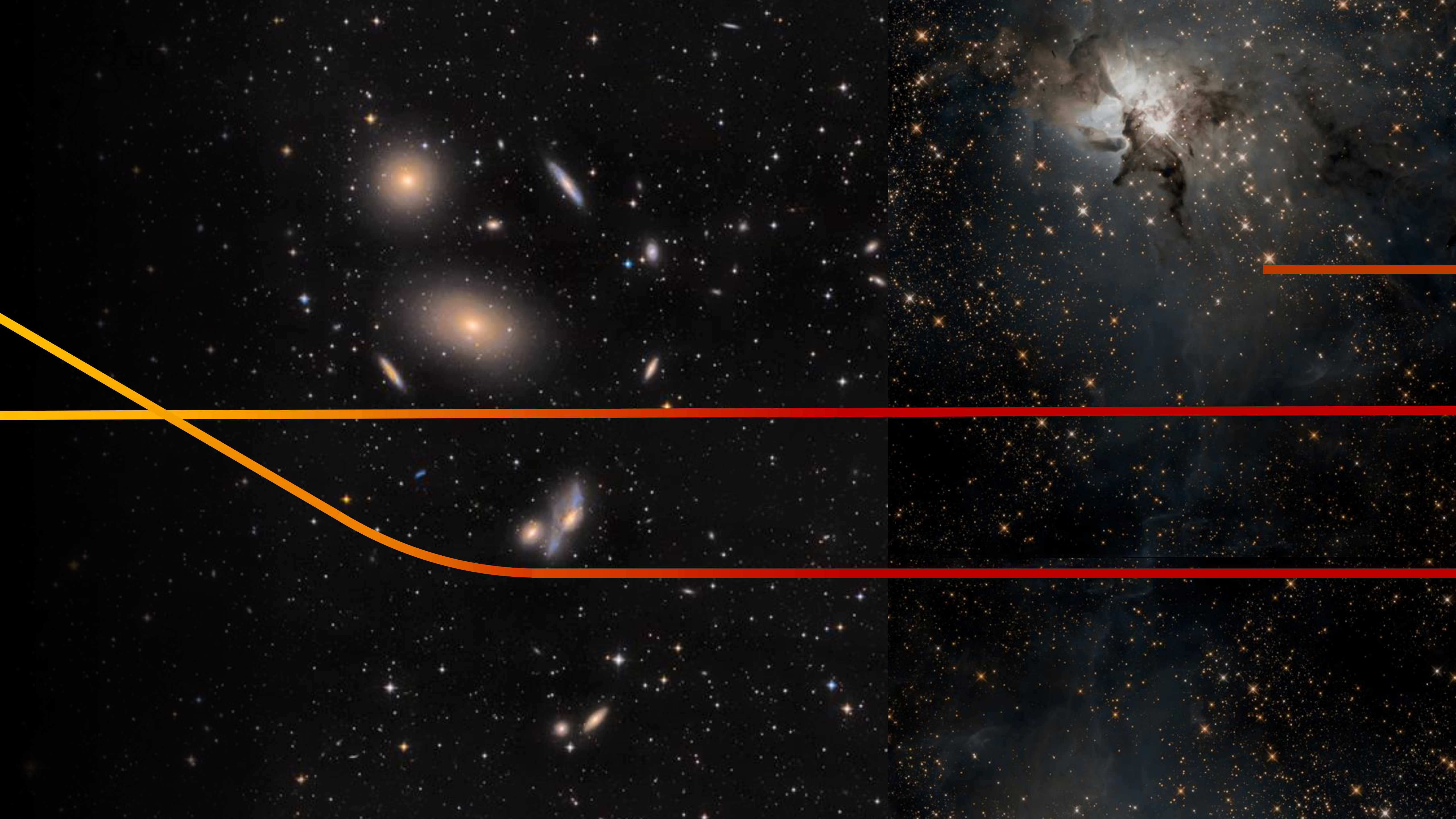
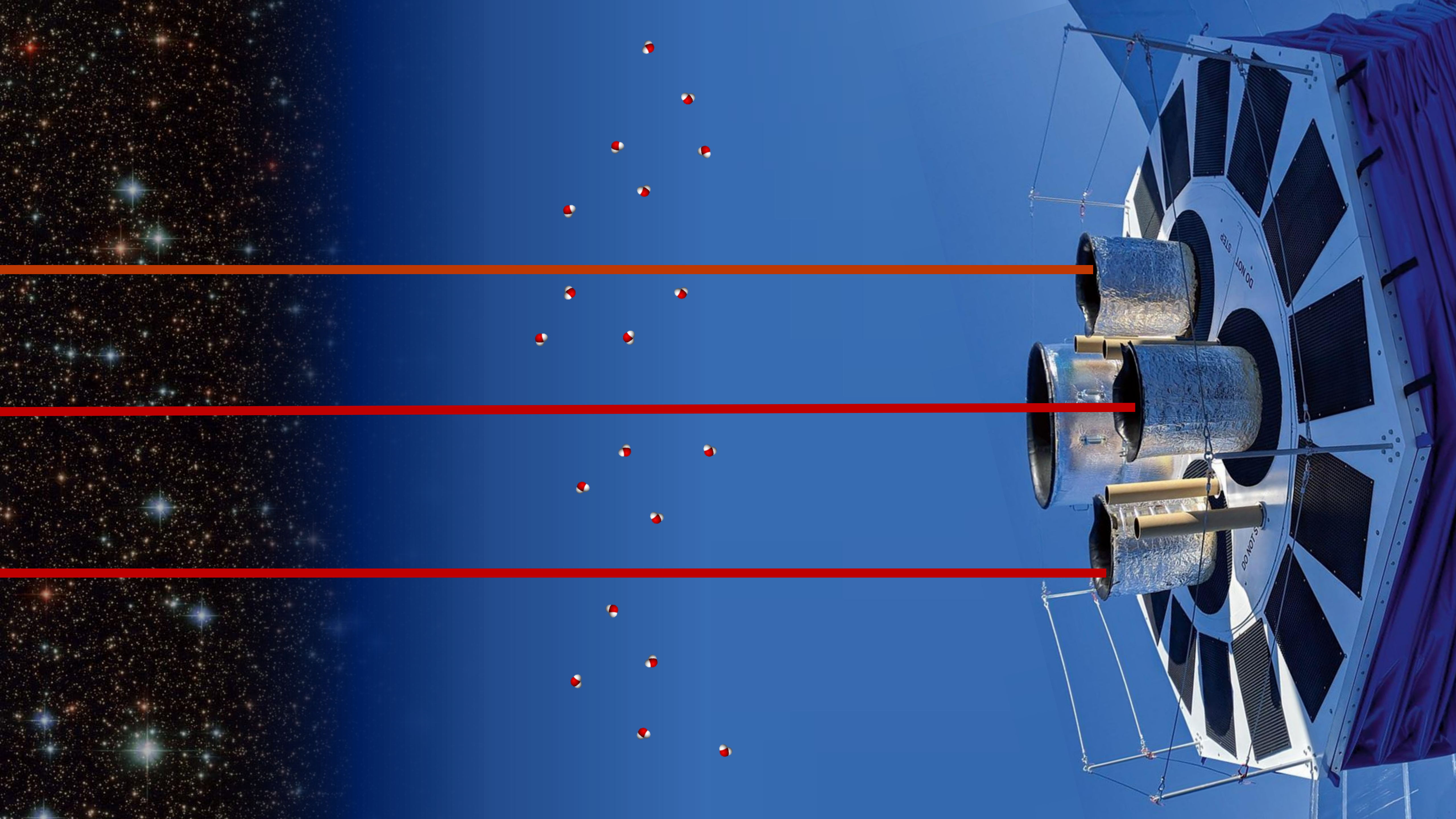
Windows to the Universe:

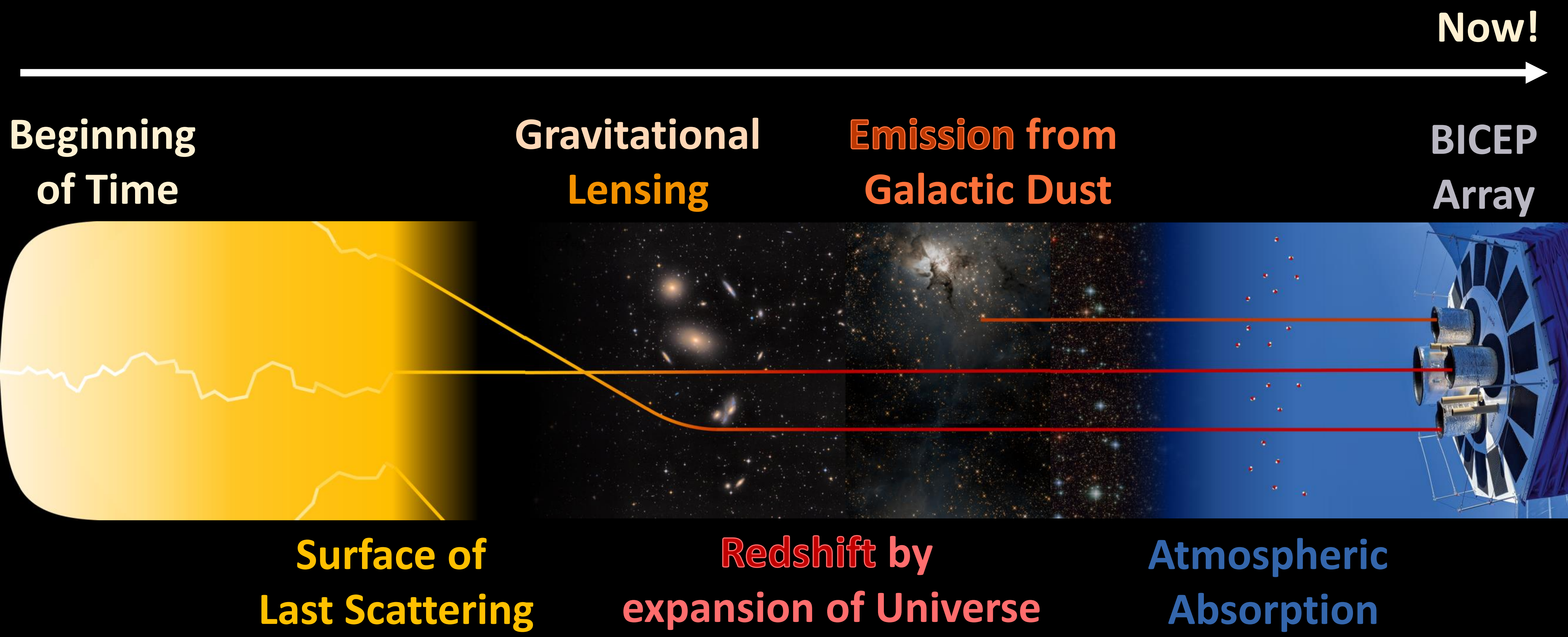
Increasing the Sensitivity of High Throughput Millimeter Telescopes

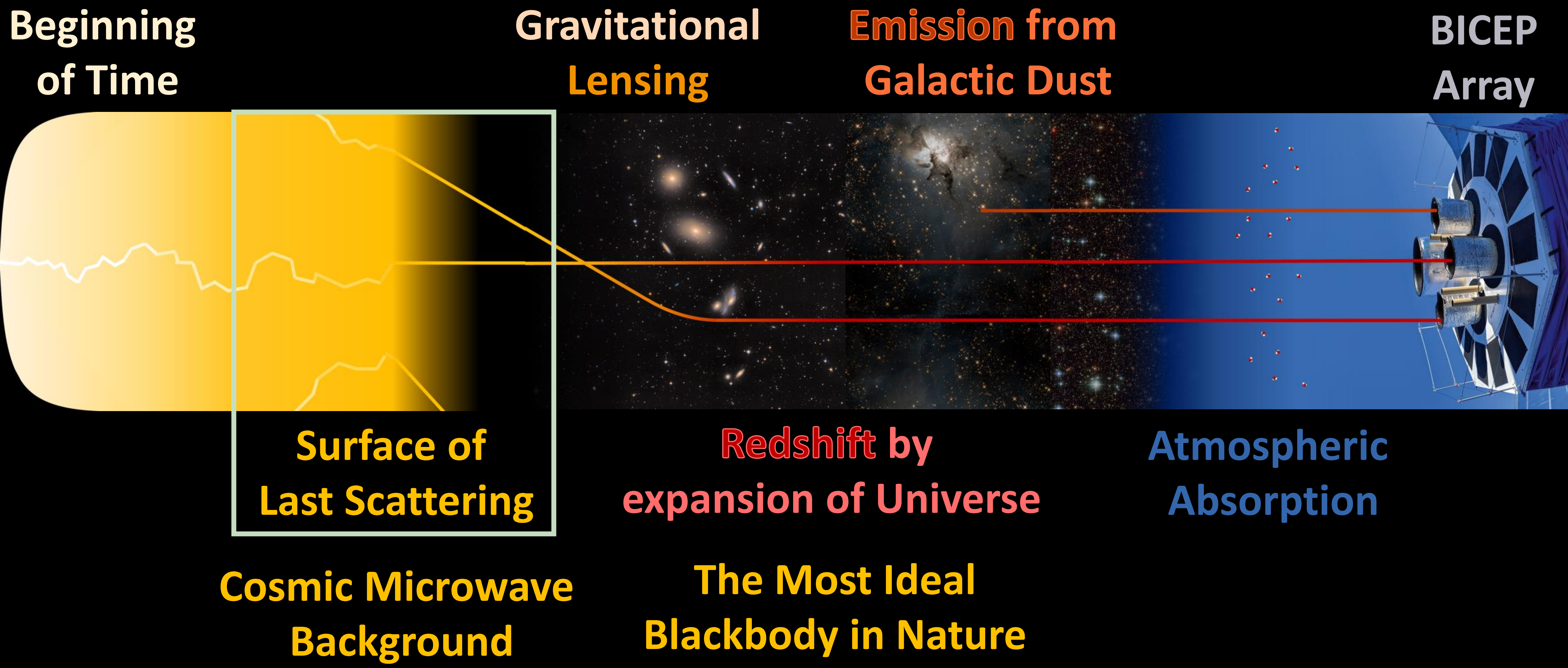
May 6th, 2025
Miranda Eiben
Public Thesis Defense Talk

What happened at the beginning of time?



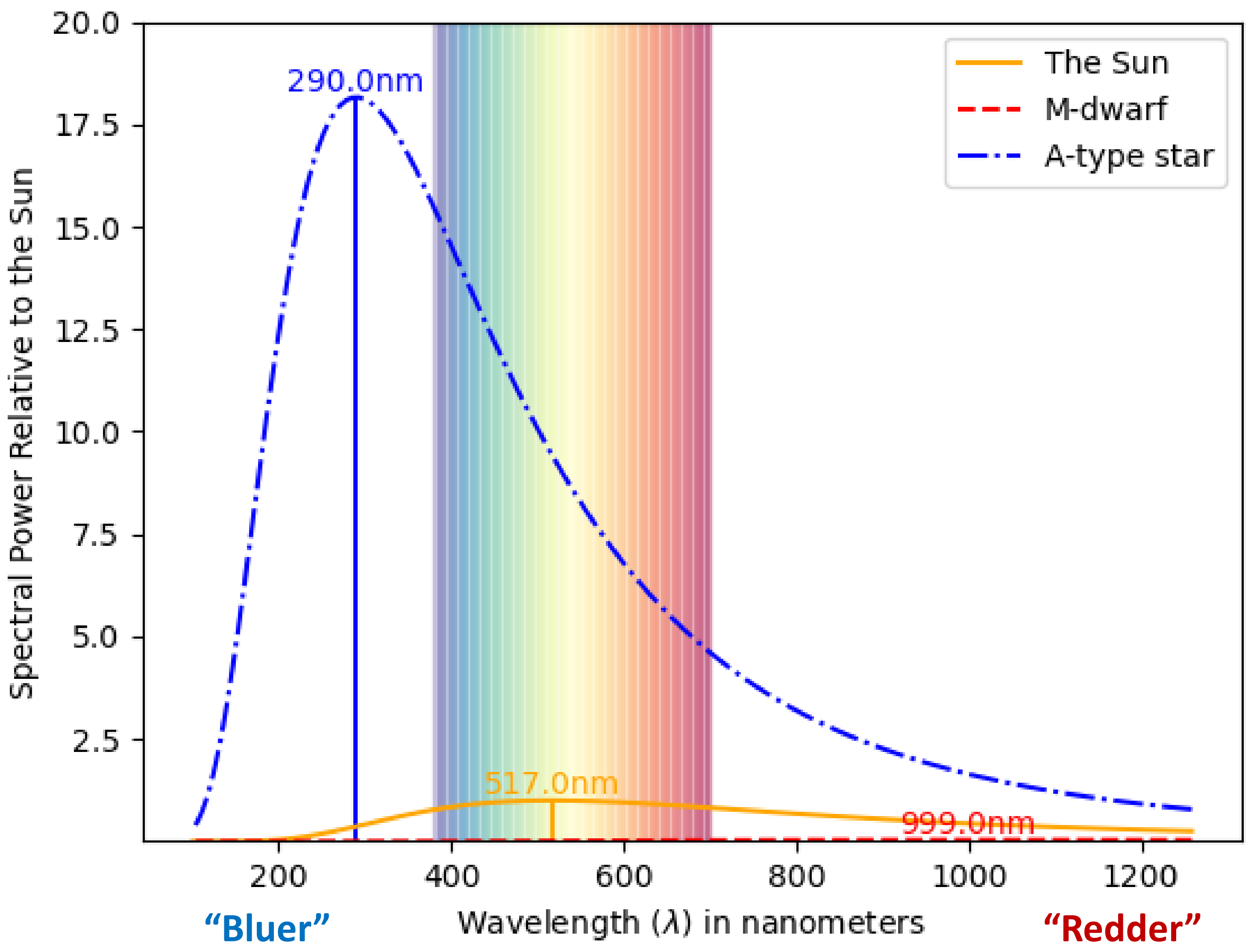



Now!
Beginning of Time
Gravitational Lensing
Emission from Galactic Dust
BICEP Array
Surface of Last Scattering
Redshift by expansion of Universe
Atmospheric Absorption



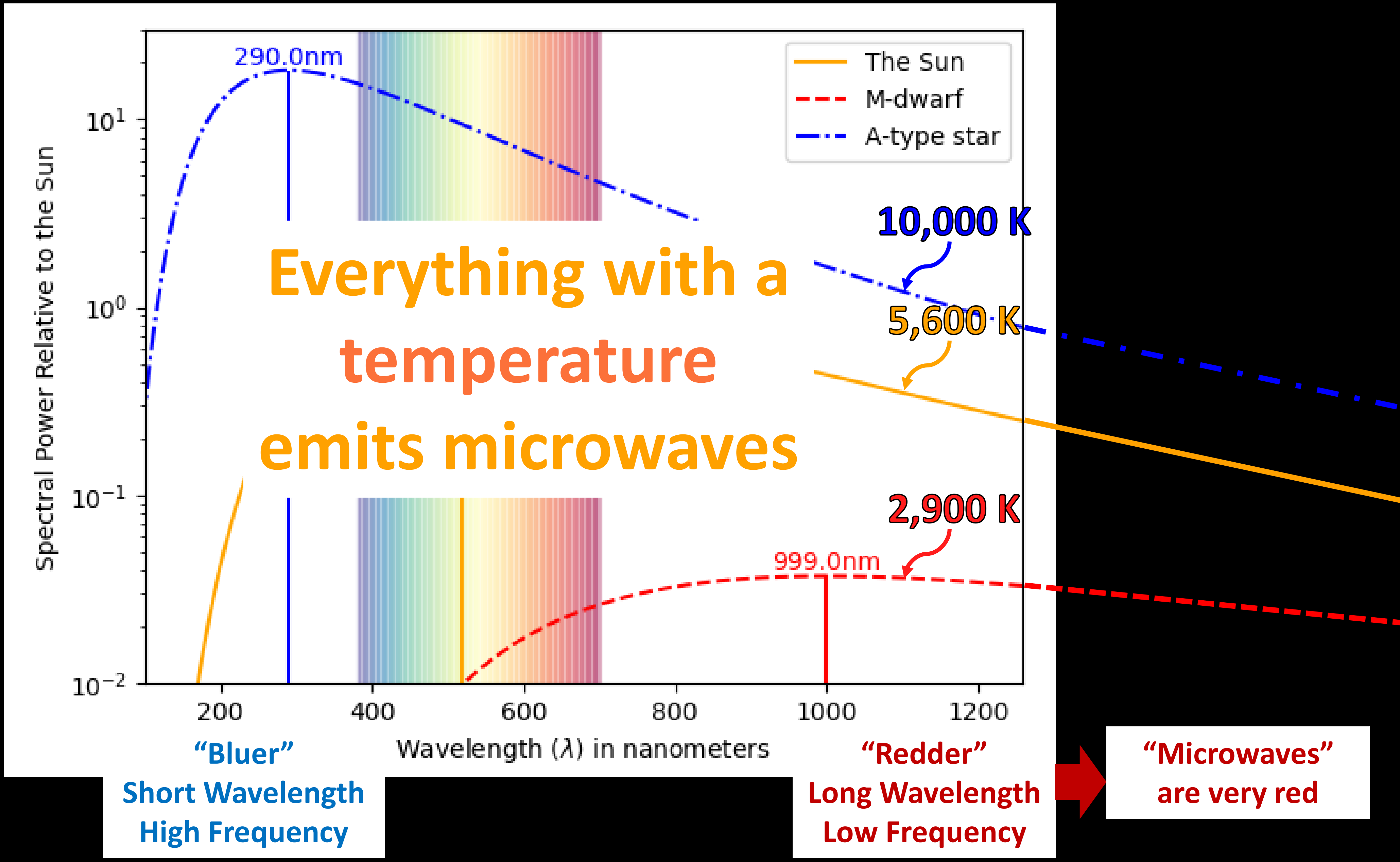
Beginning of Time
Gravitational Lensing
Emission from Galactic Dust
BICEP Array
Surface of Last Scattering
Redshift by expansion of Universe
Atmospheric Absorption
Cosmic Microwave Background
The Most Ideal Blackbody in Nature

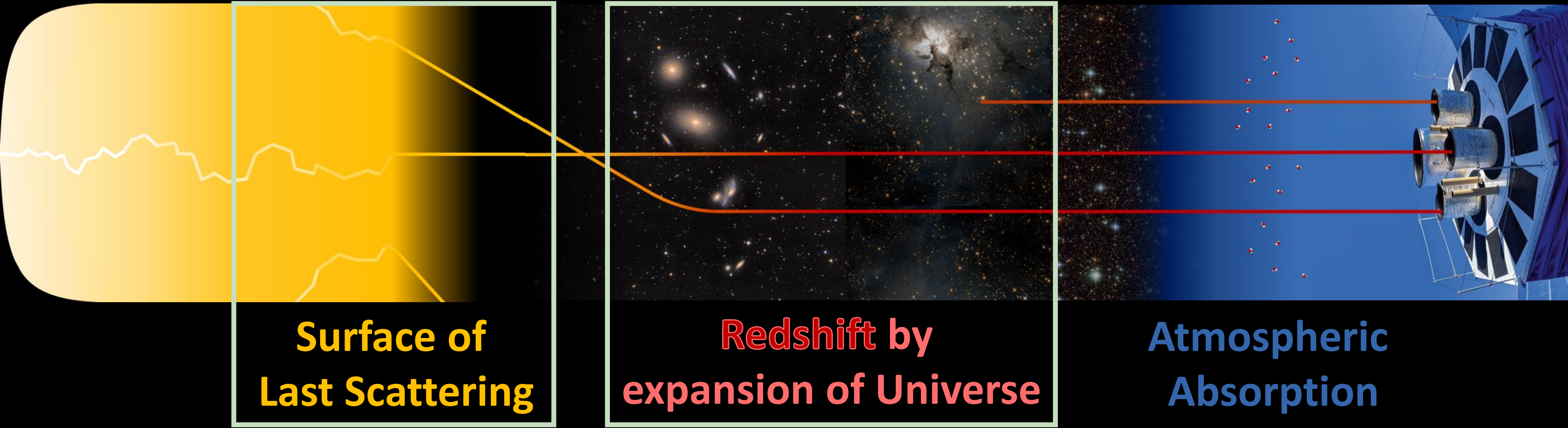
Wait, what’s a blackbody?



“Bluer”
Short Wavelength
High Frequency

“Redder”
Long Wavelength
Low Frequency


290.0nm
The Sun
M-dwarf
A-type star
10,000 K
5,600 K
2,900 K
999.0nm
Everything with a temperature emits microwaves
Spectral Power Relative to the Sun
Wavelength (λ) in nanometers
"Bluer"
Short Wavelength
High Frequency
"Redder"
Long Wavelength
Low Frequency
"Microwaves" are very red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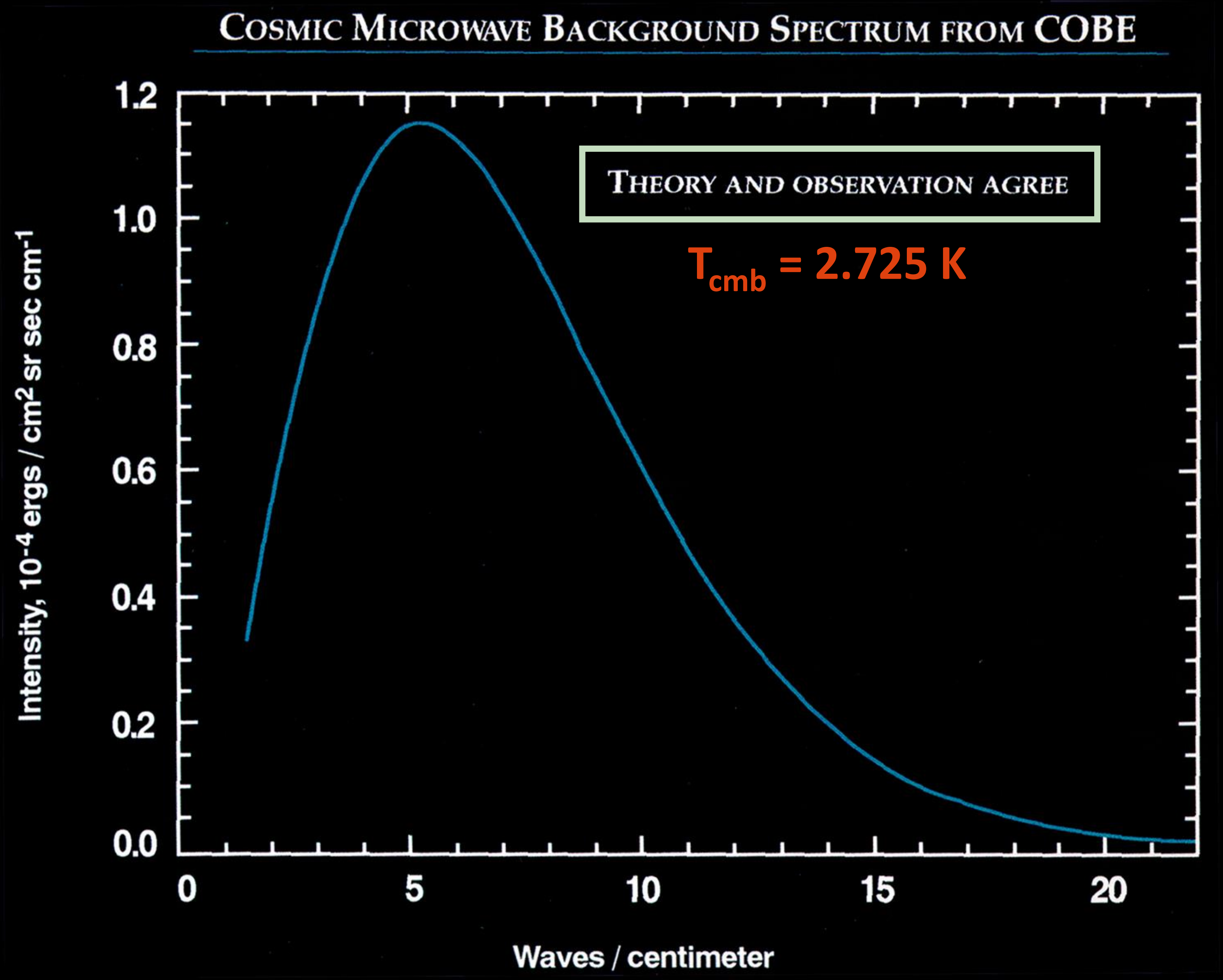
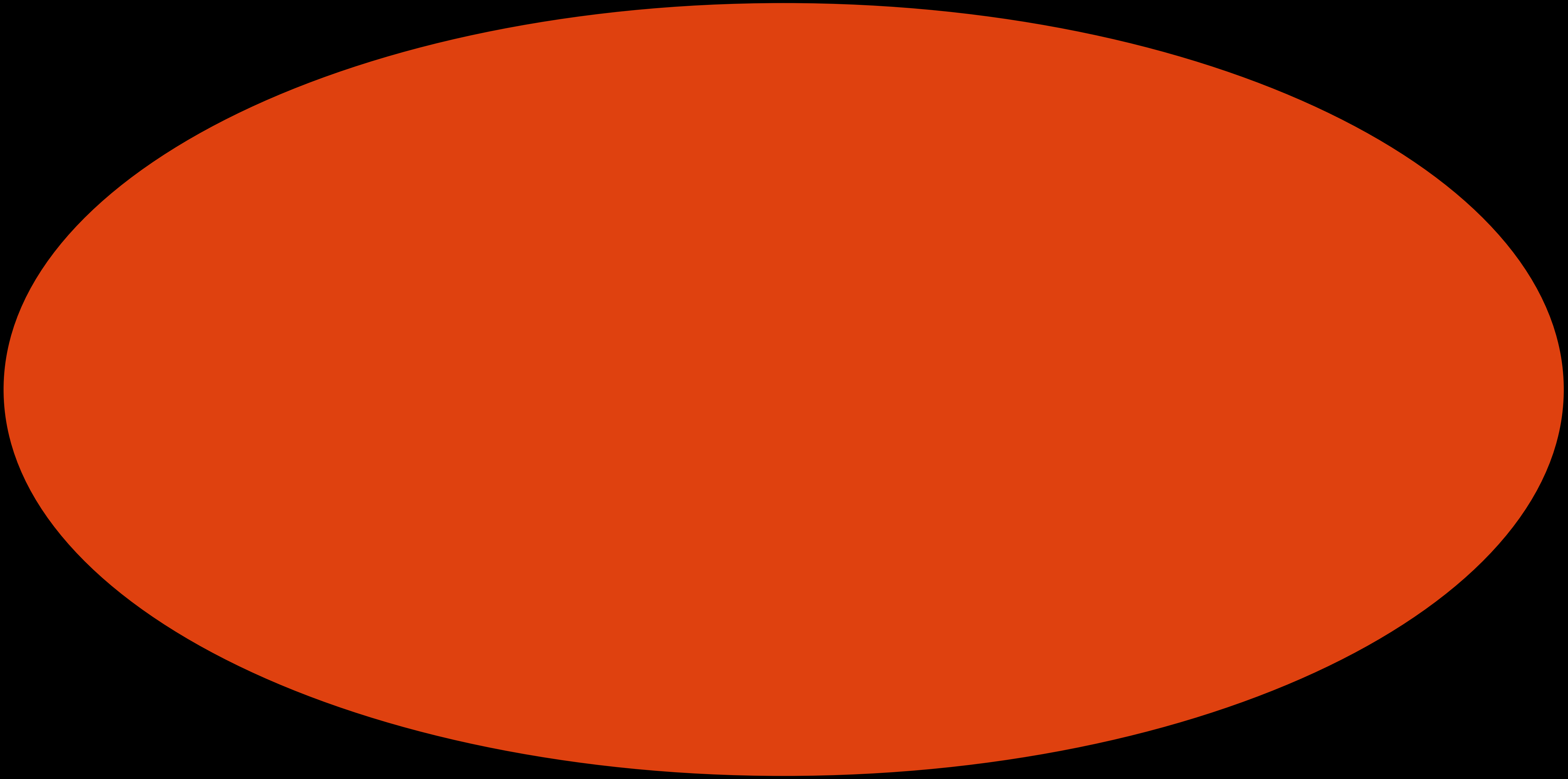
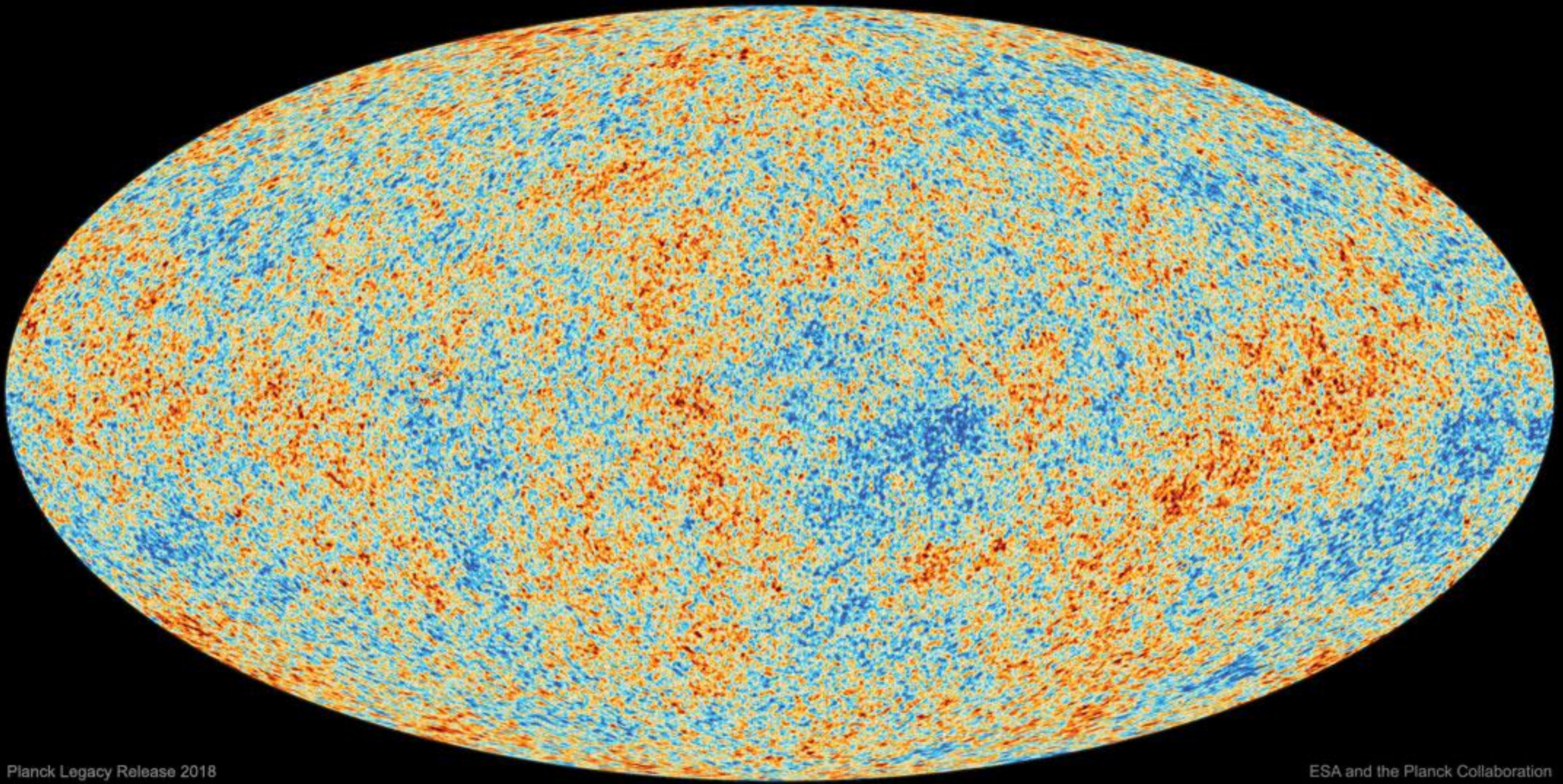
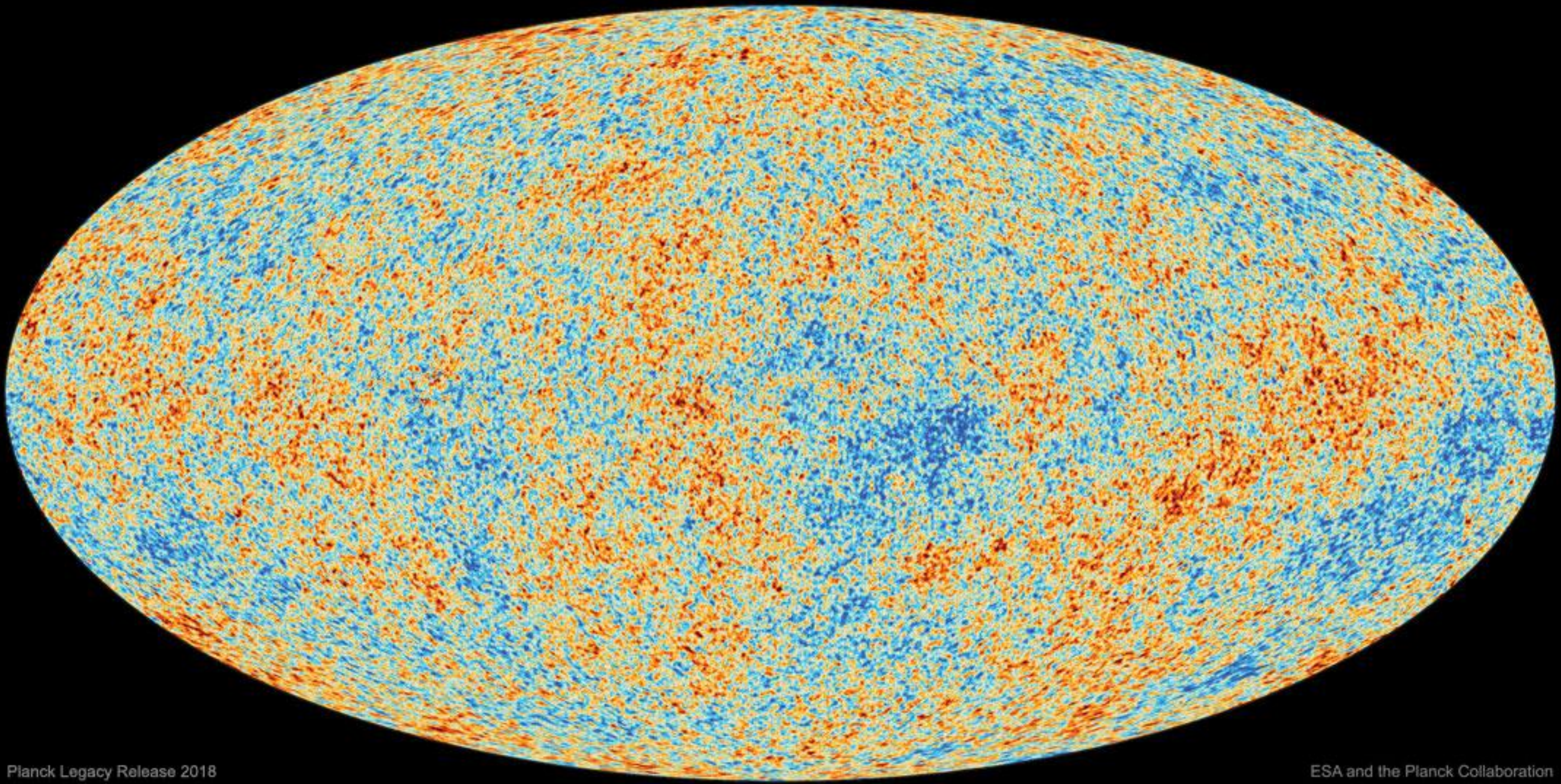

Cosmic Microwave Background Spectrum from COBE
Theory and observation agree
T_{cmb} = 2.725 K
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}
Waves / centimeter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20



$T_{cmb} = 2.725$ K



$\Delta T_{cmb} \approx 0.001\ \mathrm{K} = 1\ \mathrm{mK}$

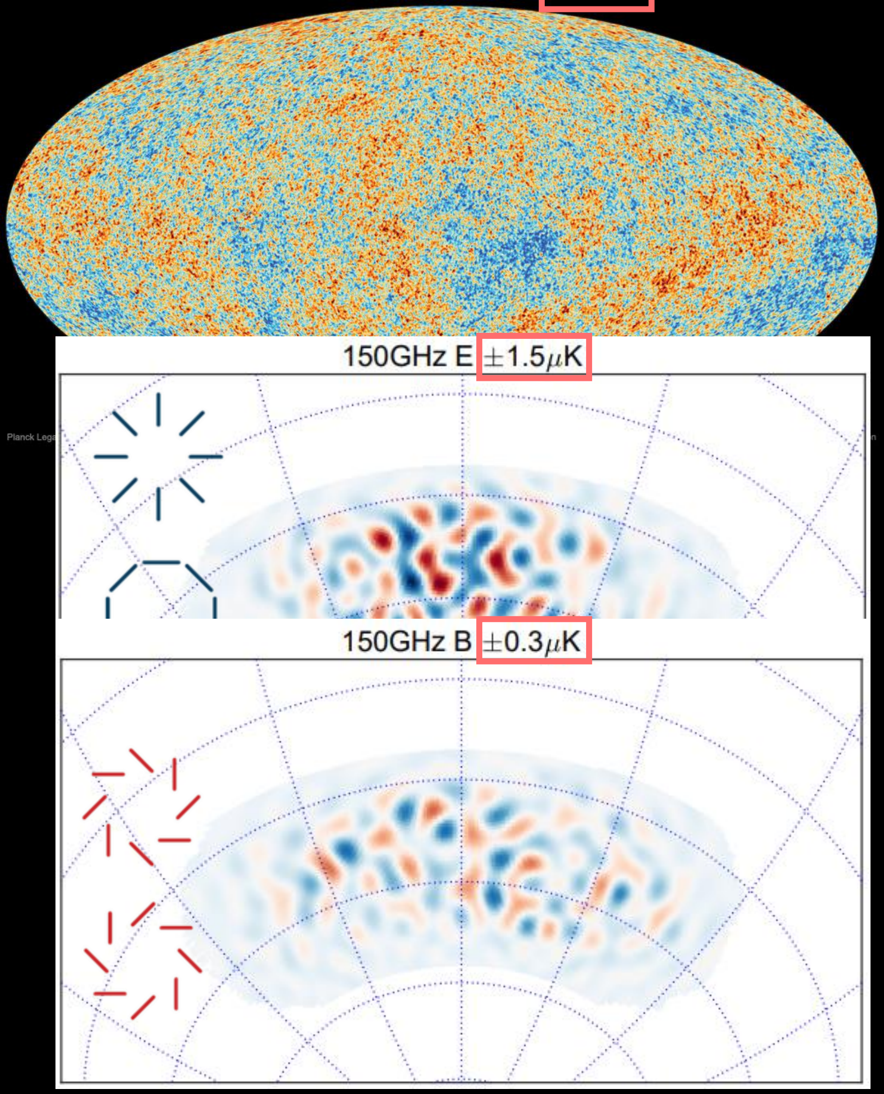


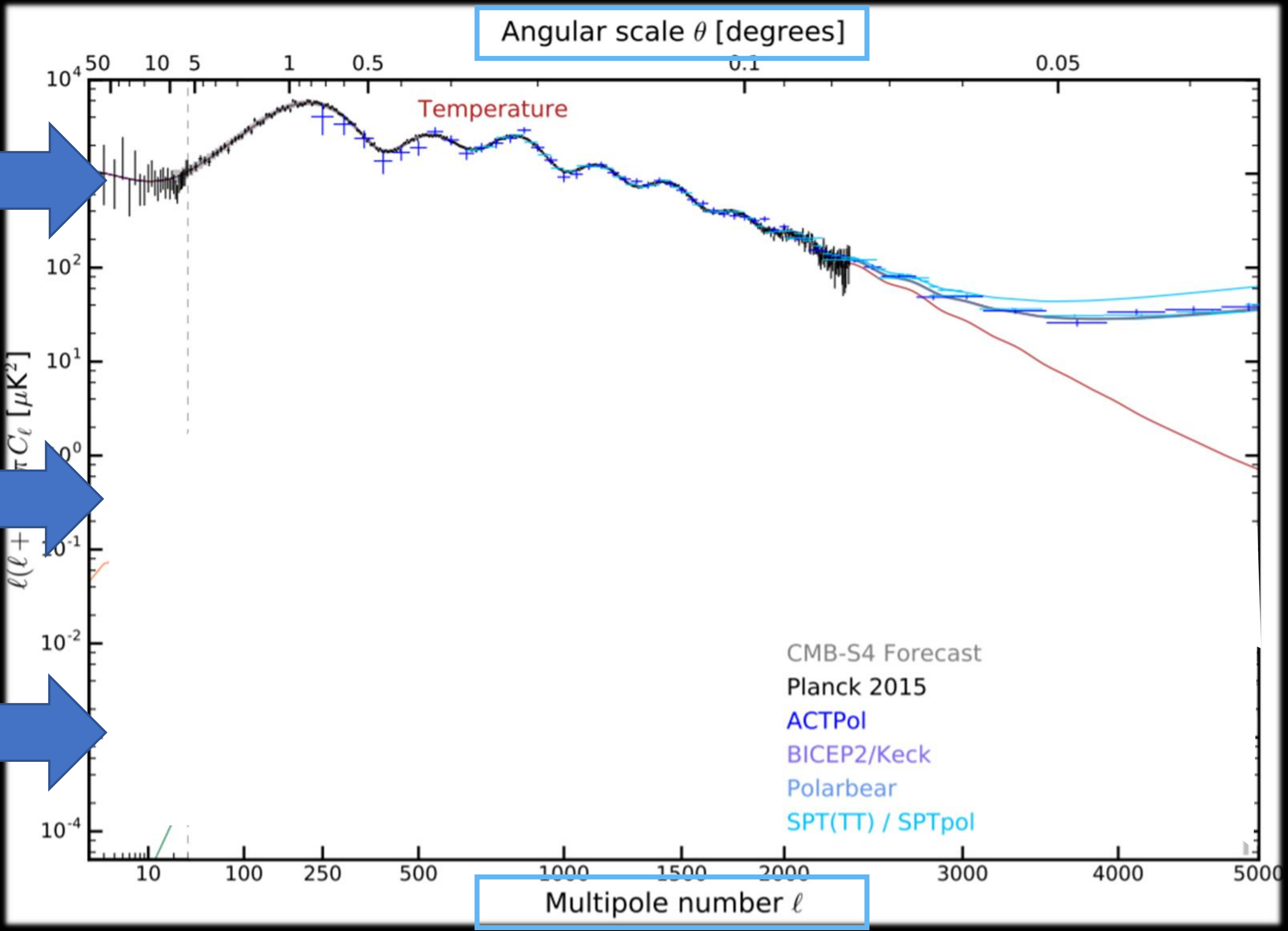
Planck Legacy Release 2018

ESA and the Planck Collaboration

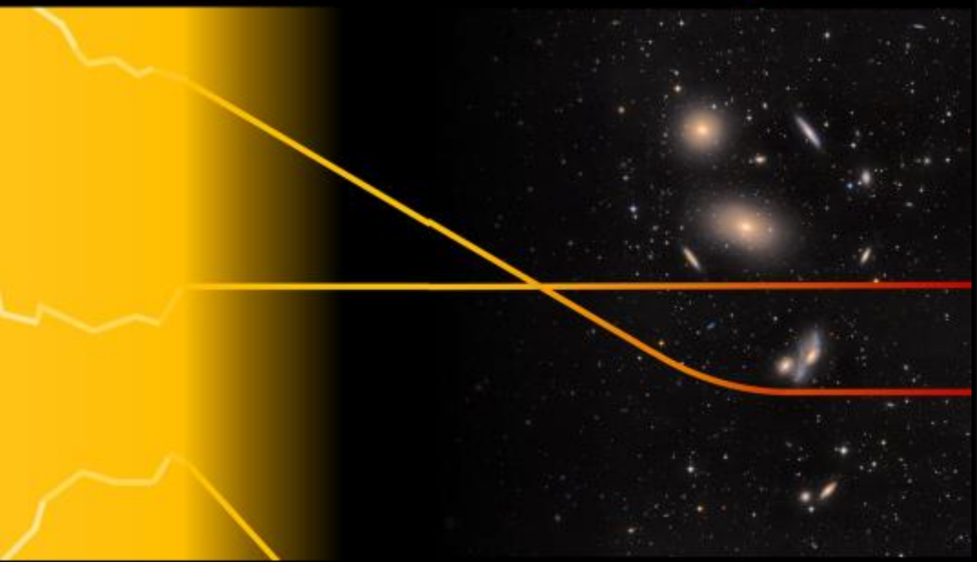
$\Delta T_{cmb} \approx 0.001\ K = 1\ mK$

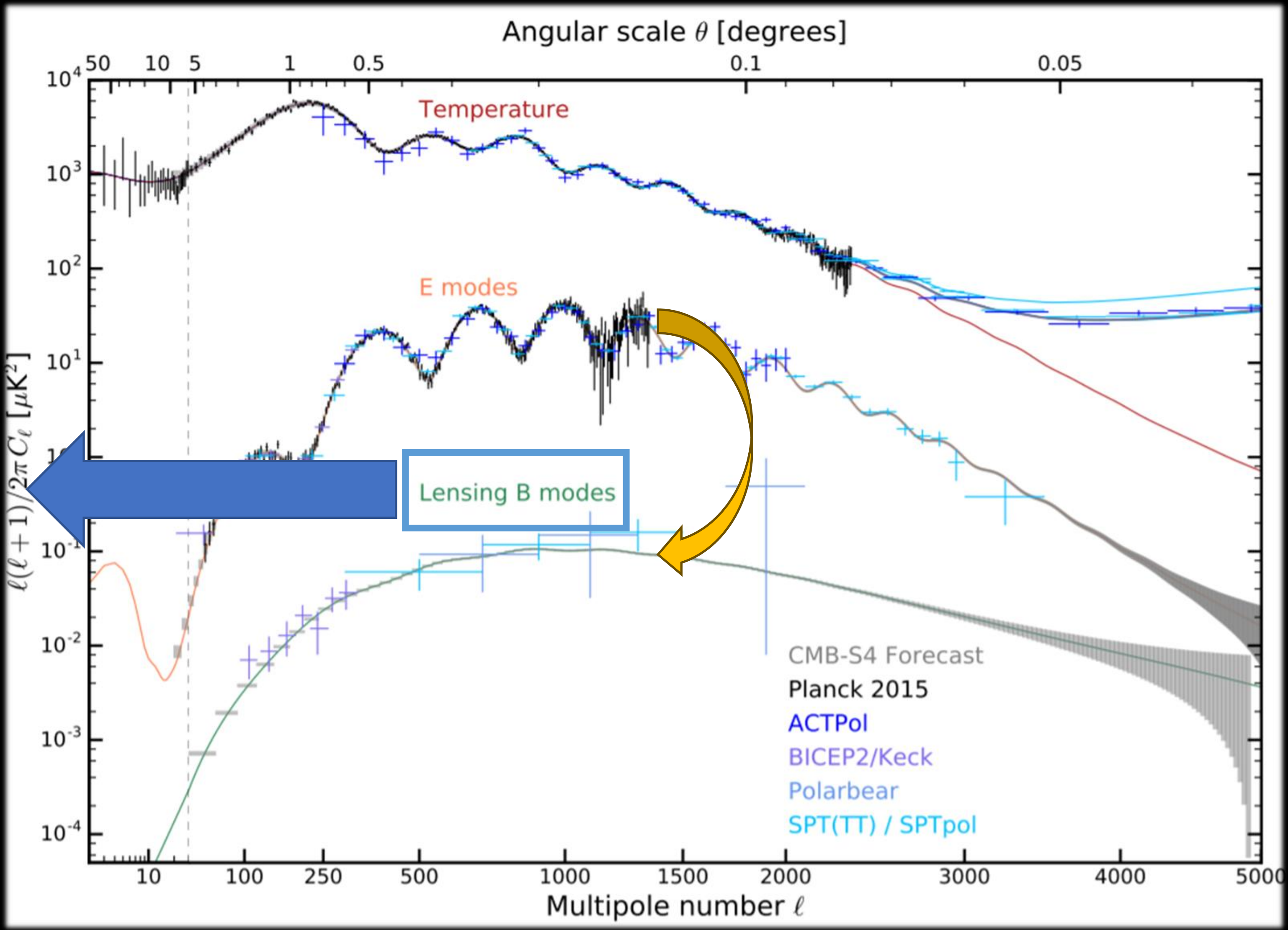
$\Delta T_{cmb} \approx 0.001$ K = $\boxed{1\text{ mK}}$

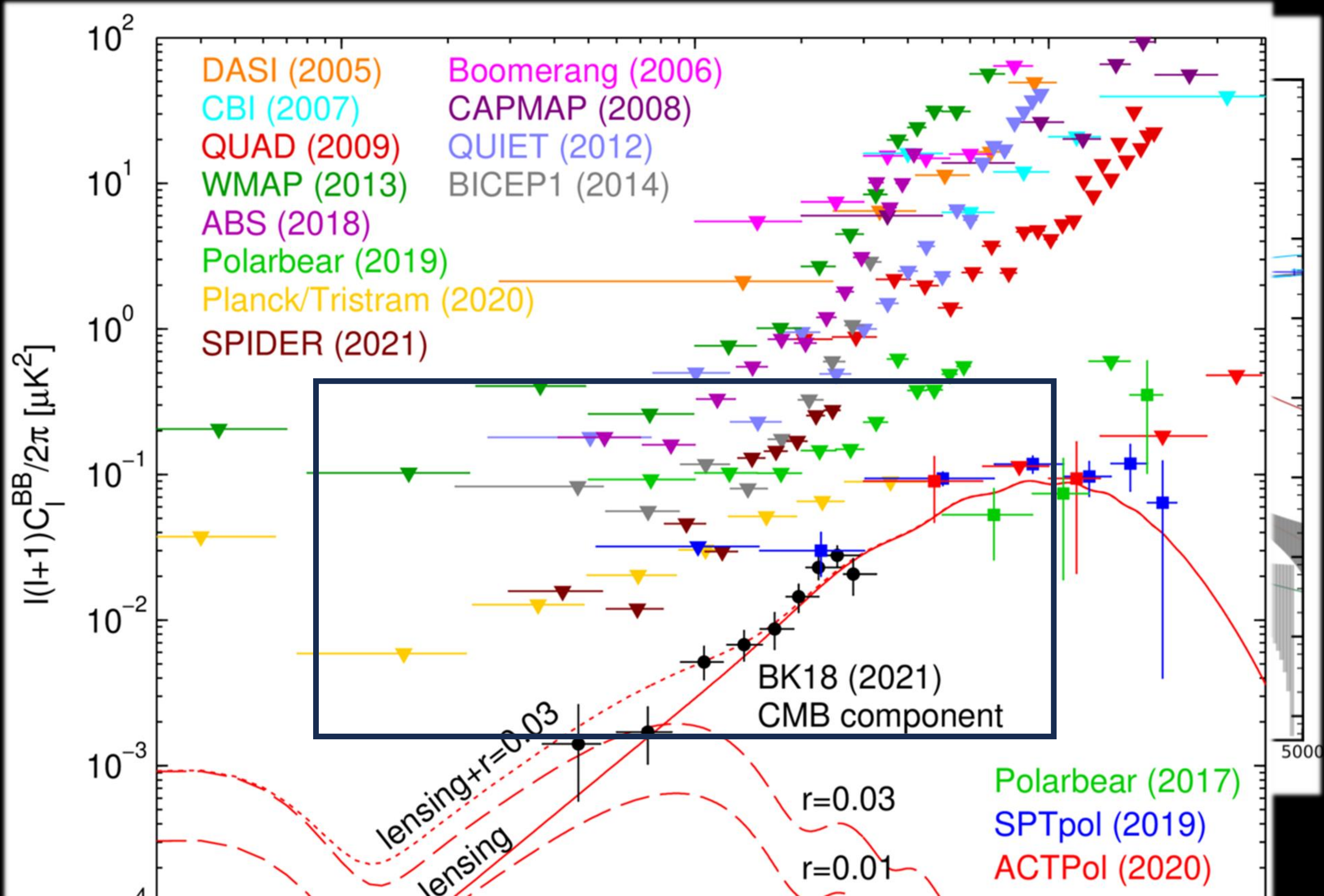




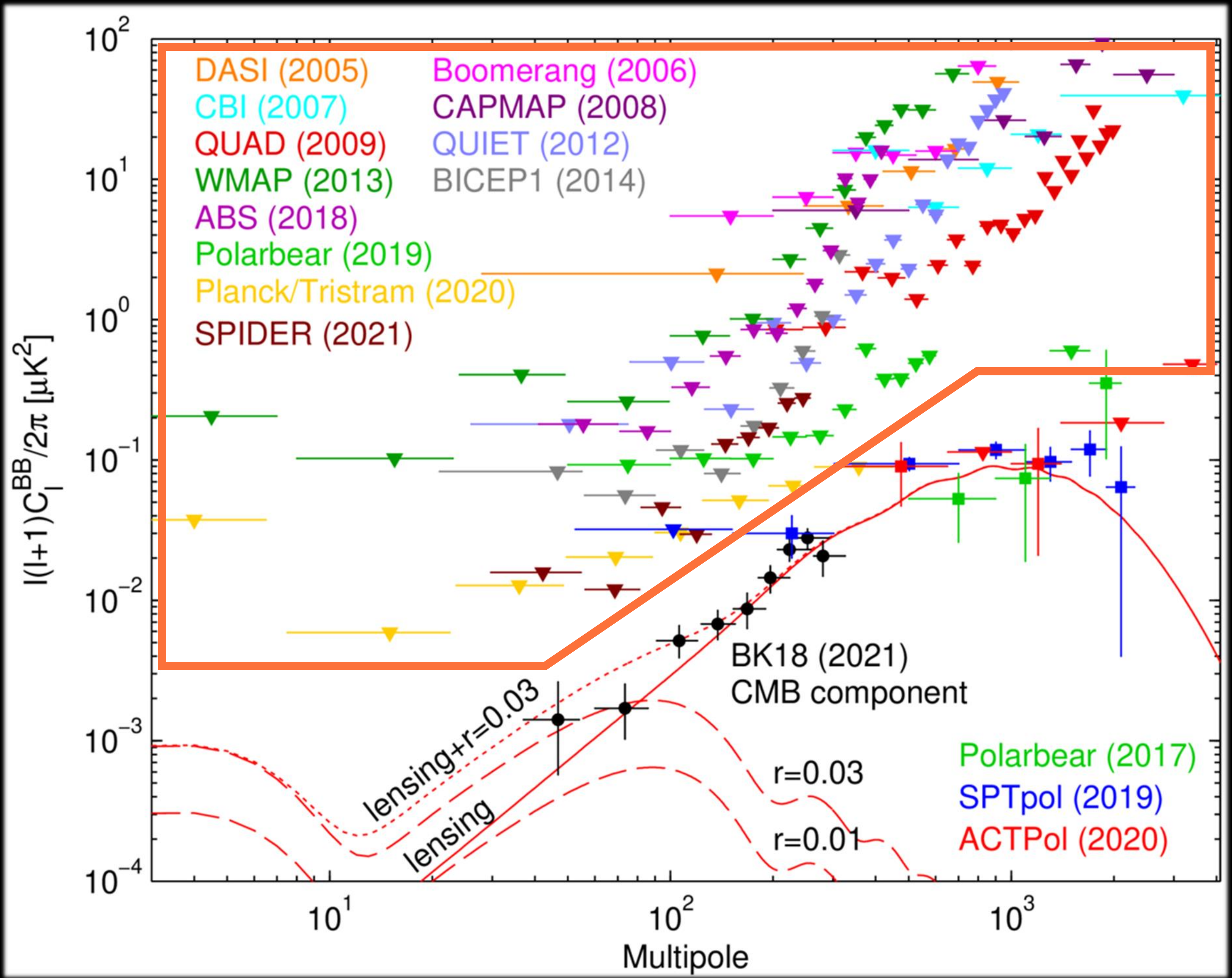
Gravitational
Lensing







DASI (2005)
Boomerang (2006)
CBI (2007)
CAPMAP (2008)
QUAD (2009)
QUIET (2012)
WMAP (2013)
BICEP1 (2014)
ABS (2018)
Polarbear (2019)
Planck/Tristram (2020)
SPIDER (2021)
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
5000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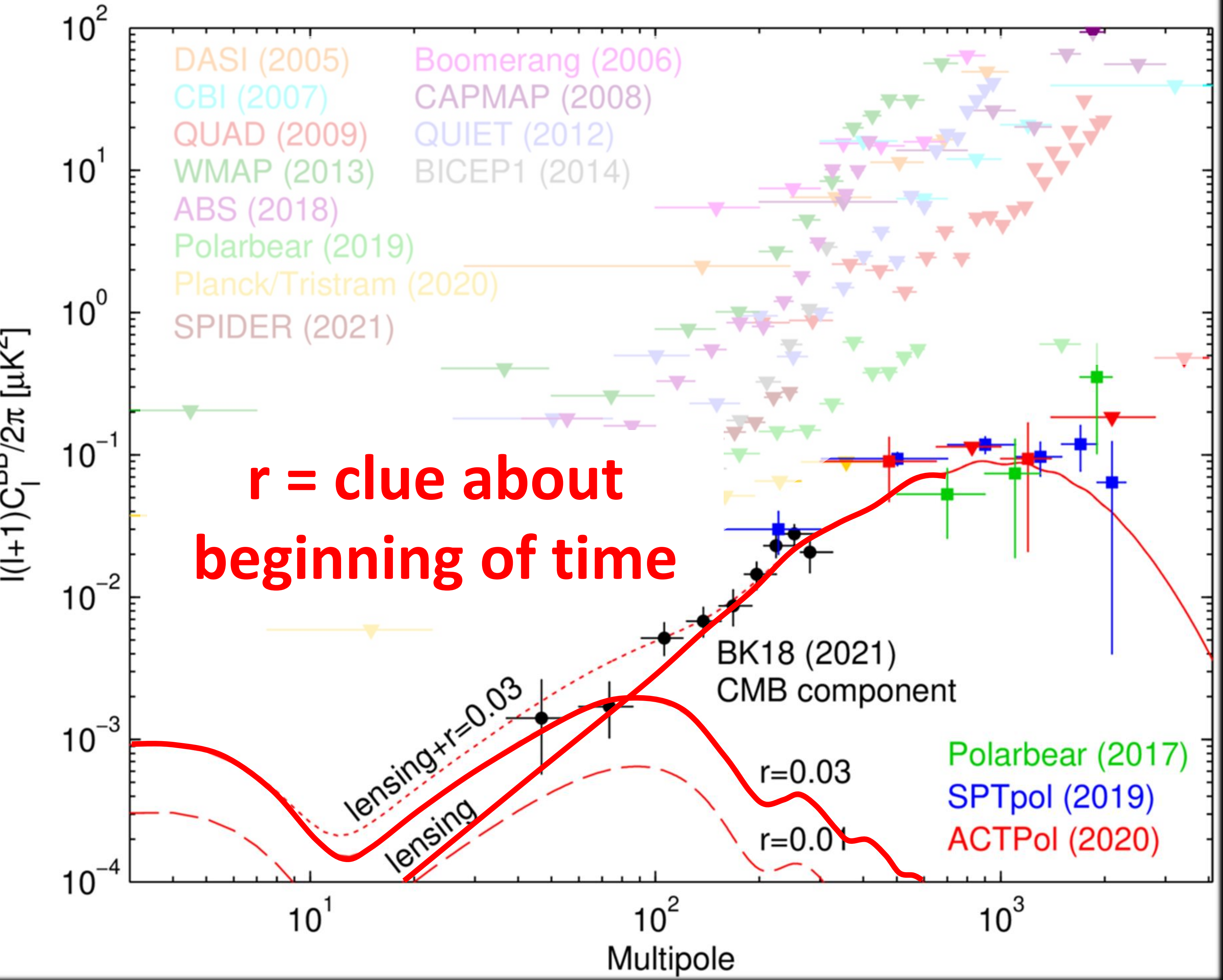
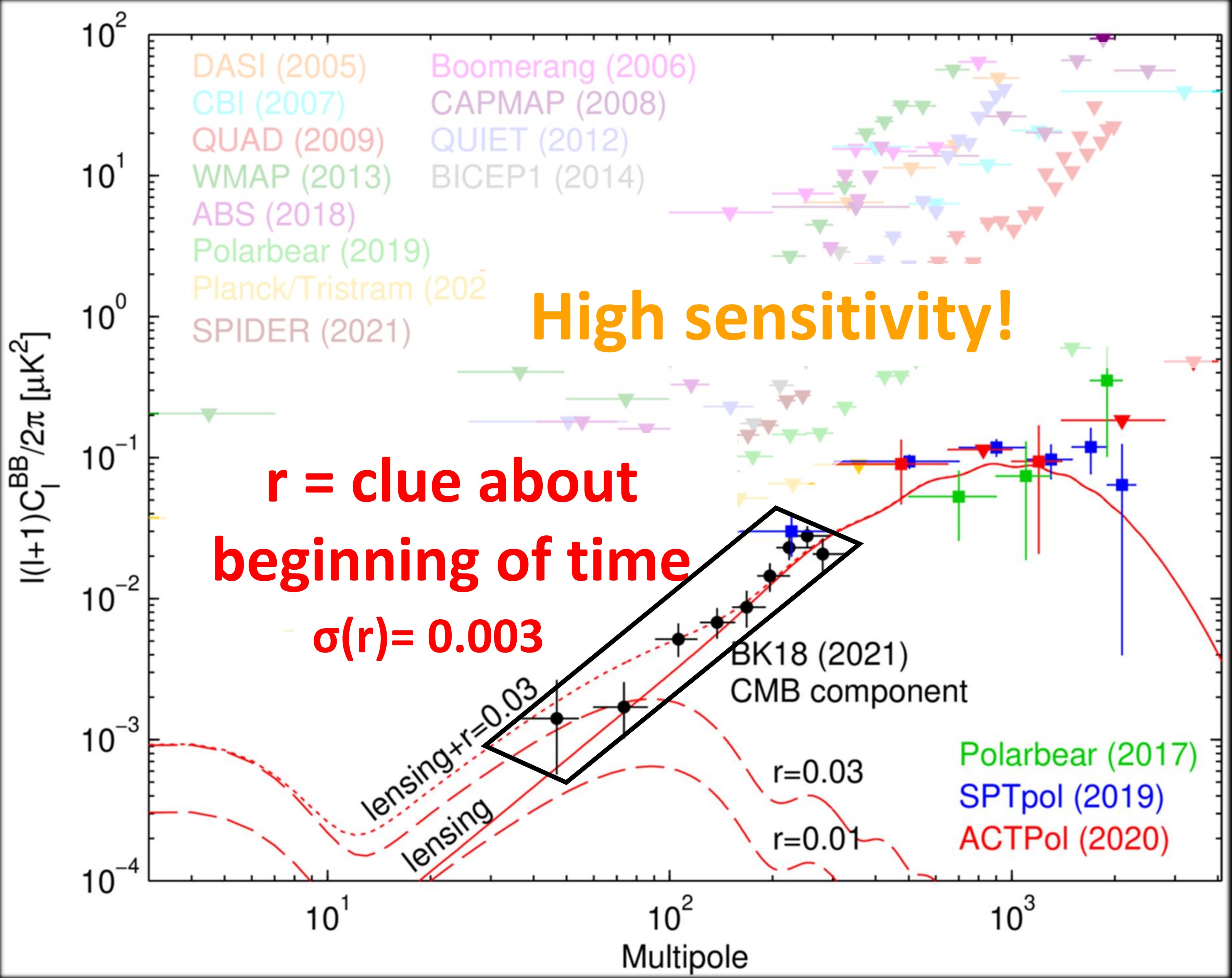
SPIDER (2021)
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

r = clue about beginning of time





DASI (2005)
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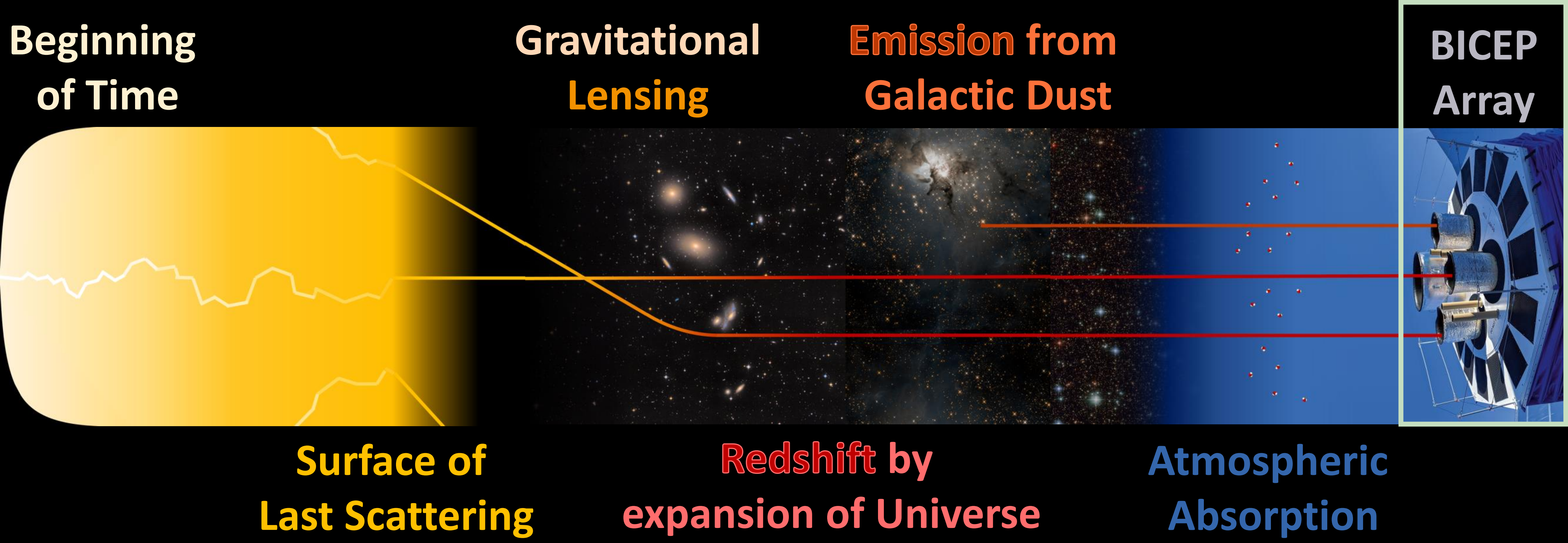
QUAD (2009)
QUIET (2012)
WMAP (2013)
BICEP1 (2014)
ABS (2018)
Polarbear (2019)
Planck/Tristram (202
SPIDER (2021)
High sensitivity!
r = clue about
beginning of time
σ(r)= 0.003
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

To constrain r to $\sigma(r) = 0.003$,
we need to build a telescope with precision to the *nanokelvin* level

$\pm$ 0.000000001 K


Beginning of Time
Gravitational Lensing
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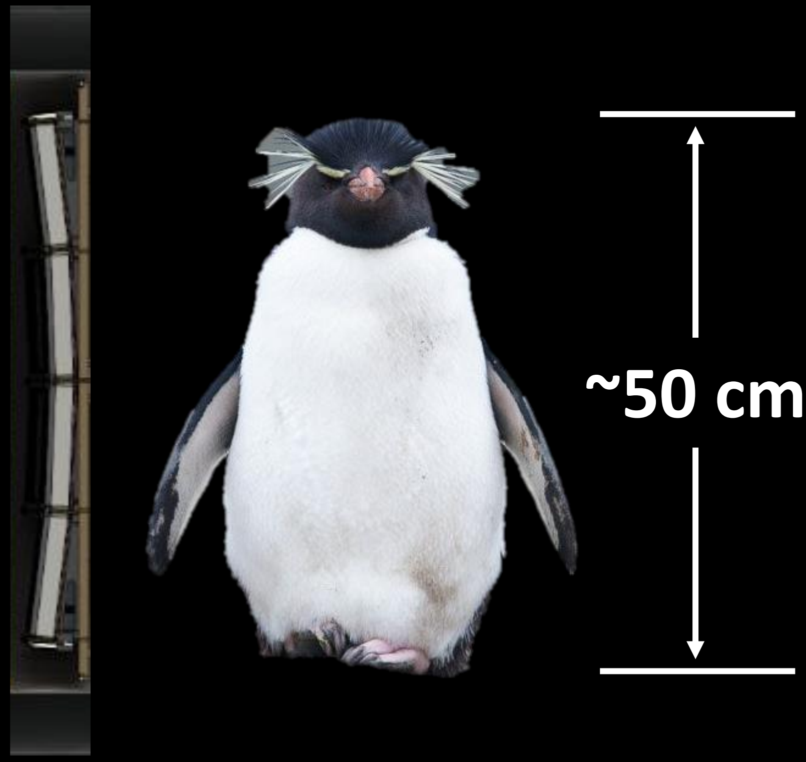
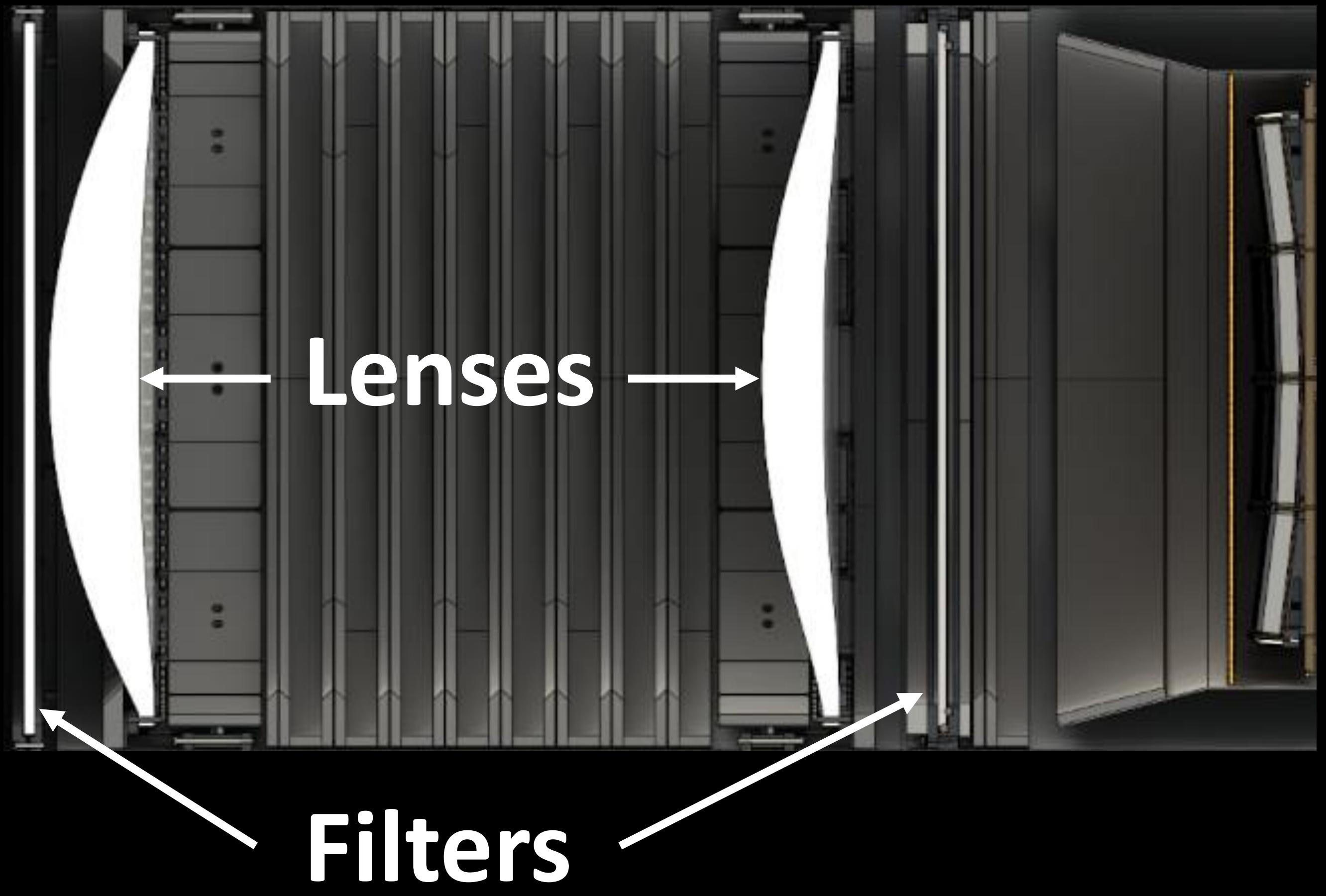
More Detectors = More Sensitivity



Power = P(   )

Simpler optics = Less Noise = More Sensitivity



Make everything cold because everything with a temperature emits microwaves

Make everything cold

Heat Transfer exists!

Conduction Convection Radiation

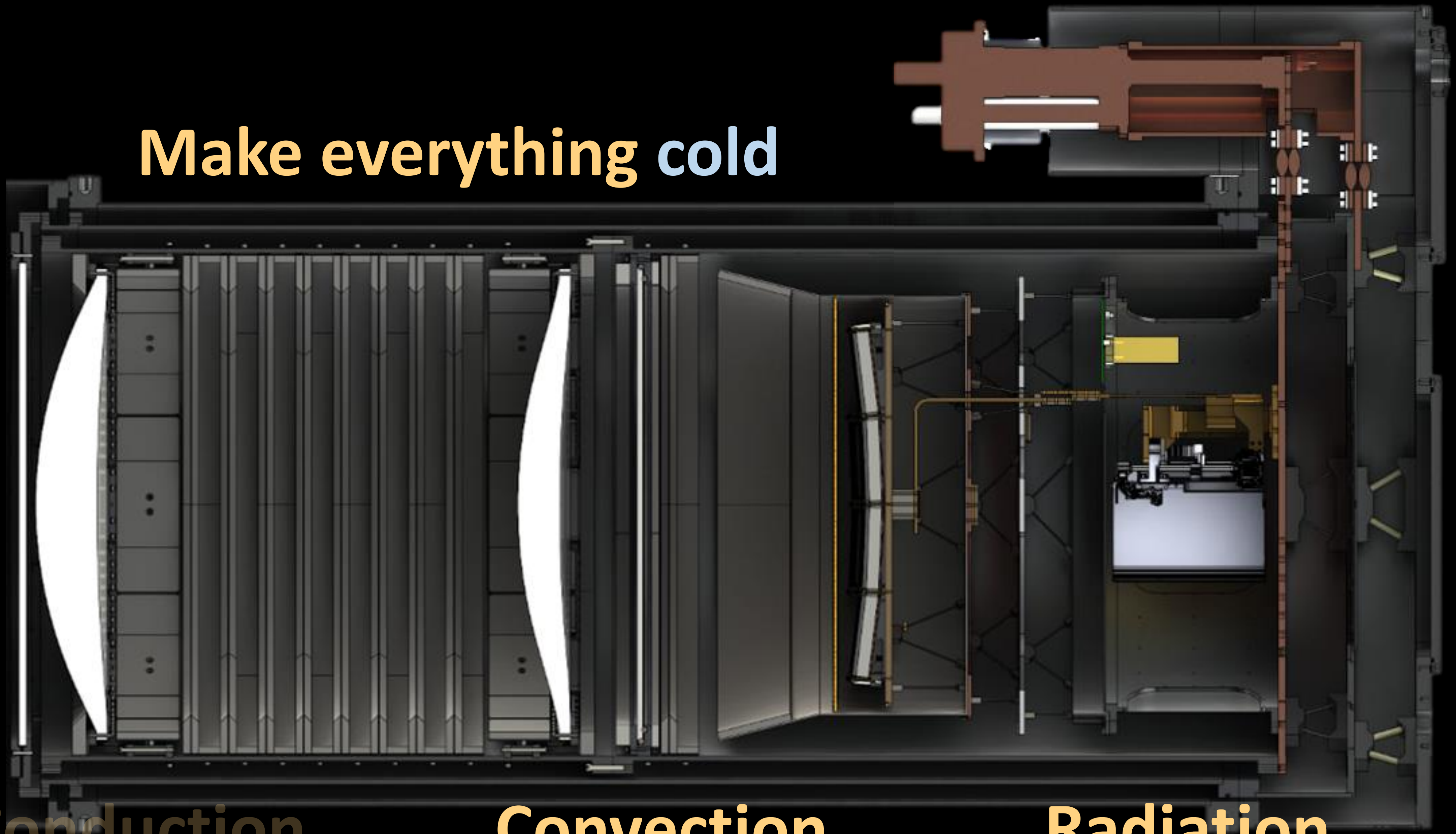
Make everything cold

Conduction Convection Radiation

Make everything cold

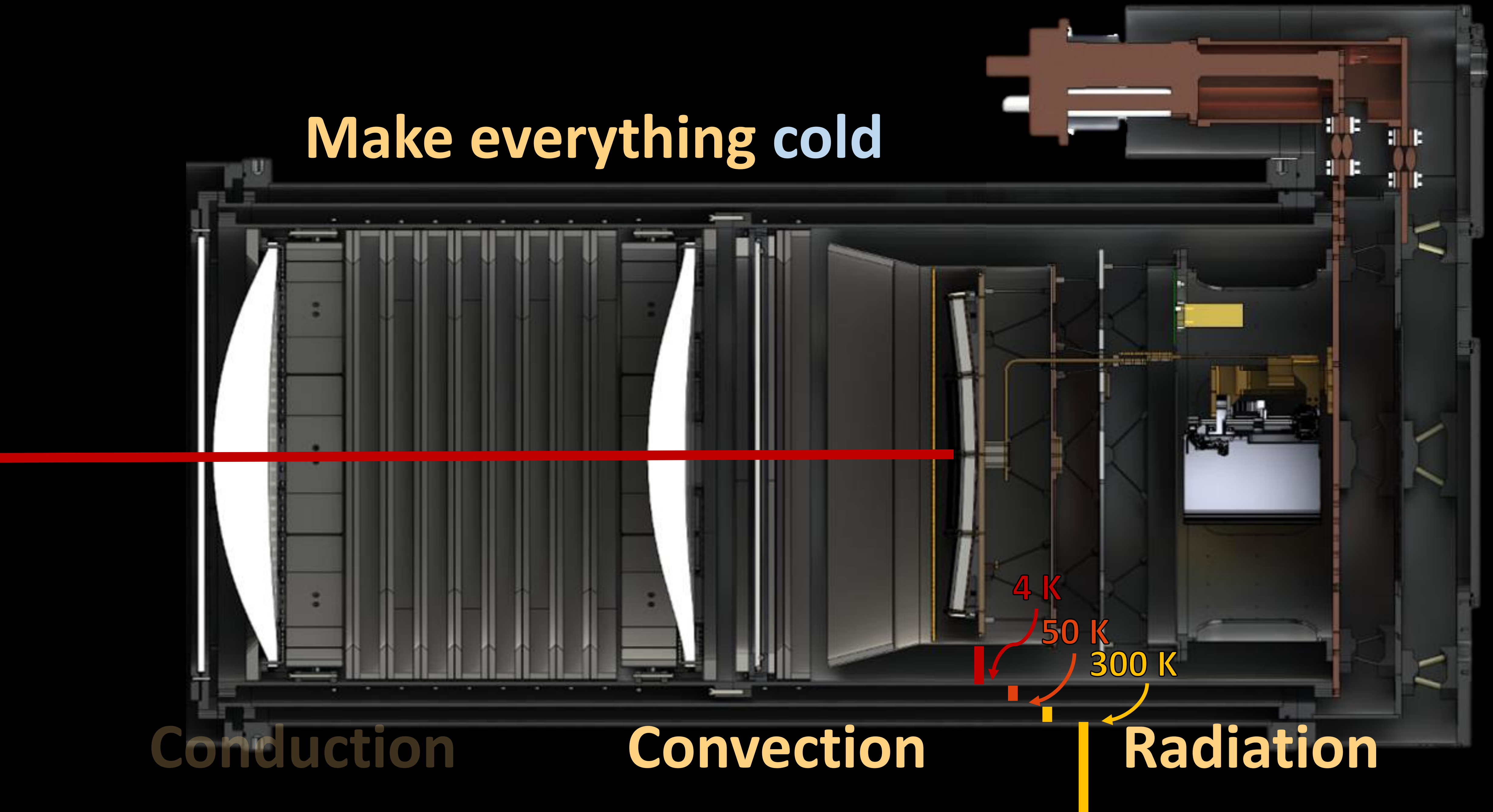
Conduction Convection Radiation

Make everything cold



Conduction Convection Radiation

Make everything cold



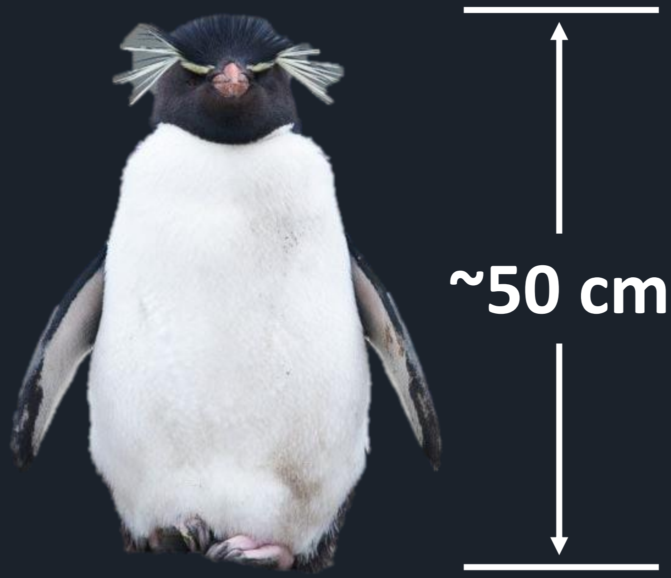
Conduction Convection Radiation

We need a vacuum window!

Make everything cold

Conduction Convection Radiation

We need a vacuum window!



1. Highly transmissive

$\text{Power} = P(\nu, \alpha, t, T)$ ↓

M
Pr
Th
Immutable

2. Strong enough e atmosphere

$\text{Stress} = \sigma(E, t, F_{atm})$ ↑

$F_{atm} \approx$ few tons

Common microwave vacuum window materials:

Quartz

Not big enough

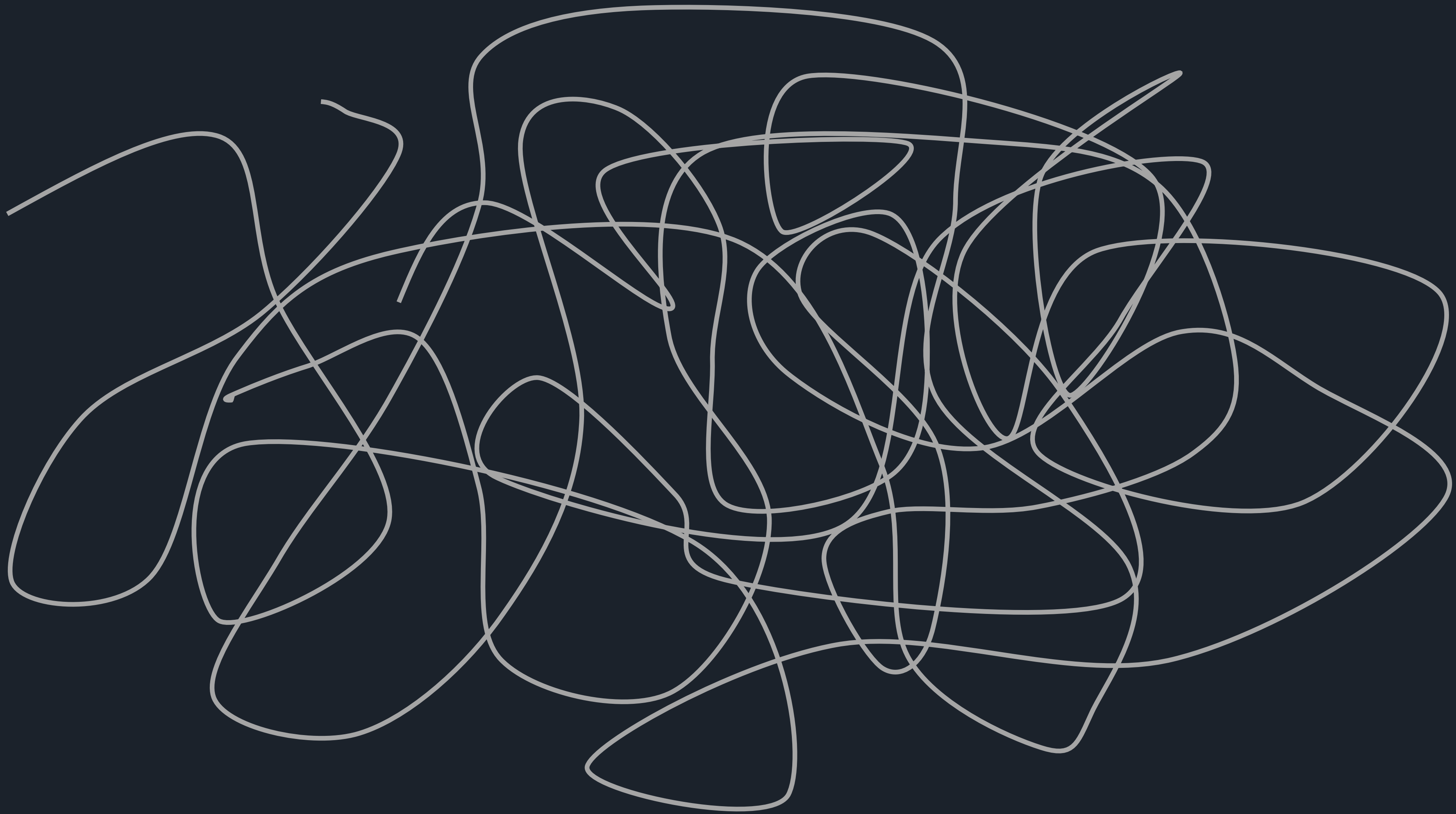
Plastic foam

Too thick

Polyethylene

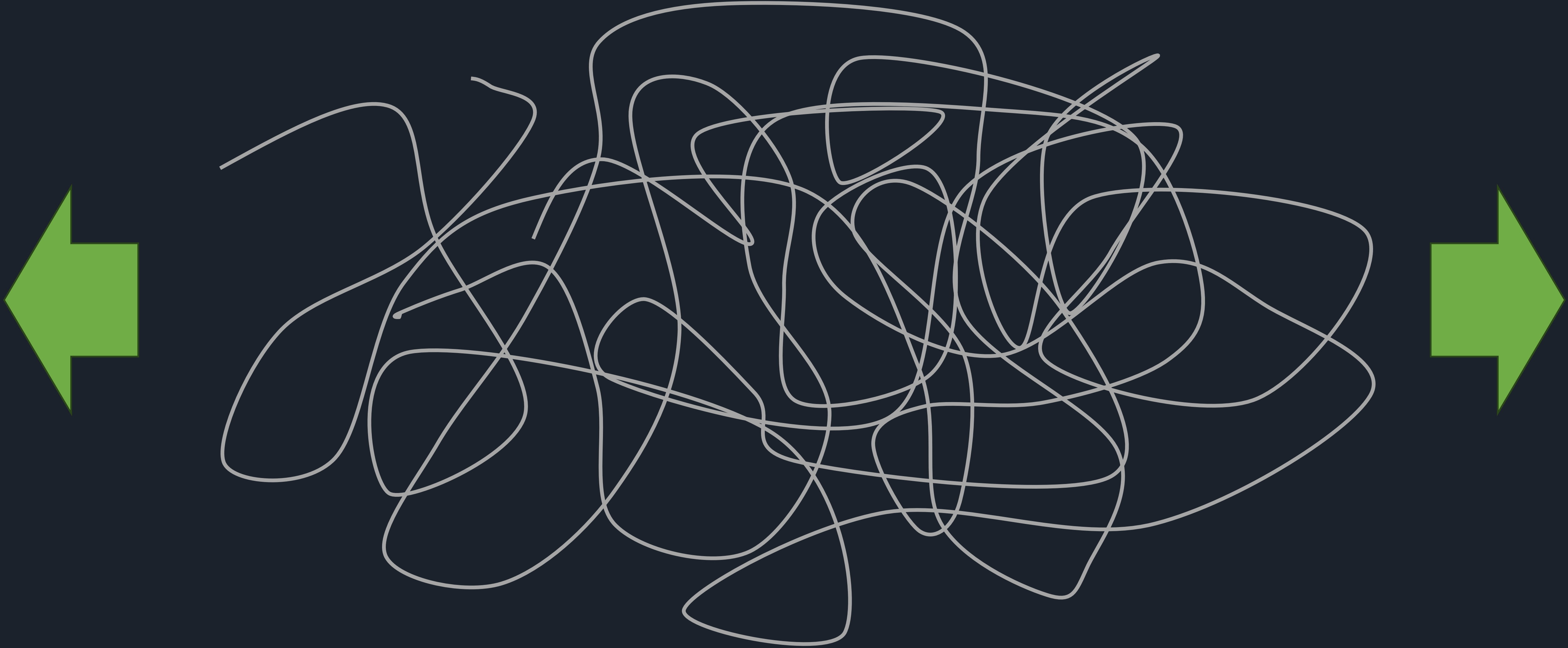
Kinda weak...

Polyethylene is weak because…



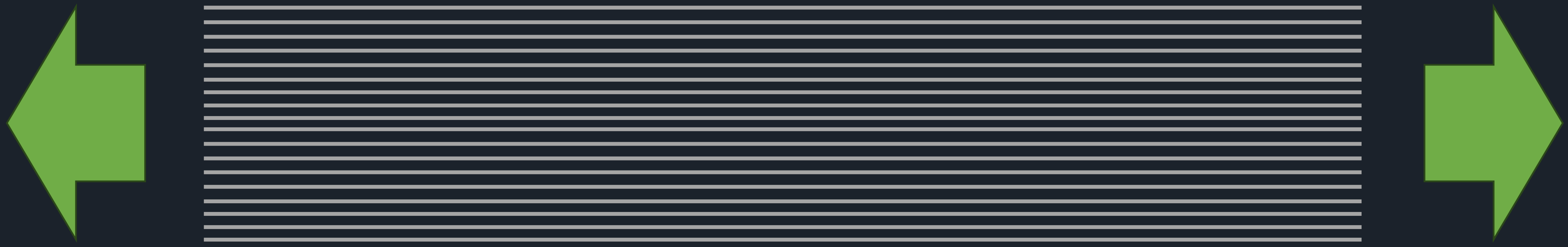
High Density Polyethylene (HDPE)

Polyethylene is weak because…



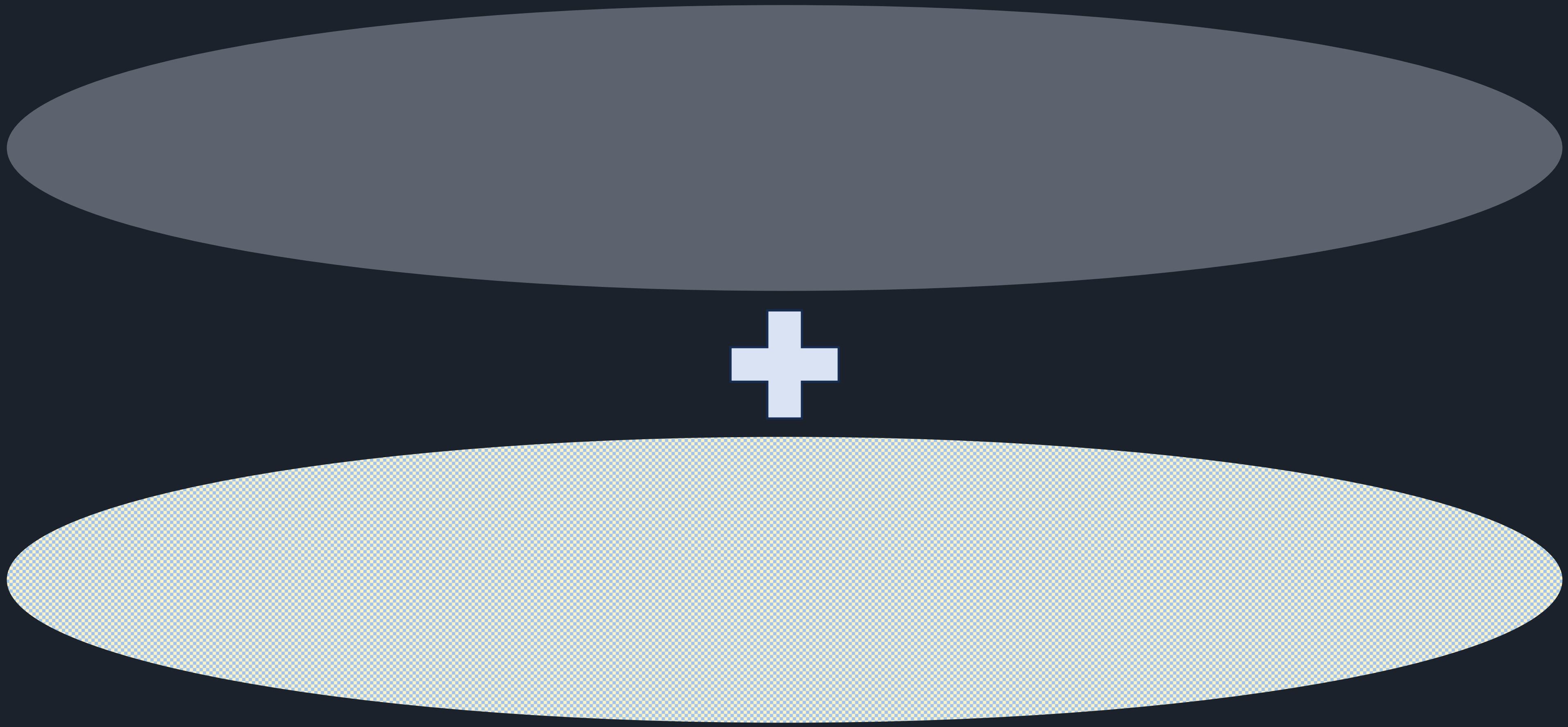
High Density Polyethylene (HDPE)

If we align the molecules:



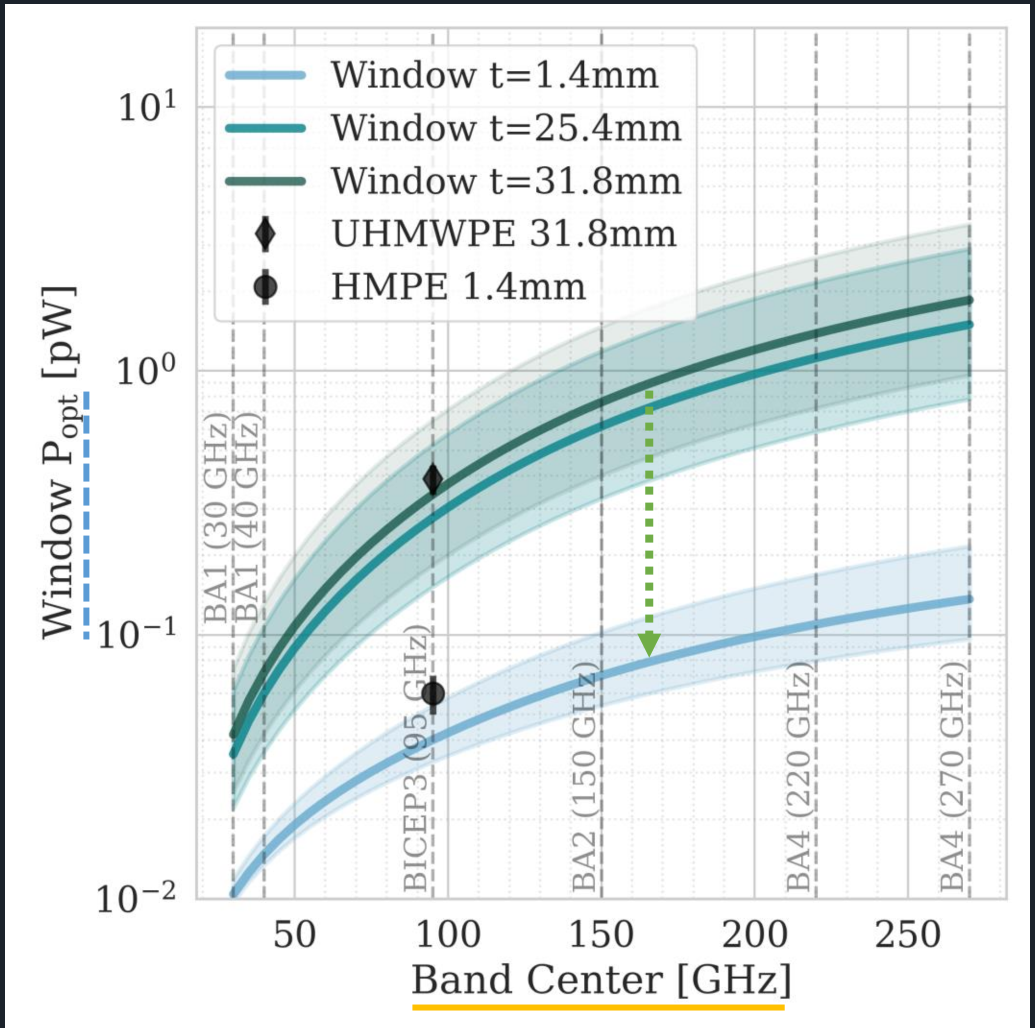
High Modulus Polyethylene (HMPE)

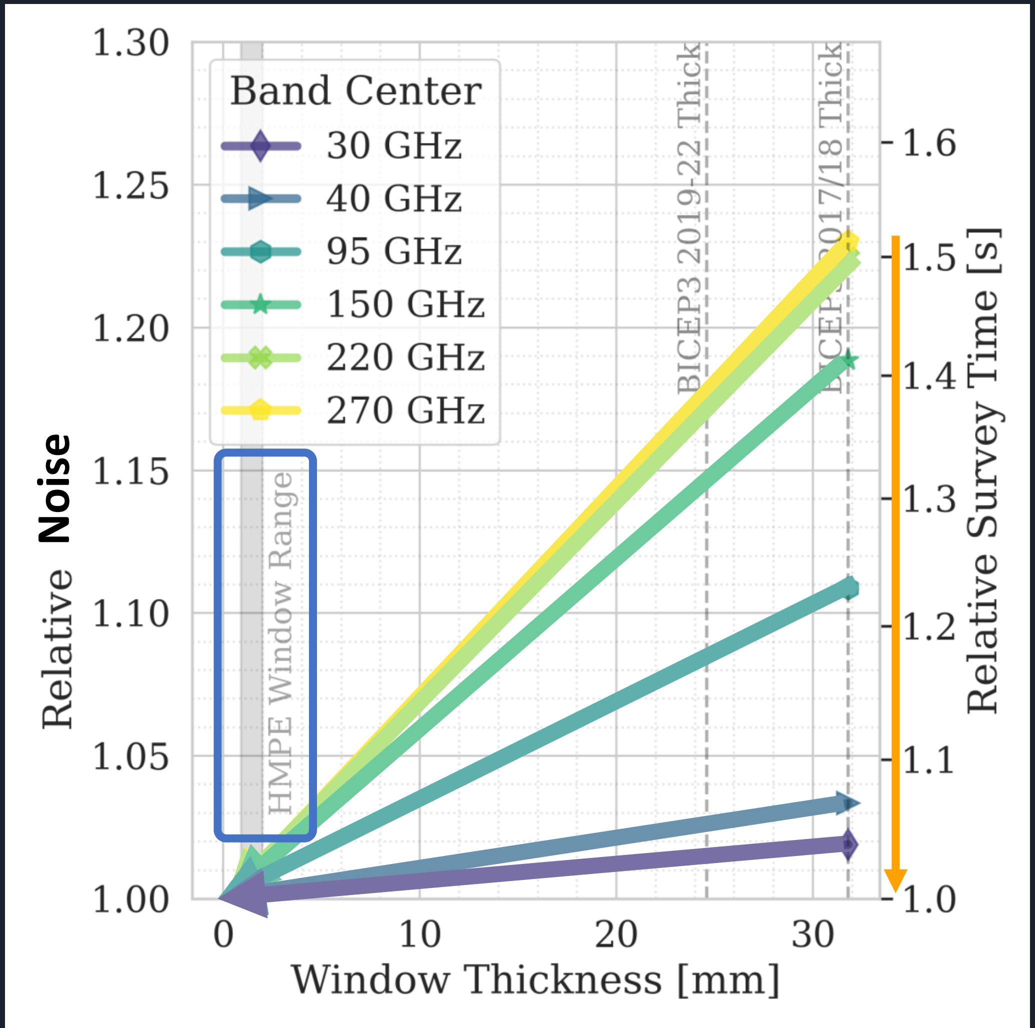
LDPE



HMPE

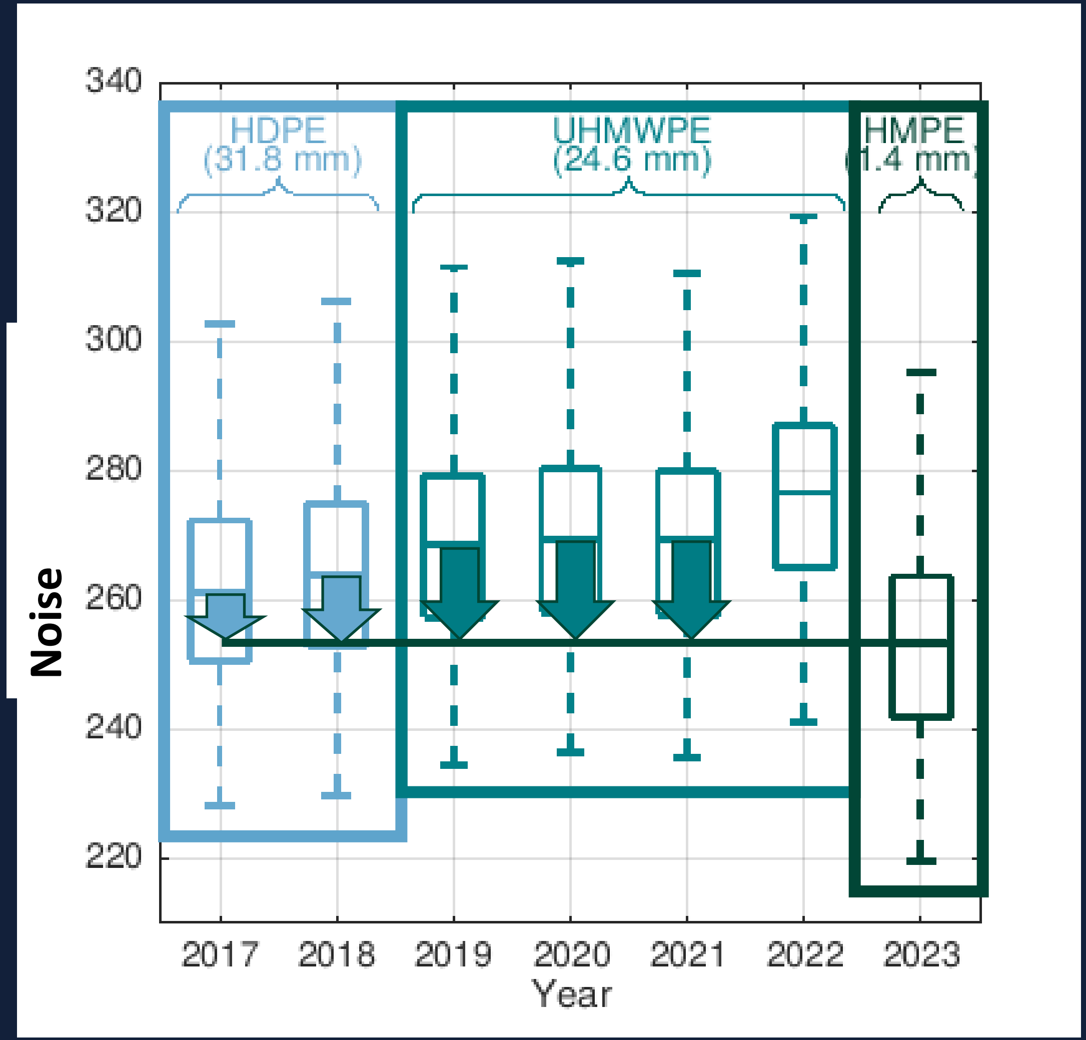
Heat Compression



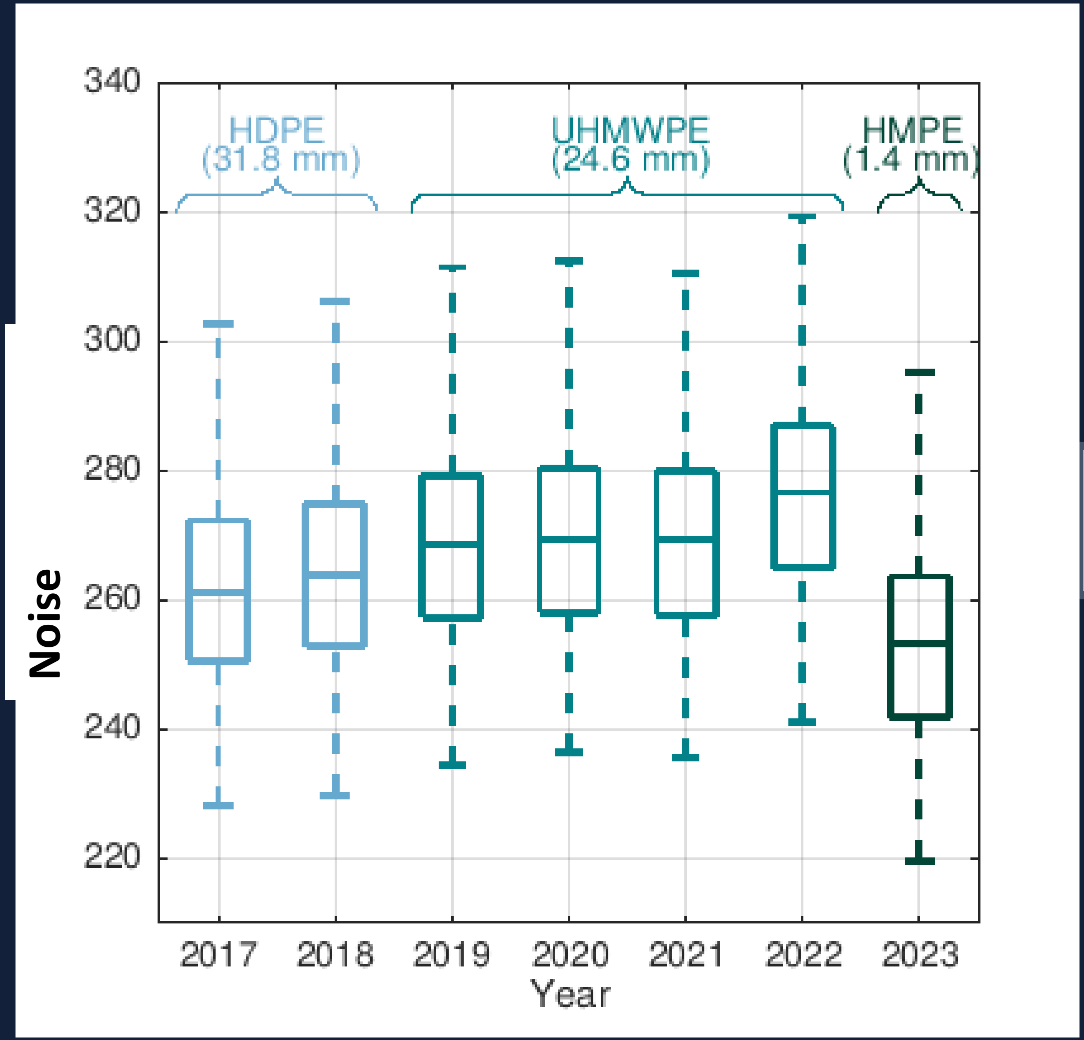


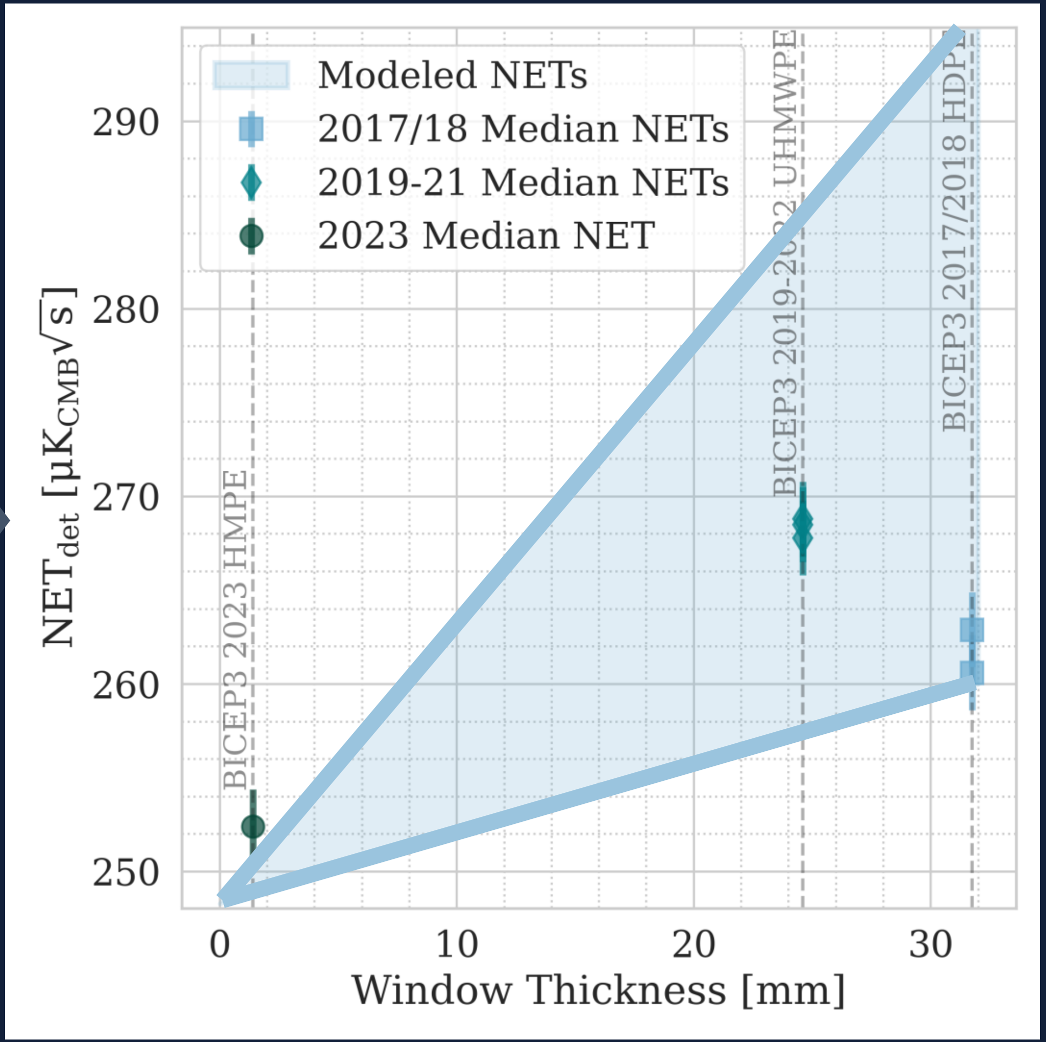
Power = $P(\nu, \alpha, t, T)$ Less Noise = Faster Survey

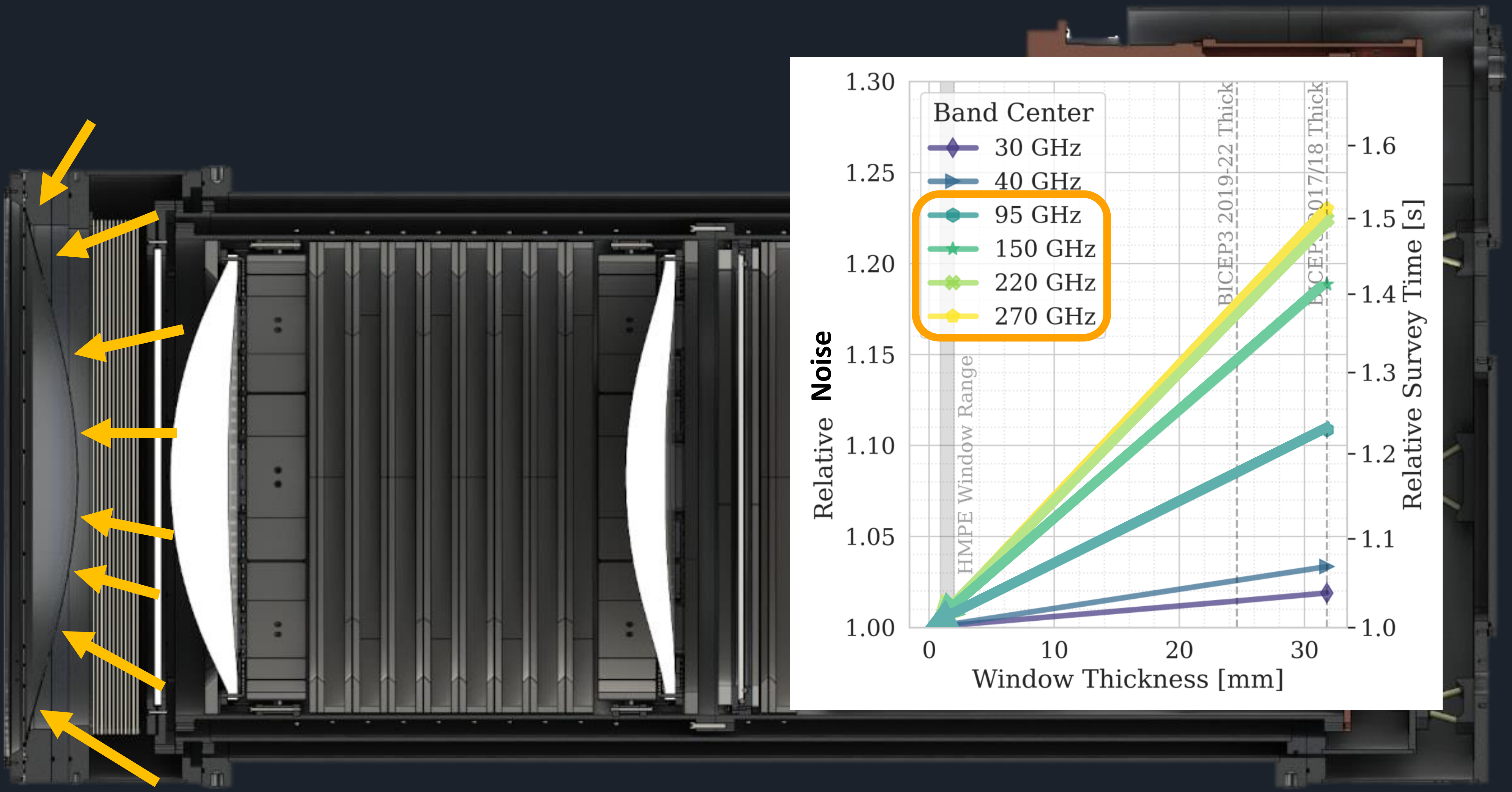
Measure Per Det Noise Equivalent Temp (NET) on BICEP3



Model the Per Det NET







Band Center
30 GHz
40 GHz
95 GHz
150 GHz
220 GHz
270 GHz
HMPE Window Range
BICEP3 2019-22 Thick
BICEP3 2017/18 Thick
Relative Noise
Relative Survey Time [s]
Window Thickness [mm]
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0
10
20
30
1.6
1.5
1.4
1.3
1.2
1.1
1.0

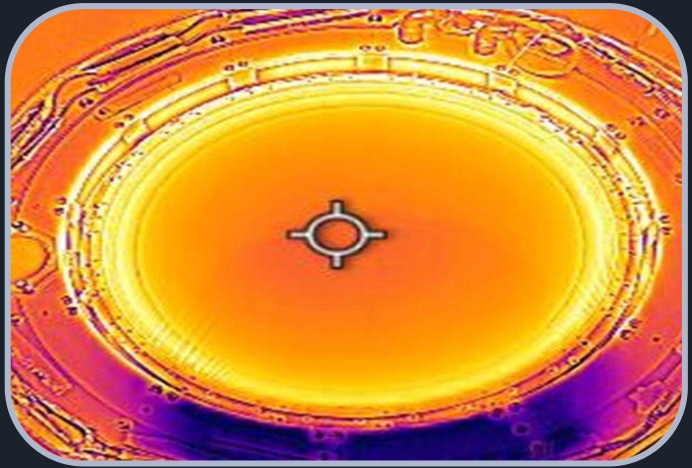
Mechanical: Choose your adventure!

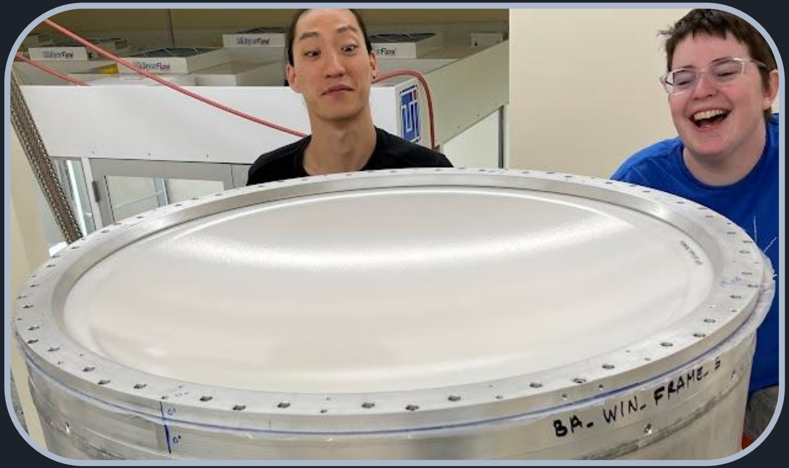
Point up!

Point left!

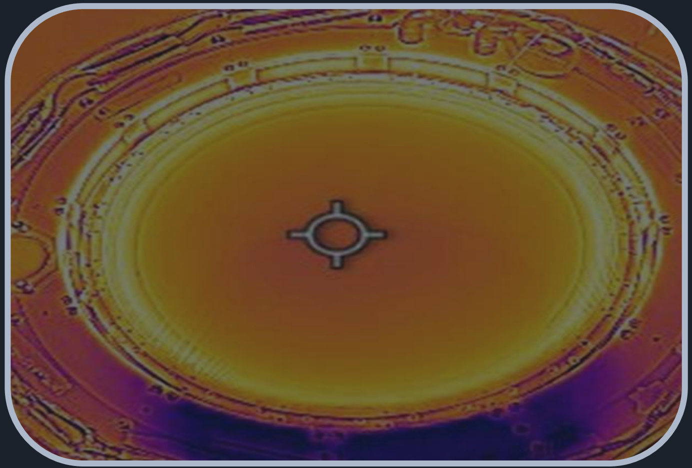
Point right!

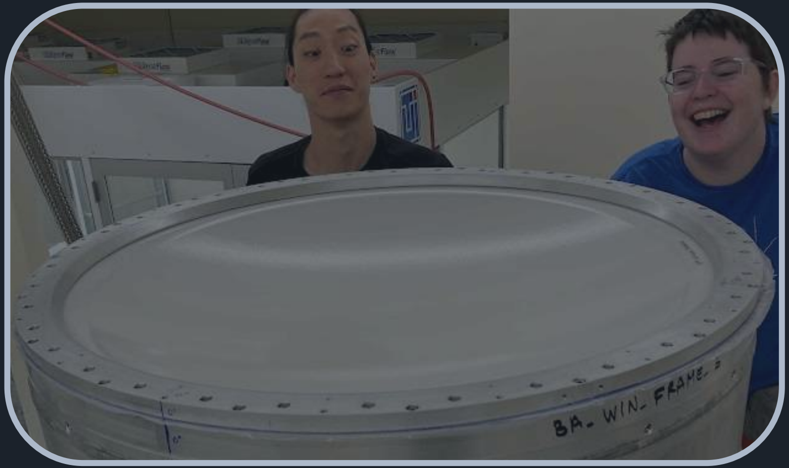
Mechanical: Choose your adventure!





Mechanical: Choose your adventure!



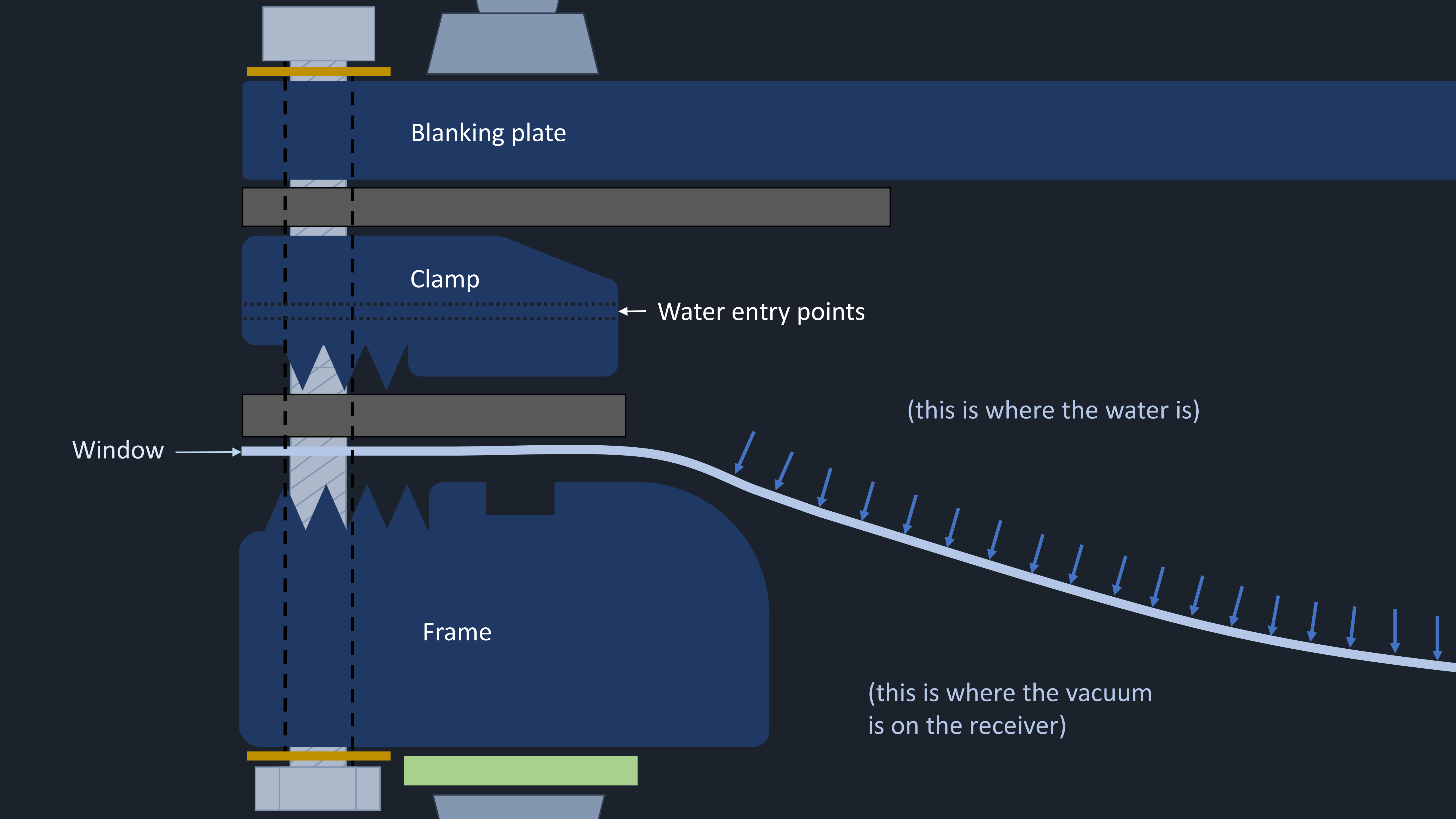


How strong is the HMPE laminate?

$$\text{Safety Factor} = \frac{\text{Ultimate Tensile Strength}}{\text{Max Stress on the Window}}$$

$$\text{Stress} = \sigma(E, t, F_{atm})$$

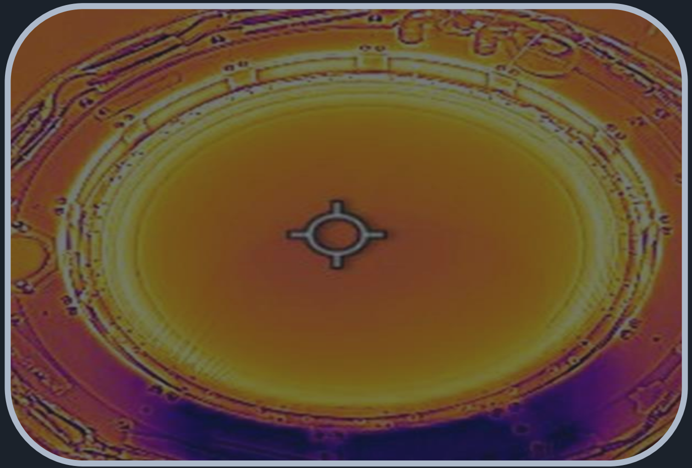
Window Material	Ultimate Tensile Strength (MPa)	Thickness for Safety Factor of 3 (mm)
HDPE	20-25	17.7
UHMWPE	22-40	13.6
HMPE Laminate	120-135	1.4

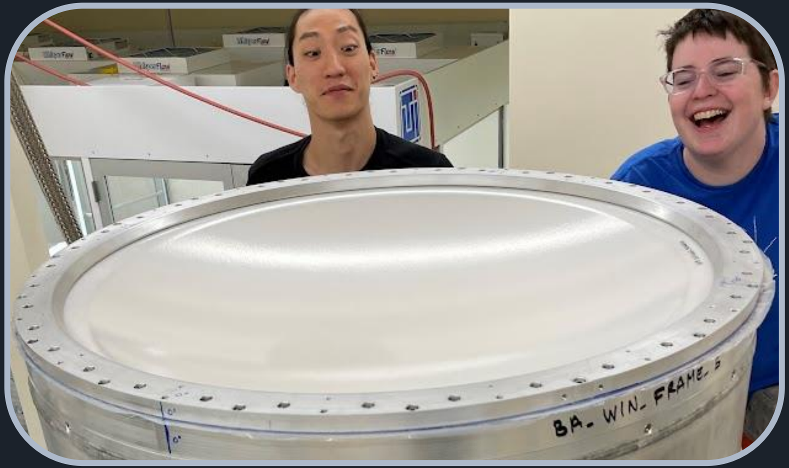

Blanking plate
Clamp
Water entry points
(this is where the water is)
Window
Frame
(this is where the vacuum
is on the receiver)

Safety factors of 5.7 at sea level, 8.2 at South Pole

We got to 85 pounds per square inch

Mechanical: Choose your adventure!





What about permeation of gas?

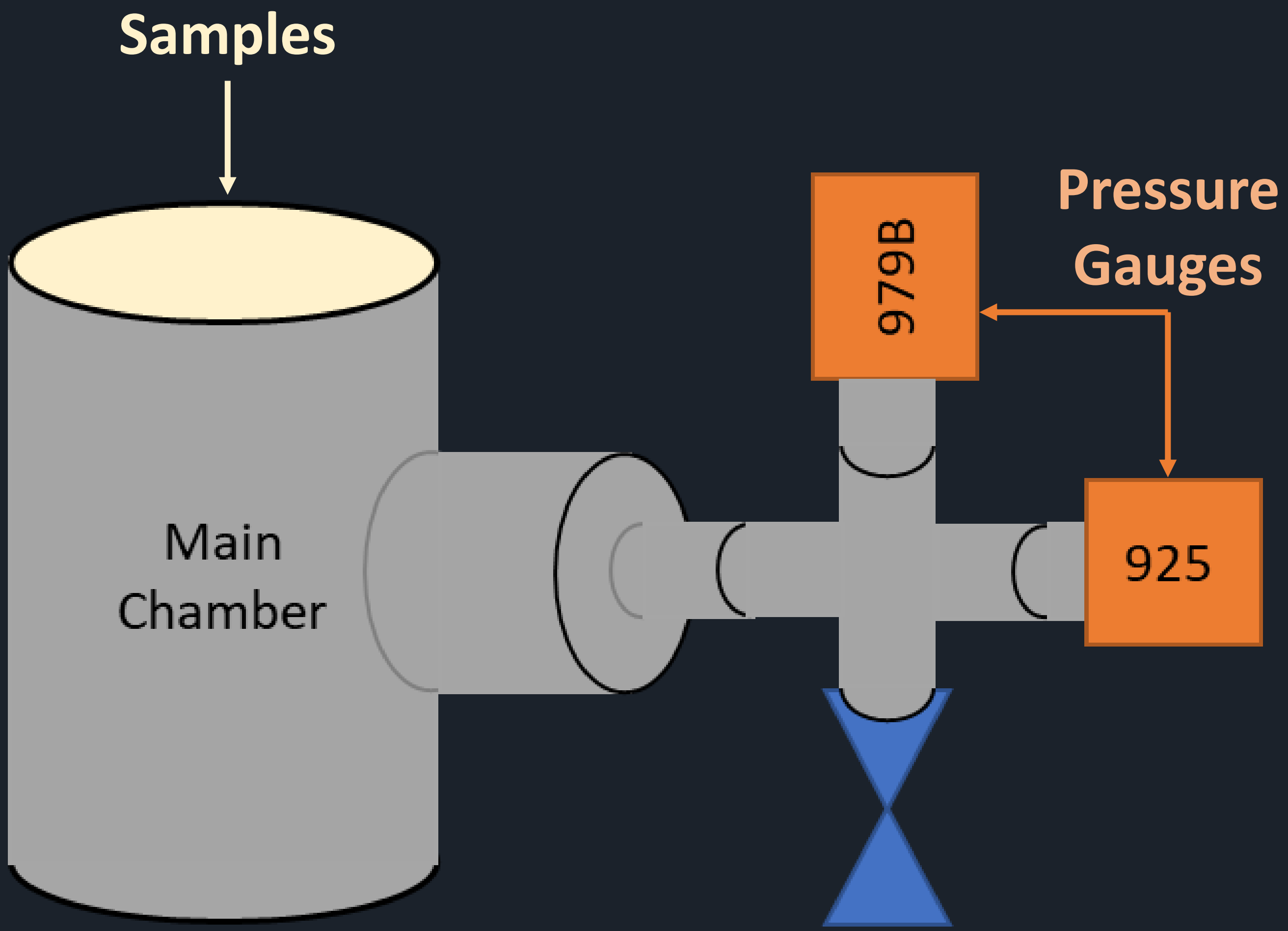
Atmosphere

Polymer

Vacuum

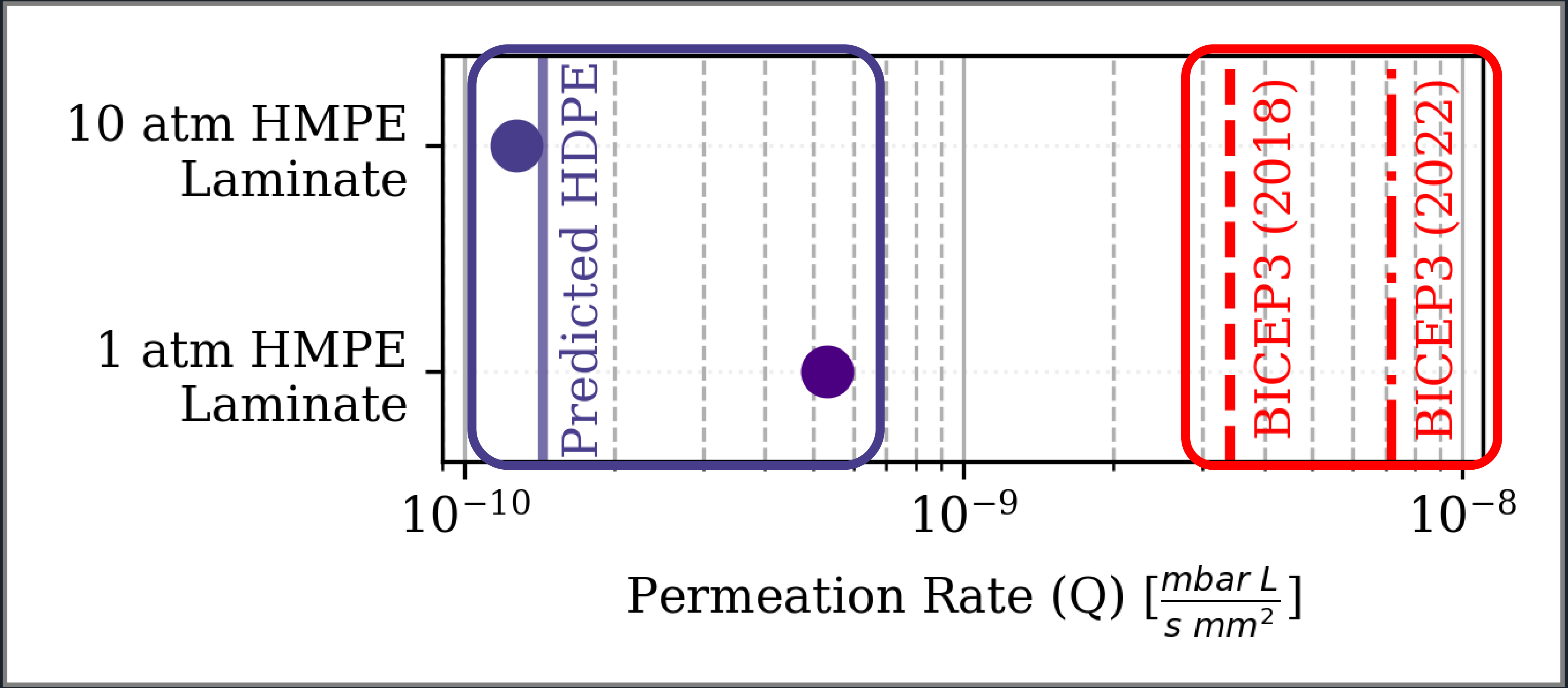
$$\text{Permeation Rate} = Q \propto \frac{1}{t}$$

Convection



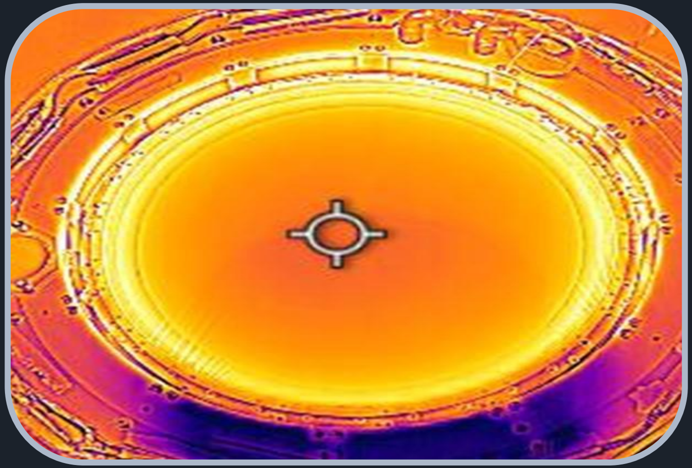
Measure how much gas got into the system over time

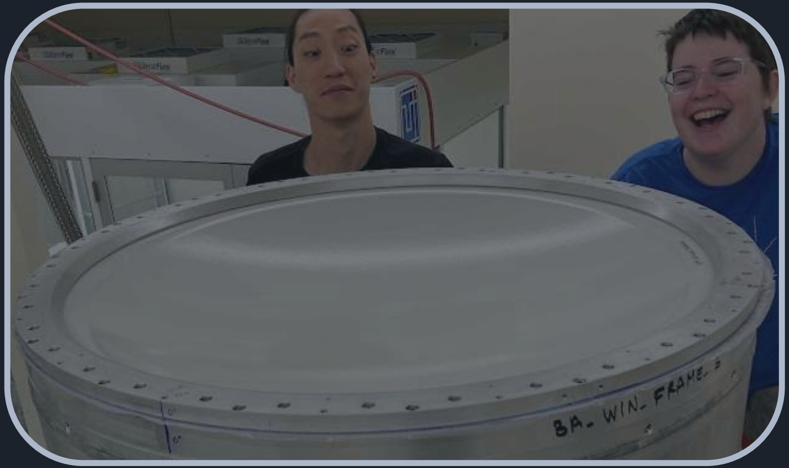
Too much permeation
= thermal problems



Convection

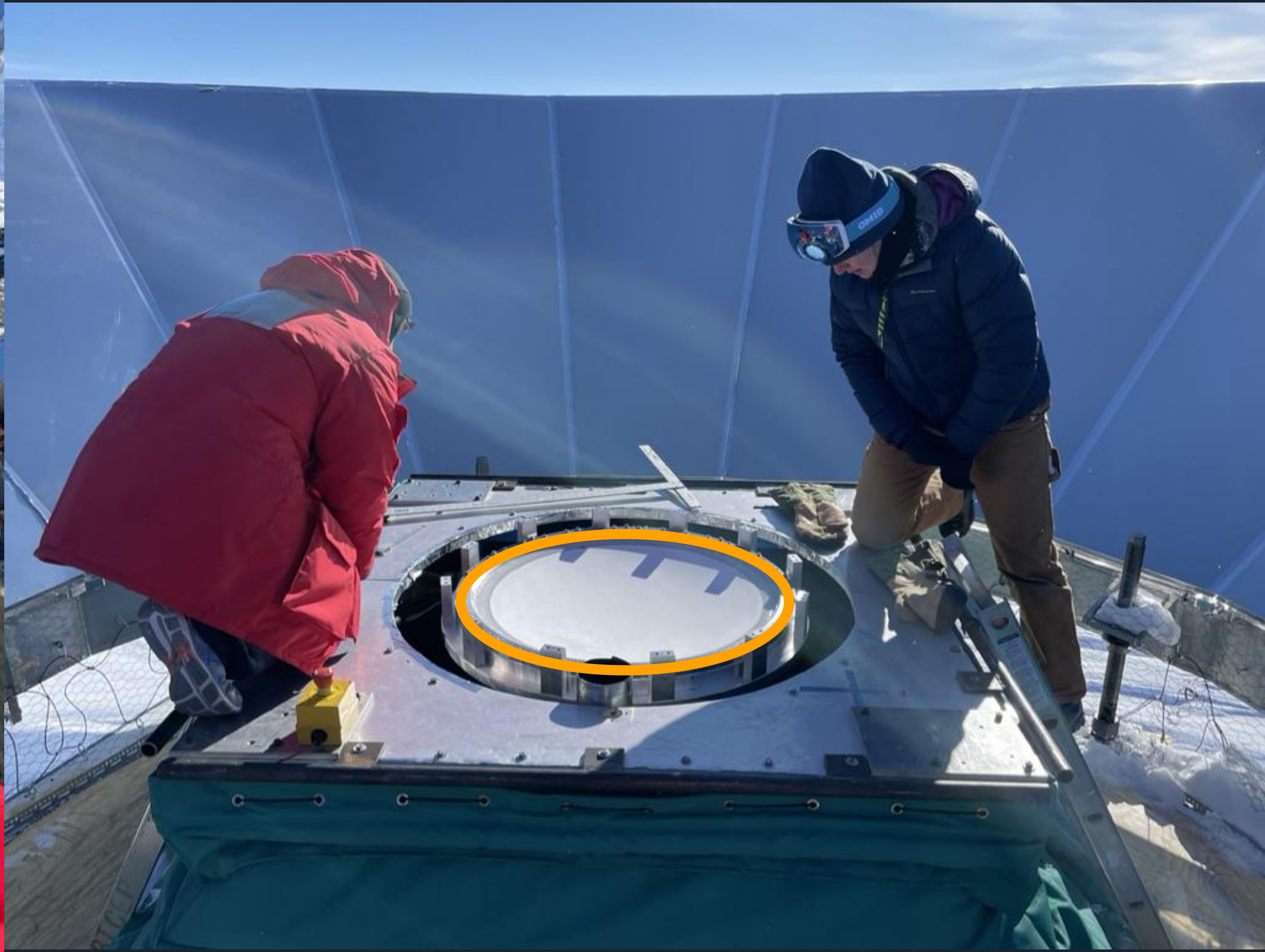
Mechanical: Choose your adventure!





What about the environment around the window?

It is very cold at the South Pole




-12.2°C

Things we have dropped on the window:

Optical: Choose your adventure!

Optical Tests
at Home

Optical Tests
on BICEP3

Optical: Choose your adventure!

Optical Tests at Home

Optical Tests on BICEP3

Index of refraction

Birefringence

Optical: Choose your adventure!

Optical Tests at Home

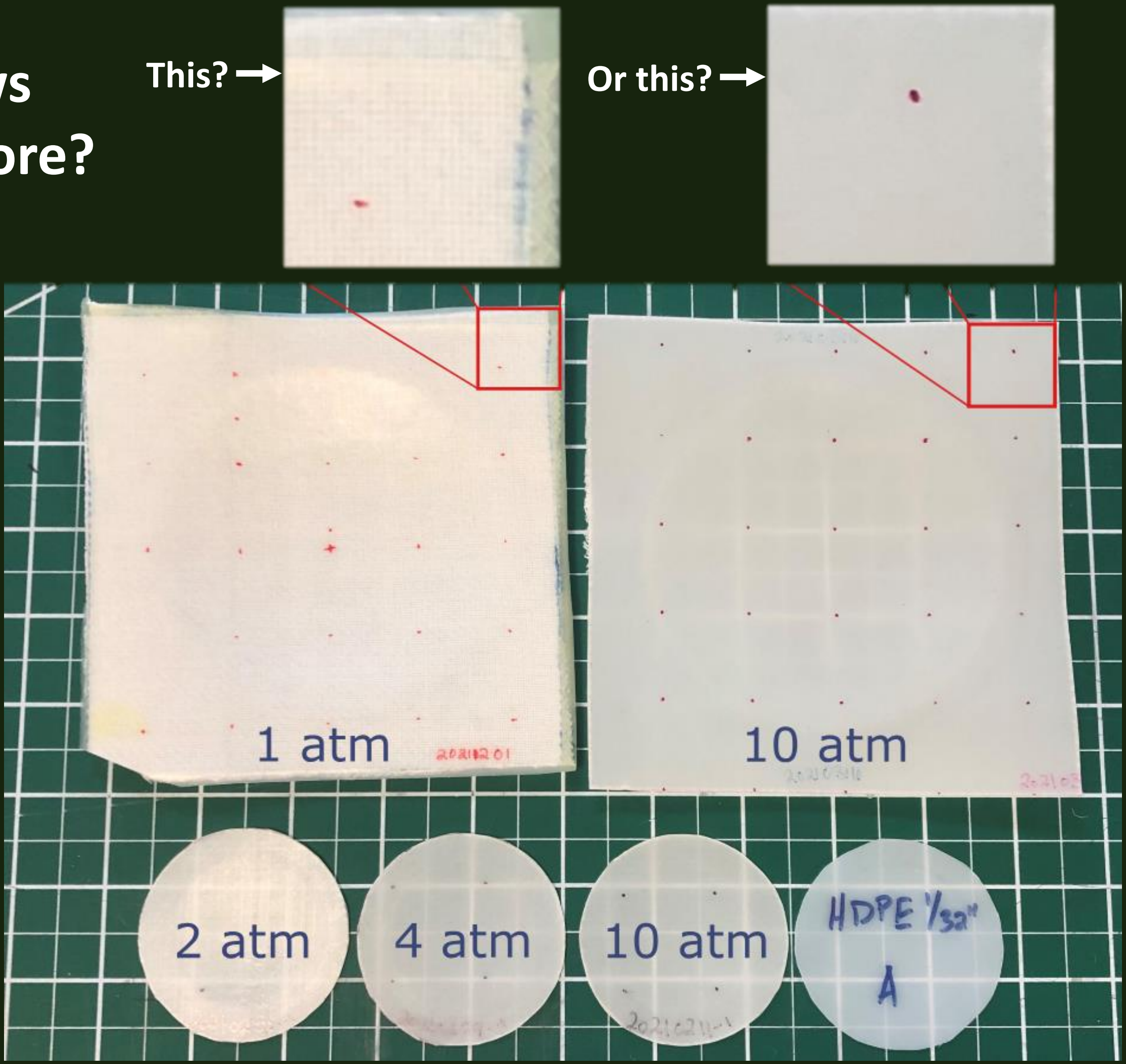
Optical Tests on BICEP3

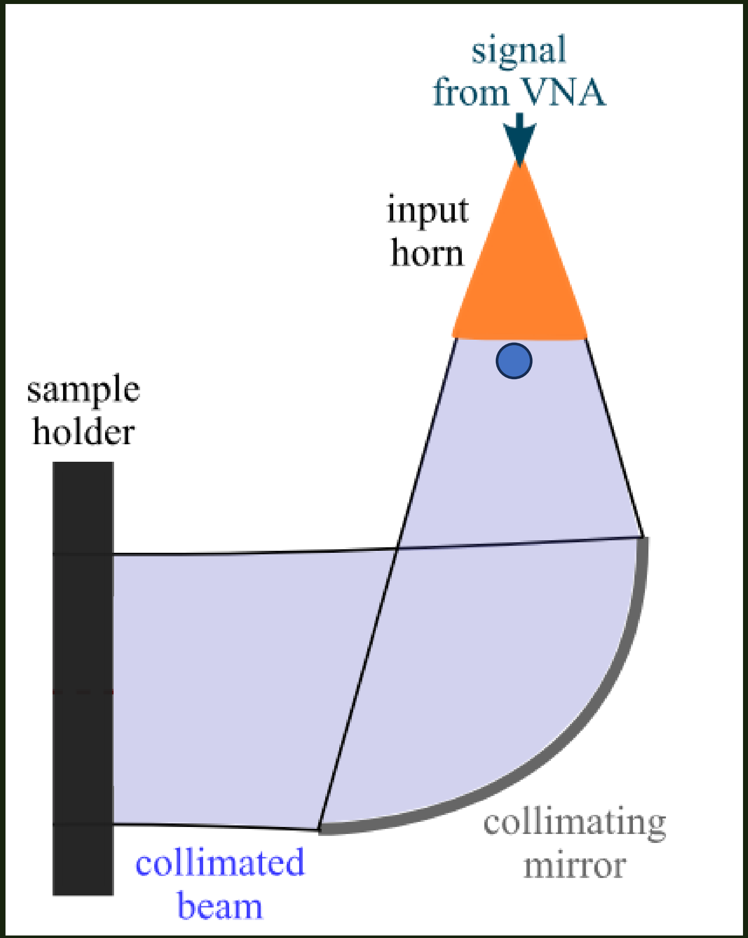
Index of refraction

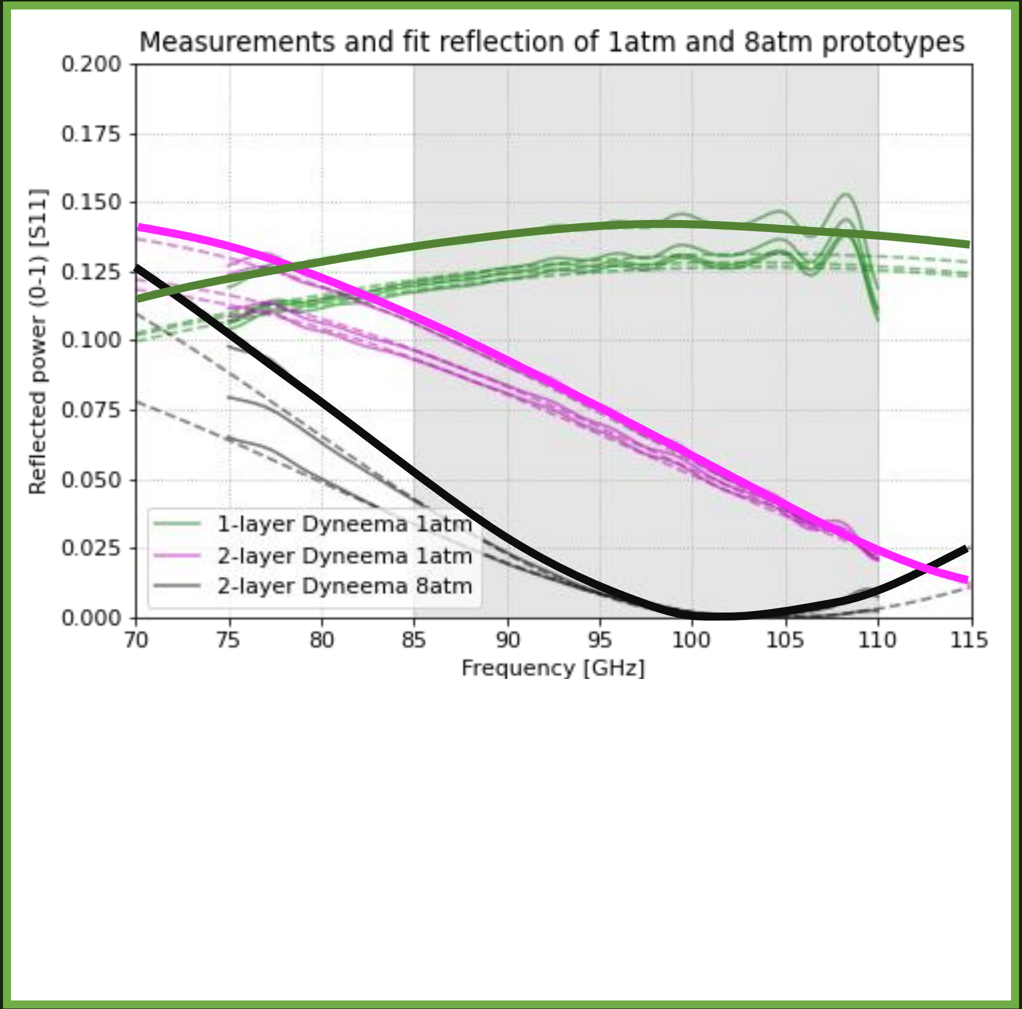
Birefringence

What is the index of refraction of the laminate?

Which slows down light more?




signal
from VNA
input
horn
sample
holder
collimated
beam
collimating
mirror


Measurements and fit reflection of 1atm and 8atm prototypes
Reflected power (0-1) |S11|
Frequency [GHz]
1-layer Dyneema 1atm
2-layer Dyneema 1atm
2-layer Dyneema 8atm

Optical: Choose your adventure!

Optical Tests at Home

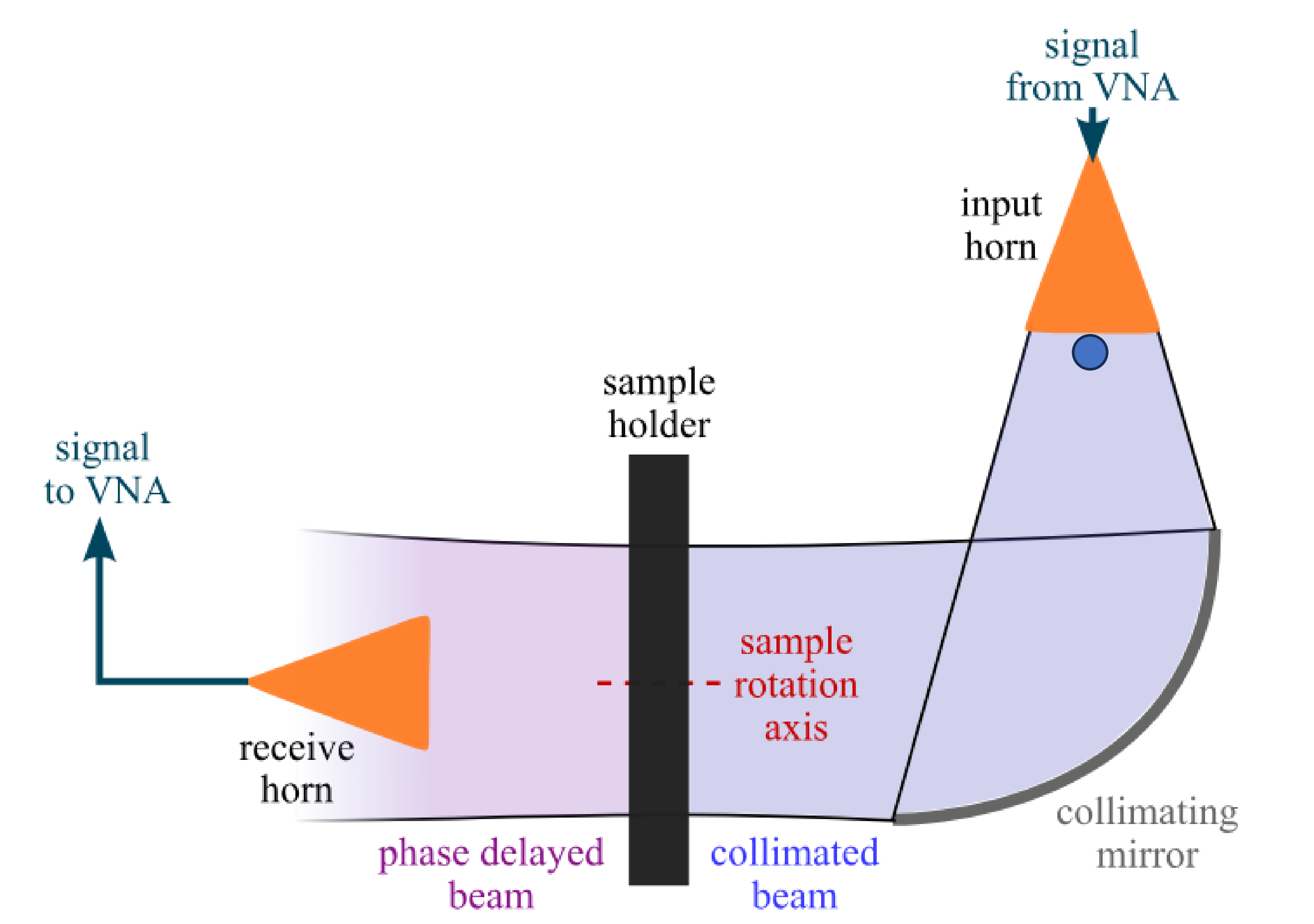
Optical Tests on BICEP3

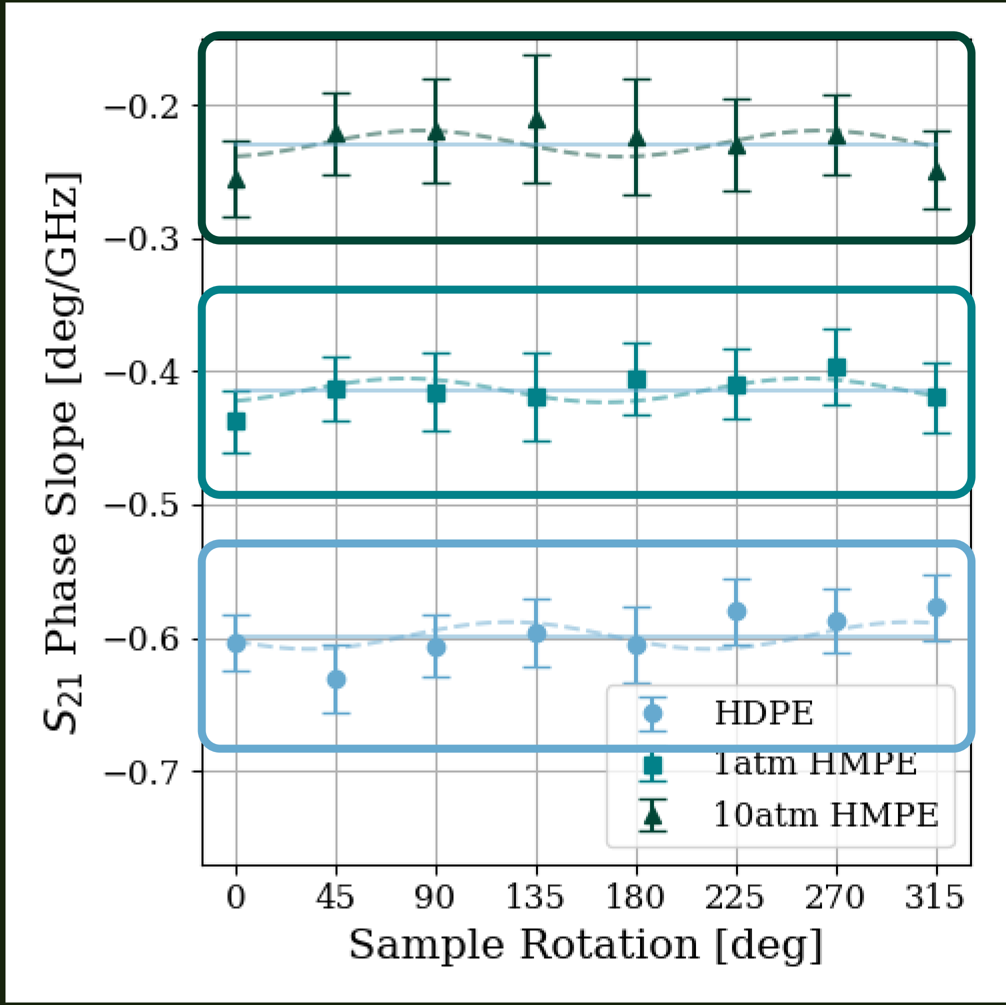
Index of refraction

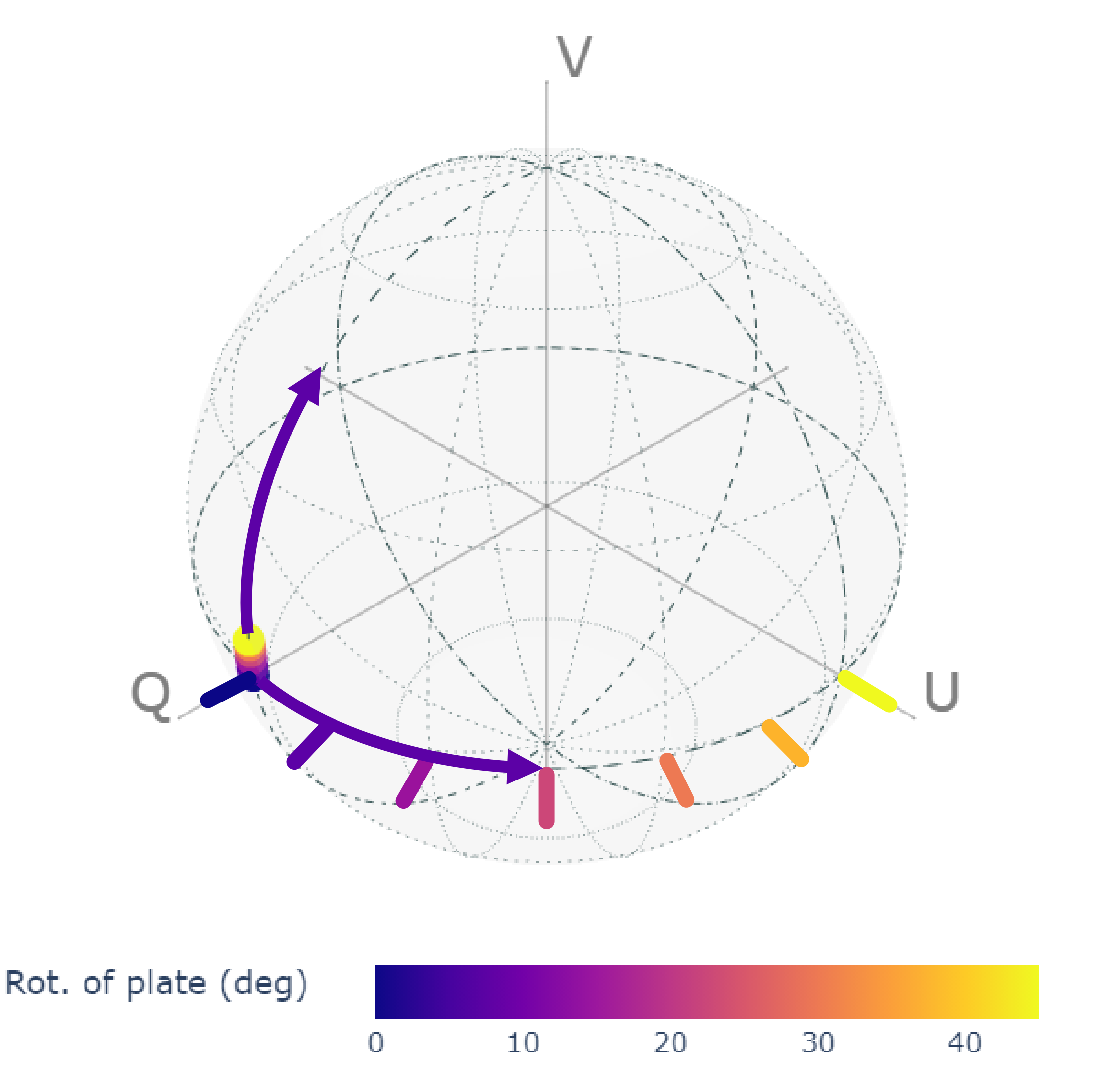
Birefringence

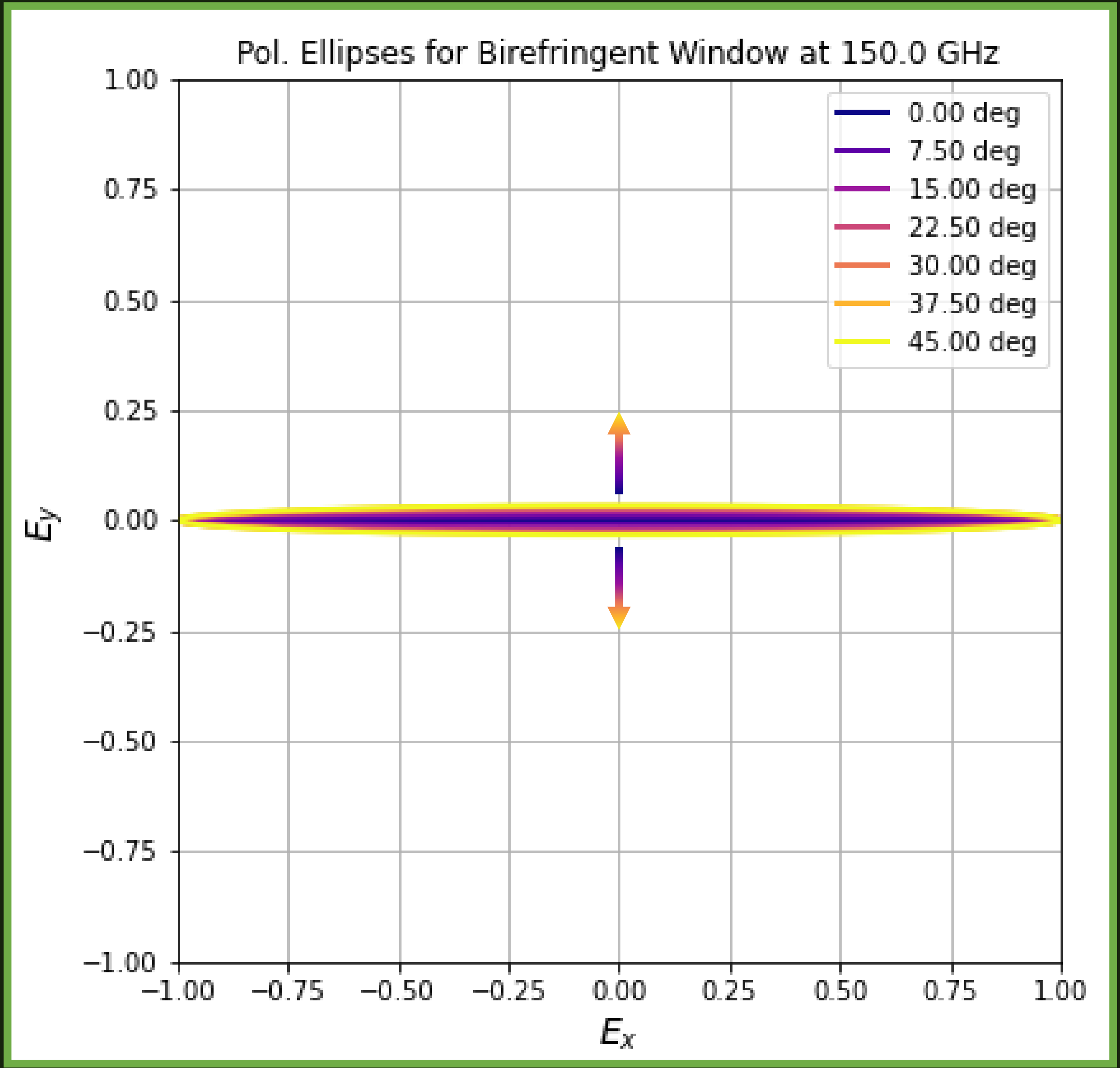
What about polarization through the window?

Birefringence = different indexes of refraction at different orientations






V
Q
U
Rot. of plate (deg)
0
10
20
30
40


Pol. Ellipses for Birefringent Window at 150.0 GHz
0.00 deg
7.50 deg
15.00 deg
22.50 deg
30.00 deg
37.50 deg
45.00 deg
E_y
E_x
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00

Optical: Choose your adventure!

Optical Tests at Home

Optical Tests on BICEP3

Insertion loss

Elevation vs loading

Optical: Choose your adventure!

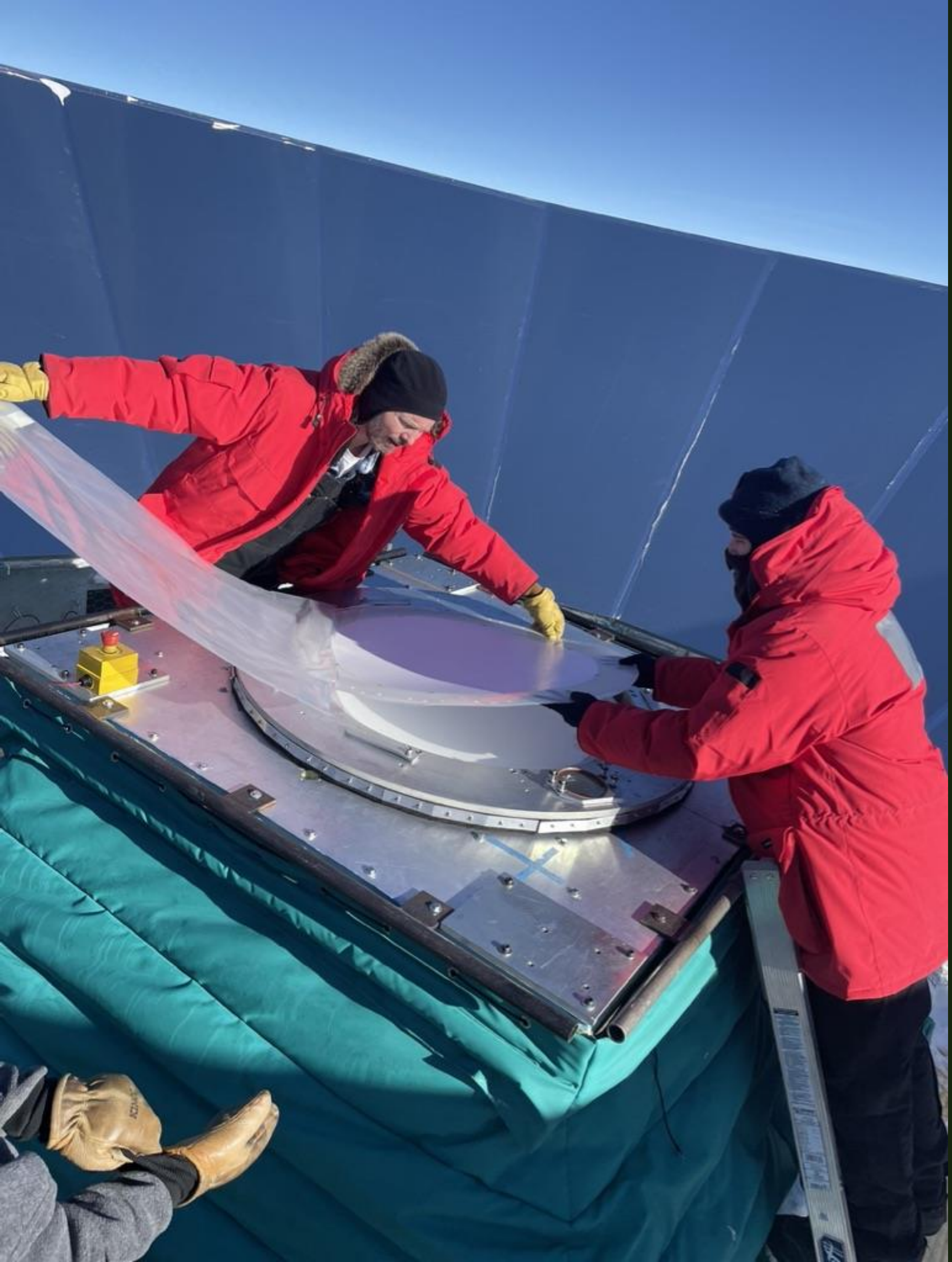
Optical Tests at Home

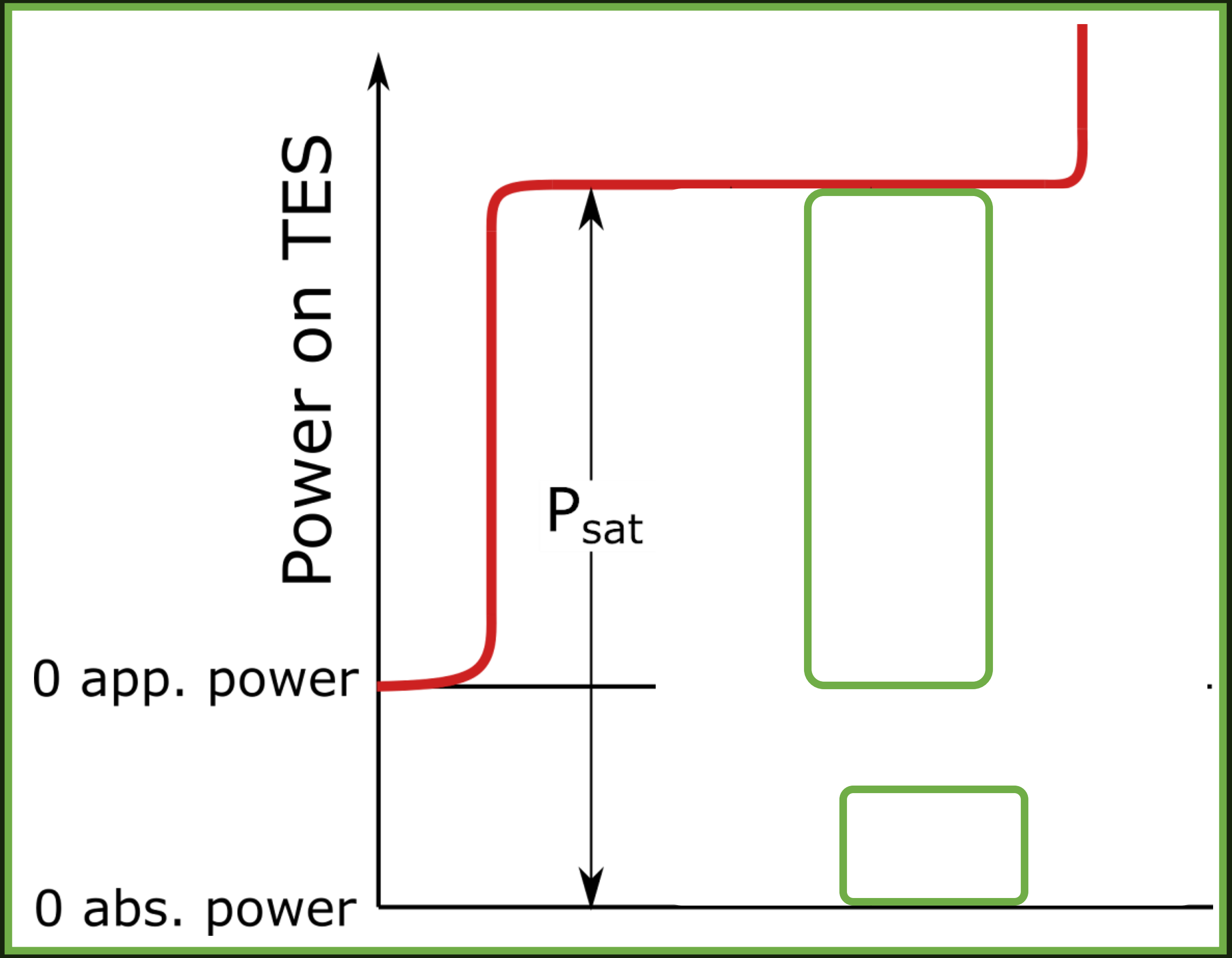
Optical Tests on BICEP3

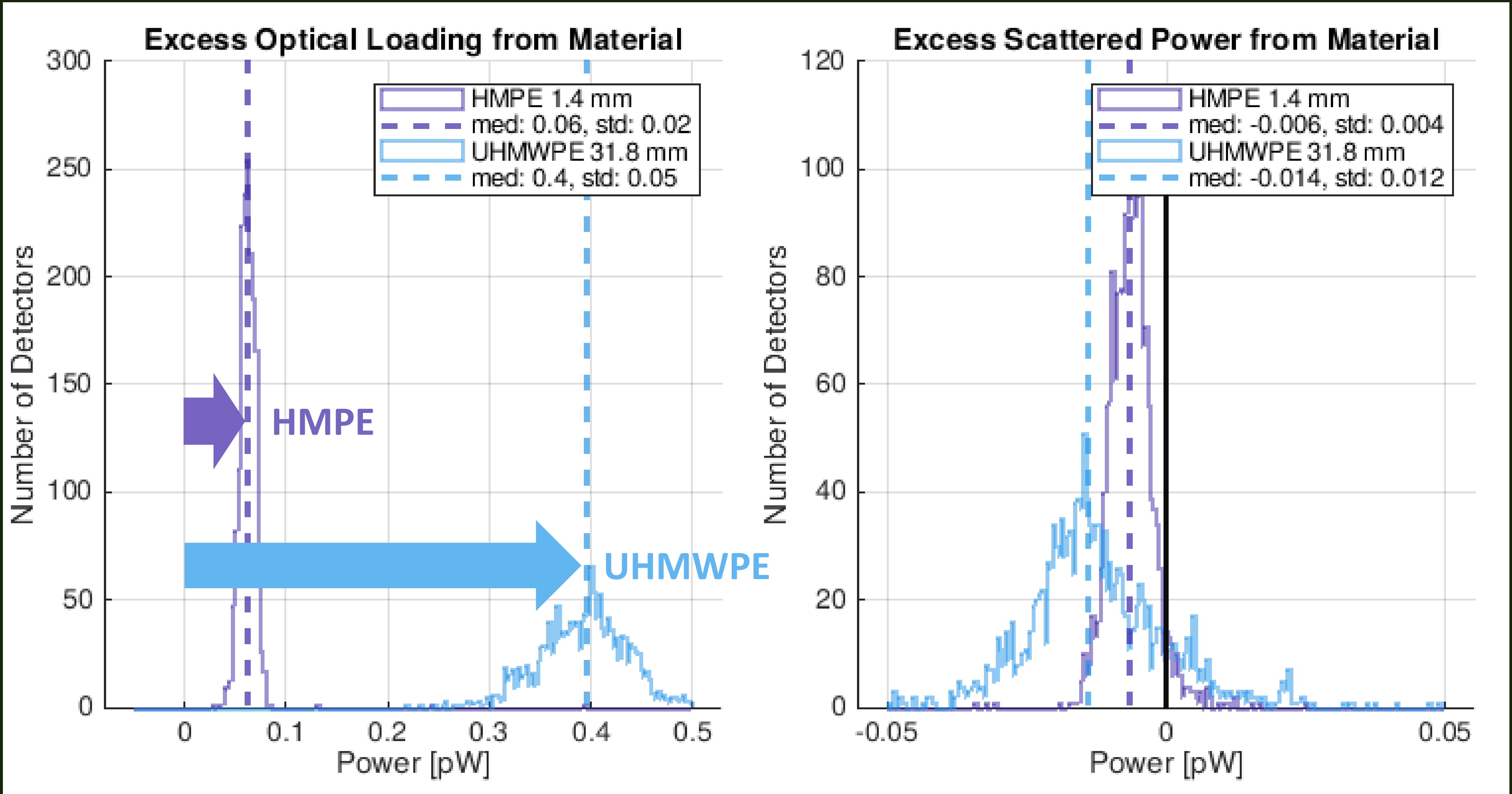
Insertion loss

Elevation vs loading

What is the optical loading from the window?




Power on TES
P_{sat}
0 app. power
0 abs. power


Excess Optical Loading from Material
Number of Detectors
Power [pW]
HMPE 1.4 mm
med: 0.06, std: 0.02
UHMWPE 31.8 mm
med: 0.4, std: 0.05
HMPE
UHMWPE
300
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
Excess Scattered Power from Material
Number of Detectors
Power [pW]
HMPE 1.4 mm
med: -0.006, std: 0.004
UHMWPE 31.8 mm
med: -0.014, std: 0.012
120
100
80
60
40
20
0
-0.05
0
0.05

Optical: Choose your adventure!

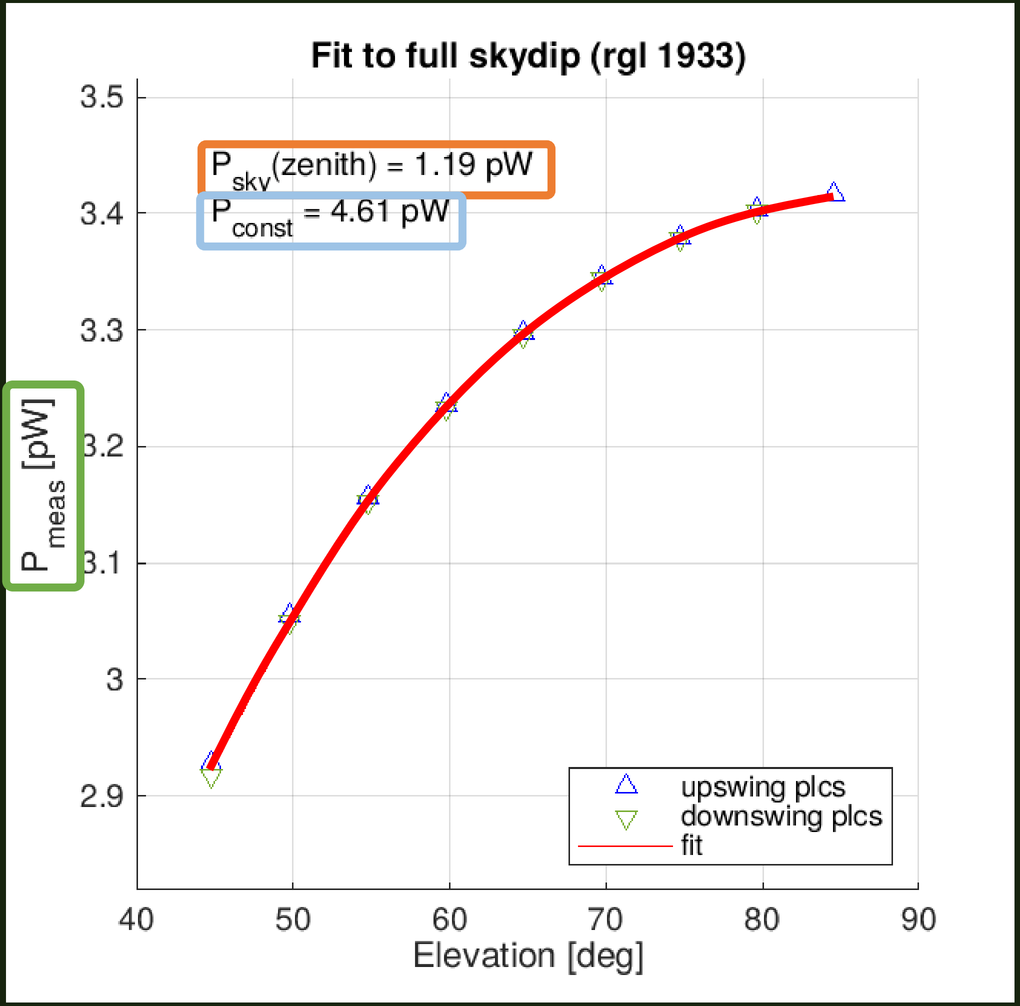
Optical Tests at Home

Optical Tests on BICEP3

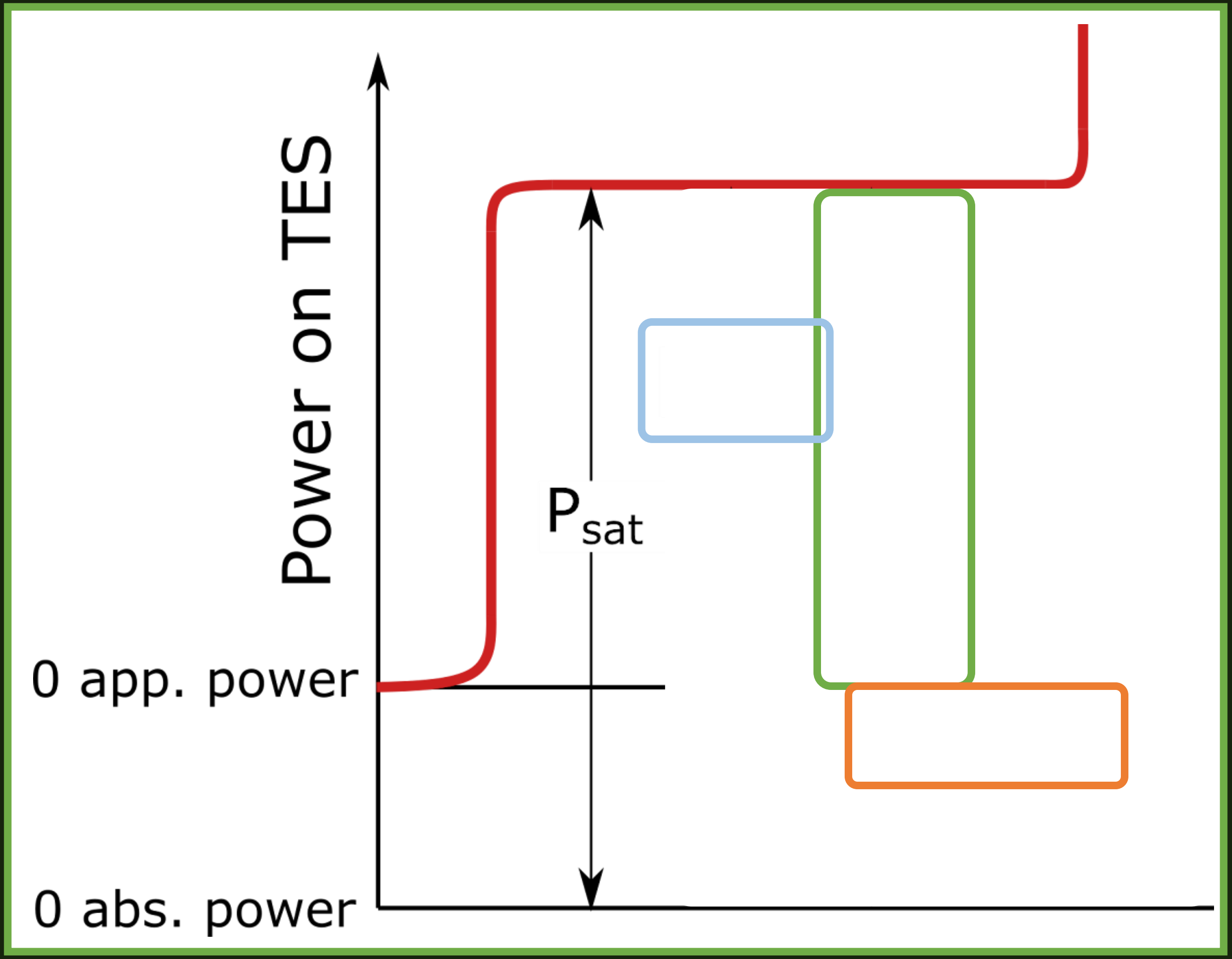
Insertion loss

Elevation vs loading

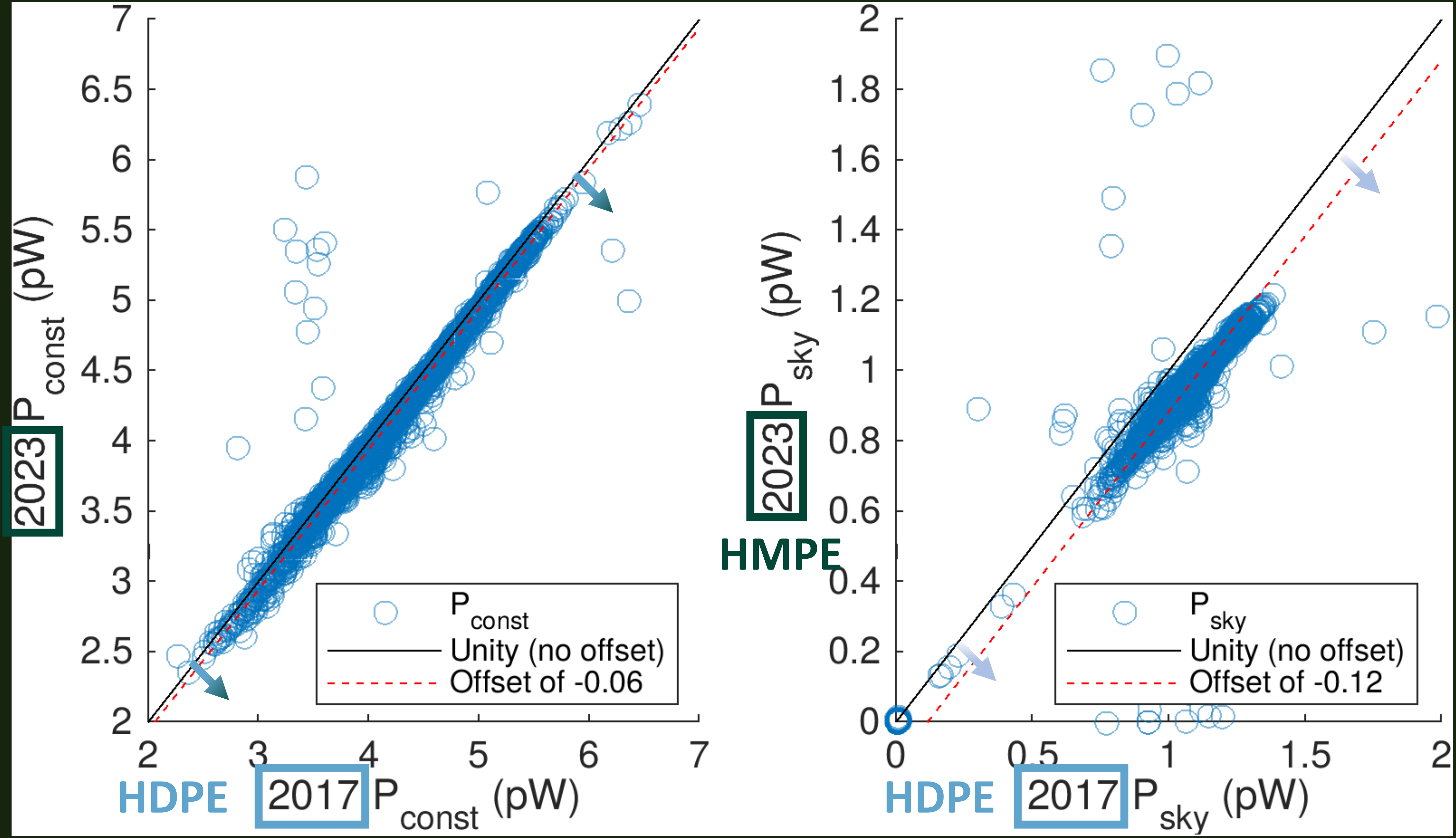
What was the change in total optical loading between years?



Fit to full skydip (rgl 1933)
P_sky(zenith) = 1.19 pW
P_const = 4.61 pW
P_meas [pW]
3.5
3.4
3.3
3.2
3.1
3
2.9
40
50
60
70
80
90
Elevation [deg]
upswing plcs
downswing plcs
fit



Power on TES
P_sat
0 app. power
0 abs. power

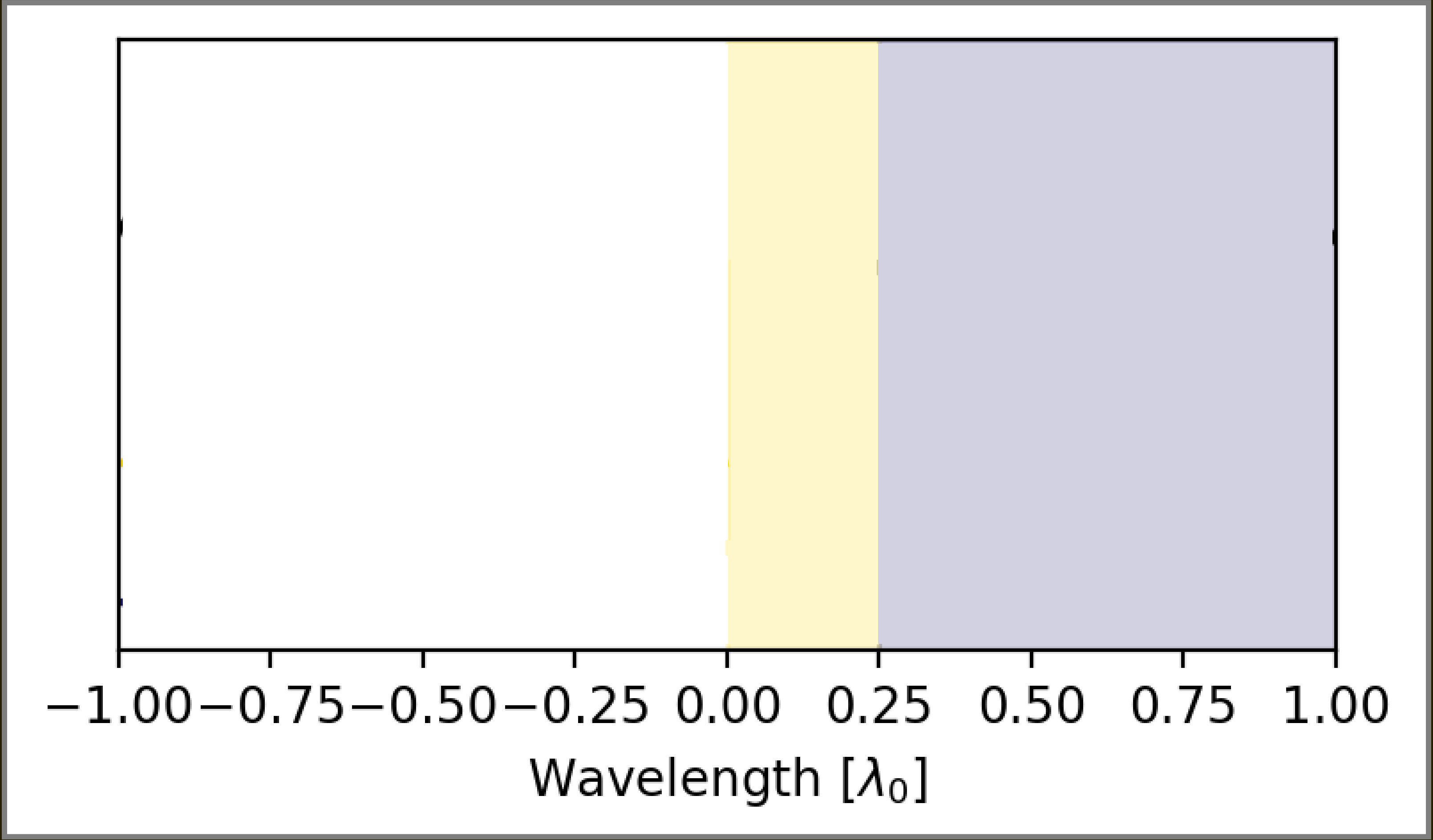


2023 P_const (pW)
HDPE 2017 P_const (pW)
P_const
Unity (no offset)
Offset of -0.06
2023 P_sky (pW)
HMPE
HDPE 2017 P_sky (pW)
P_sky
Unity (no offset)
Offset of -0.12

So we’ve solved all these problems…

… there’s one more

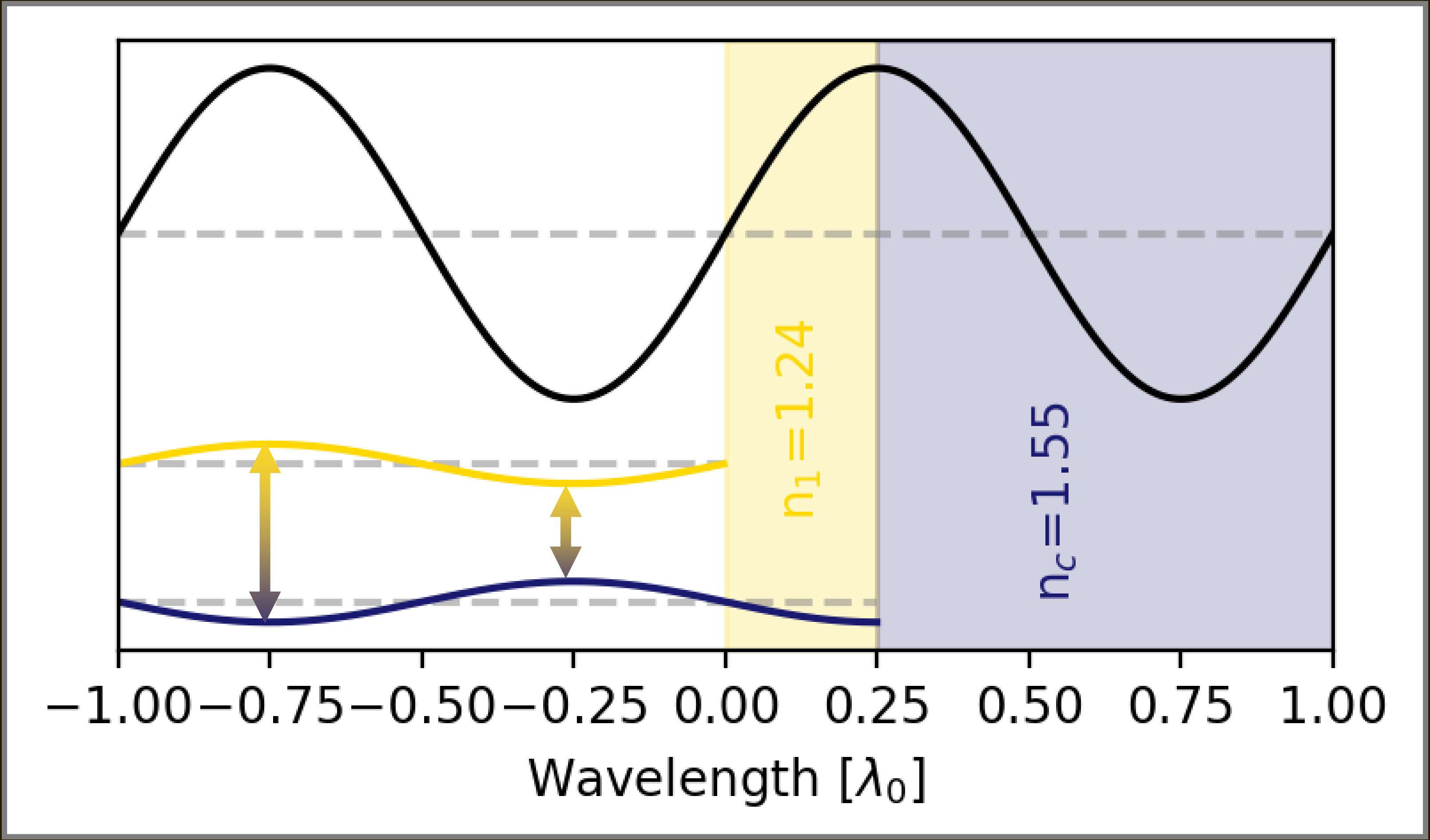
Light is a wave so when it enters a material…

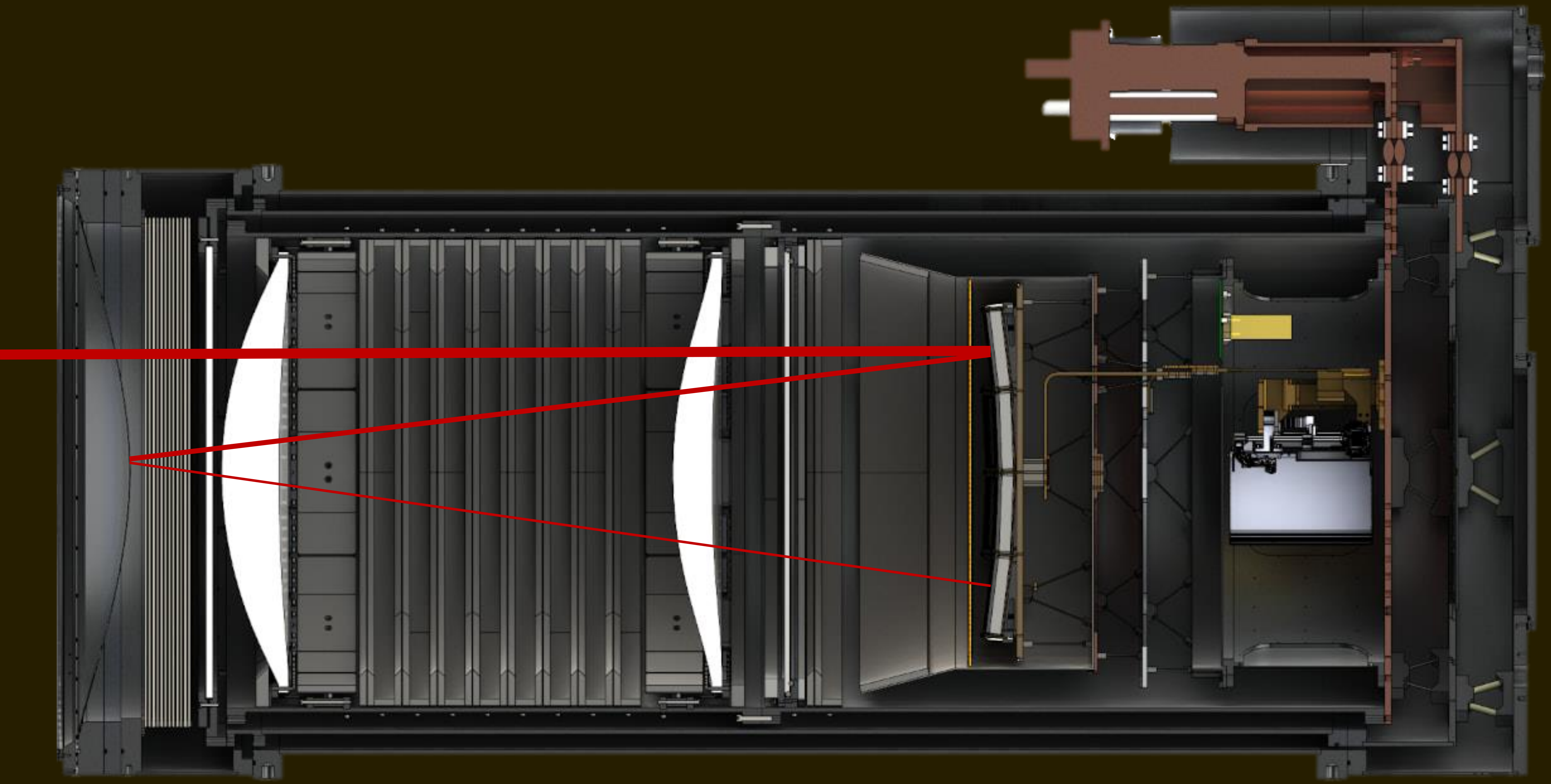


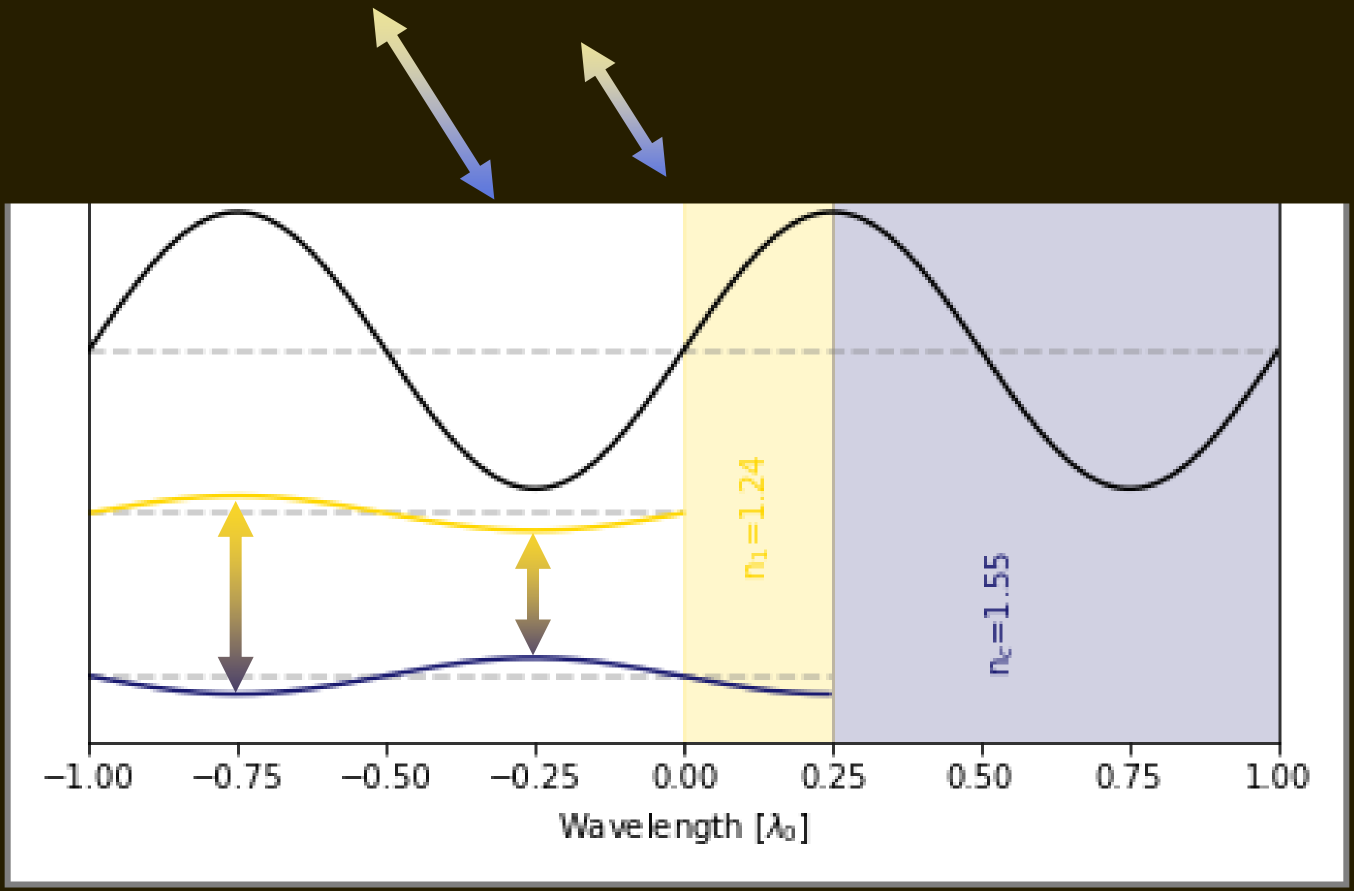
Anti-reflection layer

Right properties:

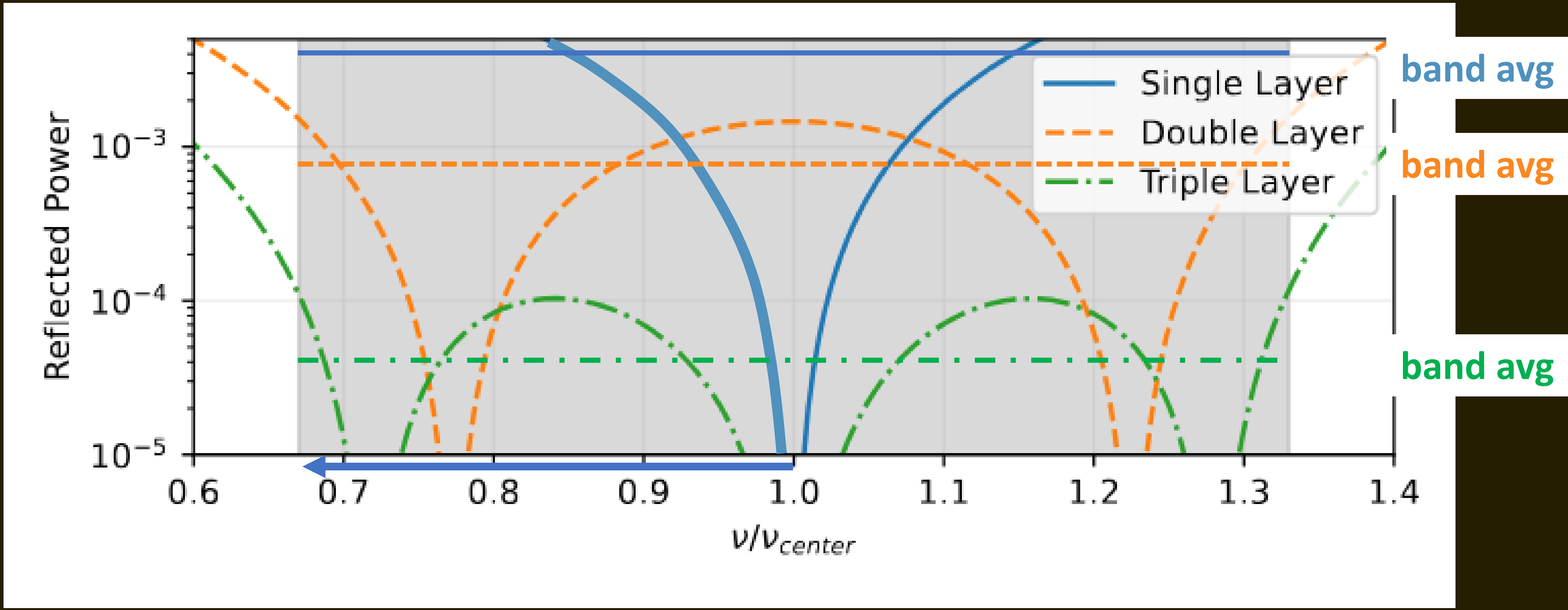
- $n_1 = \sqrt{n_c}$
- $t_1 = \frac{1}{4}\lambda$

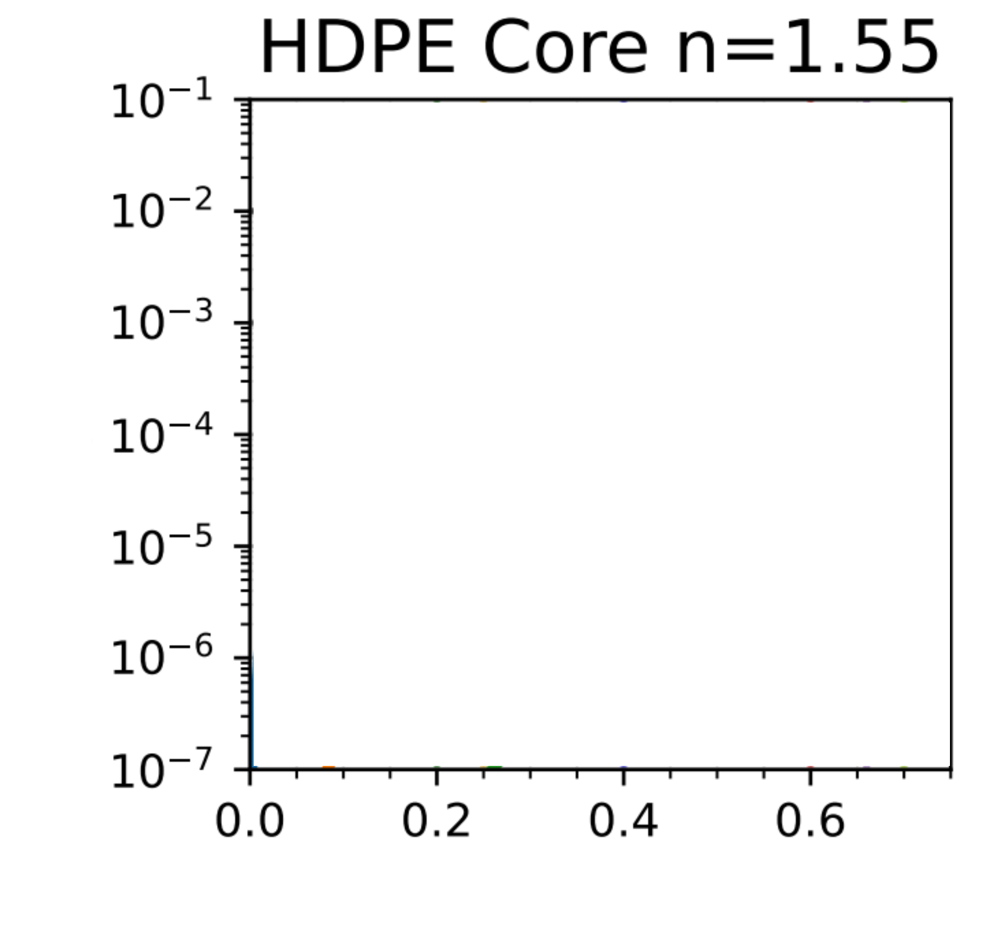


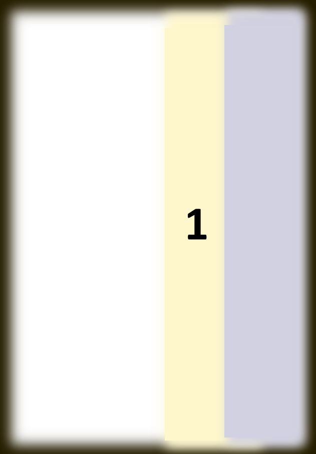




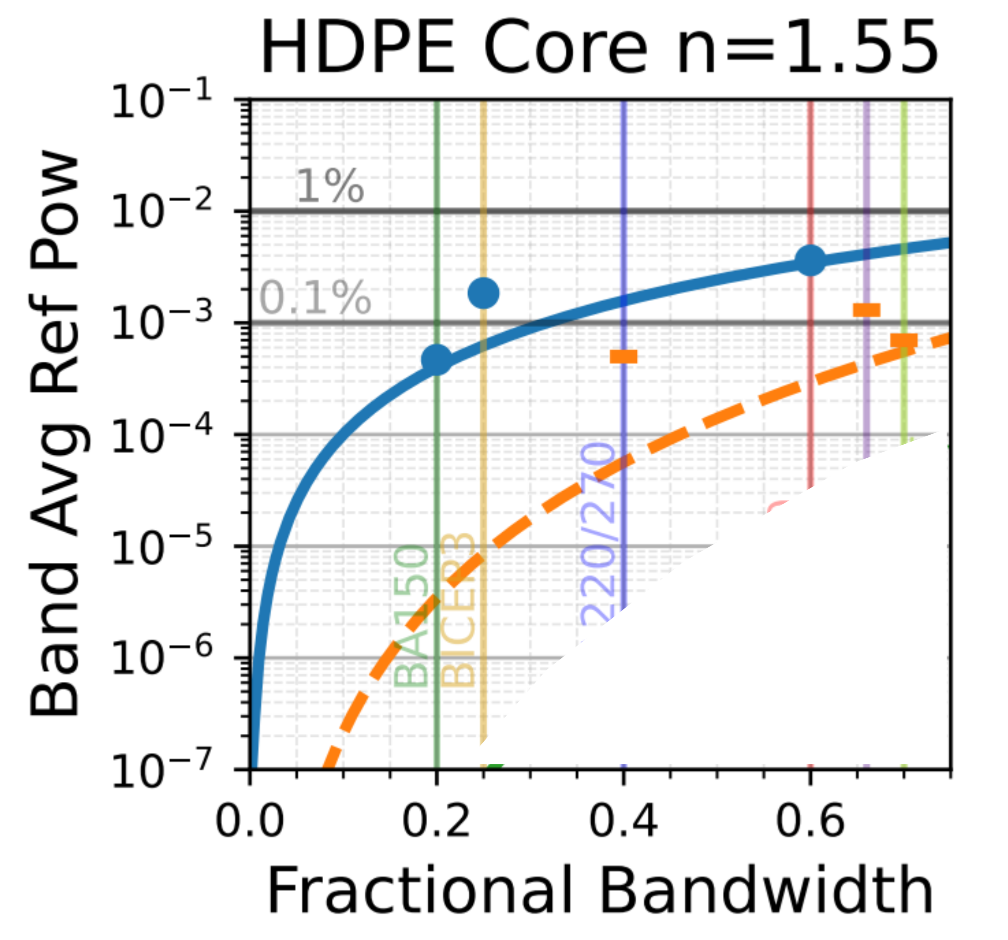
n1=1.24
nc=1.55
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
Wavelength [λ0]

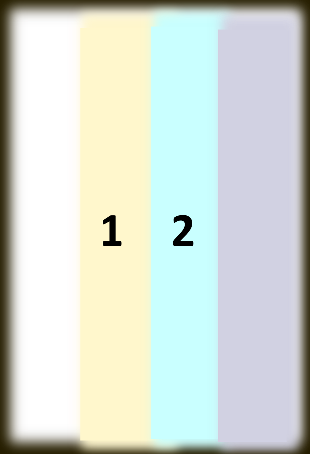

Reflected Power
10^{-3}
10^{-4}
10^{-5}
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
ν/ν_{center}
Single Layer
Double Layer
Triple Layer
band avg
band avg
band avg





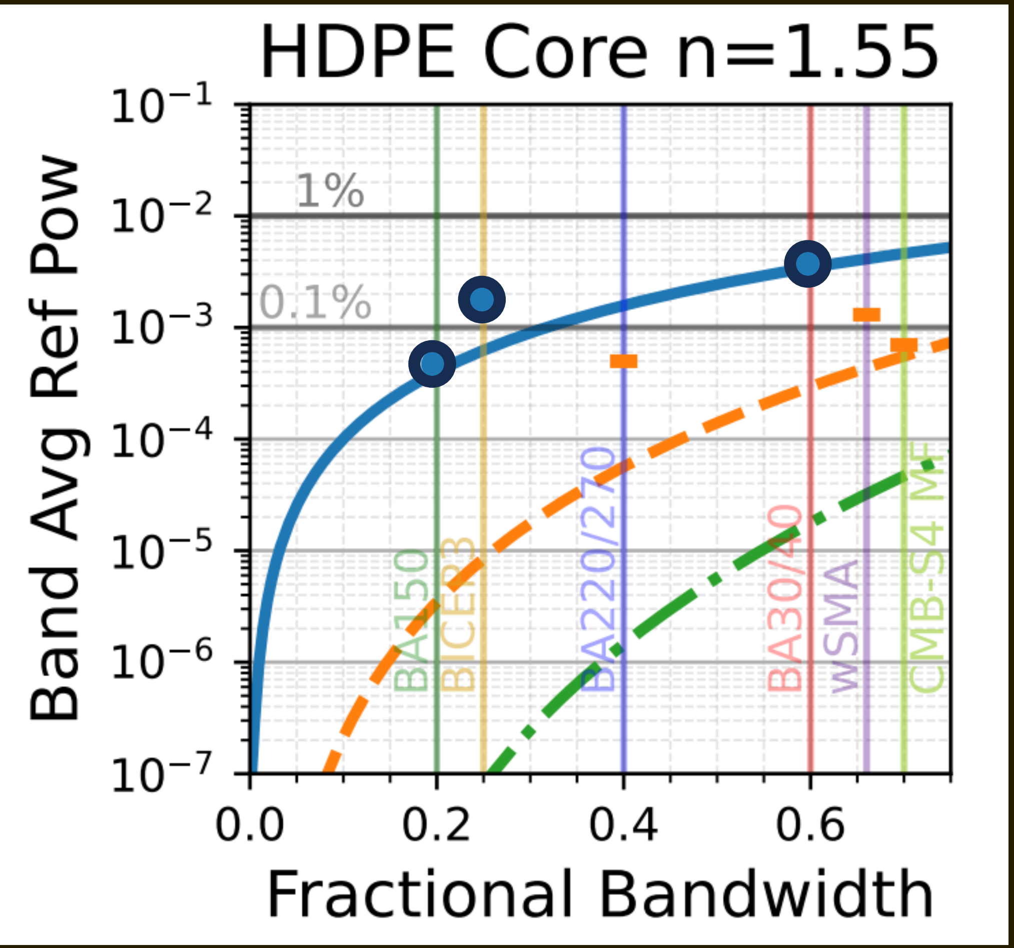
Single Layer

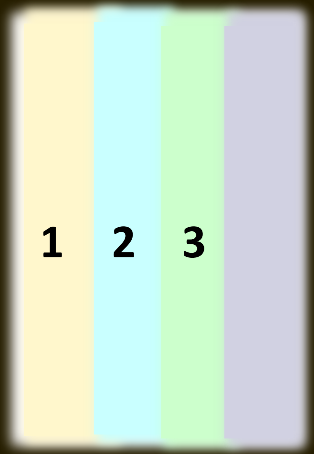




Single Layer Double Layer

Achieved AR Coats Close to Ideal!

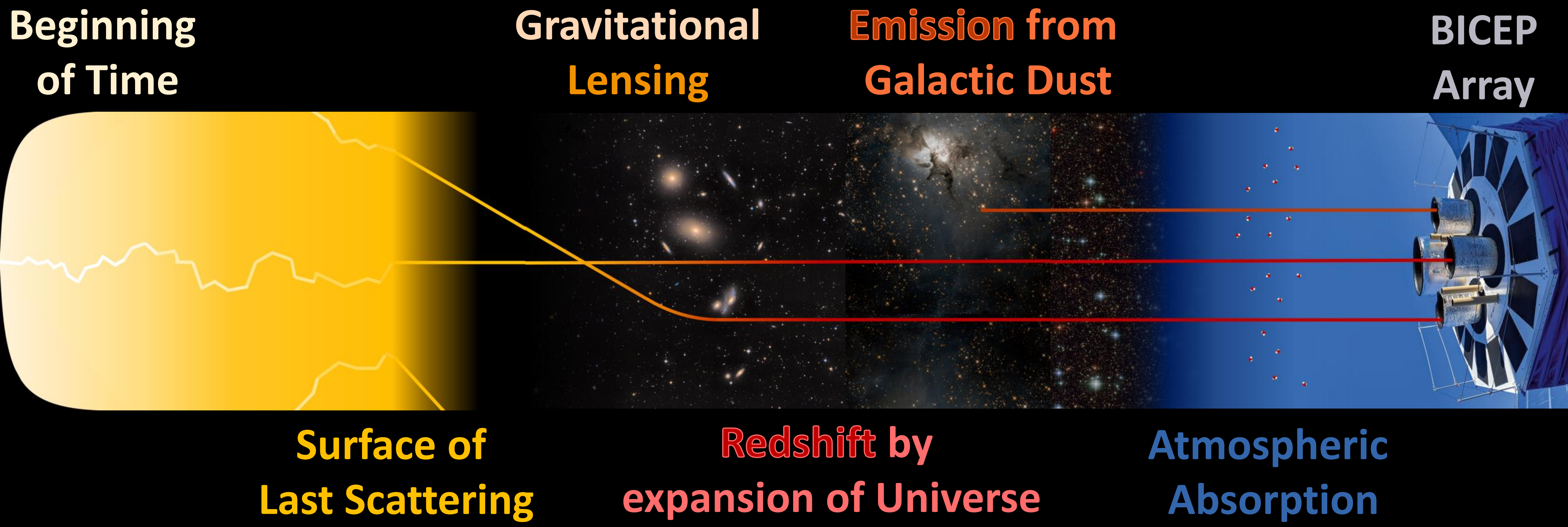




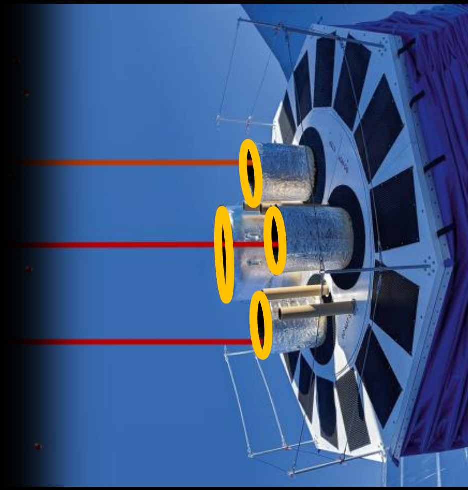
Single Layer

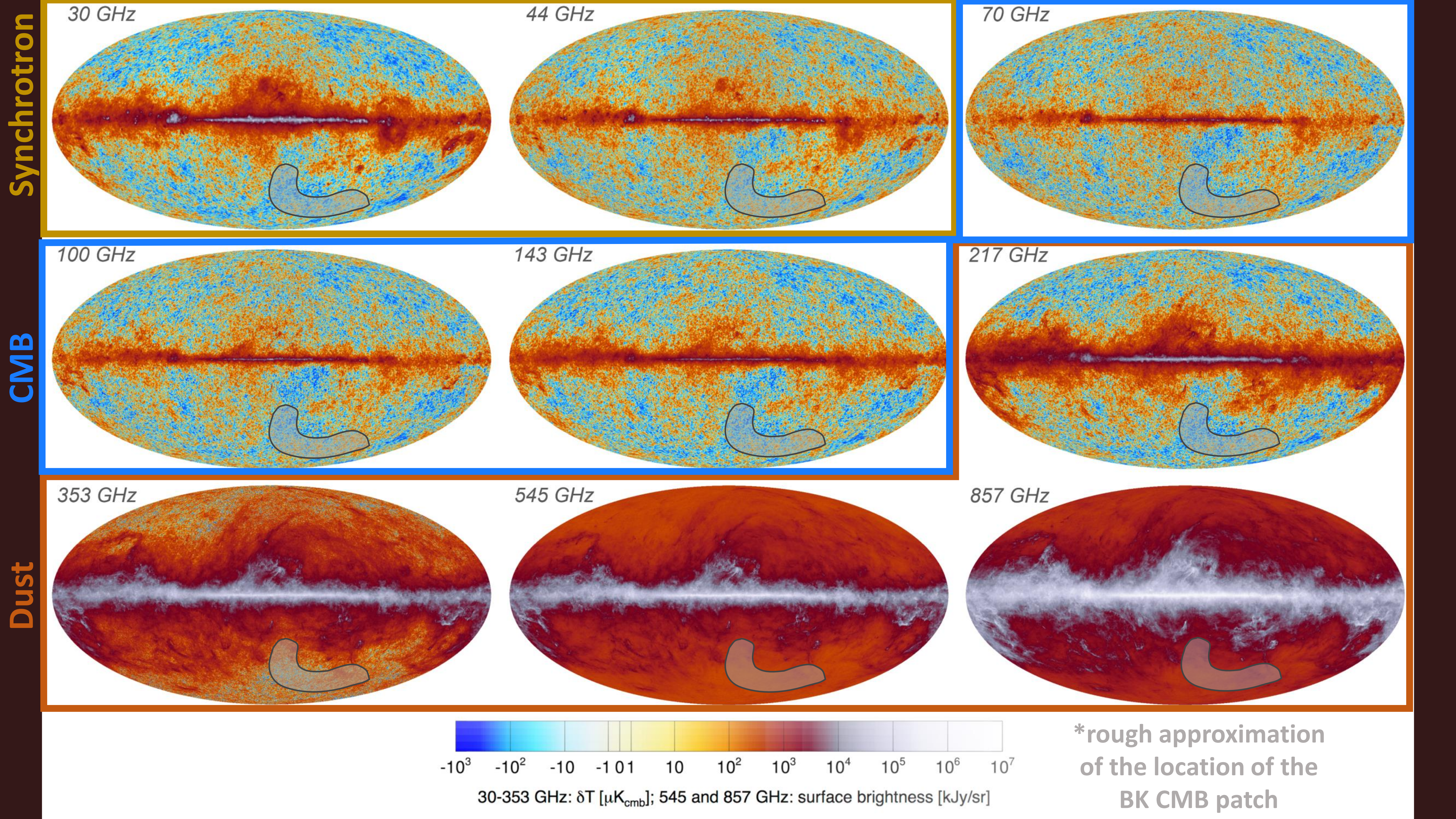
Double Layer

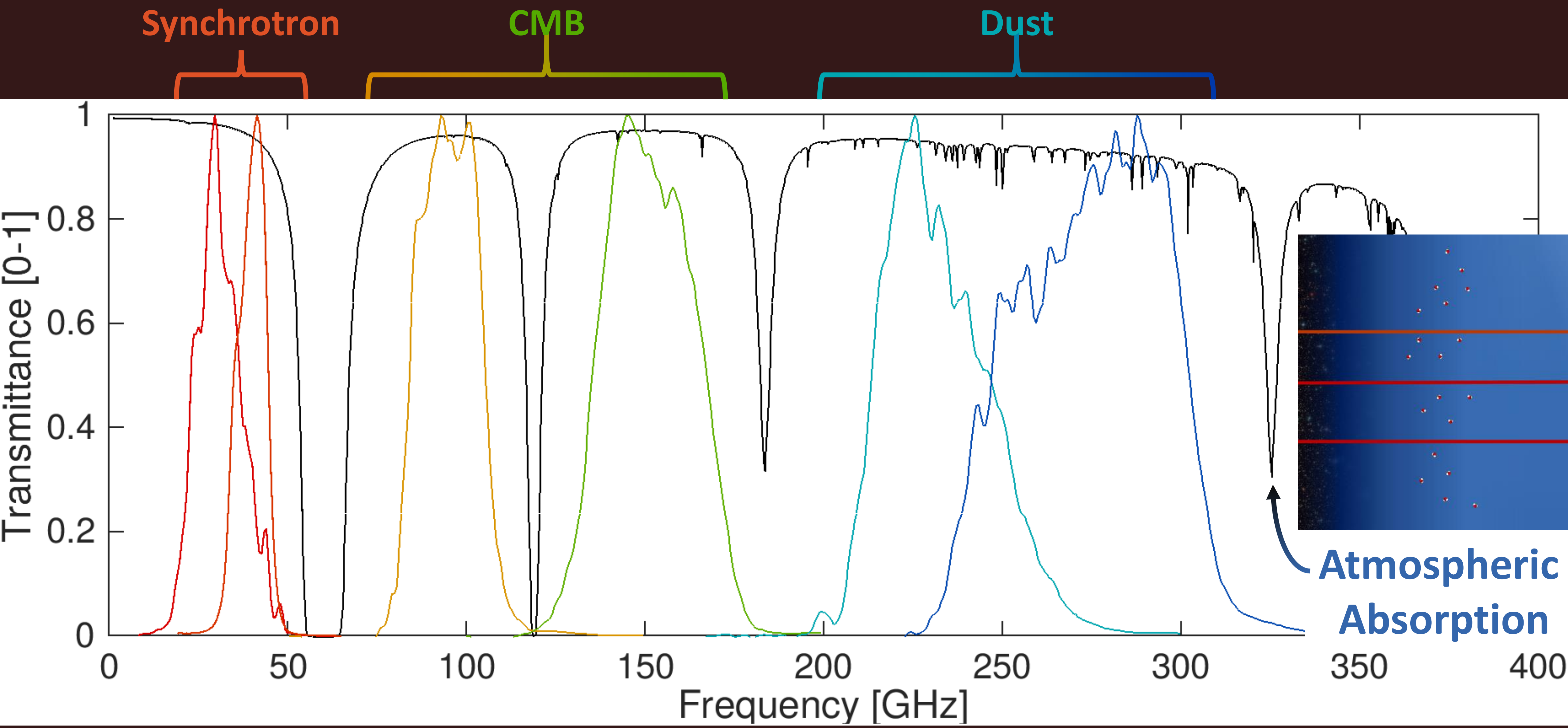
Triple Layer


Beginning of Time
Gravitational Lensing
Emission from Galactic Dust
BICEP Array
Surface of Last Scattering
Redshift by expansion of Universe
Atmospheric Absorption

BICEP Array




Synchrotron
CMB
Dust
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6 10^7
30-353 GHz: δT [μK_cmb]; 545 and 857 GHz: surface brightness [kJy/sr]
*rough approximation of the location of the BK CMB patch

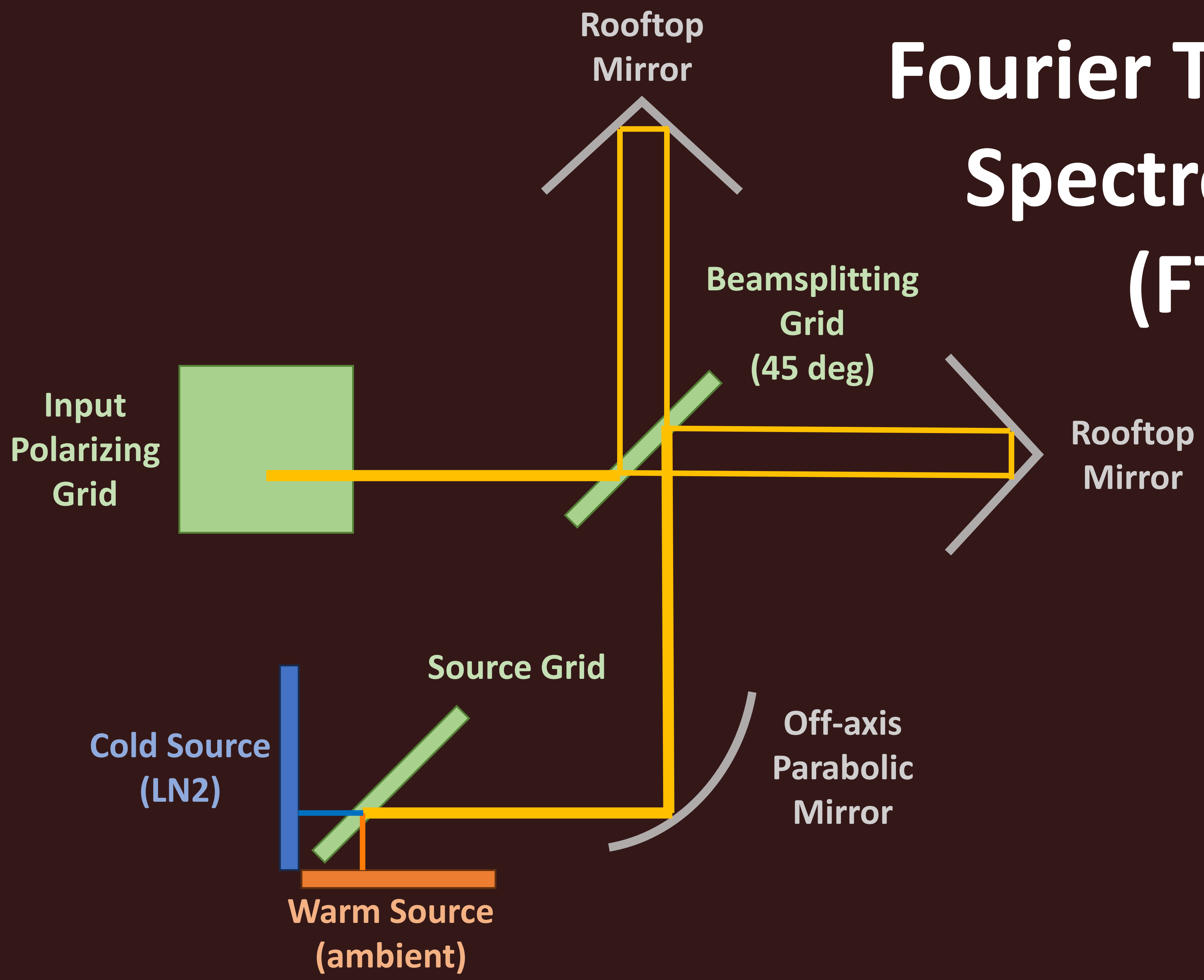

Synchrotron
CMB
Dust
Transmittance [0-1]
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
Frequency [GHz]
Atmospheric
Absorption

Since we want very high precision,

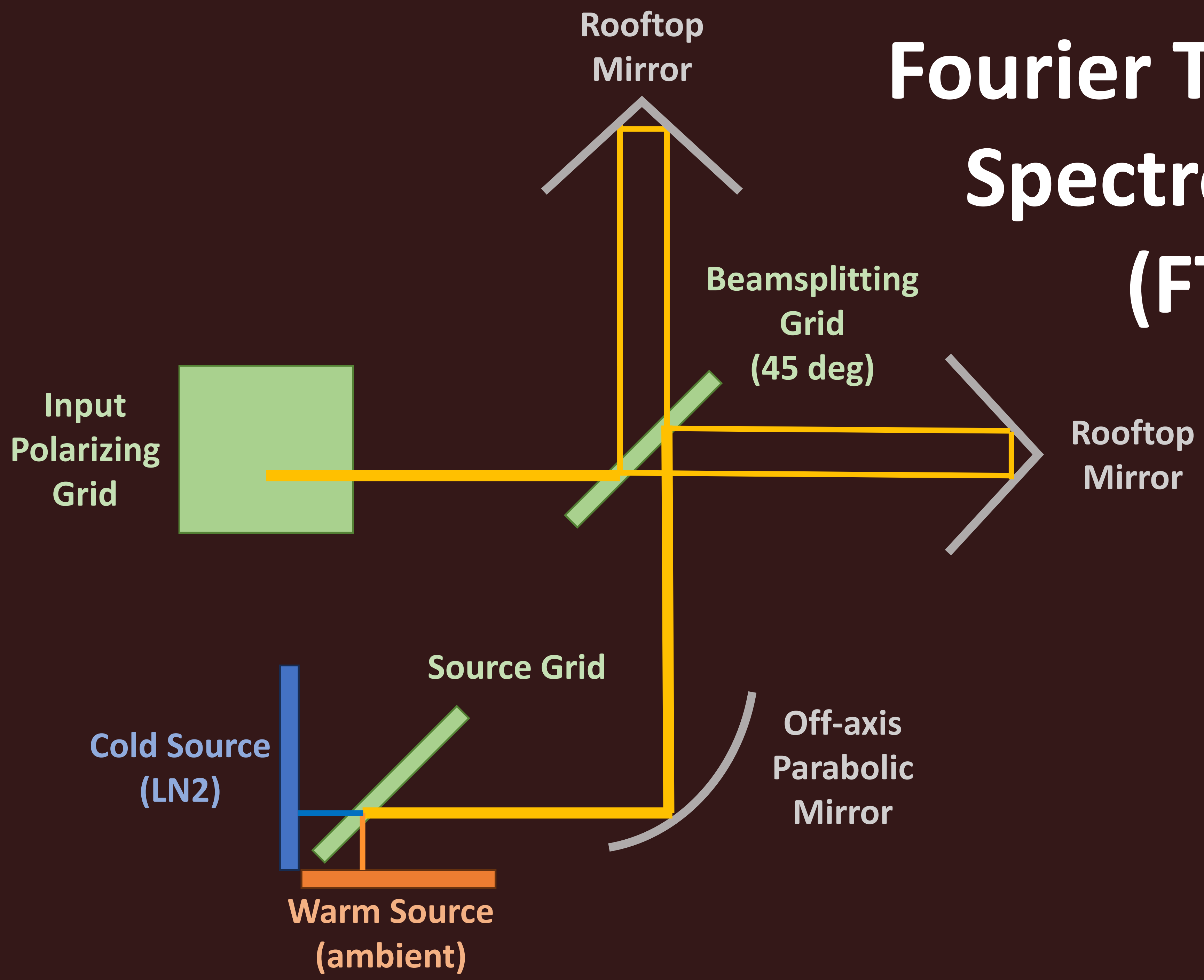
$\sigma(r) = 0.003$

we need to consider the uncertainties of the calibrators!

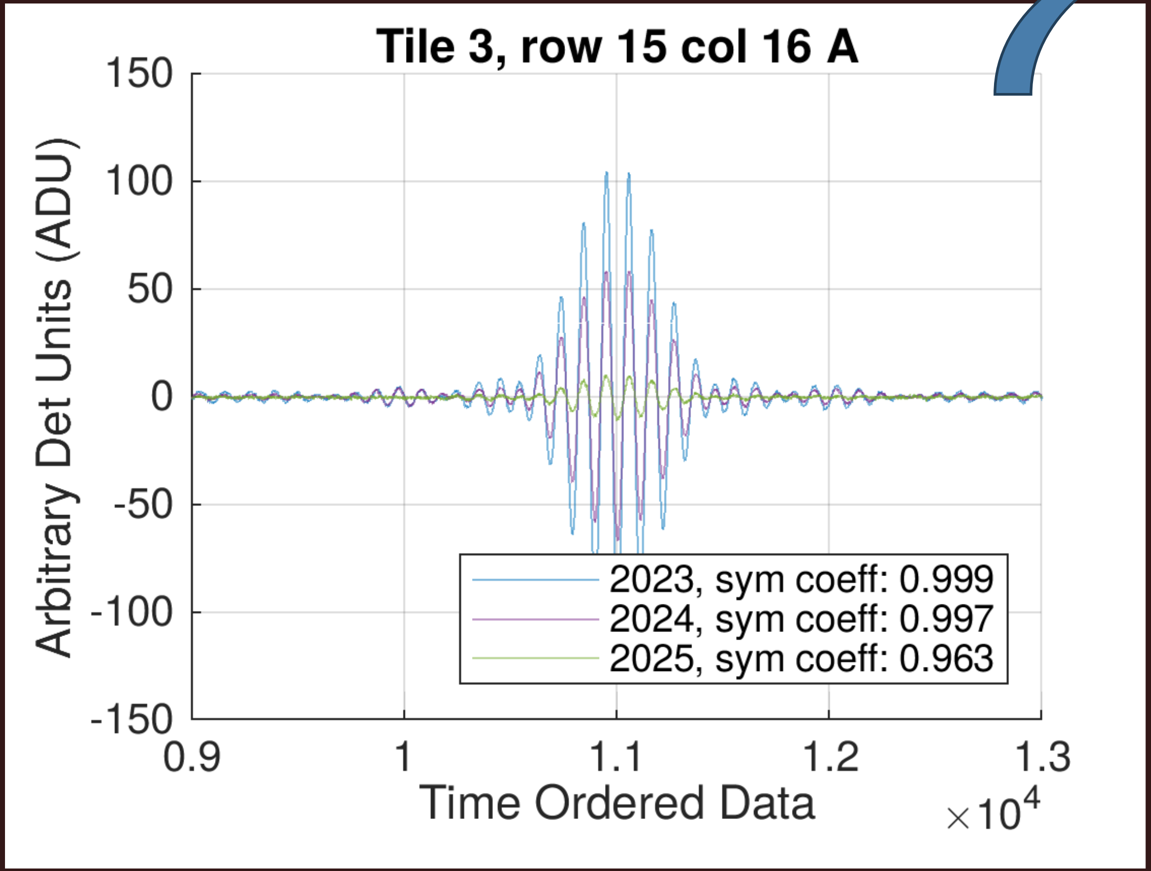
Fourier Transform Spectrometer (FTS)

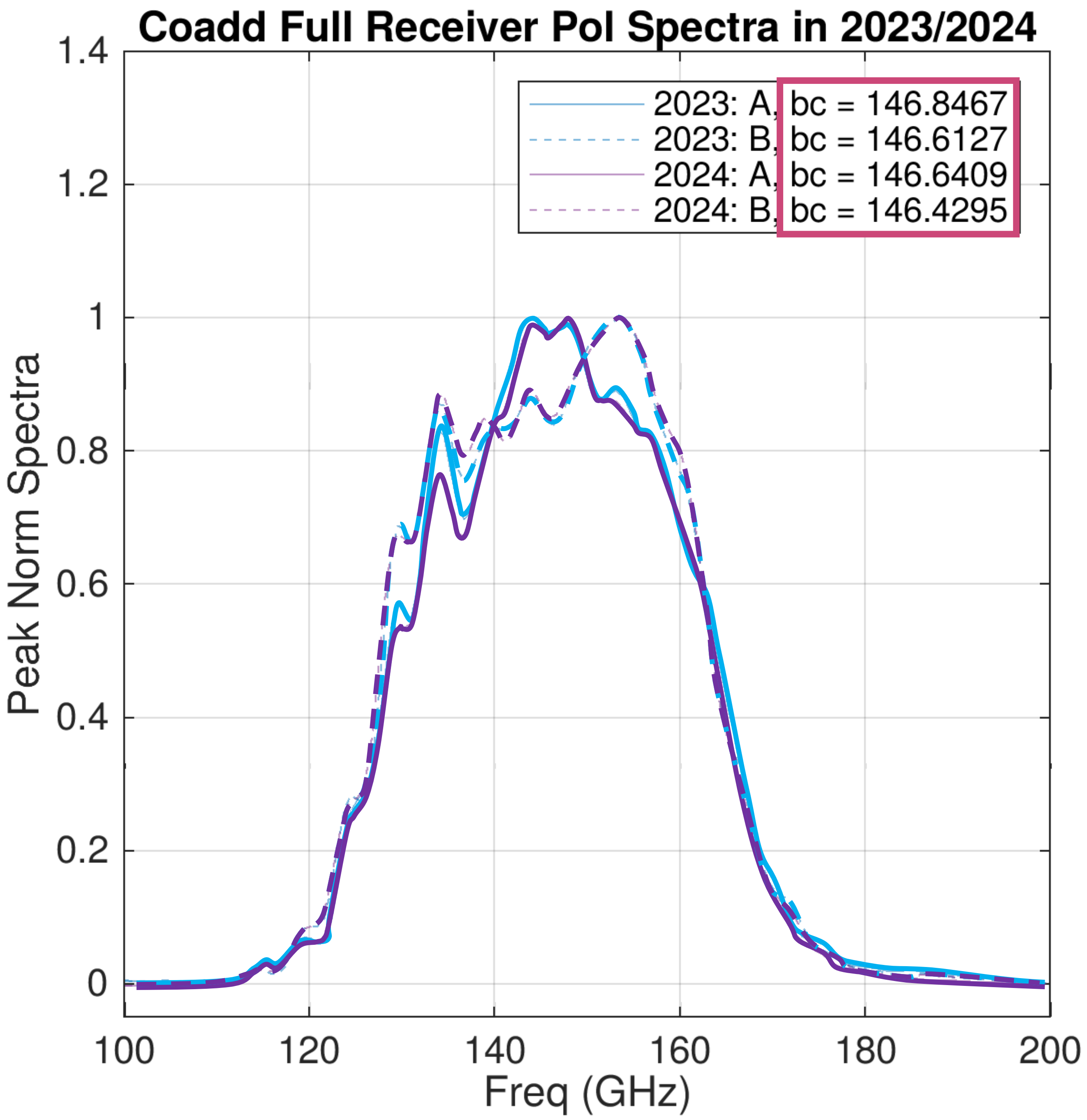


Fourier Transform Spectrometer (FTS)

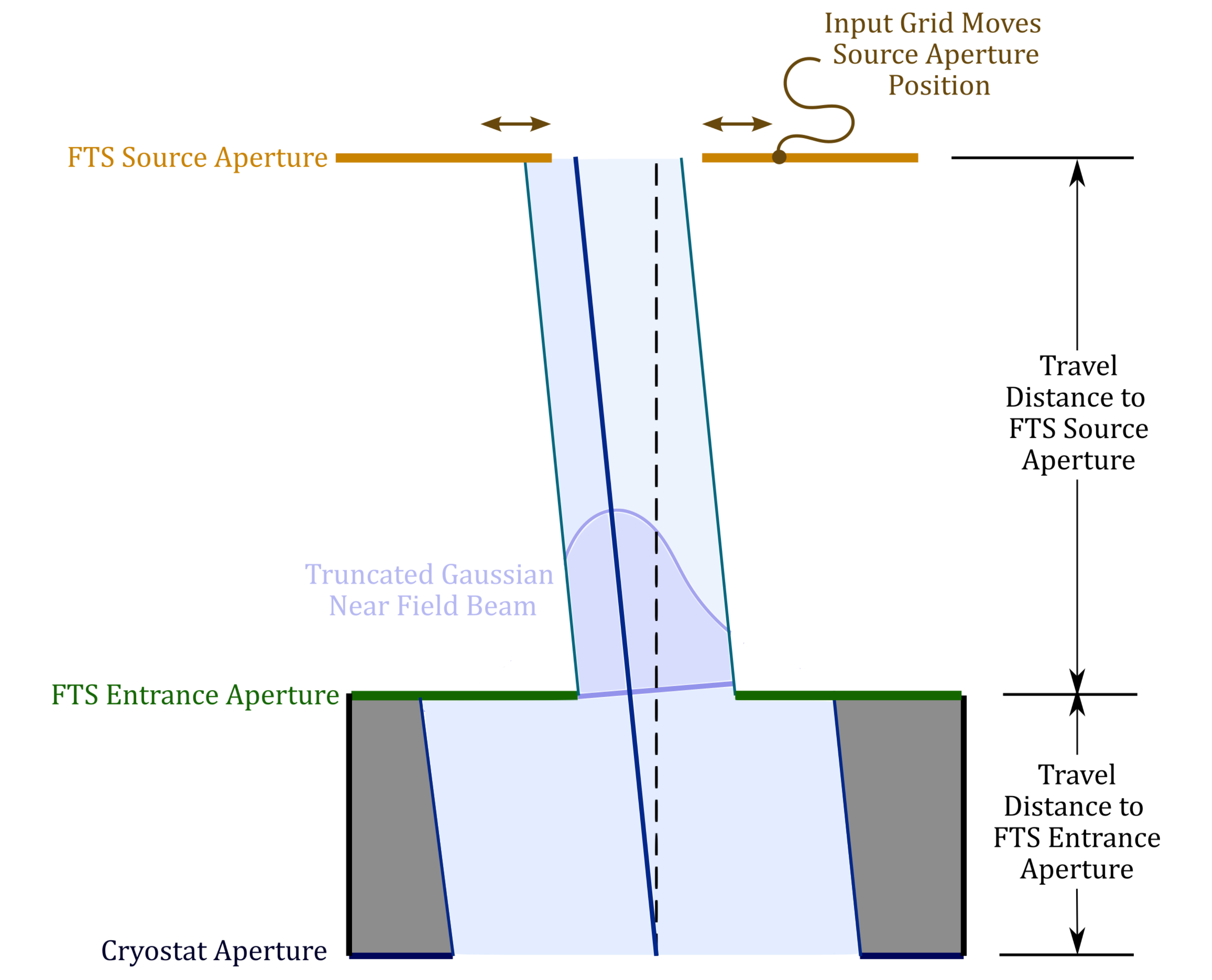


Fourier
Transform

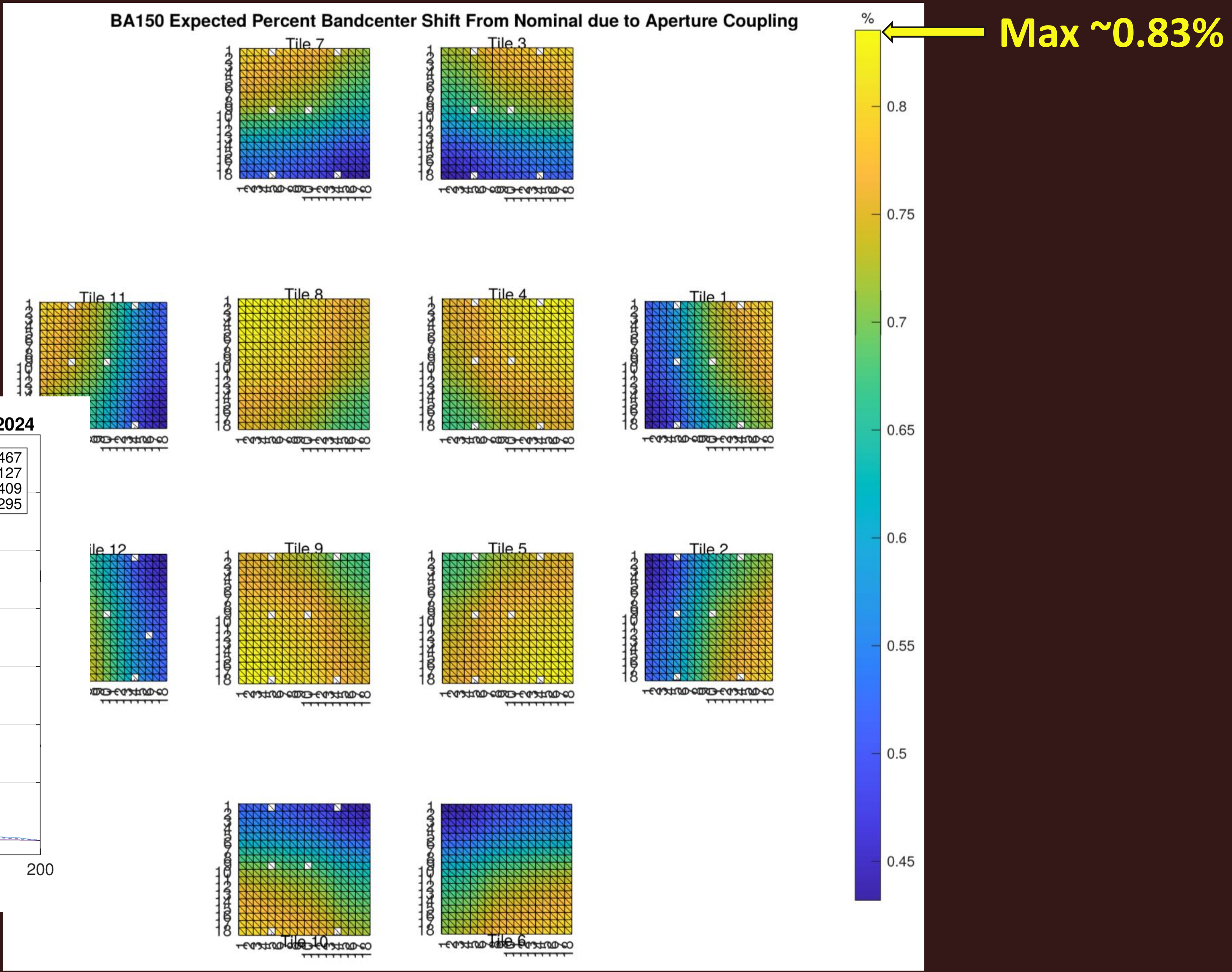


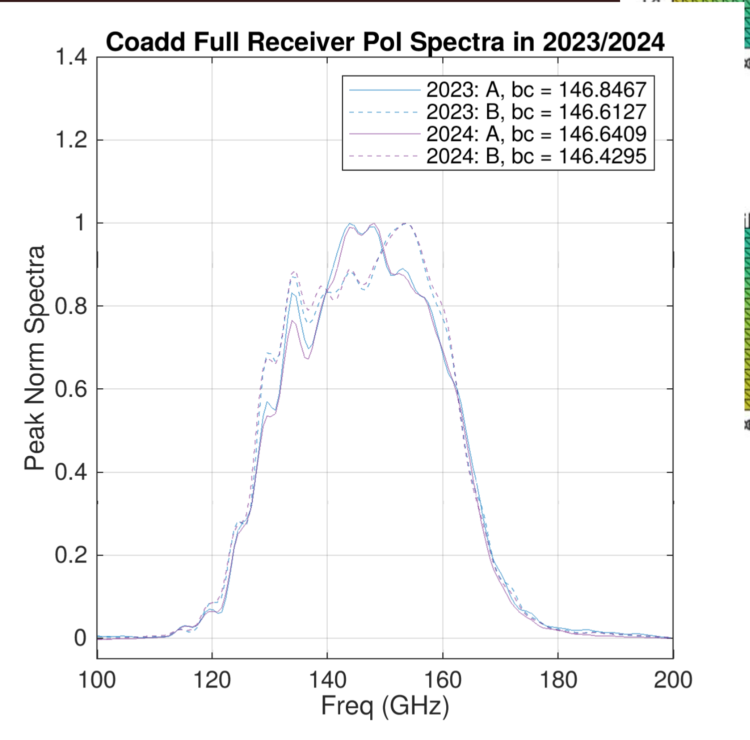


Coadd Full Receiver Pol Spectra in 2023/2024
2023: A, bc = 146.8467
2023: B, bc = 146.6127
2024: A, bc = 146.6409
2024: B, bc = 146.4295
Peak Norm Spectra
Freq (GHz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
100
120
140
160
180
200


Input Grid Moves
Source Aperture
Position
FTS Source Aperture
Travel
Distance to
FTS Source
Aperture
Truncated Gaussian
Near Field Beam
FTS Entrance Aperture
Travel
Distance to
FTS Entrance
Aperture
Cryostat Aperture

Are we right about the bandcenter? What happens if we're wrong?





8 Parameter Model to Predict Polarized Angular Power

r
Tensor to scalar ratio (primordial)

A_d
Amplitude of the dust

A_s
Amplitude of the synch

r is what we are looking for!

A_d evaluated at $\ell \sim 80$ and 353 GHz

A_s evaluated at $\ell \sim 80$ and 23 GHz

8 Parameter Model to Predict Polarized Angular Power

r
Tensor to scalar ratio (primordial)

A_d
Amplitude of the dust

A_s
Amplitude of the synch

β_d
Freq spectral index of the dust spectrum

β_s
Freq spectral index of the synch spectrum

$$\nu^{\beta_d} B(\nu, T_d)$$

$$\nu^{\beta_s}$$

8 Parameter Model to Predict Polarized Angular Power

r
Tensor to scalar ratio (primordial)

A_d
Amplitude of the dust

A_s
Amplitude of the synch

$\mathcal{D}_d \propto \ell^{\alpha_d}$

$\mathcal{D}_s \propto \ell^{\alpha_s}$

β_d
Freq spectral index of the dust spectrum

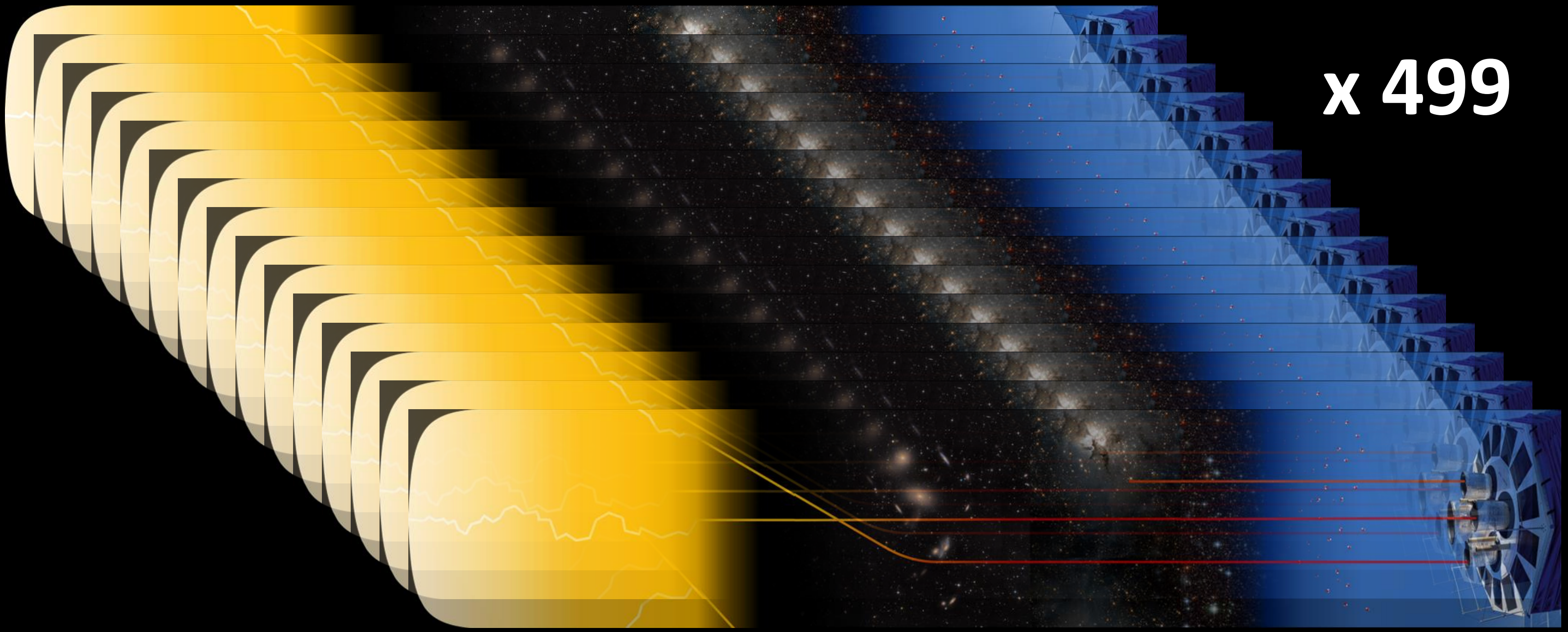
β_s
Freq spectral index of the synch spectrum

α_d
Spatial spectral index of the dust spectrum

α_s
Spatial spectral index of the synch spectrum

8 Parameter Model to Predict Polarized Angular Power

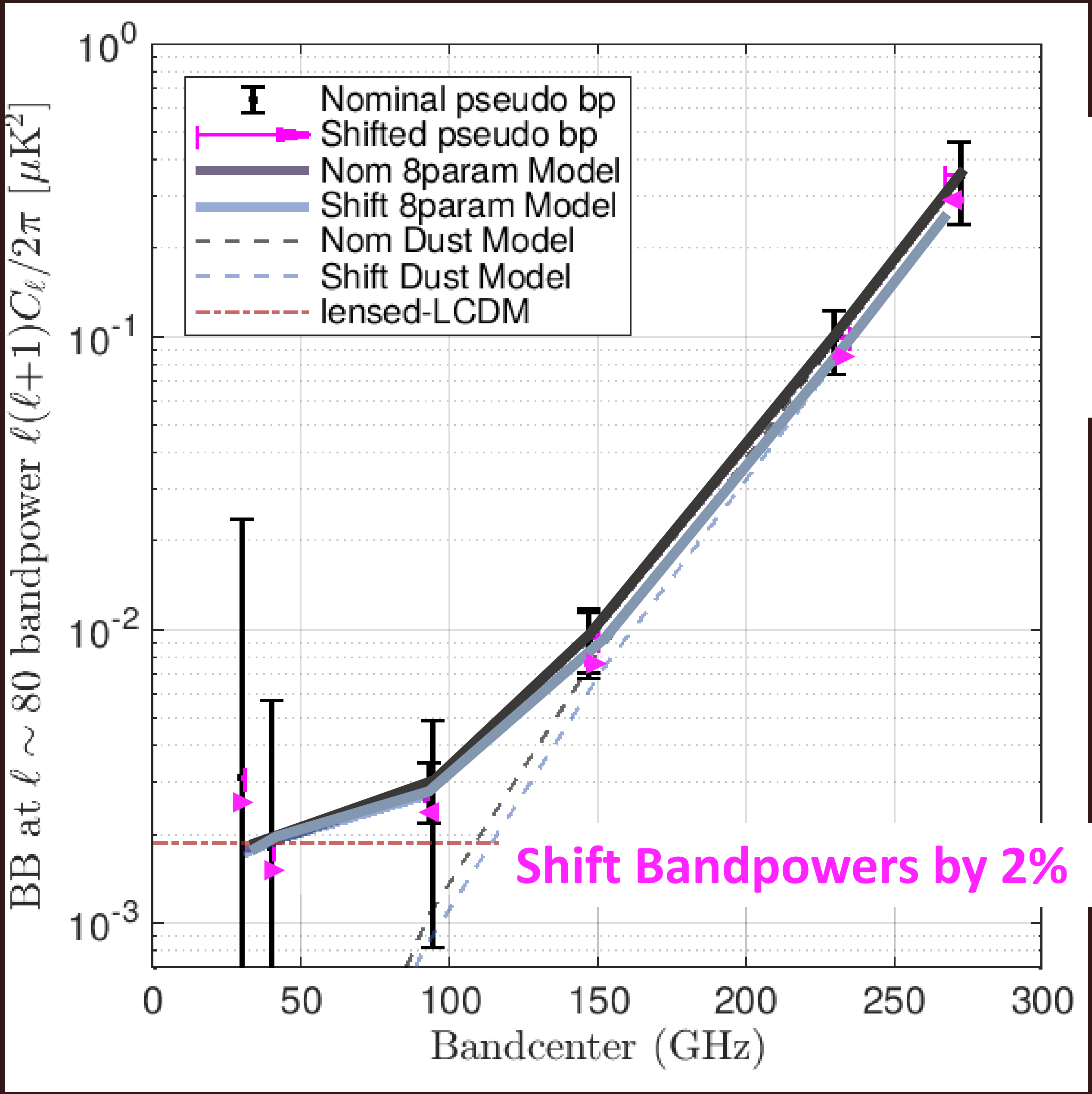
r Tensor to scalar ratio (primordial)	A_d Amplitude of the dust	A_s Amplitude of the synch	ϵ Spatial correlation b/w dust and synch
β_d Freq spectral index of the dust spectrum	β_s Freq spectral index of the synch spectrum	α_d Spatial spectral index of the dust spectrum	α_s Spatial spectral index of the synch spectrum



x 499 with slight variations of angular bandpowers based on covariance matrix

Then we find the parameters that generate the maximum likelihood for each realization of the bandpowers

Then the exact same parameter search on the same set of bandpower realizations with shifted bandpasses



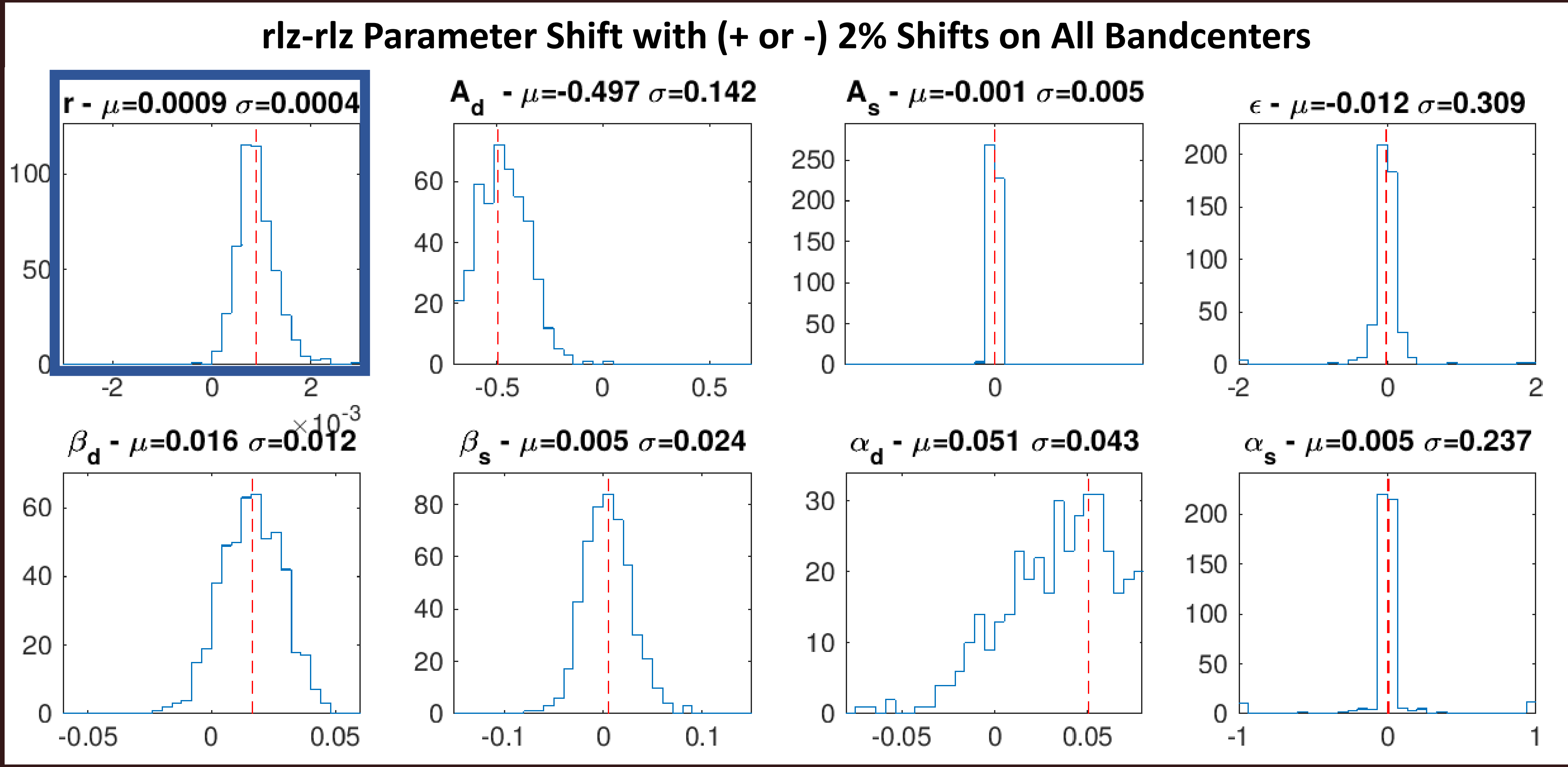
Bandpowers at nominal bandcenters

Bandpowers at shifted bandcenters

Shift Bandpowers by 2%

Change in Parameters due to Shifted Bandcenters

If σ(r)= 0.003 then Δr ~0.001 is okay … for now



Thin Windows Work!
Conducted many tests on laminate windows

Microwave AR Coats are Difficult!
But we are achieving AR coats close to the ideal

Spectroscopy is Hard!
And in the future we need to reduce our uncertainties