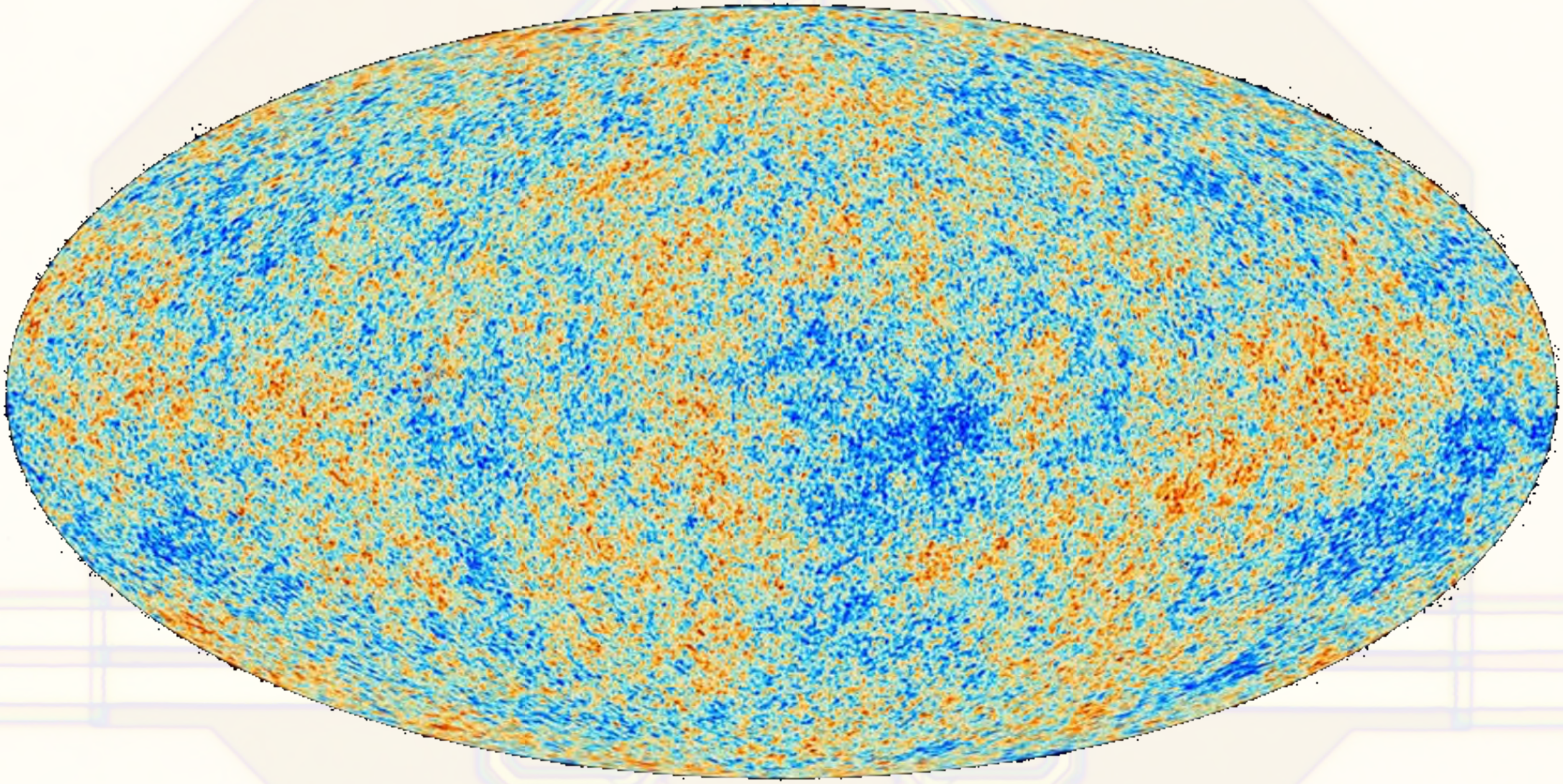
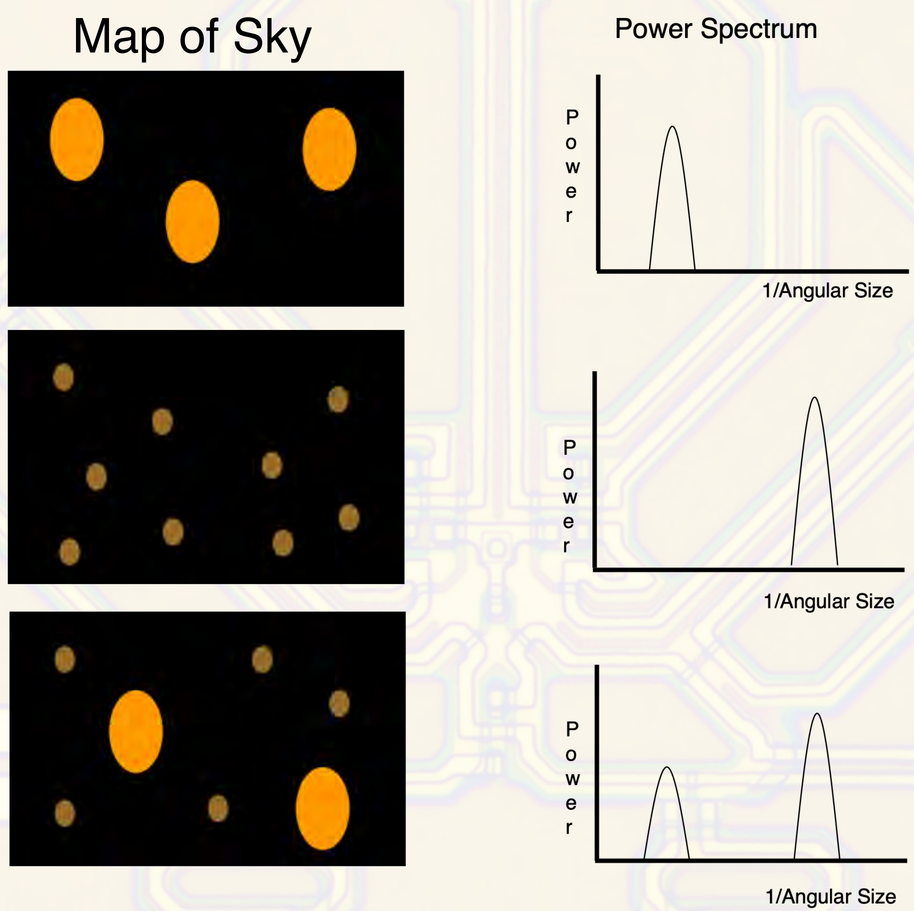
## Cosmic Microwave Background

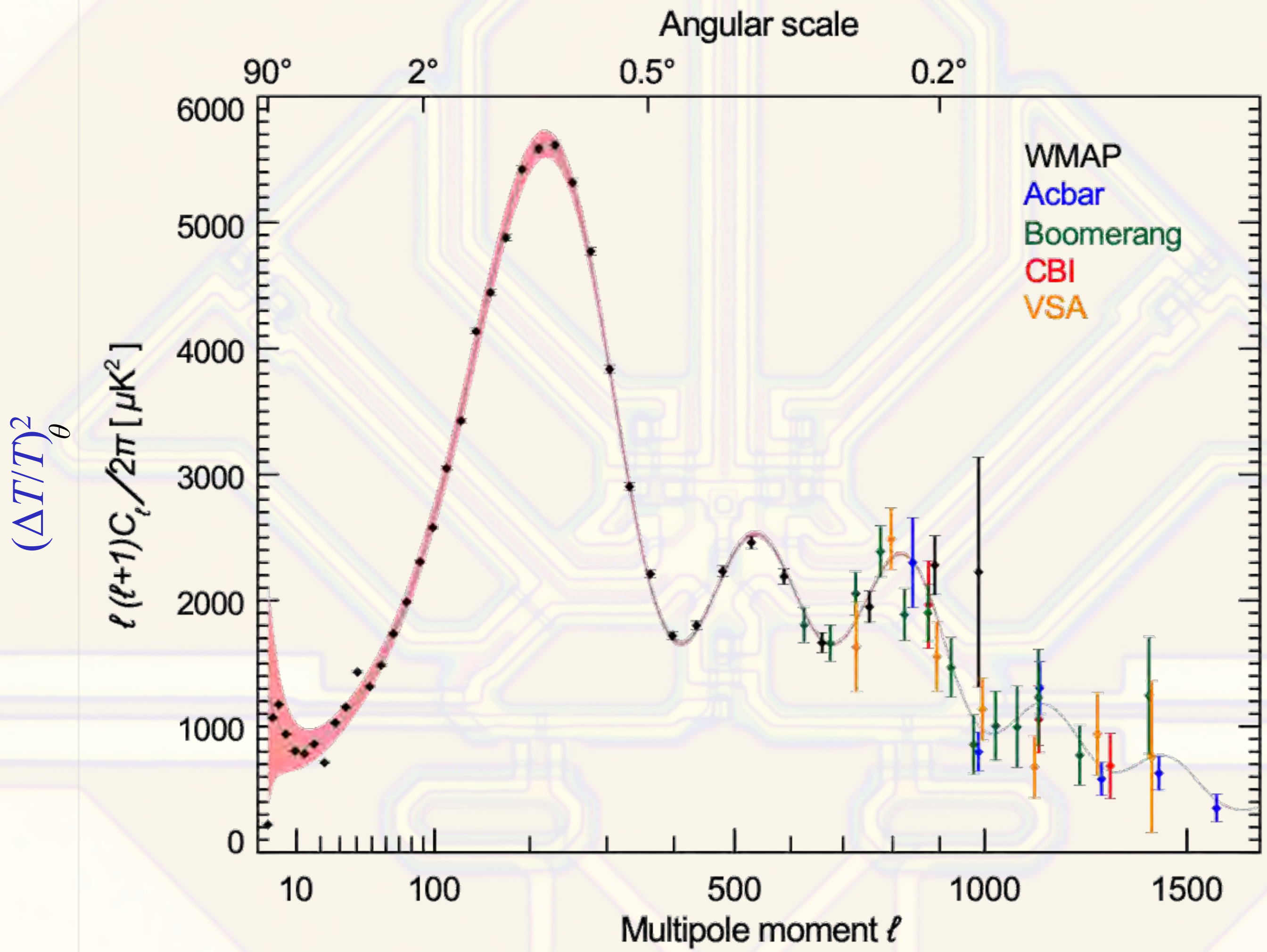


Planck Satellite CMB Map

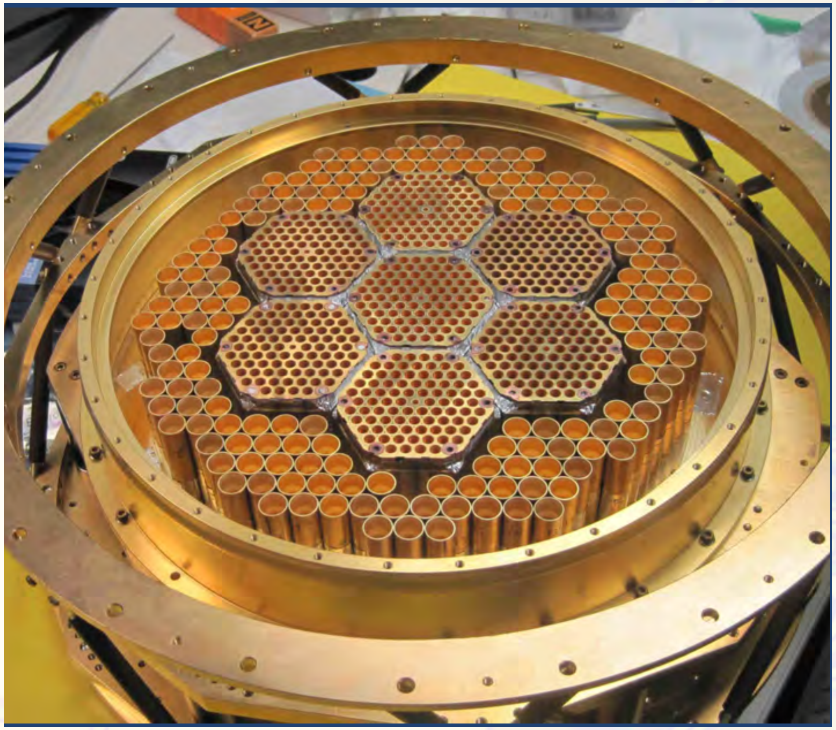
## Cosmic Microwave Background

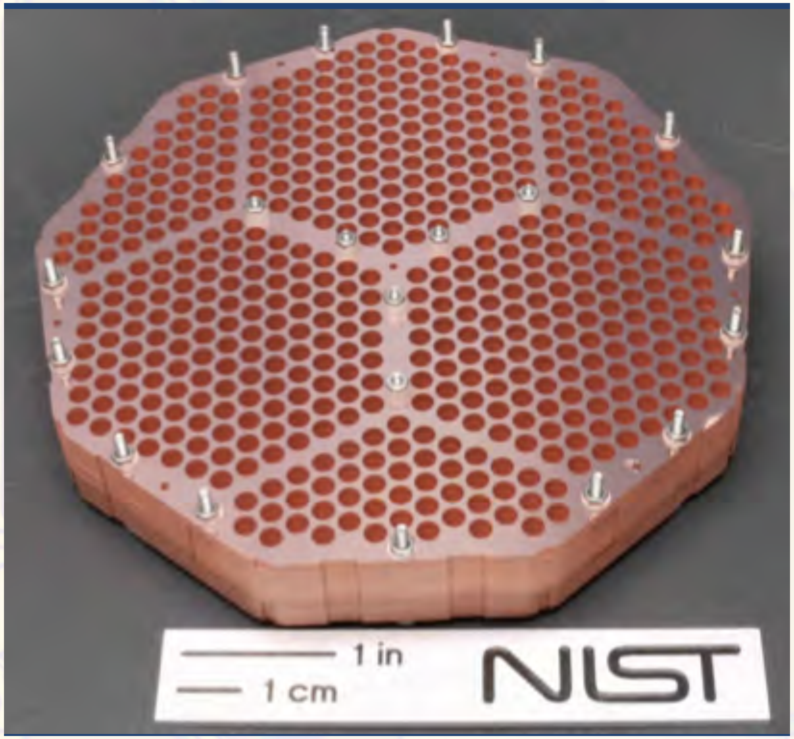


## CMB Power Spectrum



CMB detector modules





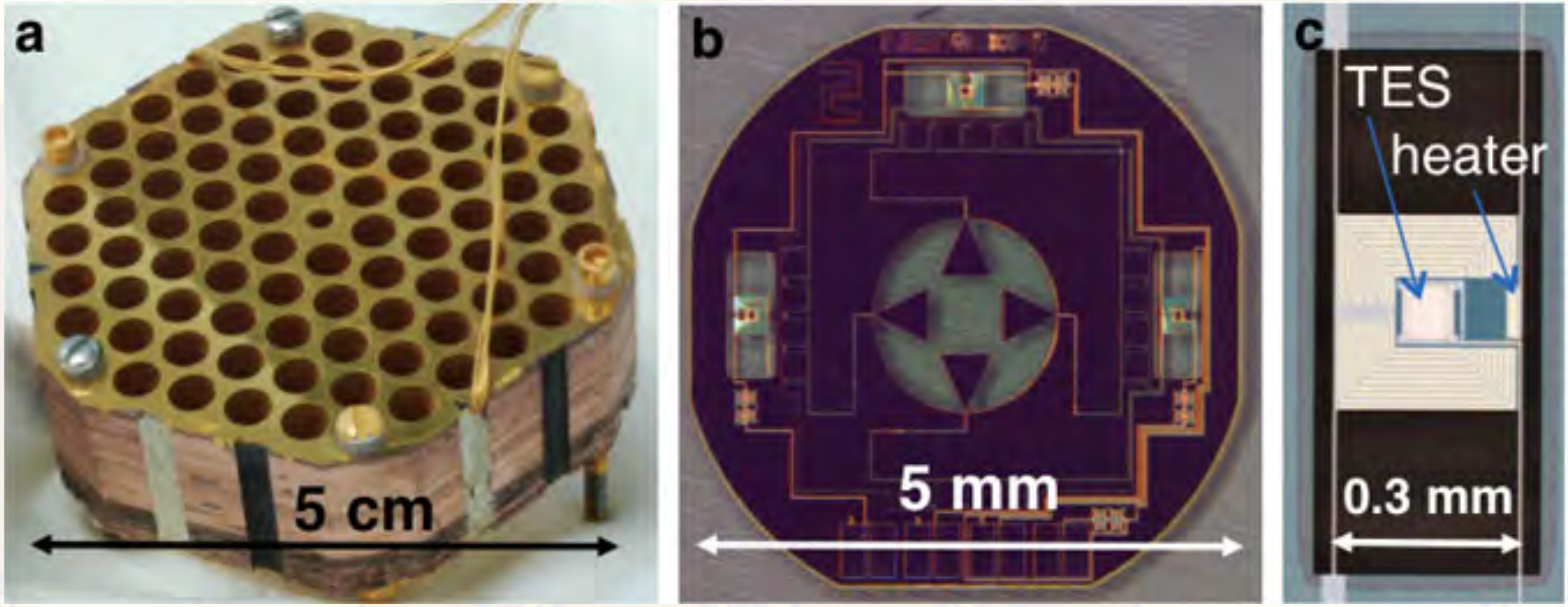

South Pole Telescope

95 GHz, 150 GHz, and 220 GHz

Atacama Cosmology Telescope

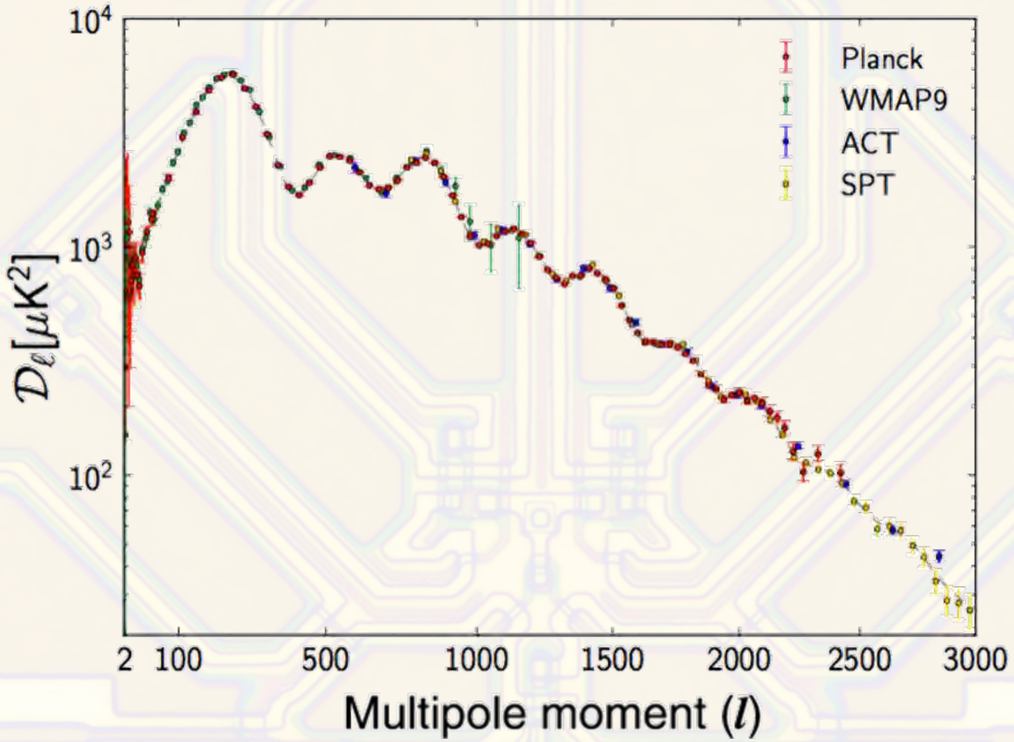
145 GHz und 280 GHz

TES detector module



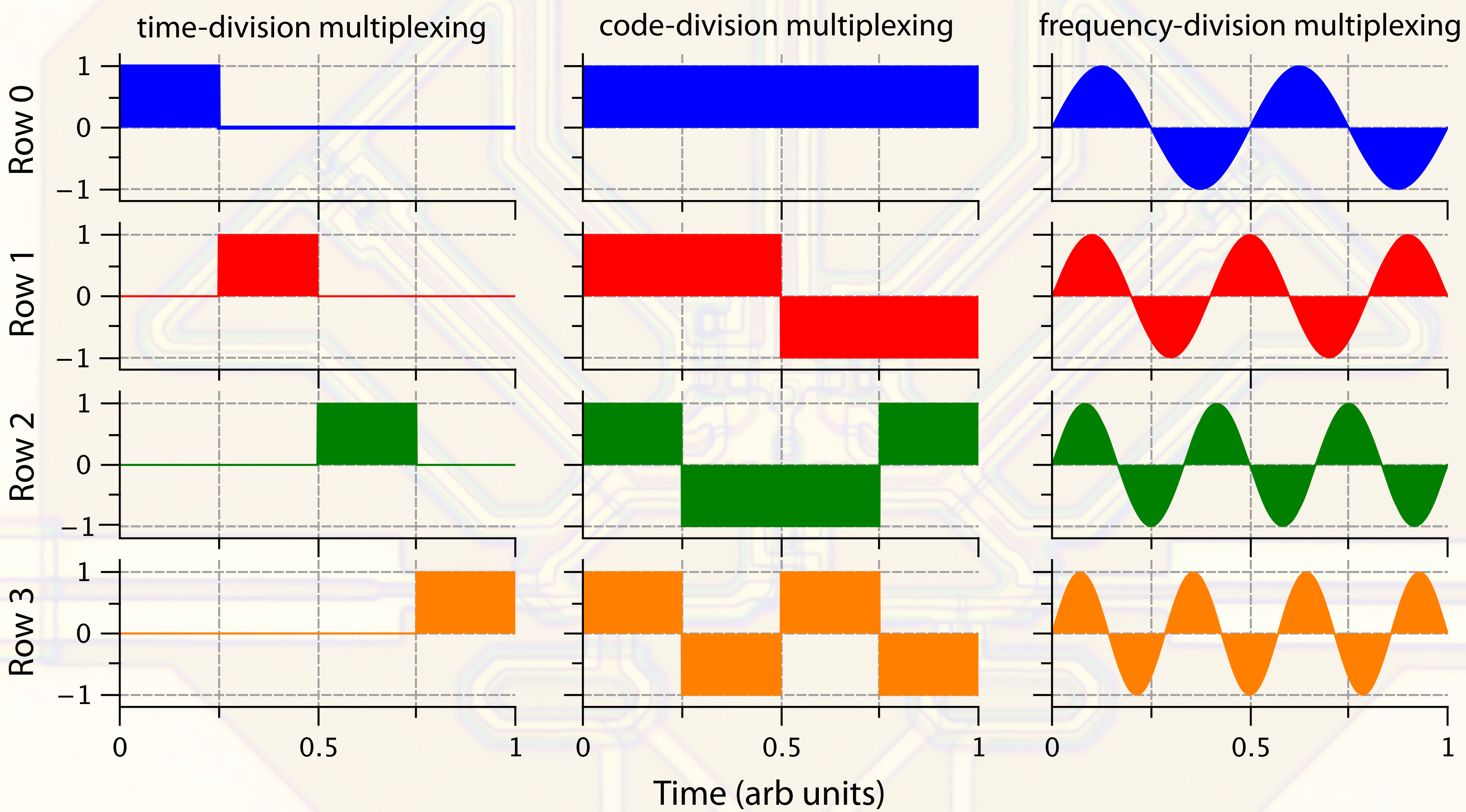
South Pole Telescope

South Pole Telescope



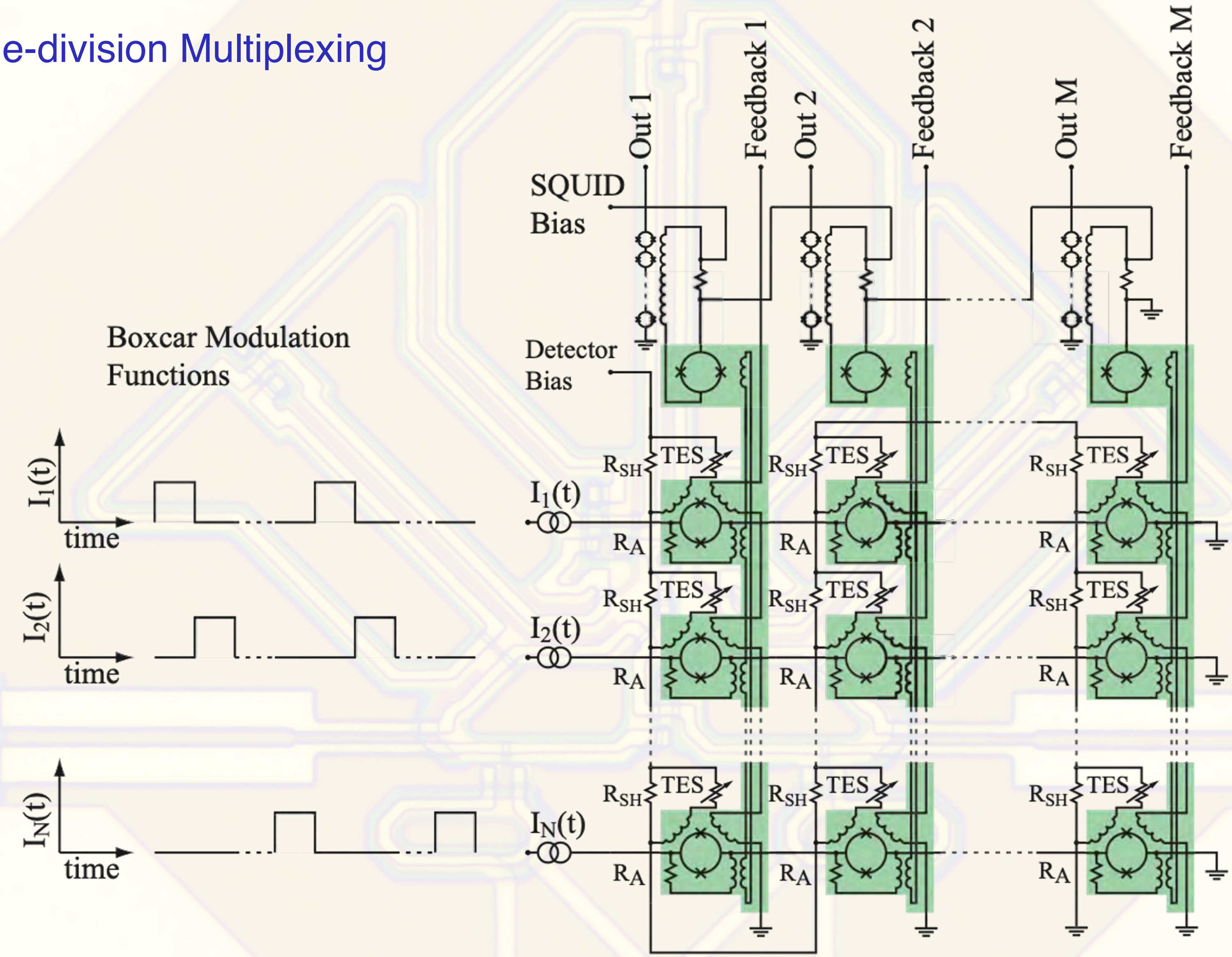
## Multiplexing Schemes

Orthogonal modulation functions for four channels

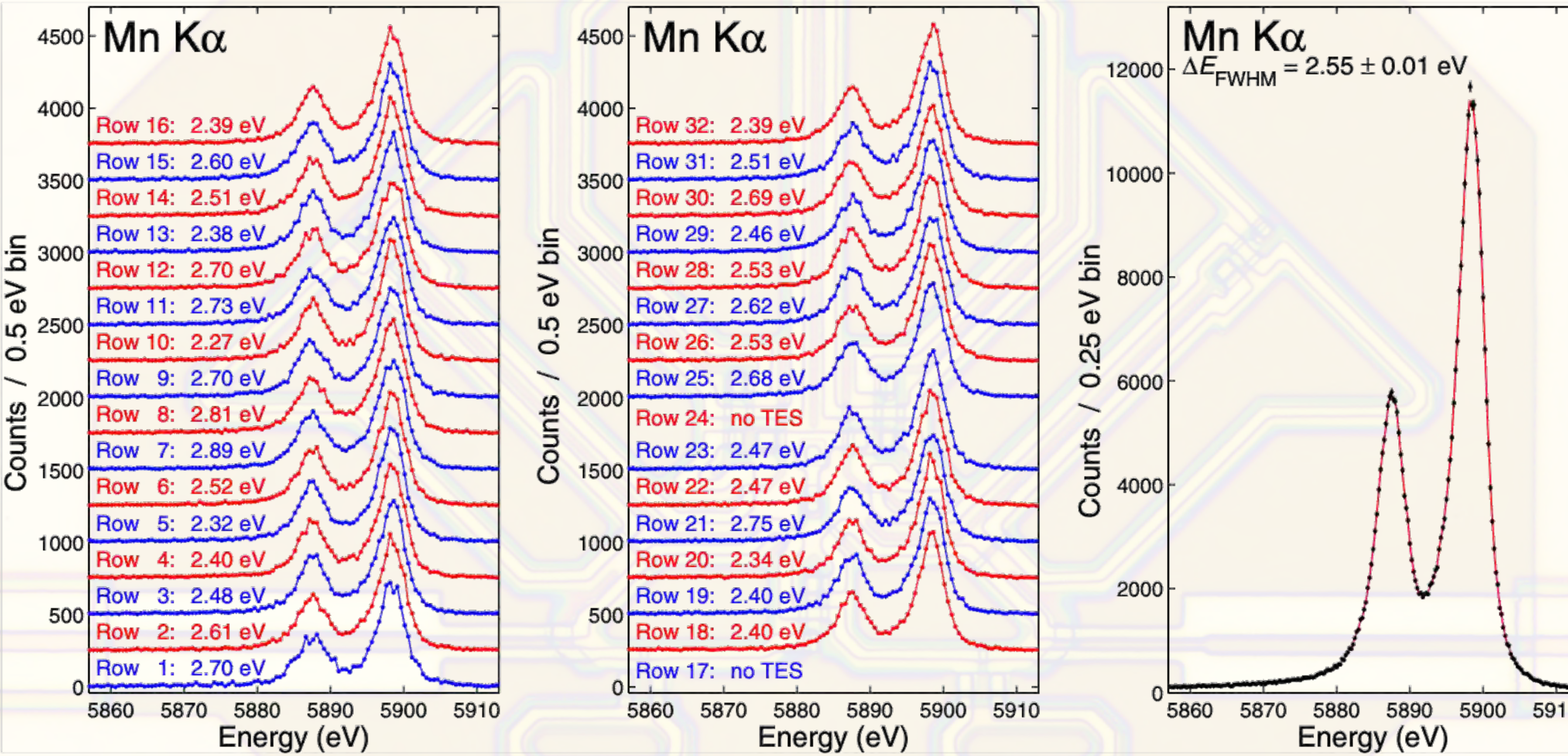


# Particle Detection

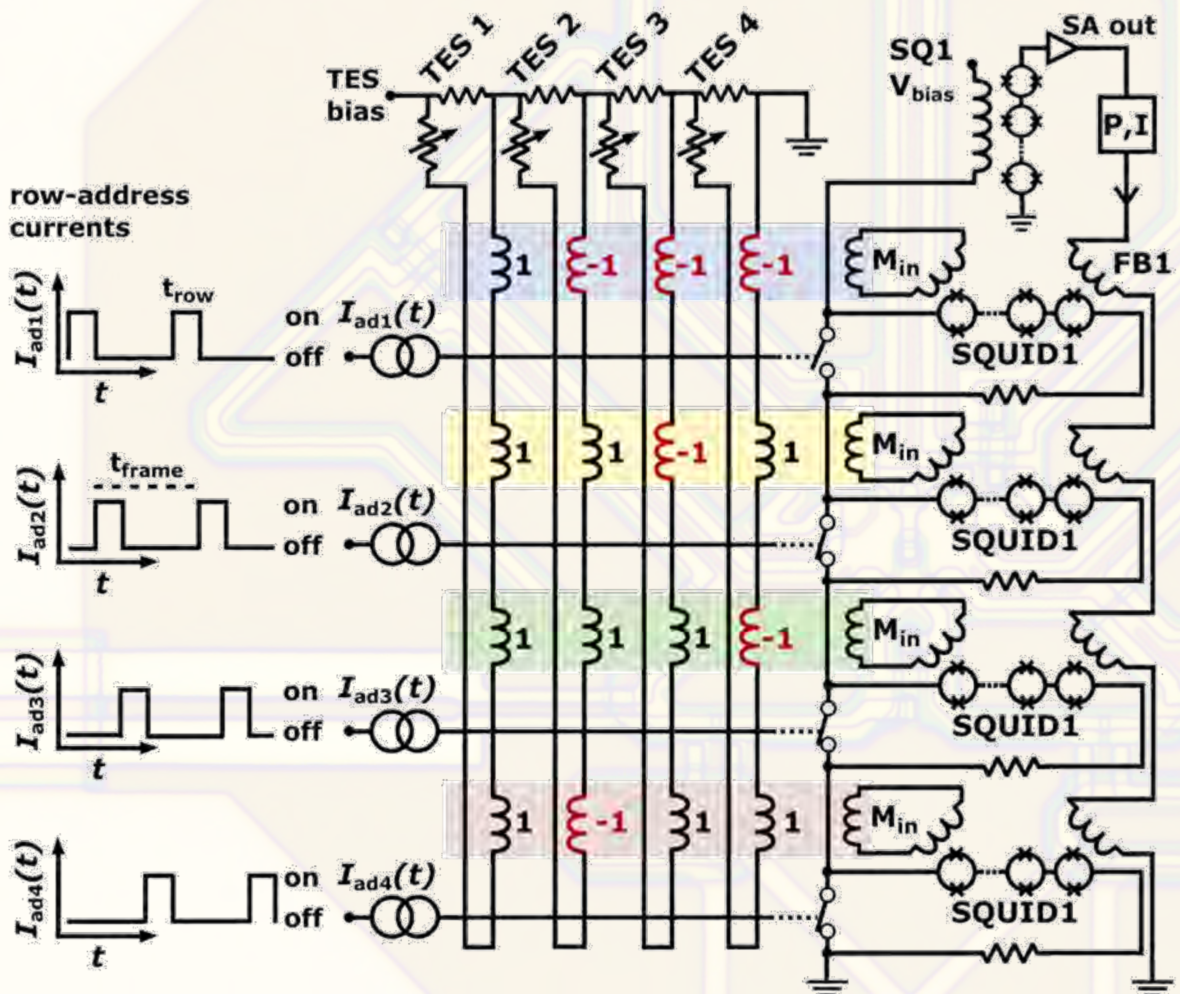
## Time-division Multiplexing



## Time-division Multiplexing



## Code-division Multiplexing

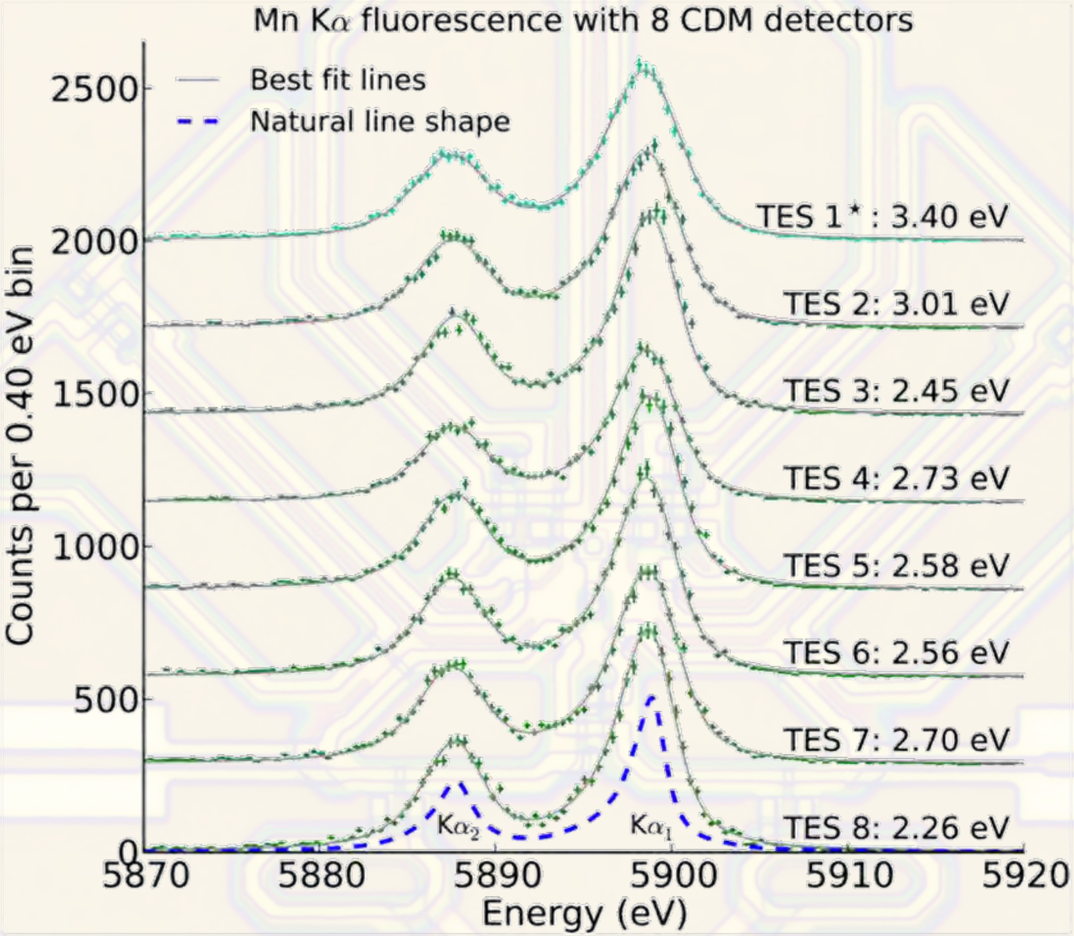



Decoding Walsh Matrix

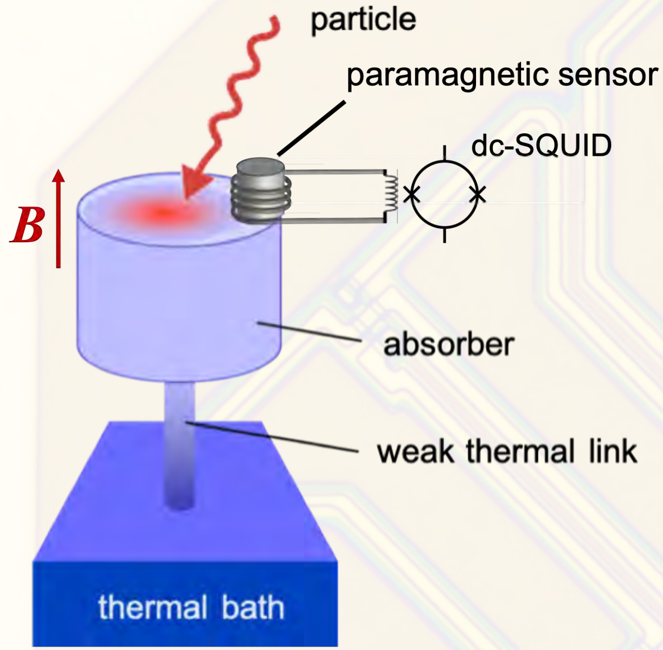
$$W_4 \equiv \begin{pmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 \end{pmatrix}$$

# Particle Detection

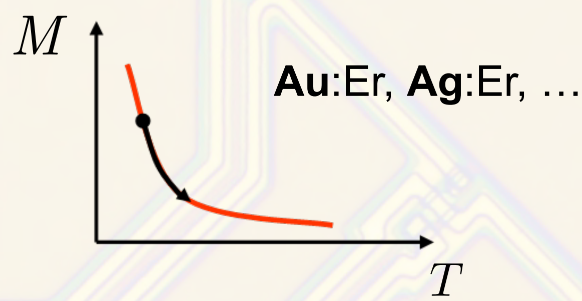
## Code-division Multiplexing



## Magnetic Calorimeters




**paramagnetic sensor:**




$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E}{C_{\text{tot}}}$$

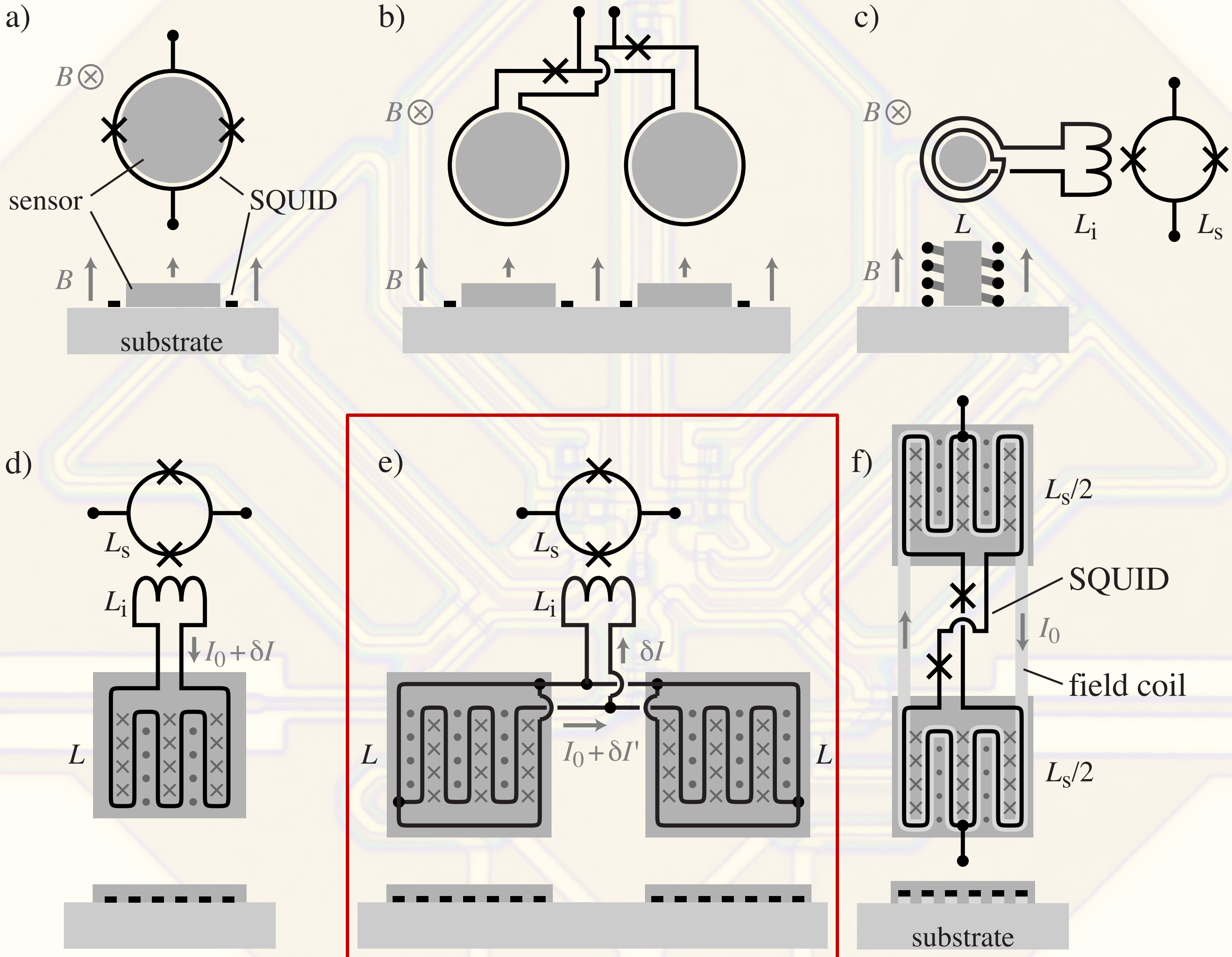
**main difference to resistive calorimeters:**

- no dissipation in the sensor
- no galvanic contact to the sensor

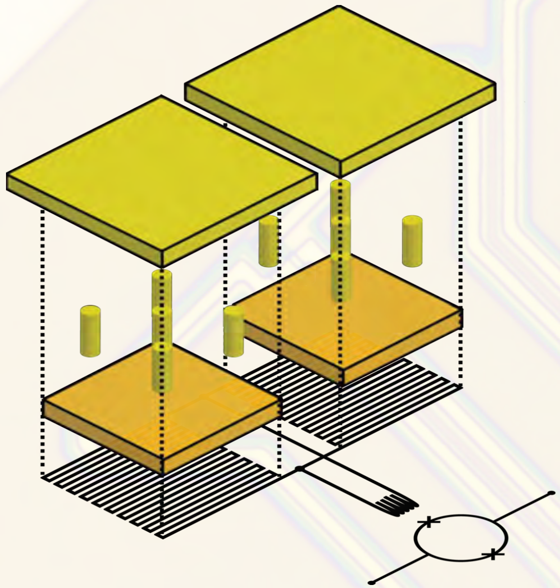
**main applications:**

| | |
|---|---|
| X-ray and g-ray spectroscopy | mass spectrometry |
| nuclear and atomic physics | nuclear forensic |
| neutrino physics | light dark matter |
| metrology | … |

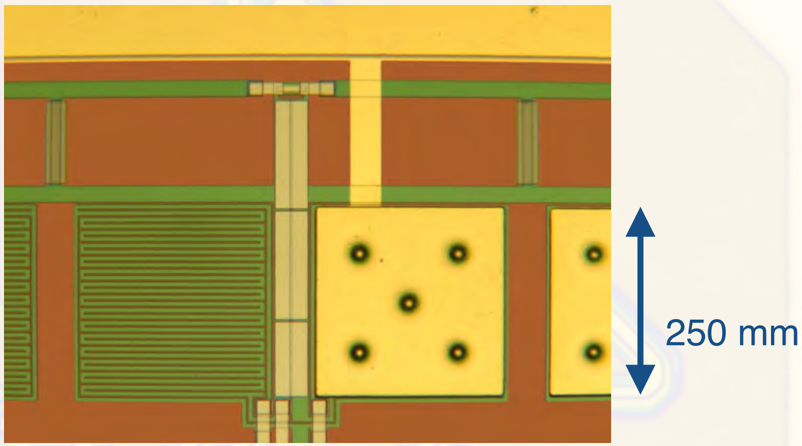
## Detector Geometries



**Energy loss by phonons escaping into substrate before they thermalize in absorber**



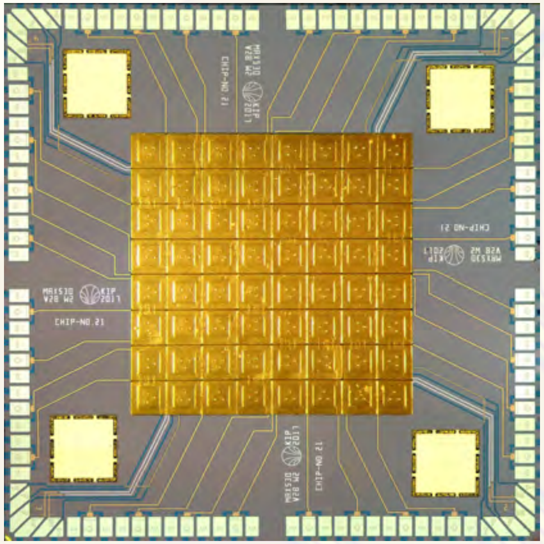
optical image of MMC detector chip



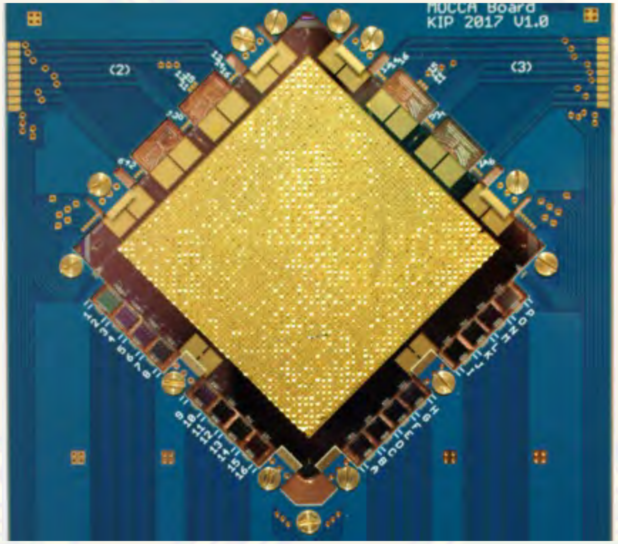

- small stems are used to minimize contact area between sensor and absorber
- phonons can only flow through stems to sensor and substrate
- for large absorbers stems allow for more complete thermalization in absorber

## Detector Realizations

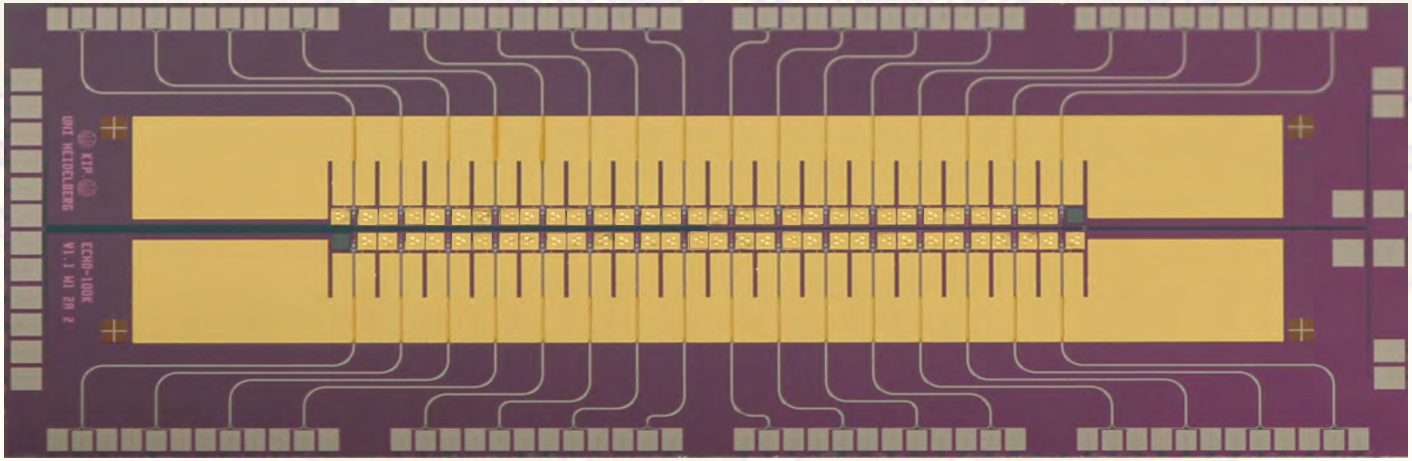
64-pixel array for x-ray and γ-ray detection



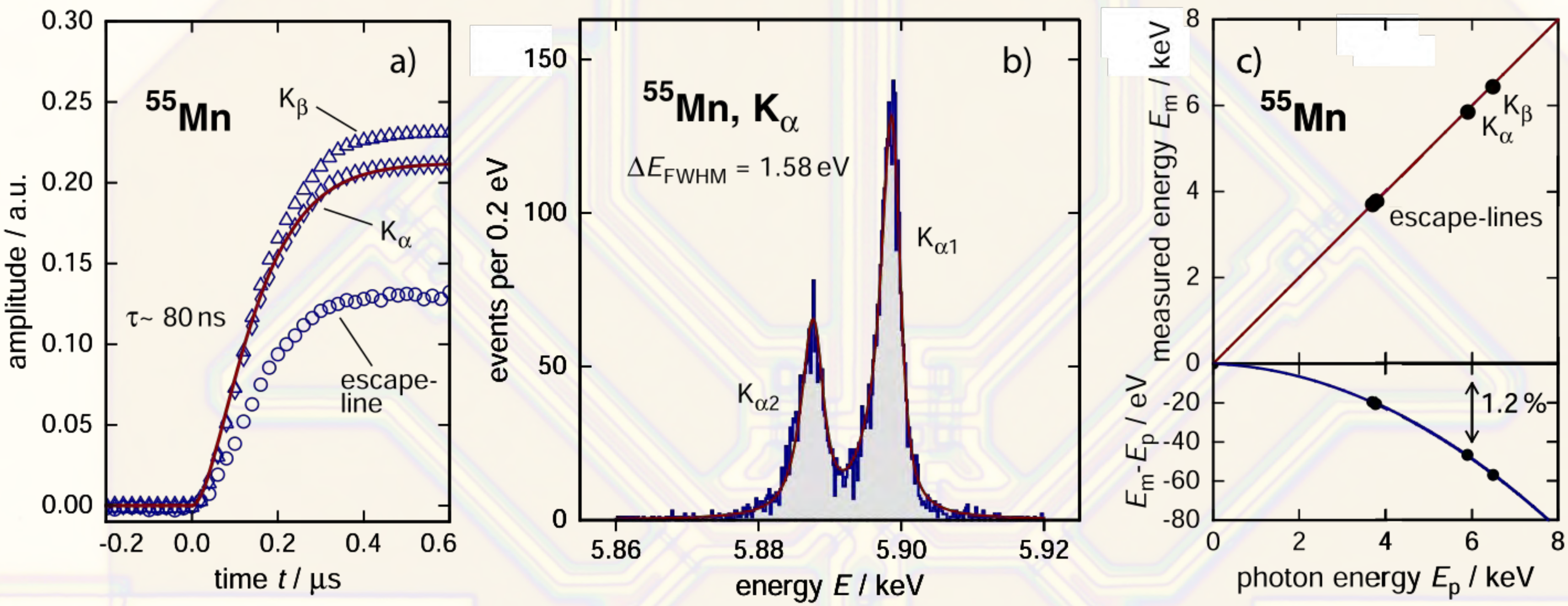
4096-pixel array for mass spectrometry




64-pixel array for neutrino mass measurements



## Performance of MMCs




**fast speed**

pileup identification

**high resolving power**

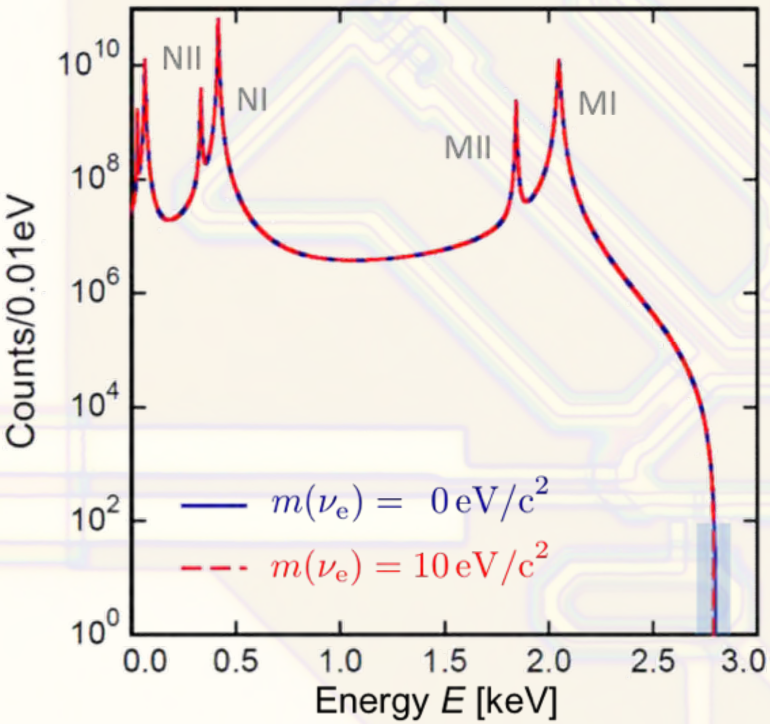
reduction of overlapping lines

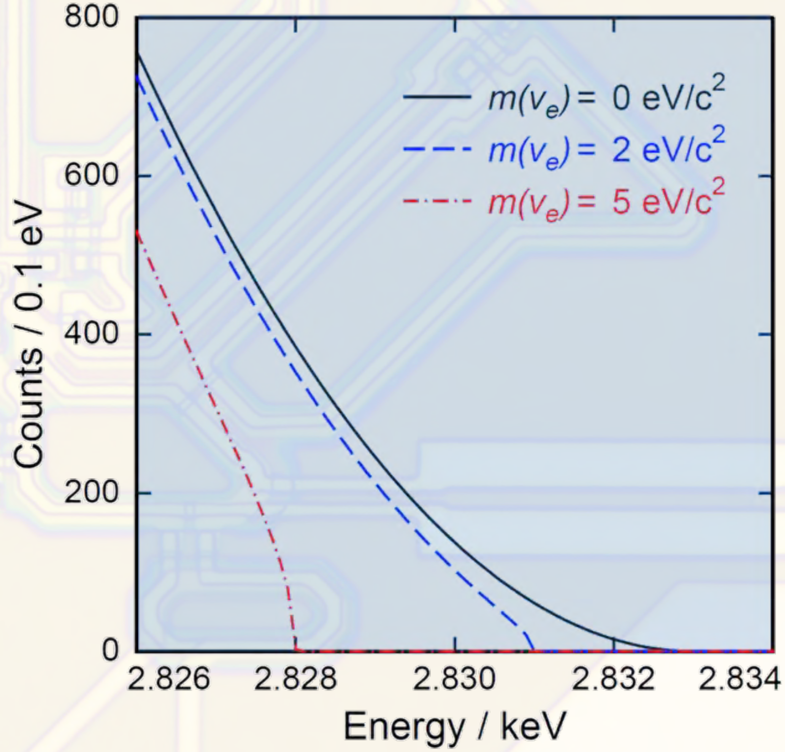
**small non-linearity**

energy scale and calibration

## Electron Capture: The Case of $^{163}$Ho

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{C}} = A\,(Q_\mathrm{EC}-E_\mathrm{C})^2\sqrt{1-\frac{m_\nu^2}{(Q_\mathrm{EC}-E_\mathrm{C})^2}}\sum_j C_j n_j B_j \phi_j^2(0)\frac{\Gamma_j/2\pi}{(E_\mathrm{C}-E_j)^2+\Gamma_j^2/4}$$

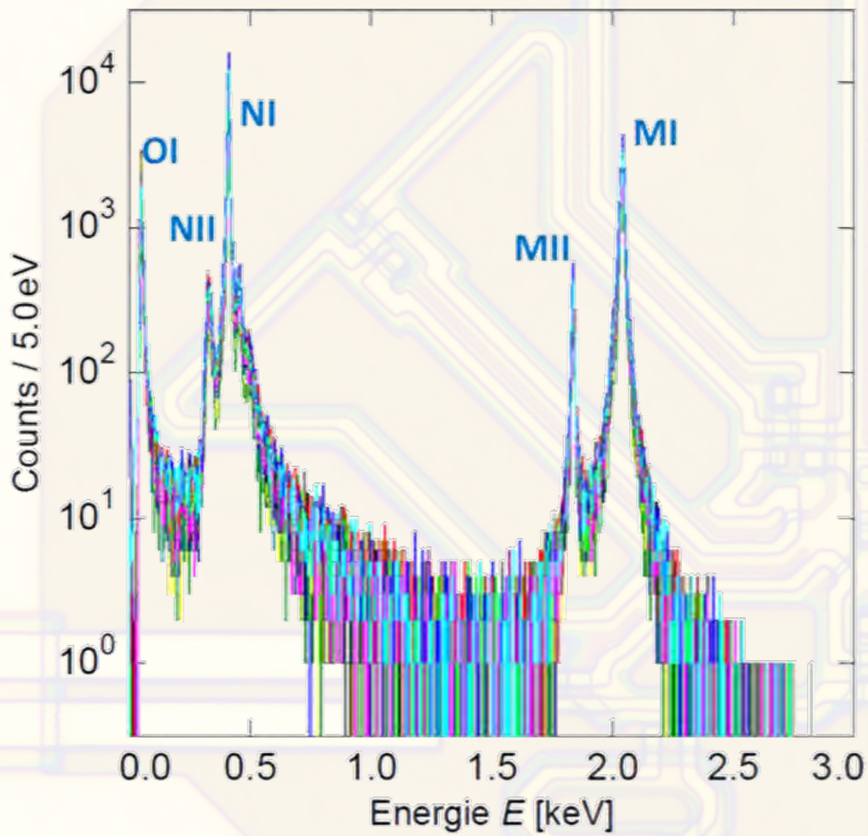


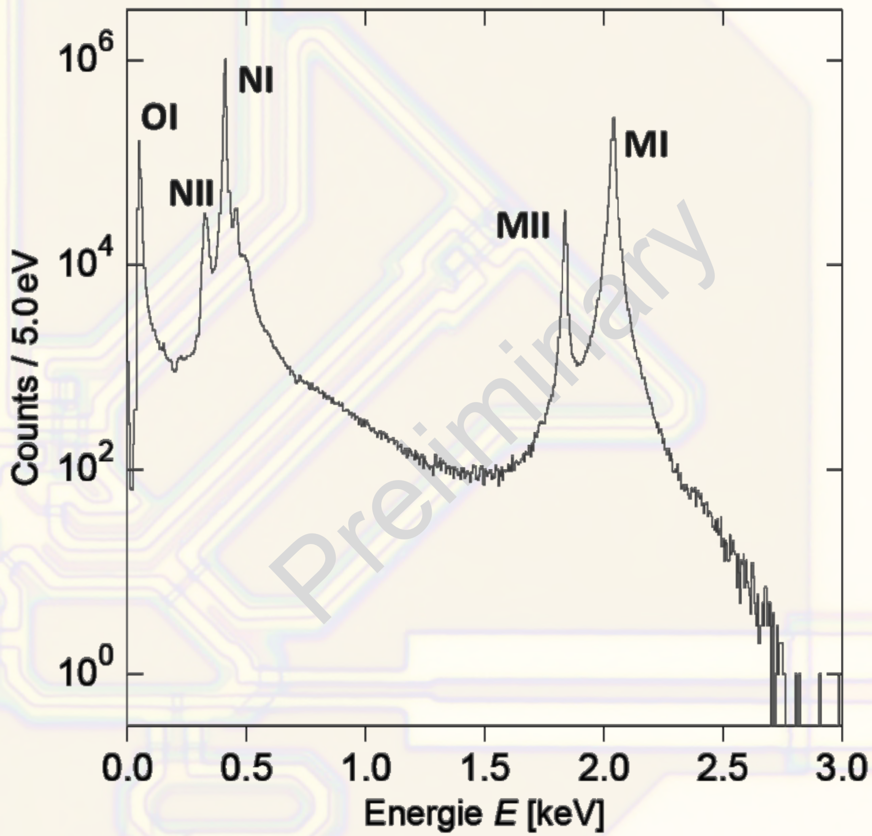
# Particle Detection

Measurement with 20 Pixel with energy resolution 6.5 eV

Individual spectra

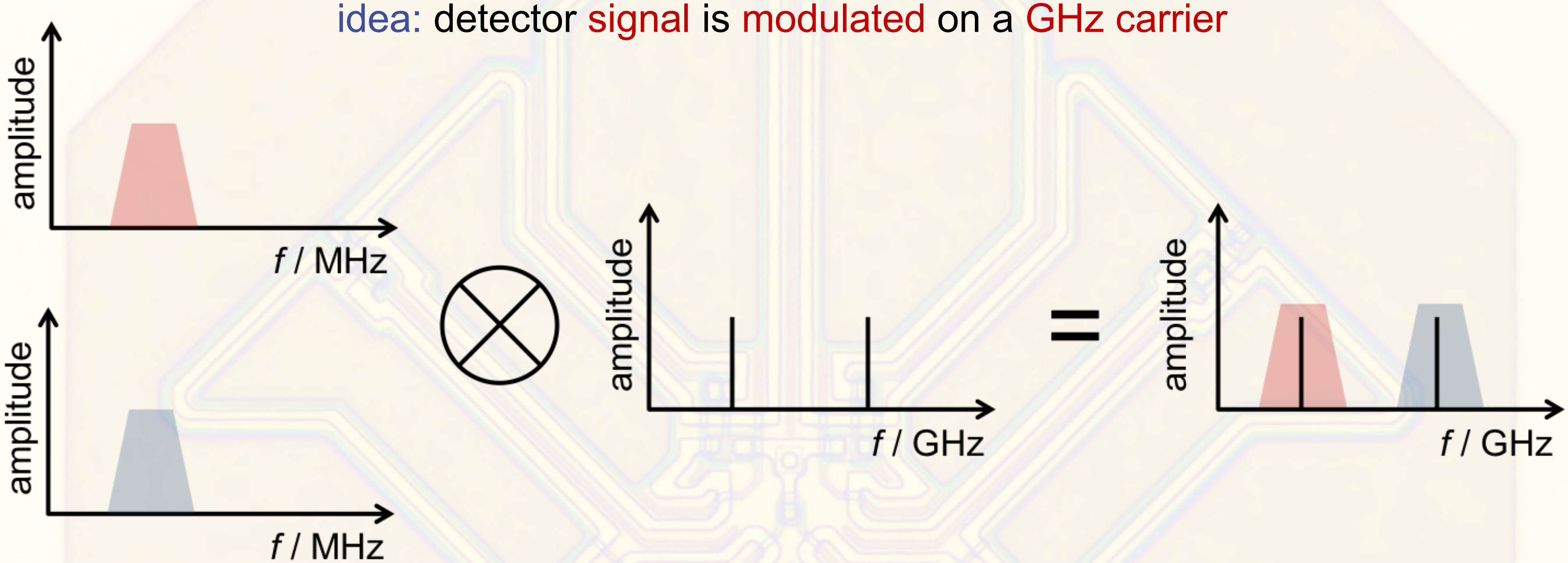



summed spectrum



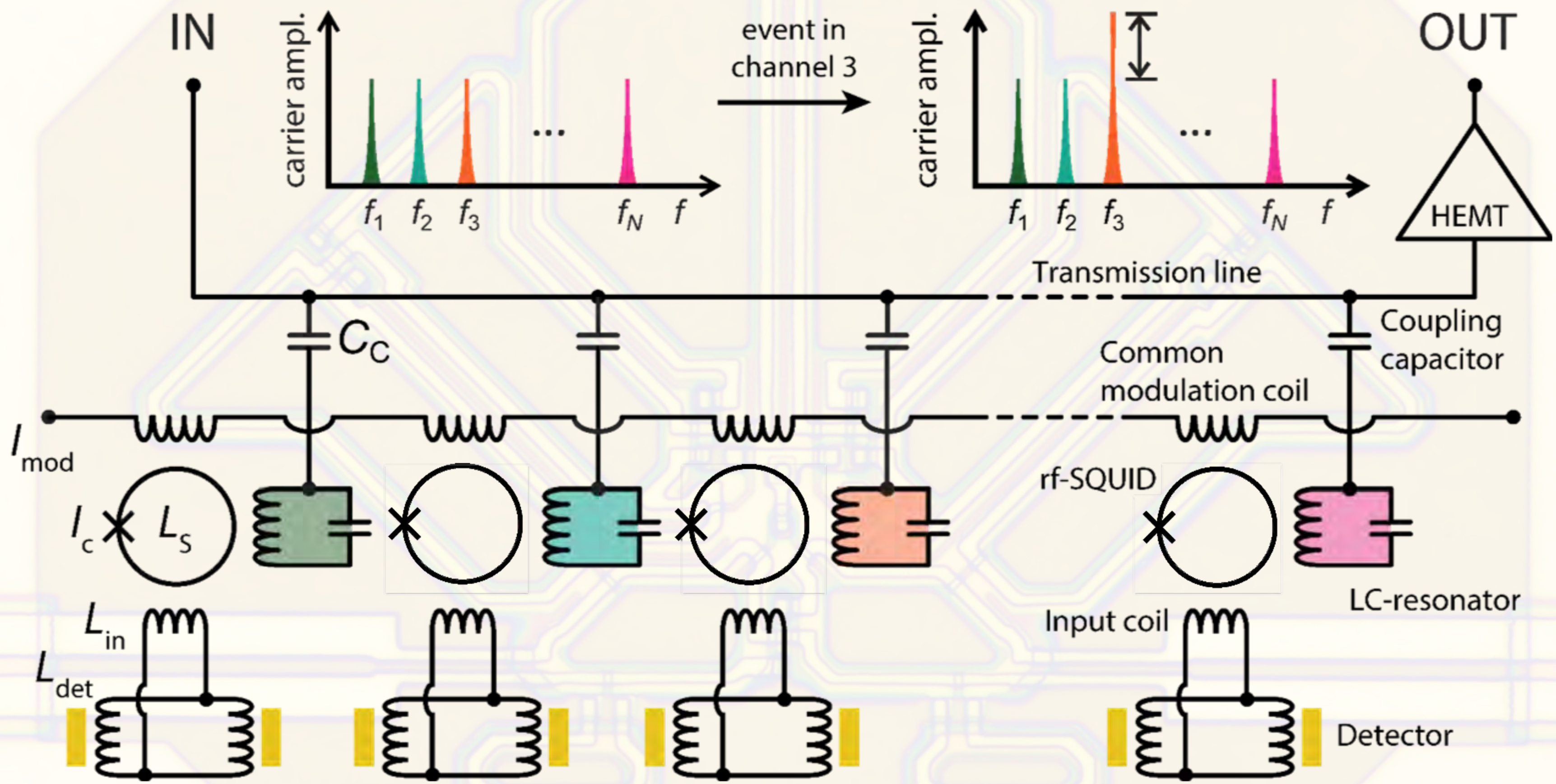
## Frequency Division Multiplexing

idea: detector signal is modulated on a GHz carrier



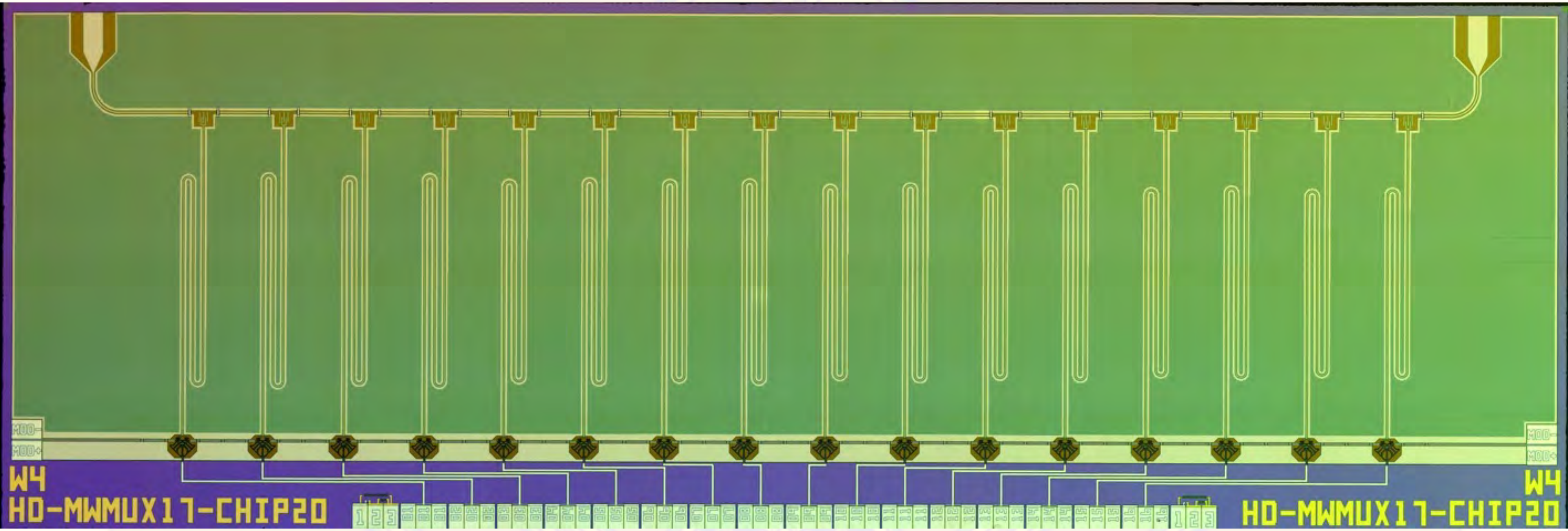

- different carrier frequencies
- non-linear element for mixing

## Microwave SQUID Multiplexer ($\mu$MUX)



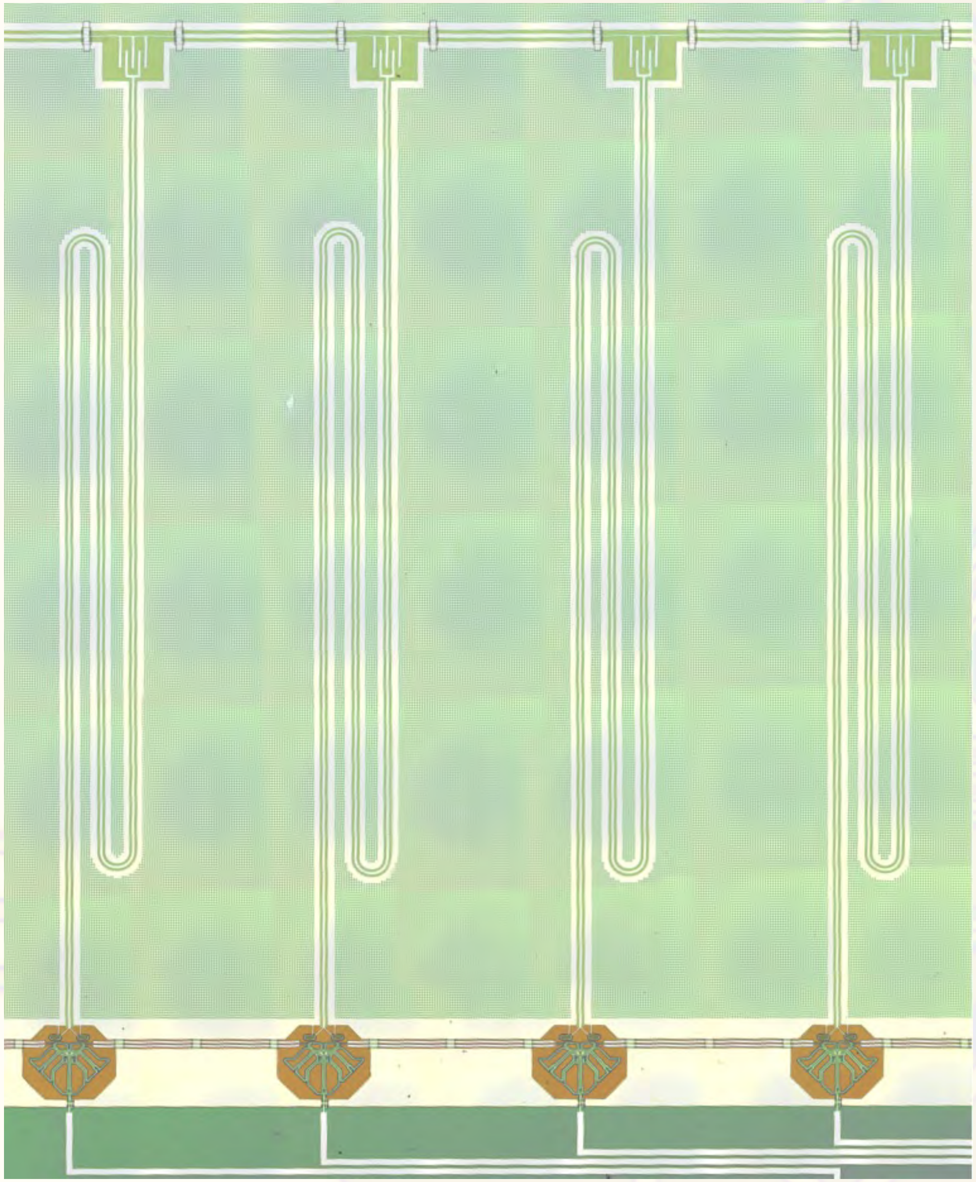

array readout using only one HEMT amplifier and two coaxes

# Particle Detection

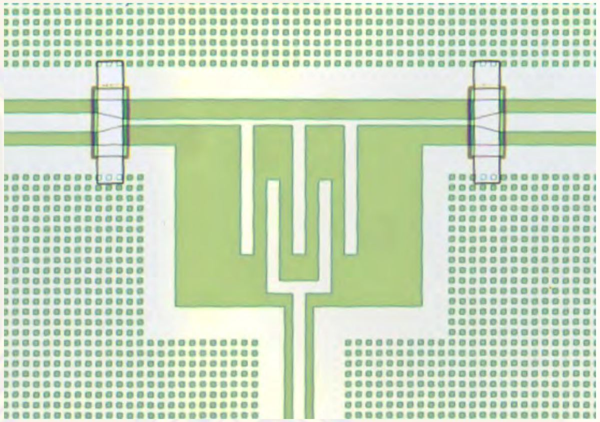



- 16 multiplexer channels with roughly equidistant spacing of ~ 25 MHz and BW ~ 1 MHz
- non-hysteretic rf-SQUID optimized for multiplexer
- Josephson junctions with high qualitiy factor
- 16 superconducting $\lambda/4$-transmission line resonator: $f_r = 4.0 \ldots 8.0$ GHz, $Q_c = 5000$
- superconducting feed line

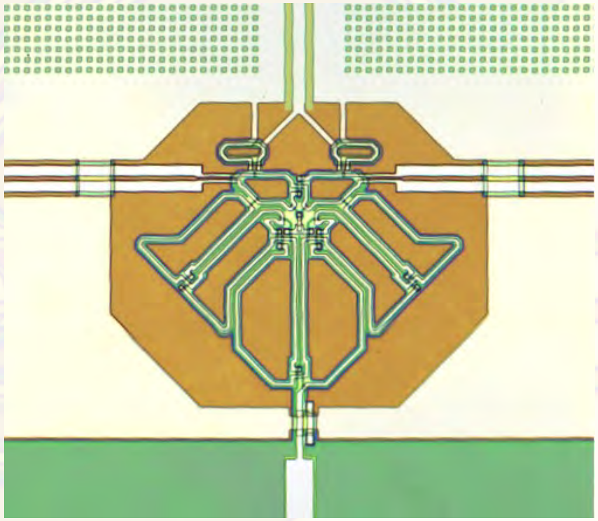
# Particle Detection



new coupling design

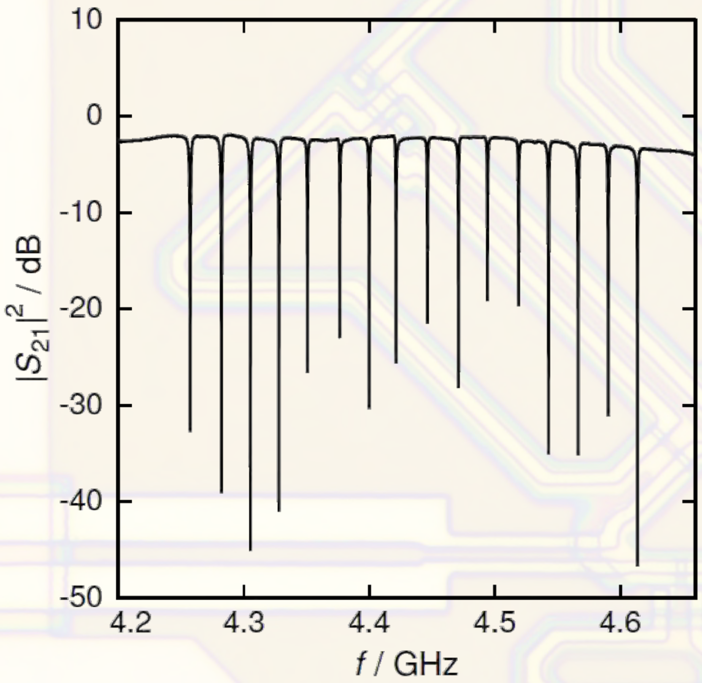


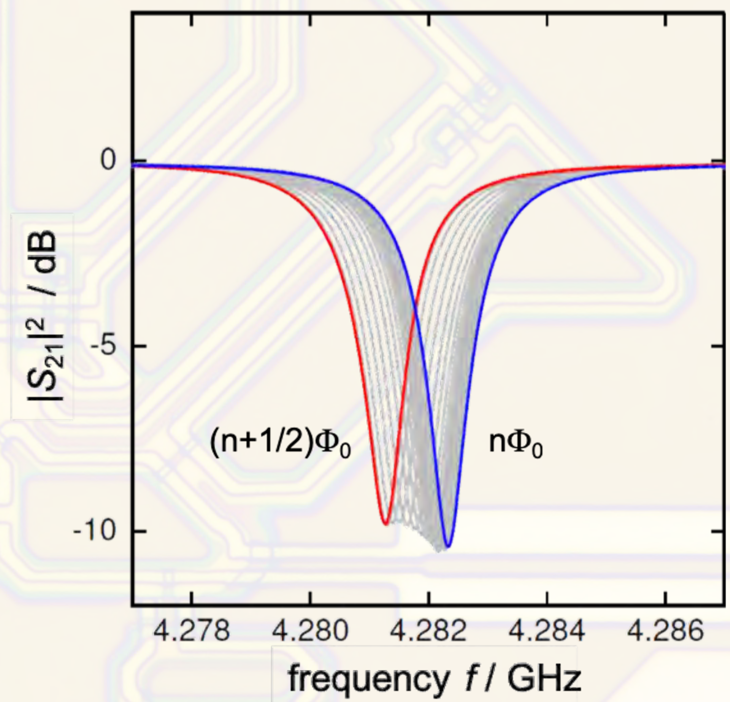
new rf SQUID design



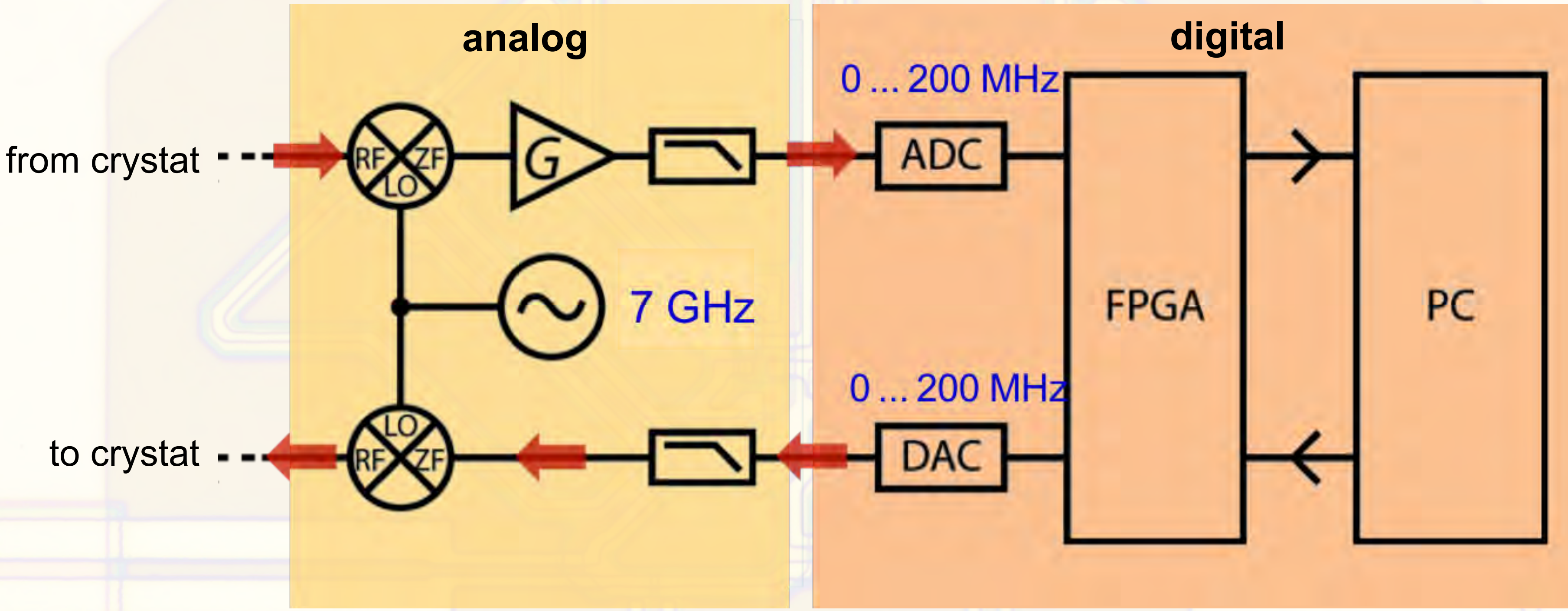
## Superconducting Resonators

16 multiplexer channels with equidistant spacing of ~ 25 MHz and BW ~ 1 MHz

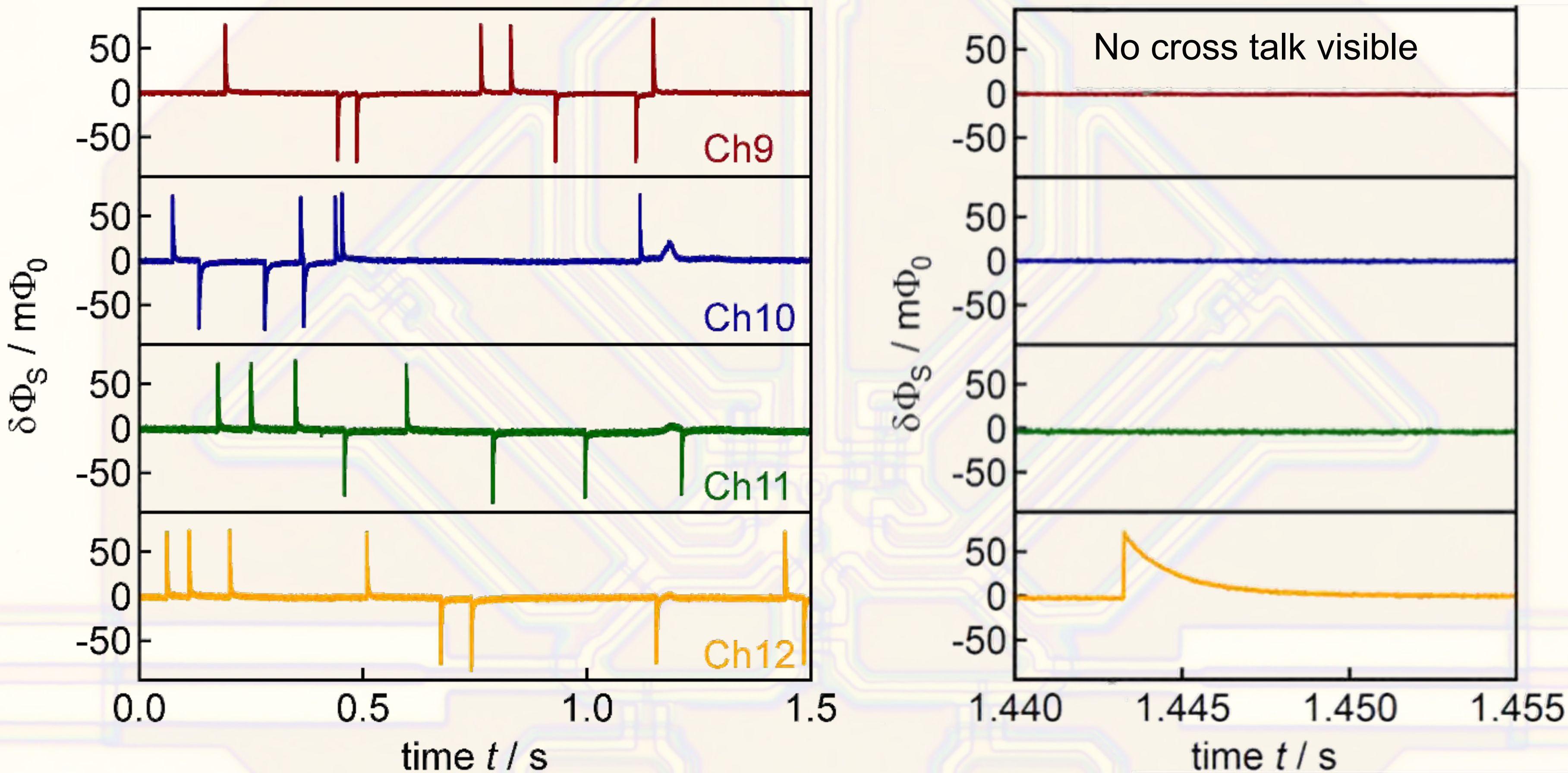


## Software Defined Radio



## Demonstration of Microwave SQUID Multiplexing




- parallel readout of 8 Pixels
- no visible cross talk