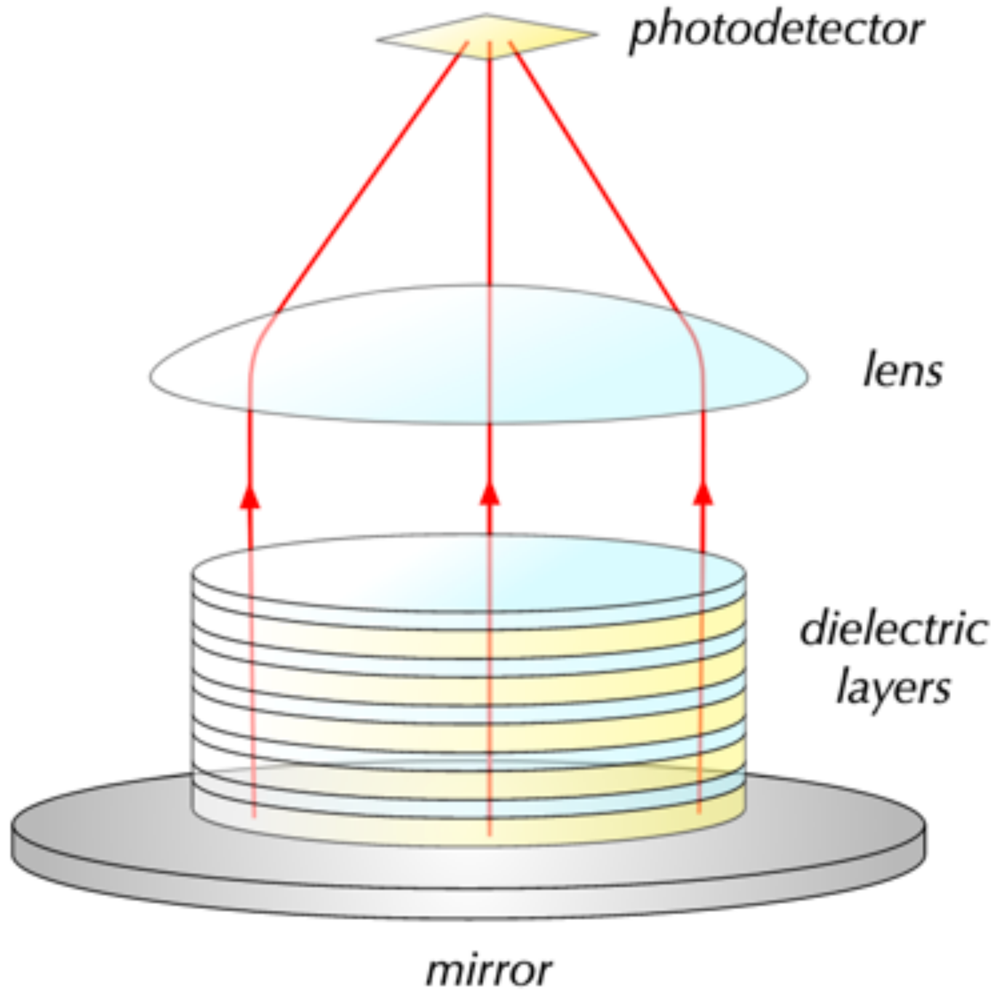
Extending the Reach of Dielectric Haloscopes

Stewart A. Koppell, Dip Joti Paul, Marco Colangelo, Karl K. Berggren
Research Lab of Electronics, Massachusetts Institute of Technology, Cambridge MA

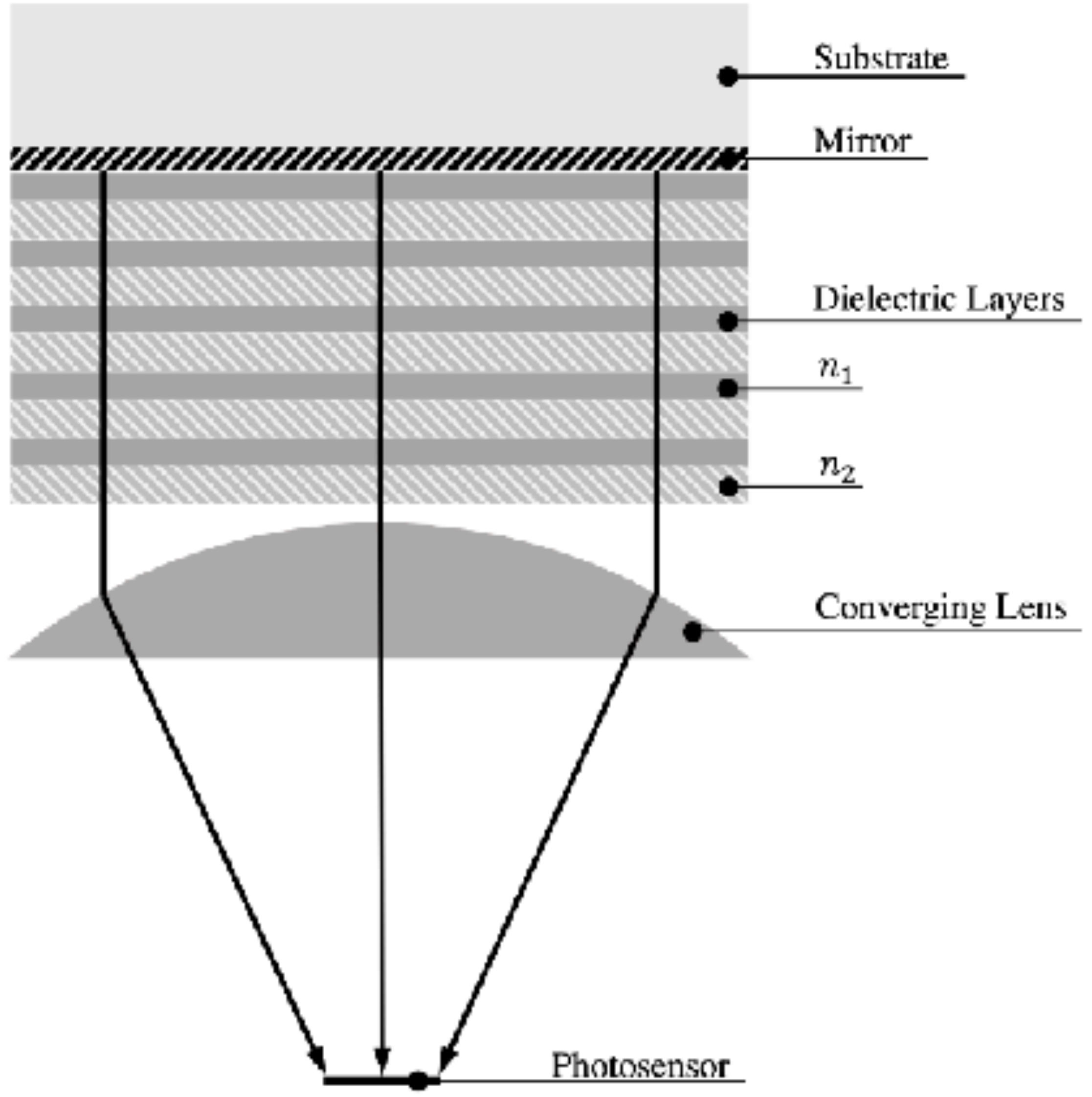
Dielectric Haloscopes

$50 meV - 10 eV$

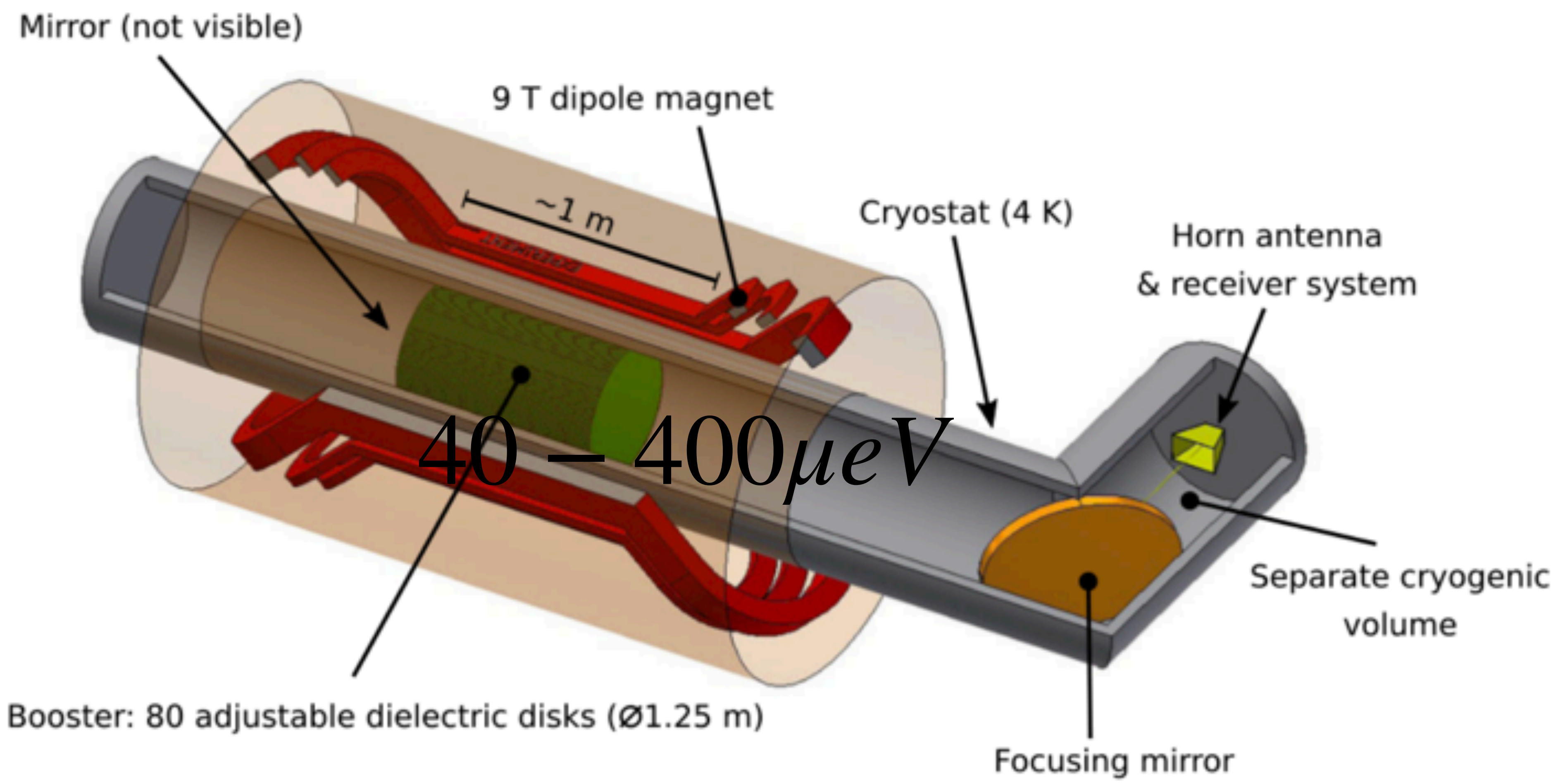
LAMPOST



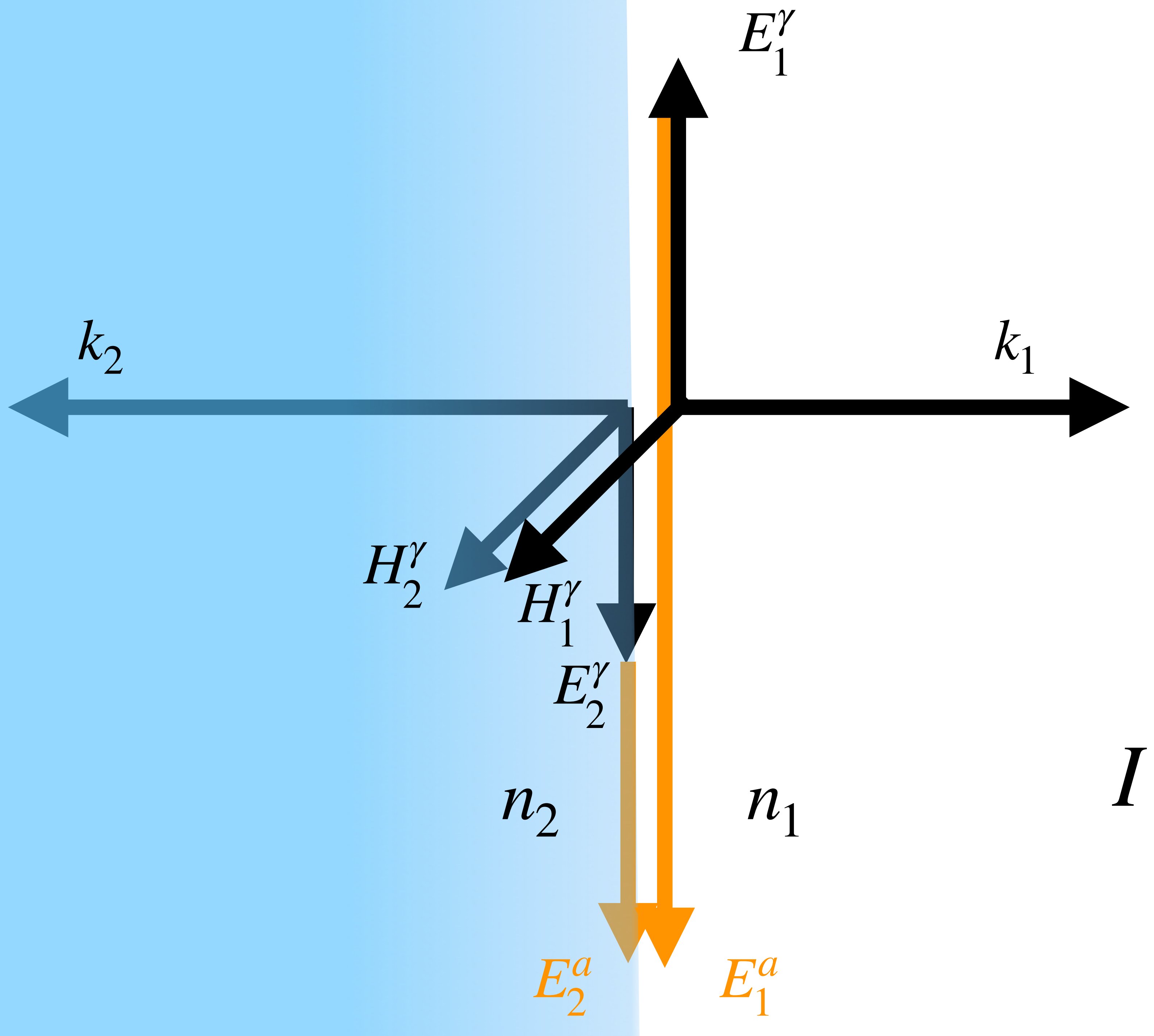
MuDhi



$40 - 400 \mu eV$



Detecting Dark Photons and Axions with Dielectric Structures



Dark Photon	Axion

$$|E_0| = k\rho_{DM}^{1/2} = g_{a\gamma} B_e a_0$$

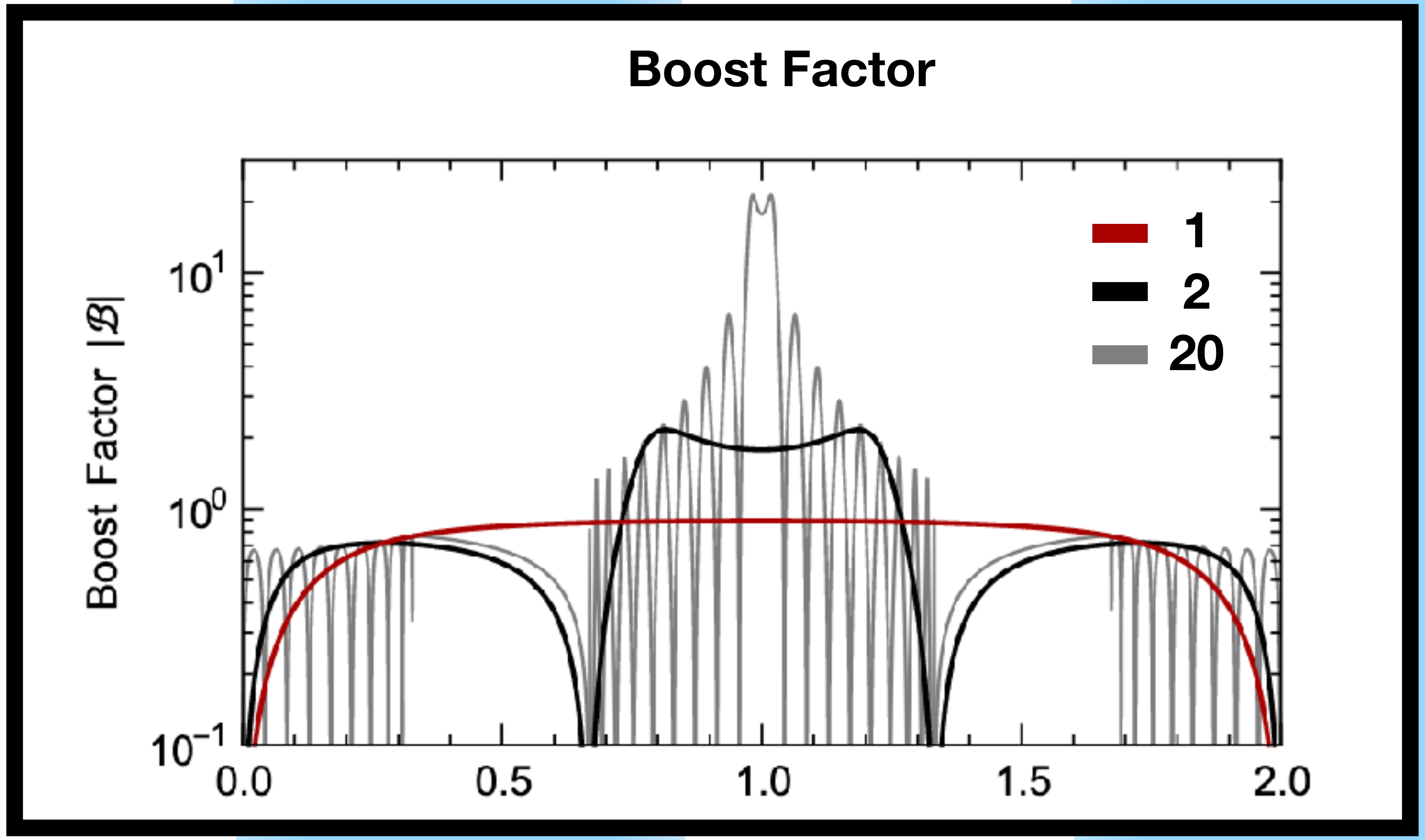
$$I = |S_1 + S_2| = \frac{E_0^2}{2}\left(\frac{1}{n_1} - \frac{1}{n_2}\right)^2 \left(\frac{1}{n_1} + \frac{1}{n_2}\right)$$

$$\leq \frac{E_0^2}{2}$$

Dielectric Haloscopes to Search for Axion Dark Matter: Theoretical Foundations

Alexander J. Millar,[a] Georg G. Raffelt,[a] Javier Redondo,[a,b] Frank D. Steffen[a]

Boost Factor From Periodic Structures



Dielectric Haloscopes to Search for Axion Dark Matter: Theoretical Foundations

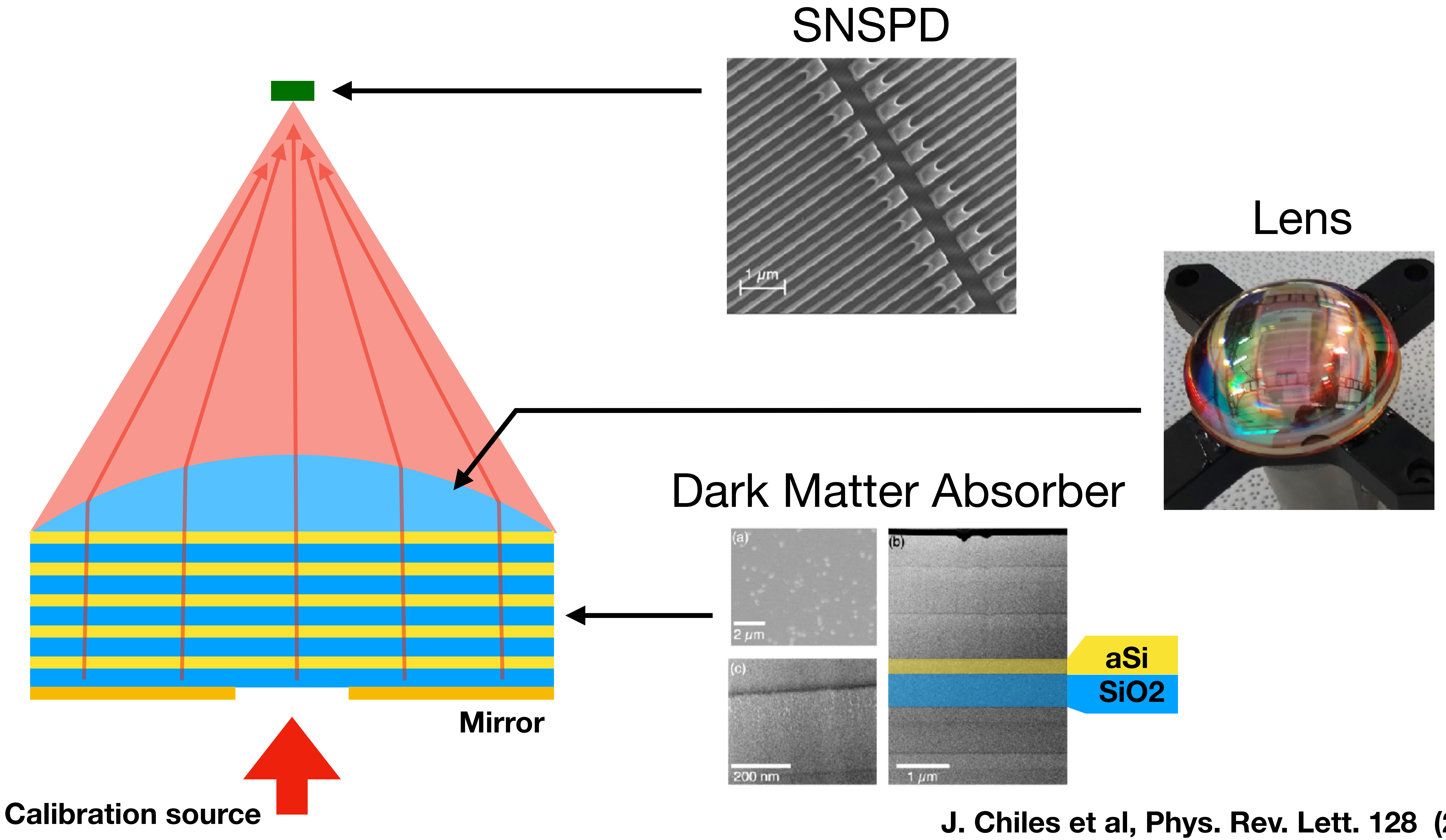
Alexander J. Millar,[a] Georg G. Raffelt,[a] Javier Redondo,[a,b] Frank D. Steffen[a]

LAMPOST

Light A’ Multi-layer Periodic Optical SNSPD Target

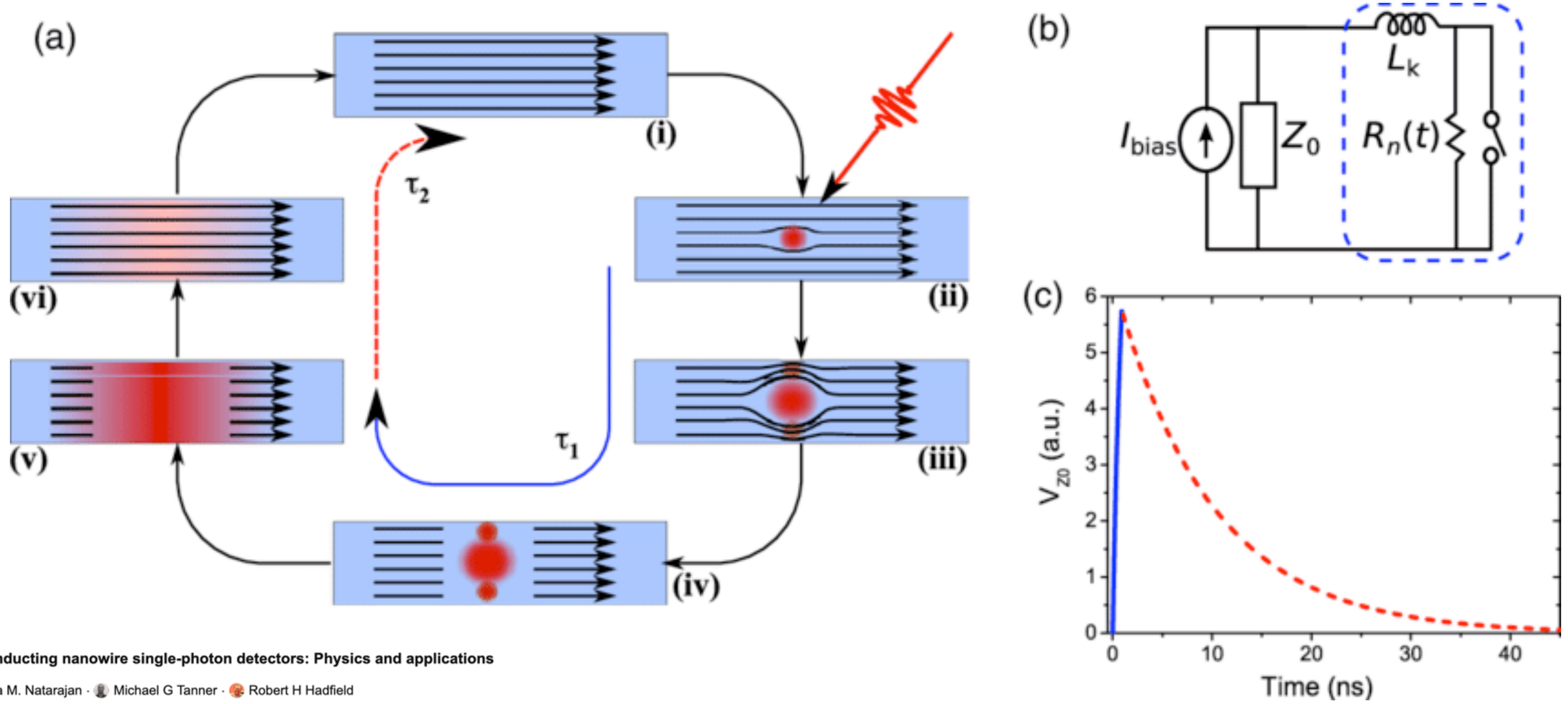
Ilya Charaev

Jeffrey Chiles



J. Chiles et al, Phys. Rev. Lett. 128 (2022)

Superconducting Nanowire Single Photon Detectors



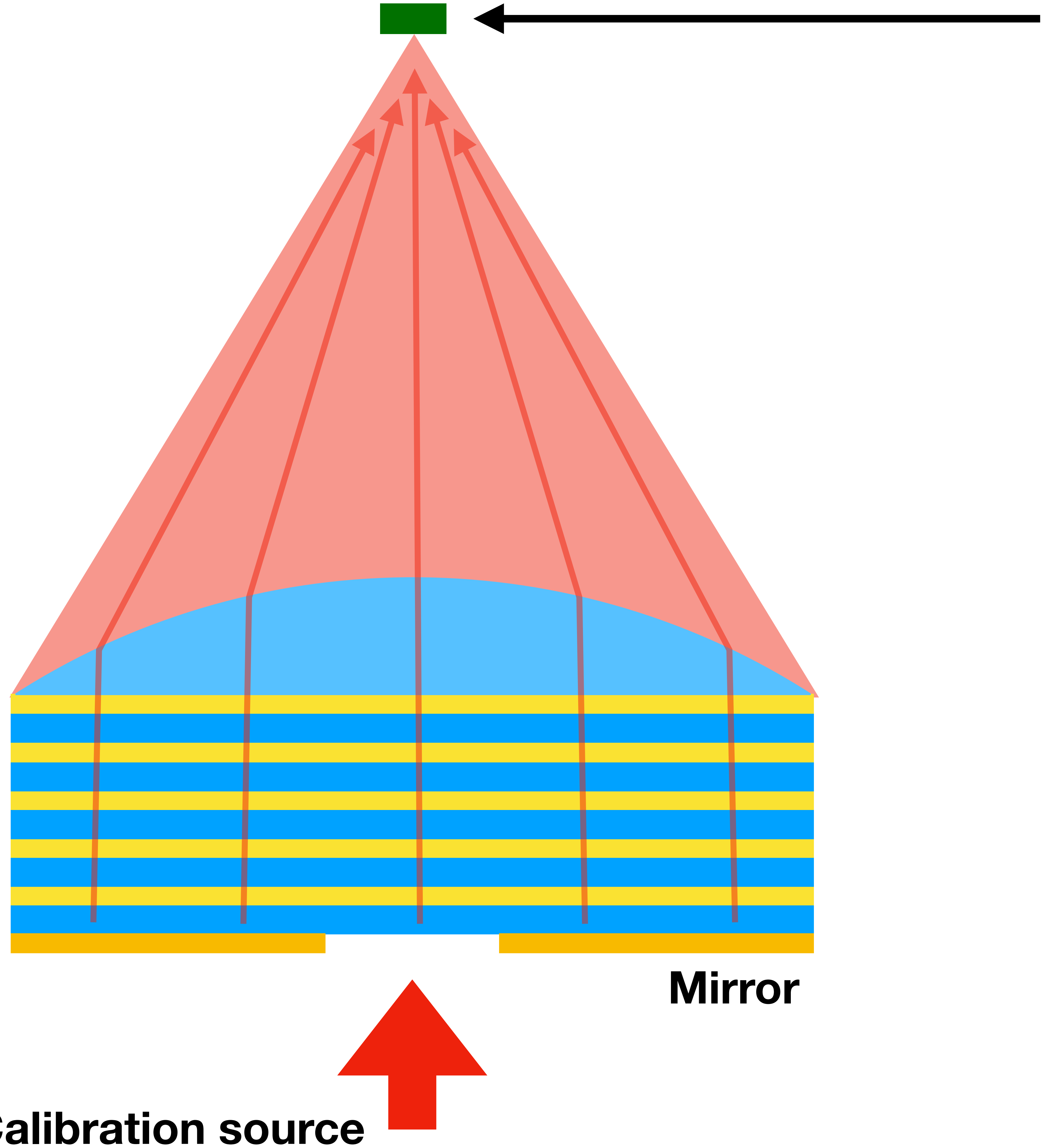
Superconducting nanowire single-photon detectors: Physics and applications

Chandra M. Natarajan · Michael G Tanner · Robert H Hadfield

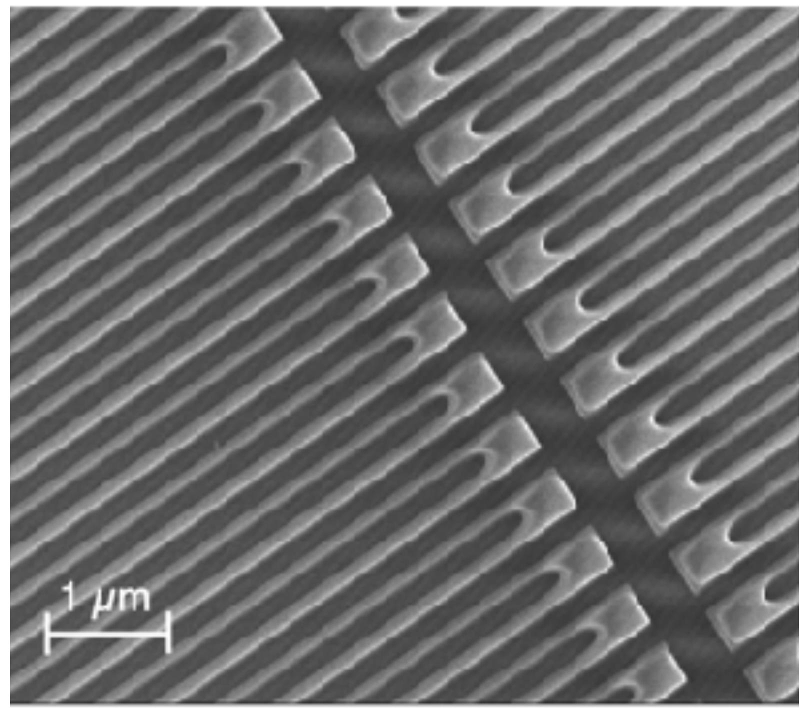
LAMPOST

Ilya Charaev

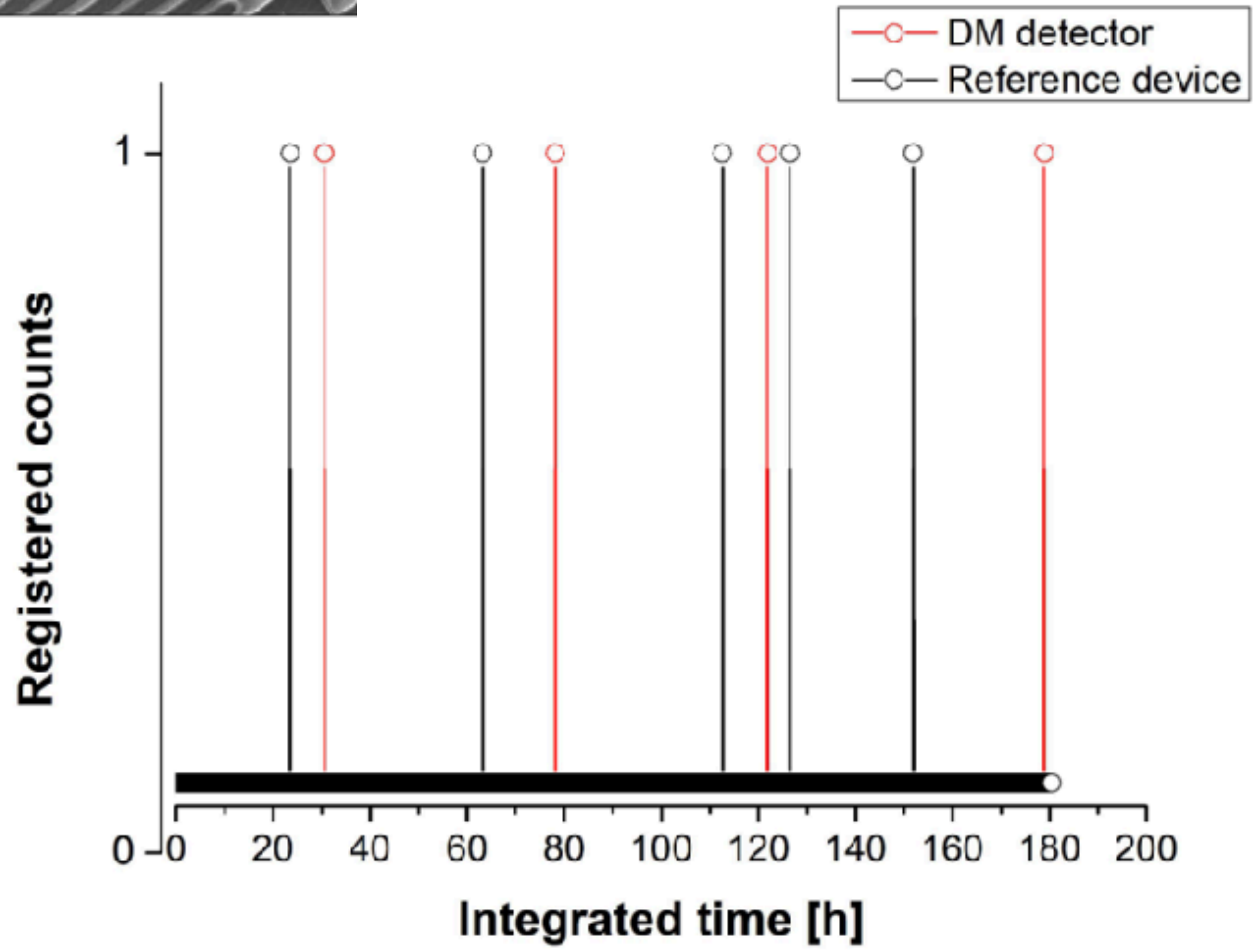
Jeffrey Chiles



SNSPD



DCR<1/day

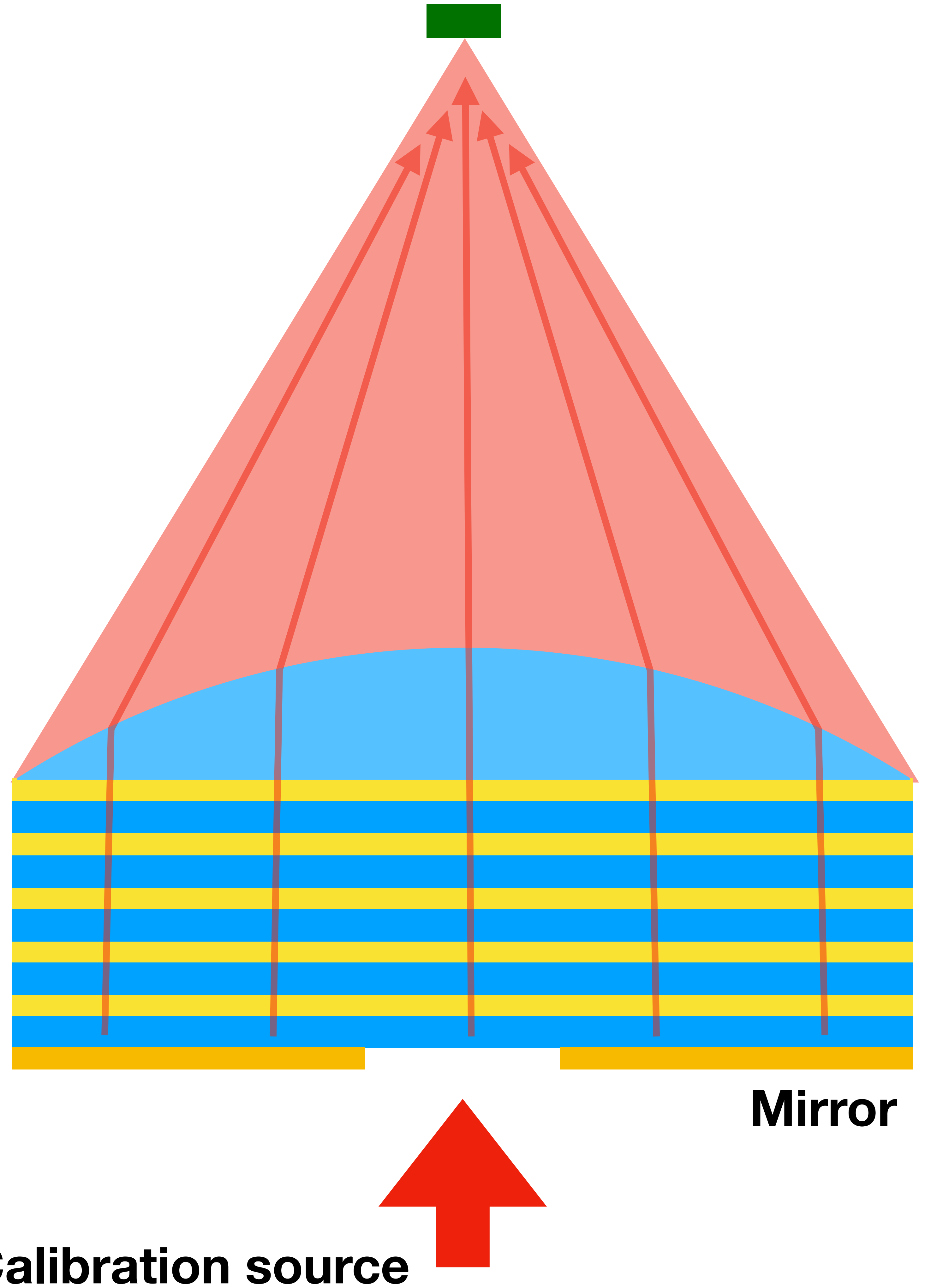


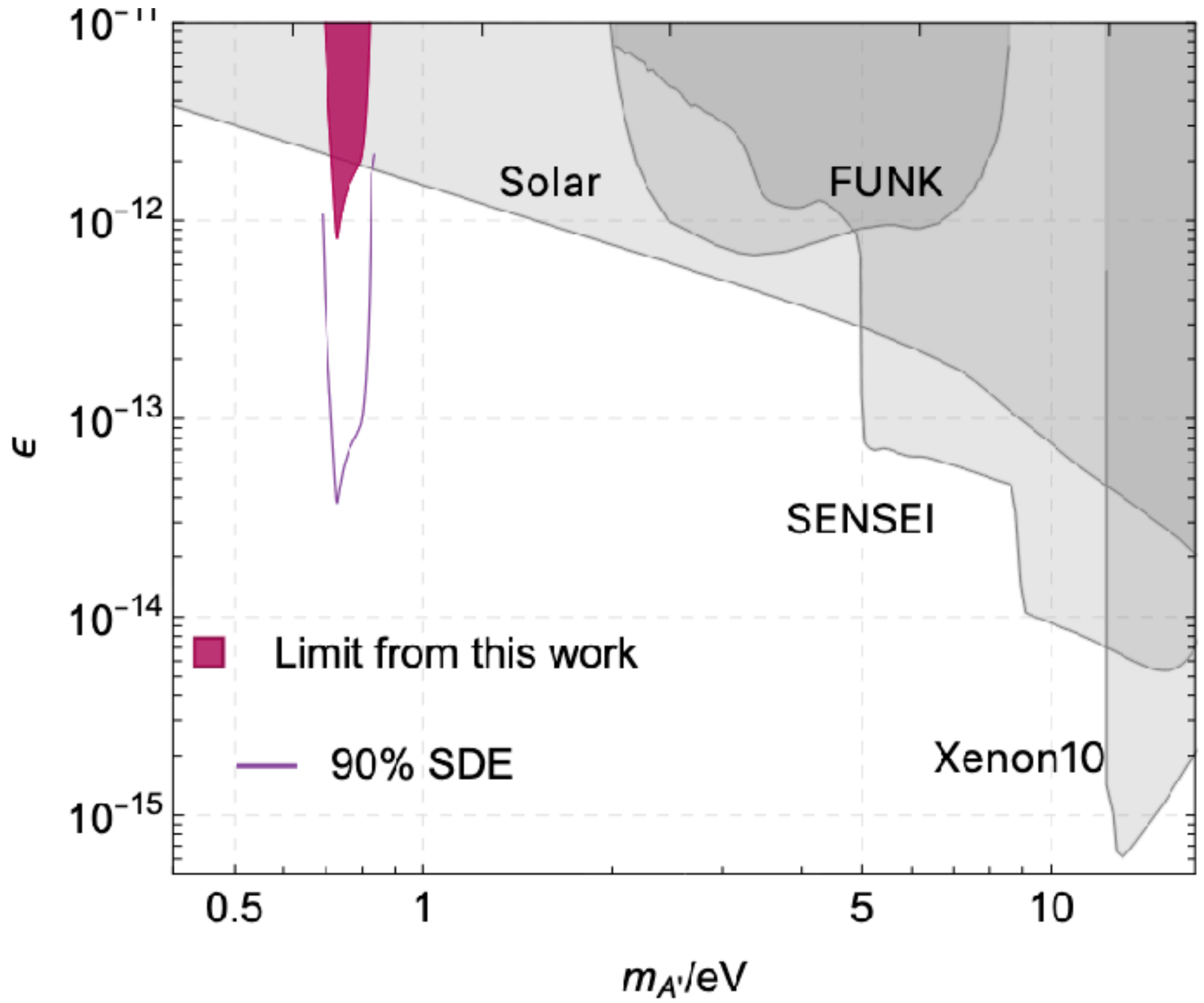
J. Chiles et al, Phys. Rev. Lett. 128 (2022)

LAMPOST

Ilya Charaev

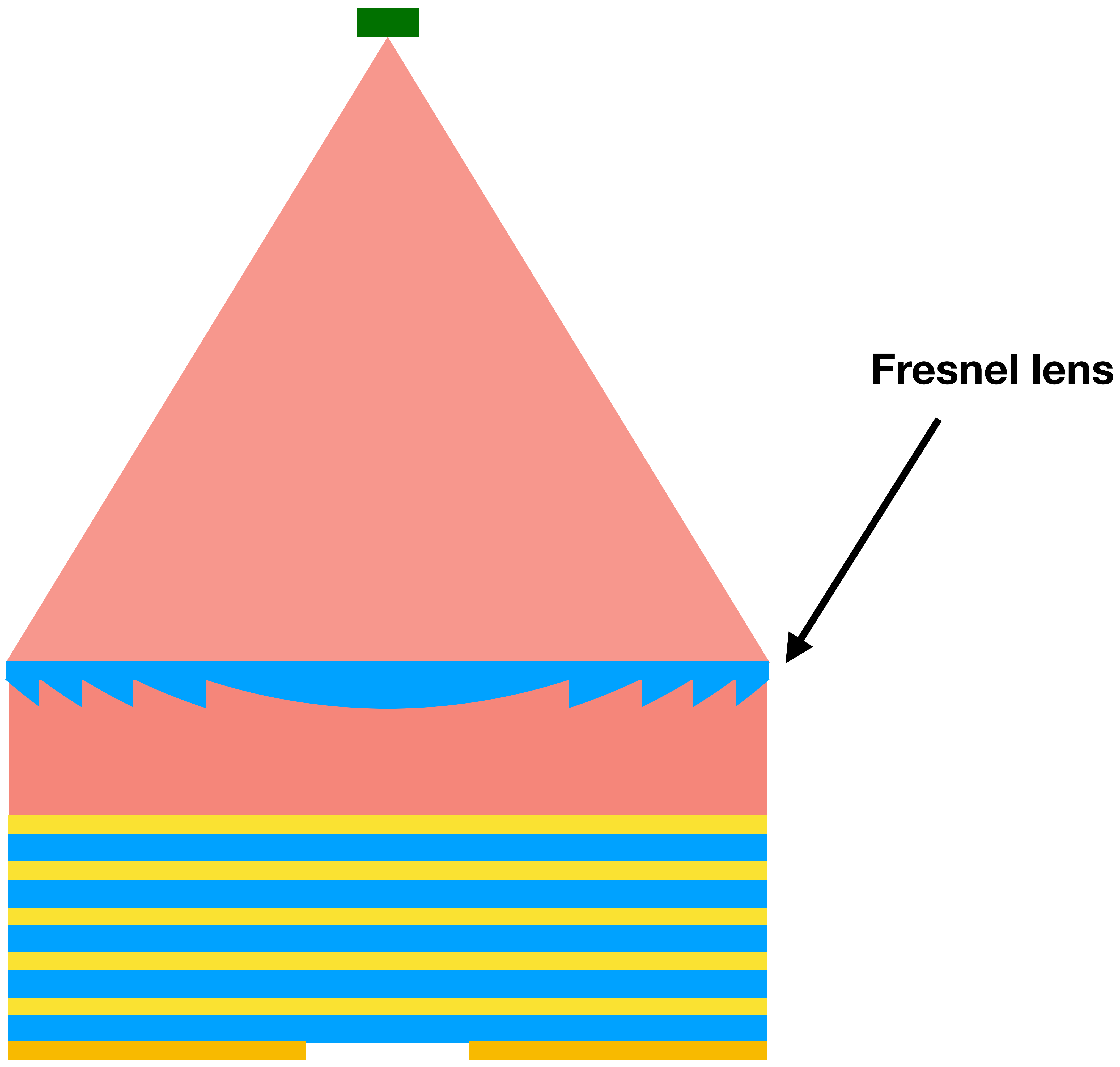
Jeffrey Chiles

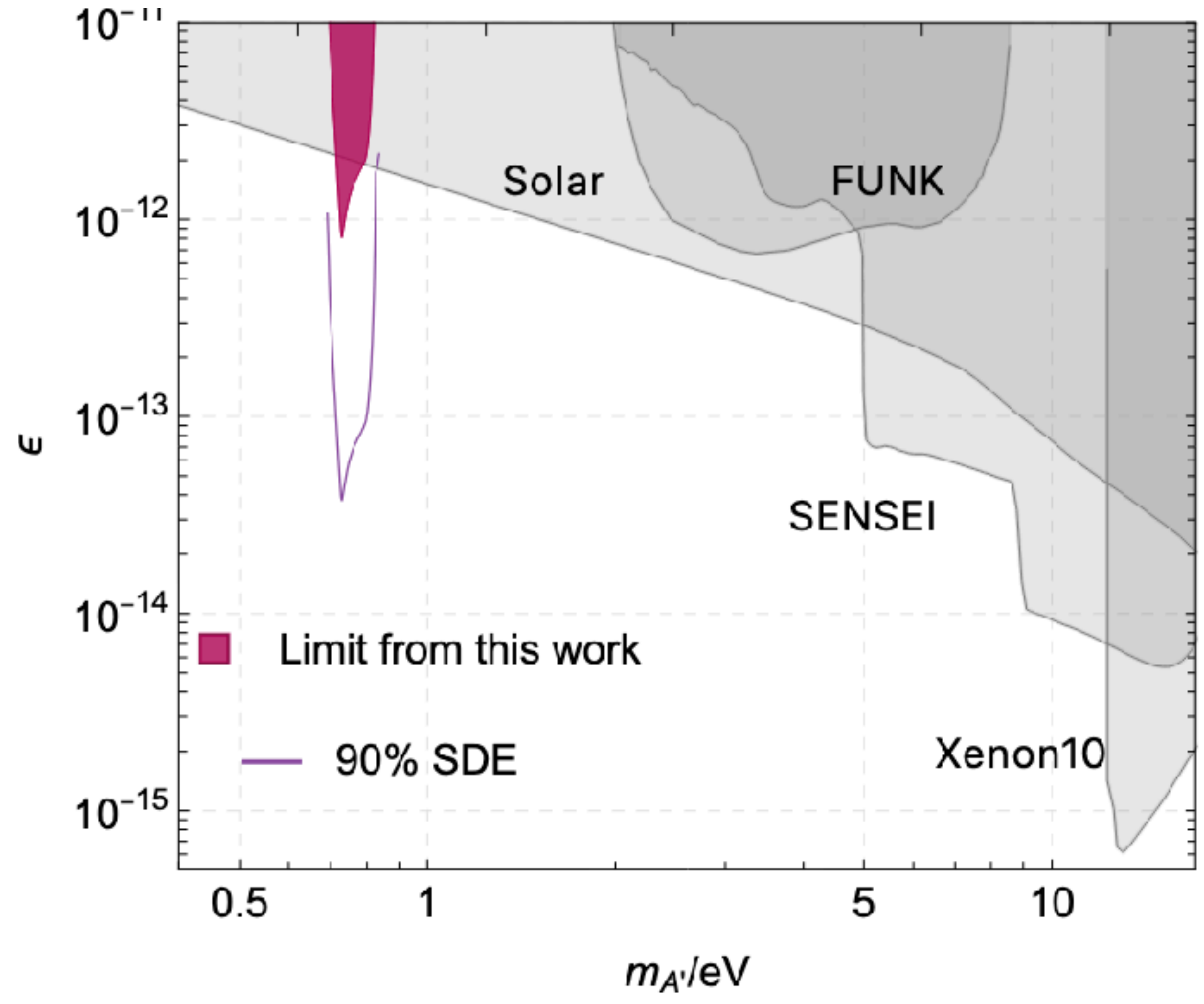




J. Chiles et al, Phys. Rev. Lett. 128 (2022)

LAMPOST 2.0


Fresnel lens


10^{-11}
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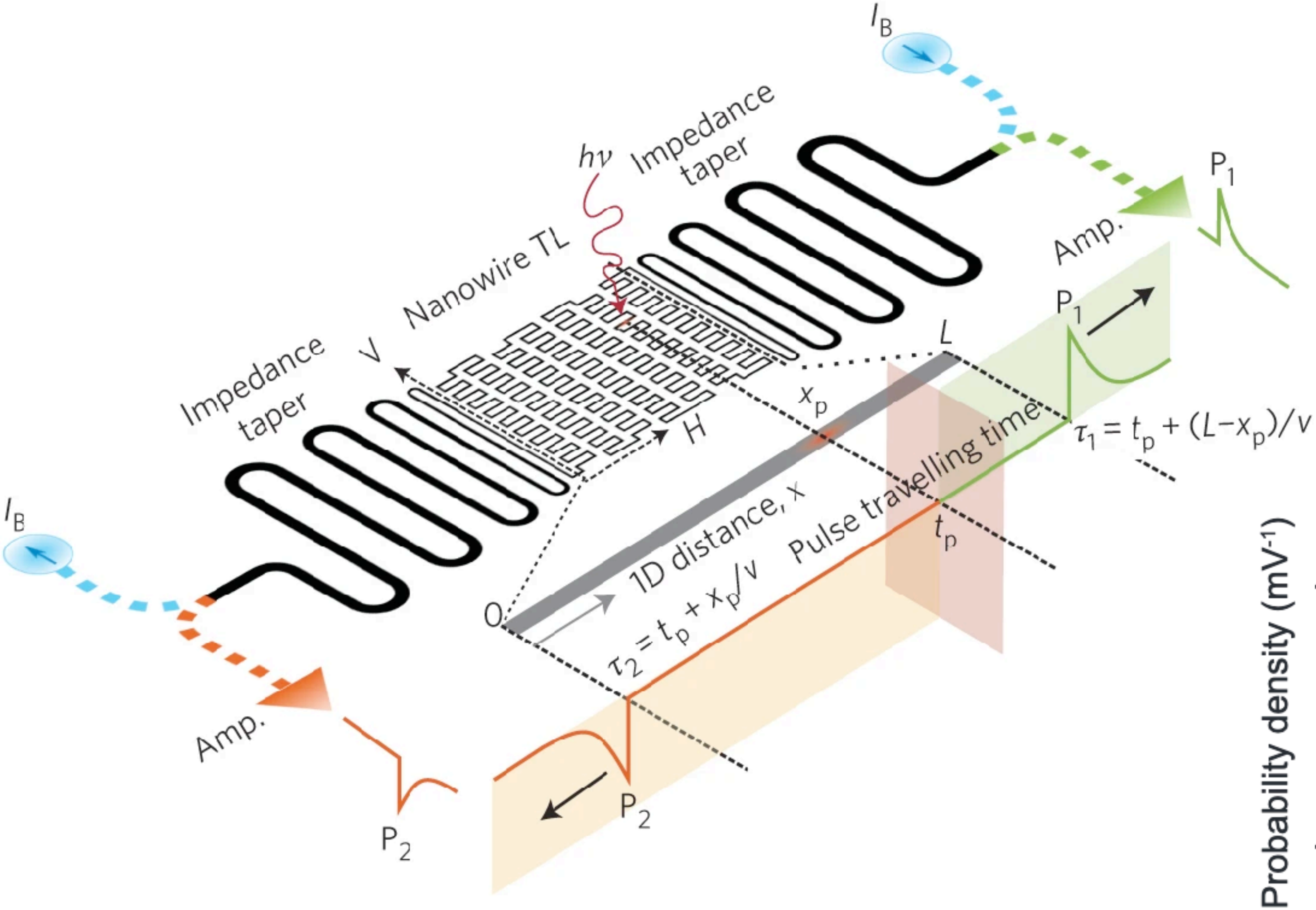
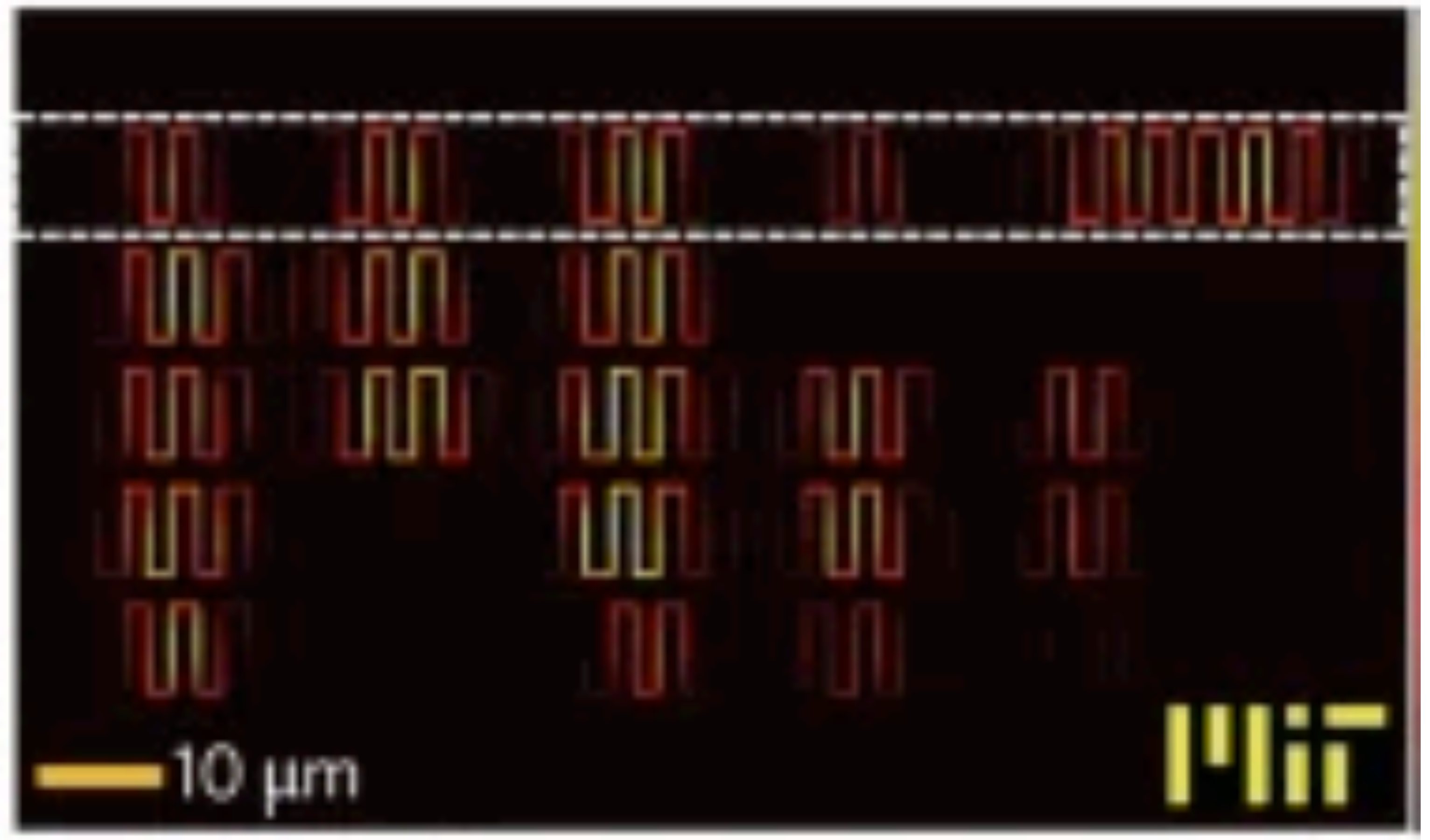
ϵ
Solar
FUNK
SENSEI
Xenon10
Limit from this work
90% SDE
0.5
1
5
10
$m_{A'}$/eV

Impedance-Matched SNSPDs

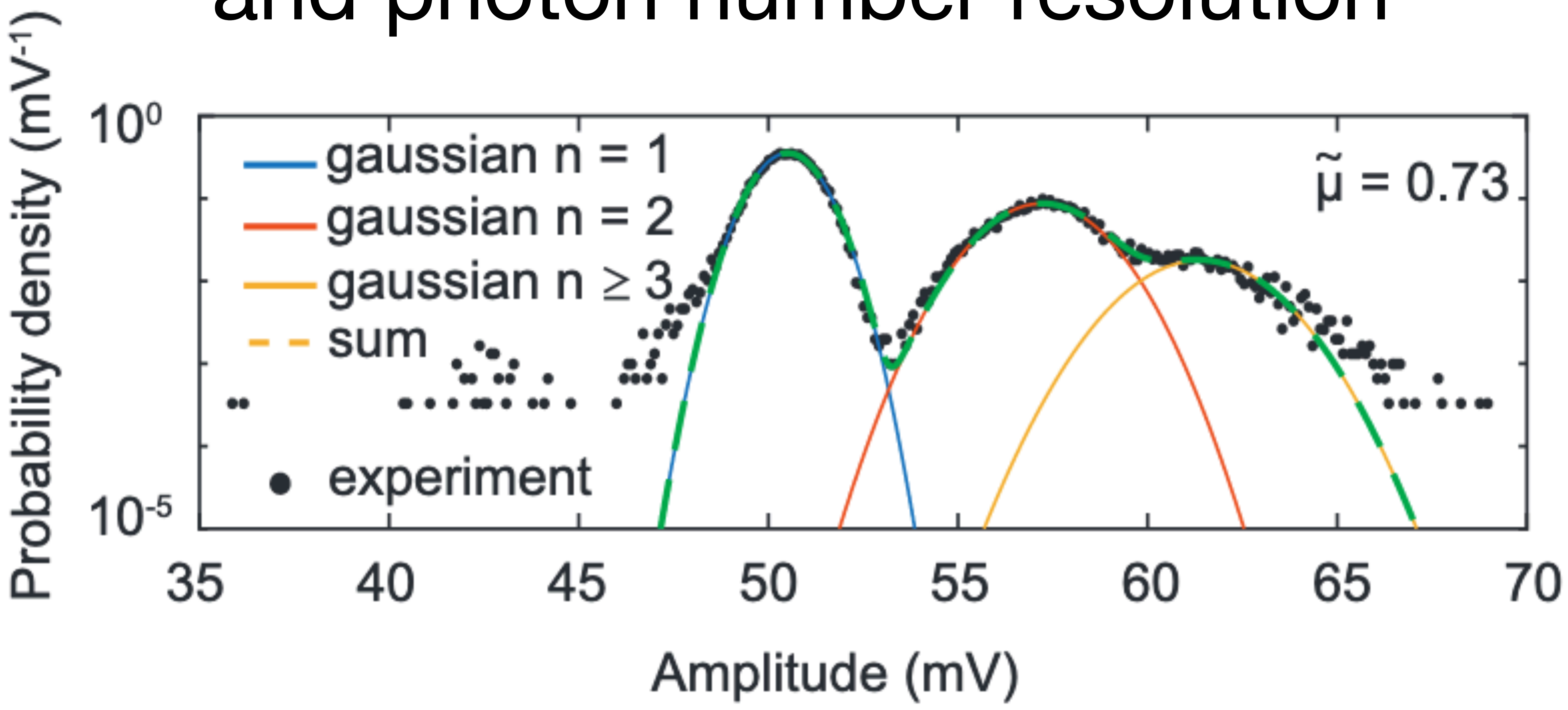


Single photon imager based on superconducting nanowire delay line
Zhao et al, 2017

For spatial resolution

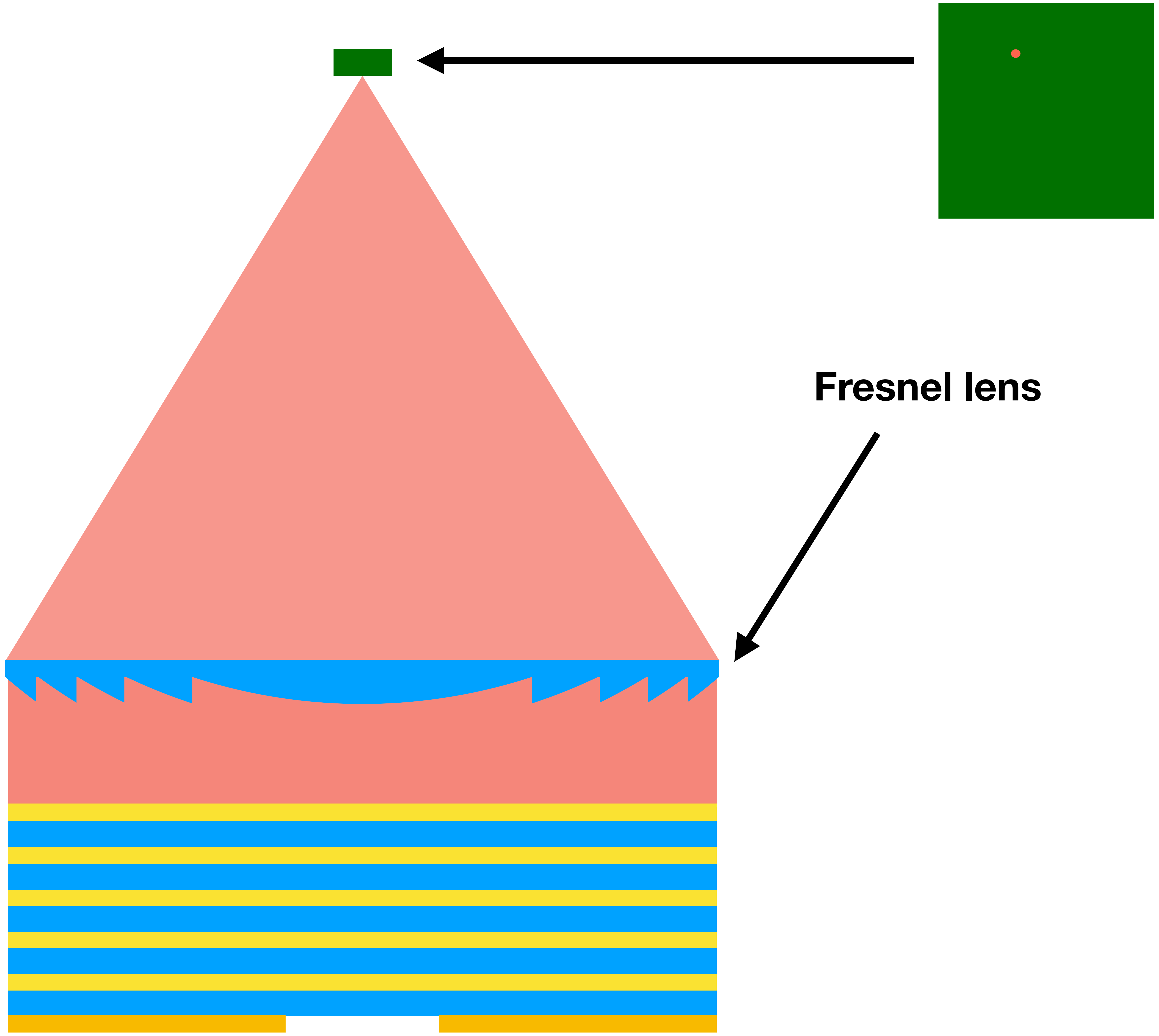


and photon number resolution



Impedance-matched differential superconducting nanowire detectors
Colangelo et al, 2021

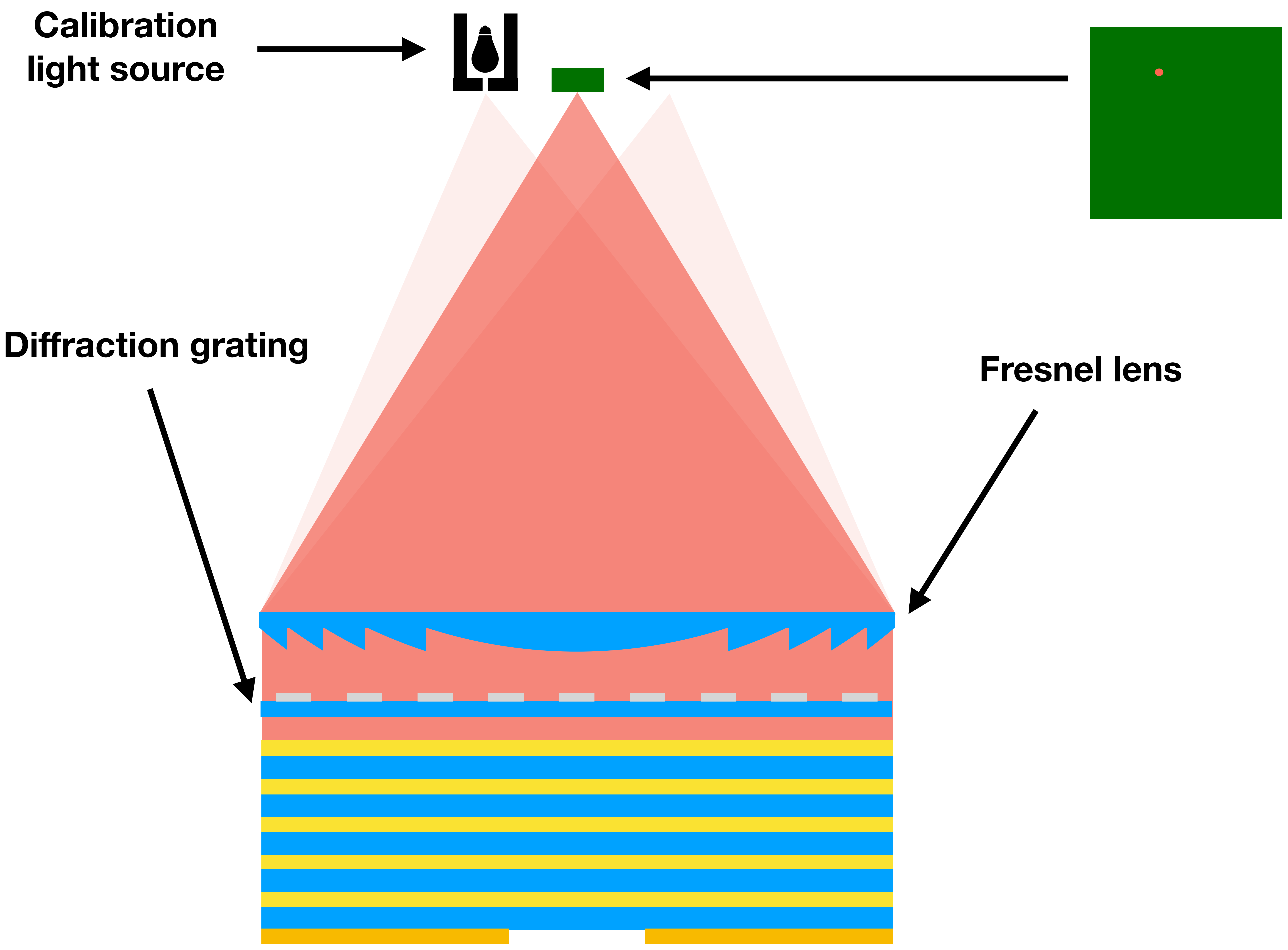
Impedance-Matched SNSPDs



1mm SNSPI

Compared to LAMPOST 1:
>400x background rejection

Impedance-Matched SNSPDs



1mm SNSPI

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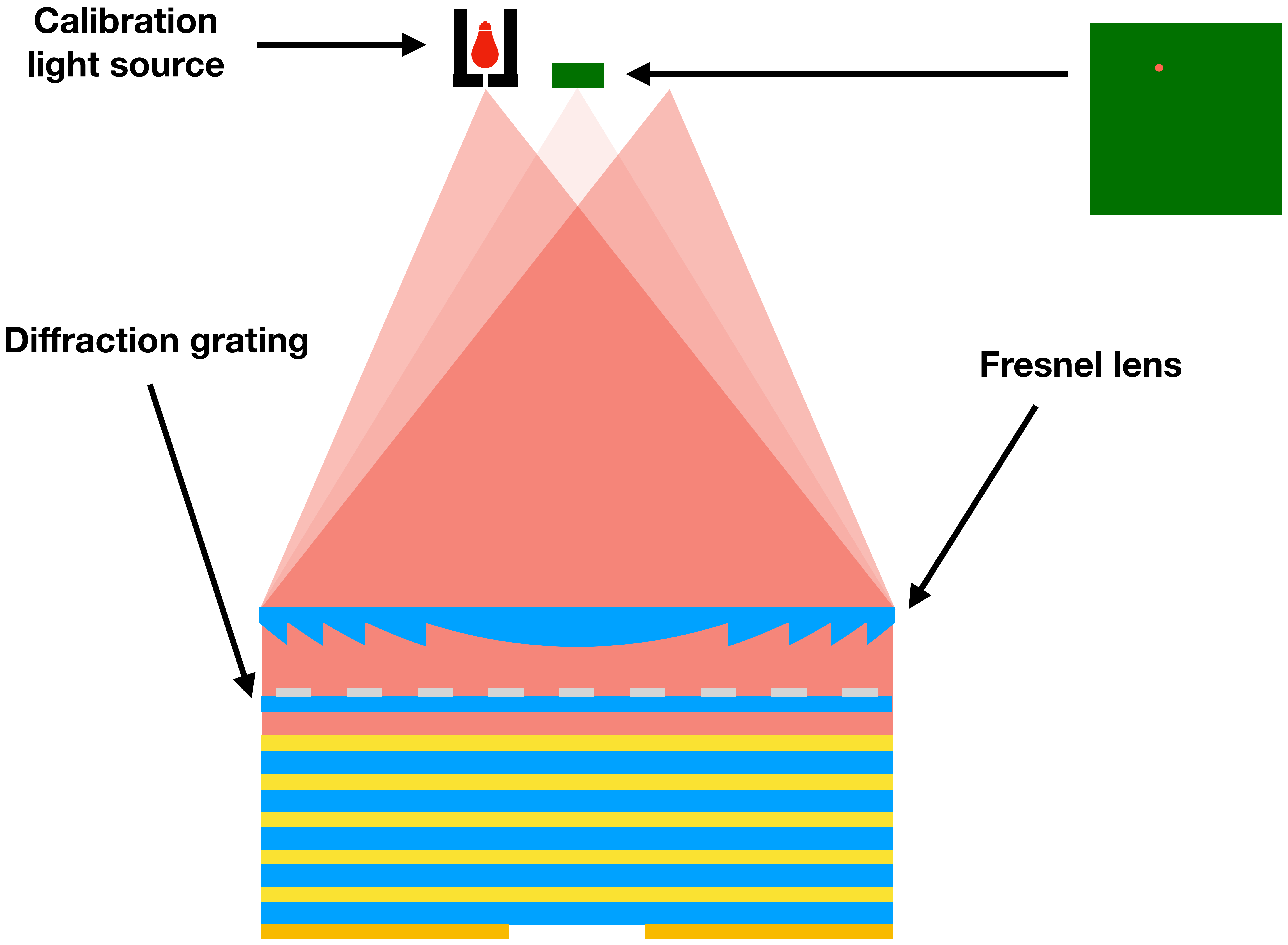
Impedance-Matched SNSPDs



1mm SNSPI

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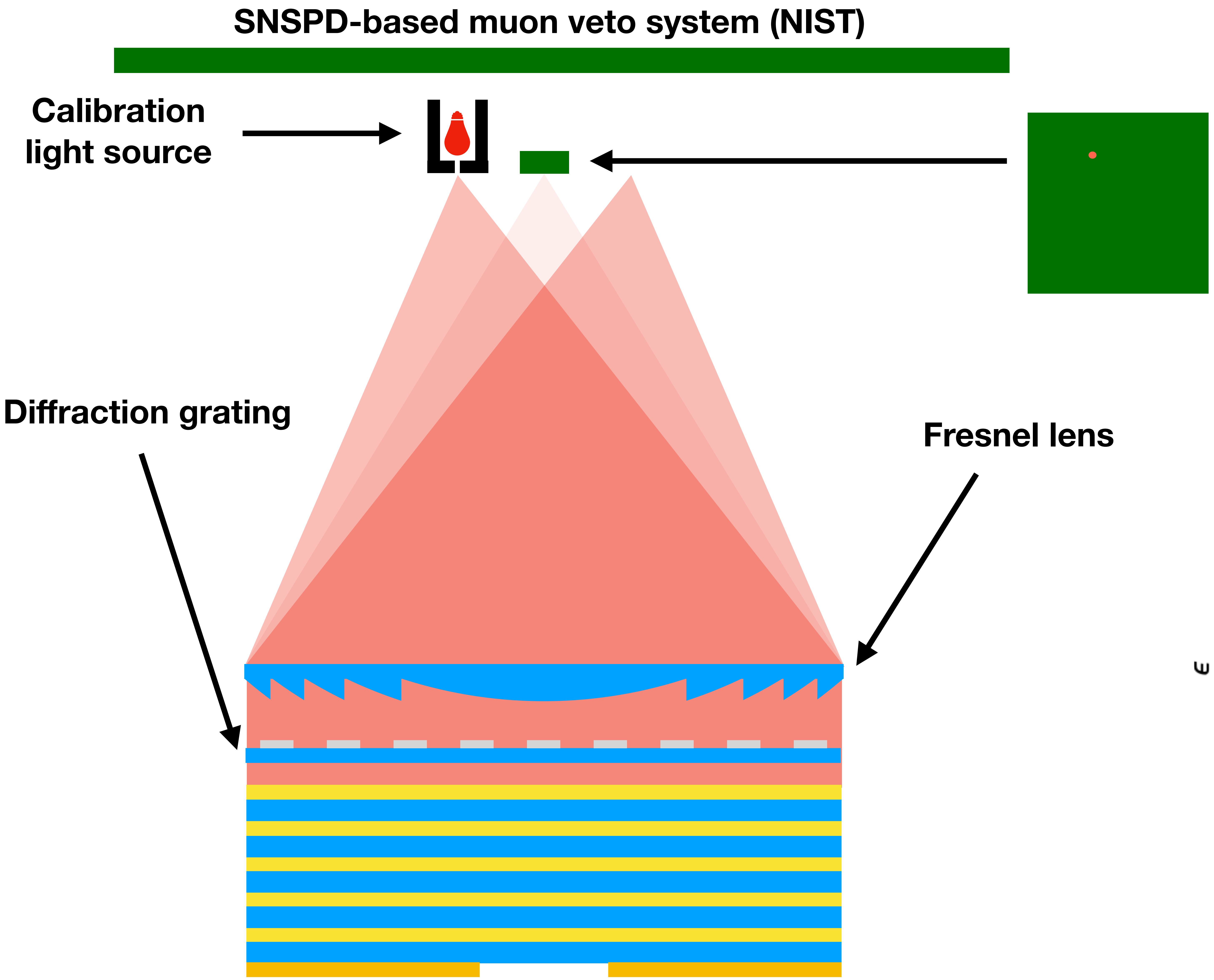
Impedance-Matched SNSPDs



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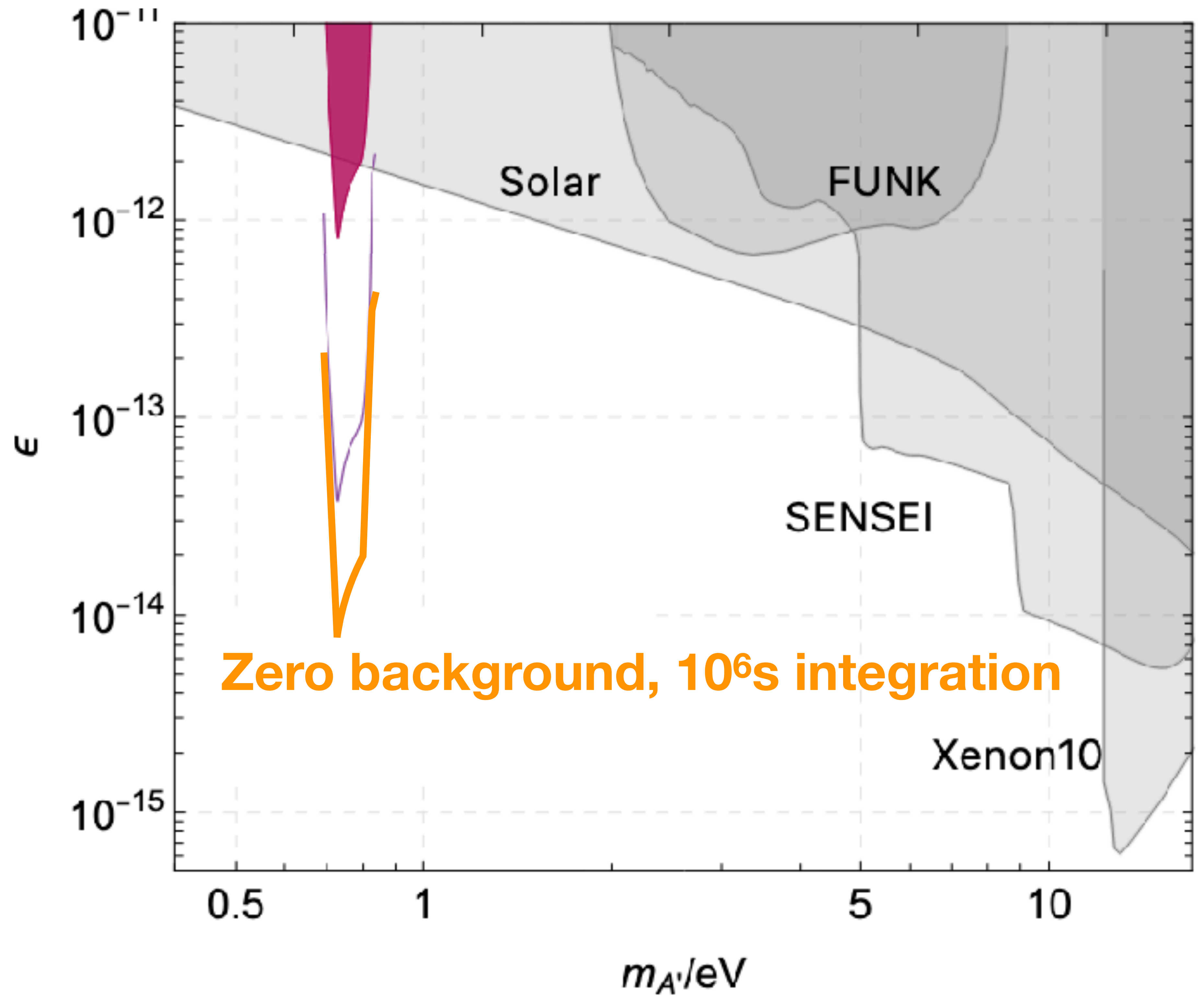
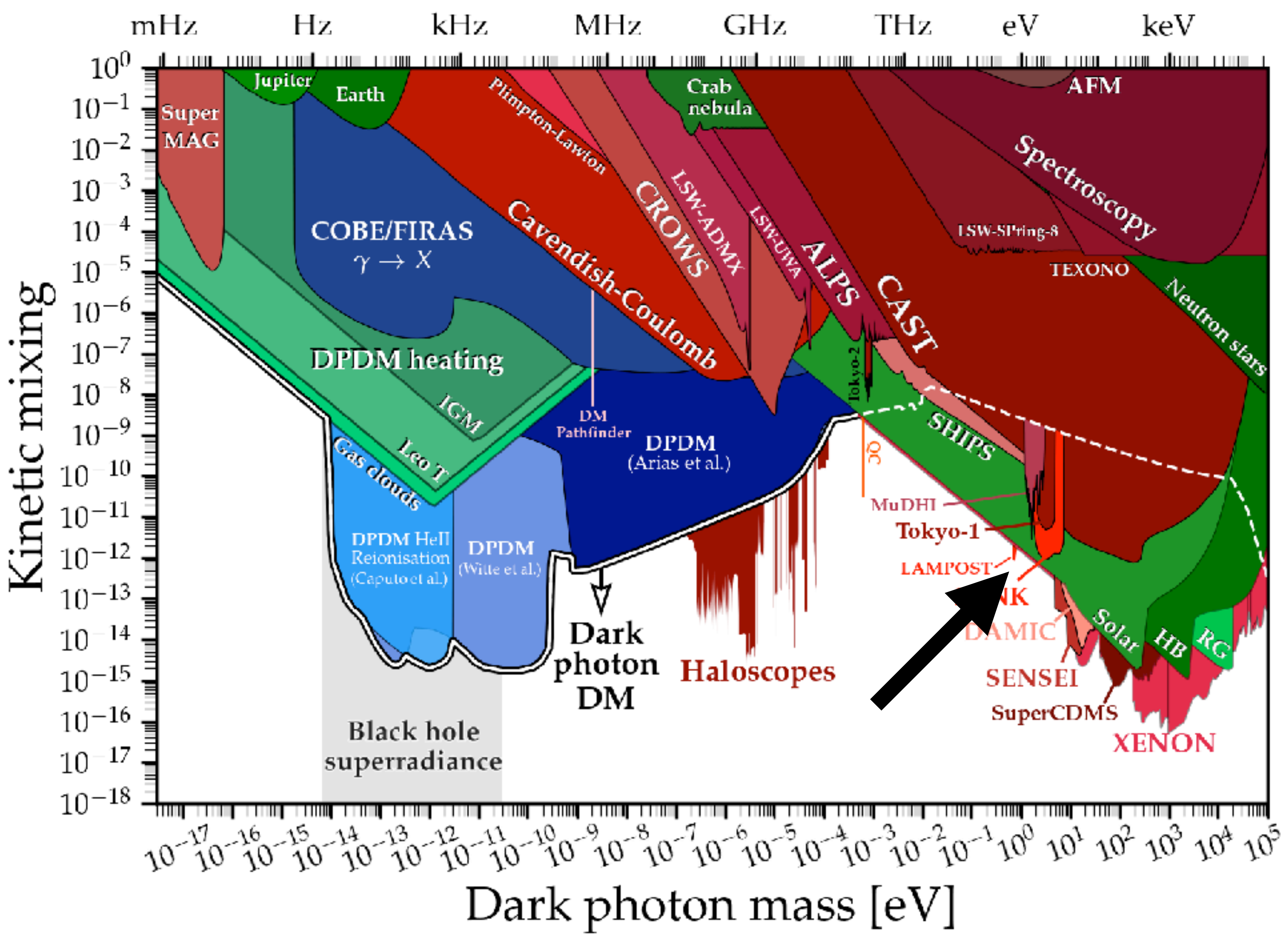
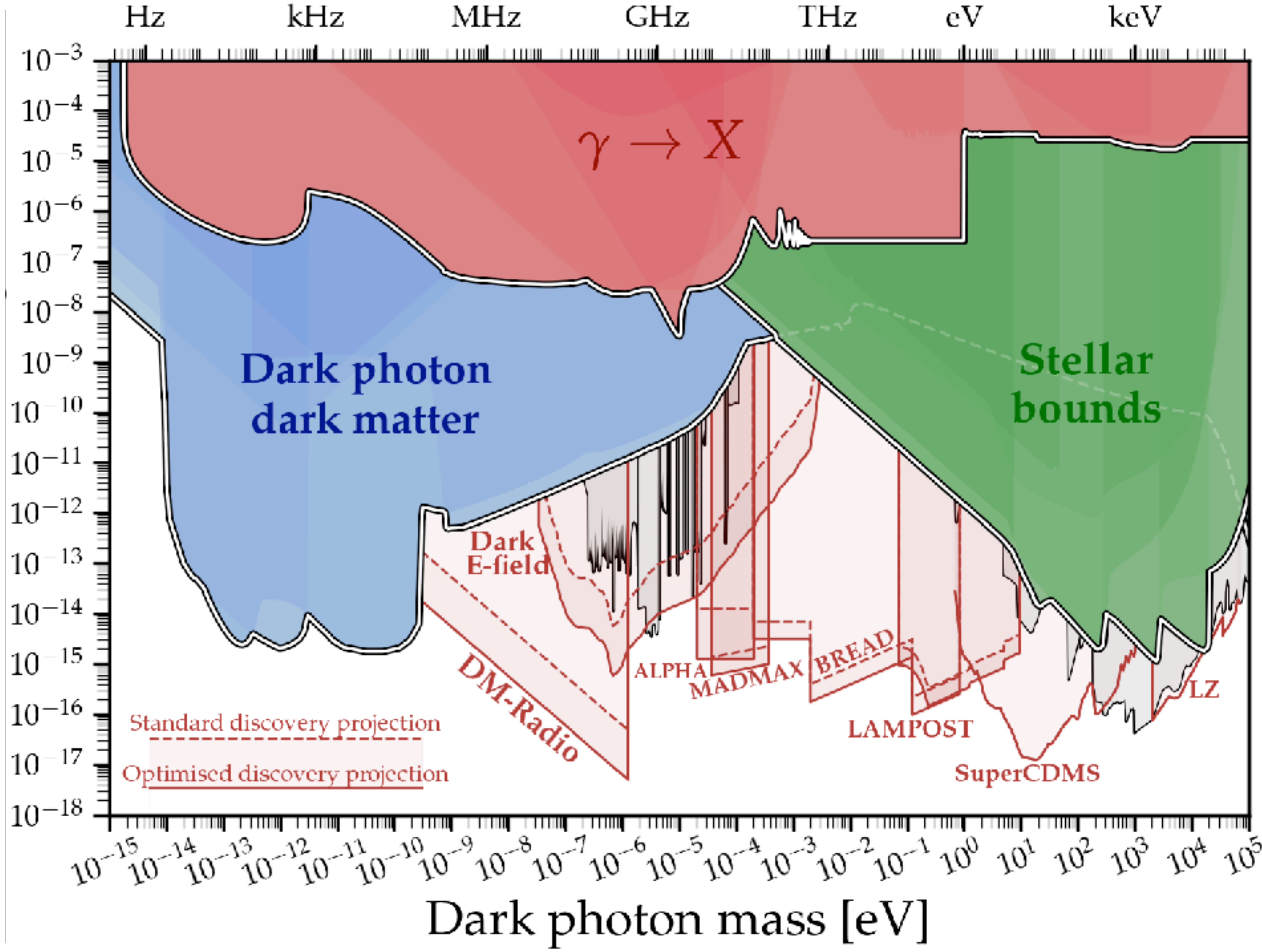


Dark Photon Reach Plots

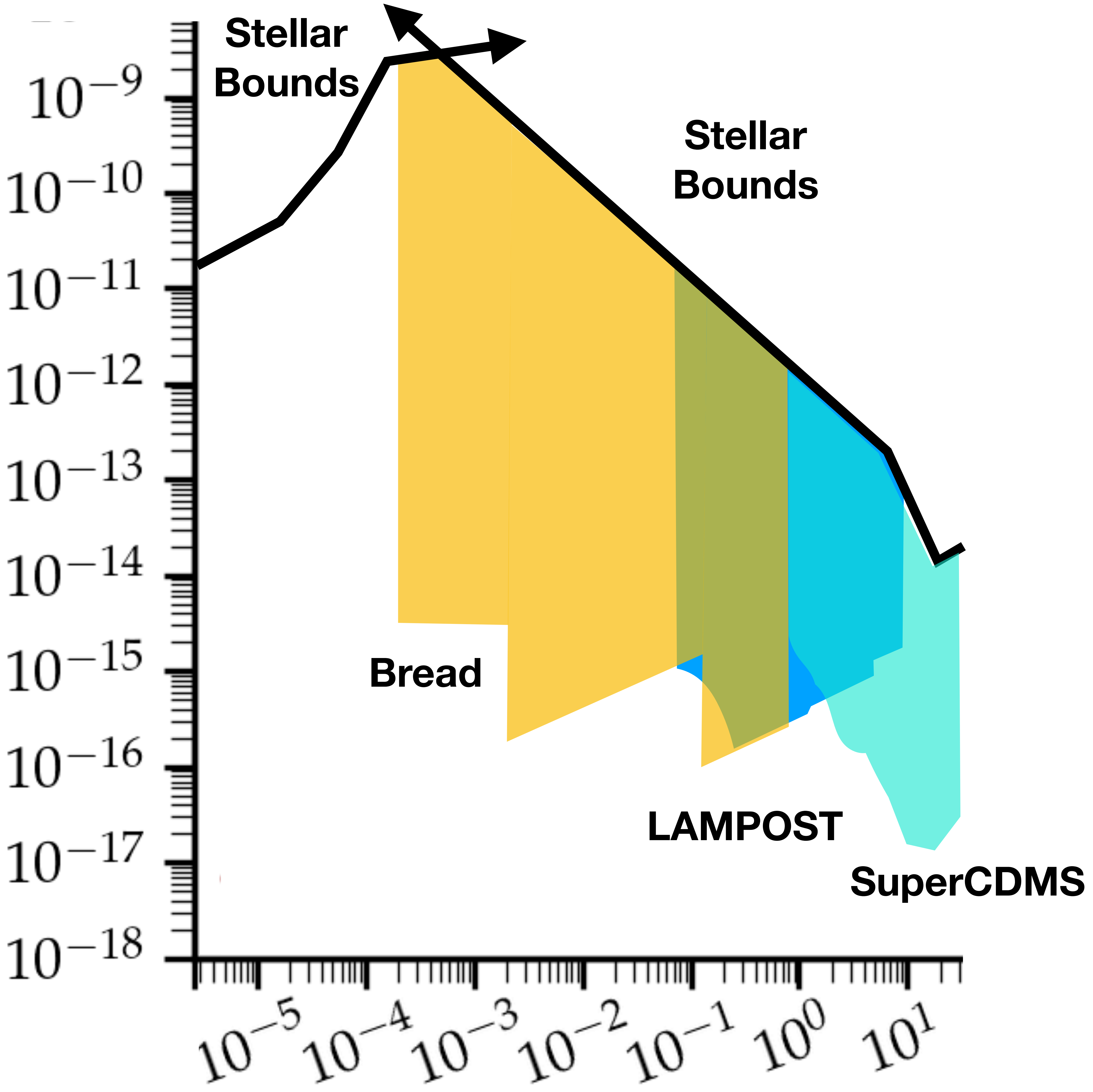
Dark photon limits: a handbook

Andrea Caputo,[1,2,a] Alexander J. Millar,[3,4,b] Ciaran A. J. O'Hare,[5,6,c] and Edoardo Vitagliano[7,d]

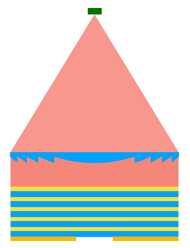




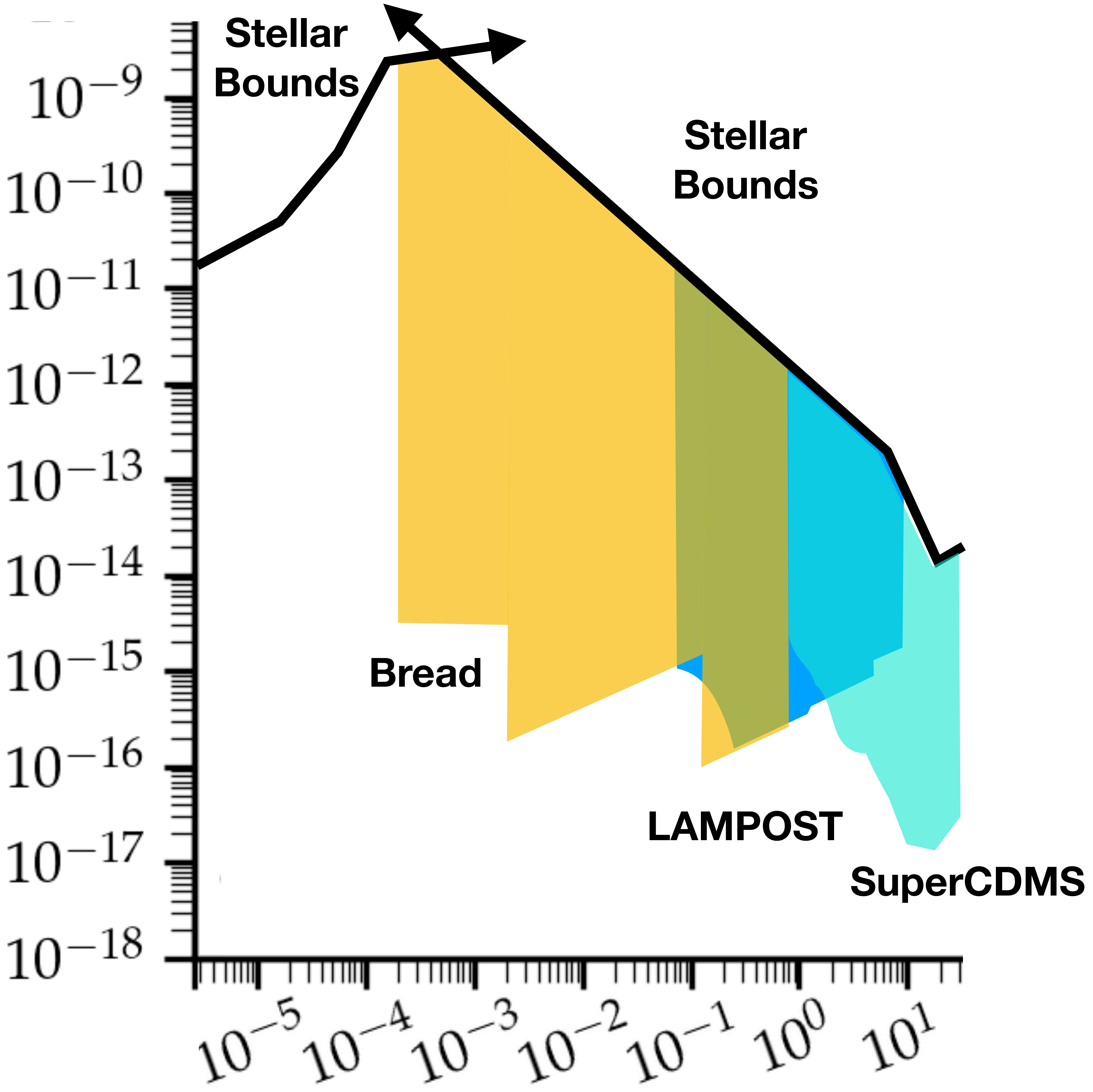
Scaling LAMPOST



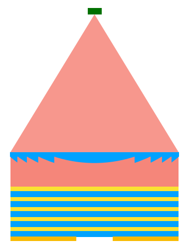
LAMPOST 1



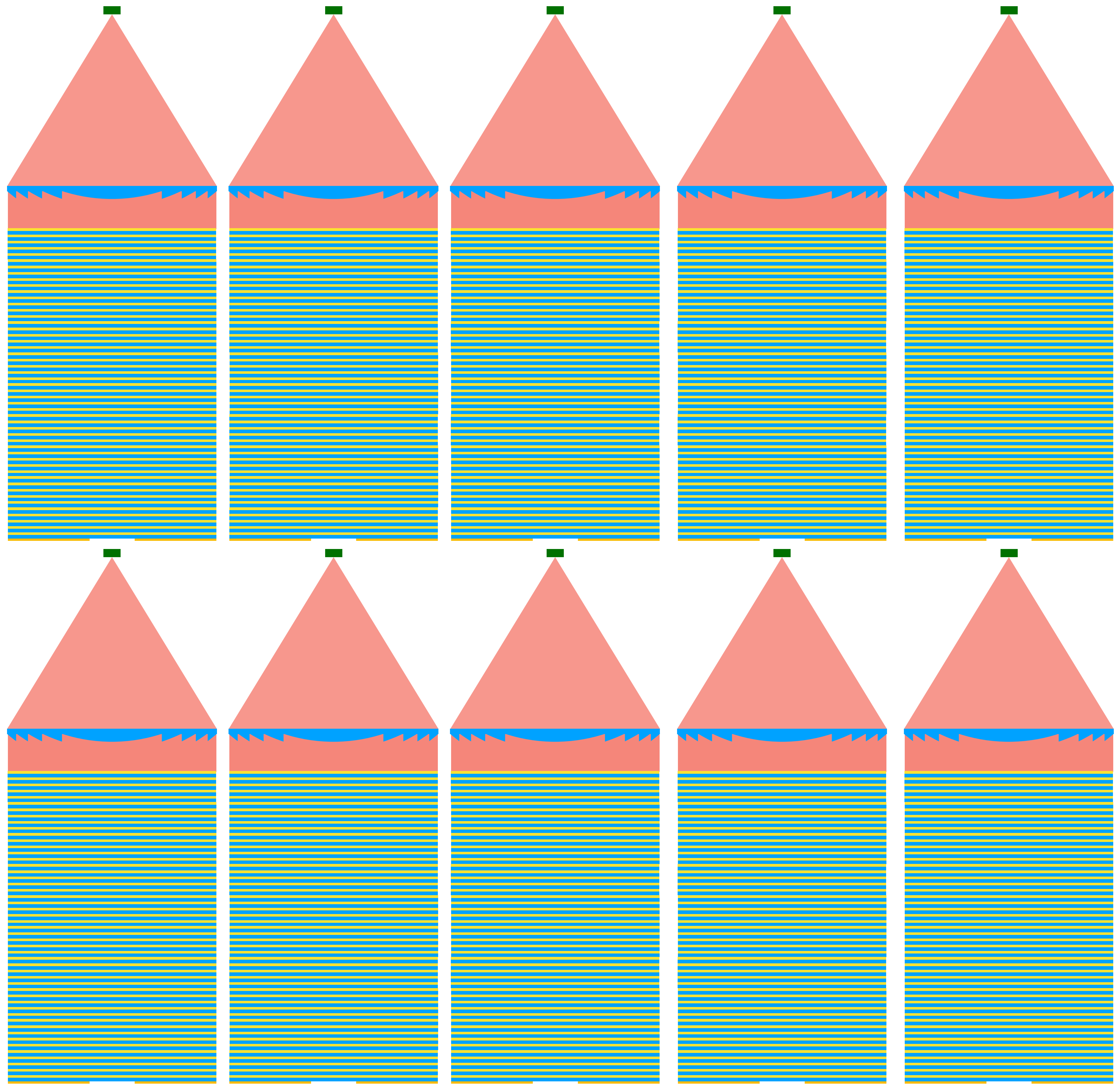
Scaling LAMPOST



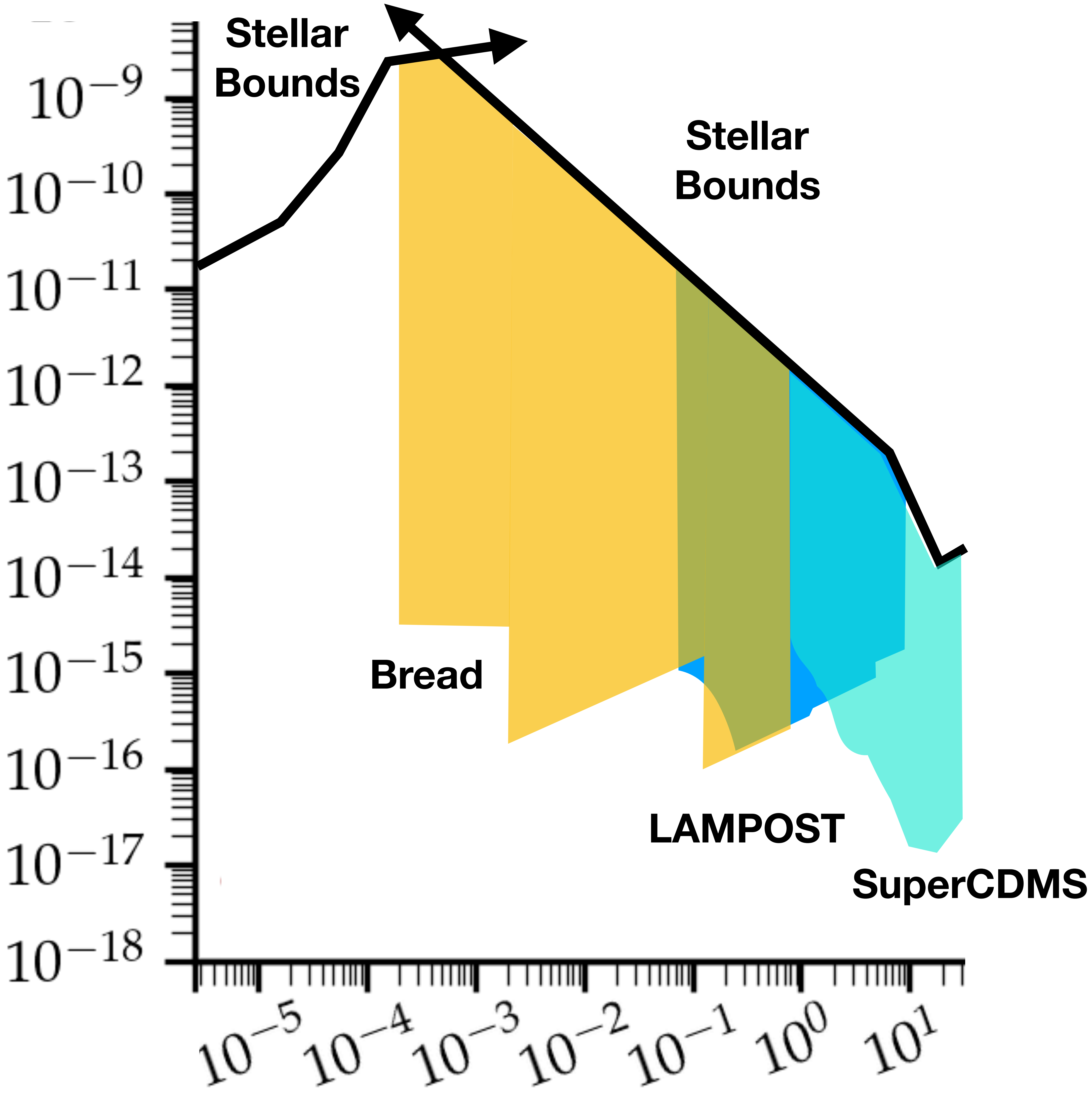
LAMPOST 1

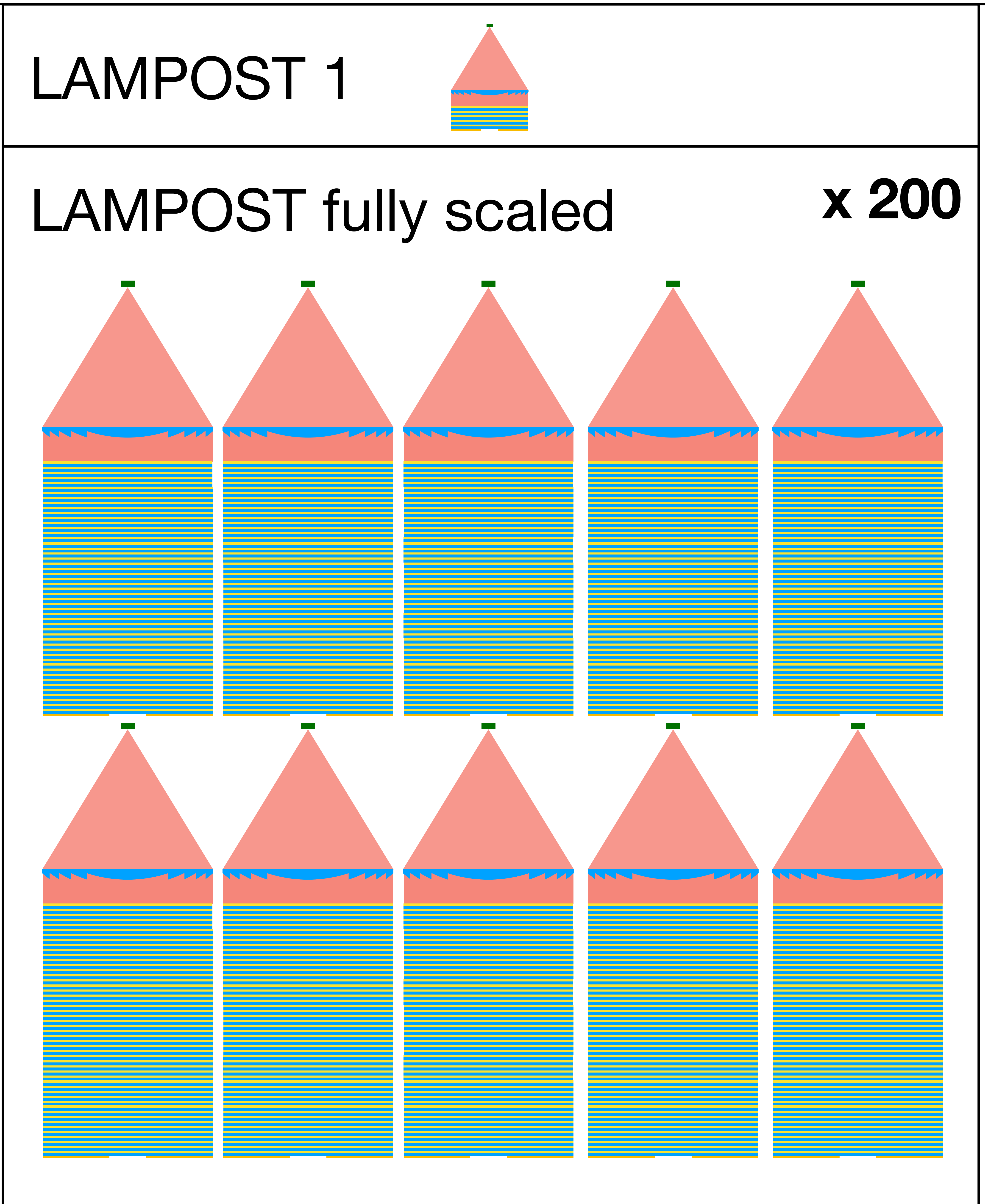


LAMPOST fully scaled

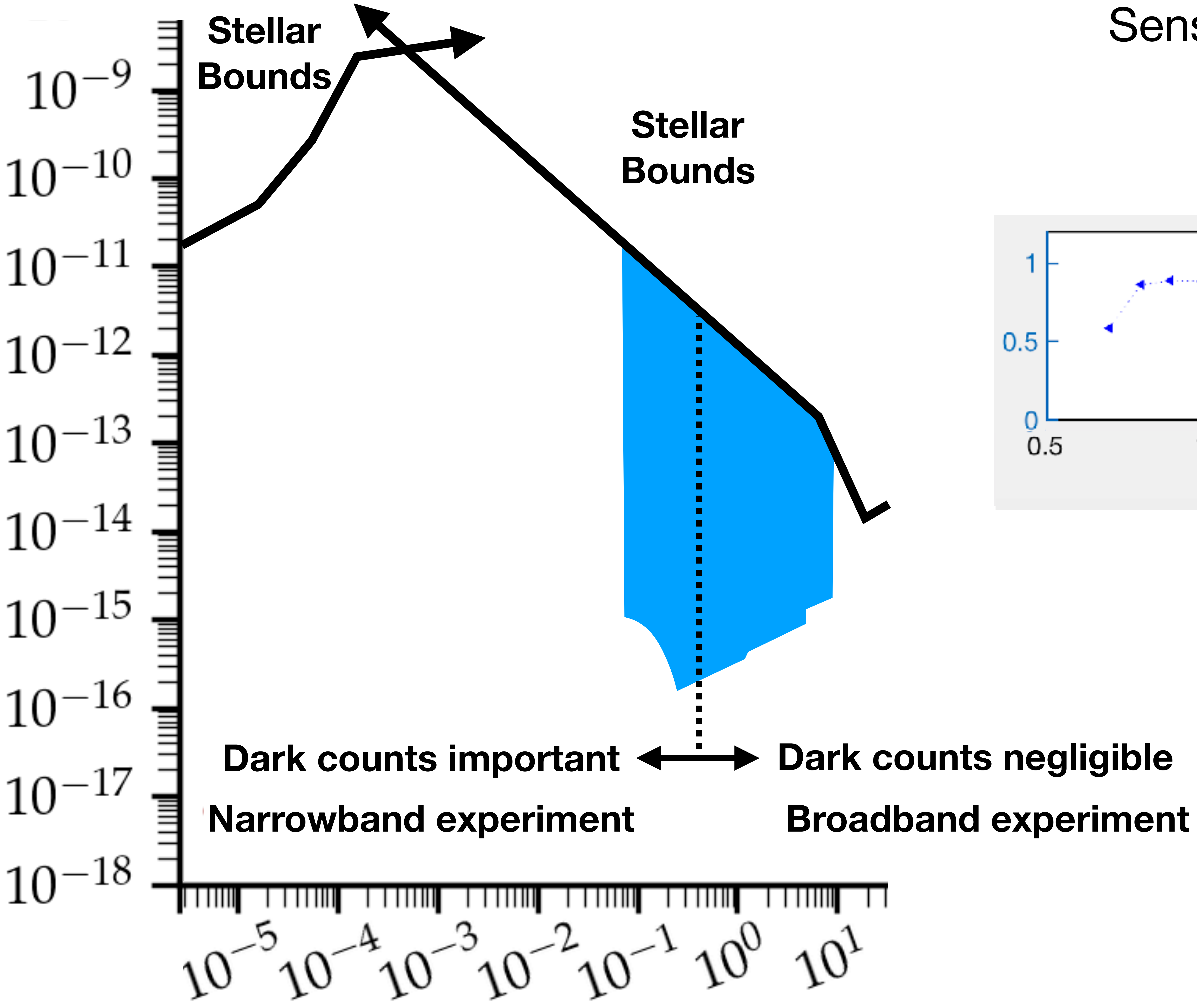


Scaling LAMPOST



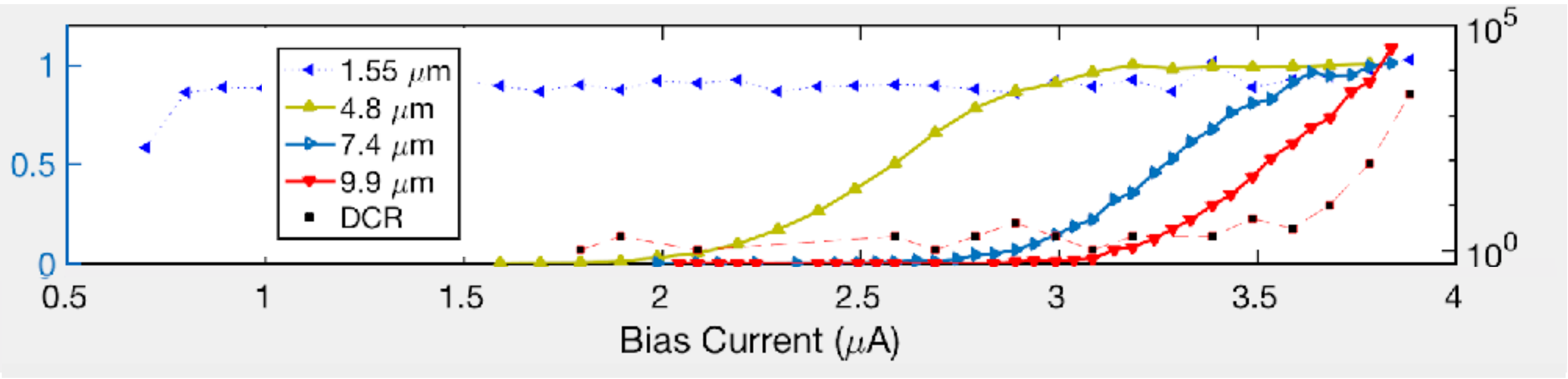


Two Detection Regimes



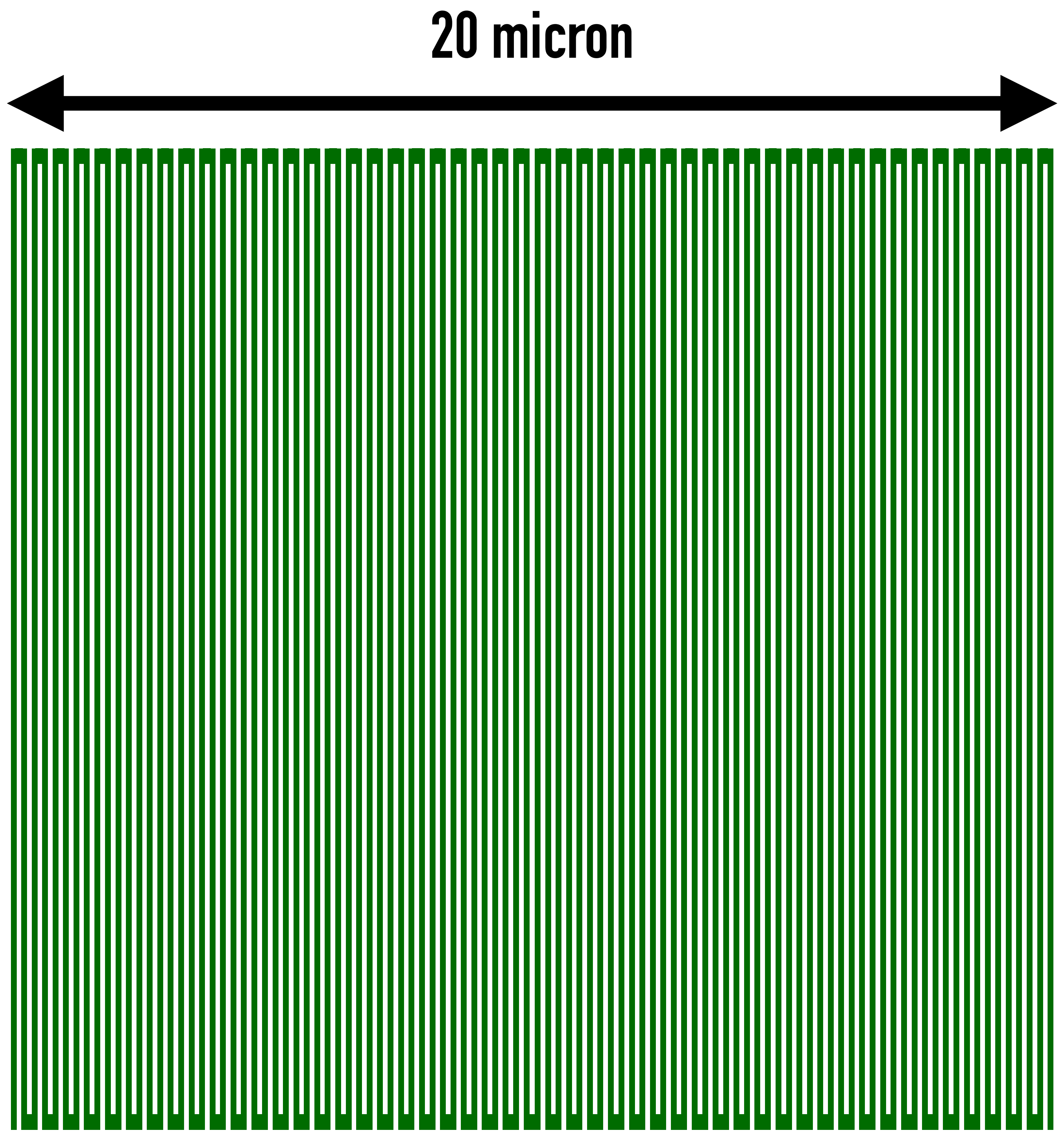
Sensitivity to longer wavelengths comes with exponentially more dark counts

Photon count rate and DCR vs bias current



LAMPOST in the Mid and Far Infrared

Nanowire length: 2mm

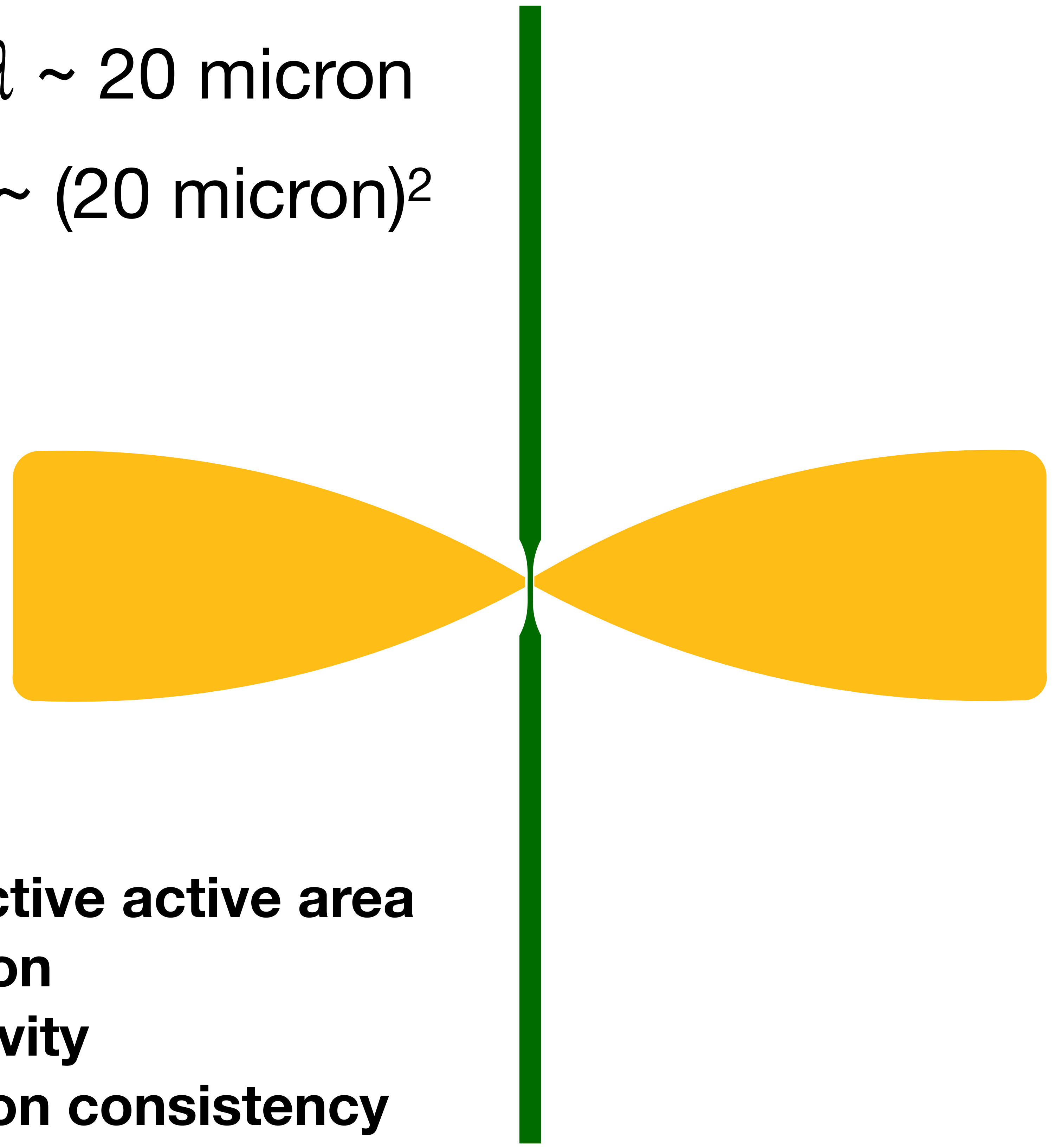


100 meanders, 50% fill, 100nm wire

Nanowire length: 1 micron

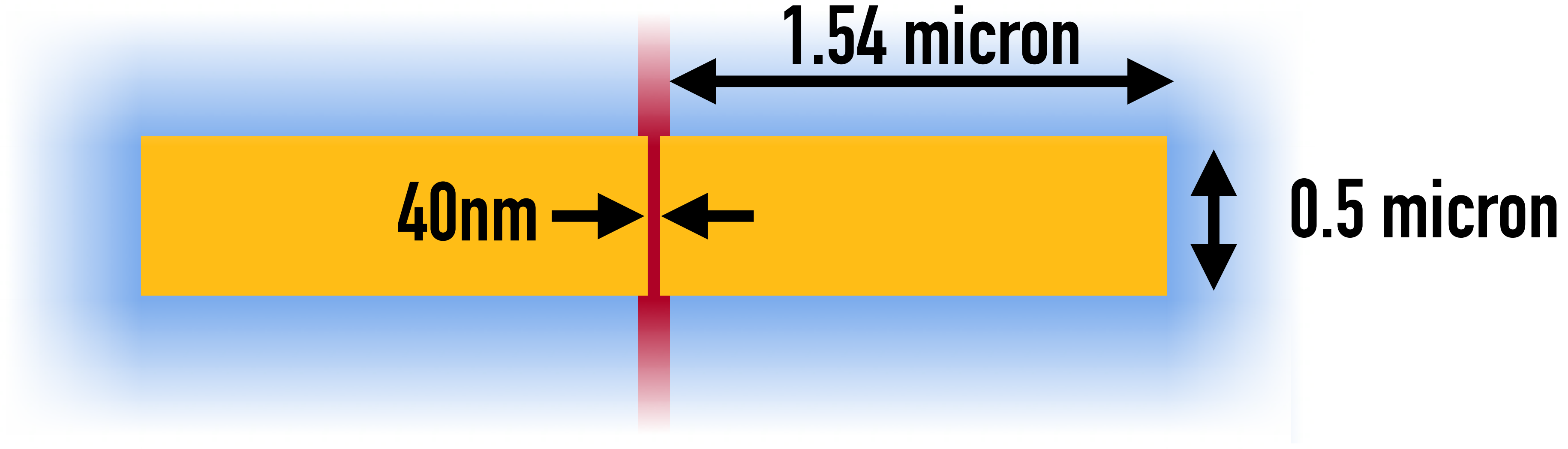
resonance: λ ~ 20 micron

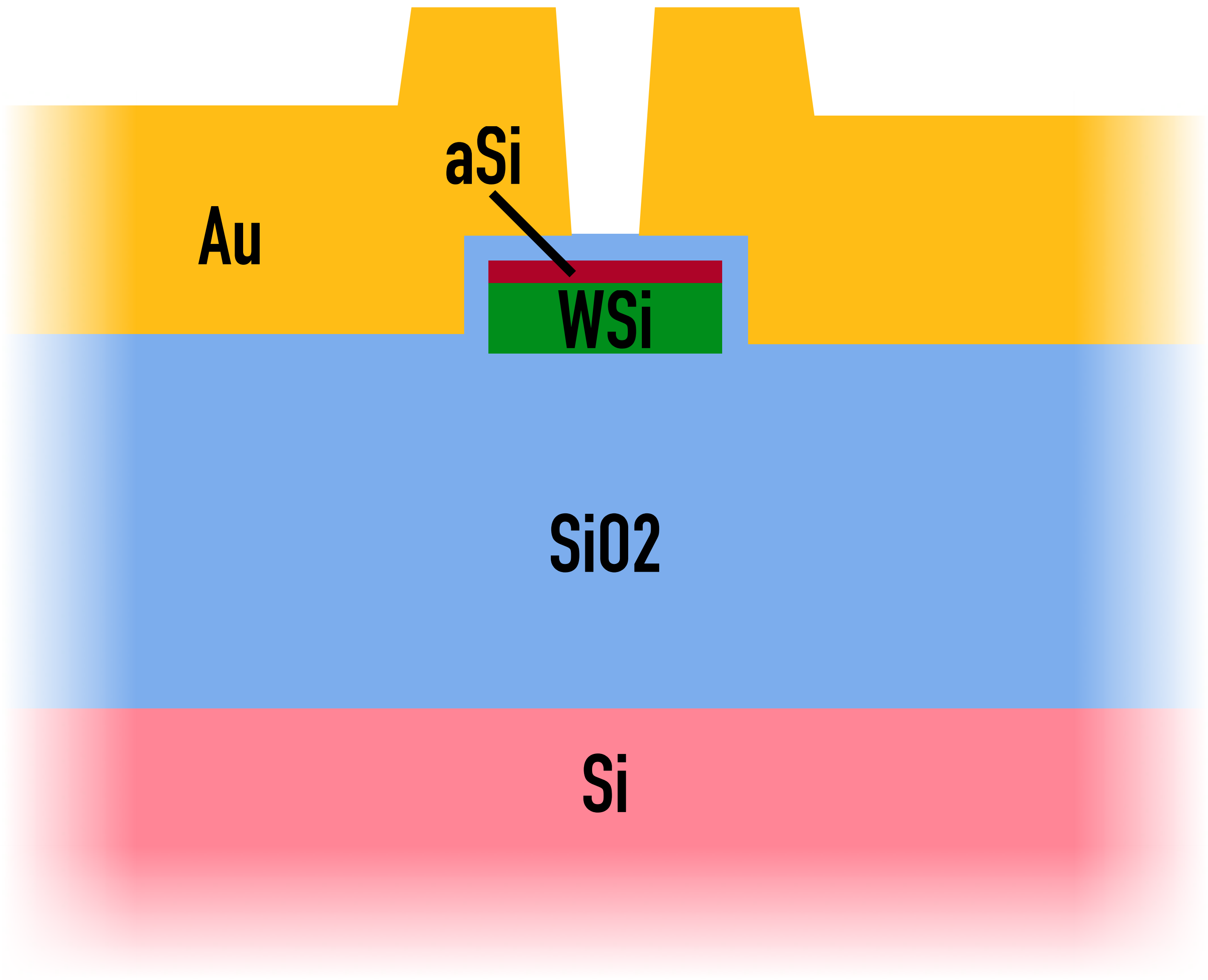
A_e ~ (20 micron)^2



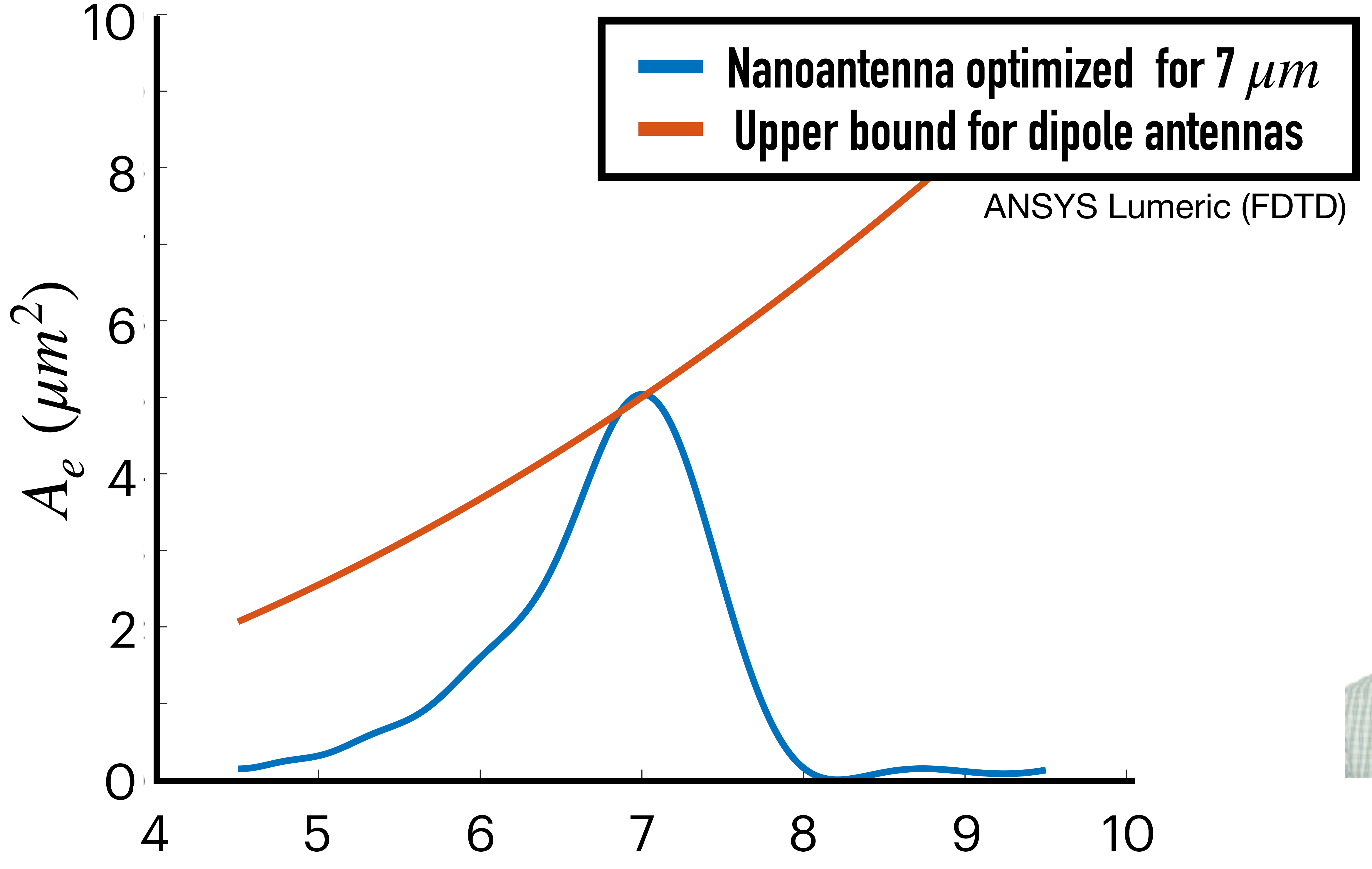
- **Equivalent effective active area**
- **Better absorption**
- **Spectral sensitivity**
- **Better fabrication consistency**

Dipole Antenna Simulation



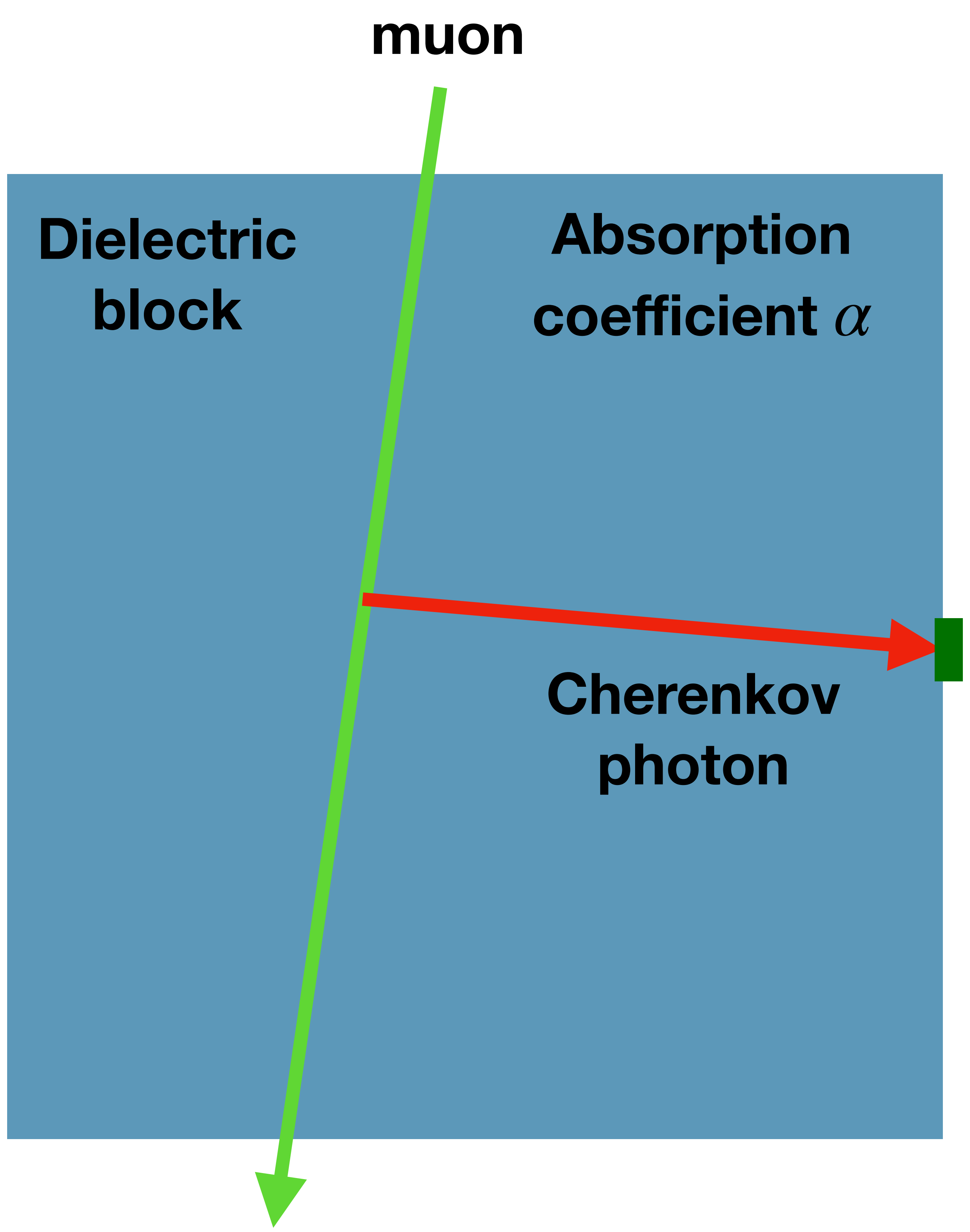


$$\text{Effective area} = \frac{\text{Power Absorbed}}{\text{Illumination Intensity}}$$



Dip Joti Paul

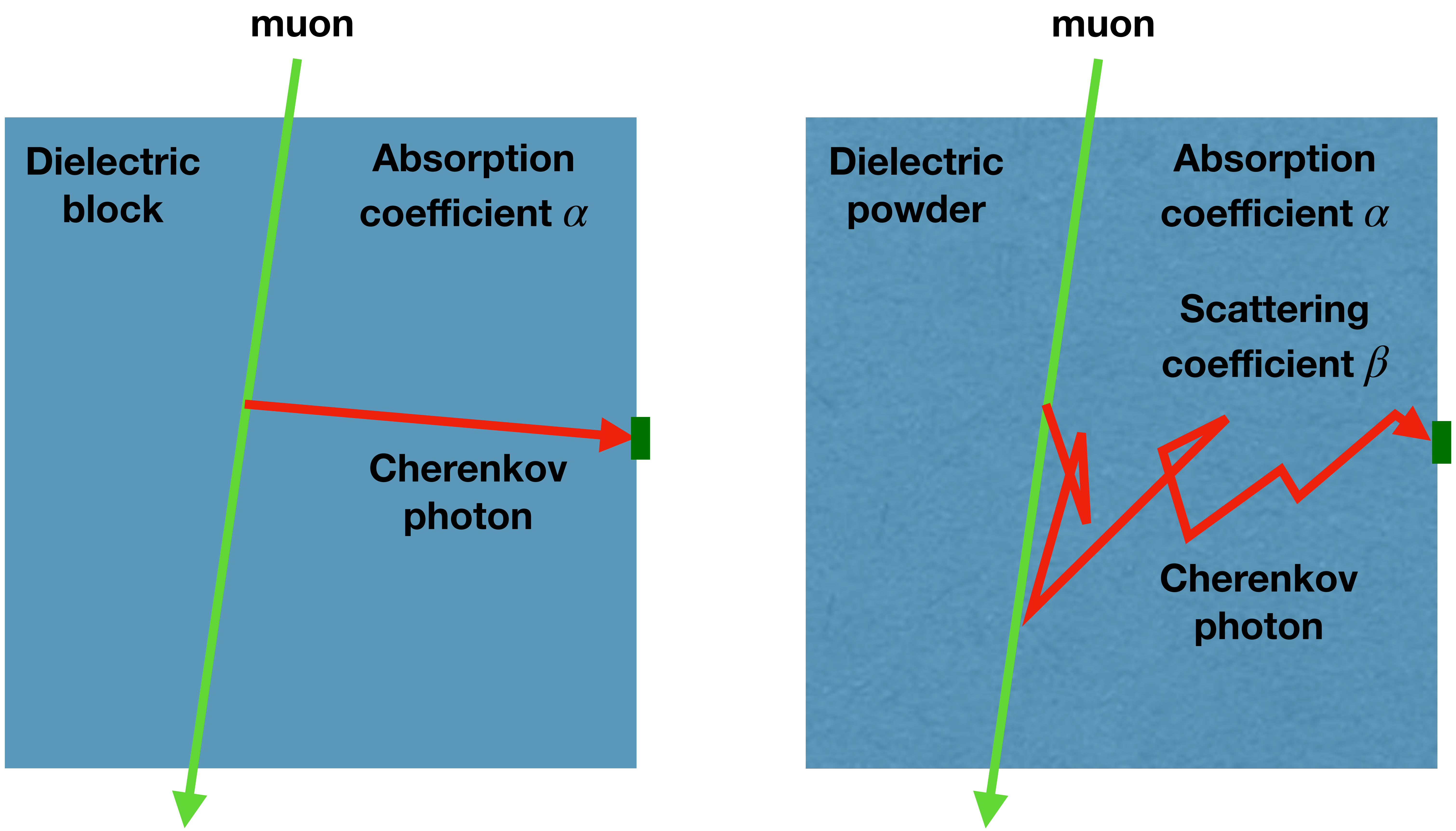
Toy Problem: Detecting Cherenkov Photos



Rate of detection $\sim \int_0^\infty 2\pi r^2 dr \frac{e^{-r\alpha}}{4\pi r^2} \sim 1/\alpha$

Experiment volume: $\alpha^{-3} \sim 1m^3$

Toy Problem: Detecting Cherenkov Photos



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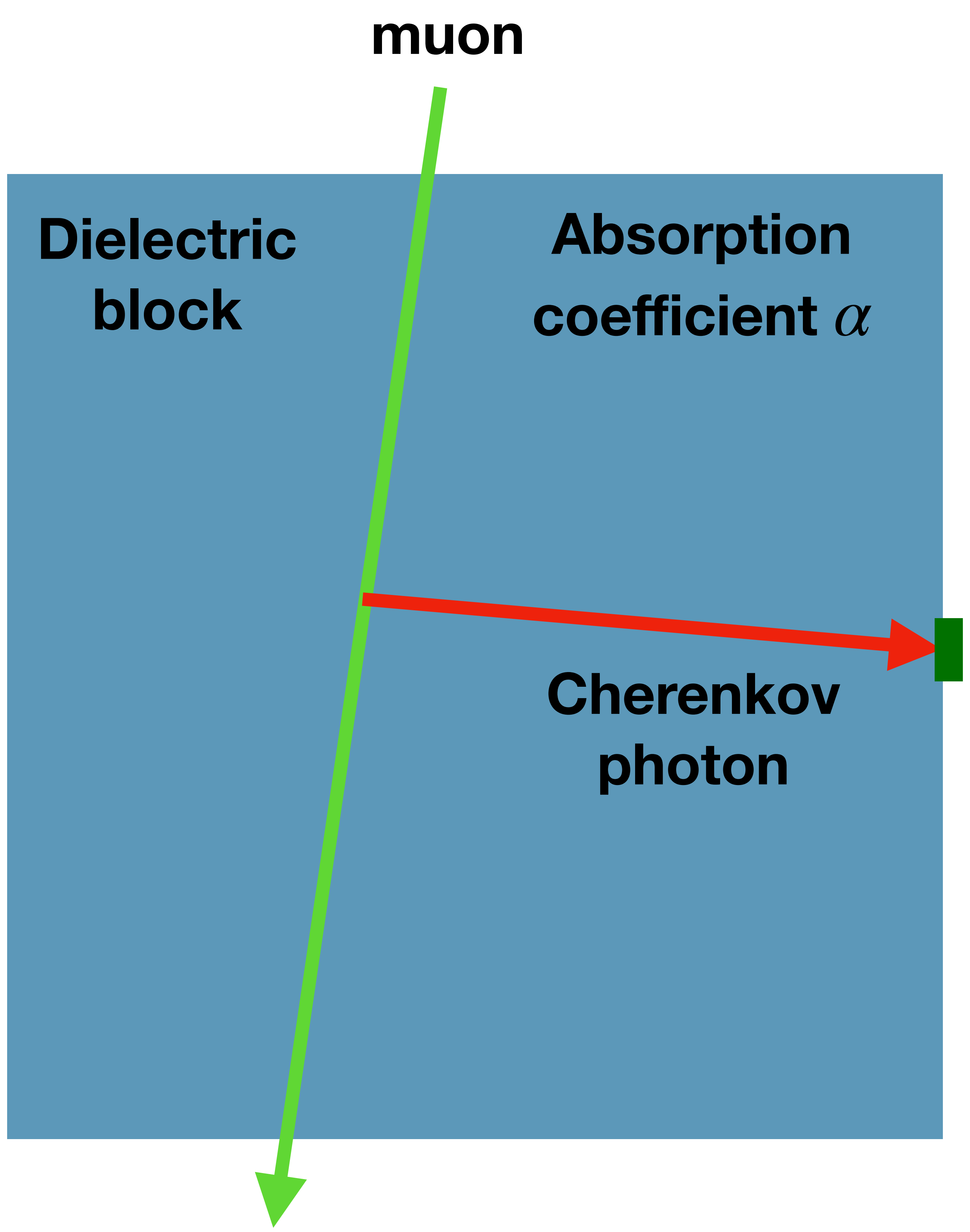

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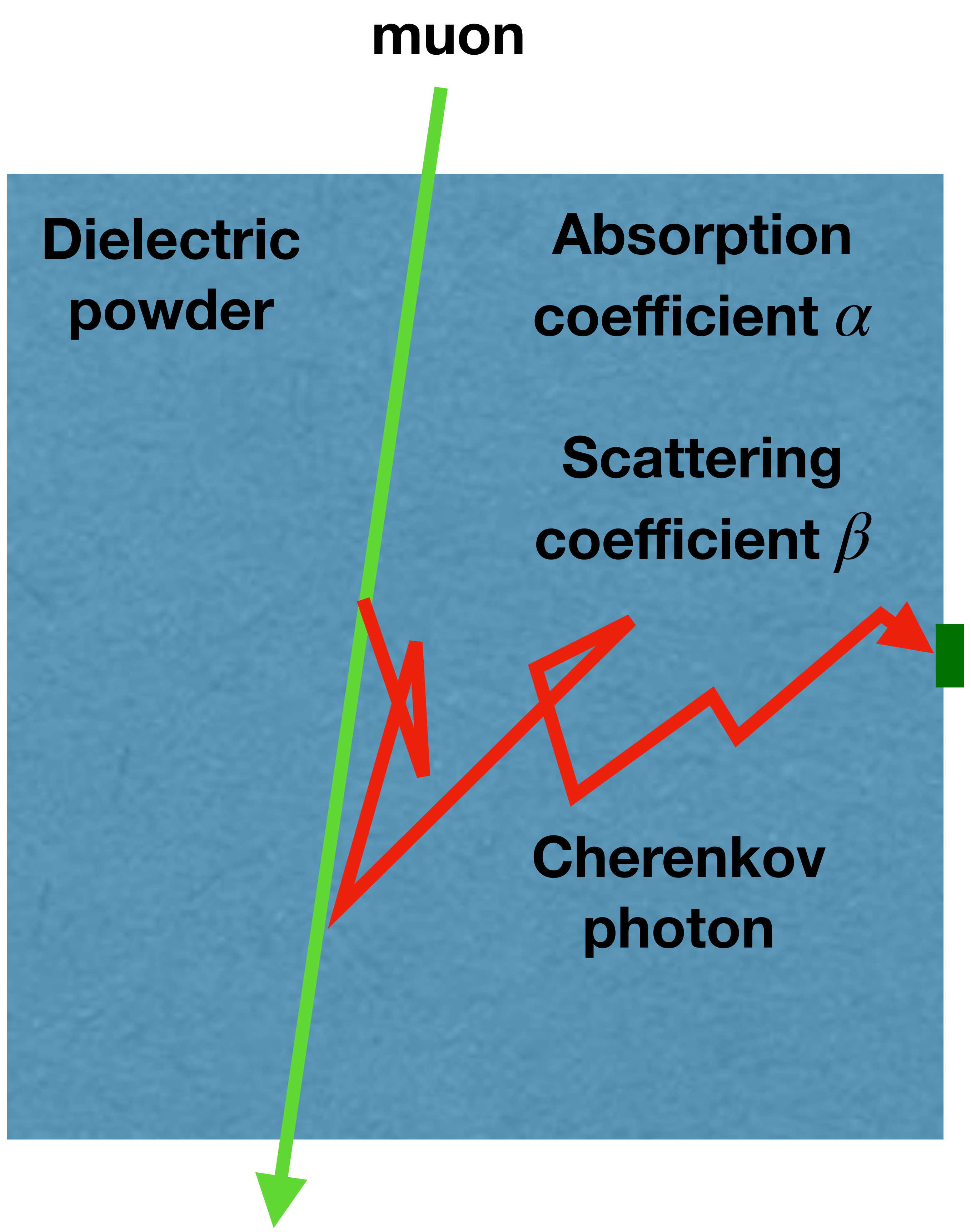
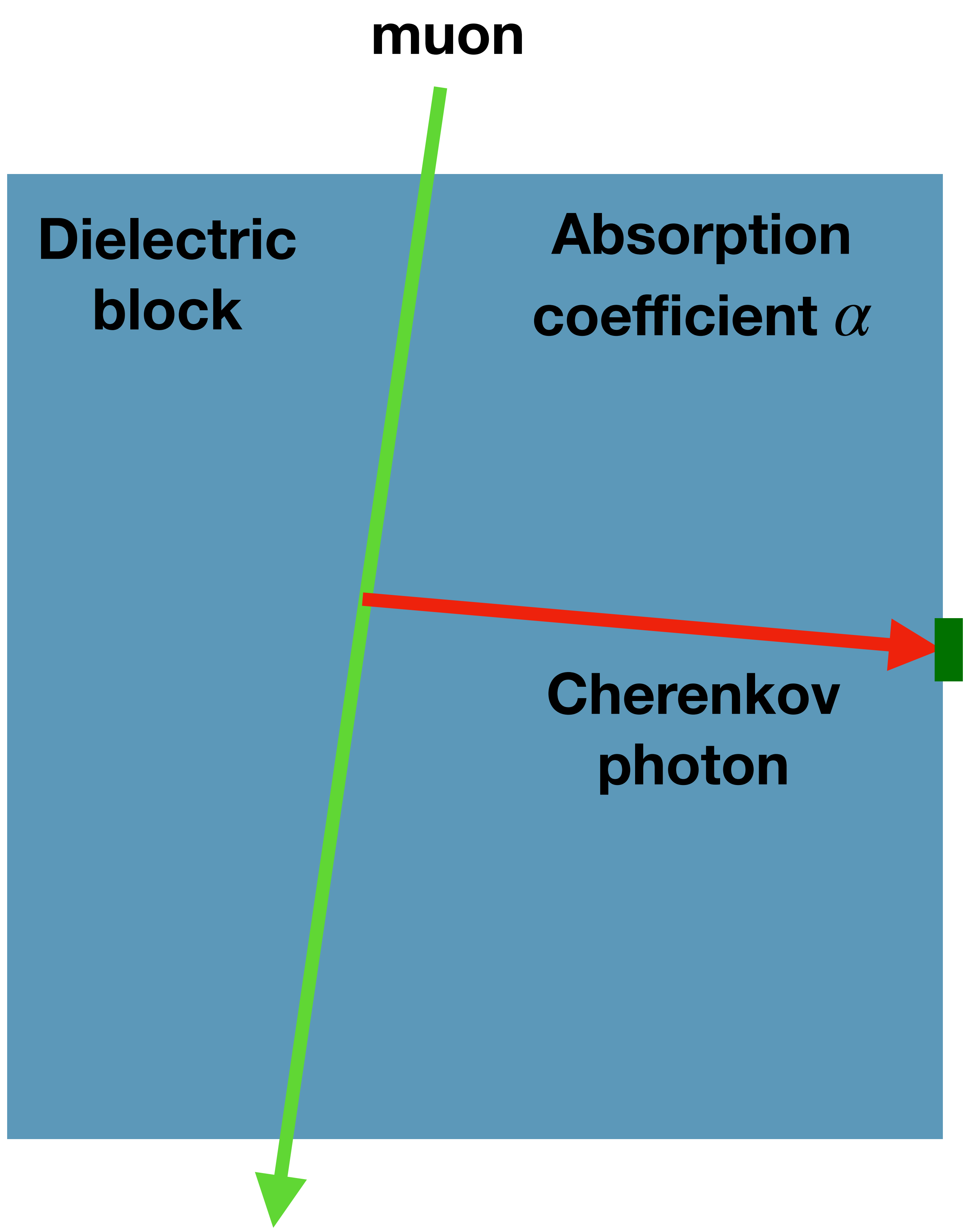


Rate of detection $\sim 1/\alpha$

Same # photons produced per second
Same # photons absorbed per second

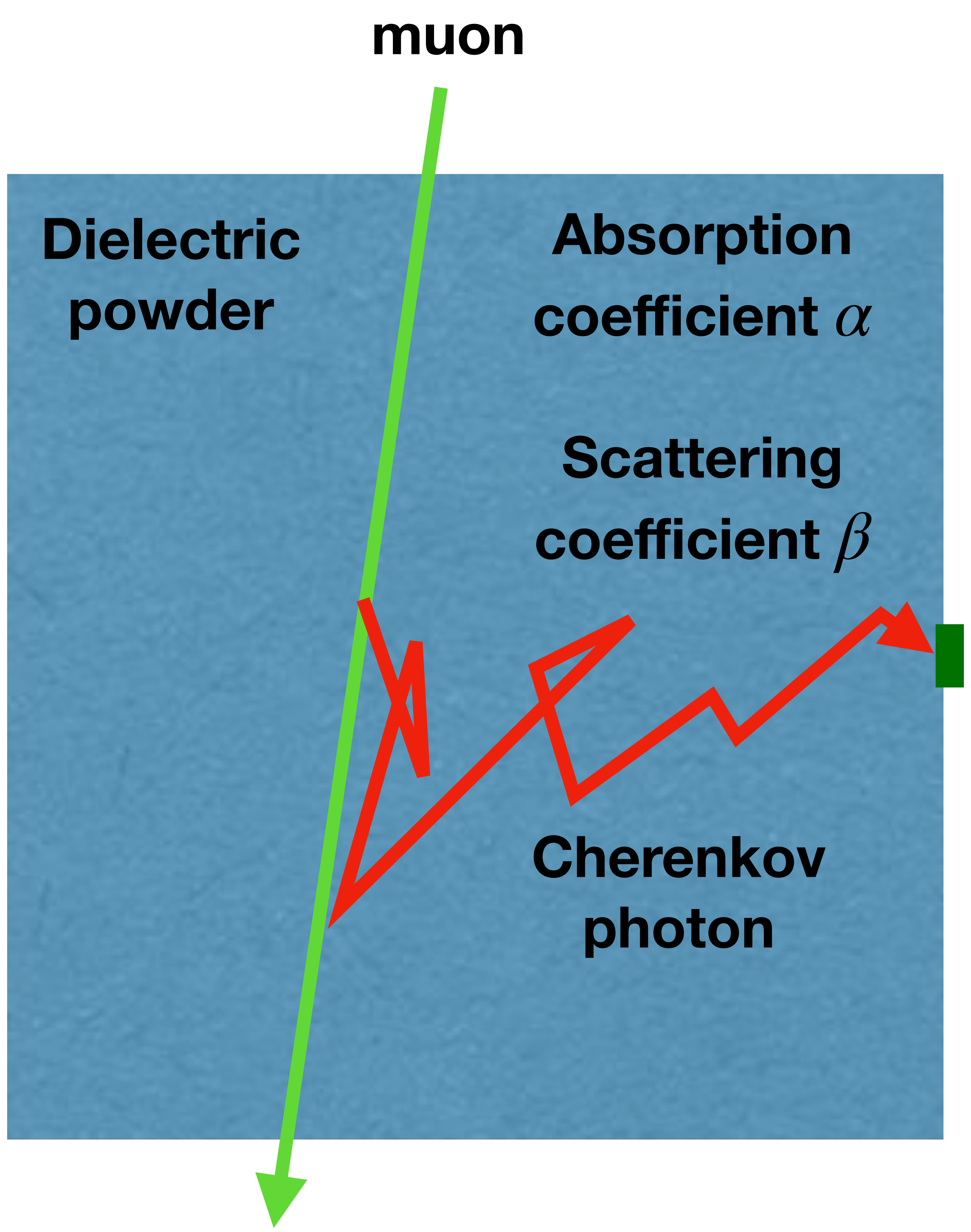
Same average optical energy density

Toy Problem: Detecting Cherenkov Photos



Rate of detection $\sim \int_0^\infty 2\pi r^2 dr \frac{e^{-r\alpha}}{4\pi r^2} \sim 1/\alpha$

Experiment volume: $\alpha^{-3} \sim 1m^3$



Rate of detection $\sim 1/\alpha$

Diffusion coefficient $\gamma \sim \sqrt{\alpha\beta}$

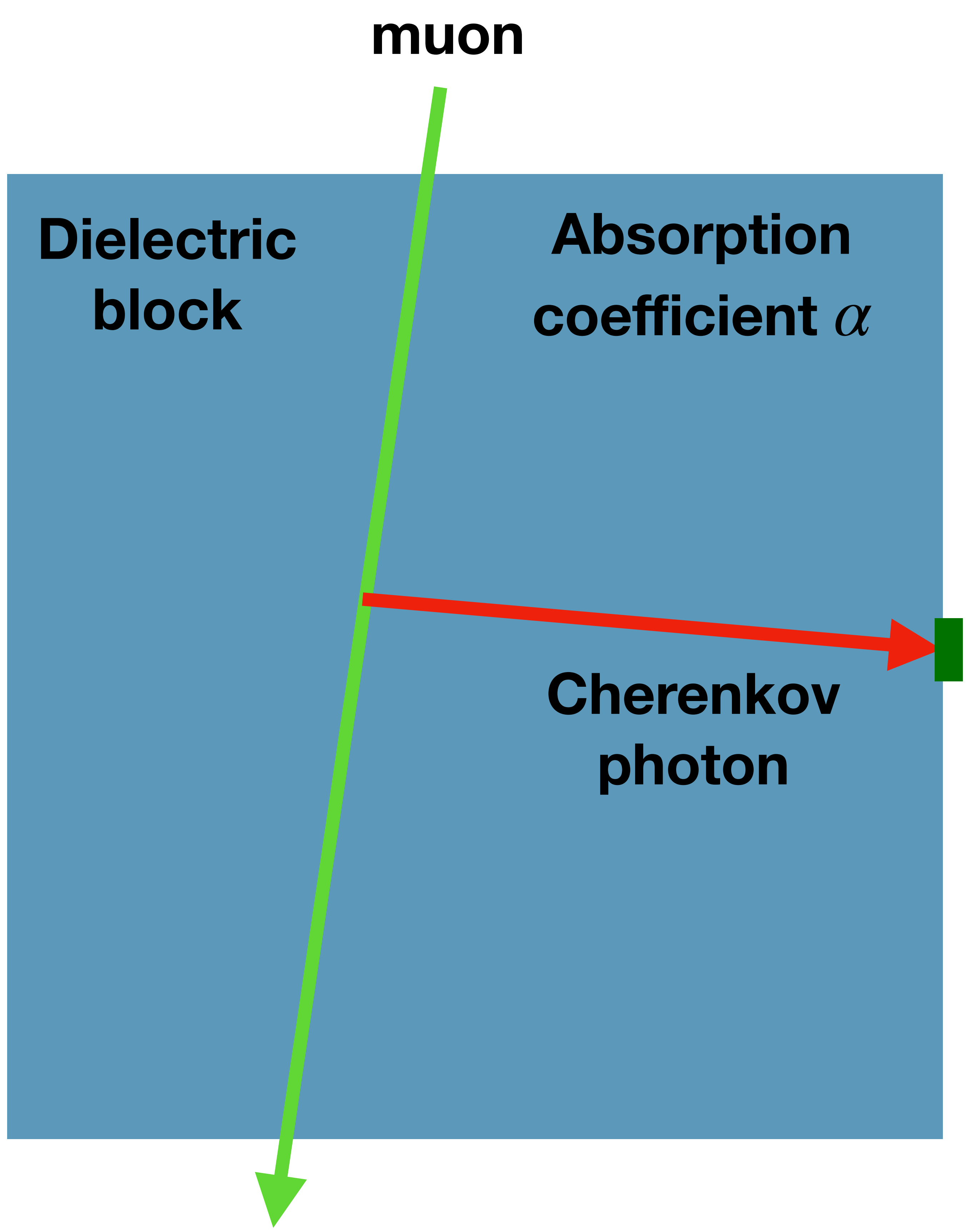
Experiment volume: $\gamma^{-3} \sim 1cm^3$

Same # photons produced per second
Same # photons absorbed per second

Same average optical energy density

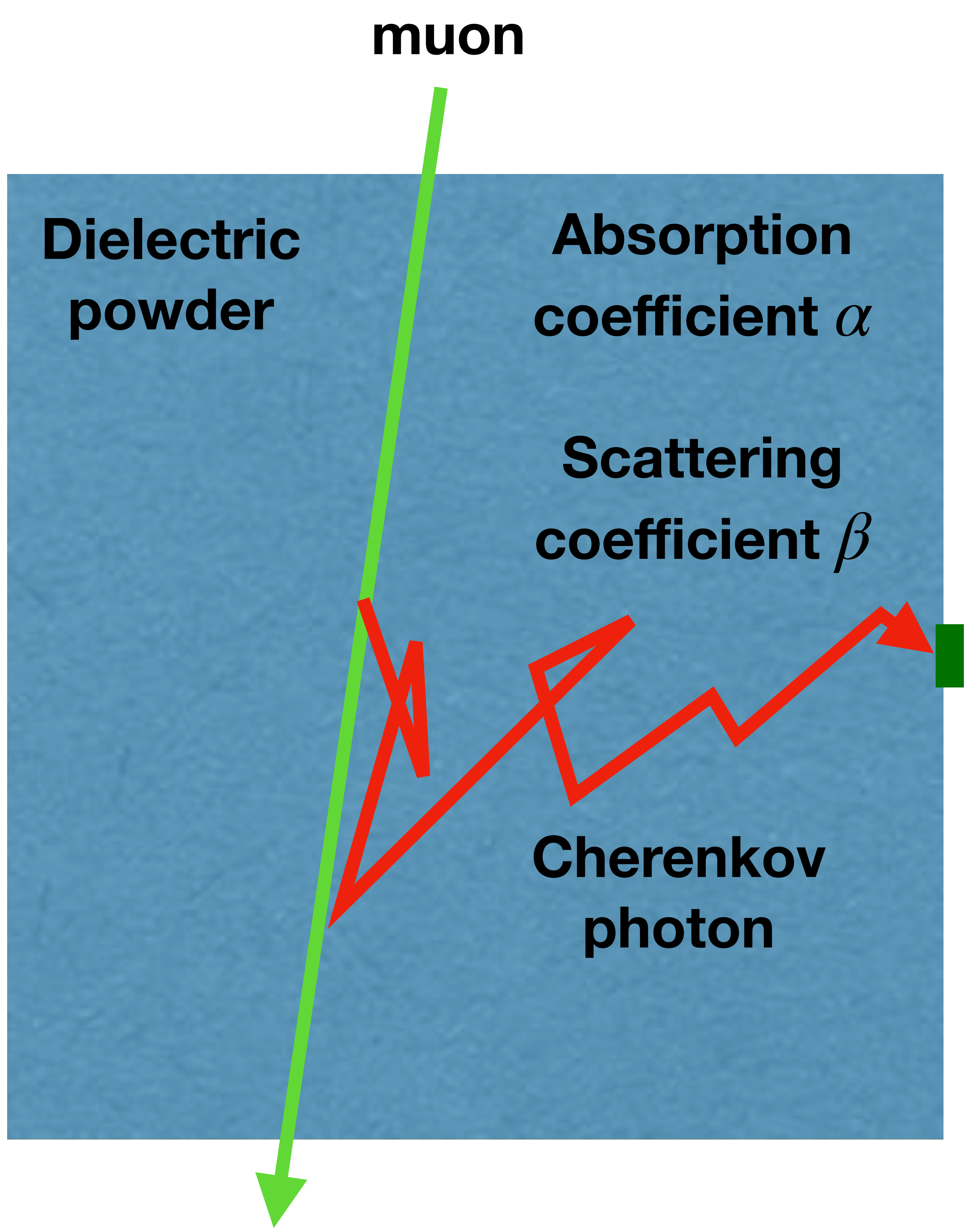
But in the scattering medium, each photon explores a smaller volume

Toy Problem: Detecting Cherenkov Photos



Rate of detection $\sim \int_0^\infty 2\pi r^2 dr \frac{e^{-r\alpha}}{4\pi r^2} \sim 1/\alpha$

Experiment volume: $\alpha^{-3} \sim 1m^3$



Rate of detection $\sim 1/\alpha$

Diffusion coefficient $\gamma \sim \sqrt{\alpha\beta}$

Experiment volume: $\gamma^{-3} \sim 1cm^3$

Different for DM

Same # photons produced per second

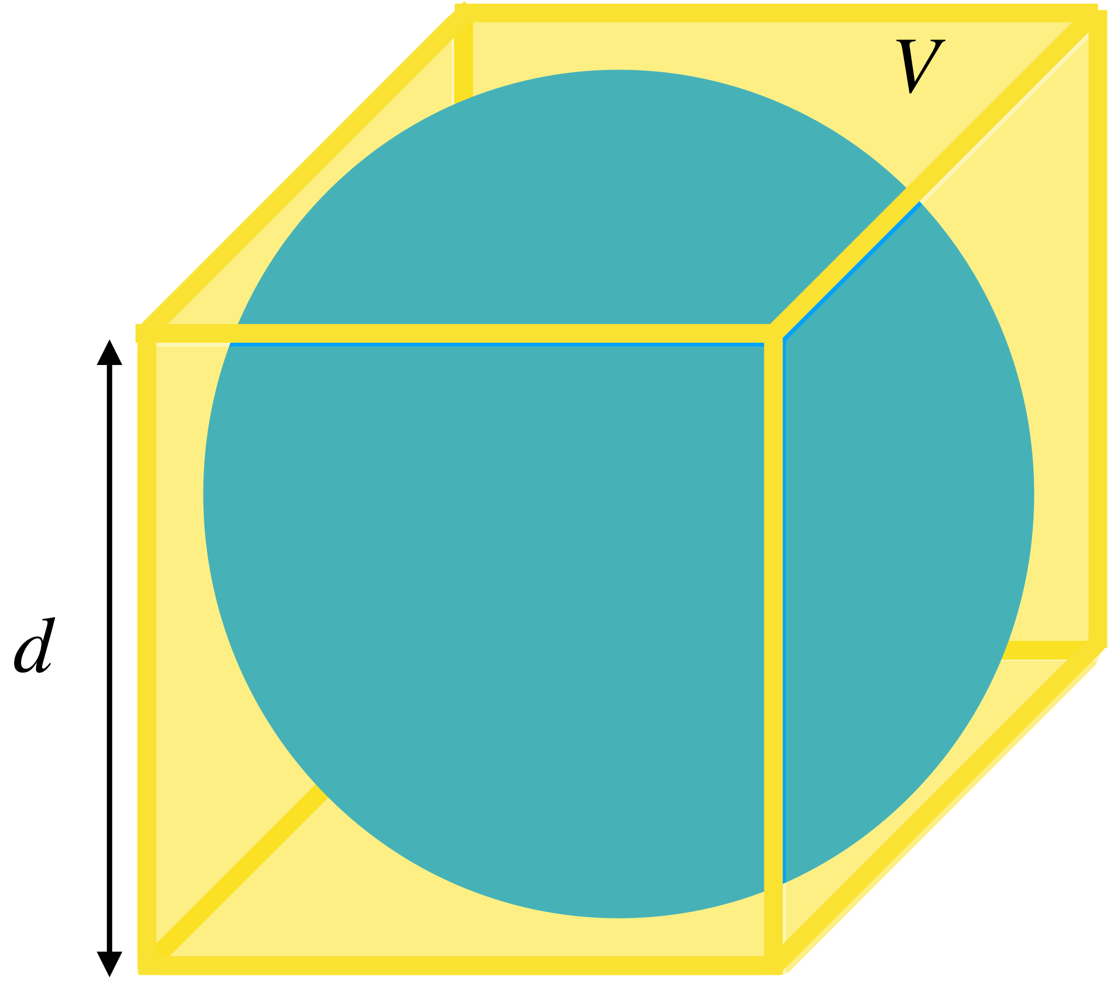
Same # photons absorbed per second

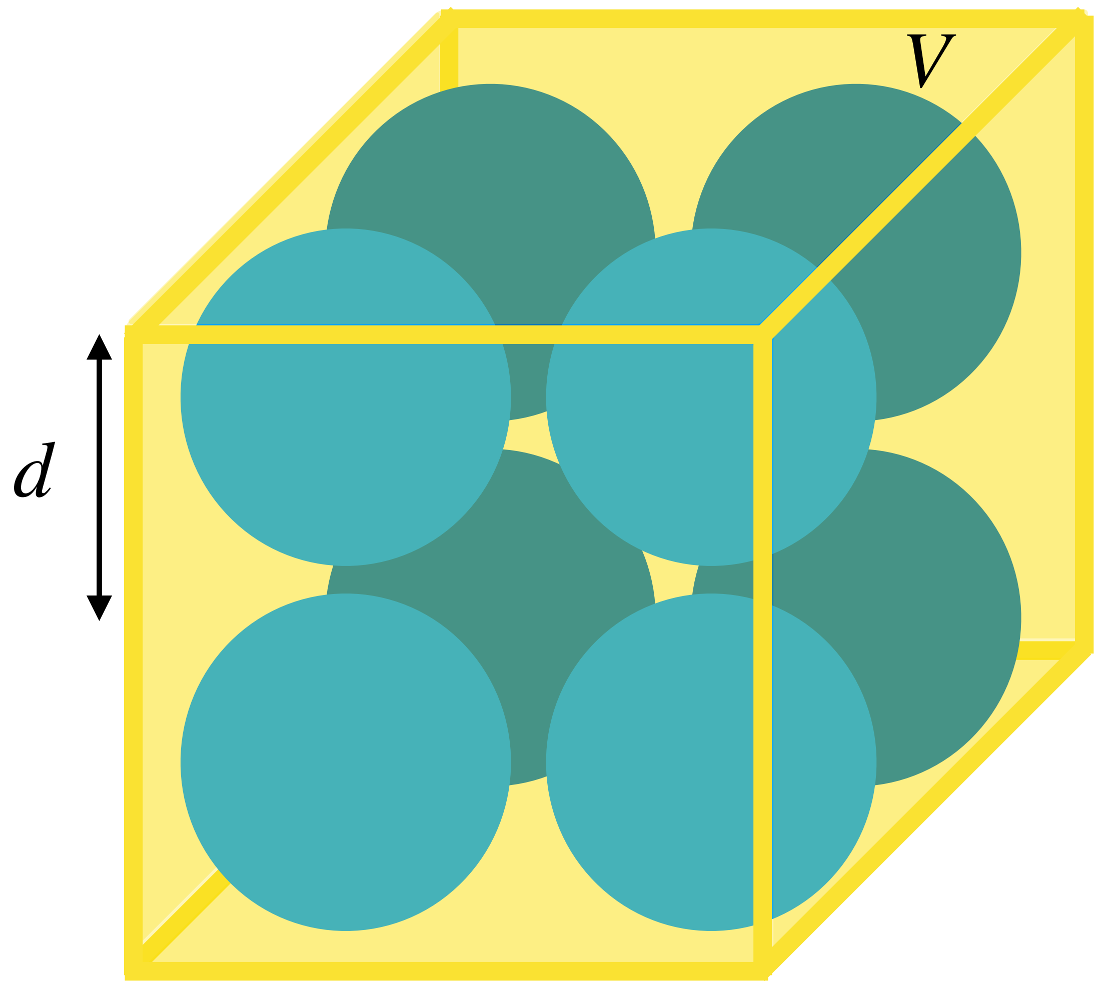
Same average optical energy density

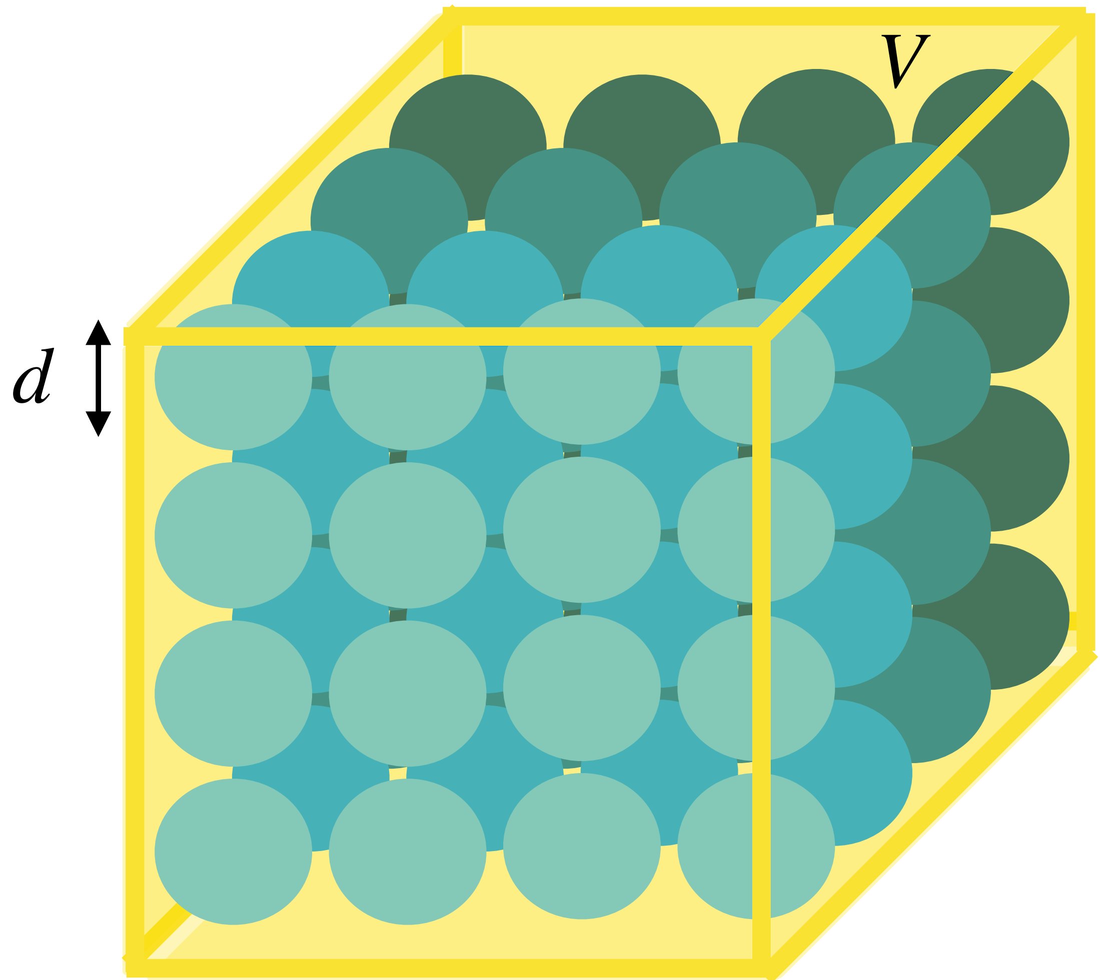
But in the scattering medium, each photon explores a smaller volume

Dark Matter Absorption by a Dielectric Sphere

Dark Matter Absorption by a Powder







Above diffraction limit: $d \gg \lambda/2\pi$

$$\frac{P}{V} \equiv \rho = \langle I \rangle \frac{\textbf{SA}}{V} = \langle I \rangle \frac{C_1}{d}$$

Densely-packed spheres: $C_1 = \sqrt{2}\pi$

Mie Scattering

$$\rho \sim \langle I \rangle Q \frac{C_1}{d}$$

Quality factor Q

Below diffraction limit: $d \ll \lambda/2\pi$

$$\rho = \langle I \rangle C_3 \frac{d^3}{\lambda^4}$$

Rayleigh scattering from $N \sim V/d^3$ **particles**

Signal Power in the Bulk

Above diffraction limit: $d \gg \lambda/2\pi$

Power per surface area

Effective volume per A_{det}

$$P_{det} = A_{det} I_0 \frac{1}{2}\left(1-\frac{1}{n}\right)^2\left(1+\frac{1}{n}\right)\frac{\sqrt{2}\pi}{d}\frac{1}{2\alpha}$$

Surface area per volume

Signal Power in the Bulk

Power per surface area — Effective volume per A_{det}

Above diffraction limit: $d \gg \lambda / 2\pi$

$$P_{det} = A_{det} I_0 \frac{1}{2}\left(1 - \frac{1}{n}\right)^2 \left(1 + \frac{1}{n}\right) \frac{\sqrt{2}\pi}{d} \frac{1}{2\alpha}$$

Surface area per volume

Plugging in some plausible numbers for SiO2 powder

If $n = 1.4,\ d = 1\mu m$**, and** $\alpha = 1m^{-1}$

$$P_{det} = 1.5 \times 10^5 A_{det} I_0$$

Signal Power in the Bulk

Above diffraction limit: $d \gg \lambda/2\pi$

Power per surface area

Effective volume per A_{det}

$$P_{det} = A_{det} I_0 \frac{1}{2}\left(1 - \frac{1}{n}\right)^2 \left(1 + \frac{1}{n}\right) \frac{\sqrt{2}\pi}{d} \frac{1}{2\alpha}$$

Surface area per volume

Plugging in some plausible numbers for SiO2 powder

If $n = 1.4,\ d = 1\mu m$**, and** $\alpha = 1m^{-1}$

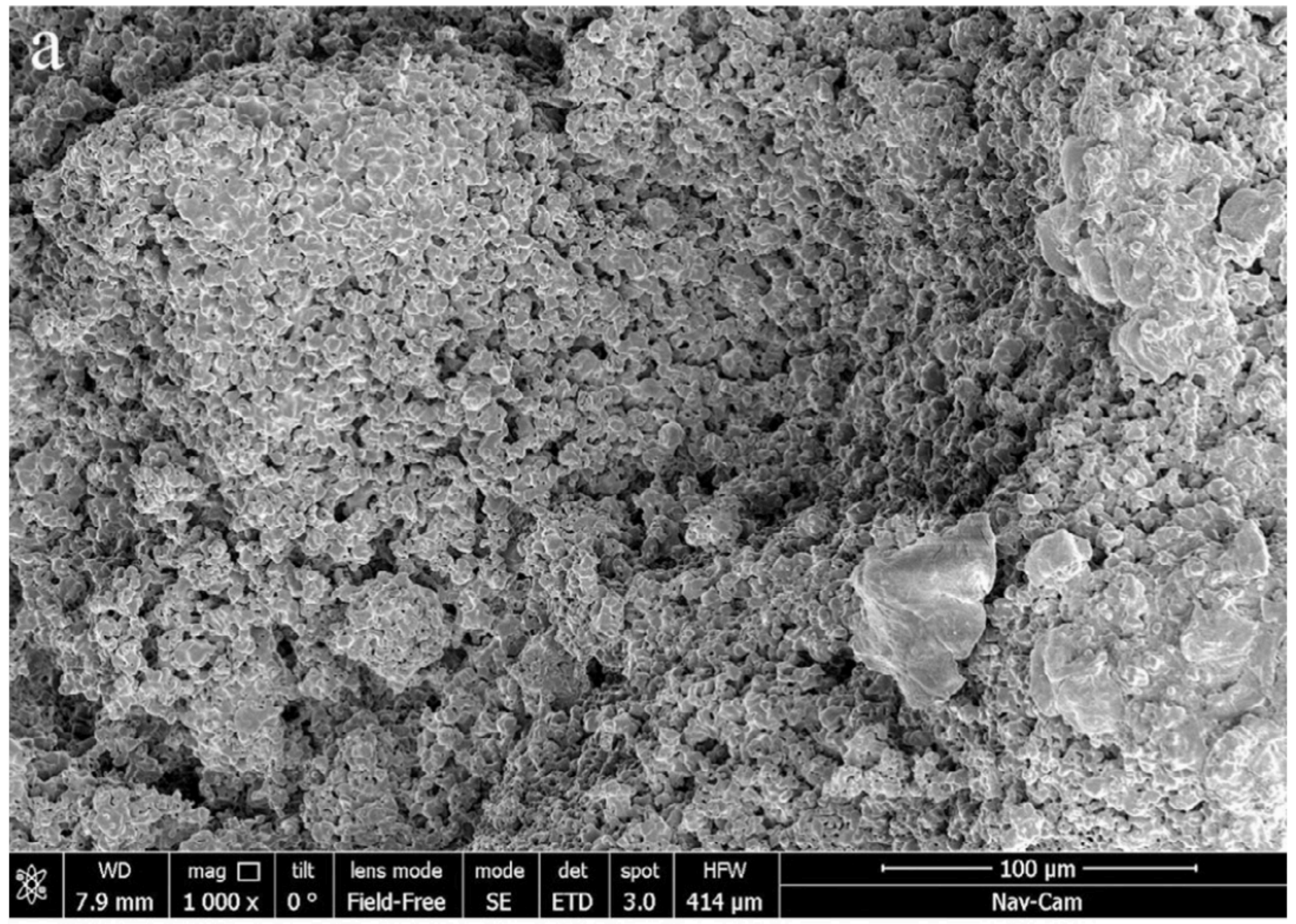
$$P_{det} = 1.5 \times 10^5 A_{det} I_0$$

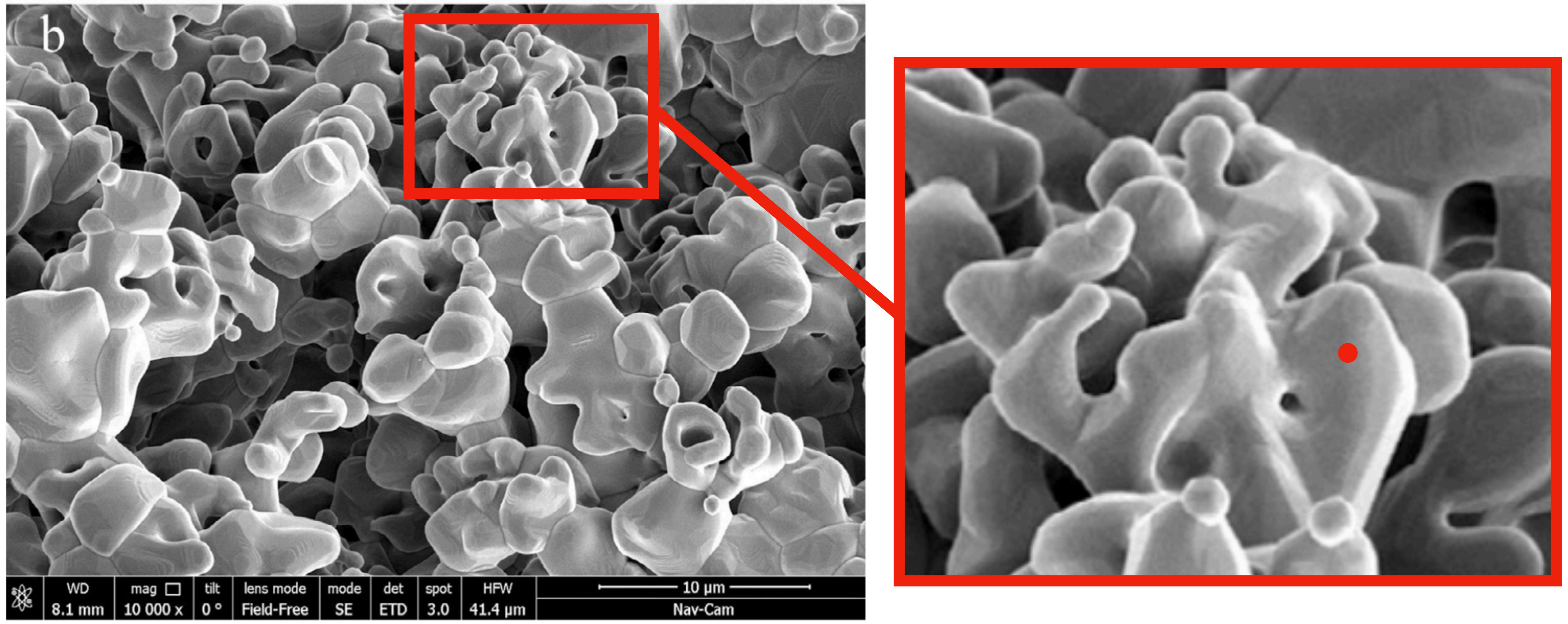
Which is equivalent to collecting photons from a mirror with area $A_{eff} = A_{det} 1.5 \times 10^5$

If $A_{det} = 1cm^2$

$$A_{eff} = 15.5m^2$$

Optical Transport in AlO2 and TiO2





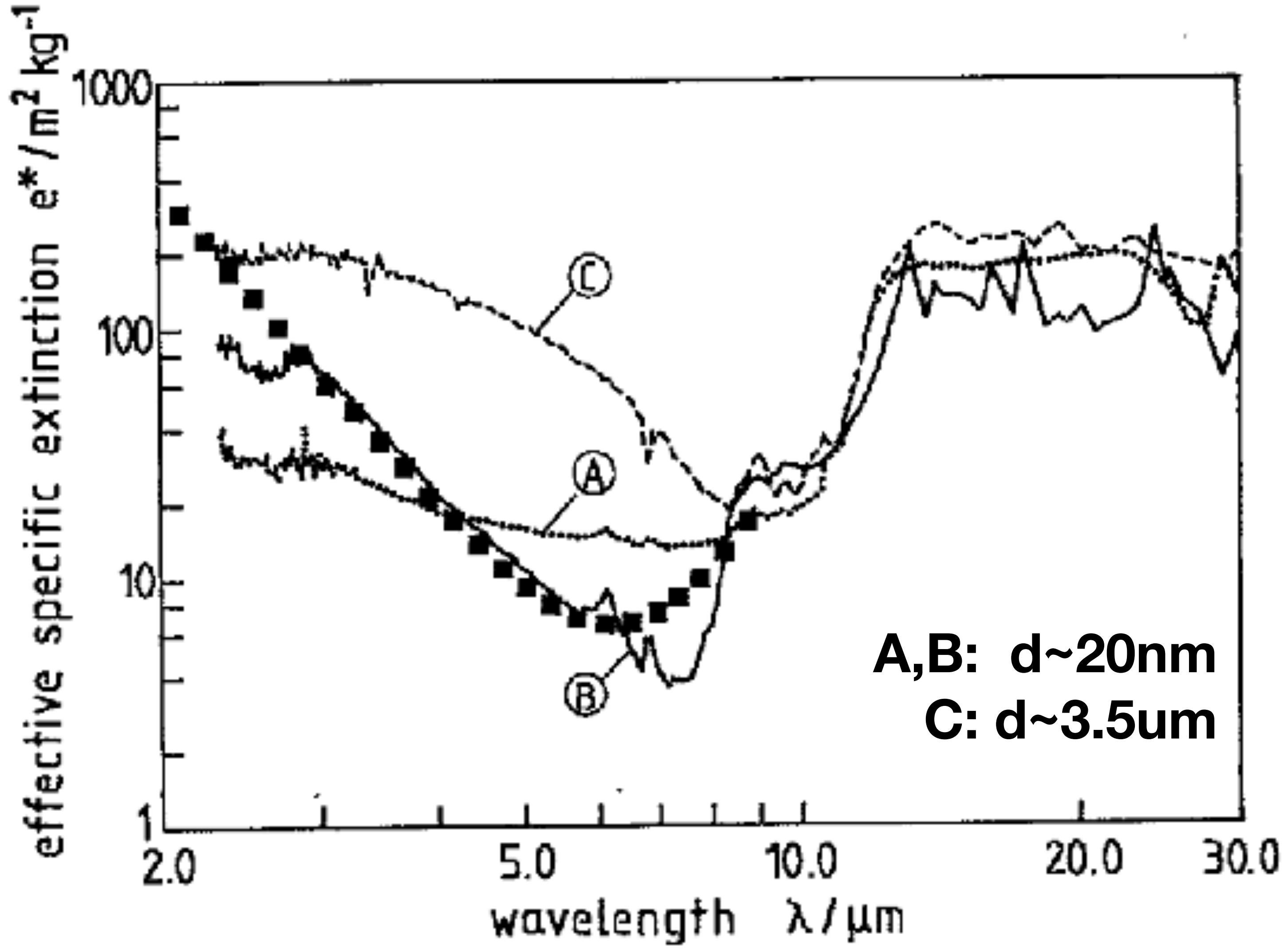
Porous Alumina

$\lambda = 0.5 - 3\mu m$

$\alpha \sim 0.1m^{-1}$

$\beta \sim 0.2cm^{-1}$

Titania Powder



$\beta \sim 0.1\mu m^{-1}$

Near-infrared optical properties of a porous alumina ceramics produced by hydrothermal oxidation of aluminum

Aleksey V. Lisitsyn [a], Leonid A. Dombrovsky [b,*], Vladimir Ya. Mendeleyev [a], Anatoly V. Grigorenko [a], Mikhail S. Vlaskin [a], Andrey Z. Zhuk [a]

[a] Joint Institute for High Temperatures, NCHMT, Krasnokazarmennaya 17A, Moscow 111116, Russia
[b] Joint Institute for High Temperatures, Izhorskaya 13-2, Moscow 625003, Russia

Infrared-optical transmission and reflection measurements on loose powders

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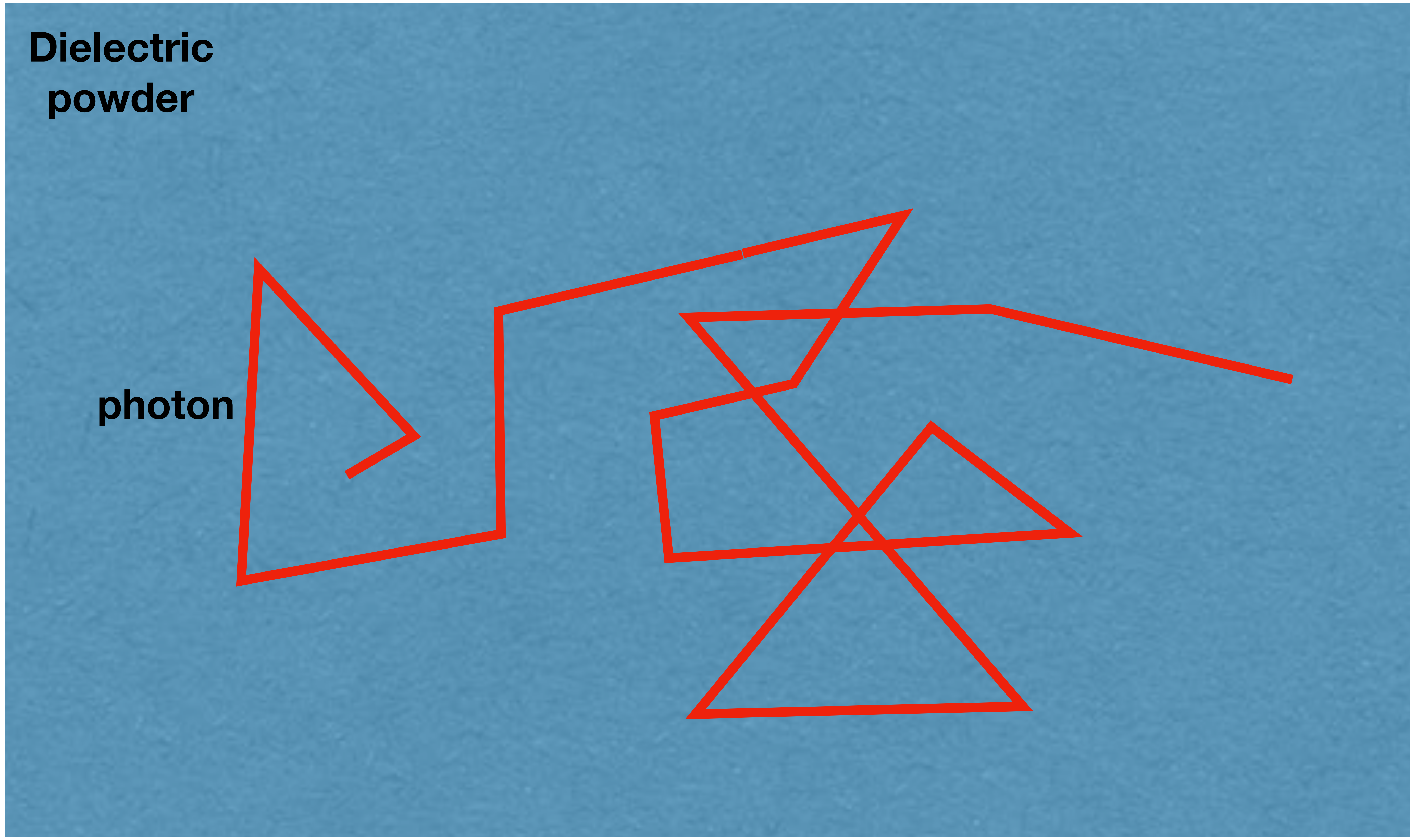
Submitted: 05 February 1993 · Accepted: 24 May 1993 · Published Online: 04 June 1998

J. Kuhn, S. Korder, M. C. Arduini-Schuster, et al.

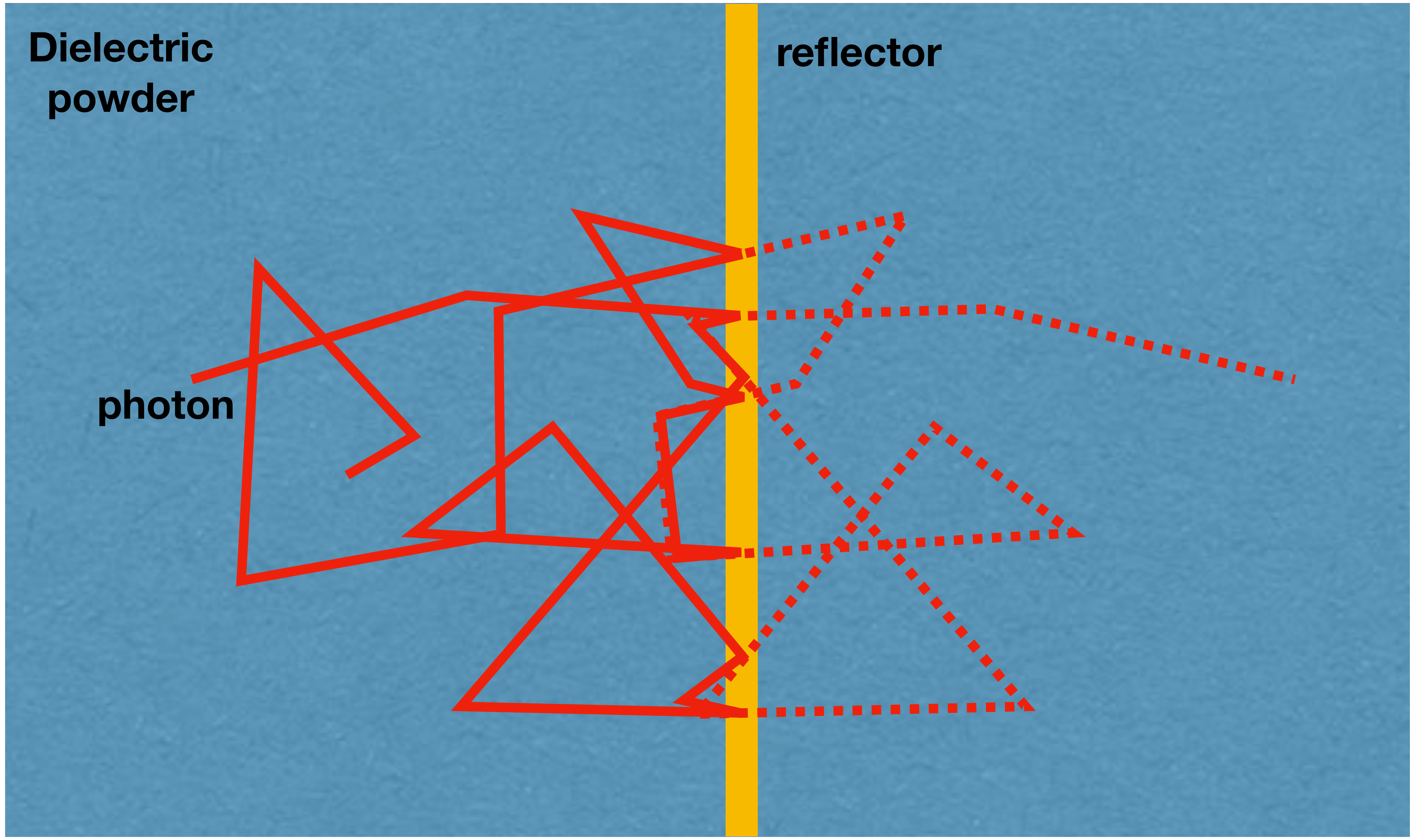
Boundary Effects



Boundary Effects: Reflective Boundary

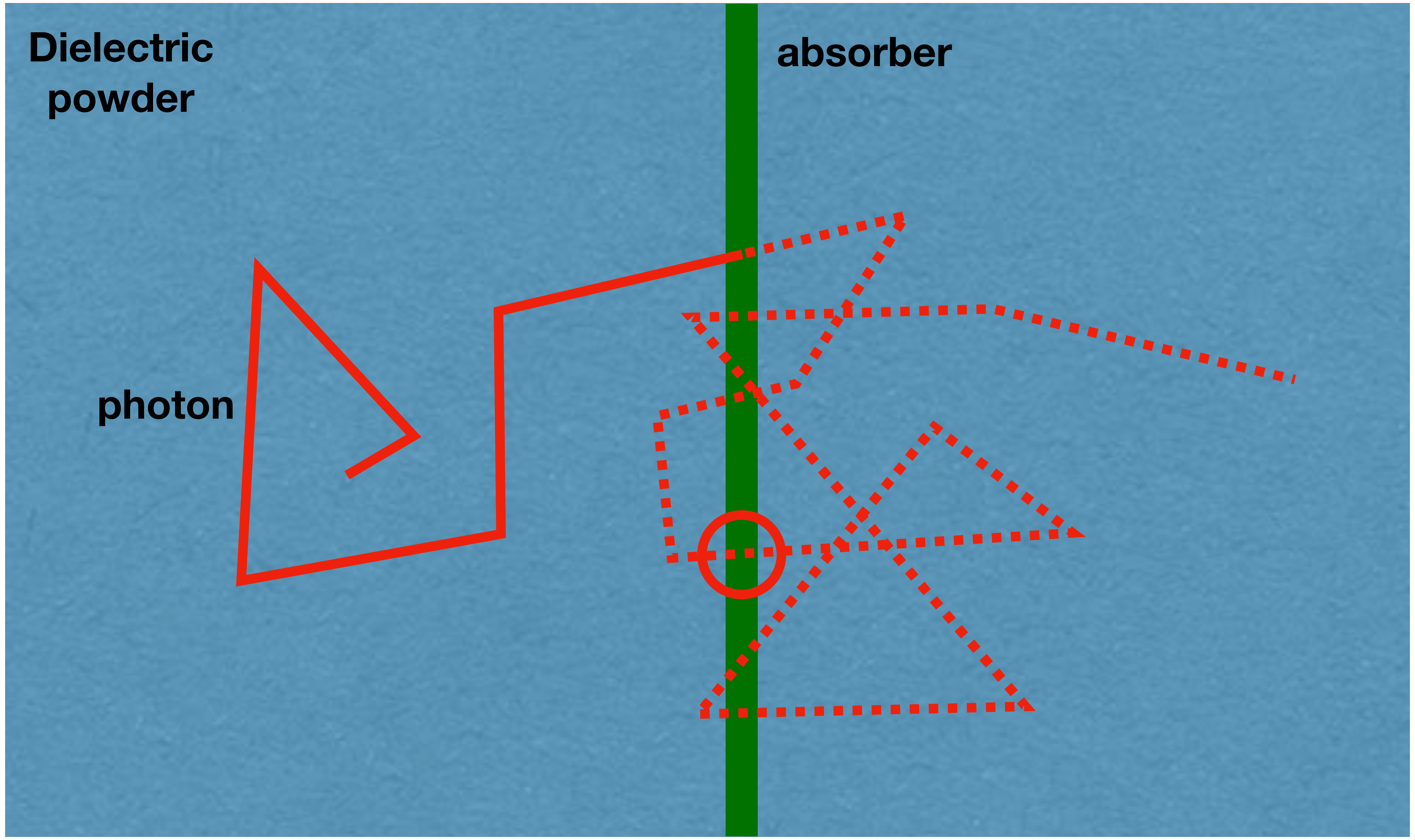
expected number of reflections

Effective absorption coefficient: $\alpha_{eff} = \alpha R^{\langle n \rangle}$



Boundary Effects: Absorbing Boundary

Absorbers cast a shadow on themselves



Optical Transport in Powder

Radiation transfer equation

Material Properties ⟷ Observables

α, β

R, τ

reflectance, optical depth

$$\partial_{\hat{n}} I_{\hat{n}}(\vec{r}) = \rho_{\hat{n}} - (\alpha + \beta) I_{\hat{n}}(\vec{r}) + \beta \sum_{\hat{n}'} I_{\hat{n}'}(\vec{r}) p(\hat{n}, \hat{n}')$$

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Radiation transfer equation

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Optical power generation — Extinction — In-scattering

Optical Transport in Powder

Radiation transfer equation

Material Properties ⟷ Observables

α, β

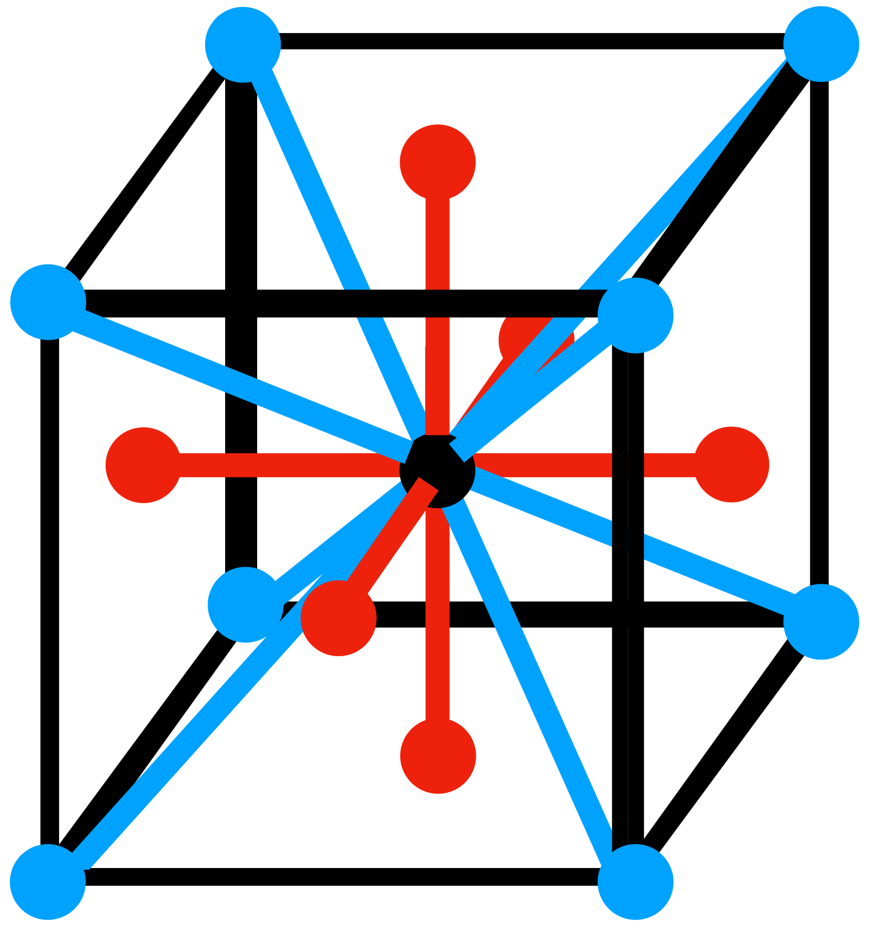
R, τ

reflectance, optical depth

$$\partial_{\hat{n}} I_{\hat{n}}(\vec{r}) = \rho_{\hat{n}} - (\alpha + \beta) I_{\hat{n}}(\vec{r}) + \beta \sum_{\hat{n}'} I_{\hat{n}'}(\vec{r}) p(\hat{n}, \hat{n}')$$

Optical power generation — Extinction — In-scattering

$$I_{\hat{n}} \in \mathbb{R}^3 \otimes S^2$$



14 angles

Quasi-3D Random Walk

Formulation as random walk

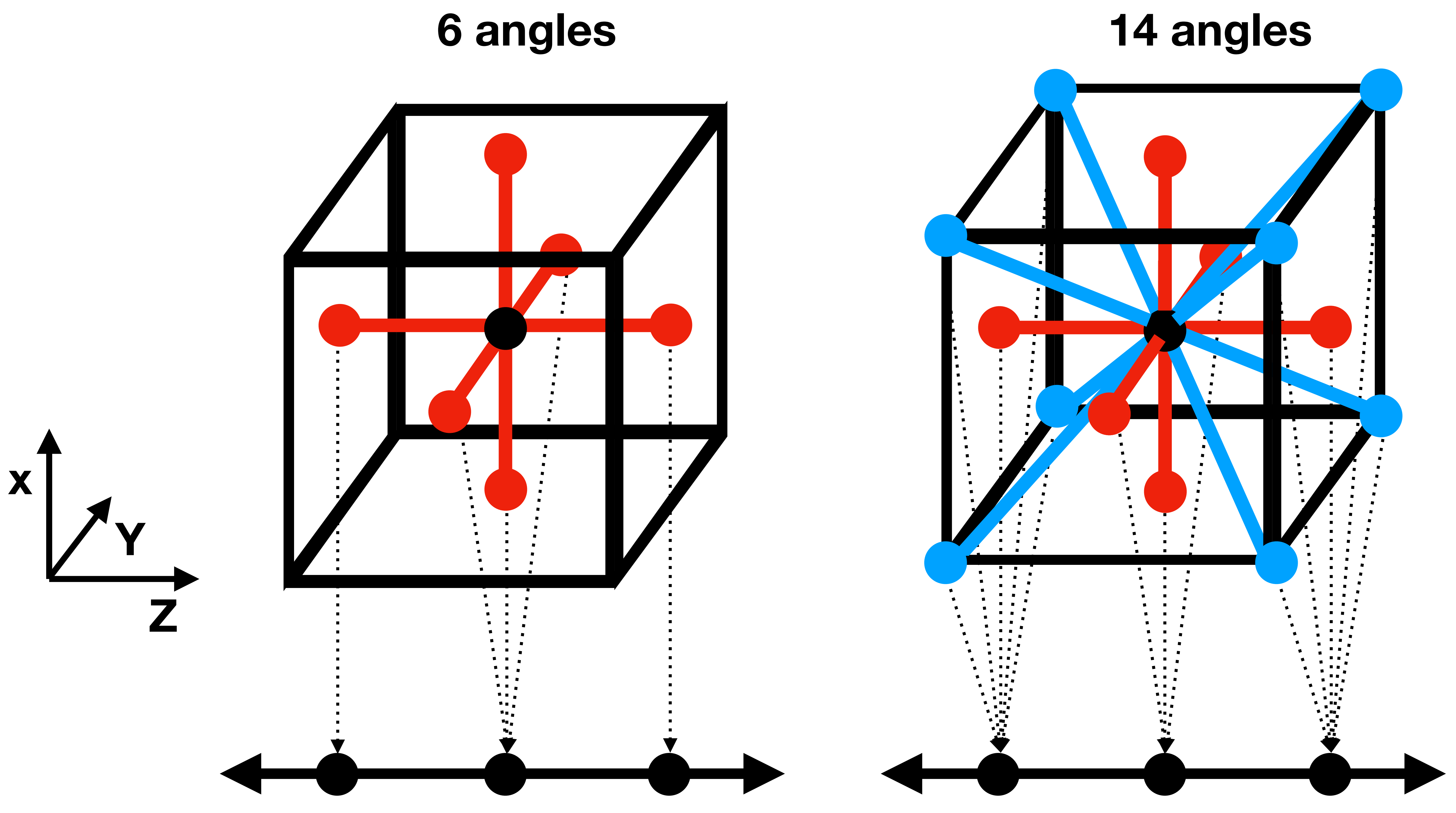
Parameters

Step size	$1/\beta$
Step direction	$p(\hat{n}, \hat{n}') =$ **const**
Walk length	$\gg 1/\alpha$

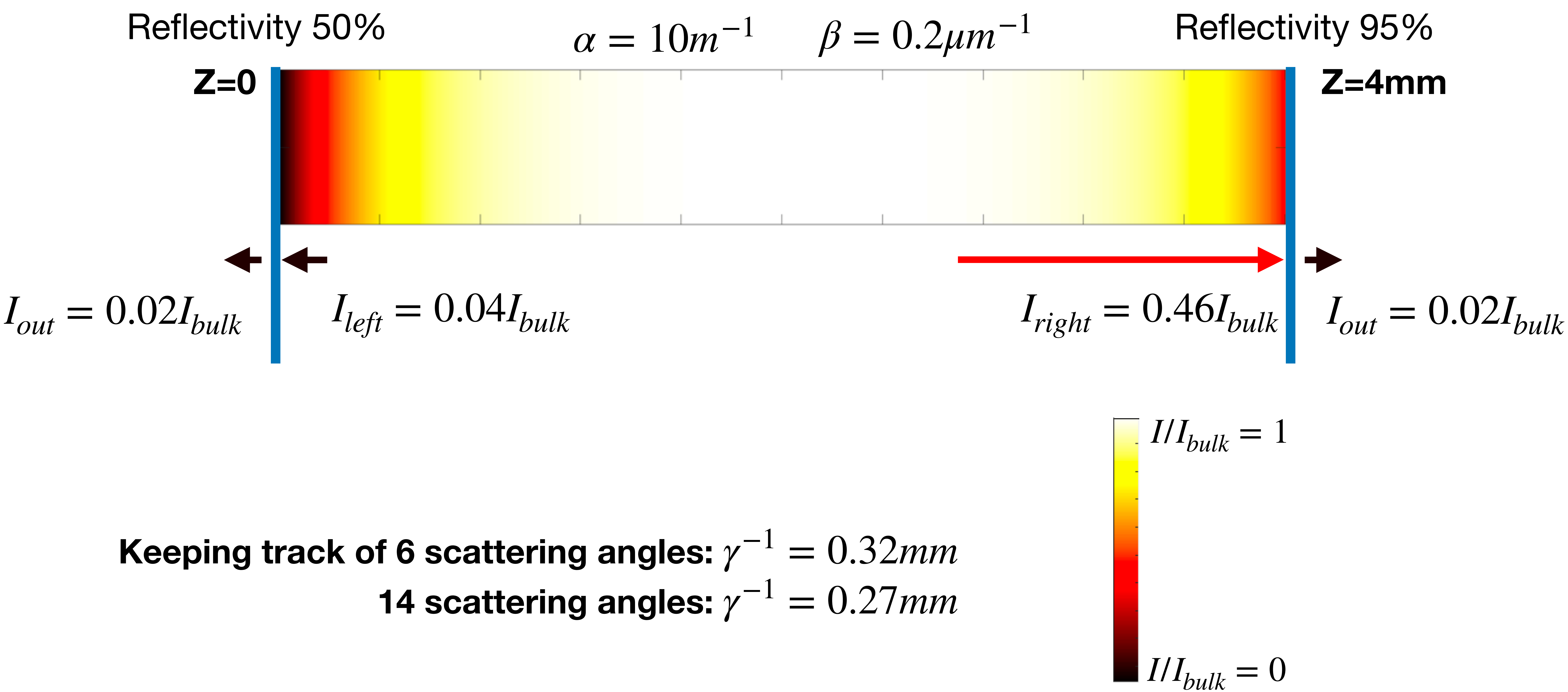
Outputs

Optical Depth	$I(z) = I_0 \exp(-z/\tau)$
Reflectance	$R = \sum_s p(z < 0)$

xy translational symmetry



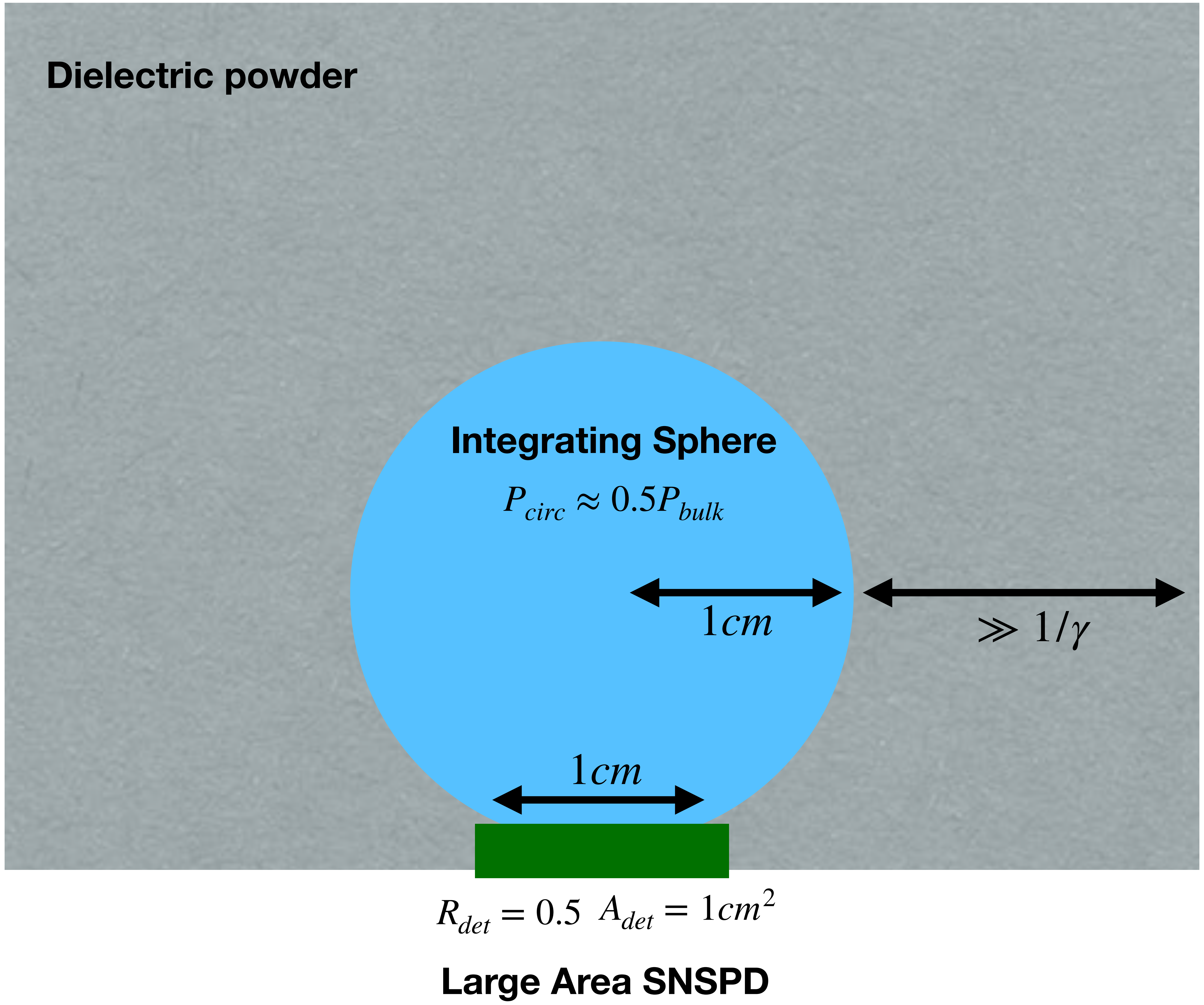
Quasi-3D Random Walk



Keeping track of 6 scattering angles: $\gamma^{-1} = 0.32mm$

14 scattering angles: $\gamma^{-1} = 0.27mm$

Experimental Scheme



Circulating power depends on effective reflectance:

$$R_{eff} = \frac{A_{IS} + R_{det}A_{det}}{A_{IS} + A_{det}}$$

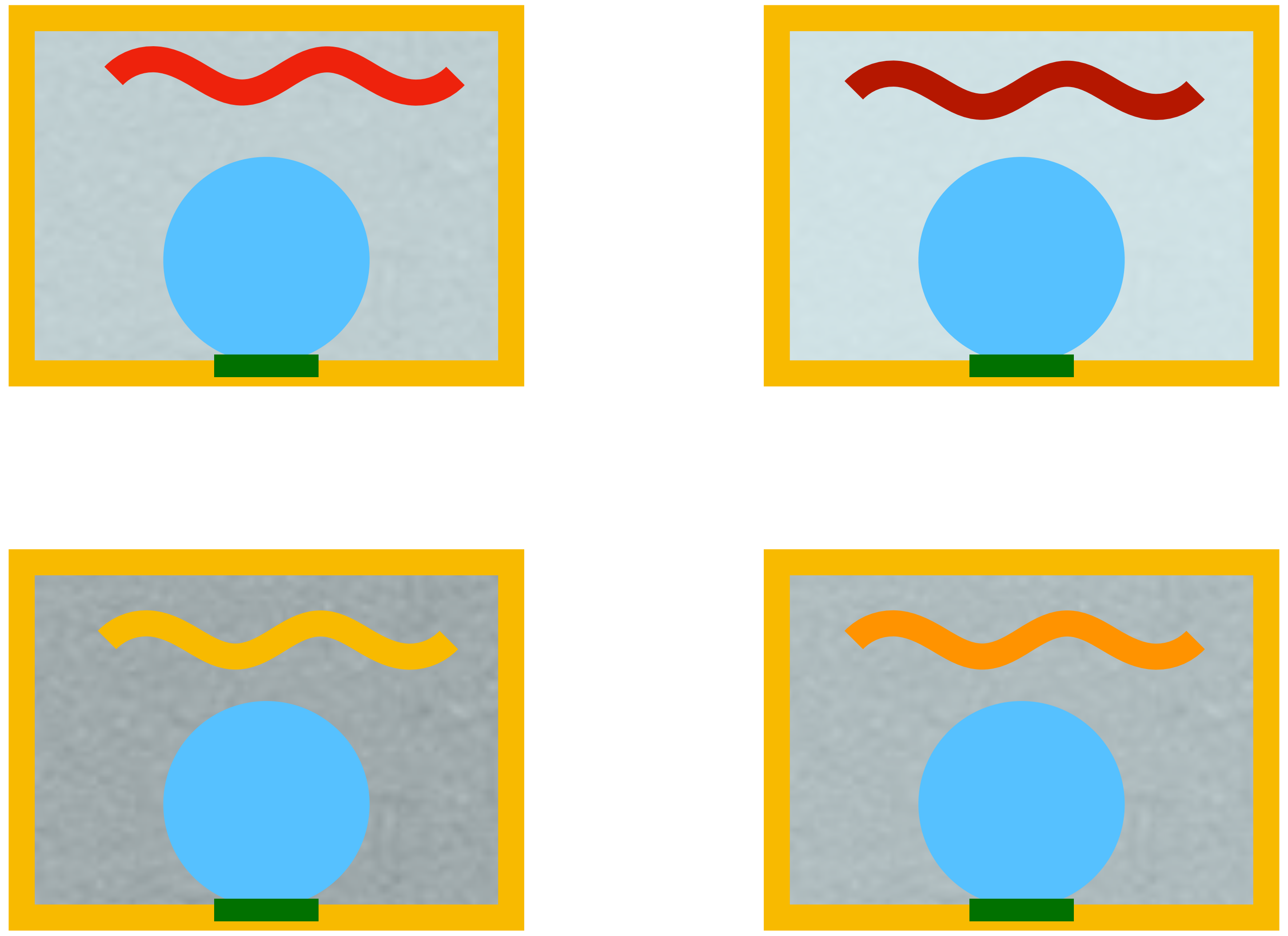
Absorbed power:

$$P_{abs} \approx P_{circ}(1 - R_{det}) \approx 0.25 P_{bulk}$$

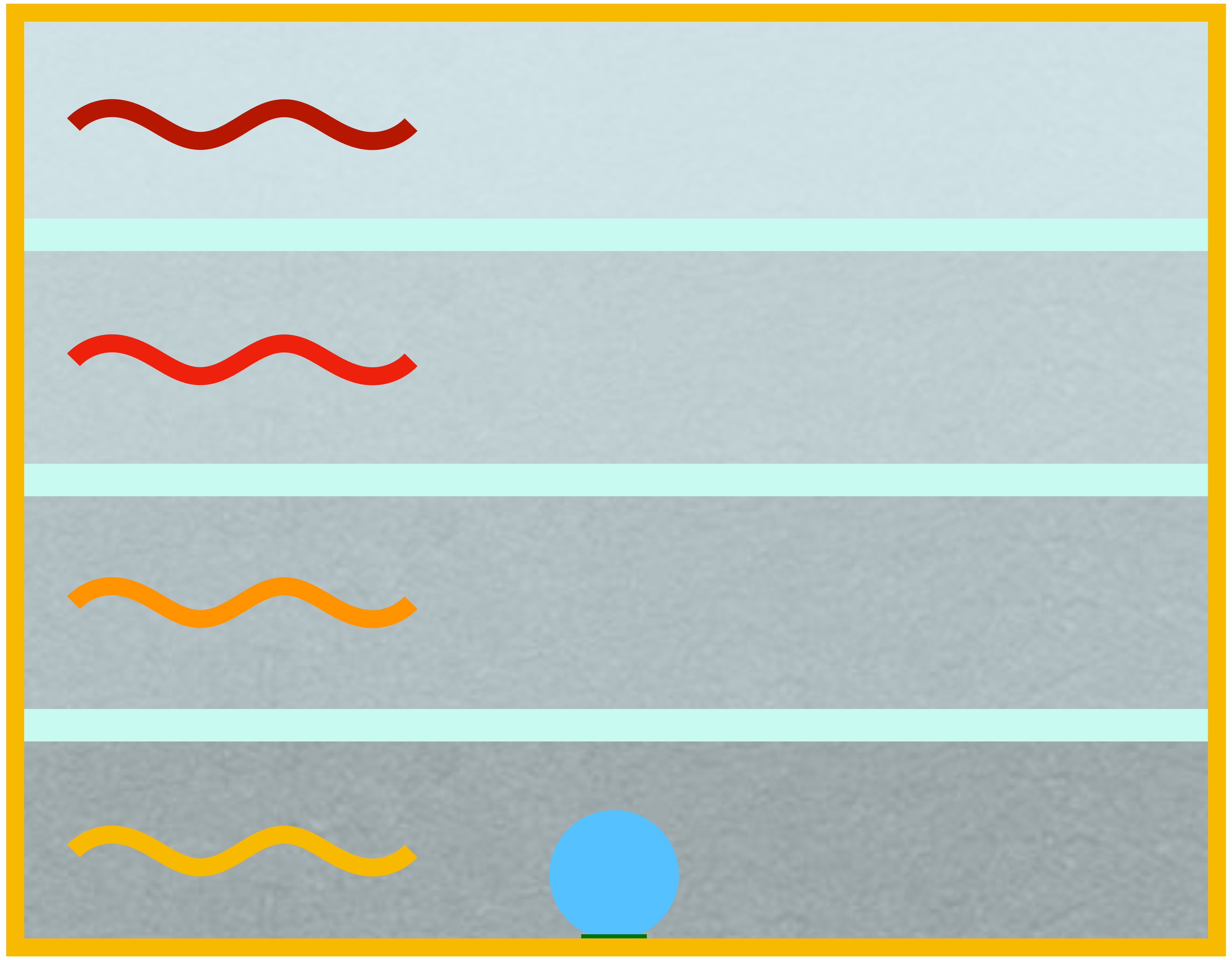
External efficiency

Scaling Up

Many cm-scale detectors could fit in 1 cryostat

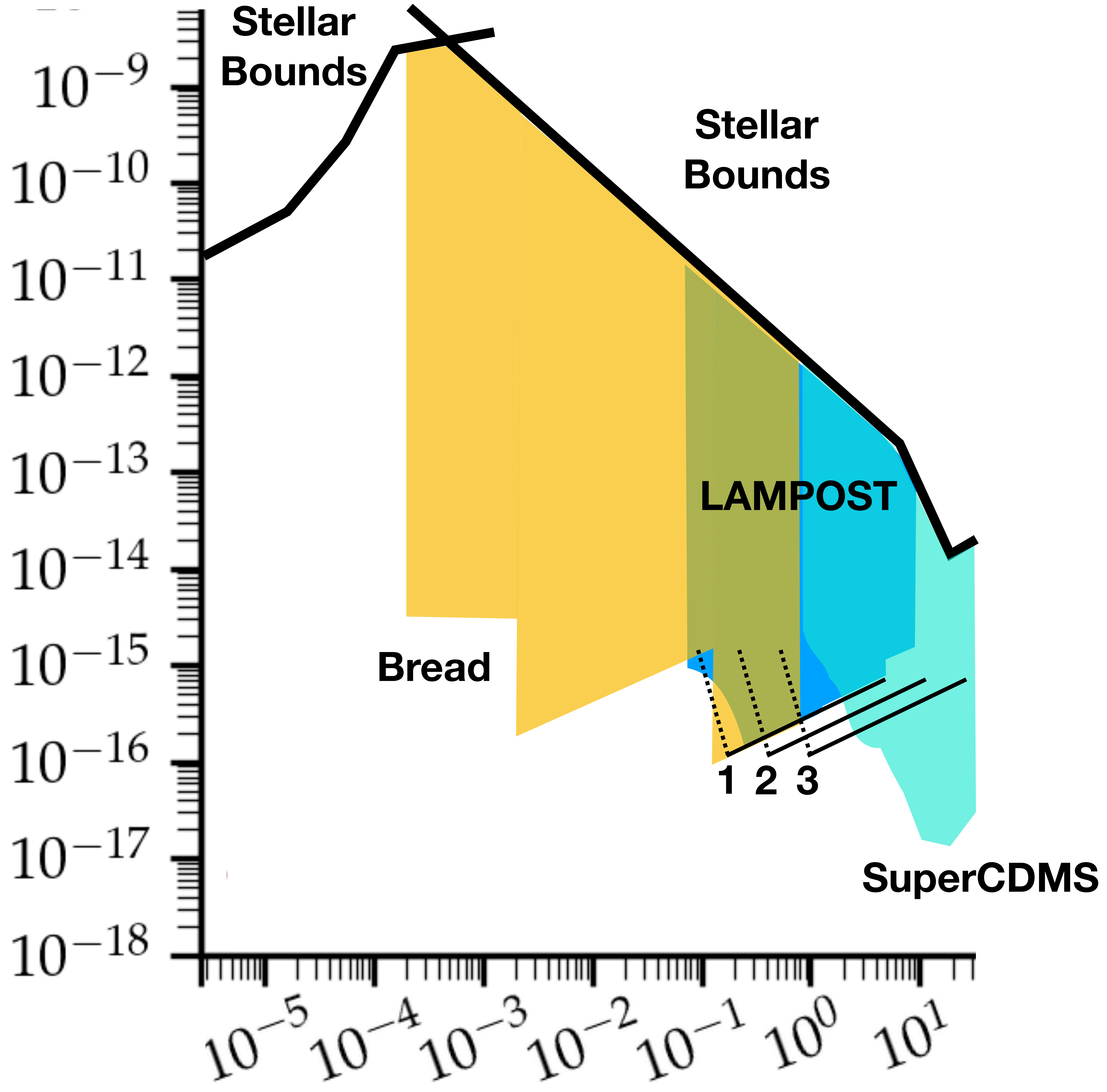


Or it may be more efficient to create one large layered detector



Dark Photon Reach with DielectricPowder

For powder with $\alpha \sim 1m^{-1}$



1. 1 micron powder
2. 500nm powder
3. 200nm powder

Challenges

- We need to measure the absorption and scattering coefficients of AlO2, SiO_2, and Si powders
- Dielectric powder absorbers should capture many Cherenkov photons: we will need an excellent muon veto system
- It may be difficult to efficiently cool the powder
- We need to fabricate and characterize large area SNSPDs

Acknowledgements

Karl Berggren

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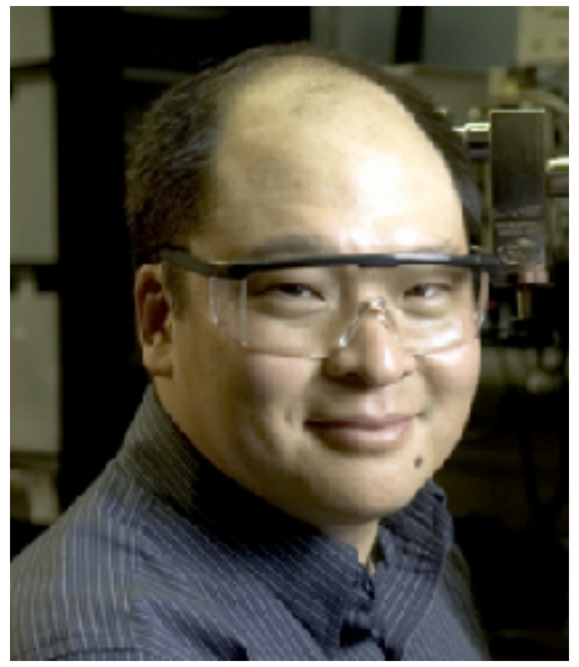

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