



Neutron stars vs. quark stars: how can they be distinguished?



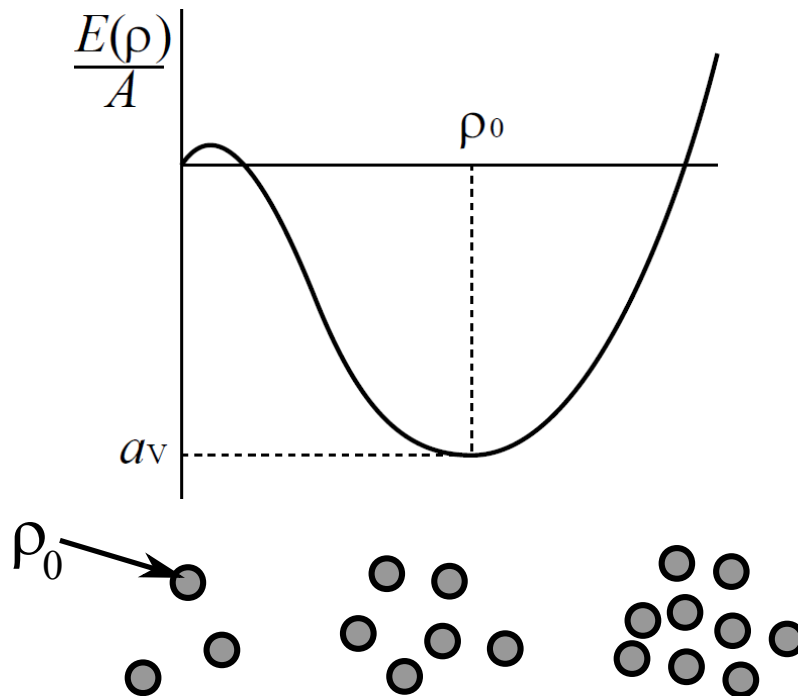
Kenji Fukushima

The University of Tokyo

— 2nd Int. Workshop on Physics at High Baryon Density (PHD2025) —

Stability of Quark Matter

Nuclear Saturation



Self-bound fermionic systems have a preferred density. Diluteness is realized as a “mixed phase” of nuclei.

This is how this world is like what we know.

Stability of Quark Matter

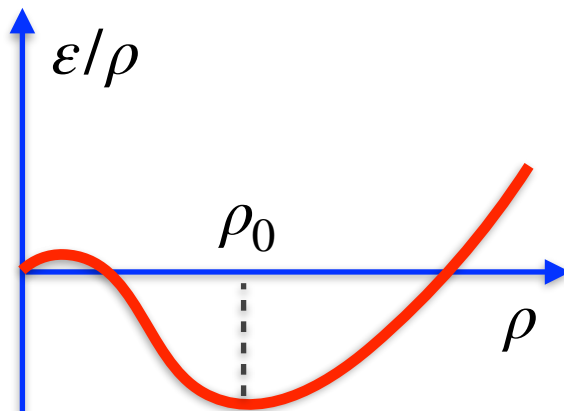


Extremal point $\rightarrow$ 1st-order PT

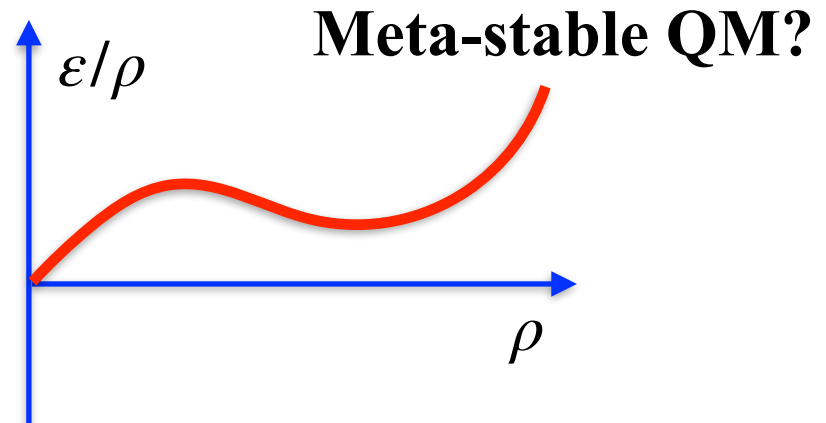
$$\frac{d}{d\rho} \left(\frac{\varepsilon}{\rho} \Big|_{\text{gas}} - \frac{\varepsilon}{\rho} \Big|_{\text{liquid}} \right) = \frac{p_{\text{gas}} - p_{\text{liquid}}}{\rho^2} = 0$$

Stationary cond.

PT cond.



Nuclear Matter

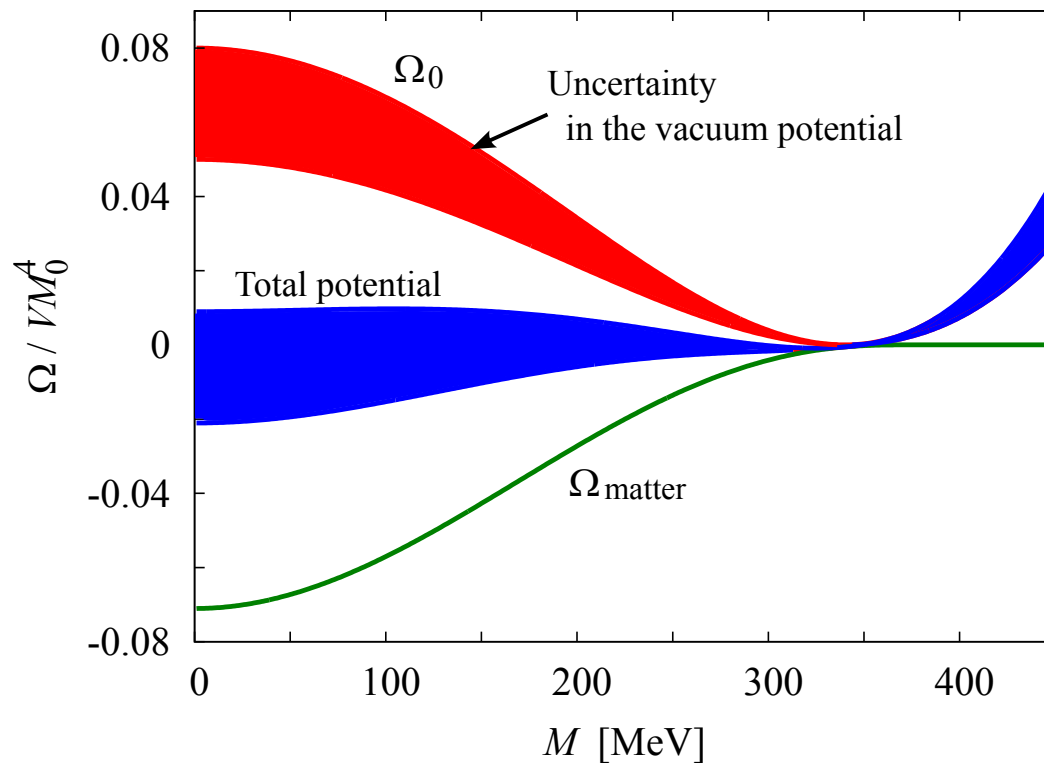


Many model studies

Stability of Quark Matter

QCD Critical Point (QCP)?

Fukushima (2012)



$$\Omega_{\text{matter}}[M]/V = - \int_0^{\mu_q} d\mu' \rho(\mu') \\ - 4N_c N_f T \int \frac{d^3 p}{(2\pi)^3} \ln(1 + e^{-\omega_p/T})$$

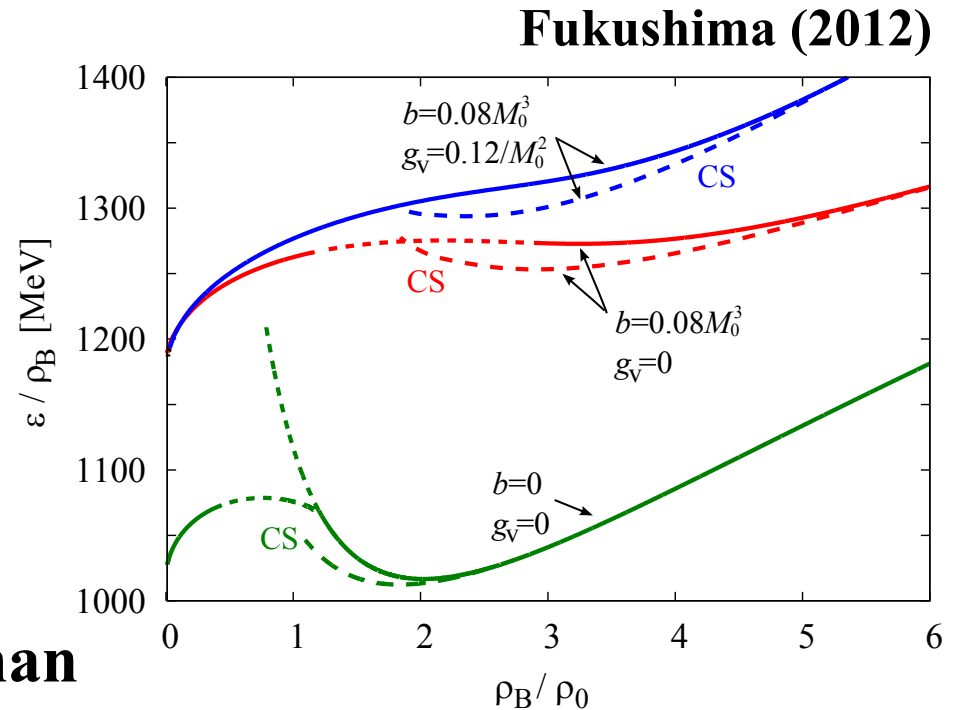
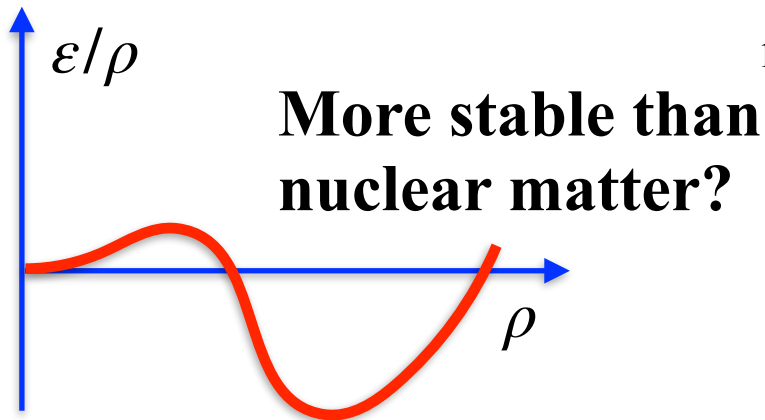
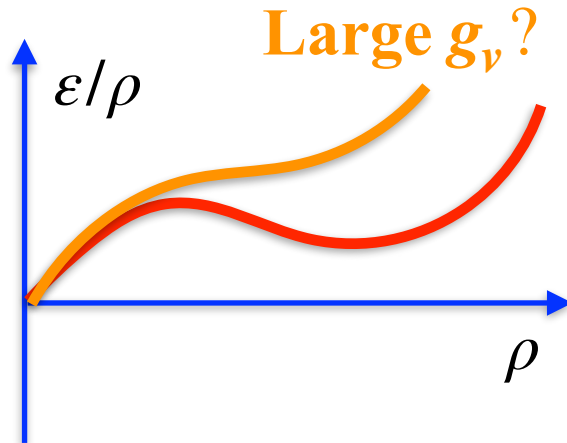
No ambiguity in the quasi-particle picture.

Uncertainty comes from the vacuum part.

Vector interaction —

$$\Omega_{\text{vec}}[M]/V = g_v \rho^2$$

Stability of Quark Matter



1D chiral spirals (CS) decrease the energy per particle, inducing another 1st-order PT.

Stability of Quark Matter



【Assertion】

The realization of strange quark matter hypothesis (Bodmer, Farhi-Jaffe, Witten) is a strong support for the existence of the QCD Critical Point on the QCD phase diagram.

【Remark】

The mixture of u , d , s is approximately charge neutral — cf. enforced neutrality in the CFL phase (Rajagopal-Wiczek).

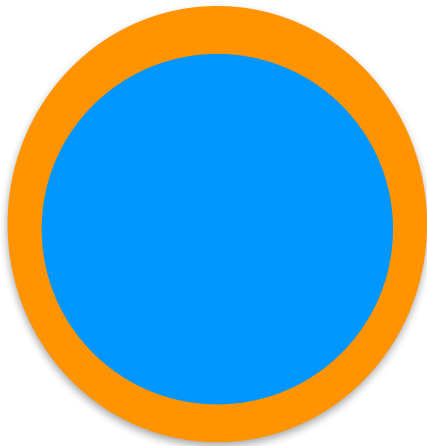
【Inverse feedback】

Quark stars of chiral spirals???

Differences



Neutron Stars



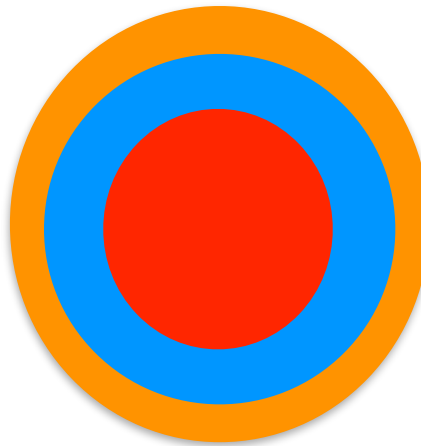
Softening in NS mergers

$R \sim 10\text{-}12\text{km} / M \sim 1.4\text{-}2.1M_{\odot}$

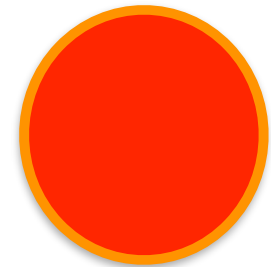
Crust $\sim 1\text{km}$

Atmosphere $\sim$ ions + electrons

Hybrid Stars



Quark Stars



Signature???

$R \sim < 12\text{km} / M \sim < 2M_{\odot}$

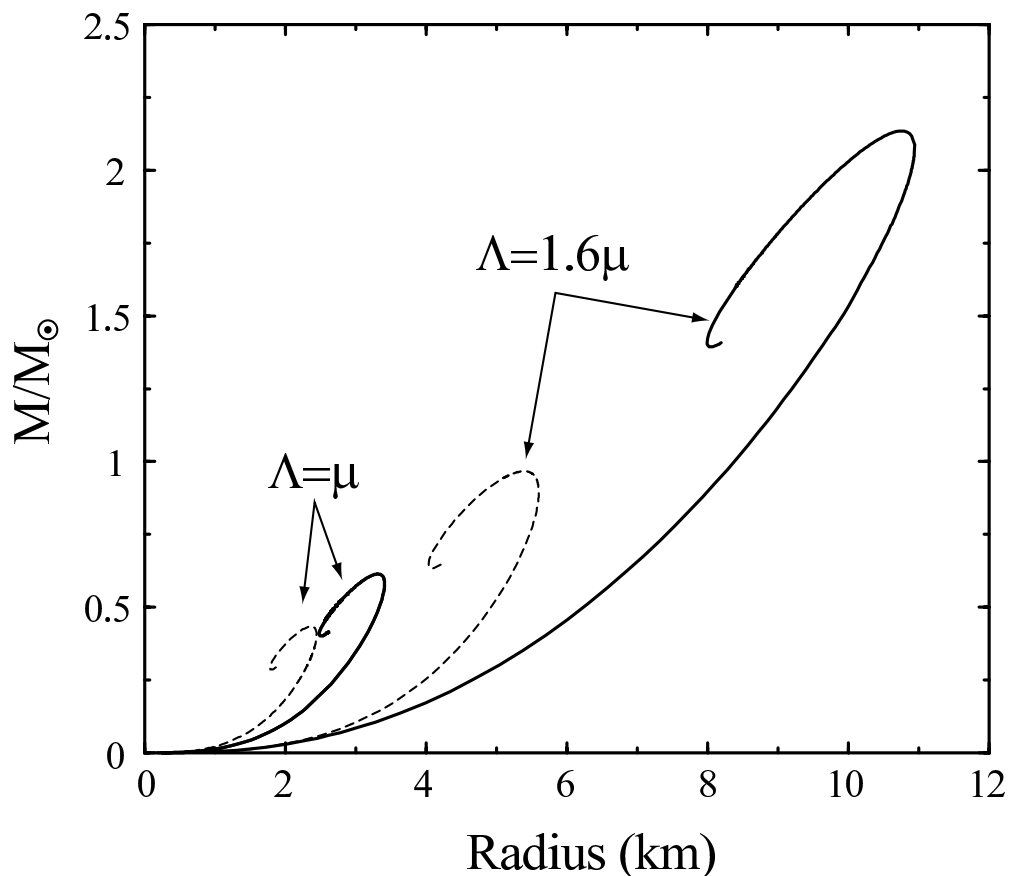
Thin crust

No atmosphere

Differences

Mass-Radius Relation of QS

Andersen-Strickland (2002)



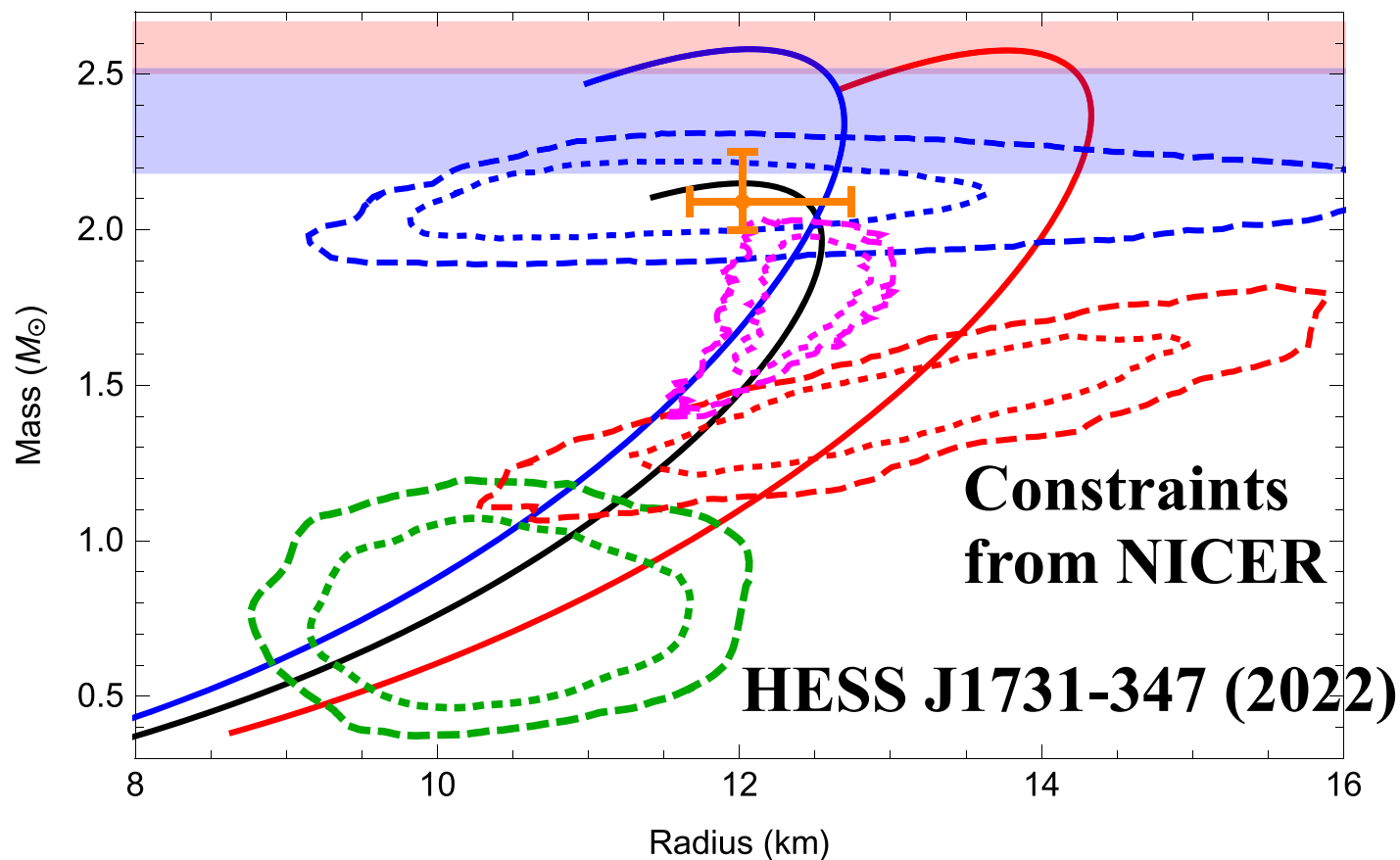
Resummed PT in QCD

This is a bit misleading since the EoS is very sensitive for such a *too small* Λ .

Quark stars may not be light nor small...

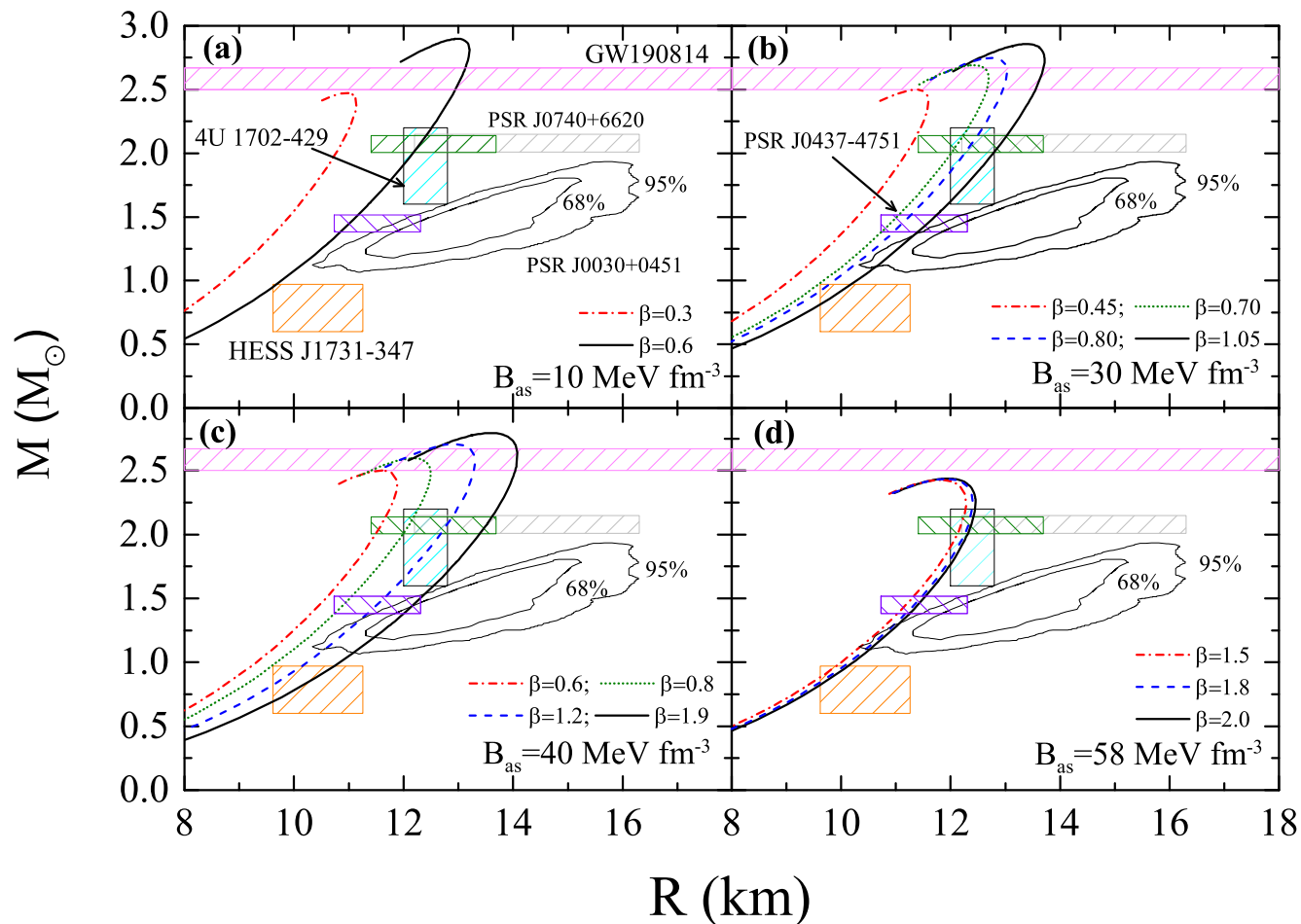
Candidate?

Clemente-Drago-Pagliara (2024)



Candidate?

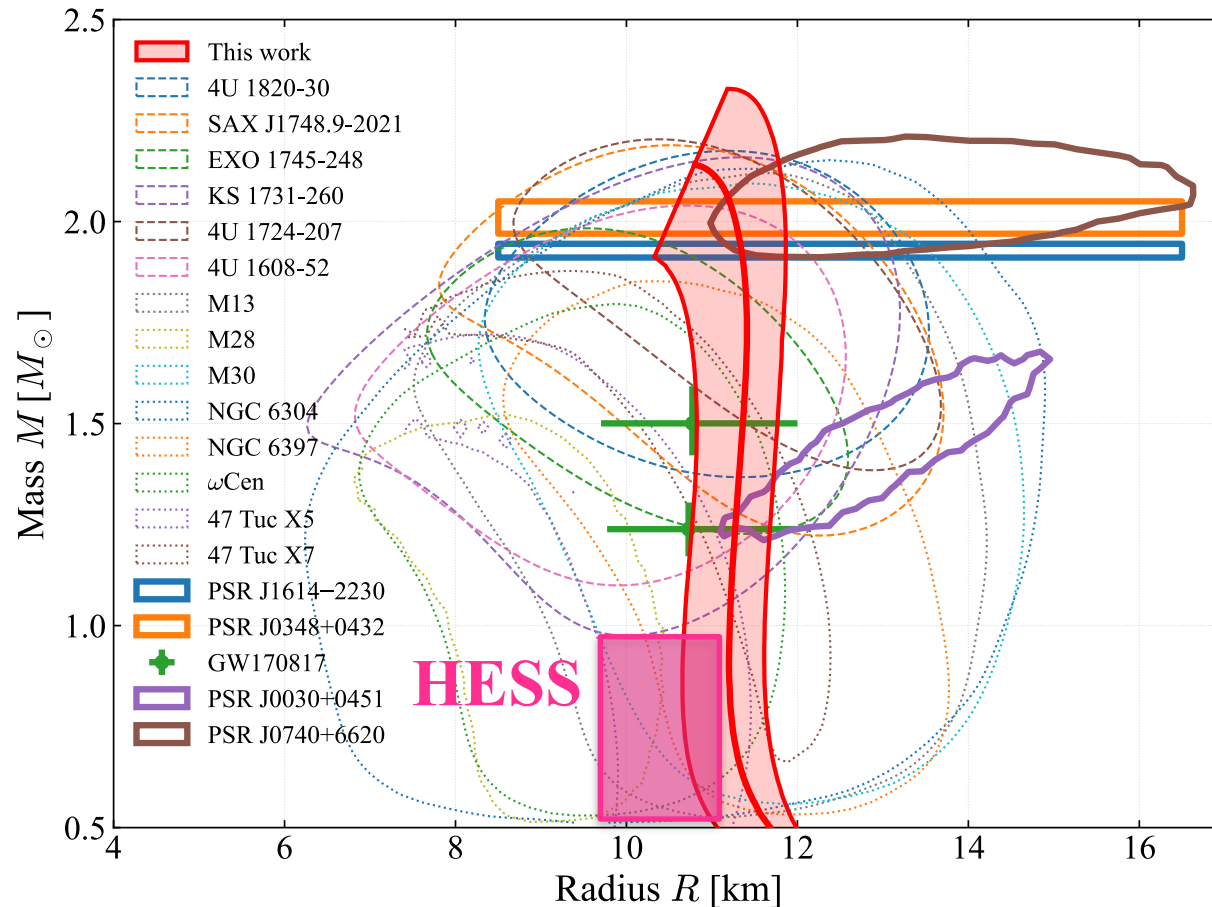
Ju-Chu-Wu-Liu (2024)



October 16, 2025 @ Wuhan, CCNU

Candidate?

Fujimoto-Fukushima-Kamata-Murase (2018-2024)



Candidate?



There is no stability bound for light NSs.

Supernovae simulations favor NSs with $M \gtrsim M_{\odot}$.

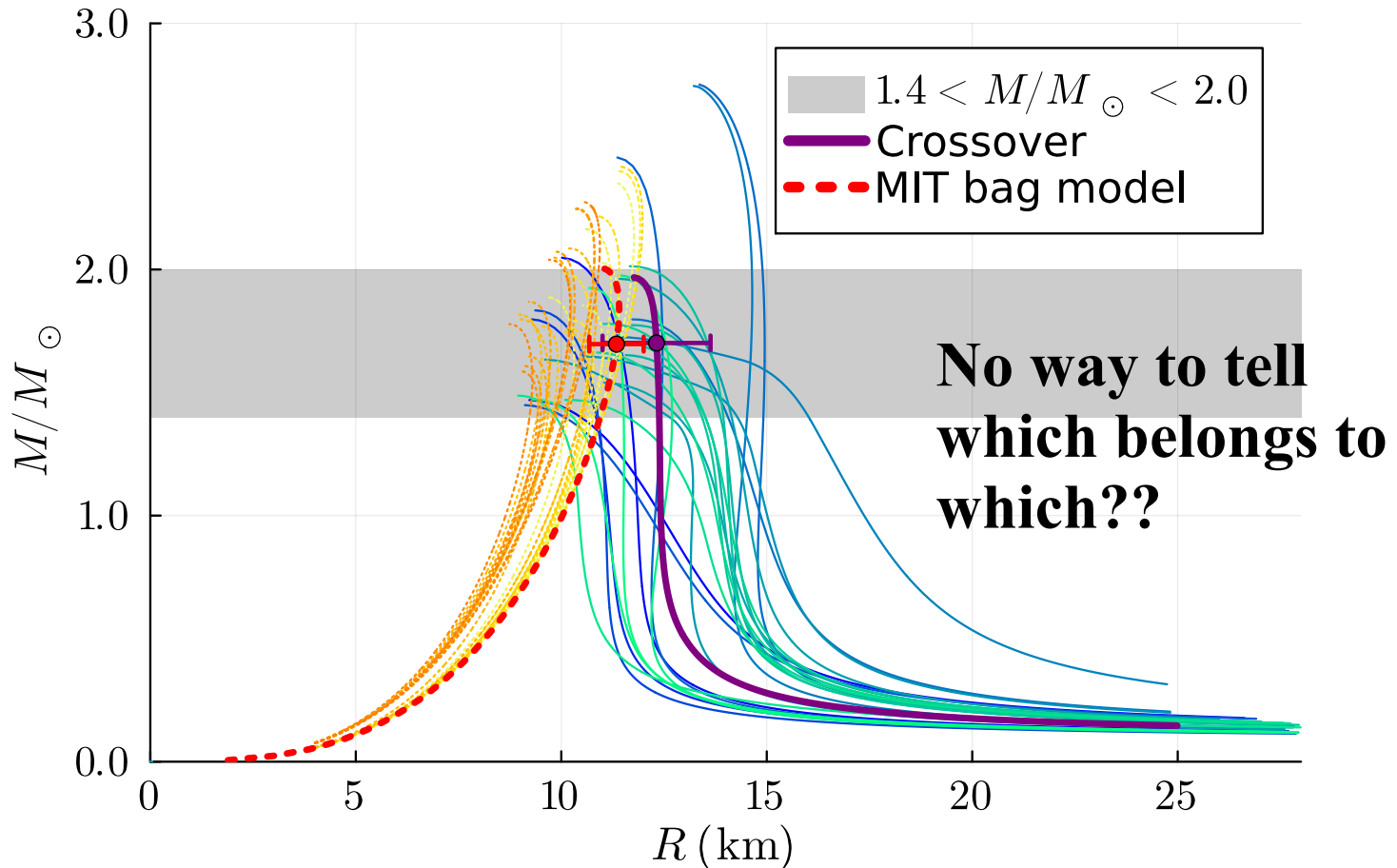
The supernova remnant of HESS may be an exceptionally light NS ?

Only from the M - R data, one can only claim possible consistency with the QS scenario...

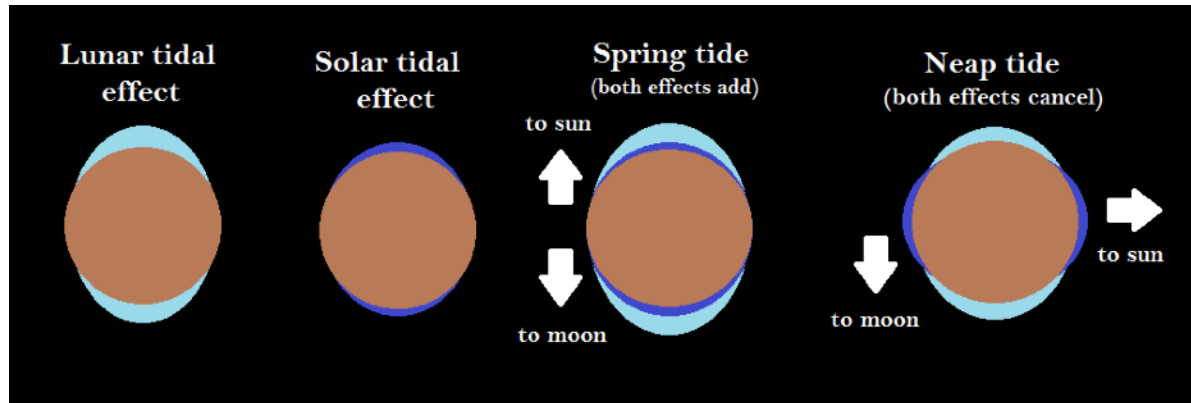
Any other observable (inferred from GW signals)?

M-R Indistinguishability

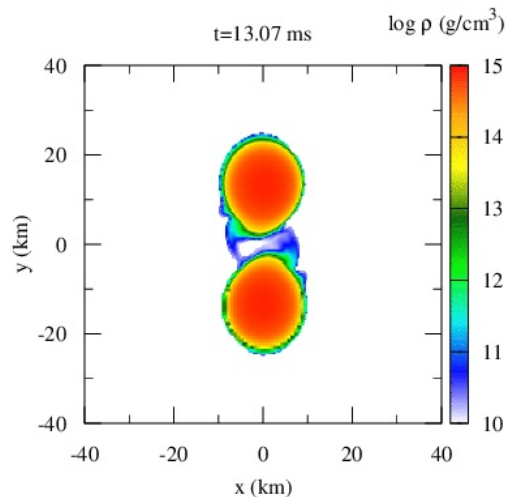
Fukushima-Minamiguchi-Uji (coming soon!)



Tidal Responses



from energyeducation



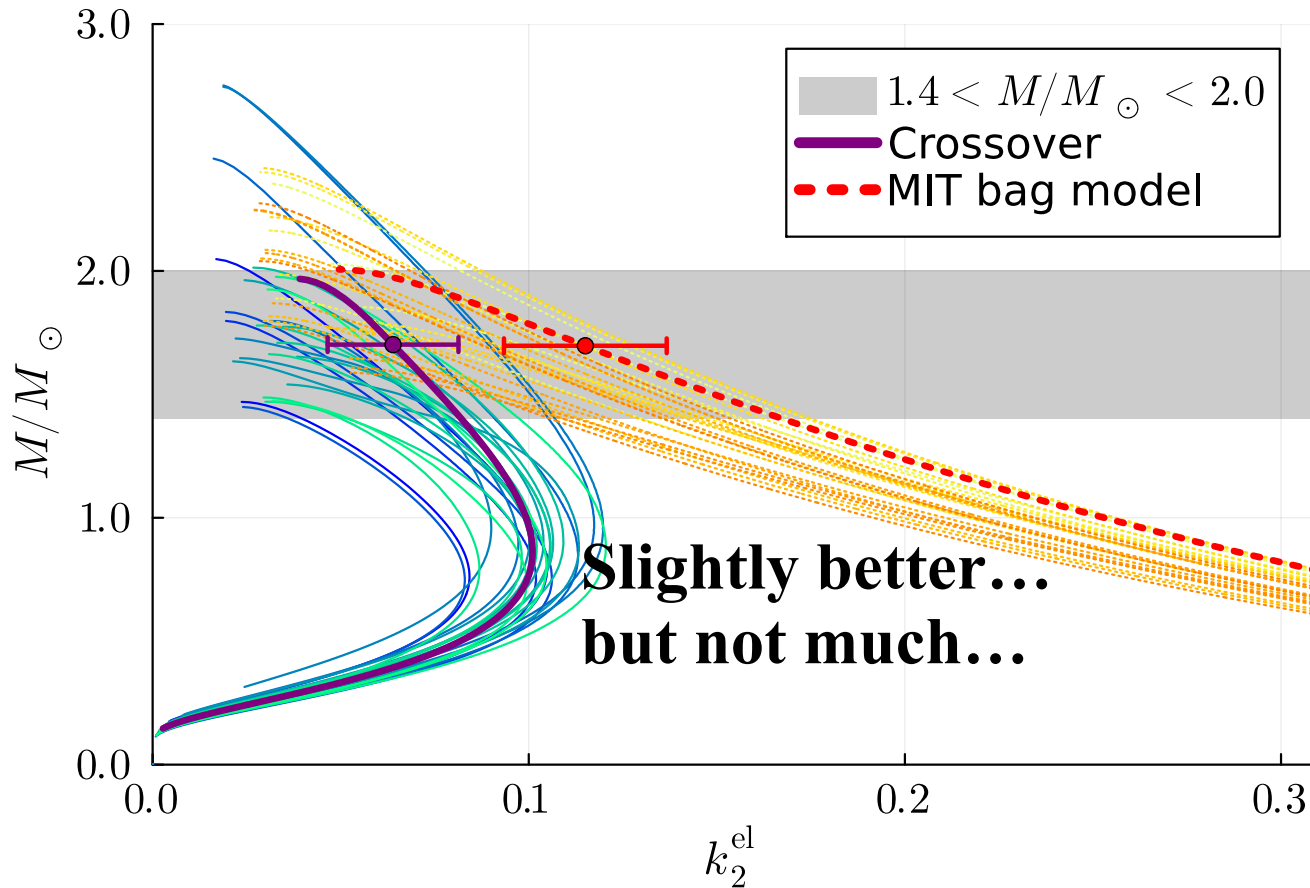
Kyutoku+

Distortion in response to the gravitational force from the binary companion. Affects the GW waveforms.

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

Tidal Responses

Fukushima-Minamiguchi-Uji (coming soon!)



$$\Lambda := \frac{2k_2^{\text{el}}}{3C^5}$$

$$C := \frac{M}{R}$$

Tidal Responses

Damour-Nagar (2009) / Binnington-Poisson (2009)

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu}$$

$$h_{\mu\nu} = h_{\mu\nu}^{\text{even}} + h_{\mu\nu}^{\text{odd}}$$

Parity-even = Electric
Parity-odd = Magnetic

$$\ell = 2 \quad h^{\text{even}} \sim a_1 P_2^{(2)}(r/M - 1) + a_2 Q_2^{(2)}(r/M - 1)$$

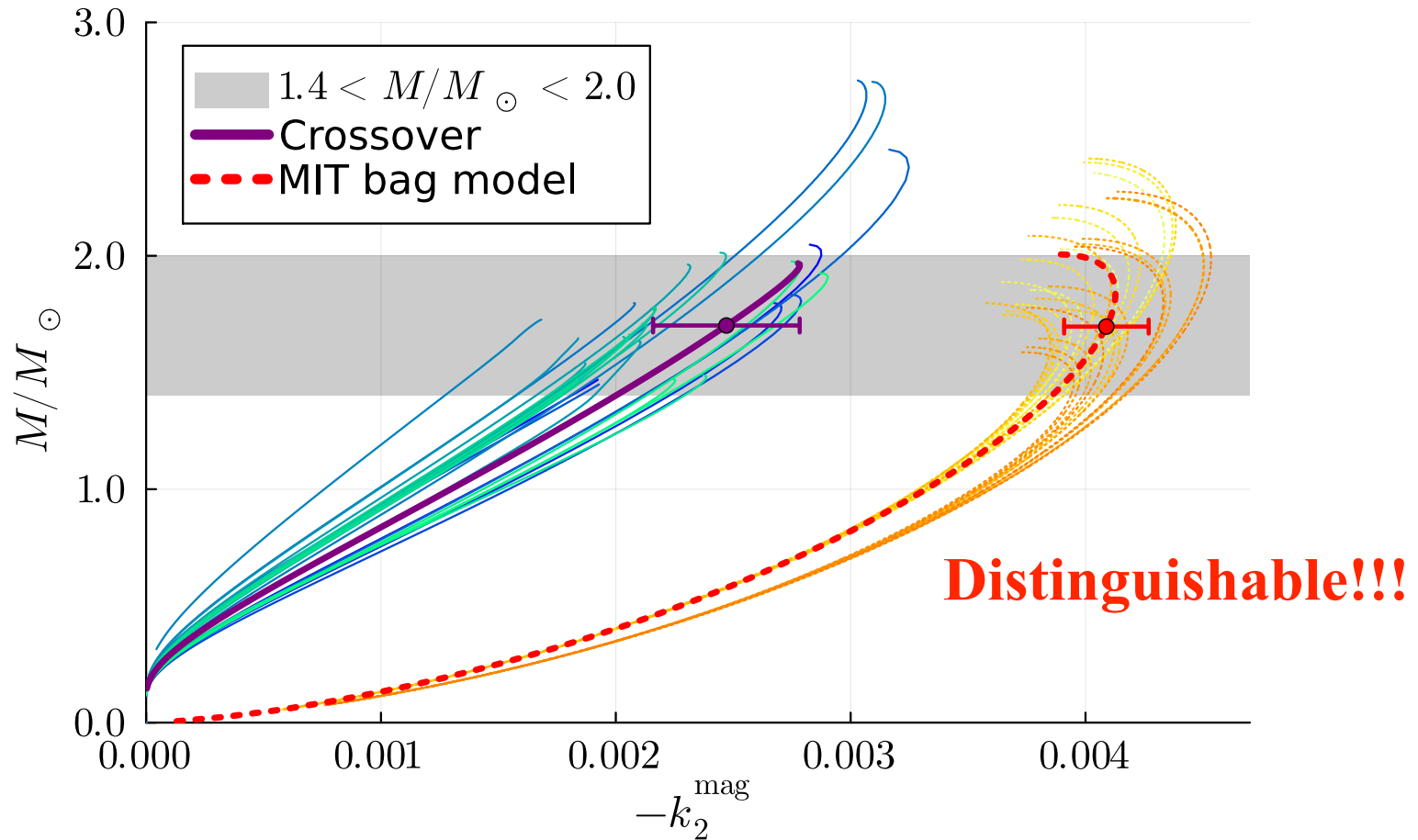
$$k_2^{\text{el}} \propto a_2/a_1$$

h^{odd} involves complicated special functions...

But the strategy to read k_2^{mag} is the same.

Tidal Responses

Fukushima-Minamiguchi-Uji (coming soon!)



Optimistic View



In the near future, we can observe the GW from the binary NS merger $\sim$ once a month = ~ 10 per year.

In 10 years, we will have the GW data of order 100, among which, there may be some NS-QS mergers.

If the waveform is seen for a long time span, k_2^{mag} can be extracted from the data.

However... nontrivial how to make the separation of two coefficients of binary stars...

Summary

■ Possible connection between HIC and NS/QS

- QCD Critical Point and Quark Star both discuss the stability / meta-stability of quark matter.
- QCD Critical Point is a necessary condition for the existence of Quark Stars.

■ Quark Star Hunting

- Small- M and small- R objects are likely candidates.
- Tidal responses: the electric component is correlated with R and not very useful to resolve the degeneracy, but the magnetic component works very well!