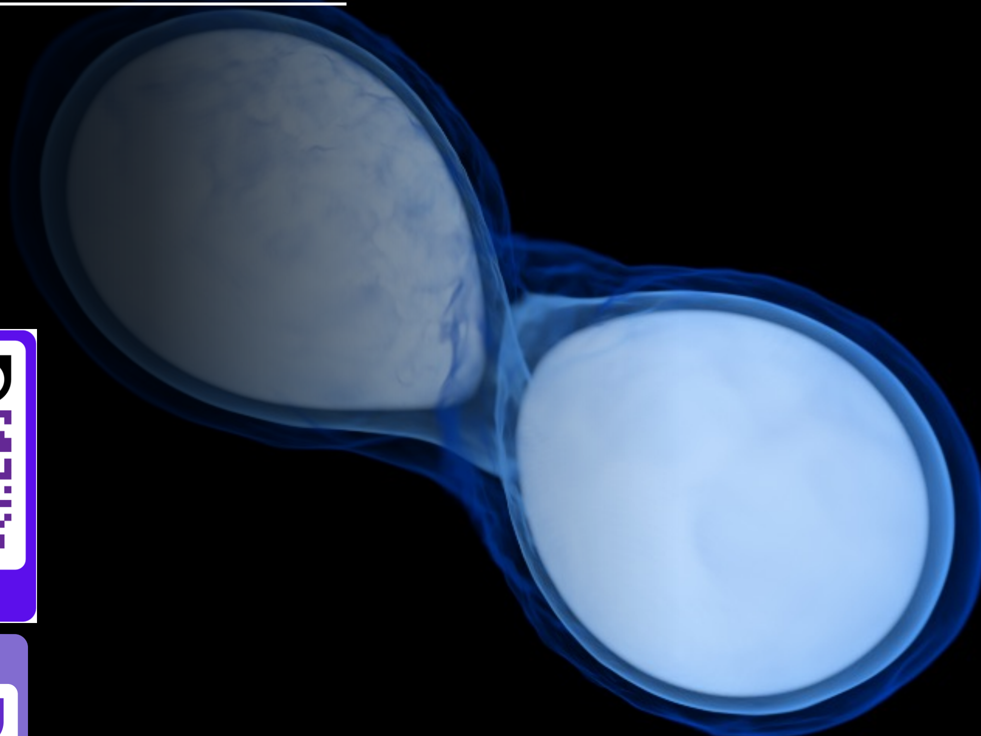
Thermal Effects in mergers of strange quark stars and neutron stars

Institute for Nuclear Theory

June 15, 2026



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University of New Hampshire

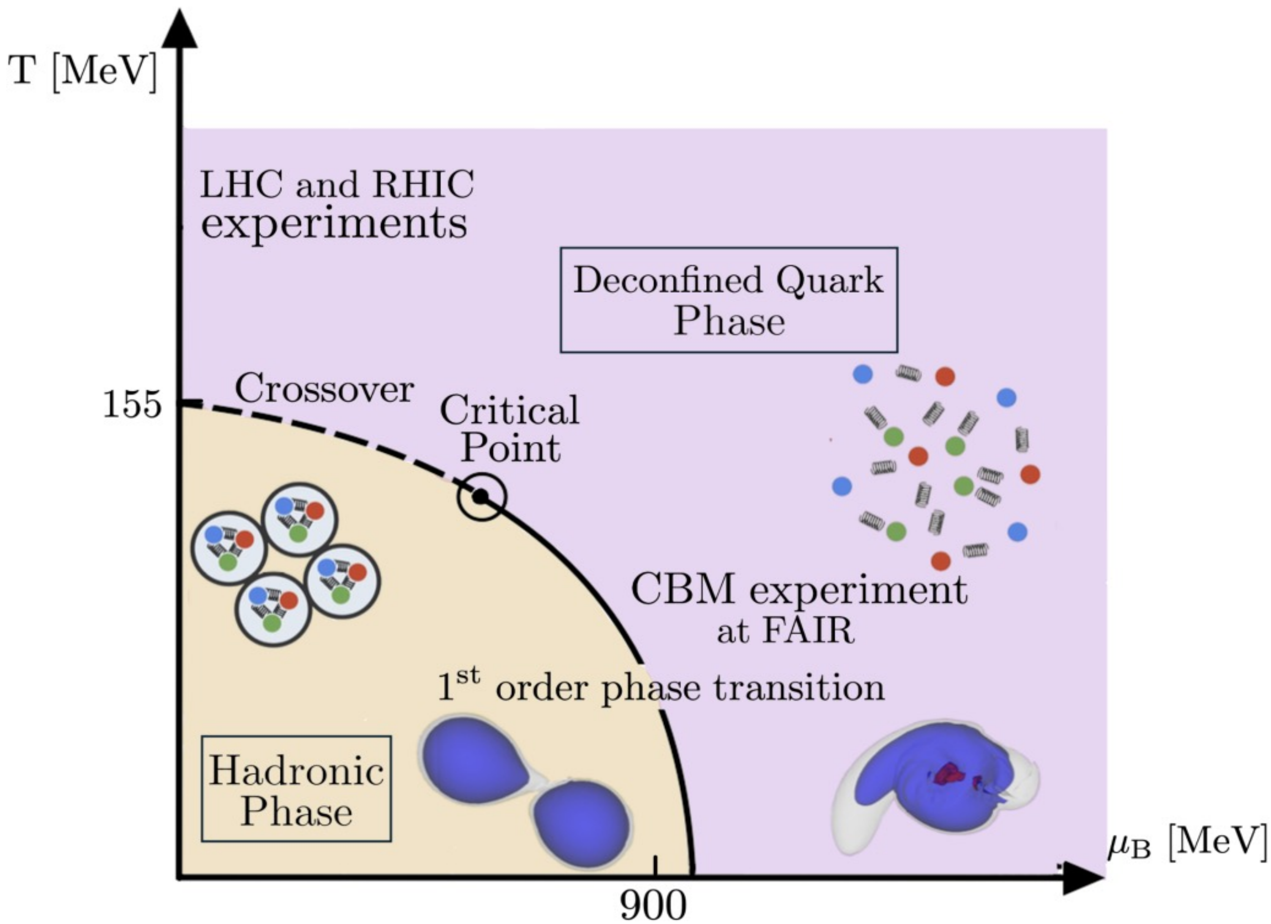
PennState

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries

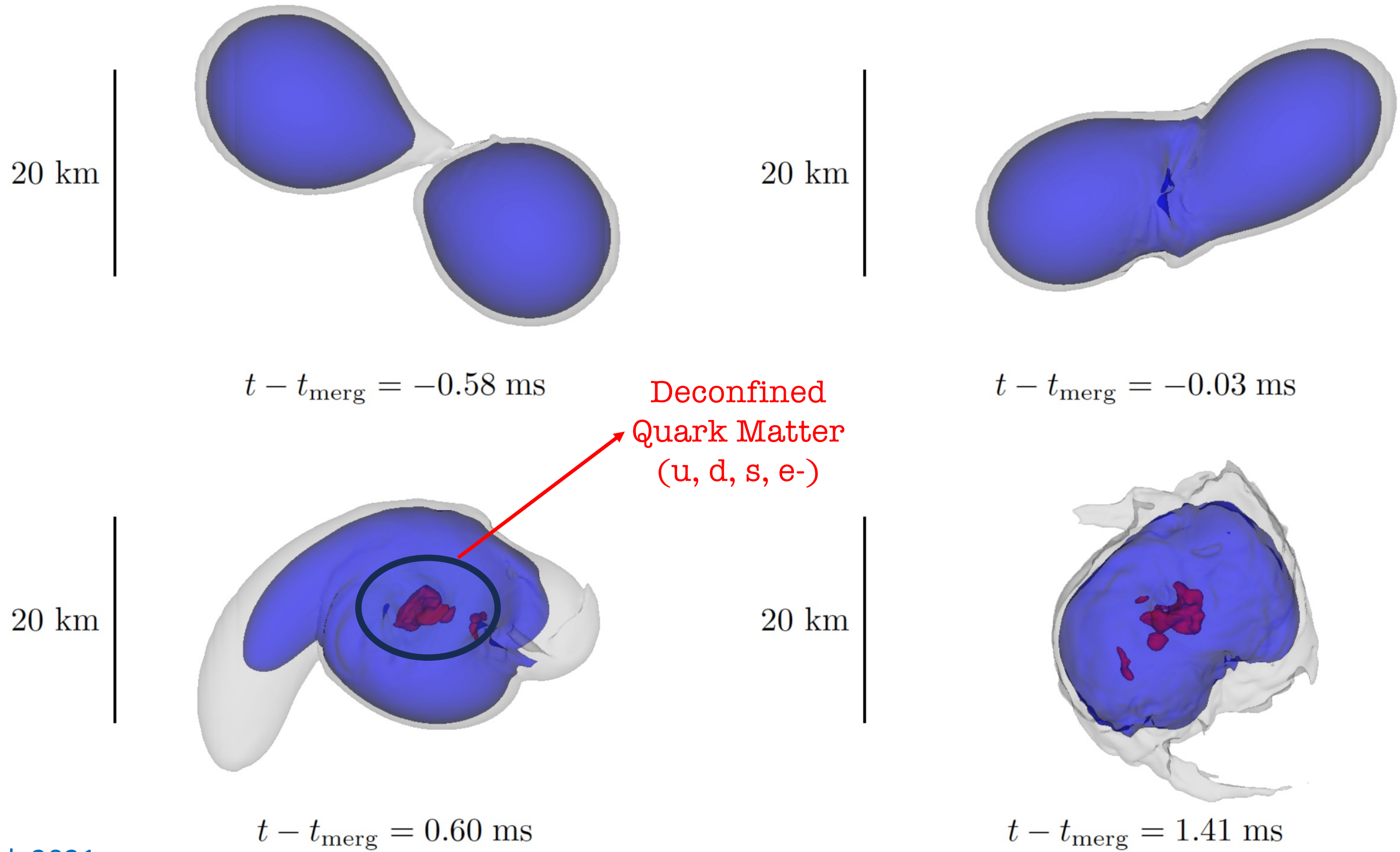
PHYSICS FRONTIER CENTER

NSF

Deconfined Quarks in BNS mergers



Deconfined Quarks in BNS mergers



Prakash et al. 2021

Deconfined Quarks in Heavy Neutron Stars

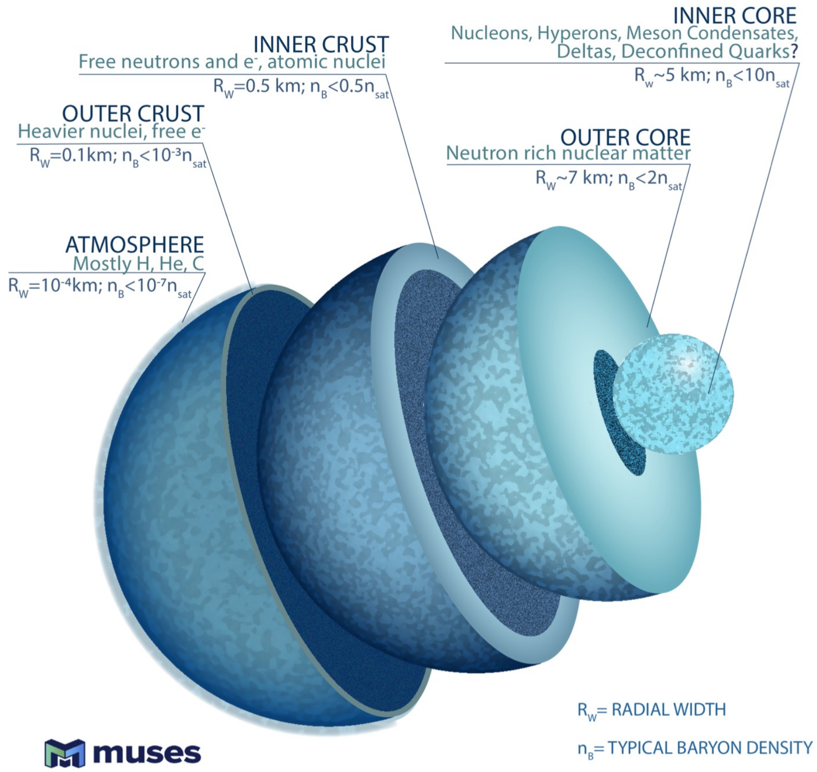


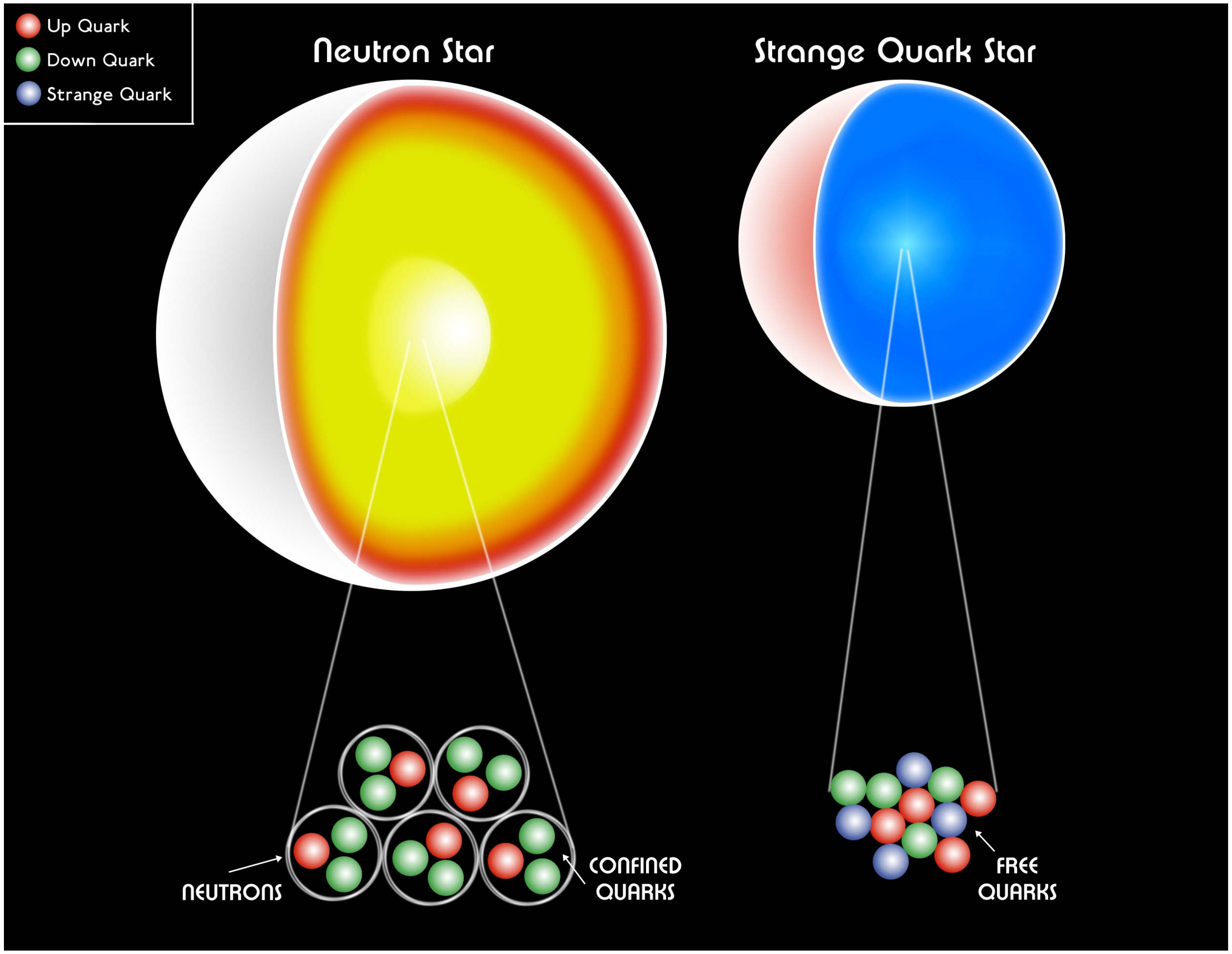
Image Credits: MUSES Collaboration

What are Strange Quark Stars?

A star made up entirely of the three lightest quark flavors (u), (d), and (s) quarks and a small number of electrons to maintain charge neutrality

Strange Stars are self-bound

Image Credits: [Chandra X-ray observatory NASA]

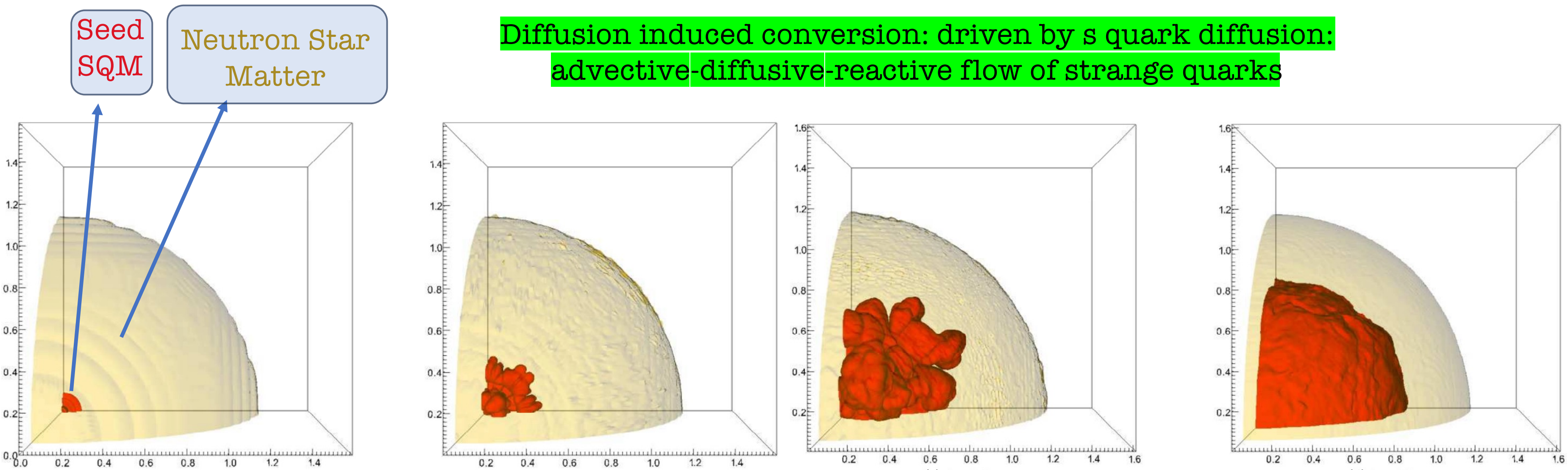


Formation Channels for Strange Quark Stars

- Bodemer Witten Hypothesis: SQM is absolutely stable. $(E/A)_{\mathrm{SQM}} < (E/A)_{\mathrm{Fe-56}} \sim 930\ \mathrm{MeV}$

- If this hypothesis were to be true, SQM being absolutely stable can convert any matter it comes into contact with, into SQM on some-timescale $\sim \tau_{\mathrm{weak}}$ or $\sim \tau_{\mathrm{shock}}$
- Other channels: supernovae, early proto-neutron star evolution, external seeding of strangelets

Diffusion induced conversion: driven by s quark diffusion:
advective-diffusive-reactive flow of strange quarks

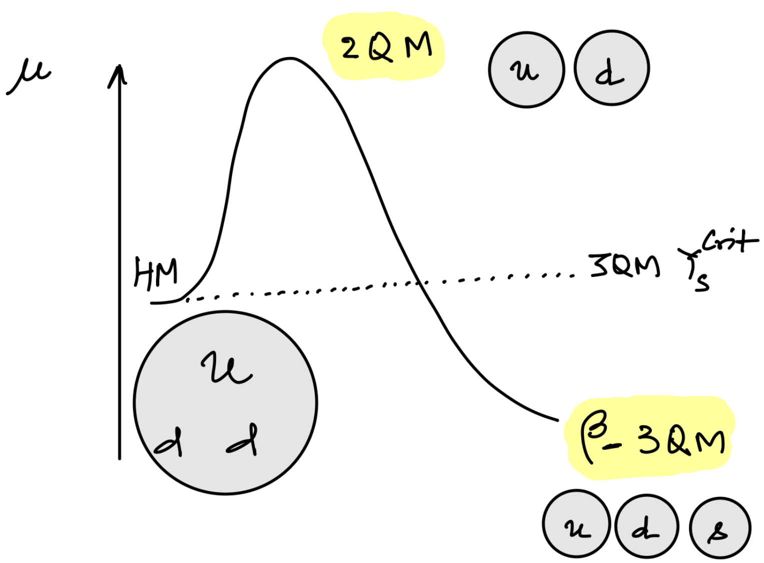


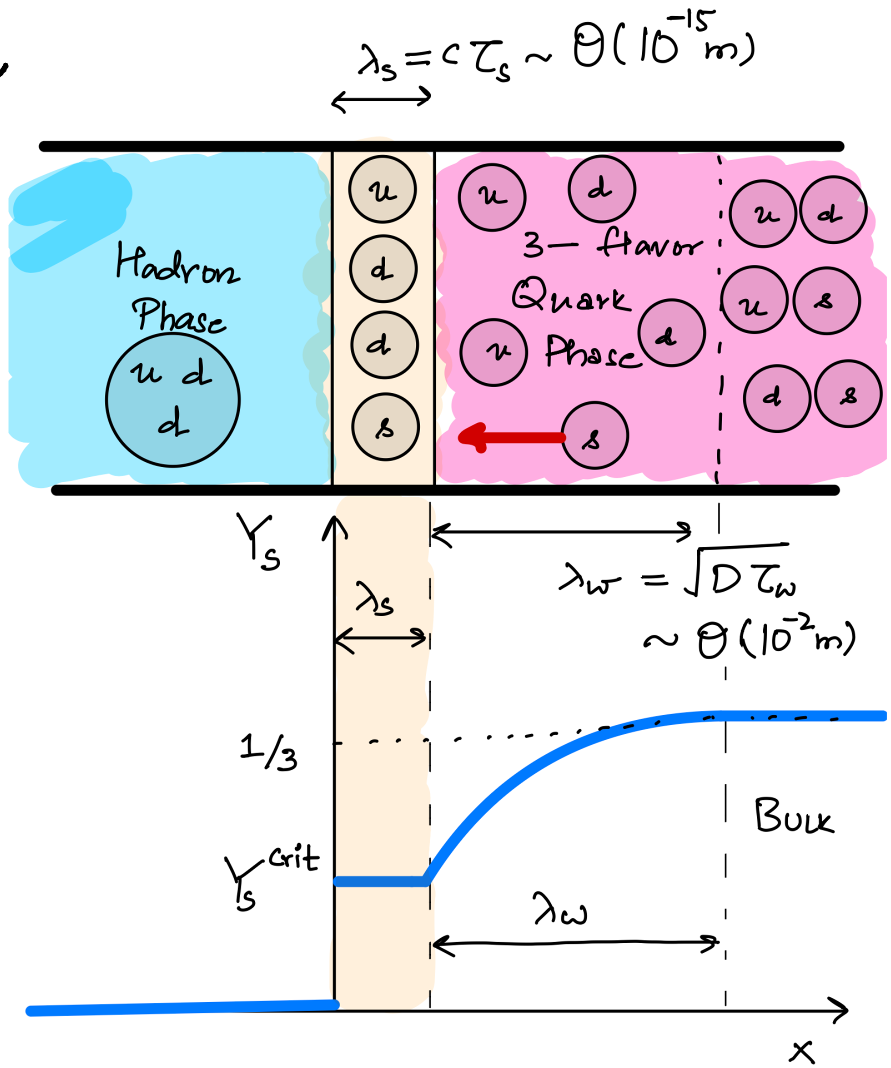
(a) $t = 0$ (b) $t = 0.7\,\mathrm{ms}$ (c) $t = 1.2\,\mathrm{ms}$ (d) $t = 4.0\,\mathrm{ms}$

Pagliara et al. 2013

Microphysical Combustion Modeling

Diffusive transport of strange quarks





$$\partial_i \left(n_q u_q^i Y_\mathrm{s}\right) \sim -\partial_i \left(D_\mathrm{s}(\mu, T)\partial^i n_q Y_\mathrm{s}\right)$$

Mergers of Strange Quark Stars: Equation of State

MIT Bag Model

$$n = \sum_i \frac{1}{3}\frac{g_s}{2\pi^2}\int_0^\infty k^2 E_i(k)\left(f_0(k,\mu_i) + f_0(k,-\mu_i)\right)\frac{dk}{m_i E_i}$$

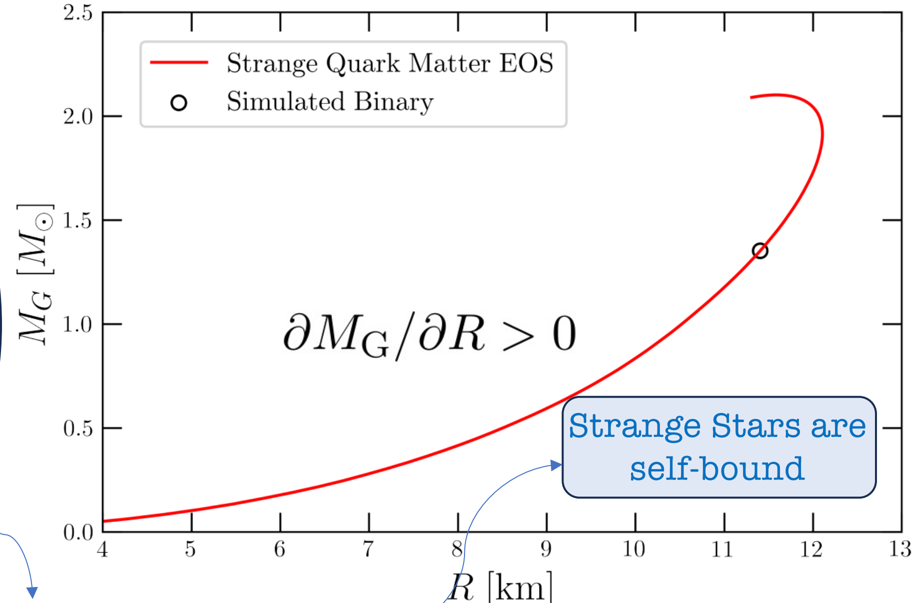
$$e = \sum_i \frac{g_s}{2\pi^2}\int_0^\infty k^2 E_i(k)^2\left(f_0(k,\mu_i) + f_0(k,-\mu_i)\right)\frac{dk}{E_i} + B$$

$$p = \sum_i \frac{1}{3}\frac{g_s}{2\pi^2}\int_0^\infty k\frac{\partial E_i(k)}{\partial k}k^2\left(f_0(k,\mu_i) + f_0(k,-\mu_i)\right)dk - B$$

$$\tilde{s} = S/V = \left(\frac{\partial p}{\partial T}\right)_{V,\mu_i}$$

$$\Omega = \sum_{i=u,d,s,e}\Omega_i^0 + \frac{3}{4\pi^2}(1-a_4)\left(\frac{\mu_b}{3}\right)^4 + B_{\rm eff}$$

Bag Constant: phenomenological description of non-perturbative aspects of QCD

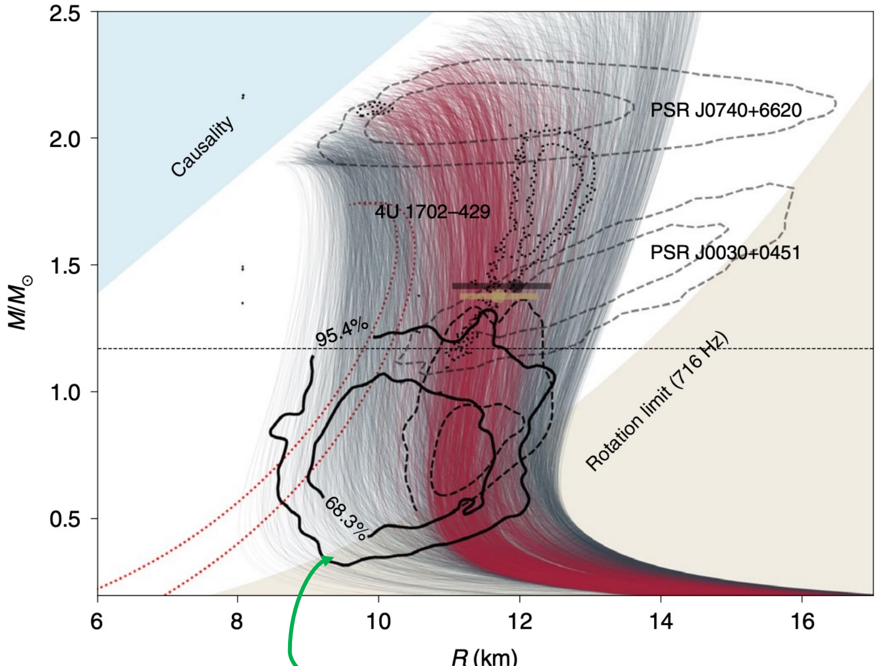


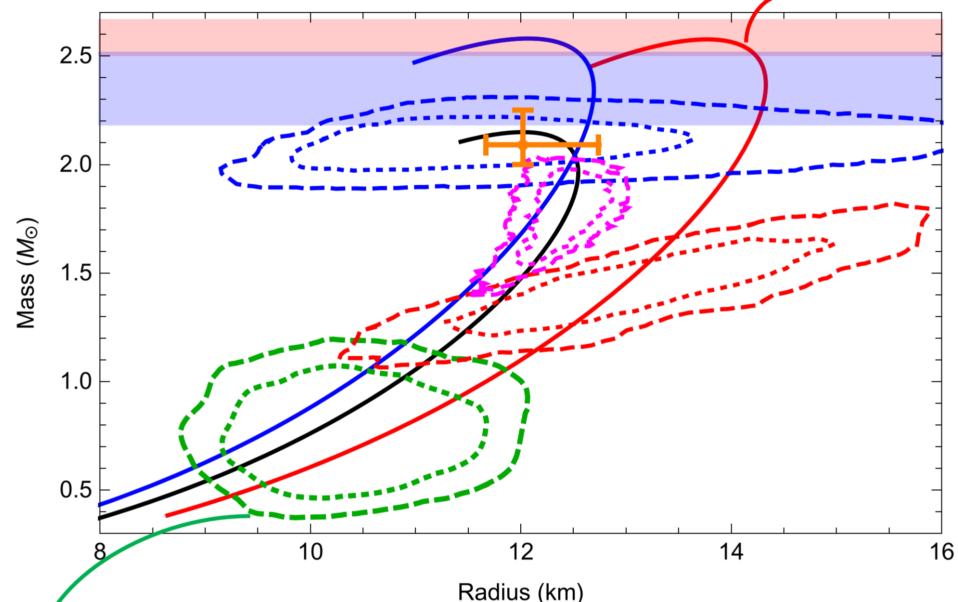
Strange Stars are self-bound

Grippa et al. 2024

Proposed Candidates :

Low mass companion 2.5 – 2.67M $\odot$
GW190814





Central Compact Object within the
Supernova remnant HESSJ1731-347

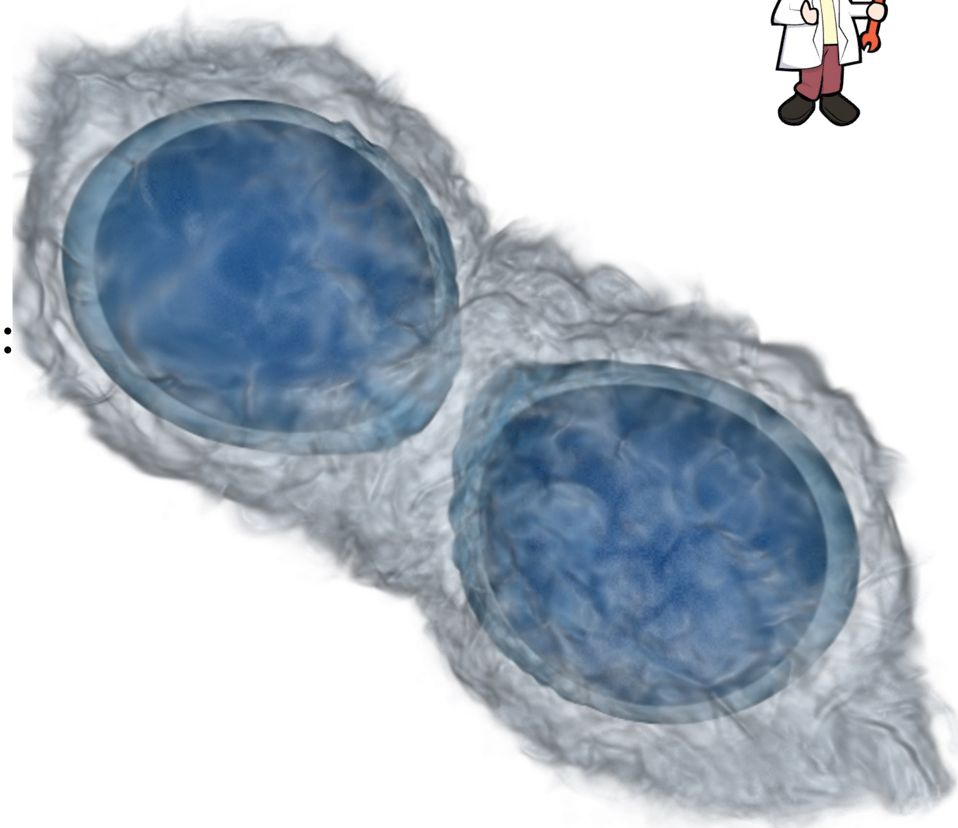
Doroshenko et al. Nature 2022

Bombaci et al. PRL 2021

Di Climente et al. 2024

WhiskyTHC (Einstein Toolkit)

- Templated Hydrodynamics Code
- High Order FD/FV methods
- Tabulated Equations of State
- Approximate neutrino transport: Leakage + M0
- Now available: M1
- No Magnetic Fields (GRHD)



Werneck et al. (2023)
Radice et el. (2014)
Nielsen et al. (2014)
Radice et el. (2022)

Mergers of Strange Quark Stars: GRHD Formalism

$$\nabla_a \left(\rho u^a \right) = 0$$

Baryon Mass conservation

$$\nabla_a T^{ab} = 0$$, where

$$T^{ab} = (e + p) u^a u^b + p g^{ab}$$

Ideal fluid energy-momentum tensor

Energy-Momentum conservation

$$G_{ab} = R_{ab} - \frac{1}{2} R g_{ab} = 8\pi T_{ab}$$

Einstein's Field equations

$$p = p(\rho, \epsilon)$$

Equation of State

Mergers of Strange Quark Stars: Simulation Dataset

EOS	m_1 [$M_\odot$]	m_2 [$M_\odot$]	M [$M_\odot$]	Λ	Resolution	$f_2^{\rm peak}$ [kHz]	Collapse	$t_{\rm BH} - t_{\rm merg}$ [ms]
Cold + Γ-Law	1.36	1.36	2.72	723.34	LR	2.836	Yes	63.35
Cold + Γ-Law	1.36	1.36	2.72	723.34	SR	2.576	No	...
Temperature dependent	1.36	1.36	2.72	723.34	LR	2.668	Yes	9.00
Temperature dependent	1.36	1.36	2.72	723.34	SR	2.682	Yes	65.40

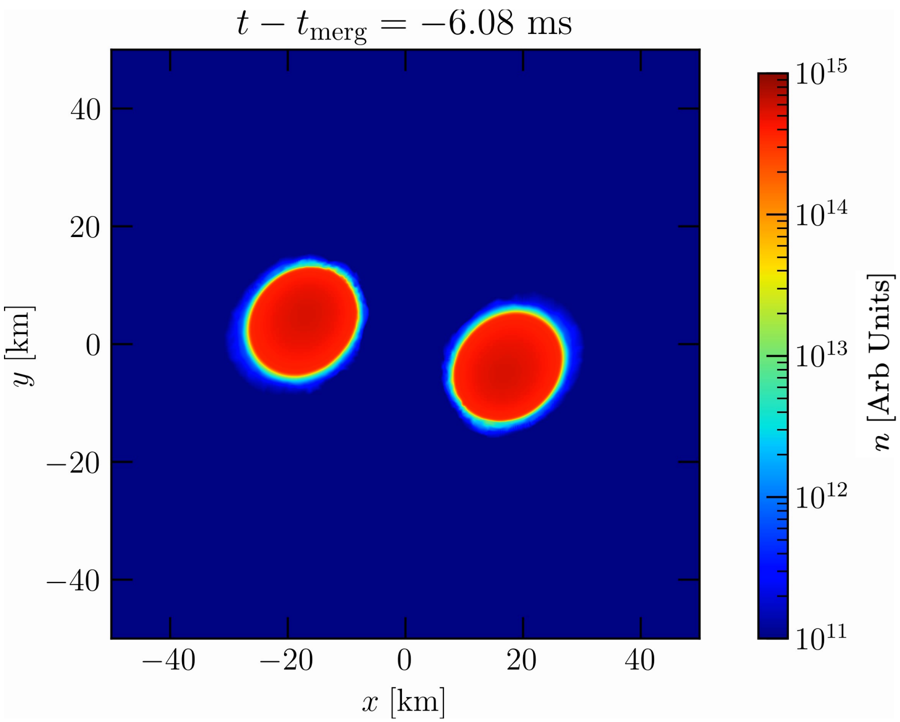
Thermal Effects

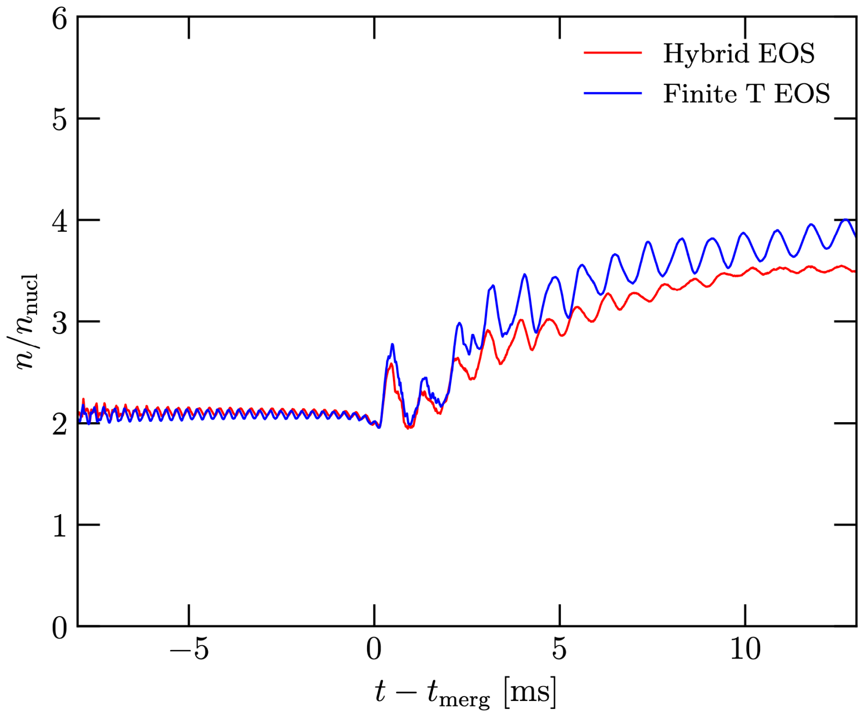
$$\Gamma - \mathrm{Law} : p = p_c + (\Gamma_{\rm th} - 1)\rho\epsilon_{\rm th}$$

$$\mathrm{Full\ finite-temperature\ tabulated\ EoS}\ p = p(\rho, T)$$

Grippa et al. 2024

Mergers of Strange Quark Stars: Results





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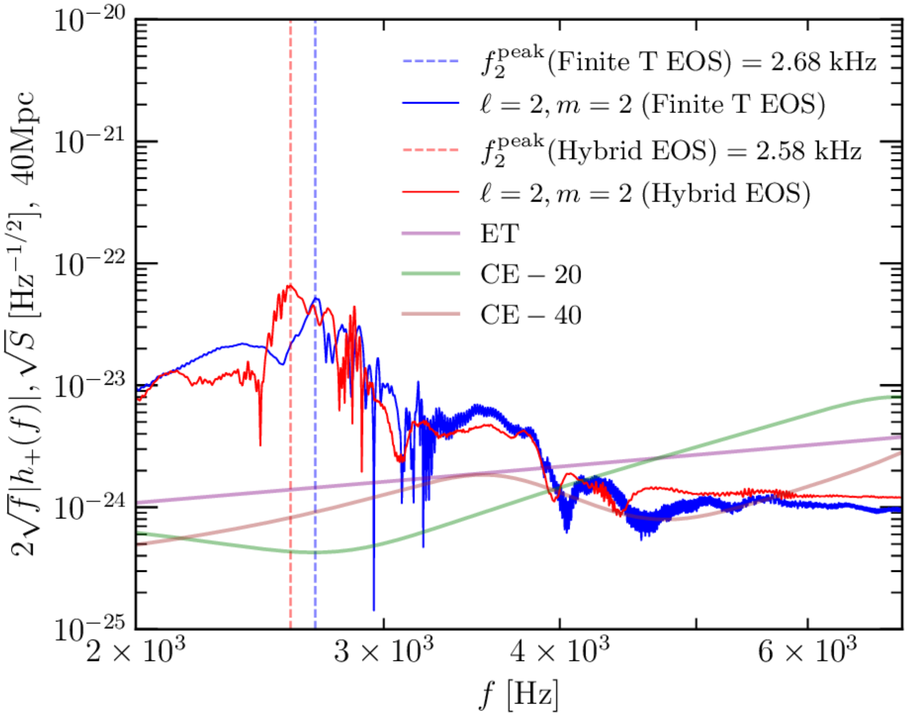
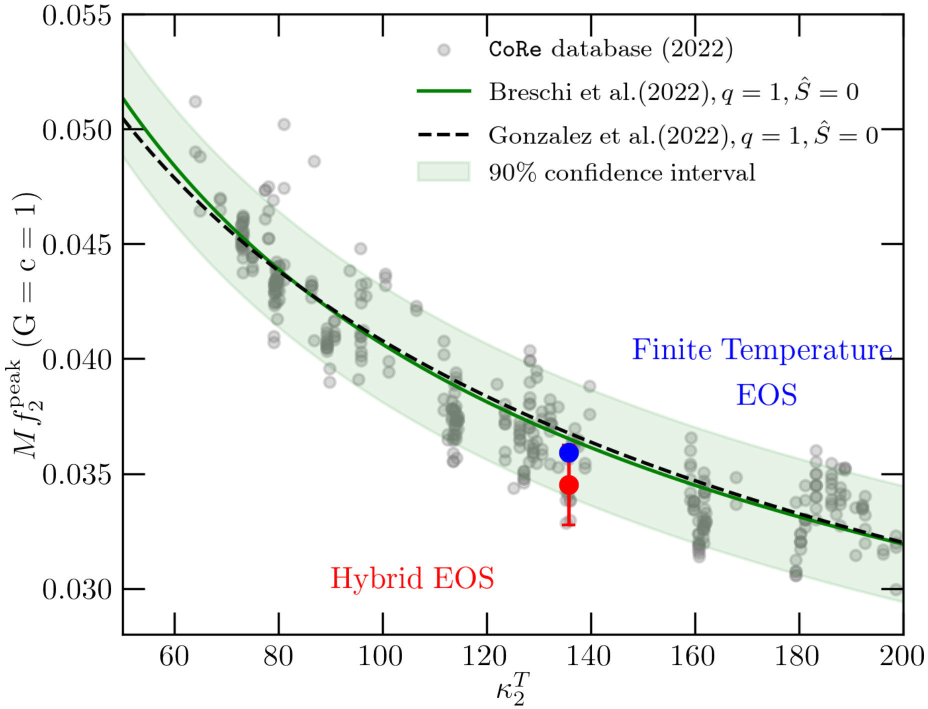
Gravitational Waves

Mergers of strange quark stars are indistinguishable from mergers of neutron stars with GWs !!!





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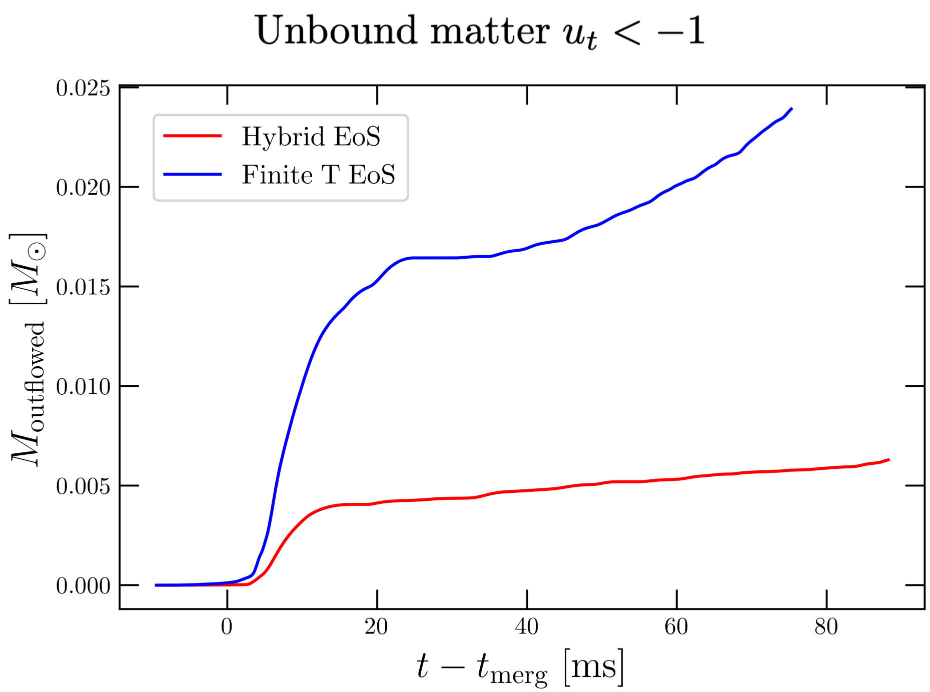
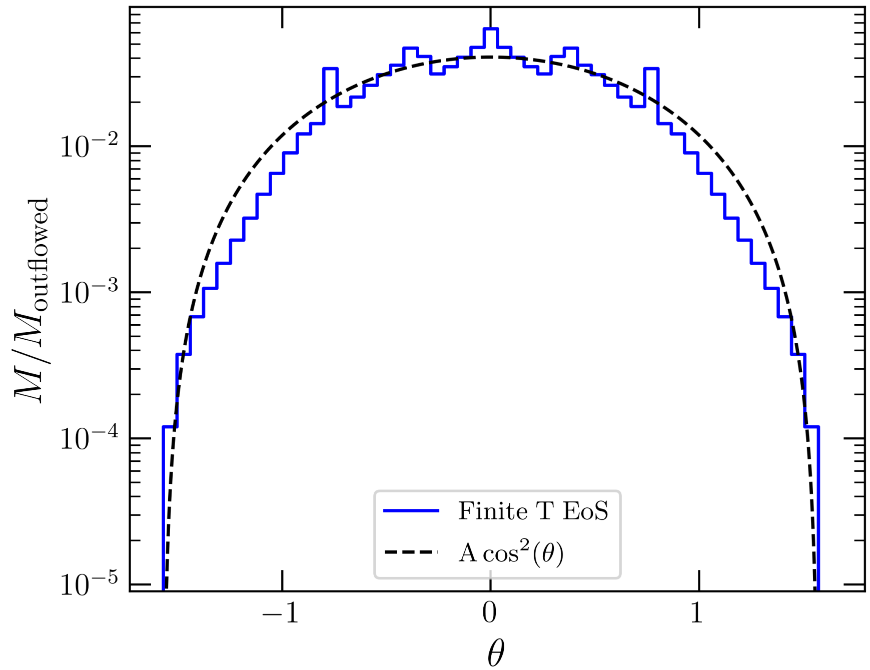
Mass Ejection





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Strangelet Flux near Earth

- Lumps of SQM which “can” contribute to the cosmic ray flux. AMS-02 experiment aboard the ISS.
- A high flux of strangelets → less compact strange stars (low value of B) and vice versa → constrains on Bag Constant (Binding energy of SQM).
- Assume SQM hypothesis is true and that all neutron stars are in fact strange stars.

Taking galactic merger event rate $\nu_{\text{merg}} \sim 40\ \text{Myr}^{-1}$

Glactic Strangelet Production Rate $\dot{M} \sim M_{\text{ej}} \times \nu_{\text{merg}} \sim 4 \times 10^{-7} \text{M}_{\odot}\text{yr}^{-1}$

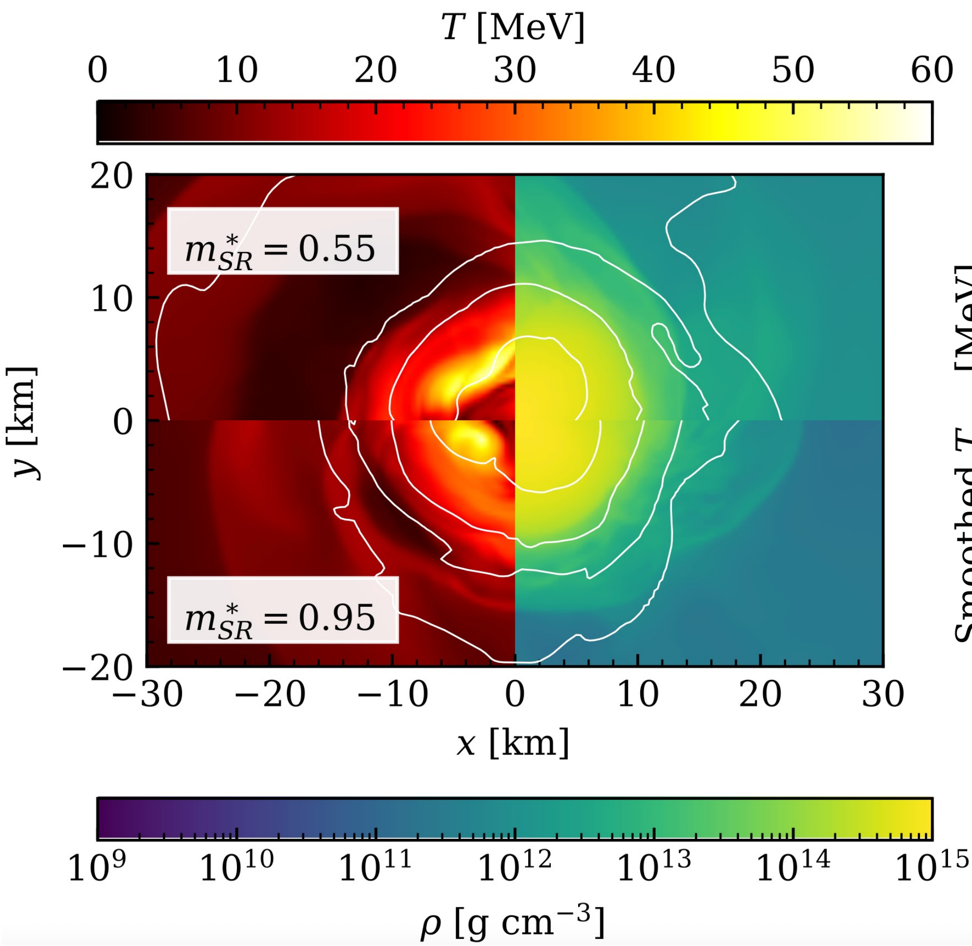
$$F \sim 8 \times 10^{8} A^{-1.067} \times \left(\frac{\dot{M}}{10^{-10} M_{\odot}\ \text{yr}^{-1}} \right) \times (\text{other scaling factors})\ \text{m}^{-2}\ \text{yr}^{-1}\ \text{sr}^{-1}$$

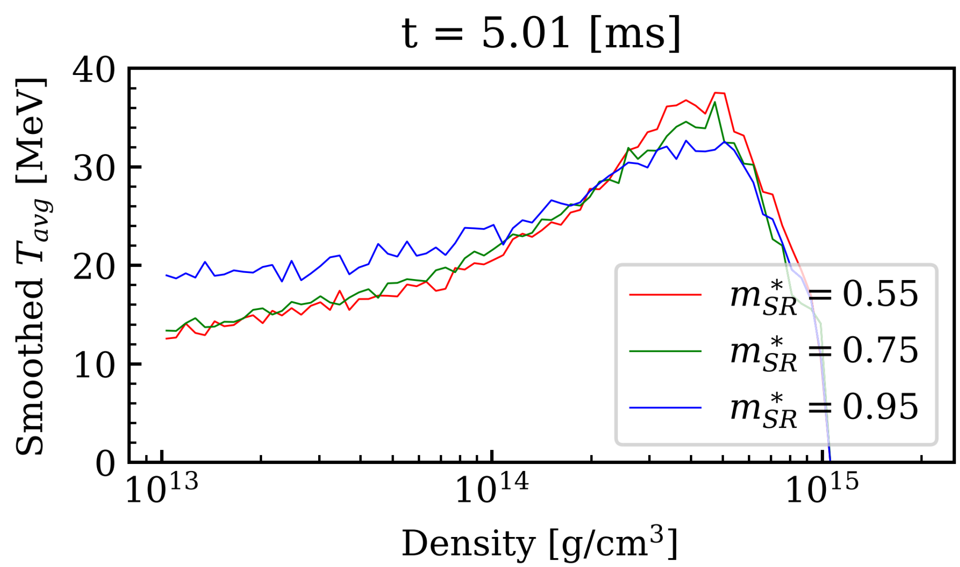
Most Uncertain to 10s of orders of magnitude

Thermal Effects in Neutron Stars

3 nucleonic EoSs with skyrme-type nucleon-nucleon interactions parameterized by effective nucleon mass which controls specific heat.

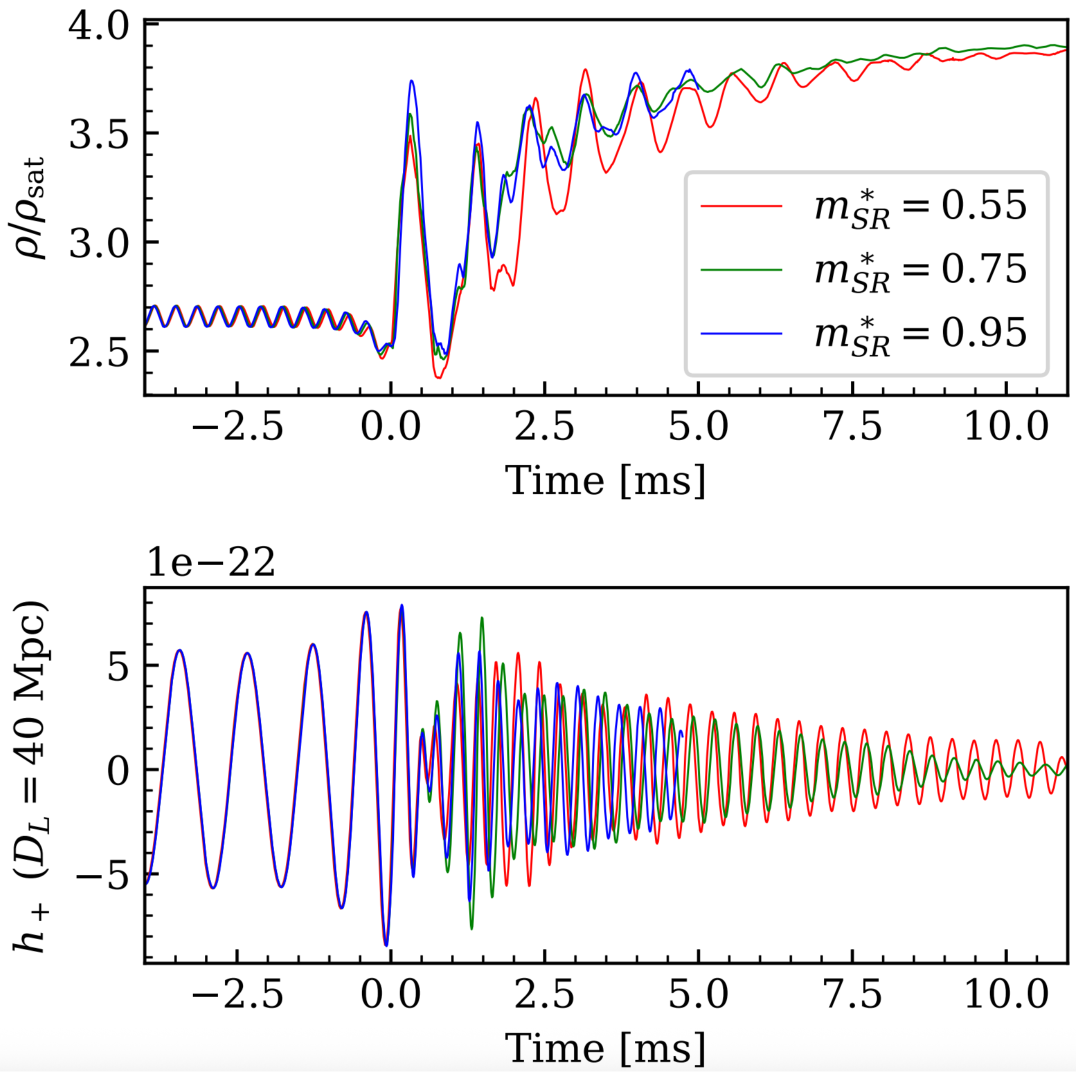
m^* $[m_n]$	f_2^{LR} [kHz]	f_2^{M0} [kHz]	f_2^{SR} [kHz]	$\mathcal{M}_{0.75}^{\mathrm{SR}}$	$\mathcal{M}_{0.95}^{\mathrm{SR}}$	$f_2^{\mathtt{NRPMw}}$ [kHz]	$\mathrm{SNR}_{\mathrm{mf}}$	D_L
0.55	2.862	2.864	2.835	0.04	0.09	$2.83^{+0.02}_{-0.02}$	$13.6^{+1.6}_{-2.7}$	56.353
0.75	2.908	2.966	2.908	N/A	0.08	$2.91^{+0.02}_{-0.02}$	$13.4^{+1.6}_{-2.5}$	56.730
0.95	2.921	2.974	3.080	0.08	N/A	$3.06^{+0.02}_{-0.02}$	$13.8^{+1.8}_{-2.2}$	49.655





Fields et al. 2023

Central Density & Gravitational Wave Emission



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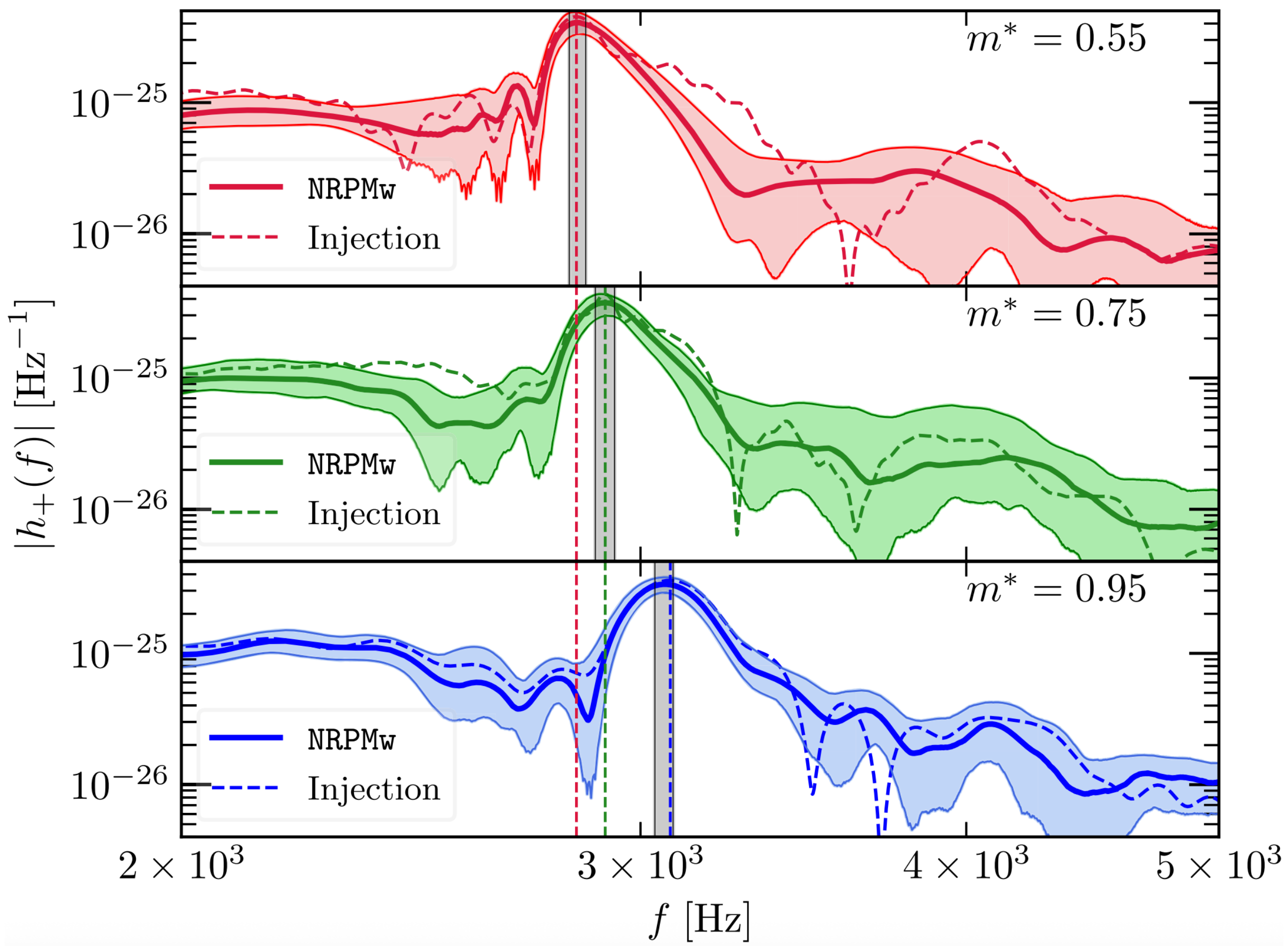
Postmerger Detectability of Thermal Effects



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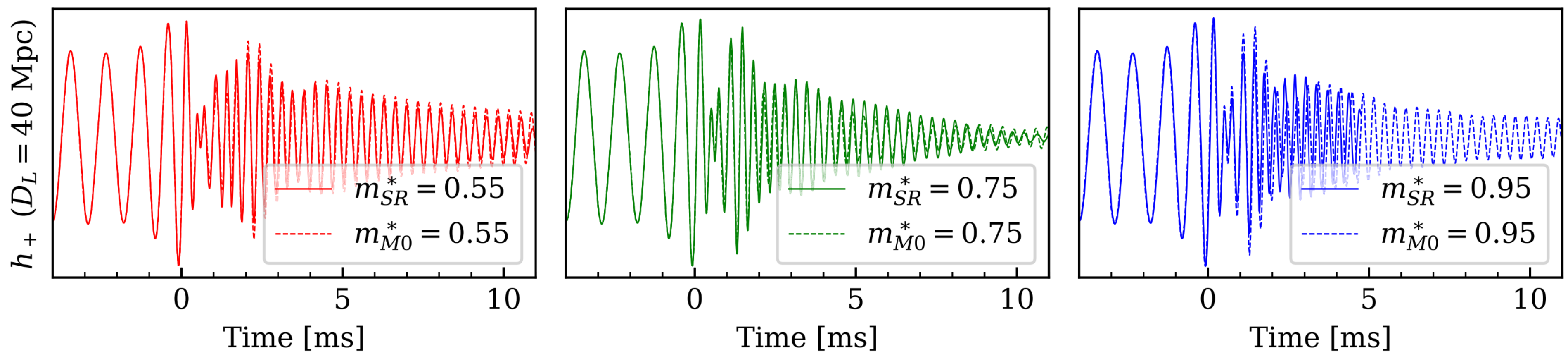
Impact of Neutrino Transport M0 vs M1



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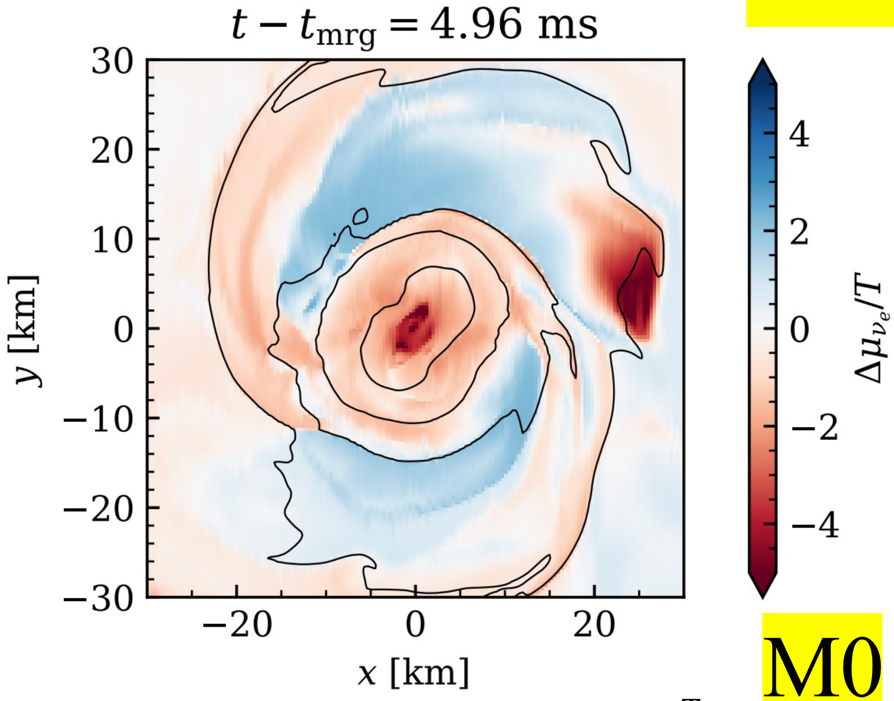
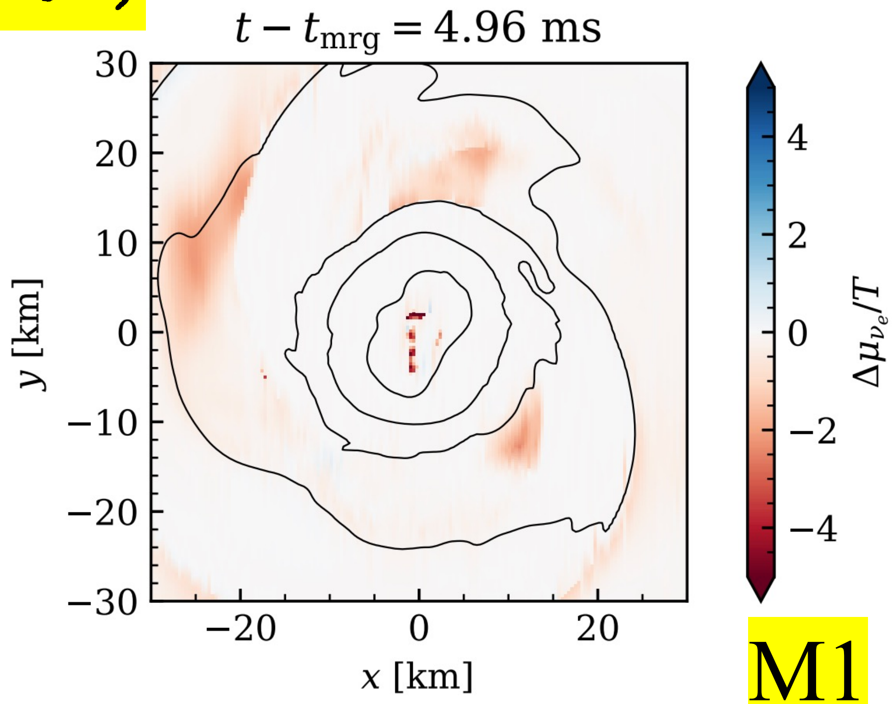
Deviation from Weak Equilibrium (Trapped neutrinos)



M0



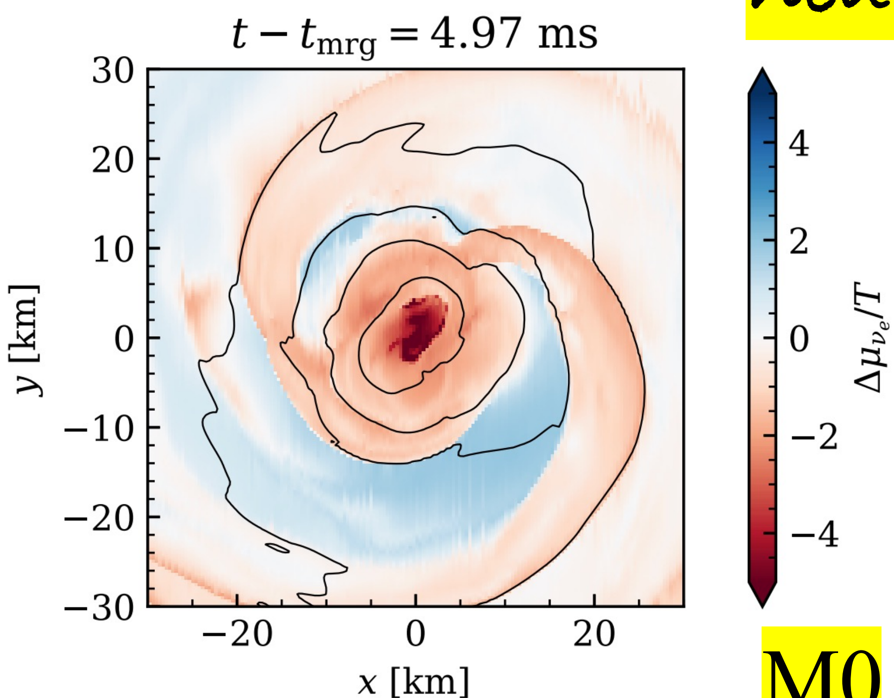
M1

$$\Delta\mu_{\nu_e} = \mu_p + \mu_e - \mu_n - \mu^T_{\nu_e}$$

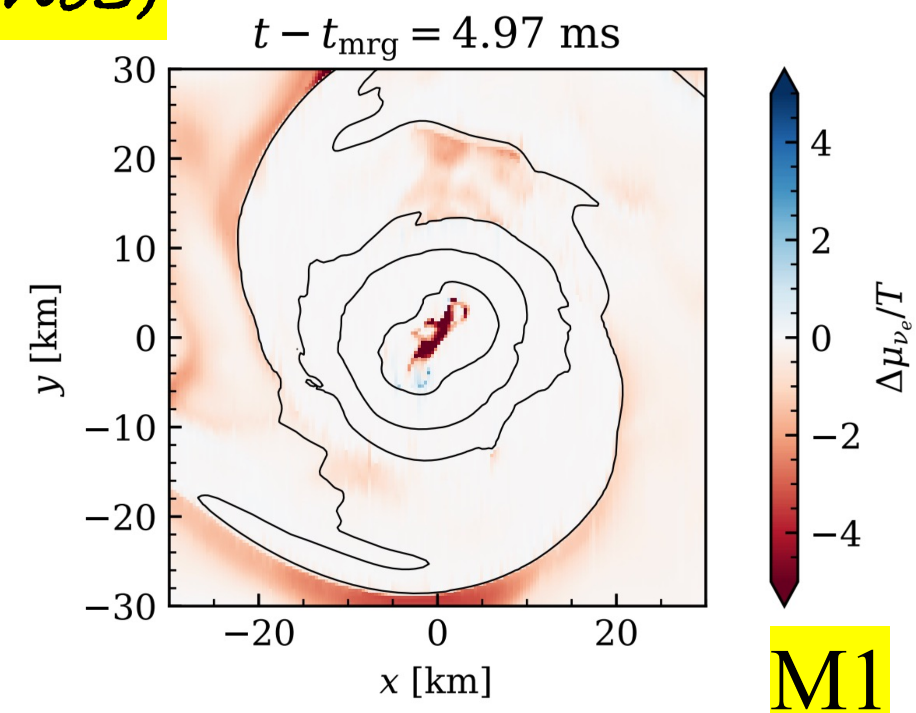
$$Y_{\nu_i} = \frac{4\pi m_b}{\rho}\left(\frac{k_{\rm B}T}{hc}\right)^3 F_2\left(\frac{\mu^T_{\nu_i}}{T}\right)$$

$$m^* = 0.55$$

Deviation from Weak Equilibrium (Trapped neutrinos)



M0



M1

$$m^* = 0.75$$

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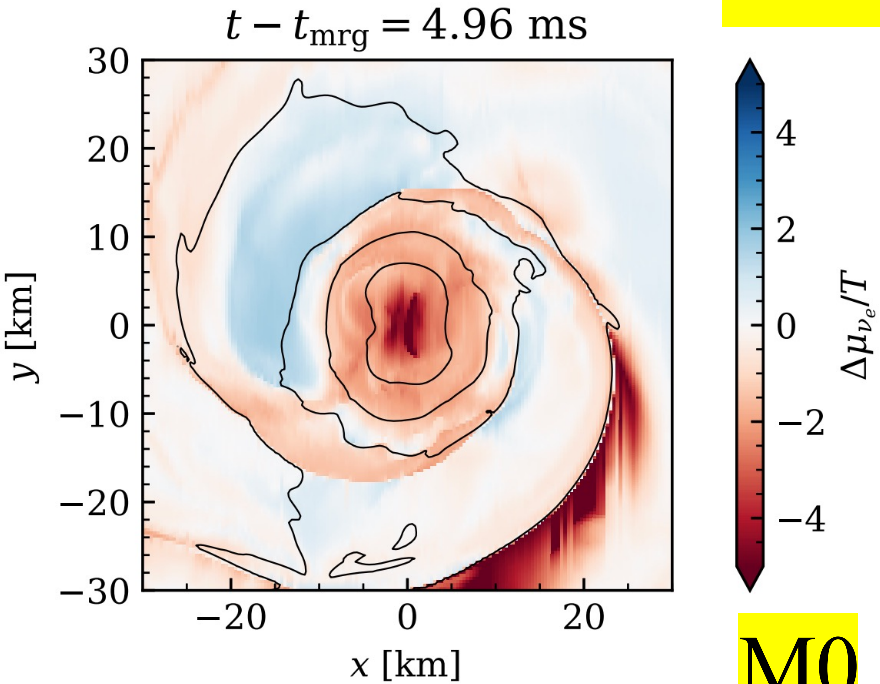
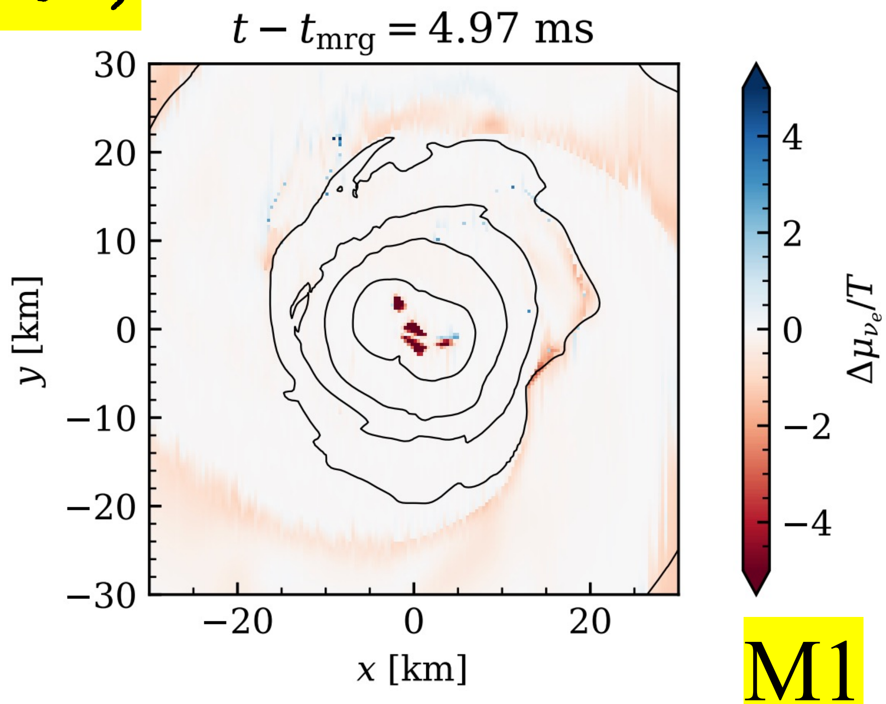
Deviation from Weak Equilibrium (Trapped neutrinos)



M0



M1

$$m^* = 0.95$$

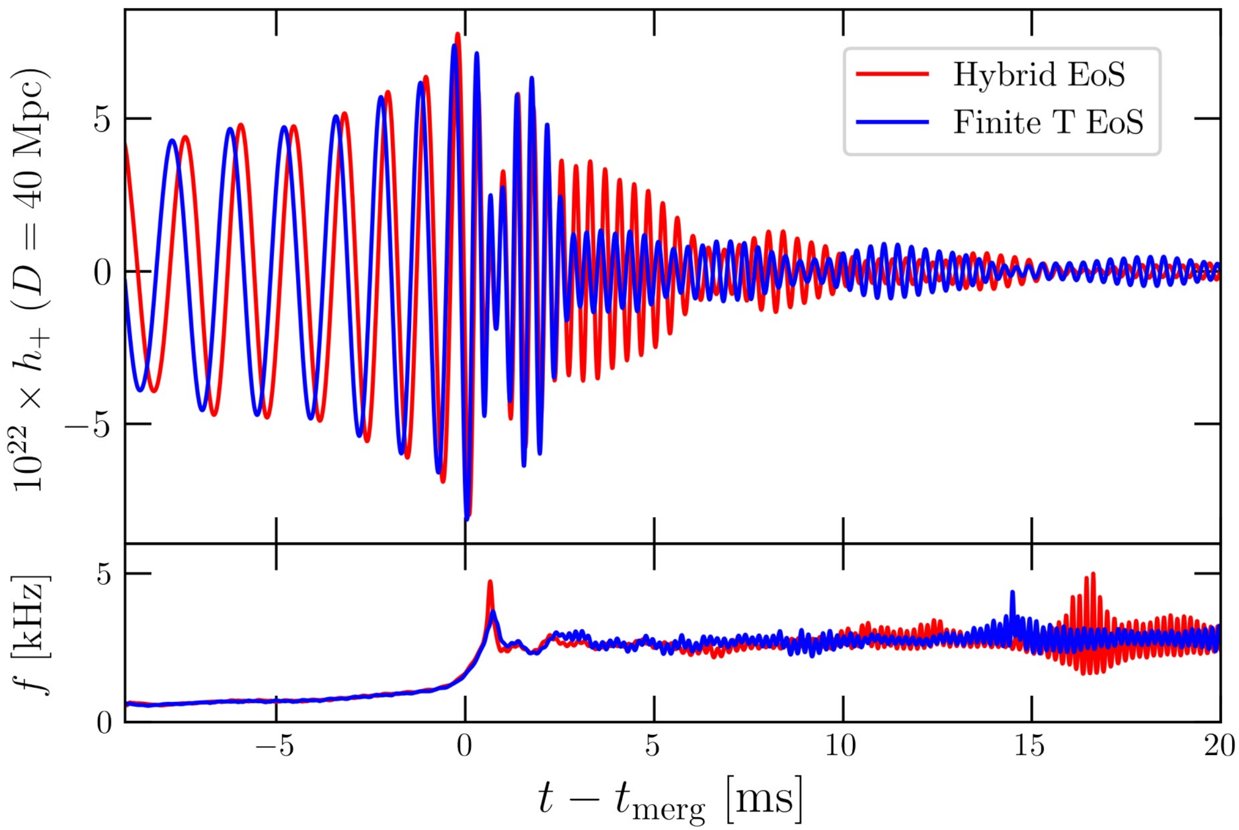
Fields et al. 2023

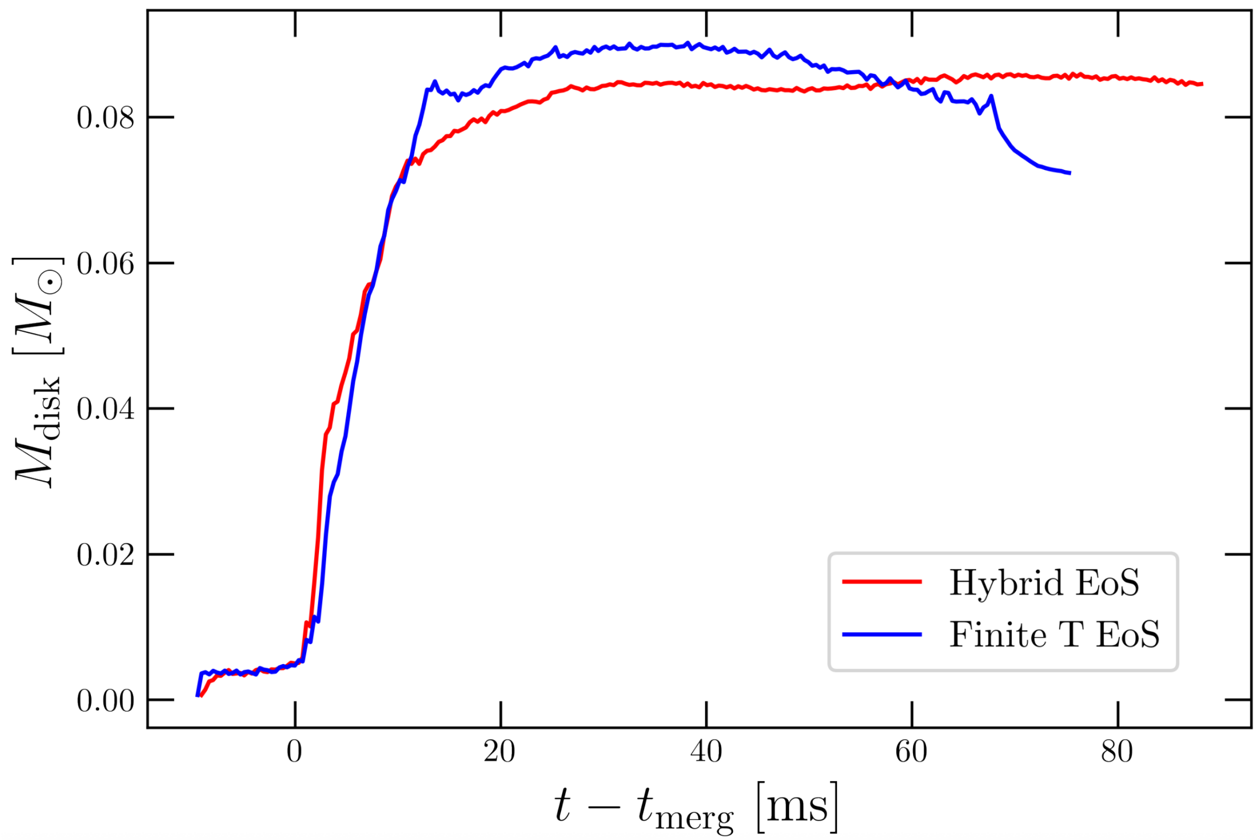
Conclusions

- Full 3+1 GRHD simulations of mergers of strange quark stars and neutron stars.
- Investigated the impact of thermal effects on remnant dynamics.
- Strange Quark mergers cannot be distinguished from mergers of binary neutron stars via gravitational waves.
- SQM mergrs are electromagnetically suppressed. Although EM burst due to crustal fracture or a neutrino signal is not ruled out.
- Neutron Star mergers with different thermal treatments can be differentiated with xG GW detectors.
- Better neutrino treatments M1 / MC are required to correctly capture the weak equilibrium.

Thank you

Gravitational Waves I




$M_{\rm disk}\ [M_\odot]$
0.00
0.02
0.04
0.06
0.08
0
20
40
60
80
$t - t_{\rm merg}$ [ms]
Hybrid EoS
Finite T EoS