Compact stars: from nuclear matter to exotic phases

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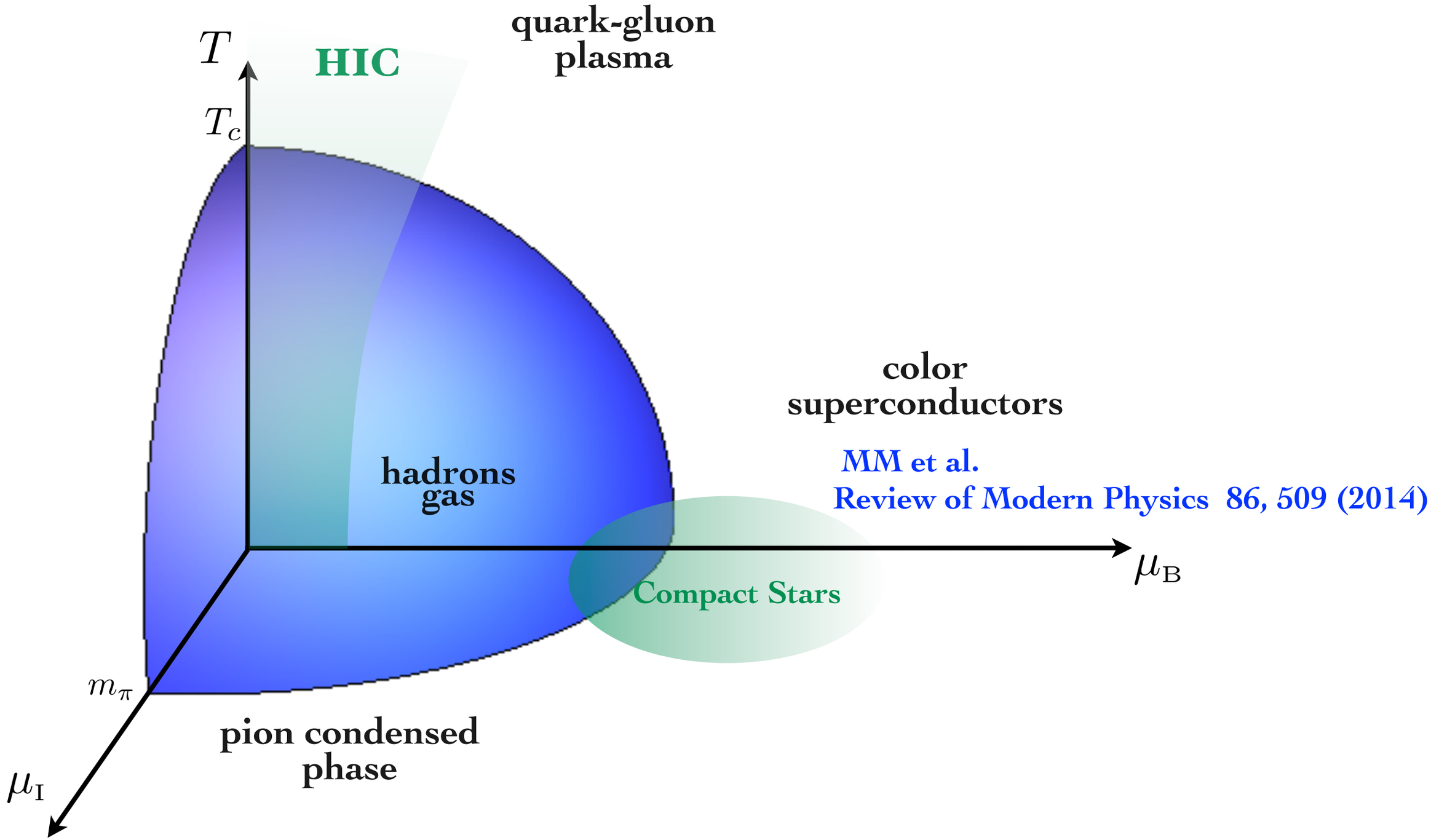
GSSI, 21 Feb 2020

Matter in extreme conditions

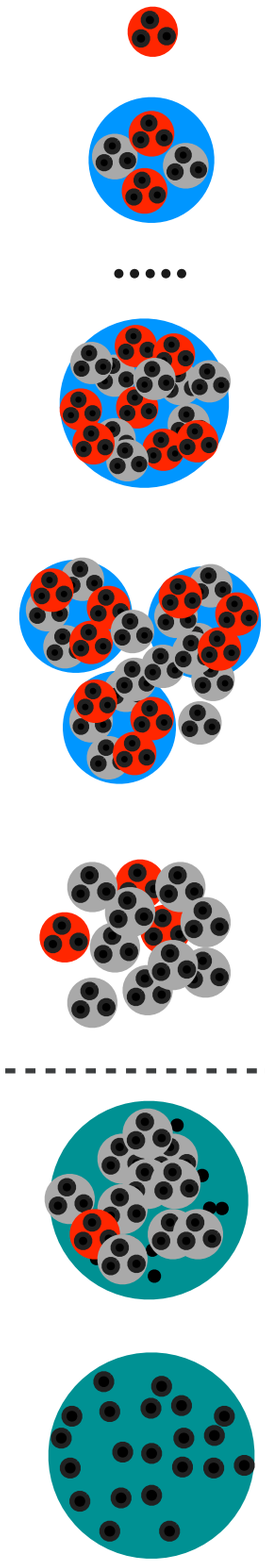
Phases of Matter



MM et al.
Review of Modern Physics 86, 509 (2014)

MM, Particles 2 (2019) no.3, 411

Increasing baryonic density



Density	Compact Star	$\alpha_s \equiv \alpha_s(\mu)$	Degrees of freedom
.....	atmosphere		light nuclei
			.....
$10\ \mathrm{g\ cm^{-3}}$	outer crust	confining	heavy nuclei
$10^{11}\ \mathrm{g\ cm^{-3}}$	inner crust		
$10^{14}\ \mathrm{g\ cm^{-3}}$			neutrons and protons
	core		
very large		strong coupling	quarks and gluons Cooper pairs of quarks?
extreme		weak coupling	Cooper pairs of quarks NGBs

Taxonomy of compact stars

Neutron star

$R \sim 10$ km $\;\; M = 1 - 2\, M_\odot$

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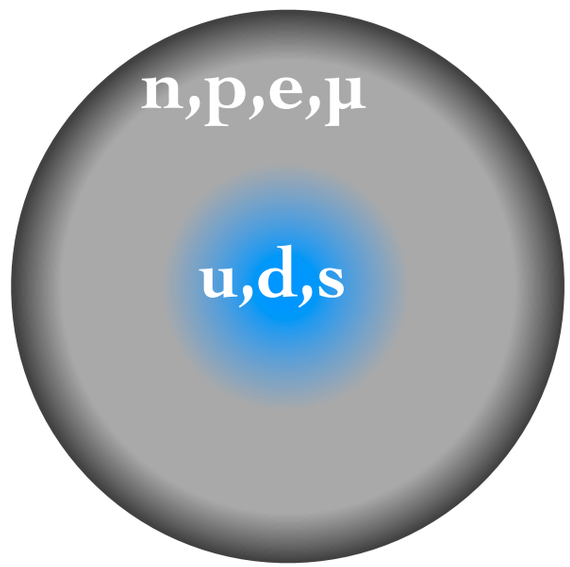
Hybrid star



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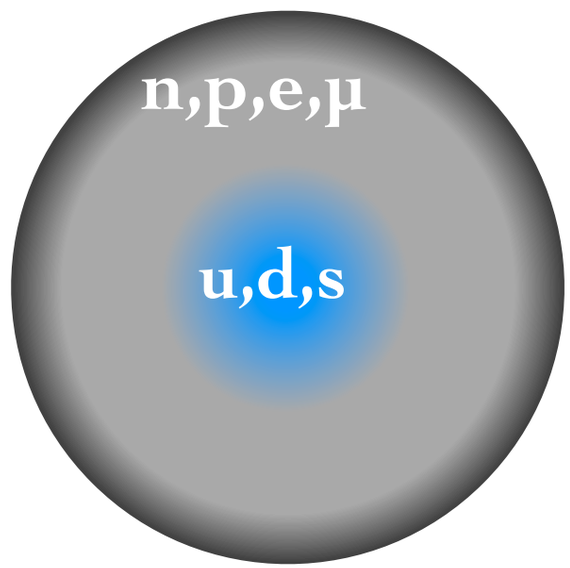

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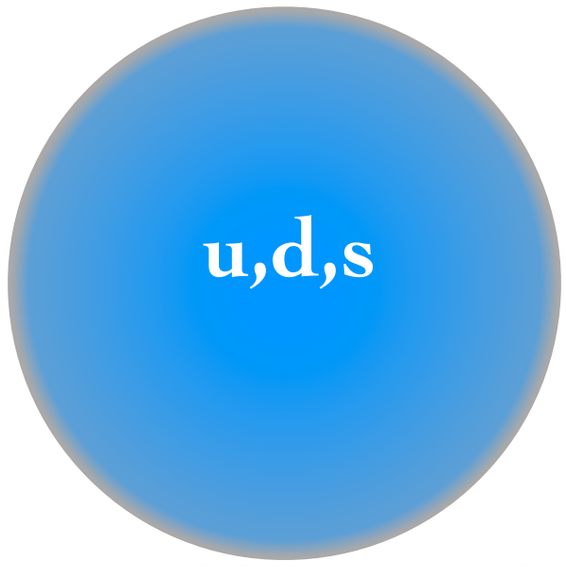
Strange star



$R \sim 0 - 10$ km $\;\; M < 3\, M_\odot$

more options...

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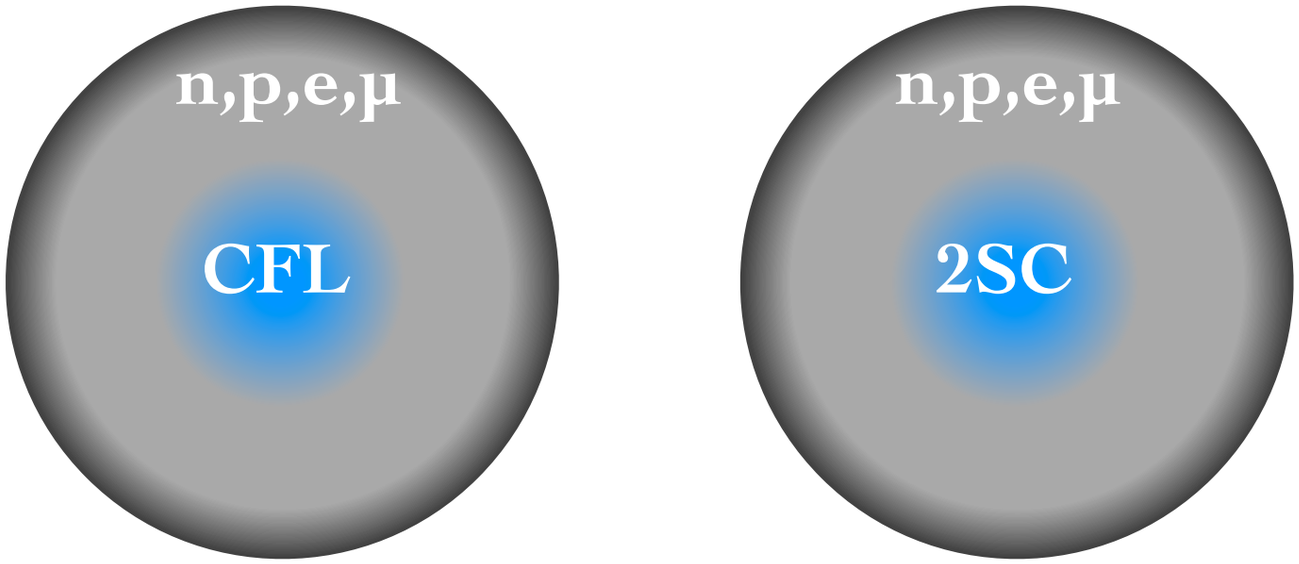

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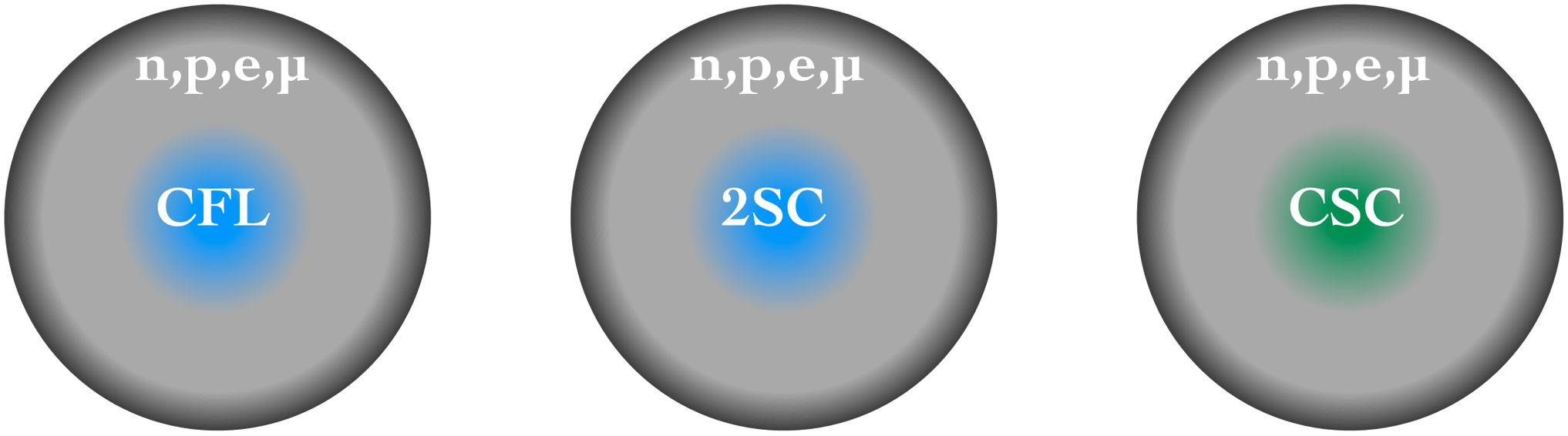

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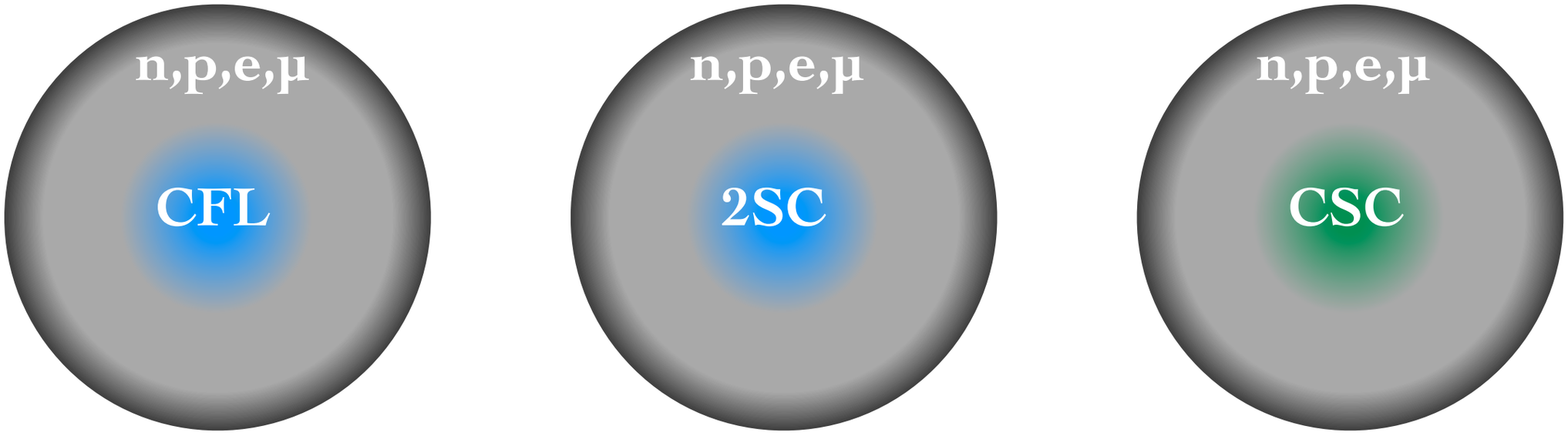
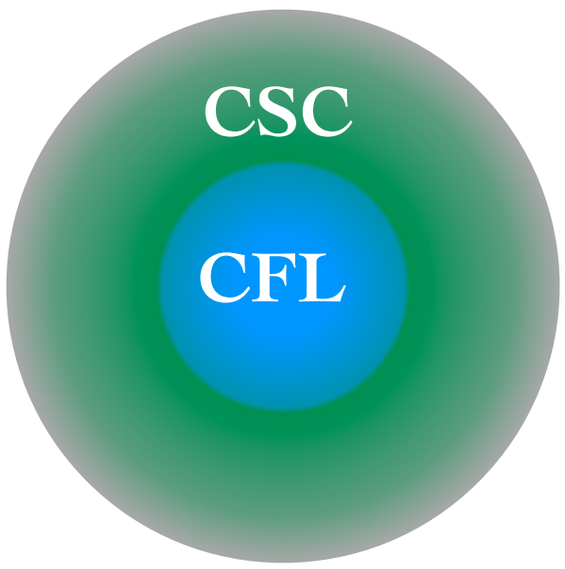
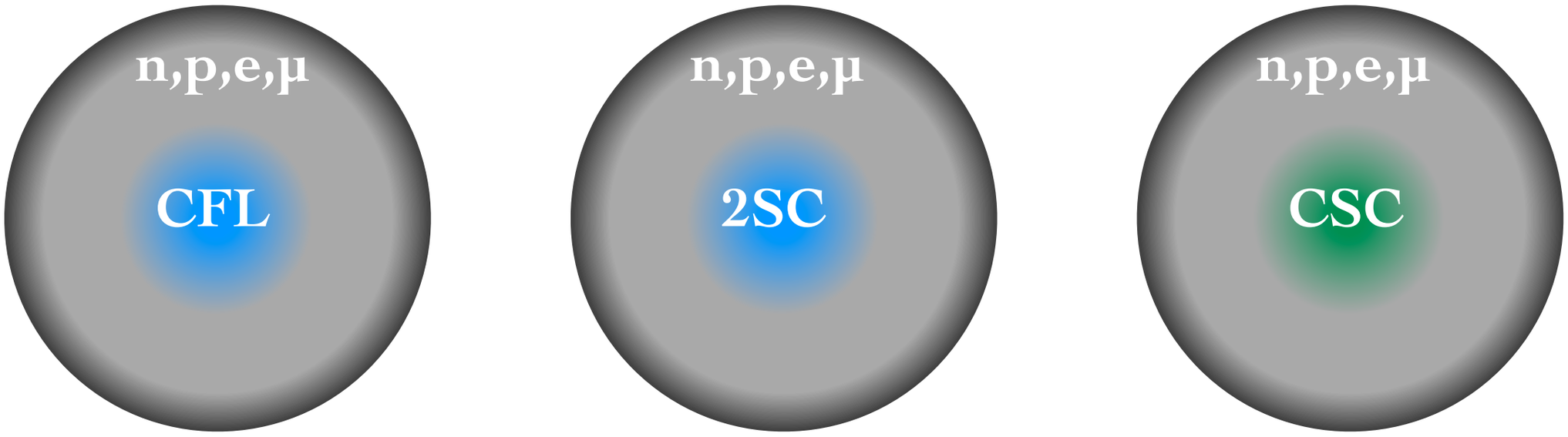
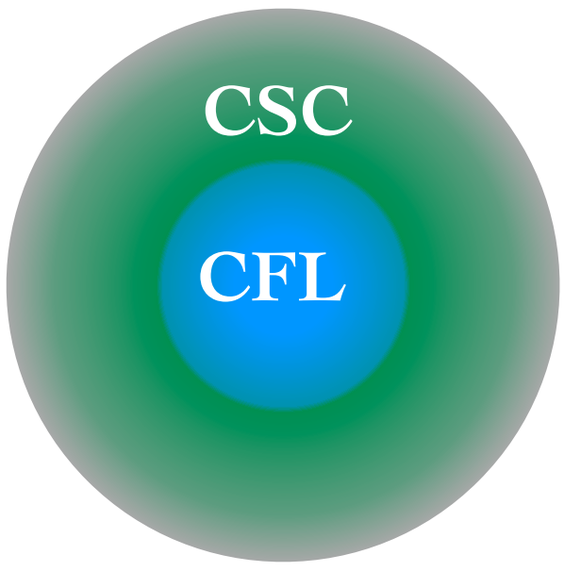




Compact Star with two crusts

more options...





Compact Star with two crusts

Problems:

1. There are many possibilities

2. The transition densities are not strongly constrained

And even more...

Stars with a core of condensed pions

Phys.Rev. D92 (2015) no.8, 085025, Phys.Rev. D93 (2016) no.5, 051503
Eur.Phys.J. A53 (2017) no.2, 35, Eur.Phys.J. C78 (2018) no.6, 441
with Carignano, Lepori, Mammarella, Pagliaroli.

1. Pions are bosons
2. Can be produced at low temperature
3. $\pi^{\pm}$ has a lifetime of about 10^{-8} s

The process $\pi_+ \to \ell^+ \nu_\ell$ is Pauli blocked if $\mu_\ell > m_\pi$ and the pion becomes stable

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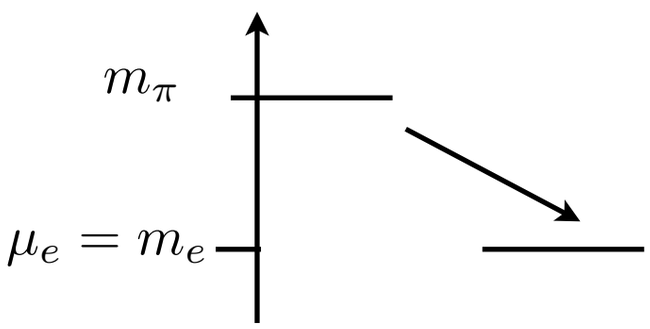

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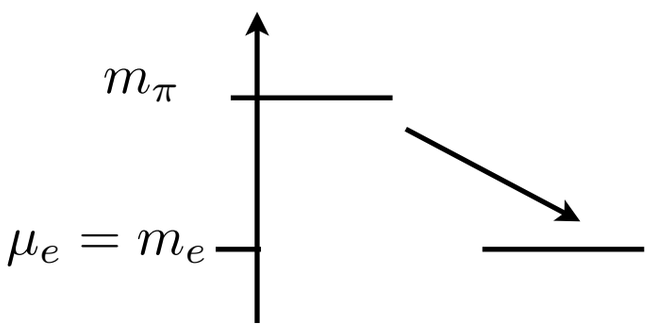

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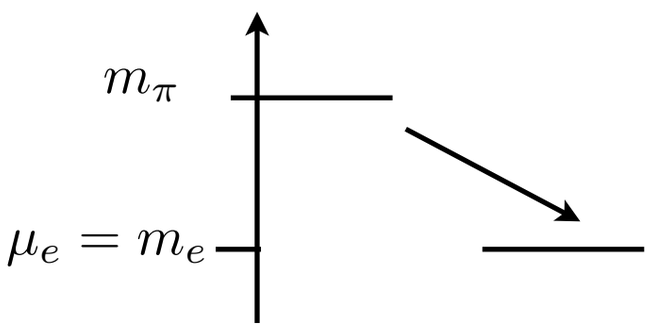

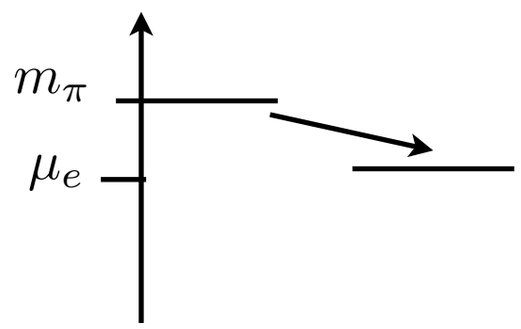

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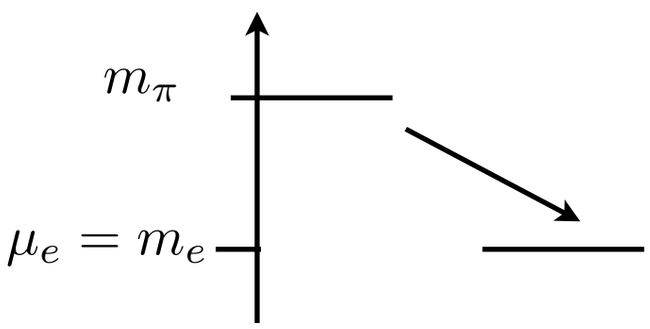

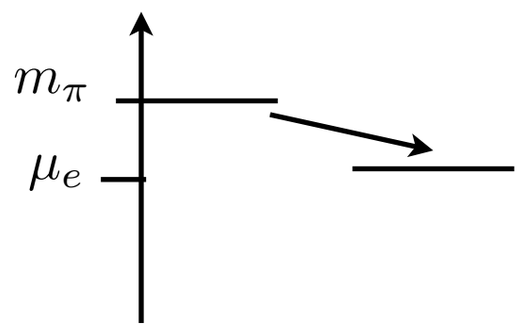

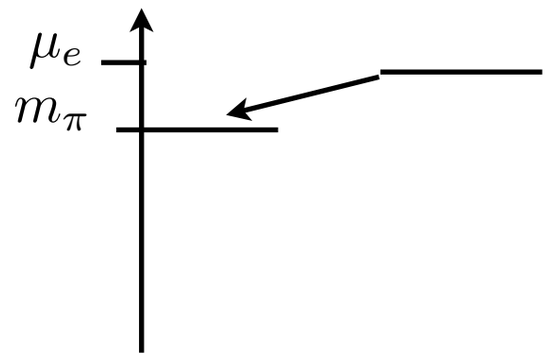

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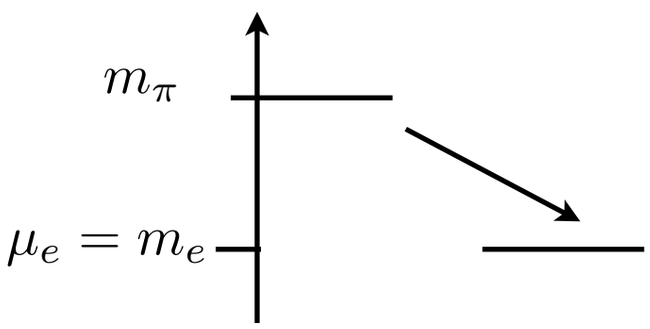
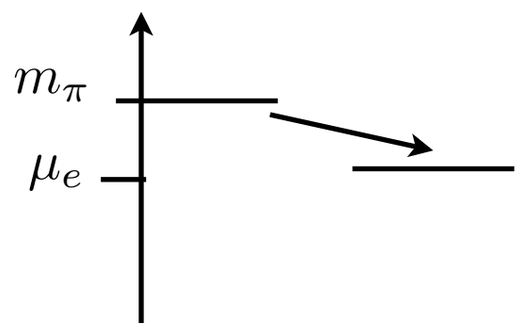
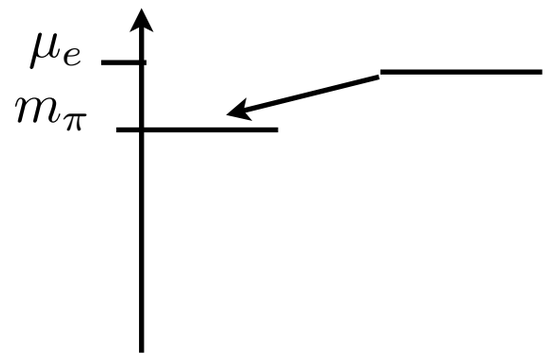






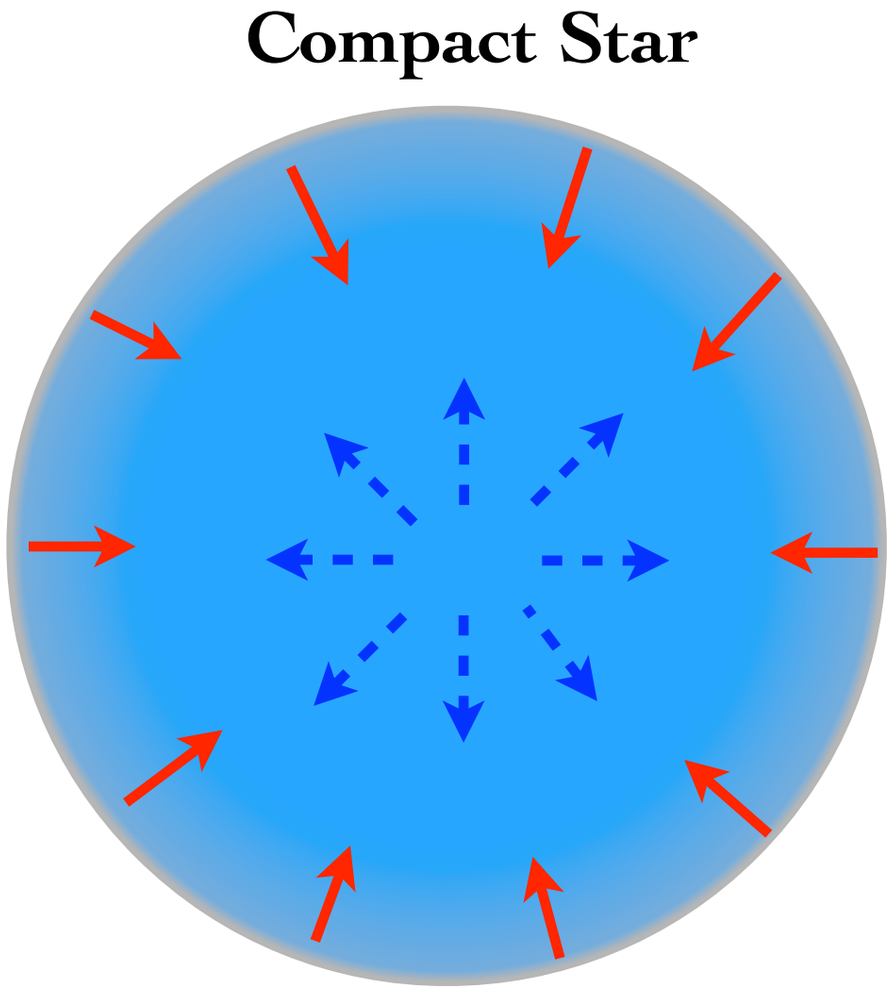
What for?

Nuclear matter in compact stars

Understanding QCD
In a regime in which different methods overlap

Hydrostatic equilibrium

Balance of forces



Fermi pressure
(+interactions)

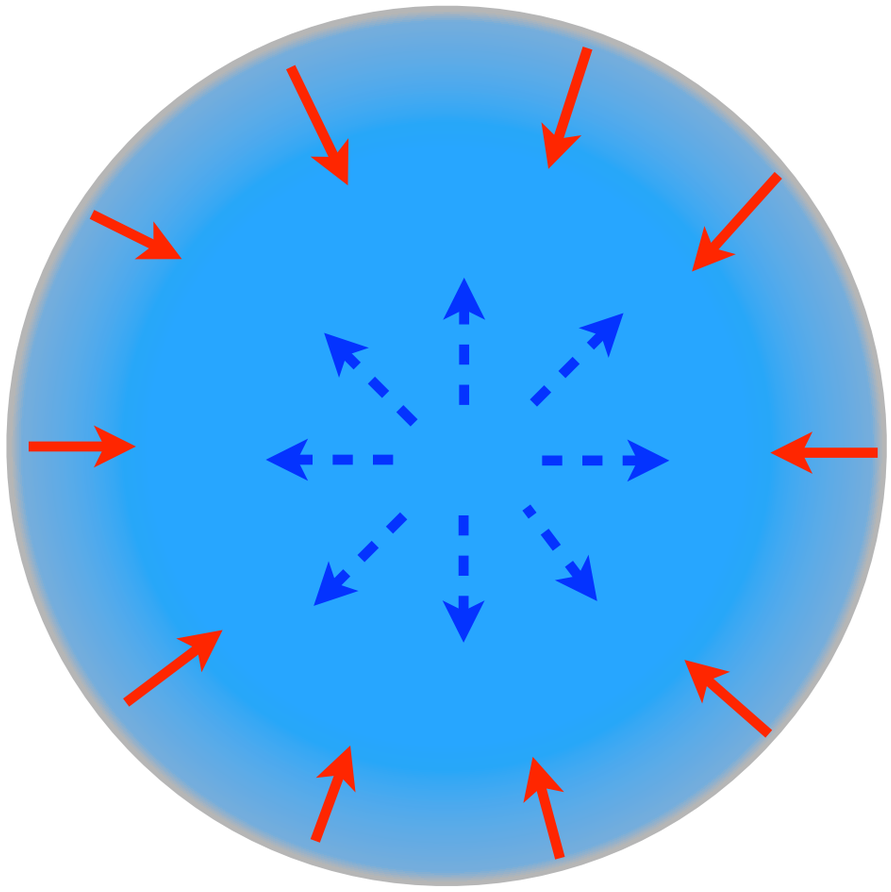
Gravity
(+interactions)

$$M \sim 1.4 M_\odot$$

$$R \sim 10\text{km}$$

Balance of forces

Compact Star



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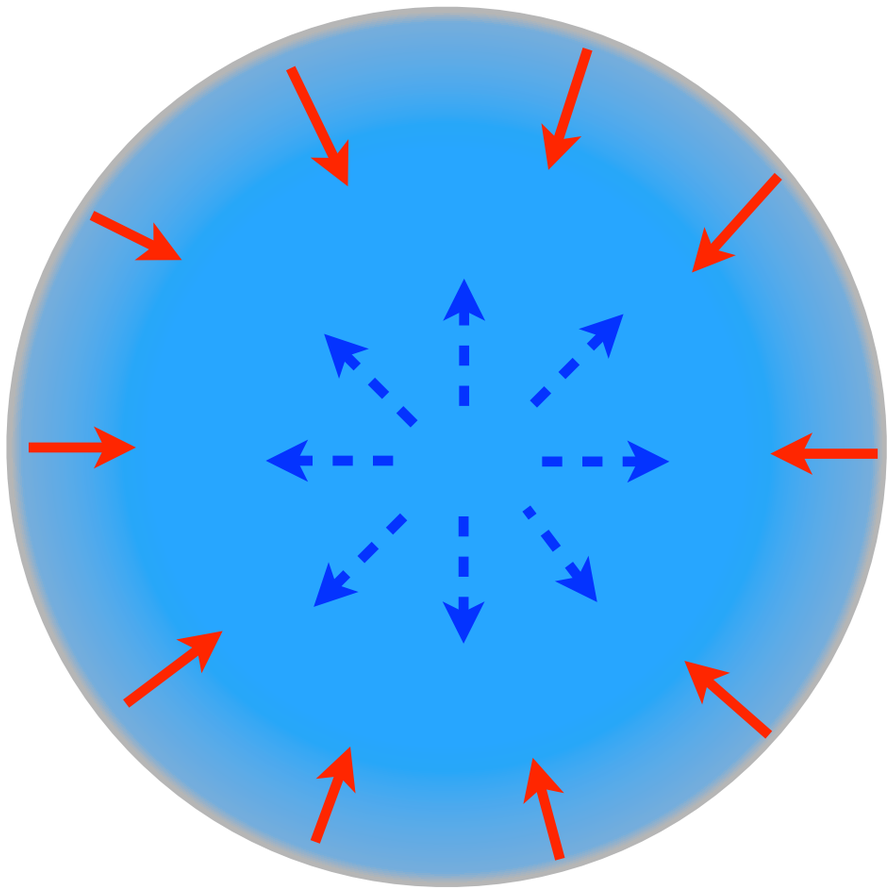

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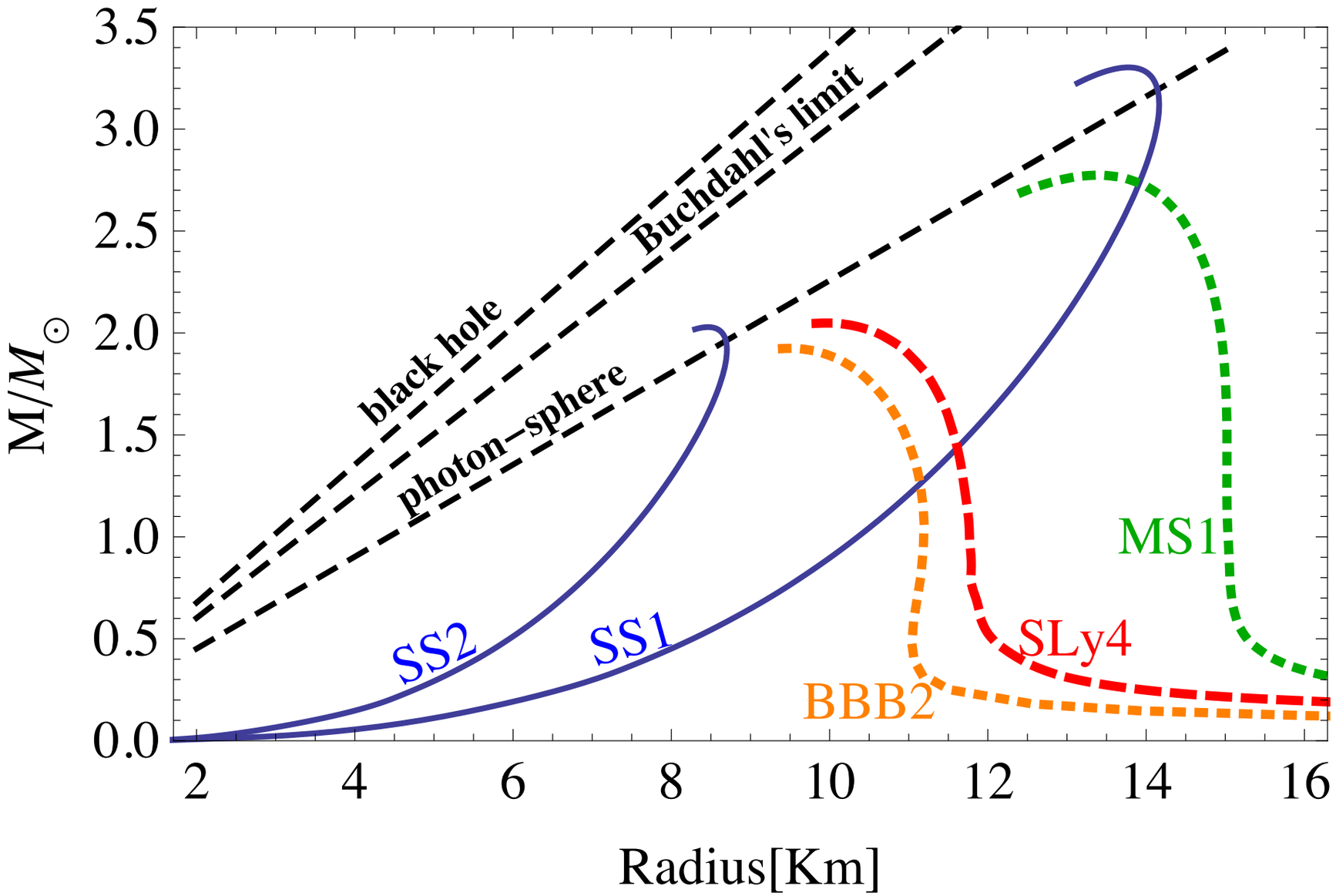
Configuration depends on the Equation of state (EoS) $p \equiv p(\rho, T)$
In compact stars the temperature is typically negligible

Discriminating the stars by mass and radius?

- **Precise simultaneous mass and radius measurements are difficult**
- **The masses are known only in binary systems**
- **The radii are indirectly estimated**



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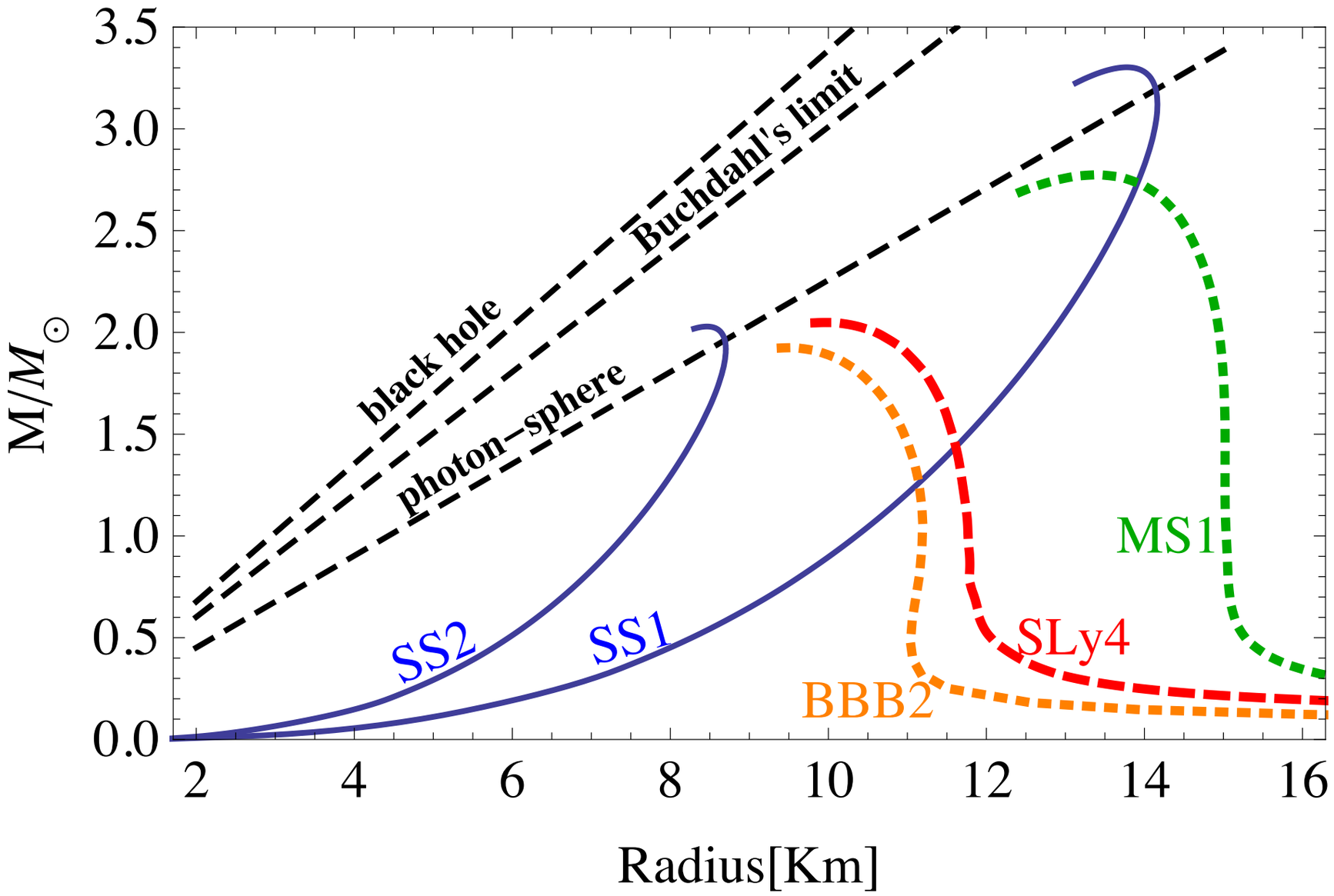

Better look at a different observable...

Radial Oscillations

F. Di Clemente, MM and F. Tonelli

Test the stellar stability

Linearly perturb the metric $g_{\mu\nu} = \mathrm{diag}(e^{2\phi}, -e^{2\lambda}, -r^2, -r^2\sin^2\theta)$

and the thermodynamic quantities p, ρ

with $\delta r = X(r)e^{i\omega t}$

define $\xi = Xr^2e^{-\phi}$

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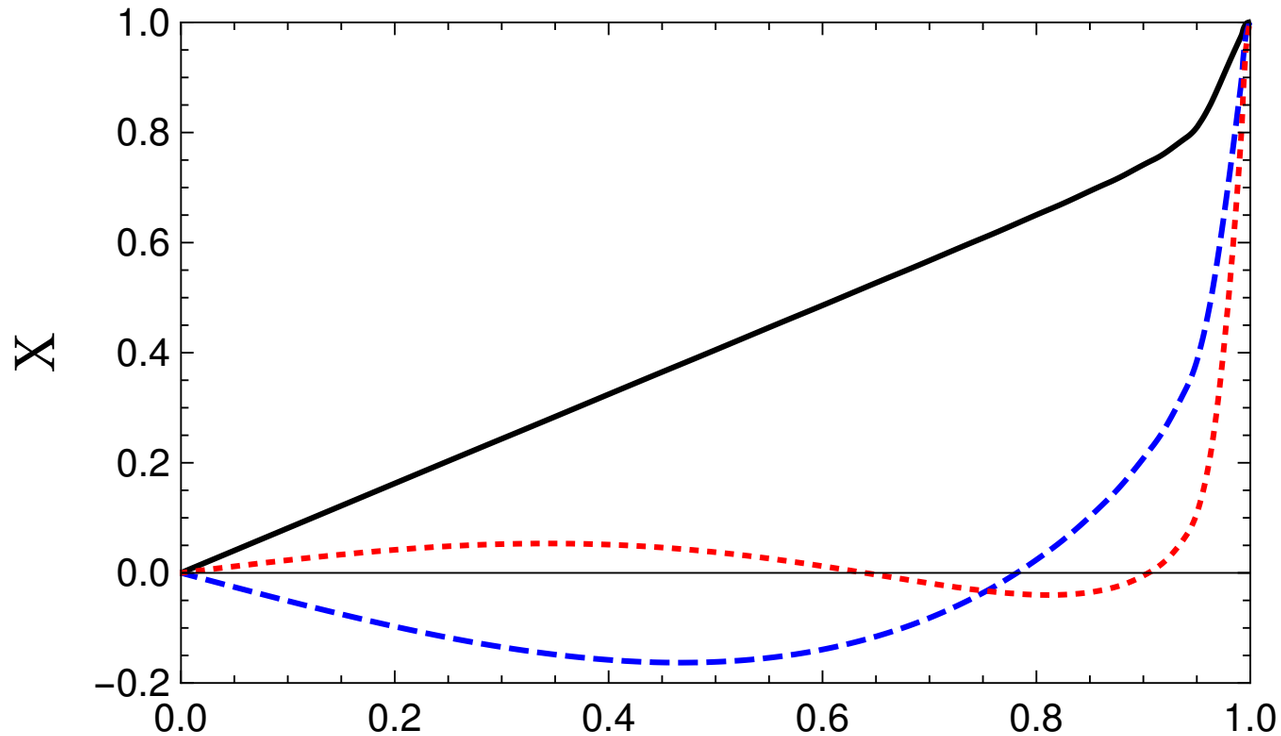
by discretization we have an eigenvalue problem

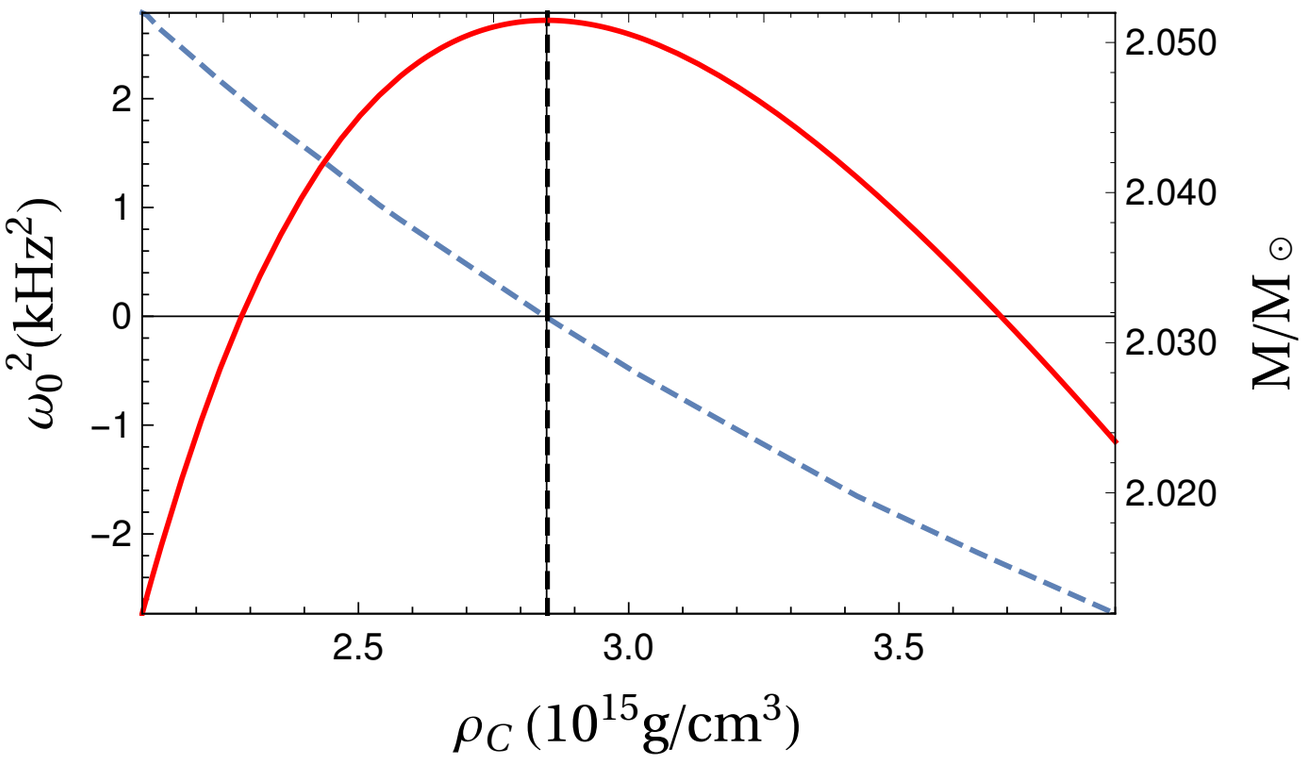
$$\omega^2 \boldsymbol{\xi} = A\boldsymbol{\xi}$$

where $\boldsymbol{\xi}^t = (\xi_1, ..., \xi_N)$

Numerical results

Radial displacement





Null mode at the maximum stellar mass

Conclusions

- **Compact stars are valuable probes of hadronic matter**

- **Equilibrium configurations, when pressure counteracts the gravitational pull**

- **We have a precise algorithm for the radial oscillation of compact stars. Look for a behavior that discriminates standard neutron stars from exotic ones.**

Thanks for your attention!