# Mirror Neutron Stars

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# Gravitational Wave Astronomy

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**.

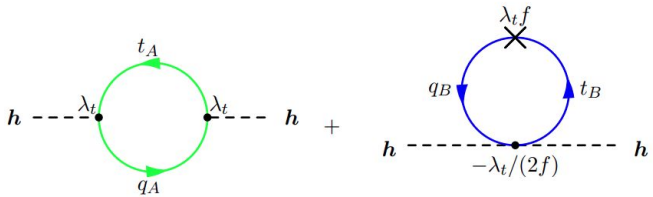
# Motivation — Why Mirror Sectors?

**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!**

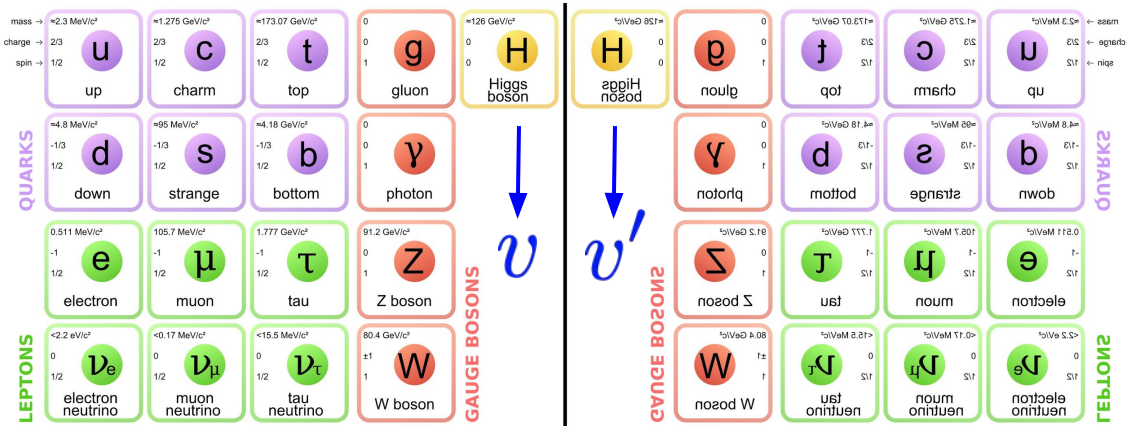
**Alternative: *Neutral Naturalness***
Family of models in which new physics is charged under a copy of SM gauge groups — *dark QCD.*




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.

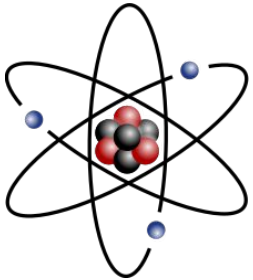


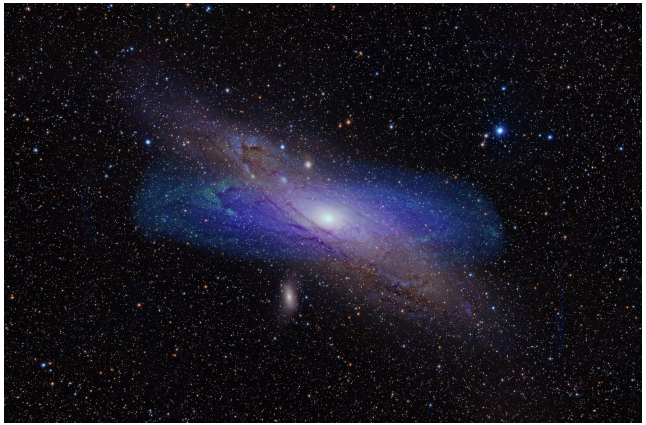

$$m'_q = \left(\frac{v'}{v}\right) m_q$$

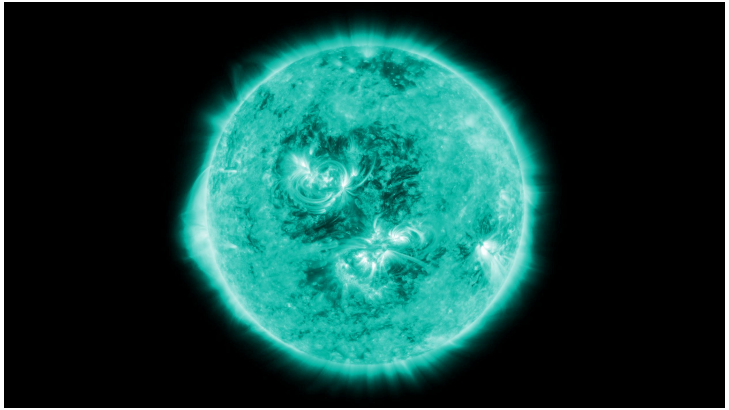
$$\Lambda'_{QCD} \approx \Lambda_{QCD}\,(0.65 + 0.41\log(1.32 + v'/v))$$

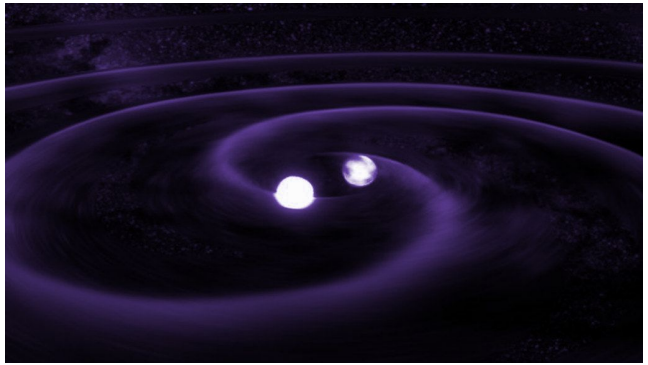
# Dark Complexity in the MTH

Mirror models could give rise to phenomena as varied as those in the visible sector...









# Modelling Neutron Star structure

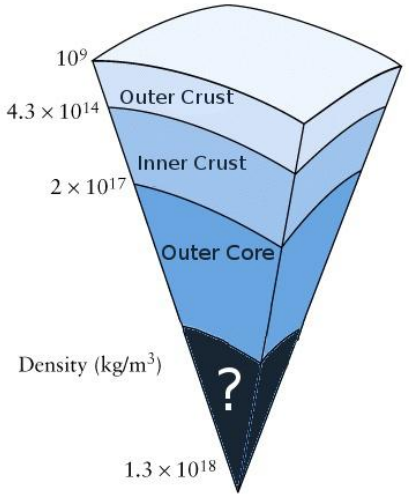
Derive full Equation of State: $P(\rho)$, $\epsilon(\rho)$; solve Tolman-Oppenheimer-Volkoff equation:

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

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:

$\omega_{\mu\nu} \longrightarrow$ Vector repulsion
$\sigma \longrightarrow$ Scalar attraction

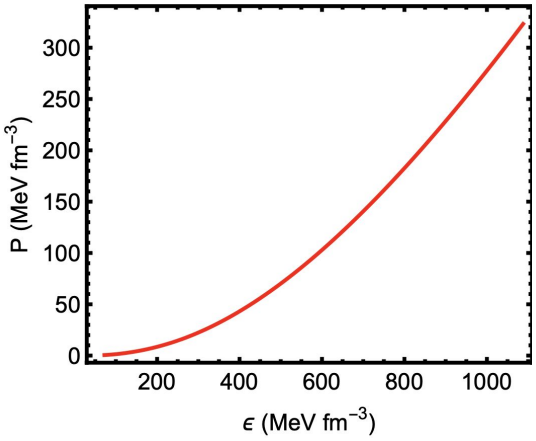
$$\mathcal{L} = \bar{\psi}\left[i\,\gamma_\mu\partial^\mu - M_0 + \gamma^0\,\mu_B - g_\omega\,\omega^\mu\,\gamma_\mu - g_\sigma\,(\sigma + i\gamma_5\,\vec{\tau}\cdot\vec{\pi})\right]\psi +$$

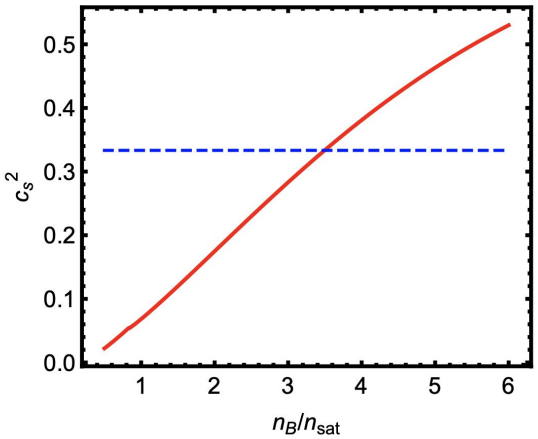
$$+\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi}\right) - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\,\omega^\mu\omega_\mu - \mathcal{U}(\sigma,\vec{\pi})$$

*[Glendenning, 1988]*

Extra ingredients:

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



# 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:

$$m_i^2 = \Lambda_{QCD}^2 \left( a_0 + a_1 \left( \frac{m_\pi}{\Lambda_{QCD}} \right)^2 + \dots \right)$$

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

...can extract coefficients from lattice data.

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

*[for instance from:*

*Jung, RBC and UKQCD collaborations, arXiv:1301.539;*

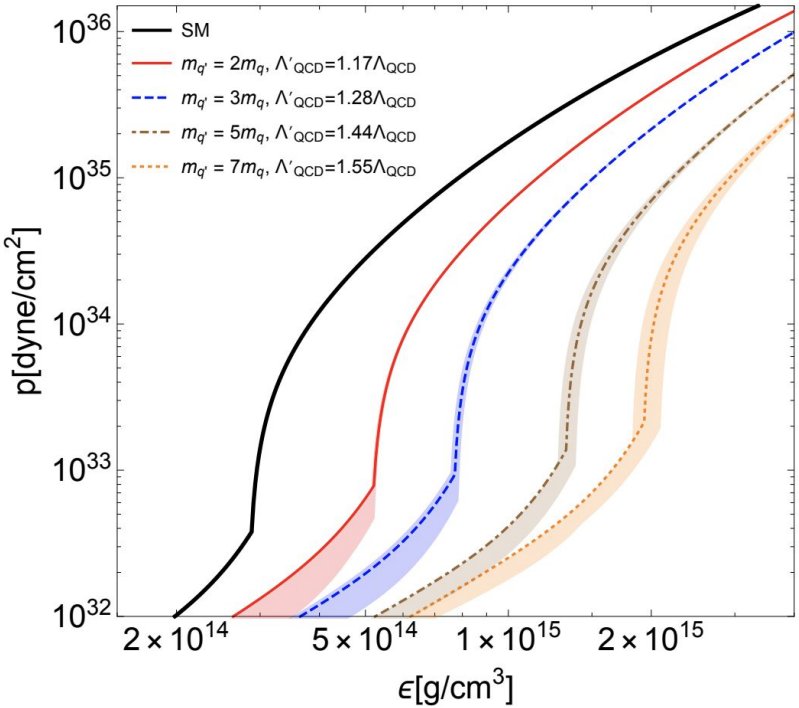
*Horsley, Nakamura, Nobile, Rakow, Schierholz and Zanotti, arXiv:1302.2233;*

*Albaladejo and Oller, arXiv:1205.6606.]*

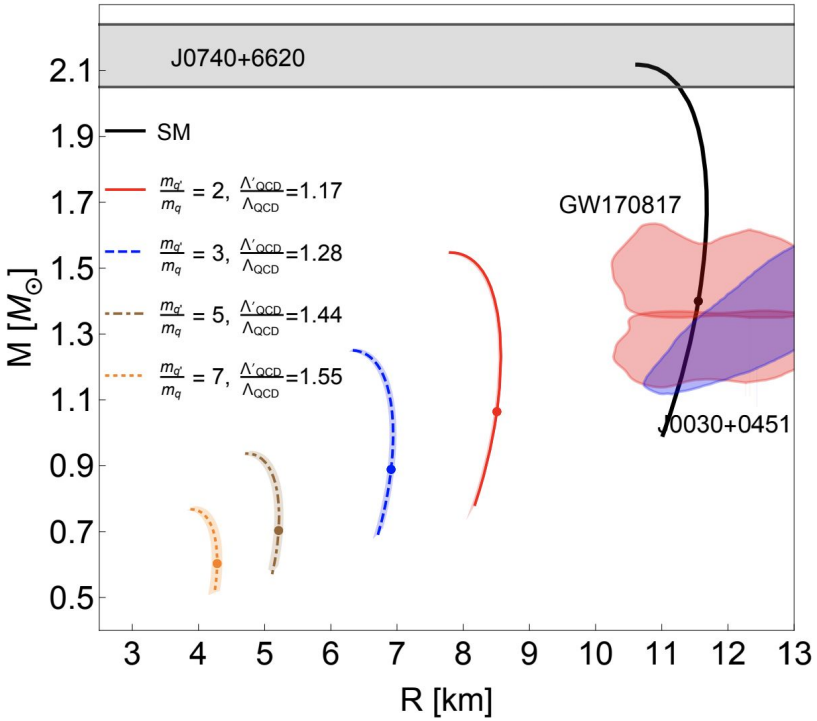
# Scaling with quark mass

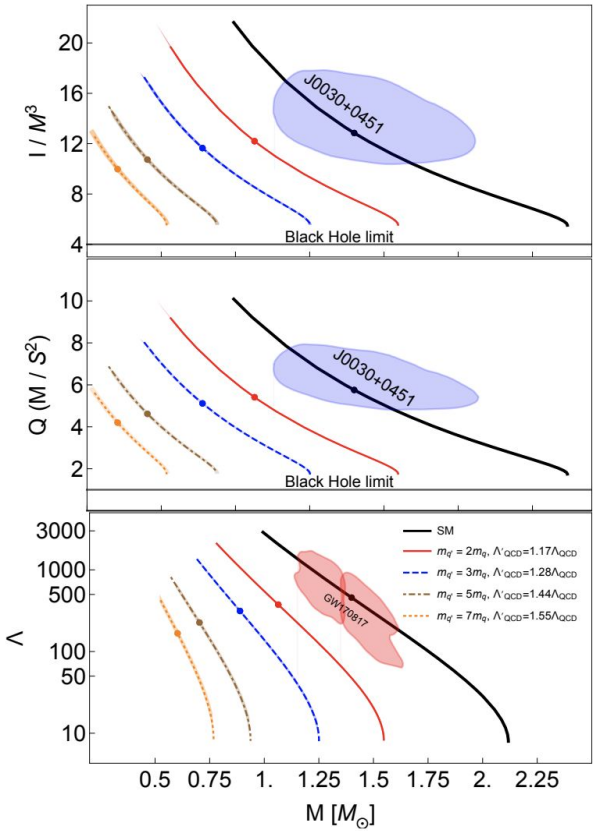
Equation of state:

To a reasonable approximation, both the pressure and energy density scale with $(\Lambda'_{QCD})^4$



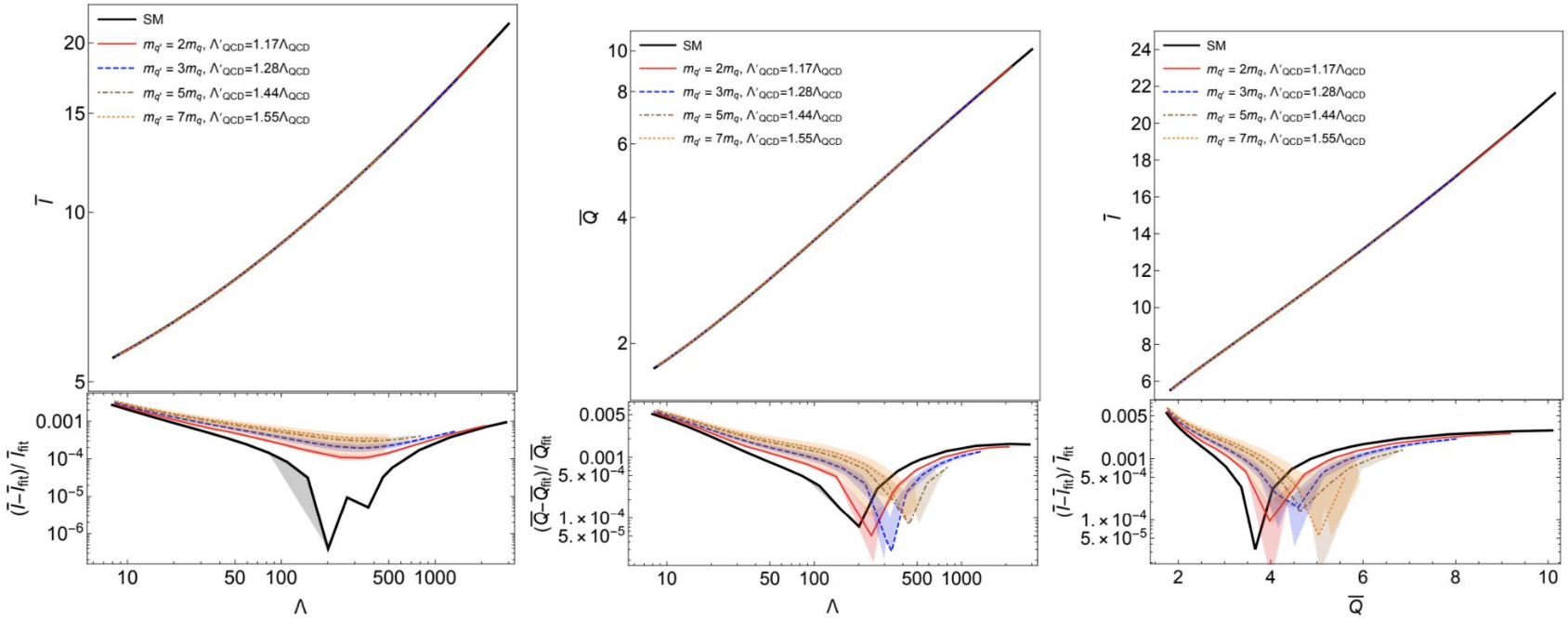
# Mirror neutron star properties



# Universal behaviour

Universal I-Love-Q relations are satisfied for Mirror Neutron Stars:



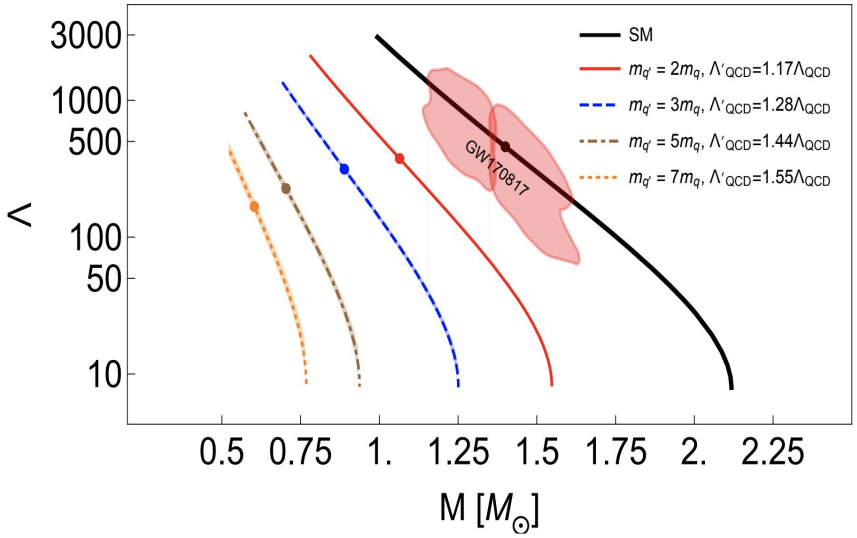
# Diagnosing a mirror neutron star merger!

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.