CEB for CMB

Chalmers University, MC2

Nizhnij Novgorod State Technical University, Laboratory of Cryogenic Nanoelectronics

Cold-Electron Bolometers for High-Performance Cosmology Experiments

Leonid S. Kuzmin

In collaboration with:
Paolo de Bernardis (Rome University), Peter Day (Caltech), Phillip Mauskopf (Cardiff University), Sumedh Mahashabde, Michail Tarasov (Chalmers), Stanislav Morugin (NGTU), Ghassan Yassin (Oxford University), Nikolay Kardashev (ASC), Dmitry Golubev (Karlsruhe University), Vyacheslav Vdovin (NSTU), Grigory Goltsman (MSPU), Alexander Andreev (KIPP), Mikhail Kupriyanov (MSU), …

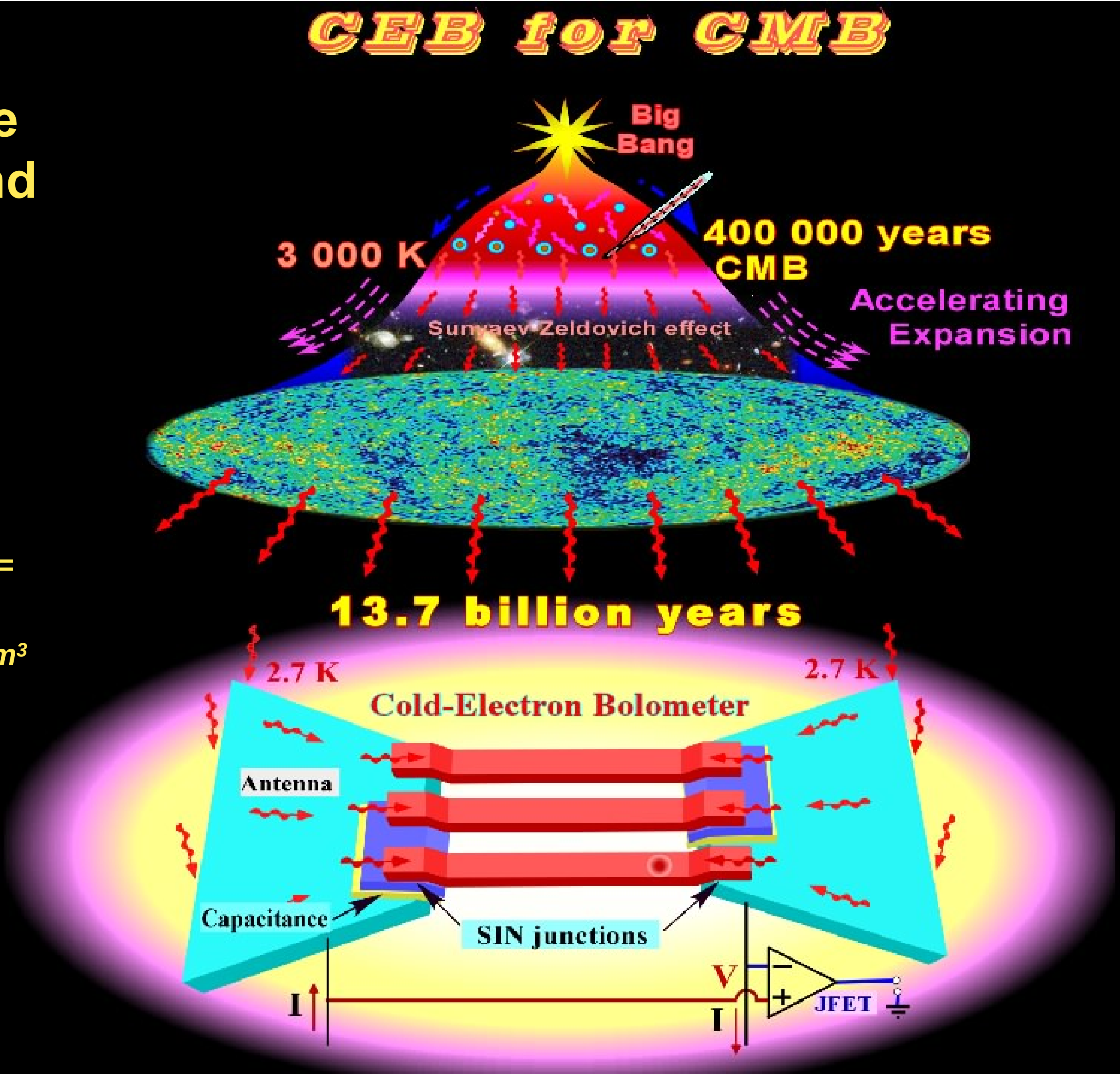
Outline

- **Cold-Electron Bolometer (CEB)**
- **Series/Parallel Array of CEBs with Cross-Slot Antenna for Polarization Measurements (Boomerang)**
- **2D arrays of CEBs for Polarization Measurements (Boomerang, LSPE)**
- **2D arrays with Dual Polarized Antennas for wide-band measurements (OLIMPO, SPICA,)**
- **Conclusions**

Cosmic Microwave Background (CMB) radiation

We collect CMB radiation from *R~ 1*10^{23} km= =100 Yottameters*

to volume ~*0.01 μm^3 (w=100 nm, h=10 nm)*



BOOMERANG-3 - balloon telescope, 2013

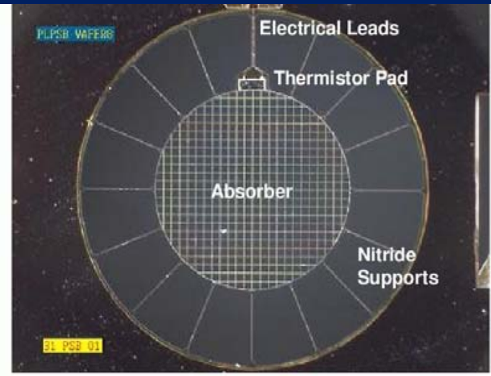
Measurements of the Cosmic Microwave Background (CMB) Polarization

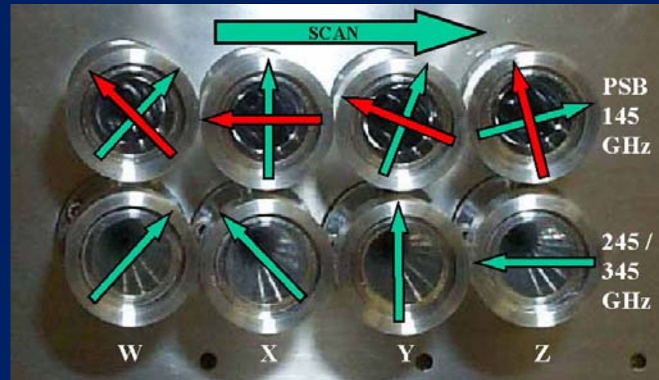
- **Cold-Electron Bolometer (CEB) for 350 GHz, (90 pxl) has been proposed for BOOMERanG-3 ! (March 2007)**
- **JPL(Jet Propulsion Laboratory) gave up to fabricate a new generation of Ge bolometers !?**
- ***CHALMERS is the only provider of CEBs for BOOMERANG-3***
- ***Collaborators: Rome University, JPL, Cardiff Un, IREE RAS, Oxford Un, NTU, MPGU, MSU, KIPP RAS, ASC RAS***

The BOOMERANG-2 telescope ready for launch in Antarctica, near vulcano Erebus.

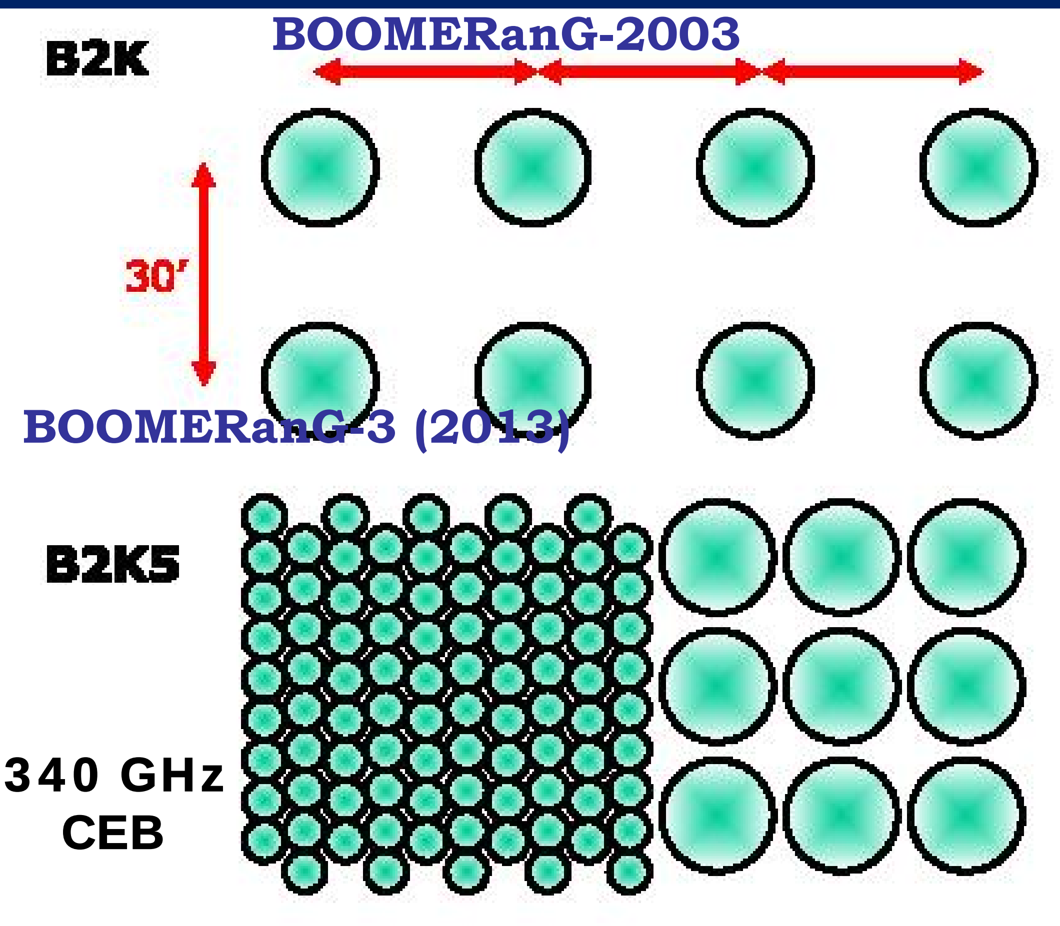
January 2003

Ge detectors at 0.3 K





The He3 refrigerator for BOOMERANG



140 GHz
CEB

Balloon telescope BOOMERANG

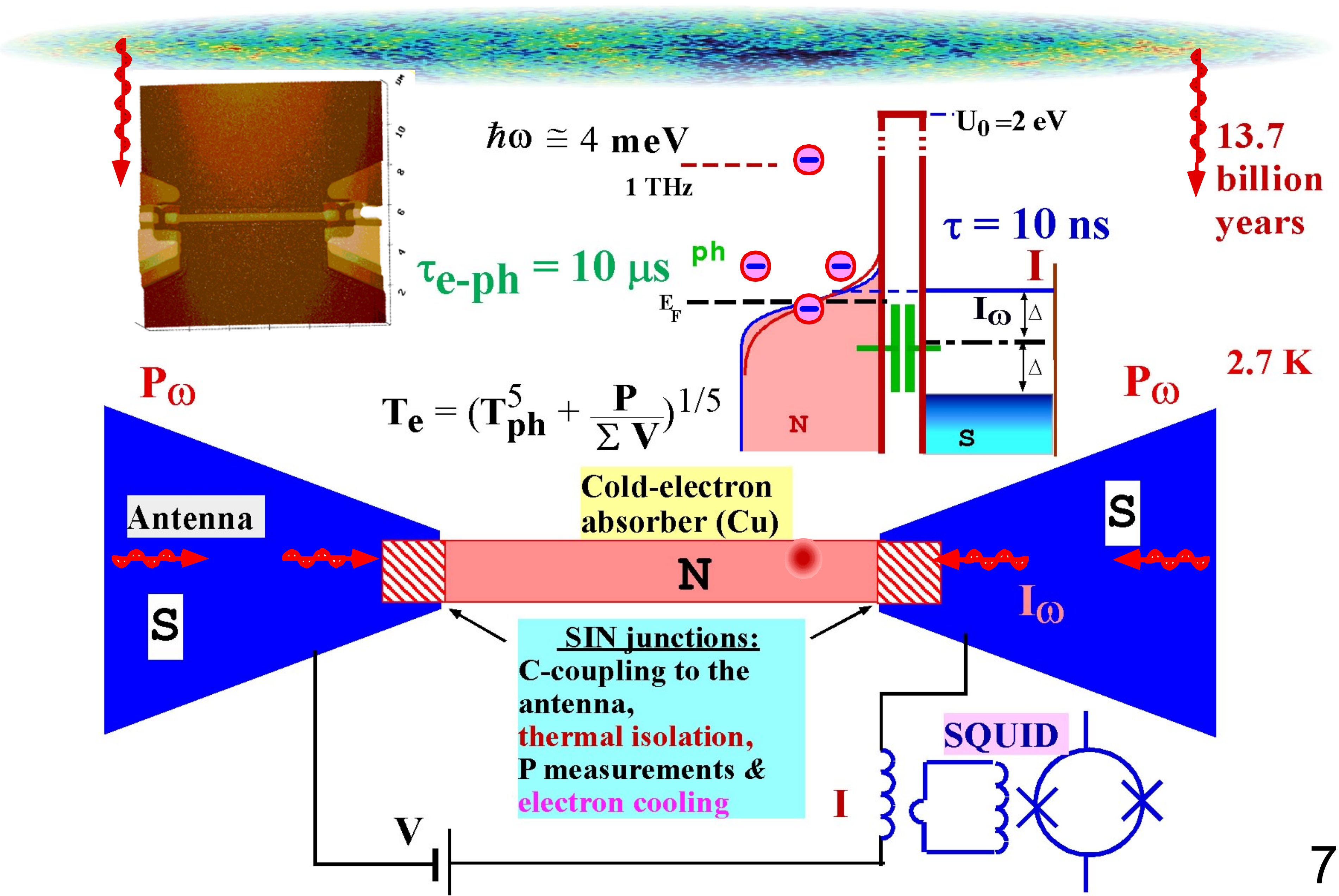
- **Channel II: 350 GHz**
- **Number of pixels: 90 (min 70, max 100)**
- **Background Power load : P_0 = 5 pW**
- **Photon noise:**

$$NEP_{phot} = \sqrt{2P_0 * hf} = 5*10^{-17} W / Hz^{1/2}$$

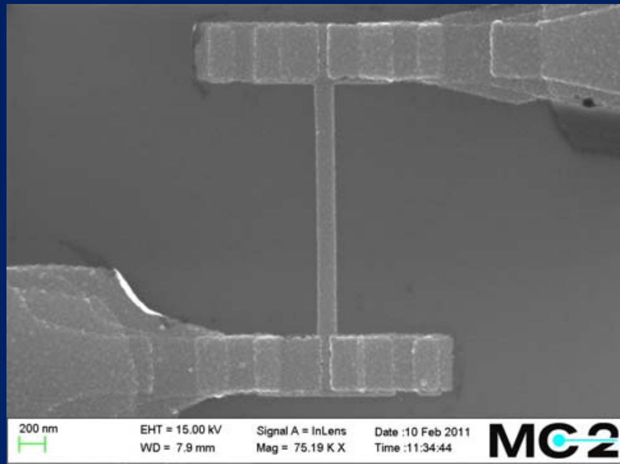
- **The NEP of bolometer: NEPbol < NEPphot.**
- **Polarization sensitivity > 23-25 dB**
- **Insensitive to Cosmic Rays!**
- **Reliable bolometers**
- **Launch – June 2014 (after OLIMPO)**

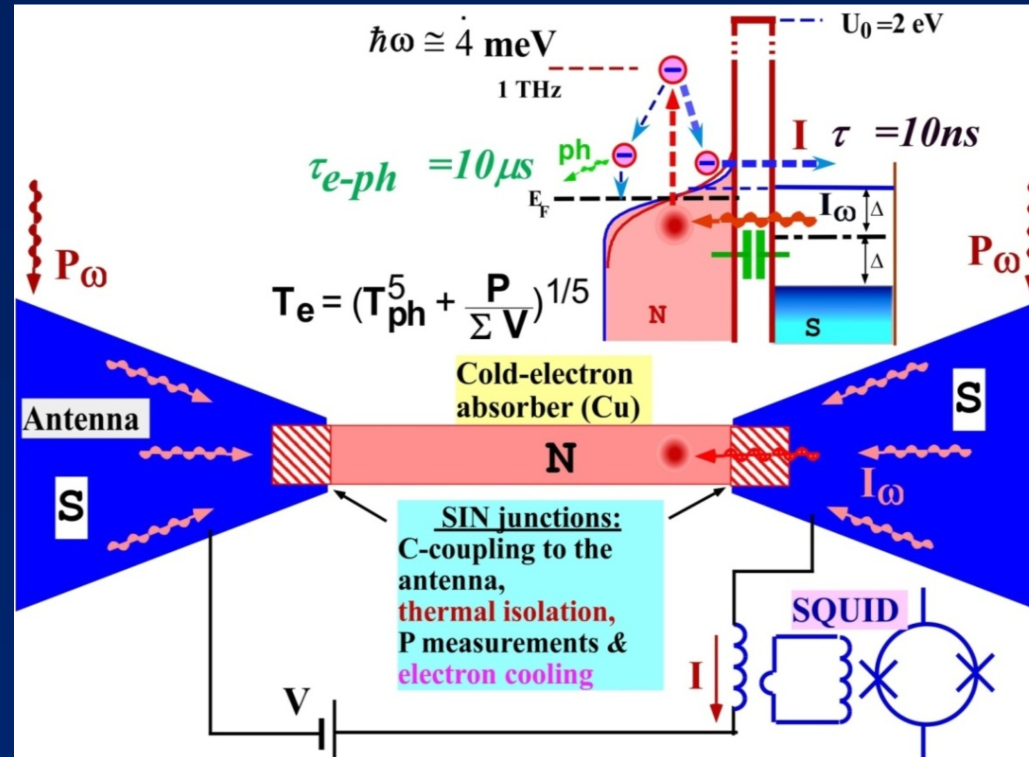
Cold-Electron Bolometer (CEB) with Capacitive Coupling to the Antenna

L. Kuzmin, 9th ISSTT (1998)- SNED (2001) – SPIE (2004)



Cold-Electron Bolometer (CEB) with Capacitive Coupling to the Antenna





Main features of the CEB:

1.High sensitivity due to electron cooling effect:

NEPceb<NEPph for any optical power load

(from 80pW for LSPE to 0.02 fW for SPICA)

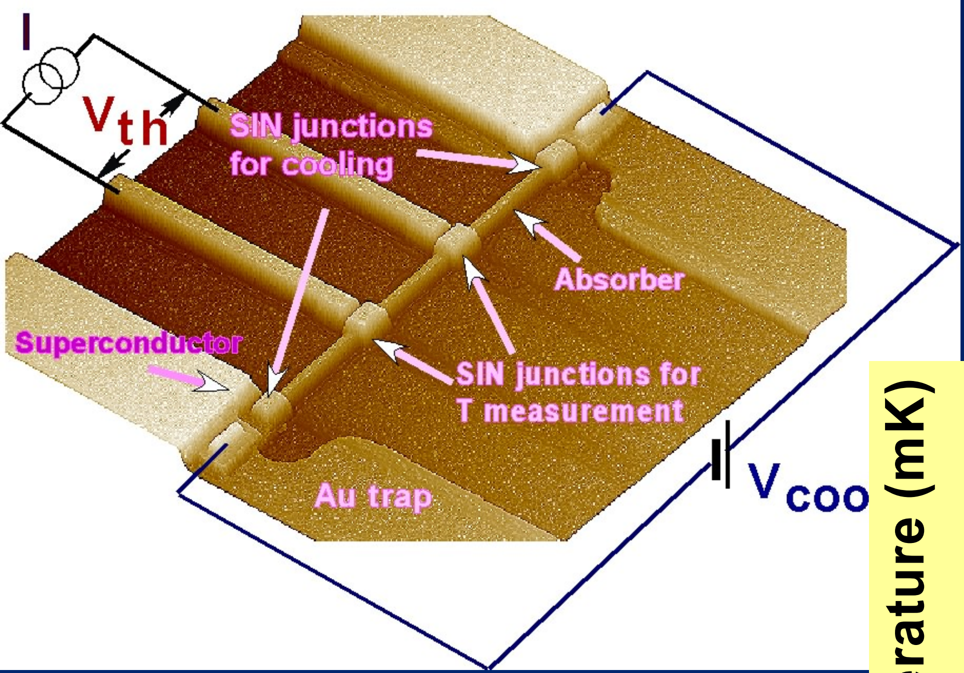
2. High dynamic range due to direct electron cooling

3. Insensitivity to Cosmic Rays (CR)

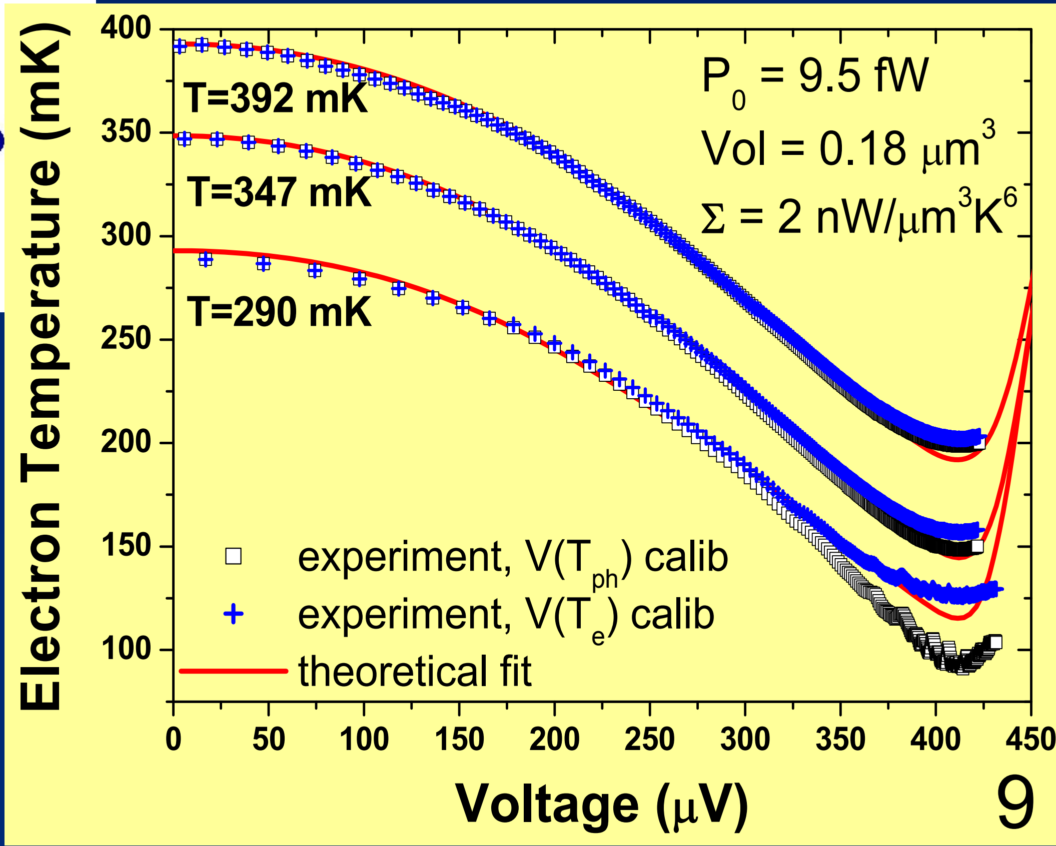
Electron Cooling Experiment

I. Agulo, L. Kuzmin M. Fominsky, and M. Tarasov

SUST, **17**, p. 400 (2004)



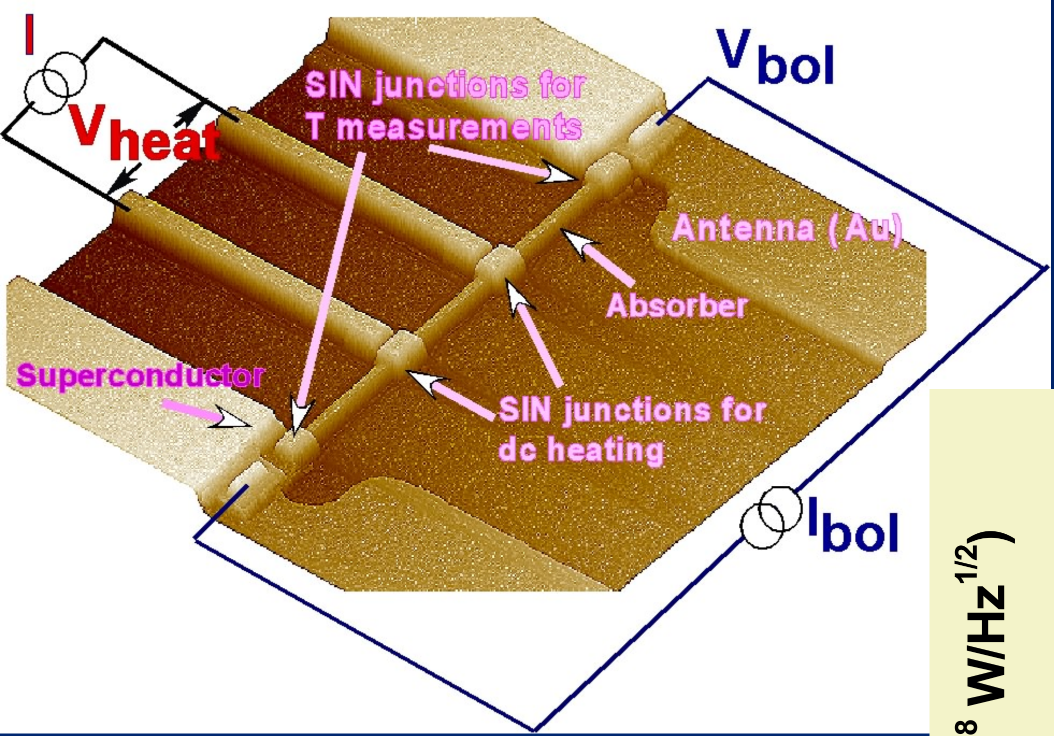
Si plane substrate



Electron cooling by SIN tunnel junctions:
Nahum, Elies, and Martinis, APL, 1994

Noise characterization of the CEB

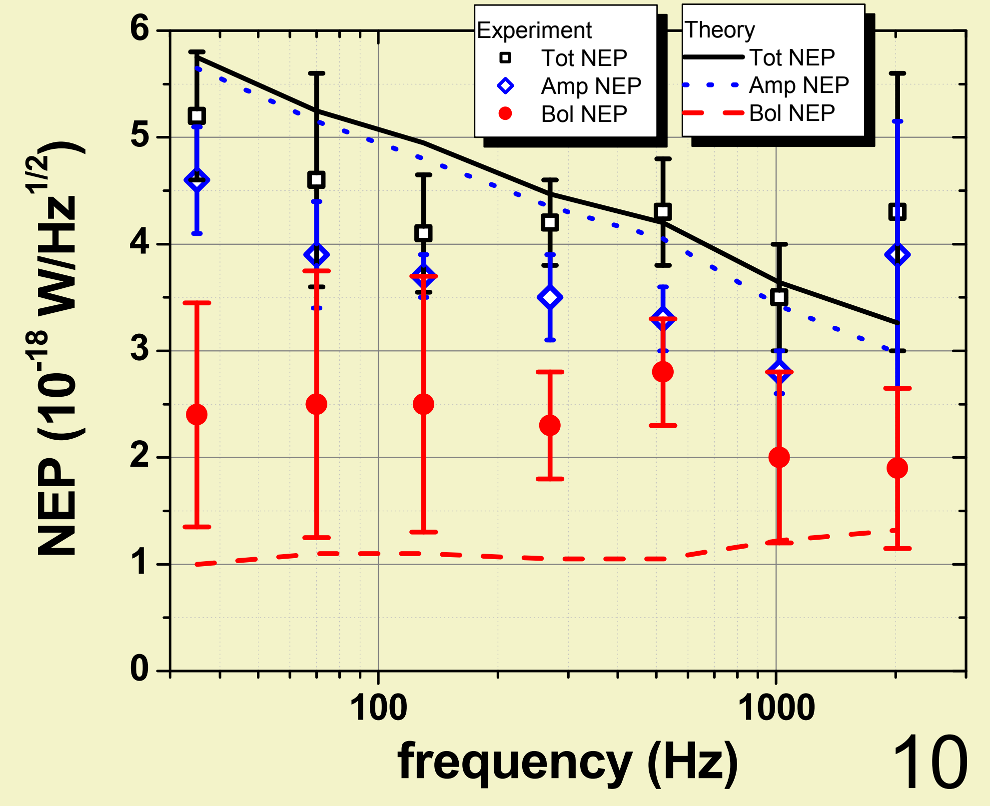
I. Agulo, L. Kuzmin, and M. Tarasov



Room T amplifier - AD743

Power load – 20 fW

NEPbol=2x10^{-18} W/Hz$^{1/2}$



Proposed projects with CEB

March 2007 -March 2012

Balloon Projects

BOOMERANG, 350 GHz (90 pxl)

Space projects

After March 2012

BOOMERANG, 350 GHz (90 pxl)
+150 GHz (9pxl)

OLIMPO 350 GHz(2 pixels) ***or***
350 GHz(23 pxl) +470 GHz(23 pxl)

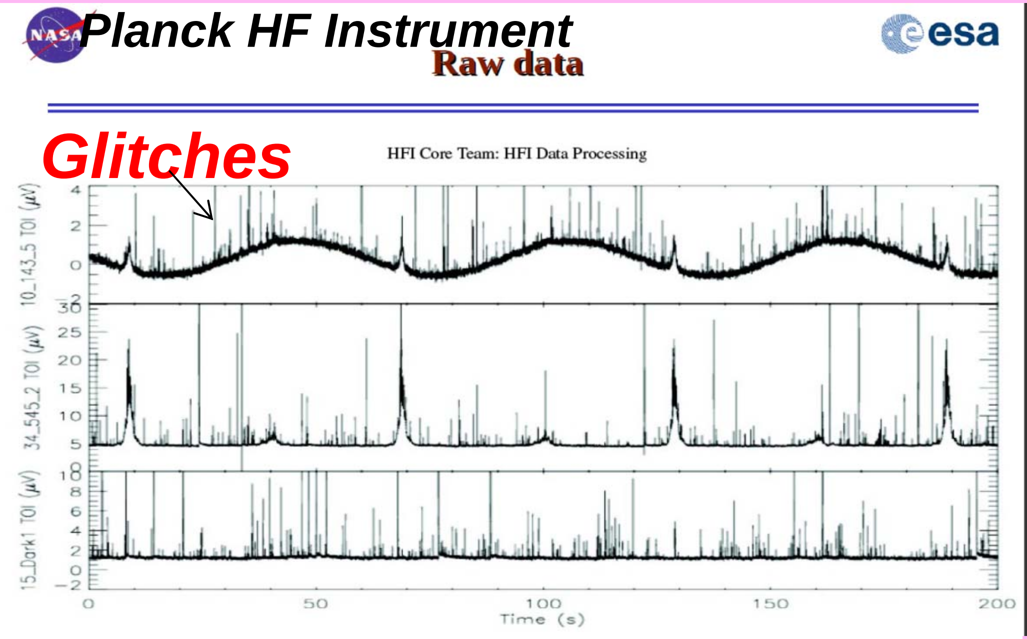
LSPE 90 GHz(24 pxl) +140 GHz(24pxl)
+220 GHz(24pxl)

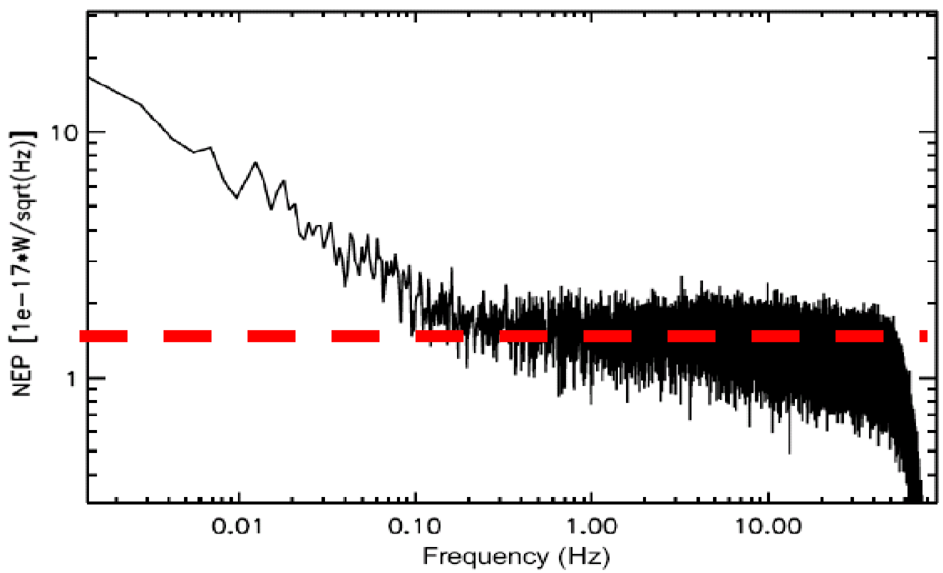
MILLIMETRON- FTS, Rome Un.-leader

2)

Detectors Count & Focal-plane real-estate

- 5 uK arcmin target (after removal of foregorunds): extremely high total sensitivity required.
- Bolometric detectors
- Sensitivity achieved by multiplication of number of detectors, not through reduction of NEP (<T & < background).
- Planck experience with 40K telescope + CMB background: **photon noise limit, with cosmic rays hits close to be important**

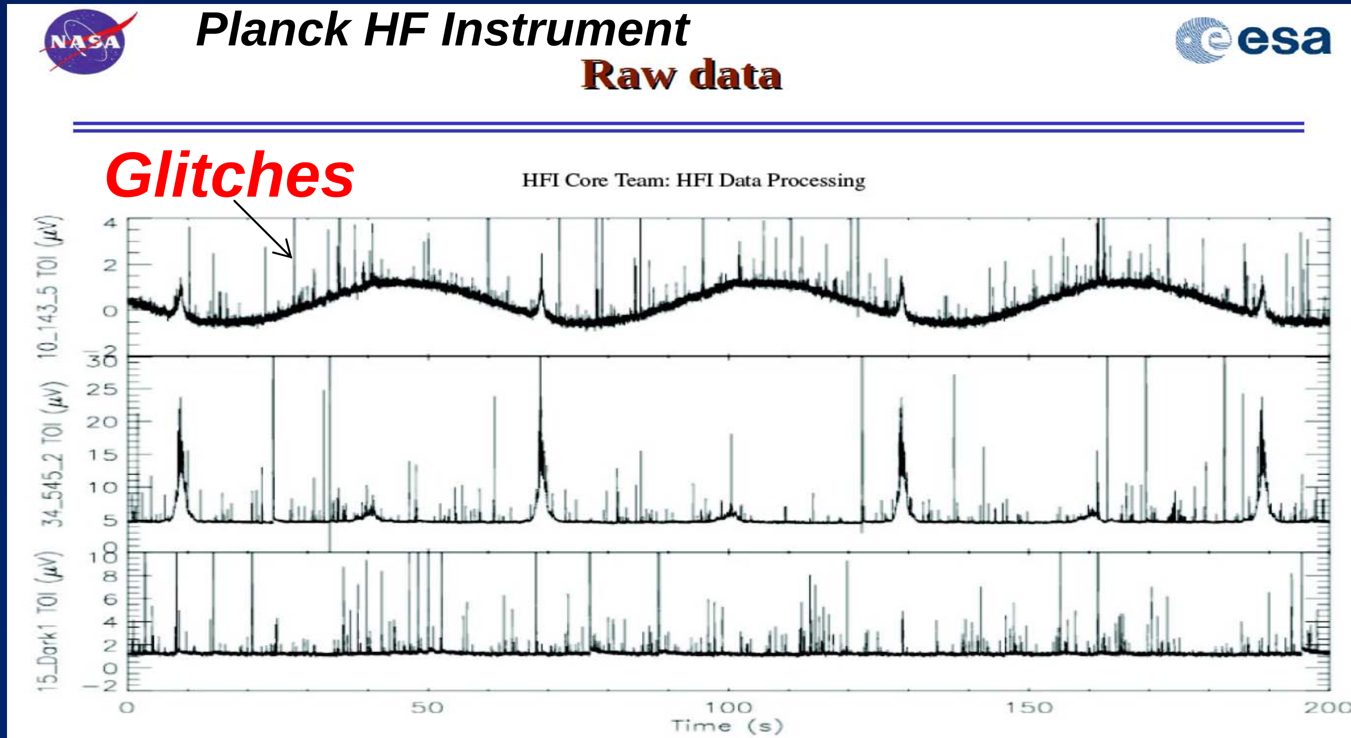




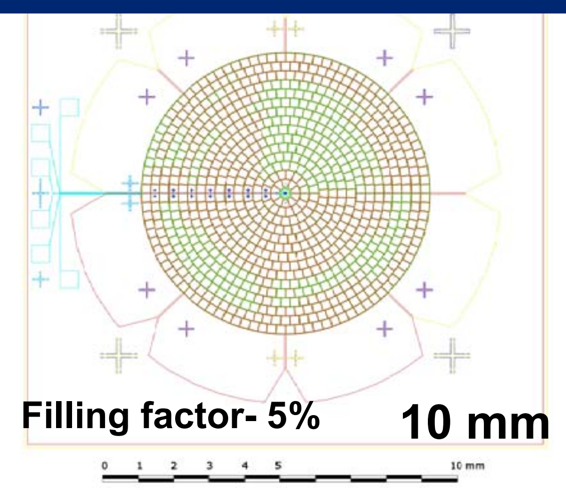
Planck HFI Core Team: *Planck* early results. IV. A&A 536, A4 (2011)

COrE
Cosmic Origins Explorer

Cosmic Rays-dramatic problem!



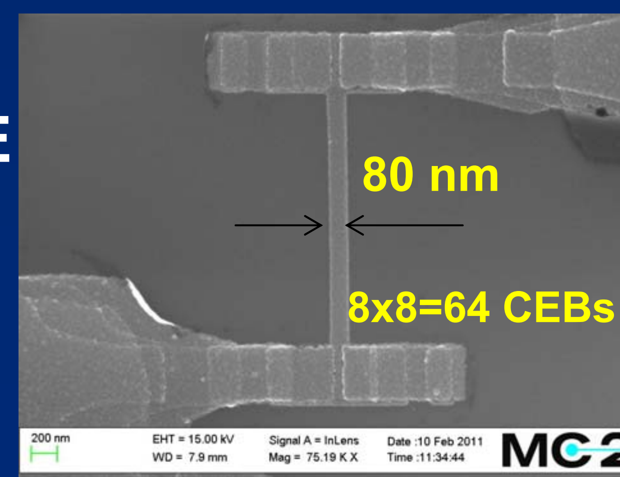
Concentration of cosmic rays for balloon experiments is more than in space and dramatically (10 times!) increased near poles!



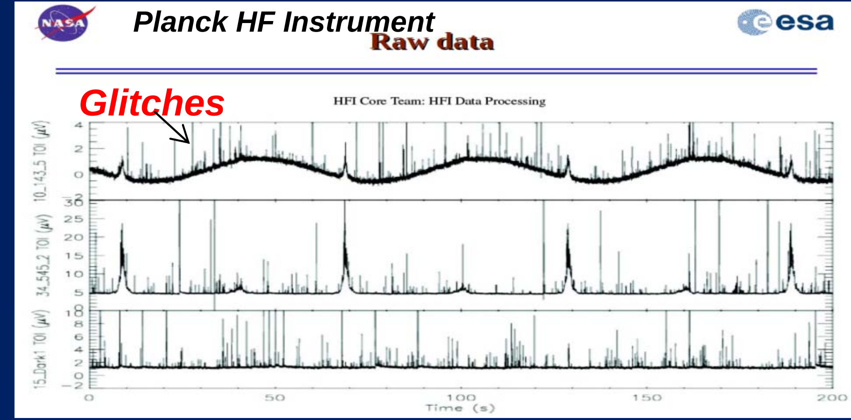
Spider-web for LSPE

CEB for LSPE

Cosmic ray test for CEB – in progress in Rome



Cosmic Rays- dramatic problem!



Cosmic ray test for CEB in Rome:

A number of tests with the CEB and a 137Cs source (660 keV photons) in front of the window have been done , but we have not been able to detect even a single event.

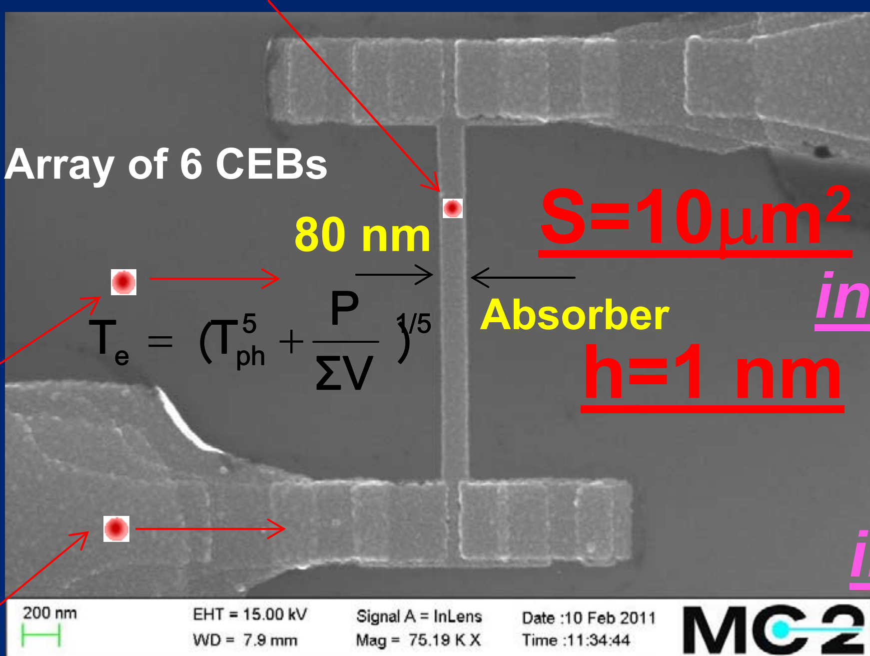
Paolo de Bernardis, August 10, 2012

Concentration of cosmic rays for balloon experiments near poles is more than in space!

CEB

Triple protection against Cosmic Rays!

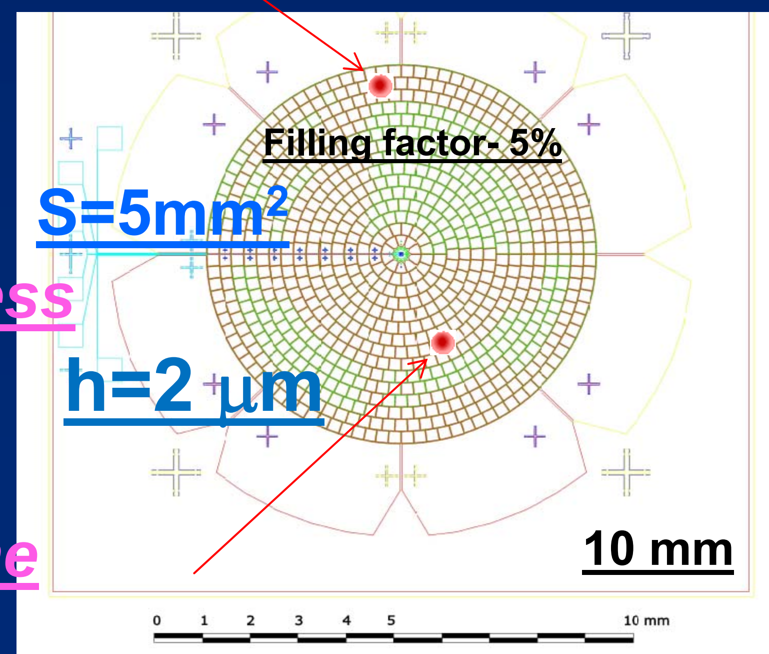
Spider-web (TES, Ge...)



Gain in Area **:1000**

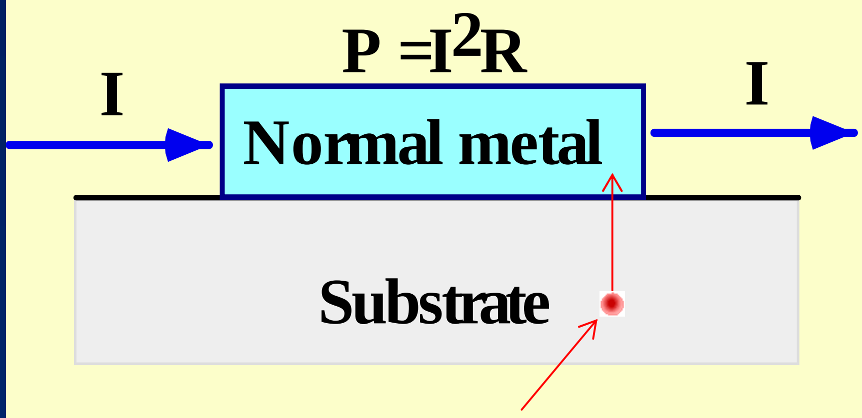
in thickness **:1000**

Gain in volume **:10^6**

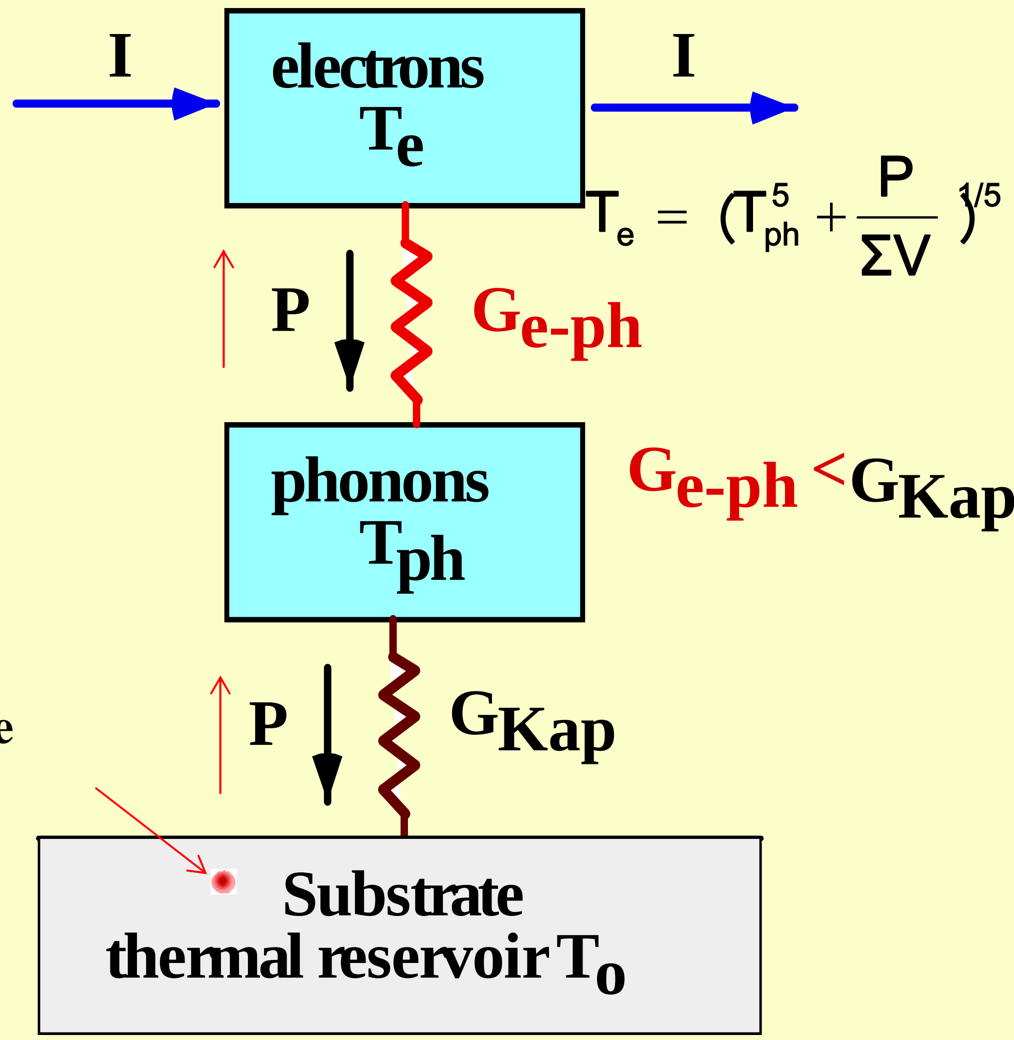


CEB: Triple protection against Cosmic Rays!

Coupling between thermodynamic subsystems



$P = -\Sigma V (T_e^5 - T_{ph}^5)$
- energytransfer from electrons tophonons



$G_{e-ph} = dP/dT = 5 \Sigma V T_e^4$ - thermal conductance

$G_K = 1/R_K = A/K\, T_{ph}^3$ - Kapitza conductance

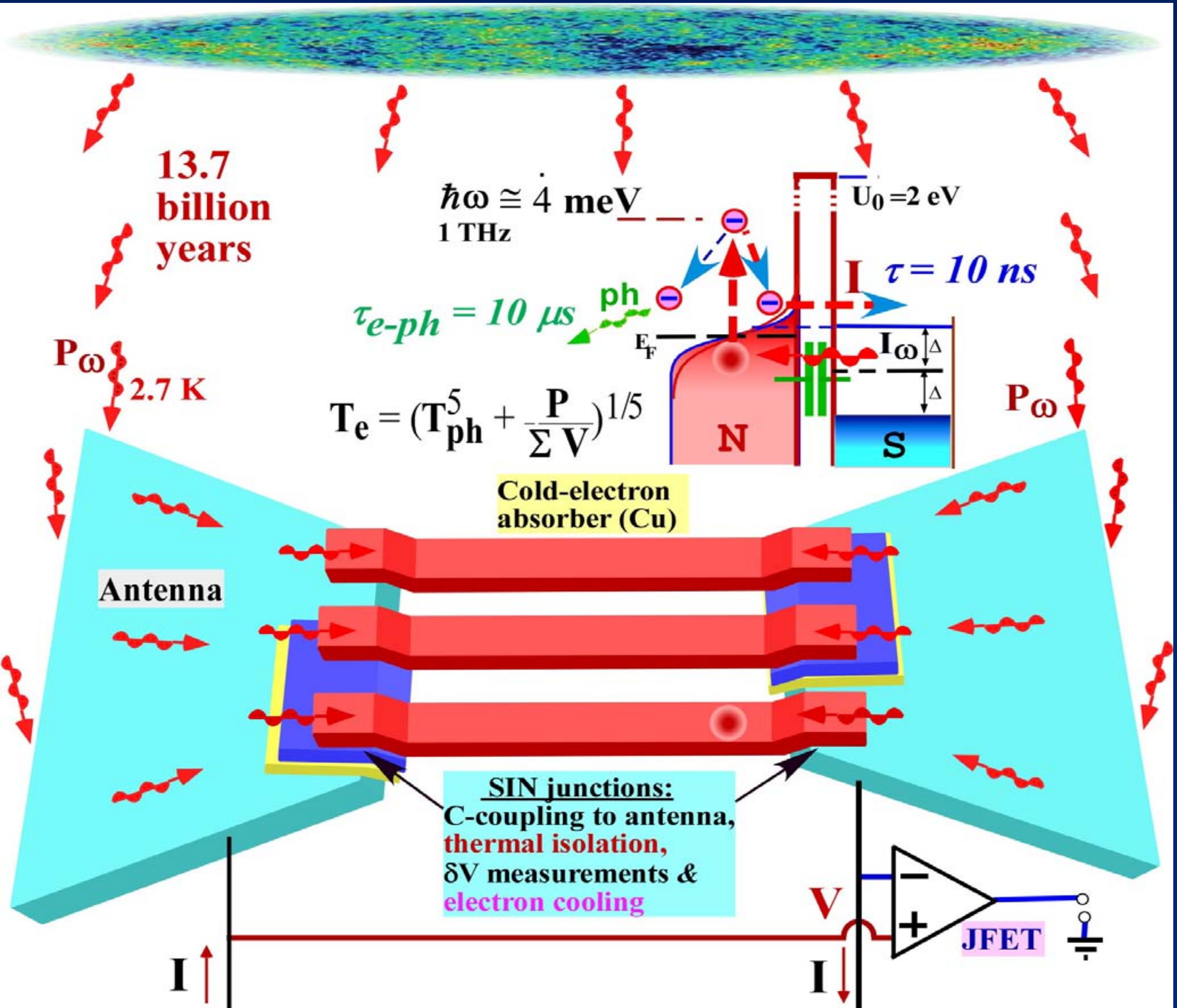
$T = 100$ mK

$G_{e-ph} = 5*10^{-14}$ W/K

$G_K = 2*10^{-12}$ W/K

Parallel/Series Array of CEBs

with SIN junctions in *current-biased mode* with JFET readout



for BOOMERanG Balloon Telescope

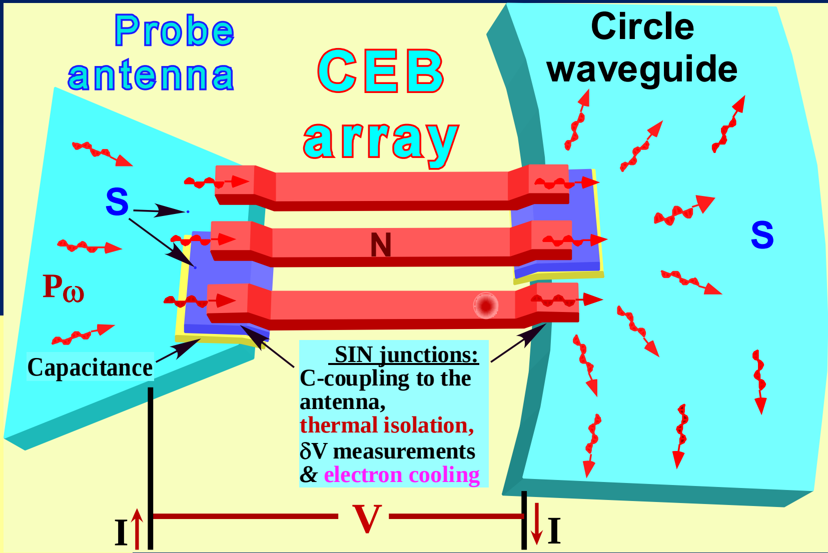
Po=5 pW

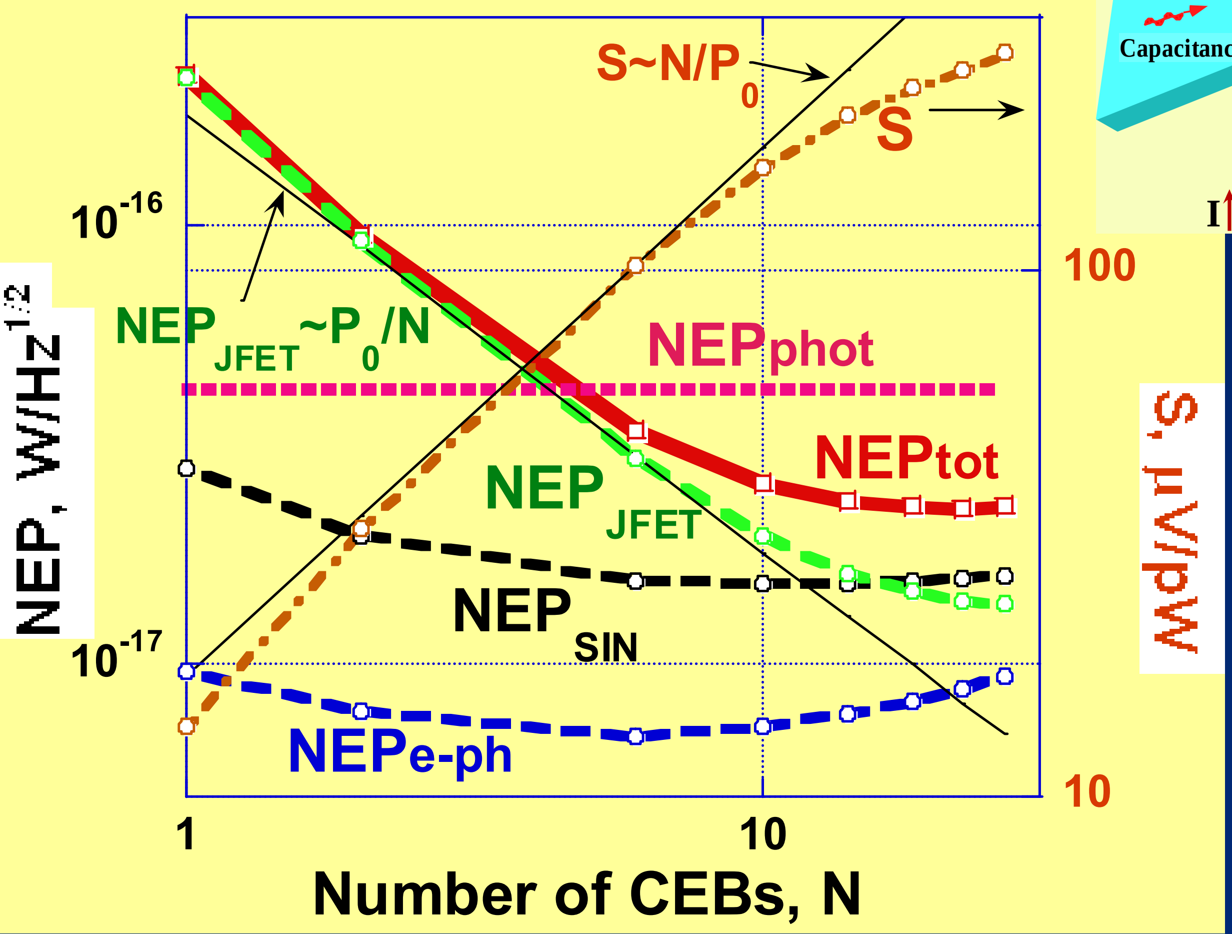
Array of CEBs

L. Kuzmin, EUCAS-07; JPCS, v. 97, 012310 (2008).

Parallel/Series Array of CEBs in current-biased mode with JFET readout.

P_0= 5 pW, f=350 GHz





Total NEP < NEPphot
S=1 μm2

R=0.5 kOhm,

Vol=0.01μm3,

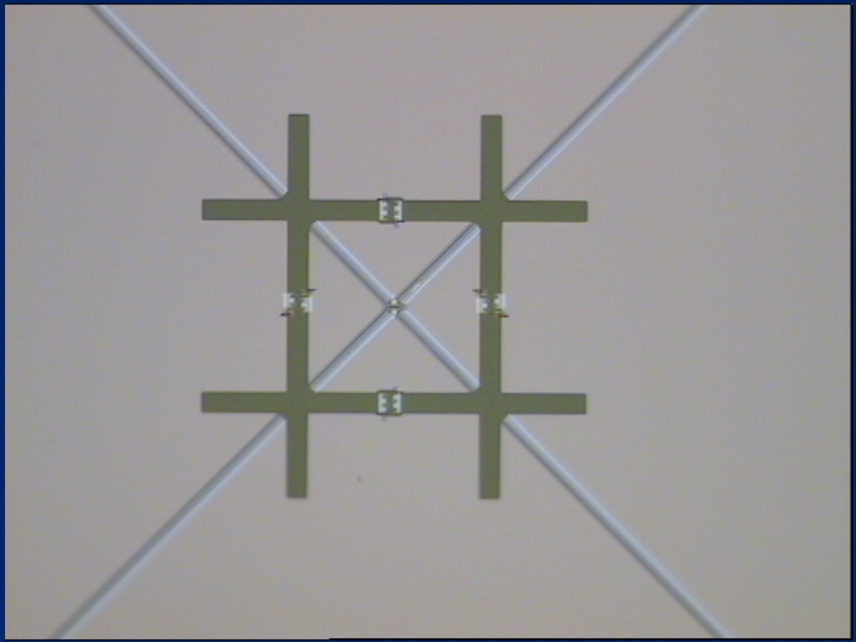
T=300 mK

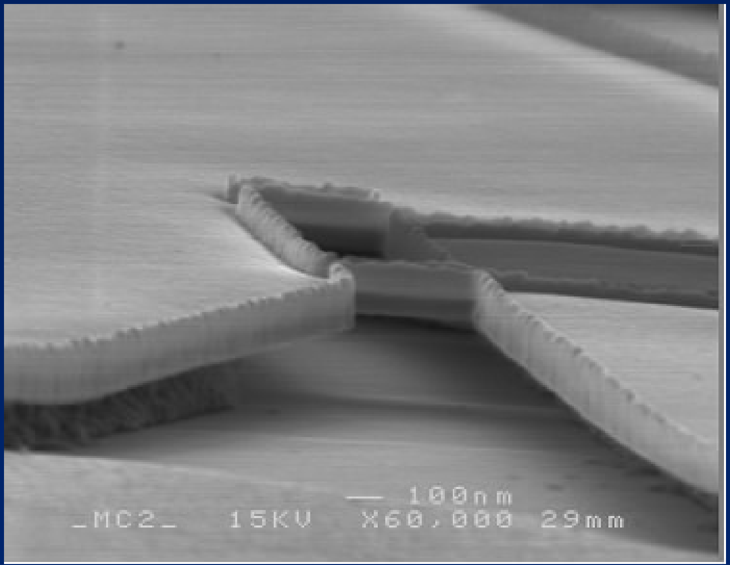
I_{JFET}=5 fA/Hz$^{1/2}$
V_{JFET}=3 nV/Hz$^{1/2}$

Optical Response of a Cold-Electron Bolometer Array Integrated with a 345 GHz Cross-Slot Antenna

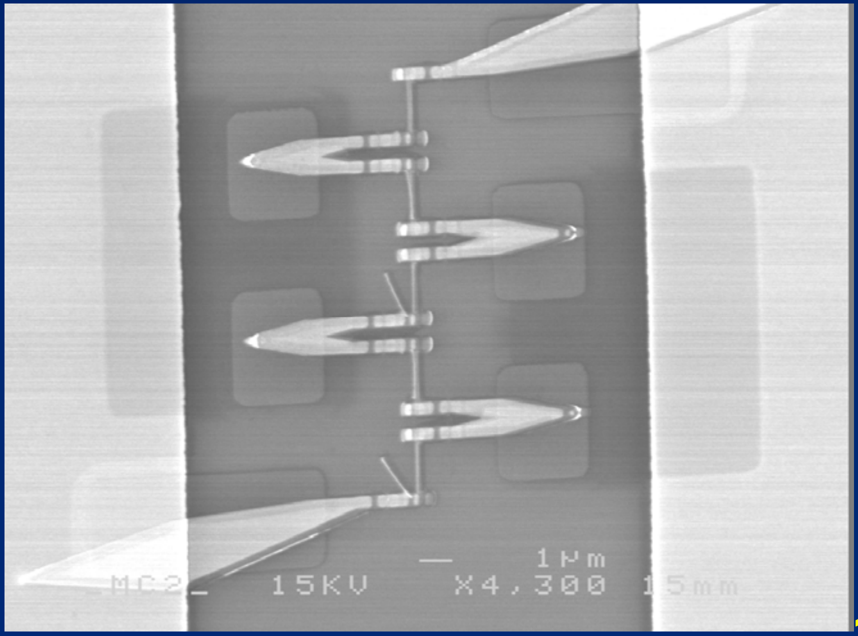
Mikhail Tarasov, Leonid Kuzmin, Valerian Edelman, Sumedh Mahashabde, Paolo deBernardis

2011 IEEE Van Duzer for the best publication in IEEE Trans on Applied Superconductivity





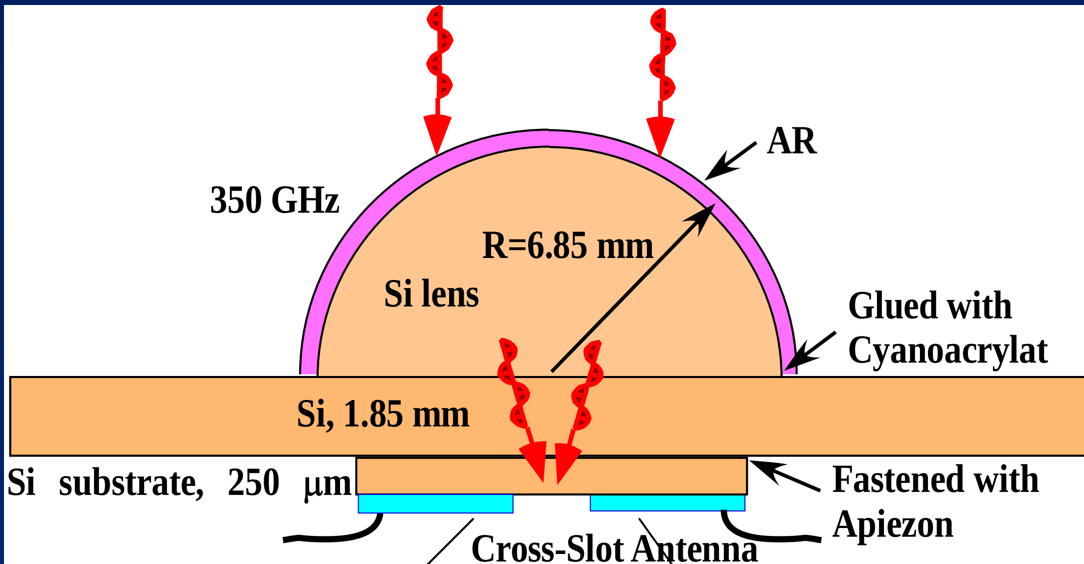
Optical image of a cross-slot antenna designed for 345 GHz
30 Ω

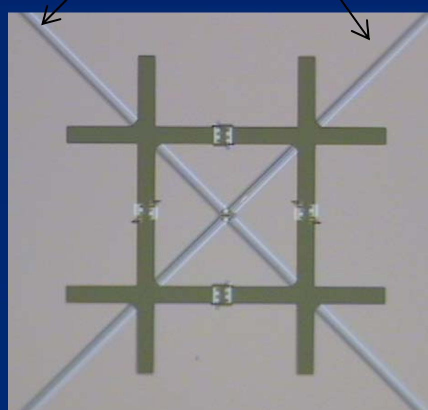


SEM image of a series/parallel array of 10 CEBs

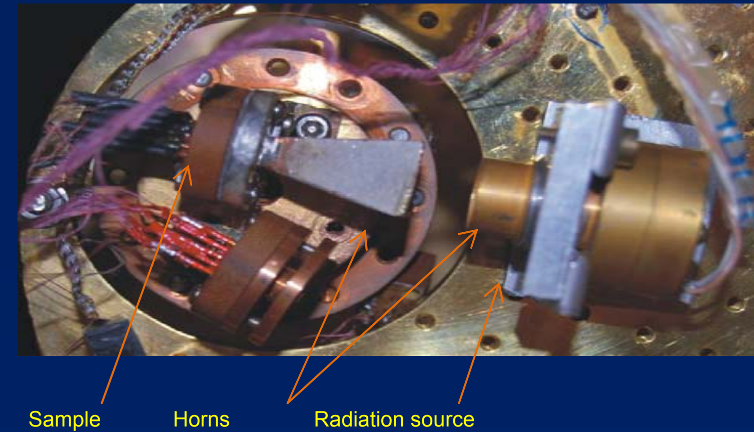
Jonas Zmuidzinas et al., Caltech/JPL – design of a cross-slot antenna

Si lens coupled to a planar Si substrate with a cross-slot antenna including a Series/Parallel Array of CEBs





Jonas Zmuidzinas et al., Caltech/JPL – design of a cross-slot antenna and a Si lens coupled to a planar Si substrate



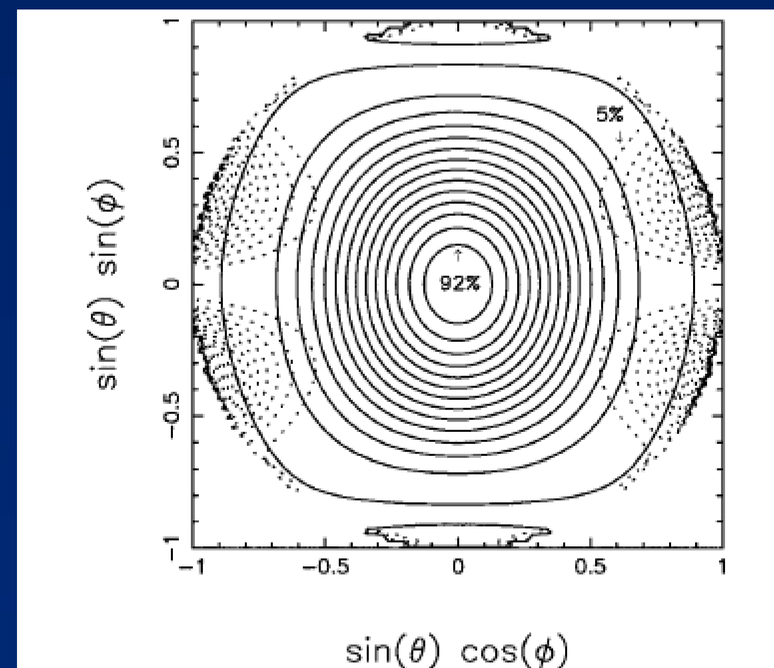
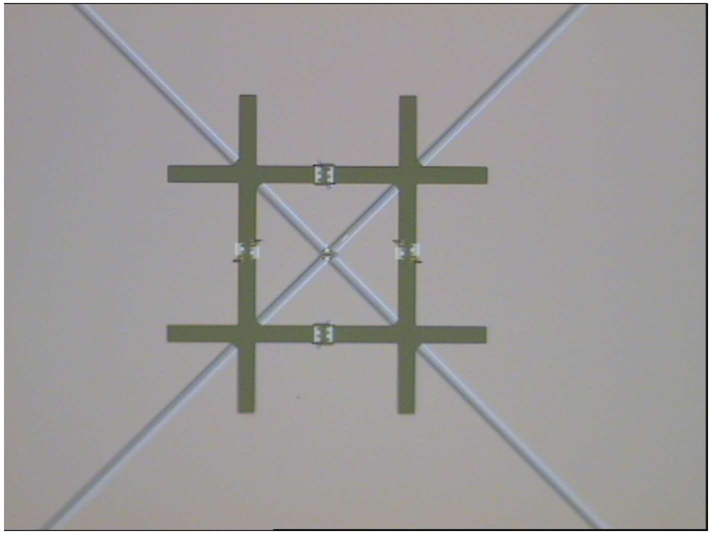
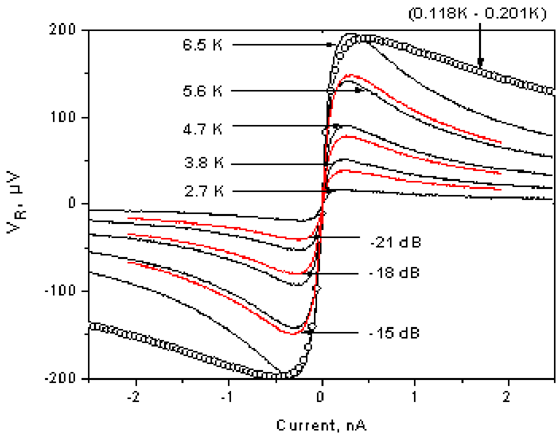


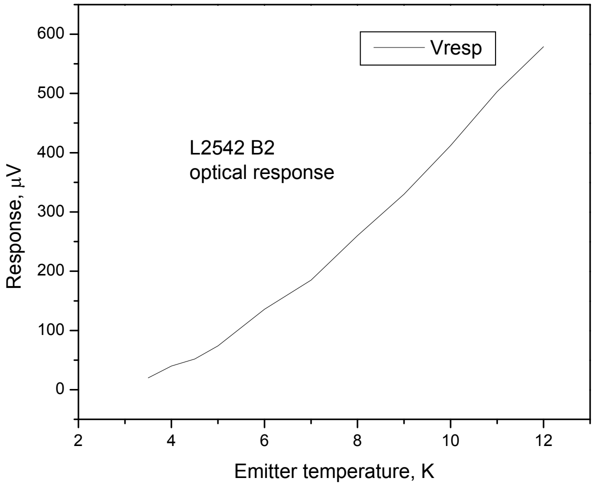
Fig. 3. Contour plots of the calculated co-polarized and cross-polarized power pattern radiated into the dielectric by the antenna. The solid lines are for the co-polarized power and the dotted lines are for the cross-polarized power. The dimensions of the slot are the same as in Fig. 2. For the co-polarized power, the contours are linearly spaced from 0.5 to 92% of the peak co-polar power in increments of 7%; and for the cross-polarized power, the contours are linearly spaced from 5 to 95% of the peak cross-polar power in increments of 5%. The quantities (θ, ϕ) are the usual polar angles with respect to $\hat{z}$.

Optical response at 350 GHz

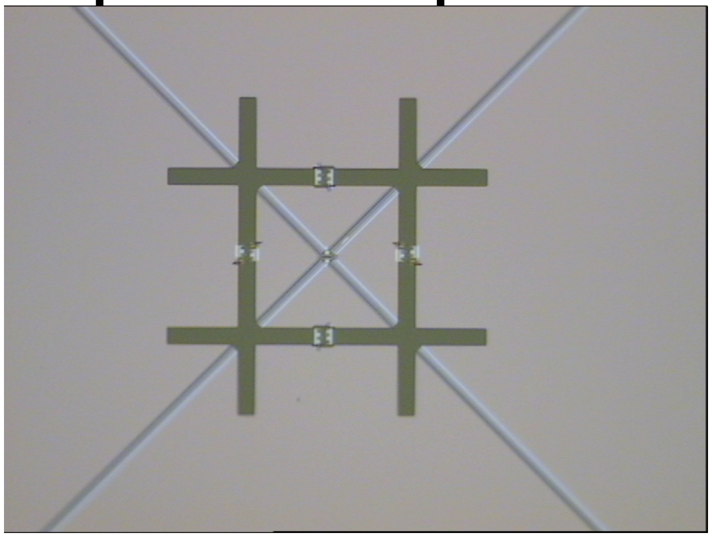


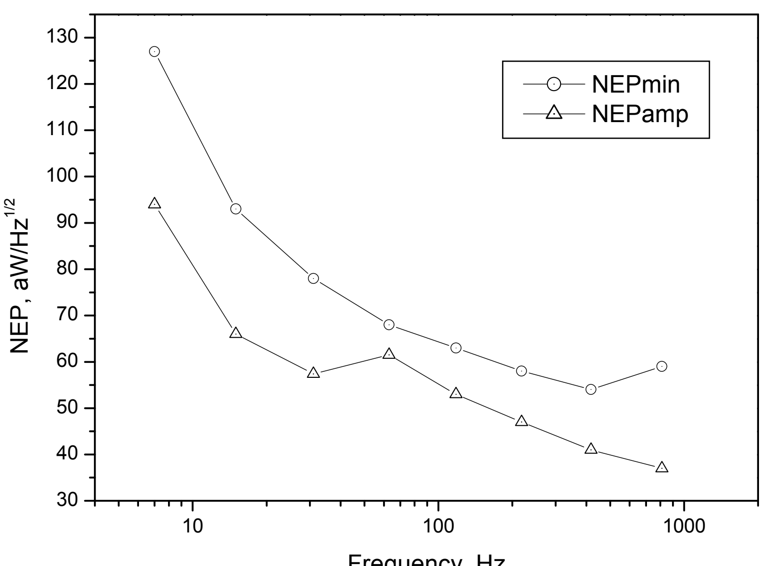


Voltage response of the bolometer array to bath temperature changes 0.118-0.2 K (open circles), to variations of blackbody source temperature 2.7 K, 3.8 K, 4.7 K, 5.6 K, 6.5 K (black lines), and also to 345 GHz radiation from BWO with additional attenuation of -21 dB, -18 dB, and -15 dB (red lines).



Optical response and Noise equivalent power





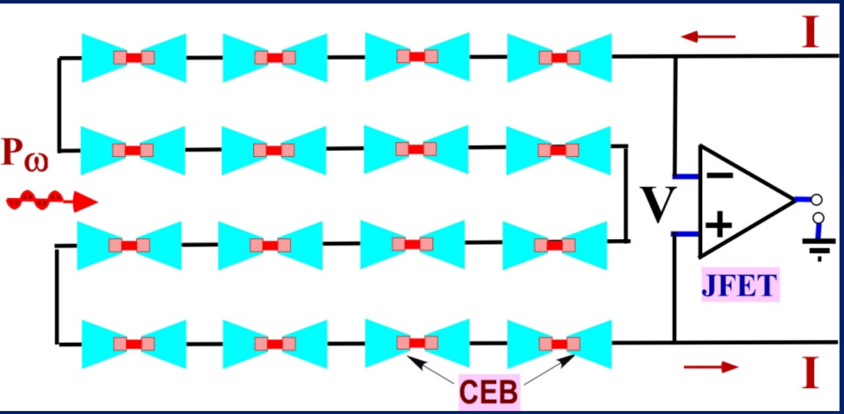
The minimum Noise Equivalent Power NEP=6*10^{-18} W/$Hz^{1/2}$ at 280 mK and corresponding value for amplifier impact NEPamp

power response V/dP=8.6*10^{8} V/W,

optical NEP=2*10^{-17} W/$Hz^{1/2}$;

Polarization resolution – 3-10 dB

Focal Plane Series Array with JFET readout

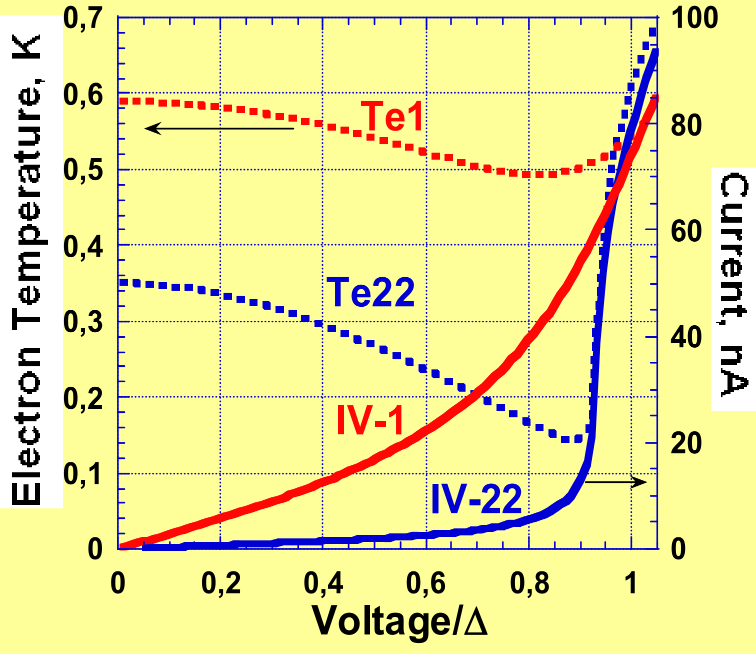


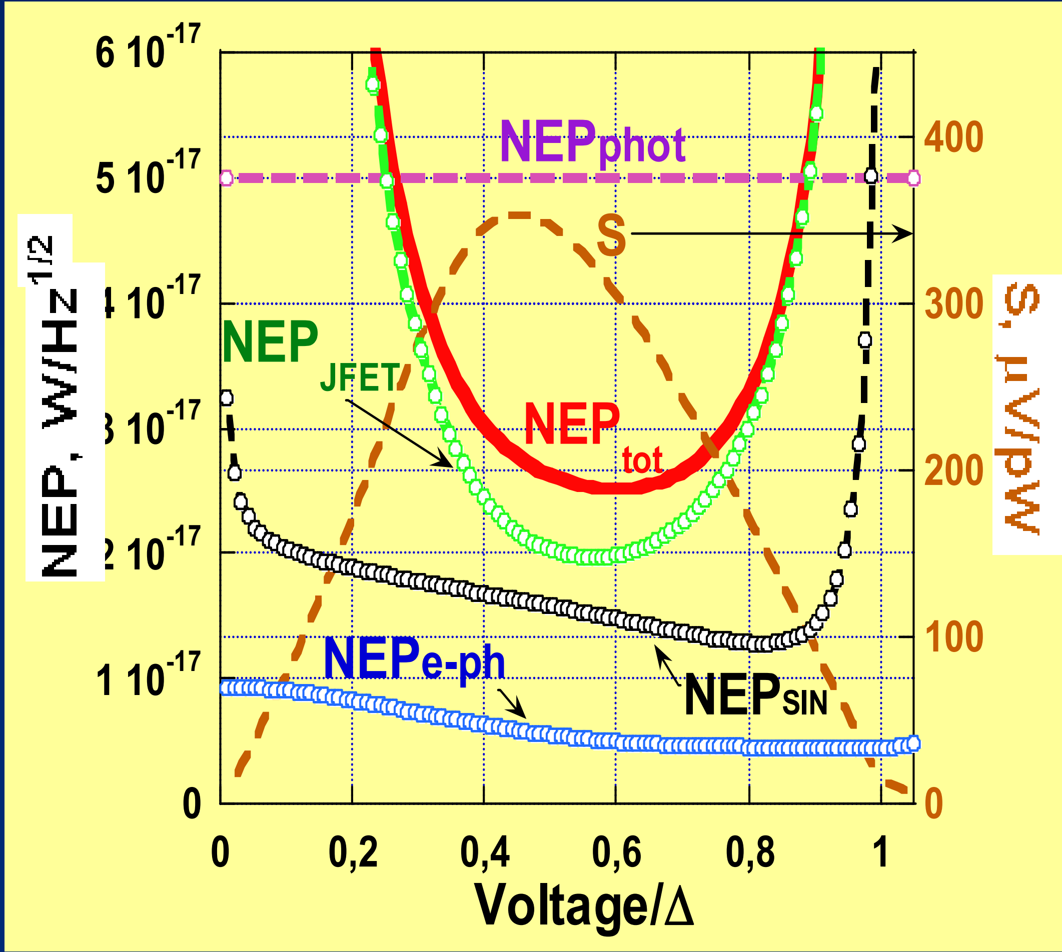
Peter Day et al.(JPL) – design for TES
L. Kuzmin (Chalmers) – NEP simulations for CEBs

Power load = 5 pW @ 350 GHz

SIN: Tc1=1.2K

S=1 μm2, R=1 kOhm,
Vol=0.005μm3, T=300 mK
I_{JFET}=10 fA/Hz$^{1/2}$, V_{JFET}=5 nV/Hz$^{1/2}$

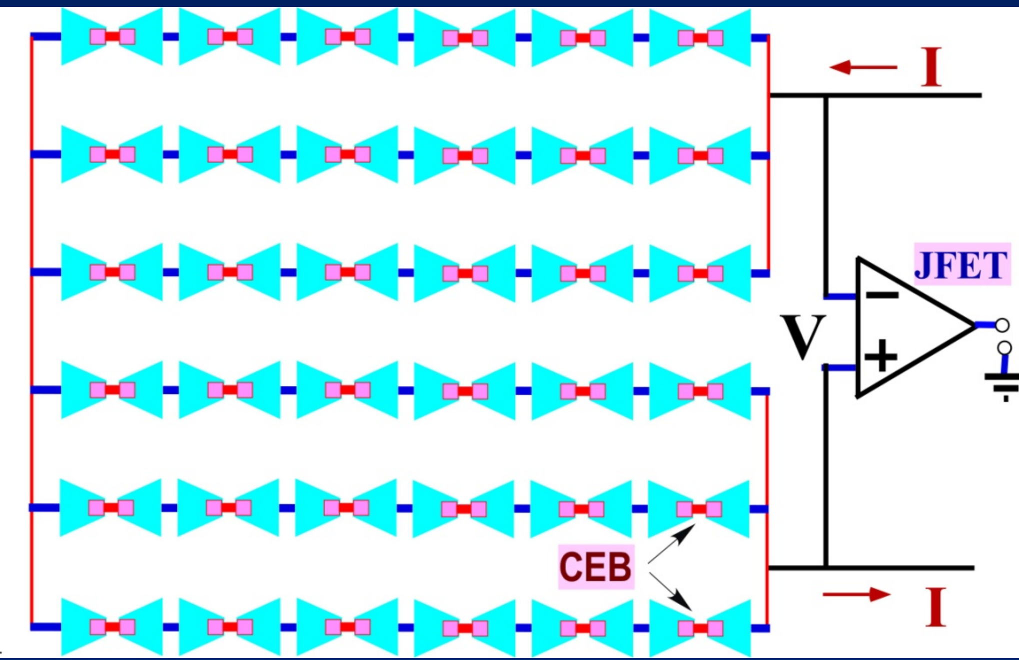




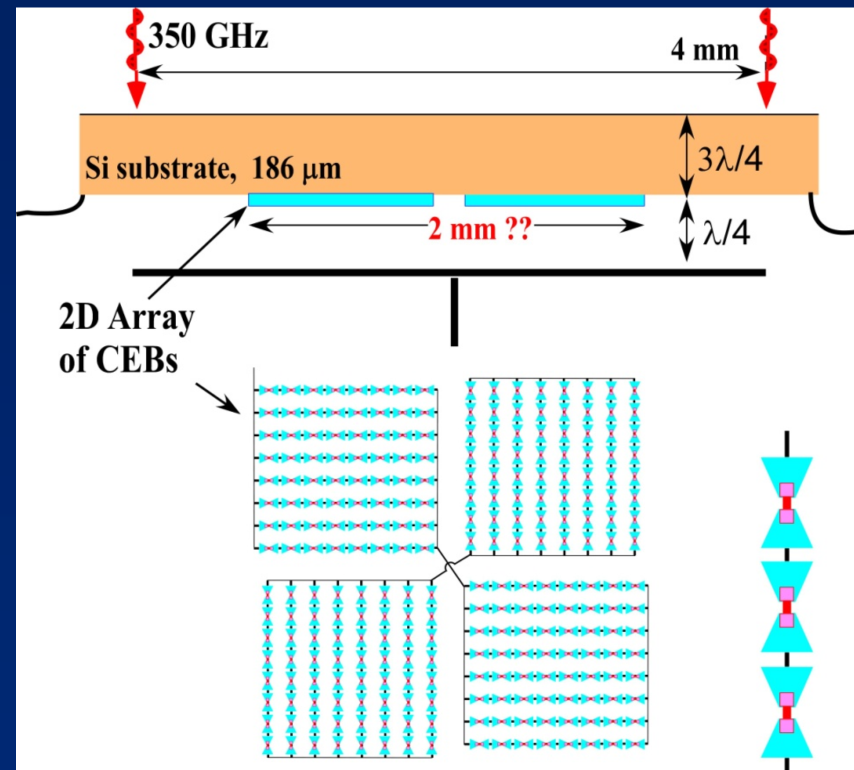
Novel Concept: **2D Array of CEBs with Focal Plane Dipole Antennas**

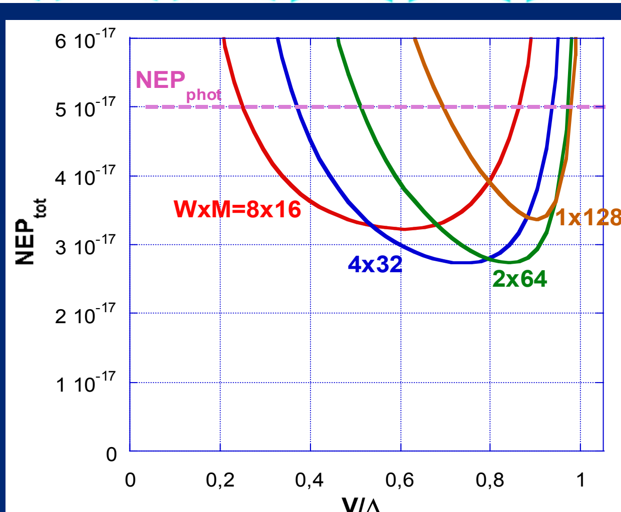
L. Kuzmin, Radiophysics and Quantum Electronics (2011)
Nanoscale Research Letters (2012)

A single polarization dipole antennas with a 2D array of CEBs (3x12) and a JFET readout



Matching: plane Si substrate +AR



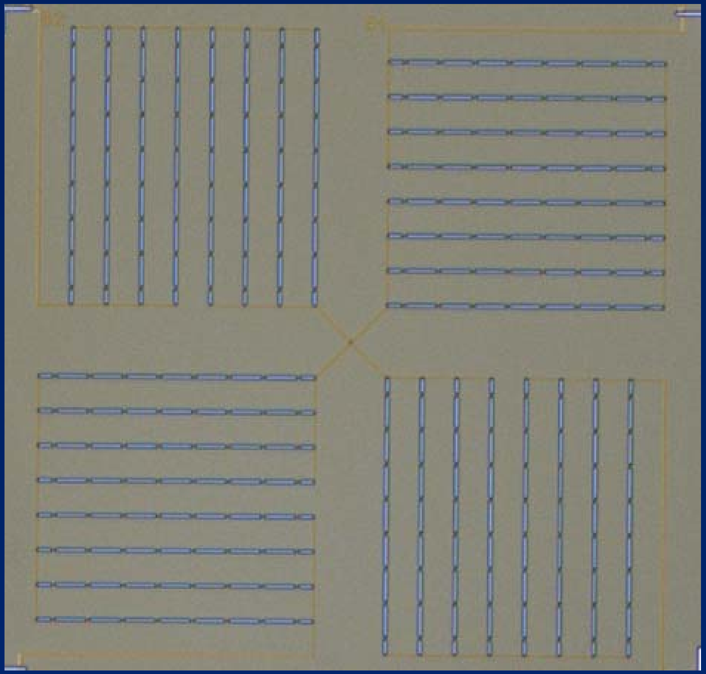


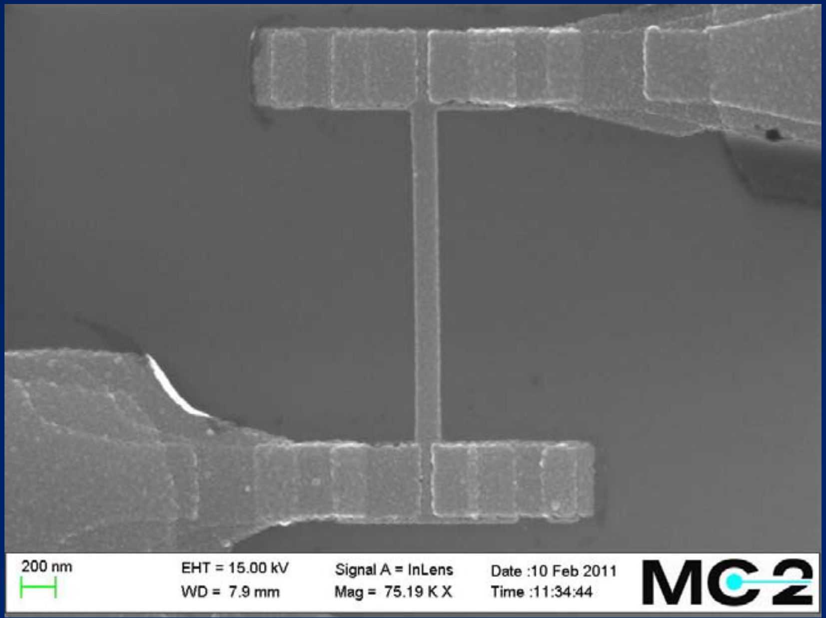
Power load = 5 pW @ 350 GHz

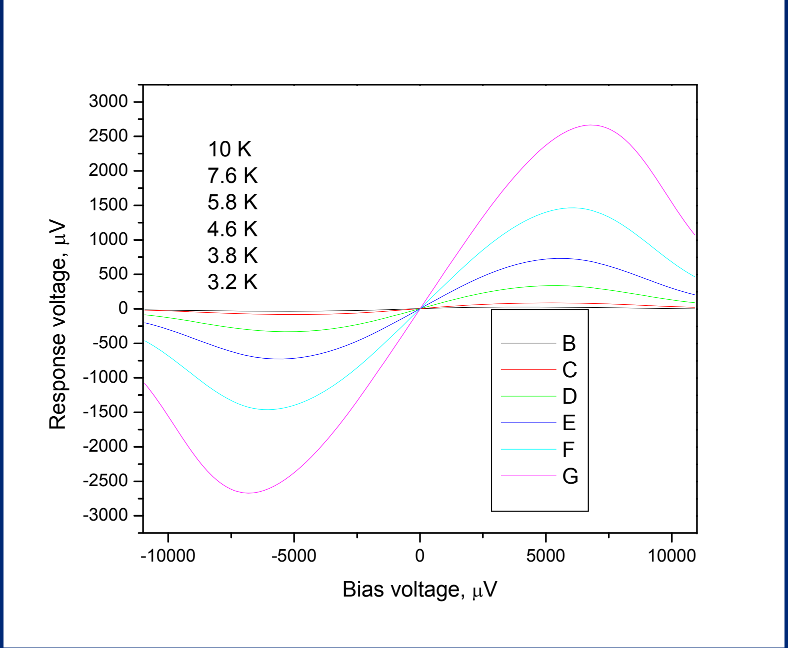
I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=3 kOhm, L=0.01mm^3, T=300 mK,

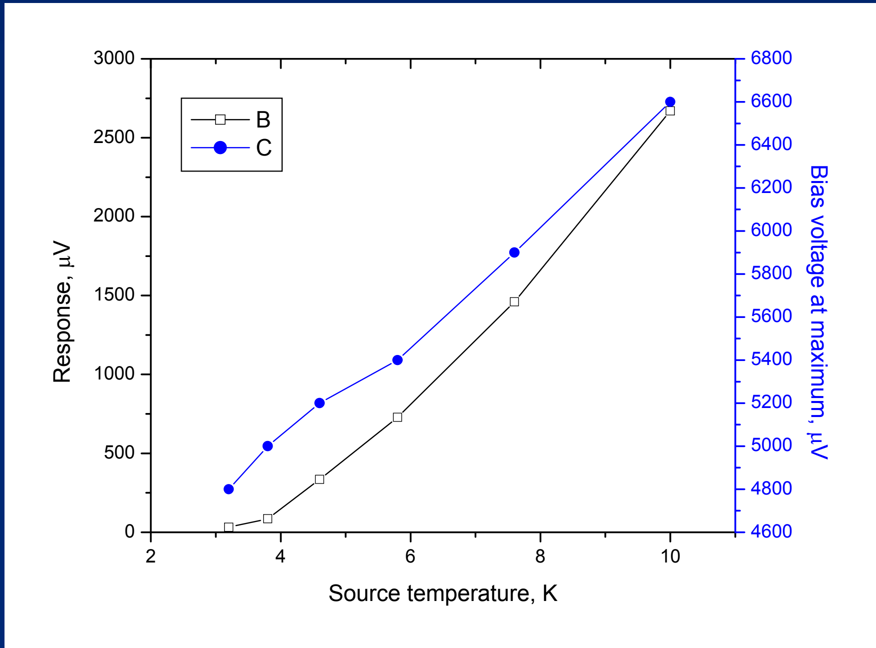
2D Array of CEBs with Focal Plane Dipole Antennas

M. Tarasov , S. Mahashabde and L. Kuzmin (2011)



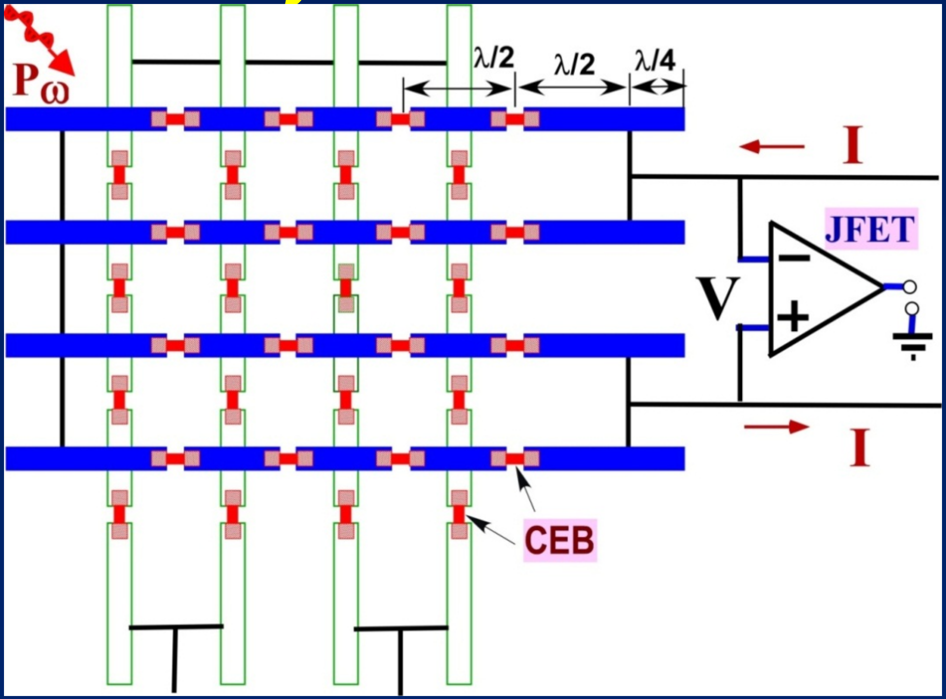


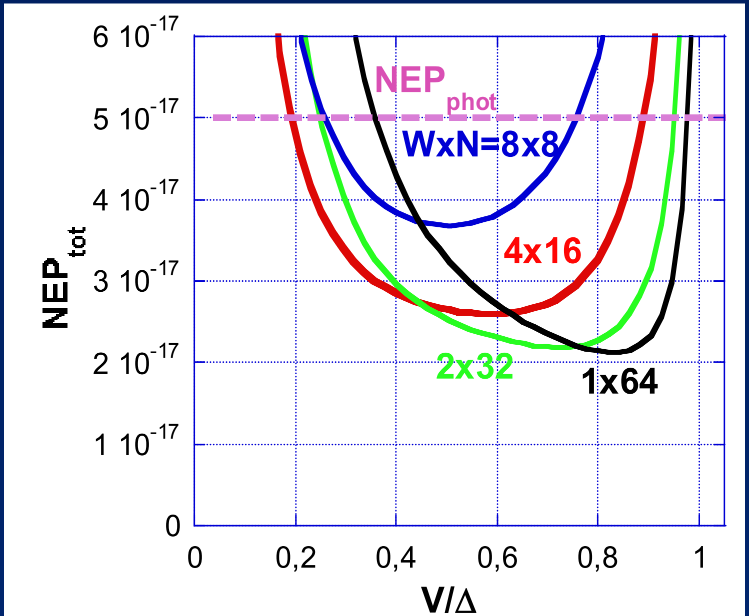


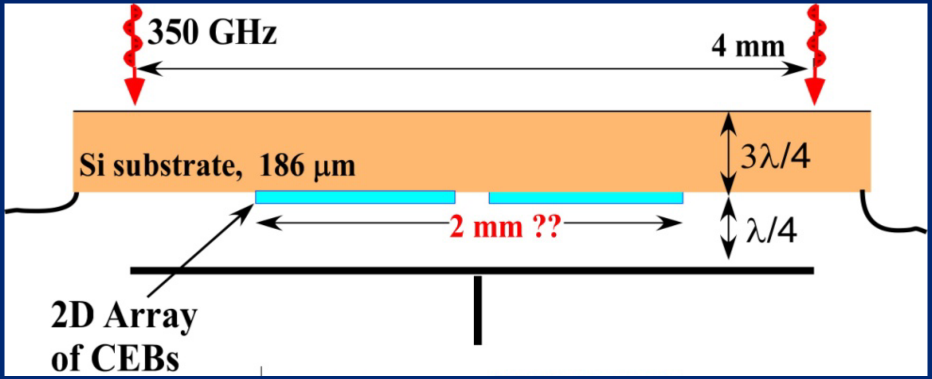


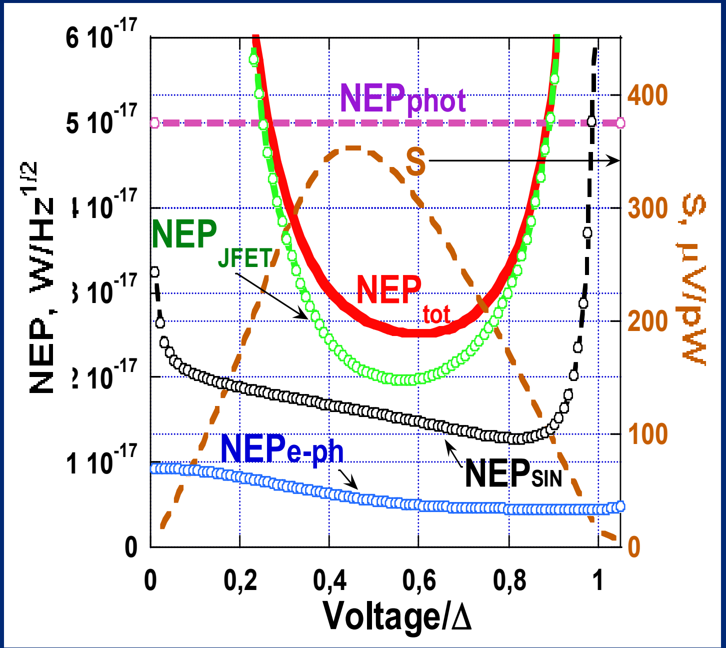
2D Arrays of CEBs with Two Polarization Dipole Antennas

L. Kuzmin, Radiophysics & Quantum Electronics (2011)









Power load = 5 pW @ 350 GHz

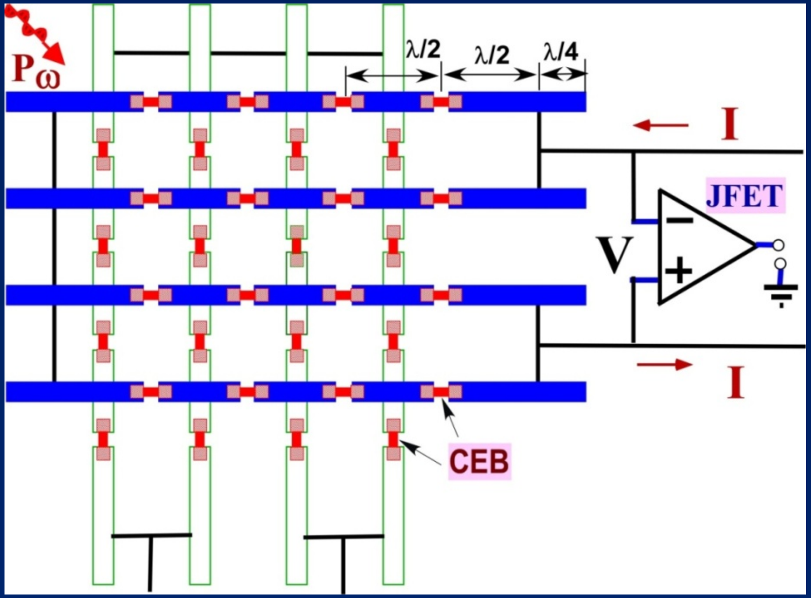
$$NEP_{CEB} = \sqrt{NEP_{SIN}^2 + NEP_{eph}^2 + NEP_{AMP}^2}$$

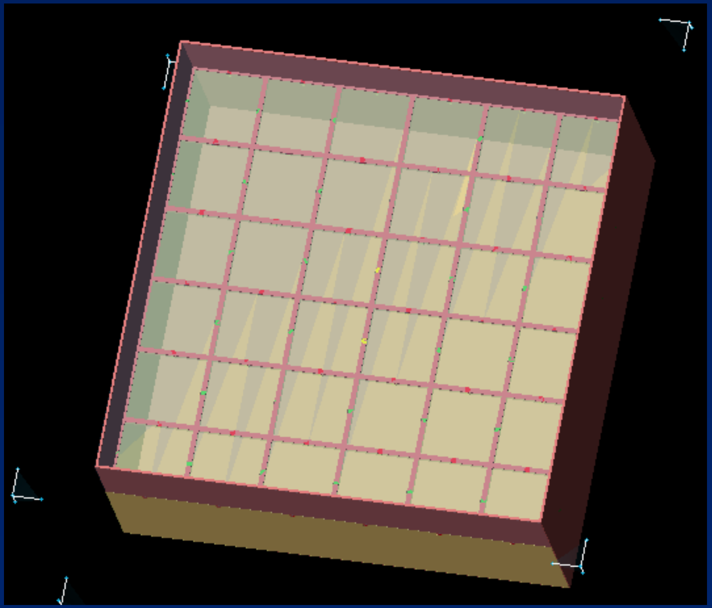
$$NEP_{AMP}^2 = \delta V_{AMP}^2 / S_V^2$$

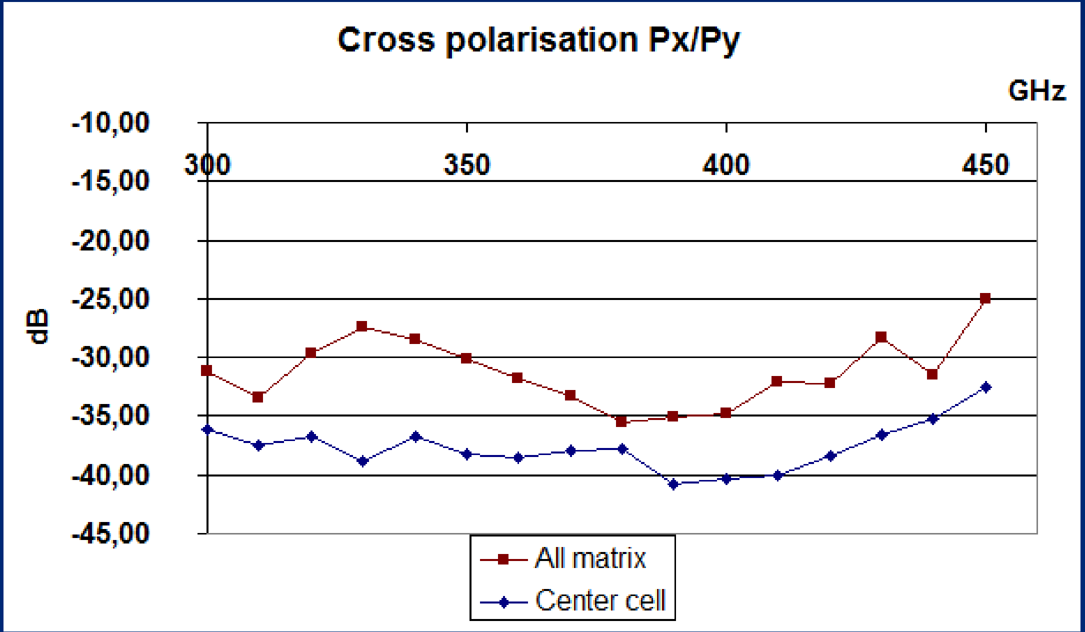
I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=3 kOhm, T=300 mK,

Cross-polarization of the 2D Array with direct overcross of the electrodes

S. Morugin and L. Kuzmin







Dependence of cross-polarization on frequency for 2D array of 16x16 CEBs

OLIMPO

S. Masi, P. de Bernardis, et al., Rome Un.,...

The OLIMPO is a mm-wave balloon telescope for measurements of the Sunyaev-Zeldovich effect.

The instrument uses four bolometer arrays at 150, 210, 350, 480 GHz, coupled to a 2.6 m diameter Cassegrain telescope

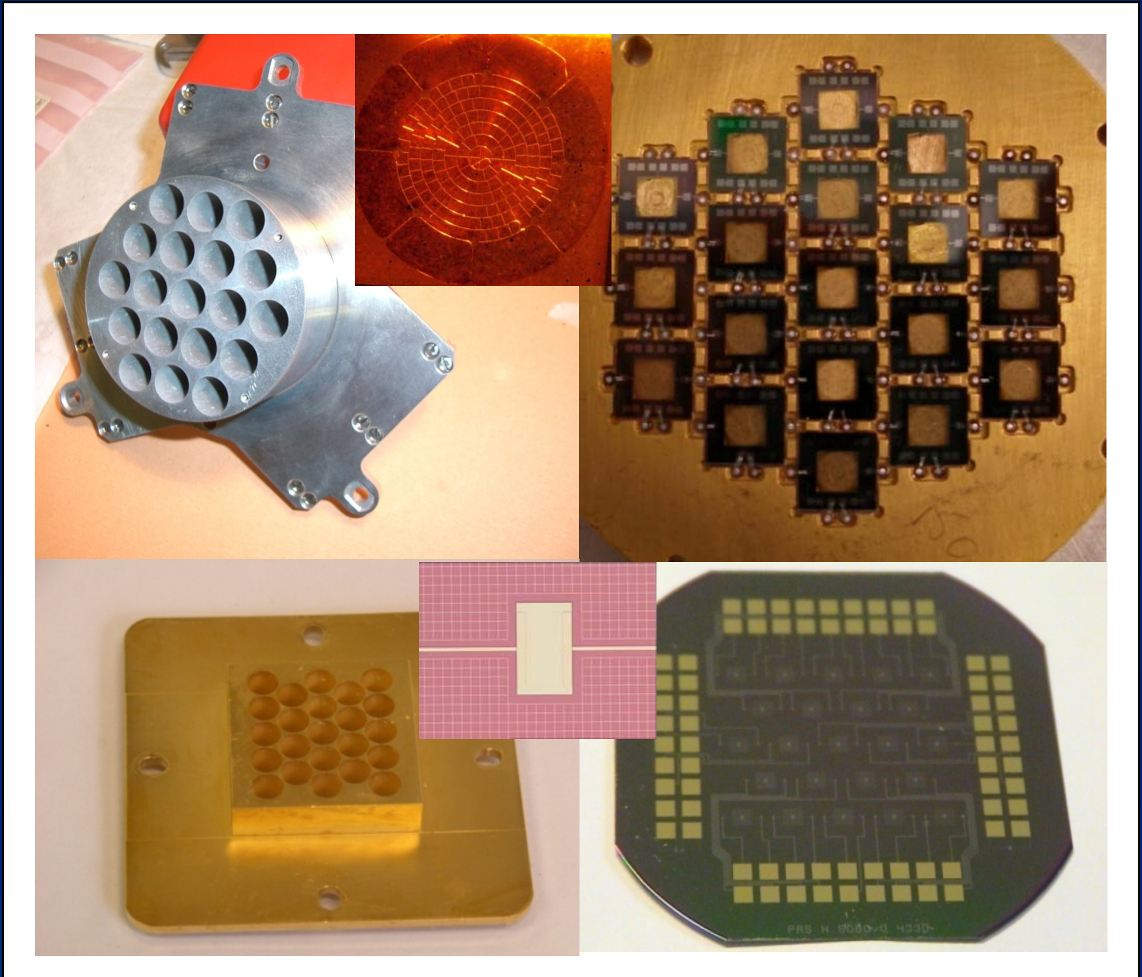
OLIMPO is a polar long-duration flight launched from Svalbard islands.

Low frequency arrays (TES)

- Buffer: Si_3N_4
- Thermistor: Ti (60nm) + Au (10/20 nm)
- Absorber/heater: spiderweb T (10 nm) + Au (5 nm),
- filling factor 5%=0.5mm^2
- CEB: S=100 um^2!
- NET150GHz=145 μK√s
- NET220GHz=275 μK√s
- Univ. Of Cardiff (Mauskopf)

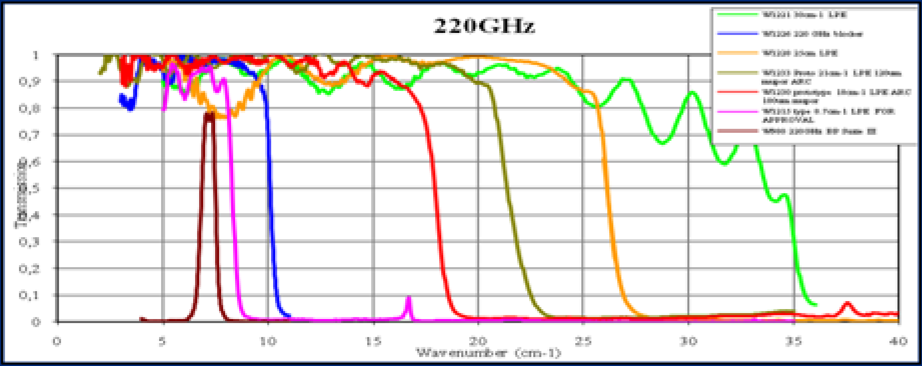
High frequency arrays

- NbxSi1-x (x=0.085)
- SiN 3x3 mm2=
- Palladium absorber
- NET340GHz=430 μK√s
- NET450GHz=4300 μK√s
- Inst. Neel Grenoble (Camus)



Filters Stacks (Ade, Tucker, Cardiff)

Bol.	ν_{eff} [GHz]	$\Delta\nu_{FWHM}$ [GHz]	Res. [‘]
19	148.4	21.5	4.2
19	215.4	20.6	2.9
23	347.7	33.1	1.8
23	482.9	54.2	1.8

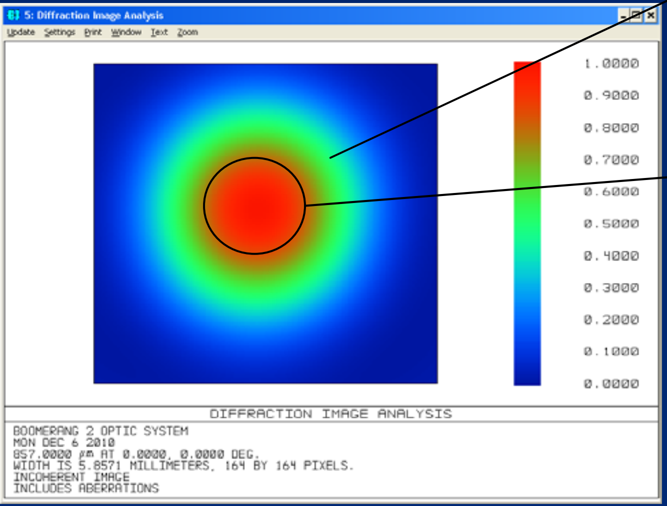


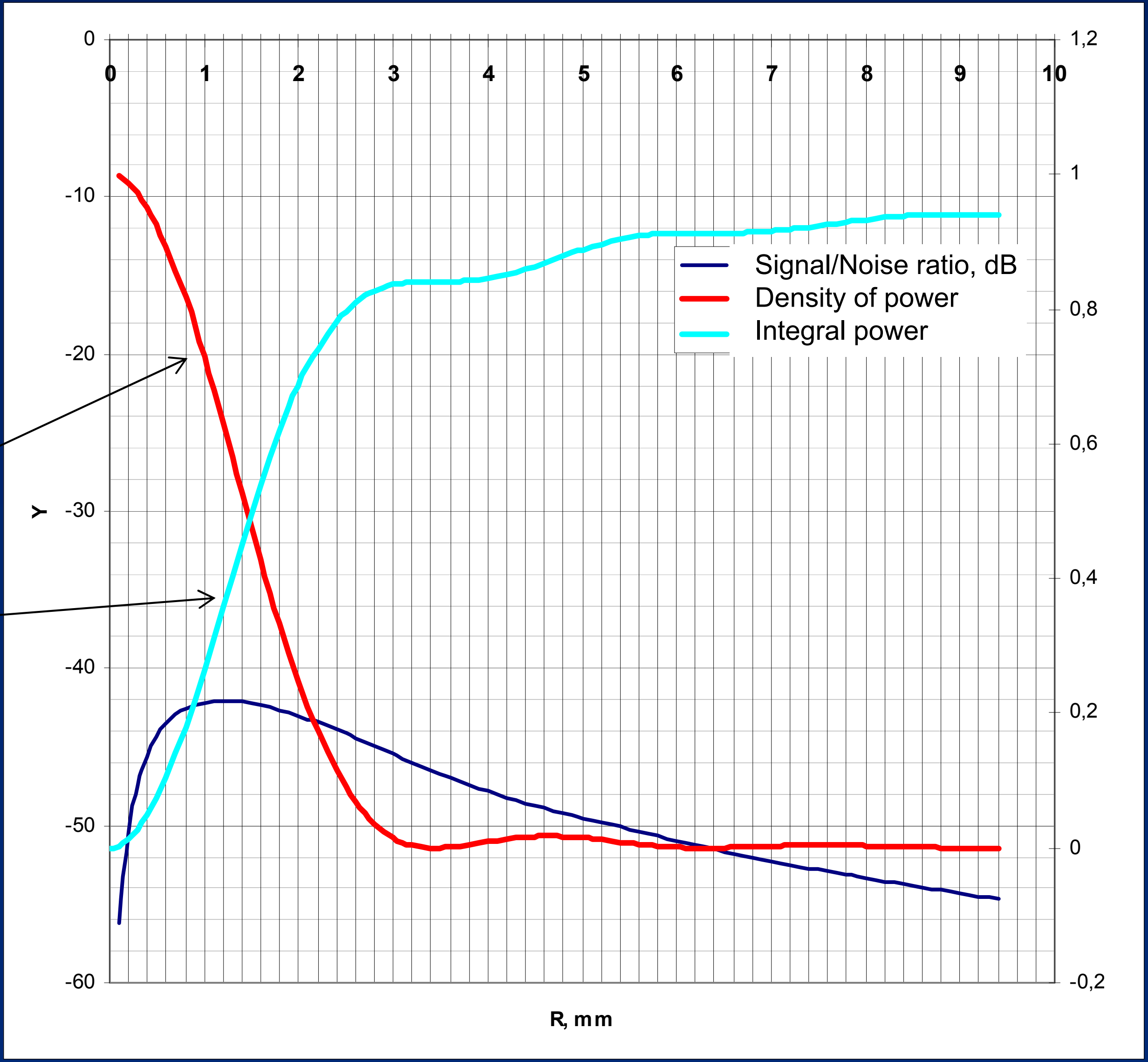
OLIMPO. Signal from a point nonuniformity of the CMB

Optical power load for OLIMPO in flight for the 350 GHz band will be about 5 pW

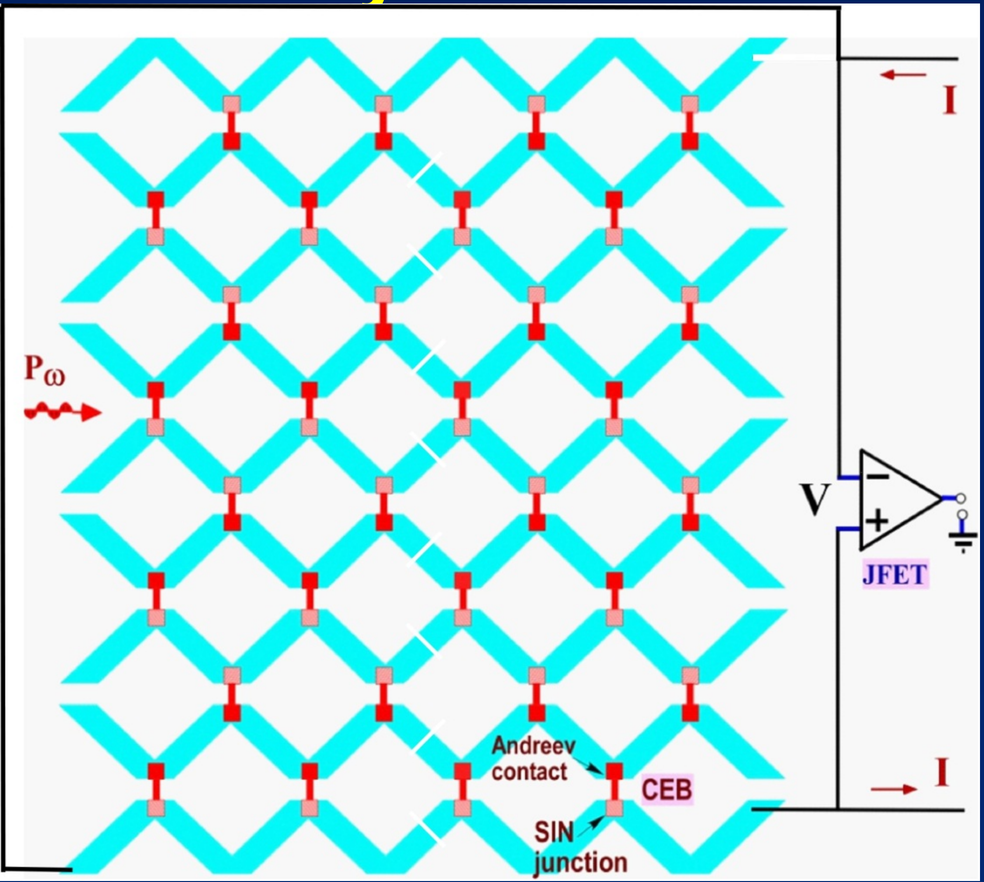
The beam feeding the detectors is 17.5 deg FWHM

The diameter of the diffraction spot is 4.8 mm

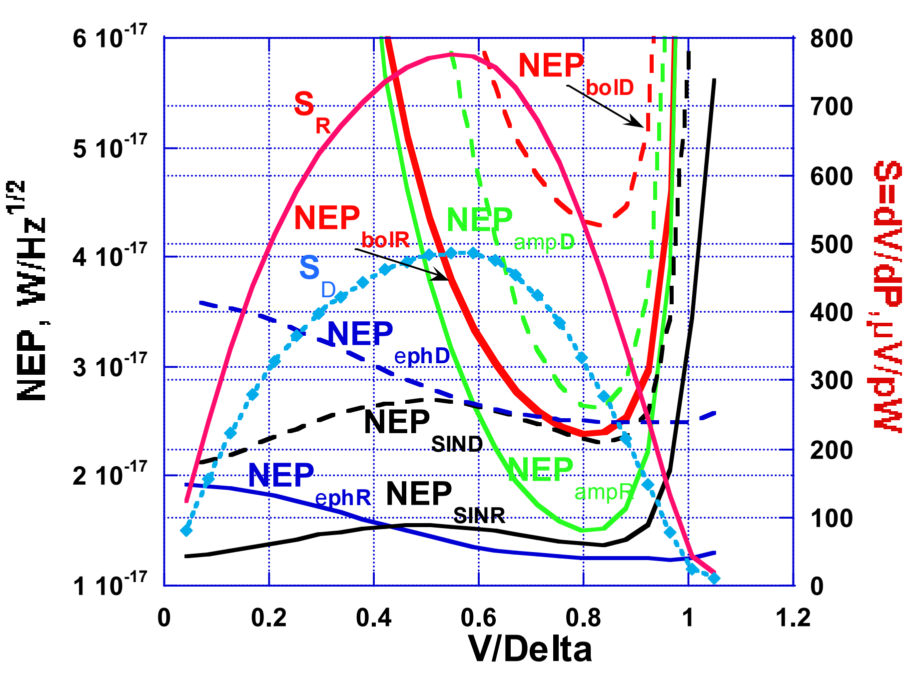


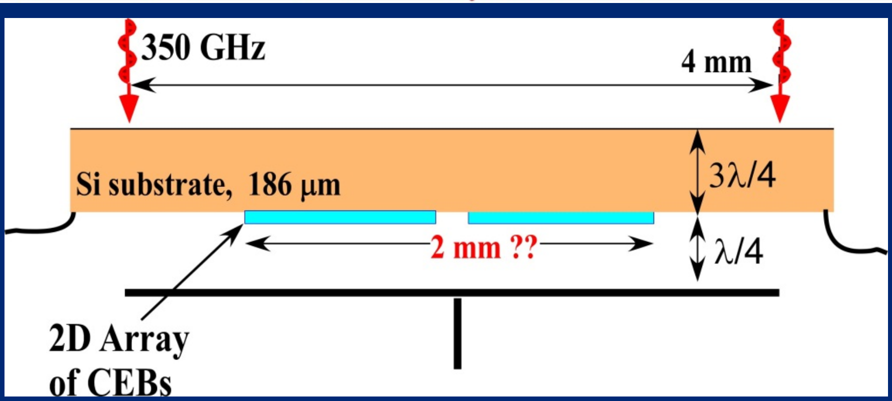


2D Array of CEBs with Dual-Polarized Antennae



NEP component for Dense and Rare arrays of CEB





16x32 CEB

Po=2pW, NEPph=3x10^{-17} W/Hz$^{1/2}$

Distance between CEBs:

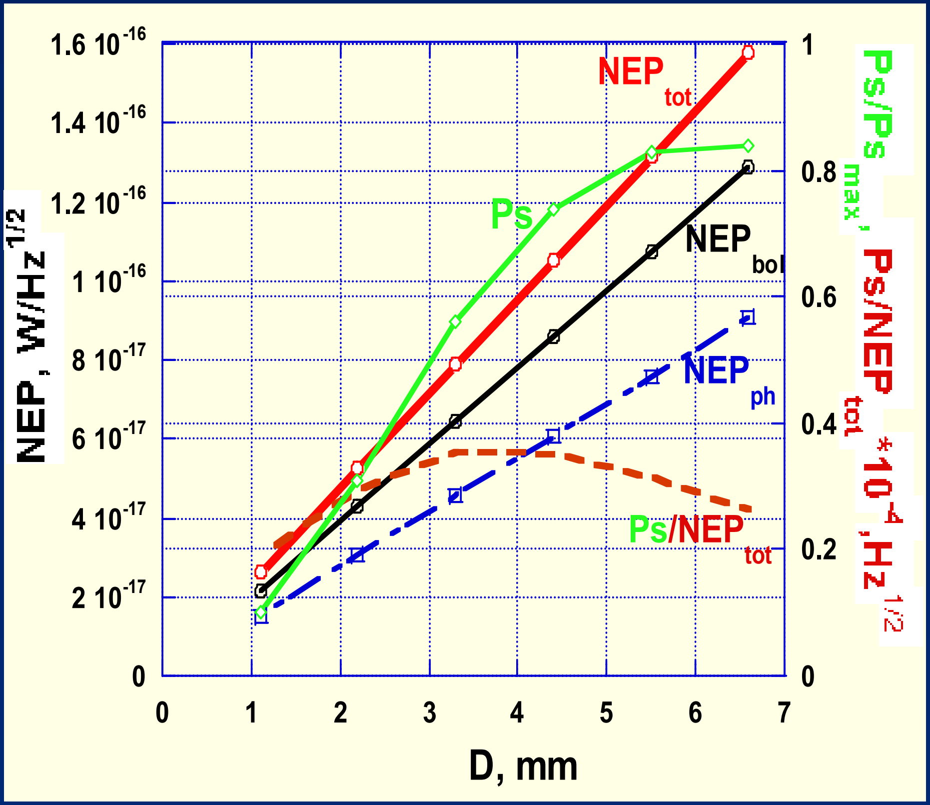
Dense Array- 100um (λ/2)

Rare Array- 200um (2λ/2)

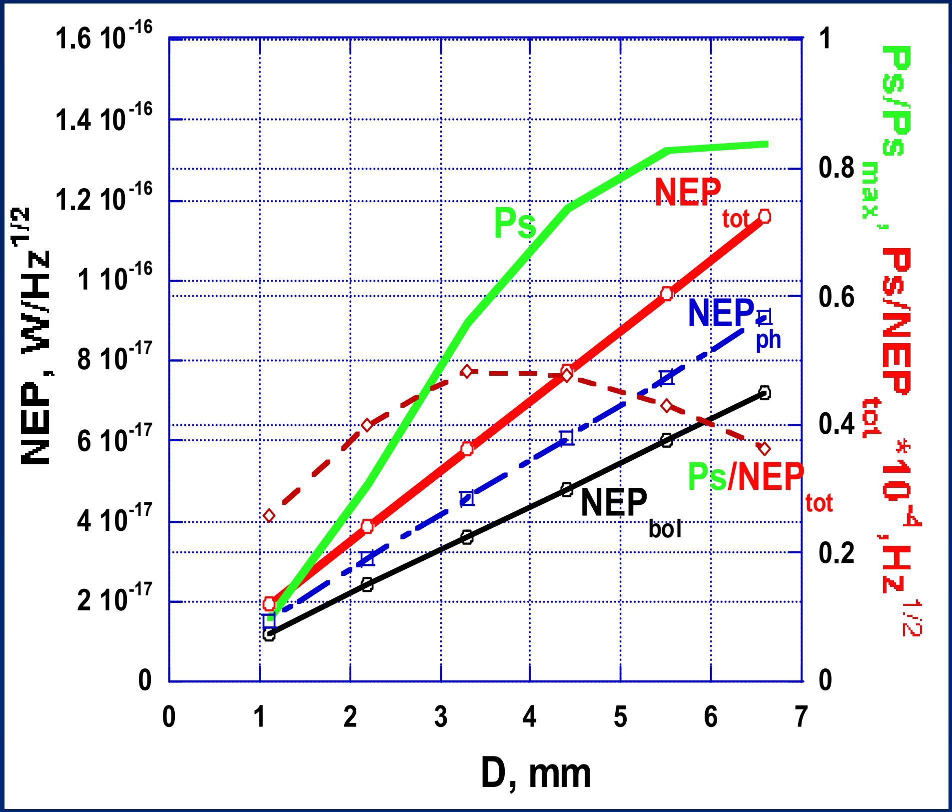
OLIMPO. Signal-to-Noise Ratio for 2D Arrays of CEBs

Distance between CEBs:

Dense Array- 100μm (λ/2),



Rare Array- 200μm (2λ/2)



Conclusions

Main features of the CEB:

1. High sensitivity due to electron cooling effect: *NEP<NEPph for any optical power load*
2. High dynamic range due to direct electron cooling
3. Insensitivity to Cosmic Rays (CR)

Applications:

-BOOMERANG-3 balloon telescope (90 CEBs @350 GHz, 9 CEBs @150 GHz – proposed recently).

-OLIMPO balloon telescope (2 CEB @350 GHz);

-LSPE (Large Scale Polarization Explorer) – 90, 140, and 220 GHz.

If CEB demonstrates insensitivity to Cosmic Rays it could be a winner for the OLIMPO and LSPE! Tests are in progress in Rome

- MILLIMETRON soace observatory, FTS