Axions and scalars in neutron star mergers

Steven Harris
Institute for Nuclear Theory, University of Washington

Dev, Fortin, SPH, Sinha, Zhang (in progress)
Fortin, Guo, SPH, Kim, Sinha, Sun arXiv:2102.12503 (IJMPD review)
Dev, Mohapatra, Zhang, arXiv:2005.00490
SPH, Fortin, Sinha, Alford arXiv:2003.09768

Pheno Conference, May 24, 2021

U.S. DEPARTMENT OF ENERGY | Office of Science

joe daniel price/Getty Images

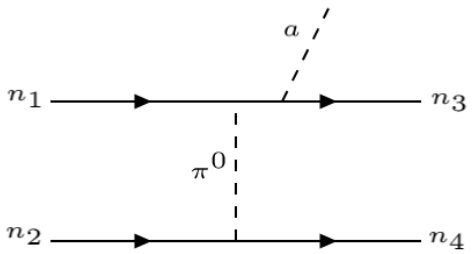
Outline

- Neutron star mergers and their "messengers"
- Axion radiative cooling of merger remnants
- Scalar thermal conductivity in merger remnants

Two candidate BSM particles

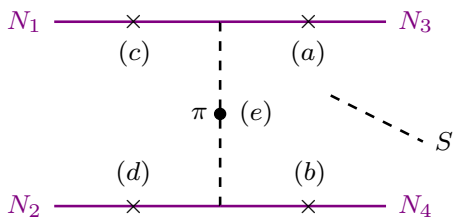
Axions

- Pseudoscalar boson introduced to solve the strong CP problem
- $\mathcal{L} \supset G_{an}\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N$
- G_{an} unknown, but constrained
- QCD axion: $m_a = 0.01\ \text{eV}\left(\frac{G_{an}}{G_{SN1987a}}\right)$
- Produced by nucleon bremsstrahlung $N + N' \to N + N' + a$



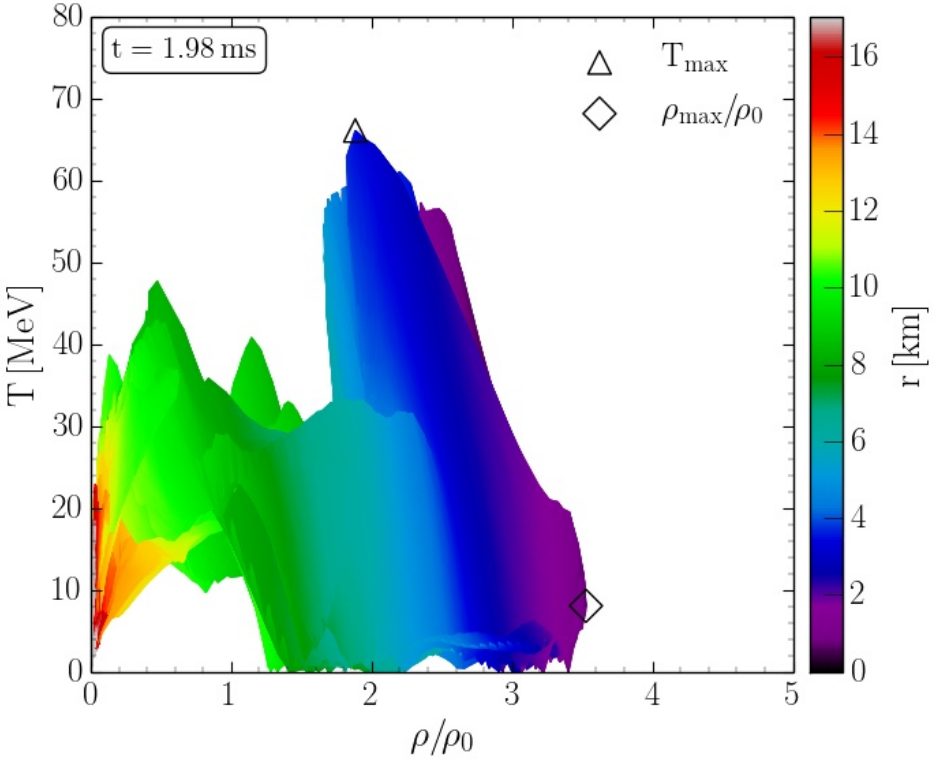
Scalars

- Scalar boson which couples to the Higgs with strength $\sin\theta$. Trickles down to couplings with SM particles
- $\mathcal{L} \supset \sin\theta\left[y_{hNN} S\bar{N}N + A_\pi S\pi^0\pi^0 + A_\pi S\pi^+\pi^-\right]$
- $\sin\theta$ and m_S unknown, but constrained
- Produced by nucleon bremsstrahlung $N + N' \to N + N' + S$.



Neutron star mergers

(Loading Video...)



Video from S. Rosswog (http://compact-merger.astro.su.se/movies.html)

Figure from Matthias Hanauske

- Merger remnant can survive (because of differential rotation) for tens to hundreds of ms.
- Most of the matter in mergers is uniform npe^- matter. Some is degenerate, some is nondegenerate.

Observables from mergers

Gravitational waves, electromagnetic, neutrino

Gravitational waves

- Sensitive to non-spherical motion of large quantities of matter
- Can only measure inspiral, at present
- 3rd generation detectors will measure postmerger signal

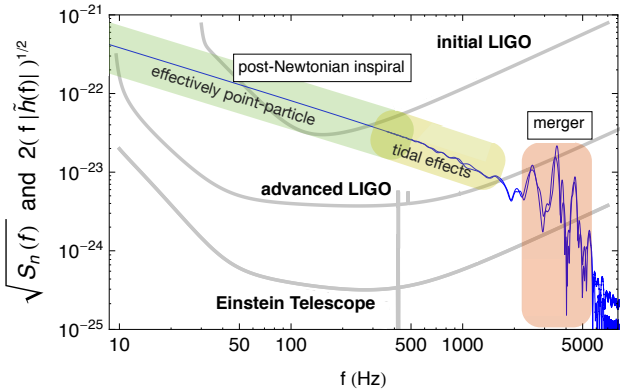


Figure from Jocelyn Read.

Electromagnetic

- Gamma-ray burst
- **Kilonova**
  - Radioactive decay of neutron-rich elements in ejecta

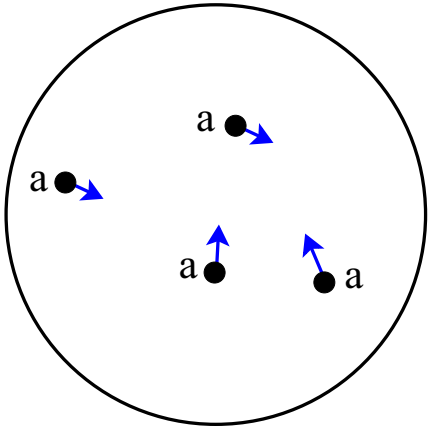
Prospects for neutrino signal:

- Expect a burst of thermal neutrinos, like in SN1987a
- NS mergers much rarer than supernovae
- Use time-correlation between GW & ν
- Hopeless to detect neutrinos from 1 merger, unless well within 3 Mpc
- $\sim 0.1 - 10$ detections per 100 Mt-years, assuming one 3rd gen. GW detector

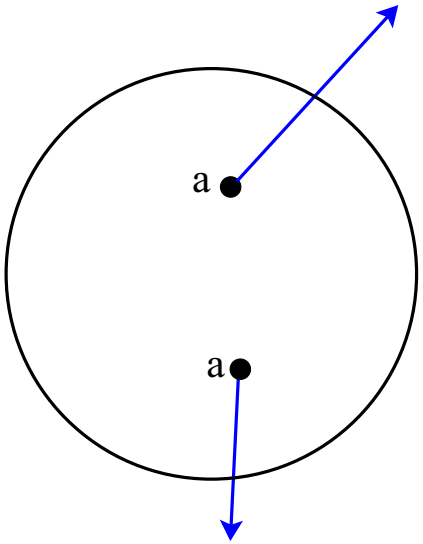
Lin & Lunardini arXiv:1907.00034

What can a BSM particle do in a merger?

- $\lambda_a < R$: If particle is trapped (like n, p, e^-) then they could thermally equilibrate matter in the merger



- $\lambda_a \gtrsim R$: If particle escapes from the merger, the remnant cools down.

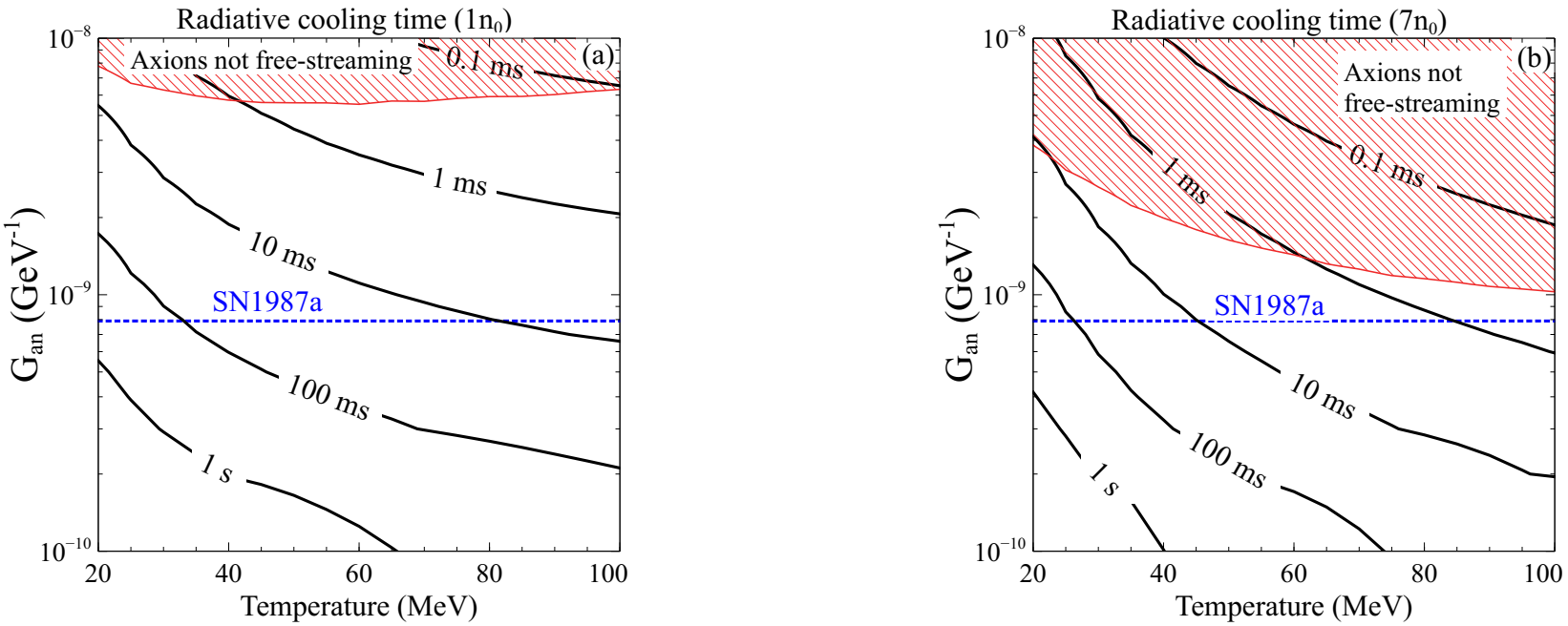


Axion cooling timescale

Axion MFP in hot, dense nuclear matter is longer than the system size. Axions escape the merger, cooling it.

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

Can significant axion cooling take place on 10 millisecond timescales, making it relevant for mergers?



Significant cooling can occur in a few milliseconds!

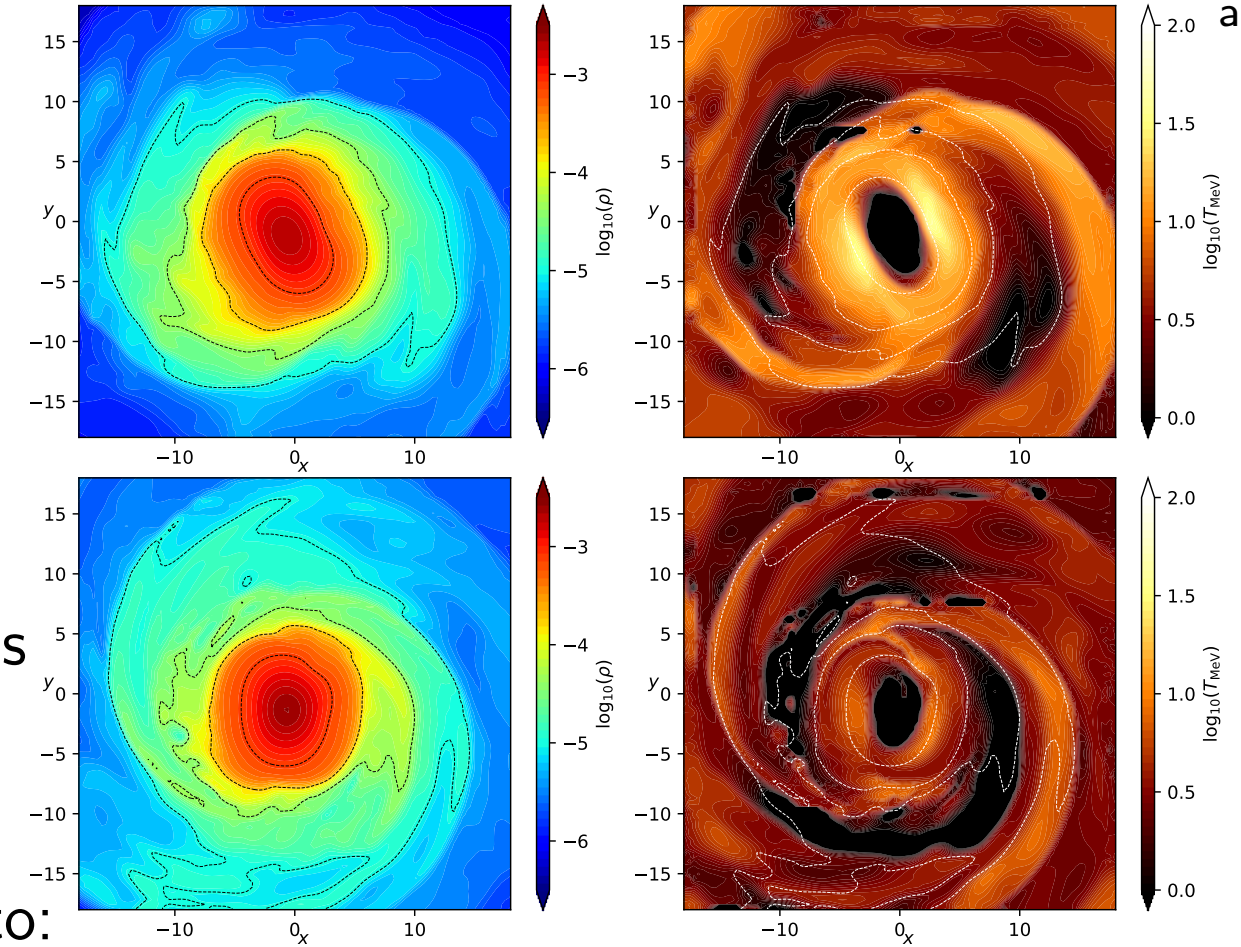
What do the simulations say?

Density | Temperature

Dietrich & Clough
arXiv:1909.01278

No axions

With axions



Axions lead to:

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

What hope remains for axions in mergers?

Axion cooling would likely affect neutrino signal from neutron star merger

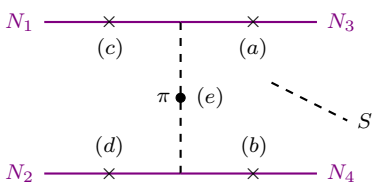
- But, NS merger would have to be really close (well within 3 Mpc) for us to detect neutrinos

Axion effect on gamma ray burst not studied?

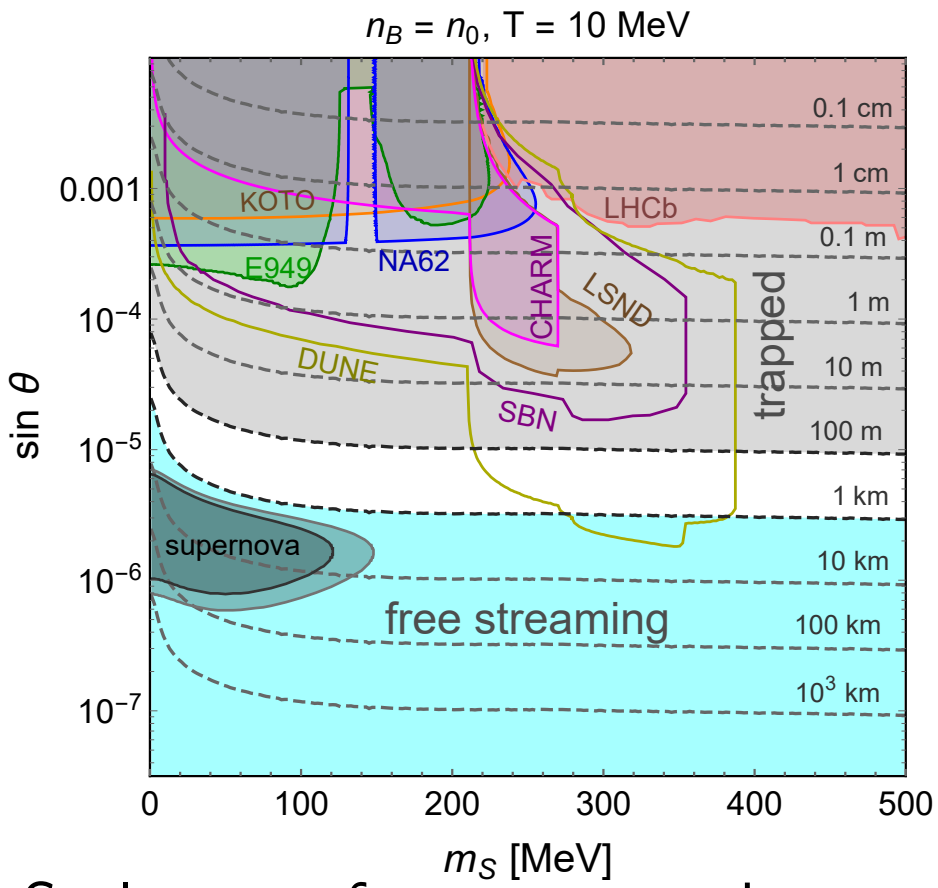
Indirect effects of axions on mergers:

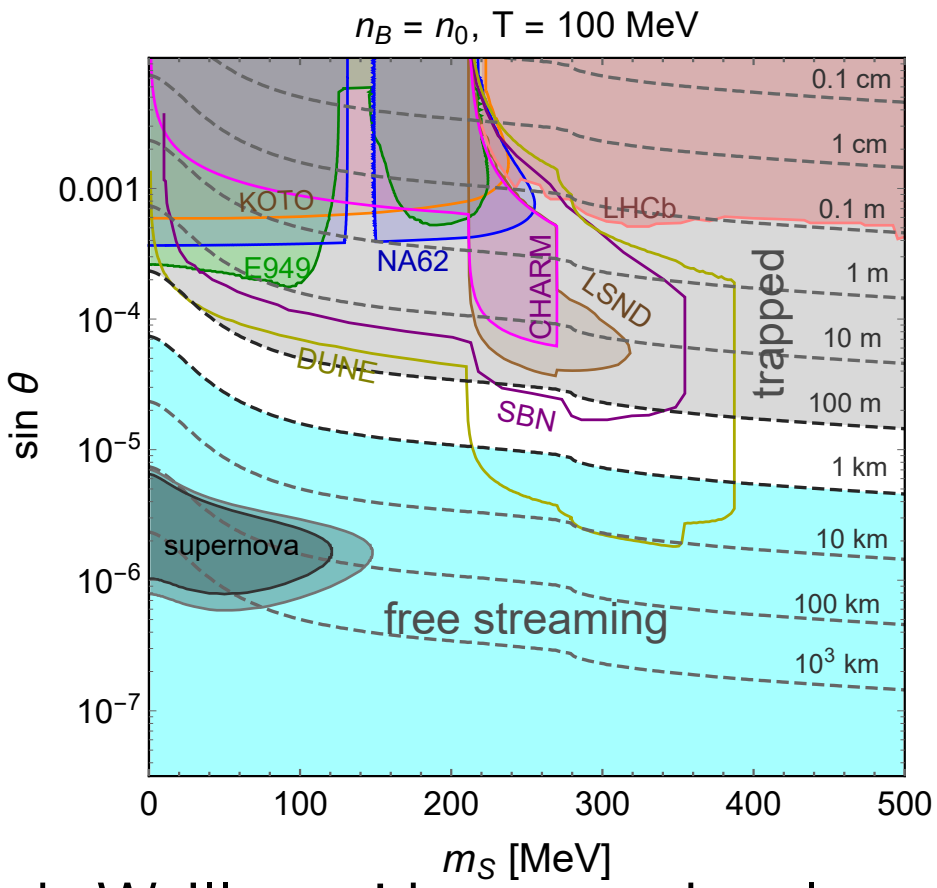
- Axion cooling could affect phase transitions in star
- Axion cooling could affect transport properties (strongly temperature dependent)
- Ultralight axions can modify inspiral dynamics

Trapped scalar particles



Mean free path of a scalar particle ($N + N' + S \to N + N'$)

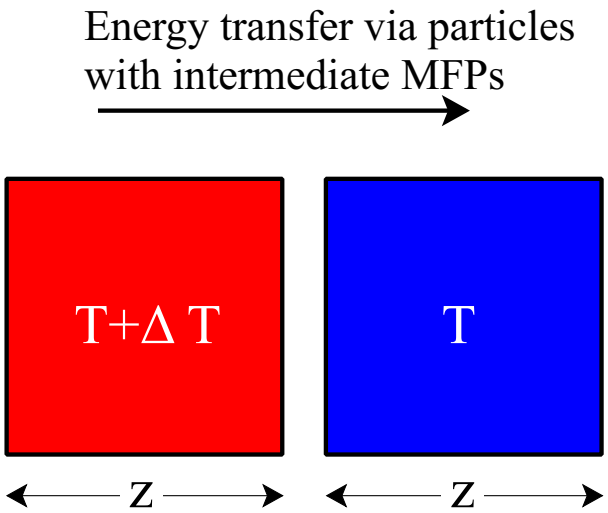




Scalars can free-stream or be trapped. We'll consider trapped scalars.

Thermal conductivity (preliminary)

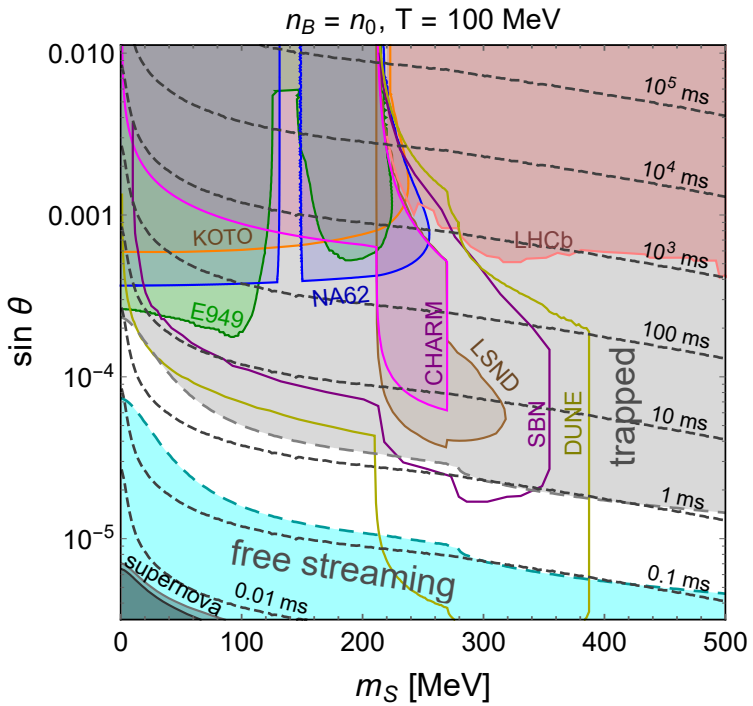
Trapped particles help thermally equilibrate fluid elements in a merger.



$$\tau_\kappa = \frac{E_{\text{thermal}}}{W_{\text{thermal}}} = \frac{c_V z^2}{6\kappa}.$$

- Particles with high density and long MFP dominate κ
- Conventionally, either e^- or ν.

Scalars could dominate thermal conductivity if they are trapped



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

Conclusions

Axions & scalars in neutron star mergers

- Gravitational wave and electromagnetic signals from neutron star mergers make them exciting arenas in which to study BSM physics
  - Very weakly interacting BSM particles (like axions) can be emitted from mergers, cooling them.
    - Difficult to find observable consequences of this cooling, given current uncertainties
  - If BSM particle interacts with intermediate strength, particle can be trapped in neutron star merger remnant.
    - Mergers probe parameter-space of scalar that no other experiment does!
    - Lots of potential consequences, including BSM contribution to thermal conductivity, shear viscosity, or...
    - Thermal conductivity term should be added to relativistic hydro equations in mergers to study dynamical effects stemming from trapped BSM particles