Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density

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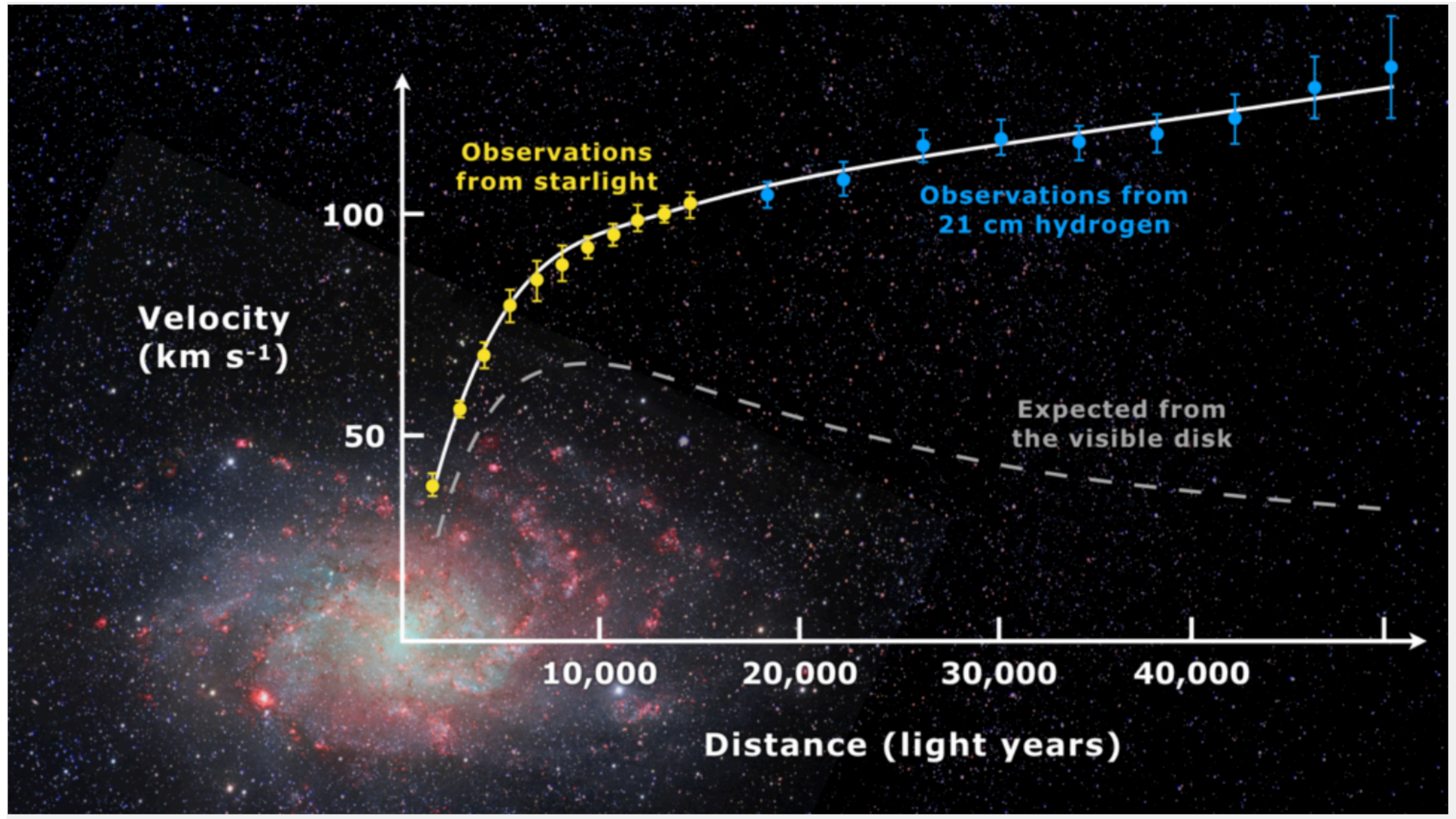
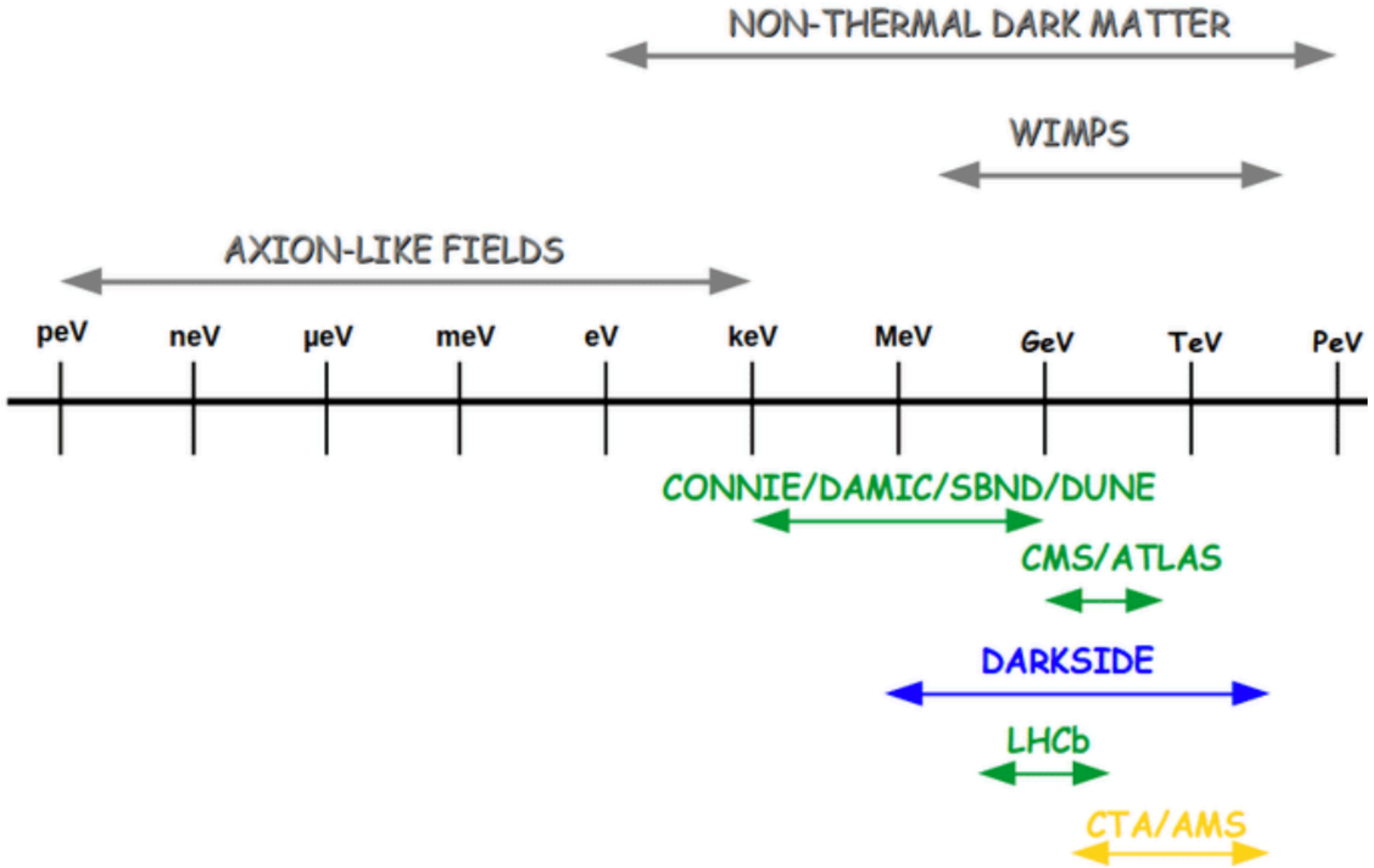
We are happy to acknowledge that this project has received support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860881-HIDDeN.

Motivation



Rotation curve of spiral galaxy Messier 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (grey line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy. Caption and credit: Mario De Leo/Wikimedia Commons, CC BY-SA 4.0



J. R. L. Santos

Suitable Dark Matter Candidate

If detectable .....What fraction?

$$g^n \rho_{\rm DM}$$

We optimistically use a case where the coupling might be possible to be measured with a single axion direct detection experiment via Haloscopes

Axion Miniclusters

Description

AMC Density

$$\rho = m_a |\psi(\boldsymbol{x}, t)|^2$$
$$= m_a \sum_i |a_i|^2 |\psi_i(\boldsymbol{x})|^2 + m_a \sum_{i \neq j} a_i a_j^* \psi_i(\boldsymbol{x}) \psi_j^*(\boldsymbol{x}) e^{-i(E_i - E_j)t}$$

Axion Miniclusters

Description

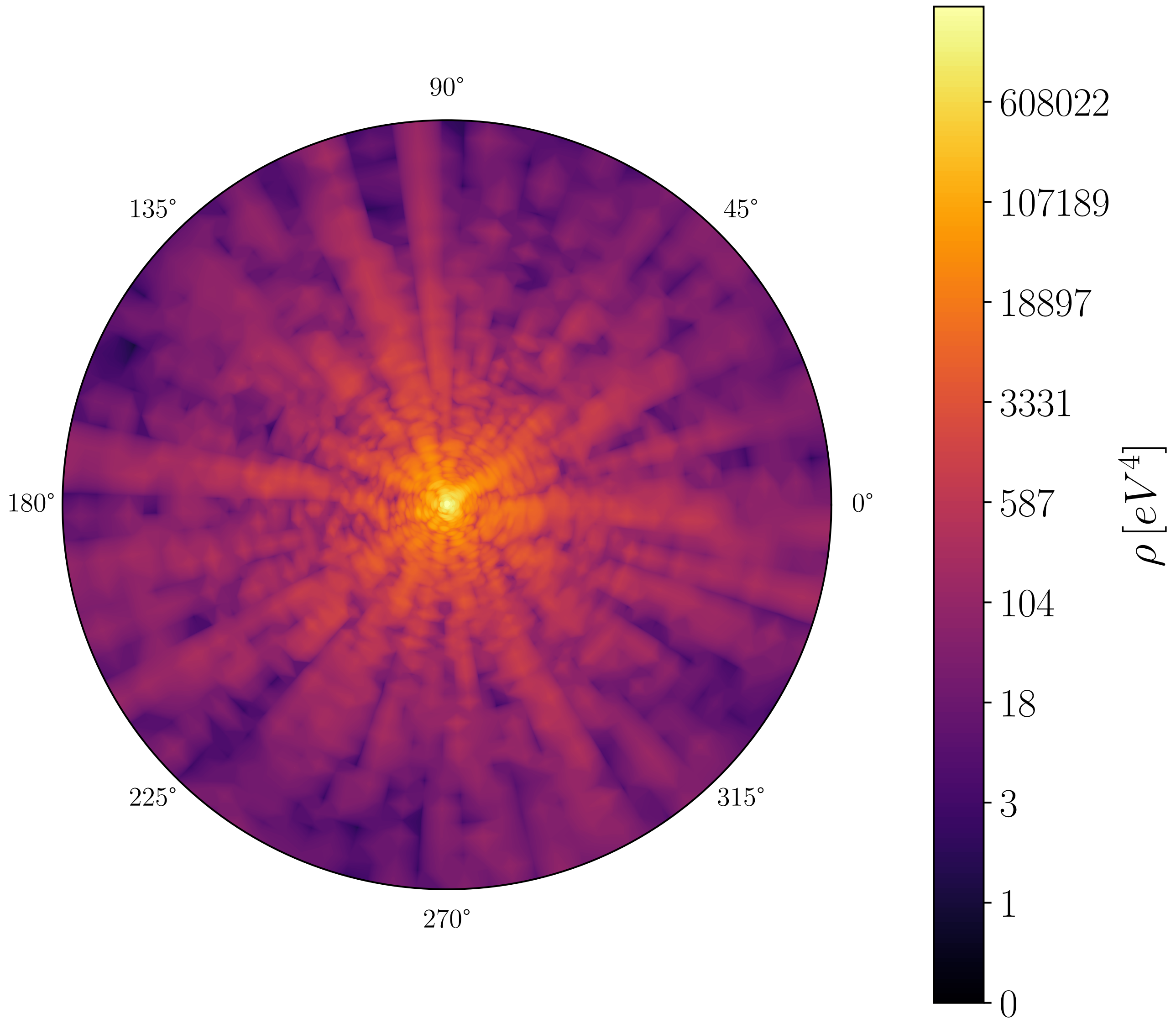
Reconstruction

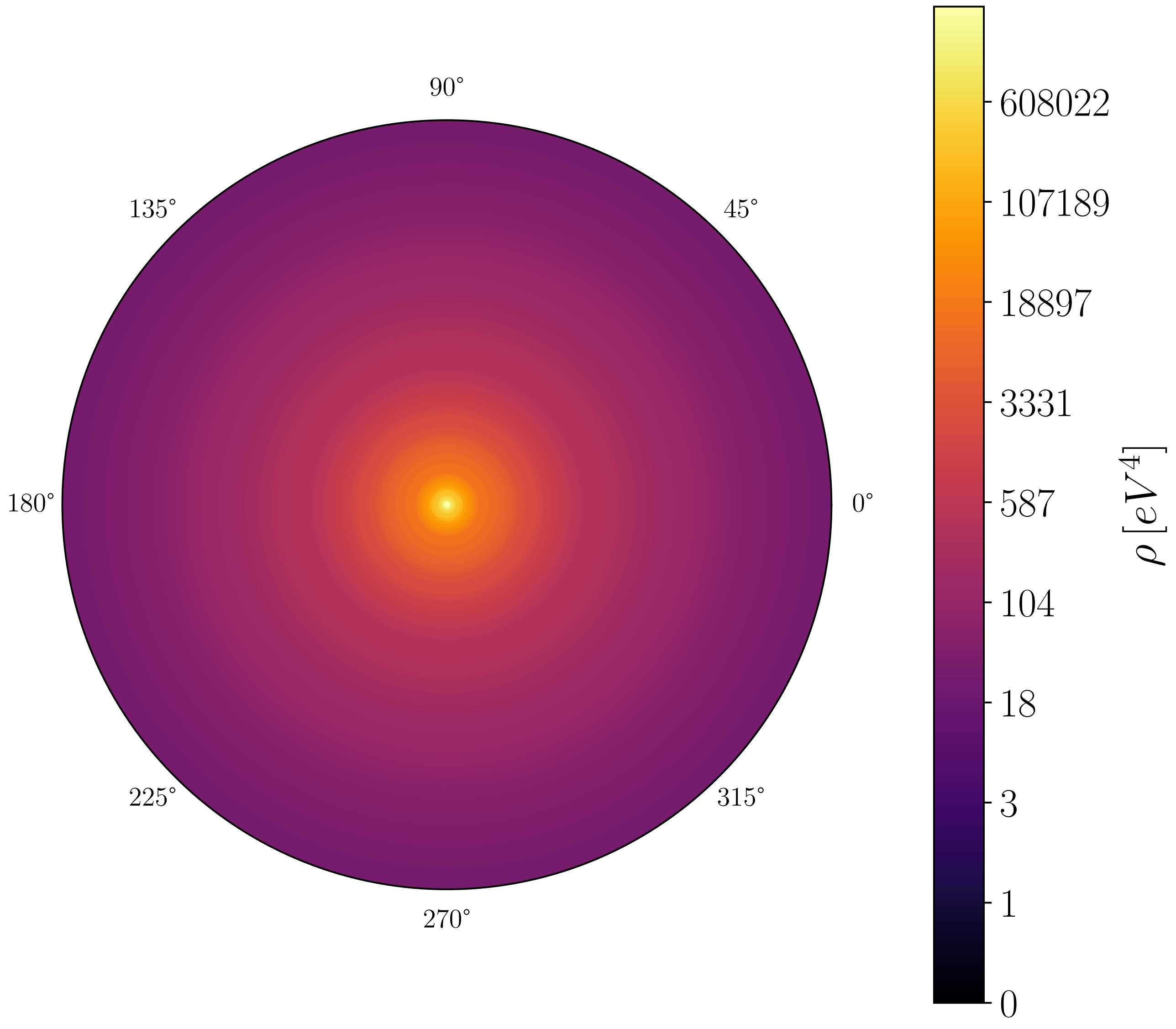
AMC Density

$$\rho = m_a |\psi(\boldsymbol{x}, t)|^2$$
$$= m_a \sum_i |a_i|^2 |\psi_i(\boldsymbol{x})|^2 + m_a \sum_{i \neq j} a_i a_j^* \psi_i(\boldsymbol{x}) \psi_j^*(\boldsymbol{x}) e^{-i(E_i - E_j)t}$$

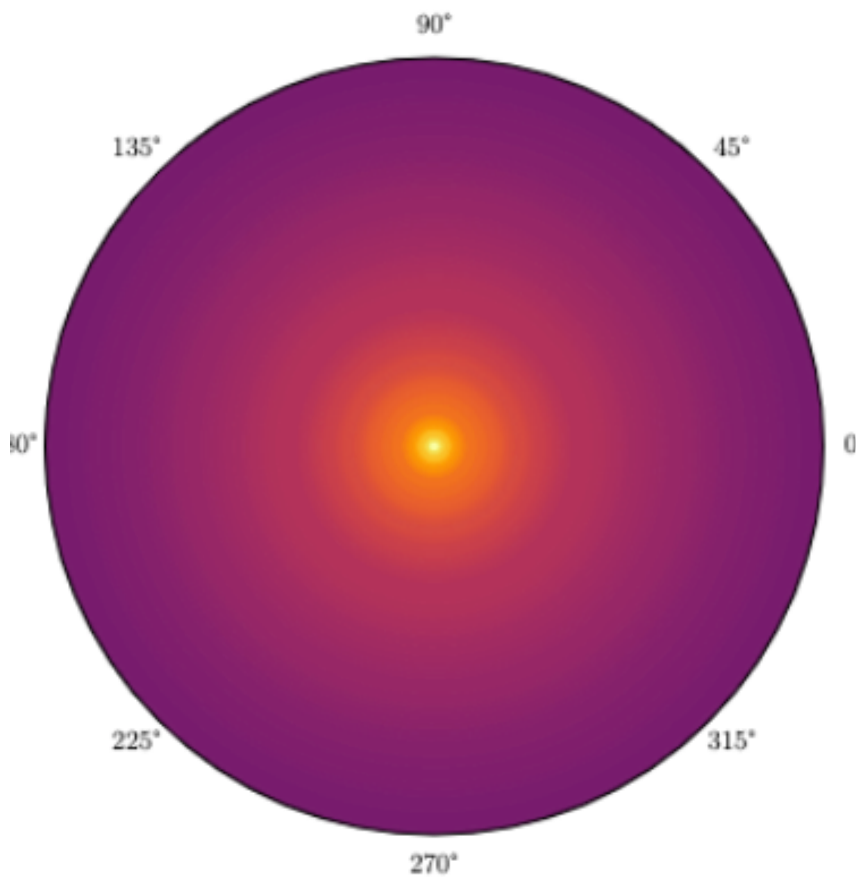
Average density contribution

Interference = granules

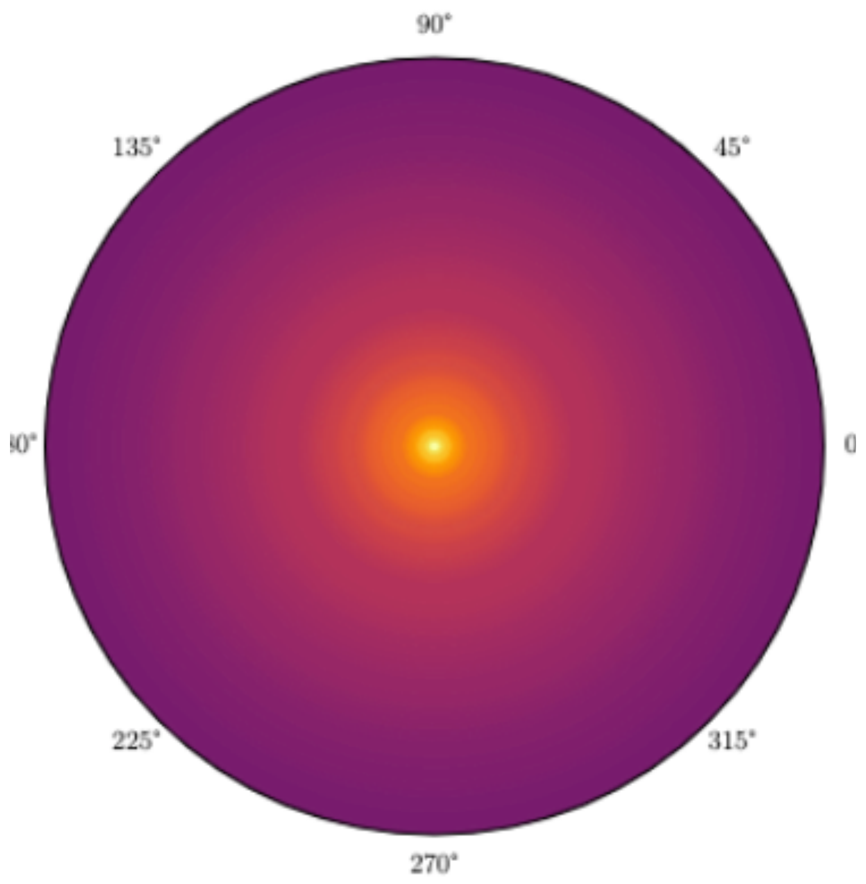




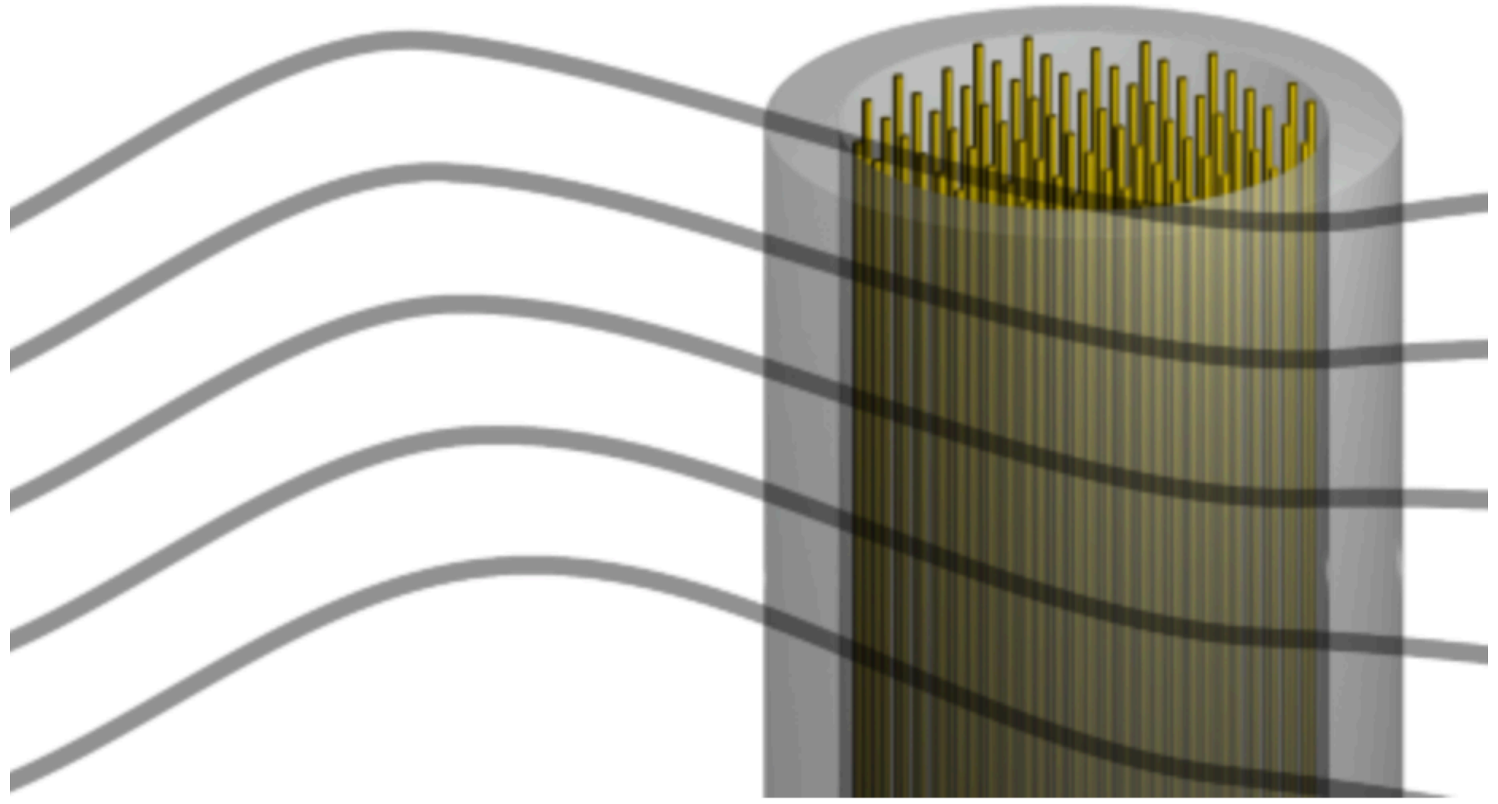
AMC



AMC

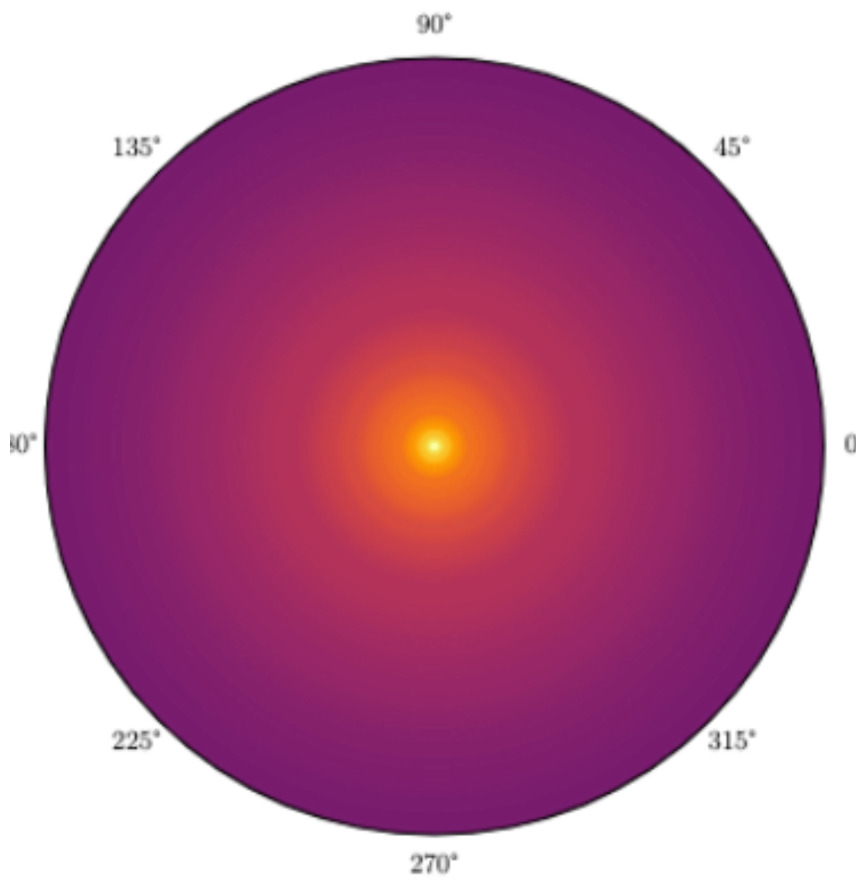


Haloscope

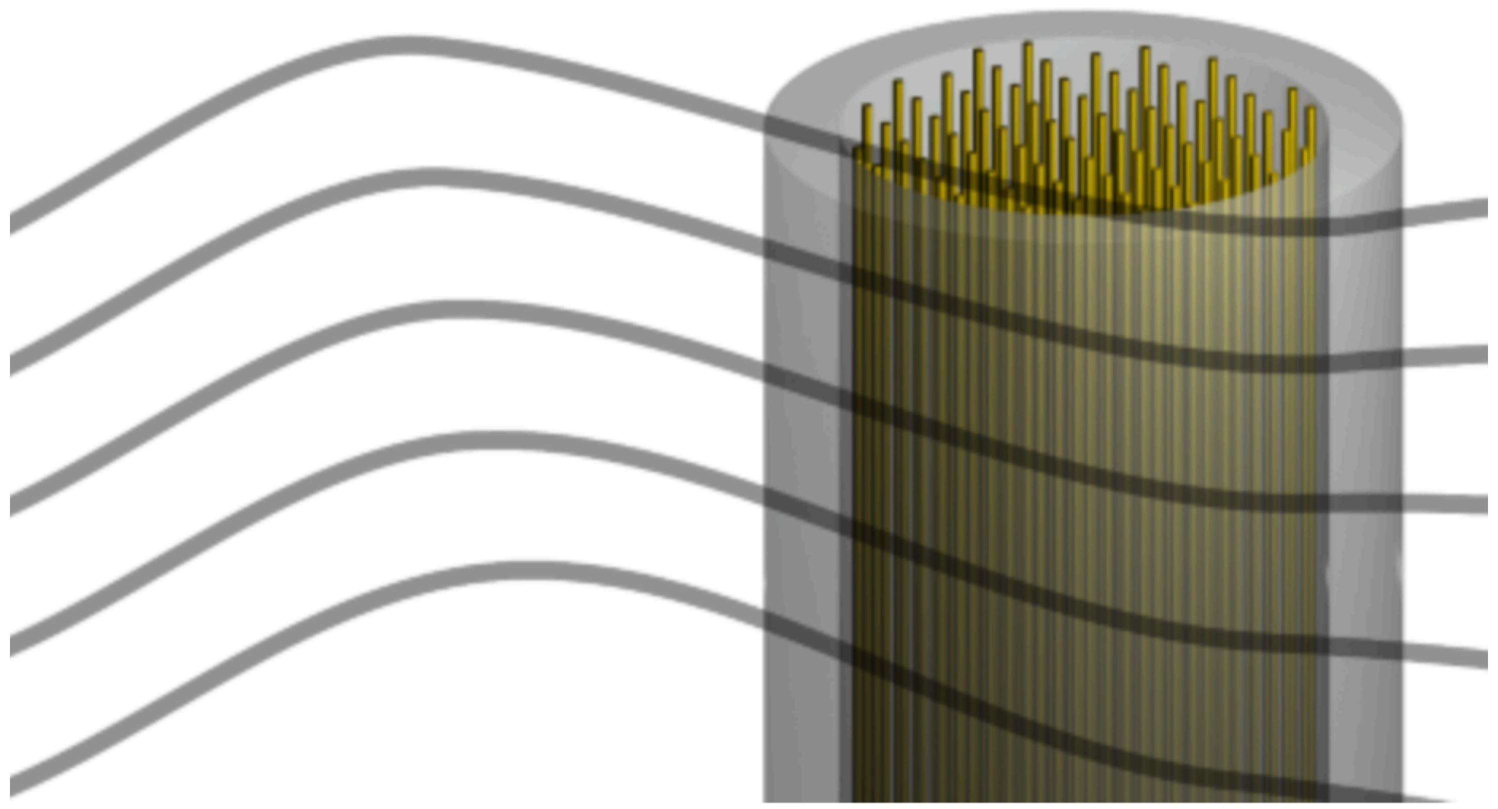


A. Millar/Stockholm University

AMC



Haloscope



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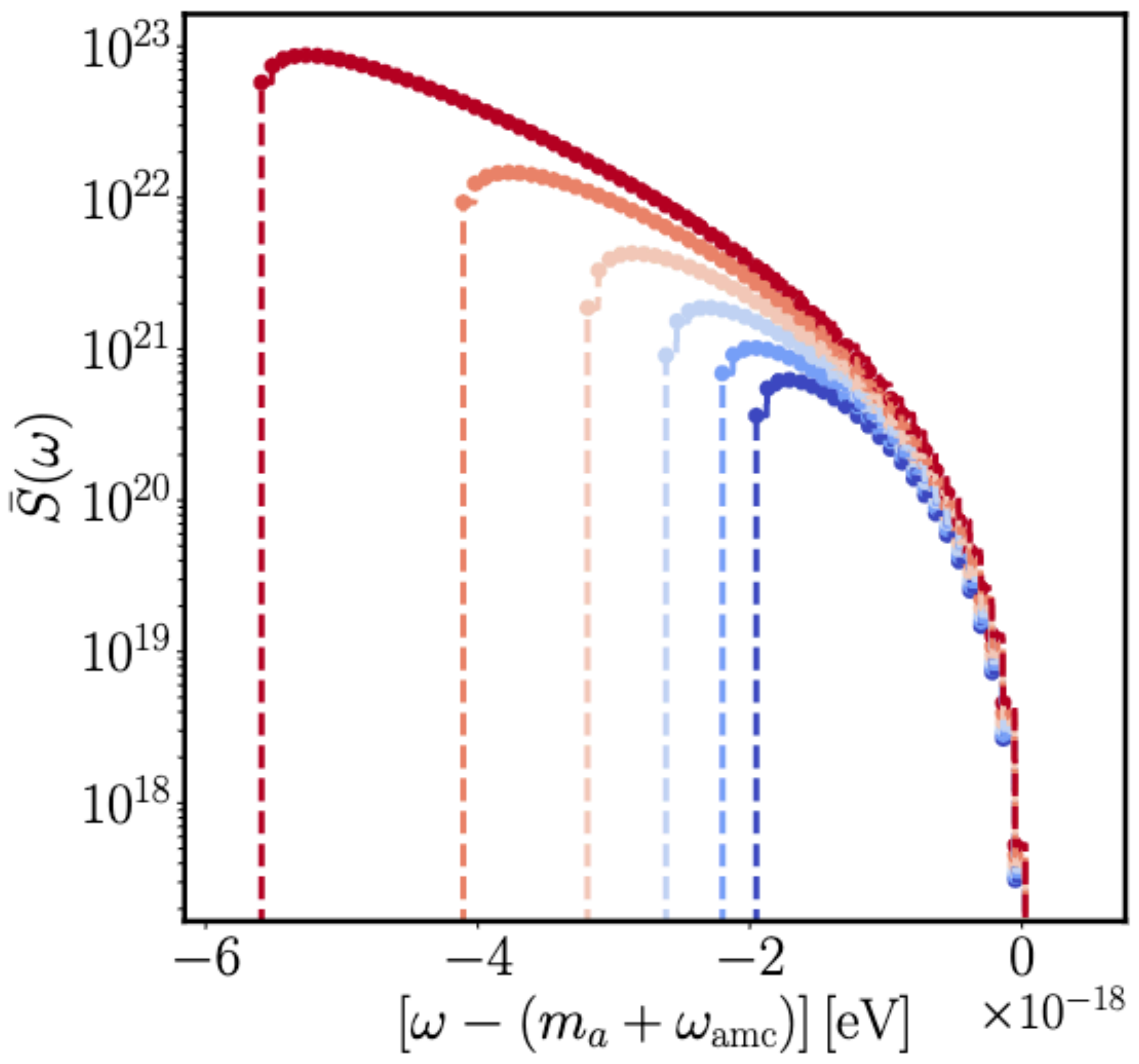
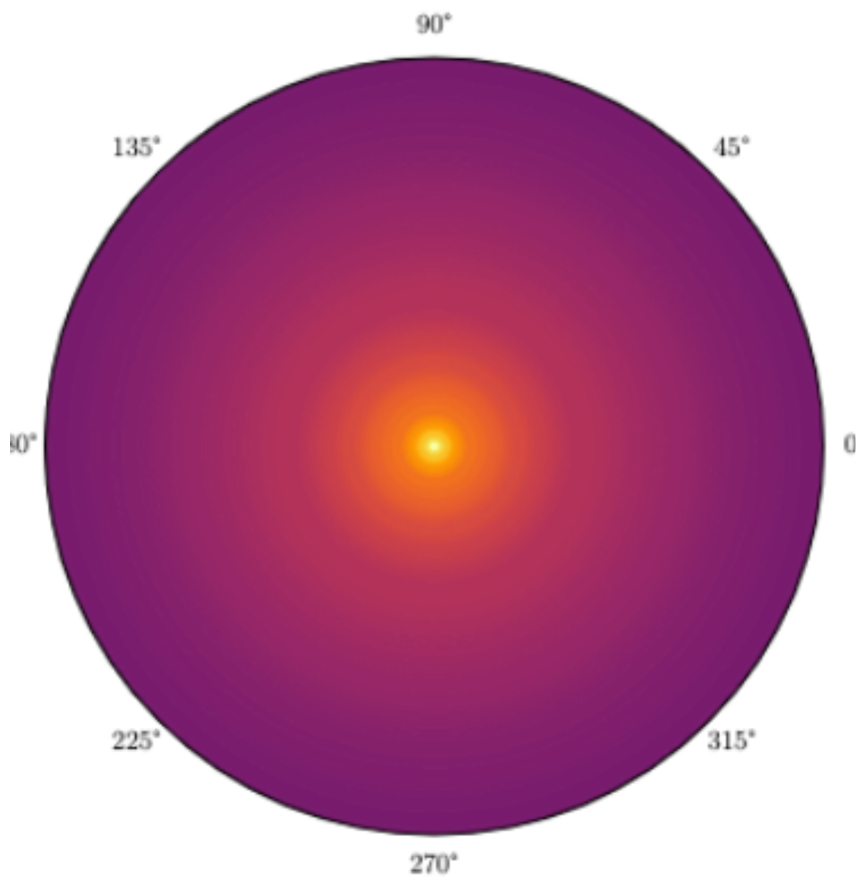
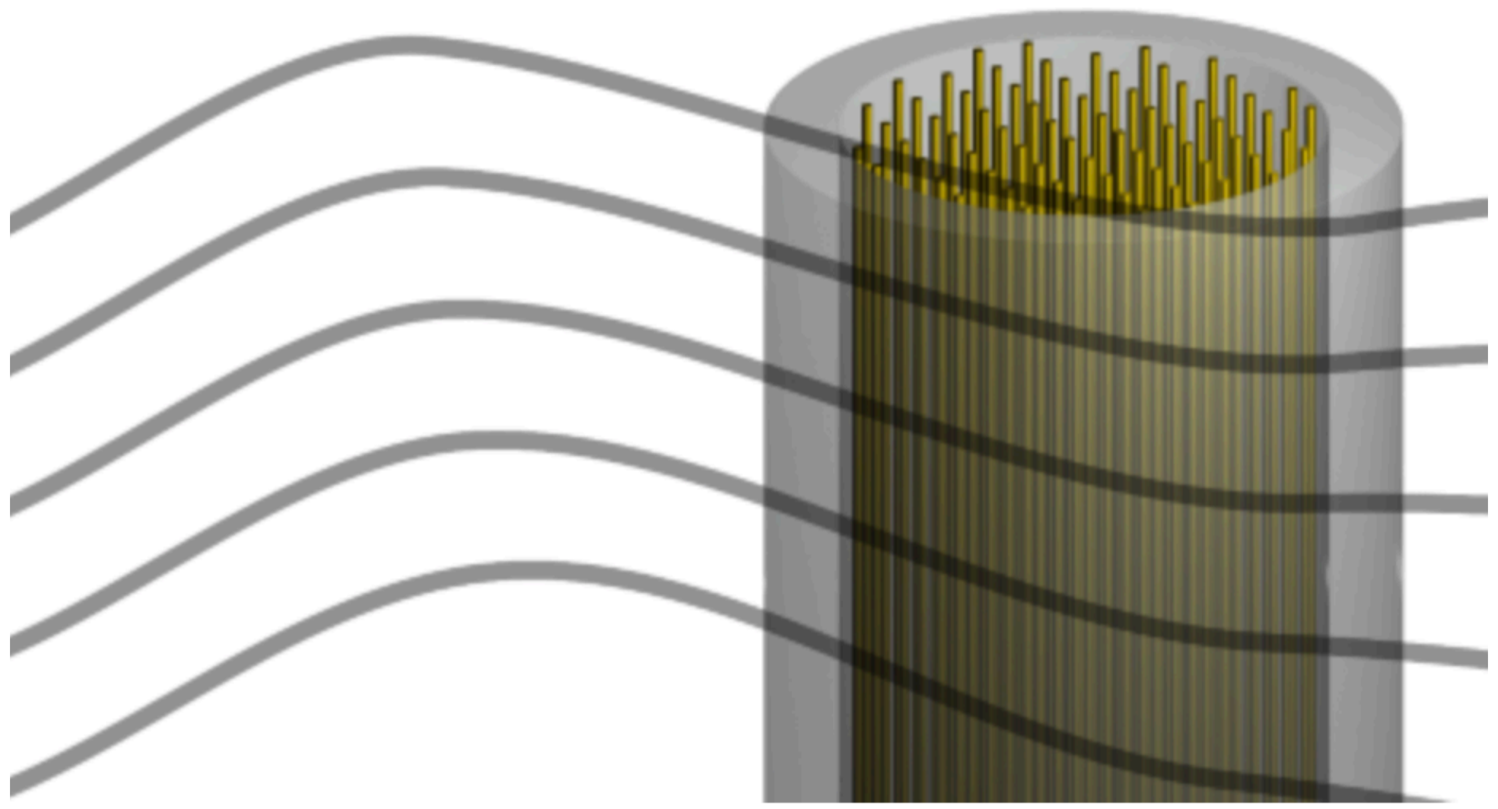


AMC



Haloscope



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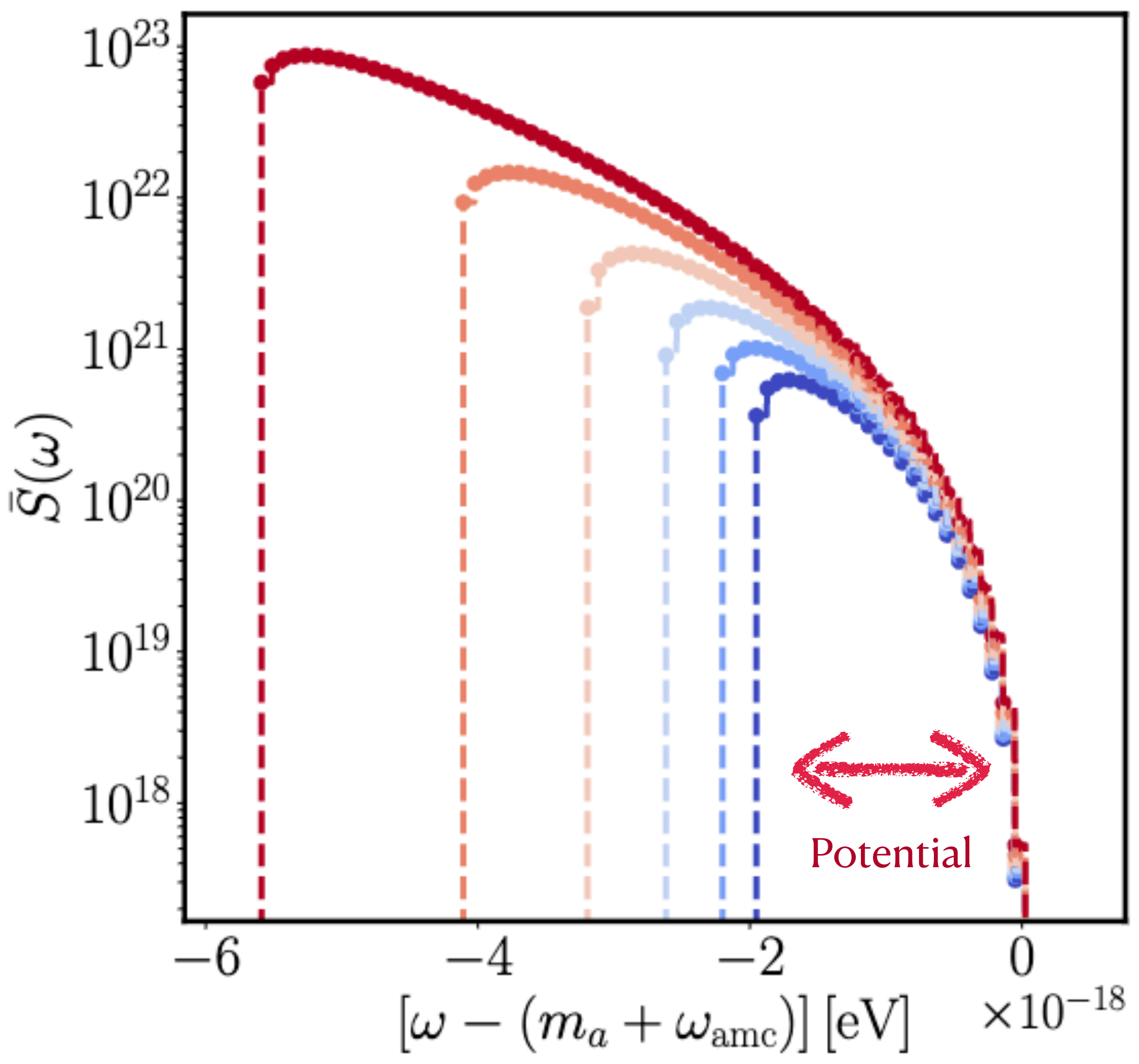
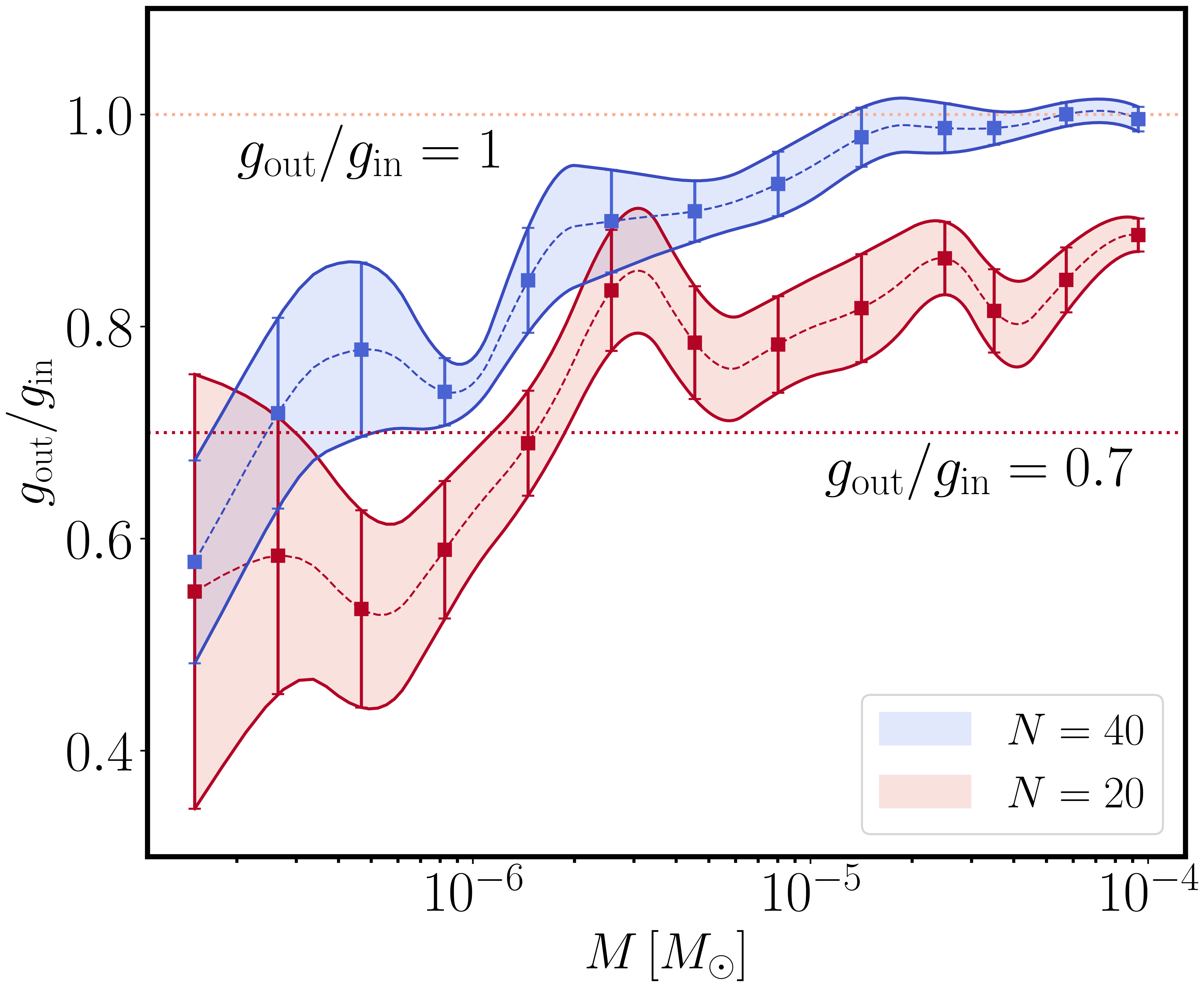
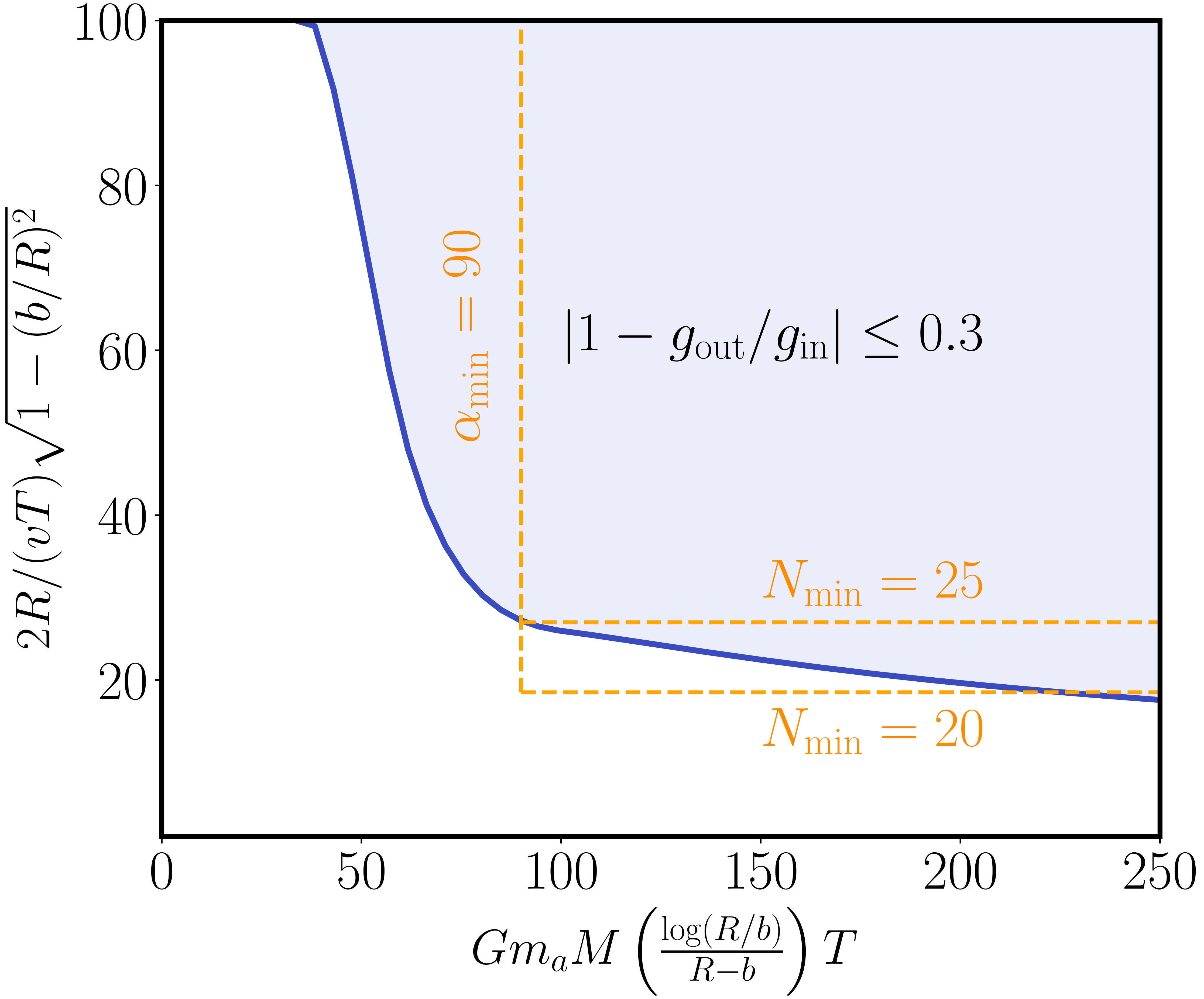
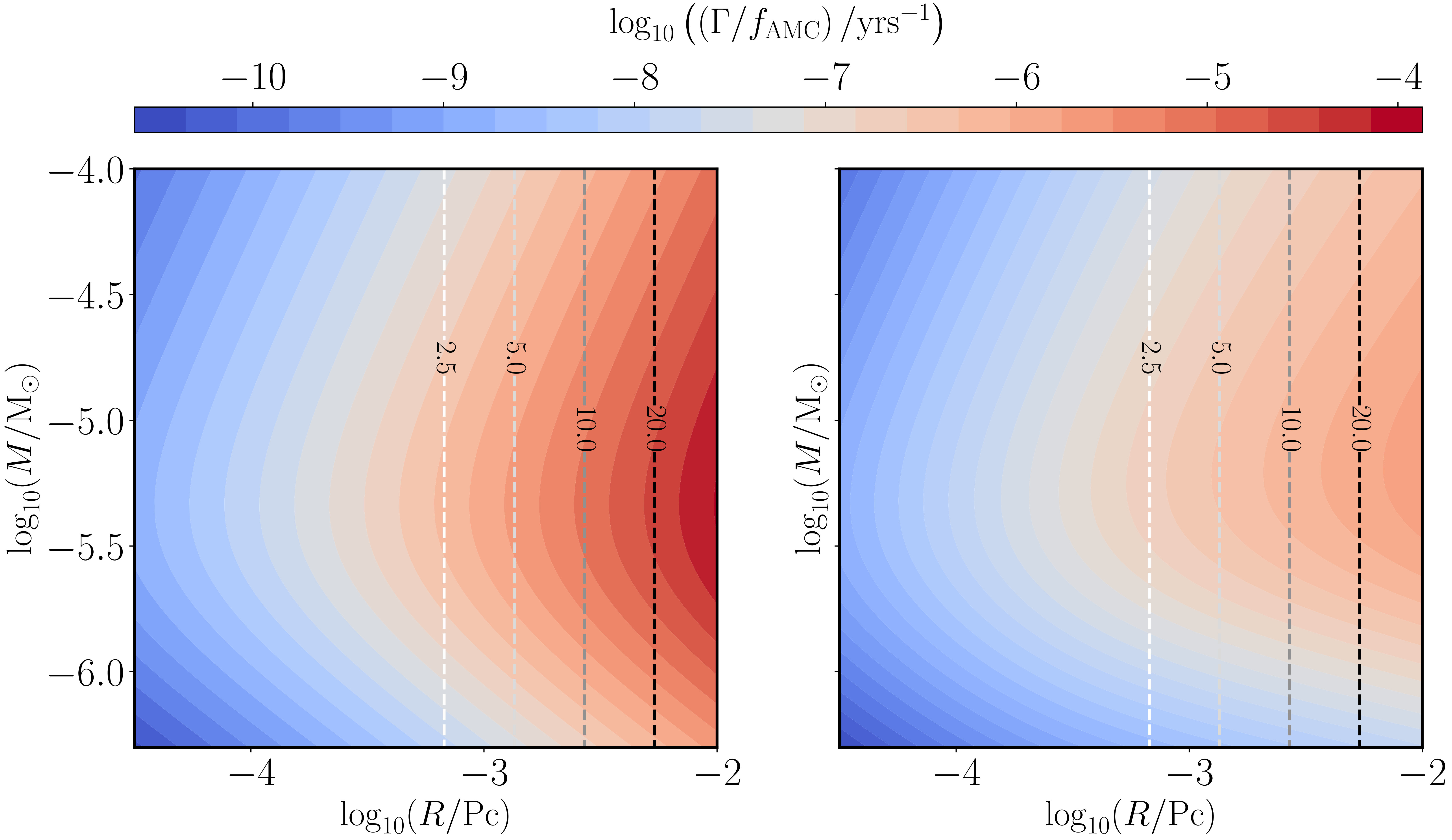


Coupling Reconstruction



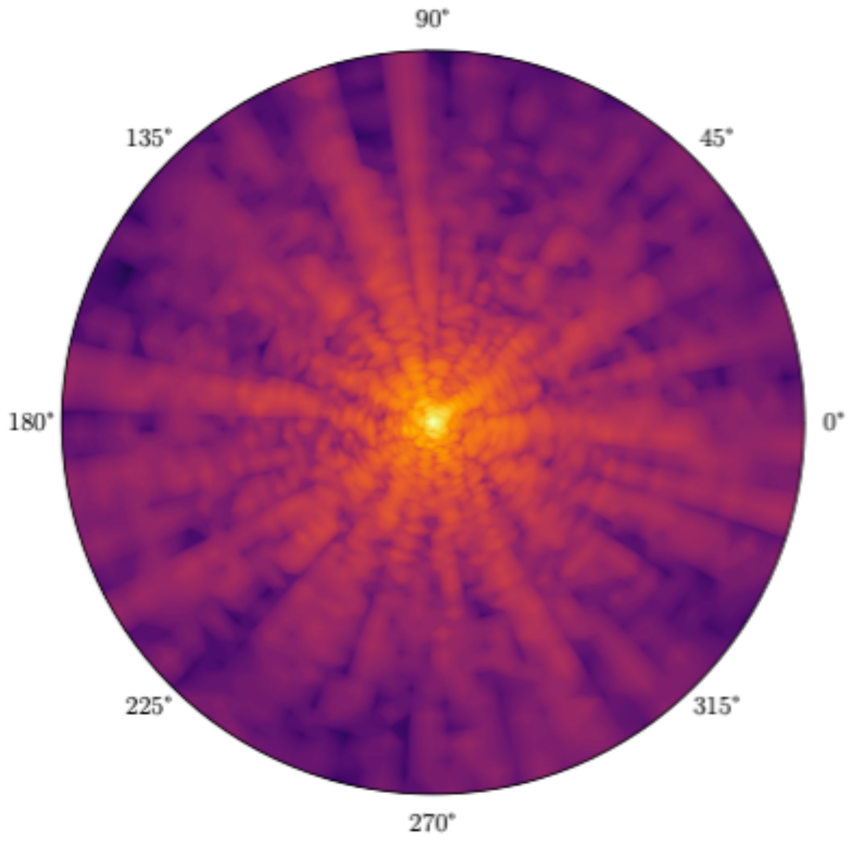


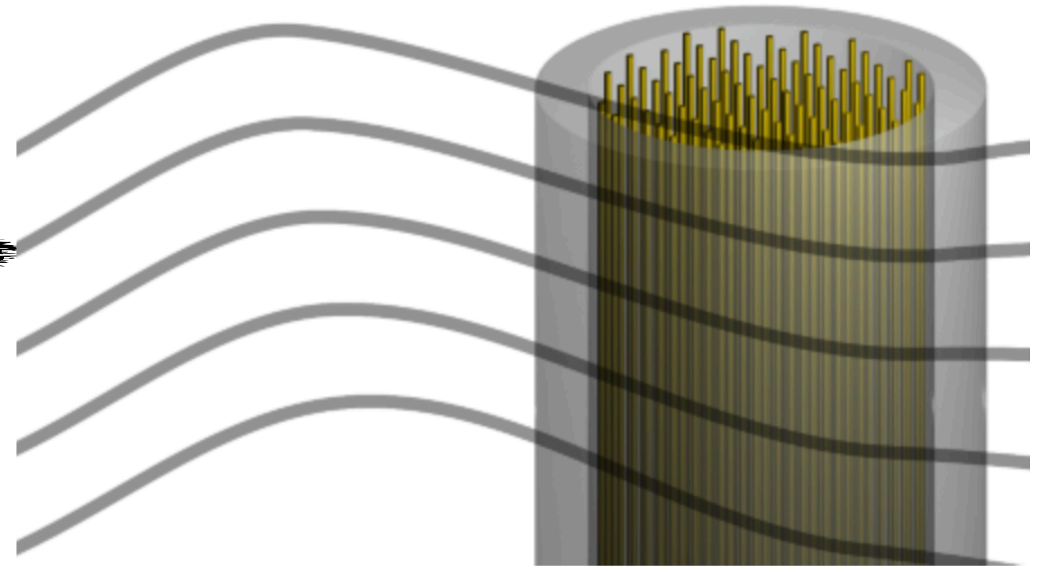
Encountering Suitable AMCs

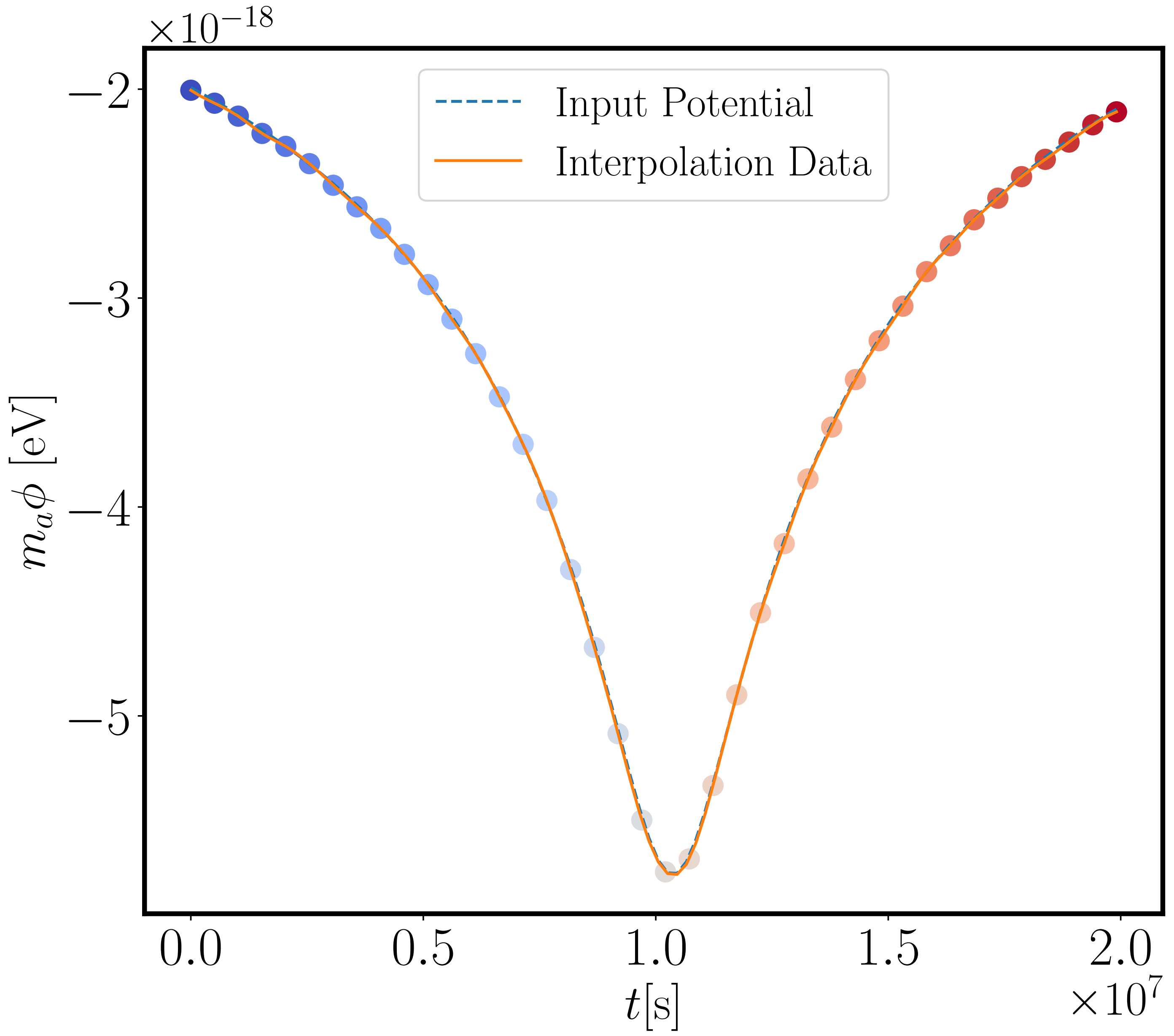


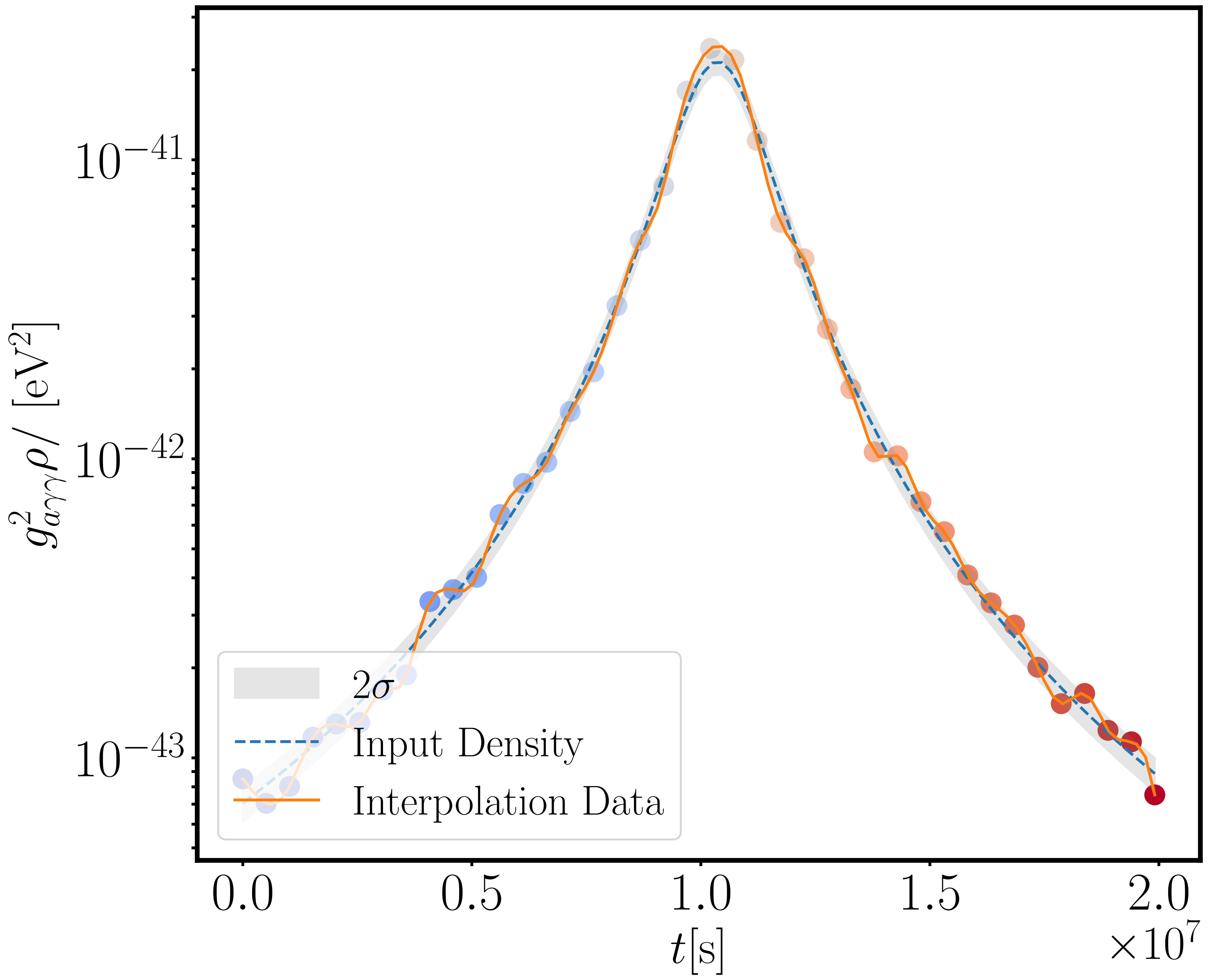
Takeaway message

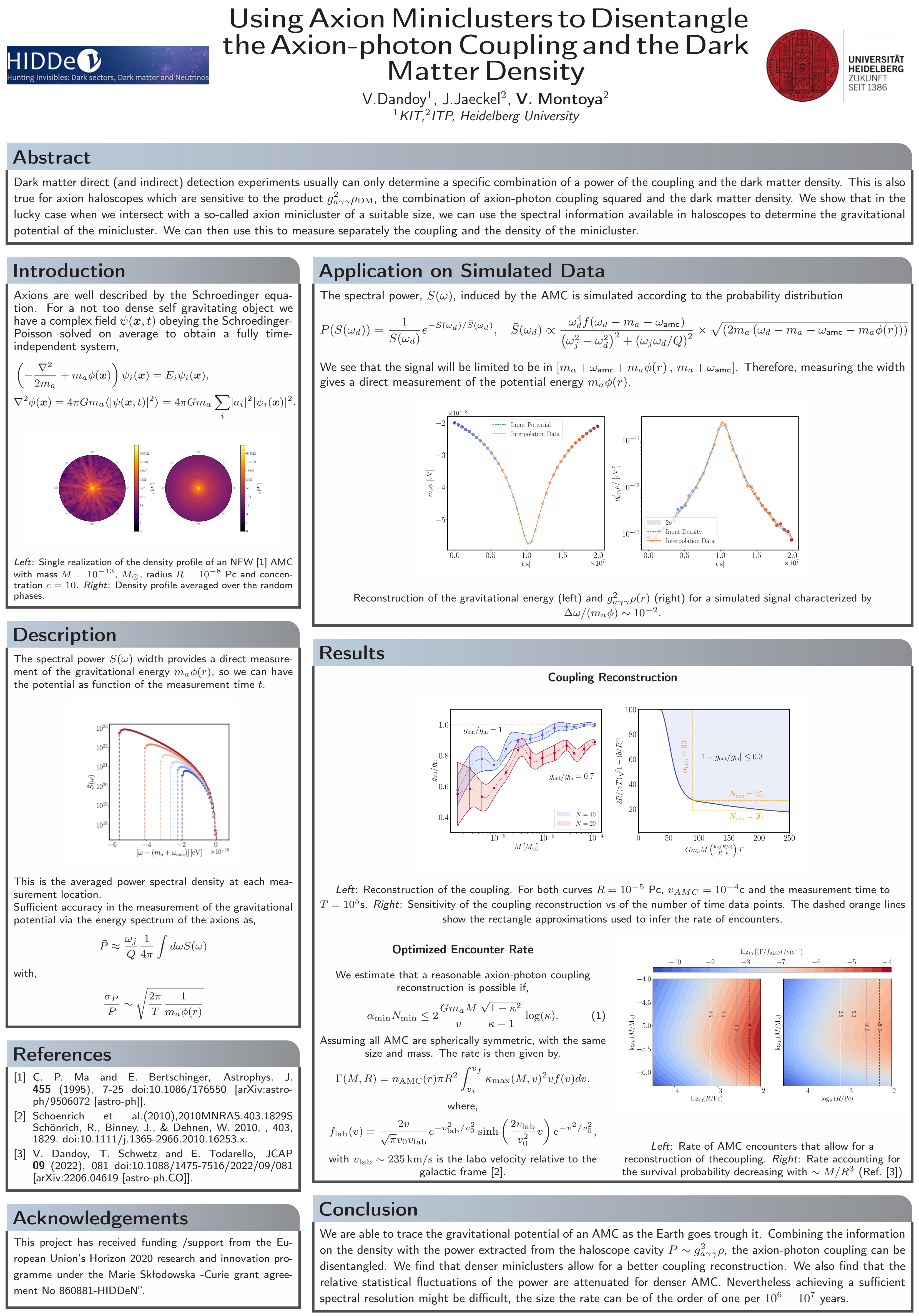
Takeaway message











Using Axion Miniclusters to Disentangle the Axion-photon Coupling and the Dark Matter Density

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HIDDeN Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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Abstract

Dark matter direct (and indirect) detection experiments usually can only determine a specific combination of a power of the coupling and the dark matter density. This is also true for axion haloscopes which are sensitive to the product $g^2_{a\gamma\gamma}\rho_{\rm DM}$, the combination of axion-photon coupling squared and the dark matter density. We show that in the lucky case when we intersect with a so-called axion minicluster of a suitable size, we can use the spectral information available in haloscopes to determine the gravitational potential of the minicluster. We can then use this to measure separately the coupling and the density of the minicluster.

Introduction

Axions are well described by the Schroedinger equation. For a not too dense self gravitating object we have a complex field $\psi(\boldsymbol{x},t)$ obeying the Schroedinger-Poisson solved on average to obtain a fully time-independent system,

$$\left(-\frac{\nabla^2}{2m_a}+m_a\phi(\boldsymbol{x})\right)\psi_i(\boldsymbol{x})=E_i\psi_i(\boldsymbol{x}),$$

$$\nabla^2\phi(\boldsymbol{x})=4\pi Gm_a\langle|\psi(\boldsymbol{x},t)|^2\rangle=4\pi Gm_a\sum_i|a_i|^2|\psi_i(\boldsymbol{x})|^2.$$

Left: Single realization of the density profile of an NFW [1] AMC with mass $M=10^{-13}$, $M_\odot$, radius $R=10^{-8}$ Pc and concentration $c=10$. *Right*: Density profile averaged over the random phases.

Description

The spectral power $S(\omega)$ width provides a direct measurement of the gravitational energy $m_a\phi(r)$, so we can have the potential as function of the measurement time t.

This is the averaged power spectral density at each measurement location.
Sufficient accuracy in the measurement of the gravitational potential via the energy spectrum of the axions as,

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

with,

$$\frac{\sigma_P}{\bar{P}}\sim\sqrt{\frac{2\pi}{T}\frac{1}{m_a\phi(r)}}$$

Application on Simulated Data

The spectral power, $S(\omega)$, induced by the AMC is simulated according to the probability distribution

$$P(S(\omega_d))=\frac{1}{\bar{S}(\omega_d)}e^{-S(\omega_d)/\bar{S}(\omega_d)},\quad \bar{S}(\omega_d)\propto\frac{\omega_d^4 f(\omega_d-m_a-\omega_{\rm amc})}{\left(\omega_j^2-\omega_d^2\right)^2+(\omega_j\omega_d/Q)^2}\times\sqrt{(2m_a\left(\omega_d-m_a-\omega_{\rm amc}-m_a\phi(r)\right))}$$

We see that the signal will be limited to be in $[m_a+\omega_{\rm amc}+m_a\phi(r)\,,\,m_a+\omega_{\rm amc}]$. Therefore, measuring the width gives a direct measurement of the potential energy $m_a\phi(r)$.

Reconstruction of the gravitational energy (left) and $g^2_{a\gamma\gamma}\rho(r)$ (right) for a simulated signal characterized by $\Delta\omega/(m_a\phi)\sim10^{-2}$.

Results

Coupling Reconstruction

Left: Reconstruction of the coupling. For both curves $R=10^{-5}$ Pc, $v_{AMC}=10^{-4}$c and the measurement time to $T=10^5$s. *Right*: Sensitivity of the coupling reconstruction vs of the number of time data points. The dashed orange lines show the rectangle approximations used to infer the rate of encounters.

Optimized Encounter Rate

We estimate that a reasonable axion-photon coupling reconstruction is possible if,

$$\alpha_{\rm min}N_{\rm min}\leq 2\frac{Gm_aM}{v}\frac{\sqrt{1-\kappa^2}}{\kappa-1}\log(\kappa). \quad (1)$$

Assuming all AMC are spherically symmetric, with the same size and mass. The rate is then given by,

$$\Gamma(M,R)=n_{\rm AMC}(r)\pi R^2\int_{v_i}^{v_f}\kappa_{\rm max}(M,v)^2vf(v)dv.$$

where,

$$f_{\rm lab}(v)=\frac{2v}{\sqrt{\pi}v_0v_{\rm lab}}e^{-v_{\rm lab}^2/v_0^2}\sinh\left(\frac{2v_{\rm lab}}{v_0^2}v\right)e^{-v^2/v_0^2},$$

with $v_{\rm lab}\sim235\,{\rm km/s}$ is the labo velocity relative to the galactic frame [2].

Left: Rate of AMC encounters that allow for a reconstruction of thecoupling. *Right*: Rate accounting for the survival probability decreasing with $\sim M/R^3$ (Ref. [3])

Conclusion

We are able to trace the gravitational potential of an AMC as the Earth goes trough it. Combining the information on the density with the power extracted from the haloscope cavity $P\sim g^2_{a\gamma\gamma}\rho$, the axion-photon coupling can be disentangled. We find that denser miniclusters allow for a better coupling reconstruction. We also find that the relative statistical fluctuations of the power are attenuated for denser AMC. Nevertheless achieving a sufficient spectral resolution might be difficult, the size the rate can be of the order of one per 10^6-10^7 years.

References

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[2] Schoenrich et al.(2010),2010MNRAS.403.1829S Schönrich, R., Binney, J., & Dehnen, W. 2010, , 403, 1829. doi:10.1111/j.1365-2966.2010.16253.x.
[3] V. Dandoy, T. Schwetz and E. Todarello, JCAP **09** (2022), 081 doi:10.1088/1475-7516/2022/09/081 [arXiv:2206.04619 [astro-ph.CO]].

Acknowledgements

This project has received funding /support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN".

Thanks!