New Physics from Multi-messenger Studies of Neutron Star Mergers

Bhupal Dev

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Washington University in St. Louis

based on

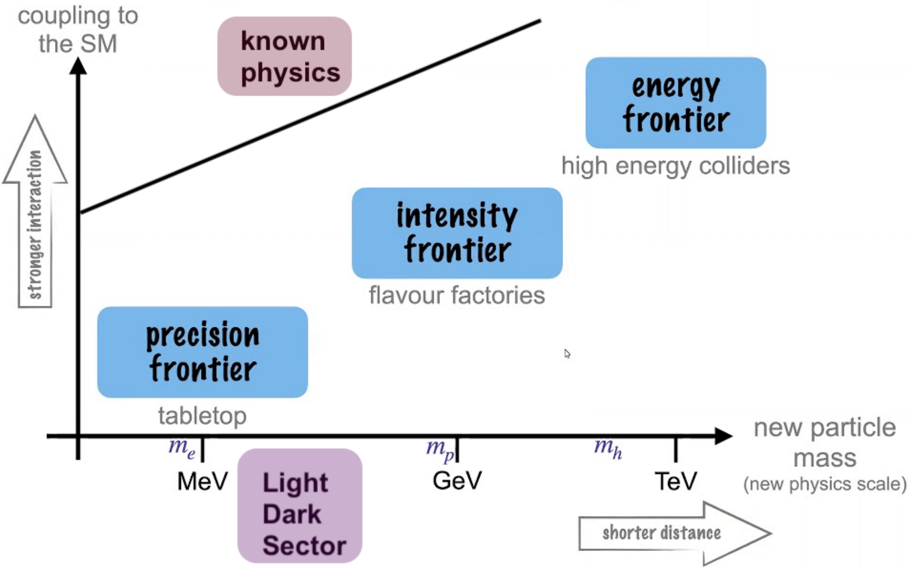
BD, Jean-François Fortin, Steven Harris, Kuver Sinha, Yongchao Zhang,
Phys. Rev. Lett. **132** (2024) 10, 101003 [arXiv: 2305.01002] and *ongoing*

S@INT Seminar

Institute for Nuclear Theory, University of Washington

March 14, 2024

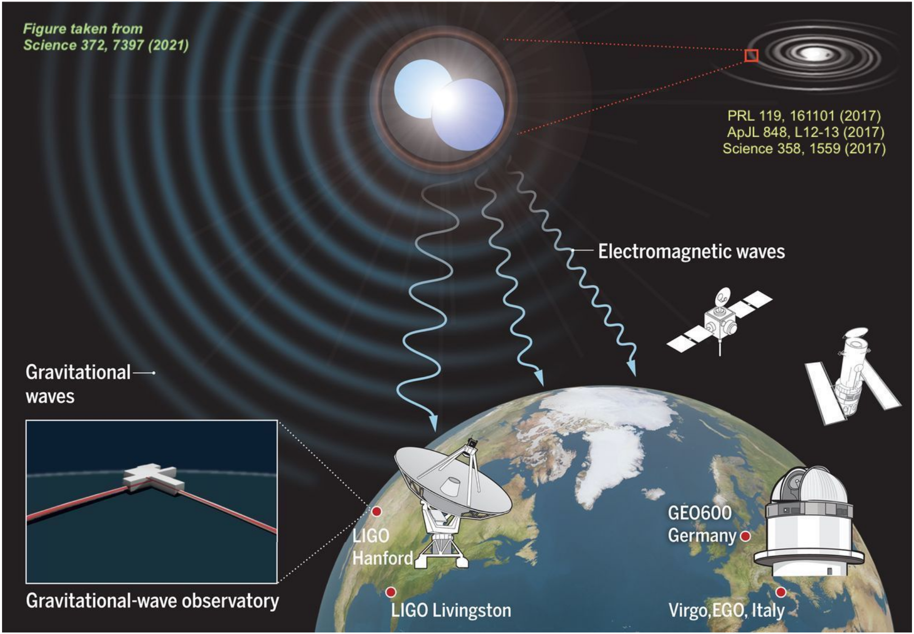
Search for New Physics



Let’s not forget the Cosmic Frontier

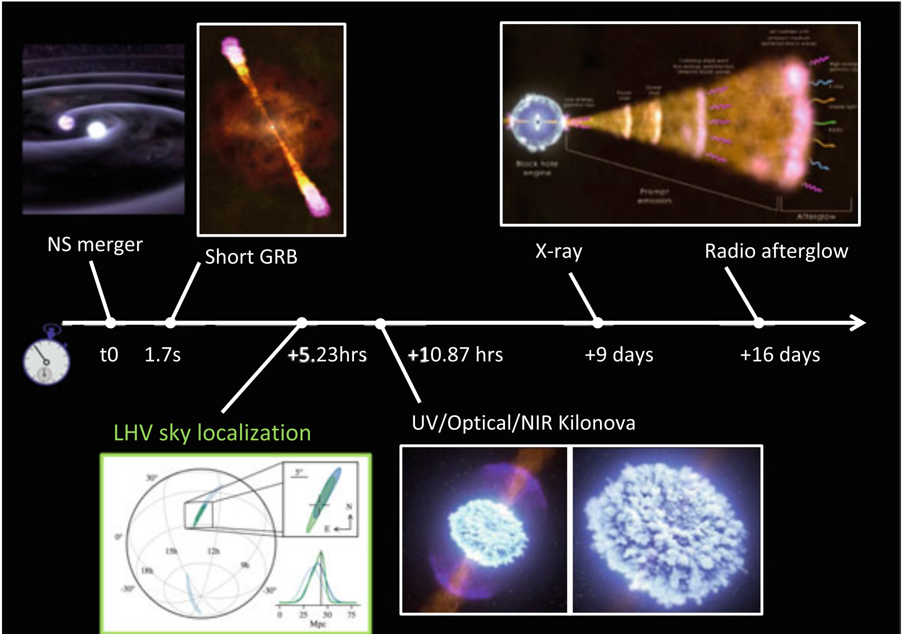
R. Sundrum (Snowmass ‘22)

Multi-messenger Observation of Binary Neutron Star Merger GW170817



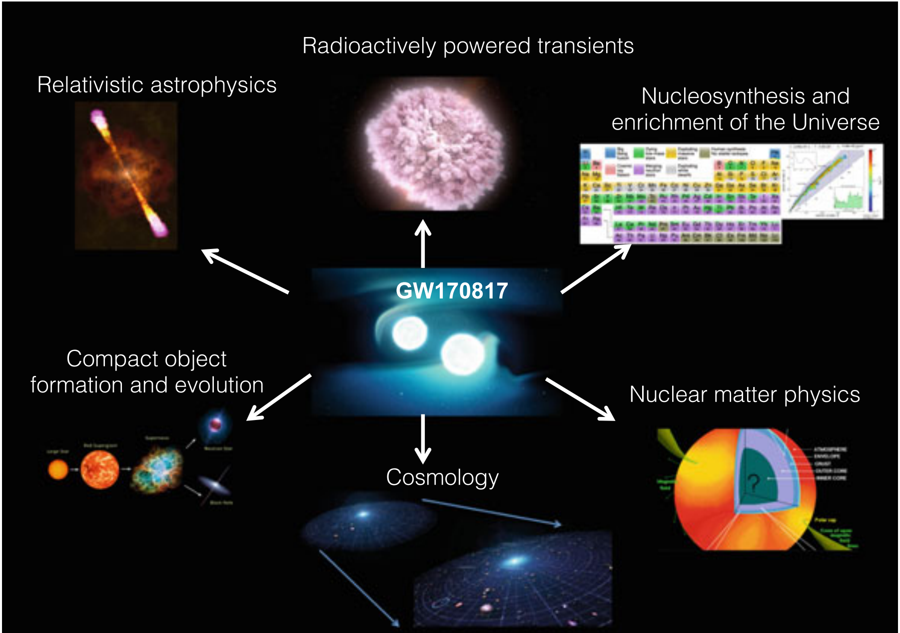
Multi-messenger Observation of Binary Neutron Star Merger GW170817

M. Branchesi, Springer Proc. Phys. **287**, 255 (2023)



Impact on many fields

M. Branchesi, Springer Proc. Phys. **287**, 255 (2023)



E.g., **Axion-like particles (ALPs)**, CP-even scalars, dark photons, light Z',....

New Physics with Neutron Star Mergers

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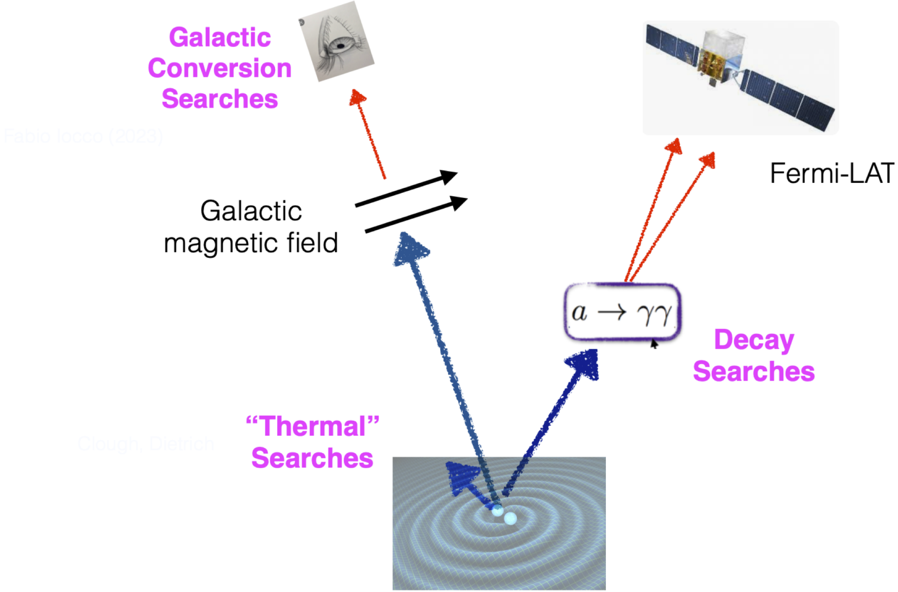
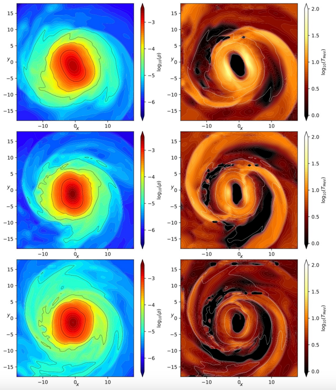


New Physics with Neutron Star Mergers

$m_a = 0$

$m_a = 0.1$ eV

$m_a = 1$ eV



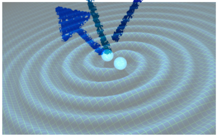
Dietrich, Clough, 1909.01278

“Thermal” Searches

Can cooling change the GW signal?

Trapping affects the shear viscosity, thermal conductivity, etc.

Difficult problem



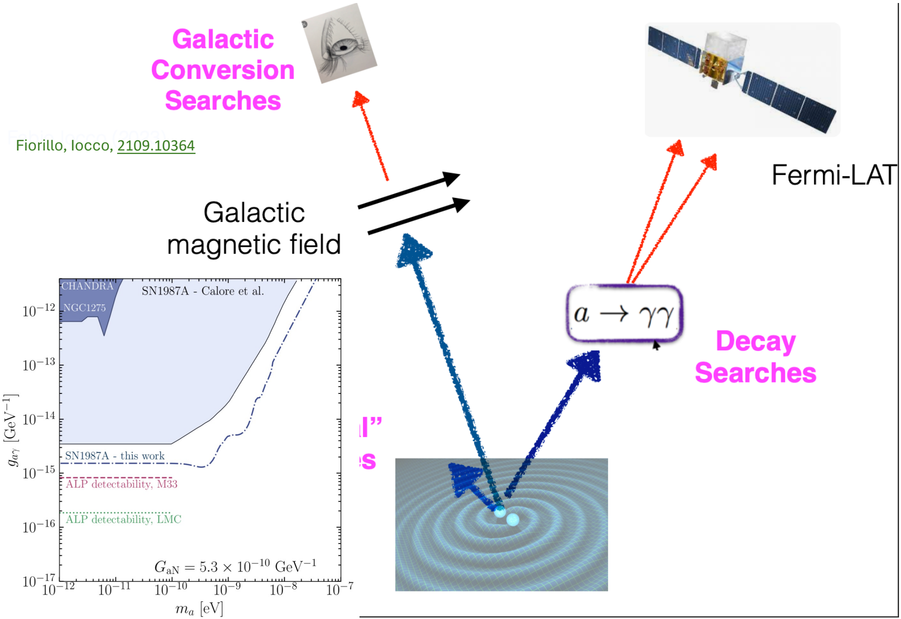
$a \to \gamma\gamma$

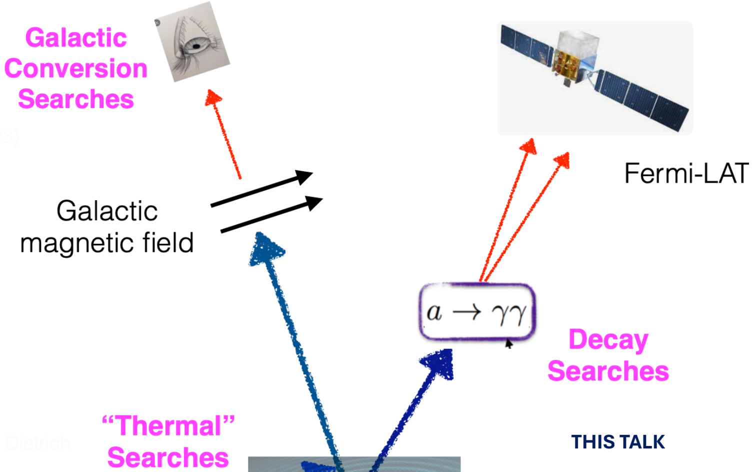
Fermi-LAT

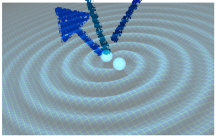
Decay Searches

New Physics with Neutron Star Mergers

Fiorillo, Iocco, 2109.10364







Can cooling change the GW signal?

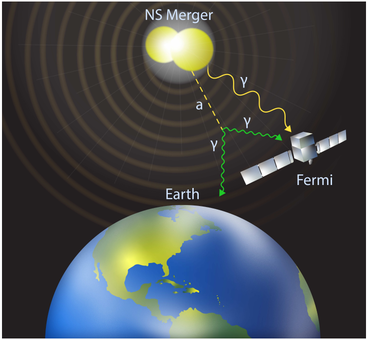
Trapping affects the shear viscosity, thermal conductivity, etc.

Difficult problem

Probing ALPs using Multi-messenger Data from GW170817

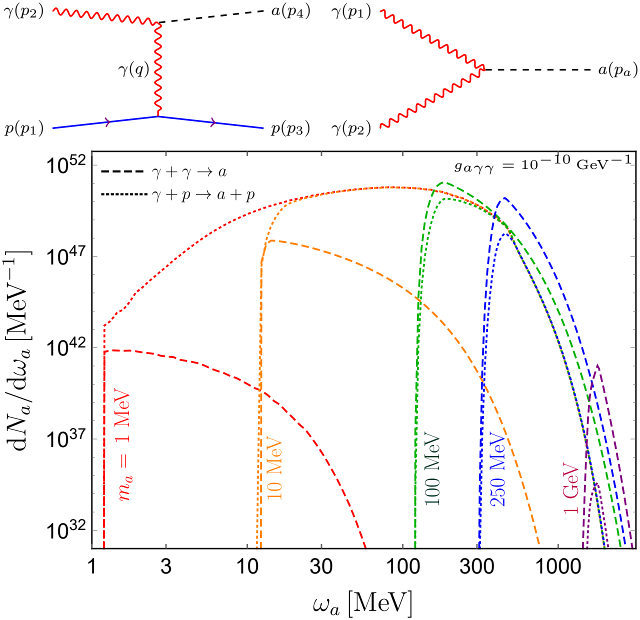
- Use generic ALP feature: Coupling to photons.

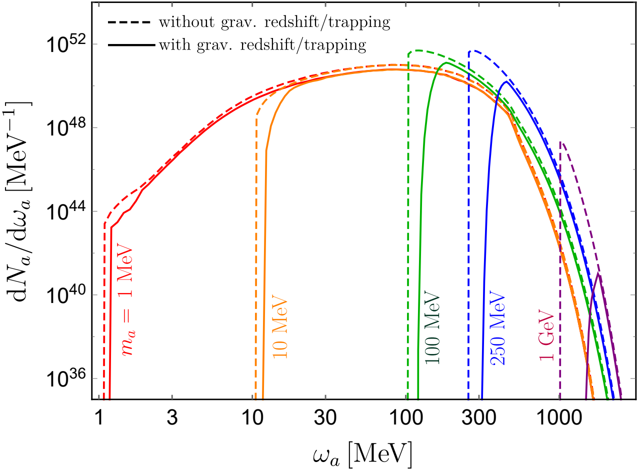
$$\mathcal{L} \supset \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \widetilde{F}_{\mu\nu} \, .$$



- Both production and decay of ALPs are governed by the same coupling $g_{a\gamma\gamma}$.
- Use GW170817 data to draw constraints in the $(m_a, g_{a\gamma\gamma})$ plane.
- Comparison with SN1987A constraints.
- Future prospects with improved gamma-ray measurements.
- Can be extended to other 'light' dark sector particles.

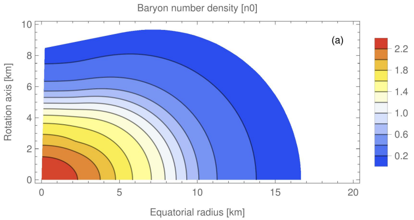
ALP Production via Primakoff and Photon Coalescence





- $E_a > m_a/\eta \gtrsim 1.5 - 1.7 m_a$.
- In contrast, for supernovae, $E_a \gtrsim 1.12 m_a$. [Caputo, Janka, Raffelt, Vitagliano, 2201.09890 (PRL '22)]
- For Schwarzschild geometry, lapse factor $\eta = \sqrt{1 - 2GM/r}$ for $r > R$.
- For axisymmetric geometry of the merger, η also depends on θ.

Merger Profiles [Camelio, Dietrich, Rosswog, Haskell, 2011.10557 (PRD '21)]



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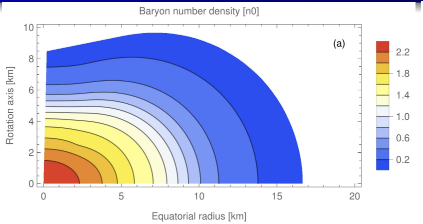

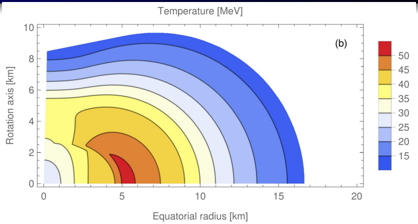

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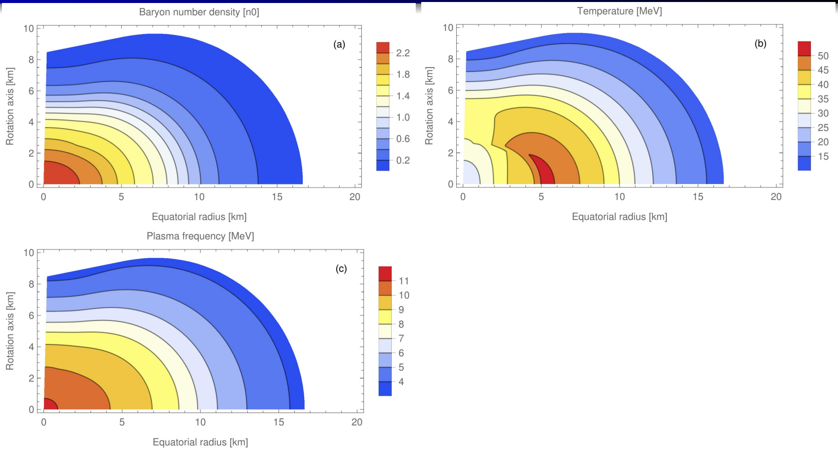

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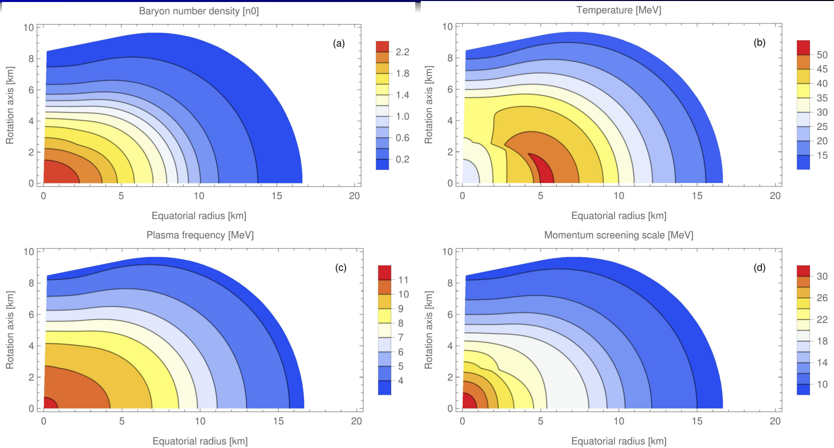

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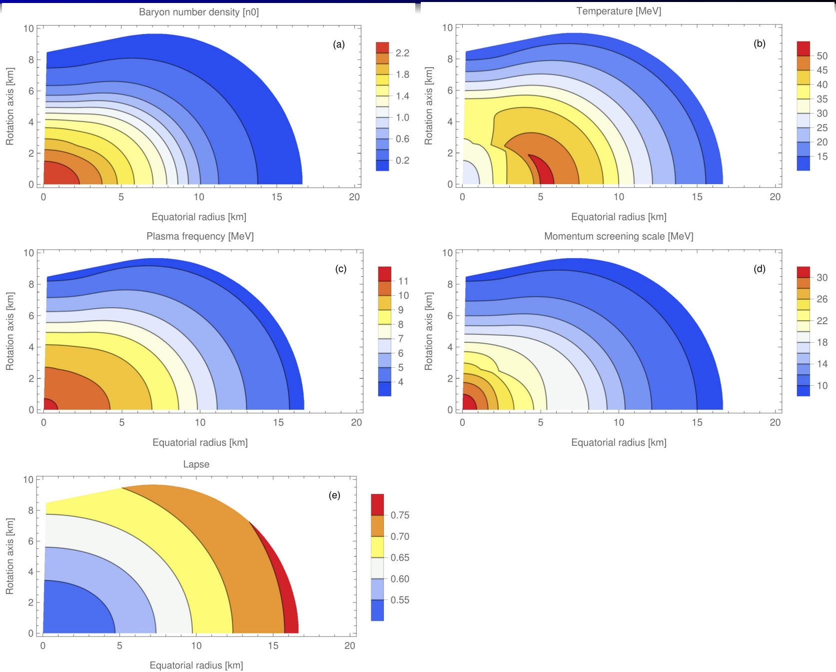

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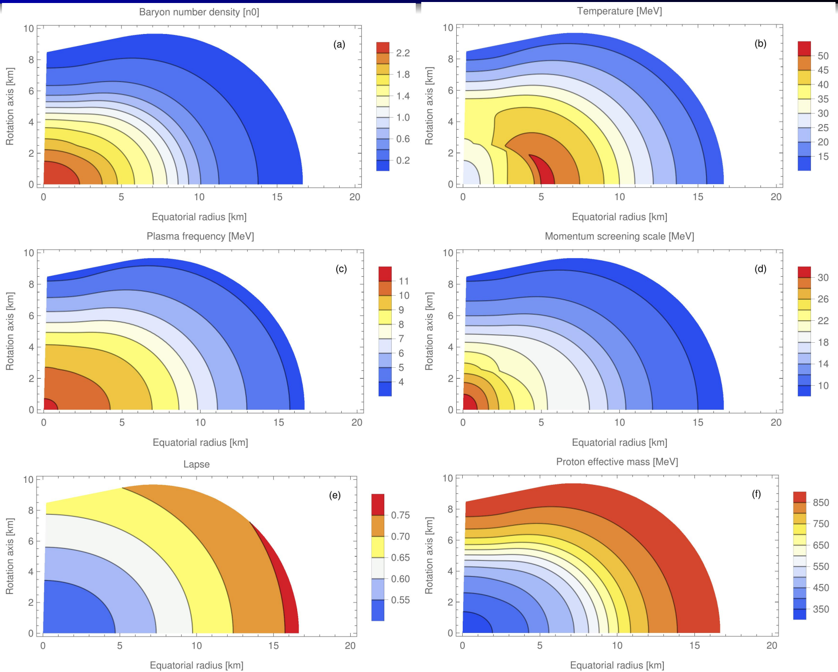
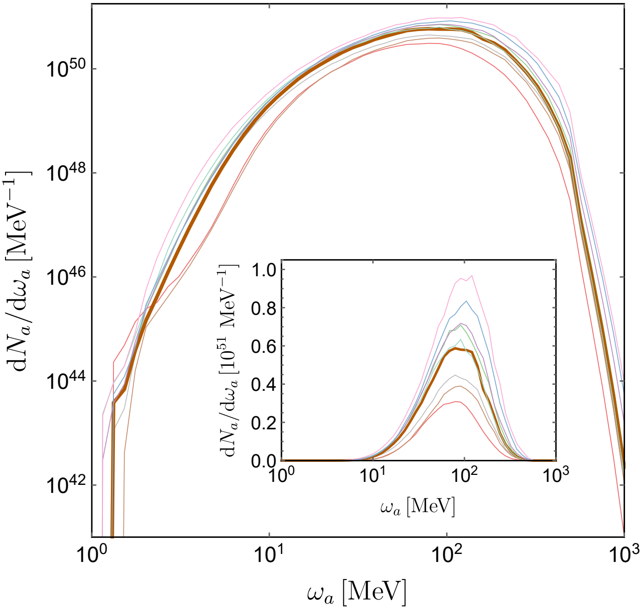
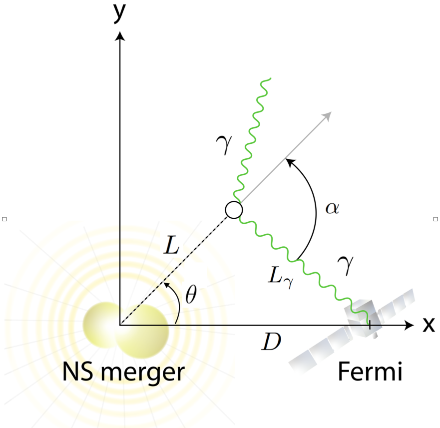


Production Rates for Different Profiles



ALP Decay and Geometry Effect



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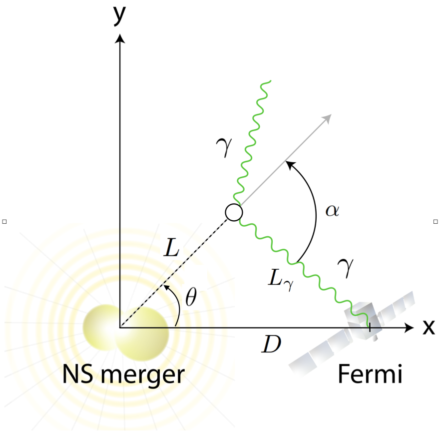
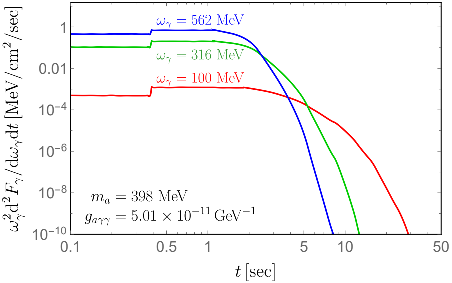


Master Formula for Photon Spectrum

$$\omega_\gamma^2 \frac{\mathrm{d}^2 F_\gamma}{\mathrm{d}\omega_\gamma \mathrm{d}t}(\omega_\gamma, D+t) = \int_{-1}^{1} \mathrm{d}z \int_0^\infty \mathrm{d}L \, \frac{\omega_\gamma^2}{4\pi D (L_\gamma + Lz)} \frac{\mathrm{d}^2 N_a}{\mathrm{d}\omega_a \mathrm{d}t}(\omega_a, D + t - L/\beta_a - L_\gamma)$$

$$\times \, \mathrm{Jac}(\omega_a, \omega_\gamma) \frac{m_a^2}{\omega_a^2 (1-\beta_a z)^2} \frac{\exp\left(-L/\ell_a\right)}{\ell_a} \Theta(L - R_\star) \Theta(L - D/\sqrt{1-z^2}) \, .$$

Spectral/Temporal Behavior ($D = 40$ Mpc)



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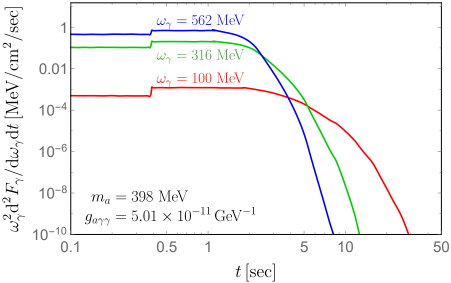

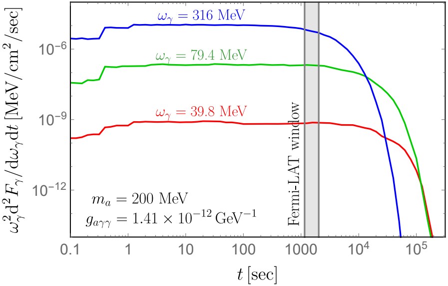

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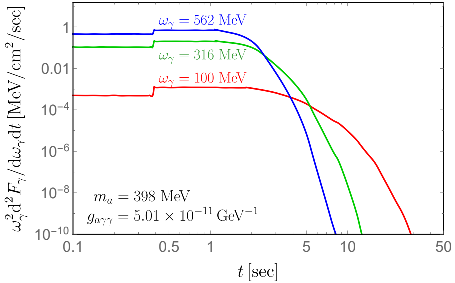

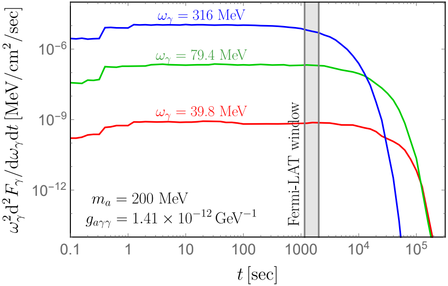

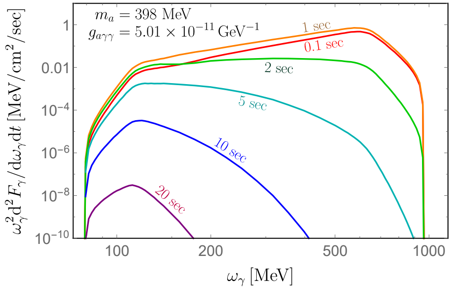

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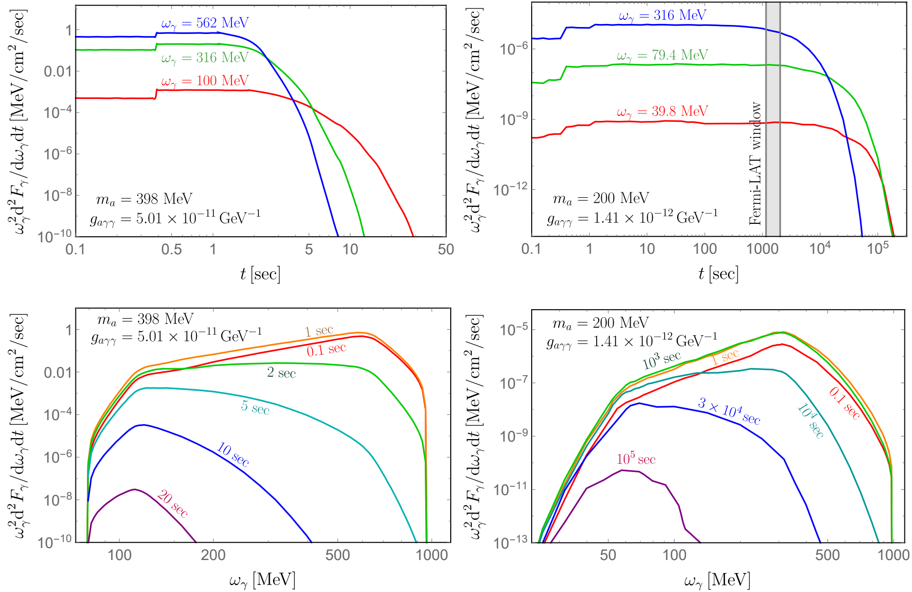
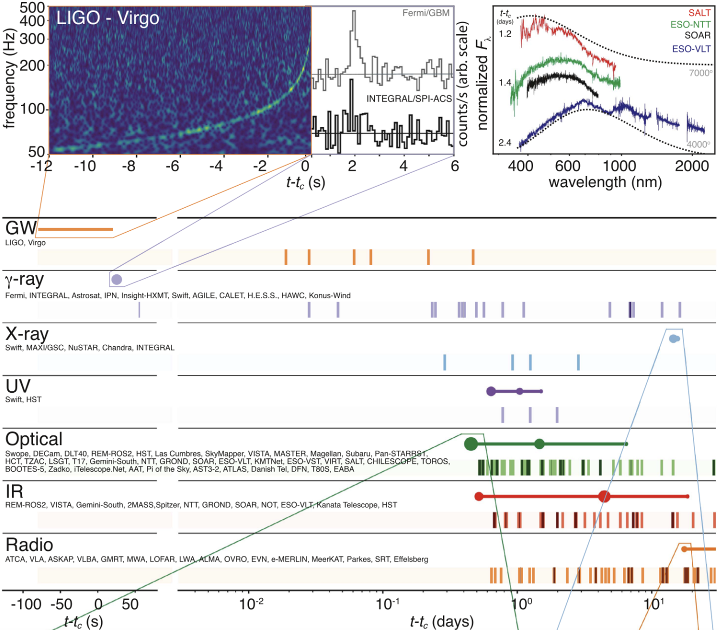


Multimessenger Analysis

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.



Why Fermi-LAT?

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)
CALET CGBM	Aug 17 12:41:04 UTC	0.0	1.3×10^{-7}[a]	10–1000 keV	Nakahira et al. (2017)
Konus-*Wind*	Aug 17 12:41:04.446 UTC	0.0	3.0×10^{-7} [erg cm^{-2}]	10 keV–10 MeV	Svinkin et al. (2017a)
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Insight-HXMT/HE	Aug 17 12:41:06.30 UTC	1.85 s	6.6×10^{-7}	0.2–5 MeV	Li et al. (2017)
Insight-HXMT/HE	Aug 17 12:46:04 UTC	300 s	1.5×10^{-7}	0.2–5 MeV	Li et al. (2017)
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	H. 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	$(8.0–9.9) \times 10^{-10}$	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)
INTEGRAL IBIS/ISGRI	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	3.6×10^{-11}	80–300 keV	Savchenko et al. (2017)
INTEGRAL IBIS/PICsIT	Aug 18 12:45:10—Aug 23 03:22:34 UTC	1–5.7 days	0.9×10^{-10}	468–572 keV	Savchenko et al. (2017)
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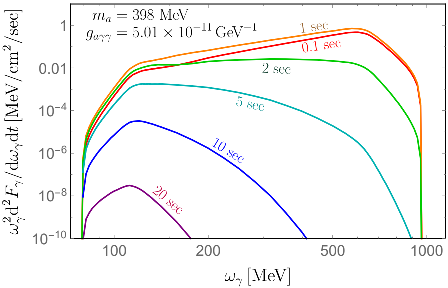
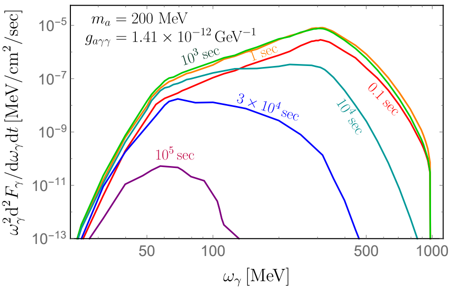
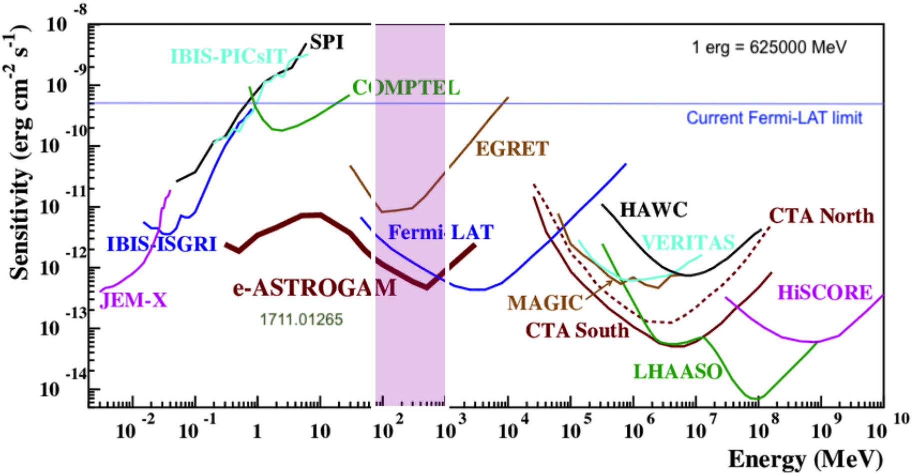


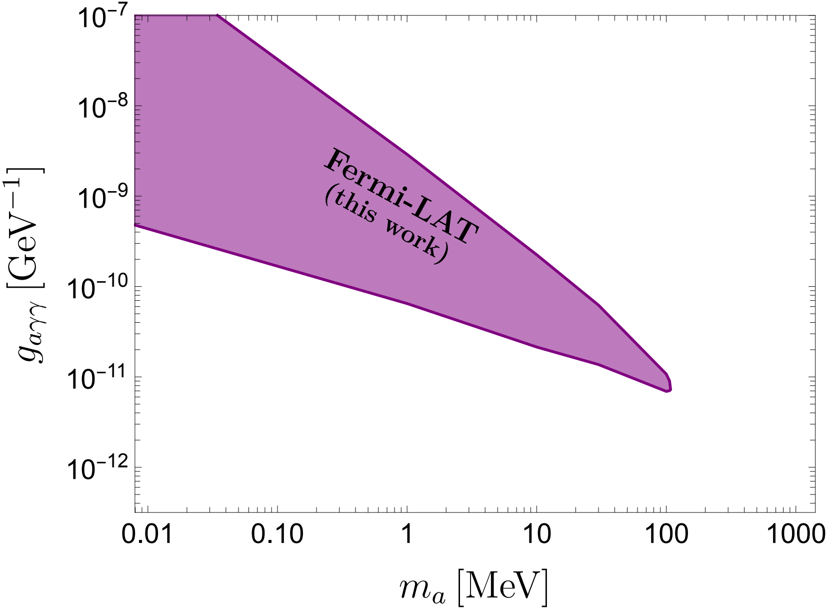


Future Sensitivity of Gamma-ray Telescopes

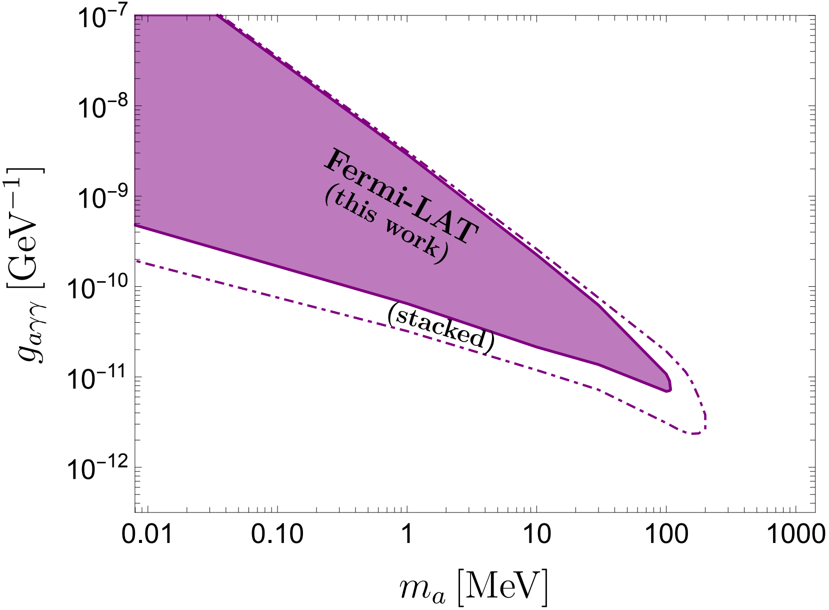


- At least 100 times better sensitivity expected with existing Fermi-LAT.
- Might further improve with future MeV gamma-ray missions (e.g., AMEGO-X, e-ASTROGAM, APT, GECCO).
- Peak sensitivity in the 50–500 MeV range is most suitable for us.

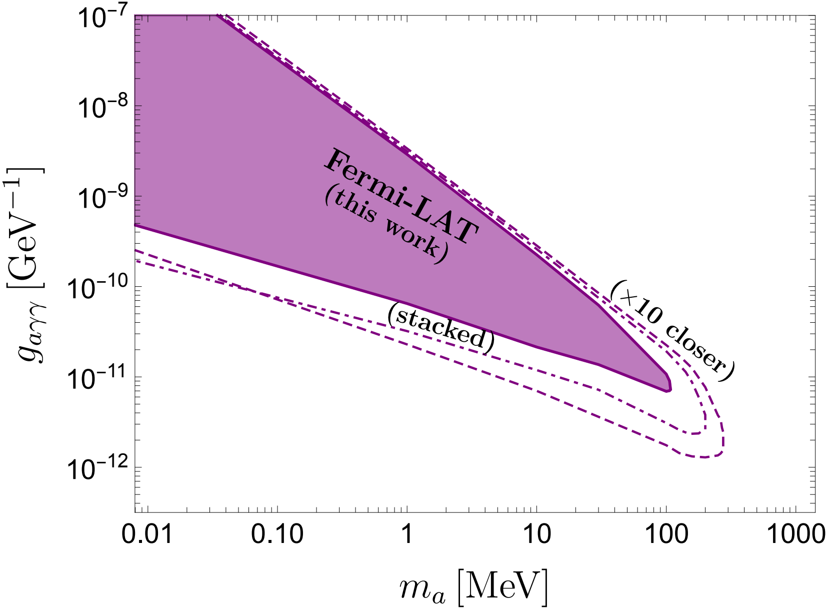
Result: GW170817 Gamma-ray Constraint on ALP



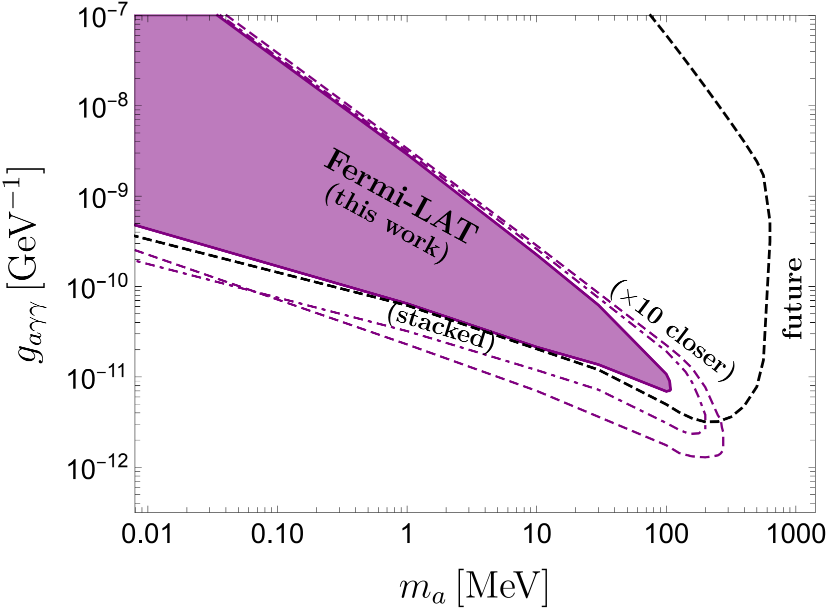
Future Sensitivity with a Stacked Analysis



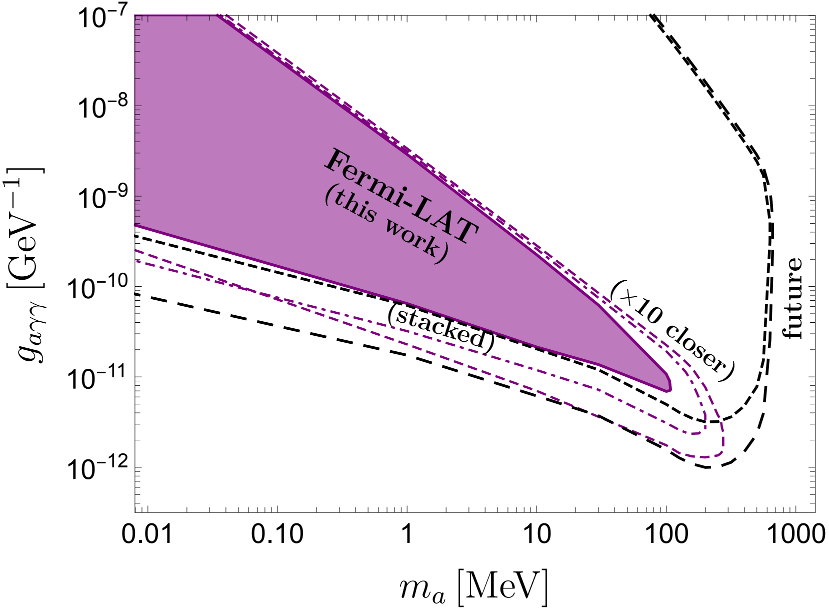
Future Sensitivity for a Nearby Source



Future Sensitivity with an Extended Observation Time Window

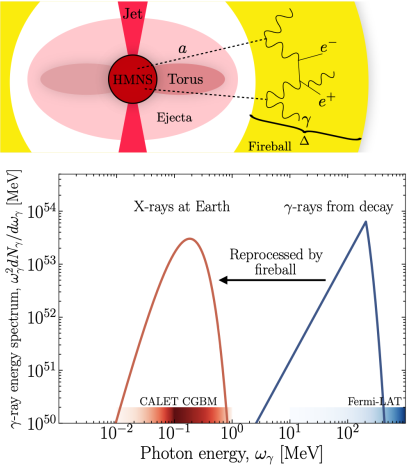


With Better Flux Sensitivity and Extended Observation Time Window



Fireball

[Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, 2305.10327 (PRL ’24)]



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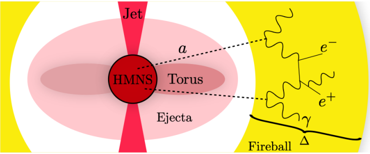
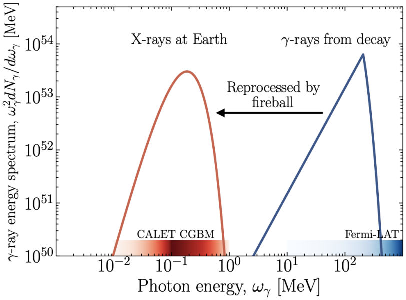
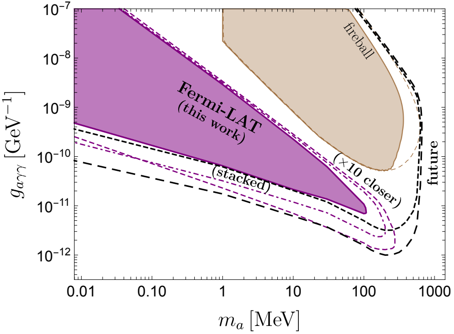
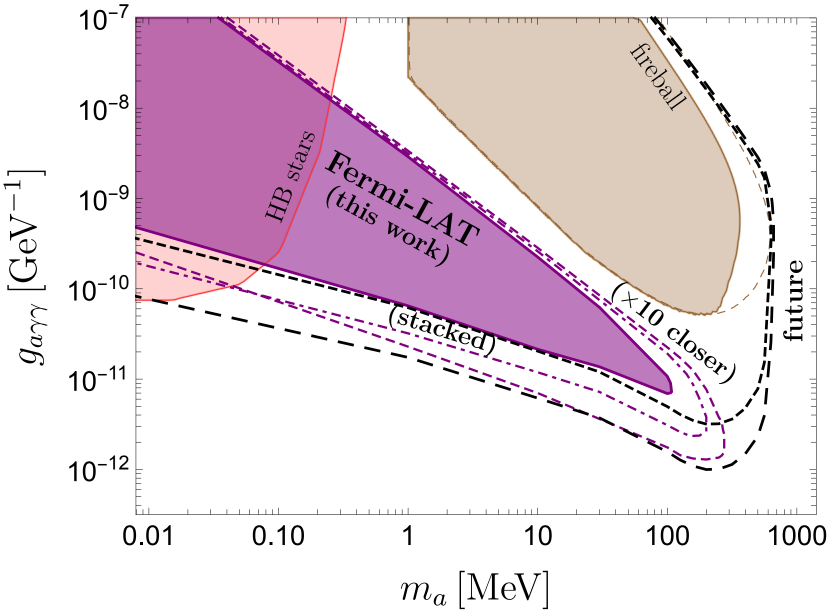






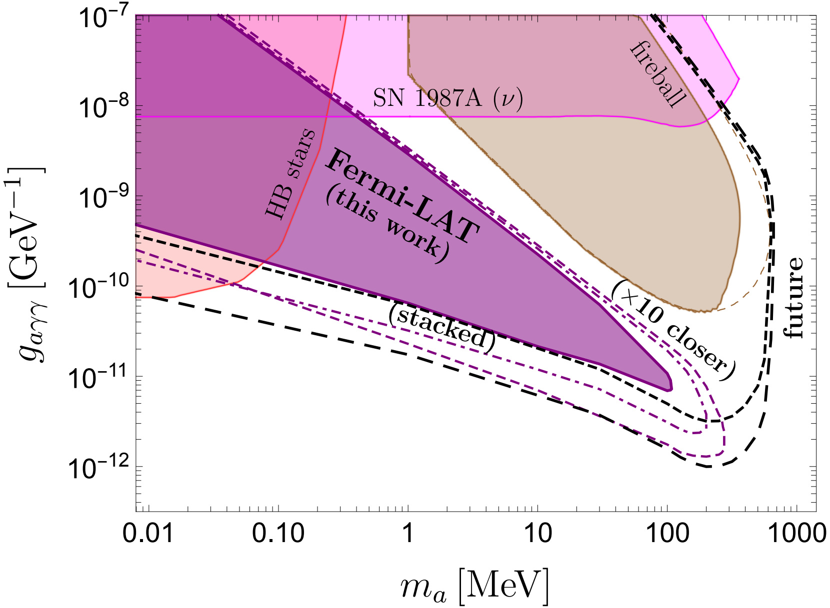
Other Constraints: HB Stars

[Lucente, Straniero, Carenza, Giannotti, Mirizzi, 2203.01336 (PRL '22)]



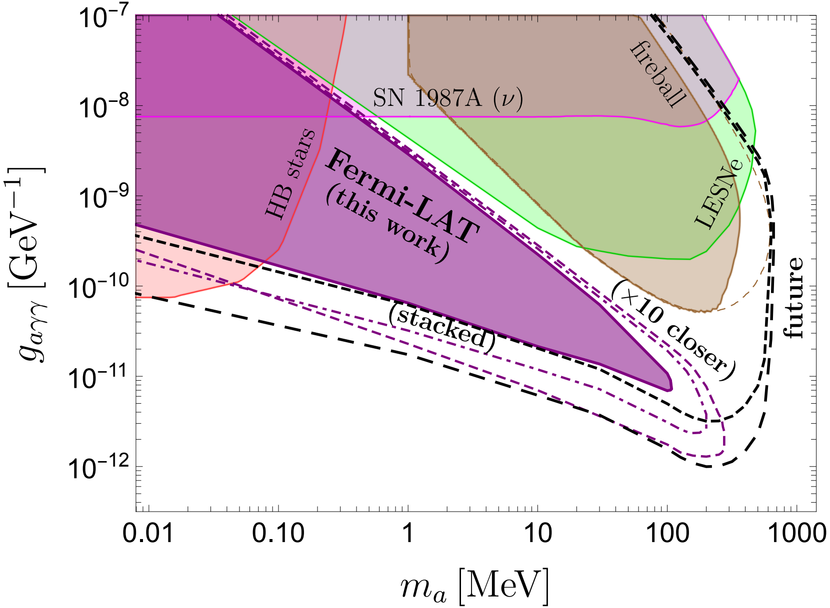
Other Constraints: SN1987A Neutrino

[Caputo, Raffelt, Vitagliano, 2109.03244 (PRD '22)]



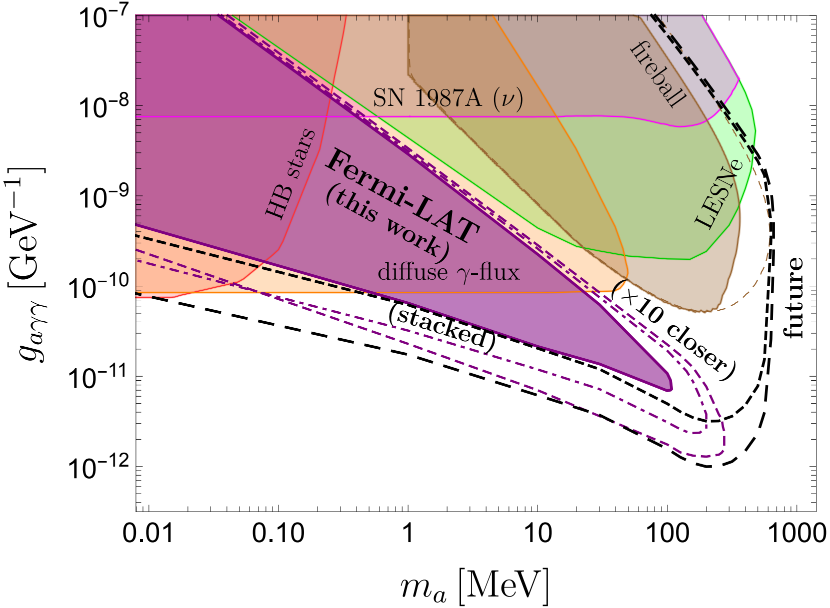
Other Constraints: Low-energy Supernova Calorimetry

[Caputo, Janka, Raffelt, Vitagliano, 2201.09890 (PRL ’22))]



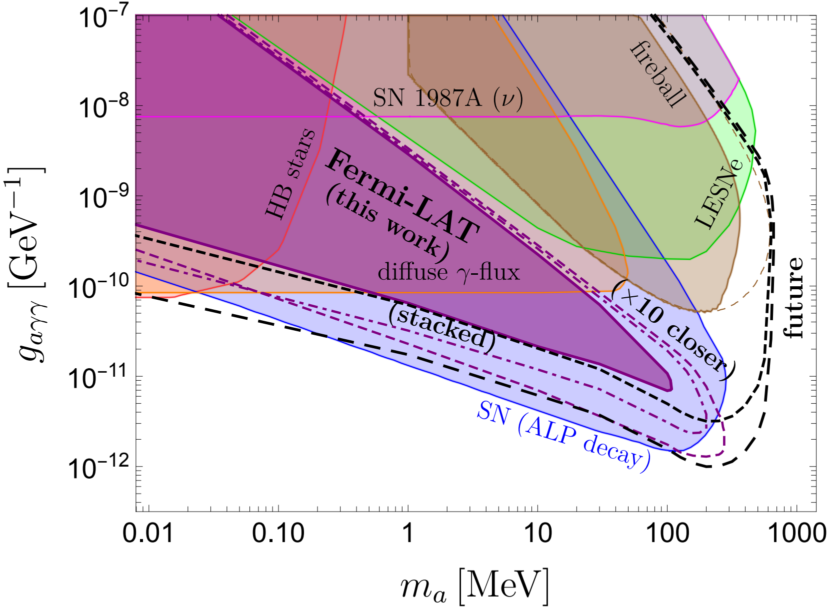
Other Constraints: Diffuse Gamma-ray Background

[Caputo, Raffelt, Vitagliano, 2109.03244 (PRD ’22)]



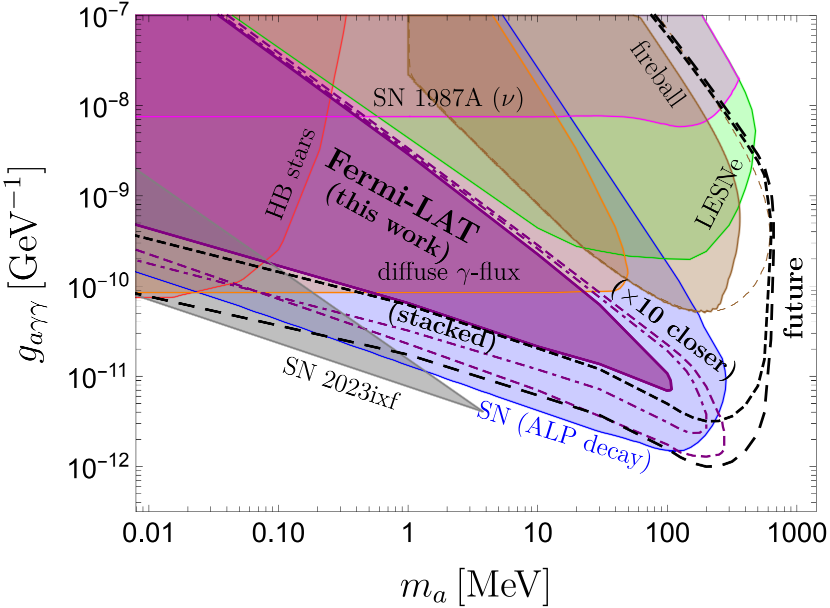
Killer Constraint: SN1987A Gamma-ray Constraint from ALP Decay

[Müller, Calore, Carenza, Eckner, Marsh, 2304.01060 (JCAP ’23)]

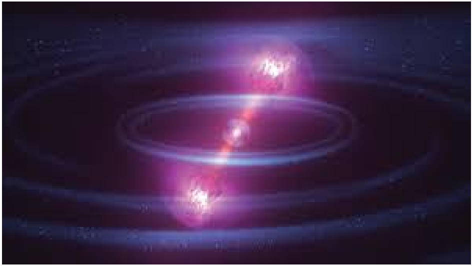


Other Constraints: ALP Decay from SN2023ixf

[Müller, Carenza, Eckner, Goobar, 2306.16397 (PRD ’24)]



Concluding Remarks: Supernovae vs NS Mergers



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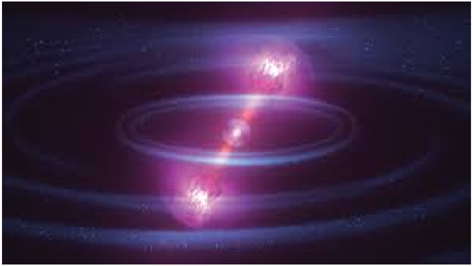

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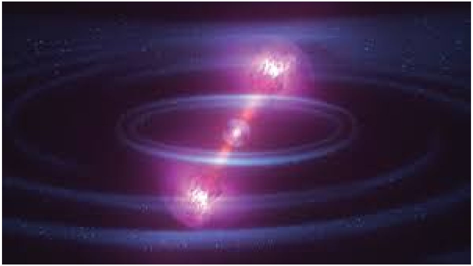

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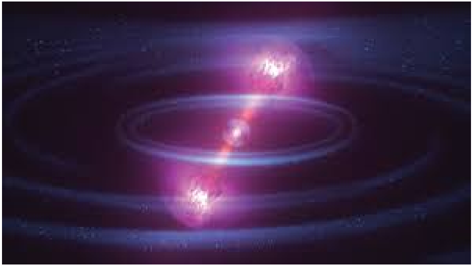

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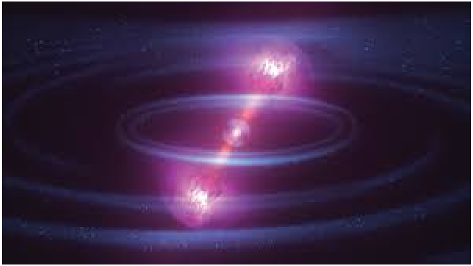

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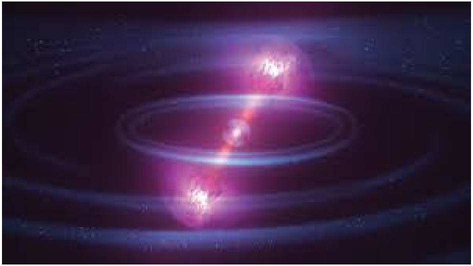

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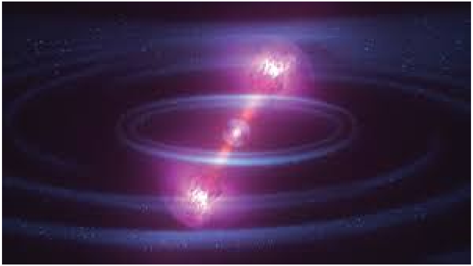

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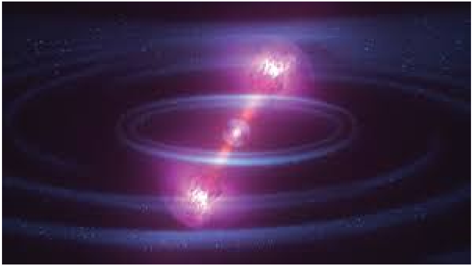

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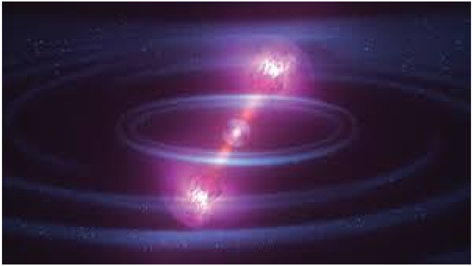

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- Possible with future early-warning system. [Sachdev et al., 2008.04288 (ApJL '20)]

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Jean-François Fortin (Laval)

Steven Harris (INT/Indiana)

Kuver Sinha (Oklahoma)

Yongchao Zhang (Southeast)

UNIVERSITIES RESEARCH ASSOCIATION

Backup Slides

ALP Couplings

$$\begin{aligned}\mathcal{L}_a \sim\ & \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{c_1}{f}\partial_\mu a \bar{f}\gamma_\mu\gamma_5 f \\ & - \frac{c_2}{f} a G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{c_3}{f} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{c_4}{f} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{c_5}{f} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} \\ & + \frac{c_6}{f^2}(\partial_\mu a)(\partial^\mu a)\phi^\dagger\phi + \frac{c_7}{f^3}(\partial^\mu a)(\phi^\dagger \iota D_\mu \phi + h.c.)\phi^\dagger\phi + \dots\end{aligned}$$

- $\frac{c_1}{f}\partial_\mu a \bar{f}\gamma_\mu\gamma_5 f$: $a \to \ell^+\ell^-$
- $a G_{\mu\nu}\tilde{G}^{\mu\nu}$: $a \to gg$
- $a F_{\mu\nu}\tilde{F}^{\mu\nu}$: $a \to \gamma\gamma$
- $a F_{\mu\nu}\tilde{Z}^{\mu\nu}$: $Z \to \gamma a$
- $(\partial_\mu a)(\partial^\mu a)\phi^\dagger\phi$: $h \to aa$
- $(\partial^\mu a)(\phi^\dagger \iota D_\mu \phi$: $h \to Za$