Constraints on axionlike particles from GW170817

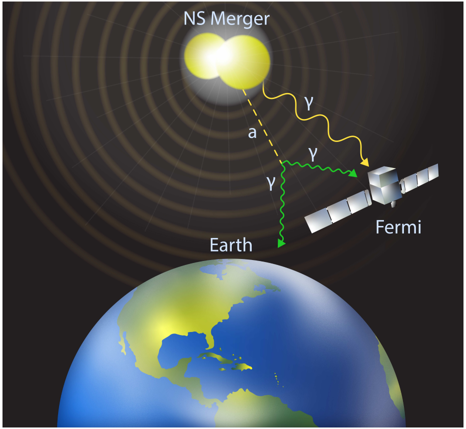
Steven Harris
Indiana University (NP3M Fellow)

Quark Confinement and the Hadron Spectrum
August 21, 2024

Dev, Fortin, SPH, Sinha, Zhang arXiv:2305.01002

Outline

- The QCD axion and axionlike particles (ALPs)
- Neutron star mergers
  - Gravitational and electromagnetic signals and detecting new physics
- ALP production and decay in merger environments
- Fermi-LAT constraints on ALPs



Axions and QCD

- QCD allows a CP-violating *theta* term

$$\mathcal{L}_\Theta = \bar{\Theta}\frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

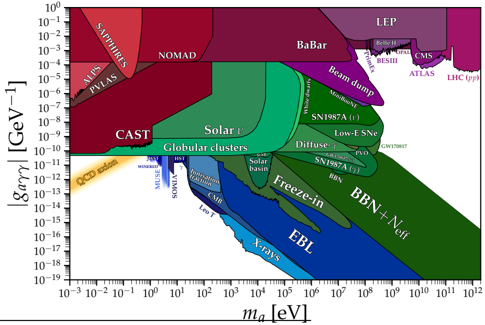
- Consequence of Θ term: neutron gets EDM $d_n \propto \bar{\Theta}$
- Strong CP problem: Measured d_n is very small $\Rightarrow \bar{\Theta} \lesssim 10^{-10}$.
- Peccei-Quinn (PQ) solution: A new global symmetry $U(1)_{\mathrm{PQ}}$ that is spontaneously broken at energy scale f_a.
  - Produces a pseudo-NG boson, the QCD axion, with mass $m_a \sim 1/f_a$. The axion dynamics[1] restore the CP symmetry.
- Original Weinberg-Wilczek QCD axion ($f_a \approx v_{\mathrm{EW}}$, $m_a \approx 100$ keV) quickly ruled out.
- The *invisible axion* has $f_a \gg v_{\mathrm{EW}}$. Several different models (DFSZ, KSVZ, ...) Not ruled out, but constrained.

[1] Essentially, $\bar{\Theta}$ is promoted to a dynamical bosonic field, a. Thus, the Lagrangian indicates the QCD axion-gluon coupling (which yields axion couplings to other SM particles).

Axionlike particles

- The QCD axion ($m_a \sim 1/f_a$) coupling to gluons leads to $a\gamma\gamma$ vertex. Details depend on the UV completion.
- Axionlike particles (ALPs): m_a and f_a are independent.
- We assume ALP couples only to photons[2]

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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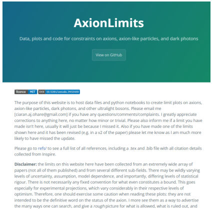


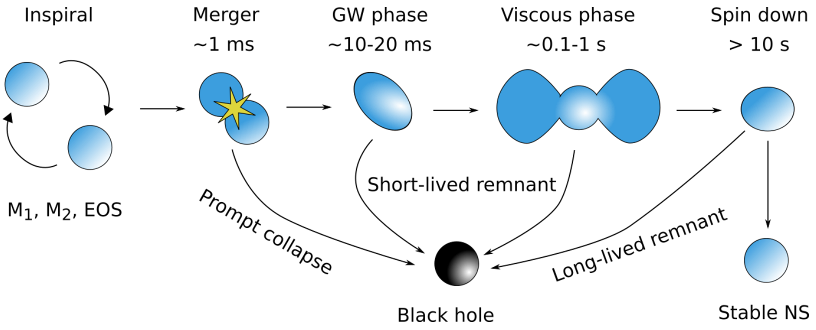
The purpose of this website is to host data files and python notebooks to create limit plots on axions, axion-like particles, dark photons, and other ultralight bosons. Please email me [ciaran.aj.ohare@gmail.com] if you have any questions/comments/complaints. I greatly appreciate corrections to anything here, no matter how minor or trivial. Please also inform me if a limit you have made isn't here, usually it will just be because I missed it. Also if you have made one of the limits shown here and it has been revised (e.g. in a v2 of the paper) please let me know as I am much more likely to have missed the update.

Please go to refs/ to see a full list of all references, including a .tex and .bib file with all citation details collected from Inspire.

Disclaimer: the limits on this website here have been collected from an extremely wide array of papers (not all of them published) and from several different sub-fields. There may be wildly varying levels of uncertainty, assumption, model dependence, and importantly, differing levels of statistical rigour. There is not necessarily any fixed convention for what even constitutes a bound. This goes especially for experimental projections, which vary considerably in their respective levels of optimism. Therefore, one should exercise some caution when reading these plots: they are not intended to be the definitive word on the status of the axion. I more see them as a way to advertise the many ways one can search, and give a *rough* picture for what is allowed, what is ruled out, and

[2] A system containing a lot of photons could produce a lot of ALPs!

Neutron star mergers



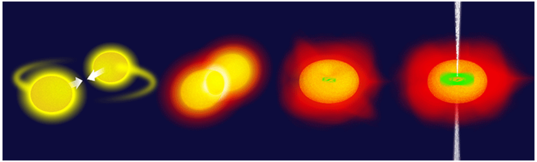
Radice, Bernuzzi, Perego arXiv:2002.03863

1. Inspiral: 100s of millions of years. Stars remain cold (keV or eV) until they collide.
2. Merger remnant: Bar shaped, sphericalizes over time. Hot, differentially rotating. Lifetime depends on total mass (and EoS)
3. Collapse to black hole (unless below TOV mass)

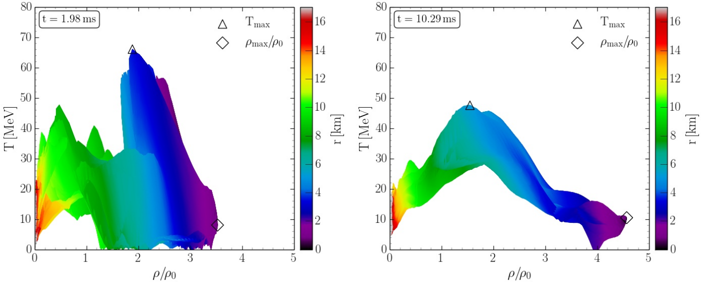
Merger Simulations

Simulations take into account most of the following:

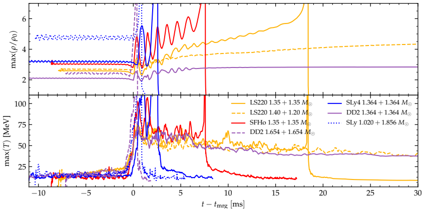
- General Relativity $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$
  - The backbone of these simulations is evolving the spacetime metric $g_{\mu\nu}$ throughout the merger
- Relativistic hydrodynamics $\nabla_\mu T^{\mu\nu} = 0,\ T^{\mu\nu} = (\varepsilon + P) u^\mu u^\nu + P g^{\mu\nu}$
  - Nuclear matter comprising the neutron stars is modeled as a "perfect fluid" (lacking viscosity)
- Nuclear equation of state $\varepsilon = \varepsilon(P)$
  - Simple estimate, or realistic nuclear physics calculation
- Electrodynamics
- Neutrino transport
- Other physics???



Neutron star merger remnants



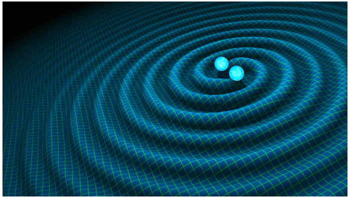
Courtesy of M. Hanauske

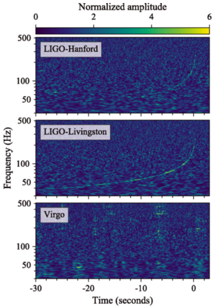


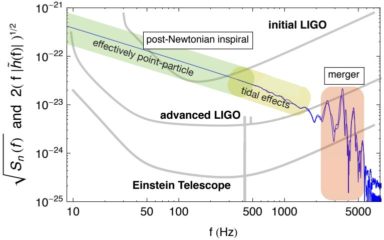
Bernuzzi arXiv:2004.06419

- Matter heated by shocks to tens of MeV
- Merger remnant differential rotation staves off collapse
- Remnant lifetime can be tens of milliseconds or even longer

NS merger gravitational wave signal







Courtesy of Jocelyn Read

- We have measured GWs from inspiral, but not postmerger. Inspiral GWs constrain total NS mass and tell us that GW170817 was 40 Mpc away.
- GW signal spikes when stars collide. Nice marker of $t = 0$.

NS merger electromagnetic signals

Early time (GRB)

- 1.7 seconds after $t = 0$, we observed a [$\mathcal{O}$(100 keV)] gamma-ray burst. Presumably powered by a rotating black hole[a].
- Other instruments set flux upper limits

[a] Thus, remnant lifetime < 1.7 s.

Late time (kilonova)

- Matter ejected from merger (dynamical, ν-driven wind, magnetic, ...)
- Ejected matter beta decays, powering kilonova
- Estimate lifetime of remnant by comparing $M_{ej}(t)$ to kilonova lightcurve

Table 3
Gamma-Ray Monitoring and Evolution of GW170817

Observatory	UT Date	Time since GW Trigger	90% Flux Upper Limit (erg cm^{-2} s^{-1})	Energy Band	GCN/Reference
Insight-HXMT/HE	Aug 17 12:34:24 UTC	−400 s	3.7×10^{-7}	0.2–5 MeV	Li et al. (2017)
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AGILE-GRID	Aug 17 12:56:41 UTC	0.011 days	3.9×10^{-9}	0.03–3 GeV	V. Verrecchia et al. (2017, in preparation)
Fermi-LAT	Aug 17 13:00:14 UTC	0.013 days	4.0×10^{-10}	0.1–1 GeV	Kocevski et al. (2017)
H.E.S.S.	Aug 17 17:59 UTC	0.22 days	3.9×10^{-12}	0.28–2.31 TeV	Abdalla et al. (H.E.S.S. Collaboration) (2017, in preparation)
HAWC	Aug 17 20:53:14—Aug 17 22:55:00 UTC	0.342 days + 0.425 days	1.7×10^{-10}	4–100 TeV	Martinez-Castellanos et al. (2017)
Fermi-GBM	Aug 16 12:41:06—Aug 18 12:41:06 UTC	±1.0 days	$(8.0\text{–}9.9) \times 10^{-10}$	20–100 keV	Goldstein et al. (2017a)
NTEGRAL IBIS/ISGRI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	2.0×10^{-11}	20–80 keV	Savchenko et al. (2017)
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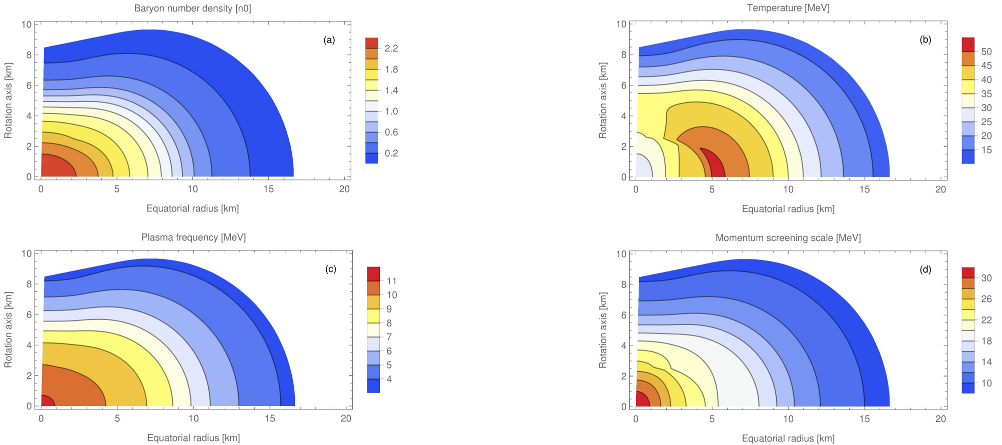
H.E.S.S.	Aug 21 + Aug 22 18:15 UTC	4.23 days + 5.23 days	2.9×10^{-12}	0.50–5.96 TeV	H. Abdalla et al. (H.E.S.S. Collaboration) (2017, in preparation)

Note.
[a] Assuming no shielding by the structures of ISS.

Estimated lifetime of GW170817 remnant: 1 second.

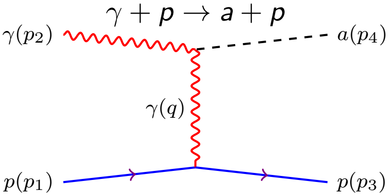
The photon in NS merger remnant

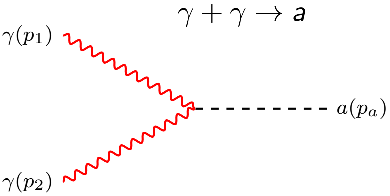
In hot, dense matter, the photon (in effect) picks up a mass $m_\gamma = \omega_{\text{pl}}$



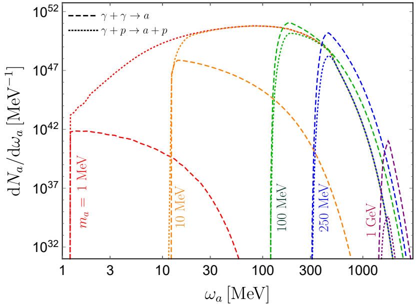
We assume the merger remnant maintains this profile from $t = 0$ through $t_{\text{collapse}} = 1$ s.

ALP production in hot, dense matter



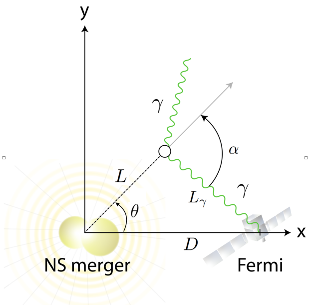


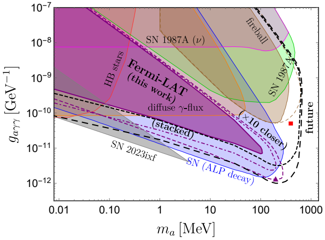
Calculate rate, integrate over merger profile.

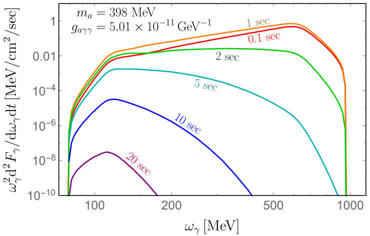


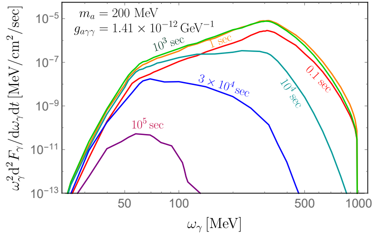
- ALP spectral peak at or above 100 MeV. (set by T or m_a).
- ALP flux prop. to $g_{a\gamma\gamma}^2$.
- We assume ALP emission is isotropic. So, GW170817 emitted a 1-sec. *shell* of ALPs.

ALP decay to photons





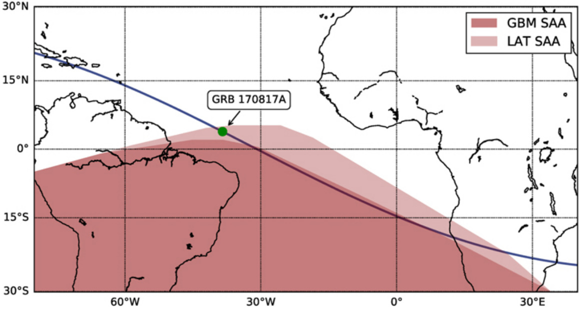




Photon signal from 1 second of ALP emission can last for hours!

GW170817 constraints (free-streaming ALPs)

Fermi-LAT observed merger from $t = 20 - 30$ mins.
Put upper limit on γ flux (100 MeV – 1 GeV).



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HAWC	[illegible]20:53:14—Aug 17 22:55:0[illegible]	[illegible].425 days	1.7×10^{-10}	4–100 TeV	Martinez-Castellanos et al. (2017)
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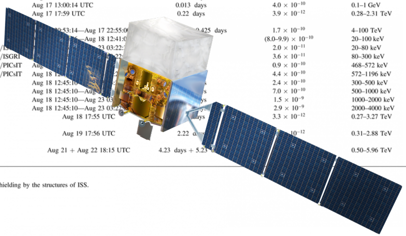
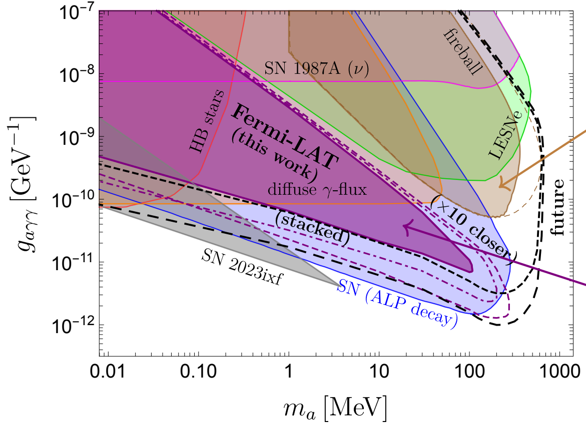
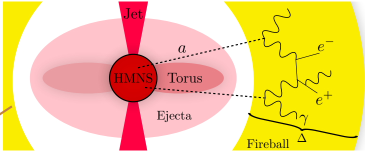
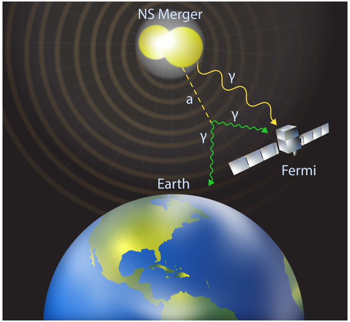


NS merger constraints



Photon fireball: Diamond, Fiorillo, Marques-Tavares, Tamborra, & Vitagliano arXiv:2305.10327

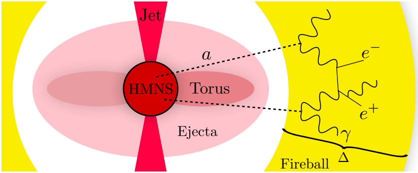


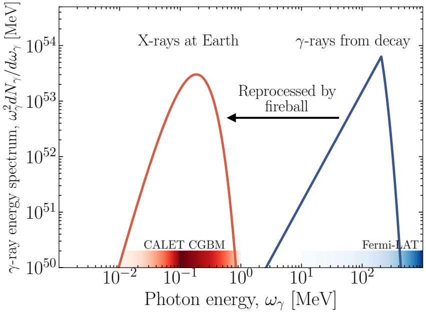


Free-streaming photons: Dev, Fortin, SPH, Sinha, Zhang arXiv:2305.01002

NS merger fireball from ALP decay

If ALP emission is very strong, ALP decay to photons could form a photon fireball[3].



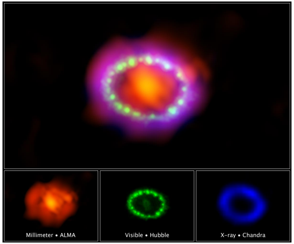


Predicted photon signal is X-rays, not gamma-rays. Constrain with CALET CGBM, Konus-Wind, Insight-HXMT/HE instead of Fermi-LAT.

[3]Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano arXiv:2305.10327

SN1987a constraints on ALPs

In 1987, we observed neutrinos and electromagnetic emission from a supernova in the Large Magellanic Cloud (50 kpc away).



- When supernovae material gets compressed/hot enough, (significant) ALP emission begins. ALPs escape SN, then decay into photons.
- The gamma-ray spectrometer on the Solar Maximum Mission (launched 1980) set upper bound on gamma-ray flux. Use to set limits on ALP emission.
- NS mergers: Far away. Clean $t = 0$. More frequent than gal. SN.
- Supernovae: Close. $t = 0$ vague. Rare in galaxy.

Conclusions

- ALPs emitted from NS merger remnant. They decay into MeV photons.
- GW170817/Fermi-LAT constraints are currently not as good as those from SN1987a.
- More investigation needed into fireball/free-streaming transition region
- Future NS mergers
  - Advantage of NS mergers - an early warning system!
  - If Fermi-LAT observed GW170817 from $t = 0.1 - 100$ s, constraints significantly improved.