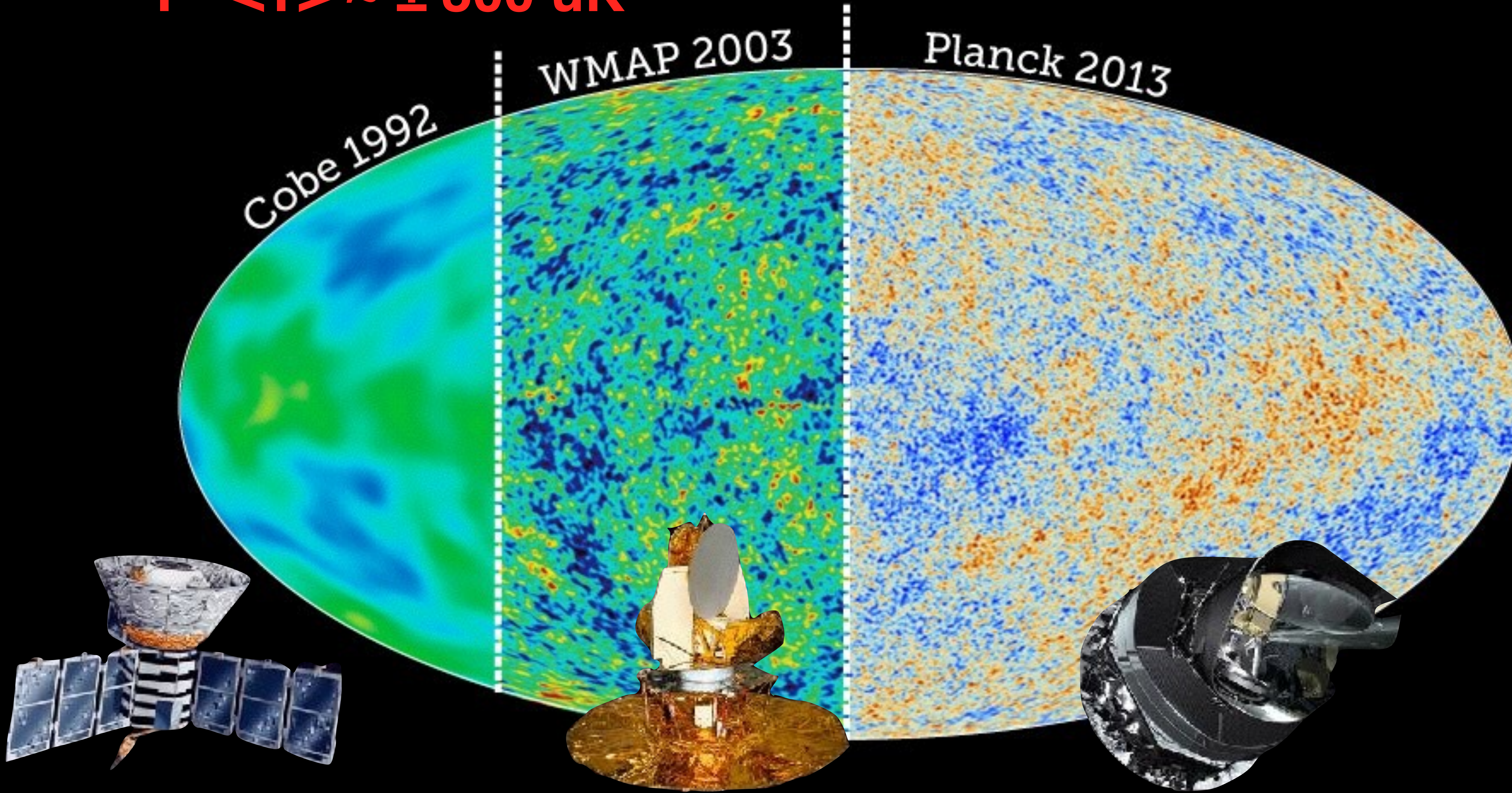
Measuring CMB Spectral Distortions from the Ground

Christopher Sheehy
Goldhaber Fellow, Brookhaven National Lab
MIT Haystack
May 9, 2017

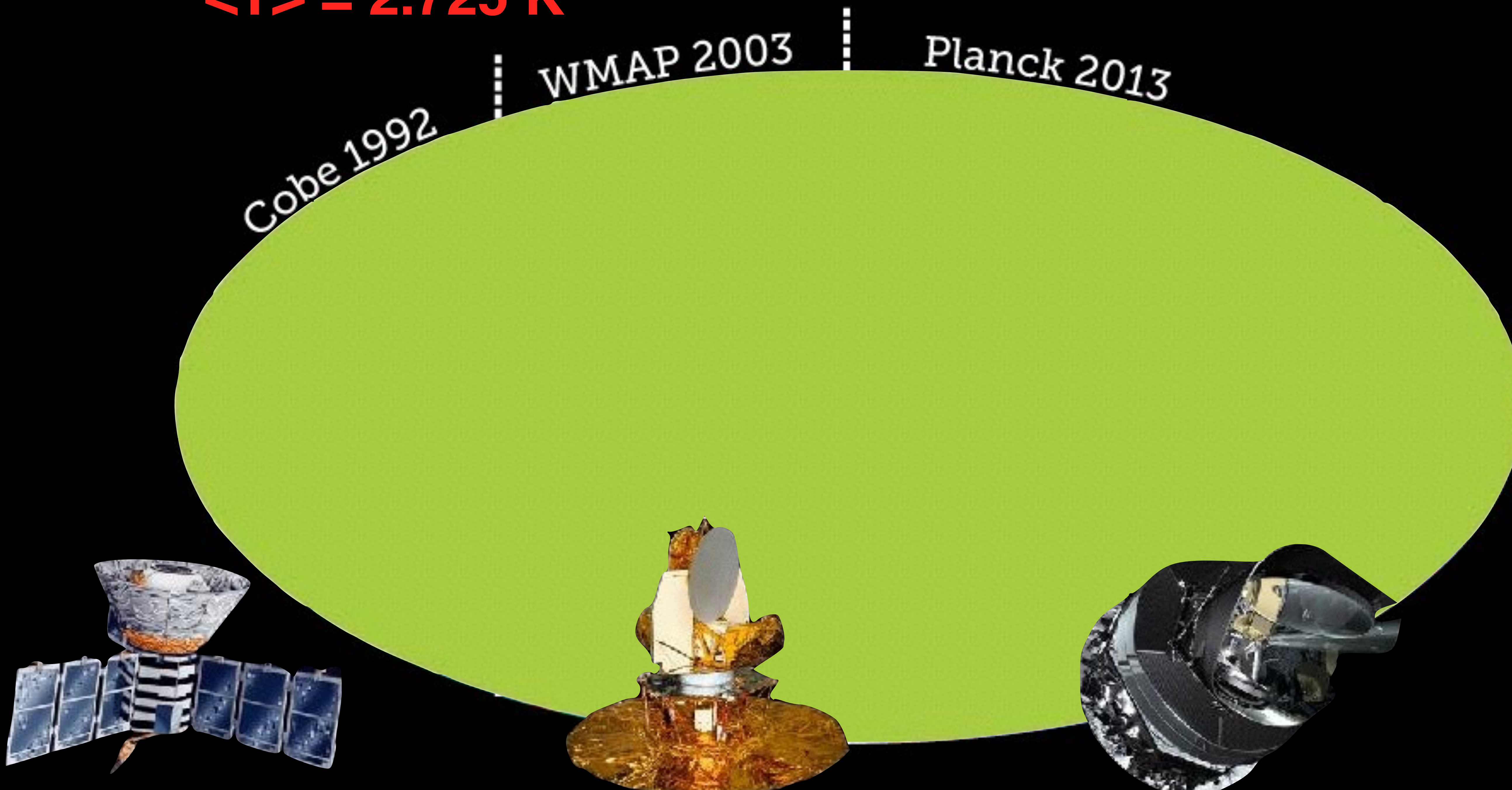
Cosmic Microwave Background

$T - \langle T \rangle \sim \pm 300$ uK



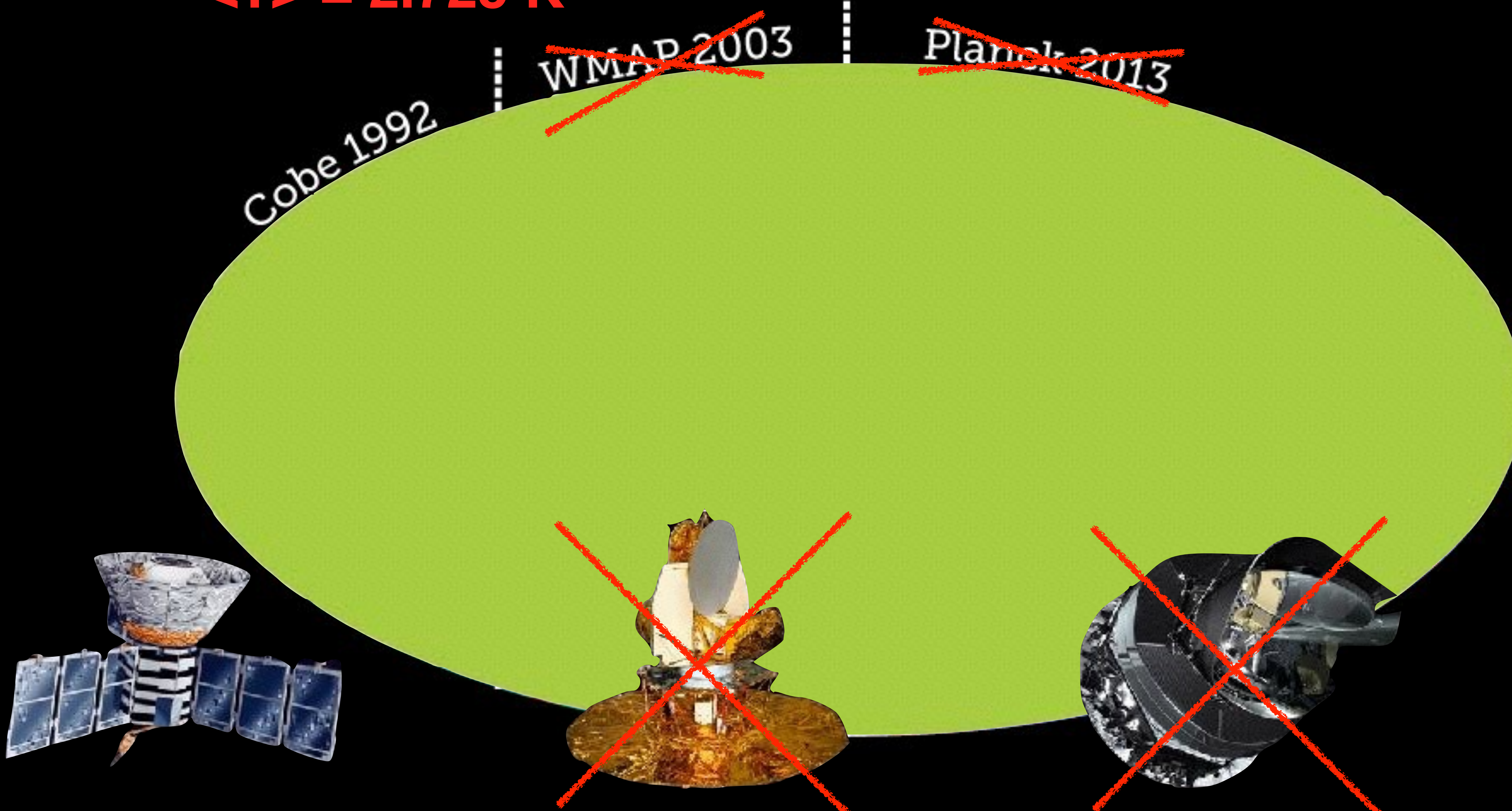
Cosmic Microwave Background

<T> = 2.725 K

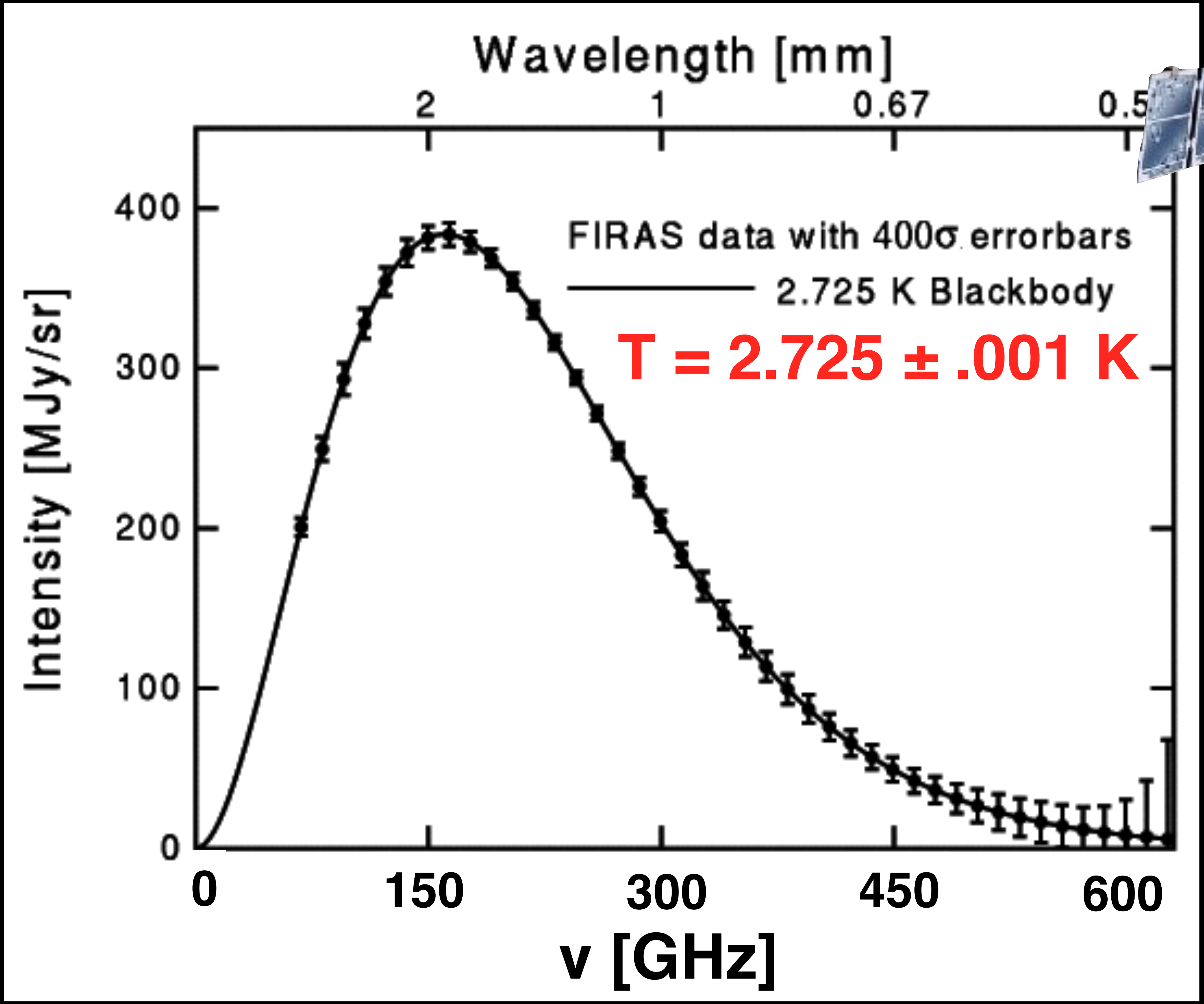


Cosmic Microwave Background

<T> = 2.725 K



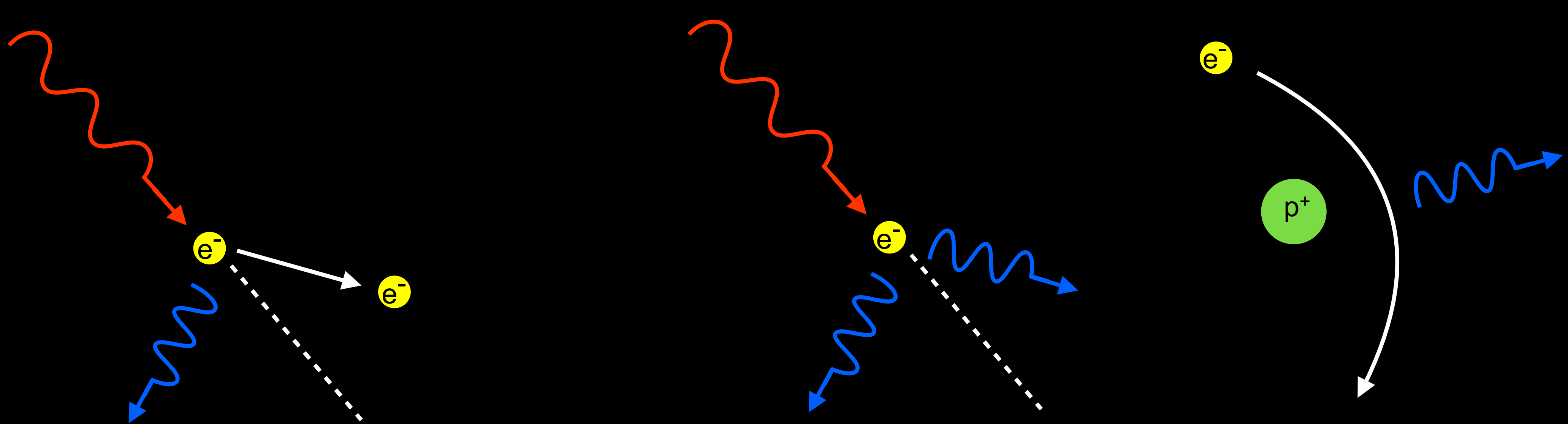
CMB Spectrum



CMB Spectrum

Why should the CMB be a blackbody?

- Imagine some energy is injected into the primordial plasma
- Two things need to happen to "maintain" the blackbody photon spectrum:
  1. photons and baryons are redistributed in energy by Compton scattering
  2. new photons are created by double Compton scattering and Bremsstrahlung



Compton scattering

double Compton

Bremsstrahlung

CMB Spectrum

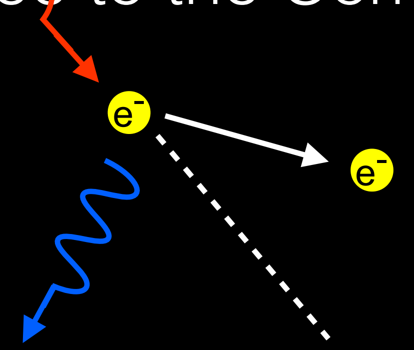
- At **$z > 2 \times 10^6$**, both processes are very efficient and any energy injected into the plasma is quickly thermalized. One parameter, T, is needed to describe the distribution of photons:

$$n(E) = 1 / [e^{E/kT} - 1] \qquad \text{(Planck spectrum)}$$

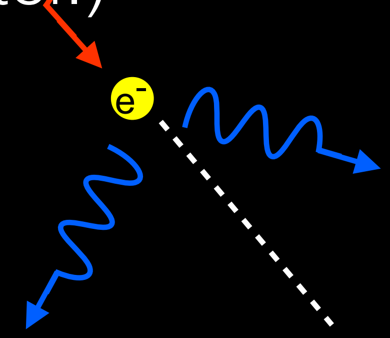
- At **$z < 2 \times 10^6$**, Compton scattering is still very efficient, so *kinetic equilibrium* is maintained between photons and baryons, but production of photons from double Compton and Bremsstrahlung cannot keep up. The photons are now described by a Bose-Einstein with non-zero chemical potential, μ:

$$n(E) = 1 / [e^{E/kT + \mu} - 1] \qquad \text{(Bose-Einstein spectrum)}$$

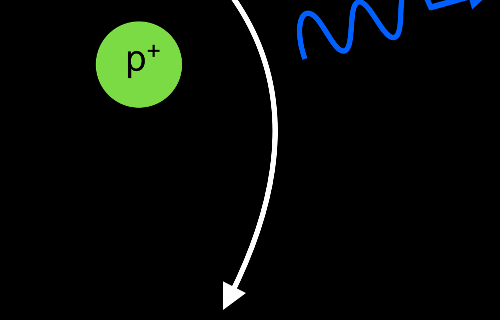
- At **$z \lesssim 2 \times 10^4$**, Compton scattering becomes inefficient, so injected energy doesn't come to equilibrium. (Referred to as y-distortions in reference to the Compton y-parameter.)



Compton scattering



double Compton



Bremsstrahlung

CMB Spectrum

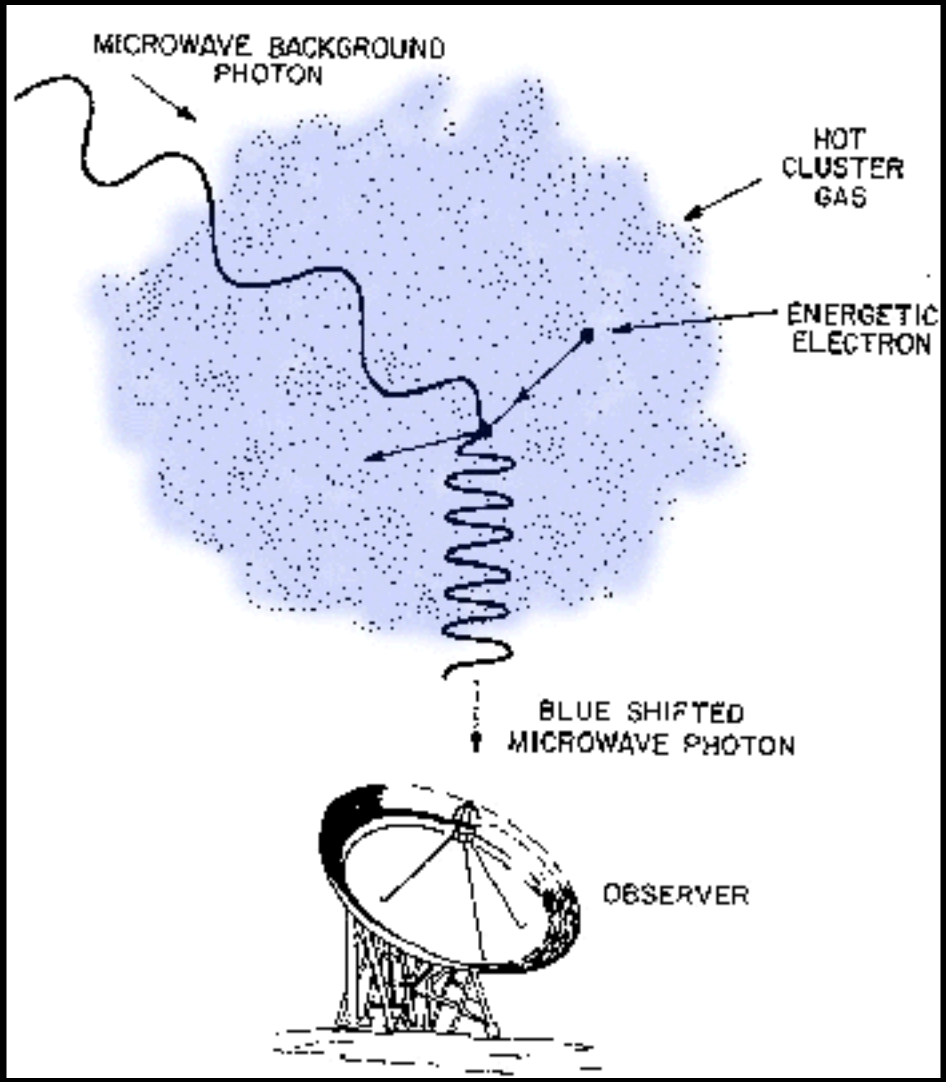
Summary: any energy added to the Universe at $z < 2 \times 10^6$ produces a spectral distortion in the CMB.

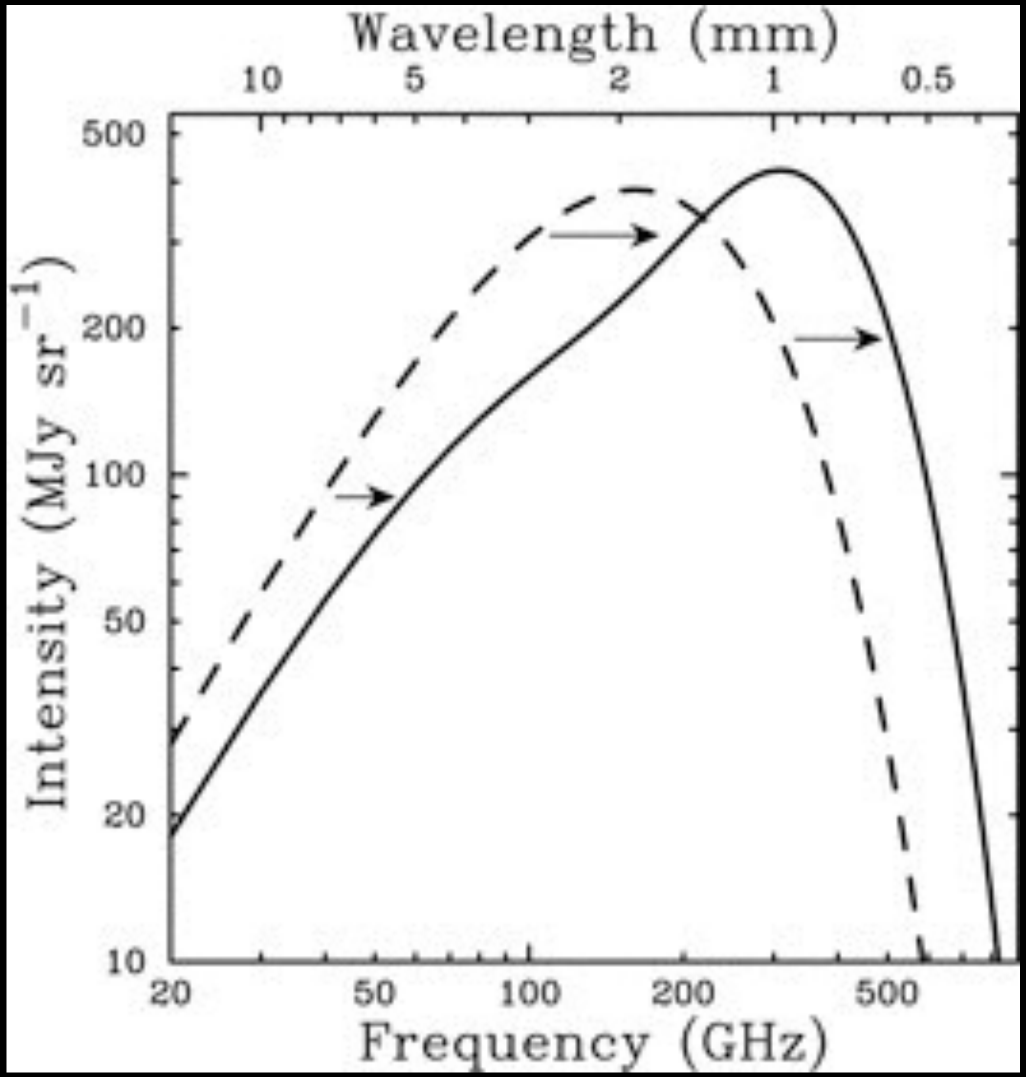
CMB Spectral Distortions

The CMB is guaranteed to deviate from a blackbody.

CMB Spectral Distortions

Late time y-distortion: energy injection from gravitational heating of (re)ionized plasma in galaxy clusters

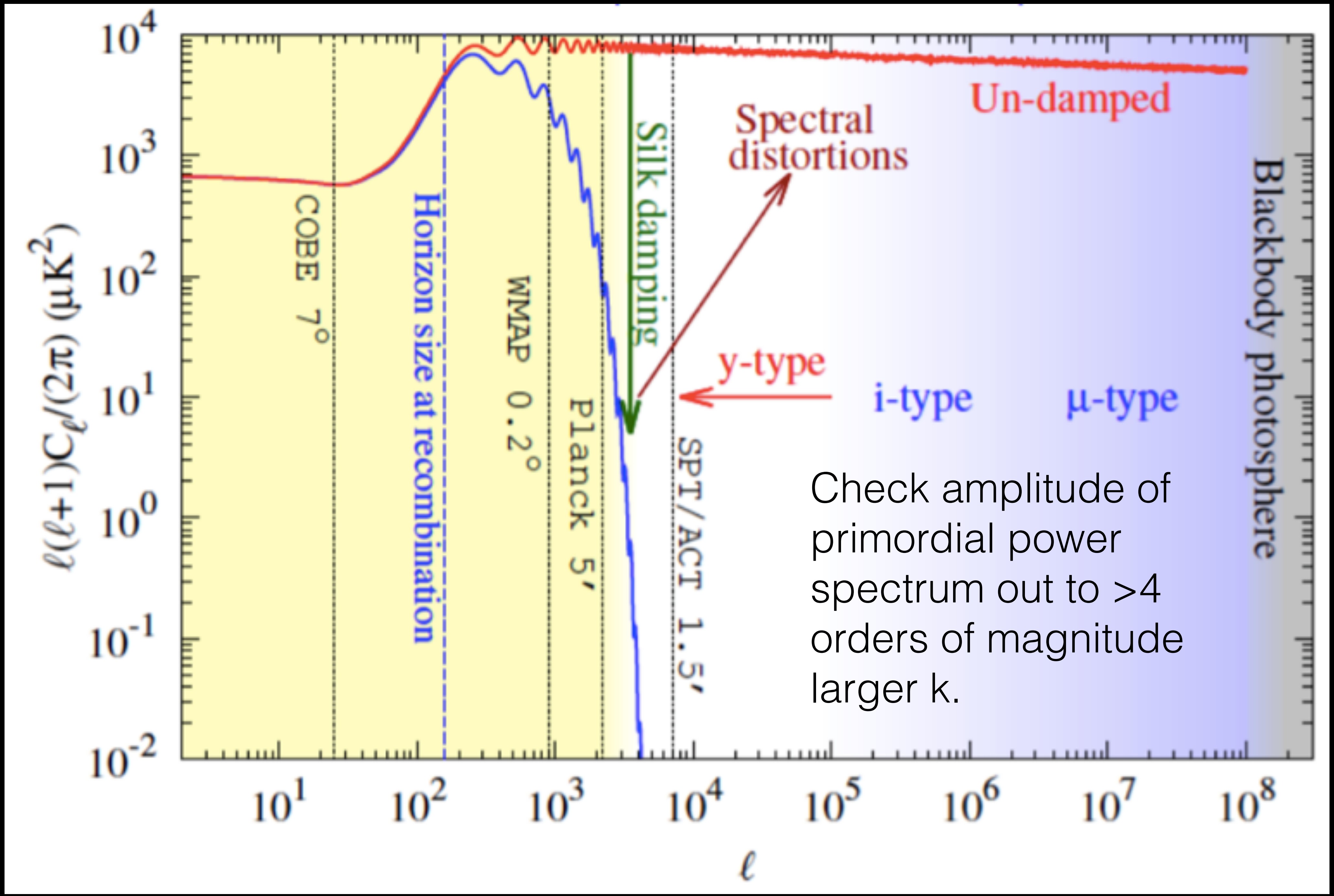




Very exaggerated! Cluster is optically thin.

CMB Spectral Distortions

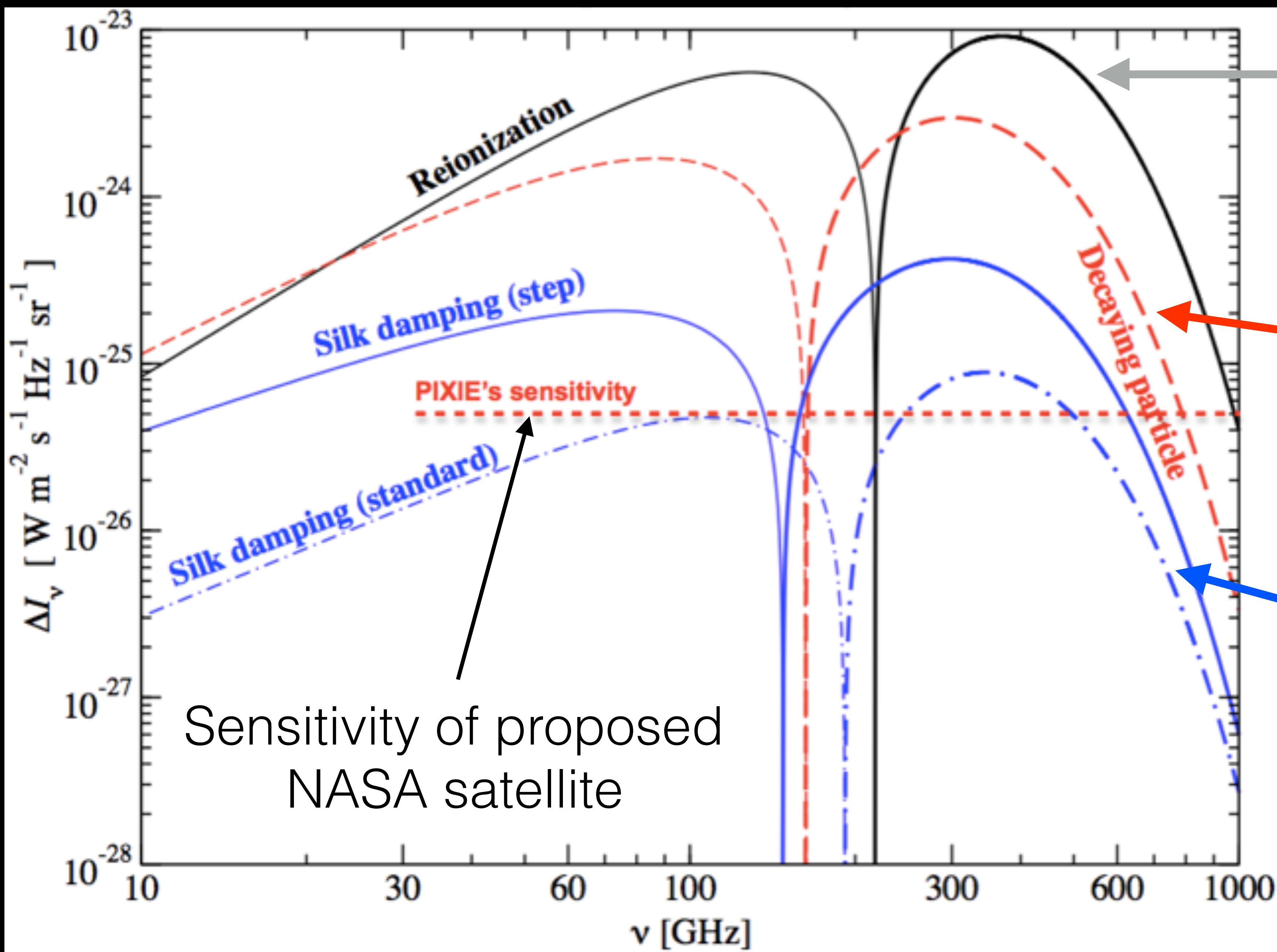
Early time μ-distortion: radiative viscosity and thermal conductivity (Silk damping) injects energy into the primordial plasma



courtesy Rashid Sunyaev

CMB Spectral Distortions

Absolute value of ΔI



courtesy Jens Chluba

$\Delta I/I \sim 10^{-6}$ - 10^{-7}
y-distortion from reionization expected

More exotic scenarios like decaying particles

$\Delta I/I \sim 10^{-8}$ - 10^{-9}
μ-distortion from Silk damping of "standard" primordial power spectrum

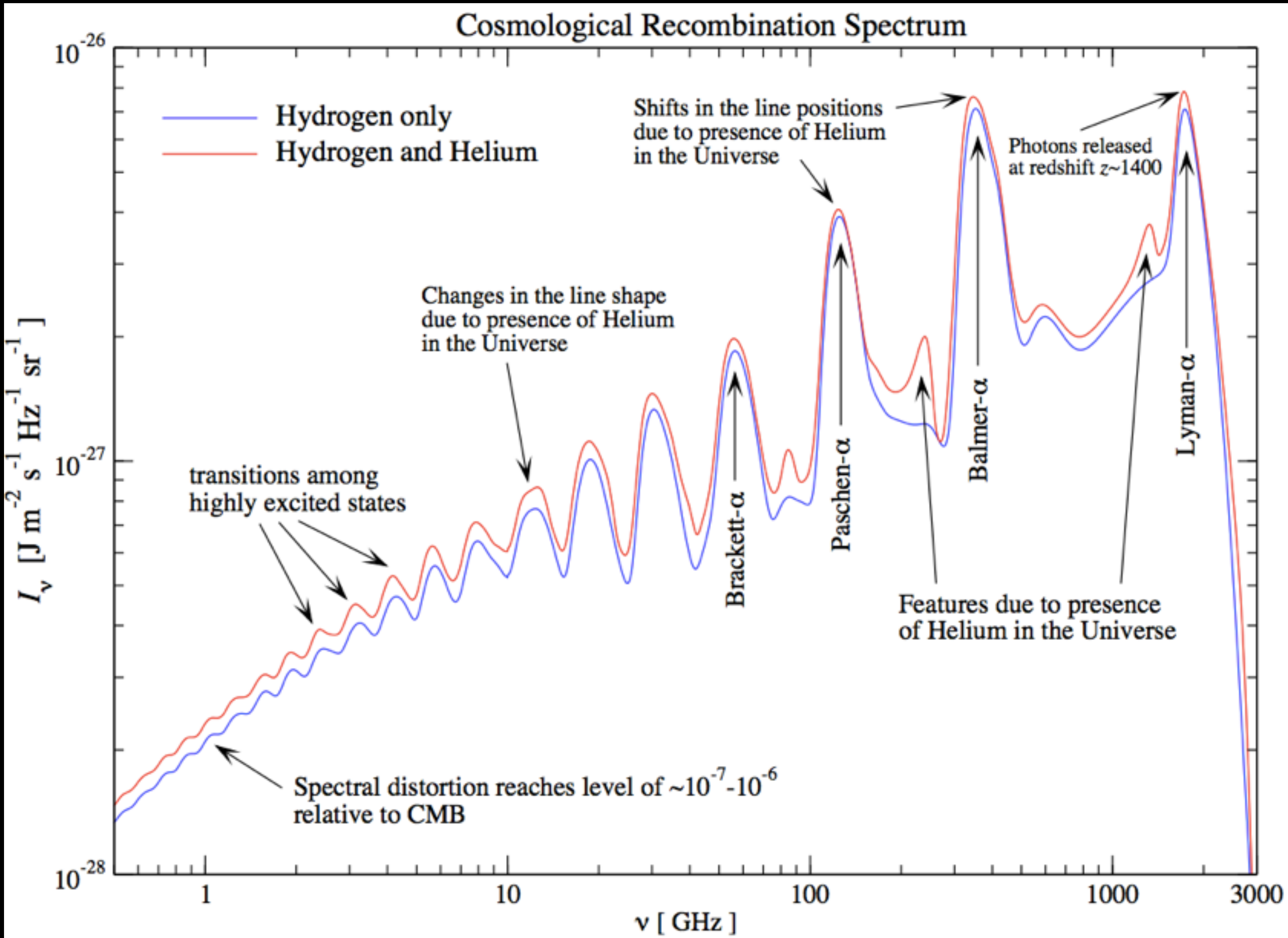
CMB Recombination Lines

- Third type of CMB spectral distortion:

  Line emission from electronic transitions of hydrogen at recombination are present in the CMB as a 10^{-8} -10^{-9} spectral distortion (of order the baryon/photon ratio)

(Rubino-Martin, et al., 2006, 2008; Chluba & Sunyaev, 2006, 2009)

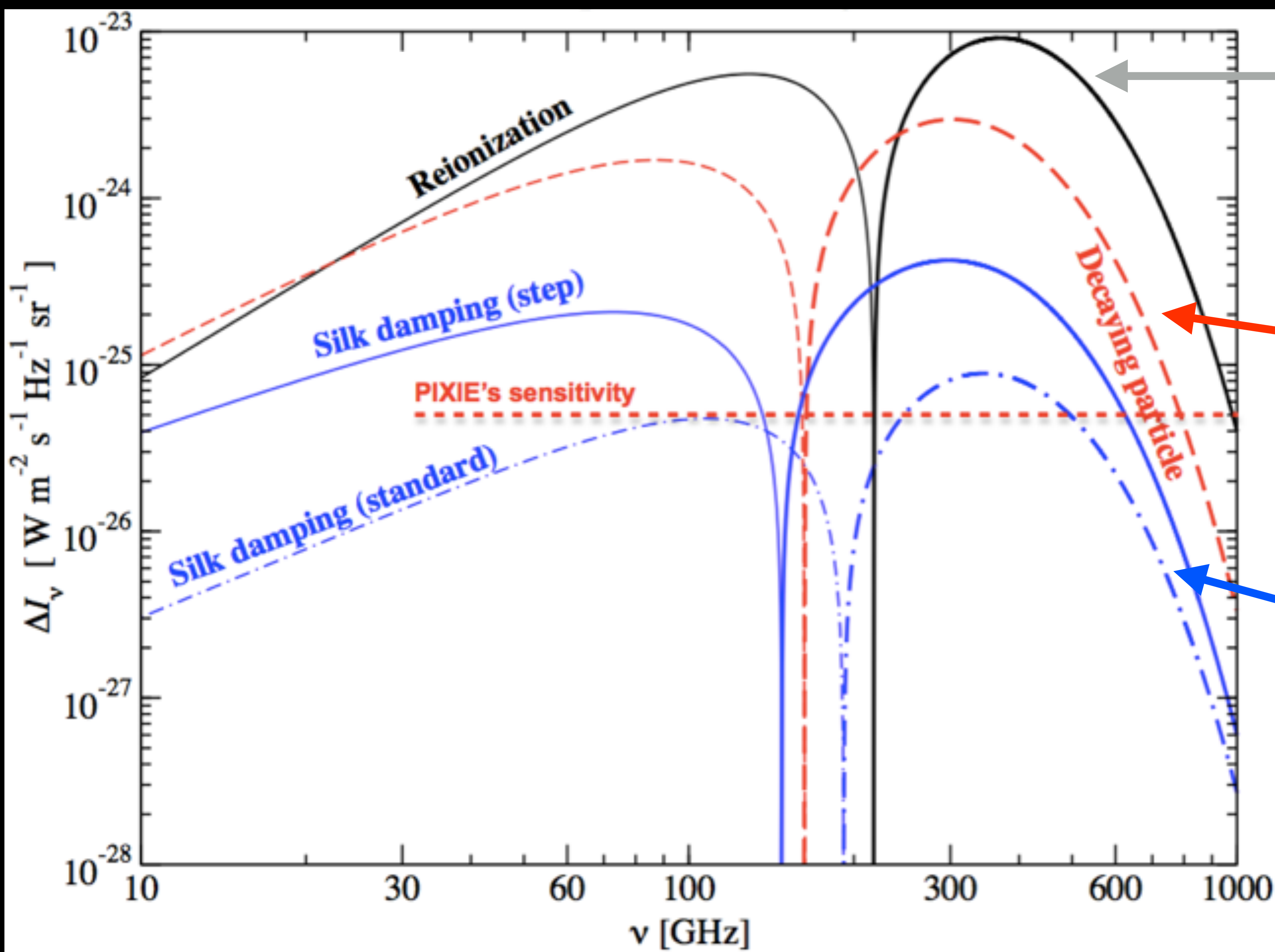
CMB spectral lines from recombination



Chluba, 2014

CMB Spectral Distortions

Absolute value of ΔI



courtesy Jens Chluba

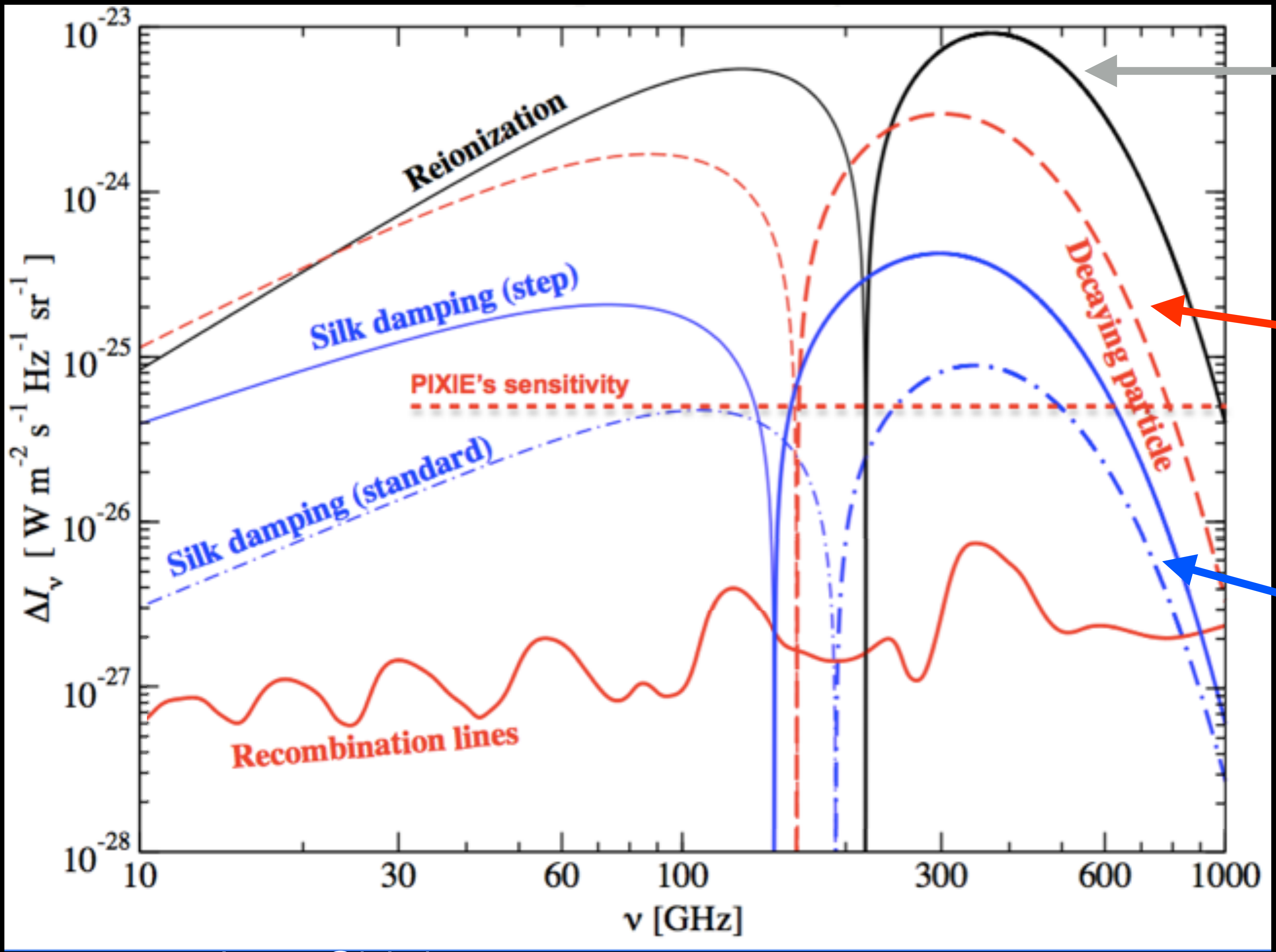
$\Delta I/I \sim 10^{-6} - 10^{-7}$
y-distortion from reionization expected

More exotic scenarios like decaying particles

$\Delta I/I \sim 10^{-8} - 10^{-9}$
μ-distortion from Silk damping of "standard" primordial power spectrum

CMB Spectral Distortions

Absolute value of ΔI



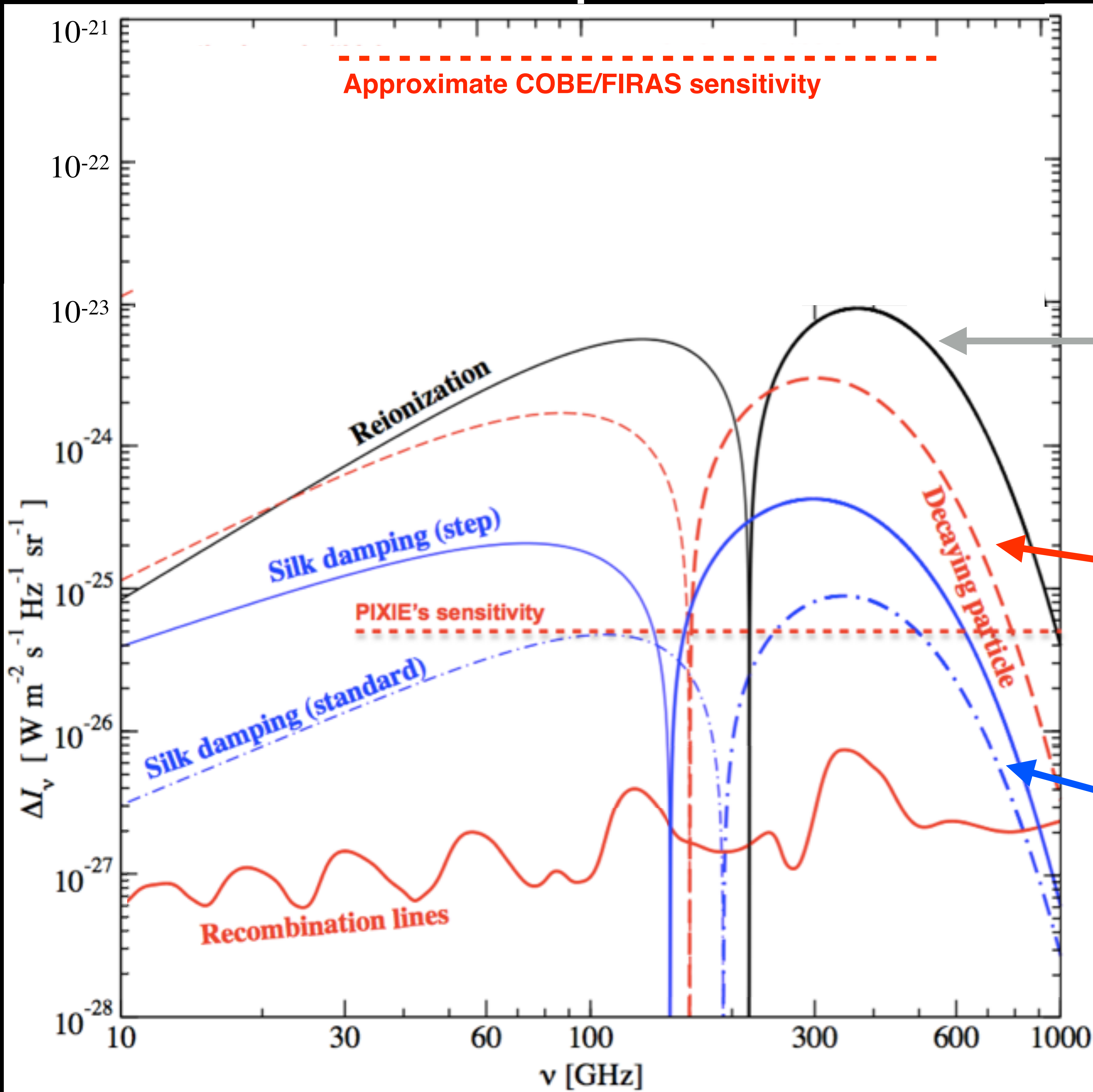
$\Delta I/I \sim 10^{-6}$ - 10^{-7}
y-distortion from reionization expected

More exotic scenarios like decaying particles

$\Delta I/I \sim 10^{-8}$ - 10^{-9}
μ-distortion from Silk damping of "standard" primordial power spectrum

courtesy Jens Chluba

CMB Spectral Distortions



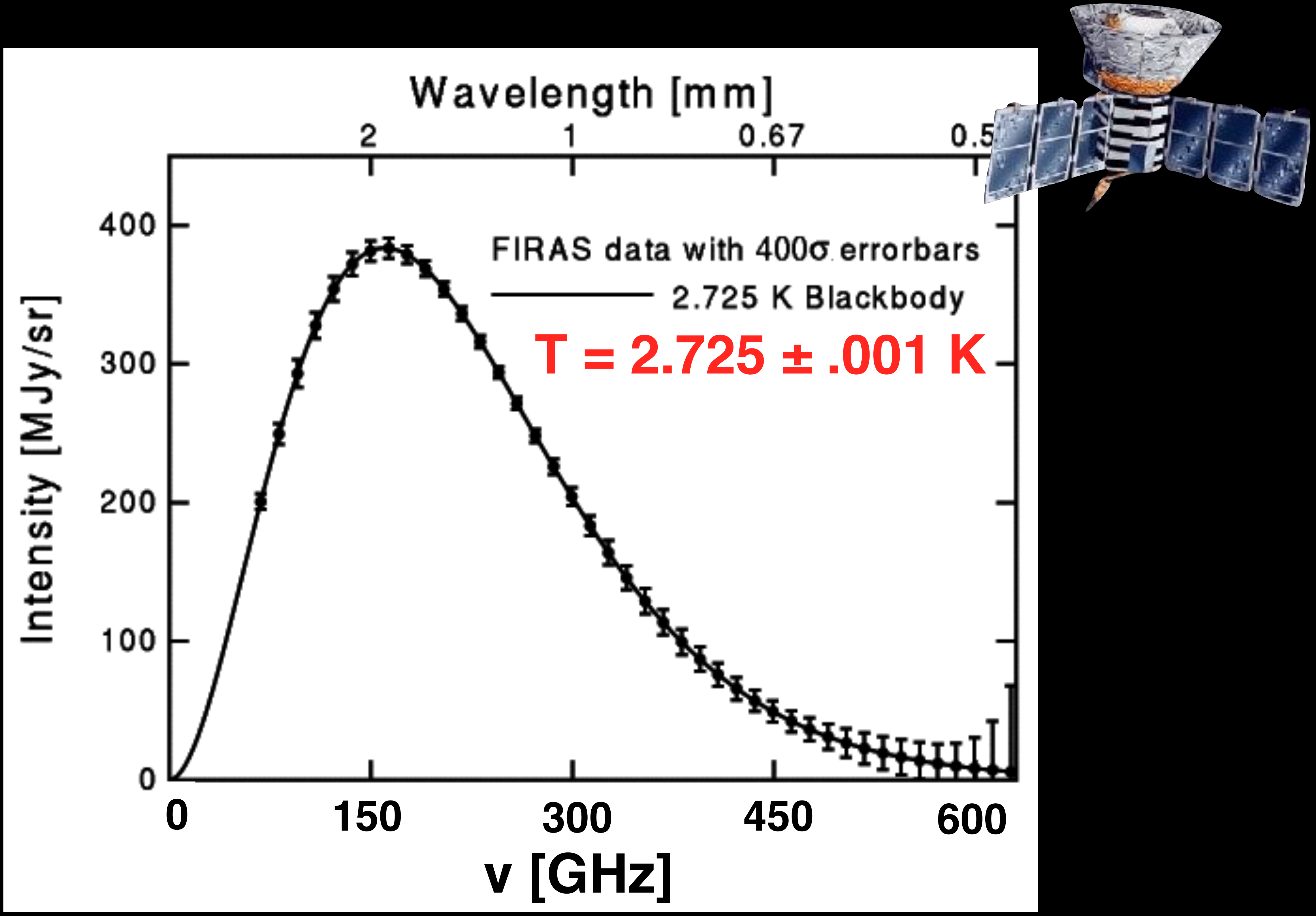
$\Delta I/I \sim 10^{-6}$ - 10^{-7}
y-distortion from reionization expected

More exotic scenarios like decaying particles

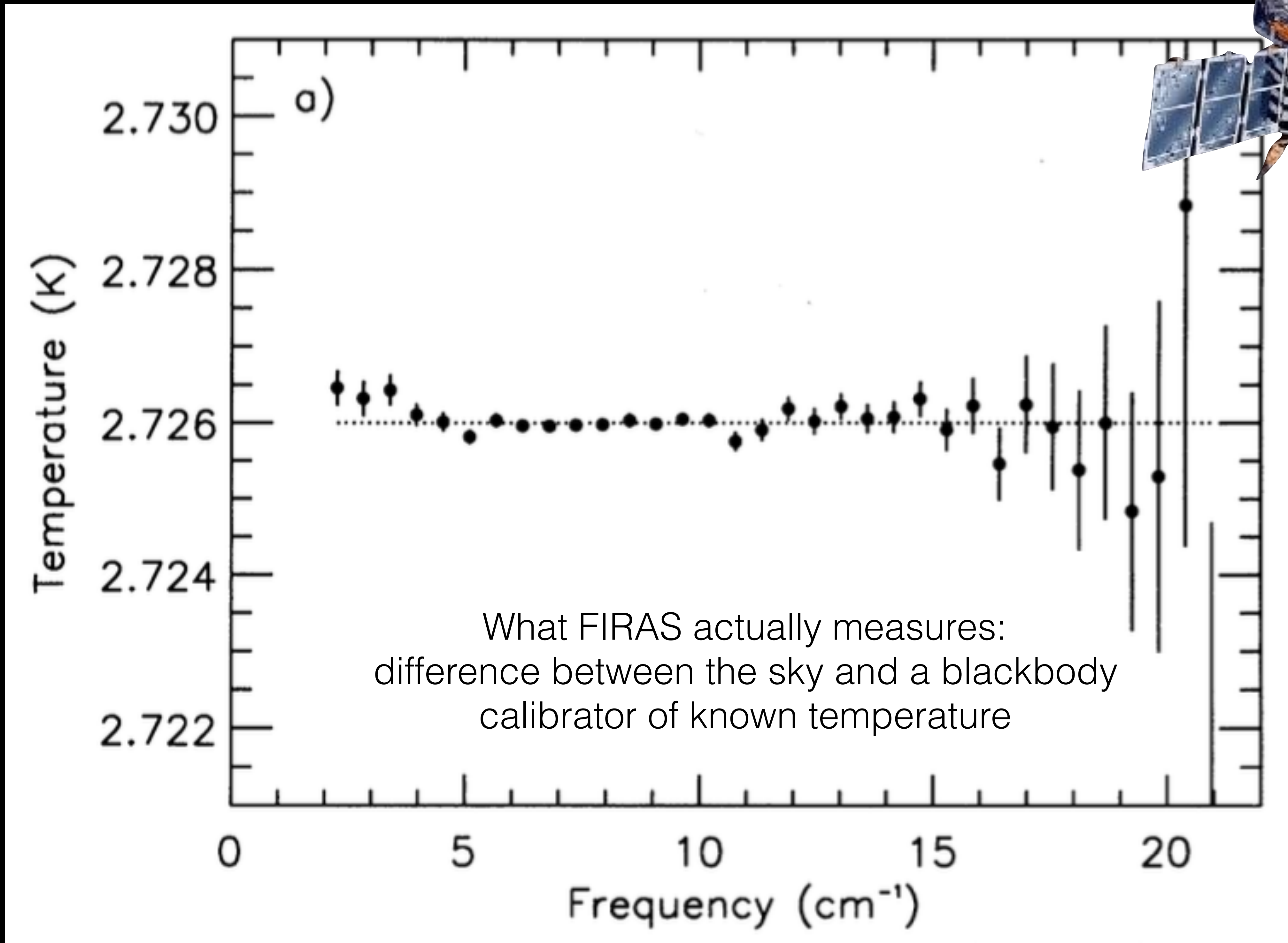
$\Delta I/I \sim 10^{-8}$ - 10^{-9}
μ-distortion from Silk damping of "standard" primordial power spectrum

courtesy Jens Chluba

CMB Spectral Distortions

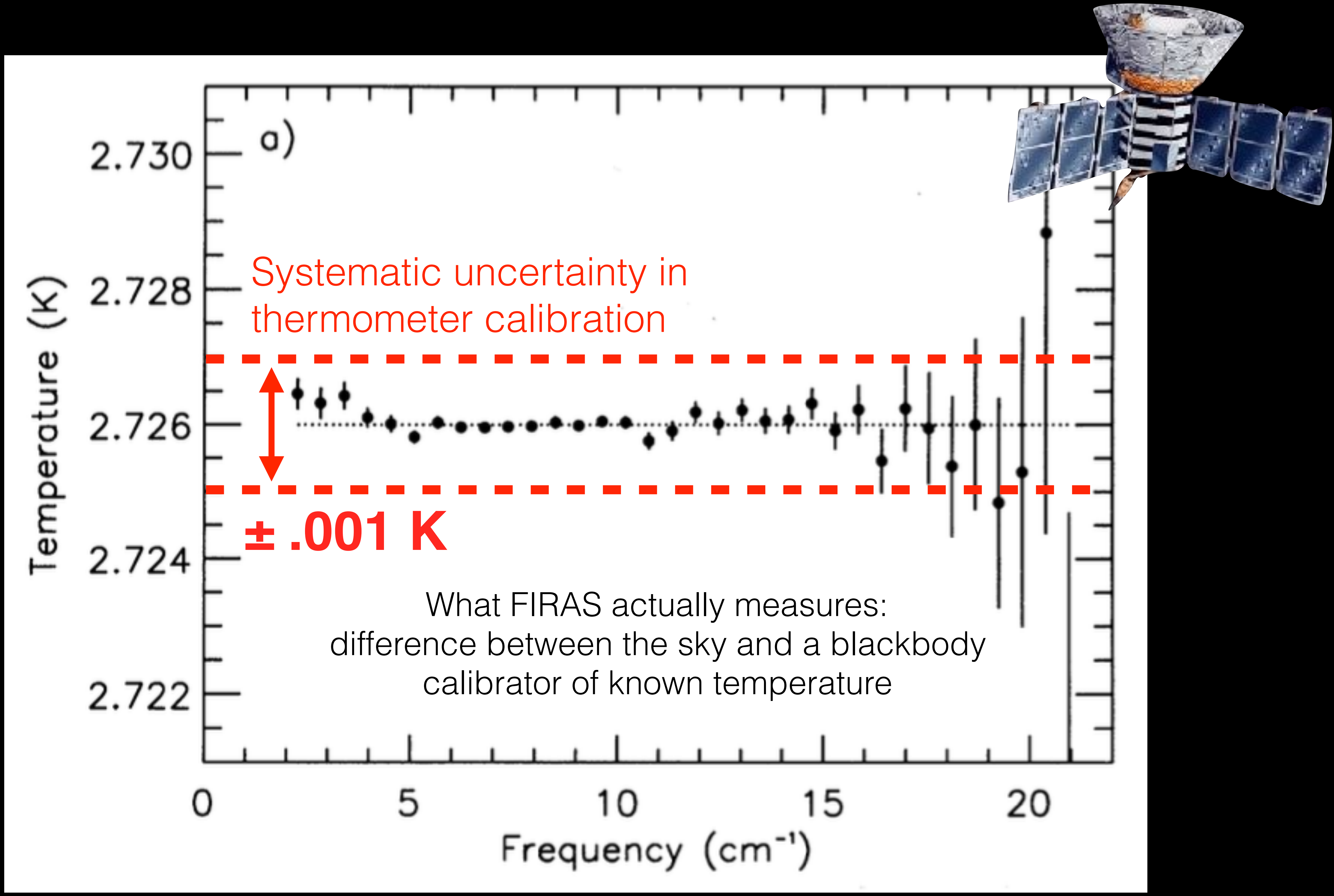


CMB Spectral Distortions



Mather et al, 1994

CMB Spectral Distortions



Mather et al, 1994

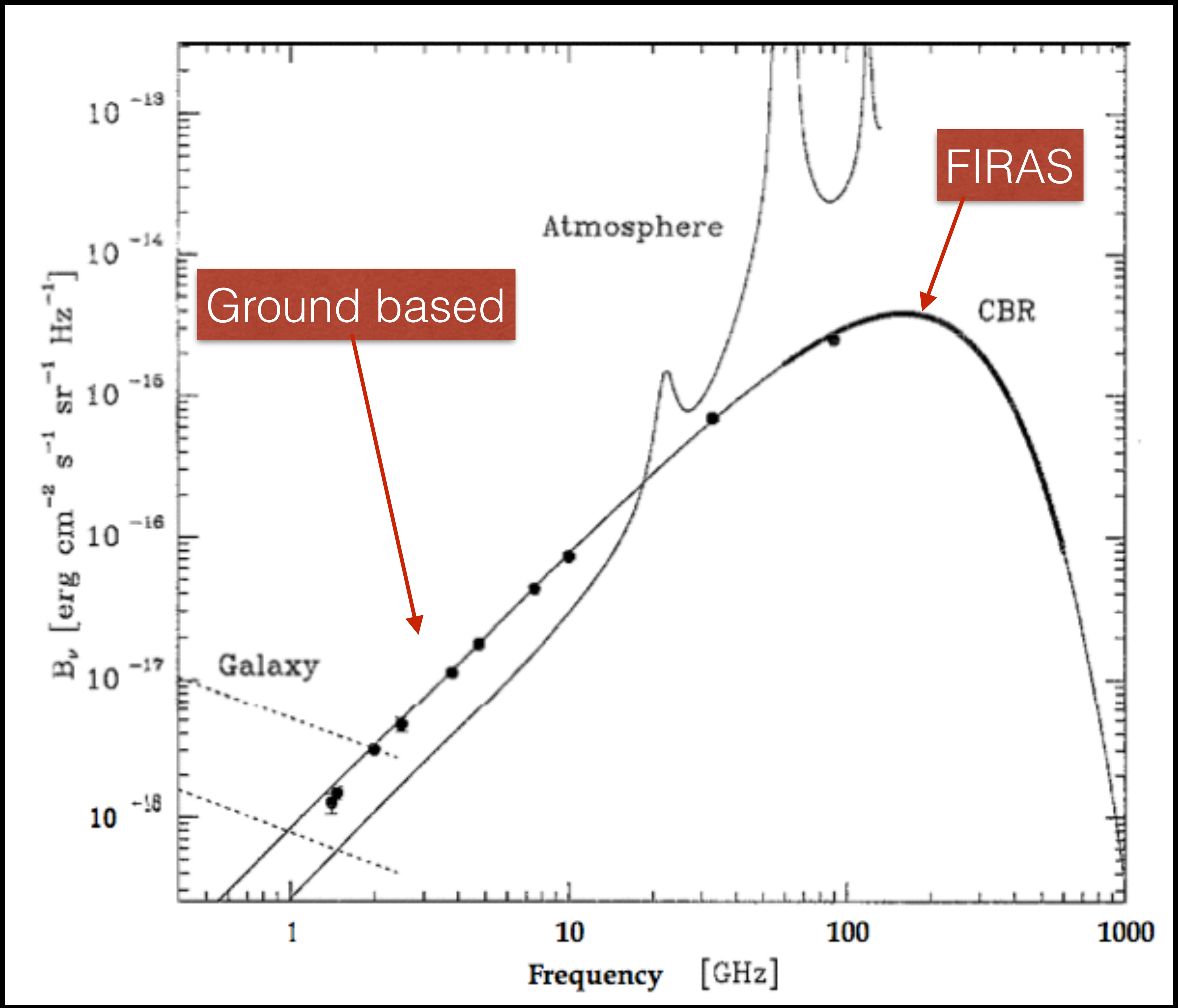
CMB Spectrum

FIRAS constrains deviation from a blackbody to $\lesssim$ few x 10^{-5}

Space is not the only place from which CMB spectrum measurements are possible.

Ground based CMB spectrum

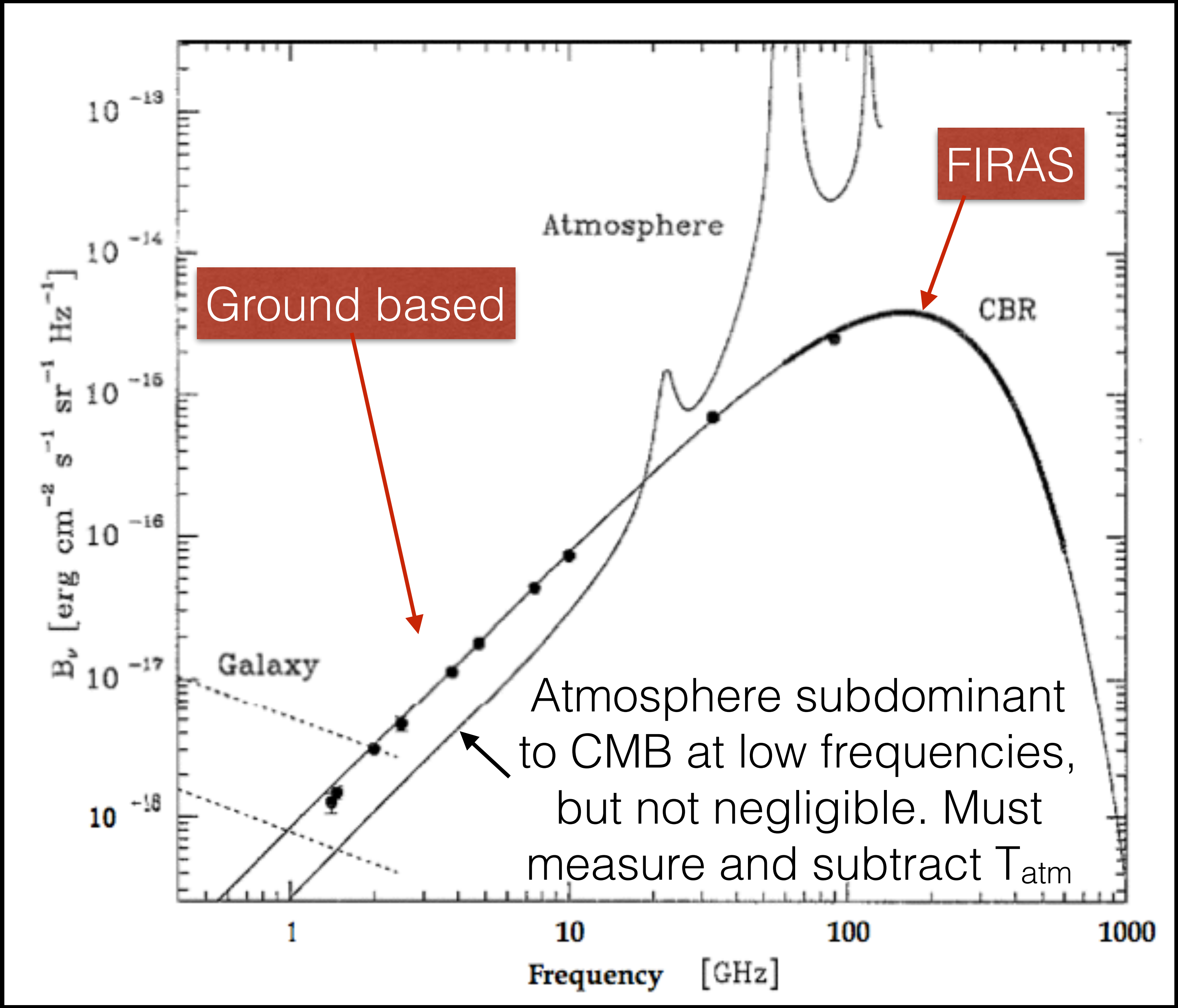
Even before FIRAS, we knew $T_{CMB} \pm .06$ K from ground based measurements and $\pm .02$ K from balloons



Bersanelli et al. 1995

Ground based CMB spectrum

Even before FIRAS, we knew T_{CMB} ± .06 K from ground based measurements and ± .02 K from balloons



Bersanelli et al. 1995

Elevation tipping

Space

Ground

Elevation tipping

Space

$\boldsymbol{\tau}_{Z}$

Ground

Elevation tipping

Space

$\boldsymbol{\tau}_Z$

$\boldsymbol{\tau} = \boldsymbol{\tau}_Z / \cos\theta_Z$

(1 / $\cos\theta_Z$ = "airmass")

Ground

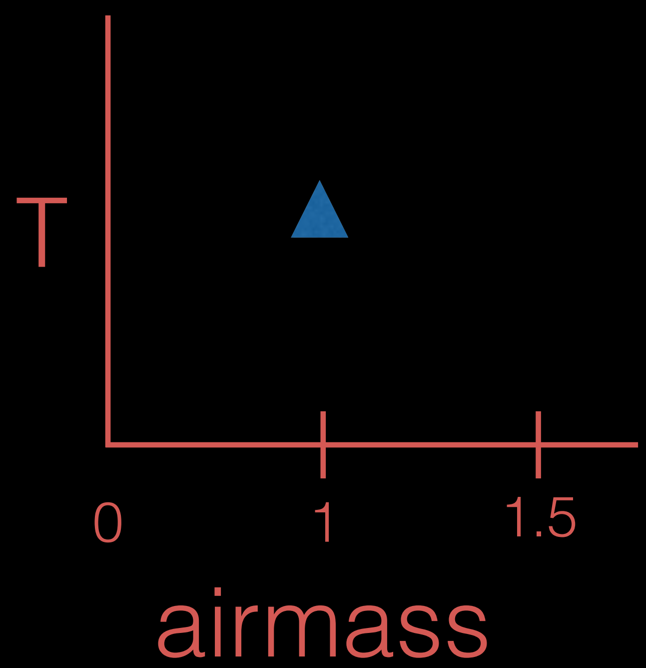
Elevation tipping

Space

$\boldsymbol{\tau}_Z$

$\boldsymbol{\tau} = \boldsymbol{\tau}_Z \,/\, \cos\theta_Z$

(1 / $\cos\theta_Z$ = “airmass”)



Ground

Elevation tipping

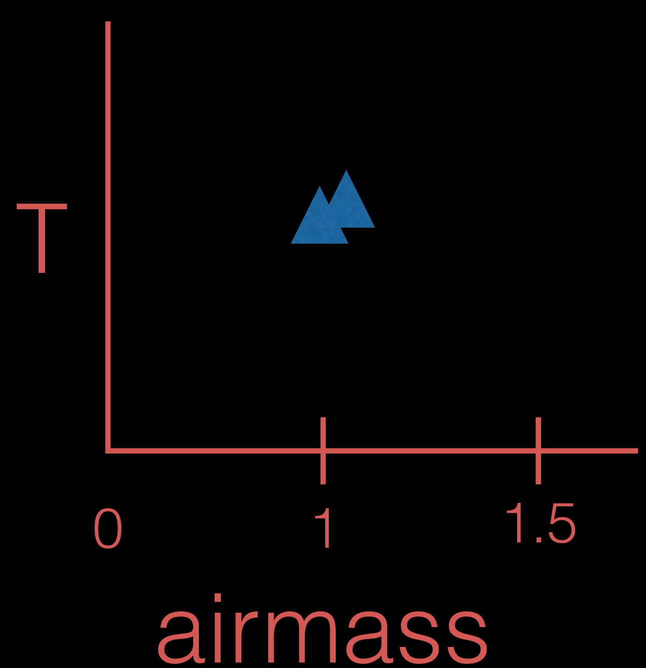
Space

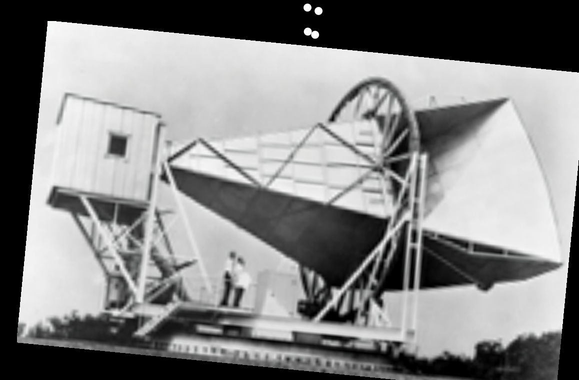
$\boldsymbol{\tau}_Z$

$\boldsymbol{\tau} = \boldsymbol{\tau}_Z / \cos\theta_Z$

($1 / \cos\theta_Z$ = “airmass”)

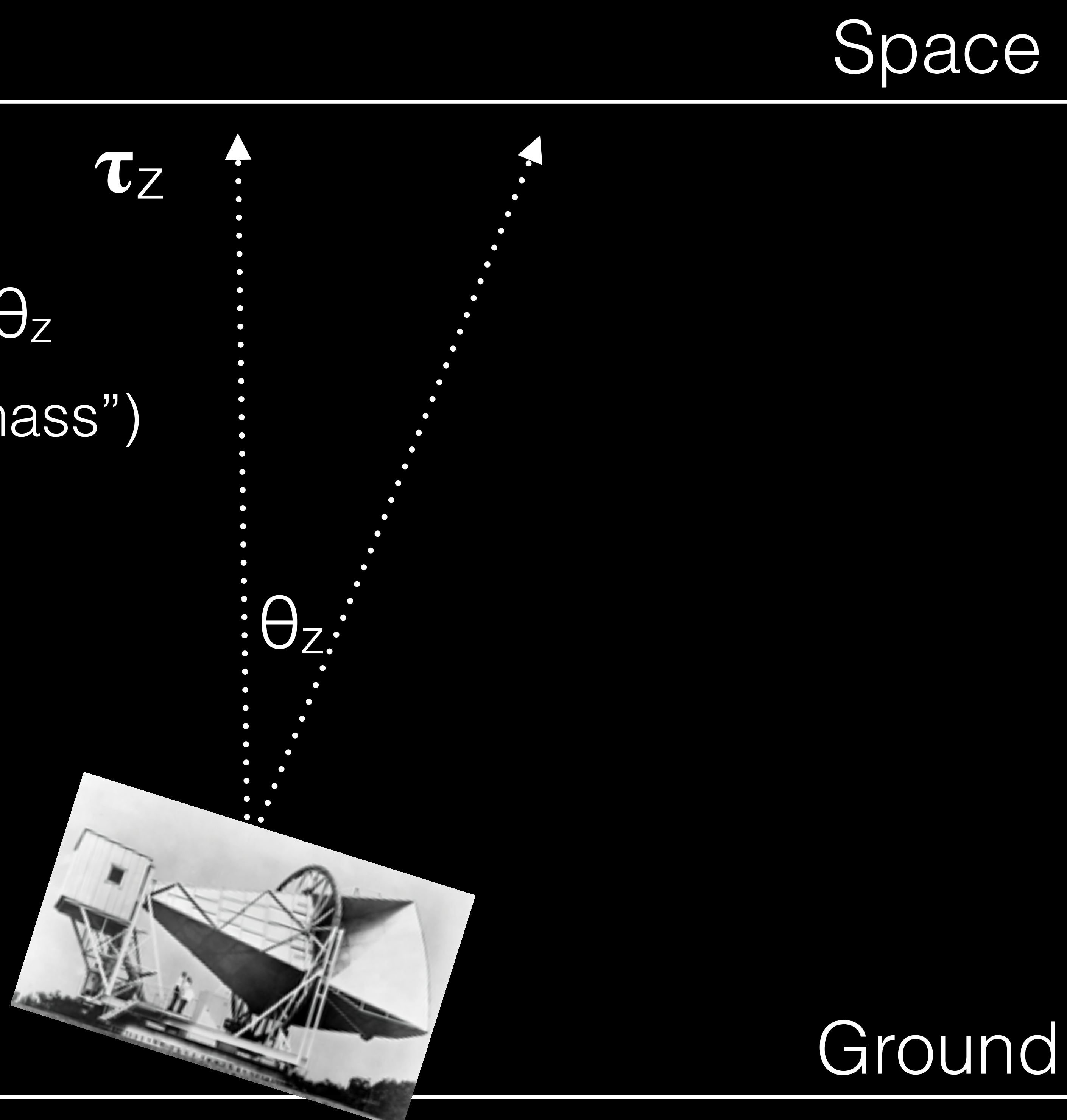
θ_Z





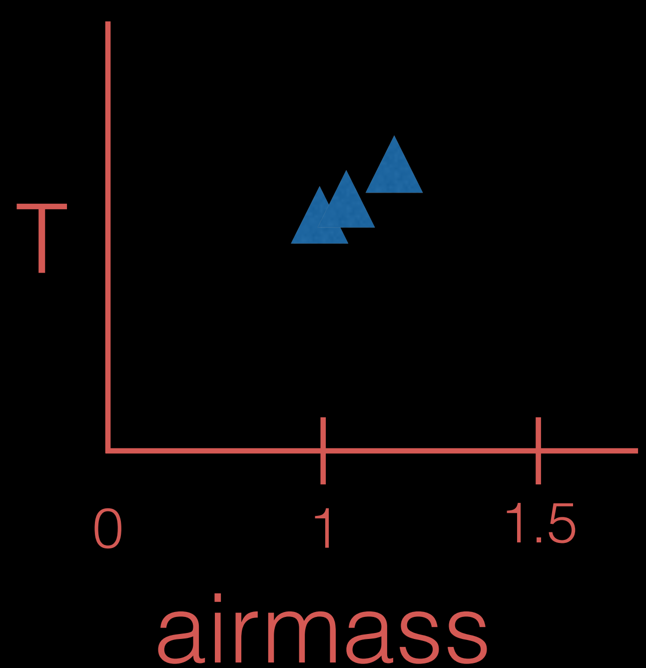
Ground

Elevation tipping

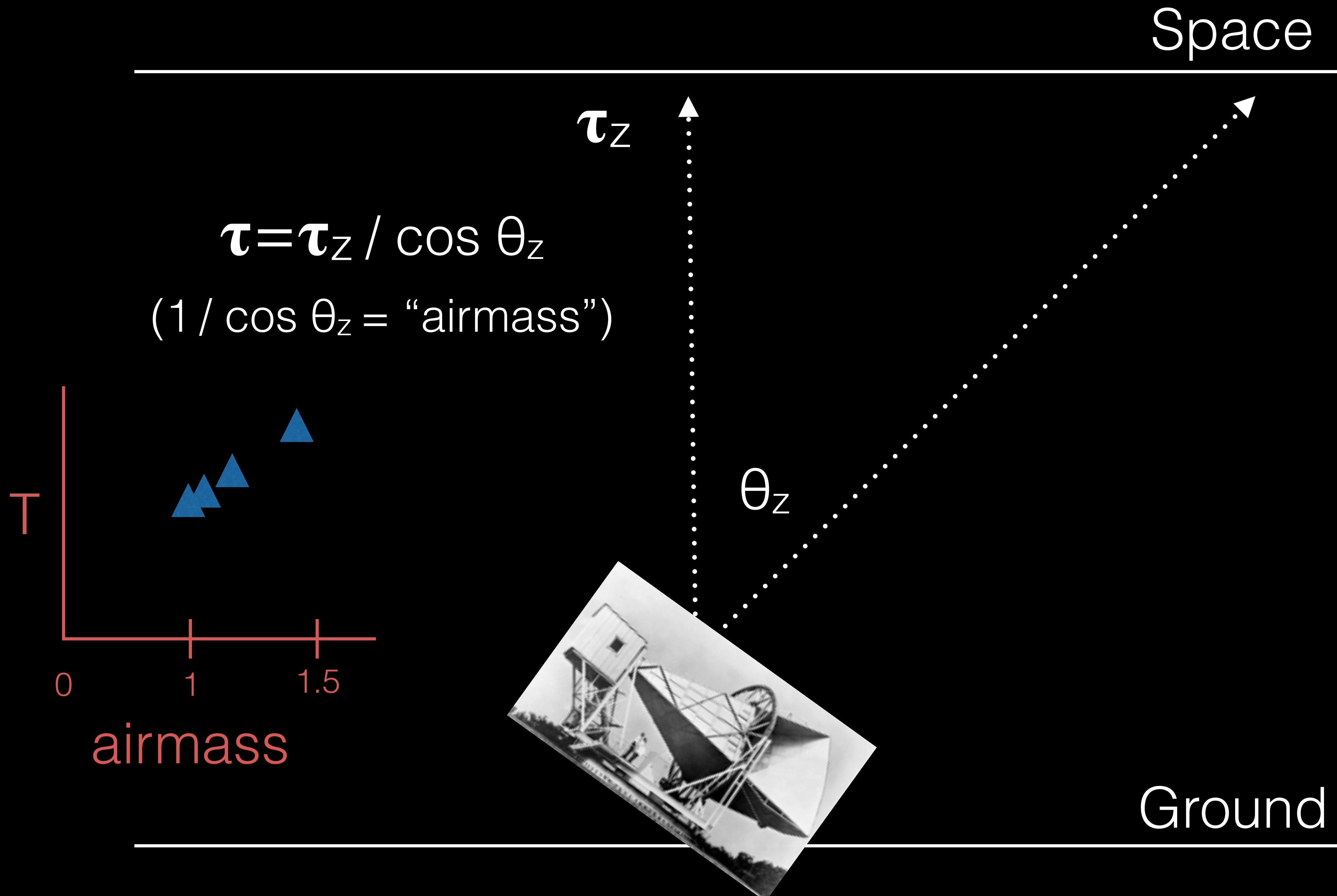


$$\tau = \tau_Z \, / \cos\theta_Z$$

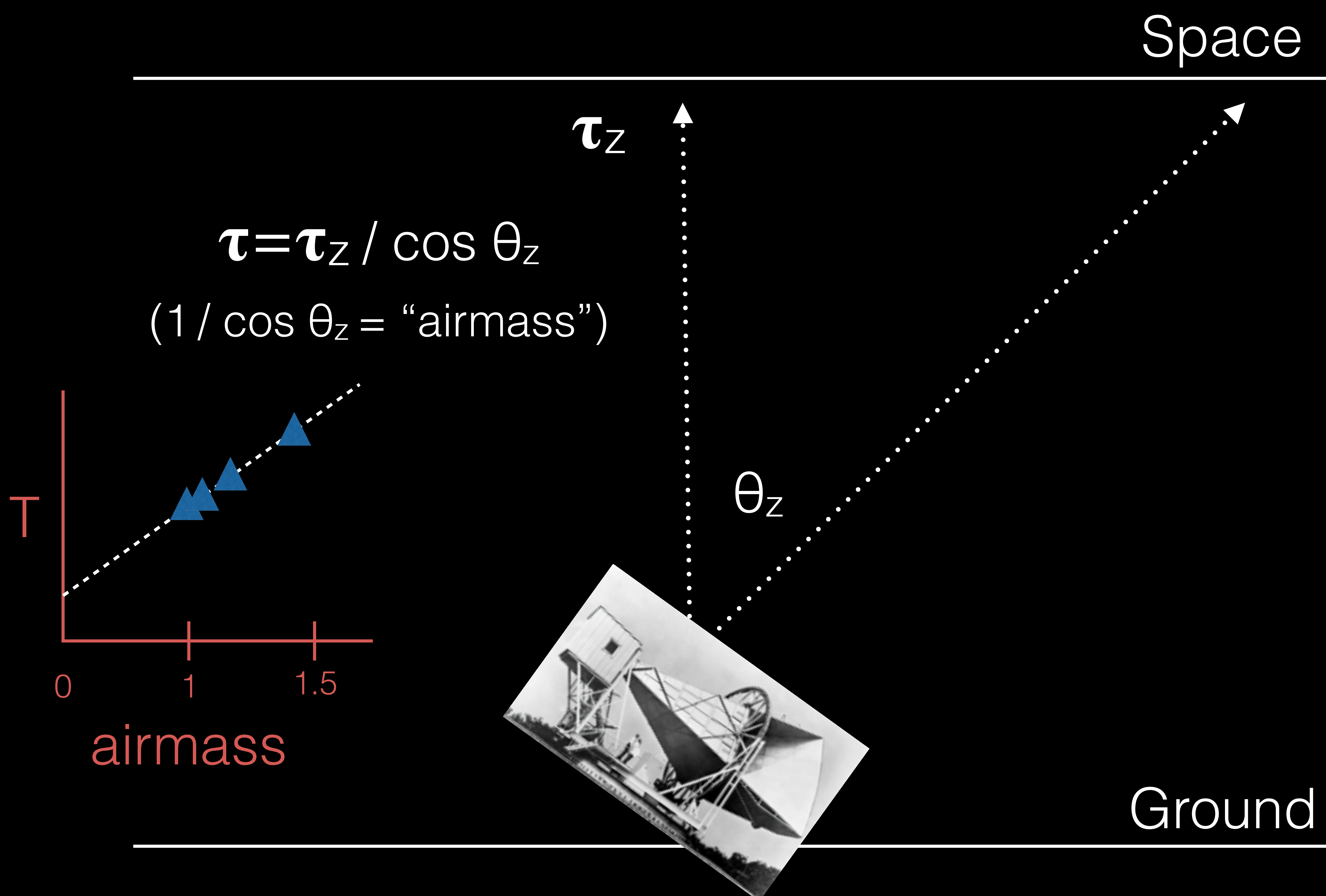
$$(1 / \cos\theta_Z = \text{“airmass”})$$



Elevation tipping



Elevation tipping



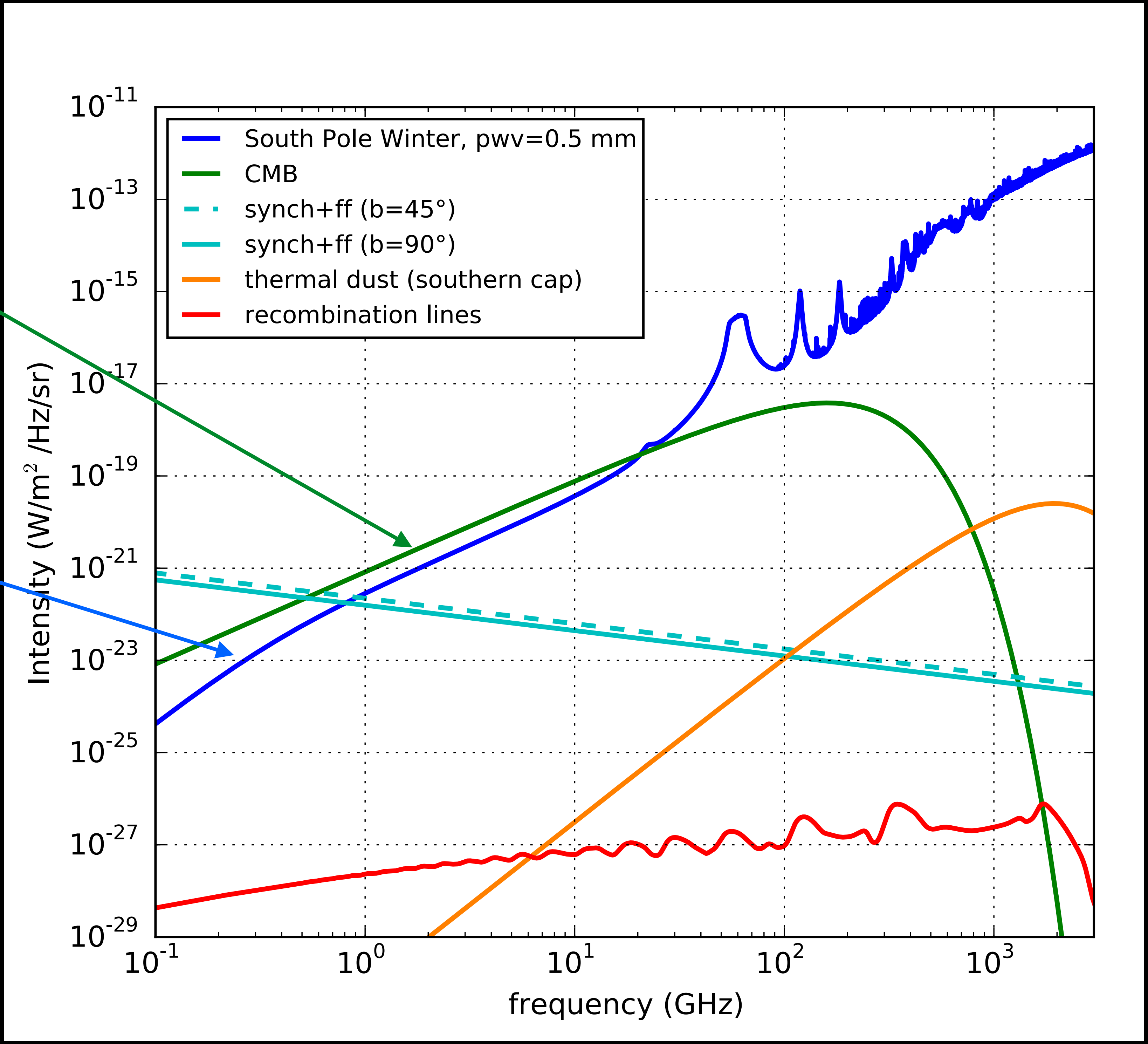
Elevation tipping

This only works at low frequencies, where the atmospheric emission is relatively low.

Atmosphere

CMB = 2.75 K

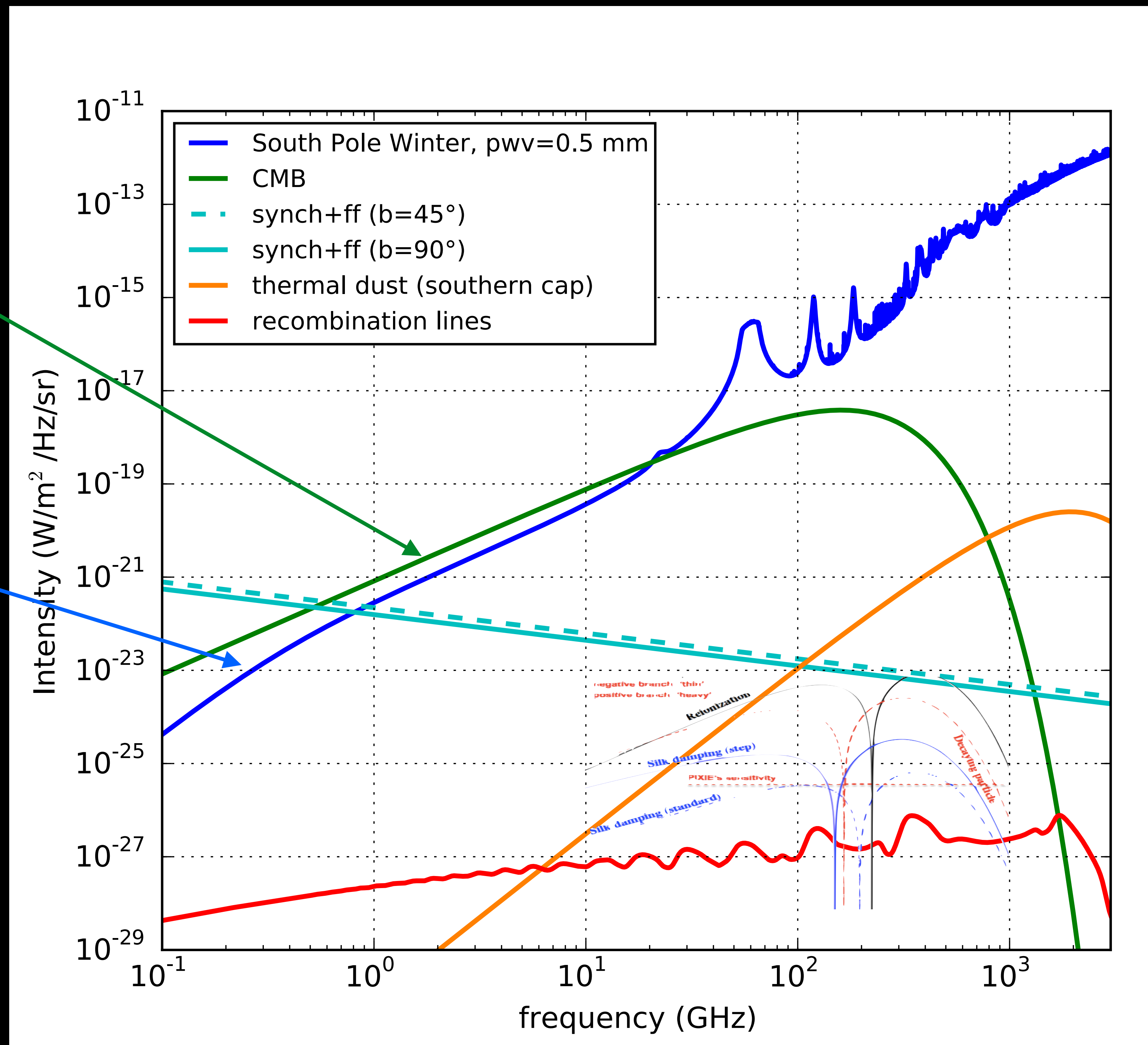
atmosphere ~ 1 K
at low frequencies



Atmosphere

CMB = 2.75 K

atmosphere ~ 1 K at low frequencies



Atmosphere

The atmosphere can only be subtracted to a finite accuracy, so it would seem that further progress can only be made from space.

Inspiration from 21-cm

- Proposal: take a page from 21-cm experiments, where the synchrotron foreground at ~100 MHz is many orders of magnitude larger than the cosmological signal.

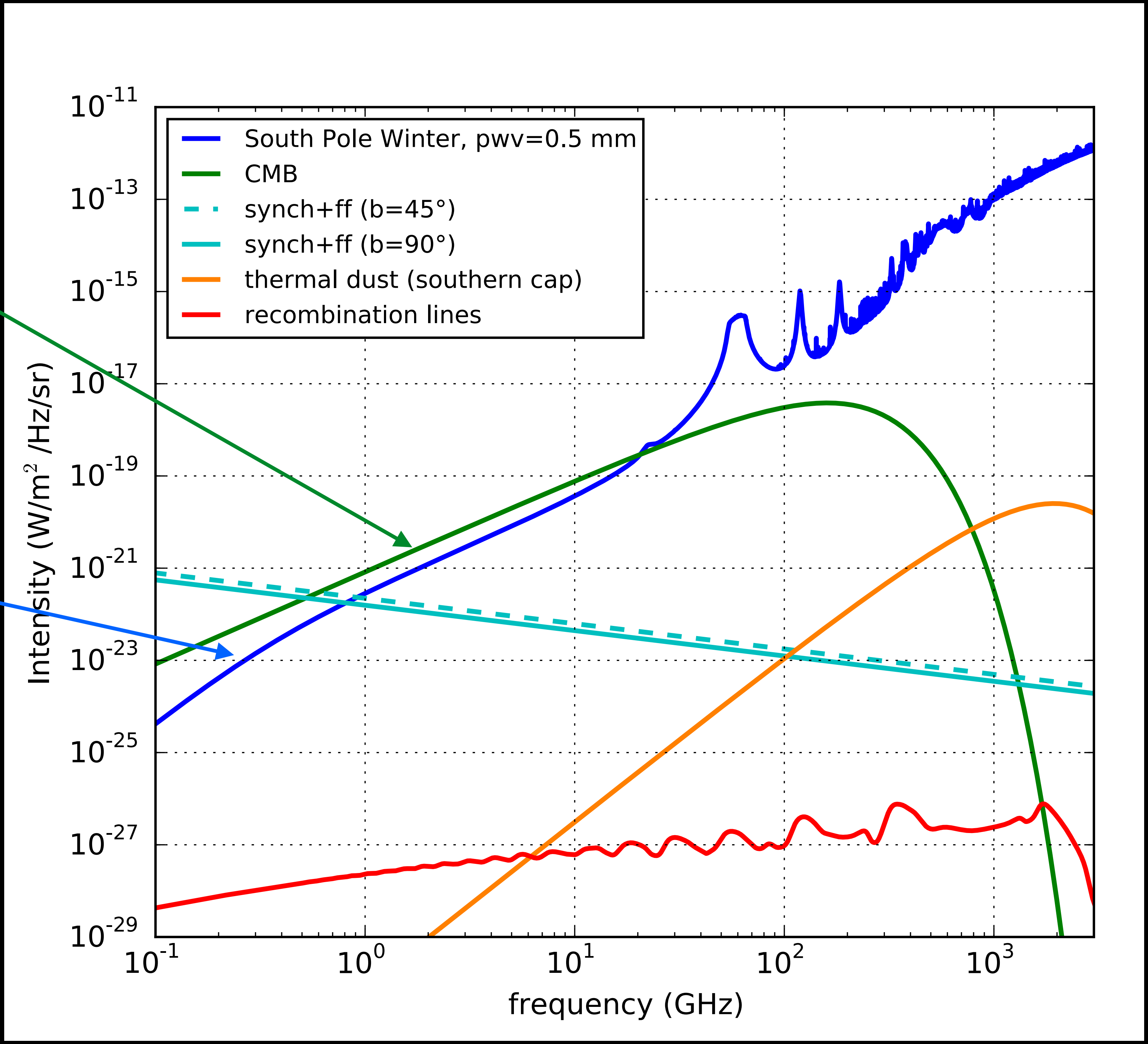
- If foregrounds are spectrally smooth, as synchrotron is expected to be, one can fit and subtract a smooth baseline to recover the non-spectrally smooth cosmological signal (in the case of 21-cm, from density inhomogeneities along the line of sight)

- Apply to CMB recombination lines: no need to make a 10^{-9} accurate *absolute* temperature measurement, just need to make highly precise *relative* temperature measurements

Atmosphere

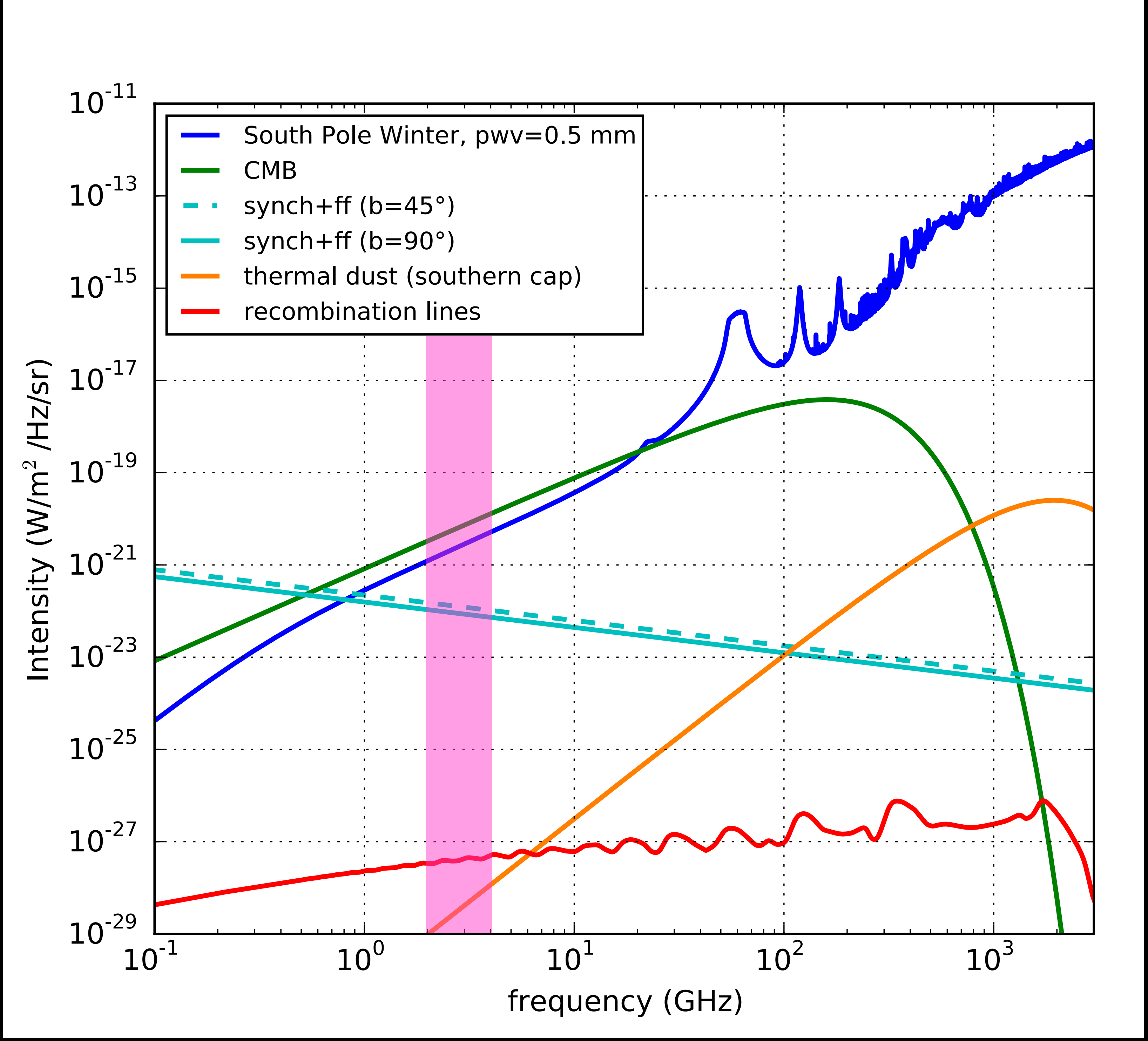
CMB

atmosphere: dominated by smooth continuum at low frequencies



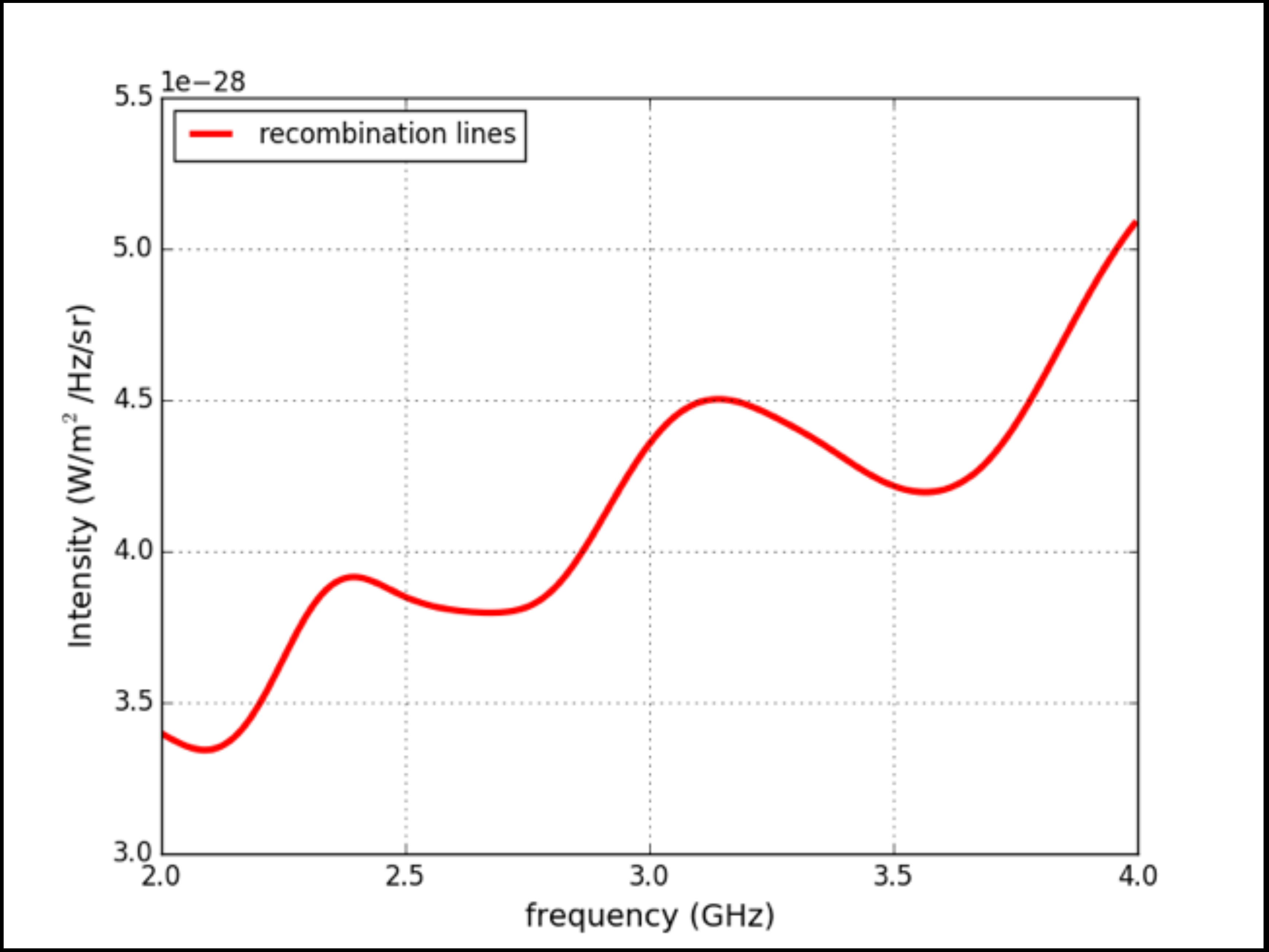
Atmosphere

Look at a window
2 GHz < f < 4 GHz
(for reasons that
will become clear
later)



Recombination lines

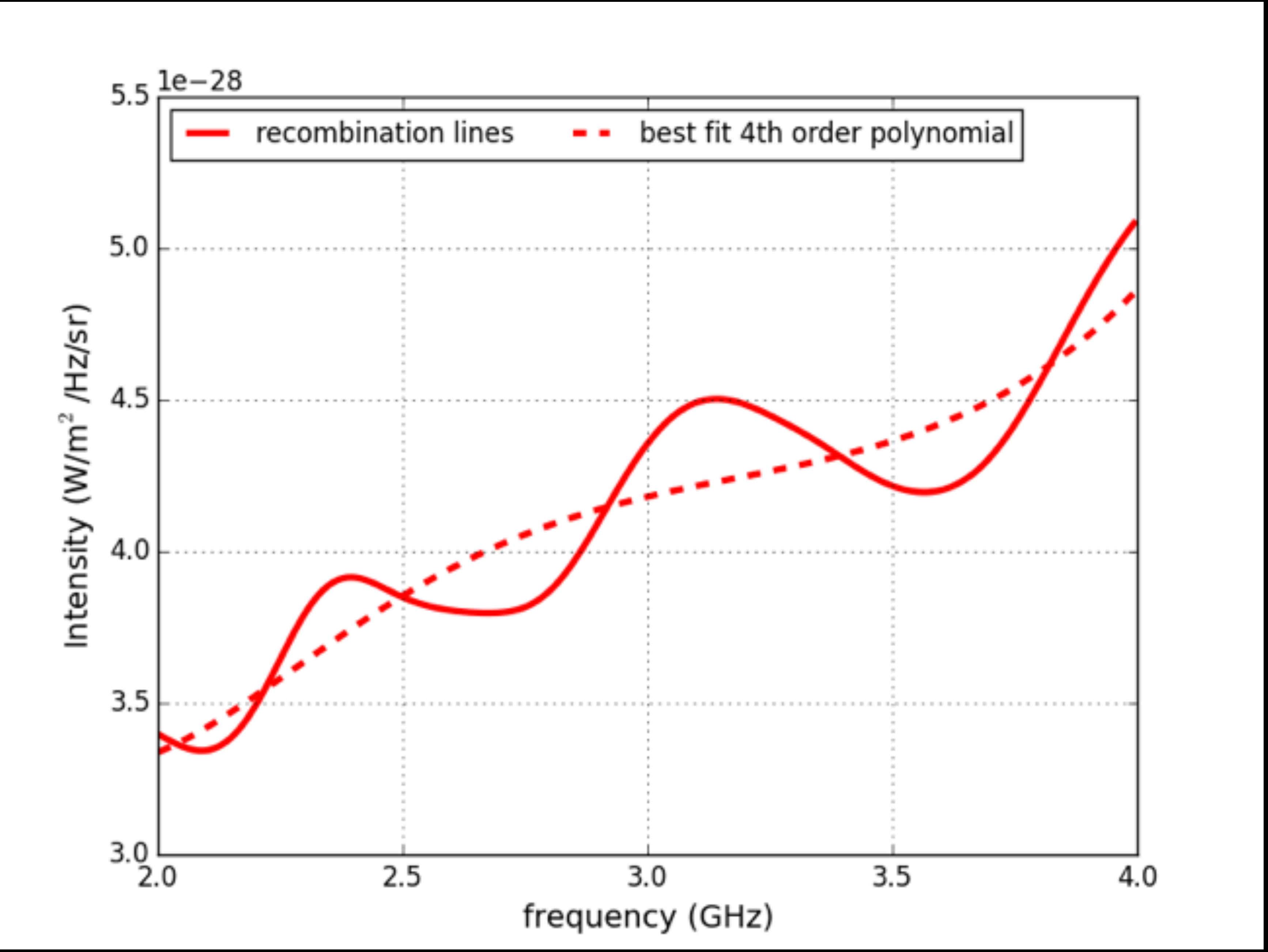
recombination line signal 2 GHz < f < 4 GHz



Recombination lines

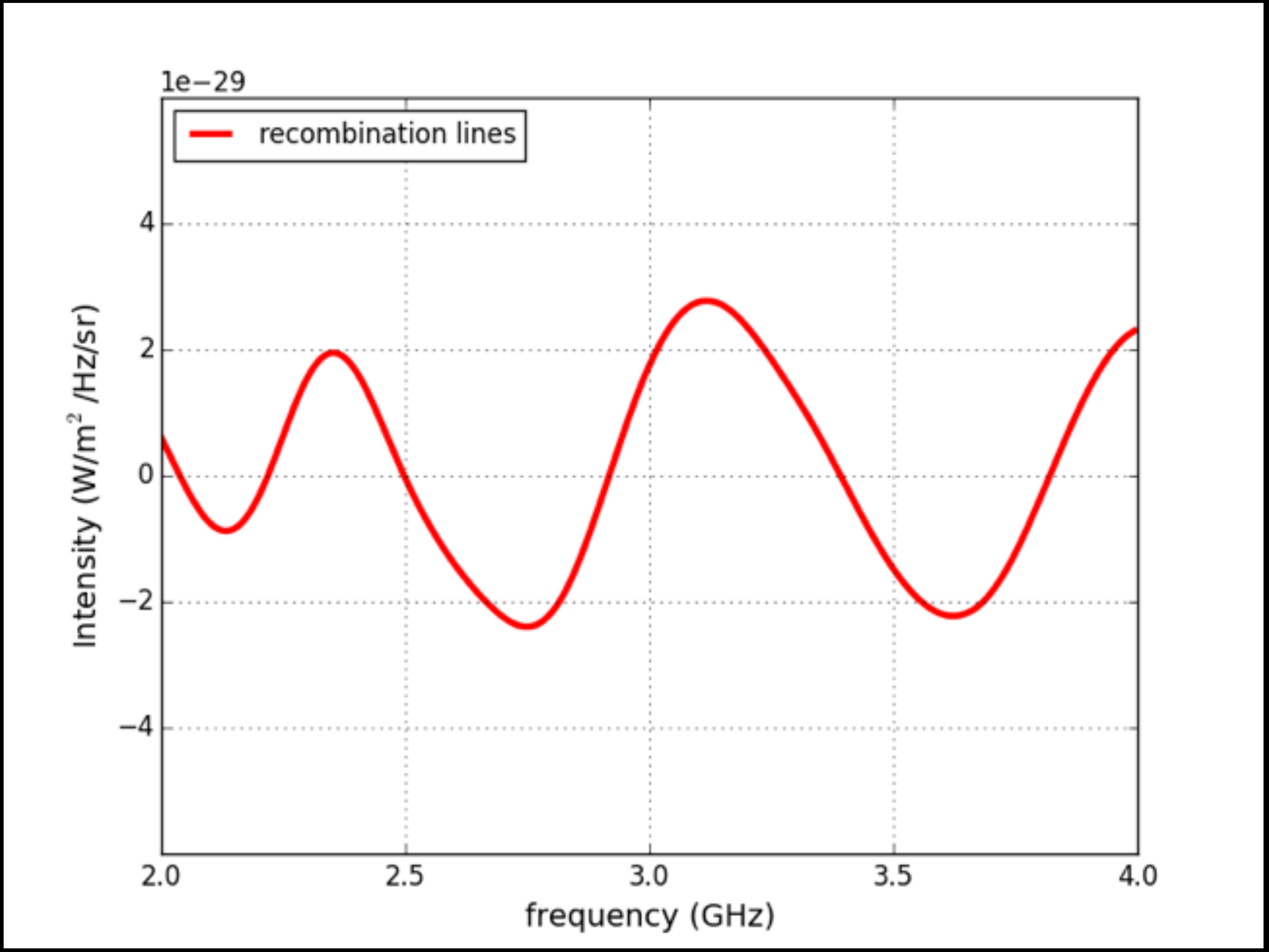
best fit 4th order polynomial

(filters some signal, can be improved with more complicated smooth functions)



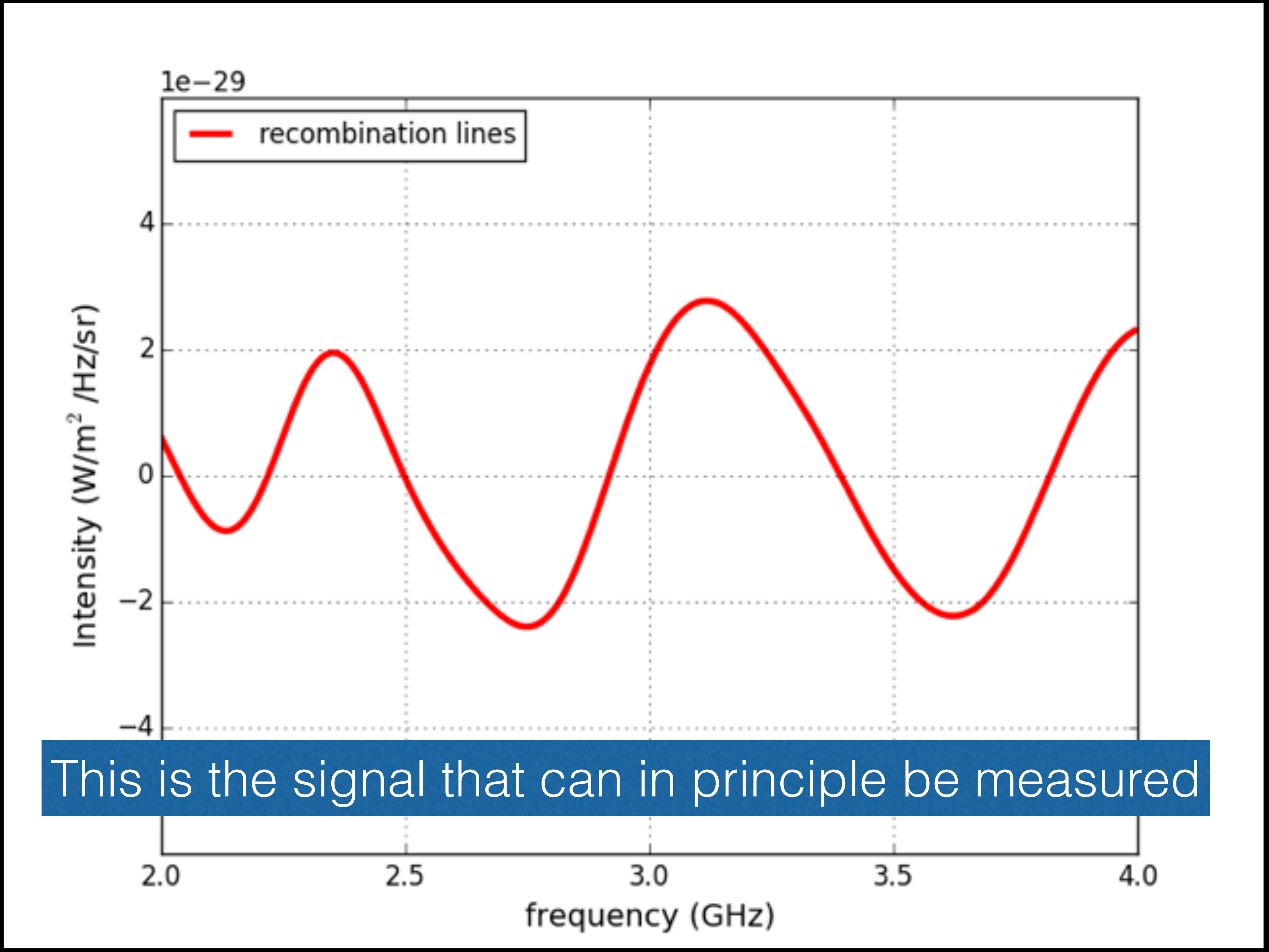
Recombination lines

after subtracting best fit 4th order polynomial



Recombination lines

after subtracting best fit 4th order polynomial

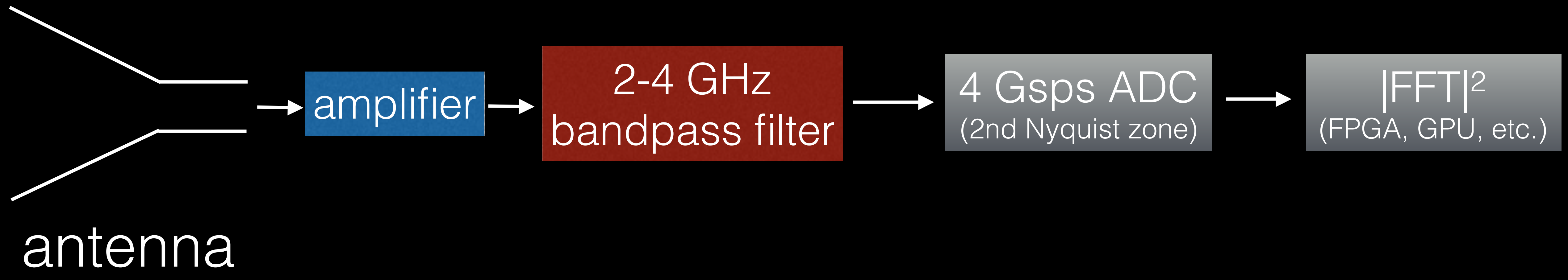


This is the signal that can in principle be measured

Recombination lines

How well can these lines be measured by a reasonable instrument in a reasonable integration time?

At GHz frequencies, can use standard radio astronomy techniques, an array of coherent radiometers and direct sampling + FFT



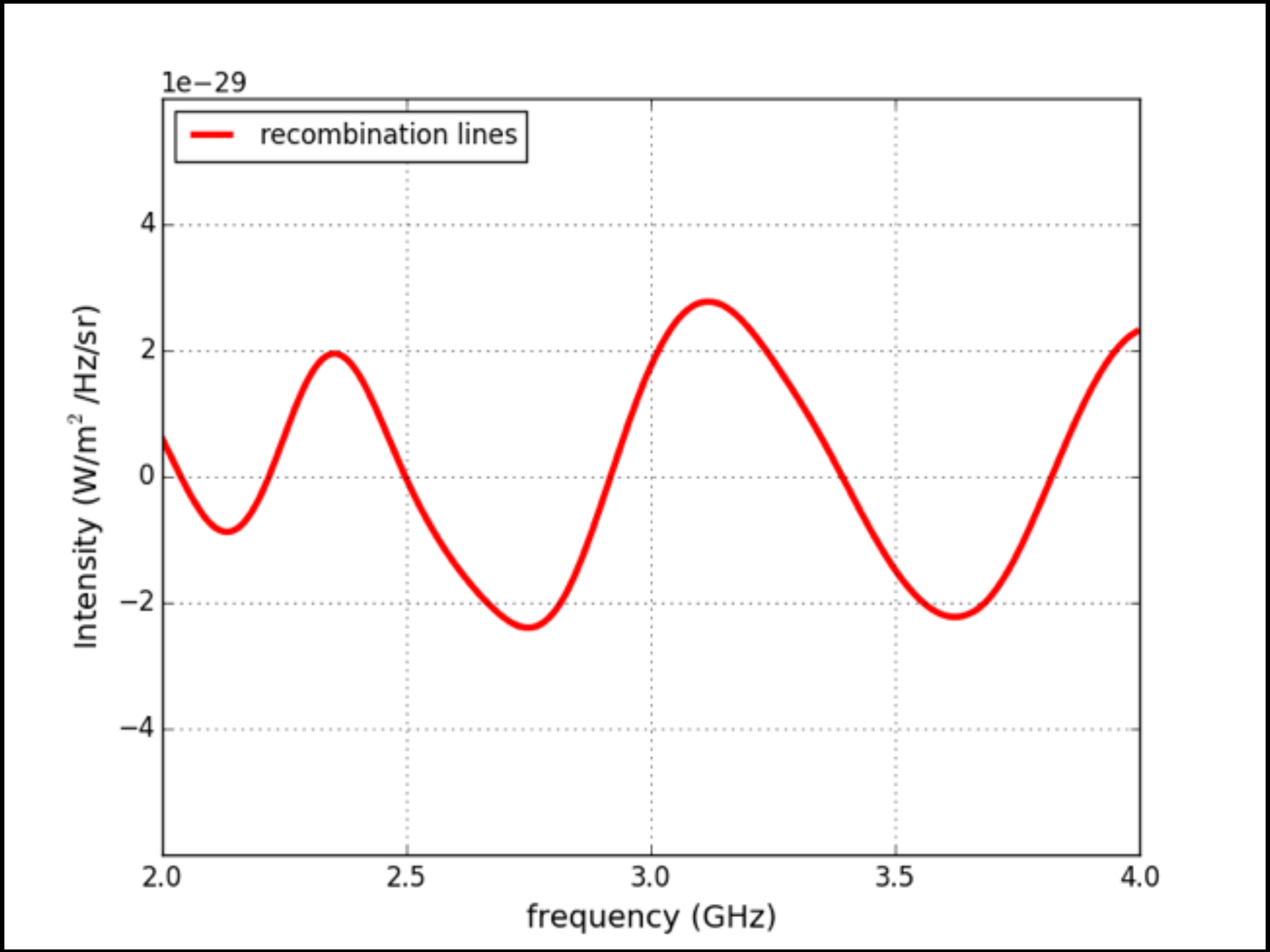
Photon noise dominated limit

- Plug in numbers to radiometer equation:

$$\sigma_T = \frac{T_{sys}}{\mathrm{sqrt}(N\ \Delta\nu\ t)}$$

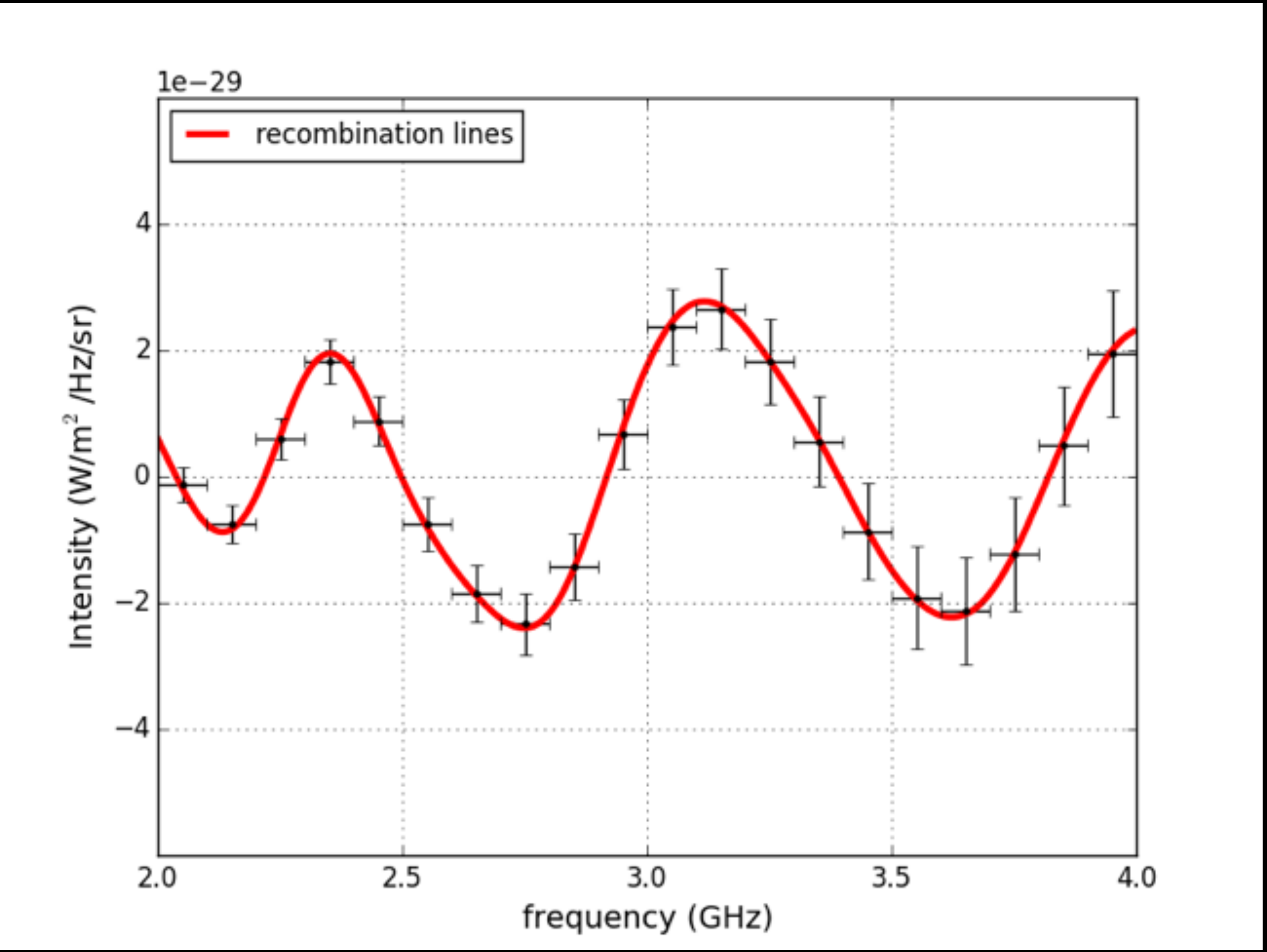
- T_{sys} = sky background = $T_{atm} + T_{CMB}$ = 3.75 K
- N = number of independent measurements, choose 1000, e.g. 500 independent dual polarization detectors
- $\Delta\nu$ = frequency bin width, choose 0.1 GHz
- t = integration time, choose 1 year

Photon noise dominated limit



Photon noise dominated limit

1000 modes, 1 yr integration, T_{sys} = 3.75 K



More realistic noise

- There exist many commercially available, surface mount low noise amplifiers (LNAs) for use in the cellular communications industry.

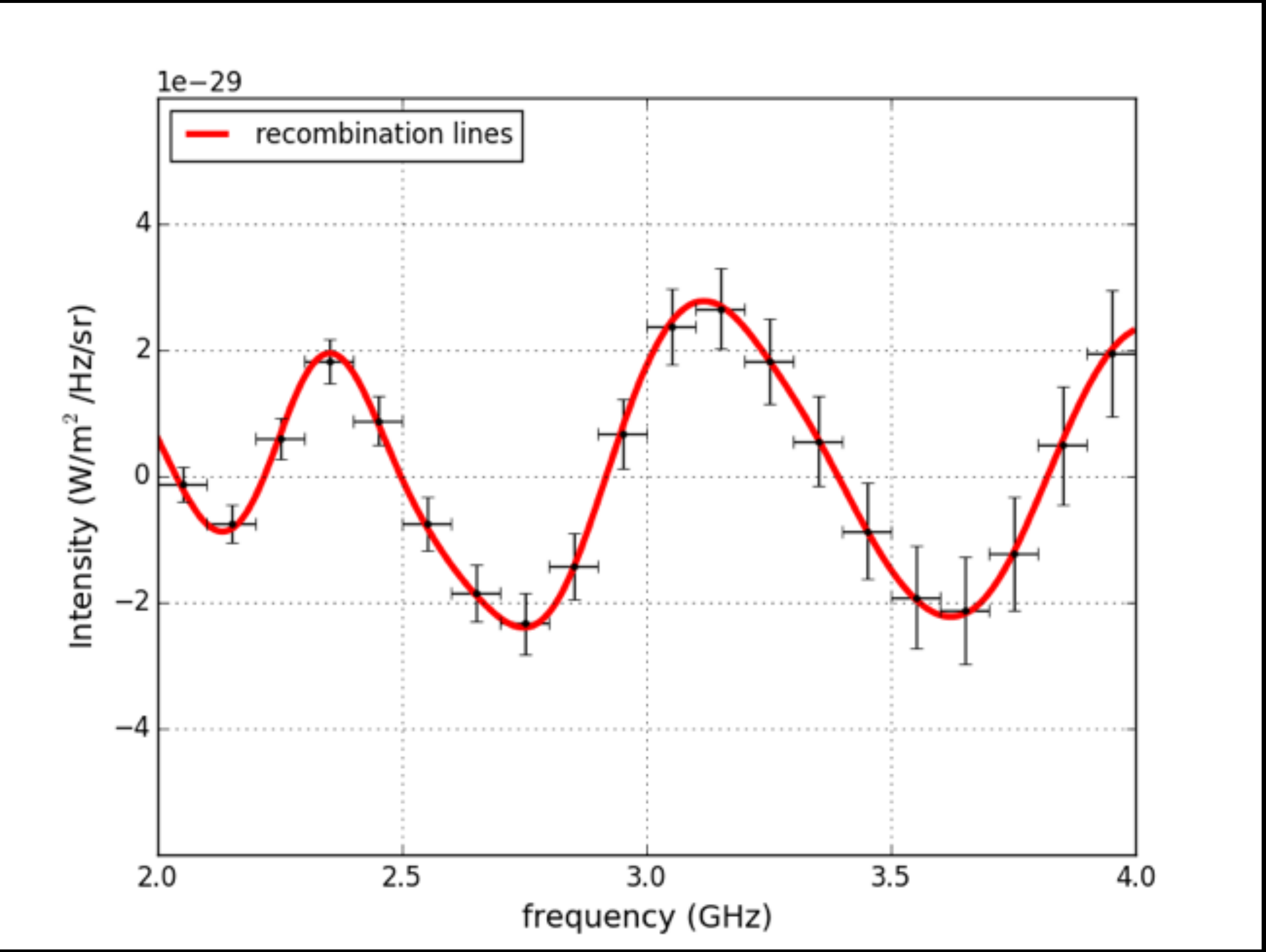
- Pick one: Avago ATF-35143 HEMT amplifier, retail \$1.50, almost the same LNA used by the CHIME 21-cm experiment

- Off the shelf noise temperature when operated at -40 C (cool but not cryogenic) increases linearly from T = 6 –14 K in the interval f = 2 – 4 GHz.

- $T_{sys} = T_{sky} + T_{amp}$ = 3.75 K + [6 K to 14 K] at 2 to 4 GHz

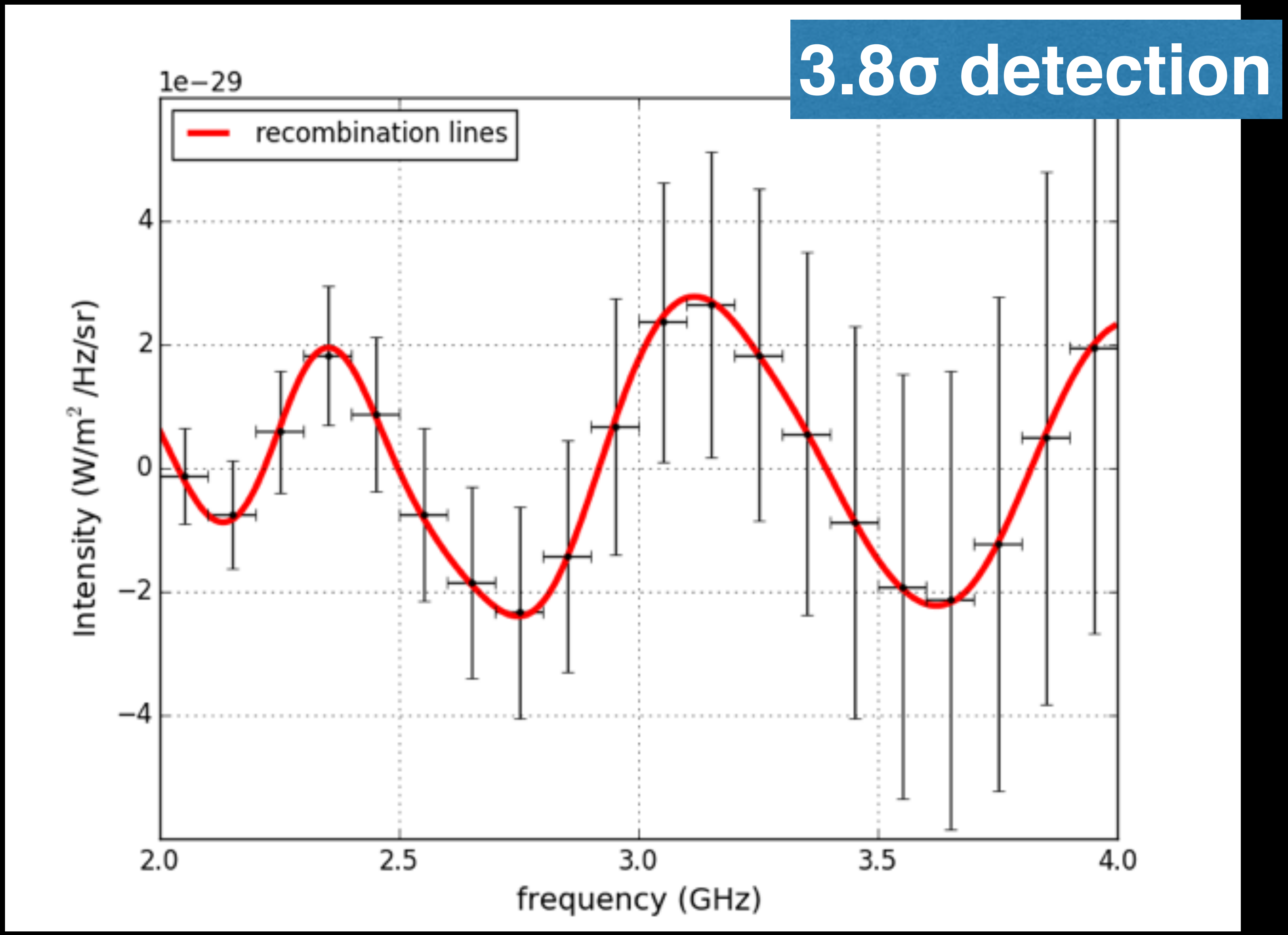
More realistic noise

1000 modes, 1 yr integration, T_{sys} = 3.75 K



More realistic noise

1000 modes, 1 yr integration, T_{sys} = 10 – 17 K

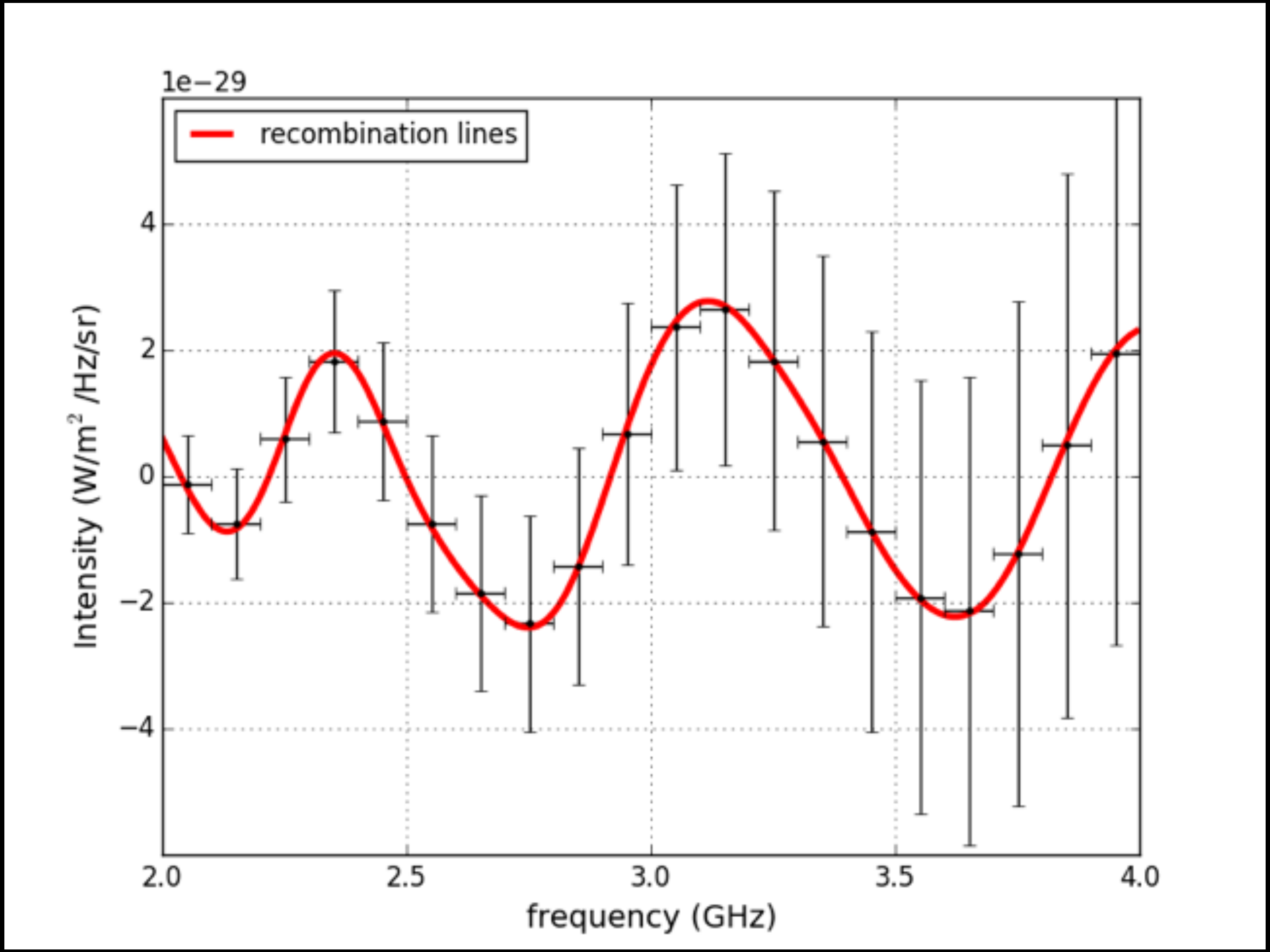


More realistic noise

Now assuming a cryogenic amplifiers can achieve a 4x noise temperature reduction, so T_{amp} = 1.5 - 3 K at 2 - 4 GHz

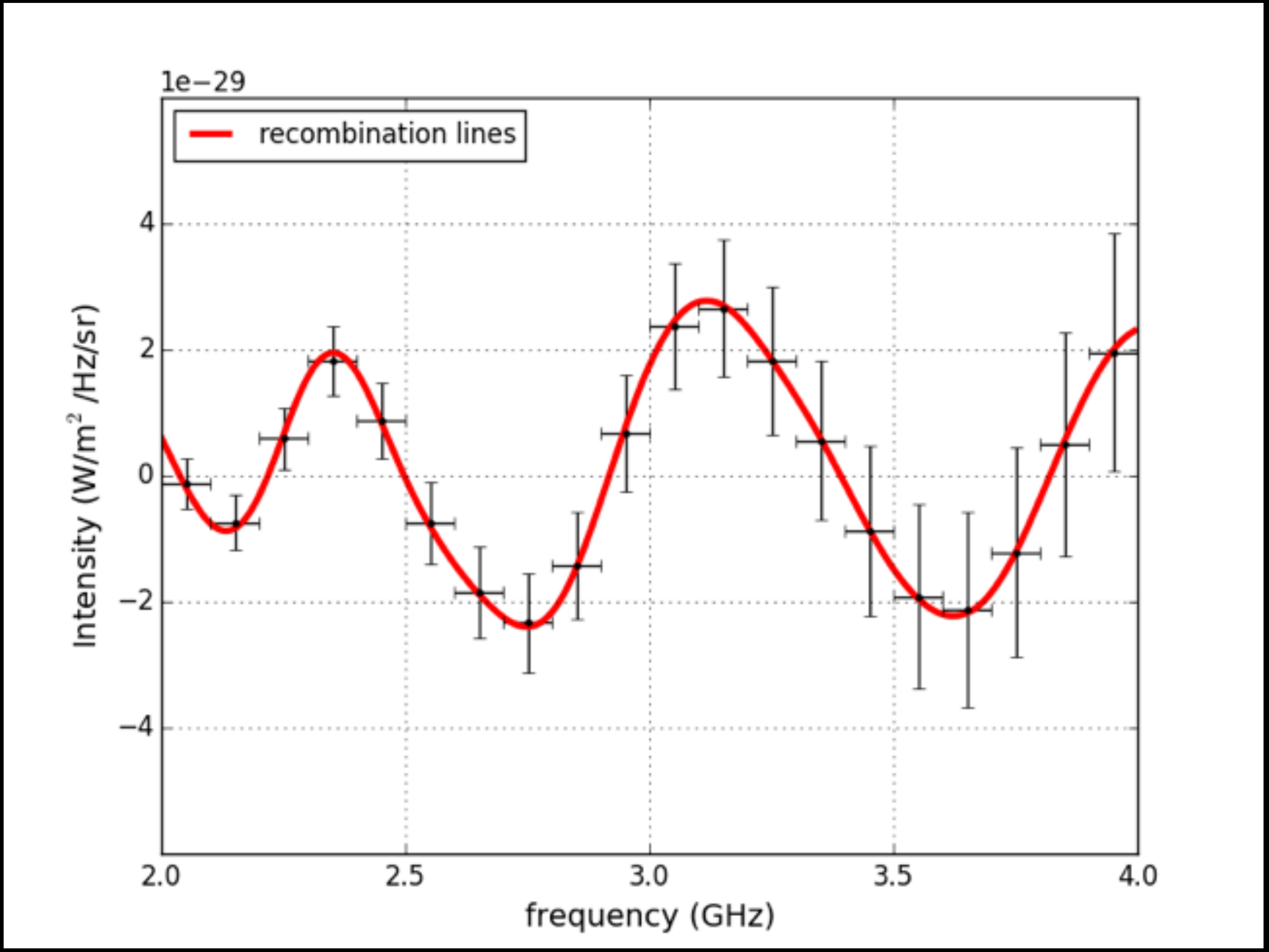
More realistic noise

1000 modes, 1 yr integration, T_{sys} = 10 – 17 K



More realistic noise

1000 modes, 1 yr integration, T_{sys} = 5.5 – 7 K



Science

Science that can be done (bulk of theoretical effort has gone into the mu and y distortions so far, but…):

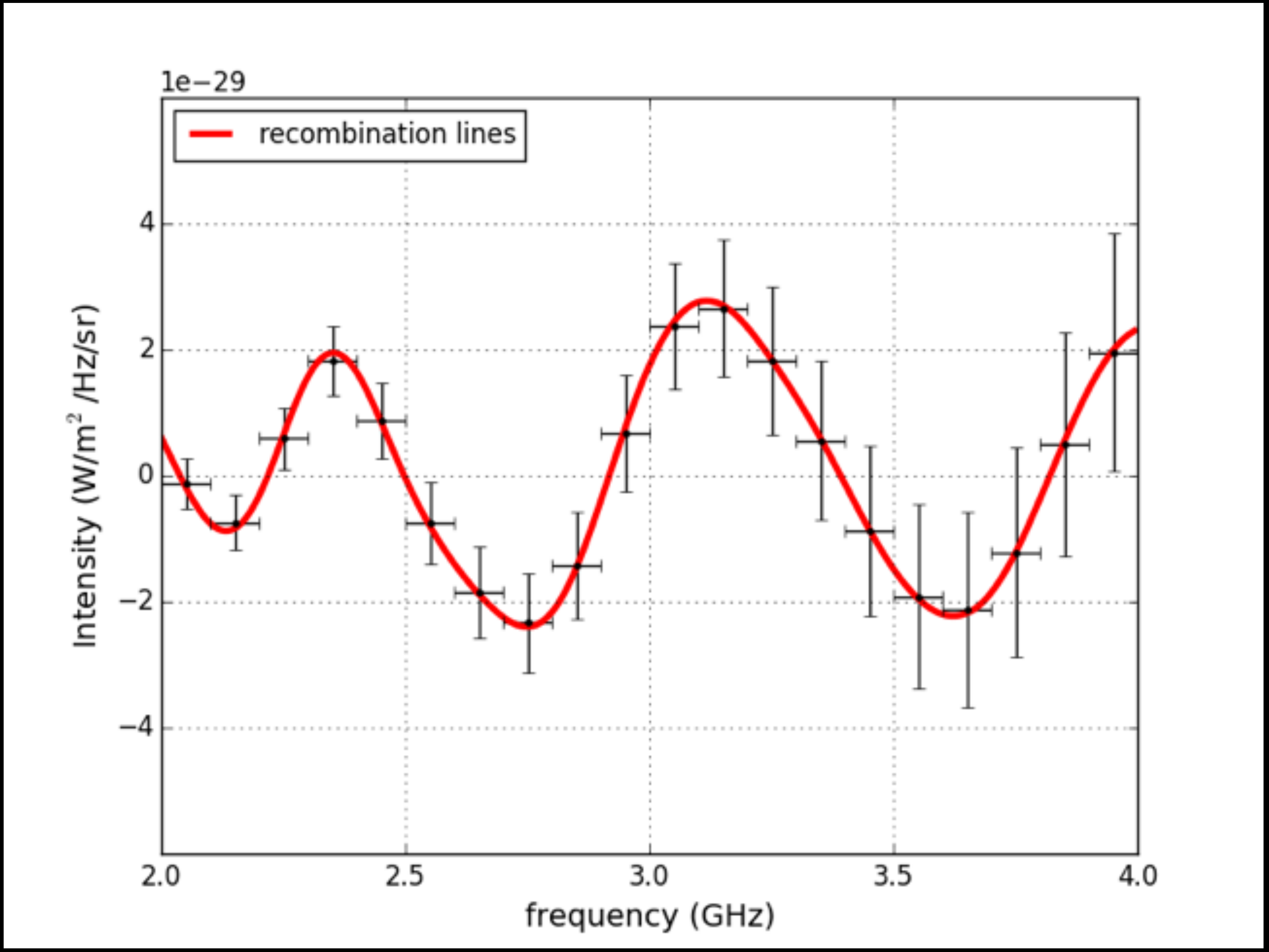
- important check on recombination physics

- look for energy injection prior to hydrogen recombination which affects line shapes and positions

- example: helium recombines before hydrogen, which produces non-thermal photons. This changes the hydrogen lines' positions and shapes

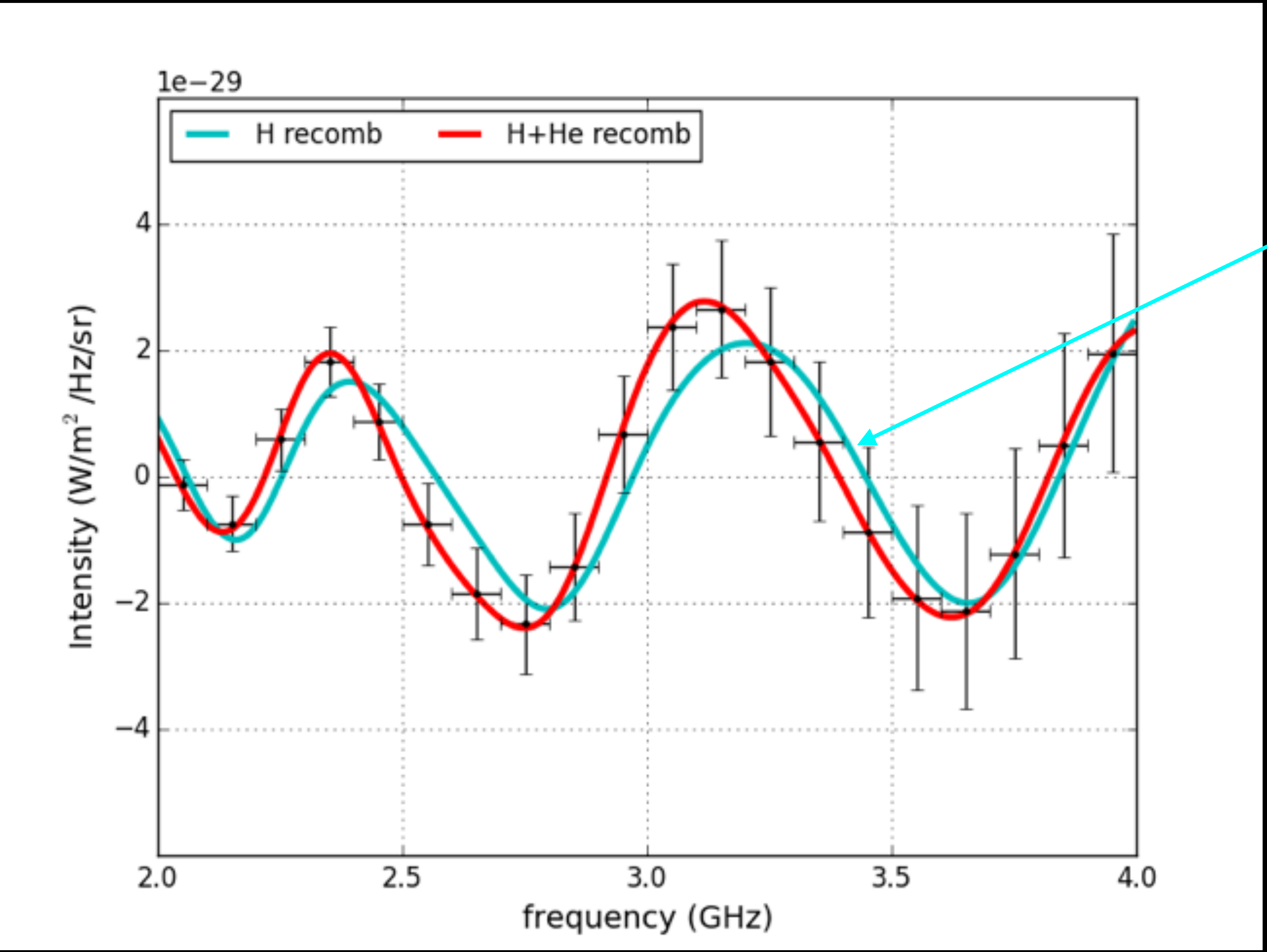
Science

1000 modes, 1 yr integration, T_{sys} = 5.5 – 7 K



Science

1000 modes, 1 yr integration, $T_{sys} = 5.5 - 7$ K



Without taking into account helium

(thanks to Jens Chluba and Yacine Yacine Ali-Haimoud)

Science

Possible **direct, clean measurement of $\mathbf{Y_P}$** at high redshift, before contamination by stars.

(Cannot do parameter constraints until the fast computation code becomes publicly available, which I am told it will be soon.)

Instrumental challenges

- Gain flatness
  - if instrumental gain is not smooth to 1 part in 10^9, the smooth CMB will appear to have wiggles, contamination the measurement
  - need a calibration source that is known to be smooth to 1 part in 10^9
  - Pyramidal eccosorb is black to 1 part in 10^6, might be possible to improve upon, especially since it does not need to be isothermal
- 1/f noise
  - because this is not an absolute intensity measurement, and because direct sampling can acquire a spectrum on very short timescales, probably not an issue
- RFI
  - unlike the ultra-low frequencies of high redshift 21-cm, at a few GHz, RFI doesn't propagate nearly as far (think how hard it can be to get wifi), so maybe not so bad from good sites
  - satellite communication bands a possible issue
- Beams
  - frequency dependent beams couple anisotropy into frequency modulations
  - horizon response produces multipath interferometric fringing

Instrumental challenges

The instrumental challenges are significant, but if a ground based relative intensity measurement is in principle possible, an instrument on the ground is *no less sensitive* than one in space, so worth the effort!

Can learn from the experience of global 21-cm experiments (e.g. EDGES here at Haystack.) Higher frequency makes things easier — lower synchrotron, high directivity antennas, etc.

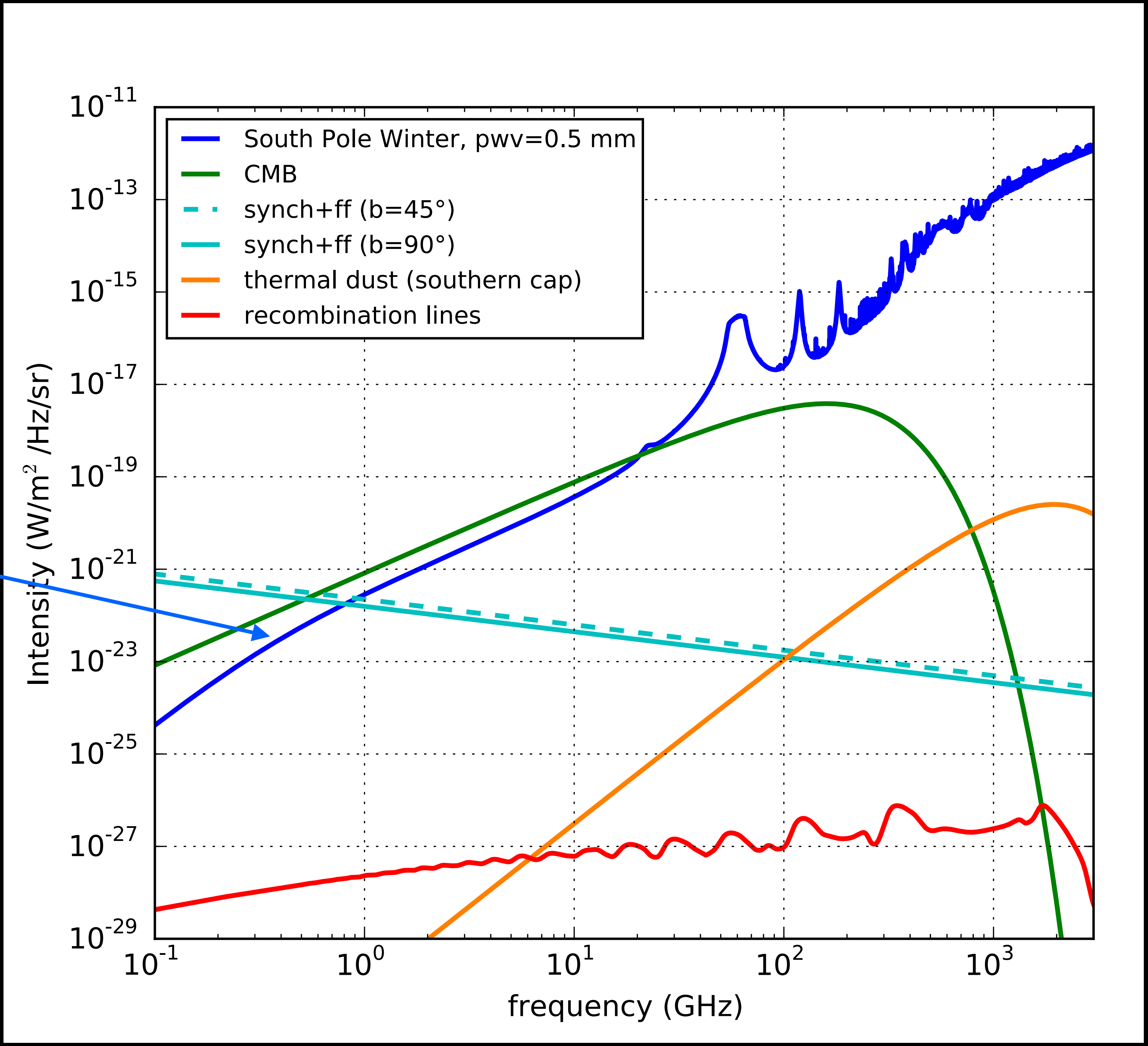
I am not the first person to think of this: APSERa is a proposed project using non-pointing, roughly isotropic antennas — see Rao, Subrahmanyan, Shankar, and Chluba (ApJ 2015)

Major wrinkle

Atmospheric emission is not actually smooth, even at low frequencies. This has not yet been fully appreciated.

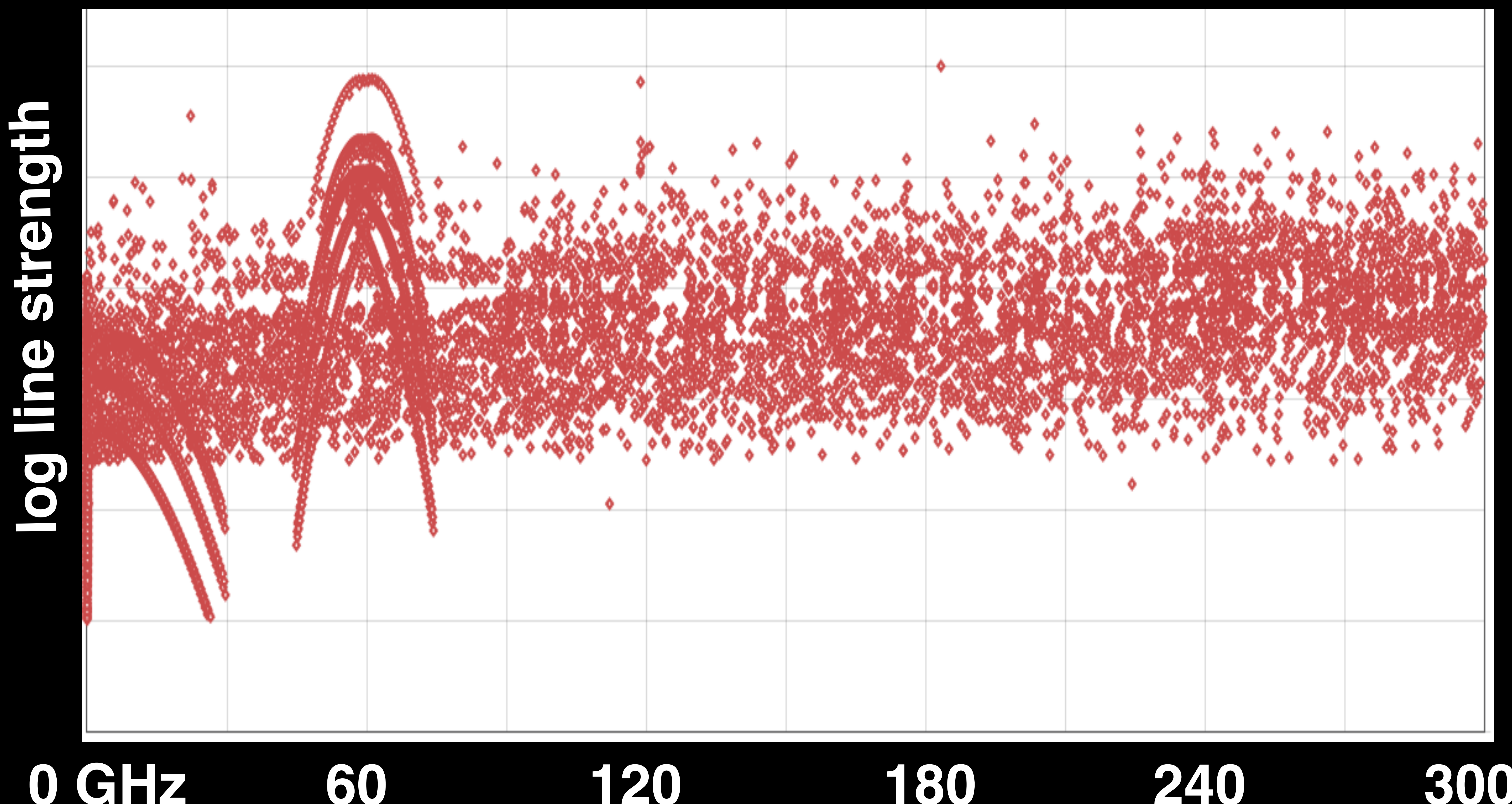
Atmospheric lines

we need the atmosphere to be smooth to 1 part in 10^9

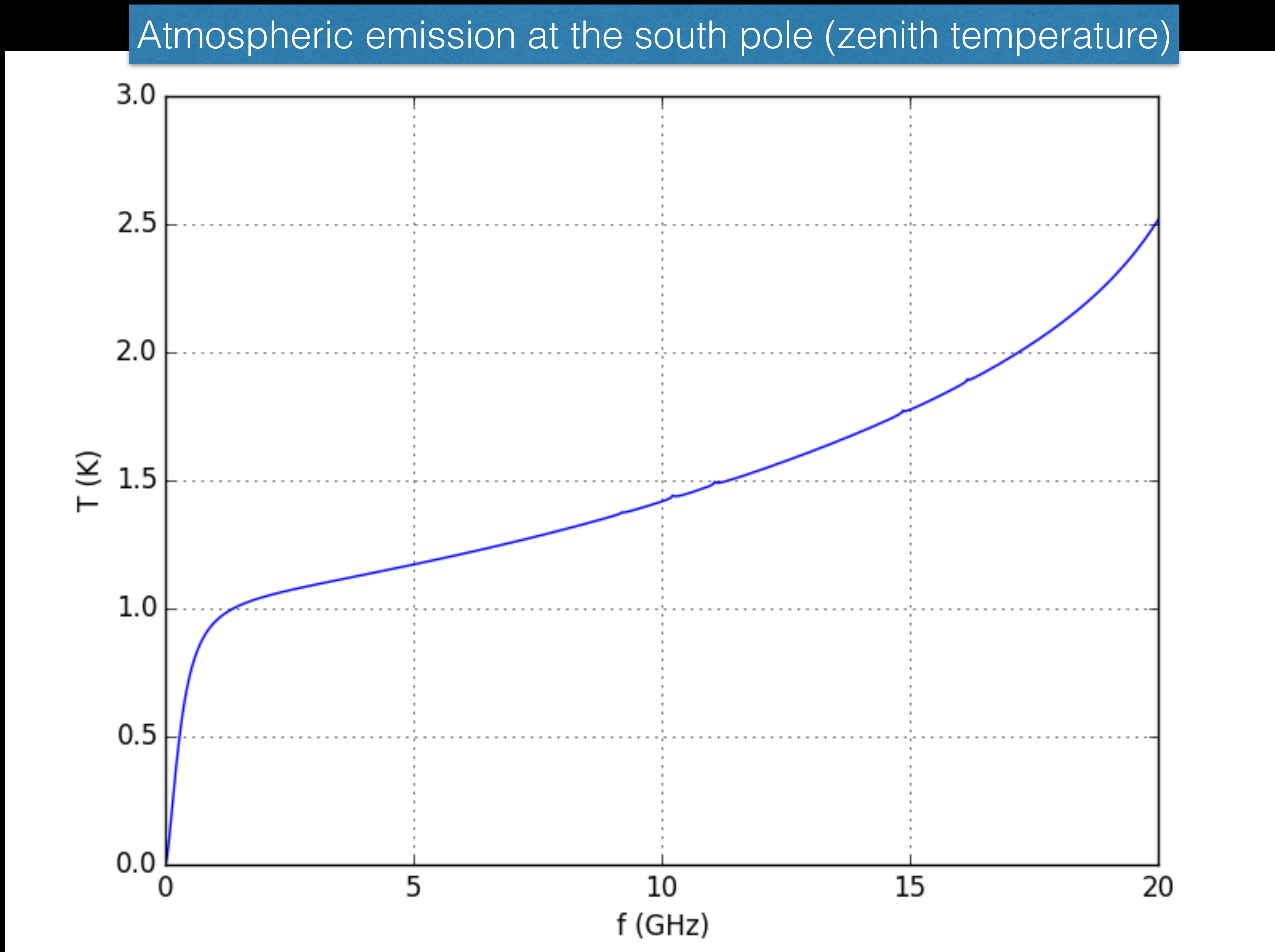


Atmospheric lines

HITRAN database

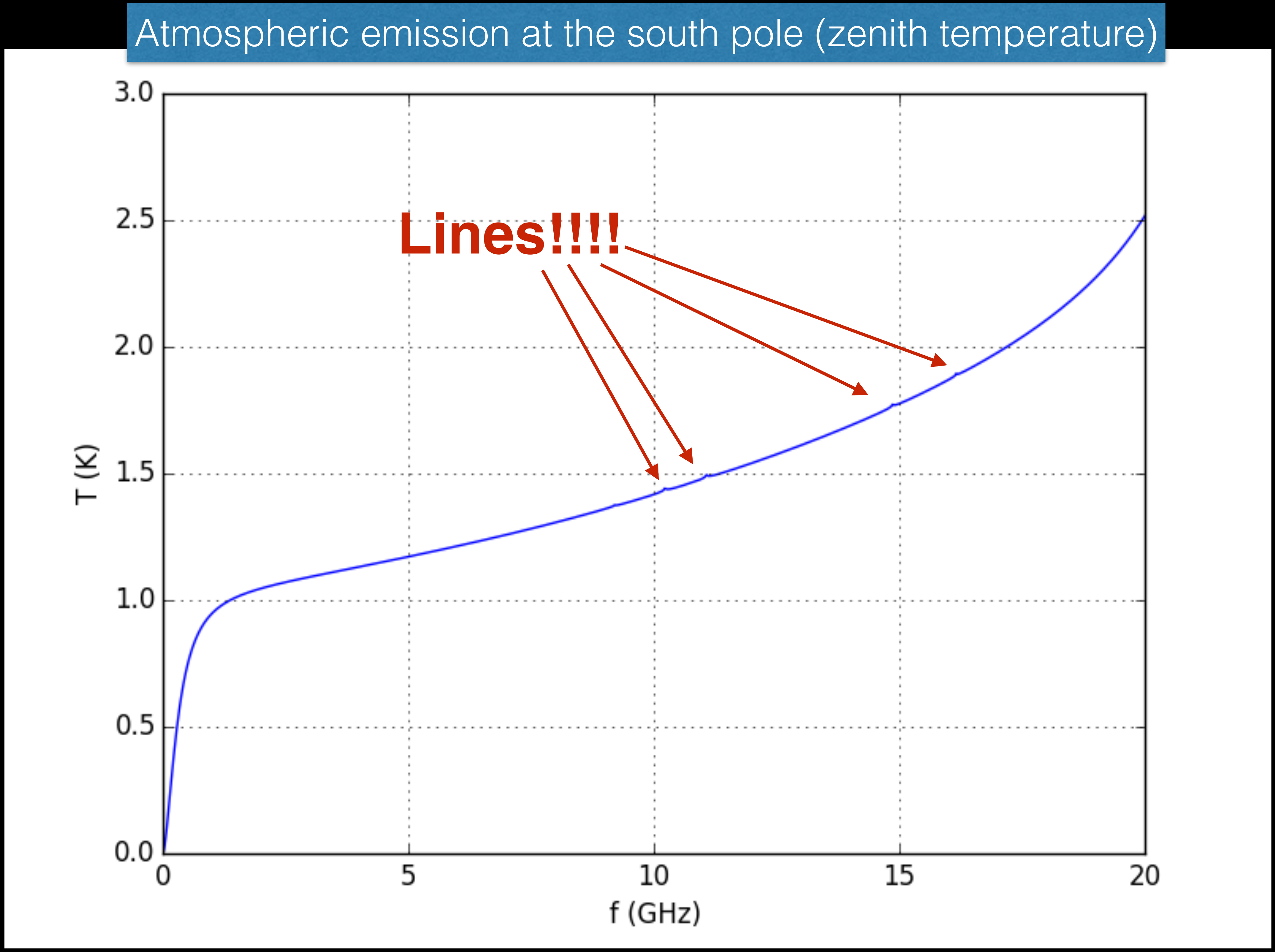


Atmospheric lines



using am radiative transfer code

Atmospheric lines



using am radiative transfer code

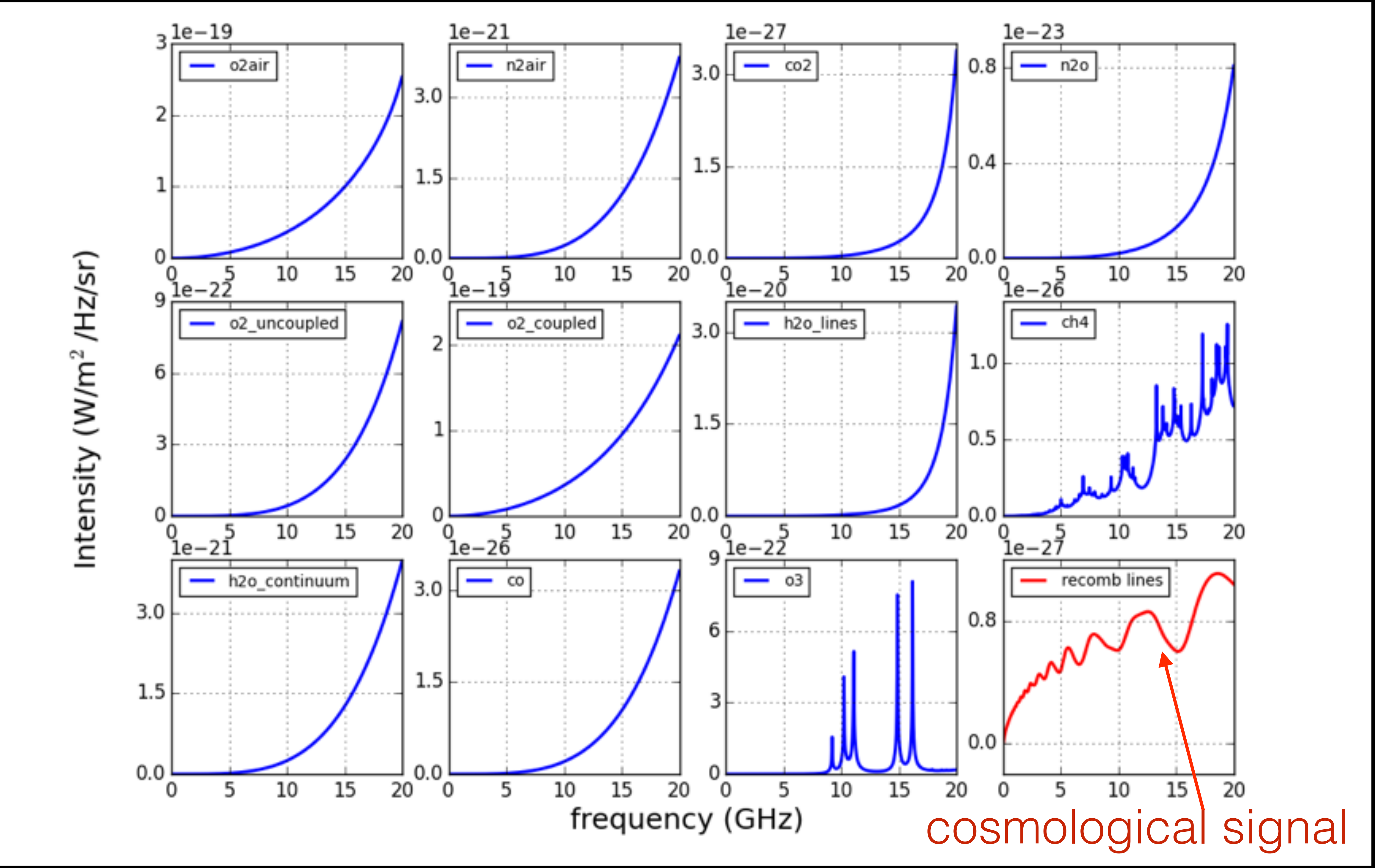
Atmospheric lines

- The “am” atmospheric radiative transfer code (c.f. Scott Paine) is industry standard.
- Output is 7 significant digits floating point
- Lines smaller than ~1e-6 of the continuum do not show up, but we need to be aware of lines larger than 1e-9 of the continuum
- Solution: break emission down into constituent molecular species and approximate total atmospheric emission as sum. This is a very good approximation because the total atmospheric optical depth is <<1.

Atmospheric lines

Model atmospheric emission broken down by molecular constituent

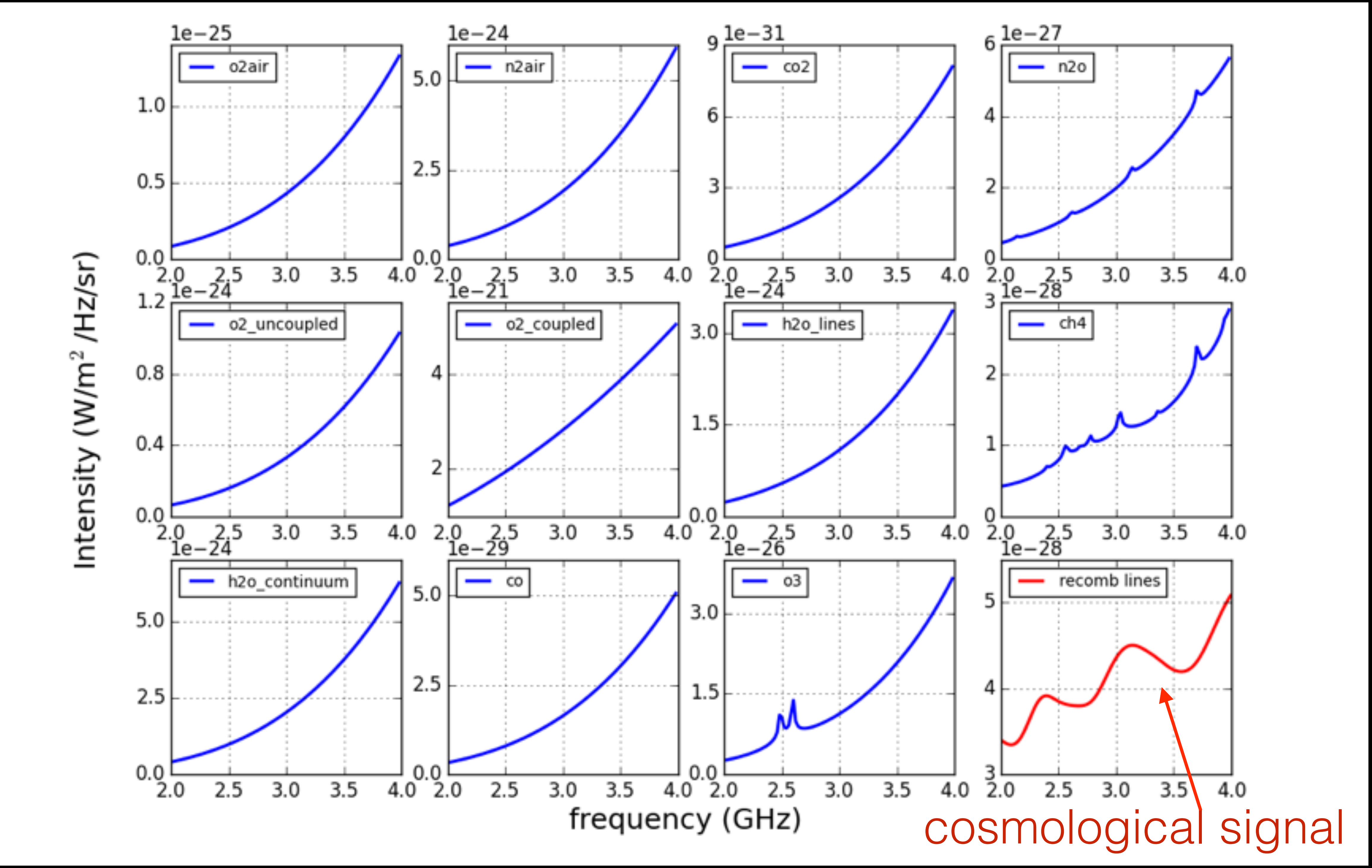
0-20 GHz



Atmospheric lines

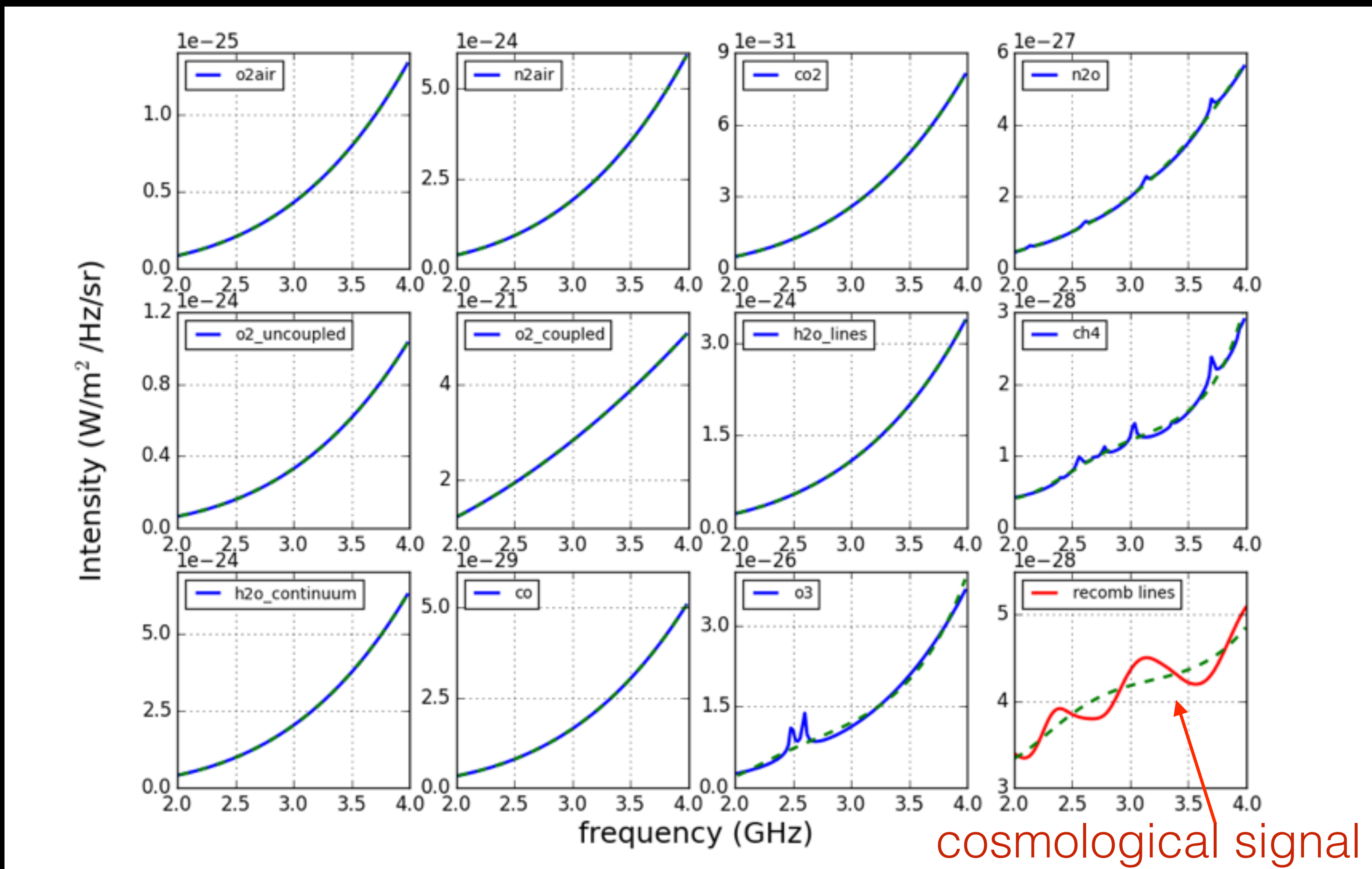
Model atmospheric emission broken down by molecular constituent

2-4 GHz



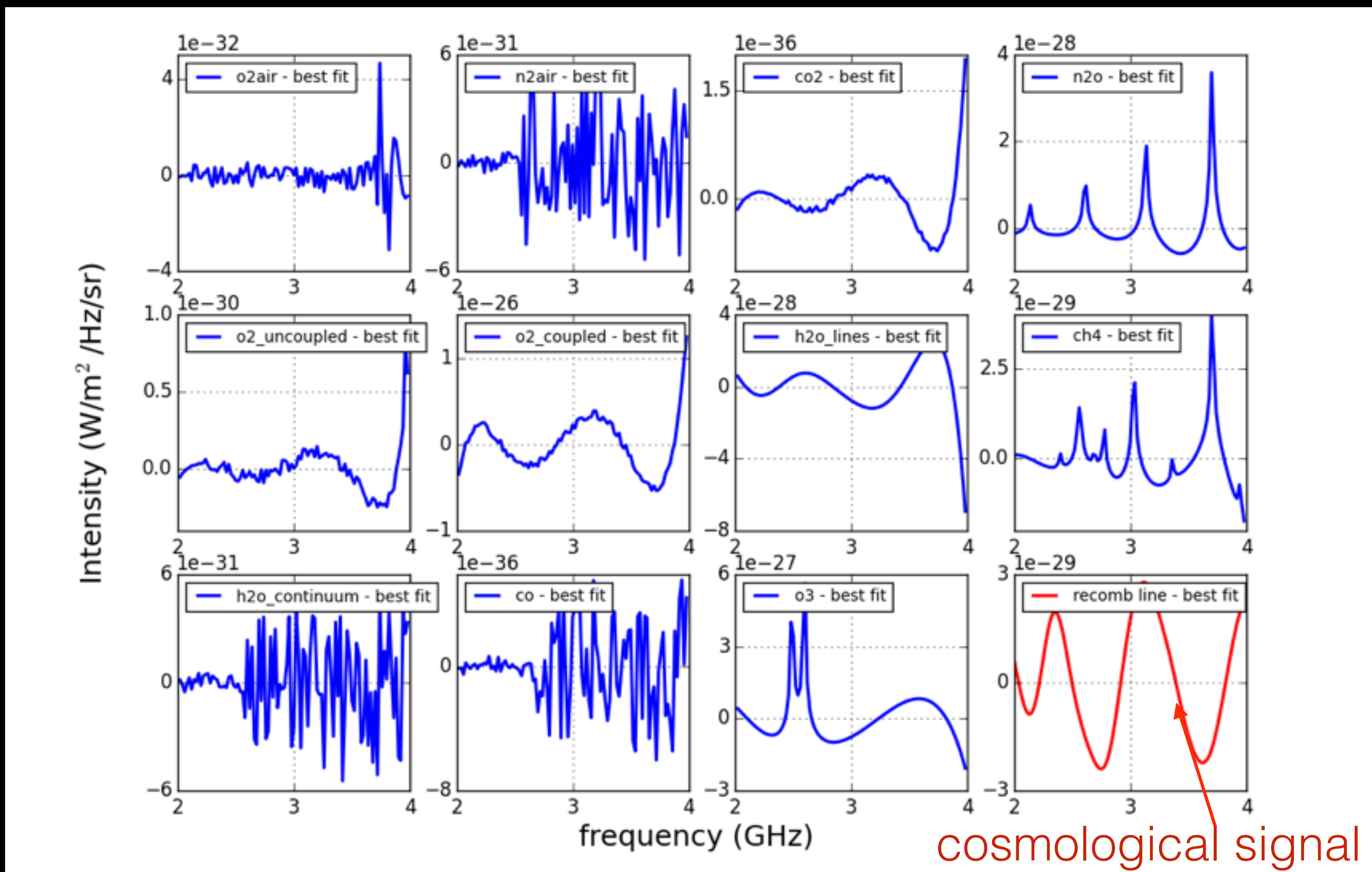
Atmospheric lines

Best fit baseline (spectrally smooth-ish 4th order polynomial)



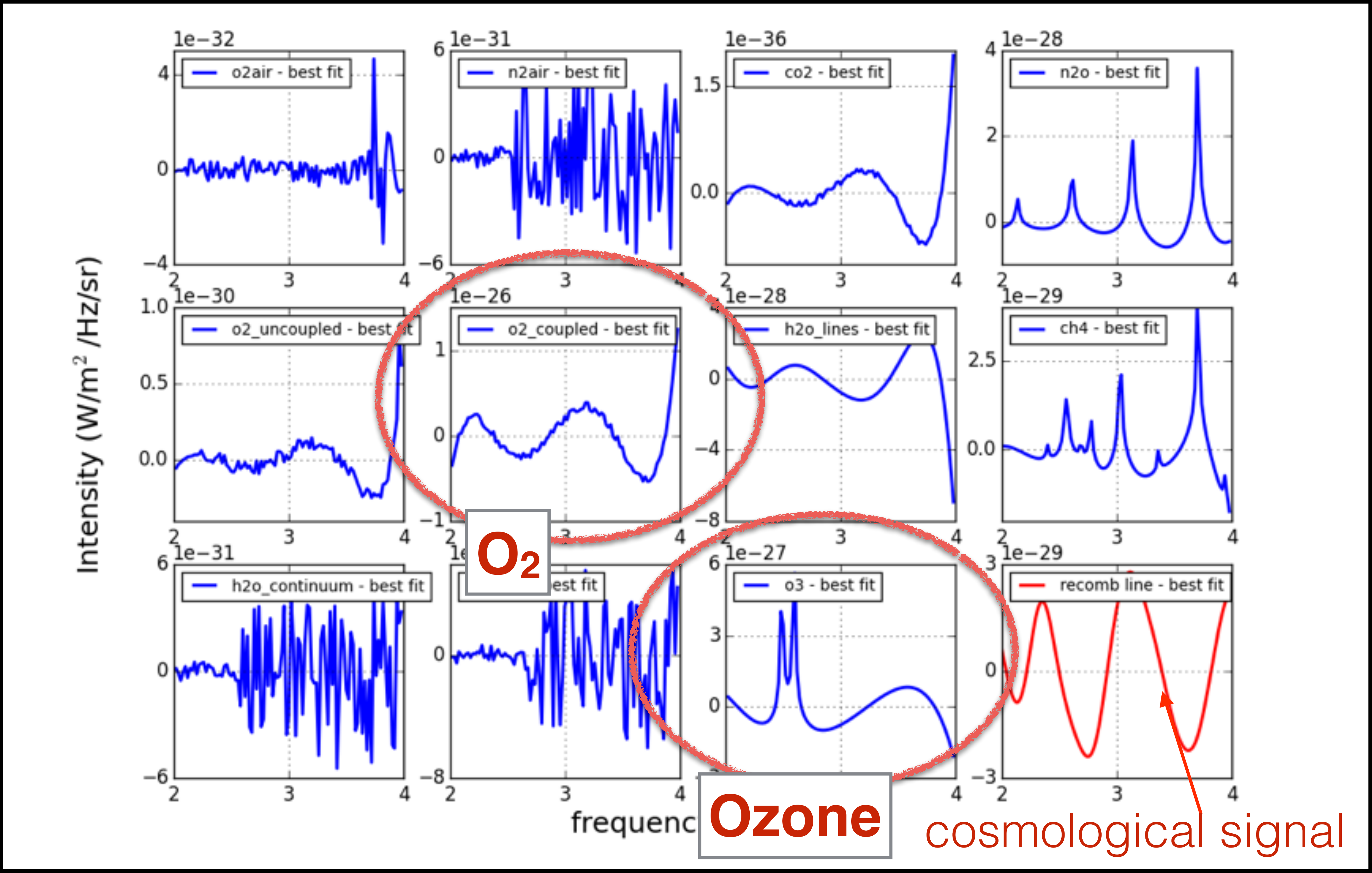
Atmospheric lines

After subtracting baseline



Atmospheric lines

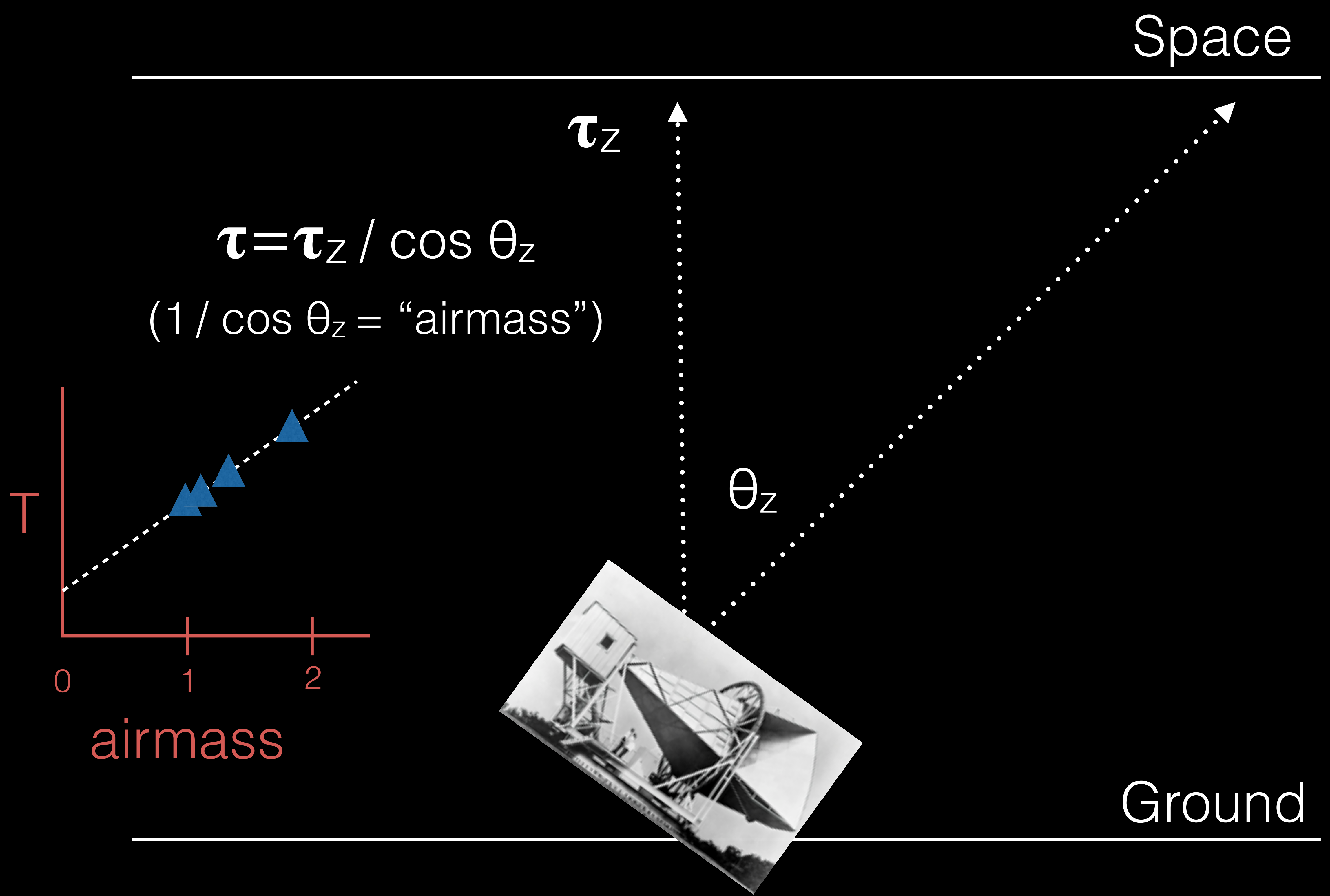
After subtracting baseline



Atmospheric lines

- Baseline subtracted atmospheric spectrum has oxygen and ozone lines that are ~100x the amplitude of the recombination lines
- The amplitude of the atmospheric lines modulates with airmass (e.g. with observing elevation) and can potentially be distinguished from the isotropic cosmological signal
- Solution: use elevation tipping radiometers

Elevation tipping

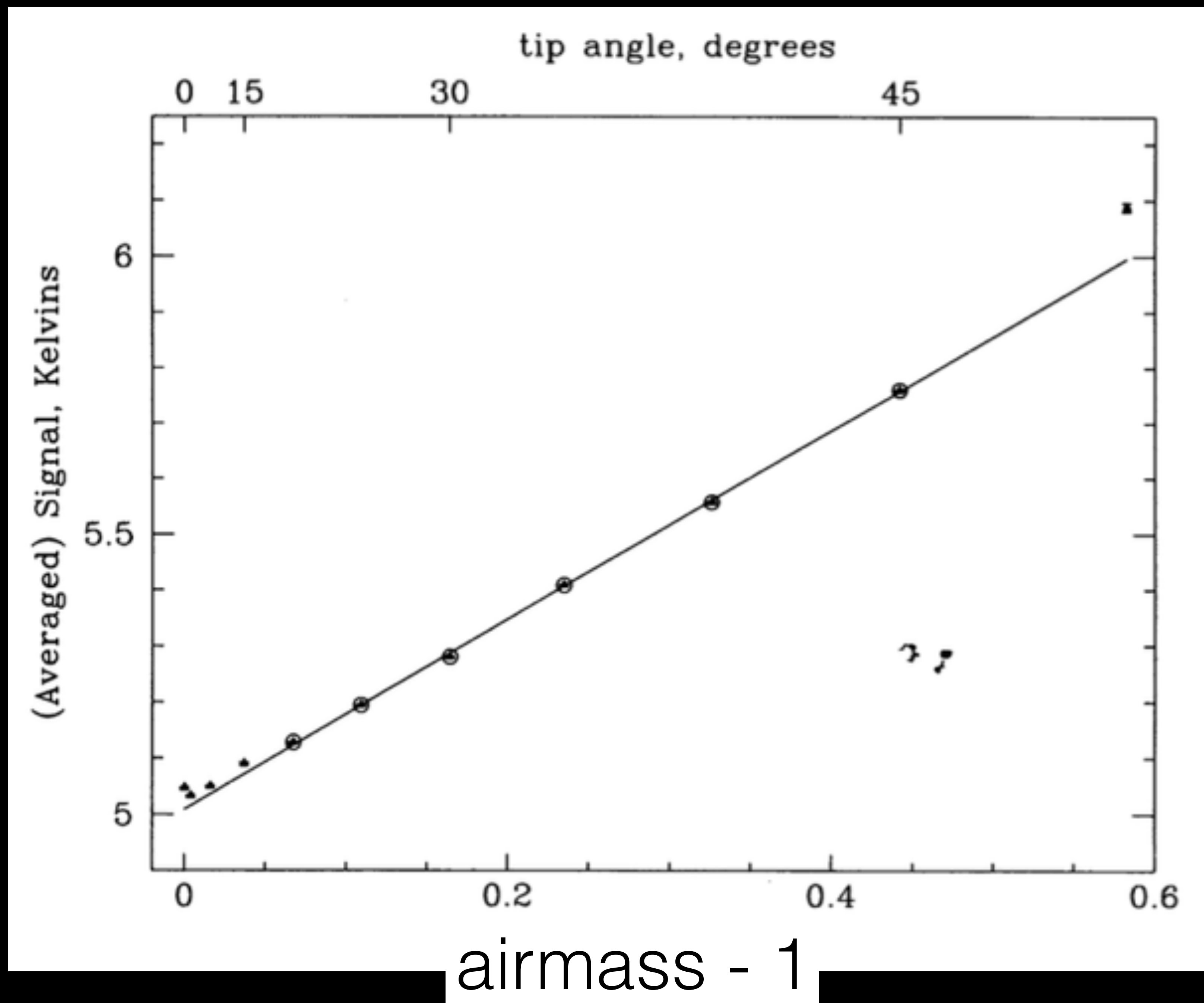


Elevation tipping

- We need to modulate atmospheric emission, extrapolate to zero airmass in each frequency bin, and subtract to sub-percent accuracy
- Method is fully empirical and does not rely on atmospheric modeling, knowledge of line shape, or knowledge of atmospheric vertical profile
- Just requires that, on average, atmospheric intensity scale linearly with airmass — true if vertical profile of the atmosphere is the same everywhere (“plane parallel”)
- There is reason to think this might work

Atmospheric lines

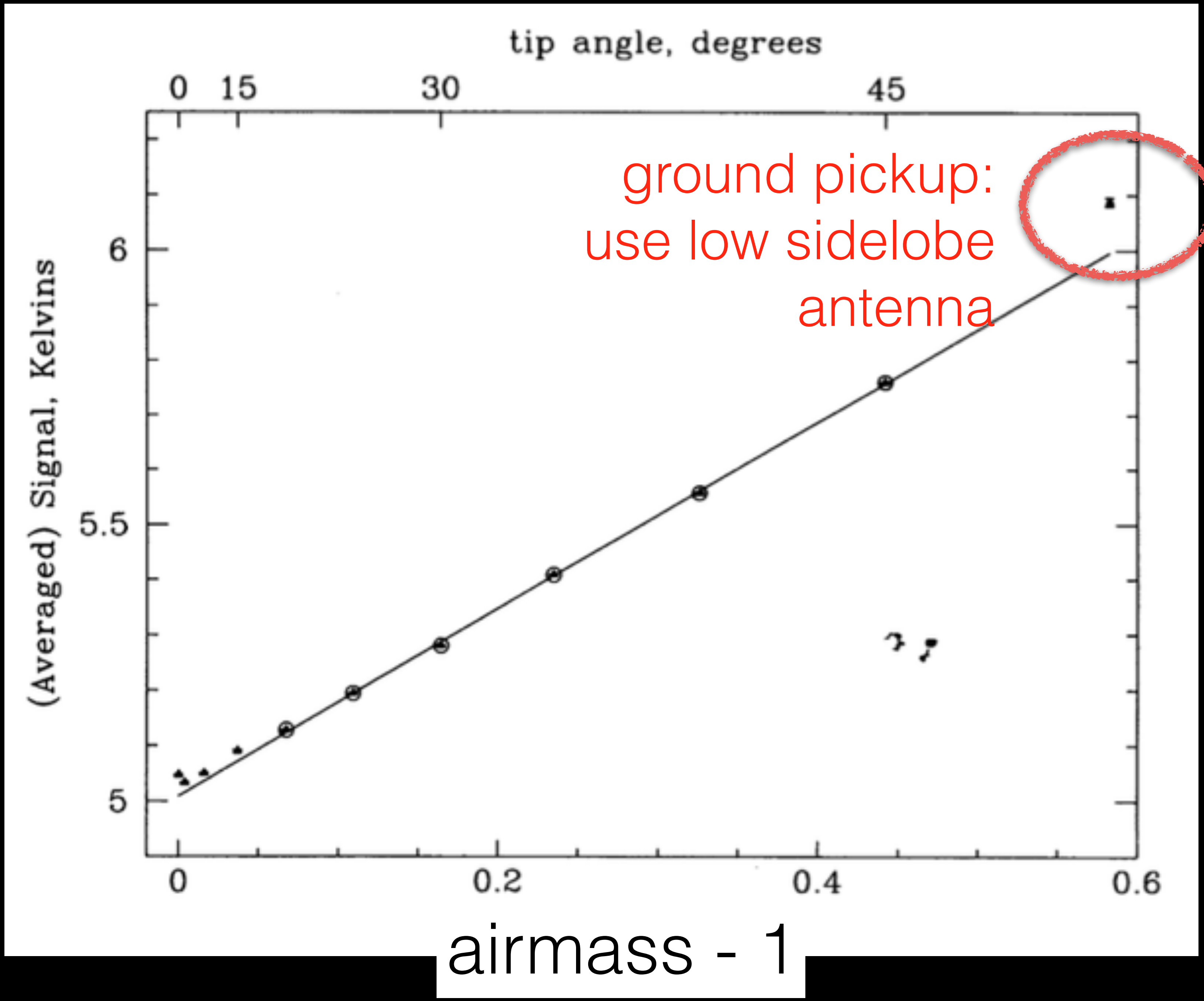
6hr elevation tip scan



Staggs et al, 1996

Atmospheric lines

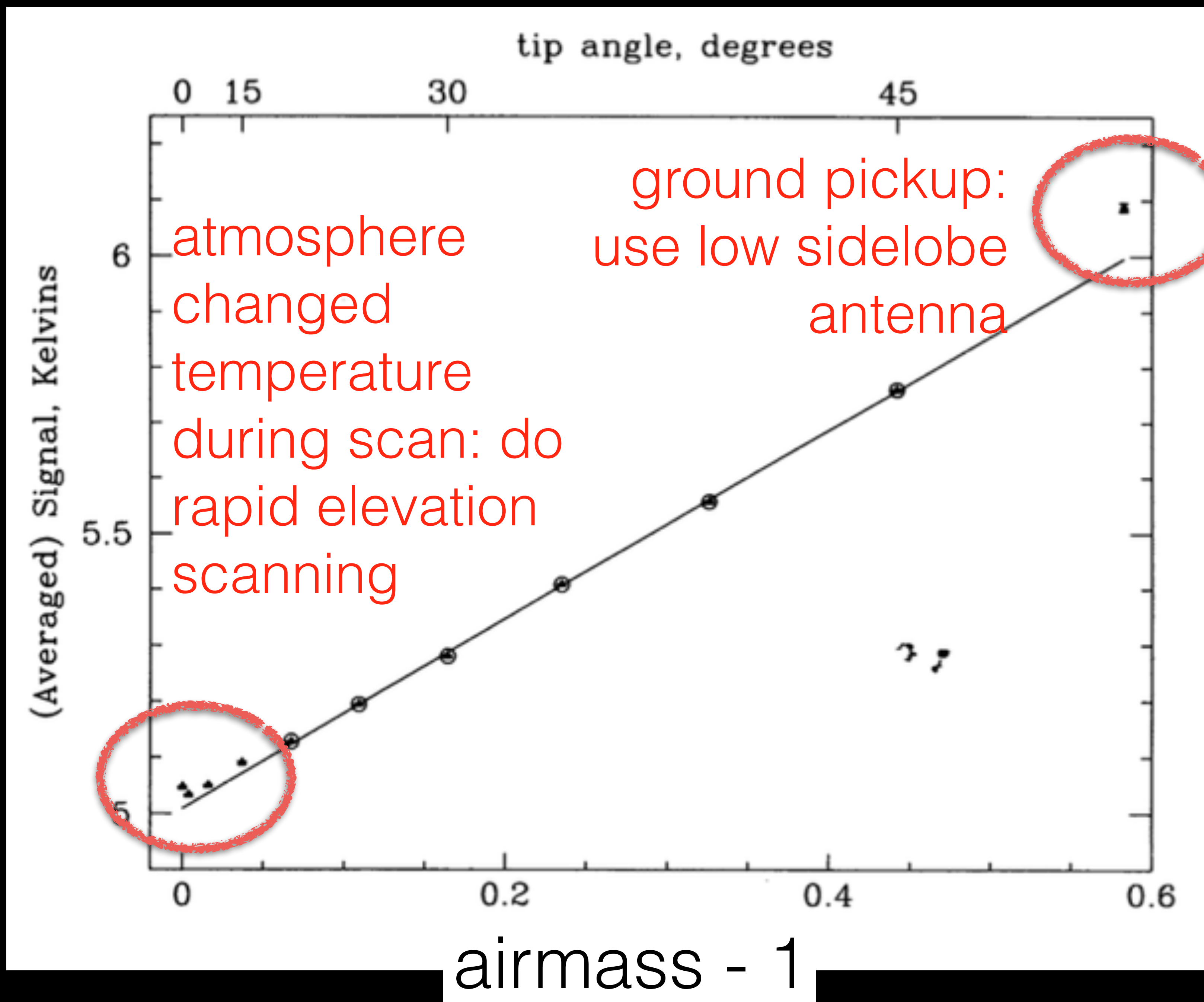
6hr elevation tip scan



Staggs et al, 1996

Atmospheric lines

6hr elevation tip scan



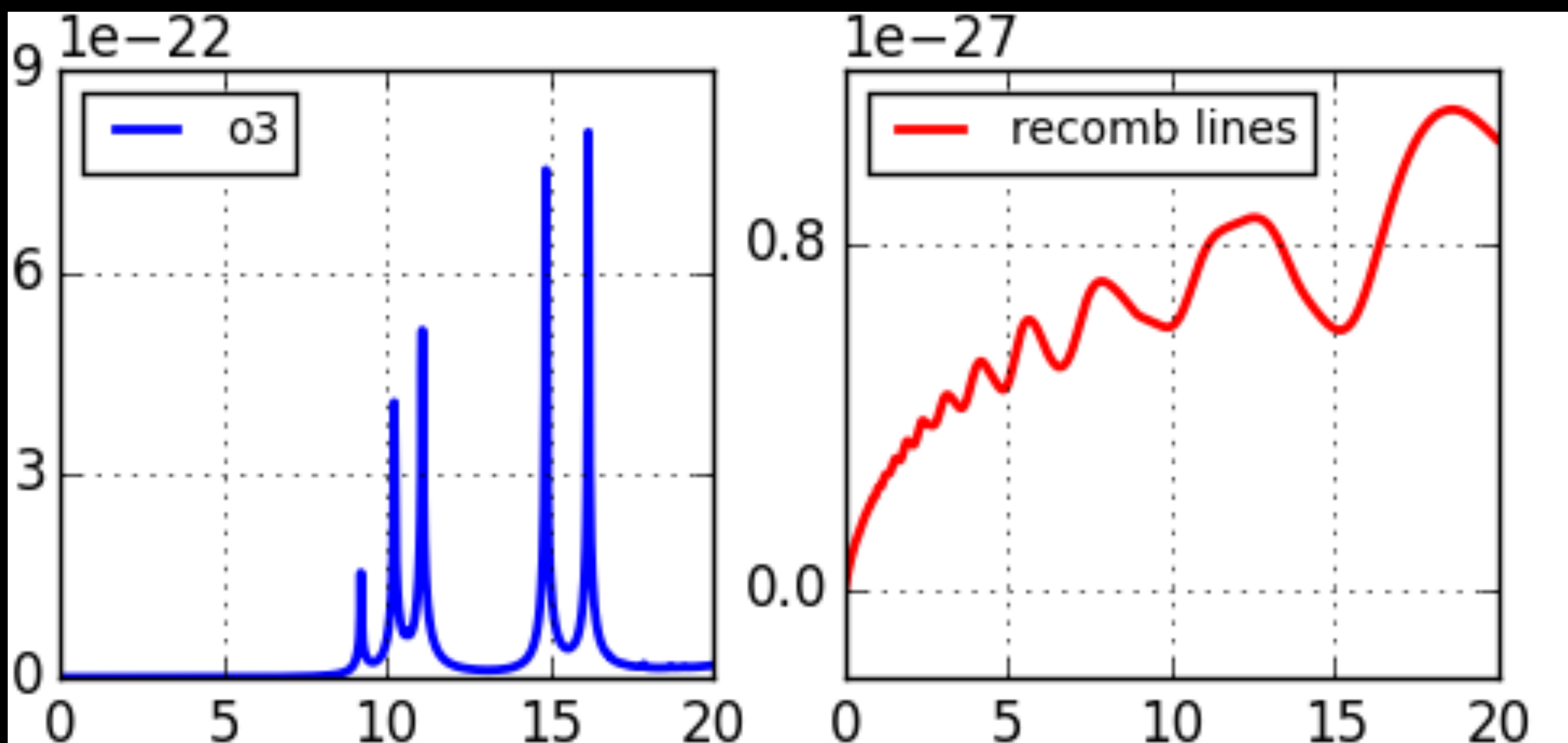
Staggs et al, 1996

Instrument to test elevation tipping method

Can build a simple instrument to test whether elevation tipping will work.

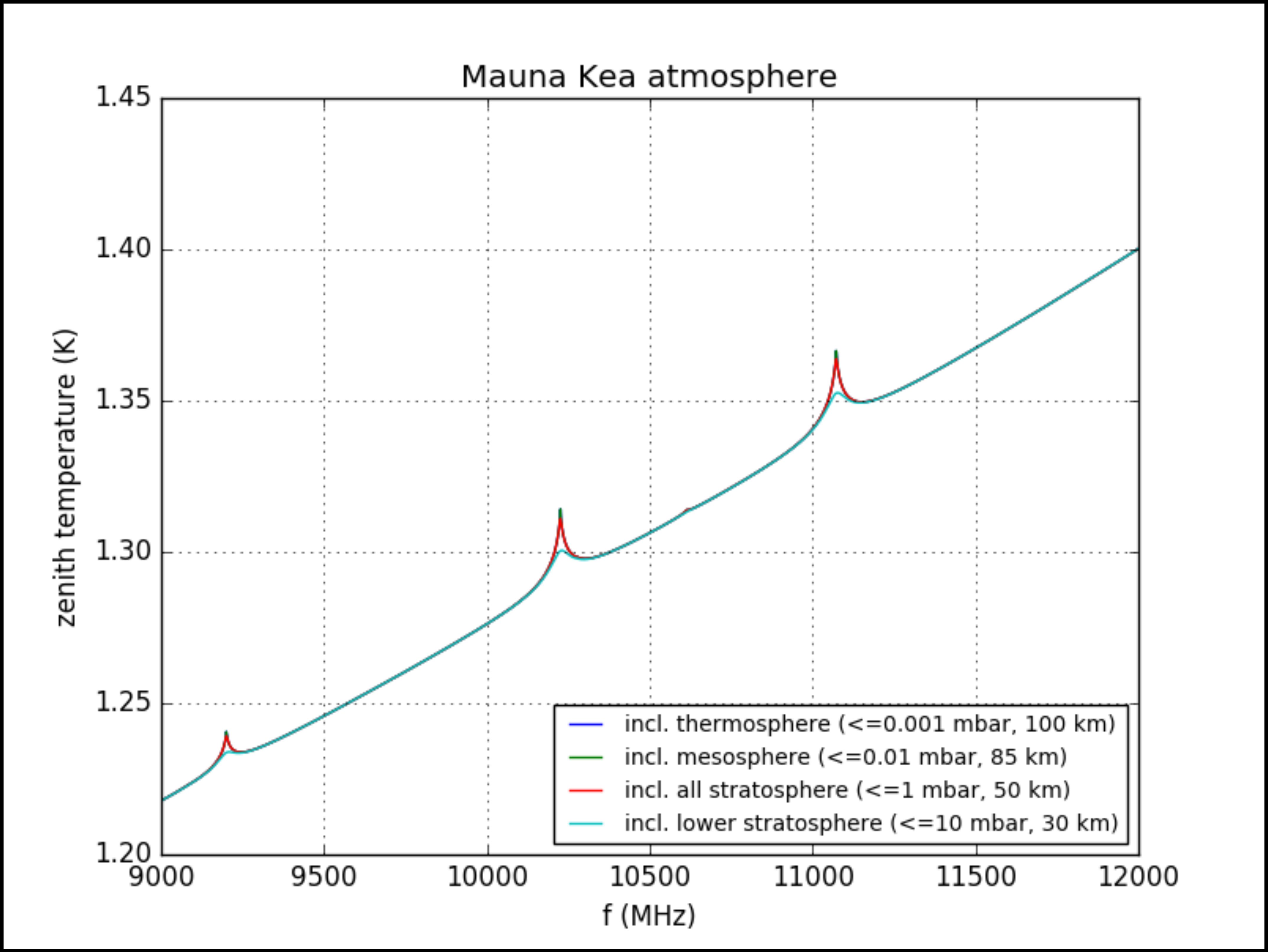
Instrument to test elevation tipping method

Recall the ozone lines that made higher frequencies undesirable: these can be measured with a single radiometer in a reasonable integration time



f (GHz)

Instrument to test elevation tipping method



Instrument to test elevation tipping method

(Small amount of seed funding from the Kavli Institute for Cosmological Physics at the University of Chicago)

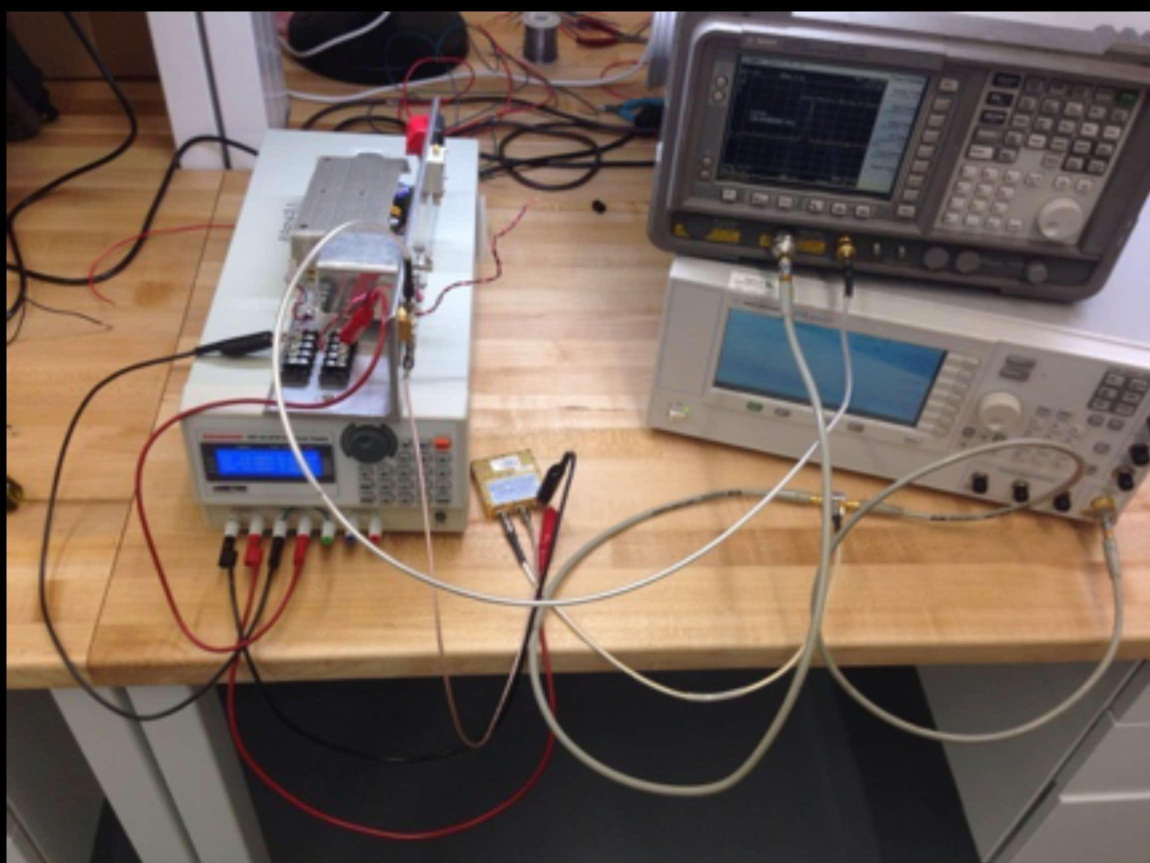
Low sidelobe X-band corrugated feedhorn

formerly of the XPER CMB experiment
(Staggs, et al. 1996)

Co-moving absorptive forebaffle

Instrument to test elevation tipping method

Front end electronics:
room temperature LNA (65 K)
10-12 GHz bandpass filter, mixer

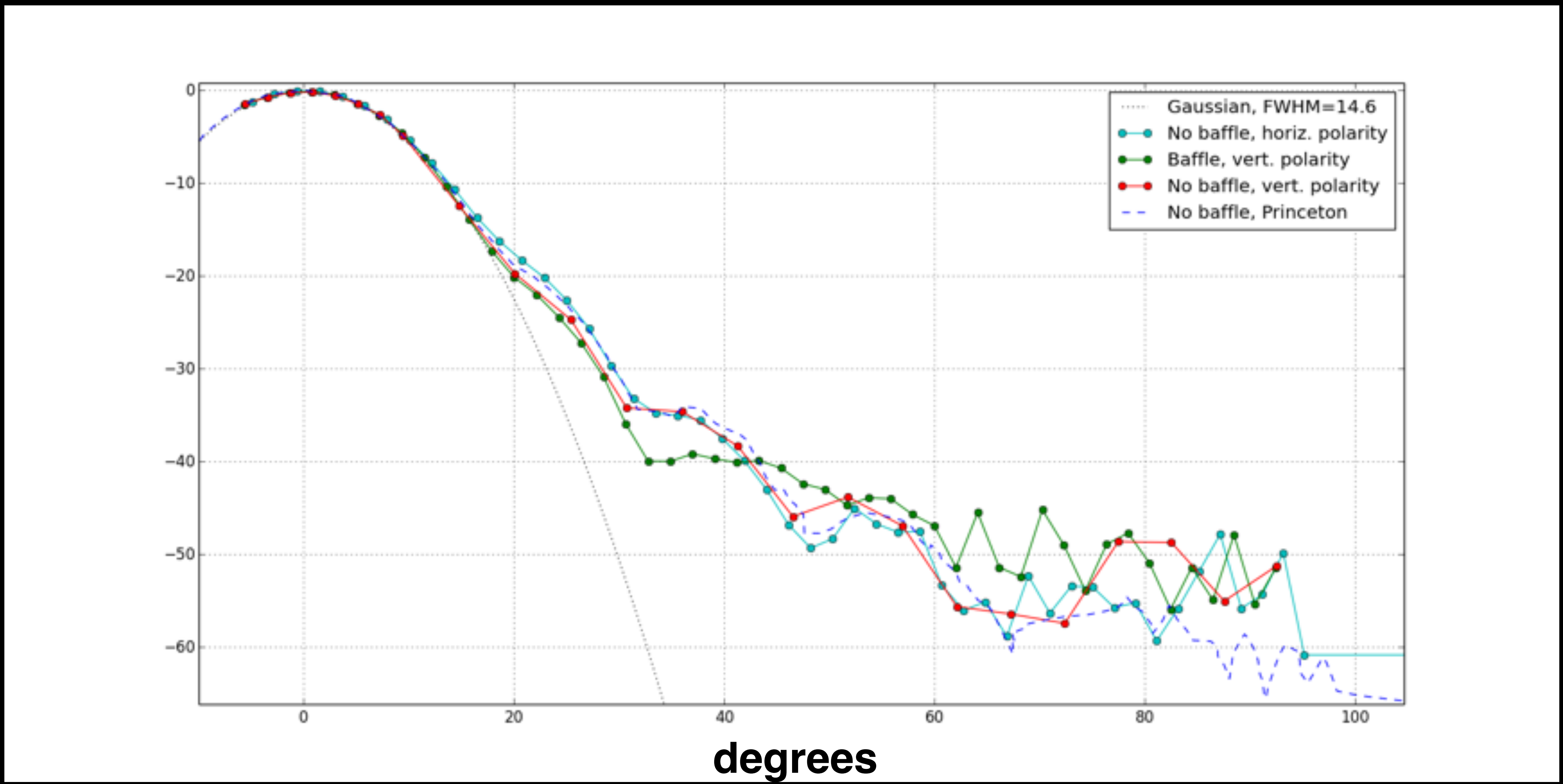


Readout:
ROACH2 FPGA based 5 Gsps FFT
spectrometer

Instrument to test elevation tipping method

Beam mapping on the roof in Chicago

Instrument to test elevation tipping method



Instrument to test elevation tipping method

Instrument to test elevation tipping method

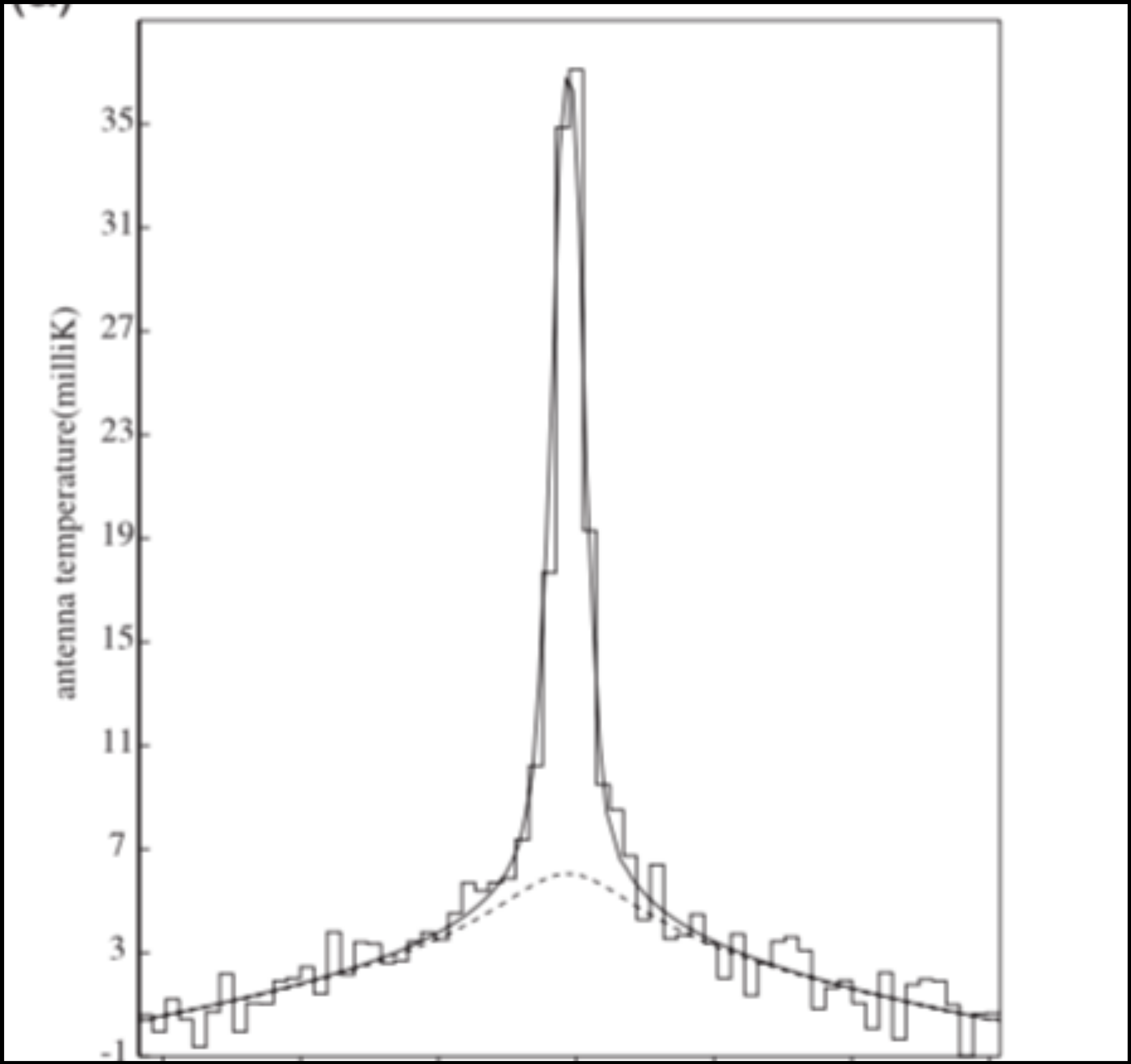
VHP-12 Eccosorb calibrator: -50 dB reflective at 1 GHz, and therefore spectrally smooth to that level

Instrument to test elevation tipping method

Results are forthcoming, still trying to diagnose source of ~mK non-flatness in the calibrated spectra, which is a good indication of the difficulty of these measurements. (Need to talk to global 21-cm people more!)

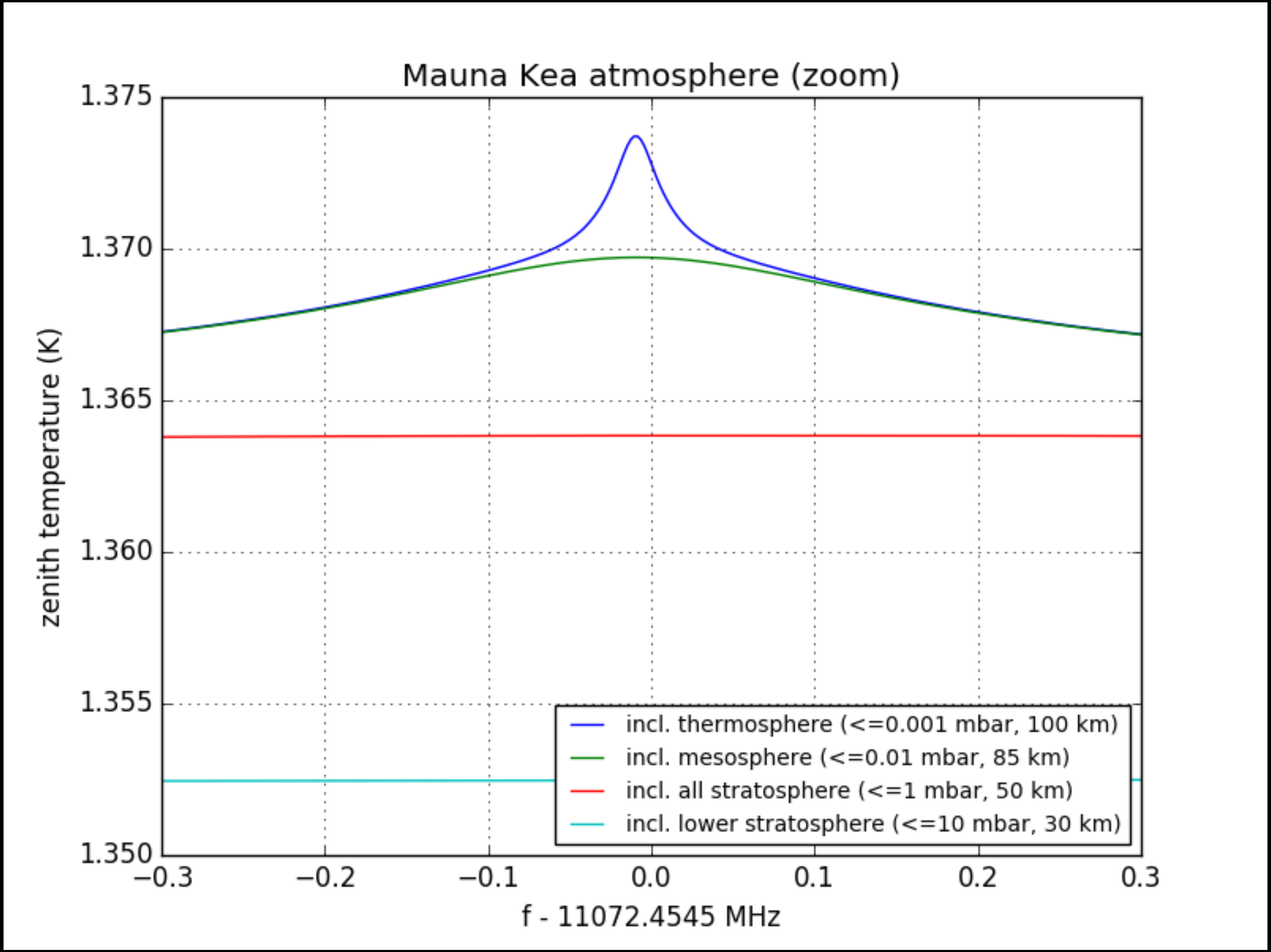
I recently learned about Haystack's MOSAIC ozone monitoring instrument (Rogers et al., 2012), which measures one of the the ozone lines my instrument is trying to measure. It measures the narrow, unbroadened core originating in the mesosphere.

Instrument to test elevation tipping method



-0.3 MHz **11.07 GHz** **+0.3 MHz**

Instrument to test elevation tipping method



Instrument to test elevation tipping method

Targeting the narrowband mesospheric ozone is perhaps a good way to test the elevation tipping method without needing to solve the problems of broadband measurements first (gain calibration, multipath interferometric fringing, etc.)

Ultimately, a science measurement requires solving these problems, but if the atmosphere won't cooperate then there's no point in trying.

Summary

- Recombination lines are a ~10^{-8} spectral distortion in the CMB
- In a window at 2-4 GHz, they can potentially be measured with high significance from the ground using coherent radiometers and direct sampling
- The presence of atmospheric emission lines that are ~100x the amplitude of the signal complicate this picture, but they can possibly be removed by elevation scanning
- Work is in progress on a small instrument to determine whether this is possible