USING AXION MINICLUSTERS TO GET THE AXION-PHOTON COUPLING

BASED ON 2307.11871

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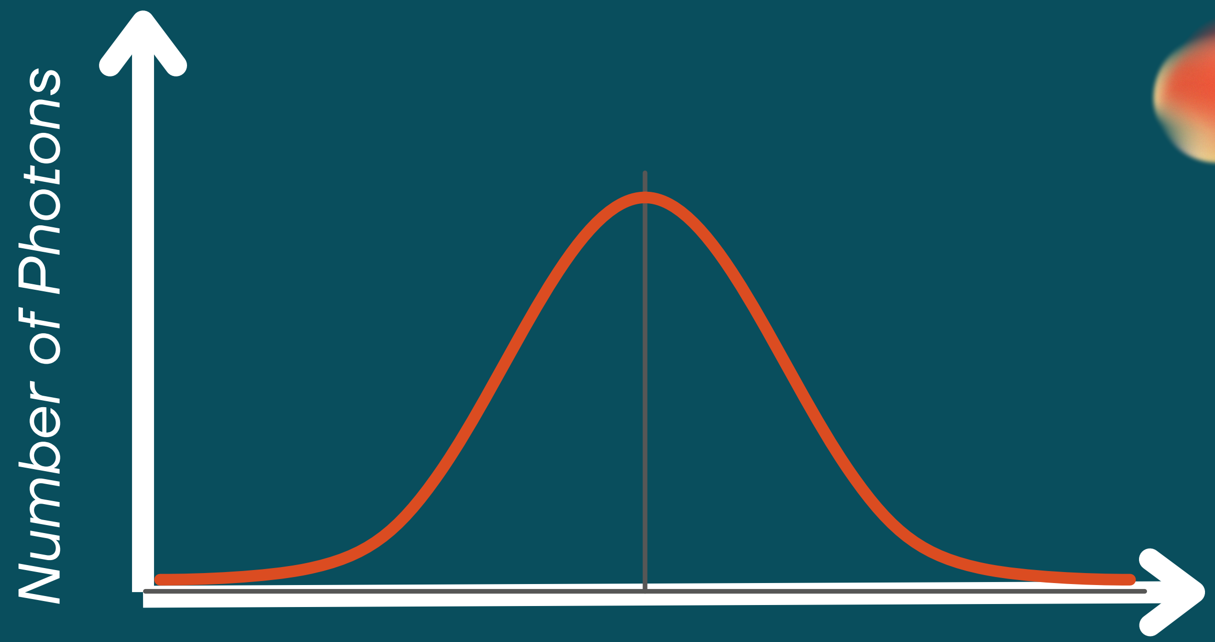
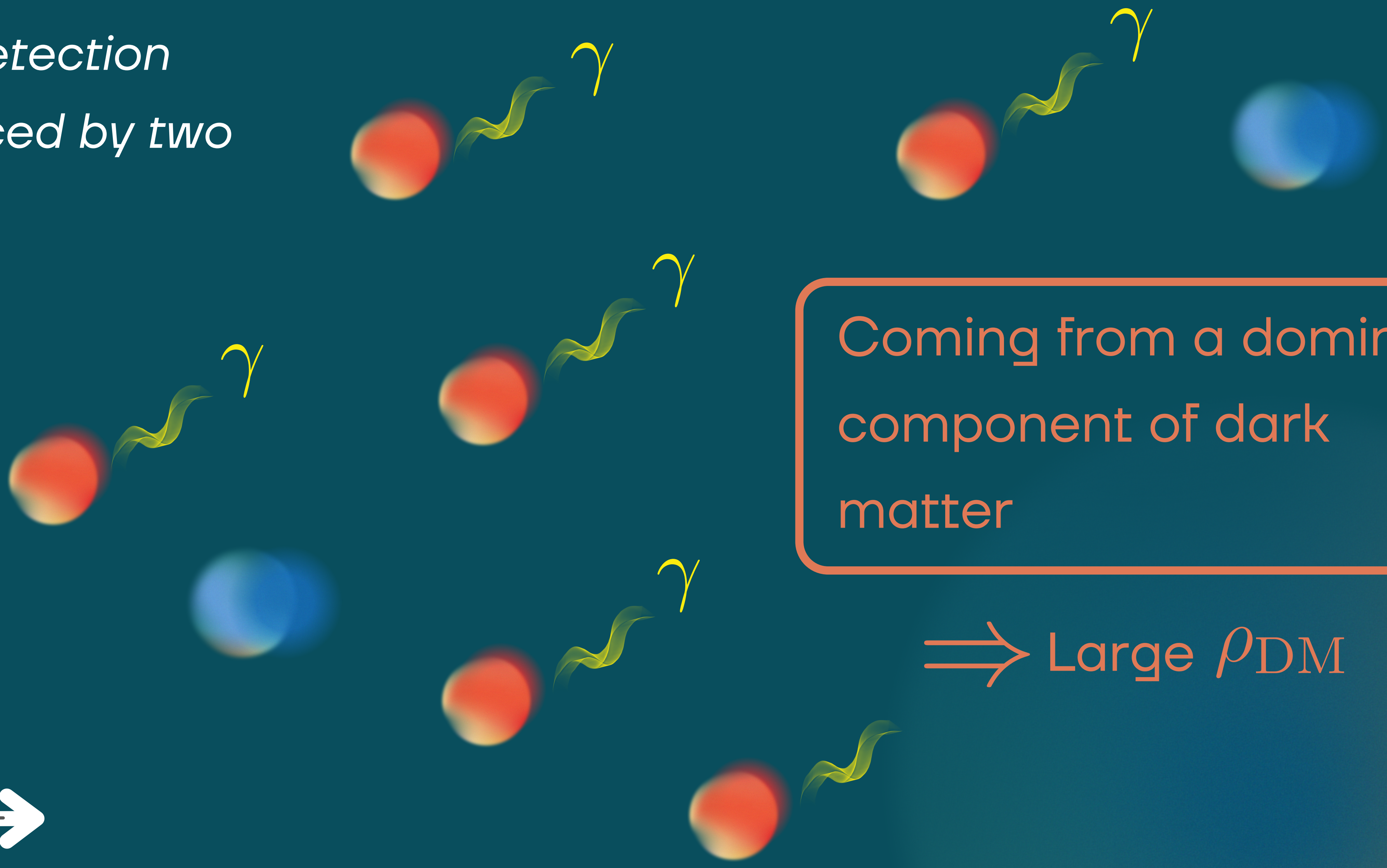
MOTIVATION

Motivation

What experiments tell us about the dark matter coupling/density ?

- *A signal in direct/indirect detection experiments can be enhanced by two effects*





Coming from a dominant component of dark matter

$\Longrightarrow$ Large ρ_{DM}

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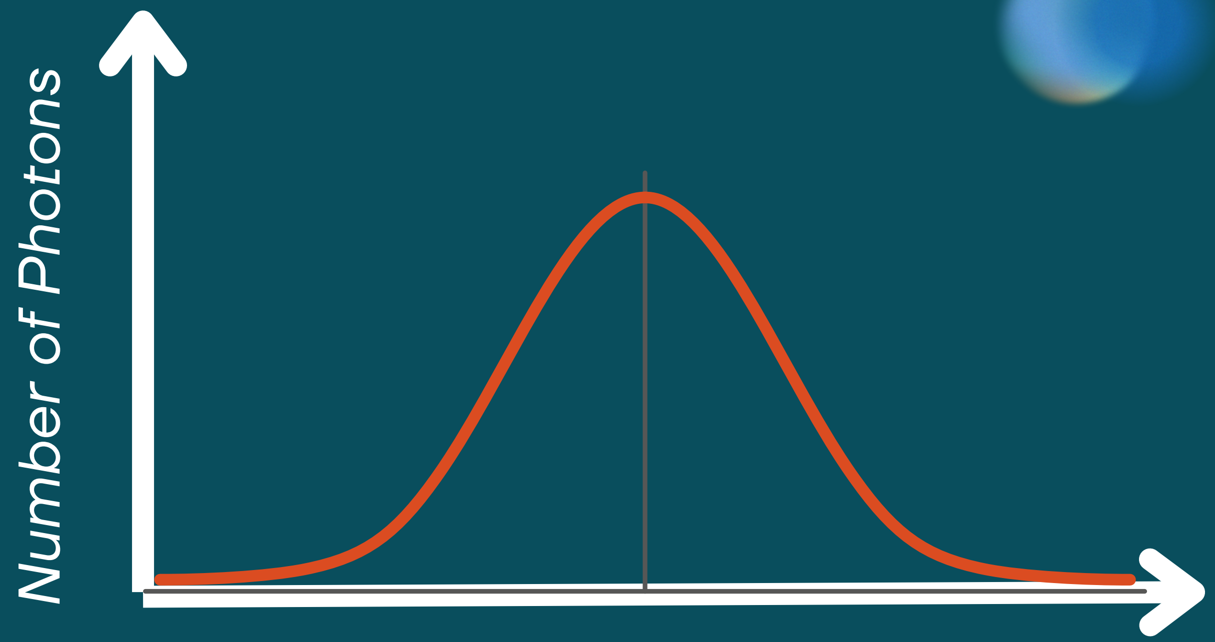
What experiments tell us about the dark matter coupling/density ?

- *A signal in direct/indirect detection experiments can be enhanced by two effects*

Coming from a sub-dominant component of dark matter but more coupled

$\Longrightarrow$ Large g_γ



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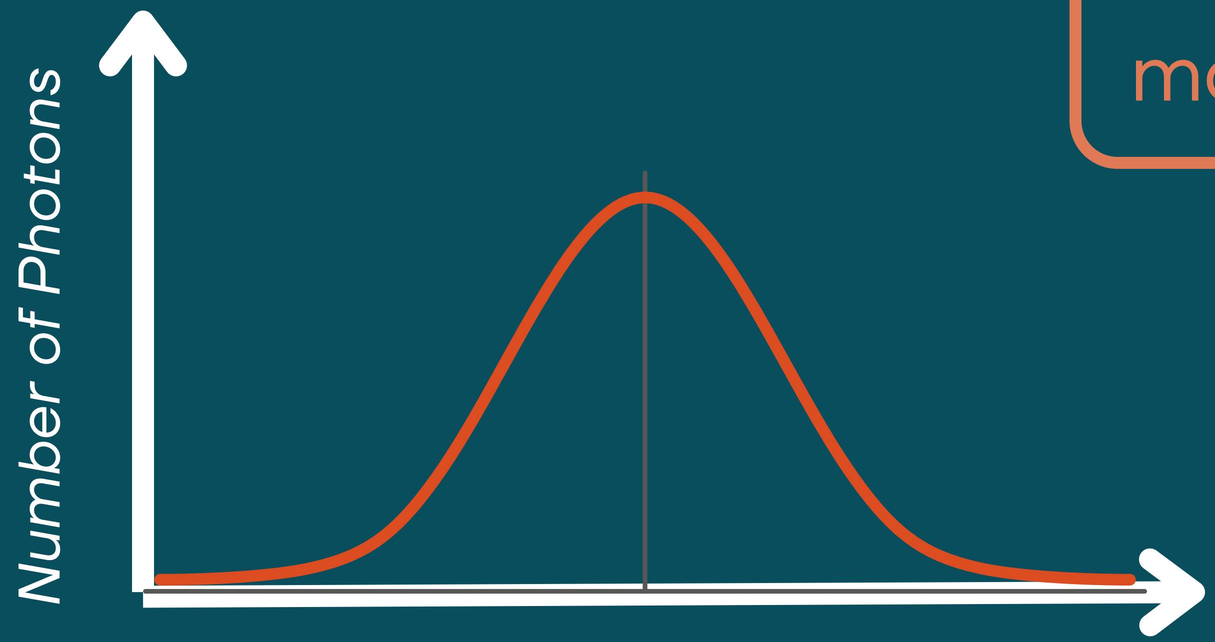
What experiments tell us about the dark matter coupling/density ?

- *If a signal is observed in direct/indirect detection, it could mean two things*



Coming from a dominant component of dark matter

$\implies$ Large $\rho_{\rm DM}$

Coming from a sub-dominant component of dark matter but more coupled

$\implies$ Large g_γ

- *We only get the degenerate information of the coupling/density:* $\rho_{\rm DM}\, g_\gamma^n$

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What experiments tell us about the dark matter coupling/density ?

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Coming from a dominant component of dark matter

Coming from a sub-dominant component of dark matter but more coupled

- *We only get the degenerate information of the coupling/density:* $\rho_{\mathrm{DM}}\, g_{\gamma}^{n}$

$\Longrightarrow$ Use two different experiments with different powers n

$\Longrightarrow$ Use Axion Miniclusters in Haloscopes

AXION MINICLUSTERS

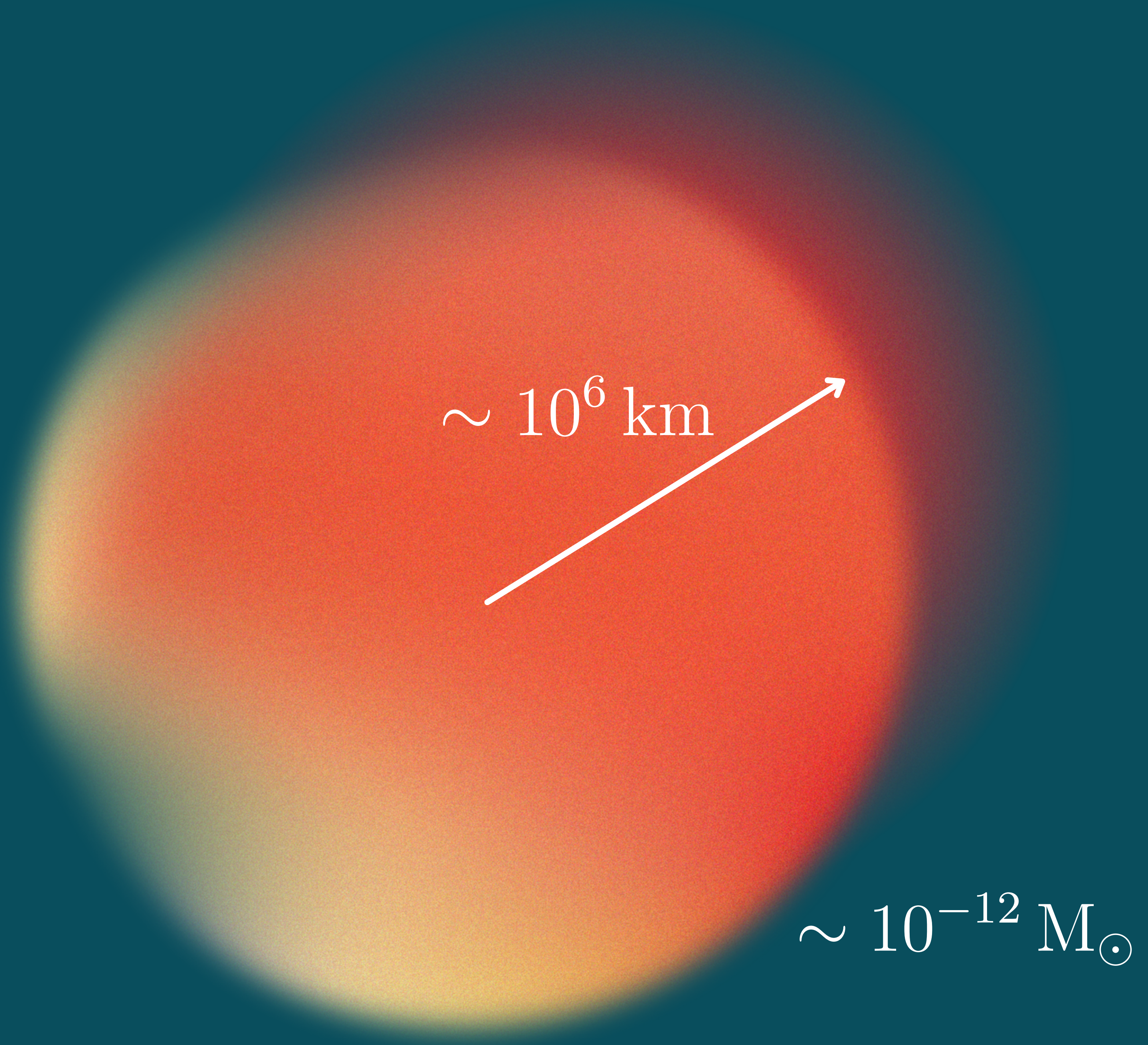
Axion Miniclusters

Prediction of the post-inflation scenario

- *Axions arise as the Goldstone boson of a U(1) spontaneously broken symmetry*
- *If the symmetry is broken after inflation, the axion field is initially inhomogeneous*

$\Longrightarrow$ *Large density fluctuations collapse early into axion miniclusters*

$\Longrightarrow$ *Broad spectrum of masses depending on the axion mass*



Axion Miniclusters

Description of an Axion Minicluster

- *The occupation number is huge:* $N \sim \left(\frac{34\,\mathrm{eV}}{m_a}\right)\left(\frac{250}{v}\right)$

- *Axions are better described via a classical field description*

$$\boxed{\begin{aligned}\psi(r,\theta,\phi) &= \sum_{nlm} a_{nlm} e^{i\phi_{nlm}} R_{nl}(r) Y_{lm}(\theta,\phi) \\ a_{nlm} &= 4\pi\sqrt{m_a \mathcal{N}_{nl} \frac{f(E_n)}{g_l(E_n)}}\end{aligned}}$$

[2206.04619]

$\Longrightarrow$ *Represents a cluster with mean density, gravitational potential and distribution function* $\rho(r)$, $\phi(r)$, $f(E)$

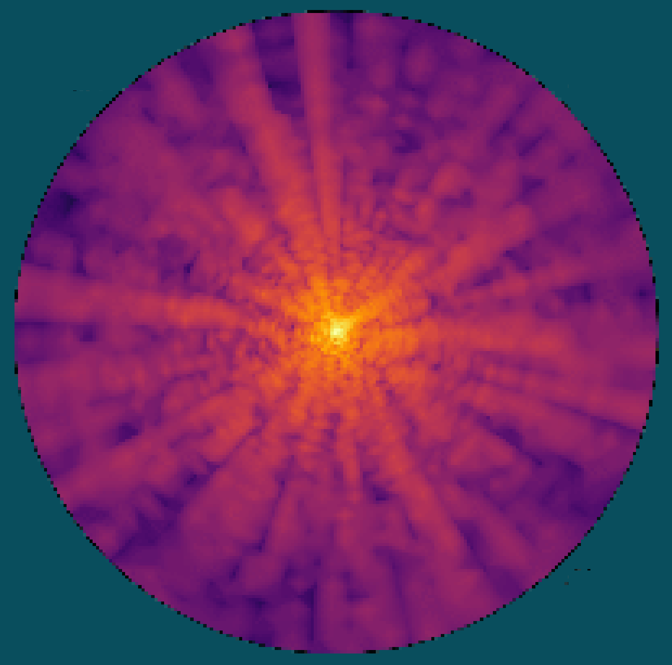
Axion Miniclusters

Wave function of the minicluster

$$\psi(r,\theta,\phi) = \sum_{nlm} a_{nlm} e^{i\phi_{nlm}} R_{nl}(r) Y_{lm}(\theta,\phi)$$

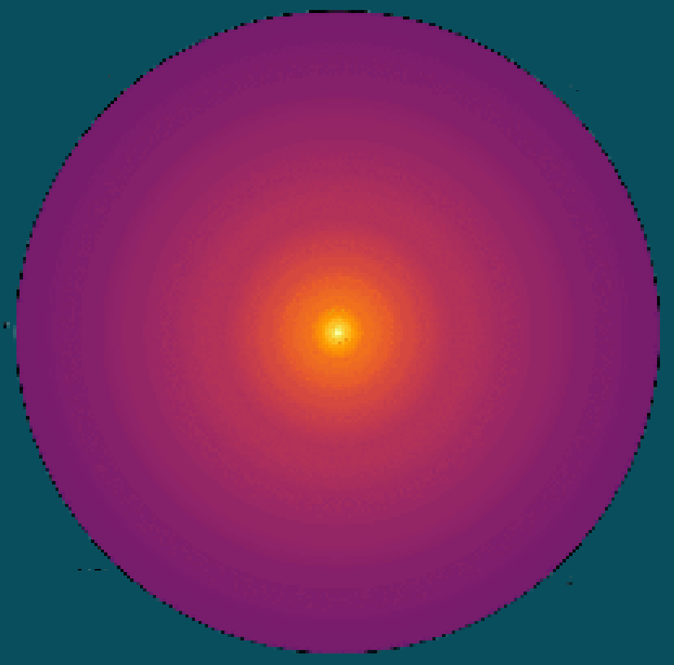
$$a_{nlm} = 4\pi \sqrt{m_a \mathcal{N}_{nl} \frac{f(E_n)}{g_l(E_n)}}$$

- *A given realization of the random phases brings granular structures in the density profile*



$$\Downarrow$$

$$P(\rho) = \frac{1}{\rho(r)} e^{-\rho/\rho(r)}$$



$$\Downarrow$$

Average over the random phases: Mean density and gravitational potential

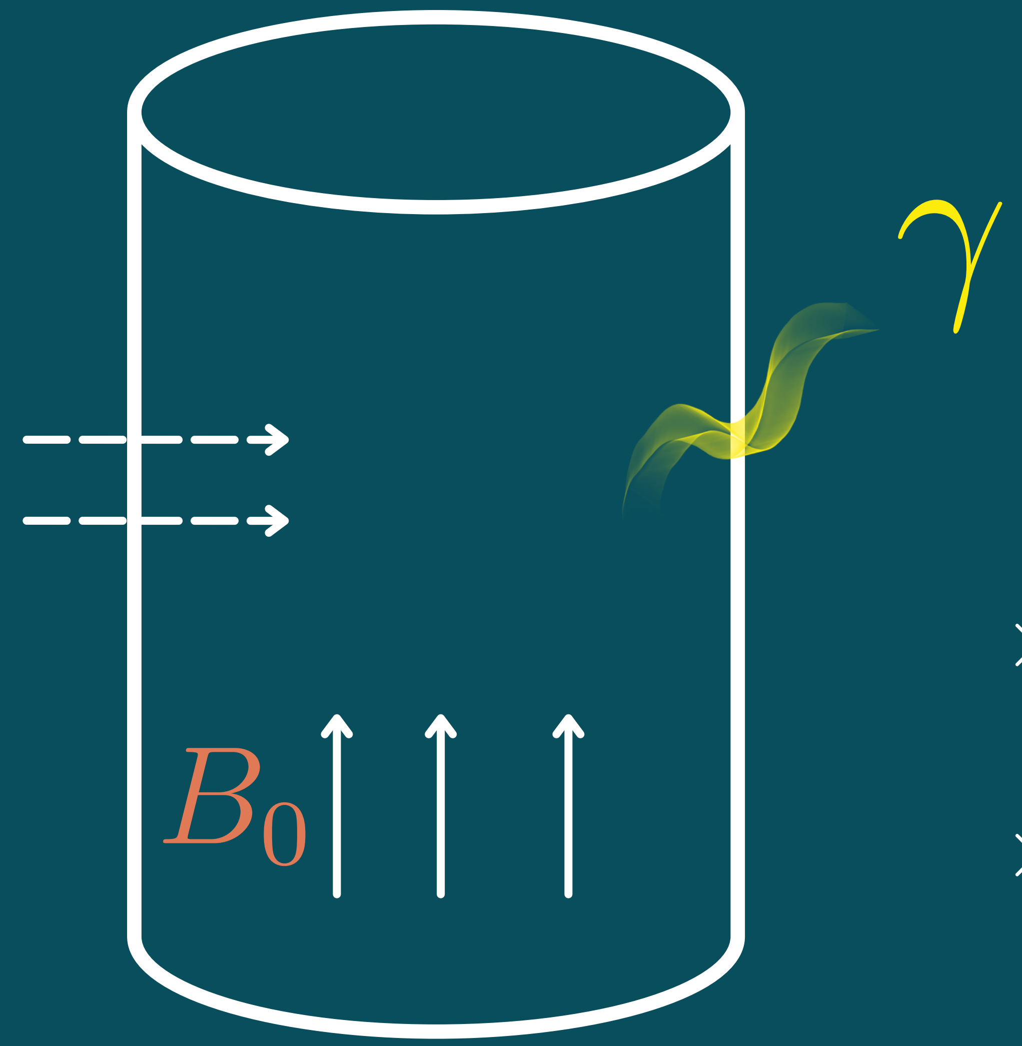
AMC IN HALOSCOPES

AMC in Haloscopes

Signal in the case of an homogeneous background

- *Haloscope experiments use the axion-photon coupling to convert the axions of the dark matter halo into photons in the presence of a strong magnetic field*

$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a^2} e^{-im_a t}$$



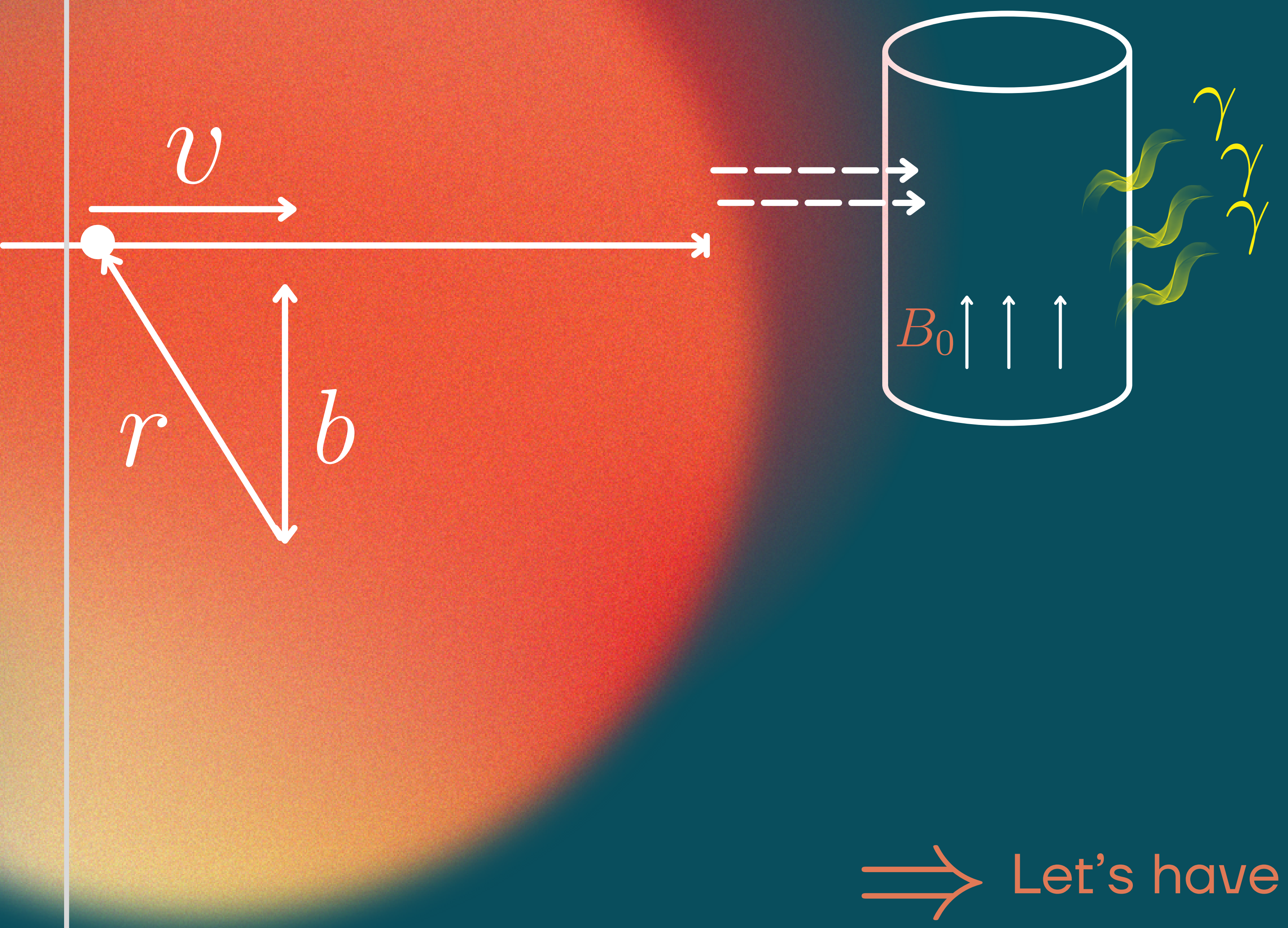
$$P = 6.3 \times 10^{-22}\mathrm{W} \times \left(\frac{\mathrm{g_{a\gamma\gamma}}}{10^{-15}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{\rho_{\rm DM}}{0.3\mathrm{GeV cm}^{-3}}\right) \times \left(\frac{\mathrm{B}}{8\mathrm{T}}\right)^2 \left(\frac{\mathrm{V}}{220\mathrm{l}}\right) \left(\frac{\mathrm{C_{nlm}}}{0.69}\right) \left(\frac{\mathrm{Q}}{70000}\right) \left(\frac{3\mu\mathrm{eV}}{\mathrm{m_a}}\right),$$

$\Rightarrow$ *No separate information on the coupling/density*

AMC in Haloscopes

Signal in the case of a minicluster

$$\psi(r,\theta,\phi) = \sum_{nlm} a_{nlm} e^{i\phi_{nlm}} R_{nl}(r) Y_{lm}(\theta,\phi)$$



- *In the case of an AMC encounter, the signal in haloscope will be enhanced.*

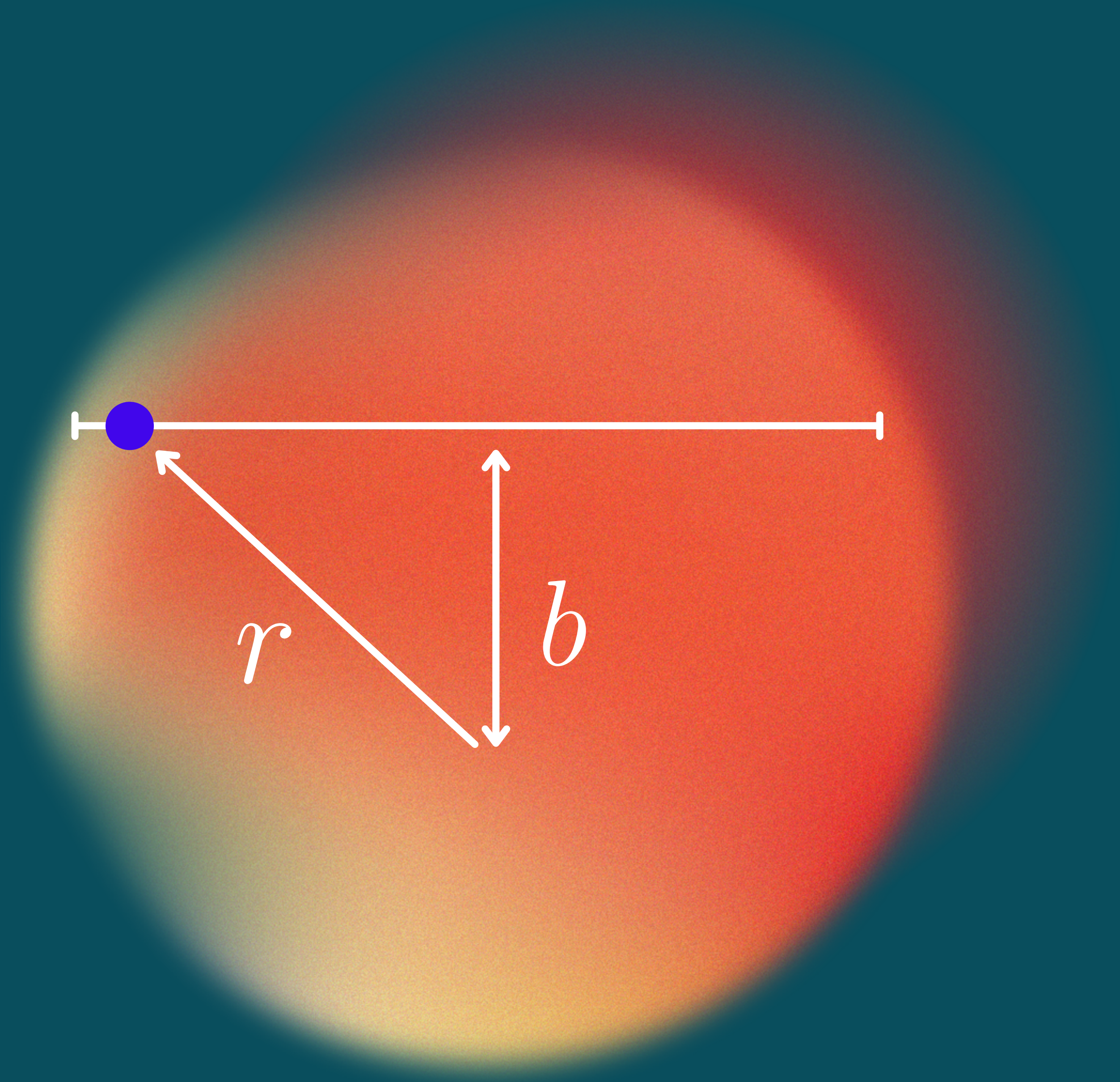
- *Since a superposition of modes enters the cavity, the spectral power carries a lot a information!*

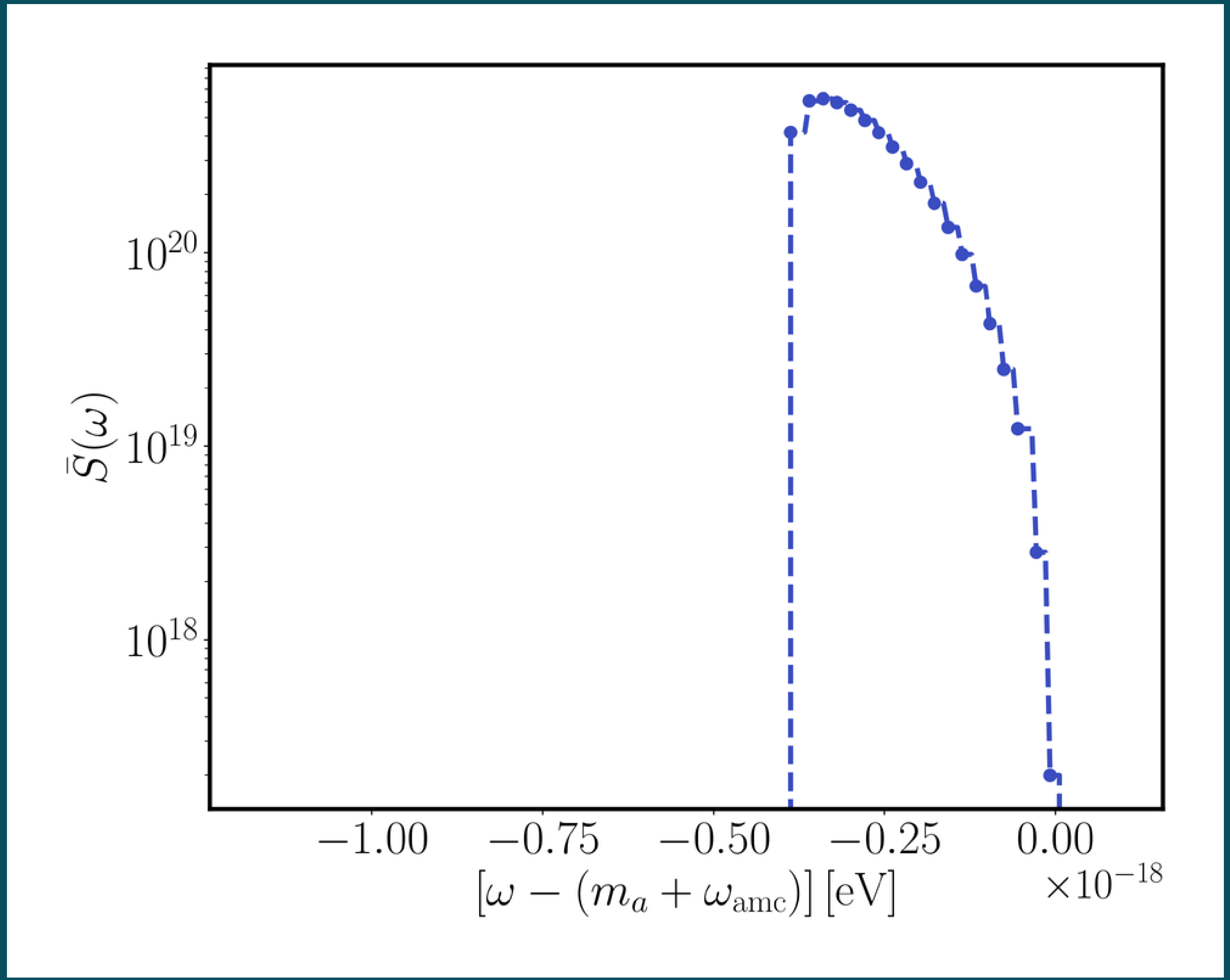
$$P \approx \frac{\omega_j}{Q} \frac{1}{4\pi} \int d\omega S(\omega).$$

$\Longrightarrow$ Let's have a look at the spectral power !

AMC in Haloscopes

Signal in the case of a minicluster



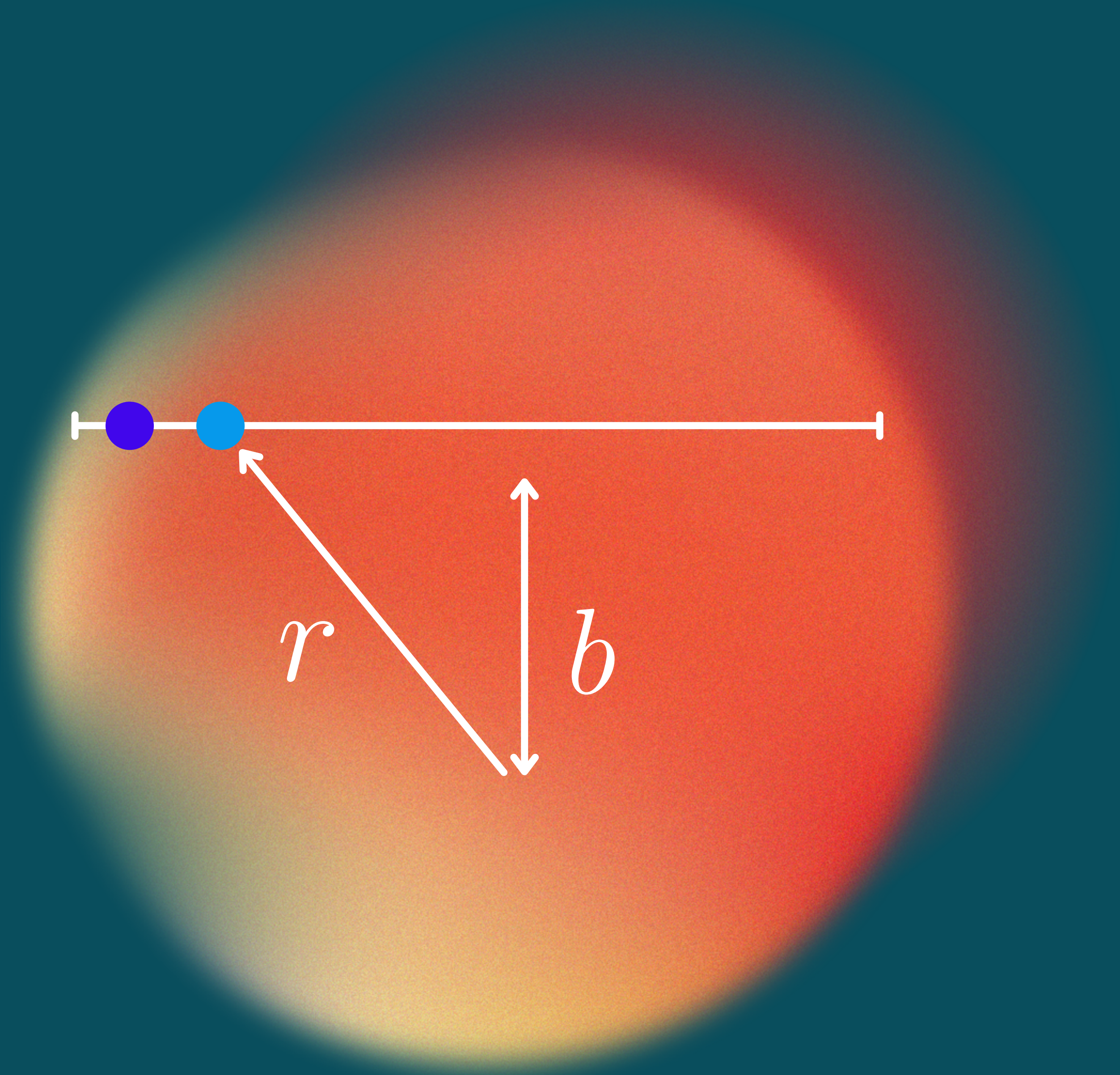


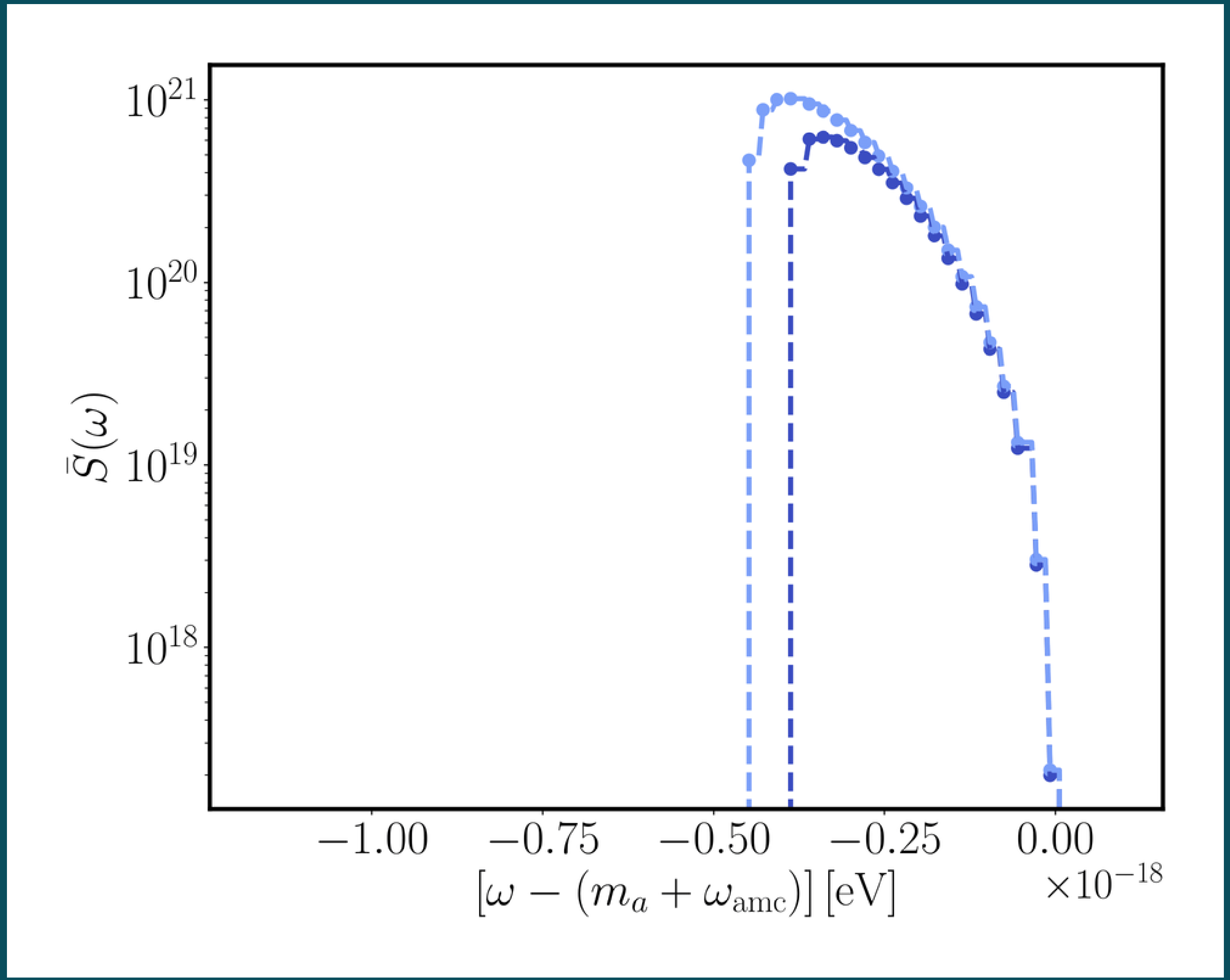
- *At each location the signal is measured during a period T*

$\Rightarrow$ *The width of the spectral power is exactly the gravitational energy* $m_a \phi(r)$ *at the location of the measurement*

AMC in Haloscopes

Signal in the case of a minicluster





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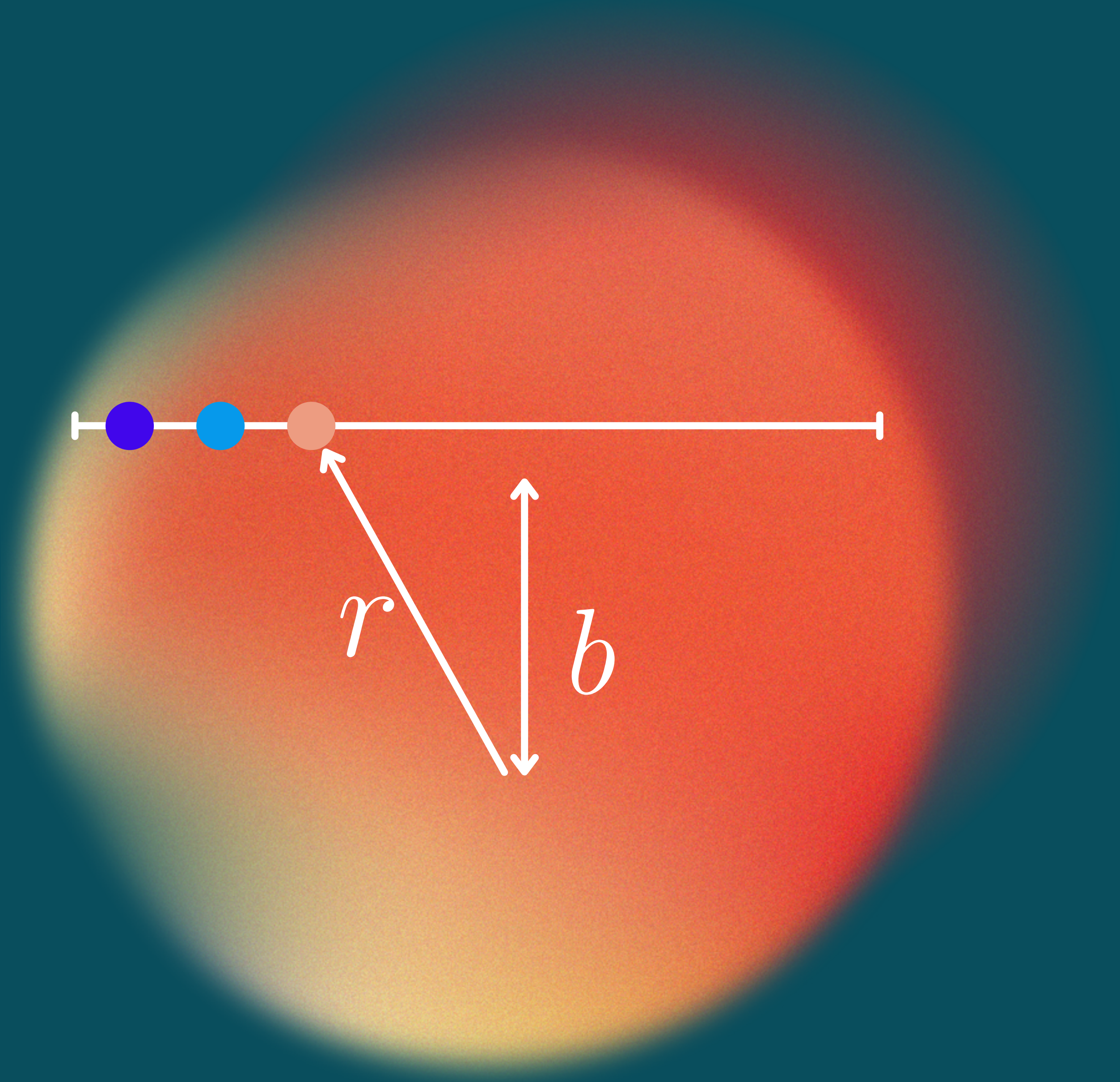

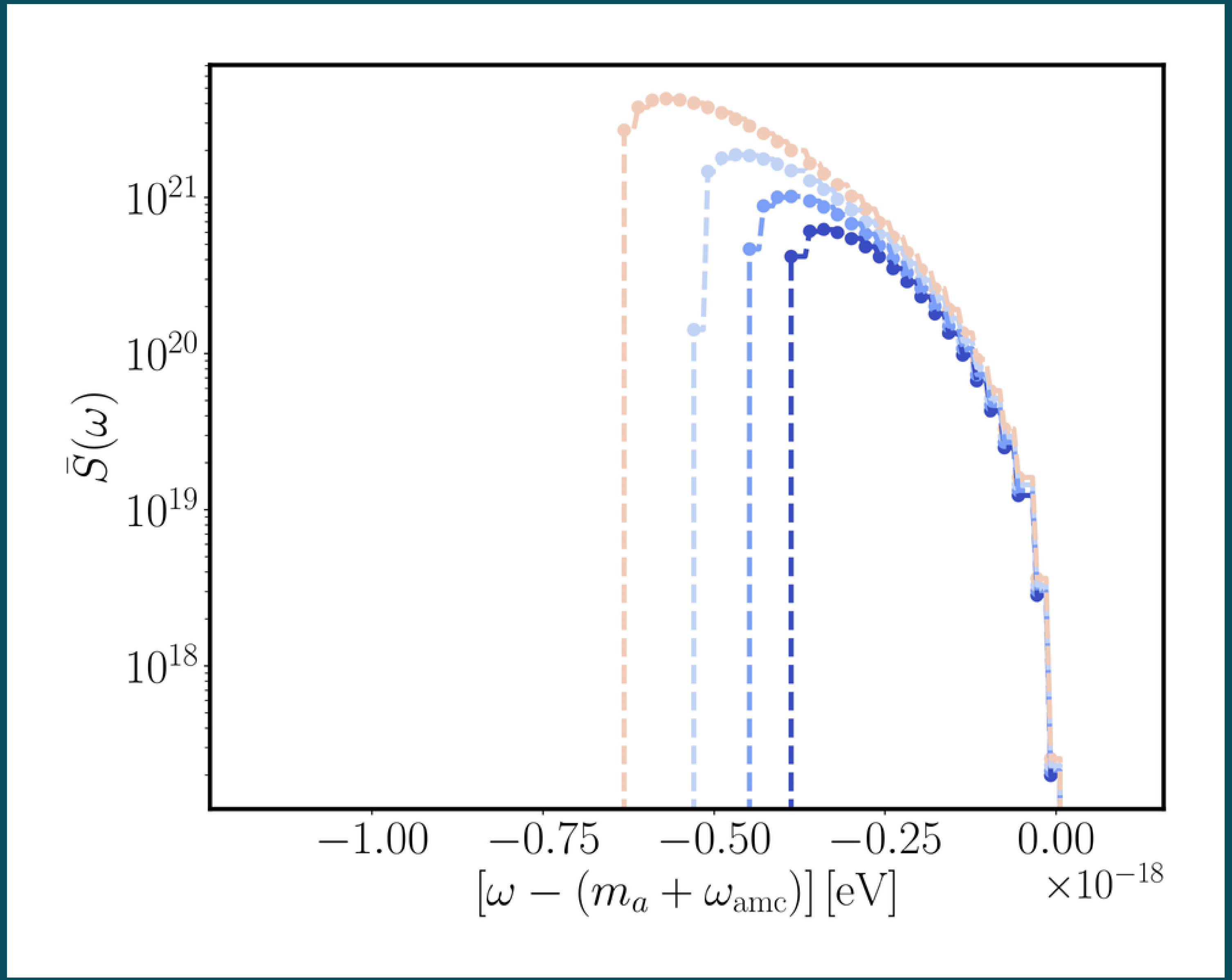

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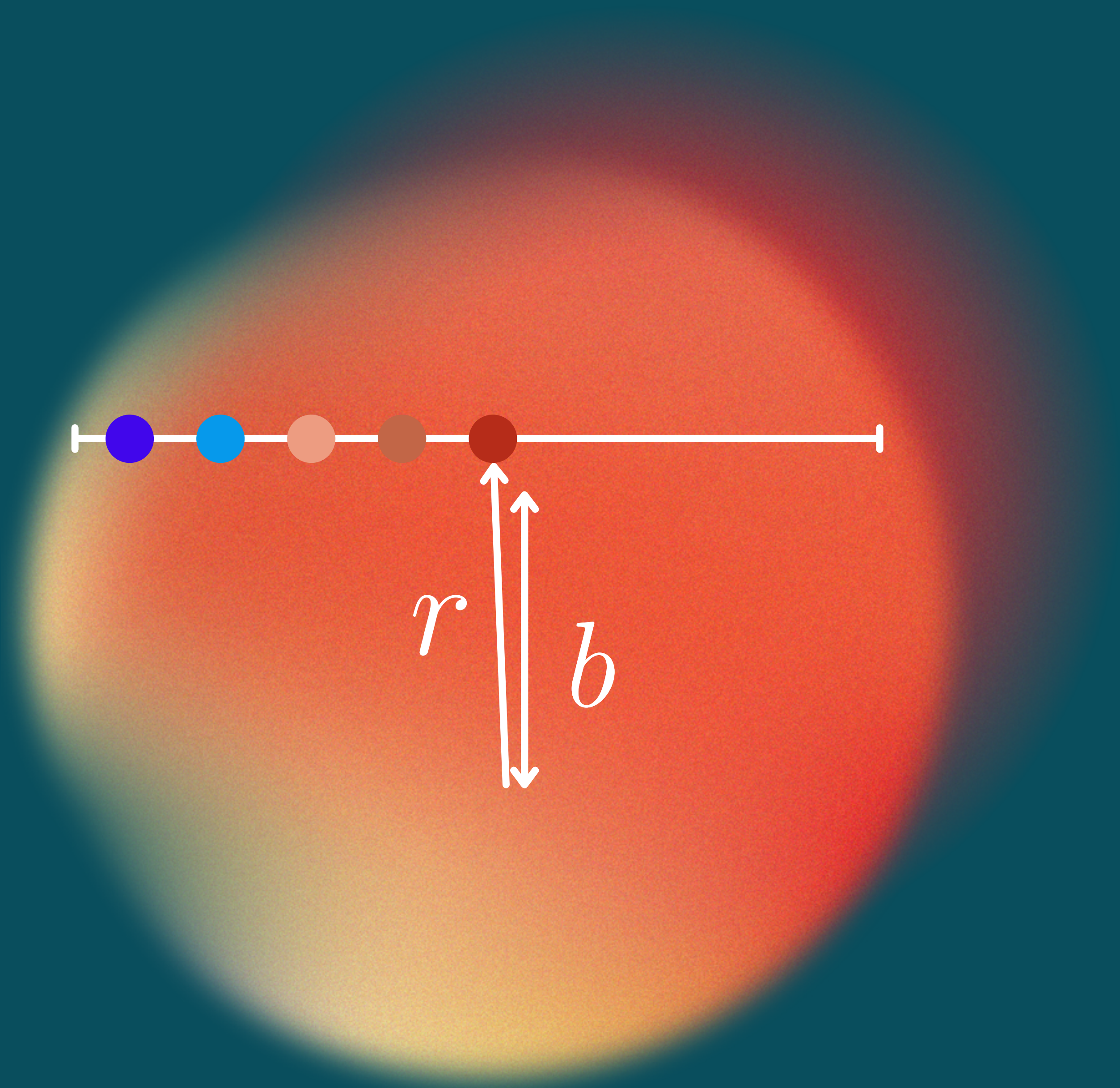

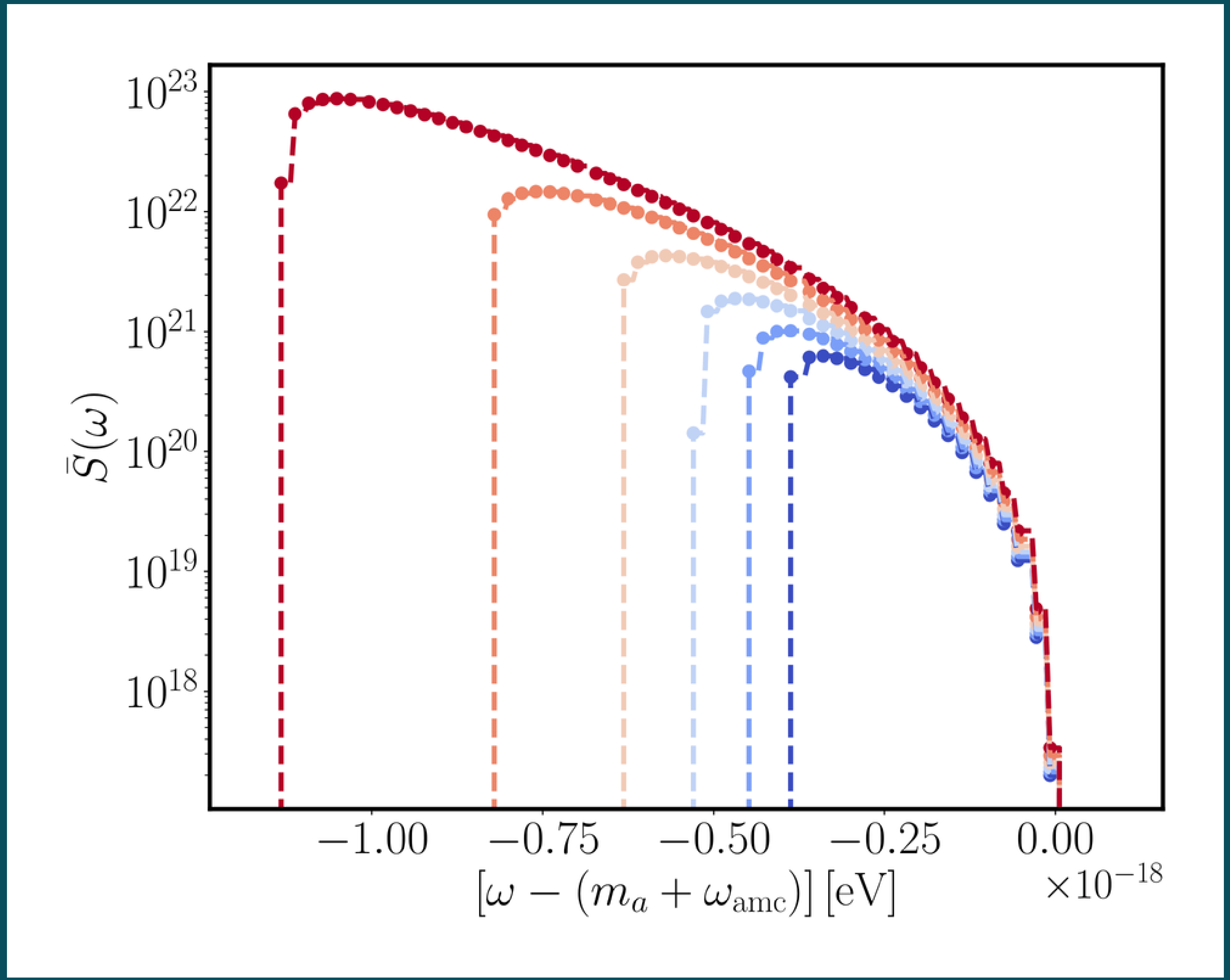

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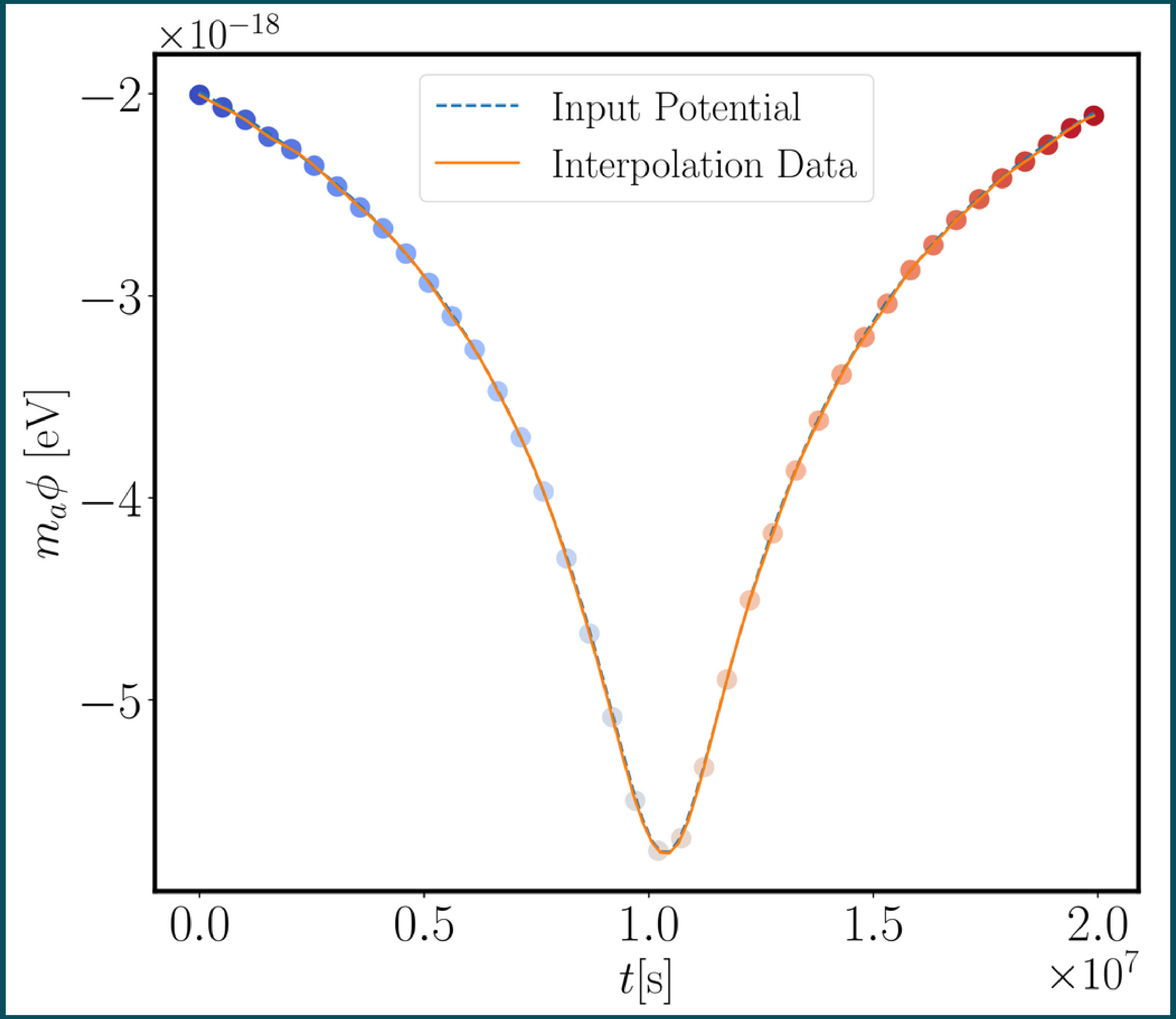
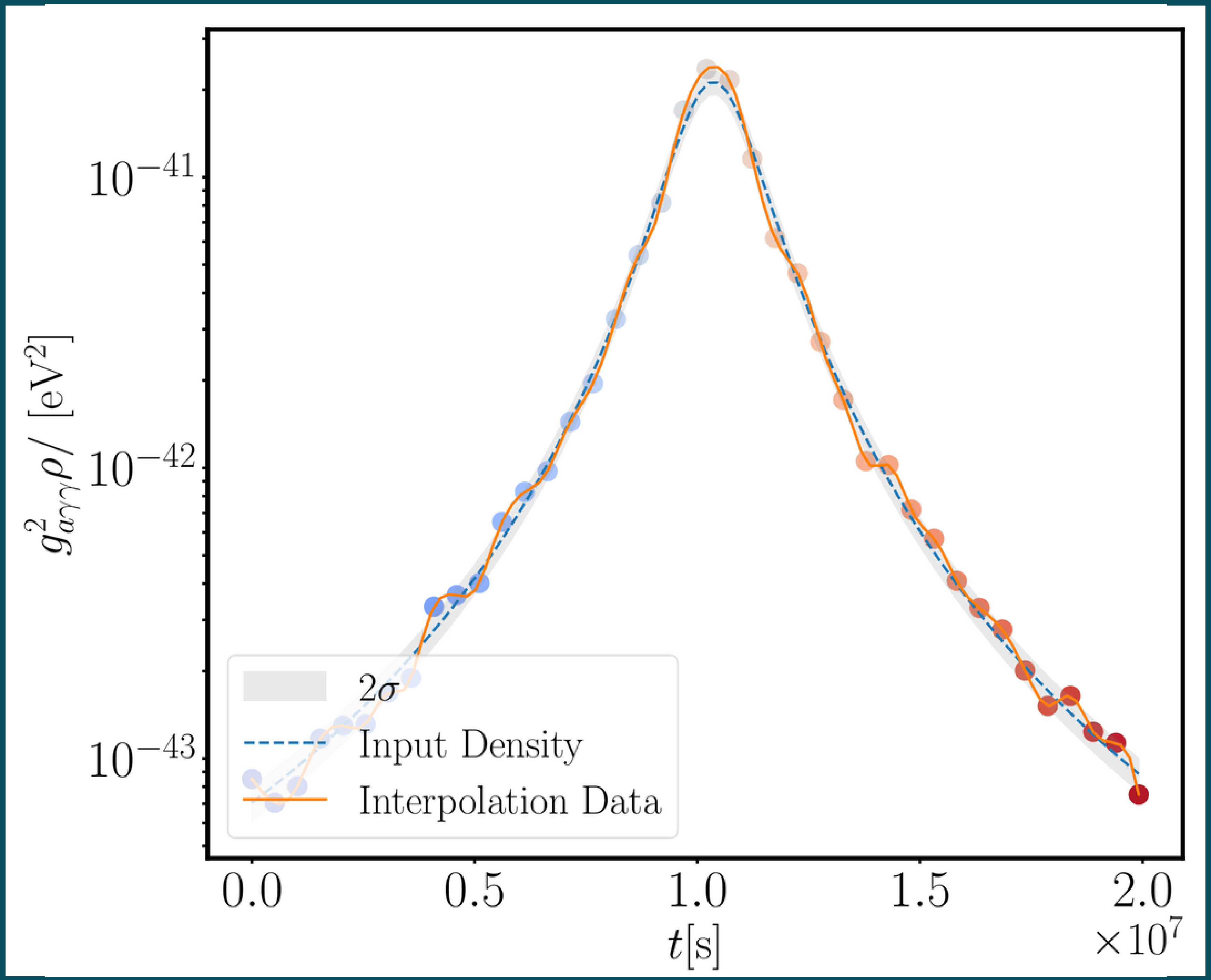


$\Rightarrow$ *Each measurement run provides the gravitational energy* $m_a\phi(r)$

- *The finite binning creates a natural error on the gravitational potential determination*
- *The relative error decreases as* $\sim 1/\left(m_a\phi(r)\, T\right)$
- *The granules are not affecting the width of the spectral power !*

AMC in Haloscopes

Signal in the case of a minicluster

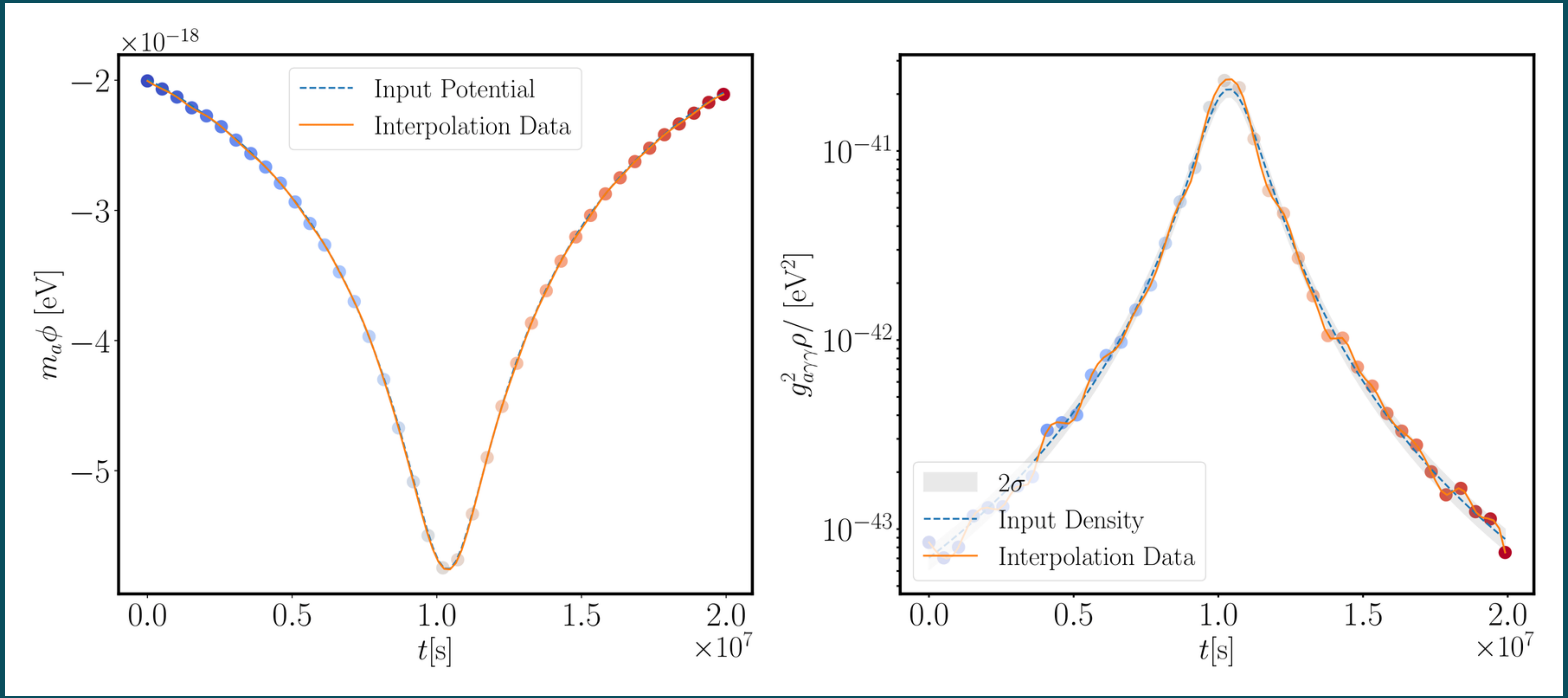


$\Rightarrow$ *As usual, the power provides a measure of $g^2_{a\gamma\gamma}\rho(r)$ at each location*

- *Since the minicluster has some random granular structures, the power gets some deviation from the mean power*
- *The relative deviation increases as $\sim 1/\sqrt{m_a\phi(r)\,T}$*

AMC in Haloscopes

Signal in the case of a mini cluster



Better precision for denser miniclusters and for longer measurement run

$\Longrightarrow$ *Each measurement run provides the gravitational energy* $m_a\phi(r)$

$\Longrightarrow$ *As usual the power provides a measure of* $g^2_{a\gamma\gamma}\rho(r)$

AMC in Haloscopes

Reconstruction of the coupling

- *The density and the gravitational potential are related via the Poisson equation in time coordinate*

$$\frac{\ddot{\phi}(t)}{\dot{r}(t)^2} + \frac{2\dot{\phi}(t)}{\dot{r}(t)r(t)} - \frac{\ddot{r(t)}\dot{\phi}(t)}{\dot{r}(t)^3} = 4\pi G\rho(t)$$

$$r(t) = \sqrt{b^2 + \left(vt - \sqrt{R^2 - b^2}\right)^2}$$

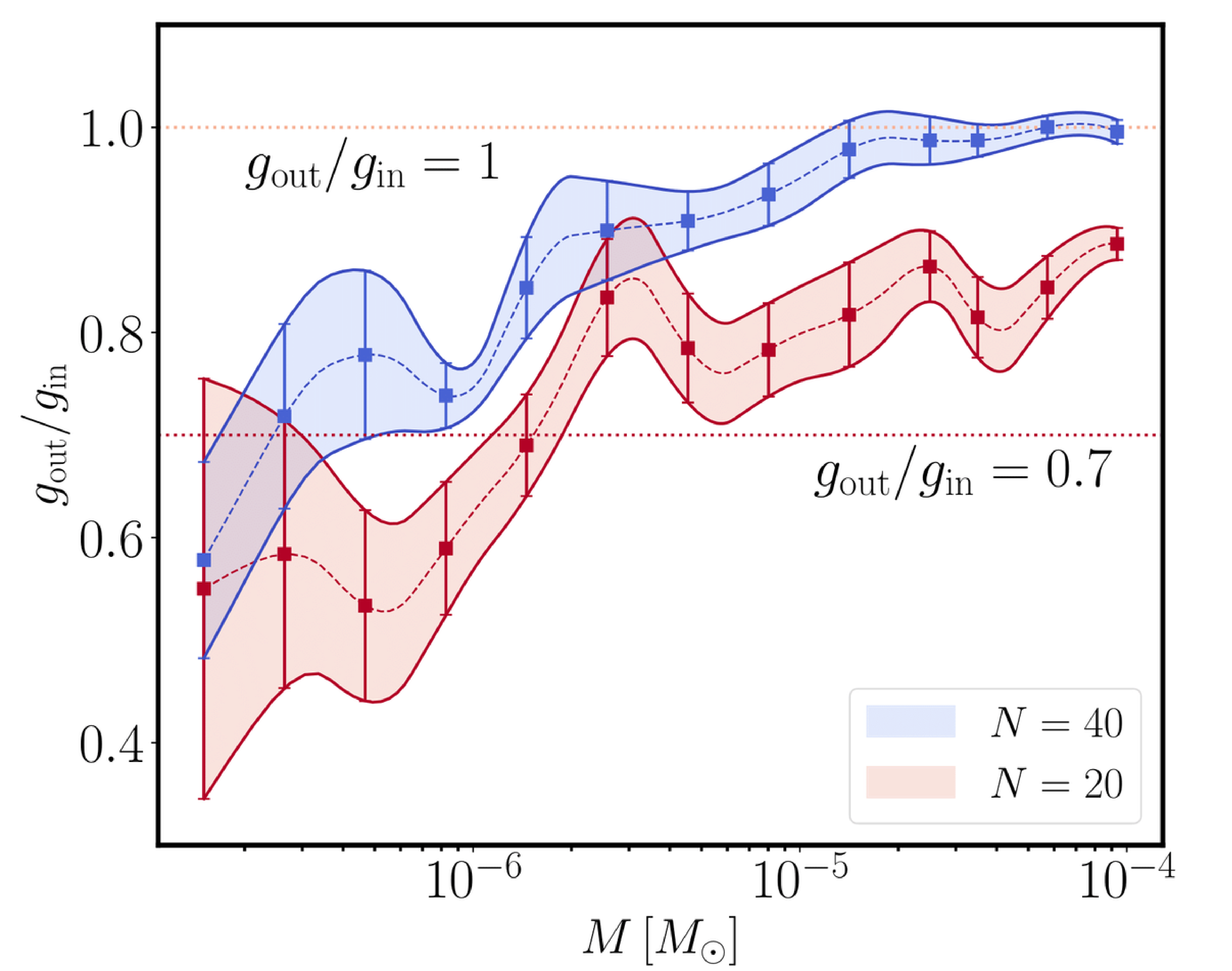
Procedure :

- Create the function $\mathcal{F}(b, R, g_{a\gamma\gamma}; t_i) = \frac{g_{a\gamma\gamma}^2}{4\pi G}\left(\frac{\ddot{\phi}_{\text{out}}(t_i)}{\dot{r}(t_i)^2} + \frac{2\dot{\phi}_{\text{out}}(t_i)}{\dot{r}(t_i)r(t_i)} - \frac{\ddot{r(t_i)}\dot{\phi}_{\text{out}}(t_i)}{\dot{r}(t_i)^3}\right).$

- Maximize $\mathcal{L}(b, R, g_{a\gamma\gamma}) = \sum_i \log\left(\frac{(g_{a\gamma\gamma}^2\rho(t_i))_{\text{out}}}{|(g_{a\gamma\gamma}^2\rho(t_i))_{\text{out}} - \mathcal{F}(b, R, g_{a\gamma\gamma}; t_i)|}\right)$

AMC in Haloscopes

Reconstruction of the coupling



$\Rightarrow$ *Better reconstruction for denser miniclusters*

$\Rightarrow$ *Reconstruction is sensitive to the number of measurements we take*

$\Rightarrow$ *For QCD axion mass, it is expected to be efficient for heavy miniclusters*

Conclusion

- *Direct/Indirect detection experiments can only give access to a degenerate product of the density and the coupling*
- *We have shown that axion miniclusters are capable of providing extra-information on the gravitational potential along the path of the cluster*
- *Using the Poisson equation, it can be used to disentangle the density-coupling product*
- *It has been shown that this could be efficient for relatively dense axion miniclusters.*