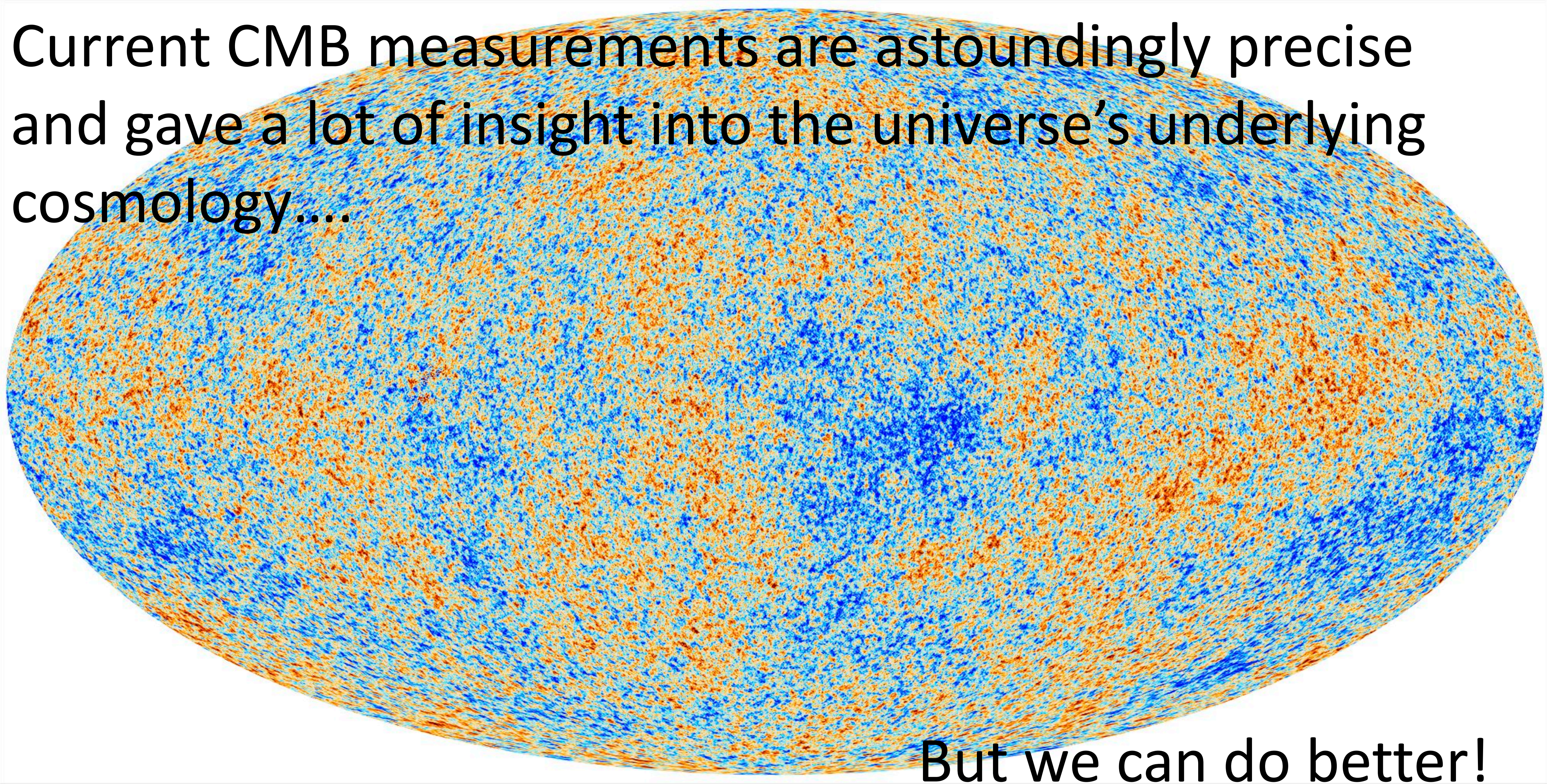
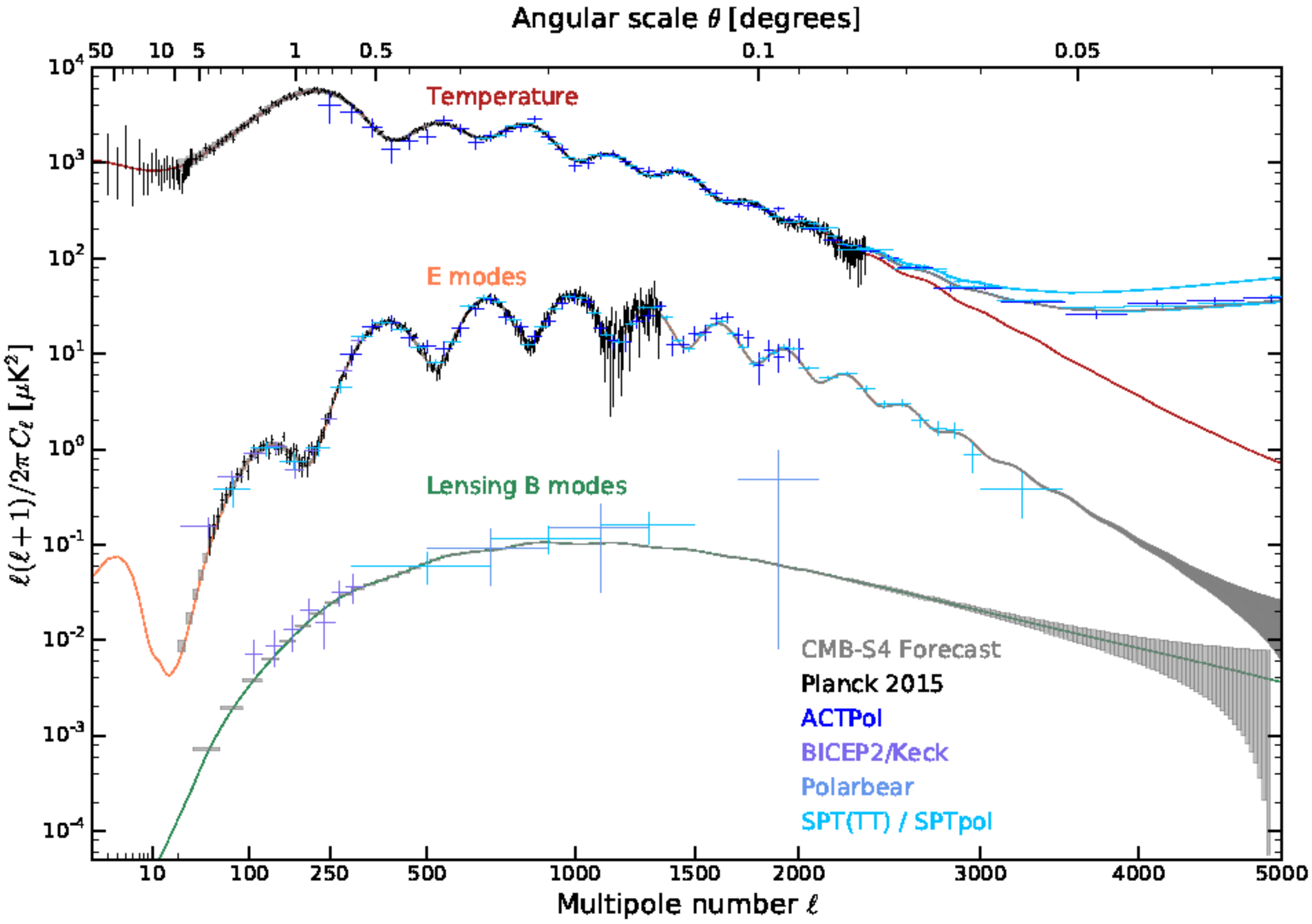
Making Next Gen CMB Detectors

Amy Tang



Current CMB measurements are astoundingly precise and gave a lot of insight into the universe’s underlying cosmology….

But we can do better!


Angular scale θ [degrees]
50
10
5
1
0.5
0.1
0.05
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)/2\pi\, C_\ell\ [\mu K^2]$
Temperature
E modes
Lensing B modes
CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
10
100
250
500
1000
1500
2000
3000
4000
5000
Multipole number ℓ

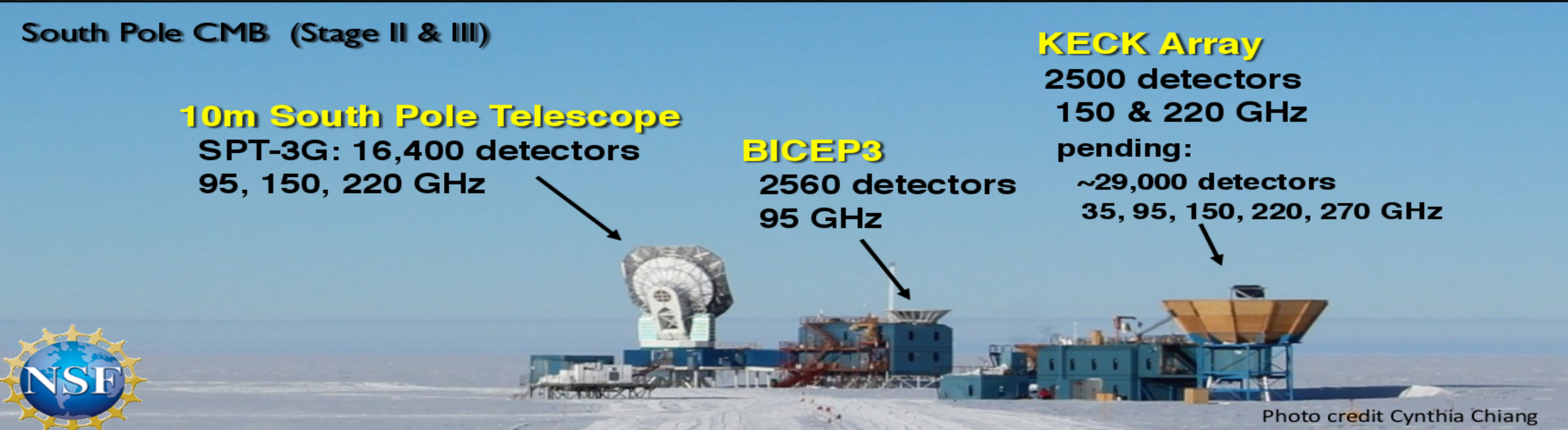
Atacama CMB (Stage II & III)

CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz

Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz

ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz

Photo: Rahul Datta & Alessandro Schillaci



South Pole CMB (Stage II & III)

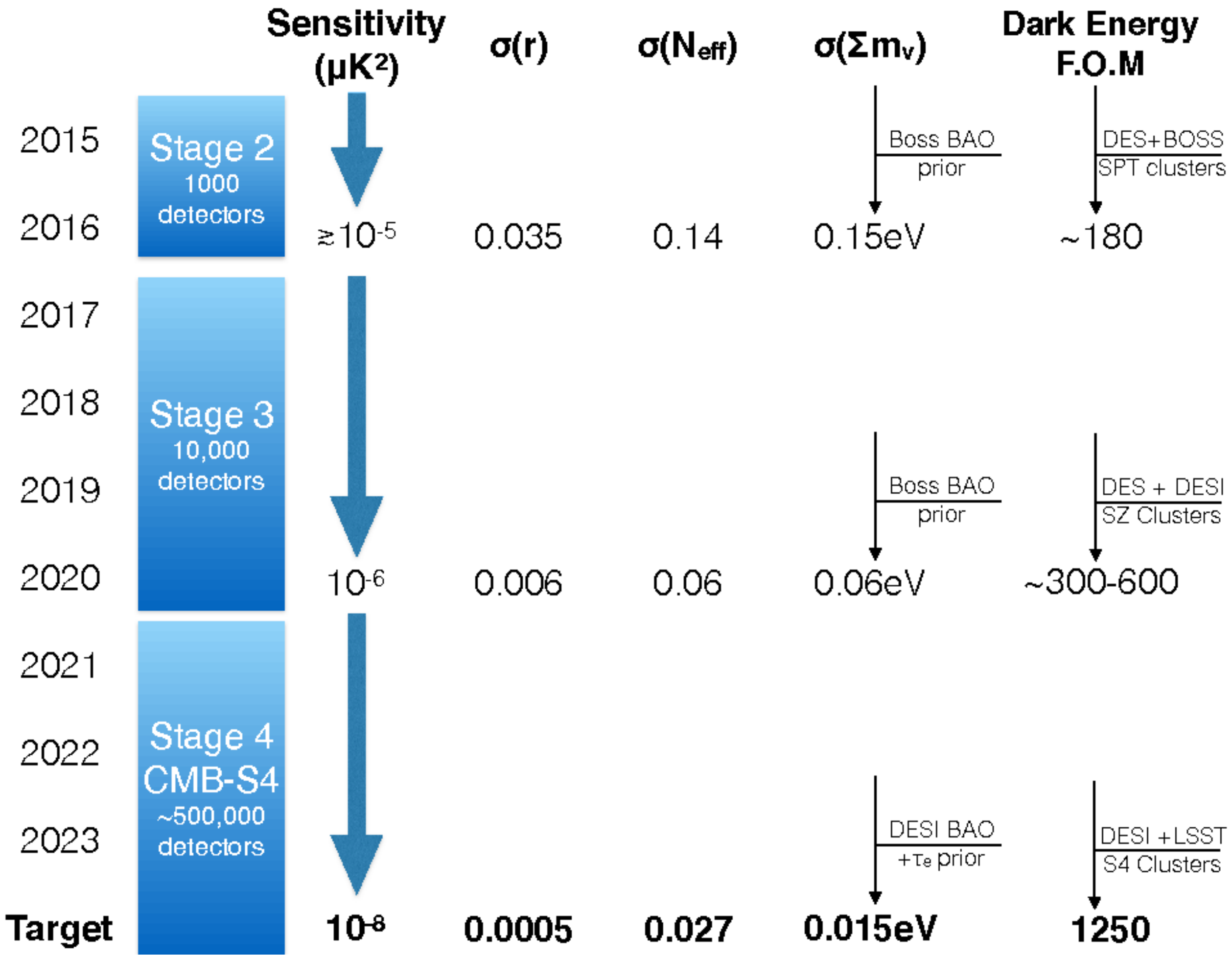
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

KECK Array
2500 detectors
150 & 220 GHz
pending:
~29,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang

CMB-S4

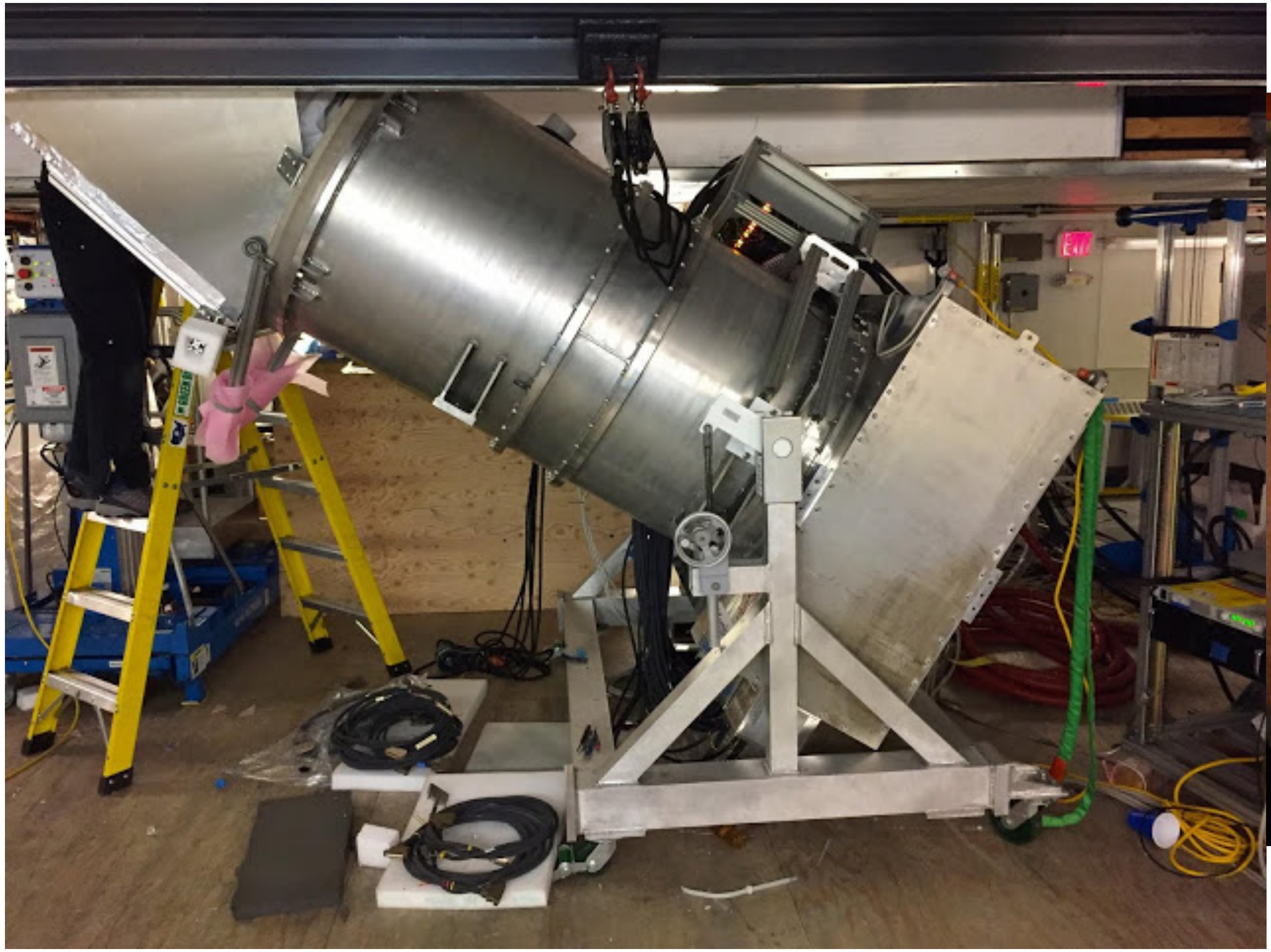


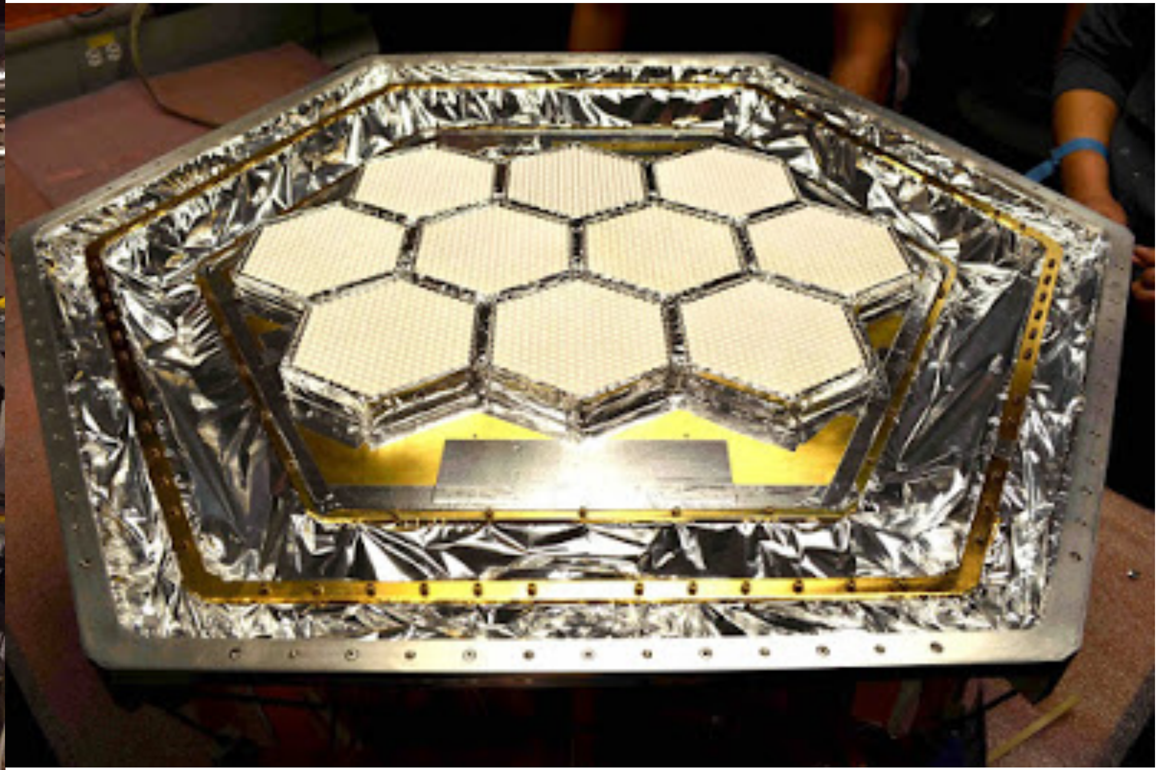
		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

- Science goals: inflation, neutrino masses hierarchy, dark energy, CMB lensing, … many more!


Caution
Heavy ~~vehicles~~ Instrumentation
~~turning~~ ahead

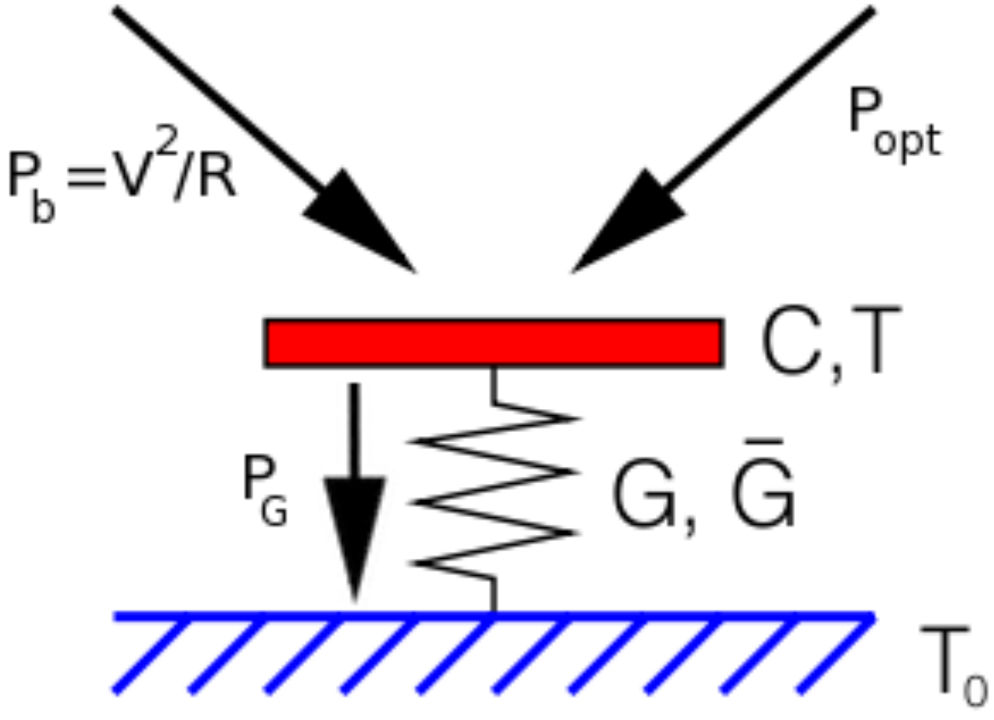
Detectors

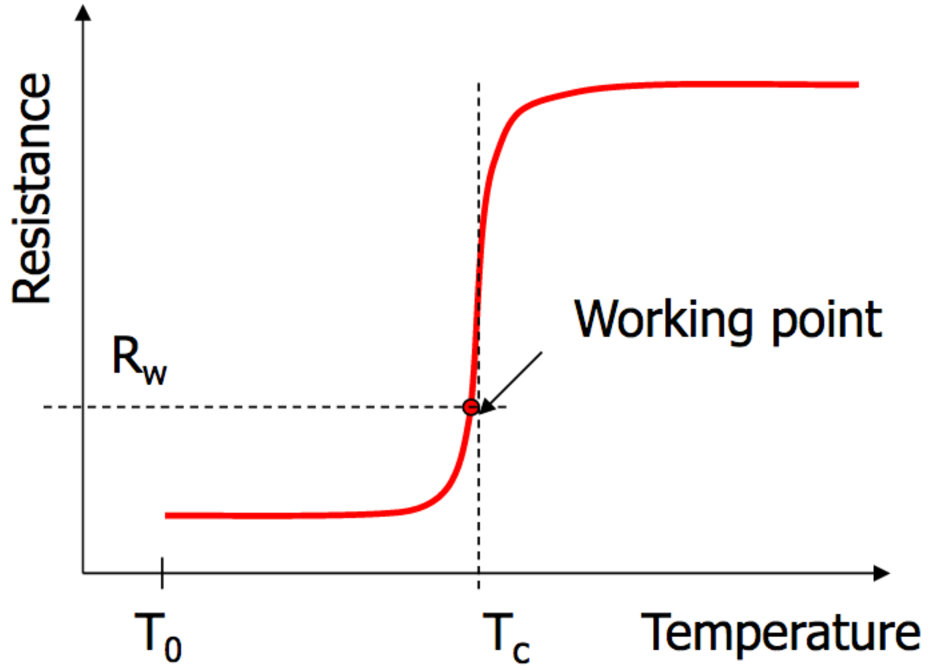




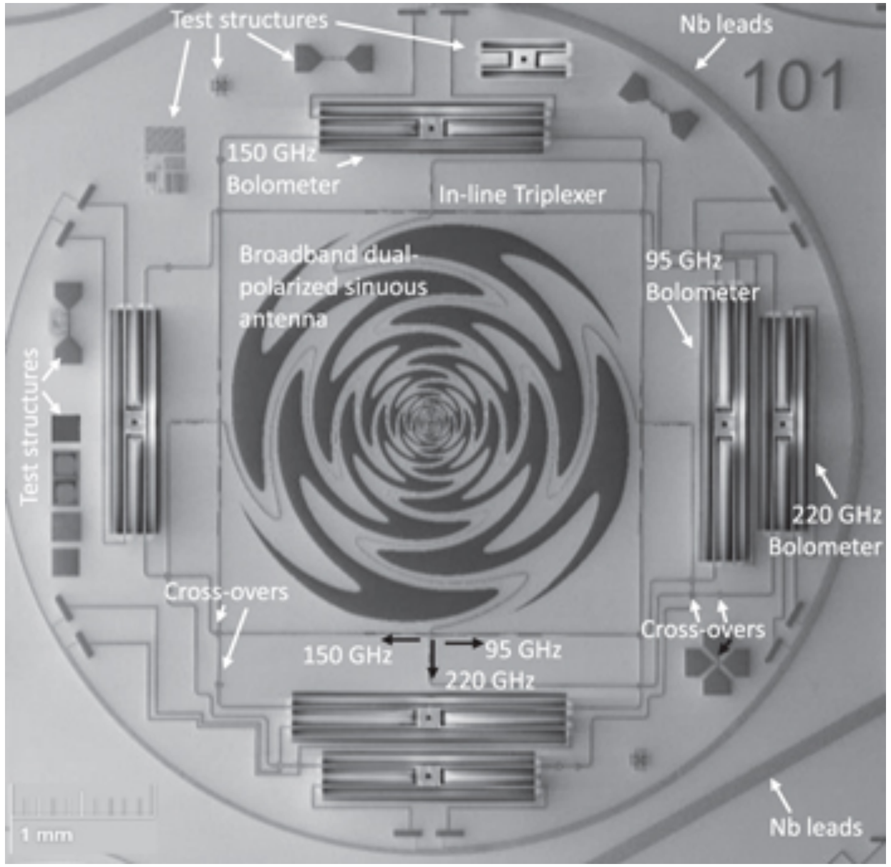
TES Bolometers

- Pins detector T and R a constant value in transition
- Negative electrothermal feedback: As P_{opt} increases, R increases, cutting off P_{bias}

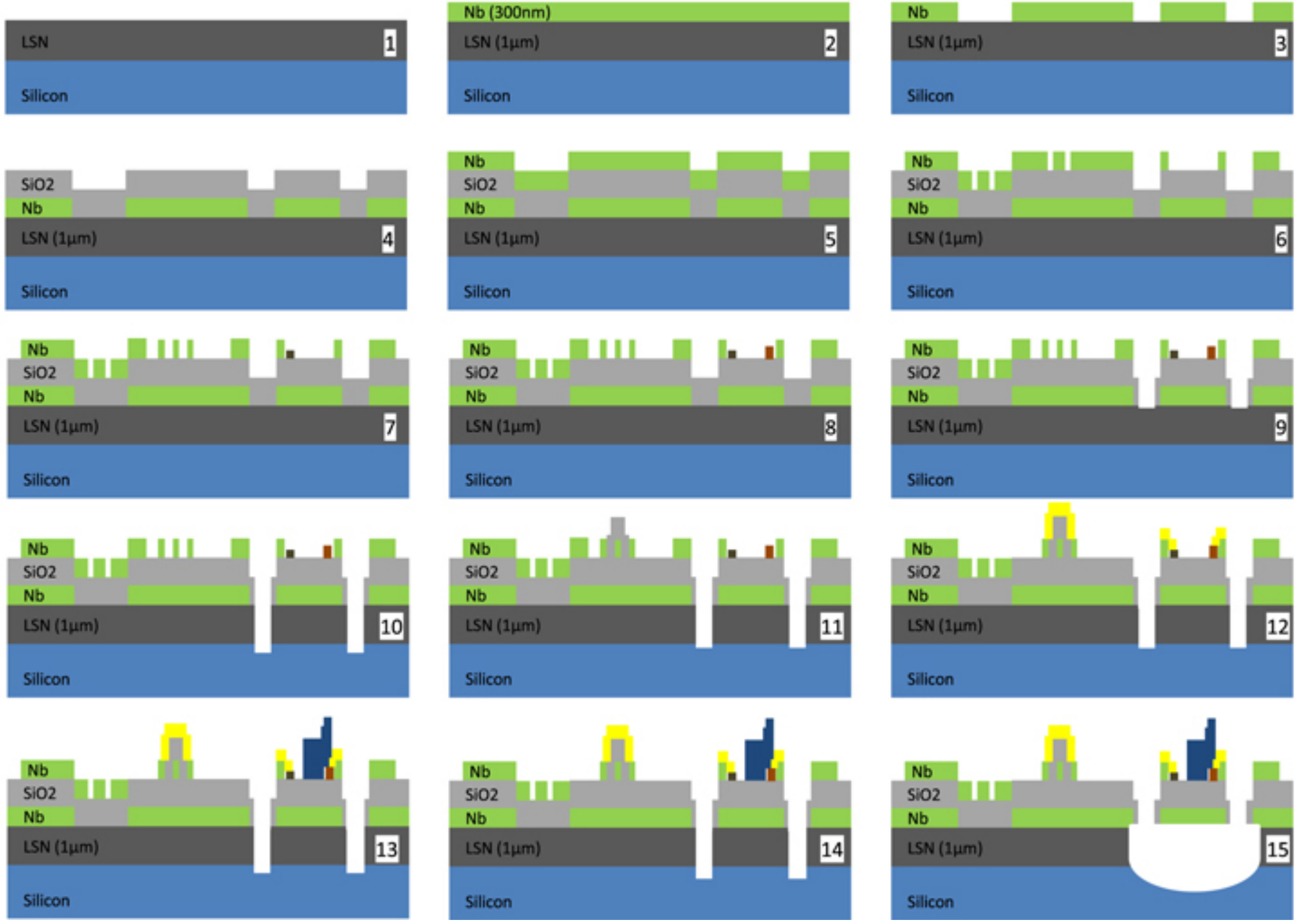


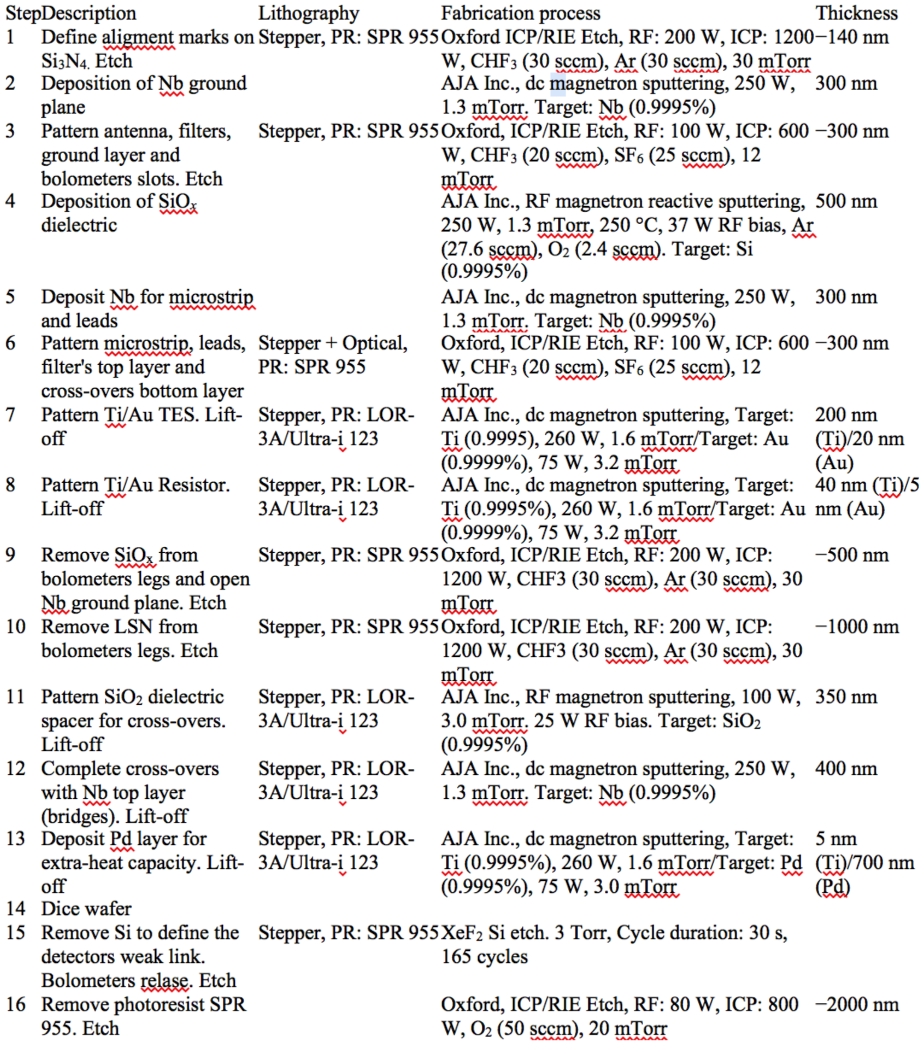


3G Detectors



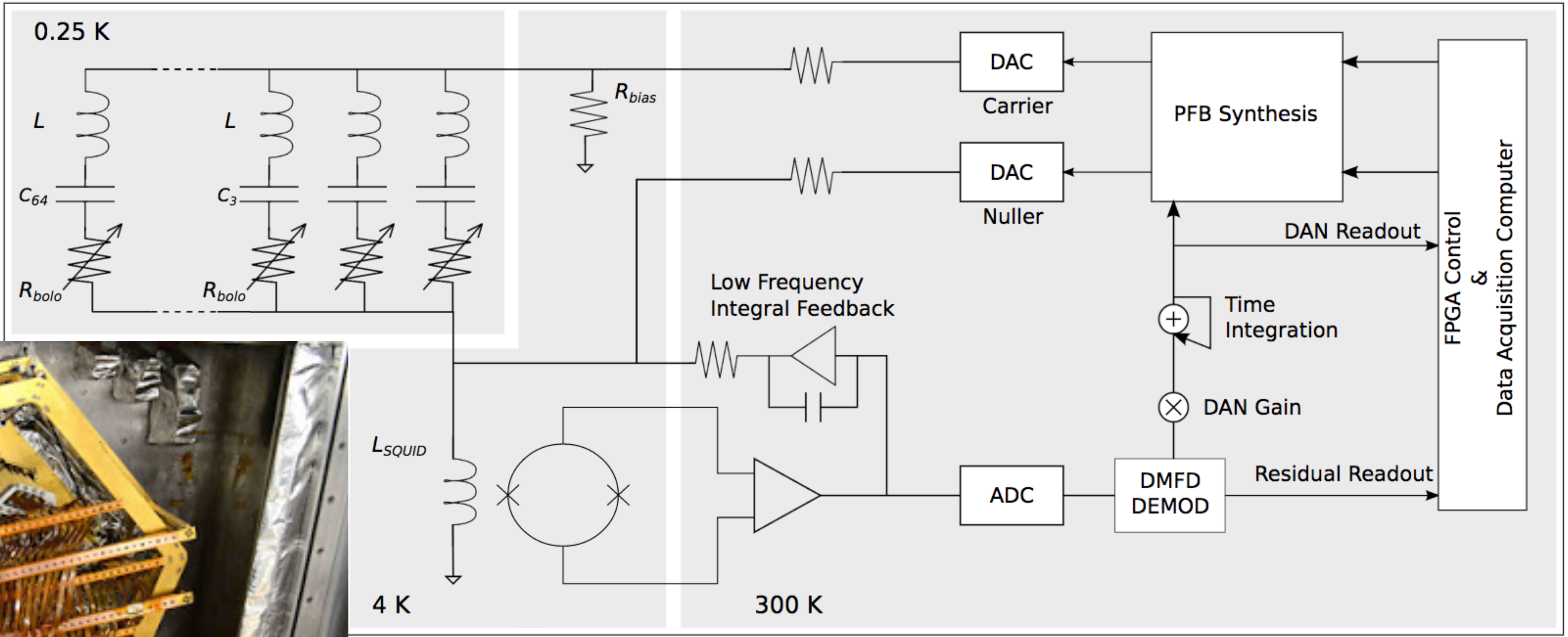
Fabrication of TES Bolometers

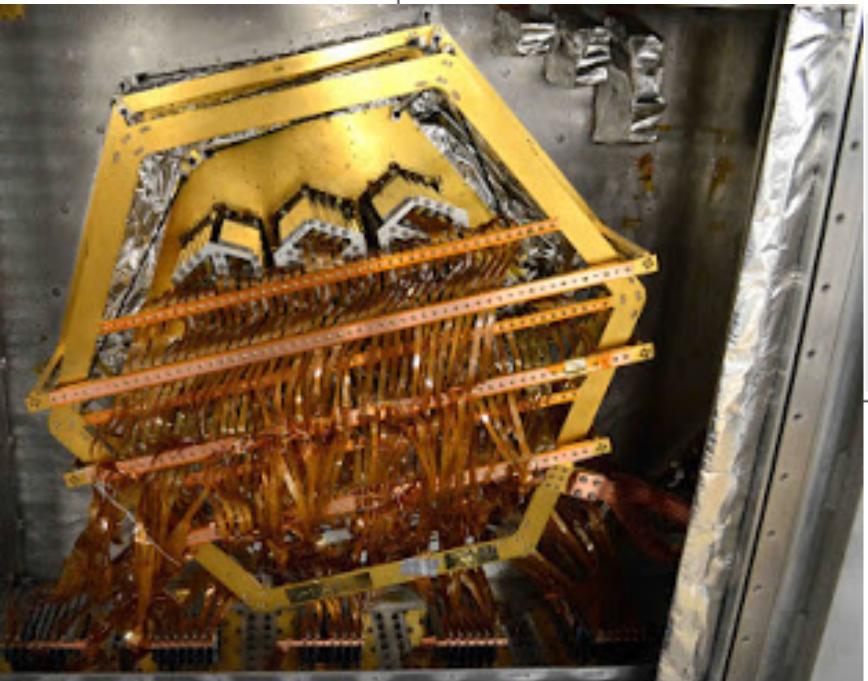




Step	Description	Lithography	Fabrication process	Thickness
1	Define aligment marks on Si_3N_4. Etch	Stepper, PR: SPR 955	Oxford ICP/RIE Etch, RF: 200 W, ICP: 1200 W, CHF_3 (30 sccm), Ar (30 sccm), 30 mTorr	−140 nm
2	Deposition of Nb ground plane		AJA Inc., dc magnetron sputtering, 250 W, 1.3 mTorr. Target: Nb (0.9995%)	300 nm
3	Pattern antenna, filters, ground layer and bolometers slots. Etch	Stepper, PR: SPR 955	Oxford, ICP/RIE Etch, RF: 100 W, ICP: 600 W, CHF_3 (20 sccm), SF_6 (25 sccm), 12 mTorr	−300 nm
4	Deposition of SiO_x dielectric		AJA Inc., RF magnetron reactive sputtering, 250 W, 1.3 mTorr, 250 °C, 37 W RF bias, Ar (27.6 sccm), O_2 (2.4 sccm). Target: Si (0.9995%)	500 nm
5	Deposit Nb for microstrip and leads		AJA Inc., dc magnetron sputtering, 250 W, 1.3 mTorr. Target: Nb (0.9995%)	300 nm
6	Pattern microstrip, leads, filter's top layer and cross-overs bottom layer	Stepper + Optical, PR: SPR 955	Oxford, ICP/RIE Etch, RF: 100 W, ICP: 600 W, CHF_3 (20 sccm), SF_6 (25 sccm), 12 mTorr	−300 nm
7	Pattern Ti/Au TES. Lift-off	Stepper, PR: LOR-3A/Ultra-i 123	AJA Inc., dc magnetron sputtering, Target: Ti (0.9995), 260 W, 1.6 mTorr/Target: Au (0.9999%), 75 W, 3.2 mTorr	200 nm (Ti)/20 nm (Au)
8	Pattern Ti/Au Resistor. Lift-off	Stepper, PR: LOR-3A/Ultra-i 123	AJA Inc., dc magnetron sputtering, Target: Ti (0.9995%), 260 W, 1.6 mTorr/Target: Au (0.9999%), 75 W, 3.2 mTorr	40 nm (Ti)/5 nm (Au)
9	Remove SiO_x from bolometers legs and open Nb ground plane. Etch	Stepper, PR: SPR 955	Oxford, ICP/RIE Etch, RF: 200 W, ICP: 1200 W, CHF3 (30 sccm), Ar (30 sccm), 30 mTorr	−500 nm
10	Remove LSN from bolometers legs. Etch	Stepper, PR: SPR 955	Oxford, ICP/RIE Etch, RF: 200 W, ICP: 1200 W, CHF3 (30 sccm), Ar (30 sccm), 30 mTorr	−1000 nm
11	Pattern SiO_2 dielectric spacer for cross-overs. Lift-off	Stepper, PR: LOR-3A/Ultra-i 123	AJA Inc., RF magnetron sputtering, 100 W, 3.0 mTorr. 25 W RF bias. Target: SiO_2 (0.9995%)	350 nm
12	Complete cross-overs with Nb top layer (bridges). Lift-off	Stepper, PR: LOR-3A/Ultra-i 123	AJA Inc., dc magnetron sputtering, 250 W, 1.3 mTorr. Target: Nb (0.9995%)	400 nm
13	Deposit Pd layer for extra-heat capacity. Lift-off	Stepper, PR: LOR-3A/Ultra-i 123	AJA Inc., dc magnetron sputtering, Target: Ti (0.9995%), 260 W, 1.6 mTorr/Target: Pd (0.9995%), 75 W, 3.0 mTorr	5 nm (Ti)/700 nm (Pd)
14	Dice wafer			
15	Remove Si to define the detectors weak link. Bolometers relase. Etch	Stepper, PR: SPR 955	XeF_2 Si etch. 3 Torr, Cycle duration: 30 s, 165 cycles	
16	Remove photoresist SPR 955. Etch		Oxford, ICP/RIE Etch, RF: 80 W, ICP: 800 W, O_2 (50 sccm), 20 mTorr	−2000 nm

Reading TESs





Lots of electronics!

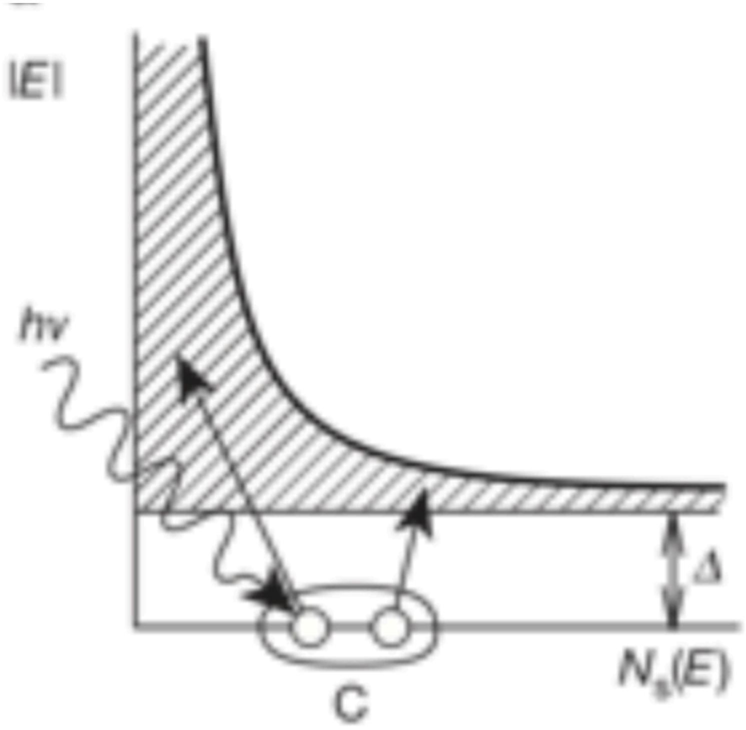
Challenges of TES

- Fabrication is difficult, especially suspended membranes. Need good control over film
- SQUIDs are tricky: extremely expensive, difficult to multiplex and readout

Let’s use KIDs!

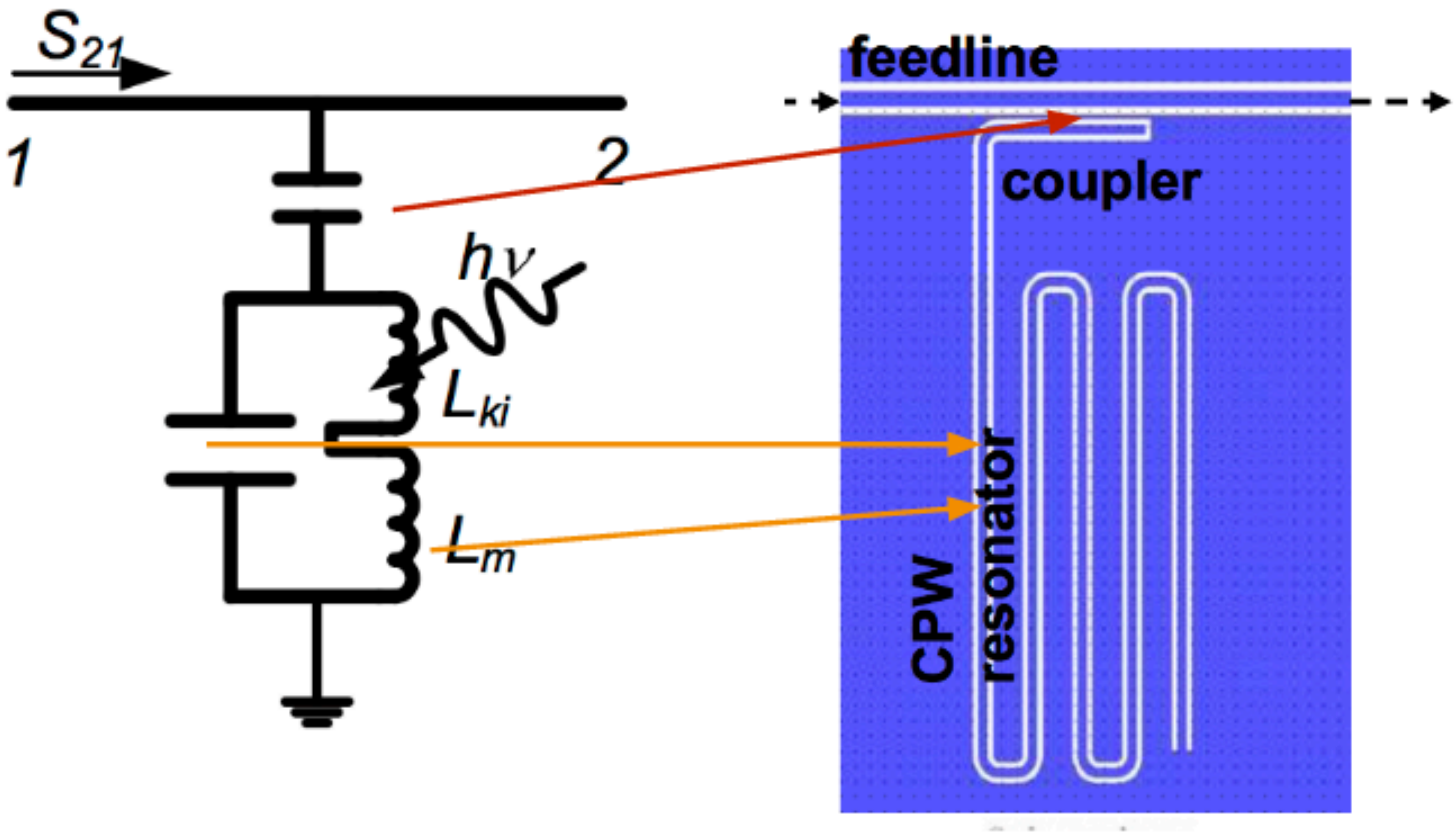
Superconductivity for Astronomers

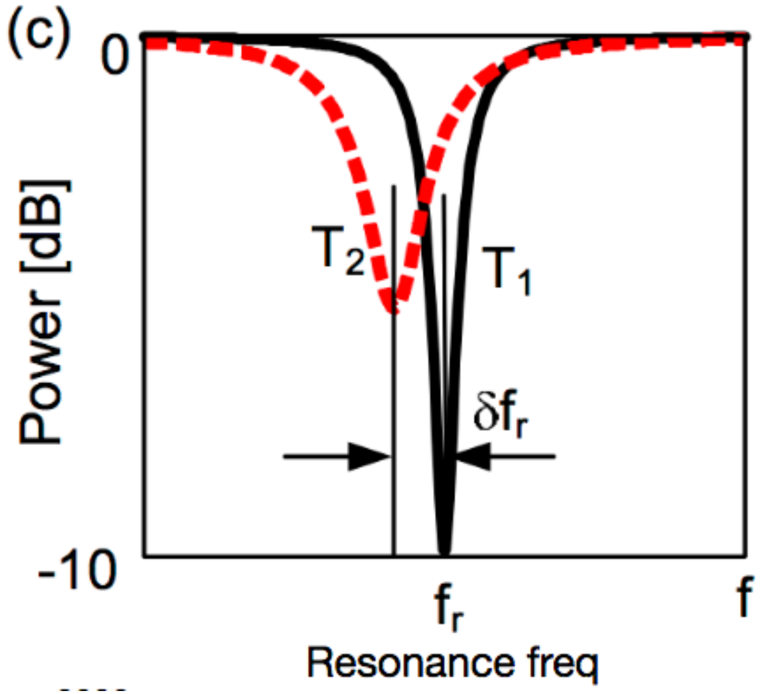
- superconductors: DC resistance is 0 for T << Tc due to Cooper pairs (paired electrons)
- photons with $E = h\nu > 2E_{gap}$ or heat break Cooper pairs -> quasiparticles



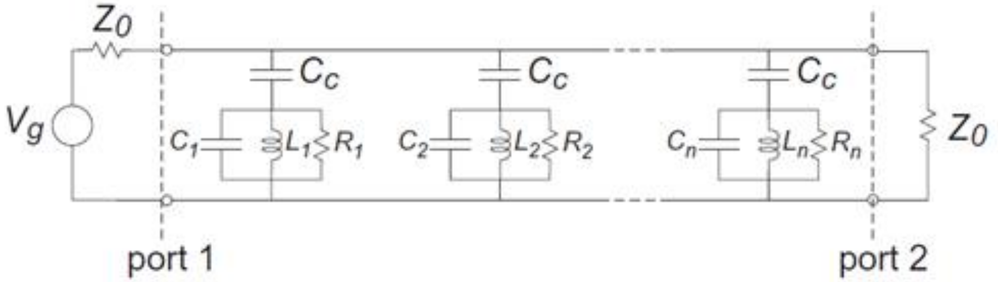
The KI in MKID

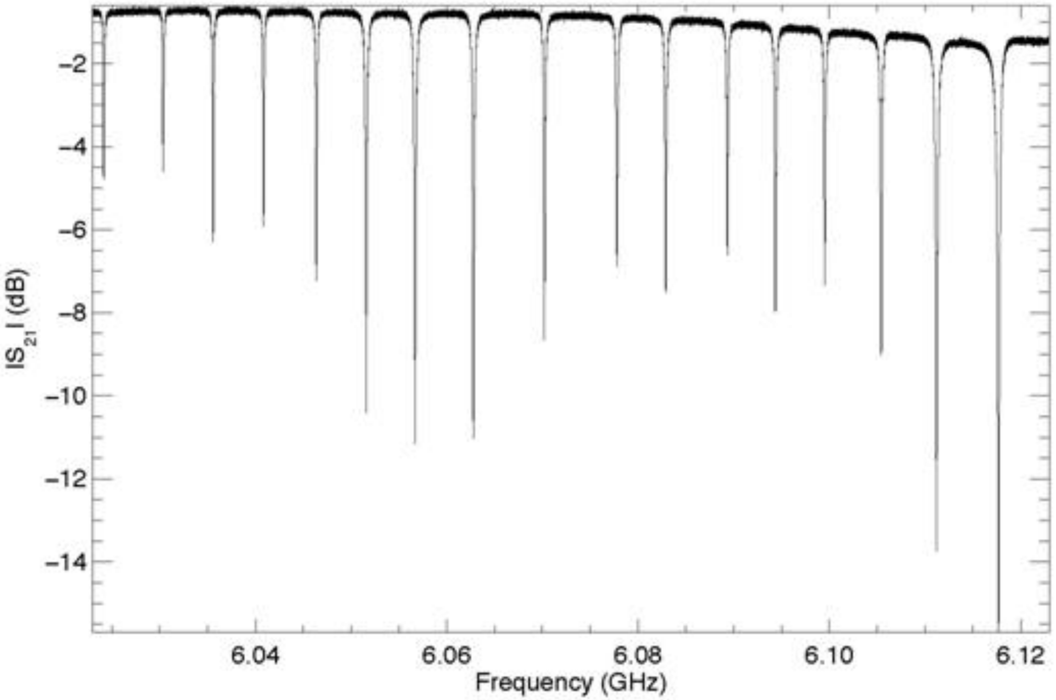
- Cooper pairs has an inertial mass, in AC field they decelerate/accelerate
  - inertial mass resists acceleration -> inductance
- kinetic inductance changes with number of quasiparticles, use a resonance circuit to see resonance frequency change when photons strike
  - can see similar effect with varying temperature, power -> use this to understand our resonators!


S_{21}
1
2
$h\nu$
L_{ki}
L_m
feedline
coupler
CPW resonator


(c)
0
-10
Power [dB]
T_2
T_1
δf_r
f_r
f
Resonance freq

Multiplexing Advantage





Most KIDs are designed to resonate at 1-10GHz and with

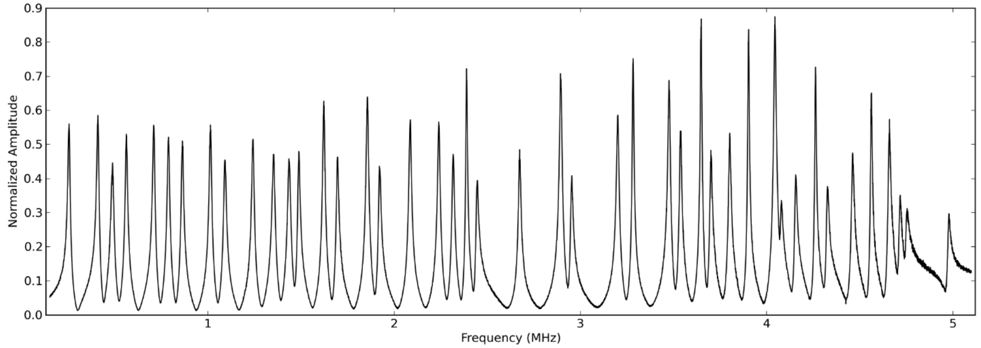
$$Q_L > 10^5.$$

Each KID will occupy a bandwidth of around

$$\Delta f = f/Q_L \sim 10\text{–}100 \text{ kHz}$$

Taking account of frequency shifts, we can pack them with spacing of

$$2\Delta f.$$

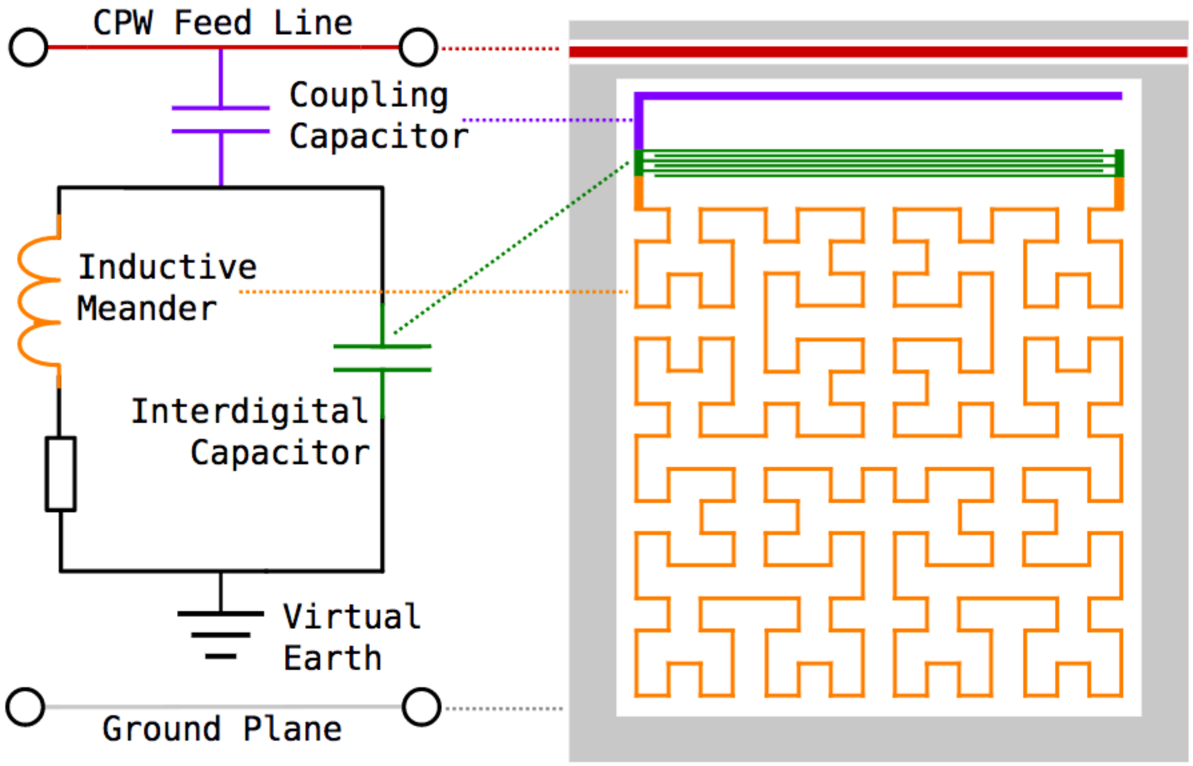


TES bolometers

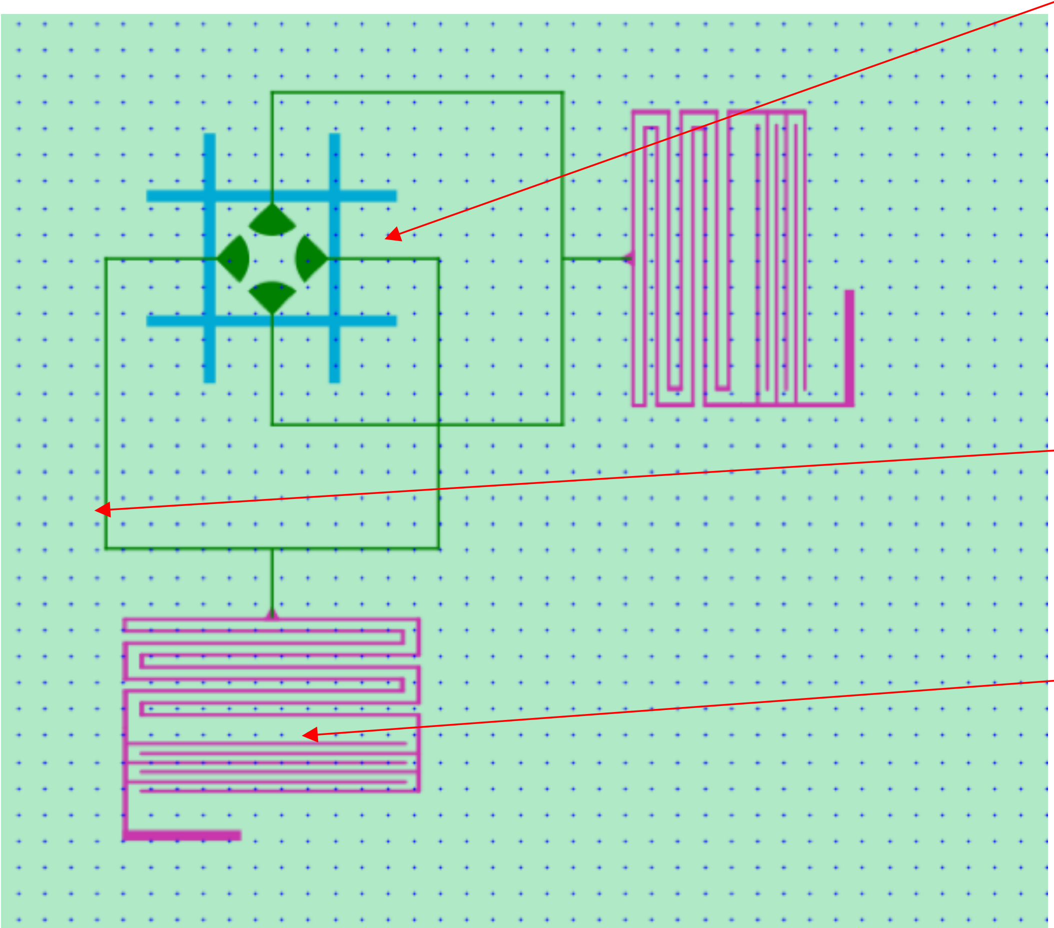
Advantages over TES

- High Q -> very easy to do frequency multiplexing, can be read out using a single cable/amplifier
- Devices very simple and easy to fabricate, very uniform results at low cost

Lumped Element KIDs (LEKIDs)



Our Design



Dual polarization twin slot antennas

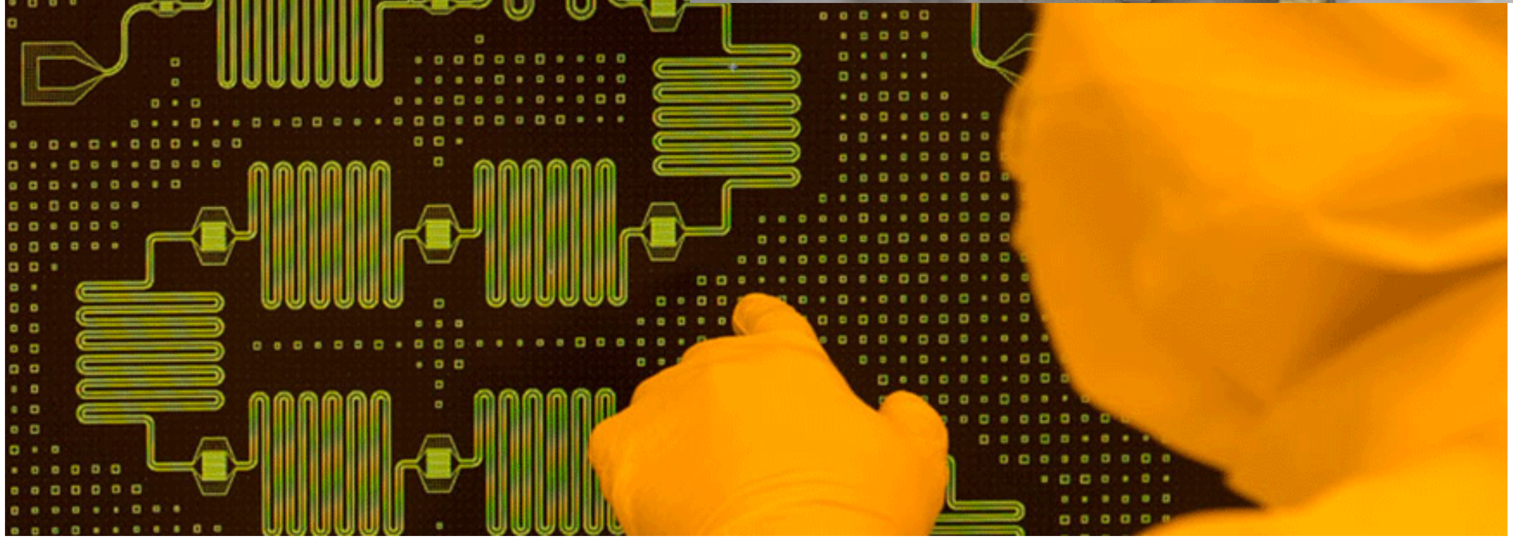
Nb stripline

Al KID

Long term goal, coupling the sinuous antenna to our KIDs

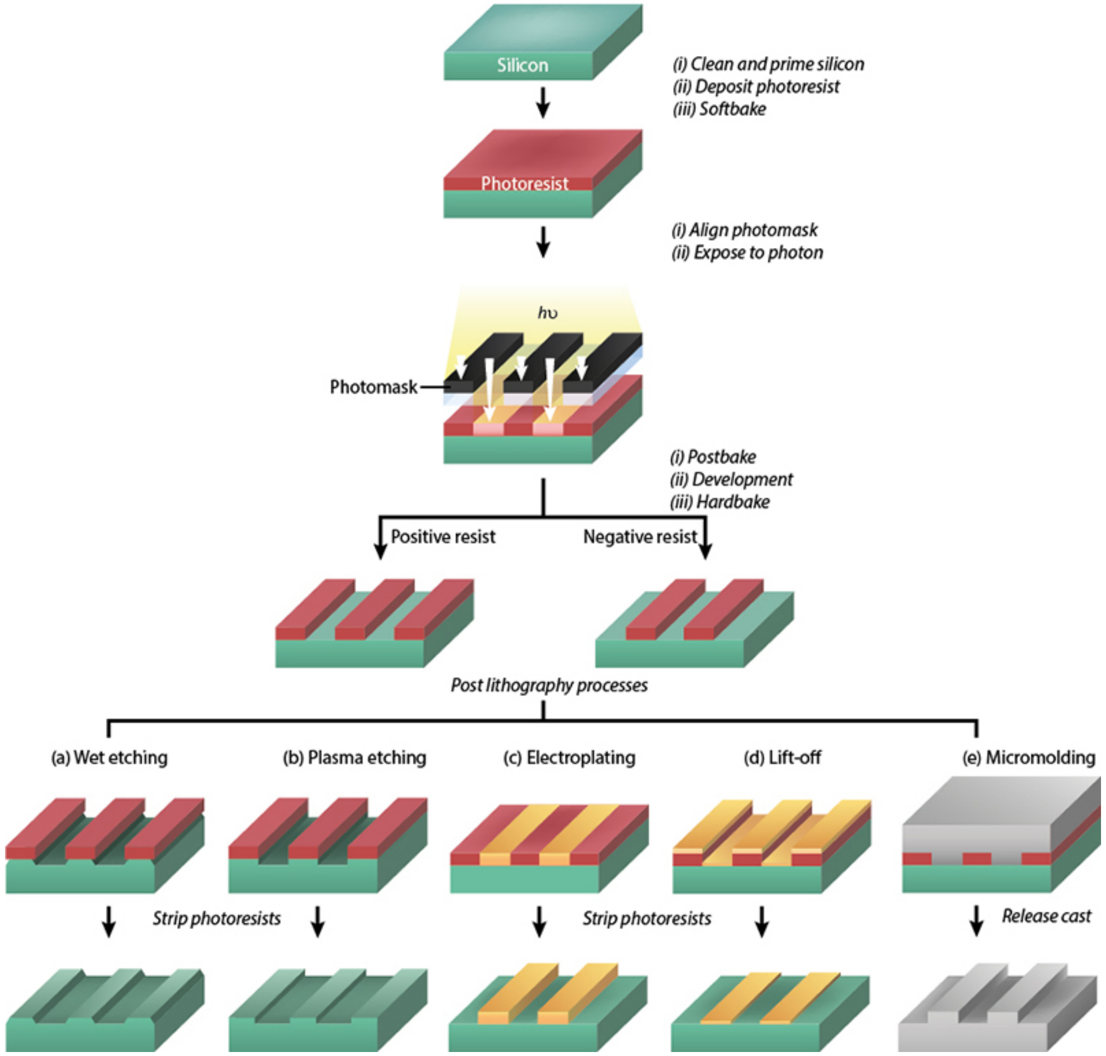
Designed by P. Barry & E. Mayer

Fabrication

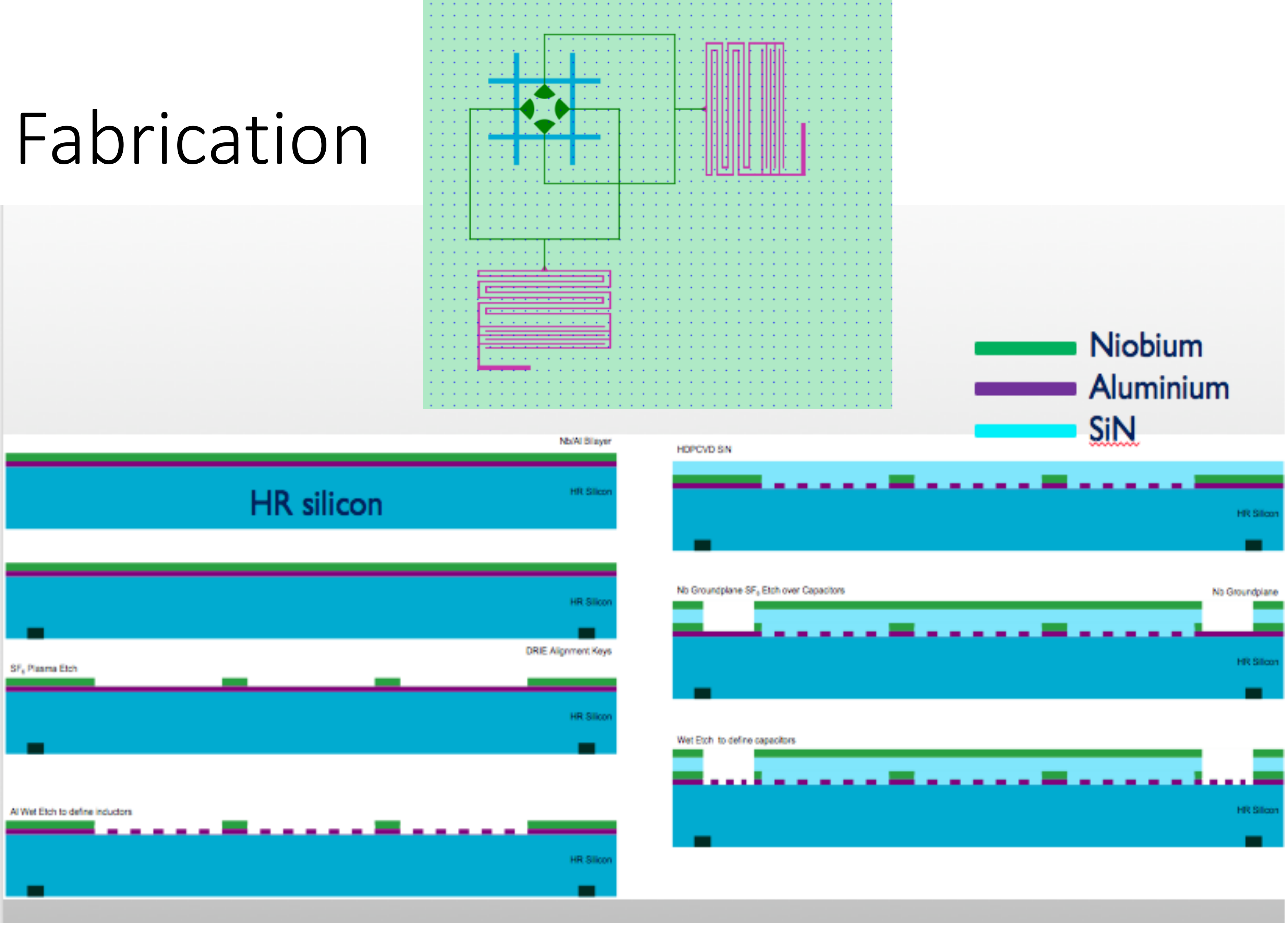


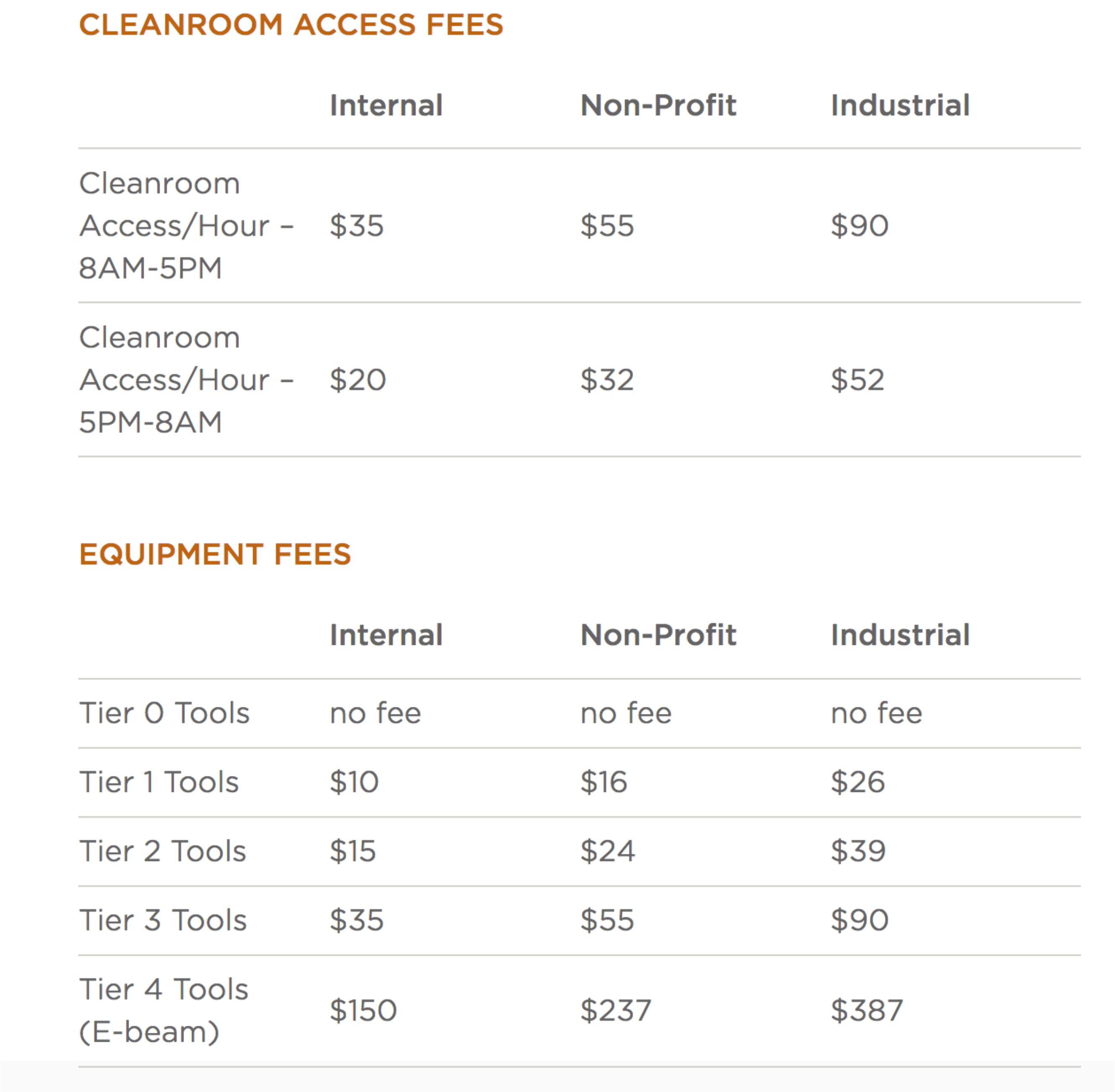
A Quick Intro into Fab…

Deposit material
Lithography
Etch
Repeat!



Fabrication





CLEANROOM ACCESS FEES

	Internal	Non-Profit	Industrial
Cleanroom Access/Hour - 8AM-5PM	$35	$55	$90
Cleanroom Access/Hour - 5PM-8AM	$20	$32	$52

EQUIPMENT FEES

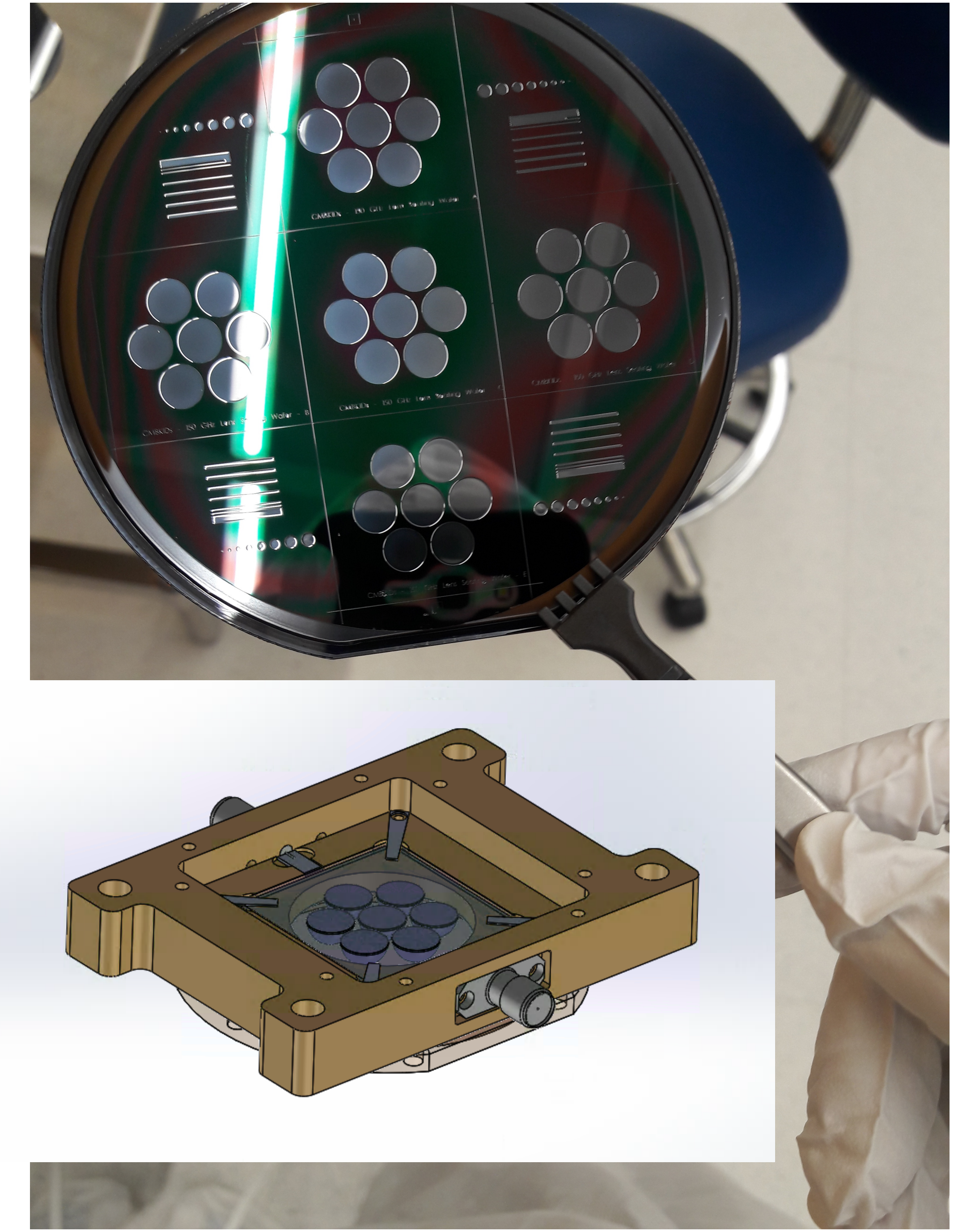
	Internal	Non-Profit	Industrial
Tier 0 Tools	no fee	no fee	no fee
Tier 1 Tools	$10	$16	$26
Tier 2 Tools	$15	$24	$39
Tier 3 Tools	$35	$55	$90
Tier 4 Tools (E-beam)	$150	$237	$387

Rates are per hour!!!

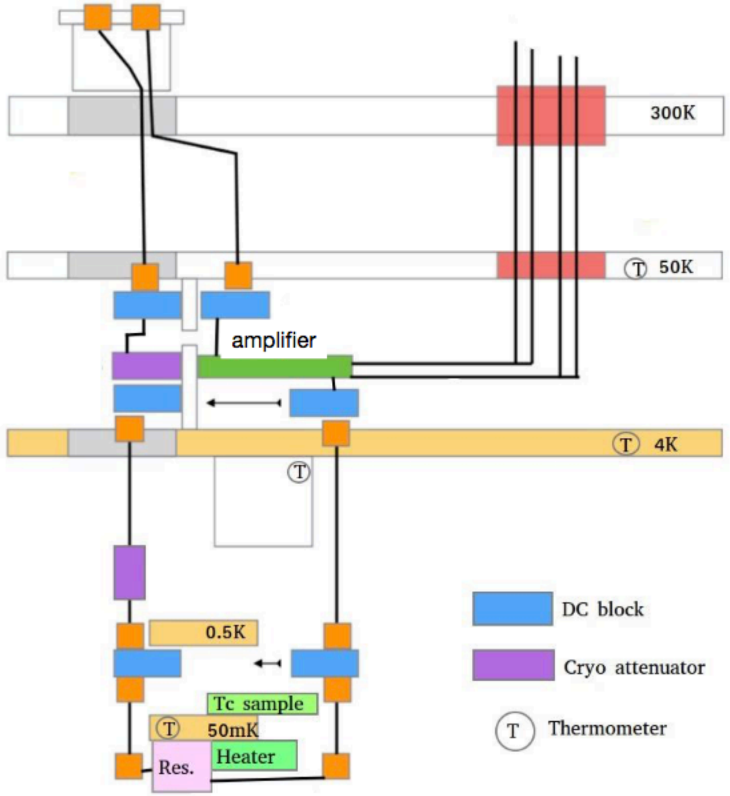
SPT : currently cost ~$3000/wafer, turnaround ~2weeks

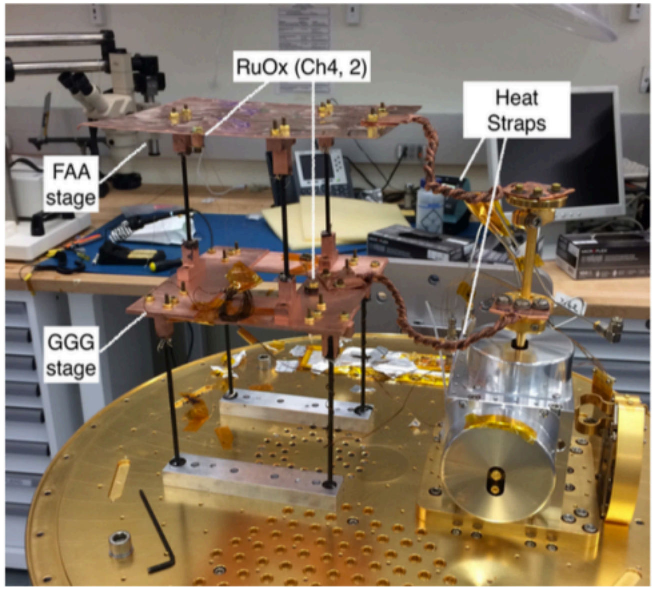
KIDs: ~$1000/wafer, turnaround <1 week, less likely to fail during fabrication

Lens Wafer Development



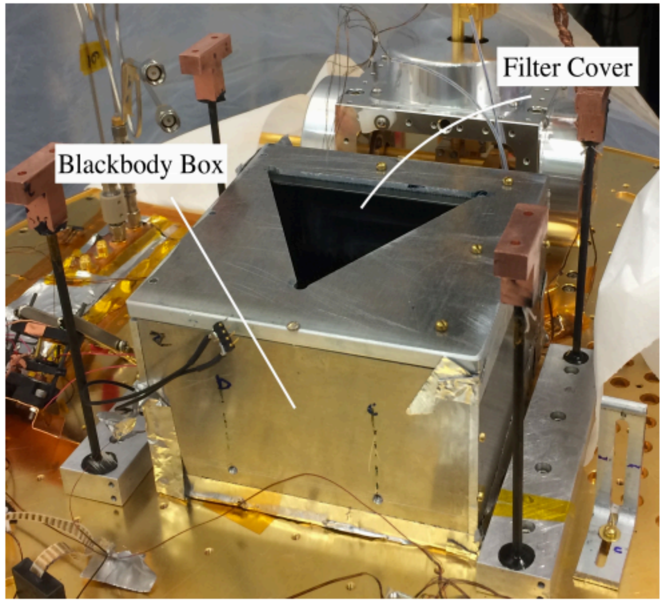
Testing set up



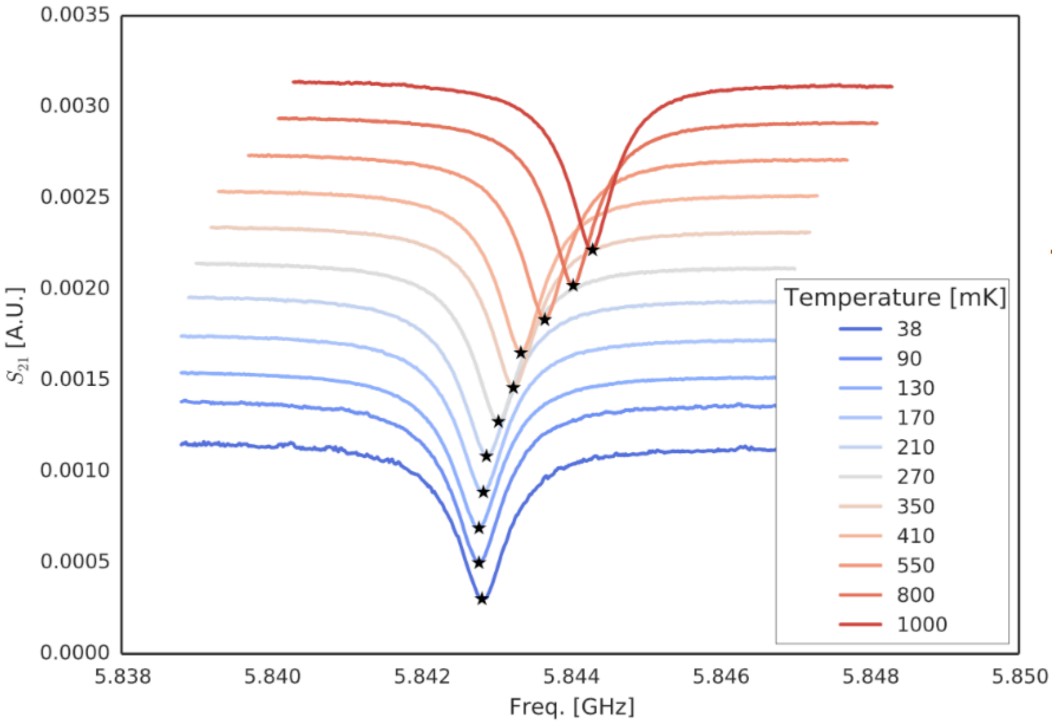


Blackbody:
T up to ~40K
Filters define bandpass ~ 90-250GHz

V. Baungally



Characterizing



- Take VNA sweeps of different powers and temperatures
- Fit the transmission gain to

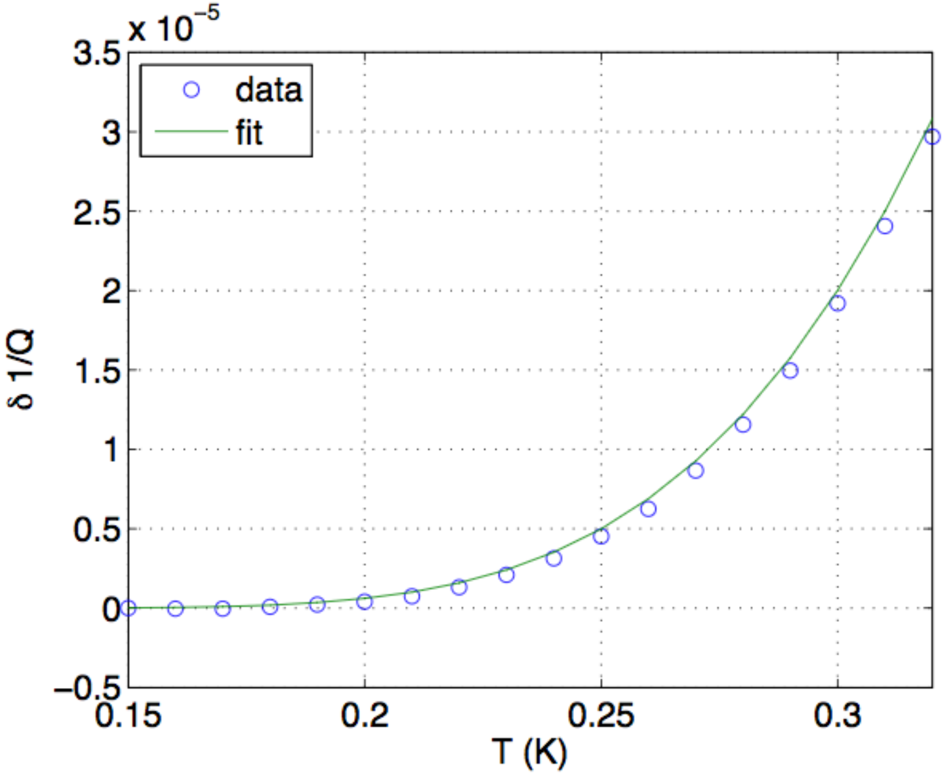
$$S_{21}(x) = \frac{1/Q_i + 2i\,(x + \delta f/f_r)}{1/Q_r + 2ix}$$

$$x = (\nu - \tilde{f}_r)/\tilde{f}_r,\ \tilde{f}_r = f_r + \delta f$$

Mattis Bardeen Loss

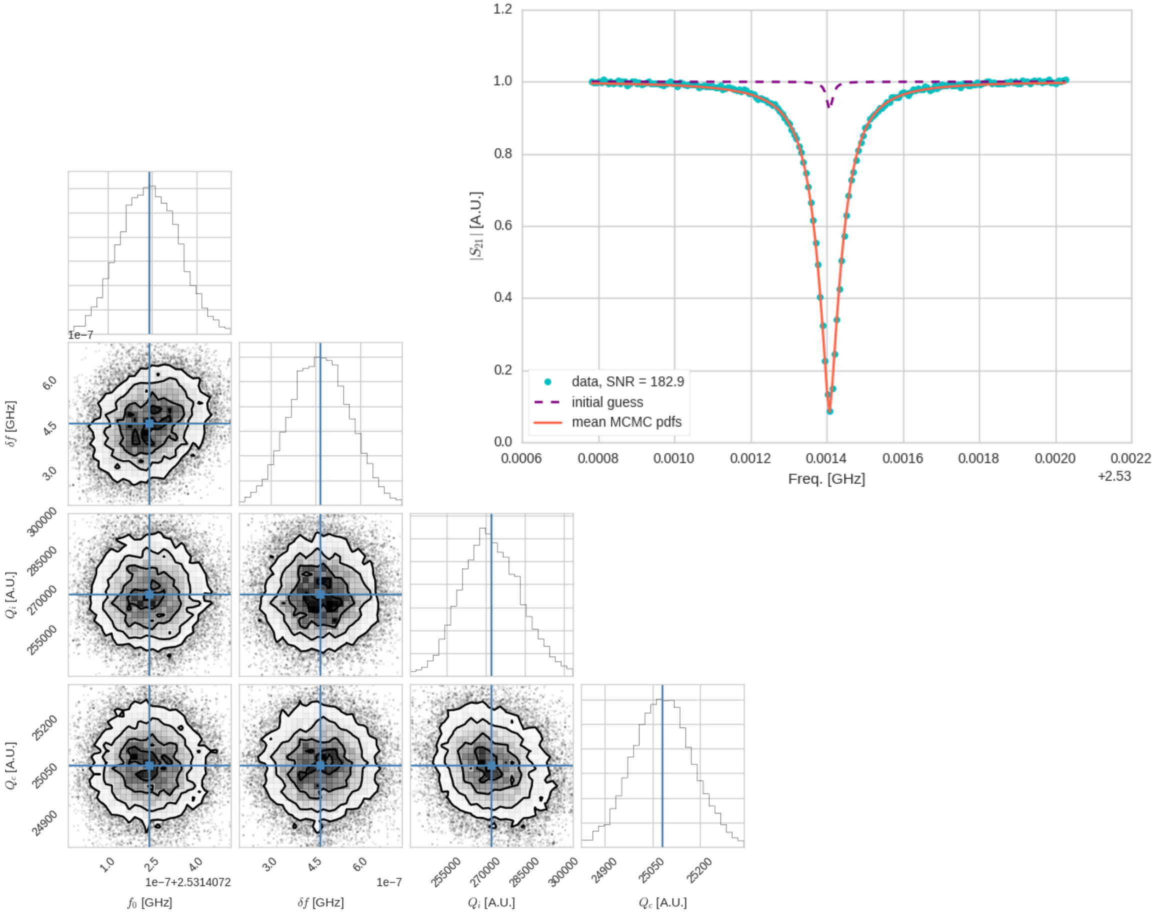
- comes from excess n_{qp} from pair breaking / T change
- depends on Egap and kinetic inductance

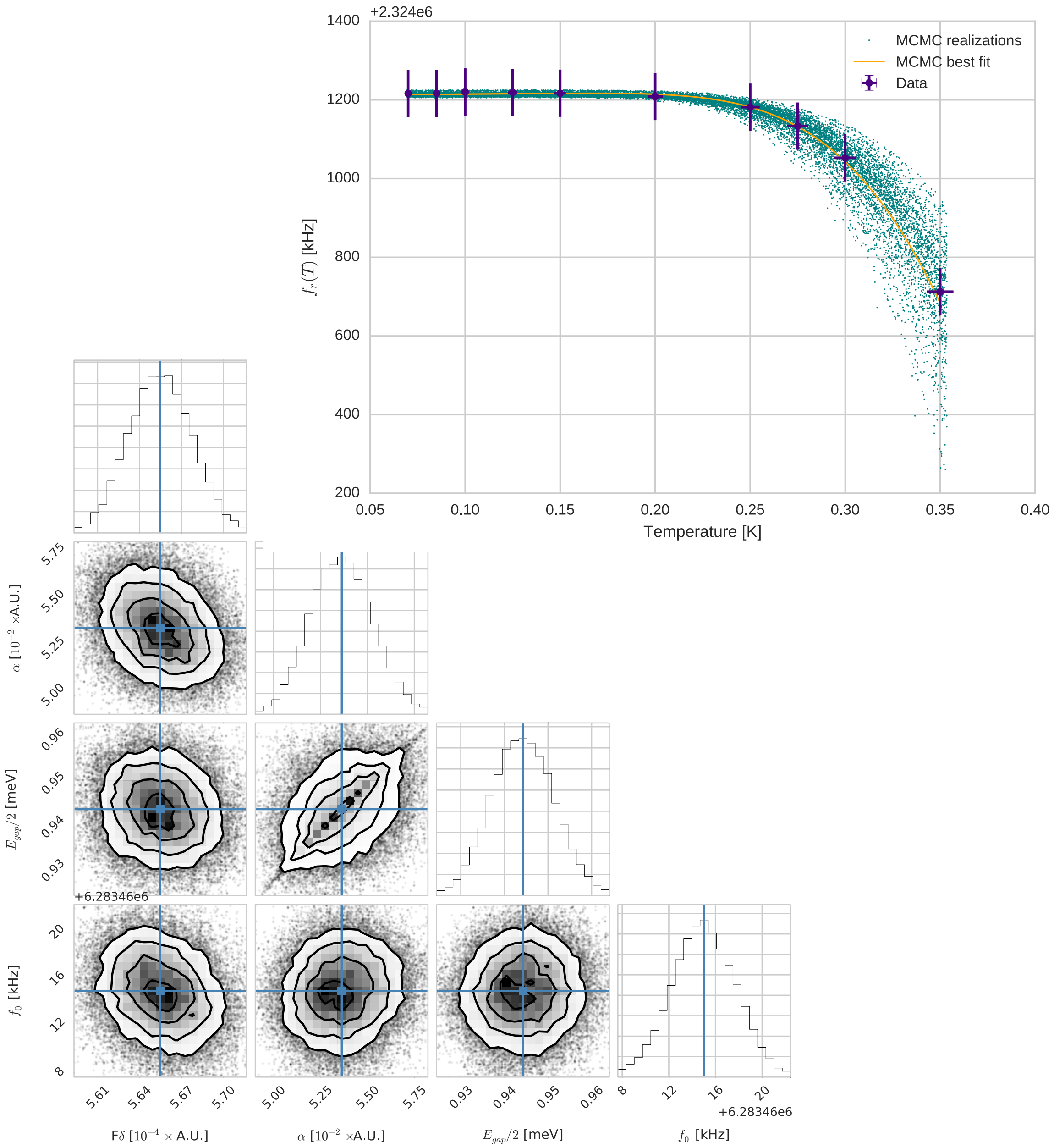
$$Q_{i,MB} \approx \frac{\pi}{4\alpha_k} \frac{e^{\Delta/(k_B T)}}{\sinh\left(\frac{hf}{2k_B T}\right) K_0\left(\frac{hf}{2k_B T}\right)},$$



(b) $\delta \frac{1}{Q_r}$ vs. T

Our KIDs


data, SNR = 182.9
initial guess
mean MCMC pdfs
$|S_{21}|$ [A.U.]
Freq. [GHz]
+2.53
1e-7+2.5314072
1e-7
f_0 [GHz]
δf [GHz]
Q_i [A.U.]
Q_c [A.U.]


+2.324e6
MCMC realizations
MCMC best fit
Data
$f_r(T)$ [kHz]
Temperature [K]
+6.28346e6
$F\delta$ [10^{-4} × A.U.]
α [10^{-2} ×A.U.]
$E_{gap}/2$ [meV]
f_0 [kHz]

KIDs Problems

- Al is easy to work with, but its Tc ~ 1K, sensitive to only >~100GHz photons
  - need very low Tc material to detect photons in 90GHz band, maybe AlMn or TiN? Both are ongoing processes!
- On sky demonstration performance

Noise Analysis

Optical Recombination Noise

$$NEP_{or} = \sqrt{4\Delta P/\eta_{pb}}$$

Thermal Recombination Noise

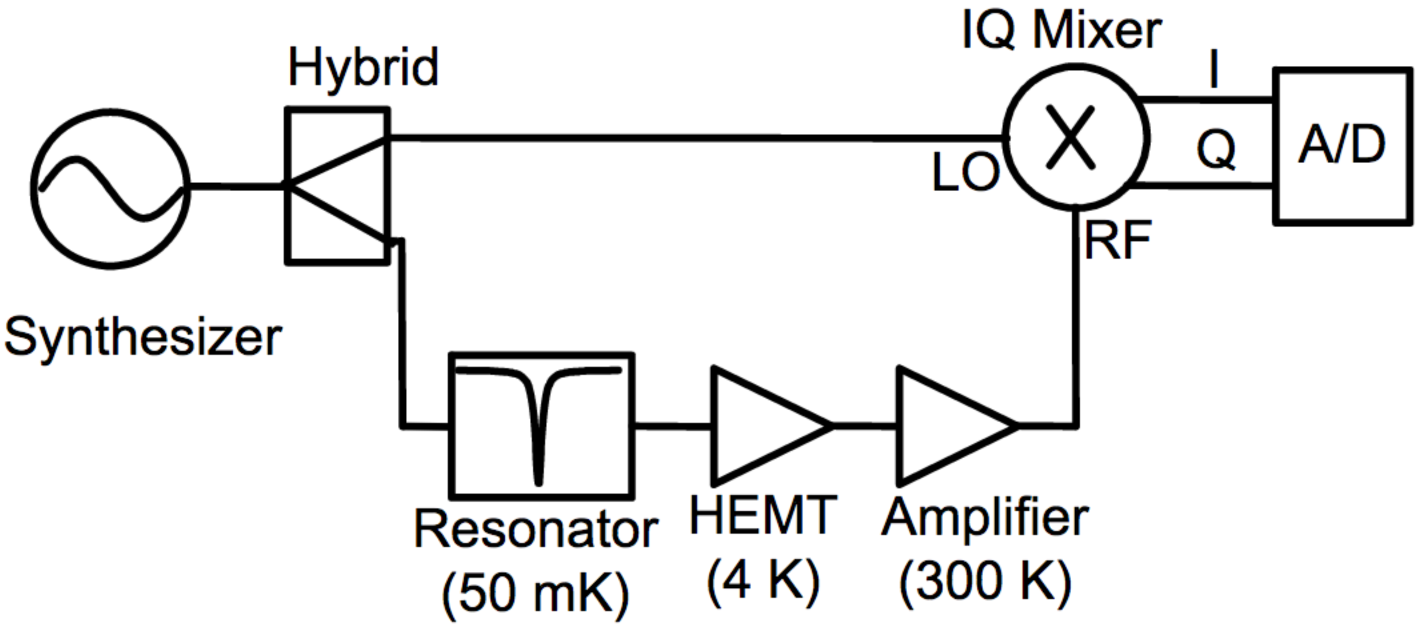
$$NEP_{tr} = \frac{2\Delta}{\eta_{pb}}\sqrt{\frac{N_{tqp}}{\tau_{qp}}}.$$

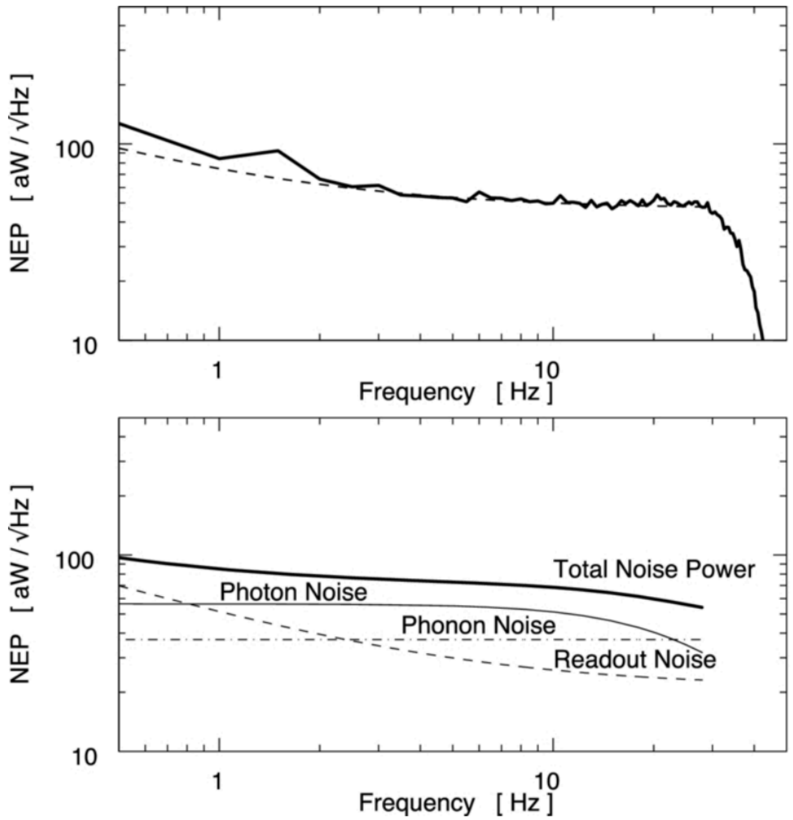
$$NEP^2_{\mathrm{total}} = NEP^2_{\gamma} + NEP^2_{\mathrm{GR}} + NEP^2_{\mathrm{TLS}} + NEP^2_{\mathrm{amplifier}} + NEP^2_{\mathrm{readout}}$$

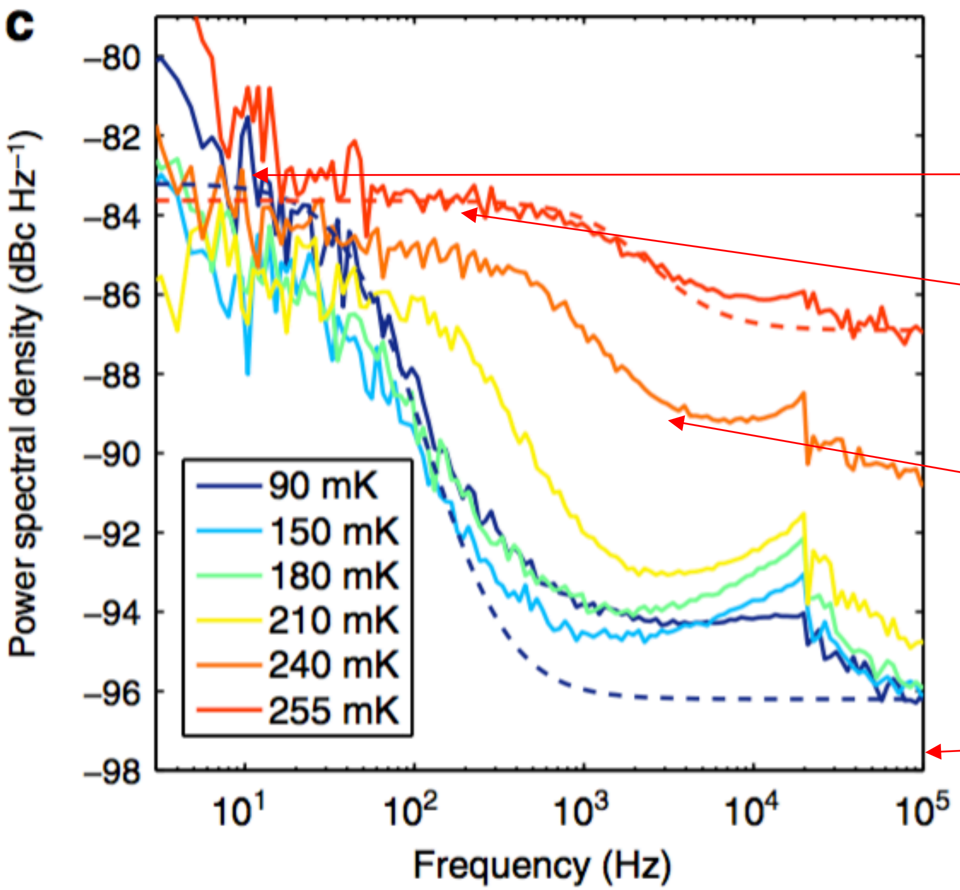
Fundamental noise for KIDs

For more detail, talk to Rito

Noise Analysis







1/f noise

Photon noise

Quasiparticle
lifetime

White noise

Coming soon!

- Measurements of optical response
- Noise measurements and (hopefully) demonstrated noise is below photon noise
- On sky performance within a year