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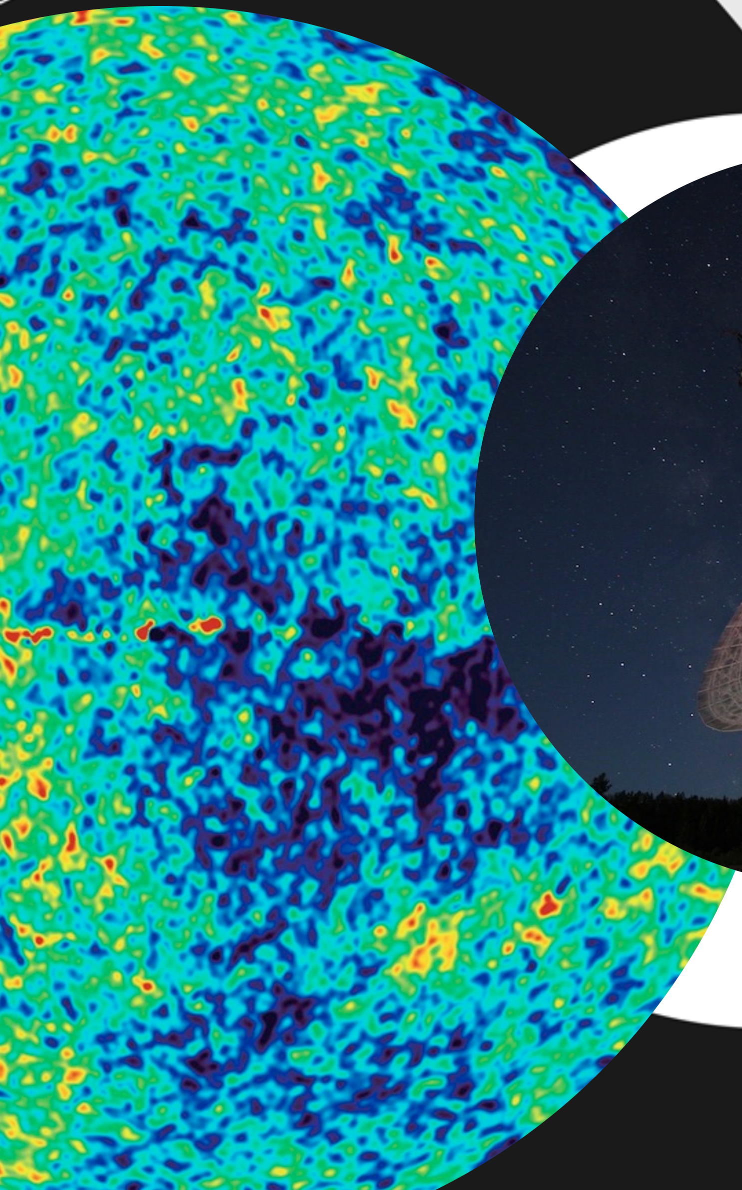
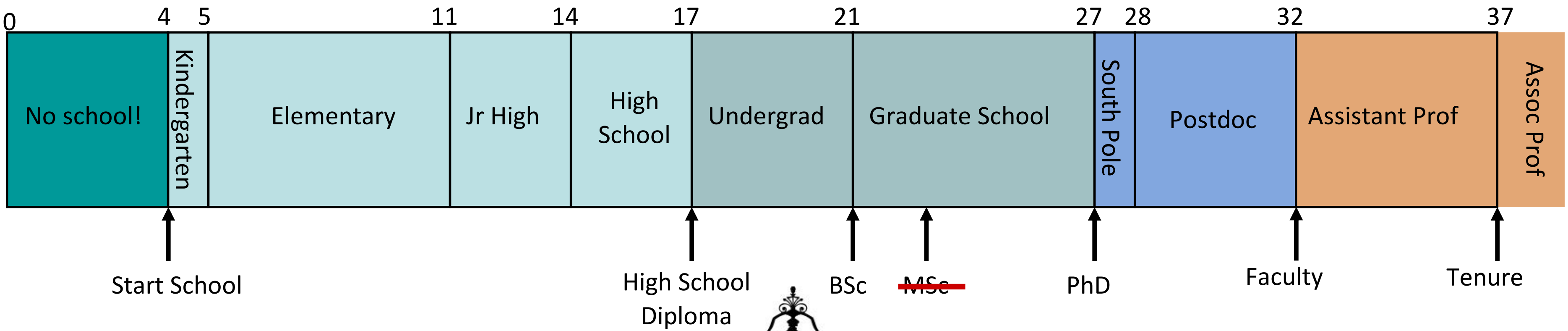


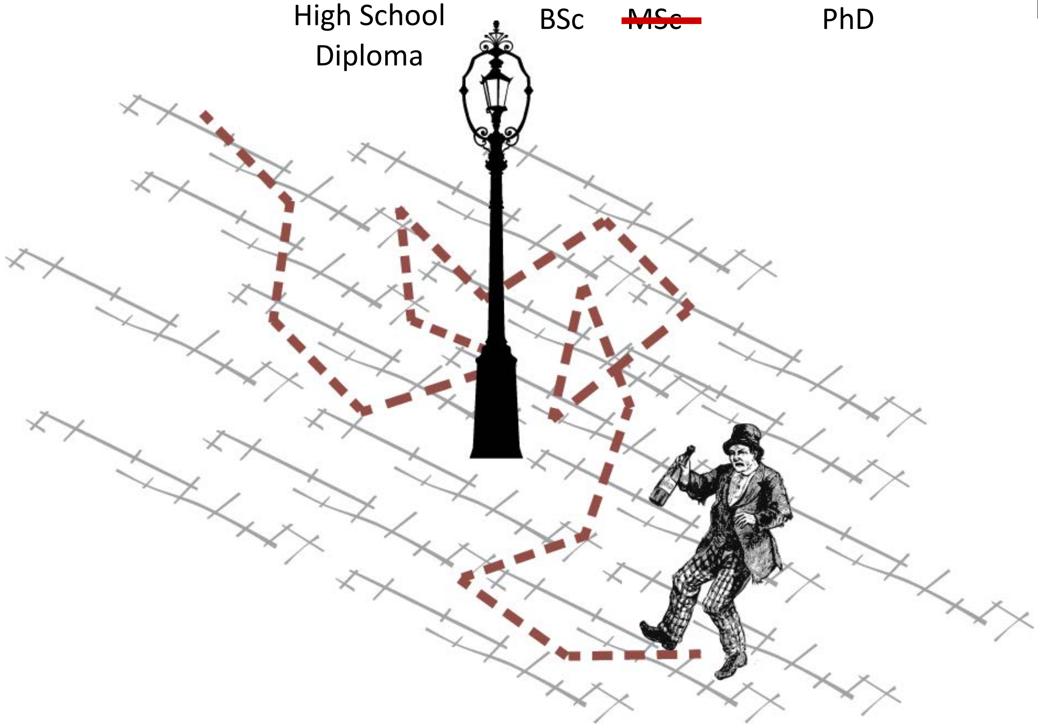
PROPERTIES AND DETECTION OF RADIO AND MICROWAVE LIGHT

Keith Vanderlinde
Assoc. Professor

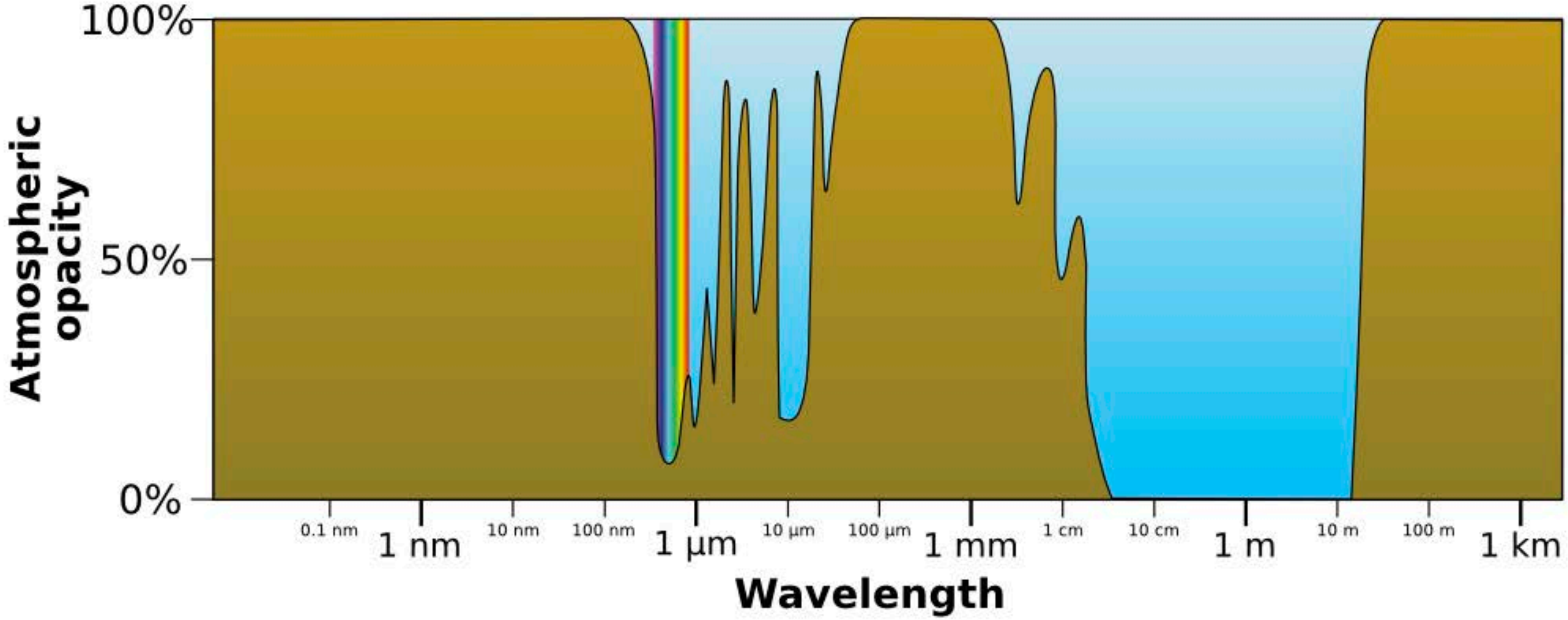
Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

How I got here…





Atmopsheric Windows



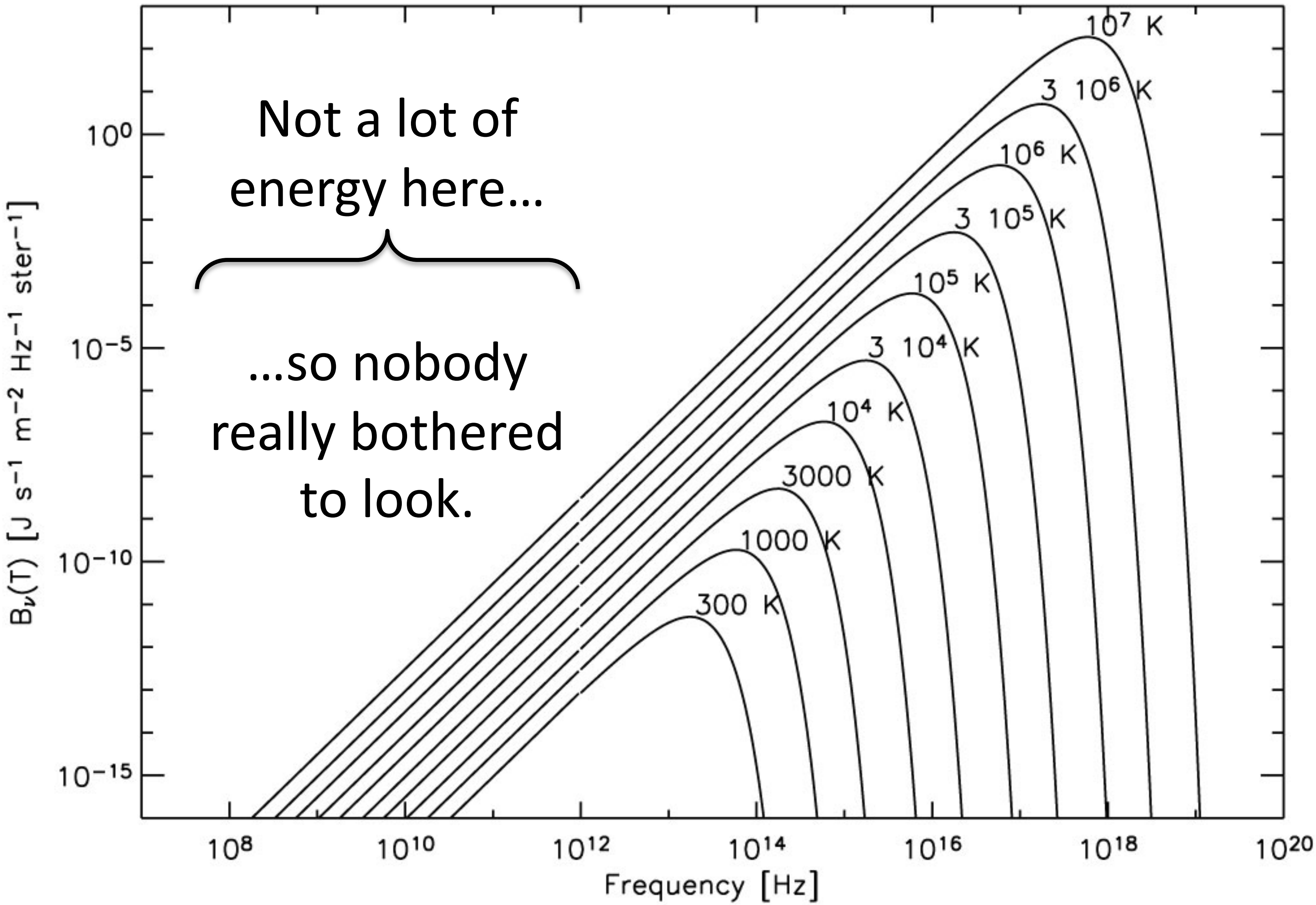
1mm – 10m
(300GHz – 30MHz)

Excellent seeing over a huge band!

Blackbody Radiation

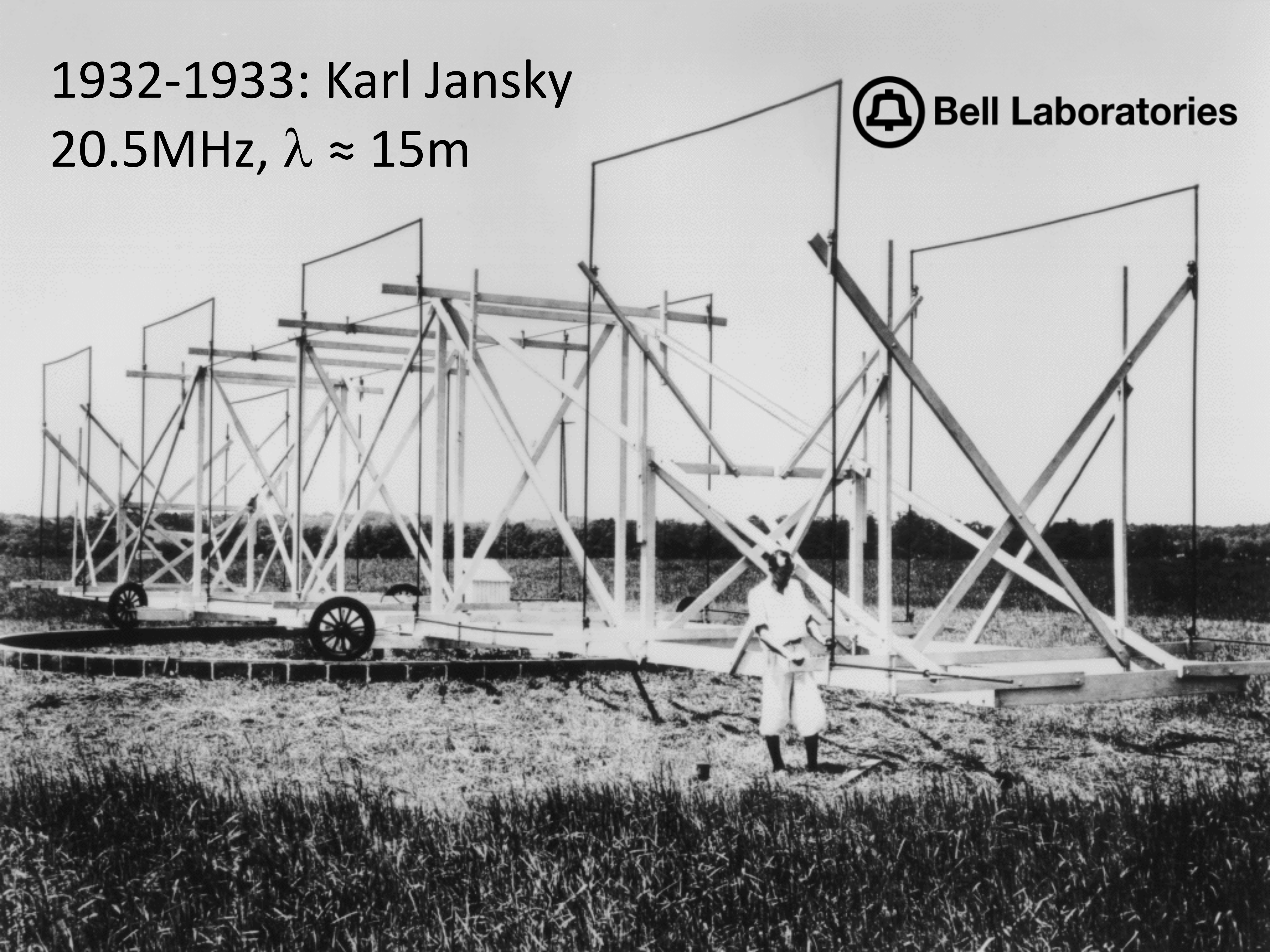
Not a lot of energy here…

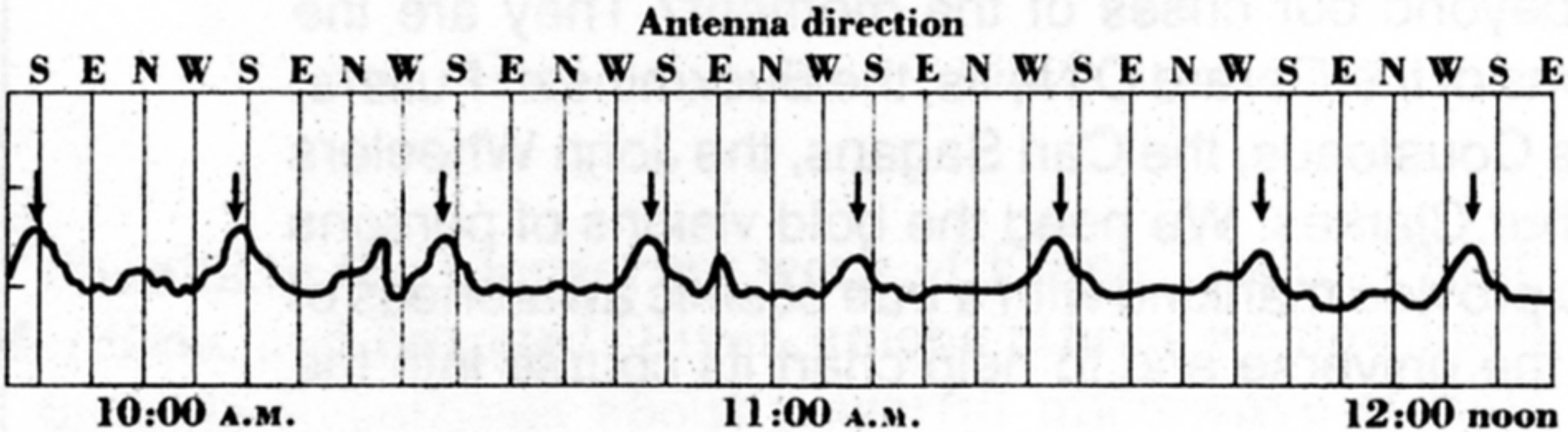
…so nobody really bothered to look.



1932-1933: Karl Jansky

20.5MHz, $\lambda \approx 15$m






NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

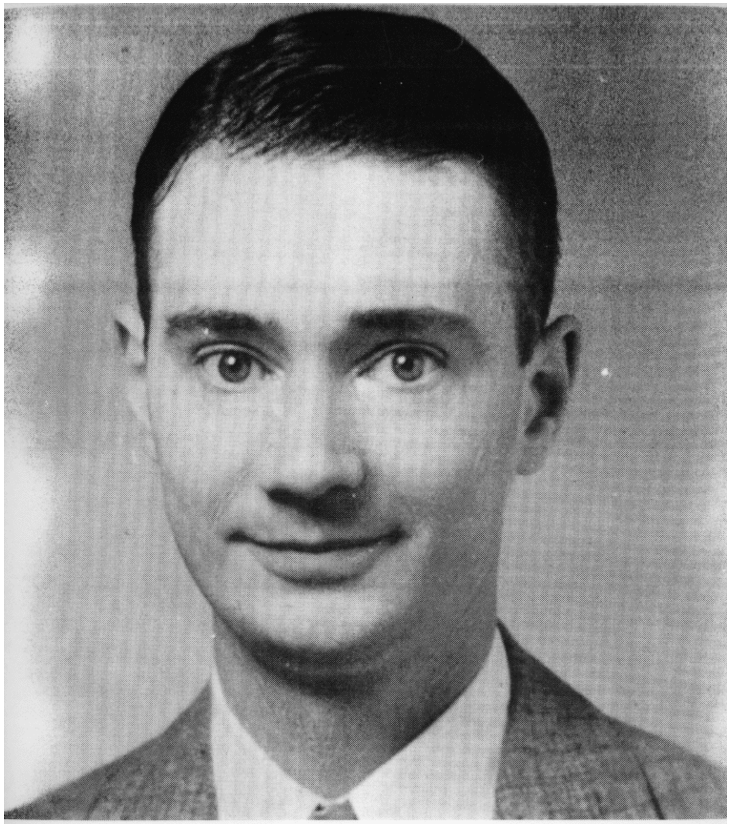
Radio Engineer with Bell Labs in 1930s.

Proposed to build a 30m parabolic dish to study radiation.

Bell labs turned him down, never did astronomy again.

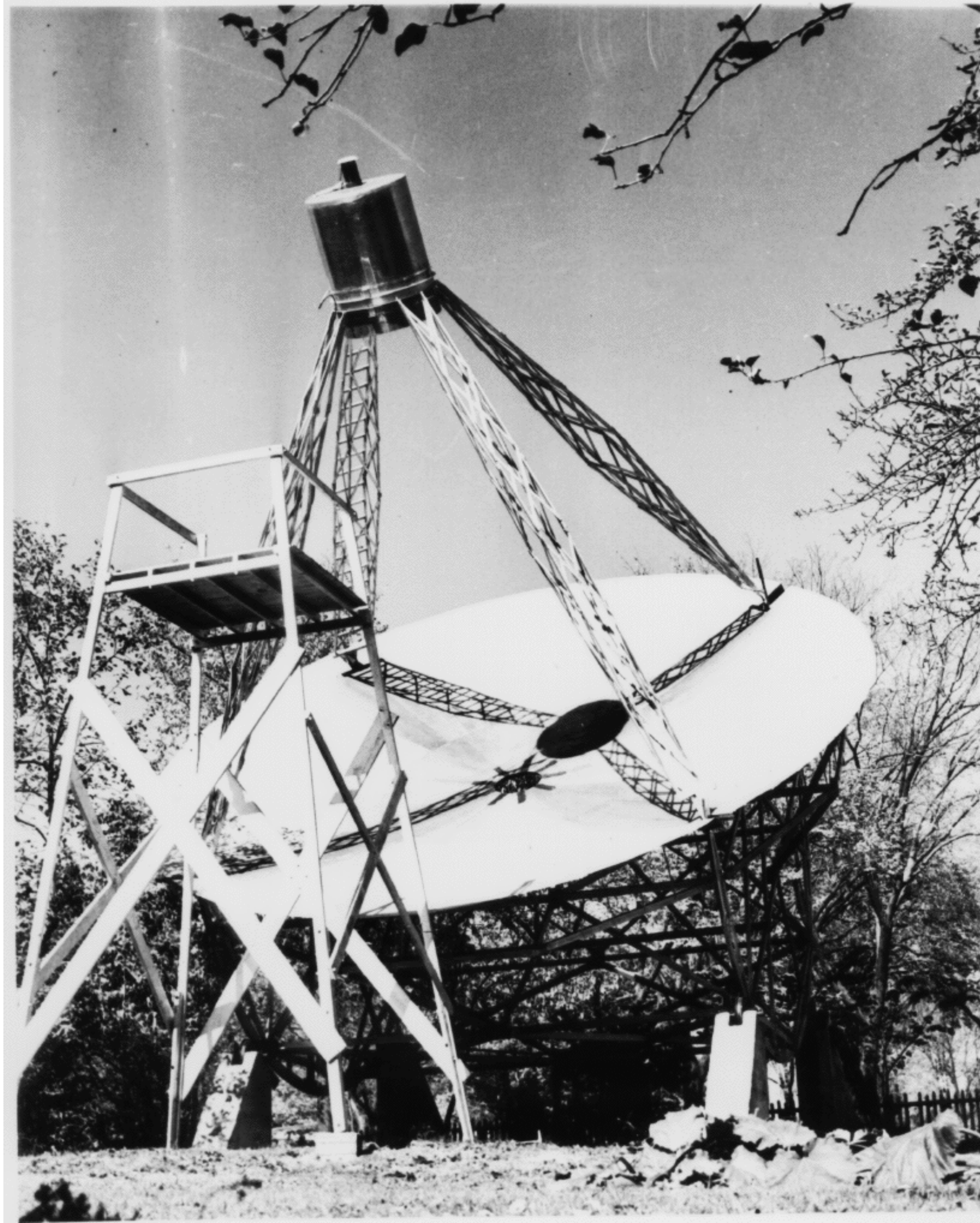
1 Jansky = 10^{-26} W m^{-2} Hz^{-1}

1937: Grote Reber



–Grote Reber, about 1937.

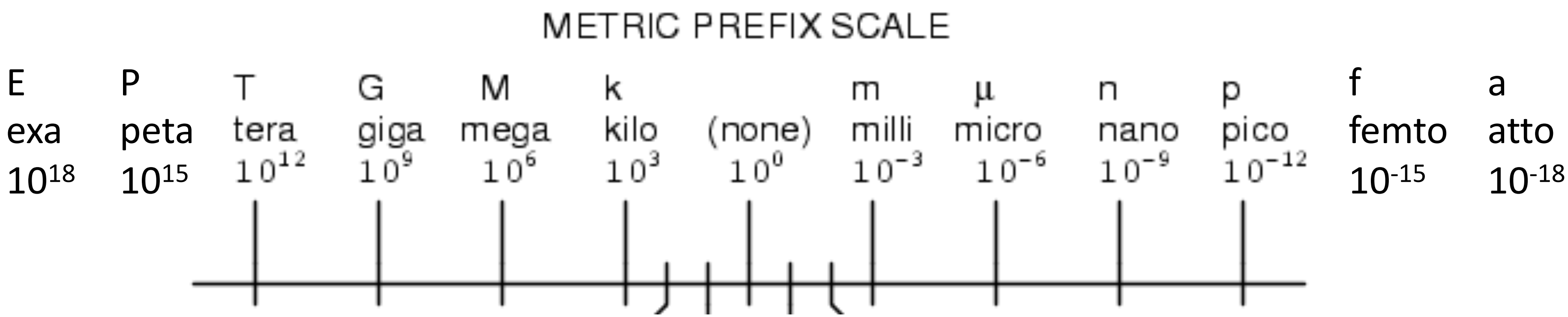
3300 MHz, $\lambda \approx 9$cm
900 MHz, $\lambda \approx 33$cm
150 MHz, $\lambda \approx 2$m



Wavelengths vs. Frequencies

Unfortunately, microwave and radio people tend to use both.

Remember: $c = \lambda\nu = 3 \times 10^8$ m/s

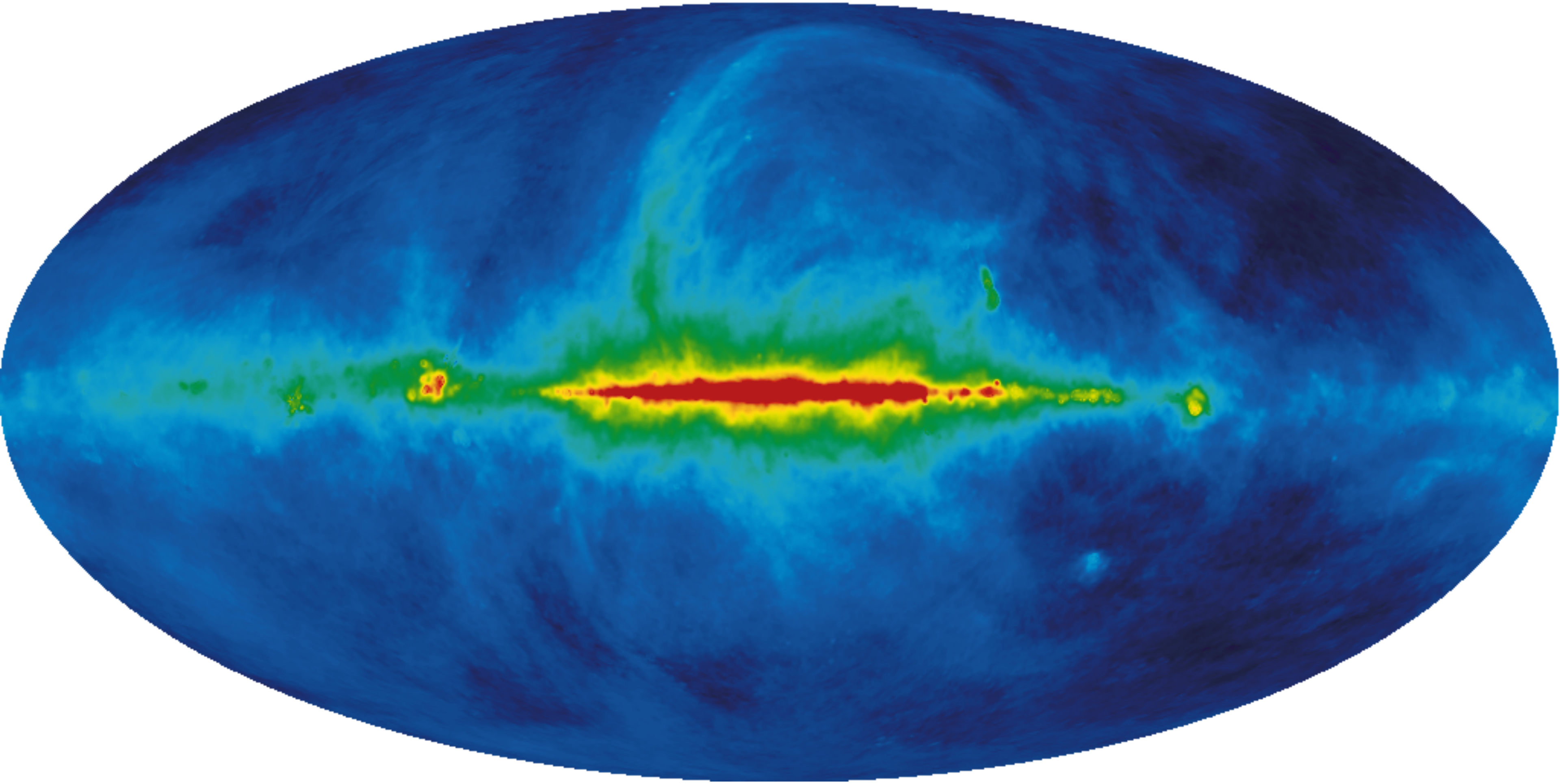


Handy reference points: $\nu = 300$ MHz $= 3 \times 10^8$ Hz $\Leftrightarrow$ $\lambda = 1$ m

$\nu = 300$ GHz $= 3 \times 10^{11}$ Hz $\Leftrightarrow$ $\lambda = 1$ mm

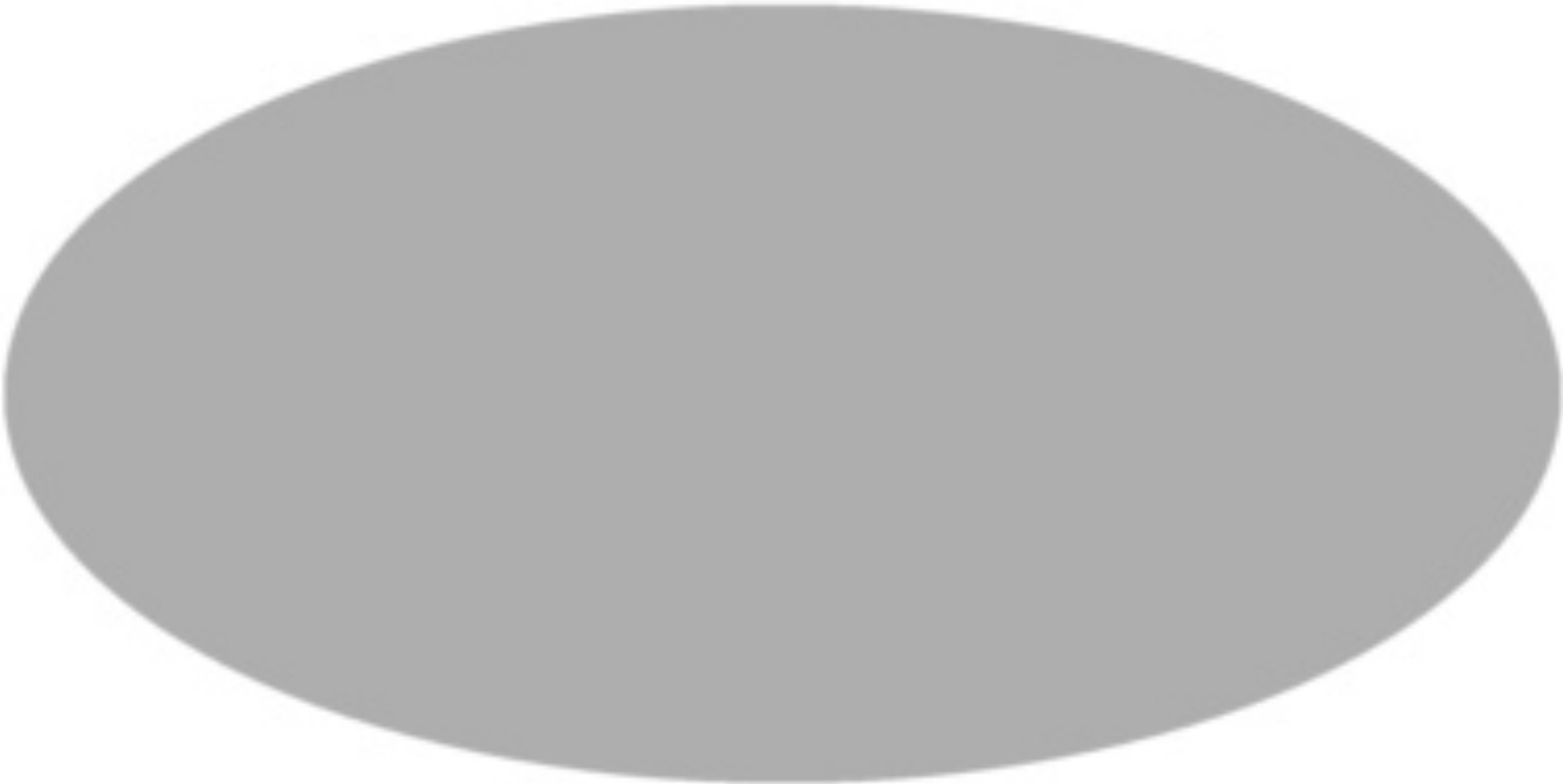
Radio Sky

(Measured at 408MHz ≈ 37cm)



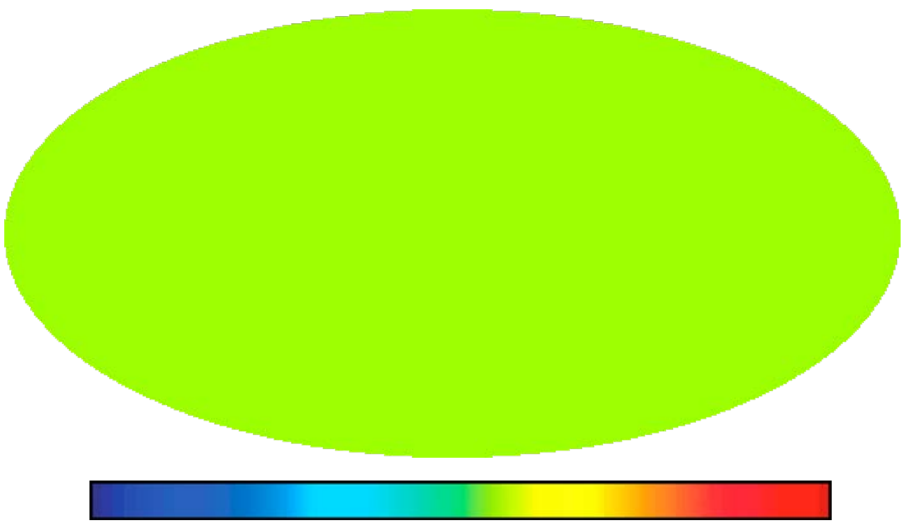
Microwave Sky

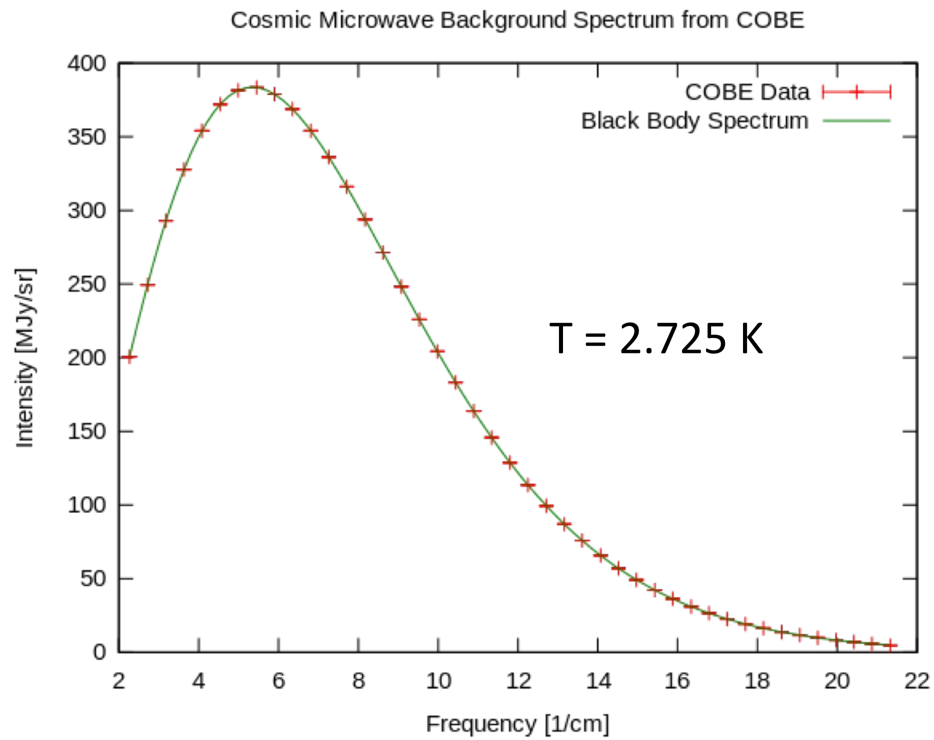
(Measured at 150GHz ≈ 2mm)



The Cosmic Microwave Background

The Sky at 90GHz

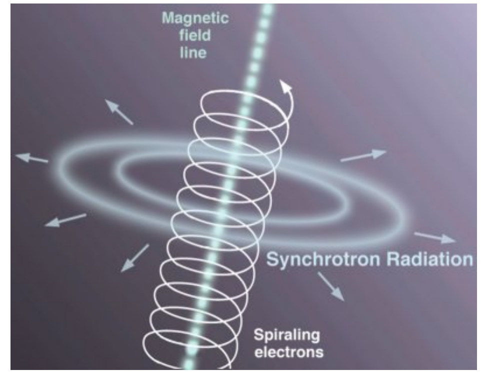




Other Sources

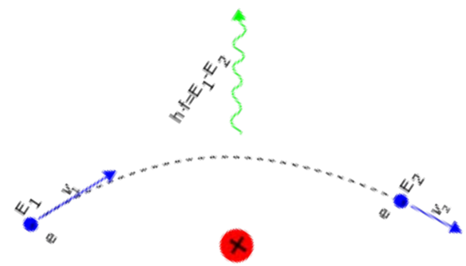
- Synchrotron

e$^-$ spiraling along magnetic fields



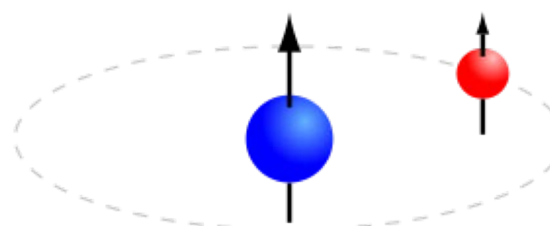
- Bremsstrahlung

"breaking radiation"
a.k.a. free-free radiation



- Spectral Lines

21cm hyperfine H
molecular lines



Low Energy Light

$$E = h\nu$$

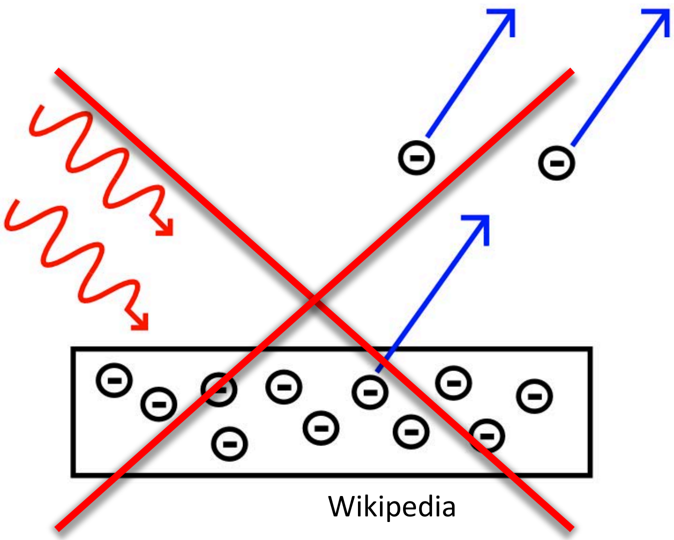
1mm (300GHz) photon:

- 200 yoctojoules
- 2×10^{-22} Joules
- 0.001eV

1m (300MHz) photon:

- 0.2 yoctojoules
- 2×10^{-25} Joules
- 0.000 001eV

Insufficient for photoelectric effect!

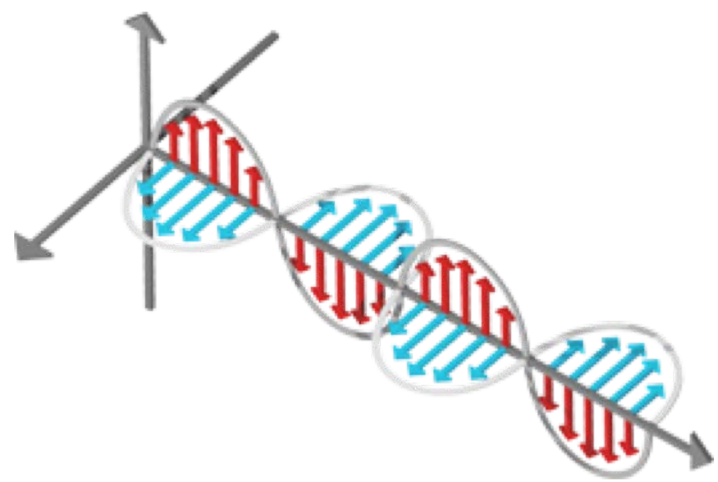


Wikipedia

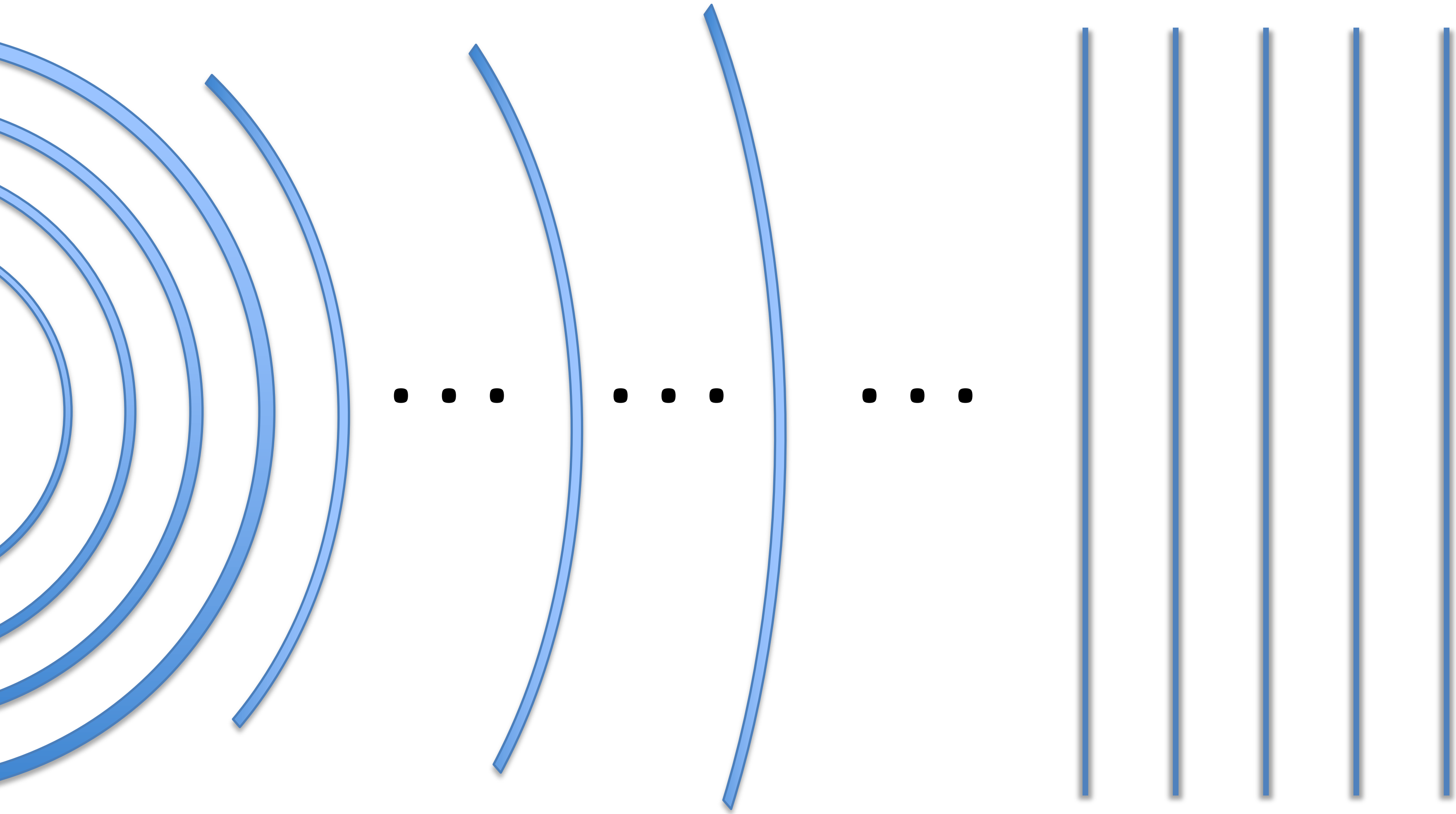
Wave-particle Duality

- Optical: eV – can photo-ionize
- Radio: μeV – negligible energy / photon

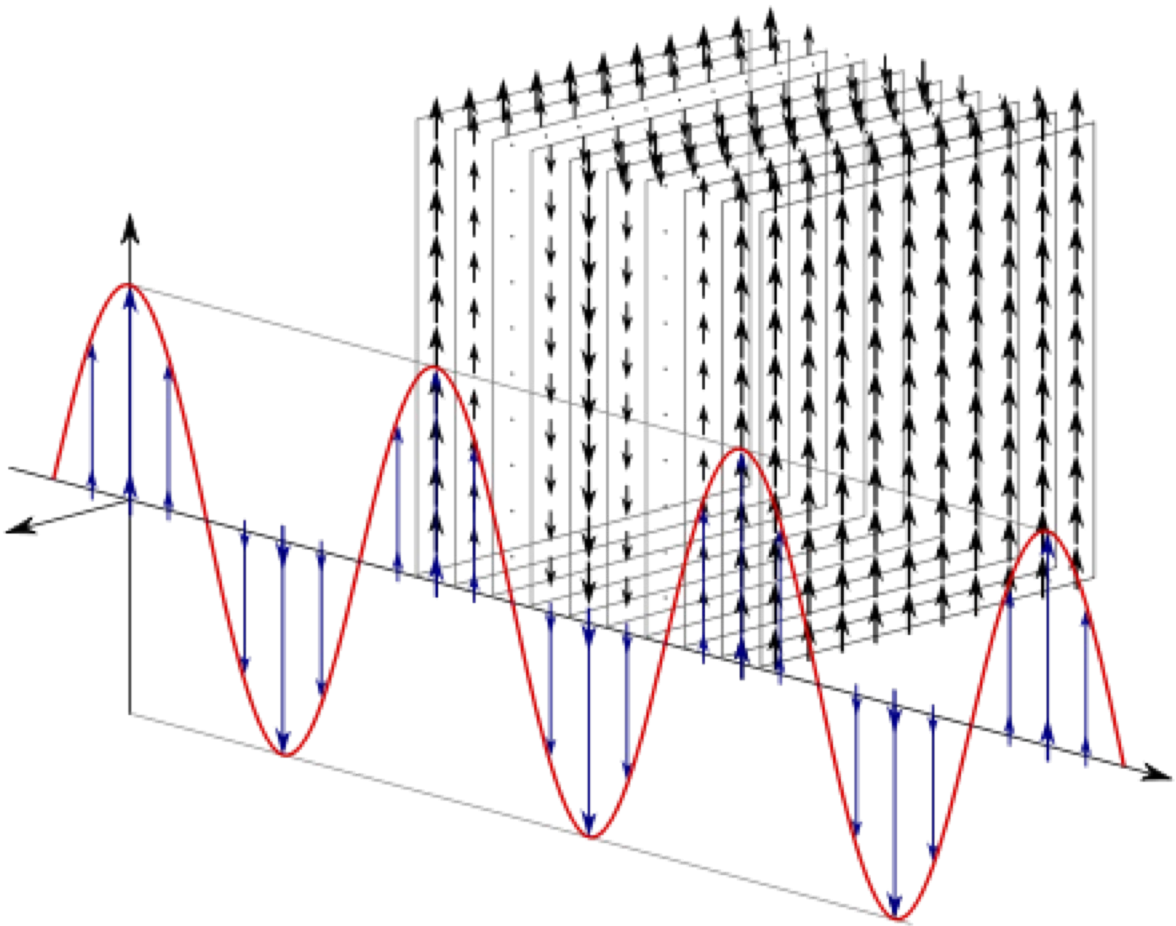
Think *waves*,
not particles.



Waves

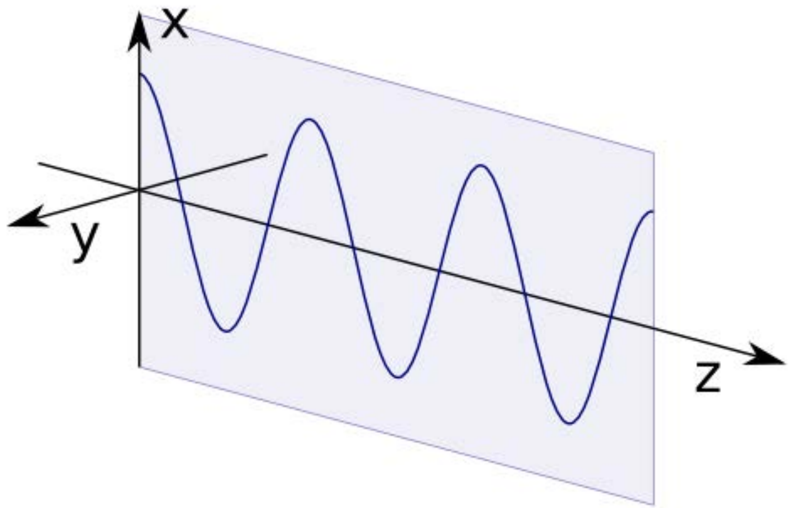


Plane waves



Linear Polarization

Plane waves



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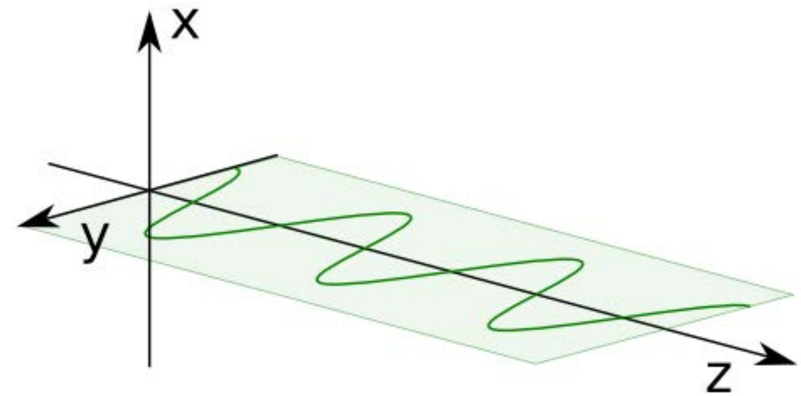
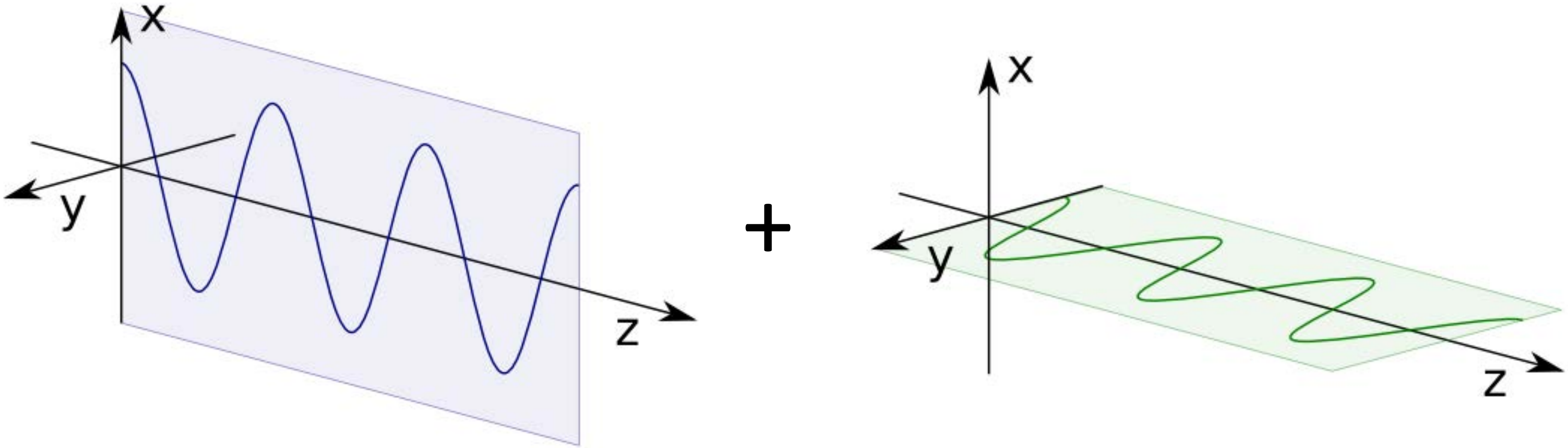


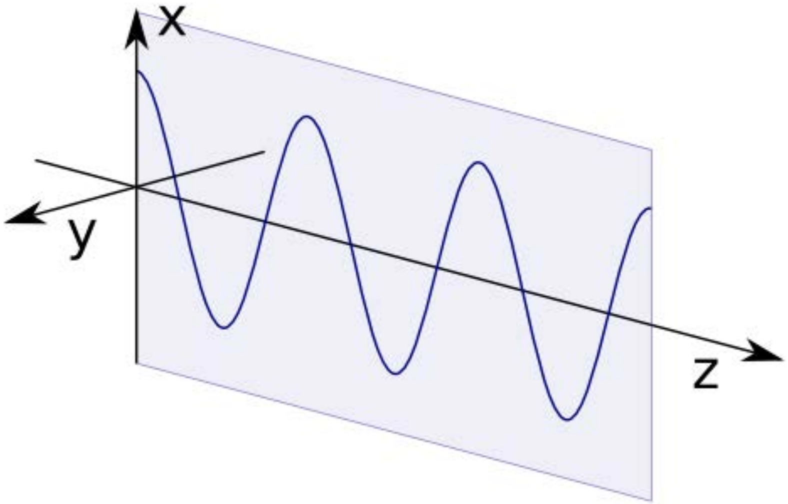
= ?

(Discuss, 1 min.)

Plane waves



Plane waves



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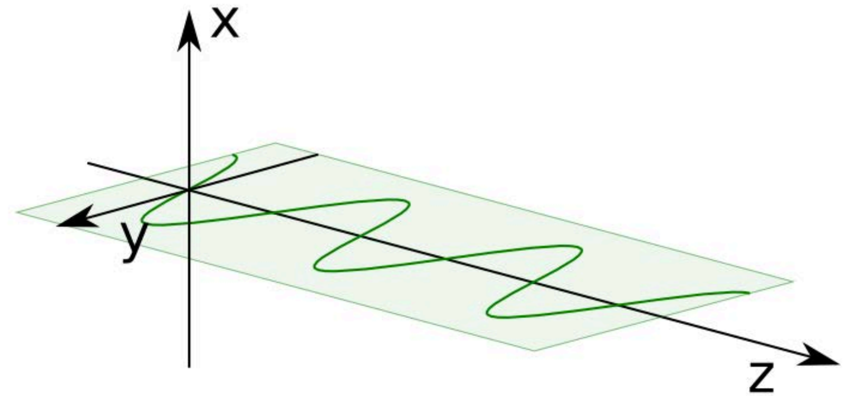


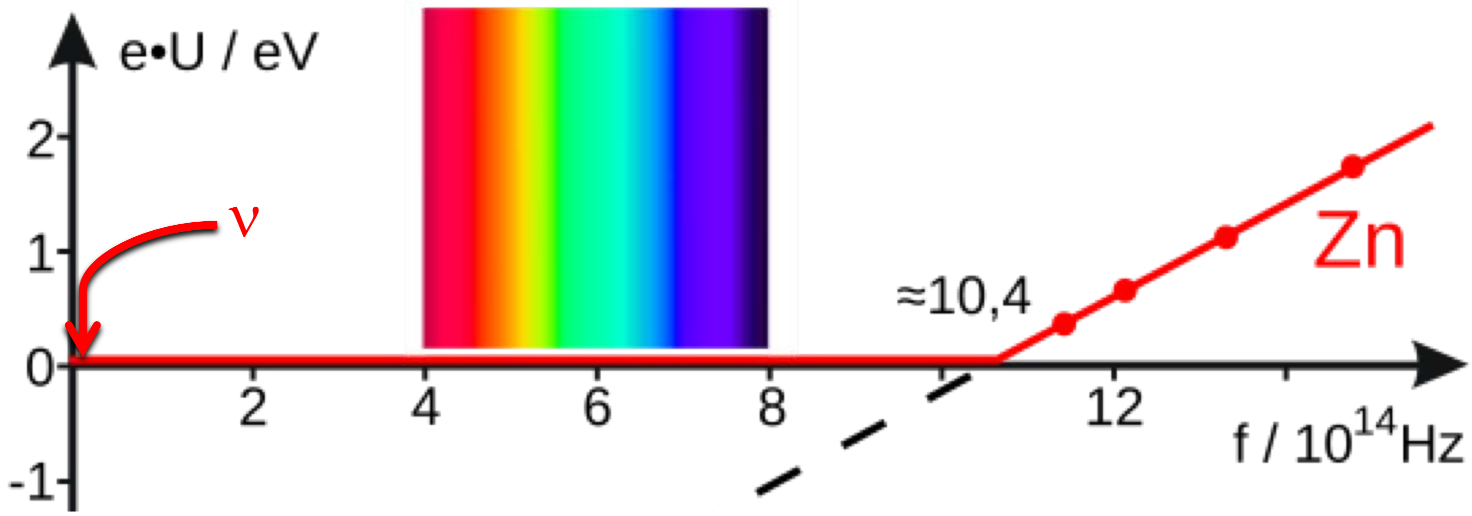
¼ wave out of phase

= ?

(Discuss, 1 min.)

Three Ways to Detect Light

1. ~~Photon Detectors~~ (well… maybe)
2. Thermal Detectors
3. Coherent Detectors



Detecting Microwave Light: Photon Detectors

Kinetic Inductance Detectors:

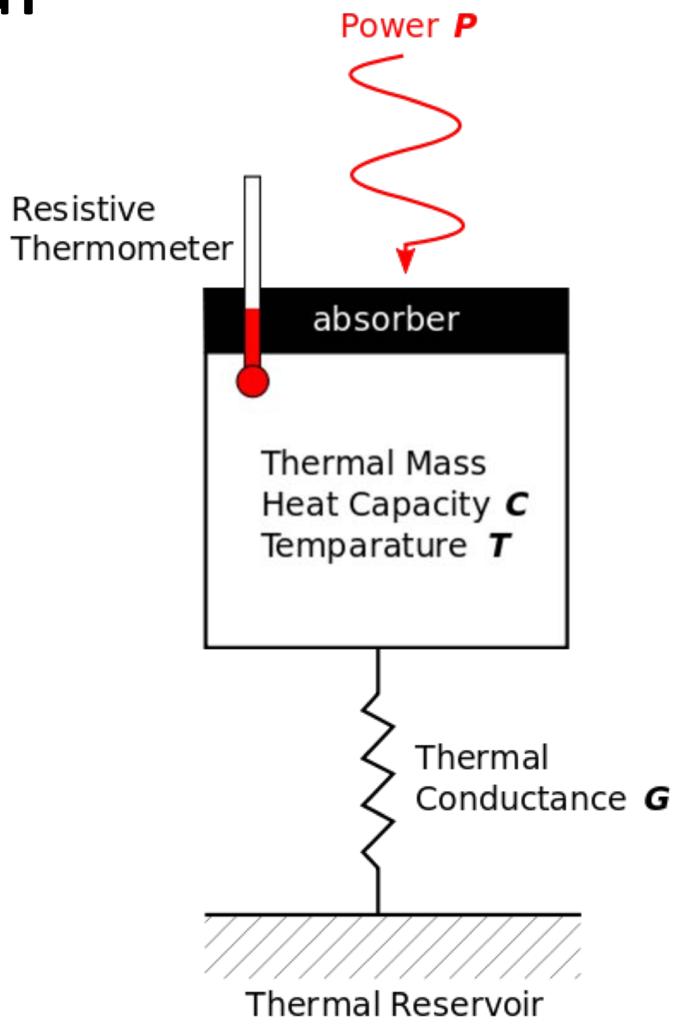
Binding energy of Cooper pairs in superconductors is of order 1meV.

➔ Can be broken by ν>300GHz ; λ<1mm

Detecting Radio Light: Thermal

Bolometers:

- just fancy thermometers
- heat up in response to power
- Presently the most sensitive detectors for microwave light



Early Bolometers

1880 – Samuel Langley develops the bolometer.

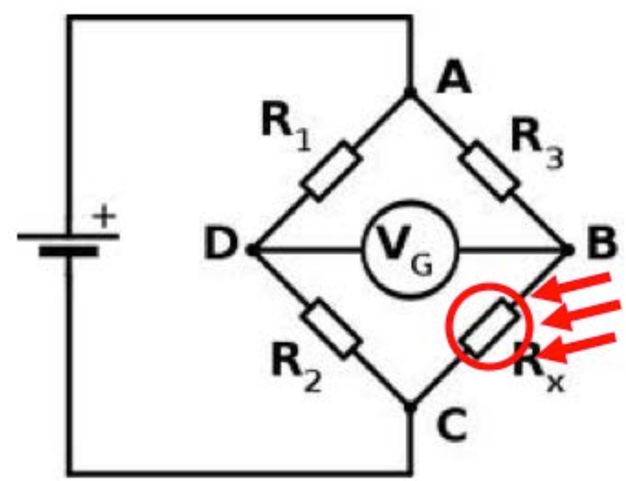
Metal resistivity known to be sensitive to temperature.

Used platinum strips, one side blackened to absorb radiation.

Could "detect the thermal radiation from a cow ¼ mile away."

Cow detection not the primary goal – measured solar IR spectrum

Wikipedia



Back-of-the-envelope!

How much thermal radiation hits a $1cm^2$ detector from a cow ¼ mile (400m) away?

Stefan-Boltzman constant: $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

Temperature of a healthy cow: 39C ≈ 312K ($T^4 \approx 10^{10}$ K^4)

Surface area of a cow: ≈ 5 m^2

Detector ≈ 1cm square

3 min, work in groups!

Detecting Radio Light: Coherent

Not only particles and power – we can record the waves.

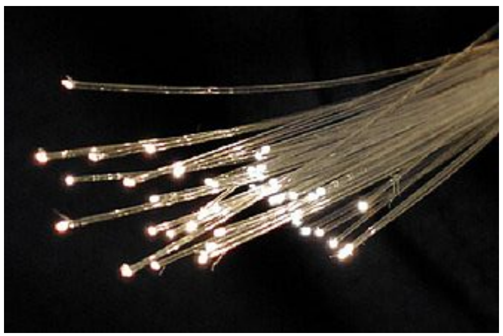
Coherent detection records both **amplitude** and **phase**.
Lets us reconstruct lots of details after the fact.

A ***feed*** couples free space waves into ***waveguide***.
There, we can manipulate, amplify, filter,
and measure the light.

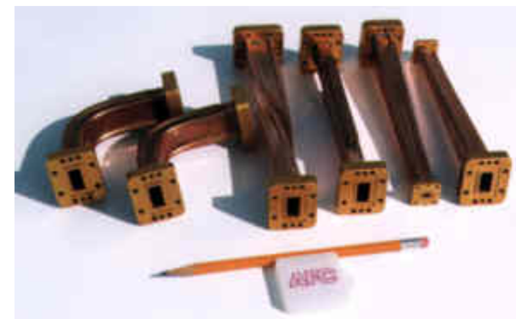
Waveguide

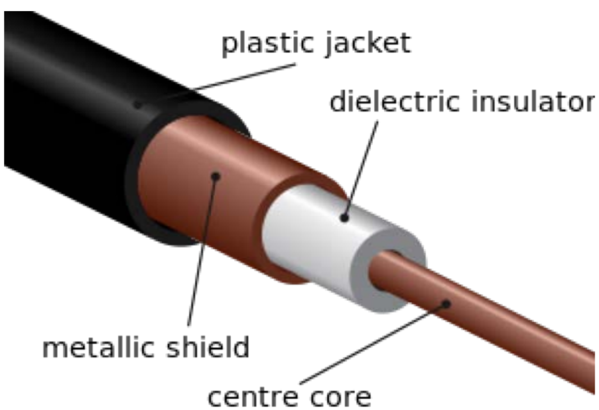
EM fields will propagate in **waveguides**.
A waveguide confines the signal to travel in one direction.

Optical:
Fiber

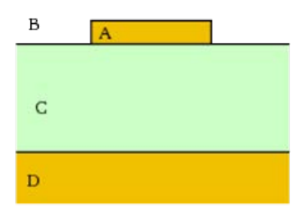


Microwave:
Metal Tubes
/ microstrip



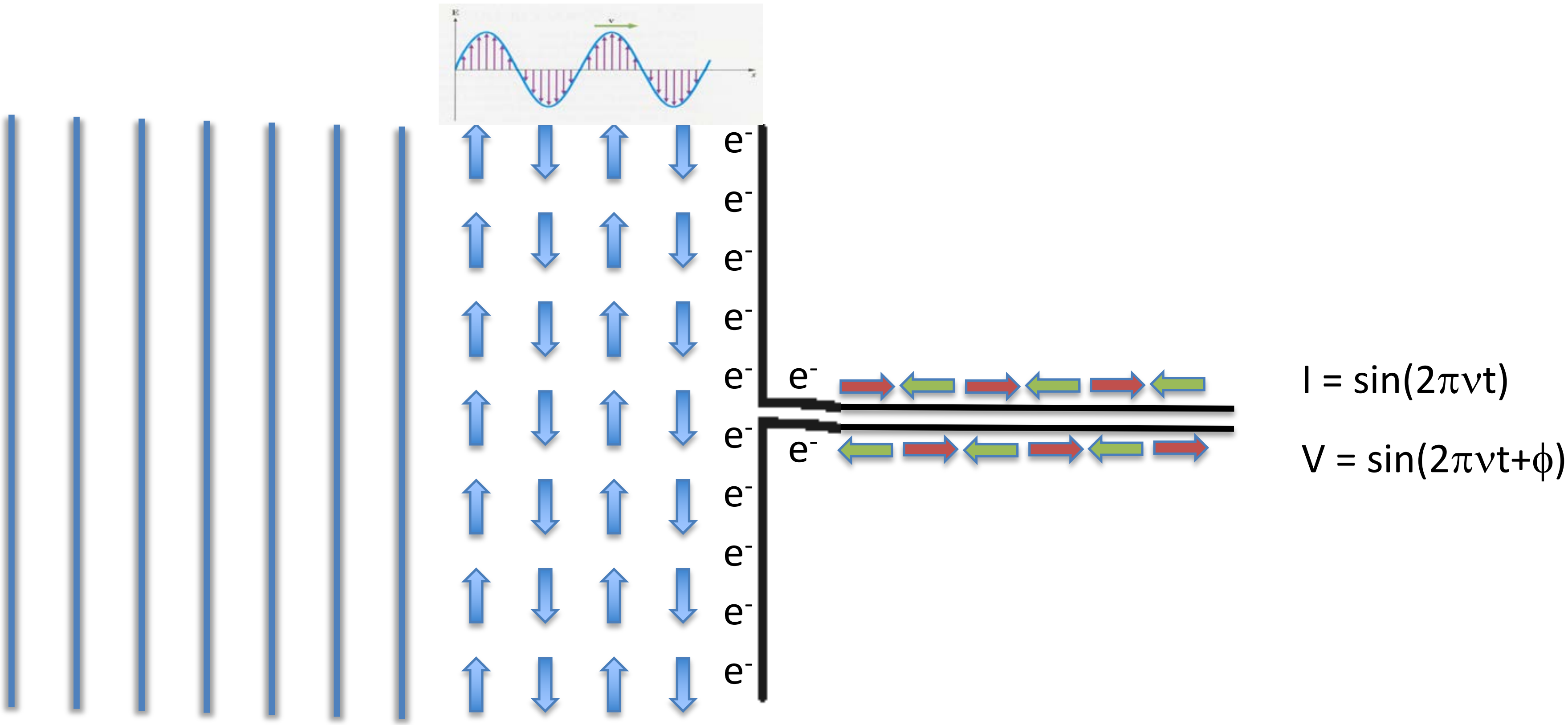


Radio:
Transmission
Lines / Cables /
Microstrip



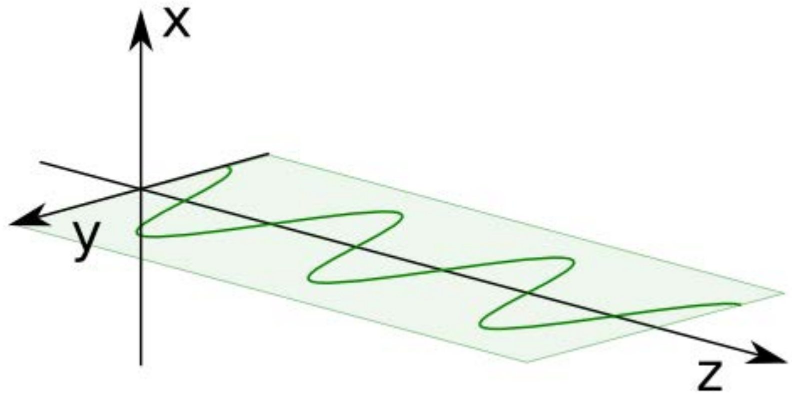
Feeds

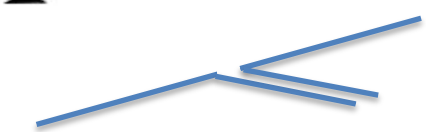
A ***feed*** couples free space waves into ***waveguide***.



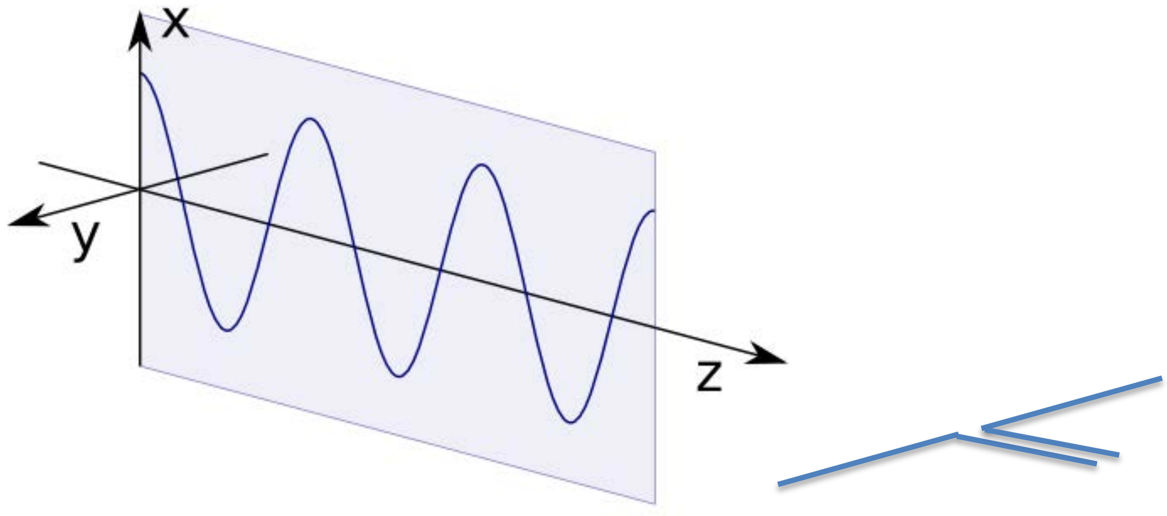
For high efficiency (to be resonant), a feed's size must be of order λ.

Thought Experiment!





Thought Experiment!

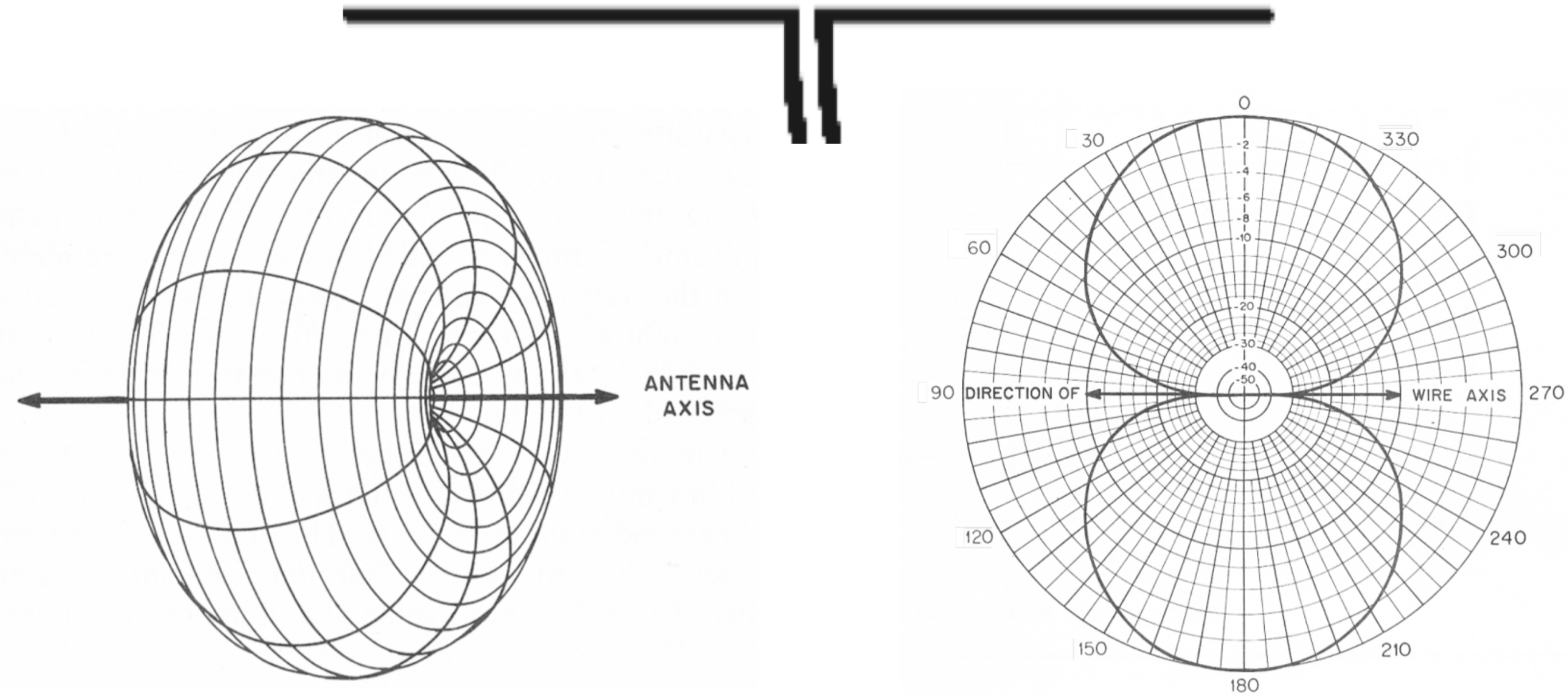


What happens?

2 min, work in groups!

Radiation Patterns

Response depends on direction / polarization of radiation.

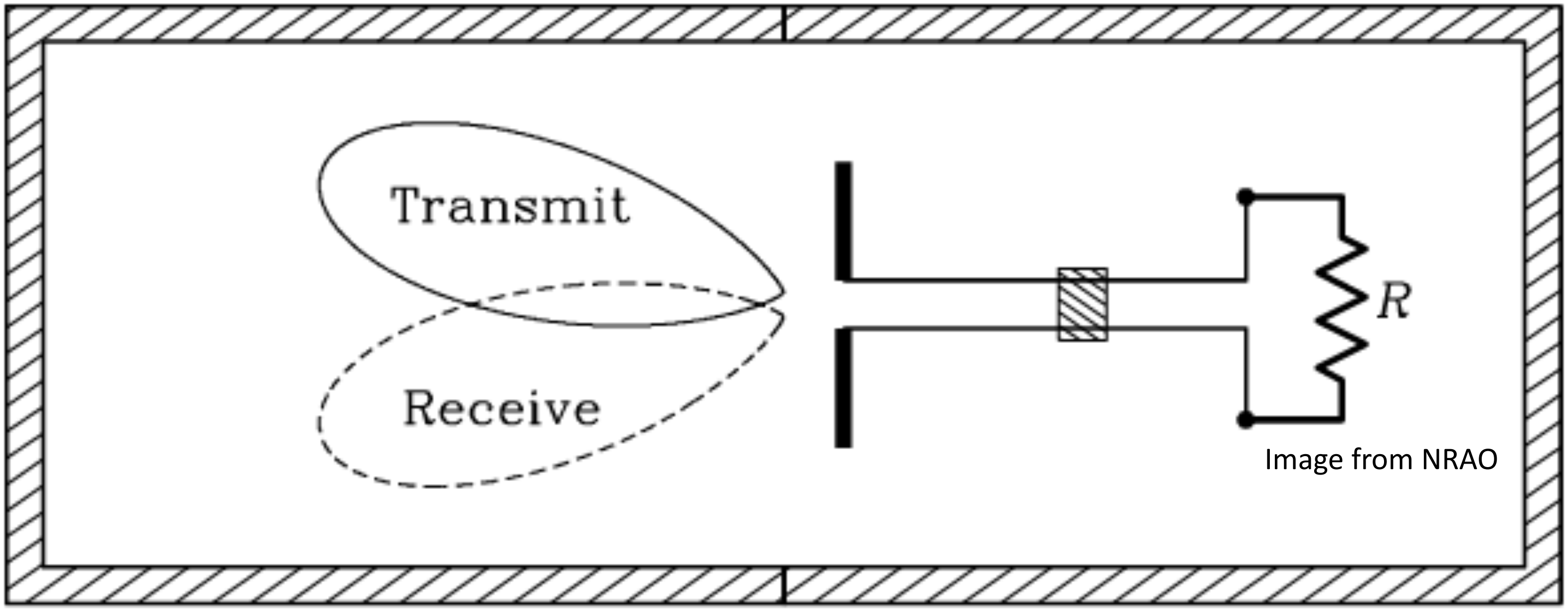


Every feed has an *effective aperture* A_e – an area over which radiation is absorbed.

The Wonderful World of Feeds

Thought Experiment!

Imagine a feed which transmitted and received differently.
We place that feed into a blackbody chamber:



What happens? (4 min, discuss with neighbours!)

Reciprocity

"An antenna can be treated either as a receiving device, gathering the incoming radiation field and conducting electrical signals to the output terminals, or as a transmitting system, launching electromagnetic waves outward. These two cases are equivalent because of time reversibility: the solutions of Maxwell's equations are valid when time is reversed." (Burke & Smith, 1997)

Transmission ⇔ Reception

Directivity / Forward Gain

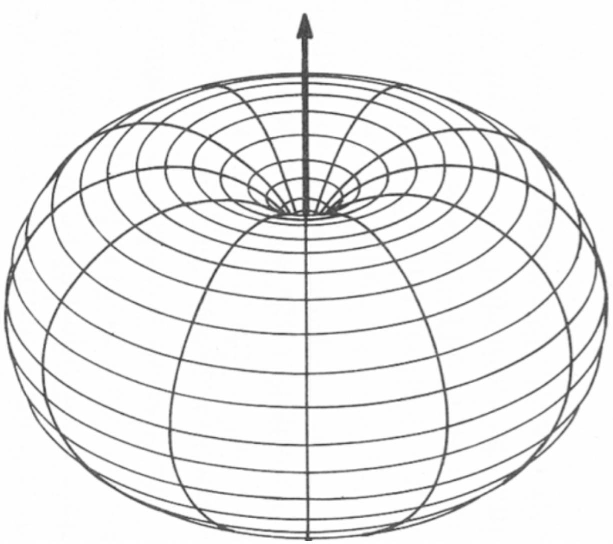
How focused is an antenna's radiation?

High gain ⇔ small beam

Isotropic feed == 0 dBi

(dBi = deciBells relative to Isotropic)

½ λ Dipole
2.15 dBi

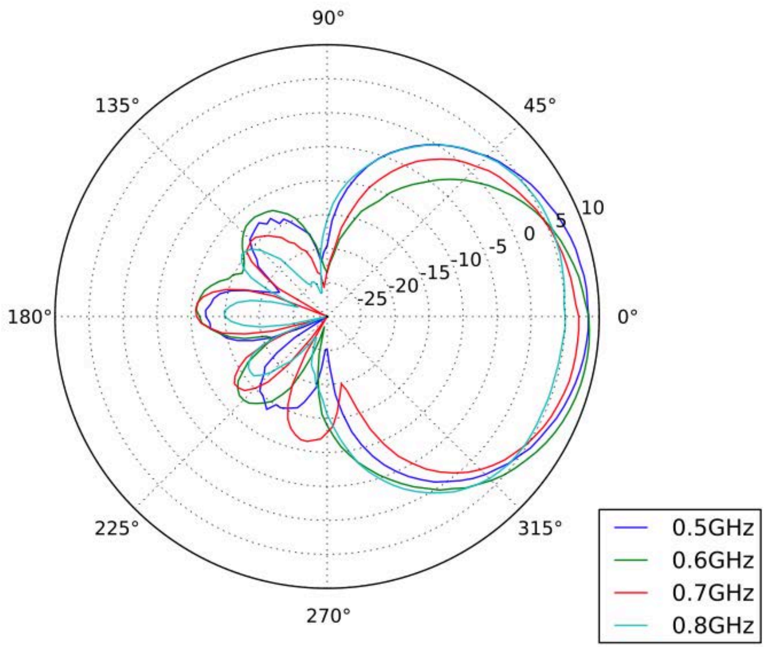


Yagi-Uda antenna
6-12dBi

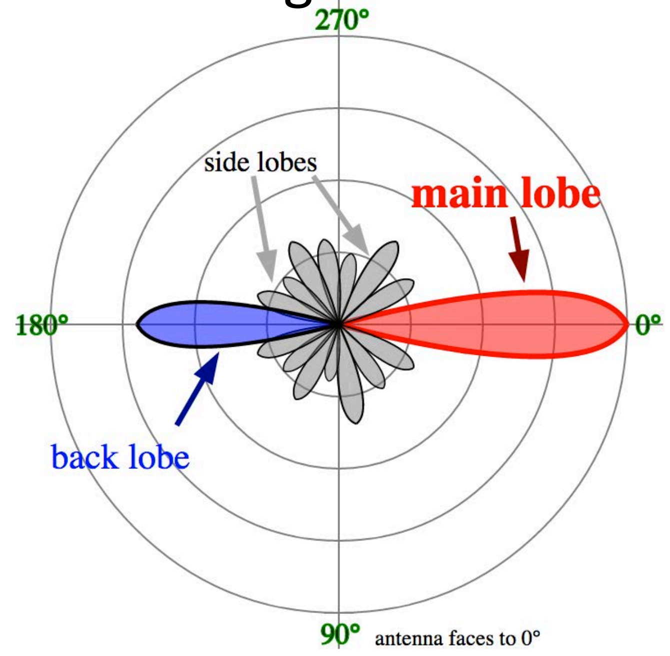
Algonquin 46m dish
70 dBi @ 5GHz

Radiation Patterns

Low Gain



High Gain

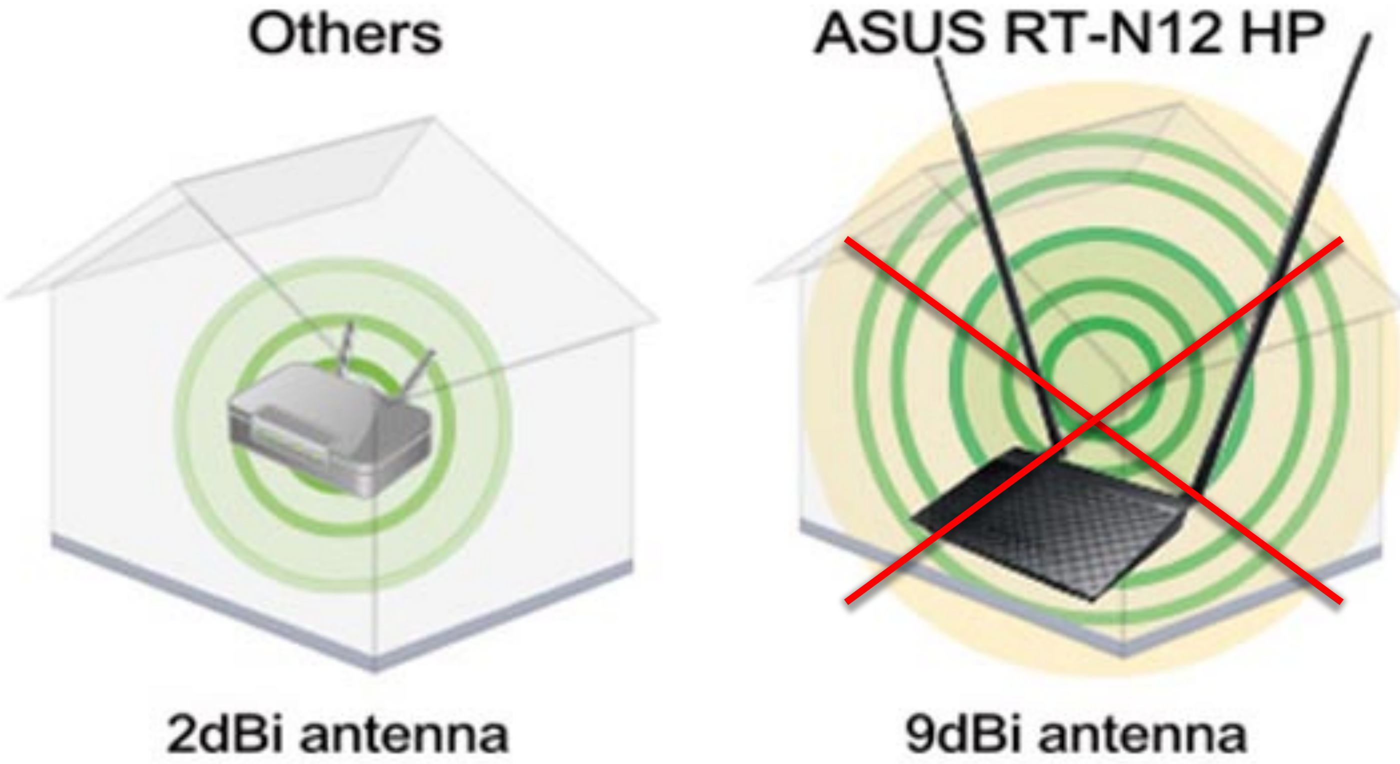


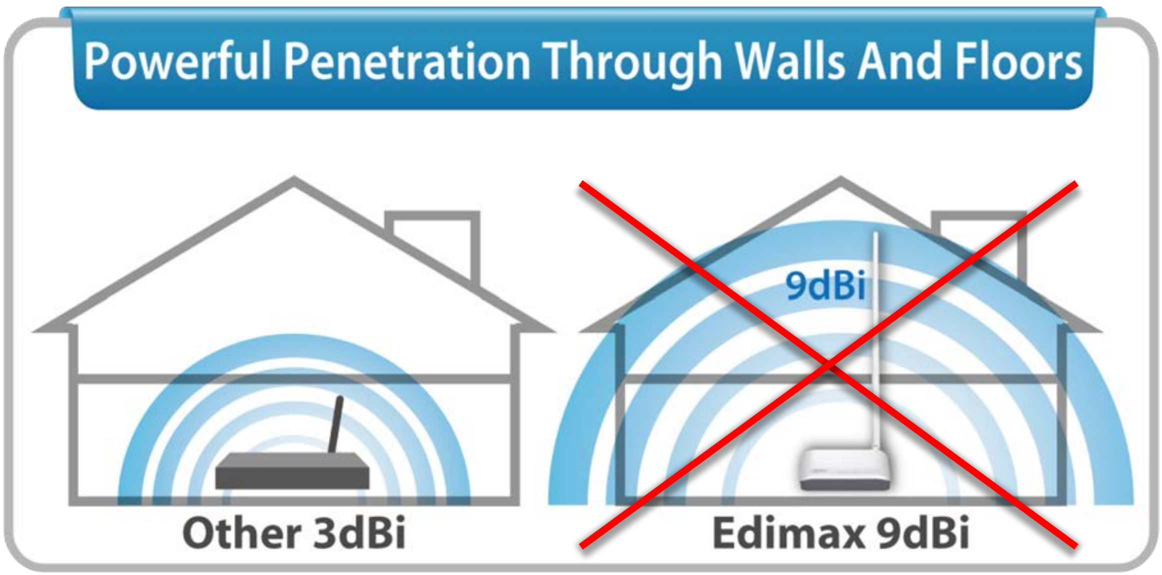
Fundamental Limit: $A_e \, \Omega = \lambda^2$

(More accurately, $\int_{4\pi} A_e d\Omega = \lambda^2$)

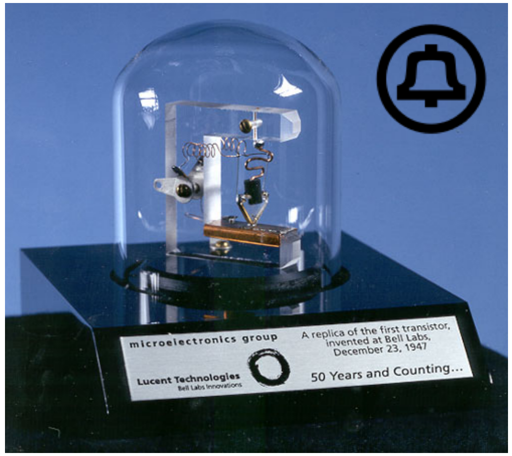
Beamwidth and gain trade off!

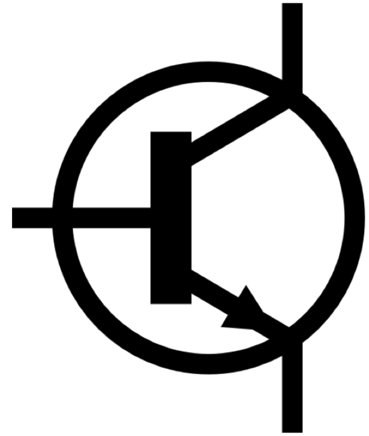
Narrow beam = high gain ←→ Broad beam = low gain


Others
ASUS RT-N12 HP
2dBi antenna
9dBi antenna


Powerful Penetration Through Walls And Floors
9dBi
Other 3dBi
Edimax 9dBi

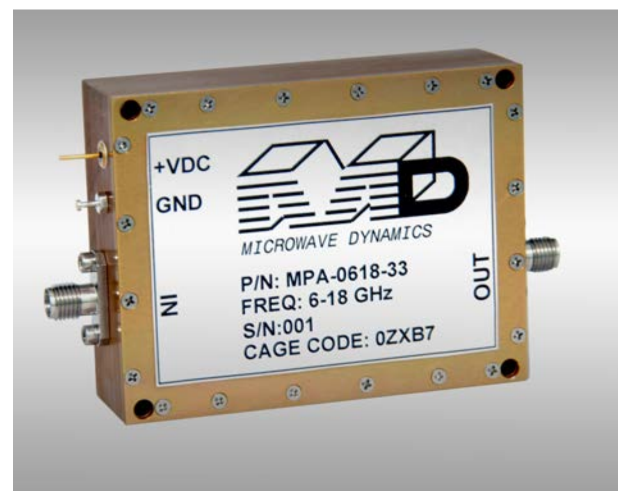
RF Amplifiers



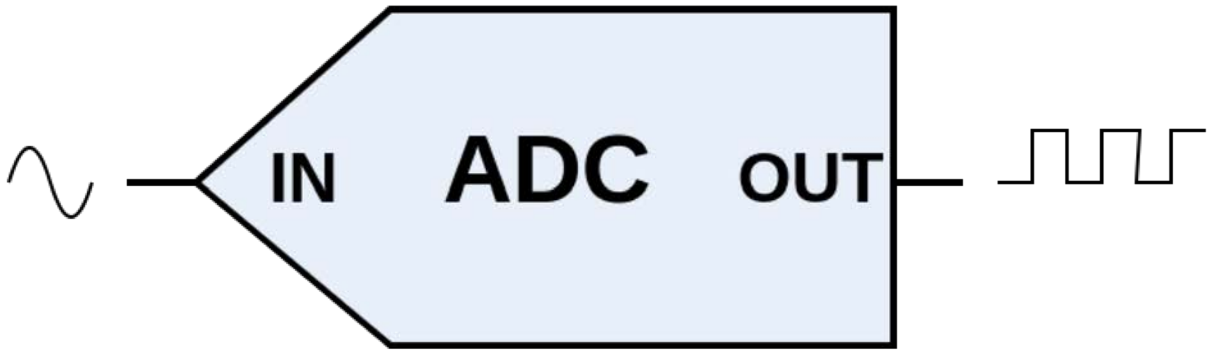


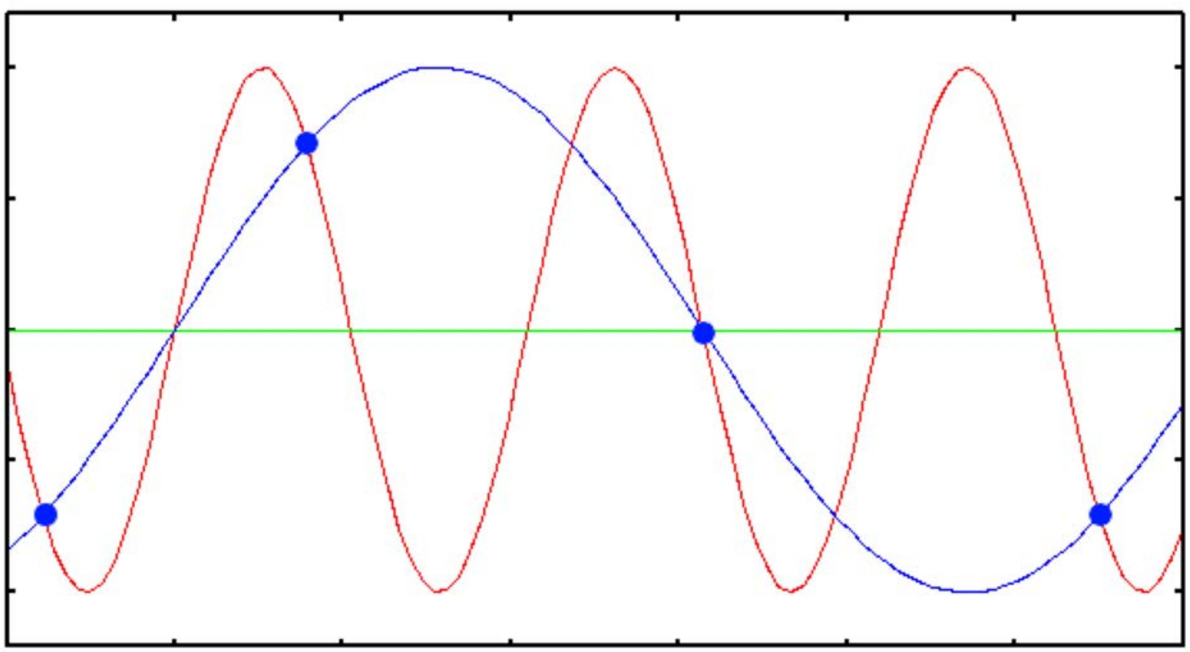
Many commercial amplifiers exist, capable of signals up to ≈100GHz.

Directly amplify the EM wave in waveguide. Bigger signals make manipulation far easier, allow us to sample and digitize.

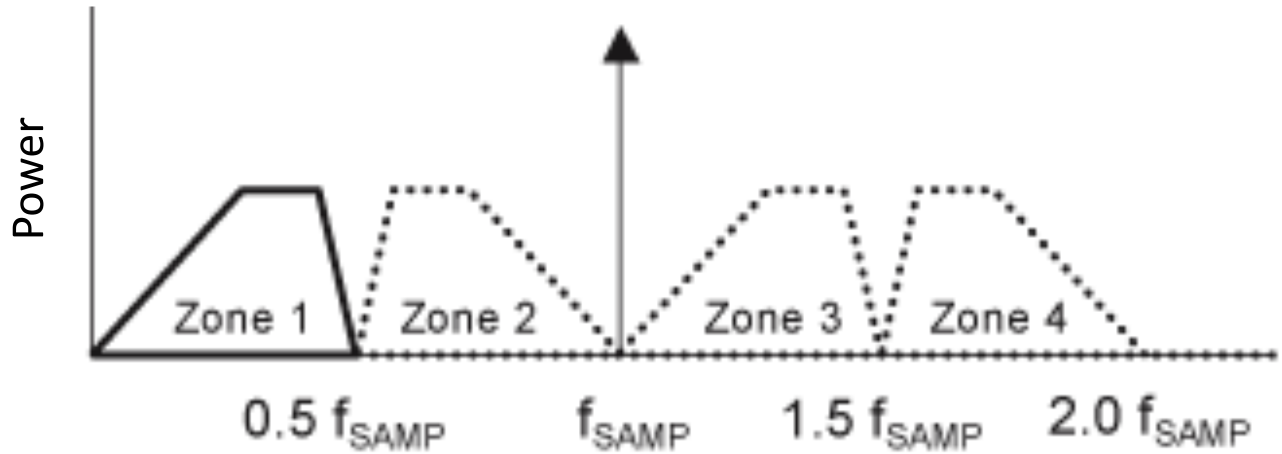


Digitizers





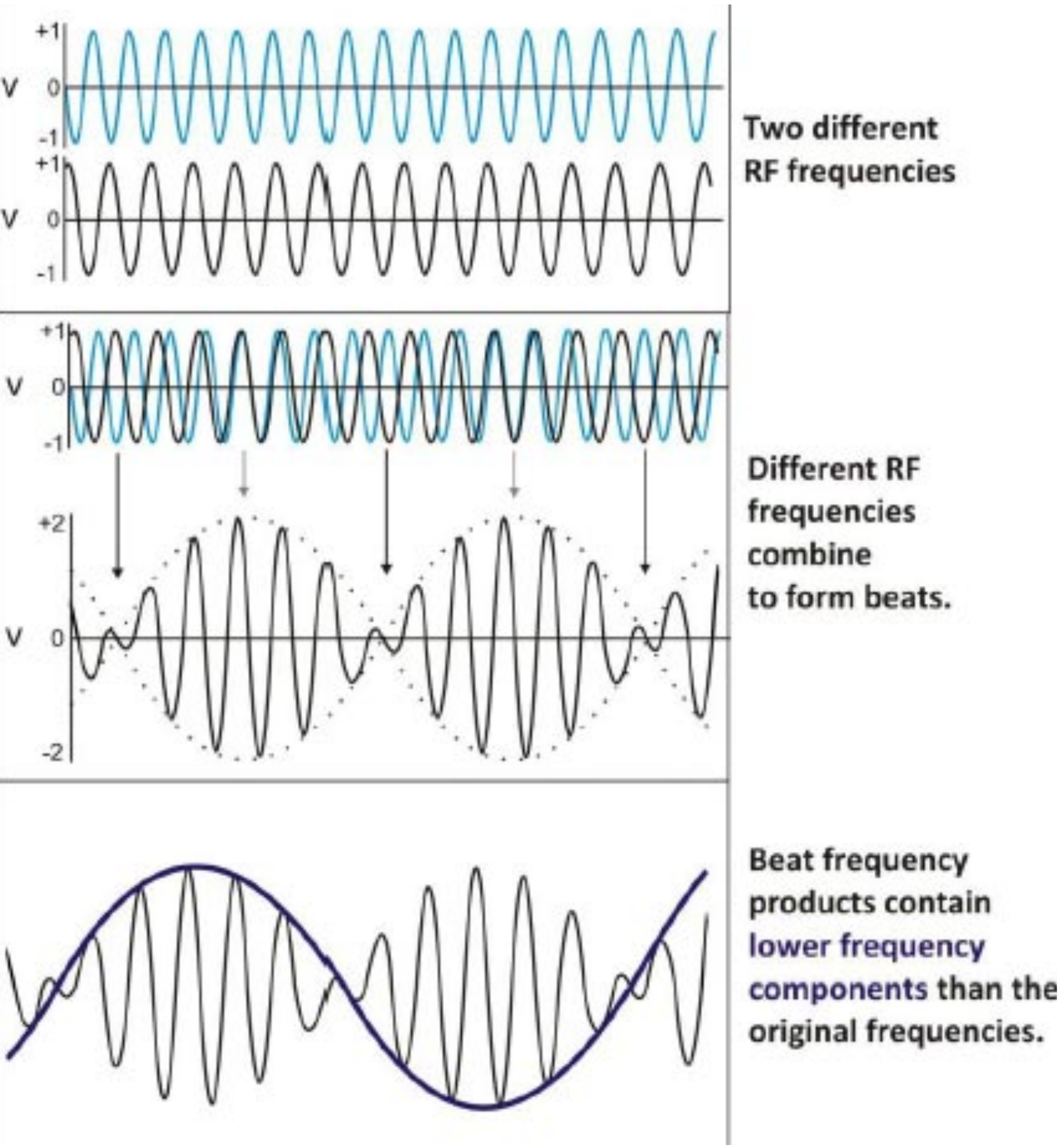
Aliasing & Nyquist

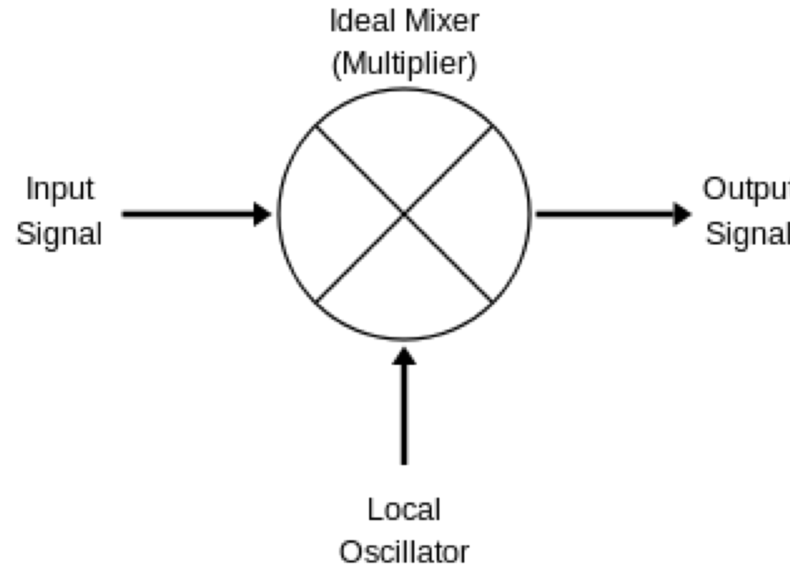


Can only distinguish $f_{samp}/2$ total bandwidth.

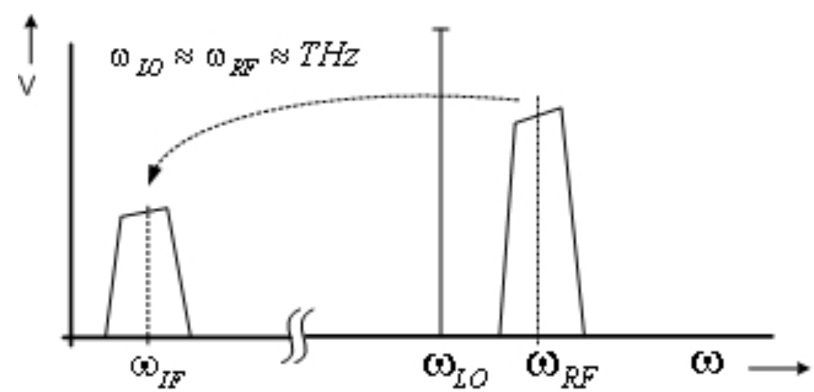
Generally need to filter the input before sampling.

Mixers

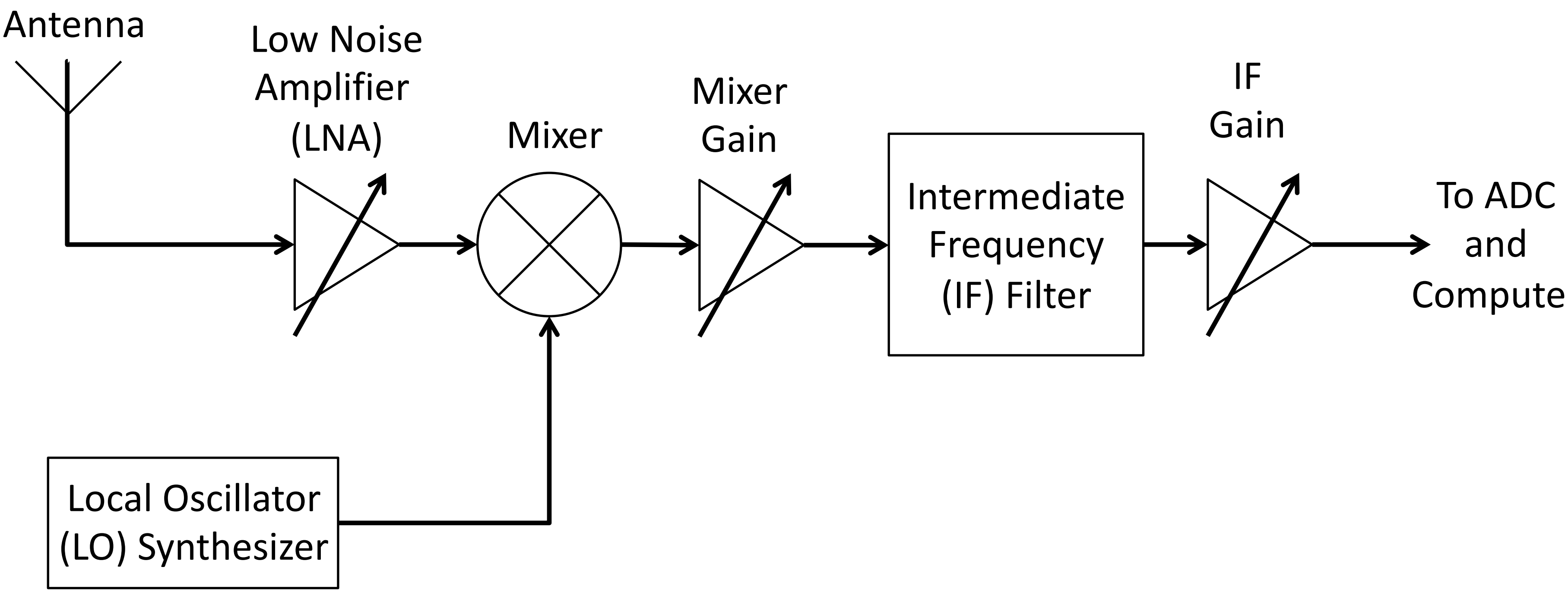




$$\sin(\omega_1 t+\phi_1)\,\sin(\omega_2 t+\phi_2) = \tfrac{1}{2}\left[\,\cos((\omega_1-\omega_2)t + (\phi_1-\phi_2)) - \cos((\omega_1+\omega_2)t + (\phi_1+\phi_2))\,\right]$$

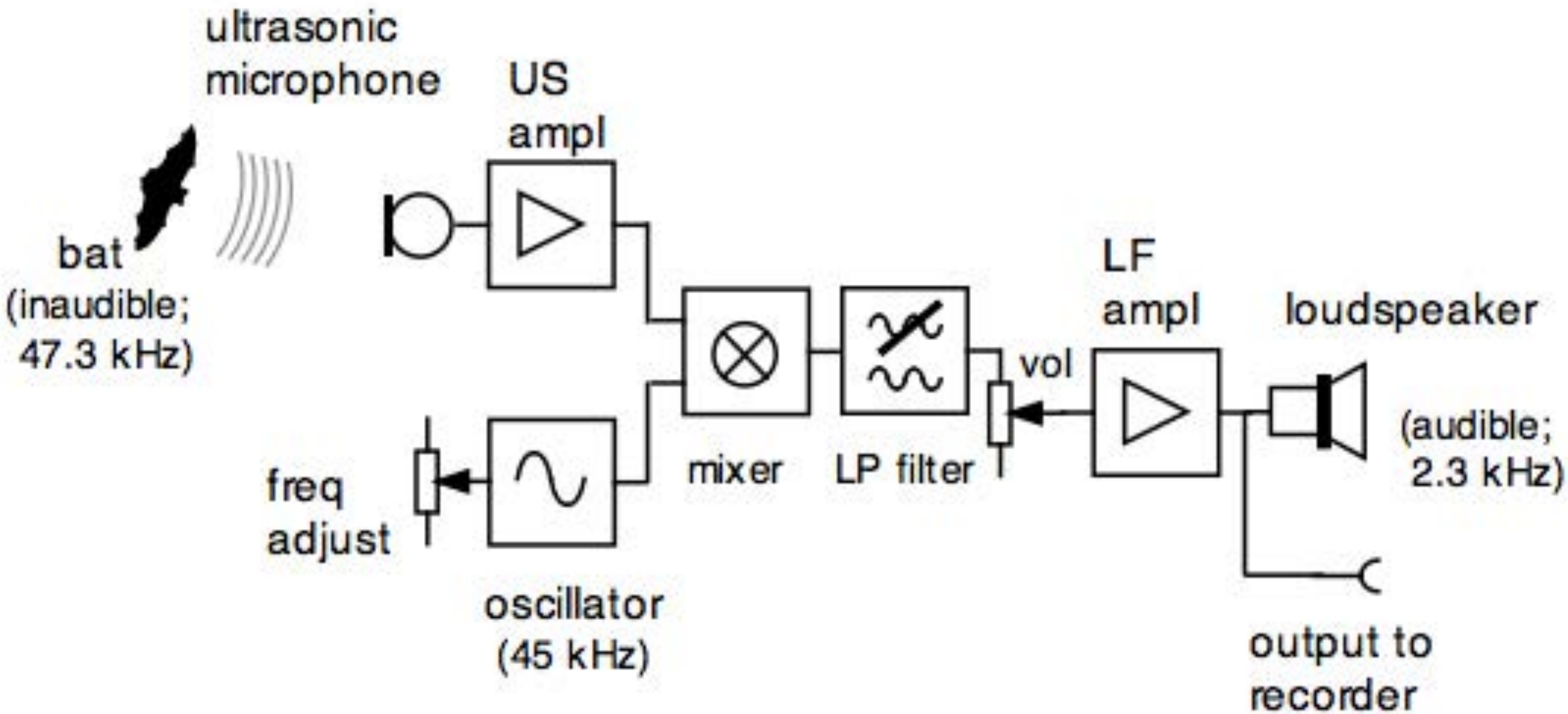


Heterodyne Detectors



Can chain together multiple stages of heterodyning.
Move the signal around as convenient for manipulation & detection!

Heterodyne Bat Detector



Digital Light

After digitization, do whatever you want to the light.

For example:

- **Channelize**: Fourier Transform to split frequencies
  (Arbitrarily fine $\Delta\nu$ resolution, no need for prisms.)

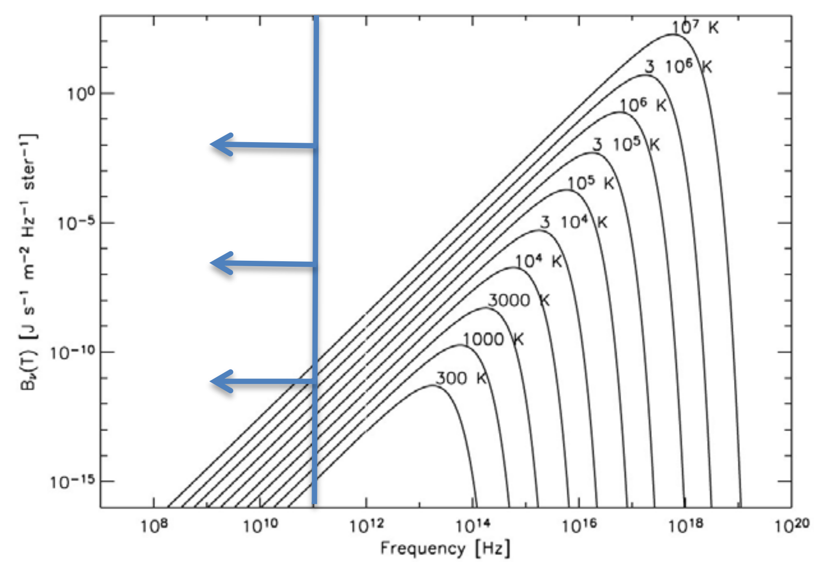
- **Integrate**: sum up incoming power $|V|^2$
  (Equivalent to a thermal detection.)

- **Correlate**: combine the light from faraway antennas
  (Rick Perley's talk Thursday!)

RJ Temperature

For radio & mm, usually kT >> hν, so we're in Rayleigh-Jeans regime.

$$B_\nu(T) = \frac{2\nu^2 kT}{c^2}$$



Within a band, blackbody power is *linearly* related to temperature.

$$\boxed{P = kT\Delta\nu}$$

(Also means thermal noise from our instrument T_{rcvr} is significant.)

"Temperature" is a frequent unit of signal & noise power.

System Temperature

We ***want*** to measure $\boxed{P_{source} = kT_{source}\Delta\nu}$

We ***can*** measure the total system power:

$$T_{\rm sys} = T_{\rm cmb} + \Delta T_{\rm source} + T_{\rm atm} + T_{\rm spillover} + T_{\rm rcvr} + \ \ldots$$

Includes all power before and after the antenna, including amplifiers, cables, pickup, crosstalk, ADCs, etc.
At low frequencies, *everything* is glowing thermally.

How do we get T_{source}?

Radiometer Equation

Low-energy detectors don't have "read noise" in electrons.
They measure light in your waveguide.

$$T_{\mathrm{sys}} = T_{\mathrm{cmb}} + \Delta T_{\mathrm{source}} + T_{\mathrm{atm}} + T_{\mathrm{spillover}} + T_{\mathrm{rcvr}} + \ \ldots$$

Bandwidth ($\Delta\nu$) and time (τ) give independent measurements, and the ***Radiometer Equation*** gives fundamental noise:

$$\boxed{N \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}}$$

Note that ***ALL*** power in the system adds to the noise.
The goal for a low-noise system is to minimize power.

Radio Frequency Interference (RFI)

Light pollution at long wavelengths.

- AM Radio
- FM Radio
- Broadcast TV
- RADAR
- Cell Phones
- CB Radio
- Electronics
- Etc…

United States RF Spectrum Allocation

3 kHz
100km

300 kHz
1km

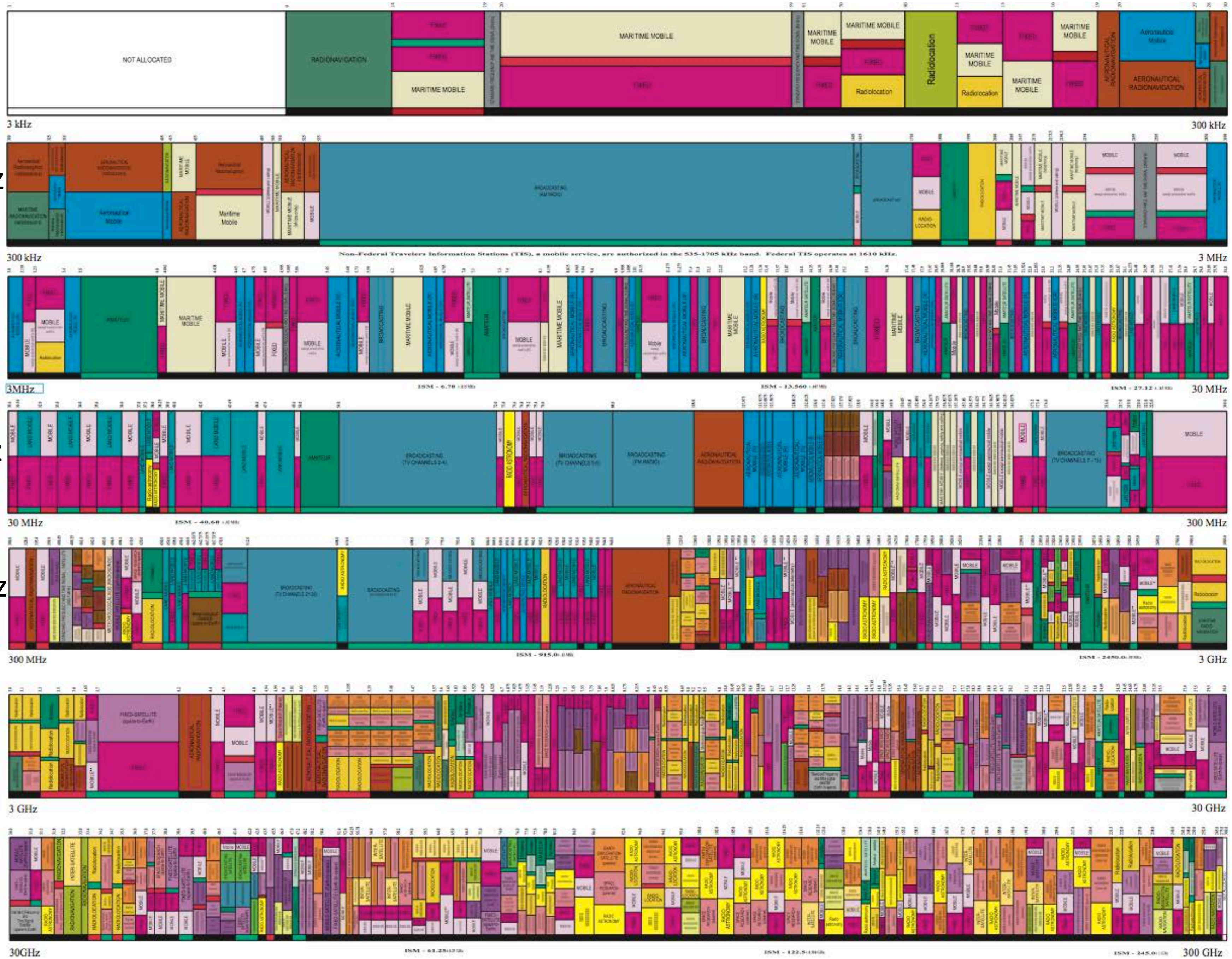
3 MHz
100m

30 MHz
10m

300MHz
1m

3 GHz
10cm

30 GHz
1cm



How bad is it?

How hot are the FM broadcasts from the CN tower?

Wikipedia

Frequency	kW	Callsign[46]	Branding
91.1 MHz	40	CJRT	JAZZ.FM91
94.1 MHz	38	CBL	CBC Radio 2
96.3 MHz	38	CFMZ	Classical 96
97.3 MHz	28.9	CHBM	boom 97.3
98.1 MHz	44	CHFI	98.1 CHFI
99.9 MHz	40	CKFM	Virgin Radio 99.9FM
100.7 MHz	4	CHIN	CHIN Radio
102.1 MHz	35	CFNY	102.1 the Edge
104.5 MHz	40	CHUM	104.5 CHUM FM
107.1 MHz	40	CILQ	Classic Rock Q 107

Wikipedia

Total: 350 kW

Back-of-the-Envelope!

What is the flux (in Jy) of the 350kW of FM radio coming off the CN tower at UofT? Assume an isotropic transmitter.

Bandwidth of FM: 20 MHz
Distance to the CN: ≈2km
1Jy = 10^{-26} W/m^2/Hz

2 mins, discuss with neighbours!

Wikipedia

Back-of-the-Envelope!

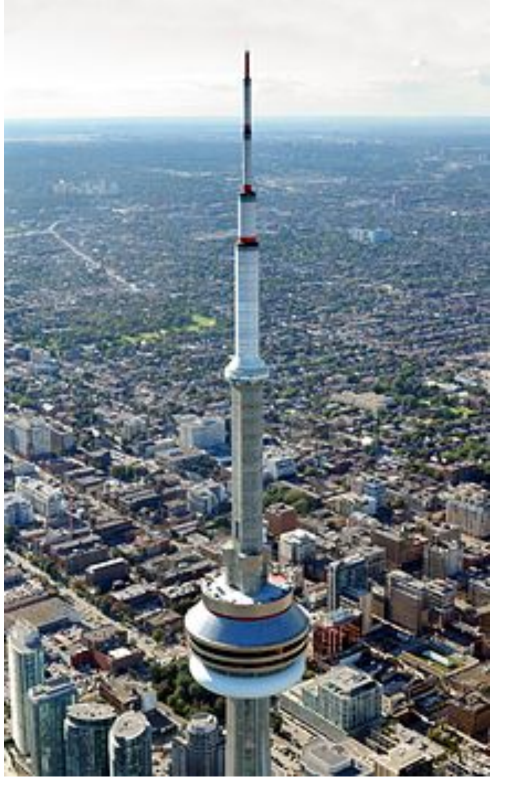
Part 2: We have a small, isotropic antenna, 85-105MHz. What temperature is the CN tower on our antenna?

Bandwidth of FM: 20 MHz

$S = 3 \times 10^{16}$ Jy

Reminder: $A_e\Omega = \lambda^2$; $P = kT\Delta\nu$

2 mins, discuss with neighbours!



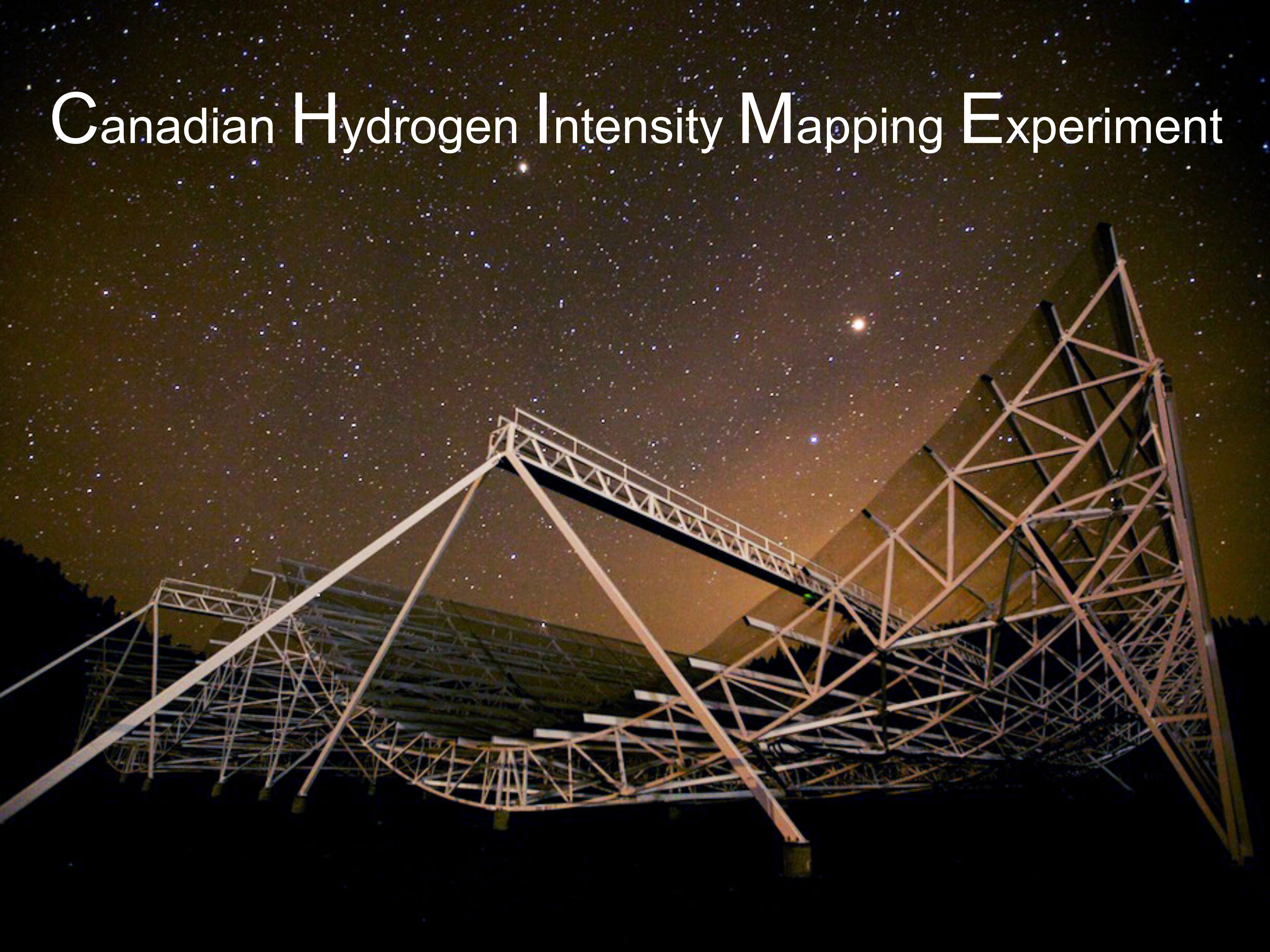
Wikipedia

Why it's hard

- Low power – there's just not much signal
- Big photons:
    - Limited array sizes – feeds are huge
    - Poor resolution – diffraction limit is not great
- Bright foregrounds – atmosphere and RFI

Why it's easy

- Daytime observing – the sky is dark
- Macroscopic equipment – fix it with a hammer!
- Diffraction-limited seeing – no need for adaptive optics
- High resolution w/ interferometry – Thursday!
- Lots to look at!

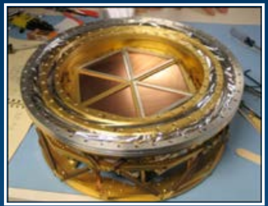

Canadian Hydrogen Intensity Mapping Experiment

CHIME: Built!

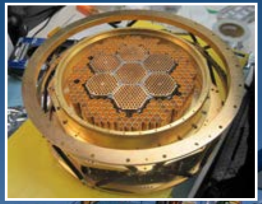
The South Pole Telescope (SPT)

10-meter primary dish, observe the CMB with arcminute resolution

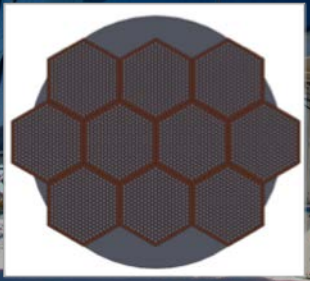
SPT-SZ (2007)
960 detectors
95,150,220 GHz



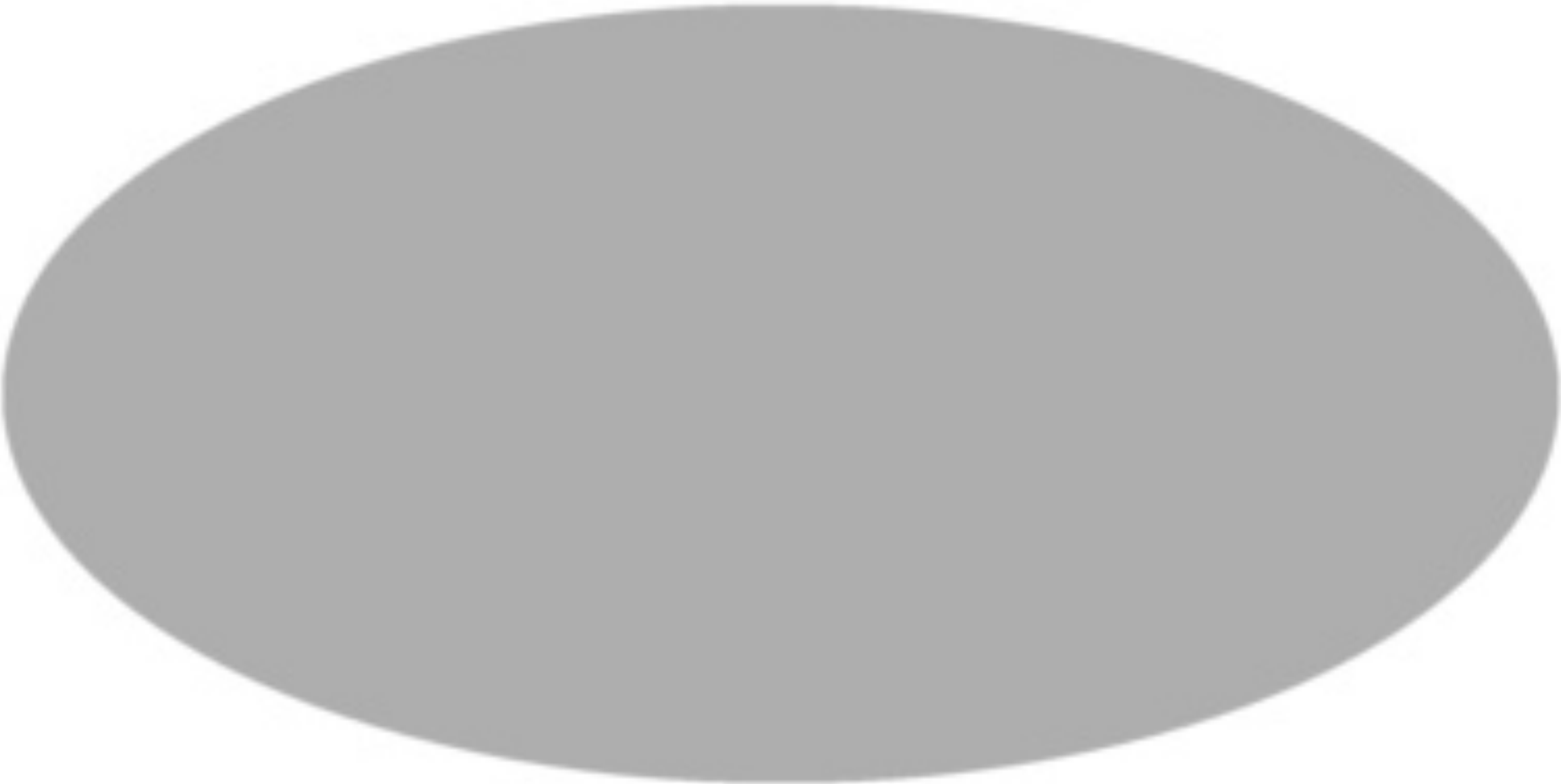
SPTpol (2012)
1600 detectors
95,150 GHz
+Polarization



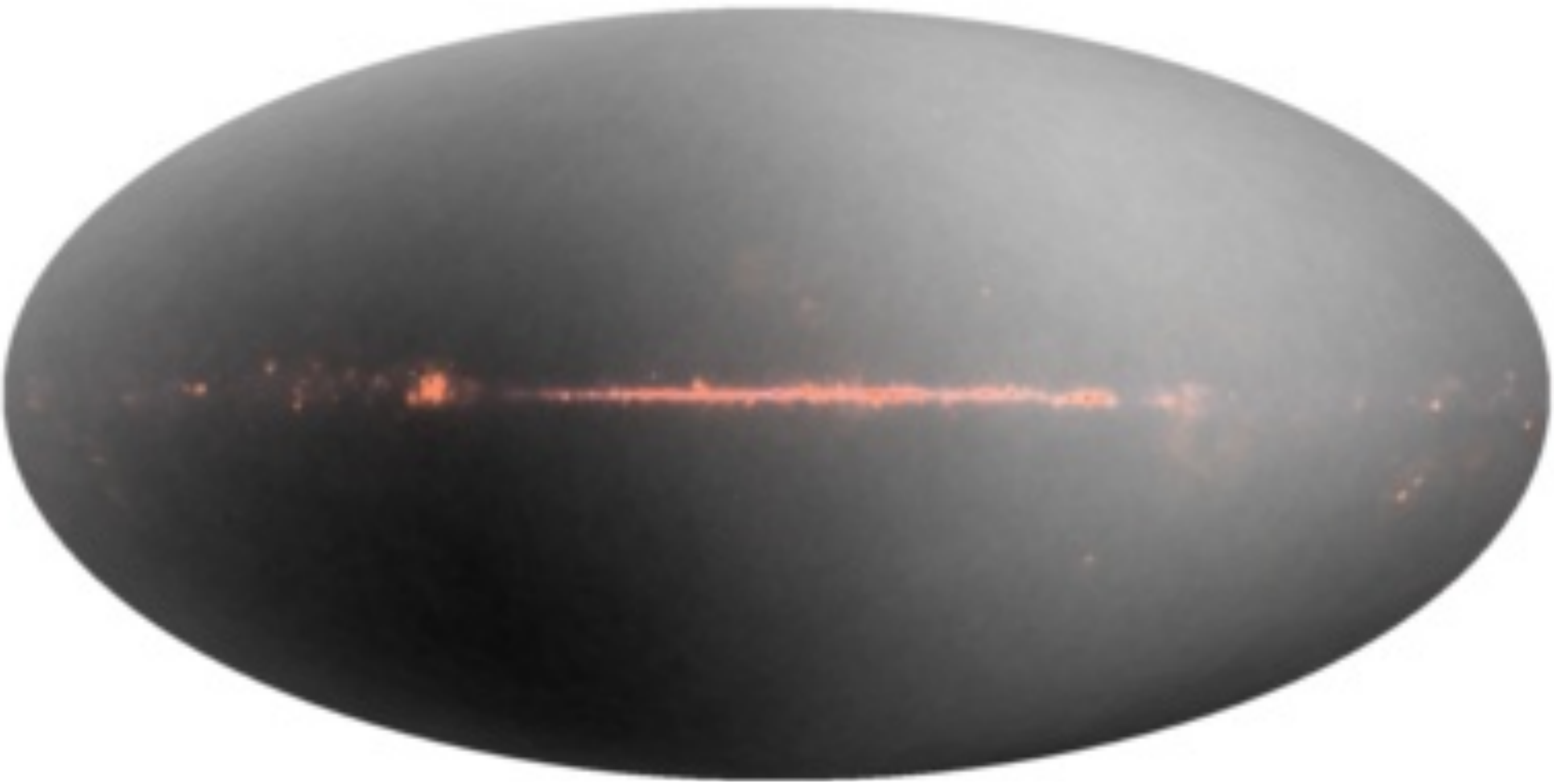
SPT-3G (2016)
≈16,000 detectors
95,150,220 GHz
+Polarization



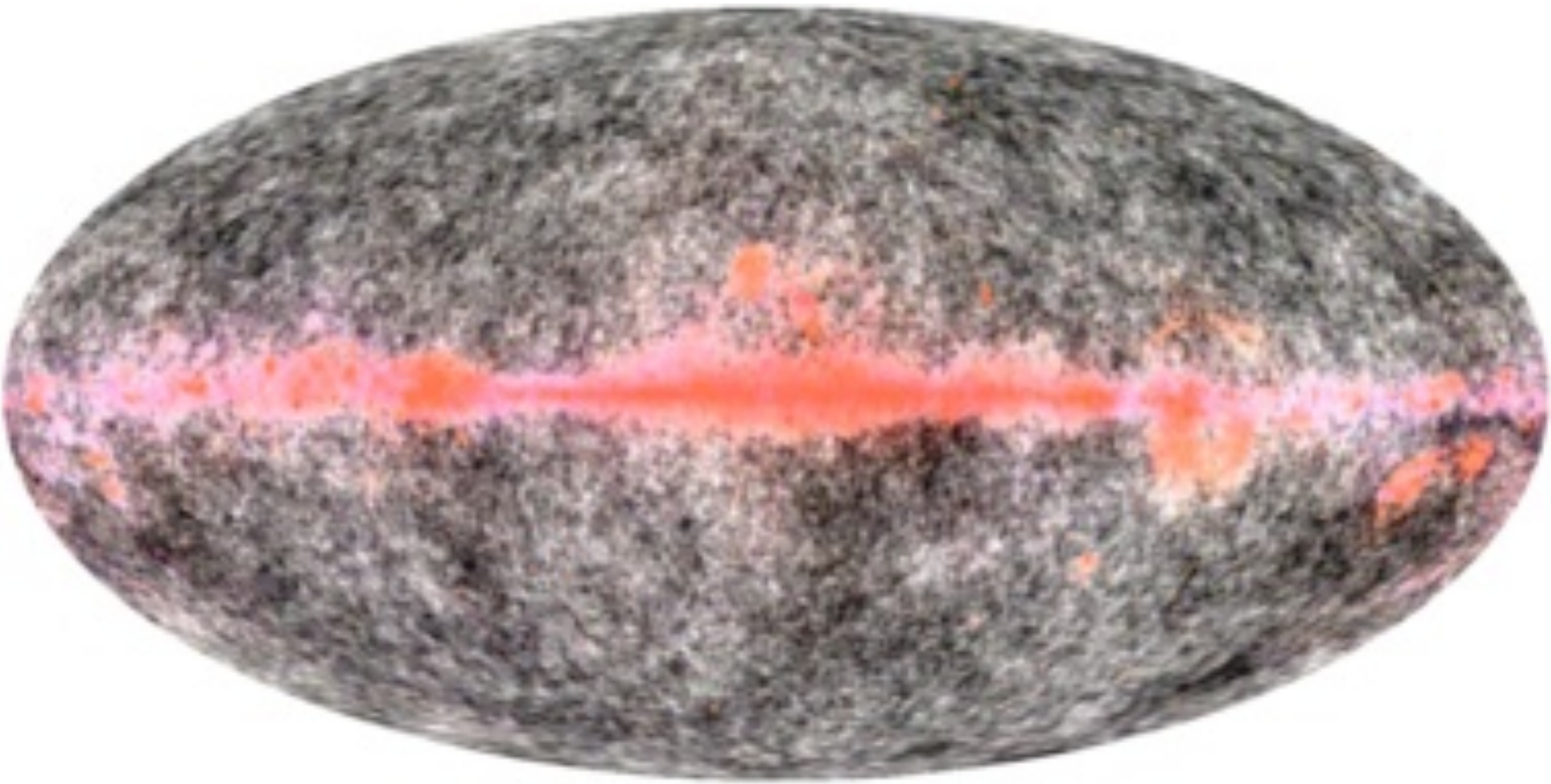
Microwave Sky



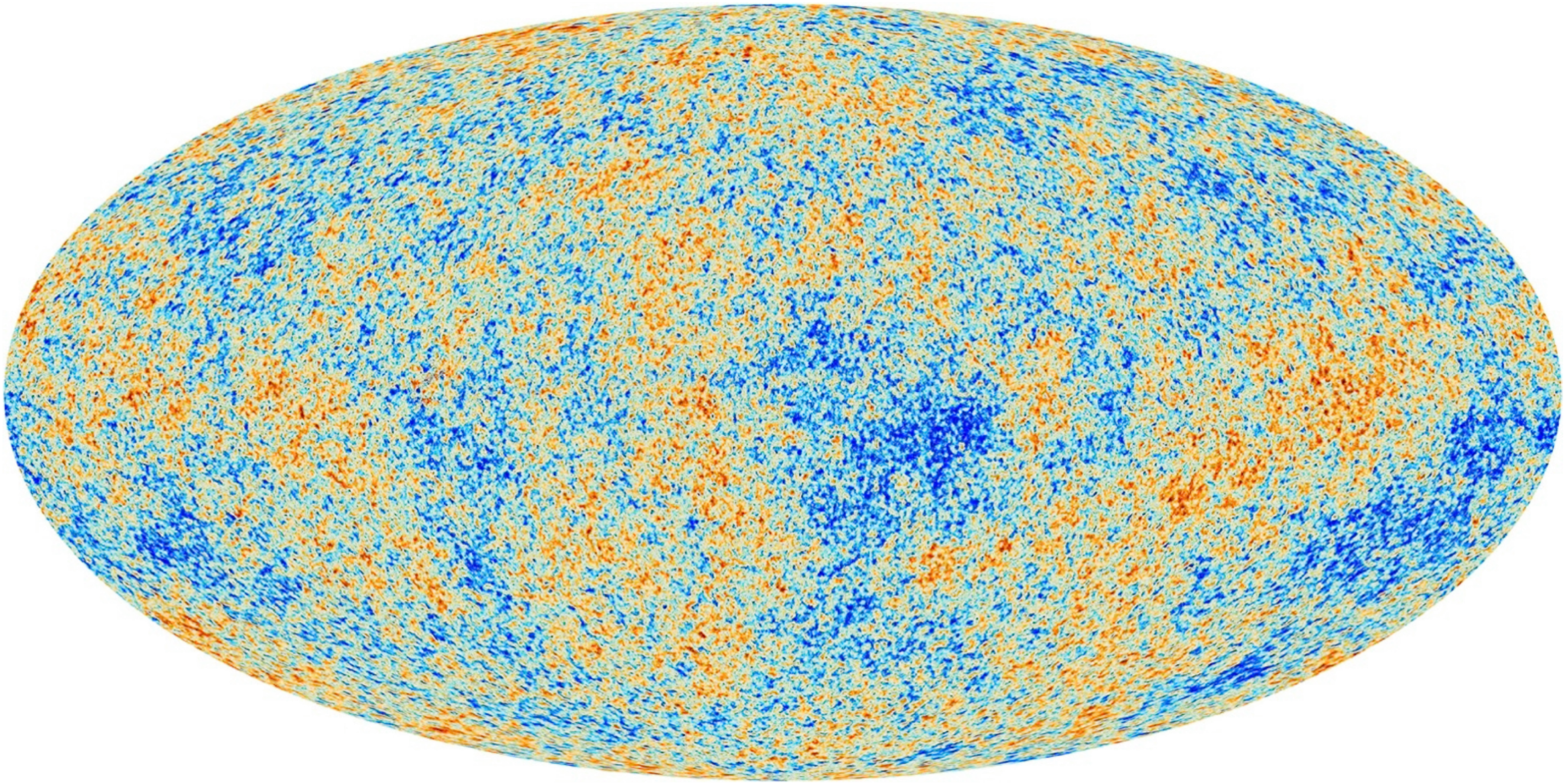
Microwave Sky



Microwave Sky



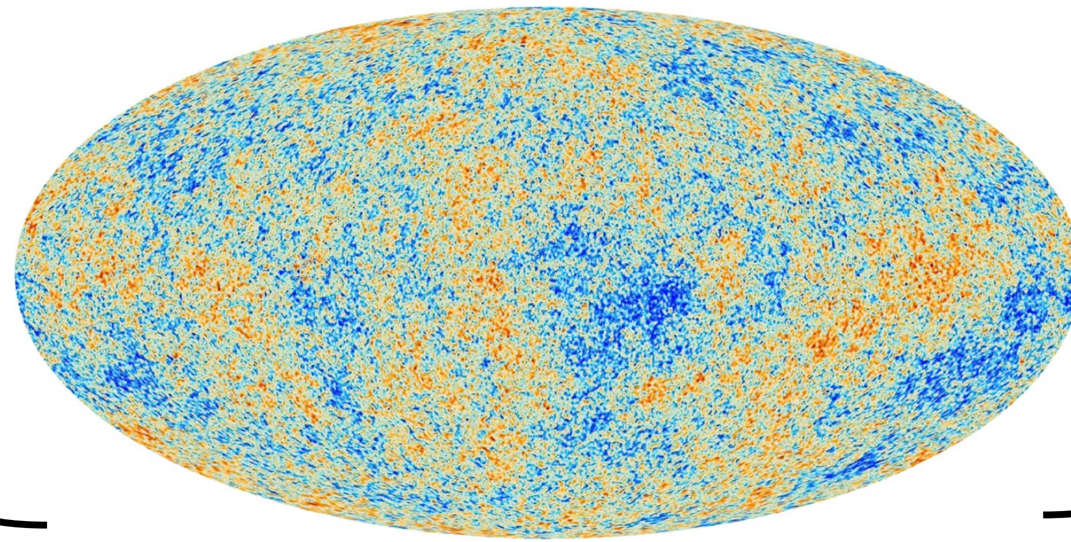
Cosmic Microwave Background



Planck Temperature (2013)

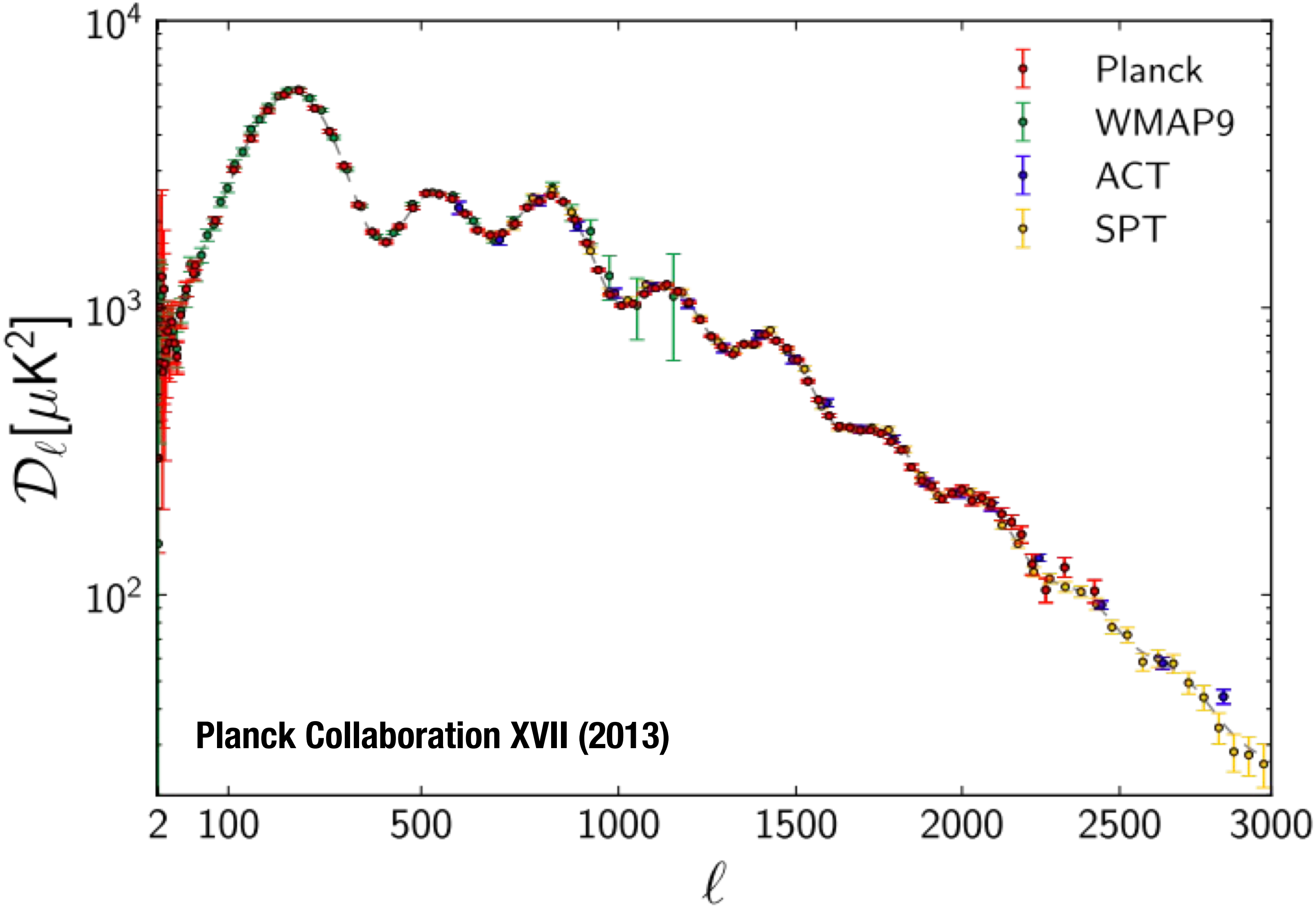
Cosmic Microwave Background

FT

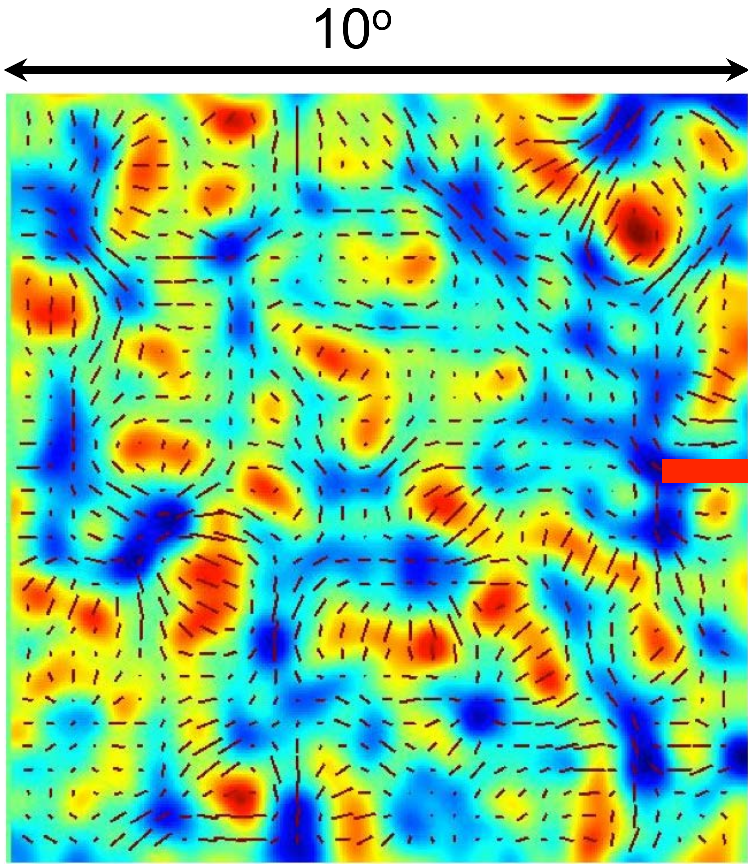


Planck Temperature (2013)

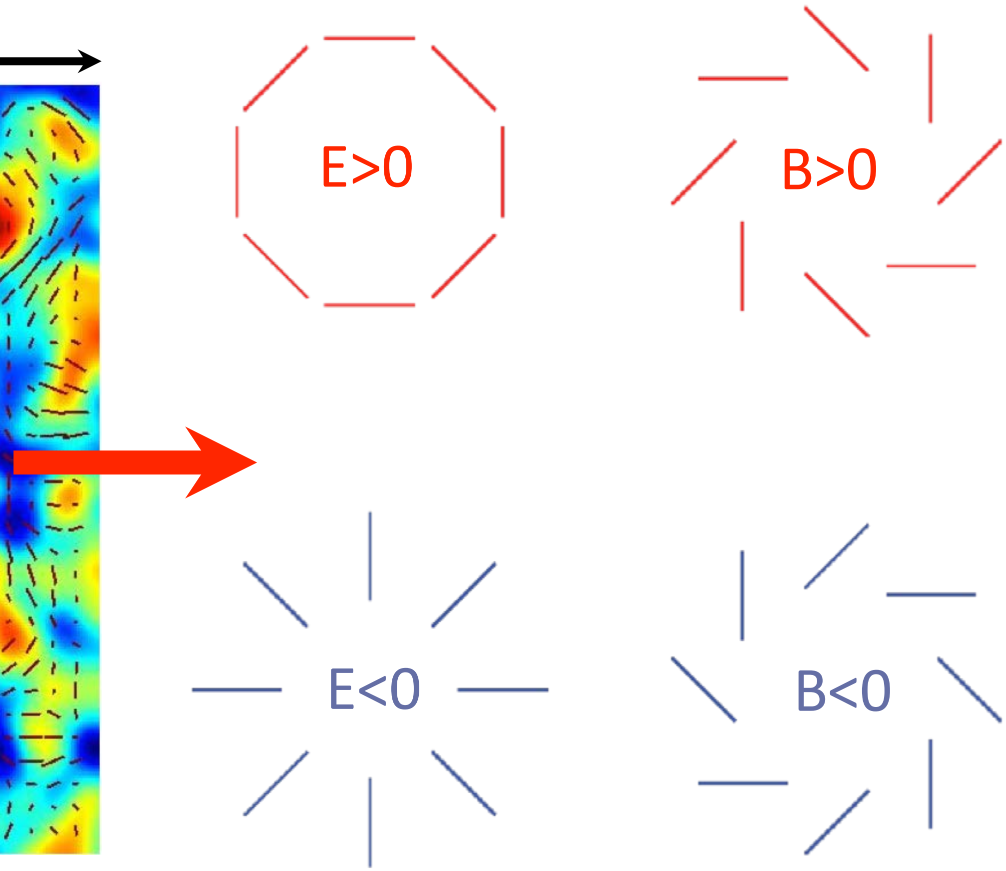
Temperature Power Spectrum
measured to very high precision



CMB Polarization Primer



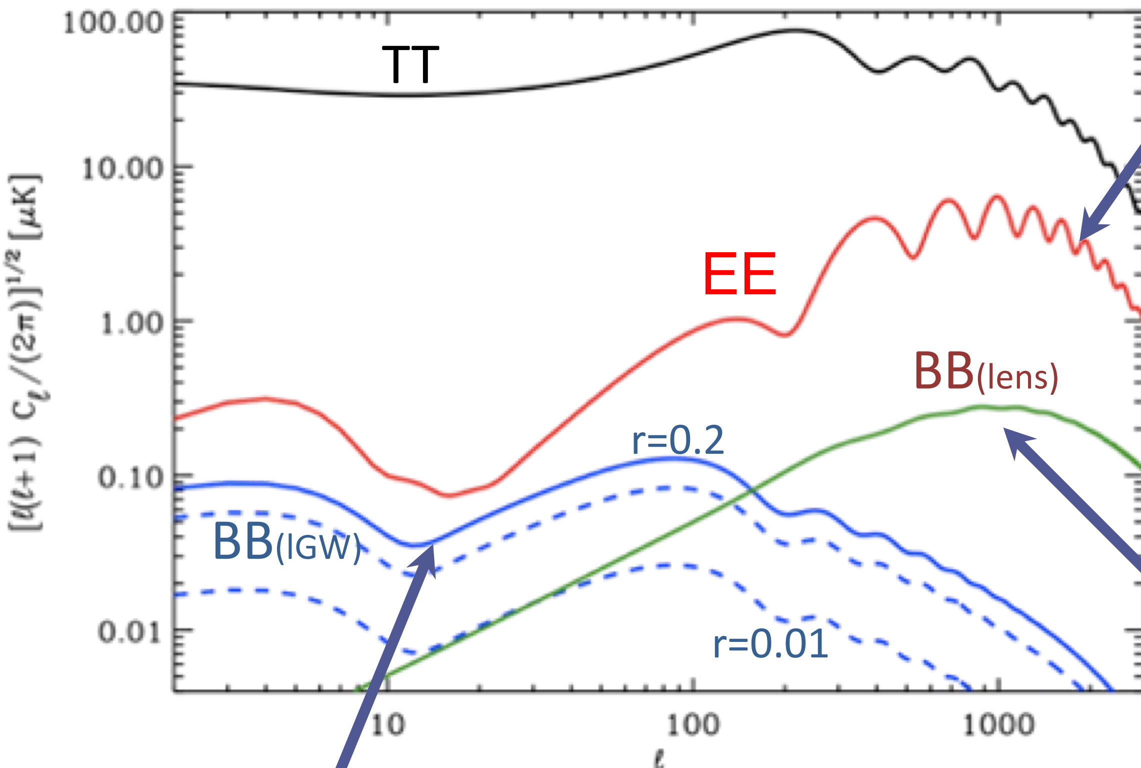
Seljak & Zaldarriaga 1998



E-modes:
Even Parity

B-modes:
Odd Parity

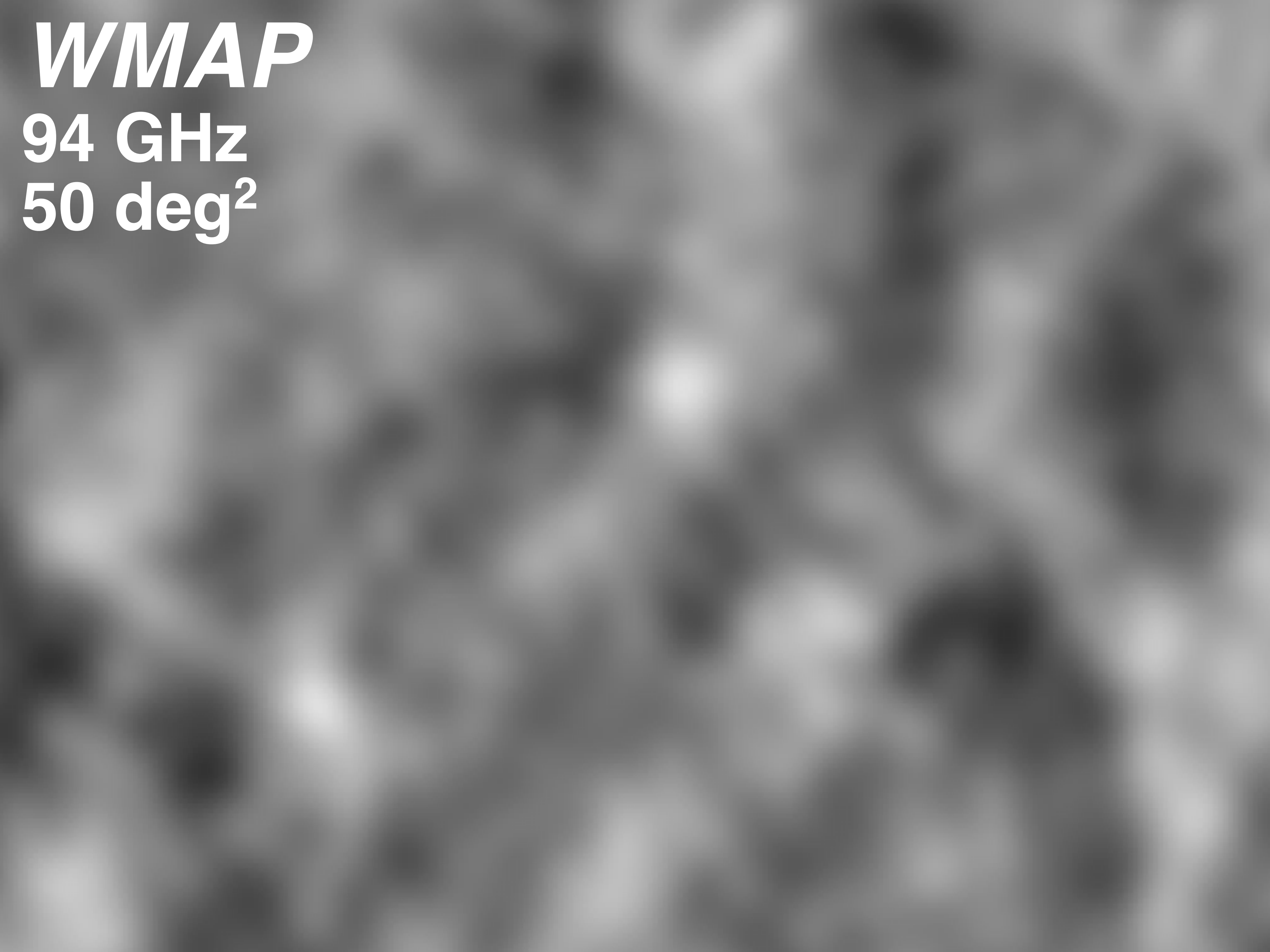
Polarization Power Spectra

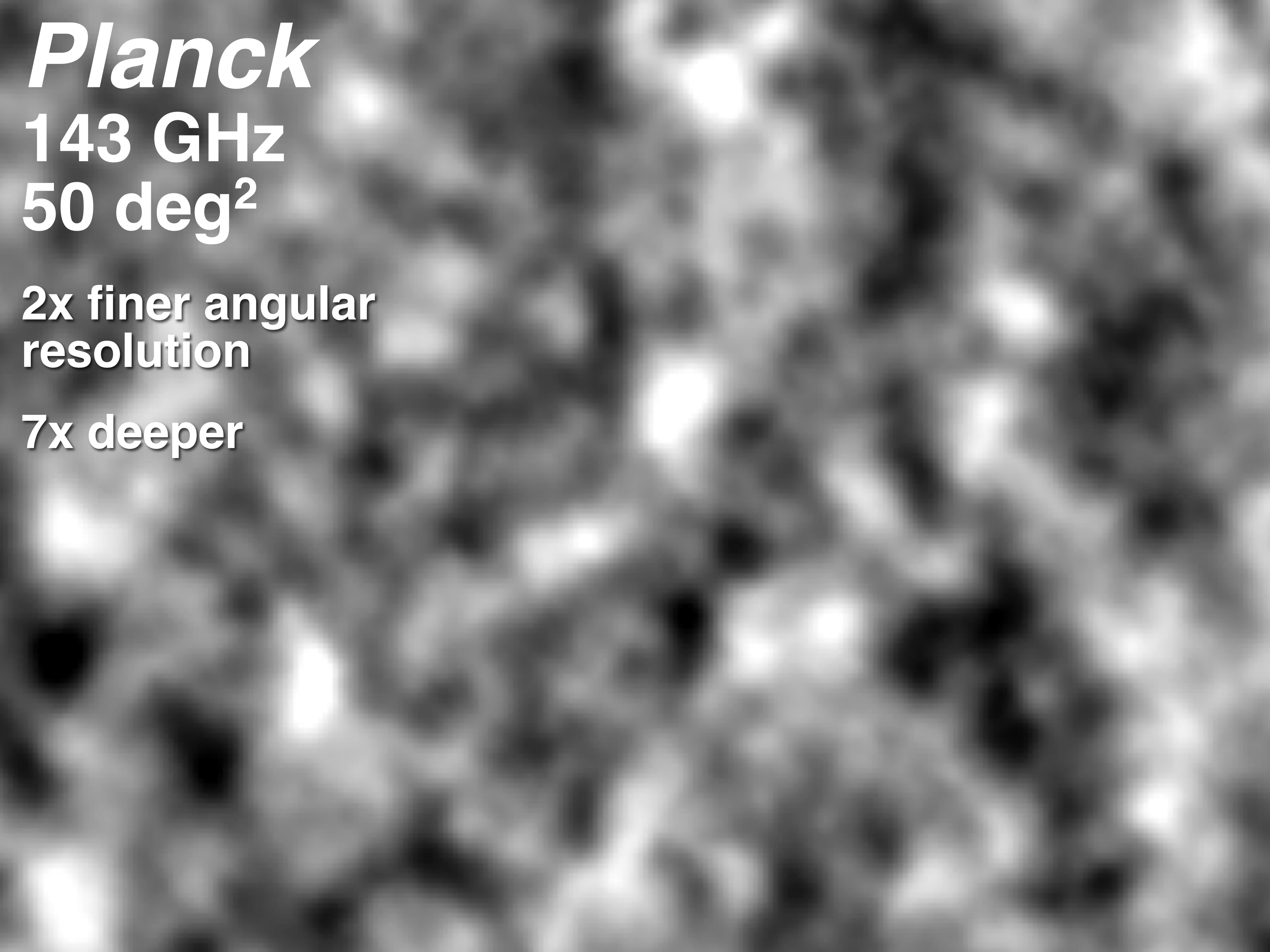


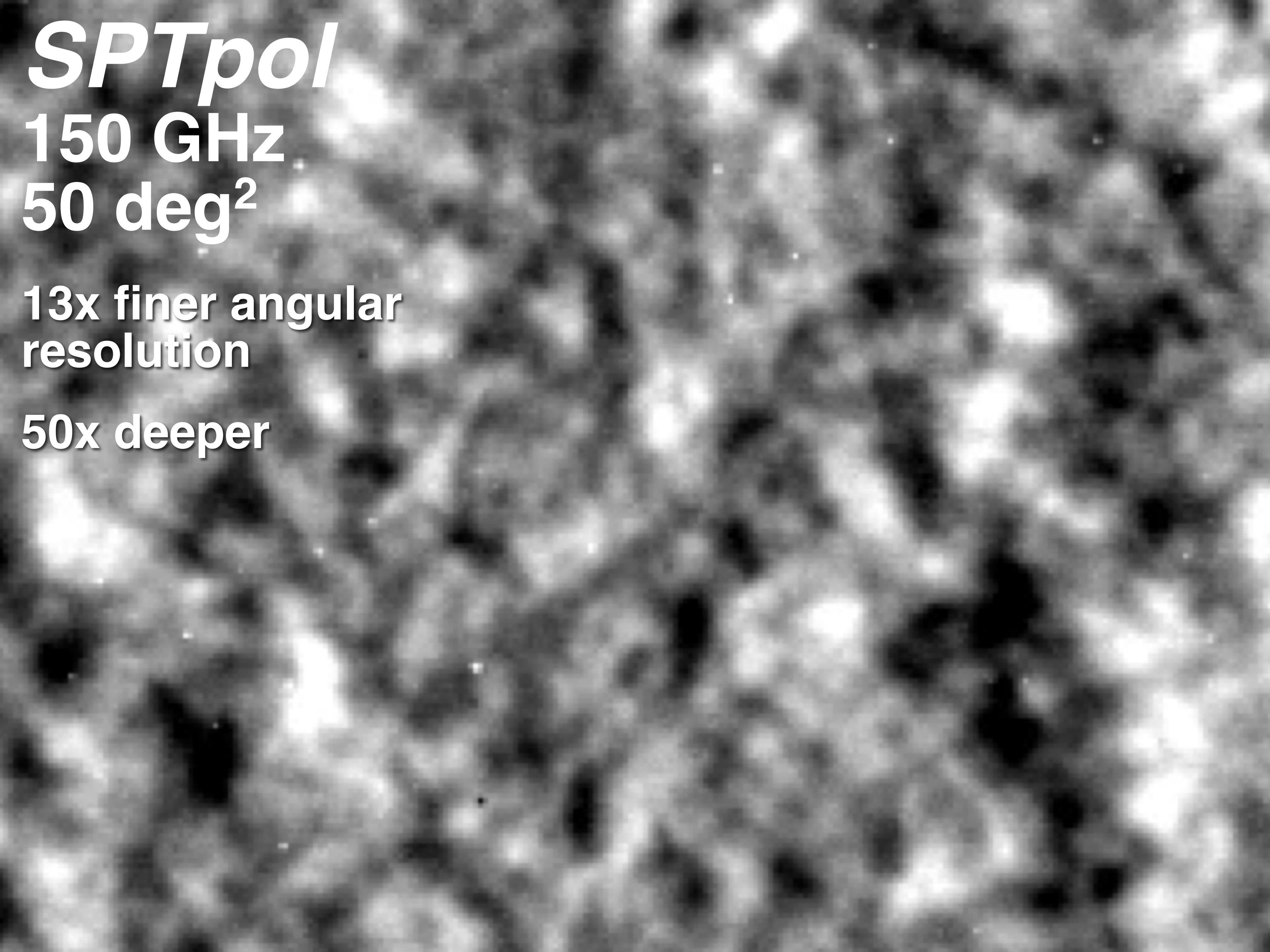
E modes Provide a second, more constraining view of the TT science

Lensing B modes probe the clustering of matter at intermediate redshifts, z~[0.5, 4] and are sensitive to neutrino masses.

Primordial B-modes arise from gravitational waves during inflation.


WMAP
94 GHz
50 deg²


Planck
143 GHz
50 deg^2
2x finer angular resolution
7x deeper


SPTpol
150 GHz
50 deg^2
13x finer angular resolution
50x deeper

How do I minimize noise?

$$N \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}} \approx \frac{\cancel{T_{\mathrm{cmb}}} + \Delta T_{\mathrm{source}} + T_{\mathrm{atm}} + T_{\mathrm{spillover}} + T_{\mathrm{rcvr}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

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1. Increase τ

   (Already at 5 year exposure.)

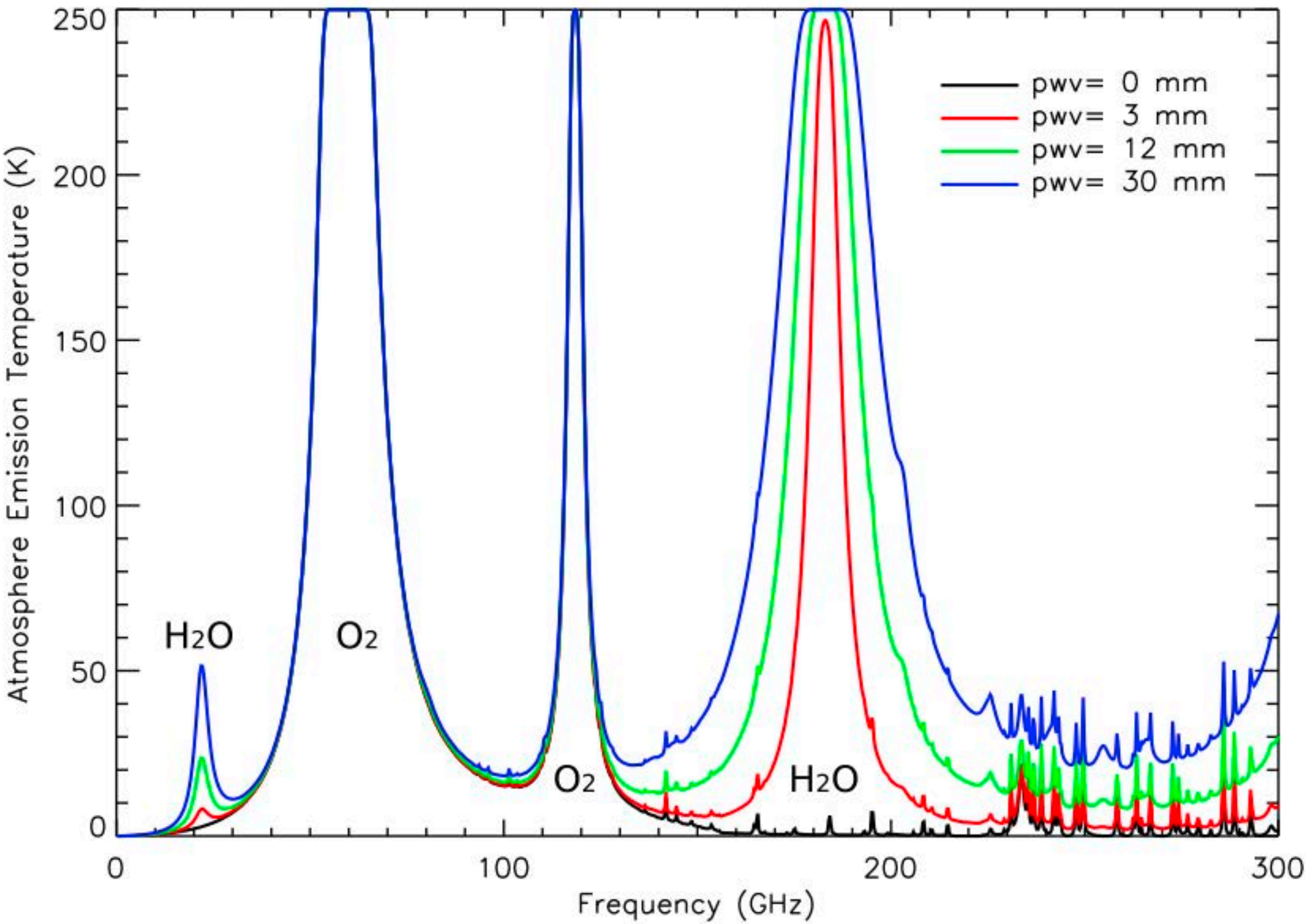
How do I minimize noise?

$$\boldsymbol{N} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}} \approx \frac{\cancel{T_{\mathrm{cmb}}} + \Delta T_{\mathrm{source}} + T_{\mathrm{atm}} + T_{\mathrm{spillover}} + T_{\mathrm{rcvr}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

1. Increase τ
   (Already at 5 year exposure.)

1. Decrease T_{atm}

Atmospheric Contamination



How do we avoid Water?

Go somewhere high & dry: the South Pole!

- **High Elevation**
  (thick ice shelf + thin atmosphere)

- **Extremely Dry**
  (very little water vapor at -70C)

- **Stable**
  (no diurnal variations, low turbulence)

Weather for South Pole Station

The date is 08-30-2008 at 2:52 PM

Temperature

-69.9 C -93.8 F

Windchill

-100.1 C -148.2 F

Wind

20.3 kts Grid 2

Barometer

667.3 mb (11111 ft)

Wintering-Over

Machinery doesn’t work in extreme cold.

People do.
Leave them!

How do I minimize noise?

$$\boldsymbol{N} \approx \frac{T_{\rm sys}}{\sqrt{\Delta\nu_{\rm RF}\tau}} \approx \frac{\cancel{T_{\rm cmb}} + \Delta T_{\rm source} + \cancel{T_{\rm atm}} + T_{\rm spillover} + T_{\rm rcvr}}{\sqrt{\Delta\nu_{\rm RF}\tau}}$$

1. Increase τ
   (Already at 5 year exposure.)

2. Decrease T_{atm}
   (Move to the driest place on earth.)

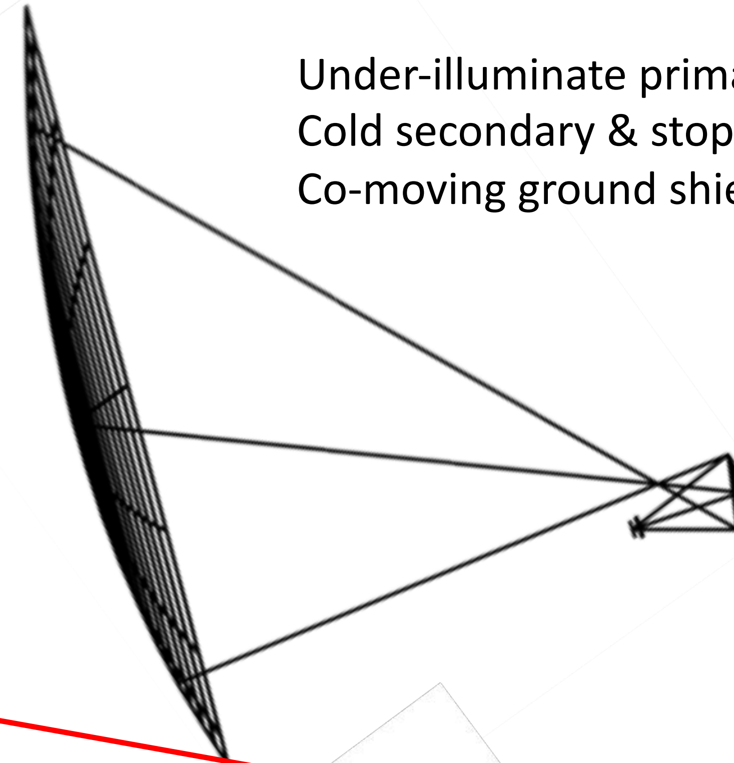
How do I minimize noise?

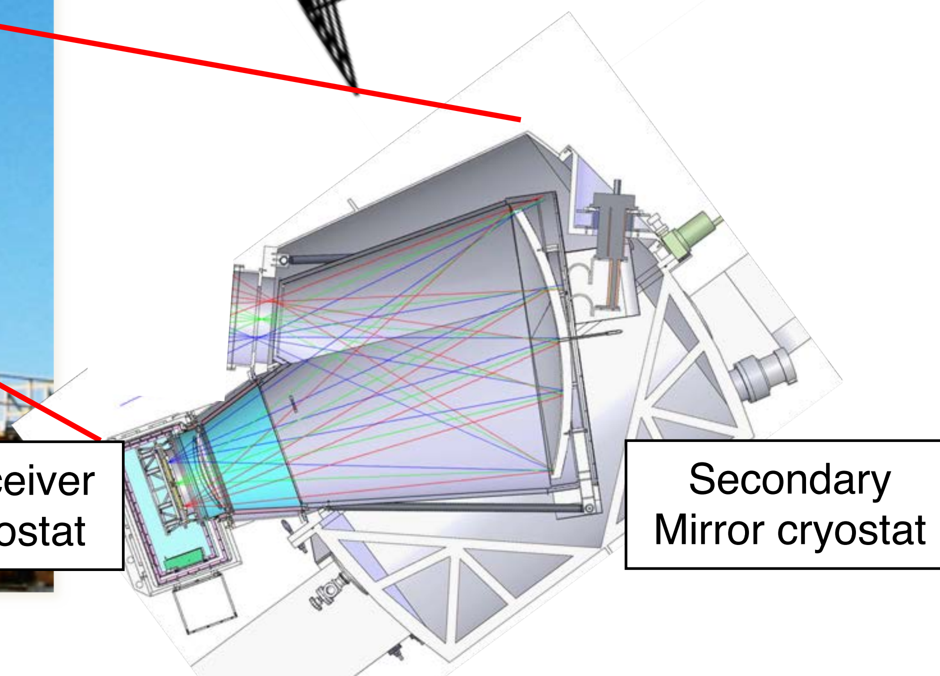
$$\boldsymbol{N} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}} \approx \frac{\cancel{T_{\mathrm{cmb}}} + \Delta T_{\mathrm{source}} + \cancel{T_{\mathrm{atm}}} + T_{\mathrm{spillover}} + T_{\mathrm{rcvr}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

1. Increase τ
   (Already at 5 year exposure.)
2. Decrease T_{atm}
   (Move to the driest place on earth.)
3. Remove ground spill

SPT Optics

Under-illuminate primary,
Cold secondary & stops,
Co-moving ground shields.





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2. Decrease T_{atm}

   (Move to the driest place on earth.)

3. Remove ground spill

   (Careful optics & shielding.)

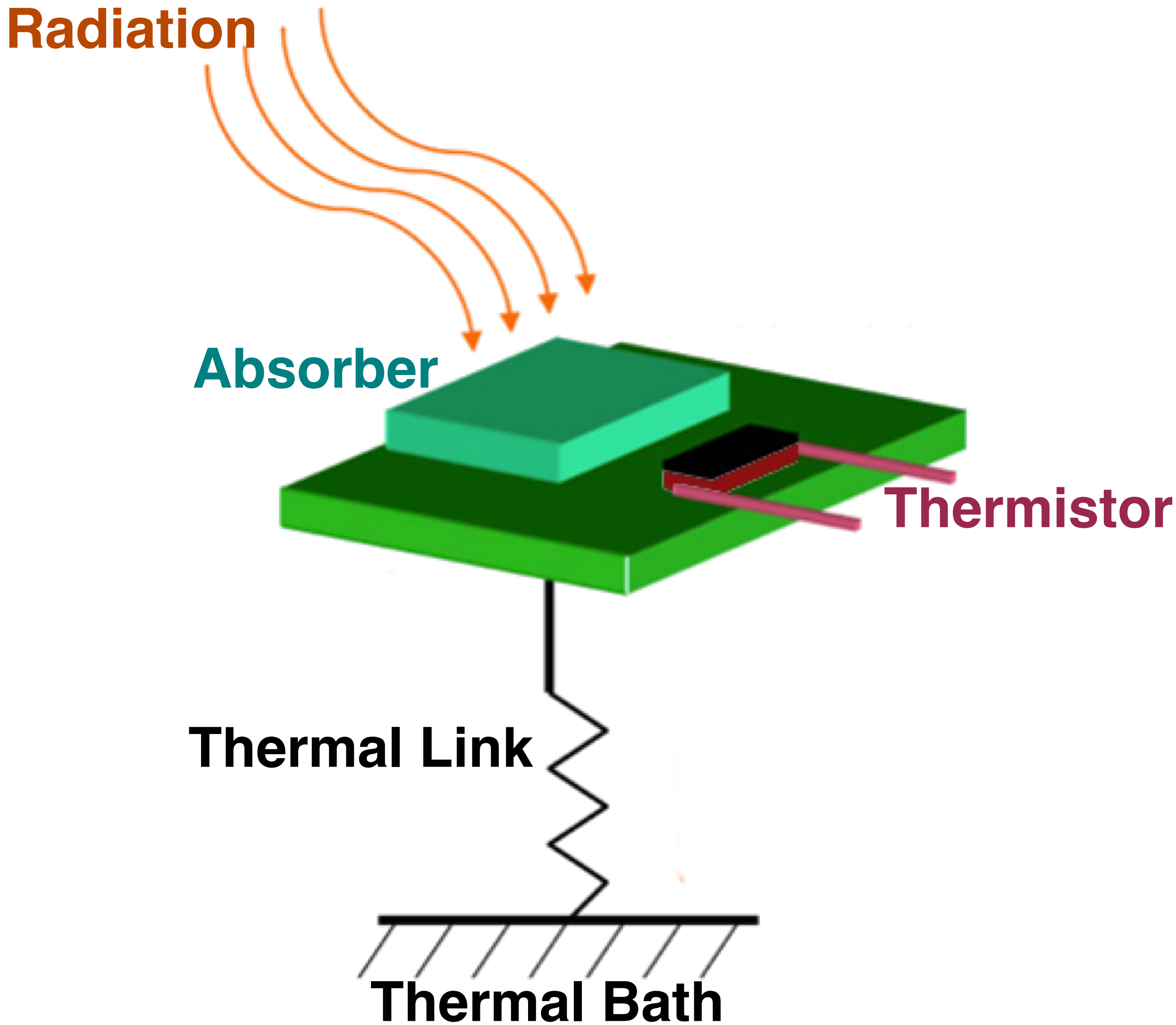
How do I minimize noise?

$$\boldsymbol{N} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}} \approx \frac{\cancel{T_{\mathrm{cmb}}} + \Delta T_{\mathrm{source}} + \cancel{T_{\mathrm{atm}}} + \cancel{T_{\mathrm{spillover}}} + T_{\mathrm{rcvr}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

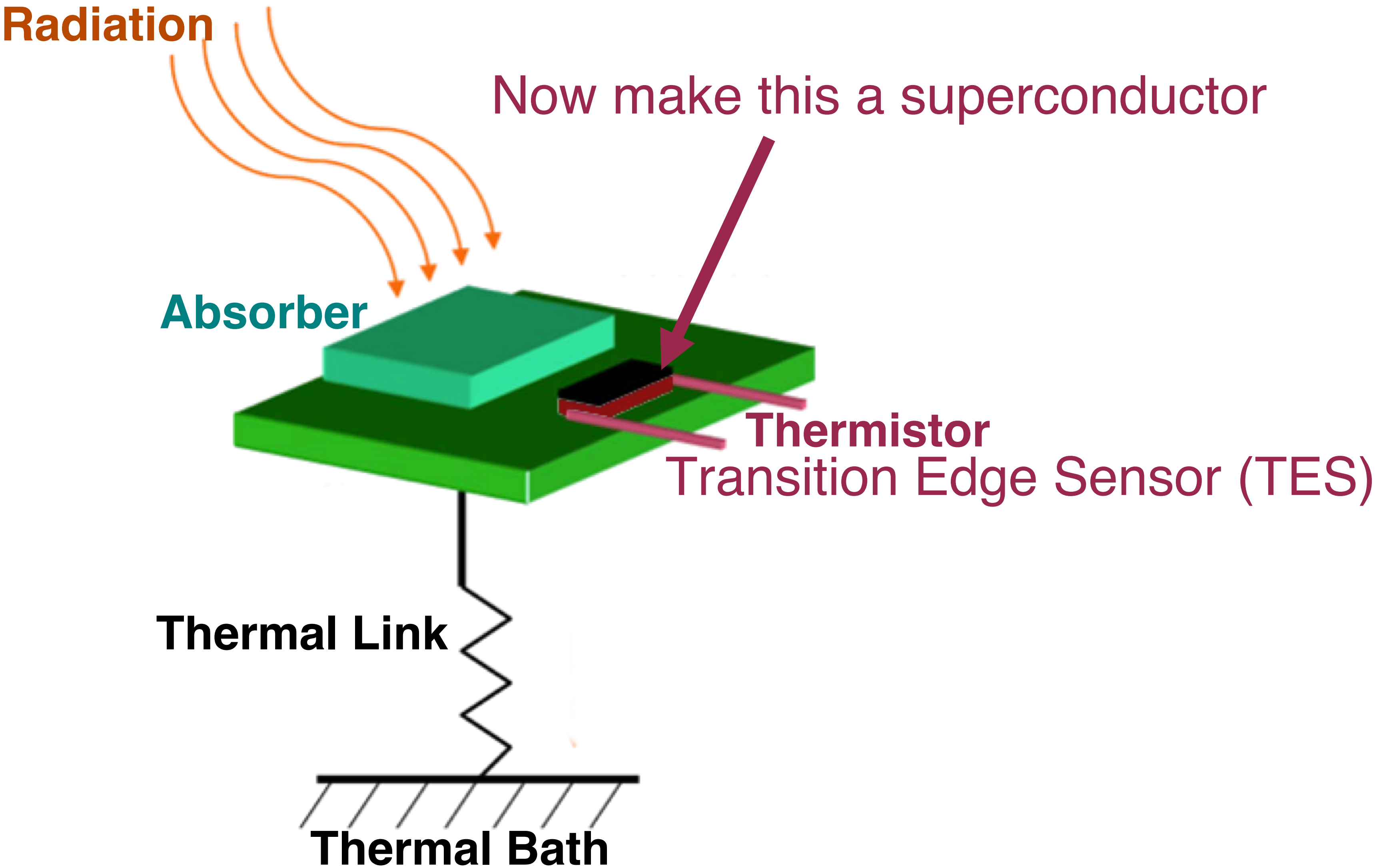
1. Increase τ
   (Already at 5 year exposure.)
2. Decrease T_{atm}
   (Move to the driest place on earth.)
3. Remove ground spill
   (Careful optics & shielding.)

4. Remove detector noise

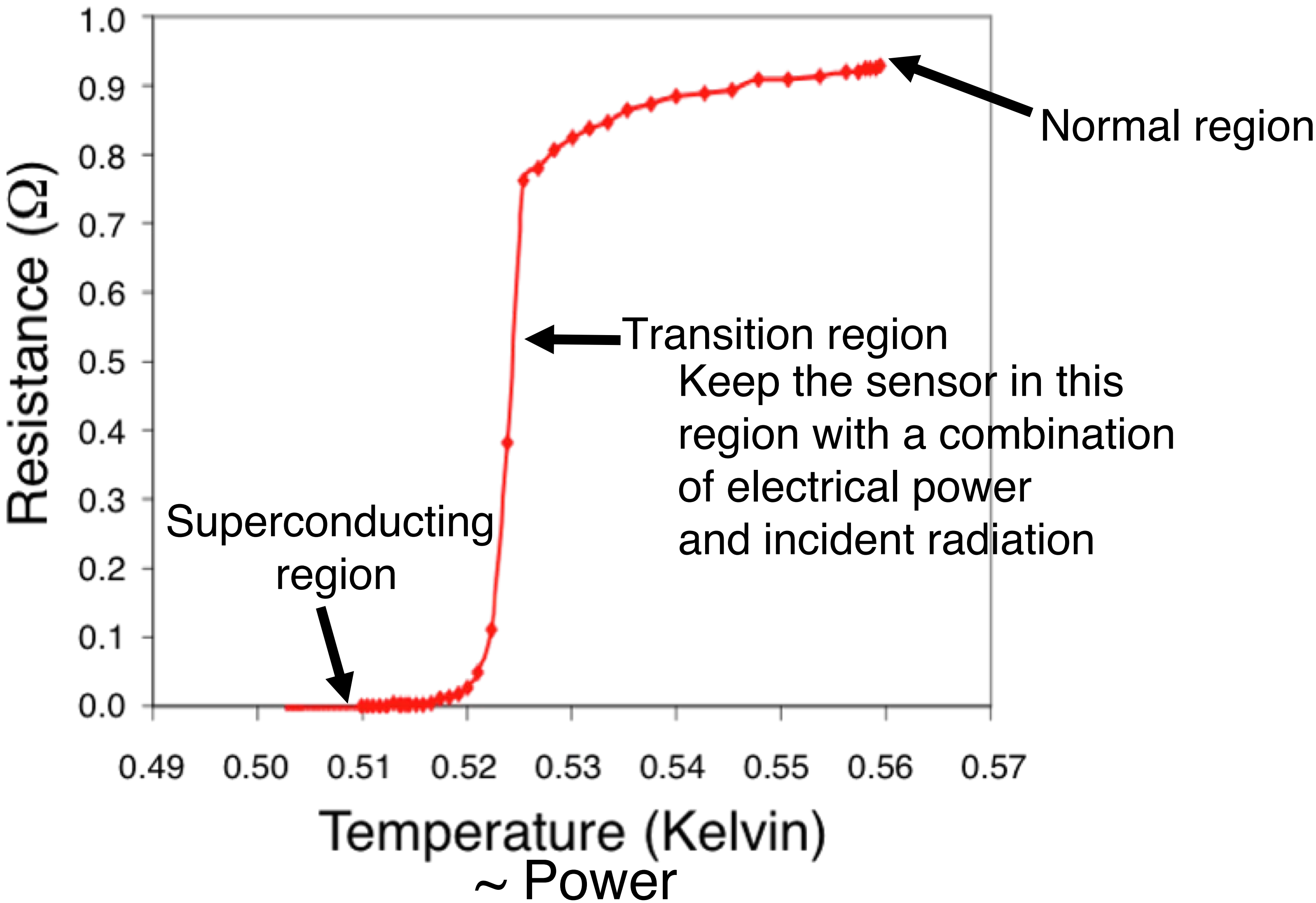
Bolometer Basics



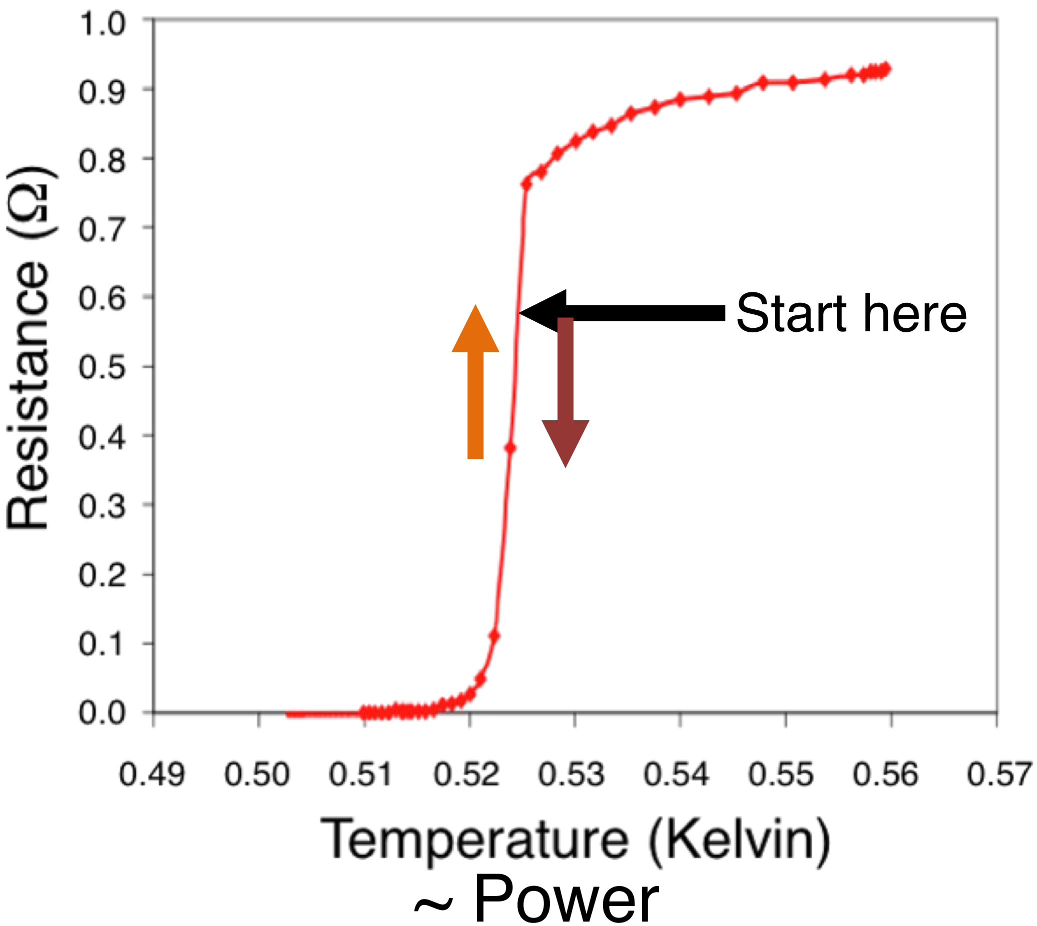
TES Bolometer Basics



Transition Edge Sensors (TES)



Transition Edge Sensors (TES)



Negative ElectroThermal Feedback

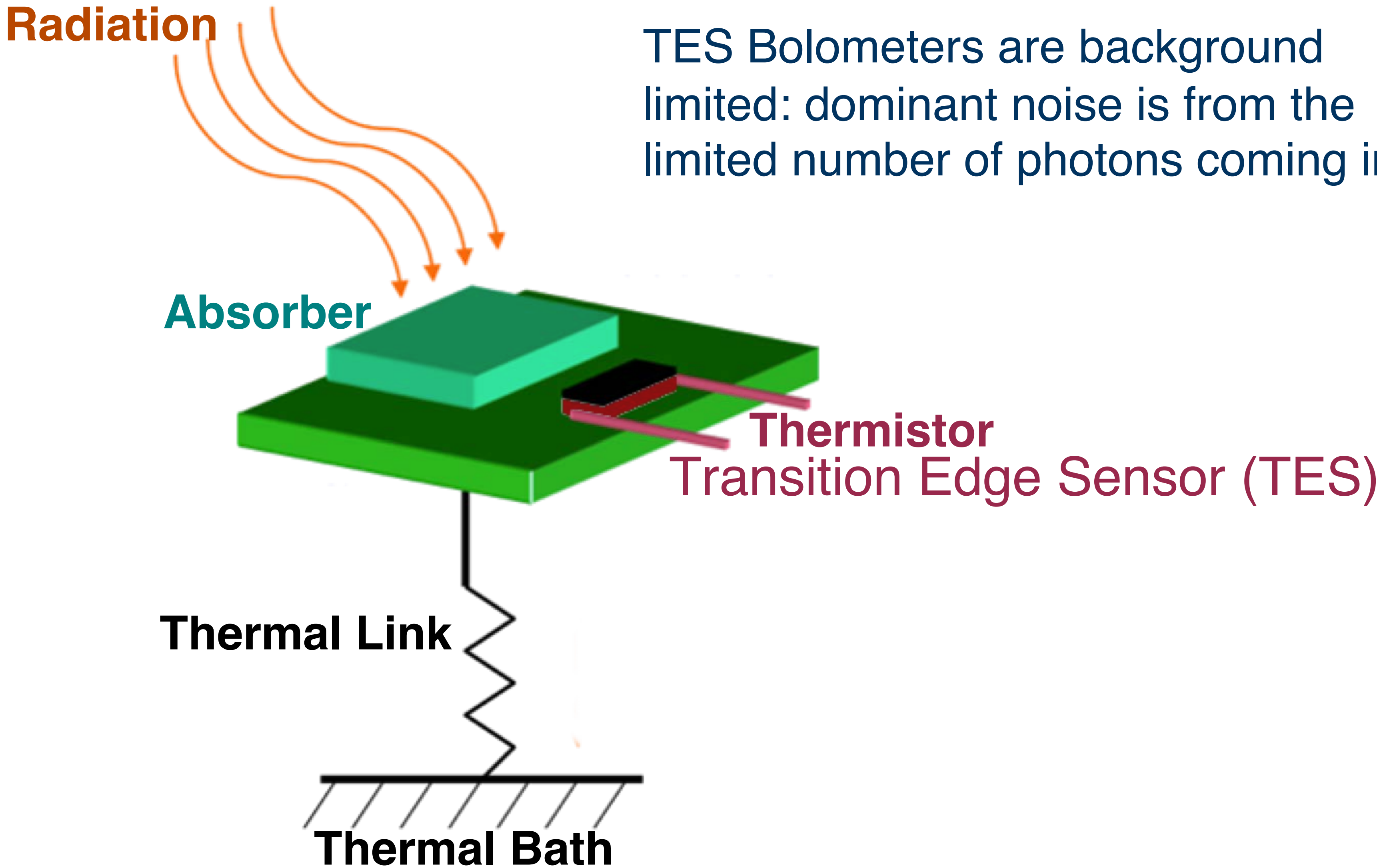
Hold voltage fixed
('voltage biased')

$$V = I\uparrow * R\downarrow$$

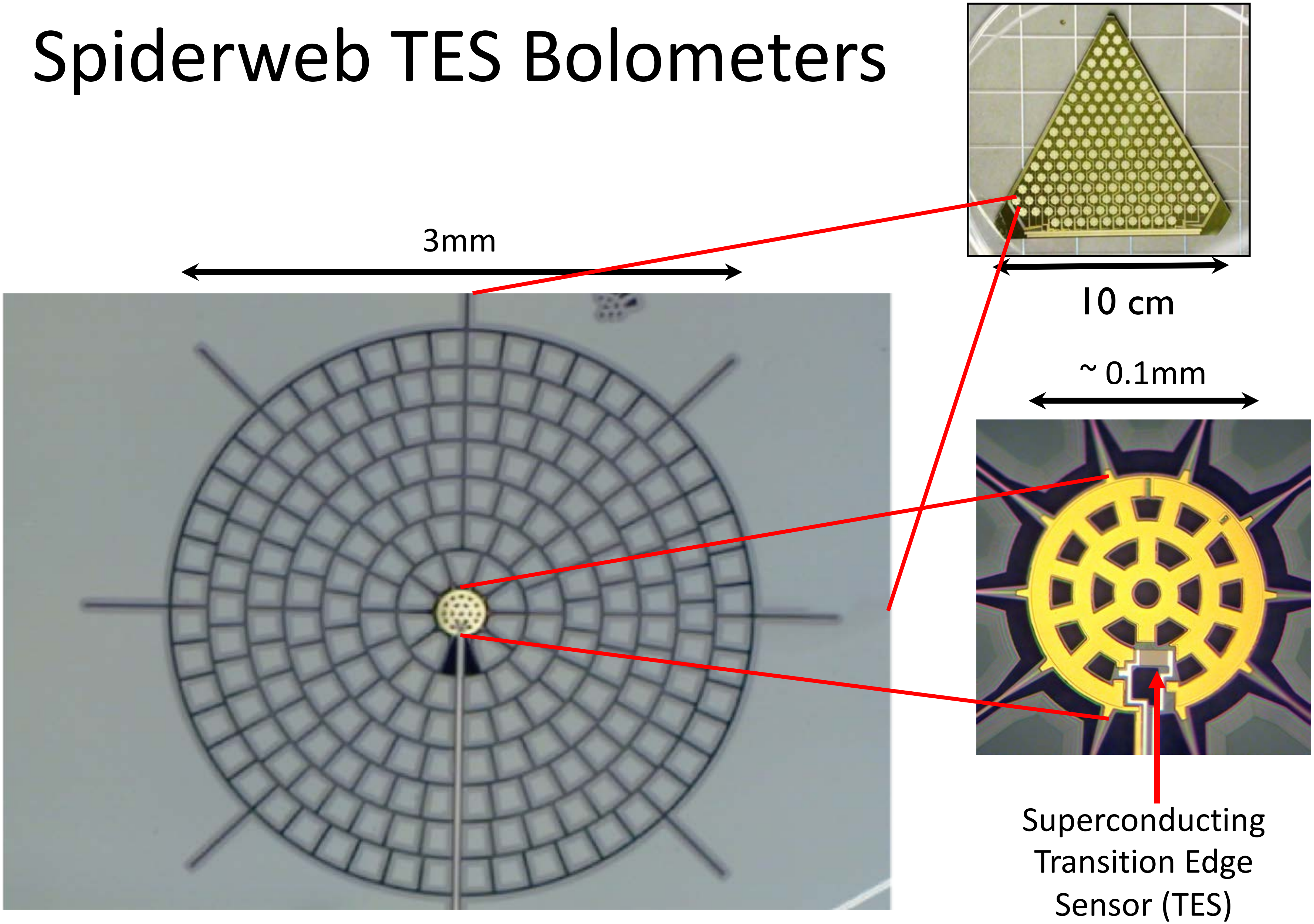
$$\uparrow P = I\uparrow * V$$

TES Bolometer Basics

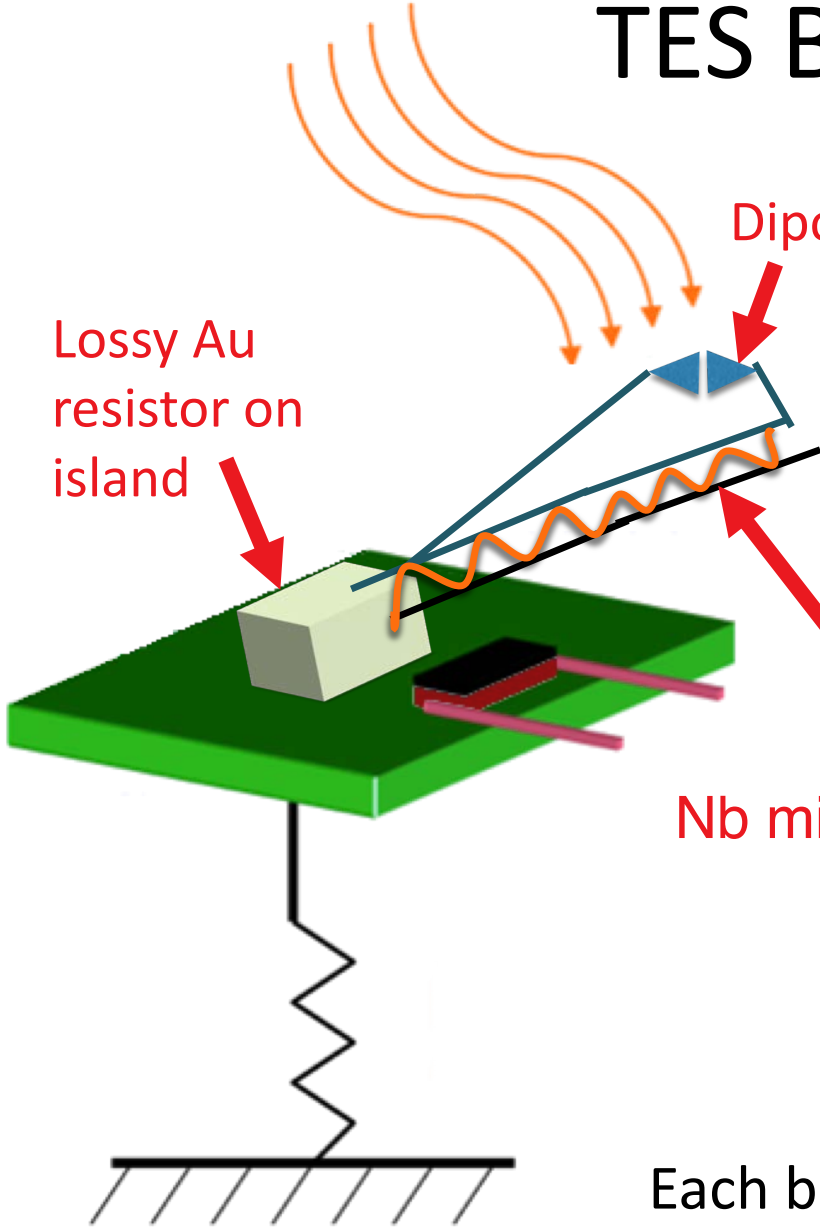
TES Bolometers are background limited: dominant noise is from the limited number of photons coming in.

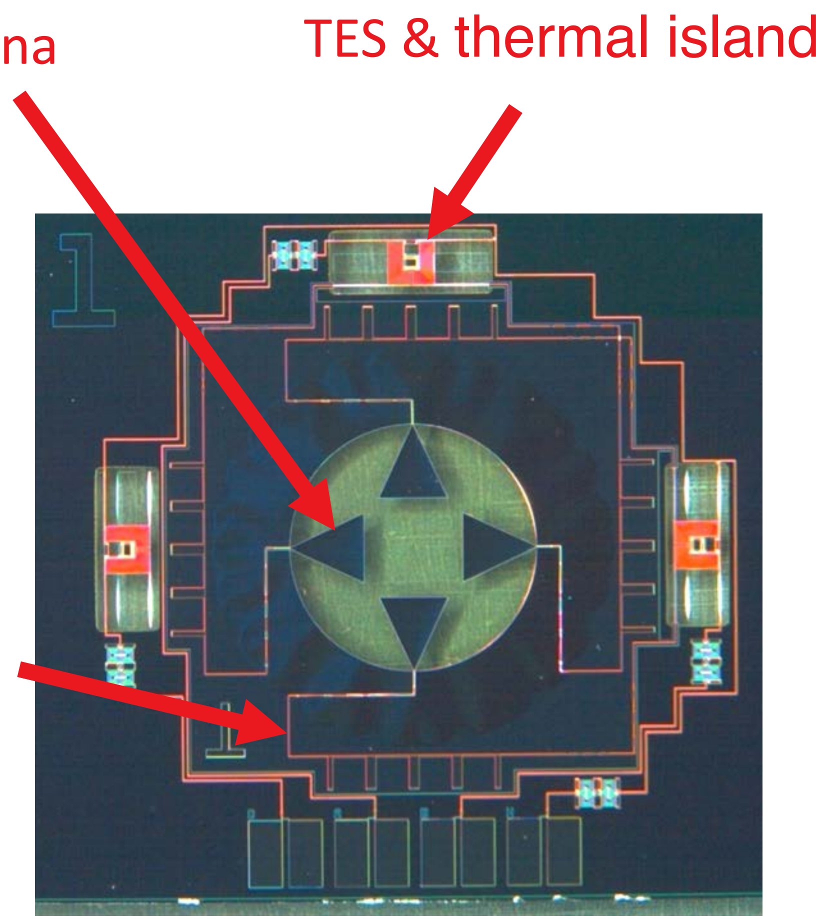


Spiderweb TES Bolometers



Antenna Coupled TES Bolometers

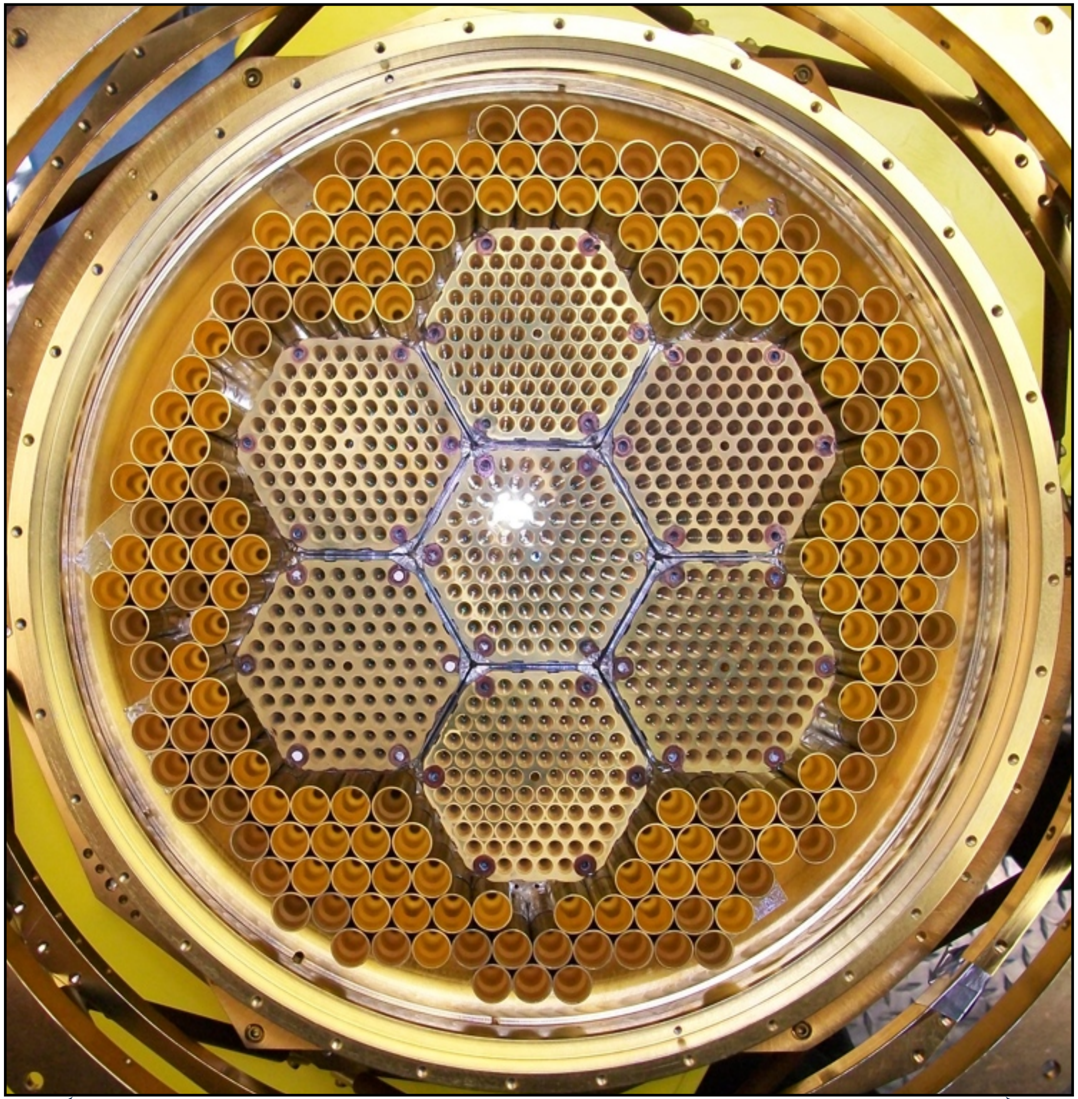




Each bolometer sees only one polarization!

SPTpol

- Total of 1536 detectors (TES bolometers).
- 588 dual-polarization sensitive pixels at 150 GHz.
- 180 dual-polarization pixels at 90 GHz.
- First light January 2012.



~21 cm

How do I minimize noise?

$$\boldsymbol{N} \approx \frac{T_{\rm sys}}{\sqrt{\Delta\nu_{\rm RF}\tau}} \approx \frac{\cancel{T_{\rm cmb}} + \Delta T_{\rm source} + \cancel{T_{\rm atm}} + \cancel{T_{\rm spillover}} + \cancel{T_{\rm rcvr}}}{\sqrt{\Delta\nu_{\rm RF}\tau}}$$

1. Increase τ
   (Already at 5 year exposure.)

2. Decrease T_{atm}
   (Move to the driest place on earth.)

3. Remove ground spill
   (Careful optics & shielding.)

4. Remove detector noise
   (Use sub-kelvin TES bolometers.)

How do I minimize noise?

$$\boldsymbol{N} \approx \frac{T_{\rm sys}}{\sqrt{\Delta\nu_{\rm RF}\tau}} \approx \frac{\cancel{T_{\rm cmb}} + \Delta T_{\rm source} + \cancel{T_{\rm atm}} + \cancel{T_{\rm spillover}} + \cancel{T_{\rm rcvr}}}{\sqrt{\Delta\nu_{\rm RF}\tau}}$$

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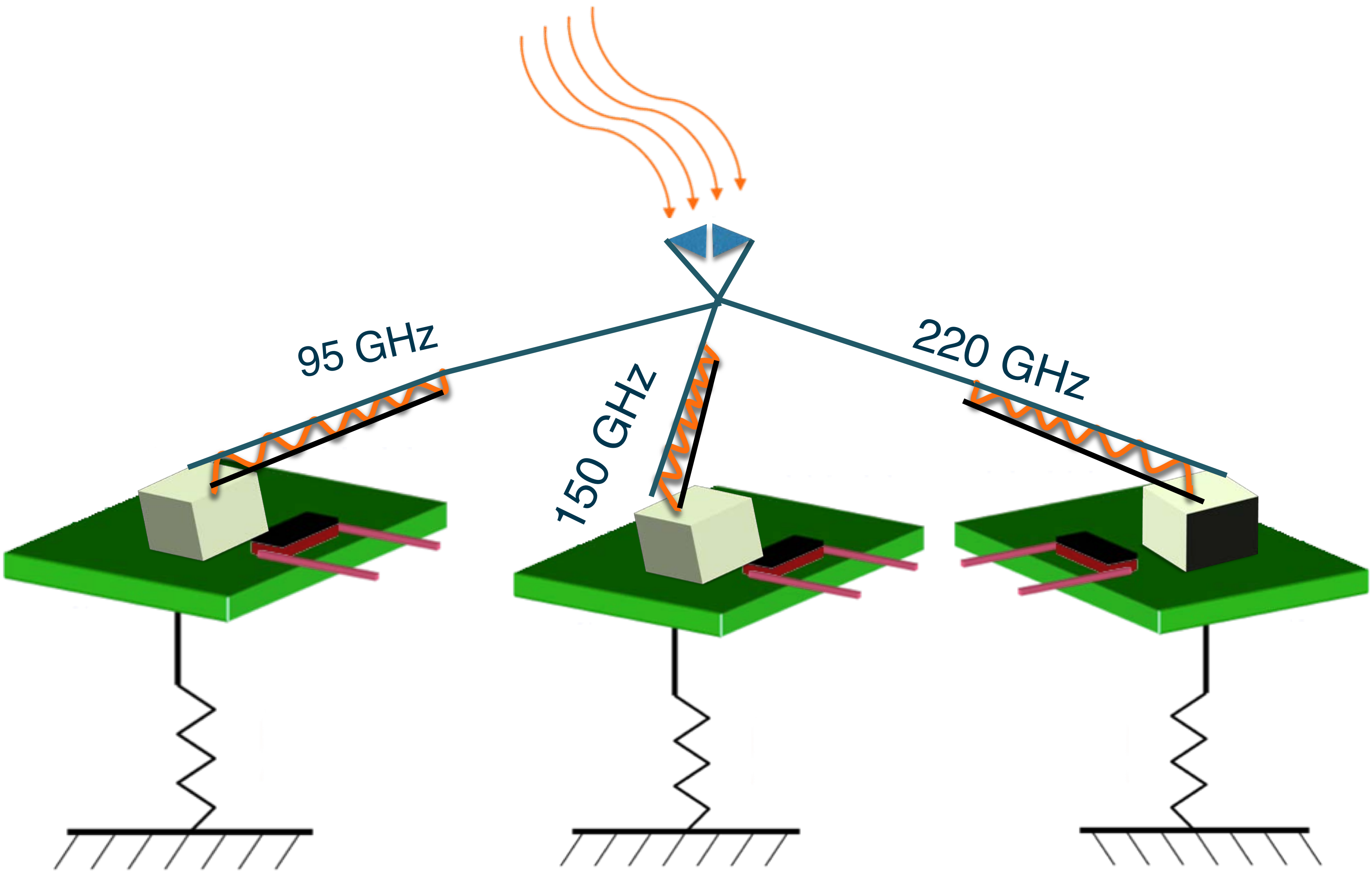
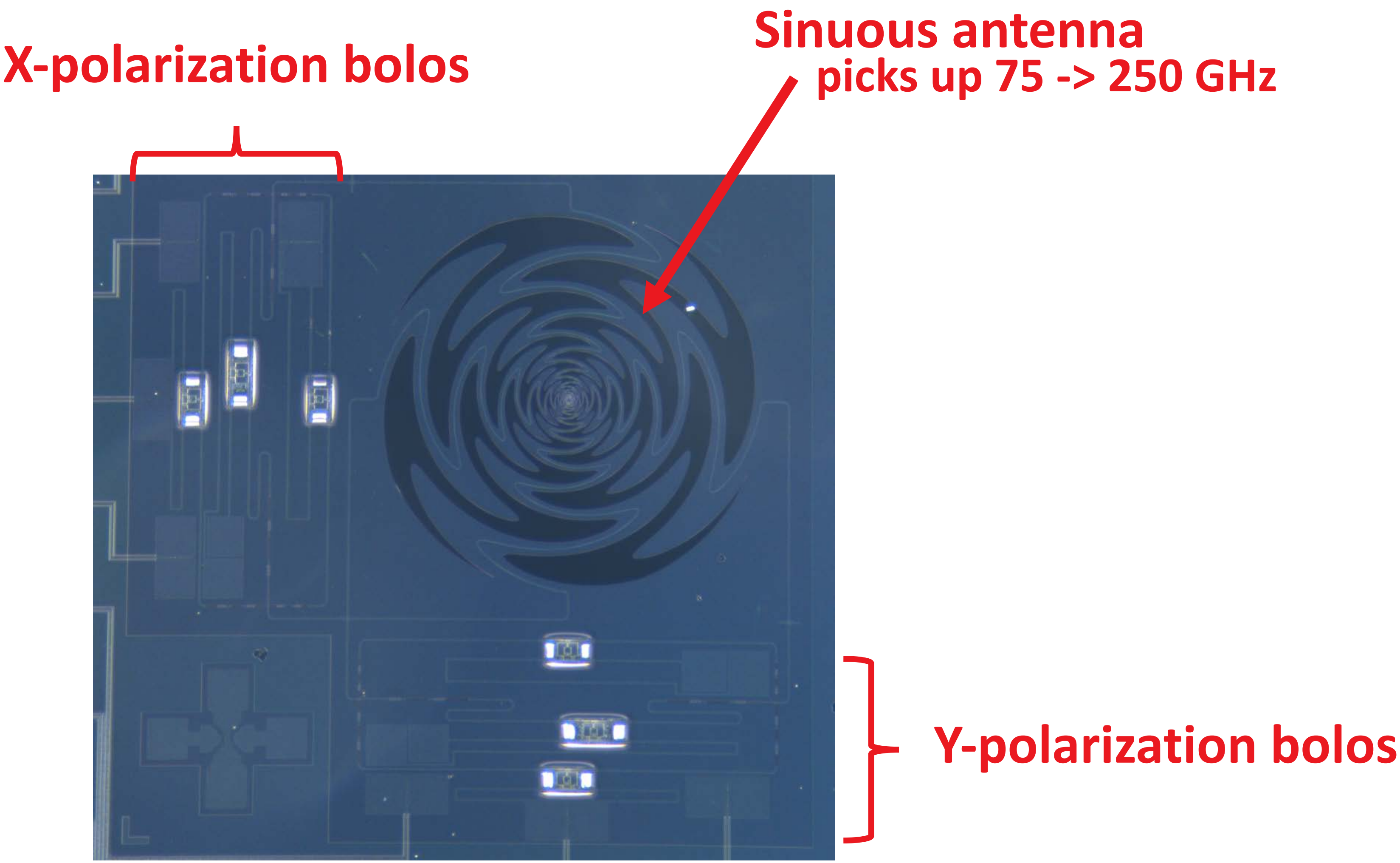
5. Increase $\Delta\nu$

Multi-Chroic Pixels

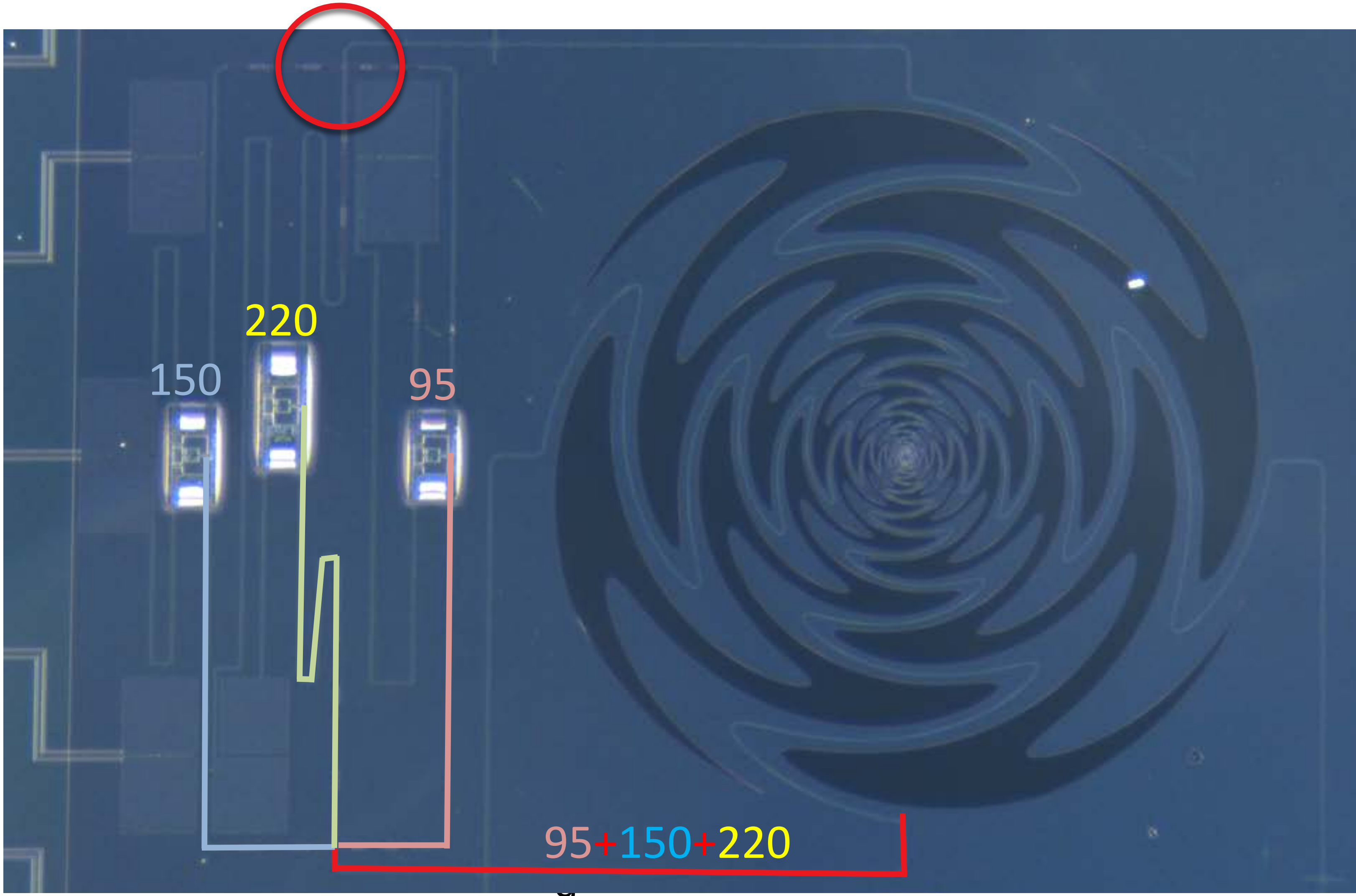


Tri-Chroic Pixel



Tri-Chroic Pixel

Triplexer – splits the signal into 3 bands



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5. Increase $\Delta\nu$

   (Multi-chroic detectors.)

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3. Remove ground spill

   (Careful optics & shielding.)

4. Remove detector noise

   (Use sub-kelvin TES bolometers.)

5. Increase $\Delta\nu$

   (Multi-chroic detectors.)

6. Moar Detectors!!!

   (Limited by optics.)

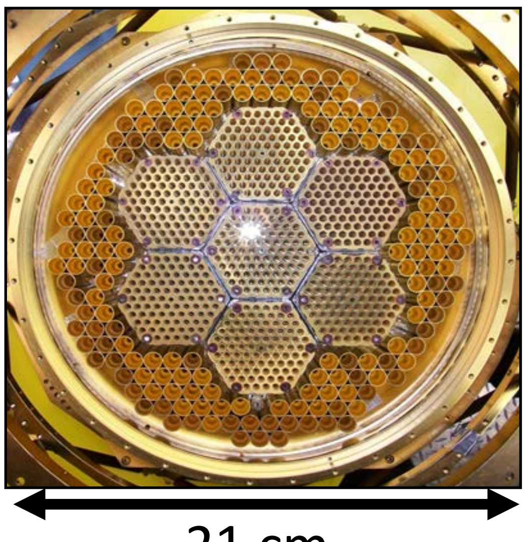
SPT-3G

SPTpol → SPT 3G

1,536 detectors

7.5 cm wafers

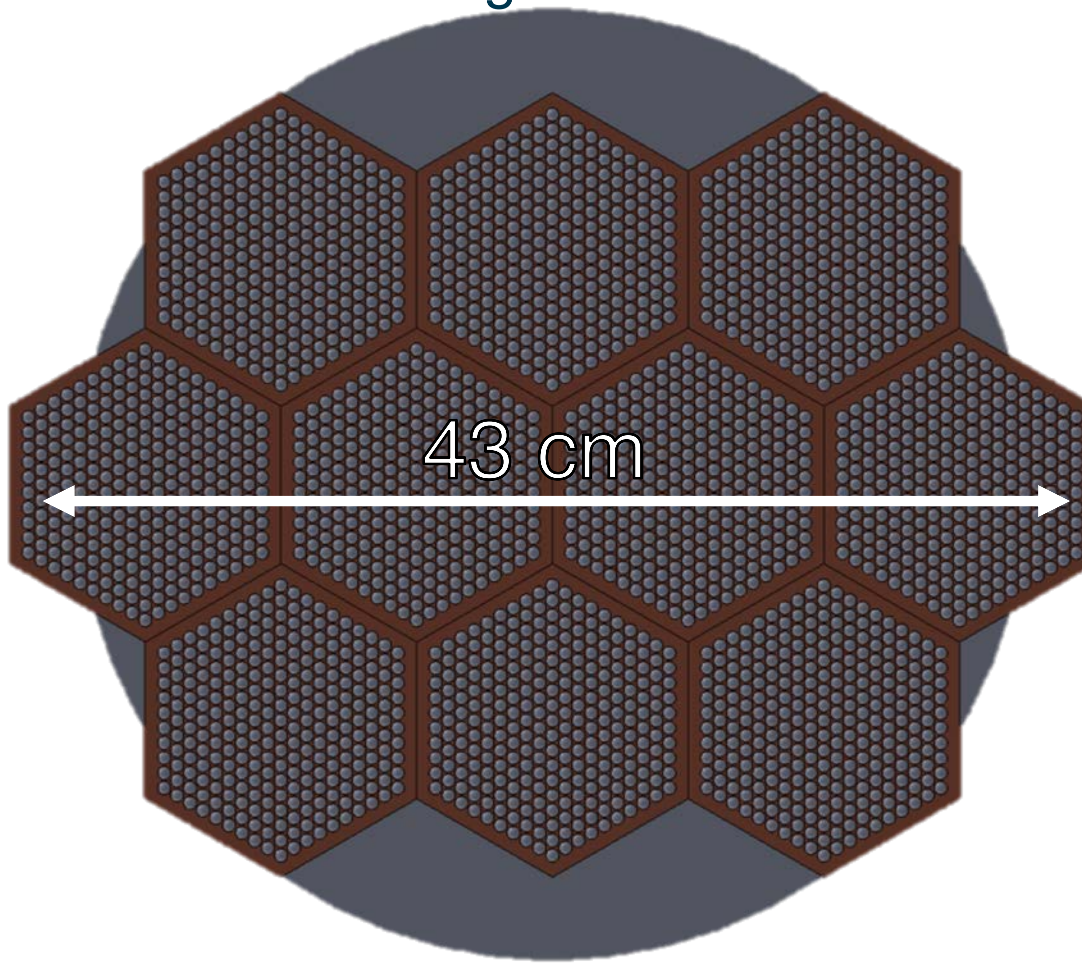
1 deg² field of view



~16,000 detectors

15 cm wafers

2.8 deg² field of view



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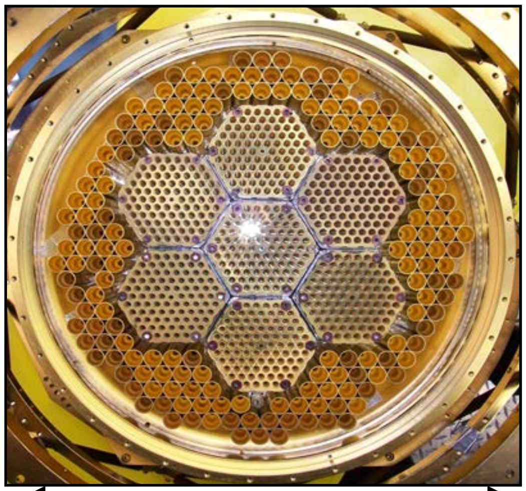
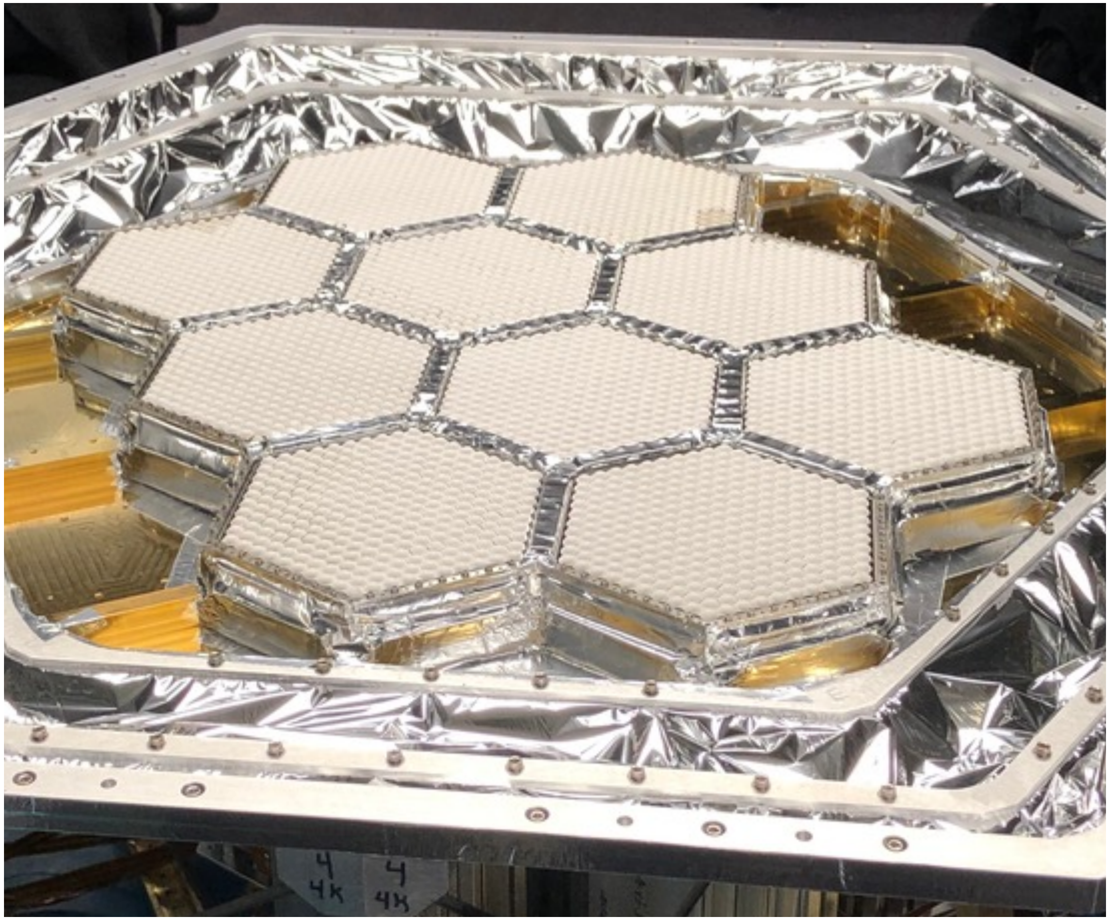


21 cm

~16,000 detectors

15 cm wafers

2.8 deg² field of view



SPT-3G

Now Live!

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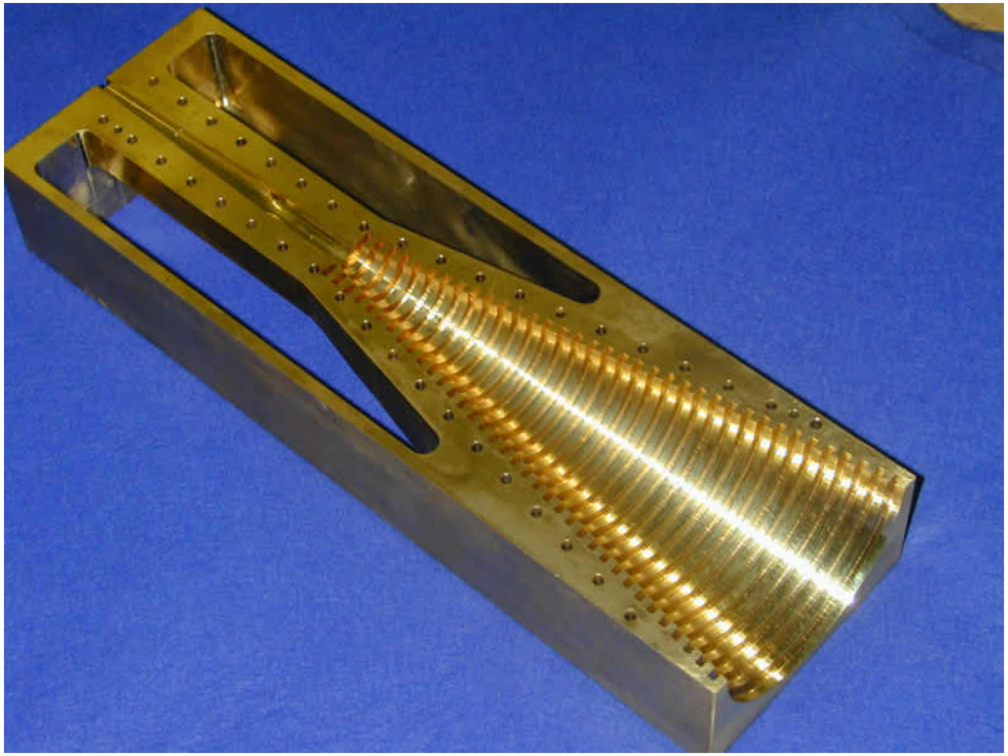
Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

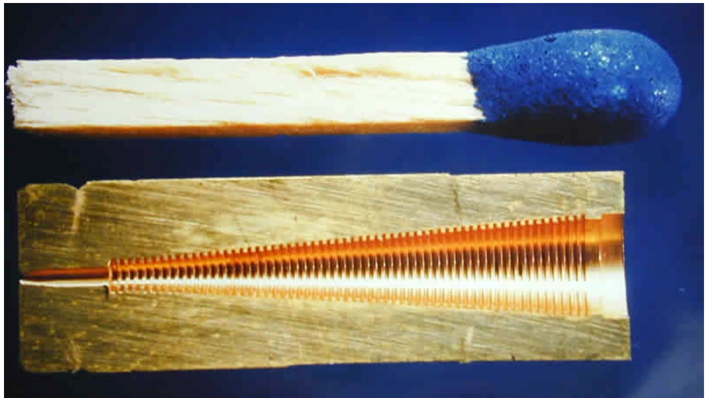
Feeds

Come in many shapes and sizes.

These feed horns couple radiation into metal waveguide.



http://www.radiometer-physics.de/



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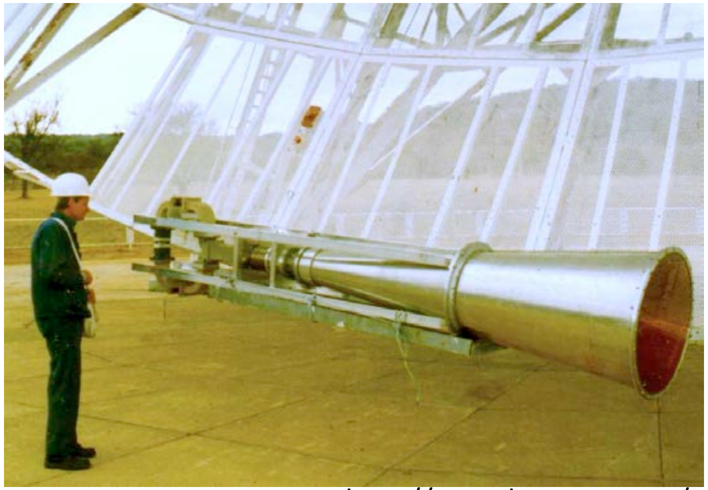

http://www.hartrao.ac.za/