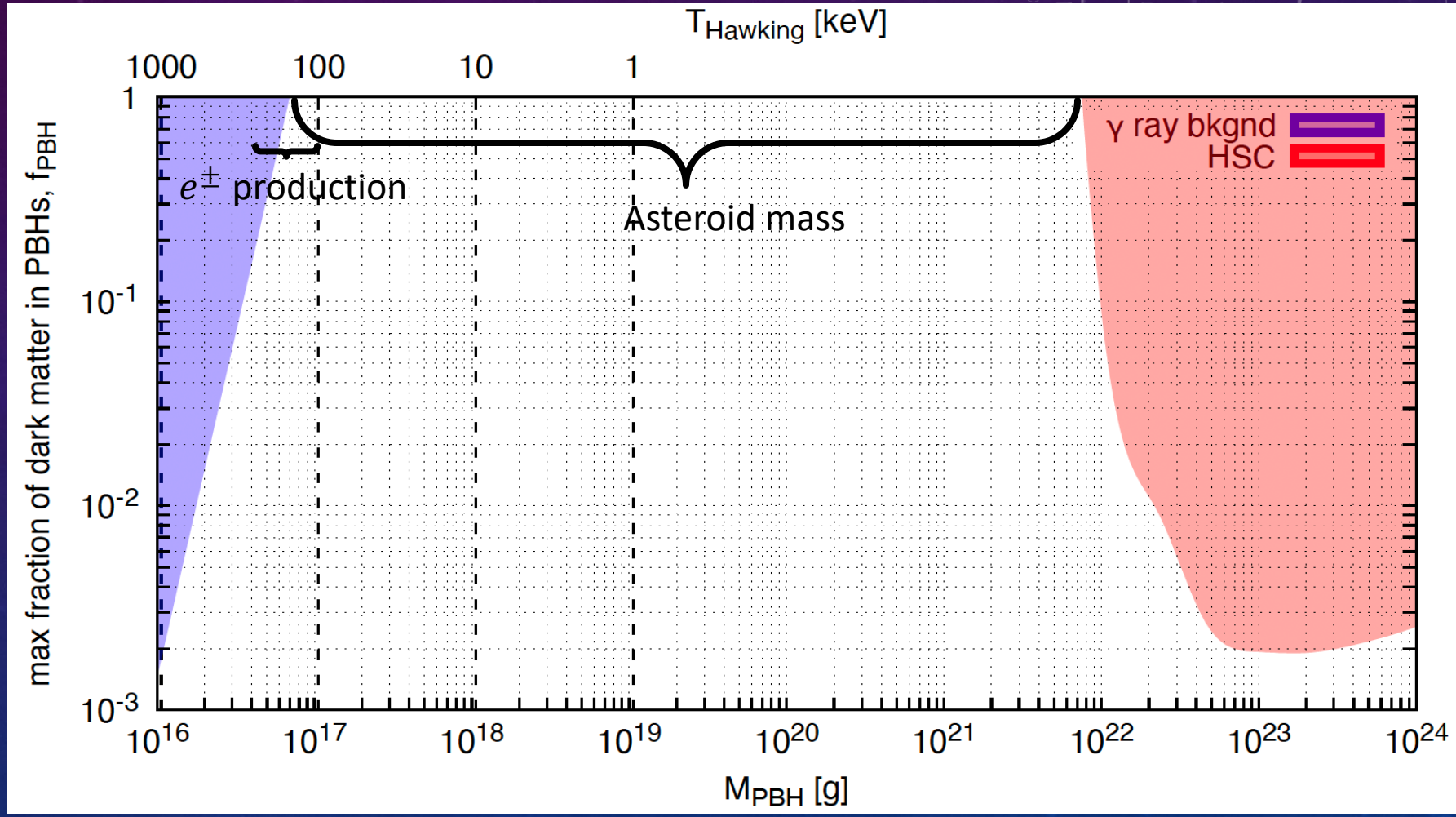
Primordial black hole (PBH) Hawking radiation: QED effects

Makana Silva, Gabriel Vasquez, Emily Koivu, Arijit Das, Christopher Hirata
Ohio State University
arXiv: 2210.01914/PRD: 107, 045004

PHENOMENOLOGY 2023 SYMPOSIUM

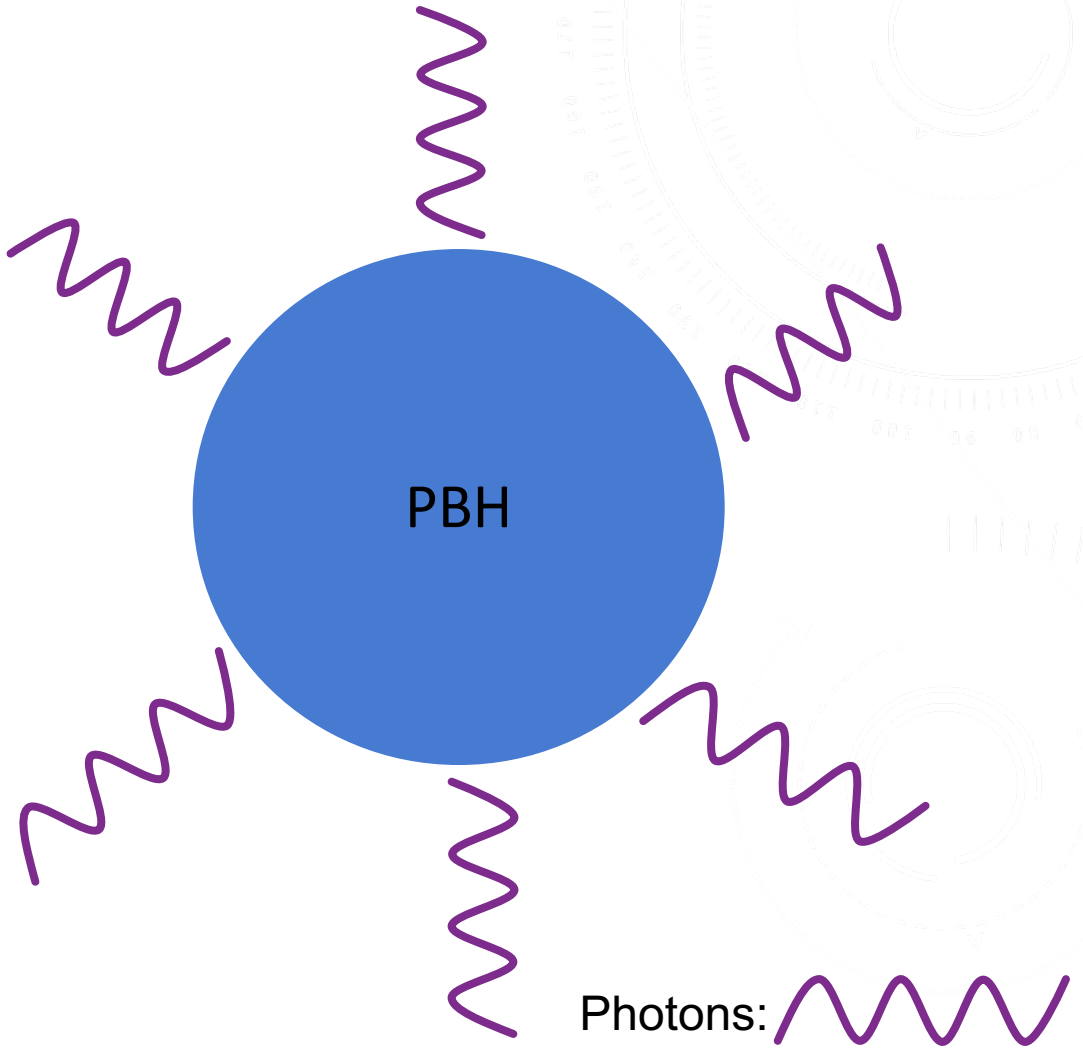
PRIMORDIAL BLACK HOLES

- Formed in early Universe
- Candidate for DM within Standard Model physics *(Montero-Camacho et. al., 2019)*
- $t_{evap} \sim 10^{67} \left(\frac{M}{M_\odot}\right)^3 years$



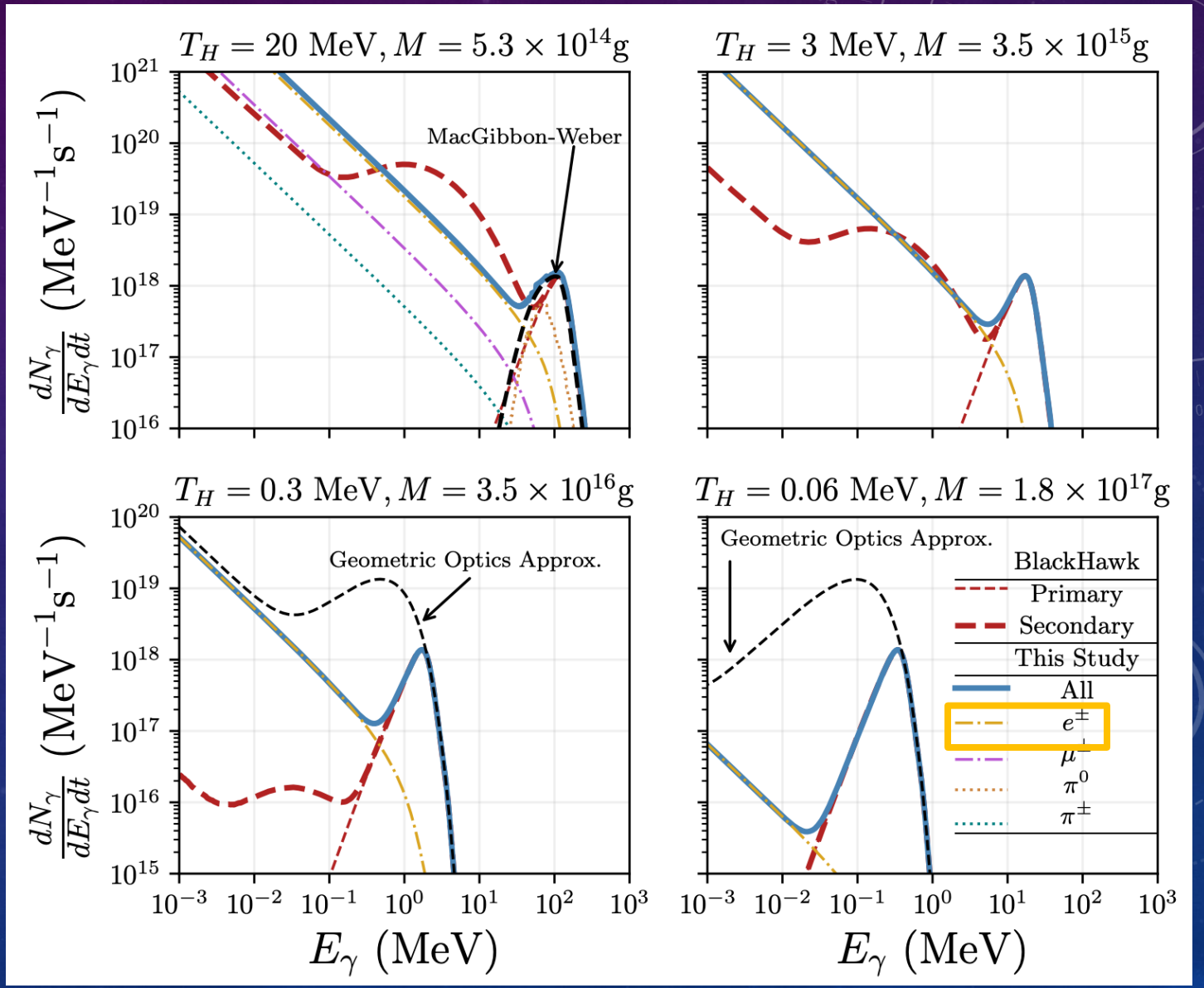
HAWKING RADIATION

- Black holes have temperature → *Hawking radiation (Hawking, 1975)*
- $T_{Hawking} = \frac{c^3\hbar}{Gk_b}\frac{1}{8\pi M}$ → Smaller masses = high temperature
- $M < 10^{17} g$ *(*$T_{Hawking} \sim 100$ *keV),* thermal emission of electron-positron pairs



CORRECTIONS TO HAWKING RADIATION

- ***Interactions*** ($O(\alpha)$ corrections) could produce dominant signal for lower mass range of asteroid mass PBHs *(Coogan et. al., 2019)*



COOGAN ET. AL., 2019

- $O(\alpha)$ correction to Hawking radiation in flat spacetime
- Various particles ($e^{\pm}, \pi^{\pm}$, etc.)

OUR WORK

- Analytic expression for $O(\alpha)$ correction using quantum electrodynamics in curved spacetime (Schwarzschild)
- Only $e^{\pm}$

High energy surveys could provide constraints on PBH DM from interactive QED effects

NASA, 2020

$$\left.\frac{dN_\gamma^{(1)}}{dt\,d\omega}\right|_{\rm diss} = \frac{1}{2\pi}\sum_{\ell m_\gamma p}\frac{d}{dt}\langle \hat{a}^\dagger_{{\rm out},\ell m_\gamma\omega(p)}\hat{a}_{{\rm out},\ell m_\gamma\omega(p)}\rangle_{\rm diss}$$

$$= \frac{e^2}{2\pi}\sum_{\ell=1}^{\infty}\sum_p\int\frac{dh}{2\pi}\sum_{kk'}\Delta(j,j',\ell)\delta_{ss'(-1)^{k+k'+\ell},(-1)^p}$$

$$\times\Bigg[|R_{1,\ell,\omega}|^2\Bigg\{\frac{2}{e^{8\pi M(\omega+h)}+1}|[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]|^2$$

$$+\frac{1}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega-h)}+1)}|[\![I^{++}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]|^2$$

$$+\frac{2e^{8\pi Mh}}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega+h)}+1)}|[\![I^{-+}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]|^2\Bigg\}$$

$$+\frac{|T_{1,\ell,\omega}|^2}{e^{8\pi M\omega}-1}\Bigg\{-|[\![I^{++}_{{\rm in},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!]|^2+\frac{2e^{8\pi M\omega}}{e^{8\pi M(\omega+h)}+1}|[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!]|^2$$

$$-\frac{2}{e^{8\pi Mh}+1}\Big(e^{8\pi Mh}|[\![I^{++}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!]|^2+|[\![I^{-+}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!]|^2\Big)\Bigg\}+$$

$$+{\rm Re}\,T^*_{1,\ell,\omega}R_{1,\ell,\omega}\Bigg[\frac{2(2e^{8\pi M\omega}-1)}{(e^{8\pi M(\omega+h)}+1)(e^{8\pi M\omega}-1)}[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm in},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]$$

$$+\frac{1}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega-h)}+1)}[\![I^{++}_{{\rm up},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2e^{8\pi Mh}}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega+h)}+1)}[\![I^{-+}_{{\rm up},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]$$

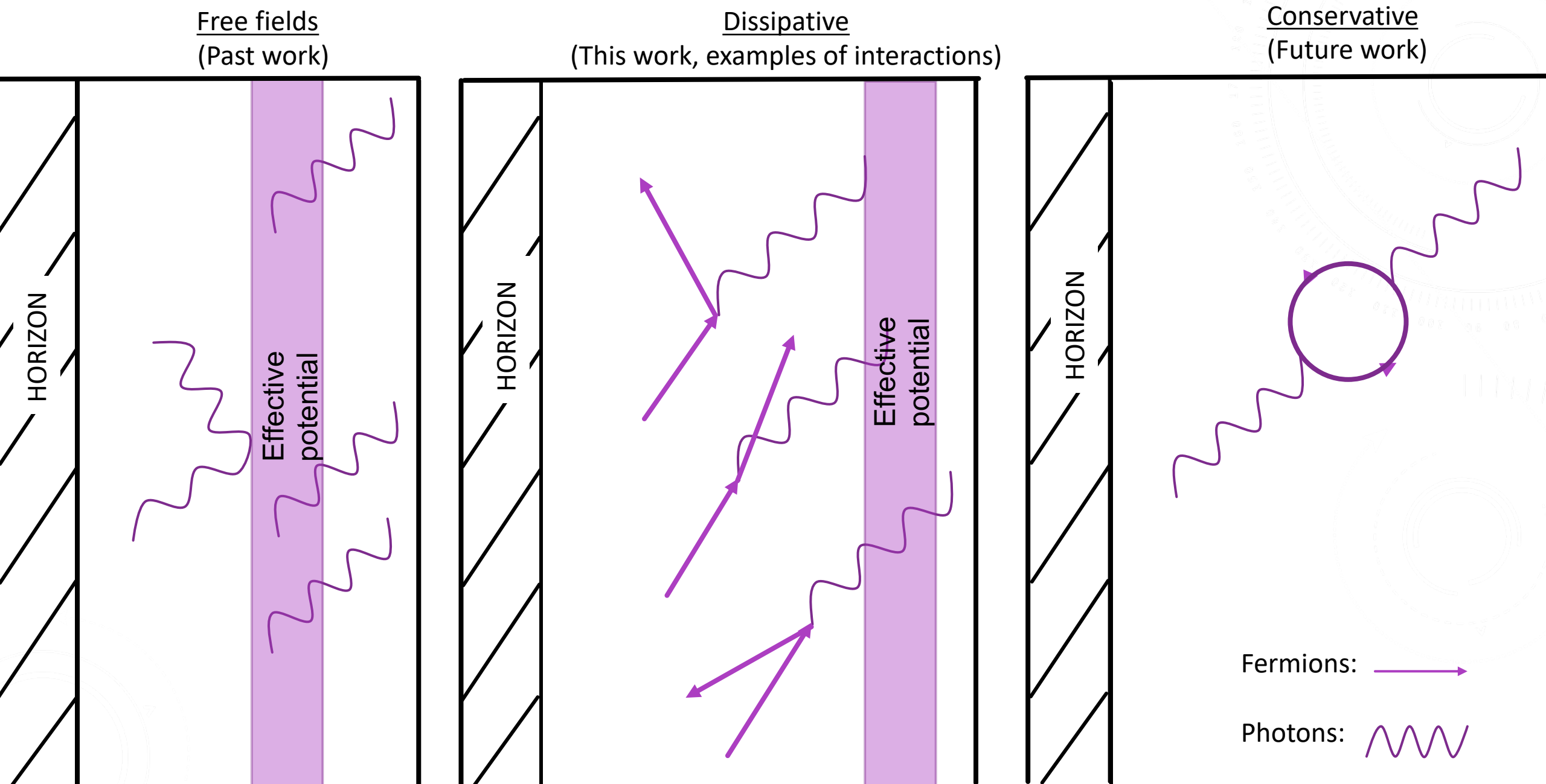
$$-\frac{1}{e^{8\pi M\omega}-1}\Big([\![I^{++}_{{\rm in},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm in},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2e^{8\pi Mh}}{e^{8\pi Mh}+1}[\![I^{++}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm up},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2}{e^{8\pi Mh}+1}[\![I^{-+}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm up},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]\Big)\Bigg]\Bigg],$$

- $O(\alpha)$ correction to Hawking spectrum
- Photons escaping BH
- It's a lot…

Types of QED interactions near horizon



$$\left.\frac{dN_\gamma^{(1)}}{dt\,d\omega}\right|_{\rm diss} = \frac{1}{2\pi}\sum_{\ell m_\gamma p}\frac{d}{dt}\langle \hat{a}^\dagger_{{\rm out},\ell m_\gamma \omega(p)}\hat{a}_{{\rm out},\ell m_\gamma\omega(p)}\rangle_{\rm diss}$$

$$= \frac{e^2}{2\pi}\sum_{\ell=1}^{\infty}\sum_p\int\frac{dh}{2\pi}\sum_{kk'}\Delta(j,j',\ell)\delta_{ss'(-1)^{k+k'+\ell},(-1)^p}$$

$$\times\Big[|R_{1,\ell,\omega}|^2\Big\{\frac{2}{e^{8\pi M(\omega+h)}+1}|[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]|^2$$

$$+\frac{1}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega-h)}+1)}|[\![I^{++}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]|^2$$

$$+\frac{2e^{8\pi Mh}}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega+h)}+1)}|[\![I^{-+}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]|^2\Big\}$$

$$+\frac{|T_{1,\ell,\omega}|^2}{e^{8\pi M\omega}-1}\Big\{-|[\![I^{++}_{{\rm in},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!]|^2+\frac{2e^{8\pi M\omega}}{e^{8\pi M(\omega+h)}+1}|[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!]|^2$$

$$-\frac{2}{e^{8\pi Mh}+1}\Big(e^{8\pi Mh}|[\![I^{++}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!]|^2+|[\![I^{-+}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!]|^2\Big)\Big\}+$$

$$+{\rm Re}\,T^*_{1,\ell,\omega}R_{1,\ell,\omega}\Big[\frac{2(2e^{8\pi M\omega}-1)}{(e^{8\pi M(\omega+h)}+1)(e^{8\pi M\omega}-1)}[\![I^{-+}_{{\rm in},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm in},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]$$

$$+\frac{1}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega-h)}+1)}[\![I^{++}_{{\rm up},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2e^{8\pi Mh}}{(e^{8\pi Mh}+1)(e^{8\pi M(\omega+h)}+1)}[\![I^{-+}_{{\rm up},k,{\rm up},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm up},k,{\rm up},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]$$

$$-\frac{1}{e^{8\pi M\omega}-1}\Big([\![I^{++}_{{\rm in},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm in},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2e^{8\pi Mh}}{e^{8\pi Mh}+1}[\![I^{++}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega-h,\omega)]\!][\![I^{++*}_{{\rm up},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega-h,\omega)]\!]$$

$$+\frac{2}{e^{8\pi Mh}+1}[\![I^{-+}_{{\rm up},k,{\rm in},k',{\rm up},\ell,(p)}(h,\omega+h,\omega)]\!][\![I^{-+*}_{{\rm up},k,{\rm in},k',{\rm in},\ell,(p)}(h,\omega+h,\omega)]\!]\Big)\Big]\Big],$$

$|R_{1,\ell,\omega}|^2$ reflection to horizon

$|T_{1,\ell,\omega}|^2$ transmission to infinity (escapes BH)

$Re\{R_{1,\ell,\omega}T^\star_{1,\ell,\omega}\}$ interference of both processes

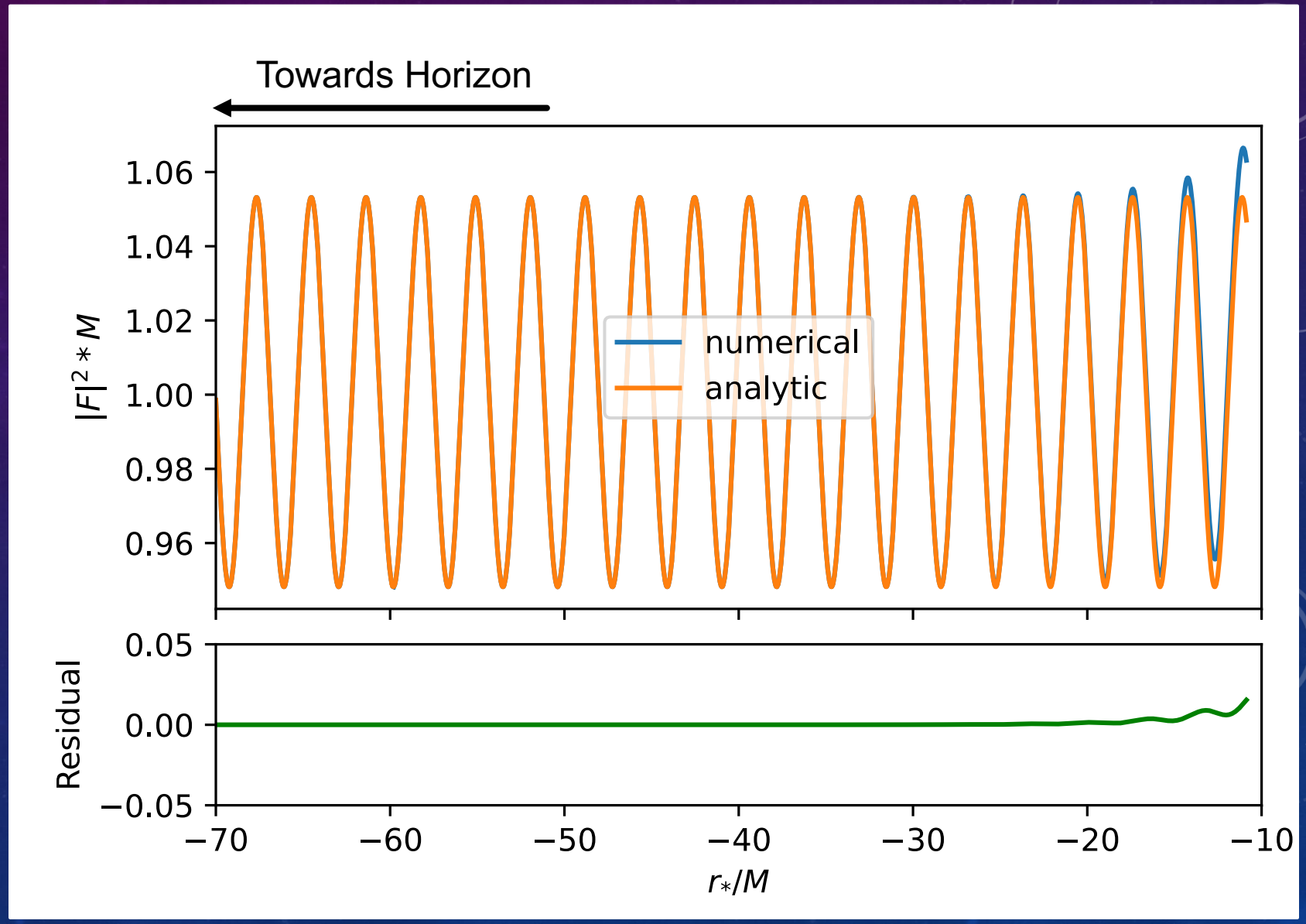
Pair production and bremsstrahlung interactions

Dissipative Interactions

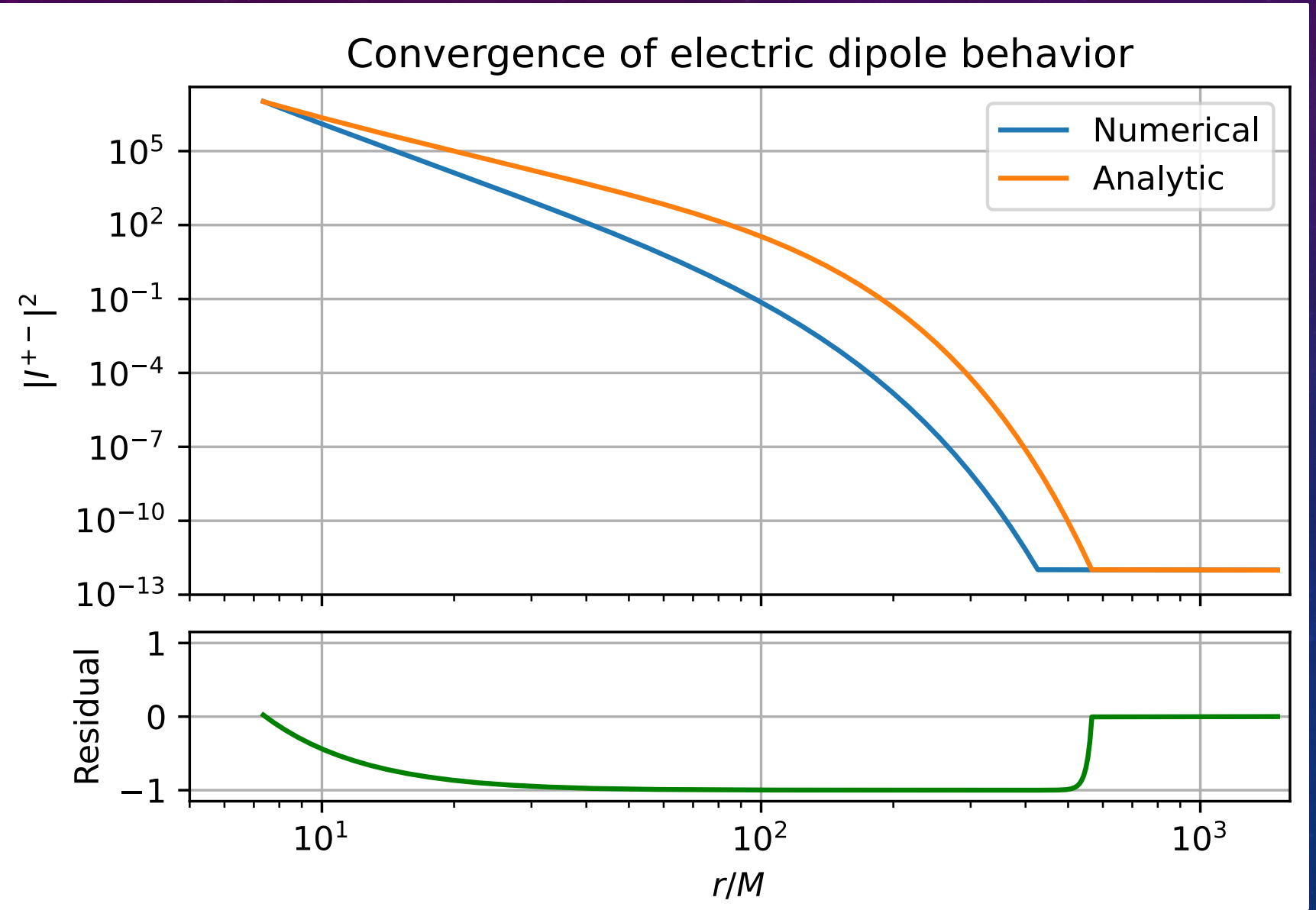
Numerical results coming soon…

CHECKS: Numeric and analytic expressions

- Wavefunctions required for corrected spectra
- Electron and photon wavefunctions near/far from horizon
- Scattering solutions



CHECKS: ELECTRIC DIPOLE TRANSITION

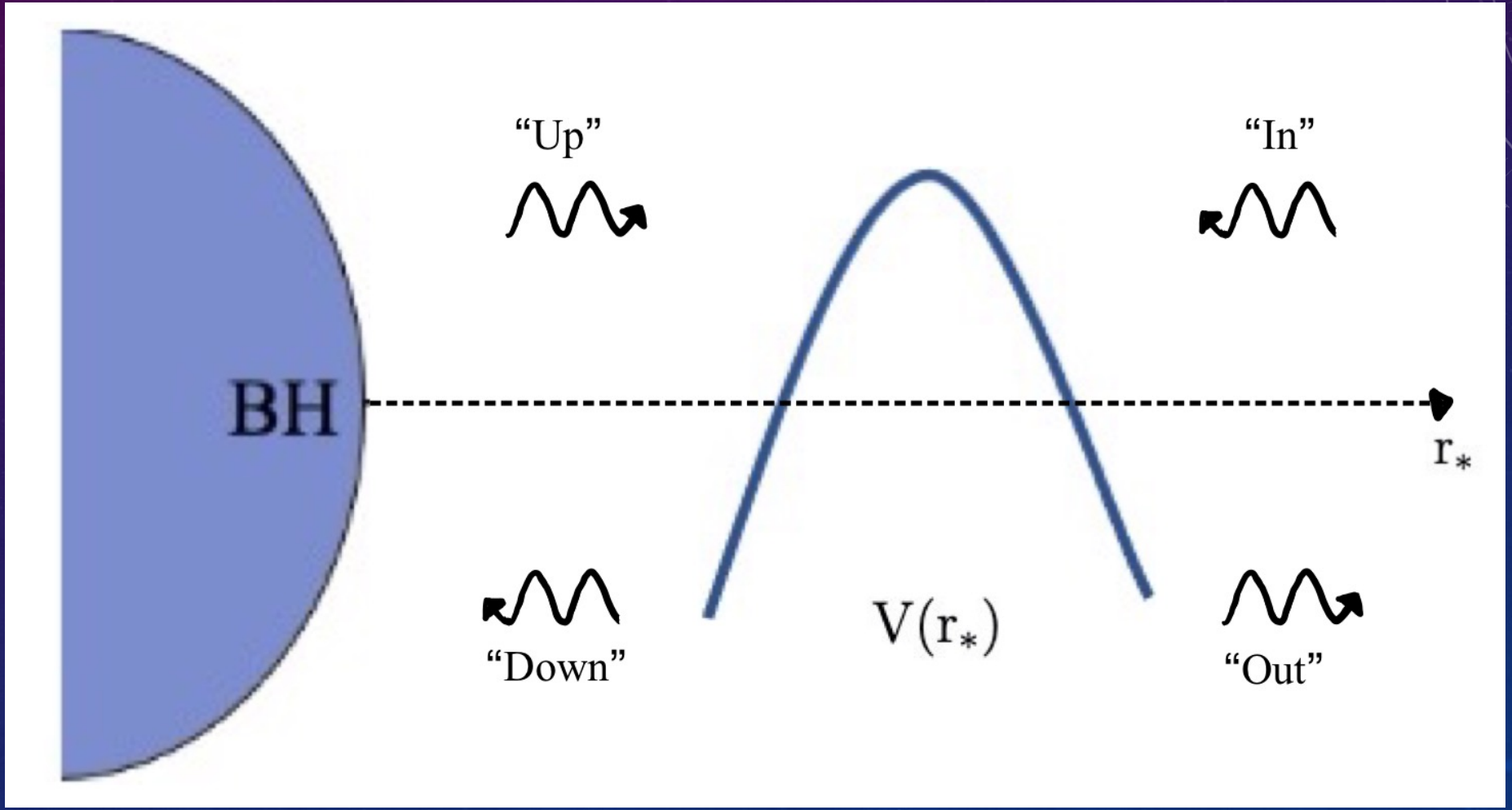


- Flat spacetime vs our calculation
- Low frequency ($\omega M \ll 1$)
- Far field ($\frac{r}{M} \ll 1$)

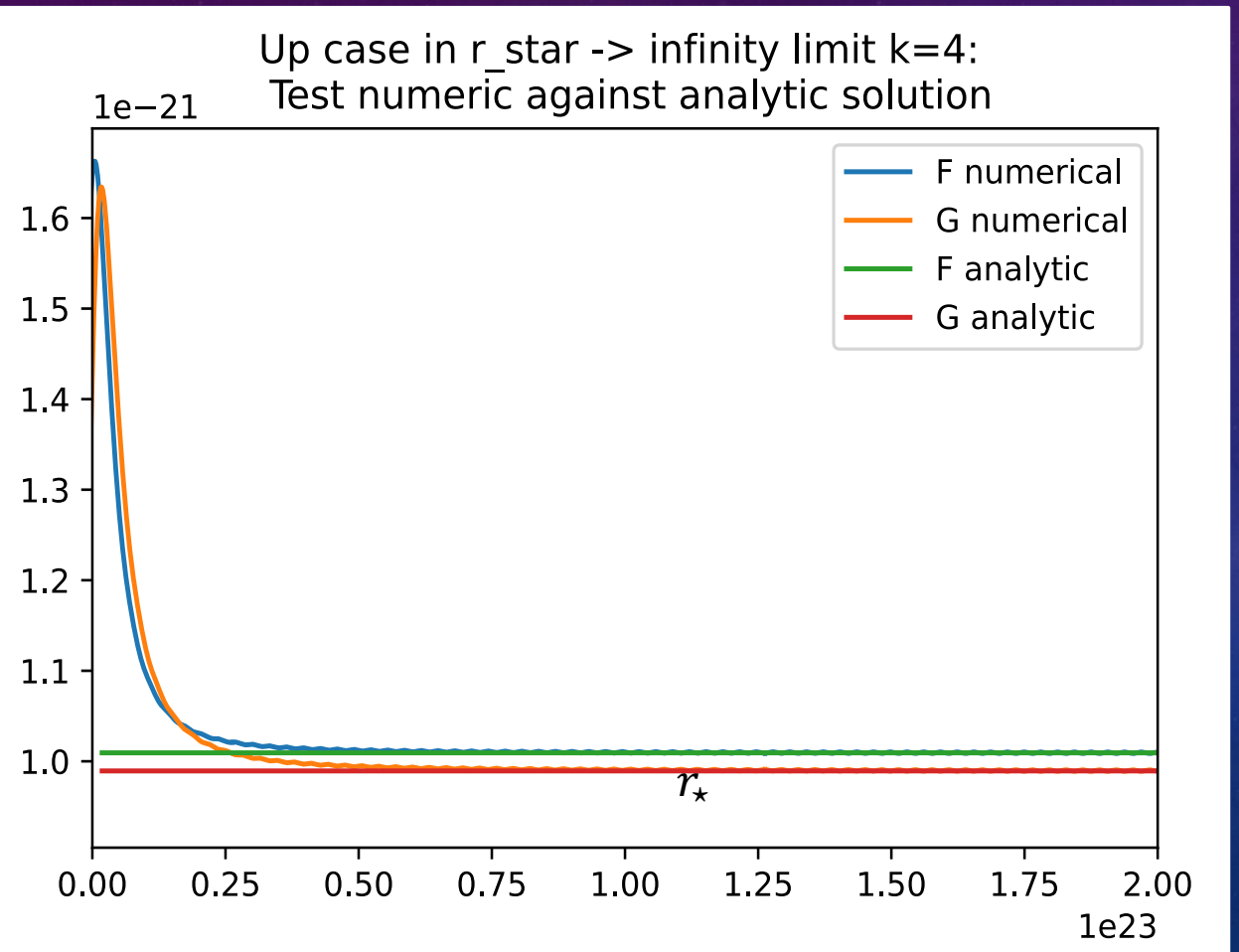
CONCLUSIONS

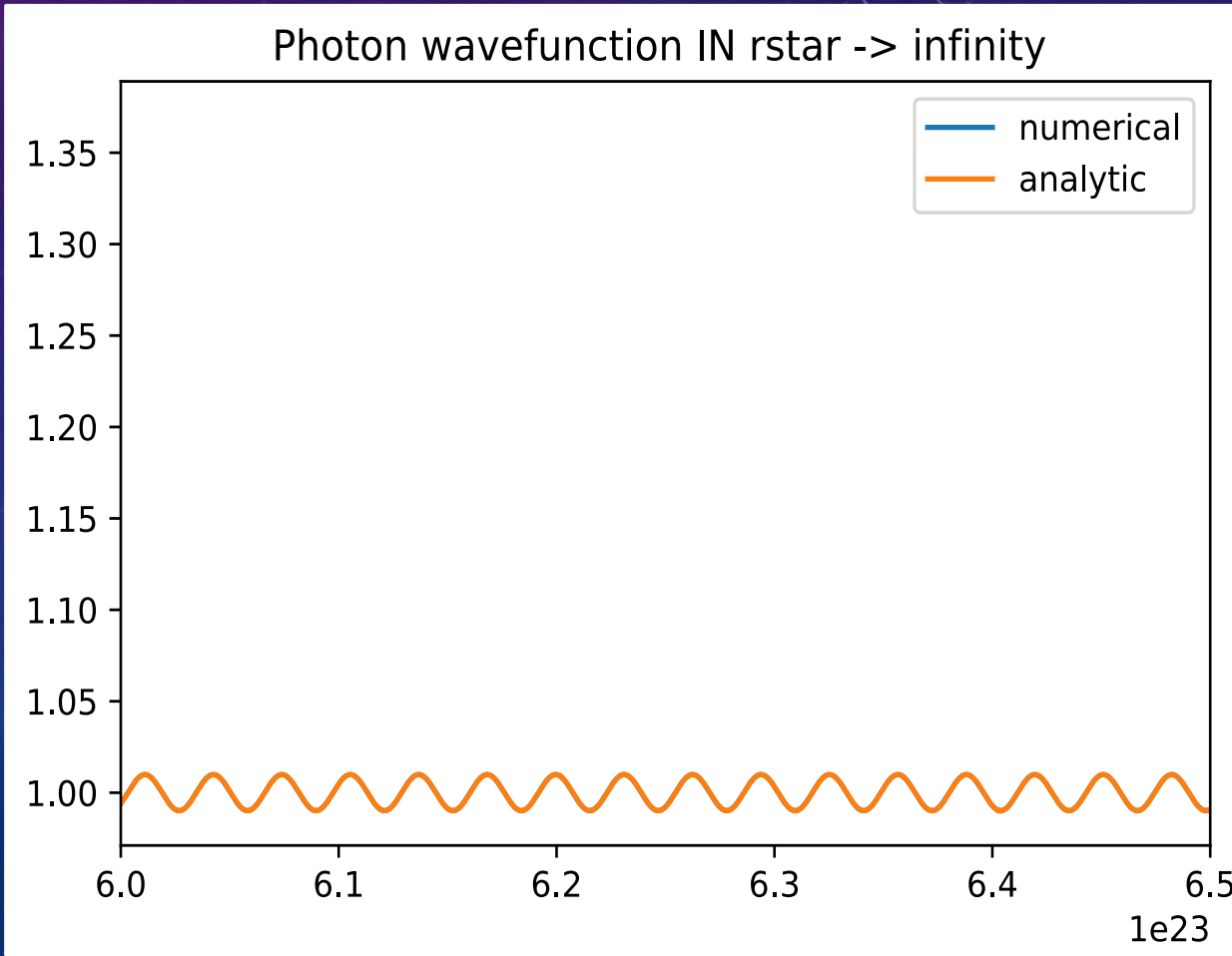
- Only the beginning…
- Compute corrected spectra over PBH asteroid mass range
- Account for conservative interactions (vacuum polarization; renormalization)
- Compute correction to Hawking spectra for spinning (Kerr) black holes
- Takeaway: ***Rigorous corrections to Hawking radiation could constrain PBHs as DM candidate via MeV surveys***

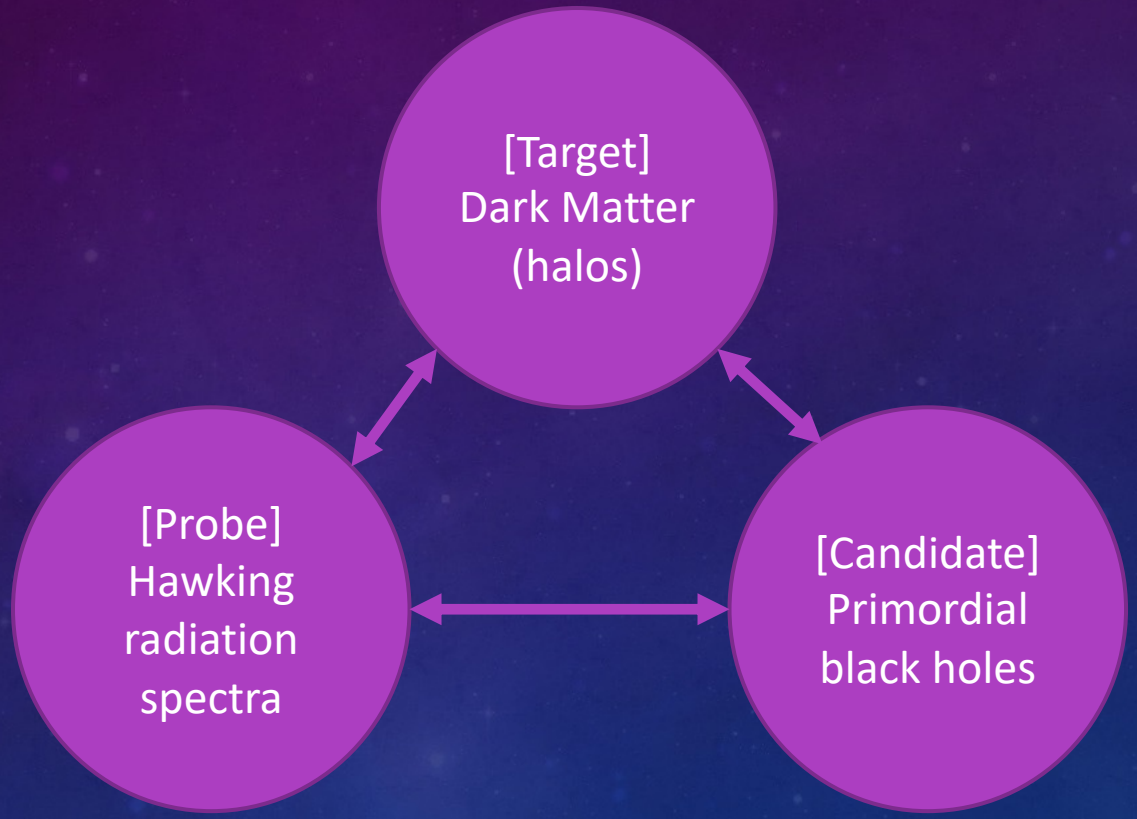
MODES FOR WAVEFUNCTIONS



RESULTS: Limiting Cases






[Target]
Dark Matter
(halos)
[Probe]
Hawking
radiation
spectra
[Candidate]
Primordial
black holes