Pulsar and neutron star probes of Dark Matter

Enrico Barausse (SISSA, Trieste, Italy)

35th Rencontres de Blois, October 21-25, 2024

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Istituto Nazionale di Fisica Nucleare
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MARIE CURIE ACTIONS
H2020-MSCA-RISE-2020
GRU 101007855
European Research Council
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ERC-2018-COG GRAMS 815673

Compact-object ~~Pulsar and neutron star~~ probes of Dark Matter

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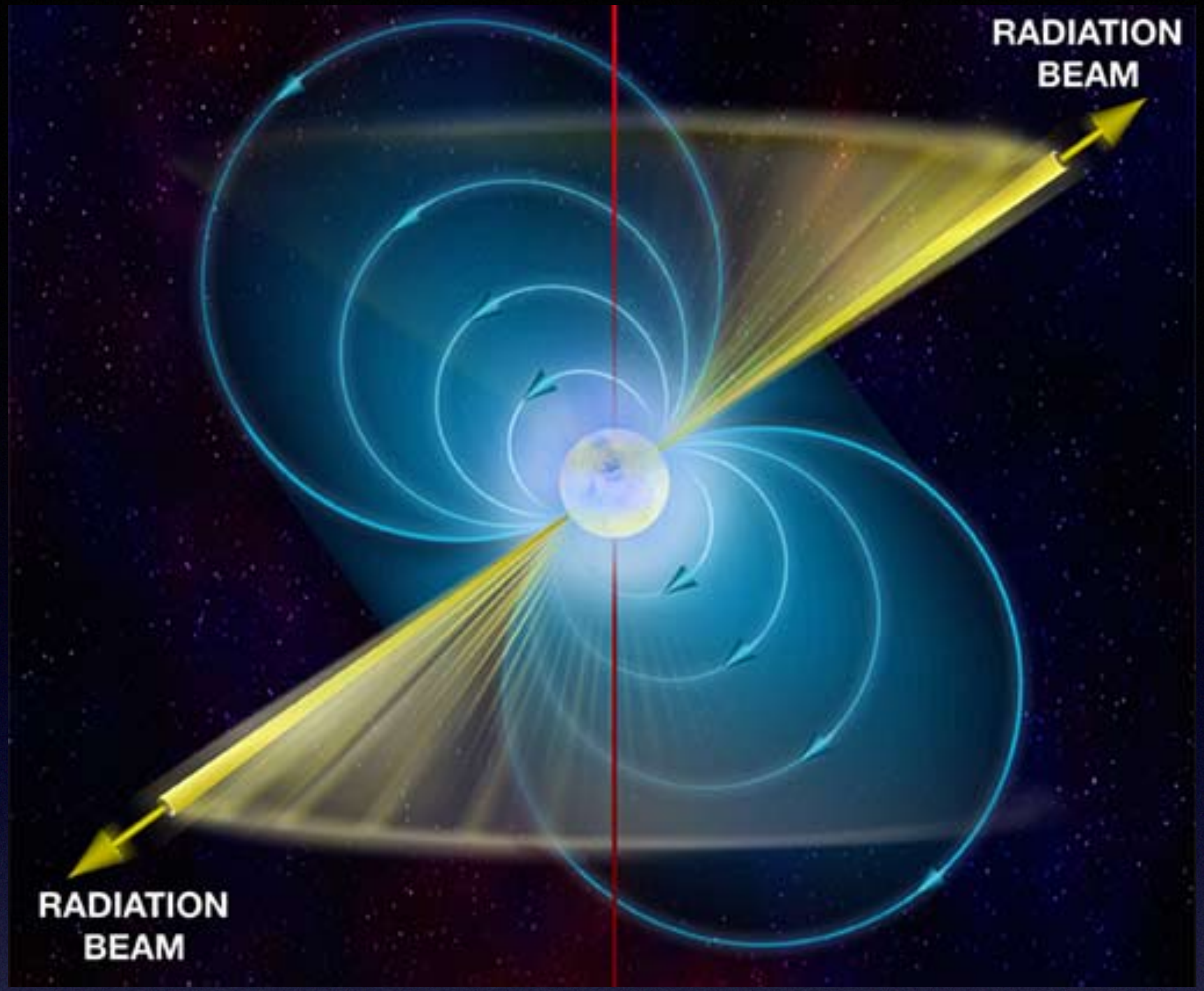
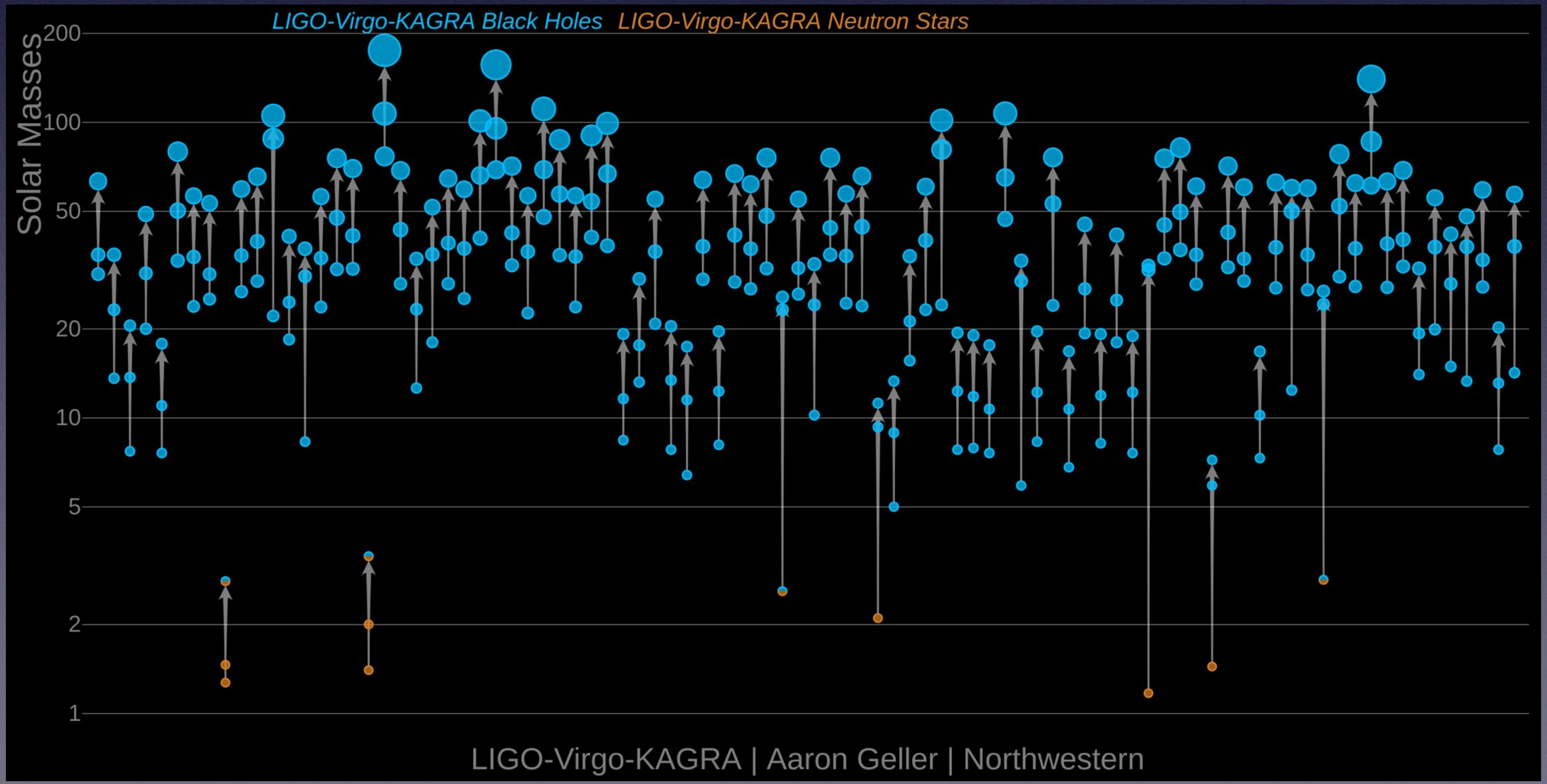
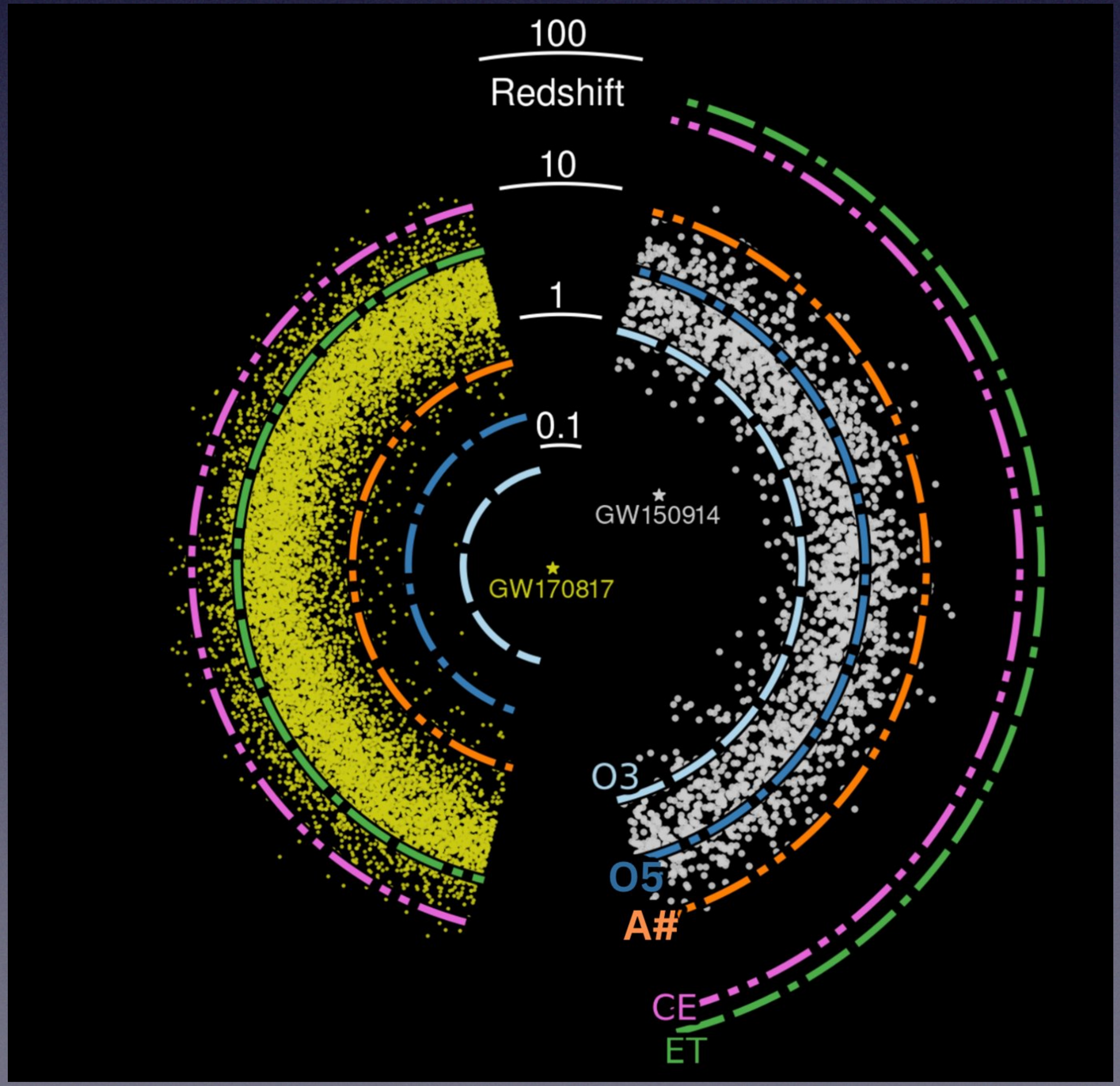
Why compact objects for DM?

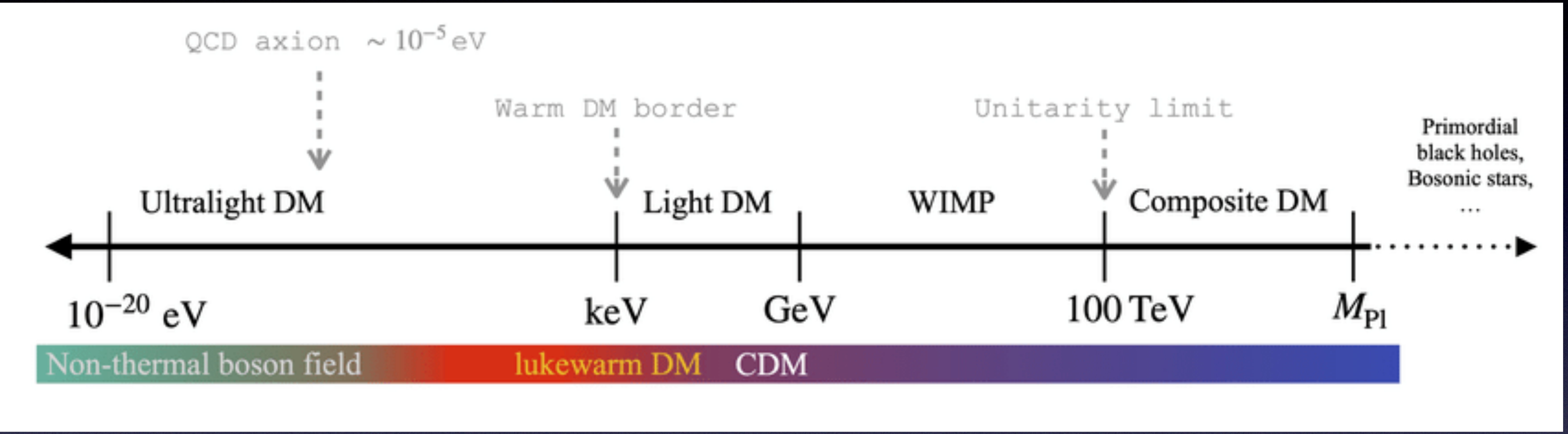
- Neutron stars: high densities & strong fields
- Millisecond pulsars: stable long term clocks
- Black holes: LVK/PTA detections, unstable with ultralight boson fields







Ultralight boson fields

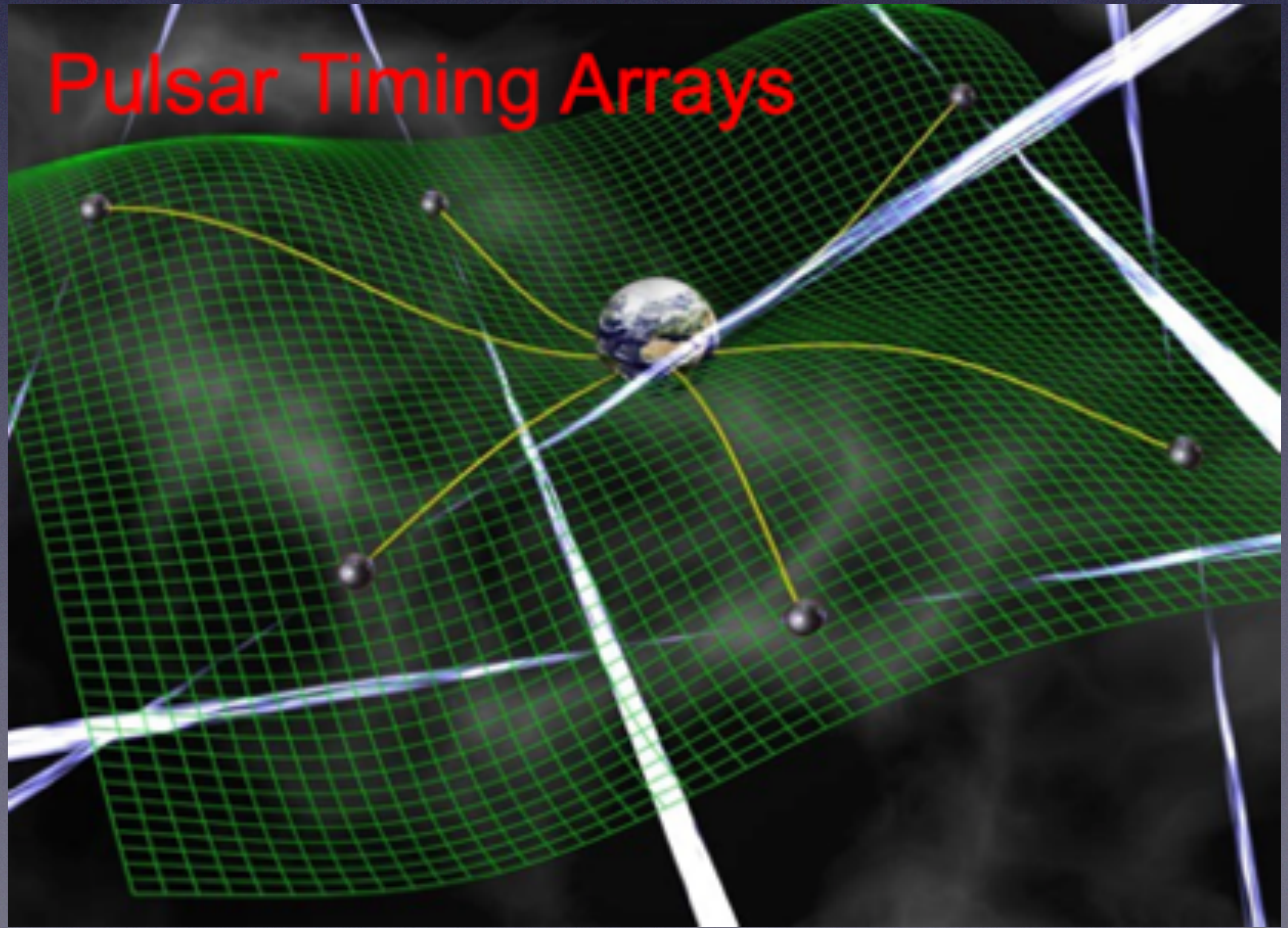


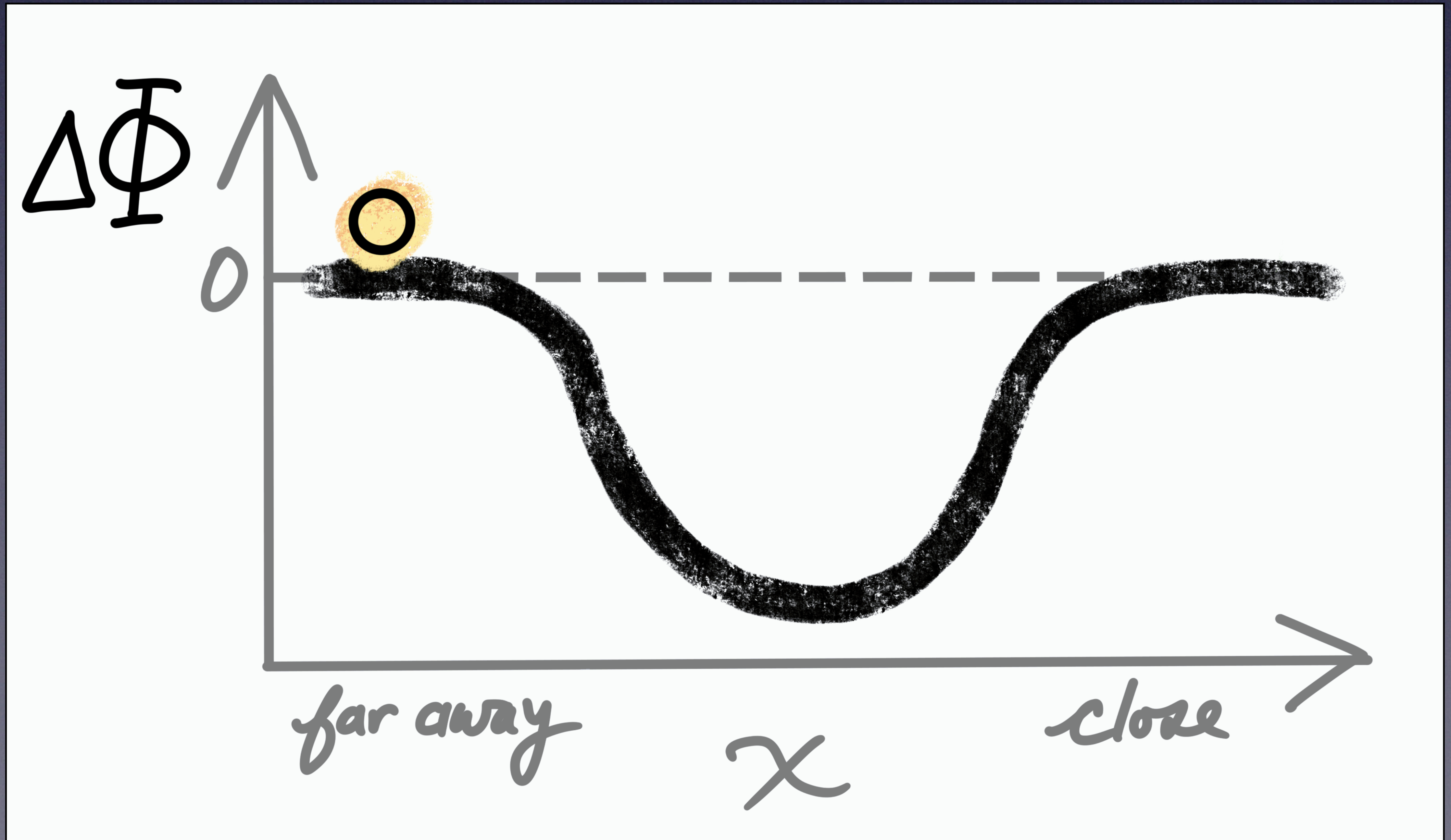
- Classical approximation (e.g. scalar field) inside galaxies due to high occupation numbers
- Recovers LCDM on large scales
- Solve small scale problems of CDM (e.g. cusp-core, satellite and too-big-to-fail problems) if mass is ~1.e-22 eV

The Khmelnitsky-Rubakov effect (2013)

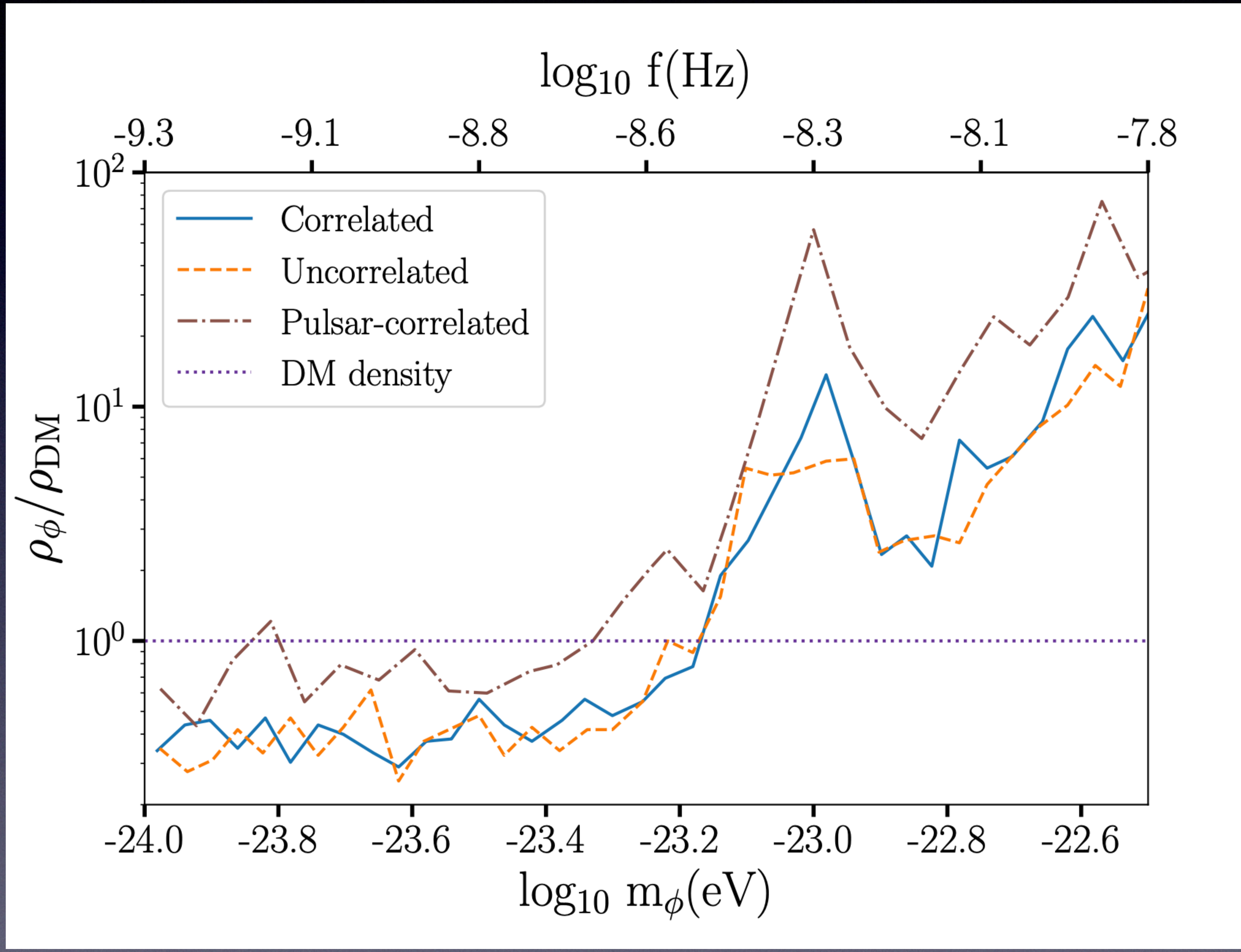
$$\Box \phi = m^2\phi \Rightarrow \phi \approx \frac{\sqrt{\rho}}{m M_p} \exp[i(mt + \gamma(\boldsymbol{x}))]$$

- Boson field with mass m oscillates on timescale 1/m within the Galaxy
- $\nabla^2 U = 4\pi G \rho_\phi$: Newtonian potential also oscillates
- Photons redshifted/blueshifted (integrated Sachs-Wolfe effect)
- 1/m ~ yr~1/nHz for m=1e-22 eV: detectable by PTAs





EPTA constraints on ultralight DM



Smarra+EB+ (EPTA) PRL 131, 171001 (2023)

$$\ell_c \simeq \frac{2\pi}{m_\varphi v_\varphi} \sim 0.4\ \mathrm{kpc}\left(\frac{10^{-22}\ \mathrm{eV}}{m_\varphi}\right),$$

$$\delta t_{\rm DM} = \frac{\Psi_{\rm c}(\vec{x})}{2m_\phi}[\hat{\phi}_{\rm E}^2 \sin(2m_\phi + \gamma_{\rm E}) - \hat{\phi}_{\rm P}^2 \sin(2m_\phi + \gamma_{\rm P})],$$

- No coupling to matter (except through gravity)
- Need to model all other effects (including GW background)
- Ultralight DM cannot be 100% of DM below 1.e-23.2 eV
- Similar results from Nanograv

How about direct coupling to SM?

- Parametrize couplings to SM particles (weak equivalence principle violations)
- Changes to pulsar moment of inertia, $I(\varphi)$
- DM field oscillates, so moment of energia (and pulsar rotational velocity) oscillate

$$\omega = S/I(\varphi)$$

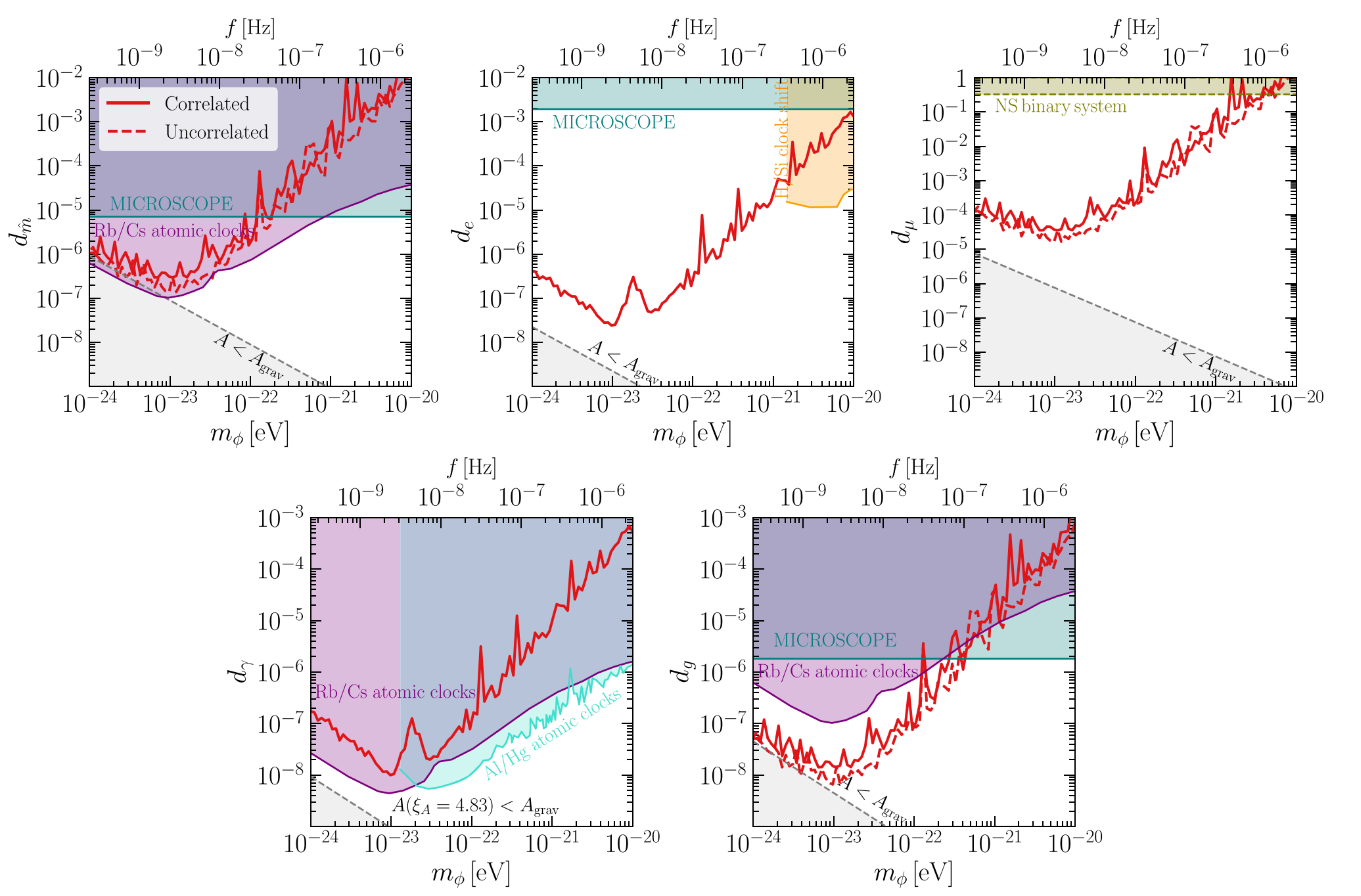
- Coupling affects atomic clocks used to time pulsars

$$\mathcal{L} \supset \frac{\varphi}{\Lambda}\left[\frac{d_\gamma}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum_{f=e,\mu} d_f m_f \bar{f} f - \sum_{q=u,d}(d_q + \gamma_q d_g) m_q \bar{q} q\right]$$

$$\Lambda = M_{\rm Pl}/\sqrt{4\pi}$$

Kaplan et al 2022

Nanograv constraints (2023)



A universal (conformal) coupling to SM?

- Write the simplest scalar tensor theory:

$$S = M_{\rm P}^2 \int \mathrm{d}^4x \sqrt{-g} \left(\frac{R}{2} - g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi \right) + S_m[\psi_m, \tilde{g}_{\mu\nu}] \qquad \tilde{g}_{\mu\nu} = A^2(\varphi) g_{\mu\nu}$$

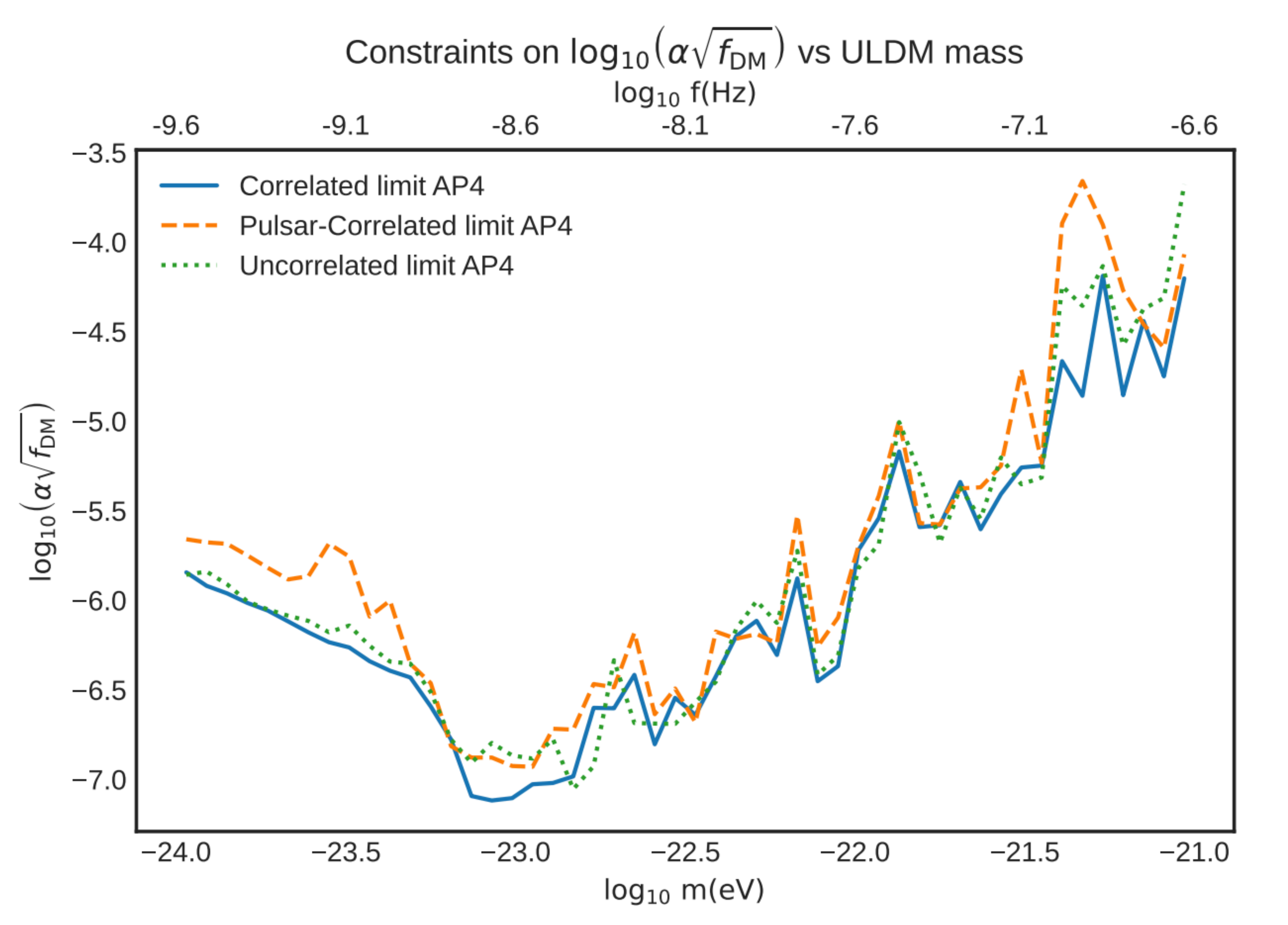
$$S = M_{\rm P}^2 \int \mathrm{d}^4x \sqrt{-\tilde{g}} A^{-2}(\varphi) \left[\frac{\tilde{R}}{2} - (1 - 3\alpha^2(\varphi))\tilde{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi \right] + S_m[\psi_m, \tilde{g}_{\mu\nu}] \qquad \alpha(\varphi) = A'(\varphi)/A(\varphi)$$

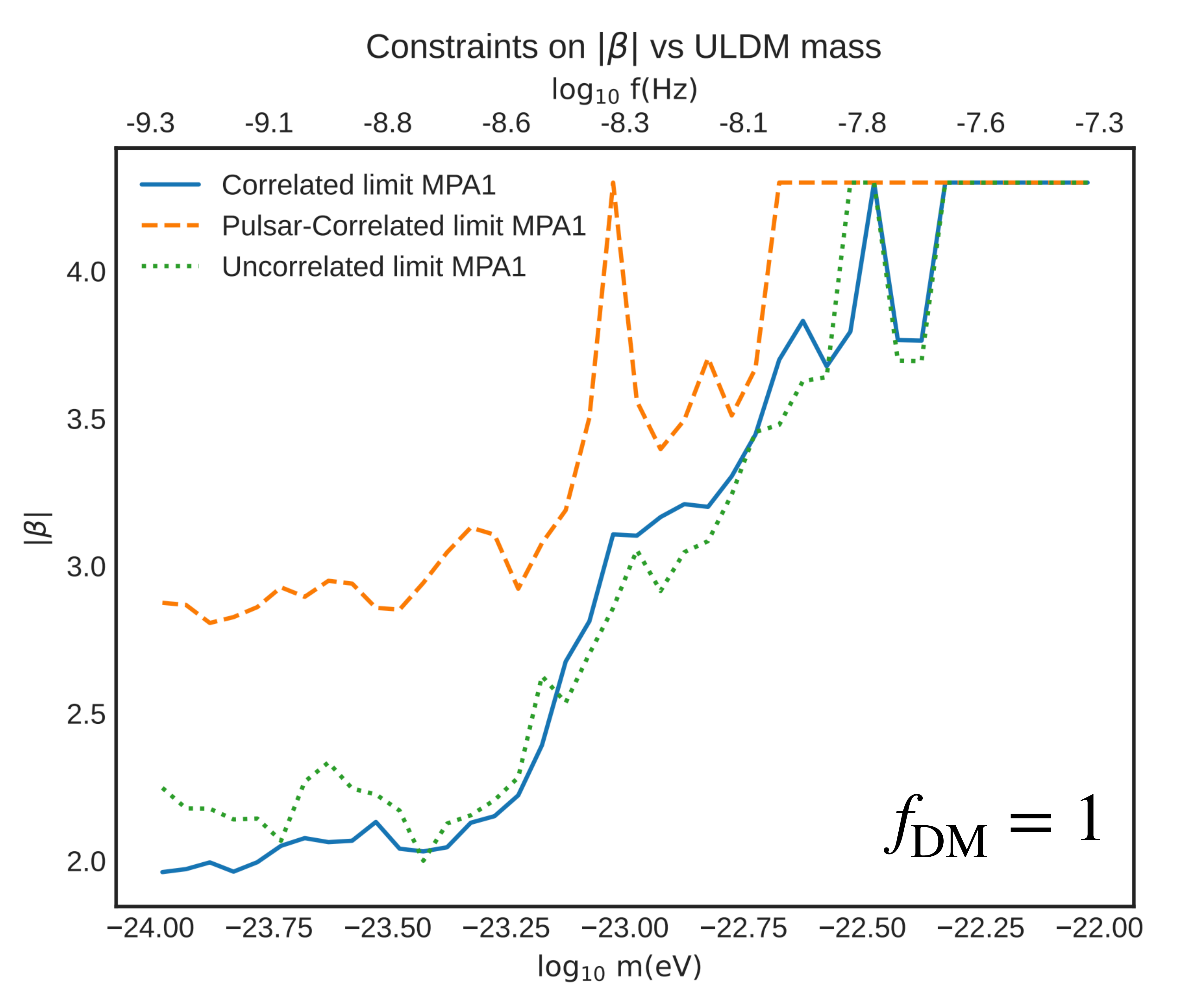
- Brans-Dicke for $A = \exp(\alpha\varphi)$, Damour-Esposito-Farèse (1993) for $A = \exp(\beta\varphi^2/2)$
- Test particles follow geodesics (weak equivalence principle), photon unaffected
- Planck mass and G renormalised by local scalar value: $M_{\rm NS} \approx M_{\rm b}\left[1 - kG(\varphi)M_{\rm b}/(R_{\rm NS}c^2)\right]$
- Motion of neutron stars does not follow geodesics (strong equivalence principle violation)

$$S = -\int m(\varphi) d\tau \Rightarrow u^\mu \nabla_\mu u^\alpha \sim \partial m/\partial\varphi$$

A universal (conformal) coupling to SM?

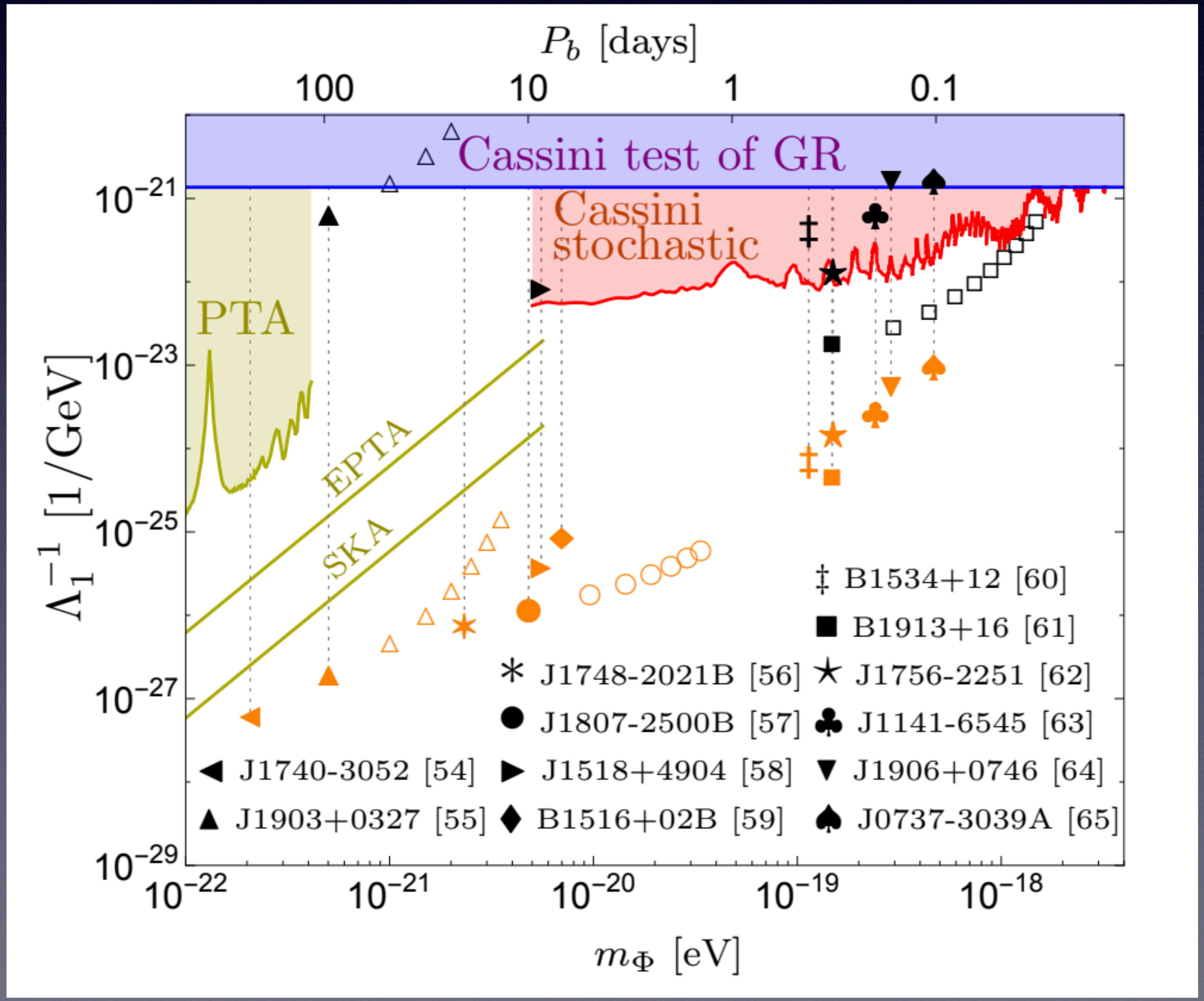
- Pulsar moment of inertia and rotational velocity change if local scalar field changes: $\omega = S/I(\varphi)$
- Scalar field variation can be caused by small mass (oscillations on timescale 1/m)
- Constraints with EPTA (Kuntz & EB 24, Smarra, Kuntz, EB+24): more stringent than Solar system/neutron star binaries



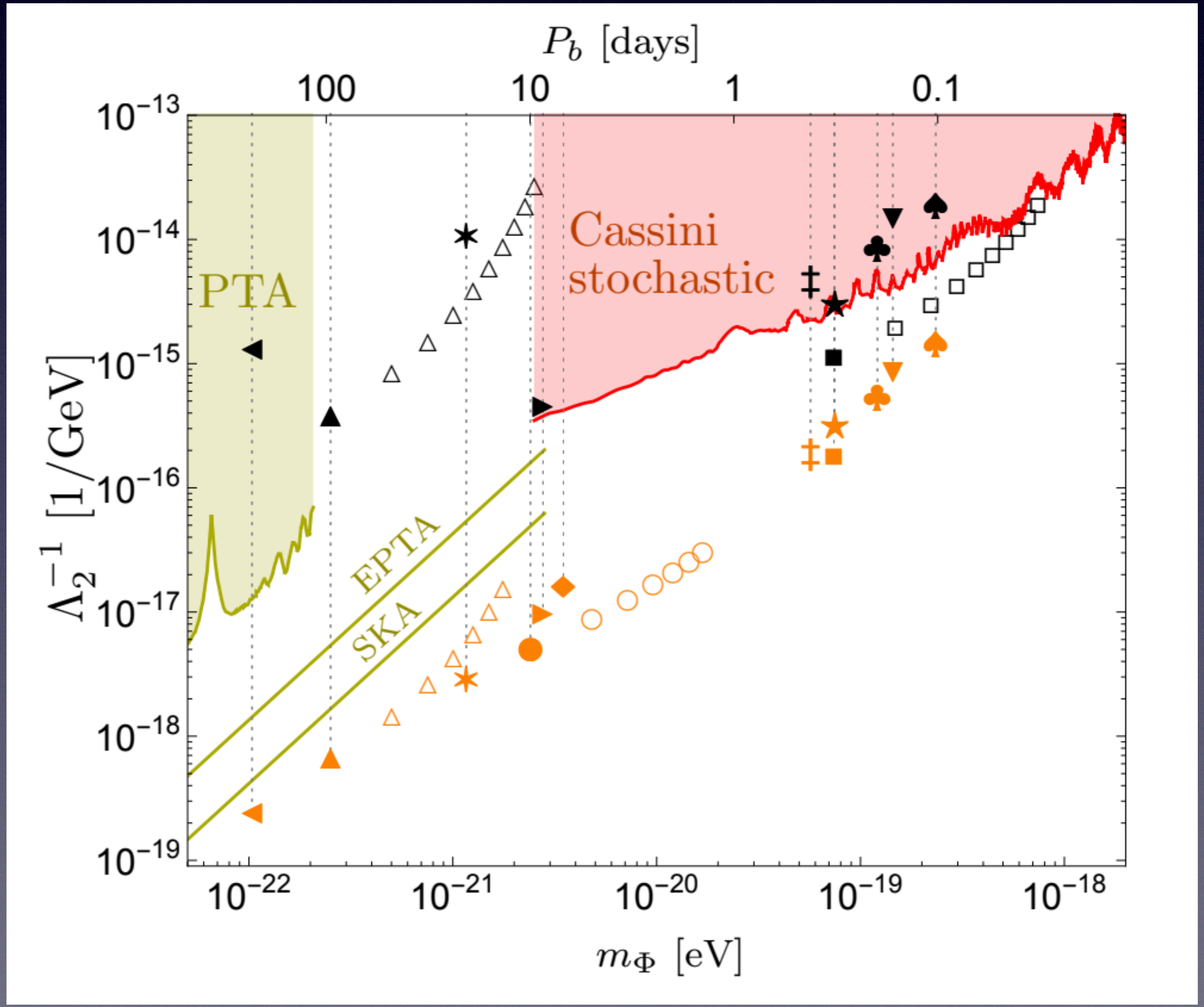


Pulsar binary resonances

(Conformal or gravitational) coupling of ultralight DM to binary pulsars can give resonances, if DM and binary frequencies are in integer/half integer ratio (Blas, Nacir Sibiryakov 2016)



$\Lambda_1^{-1} = \alpha / M_P$



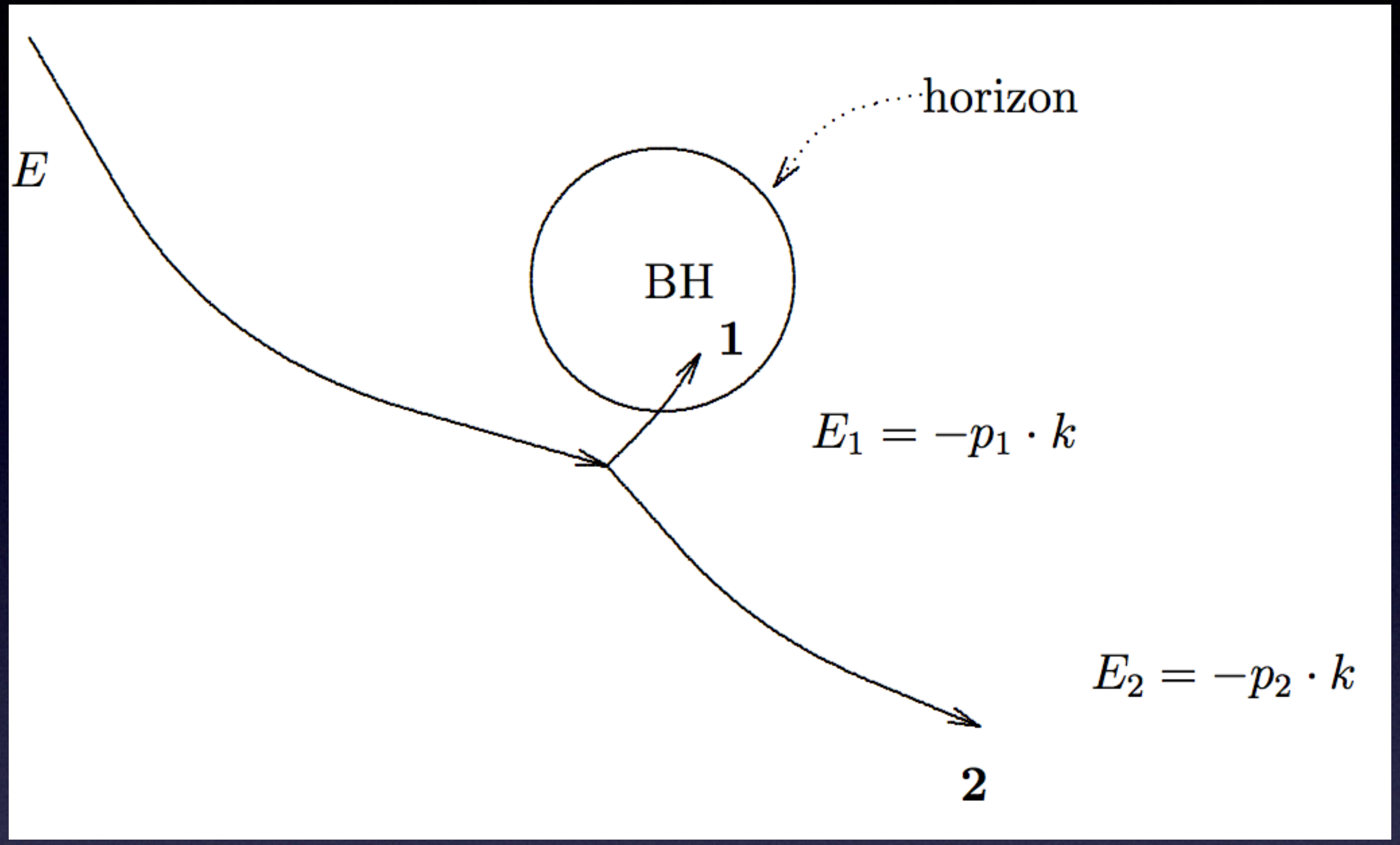
$\Lambda_2^{-1} = \sqrt{\beta} / M_P$

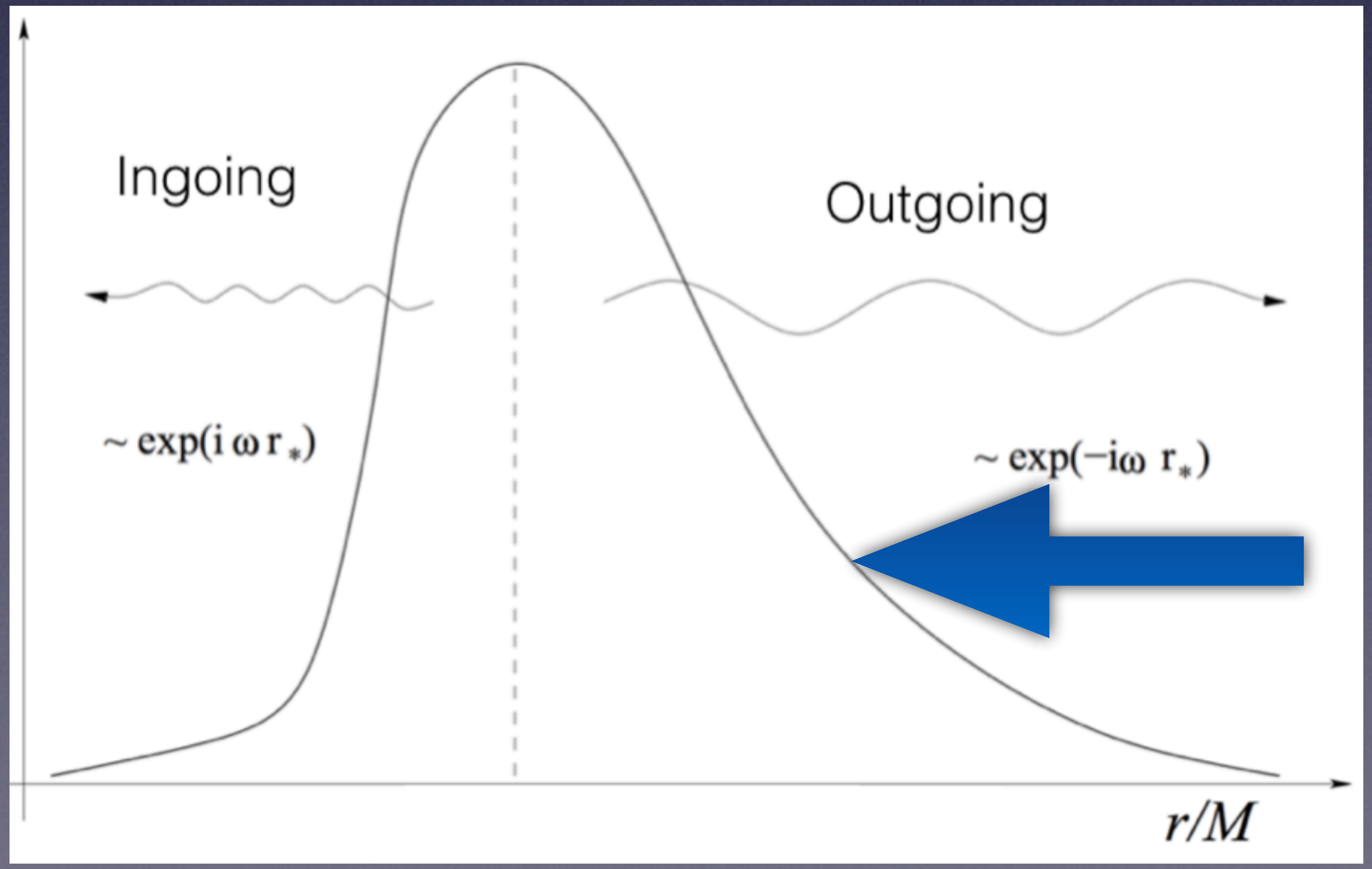
Black holes and light bosons

- Scalars form self-gravitating configurations if complex & massive (to avoid dispersion to infinity) and time dependent (to provide pressure): boson stars, oscillatons
- Around BHs, massive real (complex) scalars can form quasi-stationary (stationary) configurations: boson clouds or condensates, hairy BHs…

BH-boson condensates

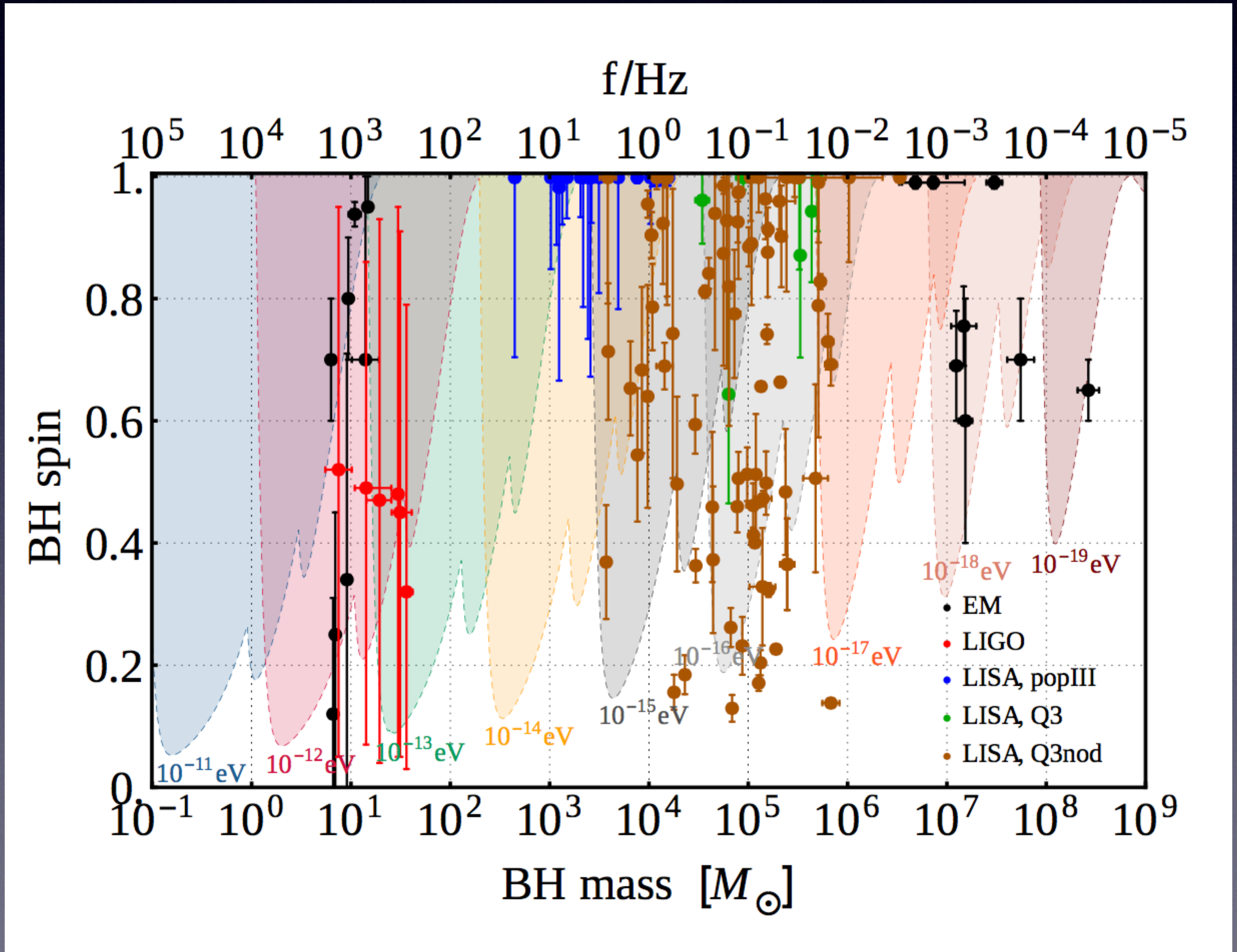
- Formation linked to superradiant instabilities/Penrose process: amplification of scattered waves with $\omega < m\Omega_H$
- BH with high enough spin and “mirror” are superradiance unstable (BH bomb; Zeldovich 71, Press & Teukolsky 72, Cardoso et al 04)
- In ergoregion, negative energy modes produced but confined (positive energy modes can escape)
- By energy conservation, more and more negative energy modes produced, which may cause instability according to boundary conditions (at infinity)





BH-boson condensates

Same instability of spinning BH + massive boson (mass acts as "mirror" and allows for bound states), but NOT for fermions, cf Damour, Deruelle & Ruffini 76

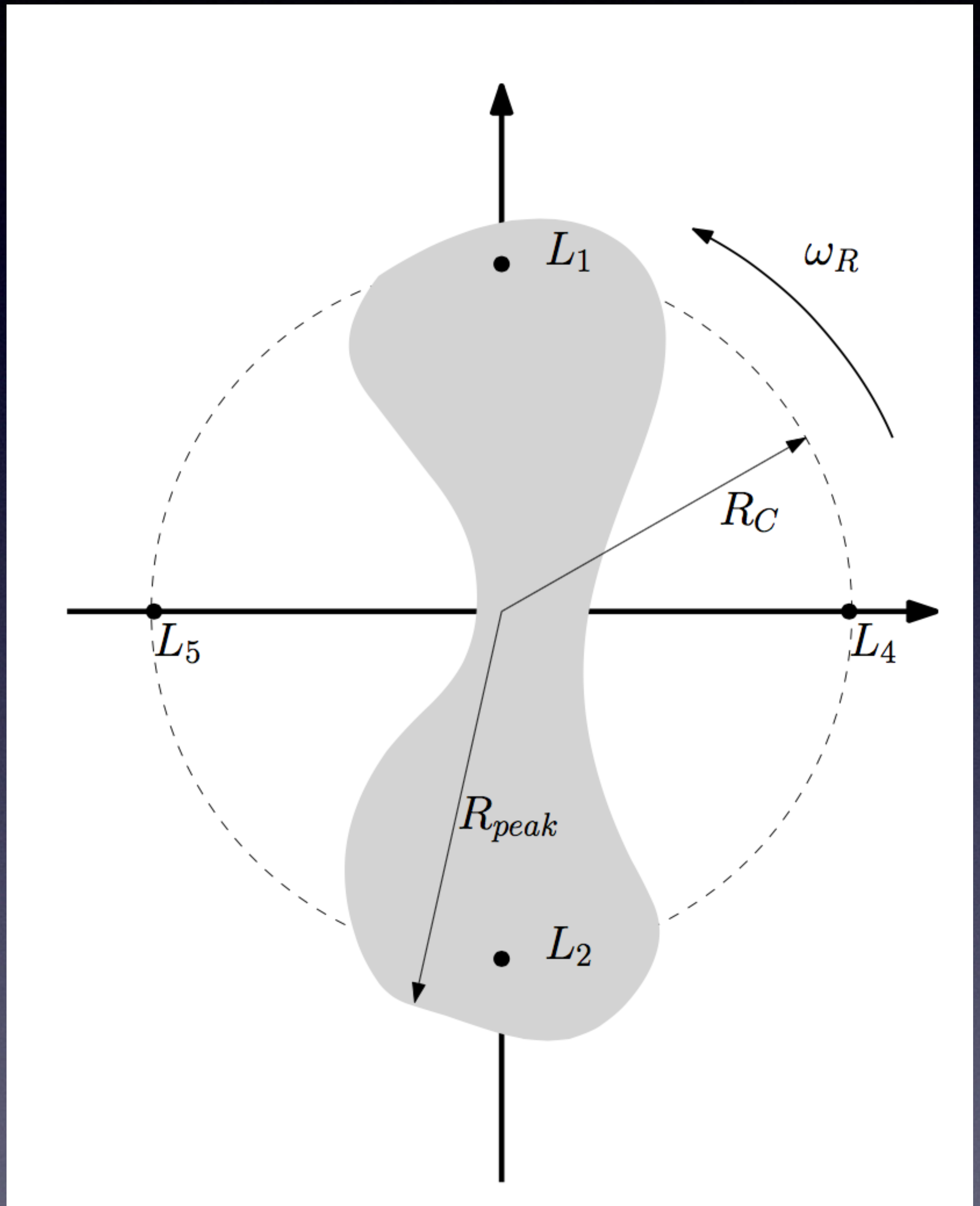


Robust vs
non-gravitational couplings

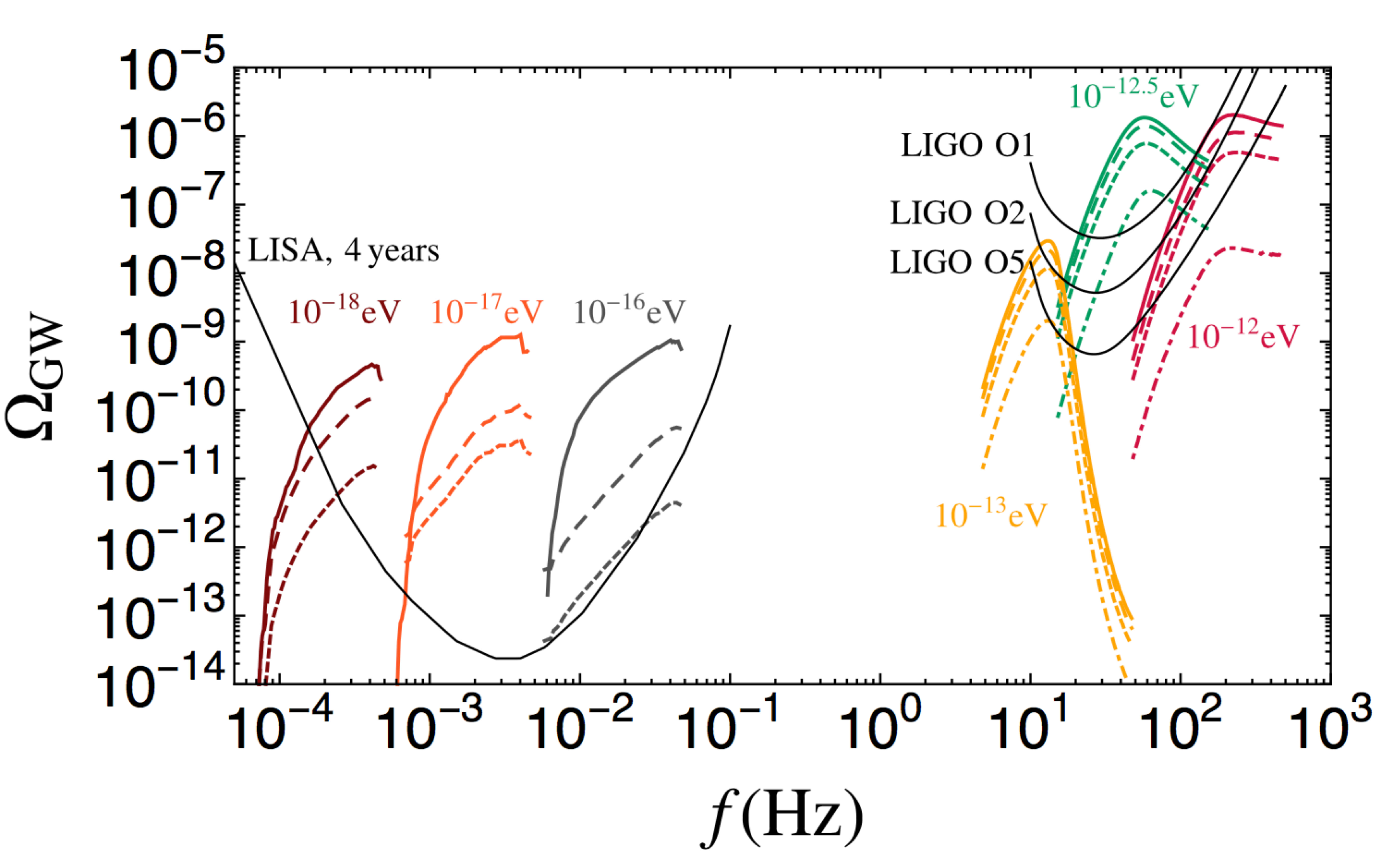
Brito+EB+2017

Instability end point

- BH sheds excess spin (and to a lesser degree mass) into a mostly dipolar rotating boson cloud with frequency ~ m
- Instability saturates when m~Ω_h
- Rotating cloud emits monochromatic gravitational waves via quadrupole formula *if non-gravitational couplings are subdominant*

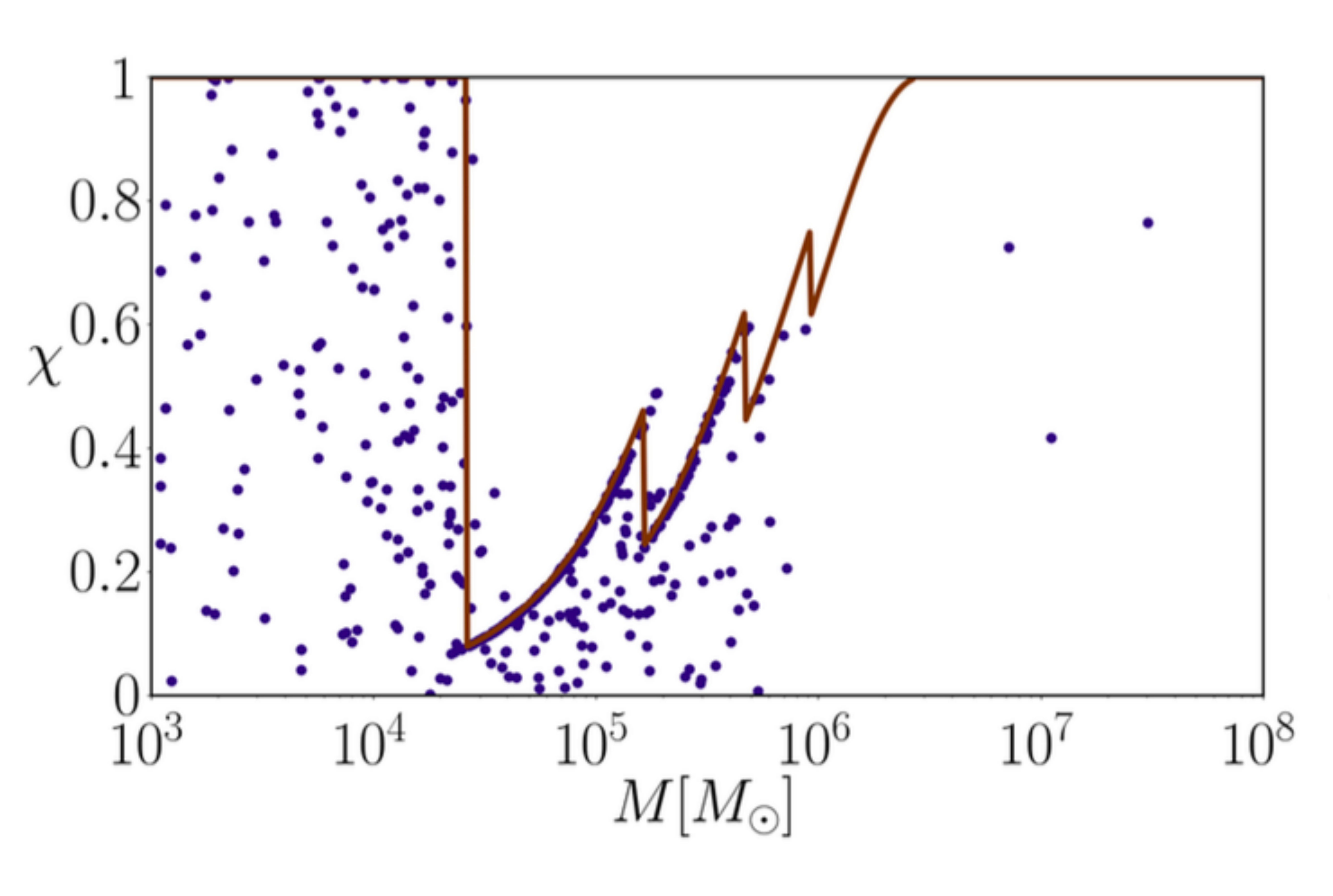


Background from isolated spinning BHs



Brito+EB+2017

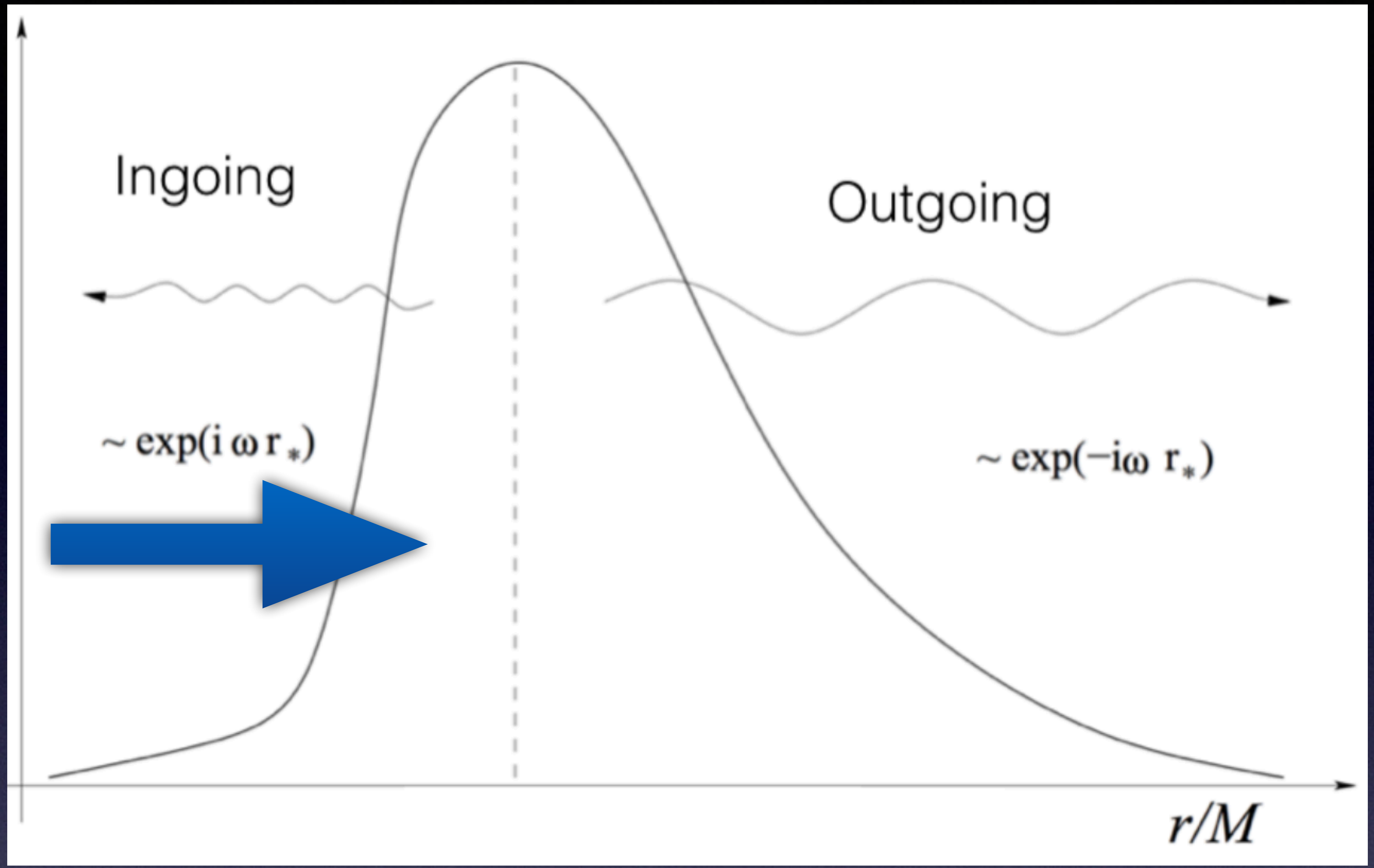
Regge plane “holes”



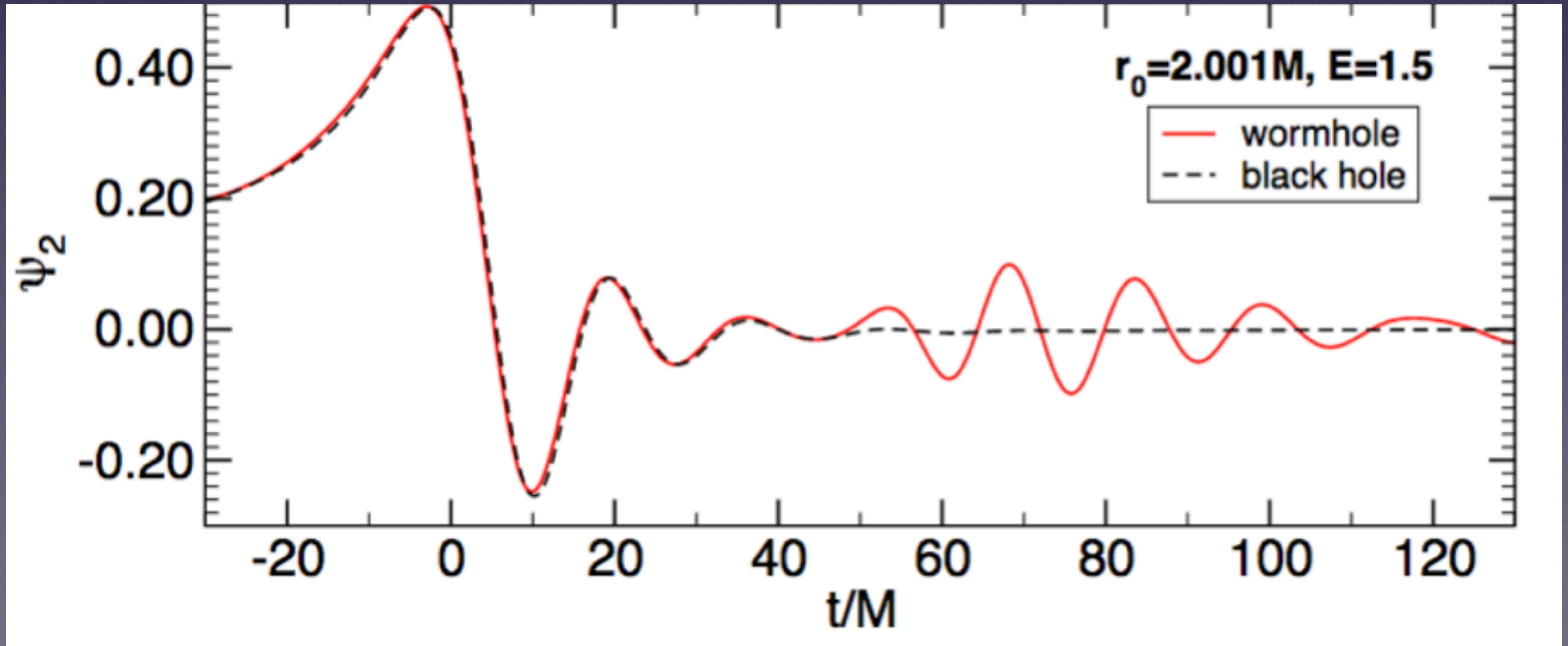
- Look for “accumulation” near instability threshold to avoid assumptions on astrophysical model
- Robust vs non-gravitational couplings

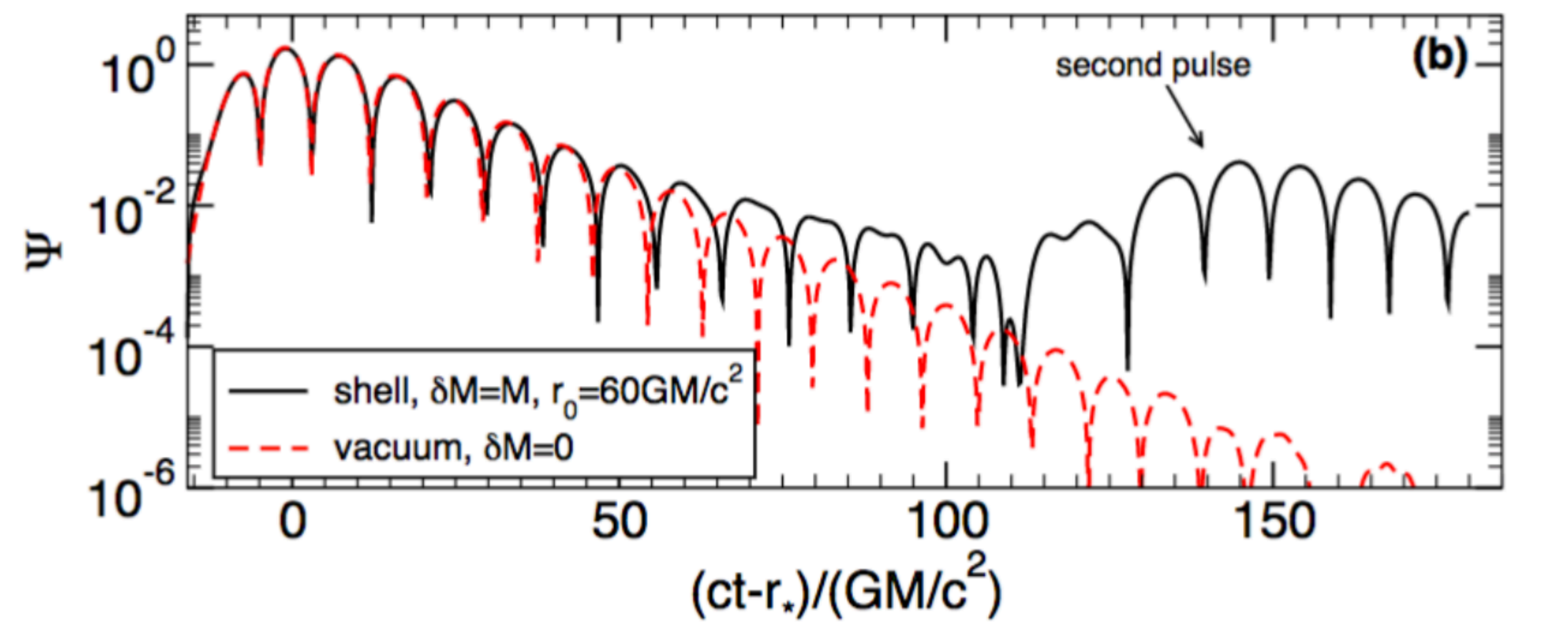
Brito+EB+2017

Superradiance from near horizon physics



- Deviations from Kerr near horizon can produce significant changes in QNM spectrum $\Delta t \sim \log[r_0/(2M) - 1]$
- Echoes or superradiance instability (for spinning BHs)

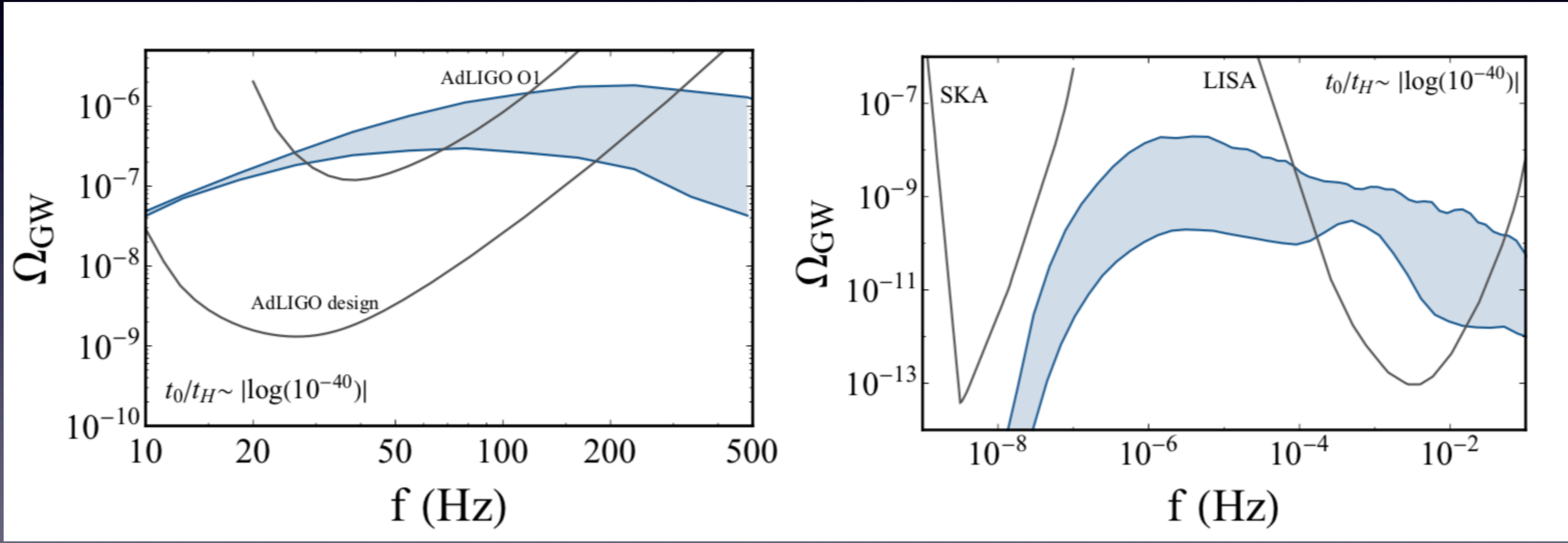




Cardoso, Franzin & Pani 2016

EB, Cardoso & Pani 2014

Bounds on BH mimickers from stochastic background



EB, Brito, Cardoso, Dvorkin, Pani 2018

Conclusions

- Pulsars probe ULDM at m~1.e-22 eV, with and without direct couplings to SM
- M<1.e-23.2 cannot be 100% of DM
- Larger masses probed by binary pulsars (resonances) and BH superradiance, up to 1.e-12 eV
- Harder to probe more larger masses/CDM: dynamical friction on binary BHs in DM-dominated dwarf galaxies
- (Some) constraints on PBH DM