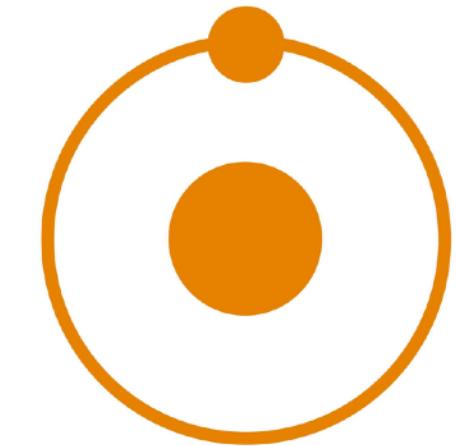
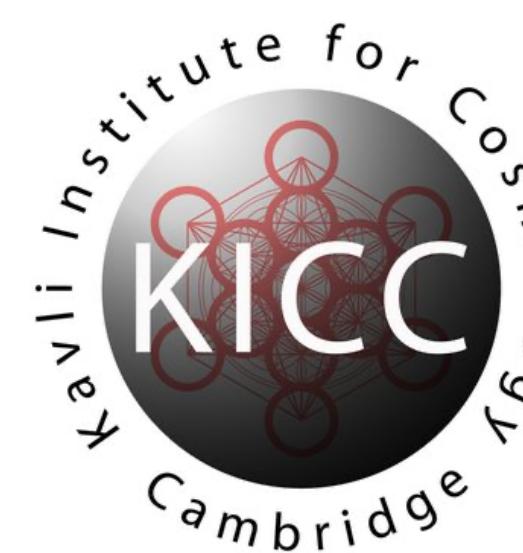
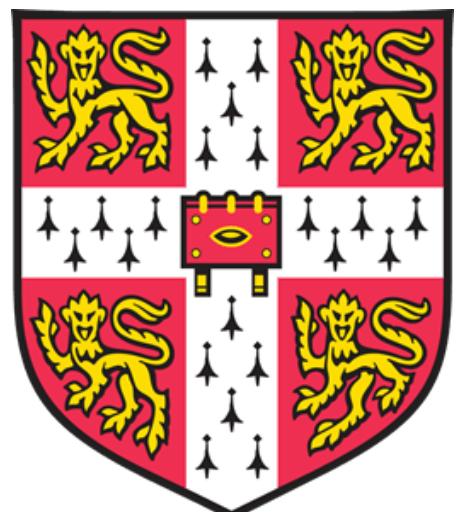


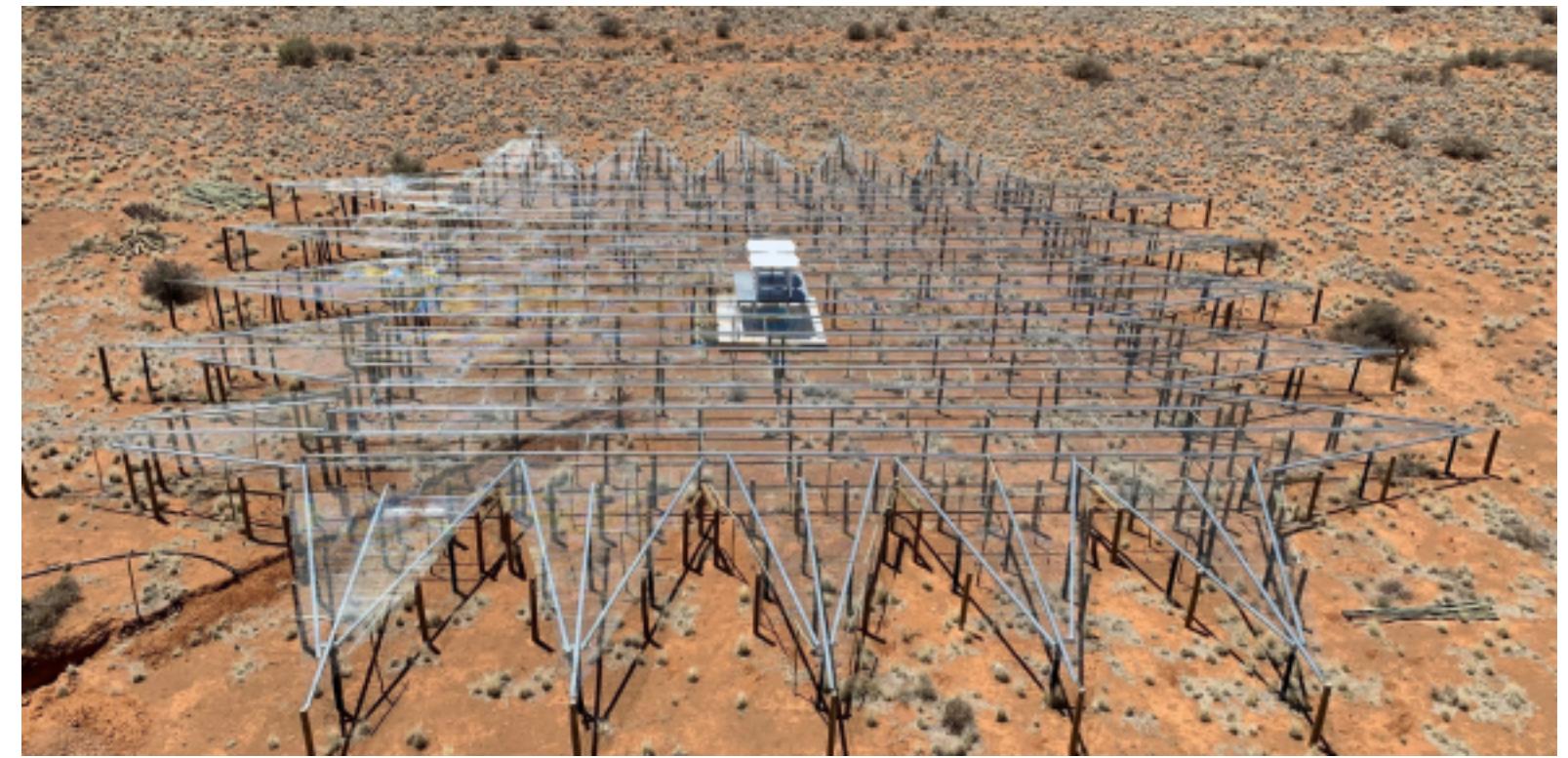
Calibration for 21 cm Cosmology

Harry Bevins
And REACH collaboration



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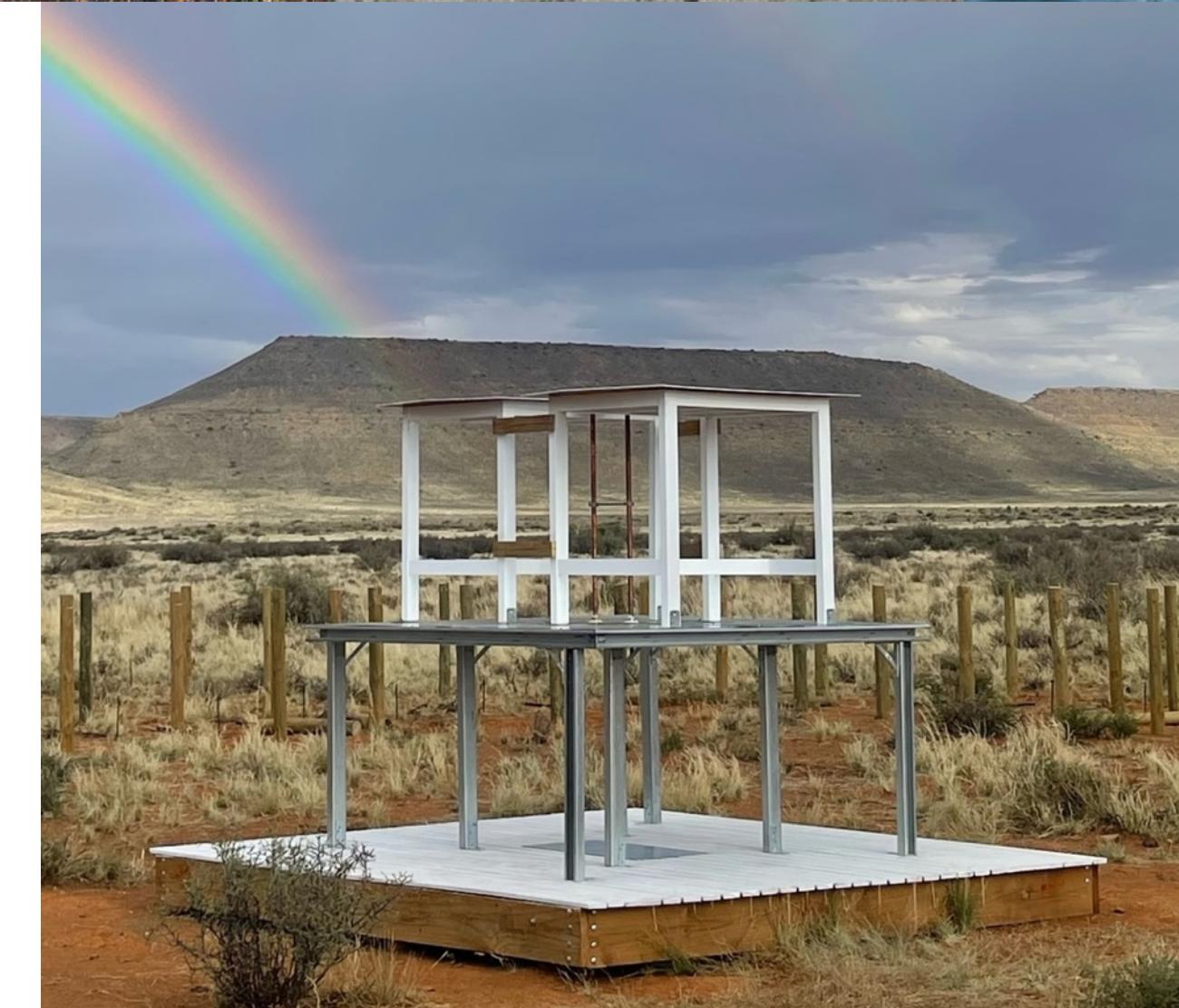
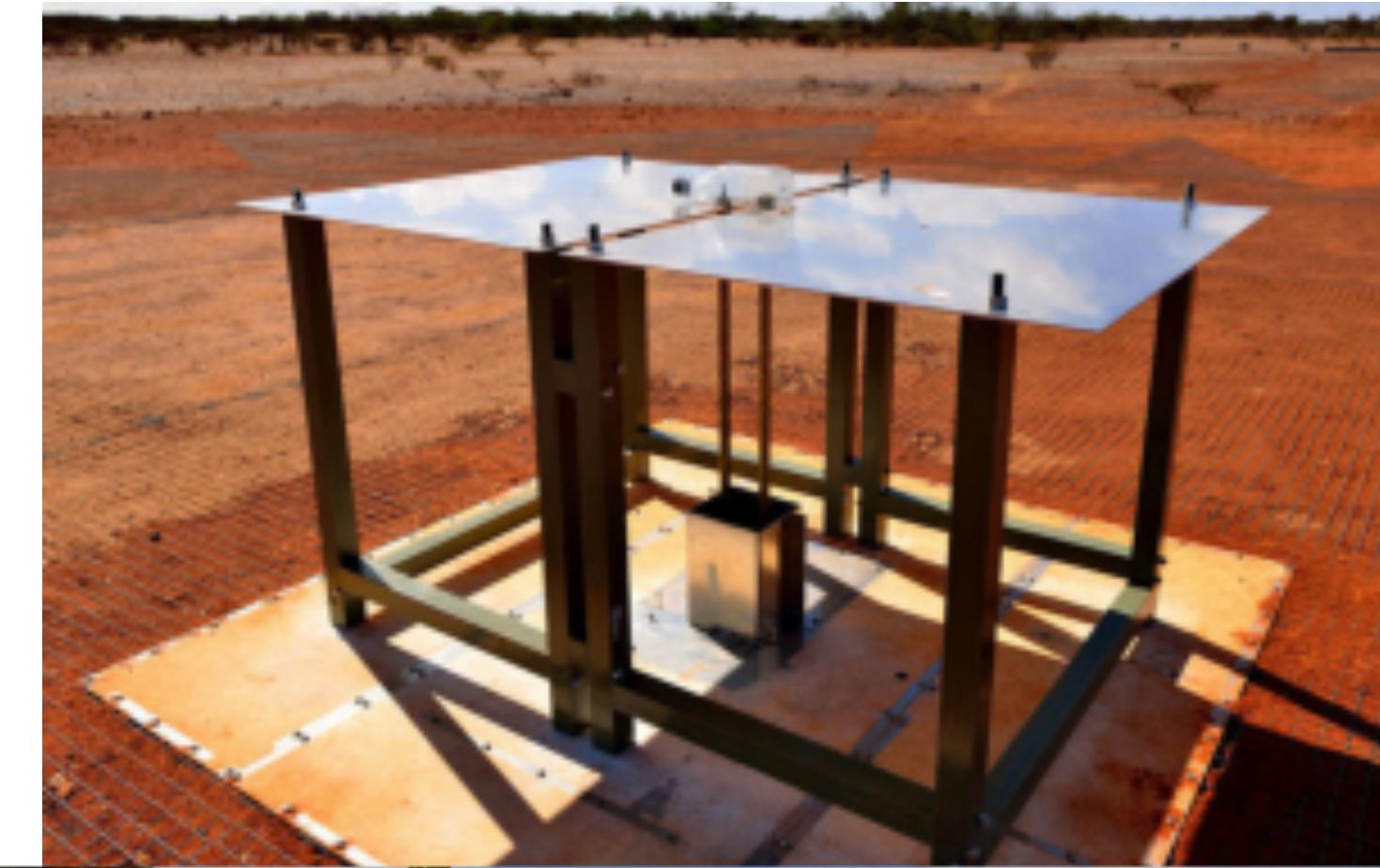
- Calibrating 21cm experiments
- Calibrating REACH
- Calibrating CosmoCube?



How do we calibrate a sky-averaged 21cm experiment?

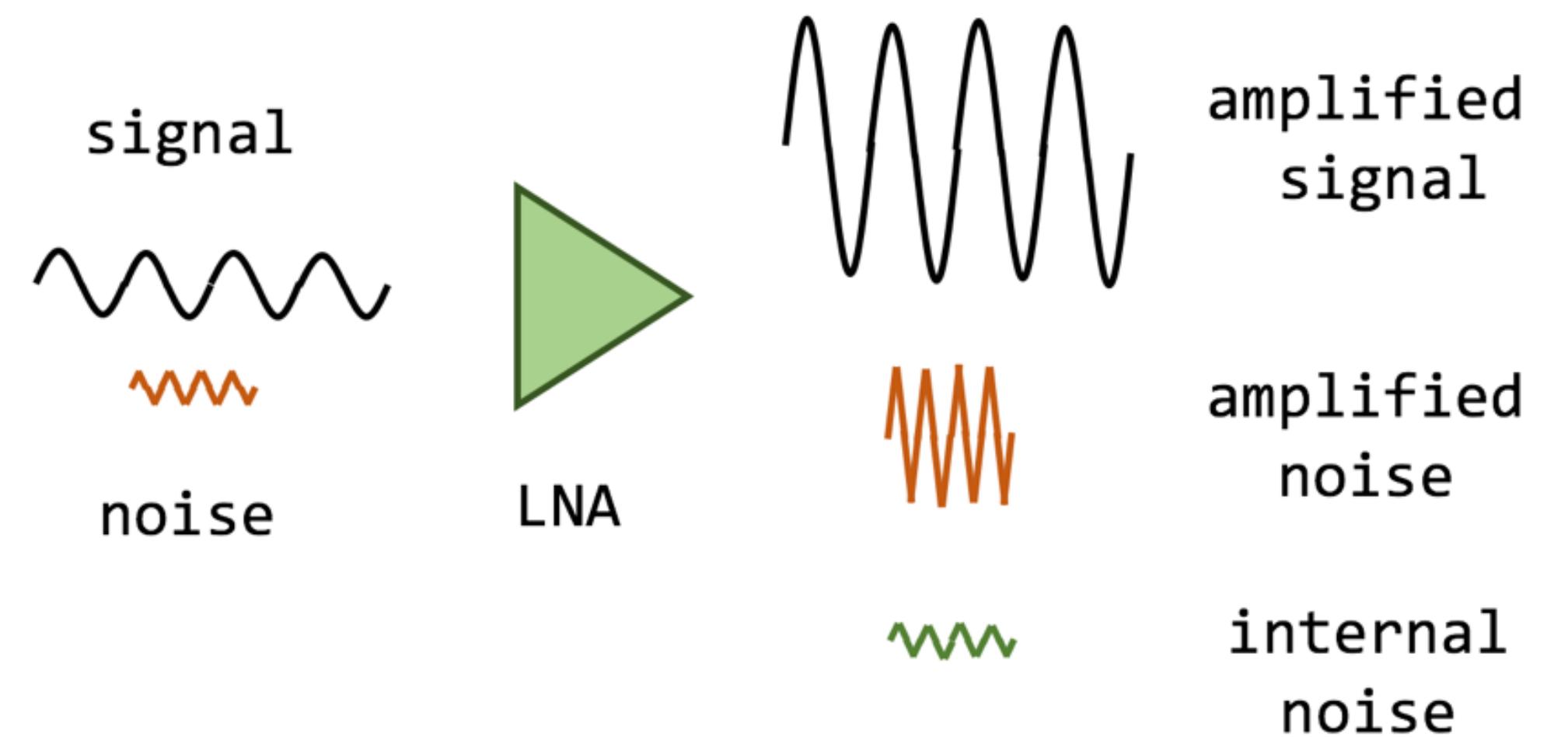
What do we measure?

- Stick a metal antenna in a remote location
- Radio waves make the electrons in the metal wiggle around
- Sets up a current on the blades and we measure a voltage that oscillates at the frequency of the incoming waves
- But this signal is very weak and we really want the sky temperature in Kelvin



Low Noise Amplifier

- We need to amplify the signal in a way that does not degrade the signal-to-noise
- Place the LNA before the spectrometer
- LNAs have a high gain but a low noise figure
- They amplify input noise and signal and introduce very little additional noise



Spectrometer and Power

- We measure an amplified voltage as a function of time
- We want temperature as a function of frequency so that we can extract redshift information
- Fourier transform the signal and convert into a power spectral density

$$V(\nu) = \int v(t)e^{-i2\pi\nu t}dt$$
$$P(\nu) \propto |V(\nu)|^2$$

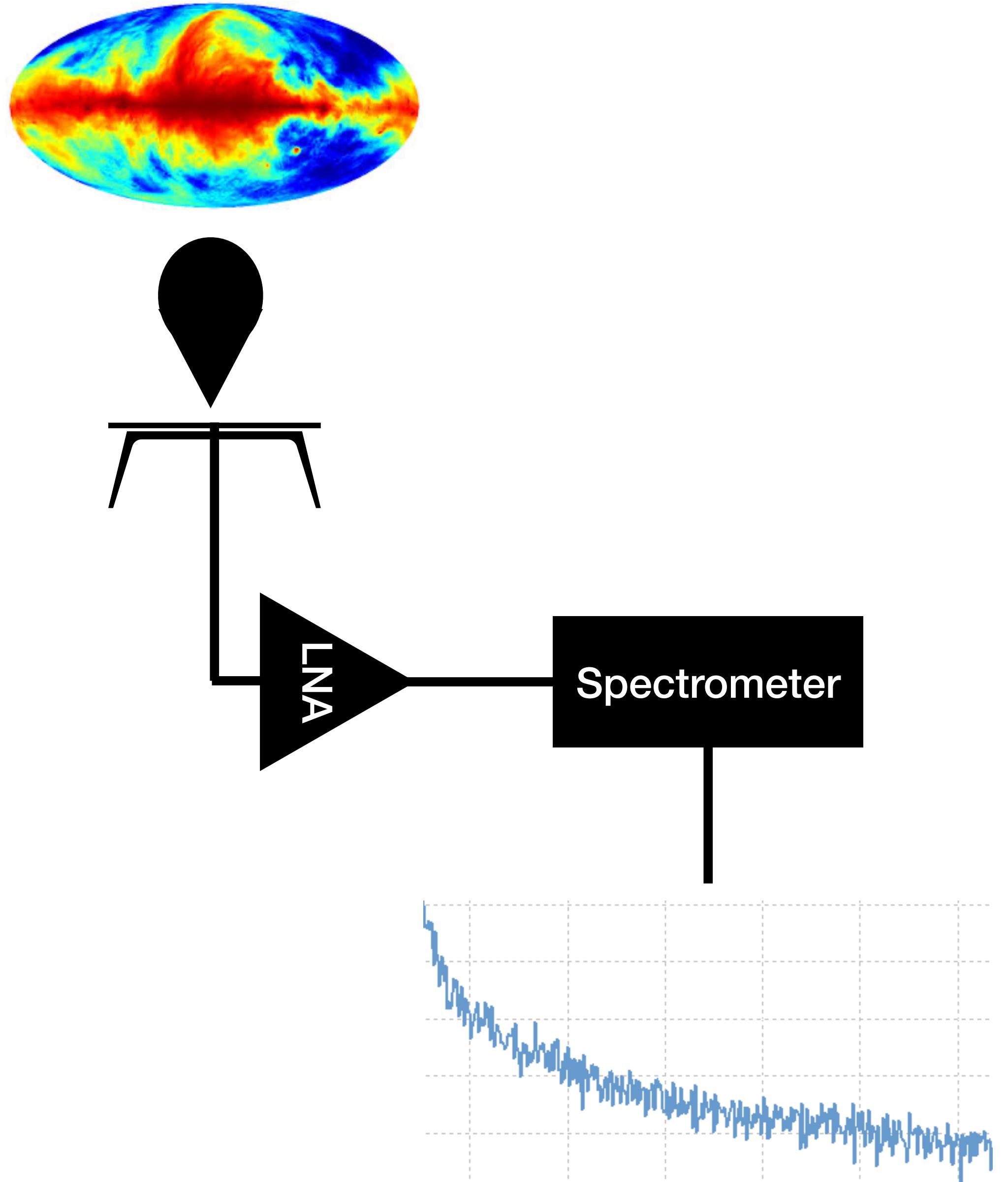


The issue?

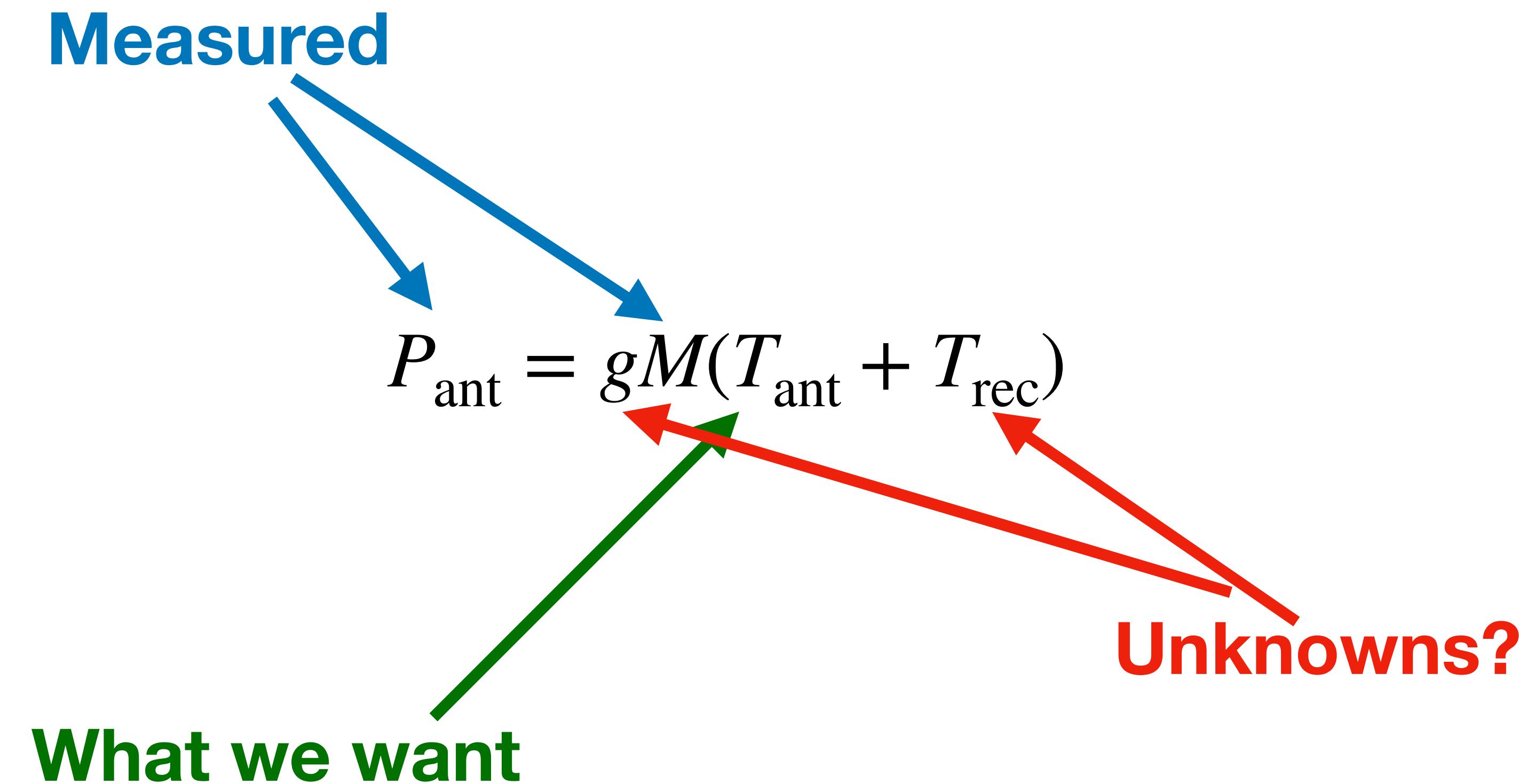
- We want T_{sky} what we get is

$$P_{\text{ant}} = gM(T_{\text{ant}} + T_{\text{rec}})$$

- T_{sky} and T_{ant} are related by the beam of the antenna (see Dominic's talk)
- g is the frequency dependent gain of the receiver chain
- M includes measured information about the reflection coefficients of the antenna
- T_{rec} is power added by the LNA and other components in the receiver chain
- Need references to solve for g and T_{rec}

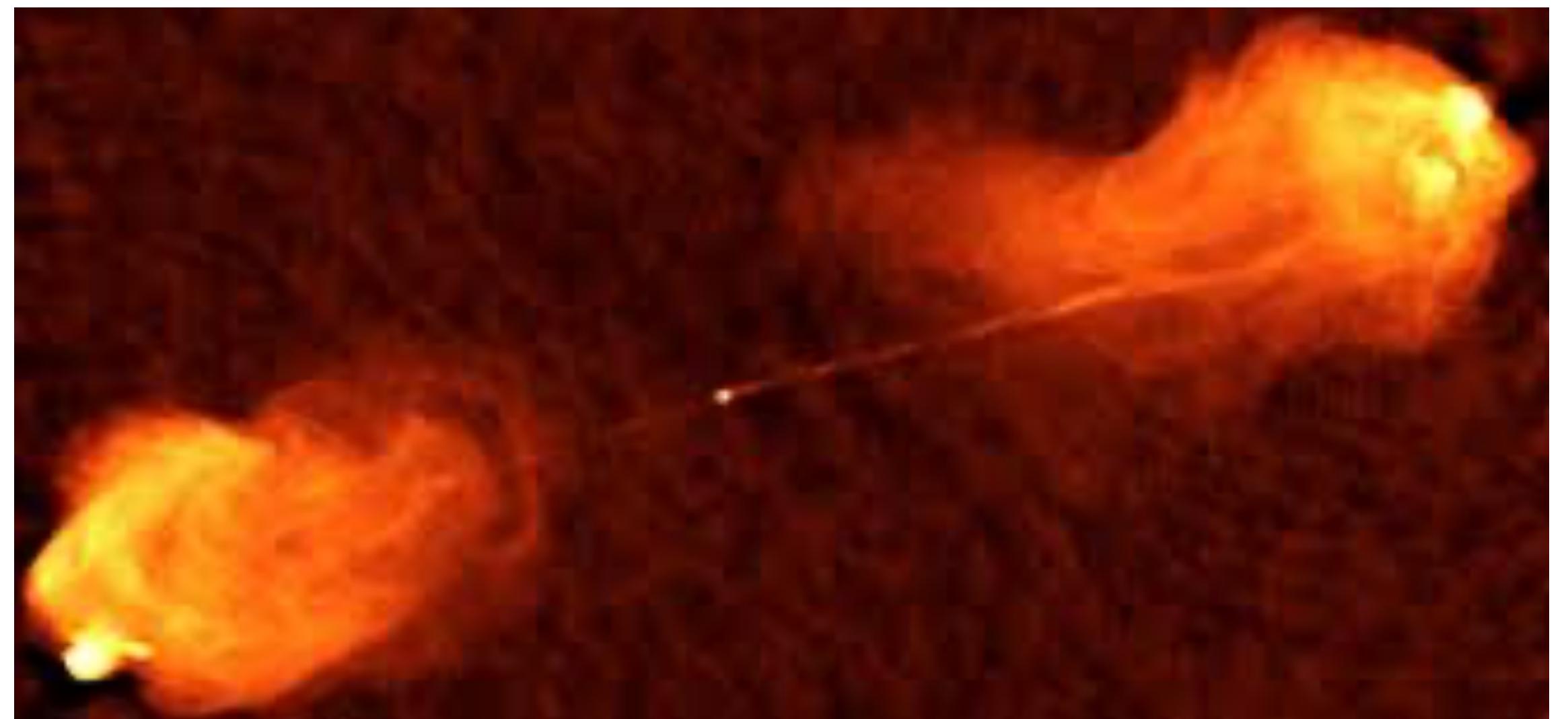


The issue?



Known sources?

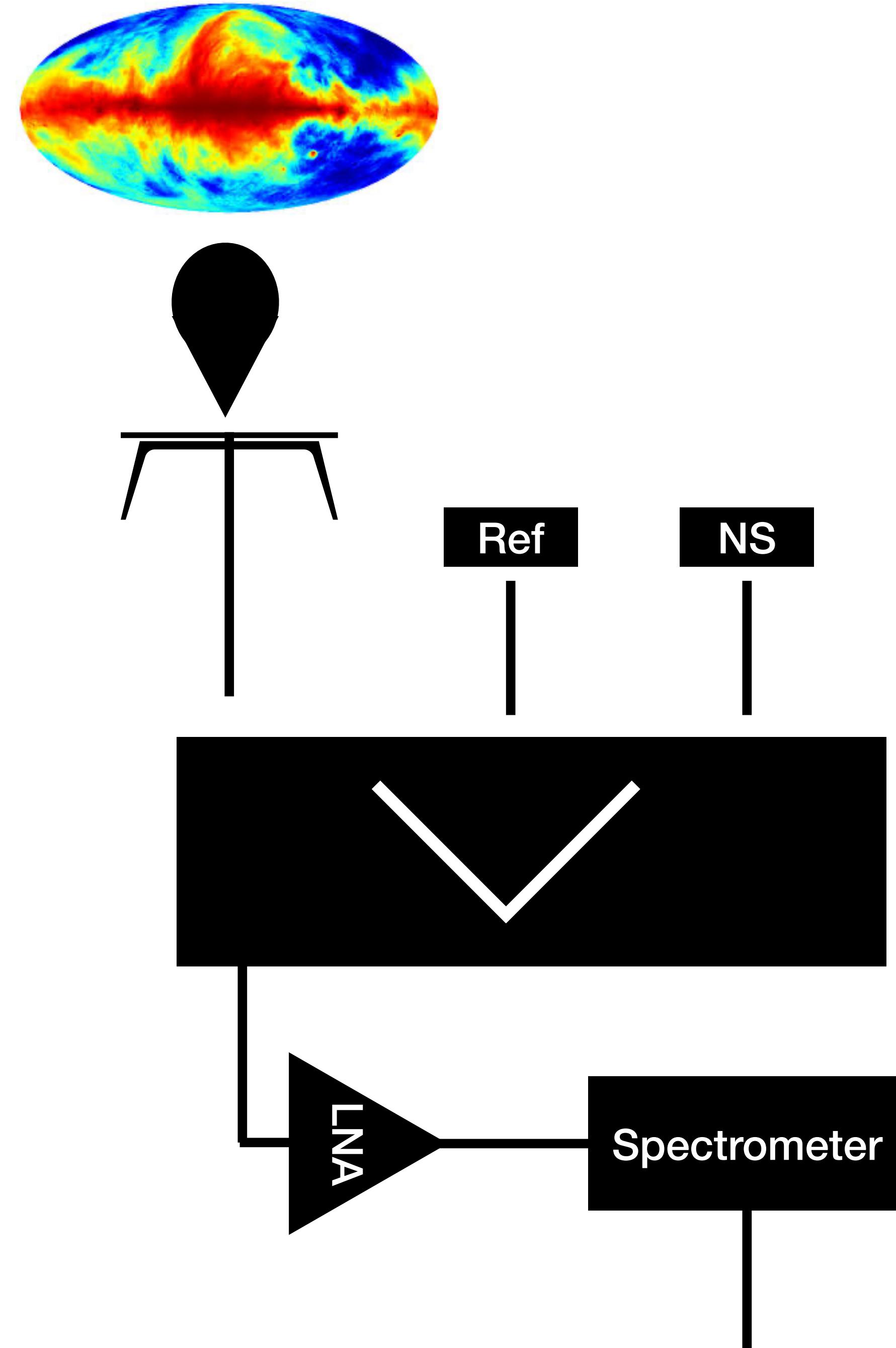
- Typically we do this by observing a known bright source like Cygnus A
- Then comparing the output of the spectrometer to our expectations
- But REACH and experiments like it have no resolution on the sky so we cannot do this
- Instead we can use reference loads and noise diodes to do Dickie Switching



Dickie Switching

- The idea behind Dickie switching is to cancel the gain
- We have a reference load which has an impedance matched to the receiver with power P_L and temperature T_L
- And a matched noise source with power P_{NS} and an effective temperature T_{NS}
- Then the temperature of our unknown is given by

$$T_{\text{ant}}^* = T_{NS} \left(\frac{P_{\text{ant}} - P_L}{P_{NS} - P_L} \right) + T_L$$

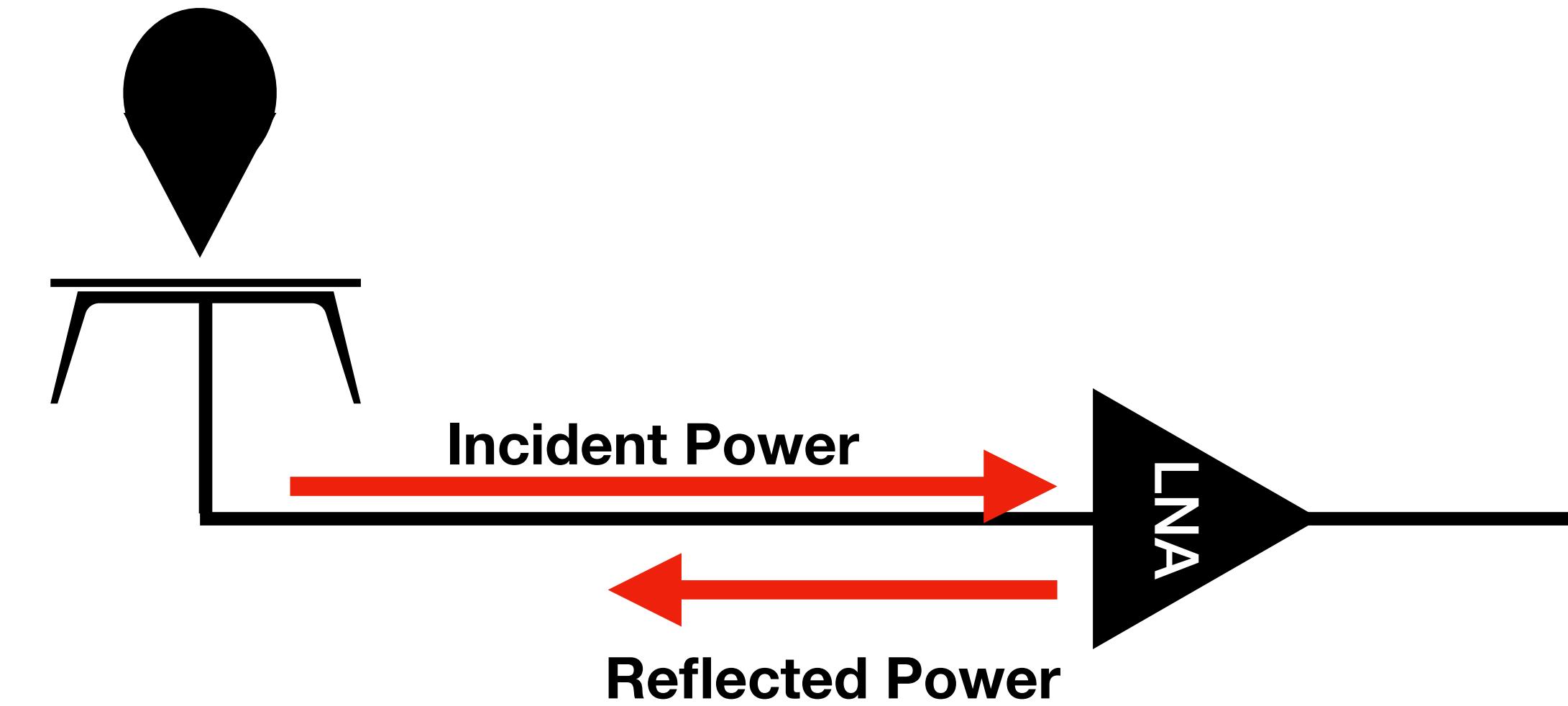


Calibrating REACH

Why Dickie Switching is not enough?

- Dickie switching cancels the gain
- But it assumes all of your sources are impedance matched including the antenna

$$P_{\text{ant}} = gM(T_{\text{ant}} + \cancel{T}_{\text{rec}})$$



- Virtually impossible to build an antenna that's matched and do 21cm with it
- So we have to solve for T_{rec} which is a function of the mismatch between the source and the receiver
- Need additional references in the system that have different mismatches covering the properties of the antenna

$$\begin{aligned} T_{\text{NS}} \left(\frac{P_{\text{source}} - P_L}{P_{\text{NS}} - P_L} \right) + T_L &= T_{\text{source}} \left[\frac{1 - |\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}|^2} \right] \\ &+ T_{\text{unc}} \left[\frac{|\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}|^2} \right] \\ &+ T_{\text{cos}} \left[\frac{\text{Re} \left(\frac{\Gamma_{\text{source}}}{1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}} \right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}} \right] \\ &+ T_{\text{sin}} \left[\frac{\text{Im} \left(\frac{\Gamma_{\text{source}}}{1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}} \right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}} \right]. \end{aligned}$$

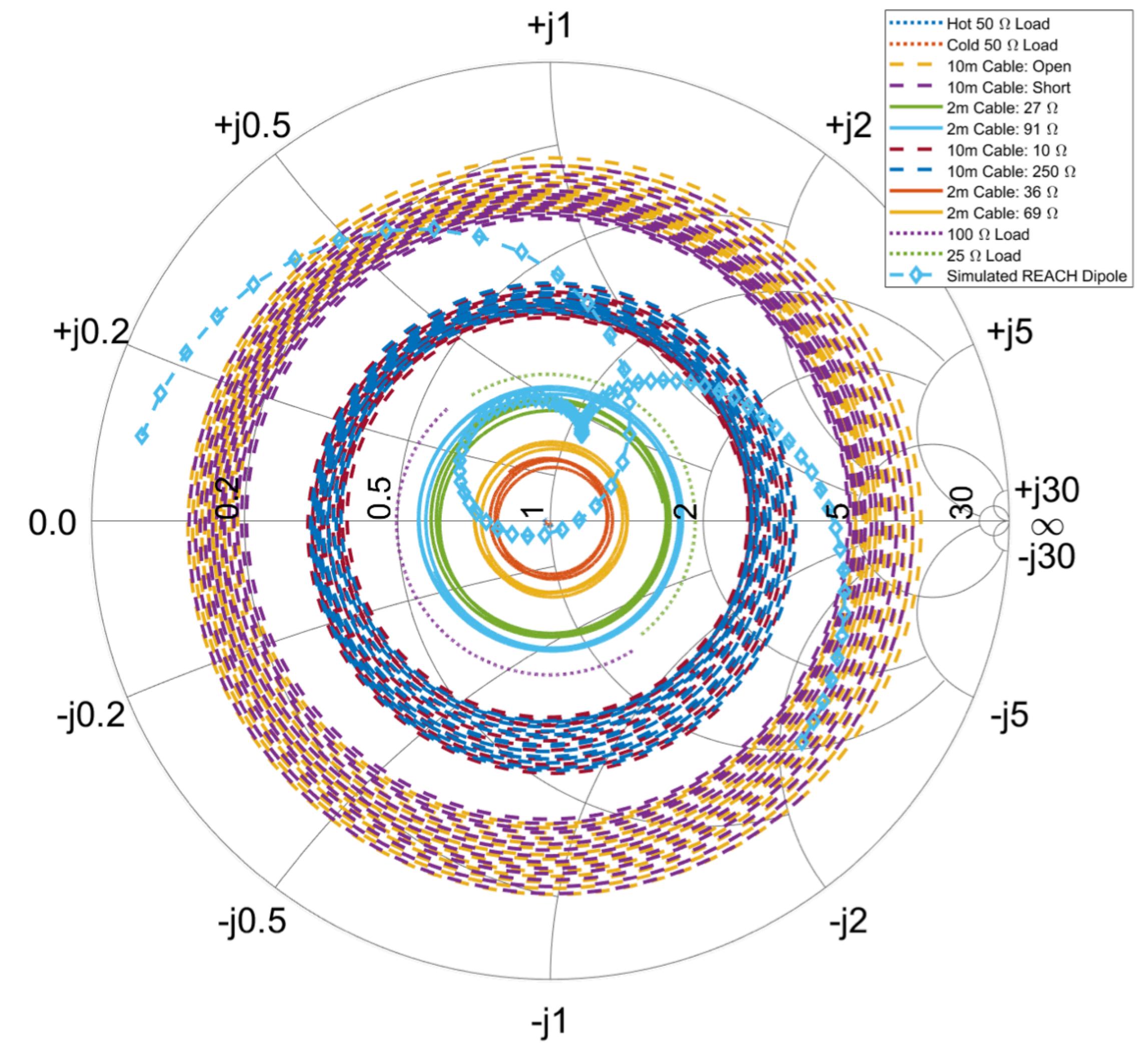
The minimum set?

- In practice we should be able to calibrate with just four different calibrators
 - Cold load: This is at ambient temperature (same as LNA) and should be matched with the LNA (i.e. have the same impedance)
 - Hot load: Heated above ambient with same resistance as LNA
 - Short: Zero (in theory) impedance source
 - Open: Infinite (in theory) impedance source

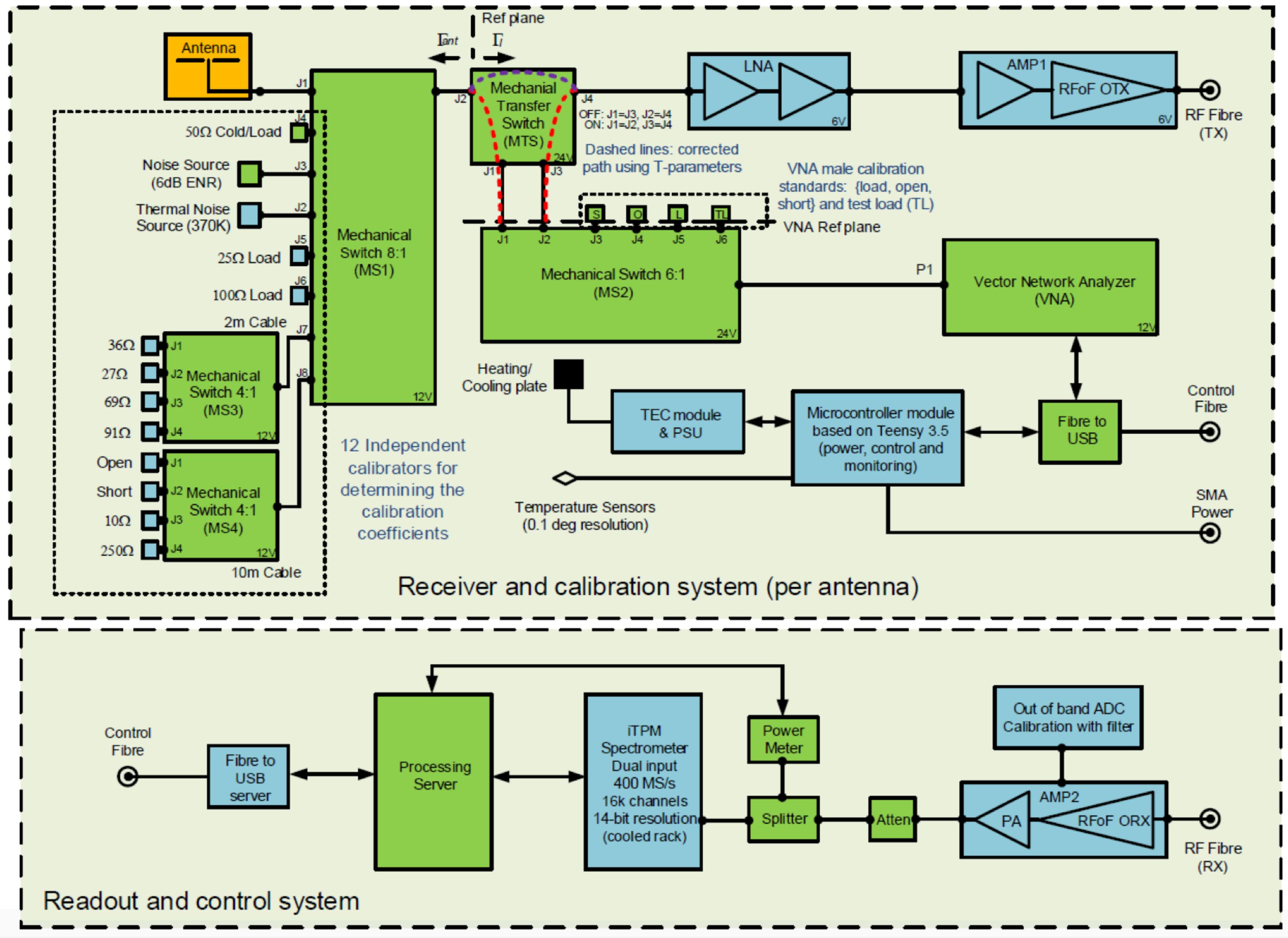


Why REACH has more?

- REACH has a whole host of calibration sources to get better coverage of the Smith chart
- Different resistances move you along with real axis
- Different cable lengths give you wrap around the imaginary axis
- However this increases the complexity of the system!
- Note that the properties change in different environments

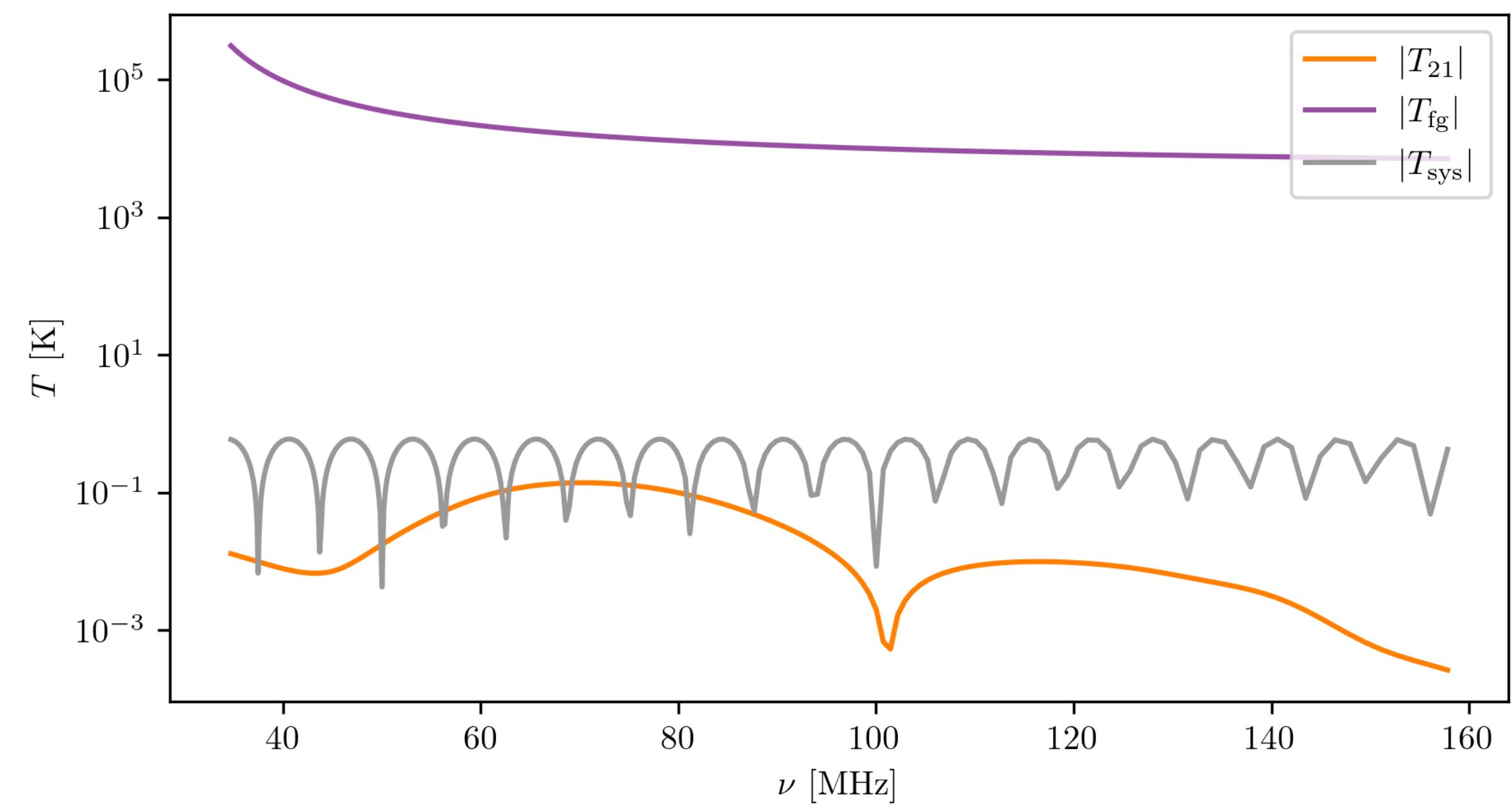


- Key Points:
 - Number of calibrators
 - Presence of switches and cables
 - In situ measurements of reflection coefficients



Okay so now what?

- In practice we observe the calibrators, a matched load (cold source) and a noise diode with a large excess temperature one after the other
- Formulate our solutions around dicky switching but account for mismatch
- Solve for the properties of the system and learn how the system deals with mismatched sources like the antenna
- Once we have solved for the system we can apply the solution to the antenna



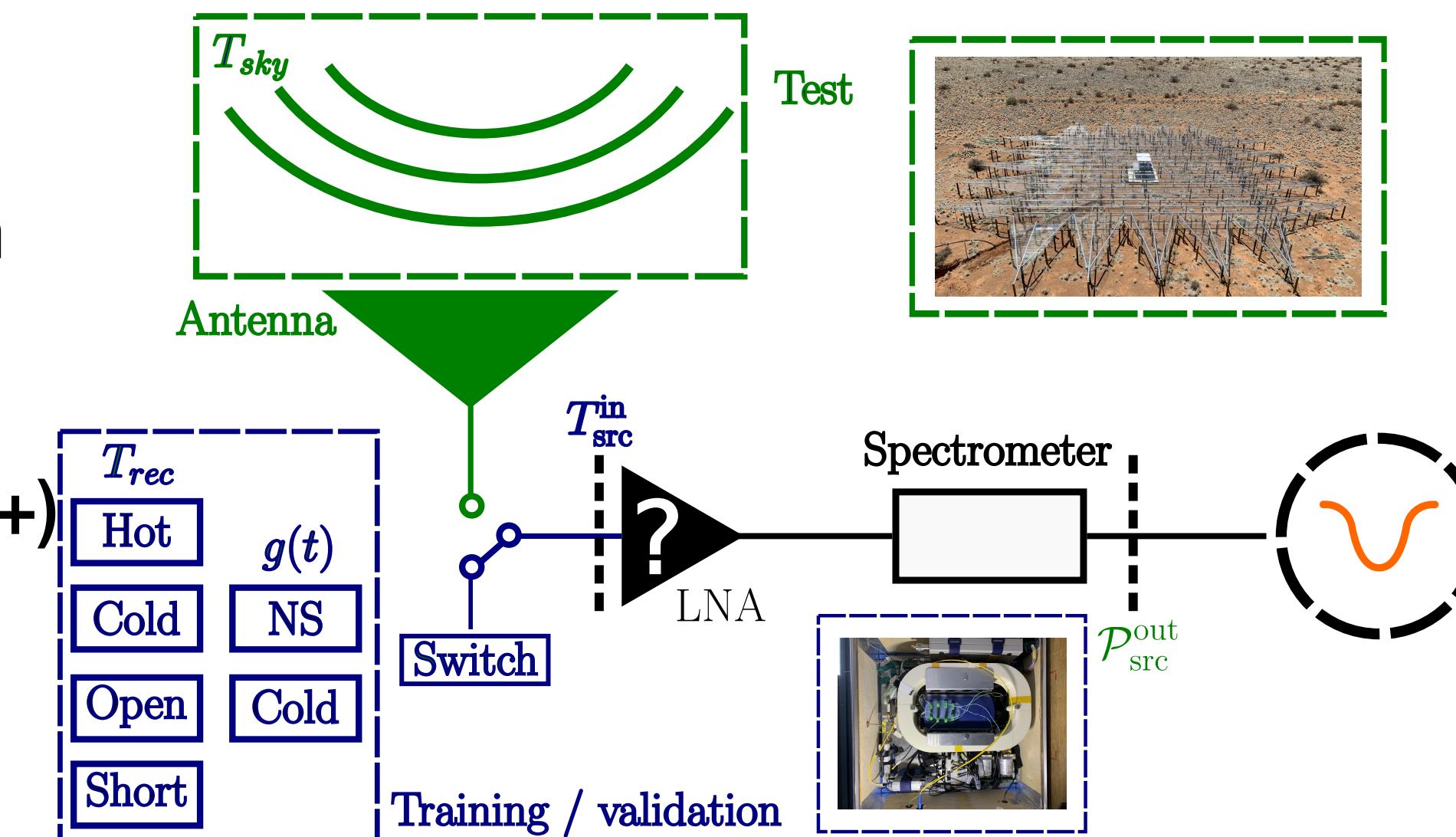
Solving the equations

- Two commonly used formalisms for T_{rec} known as noise waves (T_{\sin} , T_{\cos} , T_{unc} ; Meys 1978) and noise parameters (R_n , Γ_{opt} , T_{\min} ; Price+ 2023)

$$\begin{aligned} T_{\text{NS}} \left(\frac{P_{\text{source}} - P_L}{P_{\text{NS}} - P_L} \right) + T_L &= T_{\text{source}} \left[\frac{1 - |\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}|^2} \right] \\ &\quad + T_{\text{unc}} \left[\frac{|\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}|^2} \right] \\ &\quad + T_{\cos} \left[\frac{\text{Re} \left(\frac{\Gamma_{\text{source}}}{1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}} \right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}} \right] \\ &\quad + T_{\sin} \left[\frac{\text{Im} \left(\frac{\Gamma_{\text{source}}}{1 - \Gamma_{\text{source}} \Gamma_{\text{rec}}} \right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}} \right]. \end{aligned}$$

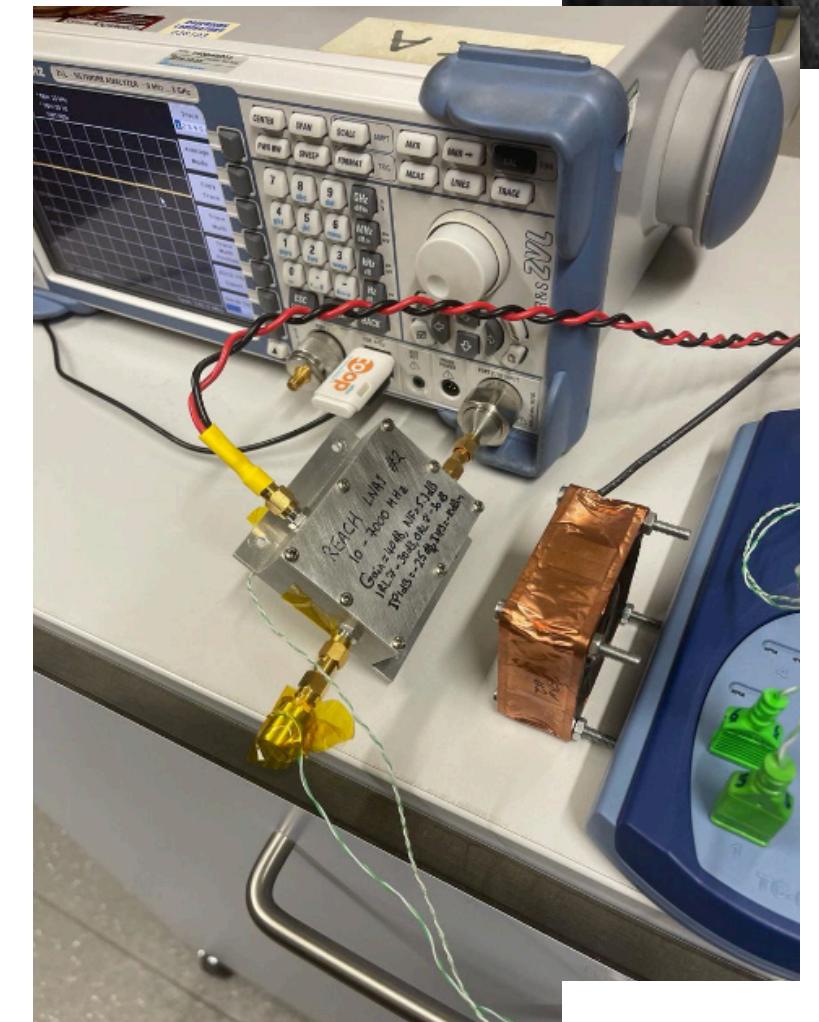


- In REACH we have been working on different methods to solve the properties of the system using both descriptions
- Using analytic descriptions and Bayesian methods (Ian Roque, Christian Kirkham+)
- And machine learning tools (Sam Leeney+)



Adjacent activities

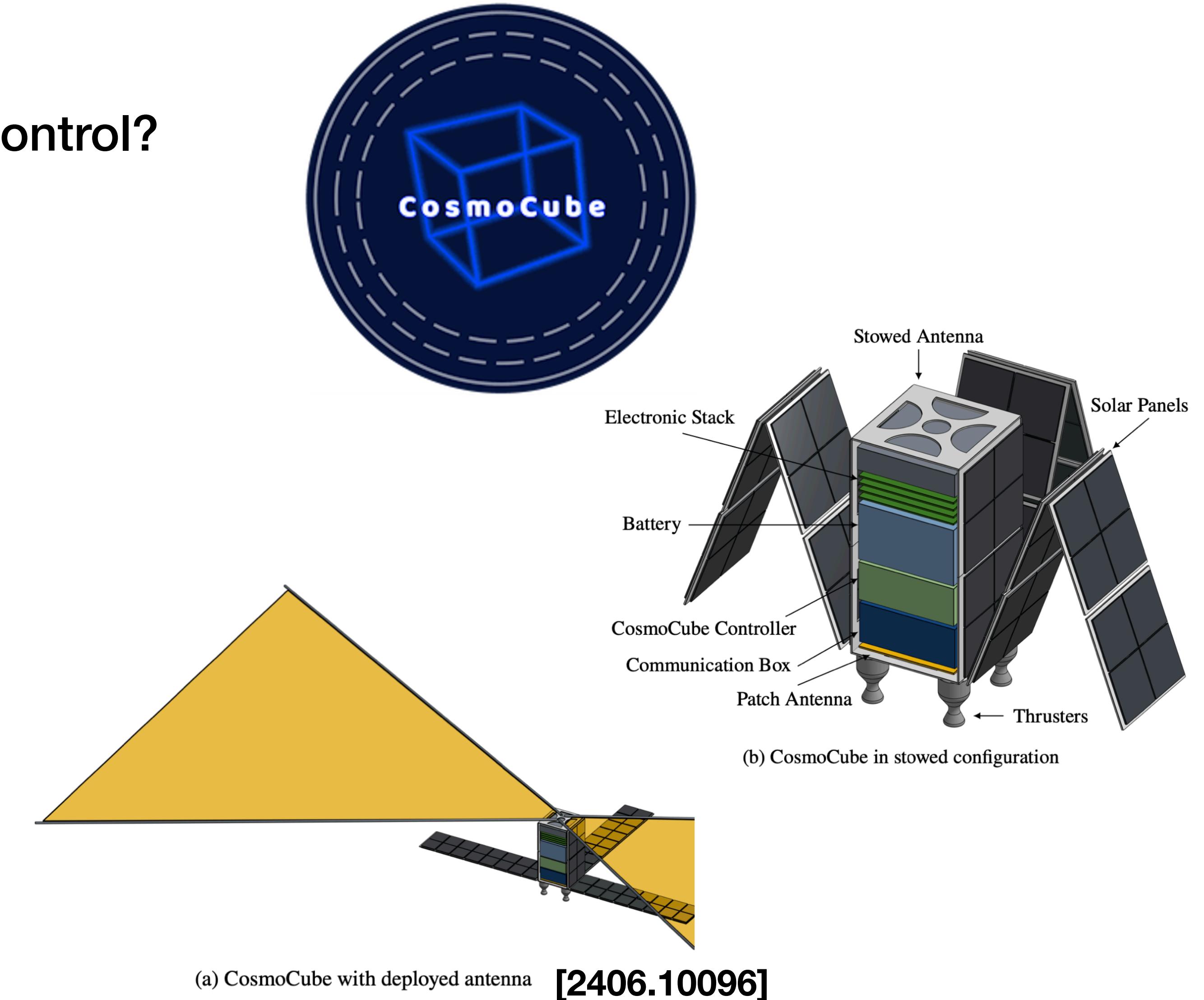
- Understanding observations and calibration techniques by building mock data sets (Kaan Artuc, Jiacong Zhu)
 - Increasing complexity and lab based observations
- Working on understanding how our calibration solutions change with bandwidth (Saswata Dasgupta)
 - Utilising data in the presence of systematics
- De embedding measurements of the components in the system with detailed modelling (Saurabh Pegwal and Dirk de Villiers)
- Maths from first principles (Dominic Anstey+)



Calibrating CosmoCube?

CosmoCube?

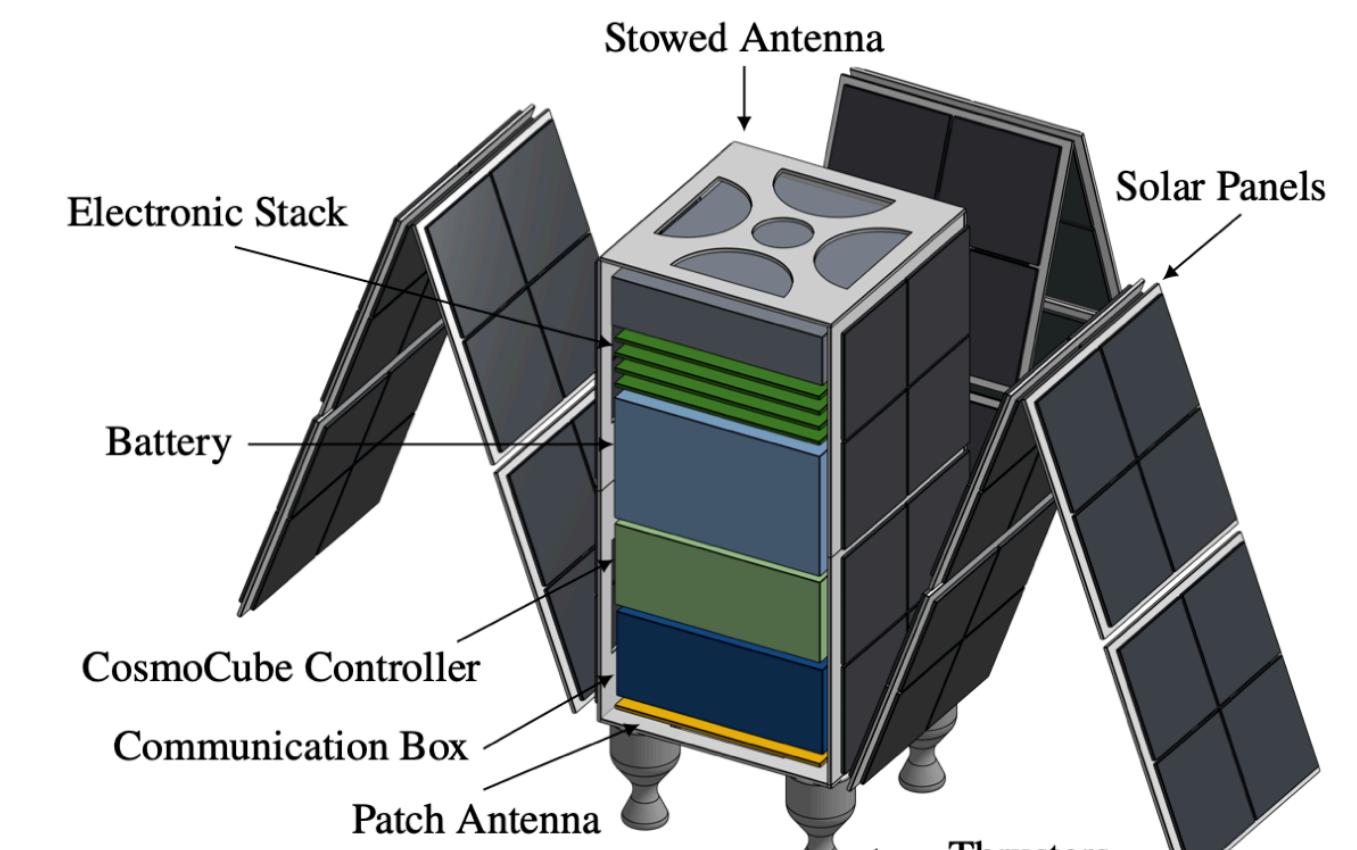
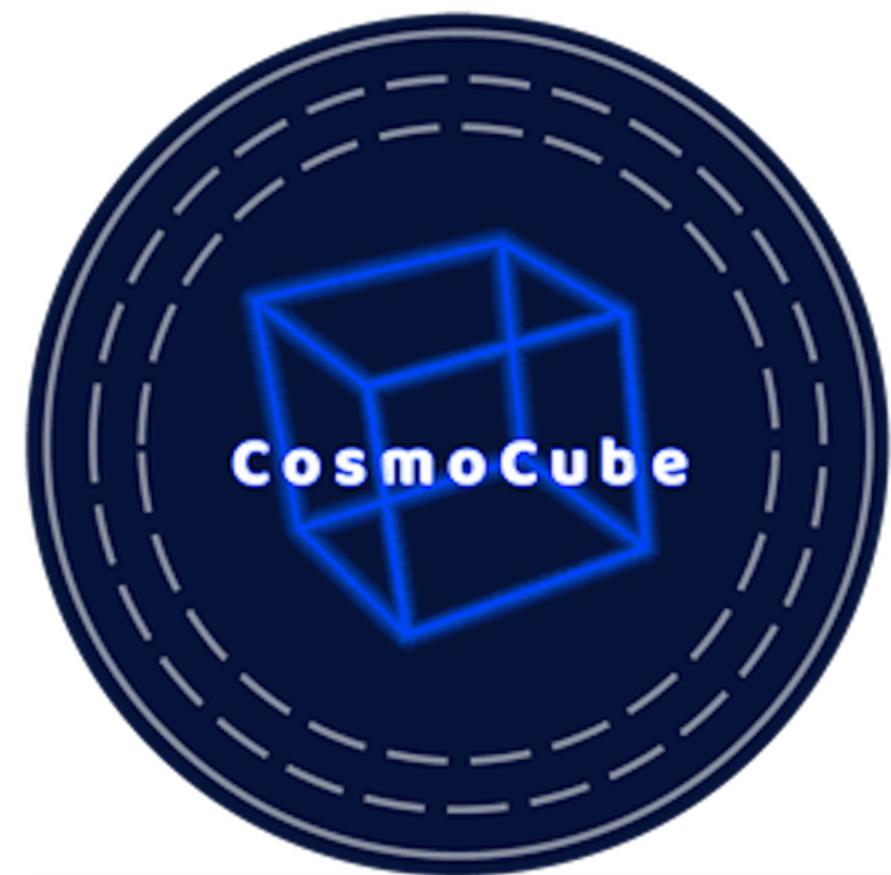
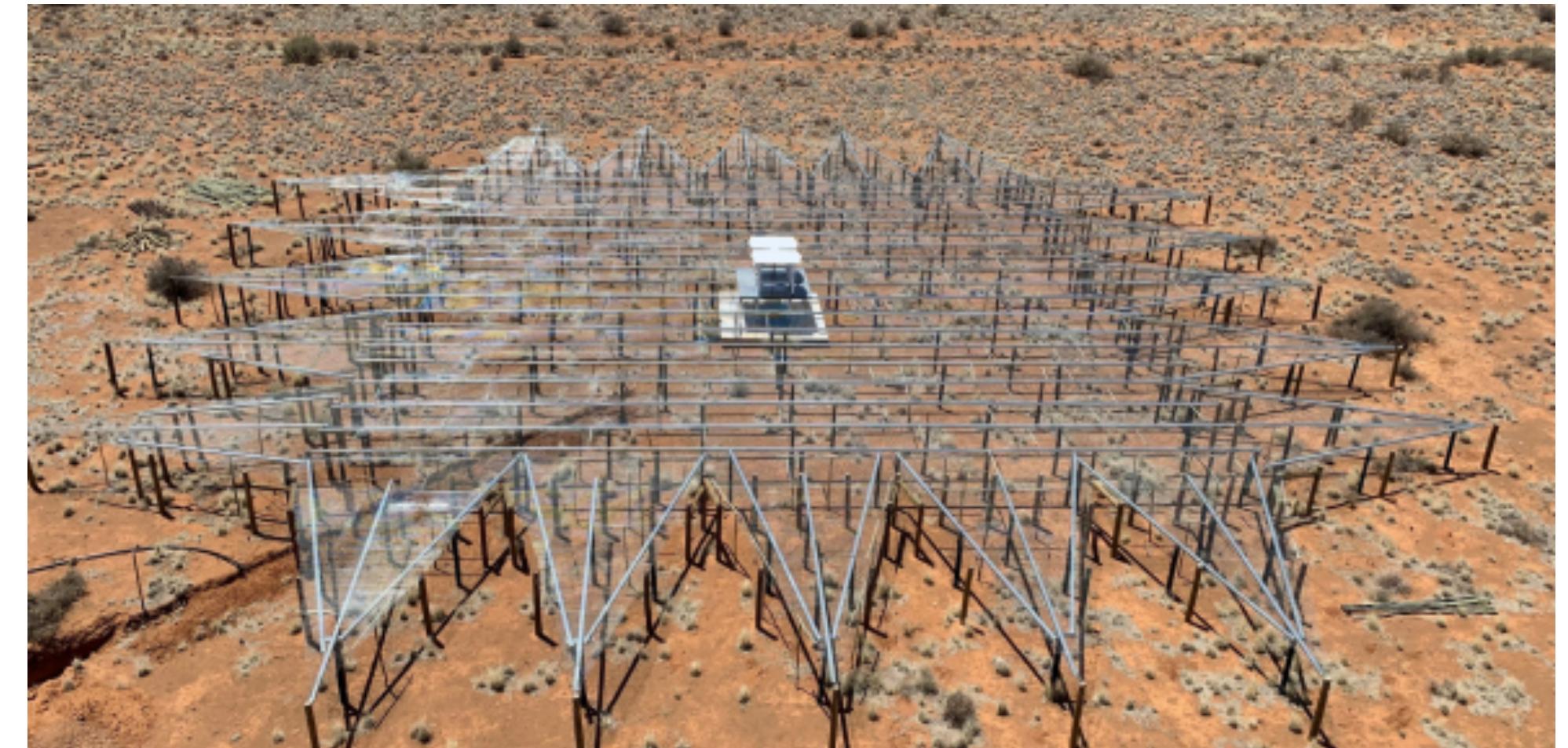
- Environment stability? And thermal control?
- Space restrictions?
- Optimal set of calibrators?
- Signal even smaller and foregrounds brighter!
- Unable to go and fix it! Need more redundancy



Conclusions

Conclusions

- Accurate calibration of our instruments is crucial for 21cm Cosmology
- We have a lot of expertise in REACH both on designing receivers and developing calibration algorithms
- Work being driven by PhD students and postdocs
- Space brings a whole host of new challenges that have to be addressed



(b) CosmoCube in stowed configuration