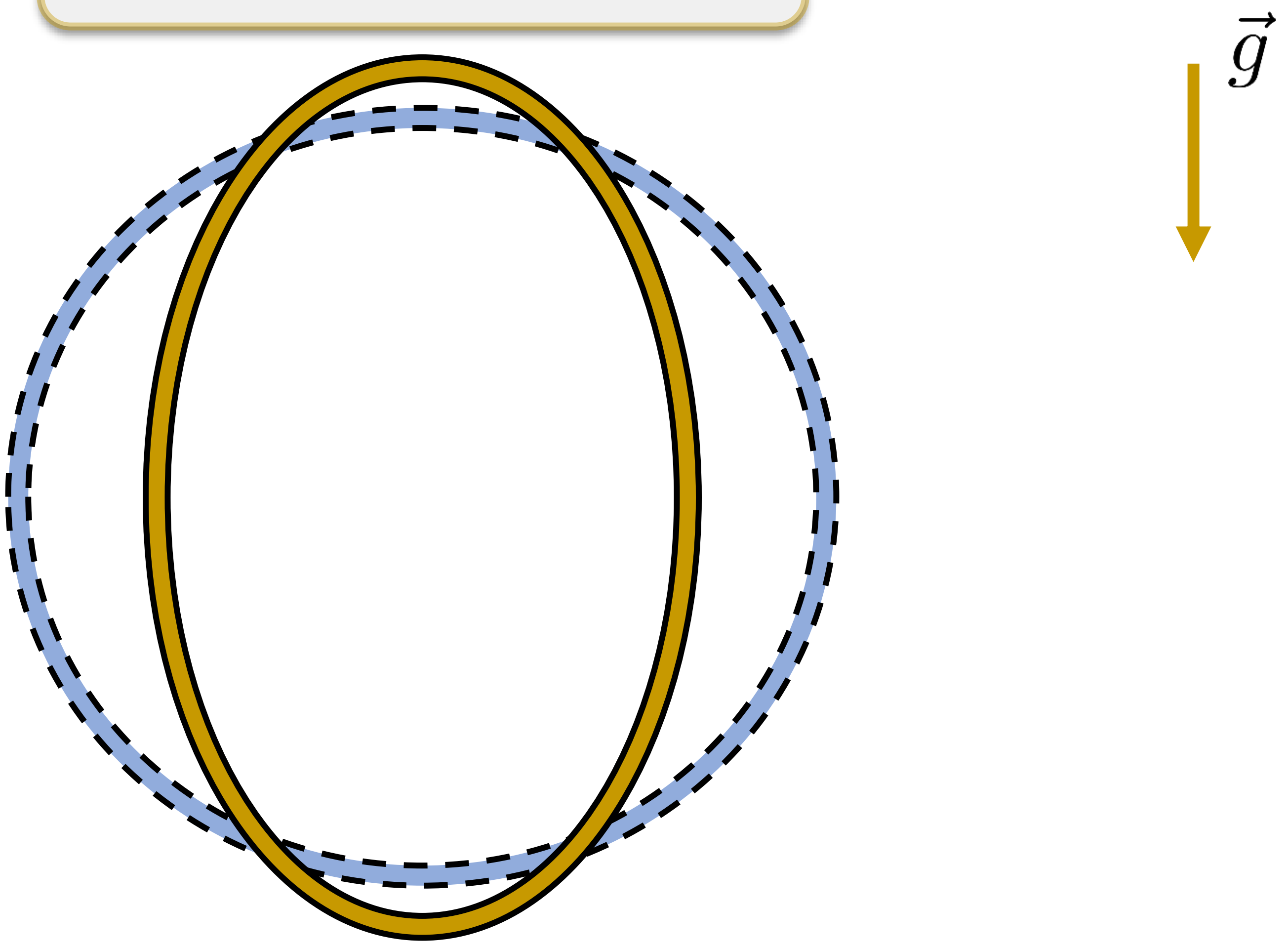

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The spherical symmetry allows us to decompose the perturbation into polar and magnetic sectors

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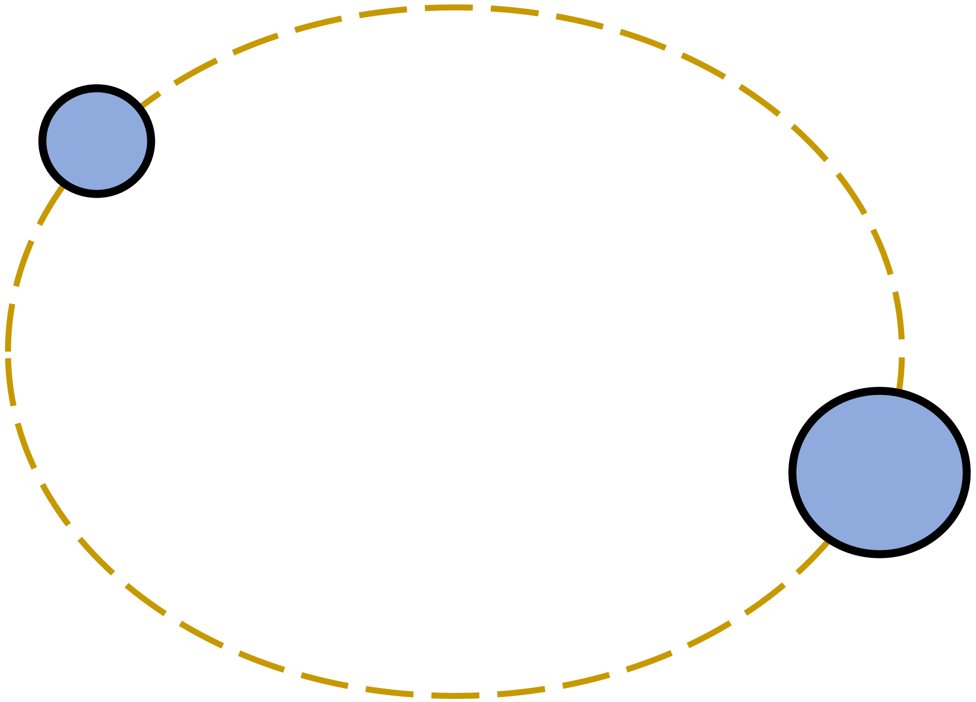

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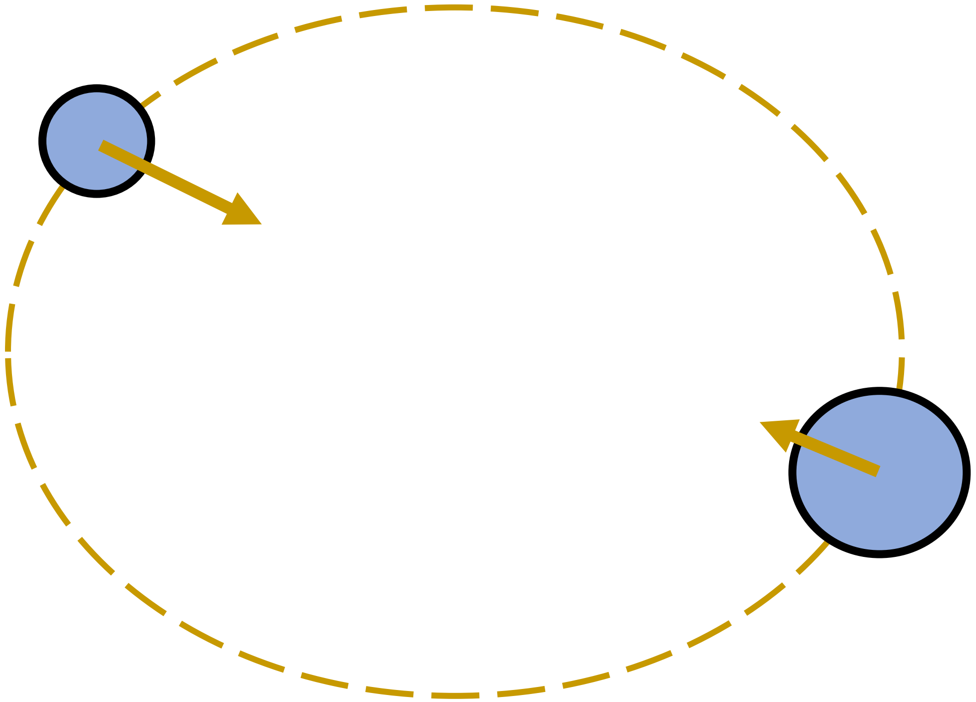

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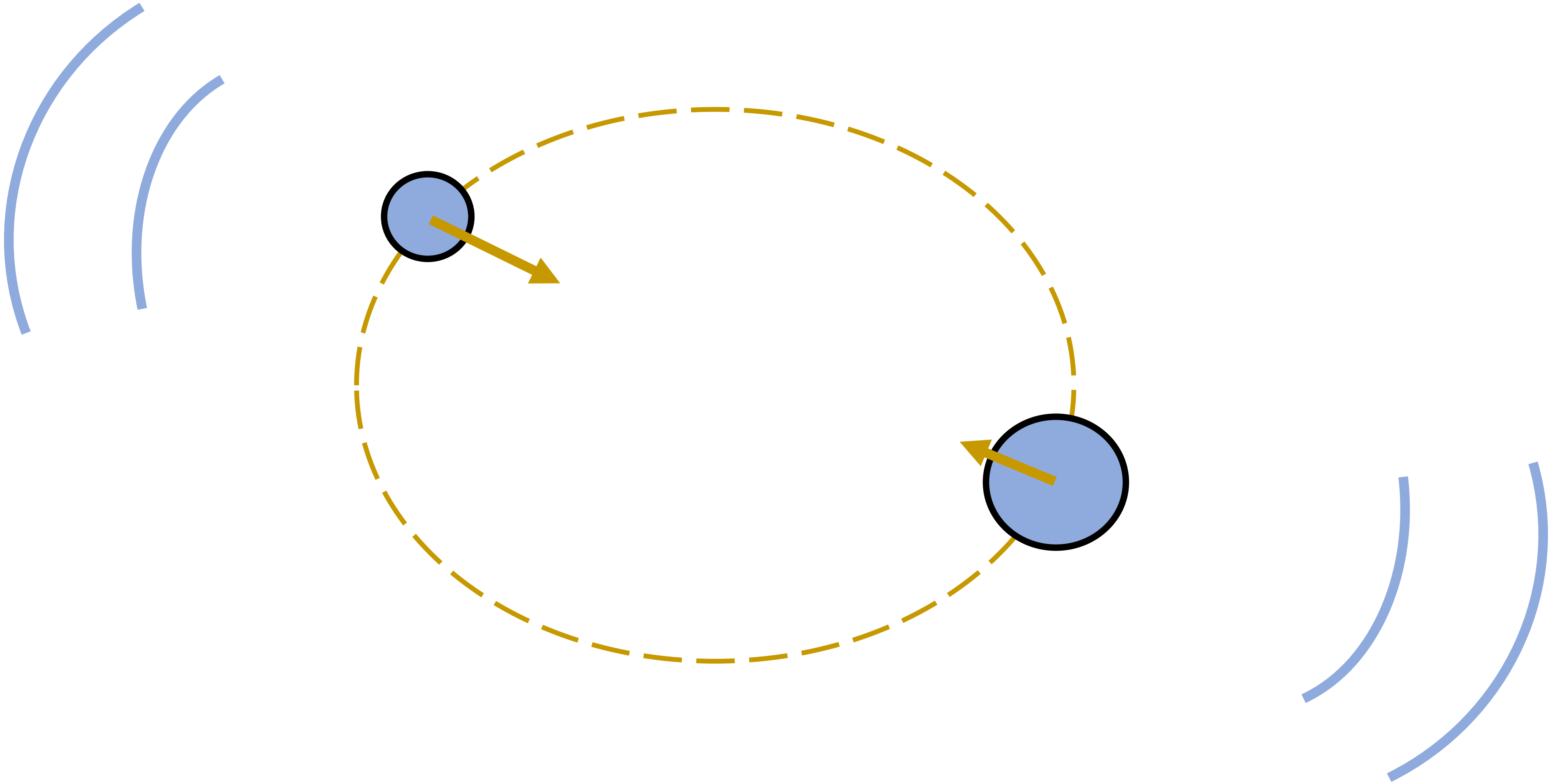
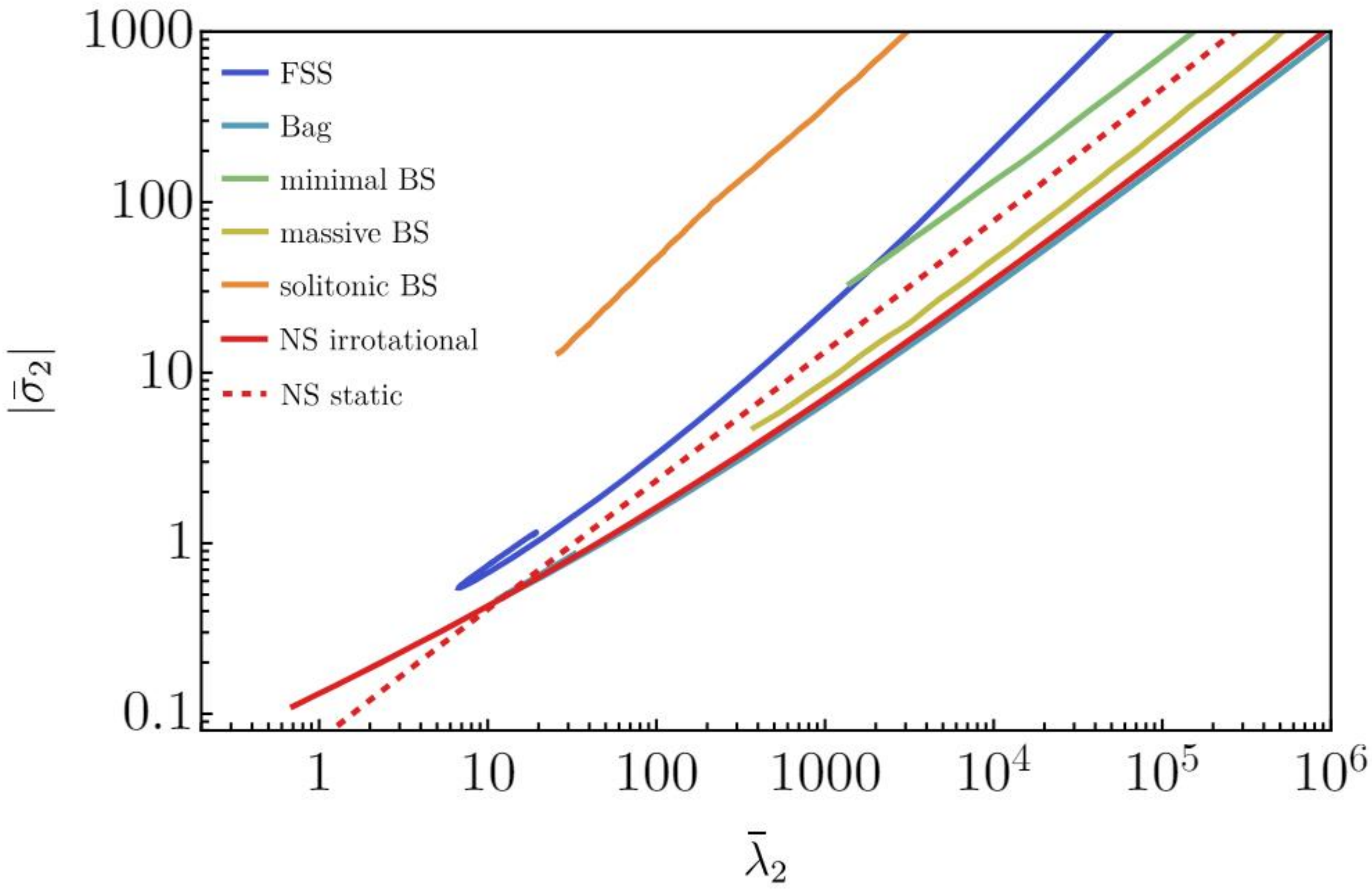


How to discriminate among compact objects?



Future directions

- Numerical simulations?

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- Cosmological abundance?

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- Cosmological abundance?
- GWs? Microlensing?

Thank you

Fermionic quantities

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

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

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

Confining regime