Mirror Neutron Stars

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Huge discovery potential for new physics:

- Early-universe phase transitions, including dark phase transitions,

- Dark compact objects, for instance boson stars, black holes formed from dark matter....

- ...and Mirror / Dark Neutron Stars, formed of Mirror Matter.
Motivation — Why Mirror Sectors?

Hierarchy Problem:
- Why the hierarchy between the electroweak scale and the scale of gravity?
- In other words, why is the Higgs boson so light?

Conventional solutions predict new states charged under QCD, with masses around a TeV... ...experimental tension!

Alternative: Neutral Naturalness
Family of models in which new physics is charged under a copy of SM gauge groups — dark QCD.

Hidden sector related to SM via discrete symmetry: Mirror Sector.
Mirror Twin Higgs model

- Concrete example of a Mirror Sector model.
- Leads to predictions for the masses of fundamental parameters and the dark QCD confinement scale.
- Useful benchmark model which describes a “slice” of the dark QCD parameter space.

\[ \Lambda'_{QCD} \approx \Lambda_{QCD} (0.65 + 0.41 \log(1.32 + v'/v)) \]
Dark Complexity in the MTH

Mirror models could give rise to phenomena as varied as those in the visible sector...
Modelling Neutron Star structure

Derive full Equation of State: $P(\rho), \epsilon(\rho)$; solve Tolman-Oppenheimer-Volkoff equation:

$$\frac{dP}{dr} = -\frac{Gm}{r^2} \rho \left(1 + \frac{P}{\rho c^2}\right) \left(1 + \frac{4\pi r^3 P}{mc^2}\right) \left(1 - \frac{2Gm}{rc^2}\right)^{-1}$$

Leads to a family of neutron star solutions as a function of their central pressure.

Crust model [following Baym, Pethick, Sutherland, 1971]: Find preferred nuclear species at a given density by minimizing total energy.

Interpolate between neutron drip line and saturation density.
Modelling Neutron Star structure — Core

Relativistic, mean-field, nucleon-meson model:

\[ \mathcal{L} = \bar{\psi} \left[ i \gamma_\mu \partial^\mu - M_0 + \gamma^0 \mu_B - g_\omega \omega^\mu \gamma_\mu - g_\sigma (\sigma + i \gamma_5 \vec{\pi} \cdot \vec{\pi}) \right] \psi + \]

\[ + \frac{1}{2} (\partial_\mu \sigma \partial^\mu \sigma + \partial_\mu \vec{\pi} \cdot \partial^\mu \vec{\pi}) - \frac{1}{4} \omega^\mu{}^\nu \omega_\mu{}^\nu + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \mathcal{U}(\sigma, \vec{\pi}) \]

[Glendenning, 1988]

Extra ingredients:

- Isospin chemical potential for asymmetric nuclear matter,
- Electrons and muons to enforce charge neutrality,
- Rho meson interactions.

\[ \omega_\mu{}^\nu \rightarrow \text{Vector repulsion} \]
\[ \sigma \rightarrow \text{Scalar attraction} \]
Scaling with quark mass

Both core and crust models generalize straightforwardly to *exotic dark QCD sectors!*

Higher confinement scale leads to **rescaling** of resonance masses and couplings:

\[ m_i^2 = \Lambda_{QCD}^2 \left( a_0 + a_1 \left( \frac{m_\pi}{\Lambda_{QCD}} \right)^2 + \ldots \right) \]

\[ m_\pi \sim \sqrt{m_{u,d}} \Lambda_{QCD} \]

...can extract coefficients from lattice data.

Most significant effect comes from rescaling of \( \Lambda_{QCD} \).

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[for instance from:]

Jung, RBC and UKQCD collaborations, arXiv:1301.539;

Horsley, Nakamura, Nobile, Rakow, Schierholz and Zanotti, arXiv:1302.2233;

Albaladejo and Oller, arXiv:1205.6606.]
Scaling with quark mass

Equation of state:

To a reasonable approximation, both the pressure and energy density scale with $(\Lambda_{QCD}')^4$.
Mirror neutron star properties

![Graph showing mirror neutron star properties with various parameters and data points.](image-url)
Universal behaviour

Universal I-Love-Q relations are satisfied for Mirror Neutron Stars:
Diagnosing a mirror neutron star merger!

Smoking gun indicators of a mirror neutron star merger:

- Combined small mass, small radius.
- Small tidal deformability, small mass.

Nonzero tidal deformability: not a primordial black hole!

No electromagnetic signatures!
Conclusions

● Dark compact objects are generic predictions of Beyond Standard Model physics.

● Gravitational wave astronomy has outstanding discovering potential for exotic new physics!

● Lattice QCD helps predict scaling behaviour for Mirror QCD.

● Smoking gun indicators of new physics from combined mass / radius / tidal deformability measurements.