Stellar Remnants in the Presence of a Light Scalar

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Fermilab

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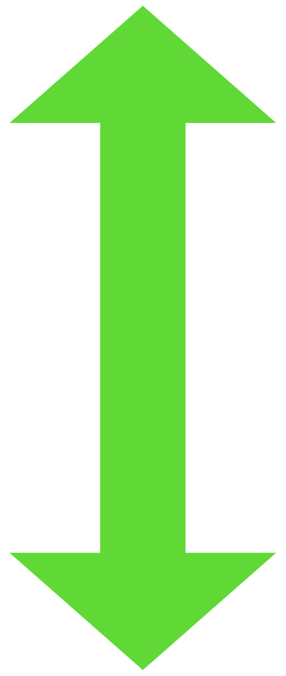
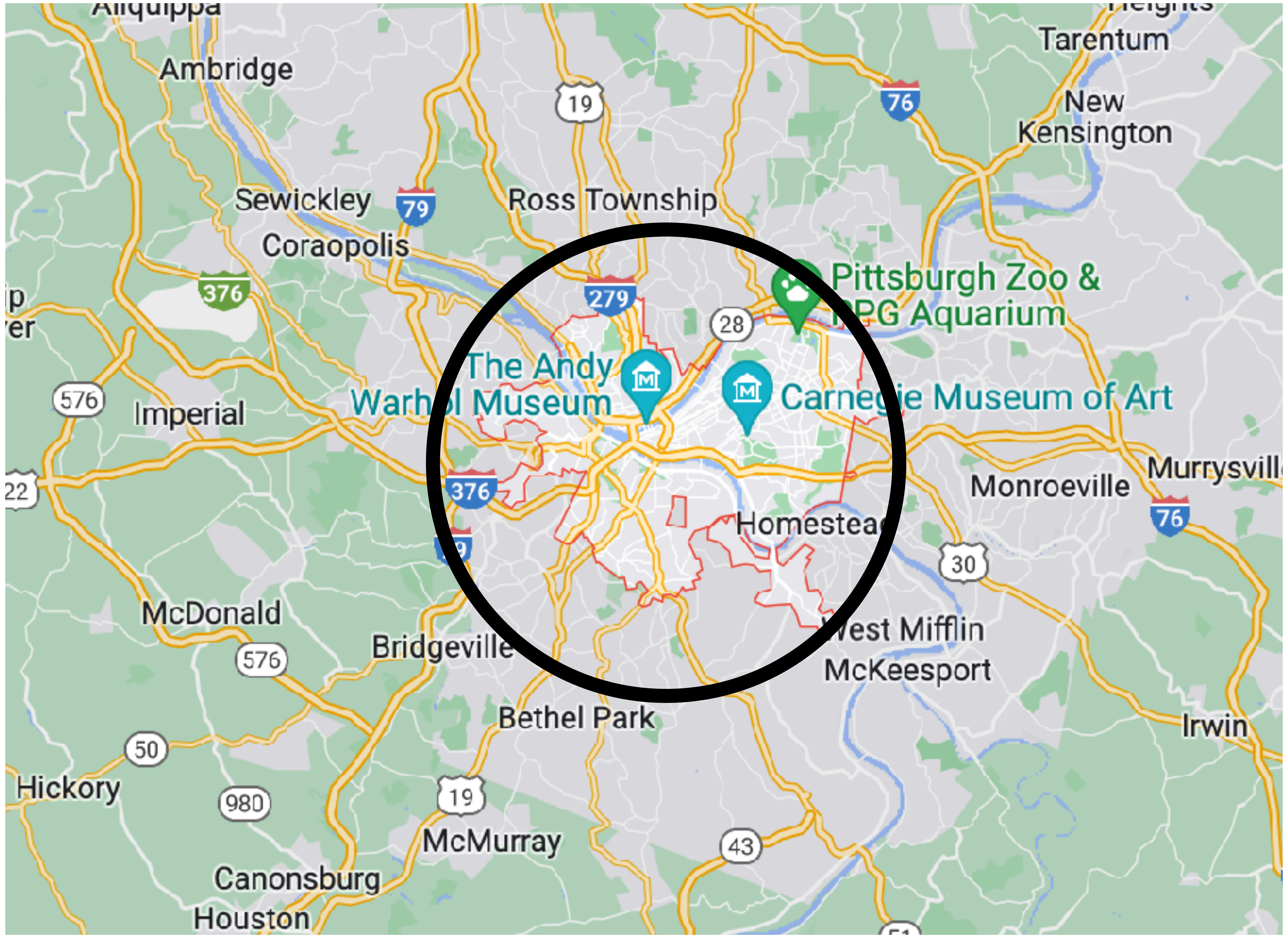
Neutron Star simplified

Gravity

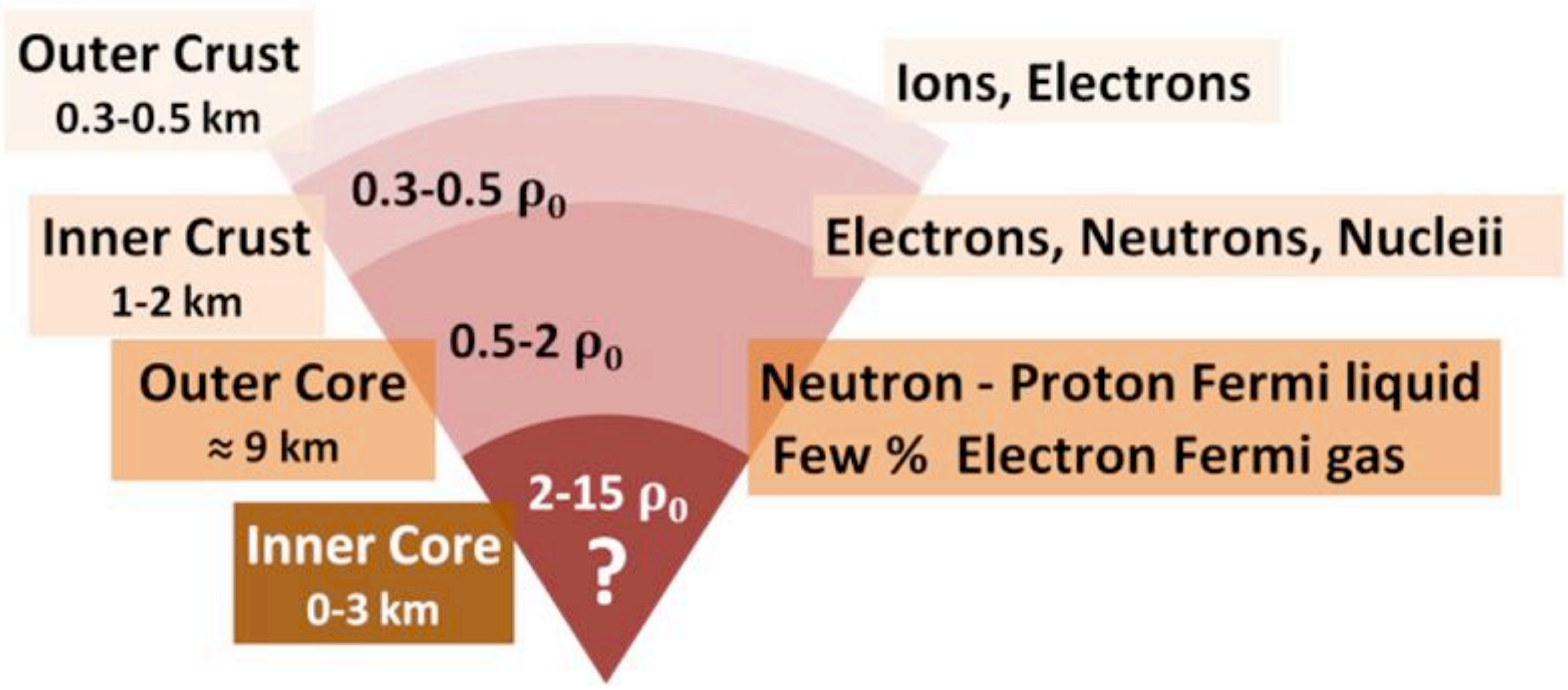


Fermi
Degeneracy
Pressure



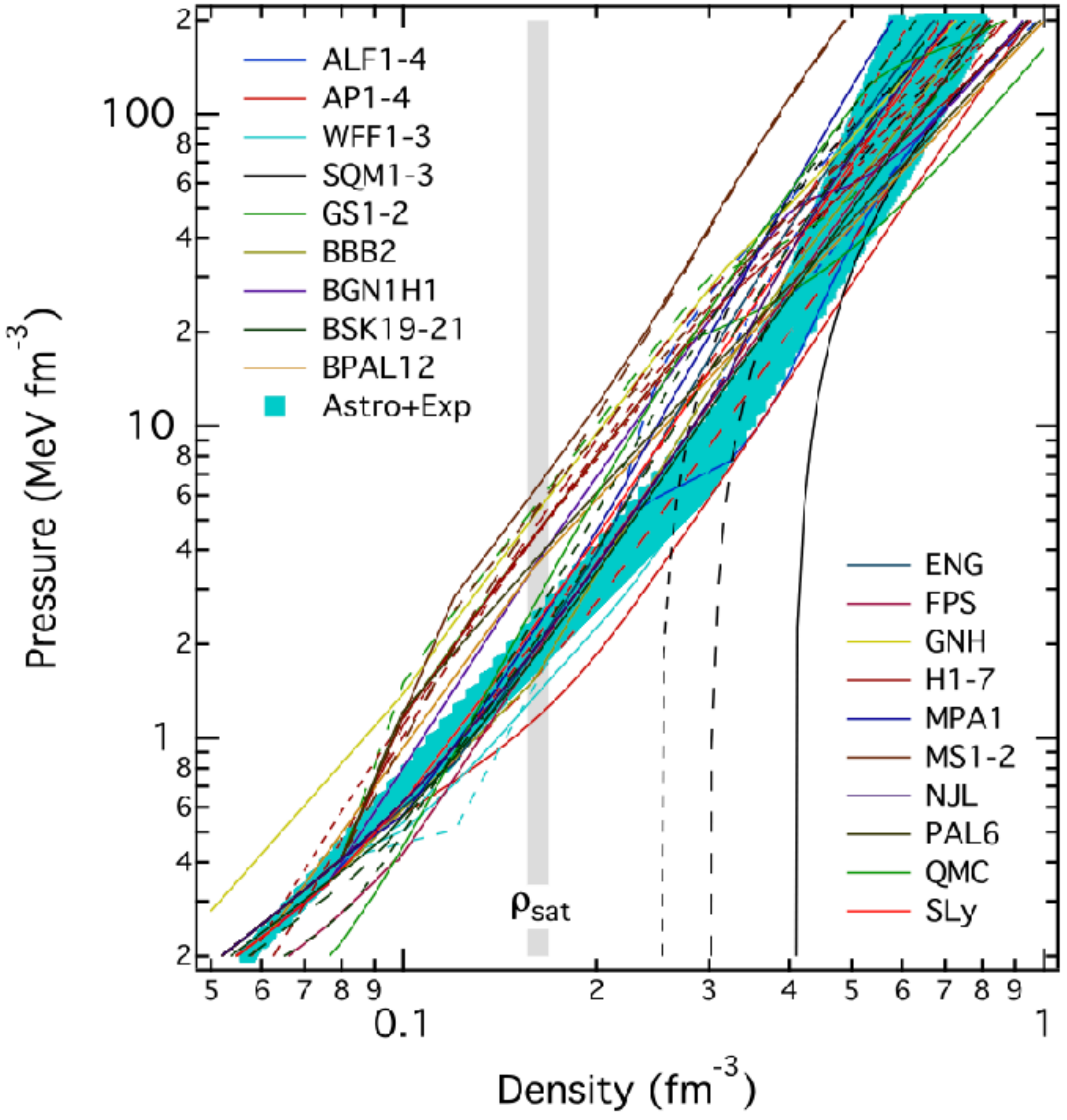
Neutron Star more realistic

$n_0 = 0.16 \text{ fm}^{-3}$

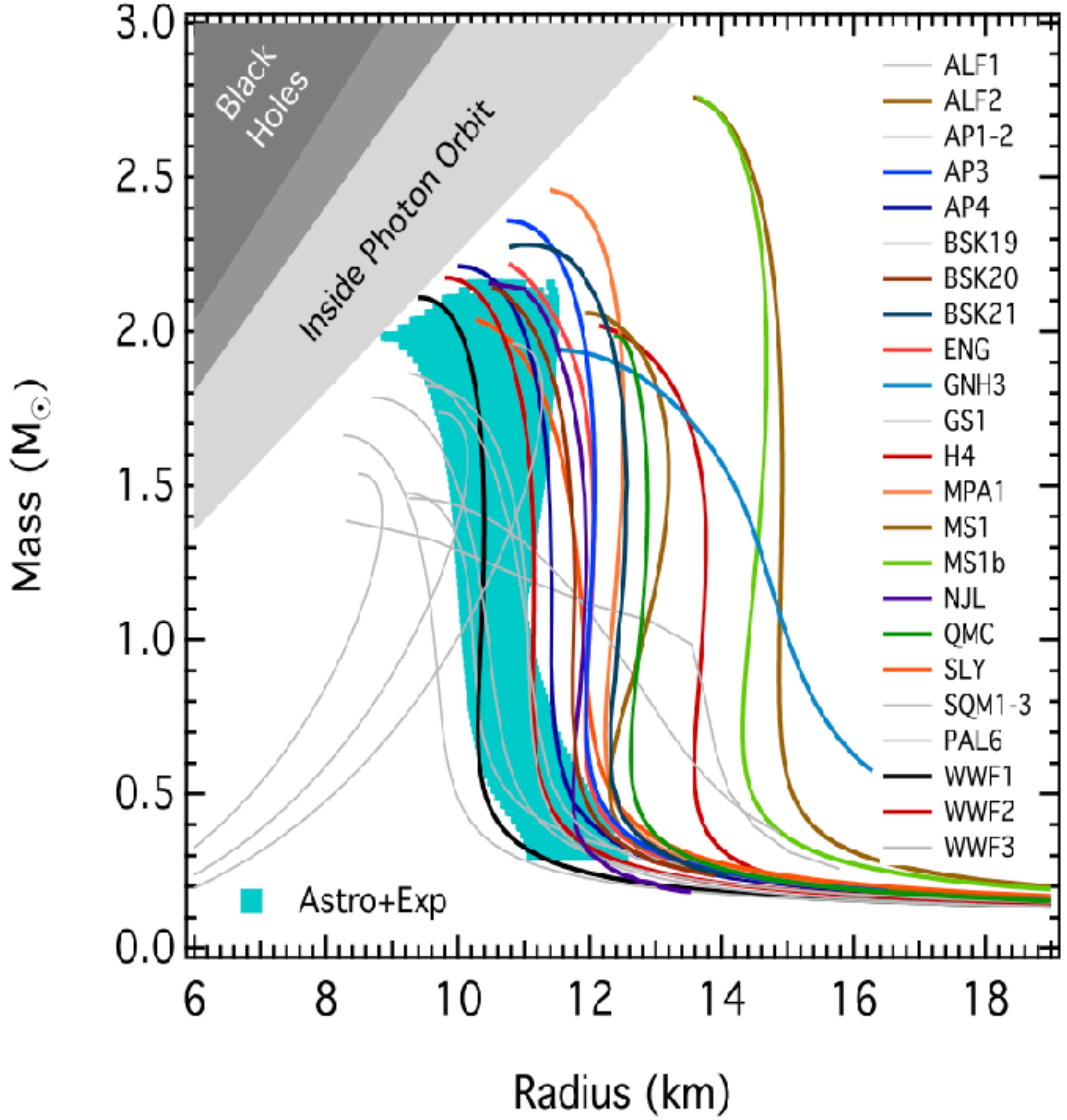


Phenomenological model: Equation of State $P = P(\rho)$

Observations can be used to constrain EoS



Feryal Ozel and Paulo Freire 2016



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Can these observations constrain any new physics?
e.g. SM matter coupled to a new light scalar?

Model: Yukawa coupled light scalar

$$g_n \phi \bar{\psi} \psi$$

Ligt scalar approximation

$$10^{-10}\text{eV} \ll m_\phi \ll 10^3\text{eV}$$

- Scalar directly contributes $P_\phi, \mathcal{E}_\phi$
- $\langle \phi \rangle \neq 0$ modifies the neutron mass

Ideal Gas + Yukawa EoS

$$\mathcal{E} = \mathcal{E}_n(\langle\phi\rangle) + V_\phi$$

$$P = P_n(\langle\phi\rangle) - V_\phi$$

$$\langle\phi\rangle = \frac{g_n}{m_\phi^2}\frac{n_n}{\langle\gamma\rangle}$$

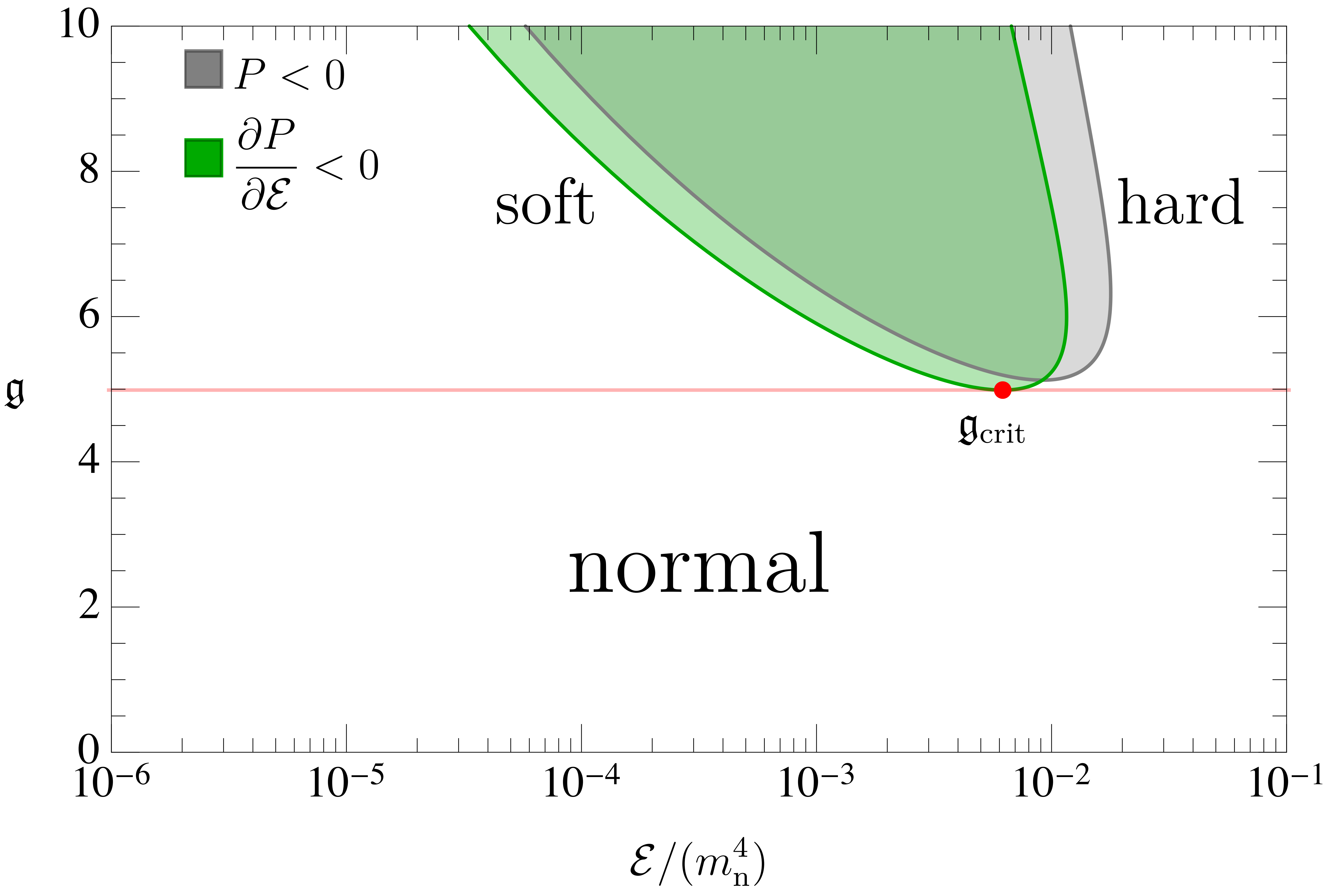
Ideal Gas + Yukawa EoS

$$\mathcal{E} = \mathcal{E}_n(\langle\phi\rangle) + V_\phi$$

$$P = P_n(\langle\phi\rangle) - V_\phi$$

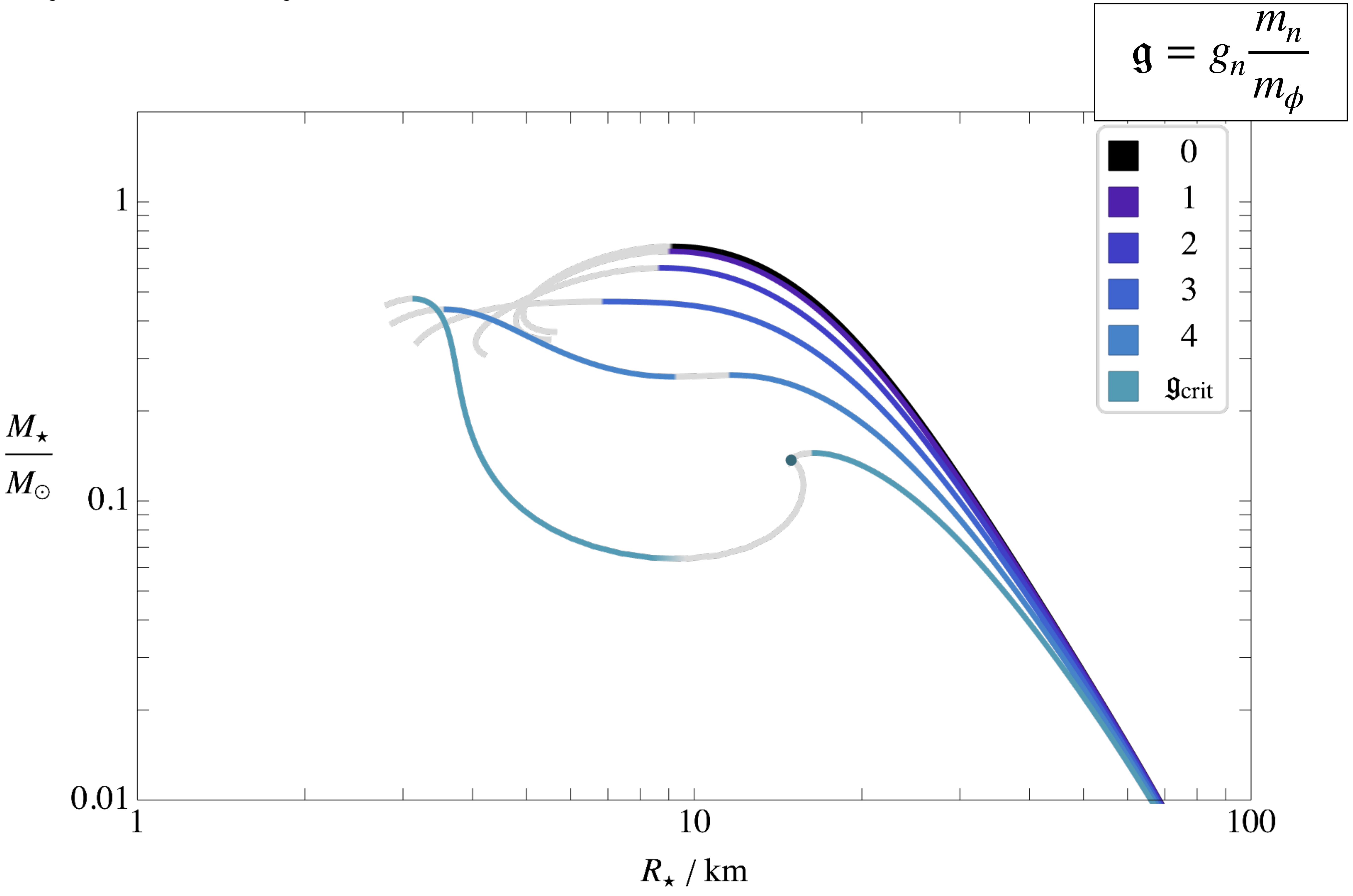
$$\langle\phi\rangle = \frac{g_n}{m_\phi^2}\frac{n_n}{\langle\gamma\rangle}$$

$$\mathfrak{g} = \frac{g_n m_n}{m_\phi} \qquad g_n \lesssim \mathfrak{g}\frac{\text{keV}}{\text{GeV}}$$



Weak coupling: normal stars

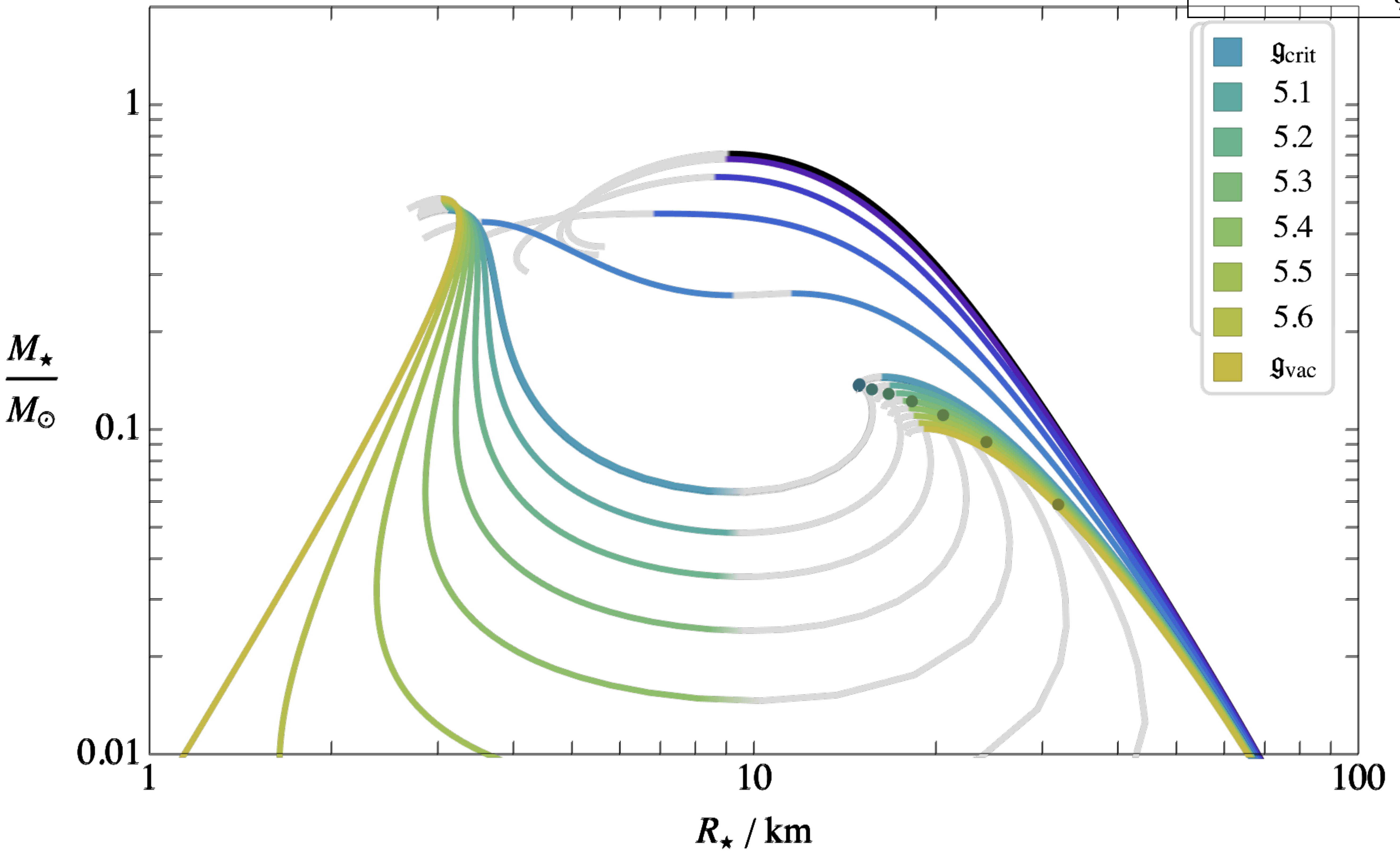
Gravitationally instability: $dM_\star / d\mathcal{E}_0 < 0$



Moderate coupling: hybrid stars

Gravitationally instability: $dM_\star/d\mathcal{E}_0 < 0$

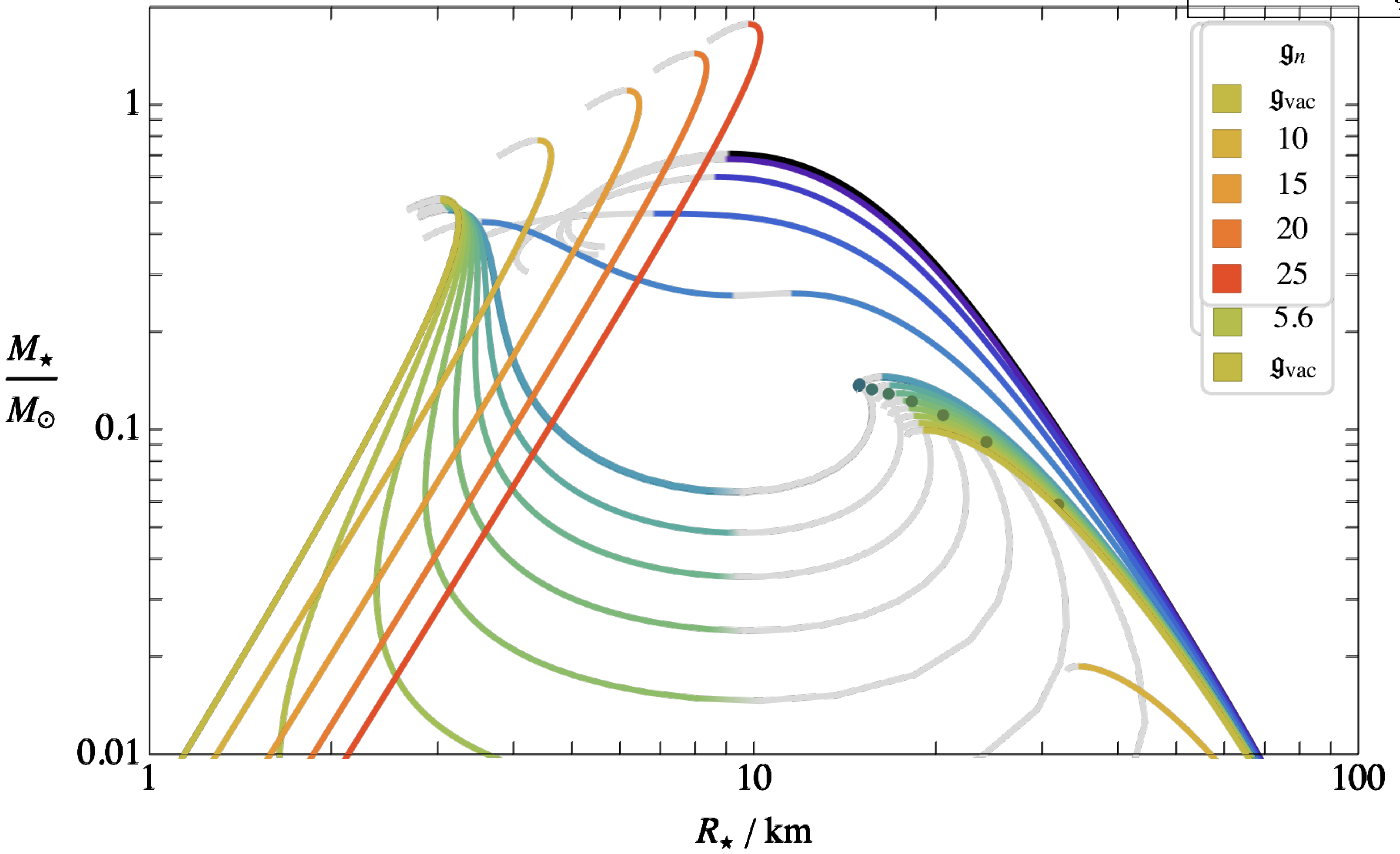
$$\mathfrak{g} = g_n \frac{m_n}{m_\phi}$$



Strong coupling: hard stars

Gravitationally instability: $dM_\star/d\mathcal{E}_0 < 0$

$$\mathfrak{g} = g_n \frac{m_n}{m_\phi}$$



Simultaneous measurement of $M_\star$ and $R_\star$ can constrain EoS.

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Easy generalization: white dwarf

Model: Yukawa coupled light scalar

$$g_e \phi \bar{e} e$$

Ligt scalar approximation

$$10^{-13}\mathrm{eV} \ll m_\phi \ll 10^3\mathrm{eV}$$

$$\mathcal{E} = \frac{n_e(\langle\phi\rangle)}{Y_e} m_u$$

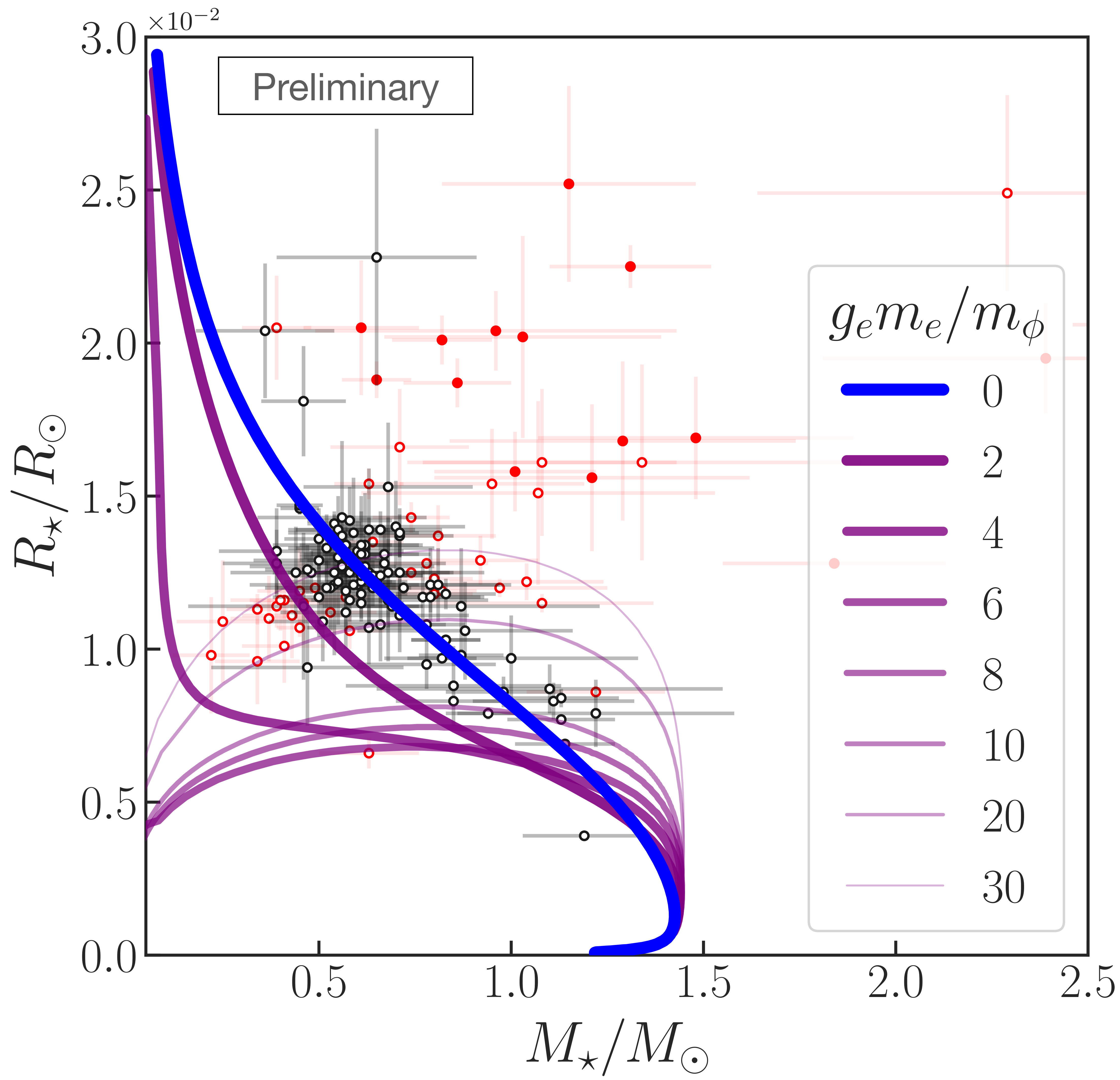
$$P = P_e(\langle\phi\rangle) - V_\phi$$

Y_e Mean number of electron per baryon
~1/2 for C/O WD

Mass vs Radius

Data from *A. B´edard, P. Bergeron, and G. Fontaine (2017)*

$$\mathfrak{g}_e = g_e m_e / m_\phi$$



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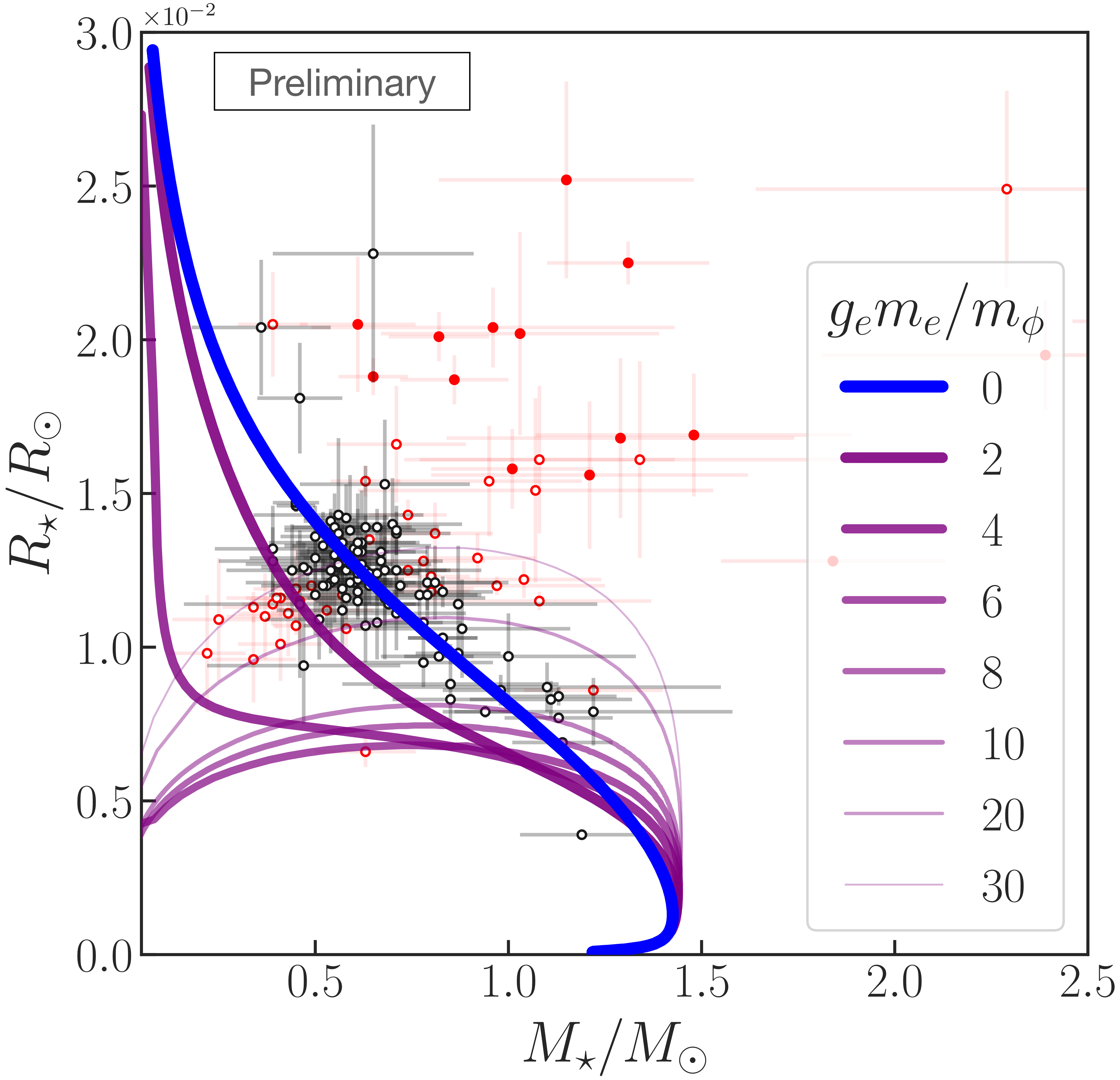
Mass vs Radius

Data from *A. B´edard, P. Bergeron, and G. Fontaine (2017)*

$$\mathfrak{g}_e = g_e m_e / m_\phi$$

on black data points

$\mathfrak{g}_e$	χ^2	p−value
0	46.7939	1
0.4	47.9185	0.999999
0.6	52.4292	0.999992
0.8	63.2406	0.999287
0.9	72.8771	0.989268
1.0	83.7809	0.917057
1.1	101.882	0.512643
1.2	120.45	0.115256
1.3	145.473	0.00374834
1.4	180.926	3.31885×10^{-6}



Constraint on electron Yukawa

$$\mathfrak{g}_e = g_e m_e / m_\phi$$

on black data points

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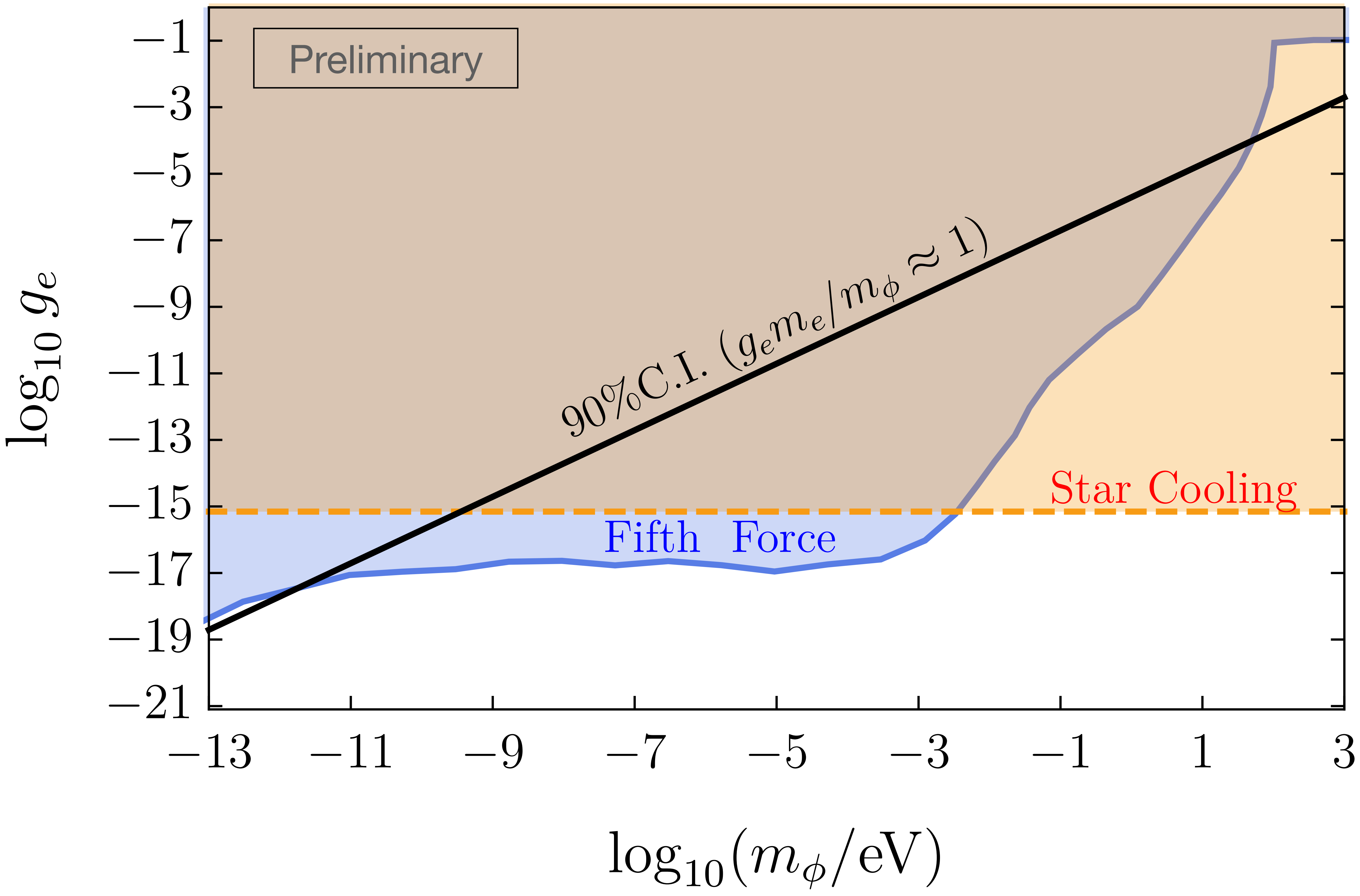

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Summary

- Yukawa coupled matter can source a scalar polarization in a finite density environment
- For a broad range of scalar mass, the scalar affects the stellar structure only through $g_f m_f / m_\phi$
- The Ideal gas +Yukawa model is not realistic for neutron stars, however, its qualitative features should hold with more realistic modeling of nuclear matter
- Simultaneous measurement of mass and radius can help constrain the new yukawa interaction.

Equation of State: Ideal Gas + Yukawa

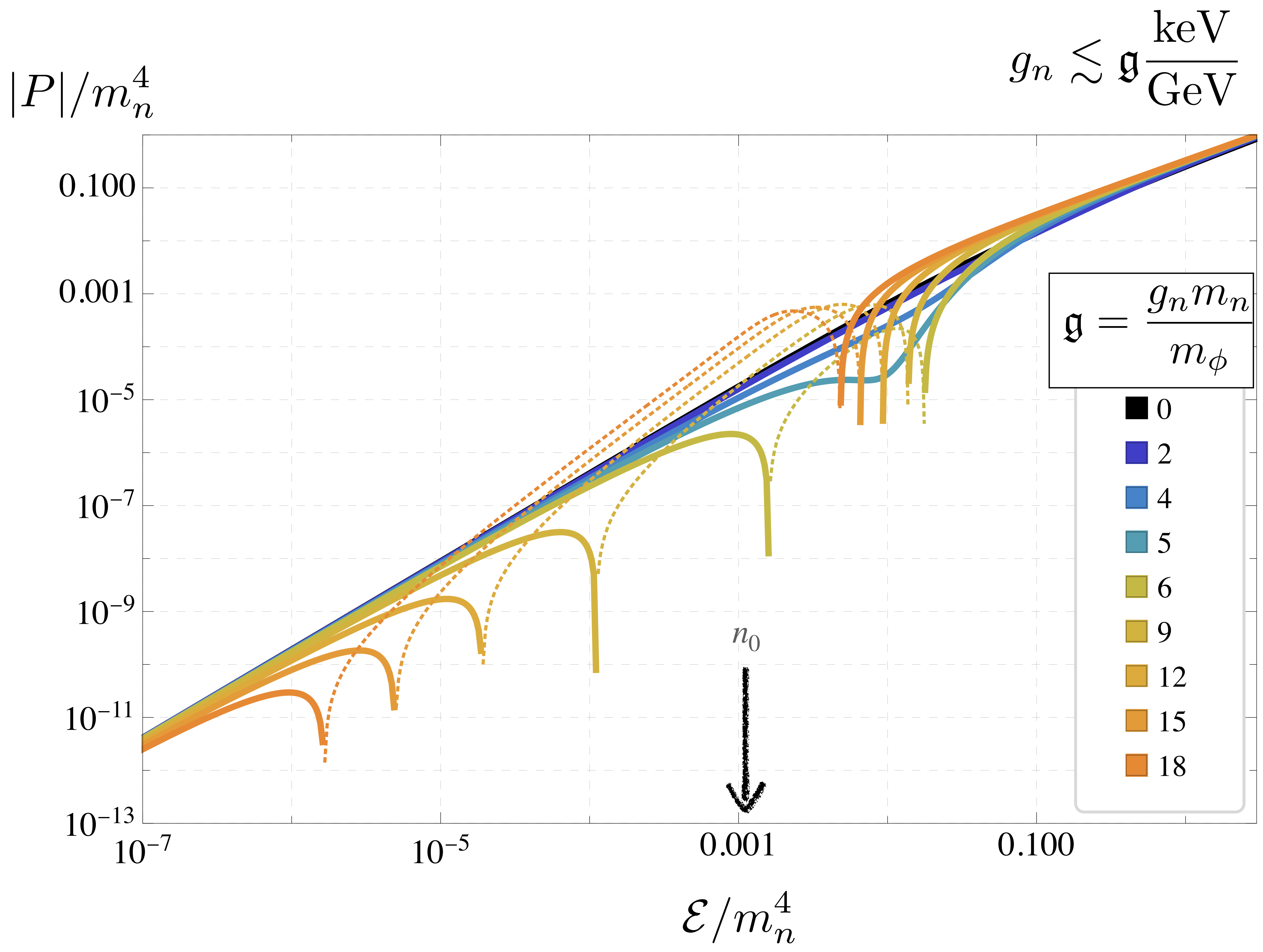
Ligt scalar approximation

$$10^{-10}\text{eV} \ll m_\phi \ll 10^3\text{eV}$$

$$\mathcal{E} = \mathcal{E}_n(\langle\phi\rangle) + V_\phi$$

$$P = P_n(\langle\phi\rangle) - V_\phi$$

$$\langle\phi\rangle = \frac{g_n}{m_\phi^2}\frac{n_n}{\langle\gamma\rangle}$$



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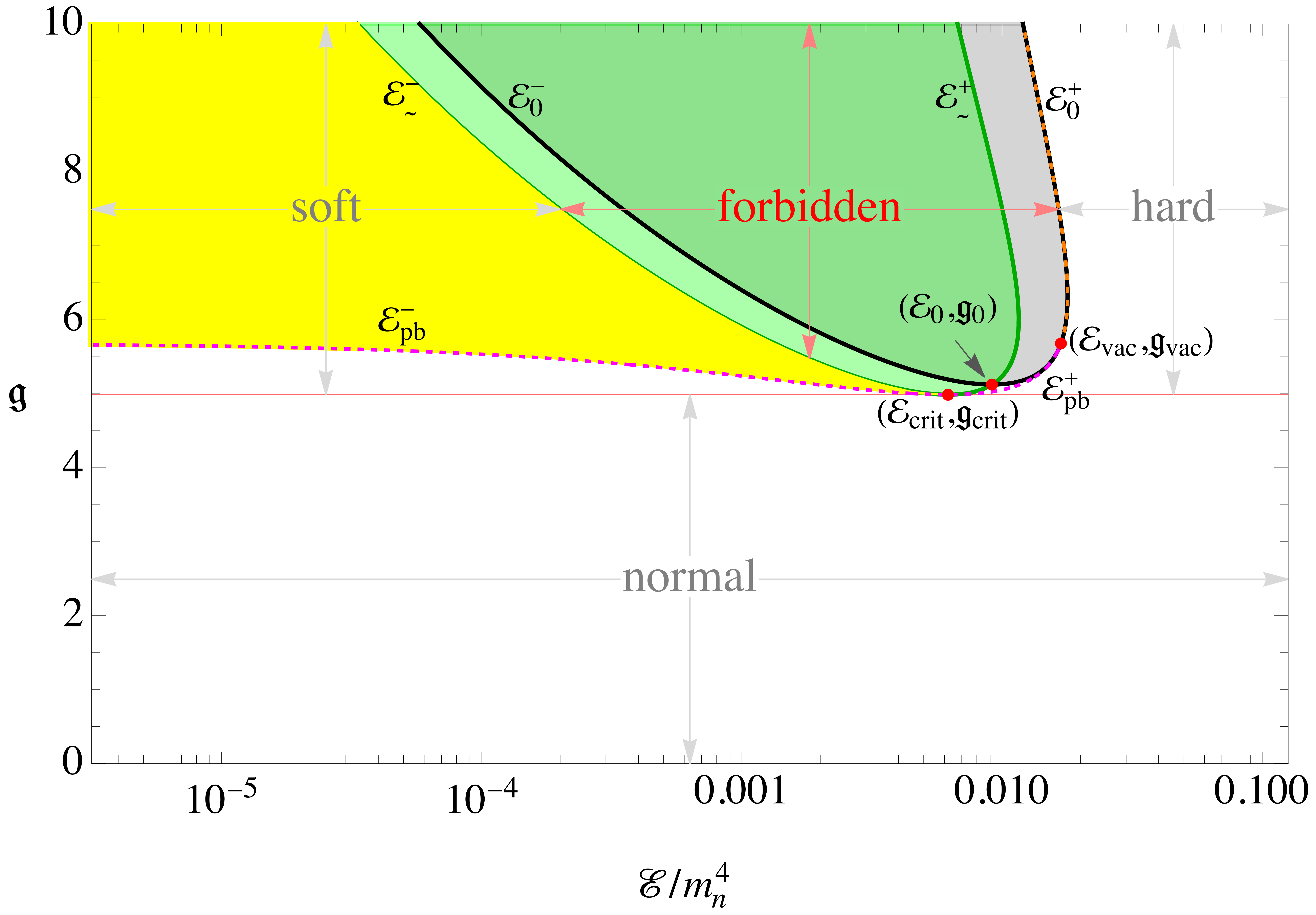
Phase diagram



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Light Scalar Approximation

- $\nabla \ln \phi \ll m_\phi$ or $\mathcal{O}(R_{NS}^{-1}) \ll m_\phi$
- Validity of mean field, $m_\phi^{-1} \ll \text{Å}$

$$10^{-10}\,\text{eV} \ll m_\phi \ll 10^3\,\text{eV}$$

$$D_\mu D^\mu \phi(r) + m_\phi^2 \phi(r) = g_n \bar{\psi}\psi$$

$$\langle \bar{\psi}\psi \rangle \xrightarrow{\textit{Ideal gas}} \tilde{n} \equiv \frac{n_n}{\langle \gamma \rangle}$$

$$\tilde{\phi}_{LSA} = g_n \frac{\tilde{n}}{m_\phi^2} \longrightarrow \mathcal{E}_\phi = -P_\phi = V(\tilde{\phi})$$

Like dark energy!

Stellar Structure: Tolman-Oppenheimer-Volkoff equation

$$G^{\mu}{}_{\nu} = 8\pi G T^{\mu}{}_{\nu}$$

Static solution + rotational symmetry + perfect fluid (isotropic P)

$$M'(r) = 4\pi\, r^2\, \mathcal{E}(r) \qquad \frac{P'(r)}{\mathcal{E}(r) + P(r)} = -\frac{G\,(M(r) + 4\,\pi\, r^3\, P(r))}{r^2\,\left(1 - \frac{2\,G\,M(r)}{r}\right)}$$

$M(r)$ = gravitational mass

$P(r)$ = pressure density

$\mathscr{E}(r)$ = energy density

- Need supply equation of state $P(\mathscr{E})$
- Surface of a star: $P(R_\star) = 0$
- Mass of a star: $M_\star = M(r \to \infty)$
- New physics can change $P(\mathscr{E})$, thus changing $(M_\star, R_\star)$

Stellar Structure

Static solution + rotational symmetry

$$G^{\mu}{}_{\nu} = 8\pi G T^{\mu}{}_{\nu}$$

spherical polar coordinates $\{t, r, \theta, \phi\}$

$$g_{\mu\nu} = \text{diag}\left(e^{2\Phi(r)}, \frac{-1}{1 - \frac{2GM(r)}{r}}, -r^2, -r^2 \sin^2\theta\right)$$

$\Phi(r)$ = gravitational potential

$M(r)$ = gravitational mass

- Perfect fluid:

  $T^{0}{}_{0} = \mathscr{E}(r)$ energy density

  $T^{i}{}_{i} = -P(r)$ pressure

- Equation of State (EoS): $P(\mathscr{E})$

ϕ sector

$$\tilde{\phi}^{;\mu}{}_{\mu} = -V'(\tilde{\phi}) + \tilde{g}\,\tilde{n} \qquad T^{\phi}_{\mu\nu} = \tilde{\phi}_{;\mu}\,\tilde{\phi}_{;\nu} + g_{\mu\nu}\left(V(\tilde{\phi}) - \frac{\tilde{\phi}^{;\xi}\,\tilde{\phi}_{;\xi}}{2}\right)$$

$$\tilde{\phi}''(r) = \frac{1}{2}\,\frac{\partial \ln \frac{e^{-2\Phi(r)}}{r^4\left(1-\frac{2\,G\,M(r)}{r}\right)}}{\partial r}\,\tilde{\phi}'(r) + \frac{V'(\tilde{\phi}(r)) - \tilde{g}\,\tilde{n}(r)}{1-\frac{2\,G\,M(r)}{r}}$$

$$\mathcal{E}_{\tilde{\phi}}(r) = +\frac{1-\frac{2\,G\,M(r)}{r}}{2}\,\tilde{\phi}'(r)^2 + V(\tilde{\phi}(r))$$

$$P_{\tilde{\phi}}(r) = -\frac{1-\frac{2\,G\,M(r)}{r}}{6}\,\tilde{\phi}'(r)^2 - V(\tilde{\phi}(r))$$

$$P^{\tilde{\phi}}_{\parallel}(r) - P^{\tilde{\phi}}_{\perp}(r) = \left(1-\frac{2\,G\,M(r)}{r}\right)\tilde{\phi}'(r)^2$$