

# Effects of dark dipole radiation on eccentric supermassive black hole binary inspirals

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**01**

## **Motivation and theoretical background**

Astrophysical questions and the effective-field-theory picture

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**02**

## **Dark dipole radiation and SMBHB evolution**

Conservative dynamics, radiation fluxes, and merger times

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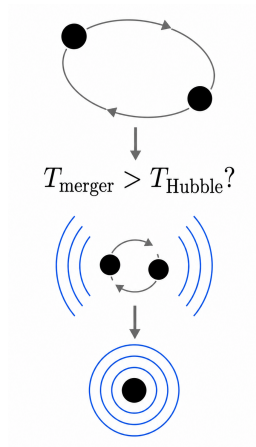
**03**

## **Probing extra bosonic fields with PTA data**

SGWB modeling and Bayesian constraints

# Could new physics bridge the final parsec?

- ▶ Near **1 pc**, stellar hardening may stall before **GW emission** dominates.
- ▶ Beyond environmental hardening, could an **extra loss channel** help bridge this gap?
- ▶ 3 body scatter? Gas/DM dynamic friction?....



Can intrinsic new physics affect both final-parsec evolution and the PTA spectrum?

# Hidden-sector fields can modify the binary itself

Light fields provide an intrinsic channel beyond environmental hardening.

## Scalar charge $q_{I\phi}$

- ▶ A scalar mediator or modified-gravity response can appear as an effective scalar charge.

## Vector charge $q_{IA}$

- ▶ A hidden U(1), dark photon, or compact charged cloud can act as a vector source.

## No-hair caveat

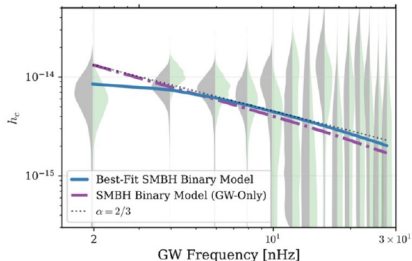
- ▶ Stable scalar/Proca hair is not generic, but an ultralight Proca charge will discharge much more slowly than the binary evolves.

## Effective description

- ▶ Replace each compact object by  $\{m_I, q_{I\phi}, q_{IA}\}$ .
- ▶ Treat the charges as fixed and only give a phenomenological description of charge.

# PTA data and SGWB spectra

- ▶ PTA data suggest a **low-frequency departure** from the circular, GW-driven power law line.
- ▶ This may reflect **eccentricity** or an **independent dissipation channel**.
- ▶ We took both effects into account.



Ref: 2306.16220

1. Can dipole radiation accelerate **final-parsec inspirals**?
2. Does it leave a measurable **PTA-SGWB signature**?

# Scalar and vector charges enter the effective action

## Point-particle sector

$$S_{\text{pp}} = \sum_{I=1,2} \left[ \int (-m_I + q_{I\phi}\phi) ds_I + q_{IA} \int A_a dX_I^a \right]$$

## Gravity + scalar + Proca fields

$$S_{\text{field}} = \int d^4x \sqrt{-g} \left[ -\frac{R}{16\pi} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}F_{ab}F^{ab} + \frac{1}{2}m_A^2 A_a A^a \right]$$

$q_{I\phi}$  and  $q_{IA}$  encode the compact object's low-energy scalar and vector charge.

# From sourced waves to dipole fluxes

$$\begin{aligned}(\square - m_\phi^2)\phi &= -n(t, \mathbf{x}) = -\sum_I q_{I\phi} \delta^3(\mathbf{x} - \mathbf{X}_I(t)) \\(\square - m_A^2)A^a &= J^a(t, \mathbf{x}) = \sum_I q_{IA} v_I^a \delta^3(\mathbf{x} - \mathbf{X}_I(t))\end{aligned}$$

**Periodic source  $\Rightarrow$  on-shell far field**

$$\Omega_n = n\Omega, \quad k_n^2 = \Omega_n^2 - m^2, \quad \Rightarrow \phi, A^\mu$$



**Scalar/vector EMTs  $\Rightarrow$  time-averaged radiation fluxes**

$$\begin{aligned}T_{ab}^{(\phi)}, T_{ab}^{(A)} &\Rightarrow \\P \text{ (energy)}, \quad \mathcal{F}_i \text{ (linear momentum)}, \quad \tau_i \text{ (angular momentum)}\end{aligned}$$



**Dipole limit  $\Rightarrow$  leading radiative order**

$$\begin{aligned}k_n a \ll 1, \quad e^{-i\mathbf{k}_n \cdot \mathbf{x}} &= 1 - i\mathbf{k}_n \cdot \mathbf{x} + \dots \\ \mathcal{F}_i^{\text{dip}} &= 0, \quad \text{keep } P_{\text{dip}} \text{ and } \tau_{\text{dip}}\end{aligned}$$

# Dipole fluxes add a second loss channel

## Energy flux

$$P_{\text{dip}} = \frac{(\gamma\mu a)^2 \Omega^4}{6\pi} \sum_{n \geq \lceil n_0 \rceil} n^2 \left[ (J'_n)^2 + \frac{1-e^2}{e^2} J_n^2 \right] \Upsilon_n, \quad \gamma = \frac{q_1}{M_1} - \frac{q_2}{M_2}$$

## Angular-momentum flux

$$\tau_{\text{dip}} = \frac{(\gamma\mu a)^2 \Omega^3}{6\pi} \sum_{n \geq \lceil n_0 \rceil} 2n \sqrt{\frac{1-e^2}{e^2}} J'_n J_n \Upsilon_n \mathbf{e}_Z.$$

$P_{\text{dip}}$  and  $\tau_{\text{dip}}$  supply the extra energy and angular-momentum loss.

# Eccentricity lowers the dipole-radiation threshold

$$n_0 \equiv \frac{m}{\Omega}, \quad n \geq \lceil n_0 \rceil, \quad \Upsilon_n = \begin{cases} \left(1 - \frac{n_0^2}{n^2}\right)^{3/2}, & \text{scalar,} \\ \left(1 - \frac{n_0^2}{n^2}\right)^{1/2} \left(2 + \frac{n_0^2}{n^2}\right), & \text{vector.} \end{cases}$$

- **Circular:** only  $n = 1$  survives, so radiation requires  $\Omega \geq m$  and  $P_{\text{dip}}^{\text{circ}} = \Omega \tau_{\text{dip}}^{\text{circ}} = (\gamma \mu a)^2 \Omega^4 \Upsilon_{n=1} / (12\pi)$ .
- **Eccentric:** high- $n$  harmonics cross the threshold even for  $\Omega \ll m$ ; in the massless limit,  $P_{\text{dip}} \propto (1 + e^2/2)/(1 - e^2)^{5/2}$ .

Higher harmonics weaken the massive-field suppression and activate dipole losses earlier.

# Flux balance determines the orbit evolution

## Kepler orbit with $\widetilde{M}$

$$E = -\frac{\mu \widetilde{M}}{2a}, \quad L = \mu \sqrt{\widetilde{M} a (1 - e^2)}.$$

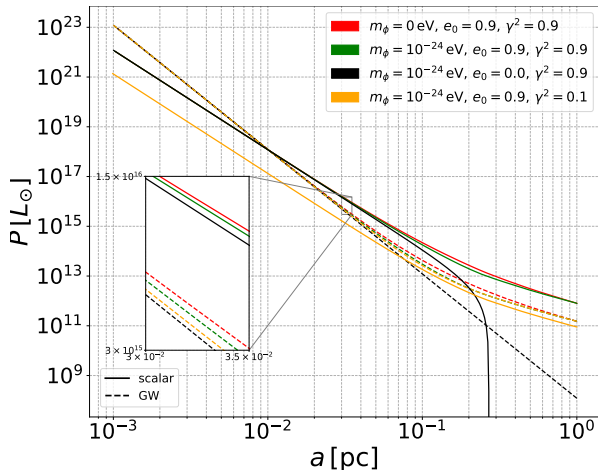
## Total radiation reaction

$$\dot{E} = -P, \quad \dot{L} = -\tau, \quad P = P_{\text{gw}} + P_{\text{dip}}, \quad \tau = \tau_{\text{gw}} + \tau_{\text{dip}}.$$

GW quadrupole (0PN) + dark dipole (−1PN)

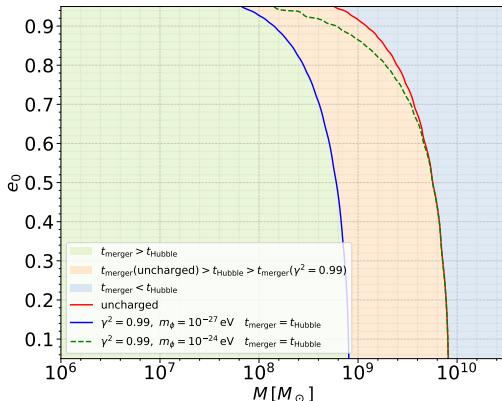
$$\begin{aligned} \dot{a} &= -\frac{2a^2}{\mu \widetilde{M}} P, & \dot{\Omega} &= -\frac{3}{2} \frac{\Omega}{a} \dot{a}, \\ \dot{e} &= -\frac{1 - e^2}{e} \frac{a}{\mu \widetilde{M}} \left( P - \frac{\tau \Omega}{\sqrt{1 - e^2}} \right). \end{aligned}$$

# Eccentricity amplifies and activates dipole losses



- Modes with  $n\Omega \geq m$  remain radiative even when  $\Omega < m$ .

# Dipole losses help, but do not close the final parsec



A large dipole strength expands the Hubble-time merger region, but low-mass binaries still require nearly maximal  $e_0$ .

# The SGWB integrates binaries over cosmic history

$$h_c^2(f; \boldsymbol{\theta}) \simeq \frac{4}{\pi f} \int dz dM dq \underbrace{\frac{d^3 n}{dz dM dq}}_{\text{population rate}} \underbrace{\frac{dE_{\text{gw}}}{df_s}}_{\text{single binary}},$$

$$f_s = (1 + z)f.$$

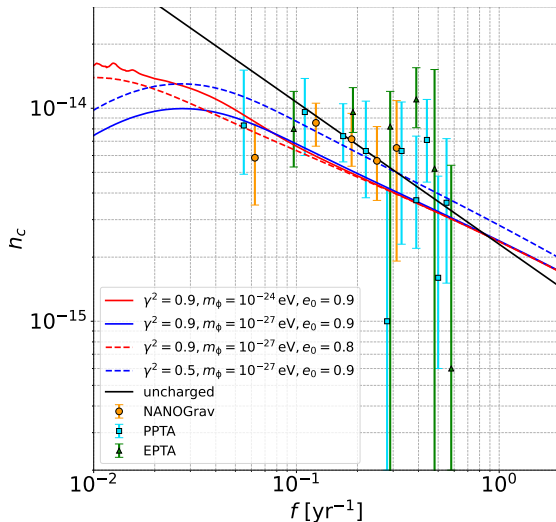
## Population physics

$$\begin{aligned} \frac{d^3 n}{dz dM dq} &= \frac{d^3 n_g}{dz dM_\star dq_\star} \frac{dM_\star}{dM} \frac{dq_\star}{dq}, \\ \frac{d^3 n_g}{dz dM_\star dq_\star} &\propto \frac{\Psi(M_\star, z')}{M_\star} \frac{\mathcal{P}_{\text{pair}}(M_\star, q_\star, z')}{T_{\text{g-g}}(M_\star, q_\star, z')} \frac{dt}{dz'}. \end{aligned}$$

- ▶ Galaxy mergers are set by  $\Psi$ ,  $\mathcal{P}_{\text{pair}}$  and  $T_{\text{g-g}}$ .
- ▶ Host-BH scaling gives  $(M, q)$ ;  $\psi_0$  fixes the overall rate.

# Field parameters reshape the low-frequency SGWB

- ▶  $\gamma^2 \uparrow$ : stronger suppression.
- ▶  $m_\phi \downarrow$ : suppression extends to lower  $f$ .
- ▶  $e_0 \uparrow$ : turnover shifts to higher  $f$ .



# PTA free spectra constrain the dark sector

## Model and priors

$$\Theta = \{\gamma^2, e_0, \psi_0\},$$

$$\gamma^2, e_0 \sim \mathcal{U}(0, 1),$$

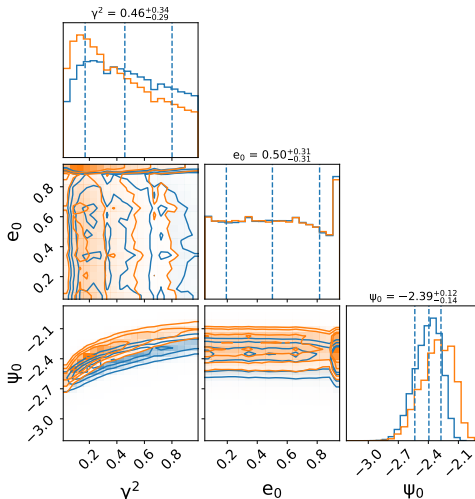
$$\psi_0 \sim \mathcal{N}(-2.56, 0.4).$$

## Likelihood

$$\ln \mathcal{L} = -\frac{1}{2} \sum_i r_i^2,$$

$$r_i = \frac{h_{c,i} - h_c^{\text{th}}(f_i)}{\sigma_i},$$

$$p(\Theta|d) \propto \mathcal{L} p(\Theta).$$



The posterior allows sizeable  $\gamma^2$ , while  $e_0$  remains weakly constrained.

# Summary

1. **Physical picture.** Dark charges generate  $-1\text{PN}$  dipole loss; eccentric harmonics activate massive radiation early.
2. **Analytic result.** General energy and angular-momentum fluxes for massive scalar/vector dipole radiation from eccentric Keplerian binaries.
3. **Final parsec.** Even at  $\gamma^2 = 0.99$ , dipole loss mainly enlarges the Hubble-time merger region; low masses still require  $e_0 \simeq 1$ .
4. **PTA fit.** The lowest five NANOGrav bins give  $\chi^2_{\min} = 1.189$ , versus 6.445 for the uncharged circular model.
5. **Posterior and reach.** At  $m = 10^{-27} \text{ eV}$ ,  $\gamma^2_{\text{med}} = 0.46$  (scalar) and 0.37 (vector);  $e_0$  remains weakly constrained. Current data are insensitive to  $m \lesssim 10^{-25} \text{ eV}$ , motivating future  $f \lesssim 1 \text{ nHz}$  measurements.

*Thanks*