Constraining Interacting Dark Energy Models via Black Hole Superradiance

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Based on work 25xx.abcde, in collobroation with Rong-Gen Cai, Shao-Jiang Wang, Xiang-Xi Zeng

Outline

1. Interacting dark energy model
2. Constraints from black hole superradiance
3. Model I: DE mediates dark 5th force in the dark sector
4. Model II: DE superradiance induced by DM spike

Outline

1. Interacting dark energy model

Interacting dark energy model

- Standard cosmologies: dark sector (DE & DM) are treated as two separate, perfect fluids
- Interacting dark energy model: non-gravitational energy exchange between DE and DM

$$\nabla_\mu T_i^{\mu\nu} = Q_i^\nu, \quad \sum_{i=\mathrm{de,dm}} Q_i^\mu = 0$$

$$\dot{\rho}_{\mathrm{dm}} + 3H\rho_{\mathrm{dm}} = Q$$
$$\dot{\rho}_{\mathrm{de}} + 3H(1+w)\rho_{\mathrm{de}} = -Q$$

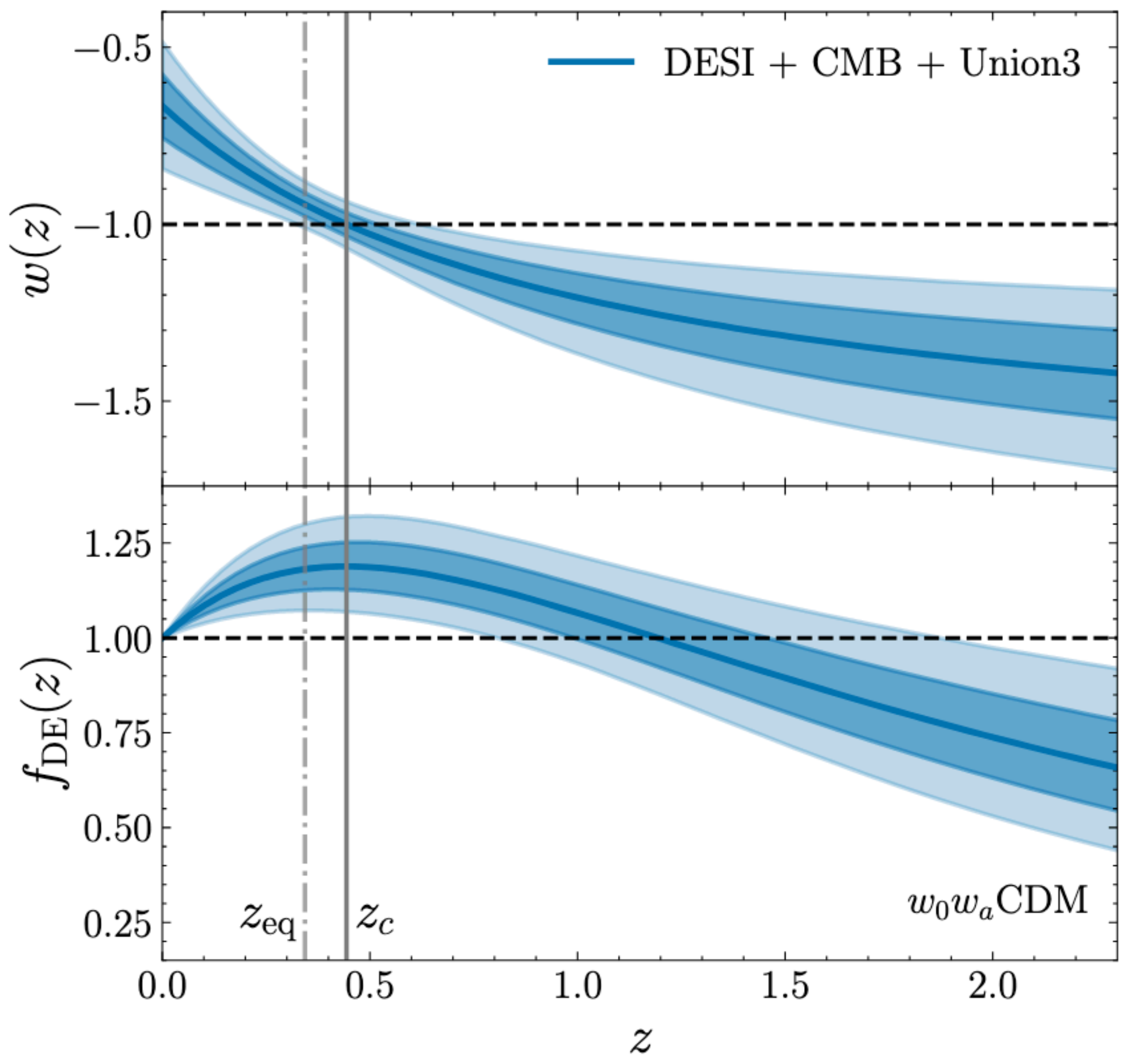
(phenomelogical) energy transfer rate

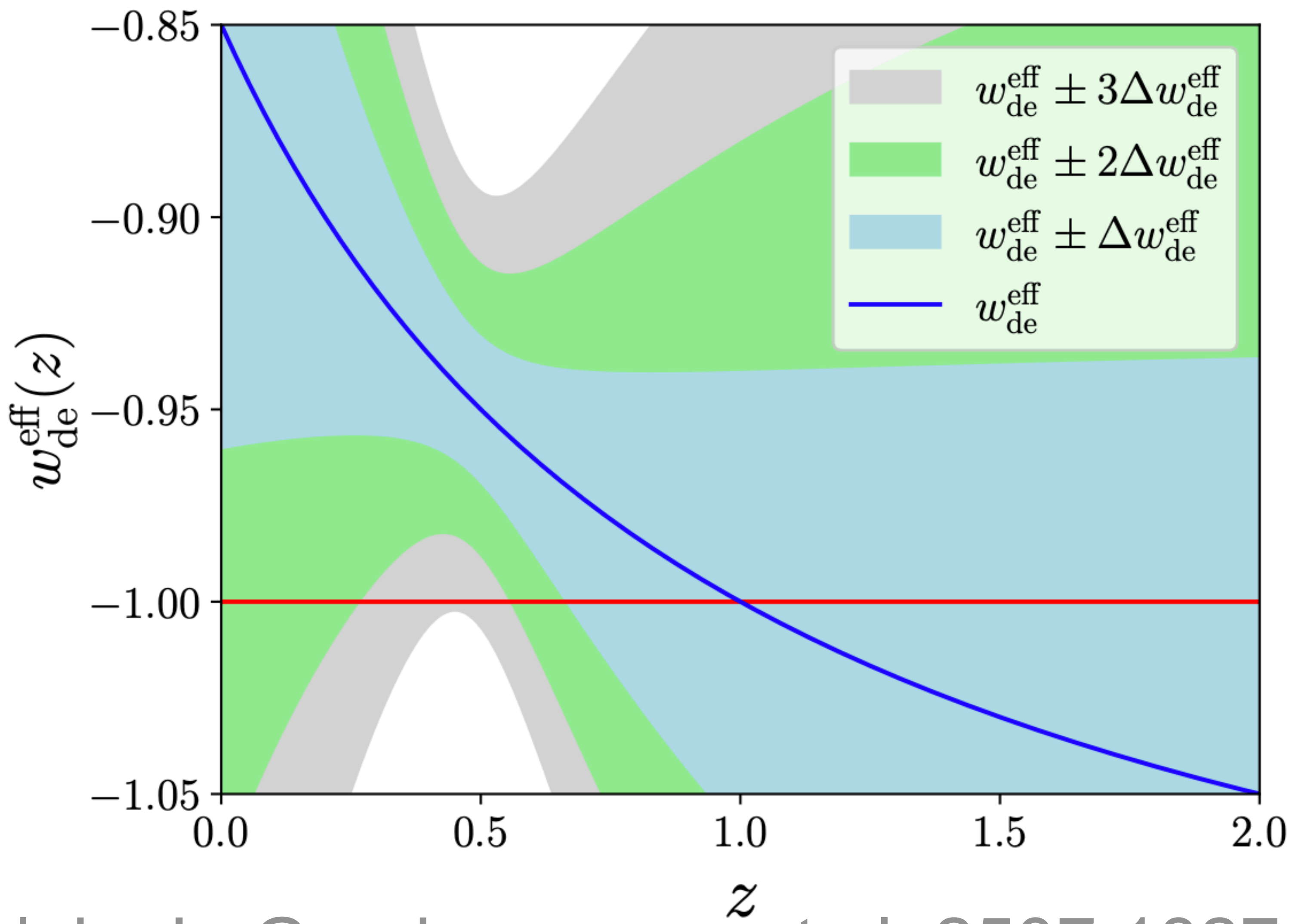
$Q = 3H\xi\rho_{\mathrm{de}}$, $Q = 3H\xi\rho_{\mathrm{dm}}$, etc…

$Q > 0$: energy flow from DE to DM

Potential mechanism to address

- The Hubble tension
- The S8 discrepancy
- Hints of dynamical dark energy





[DESI Collobration. 2503.14743] [Sêcloka L. Guedezounme et al. 2507.18274]

Field-theoretic model

A more fundamental, microscopic perspective: starting with a particle physics Lagrangian

- Two ultralight scalar minimally coupled to gravity

DE DM

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G_N} + \mathscr{L}_\phi\left(\phi, \partial_\mu \phi\right) + \mathscr{L}_\chi\left(\chi, \partial_\mu \chi\right) + \mathscr{L}_{\text{int}}(\phi, \chi) \right] \quad \mathscr{L}_{\text{int}} = -W(\phi, \chi)$$

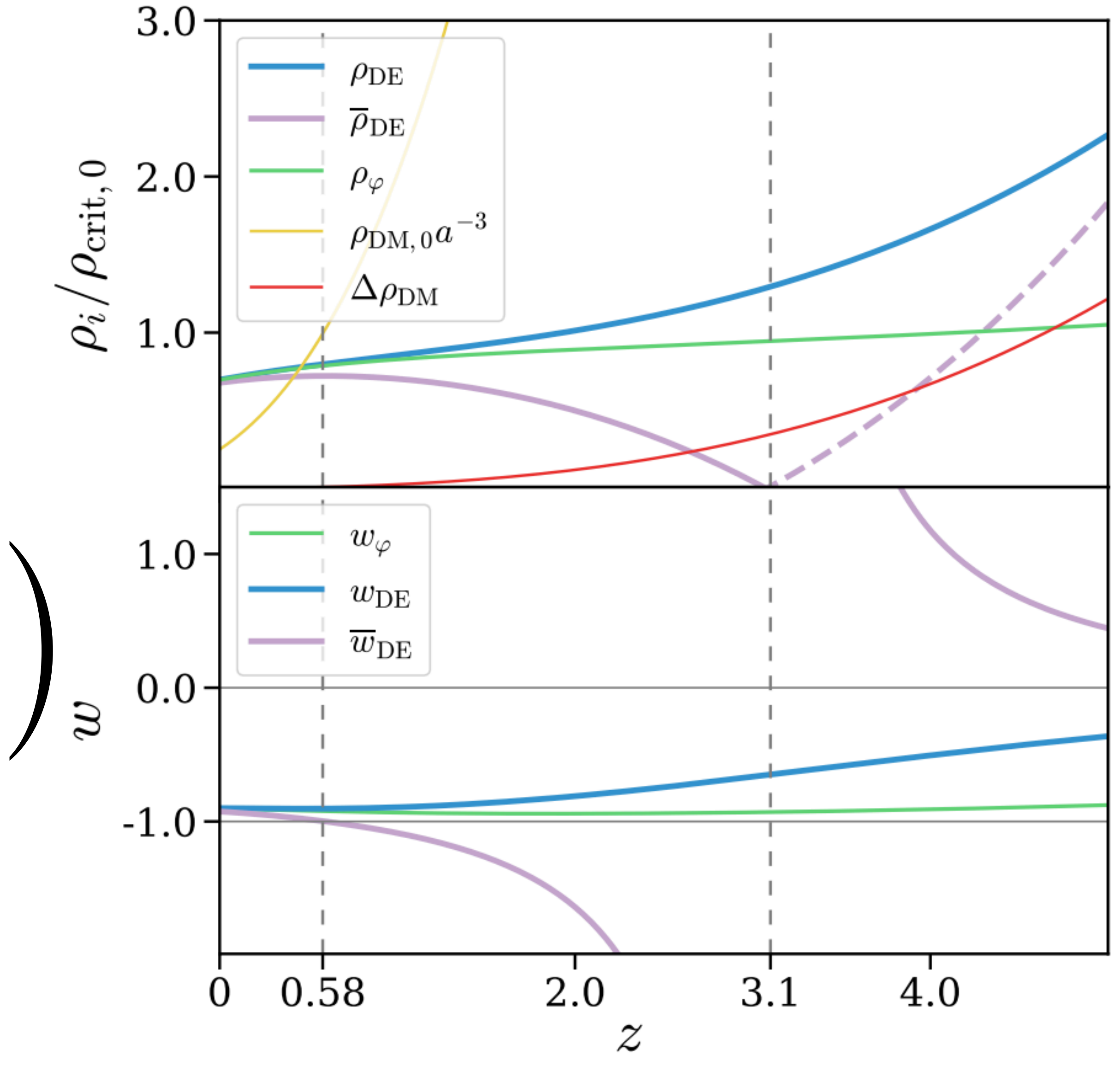
$$Q_\chi = -Q_\phi = \dot{\phi} W_{,\phi}$$

[Amin Aboubrahima and Pran Nath. 2406.19284]

- Non-minimal coupled quintessence

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G_N} - \frac{1}{2} g_{\mu\nu} \partial^\mu \Phi \partial^\nu \Phi - V(\Phi) \right] + S_{\text{DM}}\left(\Psi; \Omega^2(\Phi) g_{\mu\nu}\right)$$

$$Q_{\text{de}} = -Q_{\text{dm}} = \ln \Omega' \dot{\Phi} \rho_{\text{dm}}$$



[Jia-Qi Wang, Rong-Gen Cai, Zong-Kuan Guo and Shao-Jiang Wang. 2508.01759]

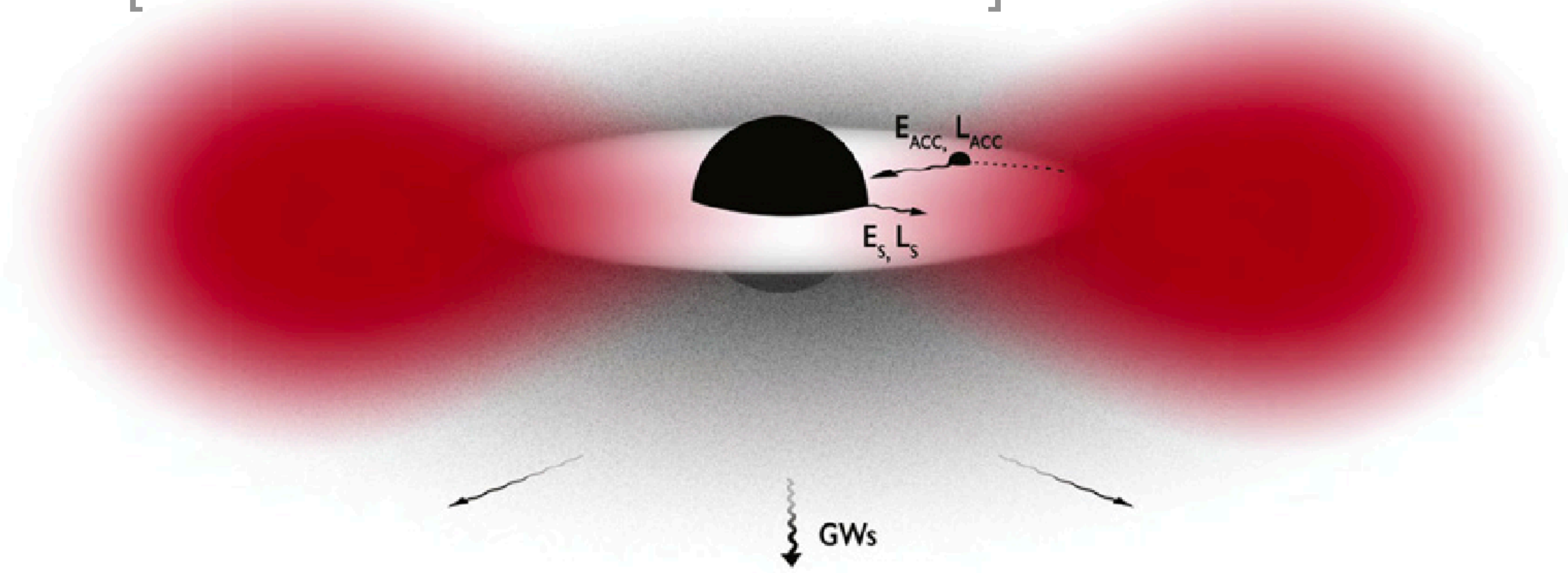
Outline

2. Constraints from black hole superradiance

Black hole superradiance

Trapped bosonic field around spinning BH with positive imaginary eigenfrequency: continuous extraction

[Richard Brito et al. 1411.0686]

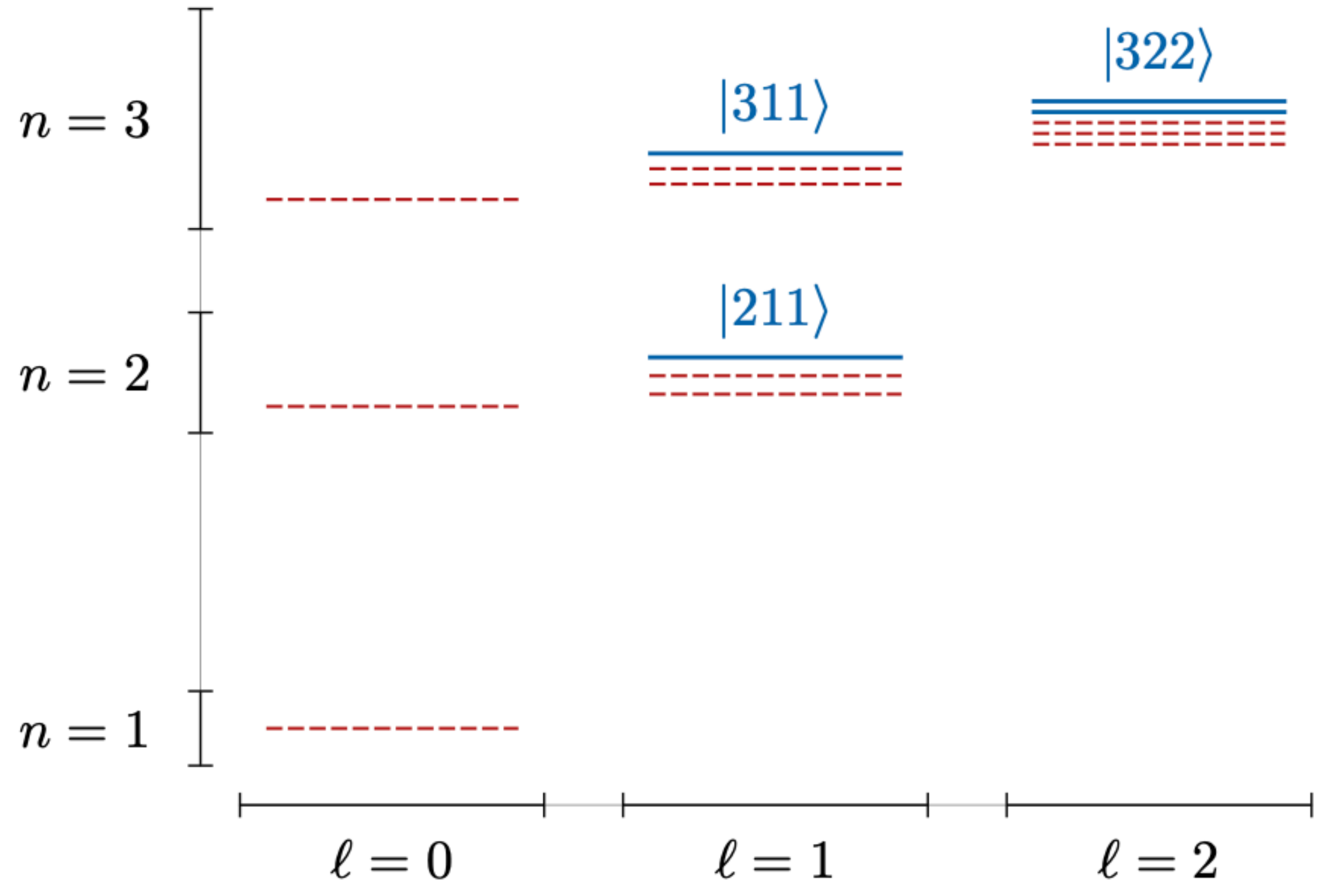


$$\omega = E + i\Gamma, \Gamma > 0 \text{ when } m\Omega_H > \omega$$

Extract $\mathcal{O}(10^{-1})$ angular momentum and $\mathcal{O}(10^{-2})$ mass of BH, a macroscopic bosonic "cloud"

- De Broglie wavelength ~ BH size $\alpha \simeq GM\mu \simeq \left(\frac{M_{\rm BH}}{M_\odot}\right)\left(\frac{m_a}{10^{-10}\rm eV}\right)$
- Hydrogen-like profile far away from the event horizon, $r_{\rm Bohr} \sim GM/\alpha^2$,

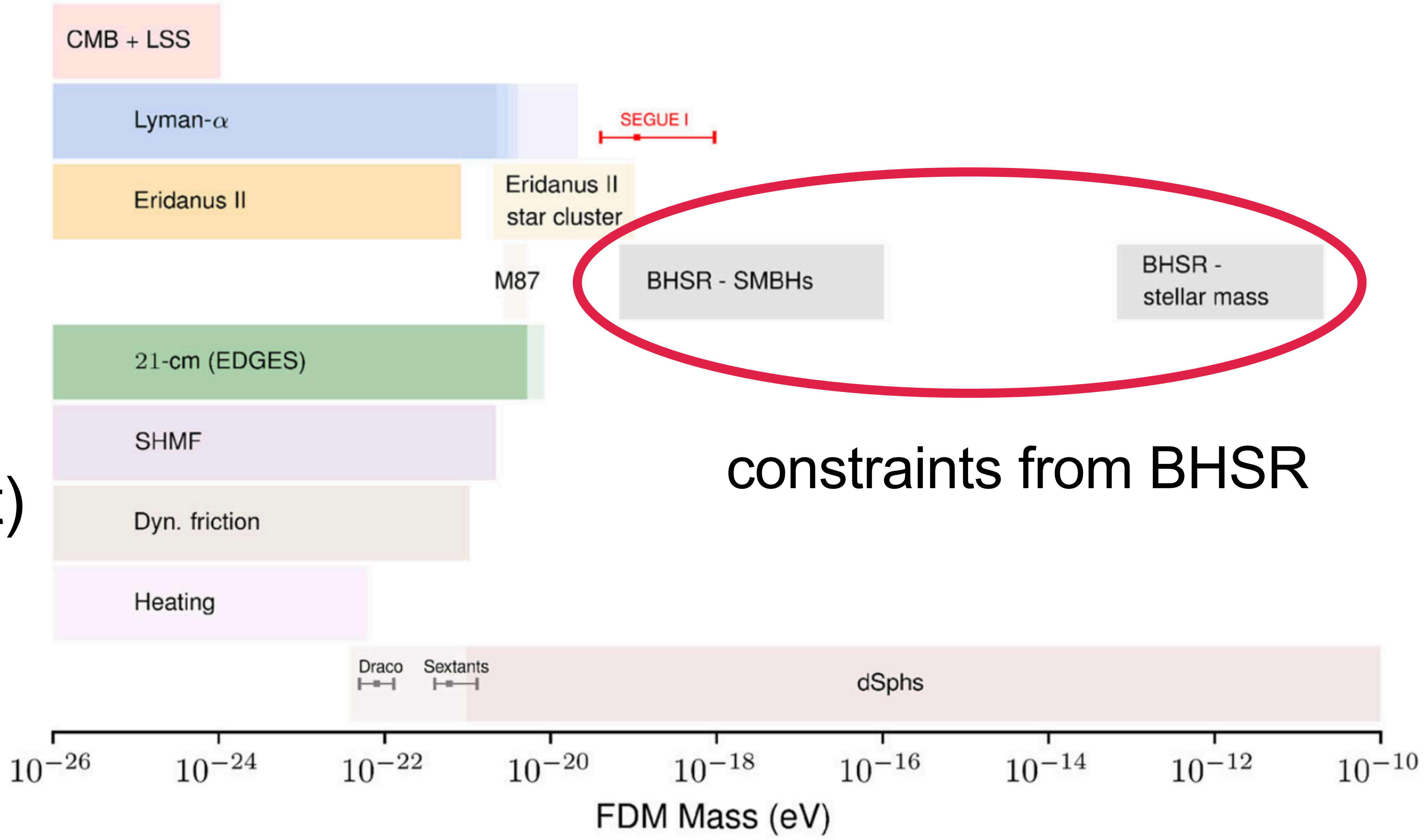
  "gravitational atom" $$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} + \mathcal{O}(\alpha^4)\right)$$



[Daniel Baumann et al. 1908.10370]

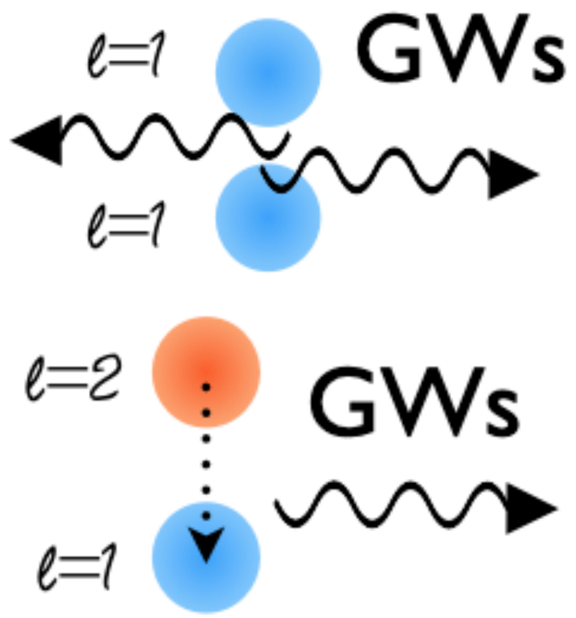
Gravitational atom as a probe of fundamental physics

- *Particle physics*: wave dark matter
  - QCD axion, ALPs, dark photon
  - Fuzzy dark matter, mass $\sim 10^{-22}\,\mathrm{eV}$
  - Searching ultralight particles via BHSR (model independent)

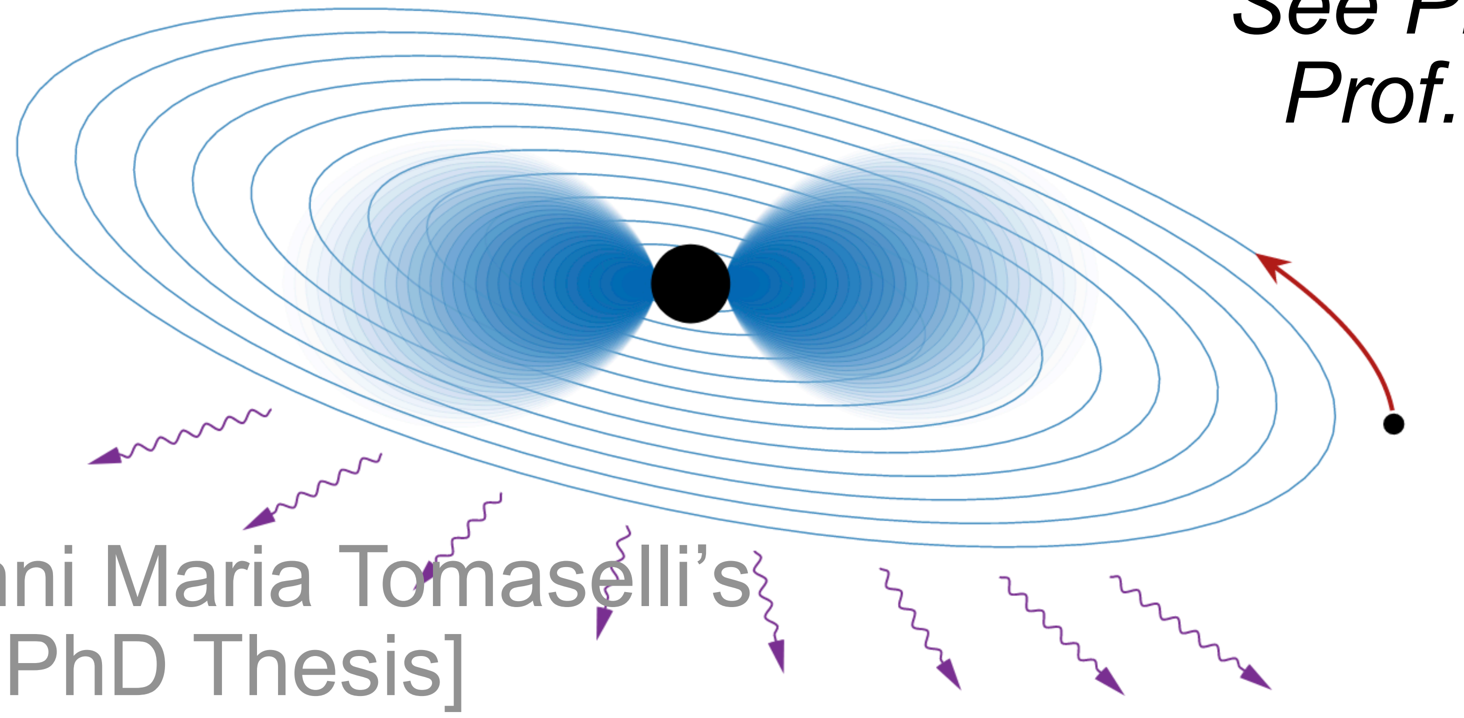


[Elisa G. M. Ferreira. 2005.03254]

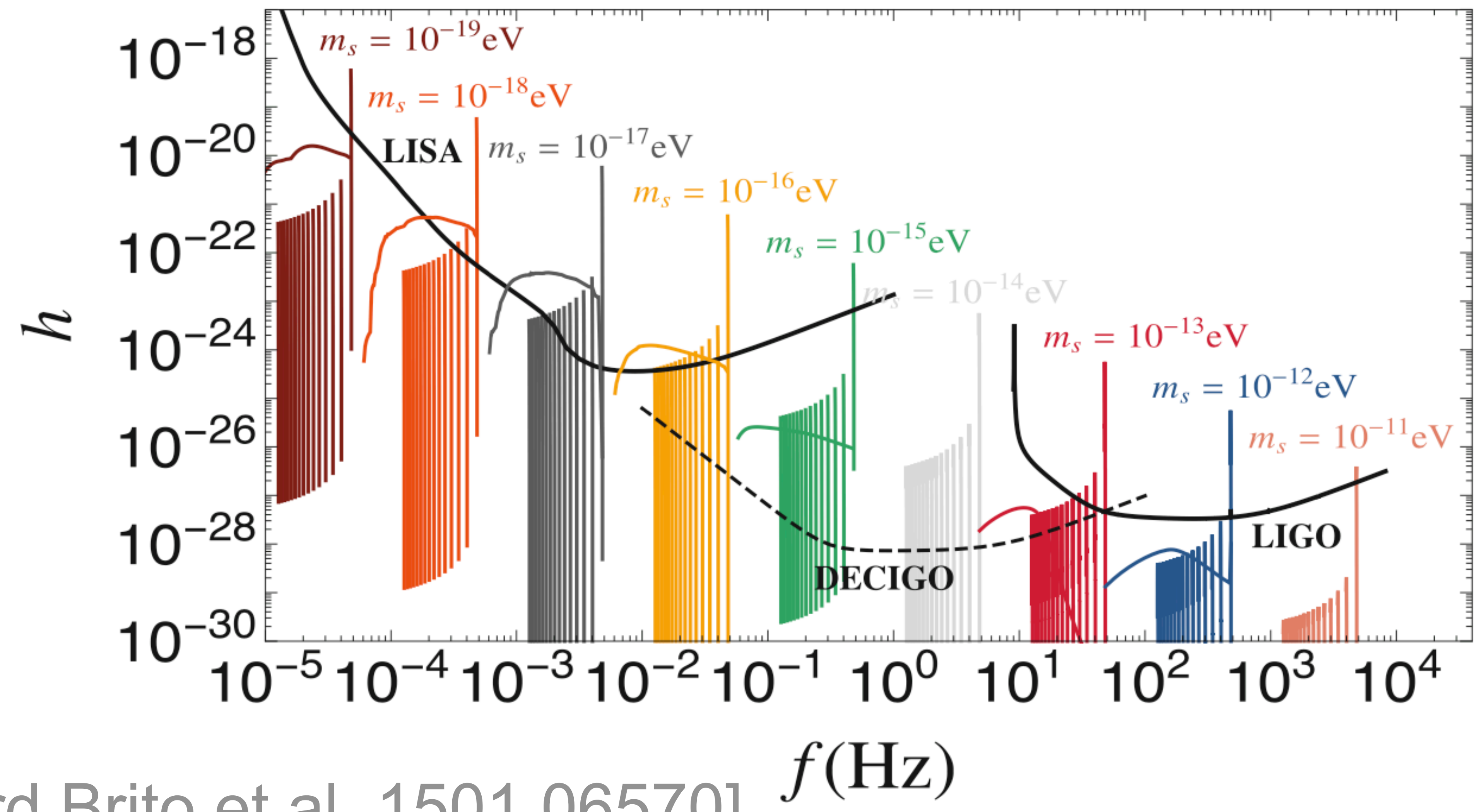
- *Gravitation physics*: novel GW signature
  - Axion annihilation: continuous GW
  - Level mixing: transient GW
  - Gravitational atom with a companion compact object



See Prof. Jun Zhang and Prof. Huan Yang's talk



[Giovanni Maria Tomaselli's PhD Thesis]

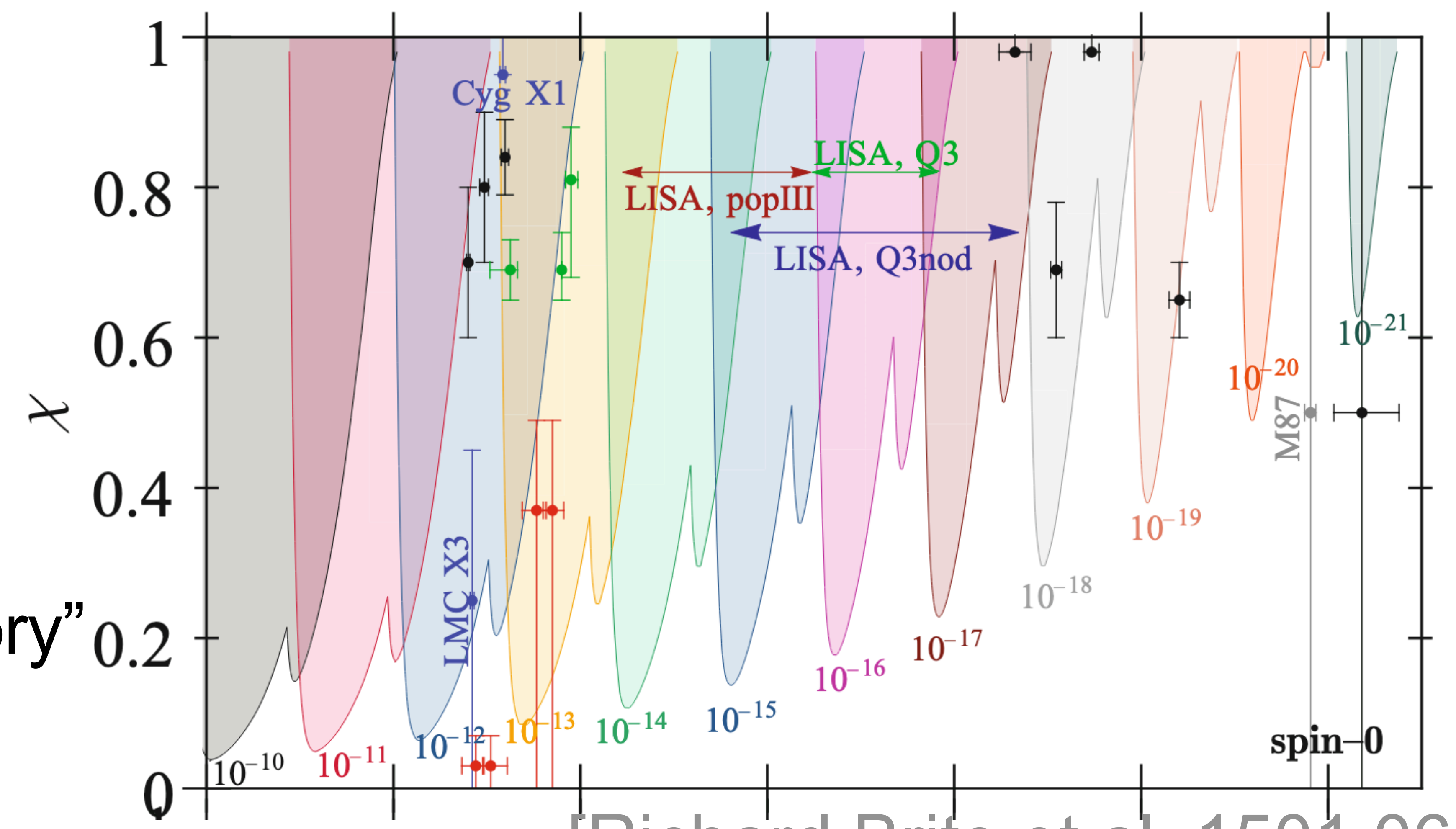


[Richard Brito et al. 1501.06570]

Constraining ultralight boson models from BHSR

- The observation of high-spin BHs (e.g., using X-ray observations, gravitational waves, etc) serves as strong evidence against the existence of ultralight bosons

"Regge trajectory"

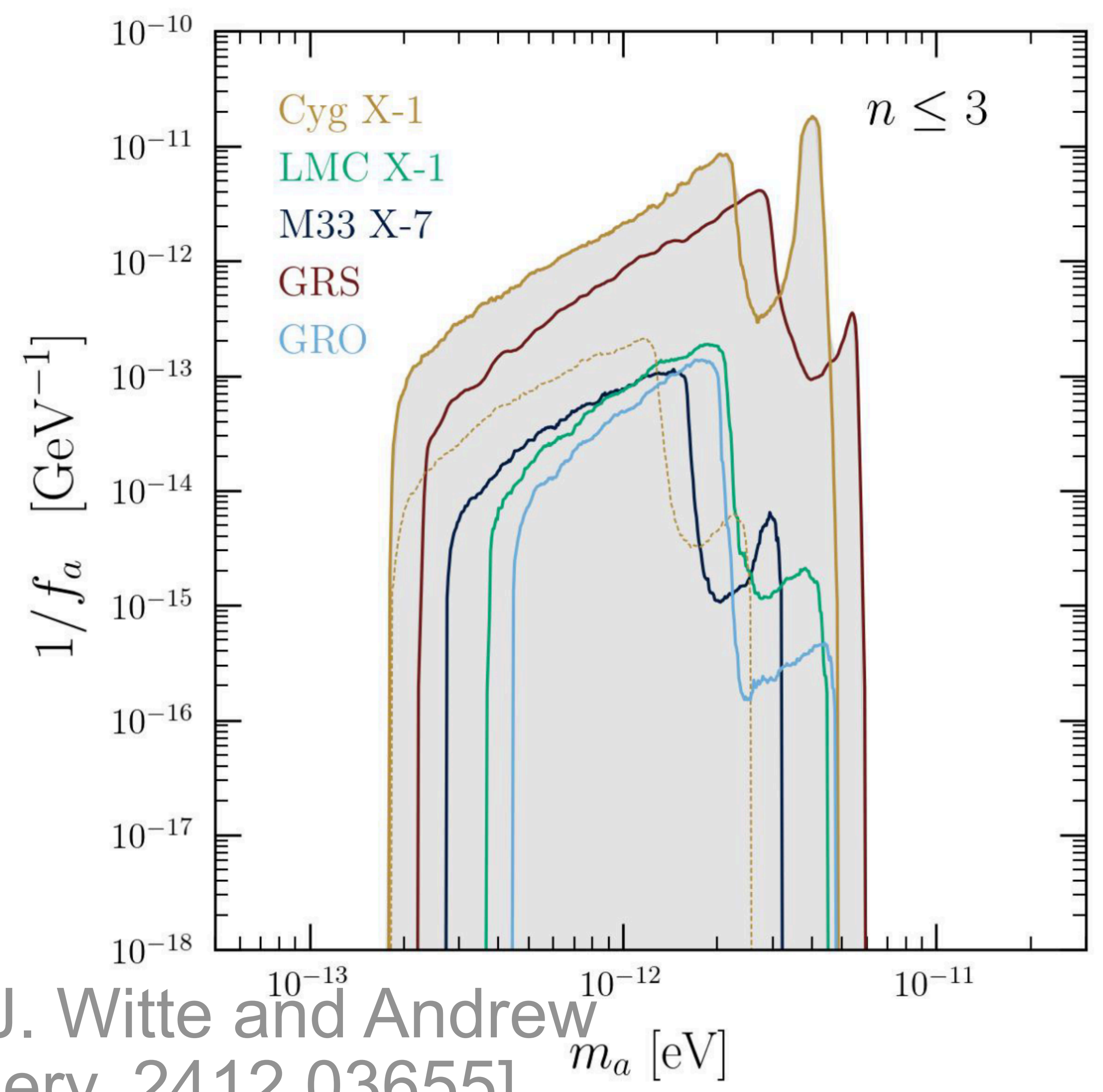


[Richard Brito et al. 1501.06570]

Constraint methodology

Any given BH *should not* have a spin higher than a certain critical value $a^{\rm crit}(M;\tau_{\rm BH};\boldsymbol{\alpha})$ where $\boldsymbol{\alpha}=(m_a,f)$ is the model parameter, once the following condition is satisfied:

- A specific mode $|n\ell m\rangle$ satisfies the SR condition
- The growth rate $\Gamma_{n\ell m}$ is large enough for the cloud to grow to a significant size within a BH timescale $\tau_{\rm BH}$



[Samuel J. Witte and Andrew Mummery. 2412.03655]

Assuming DM to be an ultralight boson…

What if we include the effect of DE-DM interaction?

Outline

3. Model I : DE mediates dark 5th force in the dark sector

DE mediates dark 5th force in the dark sector

Model I: DE field mediates a dark 5th force within DM via a trilinear coupling

$$\mathscr{L} = -\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \kappa\phi\chi^2$$

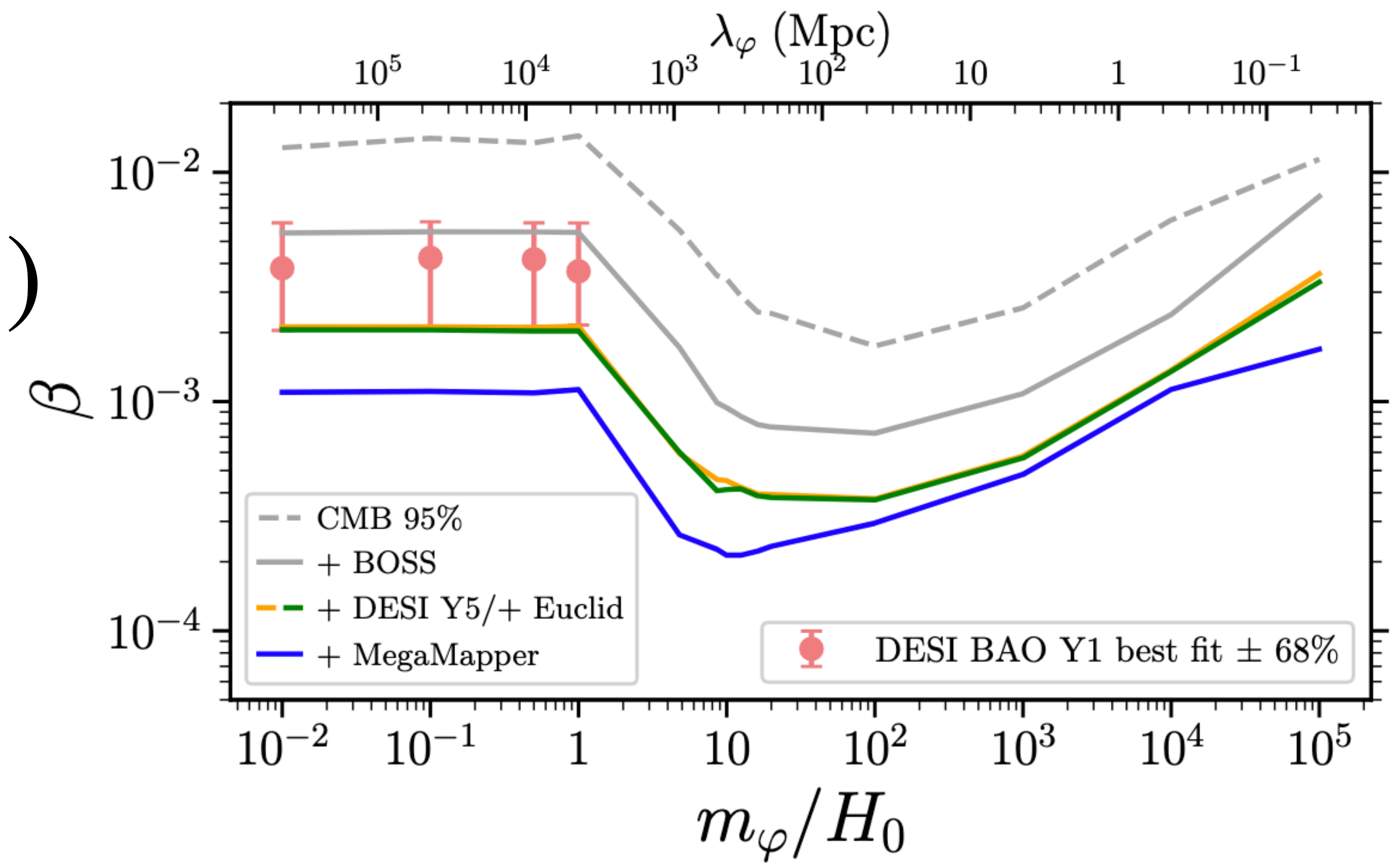
$$= -\frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_\chi^2(s)\chi^2 - \frac{1}{2G_s}\left[(\partial s)^2 + m_\phi^2 s^2\right] \quad s = G_s^{1/2}\phi$$

strength of 5th force relative to gravity

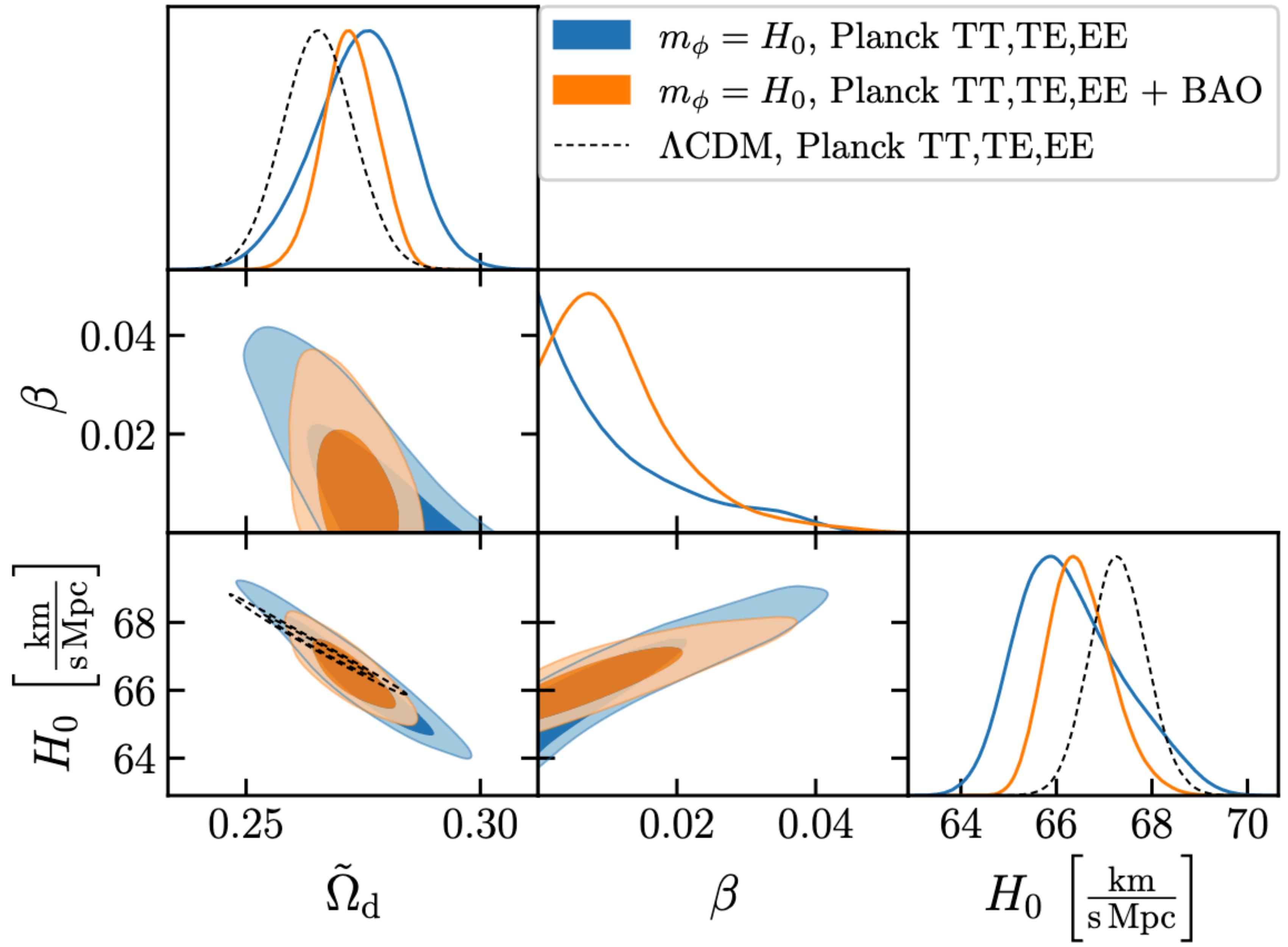
$$\beta = \frac{G_s}{4\pi G_N}$$

ϕ:DE; χ: DM

- Current CMB & BAO & LSS data constrains $\beta \lesssim \mathcal{O}(0.01)$



[Maria Archidiacono et.al. 2407.18252]



[Maria Archidiacono et.al. 2204.08484]

Constraints from BH superradiance

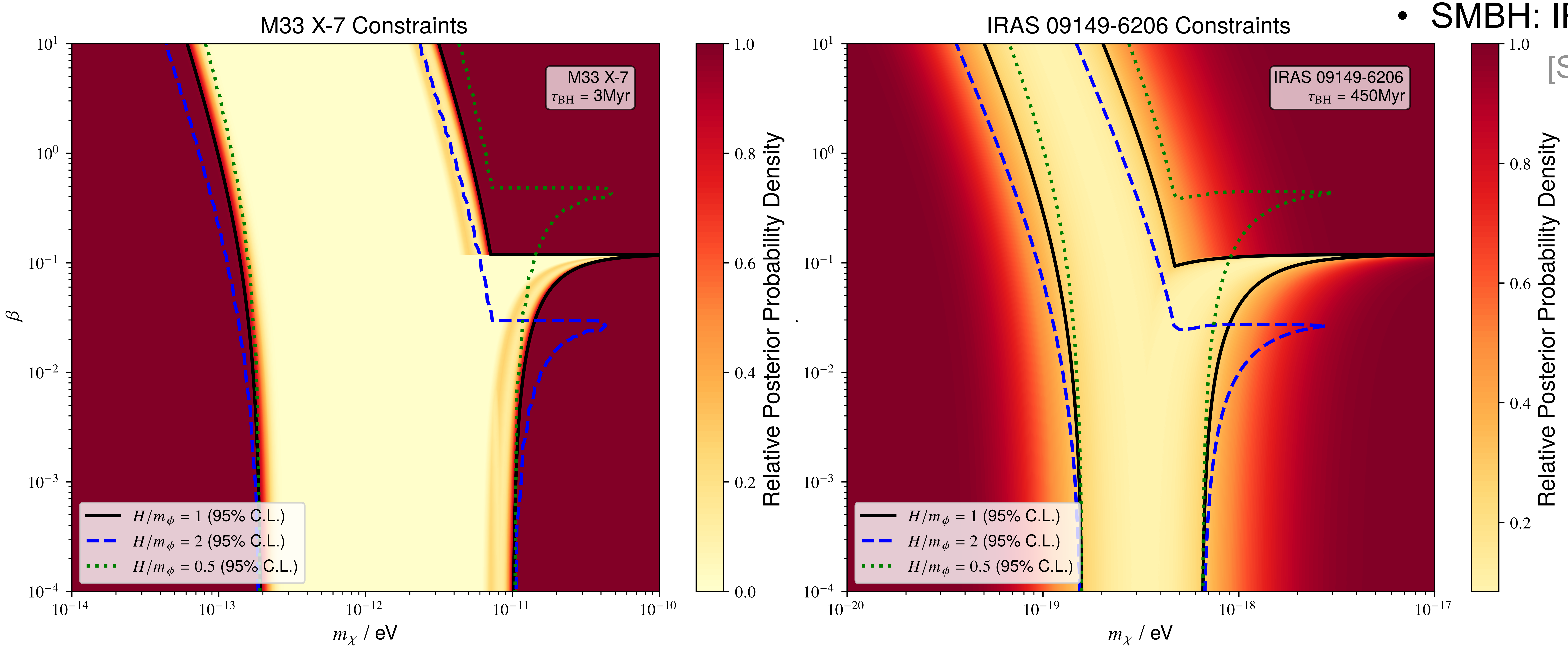
Background DE modifies DM effective mass → modifies SR instabilities around *local* BH

$m^2_{\chi,\mathrm{eff}}(\bar{s}) = m^2_\chi(1+2\bar{s})$

Ultralight scalar model parameter: $\boldsymbol{\alpha} = (m_\chi, \beta)$

$V(\bar{s}_0) \approx \rho_{\mathrm{DE}} \approx 0.7 \times 3H_0^2 M_{\mathrm{pl}}^2 \quad \Delta m^2_{\chi,\mathrm{eff}} \simeq 2.9\beta^{1/2} H_0/m_\phi$

BH data
- X-ray binary: M33 X-7
- SMBH: IRAS 09149-6206



[Sebastian Hoof et.al. 2406.1033]

Can DE itself trigger superradiance instabilities?

The answer might be yes in the context of the IDE model!

DE superradiance by effective mass enhancement

Model II: The DE field itself, rather than the DM, is the ultralight boson that triggers BH superradiance

no model assumptions

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G_N} - \frac{1}{2}g_{\mu\nu}\partial^\mu\Phi\partial^\nu\Phi - V(\Phi)\right] + S_{\rm DM}\left(\Psi; \Omega^2(\Phi)g_{\mu\nu}\right)$$

DM non-minimally coupled to gravity through DE

$$[\Box - V''_{\rm eff}(\Phi)]\Phi = 0 \quad V_{\rm eff}(\Phi) = V(\Phi) + \Omega(\Phi)\rho_{\rm DM}$$

$$V(\Phi) = \frac{1}{2}\mu_0^2\Phi^2, \ \Omega(\Phi) = 1 + \frac{1}{2}\beta\left(\frac{\Phi}{M_{\rm pl}}\right)^2$$

$$\mu_{\rm eff}^2(\mathbf{r}) = \mu_0^2 + \frac{\beta}{M_{\rm pl}^2}\rho_{\rm DM}(\mathbf{r})$$

vacuum mass $\sim 10^{-33}{\rm eV}$

local DM density $\sim 0.42\ {\rm GeV/cm^3}$, negligible mass correction…

The immense gravitational pull of an SMBH → DM spike → large mass enhancement $\Delta\mu^2 \propto \rho_{\rm spike}$

Modeling the DM spike

- A SMBH of mass M residing in a DM halo, which initially has a density profile $\rho \propto r^{-\gamma}$
- When BH grows adiabatically, the DM density also changes in the gravitational pull and forms a spike

$$\rho_{\rm sp}(r) = \rho_R \Theta(r - 4R_s)\left(1 - \frac{4R_s}{r}\right)^3 \left(\frac{R_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

$R_s = 2M$ $R_{\rm sp}$: spike radius

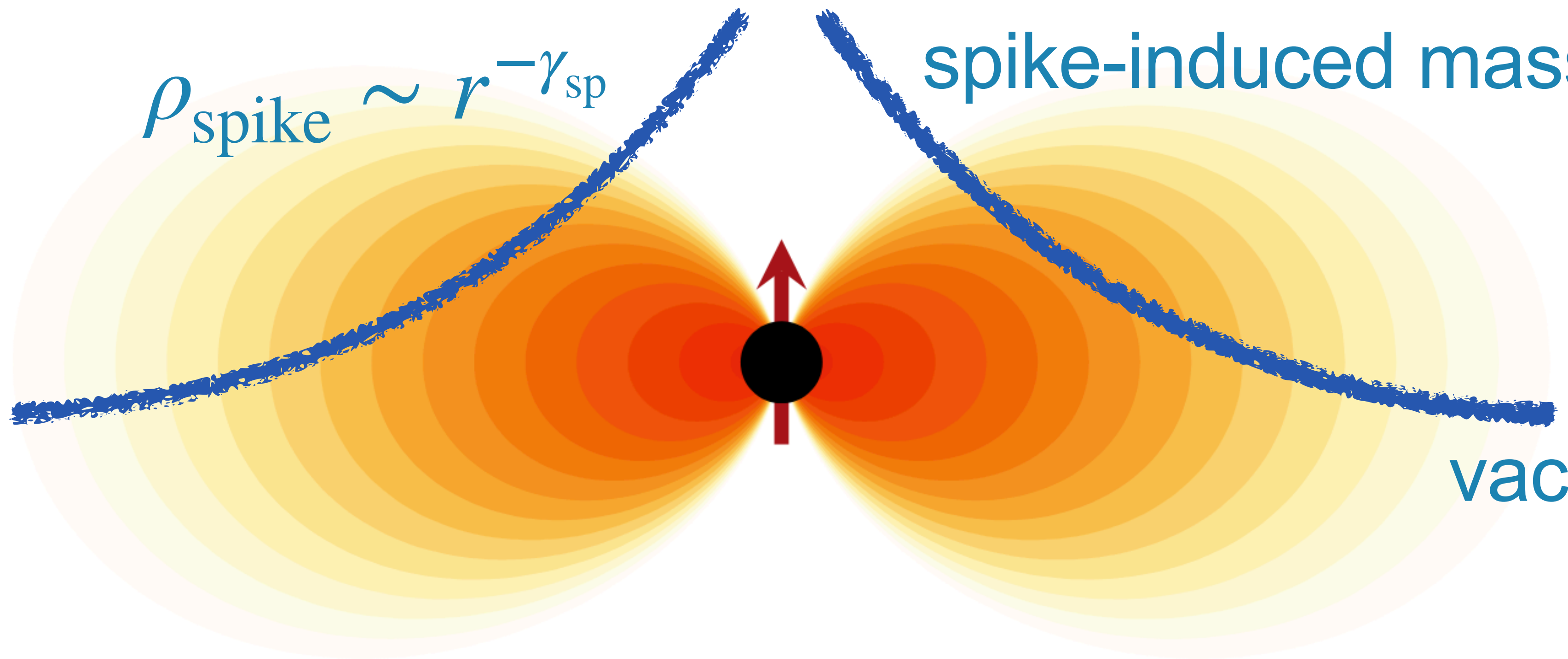
cutoff at $4R_s$

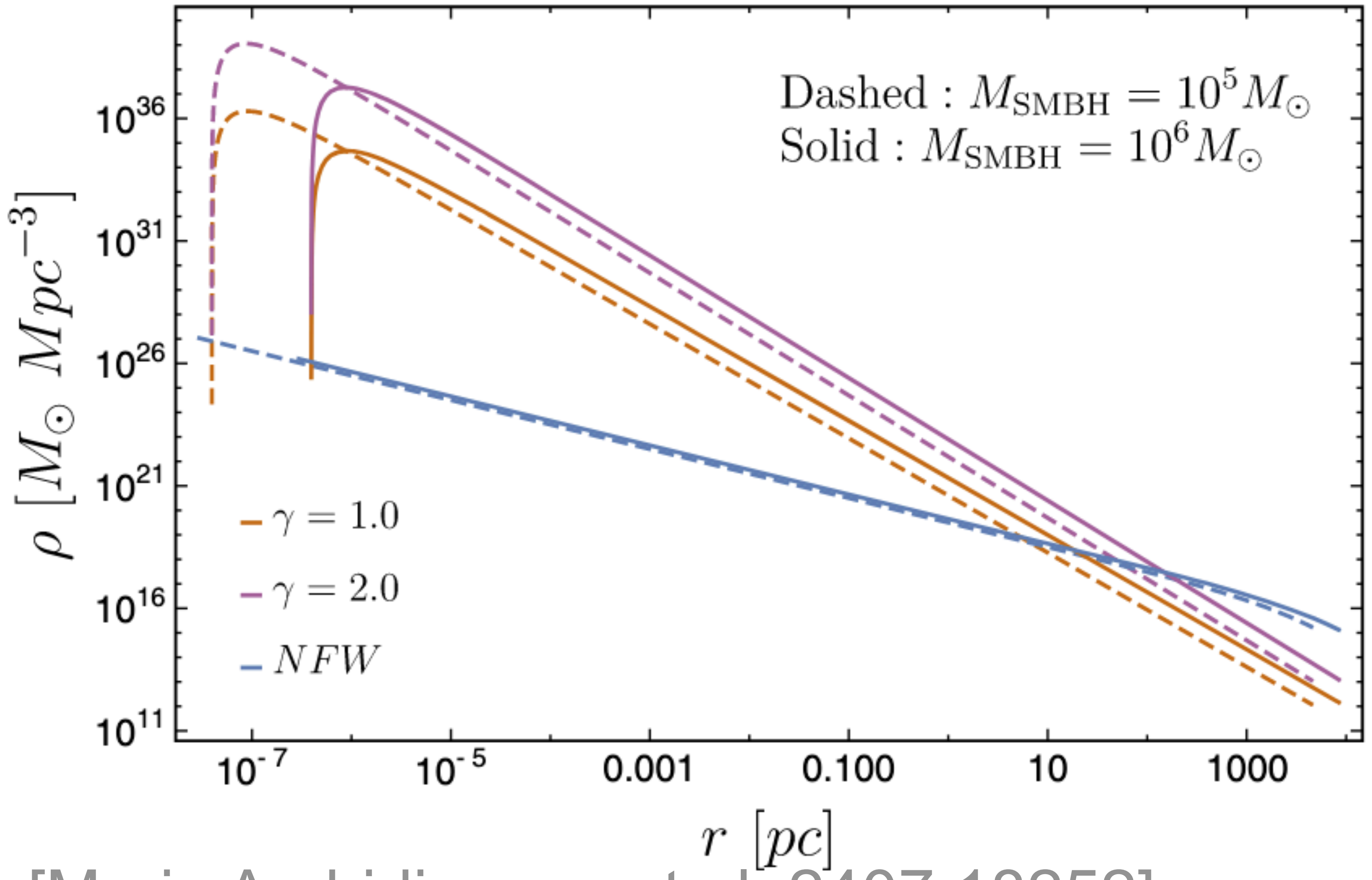
spike slope $\gamma_{\rm sp} = \frac{9 - 2\gamma}{4 - \gamma}$

- γ = 1 corresponds to the NFW profile
- γ = 2 can be chosen as the optimistic case

- For M87* with mass $M \sim 10^9 M_\odot$, the effective mass can be boosted to $\mathcal{O}(10^{-24}\,\text{eV})\beta^{1/2}$

(compared to $\mu_{\rm SR} \sim M^{-1} \sim 10^{-20}\text{eV}$)





[Maria Archidiacono et.al. 2407.18252]

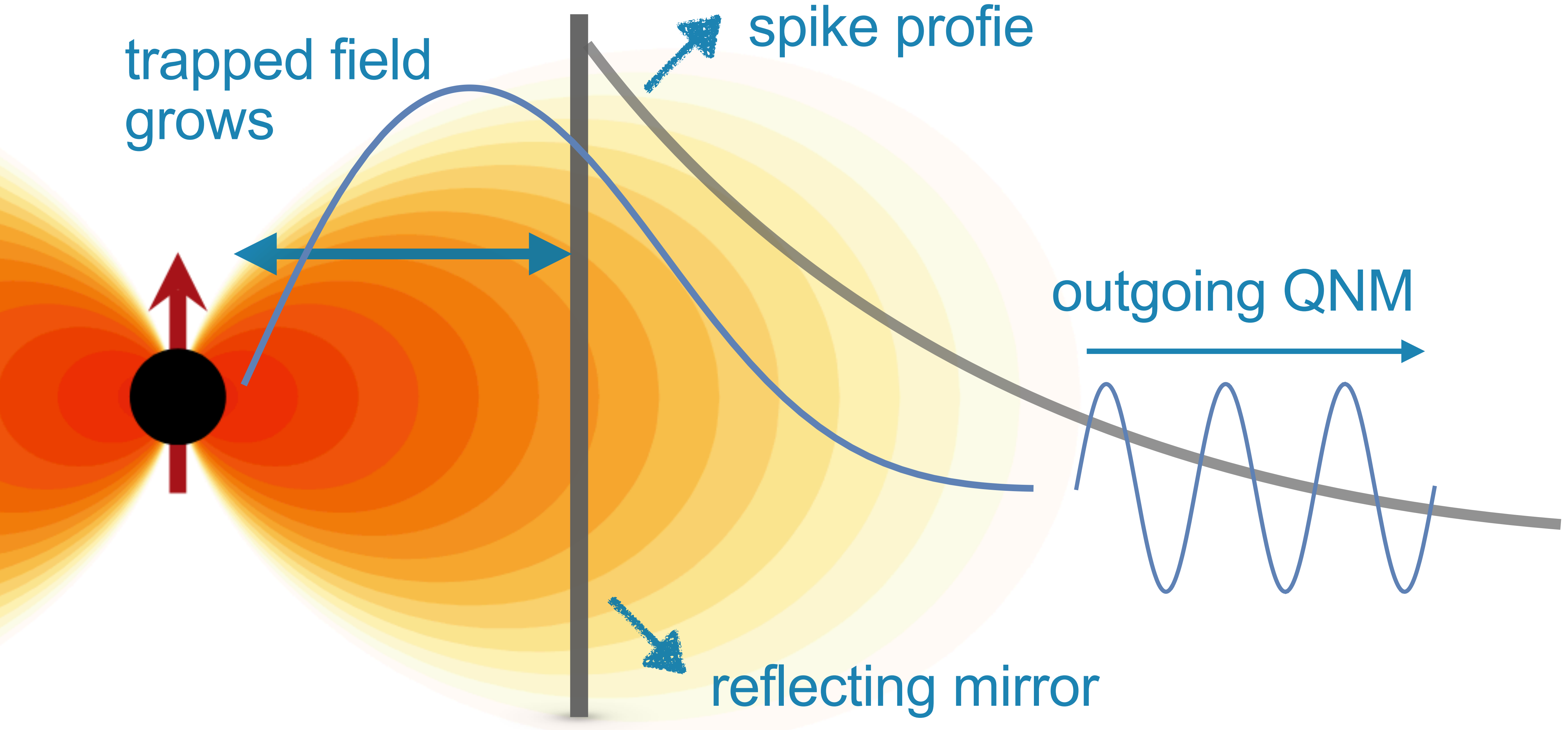
Numerical method for BHSR with a spike-induced mass profile

$$\left[\Box_{\rm Kerr} - \mu_{\rm eff}^2(r)\right]\Phi = 0 \quad \Phi(t,r,\theta,\phi) = e^{-i\omega t}e^{im\phi}R(r)S(\theta)$$

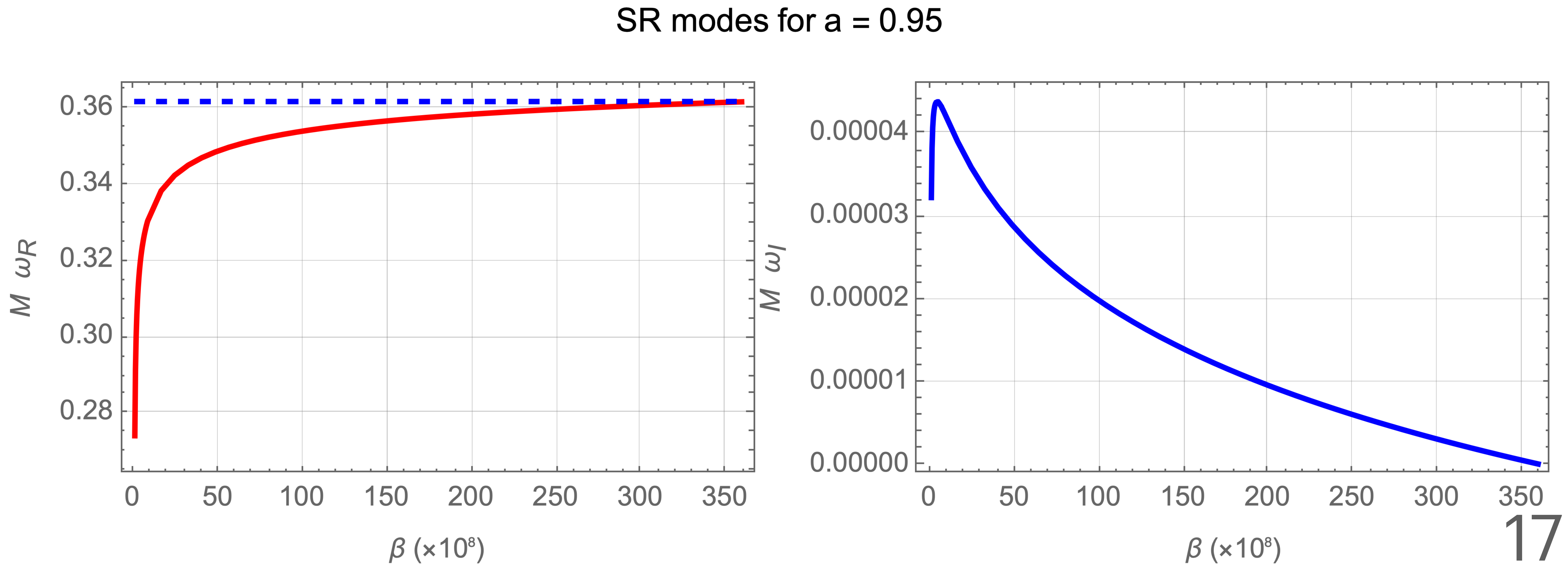
$$\frac{1}{\sin\theta}\partial_\theta\left(\sin\theta\partial_\theta S(\theta)\right) + \left(\Lambda_{\ell m} + a^2\omega^2\cos^2\theta - \frac{m^2}{\sin^2\theta}\right)S(\theta) = 0$$ continued fraction method

$\Lambda_{\ell m}$: seperation constant

$$\Delta\frac{d}{dr}\left(\Delta\frac{dR(r)}{dr}\right) + \left[K^2(r) - \left(\lambda + \mu_{\rm eff}^2(r) r^2\right)\Delta\right]R(r) = 0$$ direct integration (shooting method)



focus on the fastest-growing fundamental mode, $\ell = m = 1$



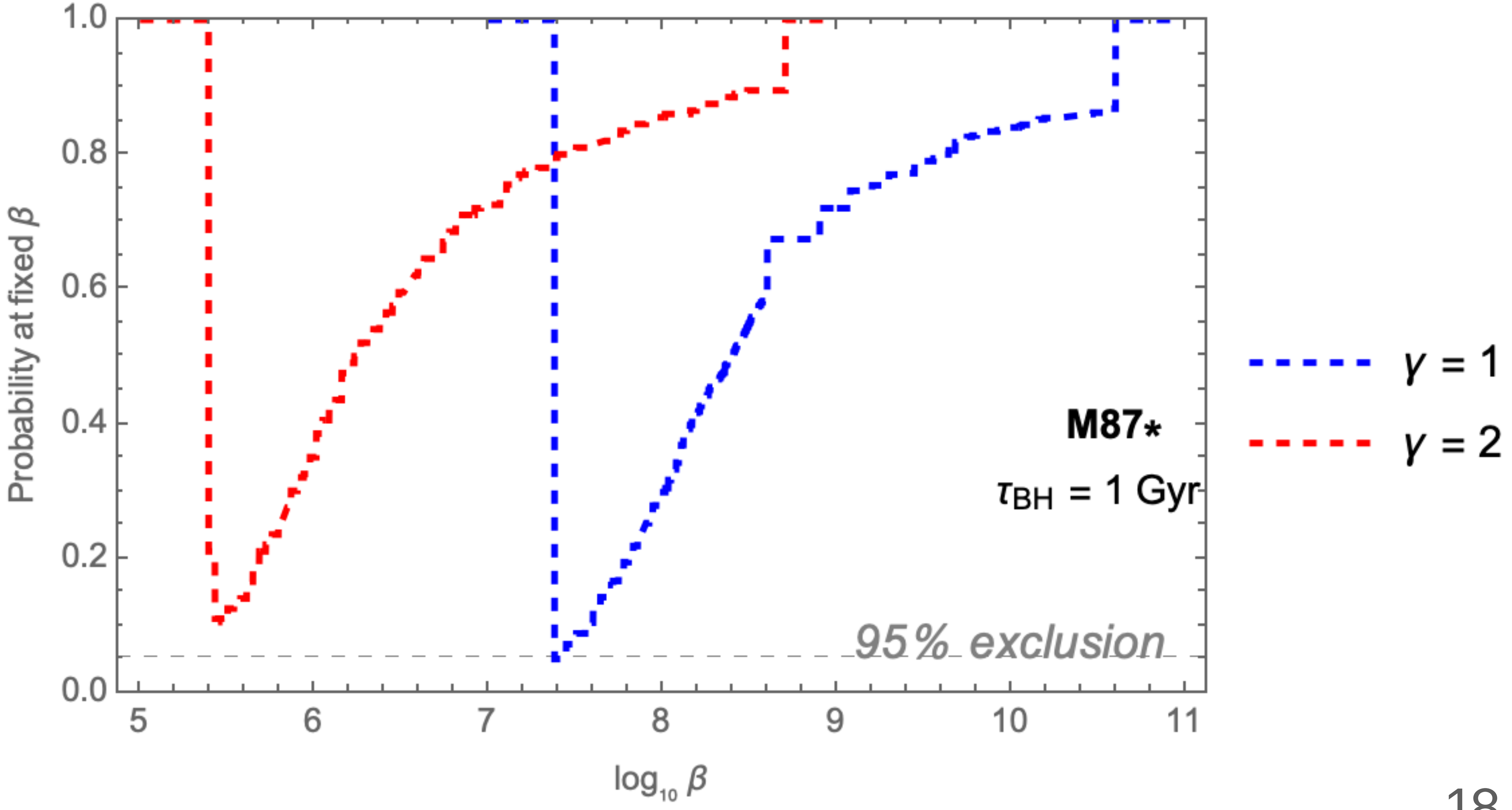
Constraints from BH superradiance

High spin measurement of M87* $a_\star = 0.9^{+0.05}_{-0.05}$ places constrains on DE superradiance model

[Fabrizio Tamburini et.al. 1904.07923]

- Two distinct scenarios corresponding to the initial halo profile index: $\gamma = 1$ (NFW) and a steeper profile with $\gamma = 2$
- For $\beta < \beta_c$, SR is not triggered for the majority of the BH samples, the model is consistent with the data
- As β approaches β_c, SR becomes efficient for most of the samples, causing the posterior probability to drop sharply
- As β increases further, the probability begins to rise again since a growing fraction of the BH samples are pushed outside the superradiant window

Ultralight scalar model parameter: $\boldsymbol{\alpha} = \beta$



Conclusion and Summary

- Our core idea: A new astrophysical probe for the field-theoretic interacting dark energy models

- The Tool: Black hole superradiance
  - Observation of high-spin black holes places constraints on ultralight boson model parameters $\boldsymbol{\alpha}$

- Application I: Constraining DE as a dark 5th force mediator
  - The DE-DM coupling modifies the DM's effective mass
  - This shifts the superradiance exclusion zone into the $\boldsymbol{\alpha} = (m_\chi, \beta)$ plane

- Application II: A New Scenario - DE Superradiance via DM Spikes
  - We propose a novel mechanism where the DE field *itself* becomes superradiant
  - A dense DM spike around a BH enhances the DE's effective mass, enabling a direct constraint on the coupling $\boldsymbol{\alpha} = \beta$

Thank You!

Back Up

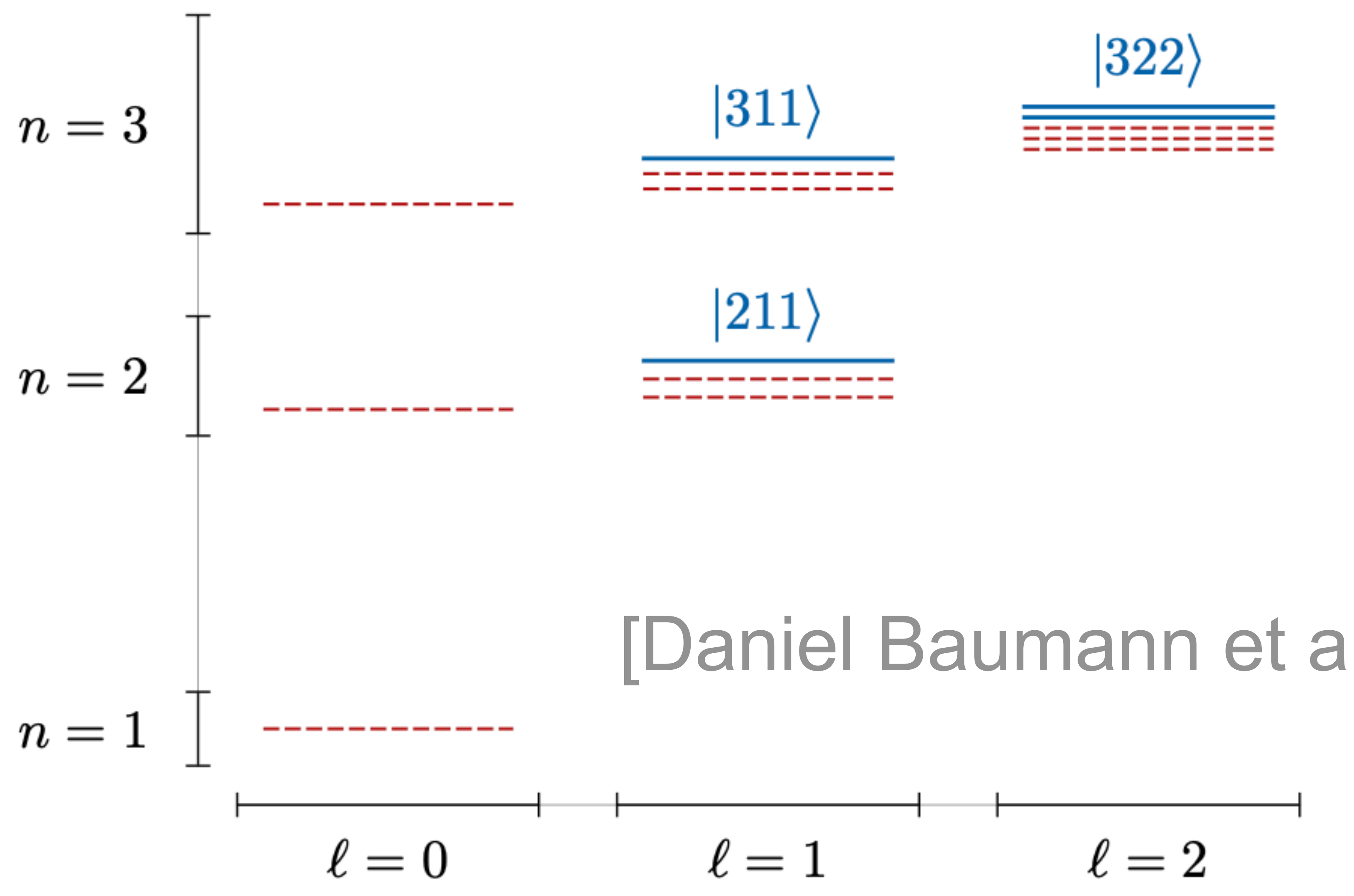
SR Energy level & Instability rate

Non-relativistic approximation (expansion in powers of α)

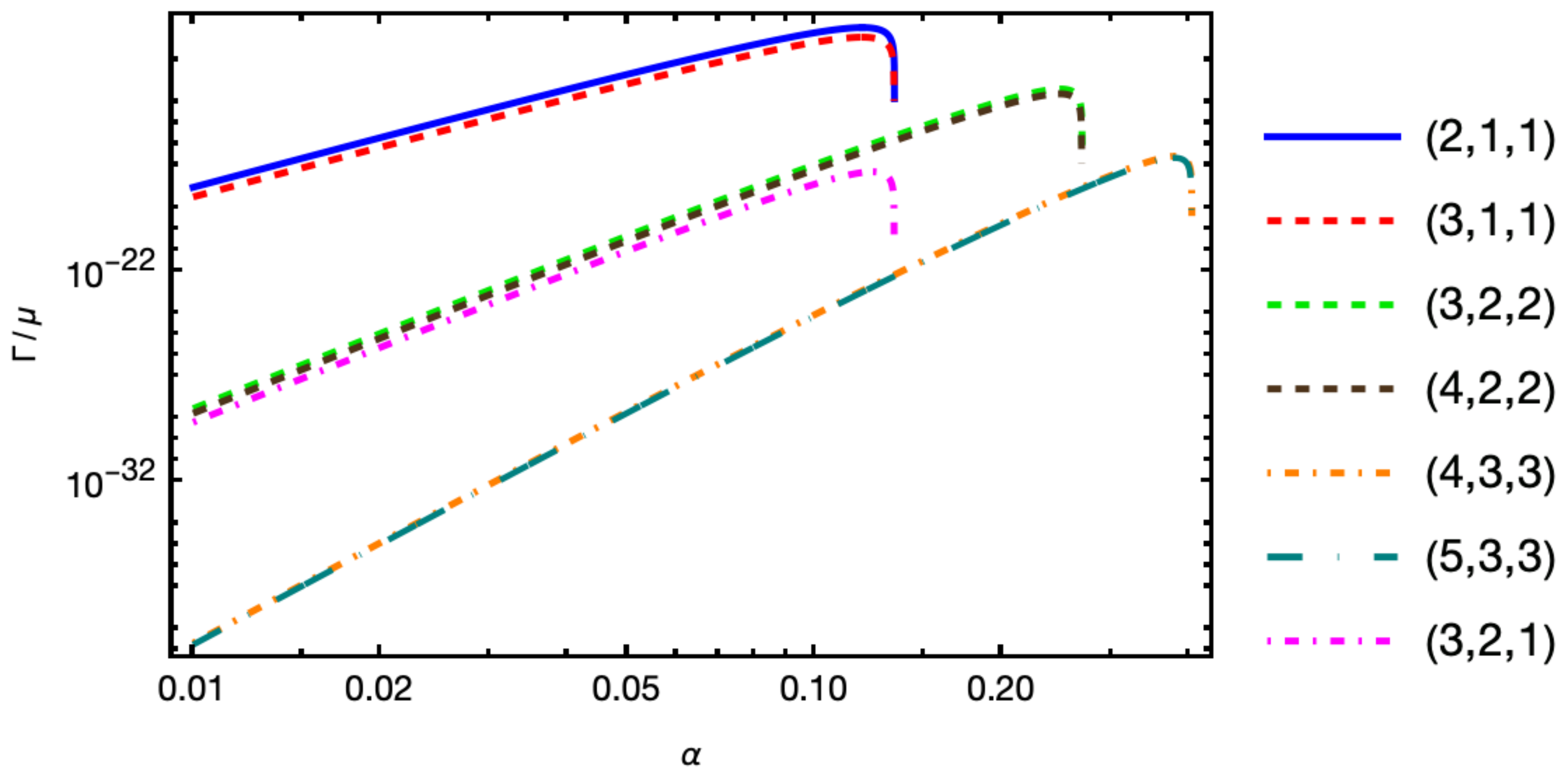
$$\omega_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - \frac{\alpha^4}{8n^4} - \frac{(3n-2\ell-1)\alpha^4}{n^4(\ell+1/2)} + \frac{2\tilde{a}m\alpha^5}{n^3\ell(\ell+1/2)(\ell+1)} + \mathcal{O}(\alpha^6)\right) + i\Gamma_{n\ell m}$$

$$\Gamma_{n\ell m} = \left(\frac{2r_+}{M}\right)\frac{2^{4\ell+1}(n+\ell)!}{n^{2\ell+4}(n-\ell-1)!}\left[\frac{\ell!}{(2\ell)!(2\ell+1)!}\right]^2 (m\Omega_H - \omega)\times\prod_{j=1}^{\ell}[j^2(1-\tilde{a})^2 + (\tilde{a}m - 2r_+\omega)^2]\alpha^{4\ell+5}$$

For $\mu \sim 10^{-14}\mathrm{eV} \sim 10 s^{-1}$, the typical growth time scale is $10^9\mathrm{yrs}$



[Daniel Baumann et al. 1908.10370]



Statisitical framewrok

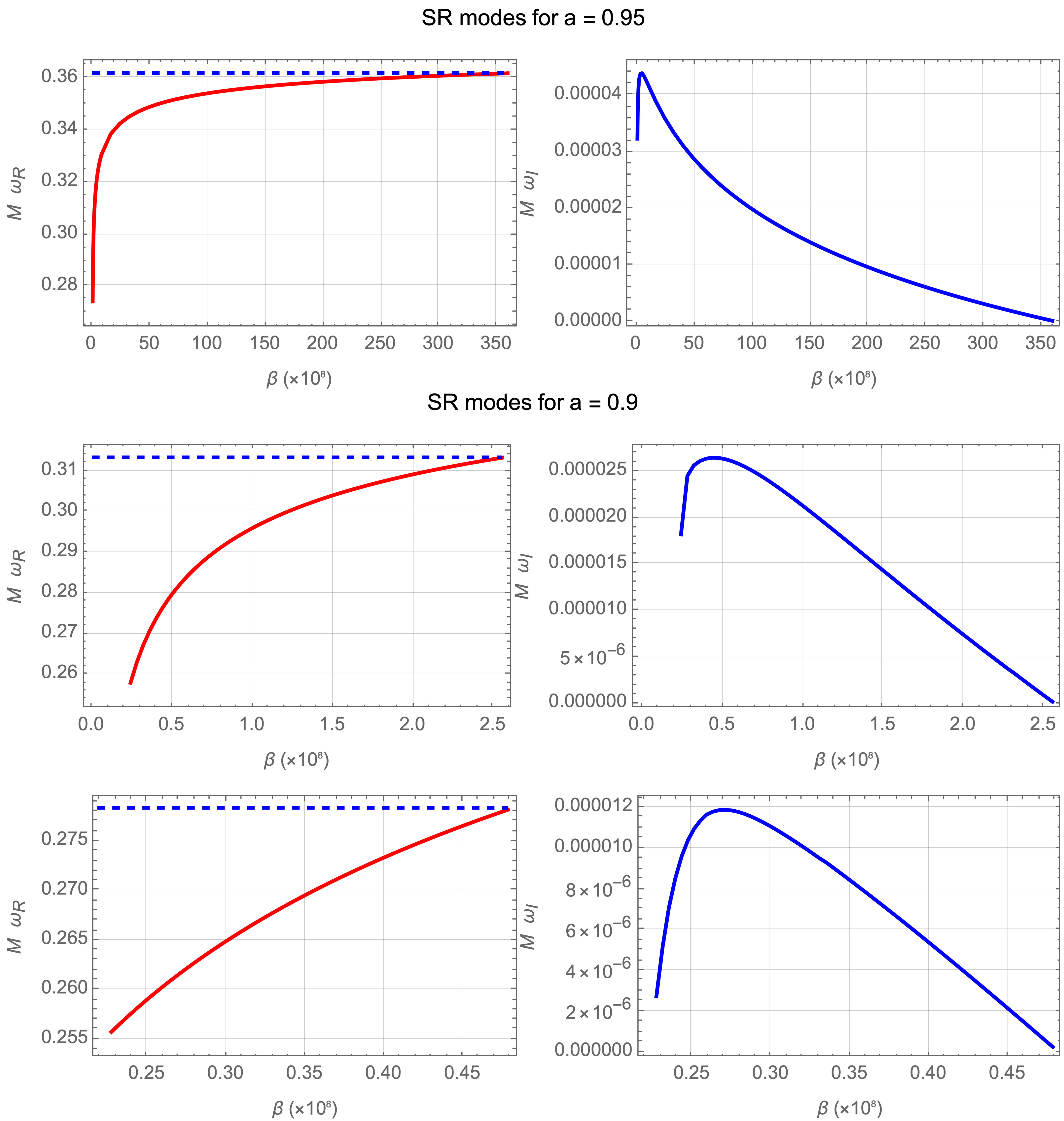
The central idea is to compute the posterior probability for our model parameters, which we denote as a vector α, given the observational data D from a BH measurement

$$
\begin{aligned}
p(\boldsymbol{\alpha}\,|\,D) &= \int p(\boldsymbol{\alpha}, \boldsymbol{\beta}_{\mathrm{BH}}\,|\,D)\,\mathrm{d}\boldsymbol{\beta}_{\mathrm{BH}} \\
&= \int p(\boldsymbol{\beta}_{\mathrm{BH}}\,|\,D)\,p(\boldsymbol{\alpha}\,|\,\boldsymbol{\beta}_{\mathrm{BH}}, \bar{D})\,\mathrm{d}\boldsymbol{\beta}_{\mathrm{BH}}\,. \\
&= p(\boldsymbol{\alpha}) \int p(\boldsymbol{\beta}_{\mathrm{BH}}\,|\,D)\,p(\tilde{a}\,|\,M, \boldsymbol{\alpha})\,\mathrm{d}\boldsymbol{\beta}_{\mathrm{BH}} \\
&\approx \frac{p(\boldsymbol{\alpha})}{N} \sum_{i=1}^{N} \Theta(\tilde{a}^{\text{crit}}(M^i; \boldsymbol{\alpha}) - \tilde{a}^i)\,.
\end{aligned}
$$

[Sebastian Hoof et.al. 2406.1033]

- Slash: removal of the redundant dependence on the data D
- Bayes' theorem: $p(\boldsymbol{\alpha}\,|\,\boldsymbol{\beta}_{\mathrm{BH}}, \bar{D}) = p(\boldsymbol{\beta}_{\mathrm{BH}}\,|\,\boldsymbol{\alpha})p(\boldsymbol{\alpha})/p(\boldsymbol{\beta}_{\mathrm{BH}})$
- The physical properties of the BH only depend on the model parameters through the superradiance condition, allowing us to factorize the likelihood as $p(\boldsymbol{\beta}_{\mathrm{BH}}\,|\,\boldsymbol{\alpha}) = p(\boldsymbol{\beta}_{\mathrm{BH}})p(\tilde{a}\,|\,M, \boldsymbol{\alpha})$
- The exclusion condition $\tilde{a} > \tilde{a}^{\mathrm{crit}}$ can be encoded in the likelihood of observing a BH with spin $\tilde{a}$, given its mass M and our model parameters $\boldsymbol{\alpha}$
- This likelihood can be expressed as a Heaviside step function: $p(\tilde{a}\,|\,M, \boldsymbol{\alpha}) = \Theta(\tilde{a}^{\mathrm{crit}}(M, \tau_{\mathrm{BH}}, \ldots; \boldsymbol{\alpha}) - \tilde{a})$

$$\tau_{\mathrm{SR}} < \tau_{\mathrm{BH}}/\ln N_{\max} \quad N_{\max} \approx 10^{76} \left(\frac{1}{m}\right) \left(\frac{\Delta\tilde{a}}{0.1}\right) \left(\frac{M}{10\mathrm{M}_{\odot}}\right)^2$$


SR modes for a = 0.95
M ωR
M ωI
β (×10⁸)
SR modes for a = 0.9
M ωR
M ωI
β (×10⁸)
M ωR
M ωI
β (×10⁸)