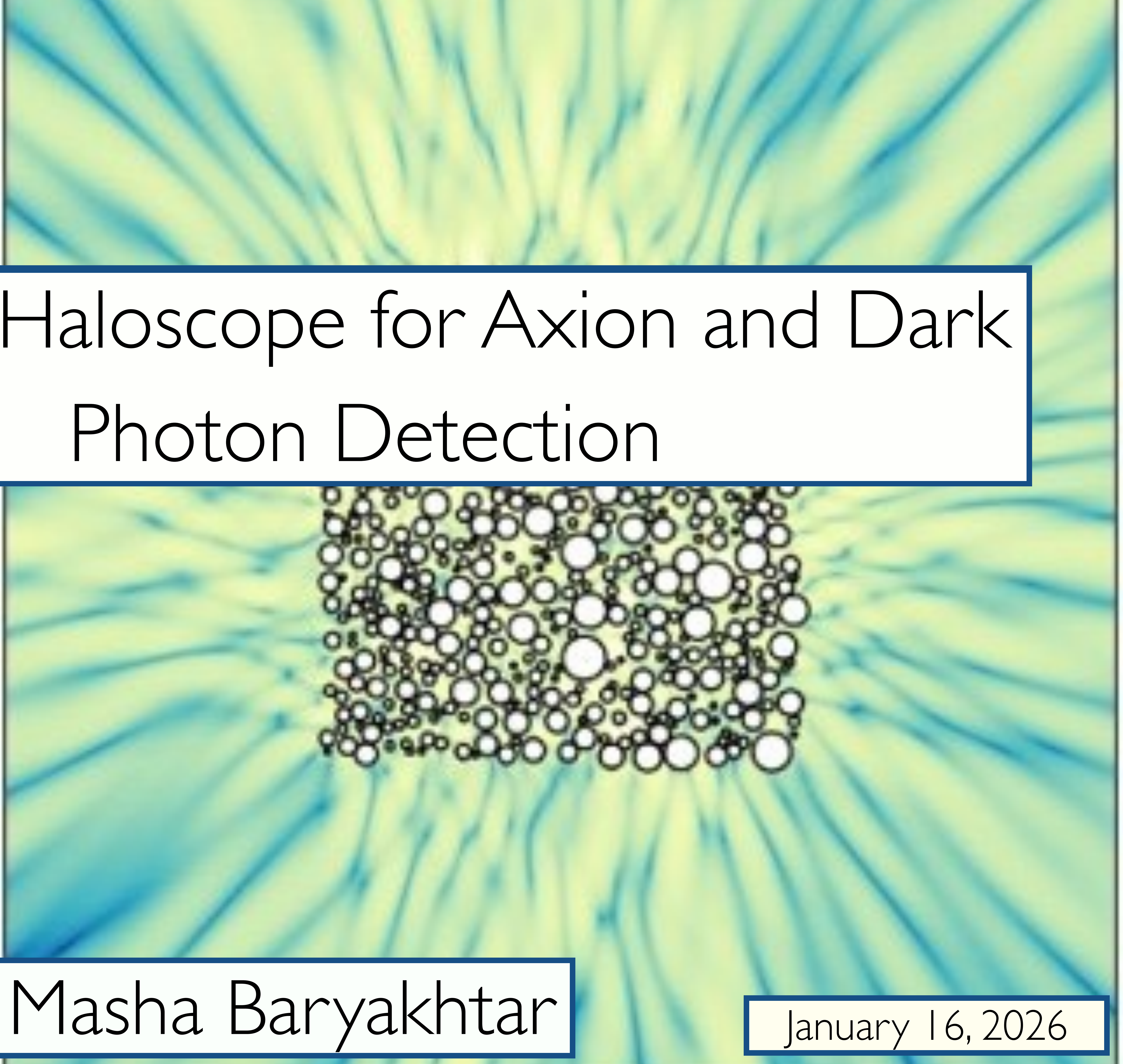
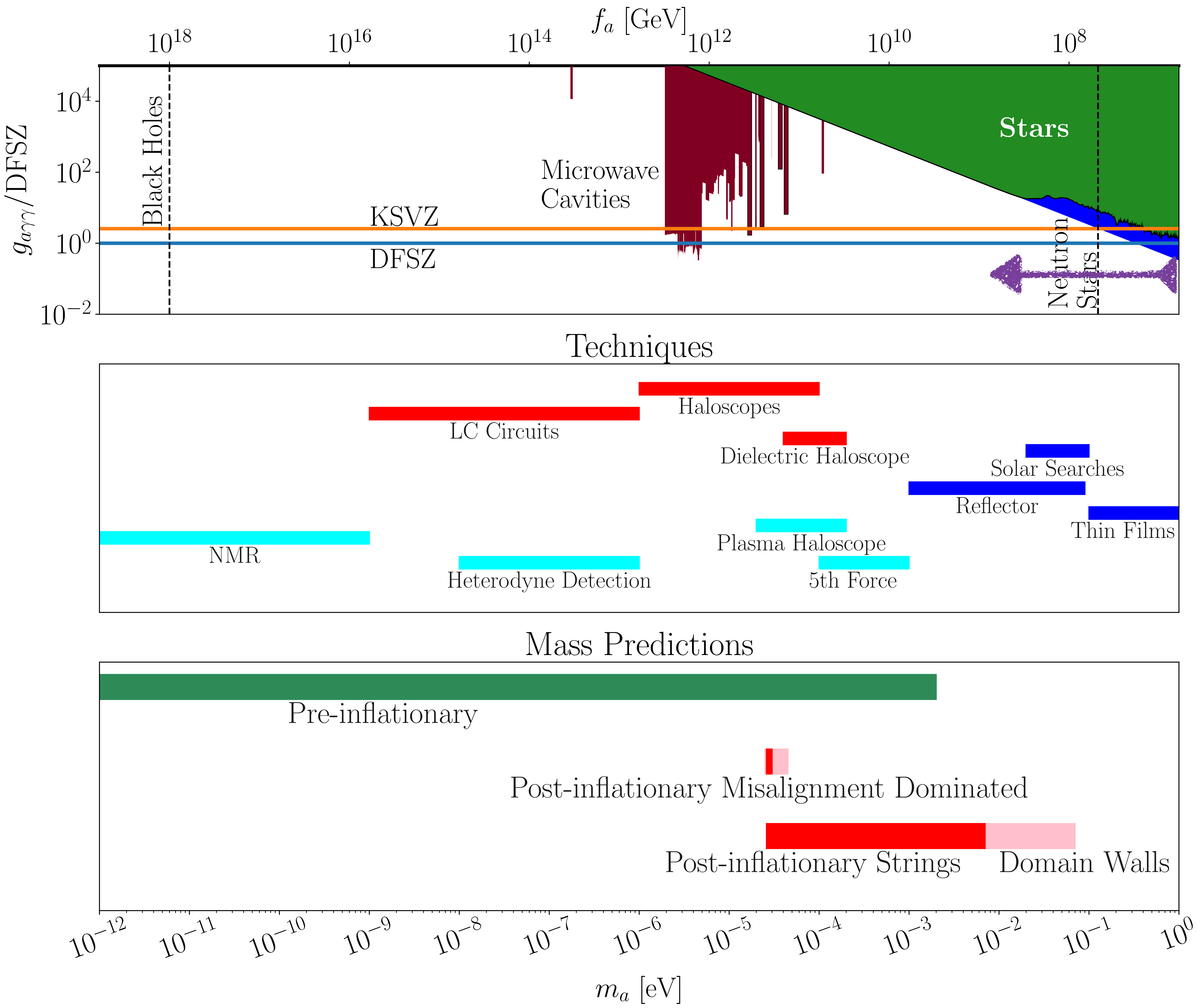
Powder Haloscope for Axion and Dark Photon Detection



Masha Baryakhtar

January 16, 2026

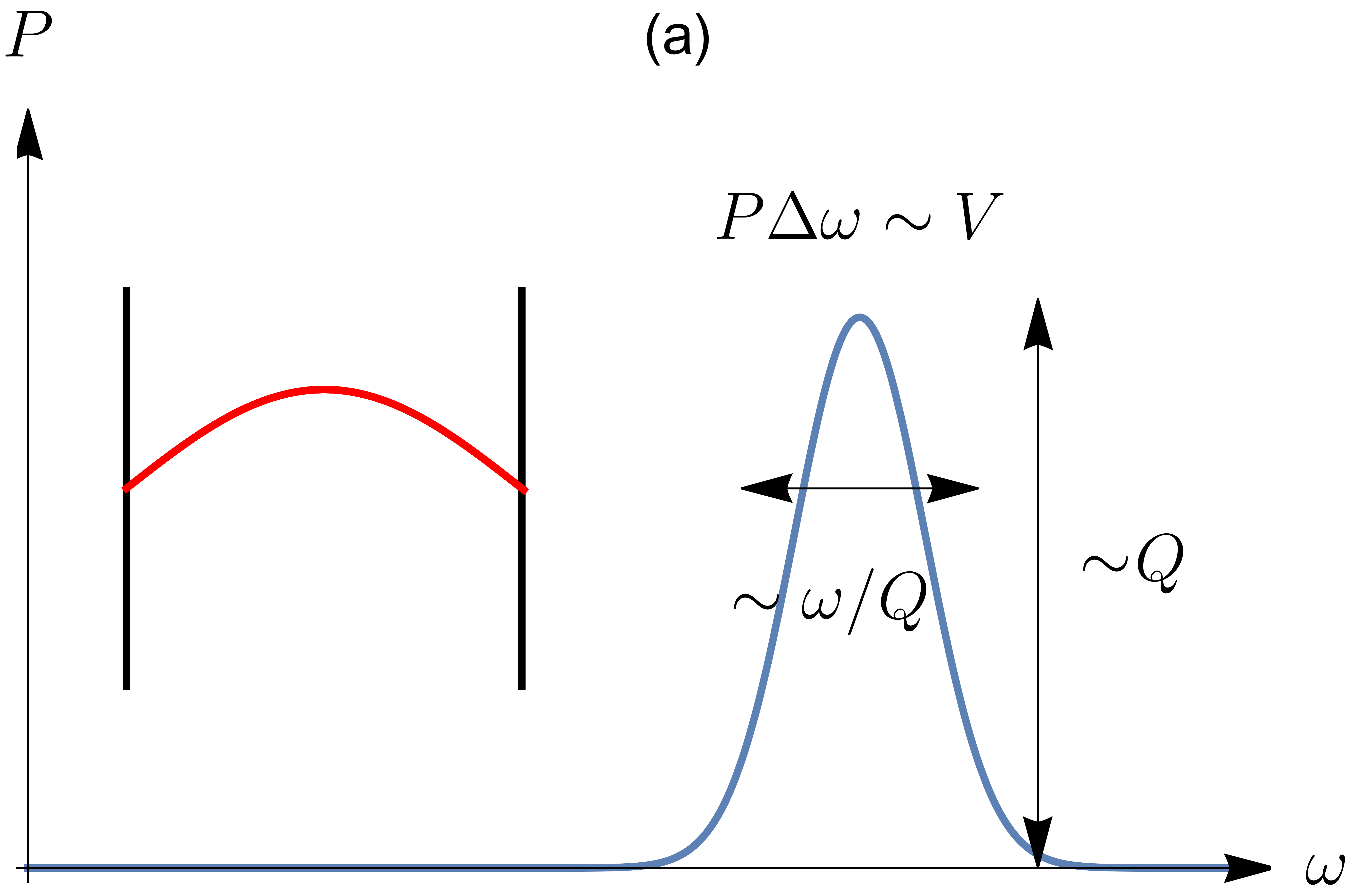
Searching for `heavier' axions



Baryakhtar, Rosenberg, Rybka ROP 2504.10607

Converting Axions to Light


ADMX

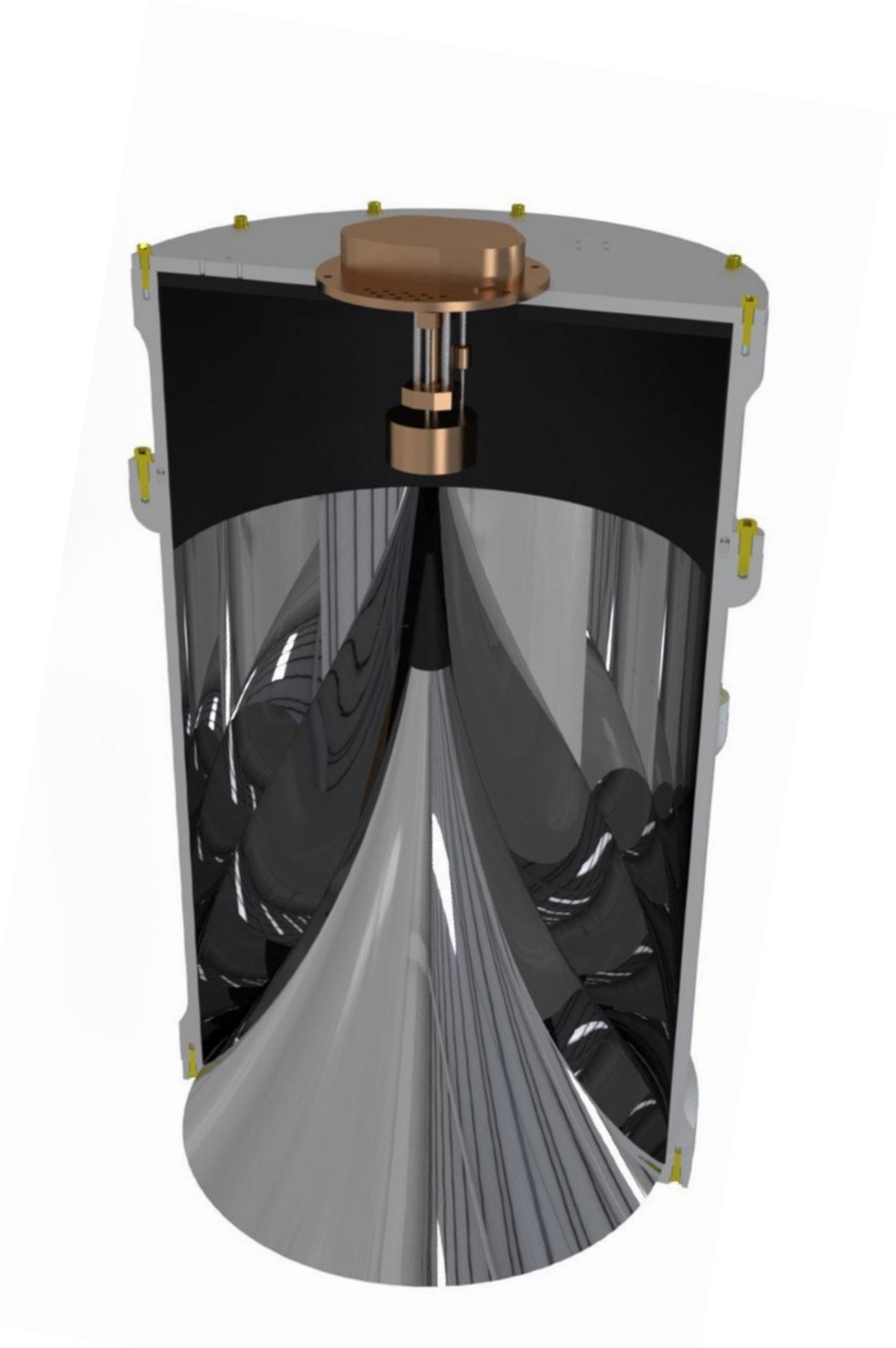


Cavity

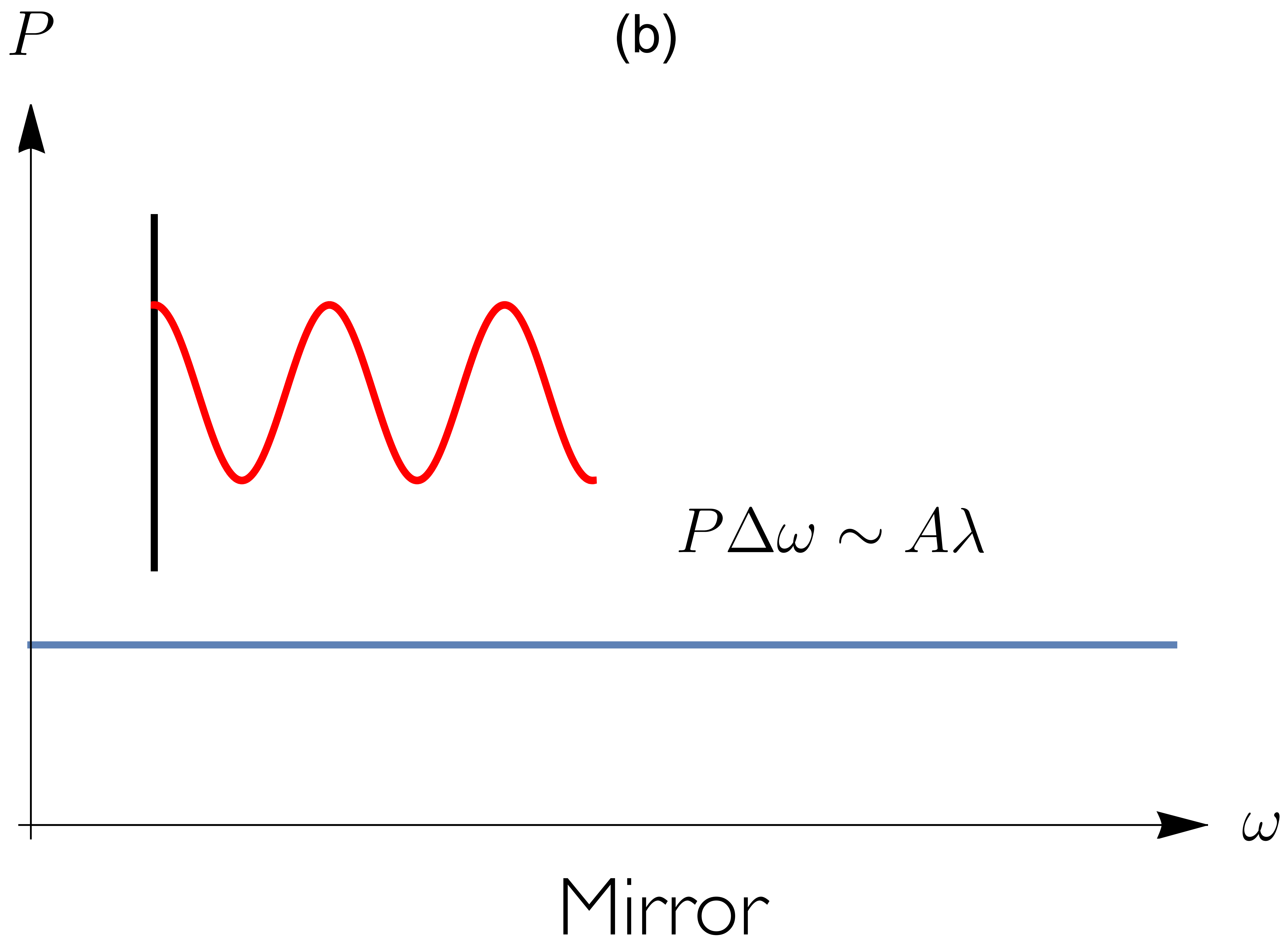
Axion DM: Background time-dependent, space-independent* current density

Emission of photons requires new momentum scale, such as the size of a cavity

Converting Axions to Light



BREAD
COLLABORATION

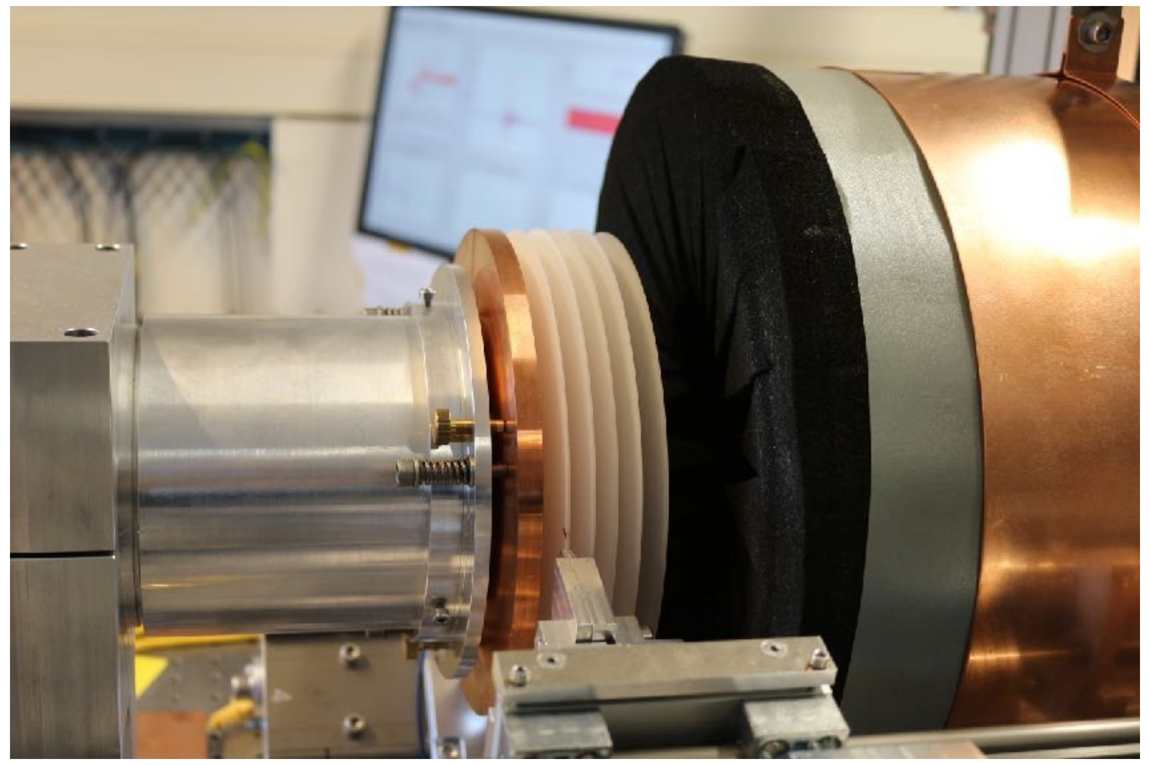


Axion DM: Background time-dependent, space-independent* current density

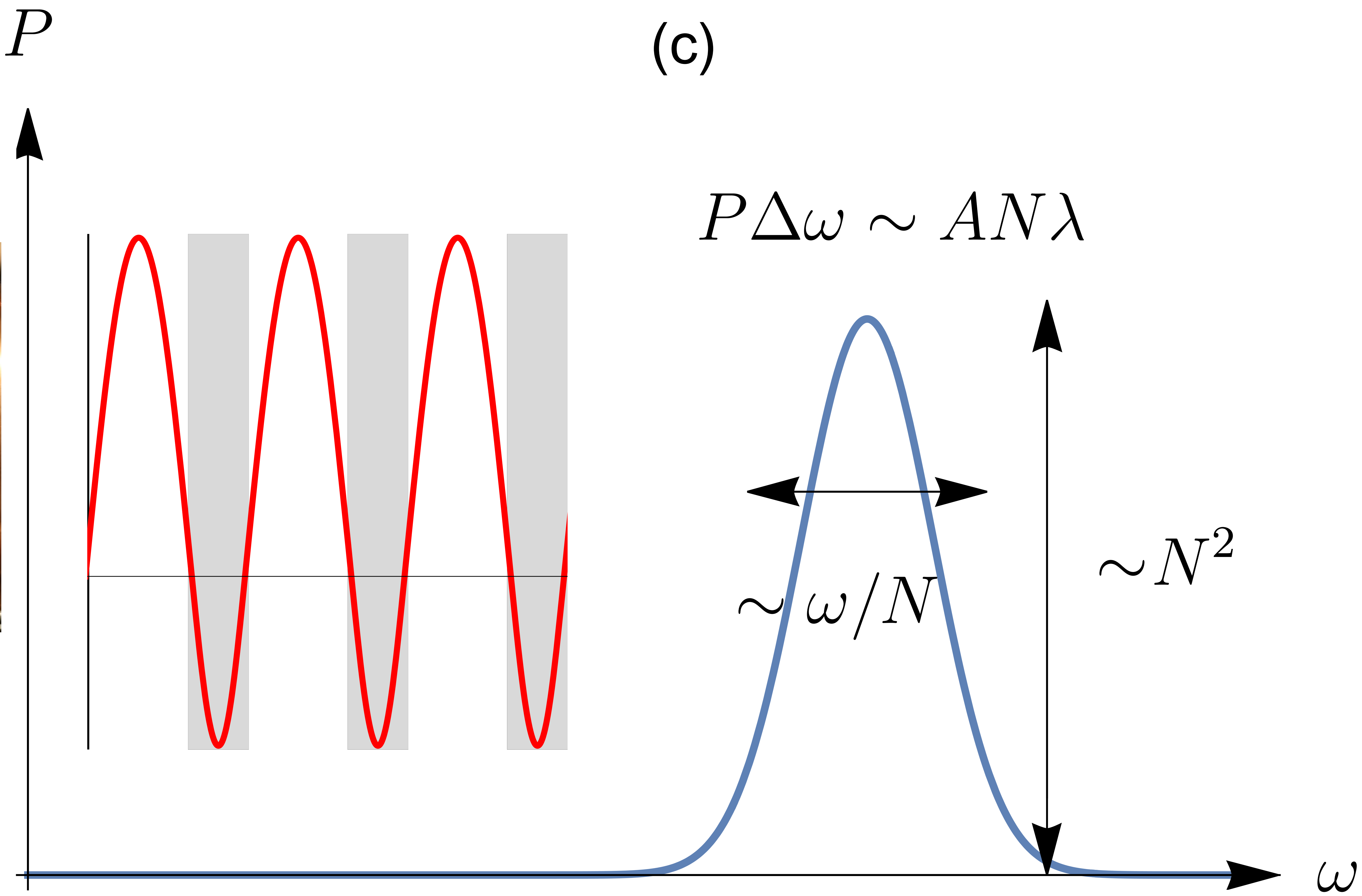
Emission of photons requires new momentum scale, such as the size of a cavity

Conversion only within a wavelength: higher mass requires new structures

Converting Axions to Light



MADMAX,
Sliced BREAD, …



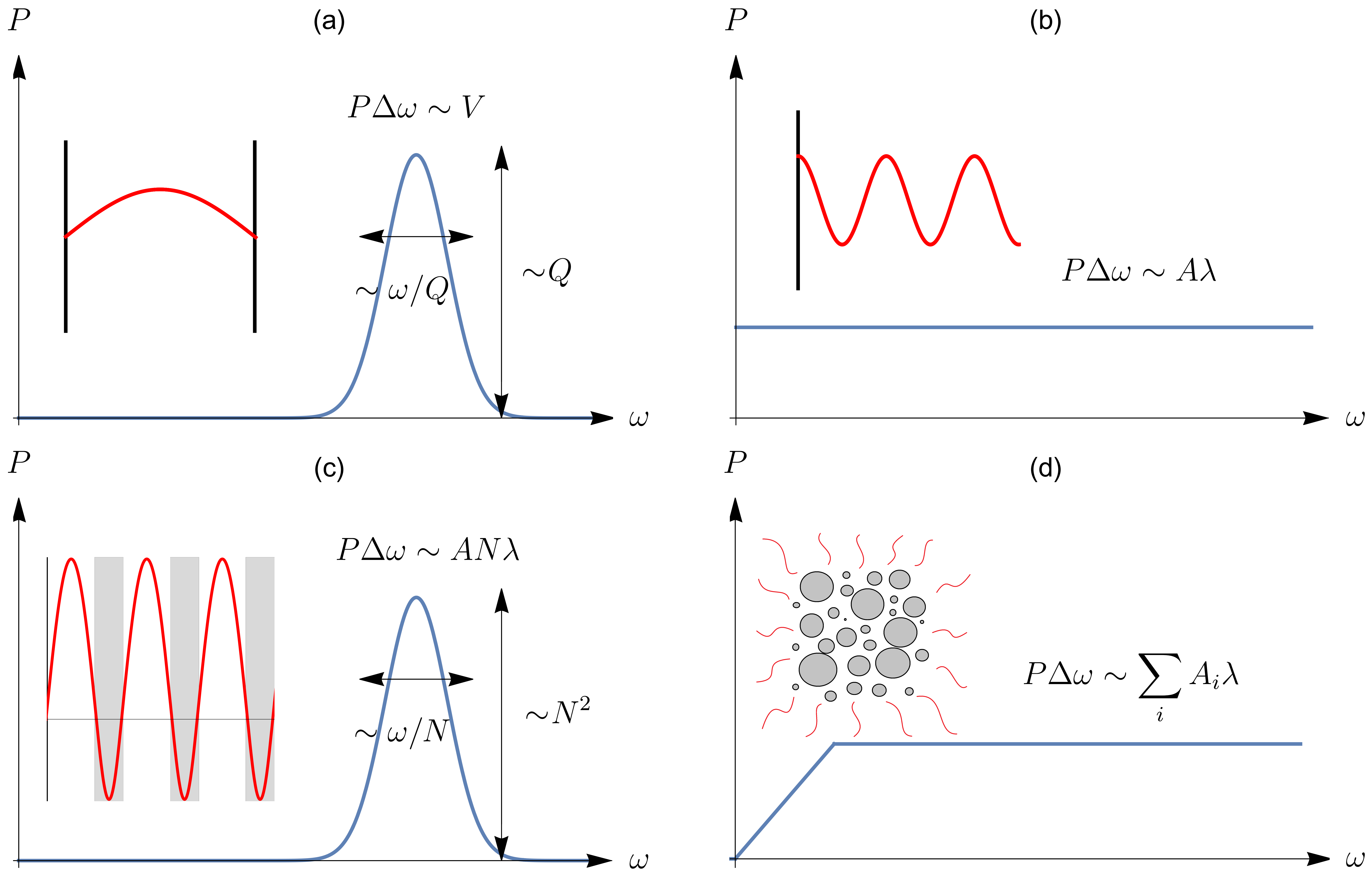
Axion DM: Background time-dependent, space-independent* current density

Emission of photons requires new momentum scale, such as the size of a cavity

Dielectric Stacks

Other approaches? Disordered Dielectrics

Power integrated over bandwidth scales with total interface area

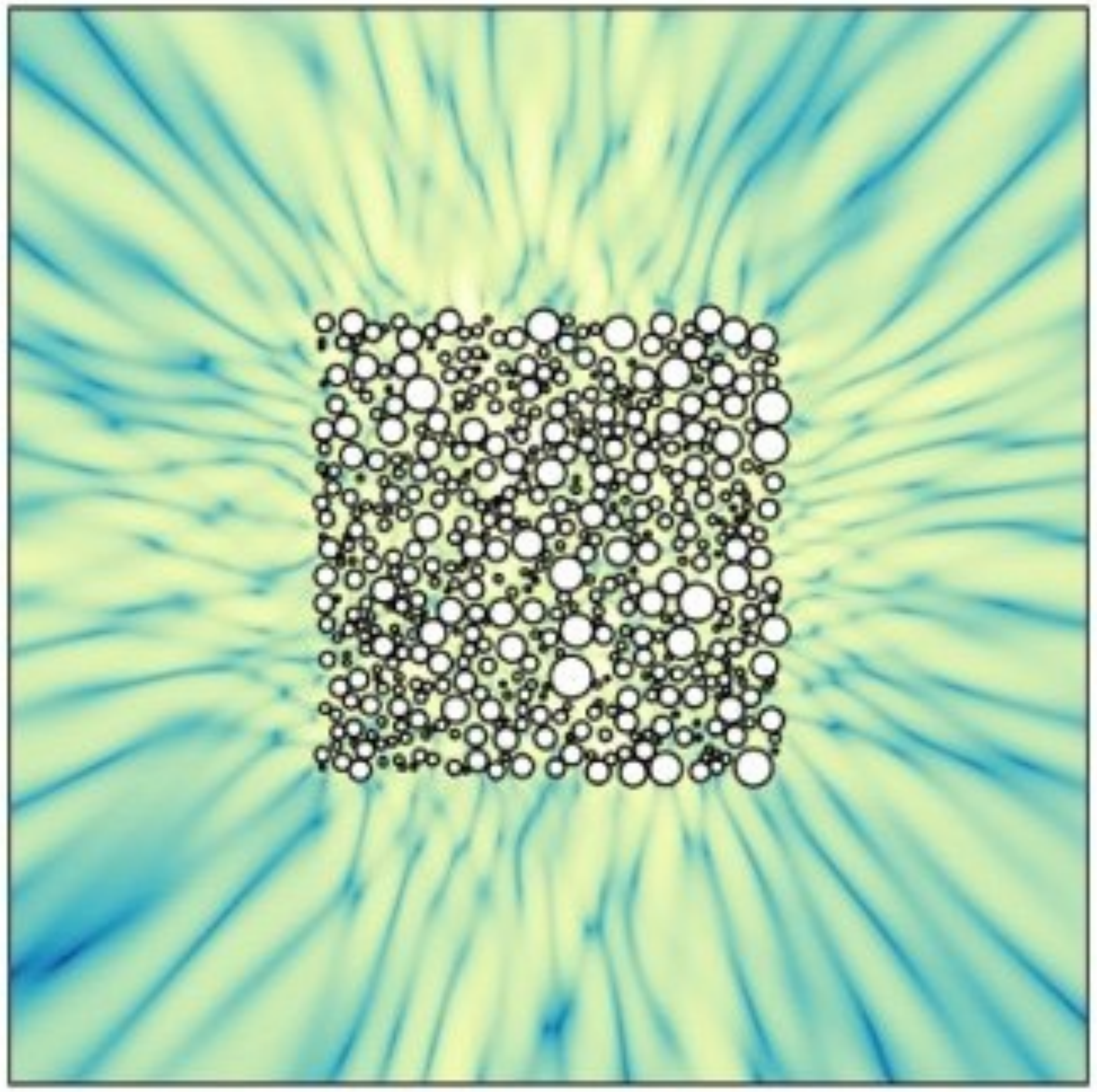


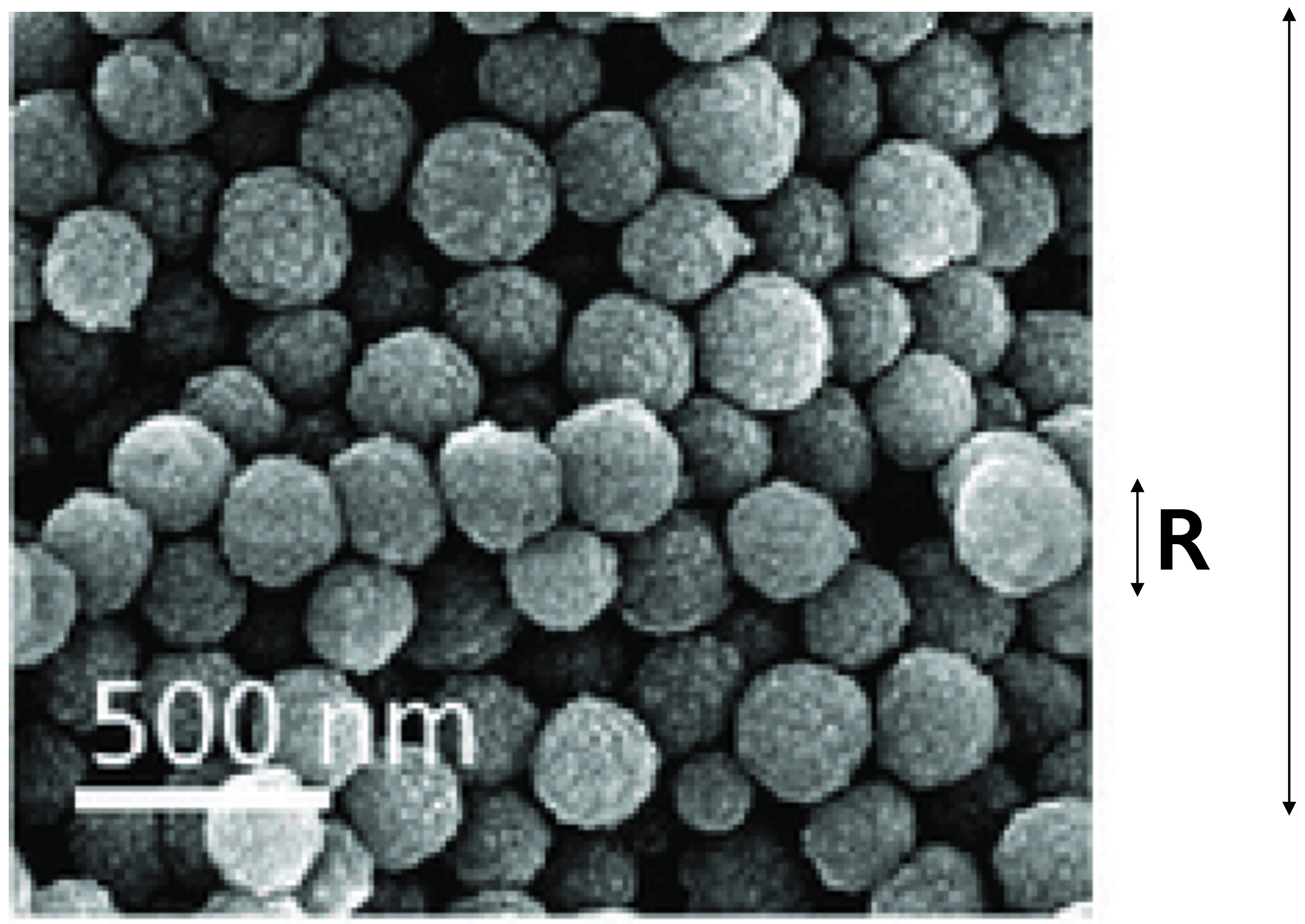
Increasing conversion area within a fixed volume

Koppell, Bittencourt, Paul, Huang, **MB**, Berggren, 2506.00115

Disordered Dielectrics: DPHaSE

Powdered Haloscope

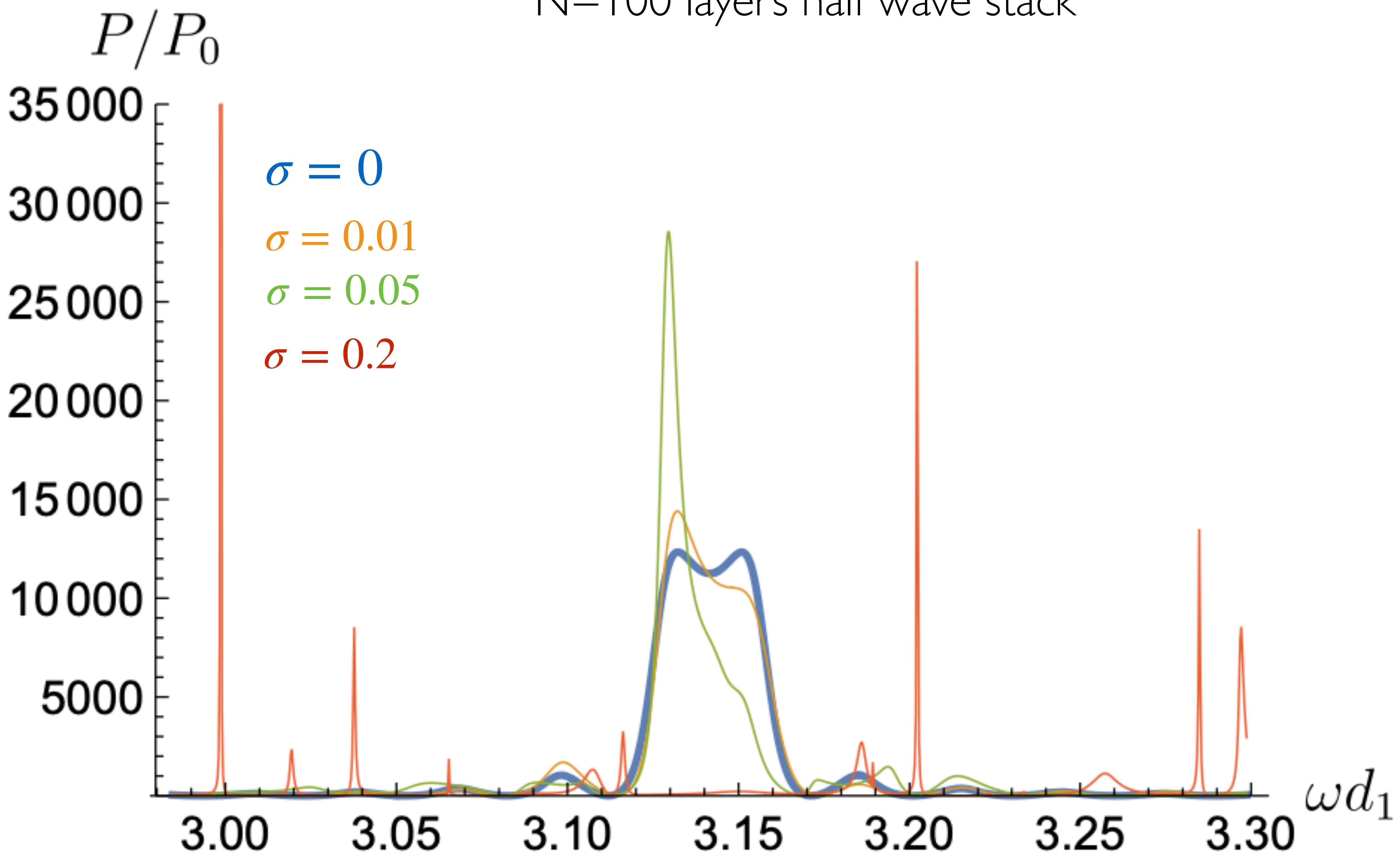




Disordered Dielectrics: 1-D

Potential problems with disorder

N=100 layers half wave stack

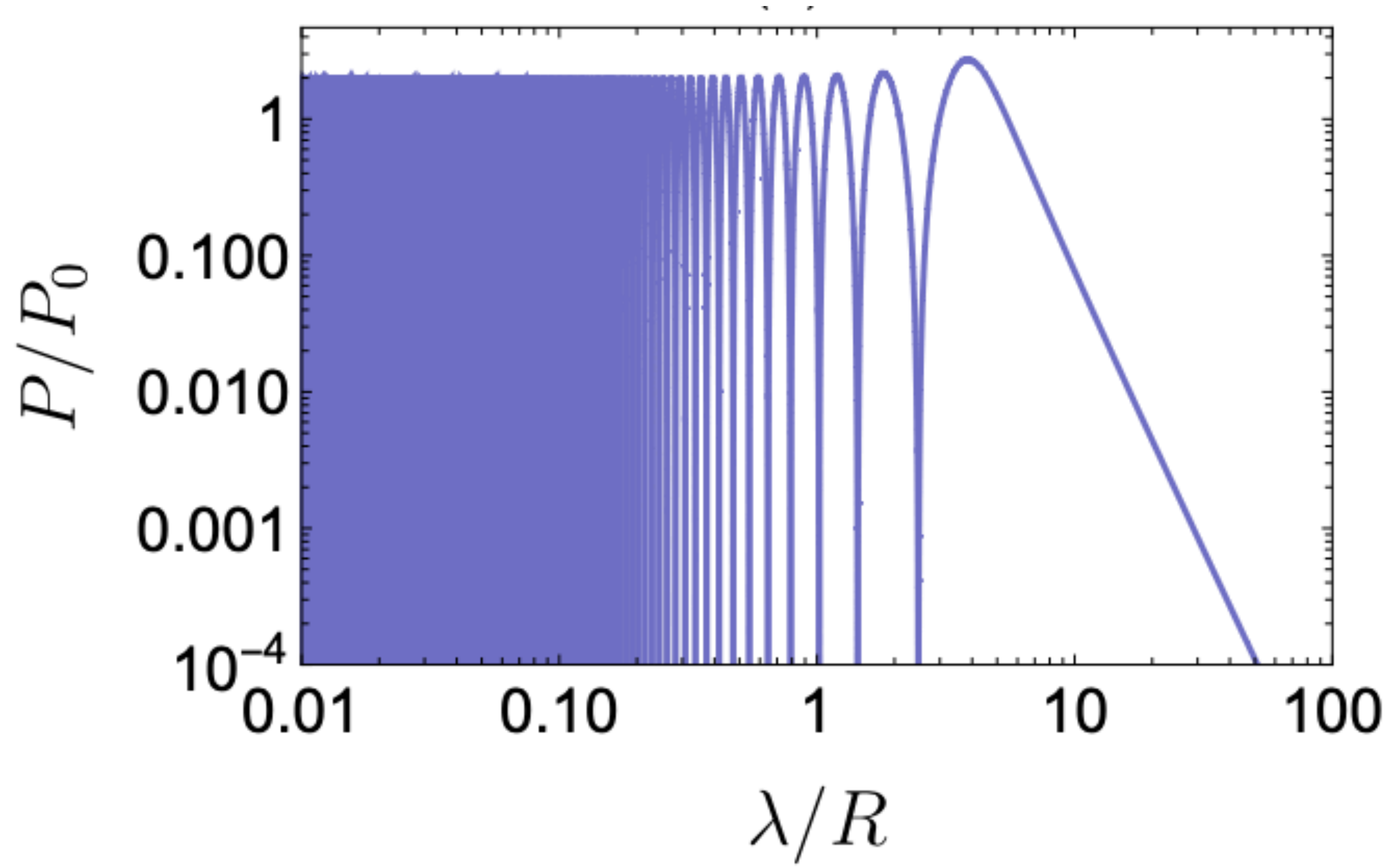


- Random layer thicknesses can lead to destructive interference
- Overall average power across frequency range is fixed, but how to know what region of parameter space you're searching?

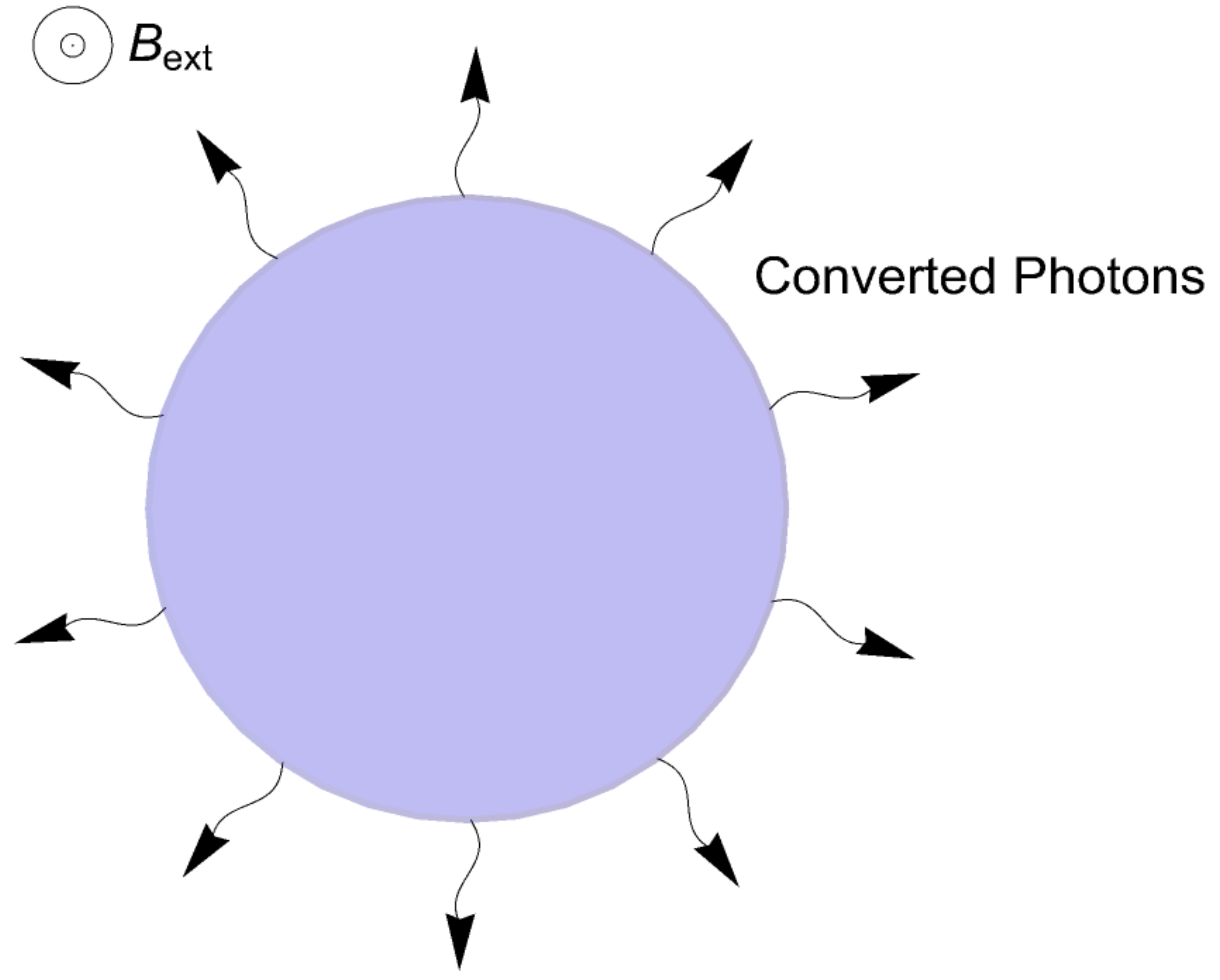
MB, J. Huang, R. Lasenby, PRD 2018

Disordered Dielectrics: Higher Dimensions

Single Sphere



$$\langle \mathbb{P}_G \rangle_\omega = \frac{E_0^2}{2}\left(1-\frac{1}{n}\right)\left(1-\frac{1}{n^2}\right)\frac{8\pi}{3}R^2,$$



$E_0^2/2$	Fibers (2D powder)	Spheres (3D powder)
axion	$(g_{a\gamma\gamma}B_{\rm ext})^2 \frac{\rho_{\rm DM}}{m^2}$	$(g_{a\gamma\gamma}B_{\rm ext})^2 \frac{\rho_{\rm DM}}{m^2}$
dark photon	$\frac{1}{3}\varepsilon^2\rho_{\rm DM}$	$\frac{2}{3}\varepsilon^2\rho_{\rm DM}$

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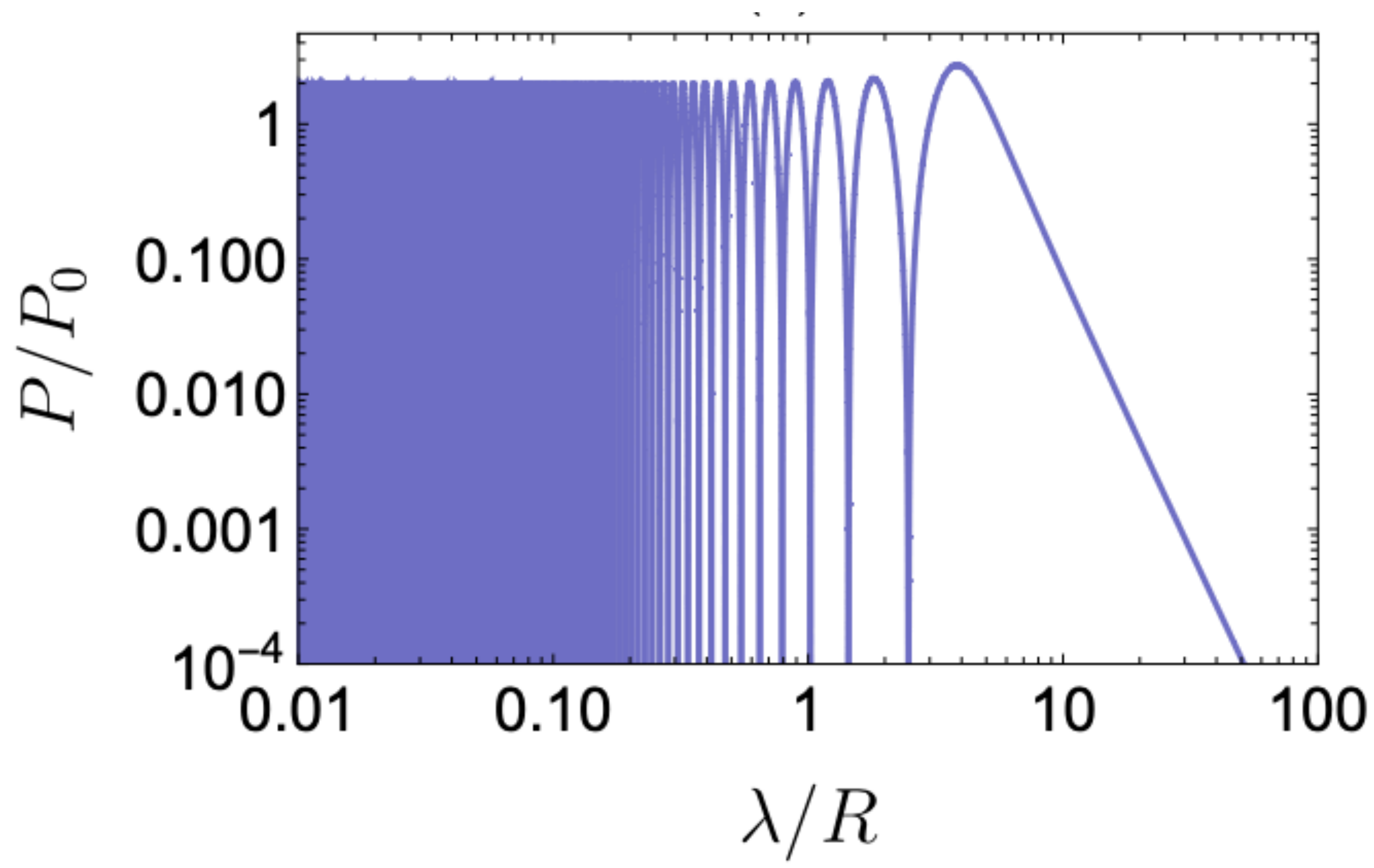
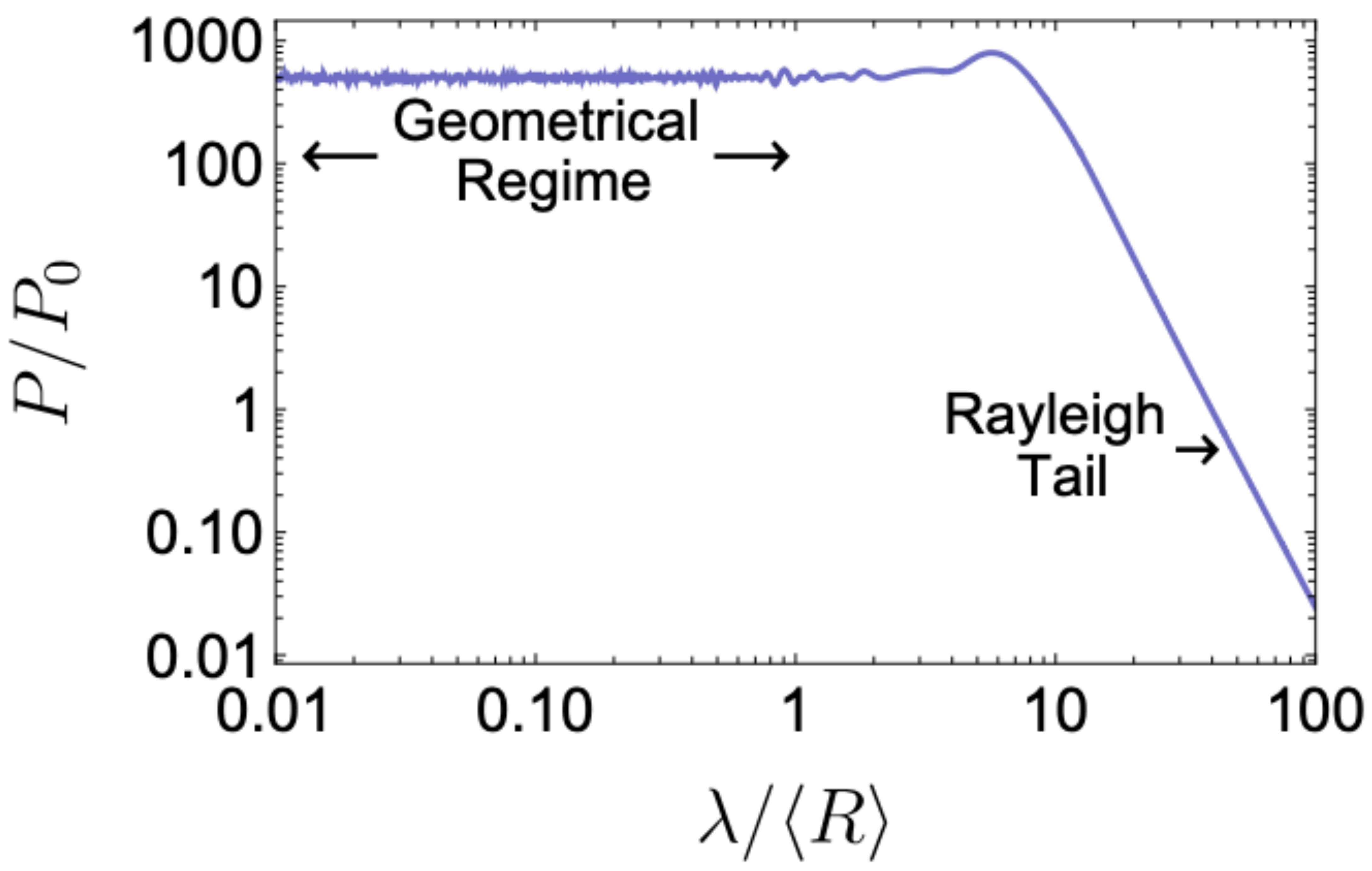
Disordered Dielectrics: Higher Dimensions

Single Sphere



500 Spheres



$$\langle \mathbb{P}_G \rangle_\omega = \frac{E_0^2}{2}\left(1-\frac{1}{n}\right)\left(1-\frac{1}{n^2}\right)\frac{8\pi}{3}R^2, \qquad \langle \mathbb{P}_G \rangle_R = \frac{E_0^2}{2}\left(1-\frac{1}{n}\right)\left(1-\frac{1}{n^2}\right)\frac{8\pi}{3}\langle R^2\rangle + \mathcal{O}(\lambda/\langle R\rangle)$$

`area law' Millar, Raffelt, Redondo, and Steffen, 2016

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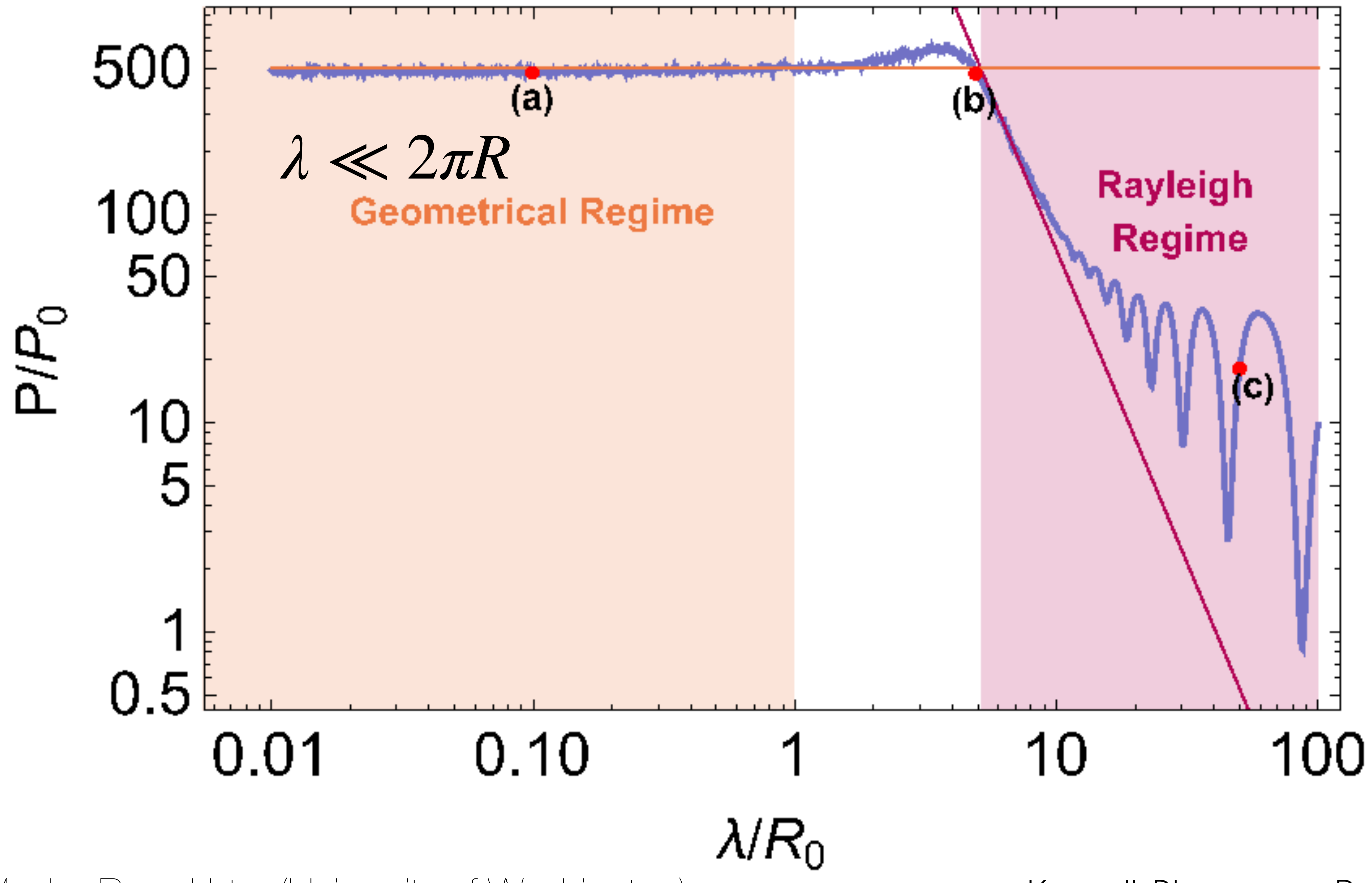
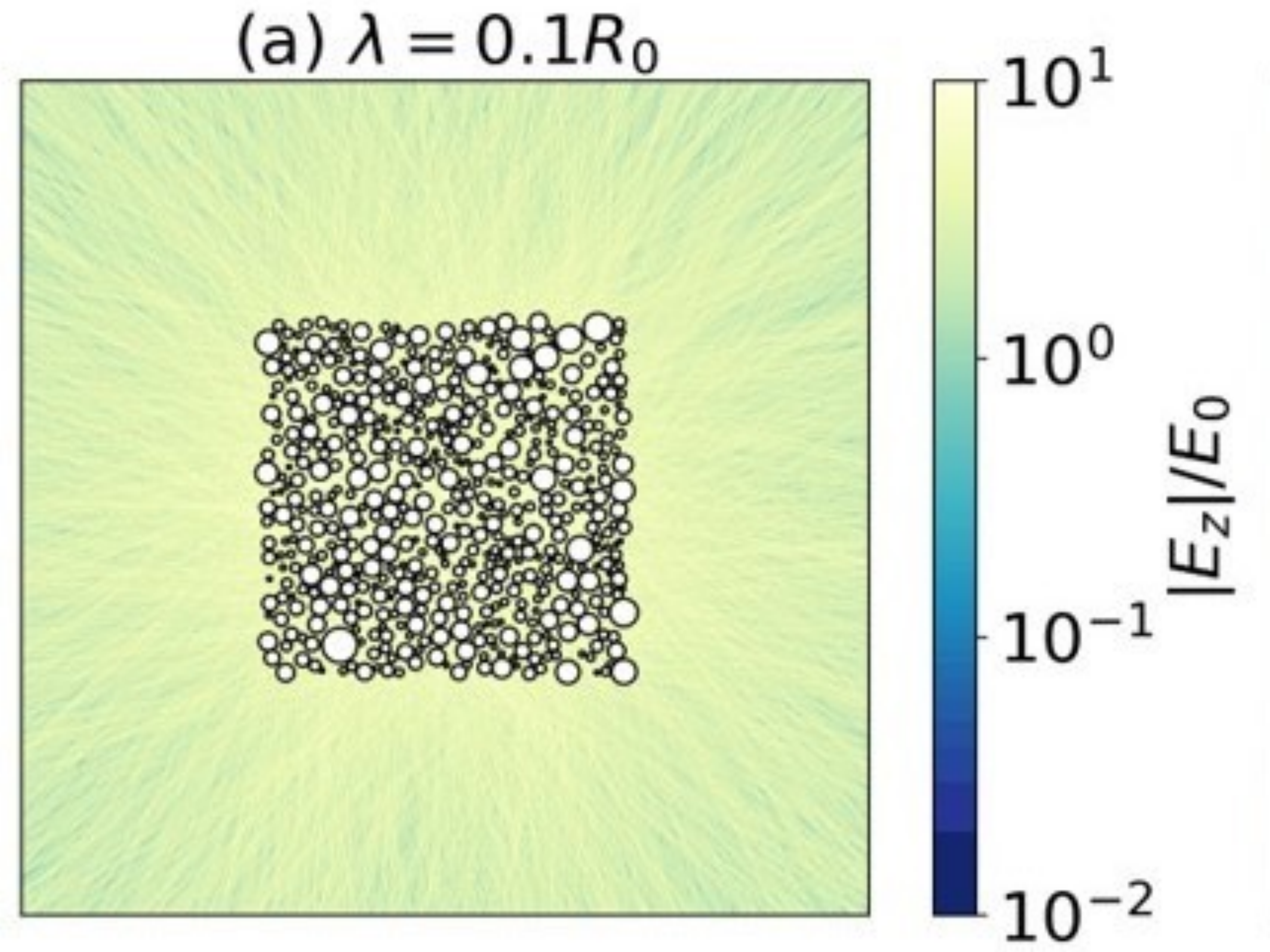
Disordered Dielectrics: 2D

- In higher dimensions, destructive interference becomes less likely: embrace the randomness
- Use a semi-analytical multiple-scattering method in 2D





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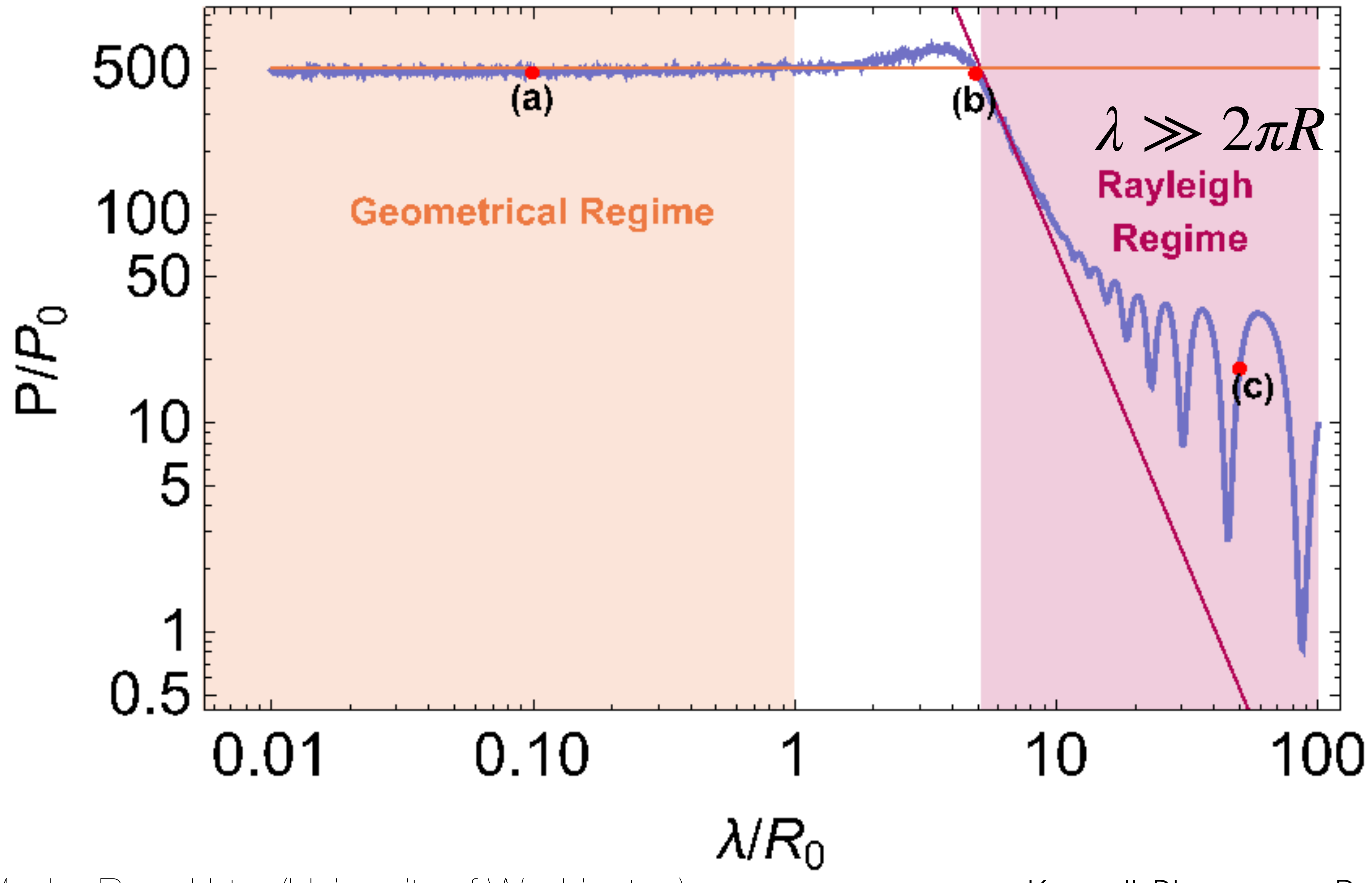

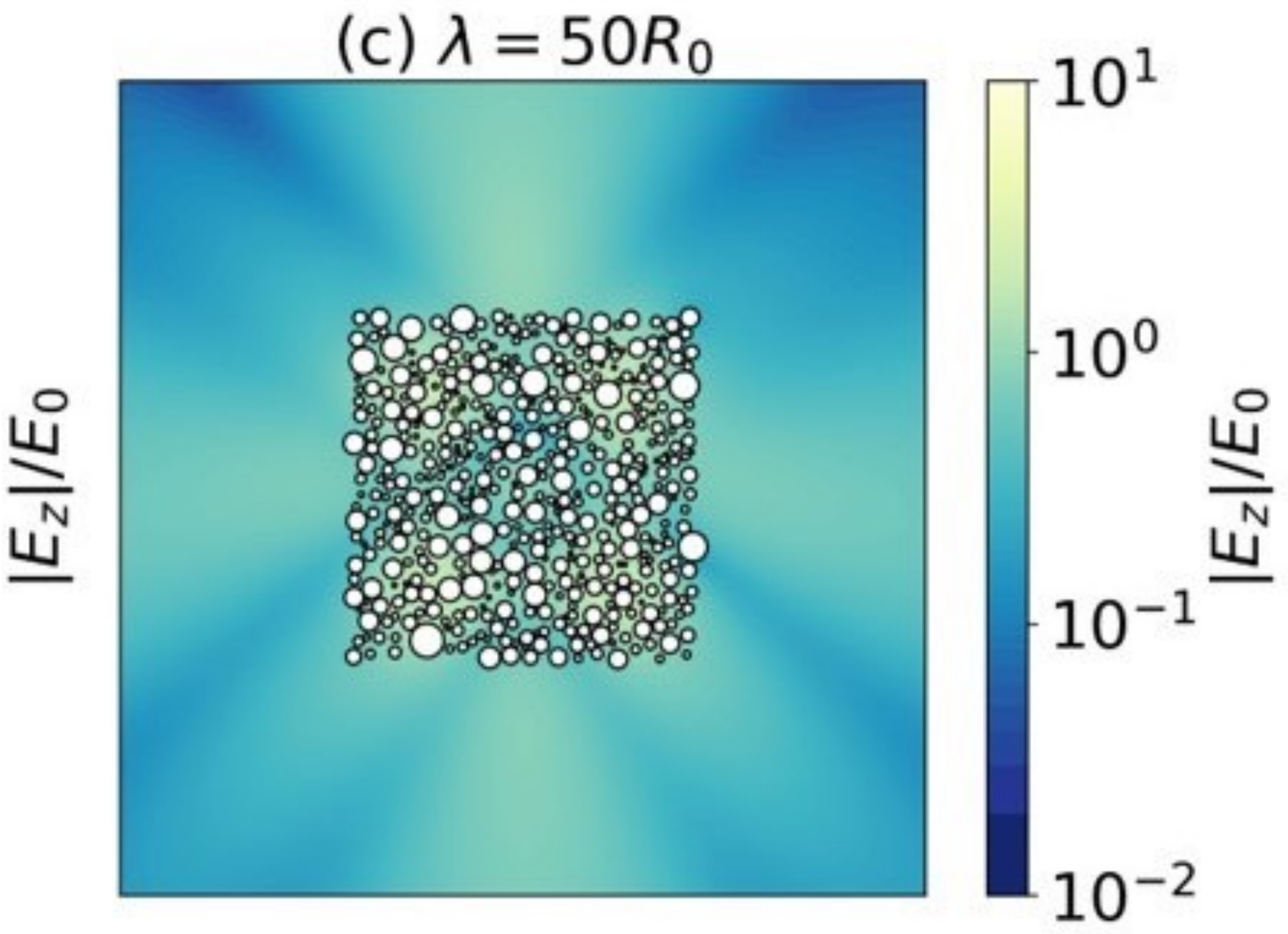

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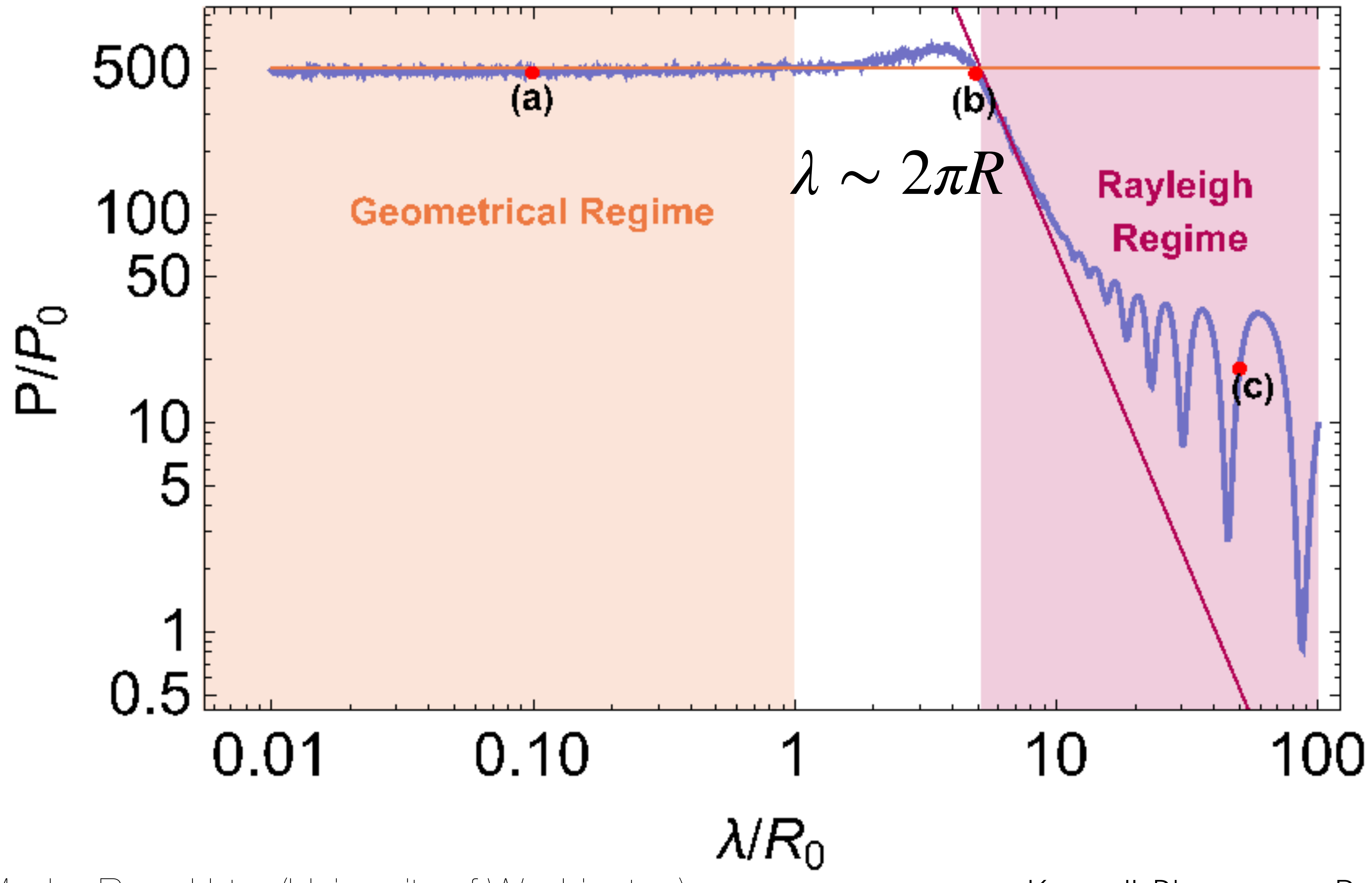

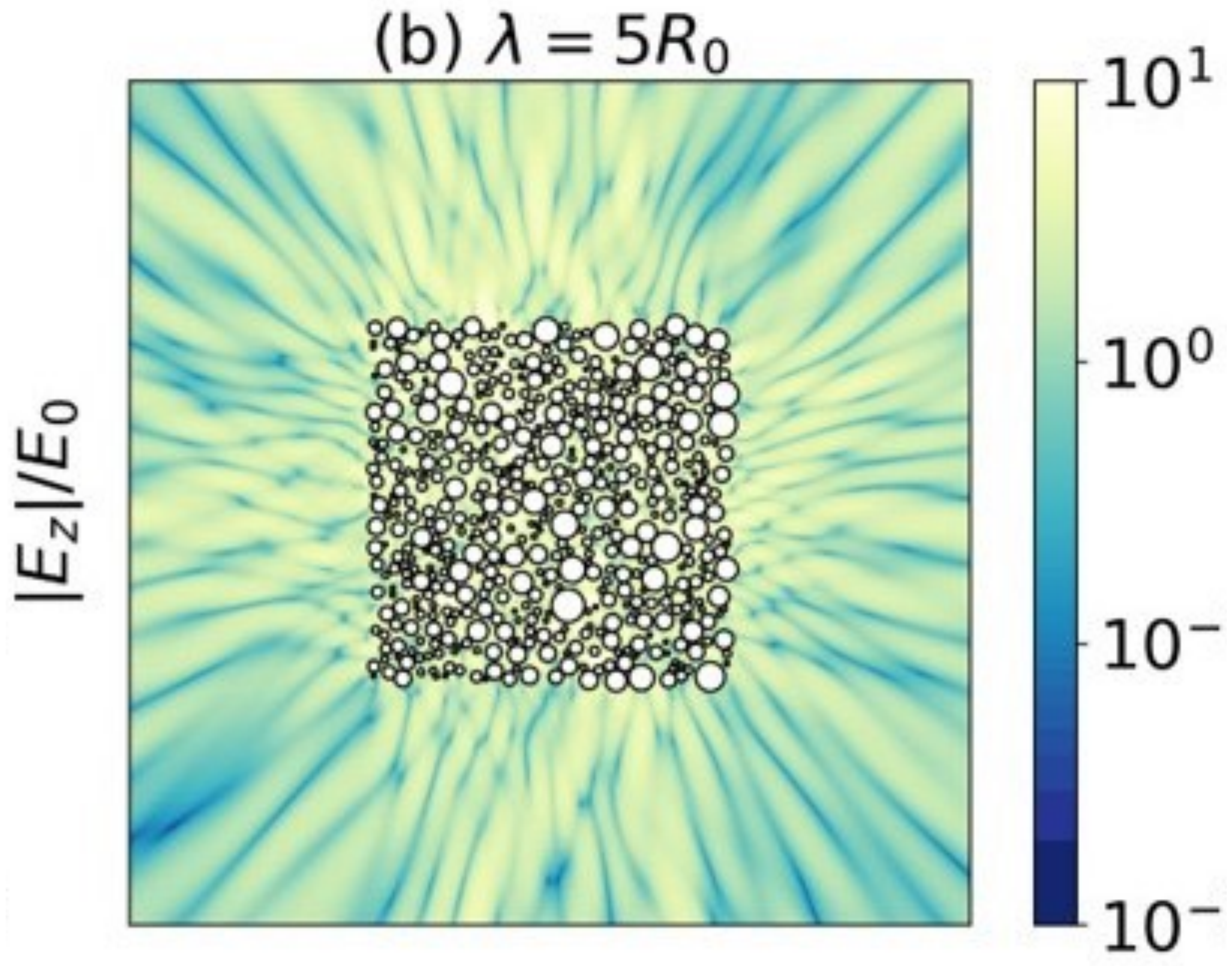

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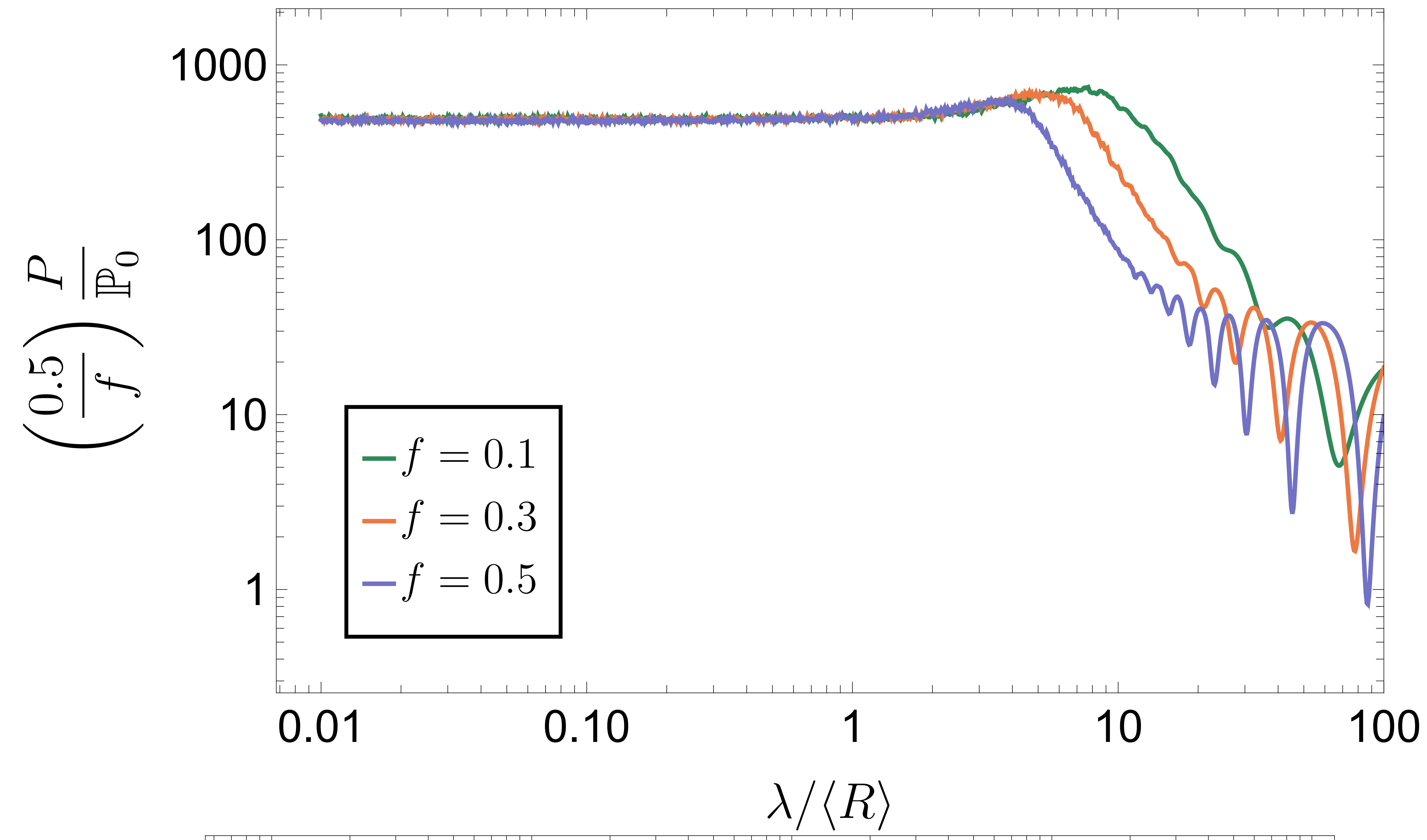

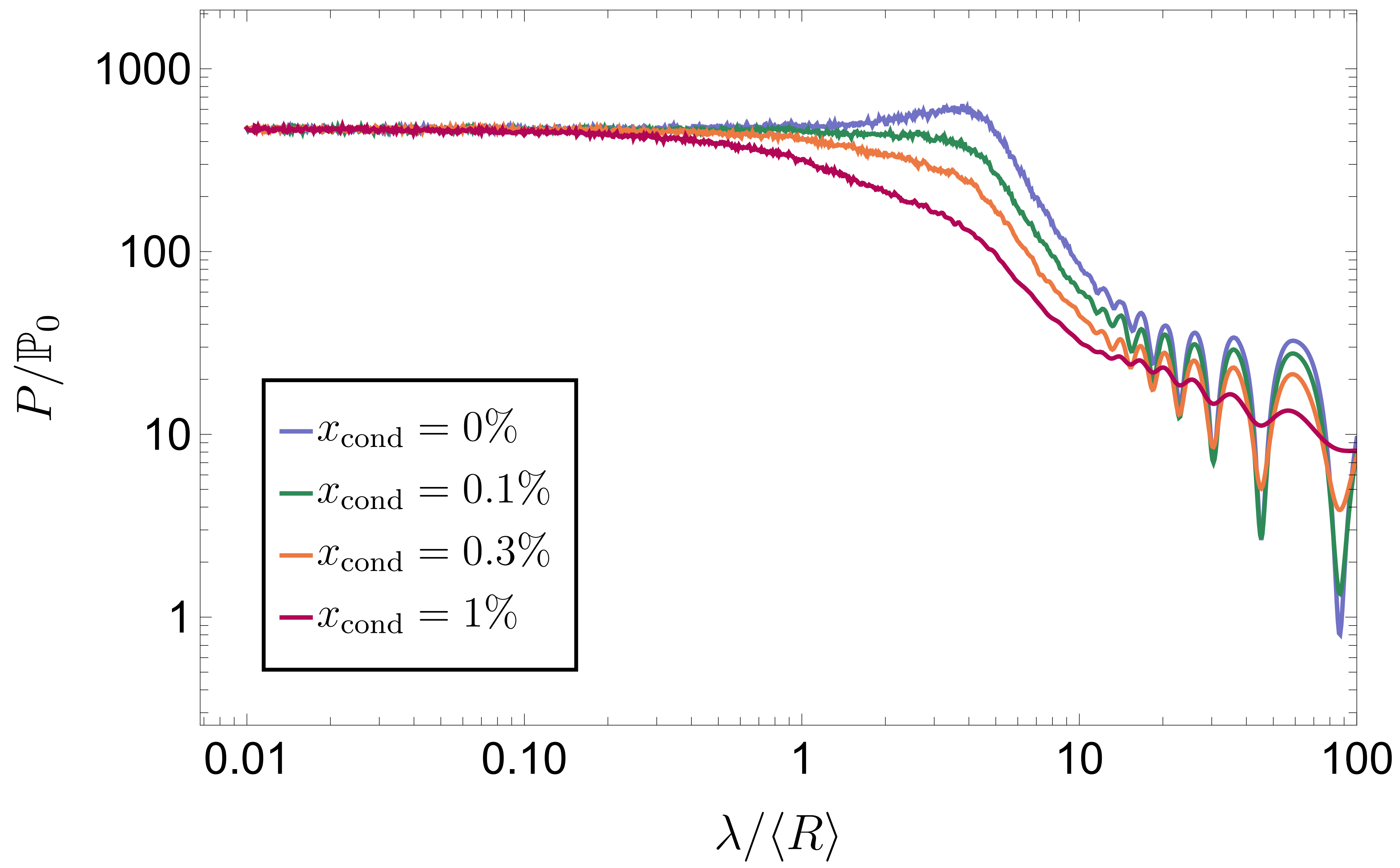

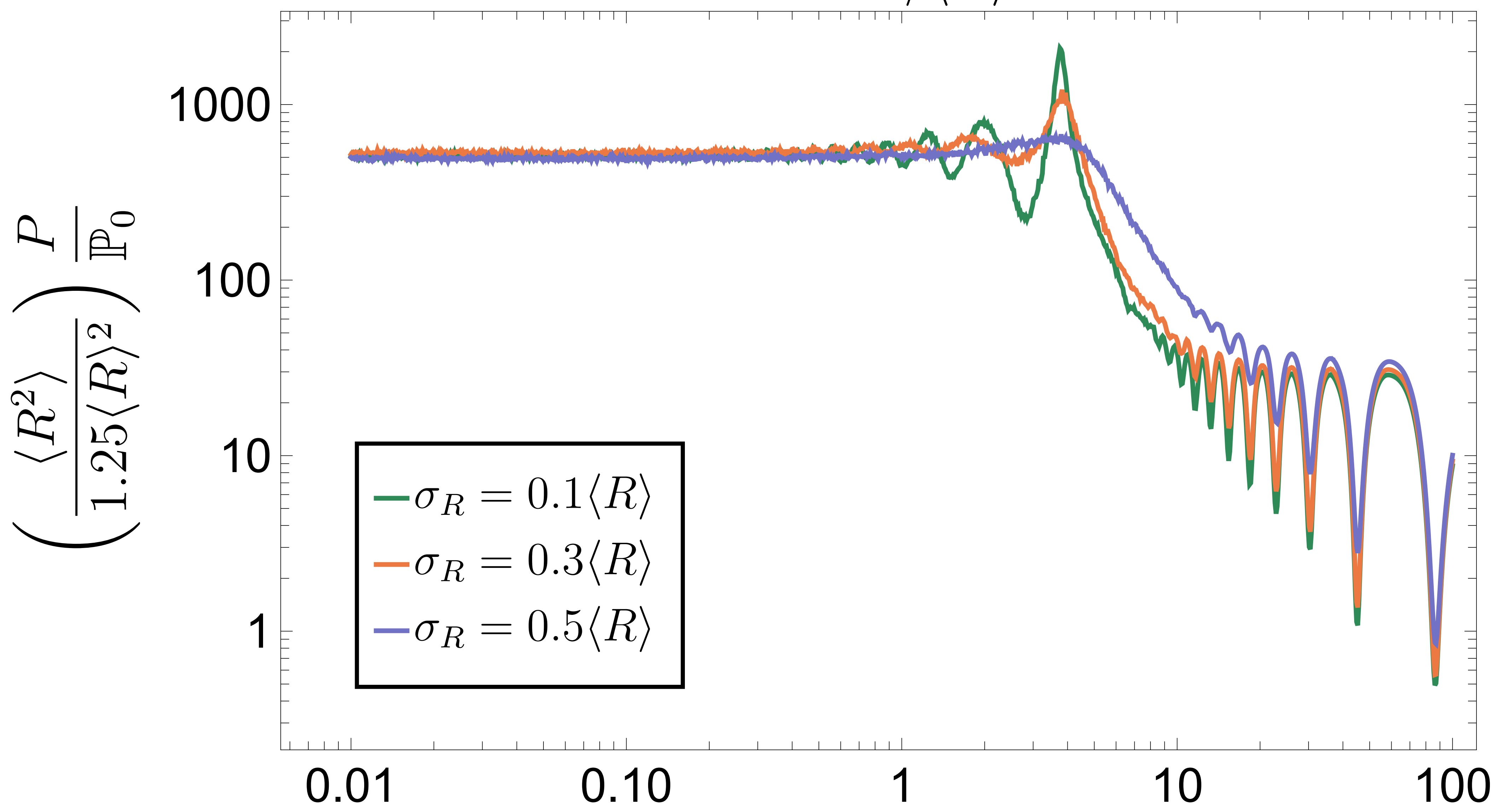

- Need to calibrate filling factor, width of radii distribution, and losses in dielectric material: all properties of photon transport

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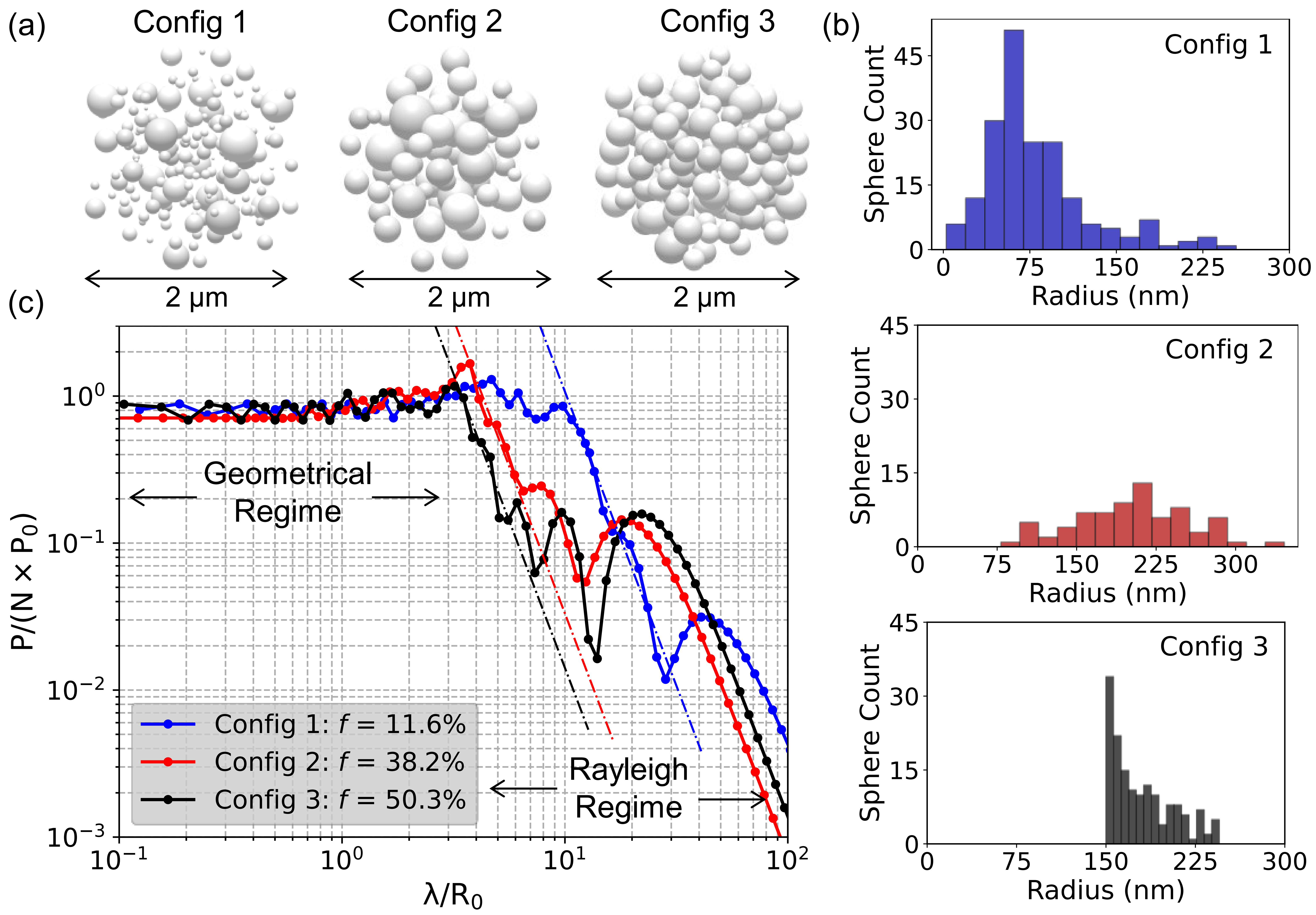
Disordered Dielectrics: 3D



- Same behavior in 3D, as seen in small scale COSMOL simulations

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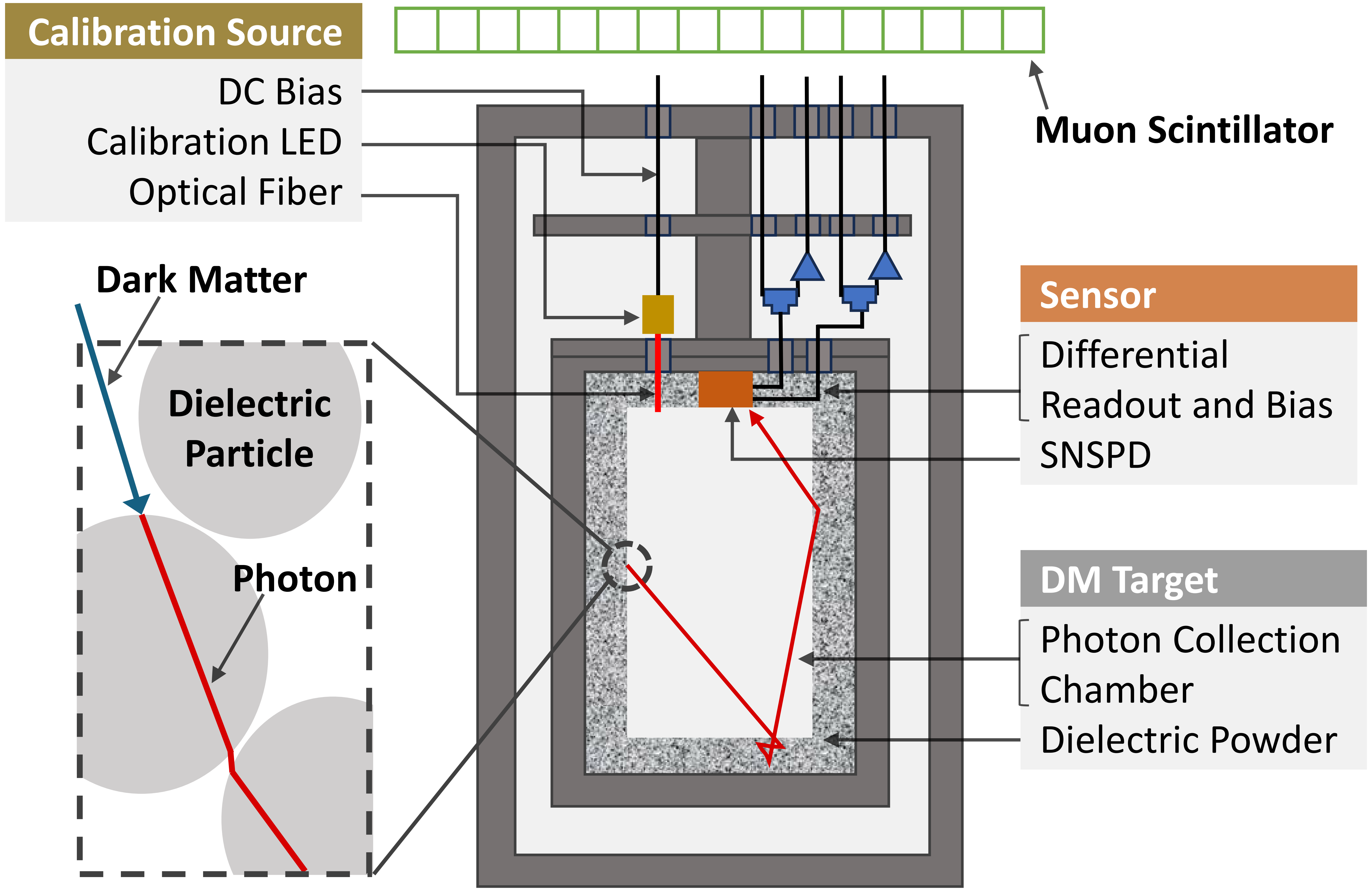
Disordered Dielectrics: DPHaSE

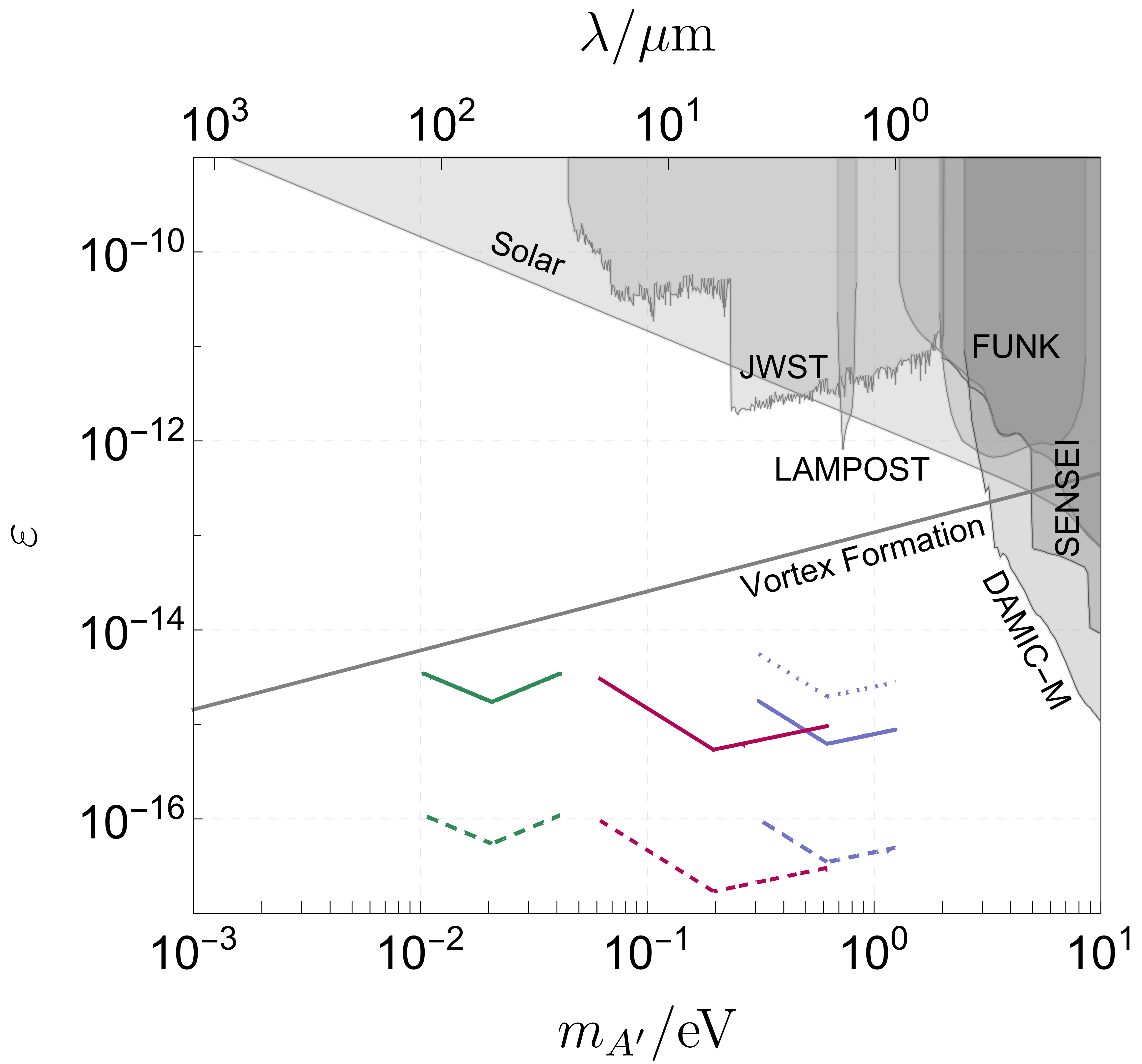
Dielectric Powder HAloscope SNSPD Experiment



- Conversion power in disordered powder is enhanced by large surface area in a compact volume
- Optical energy density near an absorbing boundary (such as a sensor) can be substantially lower.
- Collecting chamber design to avoid such losses

$$V_{\rm eff} \simeq \frac{1}{4} A_{\rm sensor} \bar{\ell}_a$$

Disordered Dielectrics: DPHaSE

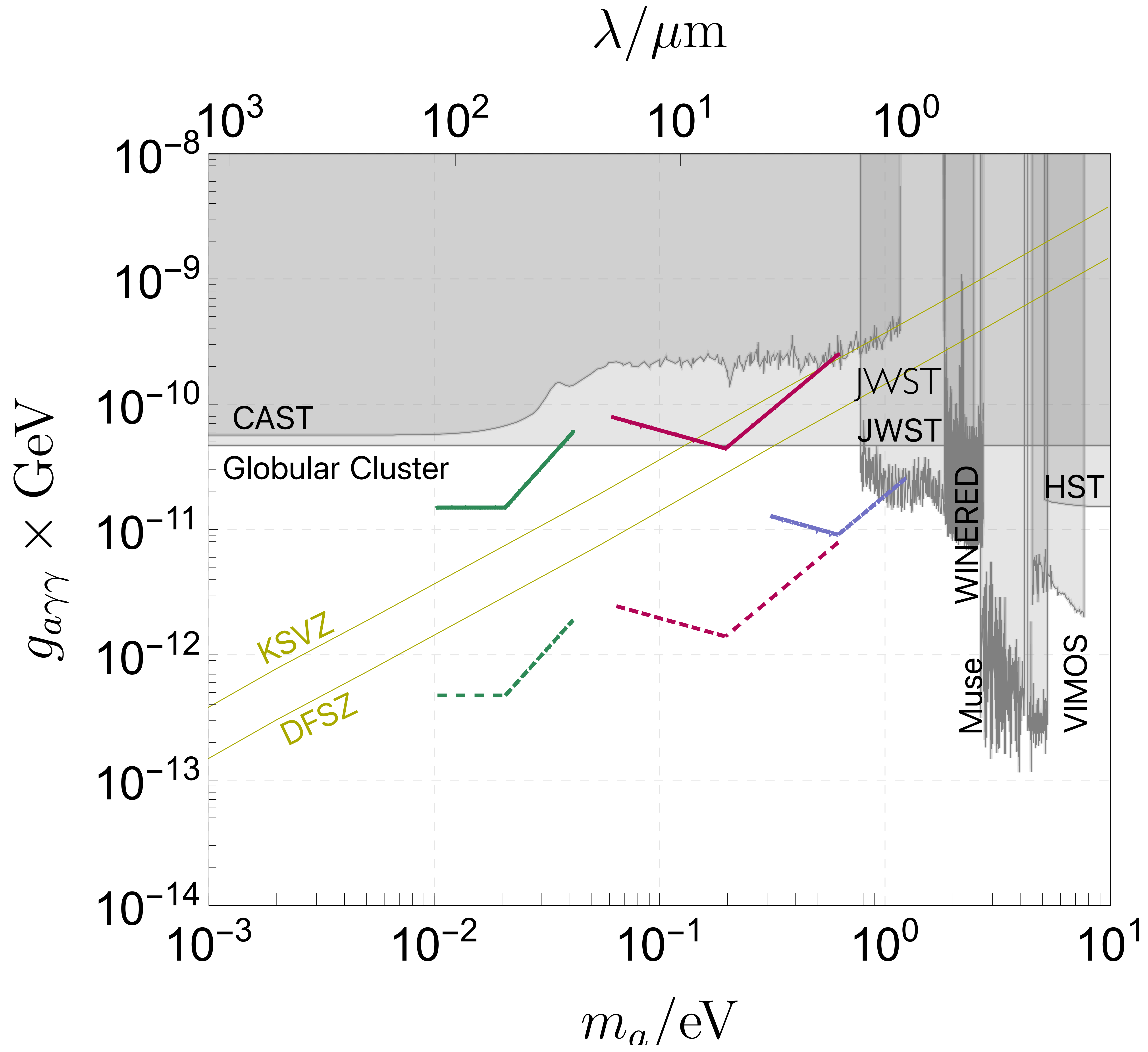


- New dark photon parameter space achievable with current technology

	parameter	Band A	Band B	Band C
	bandwidth	1-4 μm[135]	2-20 μm[136]	30-120 μm [125]
	material	alumina	KBr/NaCl	HR-Si
	n	1.7	1.5	3.4
	ℓ_a	10 m[118]	100 m[136]	1.6-6.3 m [125]
	$\langle R \rangle$	0.82 μm	2.11 μm	20.0 μm
Pathfinder	A_{sensor}	1 mm^2	—	—
	V_{eff}	5 cm^3		
	background rate	10^{-5} Hz		
Phase I	A_{sensor}	1 cm^2	1 cm^2	1 cm^2
	V_{eff}	500 cm^3	5000 cm^3	80-320 cm^3
	background rate	10^{-3} Hz	10^{-2} Hz	10^{-2} Hz
Phase II	A_{sensor}	10 cm^2	10 cm^2	10 cm^2
	V_{eff}	5000 cm^3	50 000 cm^3	800-3200 cm^3
	background rate	10^{-6} Hz	10^{-6} Hz	10^{-6} Hz
	sensor efficiency	85%	50%	50%

- Pathfinder type experiment in progress with Rybka and Berggren, funded by Quantized 2.0

Disordered Dielectrics: DPHaSE



- "Salt shaker" achieves promising potential reach!

Koppell, Bittencourt, Paul, Huang, **MB**, Berggren, 2506.00115

Powder Haloscope Broadband Detection

- Much of the parameter space remains untested volume-filling dielectric materials have been demonstrated in a range of setups to enhance the signal strength
- Broadband sensitivity to dark photon and axion DM can be achieved with a disordered dielectric medium consisting of dielectric powder with a wide distribution of powder radii
- Interesting geometries to explore, random dielectrics can give robust sensitivity for a broad search, require R&D for dielectric characterization

THANK YOU!

Backup

	parameter	Band A	Band B	Band C
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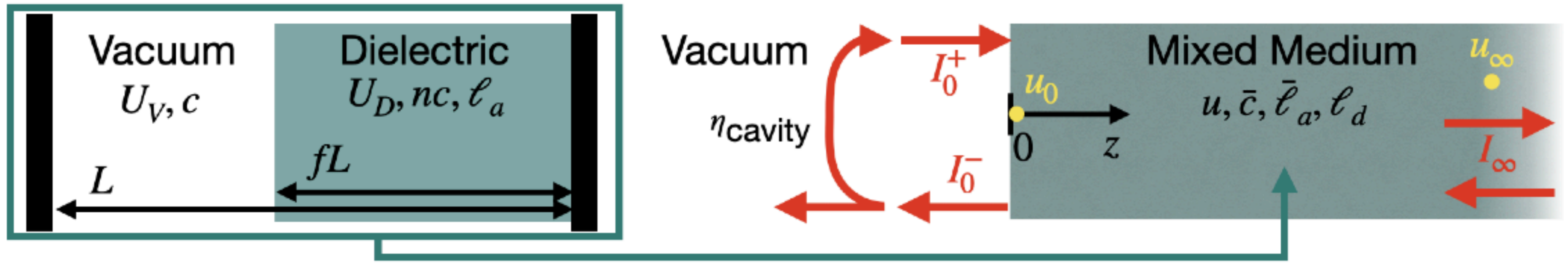
	sensor efficiency	85%	50%	50%

$$g_{a\gamma\gamma} = 4\times 10^{-11}\,\mathrm{GeV}^{-1}\left(\frac{m_a}{0.2\ \mathrm{eV}}\right) \times \left(\frac{\eta}{0.5}\right)^{-1/2}\left(\frac{\ell_a}{10^4\ \mathrm{cm}}\right)^{-1/2}\left(\frac{A_{\rm sensor}}{\mathrm{cm}^2}\right)^{-1/2}\left(\frac{\Gamma_{\rm bg}}{10^{-2}\ \mathrm{Hz}}\right)^{1/4}\left(\frac{T_{\rm exp}}{18\ \mathrm{months}}\right)^{-1/4}\left(\frac{B_{\rm ext}}{10\ \mathrm{T}}\right)^{-1},$$

$$\varepsilon = 5\times 10^{-16}\left(\frac{\eta}{0.5}\right)^{-1/2}\left(\frac{\ell_a}{10^4\ \mathrm{cm}}\right)^{-1/2}\left(\frac{A_{\rm sensor}}{\mathrm{cm}^2}\right)^{-1/2}\left(\frac{\Gamma_{\rm bg}}{10^{-2}\ \mathrm{Hz}}\right)^{1/4}\left(\frac{T_{\rm exp}}{18\ \mathrm{months}}\right)^{-1/4}.$$

Photon collection chamber



$$V_{\text{eff}} = \frac{1}{4} A_{\text{sensor}} \eta_{\text{cavity}} \frac{u_0}{u_\infty} \bar{\ell}_a.$$

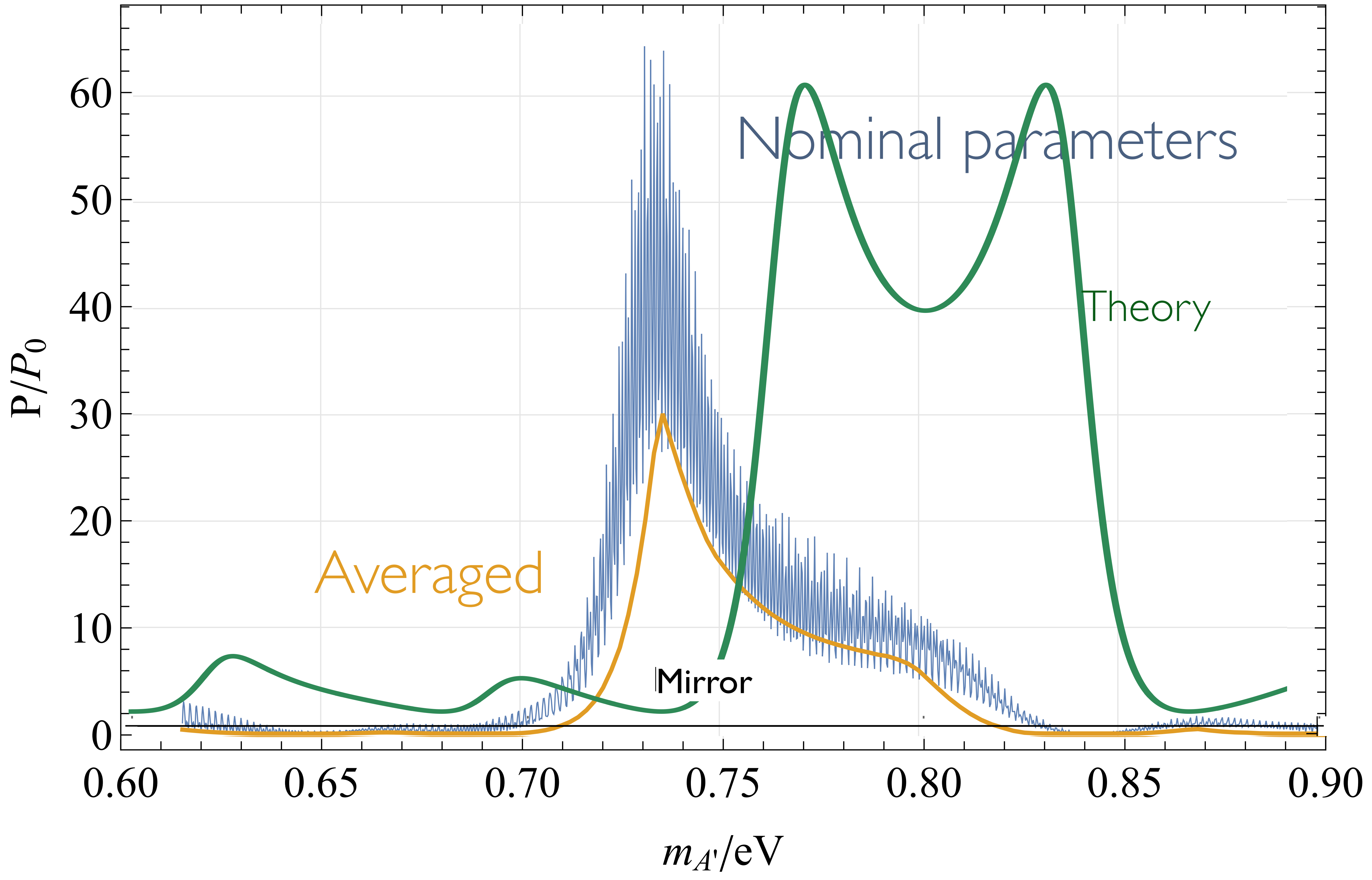
$$\frac{u_0}{u_\infty} \approx \frac{(1 - \mathbb{R}_\infty)}{(1 - \mathbb{R}_\infty) + (1 - \eta_{\text{cavity}})}$$

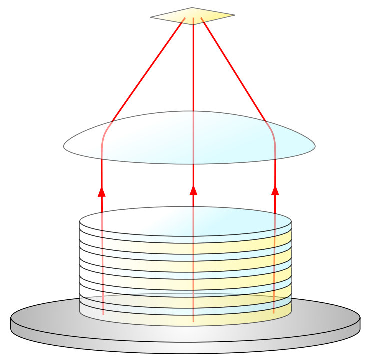
$$A_{\text{cavity}} \gg A_{\text{sensor}} (1 - \mathbb{R}_{\text{sensor}}) \frac{\bar{\ell}_a}{4\ell_d},$$

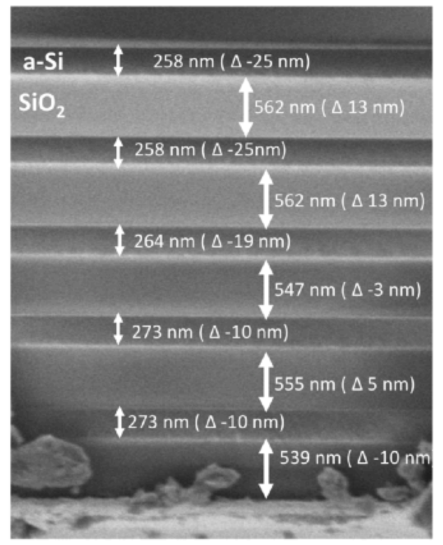
$$V_{\text{eff}} \simeq \frac{1}{4} A_{\text{sensor}} \bar{\ell}_a$$

Disordered Dielectrics: LAMPOST

Substrate, film, lens measurement uncertainty leads to etalon and decreased power within measurement error



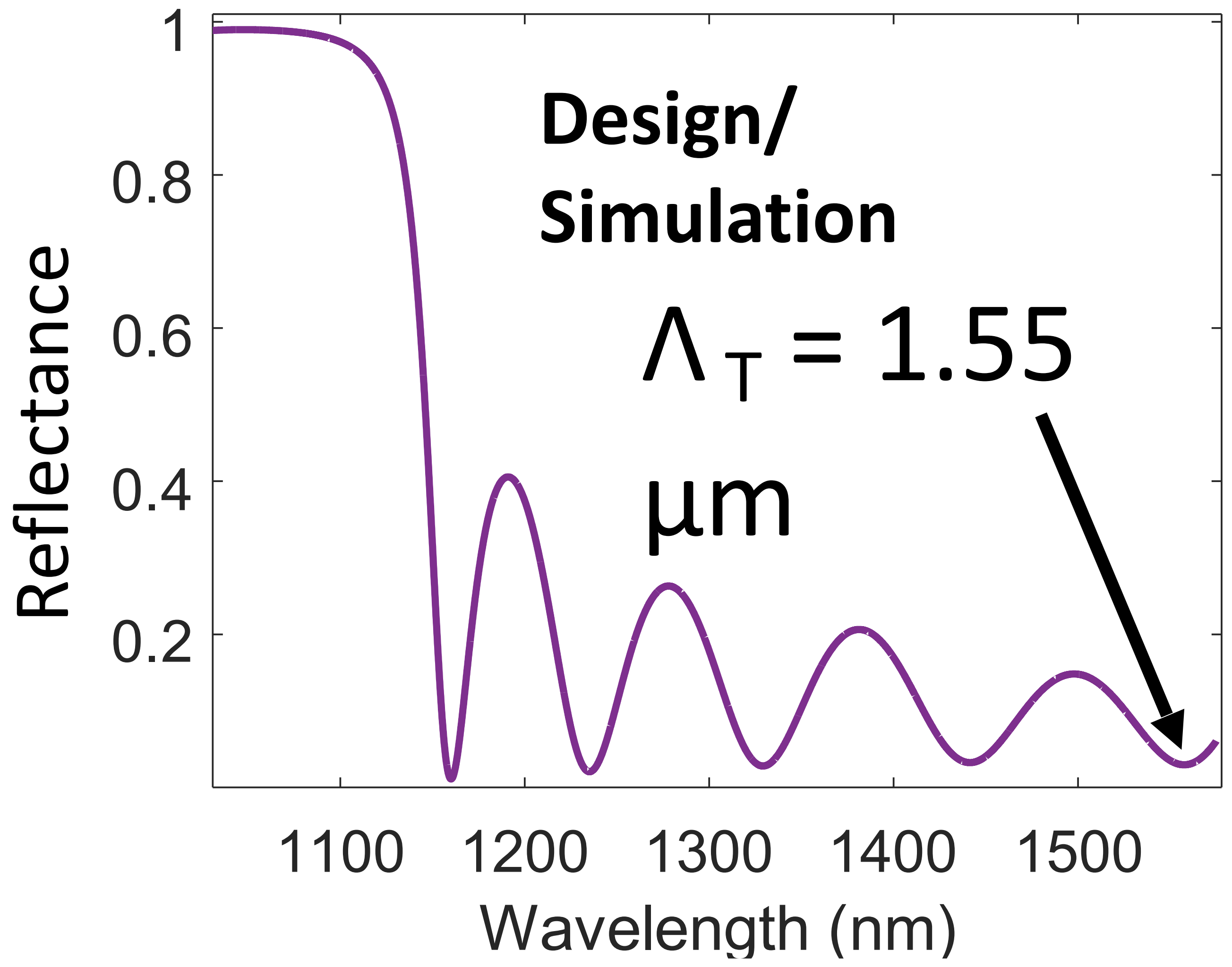


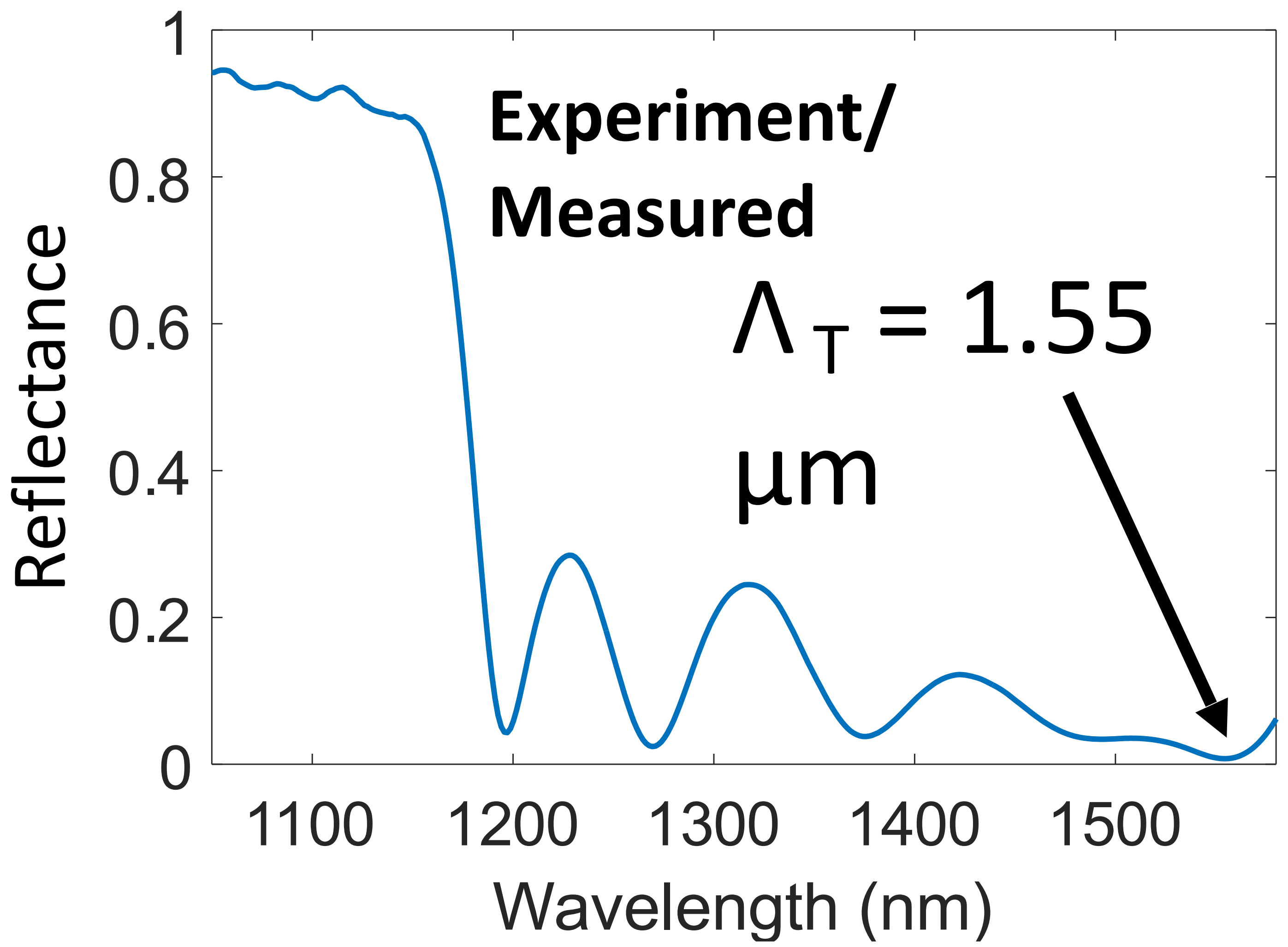


Chiles, Charaev, Lasenby, **MB**, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren PRL 2022

Multilayer target characterization

- White light interferometry
  - Fifth reflectance null after photonic bandgap indicates emission wavelength Λ_T

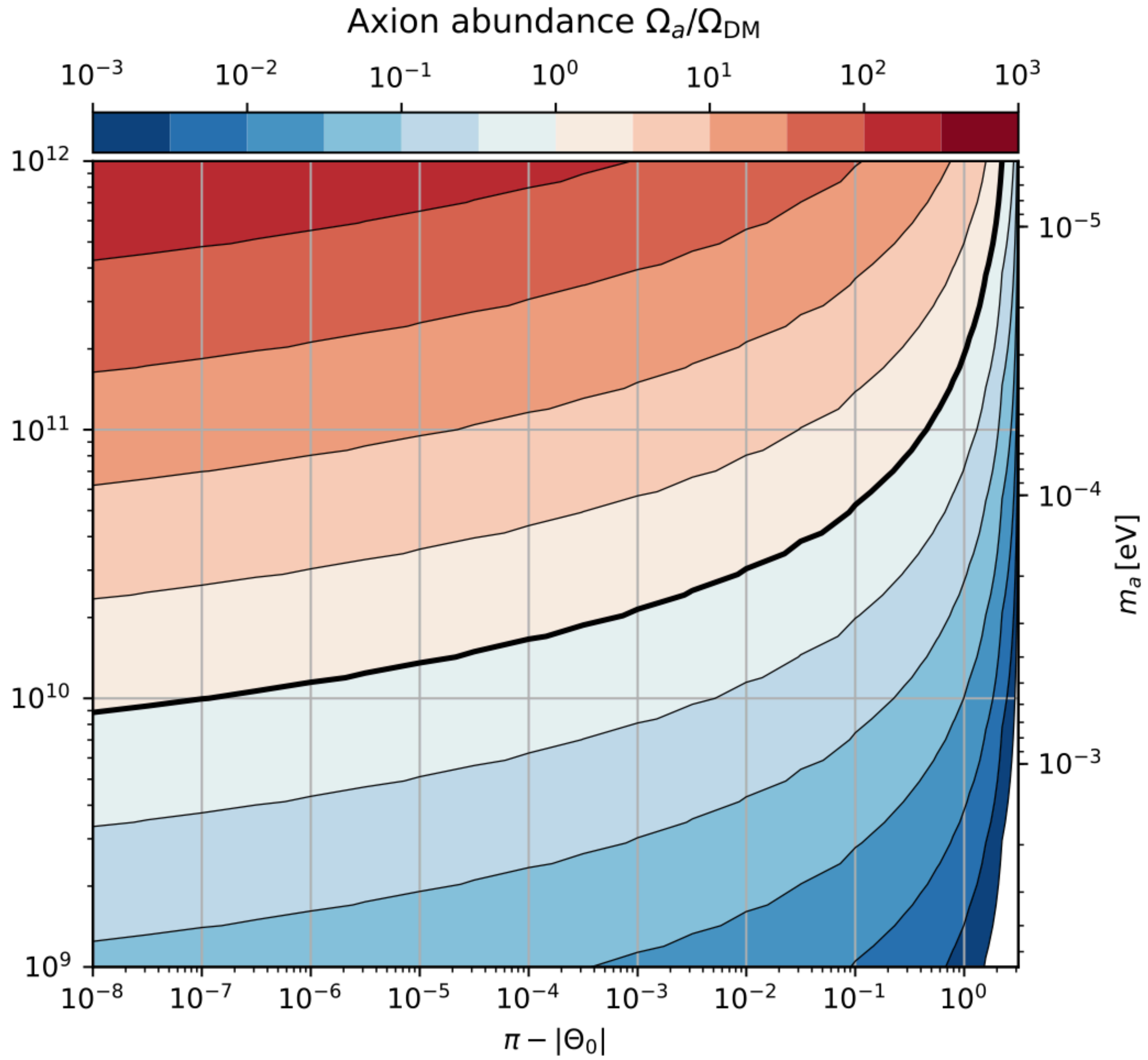




About 1 dB power loss in optical transmission through the target

Single Particle
Ensemble
$\sigma_s / \pi a^2$
2
2π
λ/a
σ_s
σ_a
$\min(\sigma_R, \sigma_D)$
$\langle\sigma_s\rangle$
$\langle\sigma_a\rangle$
$\langle\min(\sigma_R, \sigma_D)\rangle$

Heavier Axions from Misalignment



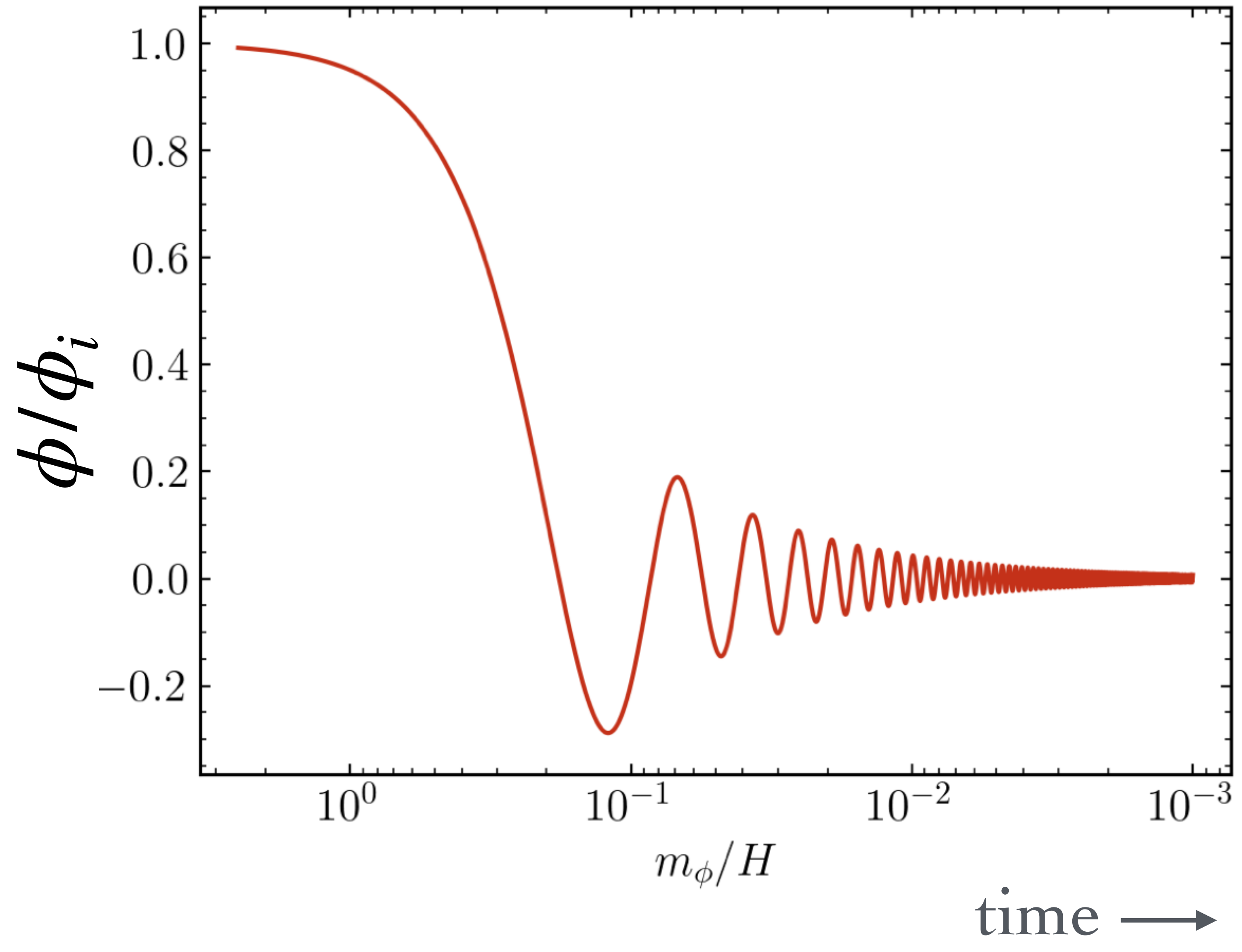
The Large-Misalignment Mechanism

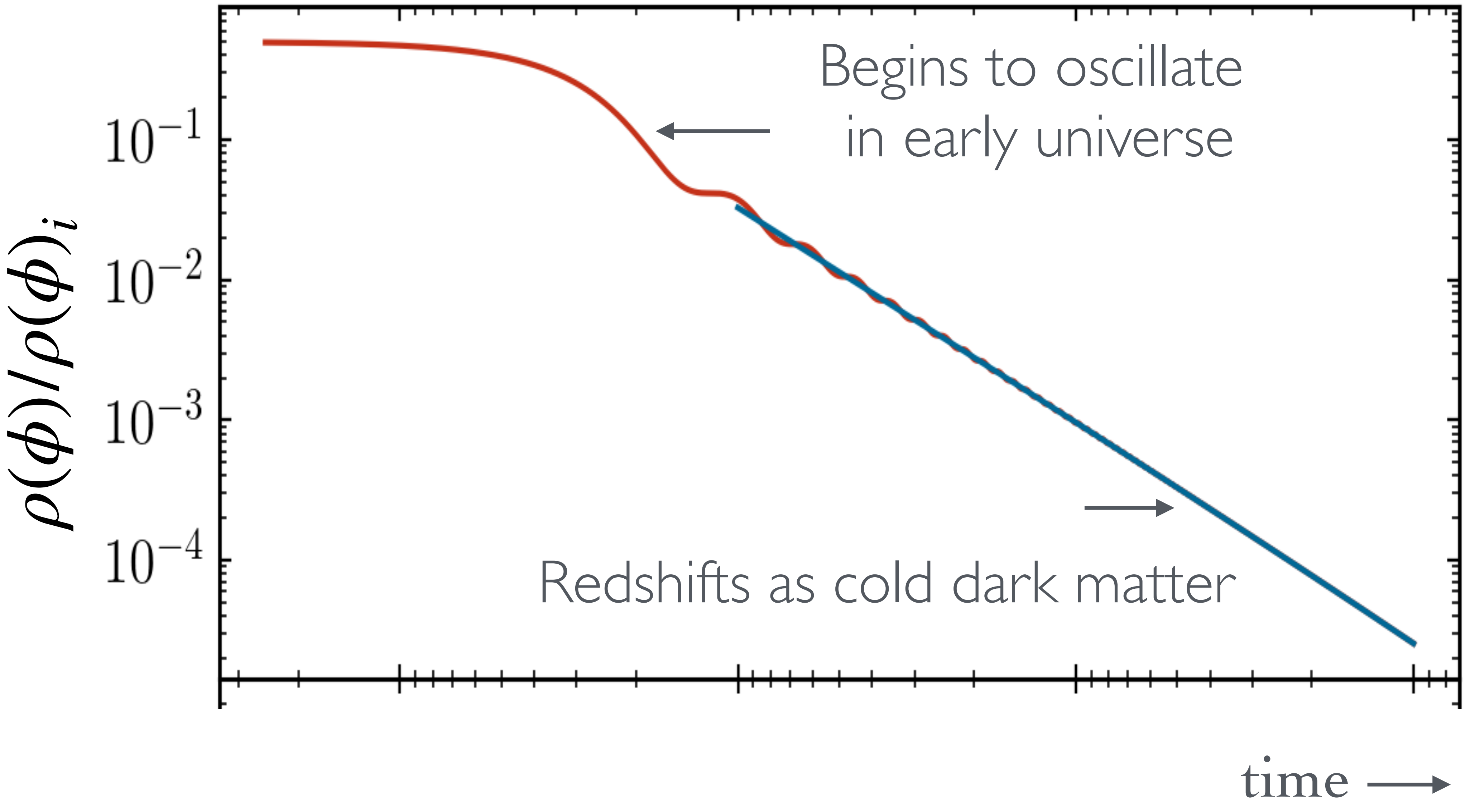
Asimina Arvanitaki, Savas Dimopoulos, Marios Galanis, Luis Lehner, Jedidiah O. Thompson, Ken Van Tilburg

Cosmological Production: Harmonic Oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

Predict DM density as a function of *mass, initial amplitude*

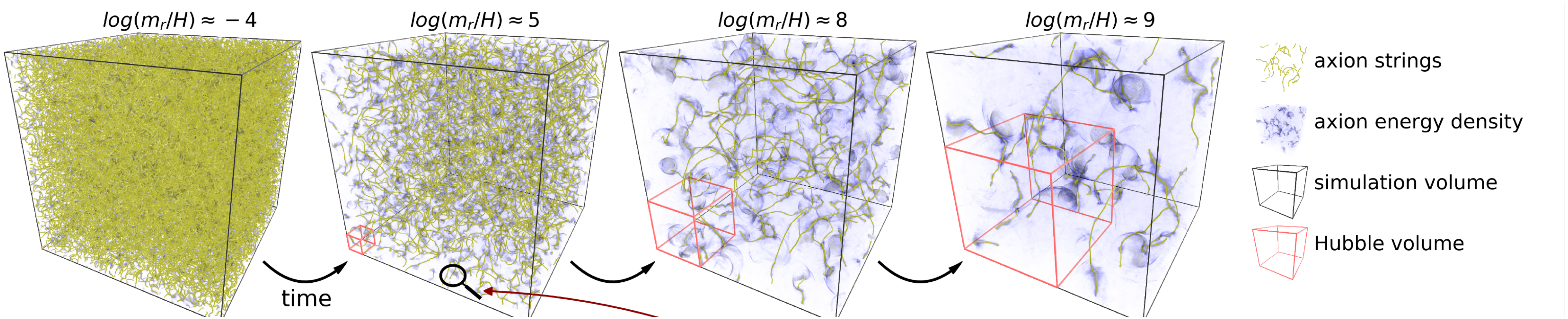




All light axions present during inflation will have *some* relic abundance today

Cosmological Production: `Heavier' Axions

If PQ axion symmetry is restored in the early universe axion strings and domain walls produce additional axions



Buschmann et al Nat Comm 2021