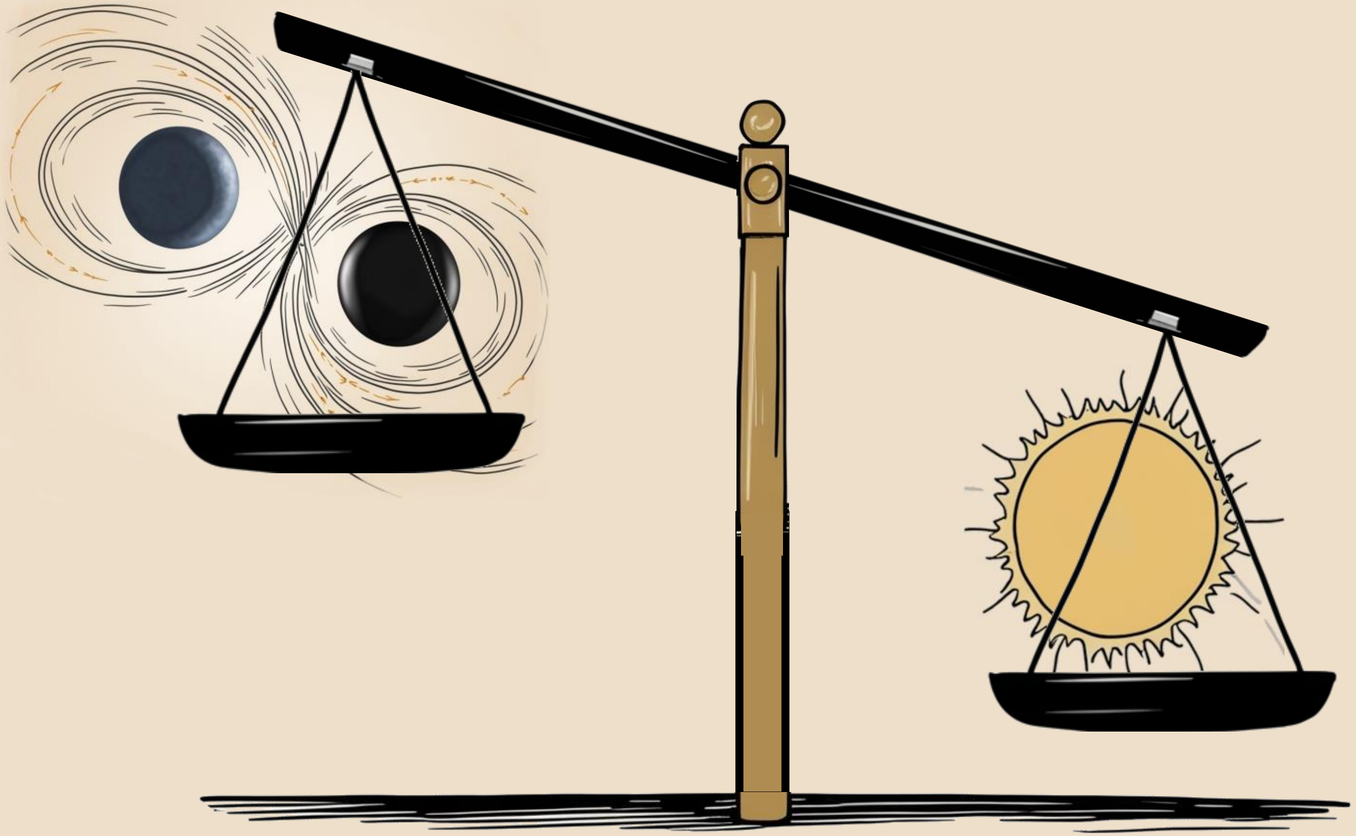
Gravitational waves from subsolar compact objects: implications for cosmology and high-density nuclear physics



Massimo Vaglio 18/09/2024

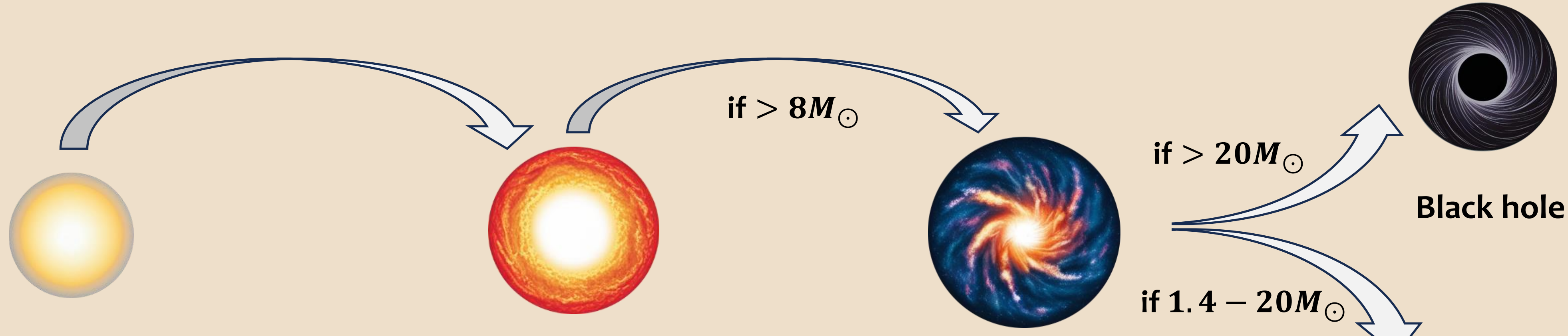
1st TEONGRAV workshop on Gravitational Waves

Based on: arXiv:2508.14287 – F.Crescimbeni, G.Franciolini, P.Pani, M.Vaglio

SISSA

Why subsolar? Standard formation scenario of BH-NS

Conventional formation models suggest that black holes (BHs) and neutron stars (NSs), should have masses exceeding the solar mass



if $> 8M_\odot$

if $> 20M_\odot$

if $1.4 - 20M_\odot$

Main sequence star

Fusion of hydrogen into helium in the core, stable equilibrium

Red giant

Hydrogen in core depleted; core contracts and heats up, outer layers expand and cool

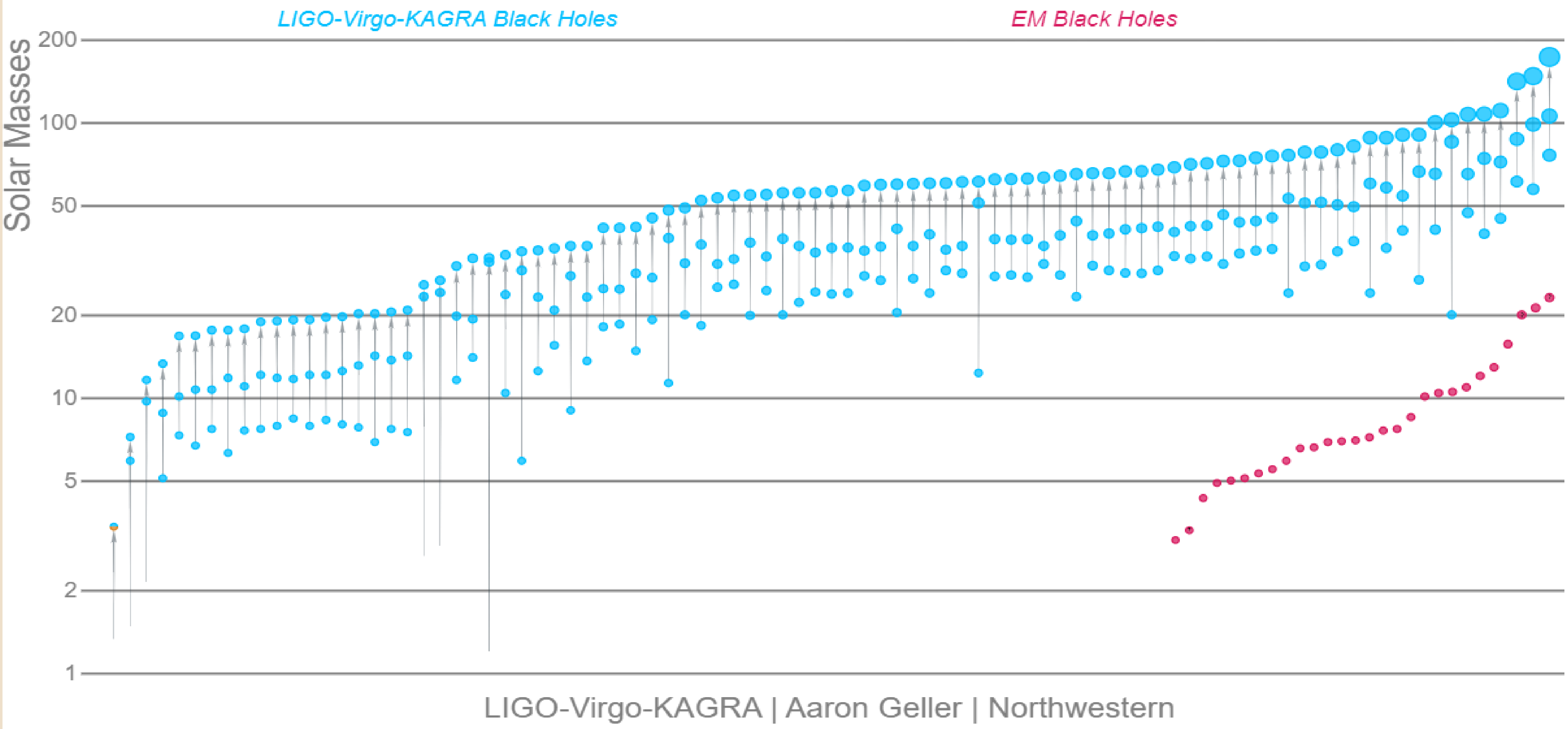
Supernova

Core collapse after fusion processes end; shockwave expels outer layers

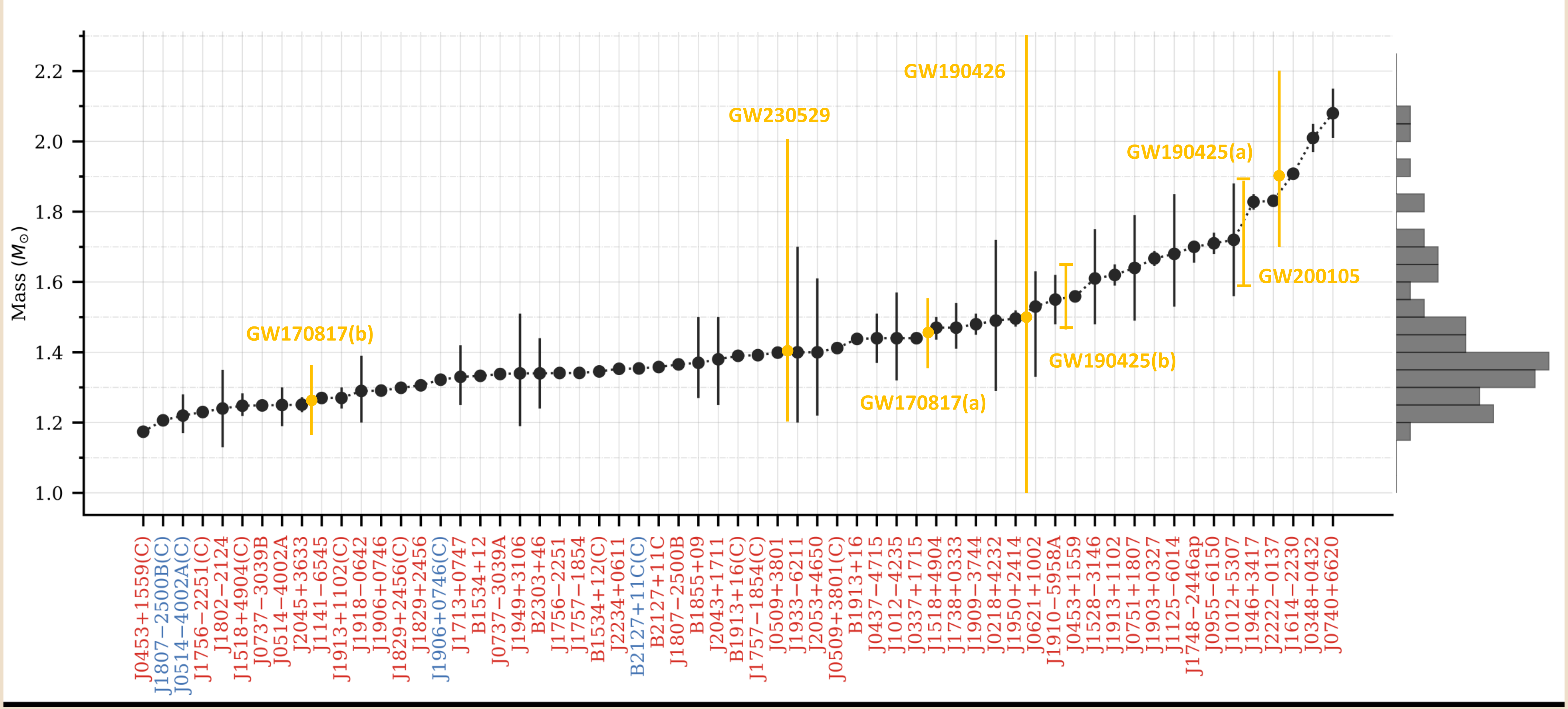
Black hole

Neutron star

Mass distribution of black holes (EM+GW)



Mass distribution of neutron stars (binary pulsars + GW)



Modified from [Paulo Freire / Vivek Krishnan]

What would be the implications of a subsolar GW event?

Methodology & models

We performed parameter estimation on real and mock data and compute the Bayes factors to compare different models

$$p(\boldsymbol{\theta}|s) = \frac{\mathcal{L}(s|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\mathcal{Z}(s)}$$

Bayes formula

$$\mathcal{B}_{A/B} = \frac{\mathcal{Z}_A}{\mathcal{Z}_B}$$

Bayes factor

We used the public software BILBY [G. Ashton et al. (2019)] and a waveform template:

Frequency-domain TaylorF2

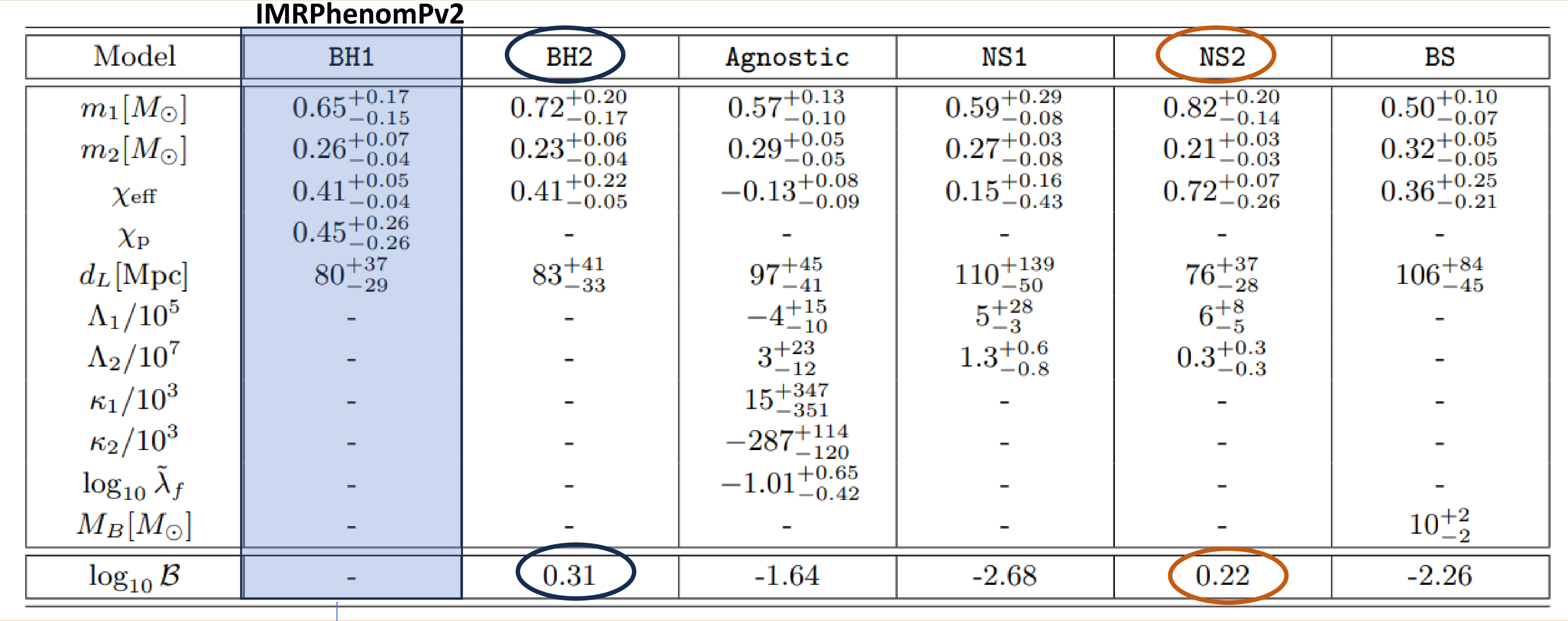
$$\tilde{h}(f,\boldsymbol{\theta}) = \mathcal{A}(f,\boldsymbol{\theta})e^{-i\phi(f,\boldsymbol{\theta})}$$

Quasicircular
Alligned spins
3.5 pN point particle
2pN spin corrections

Parameters: $\boldsymbol{\theta} = \{m_1, m_2, d_L, \theta, \phi, \theta_{JN}, \psi, t_c, \phi_c, \chi_1, \chi_2\}$

Analyzing the trigger event SSM200308

In the last concluded LVK observing run (O3b) three candidates of SSM binary BH events were identified, SSM200308 was the loudest.



IMRPhenomPv2

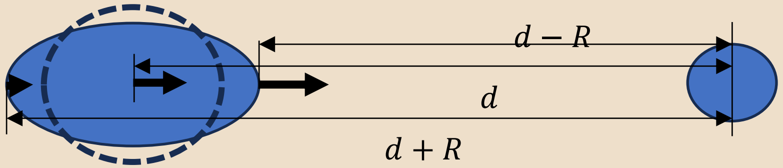
Model	BH1	BH2	Agnostic	NS1	NS2	BS
$m_1[M_\odot]$	$0.65^{+0.17}_{-0.15}$	$0.72^{+0.20}_{-0.17}$	$0.57^{+0.13}_{-0.10}$	$0.59^{+0.29}_{-0.08}$	$0.82^{+0.20}_{-0.14}$	$0.50^{+0.10}_{-0.07}$
$m_2[M_\odot]$	$0.26^{+0.07}_{-0.04}$	$0.23^{+0.06}_{-0.04}$	$0.29^{+0.05}_{-0.05}$	$0.27^{+0.03}_{-0.08}$	$0.21^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$
$\chi_{\rm eff}$	$0.41^{+0.05}_{-0.04}$	$0.41^{+0.22}_{-0.05}$	$-0.13^{+0.08}_{-0.09}$	$0.15^{+0.16}_{-0.43}$	$0.72^{+0.07}_{-0.26}$	$0.36^{+0.25}_{-0.21}$
$\chi_{\rm p}$	$0.45^{+0.26}_{-0.26}$	-	-	-	-	-
$d_L[\mathrm{Mpc}]$	80^{+37}_{-29}	83^{+41}_{-33}	97^{+45}_{-41}	110^{+139}_{-50}	76^{+37}_{-28}	106^{+84}_{-45}
$\Lambda_1/10^5$	-	-	-4^{+15}_{-10}	5^{+28}_{-3}	6^{+8}_{-5}	-
$\Lambda_2/10^7$	-	-	3^{+23}_{-12}	$1.3^{+0.6}_{-0.8}$	$0.3^{+0.3}_{-0.3}$	-
$\kappa_1/10^3$	-	-	15^{+347}_{-351}	-	-	-
$\kappa_2/10^3$	-	-	-287^{+114}_{-120}	-	-	-
$\log_{10}\tilde{\lambda}_f$	-	-	$-1.01^{+0.65}_{-0.42}$	-	-	-
$M_B[M_\odot]$	-	-	-	-	-	10^{+2}_{-2}
$\log_{10}\mathcal{B}$	-	0.31	-1.64	-2.68	0.22	-2.26

M. Prunier et al. (2023)

NS2 vs BH2

NS2 = BH2 + Tidal + Tapering $\boldsymbol{\theta}_{\boldsymbol{NS2}} = \boldsymbol{\theta}_{\boldsymbol{BH2}} \cup \{\Lambda_1, \Lambda_2\}$

Tidal



$$g_{00} = -1 + \frac{2M}{r} + \frac{3Q_{ij}}{r^3}\left(n_i n_j - \frac{\delta_{ij}}{3}\right) + O\left(\frac{1}{r^4}\right) - \varepsilon_{ij} x_i x_j + O(r^3)$$

$$Q_{ij} = -\boxed{\Lambda}\,\varepsilon_{ij}$$

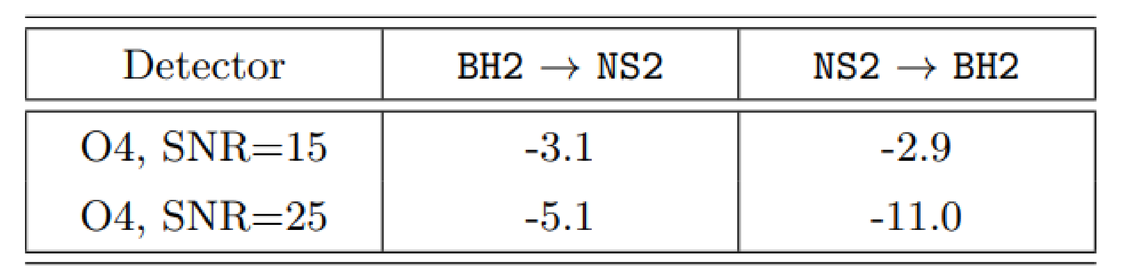
Tidal deformability, 5pN & 6pN

Tapering

$$\tilde{h}(f) \rightarrow \tilde{h}(f)\,\mathrm{T}\left(\mathrm{f} \middle| \mathrm{f_{cut}}, \mathrm{f_{slope}}\right)$$

$$\mathrm{T}\left(\mathrm{f} \middle| \mathrm{f_{cut}}, \mathrm{f_{slope}}\right) = \left[\frac{1 + e^{f_{cut}/f_{slope}}}{1 + e^{(f - f_{cut})/f_{slope}}}\right]$$

Tidal disruption

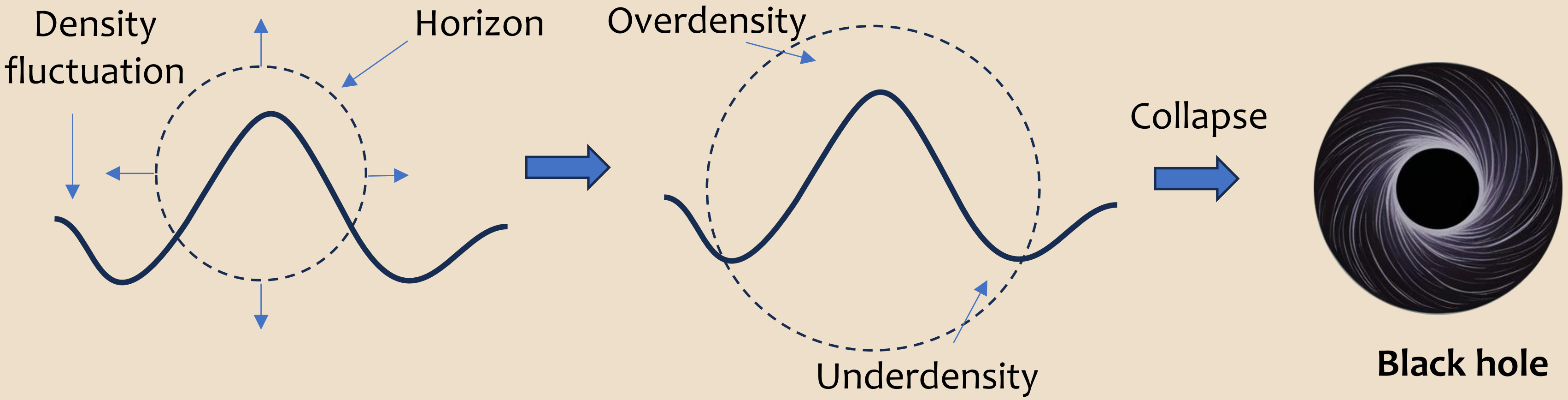


Detector	BH2 → NS2	NS2 → BH2
O4, SNR=15	-3.1	-2.9
O4, SNR=25	-5.1	-11.0

Implications for PBH: PBHs abundance

Primordial black holes are formed by collapse of overdense regions in in radiation dominated universe

$$M_{BH} \sim \frac{4\pi}{3}\rho_r H^{-3}$$ PBH Mass ~ horizon mass at the formation



Black hole

Based on a model saturating the bounds from GWTC-3, to explain an event like SSM200308 one would need

$$\frac{\rho_{PBH}}{\rho_{DM}} \equiv f_{PBH} \gtrsim \mathcal{O}(10^{-2})$$

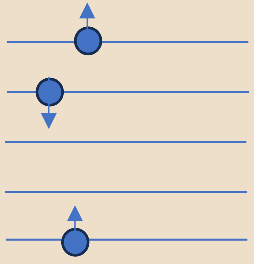
NSs equation of state (EoS)

Neutron stars are modelled as relativistic perfect fluids

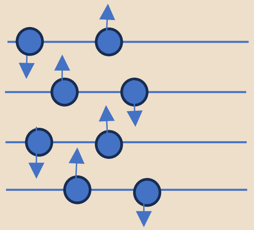
$$T_{\mu\nu} = (\epsilon + P)u_\mu u_\nu + P g_{\mu\nu}$$

$P(\epsilon)$ is the equation of state (EoS)

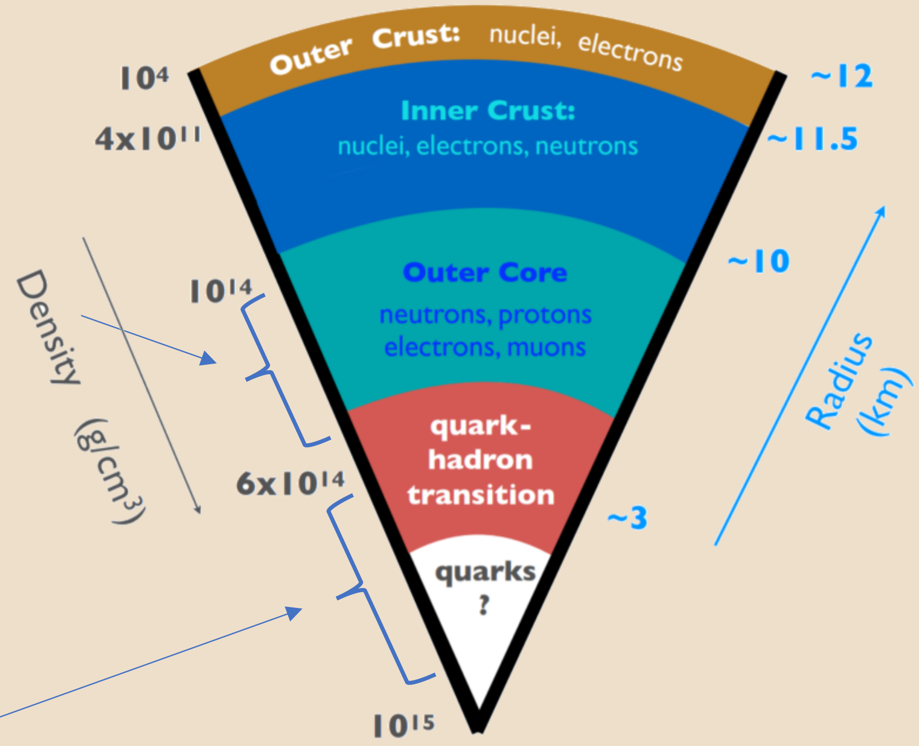
Degenerate neutron gas



Regular gas



Degenerate



State of matter largely unknown at high densities

Credit: 3G Science White Paper

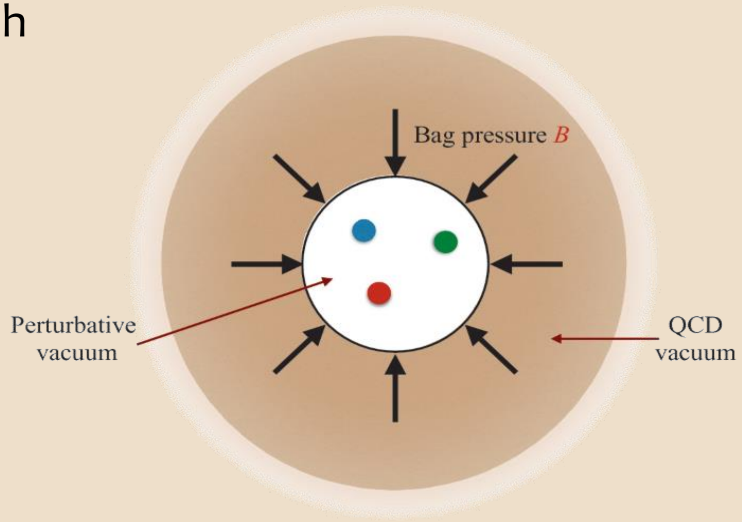
Strange quark-matter stars

Strange quark-matter models assumes a balance of up, down, and strange quarks.

EoS is obtained using perturbative QCD and an MIT-type bag model in which quarks are confined within a "bag" and interact via the strong force

J. M. Lattimer and M. Prakash (2001)

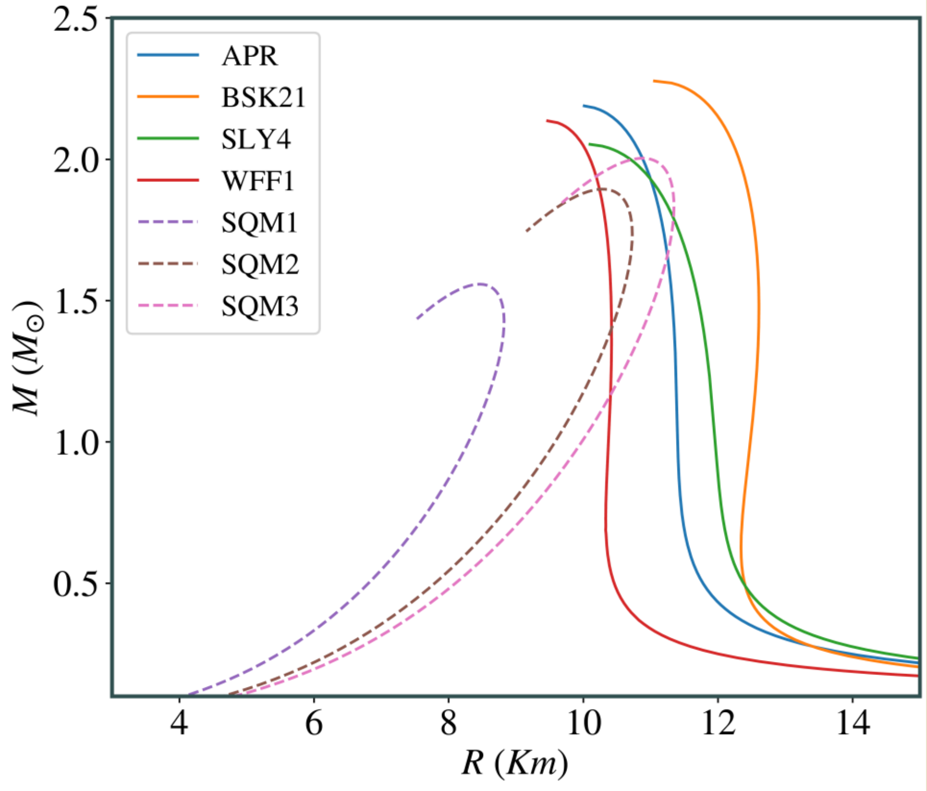
$$P(\epsilon) = \frac{\epsilon - B_{eff}}{3}$$



Features of Hadrons.
In: Journey to the Bound States.

This model often leads to a softer EoS compared to traditional neutron star matter because the pressure increase with density may be less steep

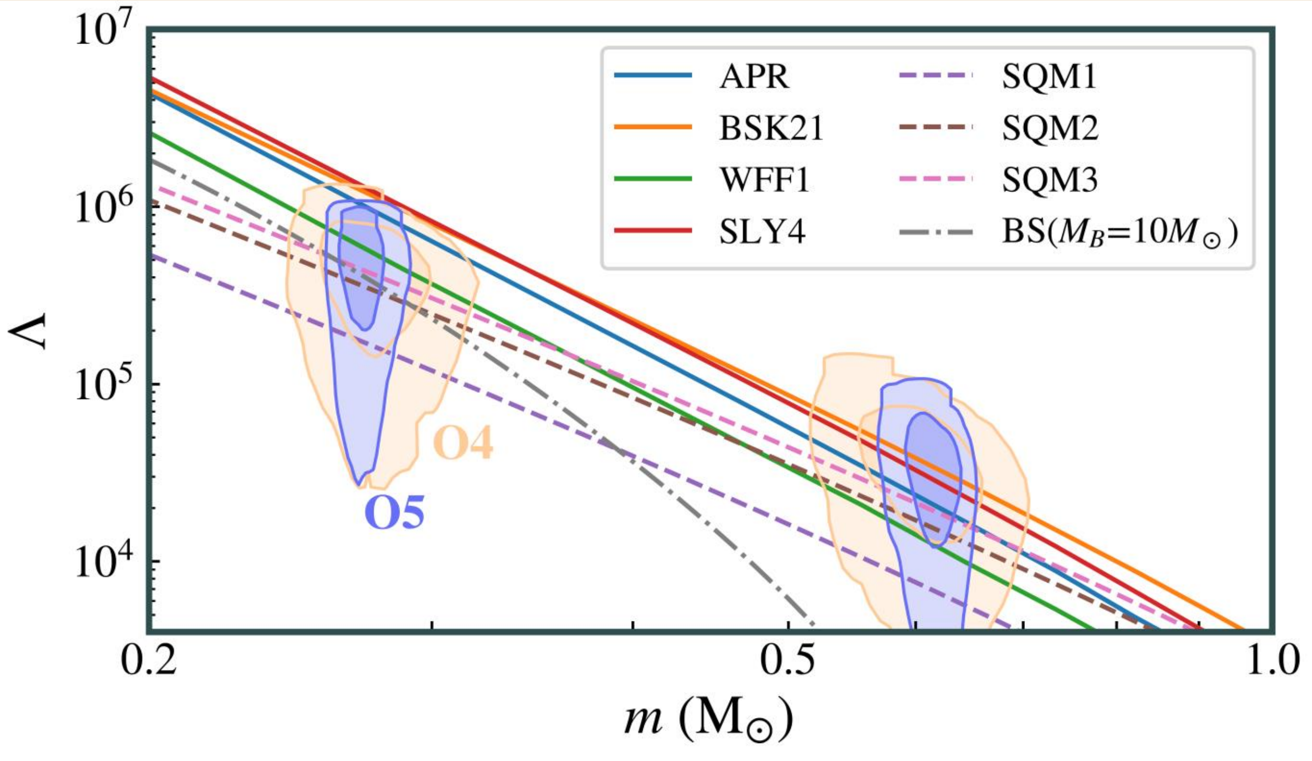
Implications for NSs: equation of state



EoS	Strongly interacting components
APR, BSK21, SLY4, WFF1	Protons and neutrons
SQM1-3	Quarks u,d,s

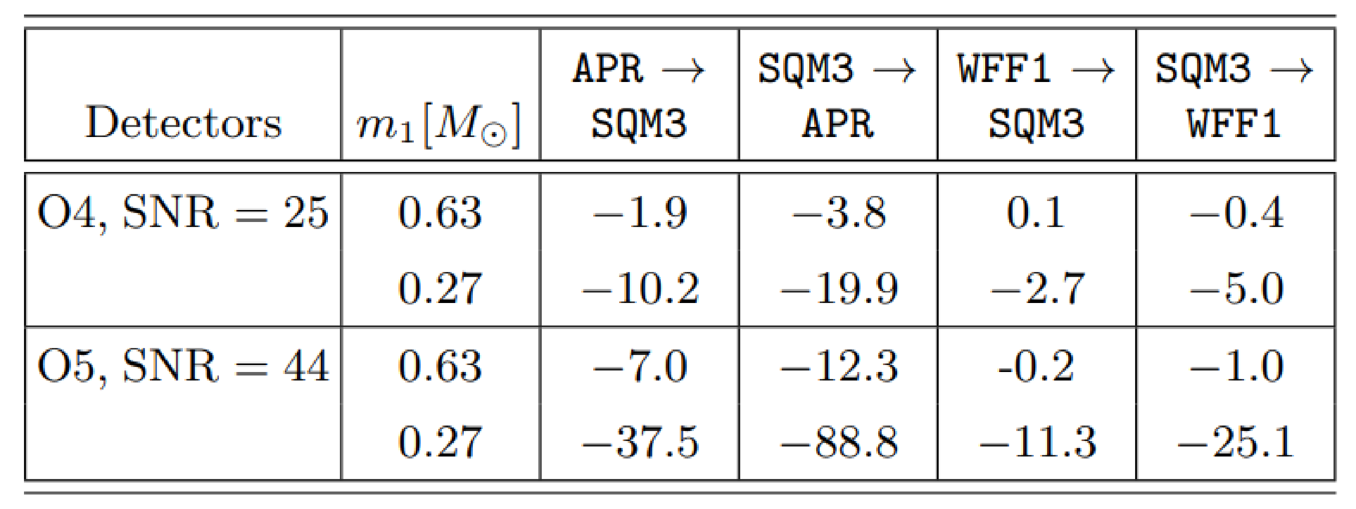
Implications for NSs: equation of state

SQM3 injected in O4 (O5) with SNR = 25 (SNR = 44)



The analysis is conservative: the inference considers Λ_1 and Λ_2 as independent

Implications for NSs: equation of state



Detectors	$m_1 [M_\odot]$	APR → SQM3	SQM3 → APR	WFF1 → SQM3	SQM3 → WFF1
O4, SNR = 25	0.63	−1.9	−3.8	0.1	−0.4
	0.27	−10.2	−19.9	−2.7	−5.0
O5, SNR = 44	0.63	−7.0	−12.3	-0.2	−1.0
	0.27	−37.5	−88.8	−11.3	−25.1

! With O4-O5 we will able to distinguish between strange stars and neutron stars in subsolar range

!! Excluding WFF1 requires higher SNR or light comparable-mass SSM binaries

Conclusions

- Already with current sensitivity one could decisively exclude some models of NSs and more exotic objects compared to the PBH hypothesis
- In O4 this distinction would be crystal-clear, confirming or ruling out a putative PBH event
- Using O4-O5 data it would be possible to use tidal-deformability measurements to decisively confirm/exclude light NSs with strange quark matter
- This opportunity is provided by the fact that quark stars have a much smaller radius and tidal deformability than ordinary-EoS NSs in the SSM range, while overall, the tidal is very large