中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

超导基础理论和实验技术讲座

National Lab for Superconductivity Lecture Series

【第103期】

# 约瑟夫森效应及其应用

王华兵

南京大学

主办 中科院物理所超导国家重点实验室、学术服务部
协办 《物理学报》 | CPL | CPB | 《物理》

# 超导线材和超导磁体

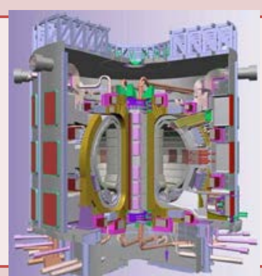
## 应用领域

MRI

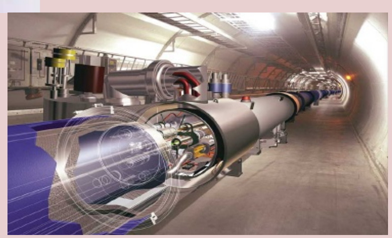
MCZ

NMR

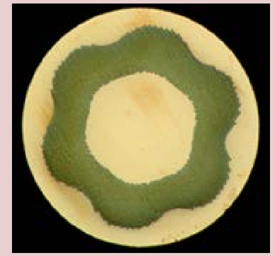
ITER

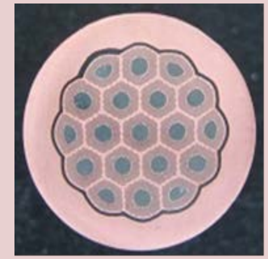


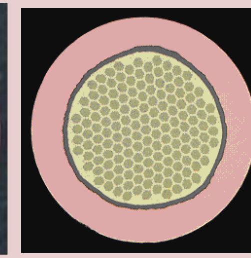
Accelerator

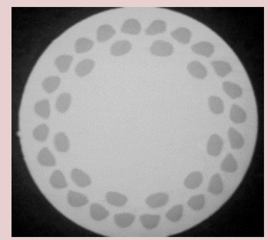


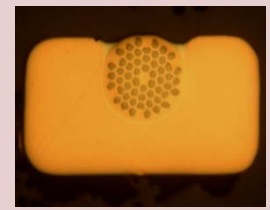
## 产 品

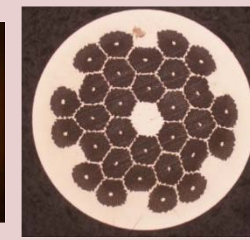

ITER-NbTi

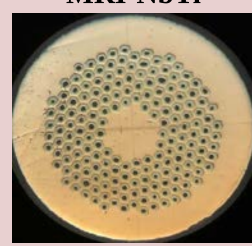

ITER-Nb3Sn


Bronze-Nb3Sn

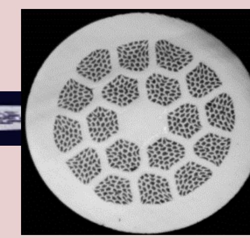

MRI-NbTi


MRI-NbTi


Low AC Loss-NbTi

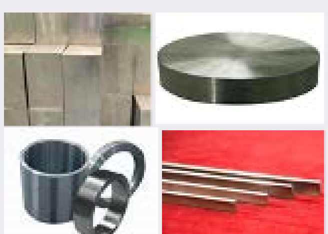

MgB2


Bi-2223


Bi-2212

超 导 磁 体

# 钛合金

| 类 型 | 产 品 | 应 用 领 域 | | |
|---|---|---|---|---|
| Large Bar |  | 航天航空<br>结构件 |  |  |
| Small Bar |  | 紧固件 |  |  |
| Wire |  | 焊接丝材<br>生物医疗 |  |  |
| Others |  | 航海<br>耐腐蚀 |  |  |

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# 约瑟夫森效应及其应用

王华兵，南京大学全职教授，国家海外高层次人才计划入选者。于南京大学获得本科和博士学位，历任南京大学、日本东北大学副教授、日本国家材料科学研究所主干、主席研究员等职。长期从事超导电子学研究，在探索器件物理、发展新型超导电子器件、推动实际应用等方面取得了一定的成绩。目前研究兴趣主要为超导量子信息技术、太赫兹技术及其应用等方面。担任欧洲应用超导国际会议、《超导科学与技术》学术期刊等国际咨询委员。主持国家自然科学基金重点研究、重大仪器等项目。

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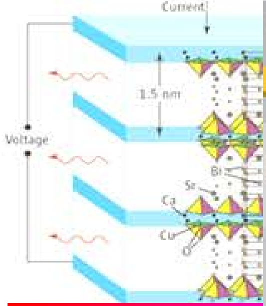
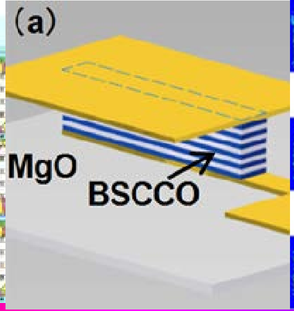
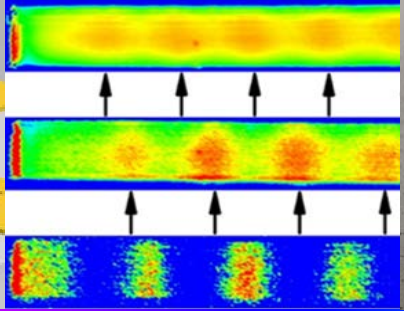
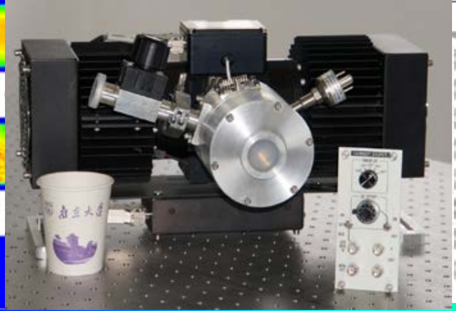
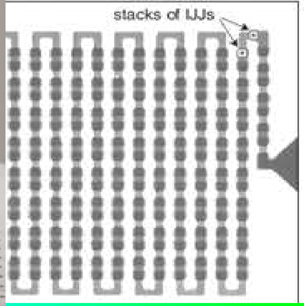






# 约瑟夫森效应及其应用


**王华兵**

**南京大学超导电子学研究所**

**Research Institute of Superconductor Electronics (RISE)**

# 约瑟夫逊器件及其应用概述

吴培亨

南京大学超导电子学研究所

（2010年12月 中科院物理所）

RISE, NJU

# Outline

- Josephson effects and junctions
- Electronic applications
- Modern superconductor electronics

# The discovery of superconductivity

112 years of liquid helium
(as of 2020)

- 1908: Heike Kamerlingh Onnes,

University of Leiden:

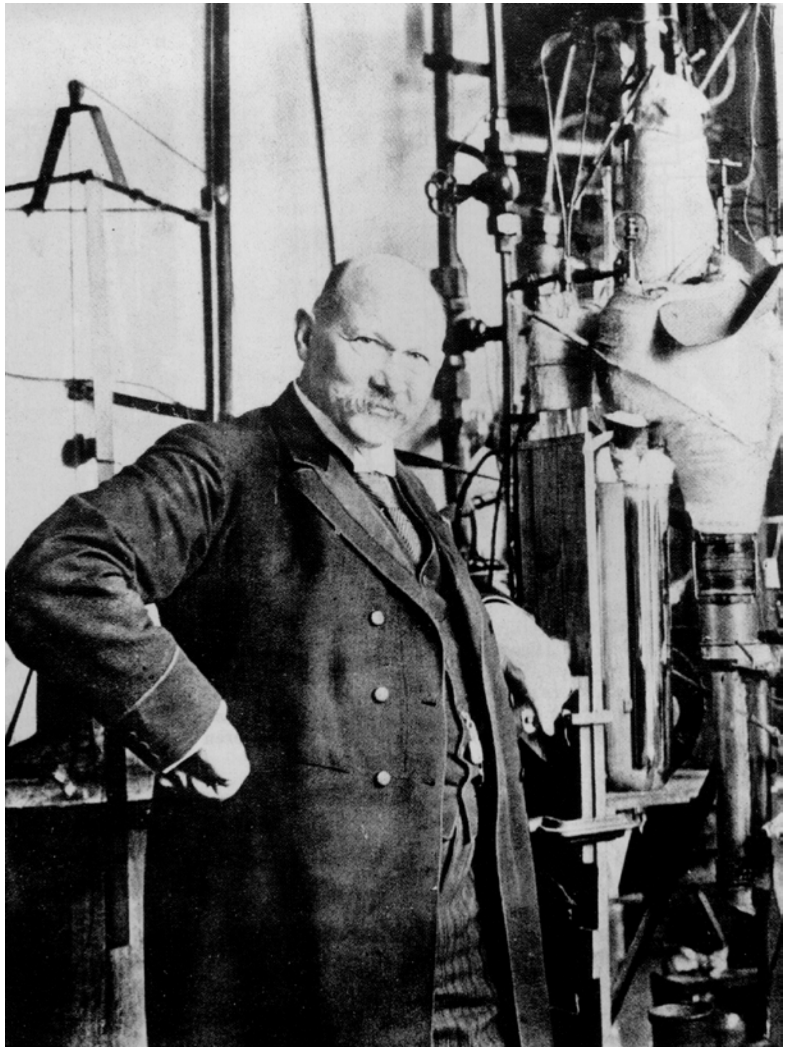
first liquification of helium

($T$= 4.2K at $p$=1 bar)

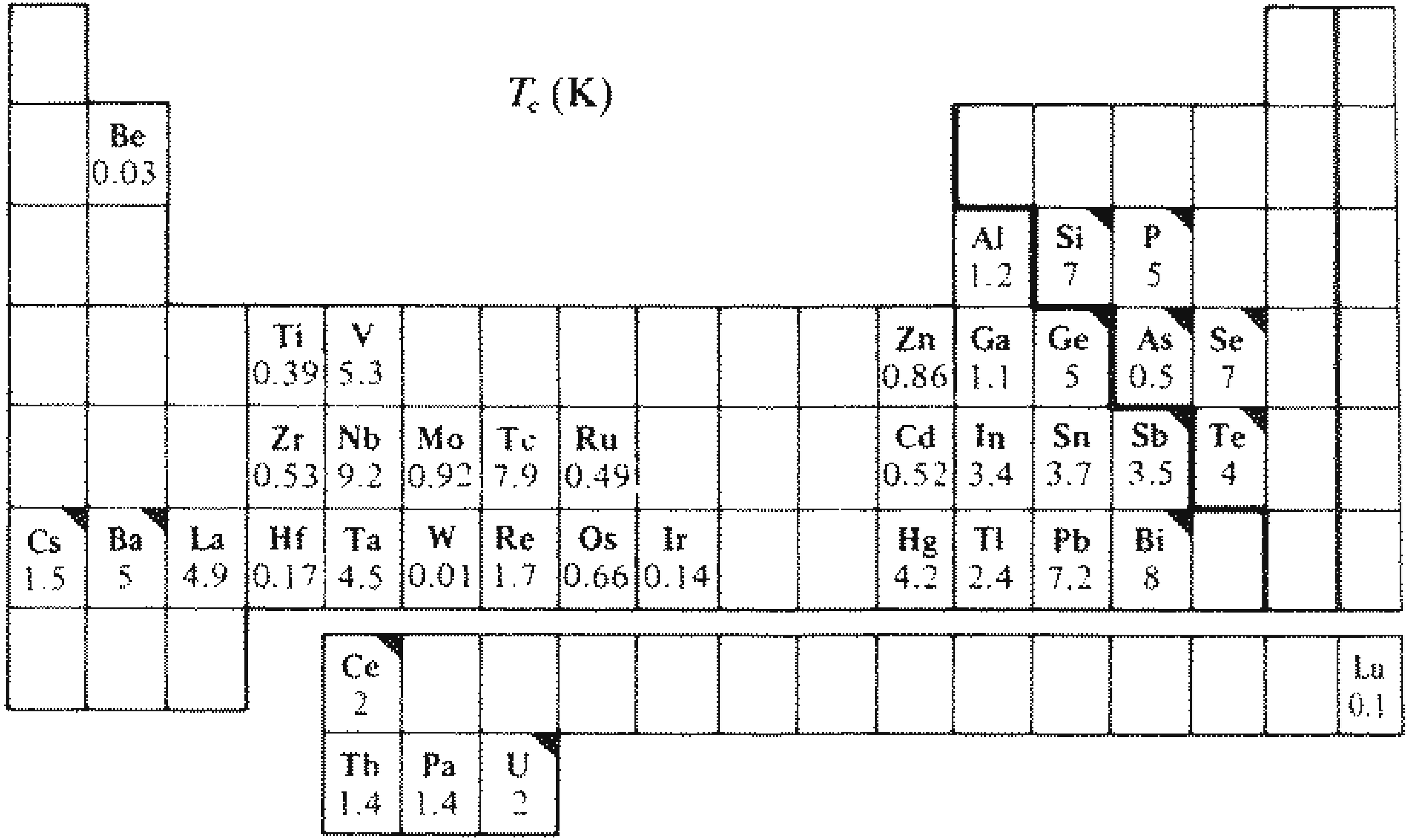
(a few drops only!)

1911: discovery of superconductivity

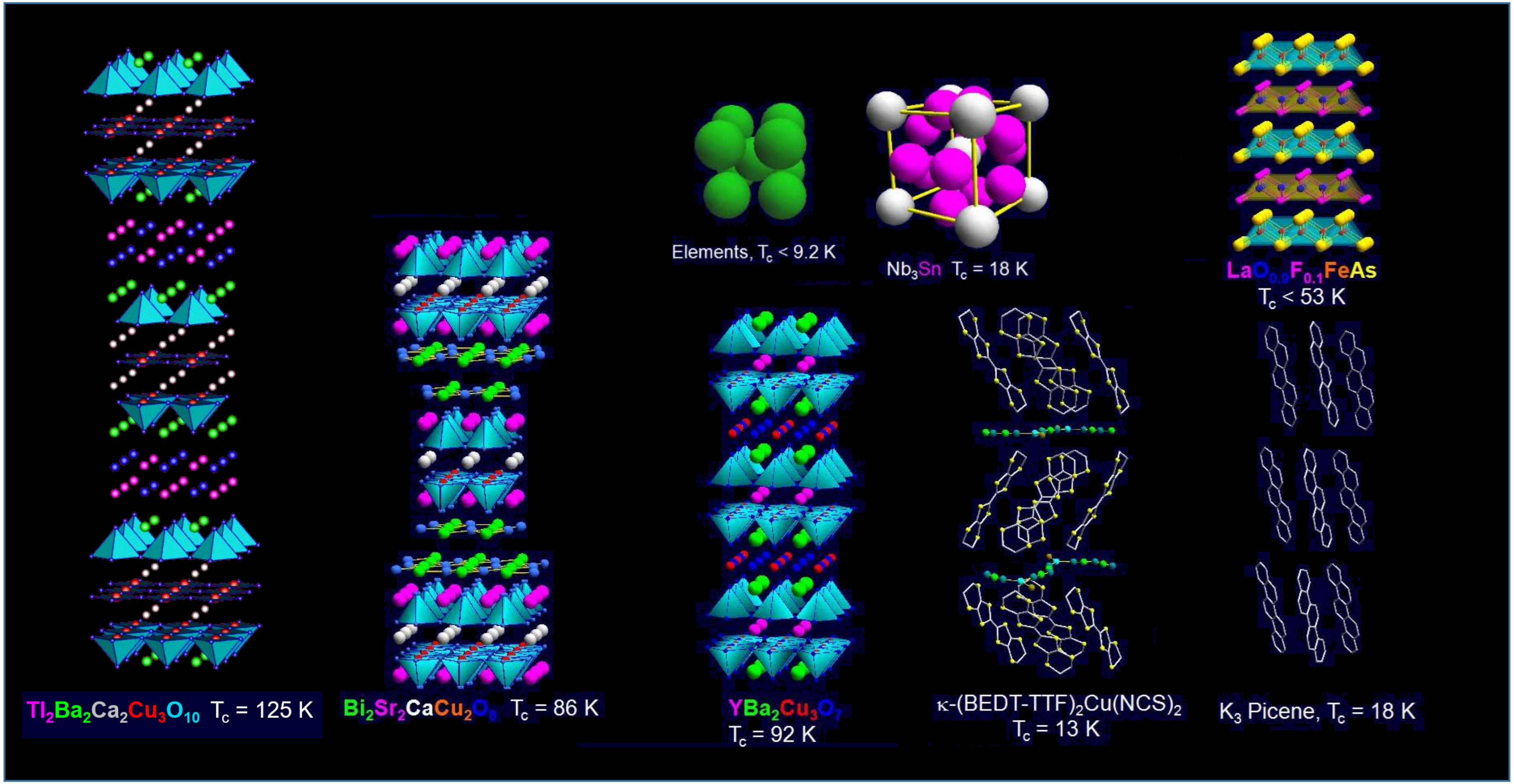
1913: Nobel prize



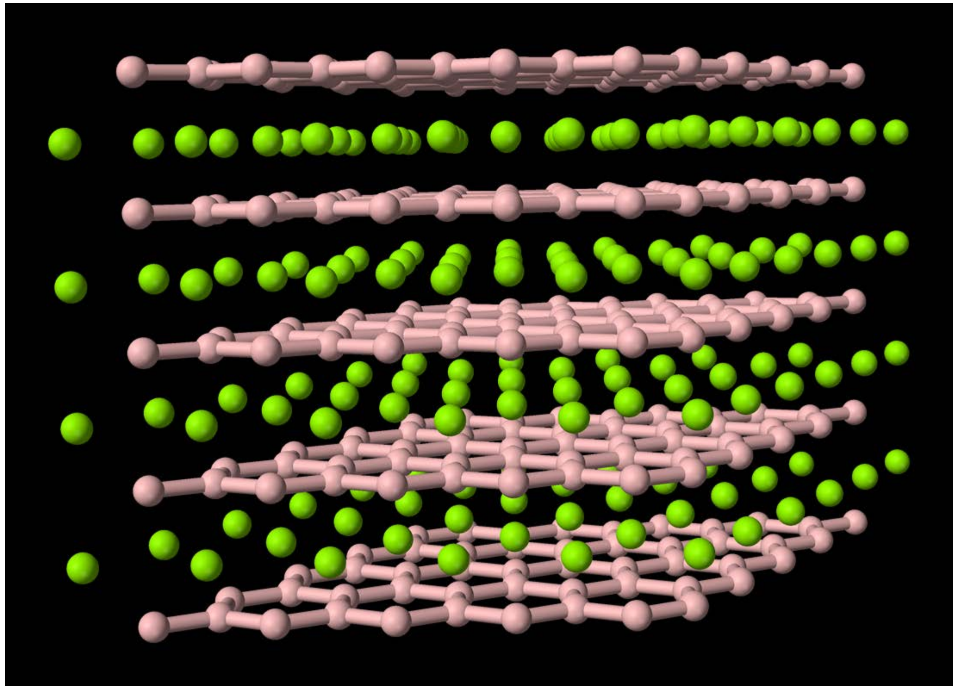
# Critical temperatures of some elements



# Superconductors



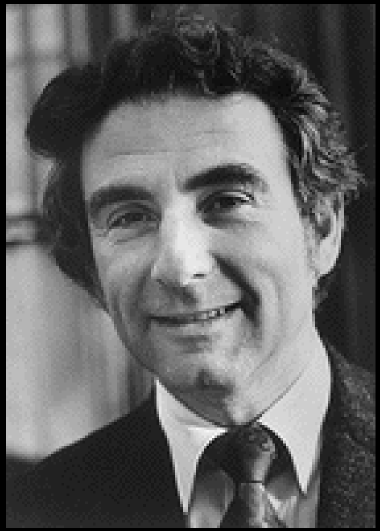
# Magnesium diboride

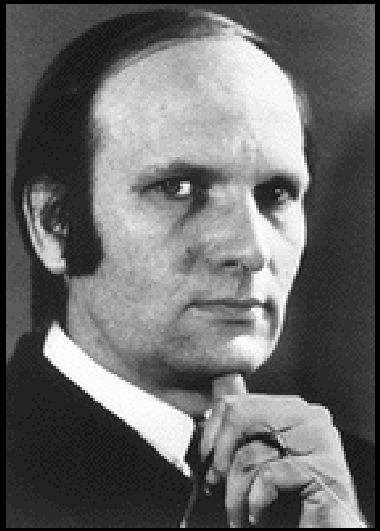


Nagamatsu, Jun; Nakagawa, Norimasa; Muranaka, Takahiro; Zenitani, Yuji; Akimitsu, "Superconductivity at 39 K in magnesium diboride". Nature, 410 (6824), 63–4 (2001).

# The Nobel Prize in Physics 1972

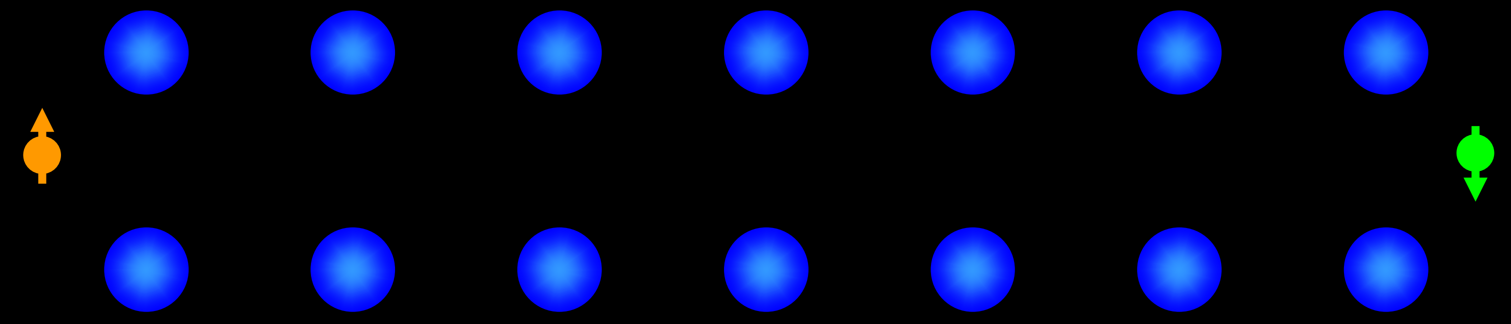
"for their jointly developed theory of superconductivity, usually called the BCS-theory"

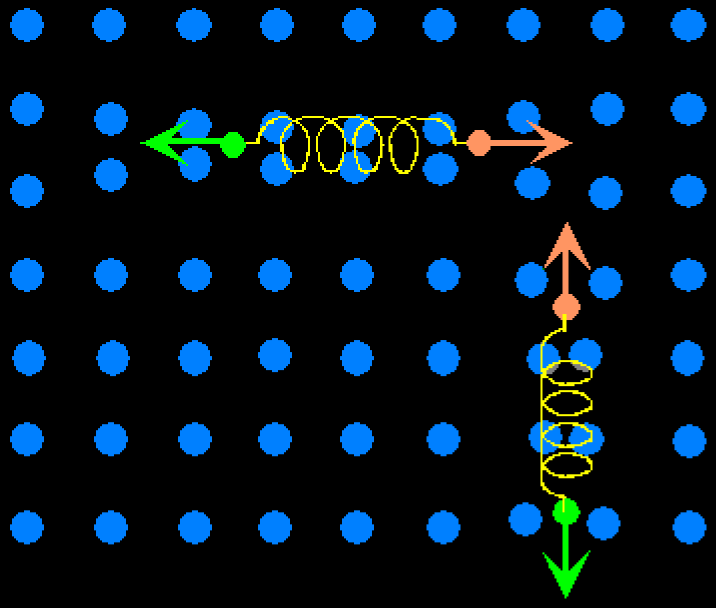




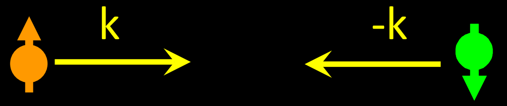
**John Bardeen** **Leon Neil Cooper** **John Robert Schrieffer**

# Current transport in conventional superconductors





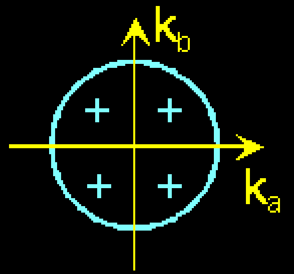
Cooper pairs:
Spin singlet state




Attractive interaction — Electron-Phonon

Coherence length: (Ginzburg-Landau) — 100 nm >> atomic distance

Order parameter: $\Delta = \Delta_0 e^{i\varphi}$
(homogeneous, isotropic)




Largely homogeneous and isotropic current transport

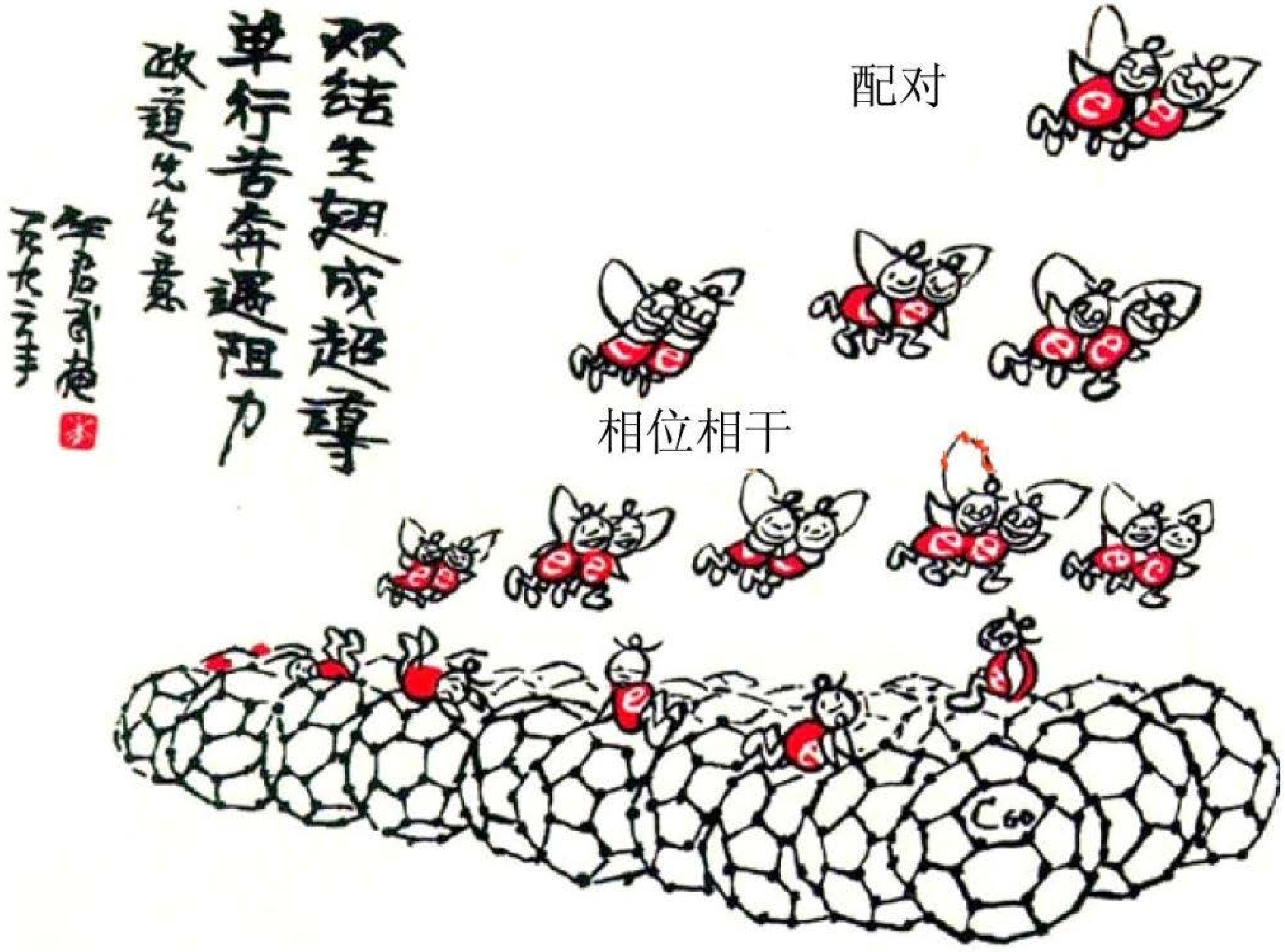
# Macroscopic wave function and phase coherence

Wave function of the condensate: $\Psi(\vec{r},t)=\Psi_0\, e^{i\varphi}$ $\quad |\Psi|^2=\rho$

Density of supercurrent: $j=\frac{e\hbar}{2mi}(\Psi^*\vec{\nabla}\Psi-\Psi\vec{\nabla}\Psi^*)-\frac{e^2}{m}|\Psi|^2\vec{A}$

$$\rightarrow\ j_z=\frac{e\hbar}{m}\Psi_0^2\left(\frac{d\varphi}{dz}-\frac{2\pi}{\Phi_0}A_z\right)$$

- Most important point is the fact that electrons are described by a single macroscopic wave function
- The phase is coherent over macroscopic distances

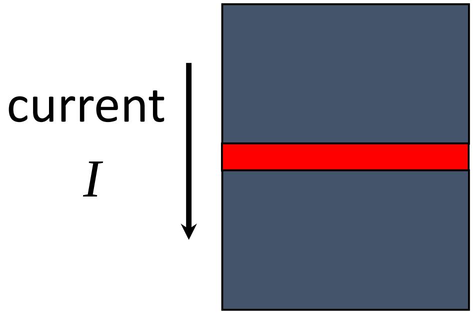


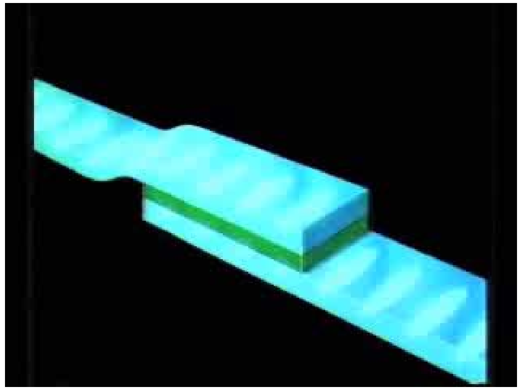

http://blog.sciencenet.cn/blog-22926-582521.html

# 超导电子器件 ---极端的手段、极端的目标

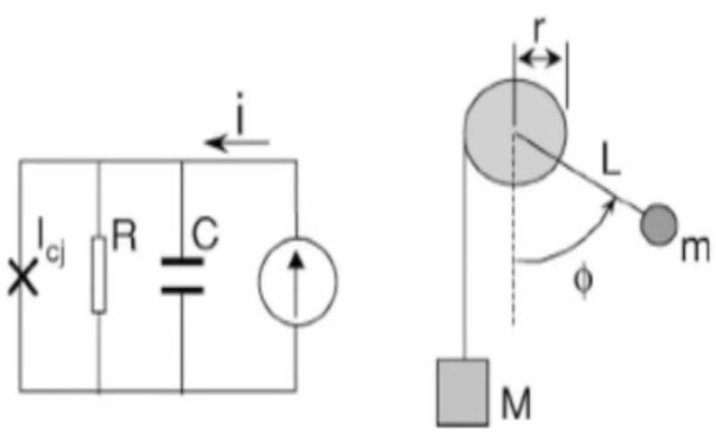
| 超导体应用于电子学的物理依据 | |
| --- | --- |
| 低微波表面电阻 | 超导微波滤波器、超导超材料 |
| 库珀对被拆对导致相变或载流子密度改变 | 超导纳米线单光子探测、临界转变传感器、动态电感检测器等 |
| 约瑟夫森效应<br>准粒子隧道效应 | 量子电压基准、超导量子干涉器件、太赫兹探测与辐射 |
| 超导人工原子 | 量子计算、信息、探测 |

# Josephson Effects (1962), named after Brian Josephson (1973 Nobel Prize in Physics)



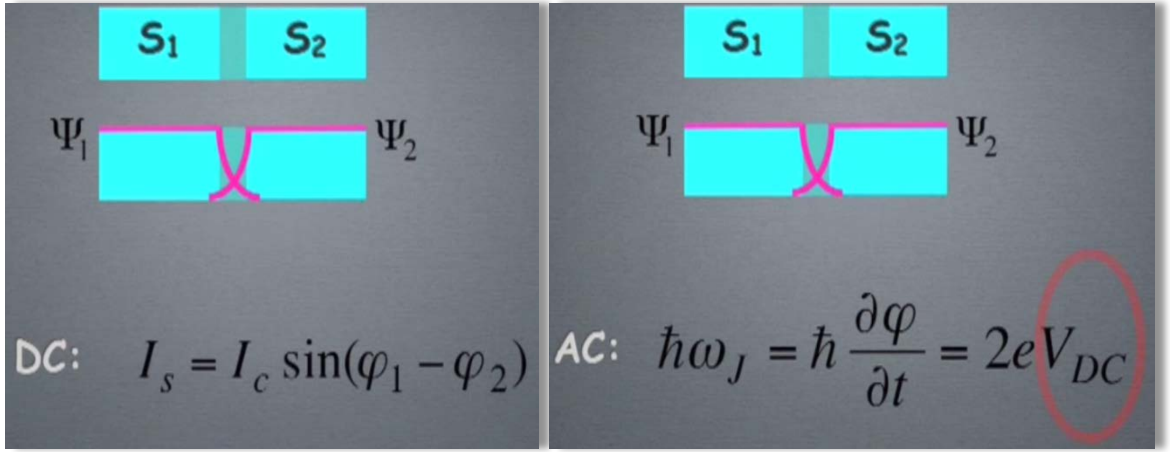
Single Josephson junction analog




Wavefunctions of superconducting electrodes:

$$\Psi_1 = |\Psi_1| \exp(i\varphi_1), \Psi_2 = |\Psi_2| \exp(i\varphi_2)$$

$$f = \frac{2e}{2\pi\hbar} V = \frac{1}{\Phi_0} V$$

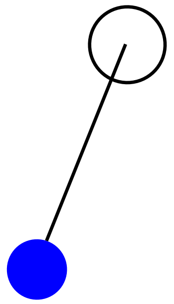



*Josephson junction is a quantum dc voltage-to-frequency converter*
*$1\mu V \leftrightarrow 483.59767$ MHz*
*$1mV \leftrightarrow 483.59767$ GHz*

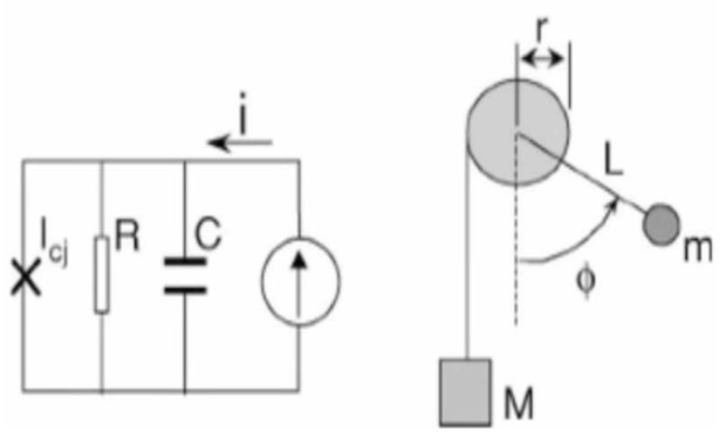
http://www.msm.cam.ac.uk/ascg/lectures/

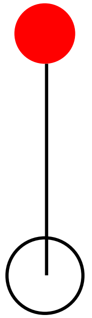
# Josephson Effects (1962), named after Brian Josephson (1973 Nobel Prize in Physics)

Anharmonic oscillator



Single Josephson junction analog



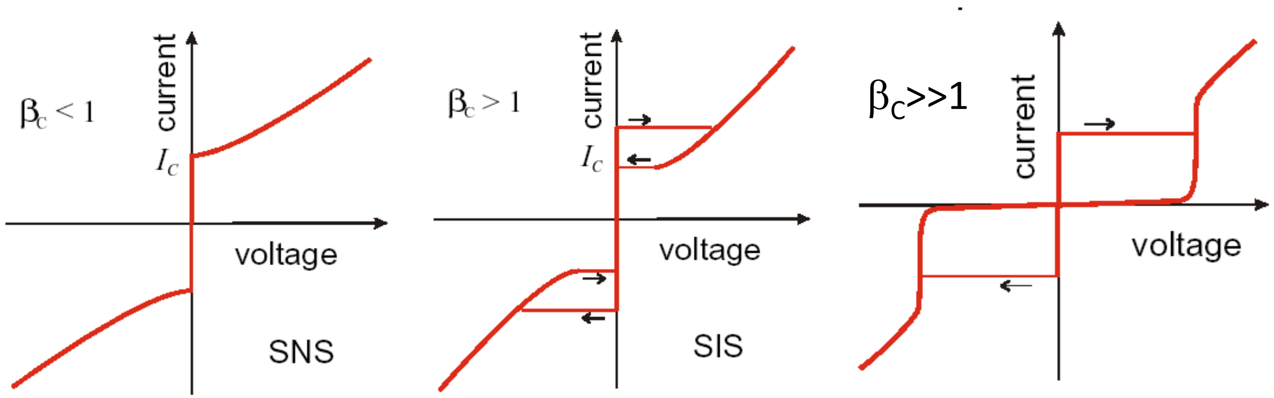



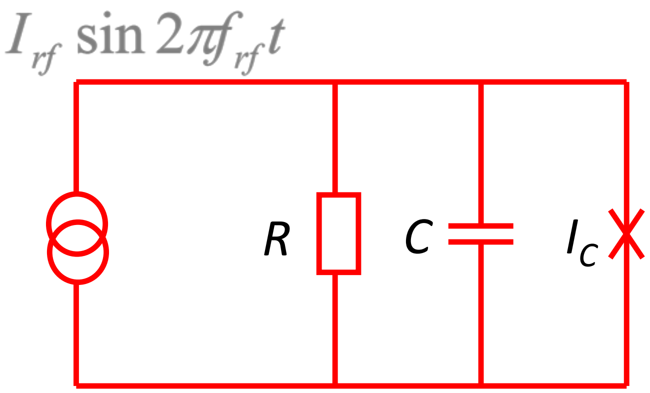
| 电学模拟 | 力学模拟 |
| --- | --- |
| 直流电流=$I_b$ | Torque=$\tau$ |
| 电容=$C$ | 转动惯量=$M_I$ |
| 电导=$1/R$ | 阻尼系数=$D_f$ |
| 最大约瑟夫森电流=$I_c$ | 重力引起的最大力矩=$mgL$ |
| 位相差=φ | 偏离竖直线的角度=φ |

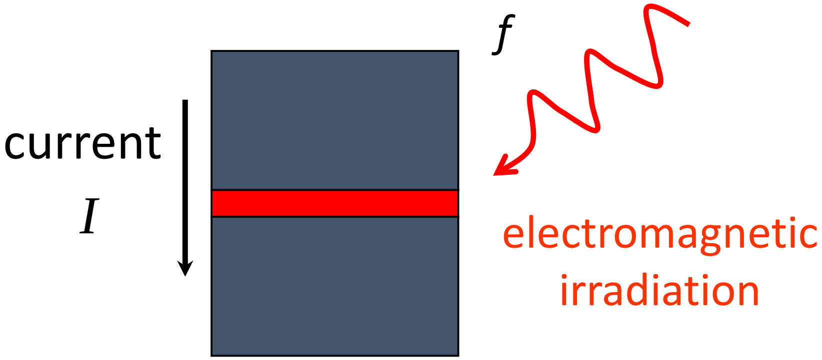
Rotating state---voltage state

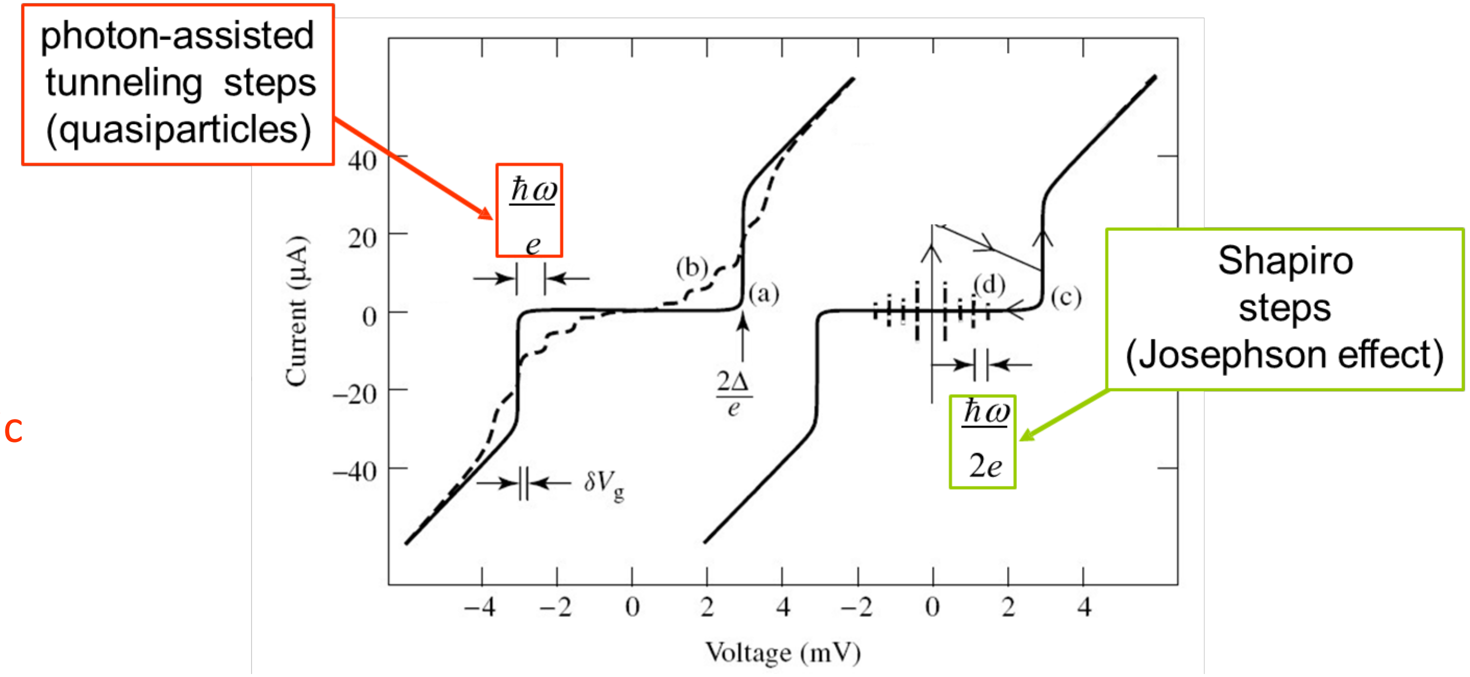
# Current-voltage characteristics determined by junction structure and barrier material.

Junction parameters are mainly critical current $I_C$, resistance $R$, and capacitance $C$.

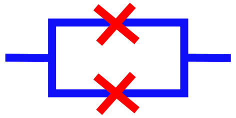


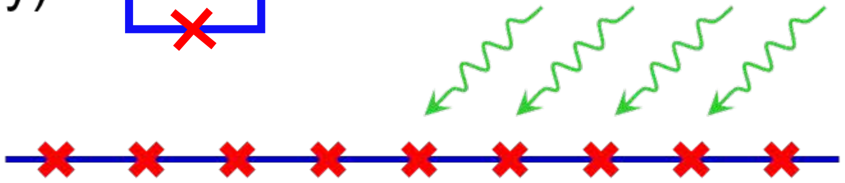



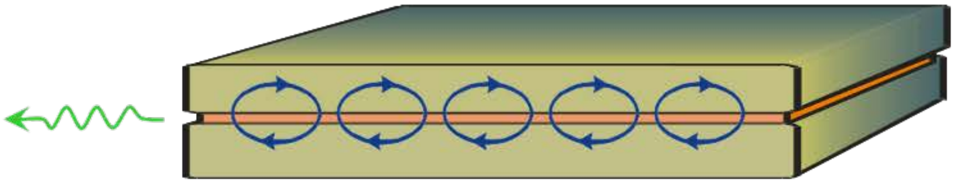
# Typical electronic applications of Josephson junctions

– SQUIDs (magnetometry)  (Superconducting Quantum Interference Device)

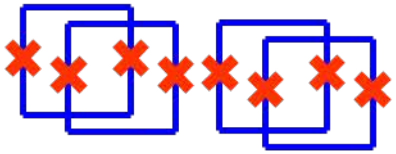
– Voltage standard



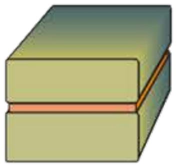
– Microwave generators
(1 GHz – 2 THz)



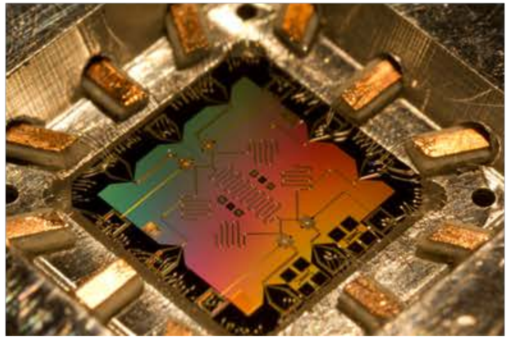
– RSFQ digital electronics



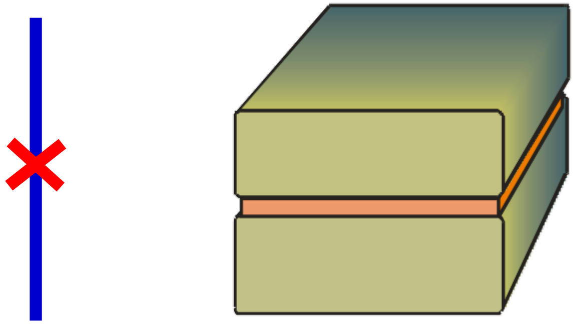
– Qubits



– Teleporters



# Fabrication of low-Tc Josephson devices

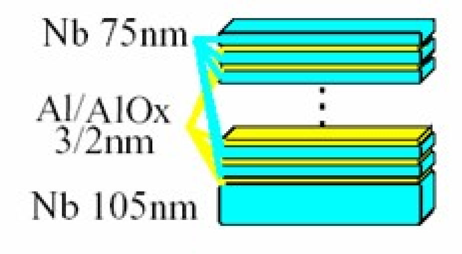


1. circuit layout (CAD)
2. fabrication of photomasks
3. deposition of superconducting and insulating layers on a wafer
4. photo (or e-beam) lithography
5. dicing the wafer into chips

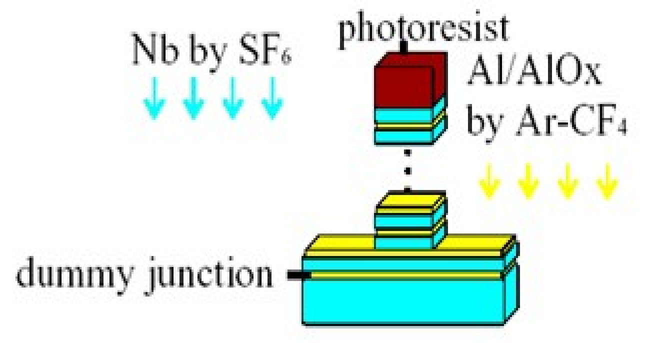
- *Nb-AlO$_x$-Nb*
  - *Nb* sputtering
  - *Al* sputtering and oxidation
  - $T_c$ = 9.2 K
  - $J_c$ from $10^2$ to $10^4$ A/cm$^2$
- *Al-AlO$_x$-Al*
  - *Al* evaporation
  - *Al* oxidation
  - $T_c$ = 1.2 K
  - $J_c$ from 1 to $10^2$ A/cm$^2$

# Fabrication of Nb-AlOx-Nb junctions

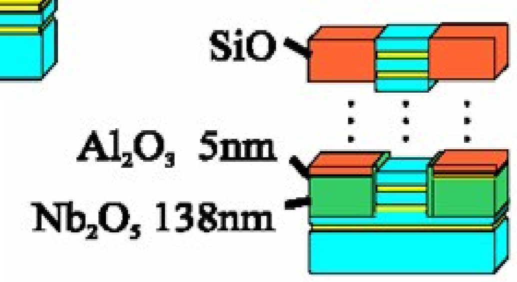
1. Deposition of a multilayer



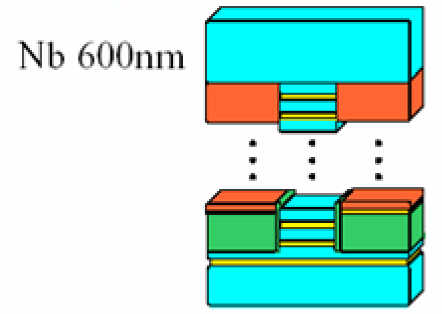

2. Reactive ion etching




3. Anodic insulation + SiO or $SiO_2$

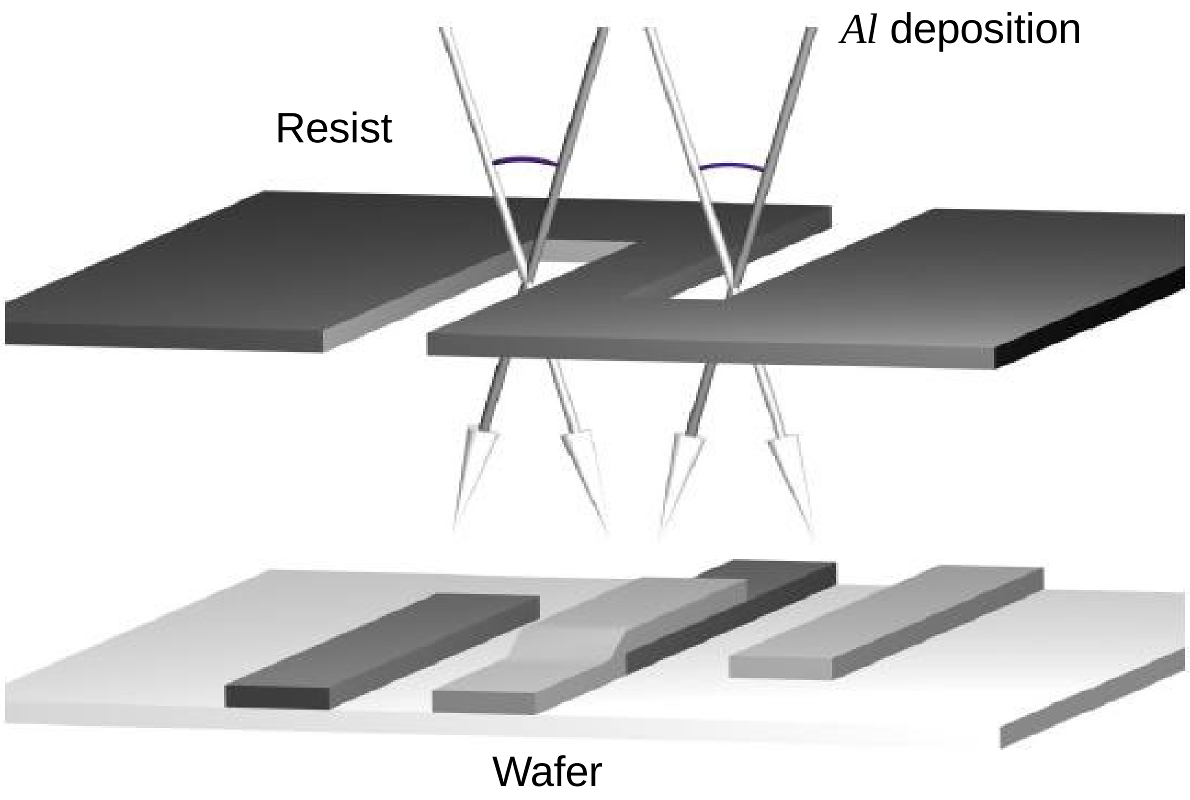



4. Nb wiring



# Shadow evaporation technique

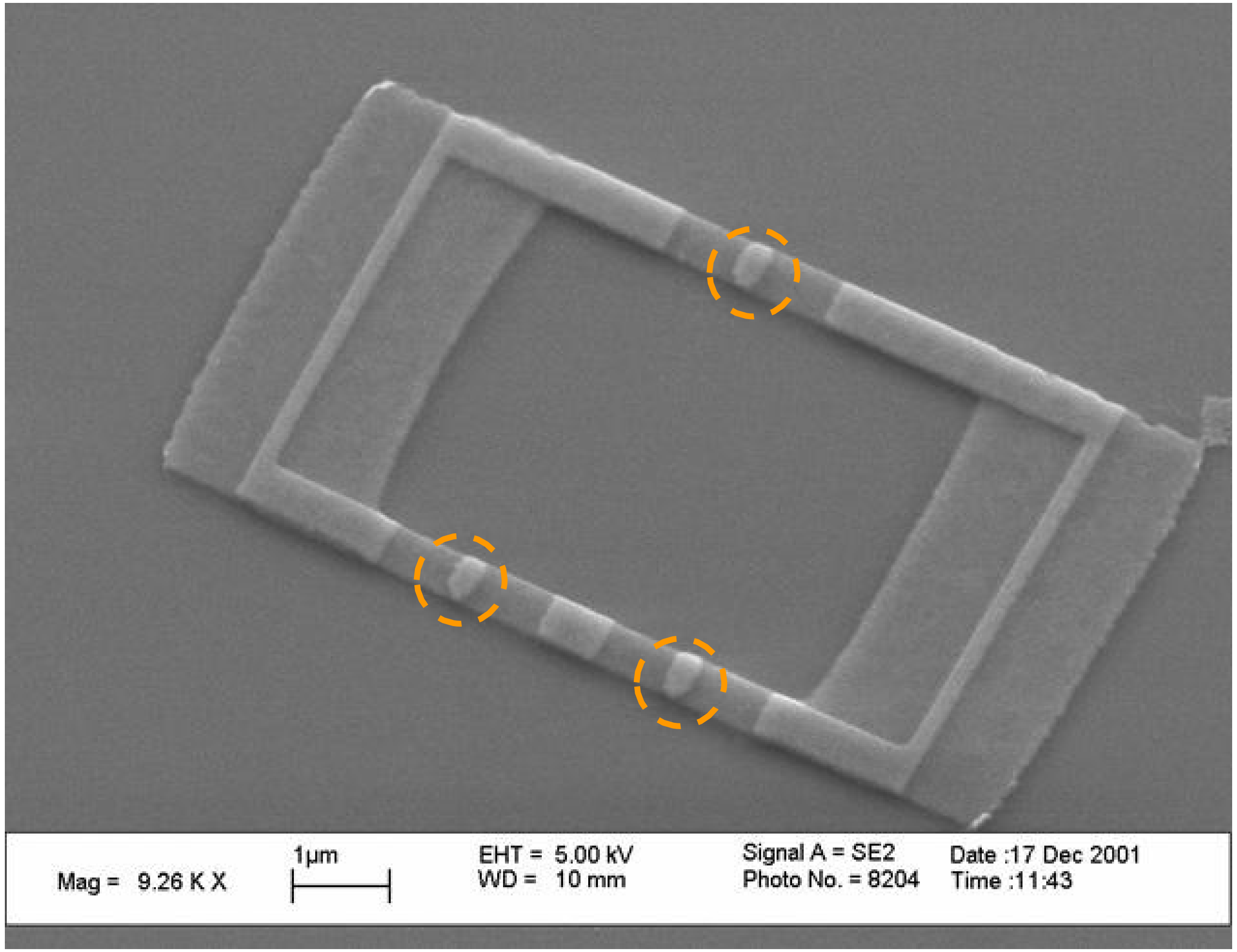
Electron beam lithography can produce JJ size < 0.1 μm

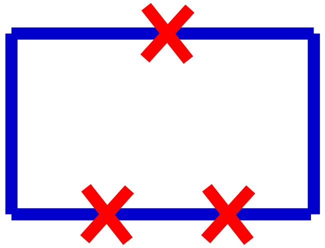



Electrom beam lithography


*Al-AlO$_x$-Al*

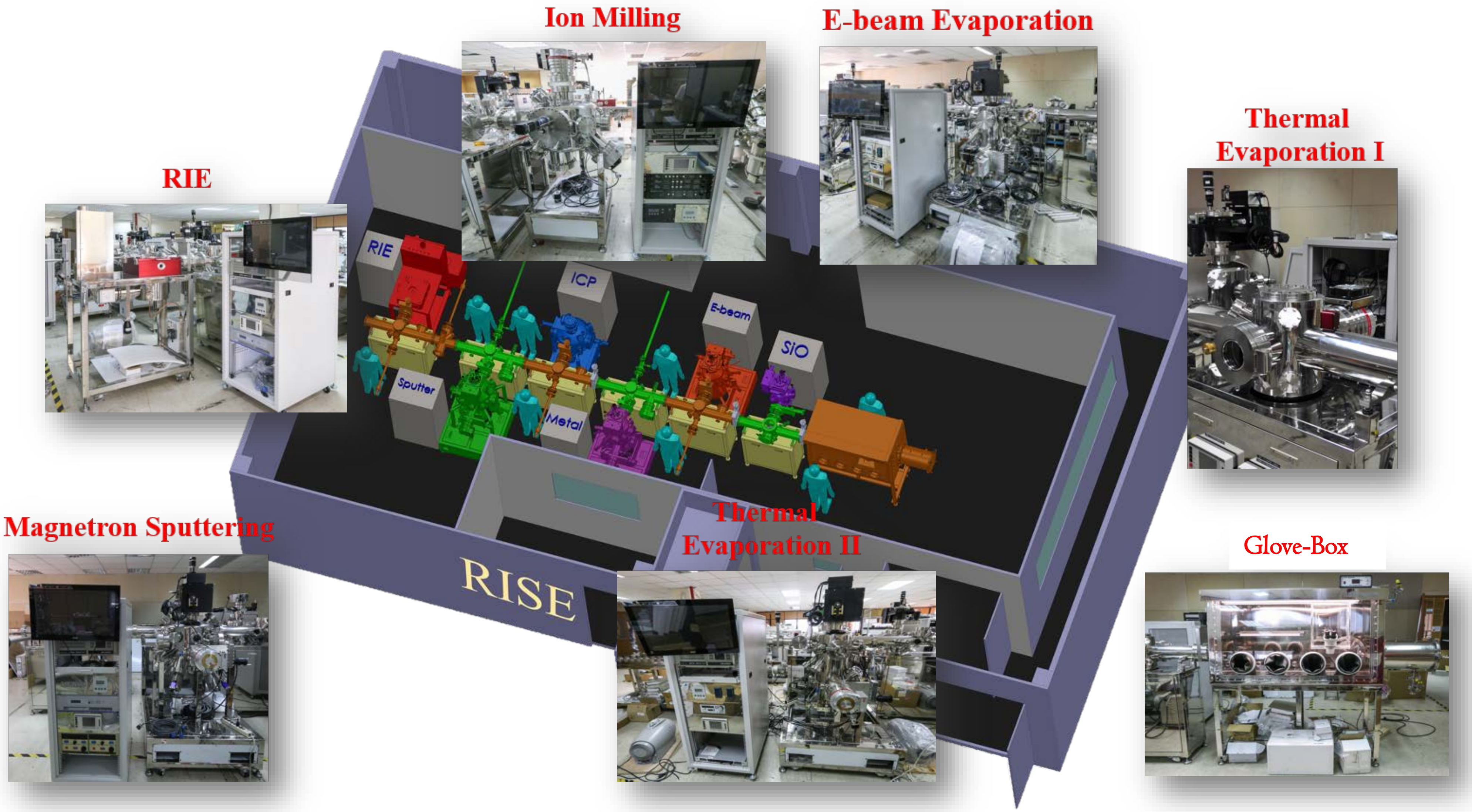
# Sub-micron Al-AlOx-Al JJs produced by electron beam lithography



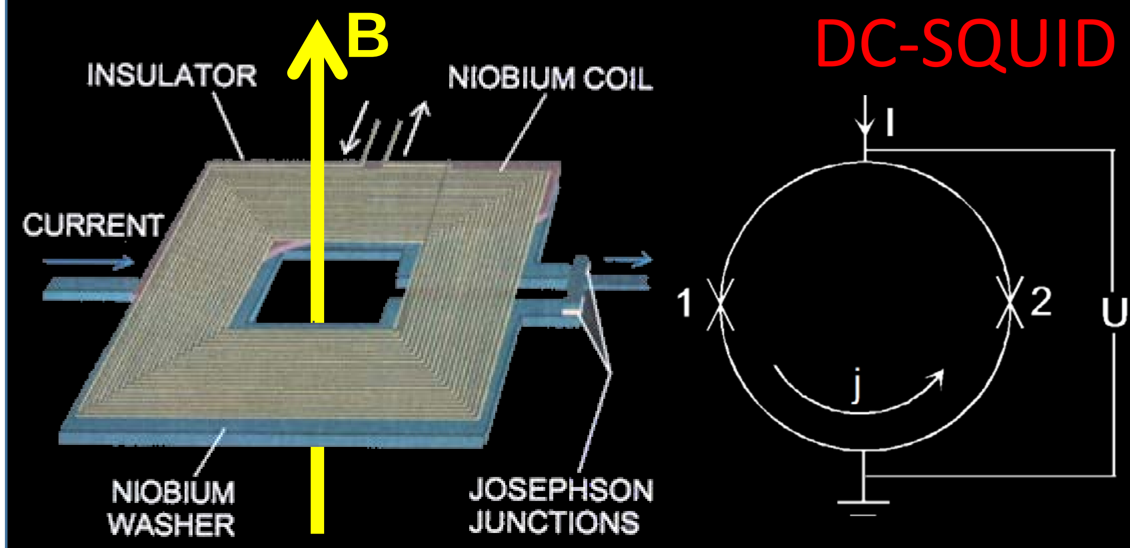



3-JJ flux qubit

# *In-situ* fabrication system



# SQUID (Superconducting Quantum Interference Device)




$$\Delta\Phi(B) + 2\Delta\Phi(i) = n \cdot 2\pi$$

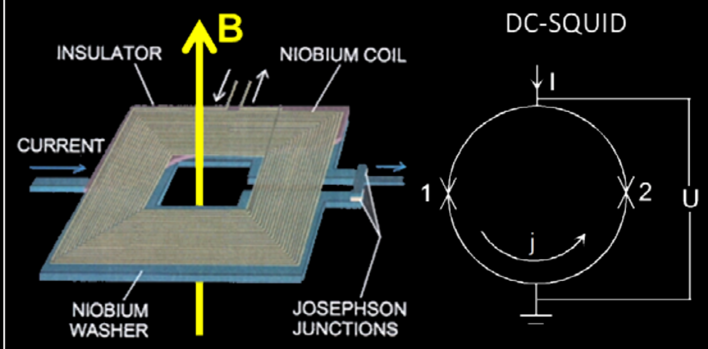
Due to B field

Due to junctions

Must be quantized

R. C. Jaklevic et al. *Physical Review Letters*. **12** (7): 159–160 (1964).

# SQUID (Superconducting Quantum Interference Device)




$$\Delta\Phi(B) + 2\Delta\Phi(i) = n \cdot 2\pi$$

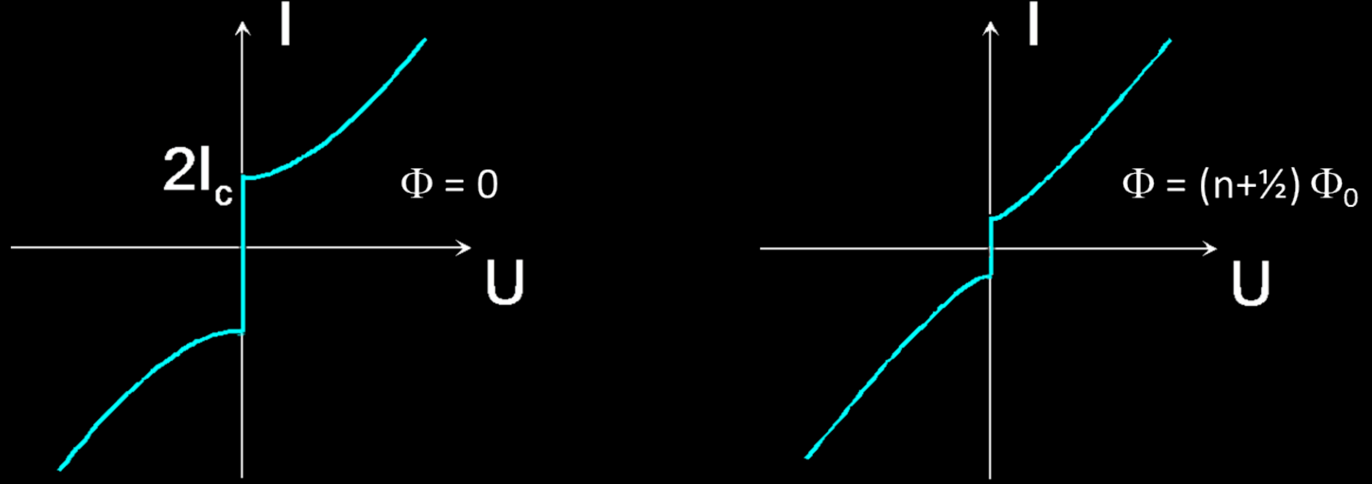
Due to B field    Due to junctions

Must be quantized

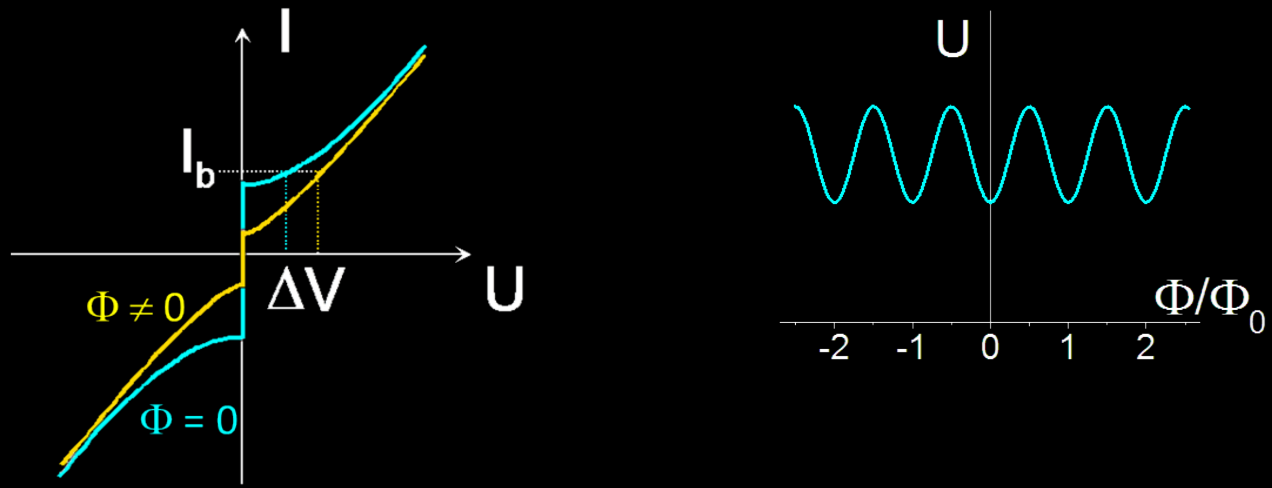
Maximum supercurrent:

$$I_{s,max} = 2I_c \cdot |\cos\pi \frac{\Phi_{ext}}{\Phi_0}|$$

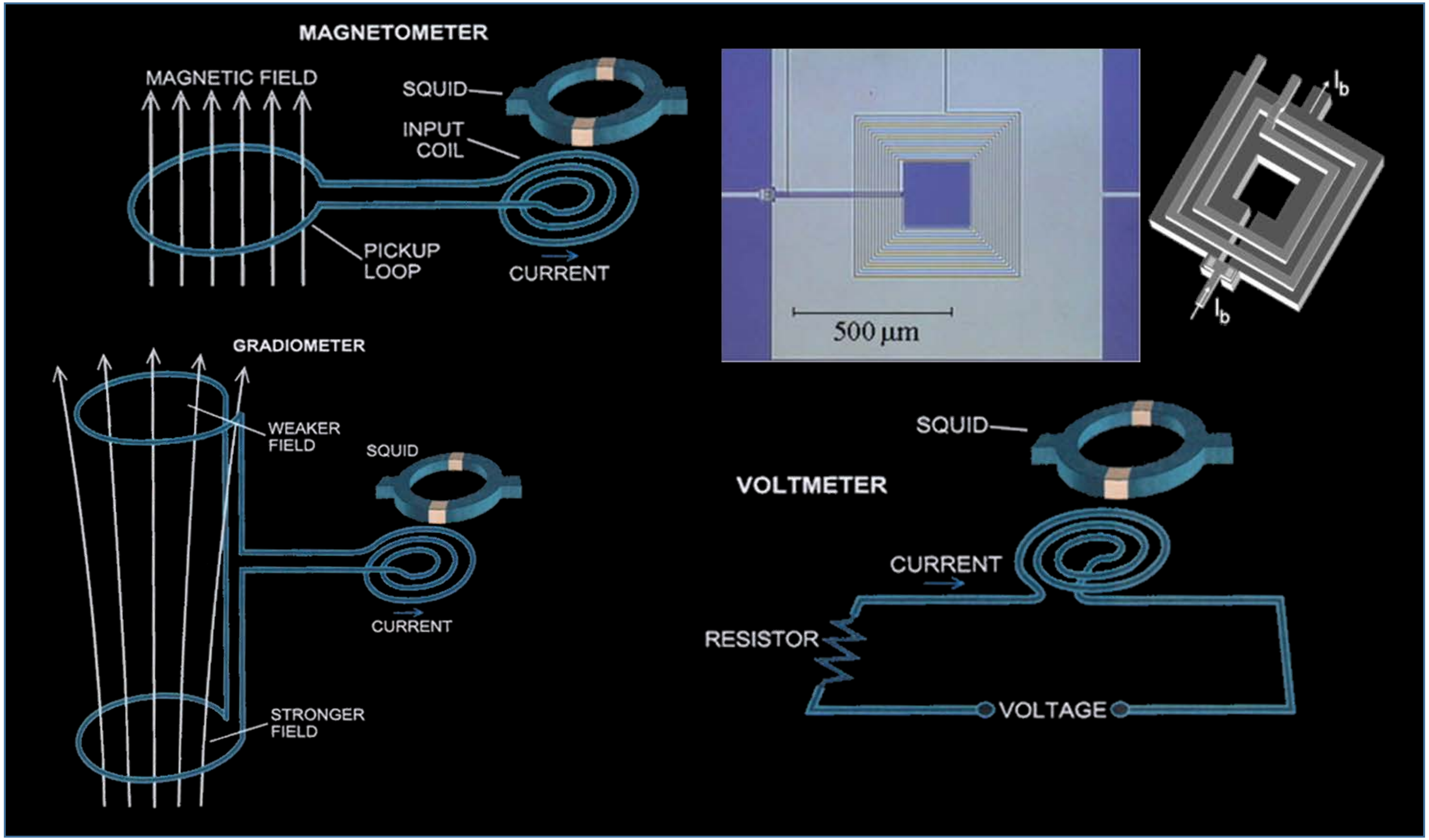
IV's



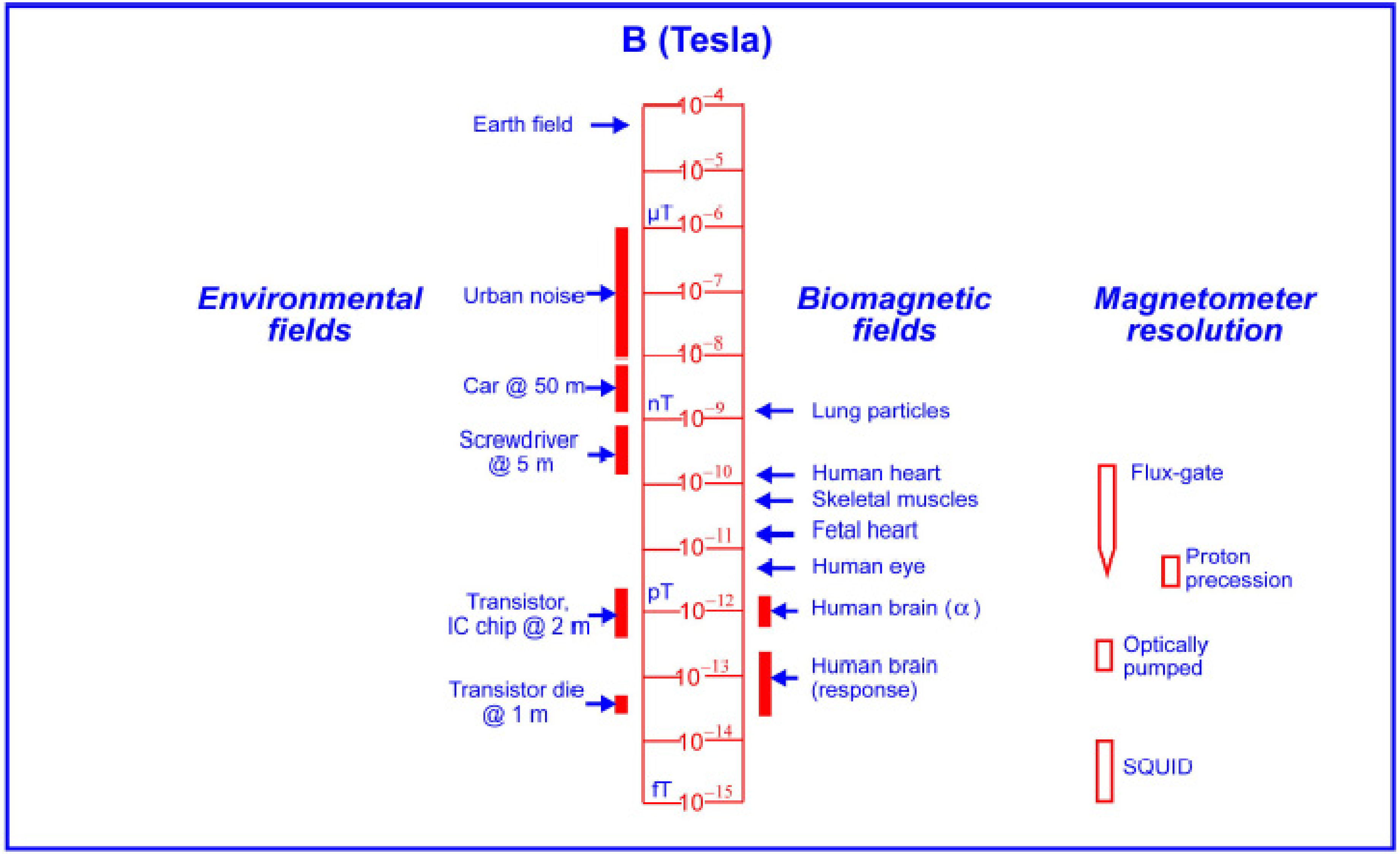

Readout procedure



# Magnetometers, gradiometers, voltmeters…..

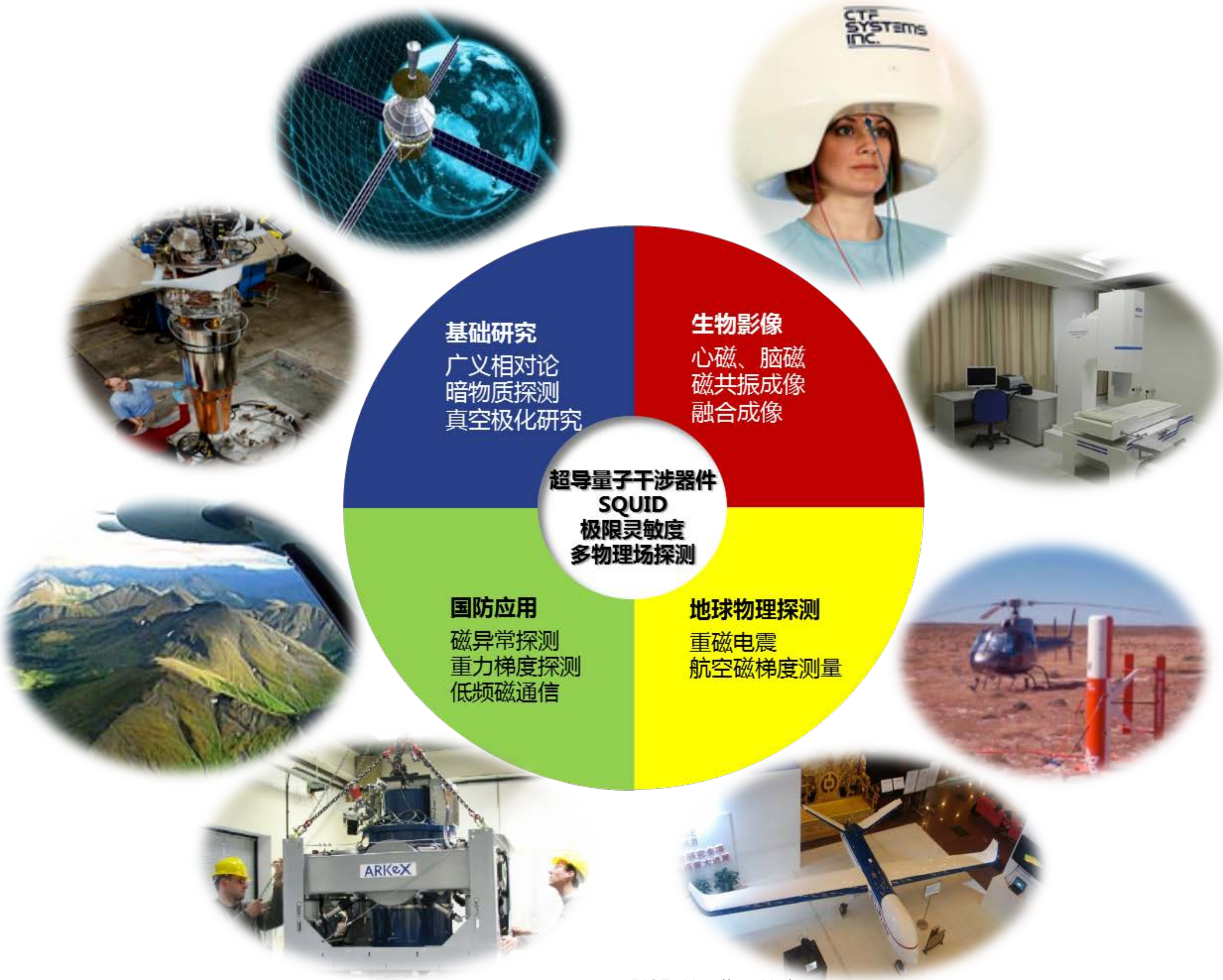


# Range of biomagnetic fields and environmental fields




After J. Vrba, CTF

# SQUID



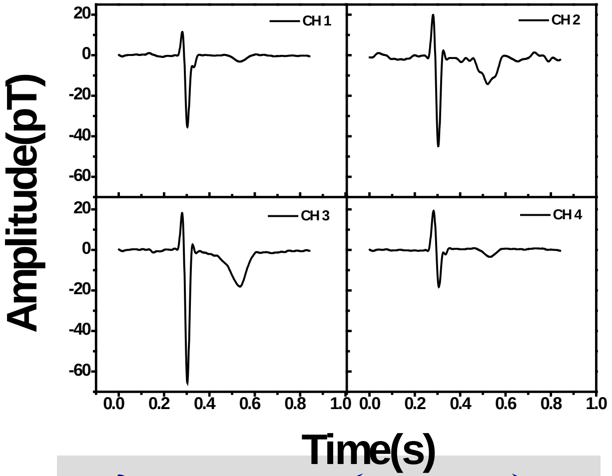

- DC-SQUID
- RF-SQUID



*Provided by Xiangyan KONG @NBU*

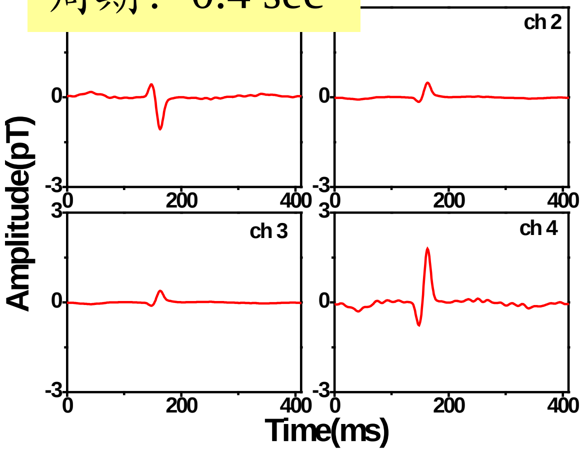
# 生物磁探测演示

幅度： 25~30pT
周期： 1.5 sec

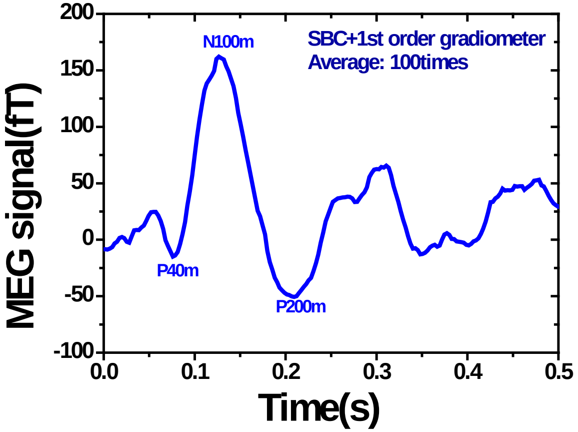



成人心磁（MCG）


幅度： 1~2 pT
周期： 0.4 sec




胎儿心磁（fetal MCG）

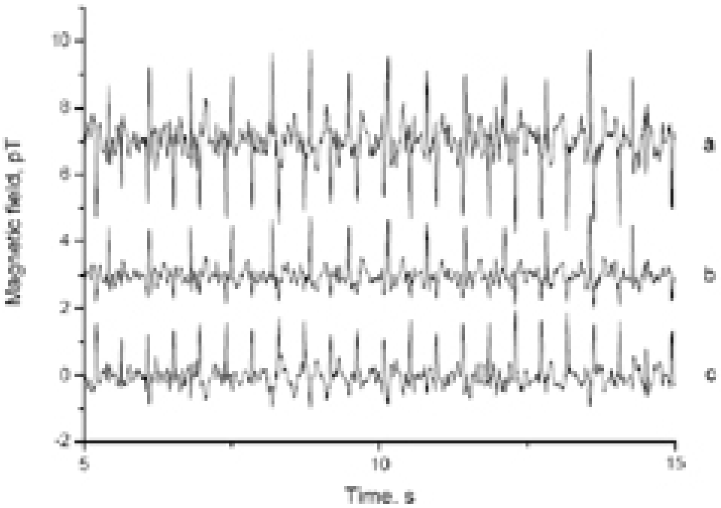


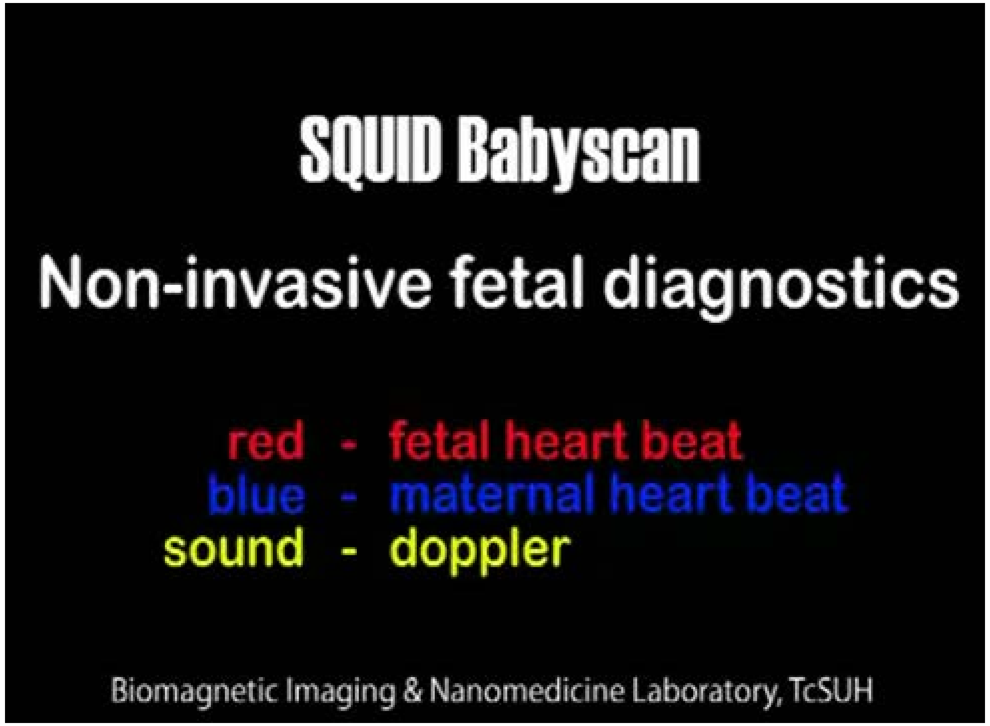

声音激励脑磁信号探测
（MEG）

*Supercond. Sci. Technol*, 26 (2013) 065002

*Provided by Xiangyan KONG @NBU*

# Magnetoencephalography: Heartbeat recording




A. Bradsdeikis,
University of Texas at Houston

# Unshielded 4ch MCG System

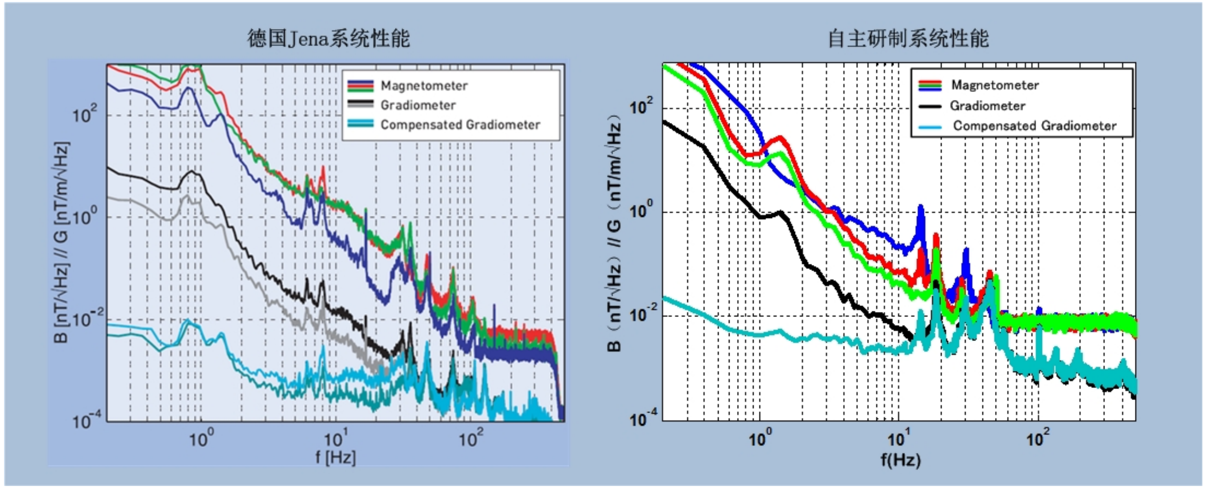
**MD-U041001, China**

| Main parameters | |
|---|---|
| Sensor | $2^{nd}$-order SQUID grad. |
| Reference | Vector SQUID mag. |
| Coil size | d=18 mm, b=50 mm |
| Channel | 4 sig.+3 ref. |
| Bandwidth | 0.1-40Hz |
| Noise level | 0.4 pTpp @ Averaged |

CSMCG
漫迪医疗

**Be the First Commercial System in China**

# 航空超导全张量磁测获得突破



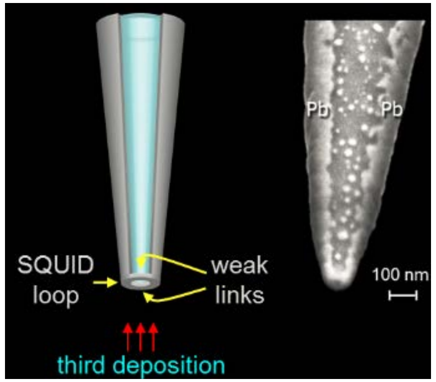

- 研制出国内首套航空超导全张量磁梯度测量装置，采用全自主研制的高性能平面梯度计，核心指标达到国际先进水平（0.02nT/m）。
- 在国家地质勘探示范区内蒙古乌兰浩特进行了测区飞行，获得了首张全张量磁梯度磁图。

# 纳米SQUID显微镜

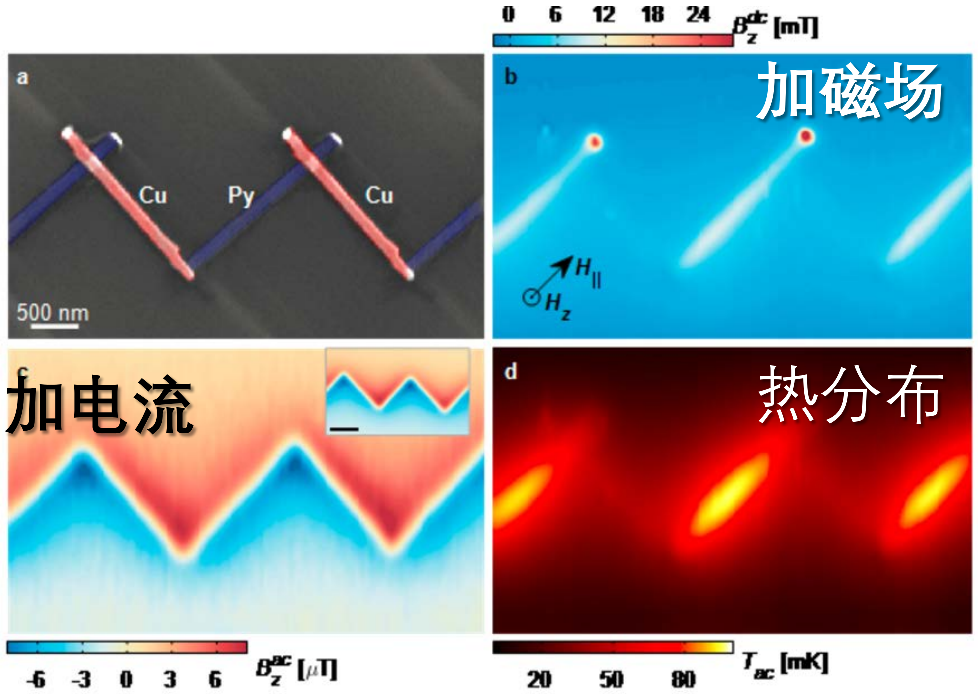
## Zeldov课题组
## 以色列

玻璃针尖端的纳米SQUID

*Nature Nanotechnology* 8, 639 (2013)

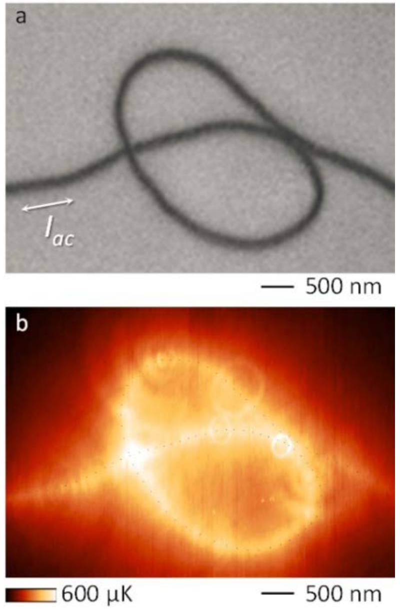



纳米电子器件磁、电、热分析

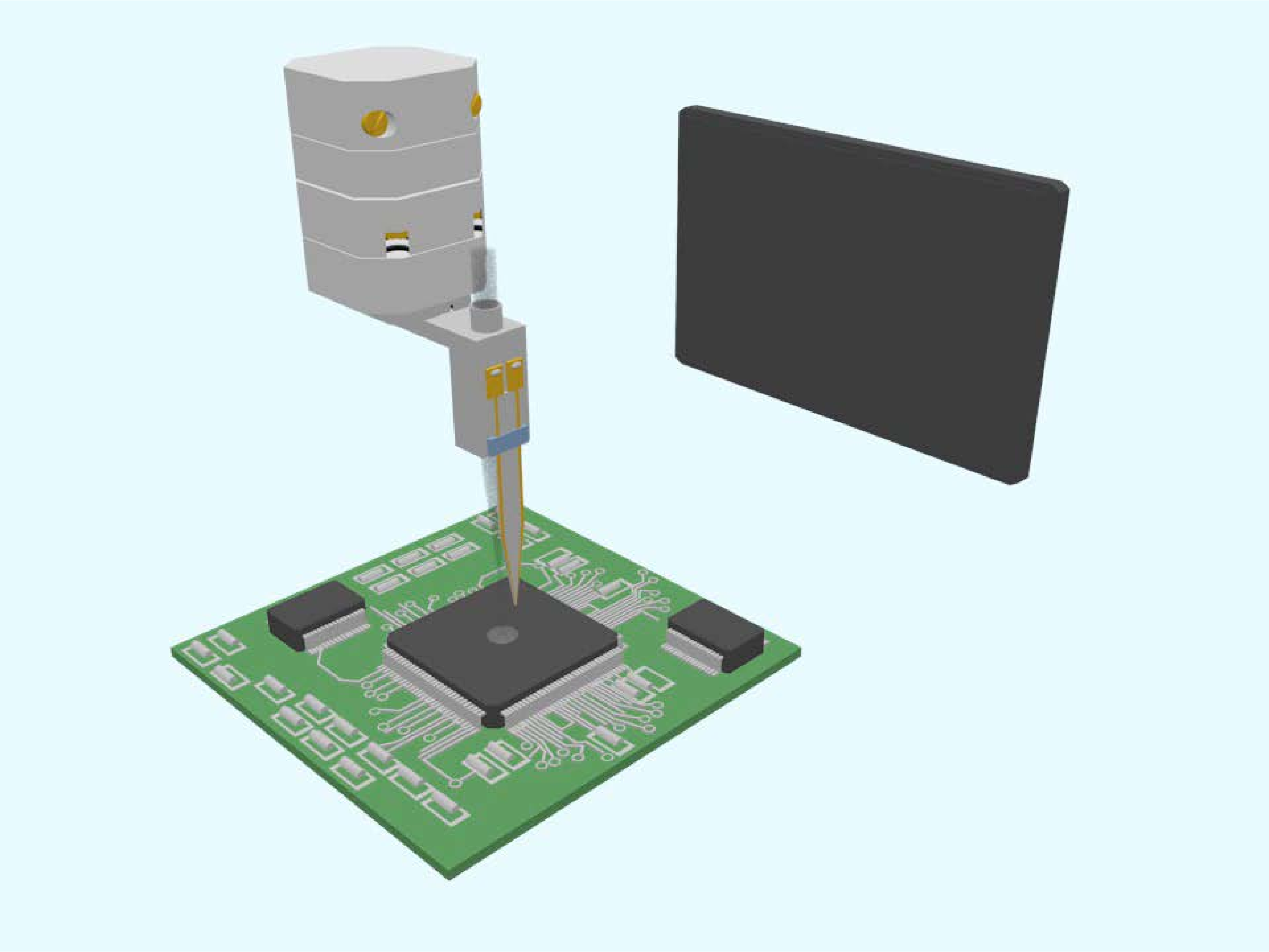



*Nature* 539, 407 (2016)

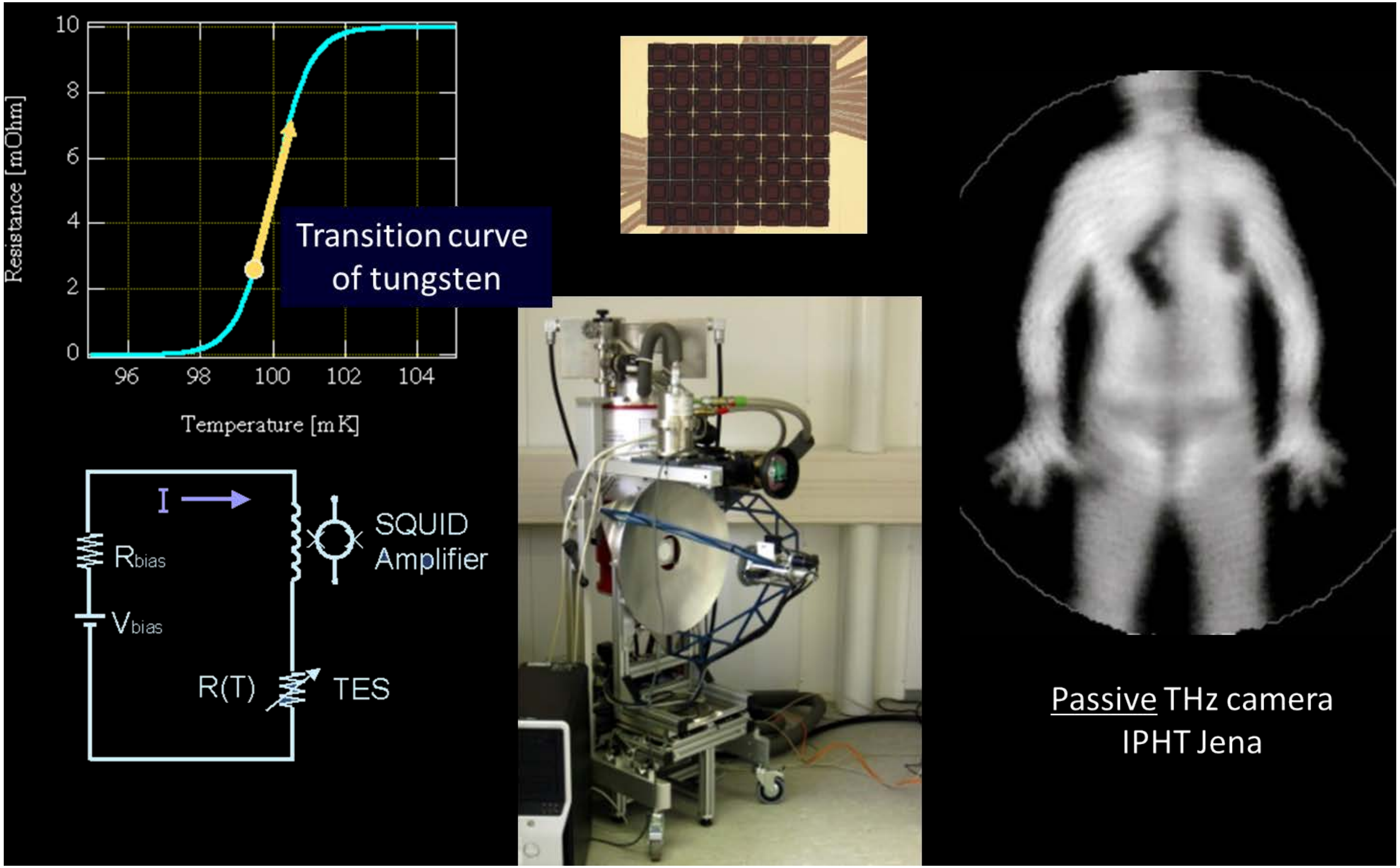
碳纳米管热分布



# 纳米SQUID显微镜

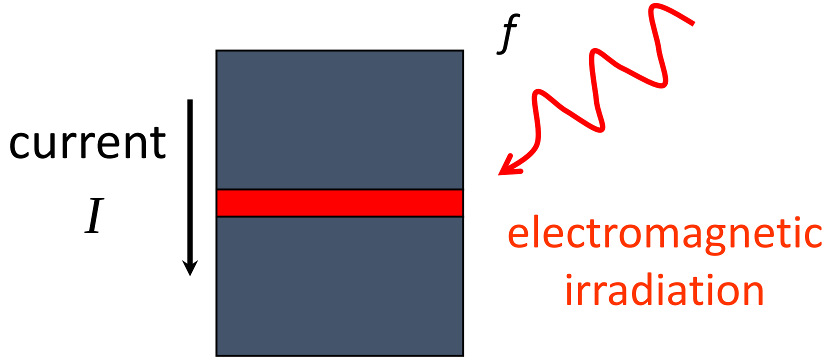


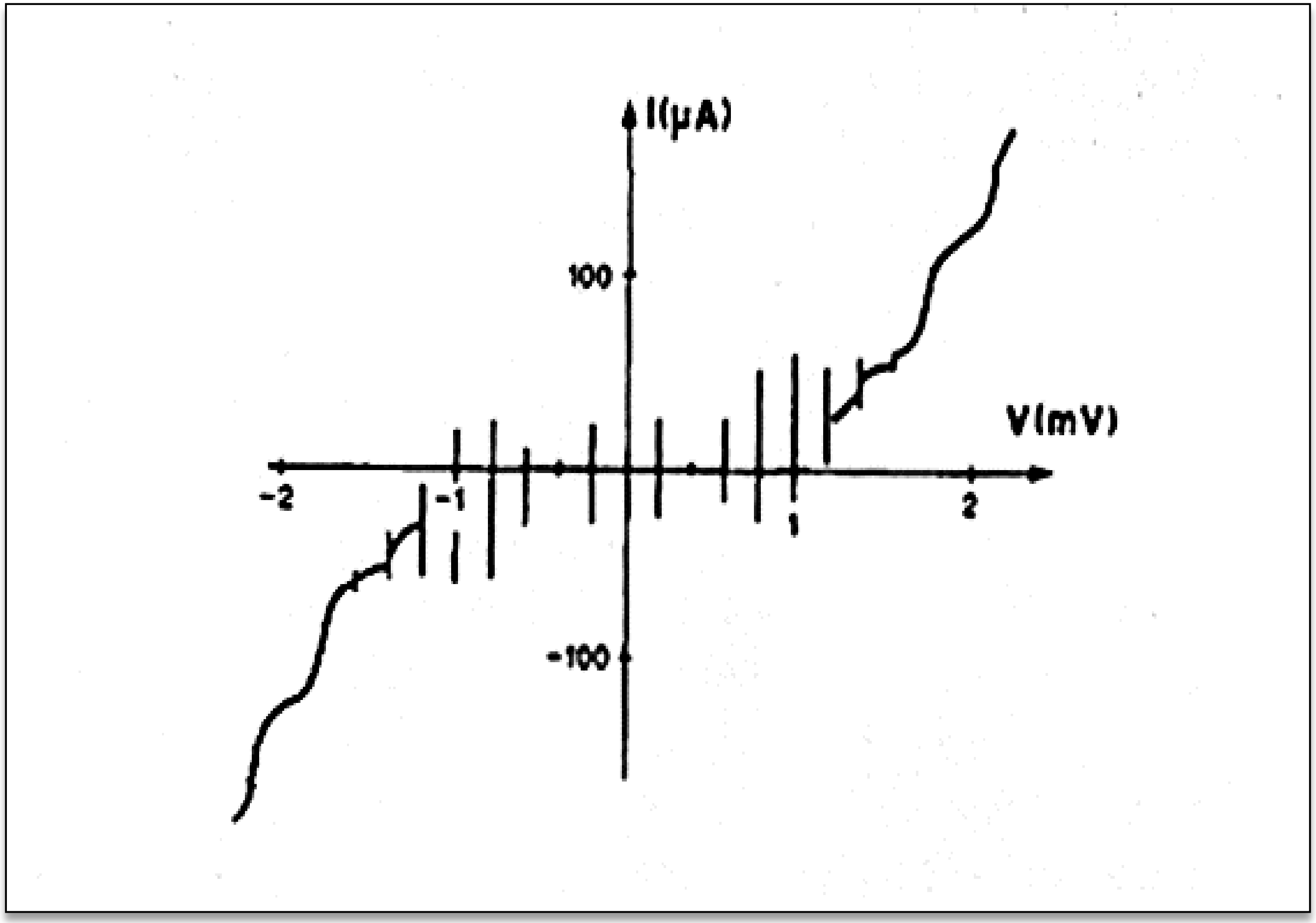
# Applications in a transition-edge bolometer



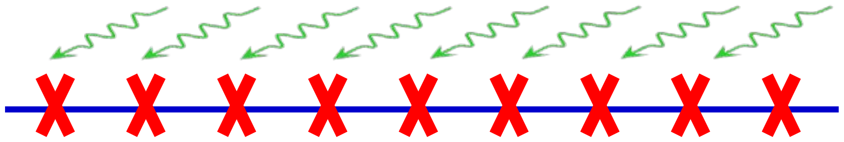
# Voltage standard with Josephson junction array

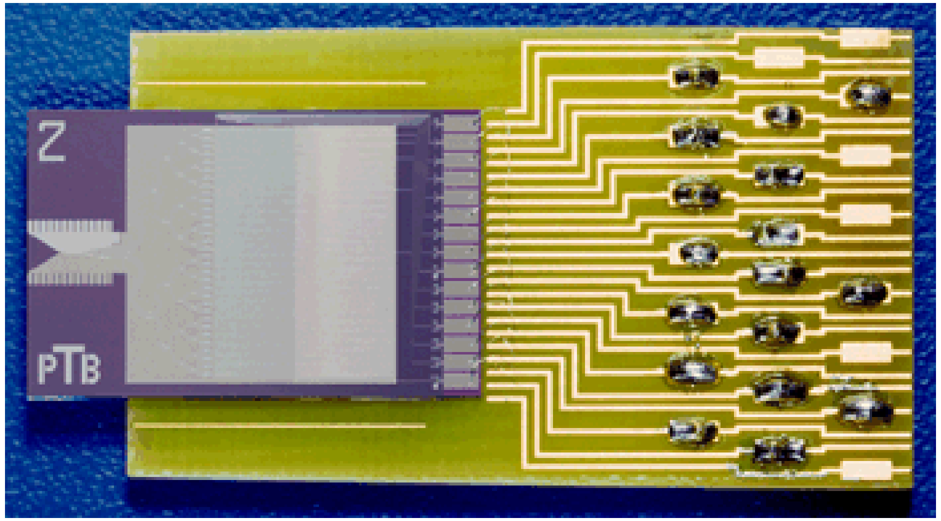
- $V_n = nfh/2e$

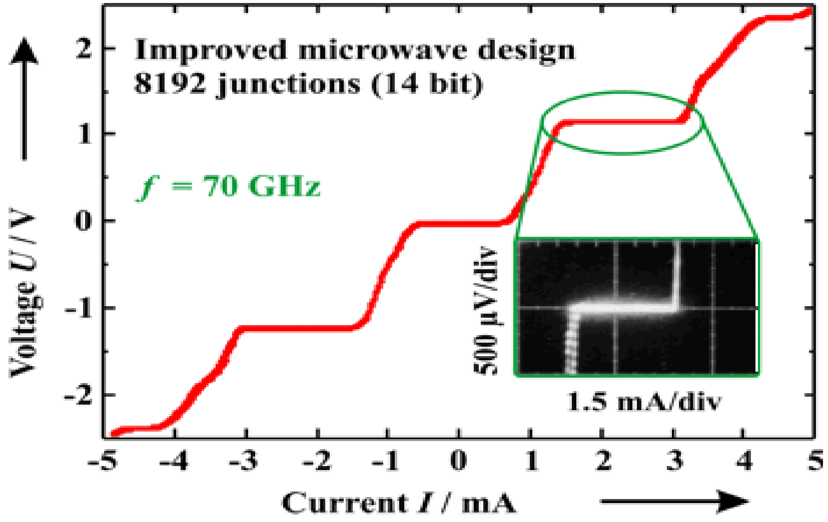


# Circuits for Josephson Voltage Standards





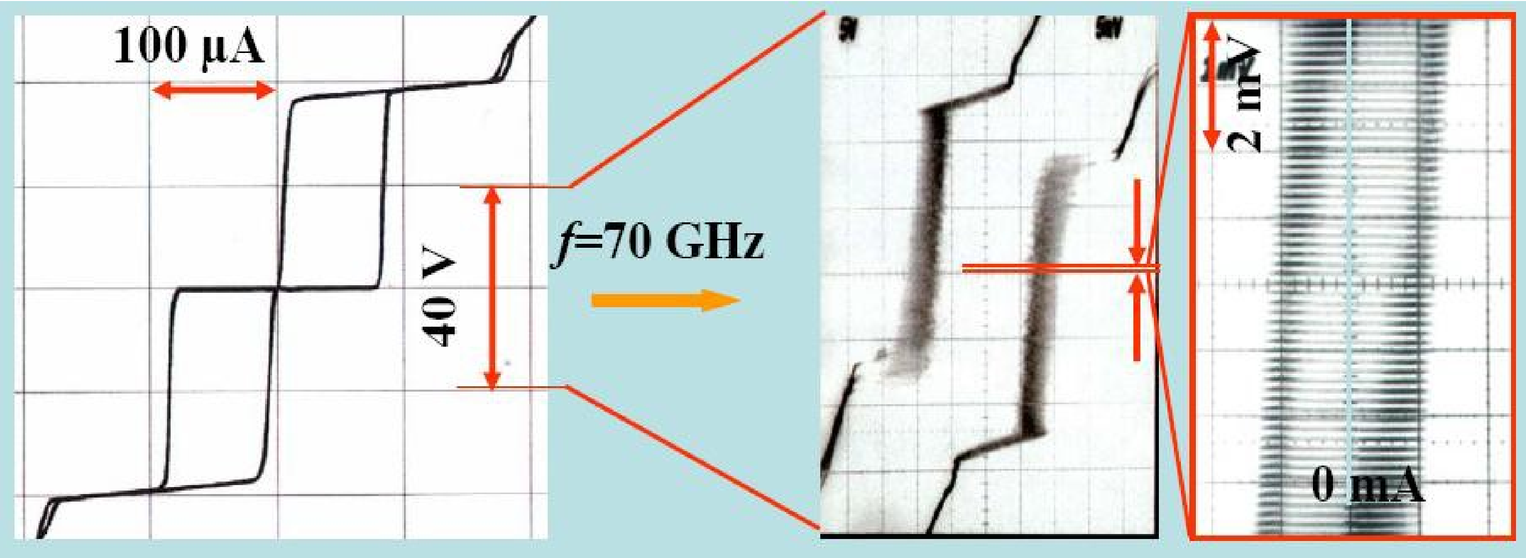

Picture of a 1-V series array consisting of 8192 SINIS junctions divided into a binary sequence

© PTB Brauschweig (group of Dr. A.B.Zorin)

# Conventional 10 V voltage standard

13 984 SIS junctions

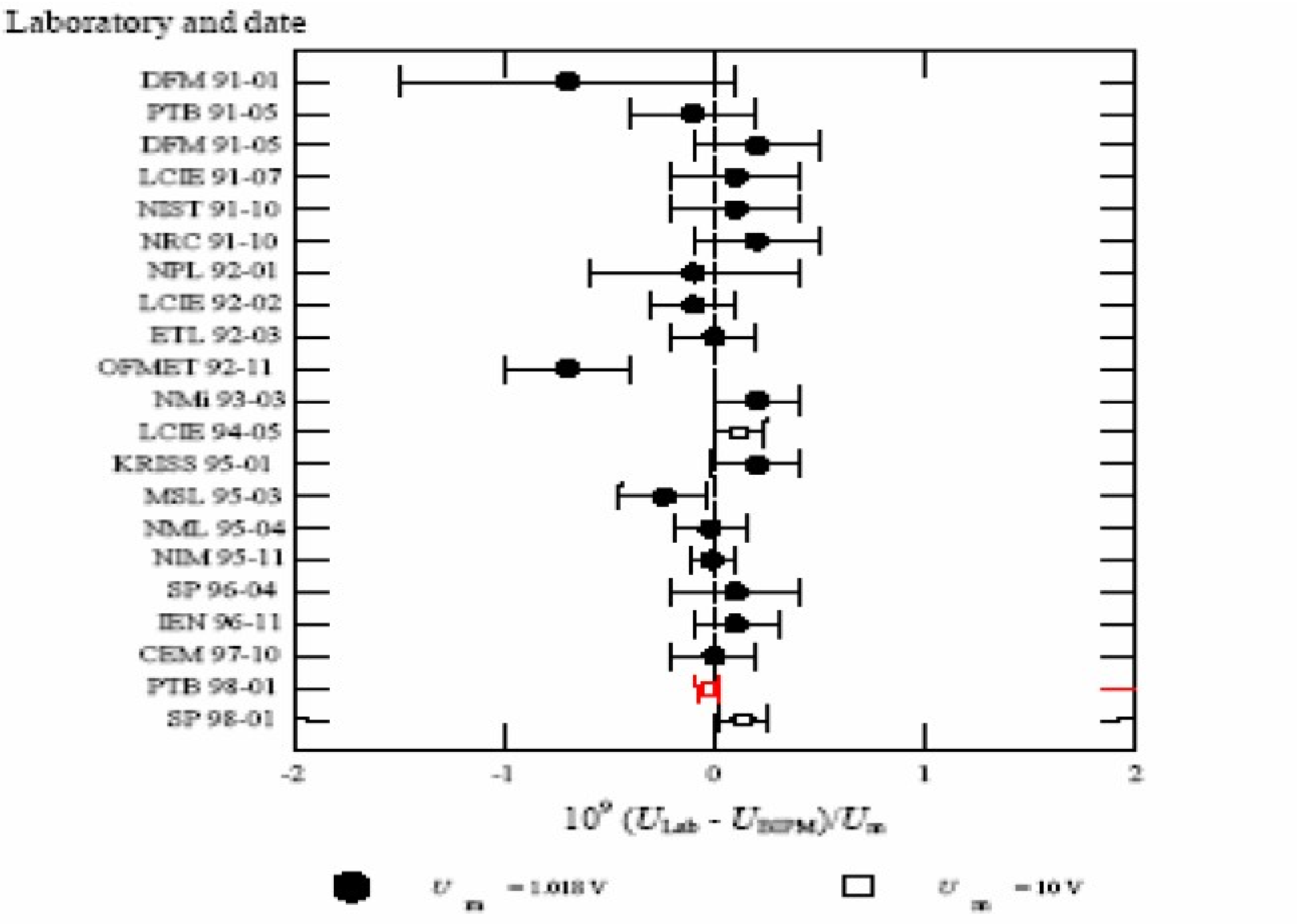
137 931 voltage steps between -10V and +10V
at I = 0; parasitic resistances not effective


•Rapid adjustment of a certain voltage is difficult
•AC-voltage generation requires rapid and programmable switching between the reference voltage steps
•To achieve a defined number of steps per junction one has to use highly damped Josephson junctions in series arrays: SINIS- or SNS-junctions

© J. Niemeyer (PTB)

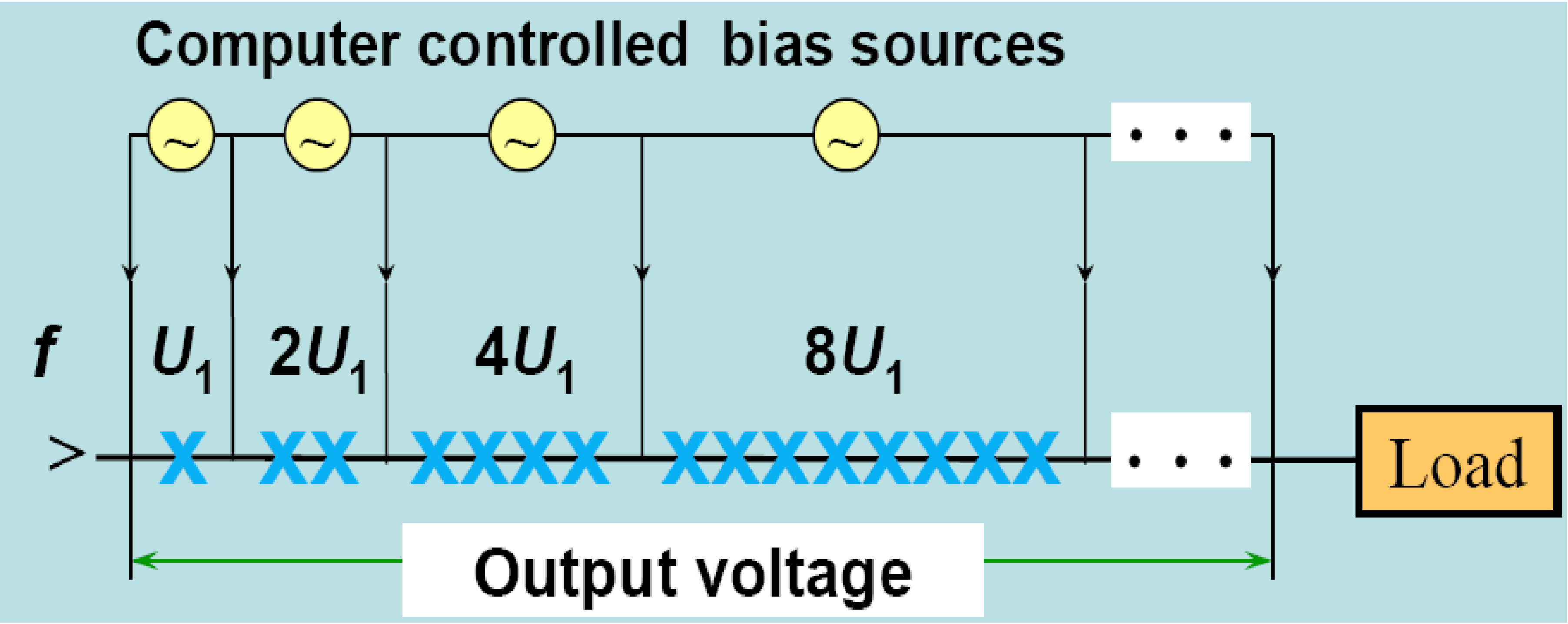
# Comparison of Josephson voltage standards




$U_{PTB} - U_{BIPM} = -3 \cdot 10^{-11}$ V with a relative uncertainty of $5 \cdot 10^{-11}$ V

© J. Niemeyer (PTB)

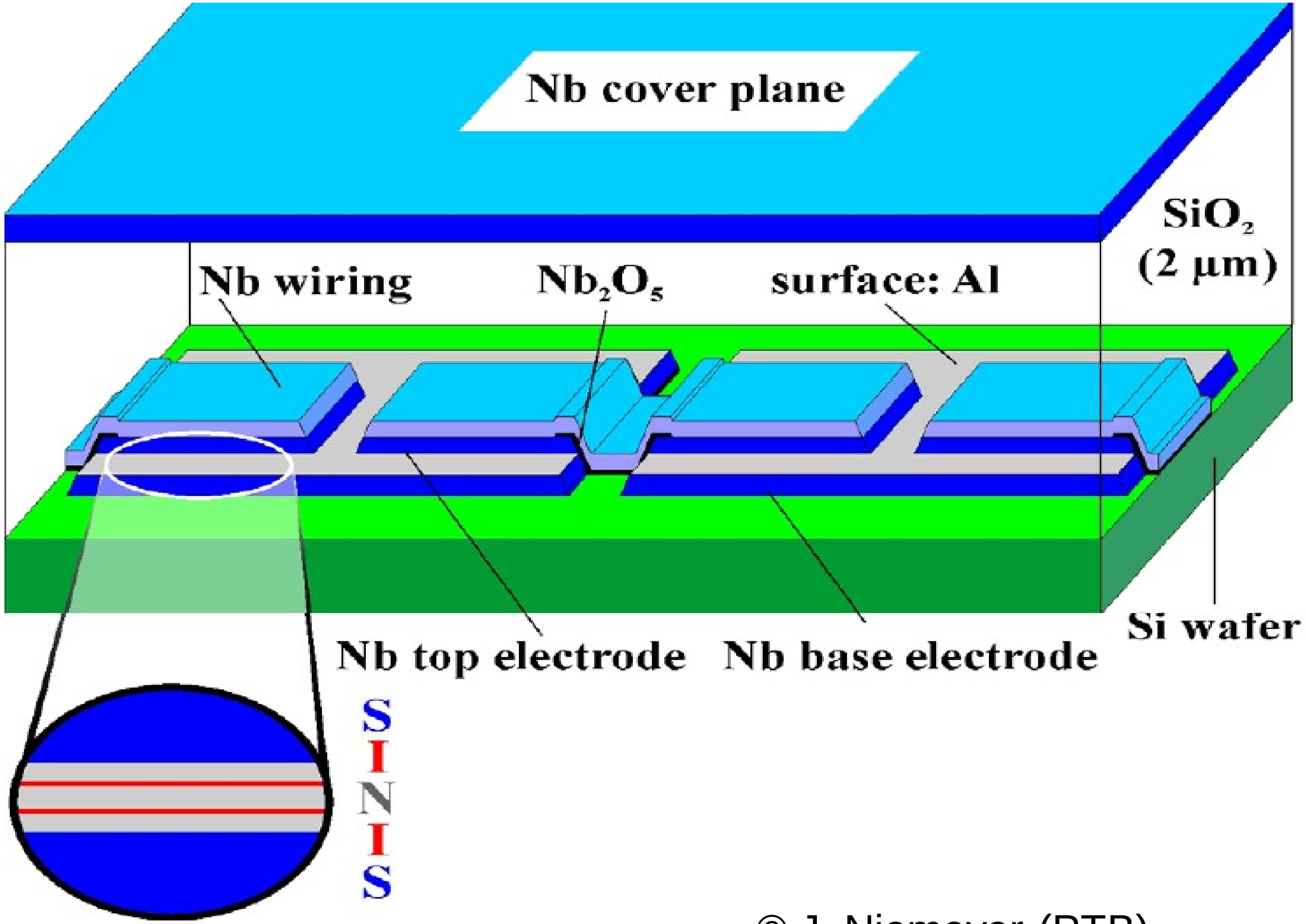
# Programmable Voltage Standard




Hamilton et al., IEEE Trans. Instrum. Meas. **44**, 223 (1995)

© J. Niemeyer (PTB)

# SINIS junctions integrated into a stripline



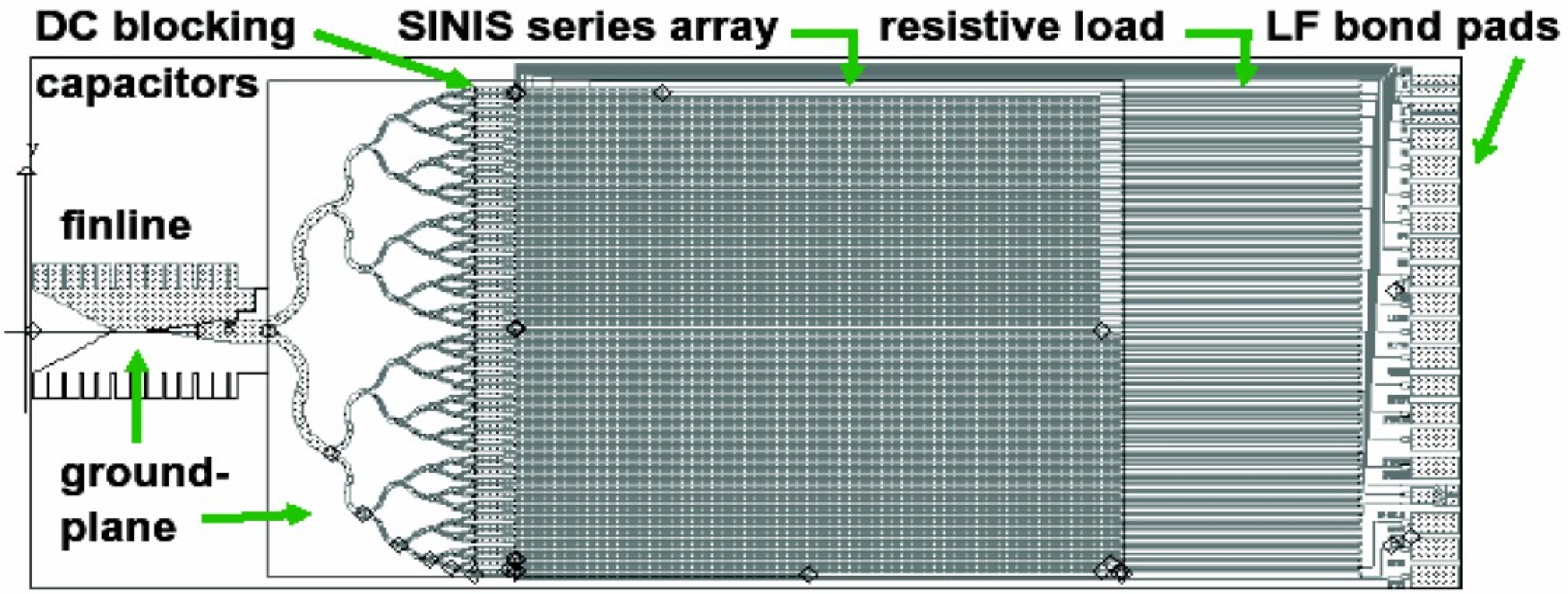

**Impedance:** 5 Ω

**Area** of a single junction:

**12 µm x 30µm**

# PTB SINIS voltage standard

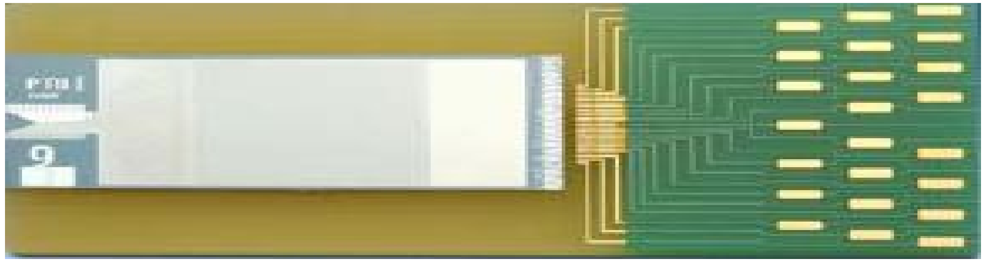
- 69,632 SINIS junctions divided into binary segments
- 128 microwave branches (containing up to 562 junctions)

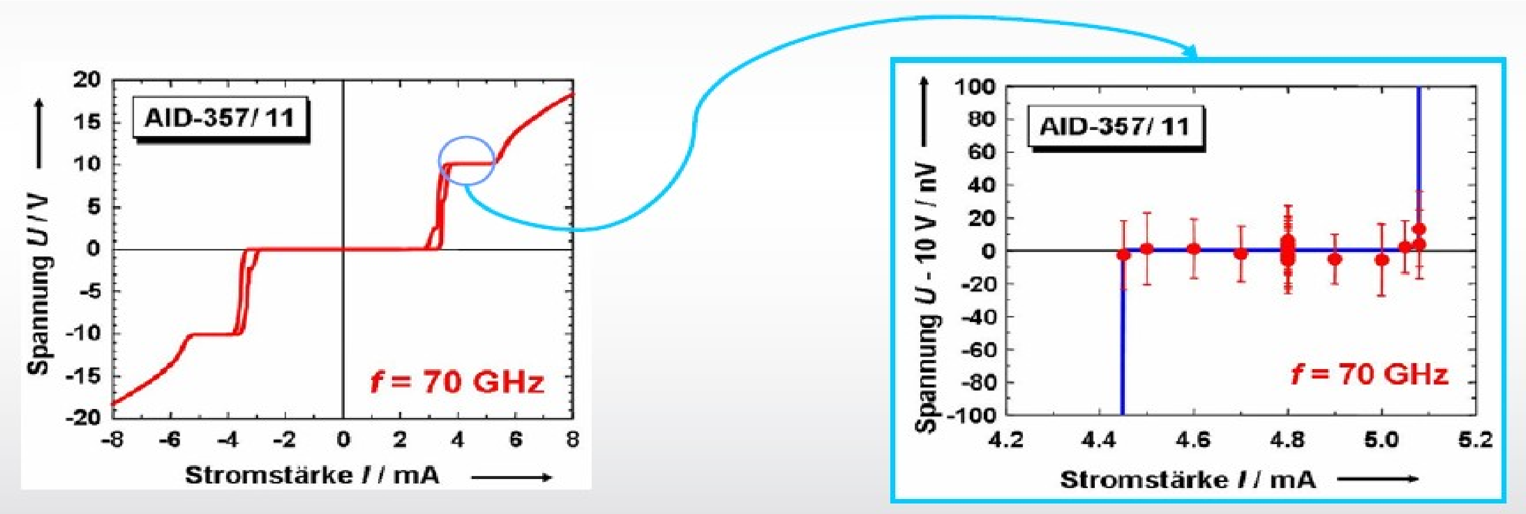



junction areas: 12 µm x 30 µm

chip size: 10 mm x 24 mm

# Programmable 10-V-Josephson-Standard



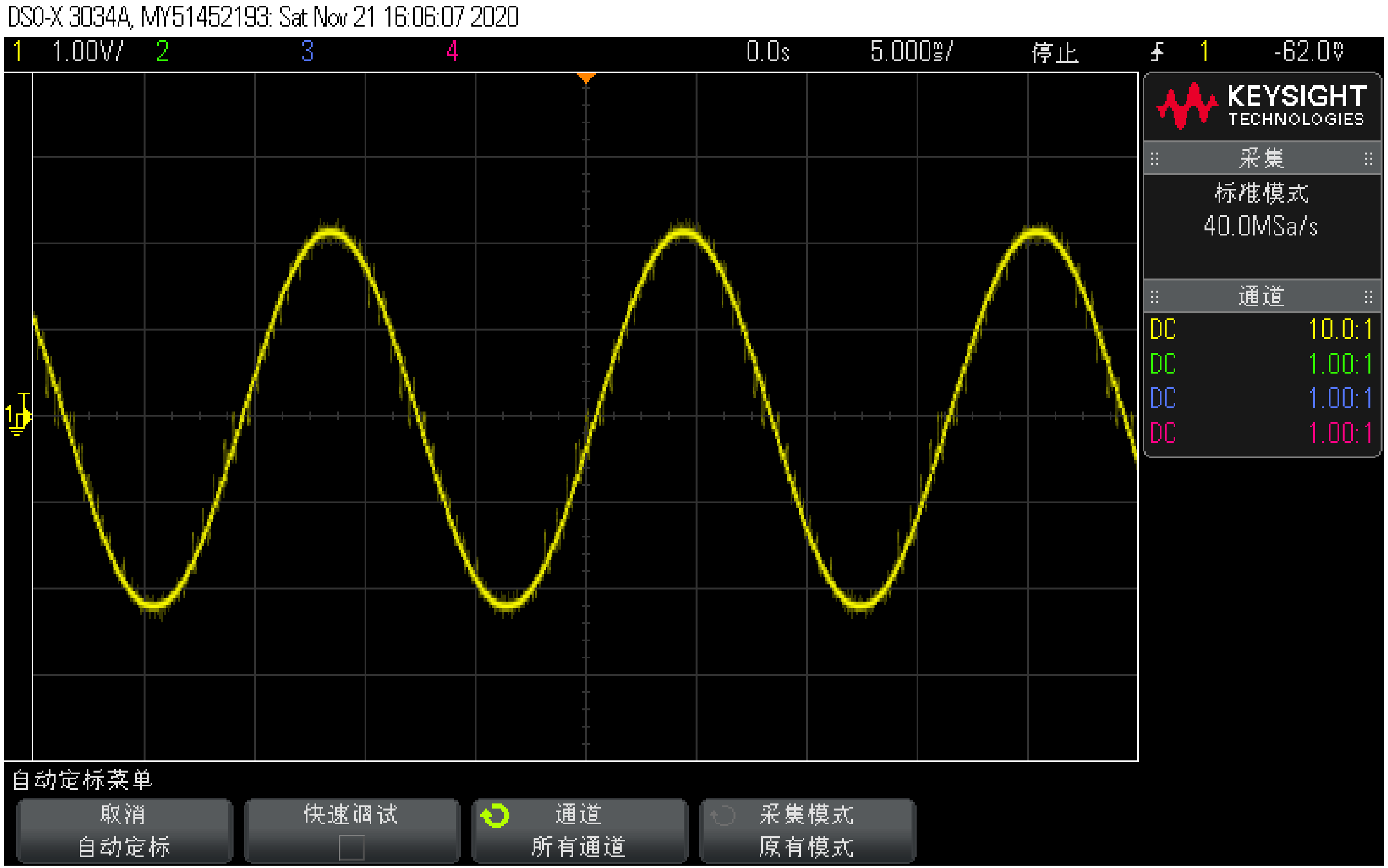



- Current step 600 µA
- 70000 SINIS Josephson contacts
- Operation with rapidly switchable computer controlled current source

Applications:

- Quantum voltmeter for AC and DC voltages
- Primary standard for the electrical power
- Linearity measurements (DC)

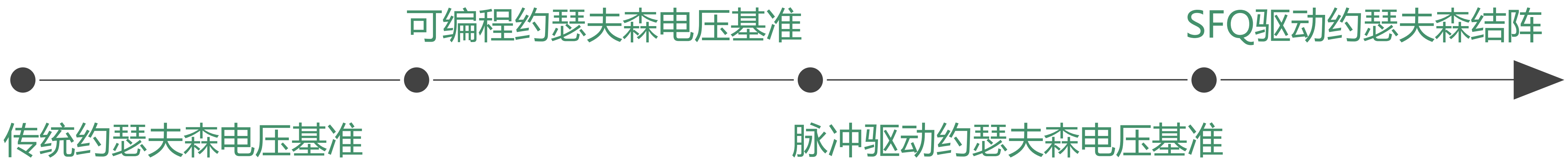
# 合成的一个正弦波

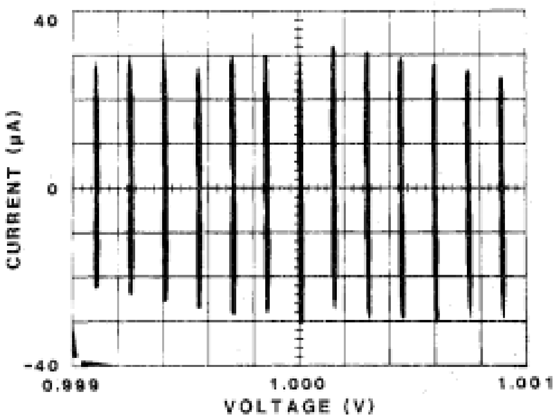


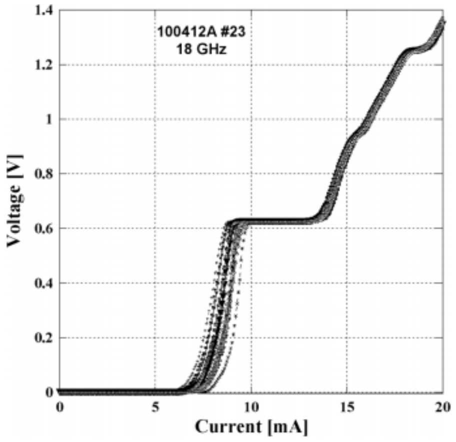

每个周期160个点，频率62.5Hz，峰峰值4.2伏的正弦波形。外部触发频率是10kHz。

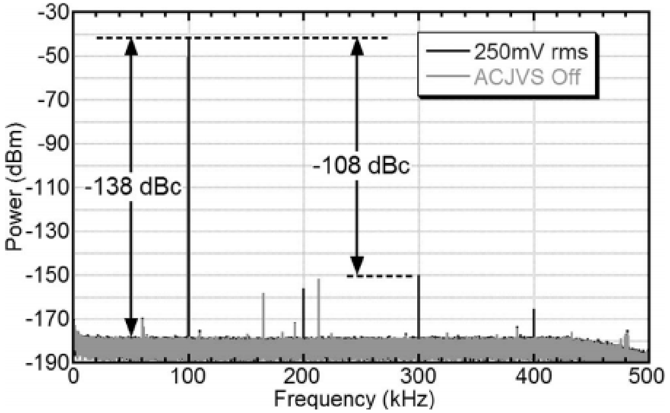
Provided by Wenhui Cao

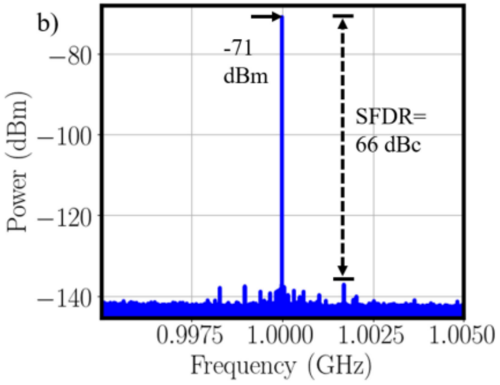
# 历史和现状




SIS Nb/AlOx/Nb

直流电压

SNS Nb/NbSi/Nb

交直流两种，电压高10 V，频率低1 kHz

交流电压，电压低，频率高
1 GHz



Provided by Wenhui Cao

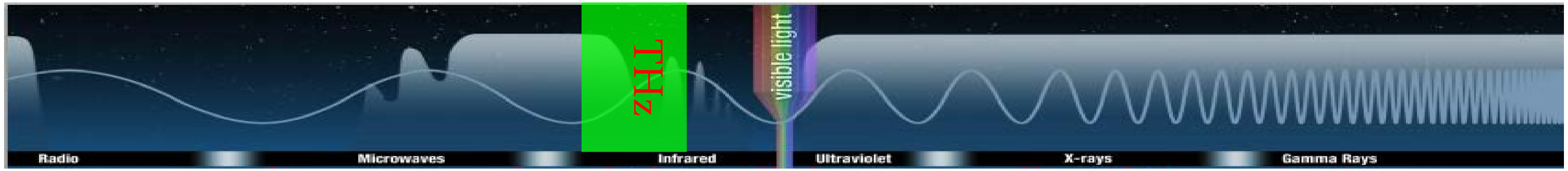
# 历史和现状

- 1962年：约瑟夫森效应提出
- 1963年：约瑟夫森交流效应，即Shapiro台阶被证实
- 1968年-1972年：尝试用Shapiro台阶标定物理常数h/2e
- 1972年-1989年：尝试固定物理常数h/2e，用Shapiro台阶标定电压。并研制出了传统型10V的约瑟夫森结阵列，电压计量精度从10-6提高到10-9
- 1990年：正式放弃使用Weston电池的实物电压标准，固定常数h/2e,改用以宏观量子现象约瑟夫森交流效应为基础的电压标准
- 1995年：提出可编程电压标准的概念
- 1996年：提出脉冲驱动型可编程电压标准的概念
- 1997年：1V可编程约瑟夫森结阵制作成功
- 2000年：10V可编程约瑟夫森结阵制作成功
- 2019年：4V脉冲驱动型任意波约瑟夫森电压标准研制成功

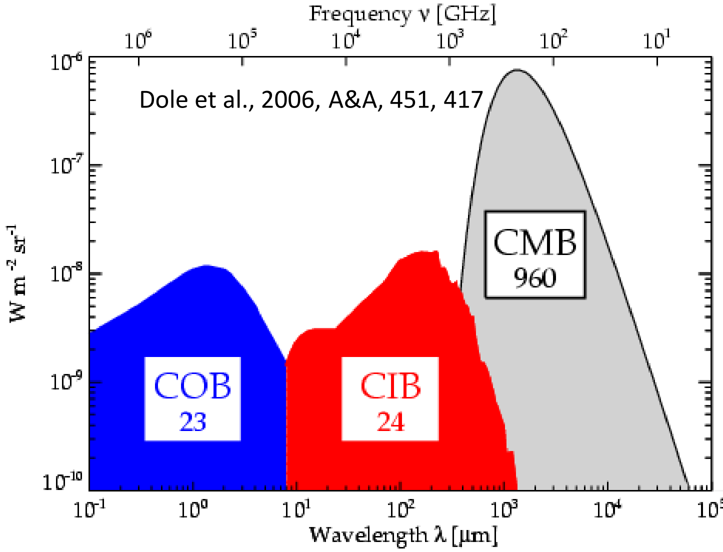


Provided by Wenhui Cao

# Terahertz Astronomy



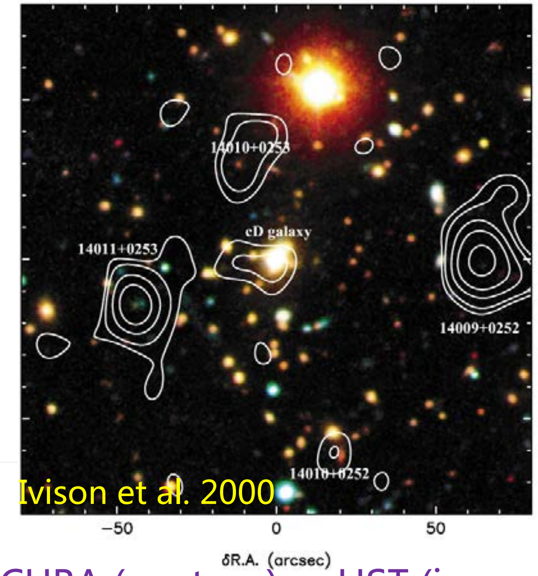

Observation at THz/FIR band -- probing cold universe: colder (information), earlier, dust-obscured objects, more spectral-line probes



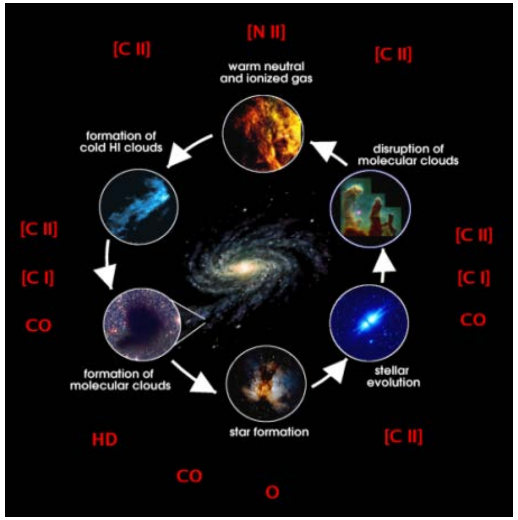

Stellar light

Stellar light absorbed & reemitted by dust

Last scattering surface




SCUBA (contour) vs HST (image)
"Dark" submm sources w/o optical IDs



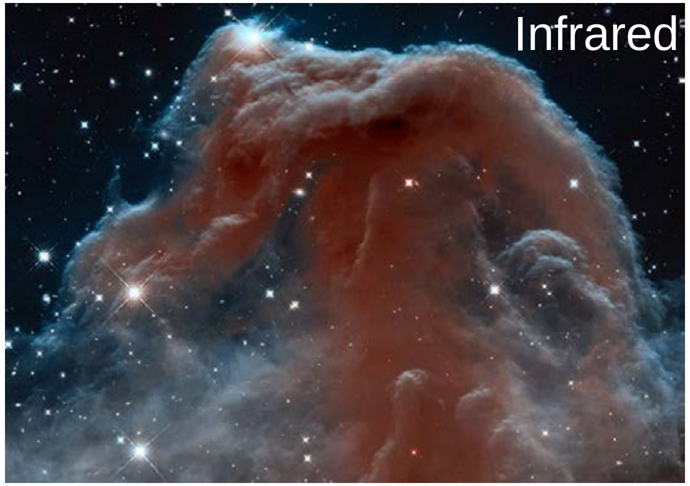

THz molecular & atomic lines ( "fingerprints" )

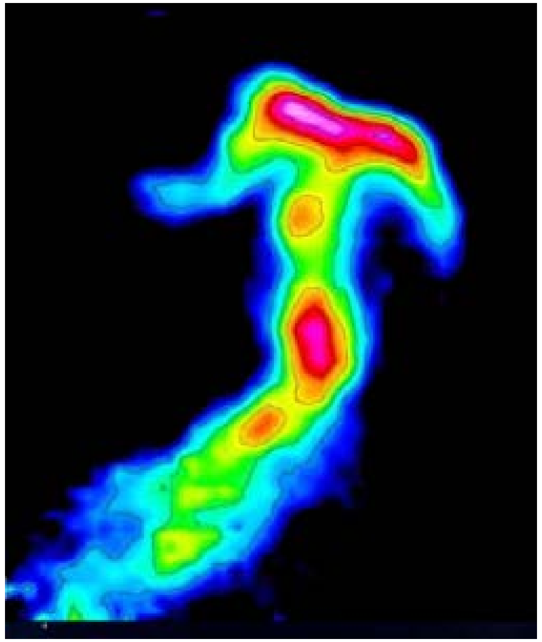
Provided by Jing Li

Credit: Dole/Ivison/Walker/HERSCHEL

# Radio astronomy

Horsehead nebula

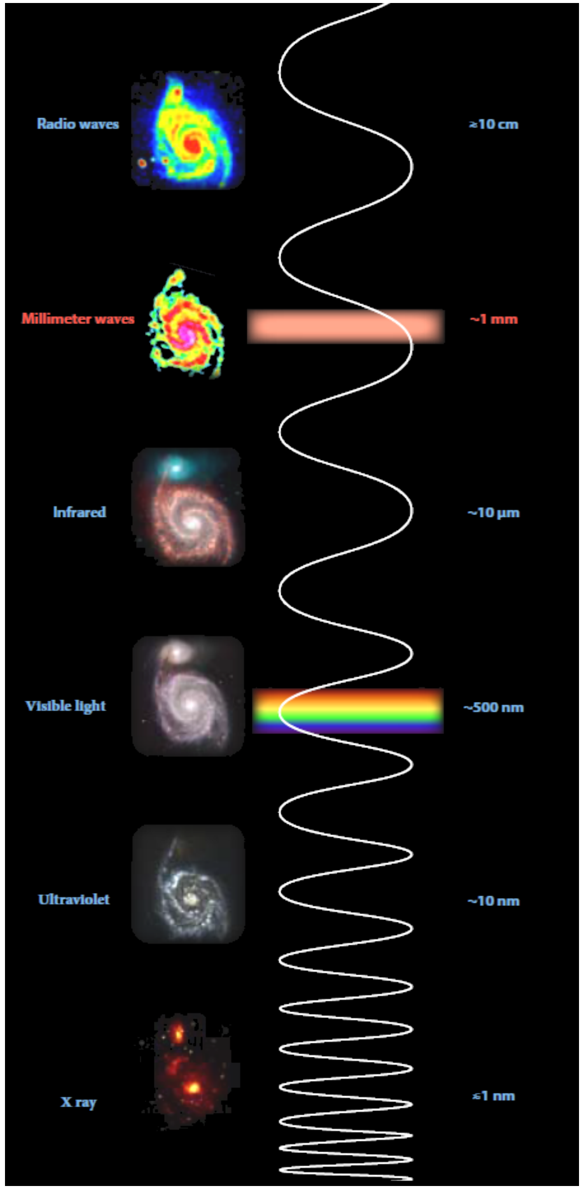



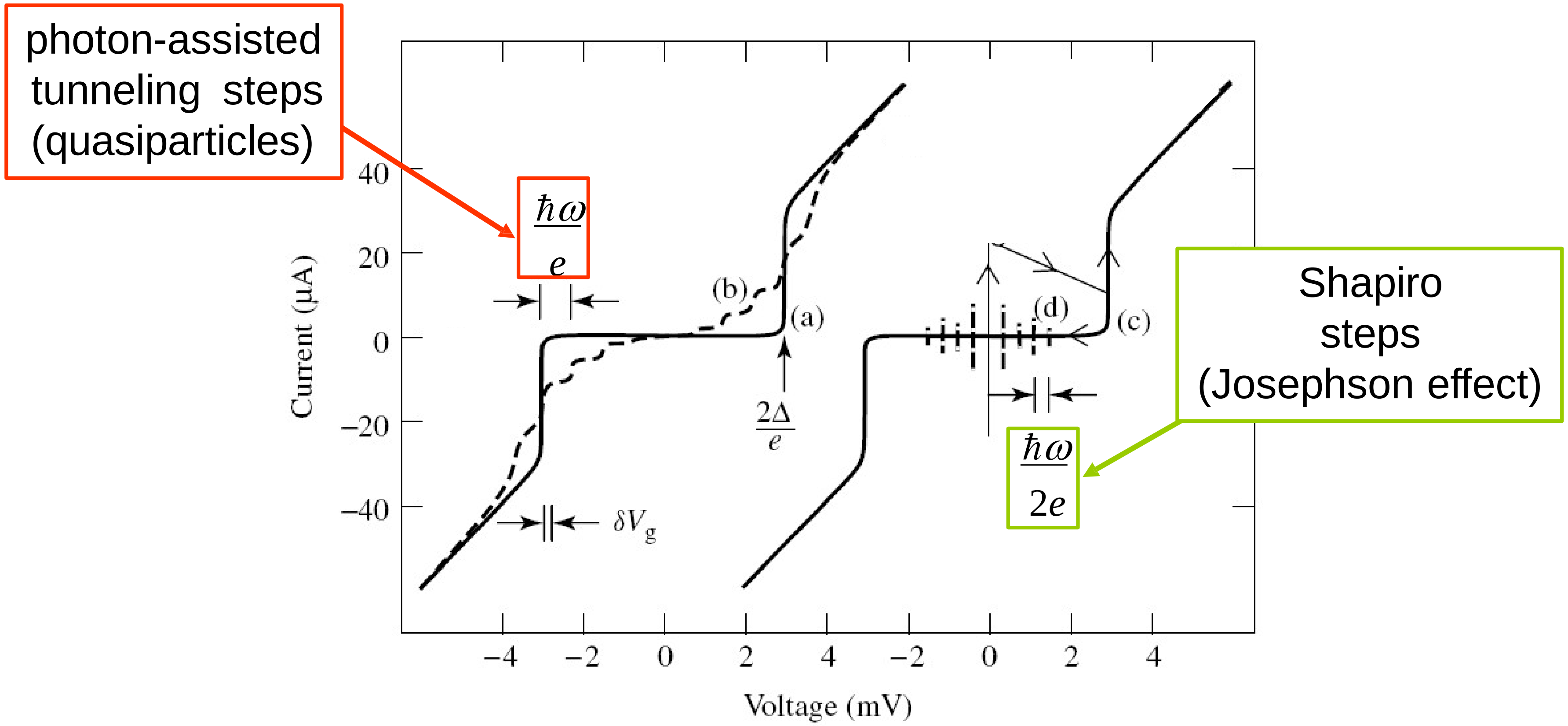
mm waves
detected by
SIS receiver

IRAM Grenoble

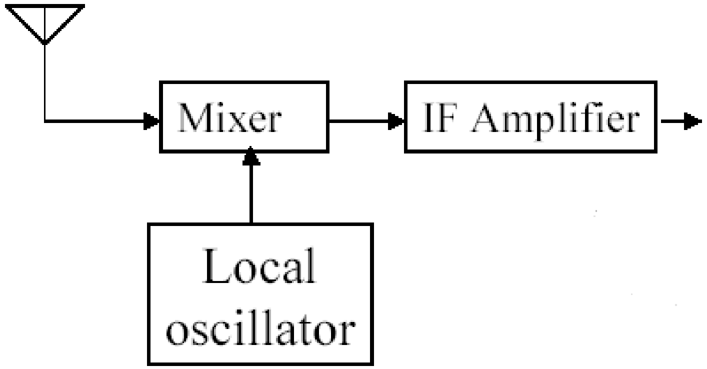
M51 Whirlpool galaxy



# Josephson tunnel junctions under microwave irradiation



# THz receiver based on superconducting tunneling junction

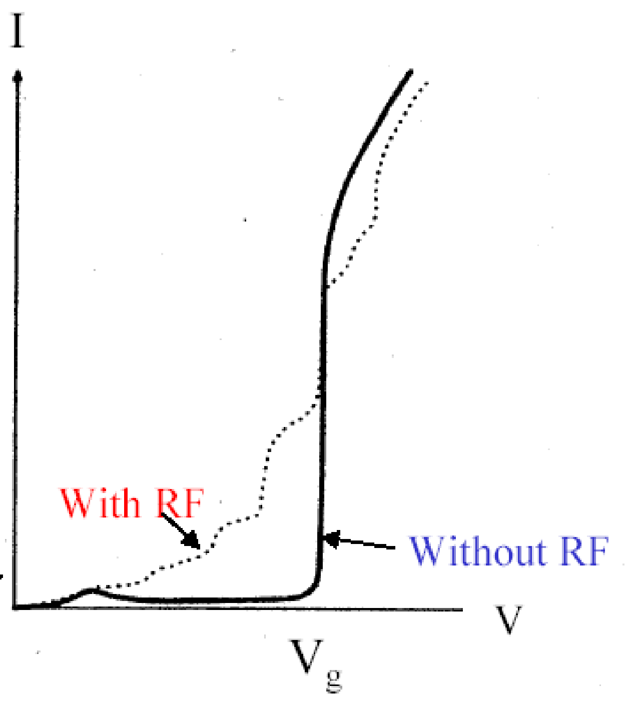



Receiver noise temperature

$$T_R = T_{mixer} + T_{IF}/G_{mixer}$$

- **Low mixer noise $T_{mixer}$**
- **Conversion gain G**

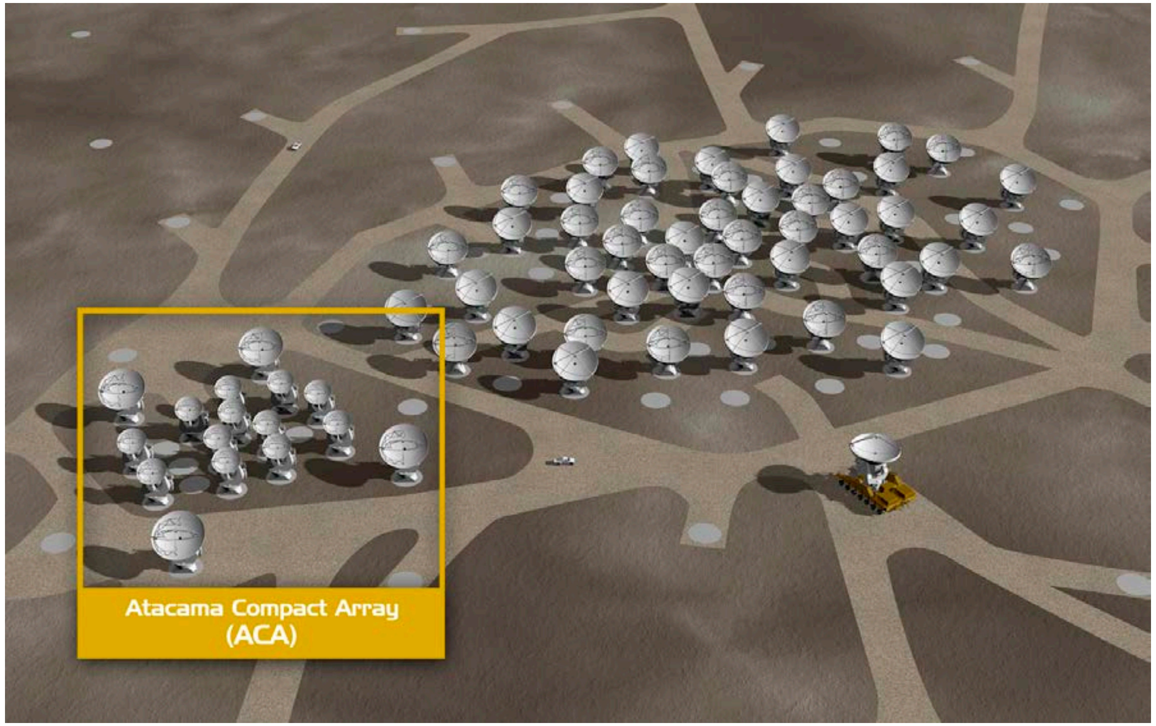
Josephson pair current is suppressed by magnetic field




SIS混频器噪声：可接近量子极限（$T_{min}=h\nu/k_b$）（$h$是普朗克常数，$\nu$是工作频率，$k_b$是波尔兹曼常数）。一般是2到10倍的量子极限。
如：加州理工大学，铌钛氮薄膜构成调谐电路，噪声温度仅为205 K@0.8 THz，5倍的量子噪声温度极限。

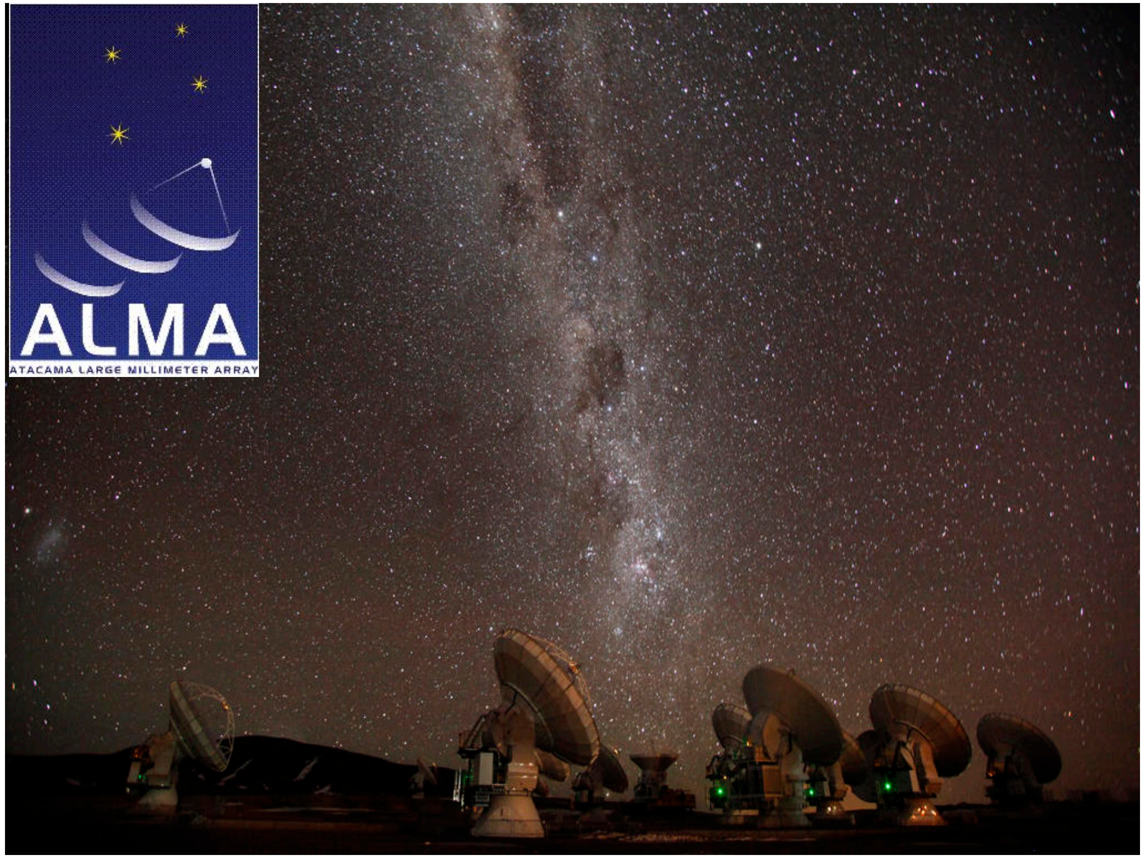
# Atacama Large Millimeter / submillimeter Array

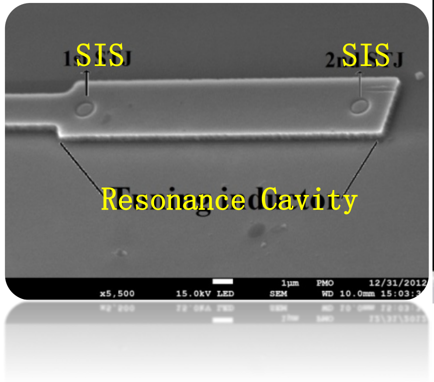
ALMA
Atacama Large Millimeter/submillimeter Array

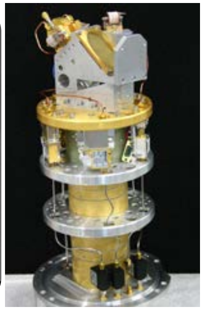



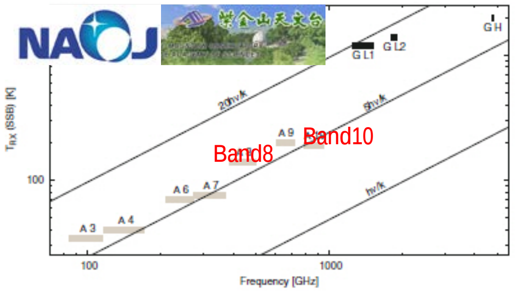

Pics from internet

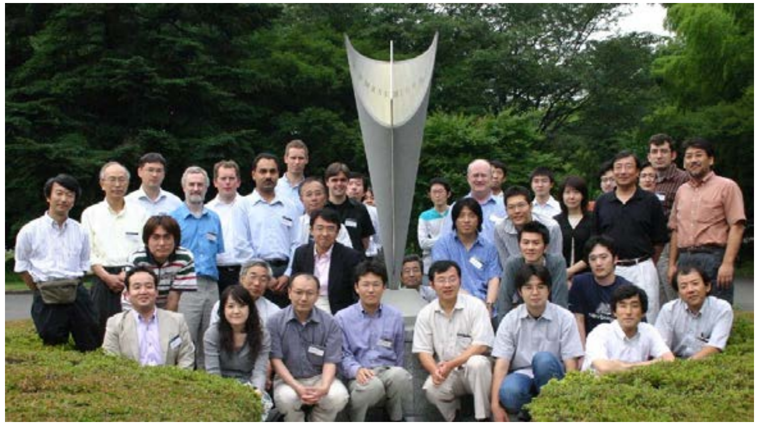
# Superconducting SIS mixers for ALMA



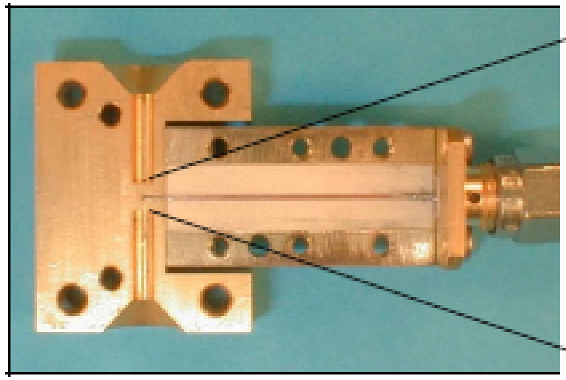



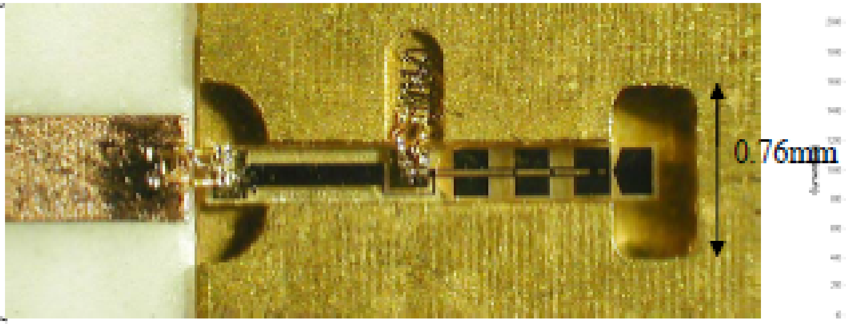


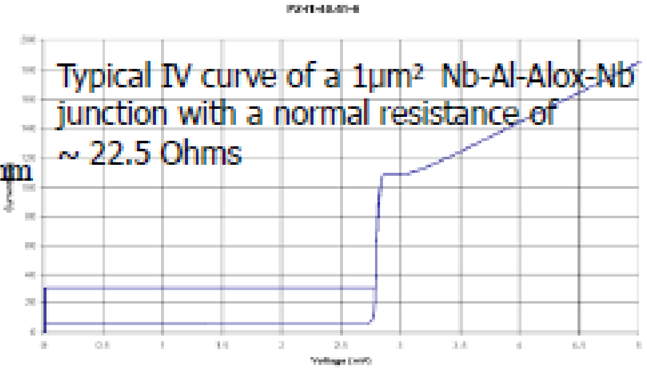
# B7 Cartridge Sideband Separating Mixer



Double Side Band mixer (DSB) with its IF circuit

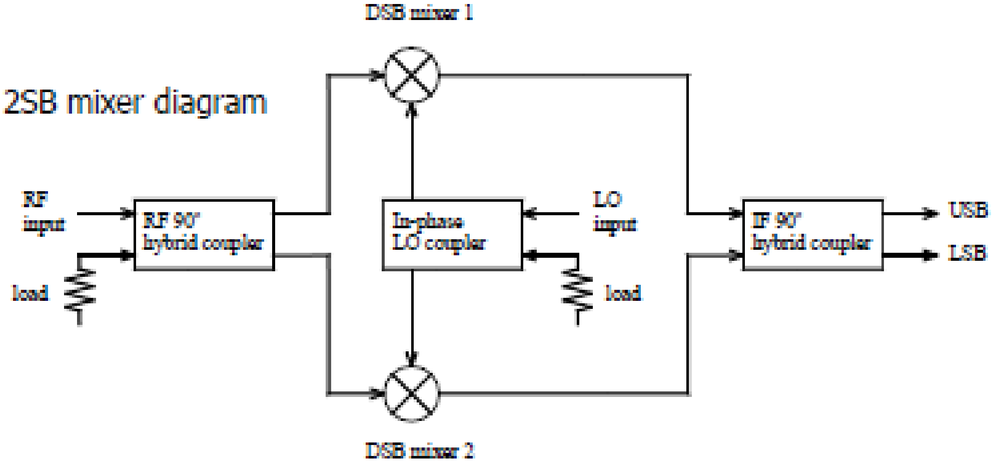


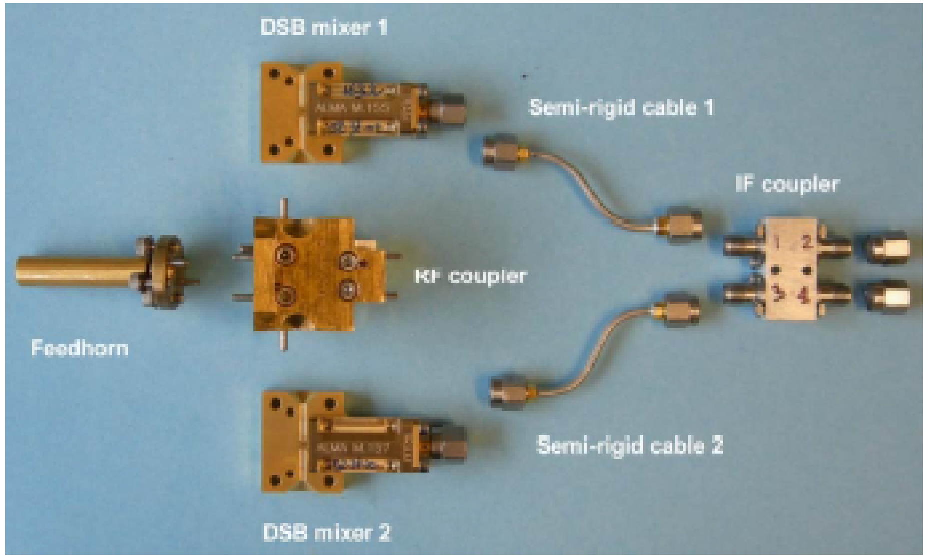

Close view of the mixer chip mounted on 80 µm thick quartz



Typical IV curve of a 1µm² Nb-Al-Alox-Nb junction with a normal resistance of ~ 22.5 Ohms

2SB mixer diagram



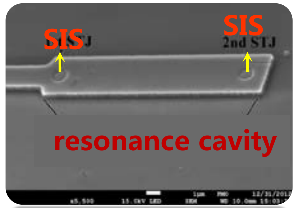



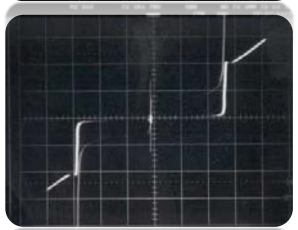


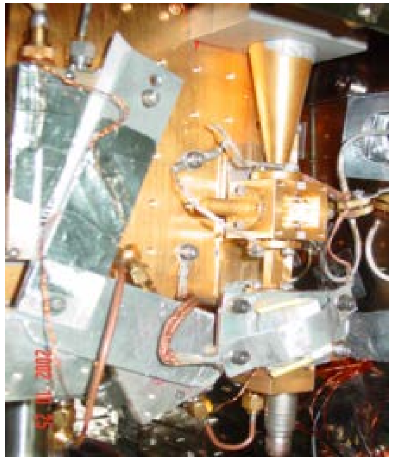

IRAM Grenoble

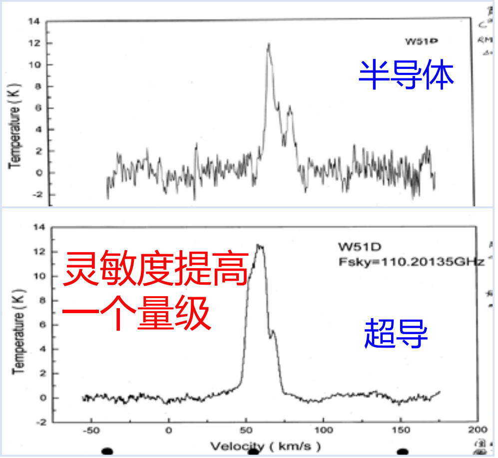
# 超导SIS隧道结混频器与我国毫米波亚毫米波射电天文的发展

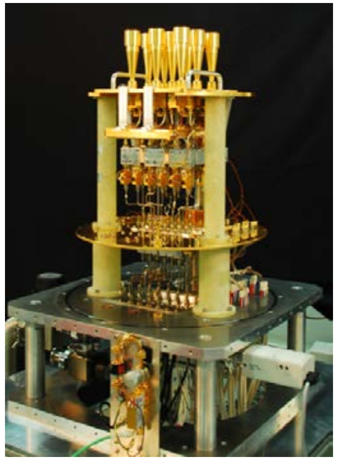
- 1982年开始建设我国第一台毫米波望远镜（13.7米，青海德令哈）
- 1995年运行3毫米波段肖特基混频接收机
- 1998年研制成功并运行我国首台毫米波超导接收机，望远镜灵敏度提升一个量级，自此我国射电天文拥有国际先进的超导探测器
- 2002年扩展成多谱线接收机
- 2010年研制成功并运行我国首台毫米波多波束接收机（财政部仪器专项），望远镜综合性能提升20倍，处于国际前沿







Provided by Jing Li

# Herschel and Planck launched with Ariane-5, May 2009


2400 liters of liquid helium

# Mixer Technology Baseline

| mixer band | frequency range | mixer element | matching circuit | feed and coupling structure |
|---|---|---|---|---|
| 1 | 480 – 640 GHz | SIS $Nb\text{-}Al_2O_3\text{-}Nb$ | Nb on Nb microstrip | corrugated horn and waveguide |
| 2 | 640 – 800 GHz | SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$ | Al on NbTiN microstrip | corrugated horn and waveguide |
| 3 | 800 – 960 GHz | SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$ | Al on NbTiN microstrip | corrugated horn and waveguide |
| 4 | 960 – 1120 GHz | SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$ | Al on NbTiN microstrip | corrugated horn and waveguide |
| 5 | 1120 – 1250 GHz | SIS NbTiN-AlN-NbTi | Al on NbTiN microstrip | lens and twin slot planar antenna |
| 6L | 1410 – 1703 GHz | HEB NbN phonon cooled | Al co-planar waveguide | lens and twin slot planar antenna |
| 6H | 1703 – 1910 GHz | HEB Nb diffusion cooled | Al co-planar waveguide | lens and twin slot planar antenna |

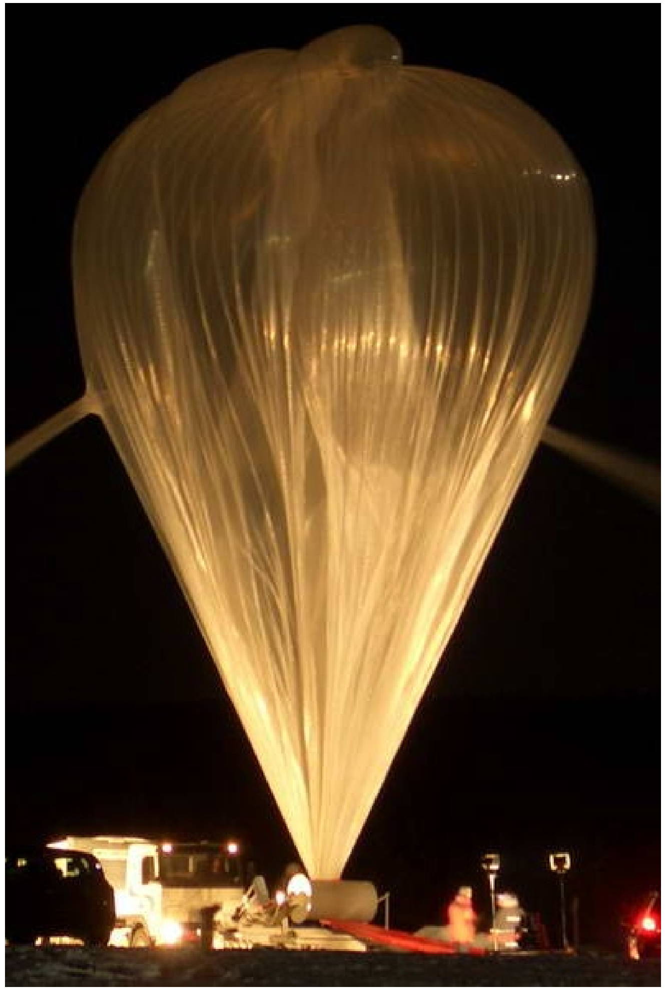
SIS = Superconductor-Insulator-Superconductor tunnel junction

HEB = Hot Electron Bolometer (fast, $\tau$ < ~16 ps)



Courtesy of Nick Whyborn

# SIR THz limb sounder



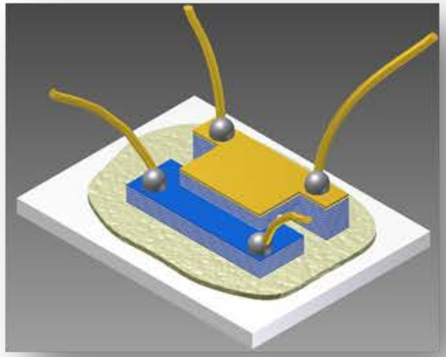
40 km altitude
(490~630 GHz， Nb FFO)

THz limb sounder of the earth's upper atmosphere
ClO, BrO, $O_3$, HCl…

Frequency limited by gap energy or highest Josephson voltage

# Compact high-Tc superconducting terahertz emitters


BiSrCaCuO-2212



# Tunable THz sources needed urgently

Can Josephson emitters pump a superconducting detector/mixer?

| | |
|---|---|
| Quantum cascade lasers | Pulse mode : 1.01W<br>Frequency: 0.68THz-3.33THz<br>(tunable under magnetic field) |
| Resonant tunneling diodes | CW mode: a few hundred μW<br>Frequency : up to 1.9THz<br>(19% of center frequency) |
| Josephson emitters | CW mode: a few hundred μW<br>Frequency: 0.3-2THz |

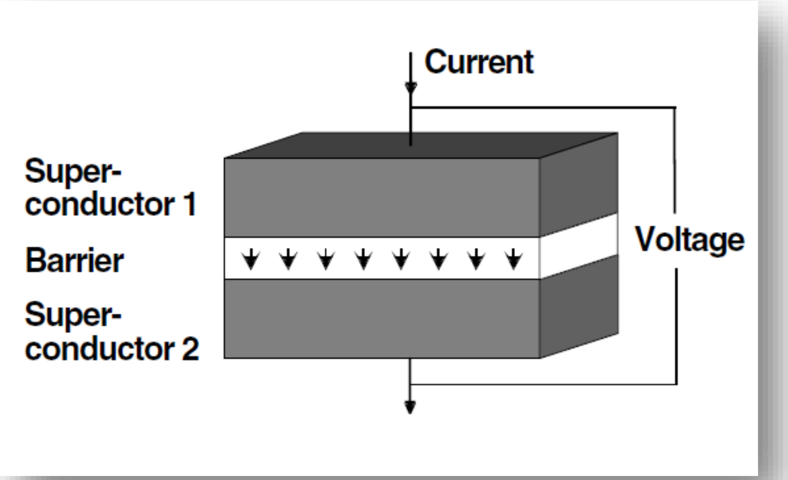
# Josephson Emitters

*Josephson oscillation*

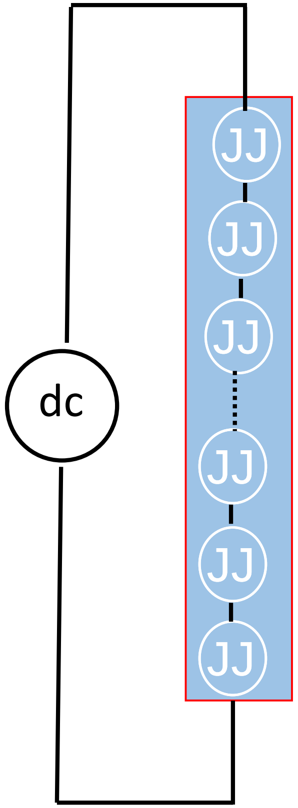
$$f = V/\Phi_0$$

1 mV $\leftrightarrow$ 0.483 THz

*Josephson junction*




Power from a single junction: 1 pW

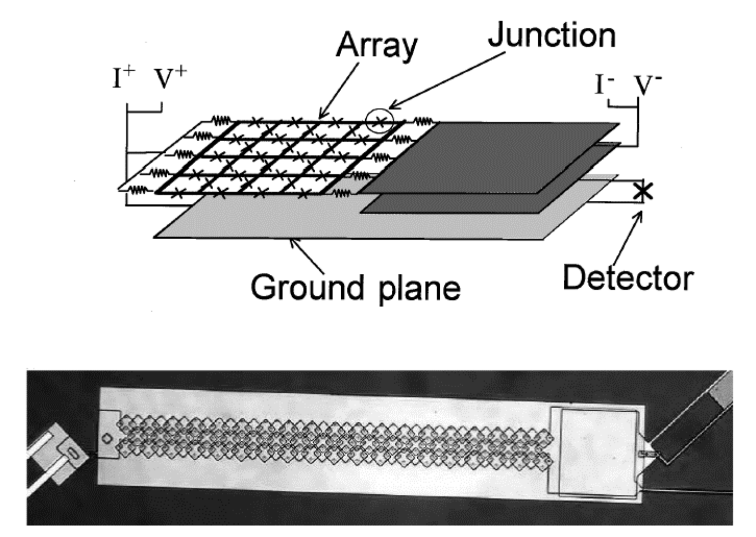



*N* coherent junctions

emission power: $P=P_0 \times N^2$

emission linewidth: $\Delta f = \Delta f_0 / N$

*Artificial Josephson junction array*




$P \propto N^2$

Power from an array: 100 μW

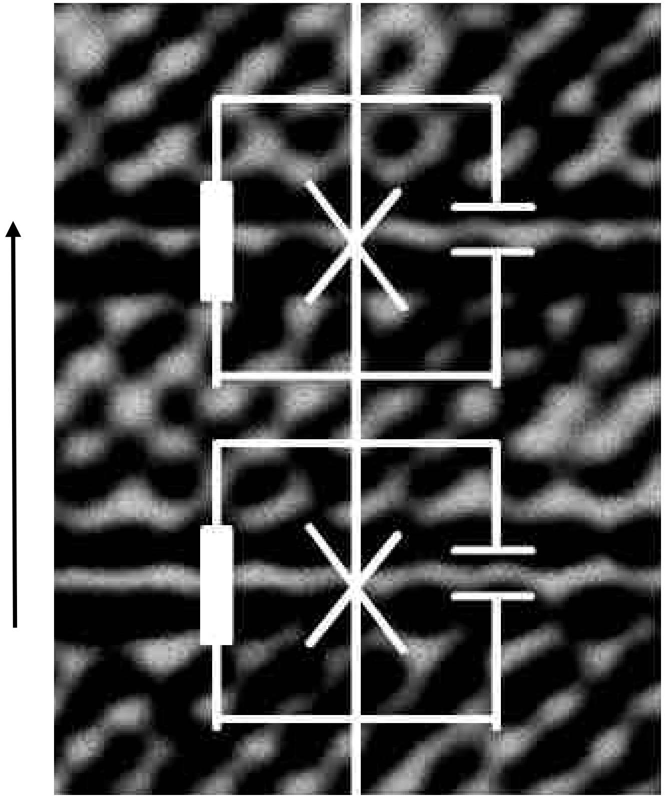
W. Buckel and R. Kleiner, Superconductivity. Wiley (2004)
P. Barbara *et al.*, *Phys. Rev. Lett.* 82, 1986 (1999)

# Intrinsic Josephson Junctions (IJJs) in high-Tc superconductors

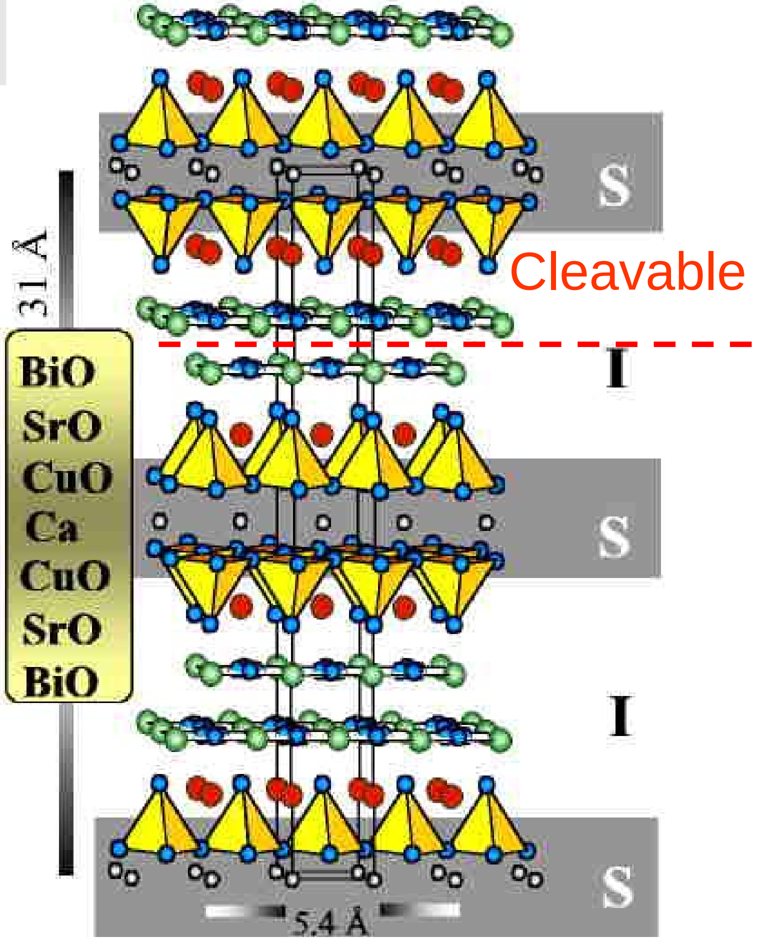
Kleiner et al., 1992

Thickness of superconducting layer: 0.3 nm
London penetration depth: 170 nm

*c*-axis

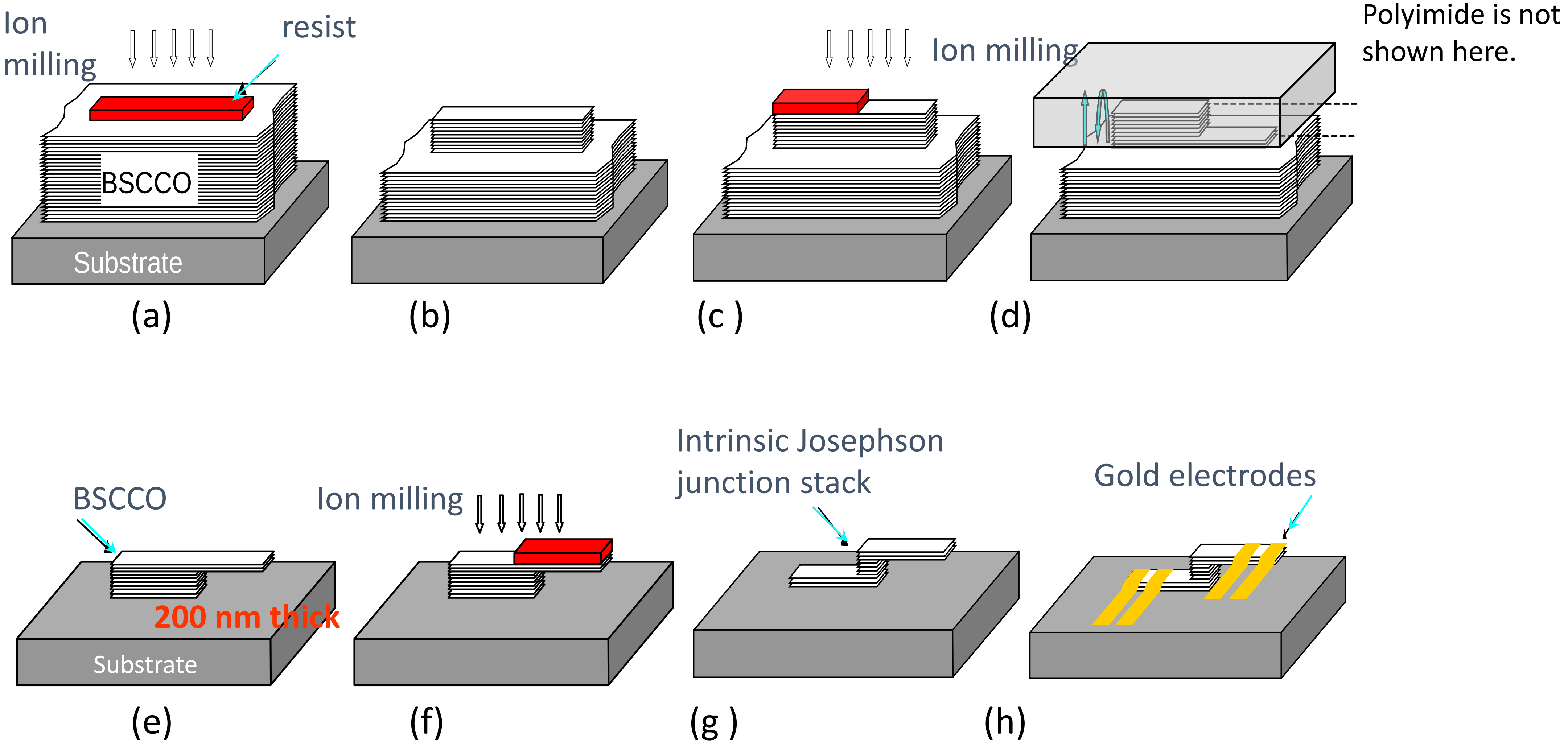


**Periodicity: 1.55 nm**




**$Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO)**

# A schematic description of the major steps involved in the double-sided fabrication process

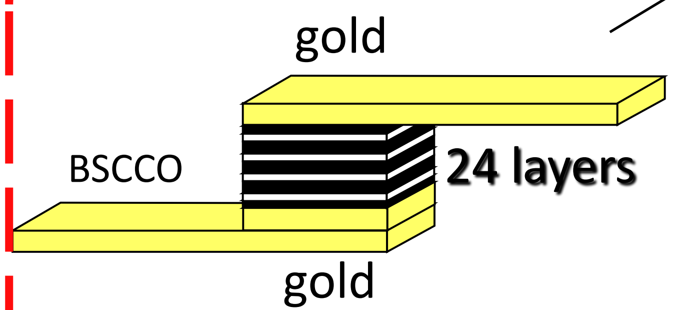





*Wang et al., Appl. Phys. Lett.*, 78(25), 4010 (2001).

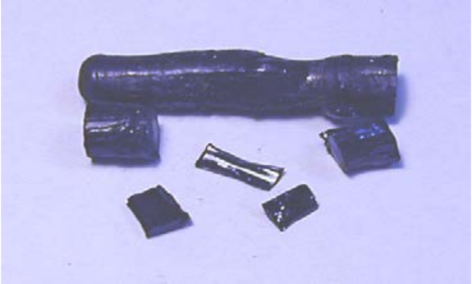
# Double-sided fabrication

Insular structure



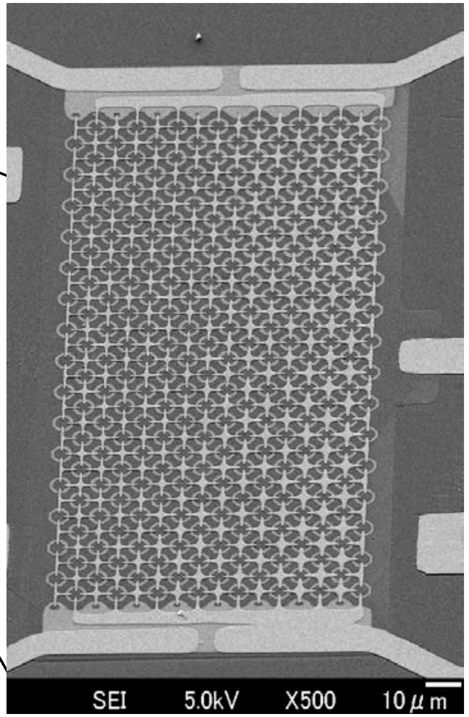

*Wang et al., IEEE Trans. on Appl. Supercond.*, 11(1), 1199 (2001).

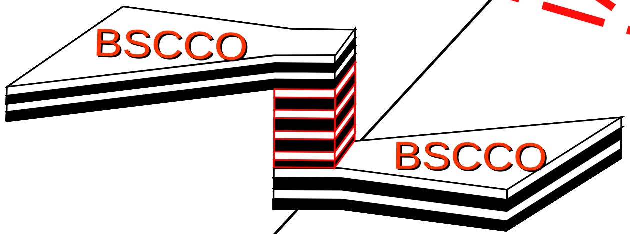
3 cm



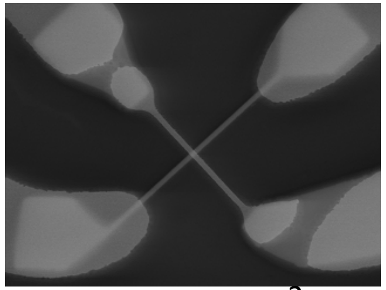
BiSrCaCuO-2212

with most powerful emission



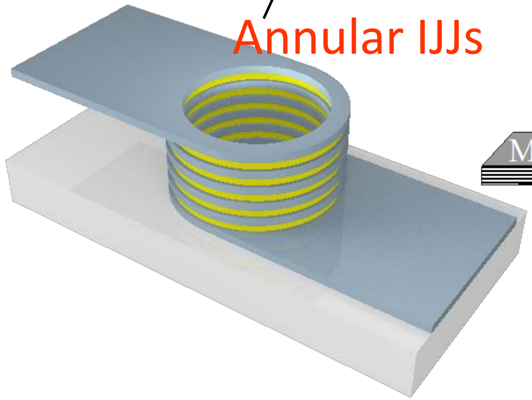



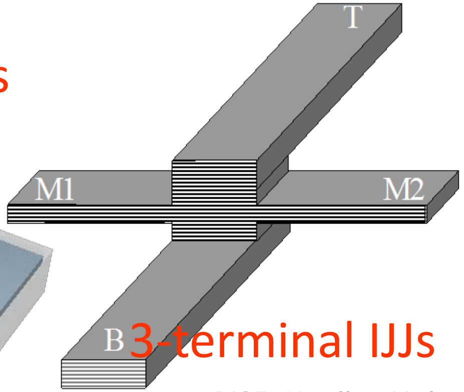

Sub-micron



$0.4 \times 0.4\ \mu m^2$

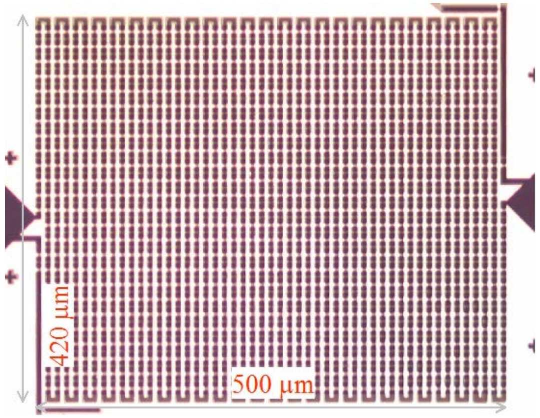
Annular IJJs





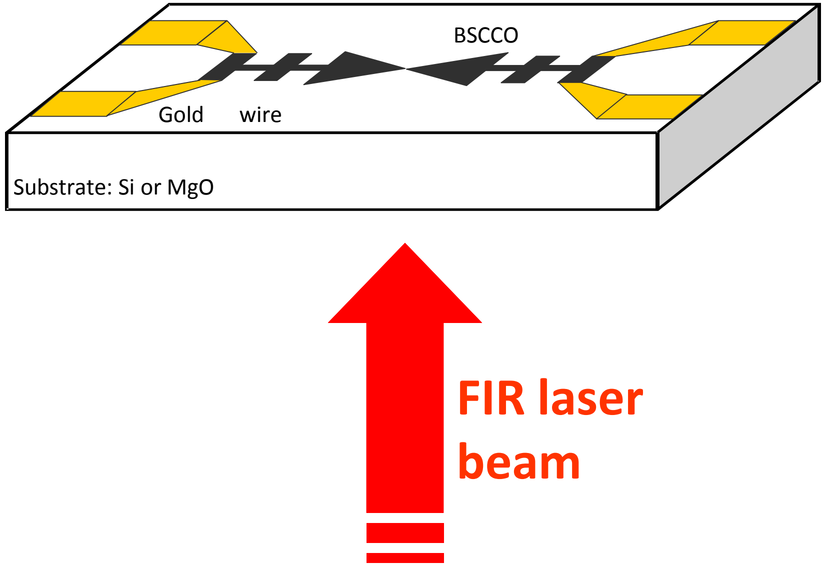

3-terminal IJJs

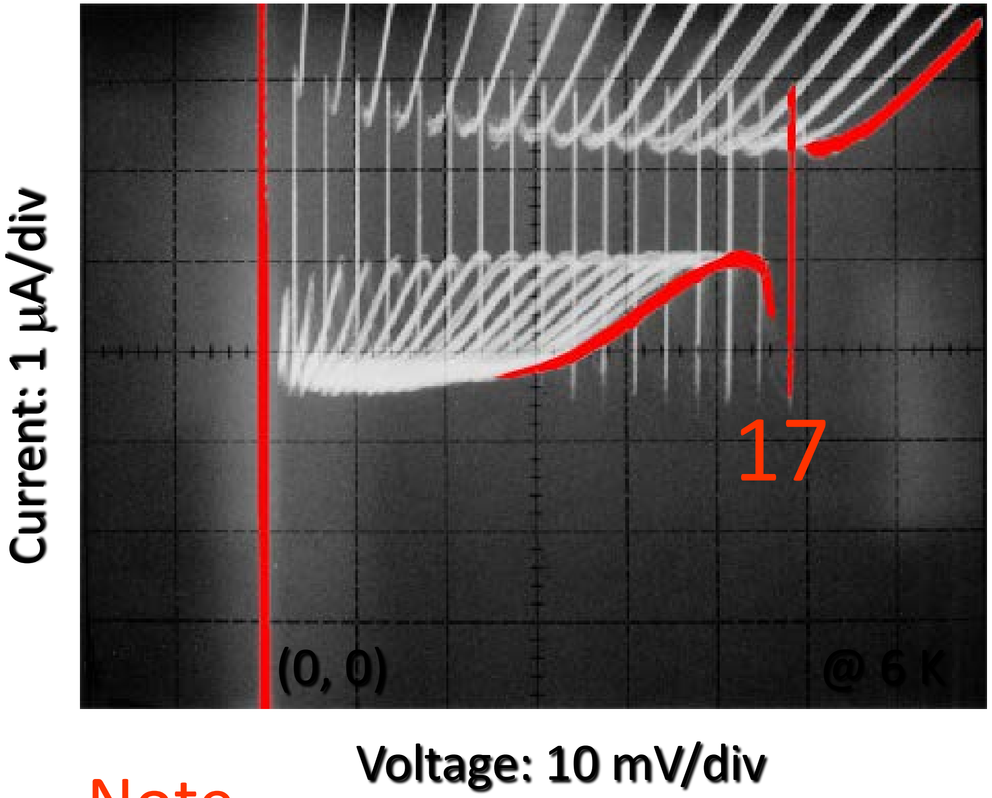
2500 stacks




RISE, Nanjing Uni.

# THz response at 1.6 THz with Shapiro steps appearing at $Nhf_{FIR}/2e$



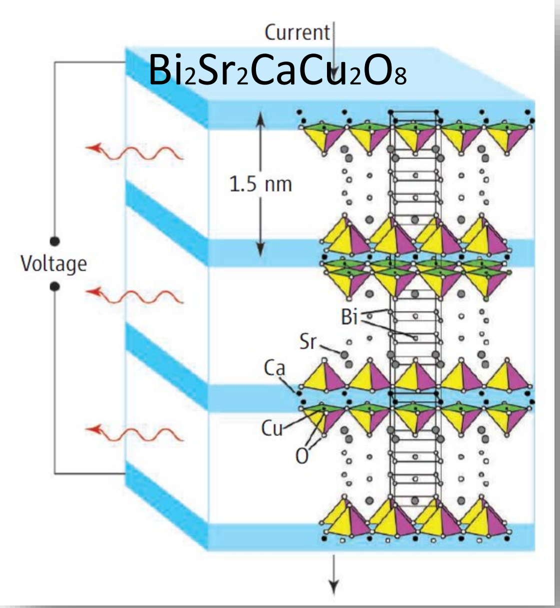




Note

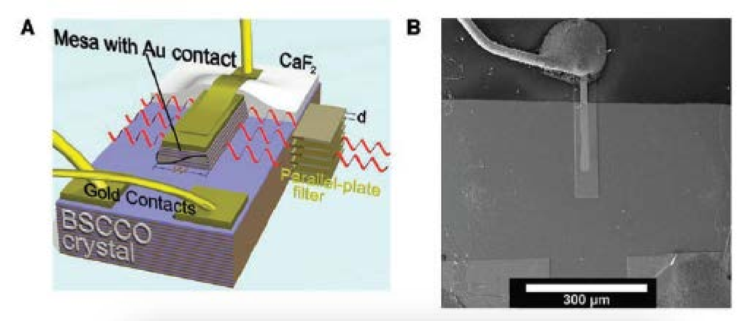
*N* is the number of junctions biased at voltage states

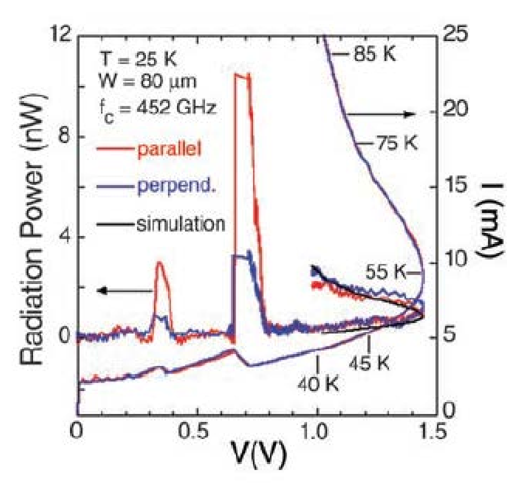
*Wang, Yamashita, and Wu, Phys. Rev. Lett.* 87, 107002 (2001).

# Intrinsic Josephson junctions (IJJs)




Coherent
CW waves



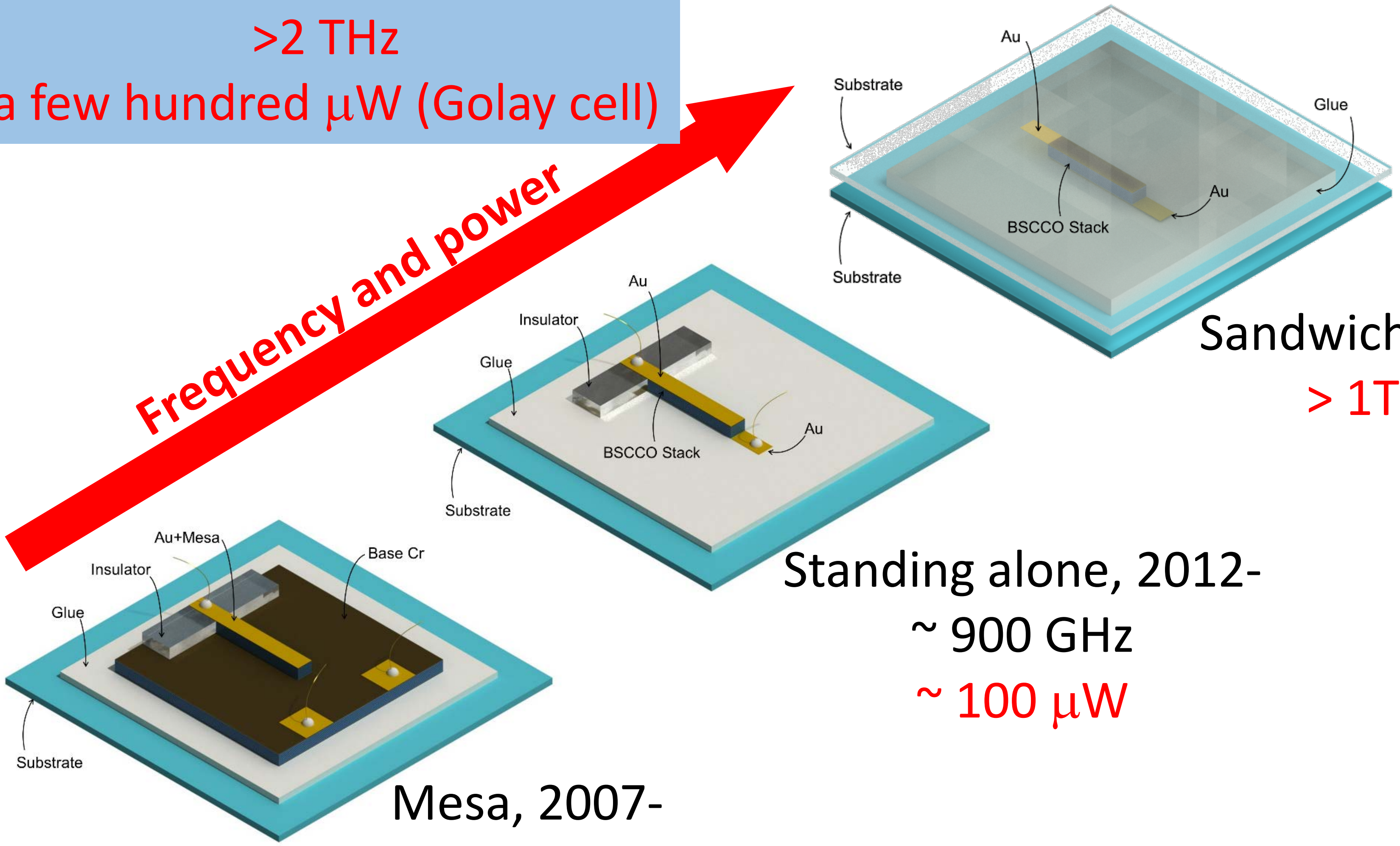




~ 300 x 50 μm²
~ 1000 junctions

L. Ozyuzer *et al.*, *Science* 318, 1291 (2007)
R. Kleiner, *Science* 318, 1254 (2007)

# Efforts to improve the performance

Sandwich, 2018
>2 THz
a few hundred μW (Golay cell)

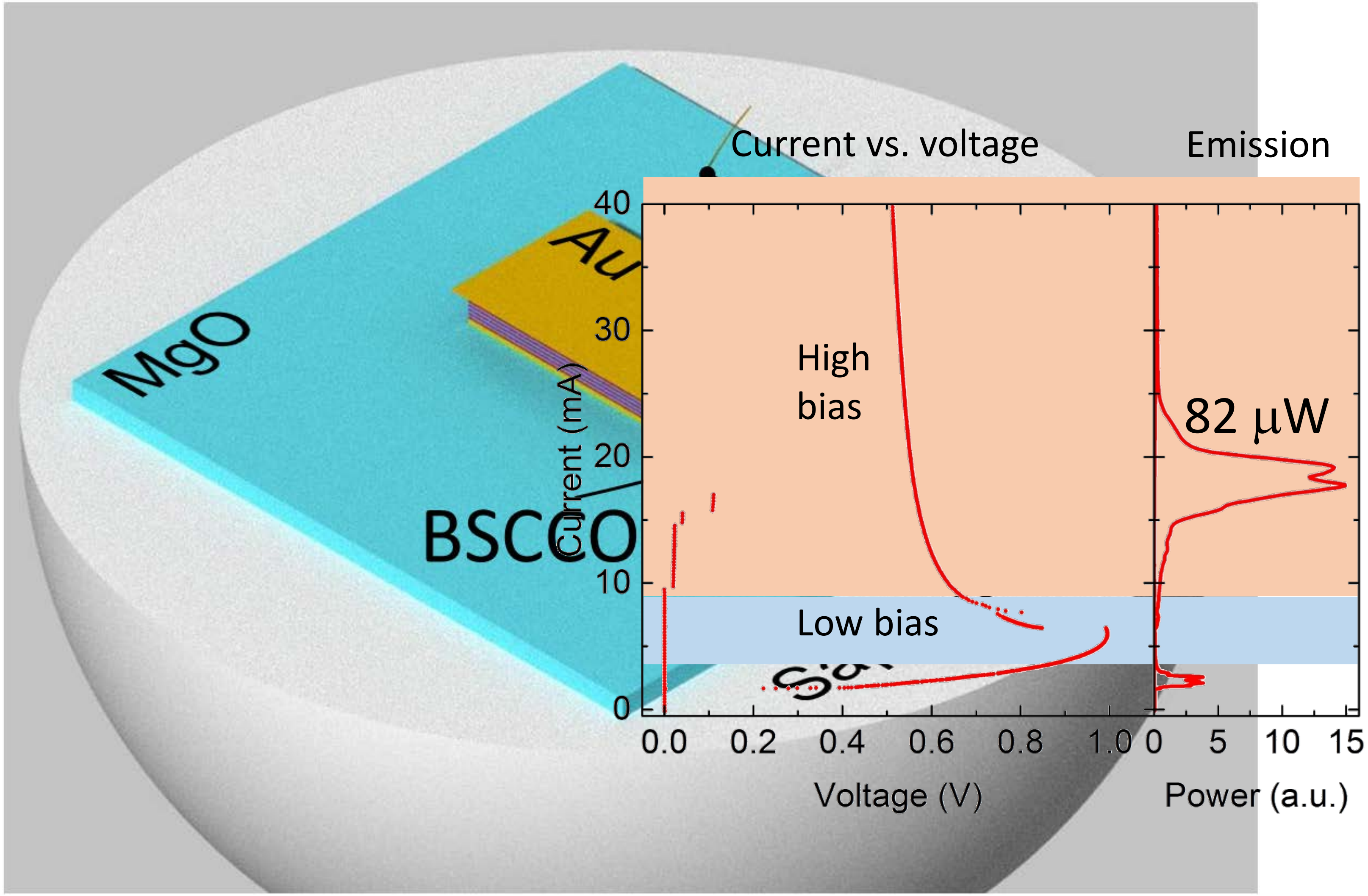



Sandwich, 2014-
> 1THz

Standing alone, 2012-
~ 900 GHz
~ 100 μW

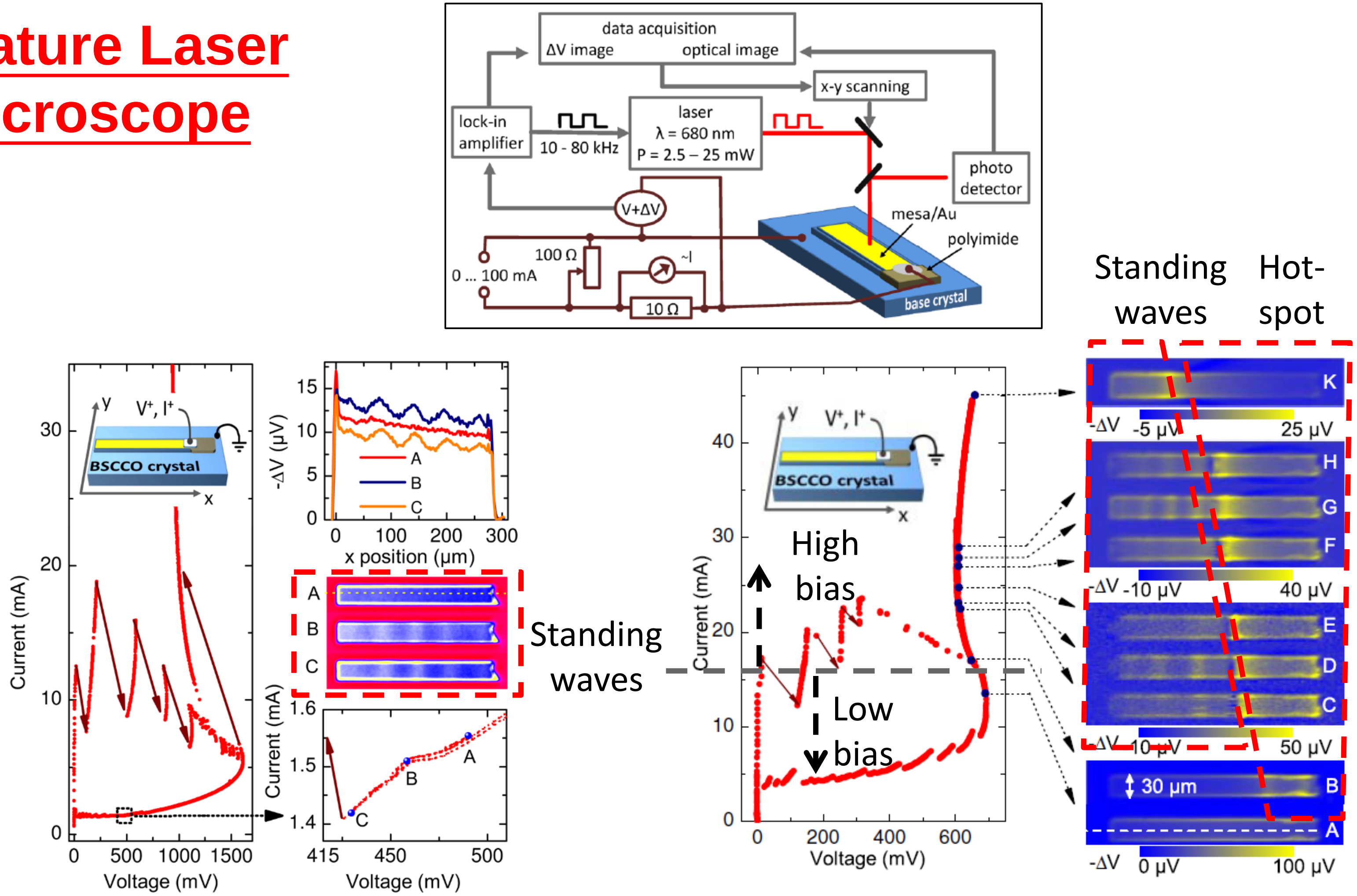
Mesa, 2007-
~ 800 GHz

# Superconductor THz emitters



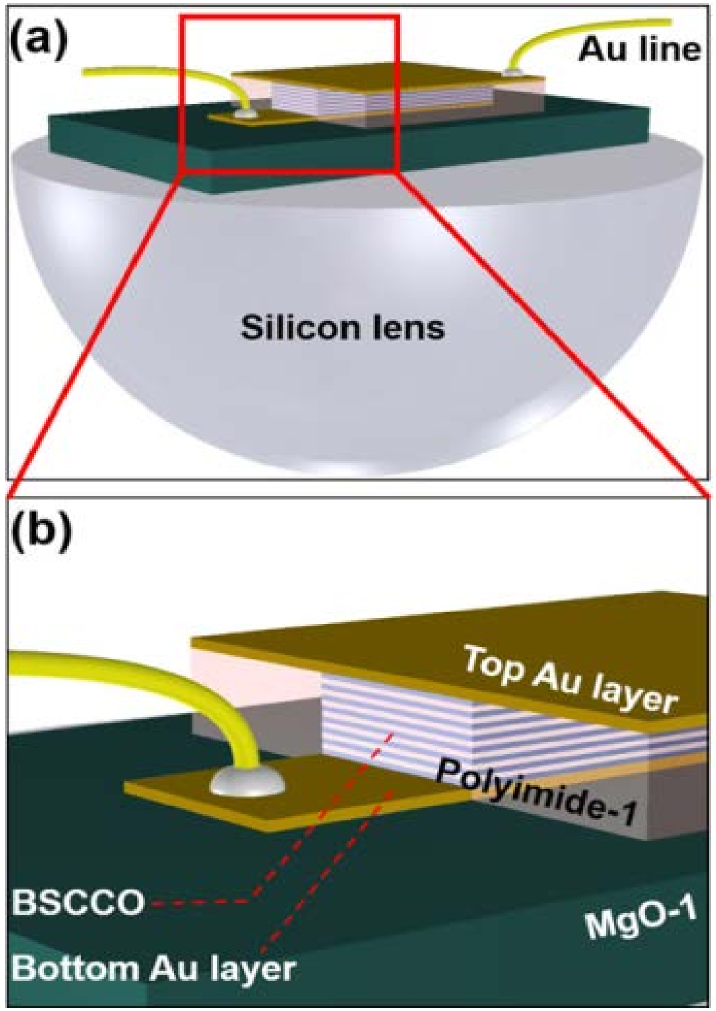
# EM standing waves and hot-spot

**Low temperature Laser Scanning Microscope**

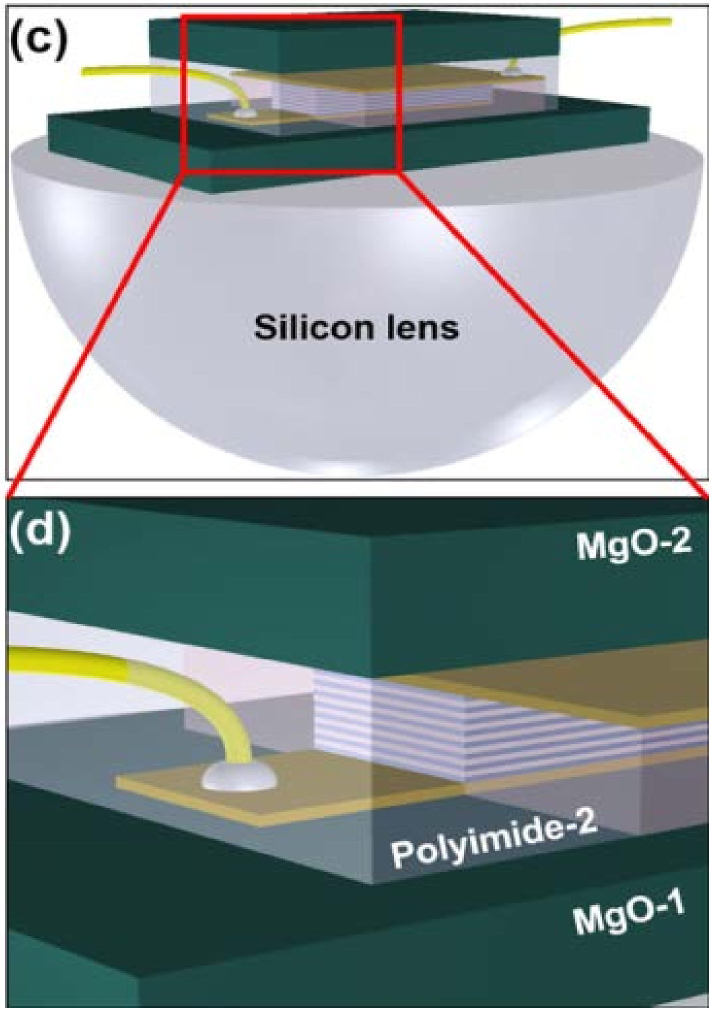



Wang et al., PRL, 2009, 2010

# Novel device structure: heat manipulation

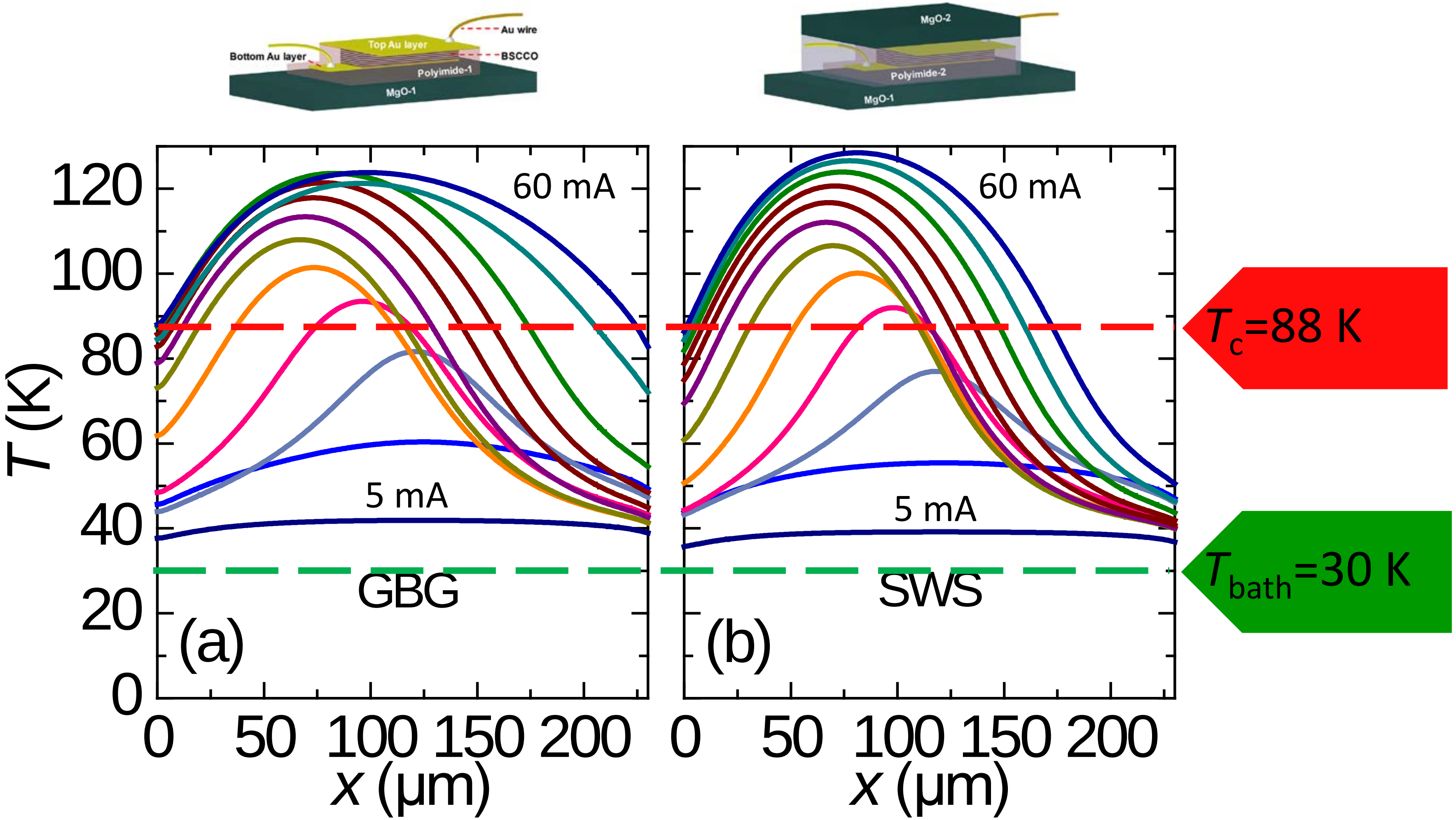



gold-BSCCO-gold (GBG)



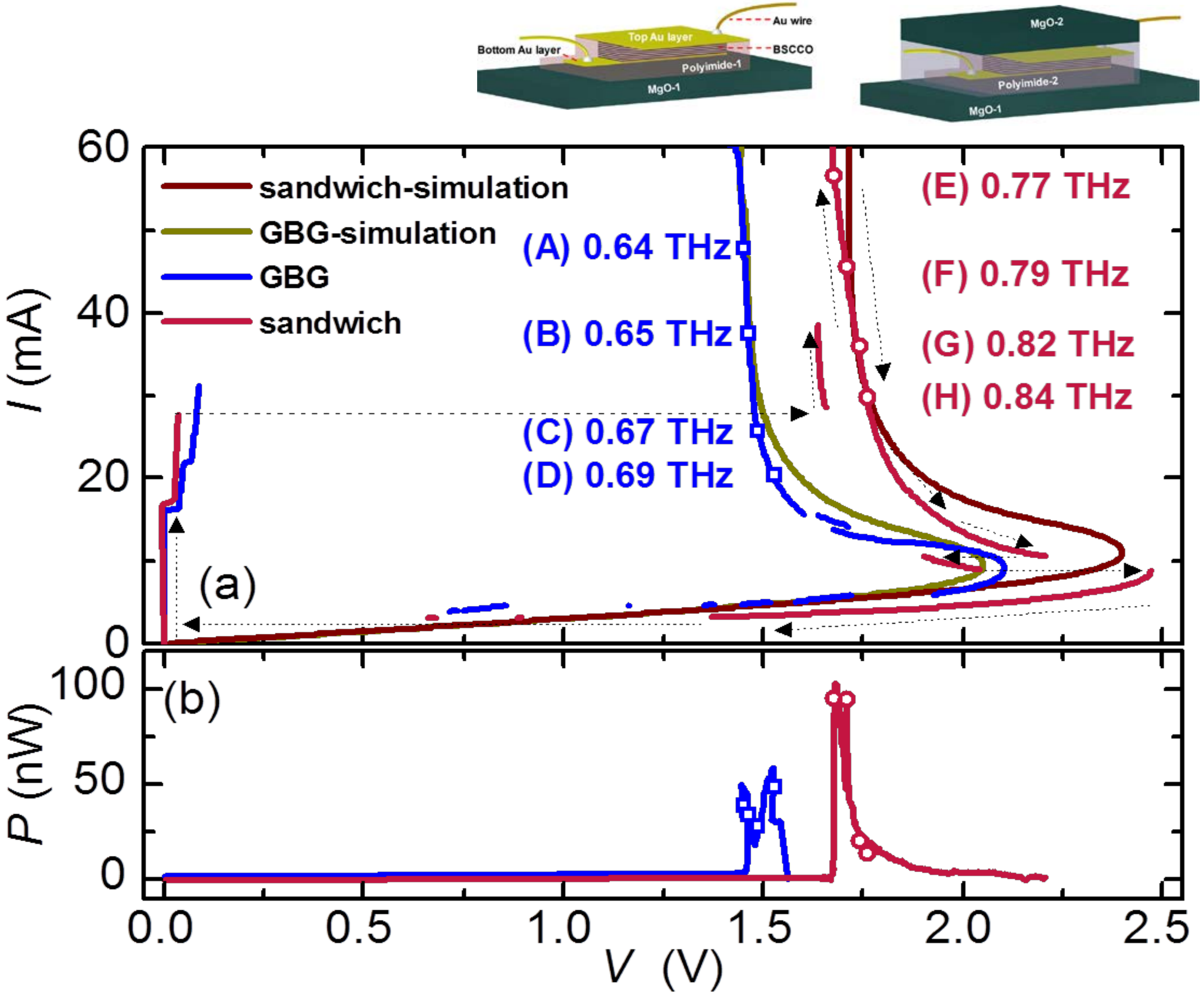

Sandwiched structure (SWS)

# Temperature distributions in GBG and SWS

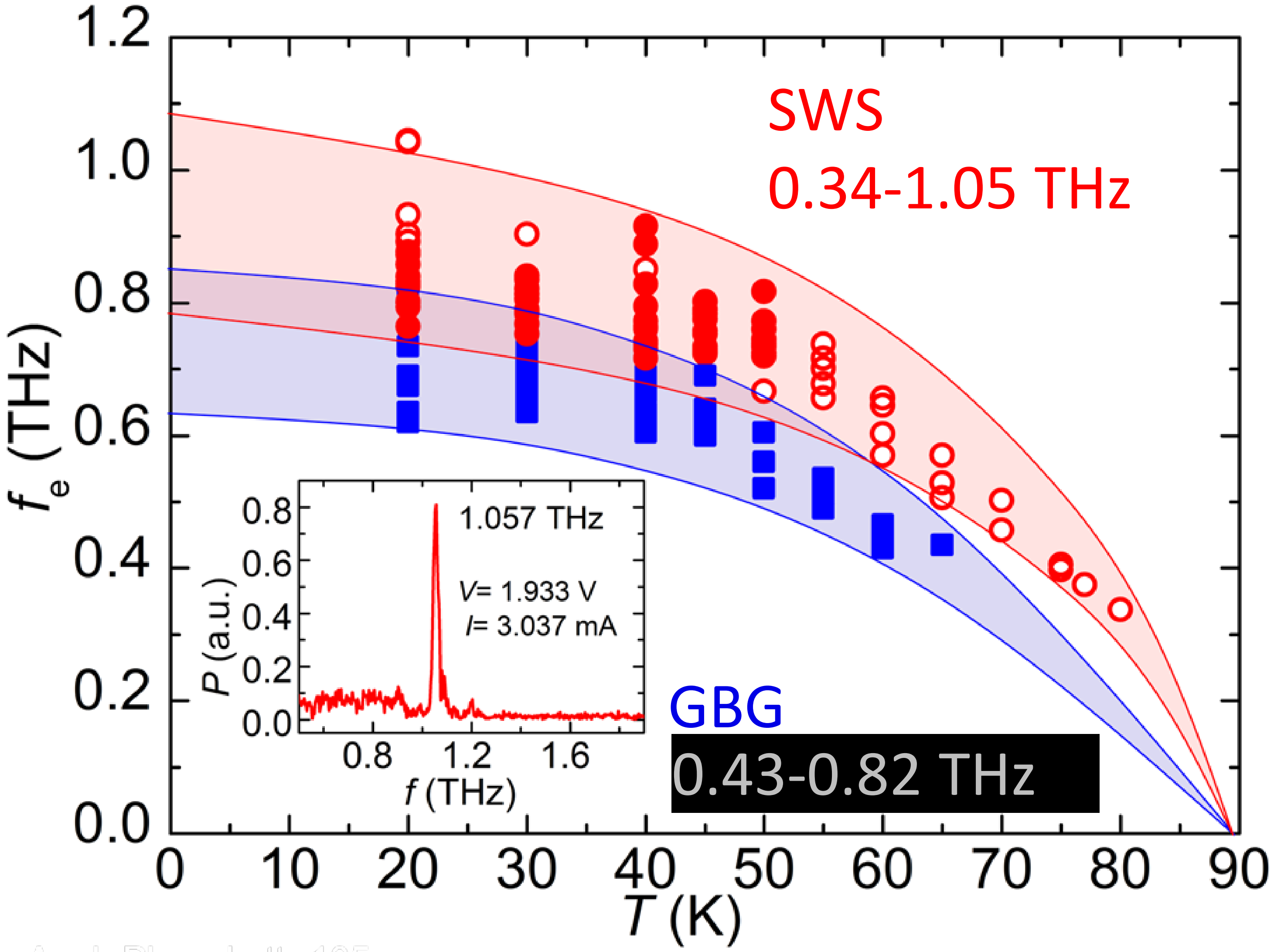



Bias currents: 5 mA to 60 mA, in steps of 5 mA.

# Remarkable difference of sample properties



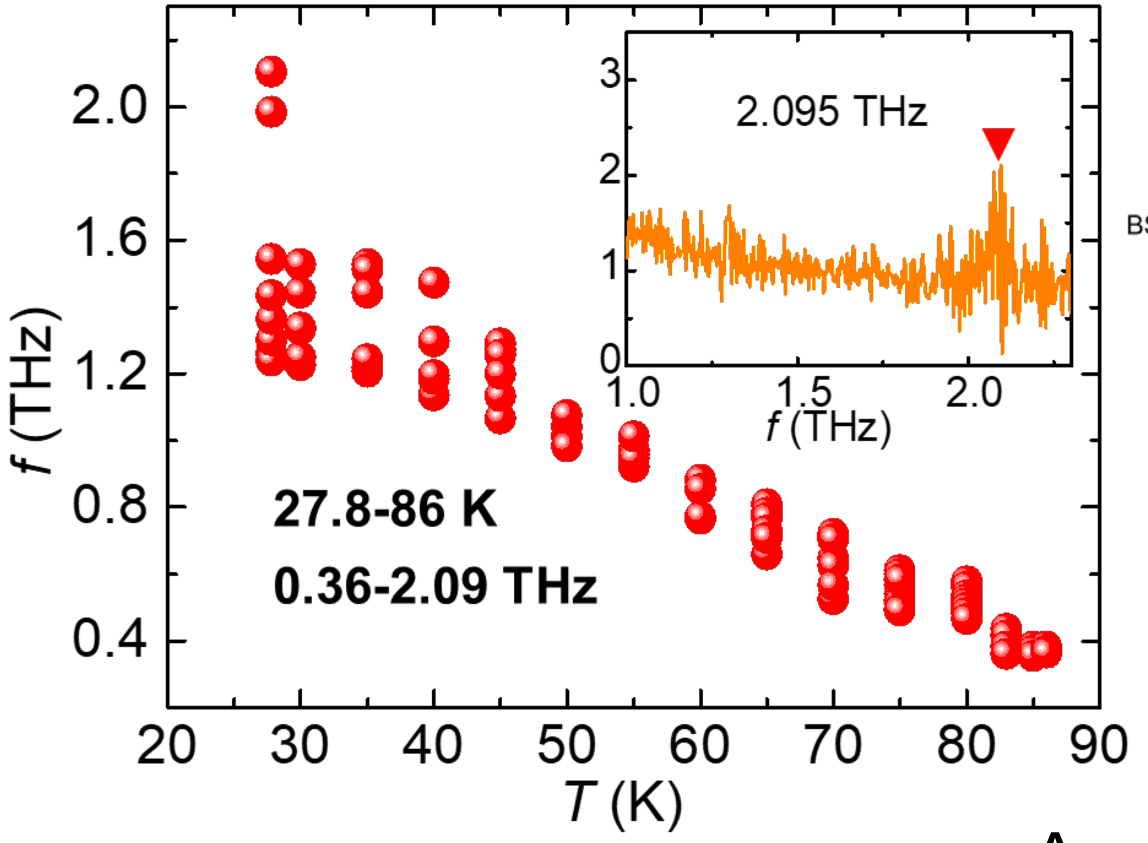
# Broad operation frequency and temperature range

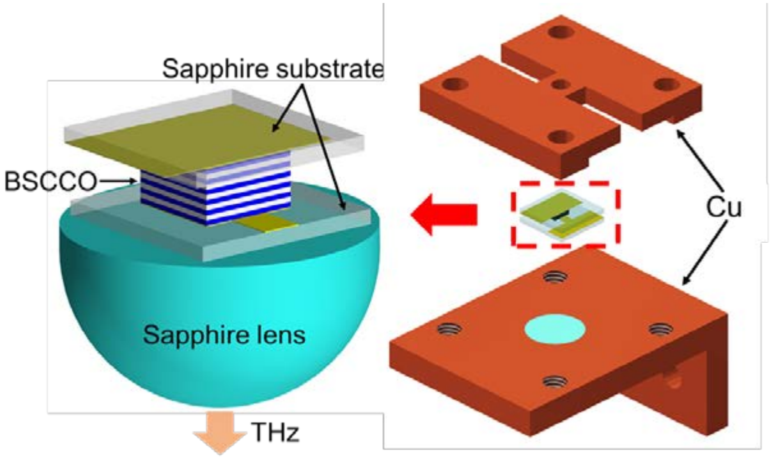



M. Ji et al., Appl. Phys. Lett. 105 , 122602 (2014)

# Emission frequency: over 2 THz

**High critical current + Sandwiched structure**



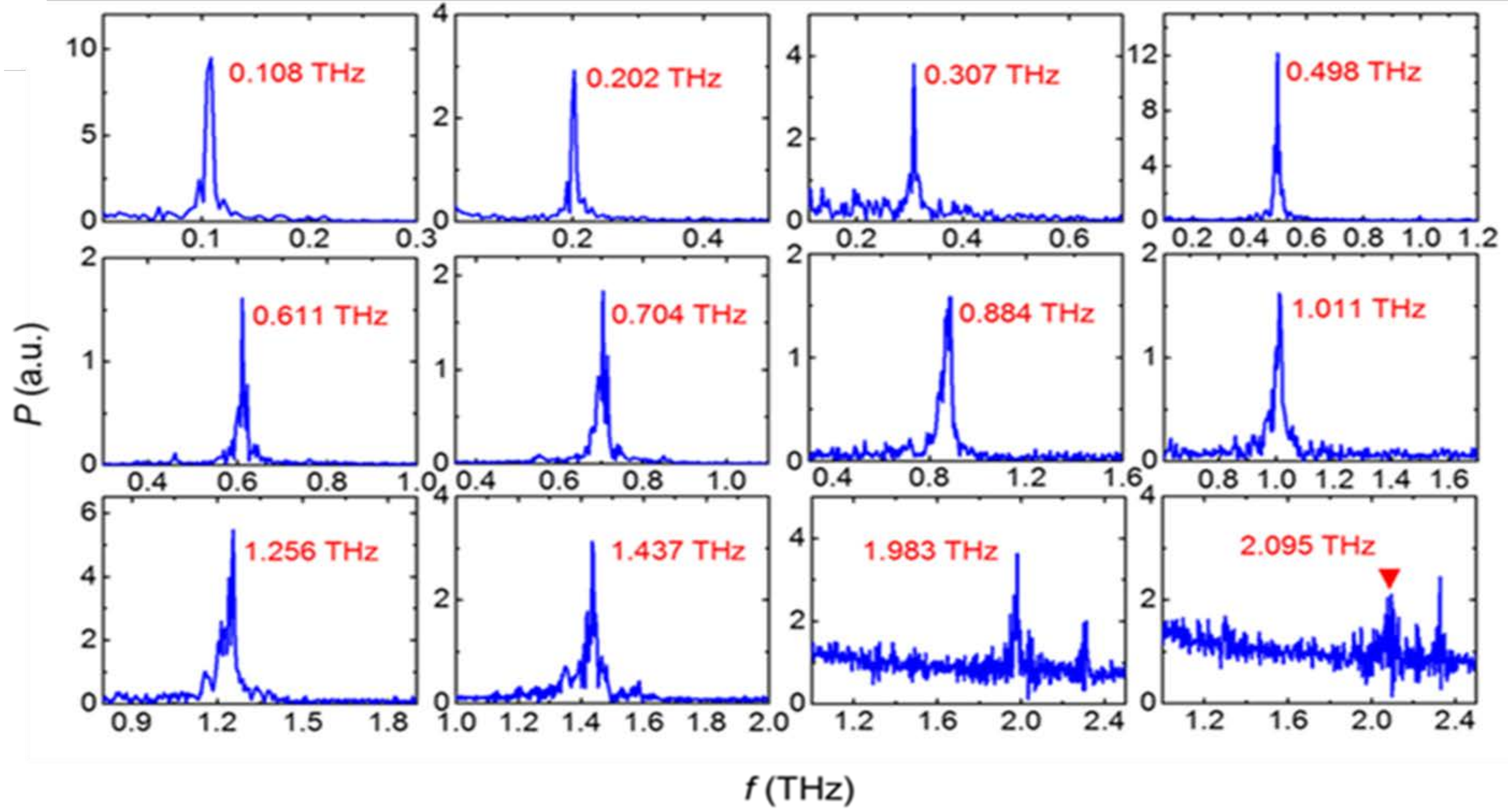

0.36 THz @ 86 K

A record high 0.576 THz @ 80 K

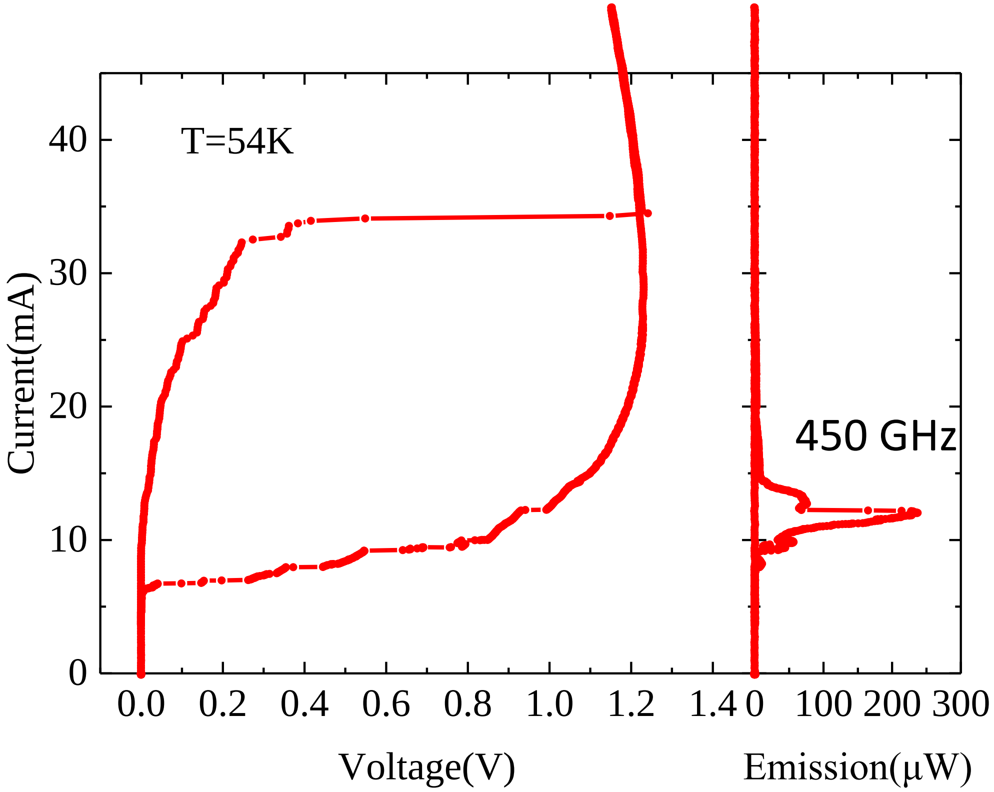
H. Sun et al. *Phys. Rev. Applied,* 2018

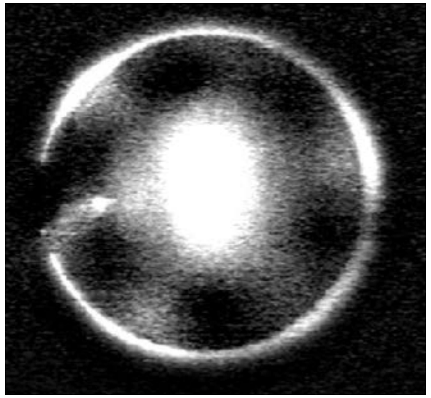
# Broad tunable frequency range

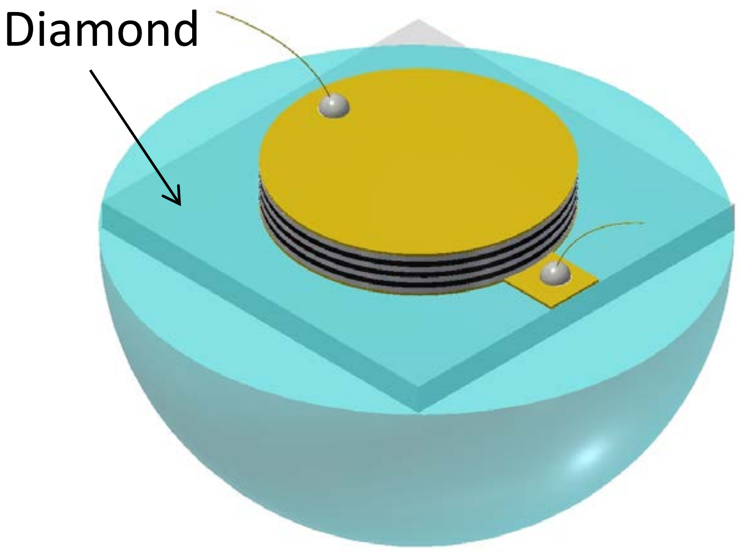
0. 108–2. 095 THz



# A disk THz emitter





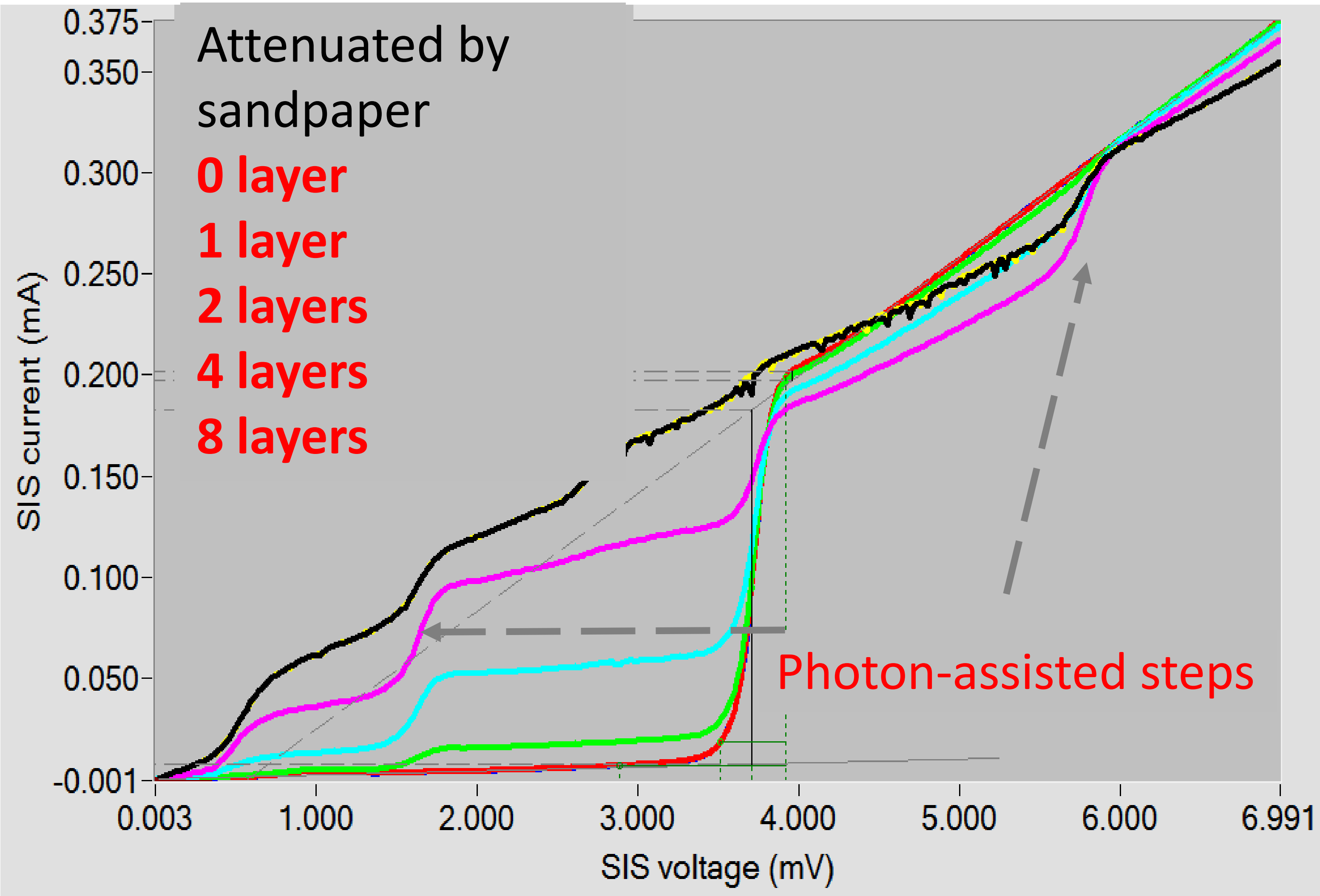

Estimated power：

238x3.3=785 μW

(Emission to substrate side)

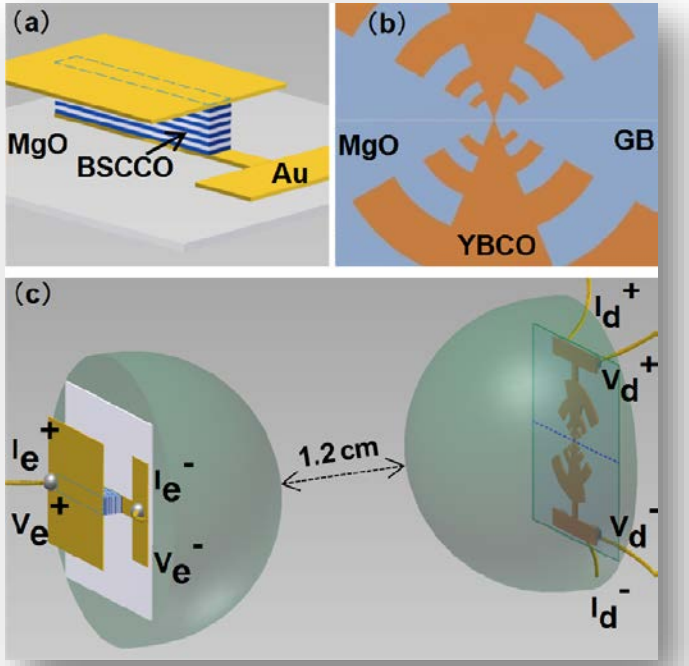
D=200μm

# Pumping an SIS mixer with an IJJs emitter

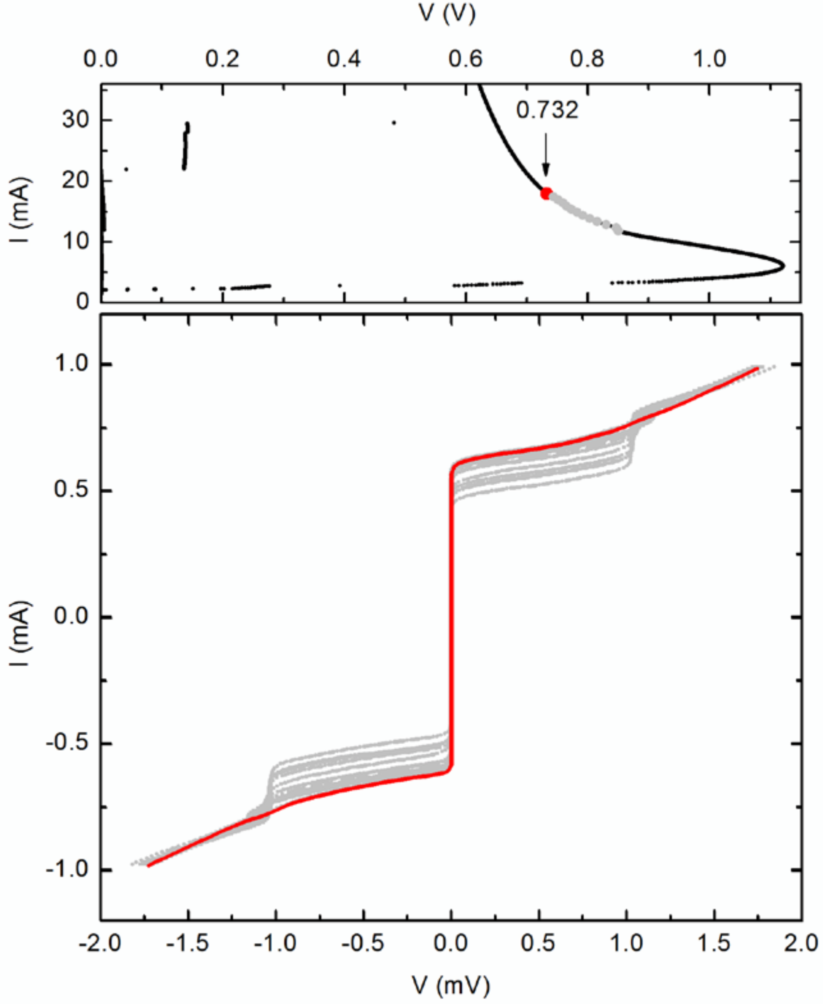


# Setup for THz emission and detection both based on high-Tc superconductors

YBCO bicrystal junction




(power detected here: 82 μW)



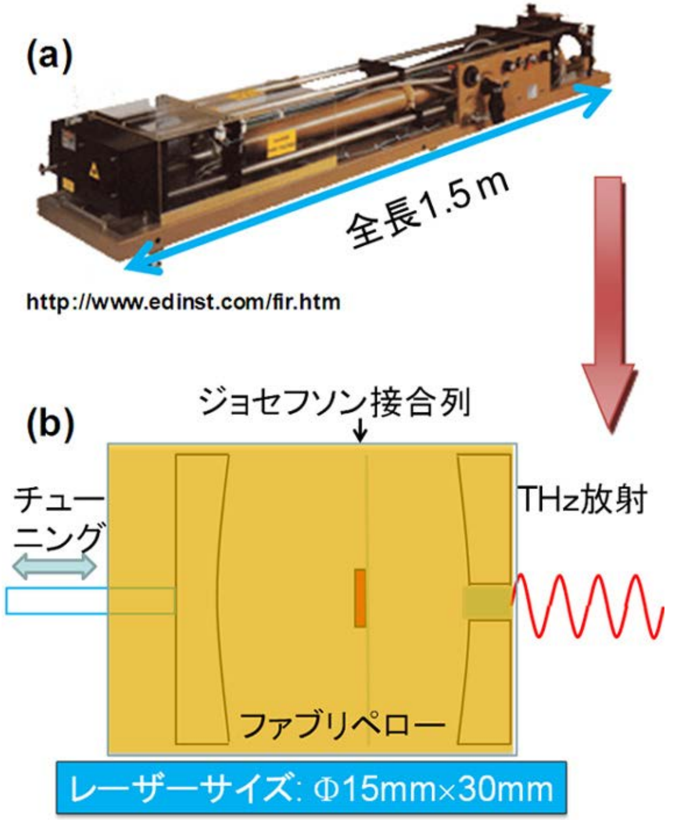
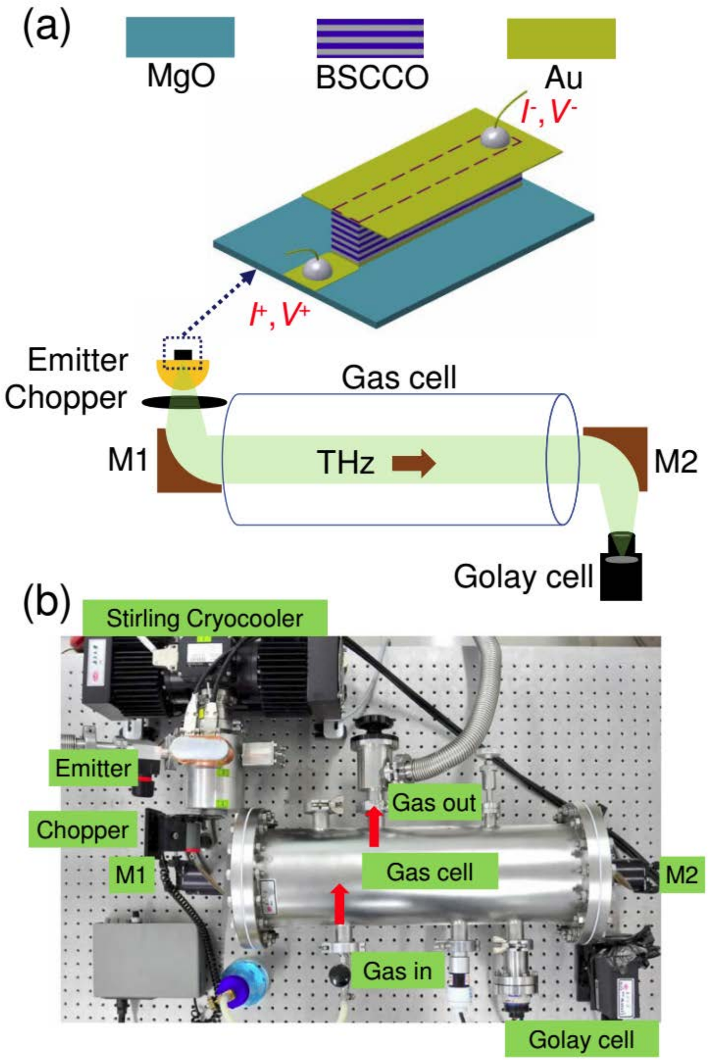
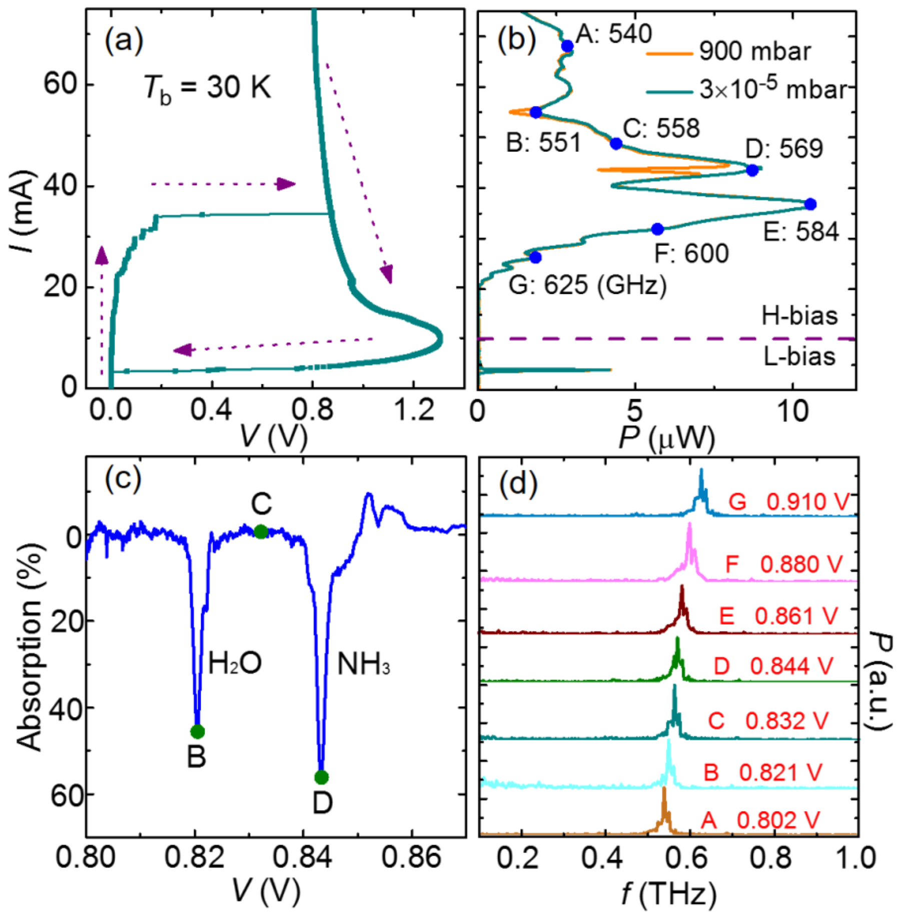




図1 二つのTHz発信器、(a)ガスレーザー、(b)ファブリペロー共振器を用いたジョセフソンレーザー。原理は同じであるが、発振器の規模、エネルギー効率、適用領域は全く異なる

Appl. Phys. Lett. 102, 092601 (2013)

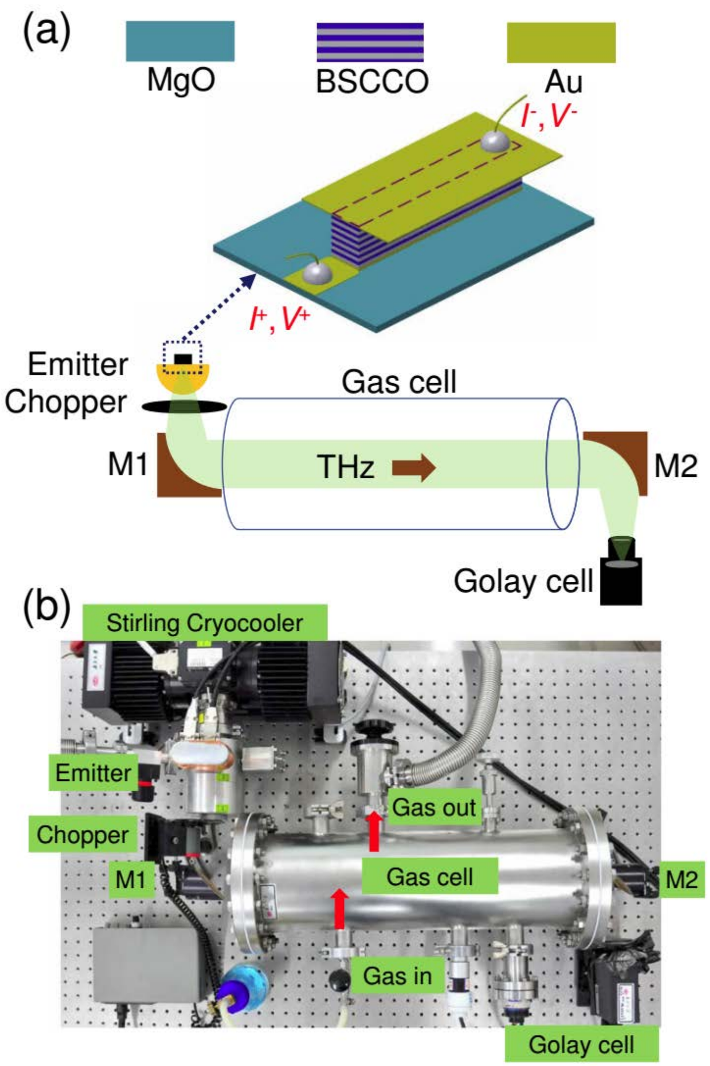
# Gas Spectroscopy

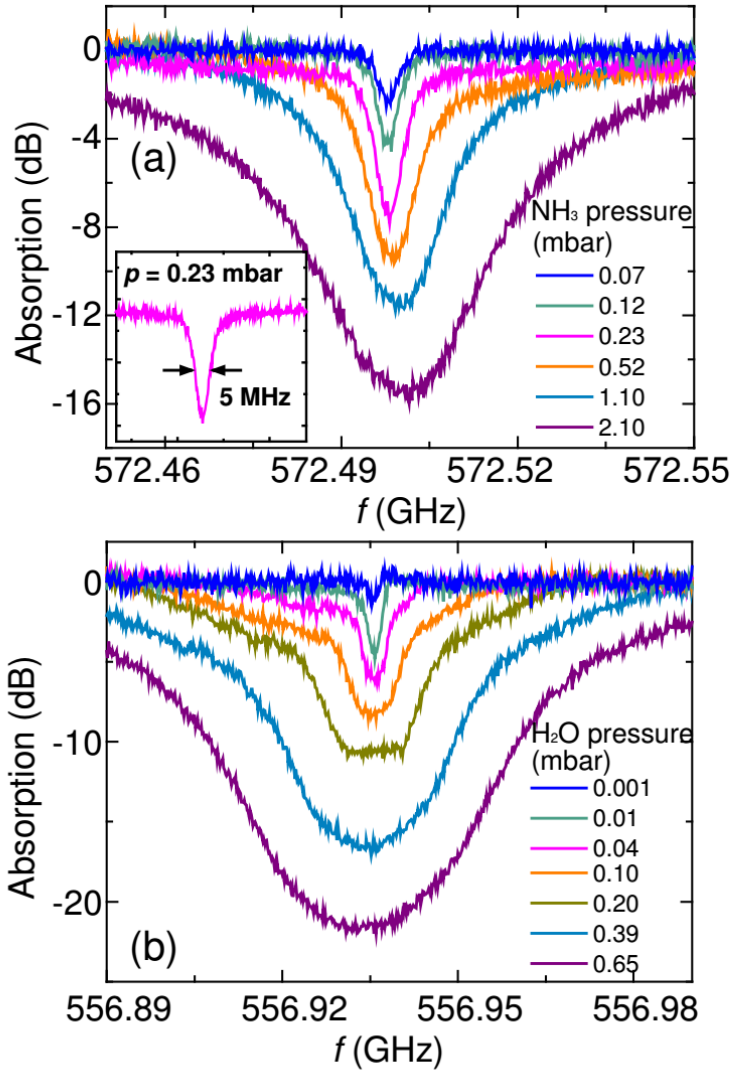



Sun et al., *Phys. Rev. Applied*, 2017

# Gas Spectroscopy

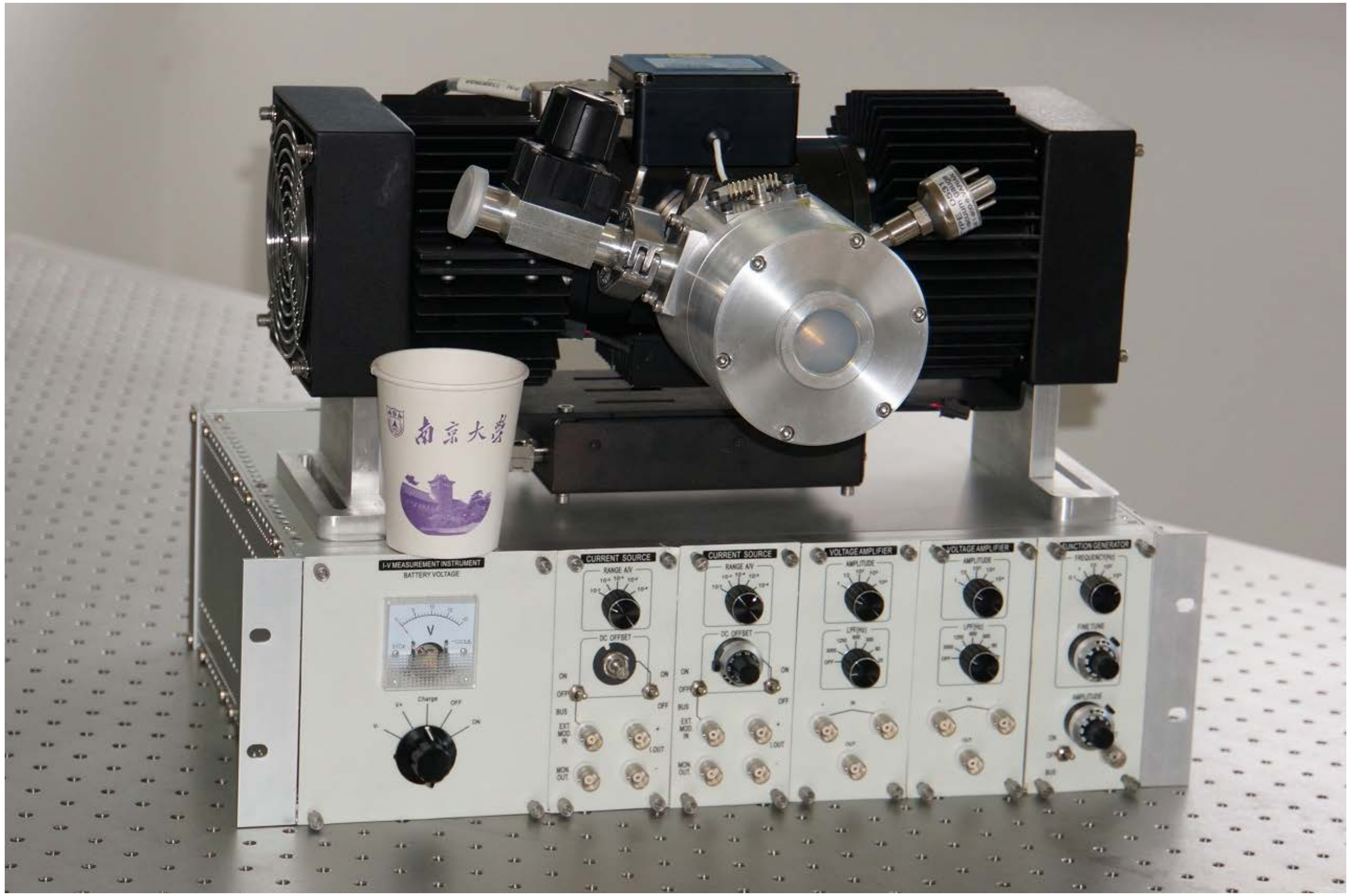



Sun et al., *Phys. Rev. Applied*, 2017

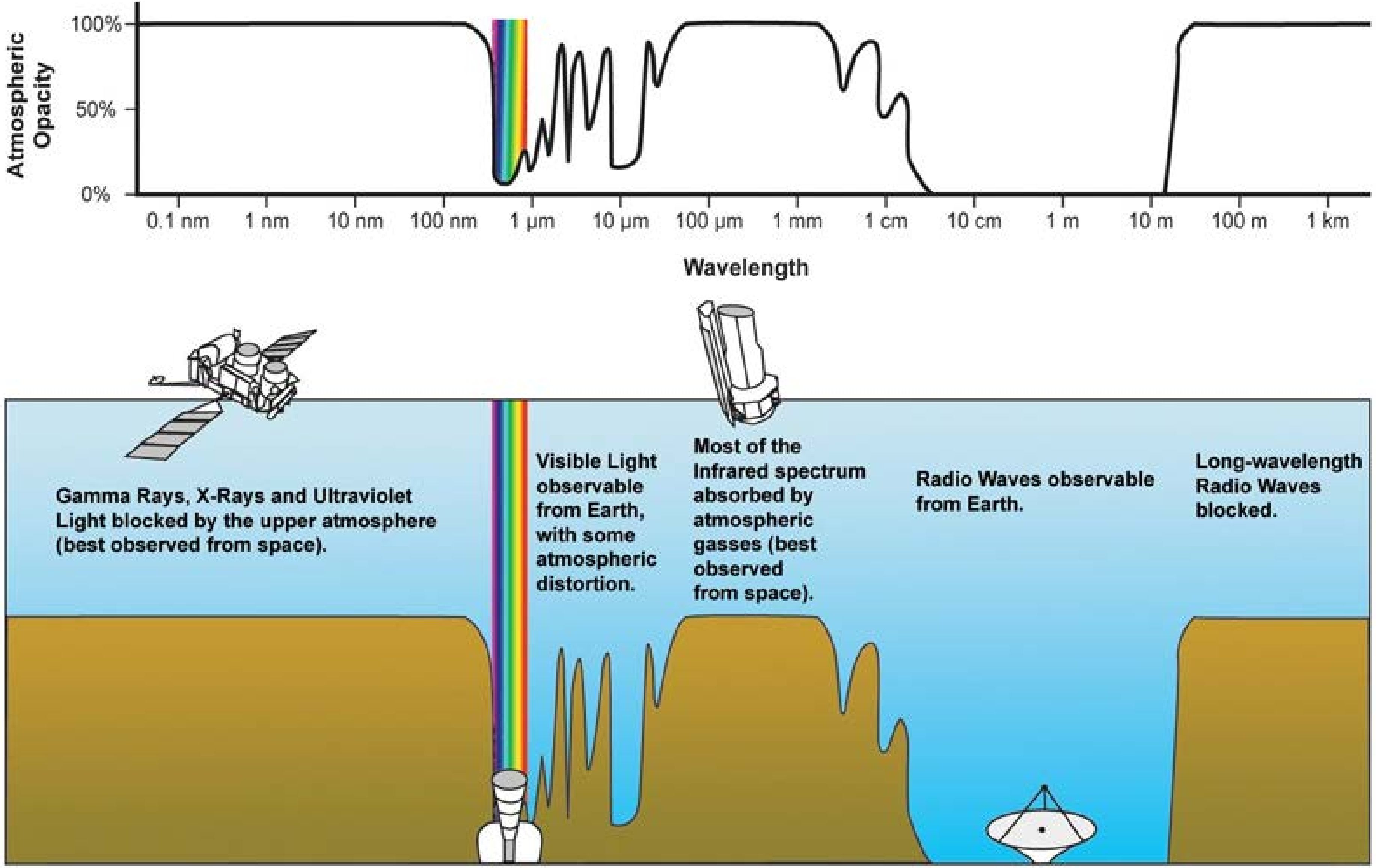
# Compact terahertz source

0.1-2.0 THz

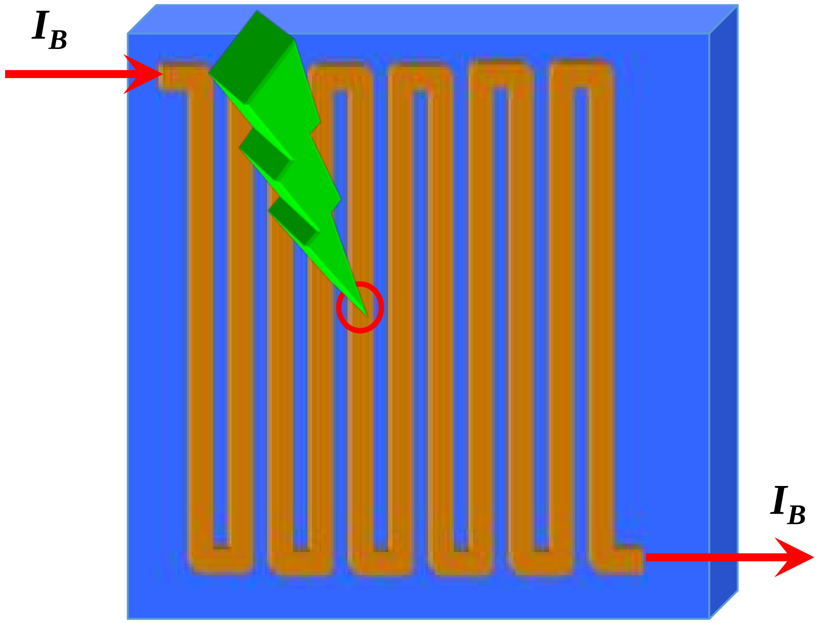



Made in China

# 大气窗口

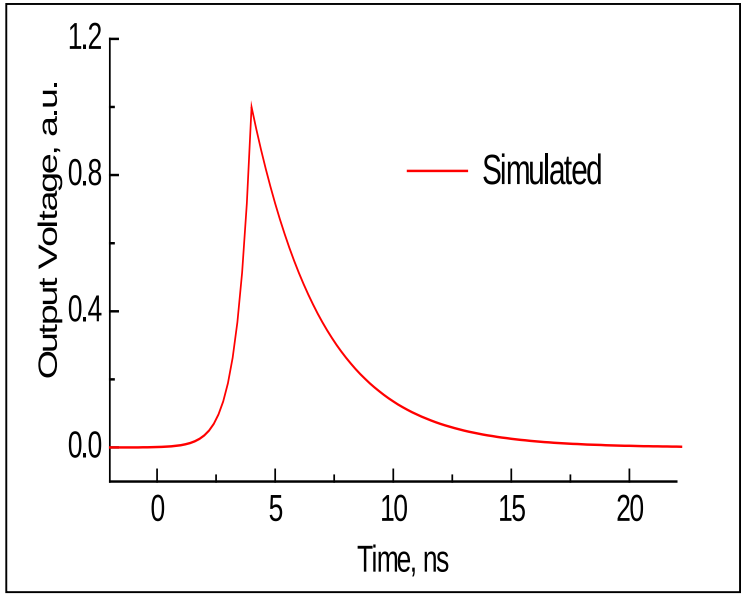

Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.

# Superconducting Nanowire Single Photon Detector (SNSPD)

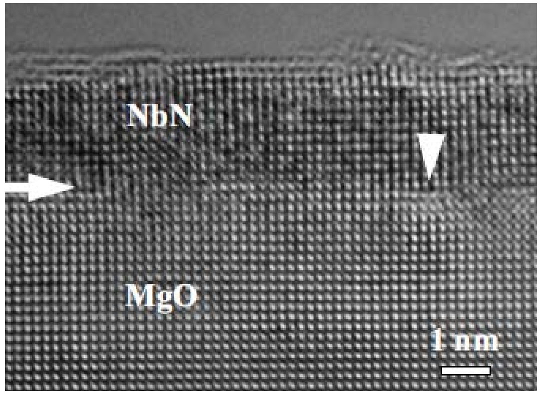




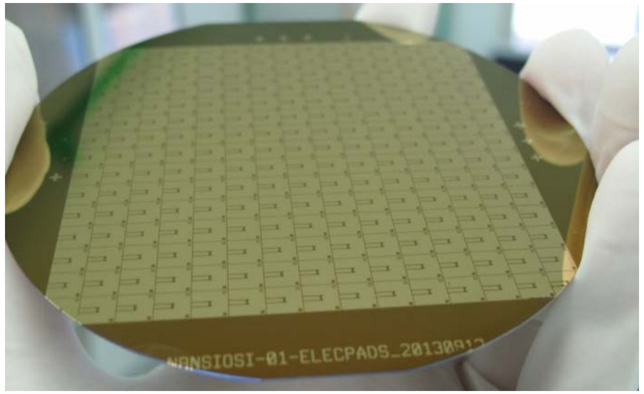
Photons of a 1W source ：
~$10^{18}$/second



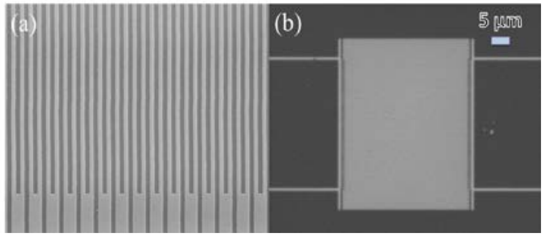
# SNSPD from films to devices



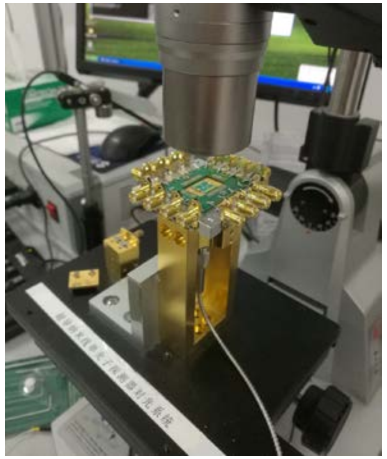

NbN/MgO



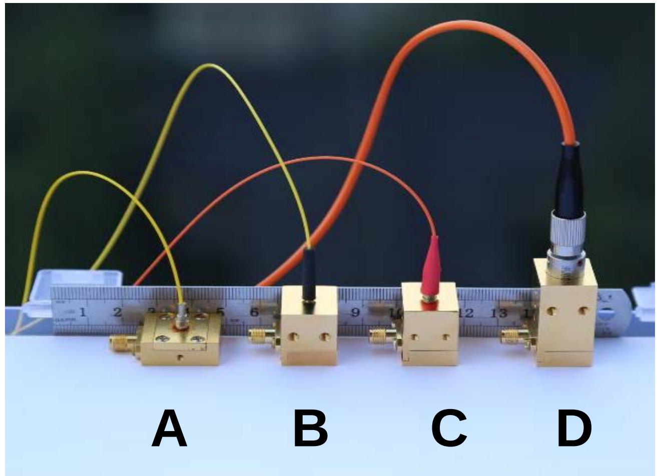
4 inch wafer



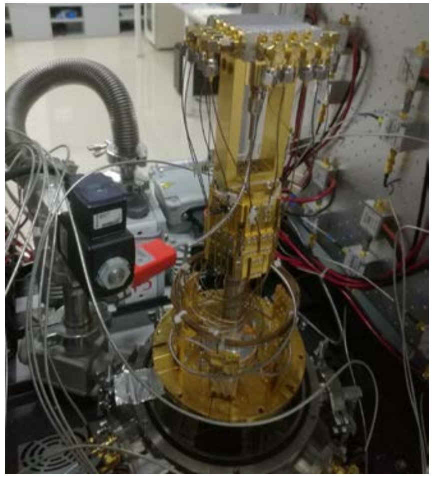

Close-up



Packaging




Various devices



Setup

# SNSPD from devices to instrument

**G 1**

1 channel/ 1 cell
SDE 3%(1.55 μm)

**G 2**

4 channels/1 cell
SDE 20%(1.55 μm)

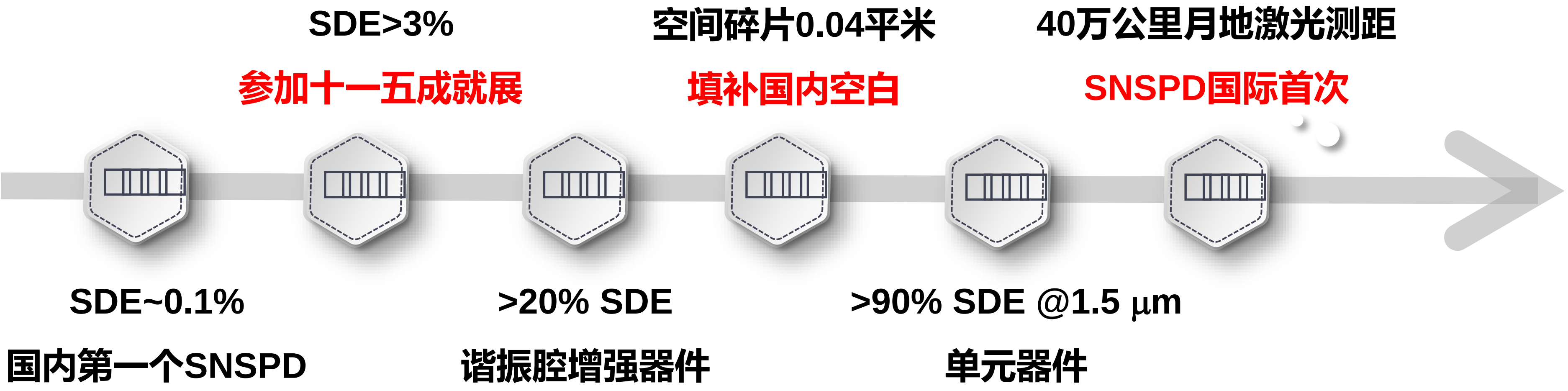
**G 2.5**

6 channels/6 cells
SDE 60%(1.55 μm)

**G 3**

6-16 channels
~90%(1 cell 1.55 μm)
73% (1×6 1.55 μm)
60% (4×4 1.06 μm)

# 南京大学SNSPD研究发展历程

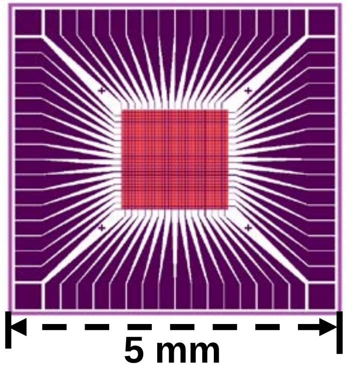


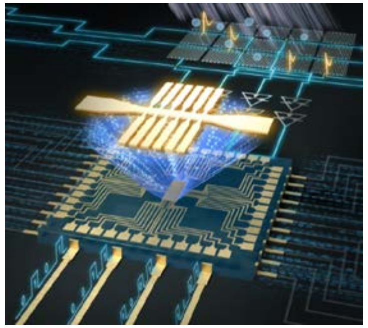

**研制SNSPD被国内外30余单位/课题组采用。**

# 阵列红外超导单光子探测器展望

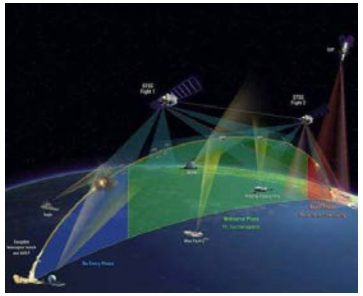
超导纳米线单光子探测技术

大阵列集成

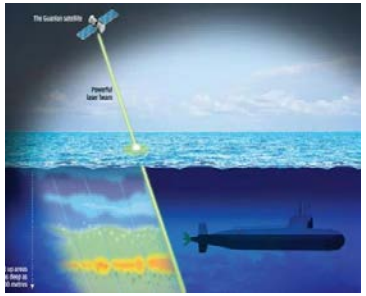


中远红外探测



天基红外



红外探潜

极限性能

探测效率

时间精度

响应速度

更多探测像元

更优探测性能

更宽响应频谱

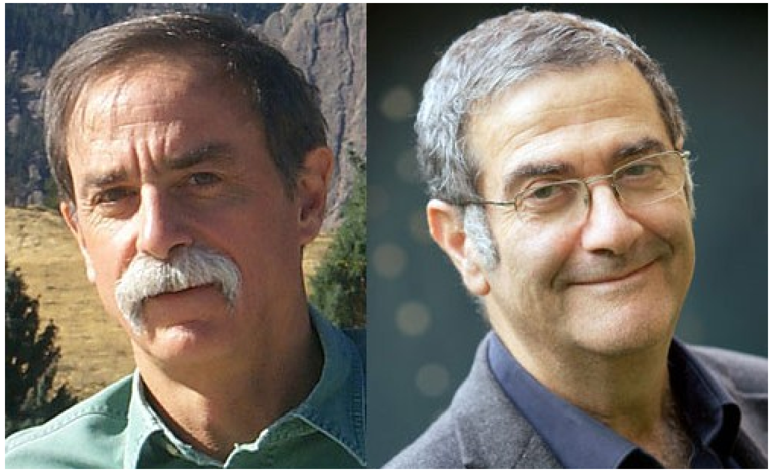
更多应用场景

# Last but not least

# 量子光学

随着上世纪初光量子概念的提出，光学研究正式步入量子阶段。经过一百多年的发展，量子光学理论不仅成为人们理解光的量子相干性及光与物质的相互作用等基本物理问题的基础，也在如**量子通信**、**量子计算**、**量子成像**及**量子超精密测量**等新兴领域起到核心作用。

**The Nobel Prize in Physics 2012**



David J. Wineland and Serge Haroche

For ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems


“墨子号” 量子通讯卫星

# 微波量子光学

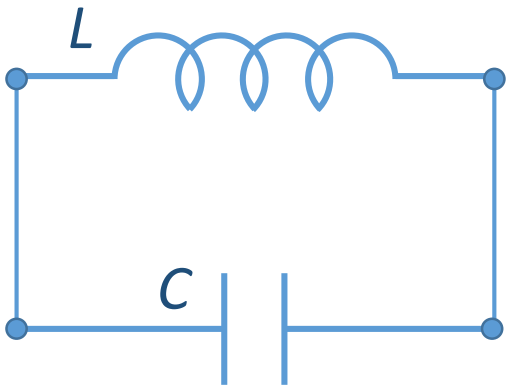
**量子光学的理论、方法和手段： 光 → 微波**

利用微波波段光量子的优势

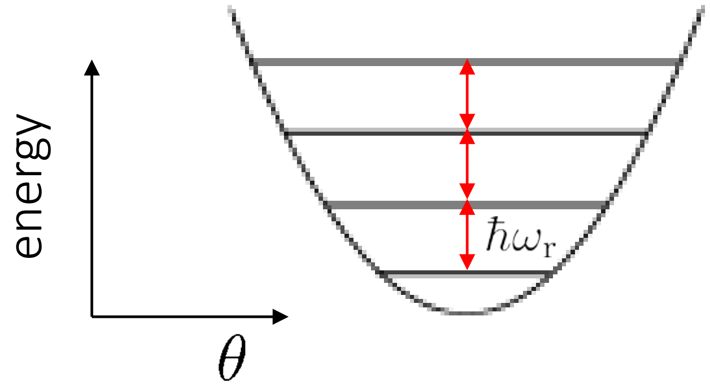
- 微波具有低损耗、高穿透性、远距离传输、覆盖范围广等特点
- 微波光子可以和固态的量子比特直接进行信息的交换、存储、处理
- 可应用于微波量子通信、微波量子雷达、量子超精密测量、射电天文等方面，大幅提高性能

# Superconducting qubit (artificial atom)

✓ *LC* resonator



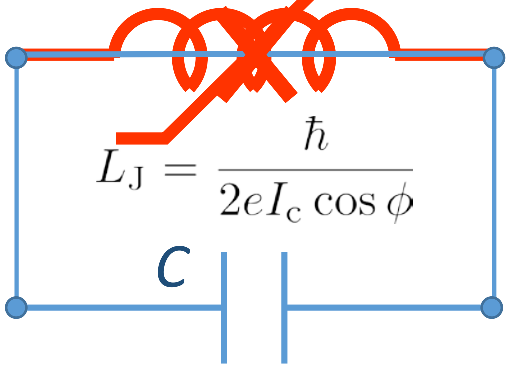

**Harmonic oscillator**



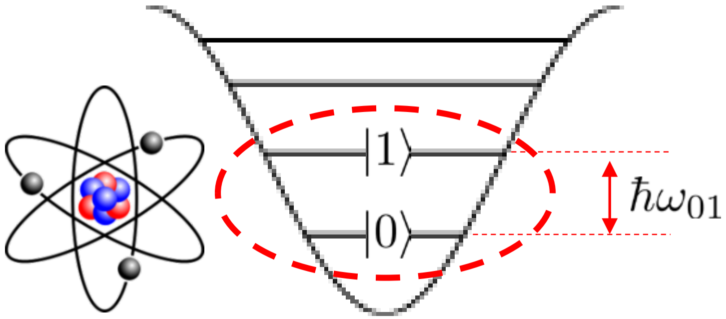

✓ Josephson junction resonator

***Nonlinear inductor***

***Josephson junction***




Anharmonic oscillator




3-30 GHz

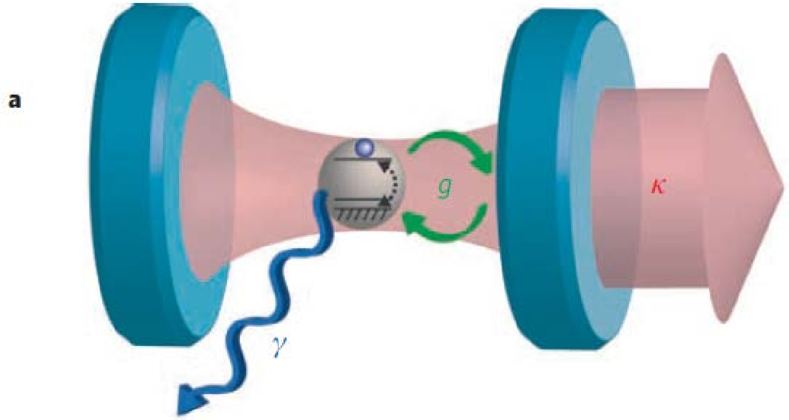
***Effective two-level system = SC qubit***

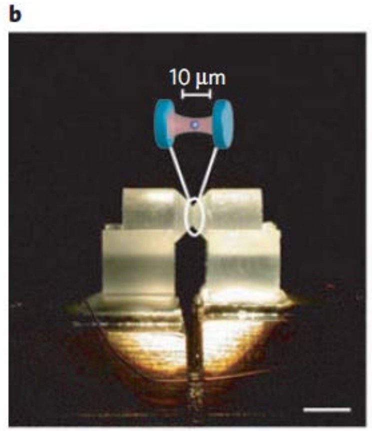
After Inomata

# Cavity quantum electrodynamics (Cavity-QED)

原子在光学谐振腔中

Alkali atoms, Rydberg atoms, ions etc



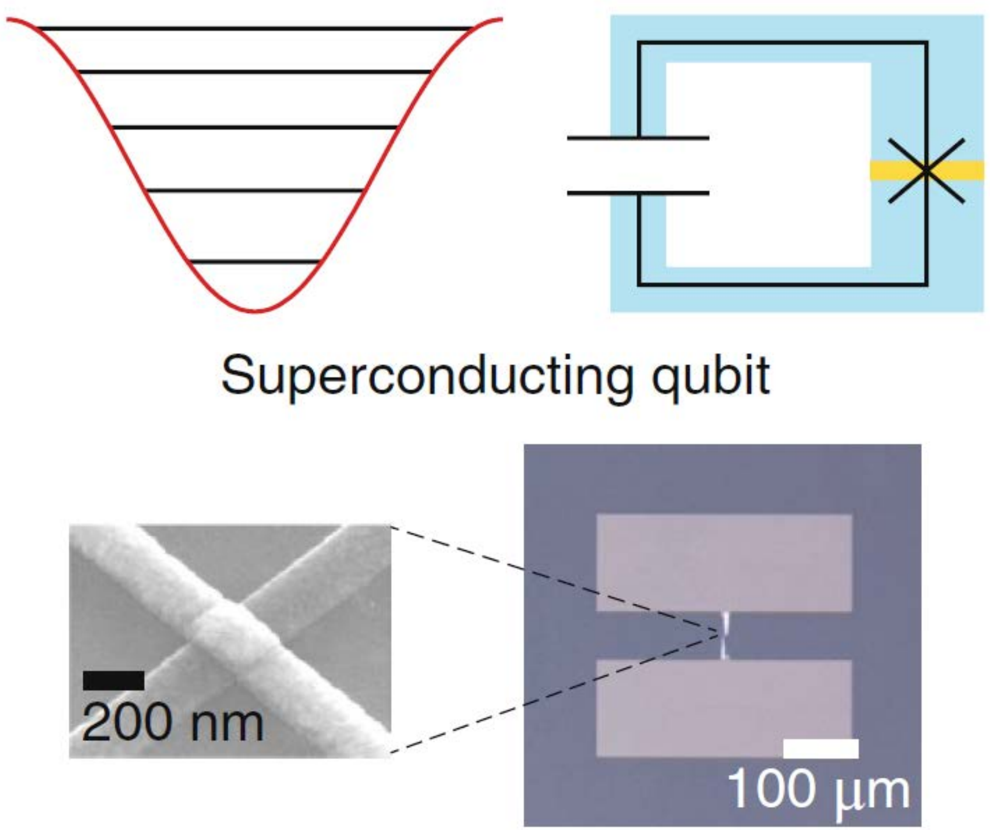



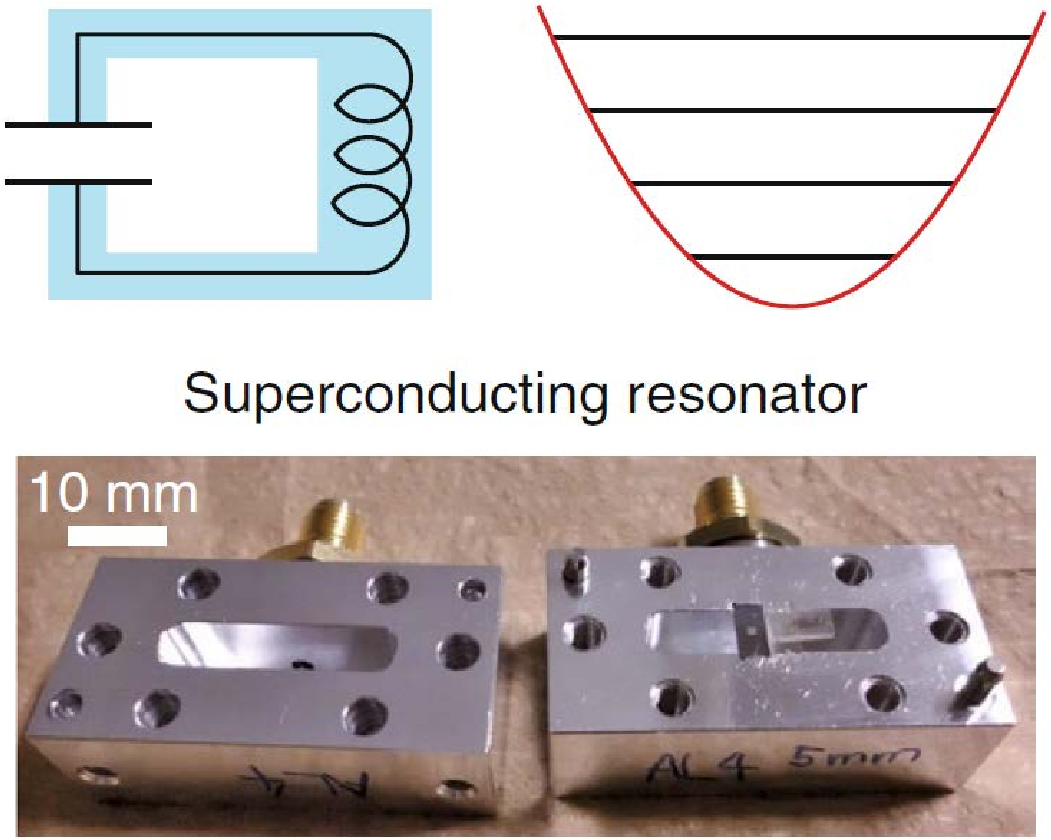

量子光学

在量子信息的研究和应用中，量子光学和腔量子电动力学(Cavity QED)发挥了重要的作用。

John Clarke & Frank K. Wilhelm, Nature 2008; J. Q. You & Franco Nori, Nature 2011

# 超导人工原子在3D腔内

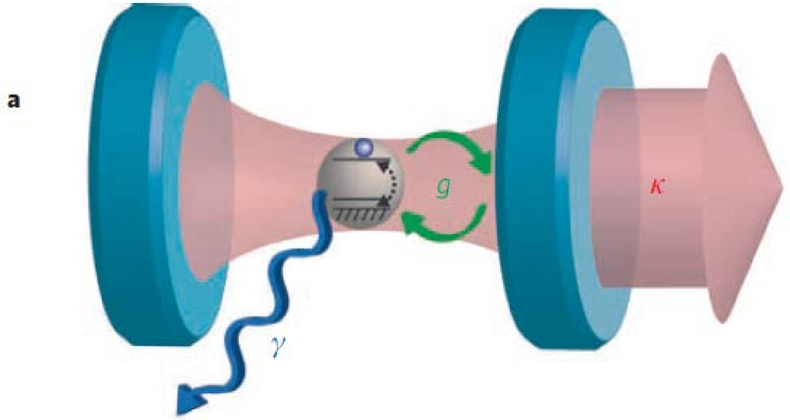


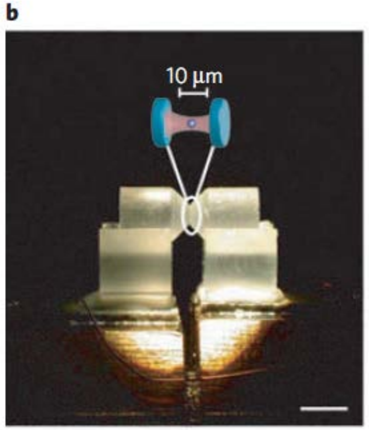




*Clerk et al.*, *Nature Physics*, **16**, 257 (2020).

# Cavity-QED → Circuit-QED

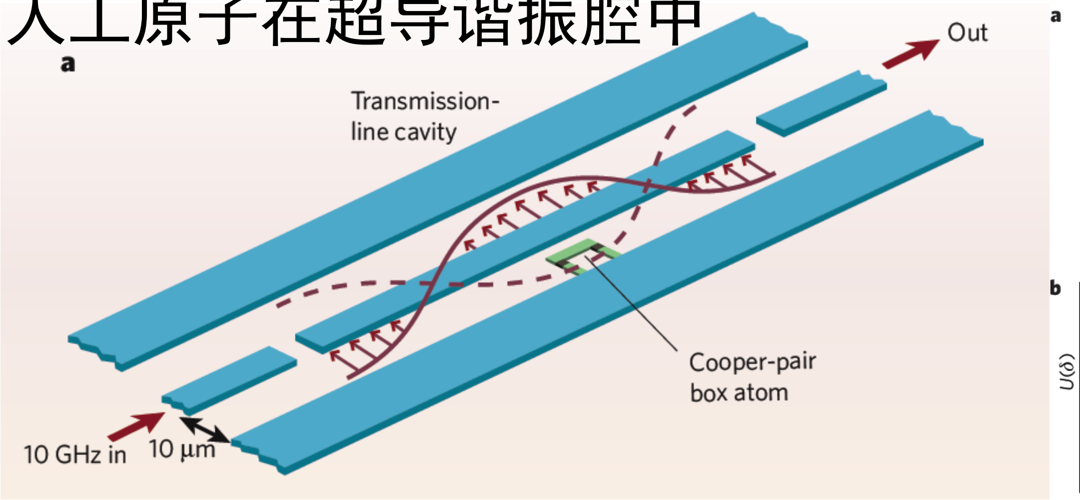
原子在光学谐振腔中

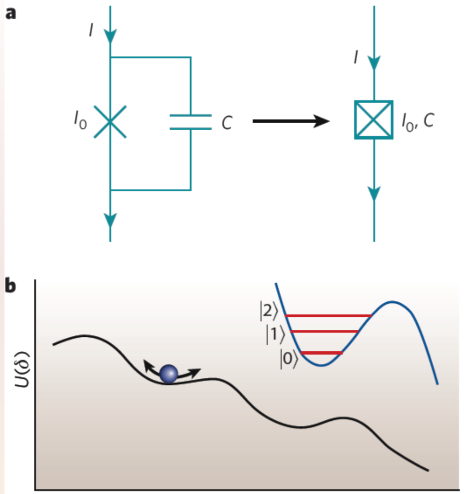



量子光学

人工原子在超导谐振腔中




微波
量子光学

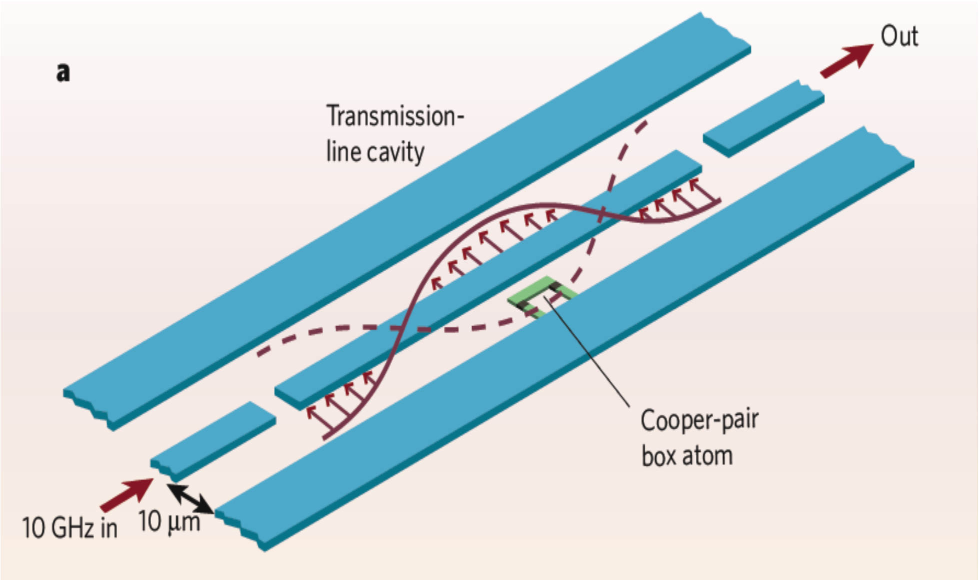
高耦合效率
易于集成



John Clarke & Frank K. Wilhelm, Nature 2008; J. Q. You & Franco Nori, Nature 2011

# 超导电路量子电动力学系统 circuit-QED

超导人工原子在超导谐振腔中




**核心技术基础：**

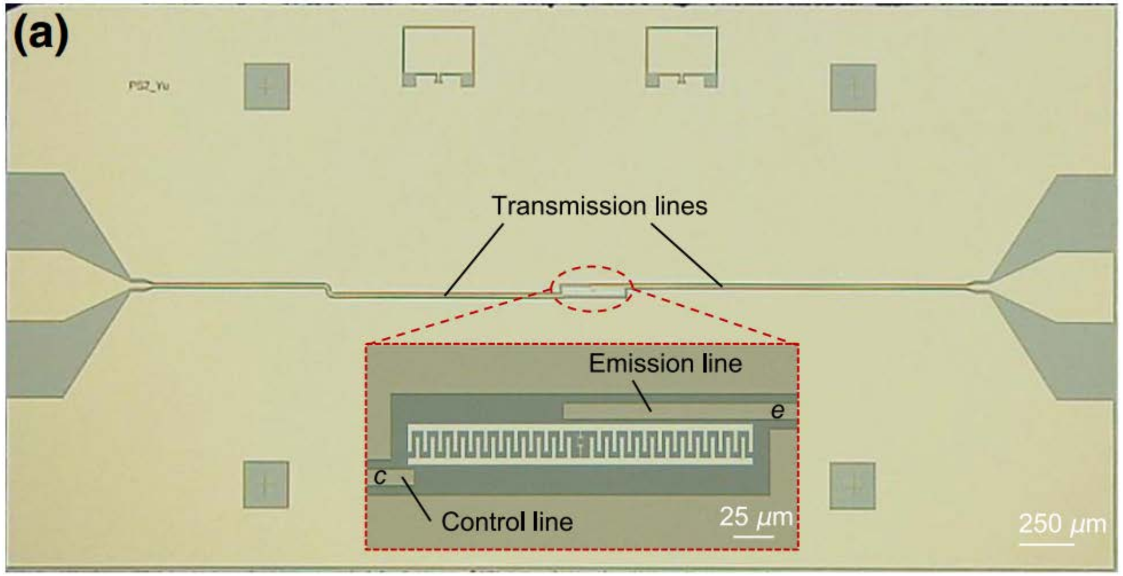
高质量超导薄膜、约瑟夫森结、低温技术

- 微波取代了可见光
- 人工原子代替了自然原子
- 准一维传输线腔代替了三维腔
- 人工原子含有数以亿计的金属原子，有效尺寸在微米量级
- 易于集成、扩展
- 人工原子有很大的偶极矩，与谐振腔有可调的耦合强度，可达到强耦合和超强耦合

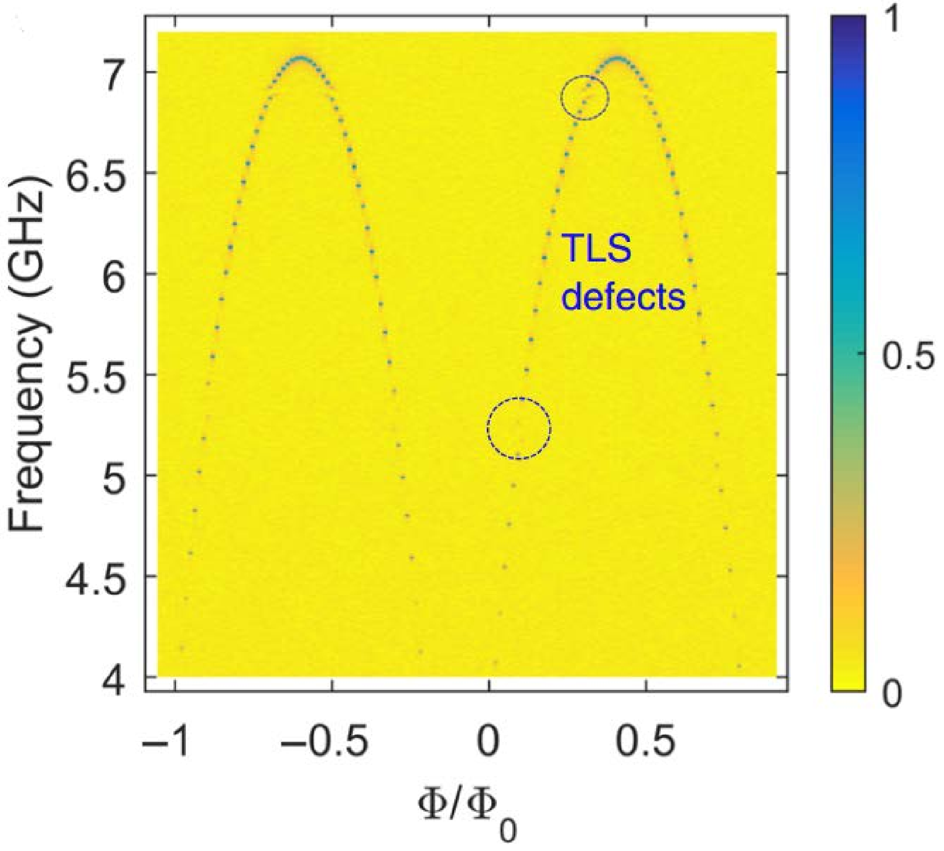
John Clarke & Frank K. Wilhelm, Nature 2008;
J. Q. You & Franco Nori, Nature 2011

# 微波单光子产生（无谐振器）

超导量子比特+开放/半无限长传输线




光子产生可控
光子频率可调

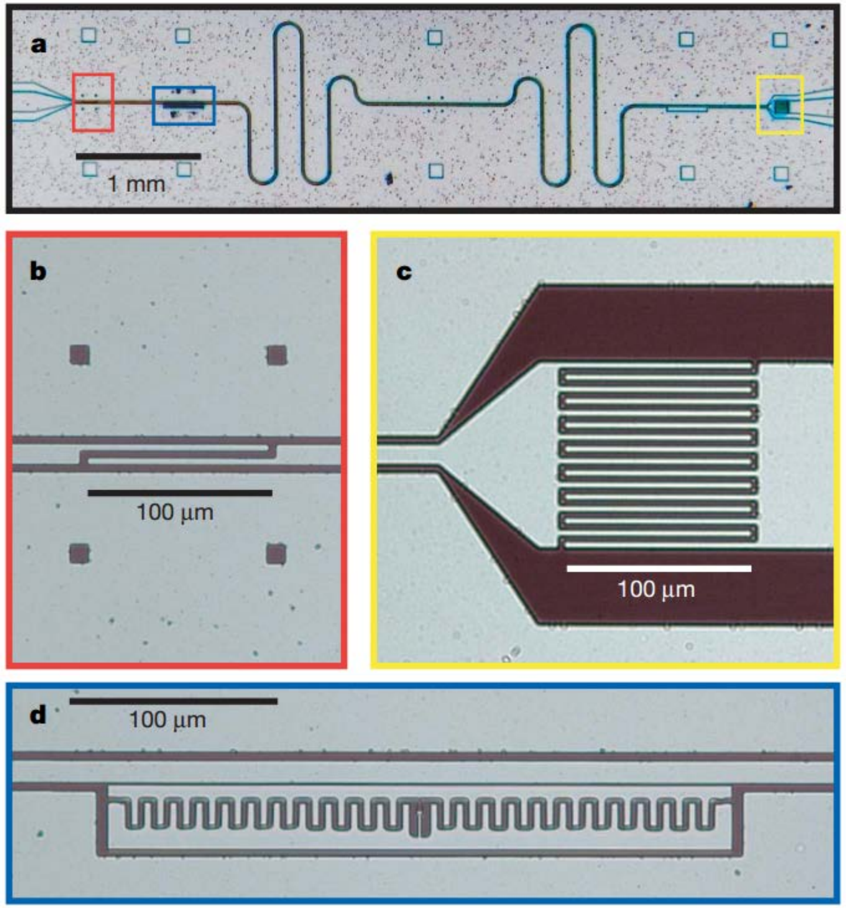


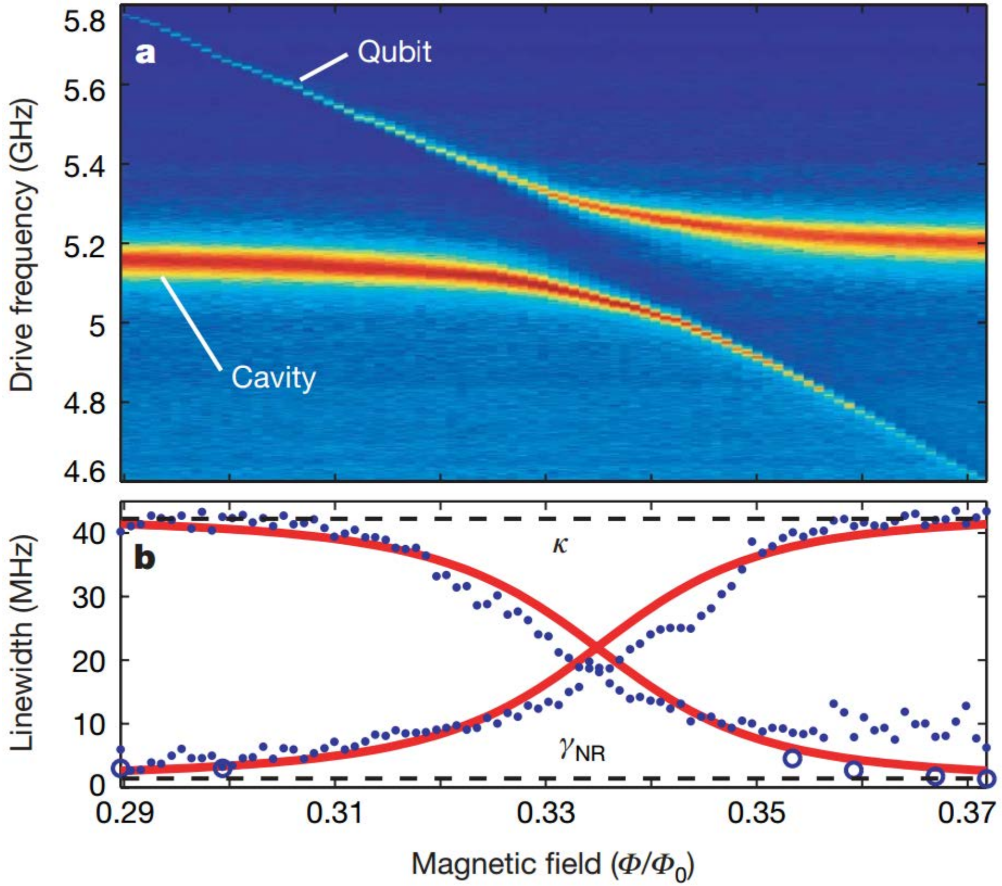

Zhou Y, et al. Physical Review Applied, 2020.

# 微波单光子产生（有谐振器）

光子产生可控
光子频率固定
可以产生多光子数态

超导量子比特+谐振器

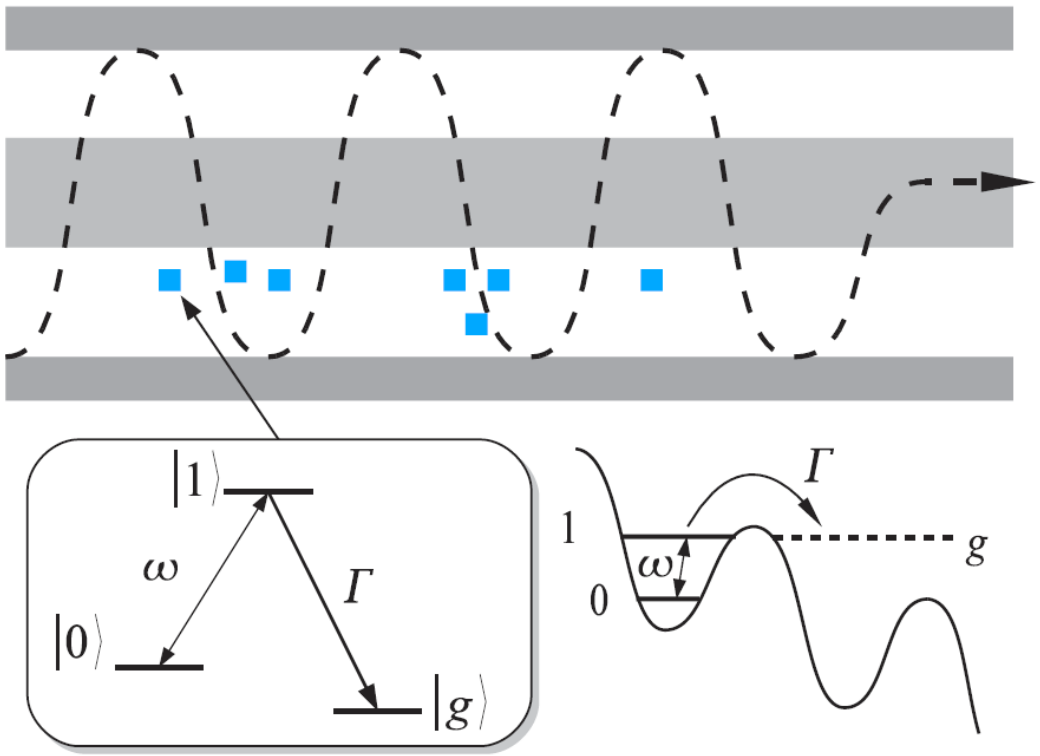



Houck A A, et al. Nature, 2007.

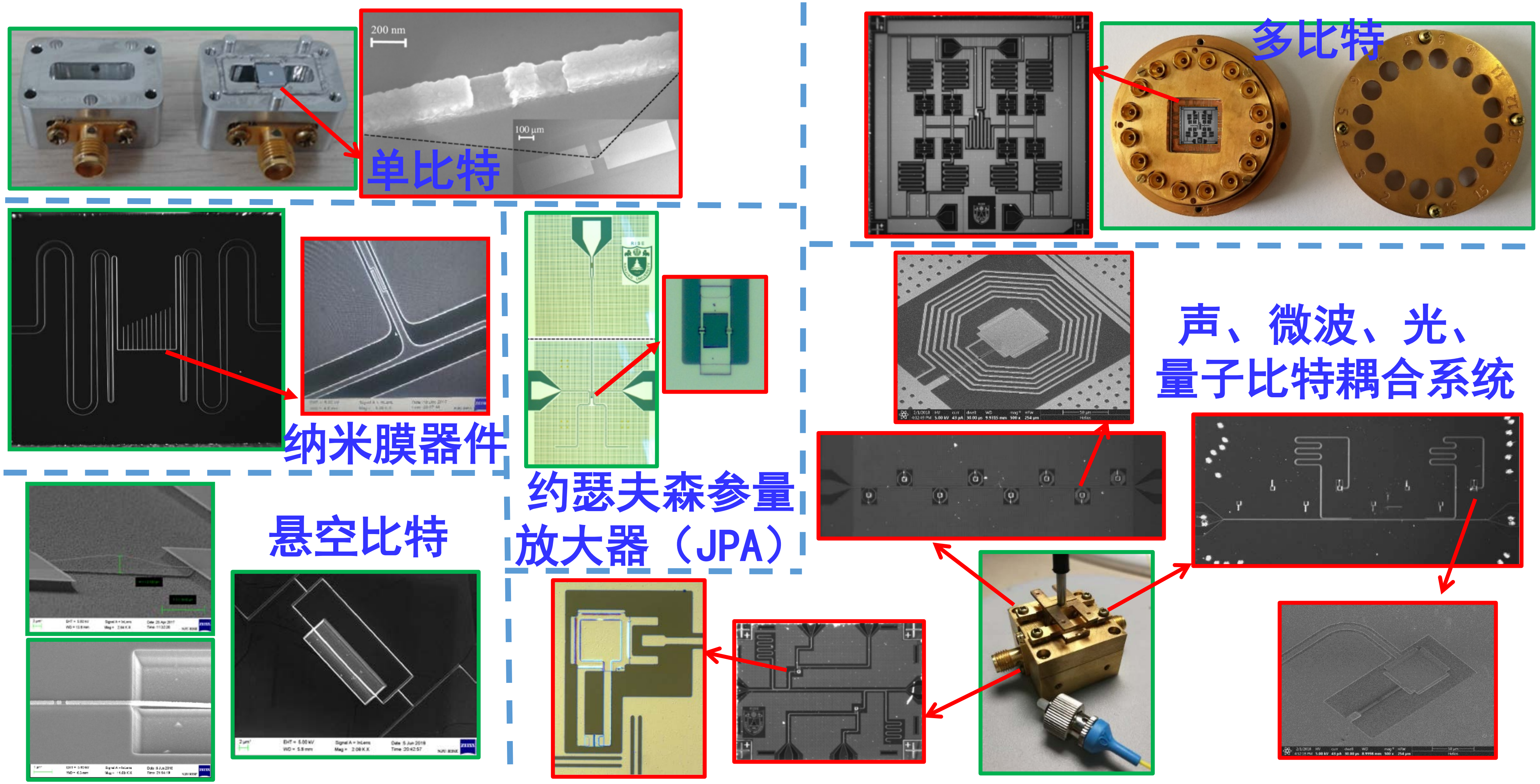
# Λ型系统探测微波光子

电流偏置的约瑟夫森结（CBJJ）

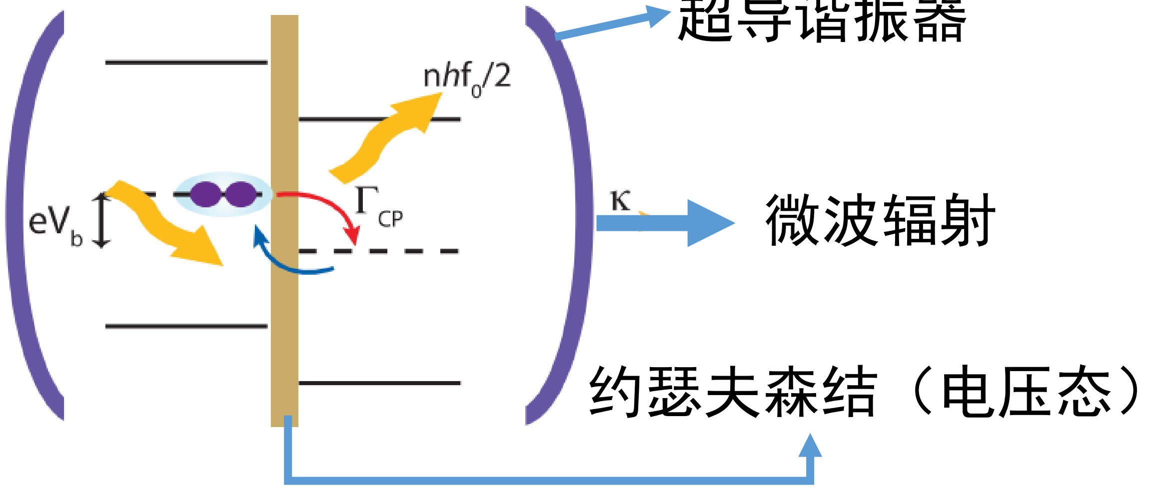



Romero G, et al. Physical review letters, 2009.

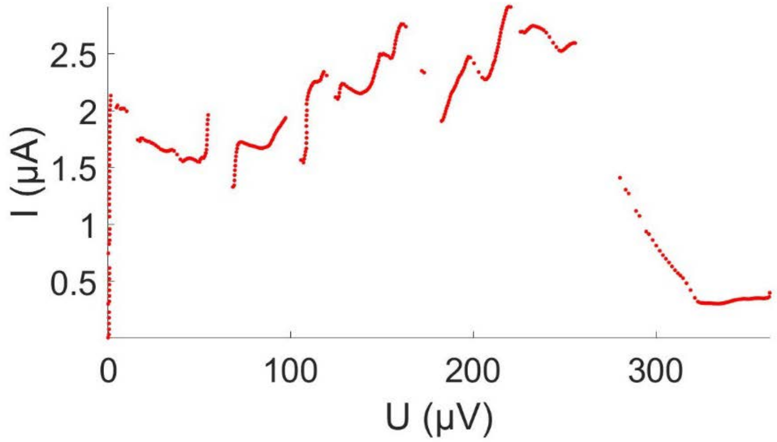
# 多种核心超导电子器件

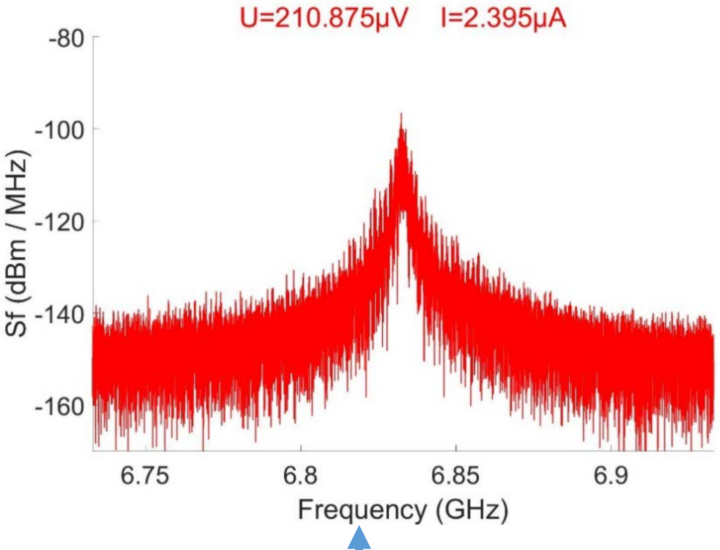


# 超导微波激射器

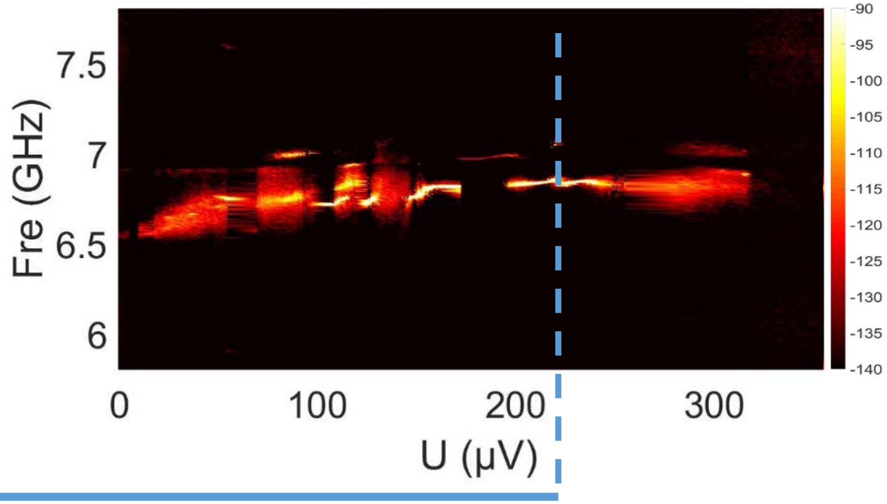



Al/AlOx/Al结IV特性



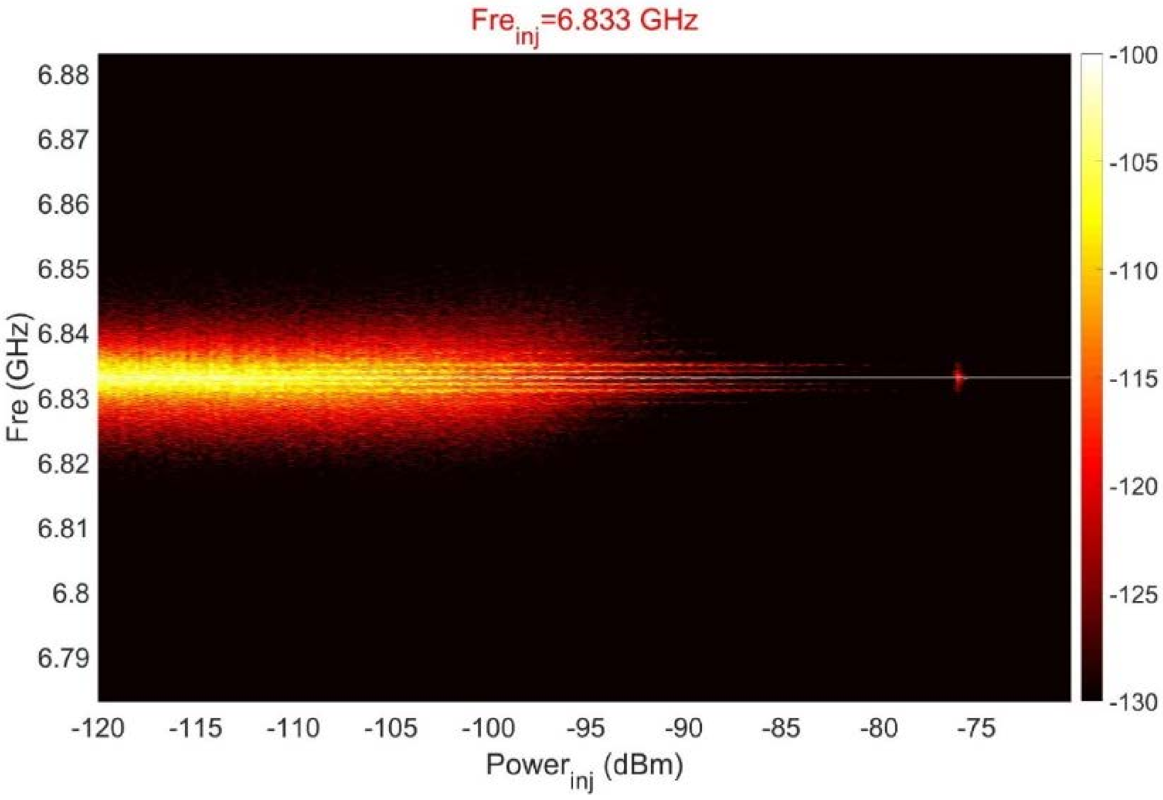



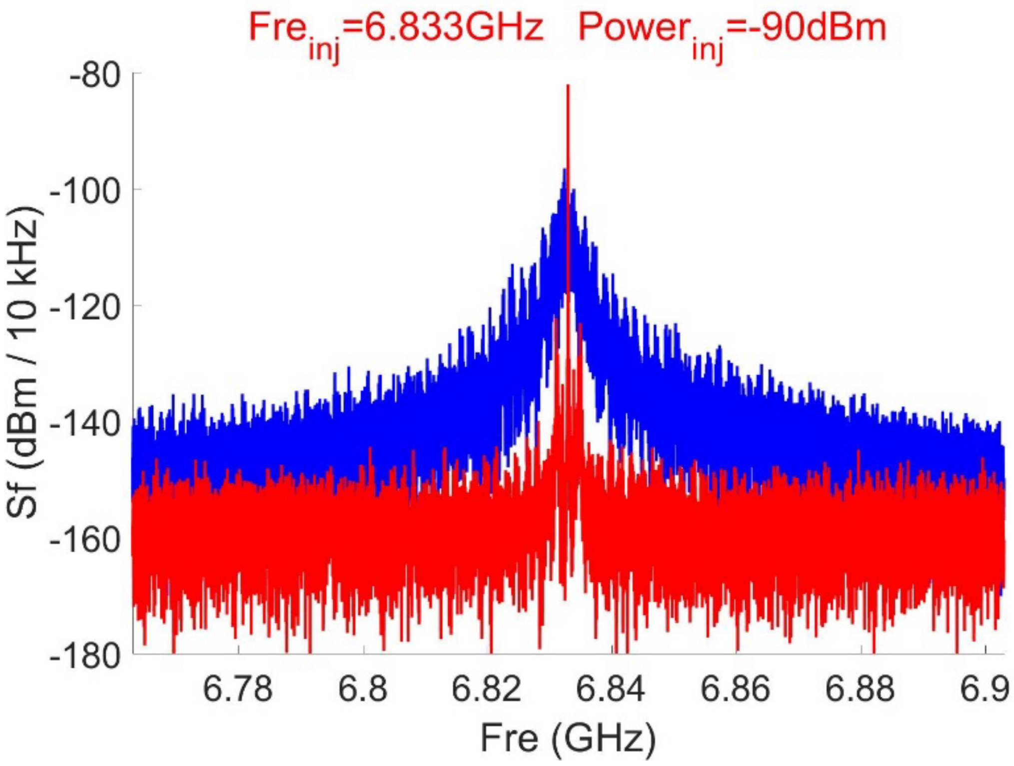

激射器在不同电压下激射信号




**[1] Cassidy et al., Science 355, 939–942 (2017)**

# 注入锁定现象

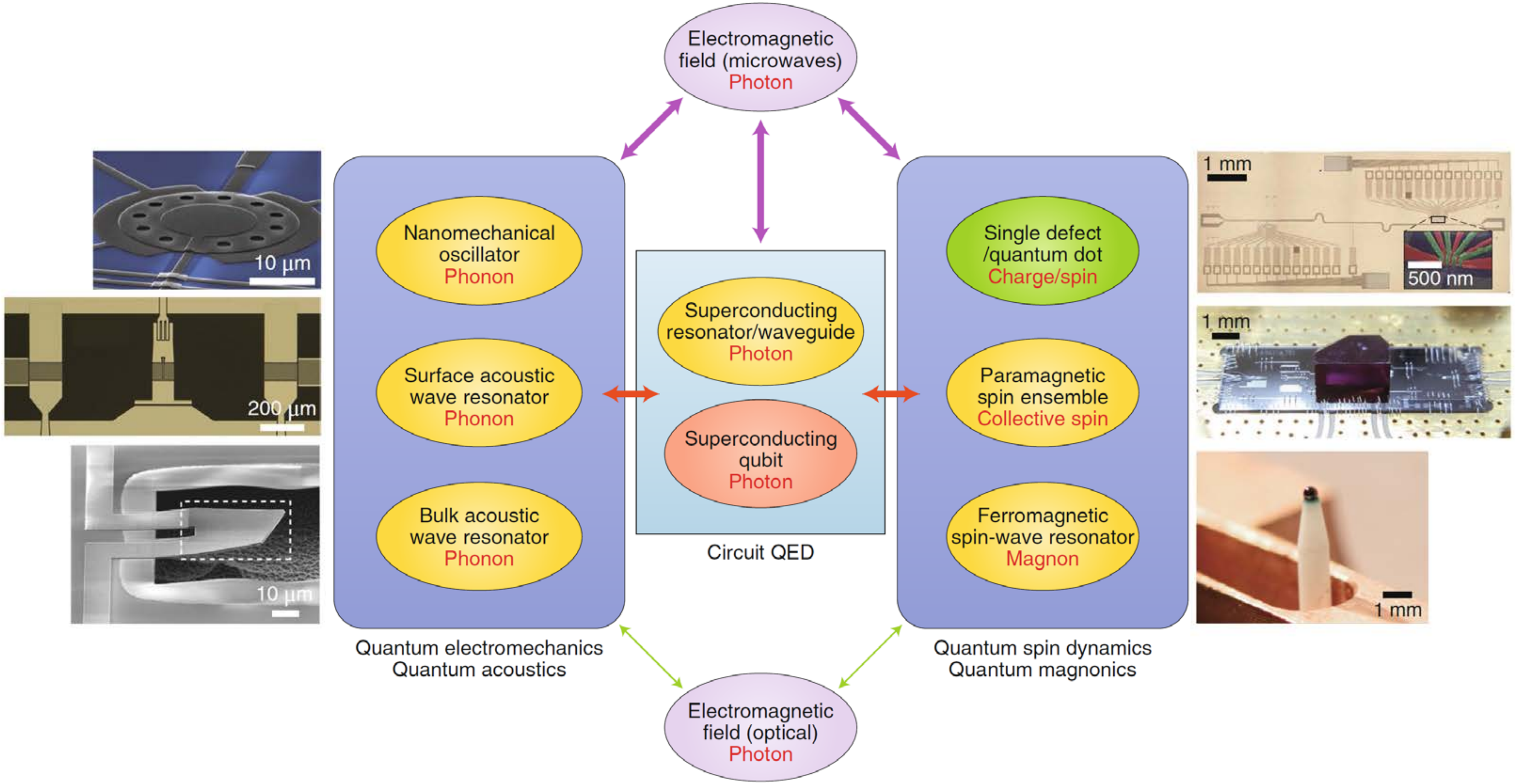



**锁模前后对比图**

**蓝：锁模前；红：锁模后**

# 以Circuit-QED为核心的混合量子系统




*Clerk et al., Nature Physics*, **16**, 257 (2020).

# 超导电子器件 ---极端的手段、极端的目标

| 超导体应用于电子学的物理依据 | |
|---|---|
| 低微波表面电阻 | 超导微波滤波器、超导超材料 |
| 库珀对被拆对导致相变或载流子密度改变 | 超导纳米线单光子探测、临界转变传感器、动态电感检测器等 |
| 约瑟夫森效应<br>准粒子隧道效应 | 量子电压基准、超导量子干涉器件、太赫兹探测与辐射 |
| 超导人工原子 | 量子计算、信息、探测 |

# Conclusion

- **Josephson effects and their classic applications**

- **Modern superconductor electronics:**

  **quantum and hybrid applications**

# 致谢


南京大学超导电子学研究所**吴培亨院士及其他所有同事**
**提供报告材料的李婧、孔祥燕、曹文会等同事**

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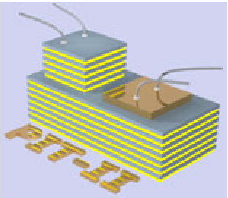
National Institute for Materials Science, **Japan**

**Dr. K. Inomata Group, and Dr. Y. Yoshida Group**
Advanced Industrial Science and Technology, Japan

**Prof. R. Kleiner Group**
Universität Tübingen, **Germany**



**Prof. Paul Müller**
Universität Erlangen-Nürnberg, **Germany**

**Prof. V. Koshelets Group**
Institute of Radio Engineering and Electronics, **Russia**

# Thank you very much for your attention!

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