Millimetron instrumentation sensitivity

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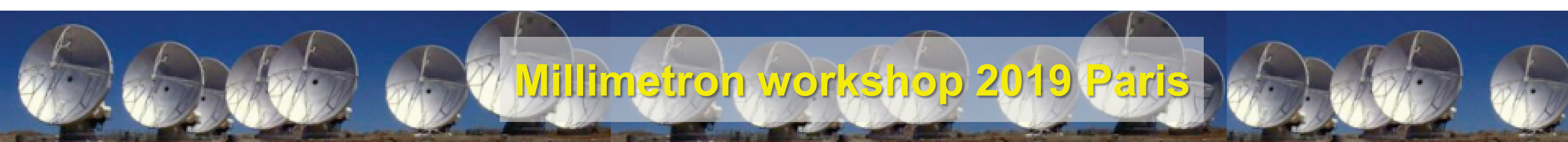
Millimetron instruments highlight

- 10 m aperture 16% obscuration – **large collecting area and spatial resiolution**
- <10K main dish temperature (40..50 K without coolers) – **extremely low background**
- Instrumentation
  - VLBI bands (simultaneous multi frequency observations)
  - Low resolution spectrometer (Differential pendulum FTS, 100…1000 GHz TBC)
  - Medium resolution imager, spectrometer (Dispersed FTS?)
  - High resolution spectrometer (heterodyne)
- What are ultimate detector requirements for Millimetron, and achievable sensitivities



Space-Earth VLBI receivers

In red, high priority (EHT) bands;

In grey TBC; depending on science cases and implementation feasibility

Band	Frequency (GHz)	IFBW (GHz)	Instantaneous bandwidth (GHz)	Polarization	T_{noise} (K)	Comments
1	33 – 50 ALMA Band 1	4-12 (HEMT)	4 (max)	Circular	<17	Post cryo capable
2	84 – 116 ALMA Band 3	4-12 (HEMT)	4 (max)	Circular	<37	Post cryo capable
3	211 – 275 ALMA Band 6	4-12 (SIS)	4 (max)	Circular	<80	Dedicated SIS receiver
4	275 - 373 ALMA Band 7	4-12 (SIS)	4 (max)	Circular	<80	Dedicated SIS receiver
5	*490-650* *HIFI band 1*	*4-12* *(SIS)*	*4 (max)*	*circular*	*< 80*	*Dedicated SIS receiver*

Long-wavelength Array Camera Spectro-Polarimeter (LACS-P) ASI instrument; FTS optimized for S-Z observations; under development at Sapienza U. Roma

	Band 1	Band 2	Band 3	Band 4
Wavelength (µm)	3000 – 1500	1500 – 850	850 – 450	450 – 300
FWHM (arcsec)	42	22	12	7.5
# of independent beams/ pixels (KID arrays)	6 / 24	9 / 36	16 / 48	25 / 100
Background power (W)	5.5×10^{-12}	3.3×10^{-12}	1.5×10^{-14}	2×10^{-15}
Detector NEP (W/√Hz)	$\leq 10^{-17}$	$\leq 10^{-17}$	$\leq 10^{-18}$	$\leq 10^{-18}$
Spectrometer resolution	~150	~250	~450	~700

Short-wavelength Array Camera/Spectro-Polarimeter (SACS)

Long slit grating spectrometers, low order

The exact wavelength ranges and spectral resolving powers; tbd

	Band 1	**Band 2**	**Band 3**	**Band 4**
Wavelength in μm **In THz**	43-80	80 - 140	140 - 230	230-400
FWHM (arcsec)	1-2”	2-4”	4-6”	6-10”
# of pixels: Camera/spectrometer	*~8000*	*~4000*	*~1200*	*~300*
Spectrometer resolution	~500-1000	~500-1000	~ 500	~ 500
Detector NEP (W/√Hz)	$<10^{-19}$	$<10^{-19}$	$<10^{-19}$	$<10^{-19}$
Polarization	y	y	y	y

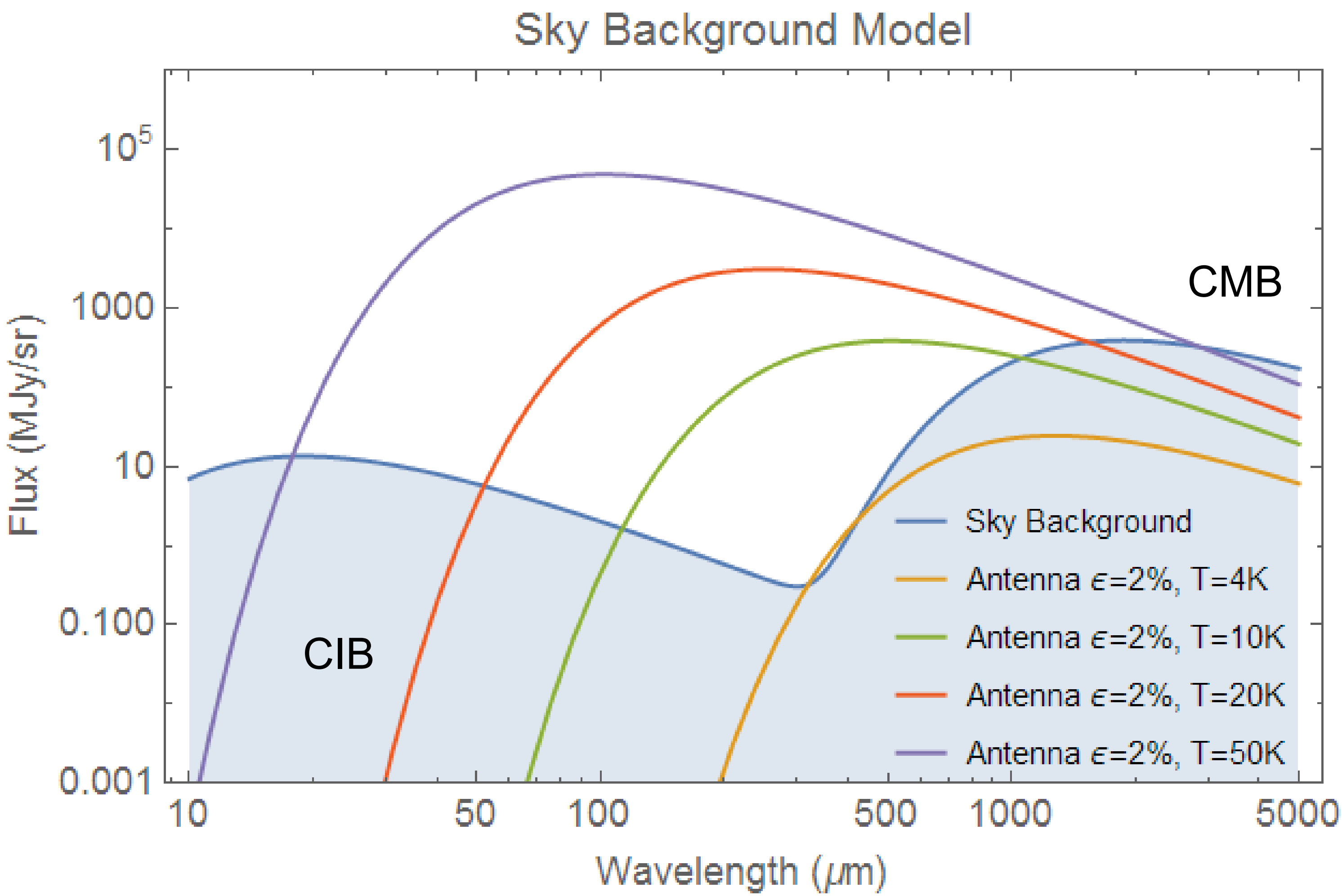
Millimetron Heterodyne Instrument for the Far-Infrared (MHIFI)

Bands: Red Priority-1; Grey, Possible Bands depending on science cases

Initial design based on Herschel HIFI

Band	Frequency (GHz/THz)	IFBW (GHz)/ Technology	Polarization	Array size/ Configuration
M1	**485 – 600**	**4-12 /(SIS)**	**H/V**	**3/Triangular**
M2	752 – 950	4-12 /(SIS)	H/V	3/Triangular
M3	**0.95 – 1.15**	**4-12 /(SIS)**	**H/V**	**7/Hexagonal**
M4	**1.60 – 2.10**	**1-6 /(HEB)**	**H/V**	**7/Hexagonal**
M5	2.45 – 3.00	1-6 /(HEB)	H/V	7/Hexagonal
M6	4.77 – 5.8	1-6 /(HEB)	H/V	7/Hexagonal
Post-cryo band	*500-600* *1.05-1.15*	*4 - 12 (Schottky)*	*H/V*	*Schottky diodes*

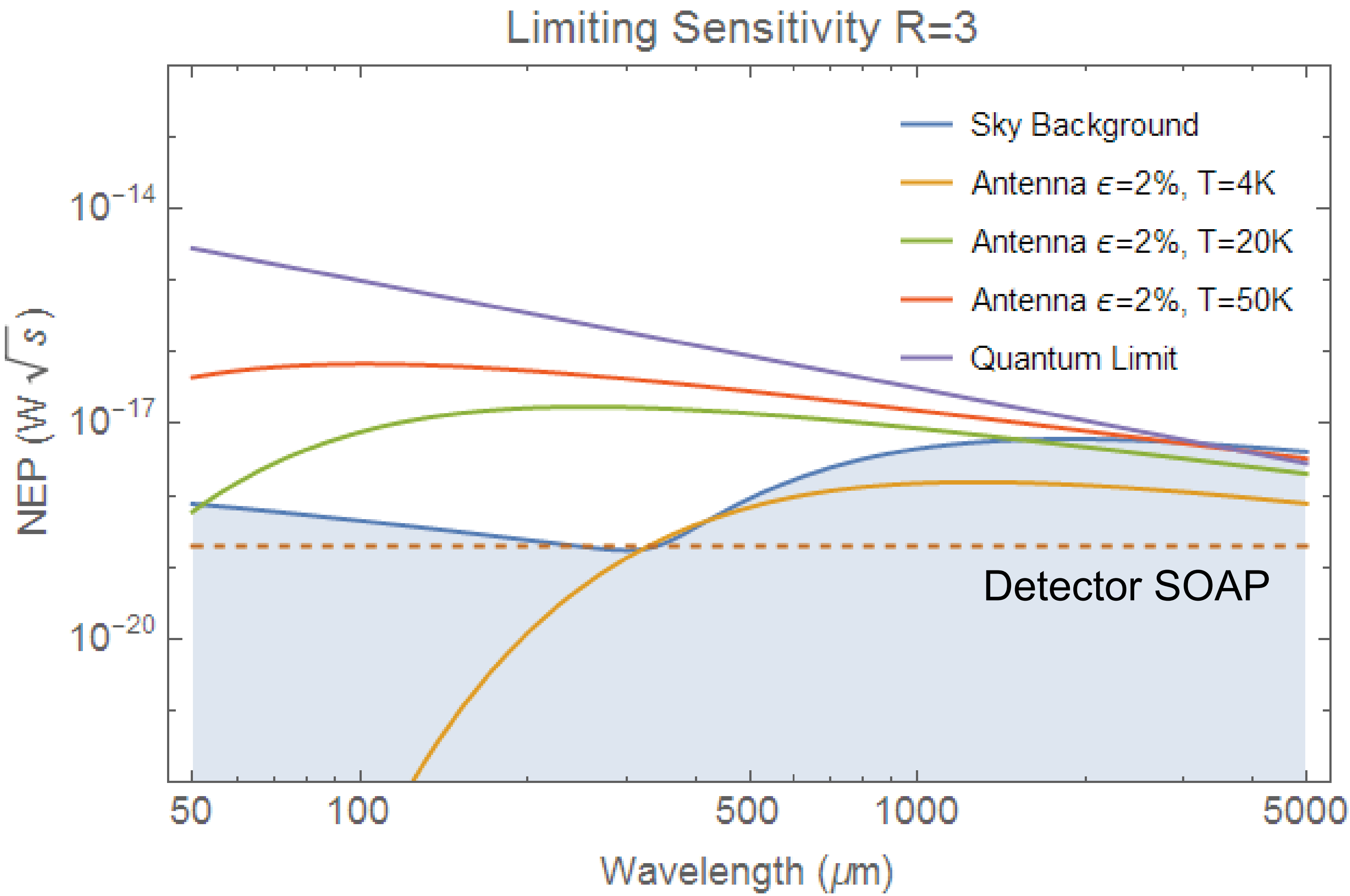
Let us consider background



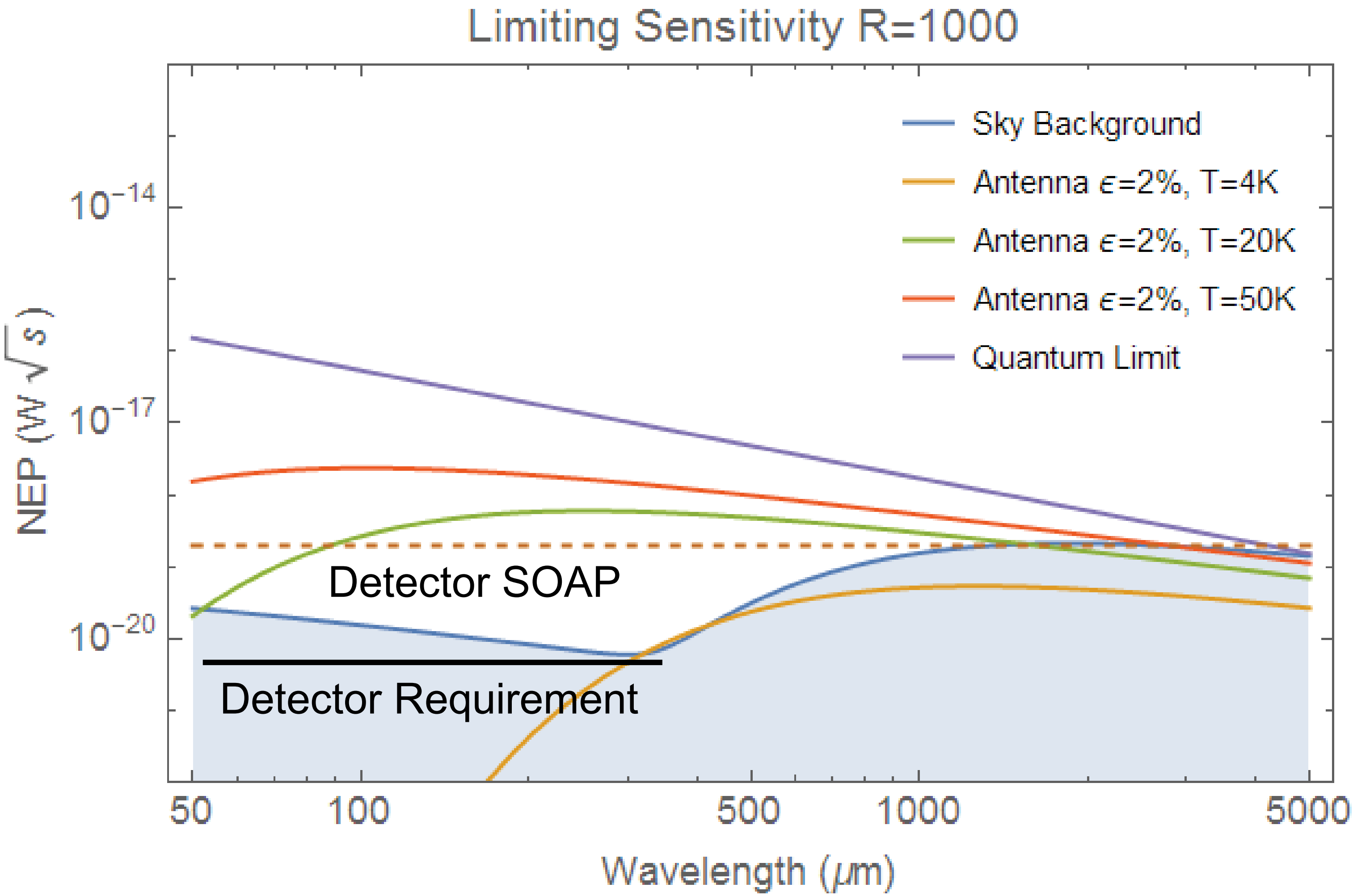
Already conclude

- Antenna temperature has most influence in the range of 35…400 micron
- To realize background limited performance antenna should be at 4 K, 10 K is not good enough
- Let us look at detector limit

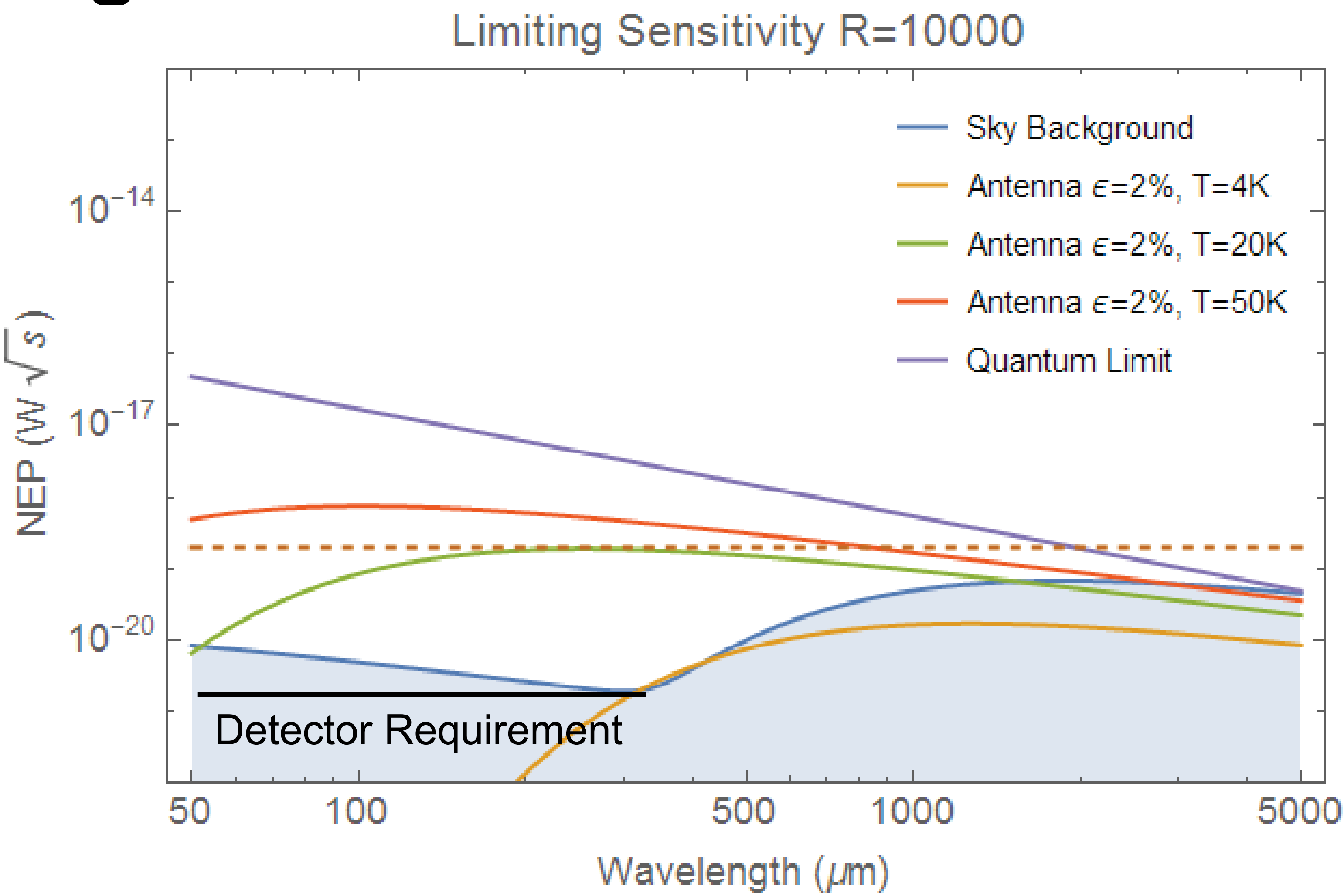
Noise at the detector level



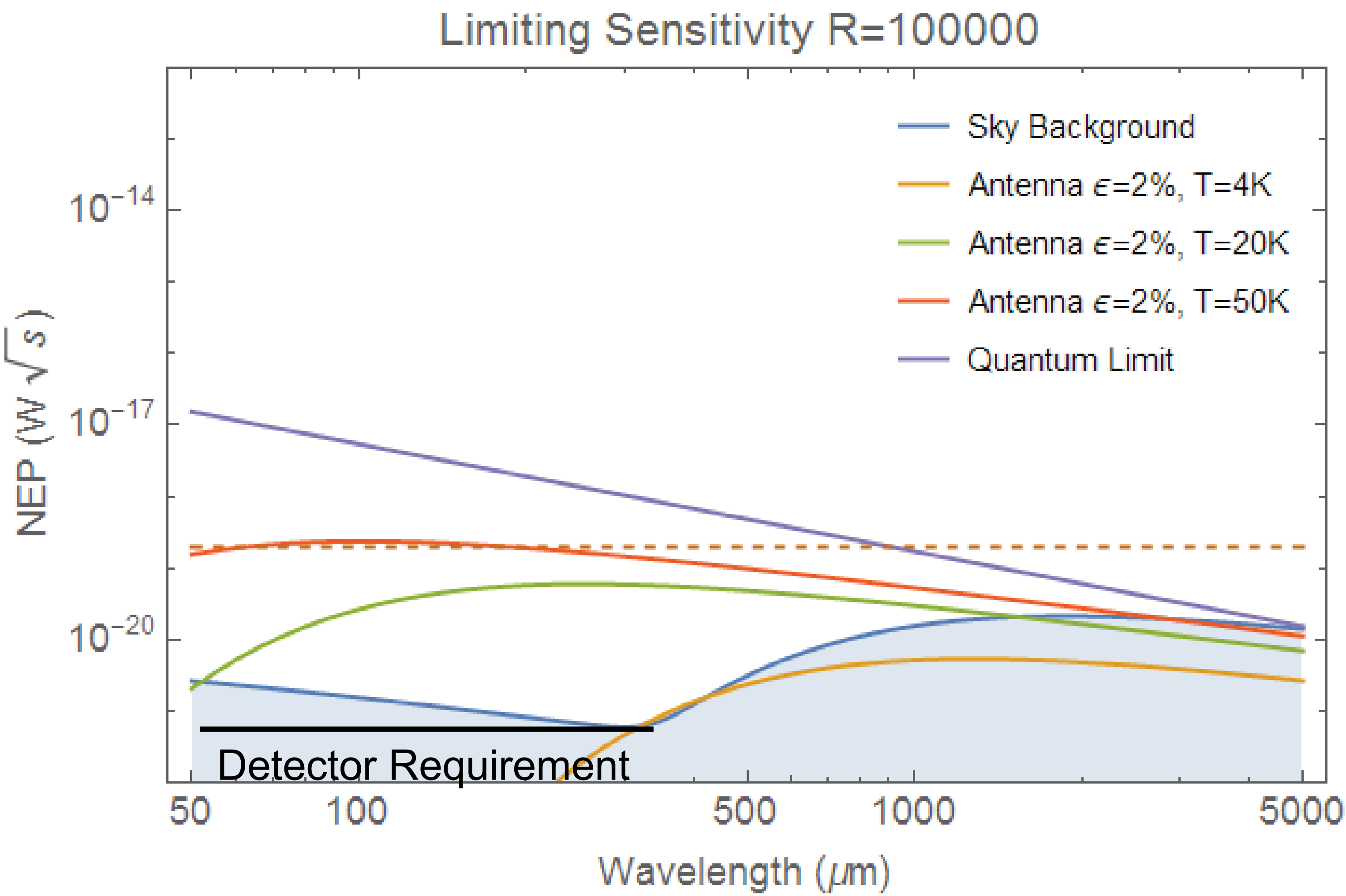
Increase resolution



High resolution



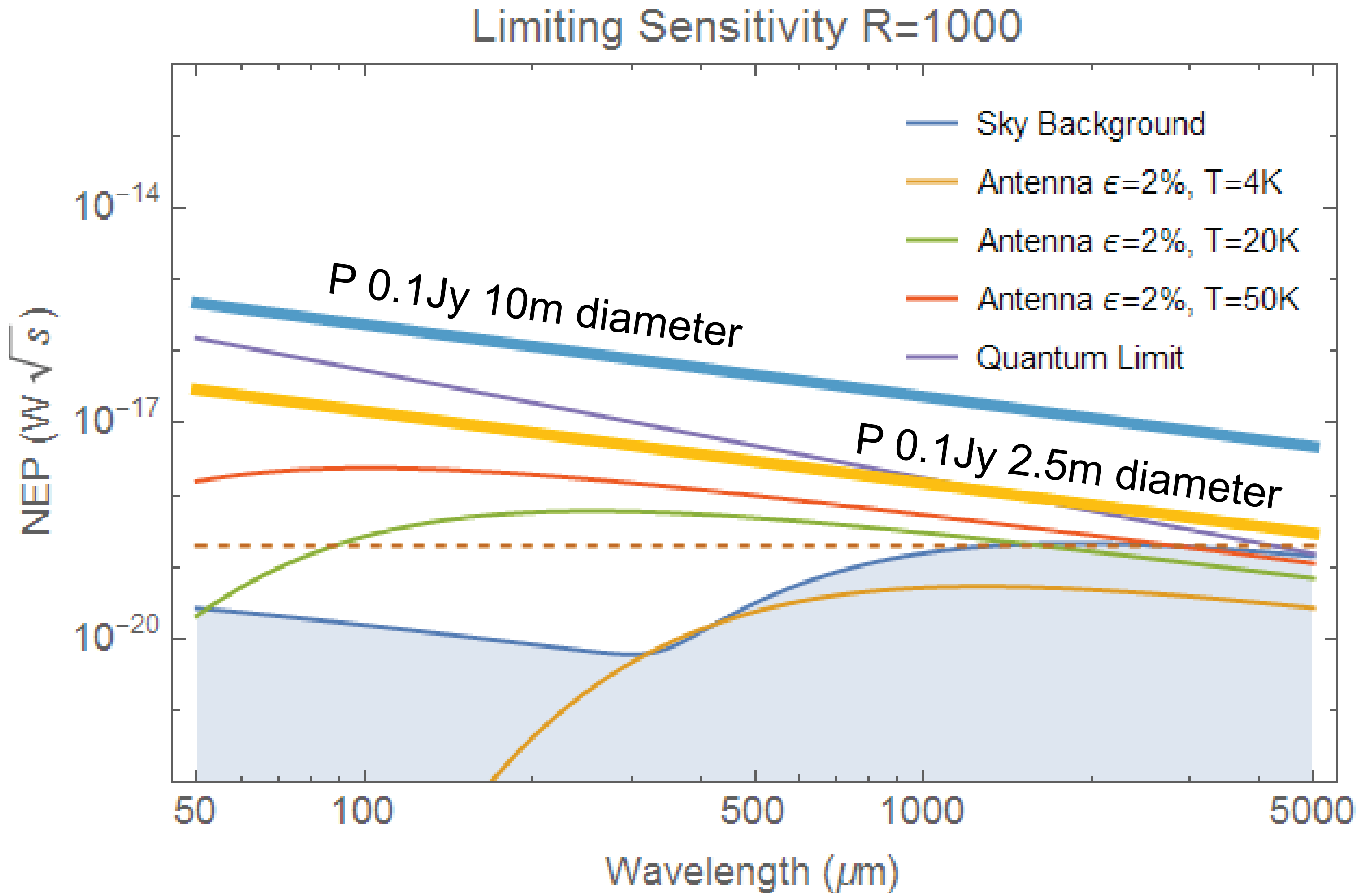
Very high res (heterodyne)



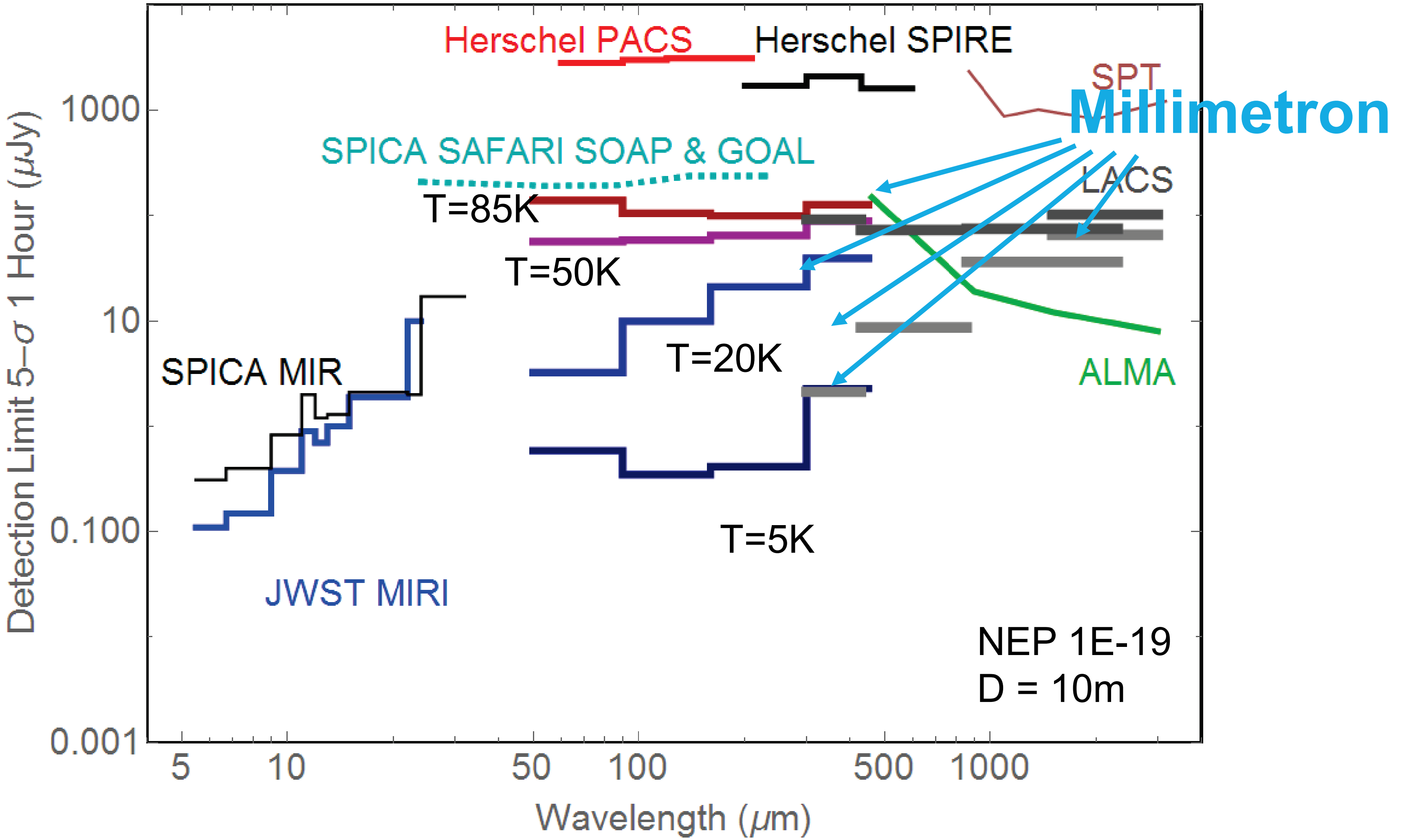
Independent of antenna size

- 1E-19 current state of art sensitivity
- 1E-19 NEP level is adequate for background limited photometry
- At R=1000 required NEP is 1E-20, or equivalent to warmer dish (10K)
- At very high resolution 1E-19 would correspond to even warmer dish. Quantum limited heterodyne system becomes competitive at longer wavelengths. Required NEP=1E-21

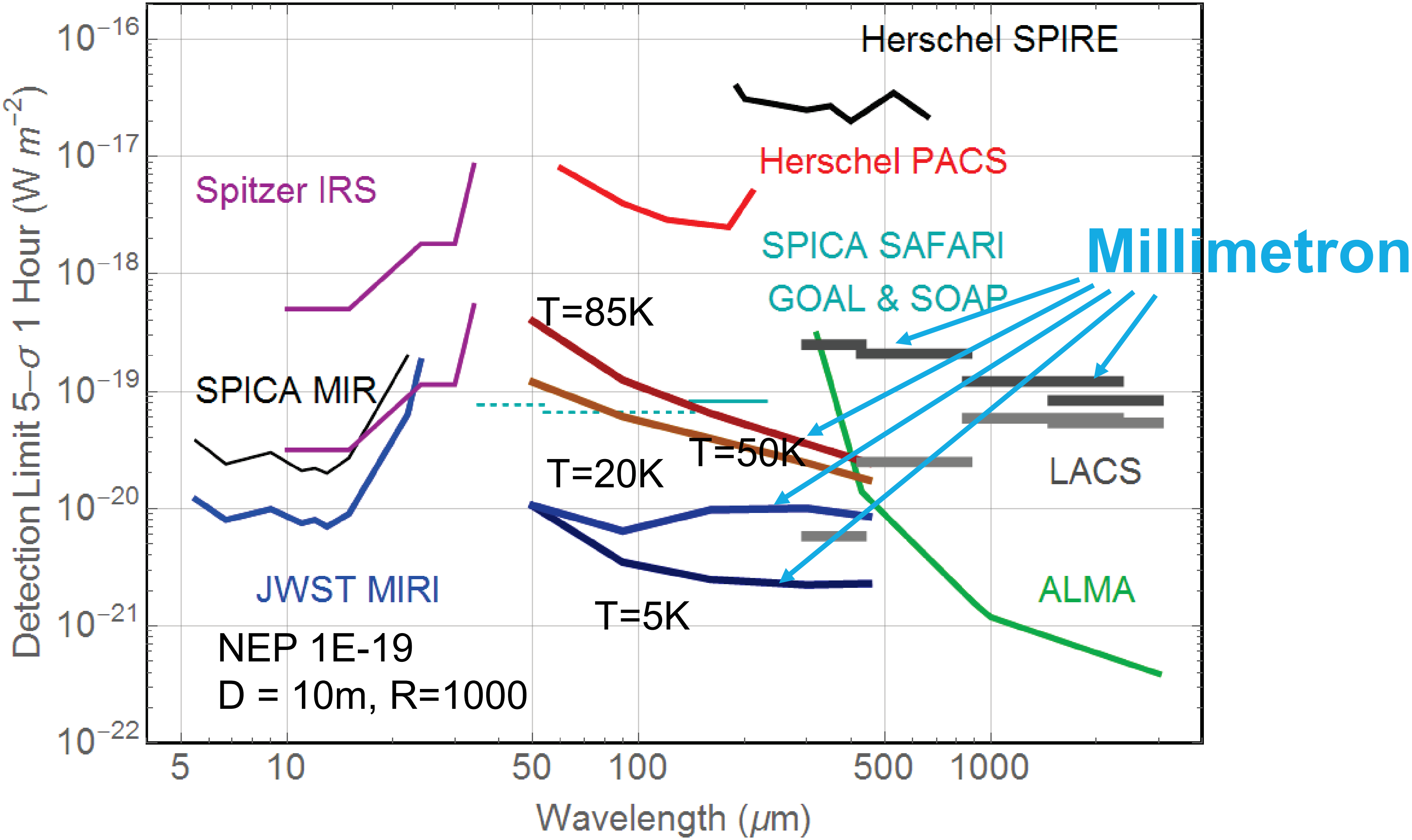
Signal to noise/ telescope size



Comparison photometry

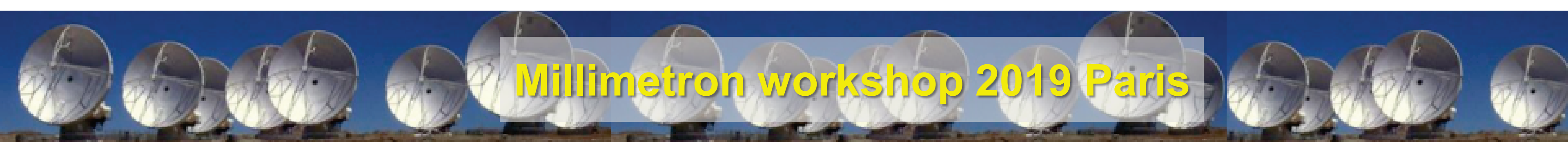


Comparison spectroscopy

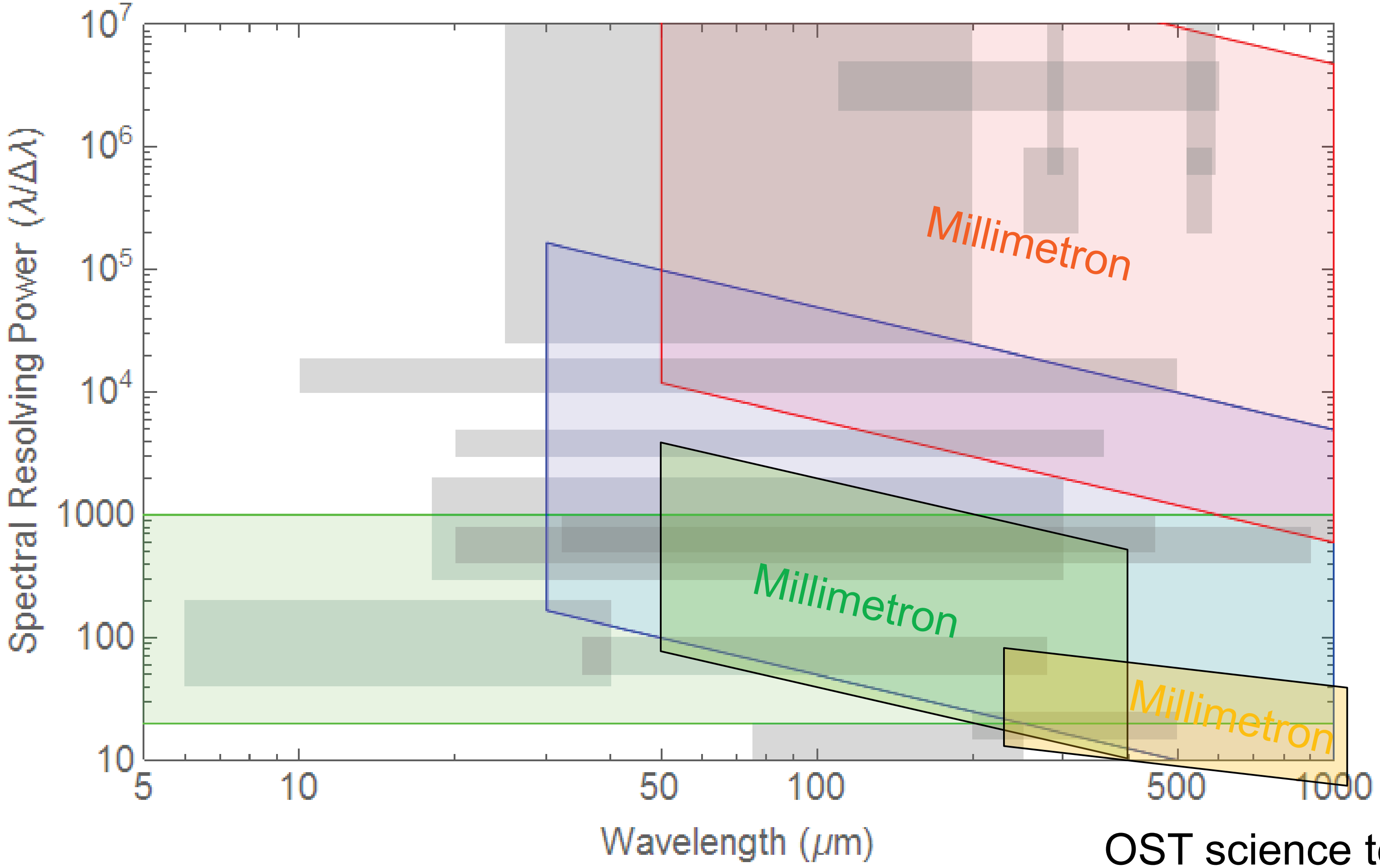


balance

- Careful balance between detector performance, antenna size and antenna temperature: wormer large dish may easily have superior sensitivity for moderate medium resolution and photometry
- For high resolution heterodyne technology is adequate while direct detectors systems are size limited

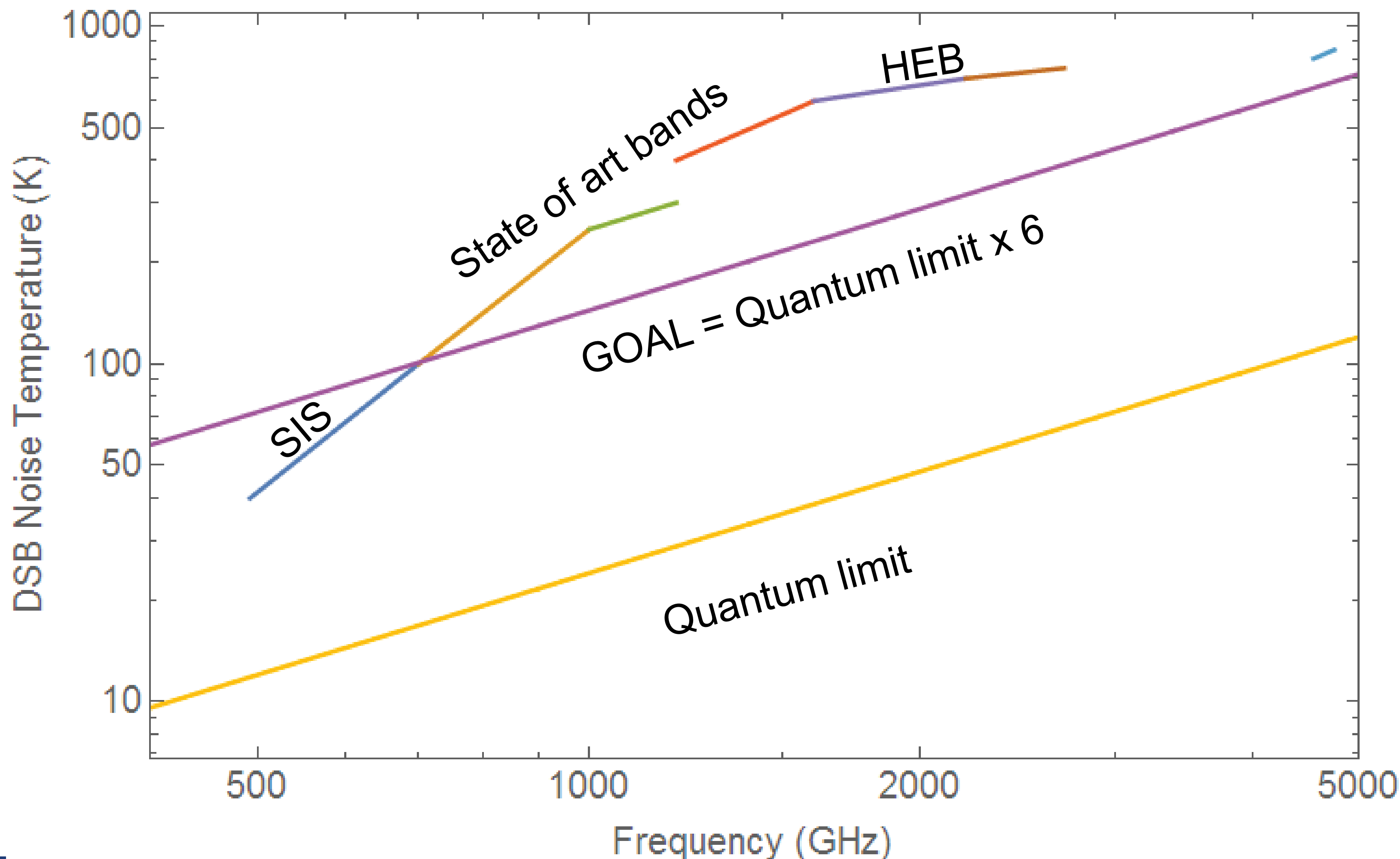


High resolution case summary

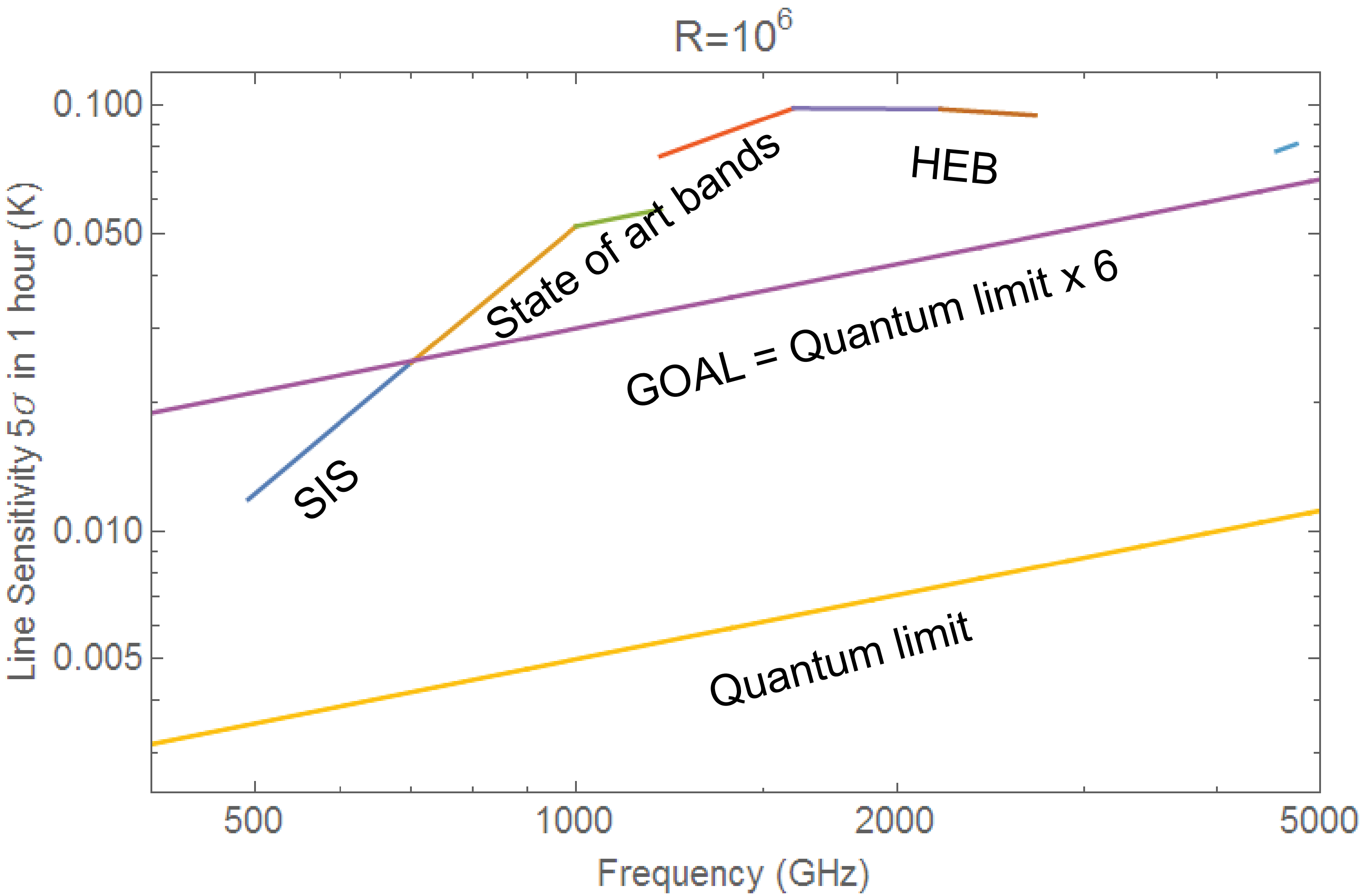


OST science team
OST white paper

Noise temperatures

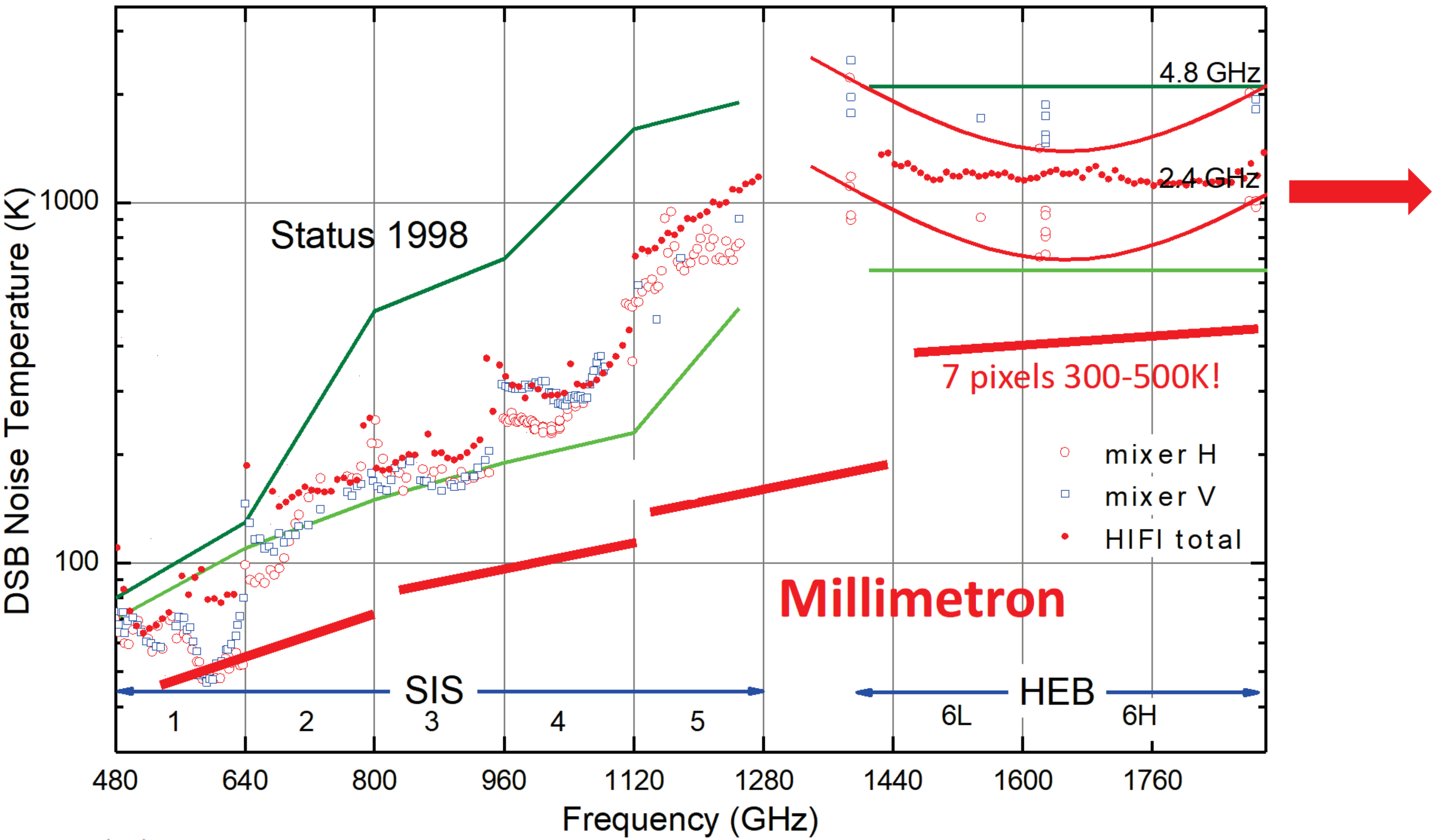


Sensitivities



Sensitivities (compared with HIFI)

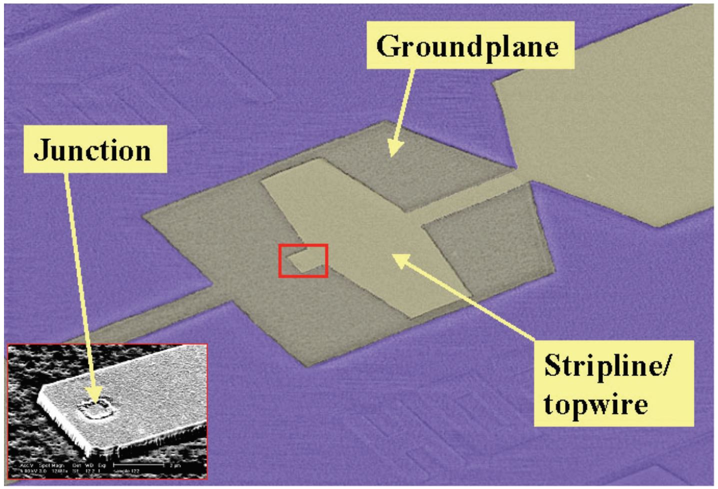
Expected Performance improvement w.r.t. Herschel-HIFI: >50 times
Increased mixer sensitivity (2-5); collecting area(10 times); Pixels (3-7)

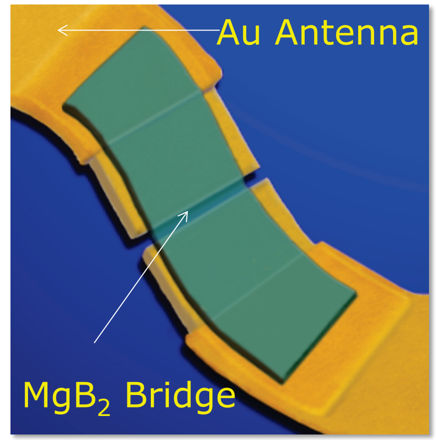


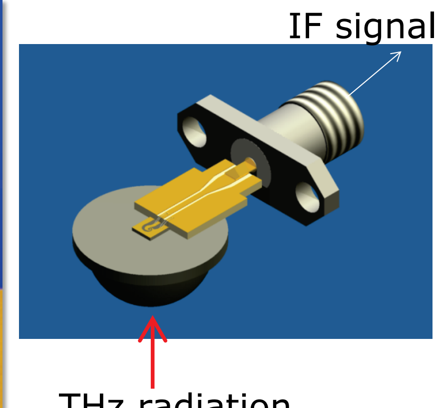
Conclusion

- Both heterodyne and direct detector development status allows for several orders sensitivity improvement relative to previous missions
- NEP of 1E-19 is current state of the art level of TES. 1E-20 is possible, 1E-21 and lower may require new principles
- Careful choice of mission telescope diameter vs temperature is needed.

Heterodyne technology status







SIS

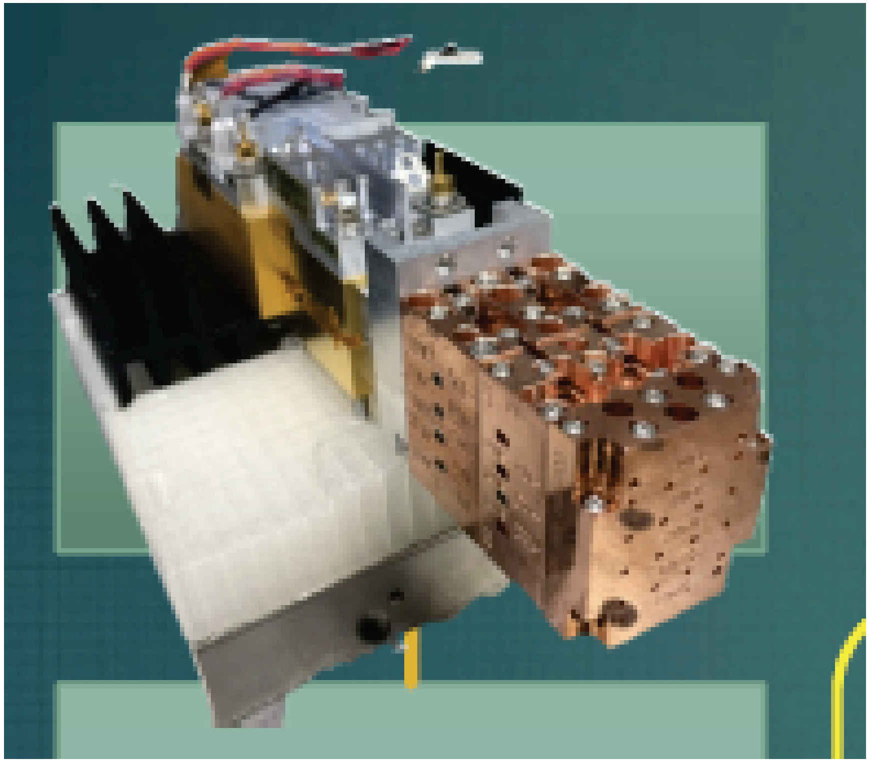
- Improve noise
- Increase complexity (2SB)
- Results of ALMA development, Radionet

HEB

- Improve noise
- Improve bandwidth
- Results of HIFI development, Radionet

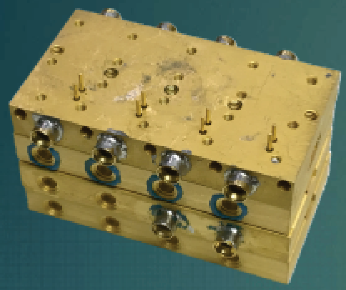
LO technology

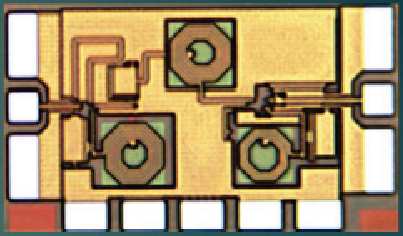
- Up to 6THz
- mWt of power 1 THz
- Multi pixel power splitting
- Wider bandwidth
- All Si WG technology

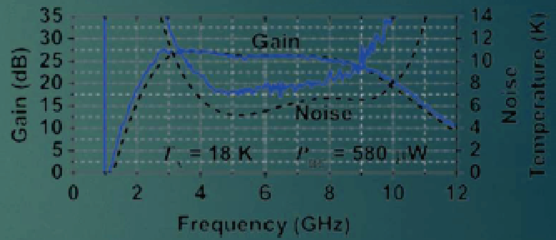


J. Siles JPL

LNA technology:







- Widely used Caltech-originated P~5-10 mW per channel

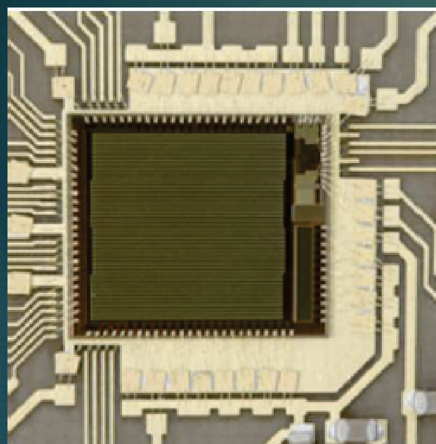
- UMass-developed low power SiGe: order of magnitude reduction in power < 1 mW in cold stages
- Better system performance if first stage is integrated with mixer

J. Kawamura

Jet Propulsion Laboratory
California Institute of Technology

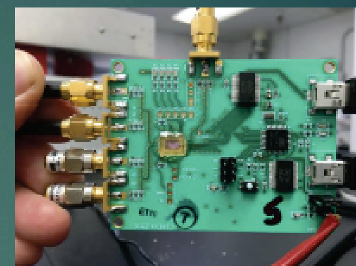
Spectrometer technology:

Omnisys HIFAS autocorrelator

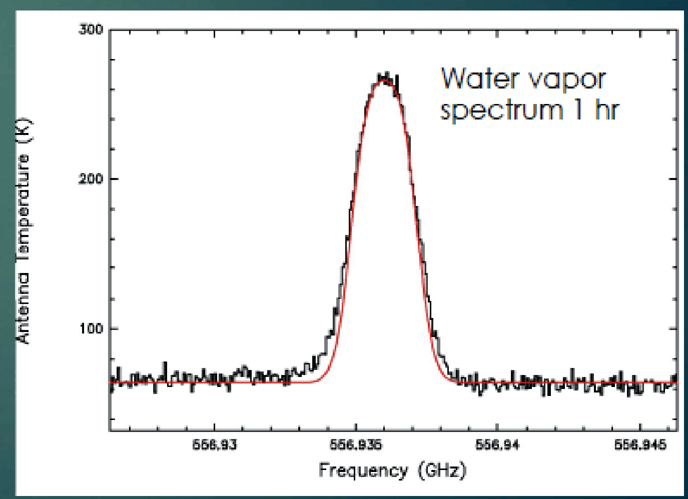


16-channel 1024-lag system (90 W)

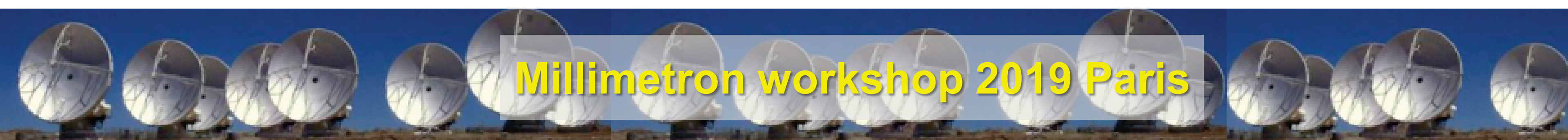
CMOS-based PFB 1 GHz BW



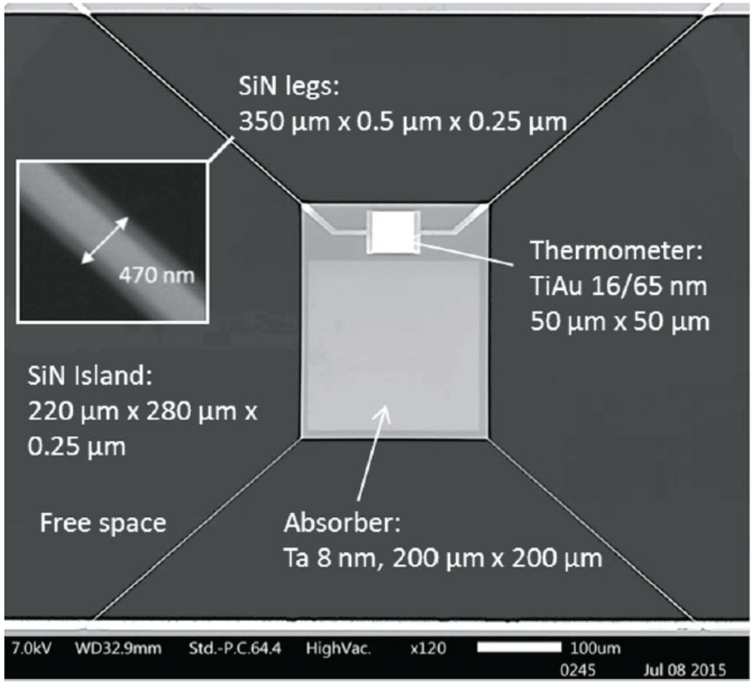
1 GHz 1024 chan (0.7 W)
Next generation 2.5 GHz?

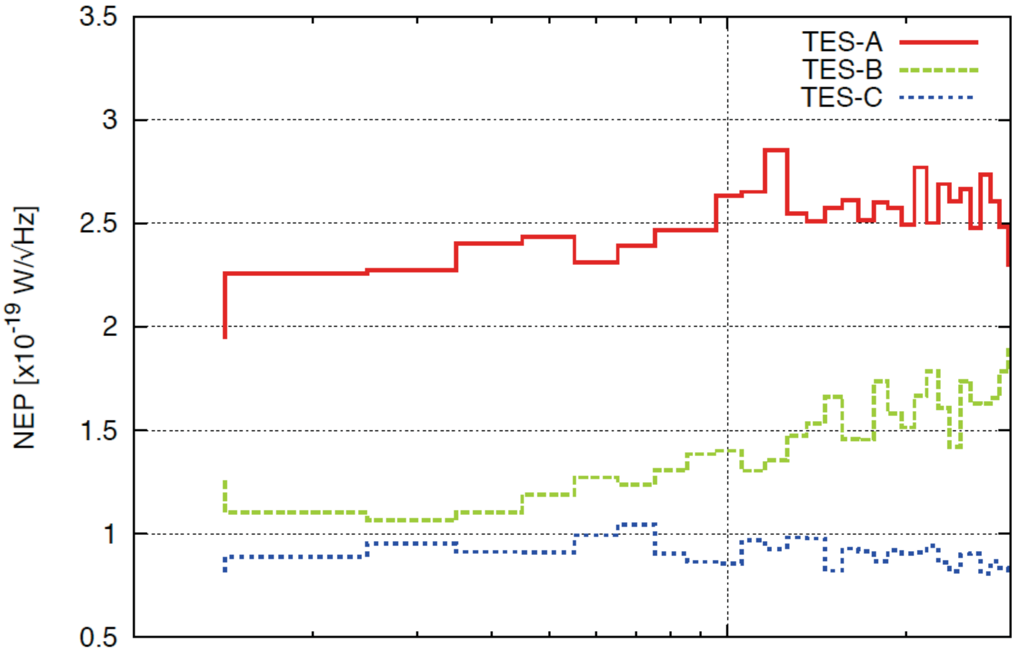


J. Kawamura et al



TES





P. Khosropanah, J.R. Gao (SRON)

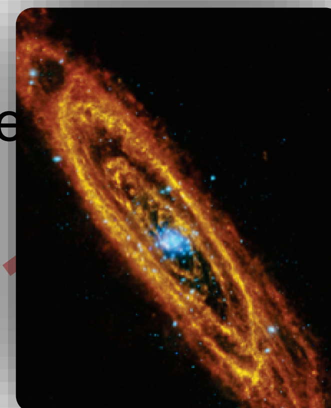
SPICA SAFARI development 1E-19 W Sqrt(Hz) deonstrated, FDM multiplexing 64 pixels in progress. 1E-20 requires development but possible, reaction time 5ms

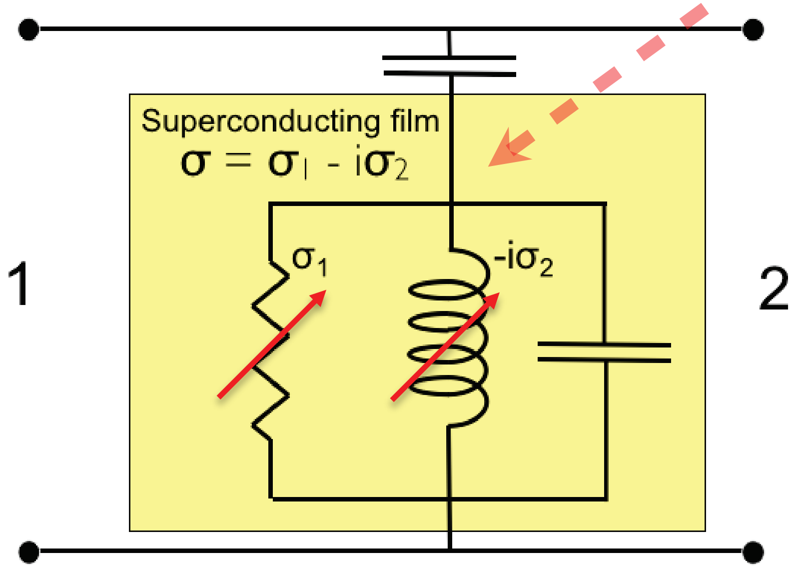
MKID principle of operation

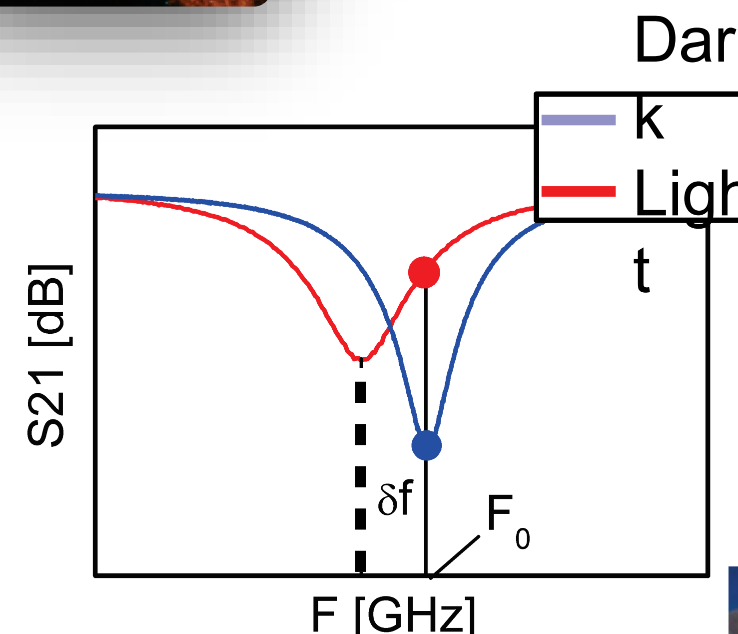
Radiation absorption

- Changes resonance feature

Can be read out using 1 frequency tone

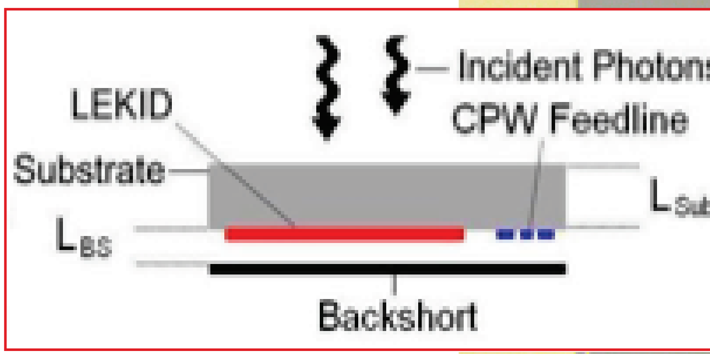


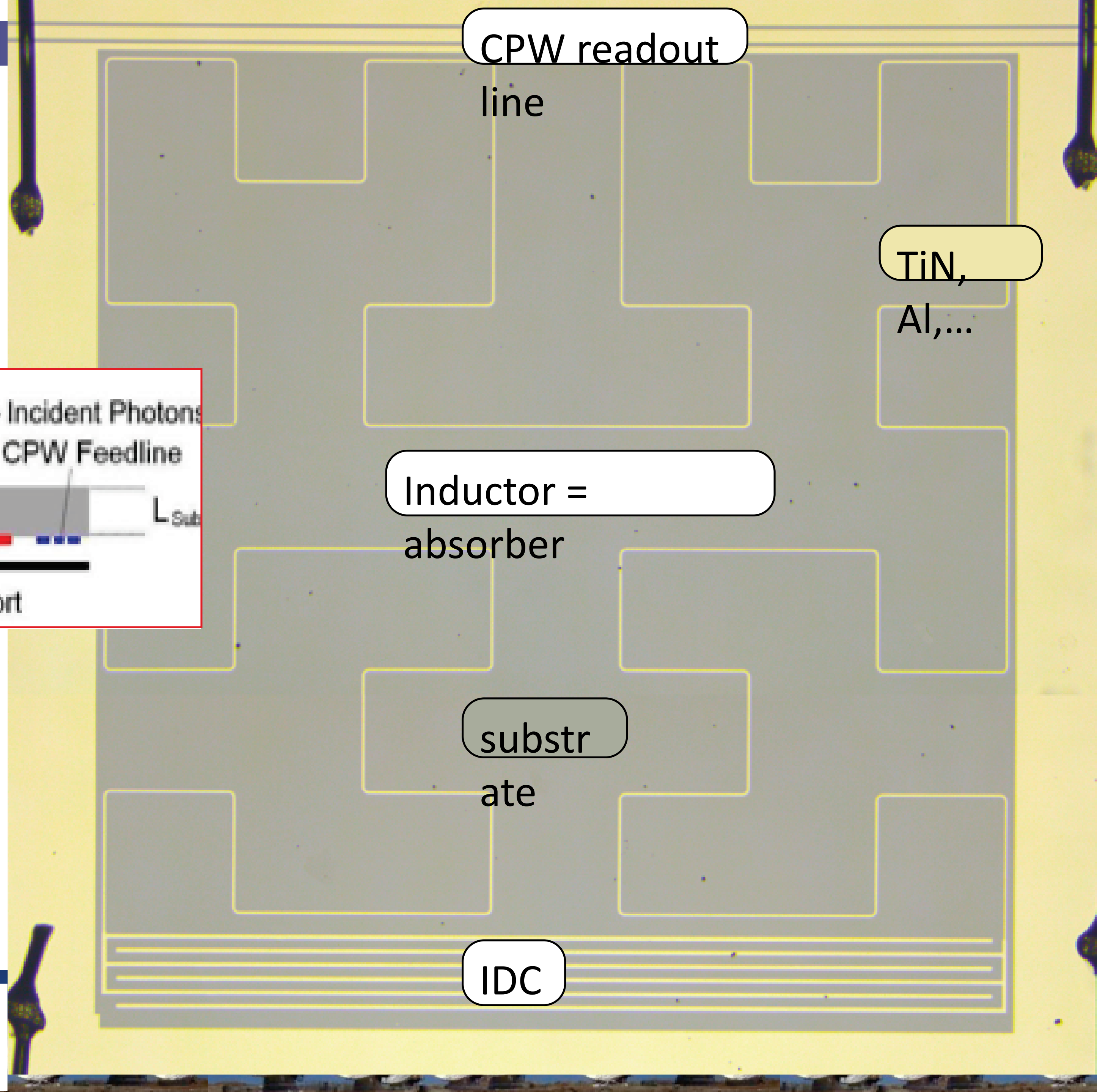




LEKID

L-C resonator

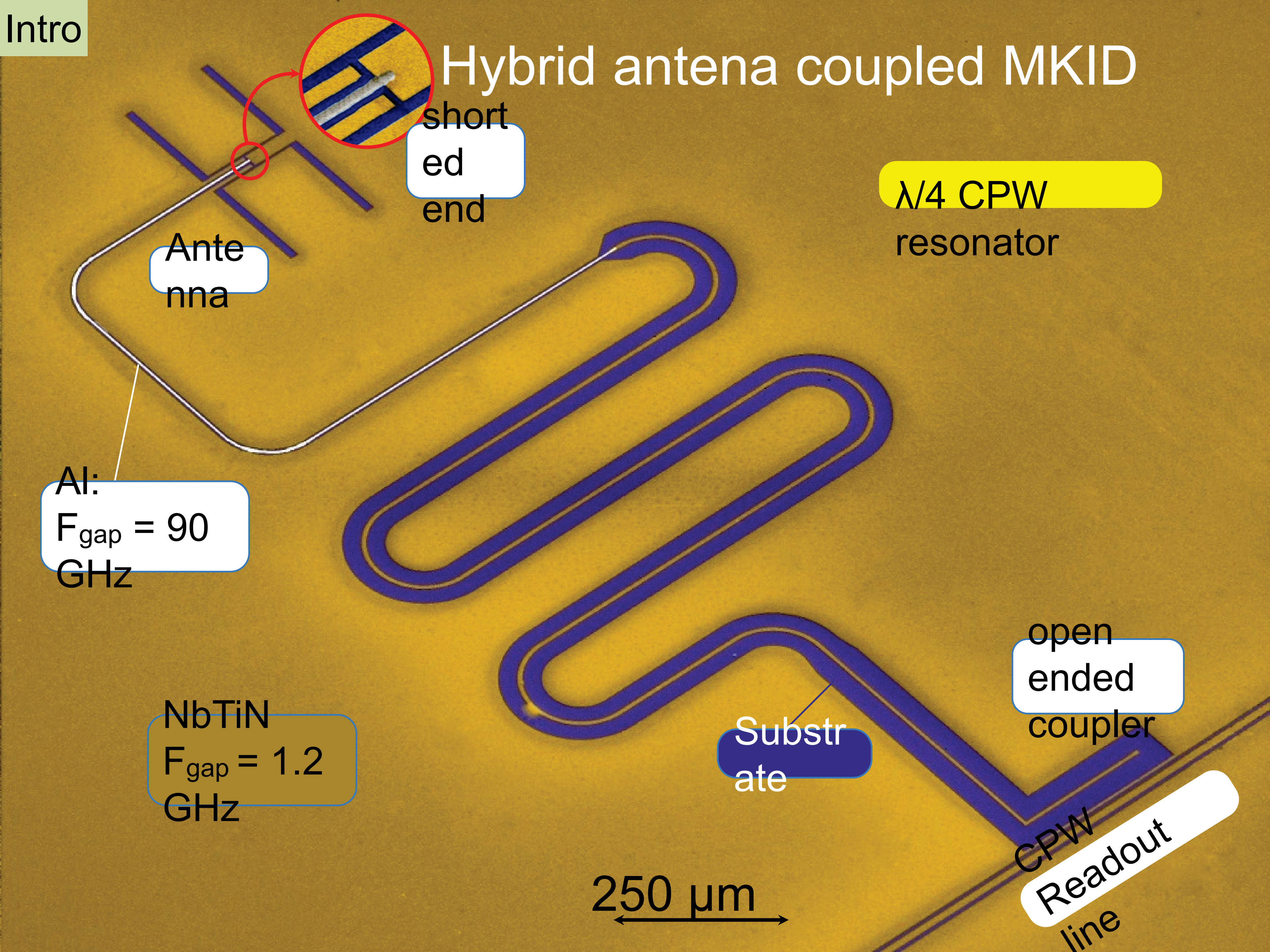




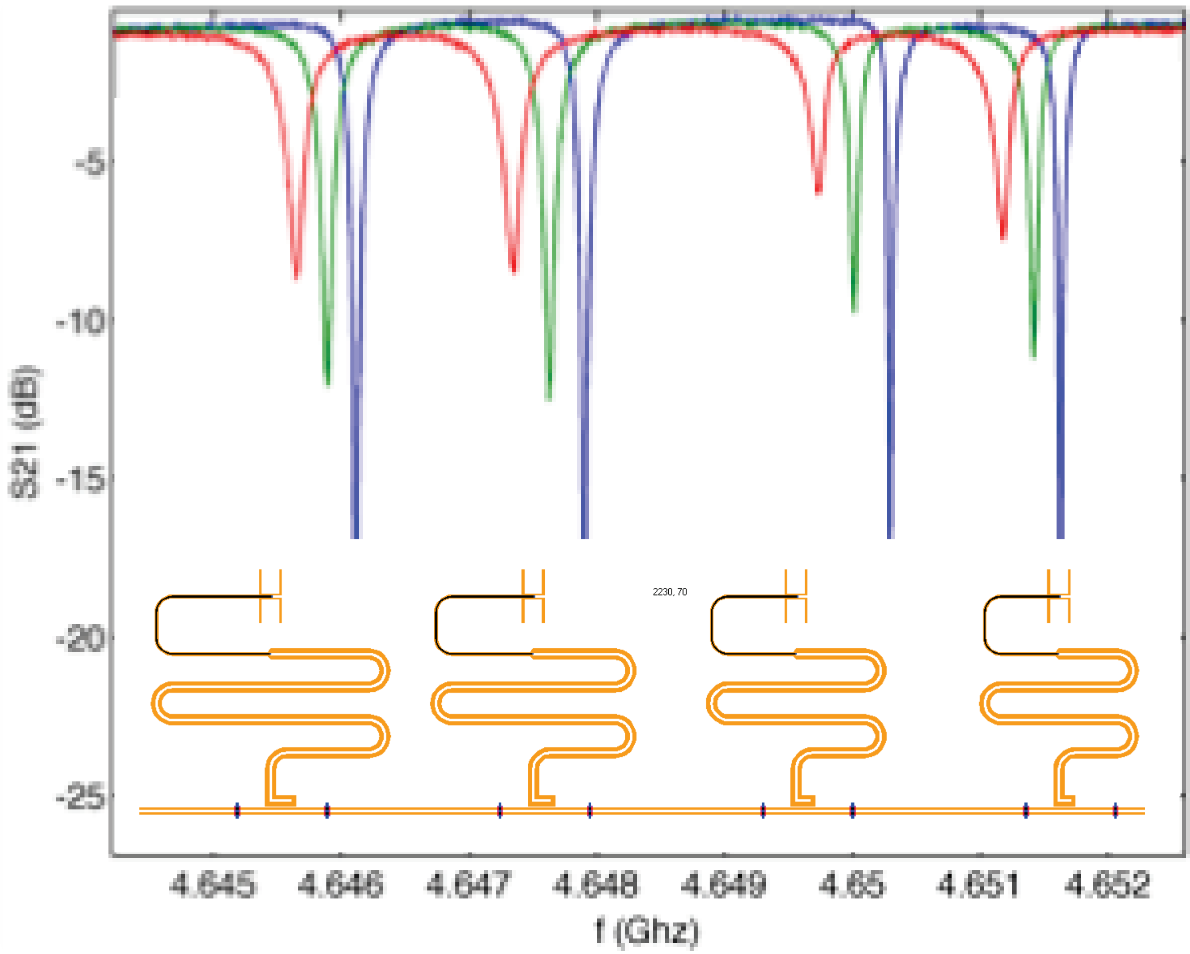
200 µm

Credit: S. Doyle

Hybrid antena coupled MKID



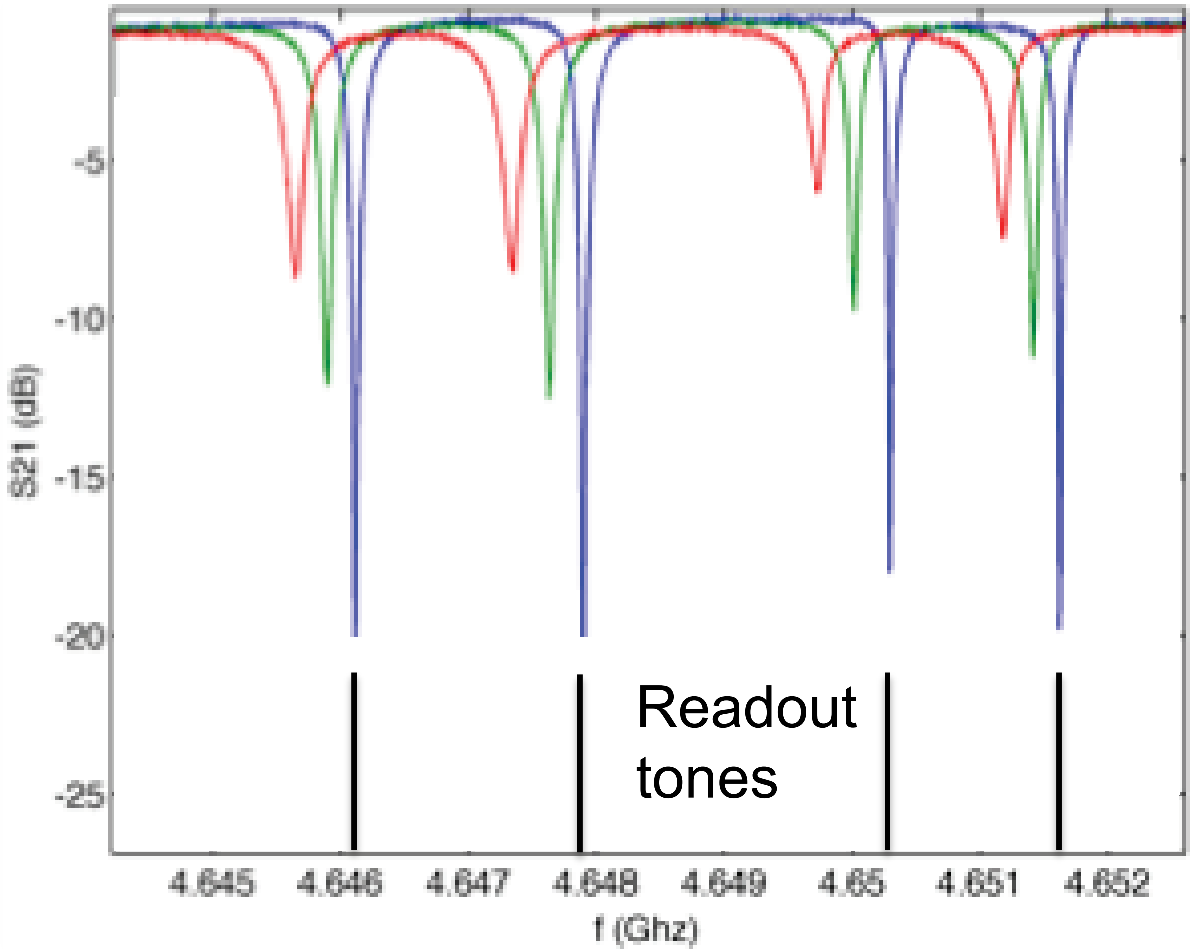
Frequency Domain Multiplexing



J. Baselmans

1000 KIDs per channel, 10 000 KIDs per channel low background is possible

Frequency Domain Multiplexing



J. Baselmans

Future Space instrumentation with MKIDs

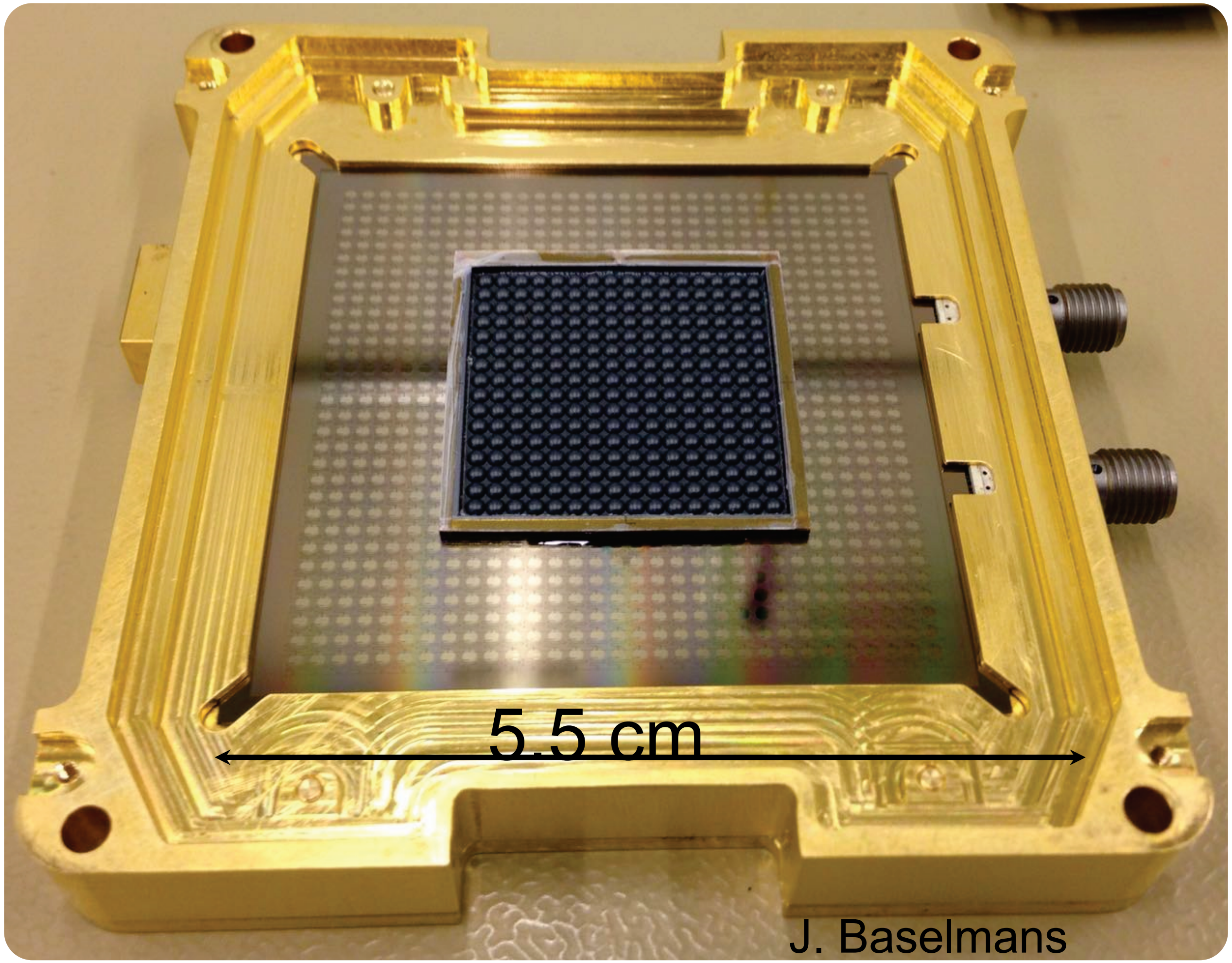
SpaceKIDs program 2012 - 2016

spaceKIDS Kinetic Inductance Detectors for Space

J. Baselmans

Type	F/ΔF	Frequency Range	Power per pixel	NEP_{ph} (W/√Hz)	# pixels
CMB observatory, space (CORE) ø 2m, T=30K	3	50-500 GHz	~100 fW	$4\cdot10^{-18}$	10^3
single dish camera, space (SAFARI,OST) ø 5m, T=5K	3	1-10 THz	30-300 aW	$>2\cdot10^{-19}$	10^4
single dish spectrometer, space (SAFARI,OST) ø 5m, T=5K	1000	0.8-10 THz	0.05-0.5 aW	$>0.5\cdot10^{-20}$	10^4

961 pixel, 850 GHz demonstrator array



Dark NEP + System yield

NEP < 5 ·10^{-19} W/√Hz

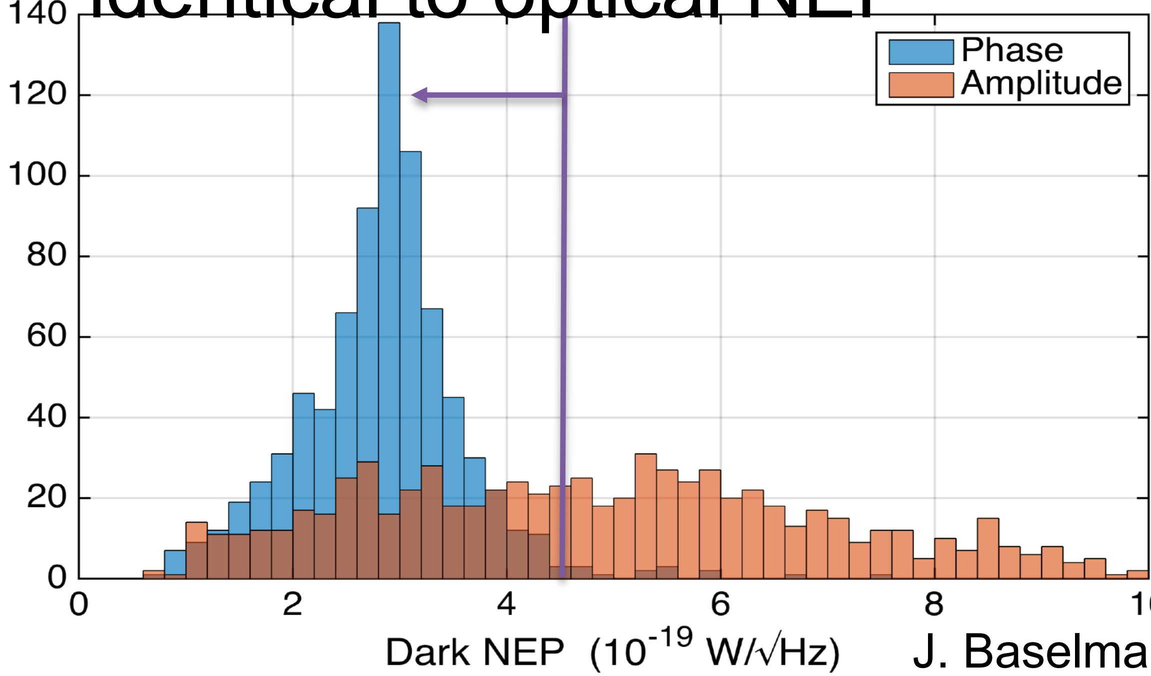
cross talk < -30 dB

Cosmic ray dataloss <10%

$\Rightarrow$ 83%

<Dark NEP> = 2.8 ± 0.8 · 10^{-19} W/√Hz

identical to optical NEP



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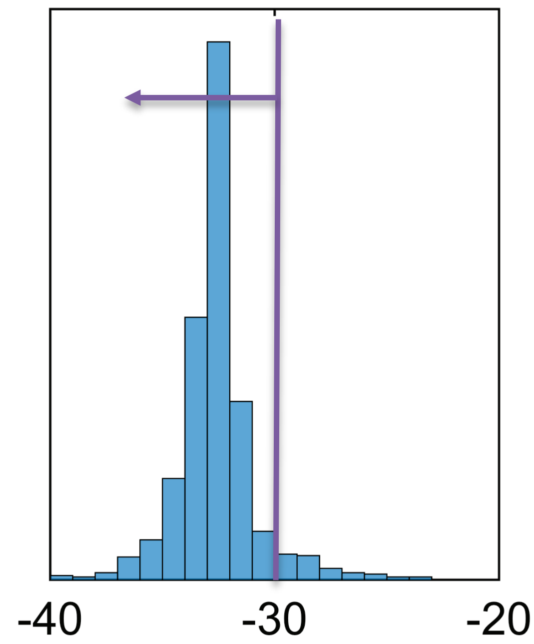
cross talk



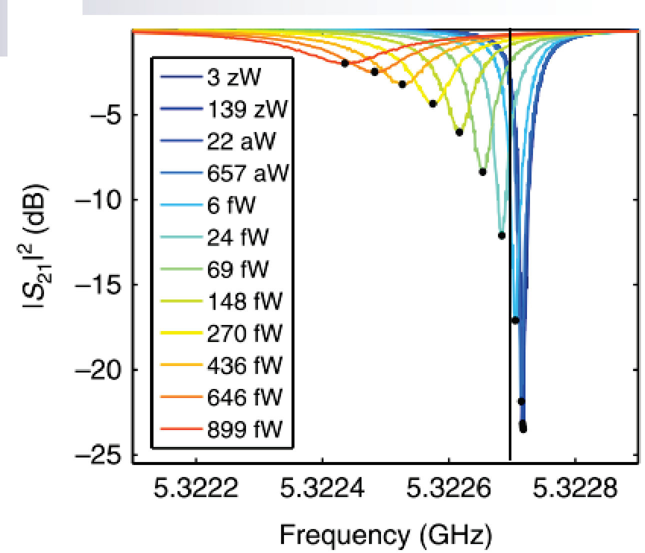
Dynamic Range

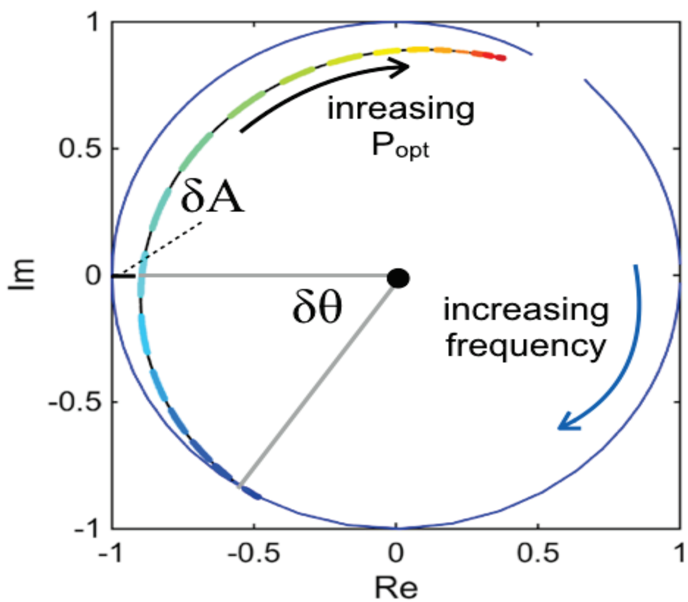
No retuning of the readout tone

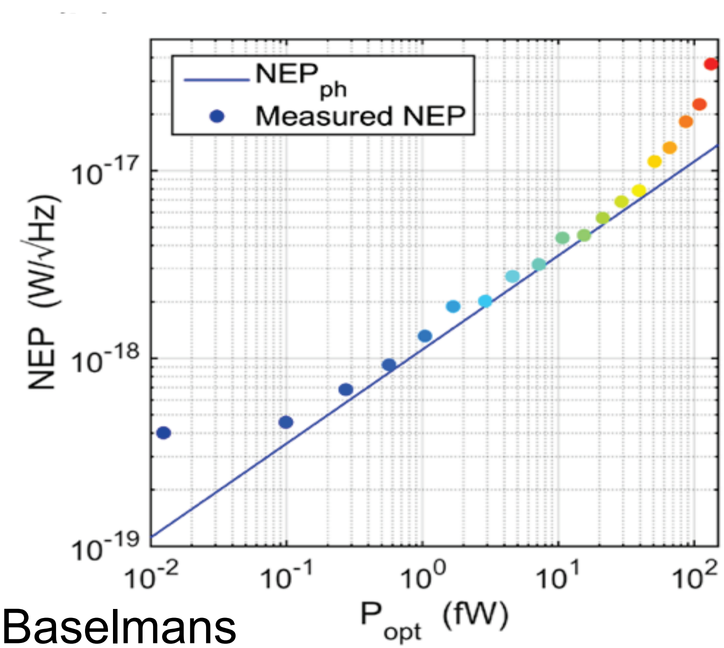
background limited: 100 aW<P_{abs}<40fW

- factor 400

$P_{Saturation}/NEP_{limit}$ = 1 x 10^5







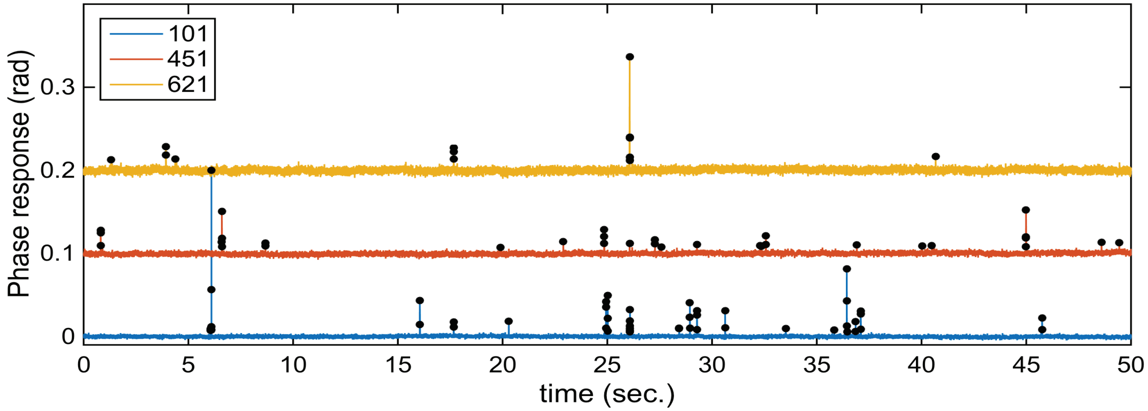
J. Baselmans

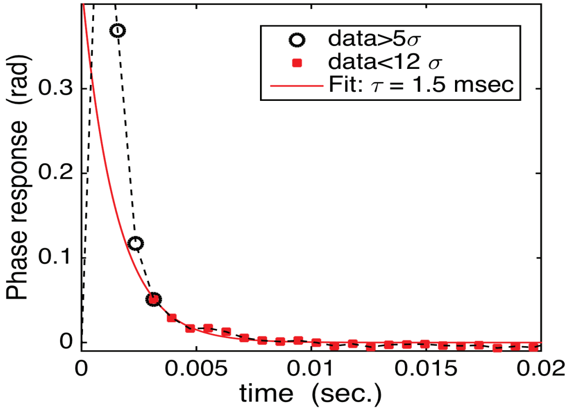
Cosmic Rays - lab tests

At negligible absorbed power
- Single glitches with time constant ~ 1 msec
- fractional dead time (>5σ): 3.2·10-4

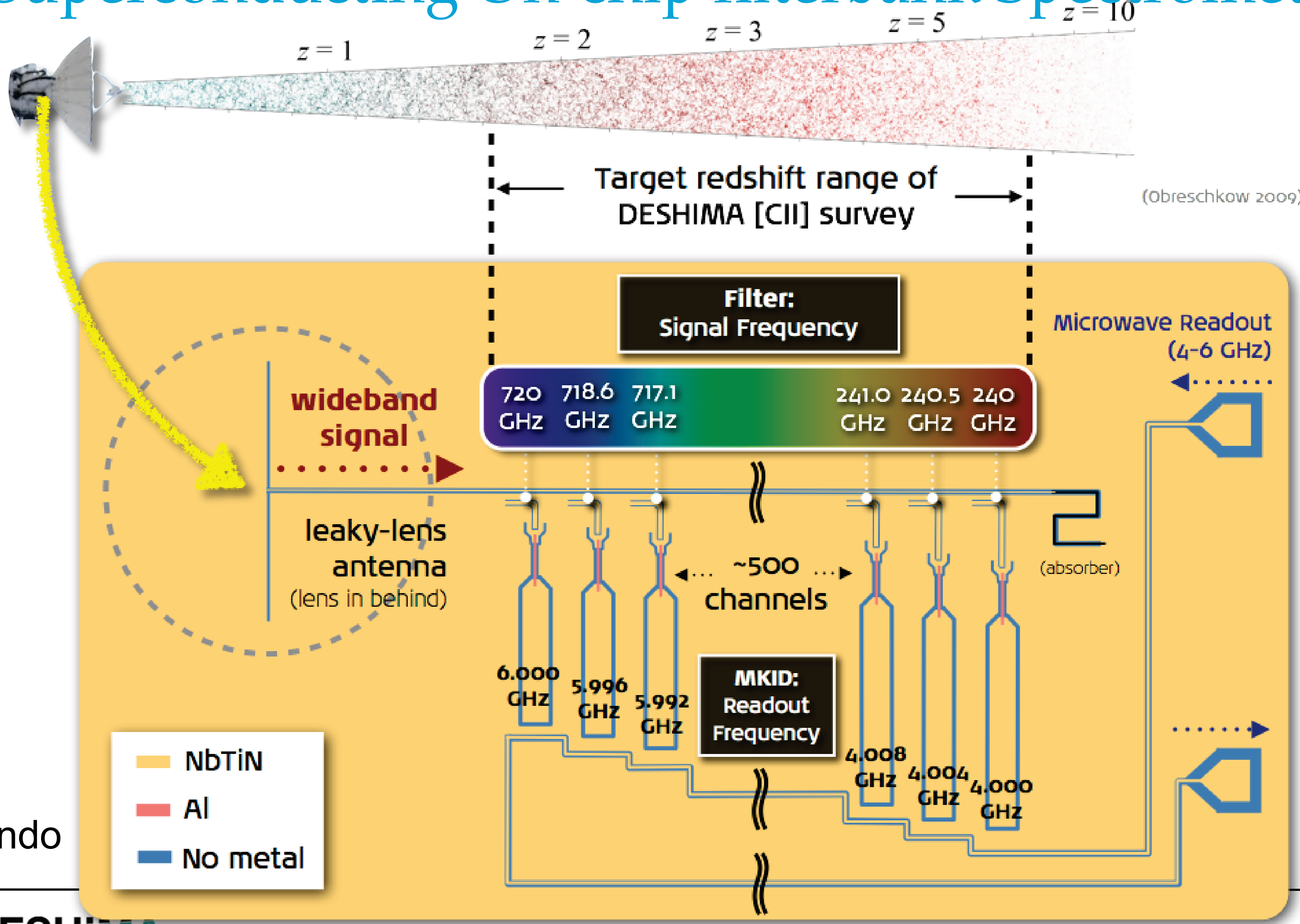
L2 estimation (ignoring energy effects): 4%

No effects on integration: Catalano, A.,et al. 2016, A&A, 592, A26



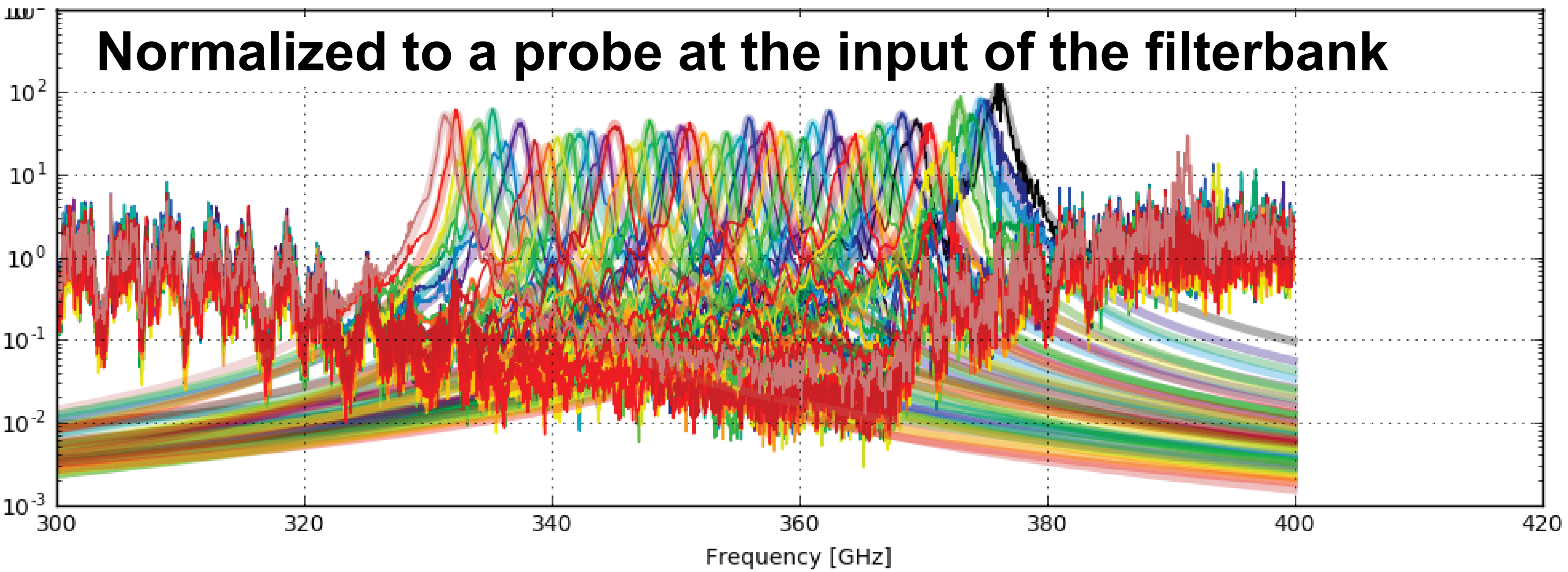


DESHIMA concept:
Superconducting On-chip filterbank Spectrometer



A. Endo

Response of a 49 channel filterbank

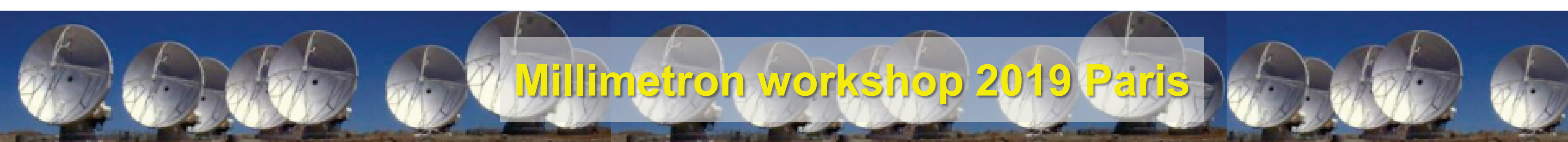


Yield = 100 % (49/49)

A. Endo

Summary direct detectors and future directions

- Both TES and KIDs are at 1E-19 NEP levels
- KIDs are ready for space, as demonstrated by SPACEKIDS program
- Main development advance, large multiplexing capabilities: KIDs 10000 pixel per readout for lower background - >100kPixels instruments.
- Complex on chips spectrometers are becoming available, DESHIMA, Superspec
- 1E-20 seems feasible for TES and KID's, 1E-21 NEP requires new development
  - Quantum capacitance detectors
  - Single photon detectors



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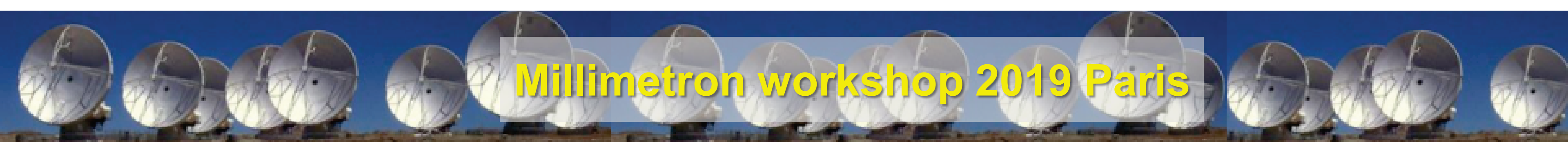
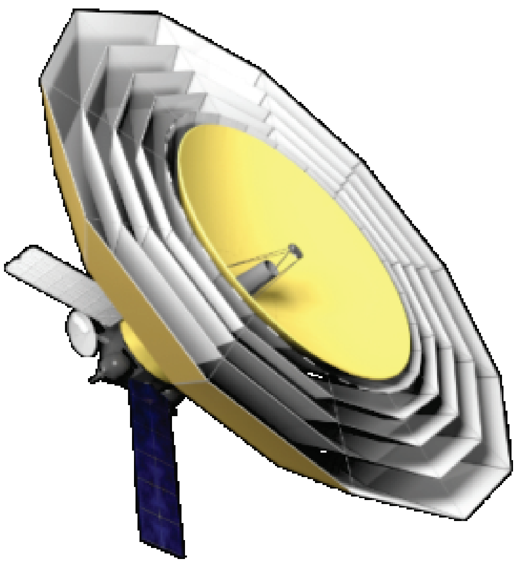
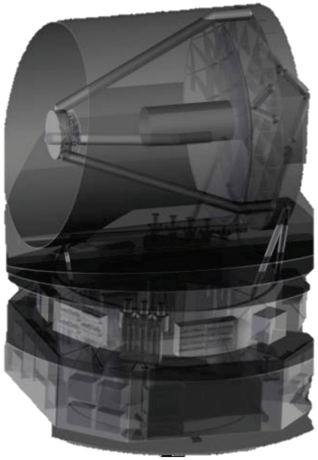


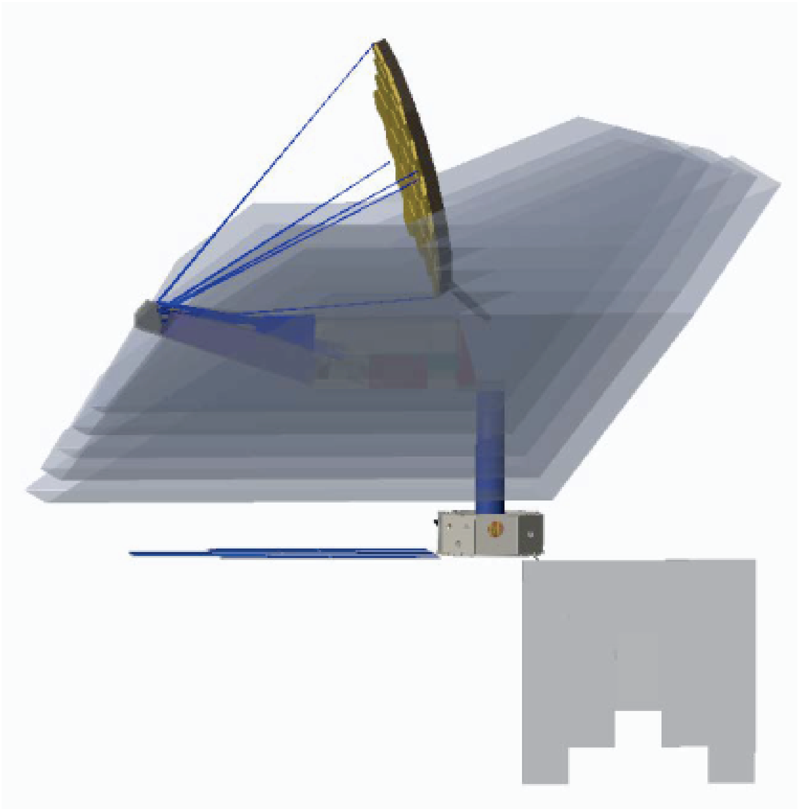
Thank you!



Millimetron design team



SPICA consortium



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