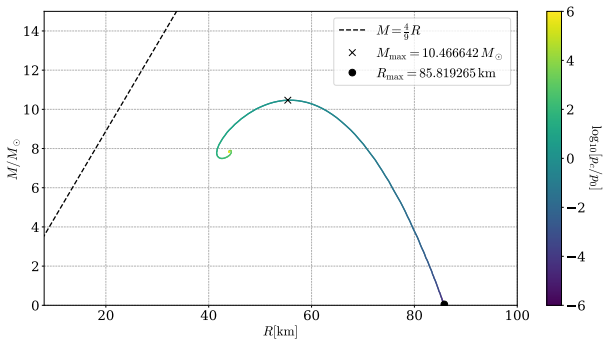


# Pion stars

- ▶ New proposal: stars made of pions
- ▶ Microscopic part: what are the thermodynamics of pions?
- ▶ Macroscopic part: hydrodynamics of astrophysical objects
- ▶ Questions: What is the mass-radius relations of pion stars? How do EM-interactions/including three quarks/loop corrections influence the star?



# Chiral perturbation theory

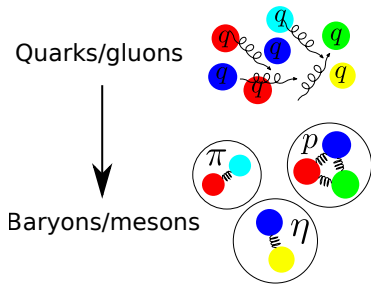
- ▶ Quarks bind into baryon (protons/neutrons) and mesons (pions) at low temperatures ( $< \sim 10^{12}$  K)
- ▶ The strong force is strong, so we can't do perturbation theory.

$$\mathcal{L} = \sum_f \bar{q}_f (\gamma^\mu [\partial_\mu - i q \lambda^a A_\mu^a] + m_f) q_f + G_{\mu\nu}^a G_a^{\mu\nu}$$

- ▶ Need an effective theory, The QCD vacuum spontaneously break a symmetry of the Lagrangian — Goldstone bosons (pions)

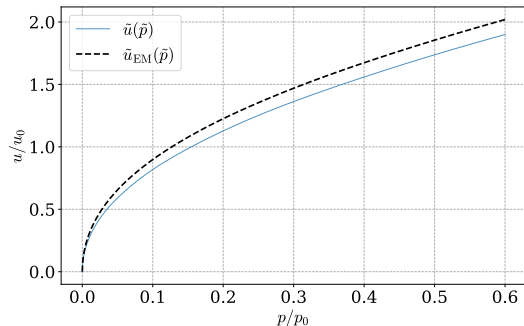
$$\mathcal{L}_{\text{eff}} = \frac{f^2}{4} \text{Tr}\{\nabla_\mu \Sigma \nabla^\mu \Sigma^\dagger\} + \frac{f^2}{4} \text{Tr}\{\chi^\dagger \Sigma + \Sigma^\dagger \chi\} + l_1 \text{Tr}\{\nabla_\mu \Sigma (\nabla^\mu \Sigma)^\dagger\}^2 + \dots$$

- ▶  $\Sigma = \exp(i\pi_a \tau_a / f) \in \text{SU}(3)$ , where  $\text{SU}(3)$  is the broken symmetry.



# Thermodynamics

- ▶ With the effective Lagrangian, we can calculate free energy density
- ▶  $\mathcal{F} = -\frac{i}{V\beta} \ln \left[ \int \mathcal{D}\pi \exp \left( i \int d^4x [\mathcal{L}_{\text{eff}} + \mu J] \right) \right]$
- ▶ Include isospin and strangeness chemical potential, EM-interactions, loops...
- ▶ Phase transitions: pion condensation
- ▶ Calculate equation of state



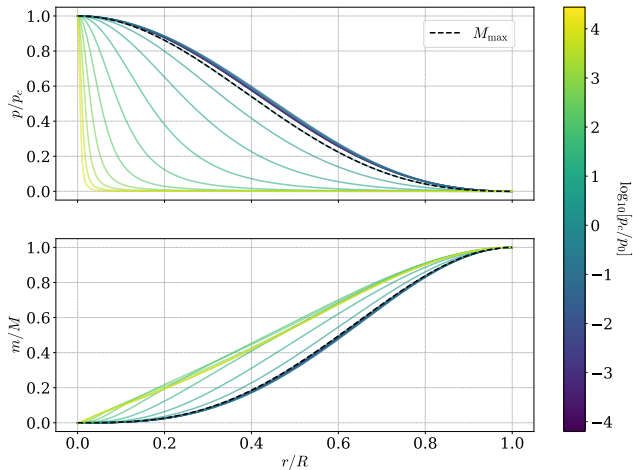
# Hydrostatic equilibrium

- ▶ TOV equation govern pressure of perfect fluids in hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G}{r^2} \frac{(u+P)(m+4\pi r^3 P)}{\left(1 - \frac{2Gm}{r}\right)},$$

$$\frac{dm}{dr} = 4\pi r^2 u$$

- ▶ Numerical integration gives  $P$ ,  $u$  and thus  $M$ ,  $R$ .



# Results

We get a family of results parametrized by central pressure.

Find explicit expression for  $R_{\max} = \frac{\pi}{\sqrt{12}} r^0$ .

