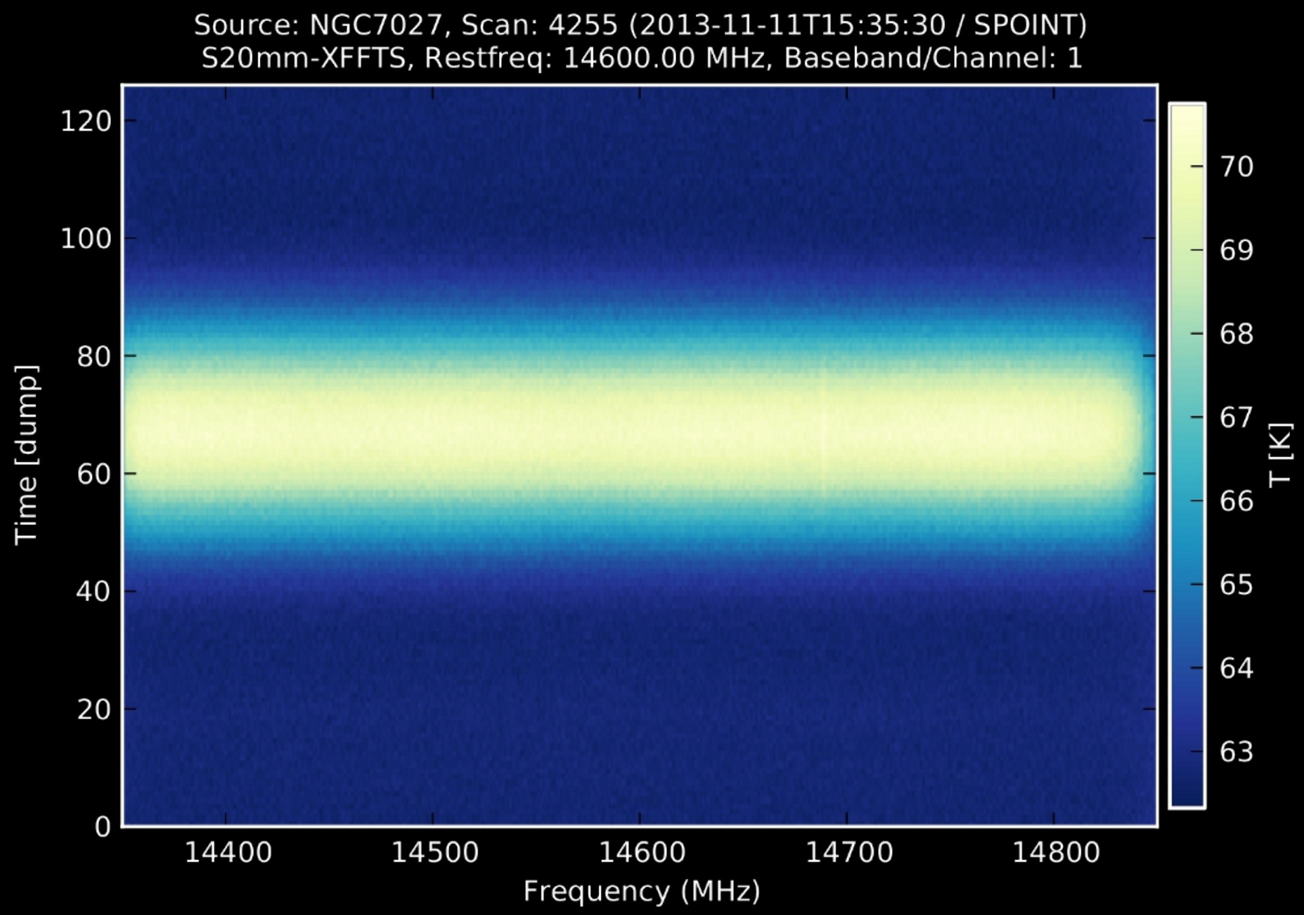
Broadband calibration for Single-dish radio telescopes

Max-Planck-Institut für Radioastronomie

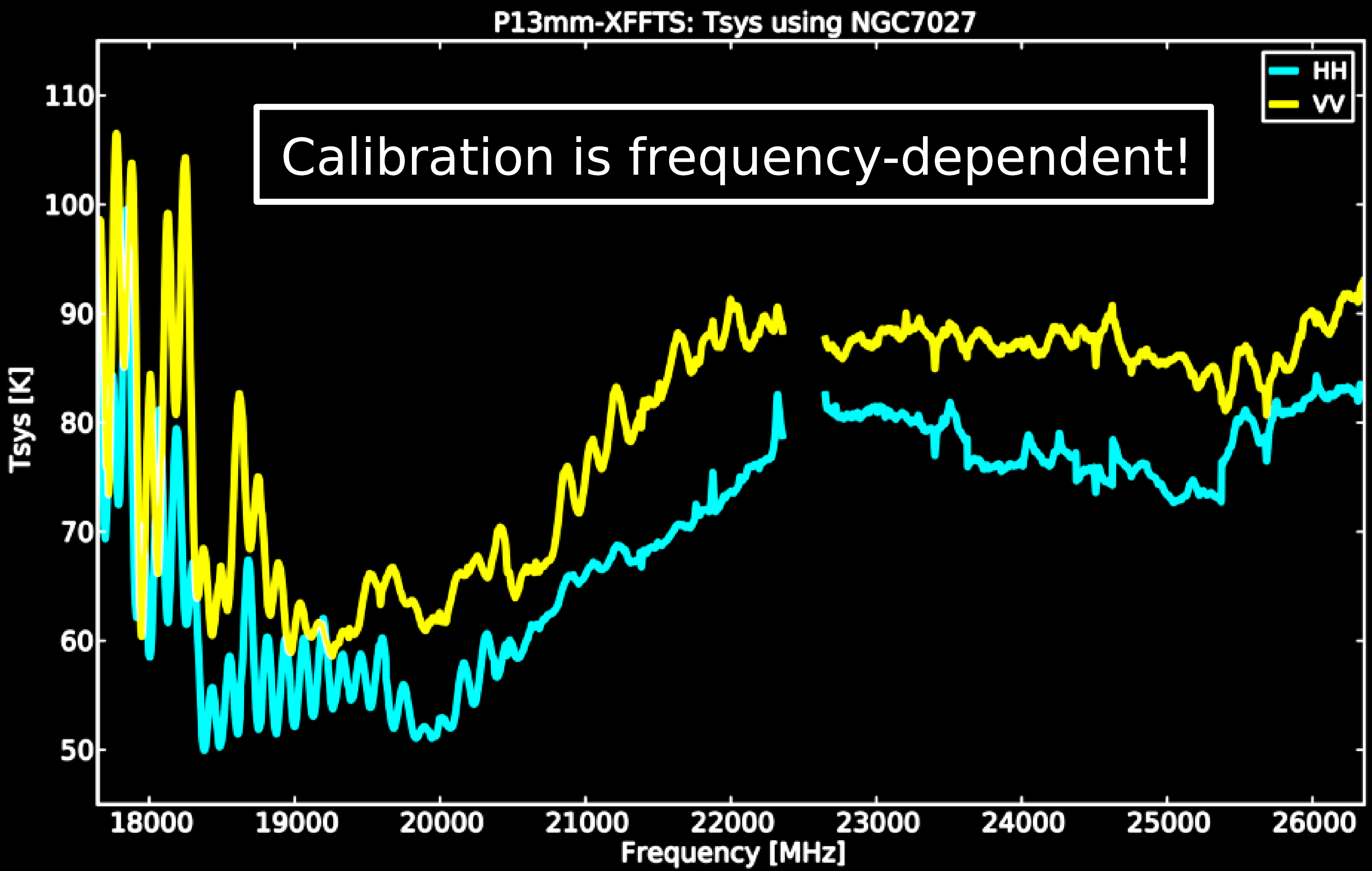


Benjamin Winkel
Alex Kraus
Uwe Bach

Effelsberg: going broadband

- New receivers:
  - UBB (0.6 – 3.0 GHz)
  - C+ (4 – 9.3 GHz)
  - Ku (12 – 18 GHz)
  - K (18 – 26 GHz)
  - Q (33 – 50 GHz)
- New Backends:
  - 64k FFTS
  - Stacking: 1+M

Effelsberg: going broadband



Overview

- Motivation
- Introduction (continuum calibration)
- Spectroscopy calibration
  - Classic
  - Unbiased
- Conclusion / Outlook

Intro: fundamental equation

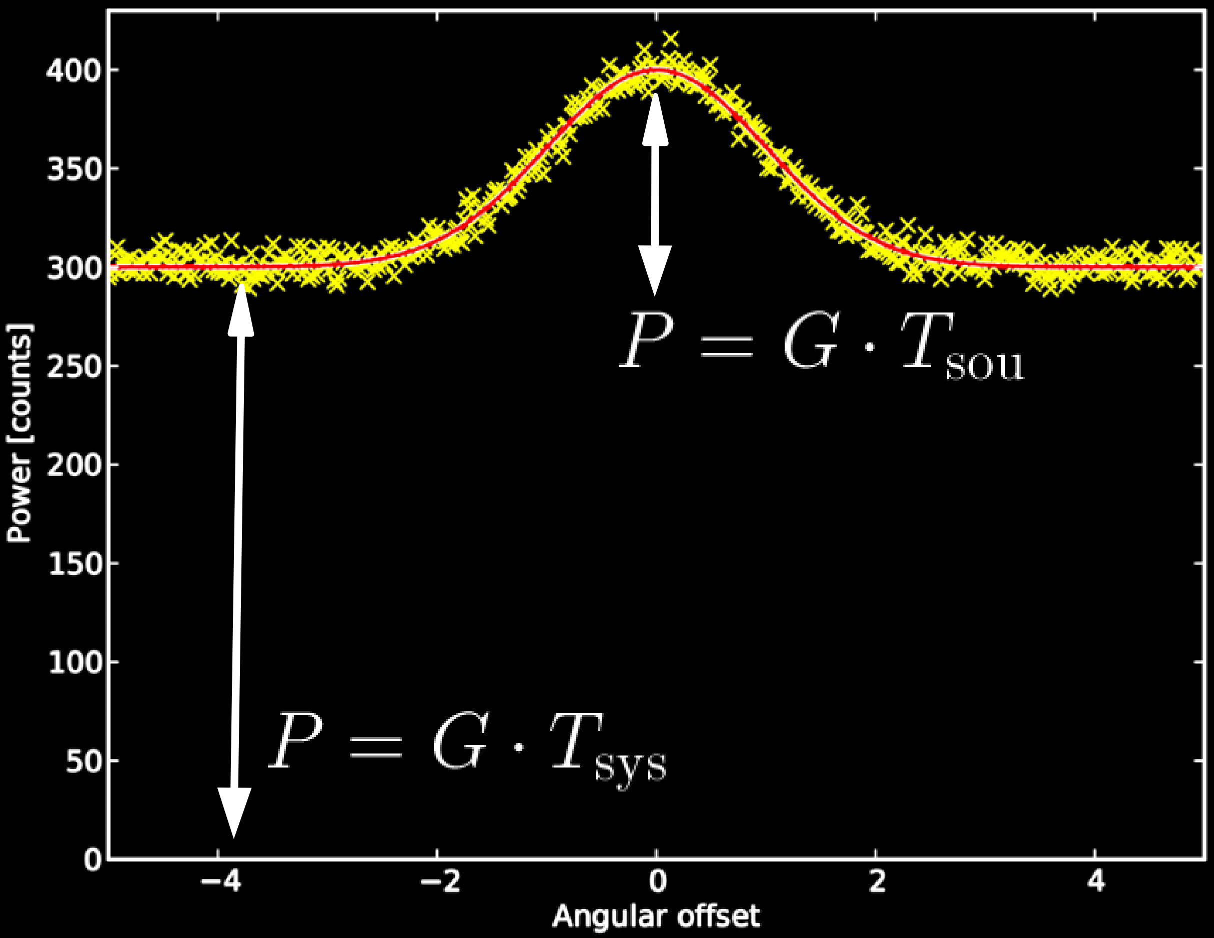
$$P[\mathrm{counts}] = G[\mathrm{counts/K}] \cdot (T_{\mathrm{sou}}[\mathrm{K}] + T_{\mathrm{sys}}[\mathrm{K}])$$

Intro: fundamental equation

$$P[\mathrm{counts}] = G[\mathrm{counts}/\mathrm{K}] \cdot (T_{\mathrm{sou}}[\mathrm{K}] + T_{\mathrm{sys}}[\mathrm{K}])$$

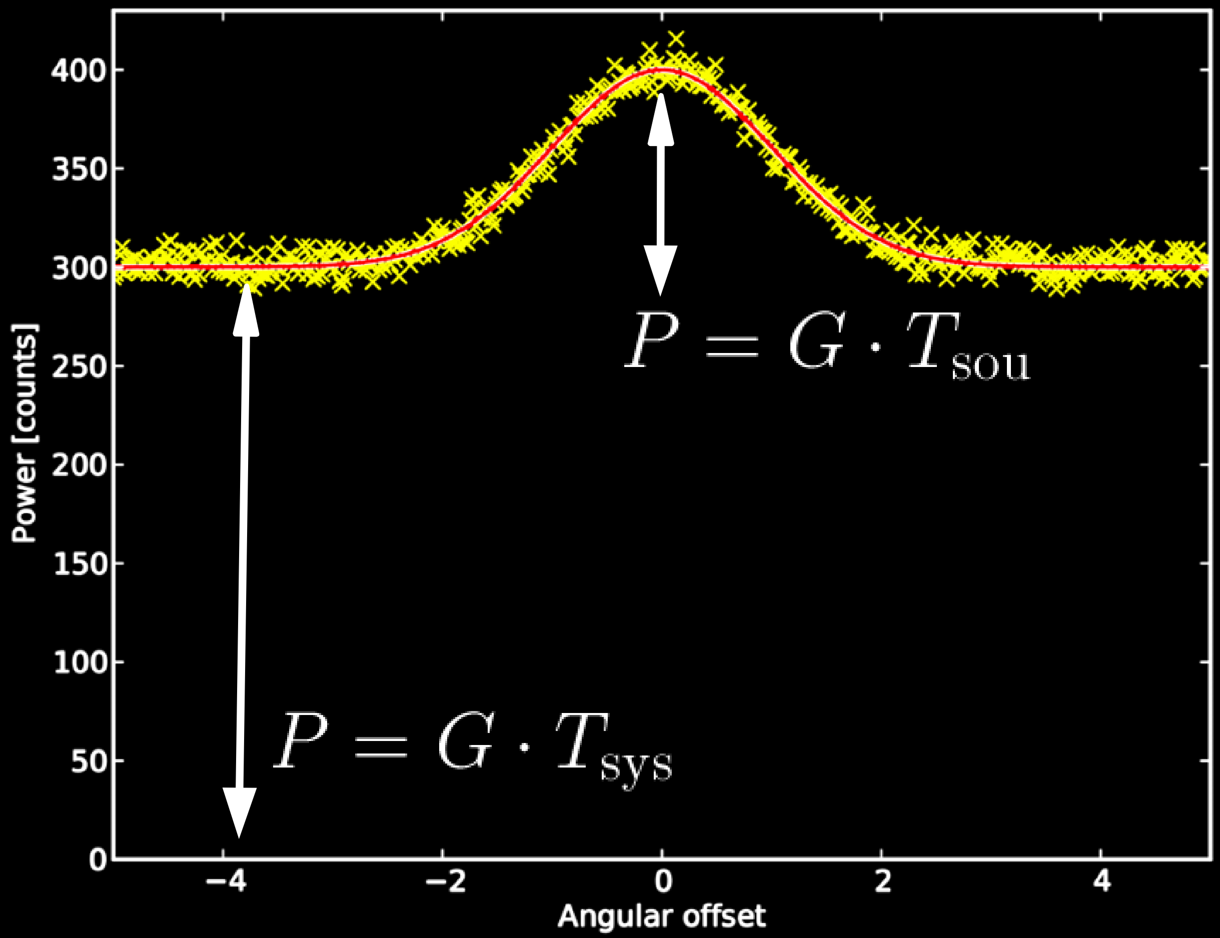
Calibrating a system means to determine G

Intro: continuum calibration



- Use known source (aka “calibrator”) to infer G

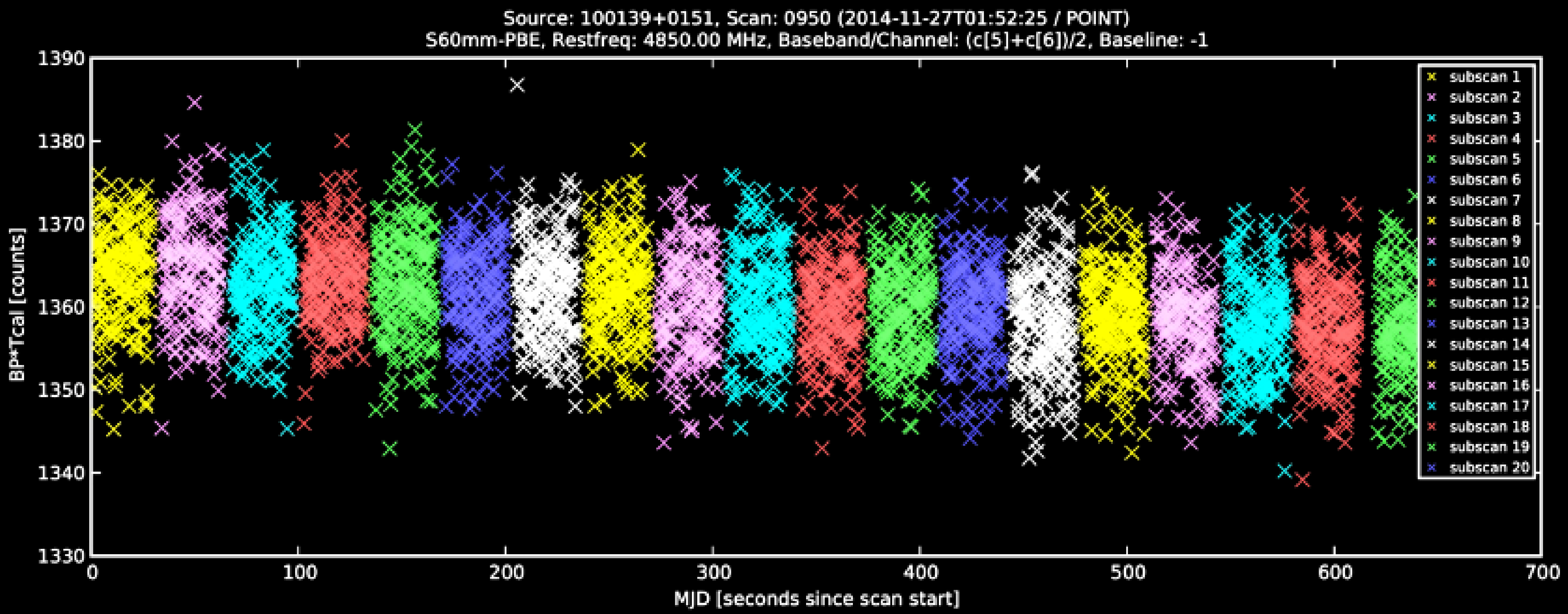
Intro: continuum calibration



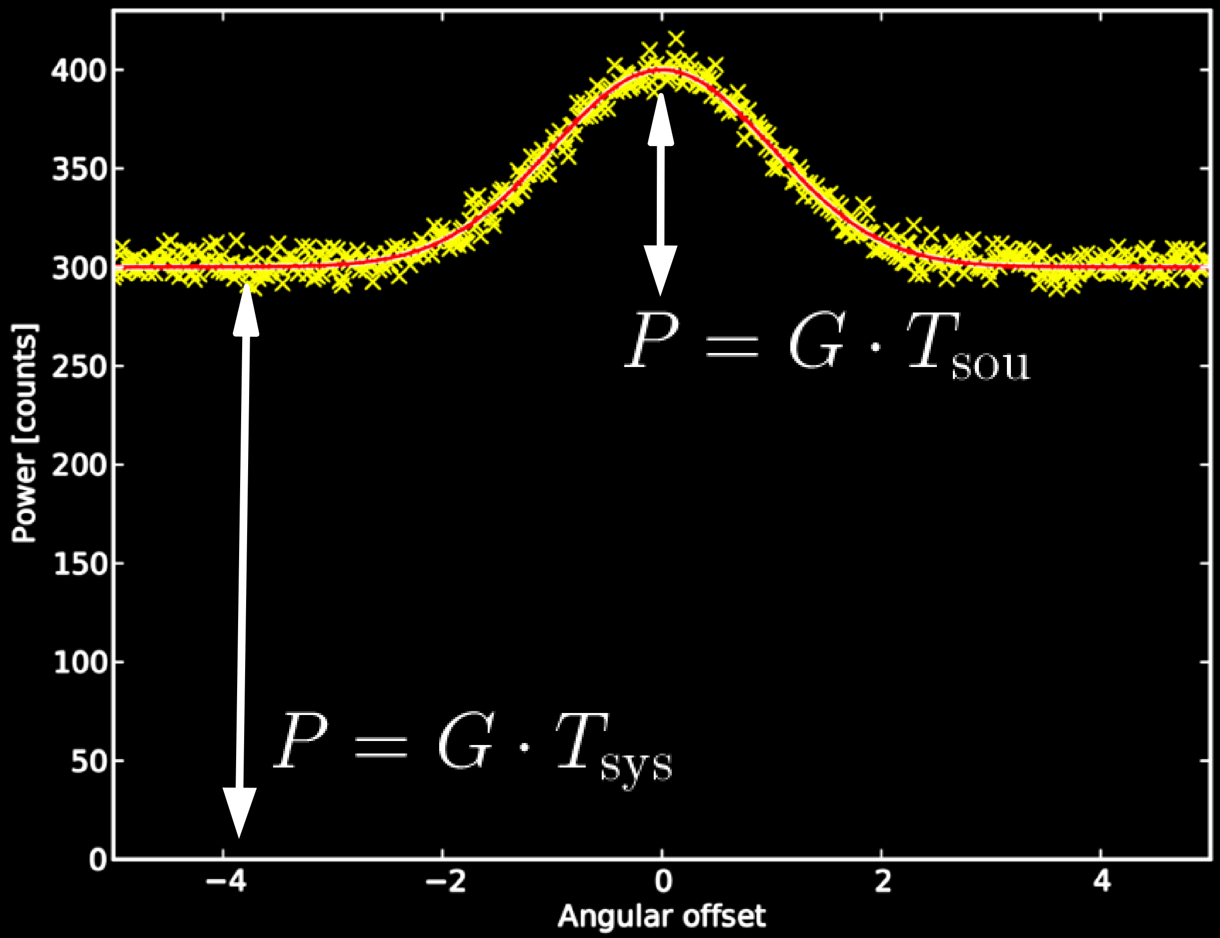
- Use known source (aka “calibrator”) to infer G
- Problem: G is not perfectly stable

Intro: continuum calibration

Gain variations

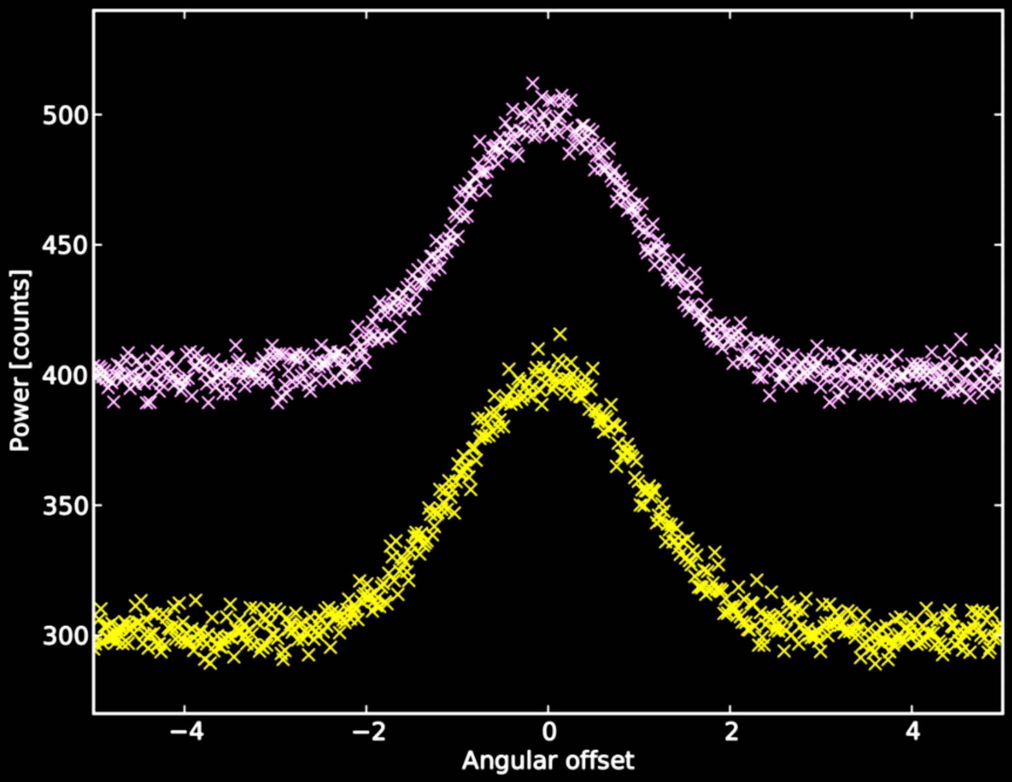


Intro: continuum calibration



- Use known source (aka "calibrator") to infer G
- Problem: G is not perfectly stable
- Solution: use a stable reference → Noise diode (T_{cal})

Solution: use a noise diode



We now have

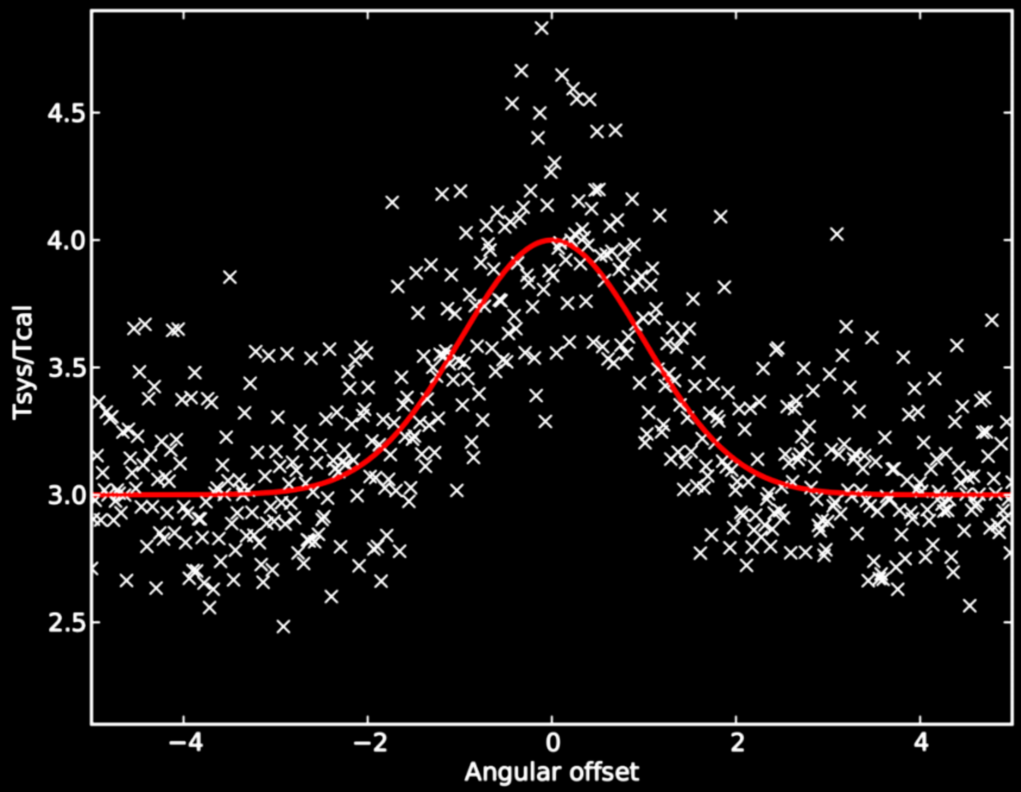
$$P = G \cdot (T_{\rm sou} + T_{\rm sys})$$

$$P^{\rm cal} = G \cdot (T_{\rm sou} + T_{\rm sys} + T_{\rm cal})$$

It follows

$$\frac{T_{\rm sys} + T_{\rm sou}}{T_{\rm cal}} = \frac{P}{P^{\rm cal} - P}$$

Intro: using a noise diode



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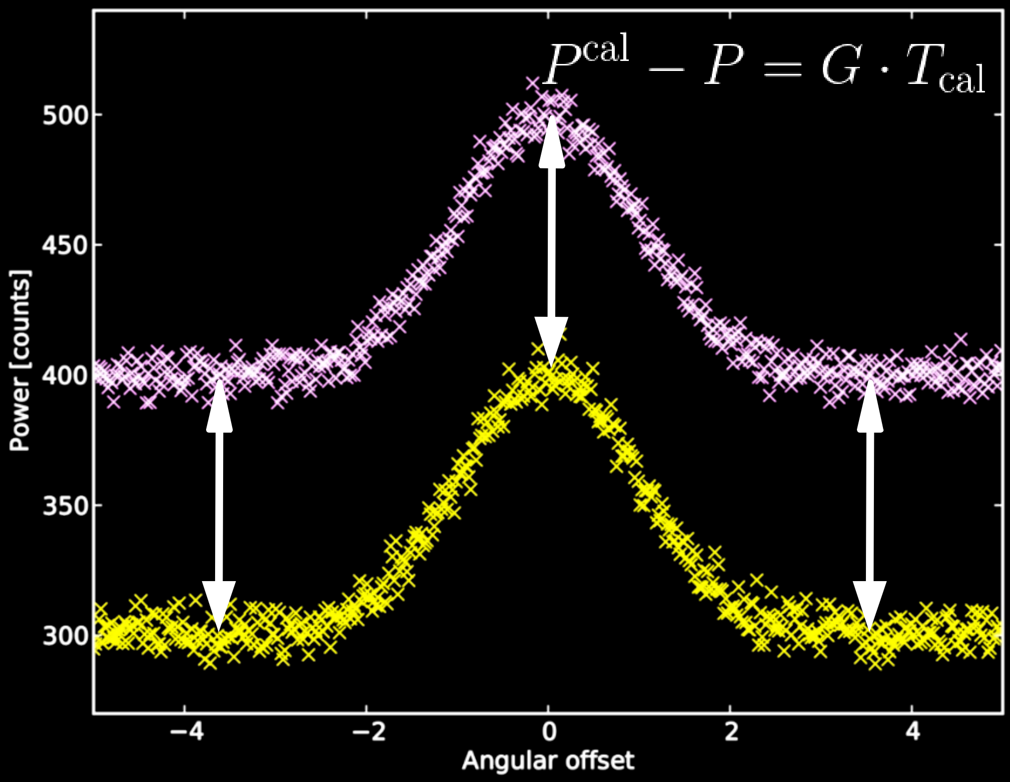
It follows

$$\frac{T_{\rm sys} + T_{\rm sou}}{T_{\rm cal}} = \frac{P}{P^{\rm cal} - P}$$

This is really noisy, because

$$P^{\rm cal} - P \ll P$$

Solution: use a noise diode



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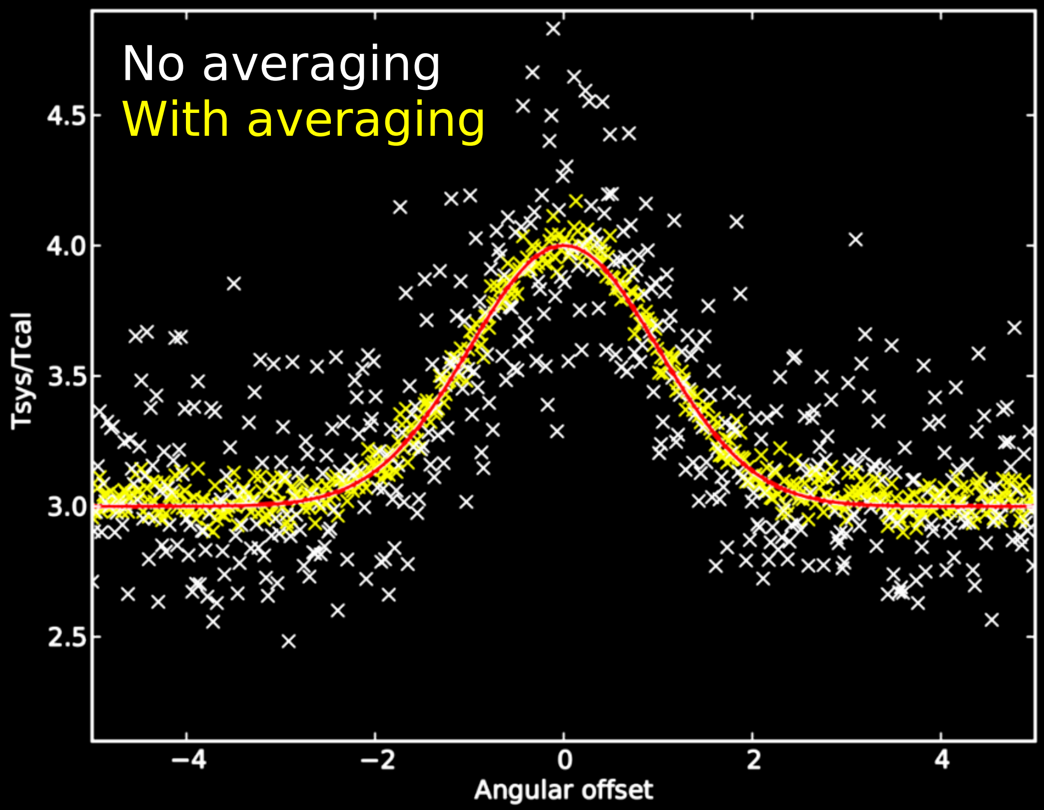
It follows

$$\frac{T_{\mathrm{sys}} + T_{\mathrm{sou}}}{T_{\mathrm{cal}}} = \frac{P}{P^{\mathrm{cal}} - P}$$

Intro: noise diode + gain model



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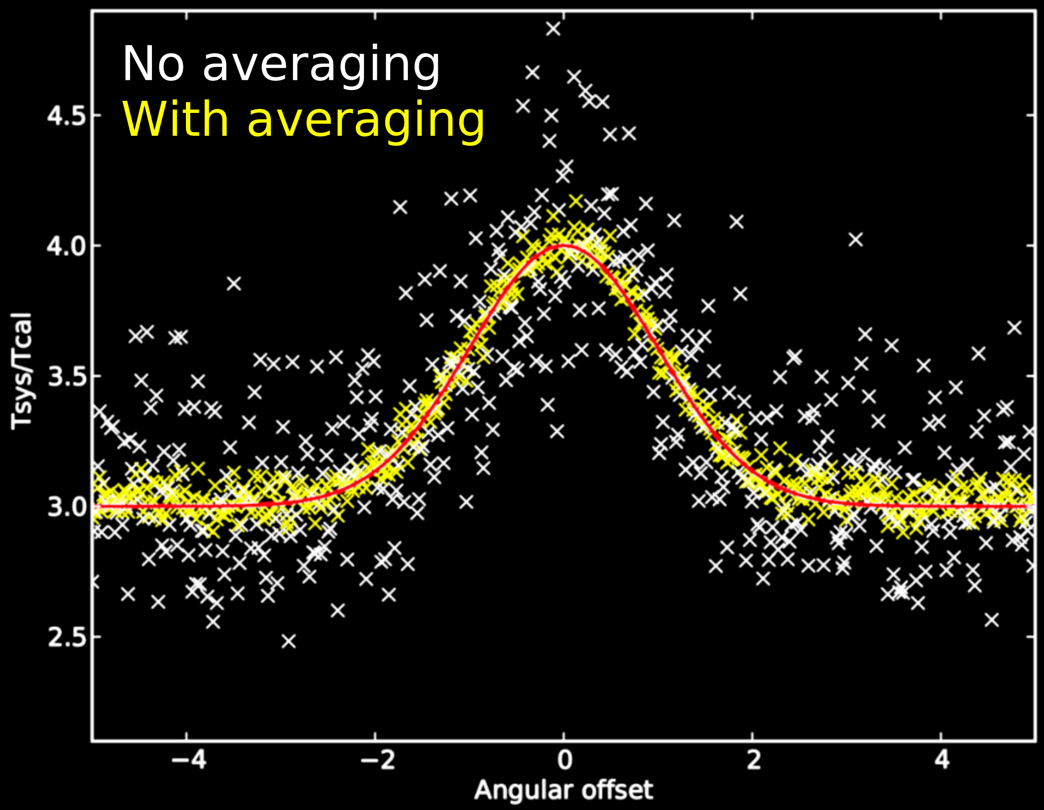
$$\frac{T_{\rm sys} + T_{\rm sou}}{T_{\rm cal}} = \frac{P}{G \cdot T_{\rm cal}}$$

.

Intro: noise diode + gain model



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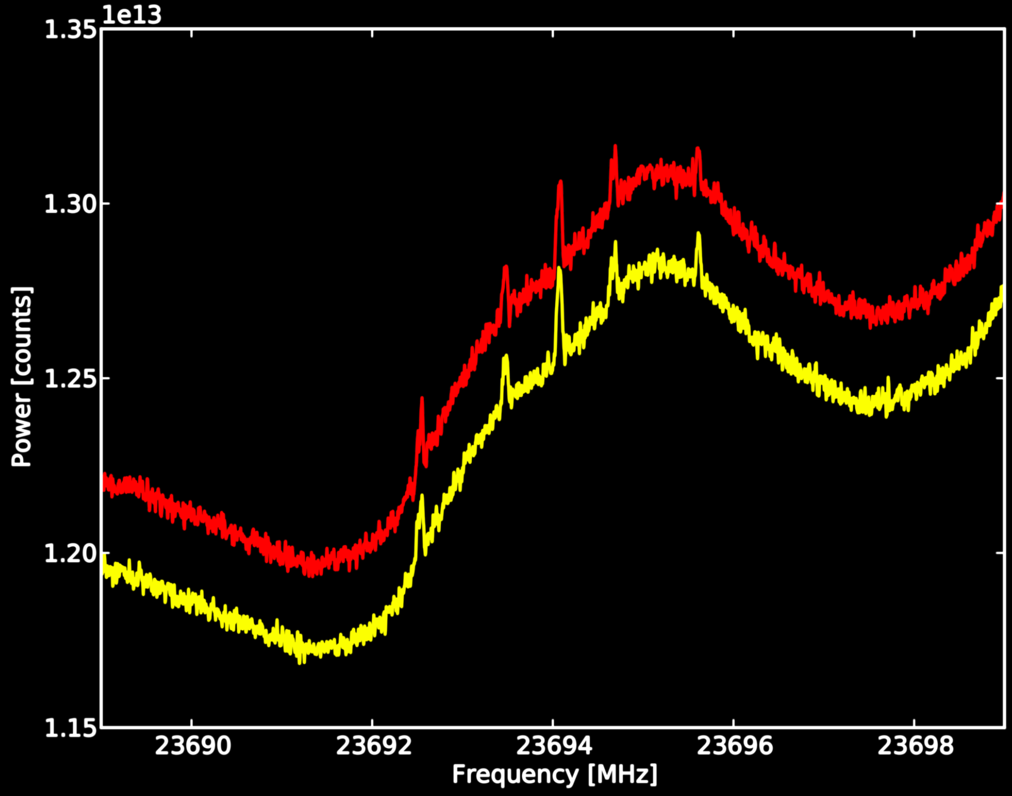
$$\frac{T_{\mathrm{sys}} + T_{\mathrm{sou}}}{T_{\mathrm{cal}}} = \frac{P}{G \cdot T_{\mathrm{cal}}}$$

.

We still need to use a calibration source to infer T_{cal}!

Spectroscopy: basics



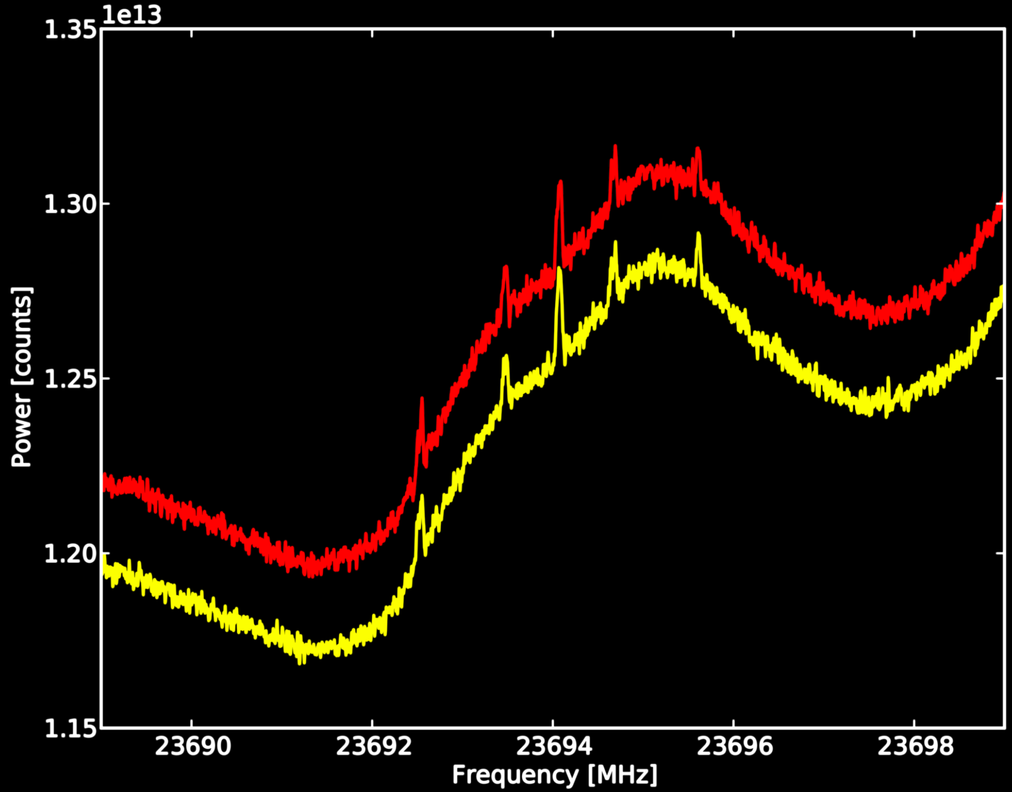
Again we have

$$P = G \cdot (T_{\rm sou} + T_{\rm sys})$$

$$P^{\rm cal} = G \cdot (T_{\rm sou} + T_{\rm sys} + T_{\rm cal})$$

But now everything is a function of frequency

Spectroscopy: basics



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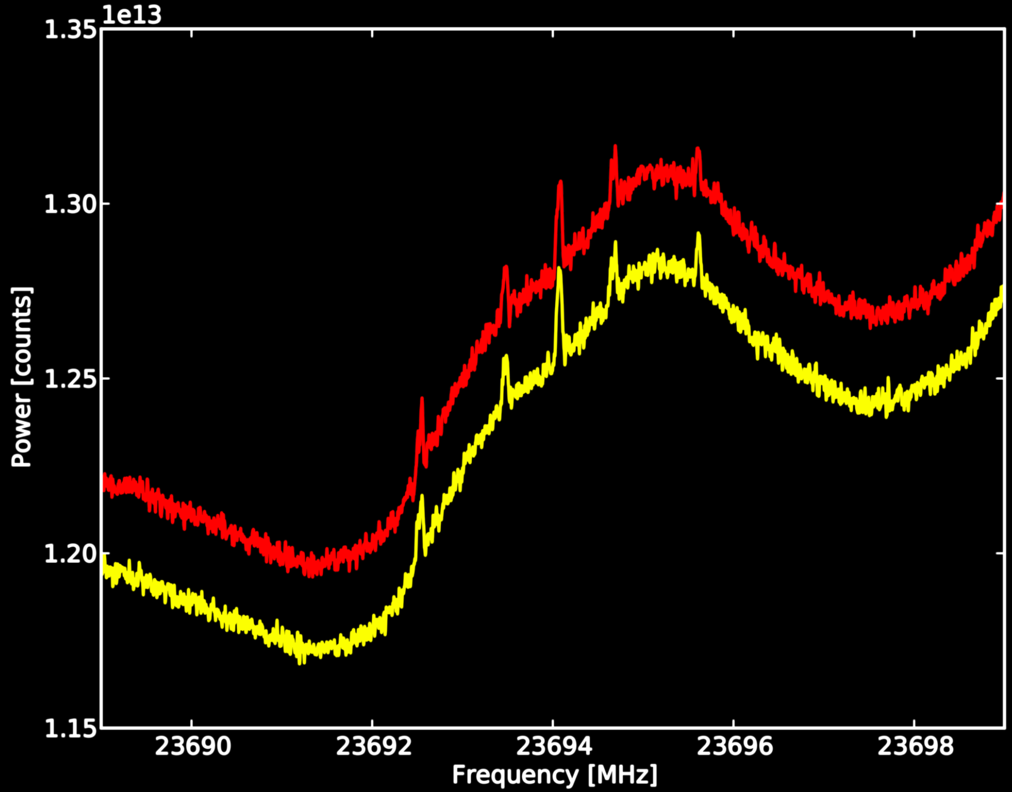
But now everything is a function of frequency

Idea:
Calibrate each spectral channel independently

(using the same method as before)

Spectroscopy: basics



Again we have

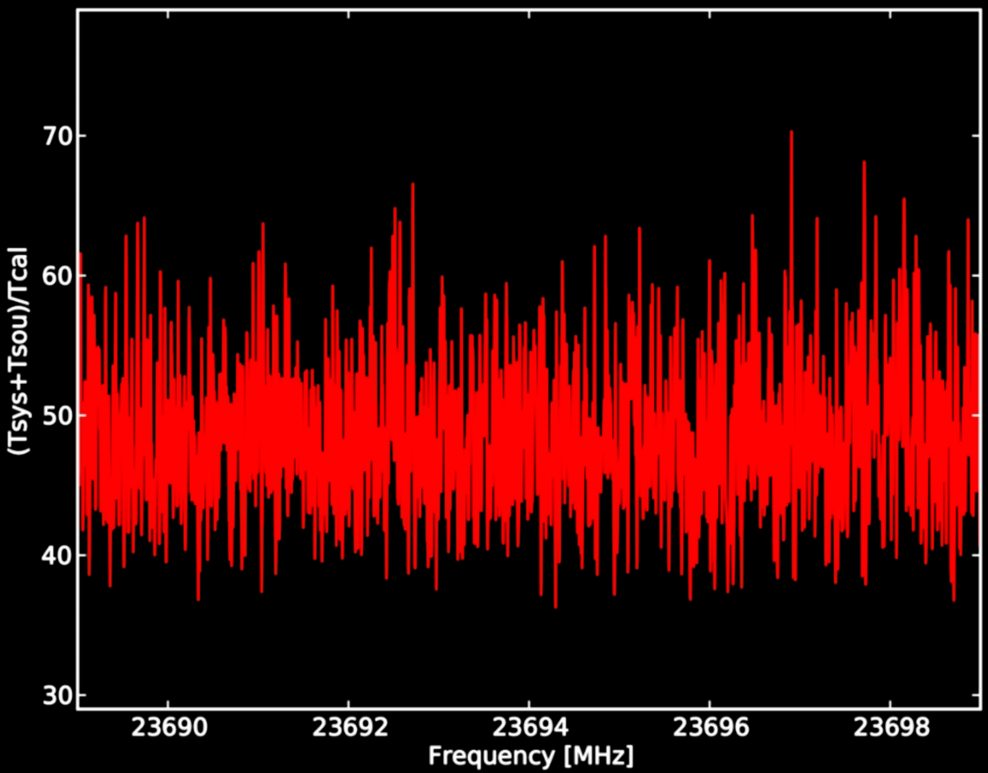
$$P = G \cdot (T_{\text{sou}} + T_{\text{sys}})$$

$$P^{\text{cal}} = G \cdot (T_{\text{sou}} + T_{\text{sys}} + T_{\text{cal}})$$

As before, but vectorized

$$\frac{T_{\text{sys}} + T_{\text{sou}}}{T_{\text{cal}}} = \frac{P}{P^{\text{cal}} - P}$$

Spectroscopy: basics



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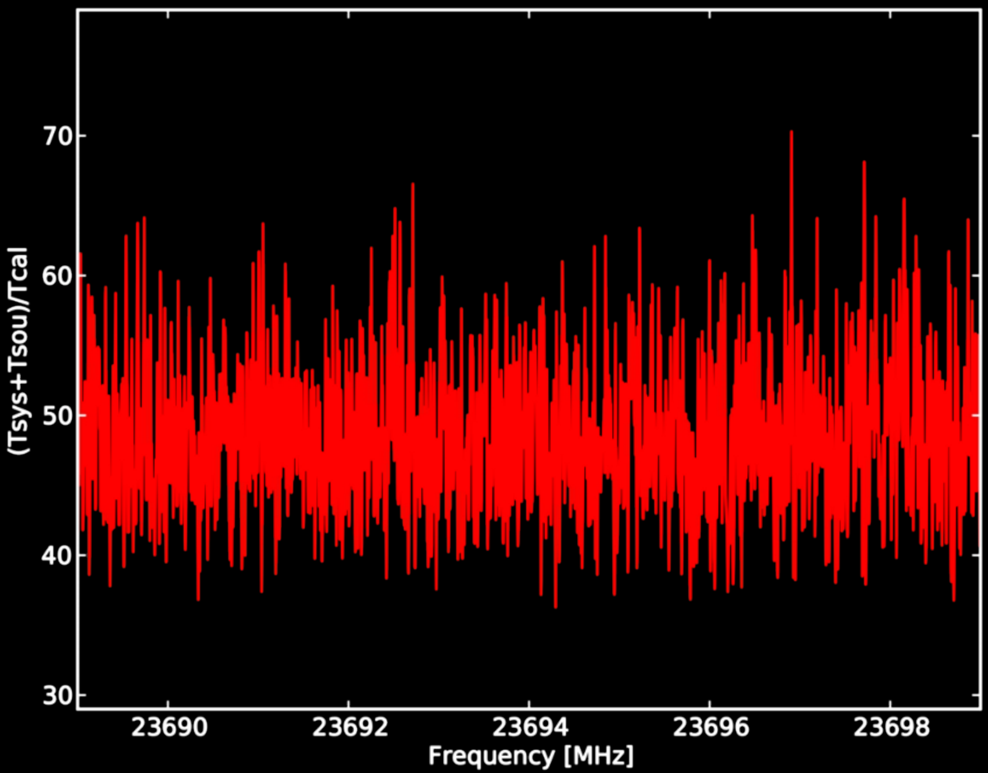
Spectroscopy: basics



Again we have

$$P = G \cdot (T_{\rm sou} + T_{\rm sys})$$

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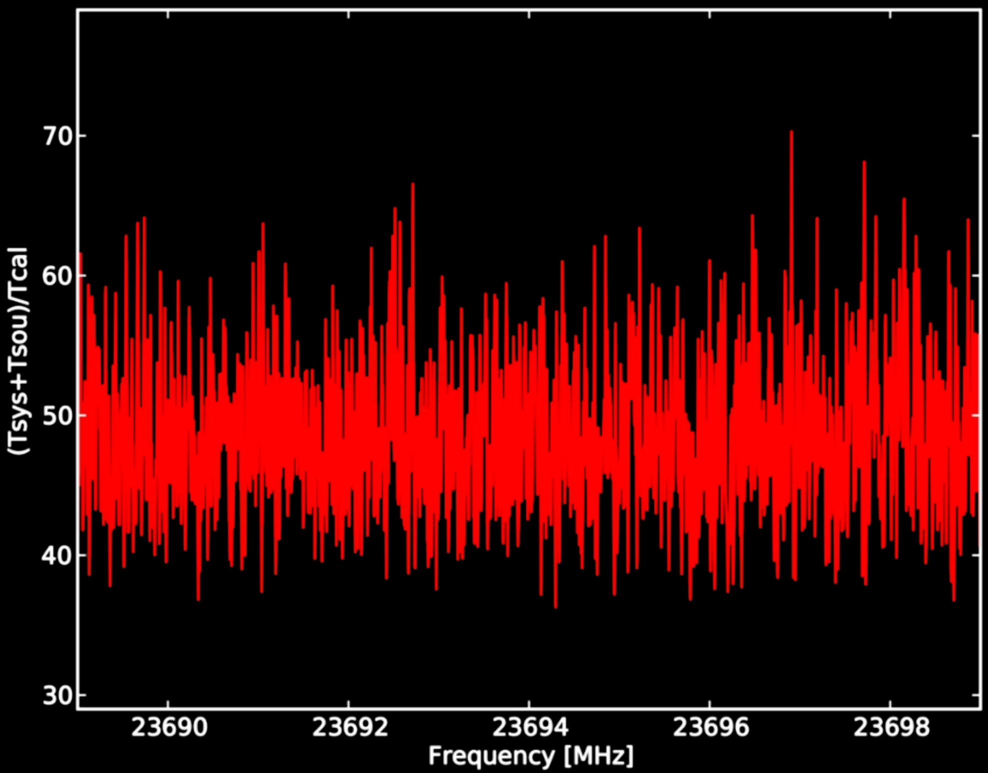
As before, but vectorized

$$\frac{T_{\rm sys} + T_{\rm sou}}{T_{\rm cal}} = \frac{P}{P^{\rm cal} - P}$$

Denominator is too small
→ numerically unstable

Spectroscopy: basics



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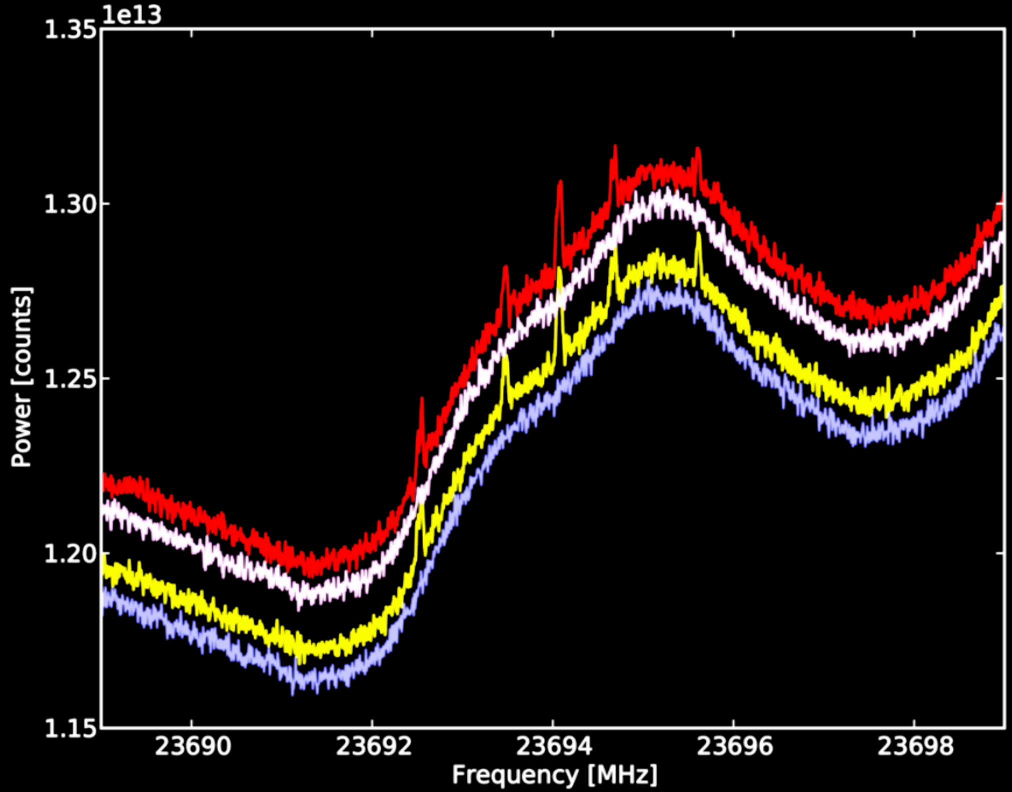
As before, but vectorized

$$\frac{T_{\rm sys} + T_{\rm sou}}{T_{\rm cal}} = \frac{P}{P^{\rm cal} - P}$$

Average in time? → only possible if G is very stable
(long integration periods needed, because of small bandwidth per channel)

Average in frequency? → only possible if G is very flat
(usually not the case, especially not for ultra-wideband systems)

Spectroscopy: position switching

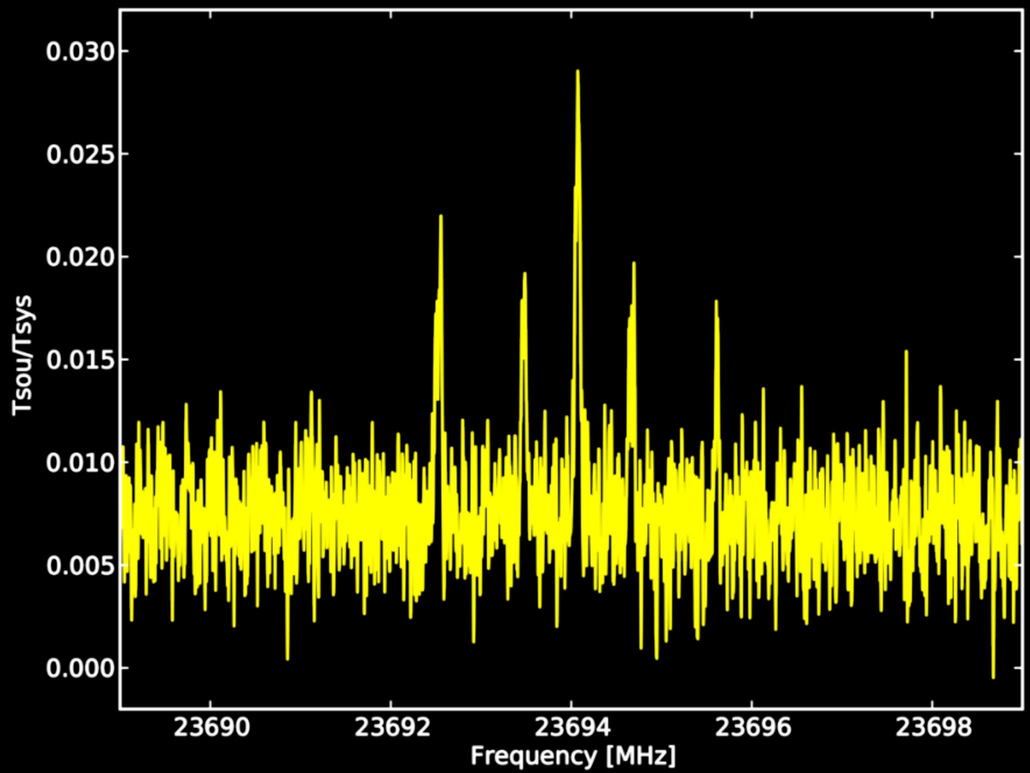


Observe ON and OFF-source

$$P_{\rm on} = G \cdot (T_{\rm sou} + T_{\rm sys})$$

$$P_{\rm off} = G \cdot (T_{\rm sys})$$

Spectroscopy: position switching



Observe ON and OFF-source

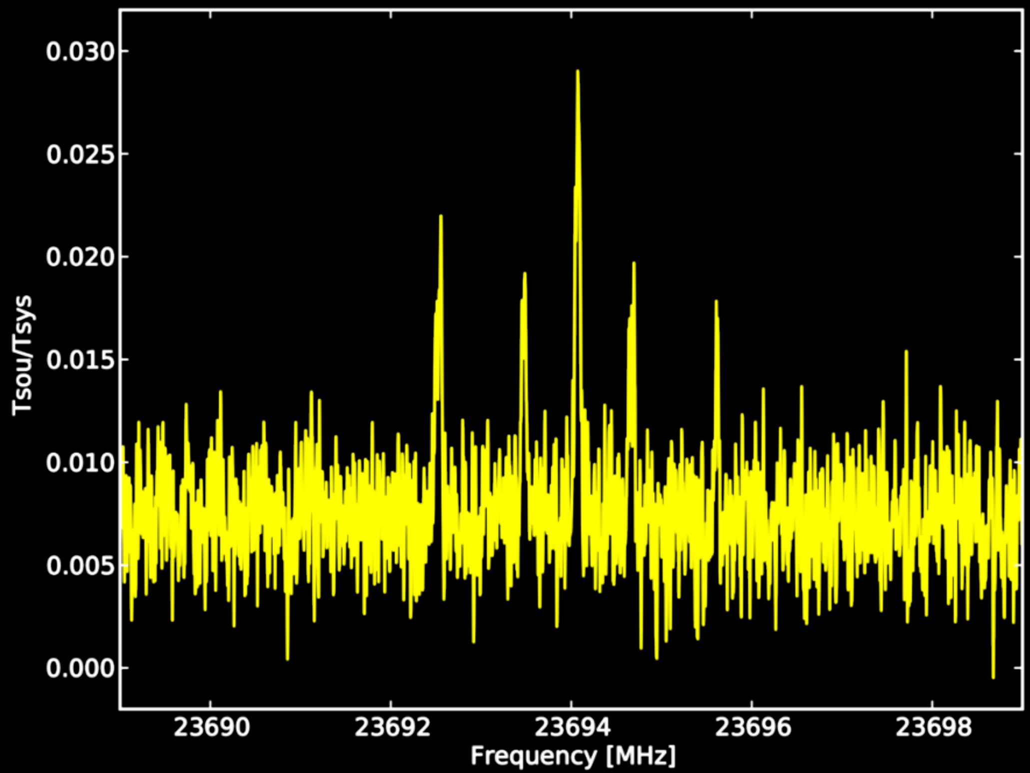
$$P_{\text{on}} = G \cdot (T_{\text{sou}} + T_{\text{sys}})$$

$$P_{\text{off}} = G \cdot (T_{\text{sys}})$$

It follows

$$\frac{T_{\text{sou}}}{T_{\text{sys}}} = \frac{P_{\text{on}} - P_{\text{off}}}{P_{\text{off}}}$$

Spectroscopy: position switching



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$$P_{\mathrm{on}} = G \cdot (T_{\mathrm{sou}} + T_{\mathrm{sys}})$$

$$P_{\mathrm{off}} = G \cdot (T_{\mathrm{sys}})$$

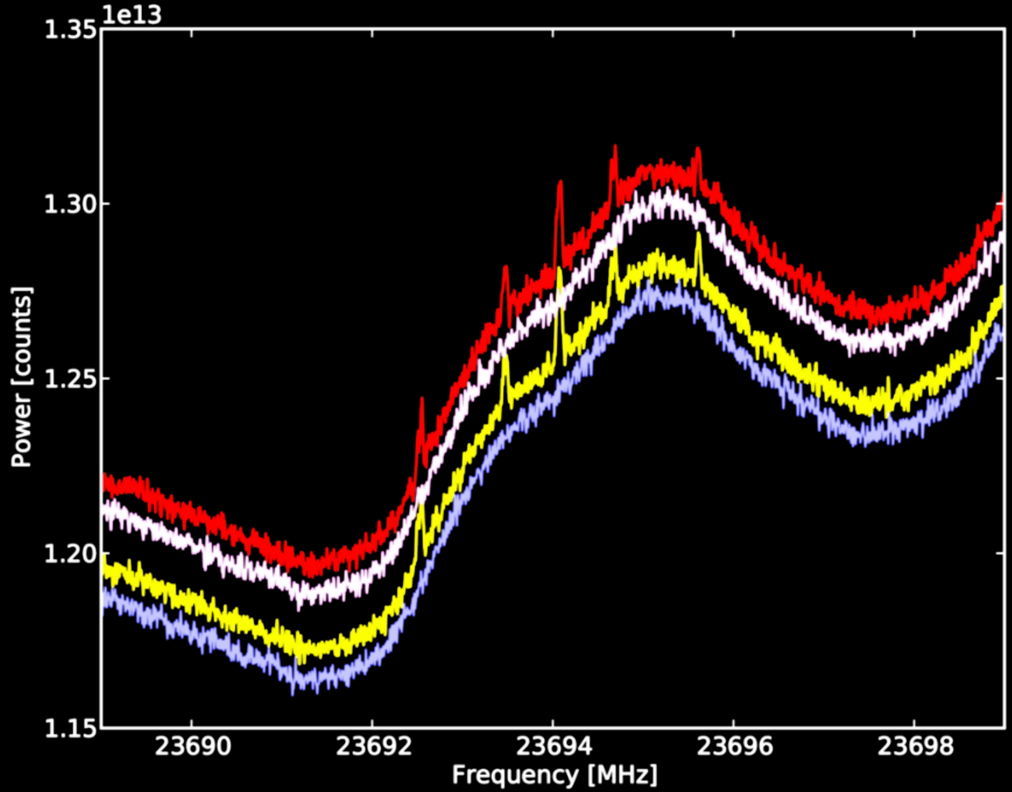
It follows

$$\frac{T_{\mathrm{sou}}}{T_{\mathrm{sys}}} = \frac{P_{\mathrm{on}} - P_{\mathrm{off}}}{P_{\mathrm{off}}}$$

But: T_{sys} depends on time and frequency

→ need to relate this to T_{cal} again

Spectroscopy: inferring T_{sys}



Observe ON and OFF-source

$$P_{\text{on}} = G \cdot (T_{\text{sou}} + T_{\text{sys}})$$
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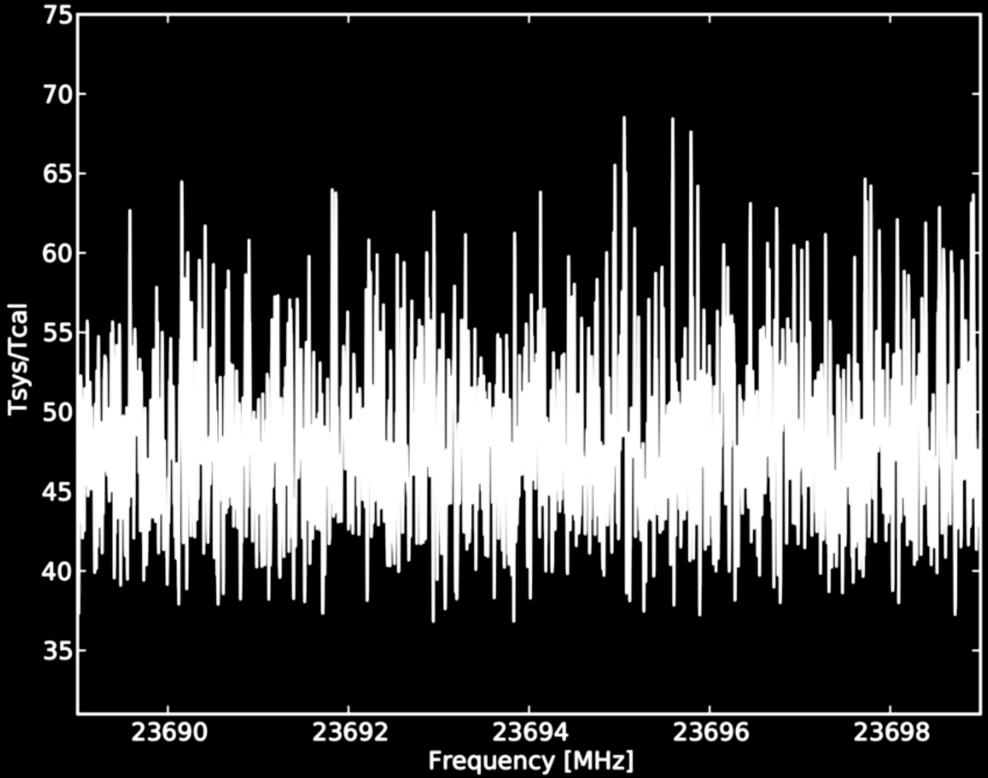
$$P_{\text{off}} = G \cdot (T_{\text{sys}})$$
$$P_{\text{off}}^{\text{cal}} = G \cdot (T_{\text{sys}} + T_{\text{cal}})$$

Compute

$$\frac{T_{\text{sys}}}{T_{\text{cal}}} = \frac{P_{\text{off}}}{P_{\text{off}}^{\text{cal}} - P_{\text{off}}}$$

Spectroscopy: inferring T$_{sys}$



Observe ON and OFF-source

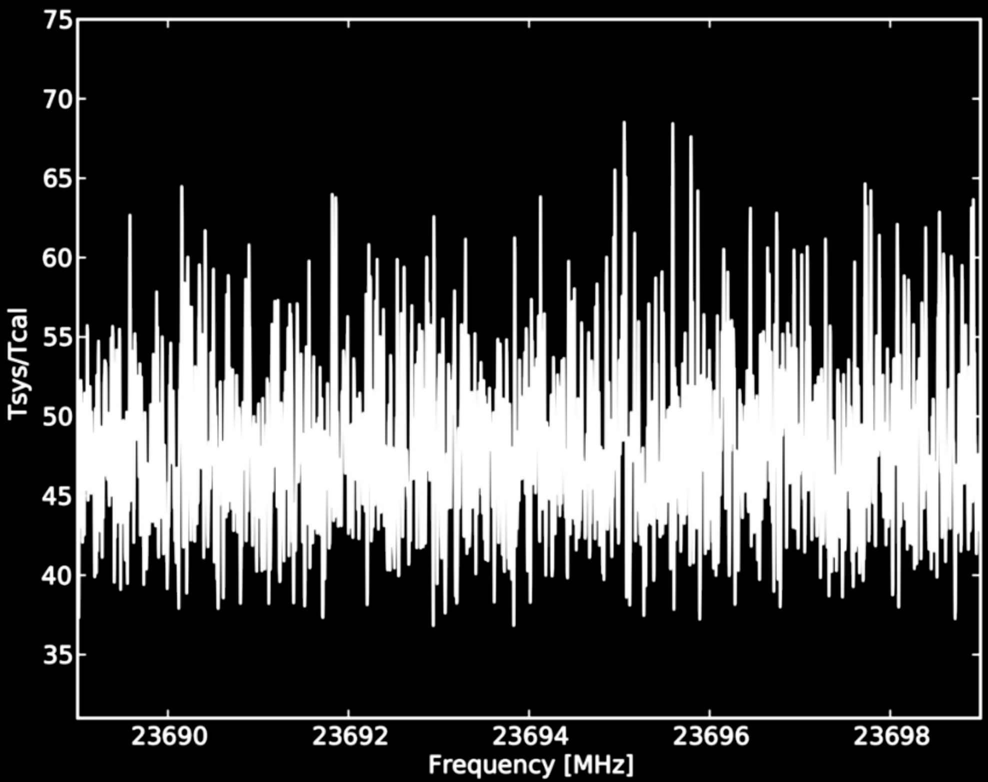
$$P_{\rm on} = G \cdot (T_{\rm sou} + T_{\rm sys})$$
$$P_{\rm on}^{\rm cal} = G \cdot (T_{\rm sou} + T_{\rm sys} + T_{\rm cal})$$
$$P_{\rm off} = G \cdot (T_{\rm sys})$$
$$P_{\rm off}^{\rm cal} = G \cdot (T_{\rm sys} + T_{\rm cal})$$

Compute

$$\frac{T_{\rm sys}}{T_{\rm cal}} = \frac{P_{\rm off}}{P_{\rm off}^{\rm cal} - P_{\rm off}}$$

This can be approximated by a constant (in frequency)!

Spectroscopy: inferring T_{sys}



Observe ON and OFF-source

$$P_{\mathrm{on}} = G \cdot (T_{\mathrm{sou}} + T_{\mathrm{sys}})$$
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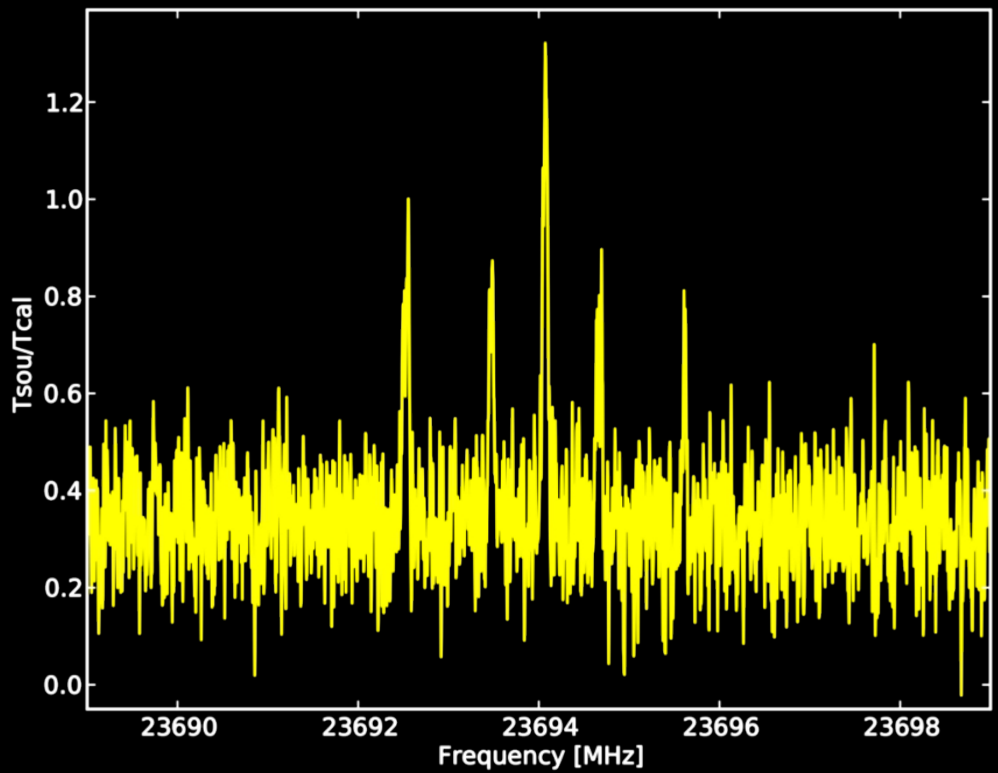
$$P_{\mathrm{off}} = G \cdot (T_{\mathrm{sys}})$$
$$P_{\mathrm{off}}^{\mathrm{cal}} = G \cdot (T_{\mathrm{sys}} + T_{\mathrm{cal}})$$

Compute

$$\frac{T_{\mathrm{sys}}}{T_{\mathrm{cal}}} = \frac{P_{\mathrm{off}}}{P_{\mathrm{off}}^{\mathrm{cal}} - P_{\mathrm{off}}}$$

However, denominator is small → numerically unstable

Spectroscopy: classic solution



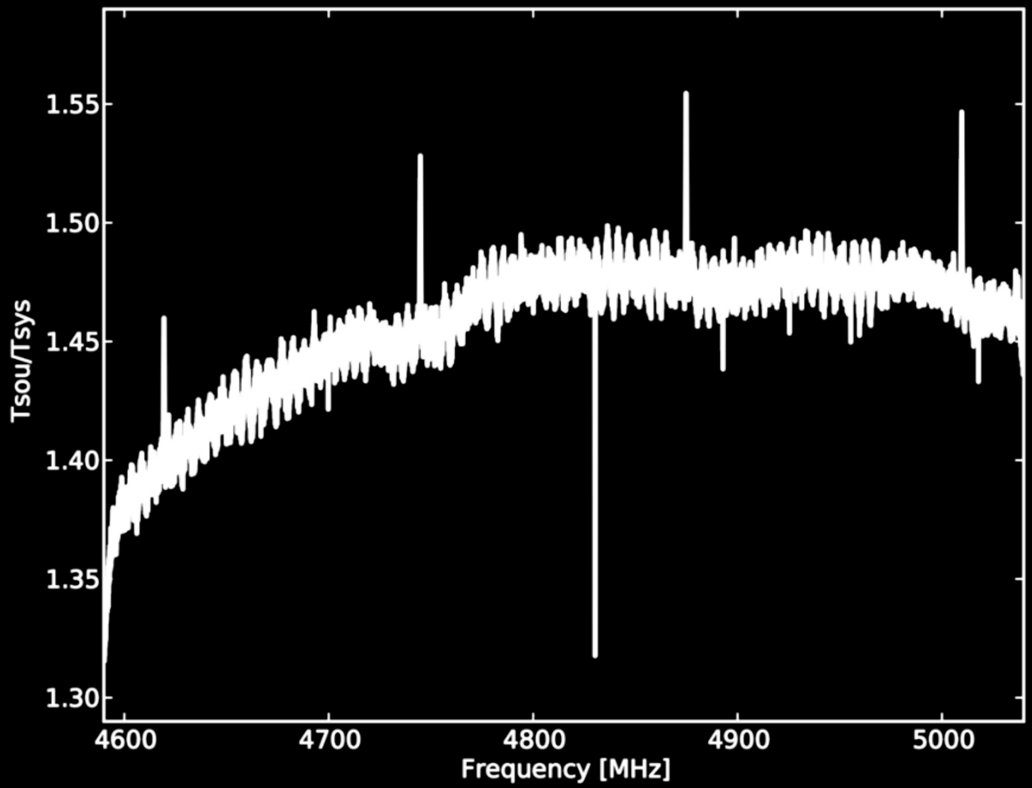
"Classic" solution

$$\frac{T_{\rm sou}}{T_{\rm cal}} = \overline{\frac{T_{\rm sys}}{T_{\rm cal}}} \frac{P_{\rm on} - P_{\rm off}}{P_{\rm off}}$$

with

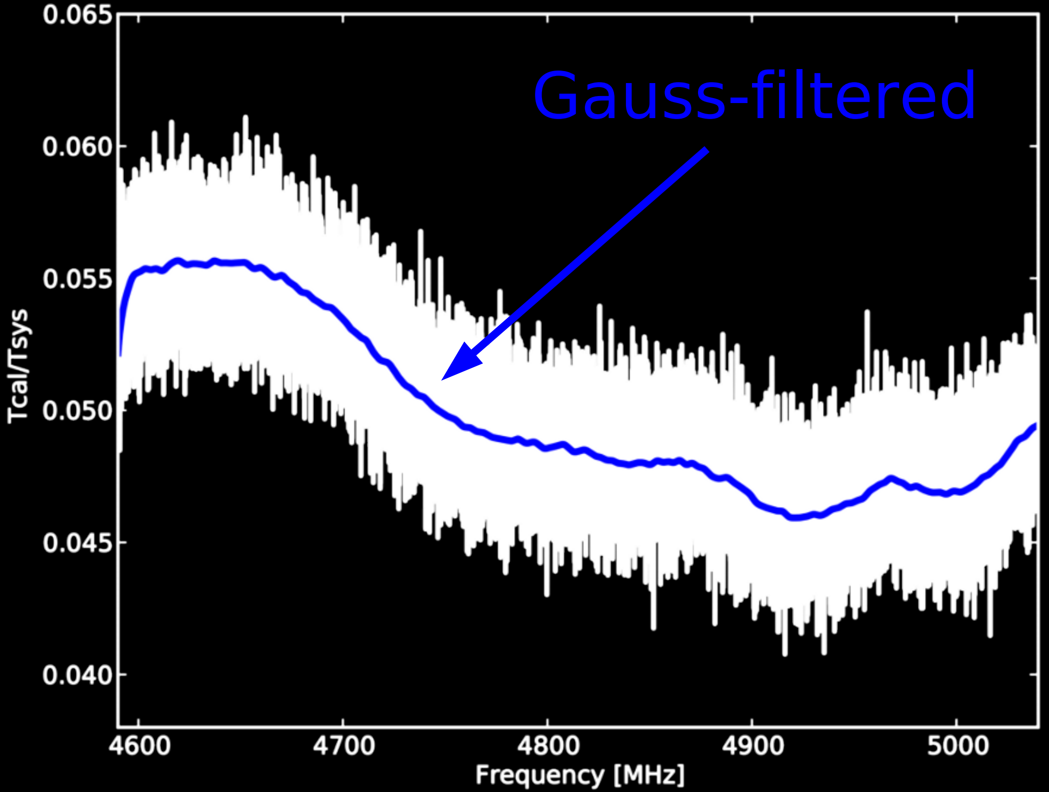
$$\overline{\frac{T_{\rm sys}}{T_{\rm cal}}} = \left\langle \frac{P_{\rm off}^{\rm cal} - P_{\rm off}}{P_{\rm off}} \right\rangle_{\nu}^{-1}$$

Spectroscopy: unbiased method



Now switch to larger bandwidth...

Spectroscopy: unbiased method

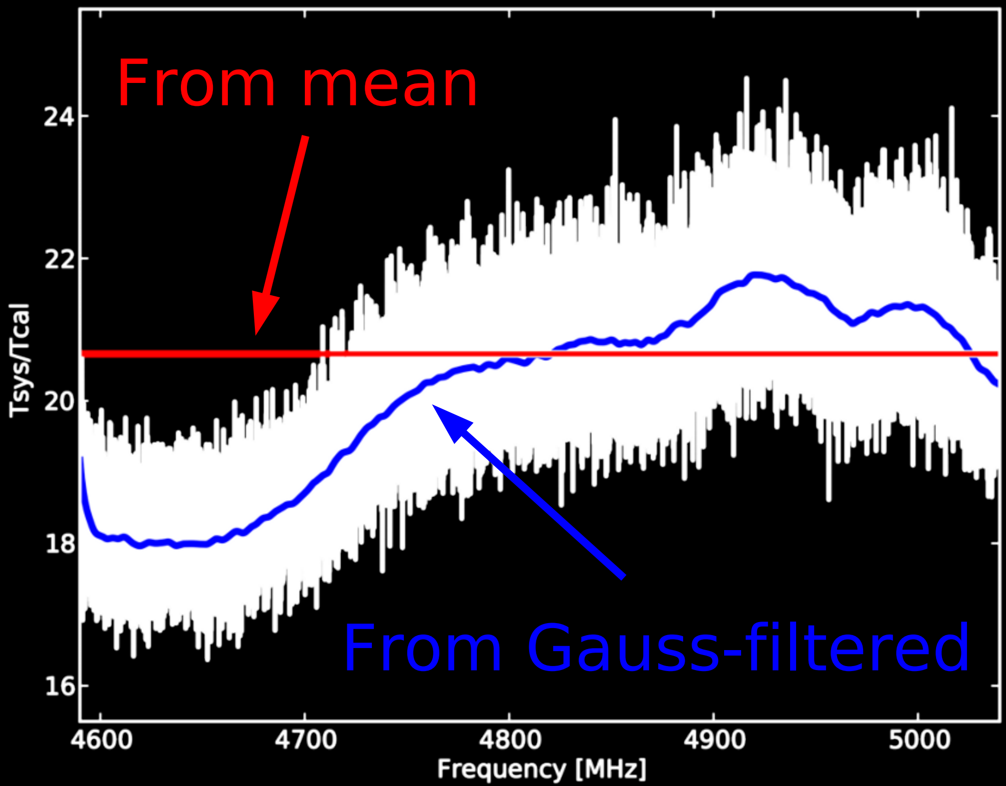


$$\frac{T_{\rm sys}}{T_{\rm cal}} = \boxed{\left[\frac{P_{\rm off}^{\rm cal} - P_{\rm off}}{P_{\rm off}}\right]}^{-1}$$

Model this quantity and invert afterwards

(avoids numerical instability)

Spectroscopy: unbiased method



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Model this quantity and invert afterwards

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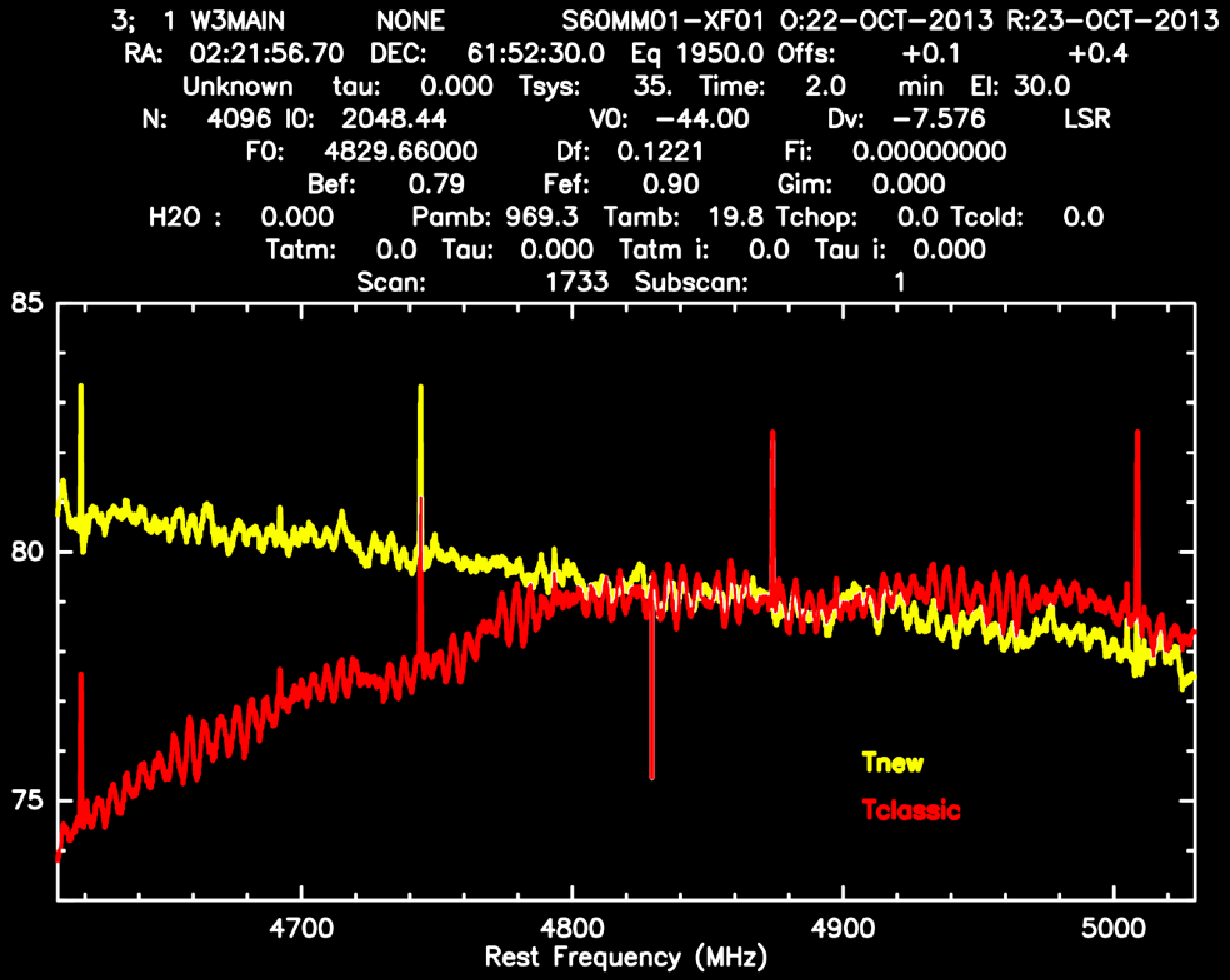
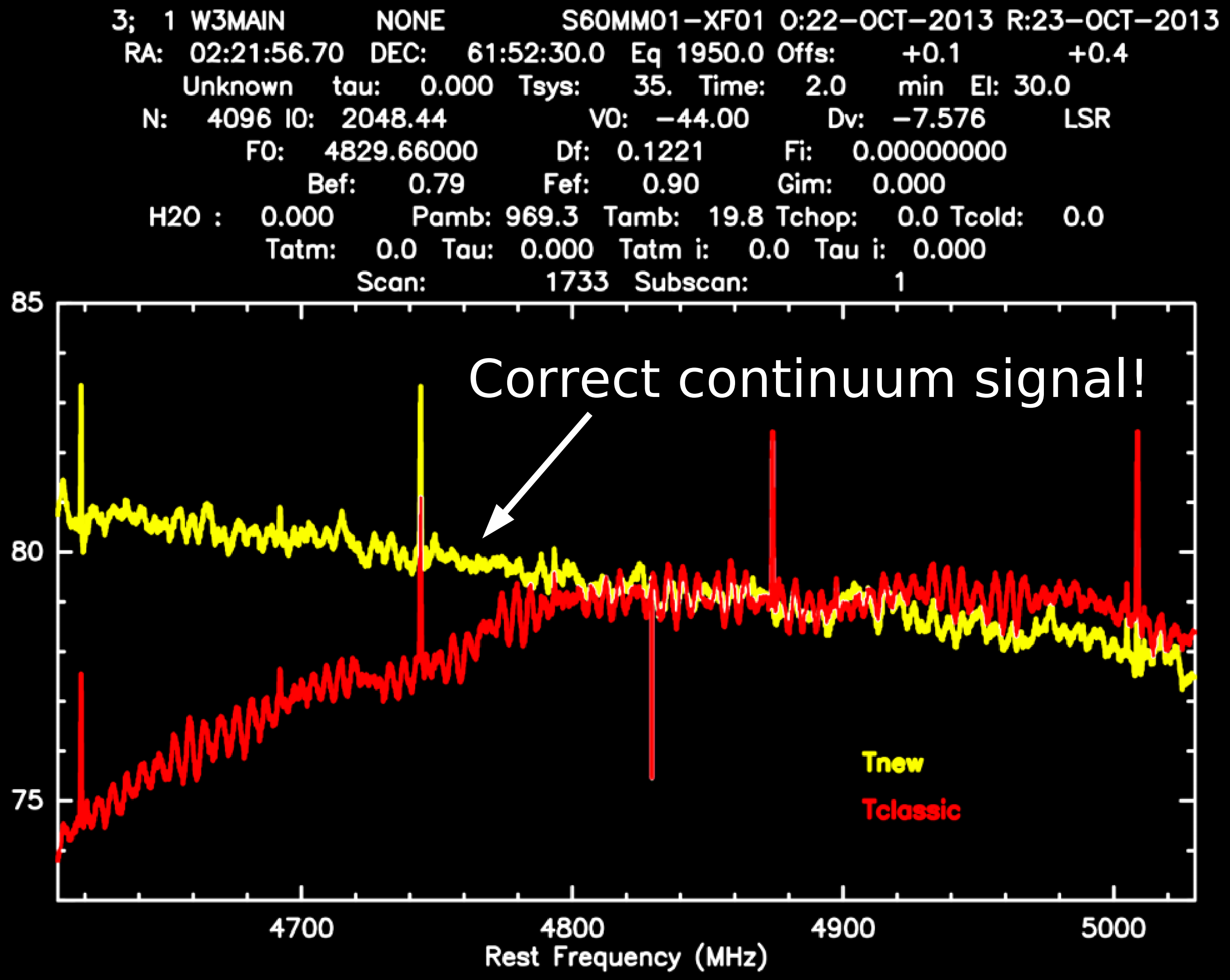
Spectroscopy: unbiased results



Spectroscopy: unbiased results



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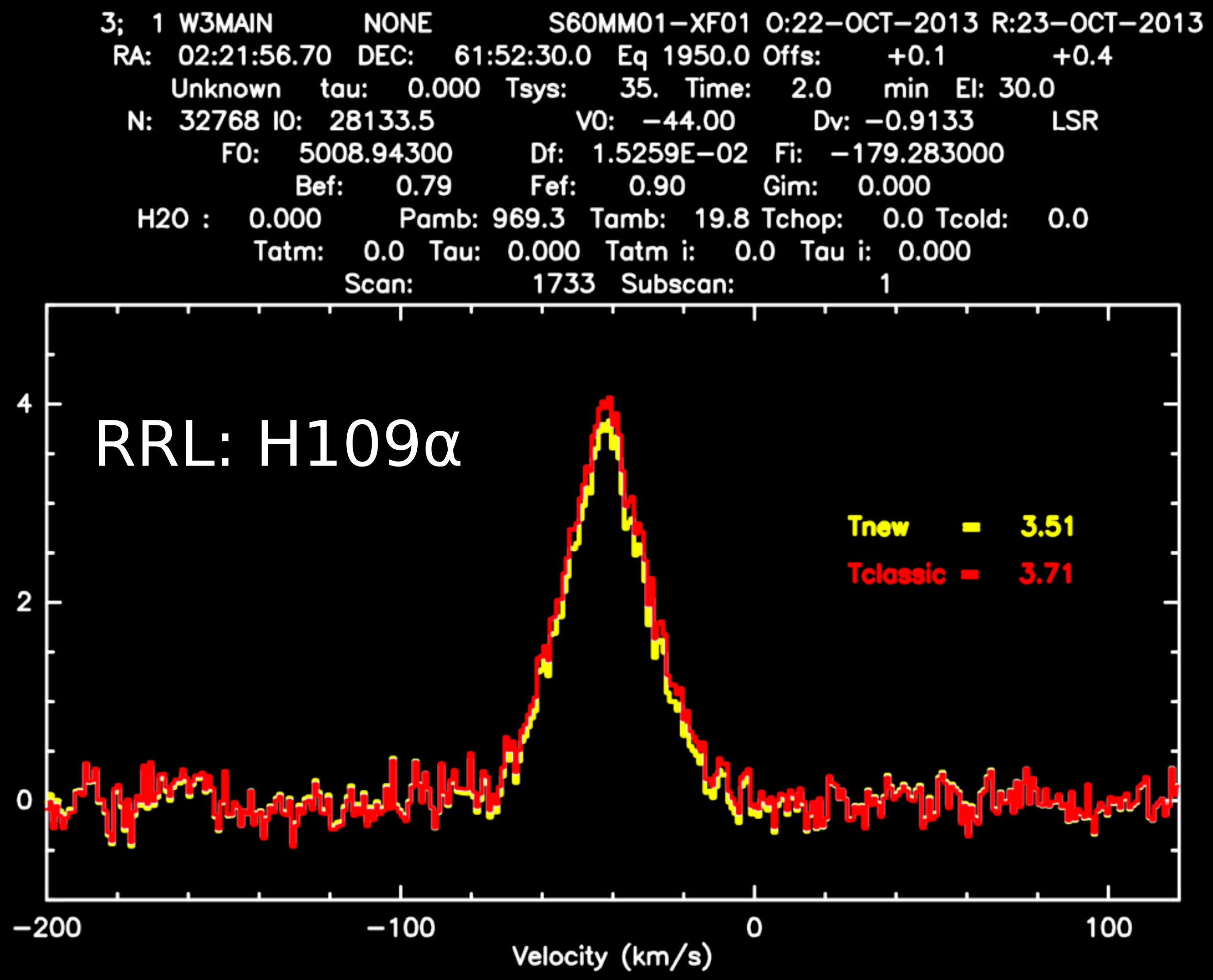

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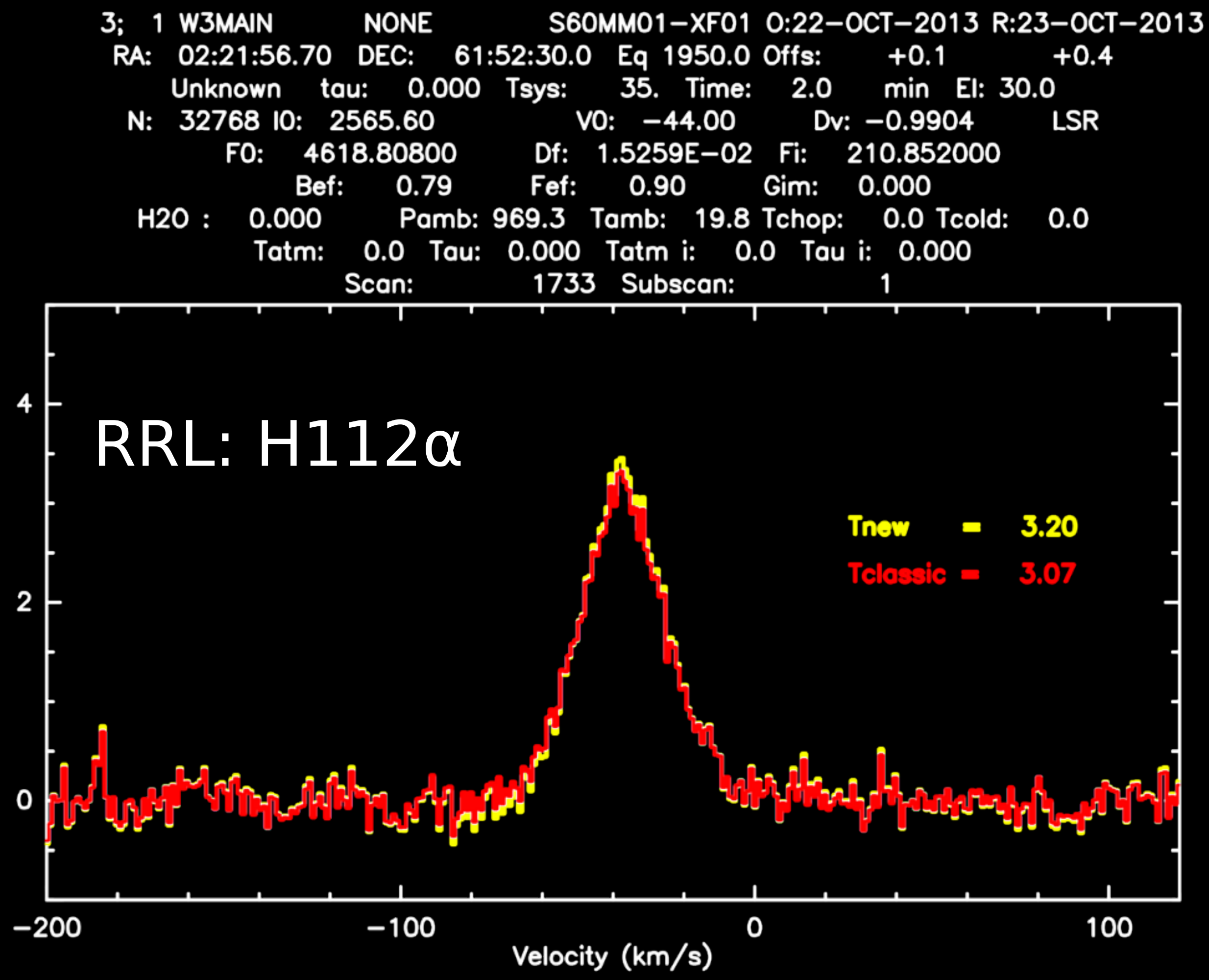

Classic method: line ratio systematically wrong!

Conclusion

Need to incorporate frequency dependence

But

- Modeling not always robust, may need supervision (e.g., in case of standing waves)
- T_{sys} may not be stable between ON and OFF
  Weather can hurt a lot!
  → Solution: cross-scanning
- Frequency dependence also for opacity, Elevation-gain curve, taper function