SIGRAV International School 2022 on Cosmology: from Theory to Observation

Observational perspectives for the Cosmic Microwave Background

Paolo de Bernardis
(University of Rome "La Sapienza" and INFN Roma)

Feb 14th and 15th, 2022

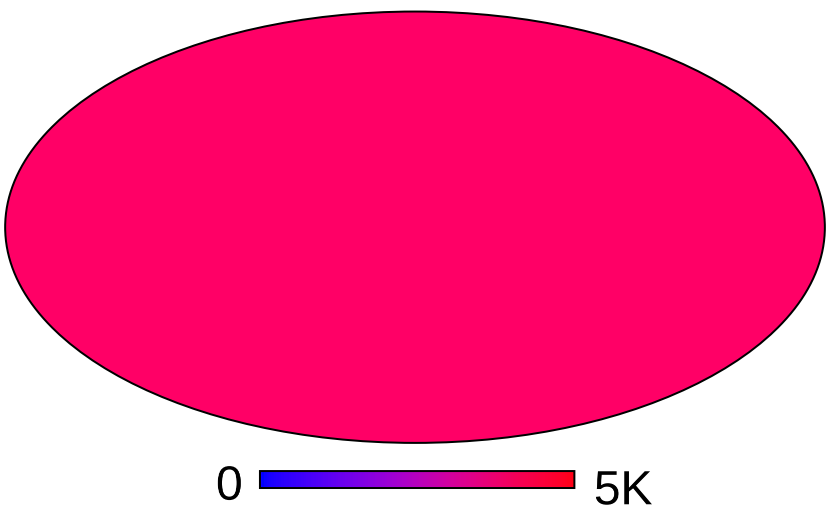
Content of the lectures :

1. The CMB. Detection of CMB photons. Noise.
2. How to measure the spectrum of the CMB and spectral distortions
3. How to measure the anisotropy of the CMB
4. How to measure the polarization of the CMB

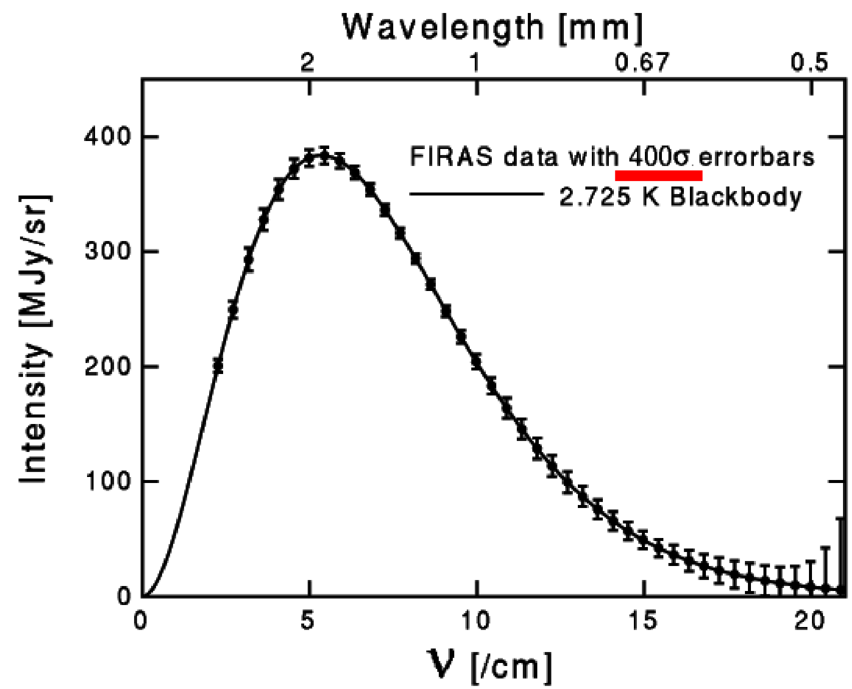
The Cosmic Microwave Background (CMB)

- Empirically:
  - The CMB is an abundant background of photons, *remarkably isotropic* over the entire sky.
  - Its specific brightness is *remarkably close to a blackbody* with a temperature T_o=2.725K

Angular distribution



Specific brightness



Specific Brightness and Blackbody Radiation

- Specific Brightness of a radiation field: $$B_\nu = \frac{dE}{dt\,dA\,d\Omega\,d\nu}$$
- Useful to describe extended sources.
- A map of the sky is a map of the specific brightness versus celestial coordinates: $B_\nu = B_\nu(\theta, \varphi)$

- When matter is in local thermal equilibirium with radiation, or close to, the radiation fiels is thermal: a blackbody or similar. Astrophysical cases:
  - Photospheres of stars
  - Surface (or atmosphere) of planets
  - Clouds of interstellar dust
  - Early Universe (CMB)
- Planck demonstrated that for the gas of photons in equilibrium in a closed isothermal cavity, the specific energy density and the brightness are:

energy density of a blackbody

$$\rho_\nu = \left[\frac{8\pi\nu^2}{c^3}\right] [h\nu] \left[\frac{1}{e^{h\nu/kT} - 1}\right]$$

Density of modes in the cavity

Energy per mode (quanta)

Occupation probability per energy level (Bose Einstein)

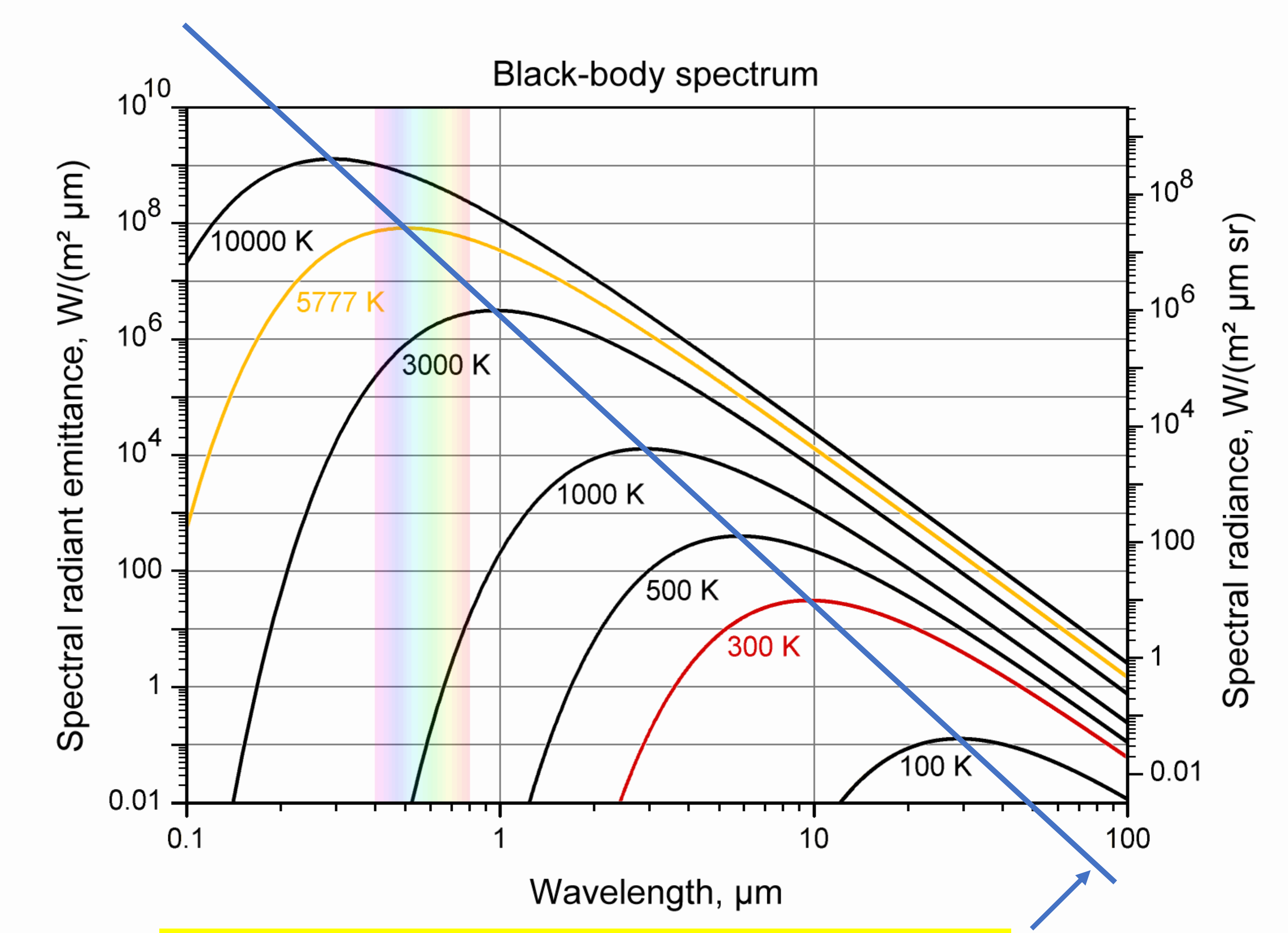
blackbody brightness

$$B_\nu = \frac{c}{4\pi}\rho_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$h = 6.62606957 \times 10^{-34}\ m^2\ kg\ /\ s$

$k = 1.3806488 \times 10^{-23}\ m^2\ kg\ s^{-2}\ K^{-1}$

Blackbody Brightness for different temperatures



Locus of maxima : $\lambda_{max}T=0.0029$ m K

Blackbody Radiation

$$B(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

$$B(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{kT\lambda}}-1}$$

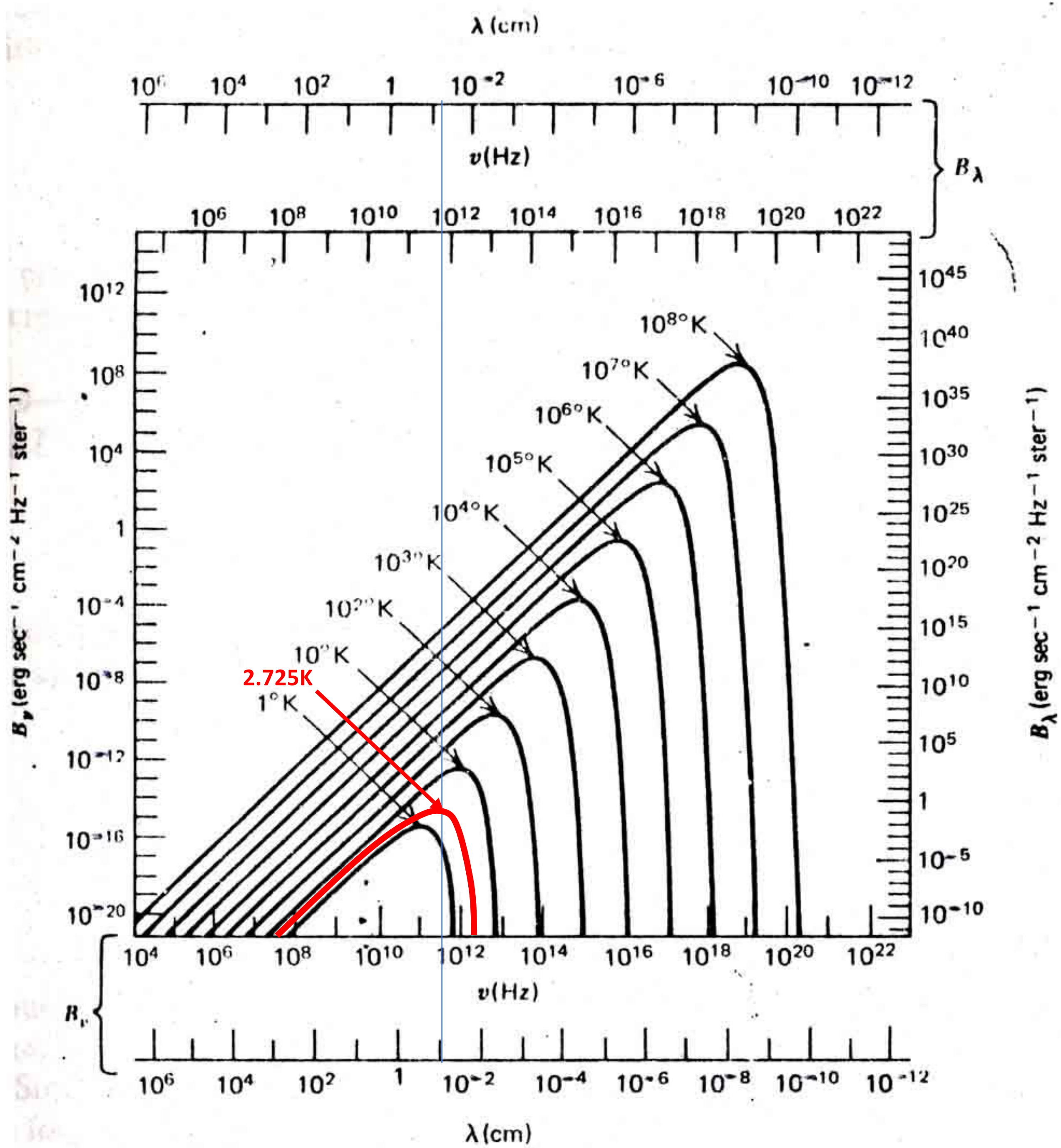
- Maximum brightness

$$\lambda_{\max}T=0.290\,cm\,K$$

- Low frequency :

$$B(\nu,T)\approx\frac{2\nu^2}{c^2}kT$$

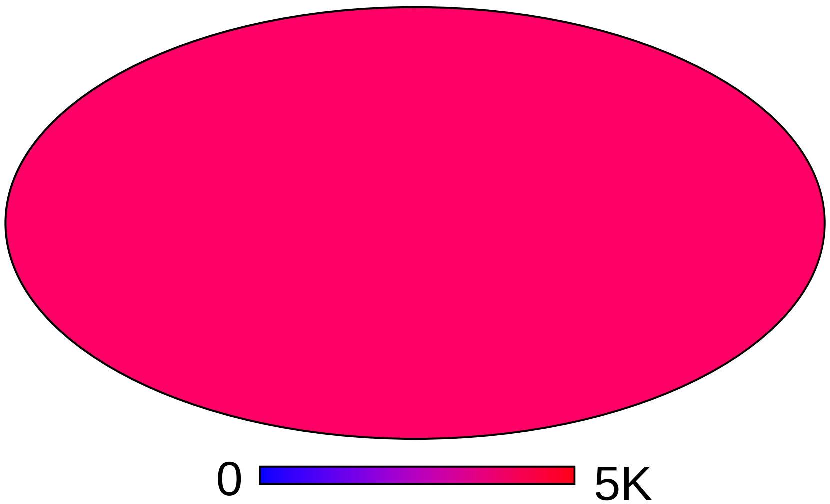
$$h\nu<<kT$$



The Cosmic Microwave Background (CMB)

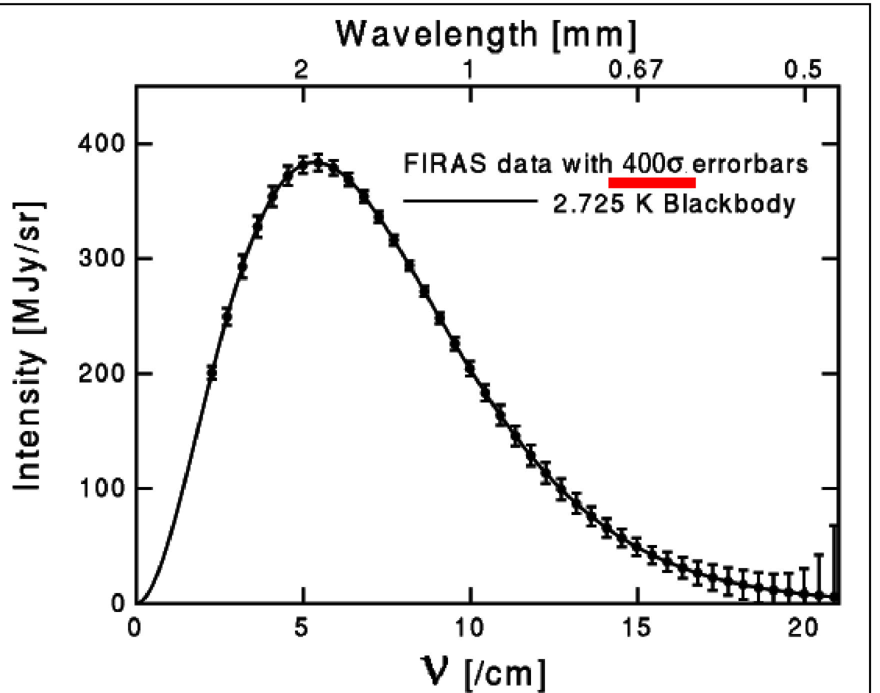
- Empirically:
  - The CMB is an abundant background of photons, *remarkably isotropic* over the entire sky.
  - Its specific brightness is *remarkably close to a blackbody* with a temperature T_o=2.725K

Angular distribution



Measured brightness temperature of the sky (K) at ν=150 GHz

specific brightness



- **Which is the scientific significance of this fact ?**

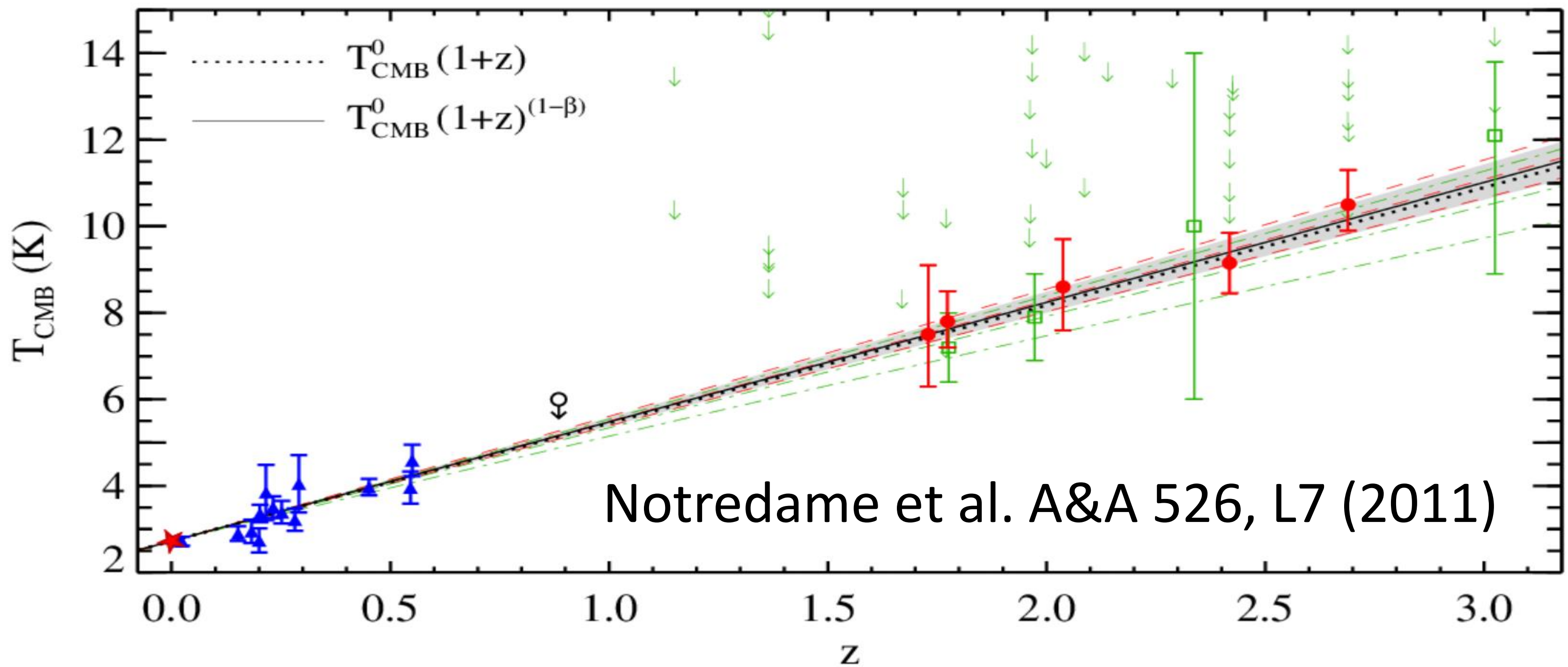
The CMB and cosmology

- While expanding, an insulated system cools down.
- So does the Universe: it expands and thus cools down.
- A blackbody spectrum in an expanding universe remains a blackbody spectrum, while its temperature changes as the inverse of the scale factor $1/a$ ($\rho_{BB} \propto T^4$ and $\rho_{BB} = n_\gamma h\nu \propto a^{-3}a^{-1} \Rightarrow T \propto a^{-1}$)
- If today we have the CMB as a cold blackbody, it's possible that it was produced in the distant past, when the Universe was denser and hotter and there was thermal contact between matter and radiation.
- If this is true, the existence of the CMB is the proof of an early hot phase of the Universe (in the *Hot Big Bang*, from George Gamow, the *Primeval Fireball* from Jim Peebles).

- But why is the CMB there at all ? A hint comes from the fact that the CMB is an *abundant* background of photons:
- for T=2.725K compute: $$n = \int_0^\infty \frac{\rho_\nu}{h\nu} d\nu = 411\ \gamma/cm^3$$
- This is 9 orders of magnitude larger than the density of baryons in the Universe
- The universe has a very high specific entropy (photons to baryons ratio)
- When and how was that generated ?

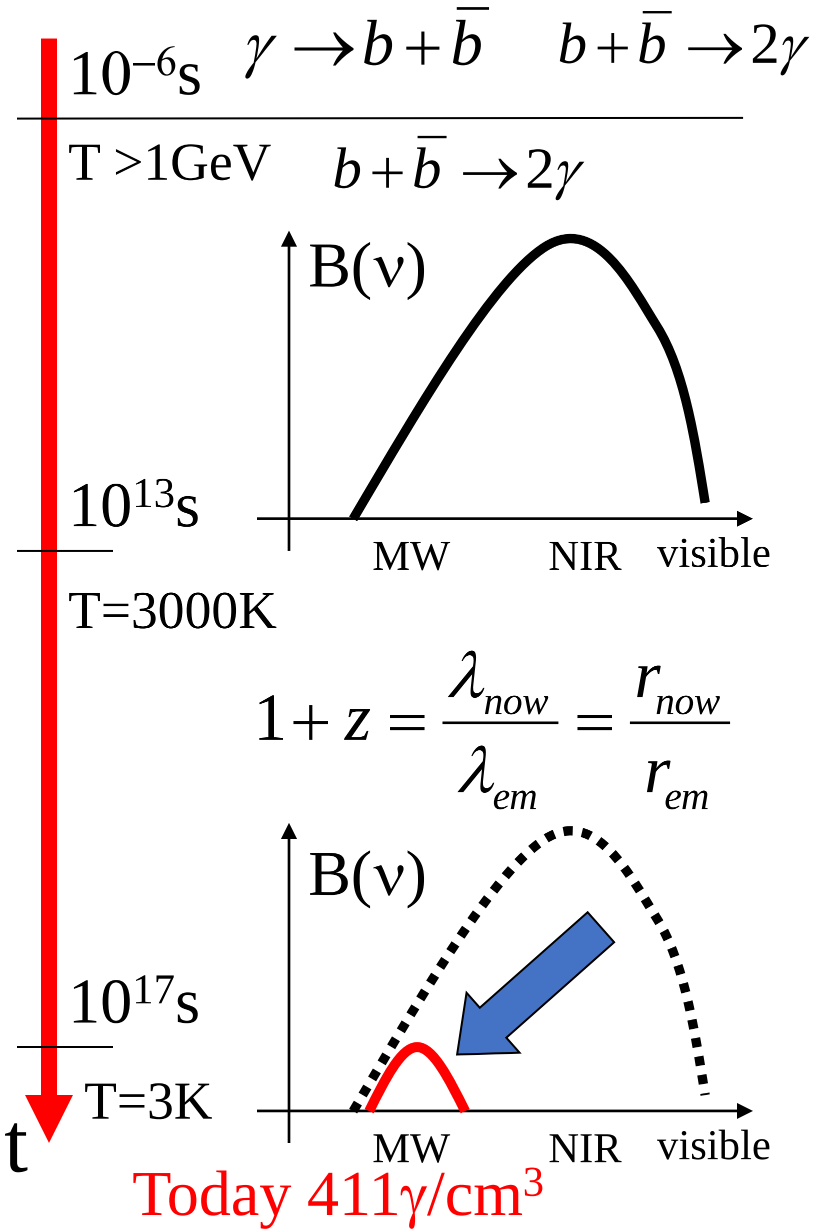
Do we have proofs that the CMB is not local ?

- The spectrum is too close to a perfect blackbody to be generated by cold dust emission or redshifted dust emission or overlaps of the above.
- The angular distribution is too smooth (small-scale anisotropy too small) to be generated by discrete sources
- Sunyaev-Zeldovich effect (see later): the CMB comes from beyond the most distant clusters of galaxies.
- The CMB temperature measured at early epochs (see later) scales as $(1/a)=(1+z)$:



$$T_{CMB}(z) = (2.725 \pm 0.002) \times (1 + z)^{1-b} \text{ K with } b = -0.007 \pm 0.027$$

Origin of the CMB in the hot Big-Bang framework



According to modern cosmology:

The CMB is an abundant background of photons, filling the whole Universe.

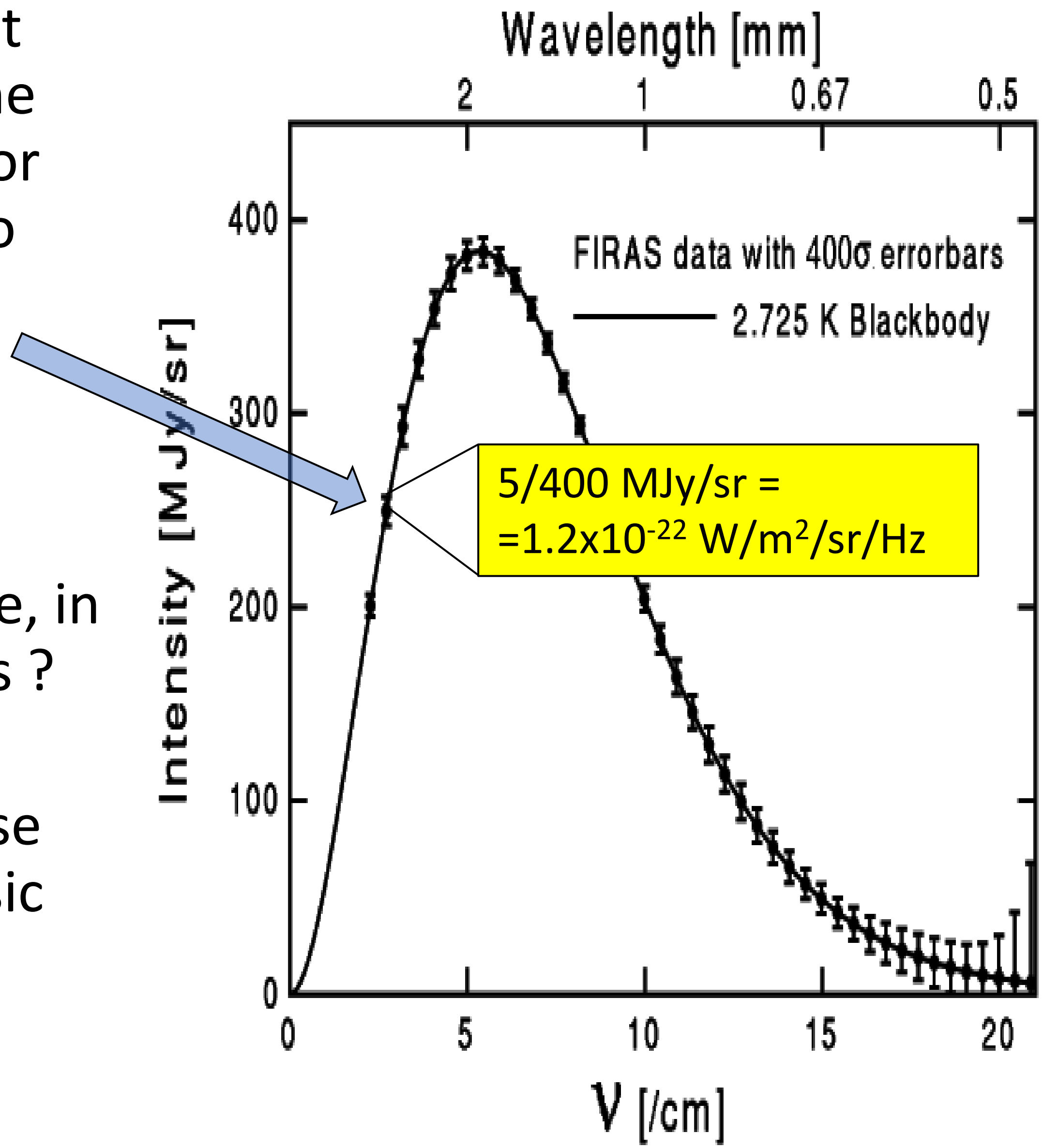
- **Generated** in the very early universe, less than 4 μs after the Big Bang from a small $b-\bar{b}$ asymmetry ($10^9\gamma$ for each baryon)
- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Released, diluted and redshifted** to microwave frequencies (z_{CMB}=1100) in the subsequent 14 Gyrs of expansion of the Universe
- So CMB photons played a key role during baryogenesis, nucleosynthesis, recombination.
- **For us: they form our best tool for cosmological investigation, since they carry informations about all the phases of the evolution of the universe.**

How do we measure the CMB ?

- In terms of photons, the CMB (a 2.725K blackbody) consists of **411 γ/cm^3**, isotropically distributed, with an average energy per photon of **6×10^{-4} eV**.
- This is a problem for the detectors, because the energy of CMB photons (meV) is very small compared to thermal energy and atomic and even molecular transitions, so complex detection processes are needed just to detect photons. In addition, we want a high quality (small error) measurement.
- So, we need **(1)** very **low noise detectors for very-low-energy photons.**
- The second problem comes from the environment:
  - From a solid angle of 1 deg^2 and in a telescope area of 1 m^2 we collect about **3×10^{12} CMB photons/s**.
  - Meanwhile, the telescope mirror and the Earth atmosphere, in excellent observing conditions produce **~10^{14} photons/s** in the same solid angle and frequency band, while our Galaxy produces **~10^{11}** photons/s.
- So we need to envisage strategies to distinguish CMB photons from local, overwhelming photons. So we need experimental techniques to **(2) minimize systematic effects in the measurement of CMB photons.**

Photon noise and Detector Noise

- In addition to be able to just detect CMB observables, the detectors must also allow for *precision measurements*. So their noise should be low. Example:
- What is detector noise, and how is it described ?
- How low the noise has to be, in case of CMB measurements ?
- In short, in an optimized measurement detector noise has to be lower than intrinsic radiation noise.



Variance and Power Spectrum

- Given *a measured observable* whose true value is to be estimated, *noise is the random fluctuation* of the instantaneous value of the measured observable.
- This can be intrinsic to the observable, or generated by the measurement apparatus: both contribute to the fluctuation of the measurements of the observable.
- Usually we select the average value as the best estimate of the true value of the observable. *The presence of noise induces an error* in such an estimate.
- The larger the *variance* of the noise, the larger the error.
- Variance and power spectrum are the appropriate statistics to describe noise in detectors and radiation.

Variance and Power Spectrum

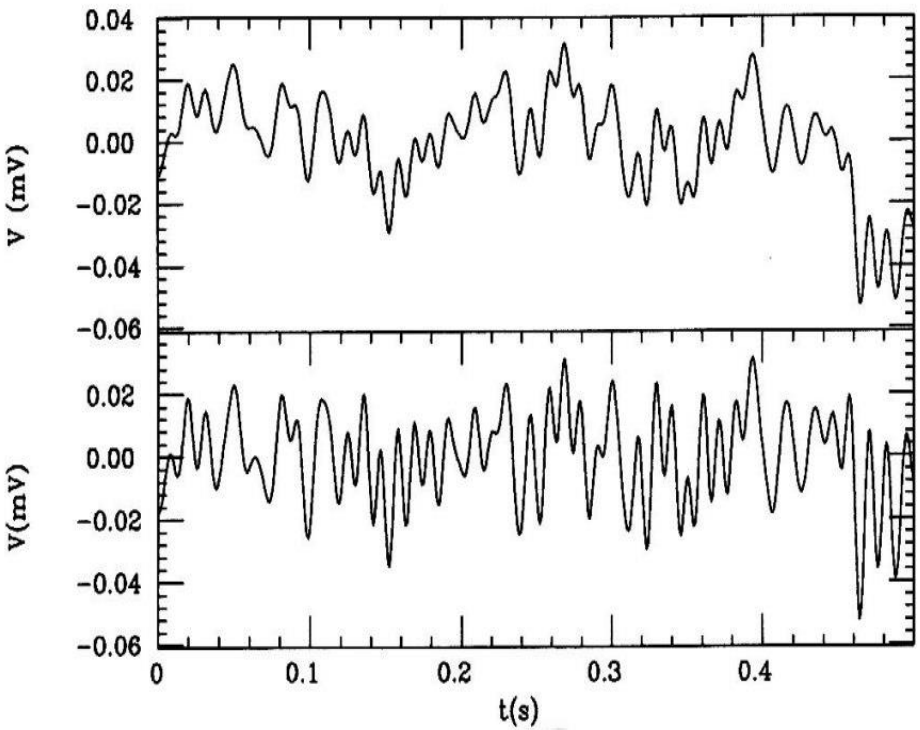
- If *y(t)* is the measured fluctuating quantity (average subtracted), its *autocorrelation* is

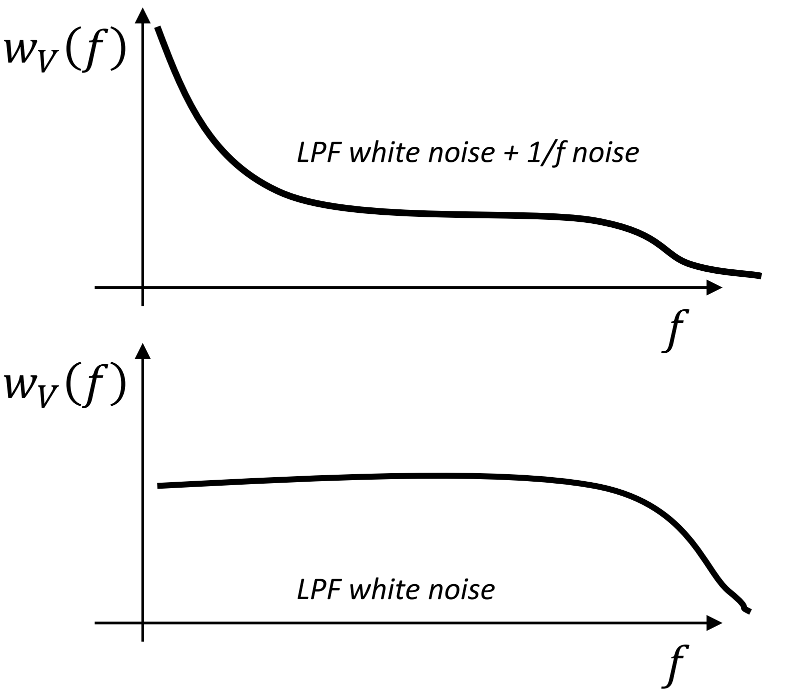
$$\psi_y(\tau) = \int_0^\infty y(t)y(t+\tau)dt$$

- and its *variance* is $\sigma_y^2 = \psi_y(0) = \int_0^\infty y^2(t)dt$
- The power spectrum of *y(t)*, $w_y(f)$ specifies the contributions to the variance coming from the different frequencies, i.e. $\sigma_y^2 = \int_0^\infty w_y(f)df$
- The *Wiener-Khintchine theorem* demonstrates that the power spectrum and the autocorrelation function are a Fourier-transform couple: $w_y(f) \underset{FT}{\leftrightarrow} \psi_y(\tau)$
- If *y(t)* is a Gaussian variable, the power spectrum $w_y(f)$ describes *completely* its statistical behaviour.

Variance and Power Spectrum

- Examples of two random variables *V(t),* with the same variance but with different power spectra:





Variance and Power Spectrum

- In the case of *radiation power measurements*, the output of the radiation detector has two fluctuating components: one proportional to the input power (which is an intrinsically fluctuating quantity, as we will see in a while), and another generated by the detector $V(t) = RP(t) + n(t)$.
- *R* is the «*responsivity*» of the detector, which is assumed to respond proportionally to the input, while *n(t)* is the detector *noise*.
- The input power is the observable, and has a constant part P_o to be estimated and a zero-average fluctuating part $P_f(t)$.
- If we know, having calibrated the detector, its responsivity, we can estimate $P_o = \langle V(t) \rangle_t$. But our job is not over if we do not estimate the uncertainty of such an estimate.

Variance and Power Spectrum

- The error on this estimate depends on the statistical properties of *n(t)* and $P_f(t)$. If these are gaussian random variables, these statistical properties are described by the power spectra $w_n(f)$ and $w_{P_1}(f)$.
- Note that $w_V(f) = R^2 w_{P_1}(f)$+ $w_n(f)$= $R^2 w_P(f)$+ $w_n(f)$.
- So it is mandatory to study the power spectra of radiation power (photon noise) and of detector noise. Both should be minimized to minimize the uncertainty in our estimates.
- It is customary to express the noise of a detector using its Noise Equivalent Power (NEP).
- With our definitions, $NEP = \frac{\sqrt{w_n(f)}}{R}$
- Its units are the same units as the observable, divided by $\sqrt{Hz}$. Remeber, in fact, that $\sigma_n^2 = \int_0^\infty w_n(f)df$
- Numerically, the NEP is the minimum signal which can be measured with the detector in 1s of integration.

Noise and integration time

- Any detector has a response time τ which limits its sensitivity at high post-detection frequencies. Data taken at intervals shorter than τ will not be independent.
- The error on the estimate of $\langle W \rangle_t$, the average power in the observation time *t*, is
- $$\sigma_{\langle W \rangle_t} = \frac{\sigma_{\langle W \rangle}}{\sqrt{N}} = \frac{\sqrt{\int_{f_{\min}}^{f_{\max}} \left\langle \Delta W^2 \right\rangle df}}{\sqrt{N}}$$
- where $\left\langle \Delta W^2 \right\rangle = w_W(f)$ is the power spectrum of the radiation power, and *N* is the number of independent measurements.
- In the integration time *t*, it will be $N = t/\tau$.

Noise and integration time

- $$\sigma_{\langle W \rangle_T} = \frac{\sigma_{\langle W \rangle}}{\sqrt{N}} = \frac{\sqrt{\int_{f_{\min}}^{f_{\max}} \langle \Delta W^2 \rangle df}}{\sqrt{N}} = \frac{\sqrt{\int_{f_{\min}}^{f_{\max}} \langle \Delta W^2 \rangle df}}{\sqrt{t/\tau}} =$$

$$\cong \frac{\sqrt{\int_{1/T}^{1/\tau} \langle \Delta W^2 \rangle df}}{\sqrt{t/\tau}} = \frac{\sqrt{\langle \Delta W^2 \rangle \left[\frac{1}{\tau} - \frac{1}{t} \right]}}{\sqrt{t/\tau}} \cong \sqrt{\frac{\langle \Delta W^2 \rangle}{t}}$$

- The noise decreases as the square root of the integration time.

$$\Rightarrow \quad \sigma_{\langle W \rangle_t} = \sqrt{\frac{\langle \Delta W^2 \rangle}{t}} = \frac{NEP}{\sqrt{t}}$$

- Notice that this applies equally to detector noise and to intrinsic radiation noise.
- Neglecting radiation noise, the uncertainty derived above is numerically equal to the detector *NEP* for 1 s of integration.

Radiation Noise

- Is the **fundamental limit** of any radiation measurement: when detector noise is negligible, only radiation noise contributes to the error.
- A steady flux of radiation is not perfectly stable. The intrinsic instability is called radiation noise, and reflects the particle-wave duality of light.
- It is the sum of Poisson noise (photon particles) PLUS interference noise (waves)
- Poisson noise: if *N* is the number of photons received in a given integration time interval *t*, $\langle \Delta N^2 \rangle = \langle N \rangle$, and:

$$\langle \Delta E^2 \rangle = (h\nu)^2 \langle \Delta N^2 \rangle = (h\nu)^2 \langle N \rangle = (h\nu)^2 \frac{Wt}{h\nu} = h\nu W t$$

- This is a typical random-walk process (variance prop. to time).
- Using Einstein's generalization $\langle \Delta\theta^2 \rangle = 2kBTt \quad \Rightarrow \quad \langle \dot{\theta}_f^2 \rangle df = 4kBT df$ we get the power spectrum and the variance of radiative power fluctuations:

$$\langle \Delta W_f^2 \rangle df = 2 \frac{\langle \Delta E^2 \rangle}{t} df = 2h\nu W df$$

Radiation Noise

- Orders of magnitude example: A He-Ne 1 mW laser beam has a perfect Poisson statistics, so

$$\sqrt{\left\langle \Delta W_f^2 \right\rangle} = \sqrt{2h\nu W} = 2.5 \times 10^{-11} \frac{W}{\sqrt{Hz}}$$

- Notice the power spectrum units (remember that the integral of the PS over frequency is the variance).
- In this case the intrinsic fluctuations per unit bandwidth are >7 orders of magnitude smaller than the signal.
- It is useless to build a complex detector with a noise of $10^{-15}\ W/\sqrt{Hz}$ for this measurement: the precision of the measurement will be limited at a level of $2.5\times10^{-11}\ W/\sqrt{Hz}$ anyway.

Radiation Noise

- Thermal radiation (like the CMB) has also wave interference noise: the correct statistics is Bose-Einstein.

$$\langle N \rangle = \frac{g}{e^{(E-\mu)/kT} - 1} \quad ; \quad \langle \Delta N^2 \rangle = T \left. \frac{d\langle N \rangle}{d\mu} \right|_{T,V}$$

$$\Rightarrow \boxed{\langle \Delta N^2 \rangle = \langle N \rangle + \frac{\langle N \rangle^2}{g}}$$

Poisson noise

Wave interference noise

Radiation Noise

- For a blackbody

$$\langle N \rangle = \frac{g}{e^{(E-\mu)/kT} - 1} \quad ; \quad g = 2\frac{\nu^2}{c^3} 4\pi V d\nu$$

$$\langle N \rangle = \frac{8\pi\nu^2}{c^3} \frac{1}{e^{h\nu/kT} - 1} V d\nu$$

$$\Rightarrow \boxed{\langle \Delta N^2 \rangle = \langle N \rangle \left[1 + \frac{1}{e^{h\nu/kT} - 1} \right]}$$

Poisson noise, important at short wavelengths

Wave interference noise, Important at low frequencies

Radiation Noise

Calculating as before:

$$\left\langle \Delta N^2 \right\rangle = \langle N \rangle \left[1 + \frac{1}{e^{h\nu/kT} - 1} \right]$$

$$\left\langle \Delta E^2 \right\rangle = (h\nu)^2 \langle N \rangle \left[1 + \frac{1}{e^{h\nu/kT} - 1} \right] = h\nu W \left[1 + \frac{1}{e^{h\nu/kT} - 1} \right] t$$

$$\left\langle \Delta W^2 \right\rangle df = 2h\nu \langle W \rangle \left[1 + \frac{1}{e^{h\nu/kT} - 1} \right] df$$

And using the Planck formula:

$$\sqrt{\langle \Delta W^2 \rangle df} = \sqrt{\frac{4k^5}{c^2 h^3}} \sqrt{A\Omega T^5} \sqrt{\int_{x_1}^{x_2} \frac{x^4 e^x}{e^x - 1} dx \; df}$$

$$\sqrt{\frac{4k^5}{c^2 h^3}} = 2.77 \times 10^{-18} \frac{W}{\sqrt{cm^2 sr \;\; Hz \;\; K^5}}$$

CMB observables

- **The spectrum**

$$B(\nu,T)=\frac{2h}{c^2}\frac{\nu^3}{e^x-1} \qquad x=\frac{h\nu}{kT}$$

- **The angular distribution**

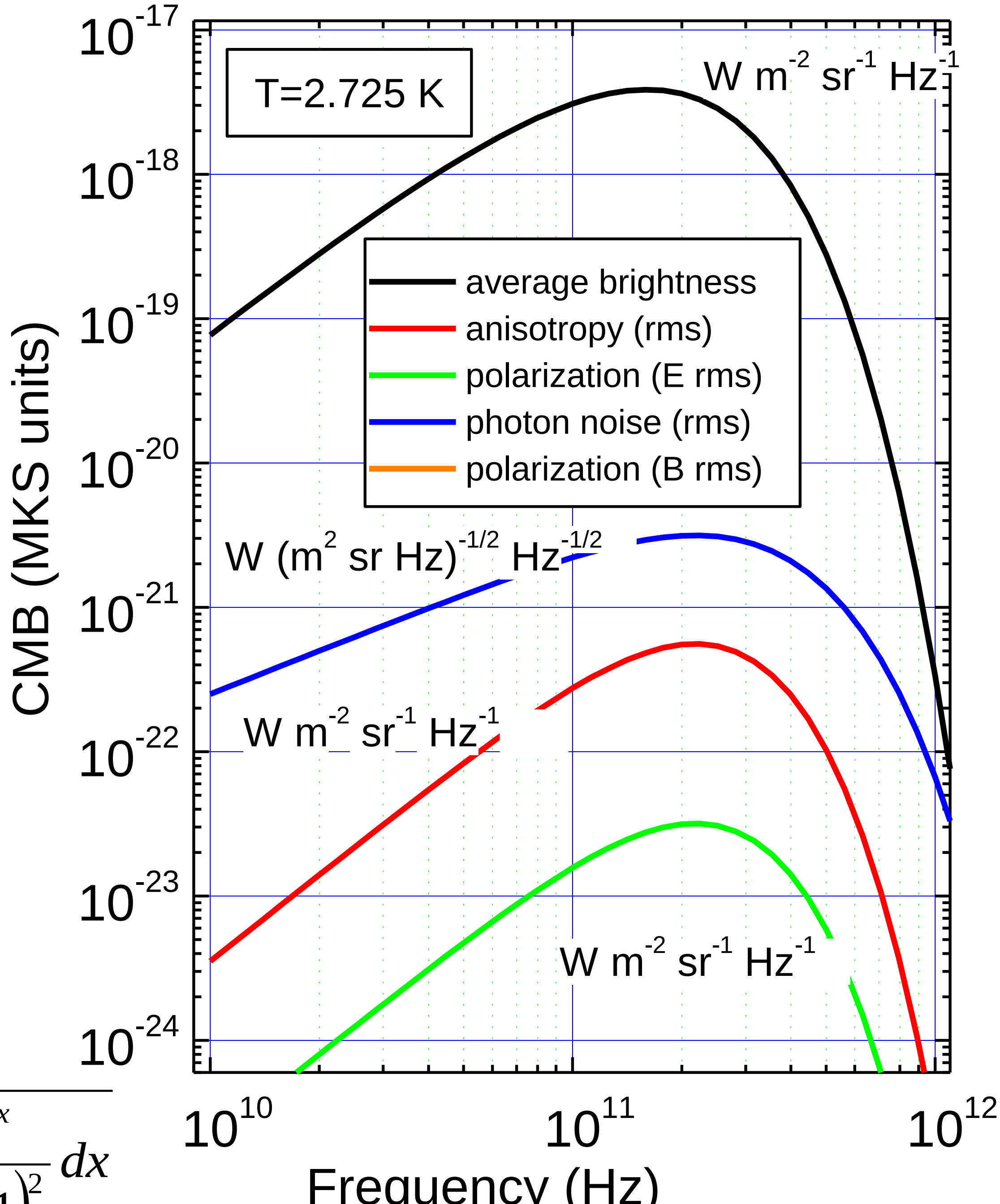
$$\Delta B(\nu,T)=\frac{xe^x}{e^x-1}B(\nu,T)\frac{\Delta T}{T}$$

- **The polarization state**

$$\Delta B_P(\nu,T)=\frac{xe^x}{e^x-1}B(\nu,T)\frac{\Delta T_P}{T}$$

- **The noise**

$$\sqrt{\langle \Delta W^2(\nu,T)\rangle dx}=\sqrt{\frac{4k^5T^5}{c^2h^3}\frac{x^4e^x}{(e^x-1)^2}dx}$$



Noise and integration time

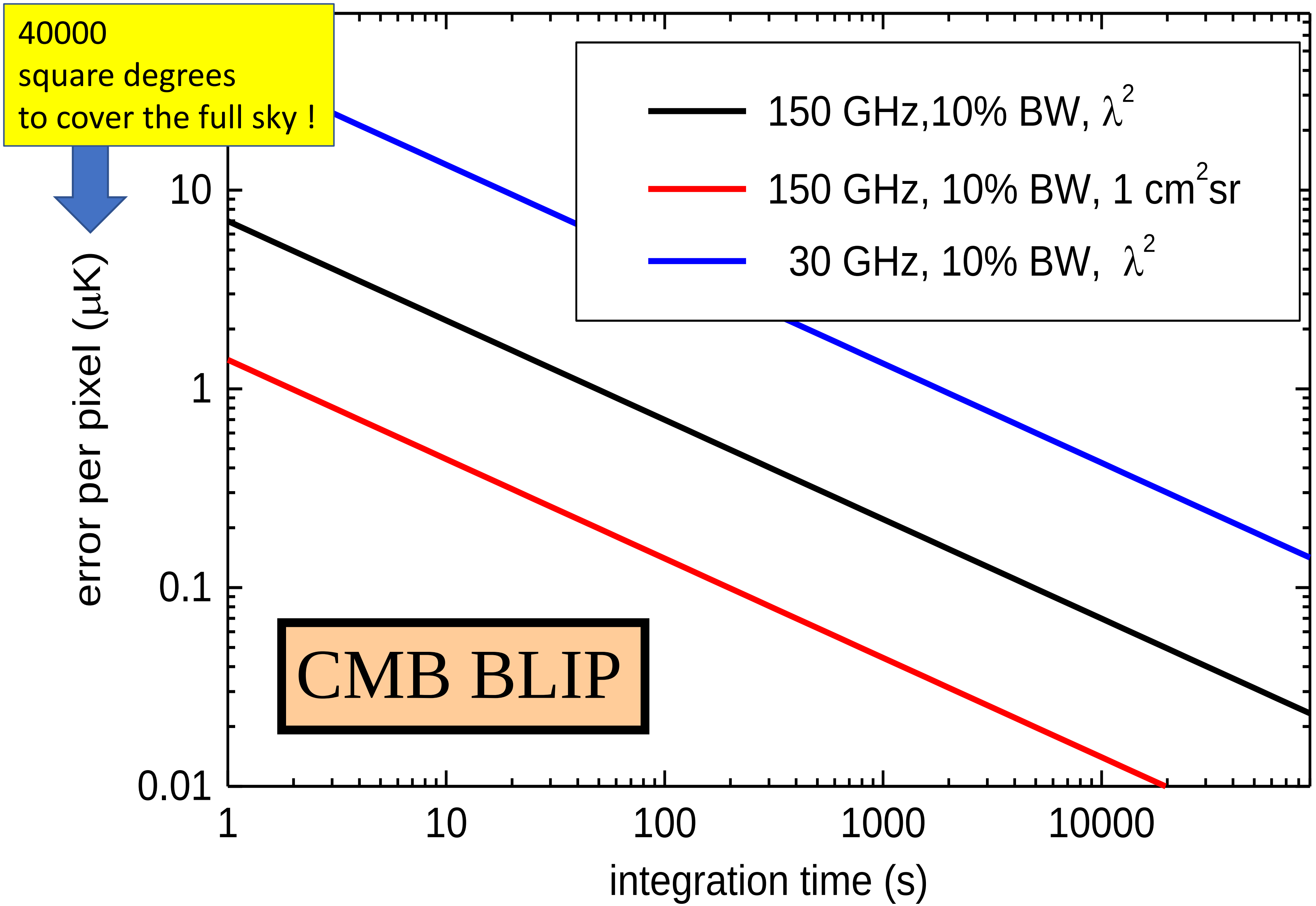
- Numerical example: CMB anisotropy (or polarization) measurement limited only by radiation noise:

$$\Delta B(\nu, T) = \frac{\Delta T}{T} \int_{x_1}^{x_2} \frac{x e^x}{e^x - 1} B(x, T) dx$$

$$\sigma\left(\frac{\Delta T}{T}\right) = \frac{\sigma(\Delta B)}{\int_{x_1}^{x_2} \frac{x e^x}{e^x - 1} B(x, T) dx}$$

$$\sigma\left(\frac{\Delta T}{T}\right) = \frac{\sqrt{\frac{4k^5 T^5}{c^2 h^3} A\Omega \int_{x_1}^{x_2} \frac{x^4 e^x}{(e^x - 1)^2} dx}}{\frac{2k^4 T^4}{c^2 h^3} A\Omega \int_{x_1}^{x_2} \frac{x^4 e^x}{(e^x - 1)^2} dx} \sqrt{\frac{1}{t}}$$

The ultimate sensitivity plot



Radiation Noise

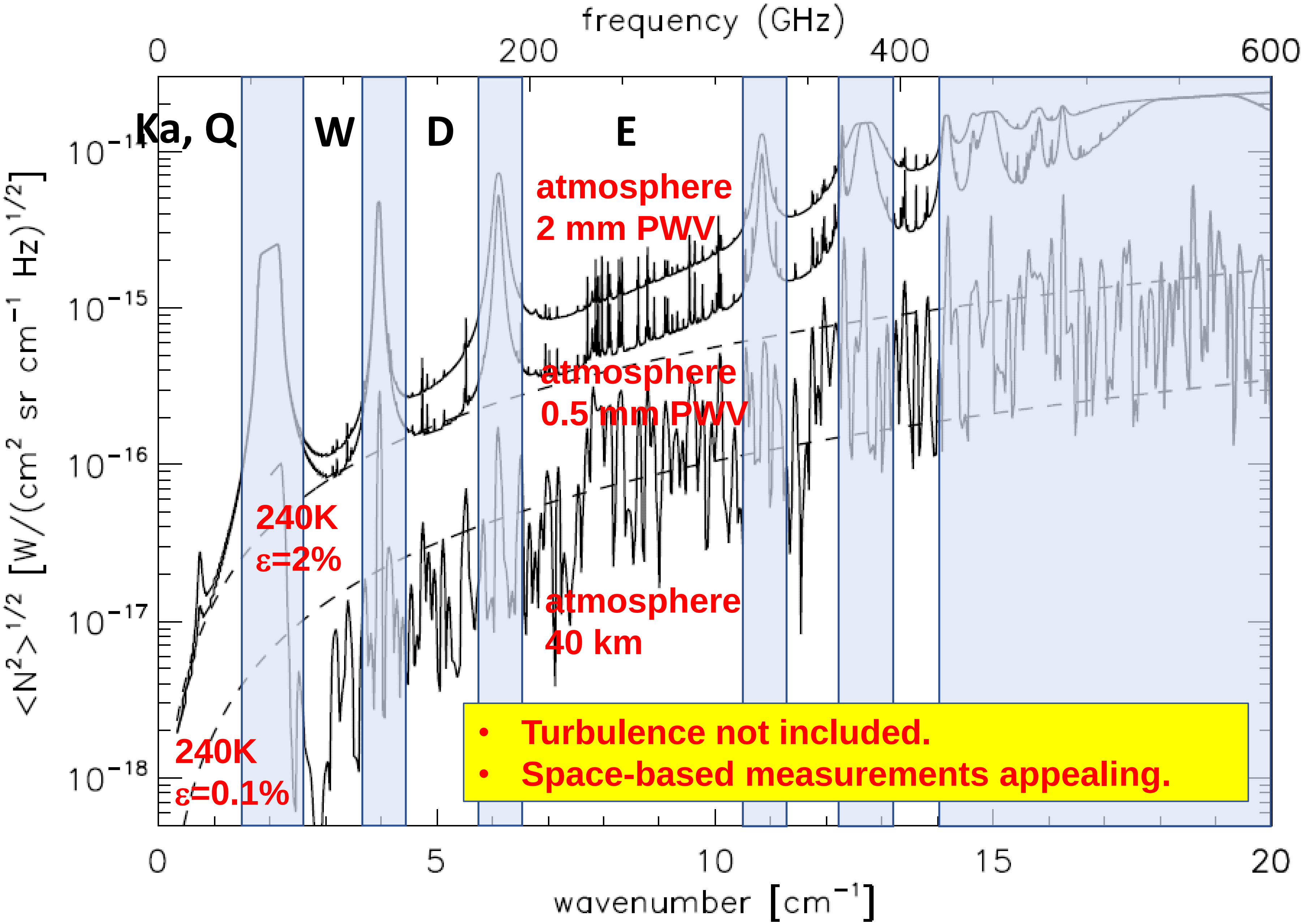
- For a grey-body with emissivity $\varepsilon < 1$
- relevant cases:
  - Radiation emitted by a mirror
  - Radiation emitted by the atmosphere in the atmospheric windows

$$N' = \varepsilon N$$

$$\left\langle \Delta N'^2 \right\rangle = \varepsilon \left\langle N' \right\rangle \left[1 + \frac{\varepsilon}{e^{h\nu/kT} - 1} \right]$$

$$\sqrt{\left\langle \Delta W^2 \right\rangle df} = \sqrt{\frac{4k^5}{c^2 h^3}} \sqrt{A\Omega T^5} \sqrt{\varepsilon \int_{x_1}^{x_2} \frac{x^4 (e^x - 1 + \varepsilon)}{e^x - 1} dx \, df}$$

Photon noise from the local environment, for CMB observations



arXiv:1510.06609

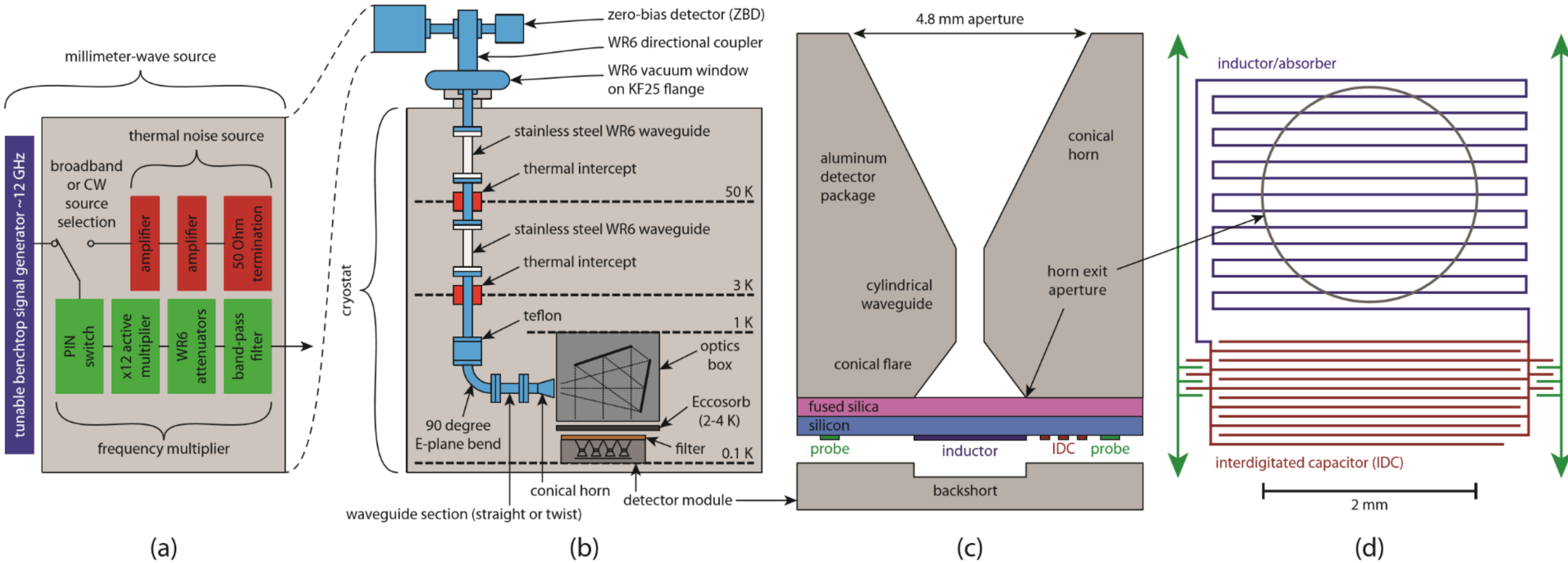
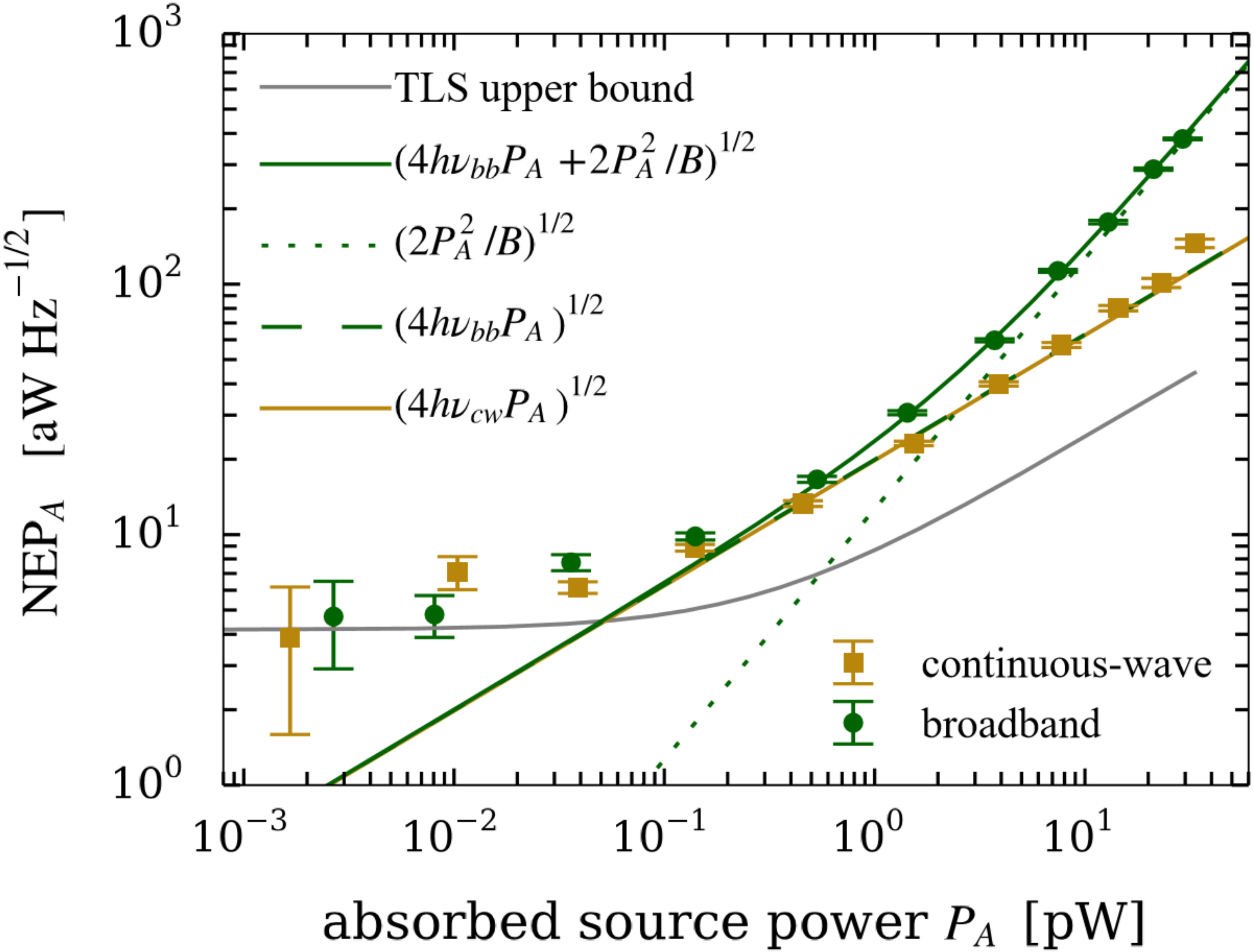


FIG. 1. Experiment schematics. **(a)** The millimeter-wave source components. **(b)** The source and cryogenic setup. **(c)** A cross-section of an array element. The inner conical flare and fused silica layer are designed for impedance matching. **(d)** The lumped circuit elements of one LEKID. Parts of this figure are reproduced with permission from H. McCarrick *et al.*, Rev. Sci. Instrum. **85**, 123117 ©2014 American Institute of Physics.

arXiv:1510.06609



Radiation noise and detector noise

- If the intrinsic noise of the detector is lower that the radiation noise, the operation mode of the detector is optimal.
- Photon-noise limited performance (analogous to BLIP, background limited infrared photodetection).
- The measurement is optimized if
  - The environment minimizes photon noise so that the dominant photon noise is the one from the CMB
  - The noise of the detectors is lower than CMB noise.
- How can we reduce detector noise below CMB photon noise ?
- To answer, we need to understand the physics of CMB detectors.

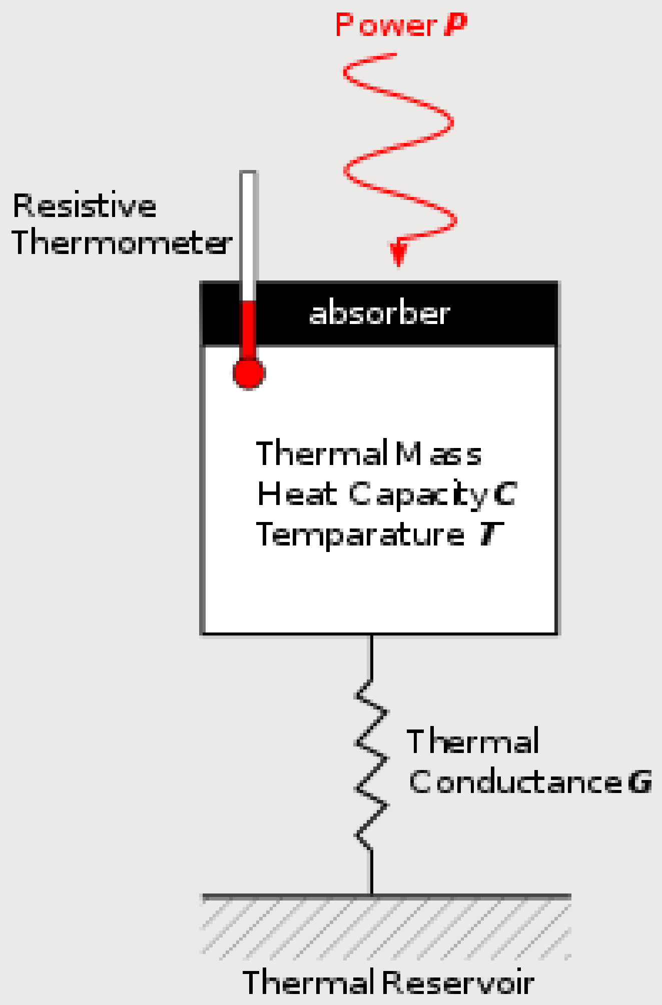
Detectors for the CMB

- A photon (or radiation) detector is a sensor producing an electrical signal which is an unequivocal function of the radiation input.
- Typical detectors :
  - a photoconductor: a doped semiconductor crystal with electrical contacts at the opposite edges, so that a static electrical field is present. Incoming photons excite electrons from the valence band to the conduction band. These are accelerated by the electric field, *producing an electrical current proportional to the incoming flux of photons*.
  - A CCD (Charge Coupled Device): here free electrons are created by incoming photons in a semiconductor pixel, in the same way as above, and are accumulated in the pixel until the integration period is over. Then are read, converting the *accumulated charge (proportional to the number of photons arrived in the integration time*) into a voltage.
- These are not sensitive to CMB photons

Detectors for the CMB

- As of today, there are three ways to detect very-low energy CMB photons:
  - *Coherent detectors*, where the EM field produces an AC current in an antenna. The AC current is **amplified** coherently before rectification and detection. They are sensitive to amplitude and phase of the EM field. High-frequency extension of *radioastronomy* techniques, does not work above 100 GHz.
  - *Thermal detectors*, integrating the thermal energy of a large number of absorbed photons (bolometers, **TESs**). They are sensitive to the amplitude of the EM field. Low-frequency extension of techniques used in *infrared astronomy*. Does not work below 40 GHz.
  - *Quantum detectors*, exploiting low-binding-energy quantum systems which are affected by the energy of CMB quanta (**KIDs**). Recent development, exploiting *superconductivity effects*. They do not work below 60 GHz.

Cryogenic Bolometers and Kinetic Inductance Detectors



Bolometer

- A bolometer is a thermal sensor of EM radiation.
- A *radiation absorber* is thermally insulated from a *thermal reservoir*, and heats up when illuminated by radiation.
- A *thermistor* (a resistor with steep temperature dependance of the resistance) is used to measure the temperature change, and infer the absorbed power.
- A bolometer is able to absorb a wide range of wavelengths (depending on the technology of the absorber) and can be optimized for operation from radio frequencies to X-rays. They are optimal detectors in the mm/sub-mm/FIR range.

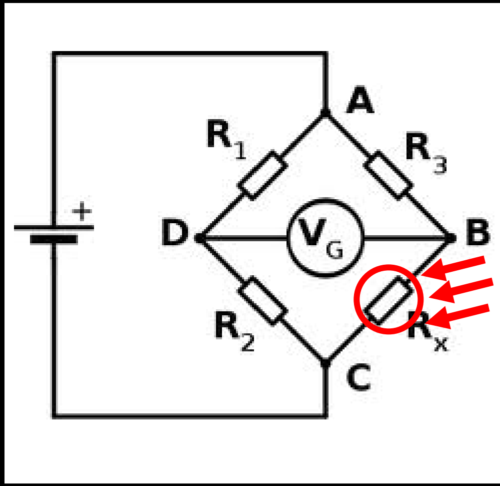
History: early days

- The infrared range has been *discovered* by astronomers!
  - Friedrich Wilhelm Herschel, using a prism and balckened bulb thermometers, detects the infrared section of the solar spectrum (calorific rays, 1800)
- The final demonstration that IR is also EM waves happens a bit later
  - Macedonio Melloni in 1829 develops the *thermomultiplier*, a sensitive IR detector. With this system he demonstrates that calorific rays have the same nature as light, also demonstrating that they have *polarization properties* exactly like light rays. He names the calorific rays “ultrared radiation”.

- The first astronomical observation is carried out soon after:
  - IR radiation from the moon is detected by Charles Piazzi Smyth in Tenerife, using a *thermocouple*. He also shows that IR radiation is better detected at higher altitudes.

History: early days

- The first bolometers were developed for astronomy, and allowed the first IR spectroscopy of an astronomical source
  - Samuel Pierpoint Langley in 1878 develops the bolometer: a thin blackened platinum strip, sensitive enough to measure *the heat of a cow from a distance of ¼ mile*.
  - The detector works because the resistance of the Pt strip changes when heated by the absorbed radiation.
  - The detector is differential: 4 strips are placed in a Wheatstone bridge but only one is blackened and exposed to incoming radiation. Common-mode effects are rejected by the bridge and tiny variations of bolometer resistance can be measured.
- With his bolometer Langley is able to measure the IR spectrum of the sun, discovering atomic and molecular lines.



Old times

- Further developments:
  - 1915 : William Coblentz uses thermopiles (an improved version of Macedonio Melloni’s detector !) to measure the infrared radiation from 110 stars, as well as from planets, such as Jupiter and Saturn, and several nebulae.
  - 1920’s : systematic IR observations with vacuum thermopiles (Seth B. Nicholson, Edison Pettit and others): diameters of giant stars
  - 1948: IR observations show that the moon is covered by dust.
  - 1950s: Lead Sulphide photodetectors – Johnson’s star photometry
  - First Semiconductor bolometers, slicing carbon resistors to make the thermistor (W. S. Boyle and K. F. Rodgers, J . Opt . Soc . Am . 49 :66 (1959))

One generation ago

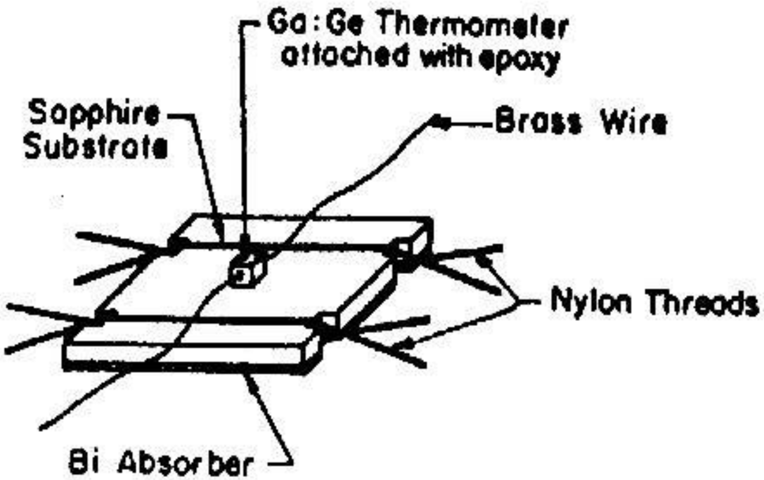
- The revolution :
  - 1961: Franck J. Low develops the first *cryogenic* Ge bolometer, boosting the sensitivity by orders of magnitude.
  - 1960's and ff. bolometers and semiconductors detectors with their telescopes are carried to space using stratospheric balloons and rockets.

- Consequence:
  - First sky surveys @ λ 100 μm
  - 1968 First IR ground based large area sky survey (2 μm, from Mt. Wilson)

Few decades ago

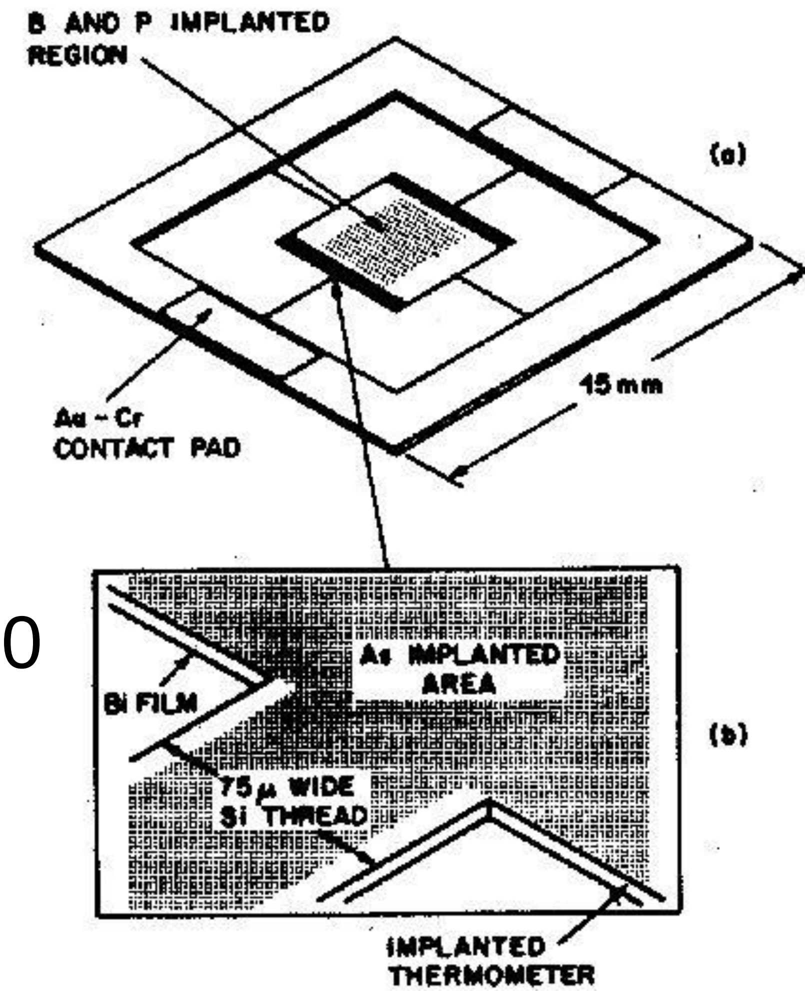
- mm-wave bolometers
  - cooled at 1.5K or 0.3K
  - operating from space
- become sensitive enough to measure the finest details of the Cosmic Microwave Background.

- Breakthrough:
  - The composite bolometer (absorber and thermistor separated and each optimized independently): N. Coron, P. Richards …



Circa 1970

Composite
Bolometer
(Coron, Richards …)

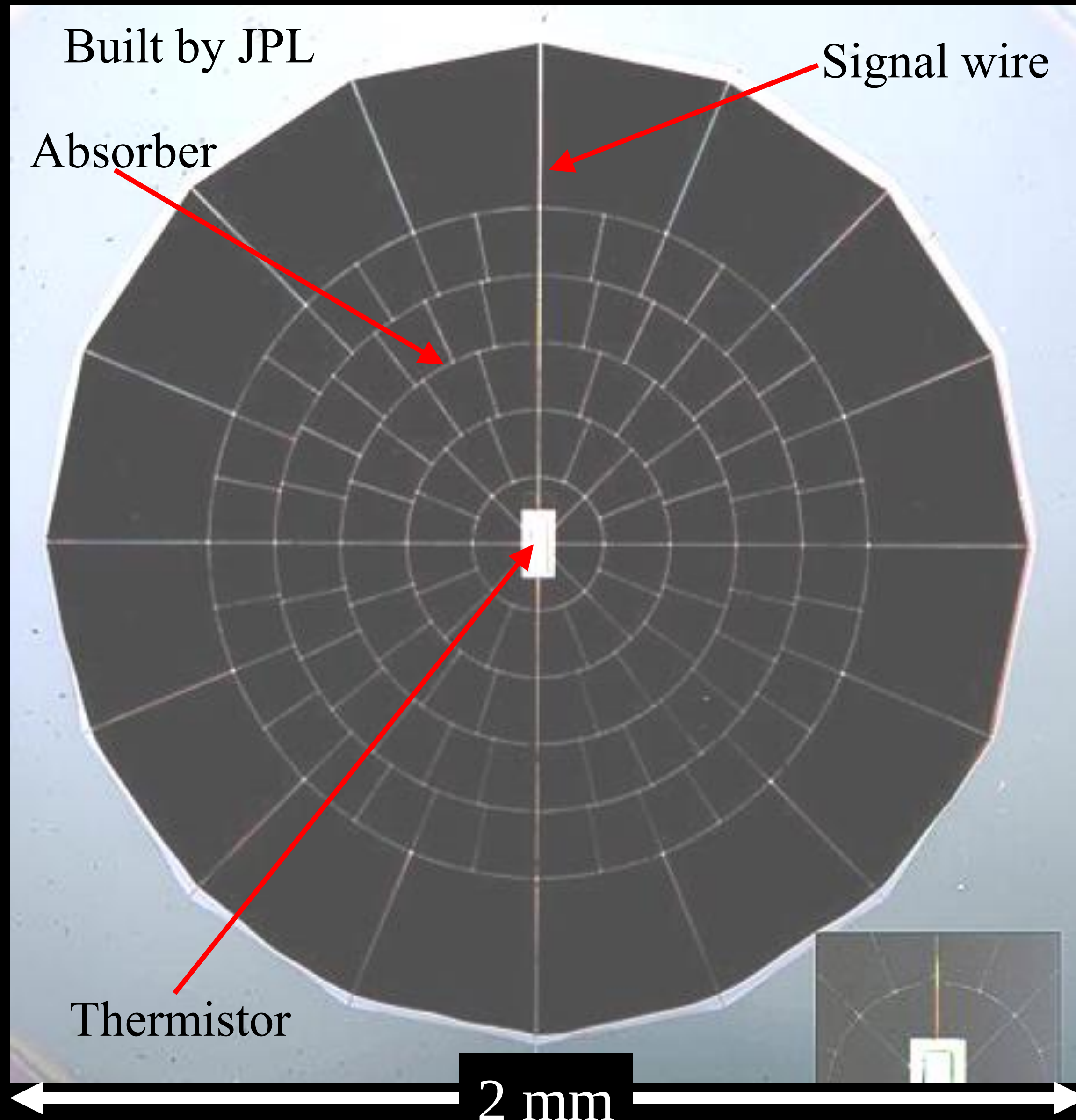


Circa 1980

monolitic
bolometer
(Goddard, ..)

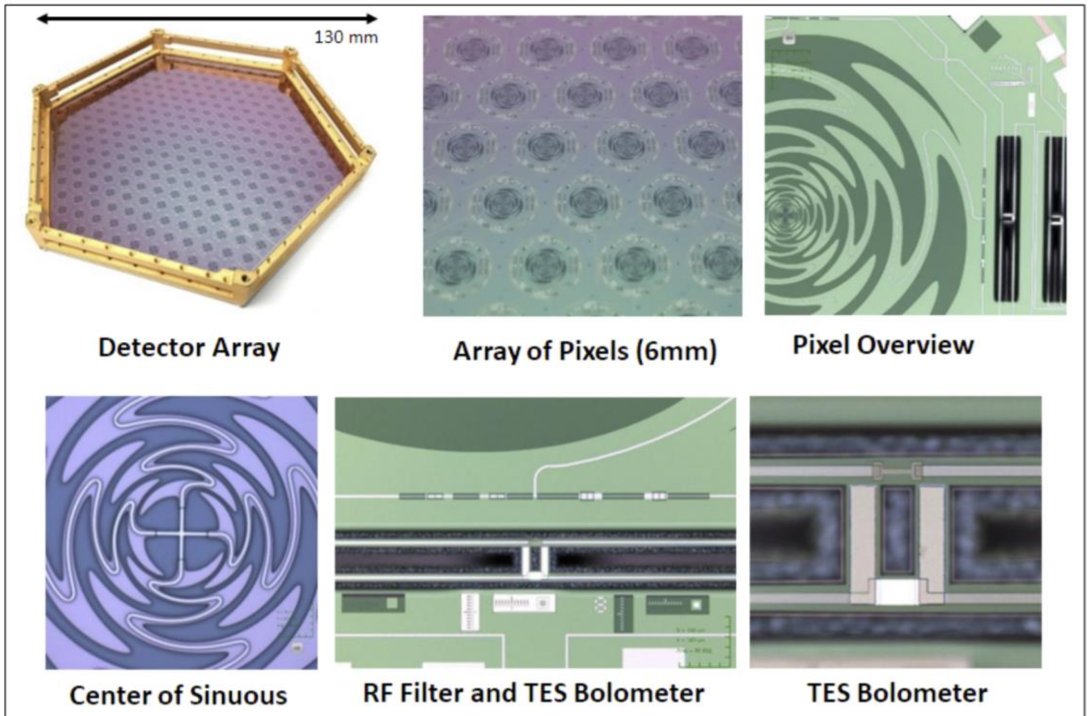
Spider-Web Bolometers

- The absorber is micro machined as a web of metallized Si_3N_4 wires, 2 mm thick, with 0.1 mm pitch.
- This is a good absorber for mm-wave photons and features a very low cross section for cosmic rays. Also, the heat capacity is reduced by a large factor with respect to the solid absorber.
- NEP ~ 2 10^{-17} W/$Hz^{0.5}$ is achieved @0.3K
- 150μK_{CMB} in 1 s
- Mauskopf *et al.* Appl.Opt. **36**, 765-771, (1997)

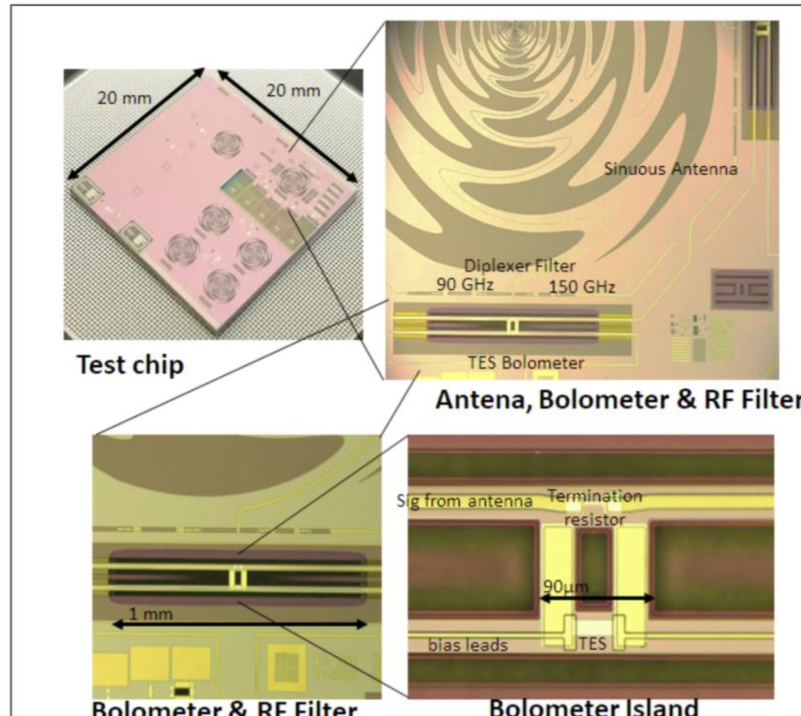


Antenna-coupled bolometers

- Radiation is collected by a suitable (planar) antenna, and transferred via suitable waveguides (e.g. coplanar) to a matched resistor, where is dissipated.
- The resistor is placed on a thermally insulated island, and its temperature is sensed by a suitable thermistor (usually a superconducting Transition Edge Sensor - TES)
- All this is built **on a Si wafer**, using advanced microfabrication technology, **and can be replicated to obtain large-format detector arrays.** ***BOOST of the MAPPING SPEED.***
- Currently moving from laboratory developments to industrial production.



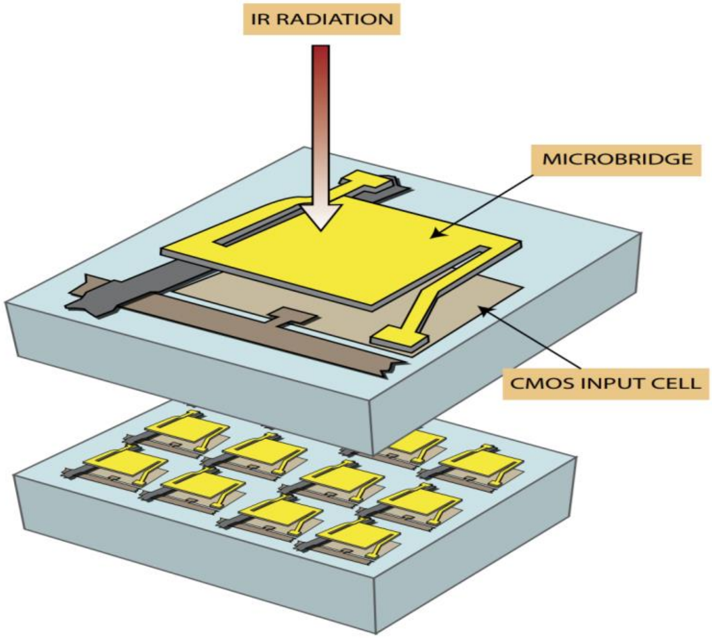
Detector Array Co-Fabricated with HYPRES



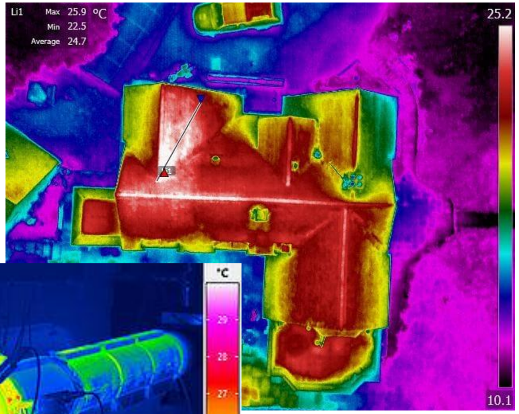
Prototype Chip Fabricated at StarCRYO

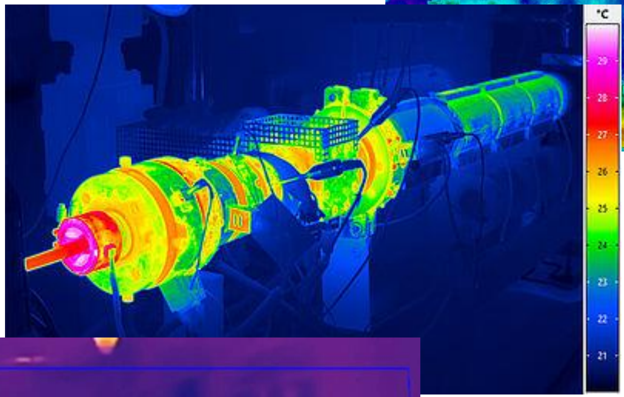
Figure from https://export.arxiv.org/pdf/1801.06991

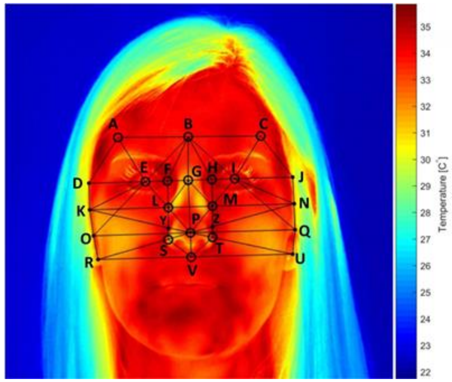
Bolometers are not just for astronomy …

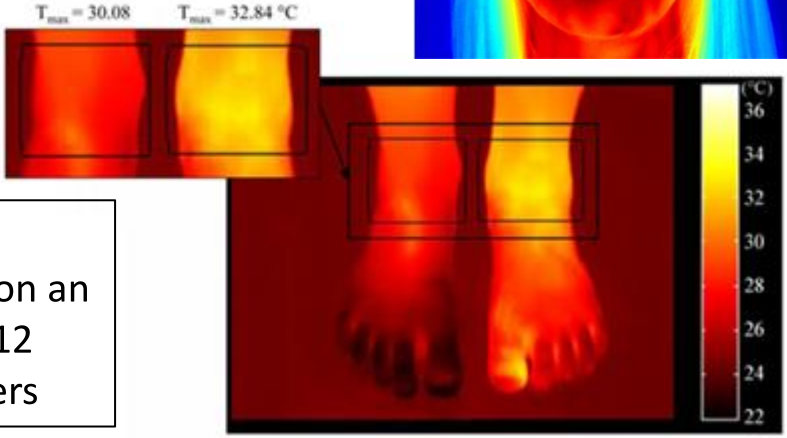


Schematical overview of a microbolometer detector. A bolometer is a small plate that floats above the surface of a Read Out Integrated Circuit (ROIC). The temperature of the plate changes when a photon falls on it.









10 μm thermal camera based on an array of 640x512 microbolometers