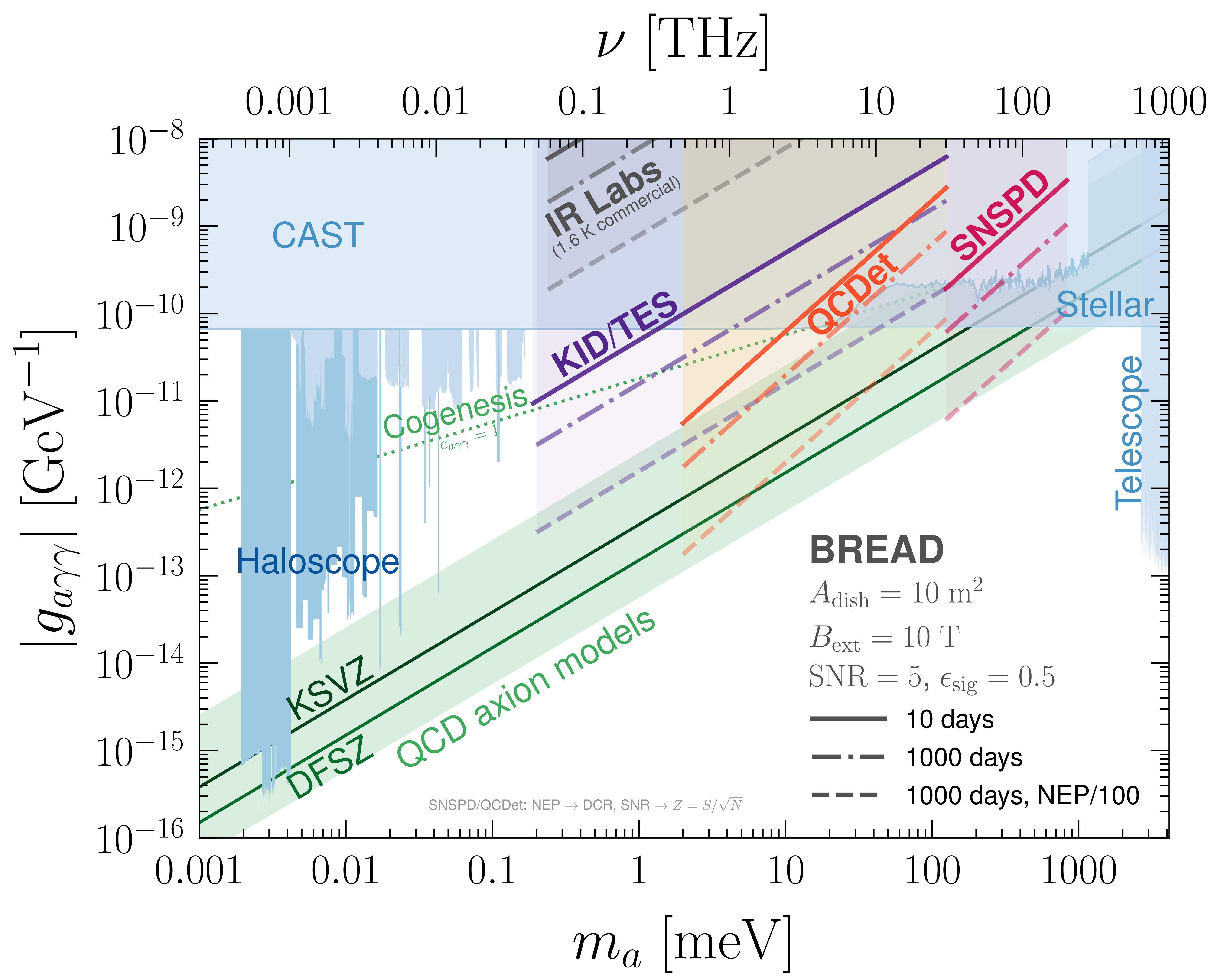
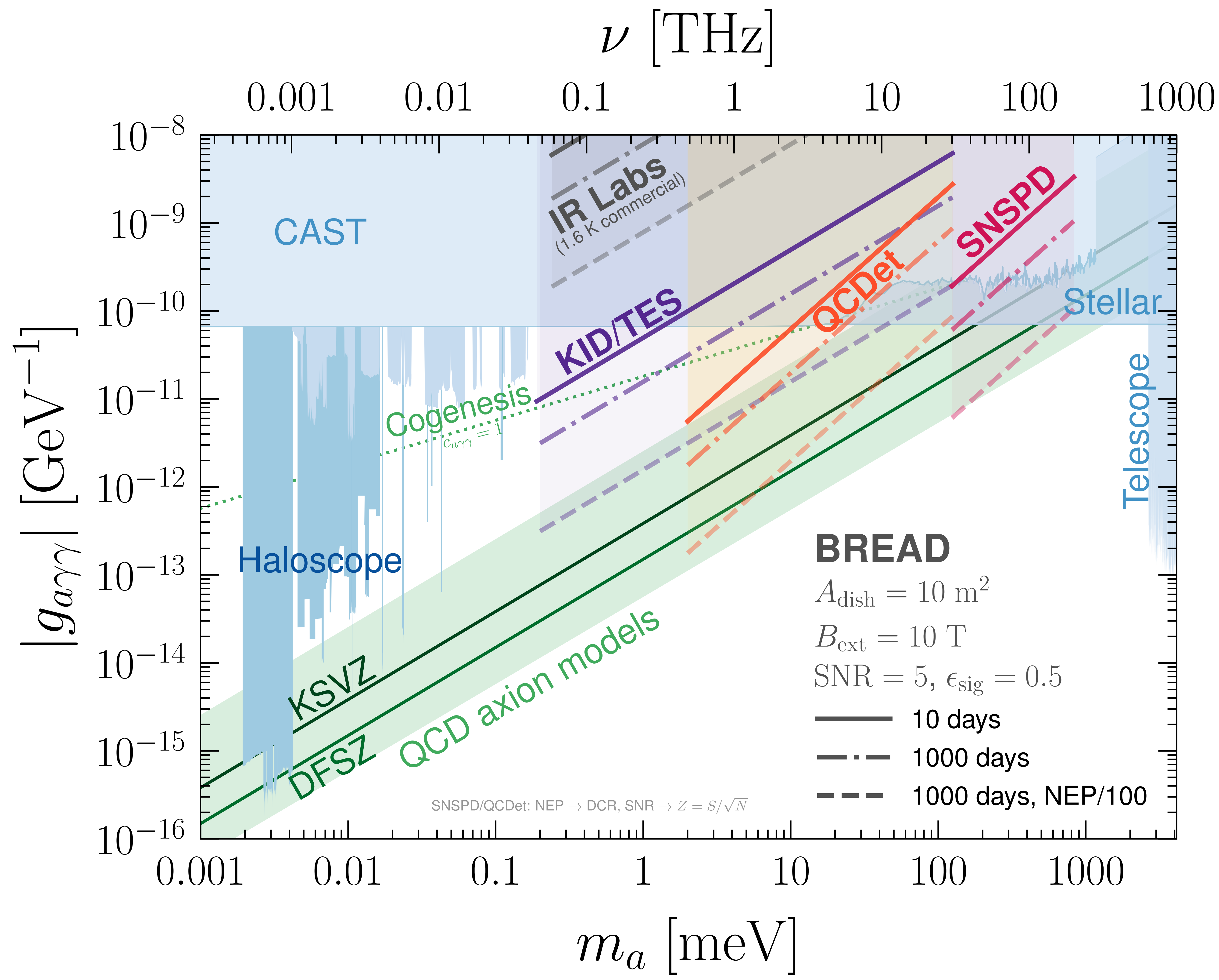
Masha Baryakhtar
University of Washington

Dielectric enhancements: TeraBREAD and beyond

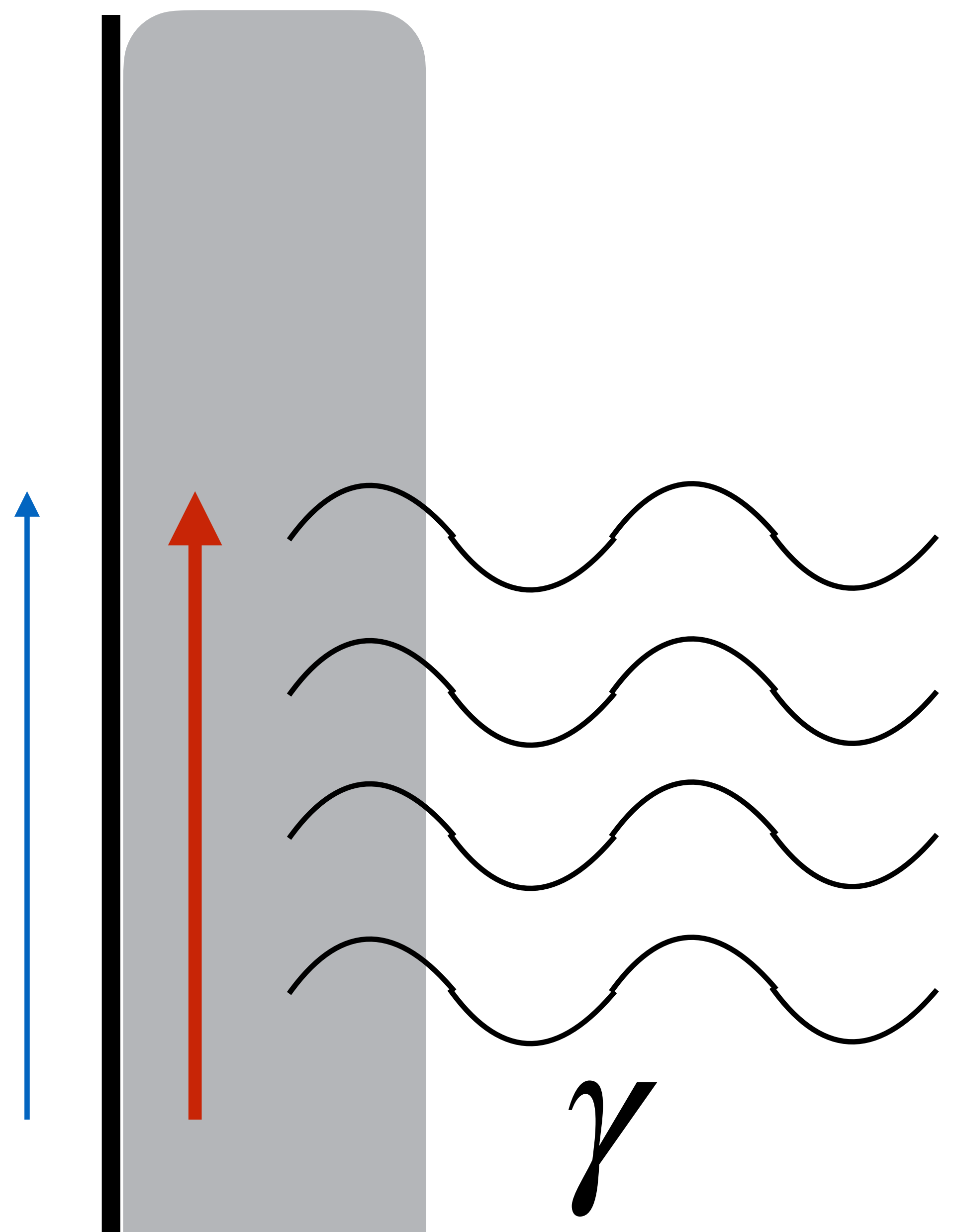
Reaching the heavier QCD axion



Reaching the heavier QCD axion

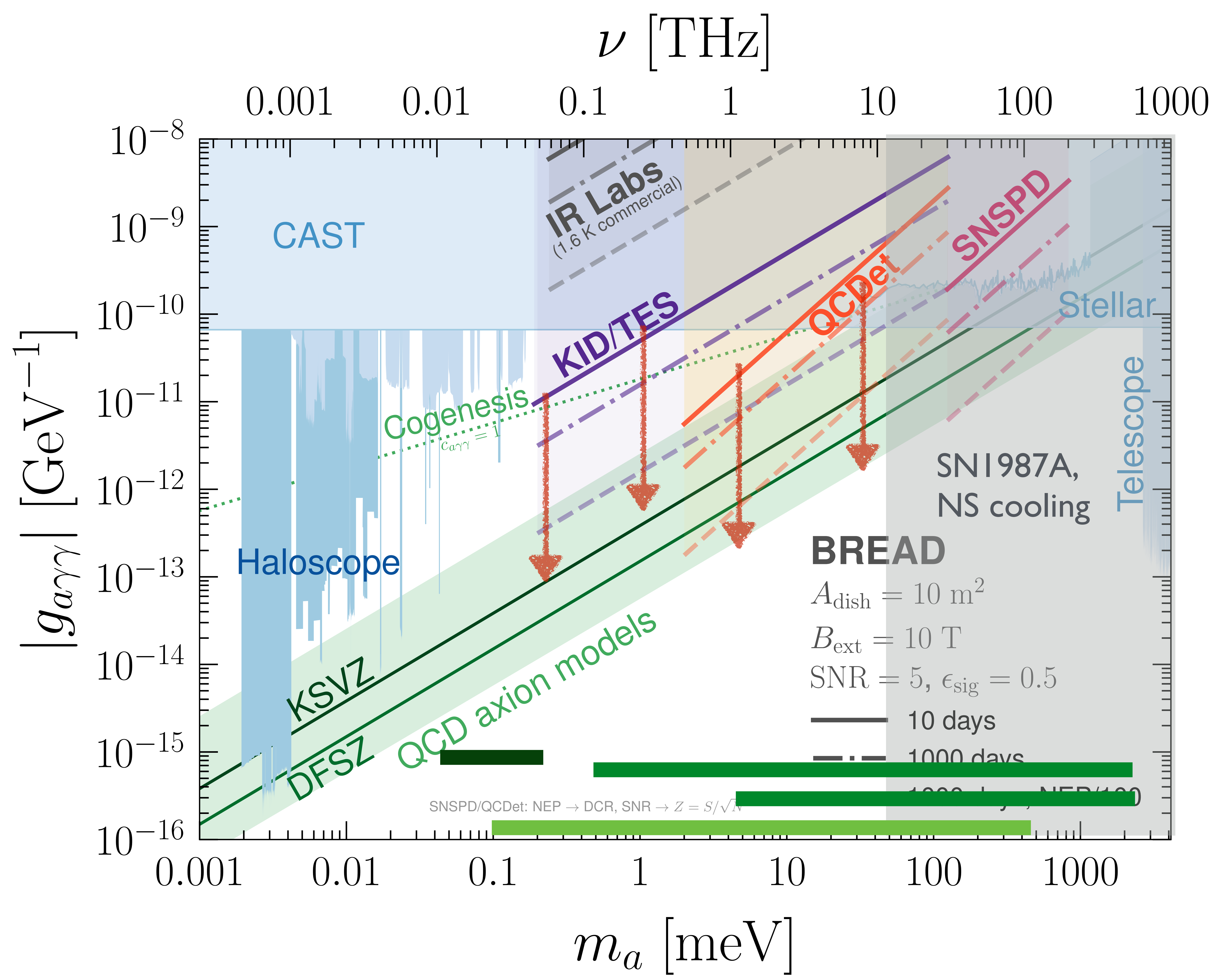


Effective volume: $V = \lambda/2 \cdot$ Area

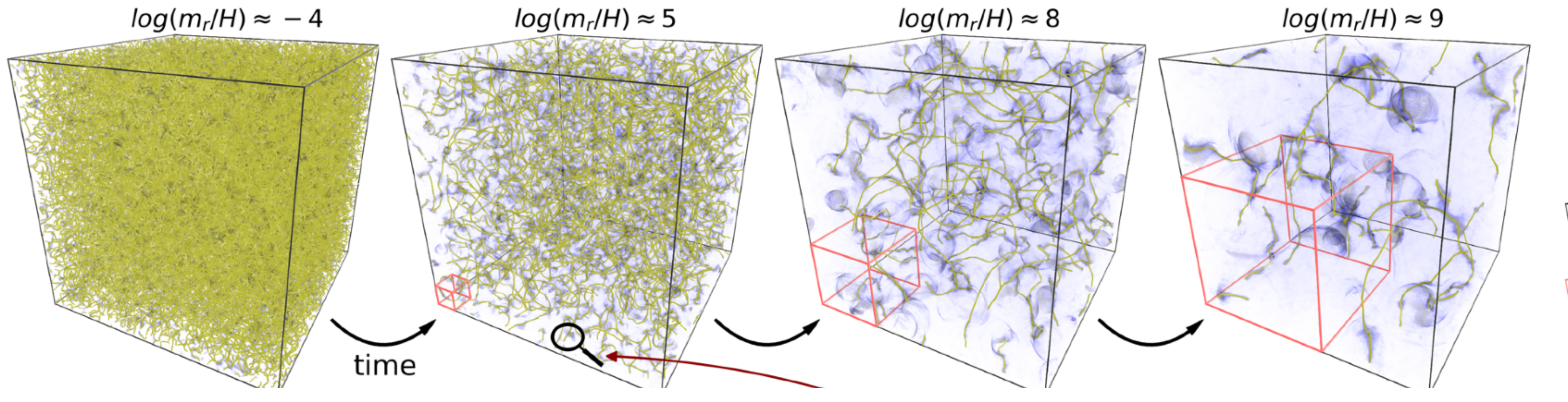


$J = g_{a\gamma\gamma} B_0 \dot{a}$

Reaching the heavier QCD axion



What does it take to reach the heavier QCD axion regime?



Buschmann et al Nat Comm 2021

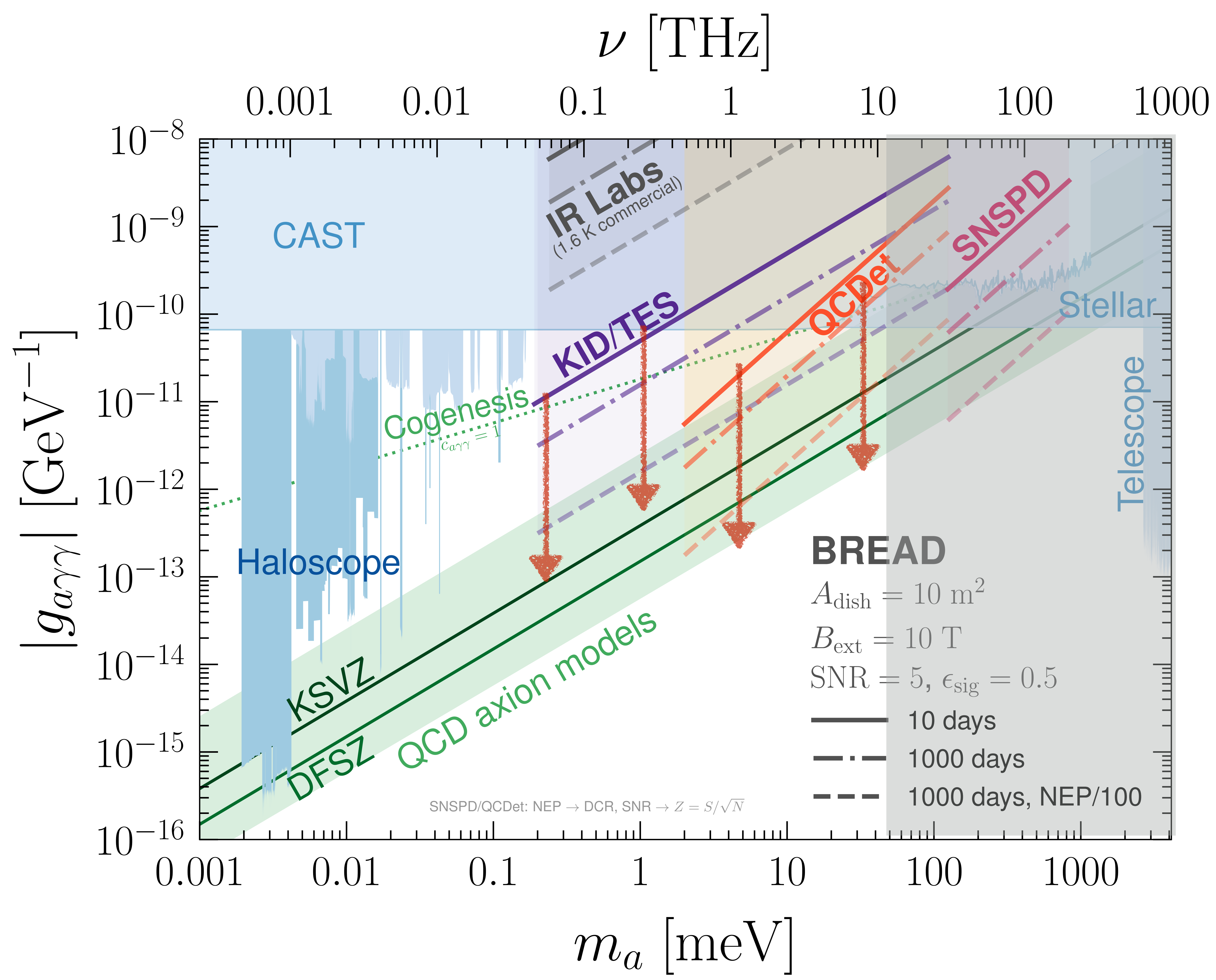
Higher mass range interesting both for string production and pre-inflationary misalignment

Buschmann et al Nat Comm 2021

Gorghetto, Hardy, Villadoro 2007.04990

Saikawa, Redondo, Vaquero, Kaltschmidt 2401.17253

Reaching the heavier QCD axion

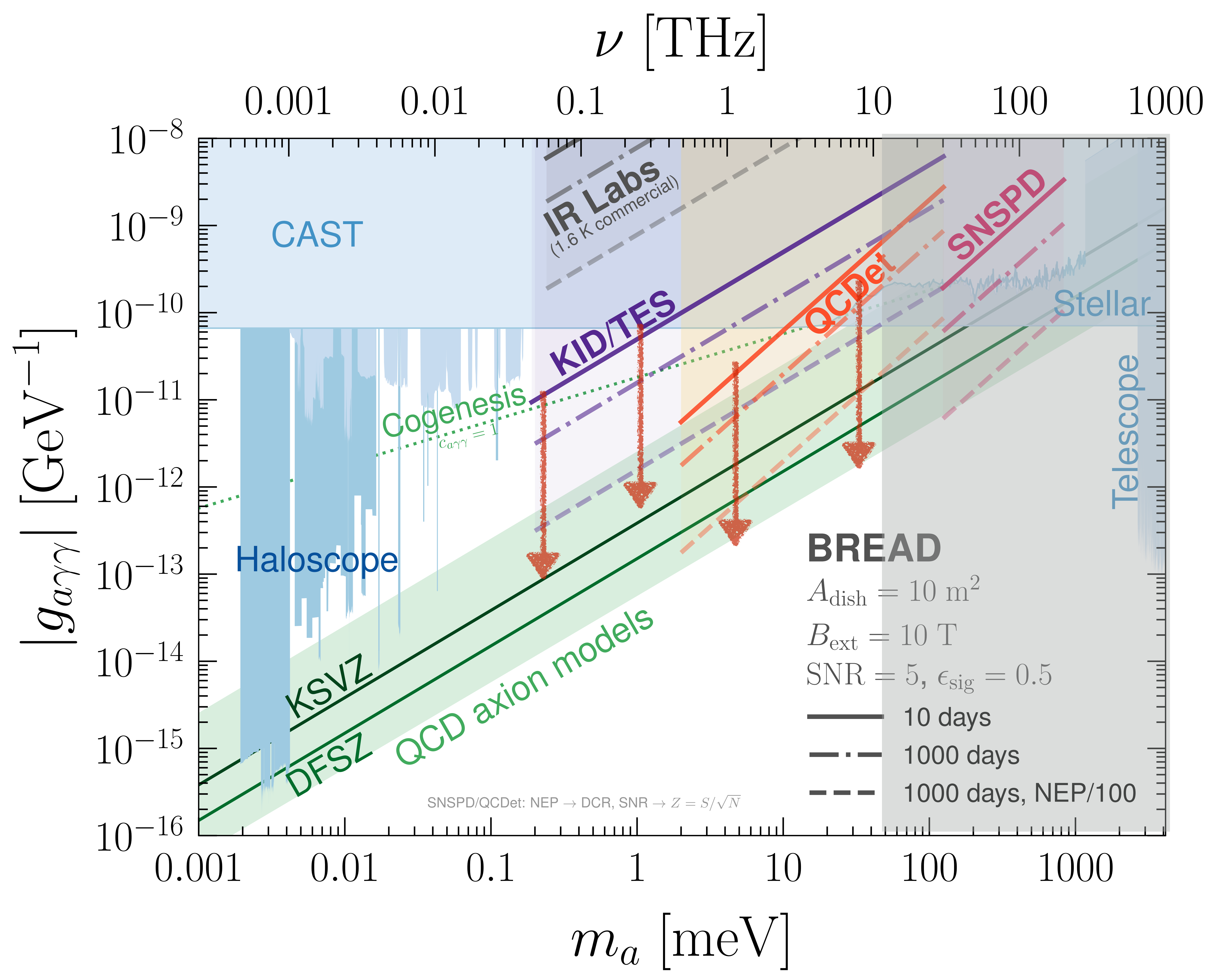


What does it take to reach the heavier QCD axion regime?

- Biggest reflectors in best magnets with current or near future photodetectors
- Not sufficient to reach DFSZ line: average power decreasing from axion amplitude at high masses

$$P_{\rm av} = (g a_0 B_0)^2 A$$

Reaching the QCD axion: Dielectric Enhancement



What does it take to reach the heavier QCD axion regime?

- Biggest reflectors in best magnets with current or near future photodetectors
- Not sufficient to reach DFSZ line: average power decreasing from axion amplitude at high masses

Increasing axion conversion effective volume

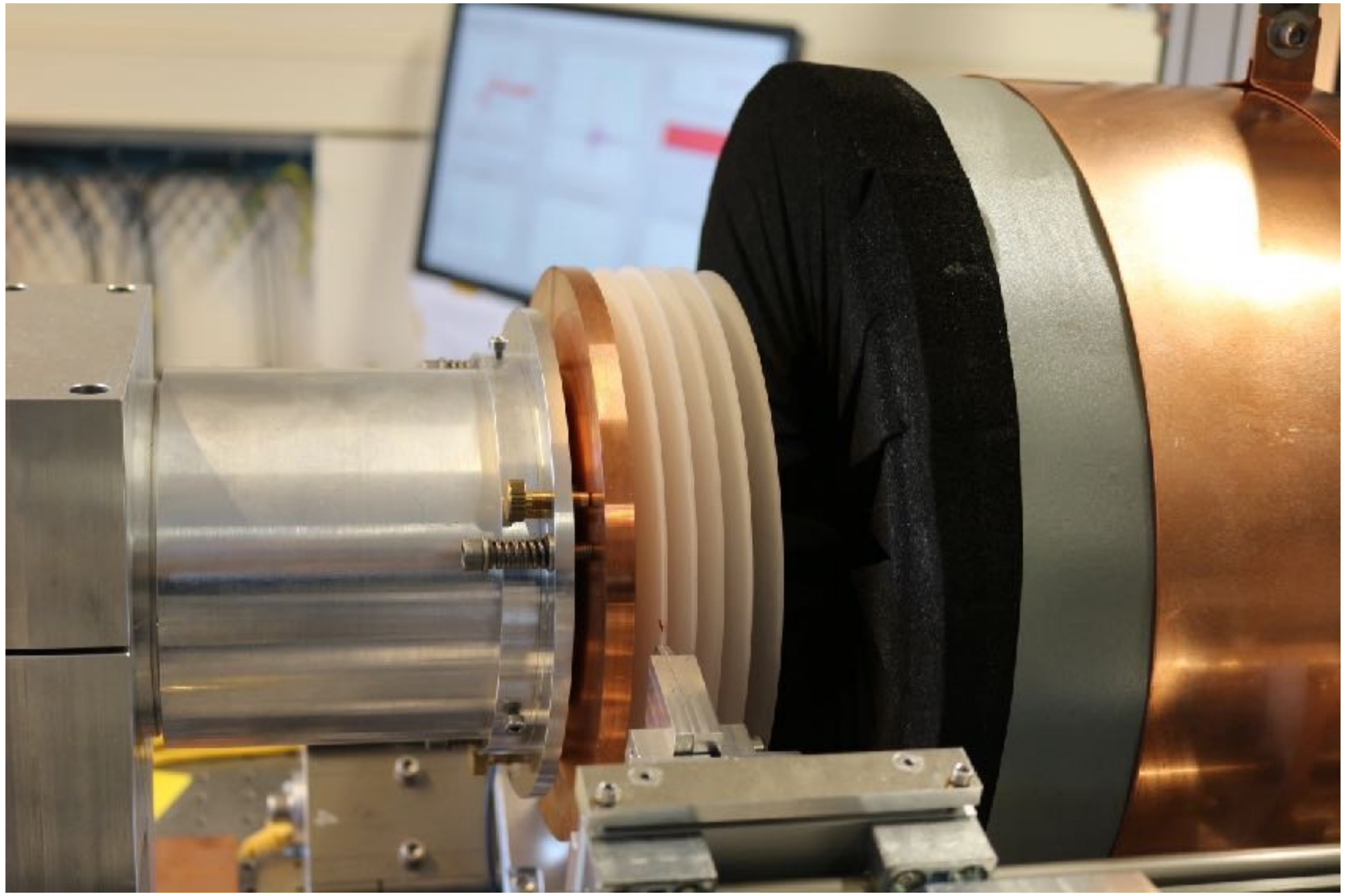
$$P_{\rm av} = (g a_0 B_0)^2 A \boxed{N\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}\left(\frac{1}{n_2}-\frac{1}{n_1}\right)^2$$

Dielectric Enhancement

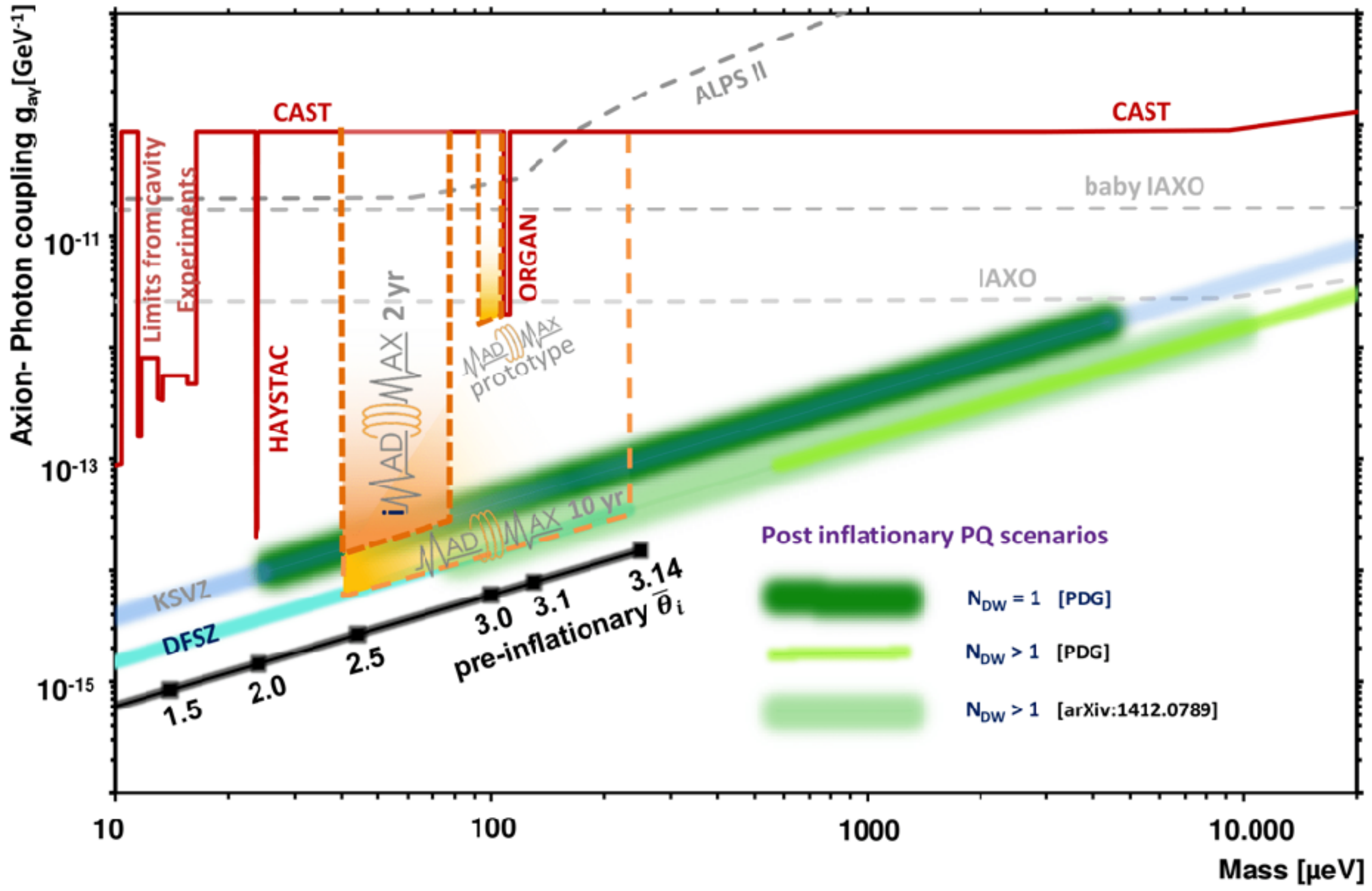
- TeraBREAD (aka SANDWICH: BREAD with layers)
  - Large scale enhancement to reach QCD axion
- Disordered dielectrics
  - Simple and robust setup at high frequencies

Dielectric Enhancement Demonstrated in Several Prototypes

MADMAX



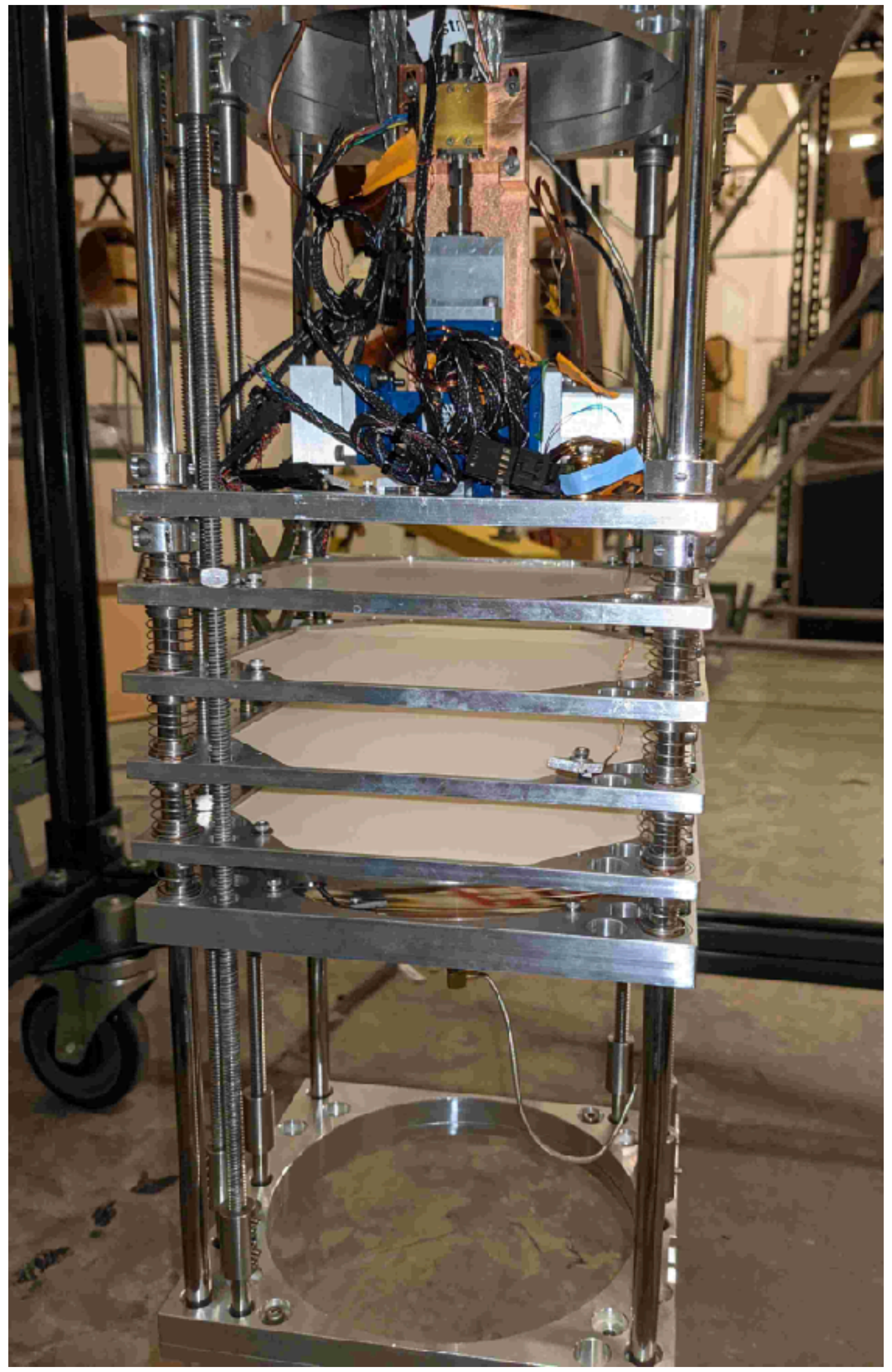
MAgnetized Disc and Mirror Axion eXperiment

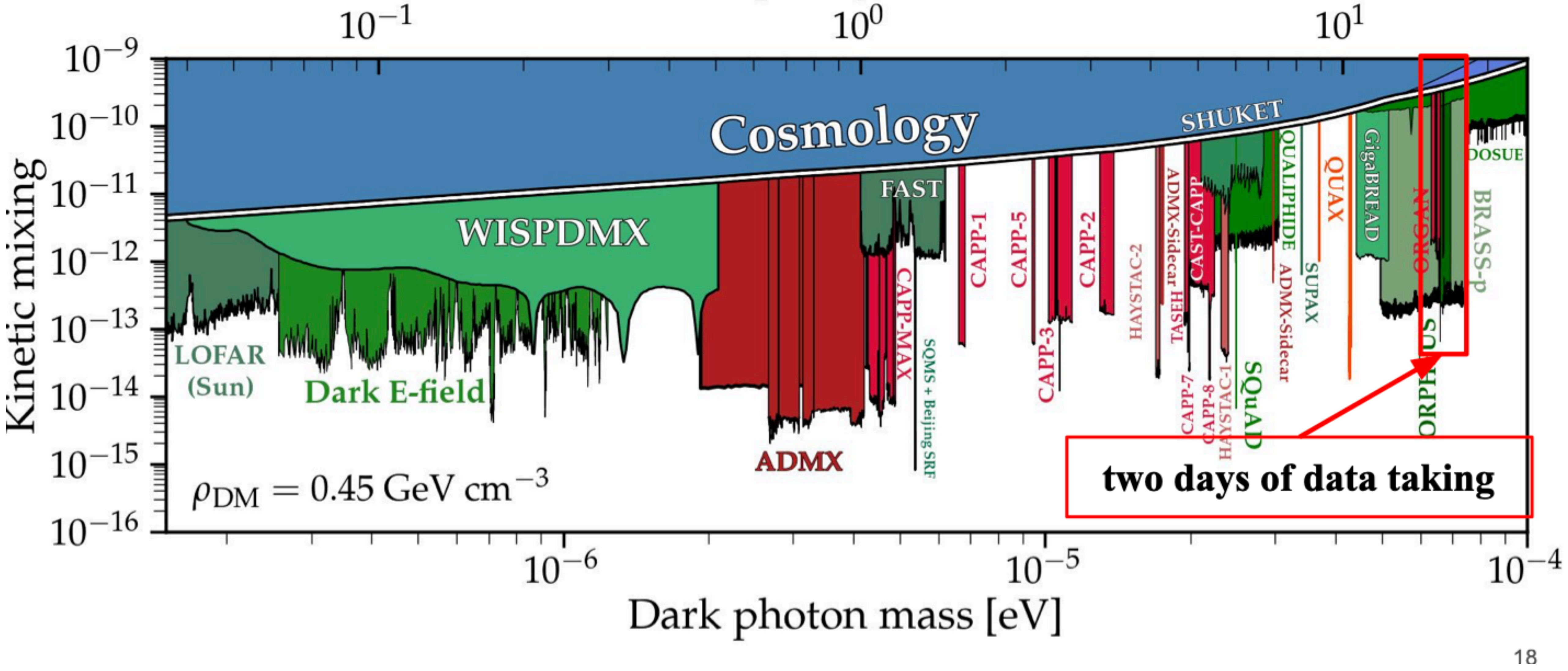


Dielectric Haloscope Proposal (Phys. Rev. Lett. 118, 091801 (2017))

MADMAX Collaboration White Paper (Eur. Phys. J. C (2019) 79: 186)

ADMX-Orpheus

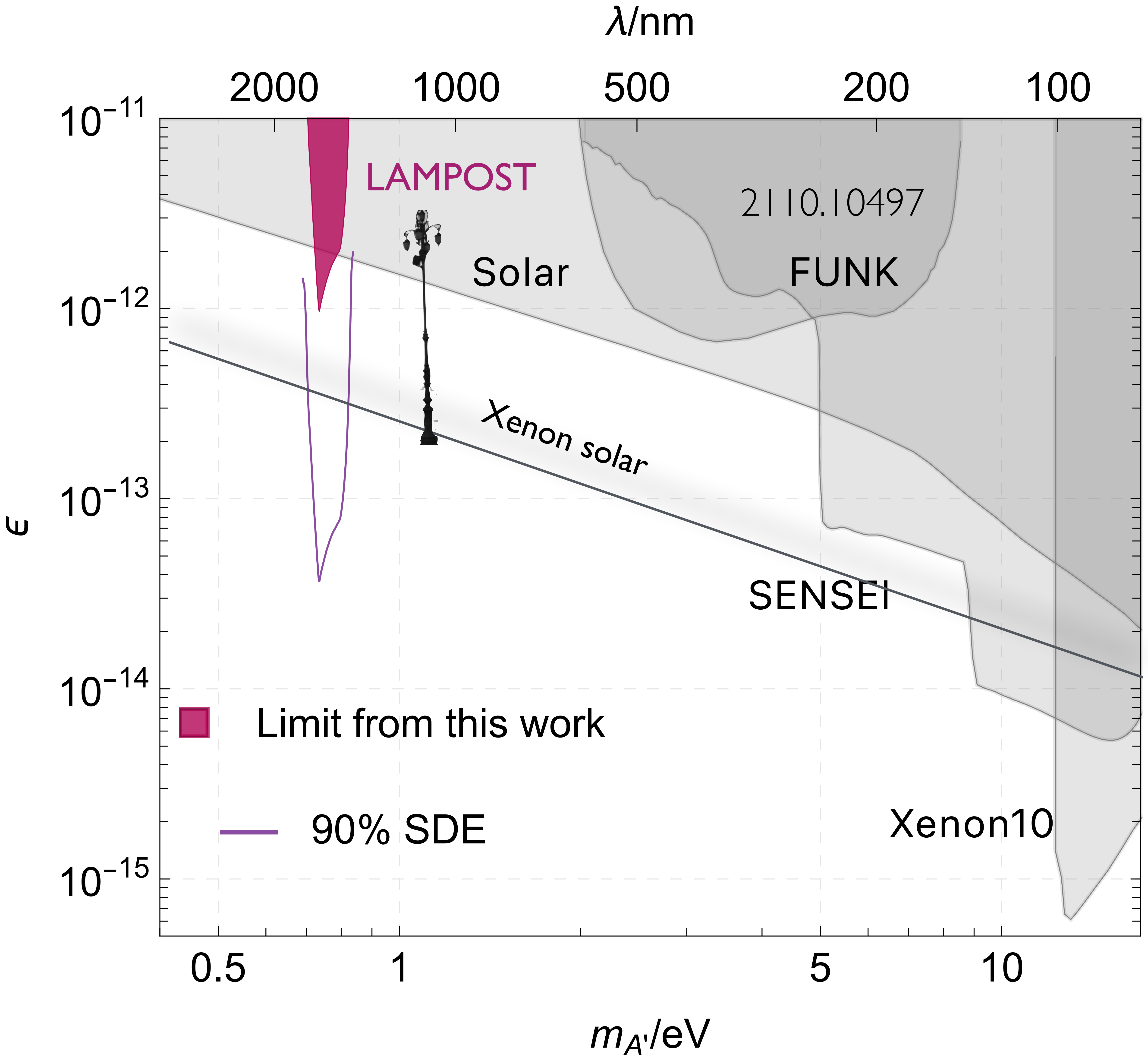


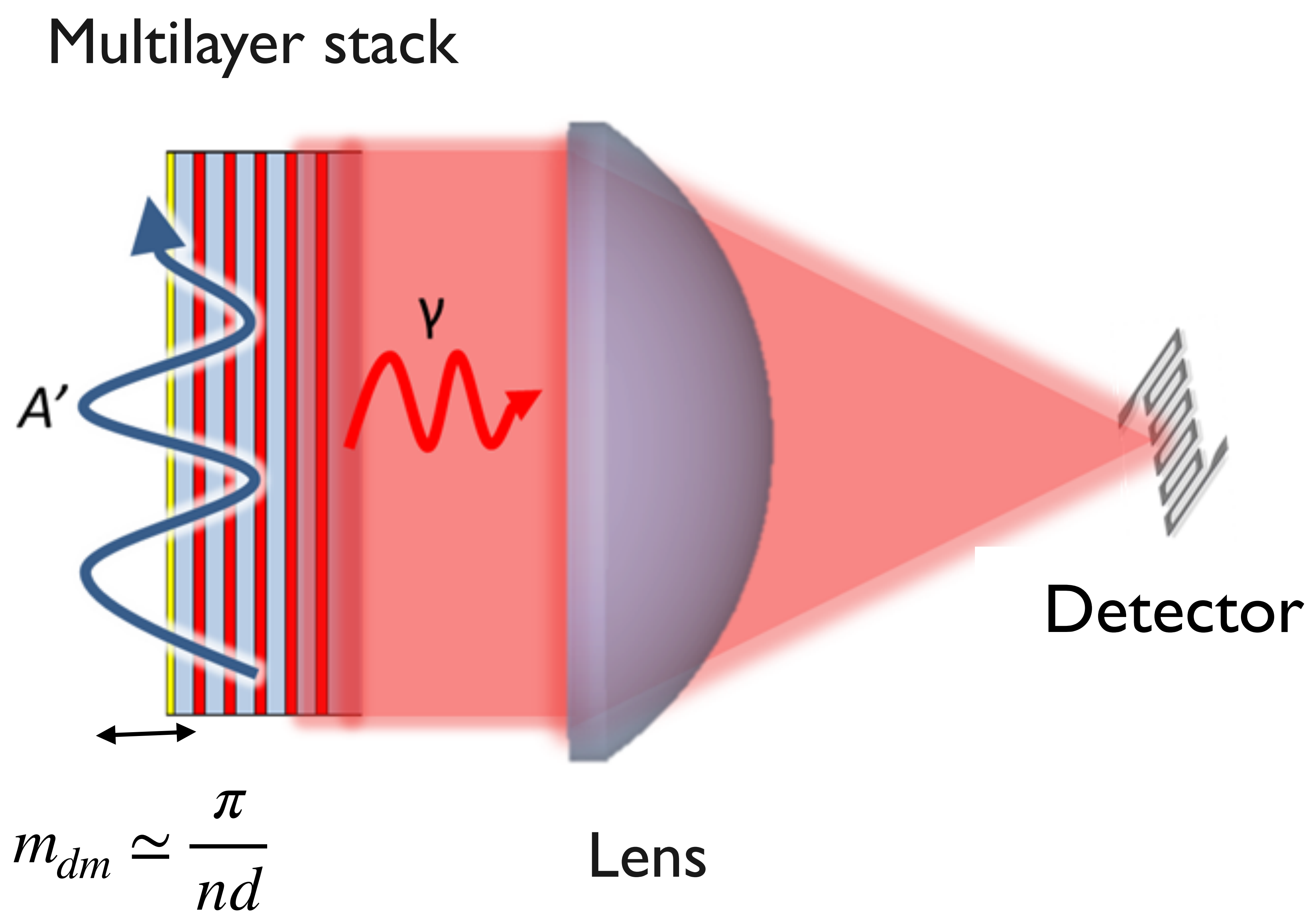


Raphael Cervantes **arXiv:2112.04542**

Carosi, Cervantes, Kimes, Mohapatra, Ottens, Rybka 2019

LAMPOST





- Prototype cuts into new parameter space with 5 days run
- 2 inch diameter, 5 period stack. Poor efficiency due to alignment control, 100-fold improvement possible

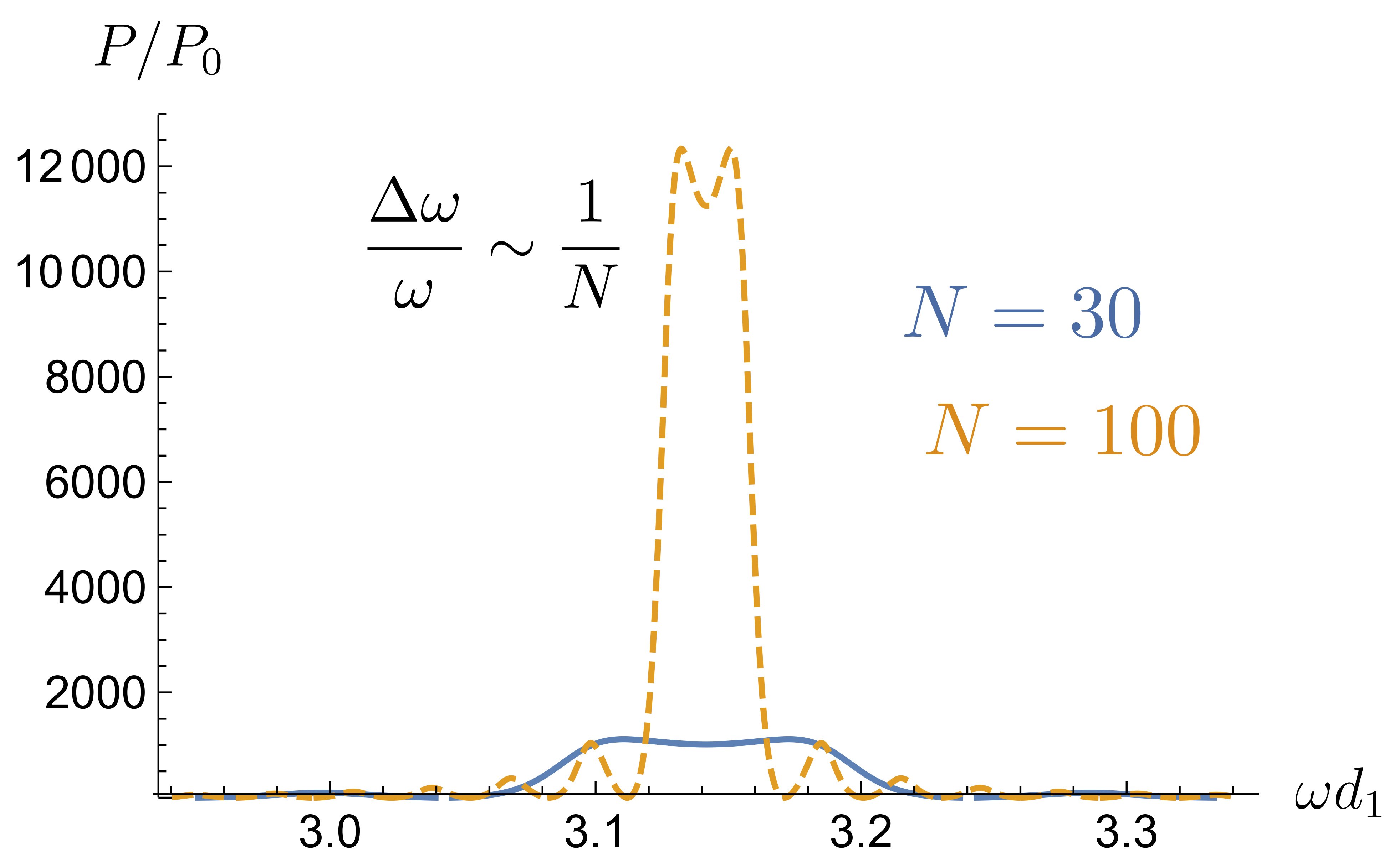
MB, J. Huang, R. Lasenby, PRD 2018
Chiles, Charaev, Lasenby, **MB**, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren PRL 2022

Converted power

- For stack of N periods, with area A, converted power from DM at half-wave frequency is

$$\langle P_{\rm abs}\rangle \simeq g^2 B_0^2 \frac{\rho_{\rm DM}}{m^2} QAN \left(\frac{1}{n_1}+\frac{1}{n_2}\right)\left(\frac{1}{n_2}-\frac{1}{n_1}\right)^2$$

- For "open cavity", $Q \propto N$
- Frequency coverage:

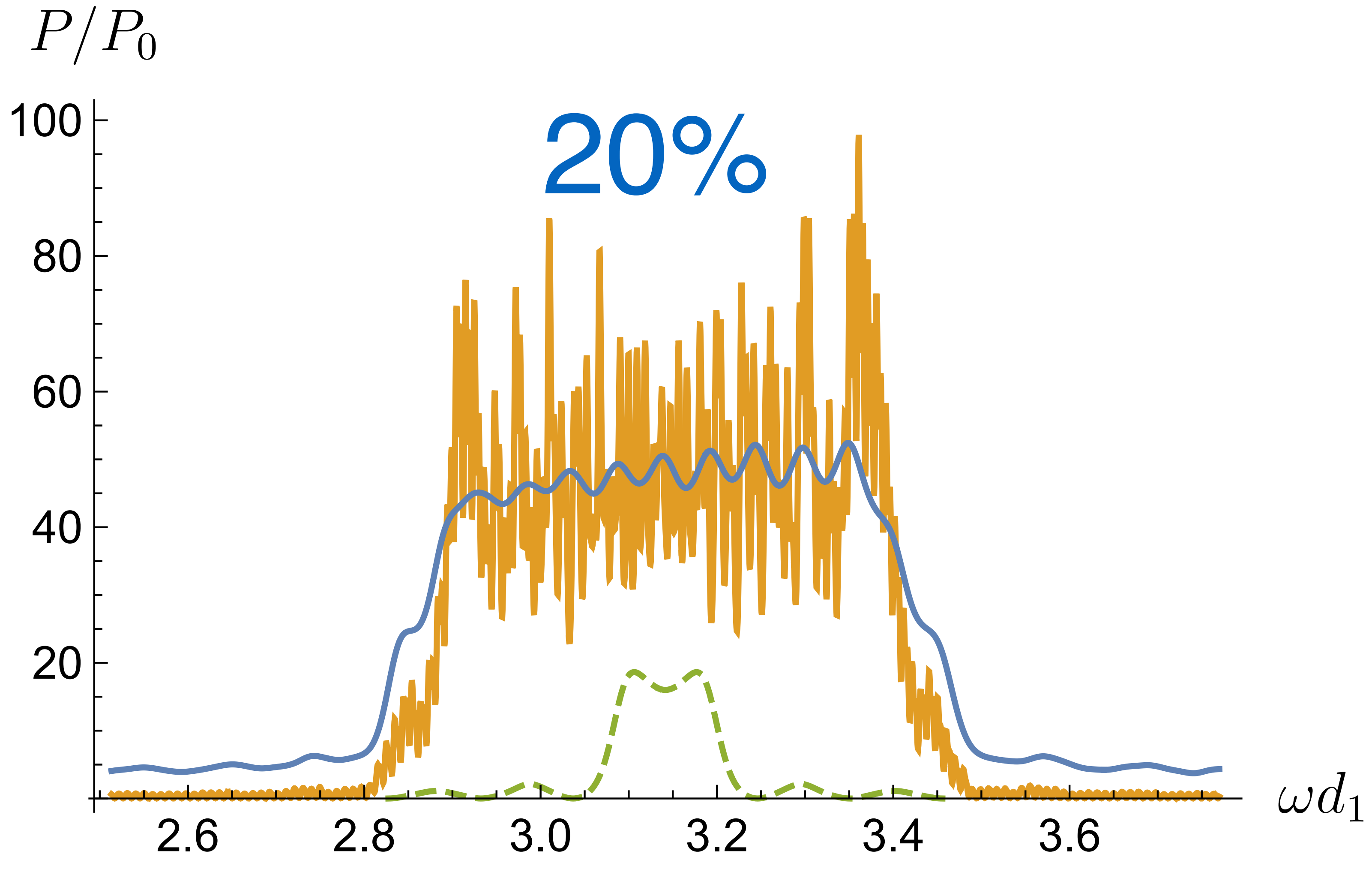


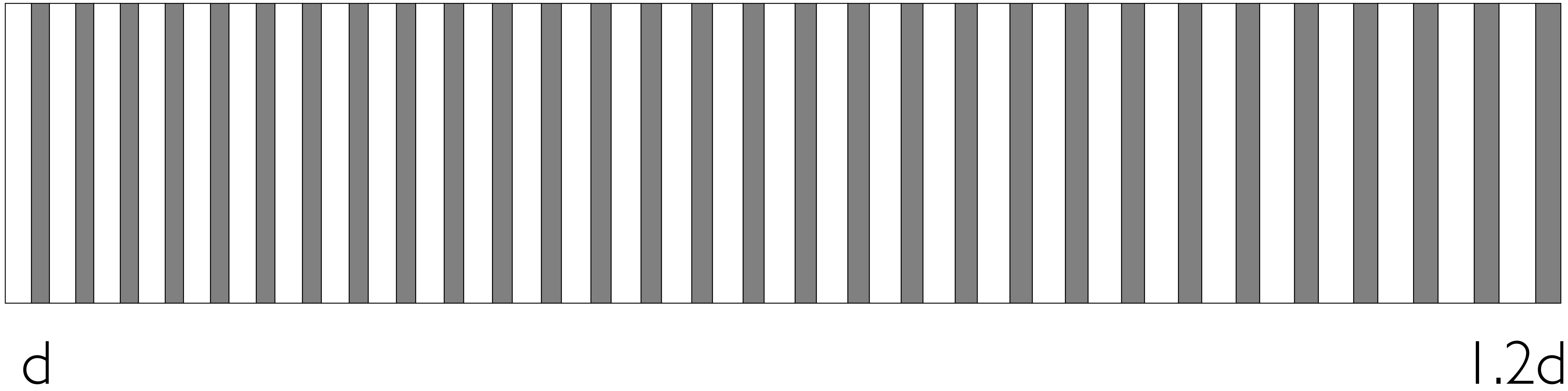
- Higher peak power compensated for by reduced bandwidth: frequency-averaged conversion power $\propto N$: gain with volume

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

Chirped stack

- Gradually increase thickness of layers
- Cover larger volume and frequency range together
- Maximum ~30% range of frequencies and need to be careful with reflections to avoid destructive interference

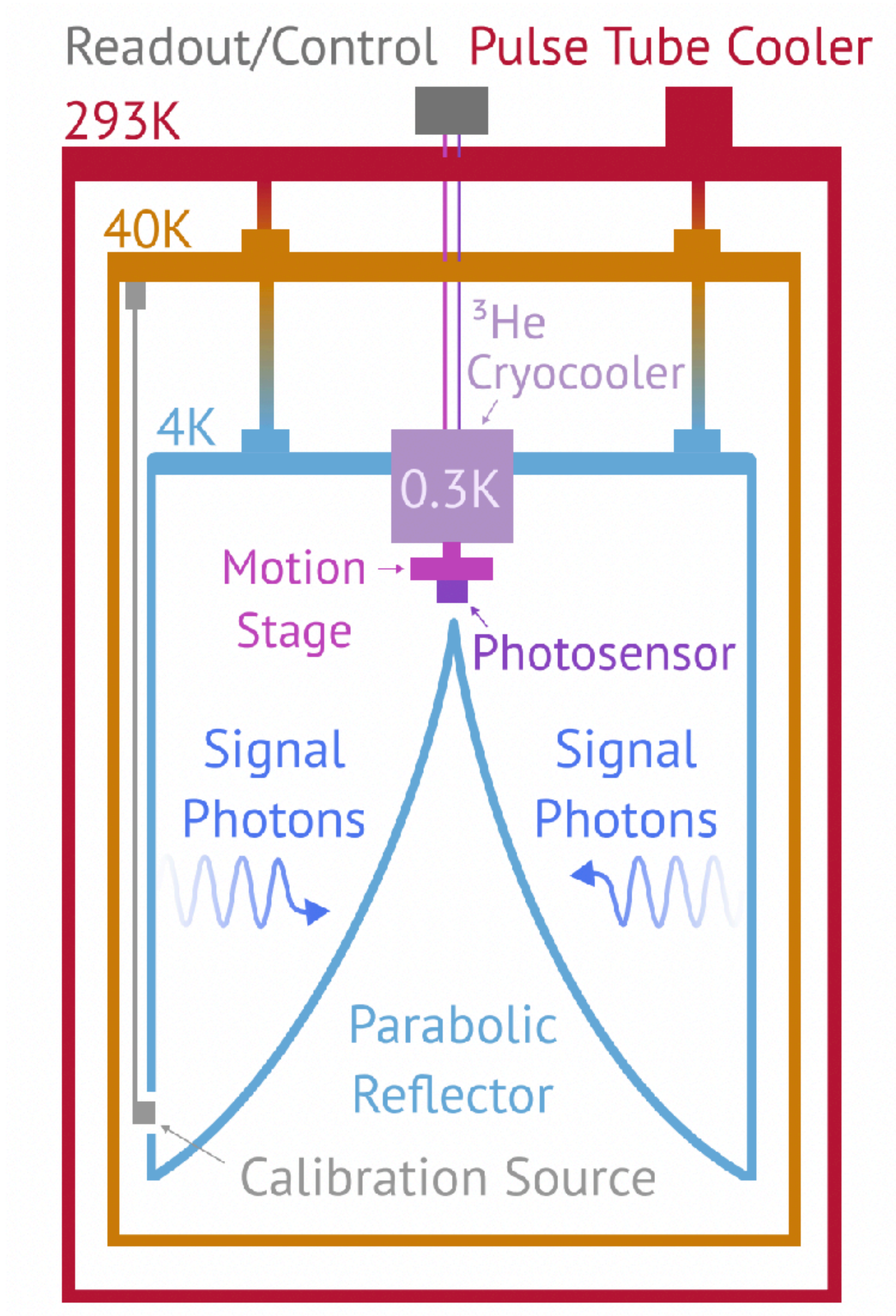




MB, J. Huang, R. Lasenby, PRD 2018

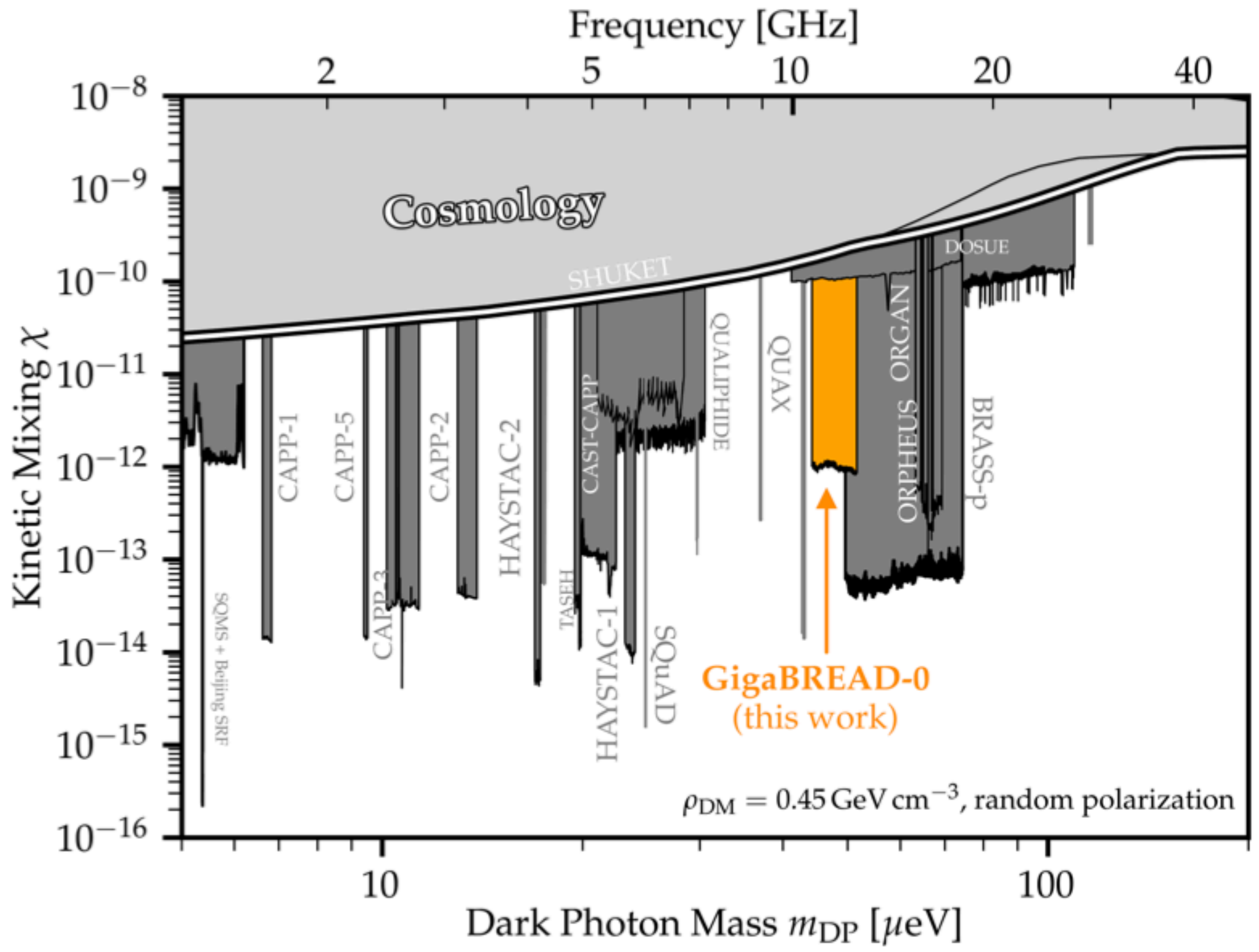
SANDWICH: BREAD with layers

Magnet-Volume Efficient Setups



BREAD
COLLABORATION

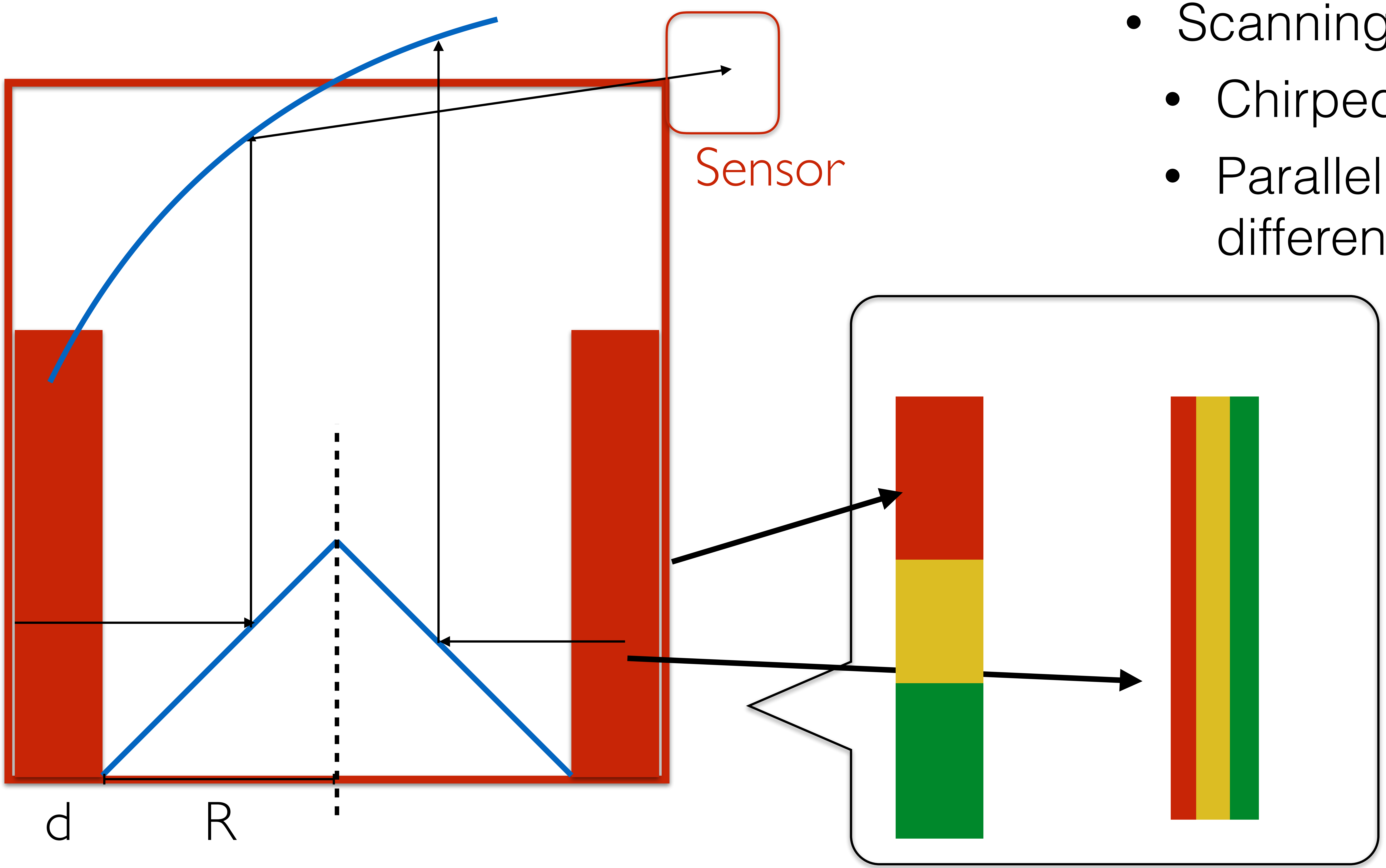
- Cylindrical geometry ideal for magnet bores
- Exciting new results from BREAD collaboration!



Stefan Knirck et al 2310.13891

Magnet-Volume Efficient Setups

Integrate Dielectric Stack

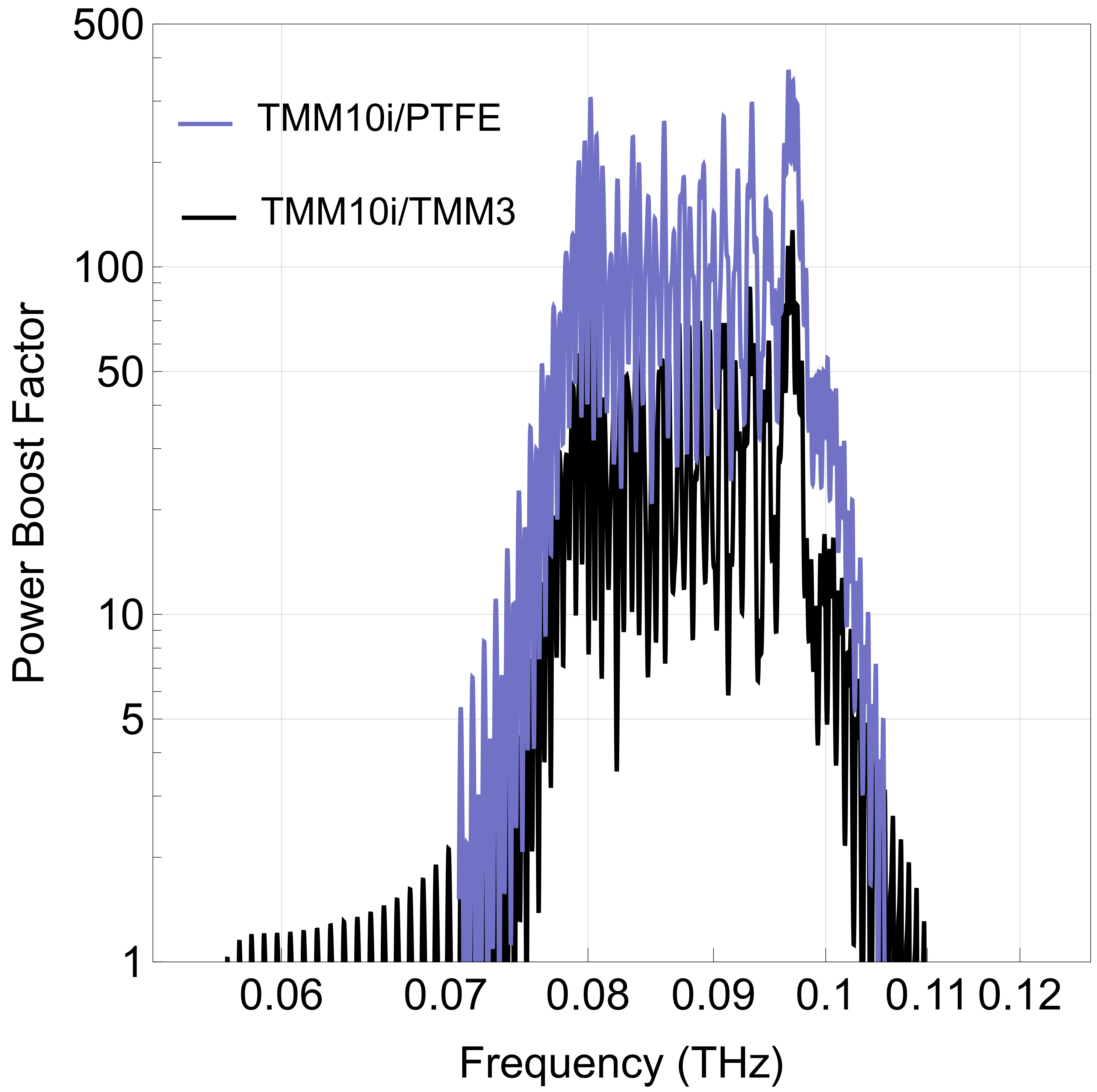


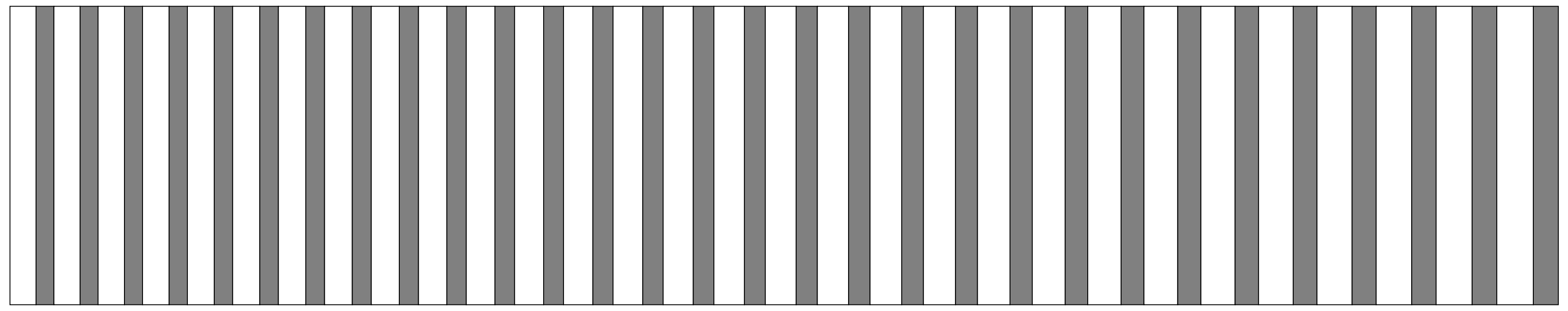
- Scanning Possibilities:
  - Chirped Stack
  - Parallel stacks of different periodicity

Baryakhtar, Huang, Knirck, Miller, Sonnenschein, Vieira

The case for SANDWICH

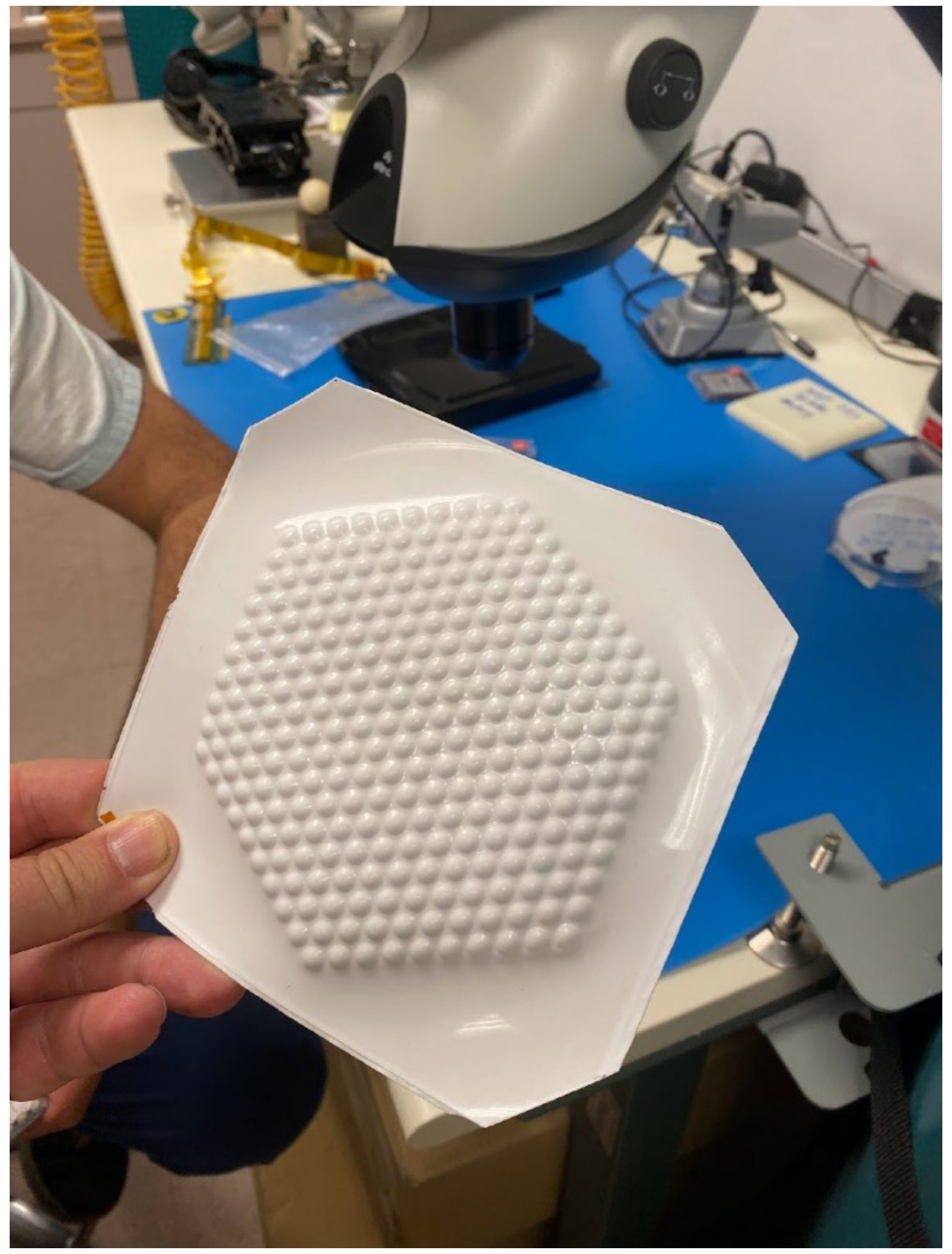
- Commercially available microwave circuit board materials could be good dielectrics for lower frequencies: flexible, good dielectric contrast
- Still poorly characterized at most frequencies, especially losses and low temperature behavior
- Mirror geometry has to be re-optimized
- Have to develop a robust calibration procedure

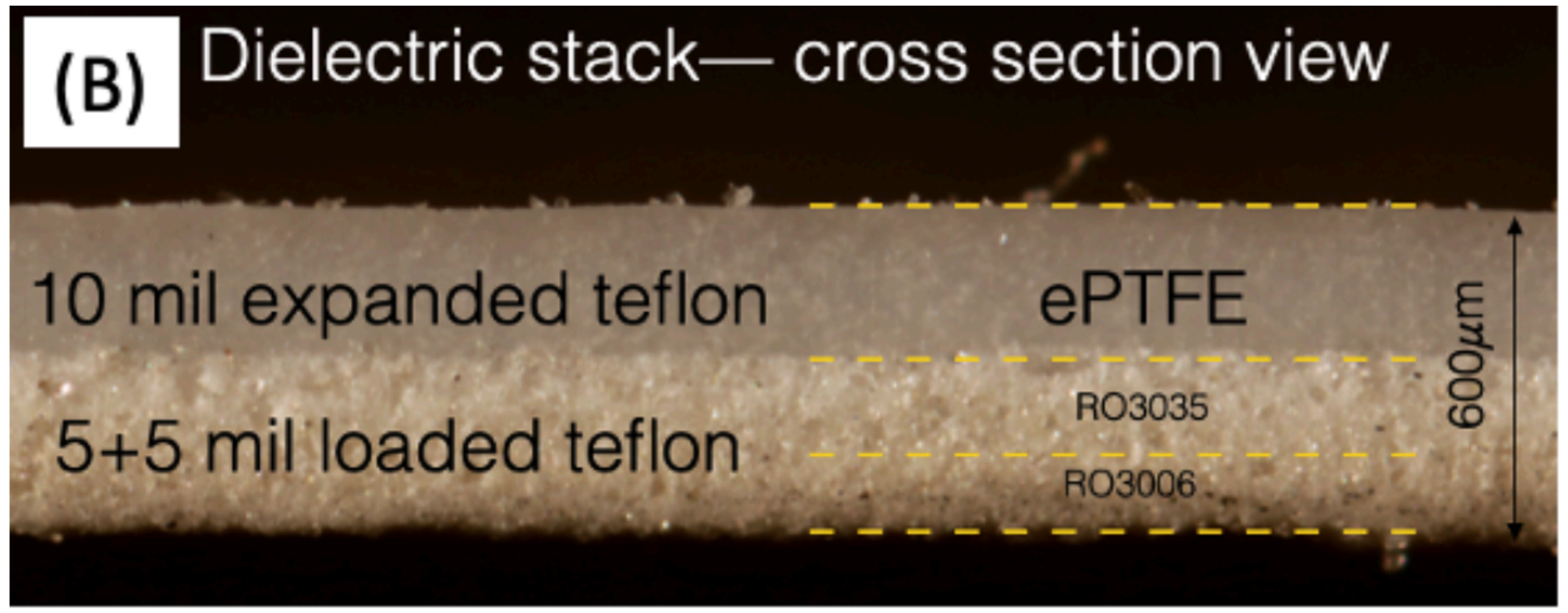




Baryakhtar, Huang, Knirck, Miller, Sonnenschein, Vieira

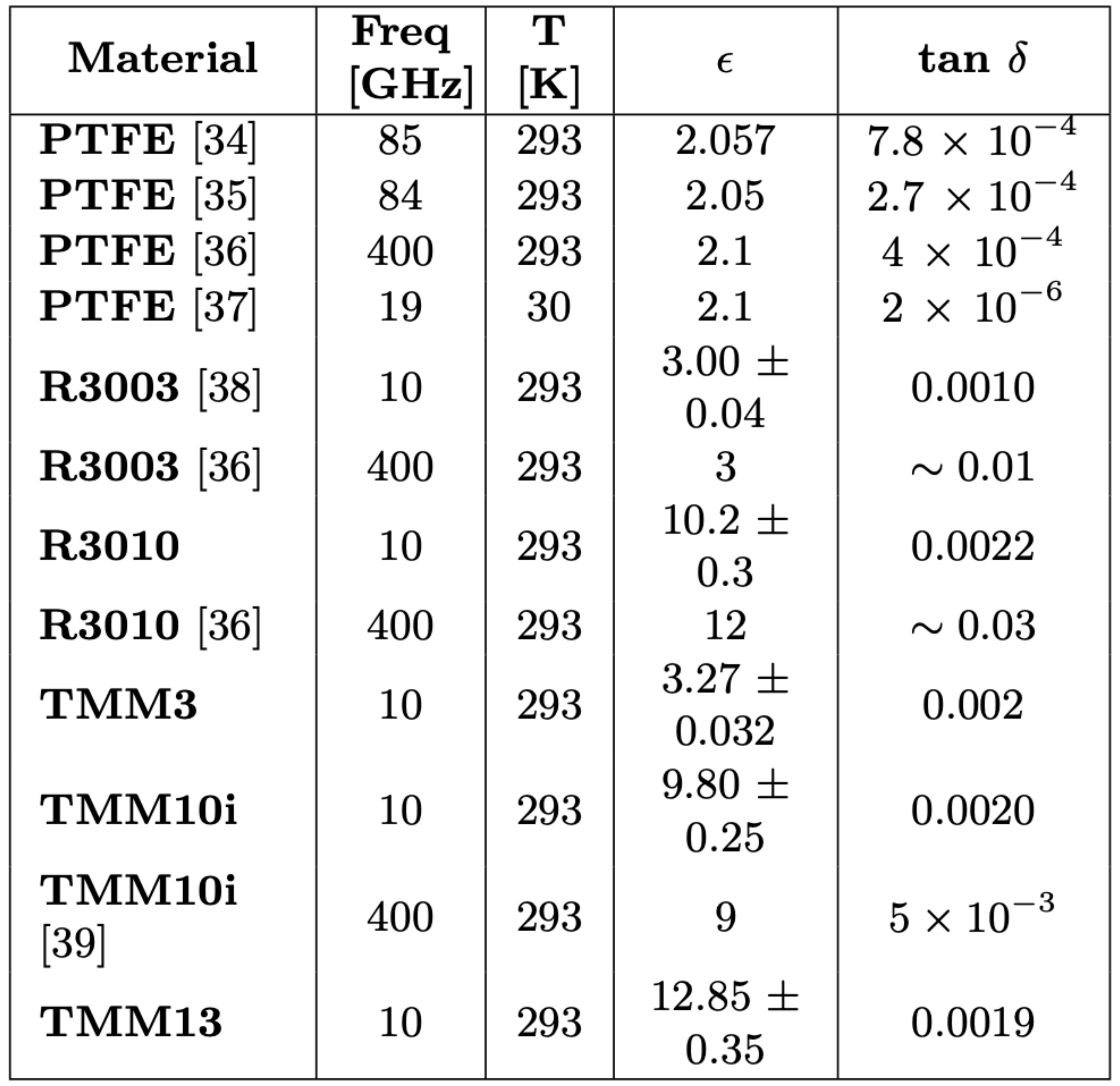
The case for SANDWICH





Baryakhtar, Huang, Knirck, Miller, Sonnenschein, Vieira

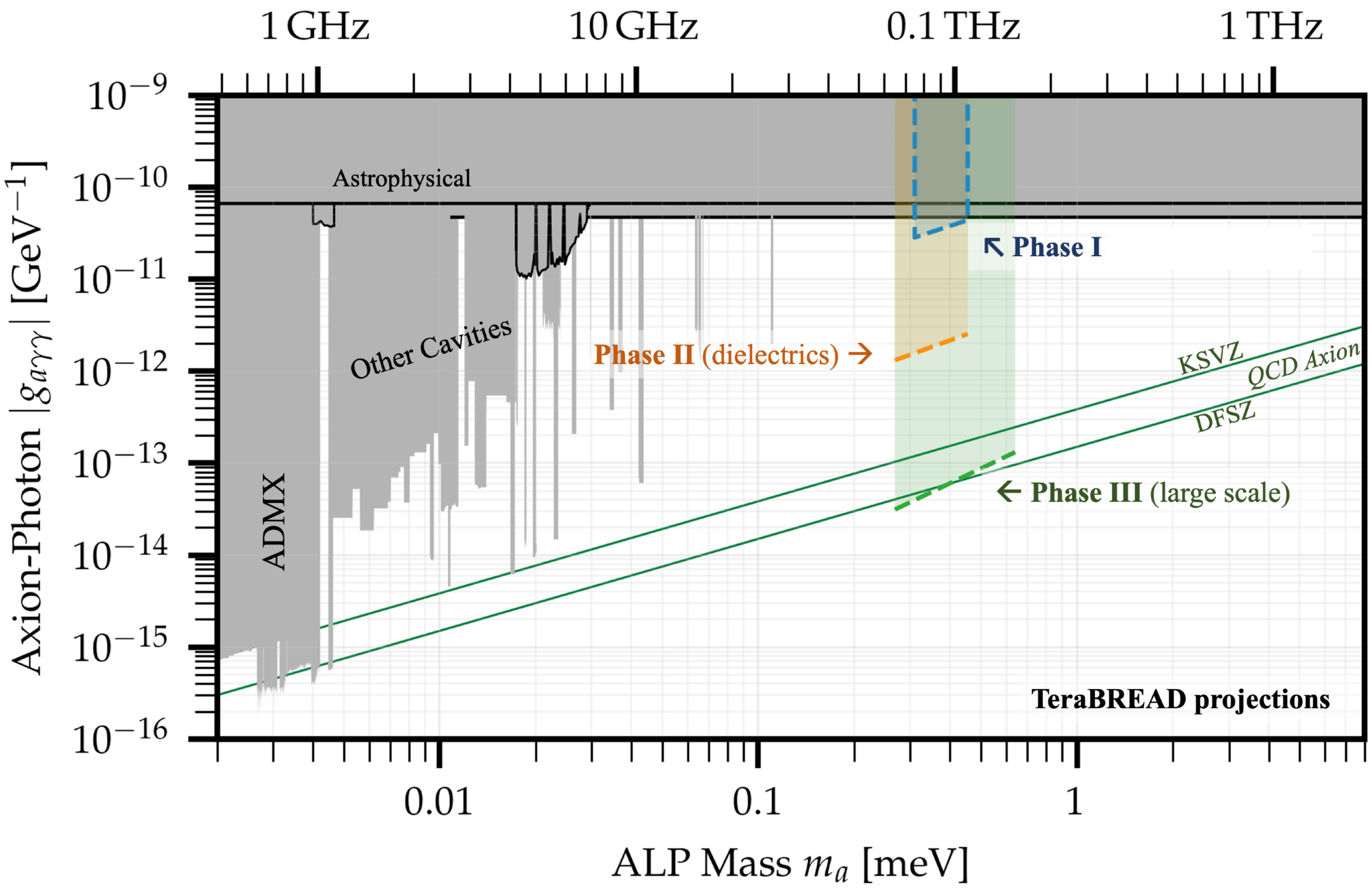
Typically composites of high-index inorganic particulates embedded in an organic matrix



Material	**Freq [GHz]**	**T [K]**	ϵ	**tan** δ
PTFE [34]	85	293	2.057	7.8×10^{-4}
PTFE [35]	84	293	2.05	2.7×10^{-4}
PTFE [36]	400	293	2.1	4×10^{-4}
PTFE [37]	19	30	2.1	2×10^{-6}
R3003 [38]	10	293	3.00 ± 0.04	0.0010
R3003 [36]	400	293	3	~ 0.01
R3010	10	293	10.2 ± 0.3	0.0022
R3010 [36]	400	293	12	~ 0.03
TMM3	10	293	3.27 ± 0.032	0.002
TMM10i	10	293	9.80 ± 0.25	0.0020
TMM10i [39]	400	293	9	5×10^{-3}
TMM13	10	293	12.85 ± 0.35	0.0019

- Low losses at cryogenic temperatures, with loss tangent less than the effective quality factor
- Maximal dielectric contrast $\epsilon_1 \sim 1$ and $\epsilon_2 \gg 1$;
- Comparable thermal properties to maintain tight dimensional tolerances

The case for SANDWICH



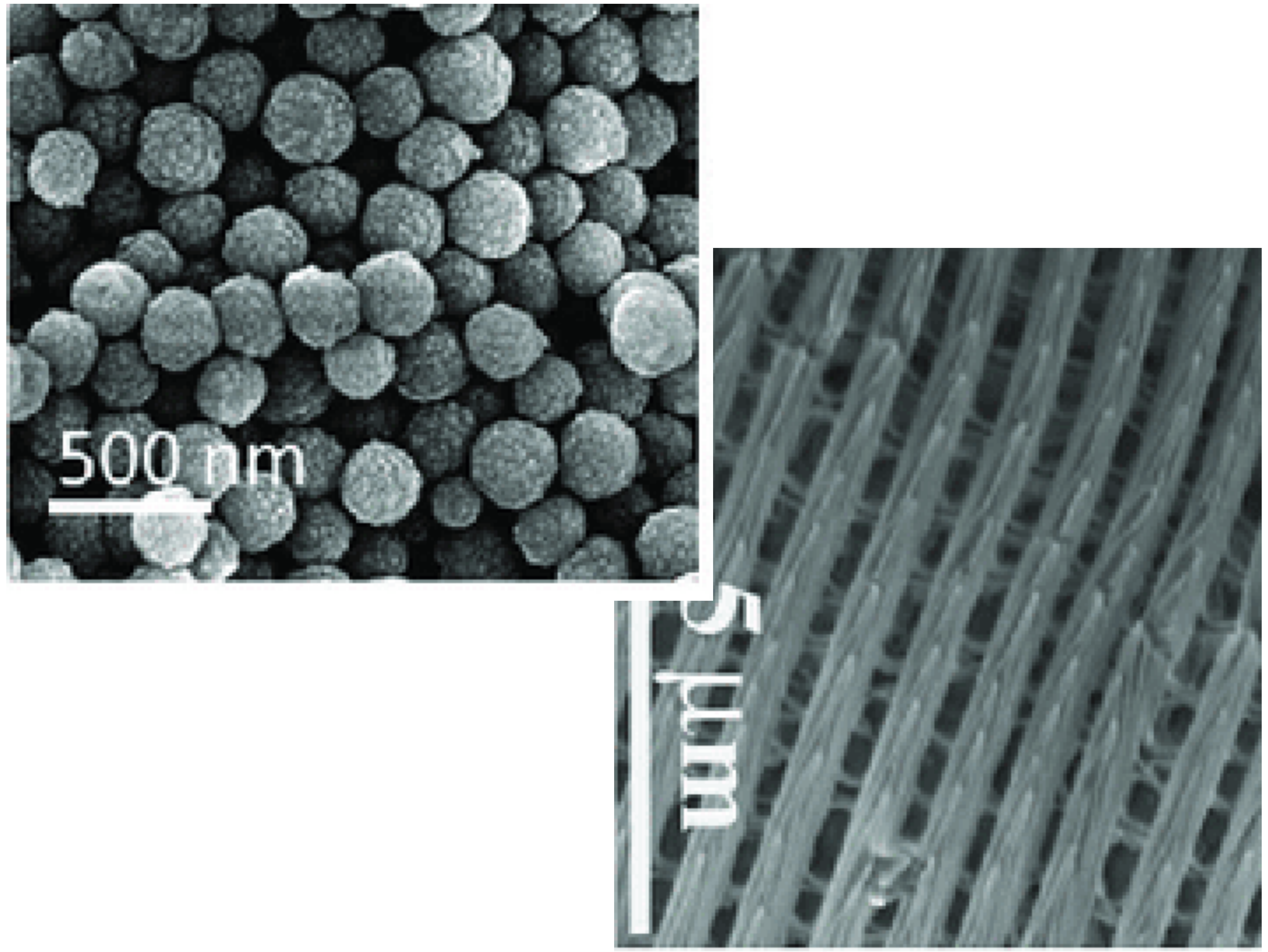
I. A = 0.5 m^2 9.4T magnetic field, off the shelf amplifier technology at 4K.

II. A = 1.5 m^2 100x signal enhancement from dielectric layers

III. A = 7 m^2 20 T magnet, 1000x enhancement from dielectrics and quantum-limited readout

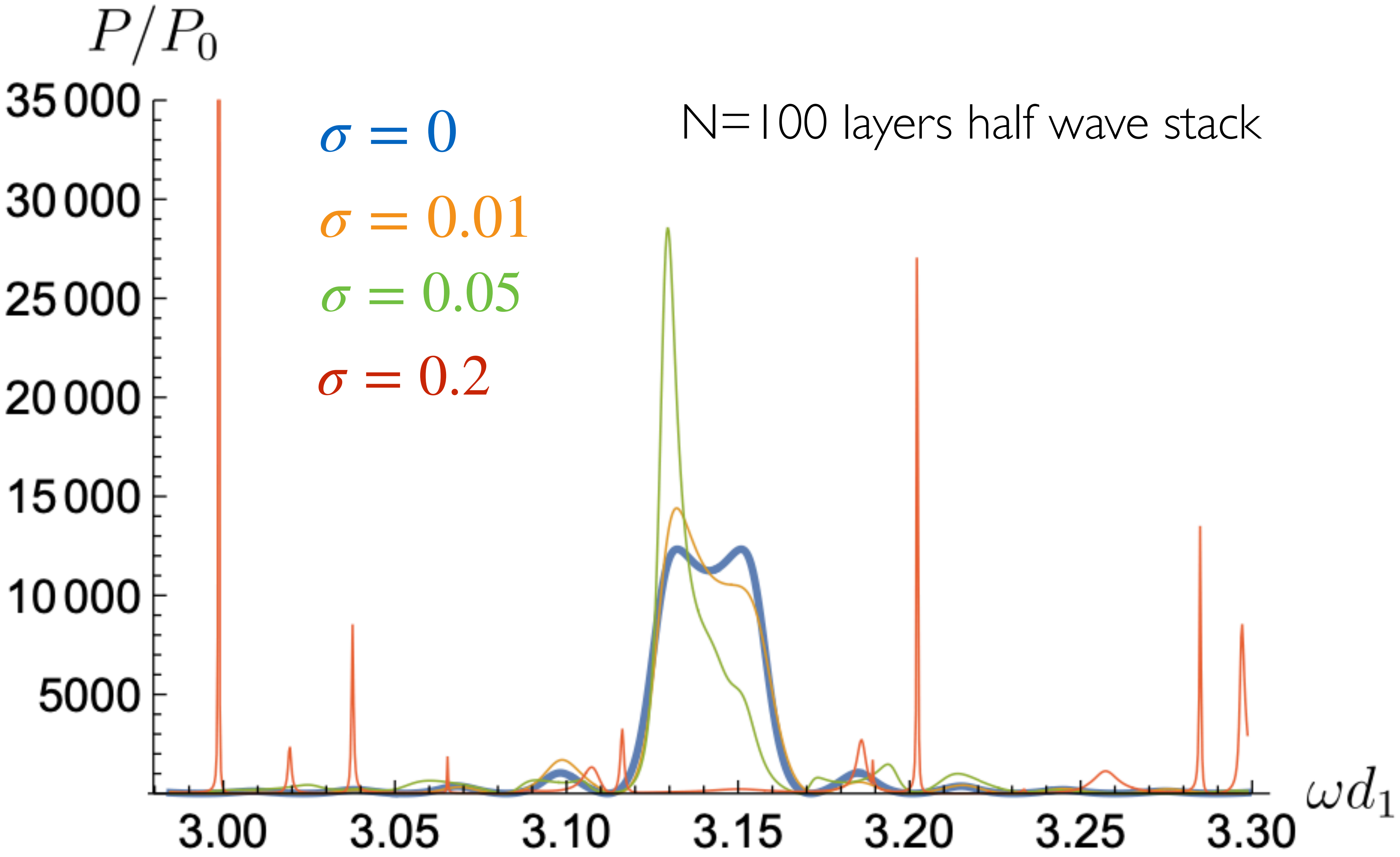
Baryakhtar, Huang, Knirck, Miller, Sonnenschein, Vieira

Disordered Dielectrics



With Otavio Bittencourt, Dip Joti Paul, Junwu Huang, Stewart Koppell Karl Berggren

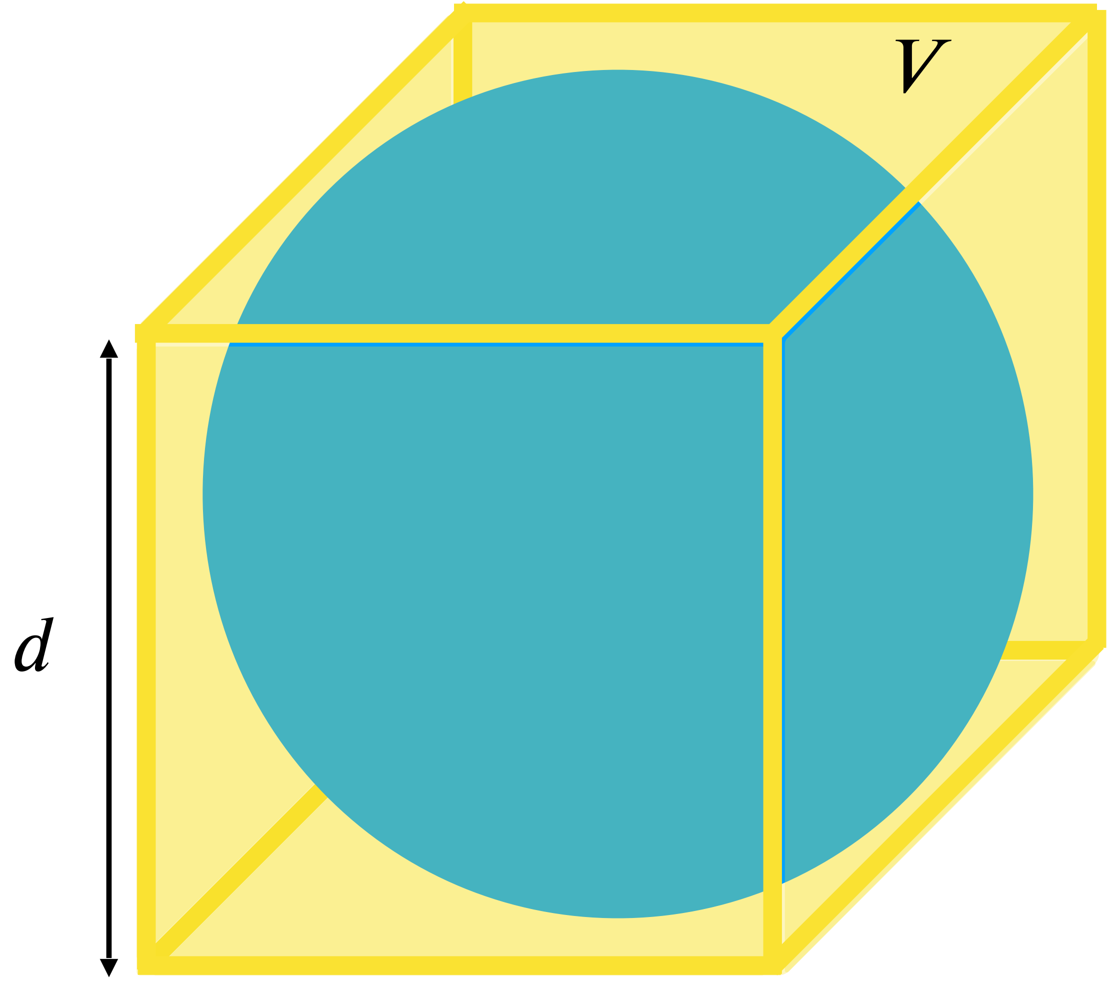
Disordered Dielectrics: 1D

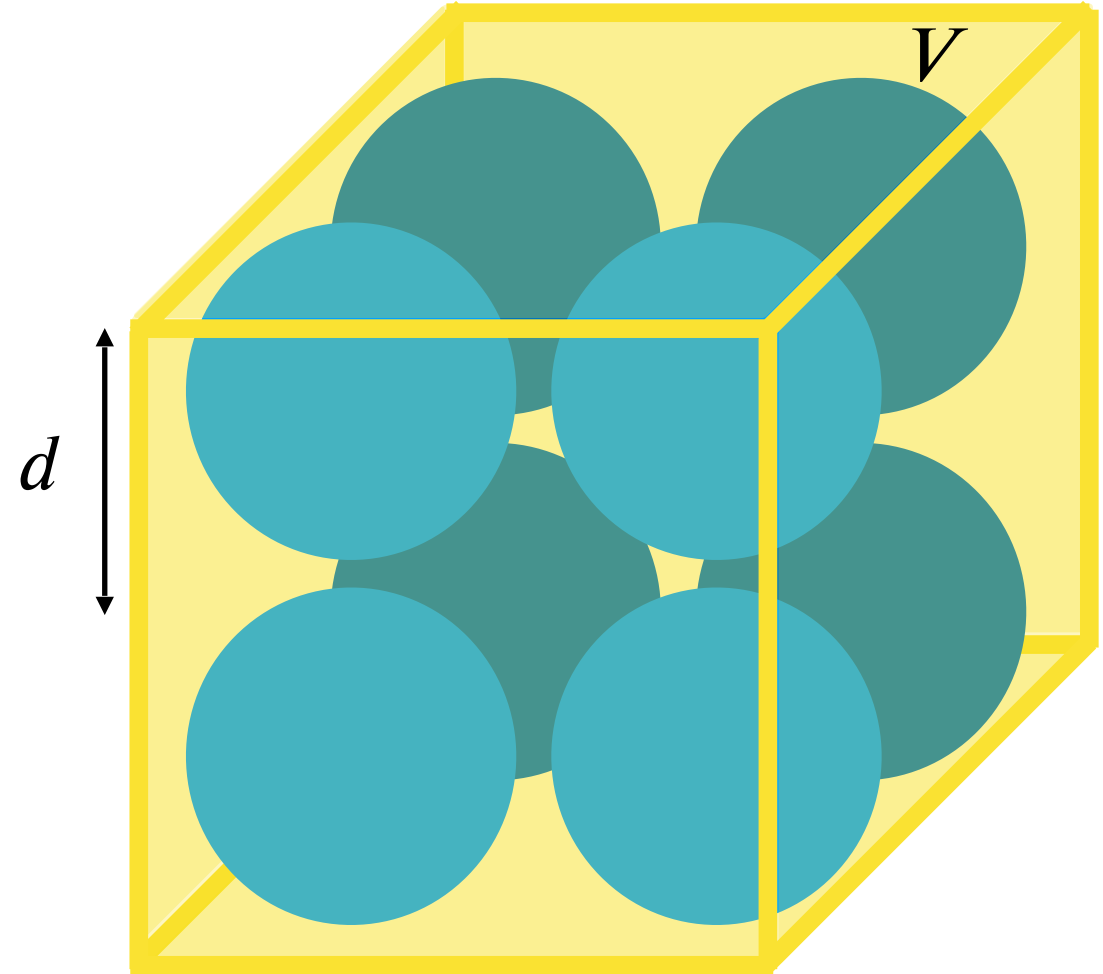


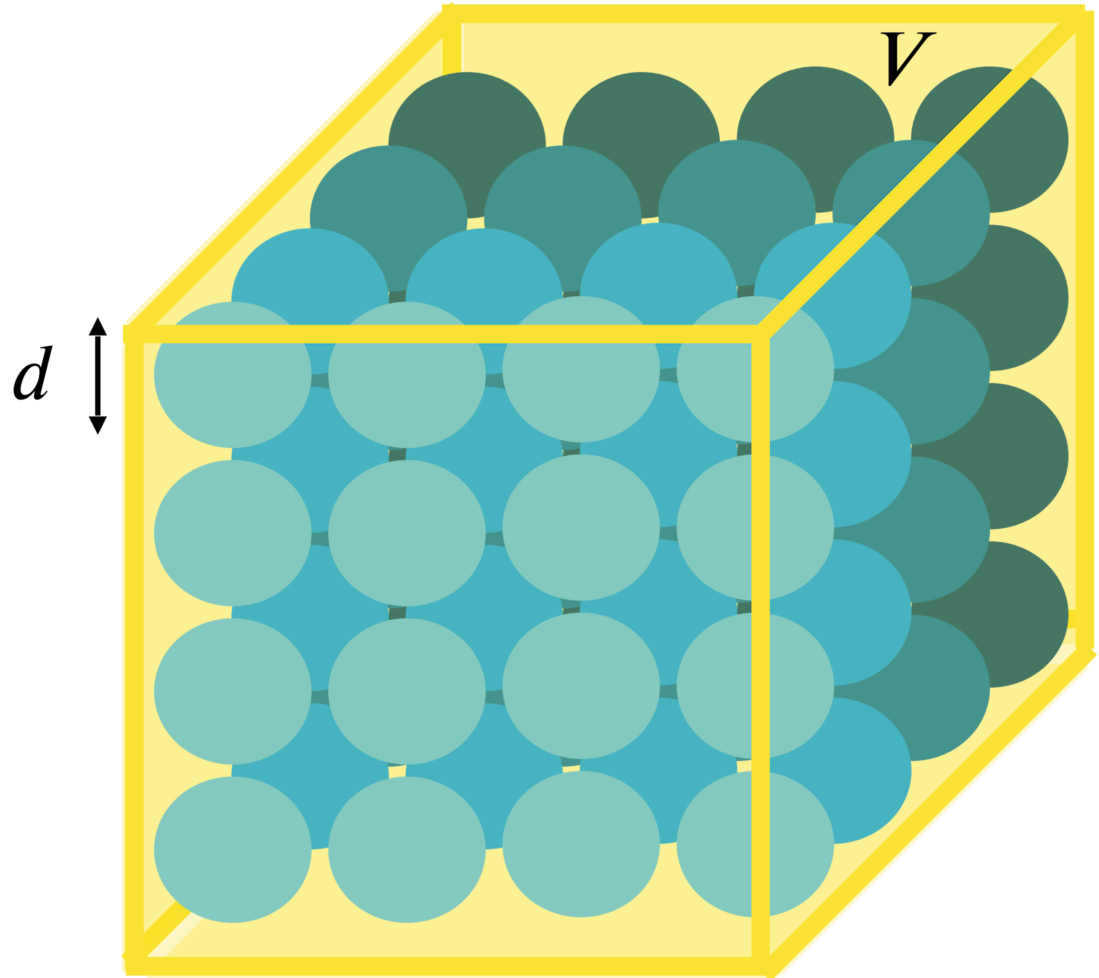
MB, J. Huang, R. Lasenby, PRD 2018

- Layers are conceptually simple and can provide high quality factor and focusing
- However, especially at large layer number (high Q), imperfections in 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?
- Have to be very stable (even under temperature changes?) and require careful characterization

Disordered Dielectrics: Higher Dimensions







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

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

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

Mie Scattering

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

Quality factor Q

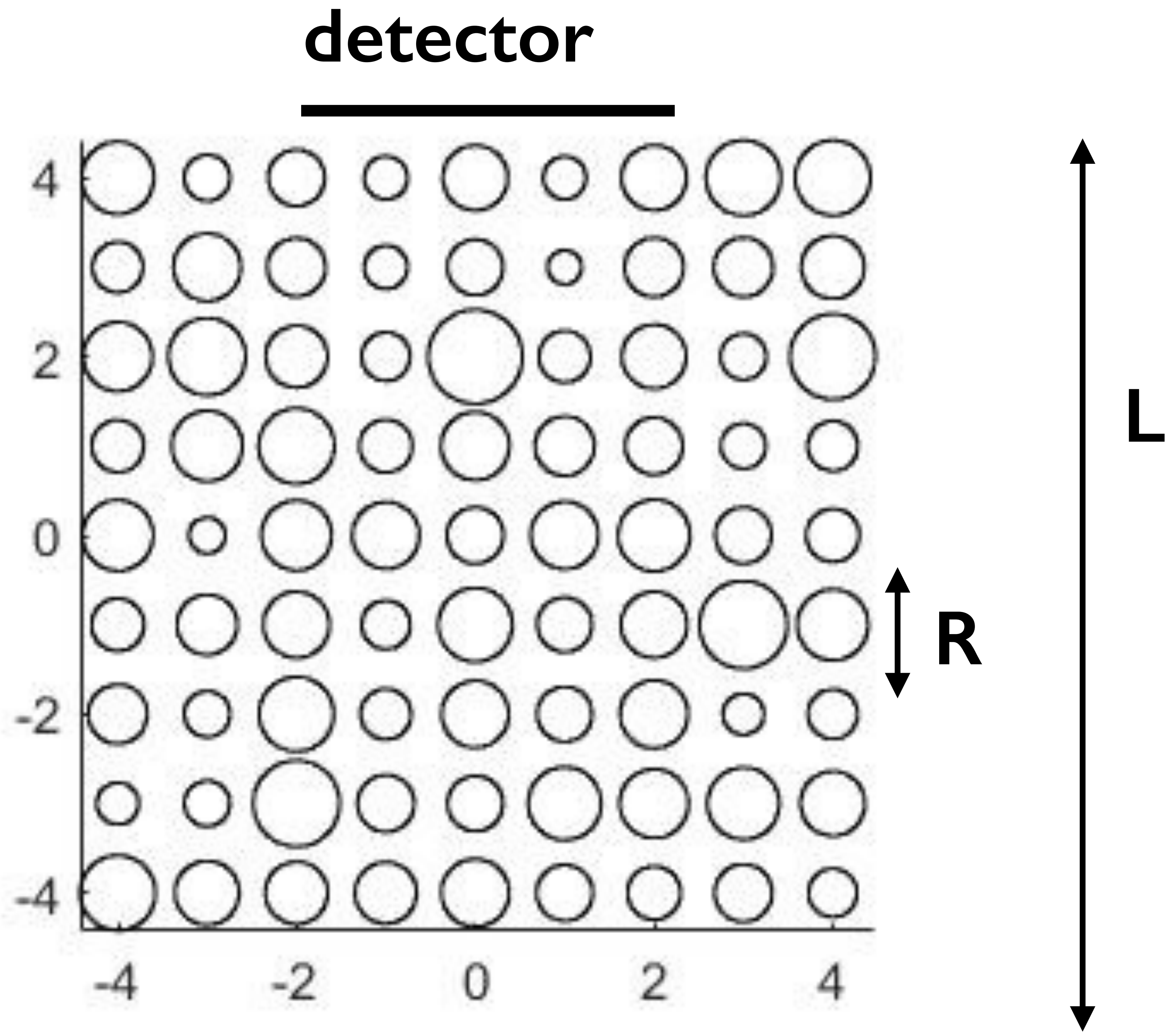
Below diffraction limit: $d \ll \lambda/2\pi$

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

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

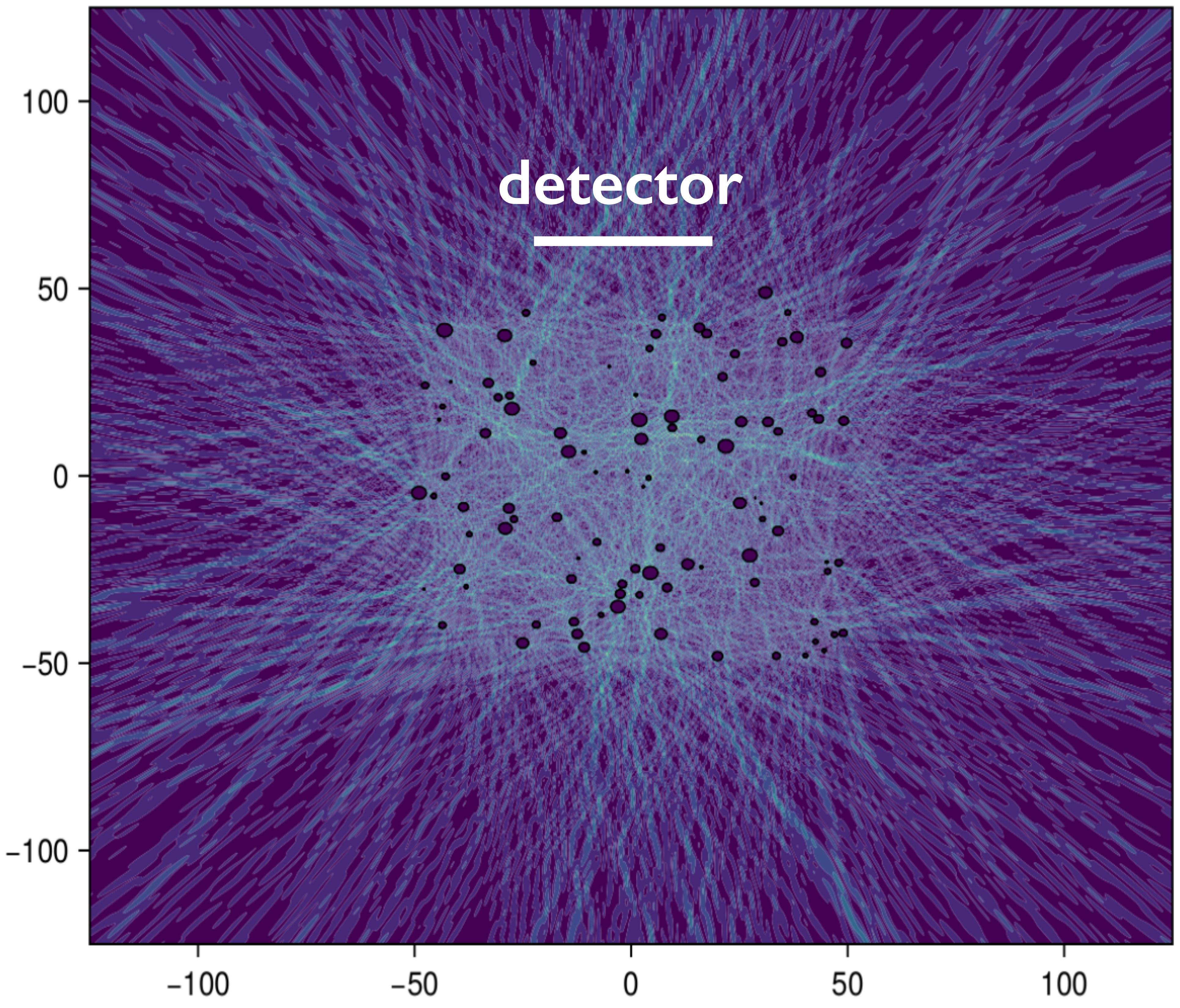
Slide credit: Stewart Koppell

Disordered Dielectrics: Higher Dimensions



$$P_{\rm av} = (g a_0 B_0)^2 A N \left(\frac{1}{n_1} + \frac{1}{n_2}\right) \left(\frac{1}{n_2} - \frac{1}{n_1}\right)^2$$

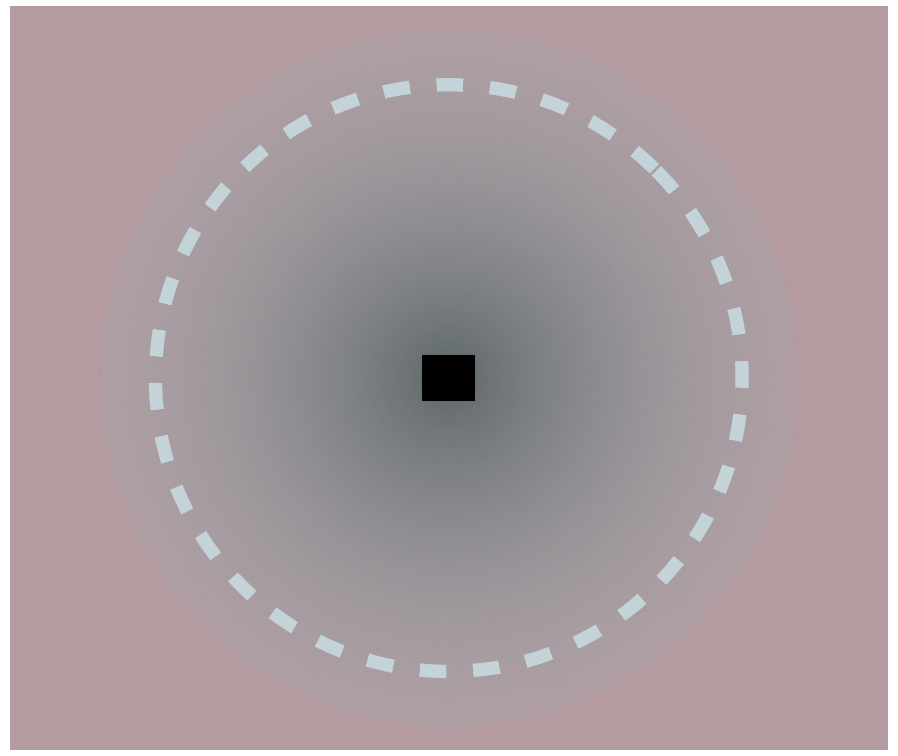
N ~ L/R



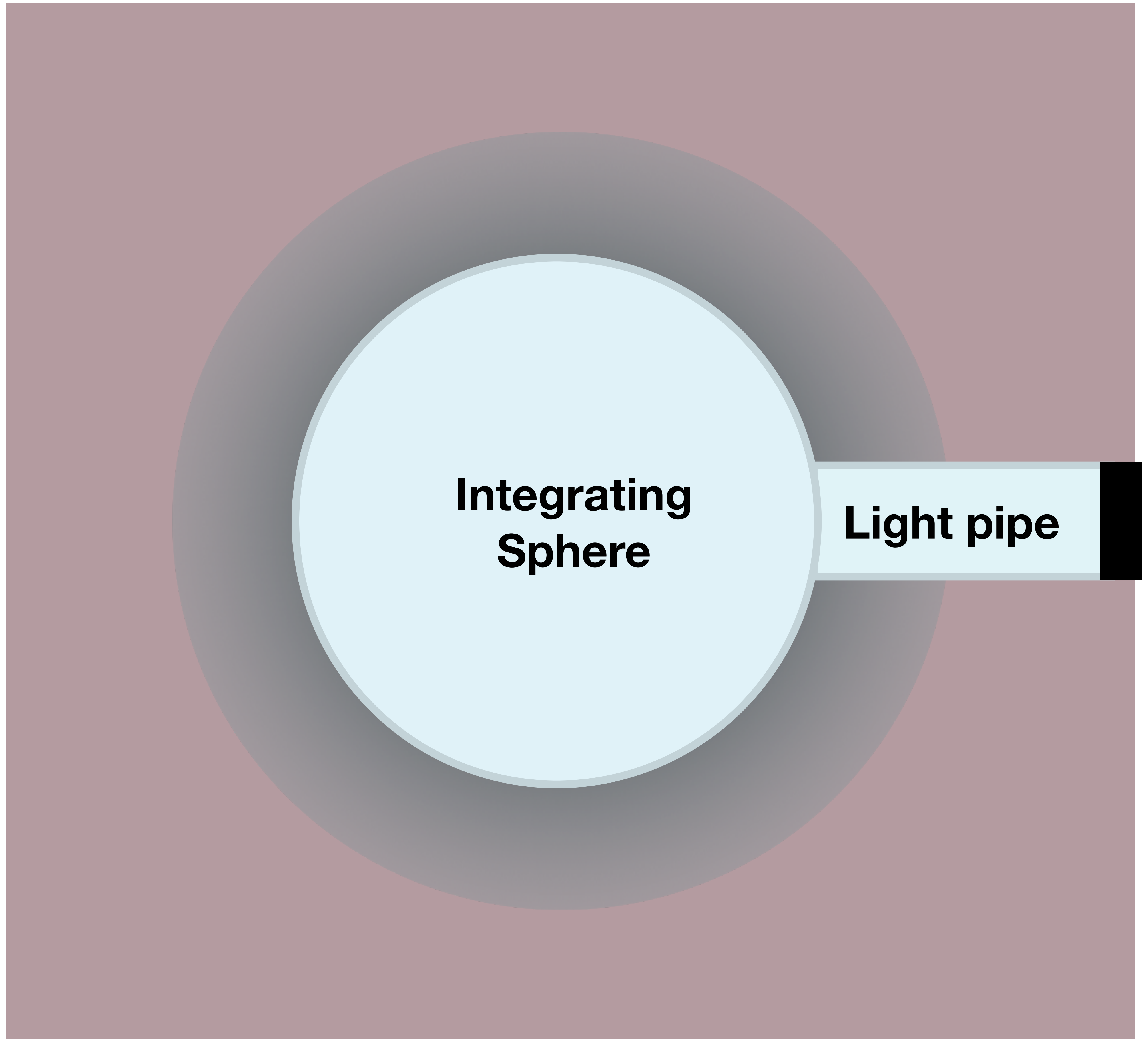
- Average power enhanced by number of cylinders (spheres)
- Downsides: no focusing, lower Q
- Upsides: no strong dependence on radius error, easy construction, benefit from randomness

Disordered Dielectrics: Higher Dimensions

SNSPD area: A
effective volume: V



For a sufficiently large integrating sphere,
SNSPD area: A **effective volume: A/α**



α = absorption coefficient

To saturate signal for SNSPD we need an integrating sphere with circulating optical power comparable to the the bulk. (the SNSPD should have negligible Impact on the average reflectivity)

E.g. for a A=1cm^2 SNSPD with reflectivity R_s~0, we need SA~100cm^2, or r~3cm

And for a powder with $\alpha = 1m^{-1}$, the effective volume is 100cm^2, Equivalent to a ~10m^2 area reflector experiment

Slide credit: Stewart Koppell

Dielectric enhancements: TeraBREAD and beyond

- Searches for heavier axions of theoretical interest and require going beyond the dish antenna concept to reach the QCD line
- Dielectric enhancements are being developed and have been demonstrated in a range of setups
- Volume-filling dielectric materials can enhance the signal strength: many interesting geometries possible including chirped stacks and random dielectrics