Opportunities of HFGW with Axion Detectors

Sung Mook Lee

CERN

JHEP 03 (2024) 128 (2306.03125)

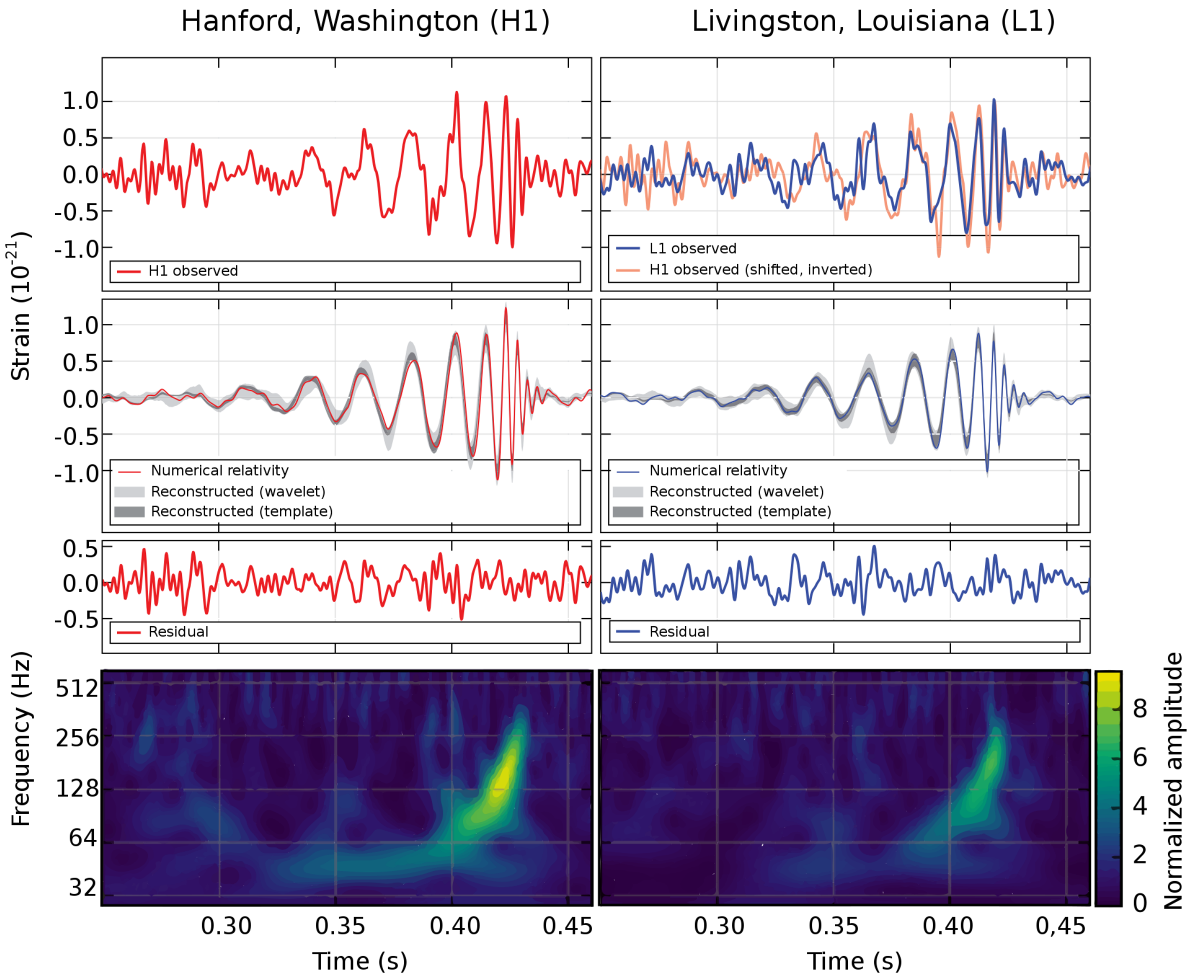
with Valerie Domcke (CERN), Camilo Garcia-Cely (Valencia, IFIC), and Nicholas L. Rodd (LBNL)

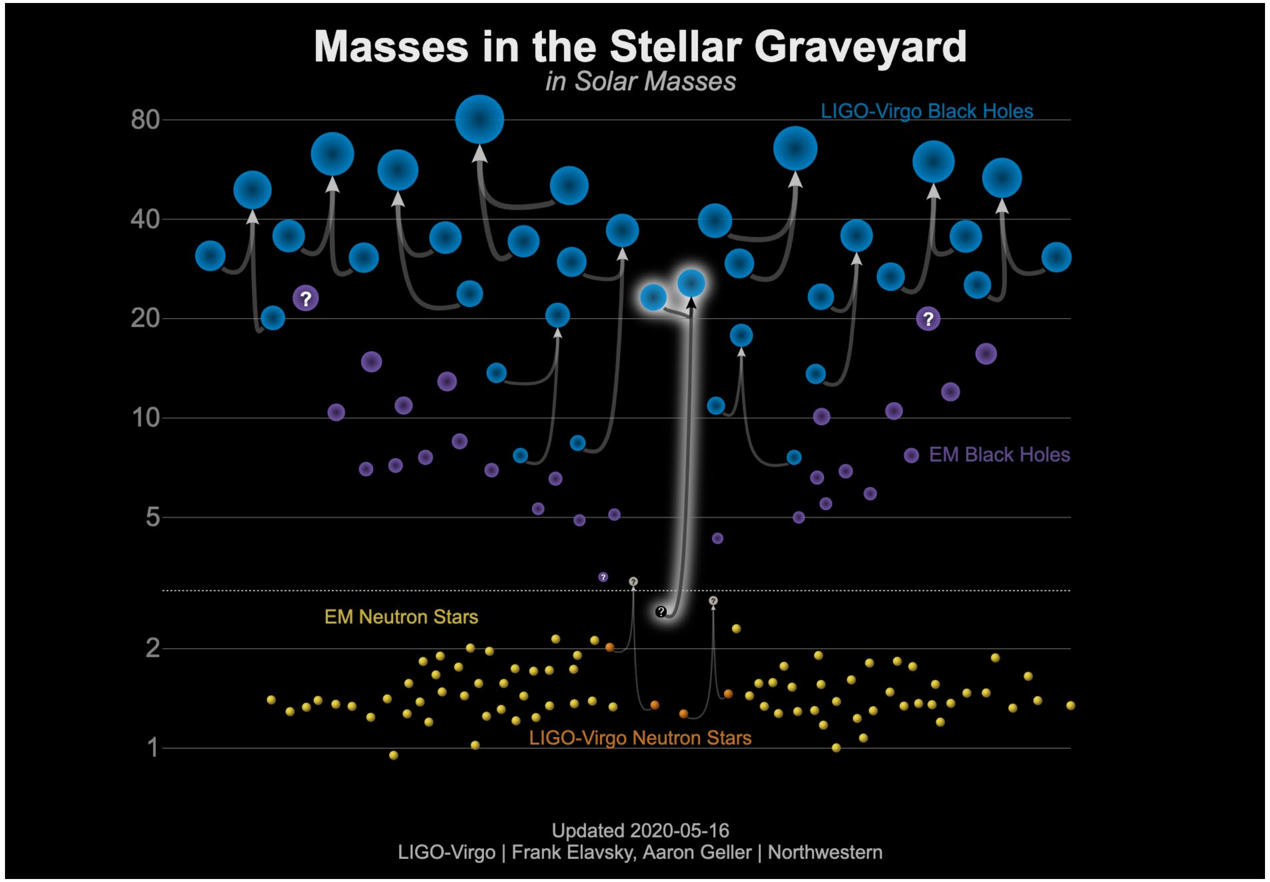
Funded by
the European Union

Outline

- **HFGW – Why?**
  - **Motivation / Source**
- **HFGW – How?**
  - **On the table : Axion Haloscope**
  - **From the sky : Neutron Star**

Detection of Gravitational Waves





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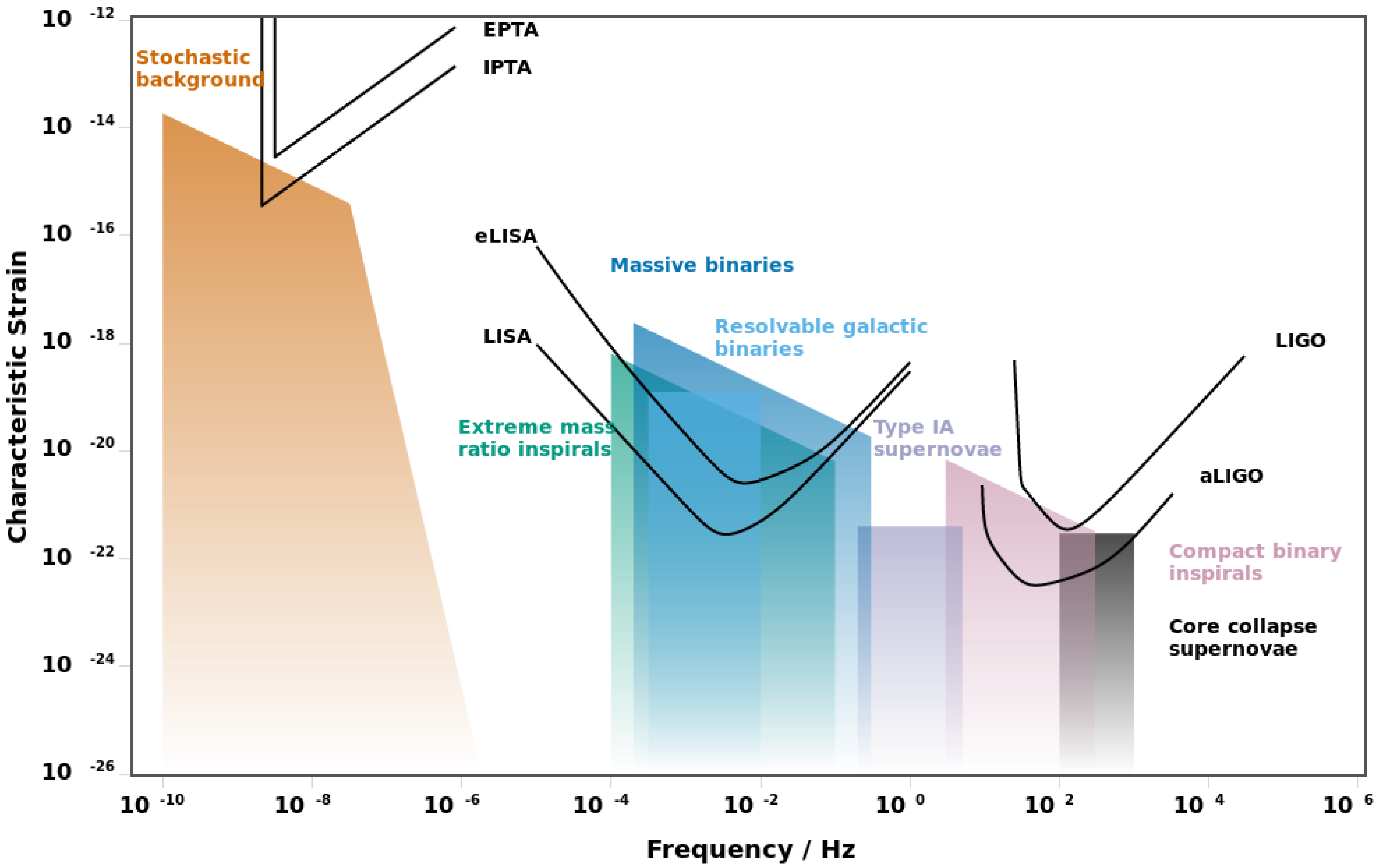

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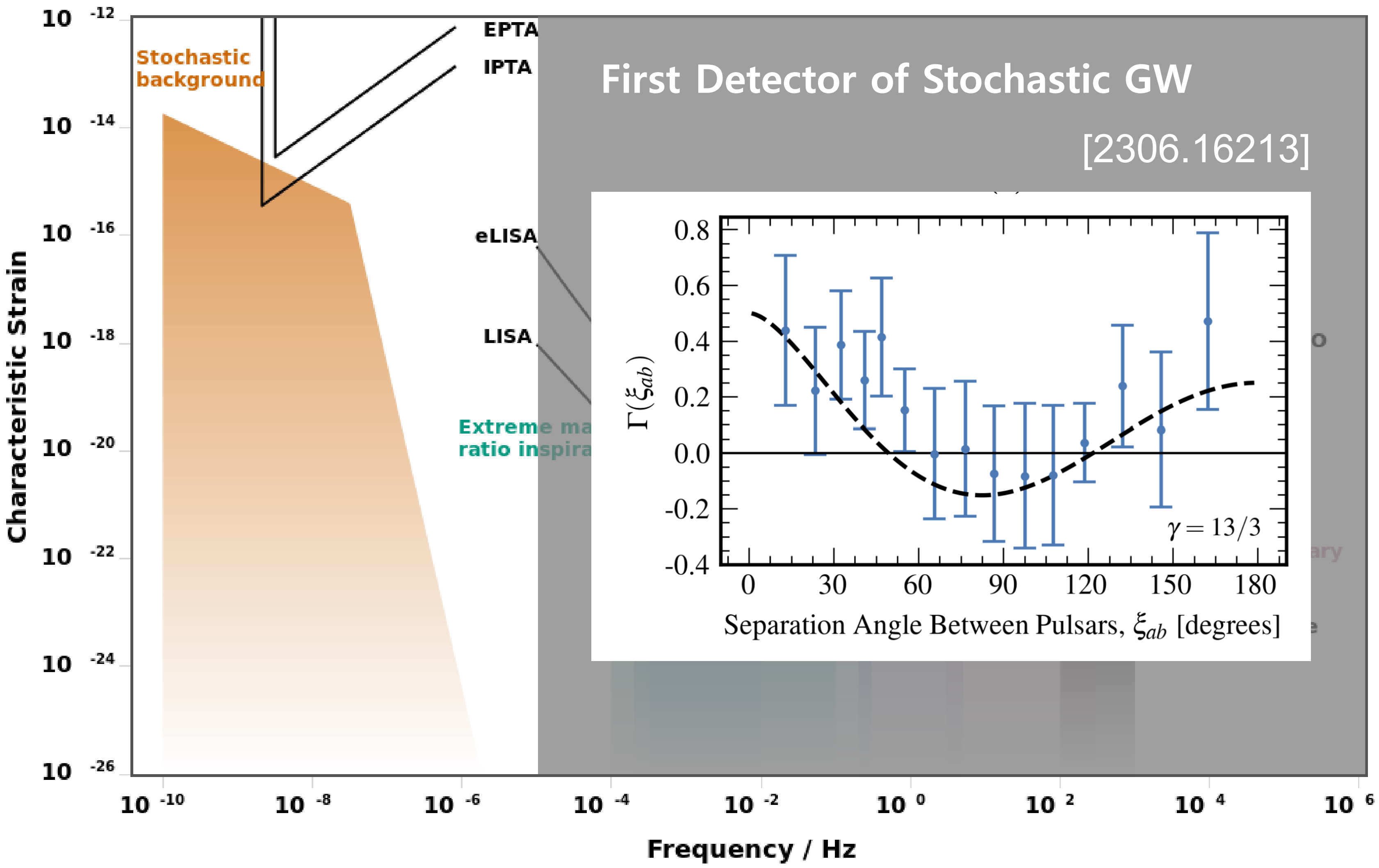

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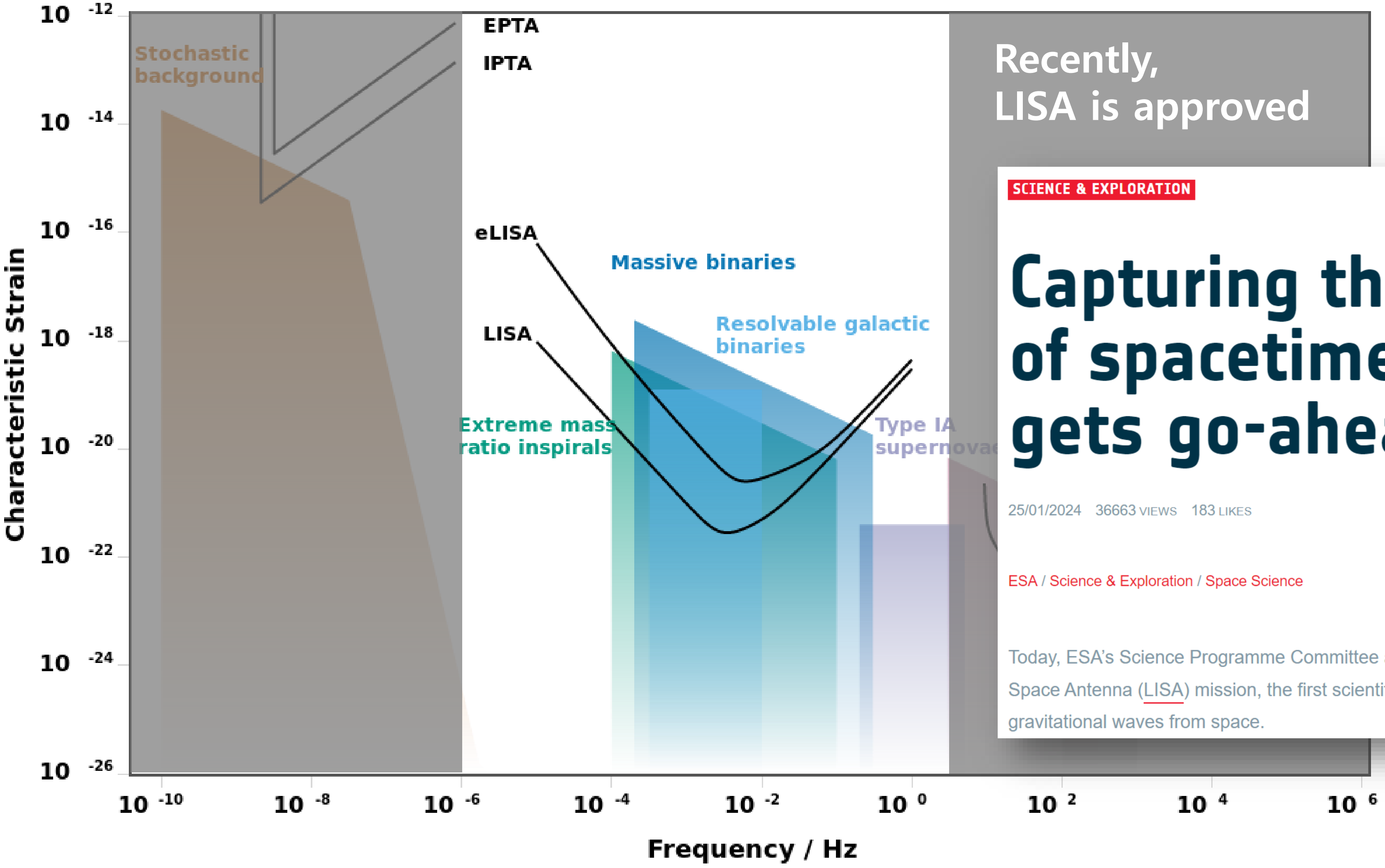


Recently,
LISA is approved

SCIENCE & EXPLORATION

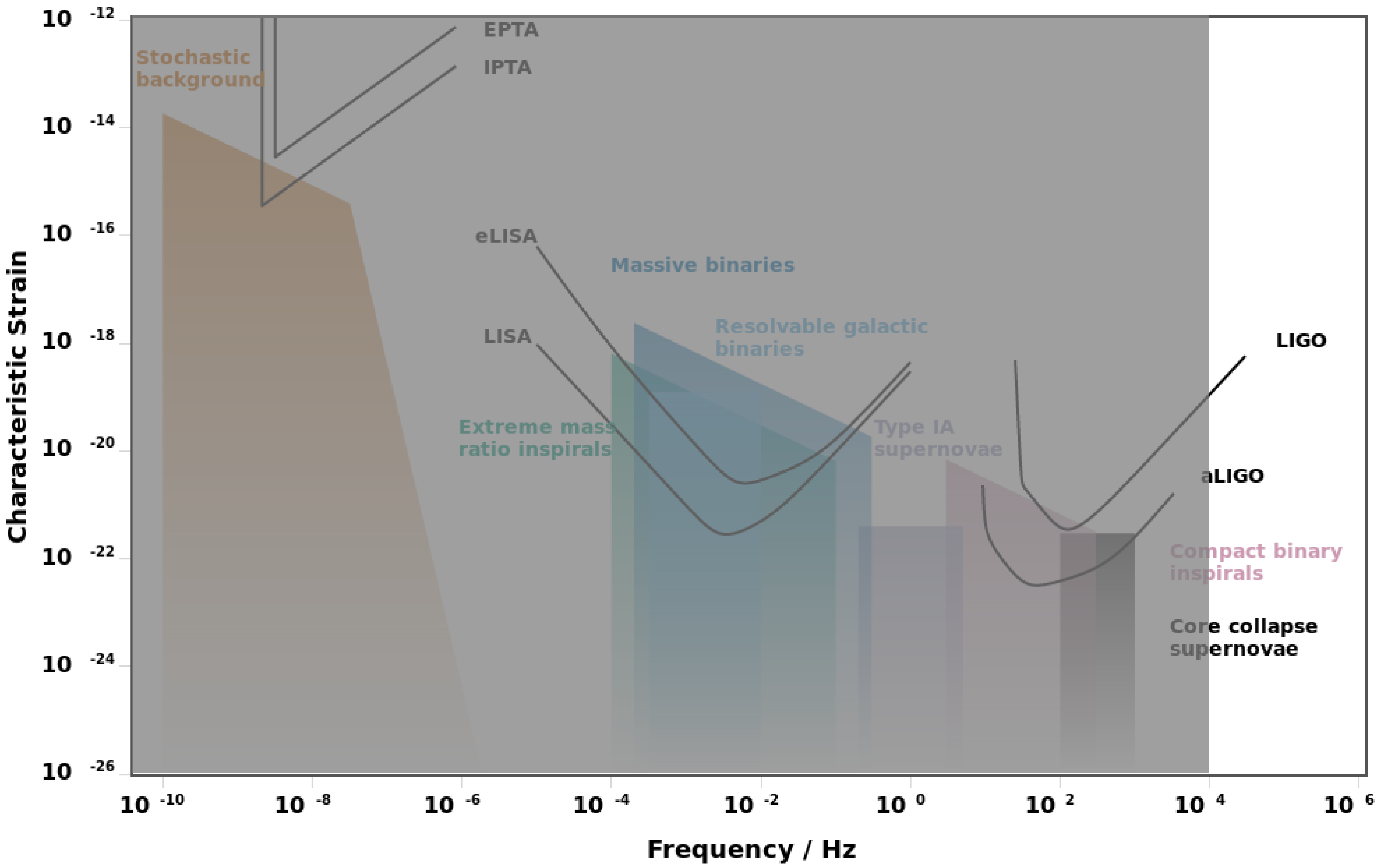
Capturing the ripples of spacetime: LISA gets go-ahead

25/01/2024 36663 VIEWS 183 LIKES

ESA / Science & Exploration / Space Science

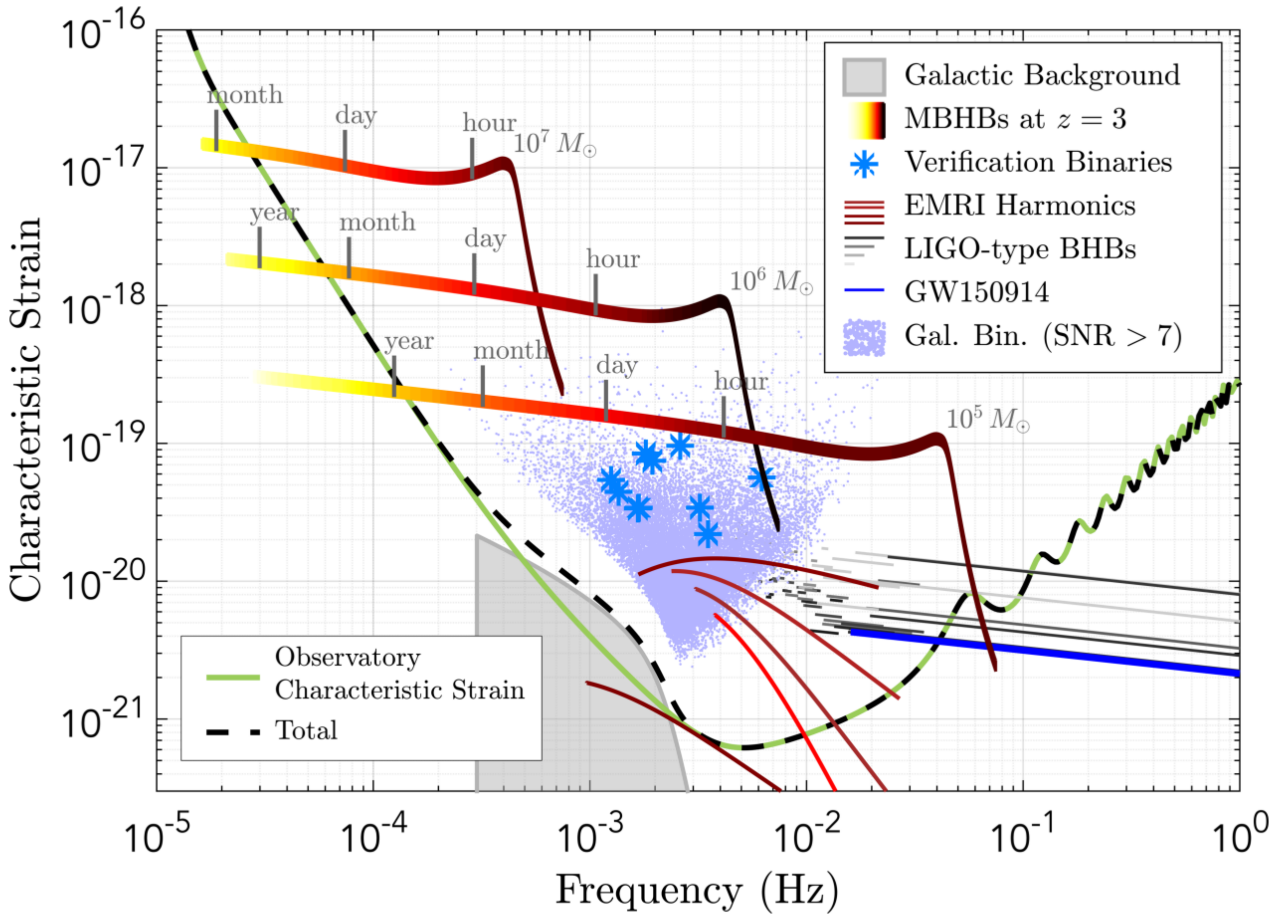
Today, ESA's Science Programme Committee approved the Laser Interferometer Space Antenna (LISA) mission, the first scientific endeavour to detect and study gravitational waves from space.

Detection of Gravitational Waves



Signals from BSM Physics?

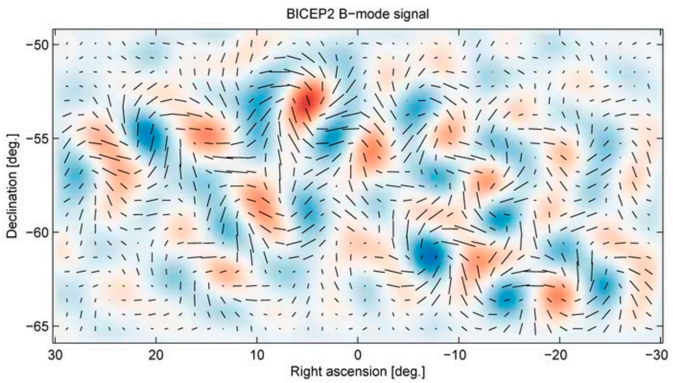
- ‘Background’ from SMBH



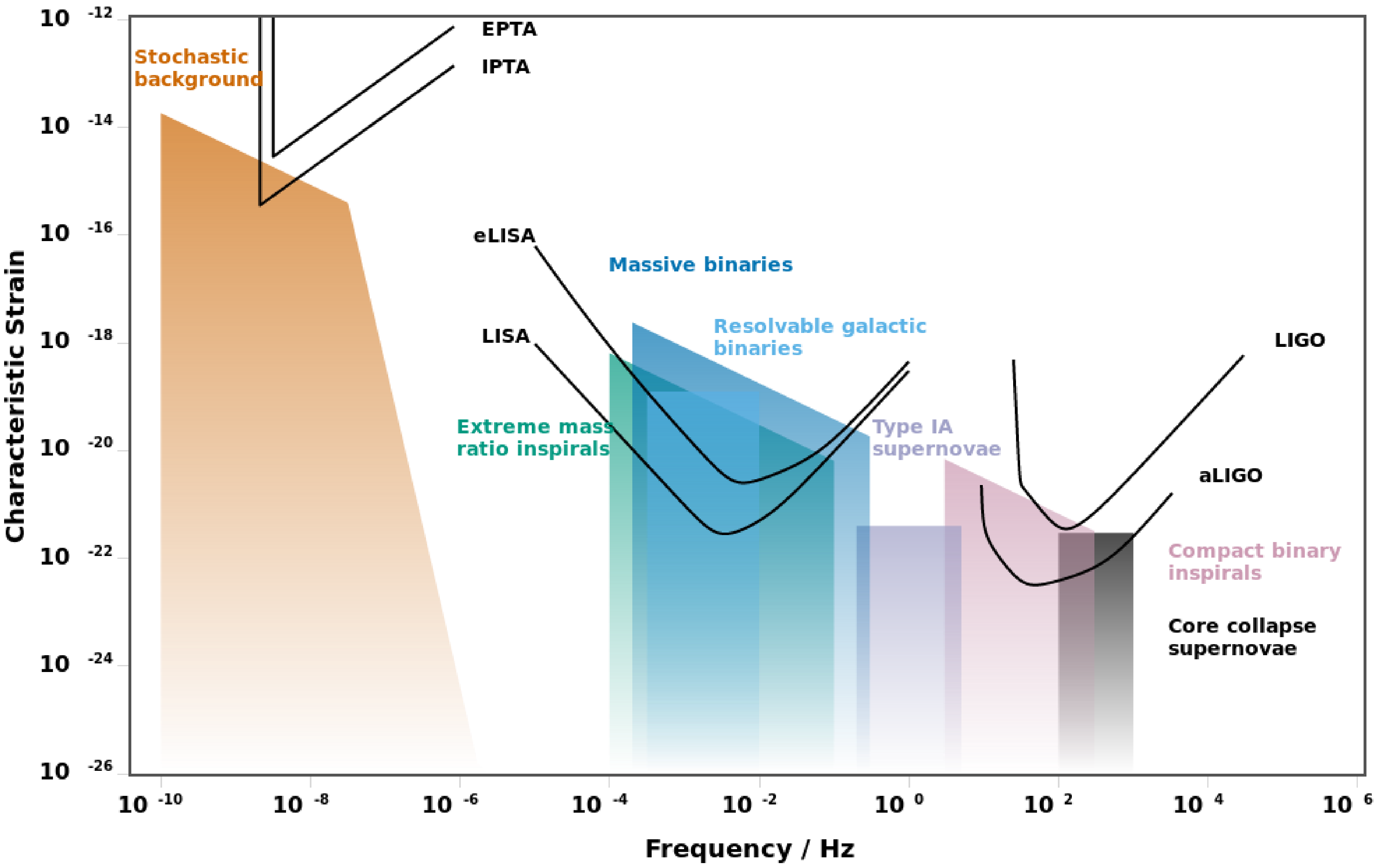
[LISA Proposal 1702.00786]

Detection of Gravitational Waves

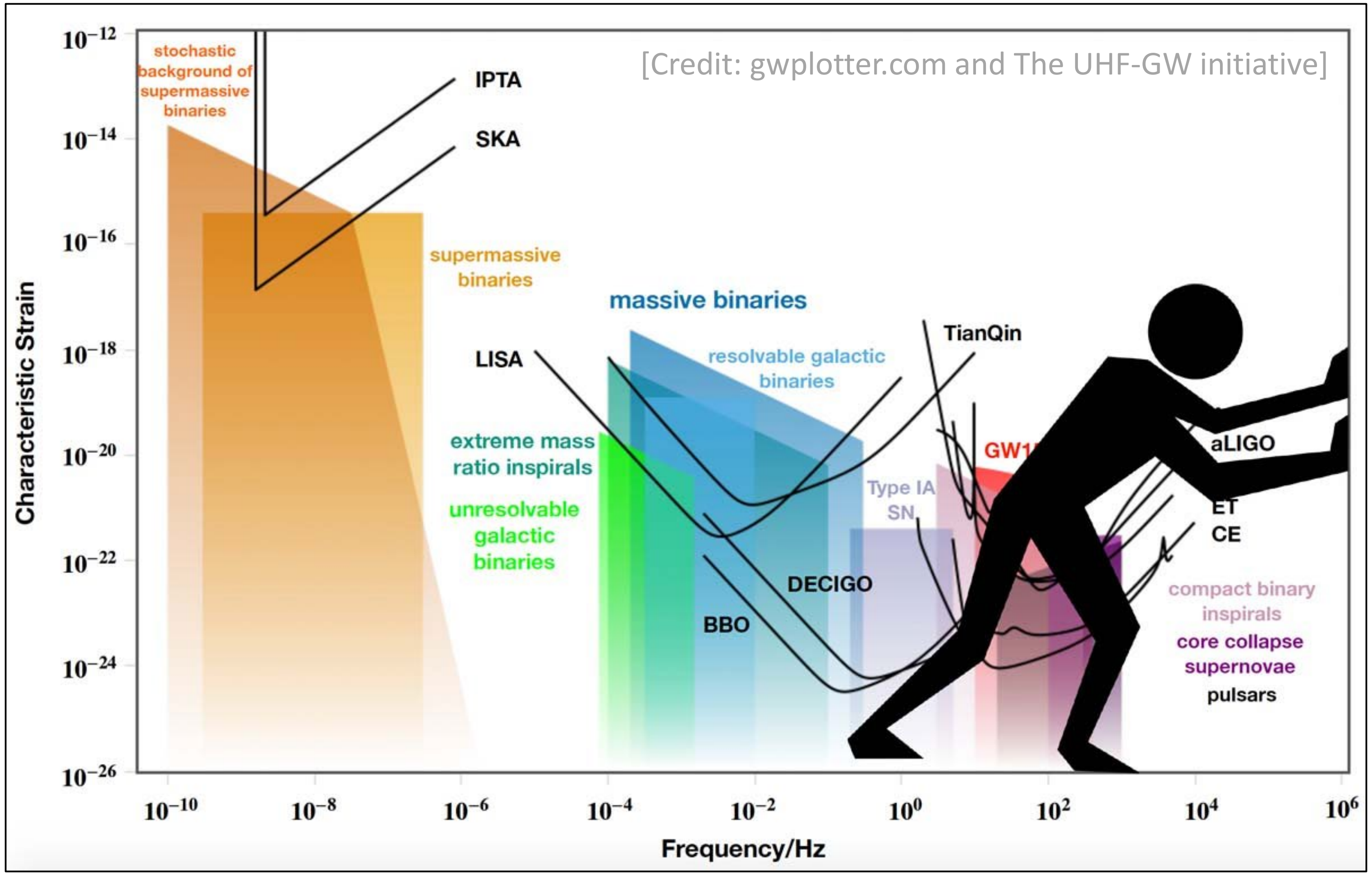
LOWER frequency



CMB B-mode Polarization



High Frequency Gravitational Waves



How can we detect GW with f > O(1MHz)?

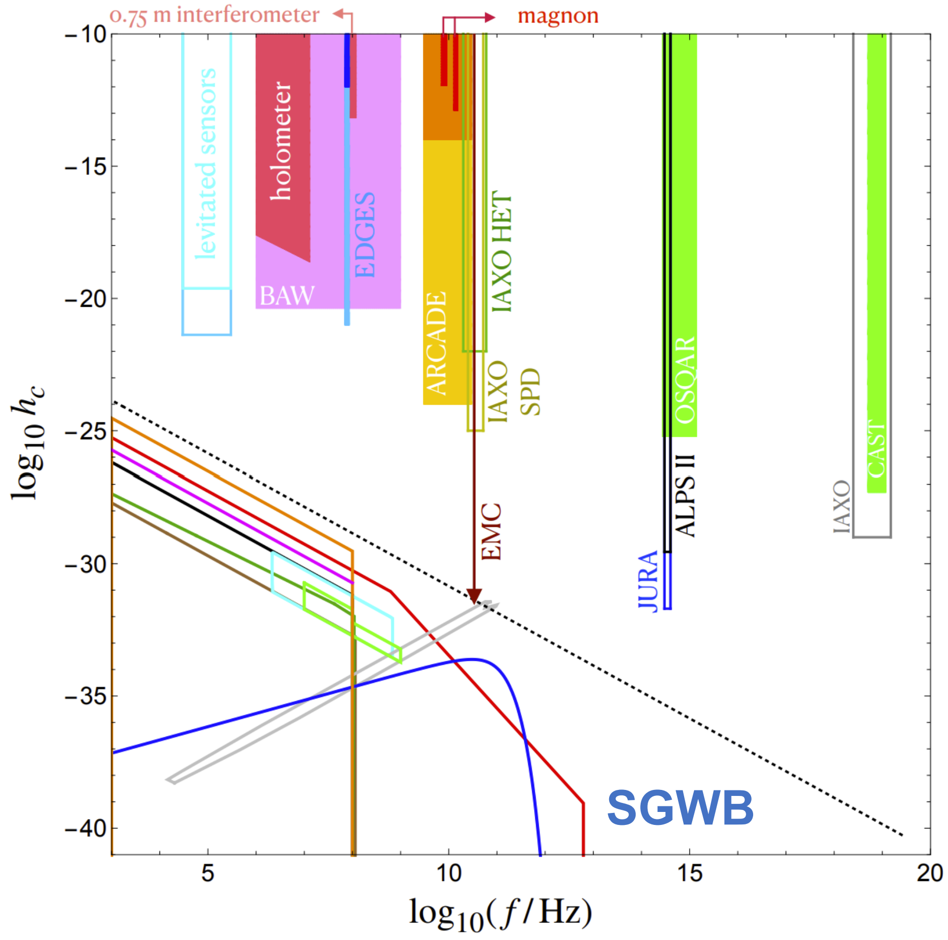
Sources of HFGW

HFGW Sources

- **Stochastic Gravitational Wave Background**
  - High frequency = Early universe

$$f_{\rm GW} \gtrsim O(1)\ \mathrm{MHz} \left(\frac{T_*}{10^8\ \mathrm{GeV}}\right)$$

[2011.12414 for review]



HFGW Sources

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[2011.12414 for review]

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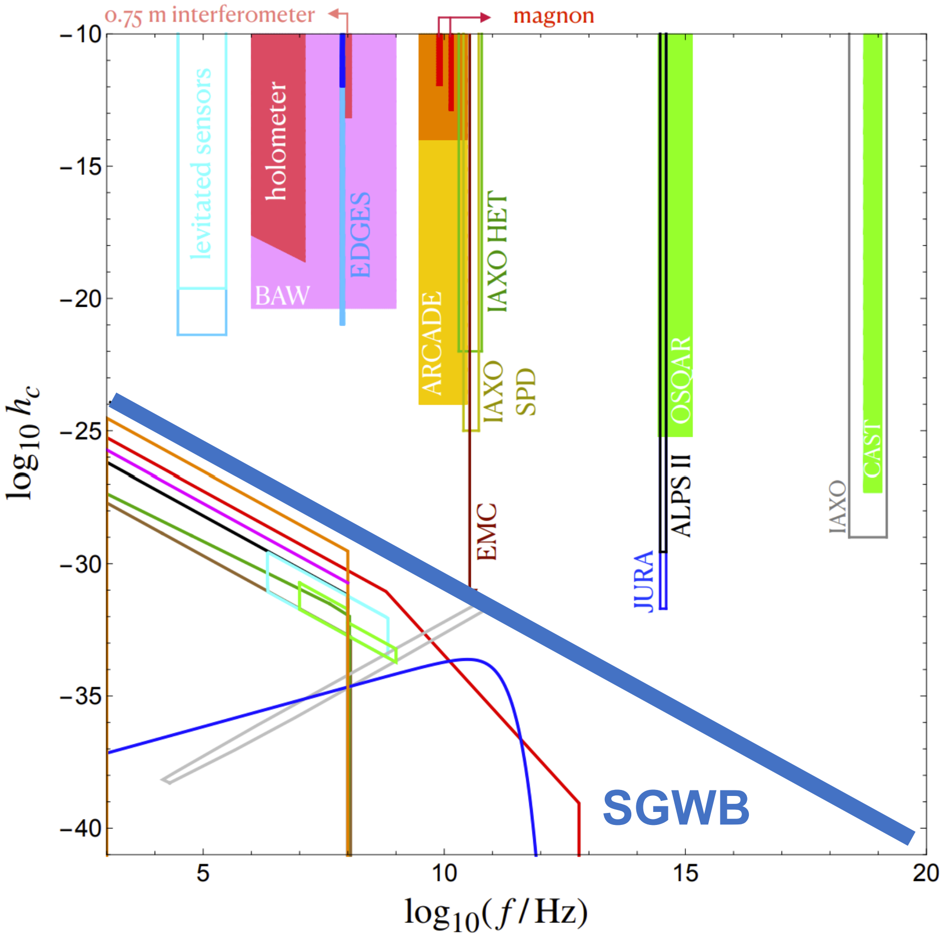
$$f_{\rm GW} \gtrsim O(1)\ \mathrm{MHz} \left(\frac{T_*}{10^8\ \mathrm{GeV}}\right)$$

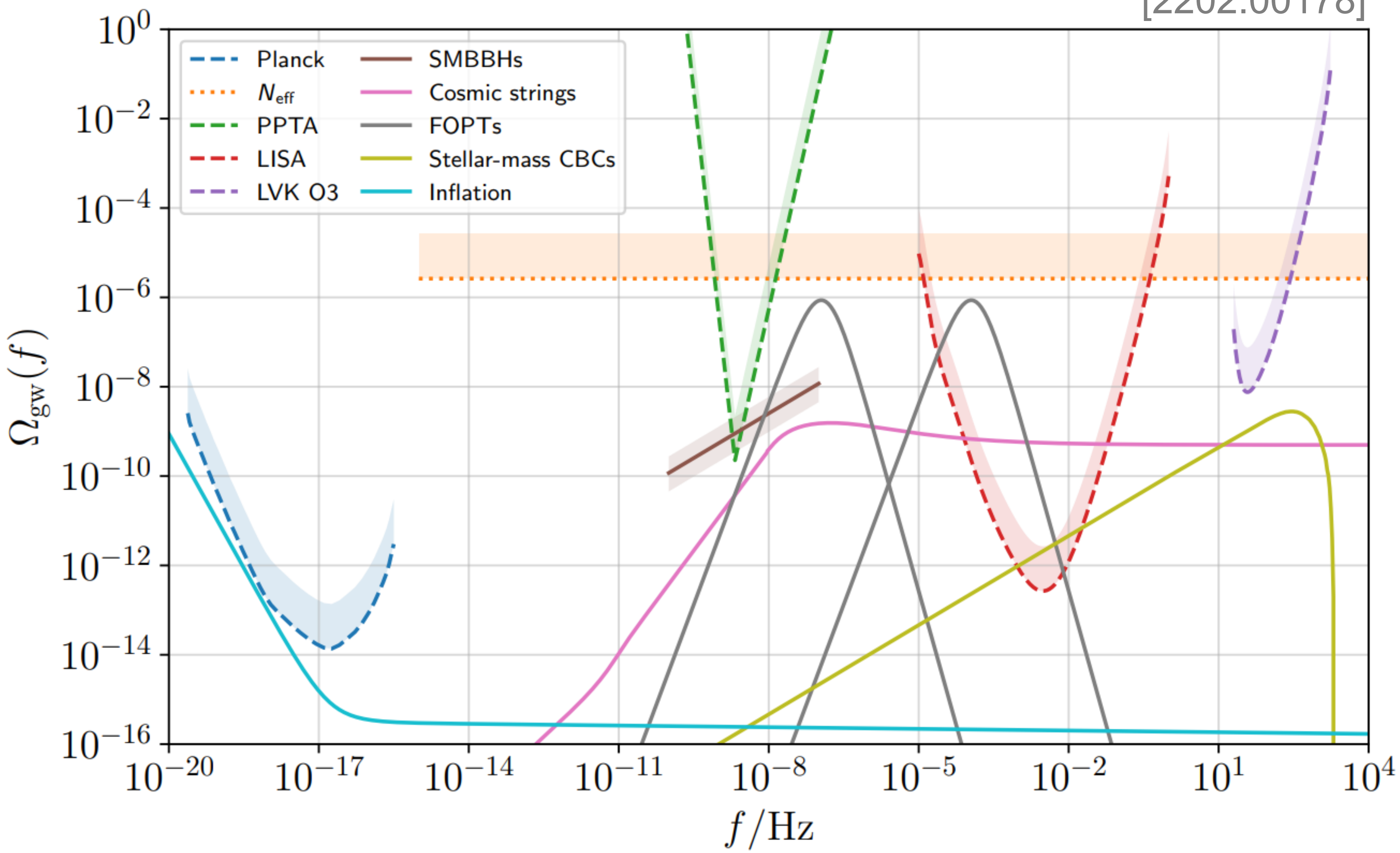
  - Constraints from BBN/CMB on $\Delta N_{\rm eff}$

$$\left(\frac{\rho_{\rm GW}}{\rho_\gamma}\right) \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \Delta N_{\rm eff} \lesssim 0.05$$



HFGW Sources

[2202.00178]



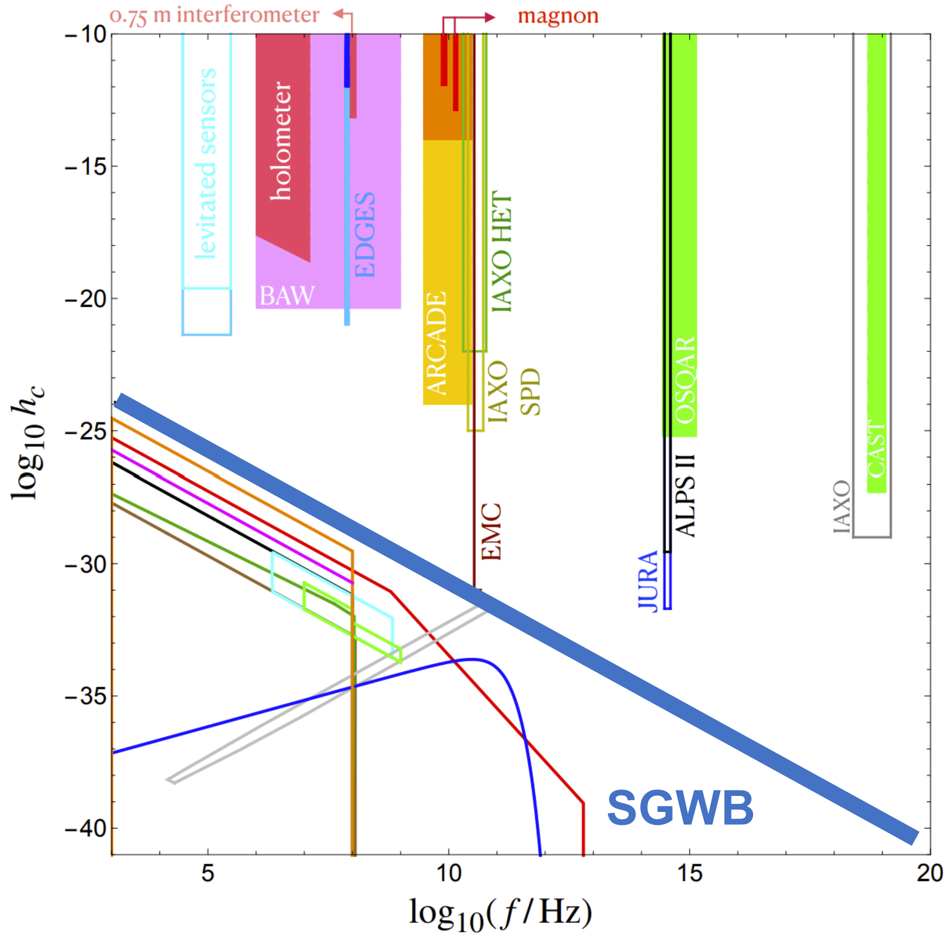
HFGW Sources

- **Localized Sources**
  - PBH binaries / exotic compact objects

$$f \simeq 220\ \mathrm{MHz}\left(\frac{10^{-5}M_\odot}{m_{\mathrm{PBH}}}\right)$$

  - Larger signals expected

[2011.12414 for review]



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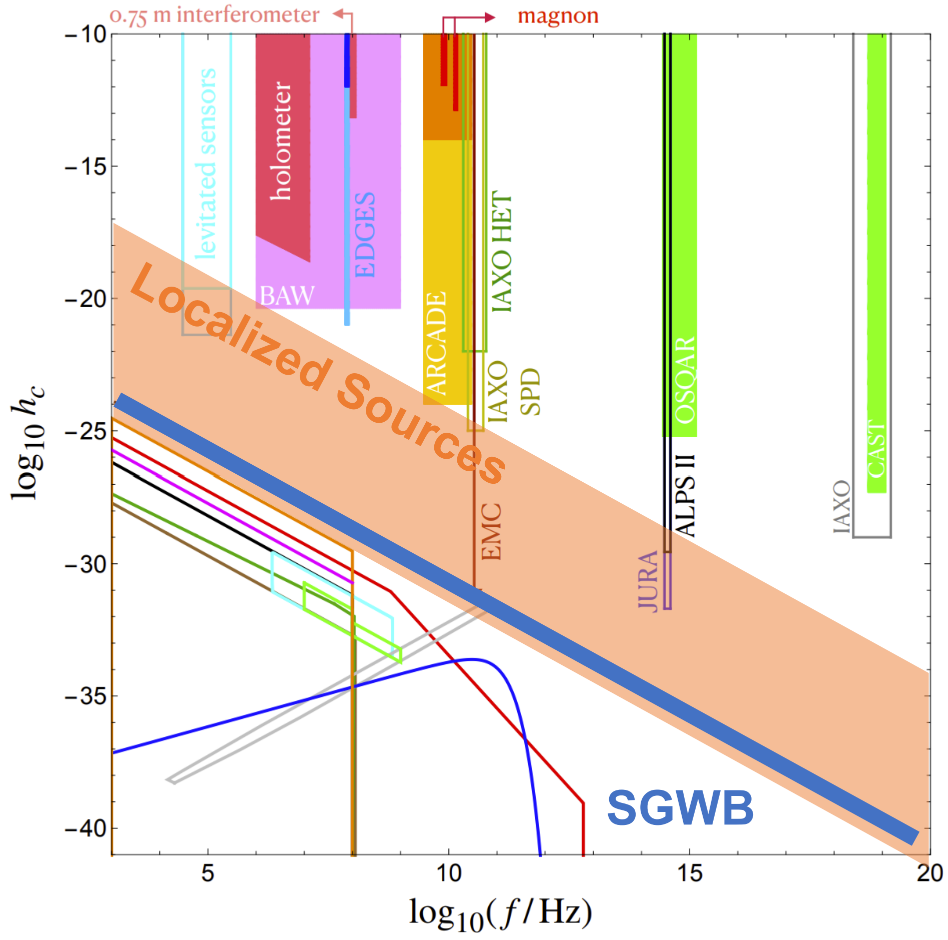

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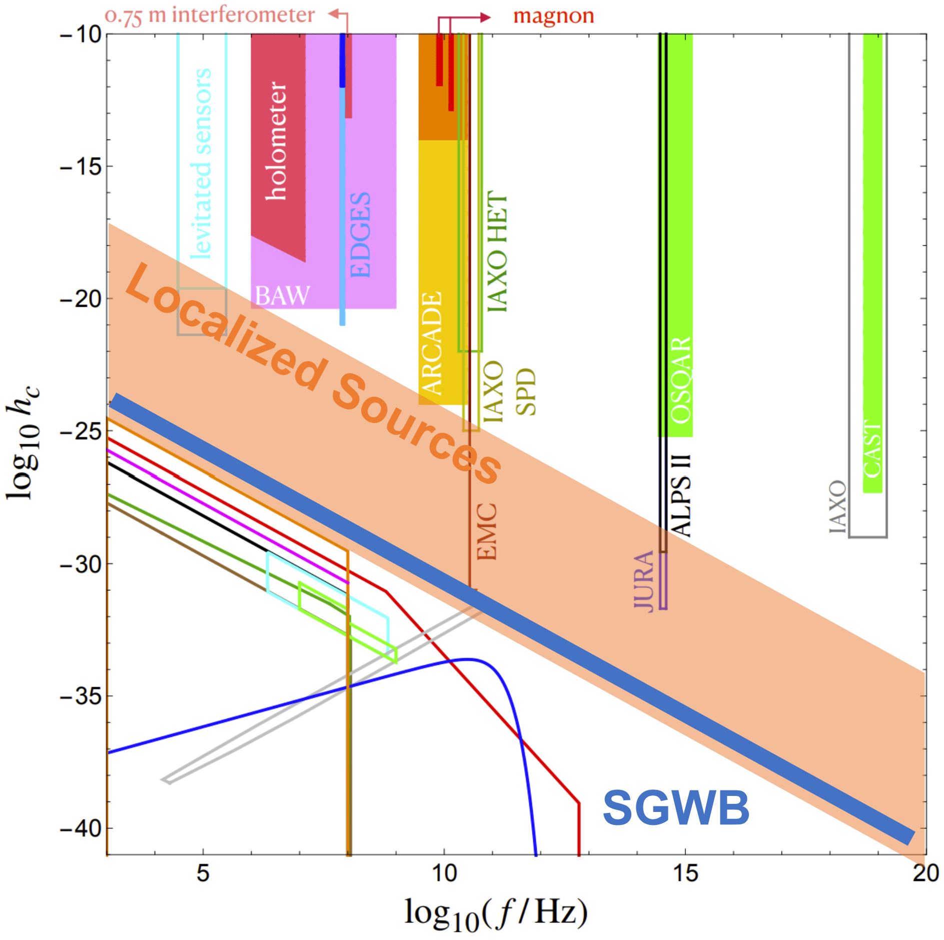

Detection of HFGW
= Smoking Gun of BSM Physics

Detection of GW

Electromagnetism in Curved Spacetime

[Gertsenshtein ‘62]
[Boccaletti, Sabbata, Fortini, Gualdi ’70]

$$\partial_\nu F^{\mu\nu} = j^\mu$$

Electromagnetism in Curved Spacetime

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$$\partial \to \nabla$$

$$\nabla_\nu F^{\mu\nu} = \frac{1}{\sqrt{-g}} \partial_\nu \left(\sqrt{-g} F^{\mu\nu} \right) = j^\mu$$

Electromagnetism in Curved Spacetime

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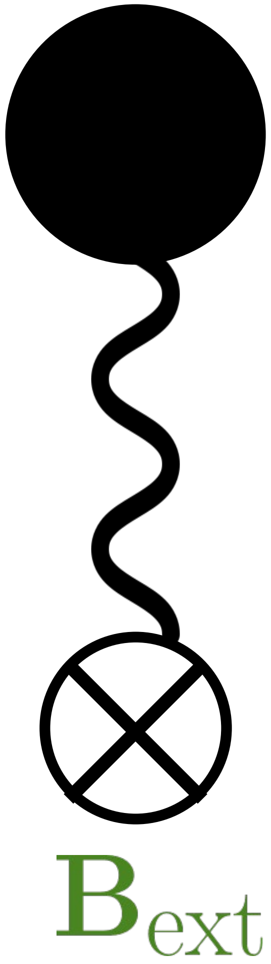
perturbation

$$\partial_\nu F^{\mu\nu} = \left(1 + \frac{1}{2}h^\mu{}_\mu\right) j^\mu + \partial_\nu \left(-\frac{1}{2}h^\alpha{}_\alpha F^{\mu\nu} + F_\alpha{}^\nu h^{\alpha\mu} + F^\mu{}_\alpha h^{\alpha\nu}\right) + O(h^2)$$

'effective current'

Electromagnetism in Curved Spacetime

[Gertsenshtein '62]
[Boccaletti, Sabbata, Fortini, Gualdi '70]



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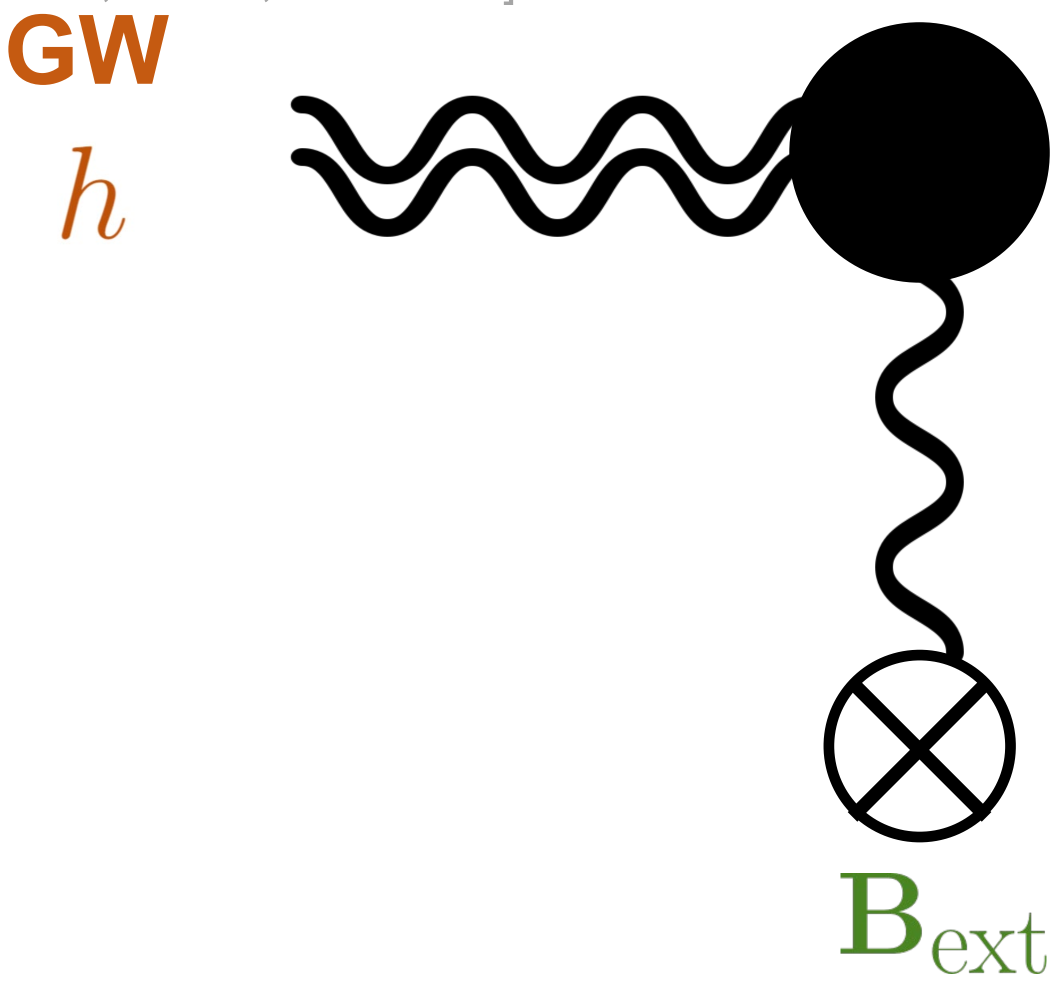

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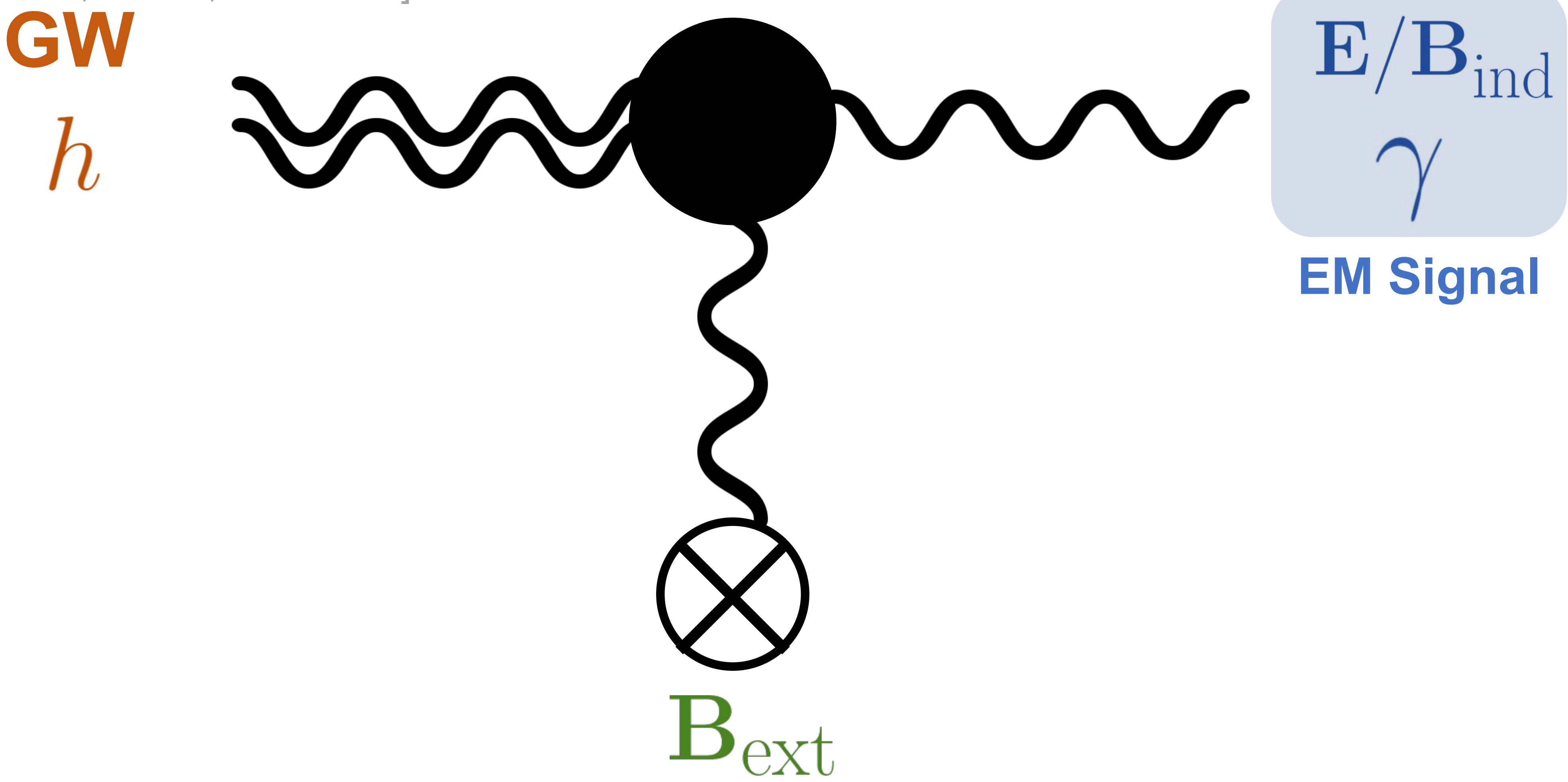


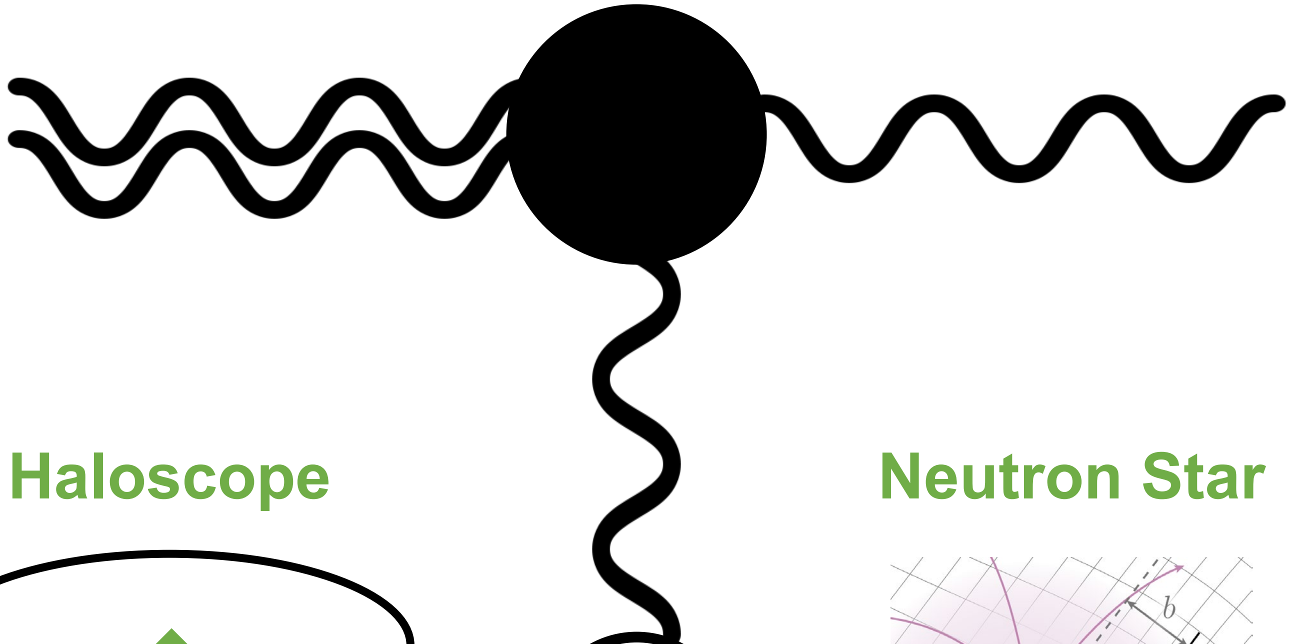
Electromagnetism in Curved Spacetime

[Gertsenshtein '62]
[Boccaletti, Sabbata, Fortini, Gualdi '70]

(Inverse) Gertsenshtein effect

GW

h

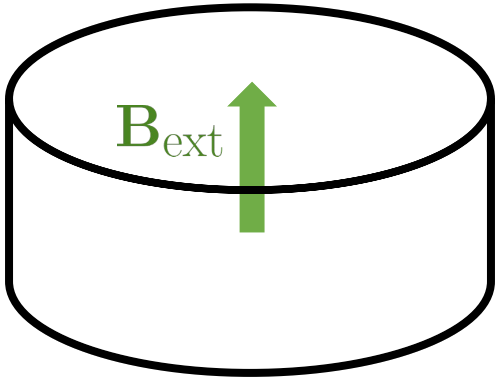


$\mathbf{E}/\mathbf{B}_{\mathrm{ind}}$

γ

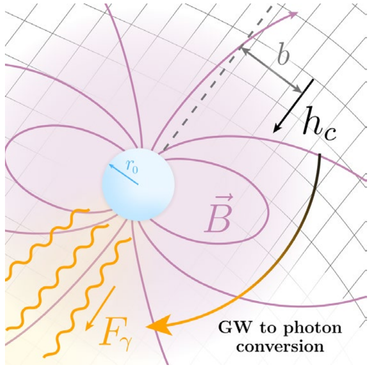
EM Signal

Haloscope



$\mathrm{B_{ext}}$

Neutron Star



Electromagnetism in Curved Spacetime

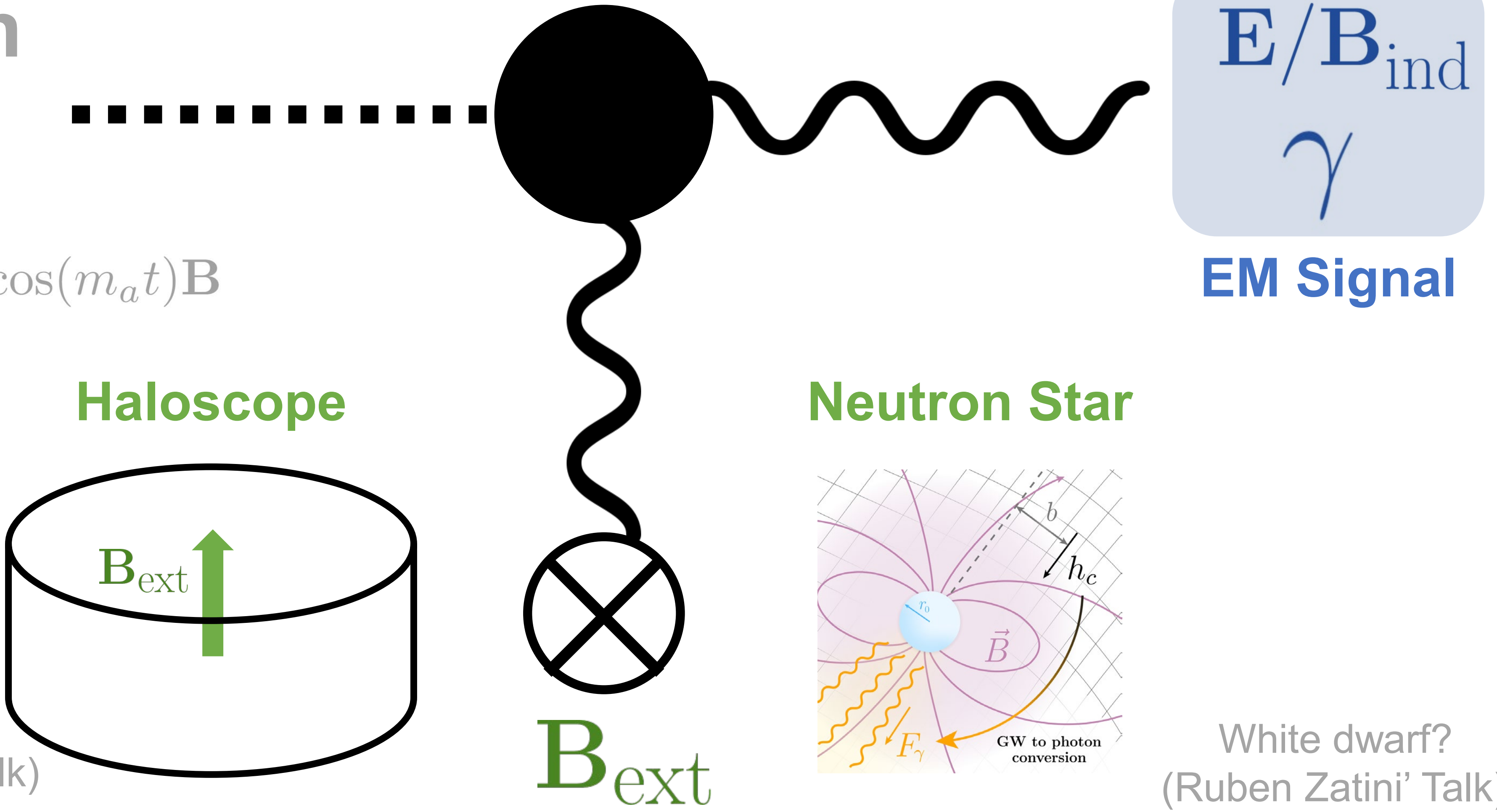
[Raffelt '86]

(Inverse) Primakoff effect

Axion

a

$\mathbf{j}_{\mathrm{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t)\mathbf{B}$



EM Signal

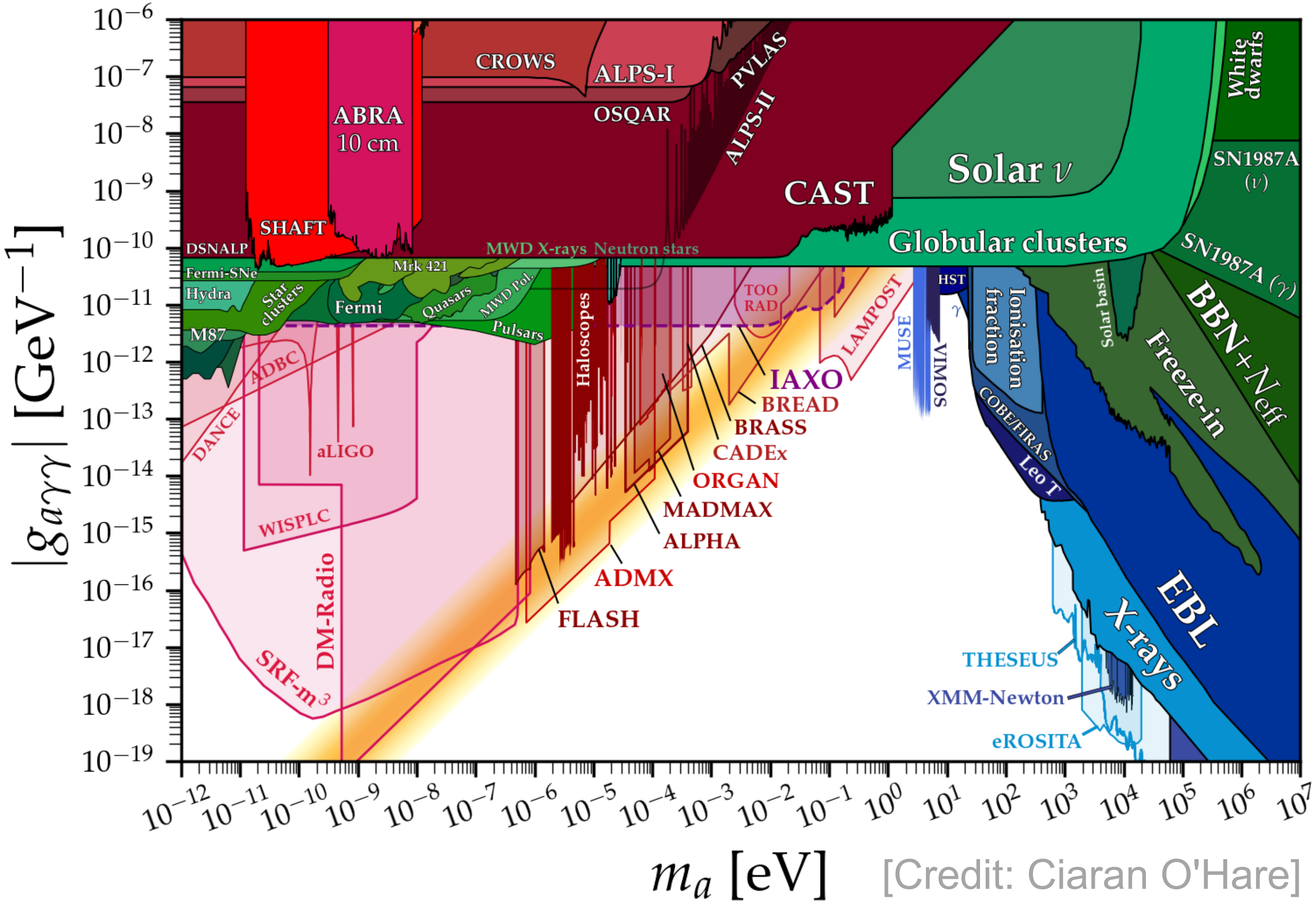
Haloscope

Neutron Star

DALI?
(Javier De Miguel's Talk)

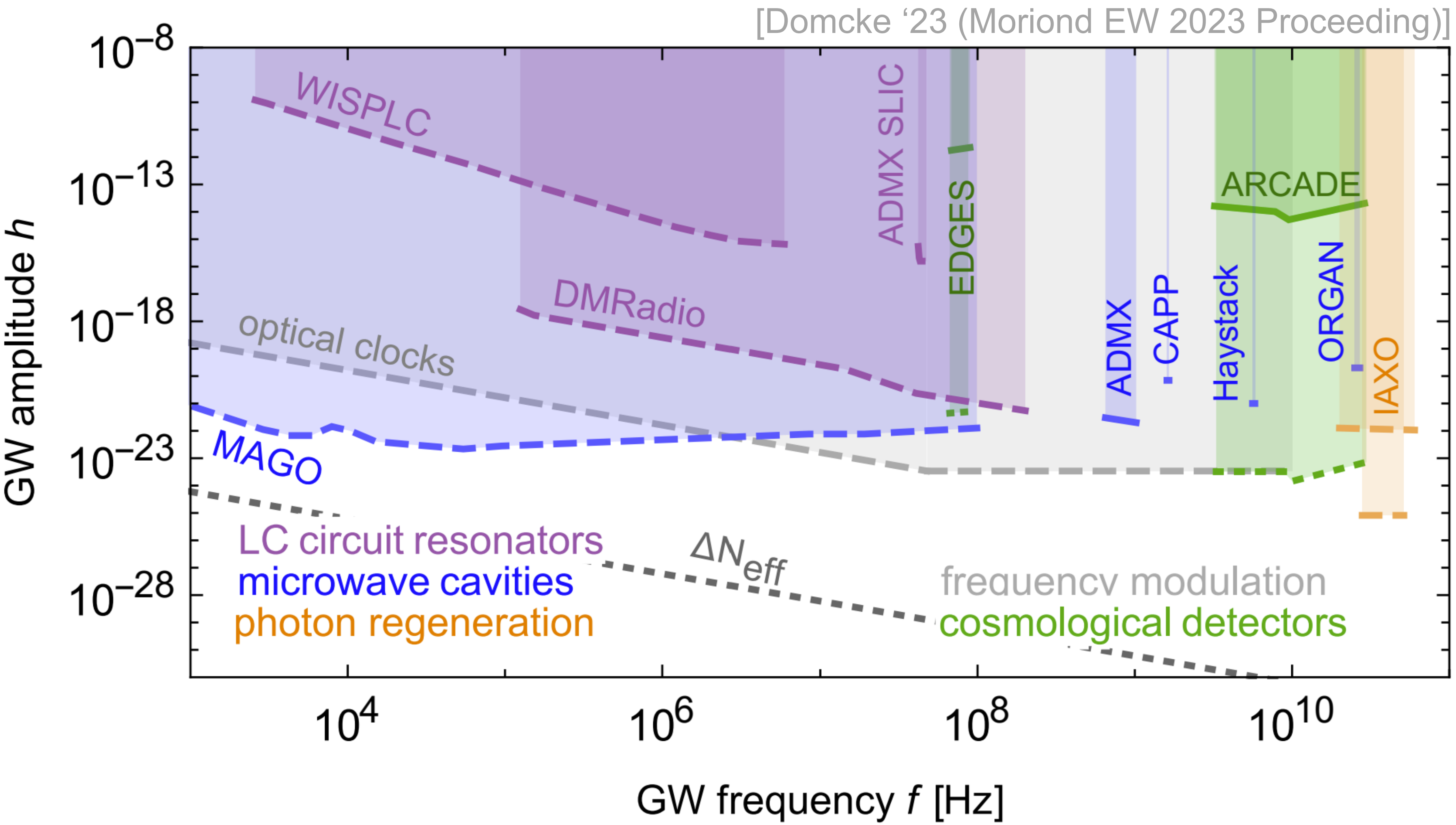
White dwarf?
(Ruben Zatini' Talk)

Axion Experiment Zoo



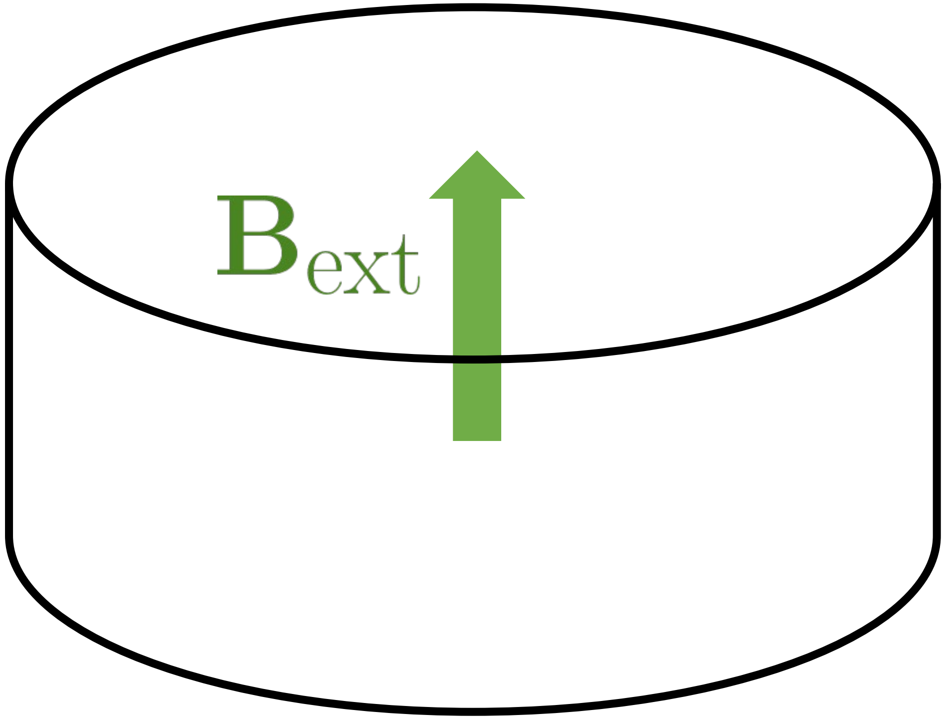
[Credit: Ciaran O'Hare]

EM-HFGW Program



HFGW on the Table: Axion Haloscope

Axion Haloscope as GW Detector



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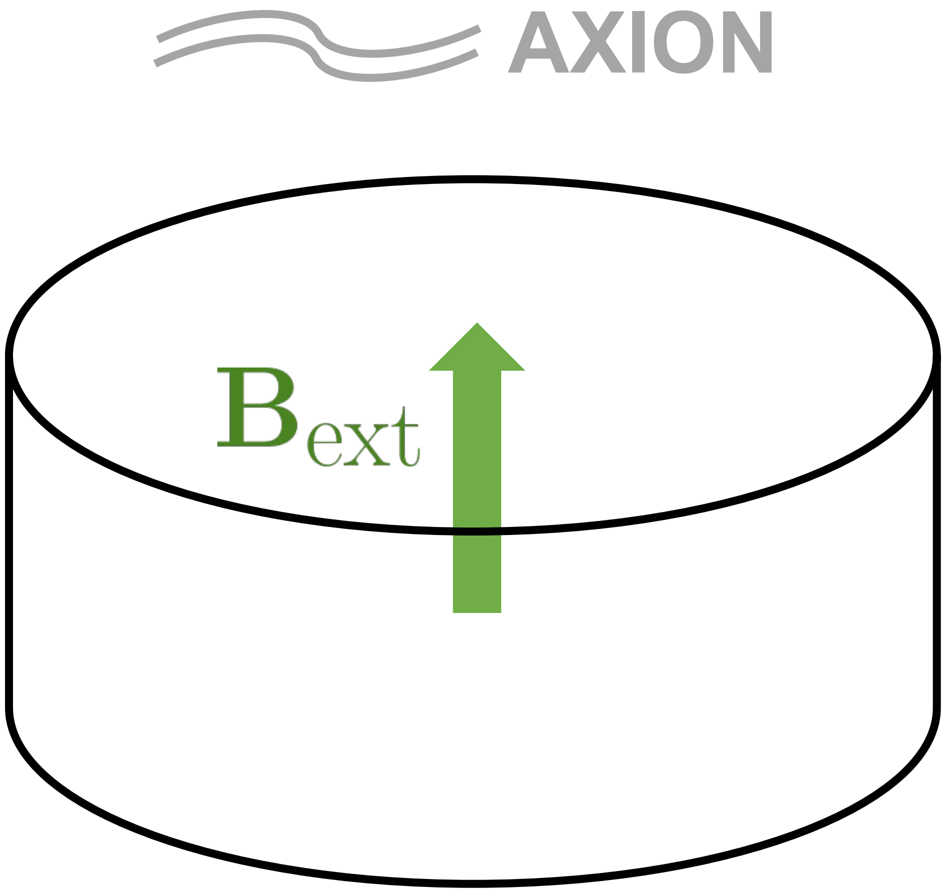

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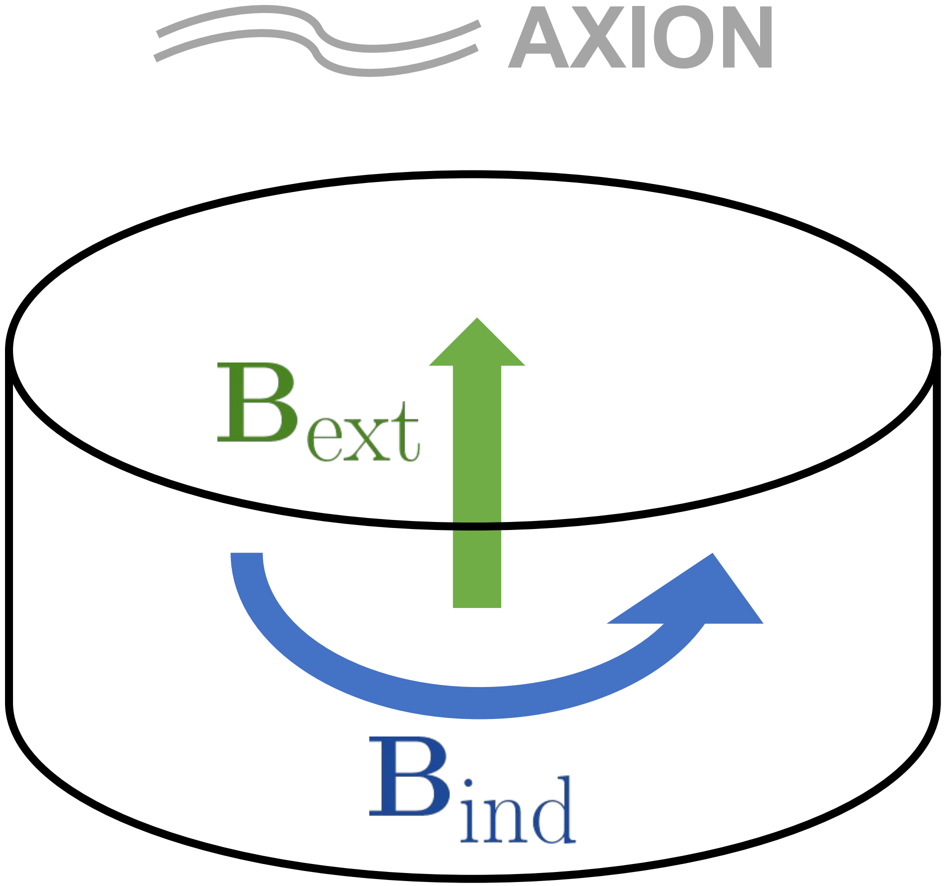

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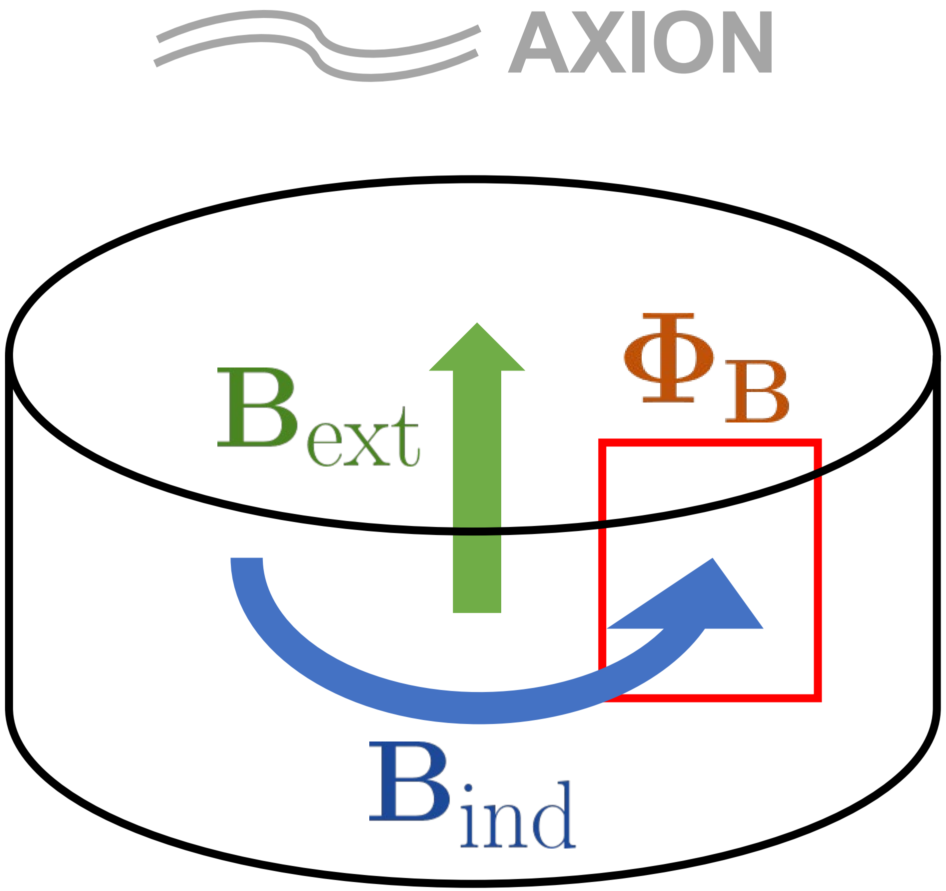

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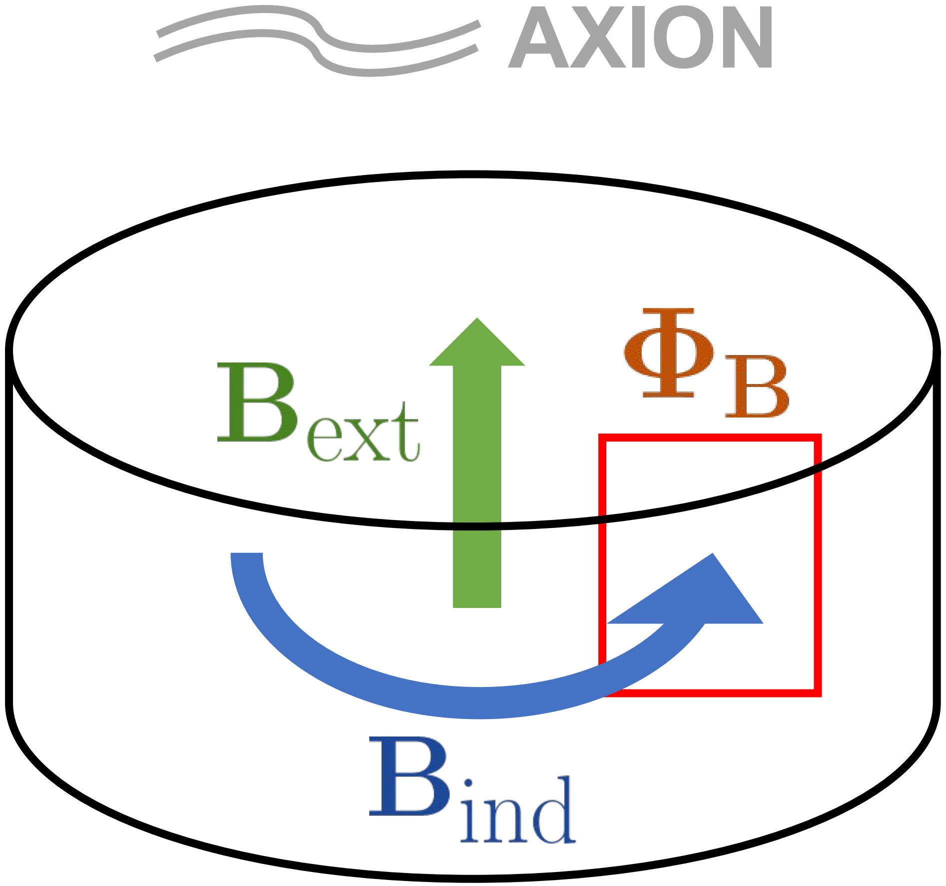
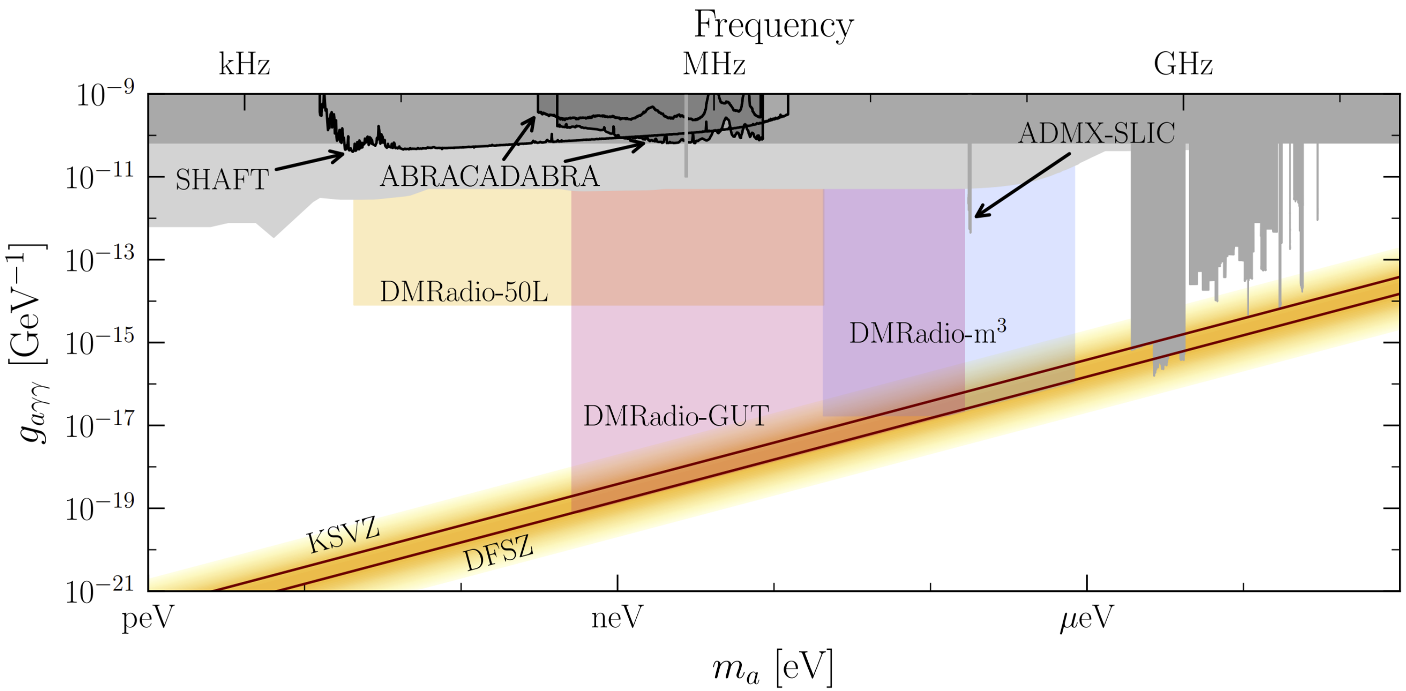


$$\Phi_{\text{Axion,Solenoid}} = \frac{1}{4} g_{a\gamma\gamma} \dot{a} B_0 l R^2$$



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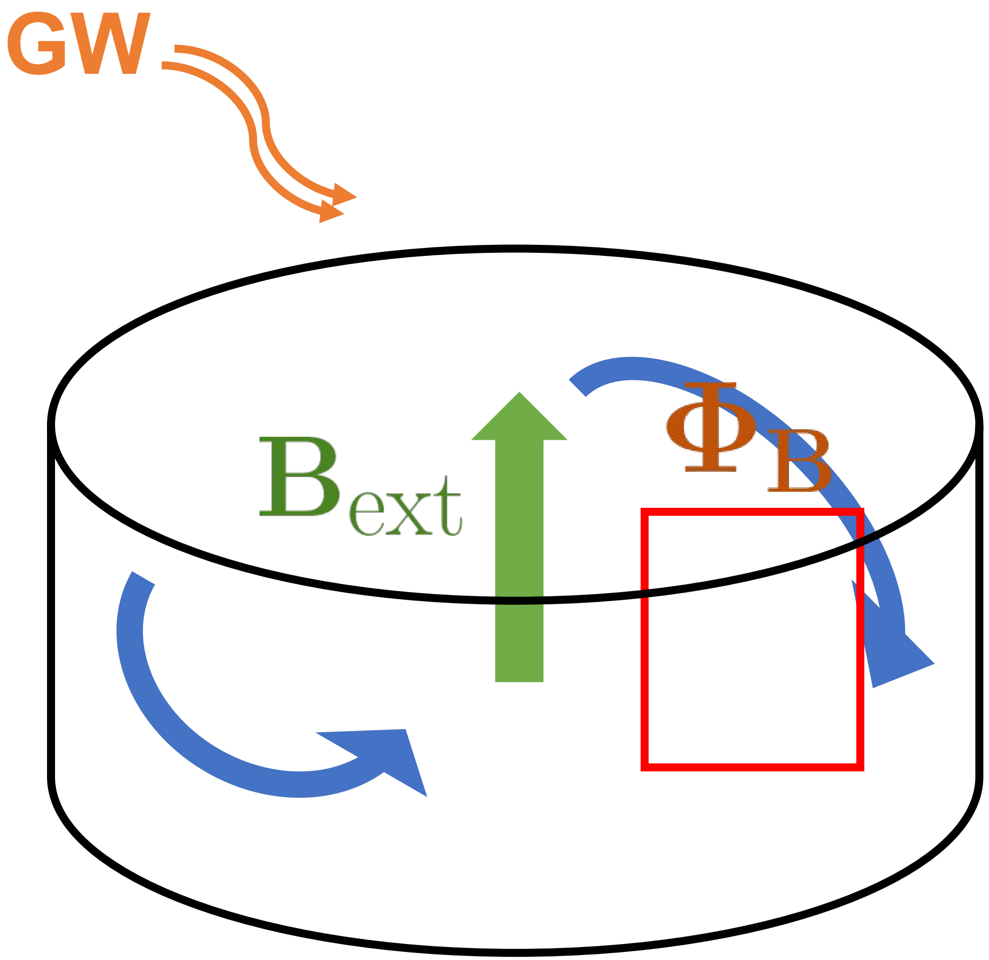

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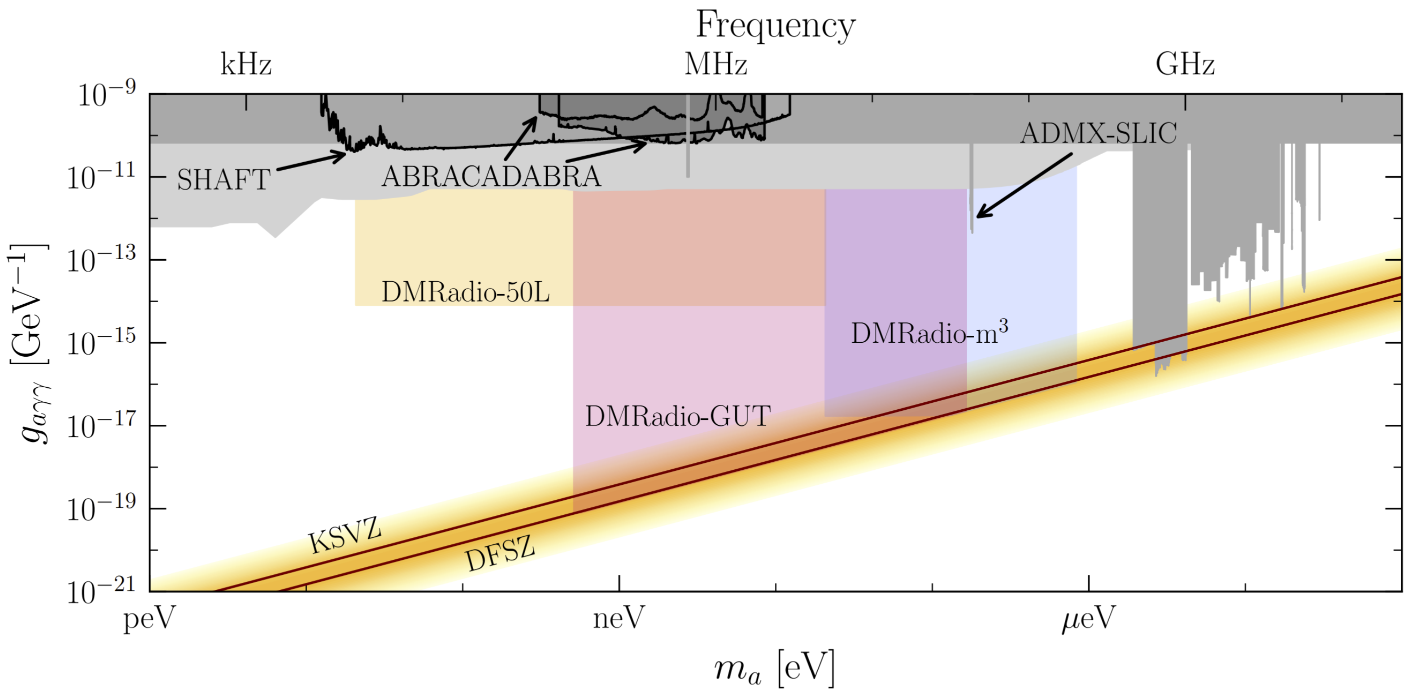
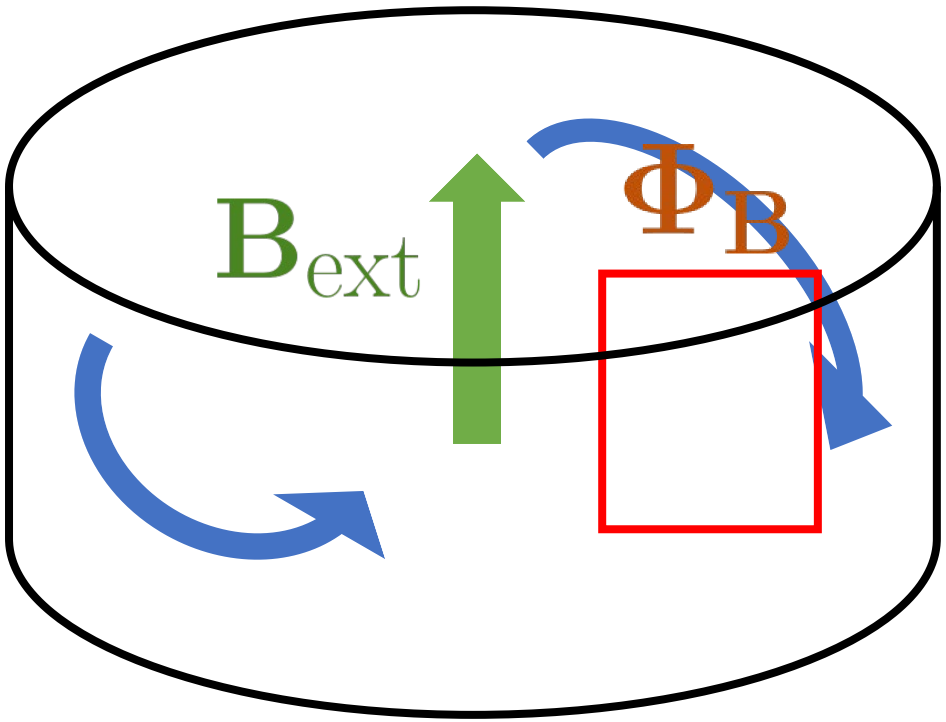
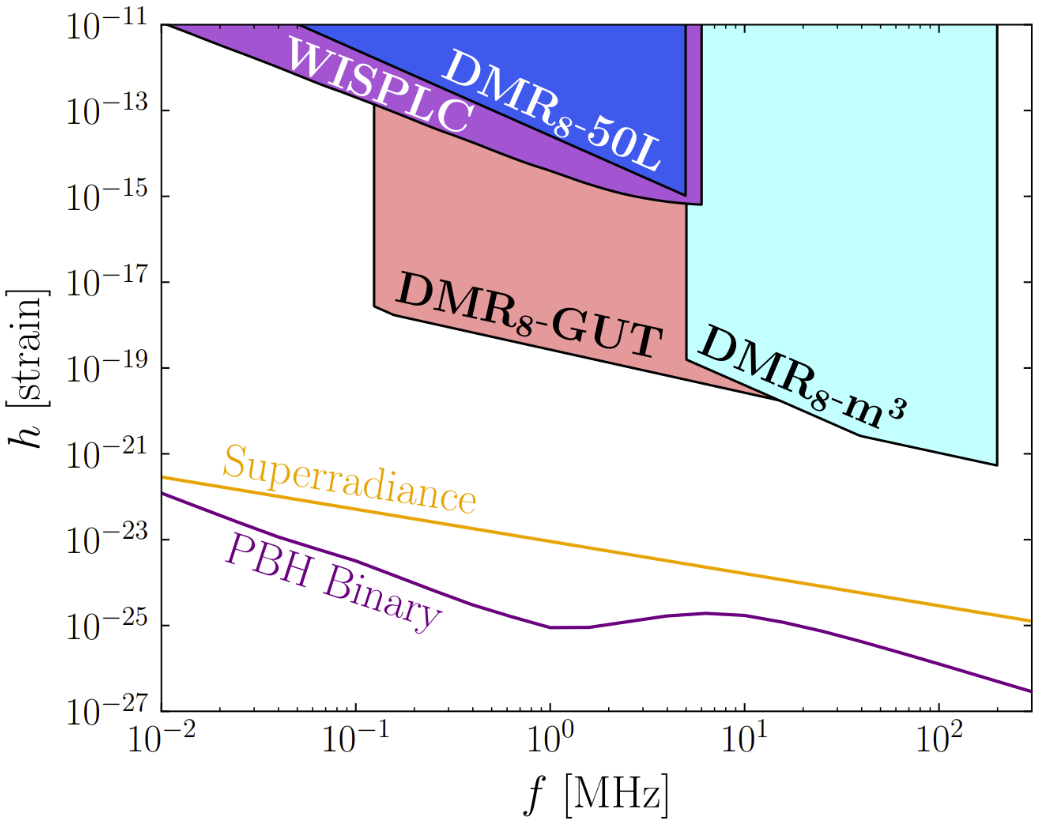


Axion Haloscope as GW Detector

[Domcke, Carcia-Cely, **SML**, Rodd '23]

$$\Phi_{\rm GW} = \frac{e^{-i\omega t}}{144}\omega^2 B_z l r(30R^2 - 13r^2)\sin\theta_h(h^+\cos\theta_h\sin\phi_L + h^\times\cos\phi_L) + \mathcal{O}[(\omega L)^3]$$





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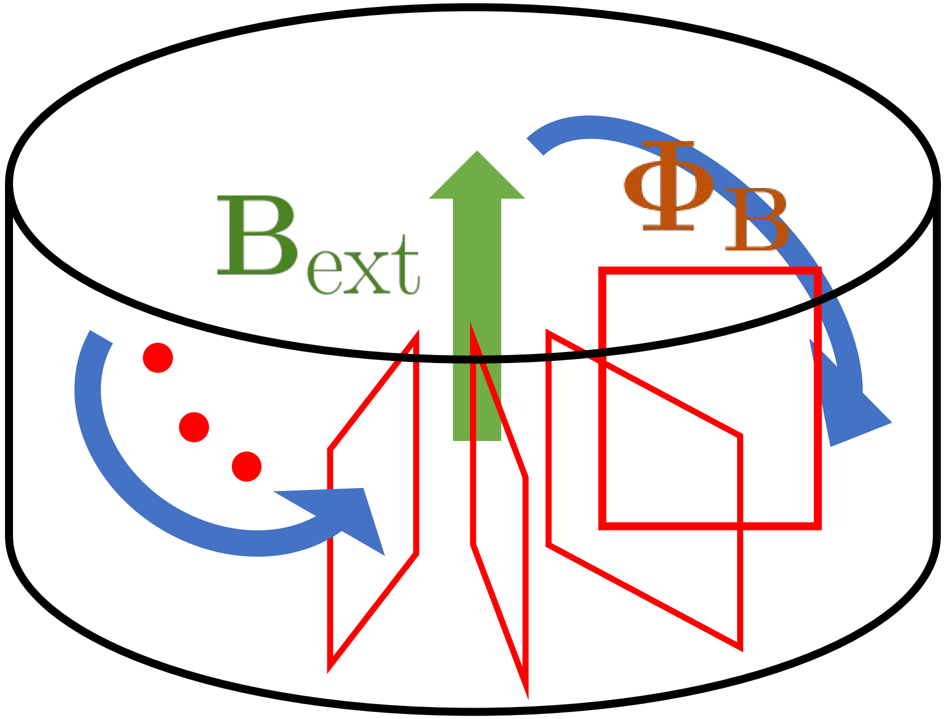

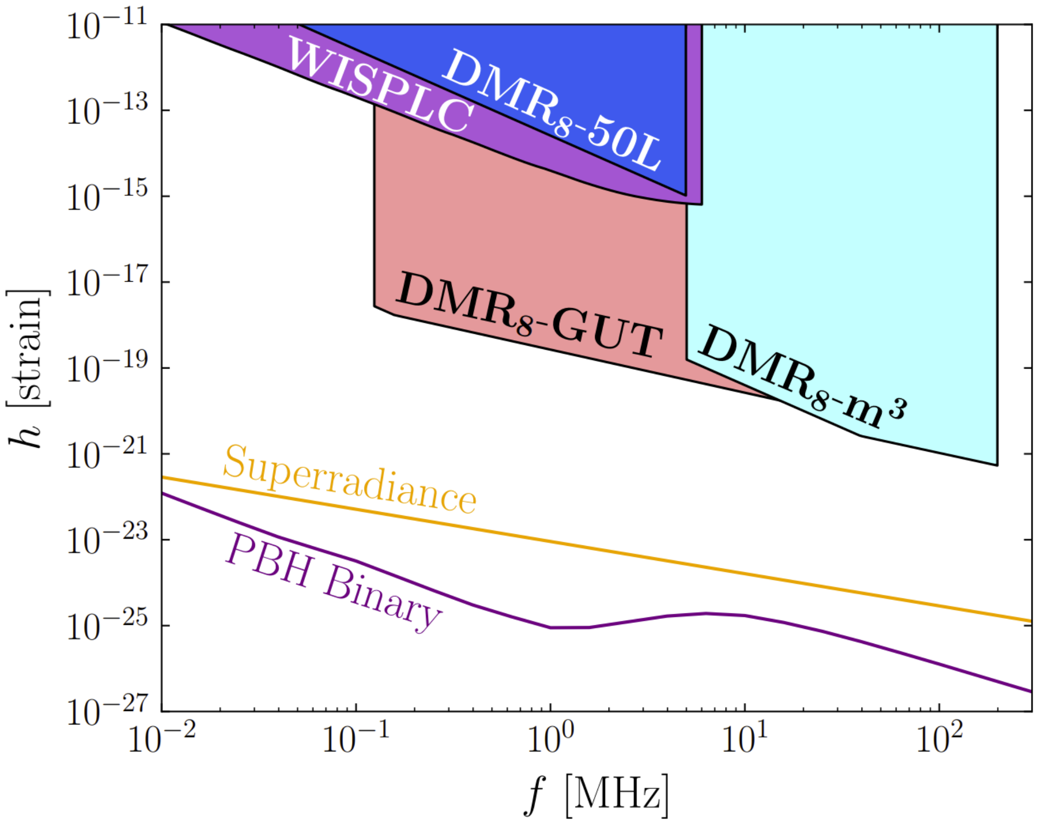

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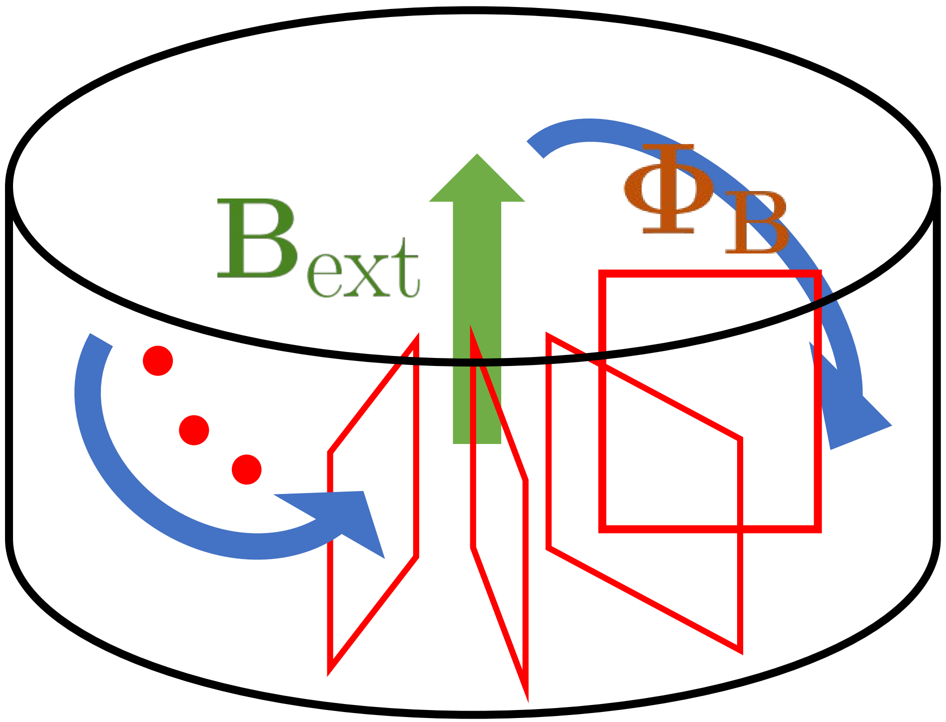
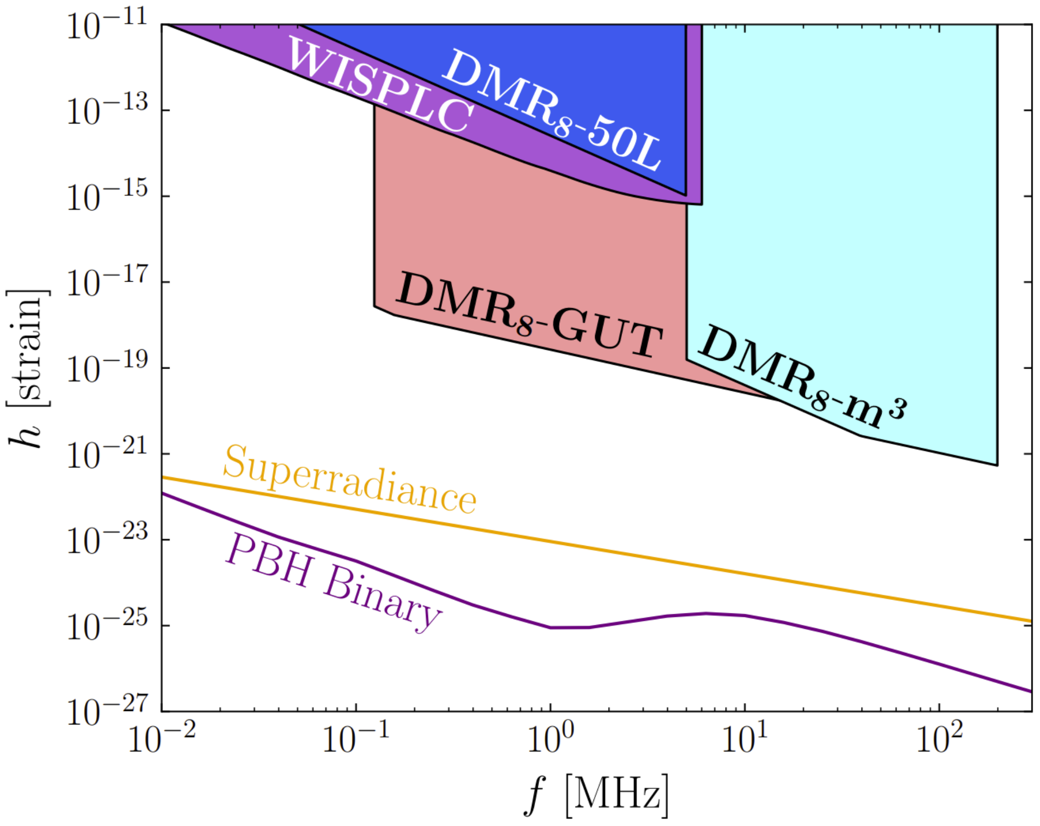


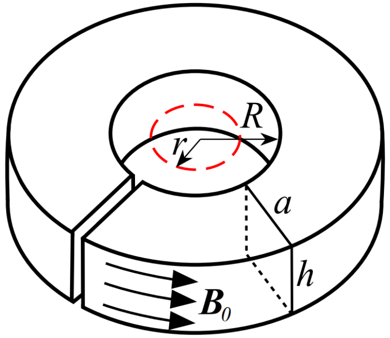


Good for Axion, Bad for GW

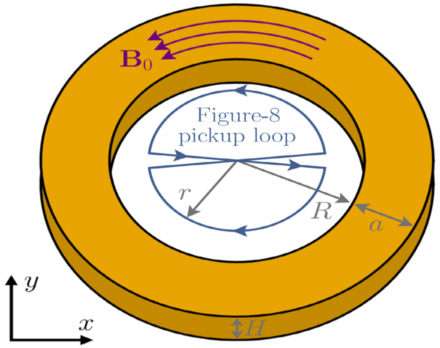
- **Cylindrical symmetry**
  - cancels leading order of GW signal

[Domcke, Carcia-Cely, **SML**, Rodd '23]

ABRACADABRA



[Kahn, Safdi, Thaler '16]



[Domcke, Carcia-Cely, Rodd '22]

Good for Axion, Bad for GW

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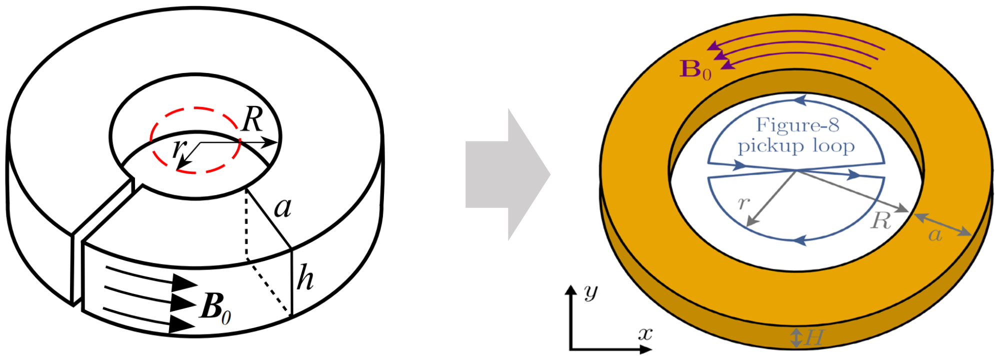
[Domcke, Carcia-Cely, **SML**, Rodd '23]

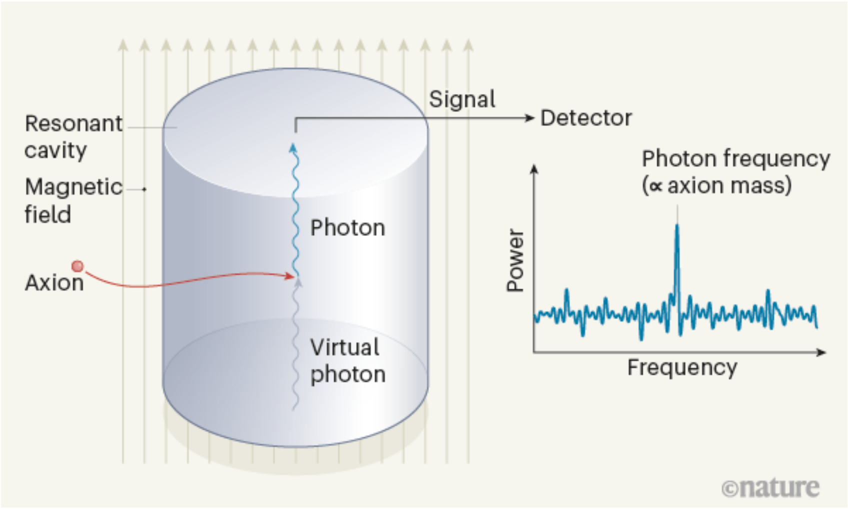
- **Resonant** vs **Broadband**

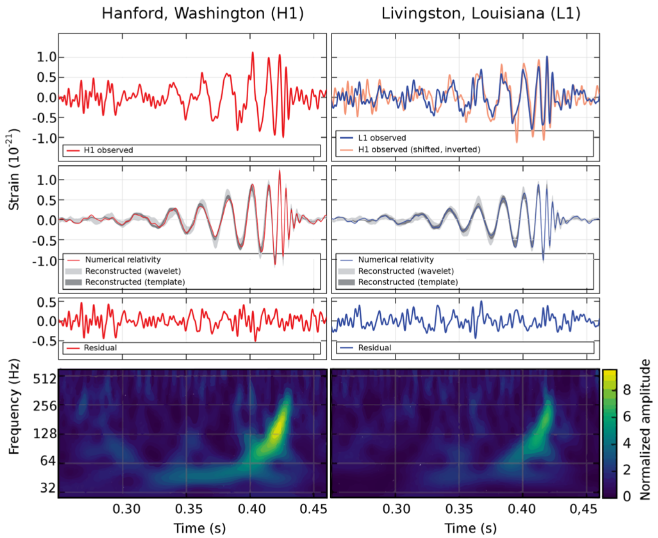
ABRACADABRA



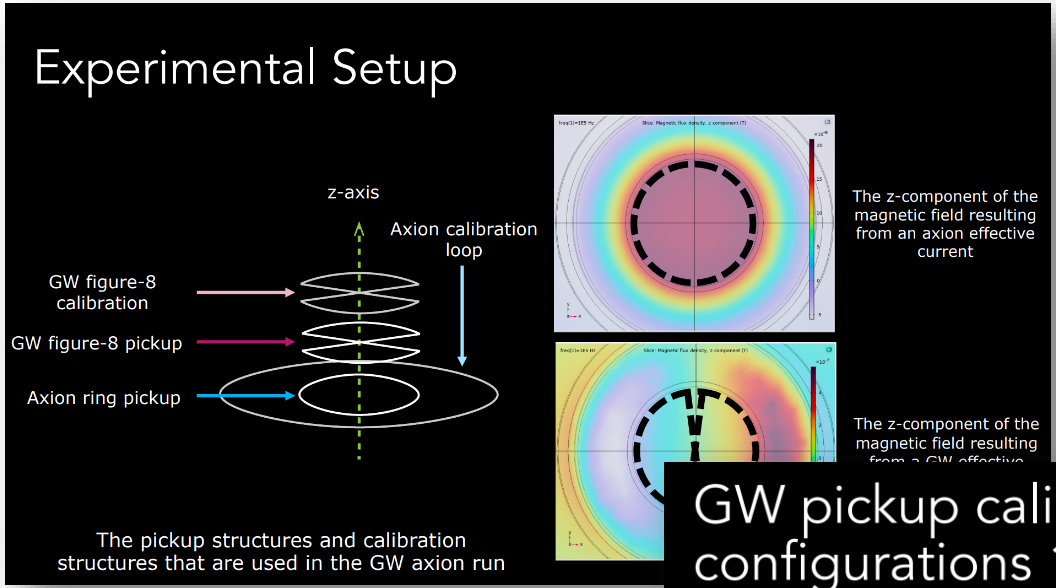
[Kahn, Safdi, Thaler '16]

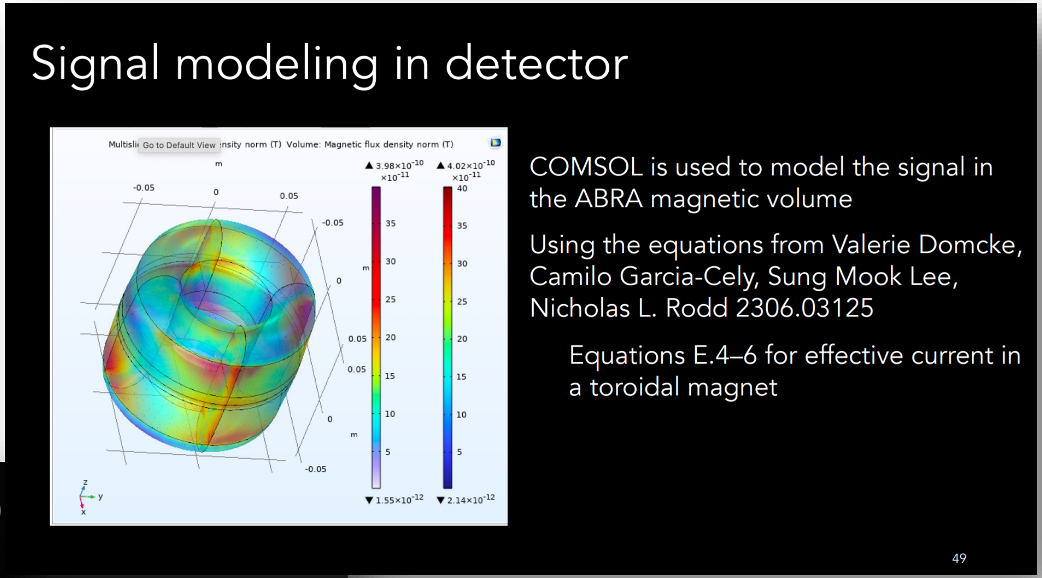
[Domcke, Carcia-Cely, Rodd '22]

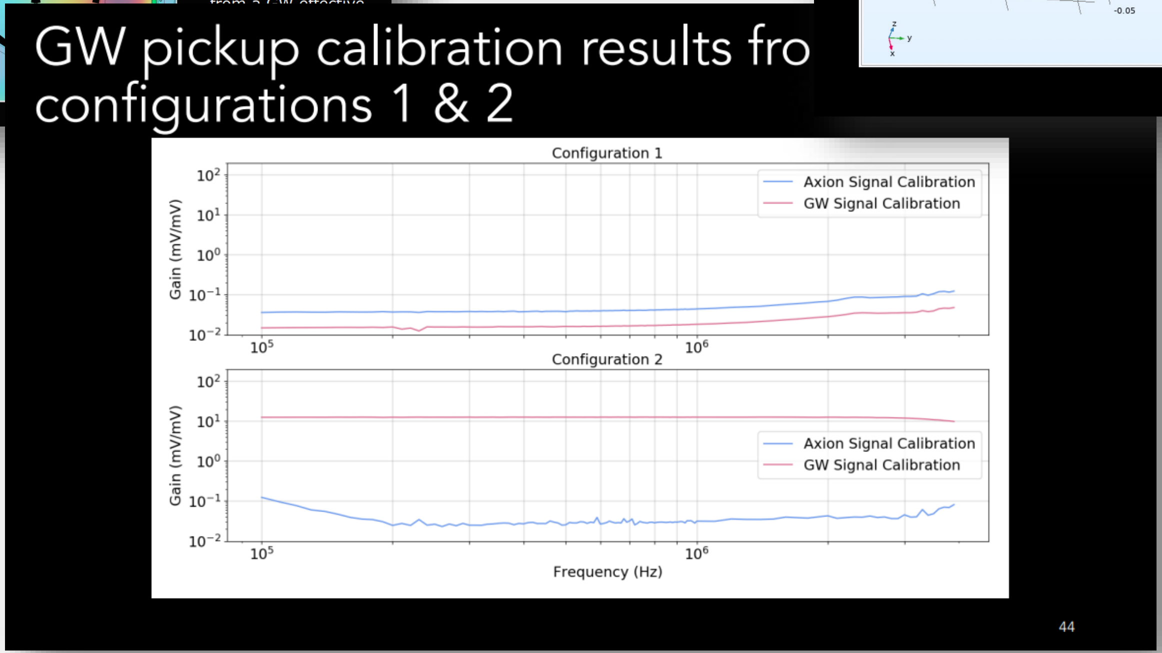




REAL experimental efforts is going on!





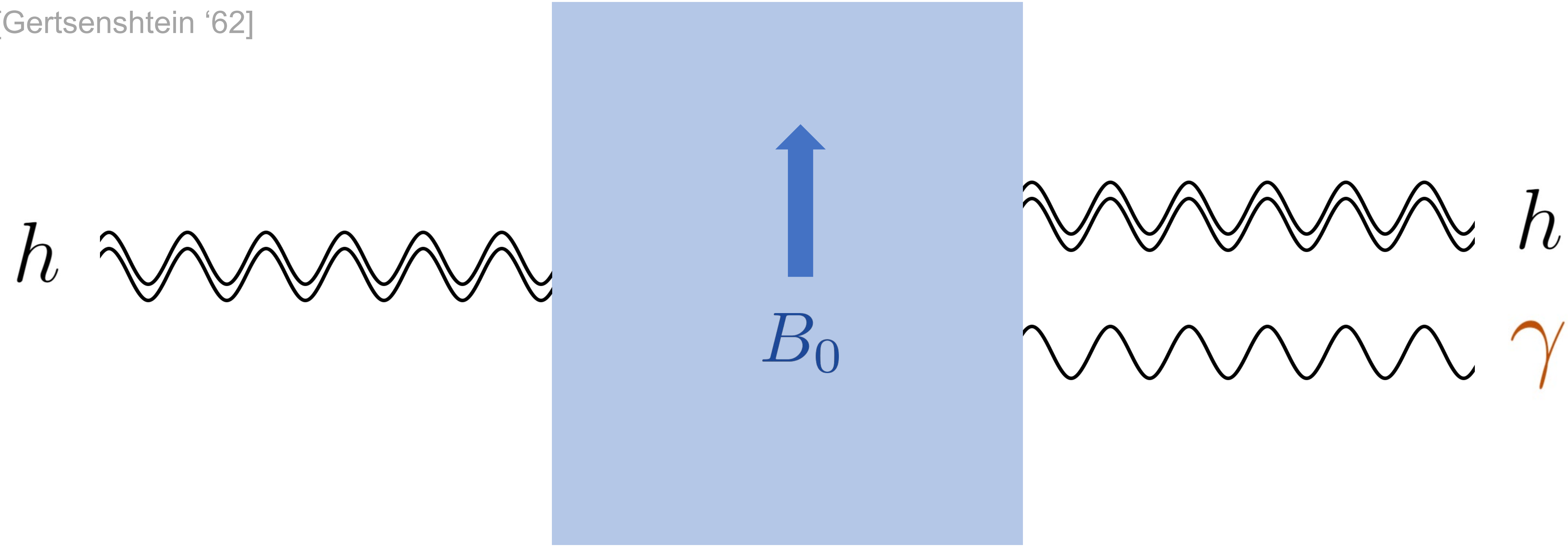


[Kaliroë Pappas's Slides @ 'UHF-GW: where to next?' workshop at CERN (Dec, 2023)]

HFGW from the Sky:
Neutron Stars

Neutron Star as GW Detector

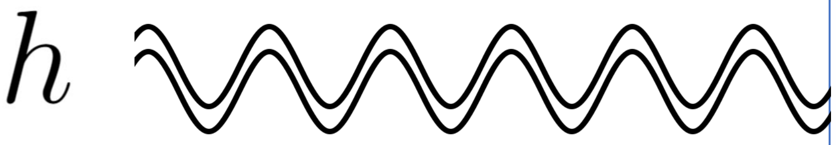
[Gertsenshtein '62]

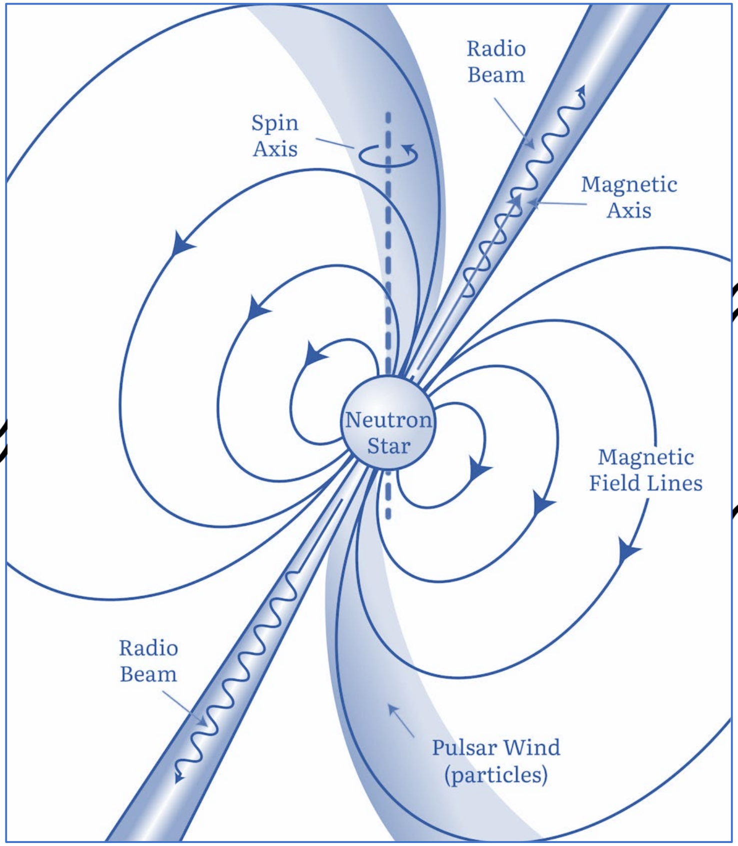


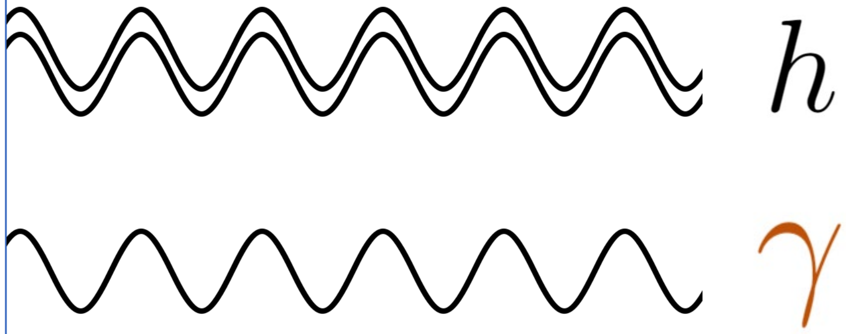
$$P_{h\to\gamma} = \sin^2\left(\frac{L}{\sqrt{2}M_P/B_0}\right) \simeq \frac{2L^2B_0^2}{M_P^2}$$

Neutron Star as GW Detector

[Ito, Kohri, Nakayama ‘23]
[Dandoy, Bertolez-Martinez, Costa ‘24]
[McDonald, Ellis ‘24]







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Neutron Star as GW Detector

[Raffelt, Stodolsky '88]

- **Effective photon mass**

$$\left(\omega - i\partial_n + \begin{pmatrix} \Delta_{||(\perp)} & \kappa B_{||}/2 \\ \kappa B_{||}/2 & 0 \end{pmatrix} \begin{pmatrix} A_{||(\perp)} \\ h_{\times(+)} \end{pmatrix}\right) = 0$$

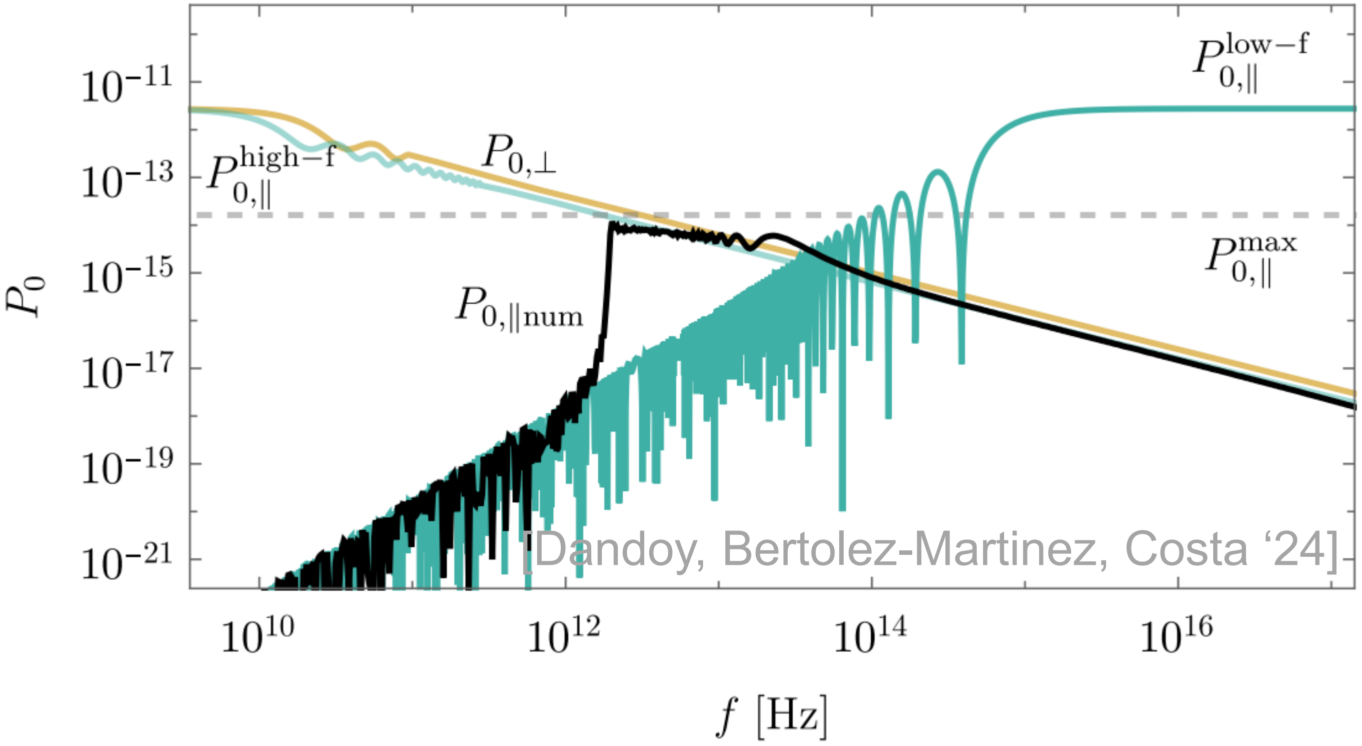
$$\Delta_{||} = \Delta_{\text{pla},||} + \Delta_{\text{vac},||} \begin{cases} \Delta_{\text{pla},||} = -\dfrac{m_{\text{pla}}^2}{2\omega} & \propto -\omega^{-1} \\ \Delta_{\text{vac},||} = \dfrac{7\alpha\omega}{90\pi}\left(\dfrac{eB_{||}}{m_e^2}\right)^2 & \propto \omega \end{cases}$$

$$m_{\text{pla}}^2 \simeq \frac{4\pi\alpha n_e}{m_e}$$

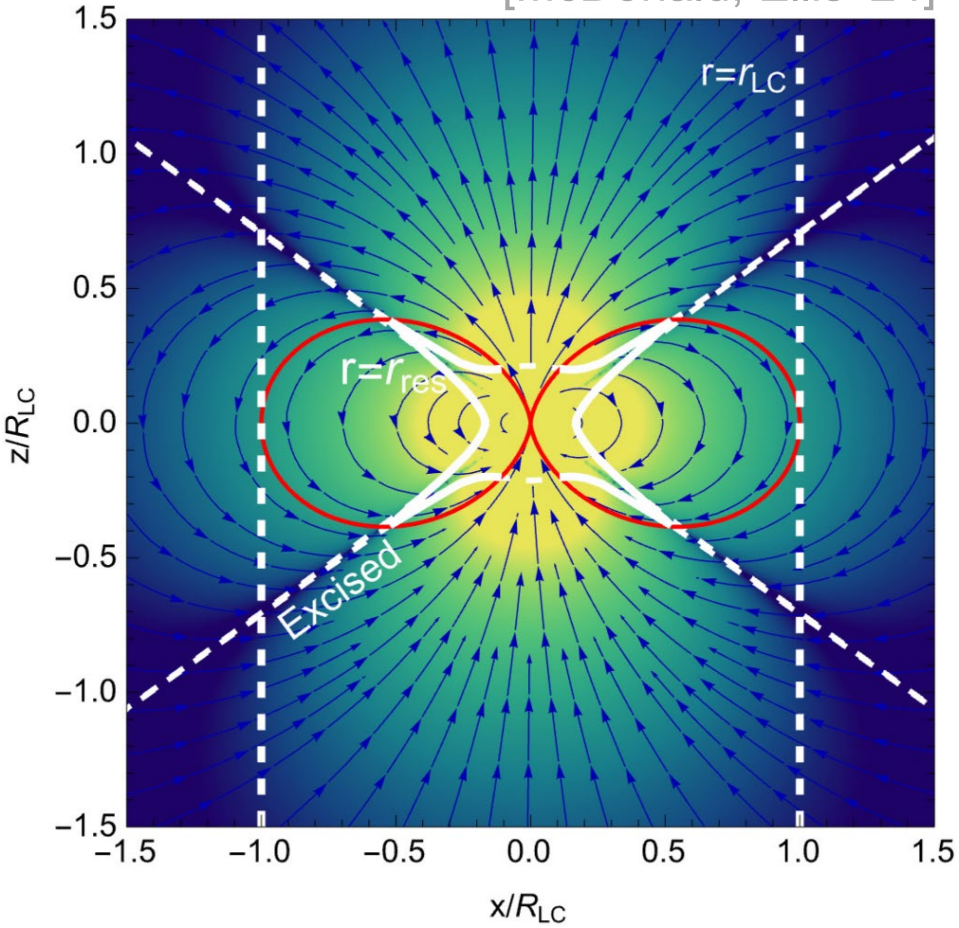
Neutron Star as GW Detector

[Raffelt, Stodolsky '88]

$$P_{\parallel(\perp)}(f) = \left| \int_{\ell_0}^{\ell_1} \mathrm{d}\ell \, \Delta_M(\ell) \exp\left\{ -i \int_{\ell_0}^{\ell} \mathrm{d}\ell' \, \Delta_{\parallel(\perp)}(\ell') \right\} \right|^2$$



[McDonald, Ellis '24]



$$S = \frac{1}{4\pi d^2} \int d\Omega_{\mathbf{k}} \int d\mathbf{\Sigma}_{\mathbf{k}} \cdot \mathbf{v}_p P_{h\to\gamma} \frac{\omega}{16\pi G} h_{\text{c,sto}}^2$$

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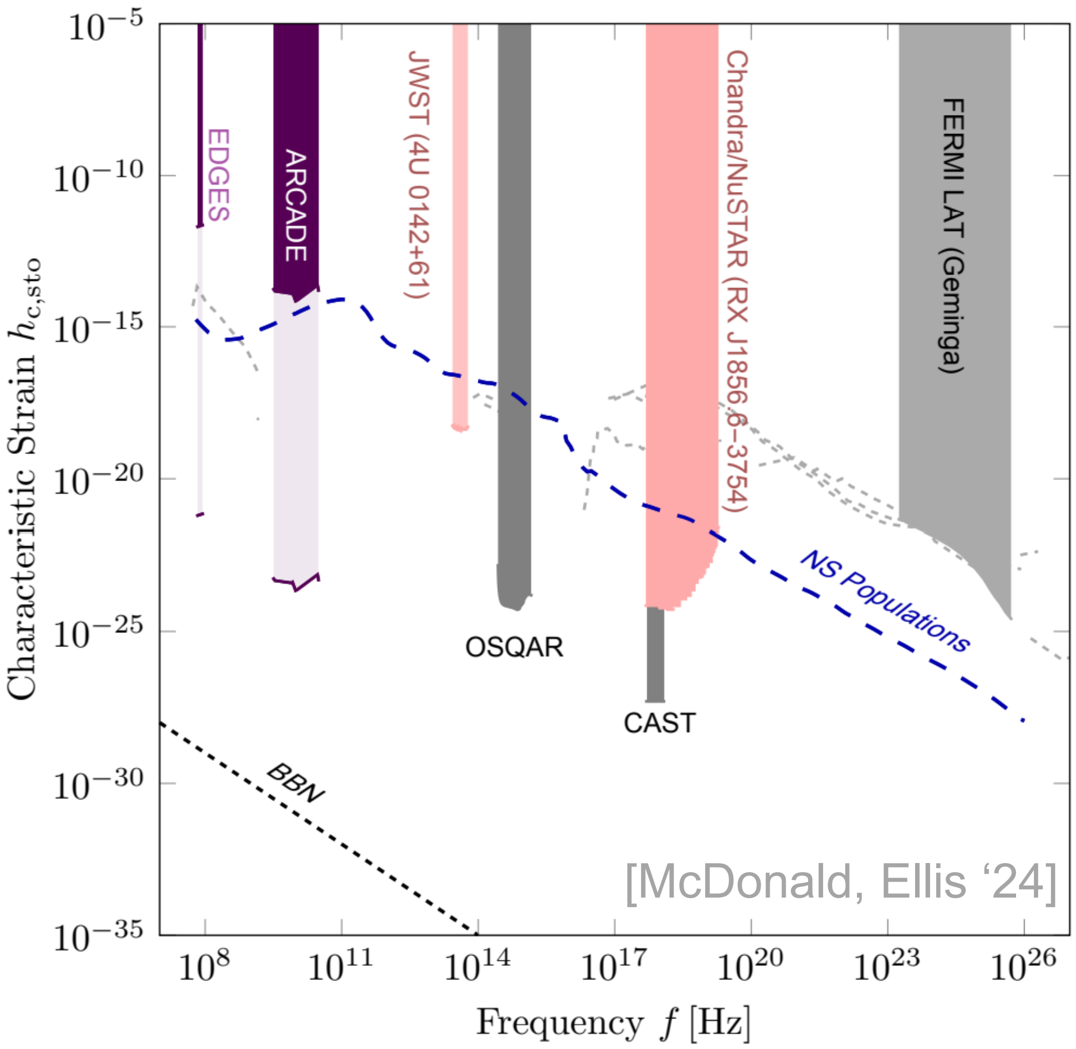

Conclusion

- Detection of HFGW is a smoking gun of BSM
  - new opportunities, interesting theoretical questions, and experimental challenges

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- Detection of HFGW is a smoking gun of BSM
  - new opportunities, interesting theoretical questions, and experimental challenges
- Strong interplay to axion experiments
  - Different sources, different strategies (e.g. geometries, resonant/broadband)
- A lot more opportunities from cosmology/astrophysics
  - New ideas are exploding!

Back Ups

Selection Rules of Cylindrical Detector

Selection Rule 1: For an instrument with azimuthal symmetry, $\Phi_h \propto h^+$ at $\mathcal{O}[(\omega L)^2]$.[16]

Selection Rule 2: For an instrument with azimuthal symmetry, the flux is proportional to either h^+ or $h^\times$, but not both. This holds to all orders in (ωL).[17]

$$\Phi \sim h^\times \omega^3 L^5$$

Selection Rule 3: For an instrument with full cylindrical symmetry, Φ_h will contain only even or odd powers of ω.

Selection Rules of Cylindrical Detector

- **Leading Orders**

[Domcke, Carcia-Cely, **SML**, Rodd ’23]

		$\hat{\boldsymbol{n}}'$		
		$\hat{\boldsymbol{e}}_z$	$\hat{\boldsymbol{e}}_\phi$	$\hat{\boldsymbol{e}}_\rho$
$\boldsymbol{B}$	$\hat{\boldsymbol{e}}_z$ **(Sol)**	h_+, even : $O[(\omega L)^2]$	$h_\times$, odd : $O[(\omega L)^3]$ **BASE**	h_+, odd : $O[(\omega L)^3]$ off-center: $O[(\omega L)^2]$
	$\hat{\boldsymbol{e}}_\phi$ **(Toro)**	$h_\times$, odd : $O[(\omega L)^3]$ **ABRA**	h_+, even : $O[(\omega L)^{\cancel{2}\ 4}]$	$h_\times$, even : $O[(\omega L)^4]$ off-center: $O[(\omega L)^3]$

- ***Optimal axion detection forbids optimal GW detection***

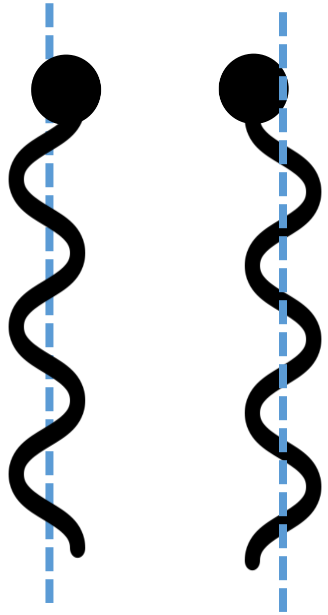
Note on Frame

- **TT frame** $h_{ij}^{TT} = (h^+ e_{ij}^+(\phi_h, \theta_h) + h^\times e_{ij}^\times(\phi_h, \theta_h))e^{i(\mathbf{k}\cdot\mathbf{r}-\omega\mathbf{t})}$

  - Coordinates fixed by geodesic of freely falling test masses

  - GW takes the simple form $h_{0\mu} = 0, h_i^i = 0, \partial_j h^{ij} = 0$

  - Detector (rigid body) looks oscillating in presence of GWs
    → makes the experimental setup & observables obscure



Note on Frame

[Berlin, Blas, Tito D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel '21]
[Domcke, Carcia-Cely, Rodd '22]

- **Proper detector frame**
  - Coordinates fixed by laboratory frame
  - More involved form

$$h_{00} = \omega^2 e^{-\mathrm{i}\omega t} F(\mathbf{k}\cdot\mathbf{r})\, r_m r_n \sum_{A=+,\times} h^A e^A_{mn}(\hat{\mathbf{k}}), \qquad F(\xi) = (e^{i\xi} - 1 - i\xi)/\xi^2$$

$$h_{0i} = \frac{1}{2}\omega^2 e^{-\mathrm{i}\omega t}[F(\mathbf{k}\cdot\mathbf{r}) - \mathrm{i}F'(\mathbf{k}\cdot\mathbf{r})][\hat{\mathbf{k}}\cdot\mathbf{r}\; r_m\delta_{ni} - r_m r_n \hat{k}_i] \sum_{A=+,\times} h^A e^A_{mn}(\hat{\mathbf{k}}),$$

$$h_{ij} = -\mathrm{i}\omega^2 e^{-\mathrm{i}\omega t} F'(\mathbf{k}\cdot\mathbf{r})[|\mathbf{r}|^2\delta_{im}\delta_{jn} + r_m r_n \delta_{ij} - r_n r_j \delta_{im} - r_m r_i \delta_{jn}] \sum_{A=+,\times} h^A e^A_{mn}(\hat{\mathbf{k}})$$

  - Description of the experimental setup and observables is straightforward

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[Berlin, Blas, Tito D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel '21]
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- **Proper detector frame**
  - Coordinates fixed by laboratory frame
  - More involved form

Leading order : $O(\omega^2 L^2)$

$$h_{00} = \omega^2 e^{-i\omega t} F(\mathbf{k}\cdot\mathbf{r})\, r_m r_n \sum_{A=+,\times} h^A e^A_{mn}(\hat{\mathbf{k}}),$$

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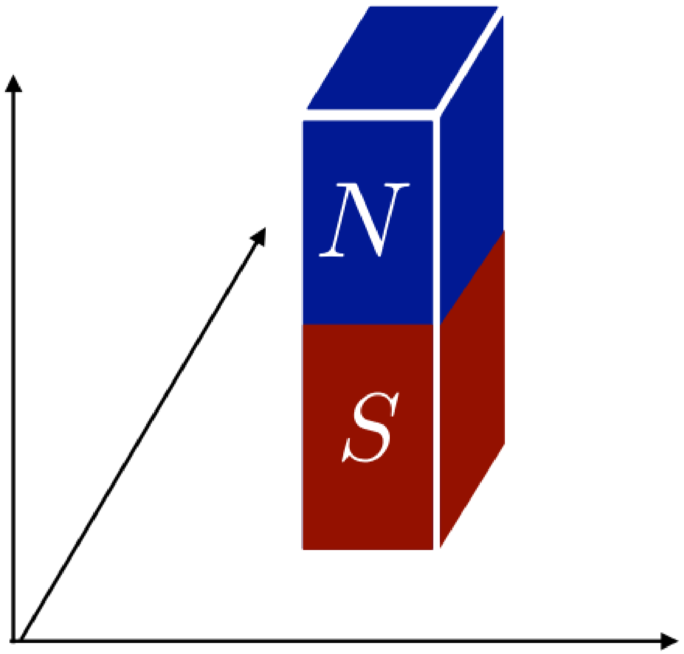
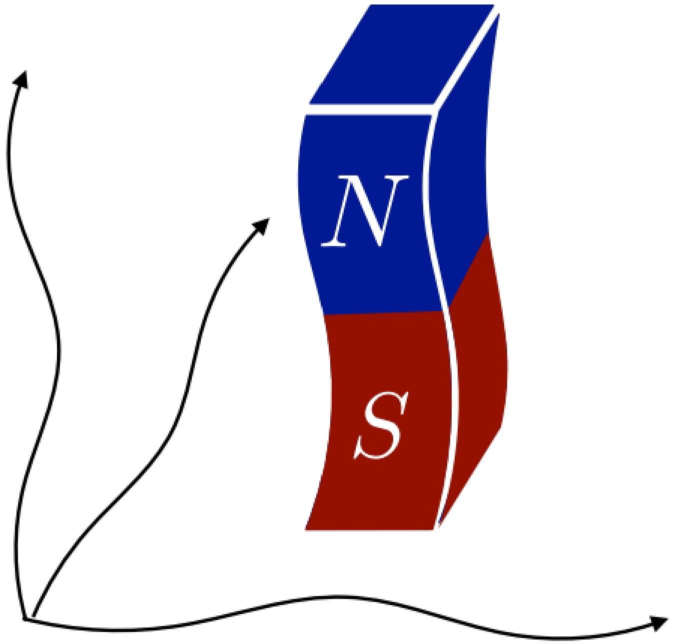
Proper detector frame



TT frame



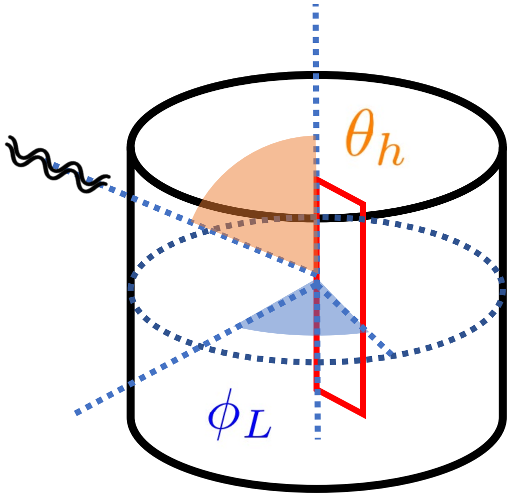
Example: Solenoidal Geometry

- For single pickup loop [Domcke, Carcia-Cely, **SML**, Rodd '23]

$$\Phi_{\rm GW} = \frac{e^{-i\omega t}}{144}\omega^2 B_z lr(30R^2 - 13r^2)\sin\theta_h(h^+\cos\theta_h\sin\phi_L + h^\times\cos\phi_L) + \mathcal{O}[(\omega L)^3]$$

leading order volume effect angular dependence

$O(\omega^2)$



- Toroidal loop (ϕ_L integration) : $\Phi_{\rm GW,Sol} = O(\omega^3)$

This cancellation *always* happens for *cylindrically symmetric* axion detectors

Example: Toroidal Geometry

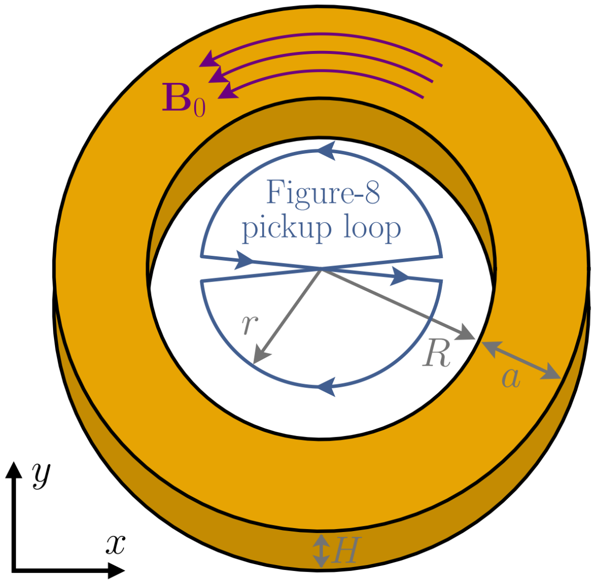
- Normal Loop

$$\Phi_{\mathrm{GW}} = \frac{ie^{-i\omega t}}{48}\omega^3 B_{\mathrm{max}}\pi r^2 Ra(a+2R)h^{\times}\sin^2\theta_h$$

- Figure-8 Loop

$$\Phi_{\mathrm{GW,Fig-8}} = \frac{e^{-i\omega t}}{3}\omega^2 B_{\mathrm{max}} r^3 R \ln\left(1+\frac{a}{R}\right) s_{\theta_h}(h^{\times}s_{\phi_h} - h^{+}c_{\theta_h}c_{\phi_h})$$

  - Kills axion sensitivity



[2202.00695]

Electromagnetism with Axion

- **Axion-Photon Coupling**

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- **Effective Current**

$$\partial_\nu F^{\mu\nu} = \partial_\nu \left(g_{a\gamma\gamma} a \tilde{F}^{\nu\mu} \right) = g_{a\gamma\gamma} (\partial_\nu a) \tilde{F}^{\nu\mu} \equiv j^\mu_{\text{eff}}$$

  - Axion is mainly sensitive to the magnetic field

$$\mathbf{j}_{\text{eff}} = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) \mathbf{B} \qquad \rho_{\text{DM}} \simeq 0.3 \text{ GeV/cm}^3$$