The Dark Timbre of GWs

Based on

The dark timbre of gravitational waves

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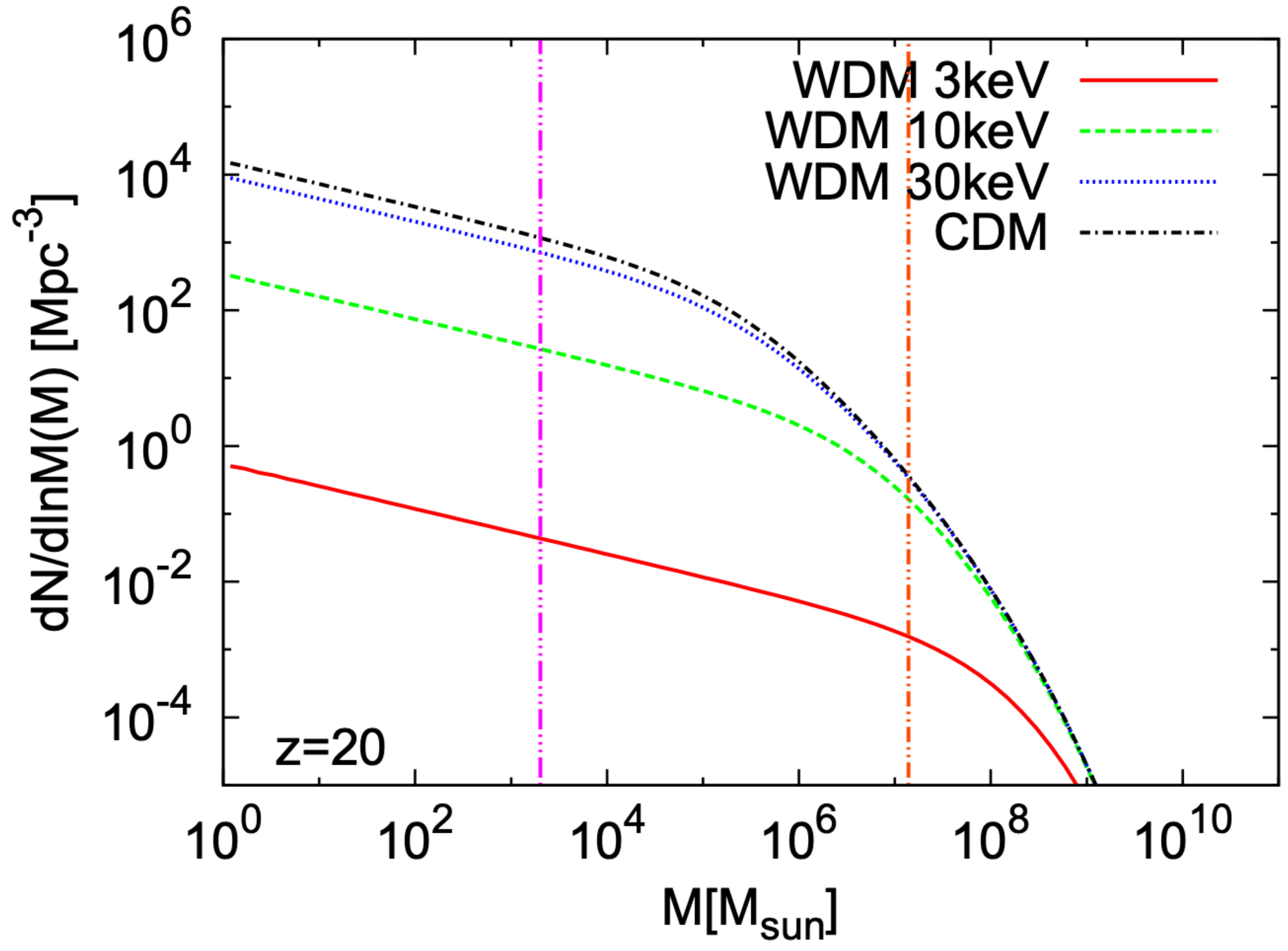
Gravitational wave timbre, the relative amplitude and phase of the different harmonics, can change due to interactions with low-mass halos. We focus on binaries in the LISA range and find that the integrated lens effect of cold dark matter structures can be used to probe the existence of $M_{\rm v} \lesssim 10\,M_\odot$ halos if a single binary with eccentricity $e = 0.3 - 0.6$ is detected with a signal-to-noise ratio $100 - 10^4$.

Motivation to search for low mass DM halos

$(M_v < 10^7\, M_\odot)$

- Mainly unconstrained with current optical searches
- because do not contain enough baryonic mass to form stars
- but contain extremely **valuable information about DM**



https://arxiv.org/pdf/1401.5563

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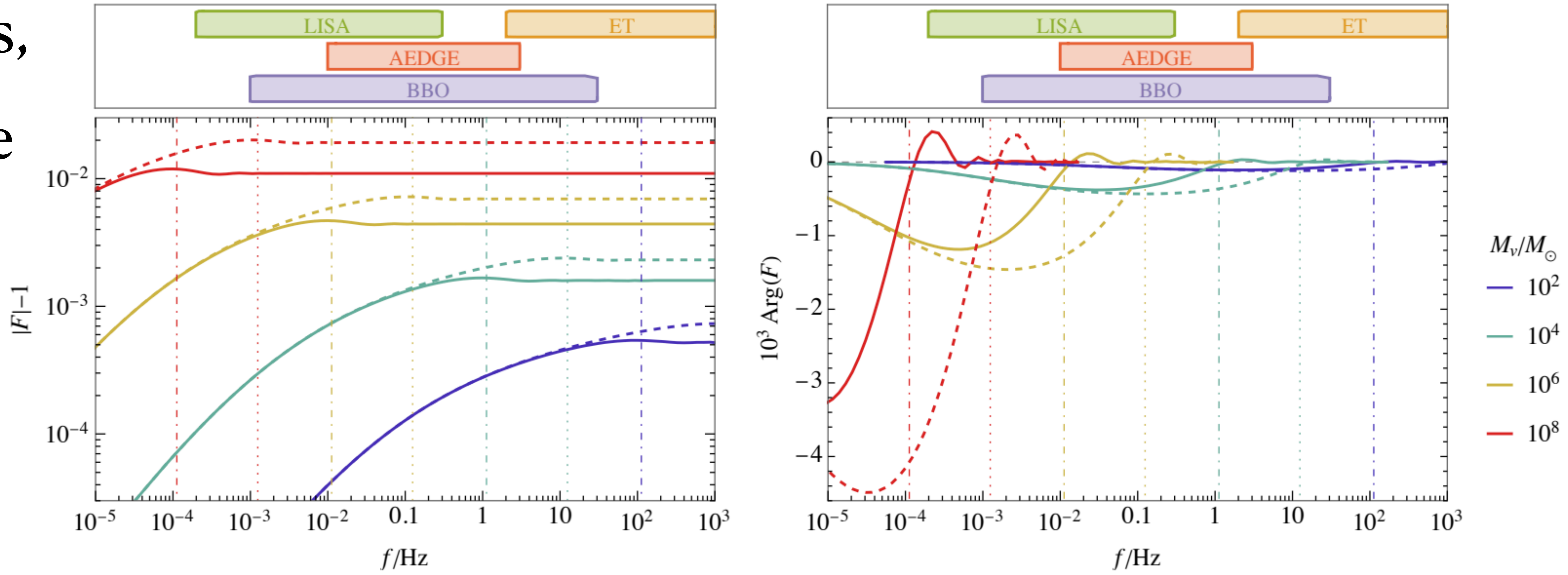
GW microlensing

https://arxiv.org/pdf/2210.13436

- GWs are coherent sources,
- wave optics effects induce frequency dependent variations
- imprints from haloes $M_v < 10^7 \, M_\odot$ are resolvable



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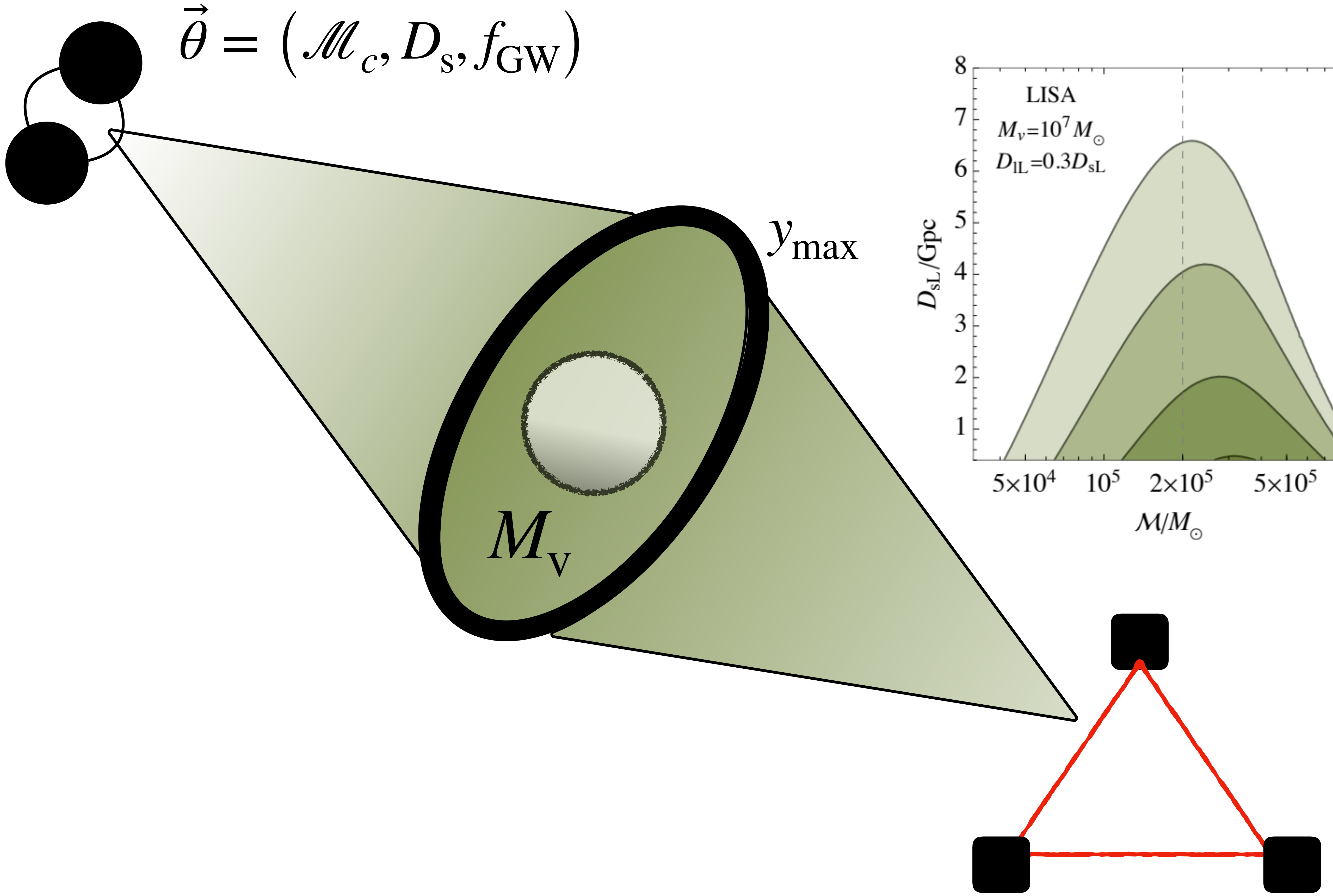
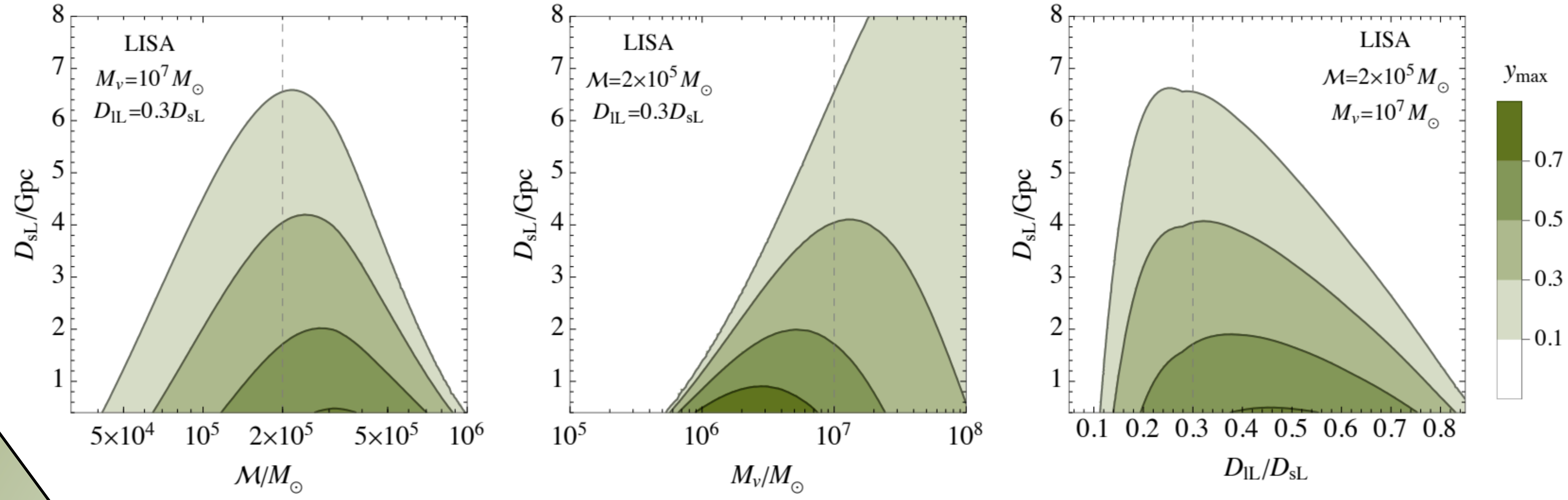
What is the problem then?





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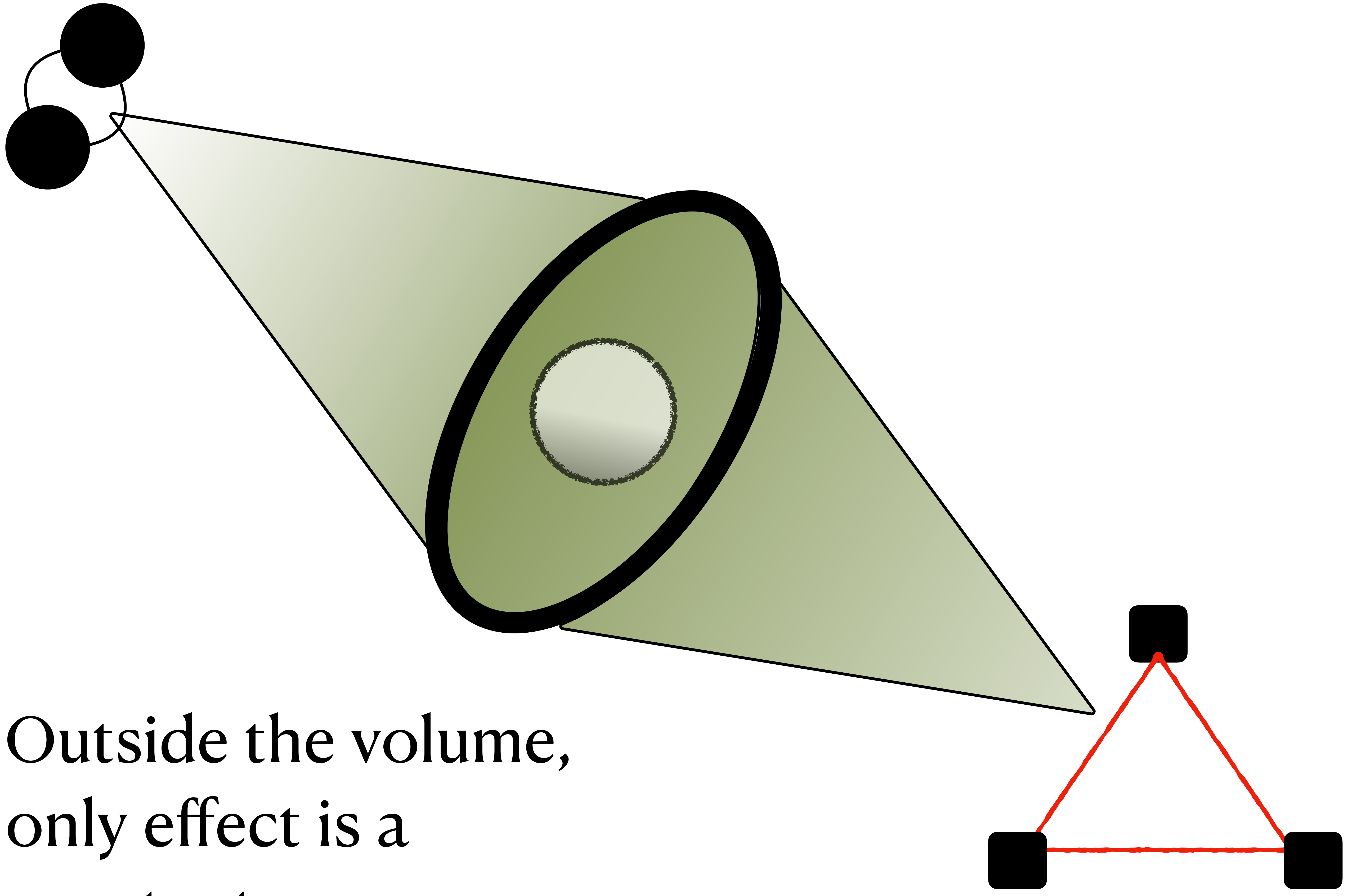

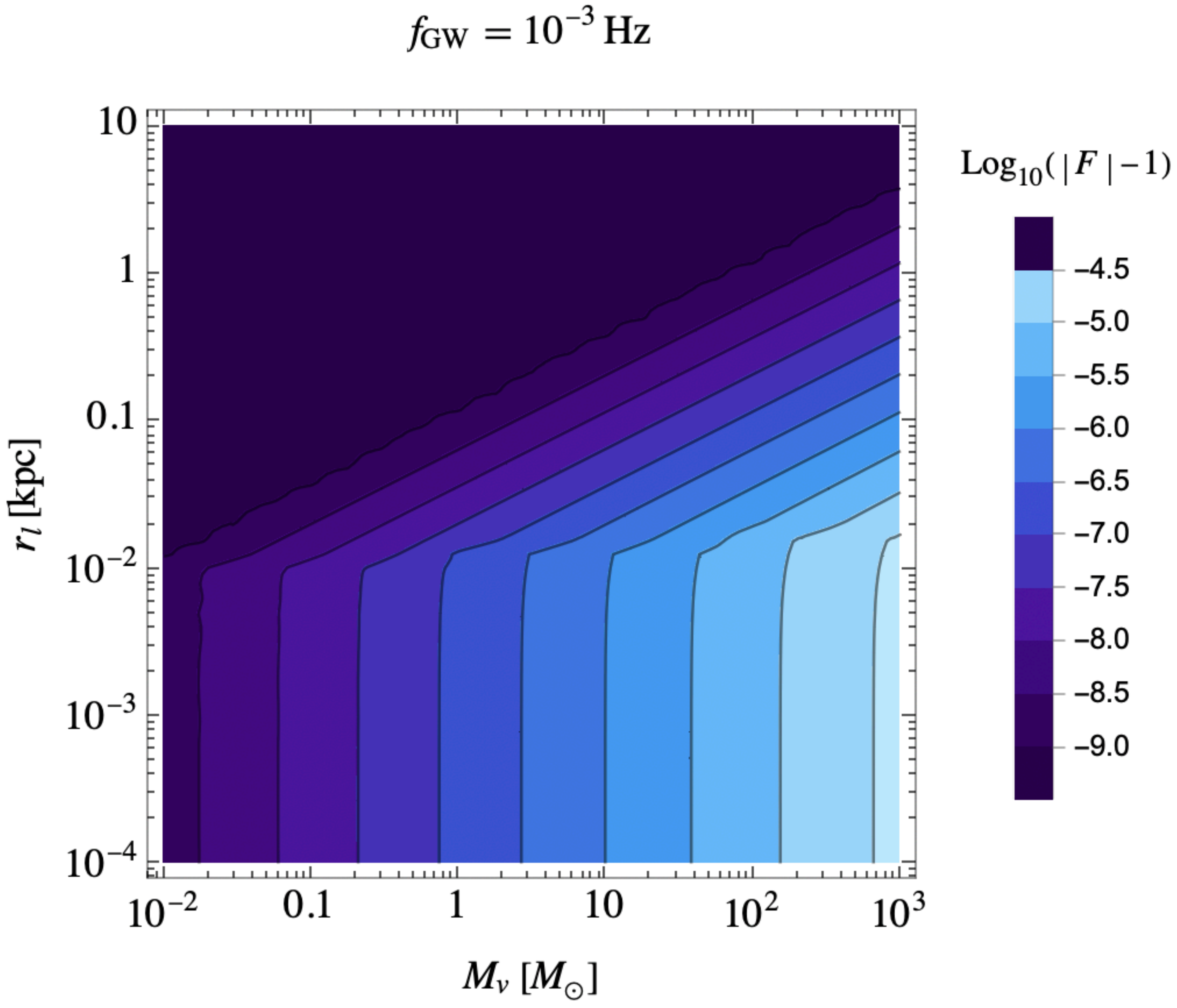

Outside the volume, only effect is a constant magnification

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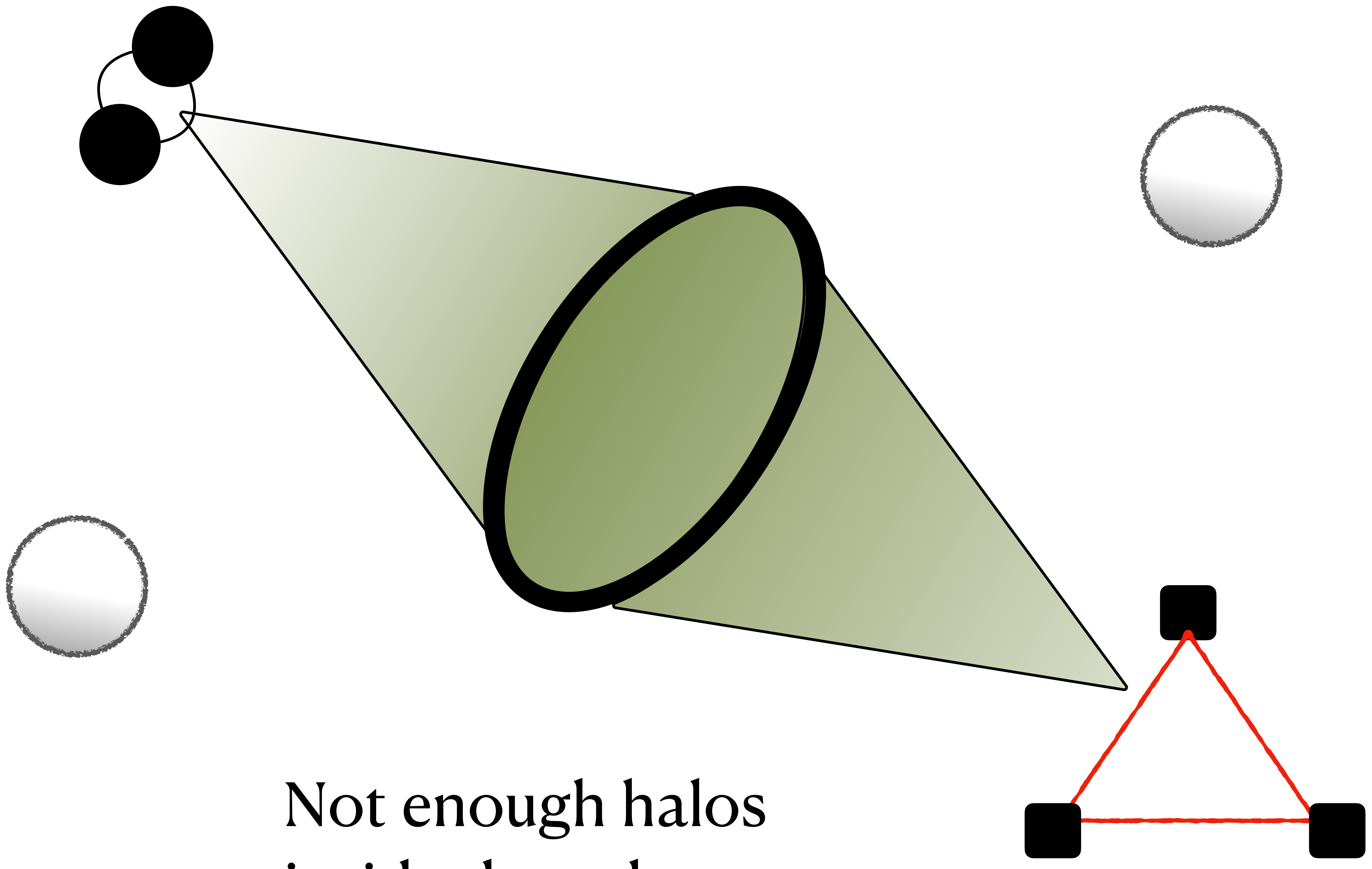

Not enough halos
inside the volume

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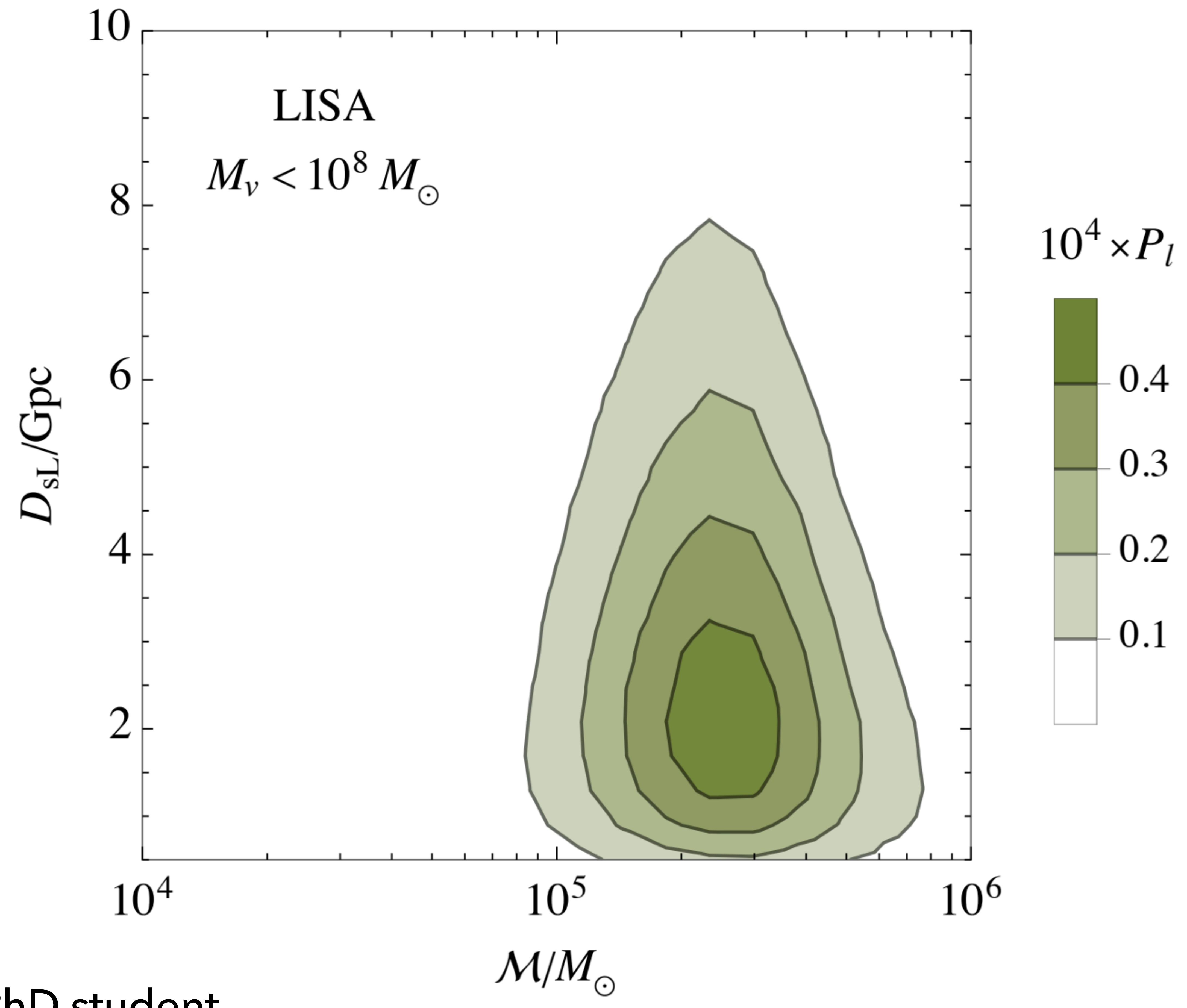

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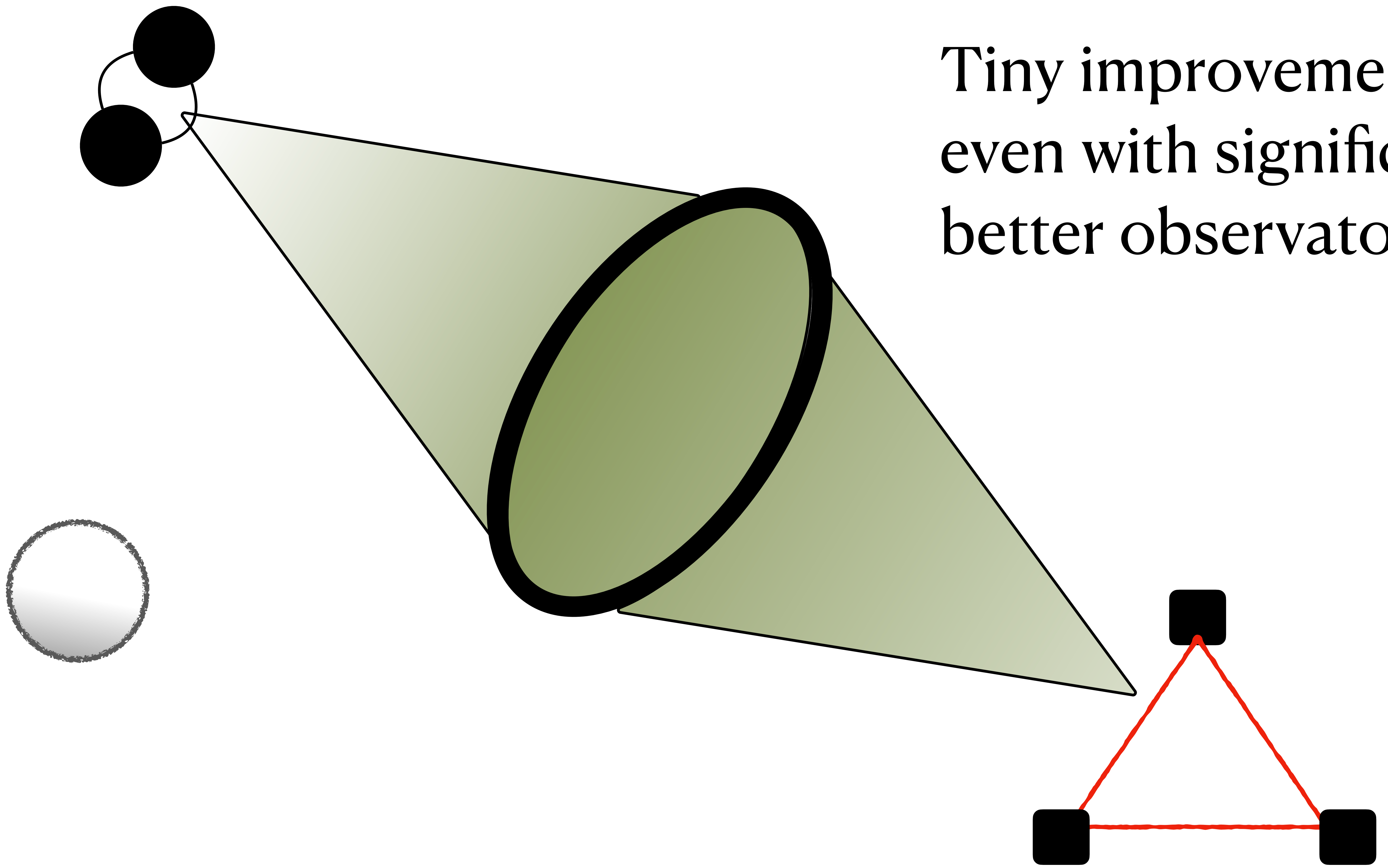
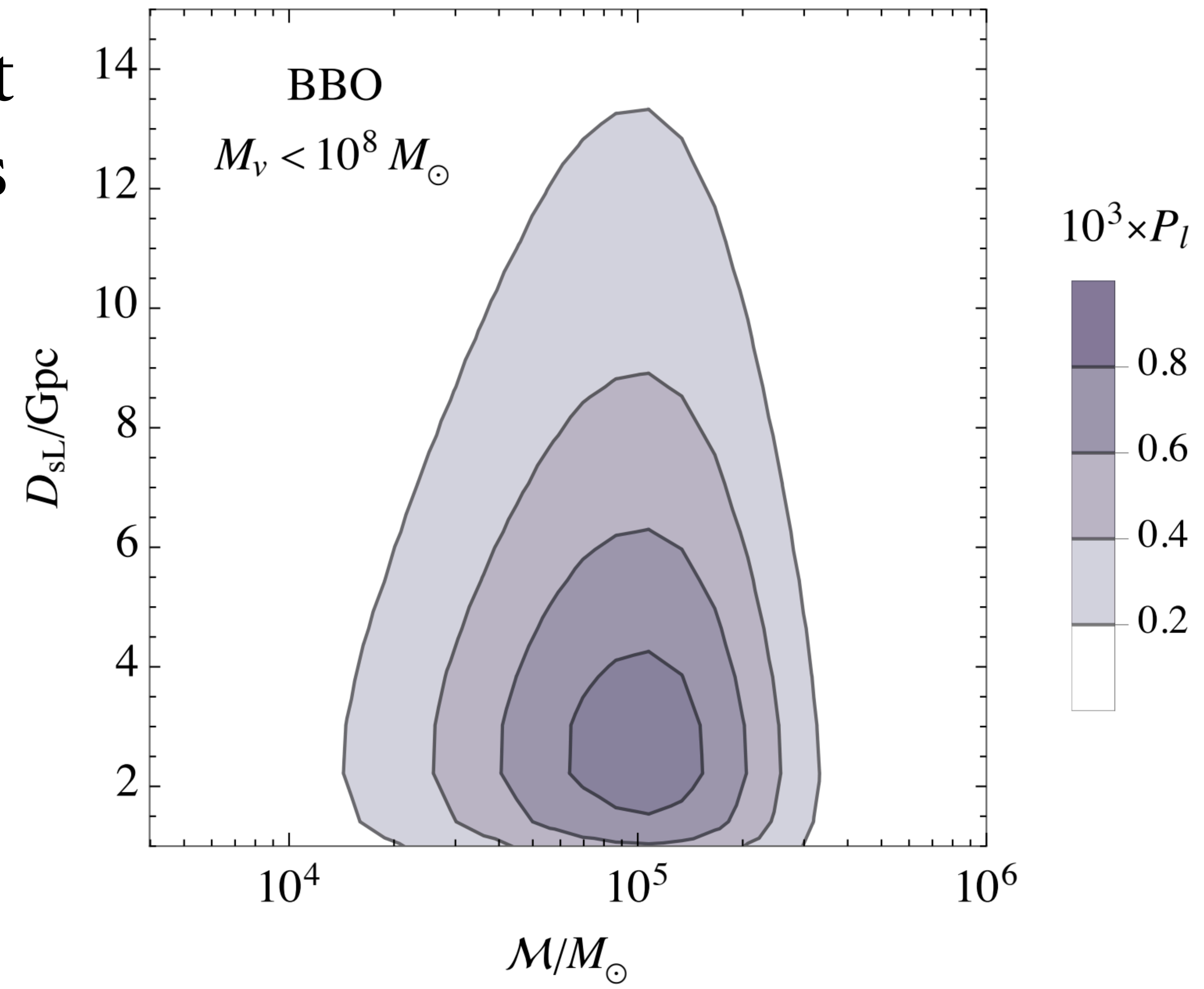


Tiny improvements even with significant better observatories

https://arxiv.org/pdf/2210.13436



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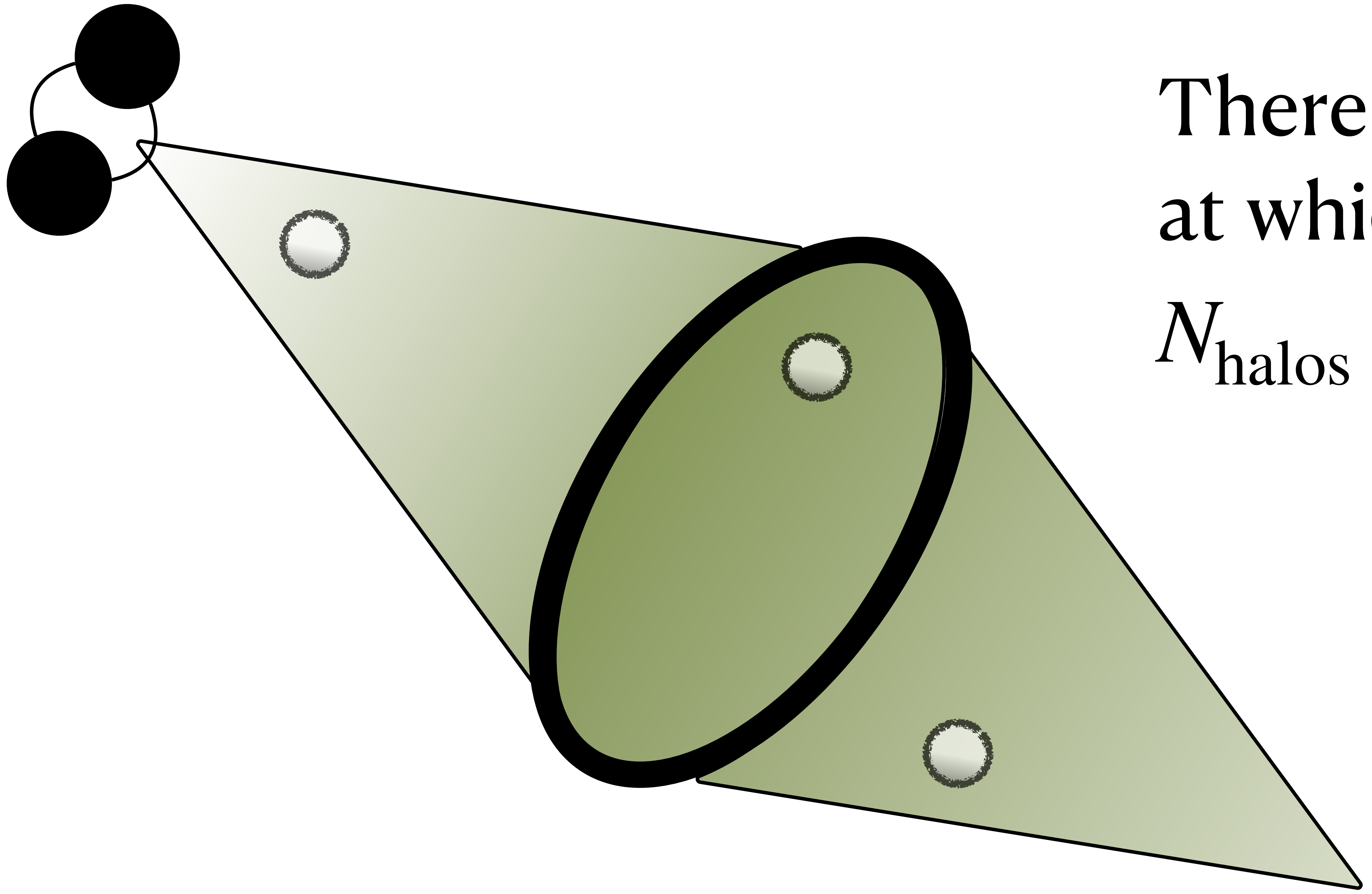
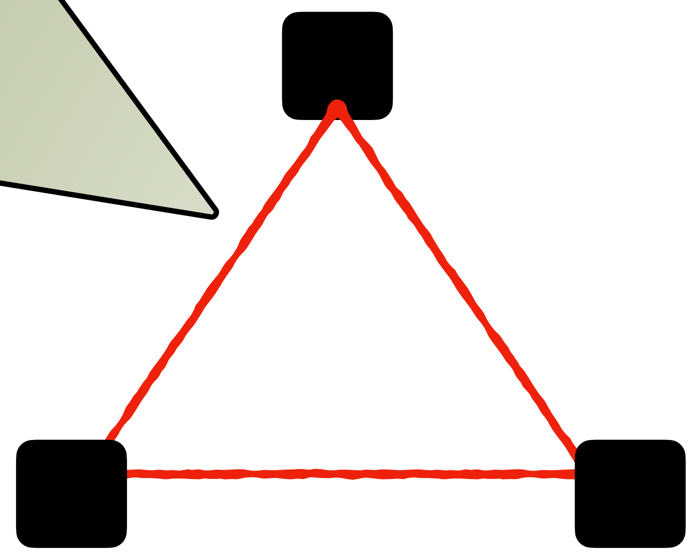
What is the idea to overcome it?



There is a halo mass at which you have $N_{\mathrm{halos}} > 1$



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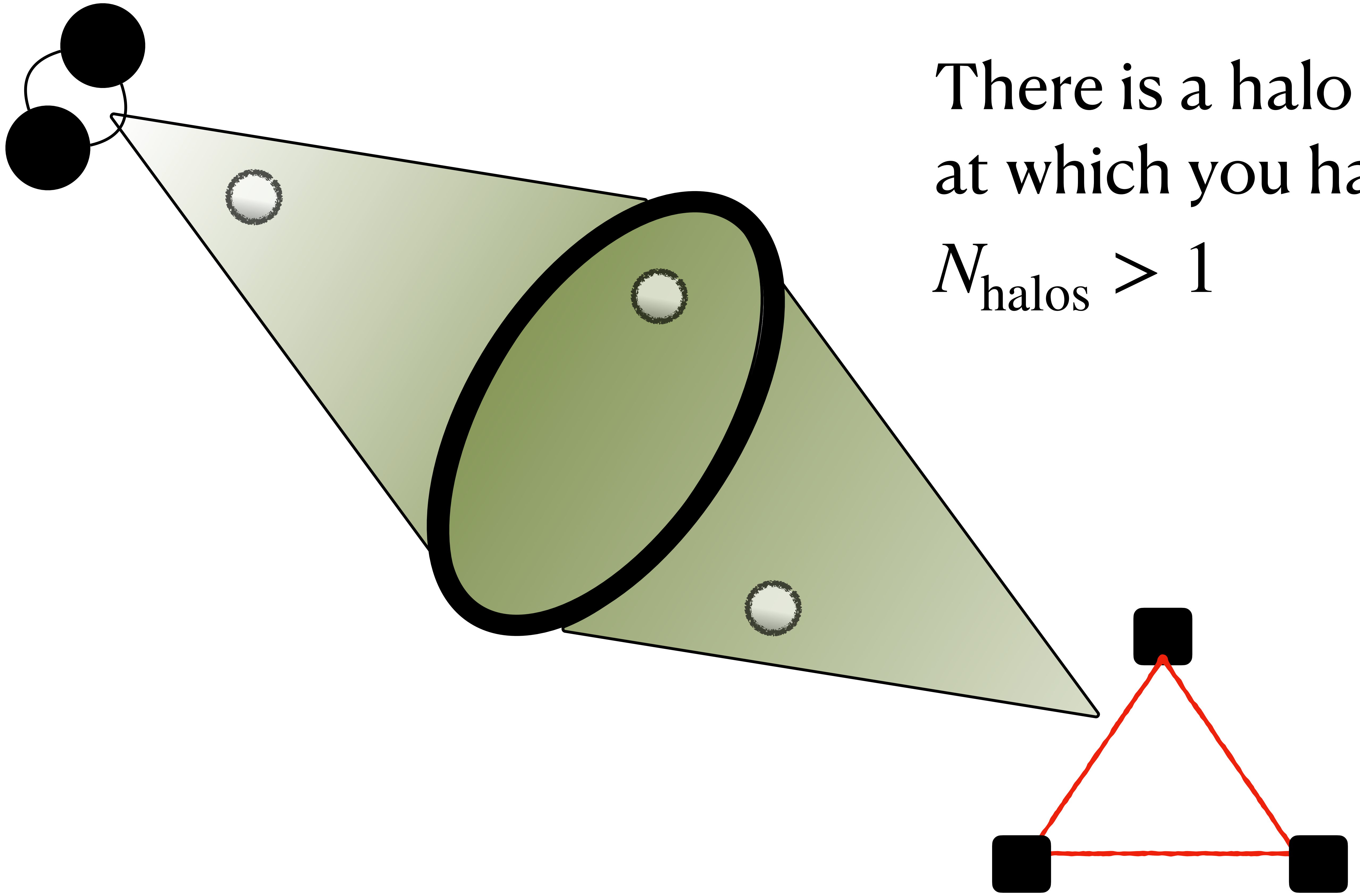
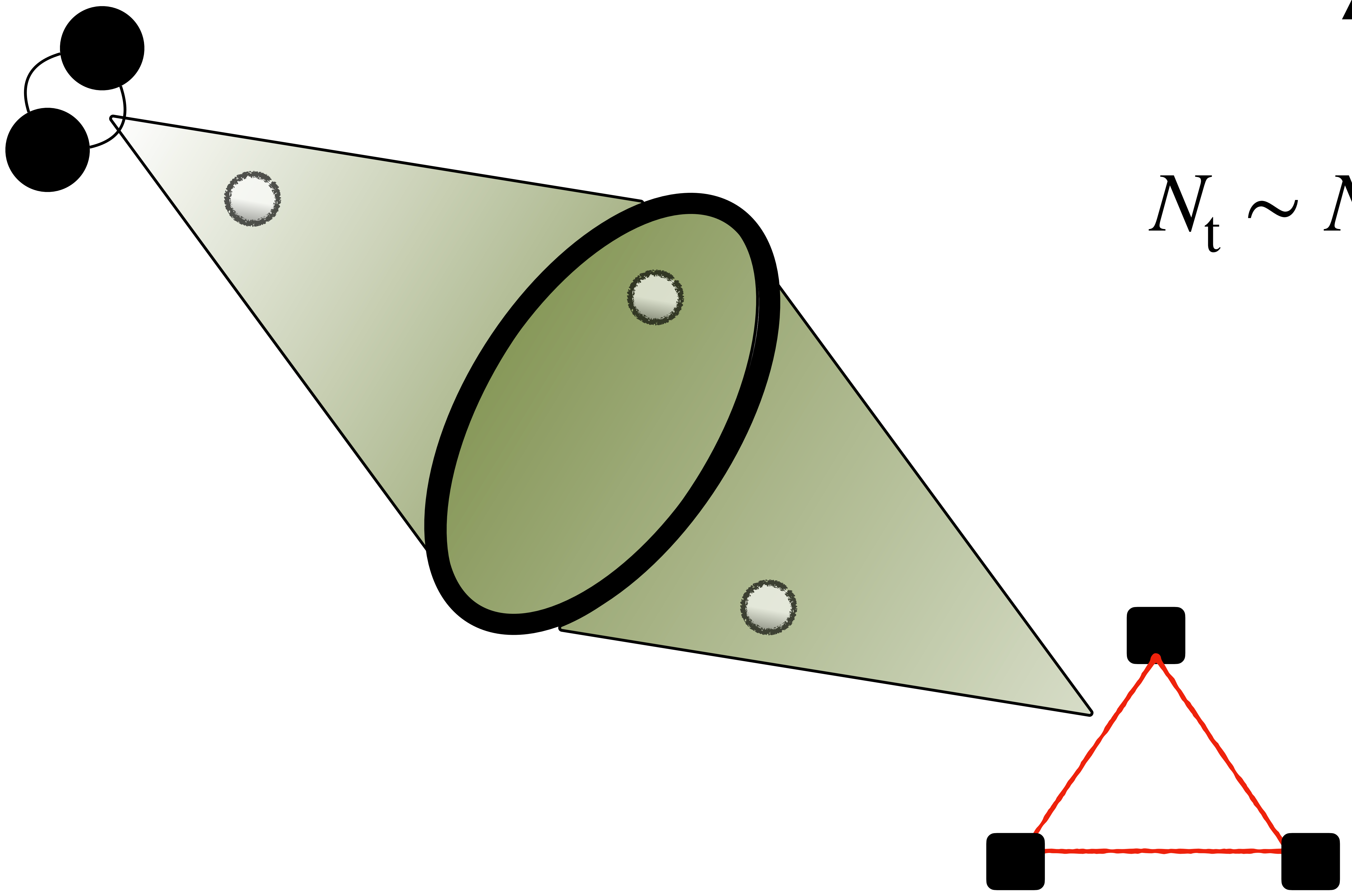


There is a halo mass at which you have $N_{\text{halos}} > 1$

But it is too light to be detectable

What is the idea to overcome it?



↑ ↓ For decreasing halo mass

$$N_t \sim N_h \times |F|$$

What wins?

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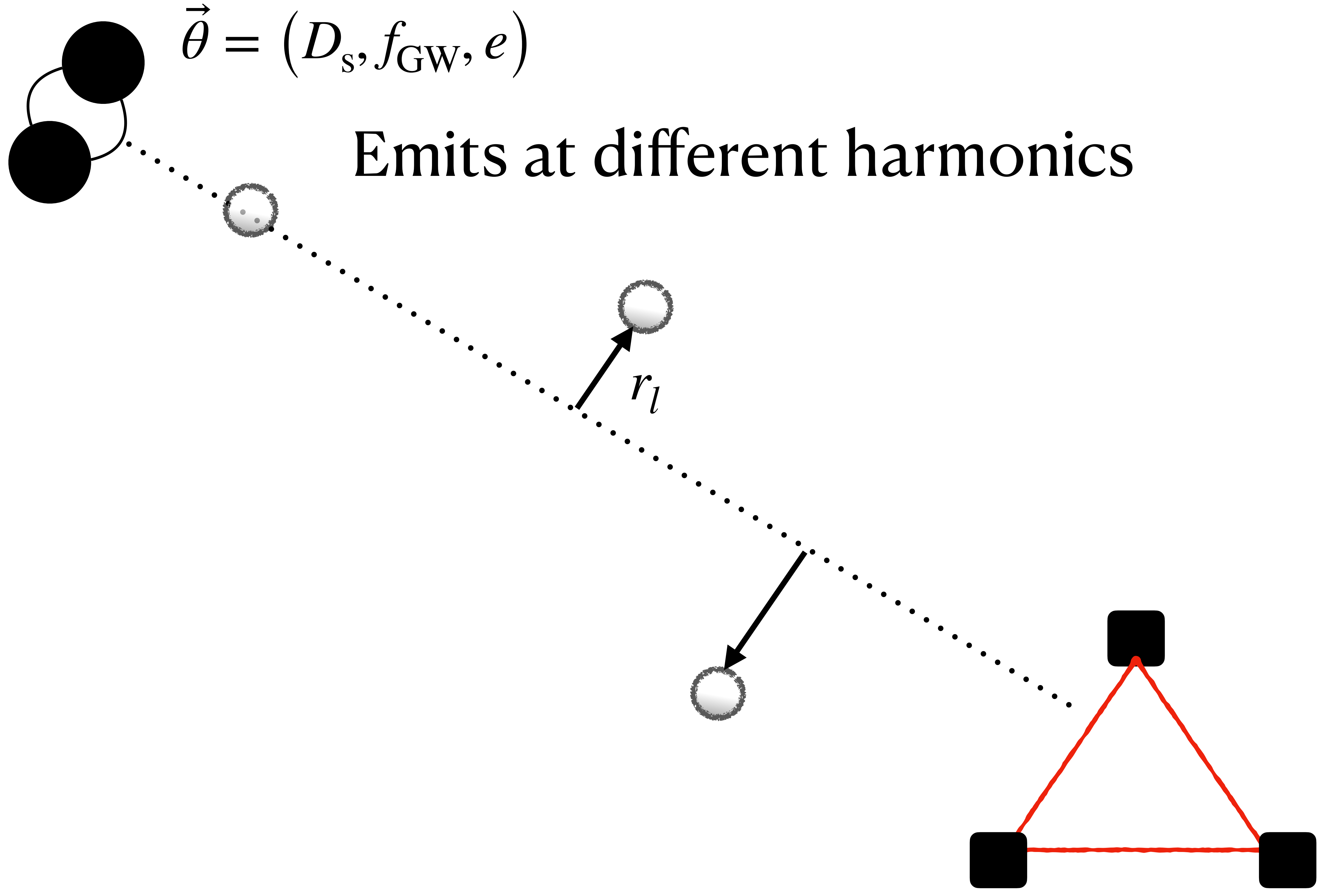
High impact parameter lensing



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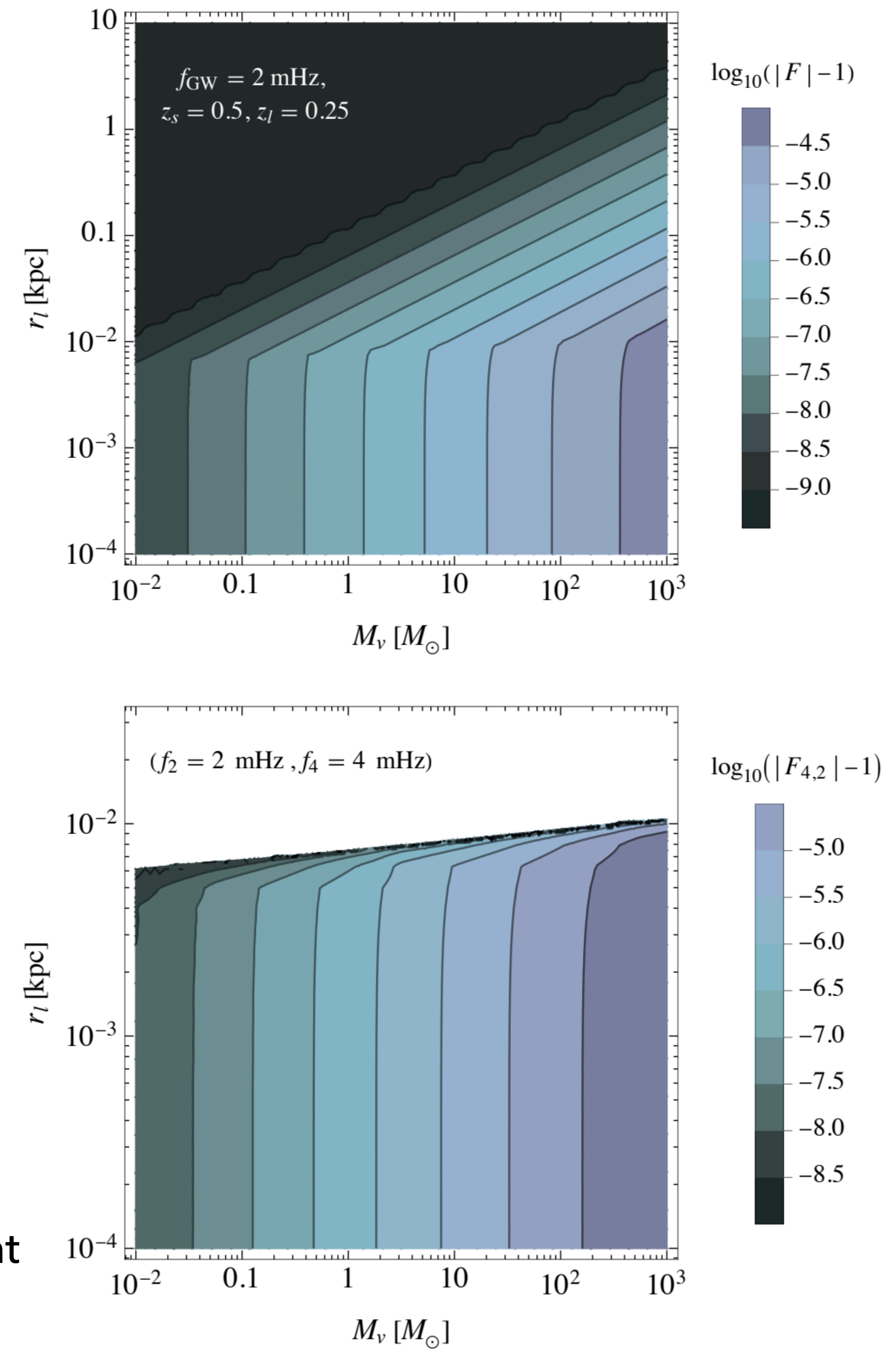

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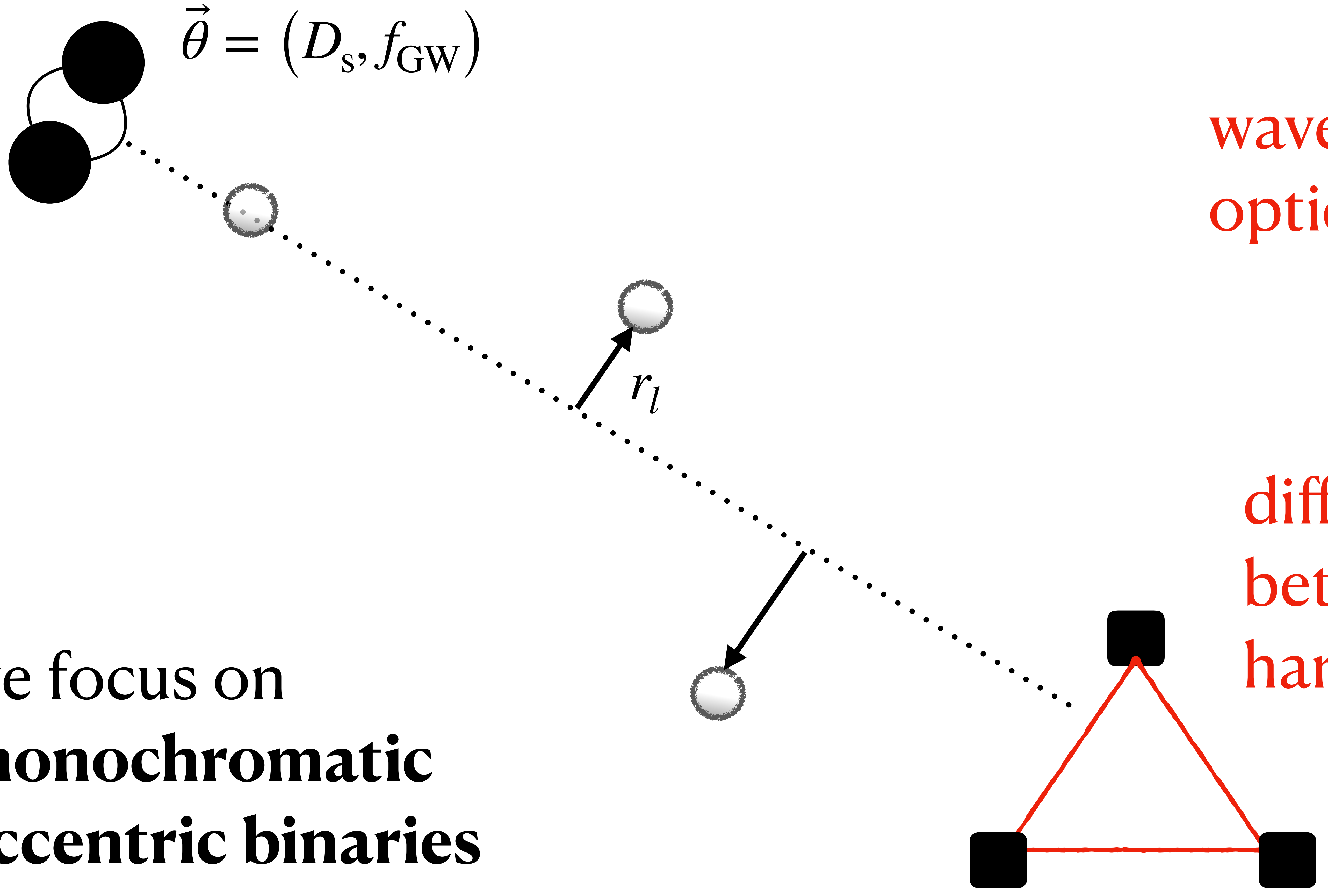
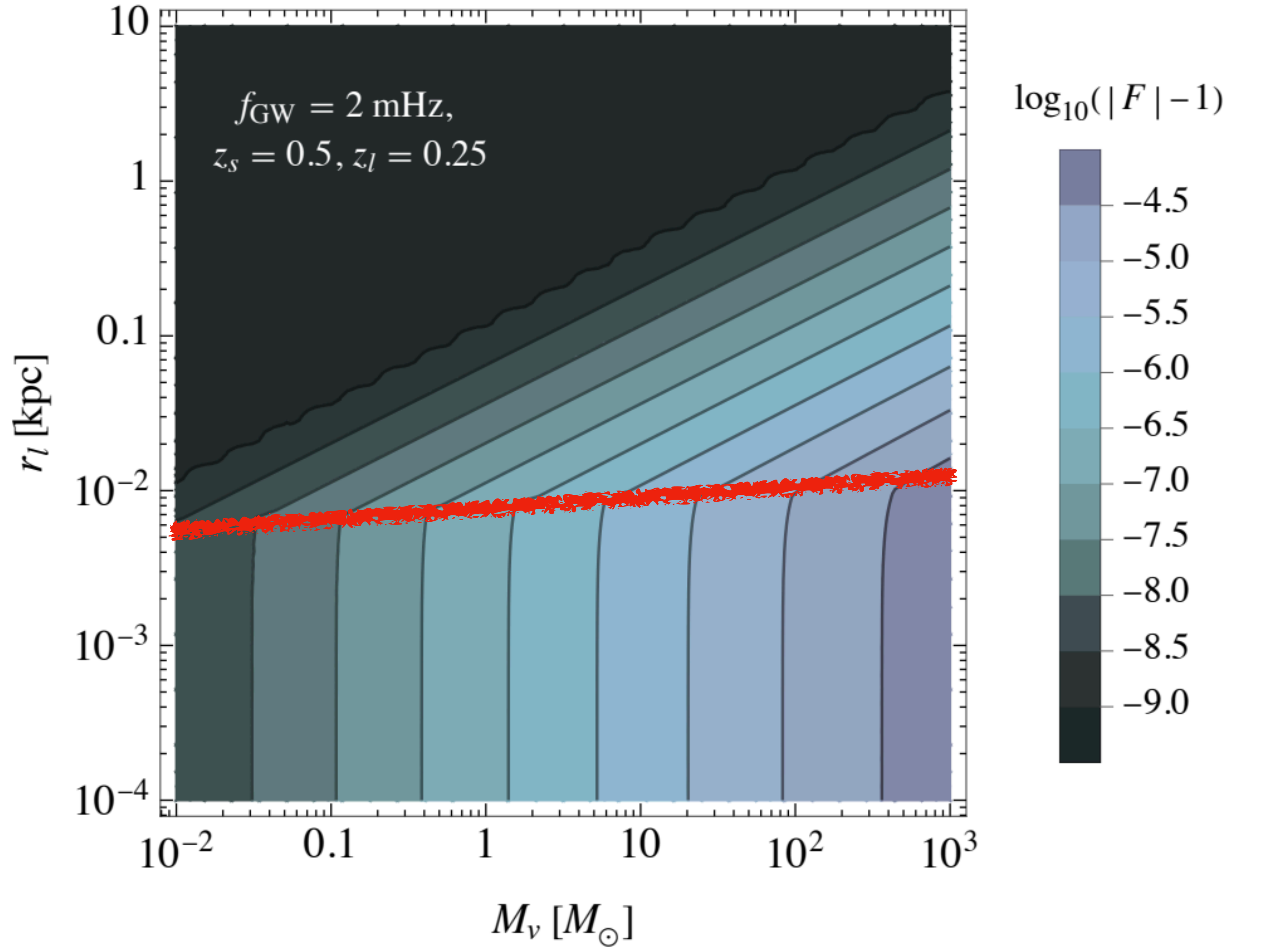
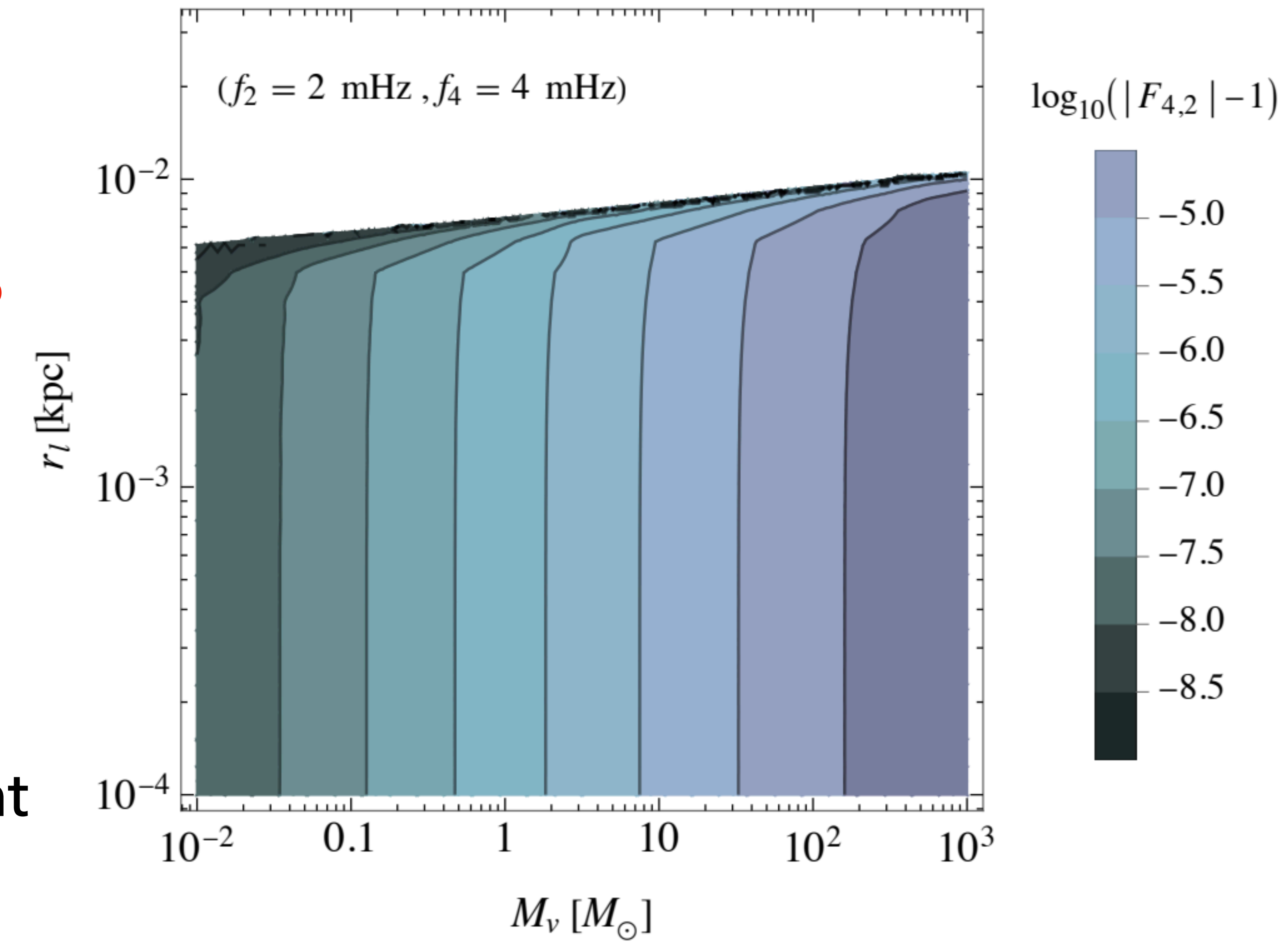


wave optics



difference between harmonics



we focus on
monochromatic eccentric binaries

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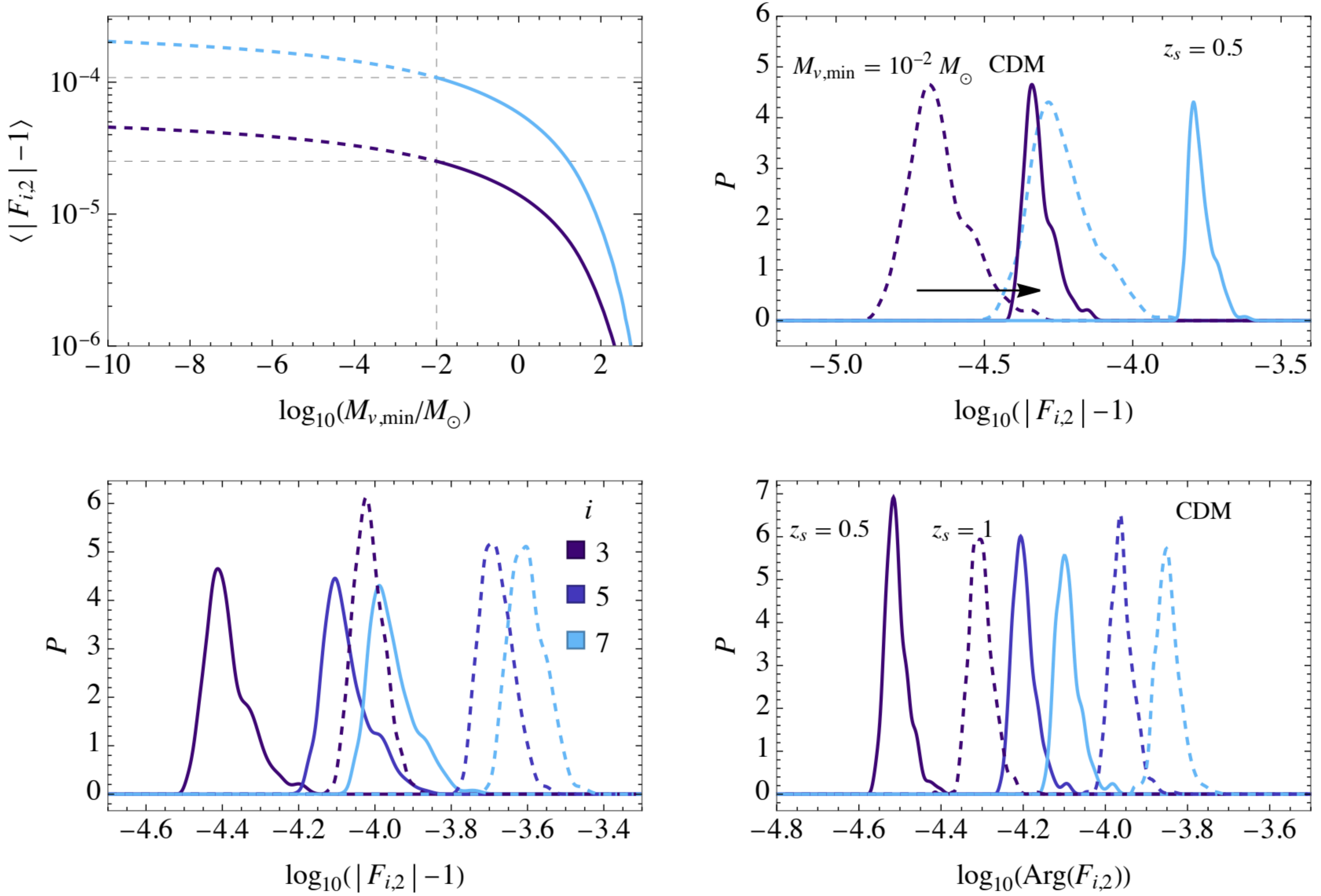

$\langle |F_{i,2}| - 1 \rangle$
10^{-4}
10^{-5}
10^{-6}
−10 −8 −6 −4 −2 0 2
$\log_{10}(M_{v,\min}/M_\odot)$
$M_{v,\min} = 10^{-2}\, M_\odot$
CDM
$z_s = 0.5$
P
0 1 2 3 4 5 6
−5.0 −4.5 −4.0 −3.5
$\log_{10}(|F_{i,2}| - 1)$
P
0 1 2 3 4 5 6
i
3
5
7
−4.6 −4.4 −4.2 −4.0 −3.8 −3.6 −3.4
$\log_{10}(|F_{i,2}| - 1)$
P
0 1 2 3 4 5 6 7
$z_s = 0.5$
$z_s = 1$
CDM
−4.8 −4.6 −4.4 −4.2 −4.0 −3.8 −3.6
$\log_{10}(\mathrm{Arg}(F_{i,2}))$

Changes the "timbre" of the signal

- The timbre is the relative amplitude and phases between the harmonics
  - is the reason why a piano and a violin sounds different even when playing the same note!

Changes the “timbre” of the signal

- The timbre is the relative amplitude and phases between the harmonics
  - is the reason why a piano and a violin sounds the same even when playing the same note,
- is the change in timber detectable?

$$\Delta\chi^2 = 4 \min_{\vec{\theta}} \int \mathrm{d}f \, \frac{|\tilde{h}(f) - \tilde{h}_{\mathrm{T}}(f, \vec{\theta})|^2}{S(f)}$$

$$\Delta\chi^2 = 4 \min_{\lambda,\phi,e'} \sum_{n=1}^{\infty} \frac{A^2 |F(f_n)\sqrt{g_n(e)} - \lambda e^{i\phi}\sqrt{g_n(e')}|^2}{S(f_n)}$$

$$= \frac{\mathrm{SNR}_2^2}{g_2(e)} \min_{\lambda,\phi,e'} \sum_{n=1}^{\infty} \frac{S(f_2)}{S(f_n)} \left| F_{n,2}\sqrt{g_n(e)} - \lambda e^{i\phi}\sqrt{g_n(e')} \right|^2$$

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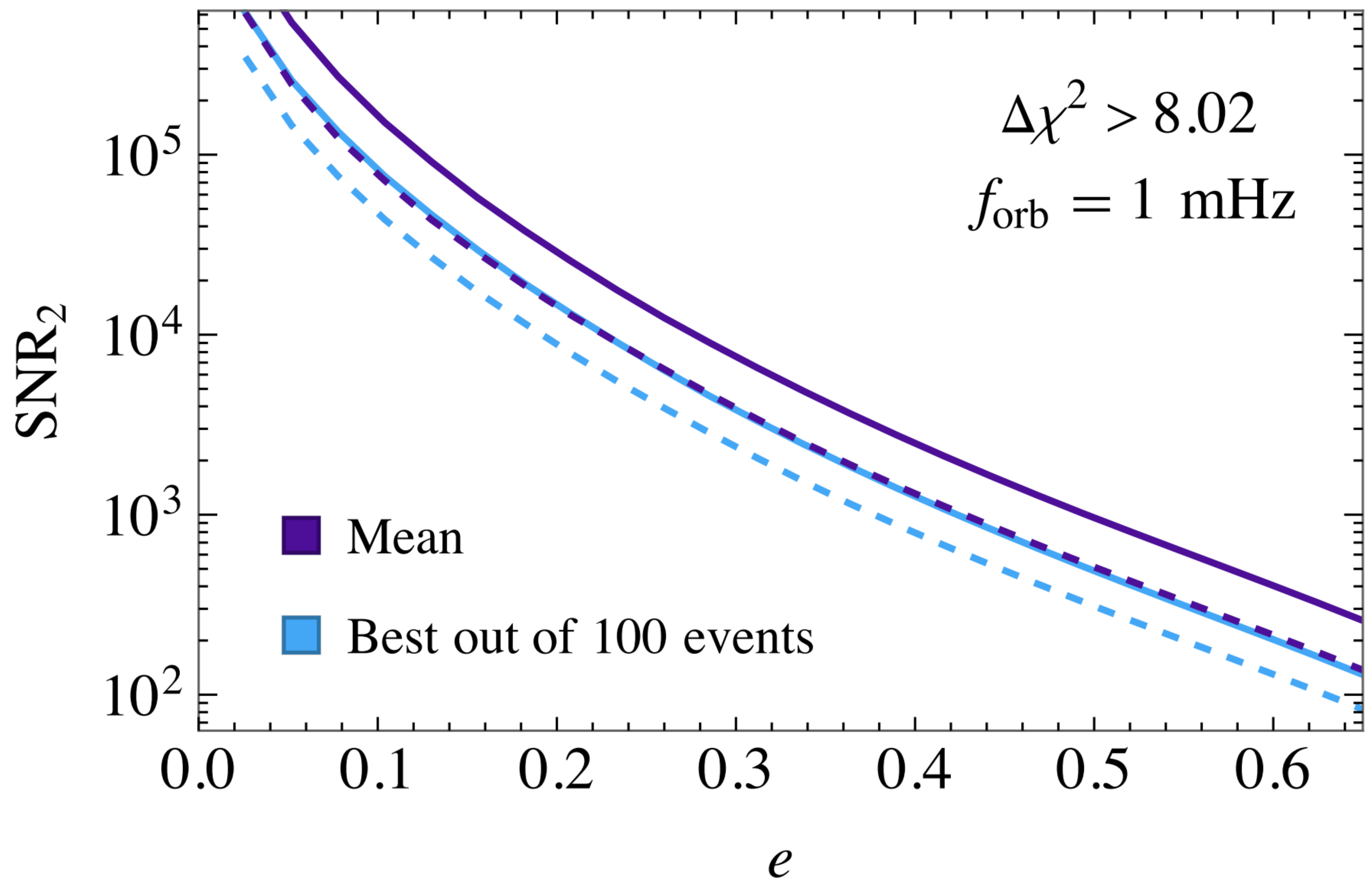
Changes the "timbre" of the signal



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We concluded that

- We have shown that the wave optics effects due to the low mass dark matter halos, $M_{\mathrm{v}} < 10\, M_{\odot}$, **induce frequency-dependent changes in the amplitude and phase of the harmonics**, the timbre of the signal.

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- This shifted timbre is detectable in the **7 dominant harmonics of the signal for signal-to-noise ratios between** $500 - 10^4$ if the binary eccentricity is $e \in (0.3, 0.6)$. If such binaries exist, LISA could probe the shifted timbre.

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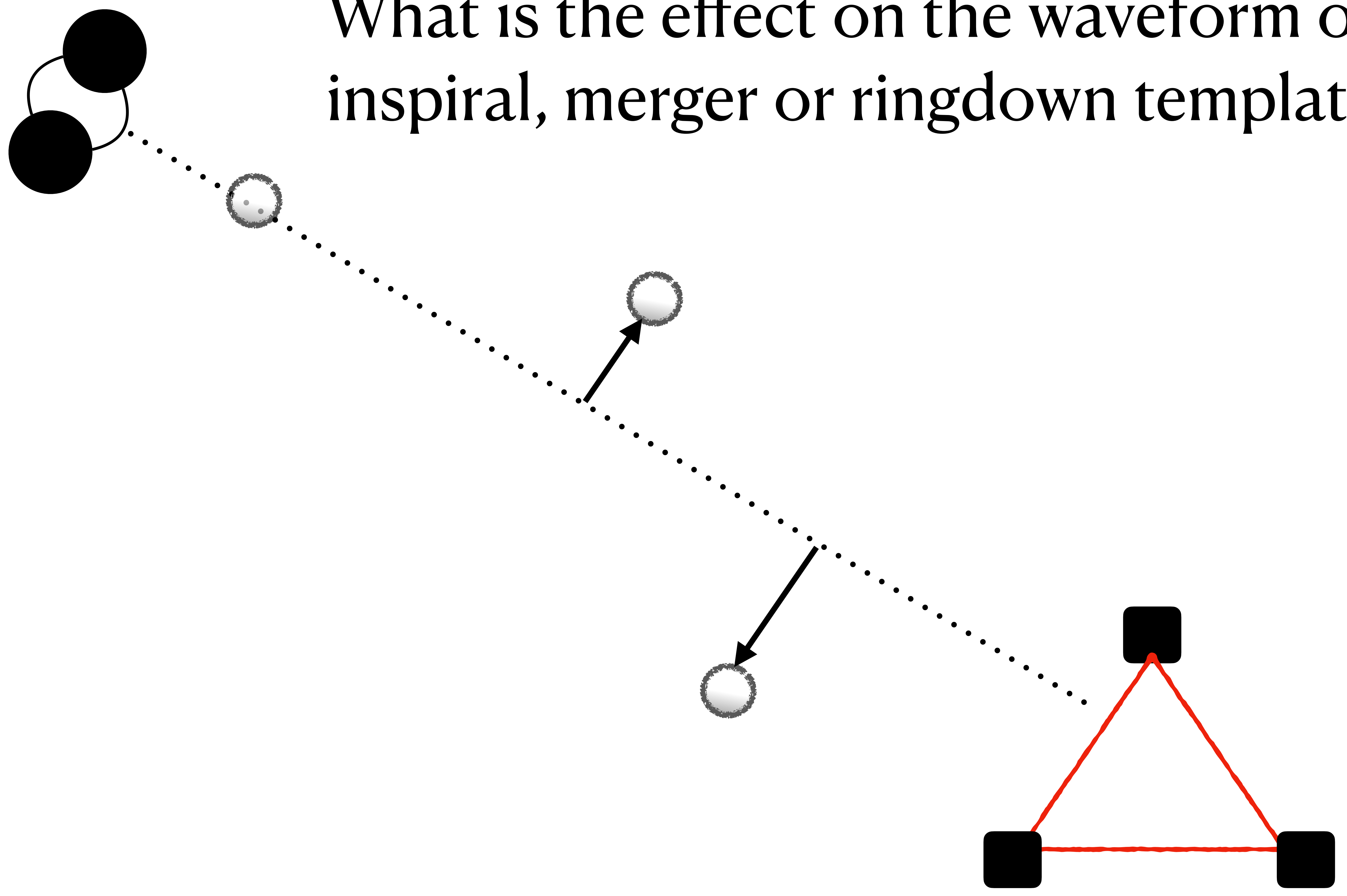
- This shifted timbre is detectable in the **7 dominant harmonics of the signal for signal-to-noise ratios between** $500 - 10^4$ if the binary eccentricity is $e \in (0.3, 0.6)$. If such binaries exist, LISA could probe the shifted timbre.
- This would open a **new avenue to test low-mass dark matter halos** which would revolutionize our understanding of DM

What is next?

What is the effect on the waveform of a inspiral, merger or ringdown template?



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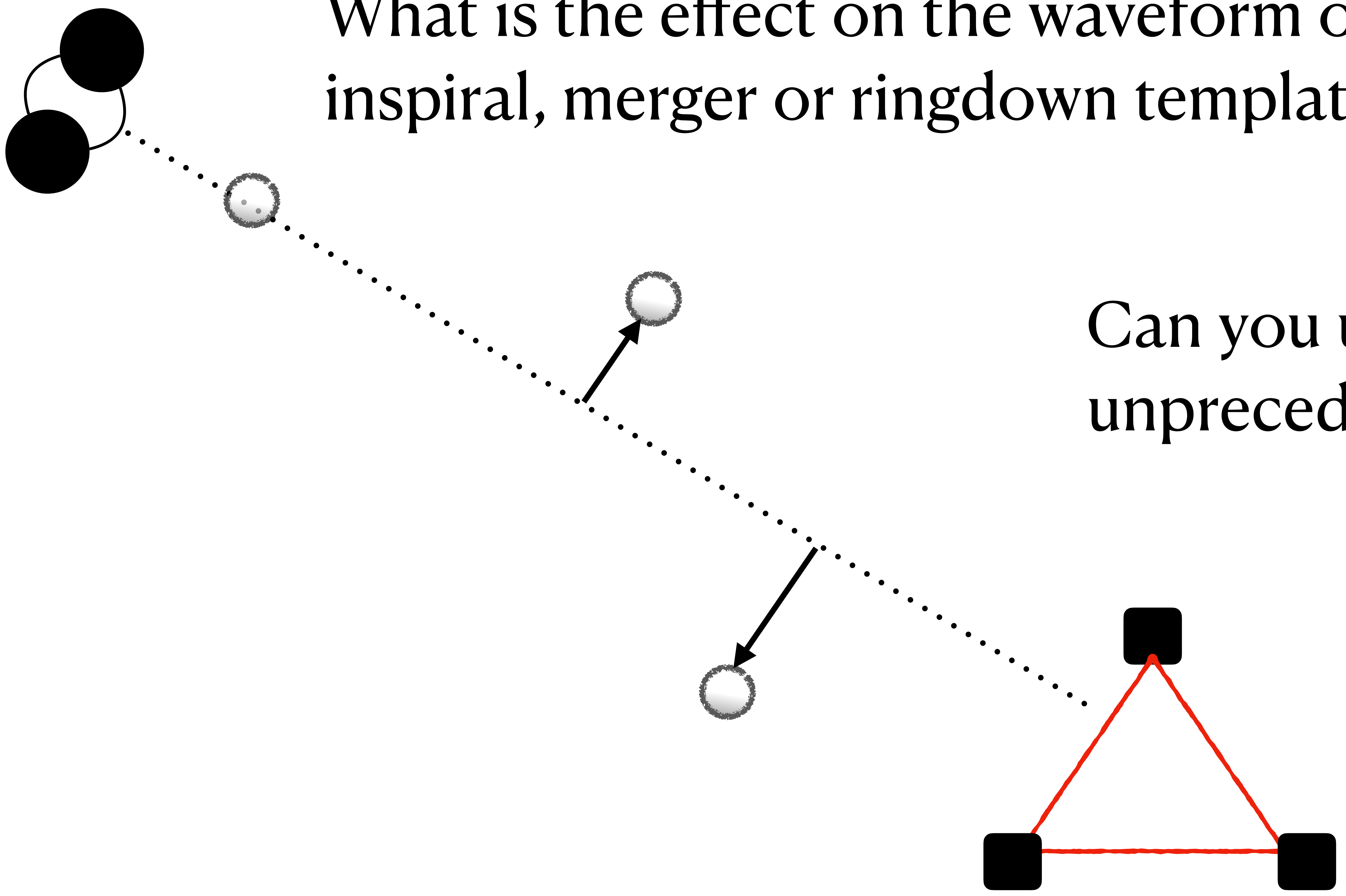
What is the effect on the waveform of a inspiral, merger or ringdown template?

Can you use it to confirm CDM to unprecedented low scales?



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