BREAD:
Broadband Reflector Experiment for Axion Detection

Stefan Knirck,

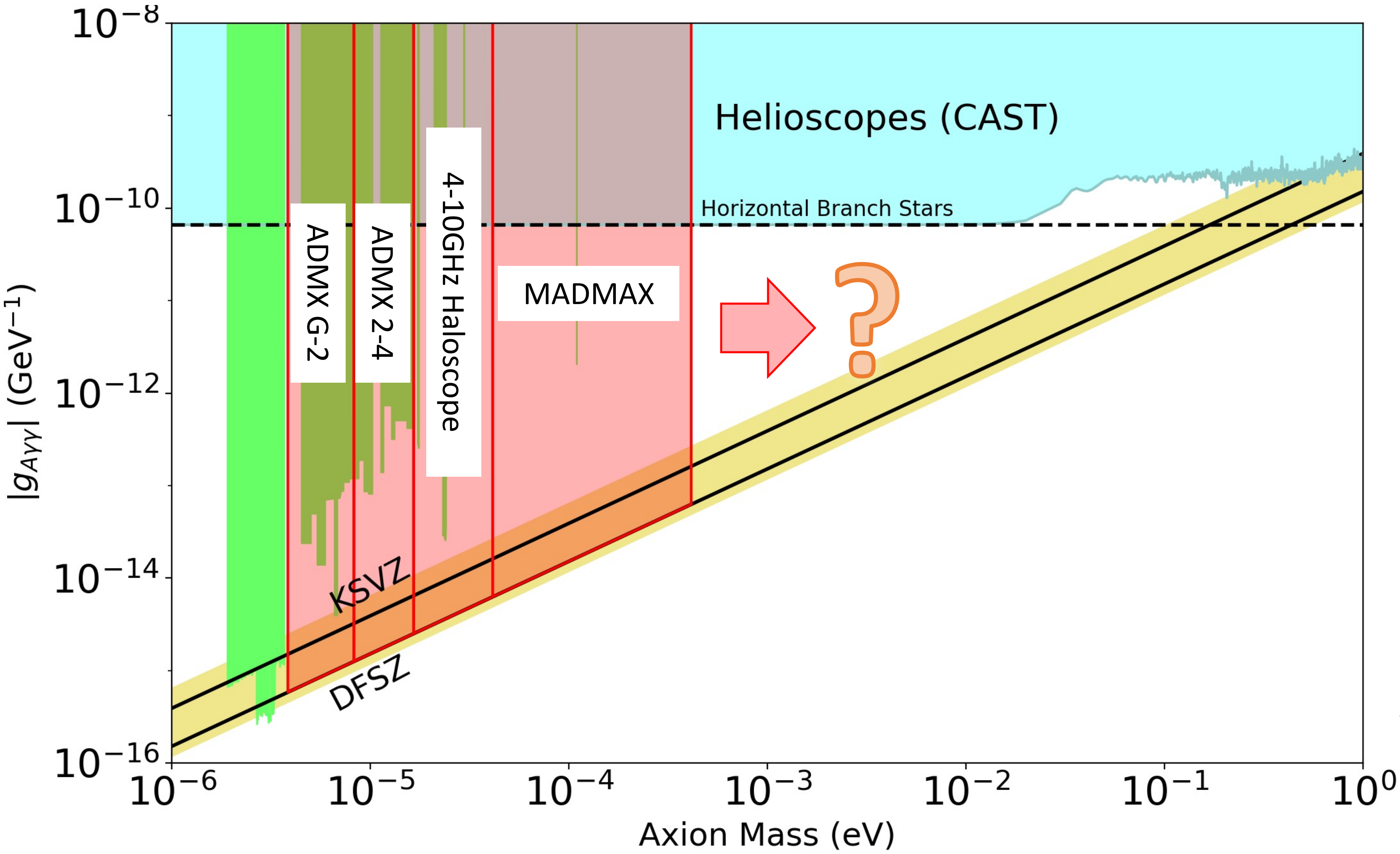
Fermi National Accelerator Laboratory

Fermilab

for the BREAD collaboration

MS Office Stock Photo

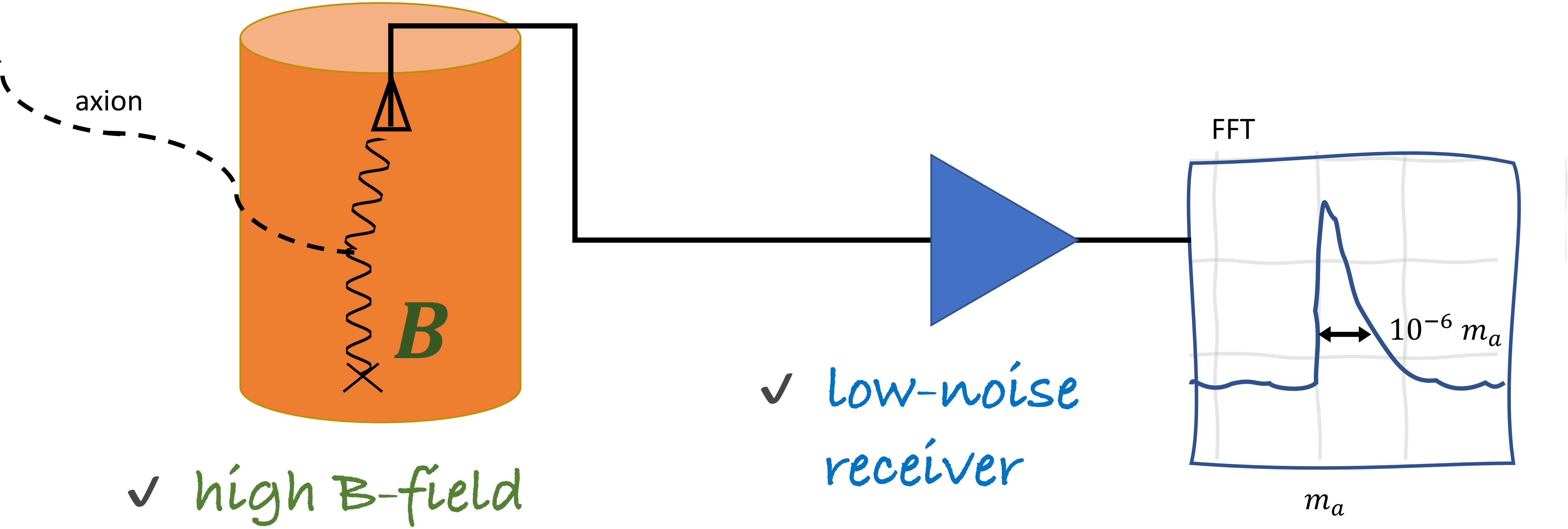
Motivation



Adapted from [Rybka et al, PDG2019]

Shopping List

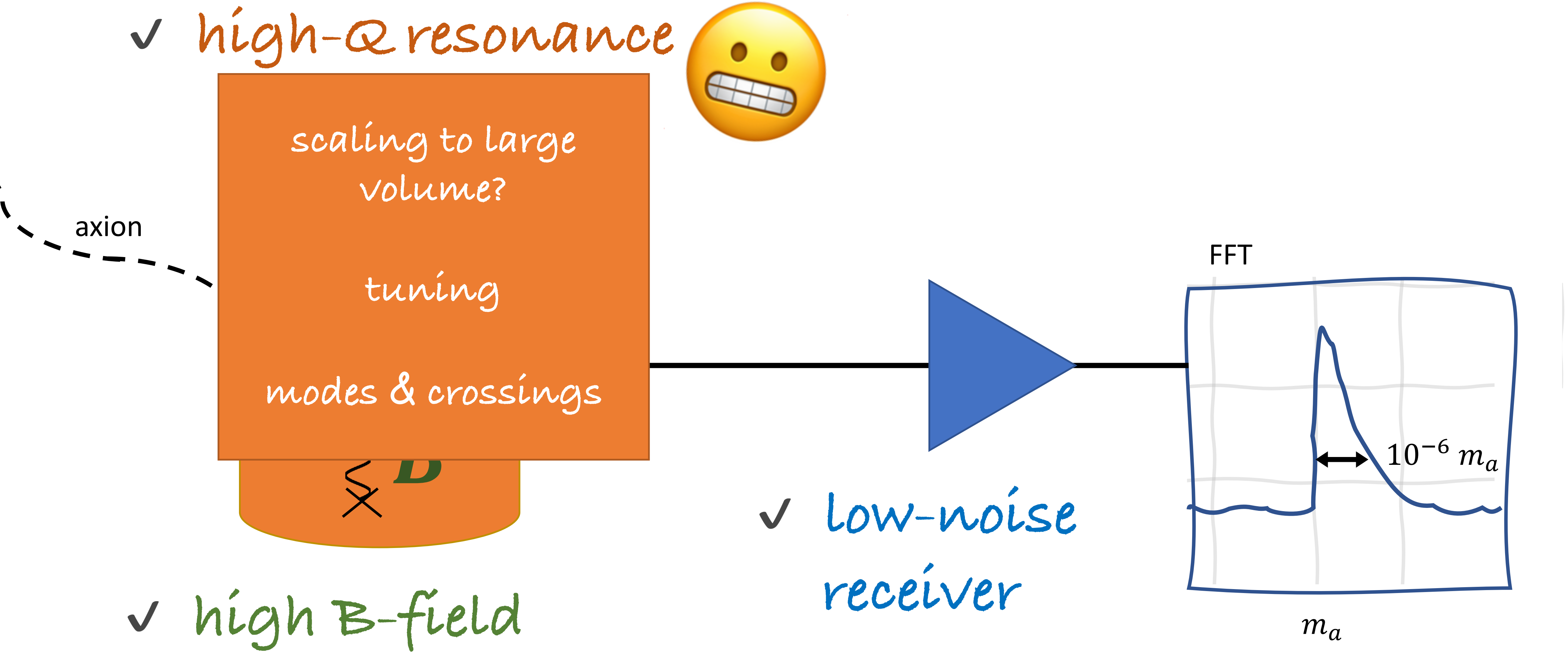
✓ high-Q resonance



✓ low-noise receiver

✓ high B-field

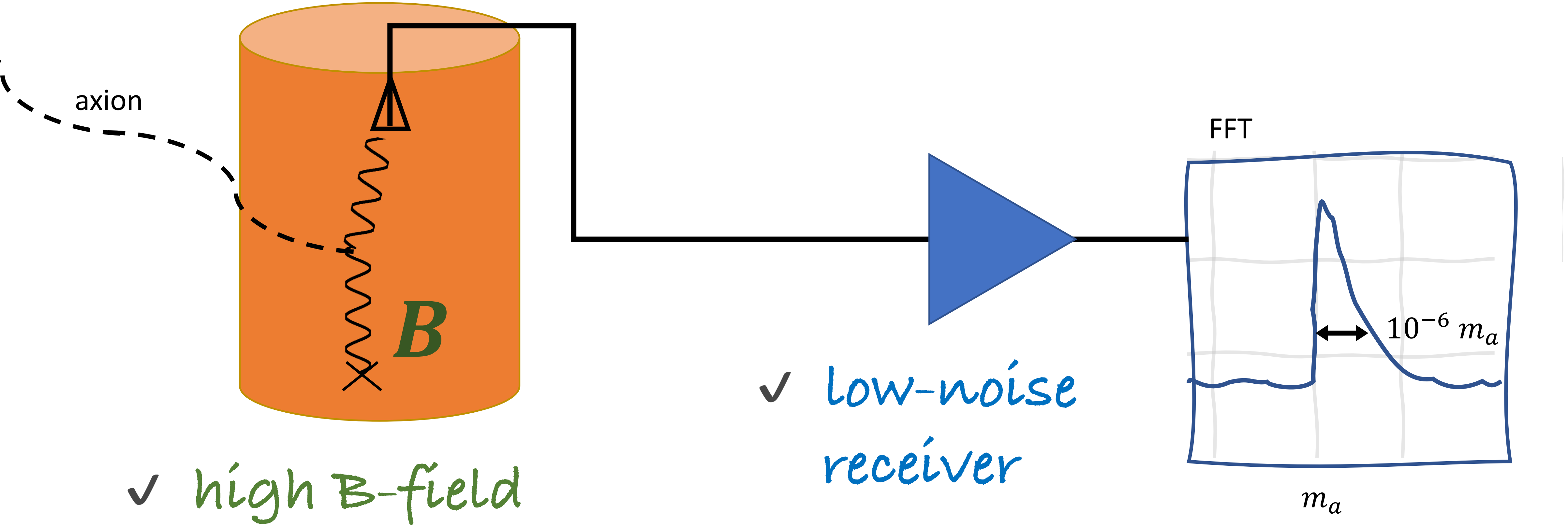
Shopping List



Shopping List

✓ ~~high-Q resonance~~

[https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Aaron_Chou-175.pdf]



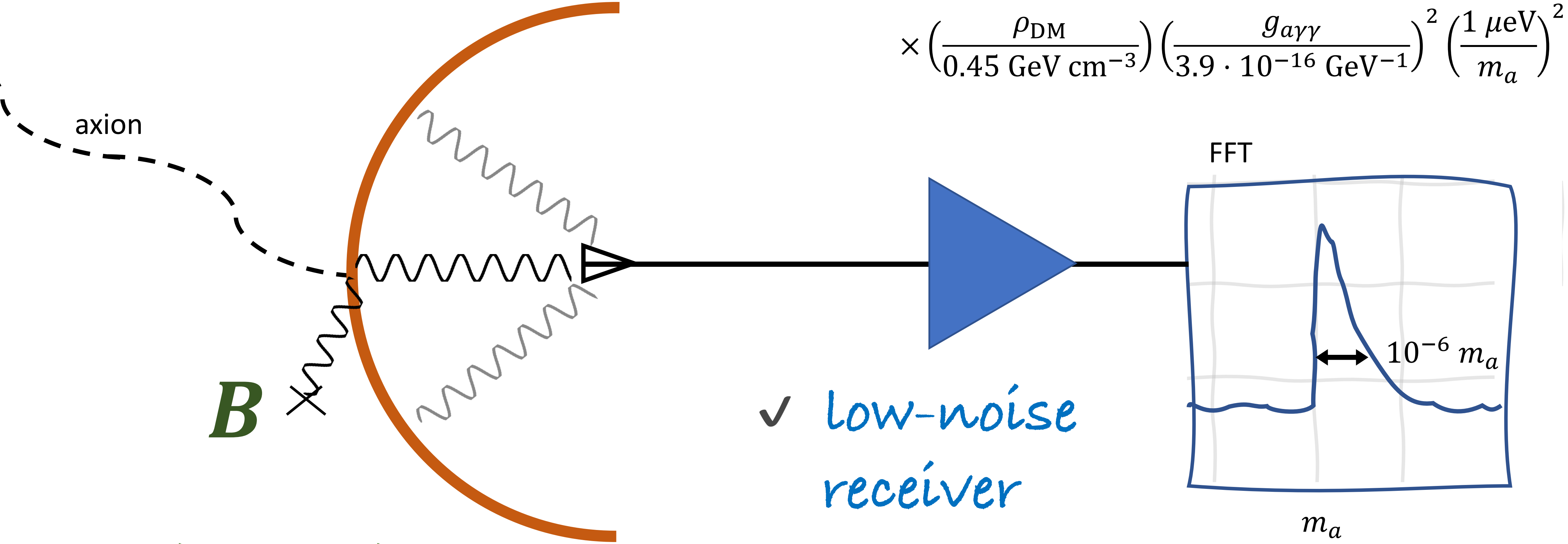
✓ high B-field

✓ low-noise receiver

Shopping List

✓ "dish antenna"
[Horns et al, arXiv:1212.2970]

$$P_{\text{sig}} = 1.2 \cdot 10^{-25}\,\text{W} \cdot \left(\frac{A}{10\ \text{m}^2}\right)\left(\frac{B_\parallel}{10\ \text{T}}\right)^2 \times \left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV cm}^{-3}}\right)\left(\frac{g_{a\gamma\gamma}}{3.9 \cdot 10^{-16}\ \text{GeV}^{-1}}\right)^2 \left(\frac{1\ \mu\text{eV}}{m_a}\right)^2$$



✓ low-noise receiver

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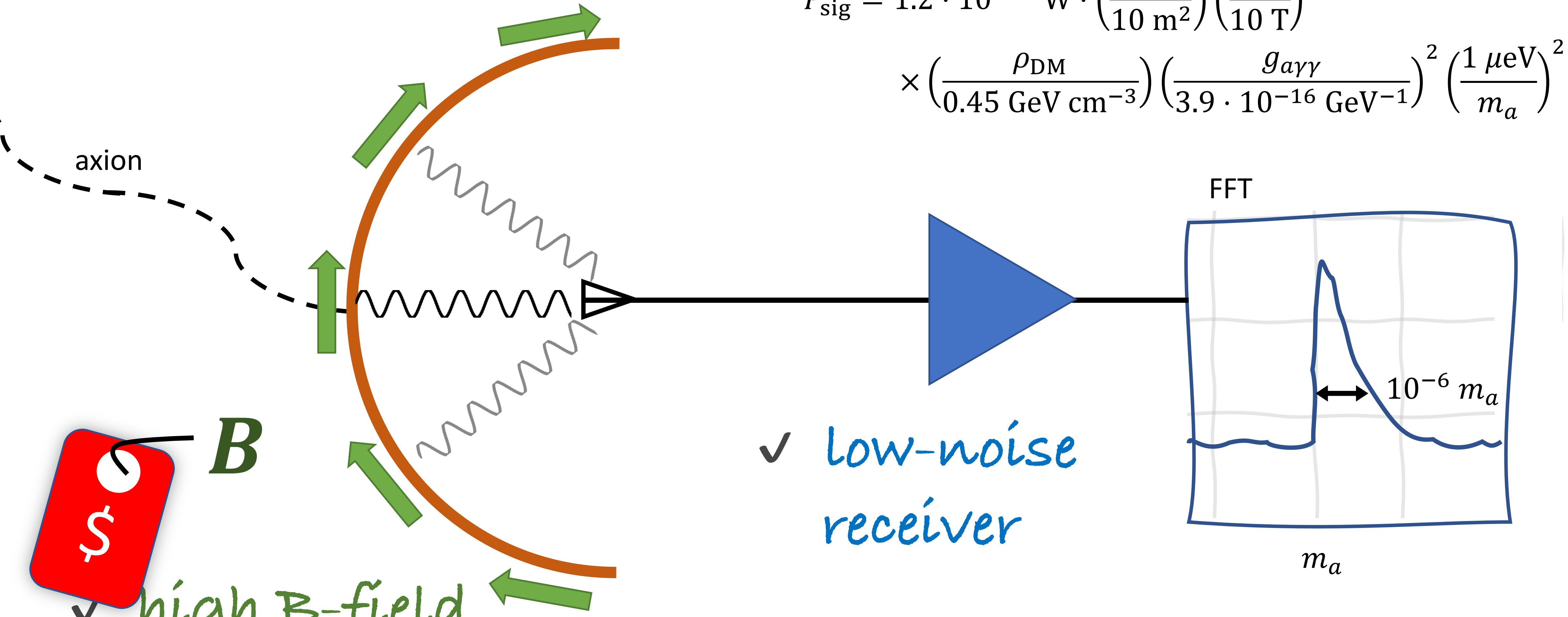


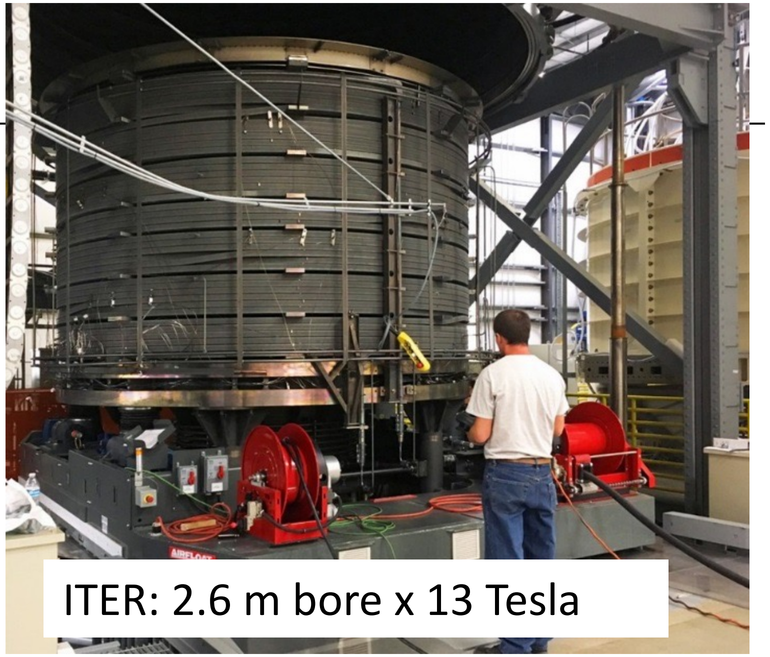
✓ low-noise receiver

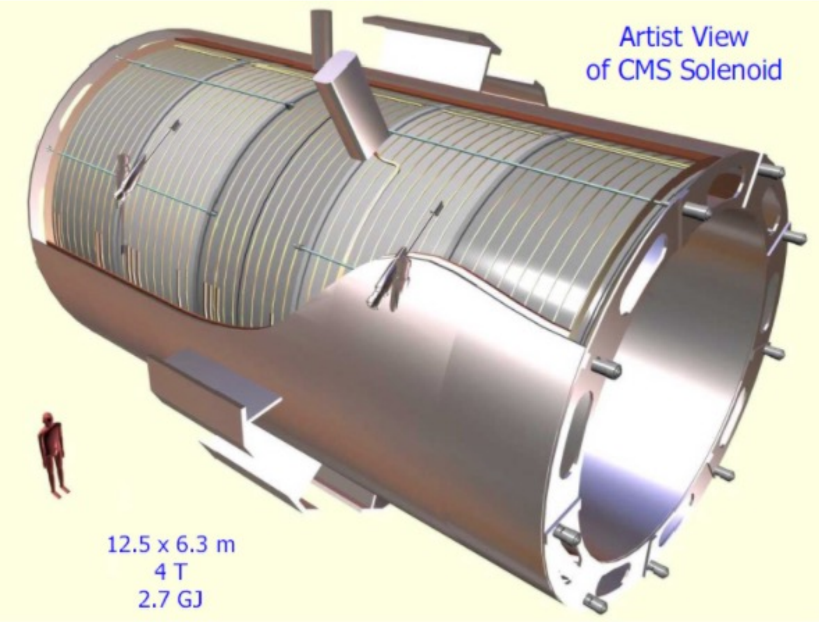
✓ high B-field

The Magnet: Solenoid

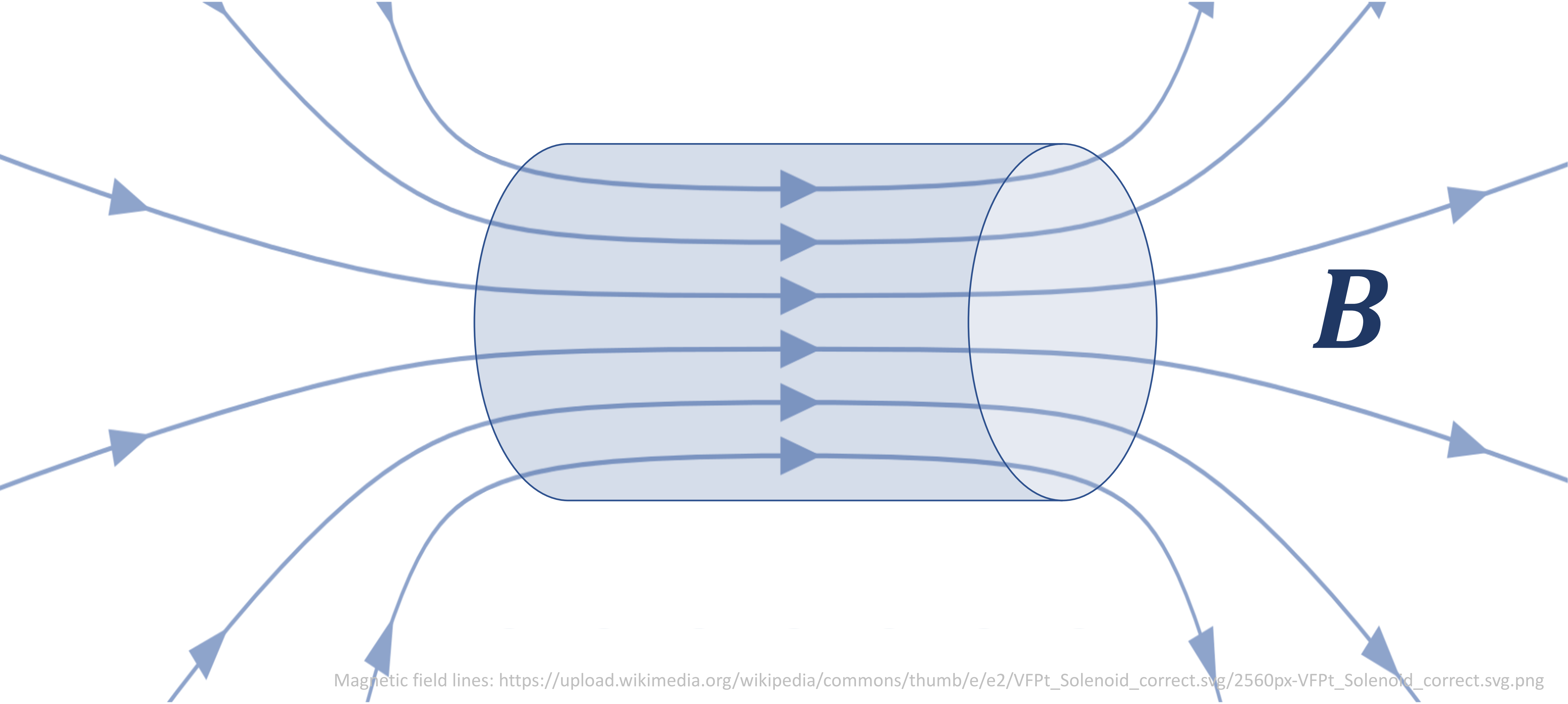
B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

Compilation by Mark Bird, NHMFL


ITER: 2.6 m bore x 13 Tesla

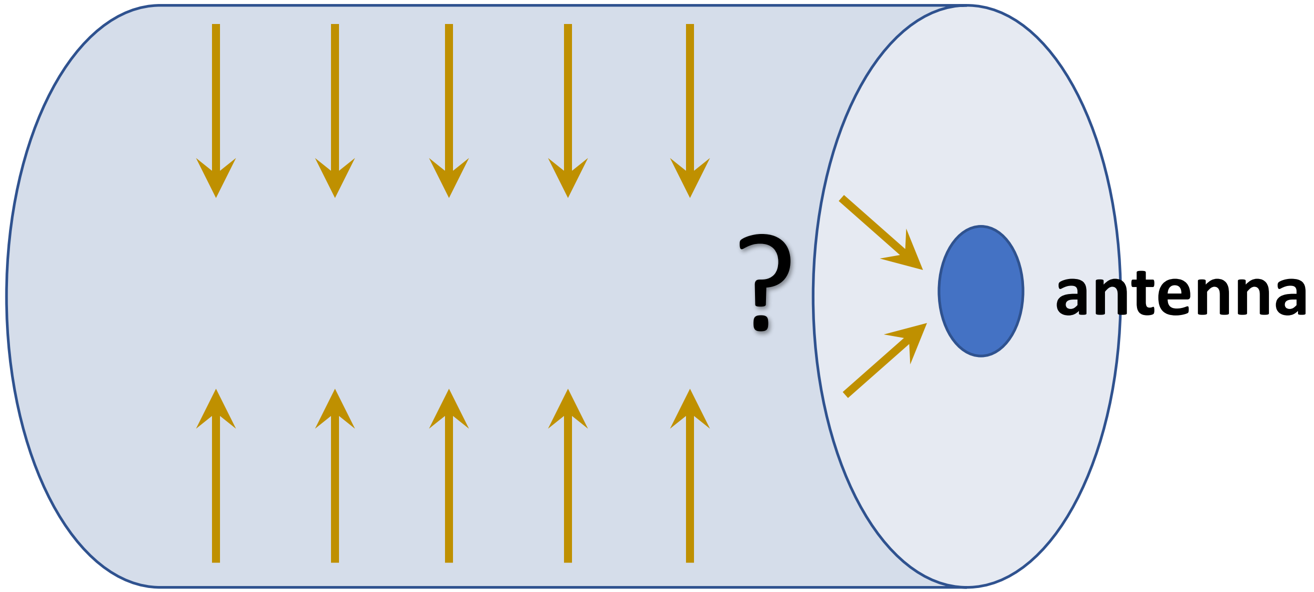


The Magnet: Solenoid

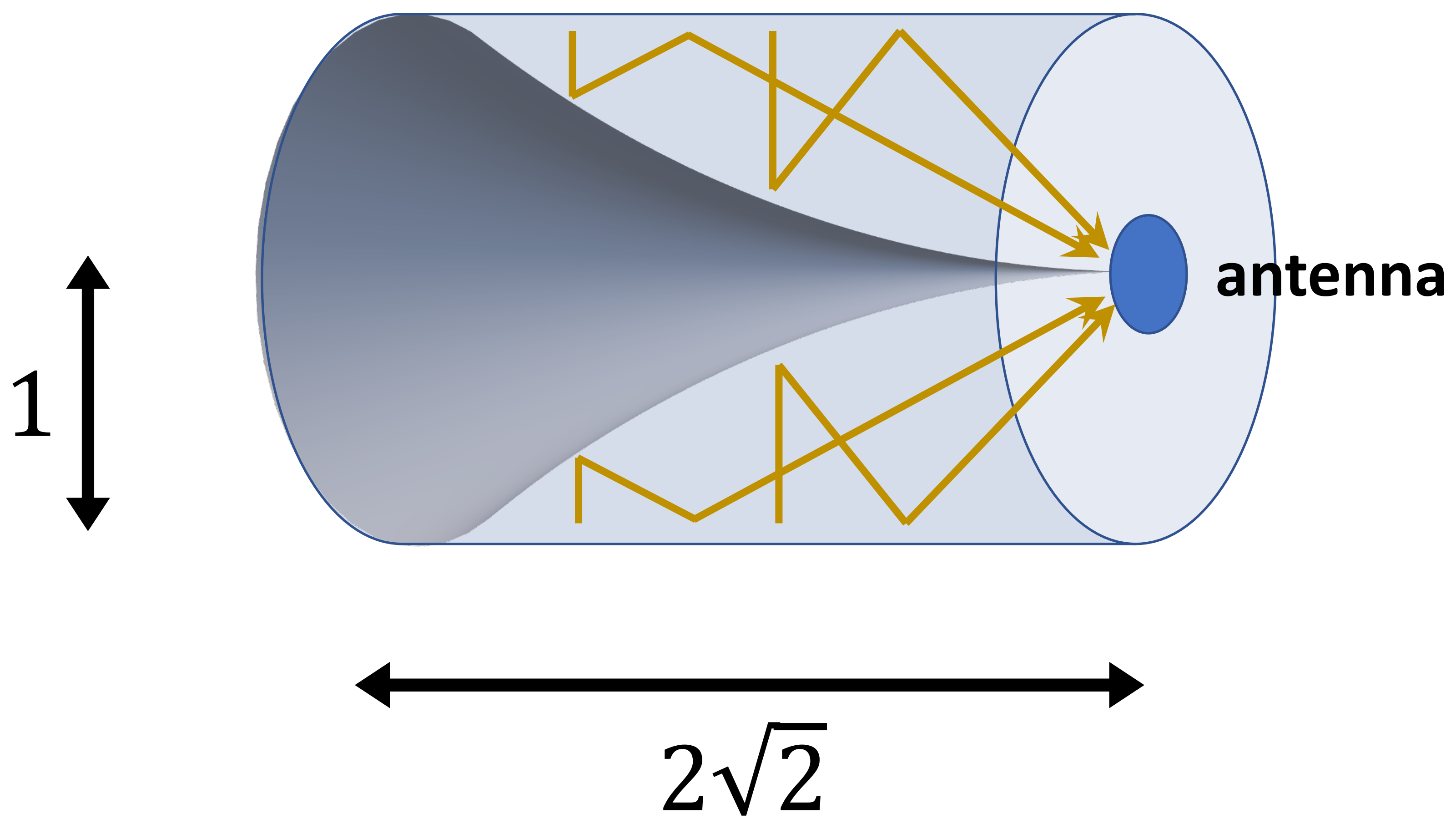


Magnetic field lines: https://upload.wikimedia.org/wikipedia/commons/thumb/e/e2/VFPt_Solenoid_correct.svg/2560px-VFPt_Solenoid_correct.svg.png

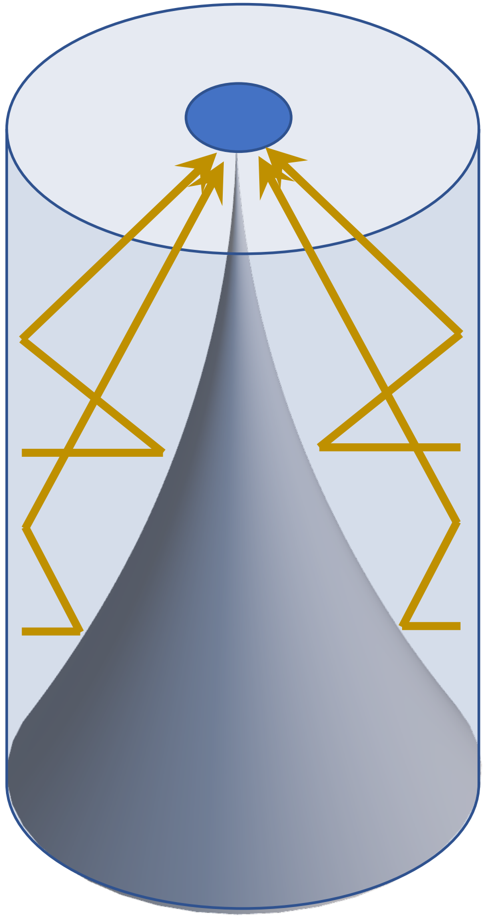
The Magnet: Solenoid

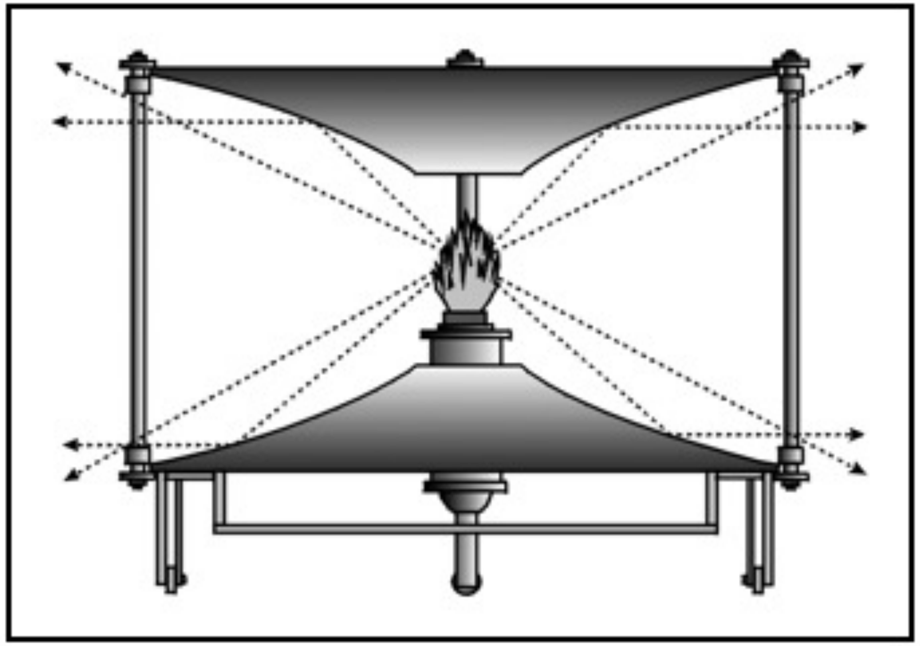


Coaxial Dish Concept



Design Legacy: 19th Century Lighthouse Mirrors





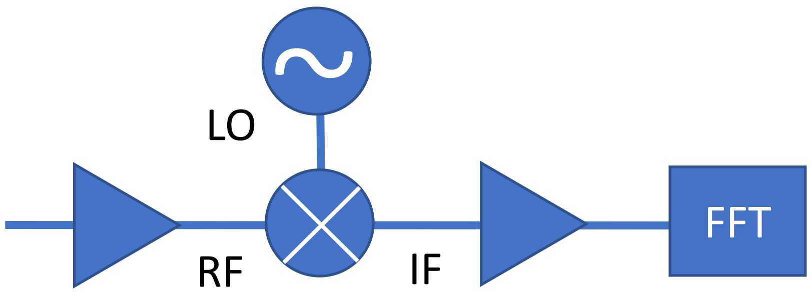
Bordier-Marcet's 'Fanal Sidereal Reflector. (1809)

Fanal Sidereal Lantern. (1811)

From https://uslhs.org/reflectors

Receiver Types

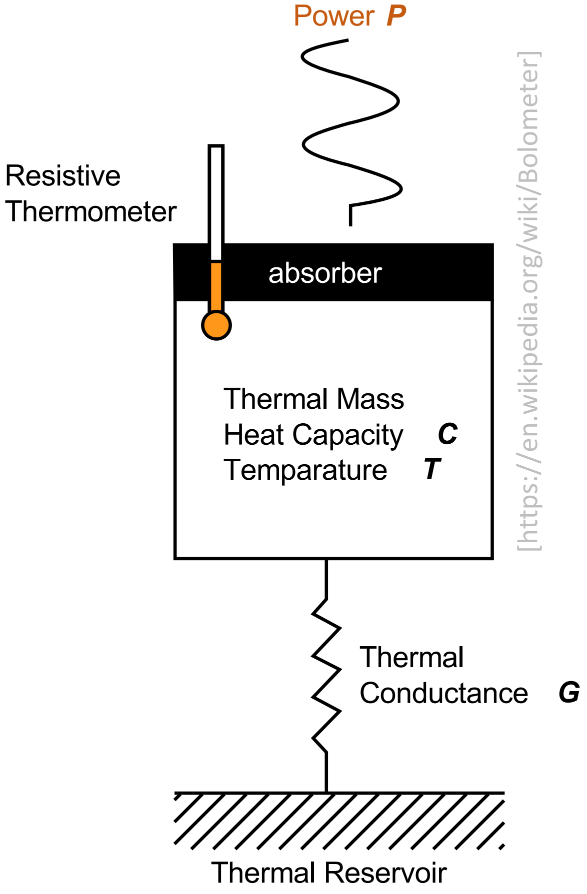
Heterodyne



- high resolution
- **Standard Quantum Limit (SQL):**
  $k_B\,T_{noise} = hf$

→ Giga-BREAD

Bolometer



[https://en.wikipedia.org/wiki/Bolometer]

NEP ~ $10^{-20}\ W/\sqrt{Hz}$

Single Photon Counting

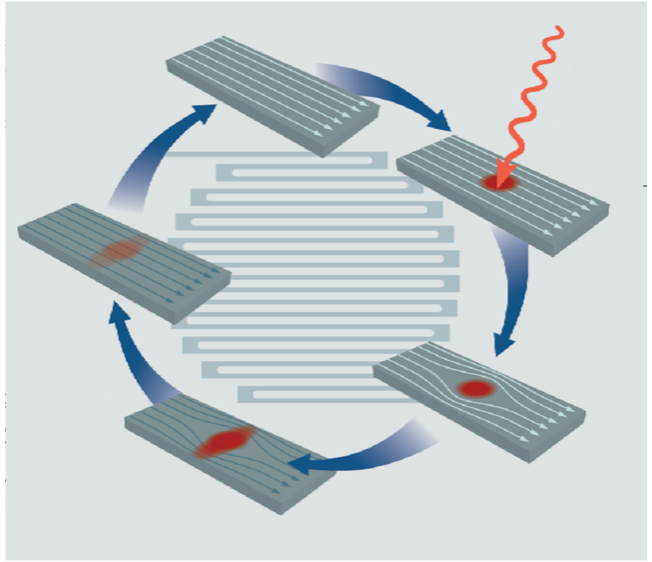


Fig.: Sae Woo Nam (NIST)

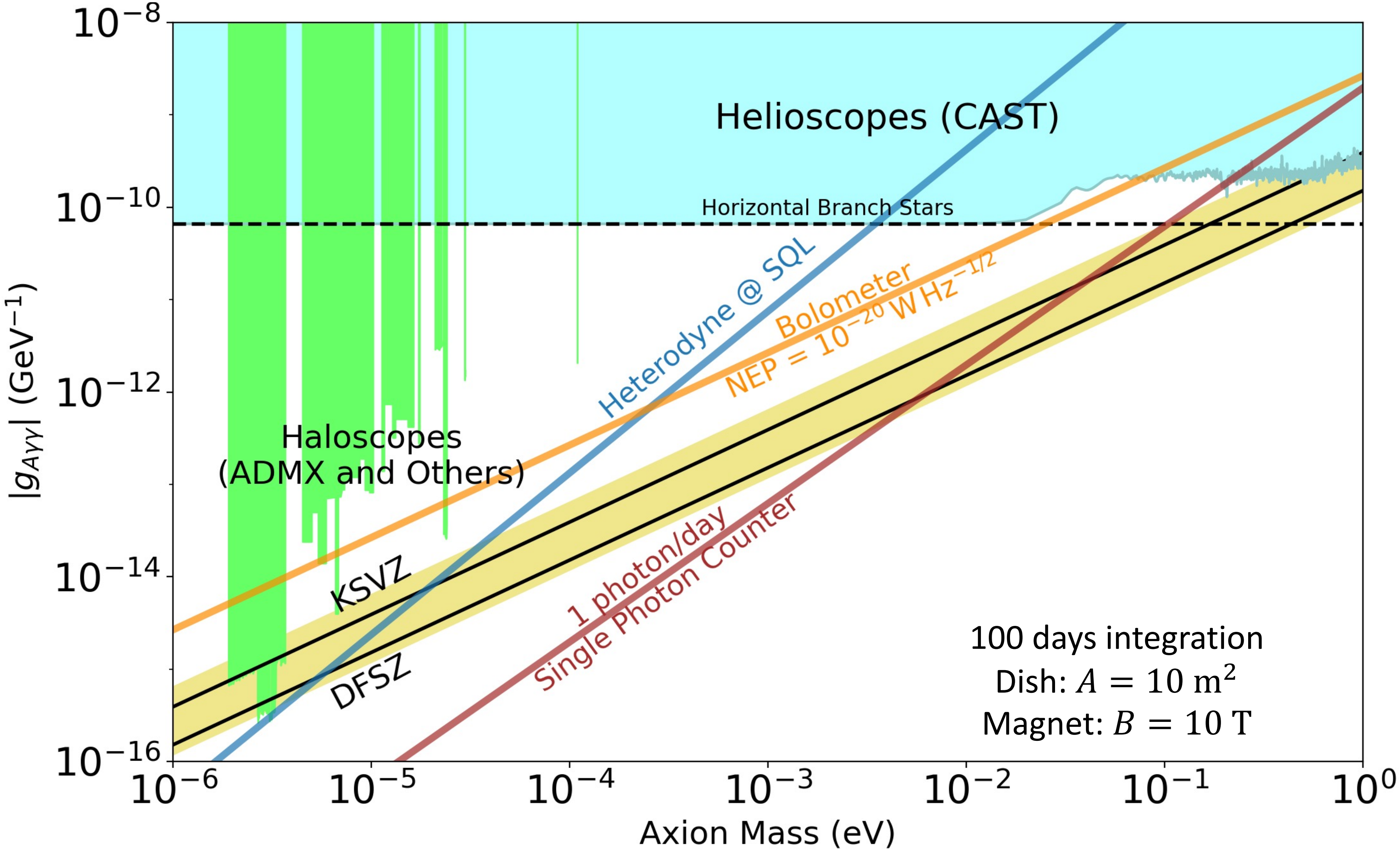
e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

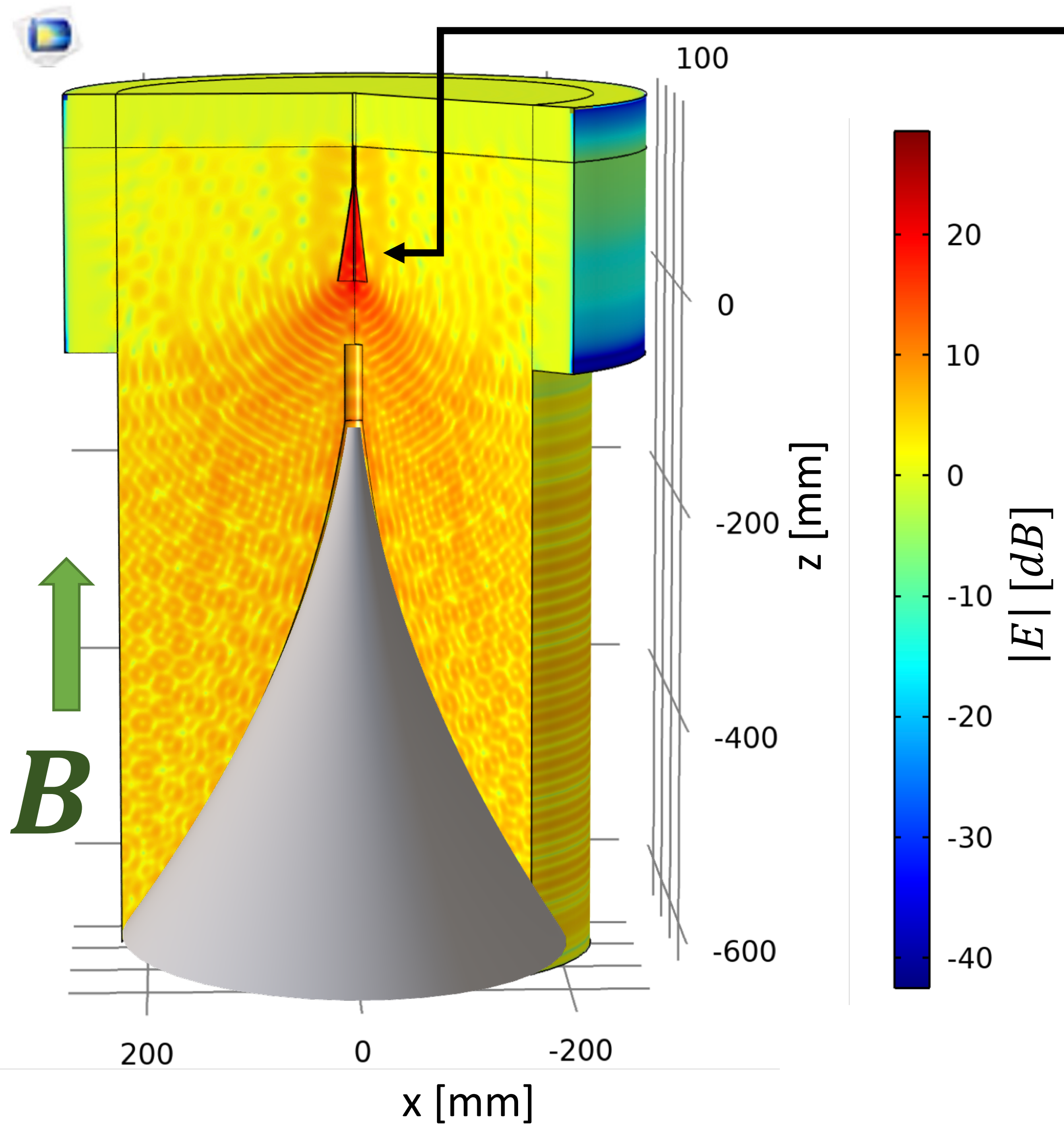
→ Tera-BREAD pilot

Sensitivity

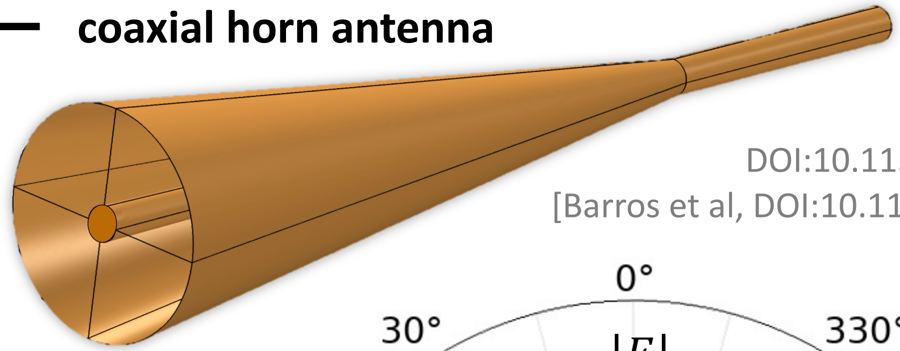


Adapted from [Rybka et al, PDG2019]

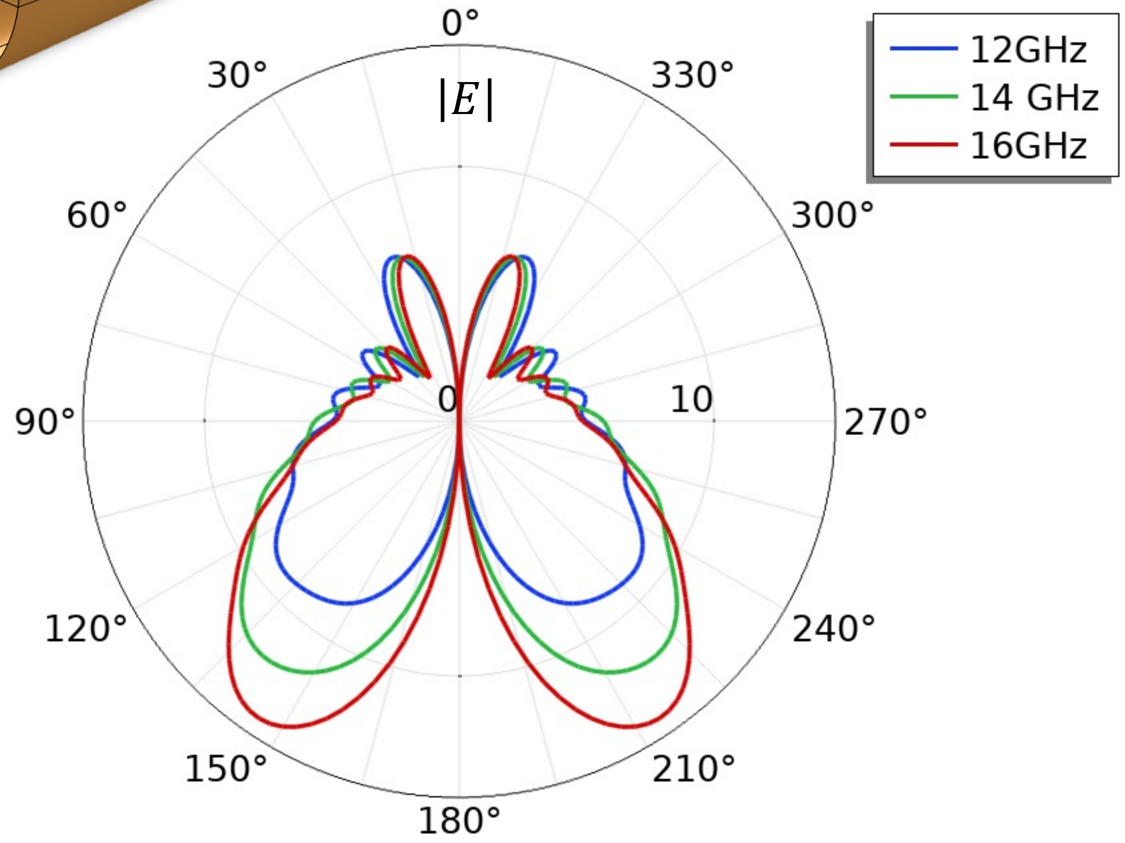
Giga-BREAD: RF Simulation



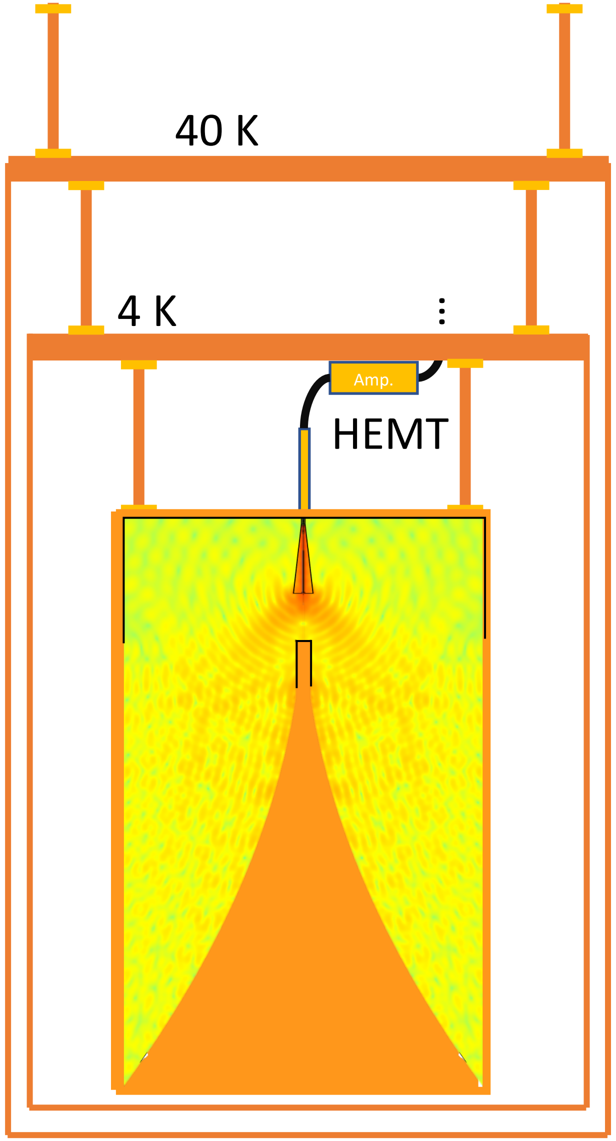
coaxial horn antenna

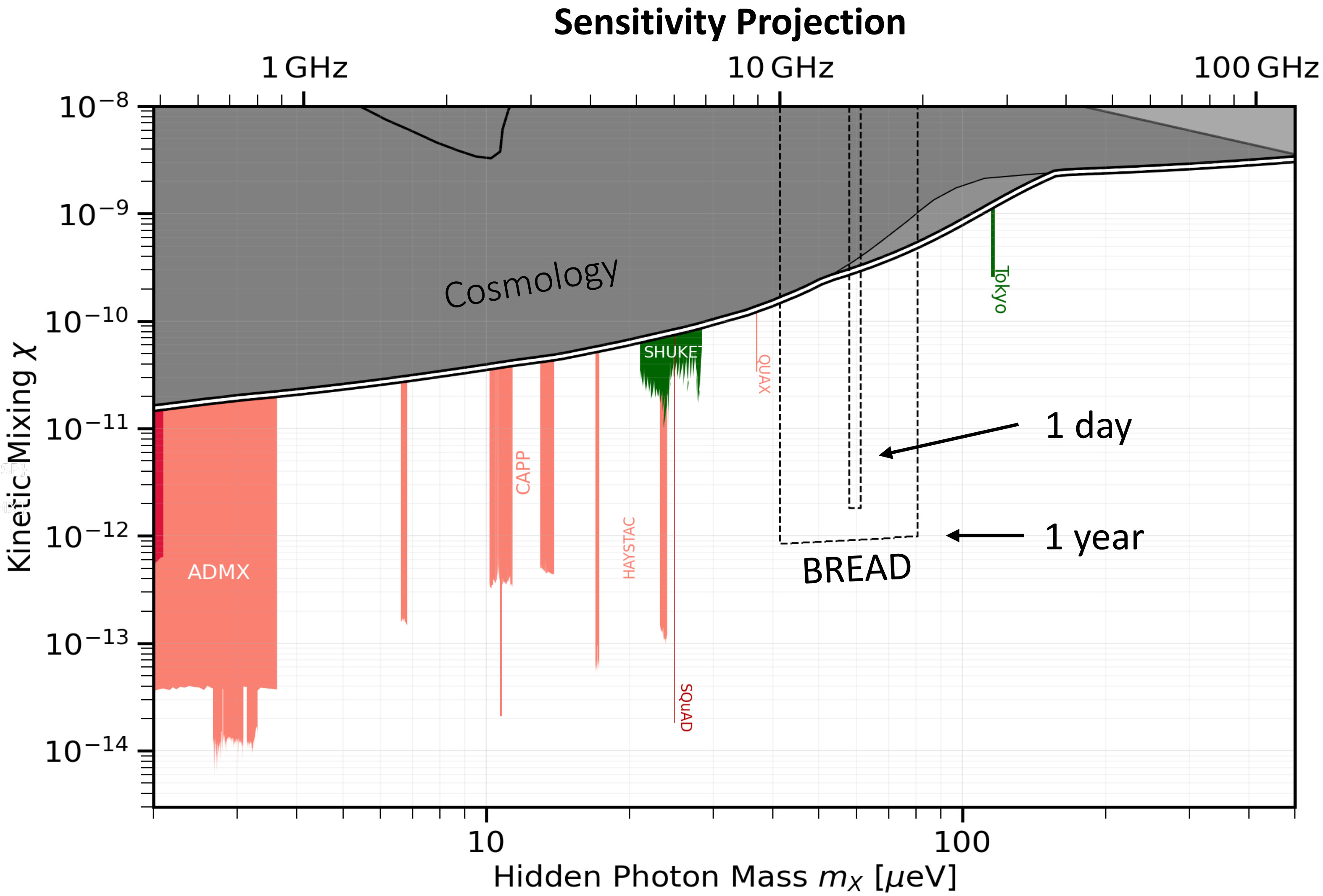


e.g. [Bykov et al, DOI:10.1134/S0020441208050126]
[Barros et al, DOI:10.1109/IMOC.2013.6646569]



Giga-BREAD: Sensitivity

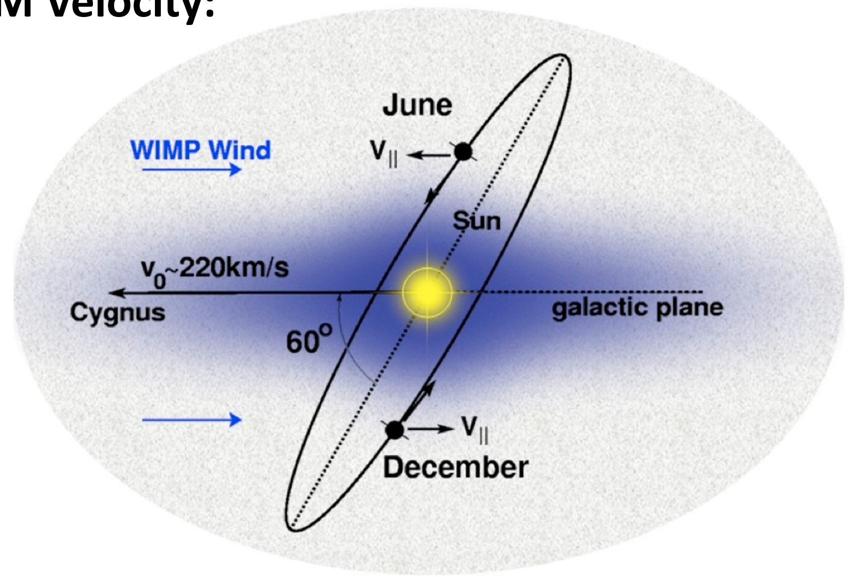




limit plot adapted from [Caputo et al., arXiv:2105.04565]

Tera-BREAD: Velocity Effects

CDM Velocity:



[https://www.hep.ucl.ac.uk/darkMatter/pictures/wind.jpg]

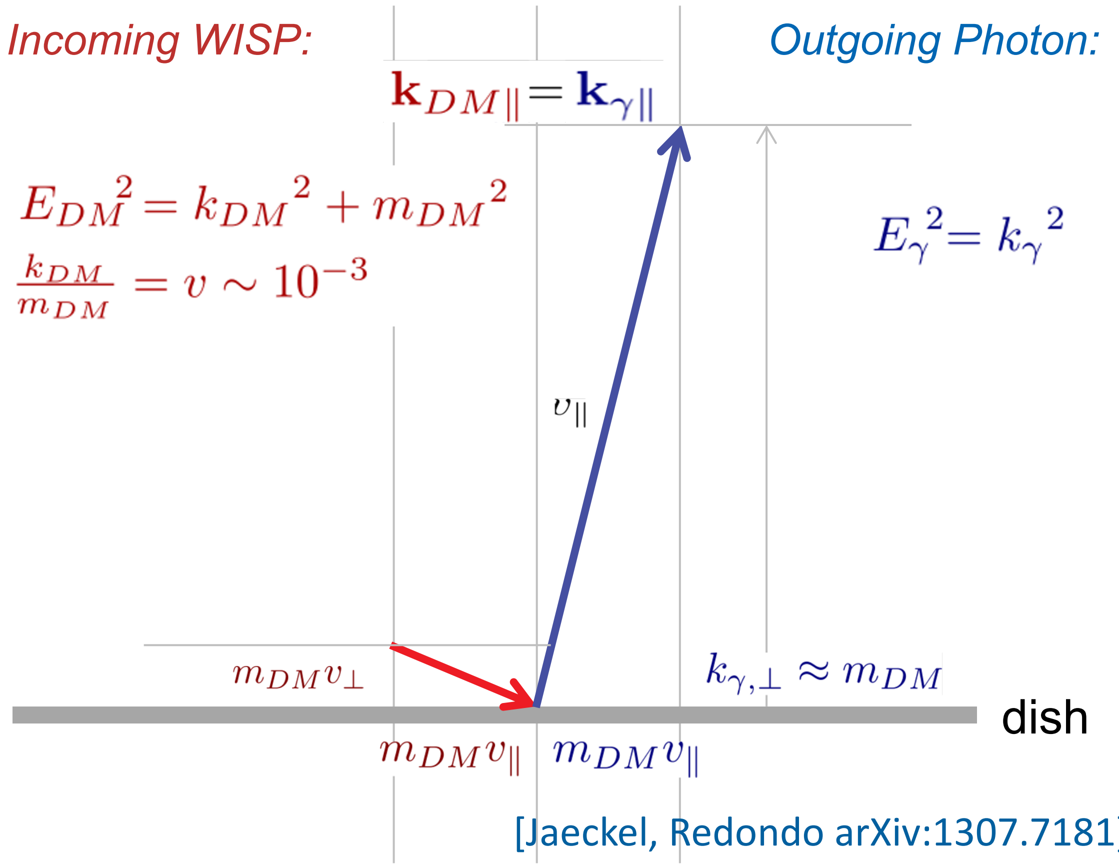
Standard Halo Model:

$$f(\boldsymbol{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{|\boldsymbol{v}-\boldsymbol{v}_{\text{lab}}|^2}{2\sigma_v^2}\right) \frac{\Theta\left(v_{\text{esc}} - |\boldsymbol{v}|\right)}{N_{\text{esc}}}$$

$$|\boldsymbol{v}_{\text{lab}}| \sim 220\,\text{km}\,\text{s}^{-1},\ \sigma_v \sim 156\,\text{km}\,\text{s}^{-1}$$

DM velocity $\sim v \sim 10^{-3}c$

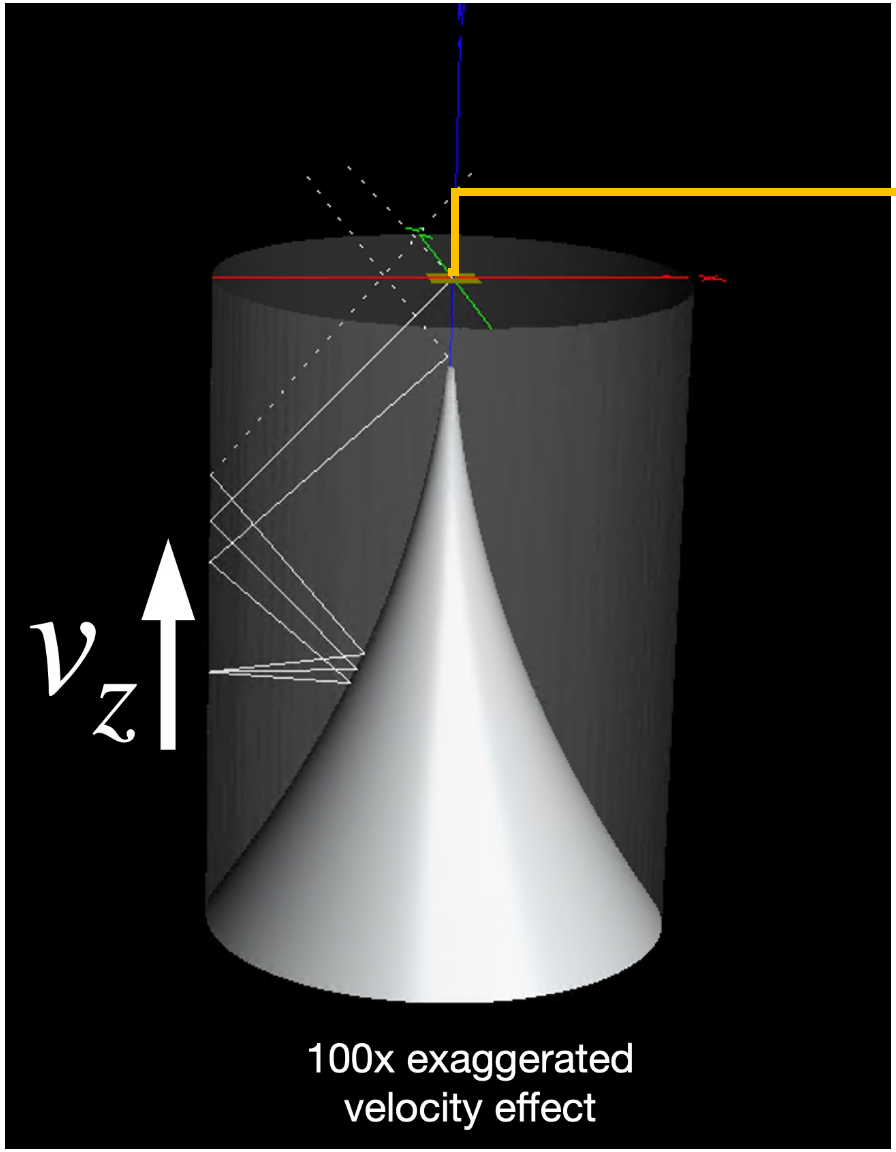
For Dish Antenna:

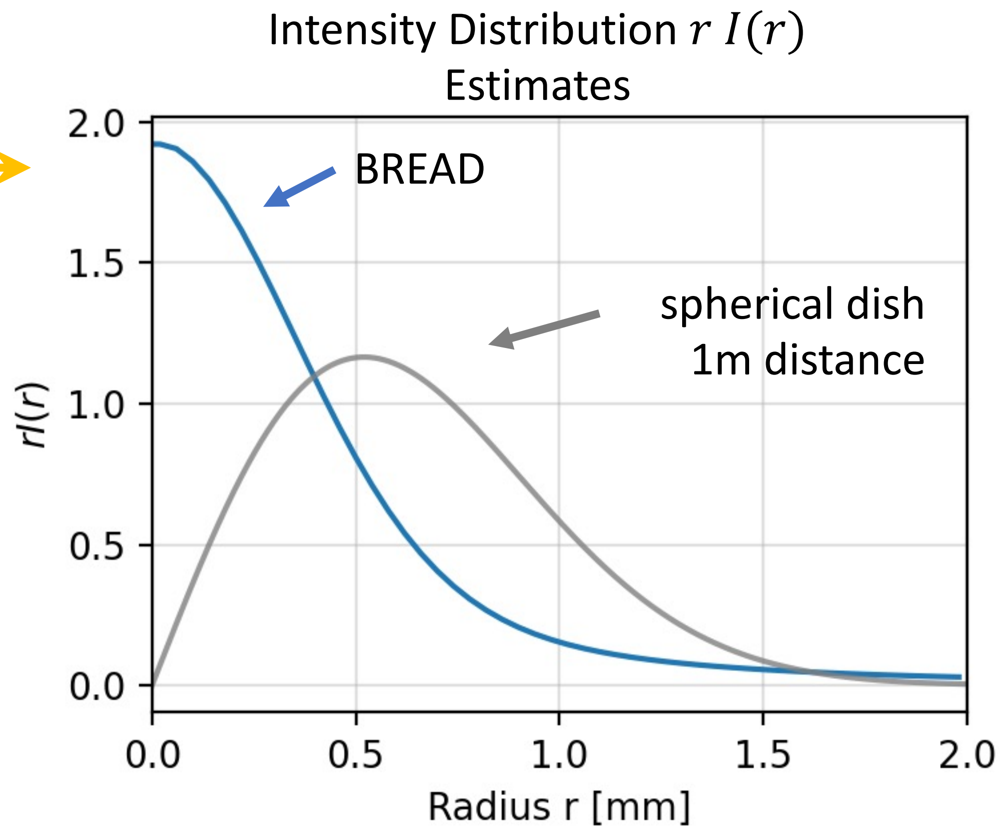


[Jaeckel, Redondo arXiv:1307.7181]
[Jaeckel, SK arXiv:1509.00371]

outgoing angle $\sim v \sim 10^{-3}c$

Tera-BREAD: Velocity Effects





Radius:

$$R = 200\text{mm}$$

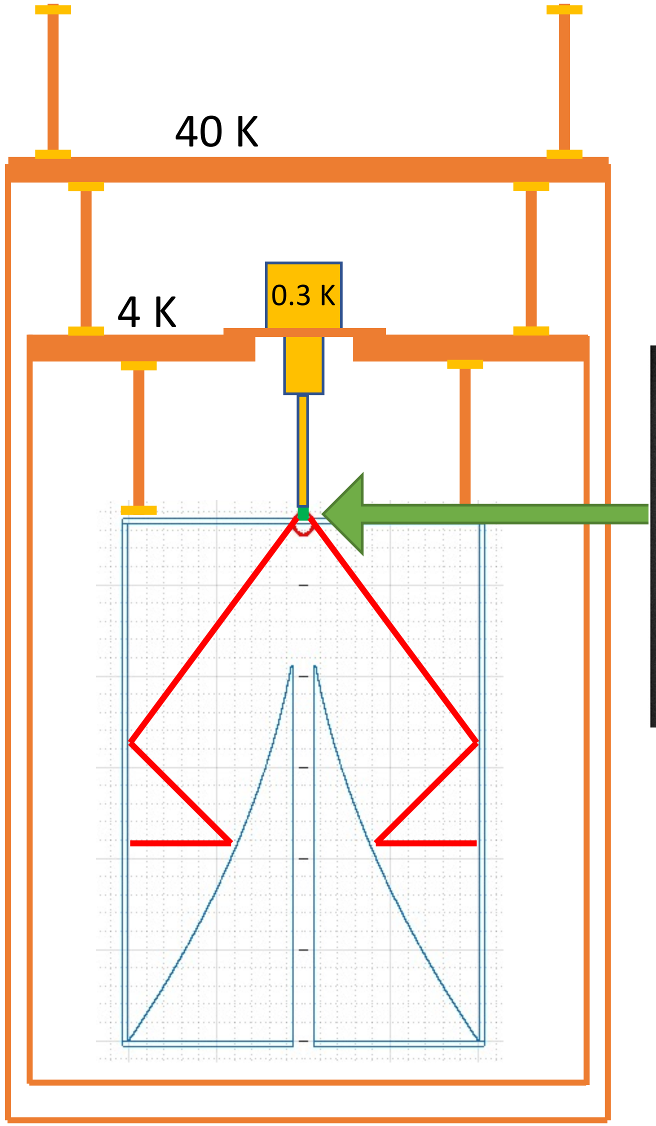
Dish Area:

$$A = 0.7\text{m}^2$$

(Pilot Experiment Dims.)

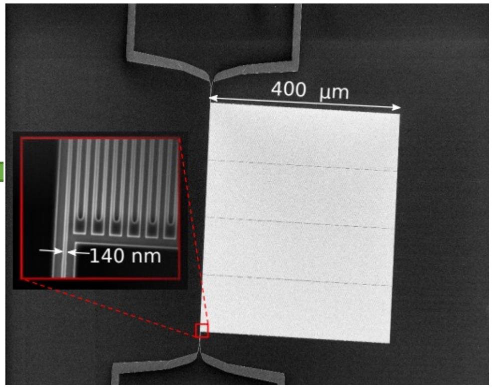
focusing velocity effect limited

Tera-BREAD Pilot



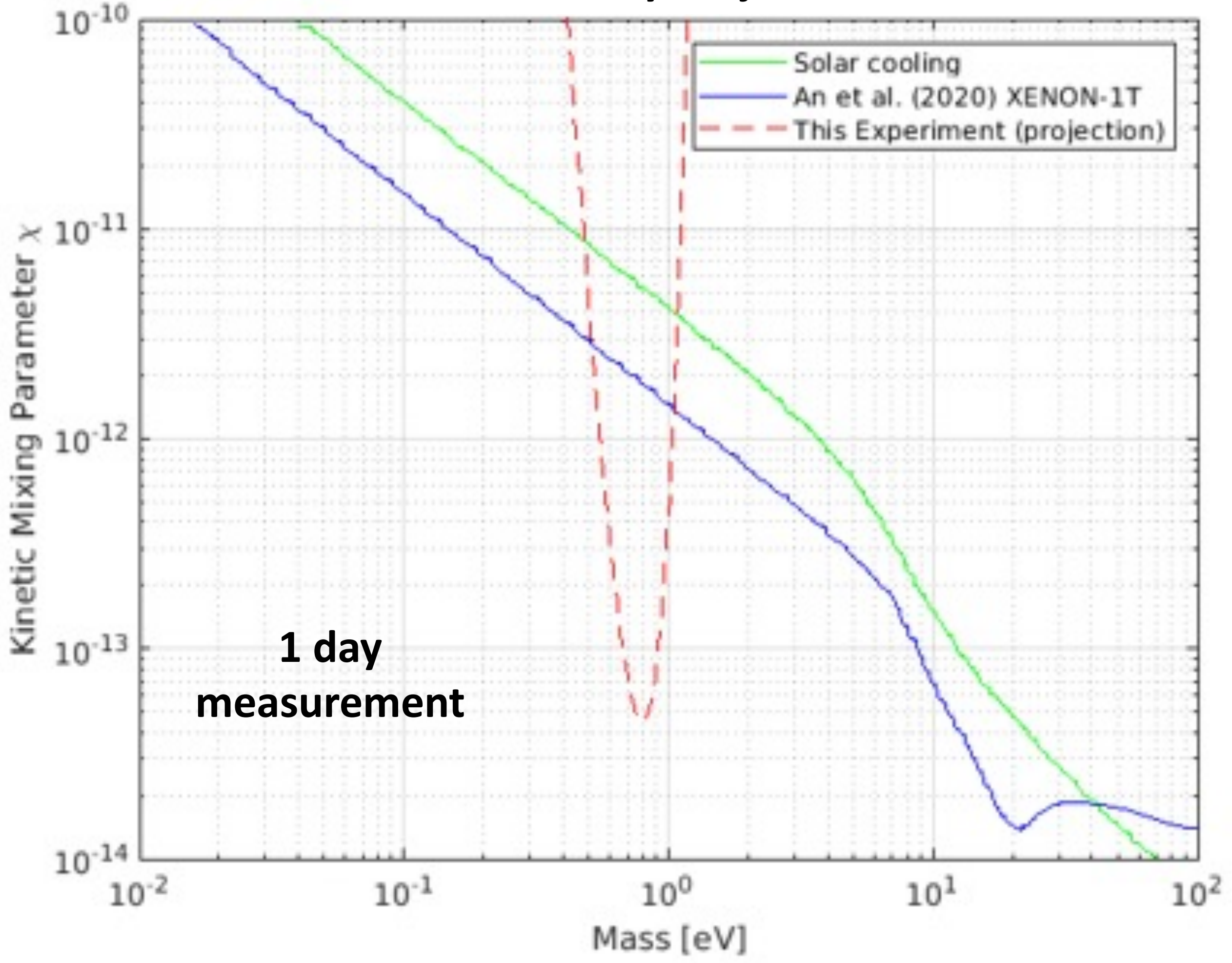
NIST/MIT SNSPD

1 photon/day dark rate



[Hochberg *et al.*, PRL 123 (2019)]

Sensitivity Projection



BREAD Collaboration

Broadband Reflector Experiment for Axion Detection (BREAD)

Pete Barry, Clarence Chang, Juliang Li, *Argonne National Laboratory*

Gianpaolo Carosi*, Lawrence Livermore National Laboratory*

Kristin Dona, Jesse Liu, David Miller, *University of Chicago*

Daniel Bowring, Aaron Chou, Mohamed Hassan, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, Andrew Sonnenschein, *Fermilab*

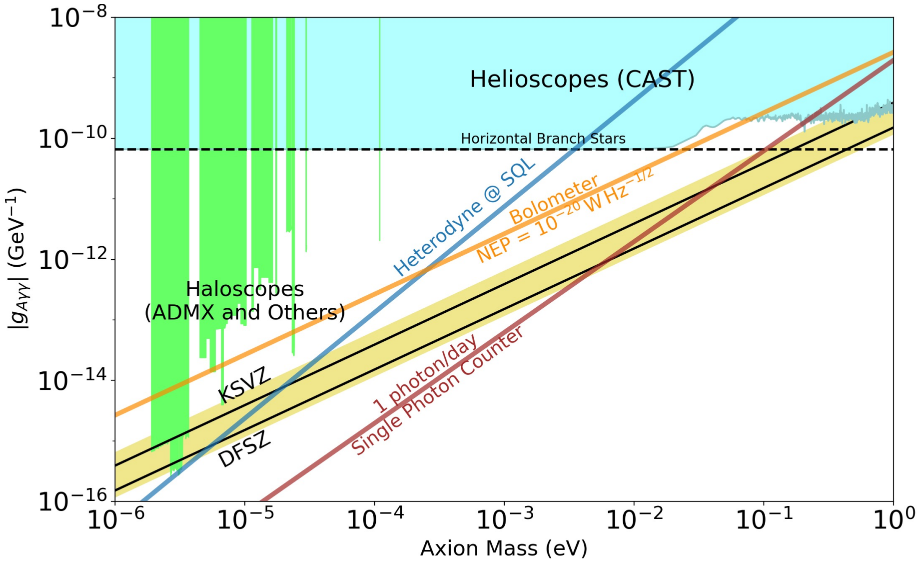
Rakshya Khatiwada, *Fermilab and Illinois Institute of Technology*

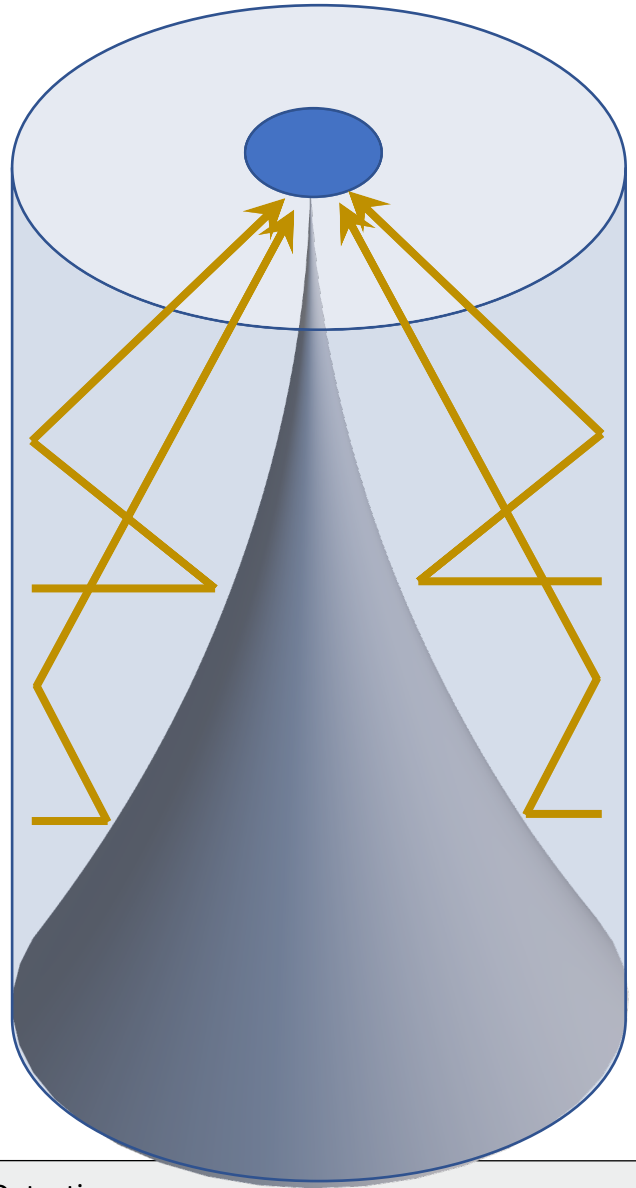
Sae Woo Nam*, National Institute of Standards and Technology*

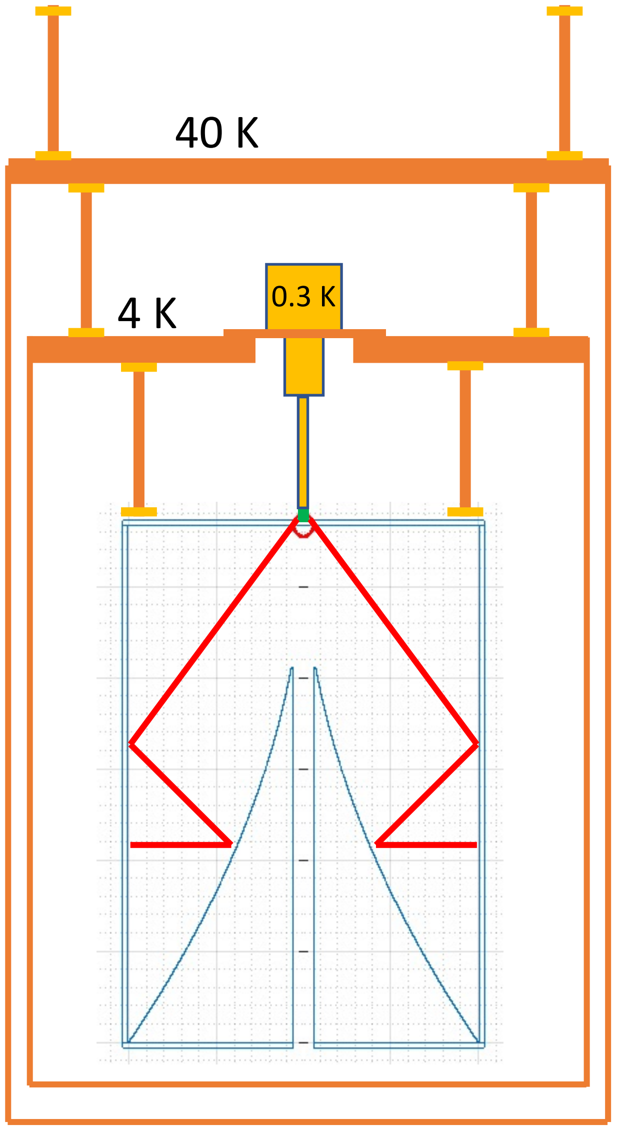
Omid Noroozian, *NASA Goddard Space Flight Center*

This work was supported by the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Grazie mille



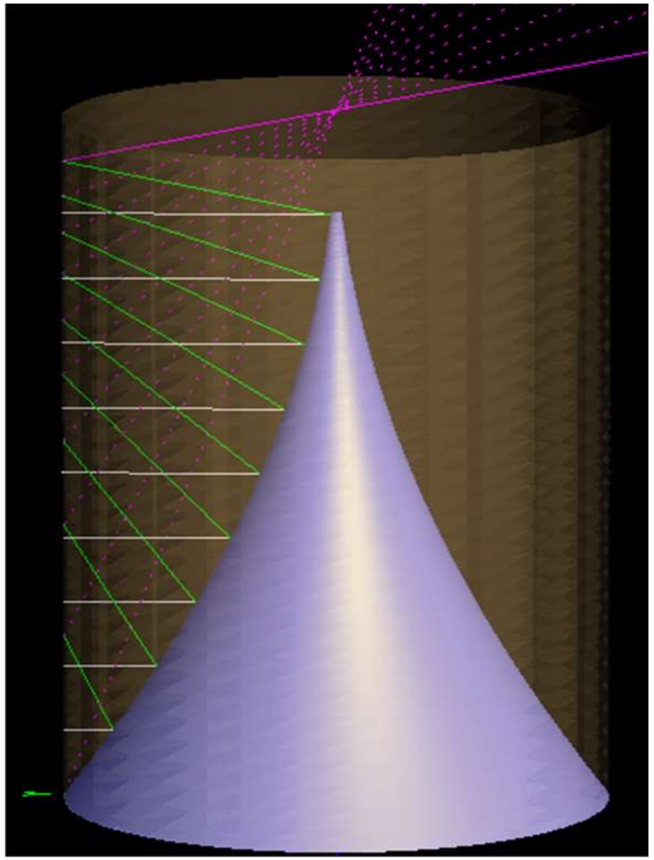




Appendix

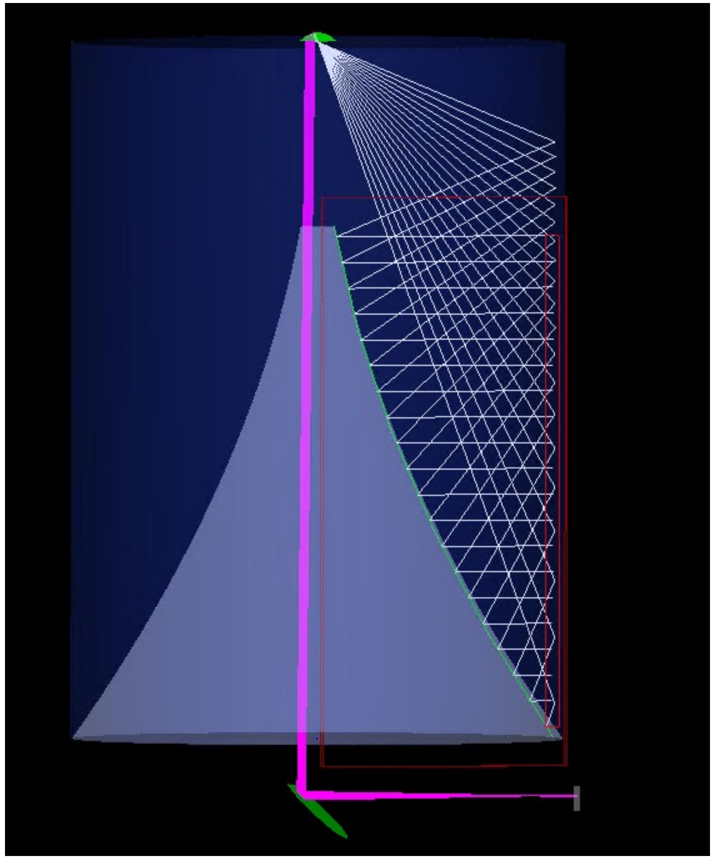
Tera-BREAD: Different Design Paths

Centered Detector



Incident Rays
from wide angles

Secondary Mirror(s)



Incident Angle
Adjustable

Receiver Types

	Microwave		mm			IR	Visible	UV
	1 GHz	10 GHz	100 GHz	1 THz	10 THz	100 THz	1000 THz	1 PHz
Photomultiplier						Mature single photon counting		
Photodiode, SIPM, APD						high dark counts		
HEMT	Phase sensitive and broadband							
Superconducting paramp JPA, TWPA	~quantum limited							
Photomixers SIS, HEM			Narrow band					
Semiconductor bolometer		Bolometers						
Transition Edge Sensor (TES)		NEP~10^{-18} $W/\sqrt{Hz}$				Superconducting photon		
Kinetic Inductance Detector (KID)						counters with		
Superconducting Nanowire SNSPD						low dark current		
Qubit								
Quantum Capacitance Detector			~10^{-20} $W/\sqrt{Hz}$					
Current Biased Josephson Junction		Developing single photon technologies for GHz- THz						

A few notable recent photon counting results

- Detection of individual 1.5 THz photons (6 meV) with *NEP 2 x* 10^{-20} *W/Hz*$^{1/2}$ Echternach *et al.*, *Nature Astronomy* 2, 90–97 (2018).
- Counting 6 GHz (25 μeV) photons by coupling to a qubit. Background ~3 Hz, Dixit *et al.*, arXiv:2008.12231v2
- Counting 14 GHz photons (58 μeV) with current-biased Josephson junction with backgrounds below 10^{-3} Hz. Kuzmin *et al.*, *IEEE Trans. Appl. Super.* 28 7 (2018) & Patras 2019.
- NIST/ MIT superconducting nanowires with high counting efficiency for 1550 nm photons (0.8 eV) and backgrounds now <1/day. Hochberg *et al.*, PRL 123 (2019).
- Counting of single photons in the previously inaccessible range from microwaves to terahertz is an exciting and rapidly moving field.
- Still a way to go before meeting needed requirements for QCD axion detection.