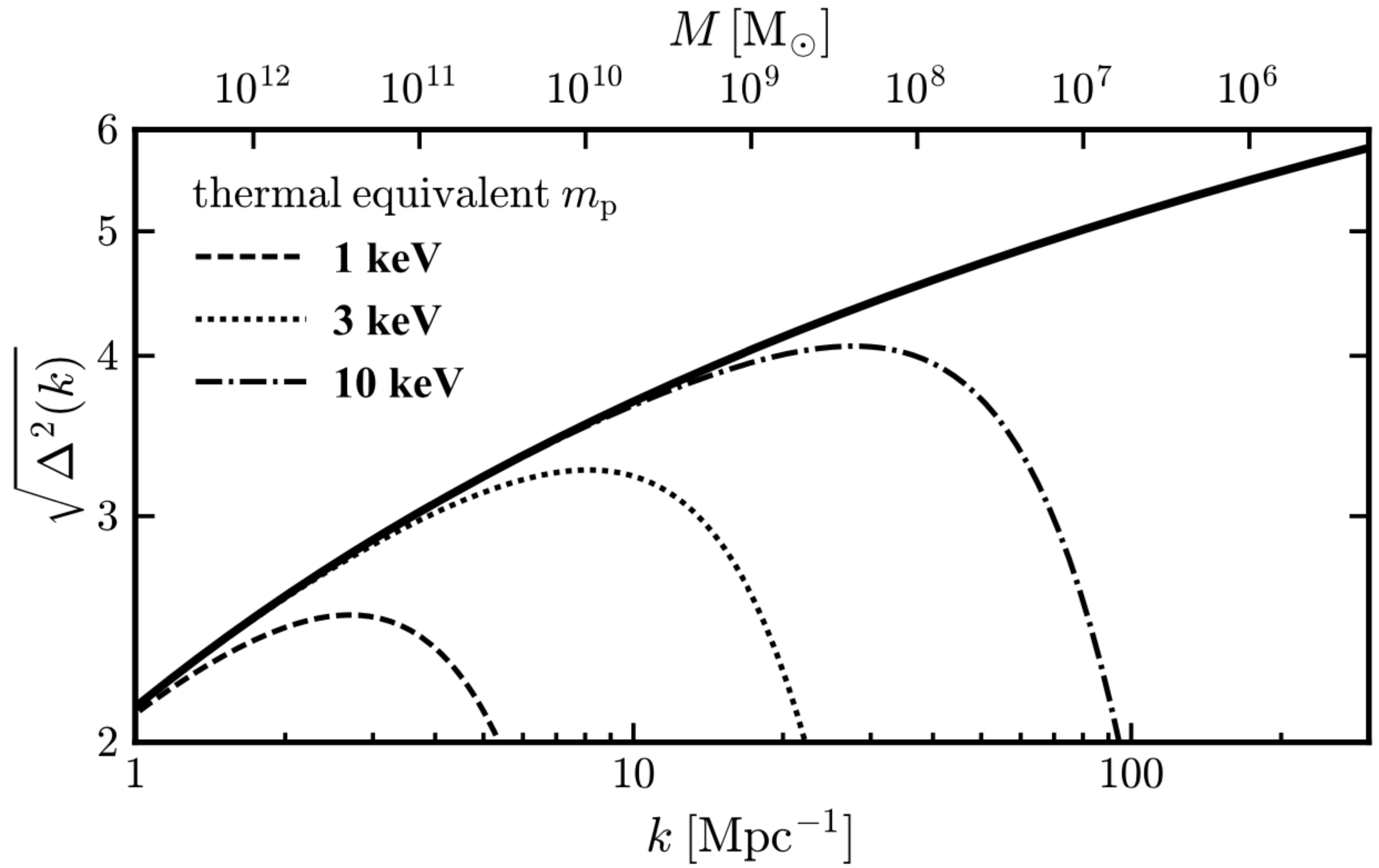
Looking for cold dark matter (CDM) subhalos with gravitational waves (GW)

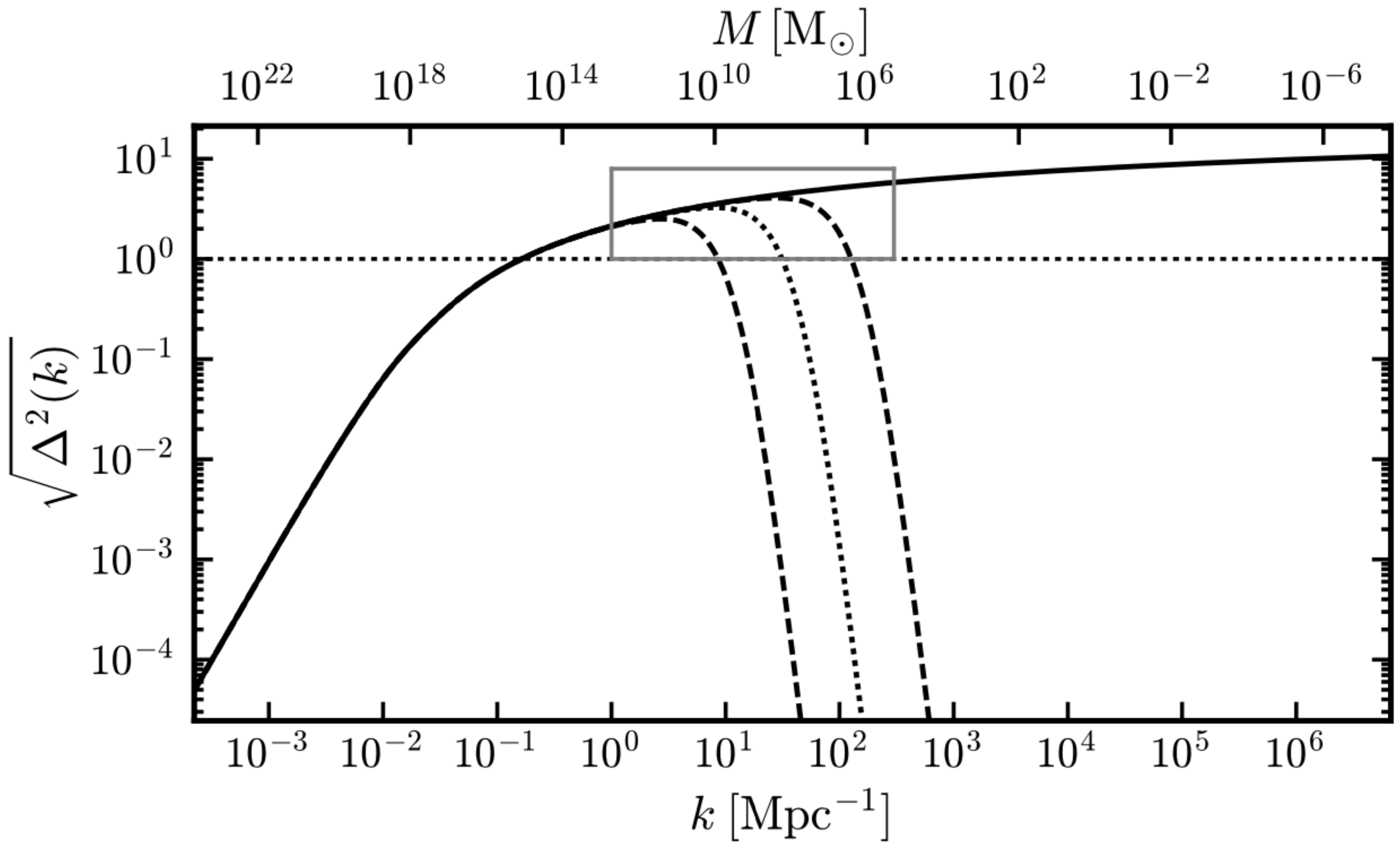
Juan Urrutia, PhD student, 2022, based on work done with Ville Vaskonen and Malcom Fairbairn

Why light DM halos are very relevant?

It is a unique prediction of CDM

Adiabatic fluctuations become linear and collapse in halos of the mass that is inside the collapsed volume.





https://arxiv.org/abs/1707.04256

Amplification function only wave effects

Light halos do not to produce more than one classical path

$$\phi_{\text{lensed}}(f) = F(f, y)\phi_{\text{unlensed}}(f)$$

How does it work?

Compute the propagator of the GW

$$\phi_{t_f} = A \prod_i \int dq_i \, e^{iS(q,t_o,t_f)} \phi_{t_o}$$

$$\phi_f(f) = F(f, y, \rho(x)) \, \phi_o(f)$$

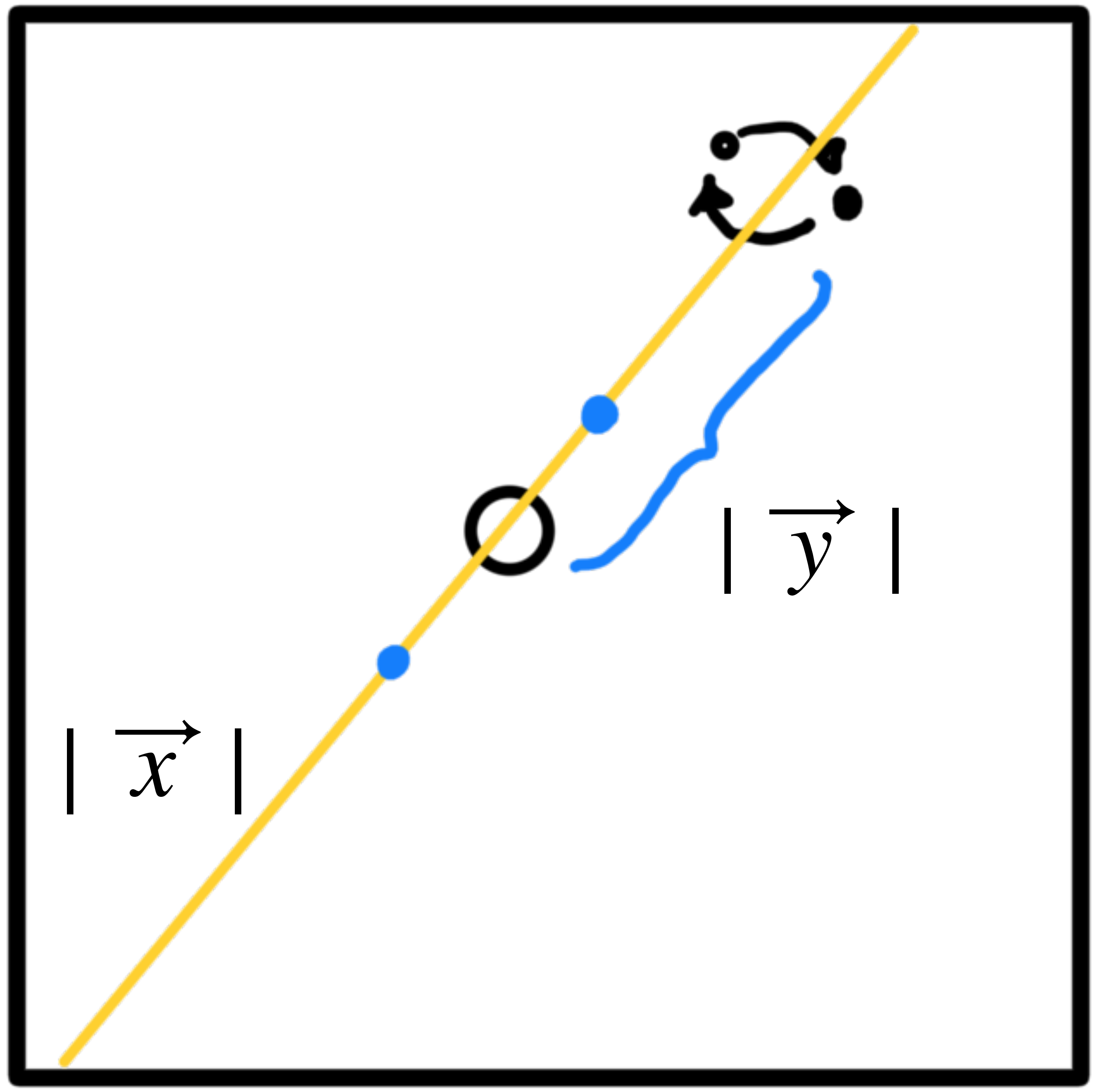
$$F = \frac{w}{2\pi i} \int_{\text{lensplane}} d\vec{x} \, e^{iwt_d(x,y)} \longrightarrow w = 8\pi M_l f \longrightarrow 8\pi M_1 R \frac{1}{\hbar}$$

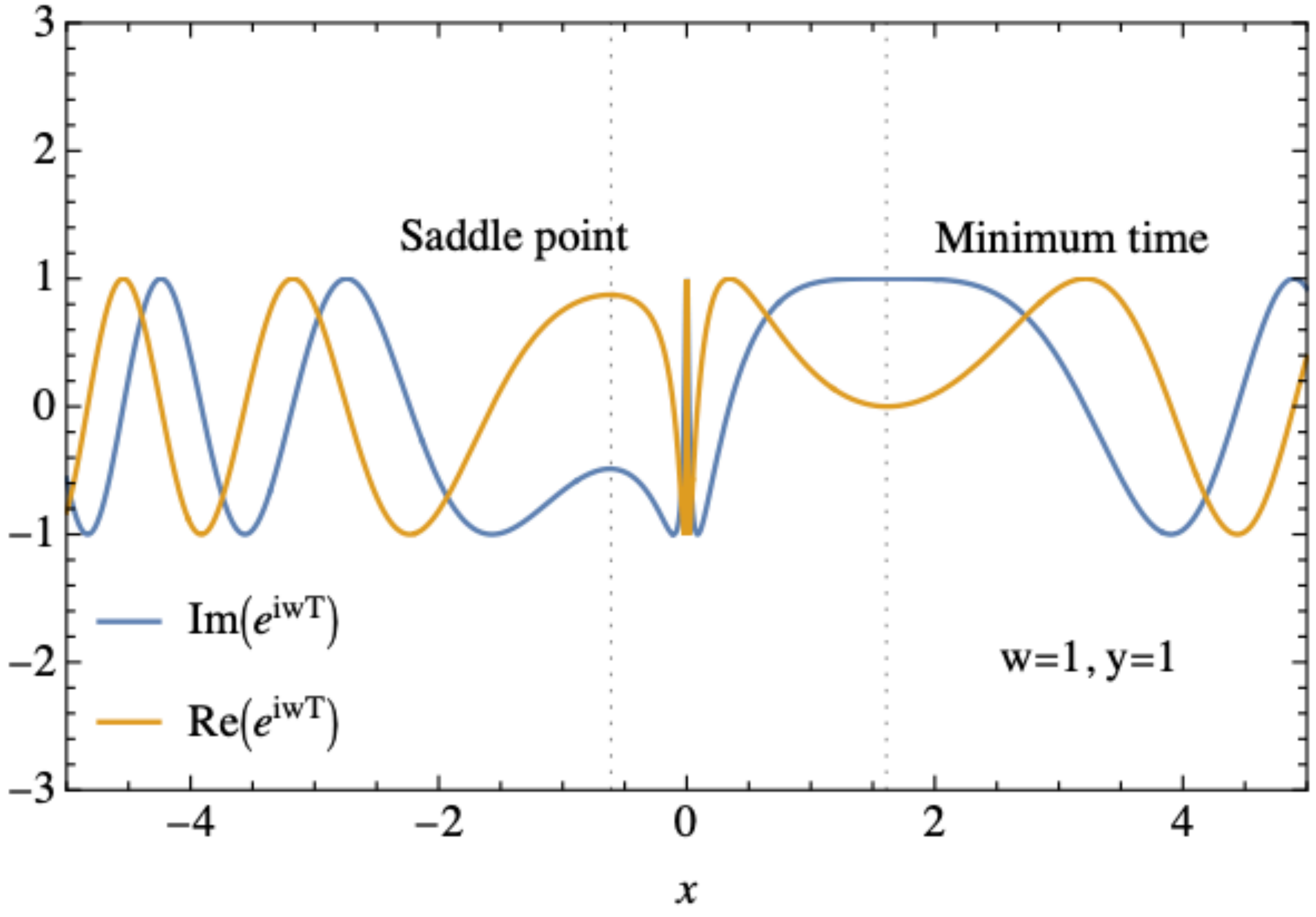
Heavier masses can be “released" to an smaller $\hbar$ so everything is going to behave more classically or less wavy

How does it work?
Wave vs classical behavior

Good for a PBH

$$\rho(r) = M_l \delta^2(x) \longrightarrow \Psi(x) = \log x \qquad M_{\mathrm{Lz}} \sim \mathcal{O}\left(1 M_\odot\right)$$





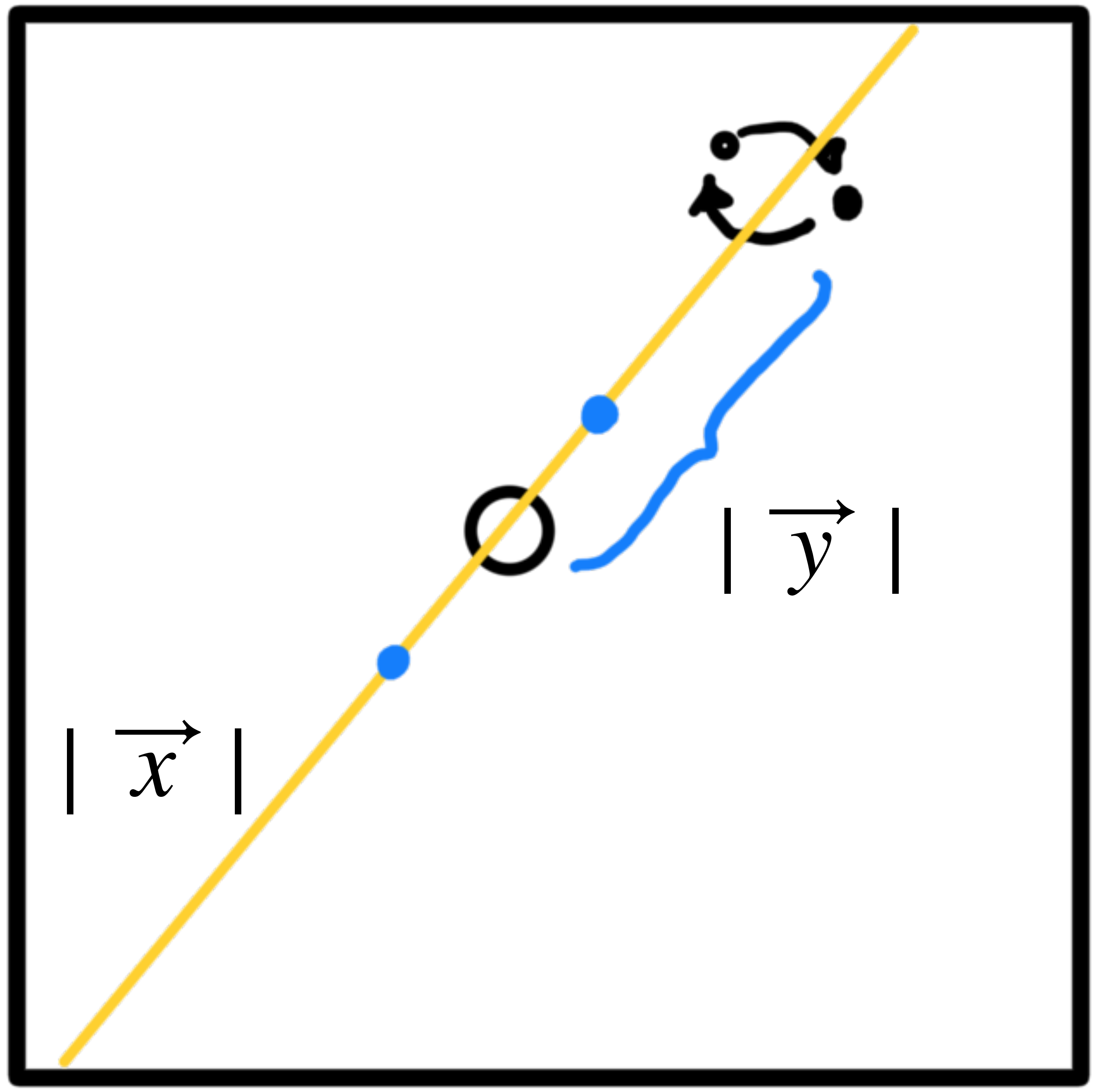
How does it work?

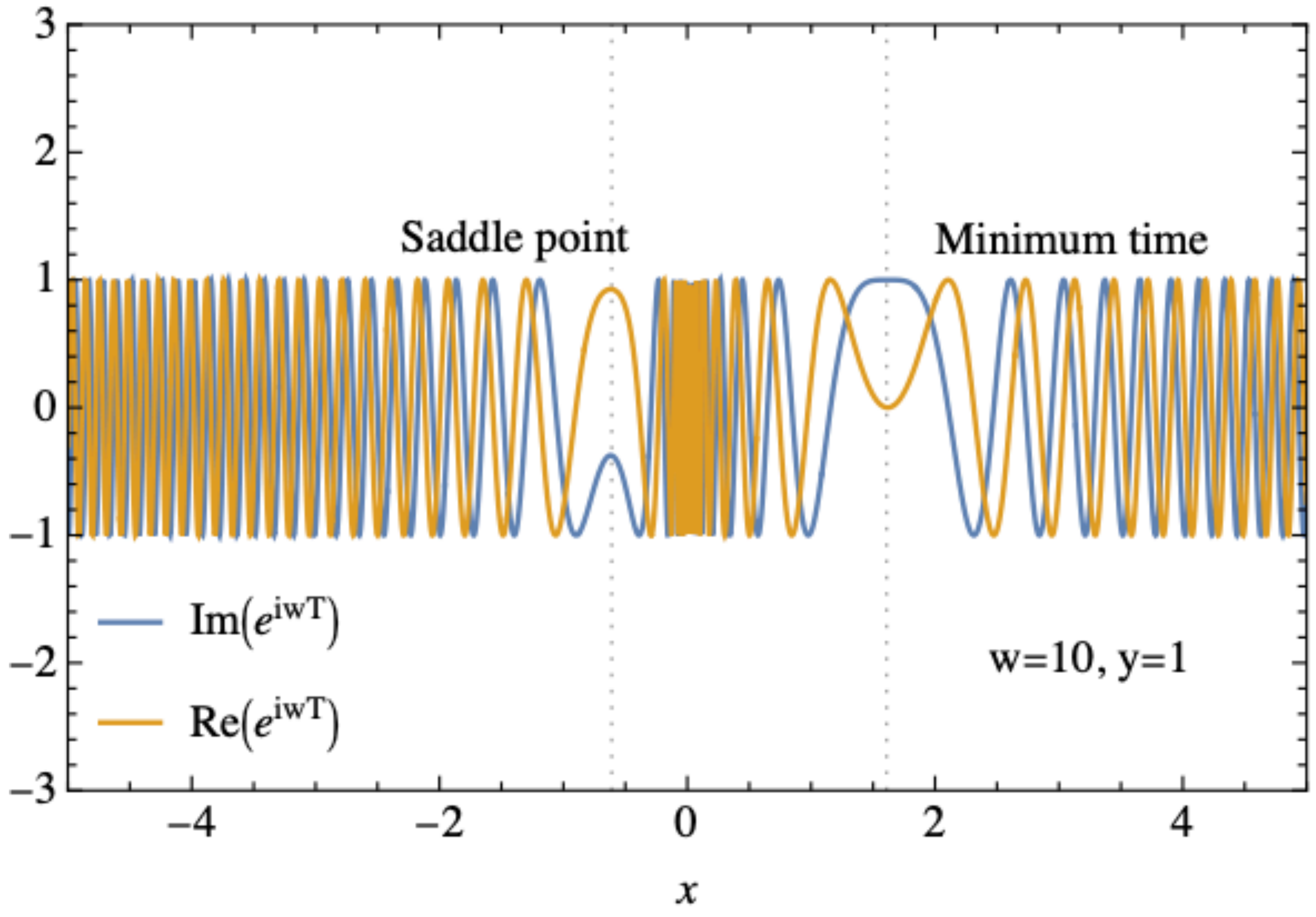
Wave vs classical behavior

Only the classical paths contribute to the integral

$\rho(r) = M_l \delta^2(x) \longrightarrow \Psi(x) = \log x$

$M_{\mathrm{Lz}} \sim \mathcal{O}\left(10^2 M_\odot\right)$





Detect the effect

We try to fit the unlensed waveform instead of Fisher analysis

$$\begin{aligned}\Delta\chi^2 &\equiv -2\left[\max_{\boldsymbol{\theta}} \ln \Lambda_T(\phi) - \ln \Lambda_{\rm opt}(\phi)\right] \\ &= \min_{\boldsymbol{\theta}} \left(\phi_{\rm opt} - \phi_T(\boldsymbol{\theta}) | \phi_{\rm opt} - \phi_T(\boldsymbol{\theta})\right) \\ &= 4 \min_{\boldsymbol{\theta}} \int {\rm d}f\, \frac{|\tilde{\phi}_{\rm opt}(f) - \tilde{\phi}_T(f;\boldsymbol{\theta})|^2}{S_{\rm n}(f)}\end{aligned}$$

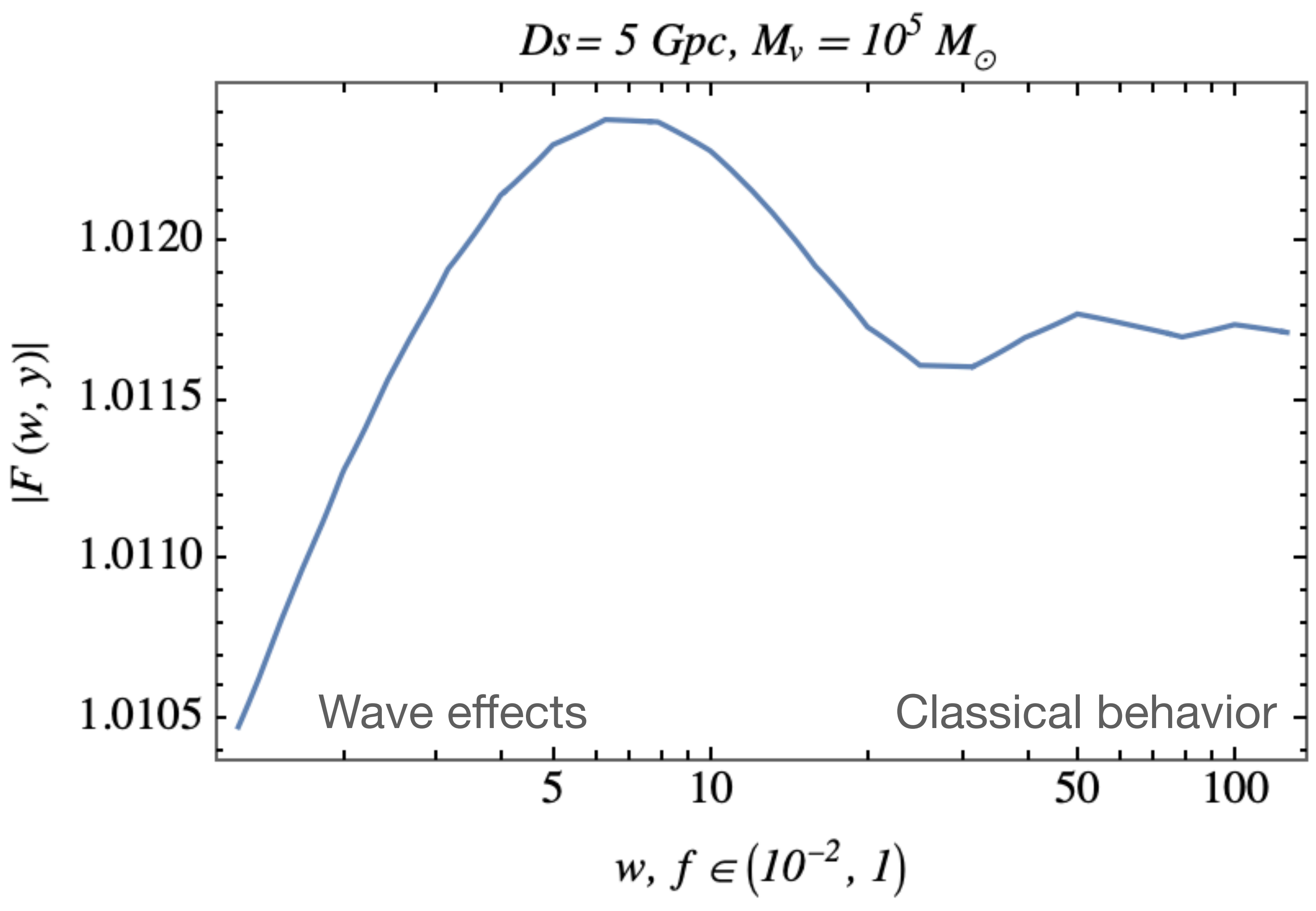
We minimize over the amplitude, the event looks closer, and with a constant shift.

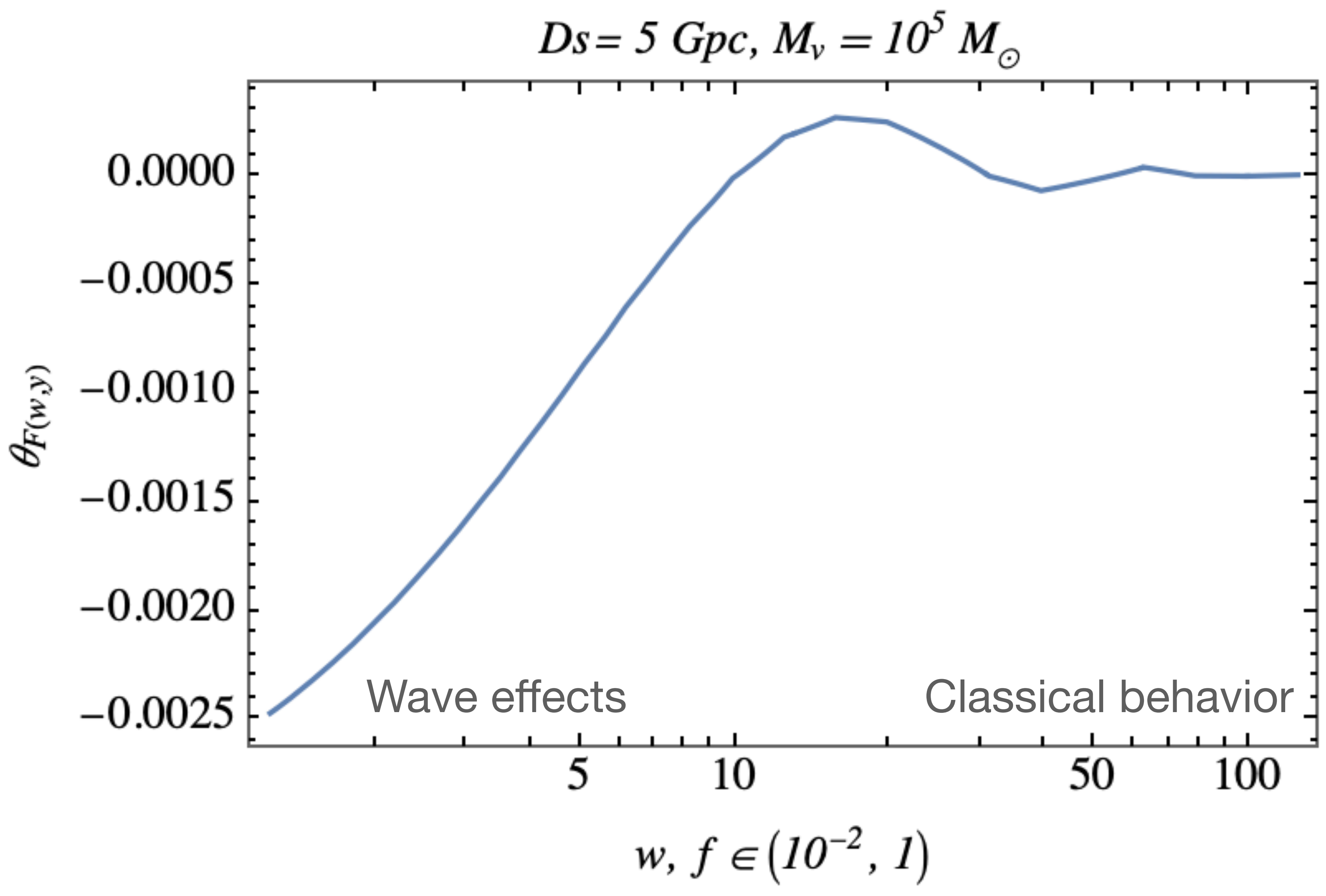
$$\Delta\chi^2 = 4 \min_{\lambda,\,\delta\phi_c} \int {\rm d}f\, \frac{A(f;\boldsymbol{\theta}_{\rm opt})^2 |F(f;\boldsymbol{\theta}_{l,{\rm opt}}) - \lambda e^{-i\delta\phi_c}|^2}{S_{\rm n}(f)}$$

Amplification function

Only wave effects

To maximize the tiny effect that the halo has on the GW we go to the atom interferometer band.





We can see how everything goes to constant values in the classical limit.

Detect the effect

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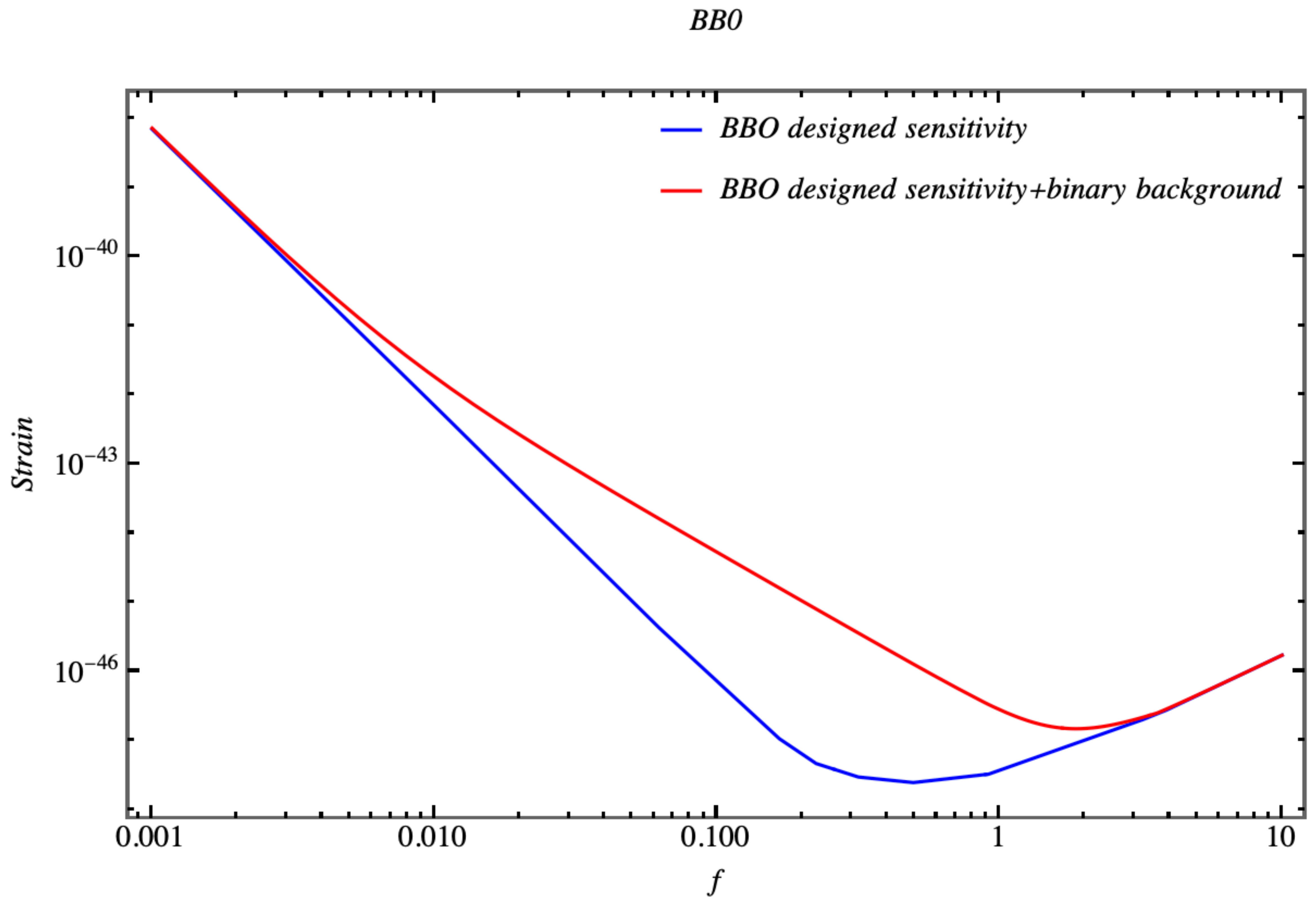
Detect the effect

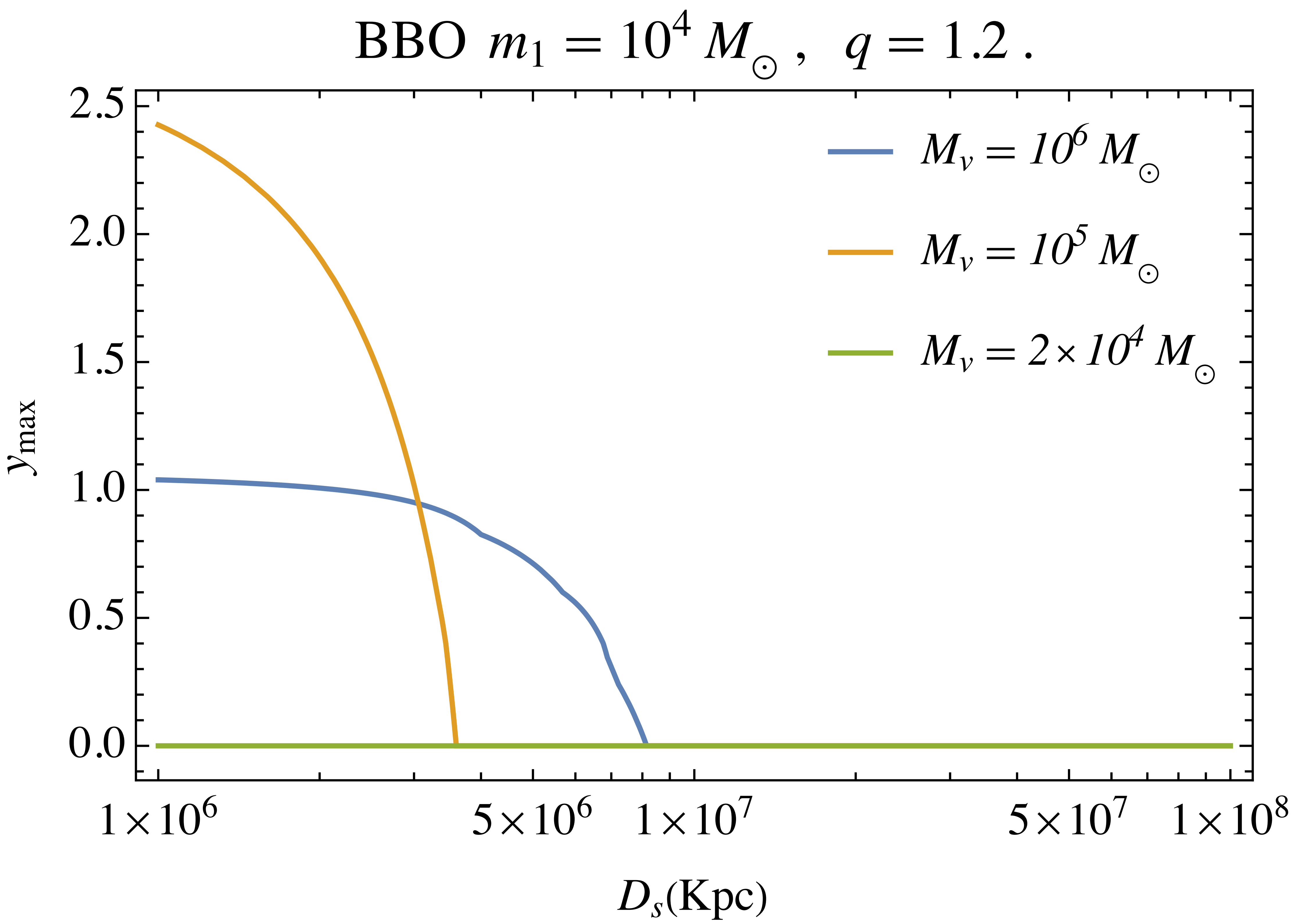
We have first considered Big Bang Observatory (BBO)

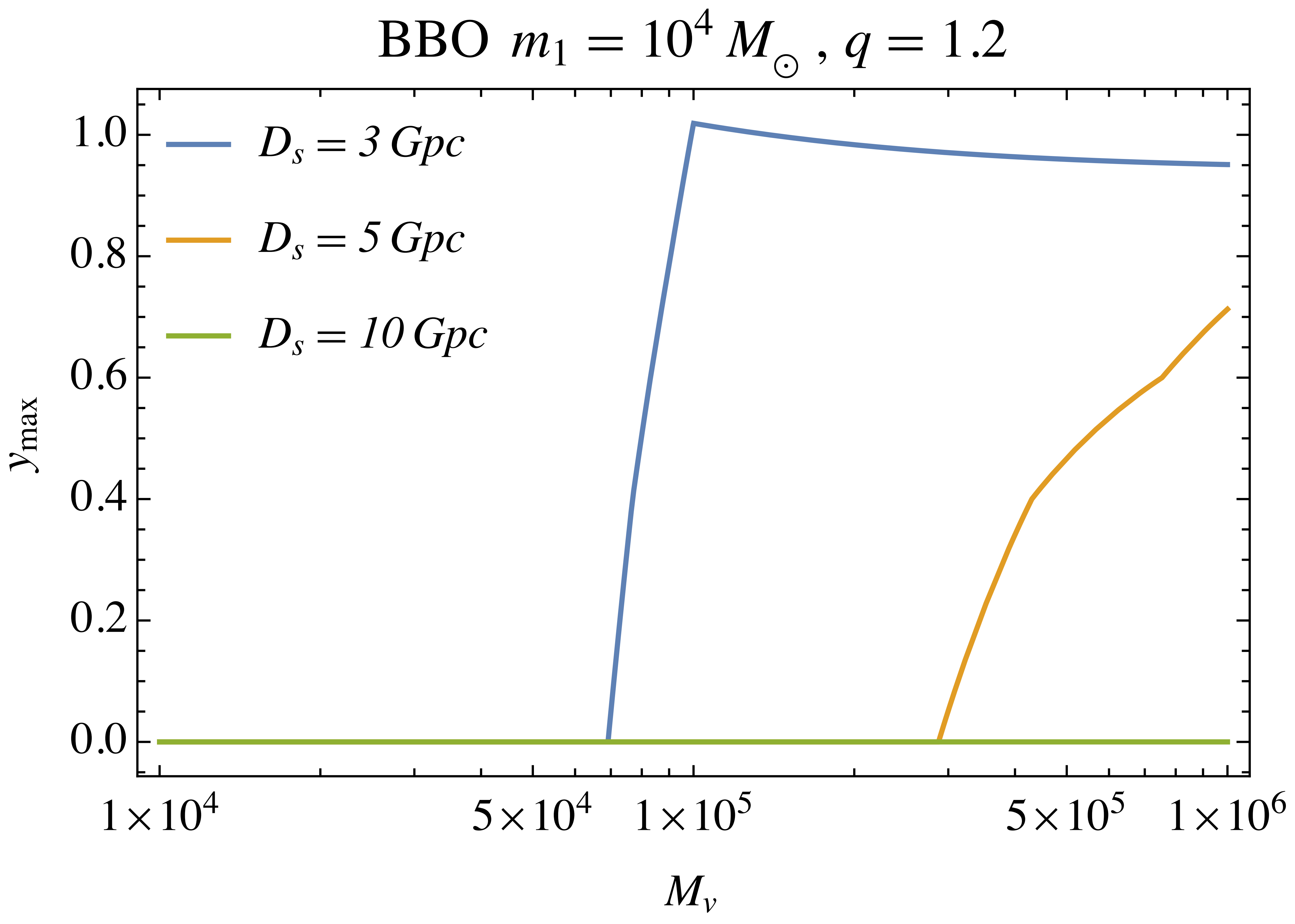
It has the best sensitivity of all the projected gravitational wave detectors, so it makes it very sensitive to unresolved background binaries



Probability of lensing

What is the probability to detect this events?





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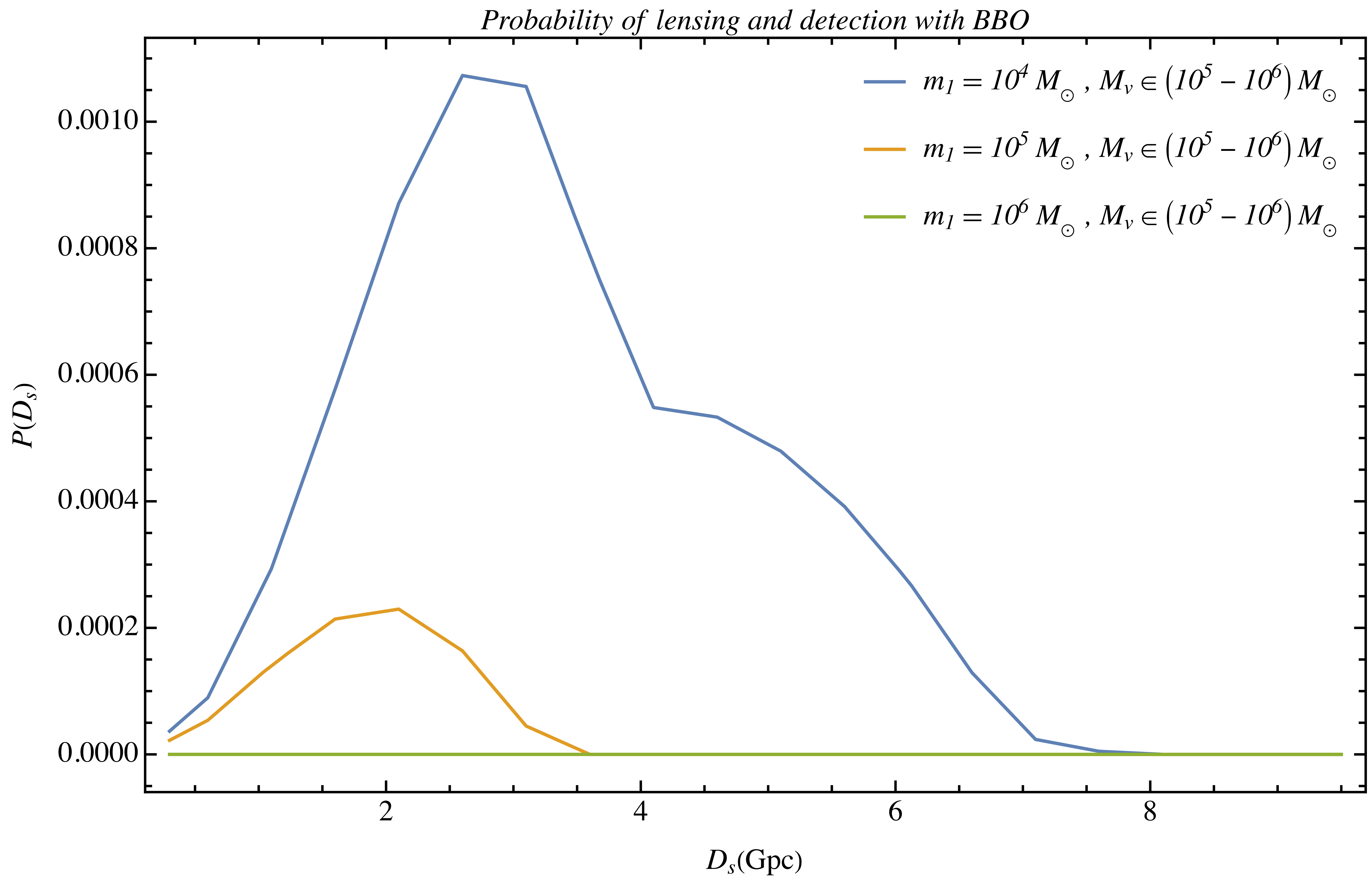

Thanks for your time!