Searching for High Frequency GW with Axion Detectors

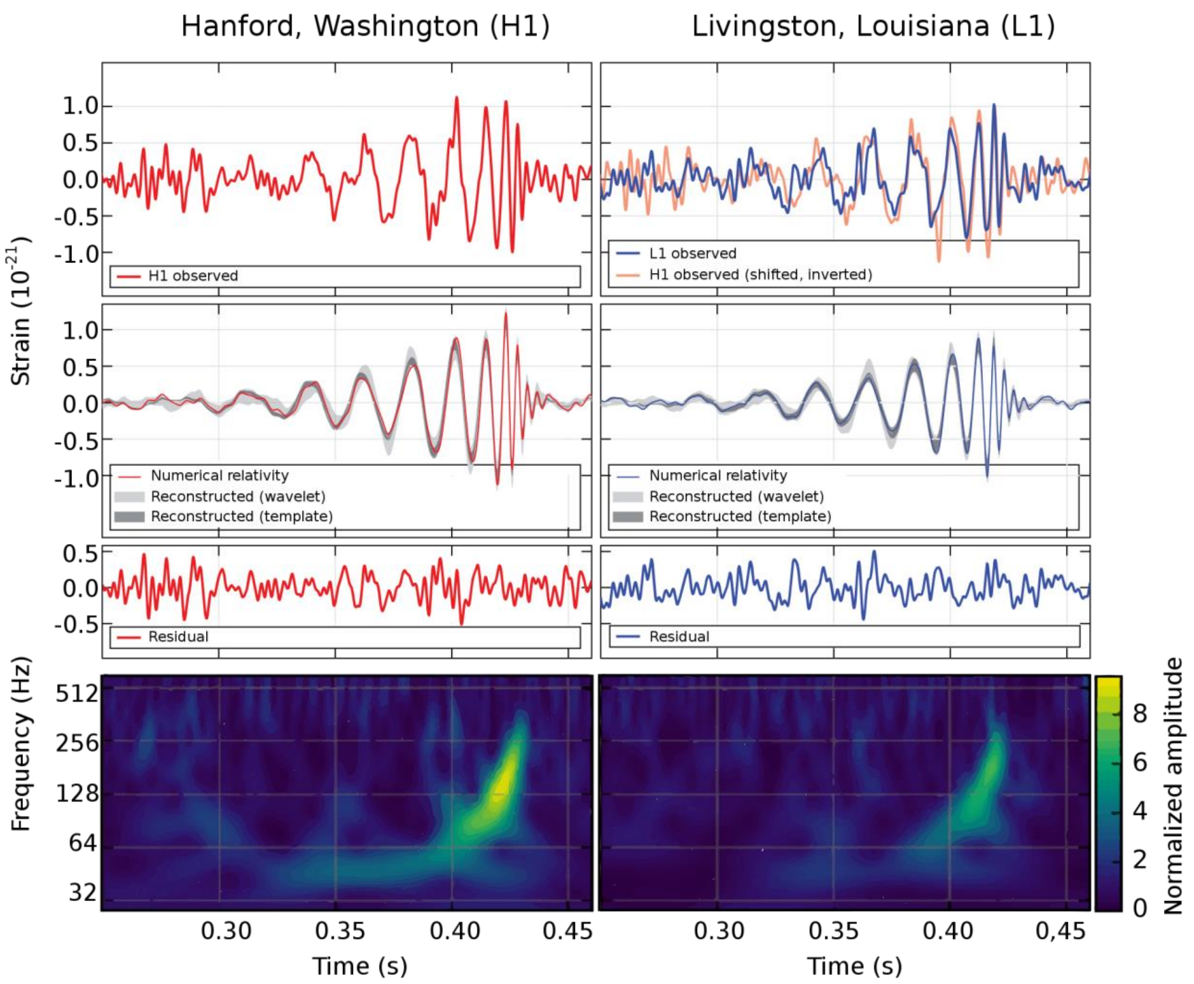
Sung Mook Lee

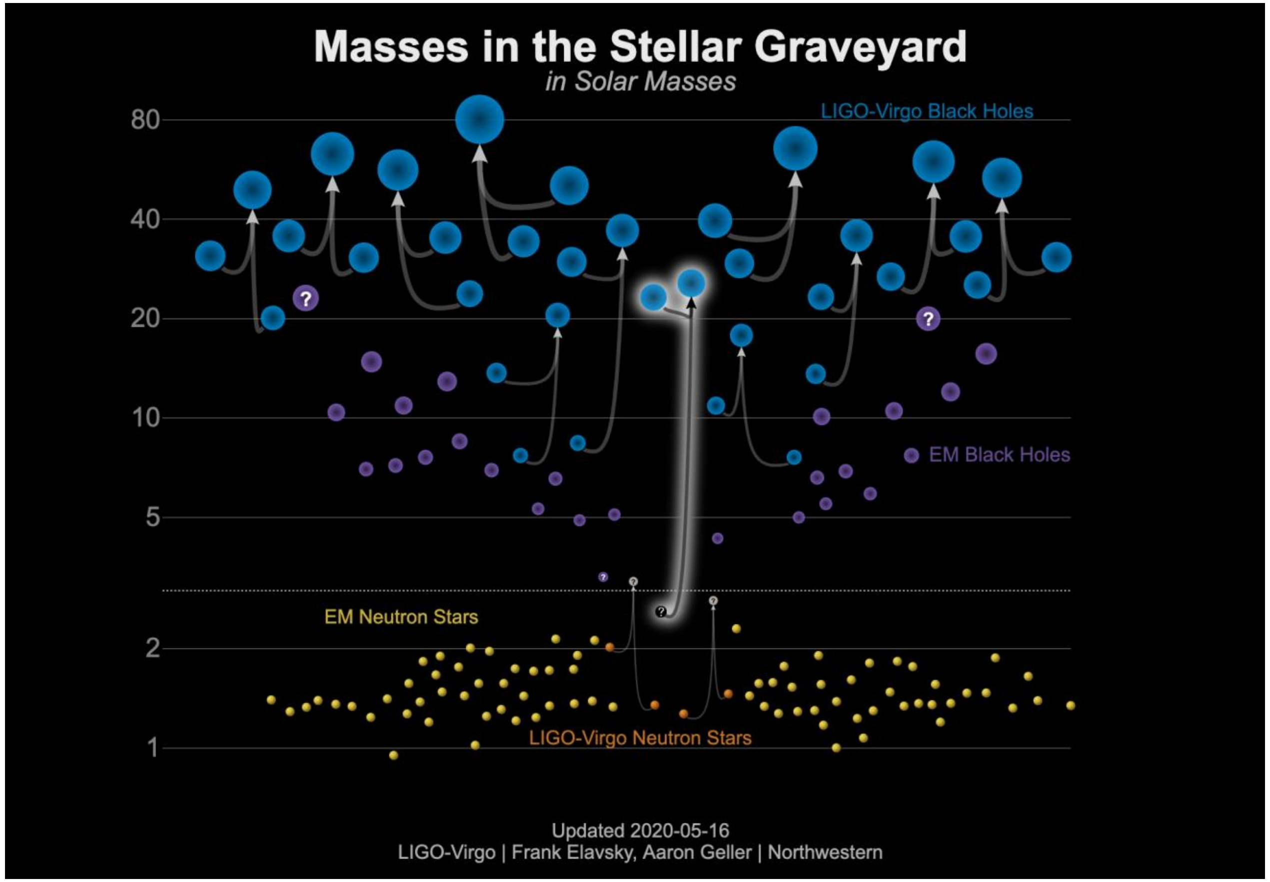
Yonsei U.

2306.03125

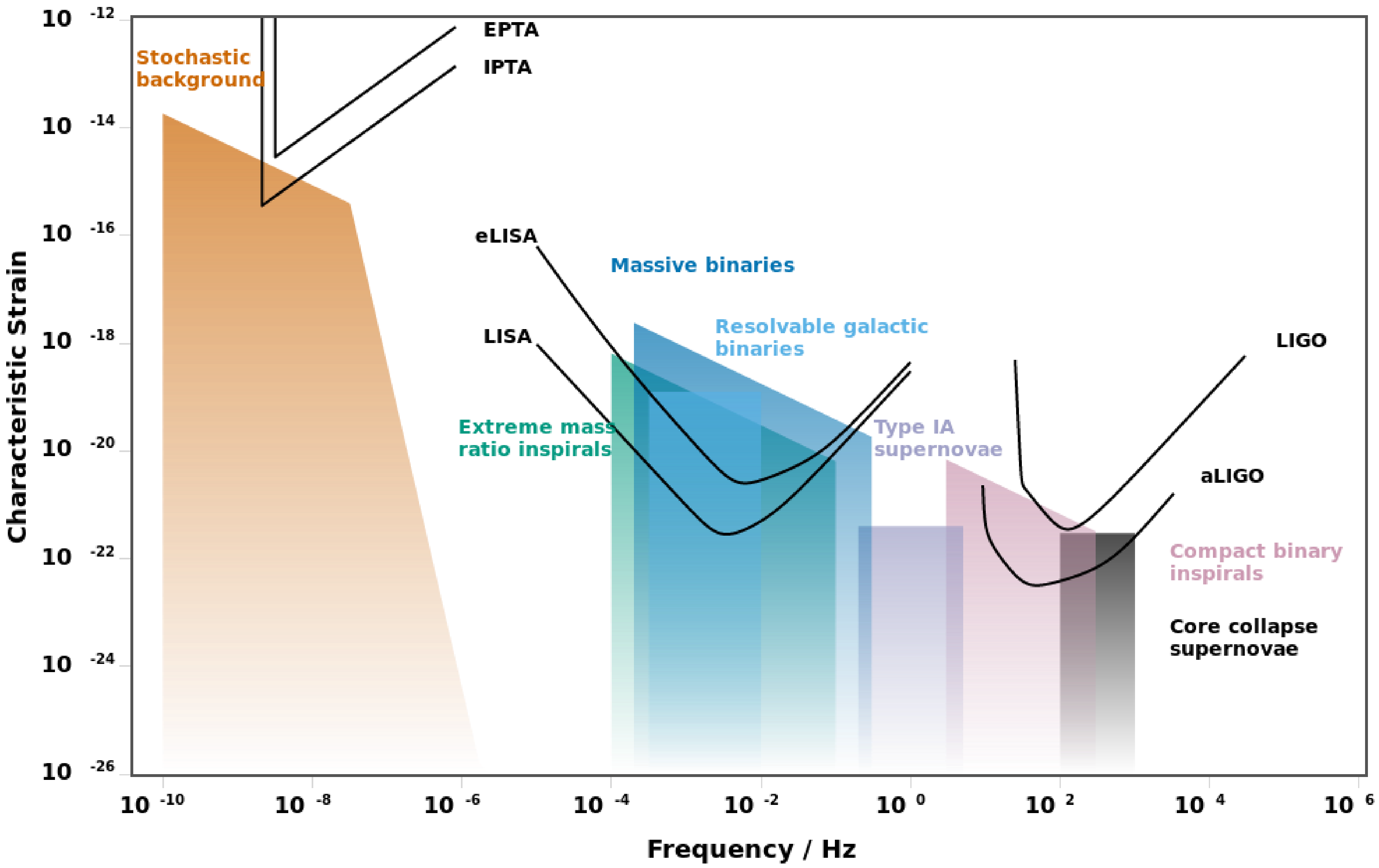
with Valerie Domcke (CERN), Camilo Carcia-Cely (Valencia, IFIC), and Nicholas L. Rodd (CERN)

Detection of Gravitational Waves





Detection of Gravitational Waves



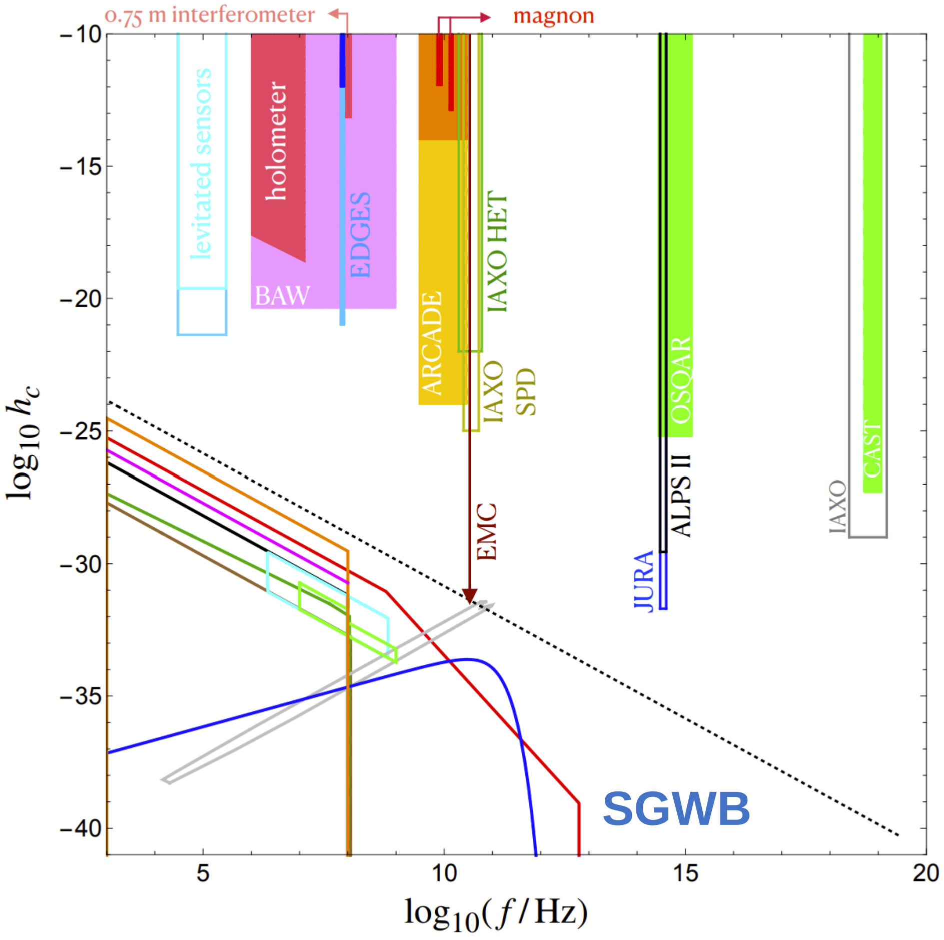
High Frequency Gravitational Wave

High Frequency Gravitational Waves

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

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

[2011.12414 for review]



High Frequency Gravitational Waves

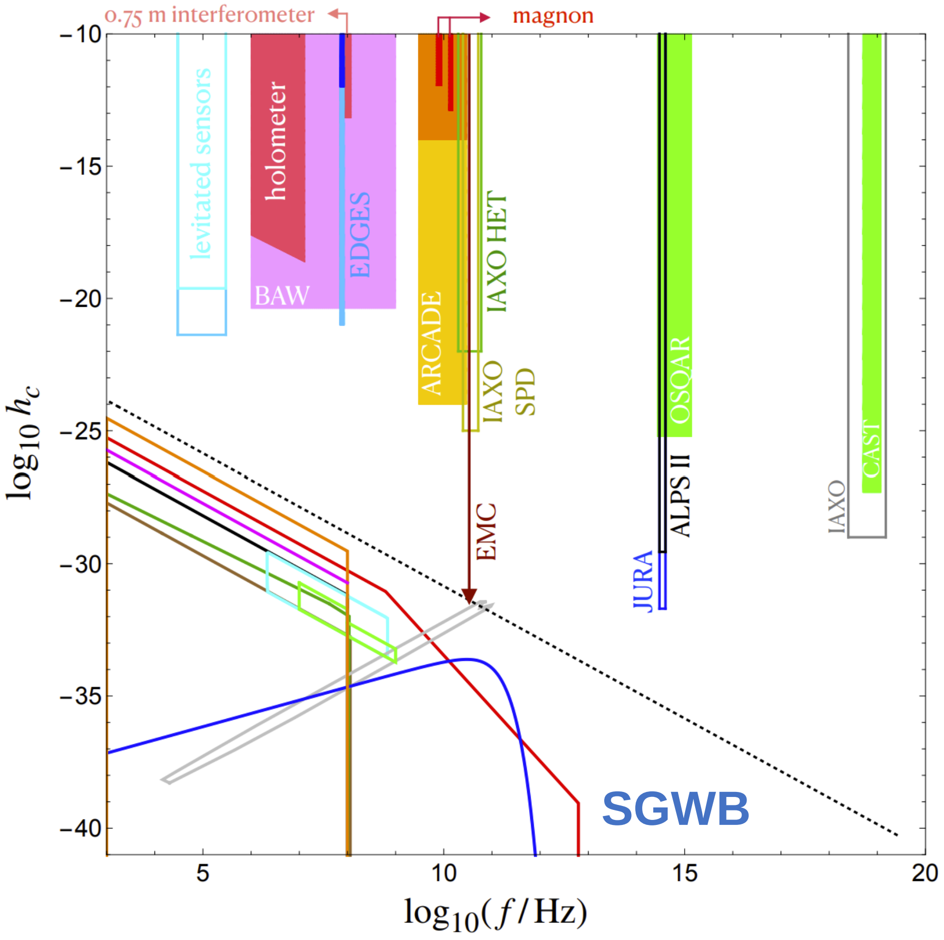
- **Stochastic Gravitational Wave Background**
  - High frequency = Early universe

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

  - Constraints from BBN/CMB on ΔN_{eff}

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

[2011.12414 for review]



High Frequency Gravitational Waves

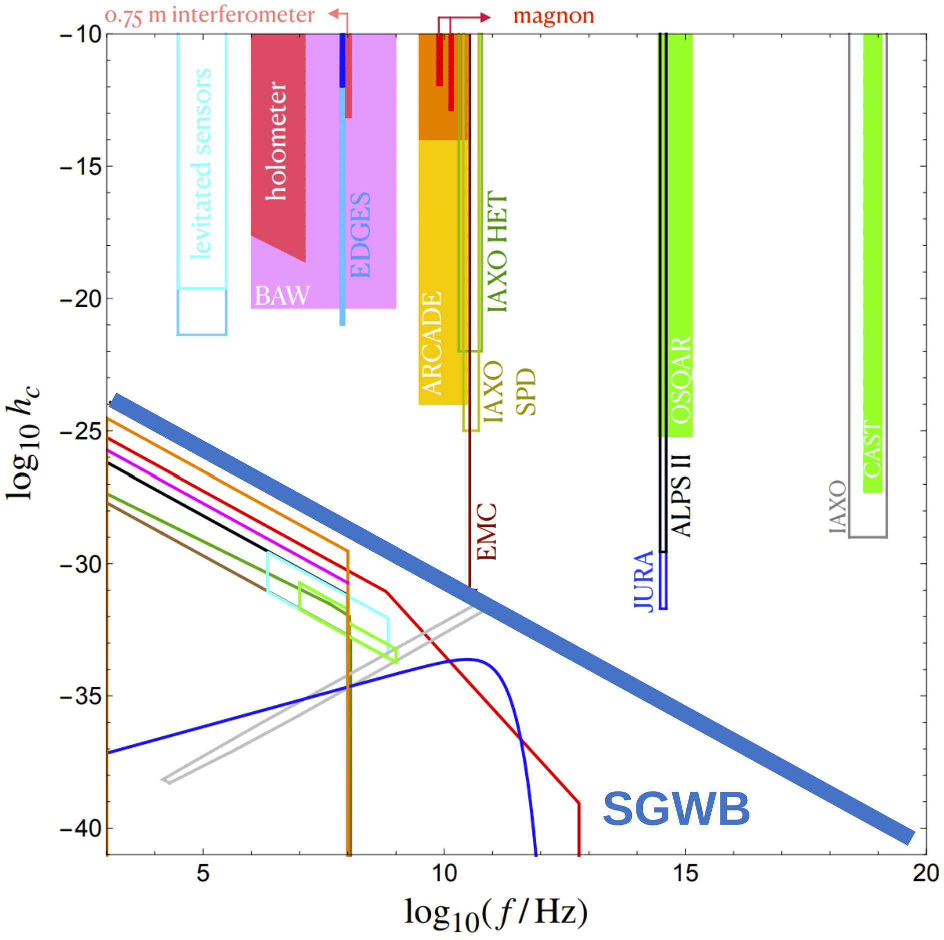
- **Stochastic Gravitational Wave Background**
  - High frequency = Early universe

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

  - Constraints from BBN/CMB on ΔN_{eff}

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

[2011.12414 for review]



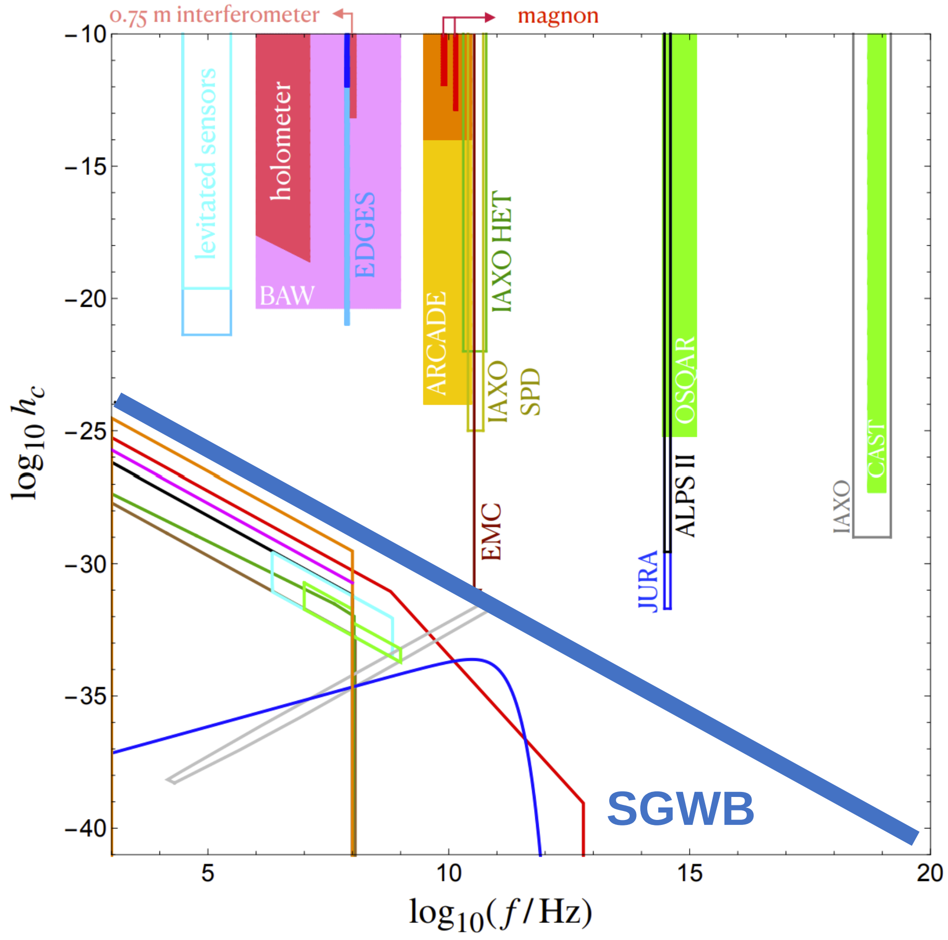
High Frequency Gravitational Waves

- **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]



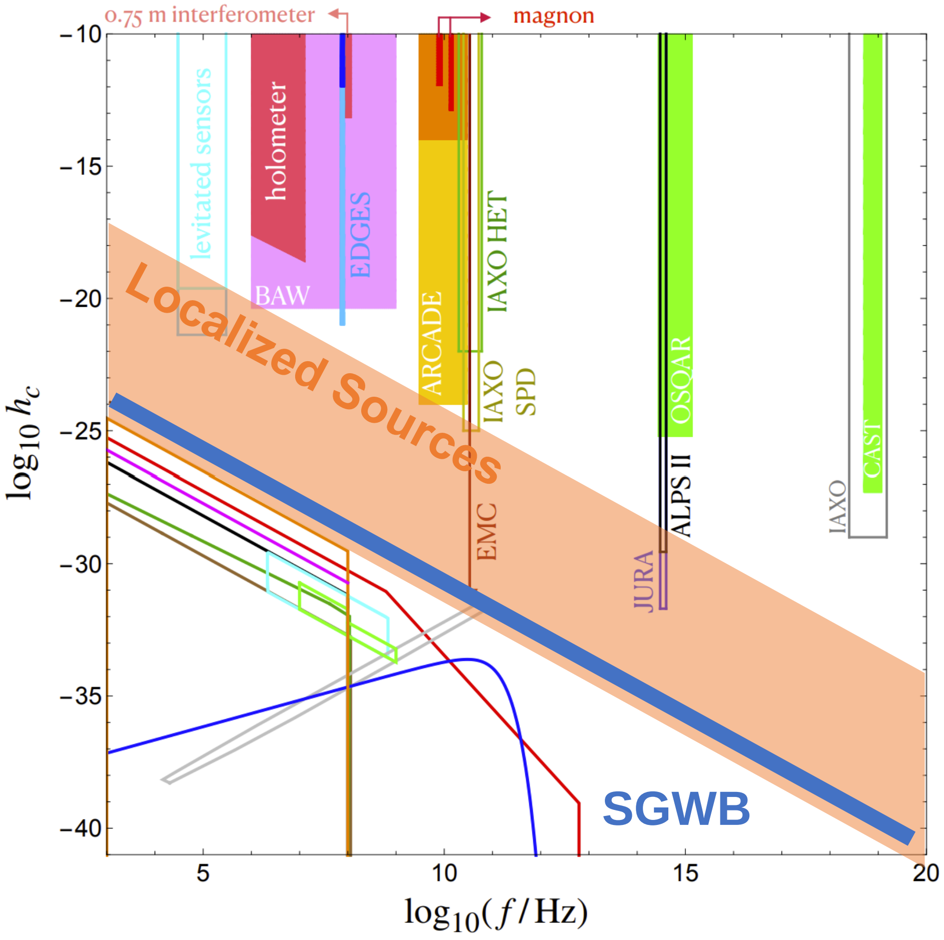
High Frequency Gravitational Waves

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

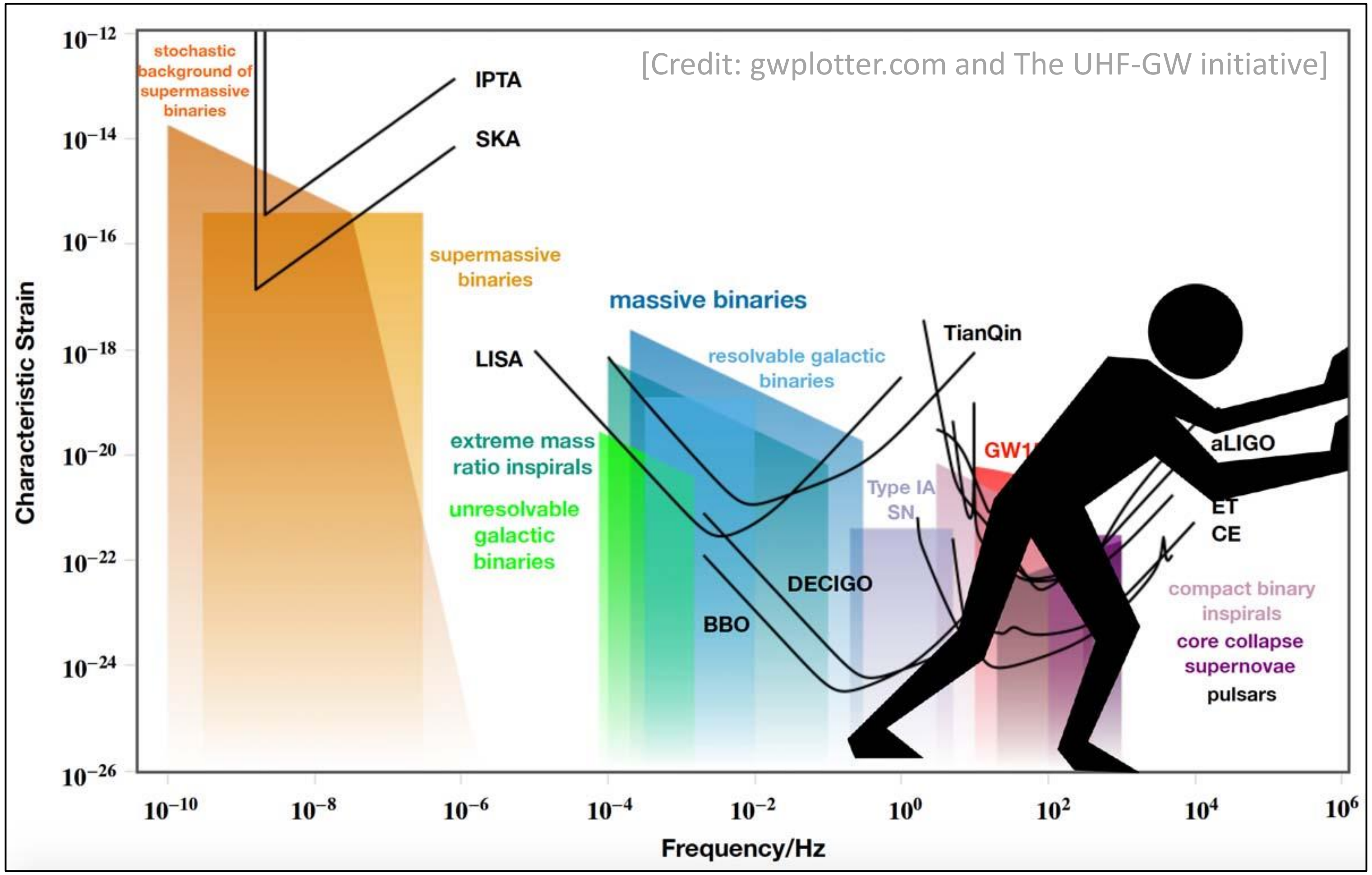
$$f \simeq 220\ \mathrm{MHz}\left(\frac{10^{-5}M_\odot}{m_{\mathrm{PBH}}}\right)$$

  - Larger signals expected

[2011.12414 for review]

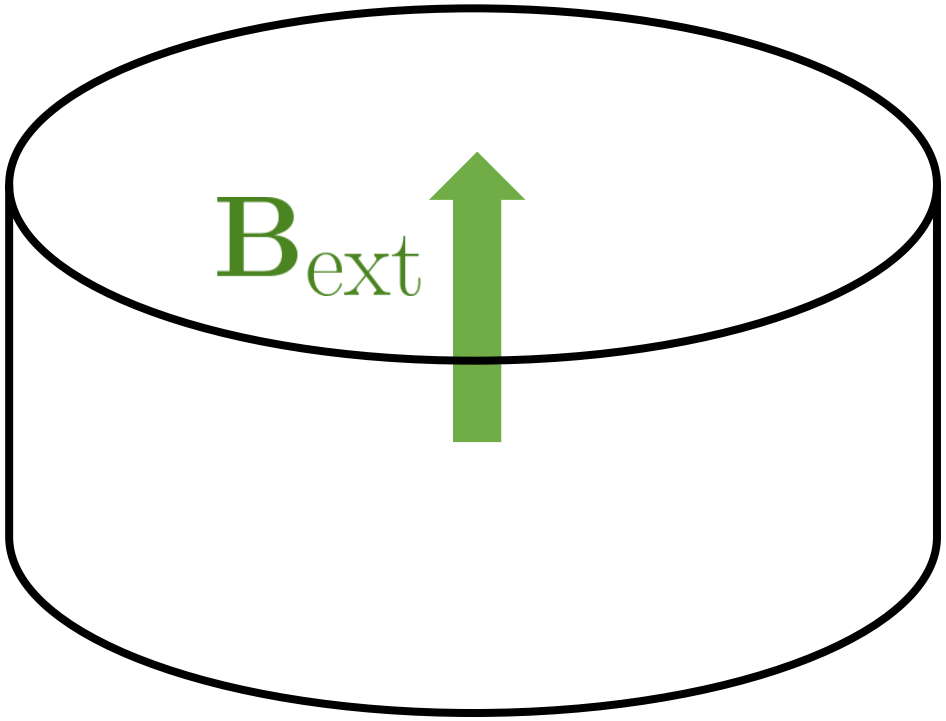


High Frequency Gravitational Waves

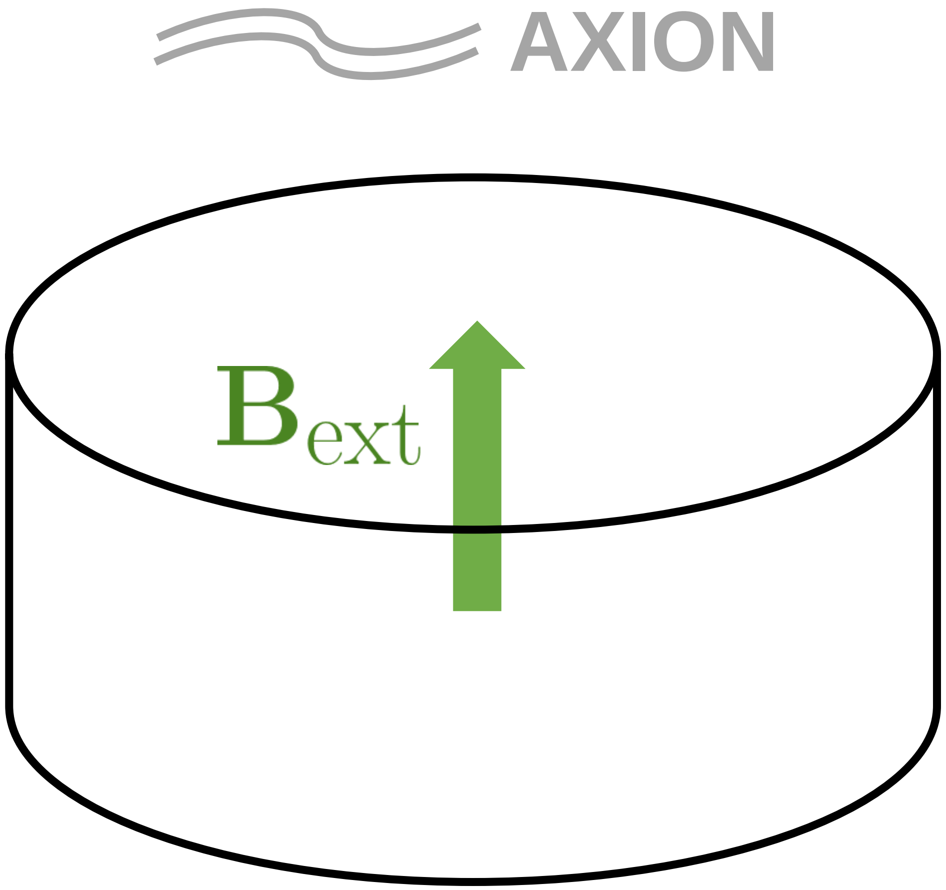


How can we detect GW with f > O(1MHz)?

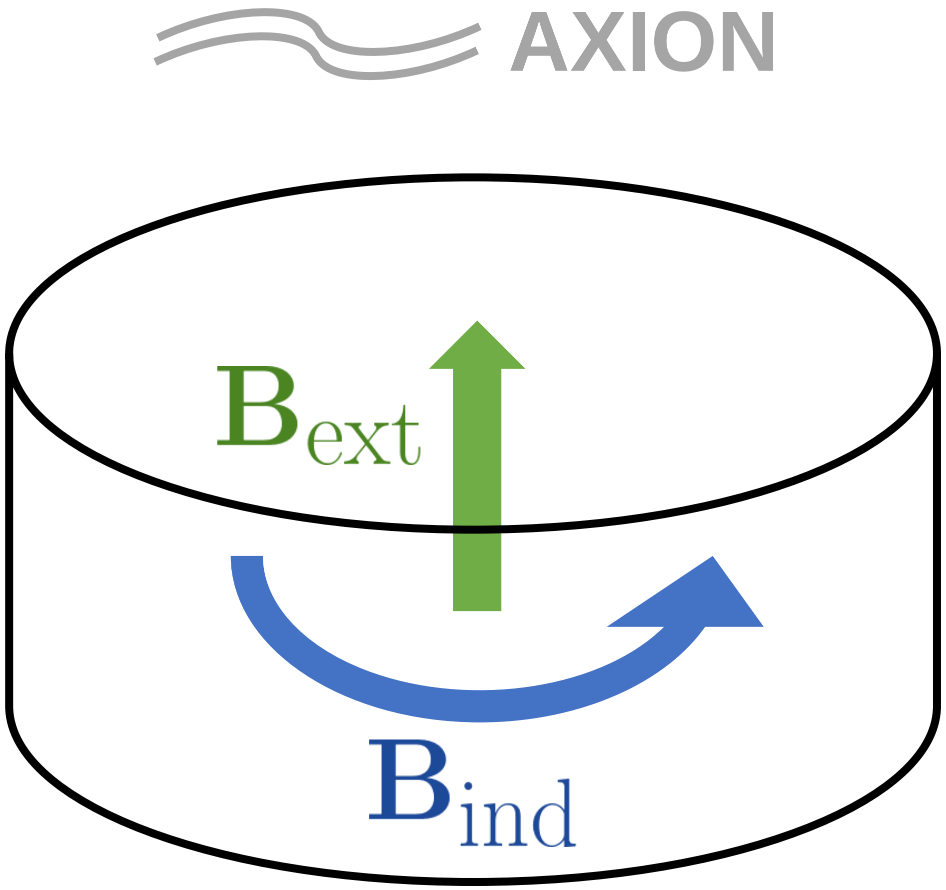
Key Idea



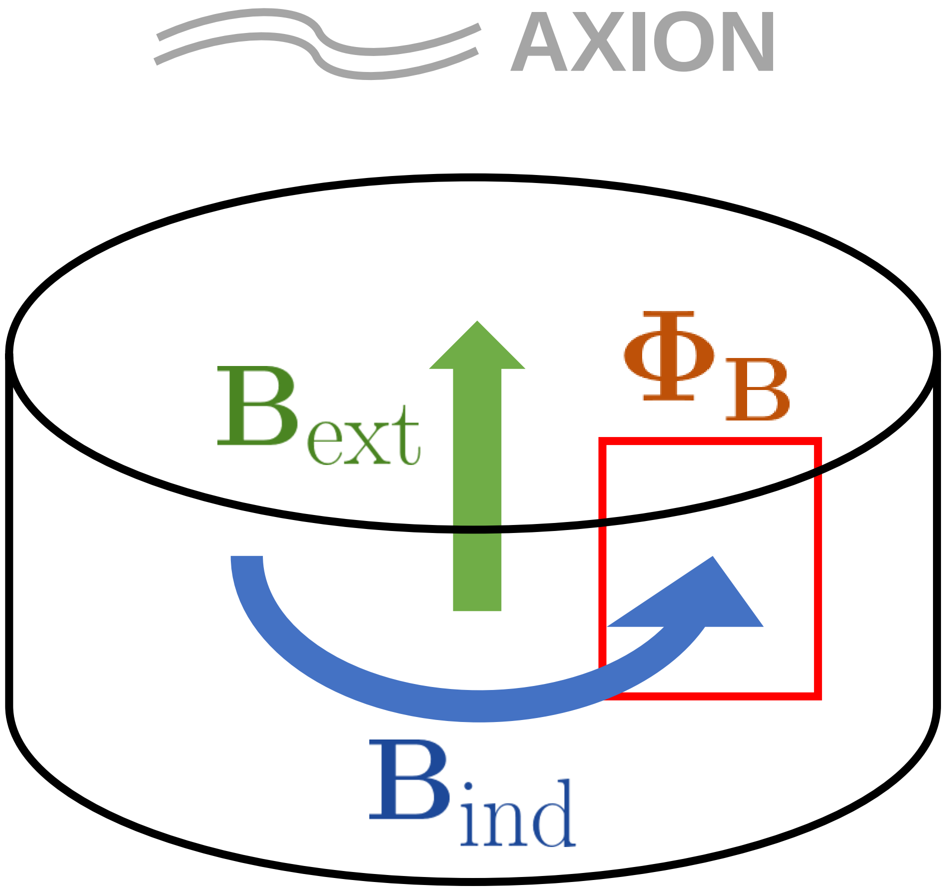
Key Idea



Key Idea

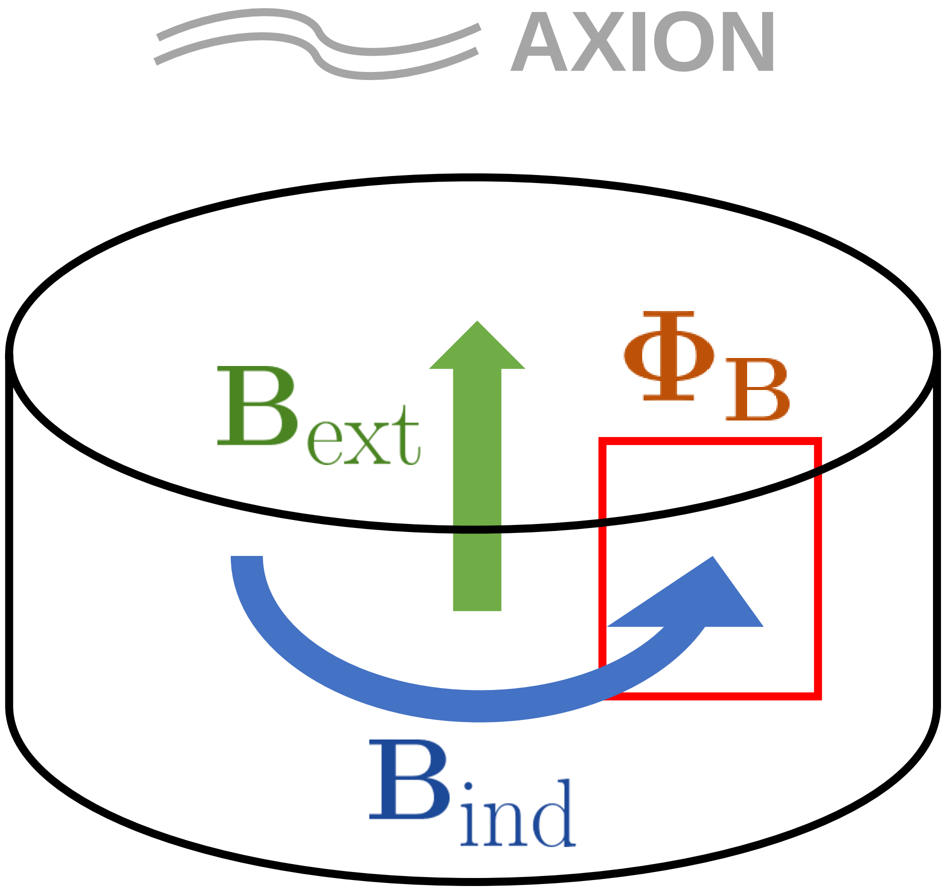


Key Idea

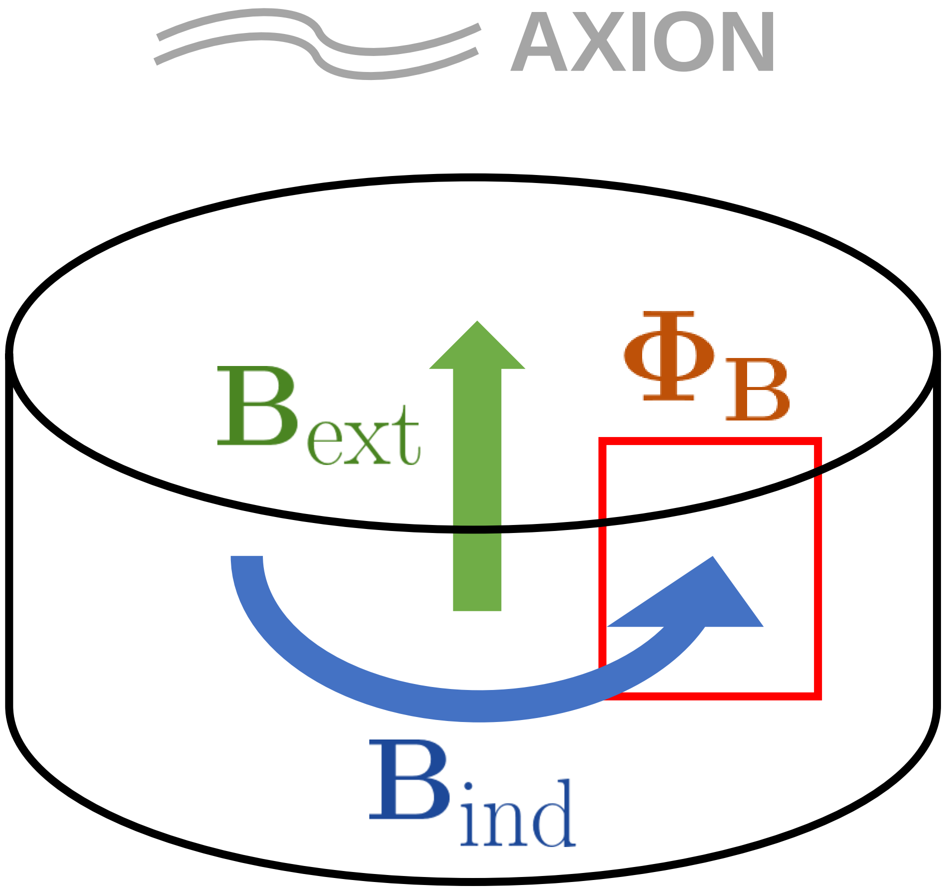


Key Idea

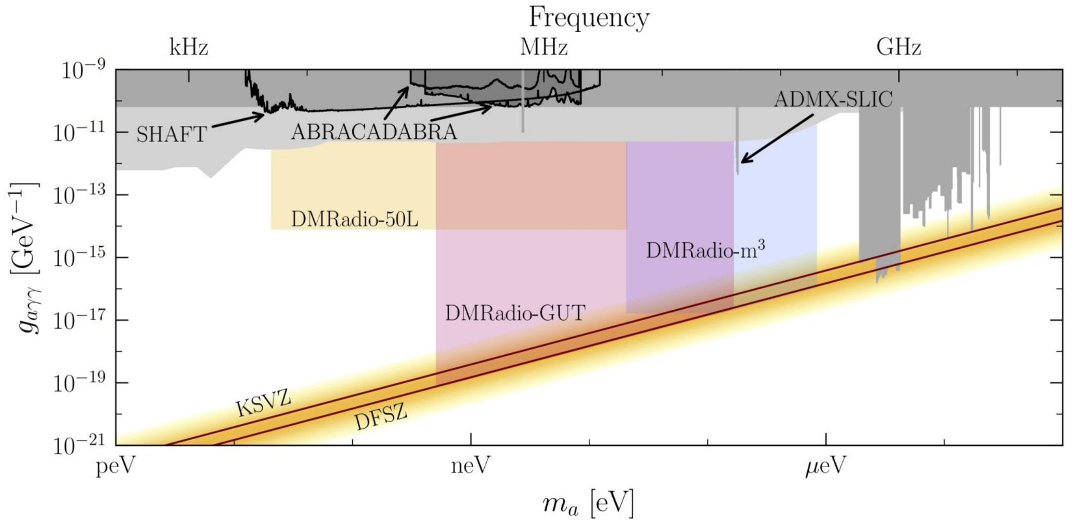
$$\Phi_{\text{Axion,Solenoid}} = \frac{1}{4} g_{a\gamma\gamma} \dot{a} B_0 l R^2$$



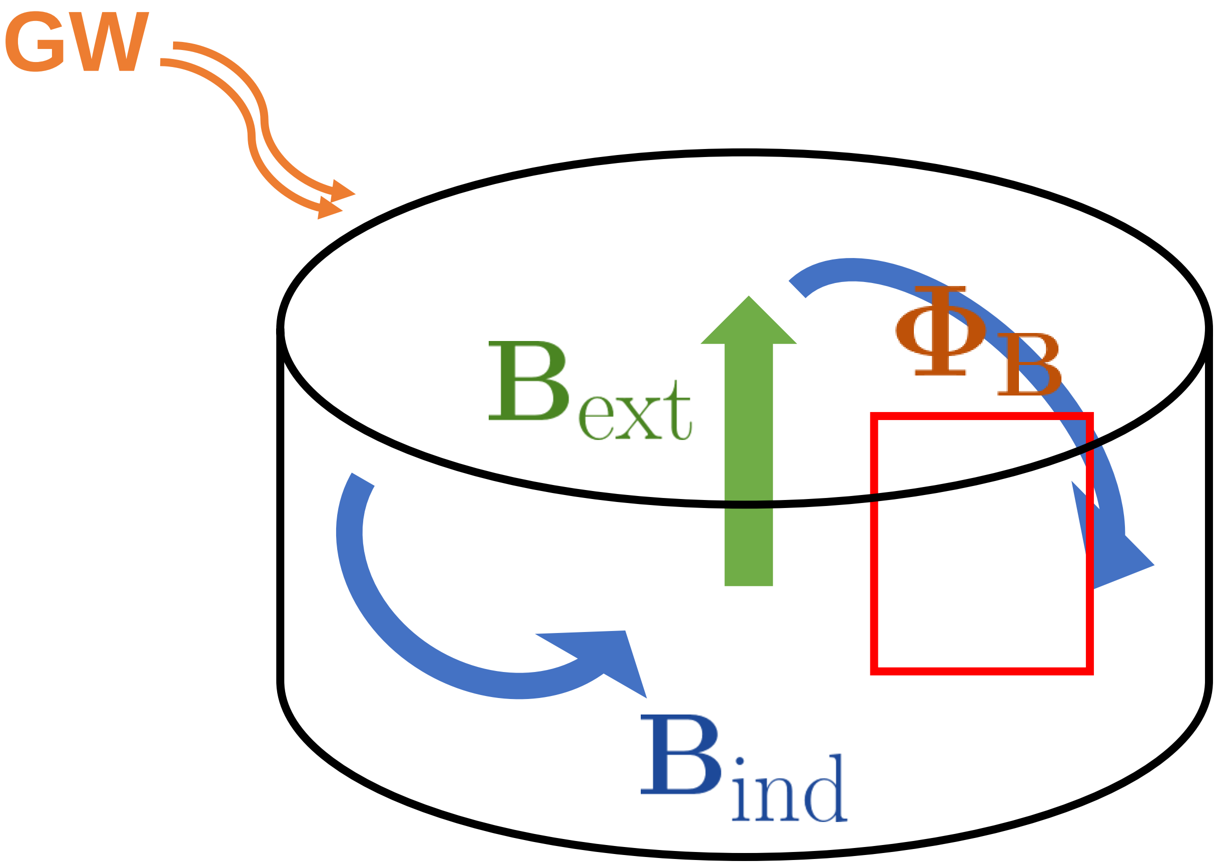
Key Idea



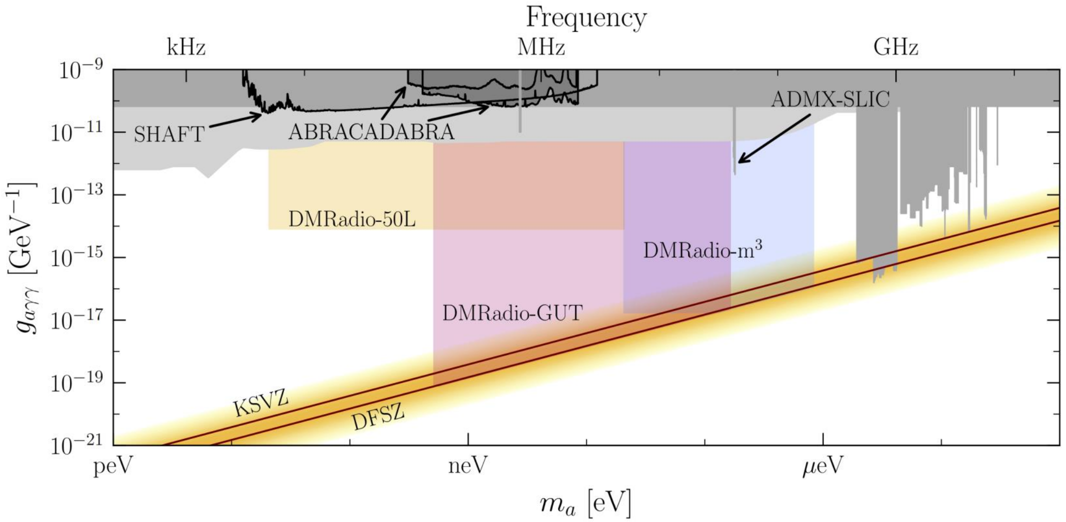
$$\Phi_{\text{Axion,Solenoid}} = \frac{1}{4} g_{a\gamma\gamma} \dot{a} B_0 l R^2$$



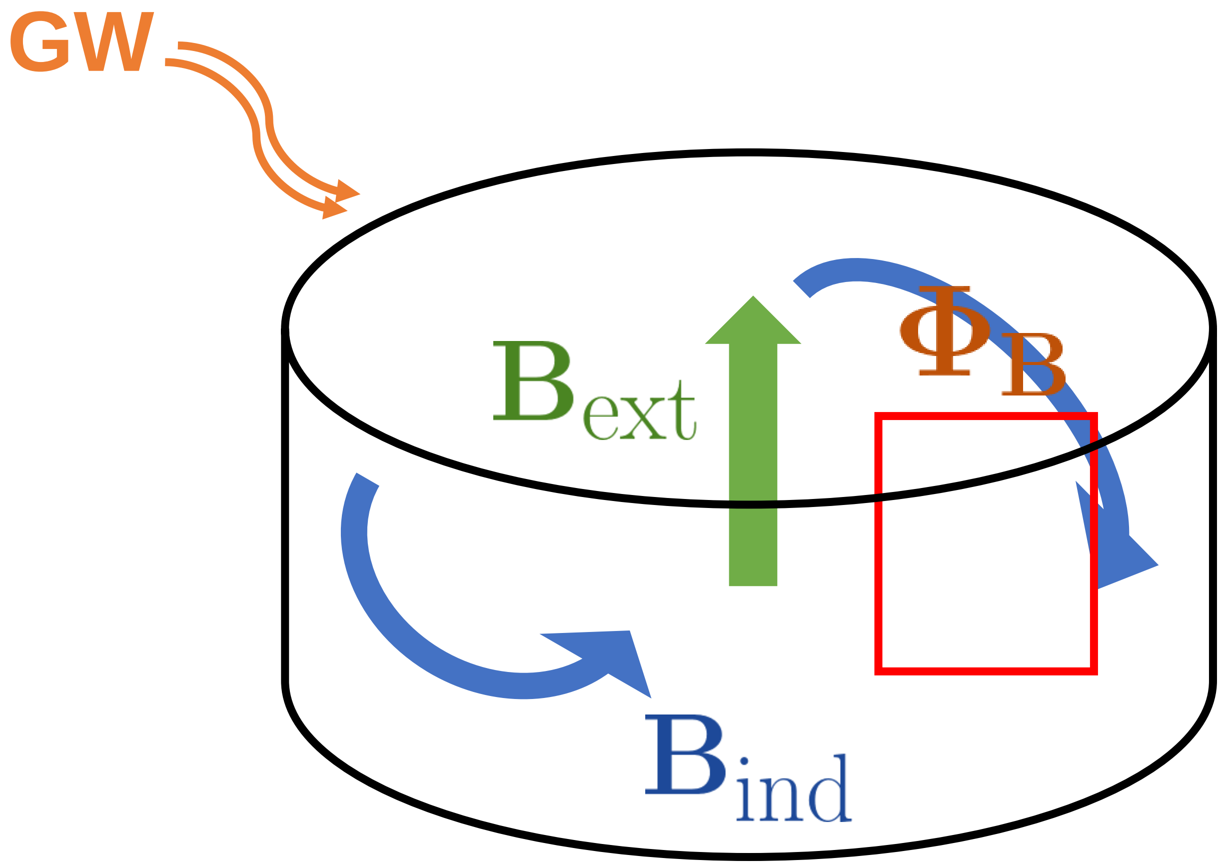
Key Idea

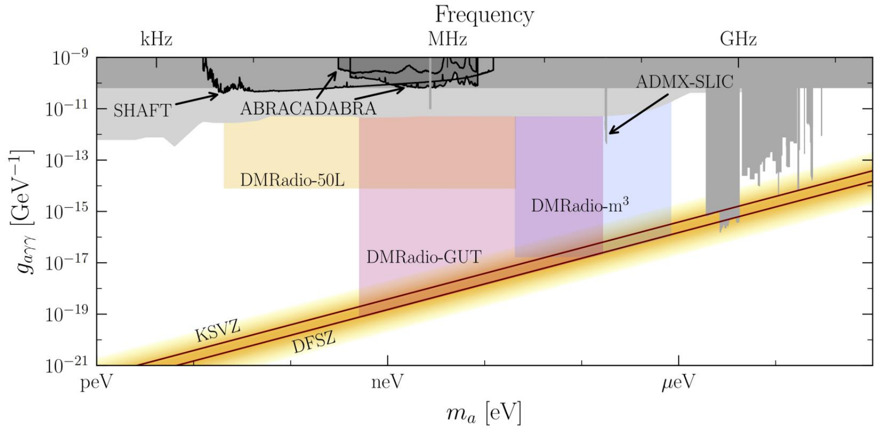


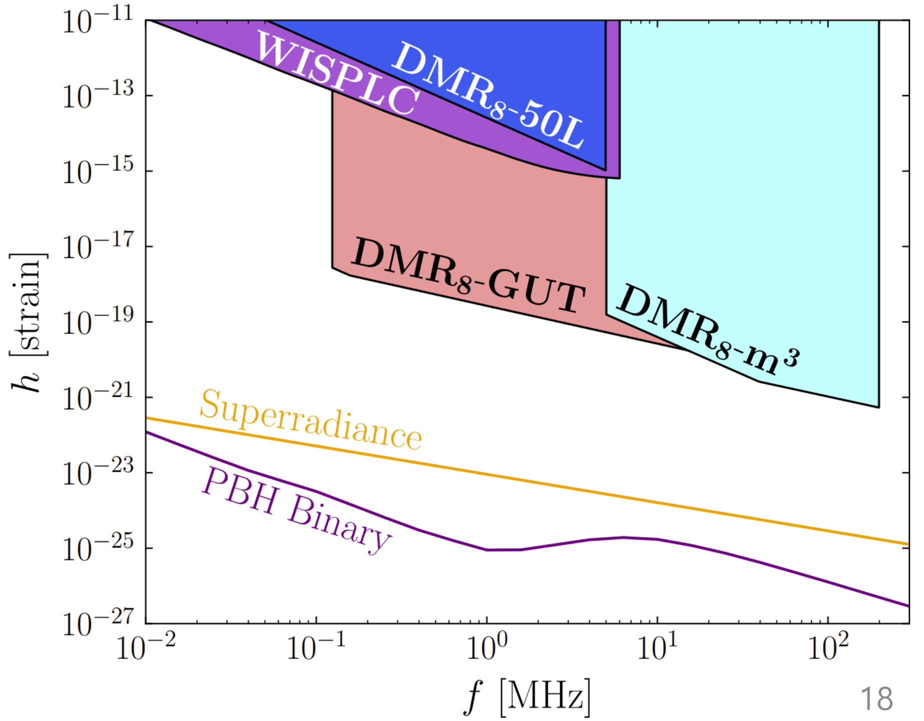
$$\Phi_{\text{Axion,Solenoid}} = \frac{1}{4} g_{a\gamma\gamma} \dot{a} B_0 l R^2$$



Key Idea

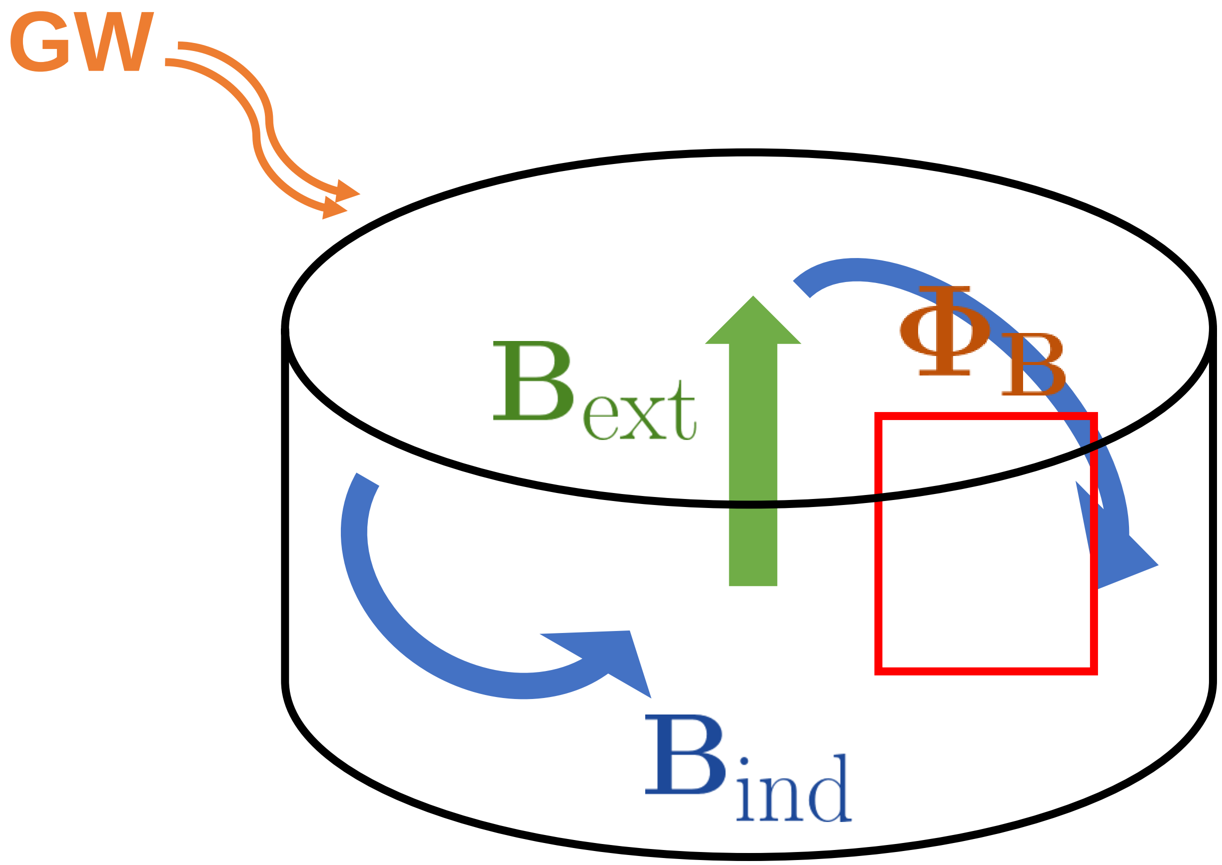

GW
Φ_B
B_{ext}
B_{ind}

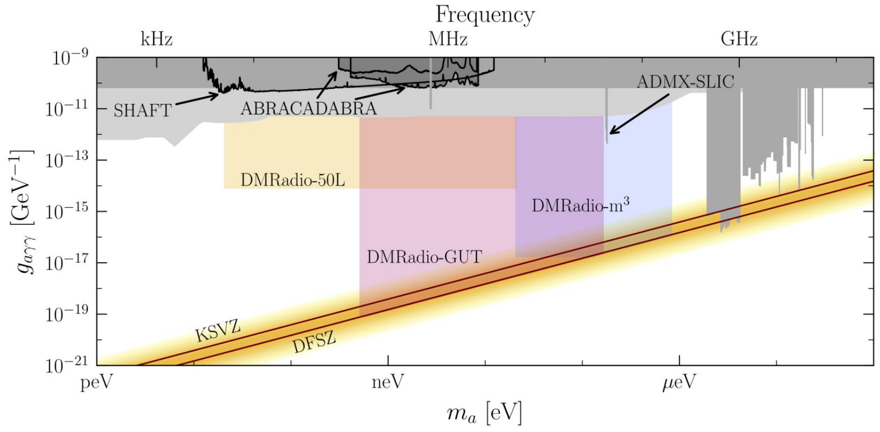

Frequency
kHz
MHz
GHz
SHAFT
ABRACADABRA
ADMX-SLIC
DMRadio-50L
DMRadio-m^3
DMRadio-GUT
KSVZ
DFSZ
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [eV]
peV
neV
μeV

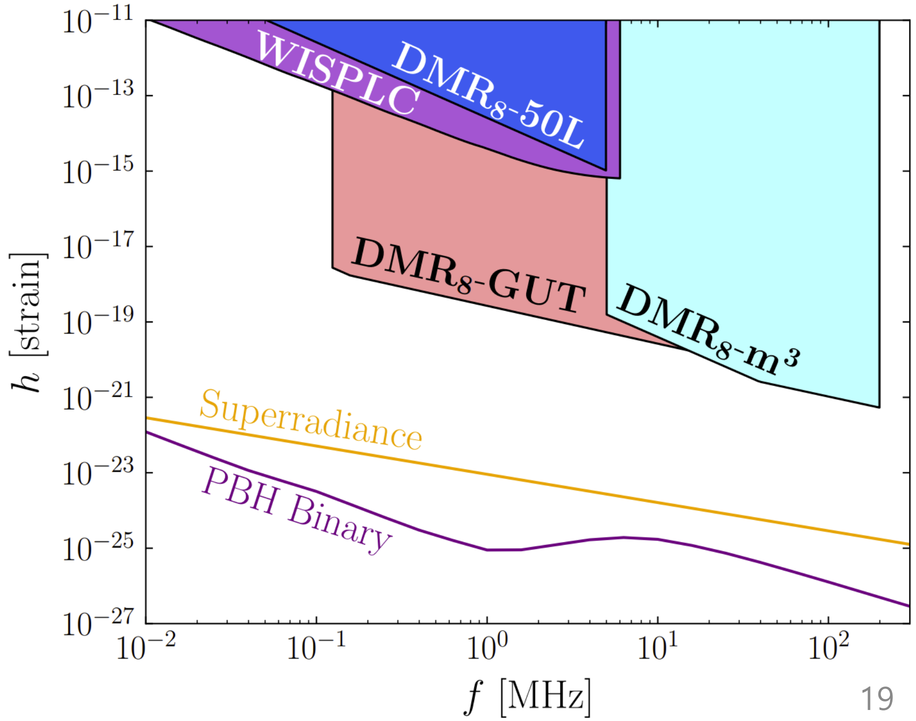

WISPLC
DMR$_8$-50L
DMR$_8$-GUT
DMR$_8$-m^3
Superradiance
PBH Binary
h [strain]
f [MHz]

Key Idea

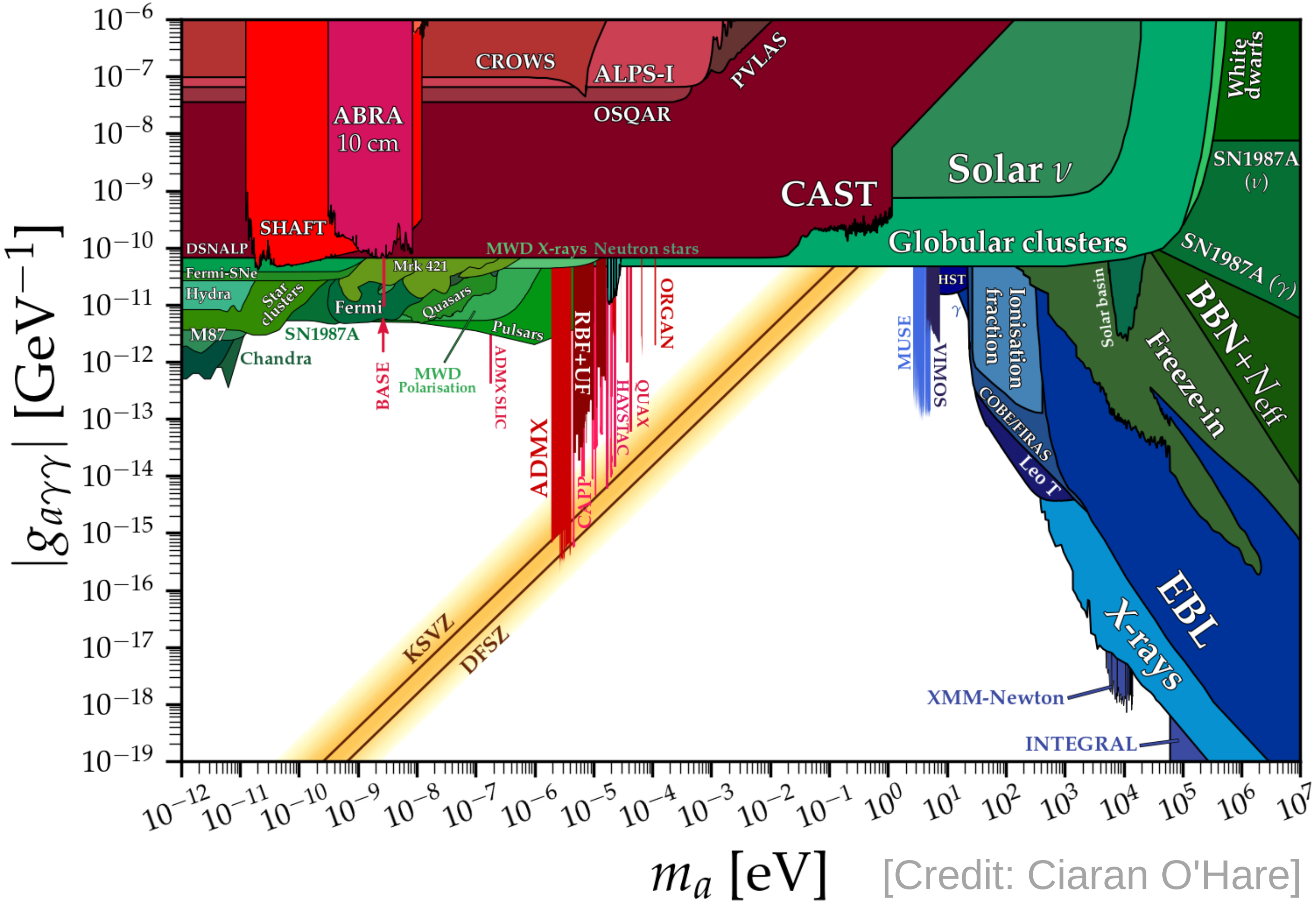
You do not need a new detector!





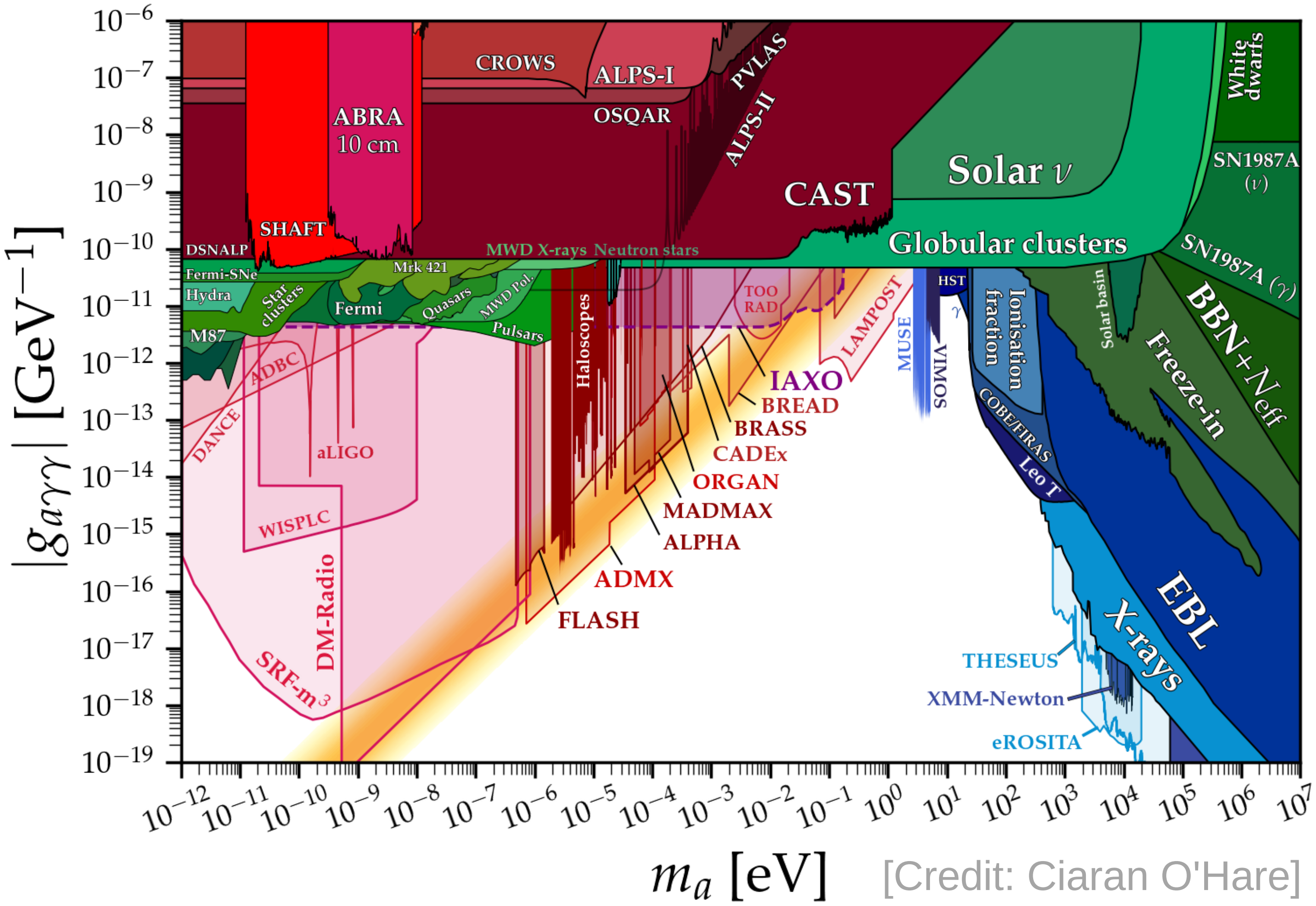


Axion Experiment Zoo



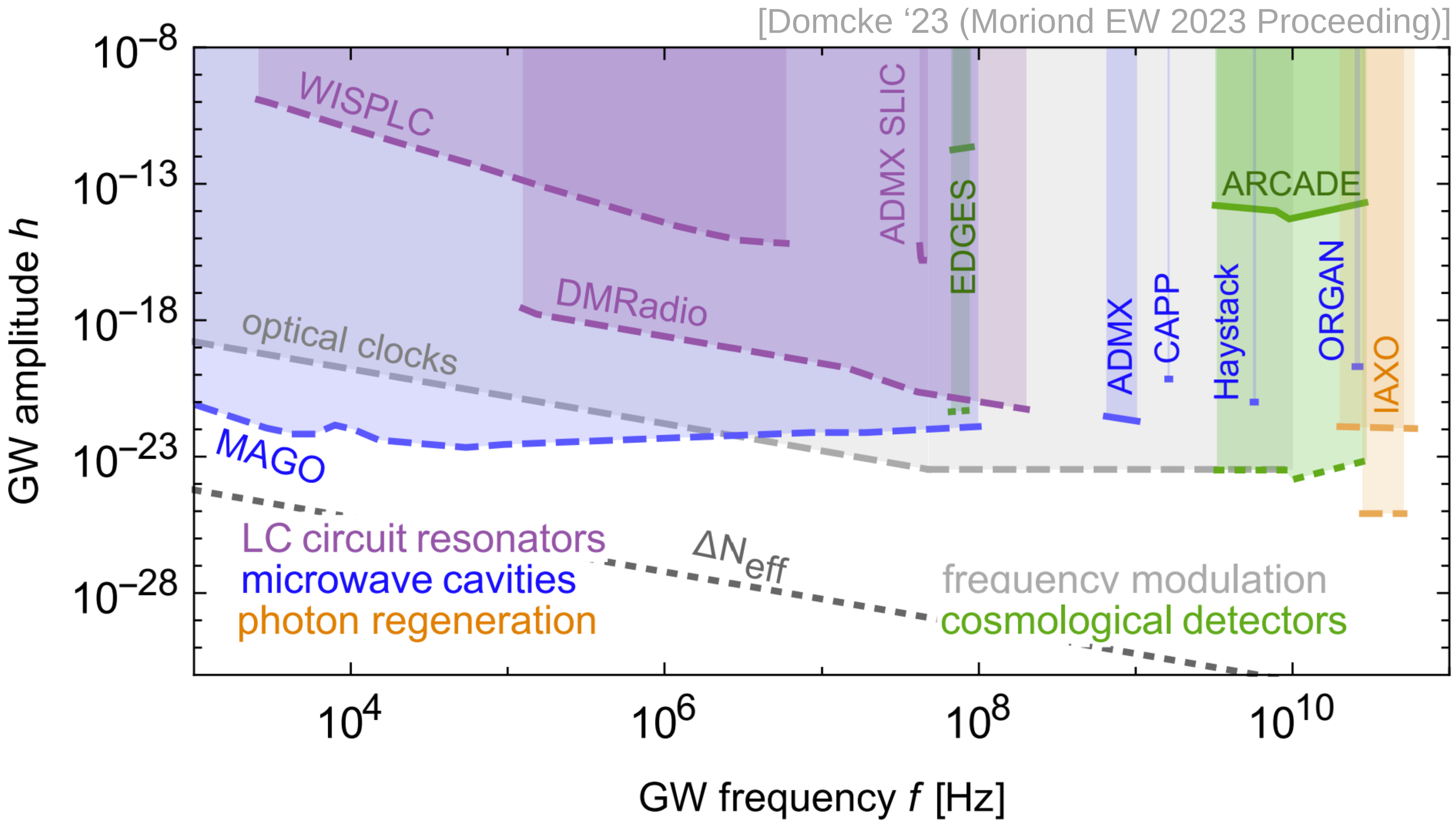
[Credit: Ciaran O'Hare]

Axion Experiment Zoo



[Credit: Ciaran O'Hare]

EM-HFGW Program



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

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

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

$$\Big\Downarrow \; \partial \to \nabla$$

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

Electromagnetism in Curved Spacetime

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

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

$$\Big\downarrow \ \partial \to \nabla$$

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

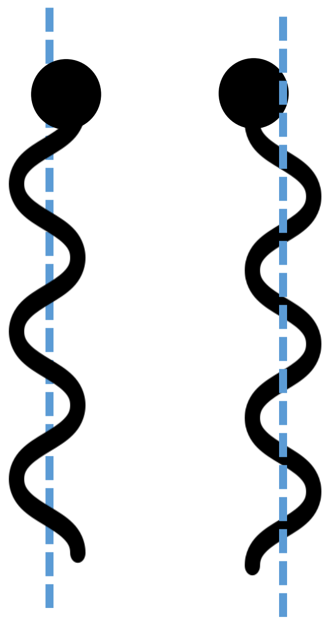
$$\Big\downarrow \ \text{perturbation}$$

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

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

- **Proper detector frame**

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

  - 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

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

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

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

$F(\xi) = (e^{i\xi} - 1 - i\xi)/\xi^2$

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

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

  - Description of the experimental setup and observables is straightforward

Axion Detectors as GW Detectors

- **Strategy**

[Domcke, Carcia-Cely, Rodd '22]

$$\Phi_{\mathrm{Axion}}(g_{a\gamma\gamma}) \quad = \quad \Phi_{\mathrm{GW}}(h_{+,\times};\theta_h,\phi_h)$$

Axion Detectors as GW Detectors

- **Strategy**

[Domcke, Carcia-Cely, Rodd '22]

$$\Phi_{\text{Axion}}(g_{a\gamma\gamma}) \quad = \quad \Phi_{\text{GW}}(h_{+,\times};\theta_h,\phi_h)$$

- **Axion detector is not optimized for GW signals**

Axion Detectors as GW Detectors

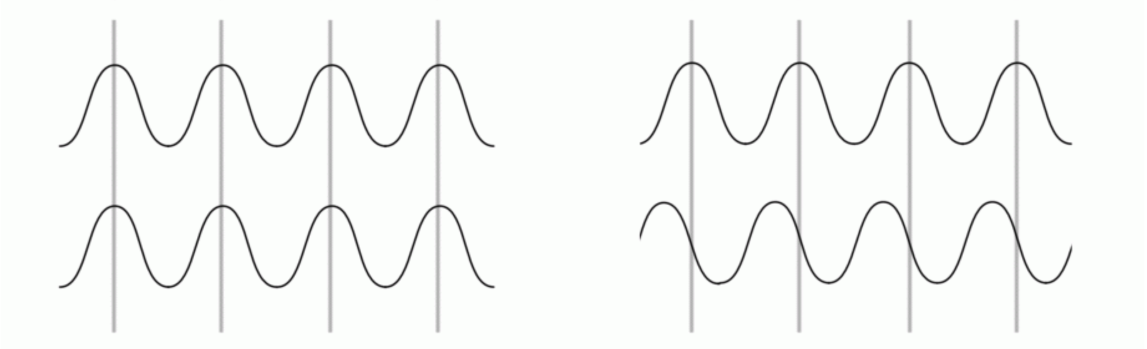
- **Strategy**

[Domcke, Carcia-Cely, Rodd ‘22]

$$\Phi_{\text{Axion}}(g_{a\gamma\gamma}) \quad = \quad \Phi_{\text{GW}}(h_{+,\times};\theta_h,\phi_h)$$

- **Axion detector is not optimized for GW signals**

$$Q^{-1} \sim \frac{\Delta\omega}{\omega}$$



Axion Detectors as GW Detectors

- **Strategy**

[Domcke, Carcia-Cely, Rodd '22]

$$\Phi_{\mathrm{Axion}}(g_{a\gamma\gamma}) \quad = \quad \Phi_{\mathrm{GW}}(h_{+,\times};\theta_h,\phi_h)$$

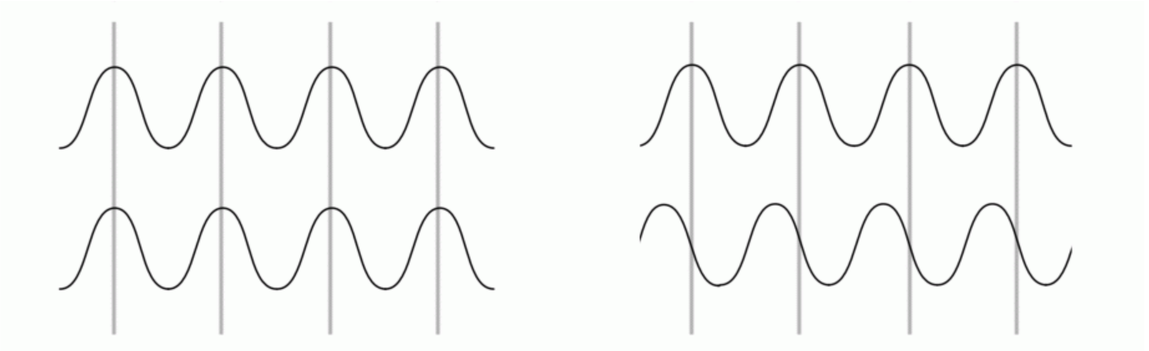
- **Axion detector is not optimized for GW signals**

$$Q^{-1} \sim \frac{\Delta\omega}{\omega}$$

  - *Coherence Ratio Factor*

$$R_c = \left(\frac{Q_a}{Q_h}\right)^{1/4}$$

(persistent signal)

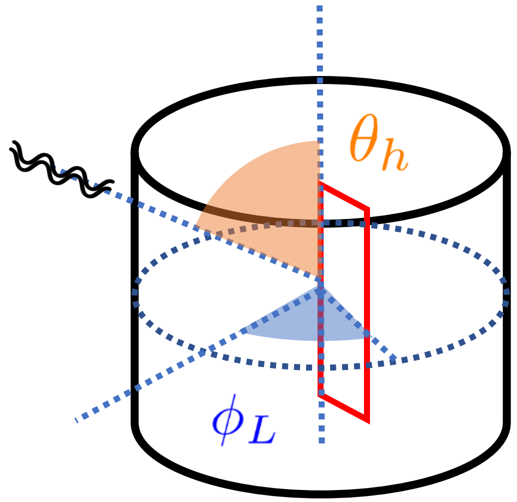


For more general cases, [Domcke, Carcia-Cely, **SML**, Rodd 23']

Example: Solenoidal Geometry

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

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



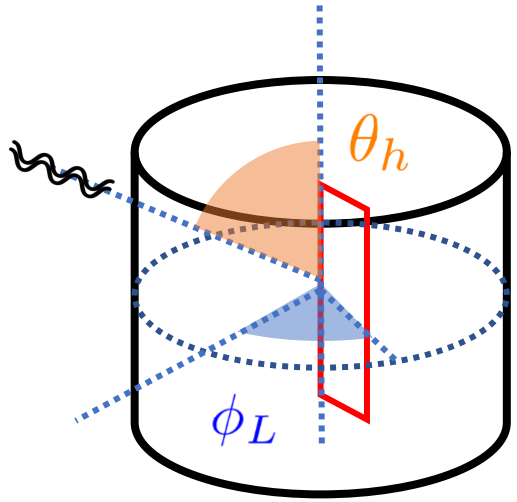
Example: Solenoidal Geometry

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

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

leading order

$O(\omega^2)$



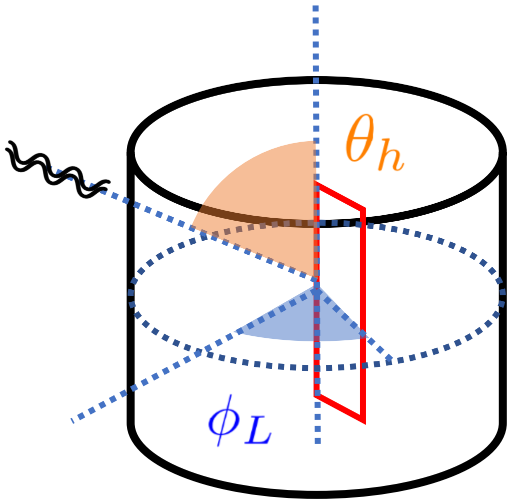
Example: Solenoidal Geometry

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

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

leading order volume effect

$O(\omega^2)$



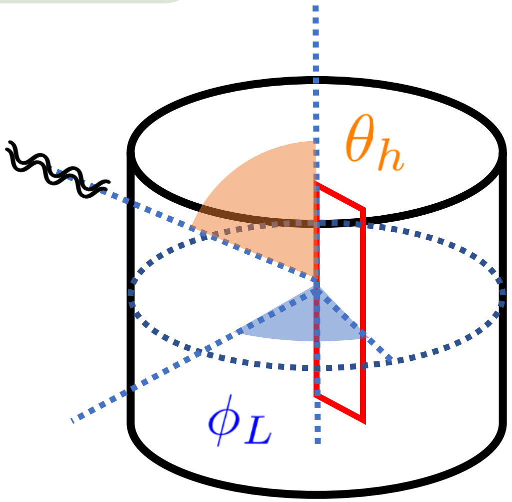
Example: Solenoidal Geometry

- 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

$O(\omega^2)$



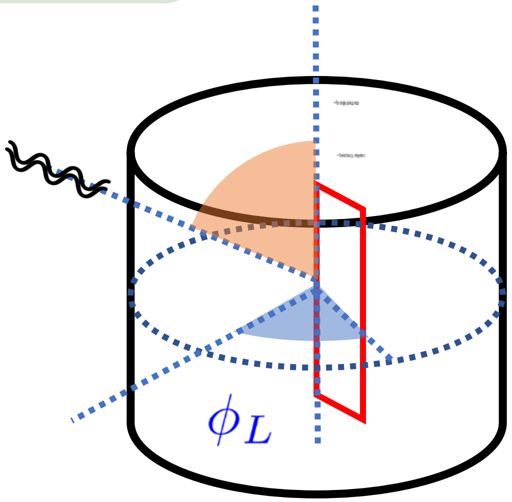
Example: Solenoidal Geometry

- 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

$O(\omega^2)$



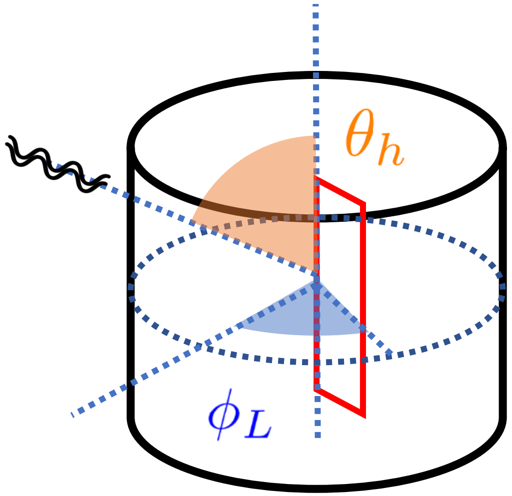
- Toroidal loop (ϕ_L integration) : $\Phi_{\rm GW,Sol} = O(\omega^3)$

Example: Solenoidal Geometry

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

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

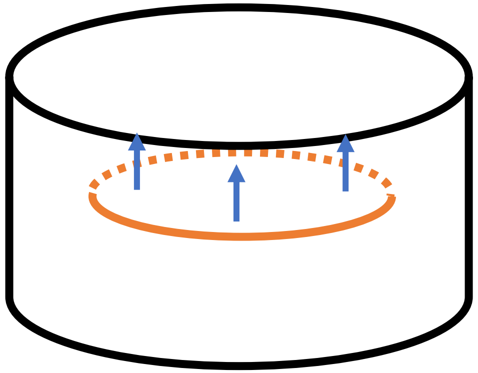
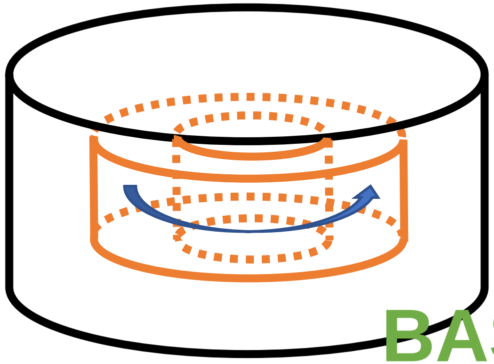
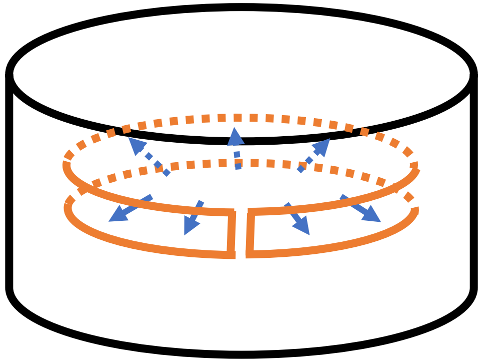
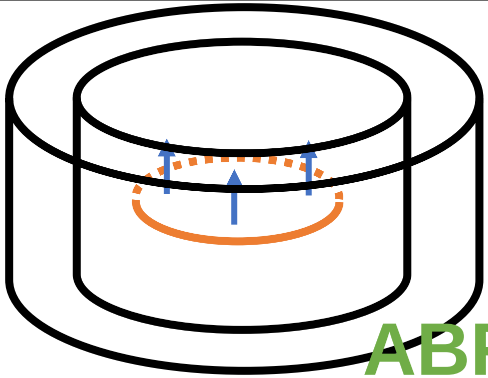
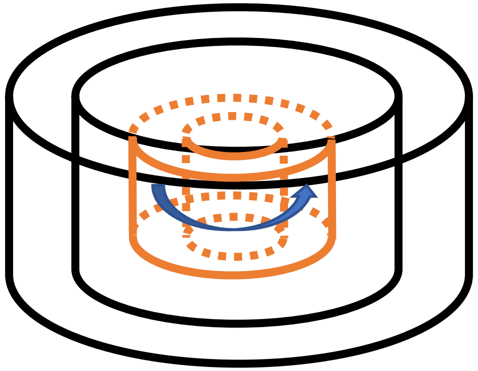
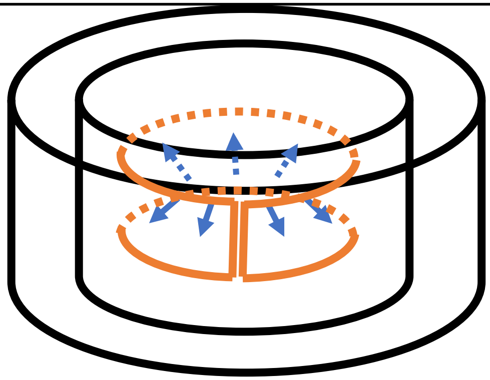
leading order $O(\omega^2)$ volume effect angular dependence



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

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

Different Geometries

		$\hat{\boldsymbol{n}}'$		
		$\hat{\boldsymbol{e}}_z$	$\hat{\boldsymbol{e}}_\phi$	$\hat{\boldsymbol{e}}_\rho$
$\boldsymbol{B}$	$\hat{\boldsymbol{e}}_z$ **(Sol)**		 BASE	
	$\hat{\boldsymbol{e}}_\phi$ **(Toro)**	 ABRA		

Different Geometries

- **Leading Orders**

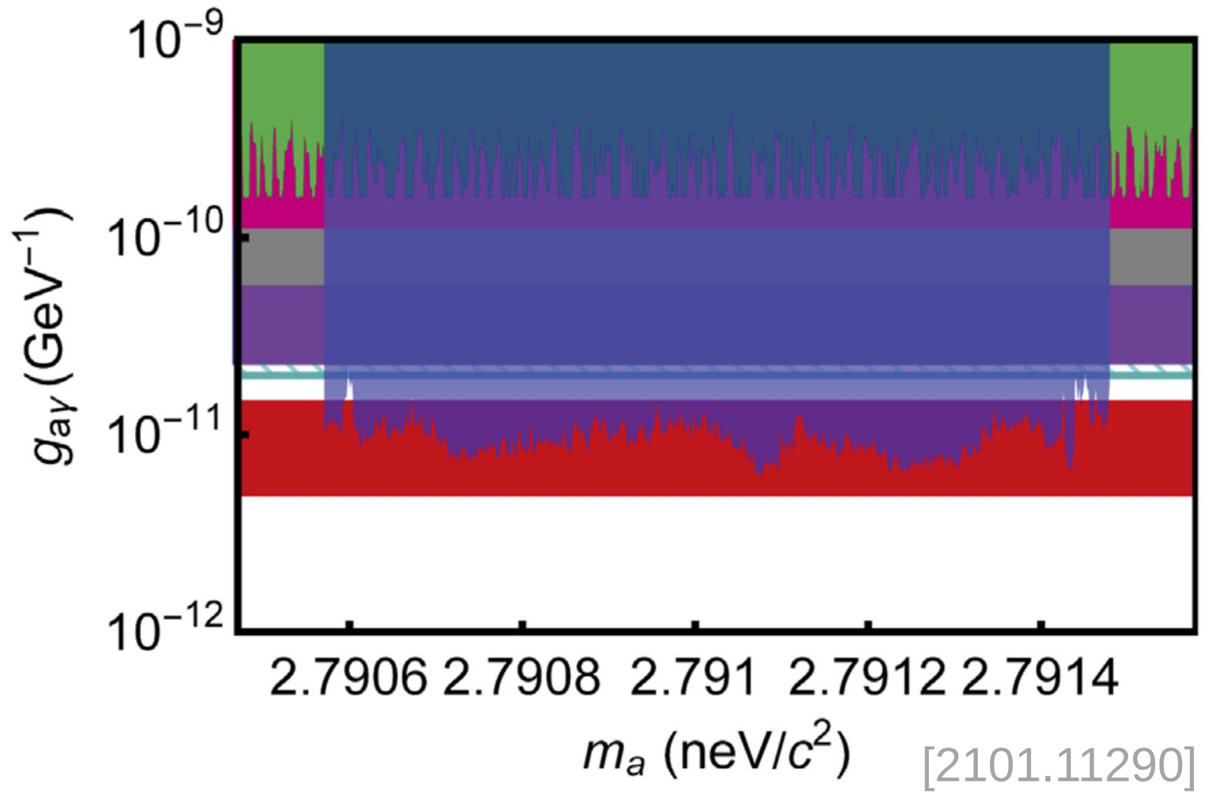
[Domcke, Carcia-Cely, **SML**, Rodd ’23]

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

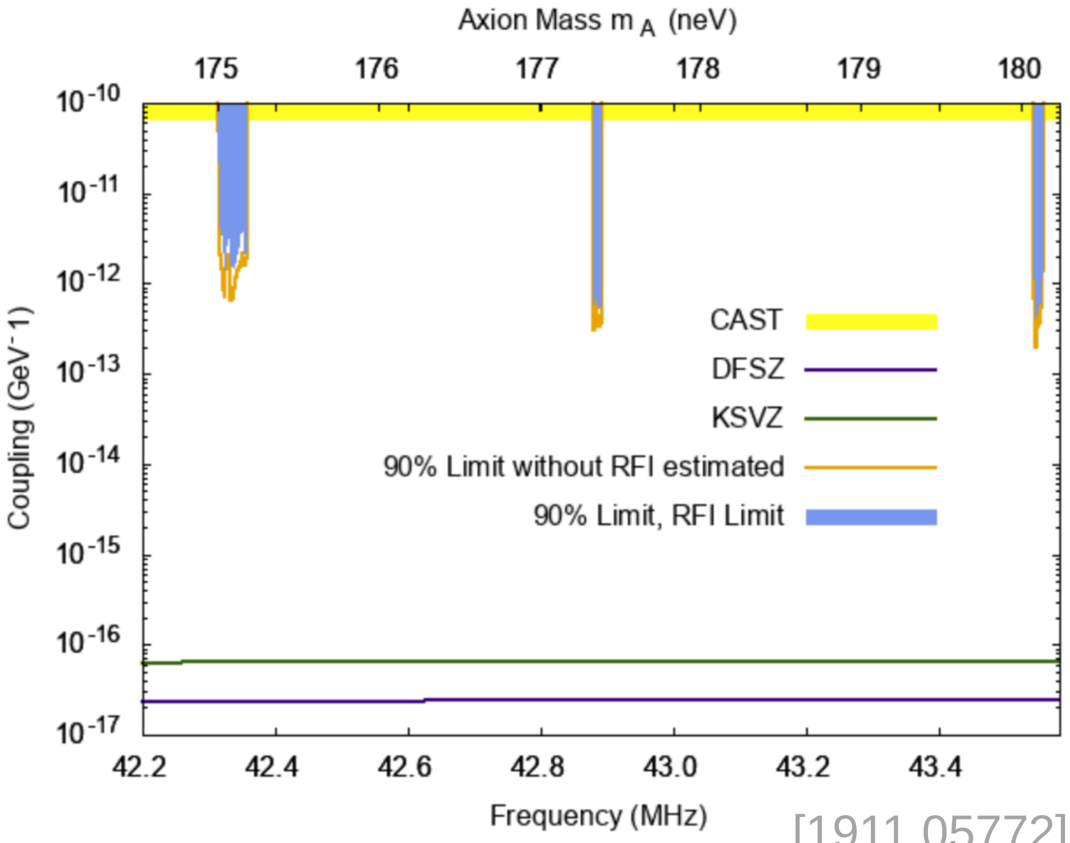
Result: Reinterpreting Axion Detectors

- **BASE**



[2101.11290]

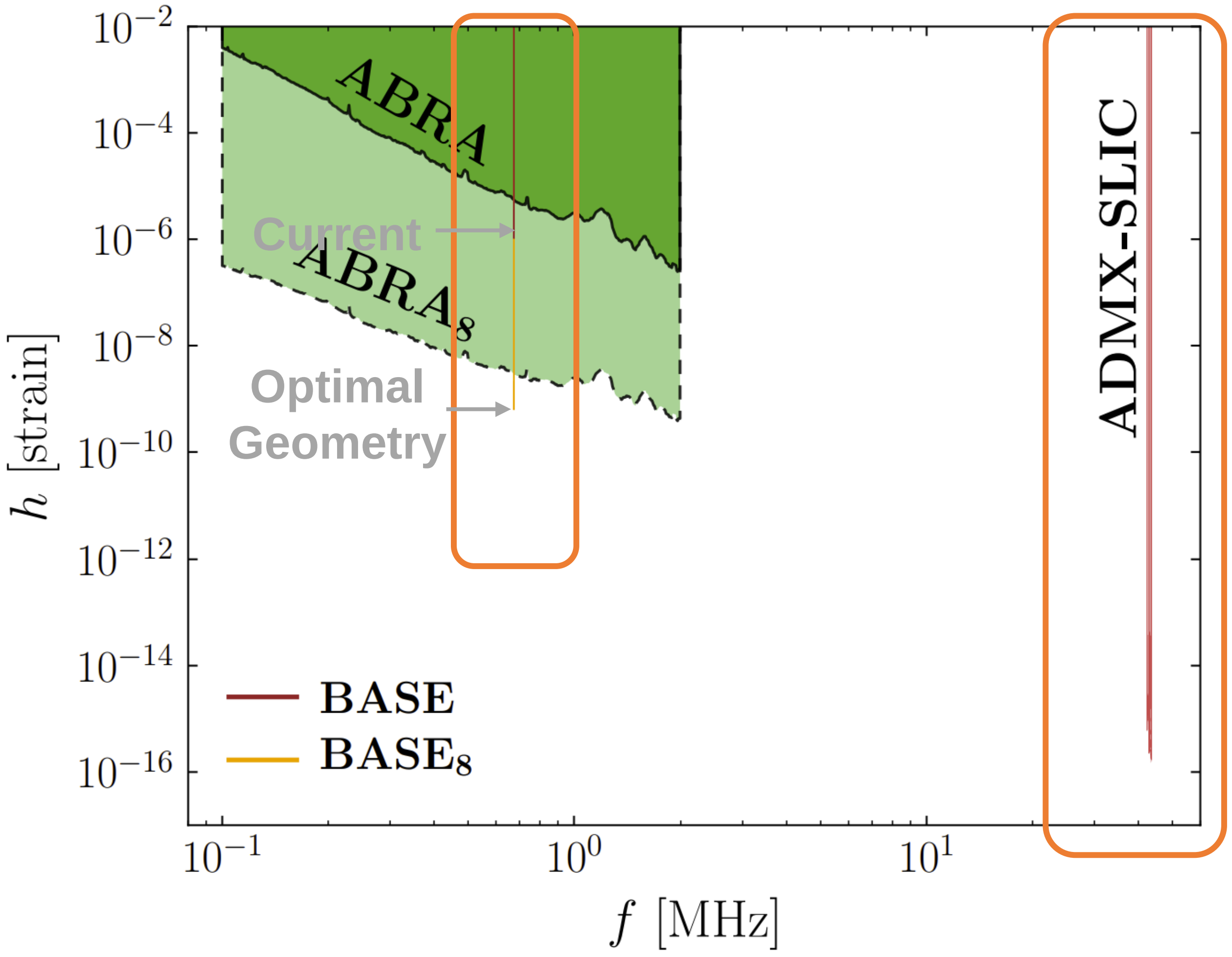
- **ADMX-SLIC**



[1911.05772]

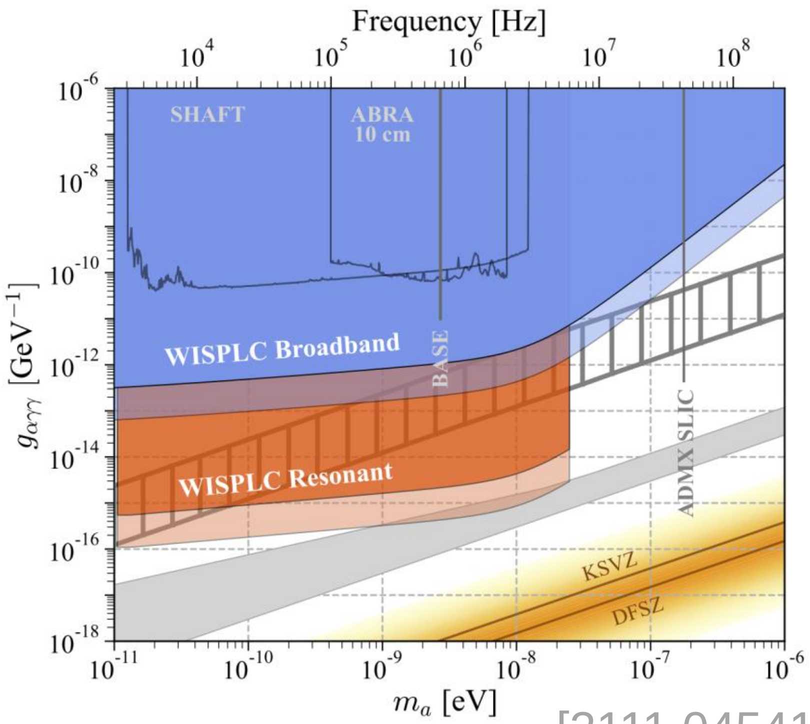
Result: Reinterpreting Axion Detectors

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



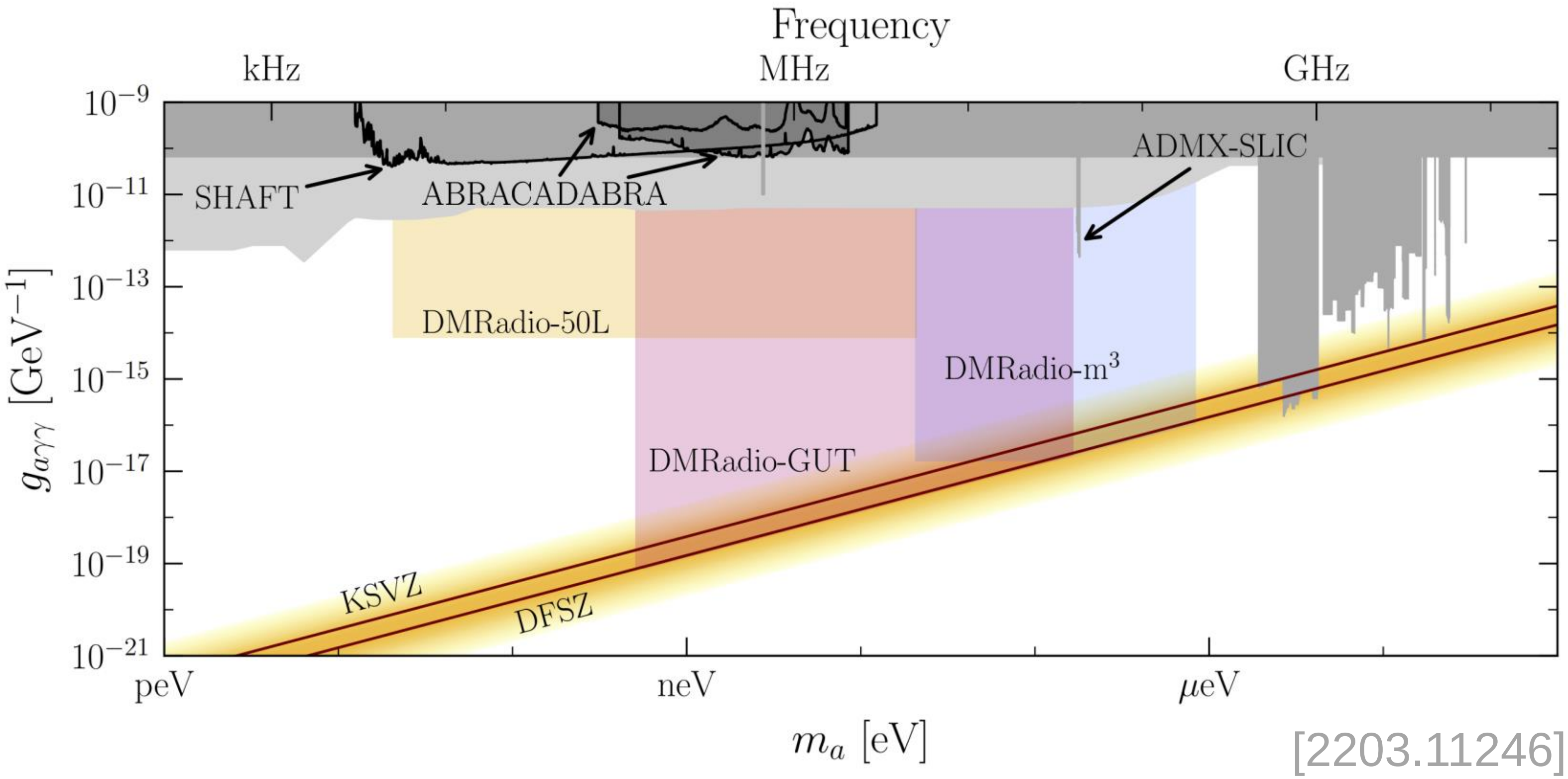
Future Prospects

- **WISPLC**



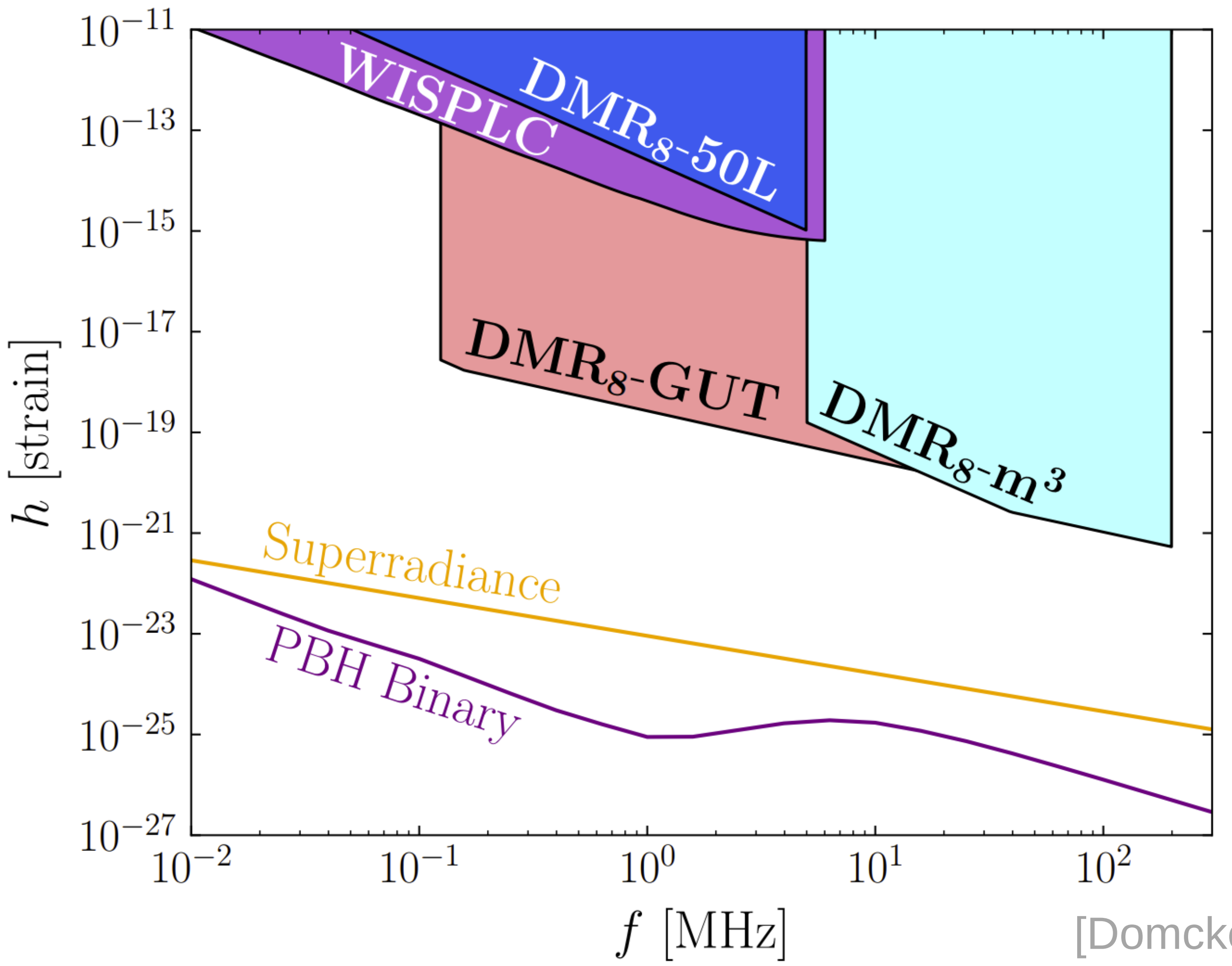
[2111.04541]

- **DMRadio Proposal**



[2203.11246]

Future Prospects



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

Conclusion

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

Conclusion

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

- We can use and reinterpret the results of axion haloscope experiments to observe/constrain high-frequency GWs (above 100 kHz).
  - Current: ADMX-SLIC, BASE, ABRACADABRA, …
  - Future: DMRadio, WISPLC, …

Conclusion

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

- We can use and reinterpret the results of axion haloscope experiments to observe/constrain high-frequency GWs (above 100 kHz).
  - Current: ADMX-SLIC, BASE, ABRACADABRA, …
  - Future: DMRadio, WISPLC, …

- Symmetry is always good for theory, but sometimes bad for experiments.
  - Need to break cylindrical symmetry

Back Ups

Axion/Scalar Electrodynamics

$$\partial_\nu F_\varphi^{\mu\nu} = \partial_\nu (g_{\varphi\gamma\gamma}\varphi F_0^{\nu\mu}) = g_{\varphi\gamma\gamma}(\partial_\nu \varphi) F_0^{\nu\mu} - g_{\varphi\gamma\gamma}\varphi j^\mu,$$

$$\partial_\nu F_a^{\mu\nu} = \partial_\nu (g_{a\gamma\gamma} a \tilde{F}_0^{\nu\mu}) = g_{a\gamma\gamma}(\partial_\nu a) \tilde{F}_0^{\nu\mu},$$

$$\nabla \cdot \mathbf{E}_\varphi = -g_{\varphi\gamma\gamma}\mathbf{E} \cdot \nabla\varphi - g_{\varphi\gamma\gamma}\varphi\rho,$$

$$\nabla \cdot \mathbf{E}_a = -g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a,$$

$$\nabla \times \mathbf{B}_\varphi = \partial_t \mathbf{E}_\varphi - g_{\varphi\gamma\gamma}(\nabla\varphi) \times \mathbf{B} + g_{\varphi\gamma\gamma}(\partial_t\varphi)\mathbf{E} - g_{\varphi\gamma\gamma}\varphi\mathbf{j},$$

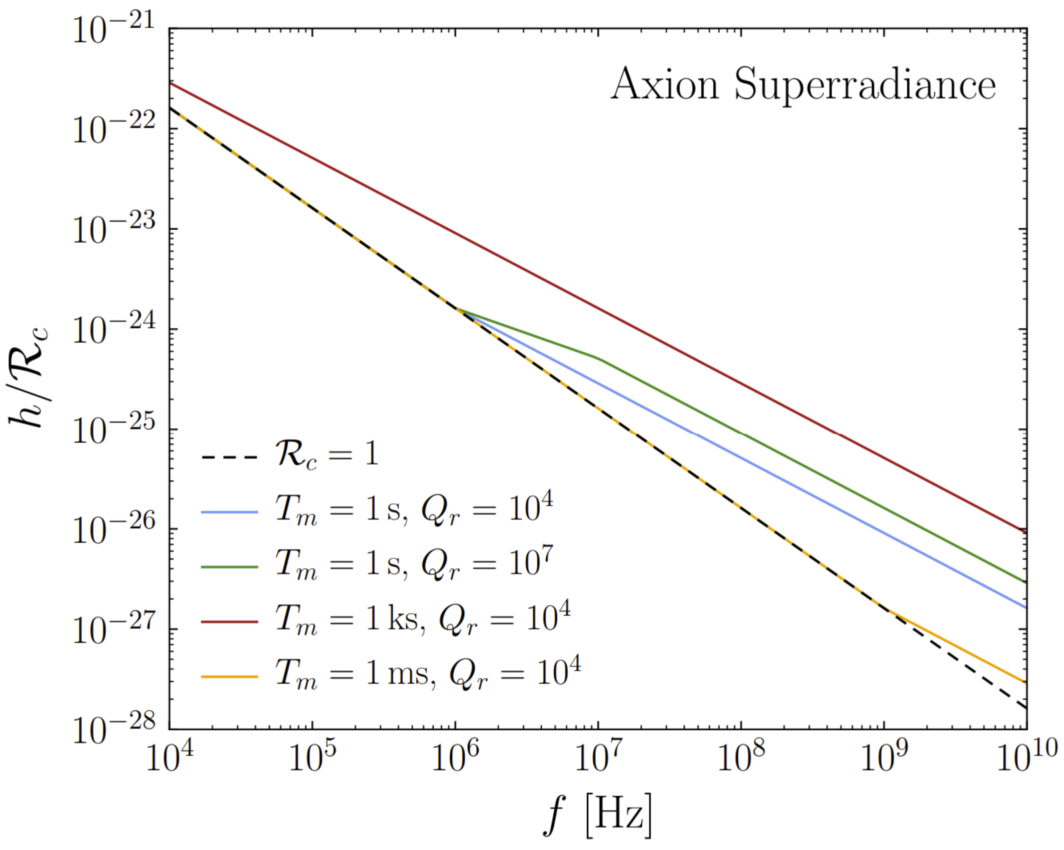
$$\nabla \times \mathbf{B}_a = \partial_t \mathbf{E}_a + g_{a\gamma\gamma}(\nabla a) \times \mathbf{E} + g_{a\gamma\gamma}(\partial_t a)\mathbf{B}.$$

Axion/Scalar Electrodynamics

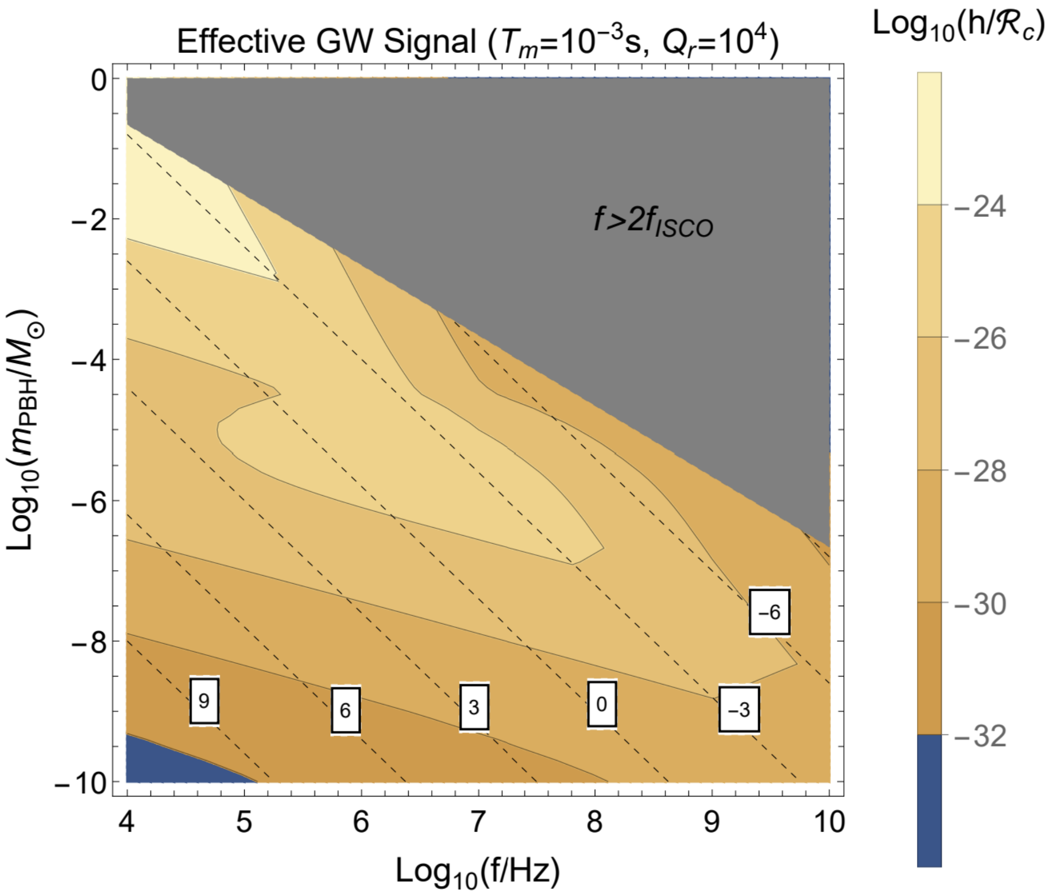
	Solenoid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_z$	Toroid: $\mathbf{B}_0 \propto \hat{\mathbf{e}}_\phi$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_z$	scalar $\Phi_a \equiv 0,\ \Phi_\varphi \neq 0$	axion (ABRA) $\Phi_a \neq 0,\ \Phi_\varphi \equiv 0$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_\phi$	axion (BASE) $\Phi_a \neq 0,\ \Phi_\varphi = 0$	scalar $\Phi_a \equiv 0,\ \Phi_\varphi \neq 0$
$\hat{\mathbf{n}}' \propto \hat{\mathbf{e}}_\rho$	scalar $\Phi_a \equiv 0,\ \Phi_\varphi = 0$	axion $\Phi_a = 0,\ \Phi_\varphi = 0$

Benchmark Signals

- Superradiance



- PBH



Benchmark Signals

$$\text{(B1)} \quad T_h = \tau_h = 1\ \text{s},\ Q_h = f_* \tau_h$$

$$\text{(B2)} \quad T_h \gg T_m,\ Q_h = 10^{10}$$

	Q_r	T_m	f_*	$\mathcal{R}_c^{(\mathrm{B1})}$	$\mathcal{R}_c^{(\mathrm{B2})}$
ADMX SLIC [16]	3×10^3	320 s[15]	50 MHz	1.6	0.1
BASE [17]	4×10^4	1 min	0.7 MHz	3.0	0.39
WISPLC [19]	10^4	1 min	(30 kHz, 5 MHz)	(6.7, 1.9)	(0.86, 0.24)
DMRadio [21]	2×10^7	(8 mins, 60 ns)	(100 kHz, 30 MHz)	(787, 1)	(0.18, 1)

Coherence Ratio Factor

- Persistent signal and a long interrogation time

$$\mathcal{R}_c = \sqrt{\frac{Q_a}{Q_h}} \left(\frac{\max[Q_h,\, Q_r]}{\max[Q_a,\, Q_r]} \right)^{1/4} \left(\frac{1}{\max[1,\, \min[Q_a,\, Q_r]/Q_h]} \right)^{1/4}$$

$$= \begin{cases} (Q_a/Q_h)^{1/2} & Q_a < Q_h < Q_r, \\ (Q_a^2/Q_r Q_h)^{1/4} & Q_a < Q_r < Q_h, \\ (Q_a/Q_h)^{1/4} & \text{otherwise.} \end{cases}$$

- Transient signal of equal duration and coherence time

$$\mathcal{R}_c = \sqrt{\frac{\tau_a}{T_{m,h}} \frac{\tau_r}{\min[T_{m,h},\, \tau_r]}} \left(\frac{T_{m,a}}{\max[\tau_a,\, \tau_r]} \right)^{1/4}$$

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.