The importance of light DM halos for SMBH and GWs

What are the implications of JWST AGNs?

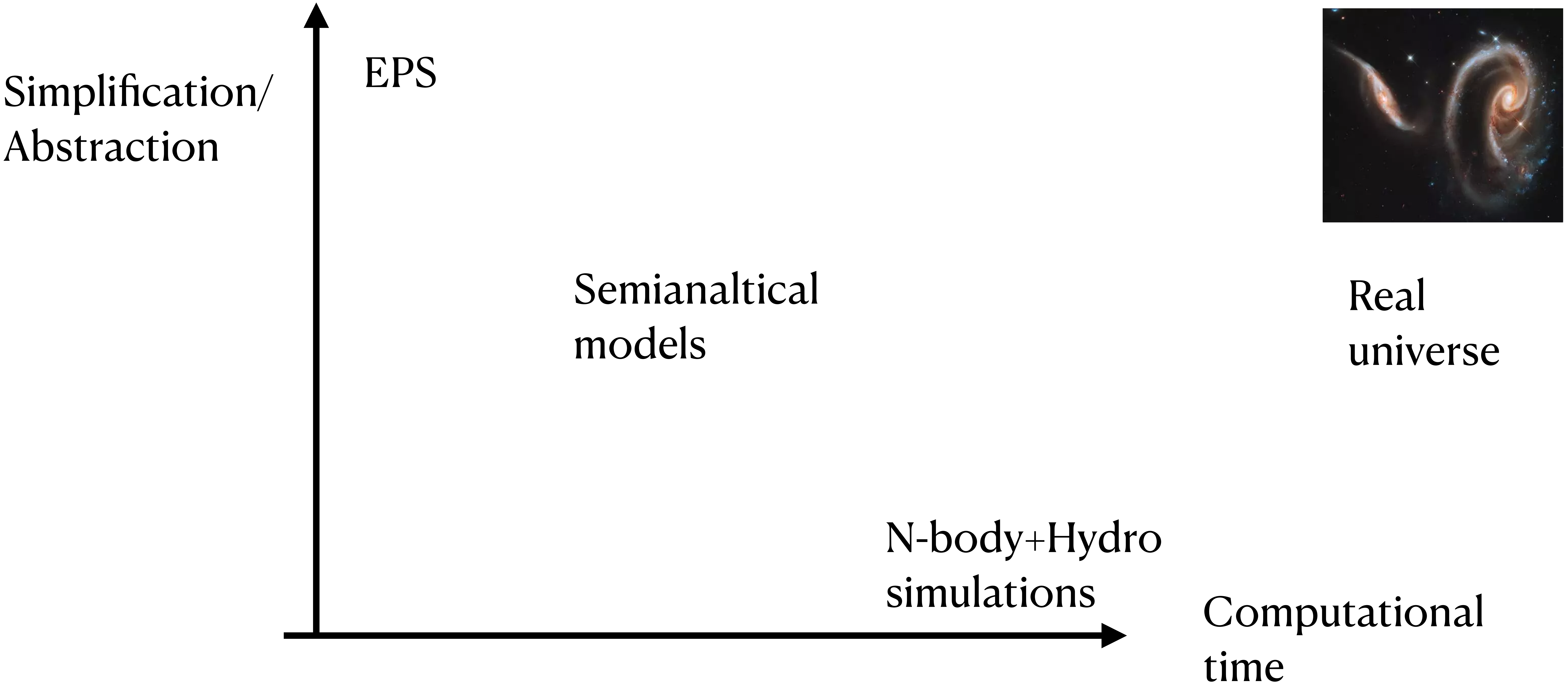
What is the origin of the JWST SMBHs?

John Ellis,[1,2] Malcolm Fairbairn,[1] Juan Urrutia,[3,4,*] and Ville Vaskonen[3,5,6]

[1] *King's College London, Strand, London, WC2R 2LS, United Kingdom*
[2] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[3] *Keemilise ja Bioloogilise Füüsika Instituut, Rävala pst. 10, 10143 Tallinn, Estonia*
[4] *Departament of Cybernetics, Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia*
[5] *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy*
[6] *Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

- Soon to appear on arXiv

The universe growth at different levels of abstraction

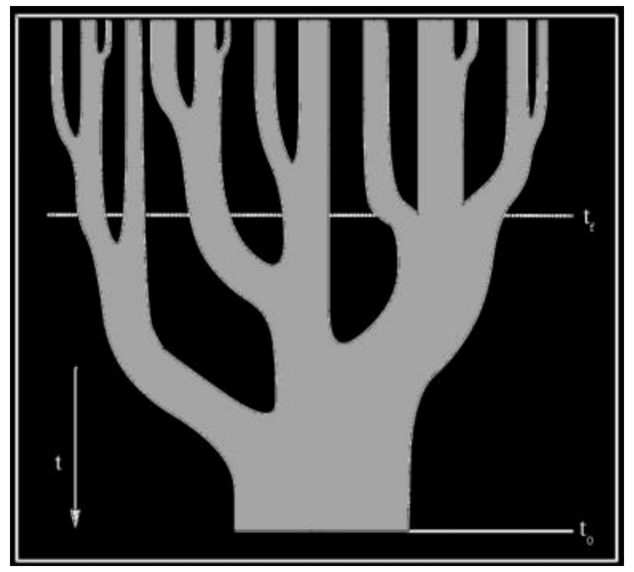


The universe growth at different levels of abstraction

Simplification/
Abstraction

EPS

Merger tree



Semianaltical
models

Where SMBH formation and
growth can be explored

N-body+Hydro
simulations

Computational
time

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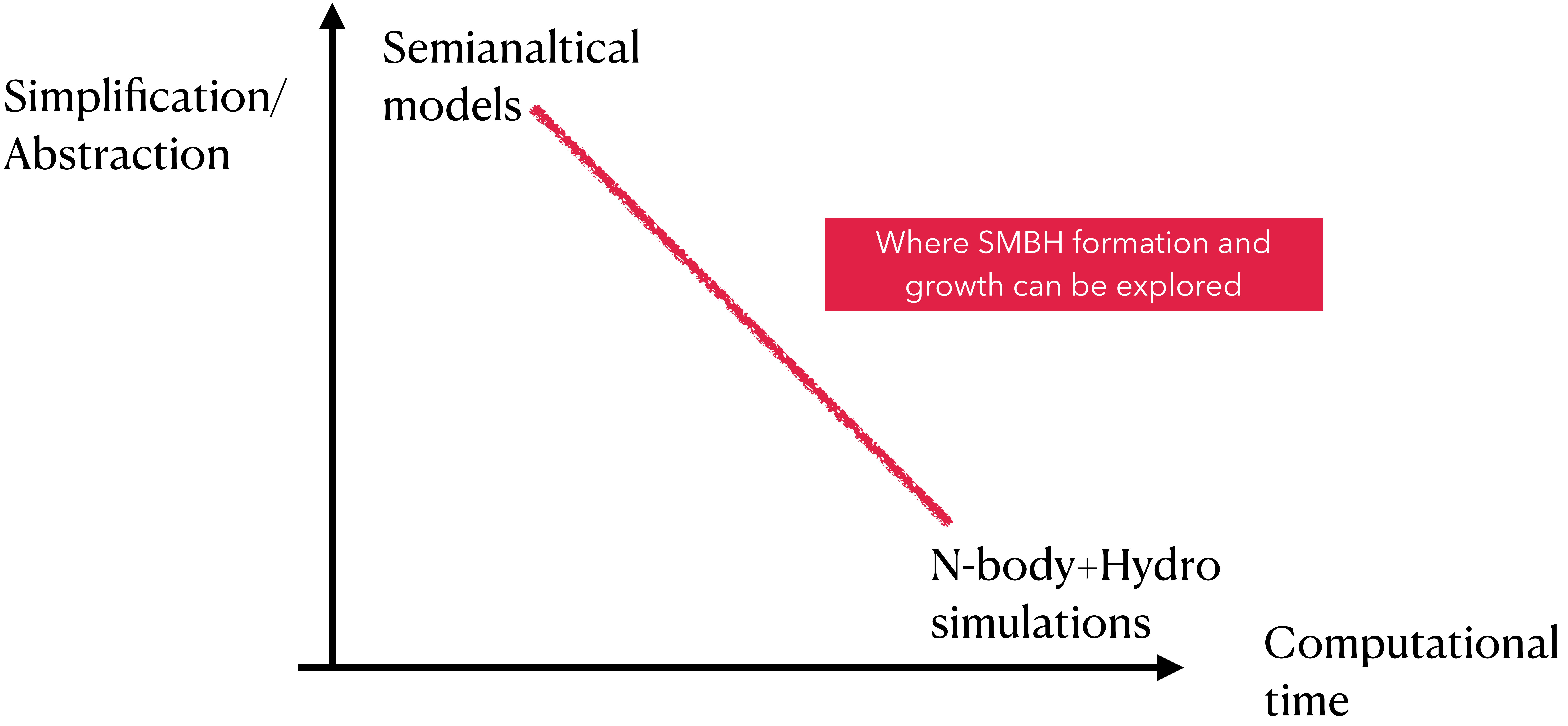
The universe growth at different levels of abstraction



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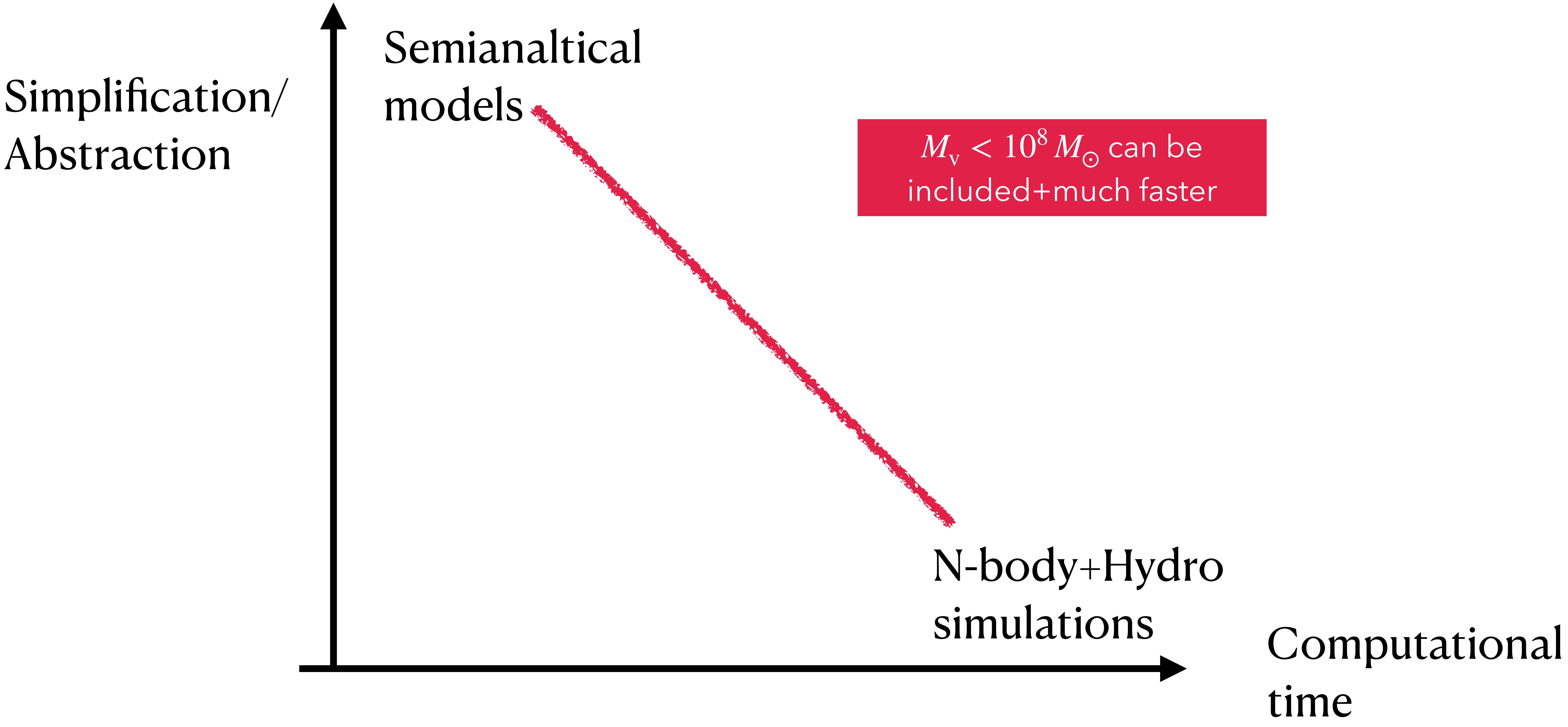

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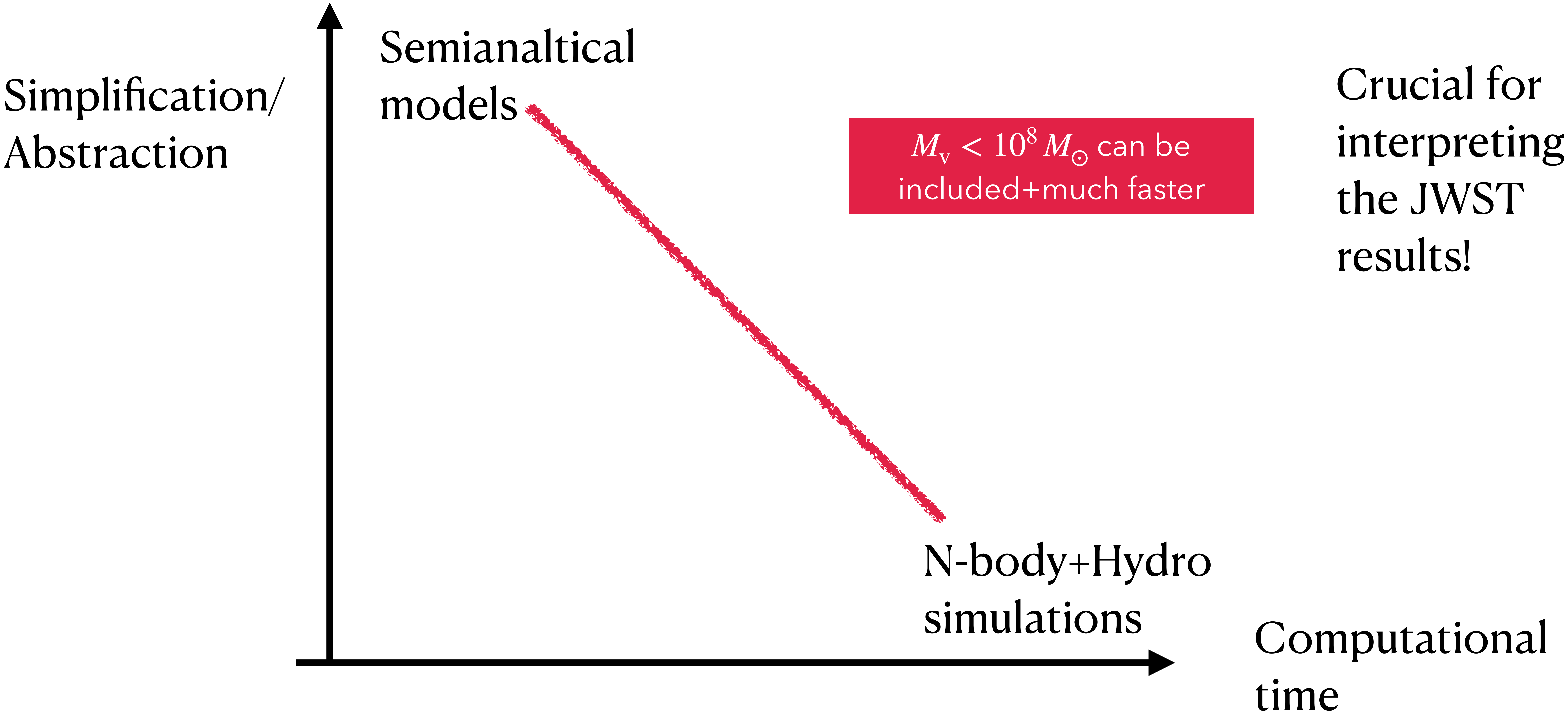
The universe growth at different levels of abstraction



Crucial for interpreting the JWST results!

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Growth beyond merger trees

- Applying the EPS formalism more directly to SMBH growth, i.e. *a SMBH inside a halo on average has had the same history as the average mass of the halo.*
- We can track the differential growth by mergers for DM, gas, stars and SMBHs.

$$M_J(M,z') + \Delta M_J^{\mathrm{merg.}}(M,z,z') = \left[\frac{\mathrm{d}n(z)}{\mathrm{d}M}\right]^{-1} \int_0^M \mathrm{d}M' \, \frac{\mathrm{d}n(z')}{\mathrm{d}M'} \frac{\mathrm{d}P(M,z|M',z')}{\mathrm{d}M} M_J(M',z')$$

$$= \int_0^M \mathrm{d}M' \left|\frac{\mathrm{d}S}{\mathrm{d}M'}\right| \frac{M}{M'} M_J(M',z') \frac{\delta_c(z') - \delta_c(z)}{\sqrt{2\pi[S(M') - S(M)]^3}} e^{-\frac{[\delta_c(z') - \delta_c(z)]^2}{2[S(M') - S(M)]}}$$

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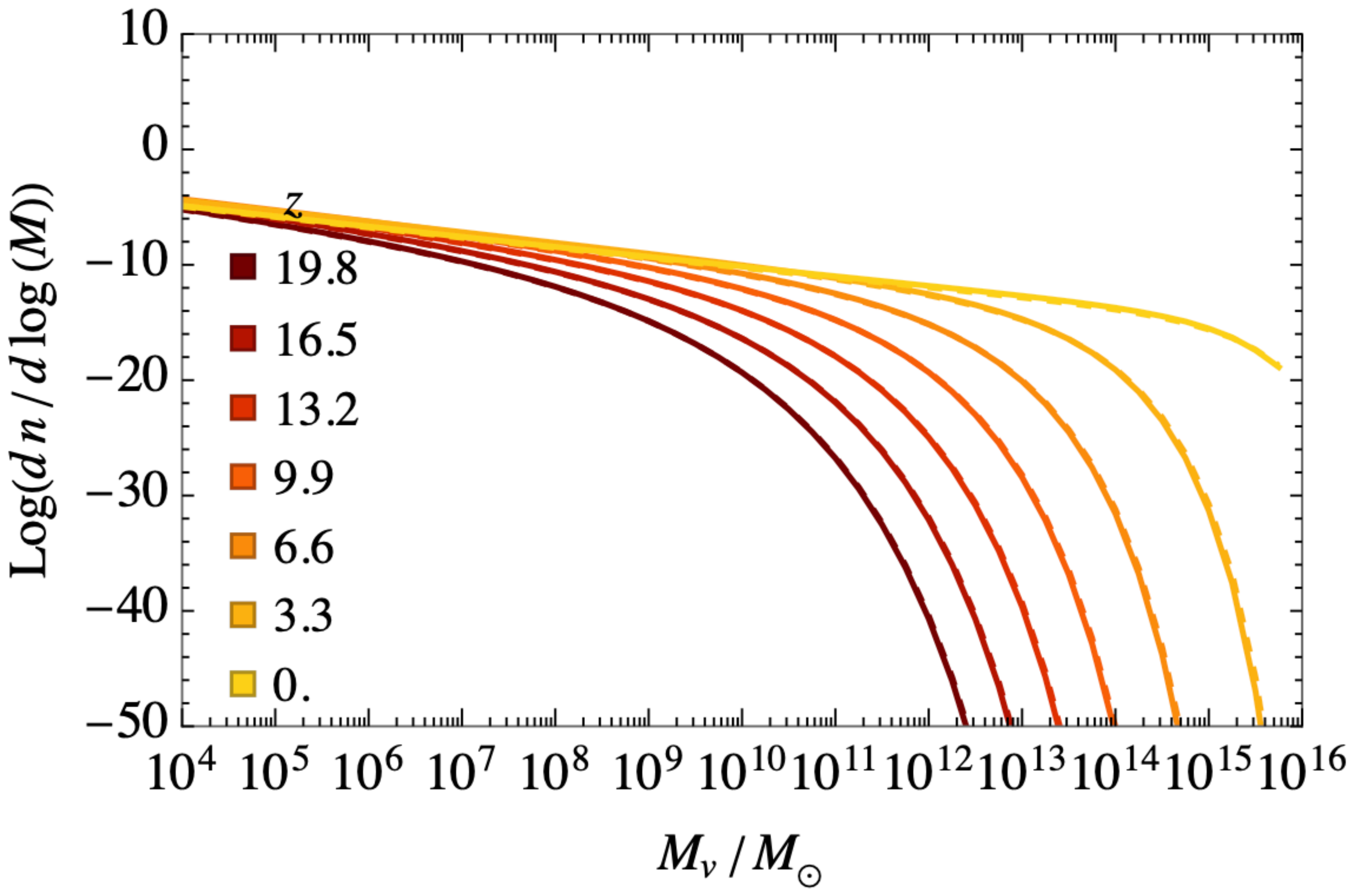
Growth beyond merger trees

- Automatically matches the EPS formalism for DM
- arbitrarily small DM halos can be taken into account



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Growth beyond merger trees

- The SMBH origin becomes the initial conditions to the solution to the coupled differential equations
- We take into account the difference between hot and cold gas

$$\dot{M}_{\rm BH}(M) = \dot{M}_{\rm BH}^{\rm merg.}(M) + \dot{M}_{\rm BH}^{\rm acc.,cold}(M_{\rm BH}, M) + \dot{M}_{\rm BH}^{\rm acc.,hot}(M_{\rm BH}, M)\,,$$

$$\dot{M}_{*}(M) = \dot{M}_{*}^{\rm merg.}(M) + \dot{M}_{*}^{\rm sf.}(M)\,,$$

$$\dot{M}_{\rm cold}(M) = f_{\rm cold}(M) f_B \dot{M} - \dot{M}_{\rm cold}^{\rm ej.}(M) - \dot{M}_{\rm cold}^{\rm heated}(M) - \dot{M}_{*}^{\rm sf.}(M) - \dot{M}_{\rm BH}^{\rm acc.,cold}(M_{\rm BH}, M)$$

$$\dot{M}_{\rm hot}(M) = f_{\rm hot}(M) f_B \dot{M} + \dot{M}_{\rm cold}^{\rm heated}(M) - \dot{M}_{\rm BH}^{\rm acc.,hot}(M_{\rm BH}, M)$$

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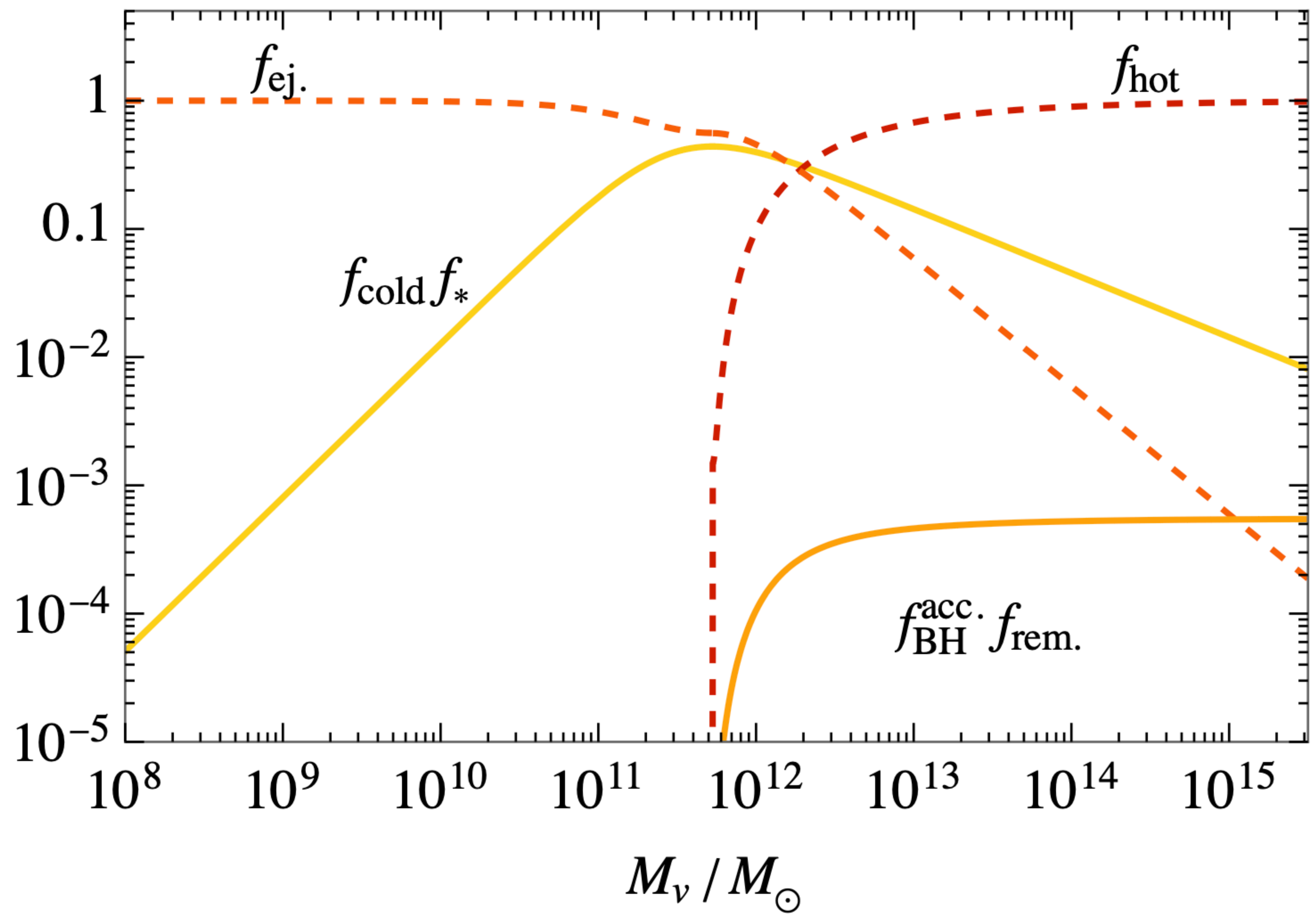
Star formation

- Ejected gas by SN feedback
- heated gas by AGN activity
- Fits high-z UV luminosity function by construction
- the AGN activity also matches UV luminosity functions

$$\dot{M}_*^{\mathrm{sf.}}(M,z) = \frac{6.4\times10^{-2}[0.53\tanh\left(0.54(2.9-z)\right)+1.53]}{(M/M_{\mathrm{crit}})^{-1.2}+(M/M_{\mathrm{crit}})^{0.5}}\dot{M}$$



https://arxiv.org/pdf/2108.01090

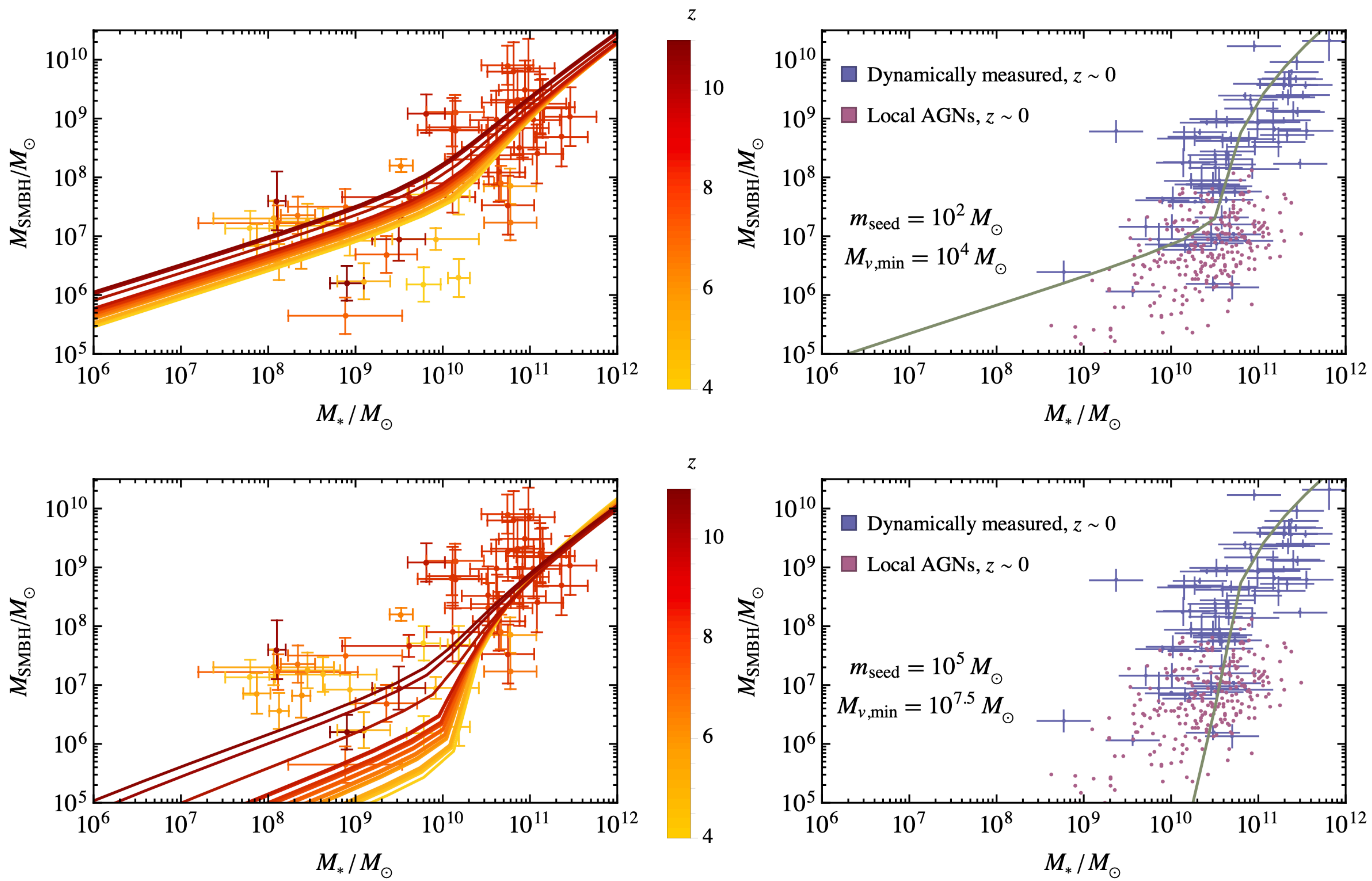
SMBH accretion

$$\dot{M}_{\rm BH}^{\rm acc.}(M_{\rm BH}, M) = \min\left\{ f_{\rm rem.}(M,z) f_B (f_1^{\rm acc.}\dot{M} + f_2^{\rm acc.} M),\ f_{\rm Edd.}\dot{M}_{\rm Edd.}(M_{\rm BH}) \right\}$$

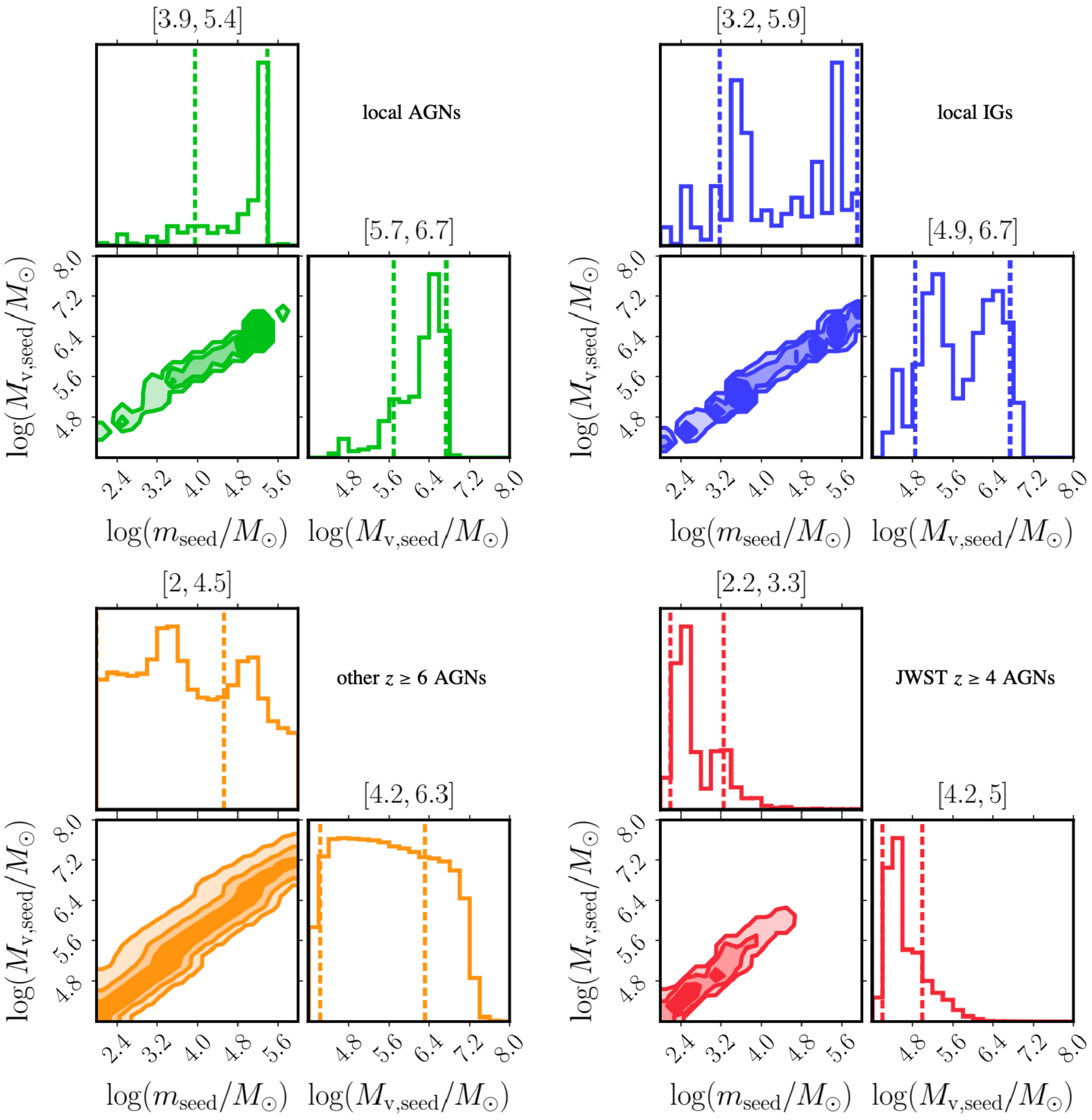
$$\dot{M}_{\rm Edd.}(M_{\rm BH}) = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_T} \approx 2.2 \times 10^{-3} m_{\rm BH}(M_{\rm BH})/{\rm Myr}$$

- Sub-Eddington accretion of both hot and cold gas
- a term proportional to the baryon accretion rate and another one proportional to the gas content
- standard practice in SAMs

Results and fits



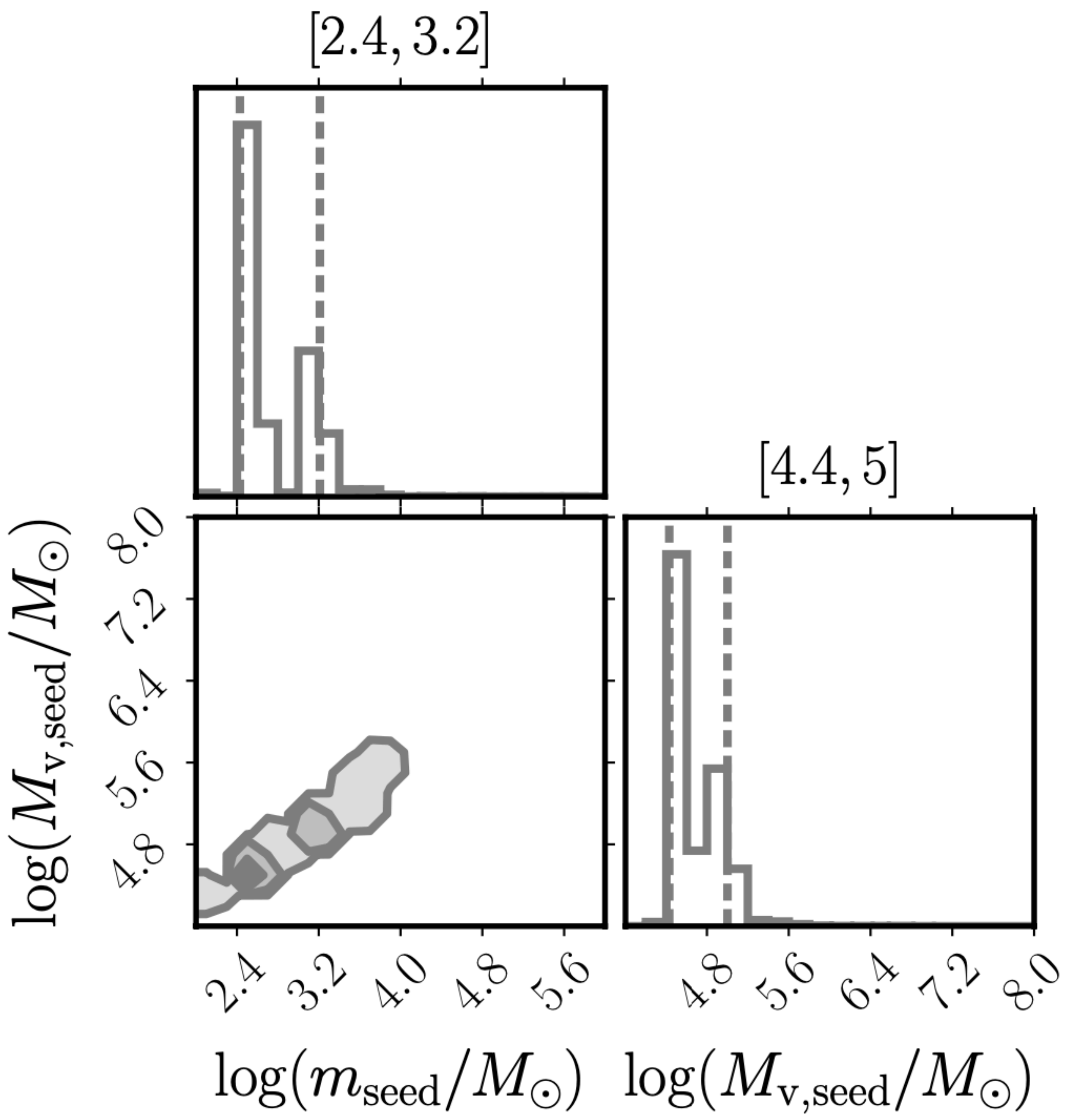
$$\boldsymbol{\theta} = (m_{\rm seed}\,, M_{\rm seed}\,, z_{\rm seed})$$

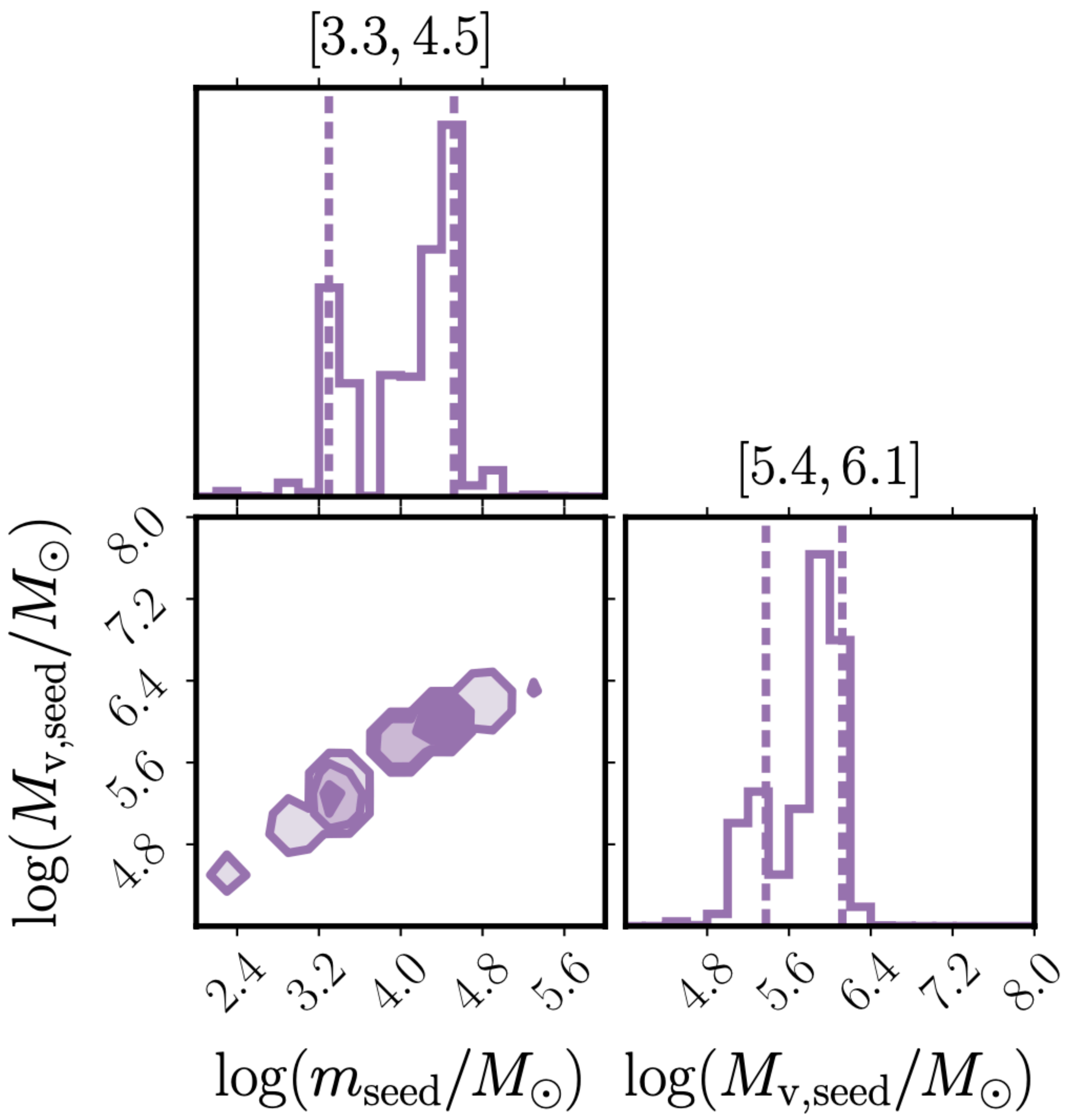


Results and fits

- All data points to a scaling relation between the BH mass and the halo mass at which these seeds are planted,
- the heaviest SMBH do not constraining seeding
- Local AGNs, (all pre JWST data), points to a heavy seed scenario
- But JWST data strongly prefers light-seed scenario.

Results and fits





- All the data except the local AGNs (gray) is compatible with the light-seed scenario
- To fit to all the data an intermediate scenario is favored (purple)

Shortcoming

- All galactic mergers do not have to induce instantaneous mergers, especially for light halos and SMBH
  - nuclear star clusters around the SMBH can do the work
  - DM only induced can also lead to short timescales although is more uncertain, only $\mathcal{O}(0.1)$ of configurations lead to thigh binaries
- It has been suggested that JWST observations, which are x-ray opaque, might be because they are accreting at super-Eddington rate, which implies lighter SMBH
- The implications of this will be explored in the arXiv version!

Propagation of GWs in a CDM universe

The dark timbre of gravitational waves

Juan Urrutia[1,2,*] and Ville Vaskonen[1,3,4,†]

[1] *Keemilise ja Bioloogilise Füüsika Instituut, Rävala pst. 10, 10143 Tallinn, Estonia*
[2] *Departament of Cybernetics, Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia*
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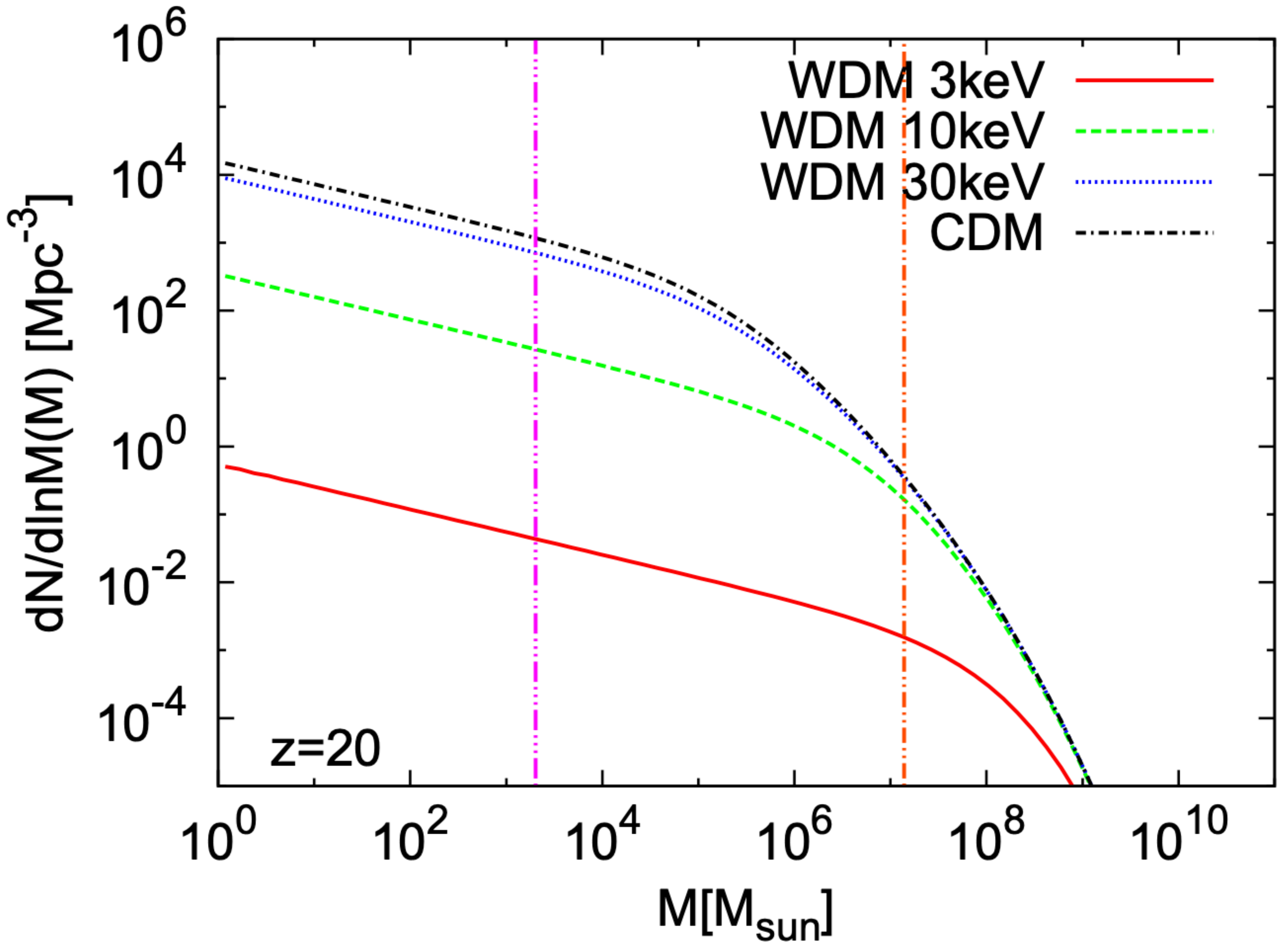
[4] *Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

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 $100 - 10^3$ and it is at $z_s = 0.5$.

- Under peer review for PRL

Motivation to search for low mass DM halos

- Mainly unconstrained with current optical searches
- do not contain enough baryonic mass to form star + SN feedback ejects any gas after first stars
- but contain extremely **valuable information about DM**

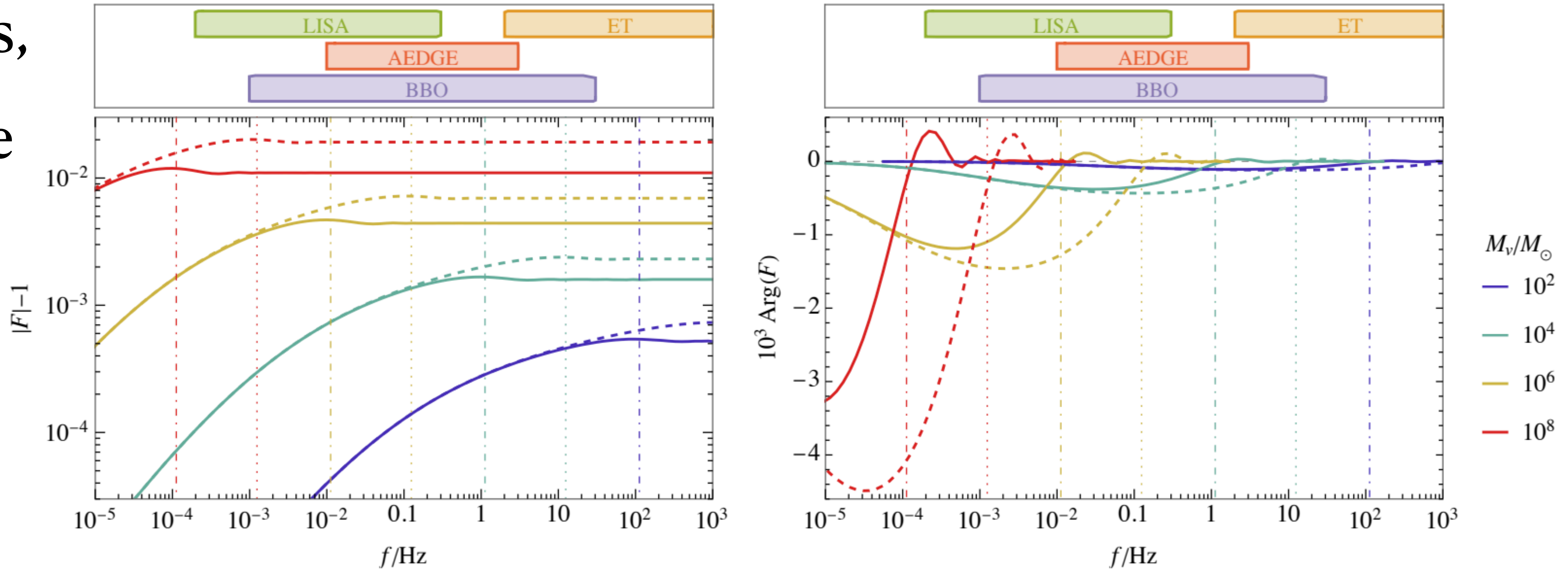


https://arxiv.org/pdf/1401.5563

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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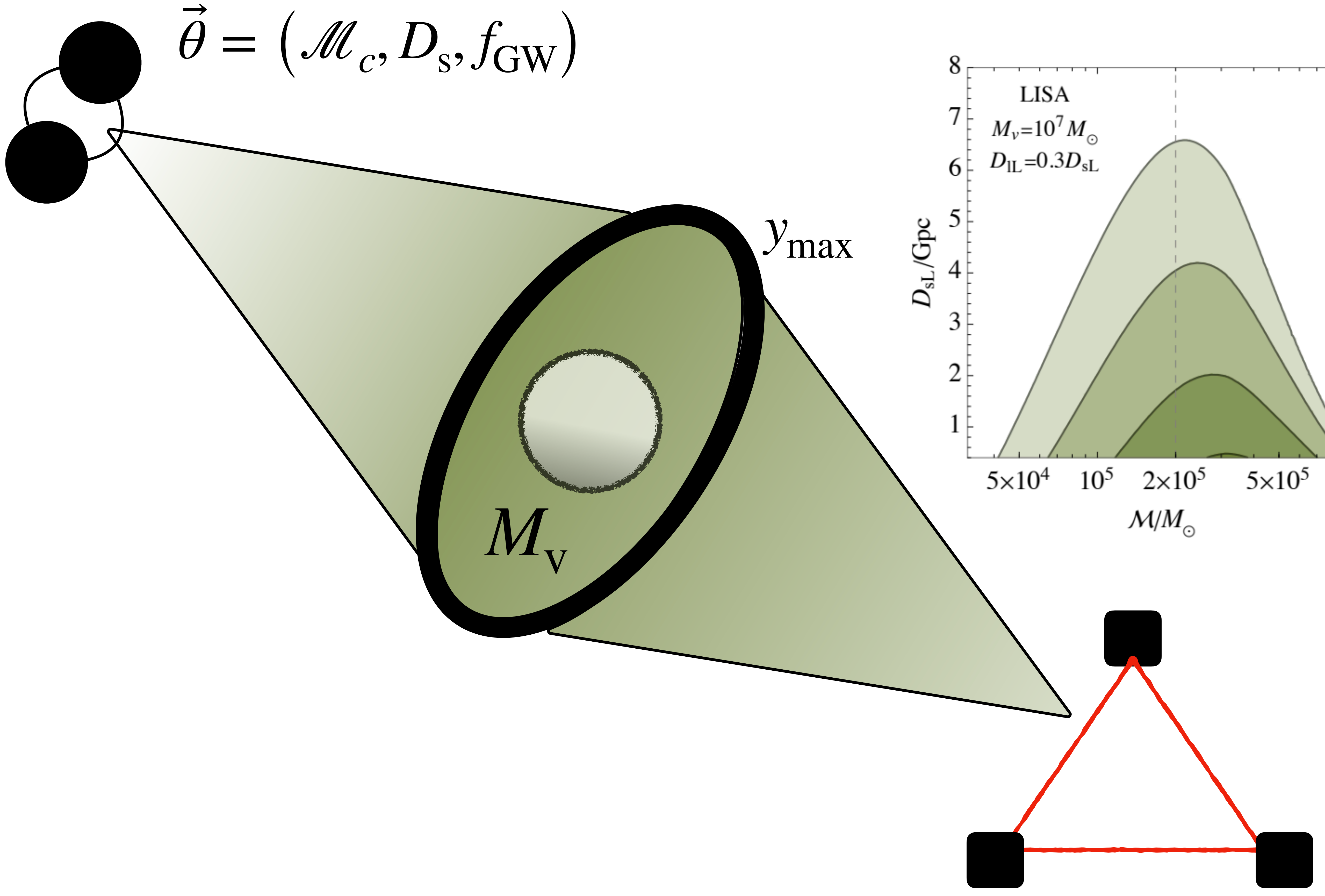
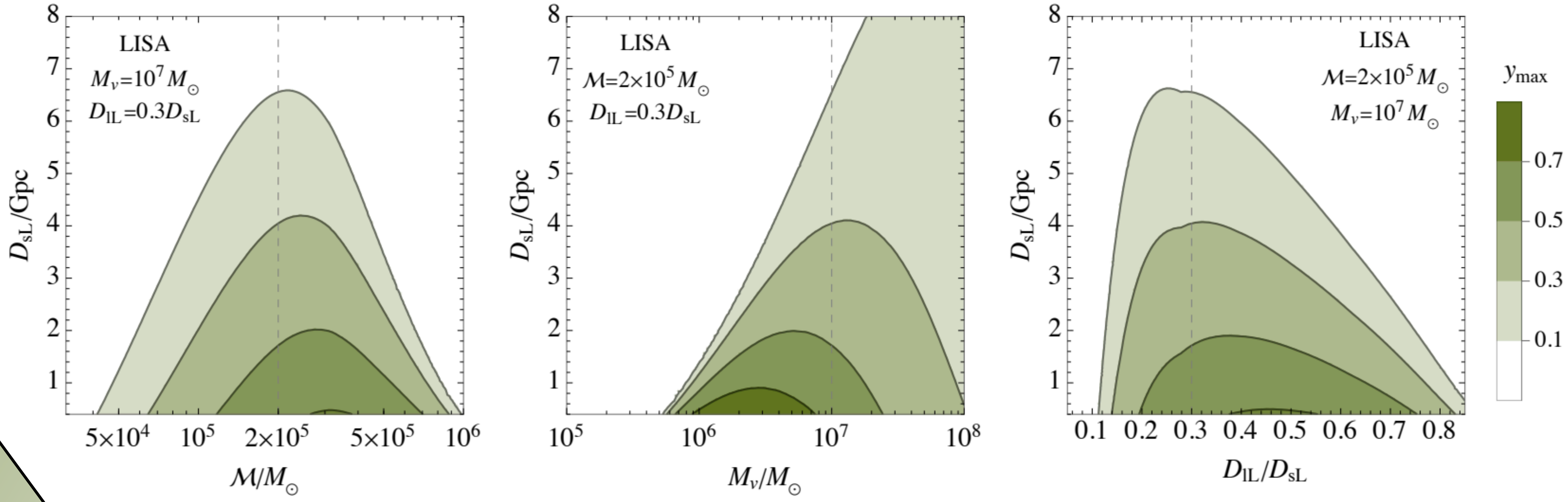
What is the problem then?





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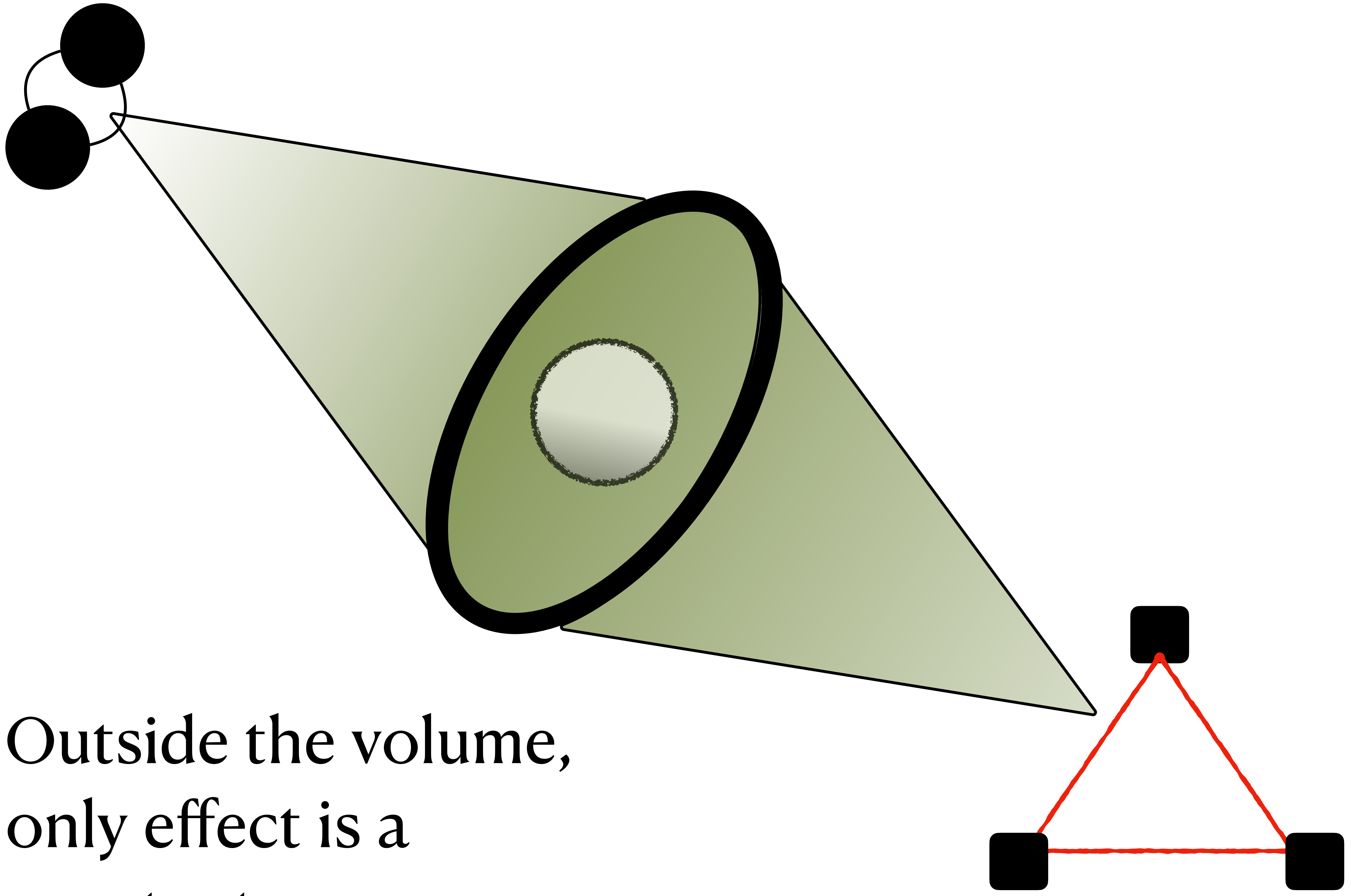
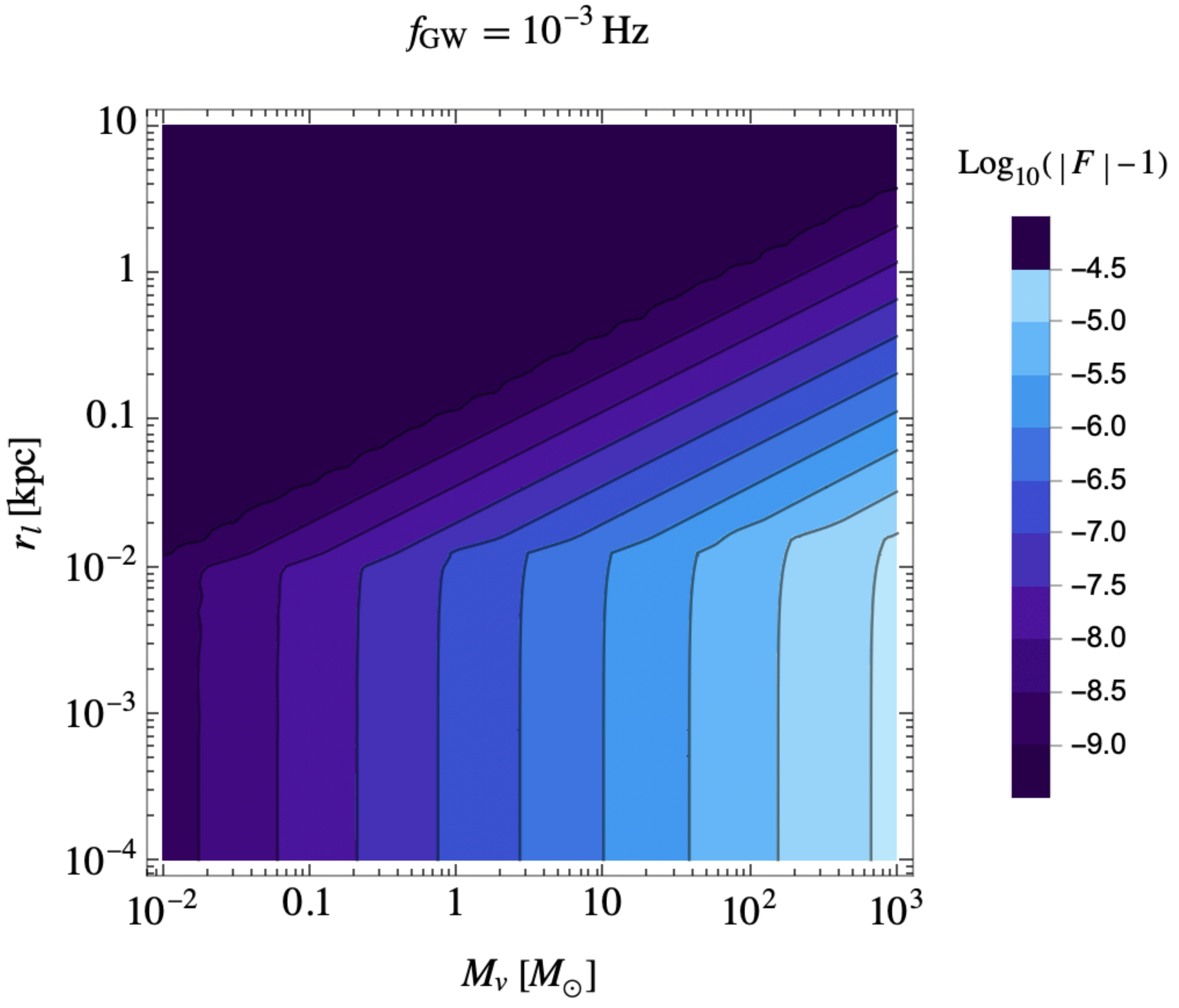


Outside the volume, only effect is a constant magnification



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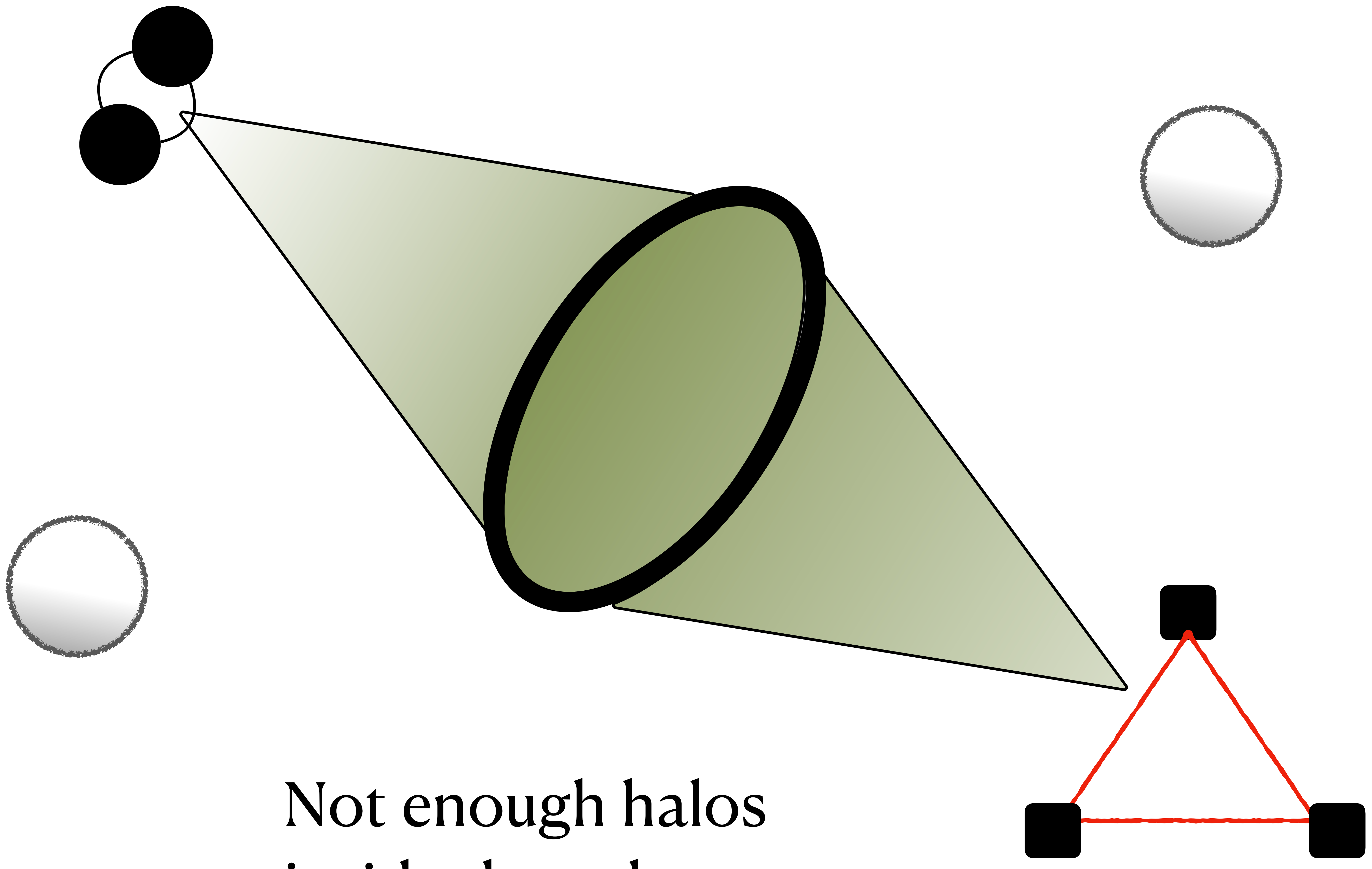

Not enough halos
inside the volume

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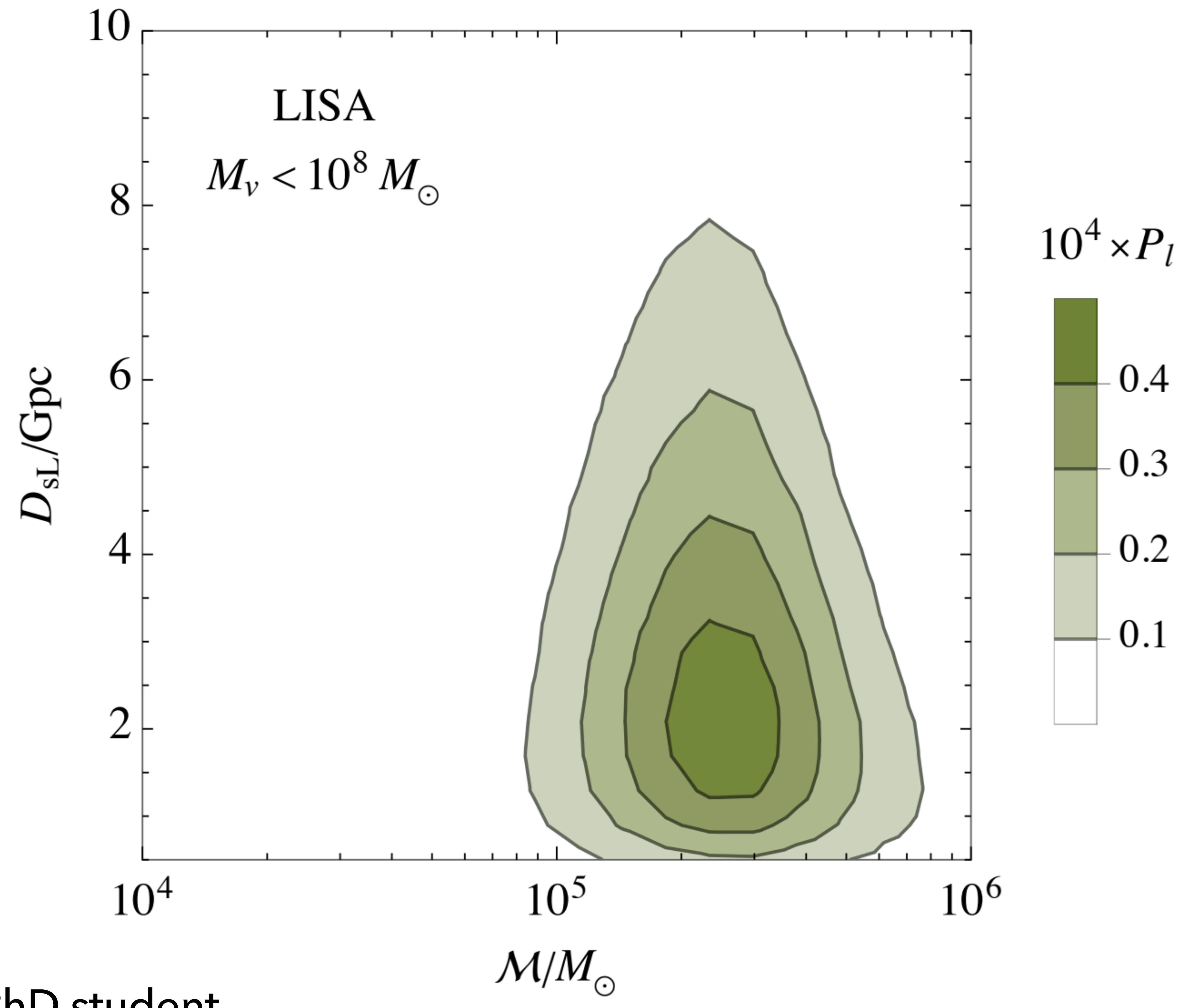
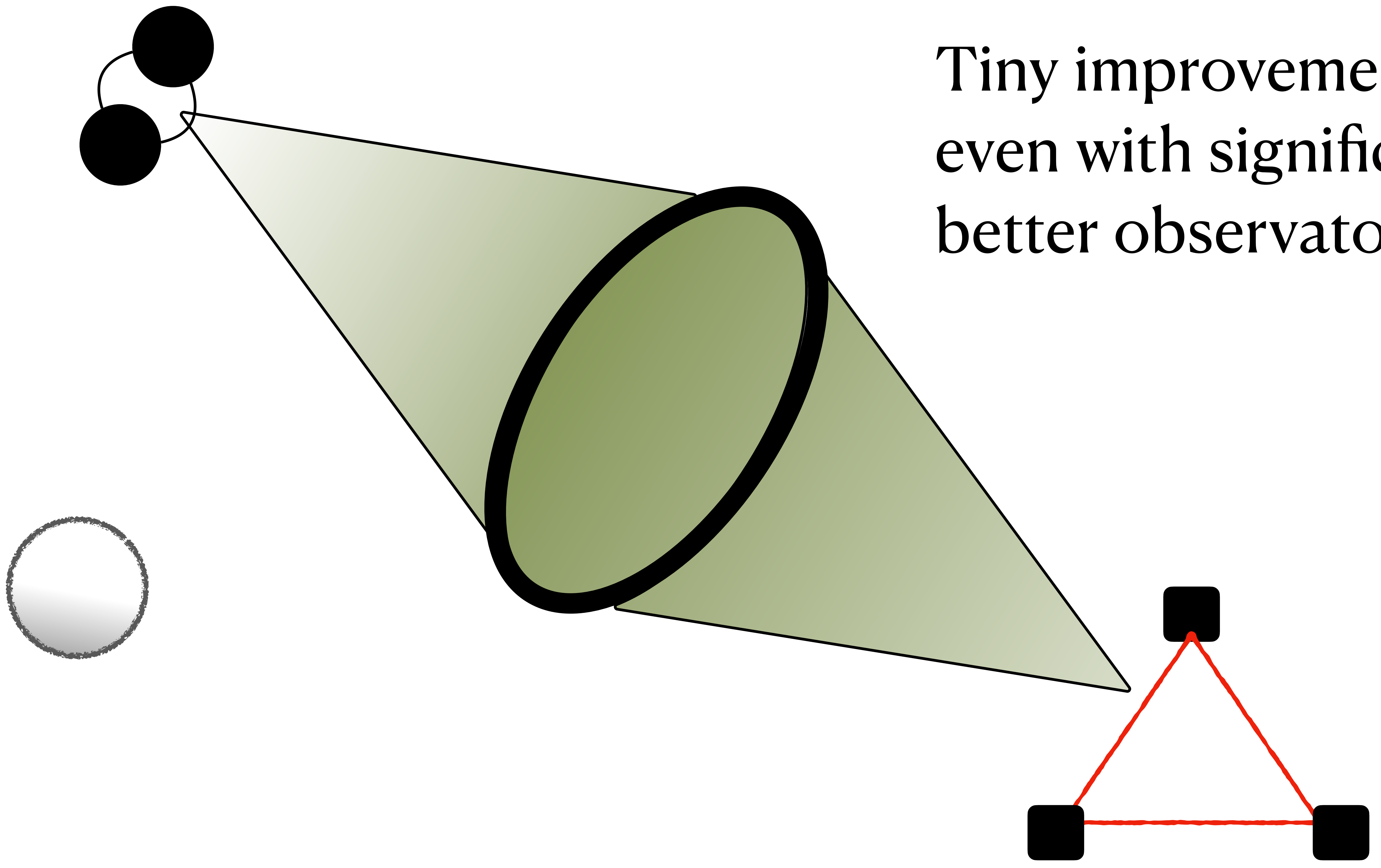
https://arxiv.org/pdf/2210.13436

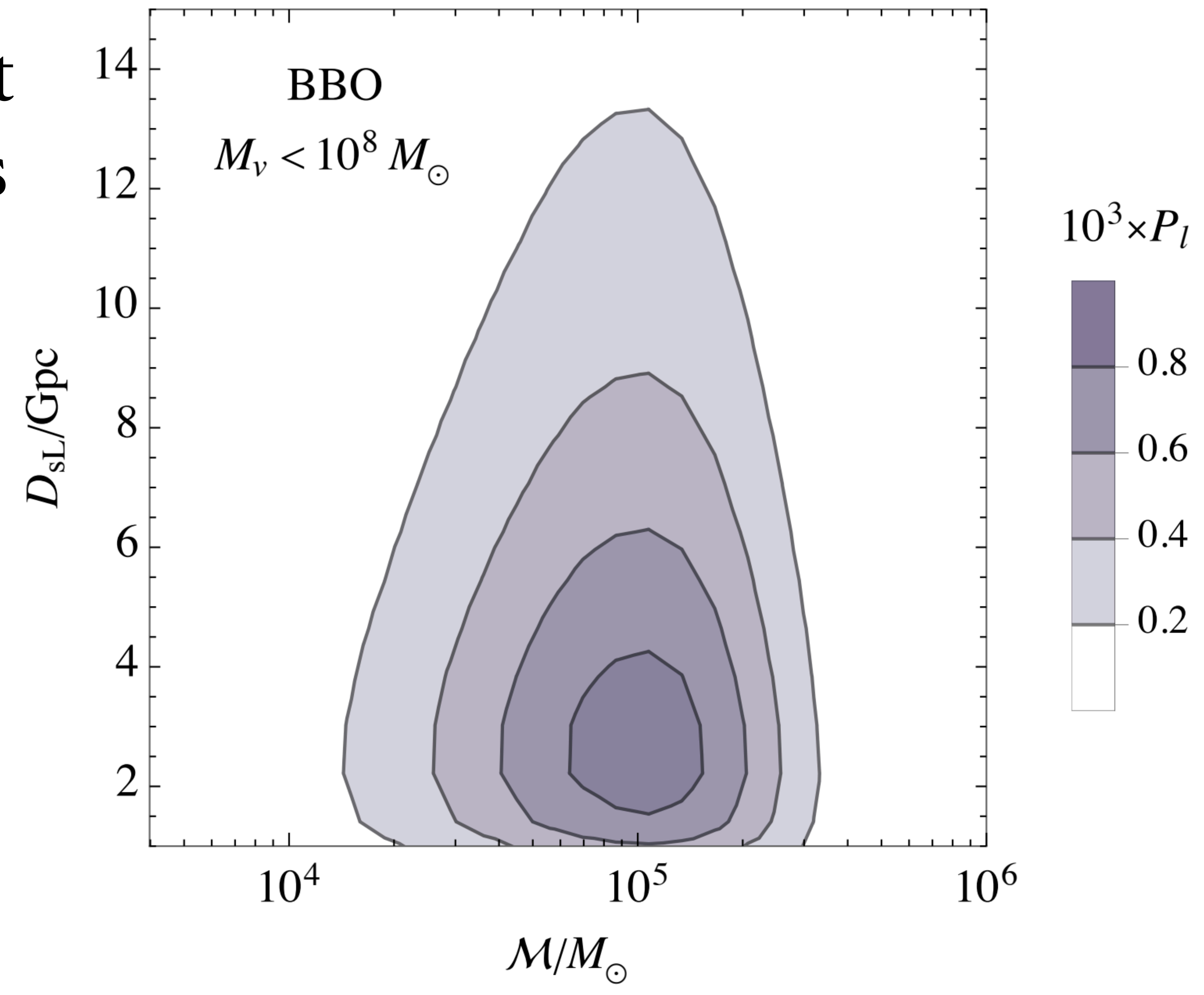


What is the problem then?



Tiny improvements even with significant better observatories

https://arxiv.org/pdf/2210.13436



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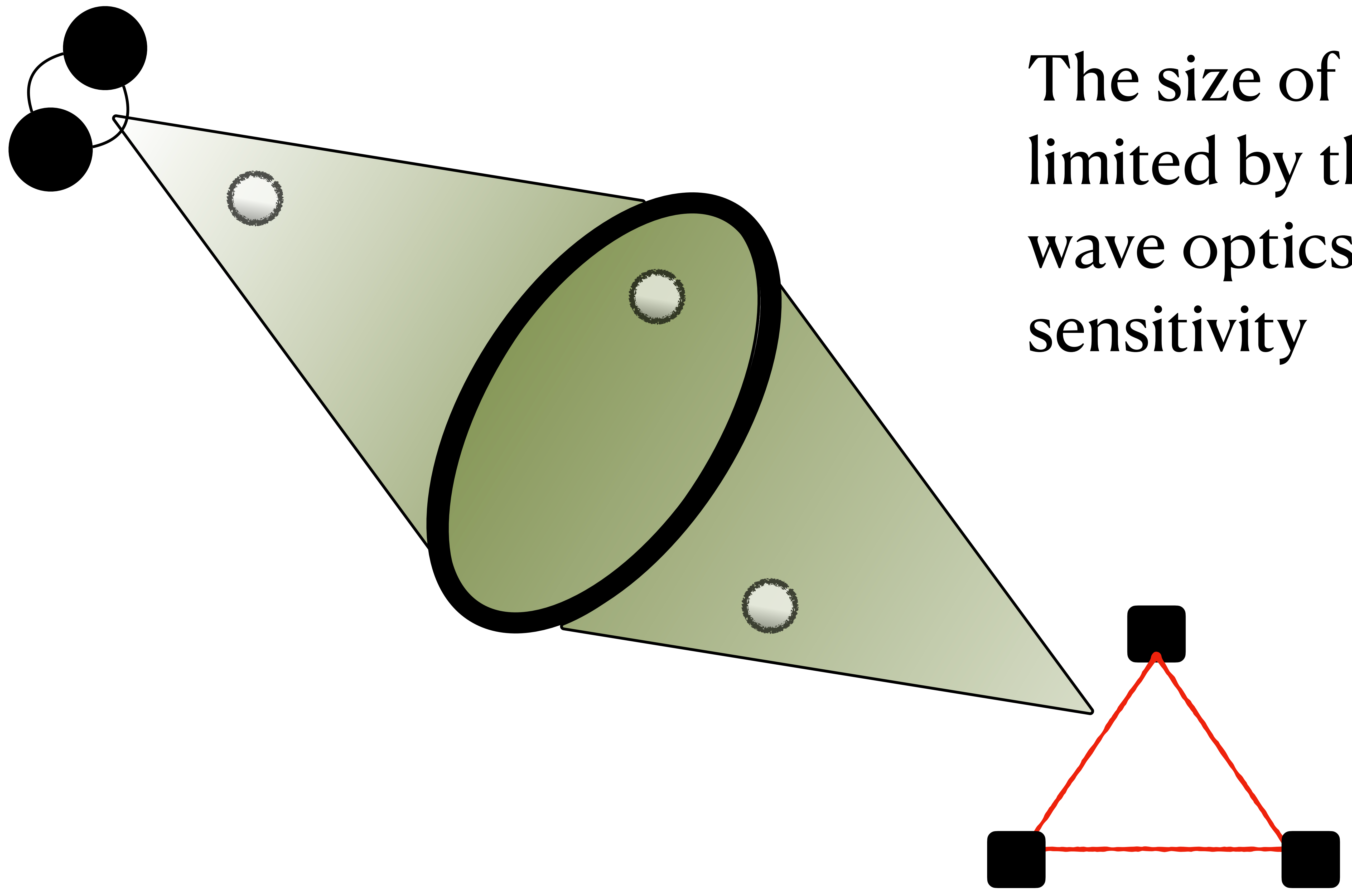
What is the idea to overcome it?



The size of this volume is limited by the physics of wave optics not the sensitivity

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

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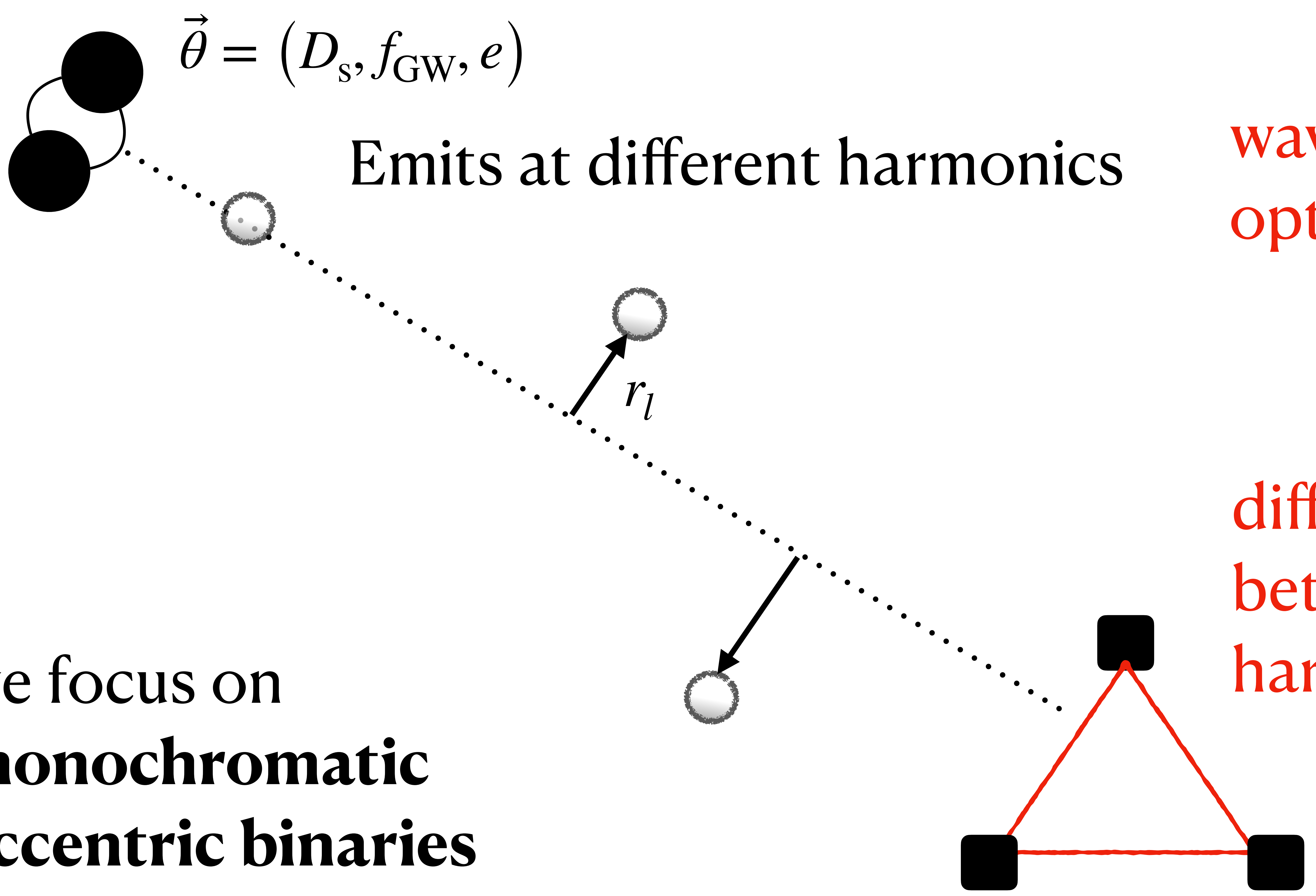
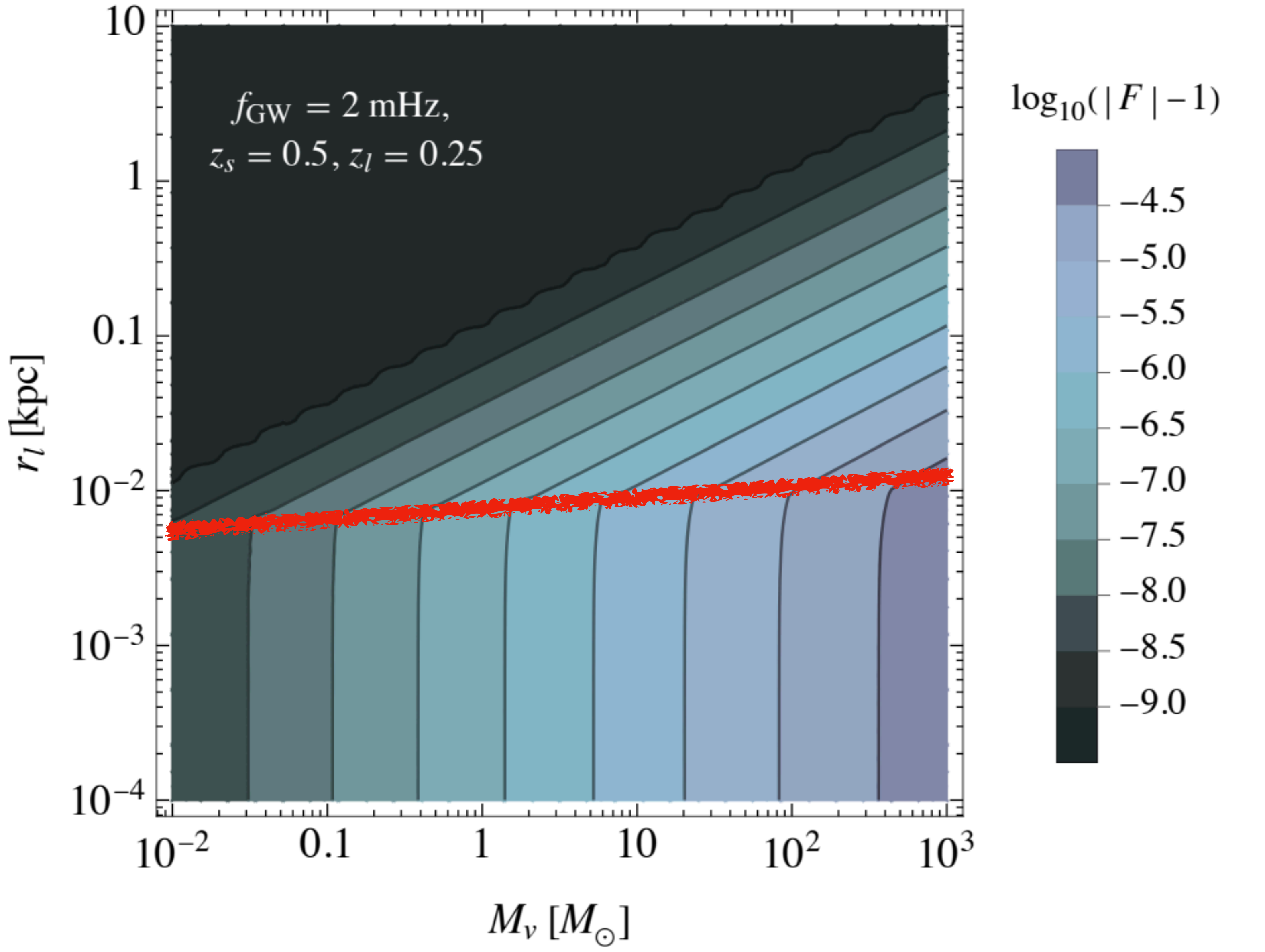
High impact parameter lensing

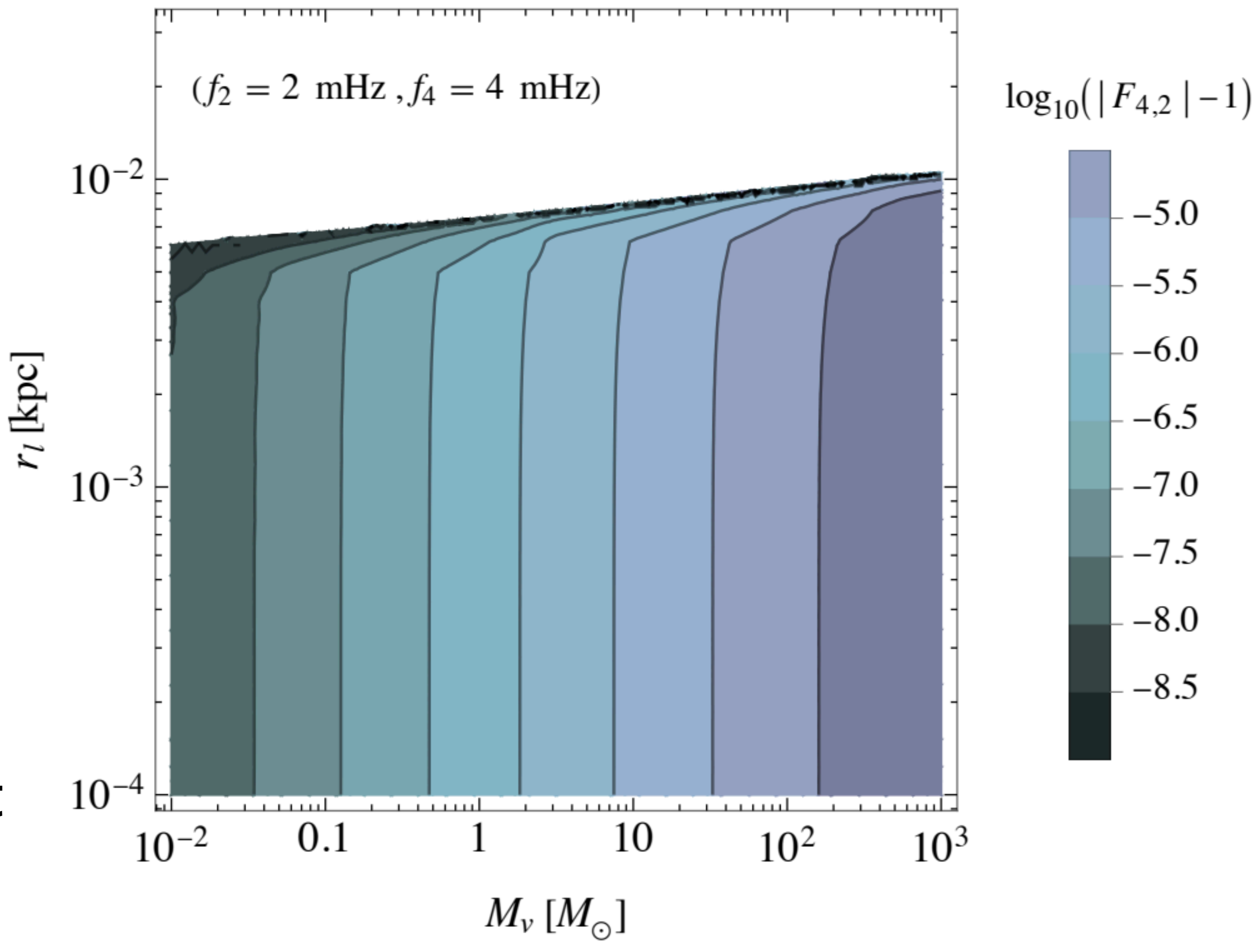


we focus on
monochromatic eccentric binaries

wave optics



difference between harmonics



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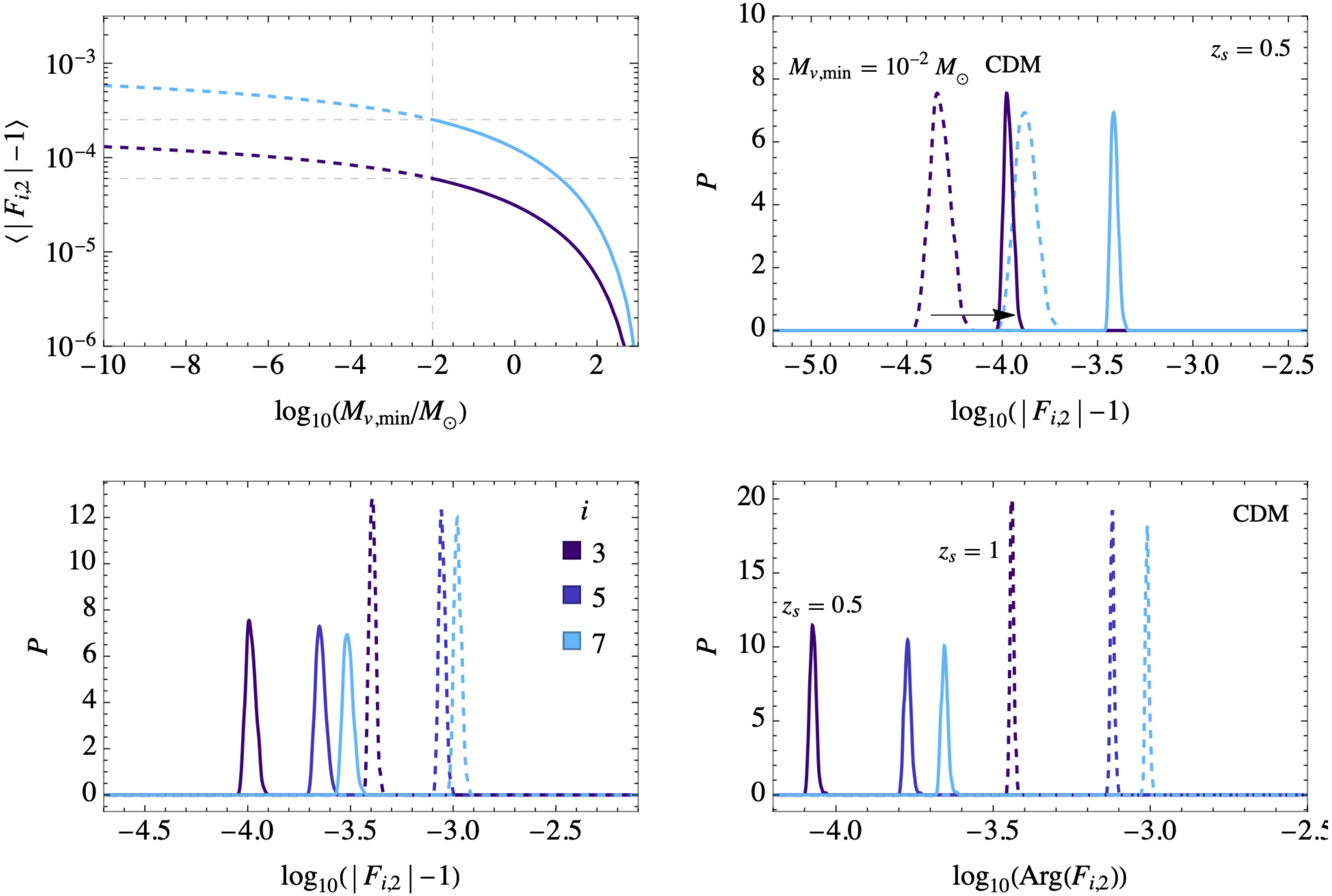


$\langle |F_{i,2}|-1 \rangle$
$\log_{10}(M_{v,\mathrm{min}}/M_\odot)$
$M_{v,\mathrm{min}} = 10^{-2}\, M_\odot$ CDM
$z_s = 0.5$
P
$\log_{10}(|F_{i,2}|-1)$
i
3
5
7
CDM
$z_s = 1$
$z_s = 0.5$
$\log_{10}(\mathrm{Arg}(F_{i,2}))$

Changes the "timbre" of the signal

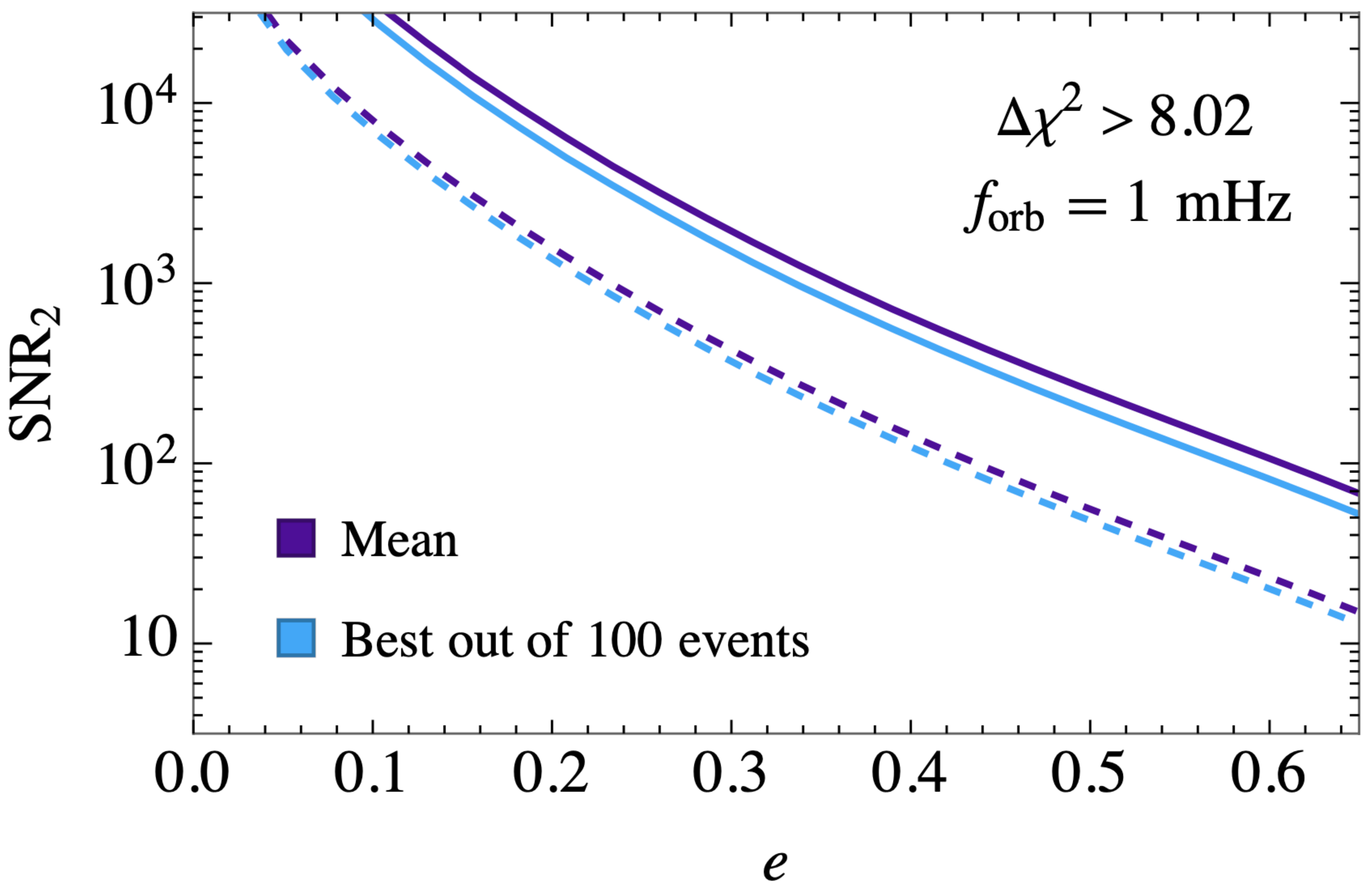
- The timbre is the relative amplitude and phases between the harmonics
  - is the reason why a piano and a violin sounds the same even when playing the same note,
- is the change in timber detectable?

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

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

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

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, $M_{\rm v} < 10\, M_{\odot}$, **induce frequency-dependent changes in the amplitude and phase of the harmonics**, the timbre of the signal.
- This shifted timbre is detectable in the **7 dominant harmonics of the signal for signal-to-noise ratios between** $100 - 10^3$ 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

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