INFN FERRARA
Istituto Nazionale di Fisica Nucleare
Sezione di Ferrara

NEUMATT
NEUtron star MATter Theory

Università degli Studi di Ferrara

Merger of a Neutron Star with a Black Hole: one-family versus two-families scenario

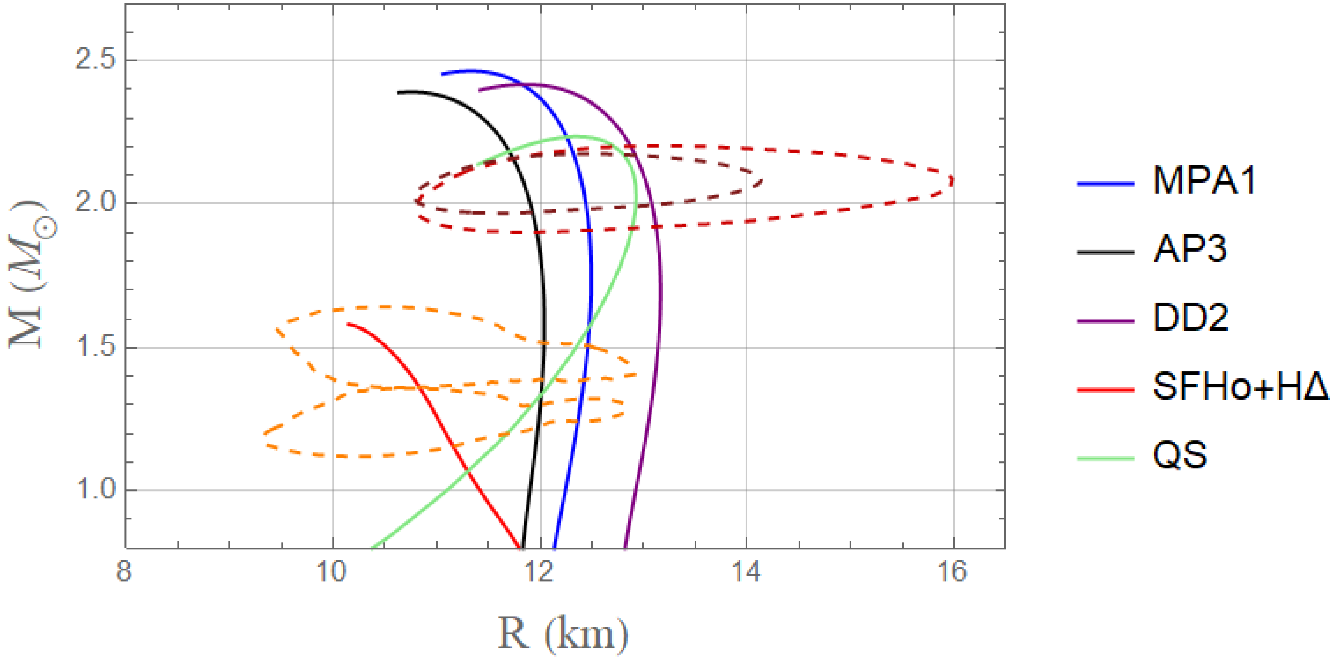
Francesco Di Clemente, Alessandro Drago, Giuseppe Pagliara, 2022, *The Astrophysical Journal*, **929** 44

Francesco Di Clemente

August 2nd, 2022

The XVth Quark confinement and the Hadron spectrum conference – Stavanger U.

The two-families scenario



Dashed orange: MR constraint on GW170817.
Red and dark red: analysis on NICER data of J0740+6620 from Riley et al. (2021) and from Miller et al. (2021).

One-family → one hadronic equation of state which is rather stiff as NICER results suggest

Two-families → coexistence of hadronic star branch and quark star branch.

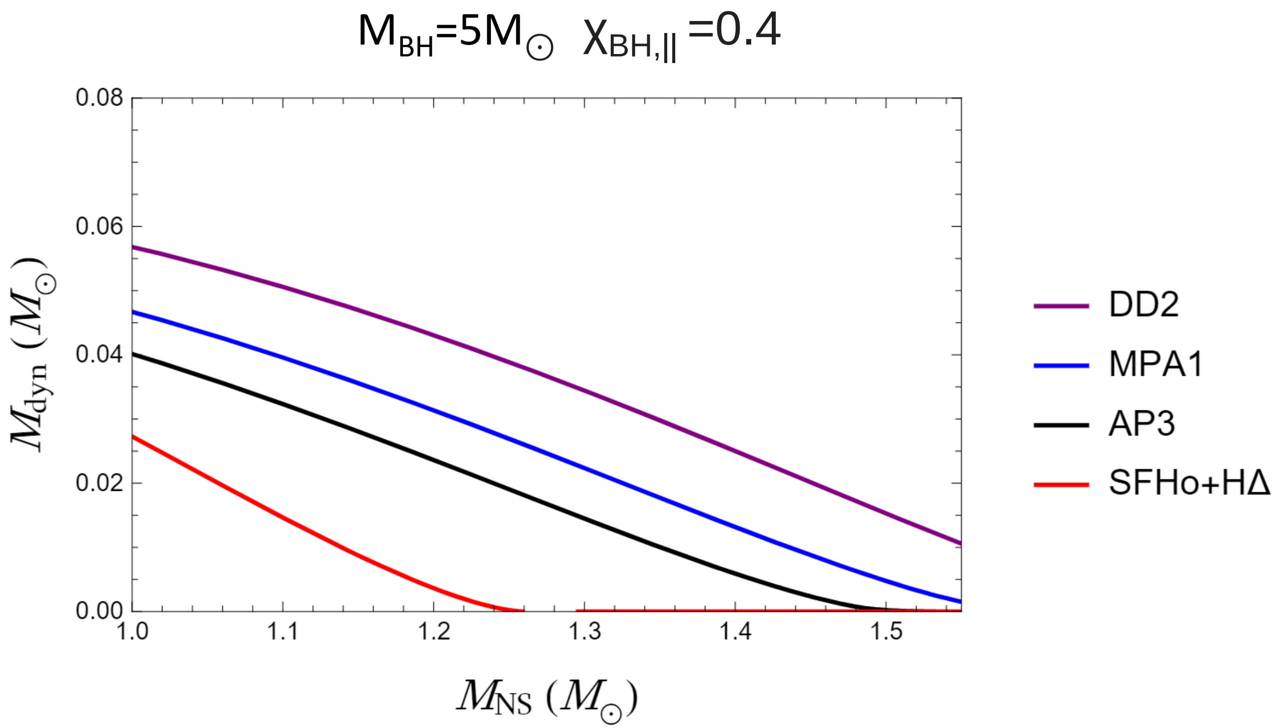
BH-NS merger – How to test the two-families scenario?

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

BH-NS merger – How to test the two-families scenario?



Gravitational unbound mass from **semi-analytical models** from Barbieri et al. (2020), Foucart et al. (2018), Kawaguchi et al. (2016)

Calculations only for the **hadronic branch.**

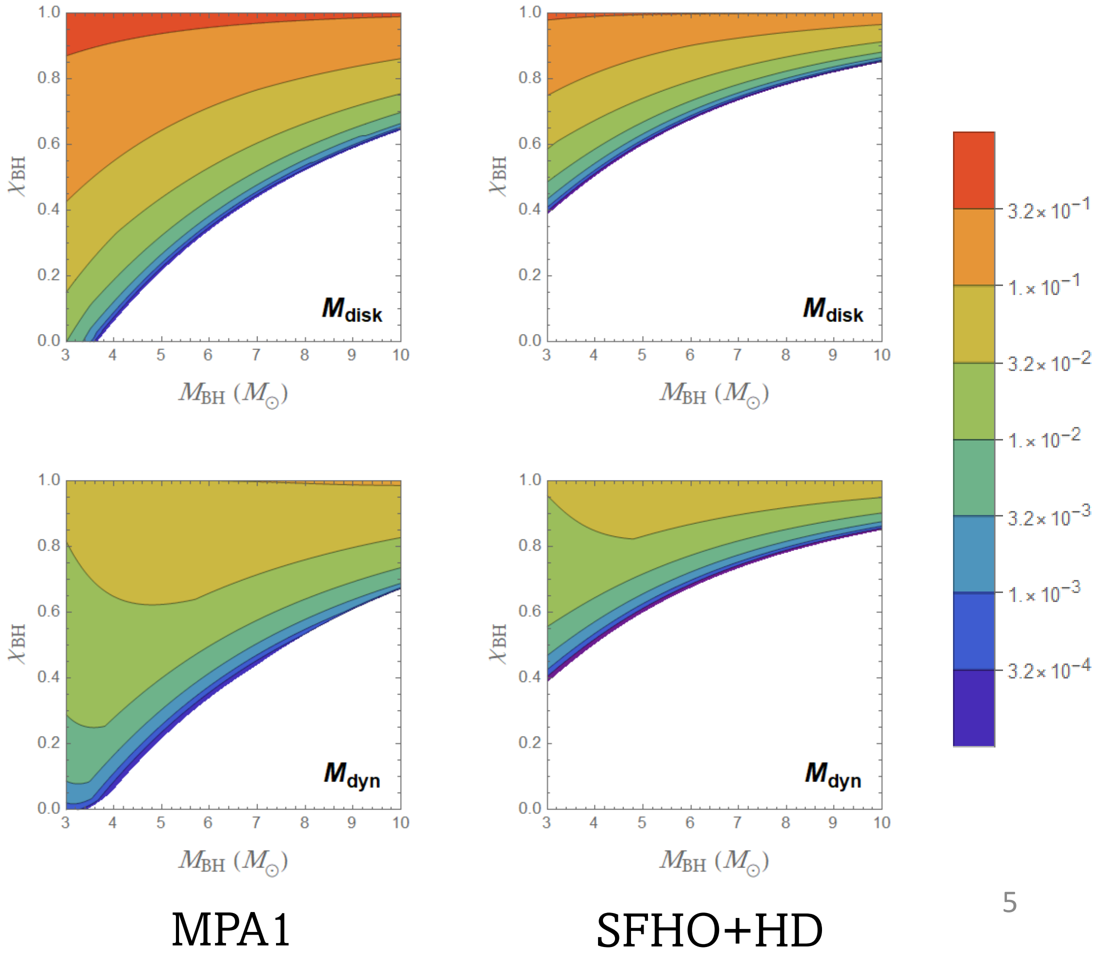
$$M_{\rm out} = M_{\rm NS}^{\rm b}\left[\max\left(\alpha\frac{1-2\rho}{\eta^{1/3}} - \beta\tilde{R}_{\rm ISCO}\frac{\rho}{\eta} + \gamma, 0\right)\right]^{\delta}$$

$$\begin{aligned} M_{\rm dyn} = M_{\rm NS}^{\rm b}\Big\{&\max\big[a_1 q^{-n_1}(1-2C_{\rm NS})/C_{\rm NS} + \\ &- a_2 q^{-n_2}\tilde{R}_{\rm ISCO}(\chi_{\rm BH,||}) + \\ &+ a_3(1 - M_{\rm NS}/M_{\rm NS}^{\rm b}) + a_4, 0\big]\Big\} \end{aligned}$$

BH-NS merger

A region of the parameter space in which we expect a **strong kilonova** signal in the one-family case, correspond to a **weak kilonova** signal in the two-families scenario.

Weak kilonova signal expected from a quark star-black hole merger (but we need more simulations!)



BH-NS merger – a toy model for observations

Original toy-model by Ng et al. (2018, PRD, 98, 083007)

$$\mathcal{L}(M_{\rm NS}, M_{\rm BH}, \chi_{\rm eff}) = \mathcal{N}(\psi(M_{\rm NS}, M_{\rm BH}, \chi_{\rm eff}); \psi_0, \sigma_\psi)\times \mathcal{N}(\eta(M_{\rm NS}, M_{\rm BH}); \eta_0, \sigma_\eta)$$

Our toy-model with an additional constraint on the chirp mass

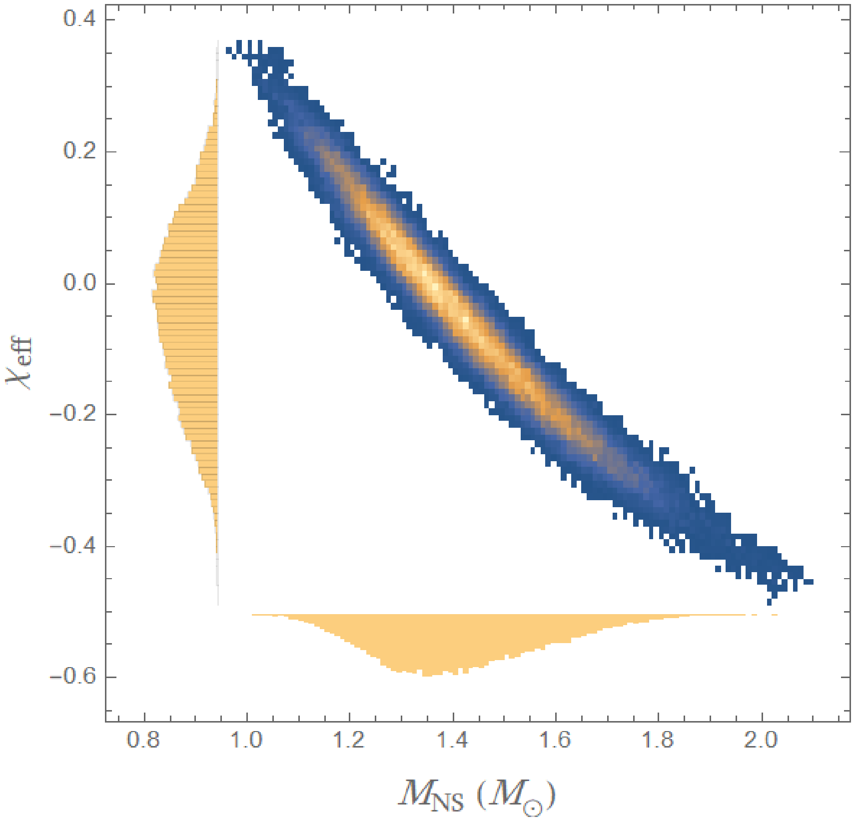
$$\mathcal{L}_{\rm total}(M_{\rm NS}, M_{\rm BH}, \chi_{\rm eff}) = \mathcal{L}(M_{\rm NS}, M_{\rm BH}, \chi_{\rm eff})\times \mathcal{N}(M_{\rm chirp}(M_{\rm NS}, M_{\rm BH}); M_{\rm chirp,0}, \sigma_{M_{\rm chirp}})$$

Toy-model which emulates Ligo-VIRGO uncertanties and correlation between physical quantities.

More realistic prediction **including uncertanties**.

Predictions based on oncoming **update of the interferometers** (O4 run) and on **next-generation telescope** (Vera Rubin Observatory)

BH-NS merger – a toy model for observations



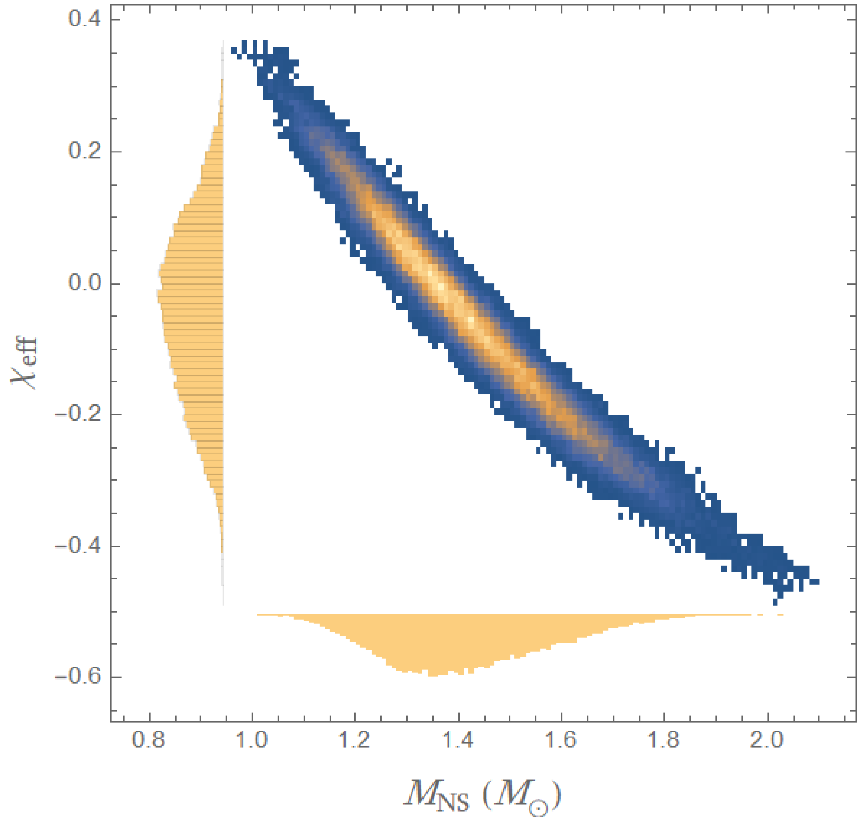
Example of the spin-mass correlation we obtain from the toy model using central values and uncertantiers based on LV analysis of GW200115

Toy-model which emulates Ligo-VIRGO uncertanties and correlation between physical quantities.

More realistic prediction **including uncertanties**.

Predictions based on oncoming **update of the interferometers** (O4 run) and on **next-generation telescope** (Vera Rubin Observatory)

BH-NS merger – simulate an observation



Example of the spin-mass correlation we obtain from the toy model using central values and uncertantiers based on LV analysis of GW200115

1 - for each event we want to analyze, we generate an ensemble of points according to the toy-model likelihood.

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, λ_{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.

BH-NS merger – LVK O4 run

Run	BNS	NSBH	BBH
Sensitive volume (10^6 Mpc^3) [i ii]			
O3	$17.5^{+1.4}_{-1.3}$	$101.1^{+6.4}_{-6.1}$	1047^{+50}_{-49}
O4	$109.0^{+6.7}_{-6.5}$	558^{+26}_{-26}	4450^{+130}_{-130}
O5	590^{+29}_{-28}	2787^{+89}_{-87}	19950^{+310}_{-310}
Annual number of detections [iii iv]			
O3	5^{+14}_{-5}	13^{+15}_{-9}	24^{+18}_{-12}
O4	34^{+78}_{-25}	72^{+75}_{-38}	106^{+65}_{-42}
O5	190^{+410}_{-130}	360^{+360}_{-180}	480^{+280}_{-180}
Median luminosity distance (Mpc) [i]			
O3	$176.1^{+6.2}_{-5.7}$	$337.6^{+10.9}_{-9.6}$	871^{+31}_{-28}
O4	$352.8^{+10.3}_{-9.8}$	621^{+16}_{-14}	1493^{+25}_{-33}
O5	620^{+16}_{-17}	1132^{+19}_{-23}	2748^{+30}_{-34}

Polina Petrov *et al* 2022 *ApJ* **924** 54

Annual number of detections

O3 13^{+15}_{-9} O4 72^{+75}_{-38}.

Median luminosity distance (Mpc)

O3 $337.6^{+10.9}_{-9.6}$ O4 621^{+16}_{-14}.

Great improvement expected for the O4 run!

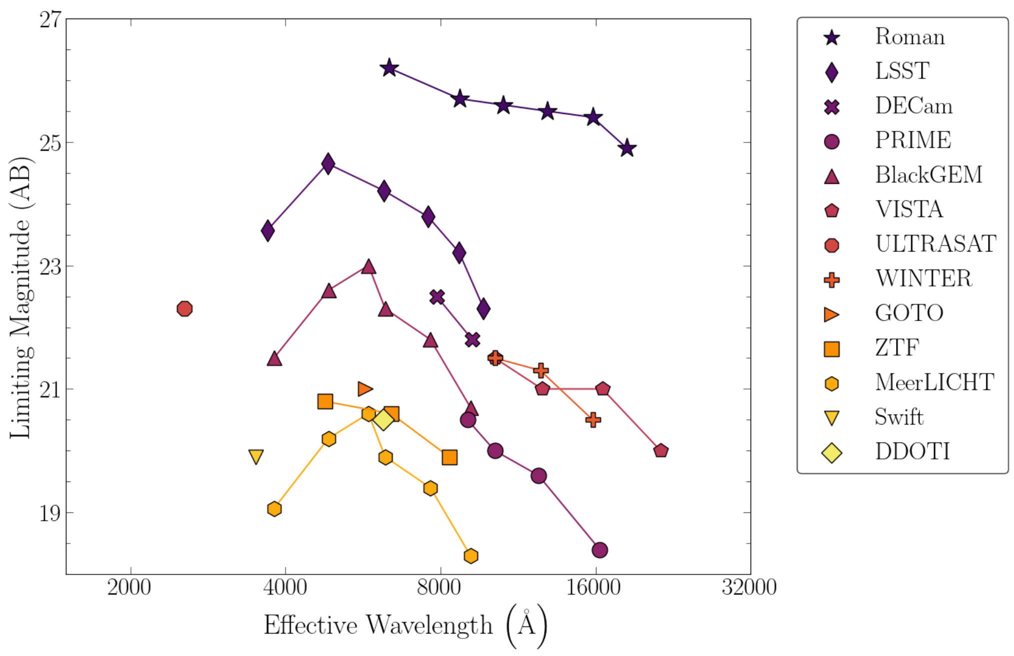
BH-NS merger – expectations

If we have an event **at 200 Mpc** *having*:

5 M⊙ central value of BH mass;
1.3 M⊙ central value of NS mass;
0.2 central value of effective adimensional spin parameter of the system

An observation with ***NO EM COUNTERPART*** *after 1 day from the merger in the g-band (within the observing range in magnitude of LSST of VRO) would be compatible with*

$\sigma \sim \sigma_{LV}$	$\sigma \sim 0.5\,\sigma_{LV}$
SFHO+HD 90%	**SFHO+HD 98%**
DD2 17%	**DD2 4%**
MPA1 33%	**MPA1 21%**
AP3 47%	**AP3 45%**

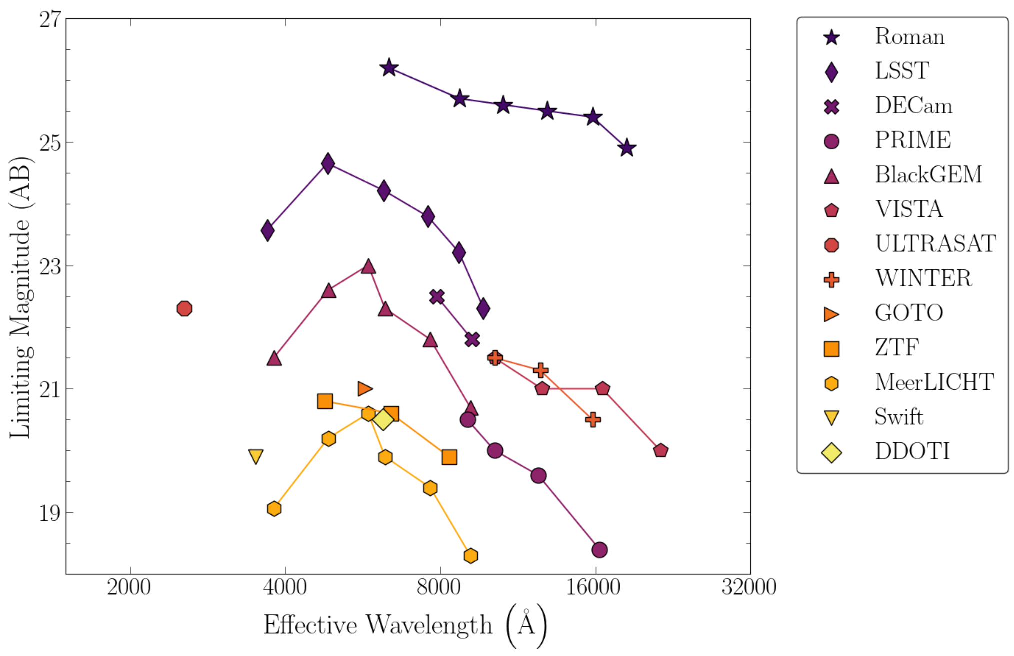


Limiting magnitude for several telescopes. Chase et al. (2021)

BH-NS merger – expectations

Roman: 0.28 square degrees
LSST: 9.6 square degrees

LSST will be a game changer for the physics of compact stars!

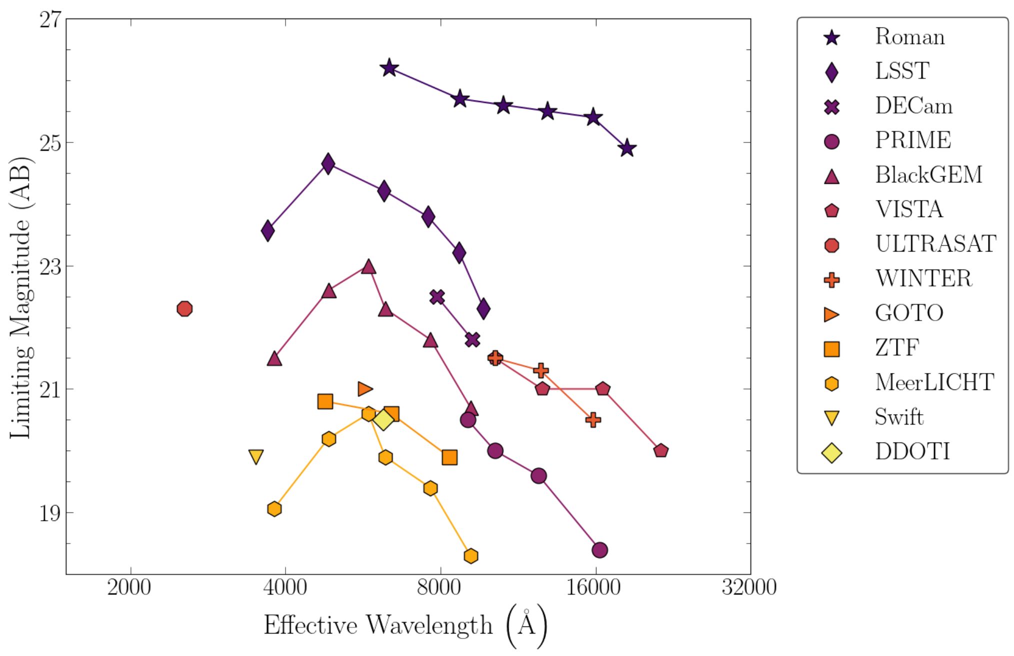


Limiting magnitude for several telescopes. Chase et al. (2021)

BH-NS merger – expectations

	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. We are considering two different uncertainties on the measurements of the central values.



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

Conclusions and Remarks

- Very strong difference in observation of KN signal by BHNS merger between one-family and two-families

- The absence of a KN can be interpreted as a softening in the EoS

- *We still need new simulations of Strange Star – Black Hole merger*

Thank you!

Francesco Di Clemente, Alessandro Drago, Giuseppe Pagliara, 2022, *The Astrophysical Journal*, **929** 44

INFN FERRARA
Istituto Nazionale di Fisica Nucleare
Sezione di Ferrara

NEUMATT
NEUtron star MATter Theory

FERRARIAE UNIVERSITAS · EX LABORE FRUCTUS · 13 91
Università degli Studi di Ferrara