New physics with neutron star mergers

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joe daniel price/Getty Images

Outline

1. Multimessenger astrophysics
    - Supernovae
    - Neutron star mergers
2. BSM physics in neutron star mergers
    - Ultralight particles
    - Trapped particles
        - Particles captured by stars
        - Particles produced in stars
    - Emitted particles

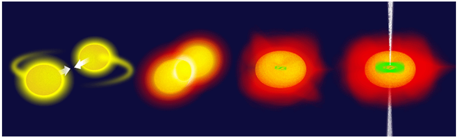
I: Multimessenger astrophysics

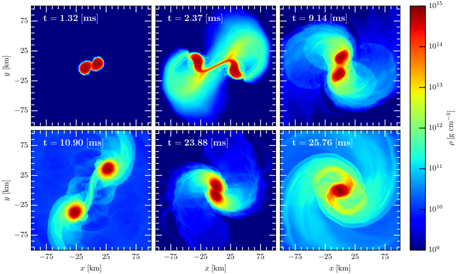
- Supernovae (see next talk)
  - Photons
  - Neutrinos
  - Gravitational waves?
- Neutron star mergers
  - Photons
  - Neutrinos?
  - Gravitational waves

Neutron star mergers

Stages of a neutron star merger

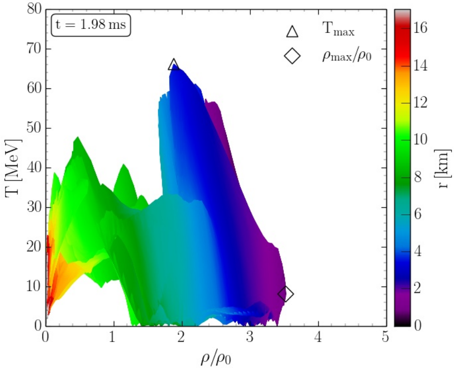
1. Inspiral
2. Merger & differentially rotating remnant (lasts 10 ms or more)
3. Collapse to black hole





Radice, Galeazzi, Lippuner, Roberts, Ott, Rezzolla arXiv:1601.02426

Nuclear matter in NS mergers



Courtesy of M. Hanauske and the Frankfurt group

Cold neutron star cores:

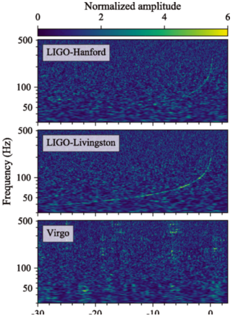
- Fermi liquid of neutrons, protons, electrons, muons
- Could contain quarks, hyperons,...

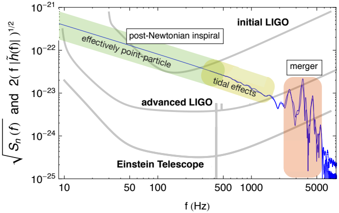
NS merger

- Matter heated to tens of MeV.
- Traps neutrinos.
- Hot, dense matter is an excellent source of new, light particles.

Observables in NS mergers: Gravitational Waves

- Gravitational waves (GWs) produced by coherent motion of large quantities of matter
- We have measured GWs from inspiral, but not postmerger
- How could BSM physics impact GW signal?
  - Needs to influence motion of large quantities of matter (inspiral, damp oscillations, ...)





Courtesy of J. Read

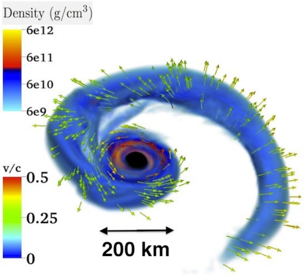
Observables in NS mergers: Electromagnetic

Short gamma-ray burst

How can BSM physics modify this?

- By modifying merger dynamics (unstudied)
- By introducing a new gamma ray production mechanism

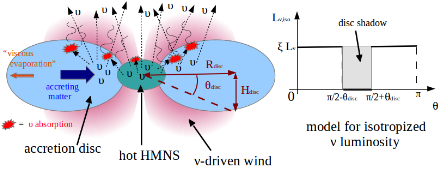
Kilonova



How can BSM physics modify this?

- Change amount of ejecta
- Change neutrino output, changing ejecta composition

Observables in NS mergers: Neutrinos



Perego, Rosswog, Cabezon, Korobkin, Kaeppeli, Arcones, Liebendoerfer arXiv:1405.6730

- Expect a burst of thermal neutrinos, like in SN1987a
- NS mergers much rarer than supernovae
- With a megaton ν detector (like Hyper-K) & a 3rd generation GW detector operating together, expect 0.1-10 merger neutrinos per century.

Lin & Lunardini arXiv:1907.00034

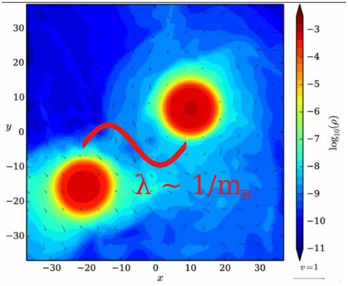
2: BSM physics in neutron star mergers

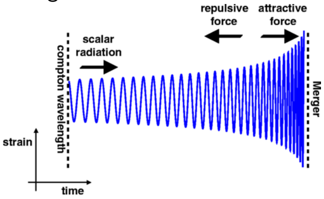
(2.1) Ultralight particles

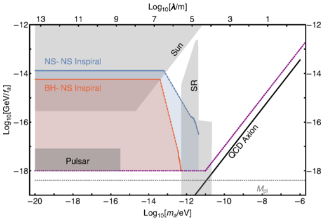
Ultralight particles can mediate an extra force between two inspiraling neutron stars.

- If $m_a \lesssim 10^{-11}$ eV, then $\lambda_C \gtrsim R_{NS}$.

Huang, Johnson, Sagunski, Sakellariadou, Zhang arXiv:1807.02133





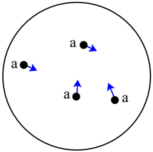


Axions, scalars, and long-range muonic forces have been discussed.

What can a BSM particle do in a merger?

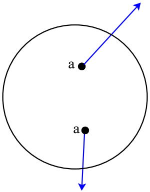
For particles that are localized (small λ_{Compton}):

- $\lambda_a < R$: If particle is trapped (like n, p, e^-) then



- Modify merger dynamics
- Participate in transport processes $(\kappa, \eta, \zeta, ...)$

- $\lambda_a \gtrsim R$: If particle escapes from the merger

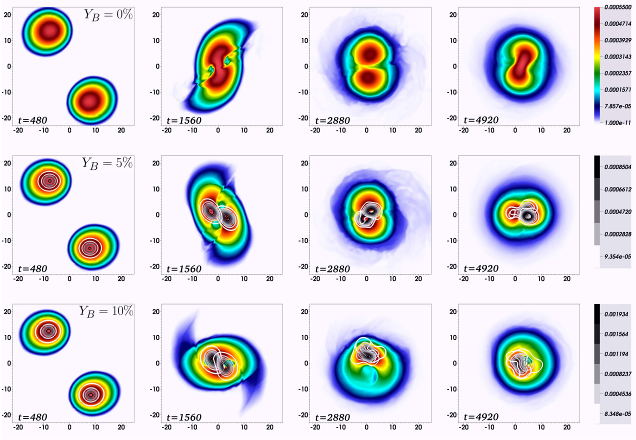


- Takes energy away from system (cooling, premature collapse?)
- Escape, then decay into SM particles

2.2 Trapped BSM particles

Trapped dark matter (1)

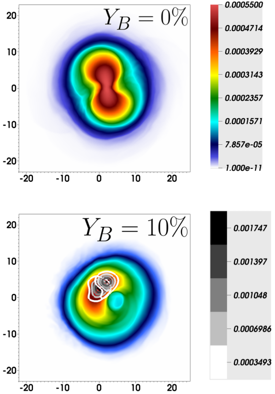
As neutron stars move through space, they can capture dark matter. Treat dark matter as a bosonic field, interacting purely gravitationally with SM matter.

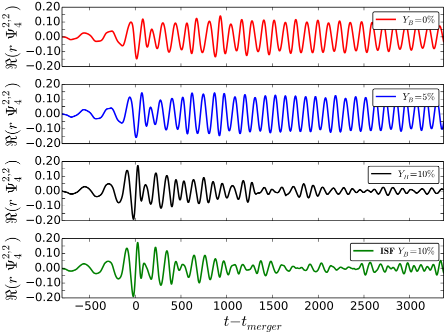


Bezares, Vigano, Palenzuela arXiv:1905.08551

Trapped dark matter (2)

Dark matter modifies SM matter motion, altering gravitational wave signal.





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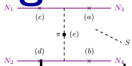
Scalar particles produced in merger

Dev, Fortin, SPH, Sinha, Zhang arXiv:2111.05852

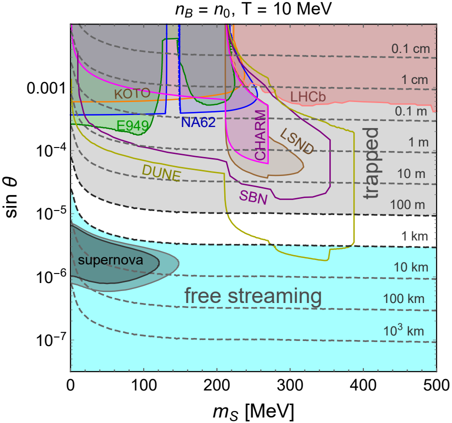


Scalars (S):

- S mixes with Higgs with strength $\sin\theta$
- This trickles down to S-couplings with SM particles
  - $\mathcal{L} \supset \sin\theta\, y_{hNN} S \bar{N} N$
  - Mixing angle $\sin\theta$ unknown, but constrained
- *Massive* scalar $\{\sin\theta, m_S\}$
- Scalar is *produced* in merger environment

Mean free path of a scalar particle

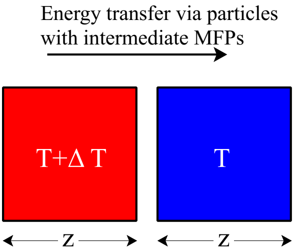
$(N + N' + S \to N + N')$



Scalars can free-stream or be trapped. We'll consider trapped scalars, which form a Bose gas. Scalars can enhance transport in the remnant.

Thermal equilibration - SM particles

Trapped particles help thermally equilibrate fluid elements in a merger.



$$dE_{\text{thermal}} = c_V V \Delta T = c_V z^3 \Delta T$$

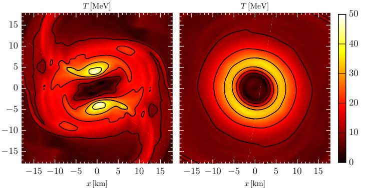
$$dE_{\text{thermal}} / dt = \kappa \frac{dT}{dz} A = \kappa \frac{\Delta T}{z} 6z^2$$

$$\tau_\kappa = \frac{dE_{\text{thermal}}}{dE_{\text{thermal}} / dt} = \frac{c_V z^2}{6\kappa}.$$

If neutrinos are trapped, neutrinos dominate thermal equilibration:

$$\tau_{\kappa,\nu} = 700 \text{ ms} \times ... \times \left(\frac{z}{1 \text{ km}}\right)^2 \left(\frac{T}{10 \text{ MeV}}\right)^2.$$

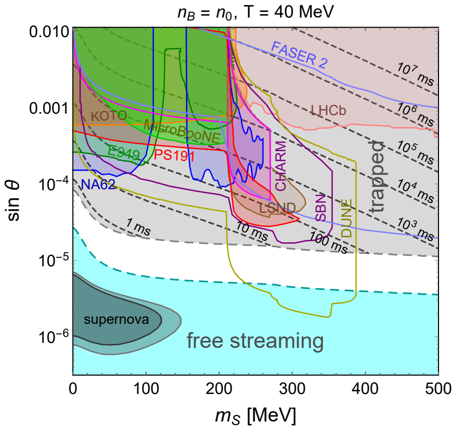
Calculations from Alford, Bovard, Hanauske, Rezzolla, Schwenzer arXiv:1707.09475

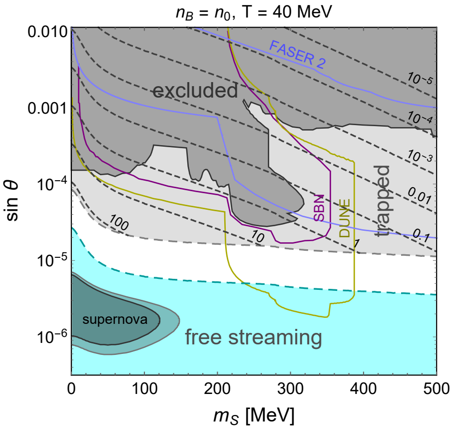


Hanauske, Takami, Bovard, Rezzolla, Font, Galeazzi, Stocker arXiv:1611.07152

Thermal equilibration timescale

Massive Bose gas of trapped scalar particles evens out temperature gradients (~ 1 km) on timescale: Dev, Fortin, SPH, Sinha, Zhang arXiv:2111.05852





Shorter-length-scale gradients are smoothed out faster ($\sim z^2$)!

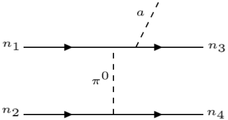
Scalars can dominate transport, even over trapped neutrinos!

2.3 Free-streaming BSM particles

Axion emission from merger remnants

Illustration by Sandbox Studio, Chicago with Steve Shanabruch for article in Symmetry Magazine

- Axions are pseudoscalar bosons introduced to explain CP symmetry in QCD
- $\mathcal{L} \supset G_{an} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N$
  - Coupling strength is unknown, but constrained.
- Axion can be produced via $N + N' \rightarrow N + N' + a$



Axions escape the merger, cooling it.

$$\frac{dT}{dt} = \frac{d\varepsilon / dt}{d\varepsilon / dT} = -\frac{Q_a}{c_V}.$$

Specific Heat

- Dominated by the particle with the most low-energy excitations - in mergers, this is the neutron
- $c_V \sim p_{Fn}^2 \delta p = p_{Fn}^2 \underbrace{\left(\frac{m_{\text{eff}}}{p_{Fn}} T \right)}_{T / v_{Fn}} = m_n^L p_{Fn} T.$

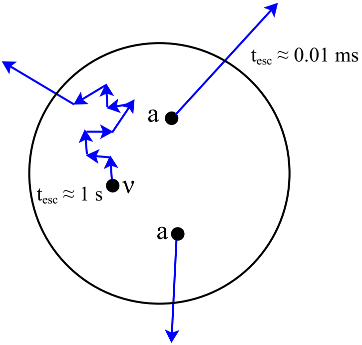
Axion emissivity

- Amount of energy emitted in axions (per volume per time) due to $n + n \rightarrow n + n + a$.
- $Q_a \sim G_{an}^2 T^6$

Axion cooling & Neutrino diffusion

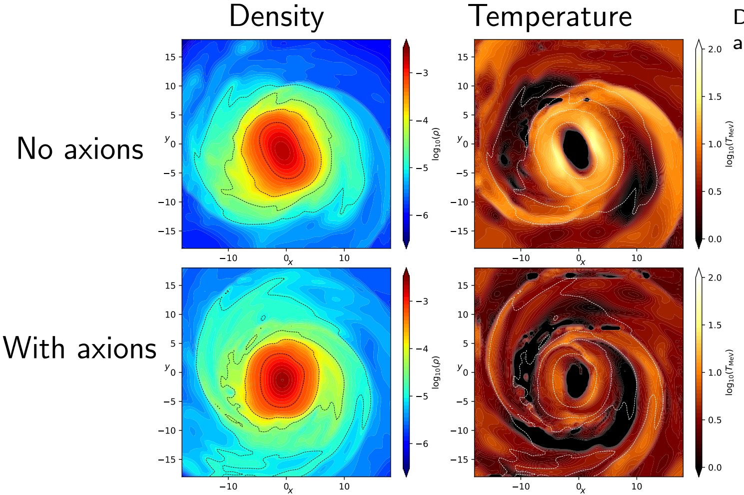
How do hot fluid elements cool down?

- Hot fluid elements trap neutrinos and thus cooling can (conventionally) only occur via neutrino diffusion. Diffusive cooling takes several seconds.
- Analytic estimates indicate that axion emission can cause cooling in milliseconds
- Rapid cooling of hot regions of the merger could be a signature of axion emission.



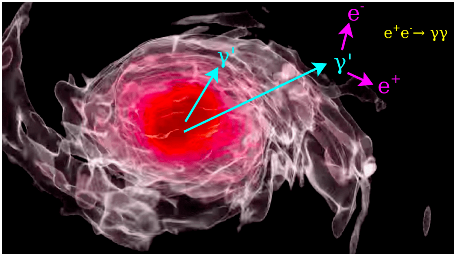
Axion cooling in BNS merger simulation

Dietrich & Clough
arXiv:1909.01278



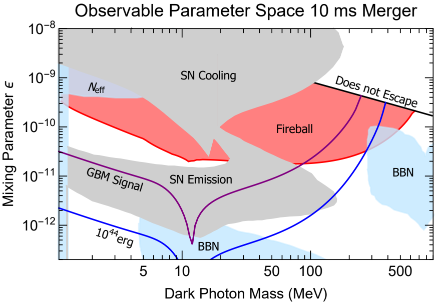
- Cooling and sphericalization observed
- Small changes in gravitational wave signal and amount of ejected material. Not measurable given current uncertainties.

Emission and then decay to SM particles



Adapted from: T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), BAM collaboration

Dark photon decay results in a e^+e^- plasma, which generates an isotropic photon signal. Could look for with Fermi GBM.



Diamond & Marques-Taveres arXiv:2106.03879

Conclusions

- Ultralight particles
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  - New particles can be produced in the hot, dense environment of a NS merger. They could contribute to transport. BSM particle transport should be done like neutrino transport. Or, at least add thermal conductivity to hydro.
- Emitted particles
  - Free-streaming particles produced in merger cool it down in millisecond timescales. Cooling does not significantly change GW signal or amount of ejecta.
    - Cooling could affect neutrino signal, could shorten quark/hadron phase transition, or could change T-dependent transport.
  - Emitted particles can decay to SM particles outside the merger. Or could modify short GRB. Should further examine these signals.