Istituto Nazionale di Fisica Nucleare

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NEUtron star MATter Theory

Do hadronic stars and strange quark stars coexist?

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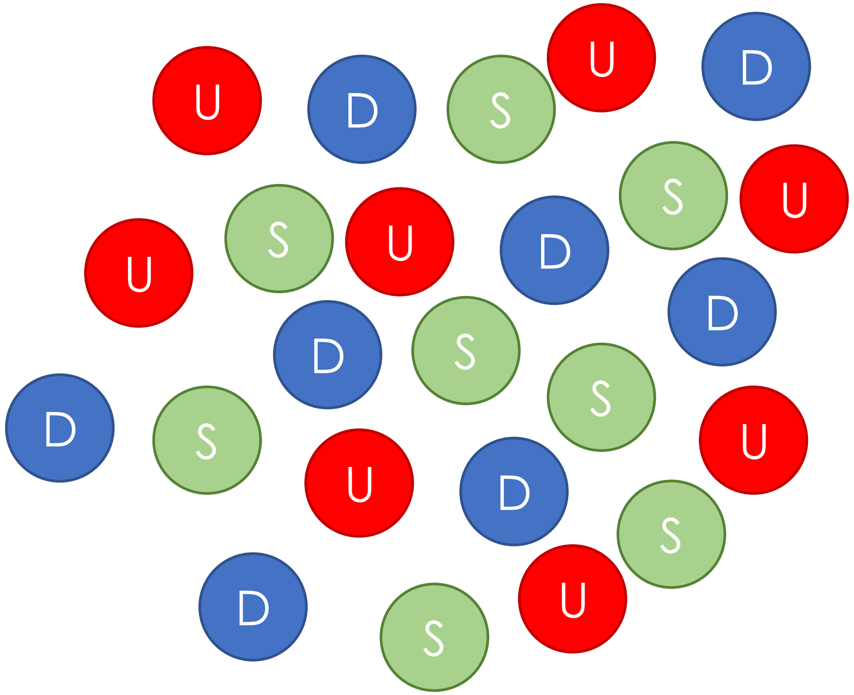
Bodmer-Witten hypothesis

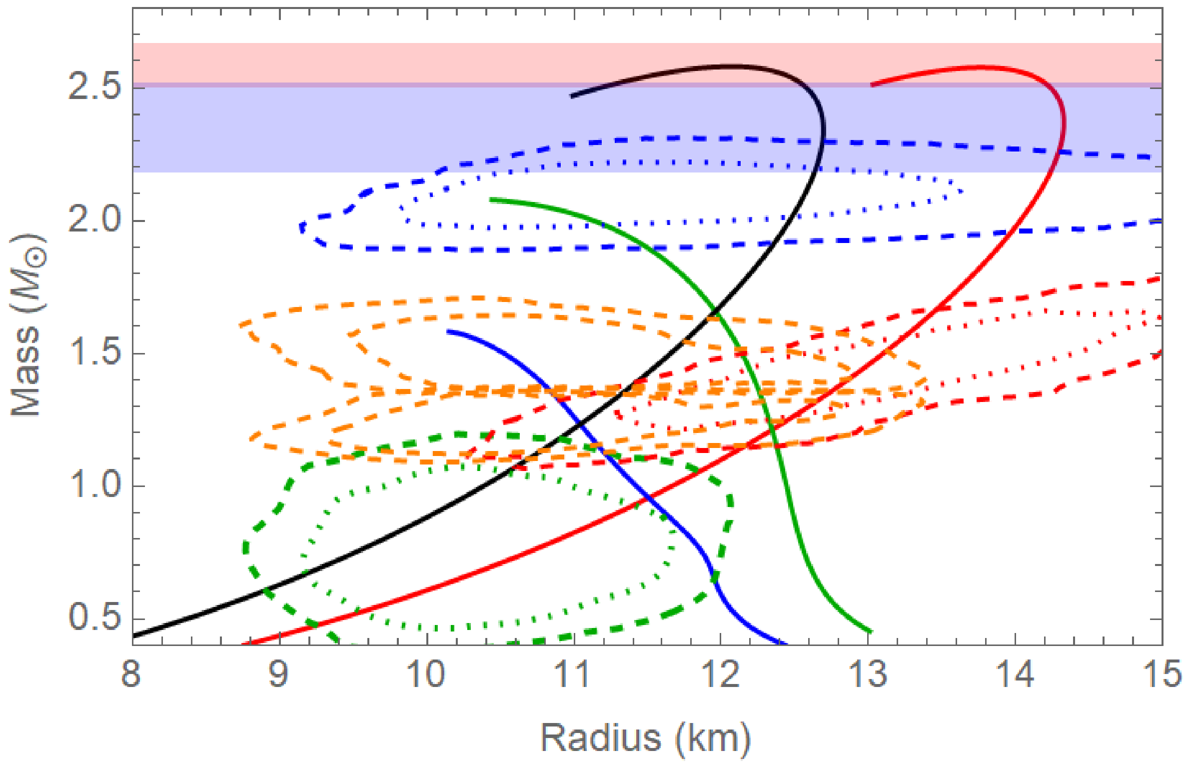
- ***uds*** quark matter "in bulk" is proposed as ground state of matter
- Energy per baryon less than the one of iron (~930 MeV/fm^3)
- It opens to the possibility of existence of ***strange stars*** (and consequent astrophysical scenarios) and of strange quark matter as ***dark matter*** (*Witten (1984)*)

It is almost impossible to observe ***hadronic matter*** decaying into ***strange matter*** because one should have a great strangeness content → this can happen in the core of neutron stars (containing hyperons)



Two-families scenario

- Coexistence of hadronic star and strange quark stars
- Soft hadronic EoS opposed to a stiff strange matter EoS
- It is a way to solve the hyperon puzzle



Mass-radius relation of QSs and HSs from Bombaci et al. (2021) (solid red), Ferrer et al. (2015) (solid black), Logoteta et al. (2019) (solid green), Drago et al. (2014) (solid blue). Dashed lines refer to GW170818, NICER experiment and HESS J1731-347 constraints.

BHNS as a way to test the scenario

BH-NS merger

↓

Dynamical Ejecta → *Semi-analytical model*

↓

Kilonova signal → *KN model (Kawaguchi et al. 2016)*

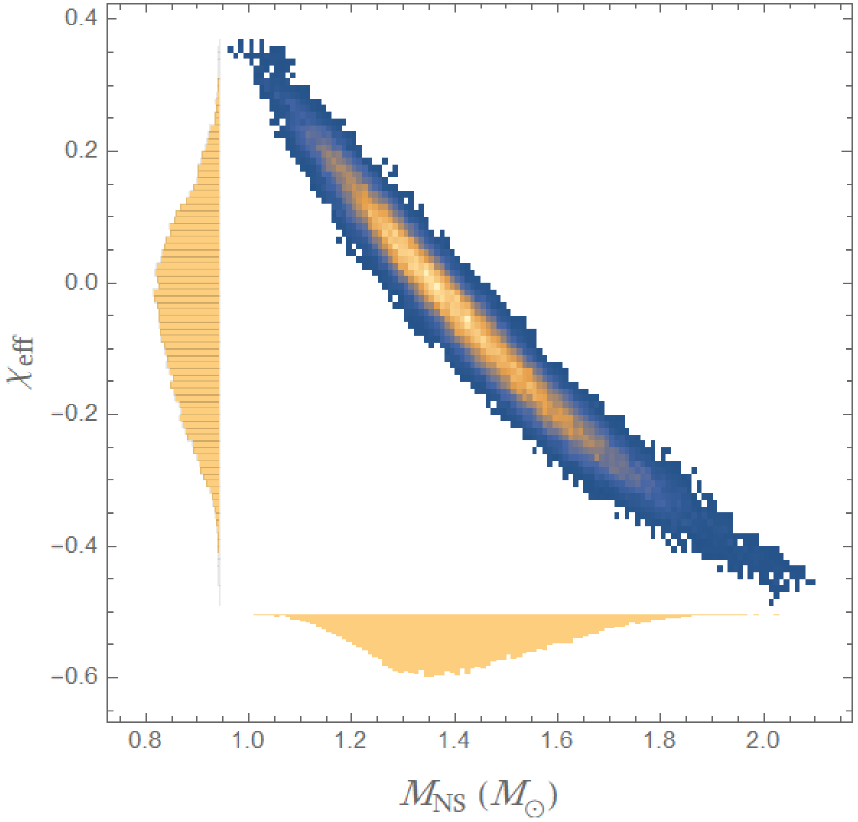
↓

Observation (simulated) → *Toy-model* (Ng et al. 2018 + improvement)

↓ ↓

Prediction on EoS compatibility with the presence of a KN signal

BHNS as a way to test the scenario



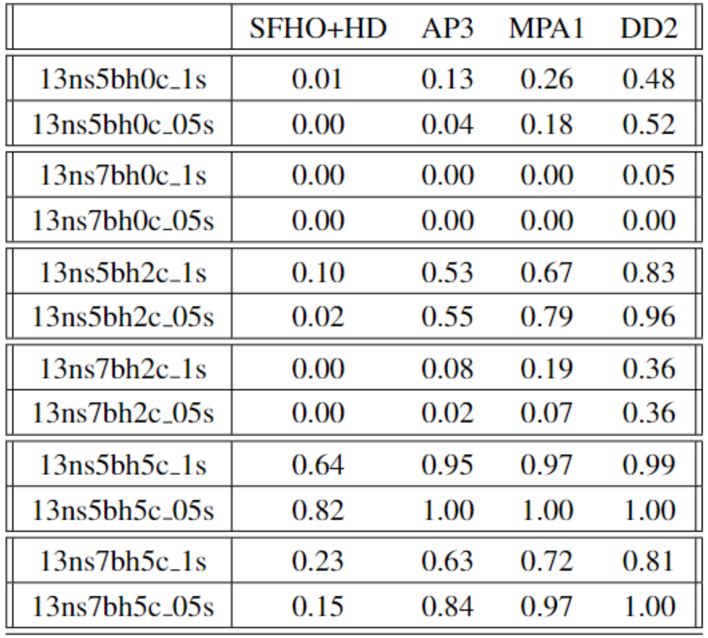
Example of the spin-mass correlation we obtain from the toy model using central values and uncertantiers based on LV analysis of GW200115. Central values and uncertainties are the input parameters of the toy-model.

1 - for each event we want to analyze, we generate an ensemble of points according to the toy-model likelihood using central values and uncertainties as inputs.

2 - we compute $\mathbf{M_{dyn}}$ for each generated point, the **bolometric luminosity**, the **bolometric magnitude** and **the bolometric correction** for a single band filter (*g-band* filter, $\lambda_{\rm eff}$ = 4830 Å) using a model developed by Kawaguchi et al. (2016, ApJ, 825, 52)

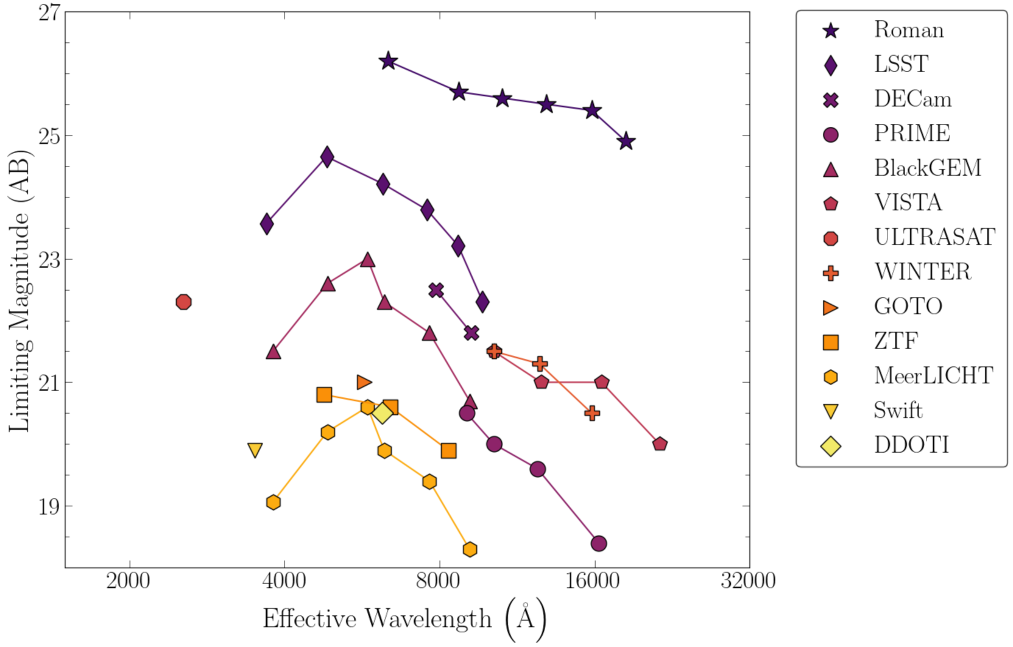
3 - we compute the fraction of the sample which generates a **visible magnitude** smaller than the limiting one of *LSST* telescope (next generation telescope).

BHNS as a way to test the scenario



	SFHO+HD	AP3	MPA1	DD2
13ns5bh0c_1s	0.01	0.13	0.26	0.48
13ns5bh0c_05s	0.00	0.04	0.18	0.52
13ns7bh0c_1s	0.00	0.00	0.00	0.05
13ns7bh0c_05s	0.00	0.00	0.00	0.00
13ns5bh2c_1s	0.10	0.53	0.67	0.83
13ns5bh2c_05s	0.02	0.55	0.79	0.96
13ns7bh2c_1s	0.00	0.08	0.19	0.36
13ns7bh2c_05s	0.00	0.02	0.07	0.36
13ns5bh5c_1s	0.64	0.95	0.97	0.99
13ns5bh5c_05s	0.82	1.00	1.00	1.00
13ns7bh5c_1s	0.23	0.63	0.72	0.81
13ns7bh5c_05s	0.15	0.84	0.97	1.00

Compatibility of each considered equation of state with a KN signal observation after 1 day from the merger (200 Mpc). We are considering two different uncertainties on the measurements of the central values.



Limiting magnitude for several telescopes. Chase et al. (2021)

Dark matter

Macros

↓

Strangelets

Gianfranco Bertone , Tim, M.P. Tait, Nature 562 (2018) 7725, 51-56

Cosmological strangelets

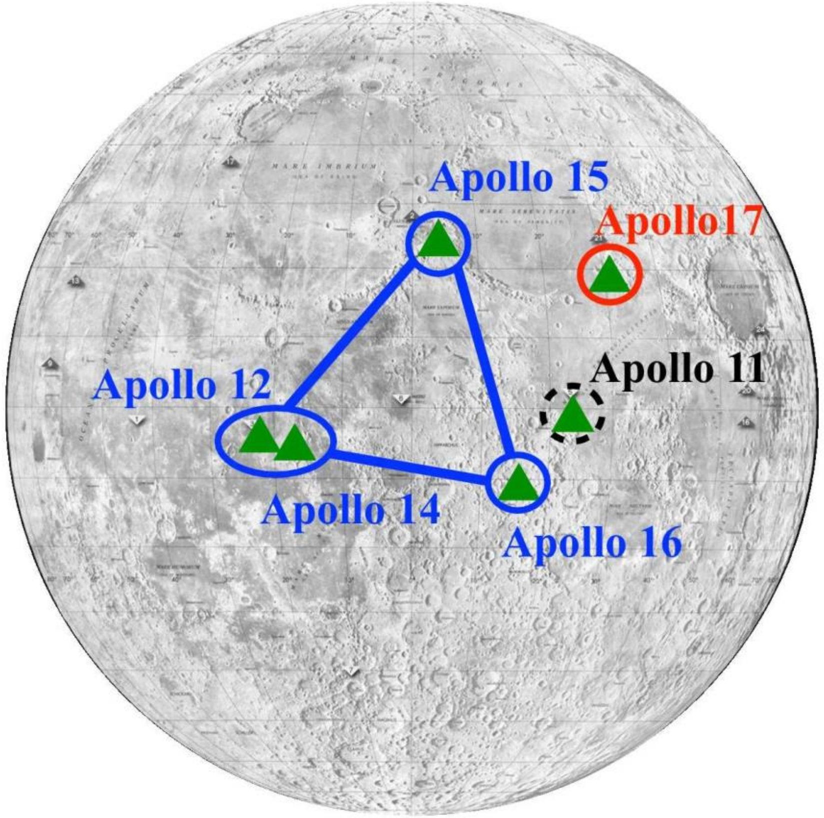
- **uds** quark matter in bulk forms at ~150 MeV (~10^{-6} s after the Big Bang)
- Because of the high temperature the strangelet's surface evaporates into hadrons (*Madsen et al. (1986), Farhi and Alcock (1985)*) up to a temperature of about 10 MeV
- Strangelets have a **mass/surface** ratio much greater than ordinary matter
- It is possible to tune two parameters in the pre-evaporation distribution and one phenomenological parameter in the evaporation equation:

$$\frac{dA}{dT_U} = \frac{2\,\mathrm{k}\,A(T_U)^{2/3}\,\beta\big(T_U^4 p(T_U,A(T_U)) - \mathrm{T}_s(T_U,A(T_U))^4 p(T_s(T_U,A(T_U)),A(T_U))\big)}{T_U^3(2\mathrm{T}_s(T_U,A(T_U)) + \mathrm{I})}$$

Observation constraints and space of parameters

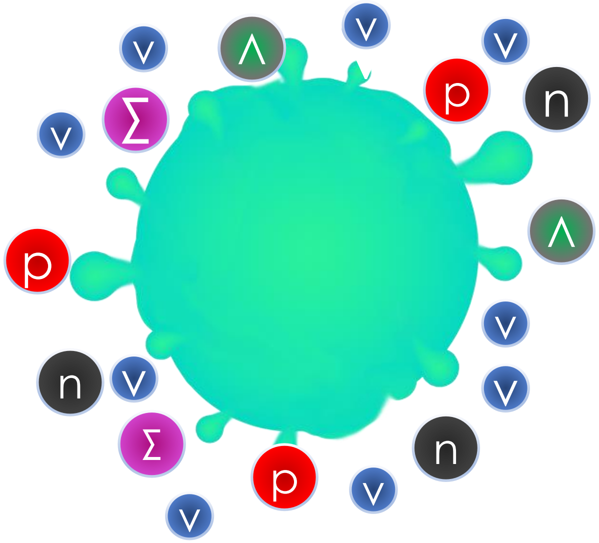
The final distribution (post-evaporation) has to obey to the following:

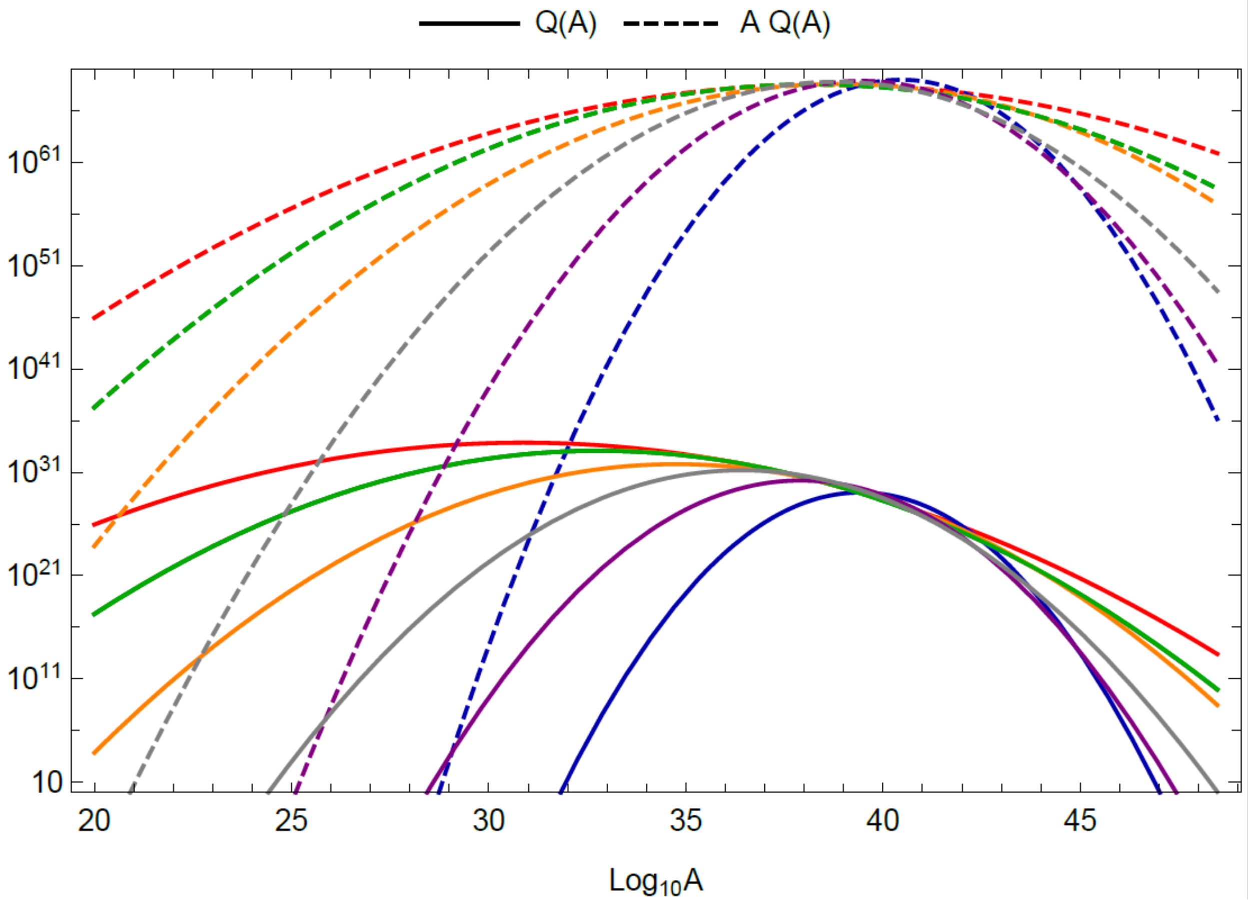
- Proto-NS conversion to SQS (*Bucciantini et al. (2022)*)
- Femtolensing and supernovae (*Sidhu and Starkman (2020), Burdin et al. (2015)*)
- Limits on the flux given by seismographs on the moon, for small mass strangelets (*Burdin et al. (2015)*)



Nunn et al. Space Science Reviews volume 216, 89 (2020)

Strangelets distribution





Distributions in number *Q(A)* and in mass *A Q(A)*, normalized to the measured mass of the Milky Way

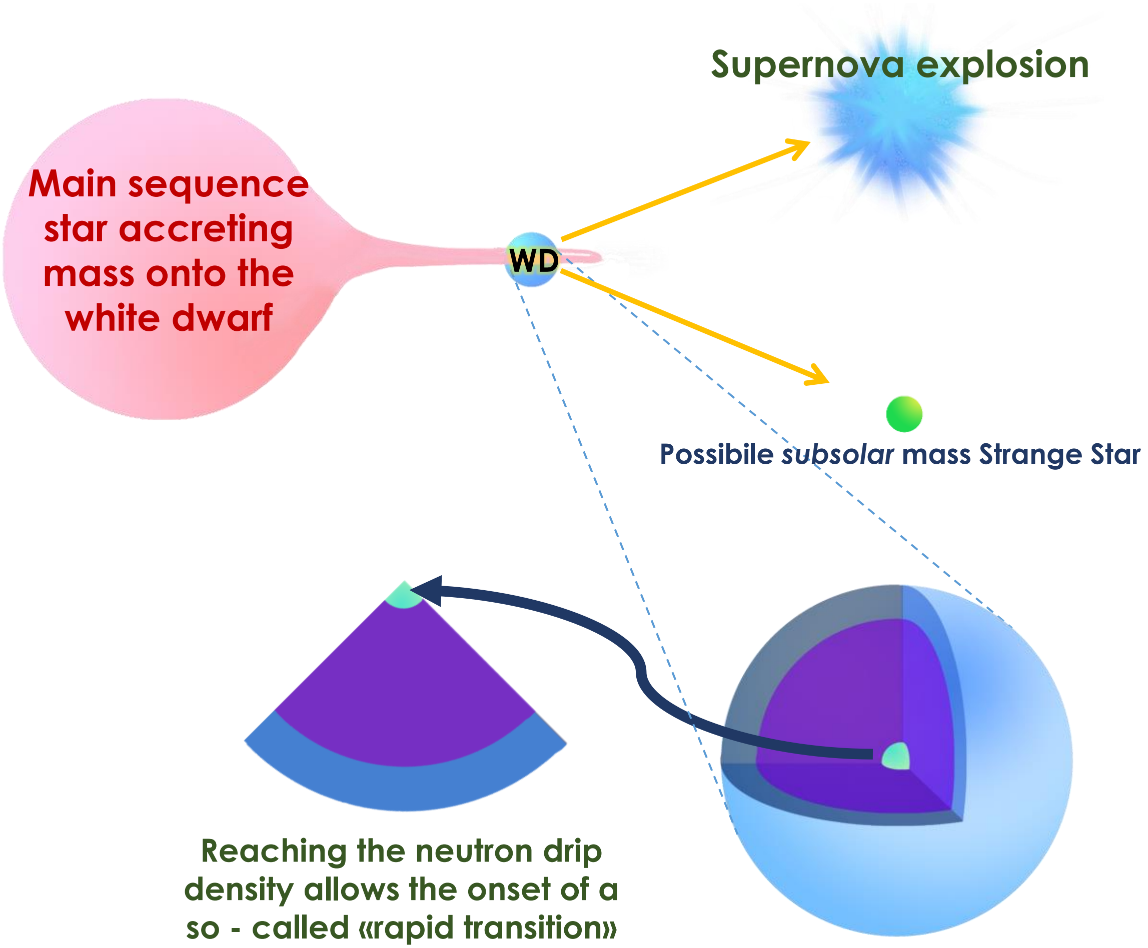
Impact on stellar evolution

Stellar object can capture strangelets given two fundamental conditions (*Madsen (1986)*):

- They must be made up of a portion of matter dense enough to be able to stop a strangelet
- The dense portion must 'live' long enough to increase exposure to these objects

Additional condition: ***position in the galaxy***. The capture rate depends on the local flux (and strangelets are very dense so you don’t have many of them anyway).

From White Dwarfs to Strange Dwarfs



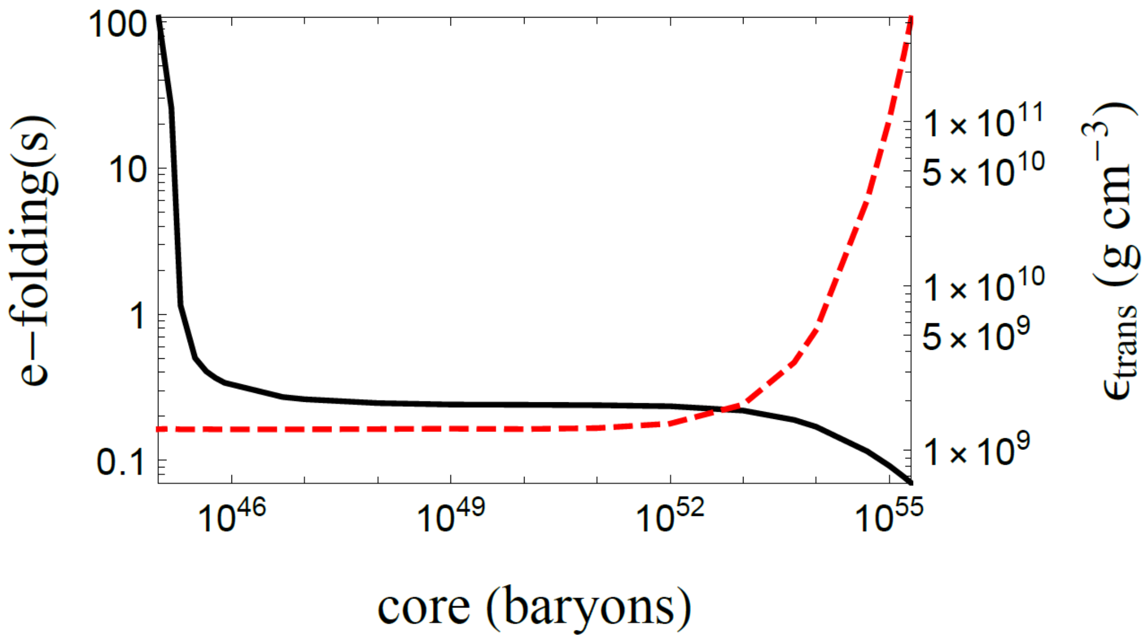
Supernova explosion

Main sequence star accreting mass onto the white dwarf

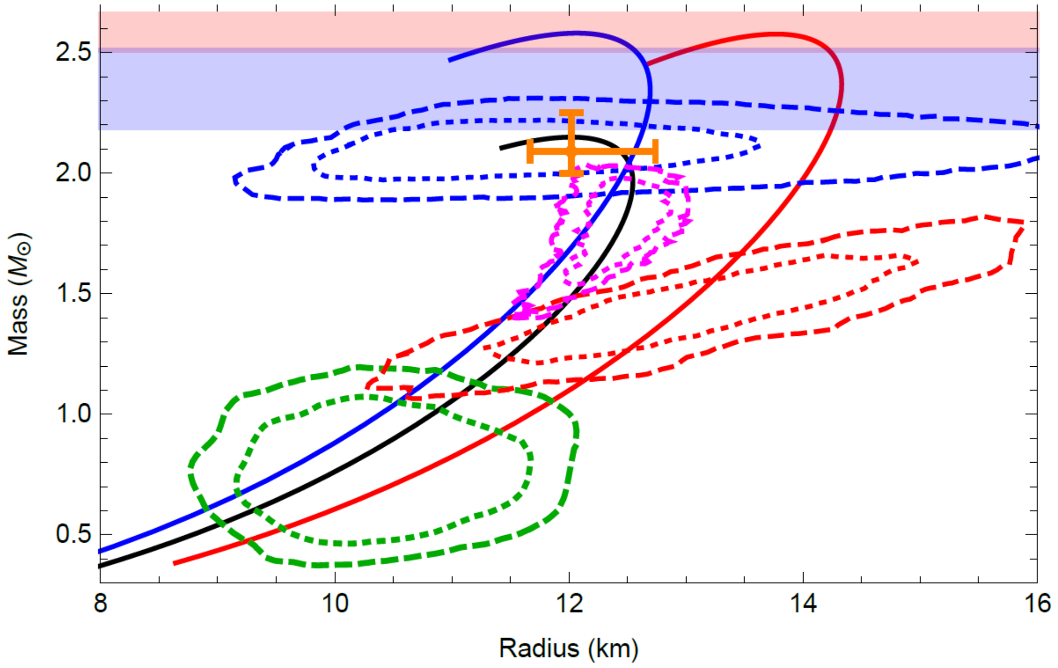
WD

Possibile *subsolar* mass Strange Star

Reaching the neutron drip density allows the onset of a so - called «rapid transition» that destabilizes the star triggering its collapse.



Hess J1731-347



M_b	M_g^{NS}	$M_{g,A}^{QS}$	$M_{g,B}^{QS}$	$M_{g,C}^{QS}$
1.28	1.17	0.99	1.00	0.95 – 1.05
1.32	1.20	1.01	1.03	0.98 – 1.08

Strange dwarfs are not the only way to produce ***subsolar mass compact objects***.

It is possible to produce a low-mass neutron star via ***electron-capture*** supernova (ECSN), but it wouldn't be a subsolar one.

The core of the progenitor, during its evolution will be dense enough to stop strangelets and depending on the exposure time and on the zone in the galaxy, it could capture one before going into an ECSN. At this point the outcome would be ***a subsolar mass strange star***.

Remarks

- Bodmer-Witten hypothesis opens to astrophysical and cosmological scenarios
- Two-families scenario is testable through BHNS mergers
- Astrophysical observables connected to strangelets existence: subsolar mass compact objects, gamma ray excess from the galactic center, solar flares (*Bertolucci, S. et al. (2016)*) etc.
- We need a more “realistic” model for strange stars

Bibliography

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