Transition-Edge Sensor Development and Application

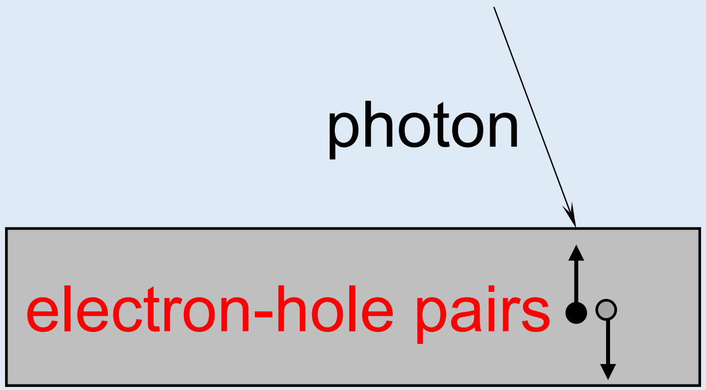
Daikang Yan

2023-10

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Superconductor Detectors

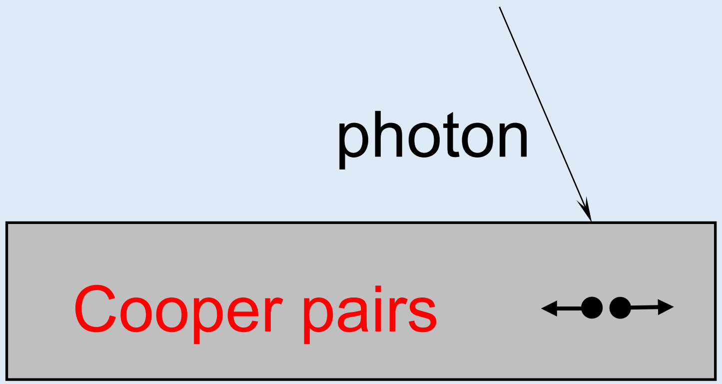
Semiconductor detector



e-h pair: ~ eV

v.s.

Superconductor detector



Cooper pair: ~ meV

Poisson noise = $1/\sqrt{N}$

The intrinsic noise level of superconductor detectors is $1/\sqrt{1000}$ times lower

→ energy resolution 30 times better

Superconductor Detectors

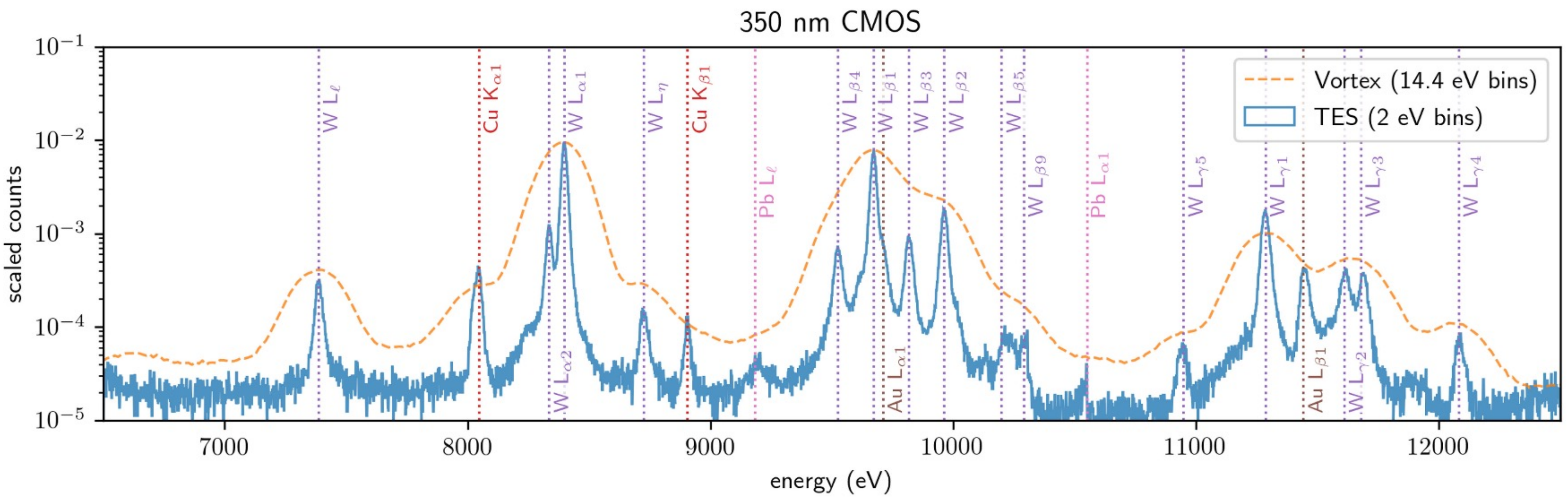


Fig. 3. Fluorescence spectra of a 350 nm CMOS integrated circuit chip, measured with a TES sensor (blue solid line) and a Vortex silicon-drift detector (orange dashed line). Prominent peaks are labeled with their corresponding element and line name.

Tejas Guruswamy et al. (2021)

Vortex (Si detector) ΔE = 130 eV

TES (Superconductor detector) ΔE = 12 ~ 15 eV

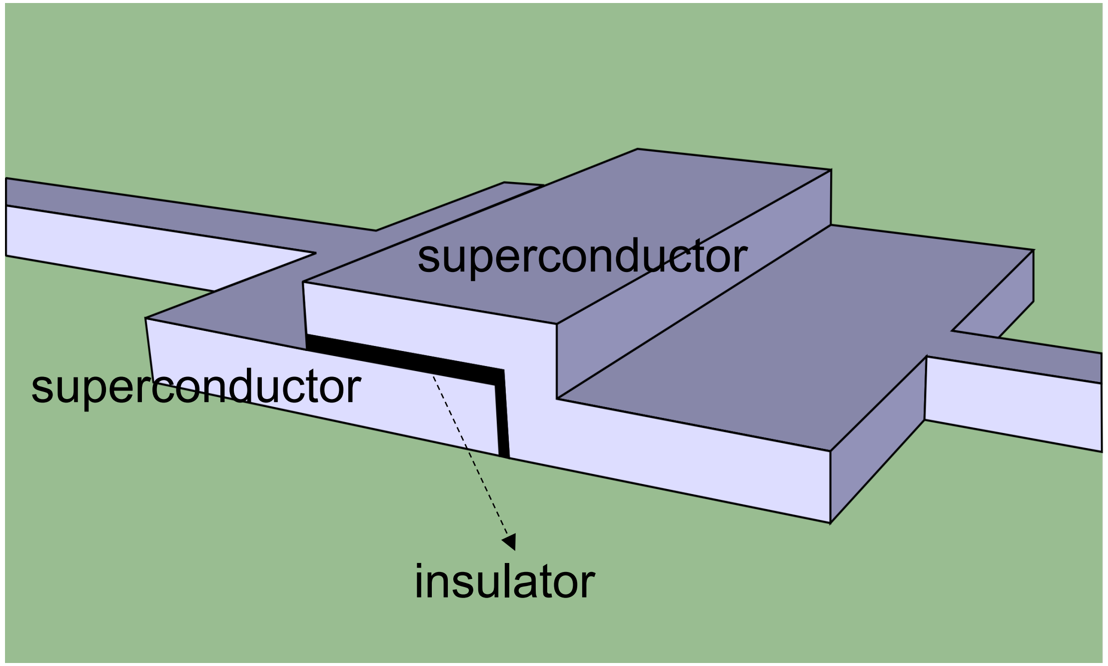
Superconductor Detectors

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

	Superconducting Tunnel Junction (STJ)	Microwave Kinetic Inductance Detectors (MKID)	Metallic Magnetic Calorimater (MMC)	Transition-Edge Sensor (TES)
mechanism	tunnelling current proportional to number of quasiparticles	quasiparticle density influences the resonant frequency of LC circuit	magnetic flux change in the paramagnetic material	resisntance change due to photon heating
ΔE (soft X-ray)	~ 10 eV	~ several 10 eV	~ 1 eV	~1 eV
ΔE (hard X-ray)	detector material too thin, low absorption	rarely developed	40 eV@60 keV (can be better)	5 eV @ 17 keV
advantage	high count rate (10^4 /s)	large array multiplexing	high energy resolution; large energy range	high energy resolution; well-developed multiplex technique
disadvantage	"low" energy resolution; small energy range	"low" energy resolution; small energy range	hard to multiplex	energy range smaller than MMC

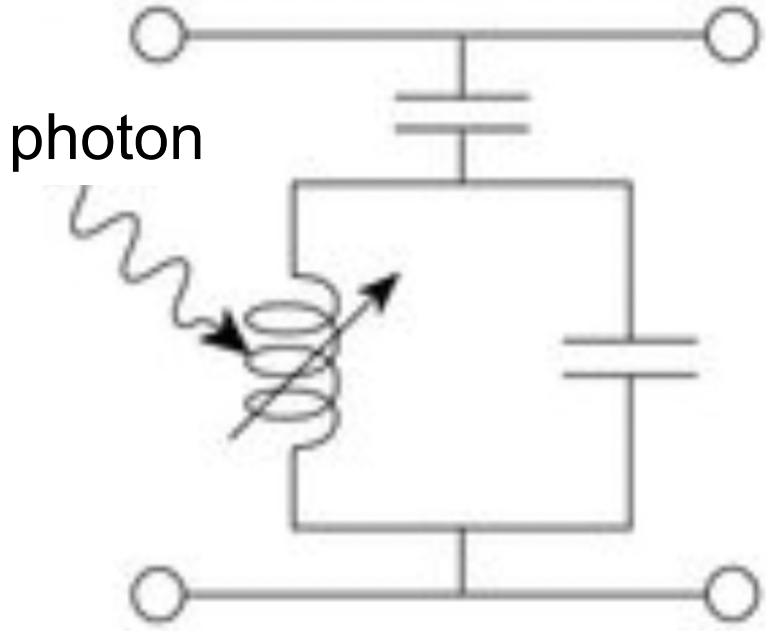
Superconductor Detectors

	Superconducting Tunnel Junction (STJ)
mechanism	tunnelling current proportional to number of quasiparticles
ΔE (soft X-ray)	~ 10 eV
ΔE (hard X-ray)	detector material too thin, low absorption
advantage	high count rate (10^4 /s)
disadvantage	"low" energy resolution; small energy range



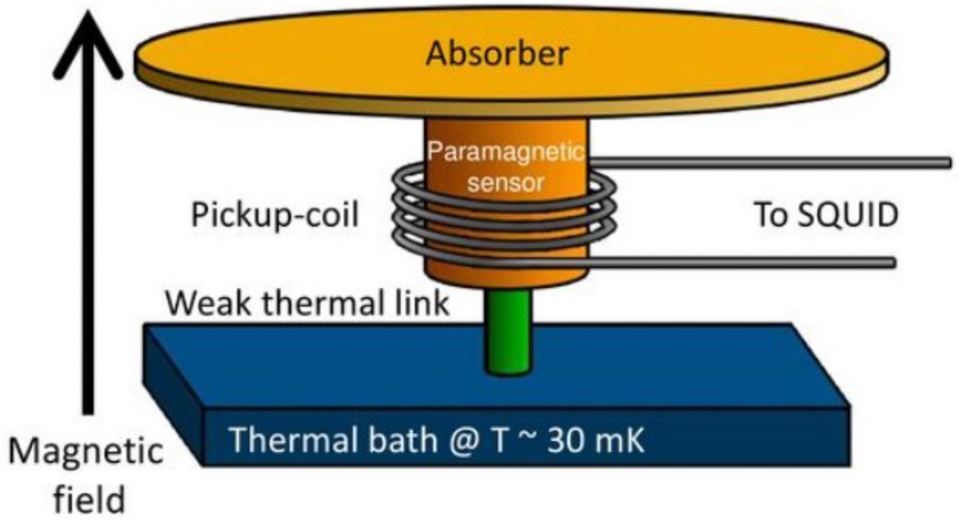
Superconductor Detectors

	Microwave Kinetic Inductance Detectors (MKID)
mechanism	quasiparticle density influences the resonant frequency of LC circuit
ΔE (soft X-ray)	~ several 10 eV
ΔE (hard X-ray)	rarely developed
advantage	large array multiplexing
disadvantage	"low" energy resolution; small energy range



Superconductor Detectors

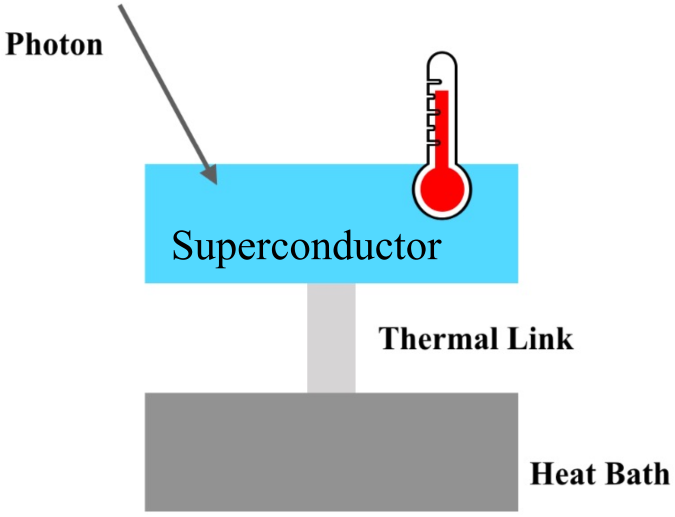
	Metallic Magnetic Calorimater (MMC)
mechanism	magnetic flux change in the paramagnetic material
ΔE (soft X-ray)	~ 1 eV
ΔE (hard X-ray)	40 eV@60 keV (can be better)
advantage	high energy resolution; large energy range
disadvantage	hard to multiplex

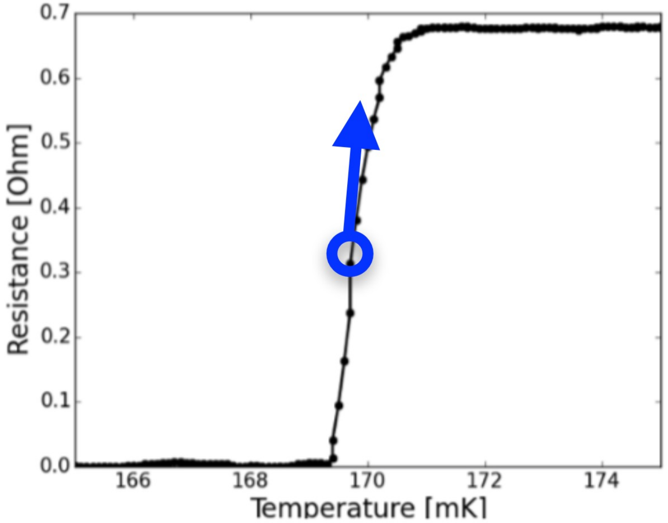


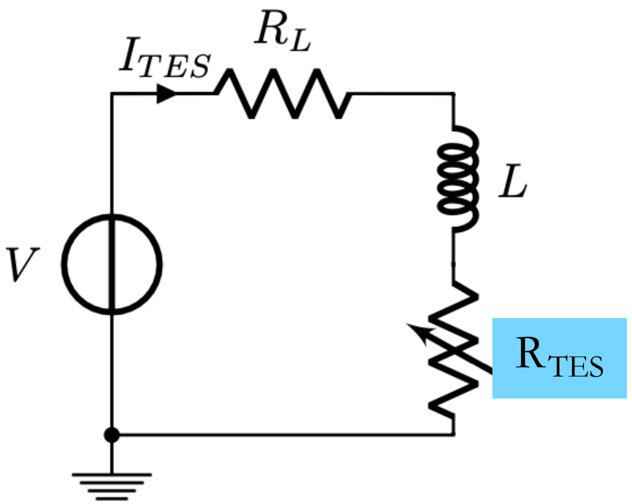
Superconductor Detectors

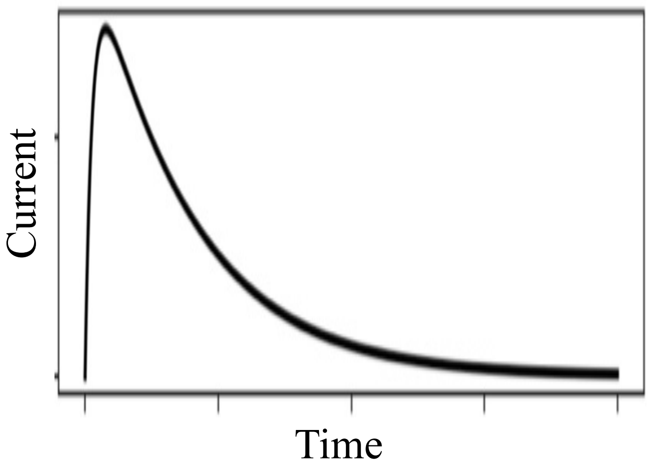
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

	Transition-Edge Sensor (TES)
mechanism	resisntance change due to photon heating
ΔE (soft X-ray)	~1 eV
ΔE (hard X-ray)	5 eV @ 17 keV
advantage	high energy resolution; well-developed multiplex technique
disadvantage	energy range smaller than MMC

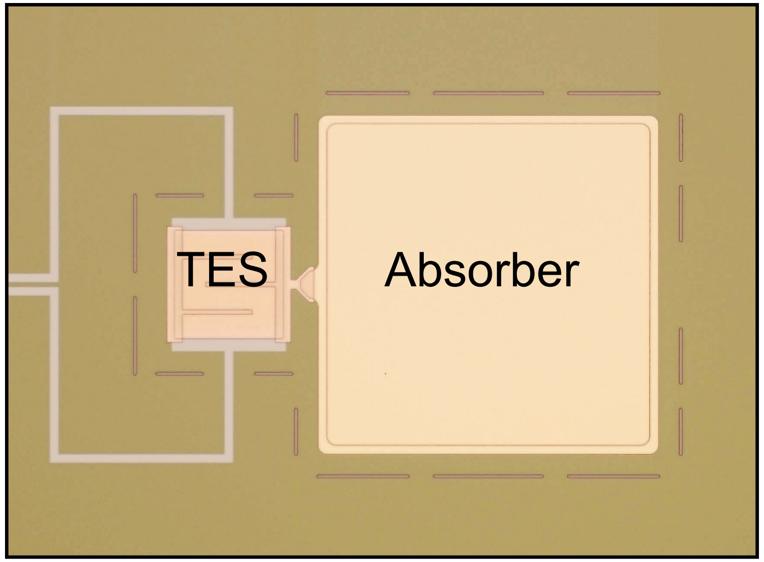


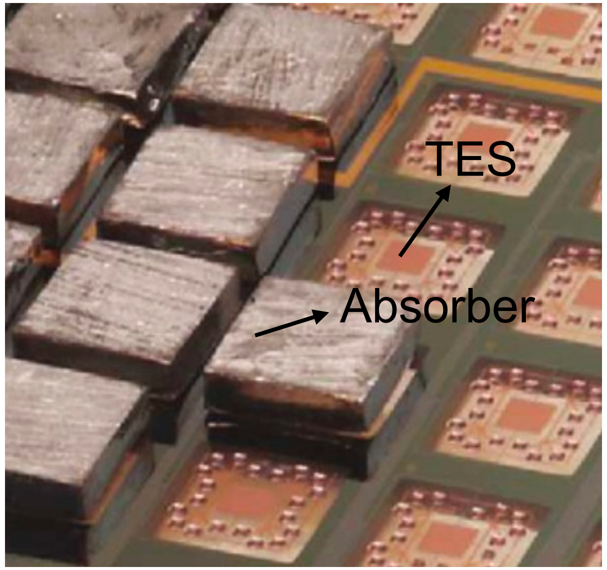


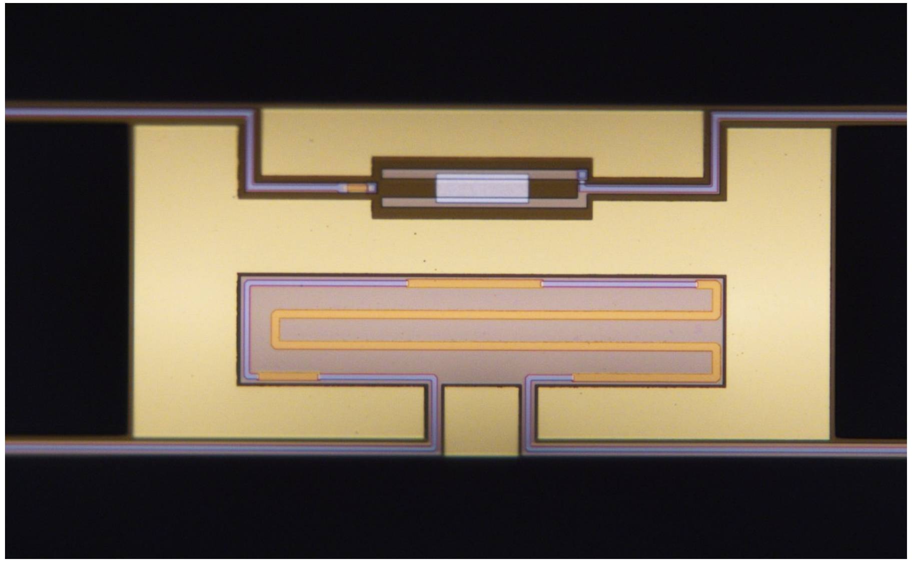




TES: Transition-Edge Sensor



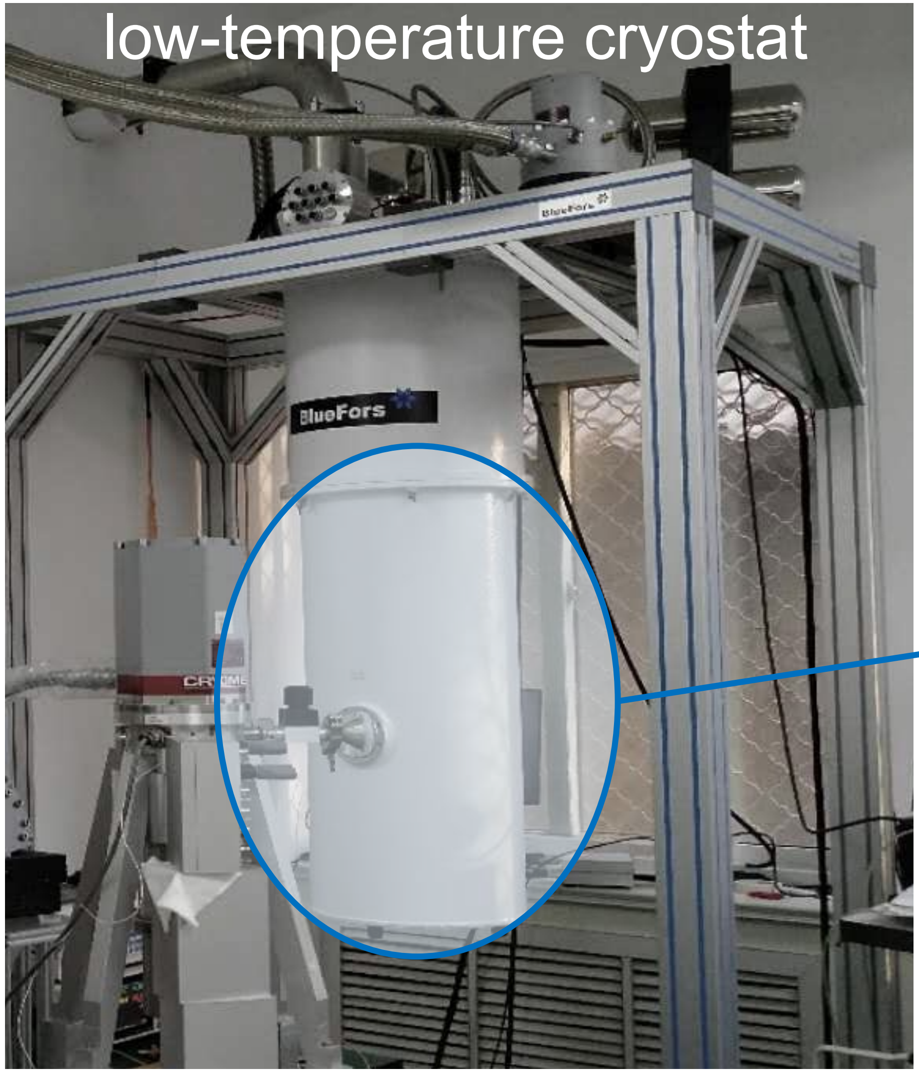


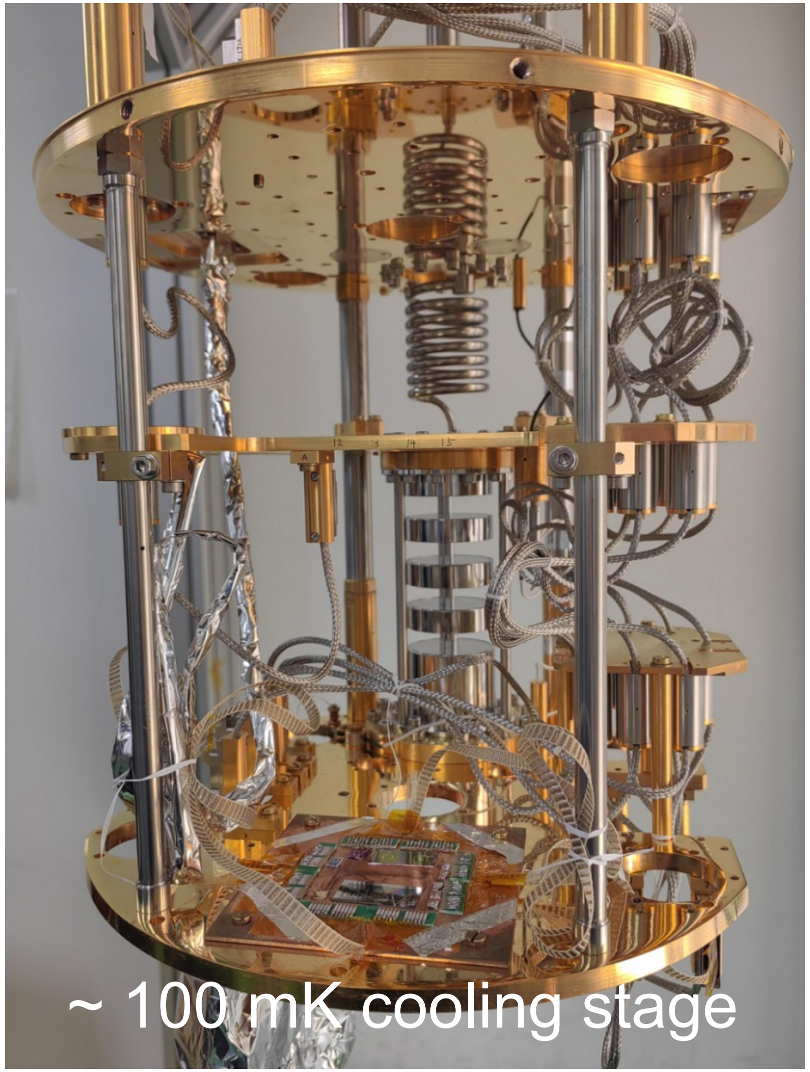


Bennett *et al*. Rev. Sci. Instrum. **83**, 093113 (2012)

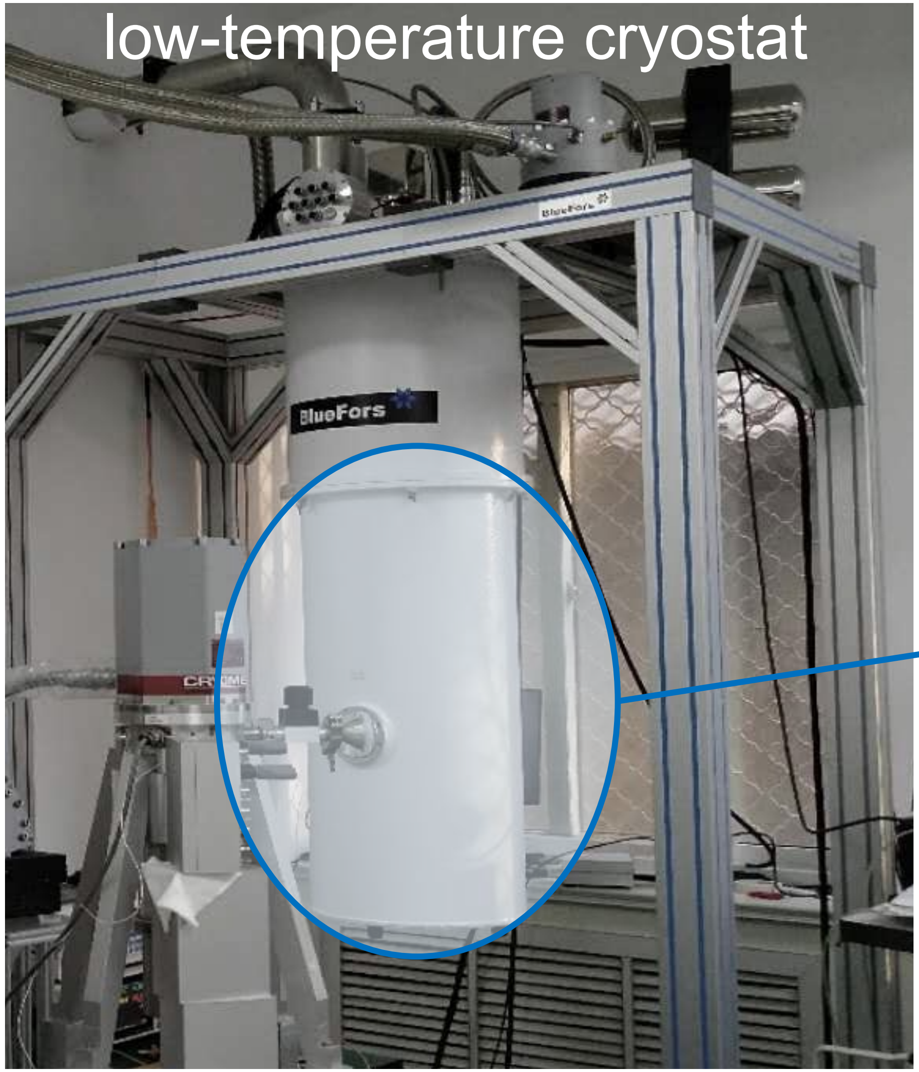
TES: Transition-Edge Sensor

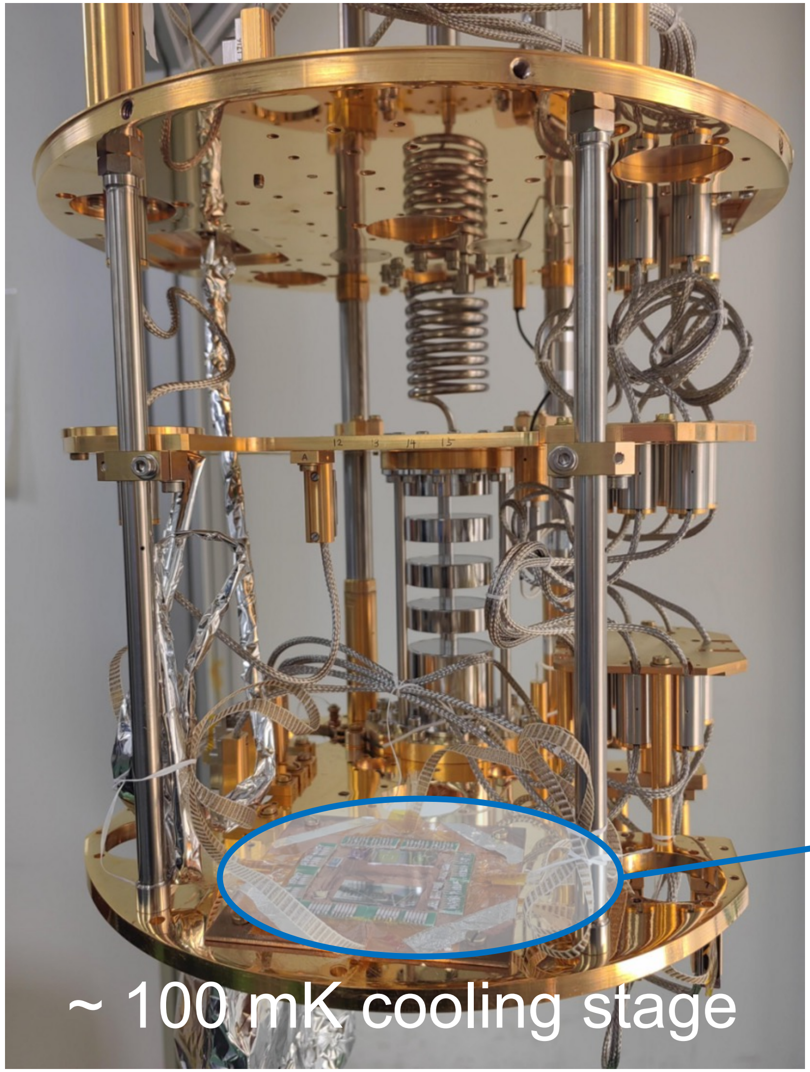
TES: Transition-Edge Sensor

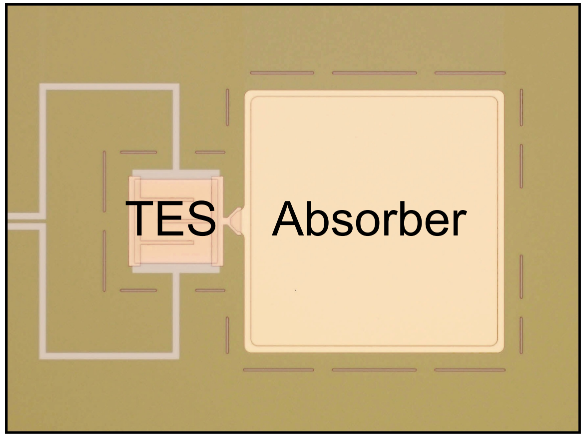




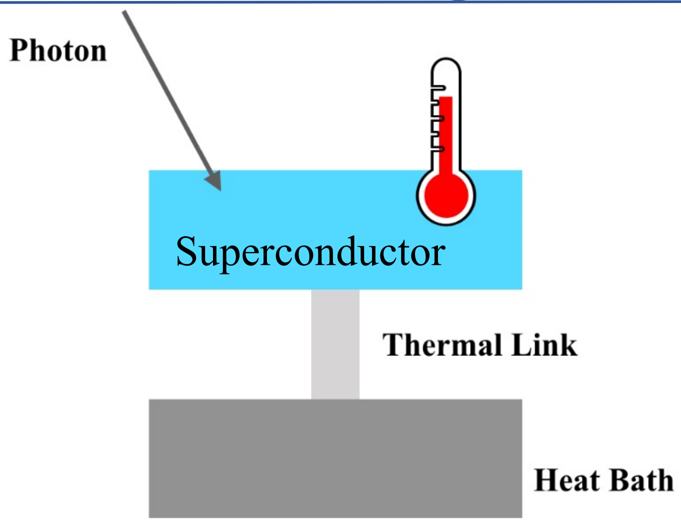
TES: Transition-Edge Sensor

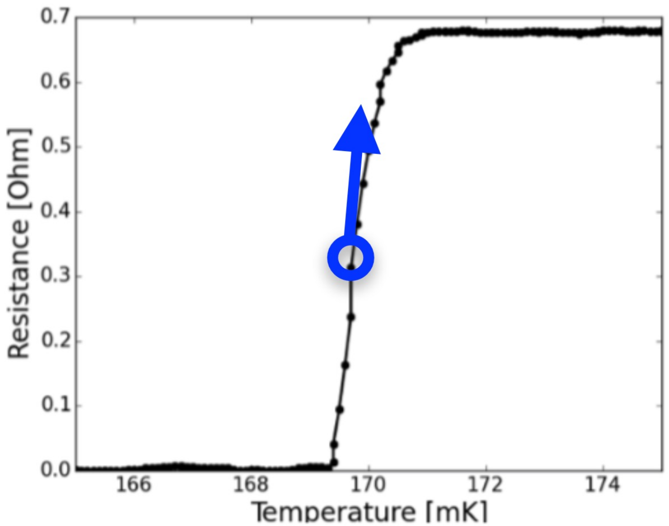


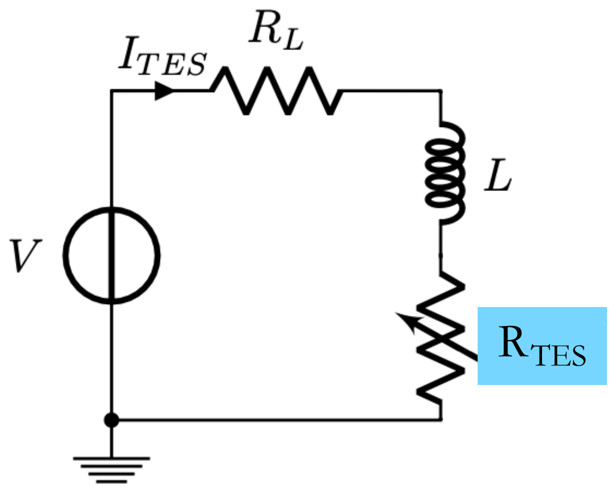




TES Design







R(T, I) relation

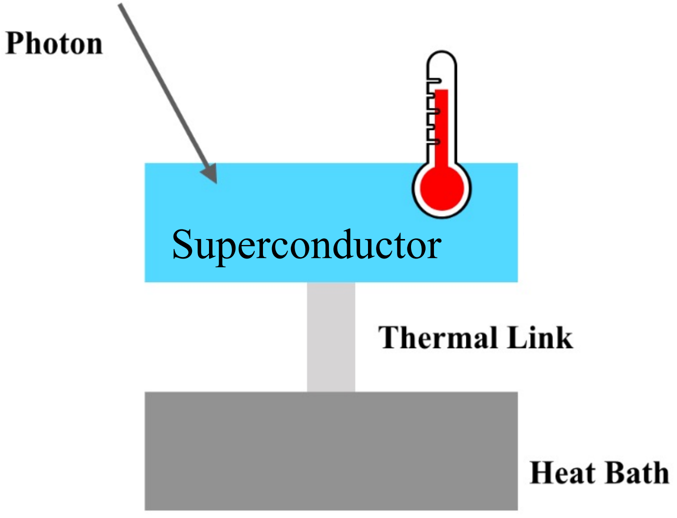
Thermal bias ← - - - - → Electrical bias

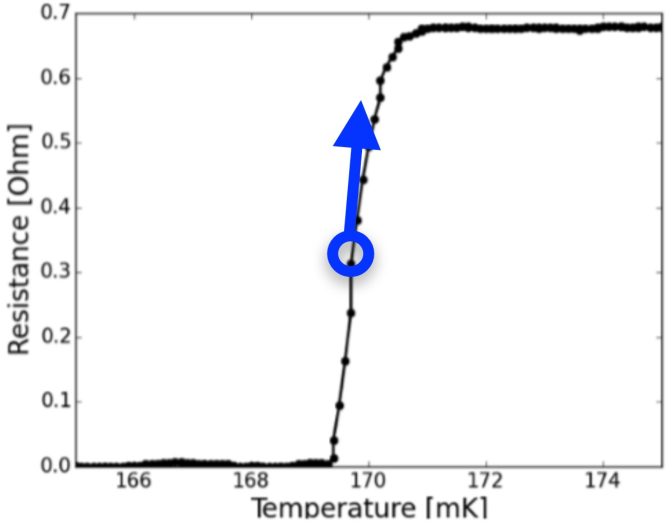
$$\frac{\mathrm{d}\delta T}{\mathrm{d}t} = \frac{I_0 R_0 (2+\beta_I)}{C}\delta I - \frac{(1-\mathscr{L}_I)}{\tau}\delta T$$

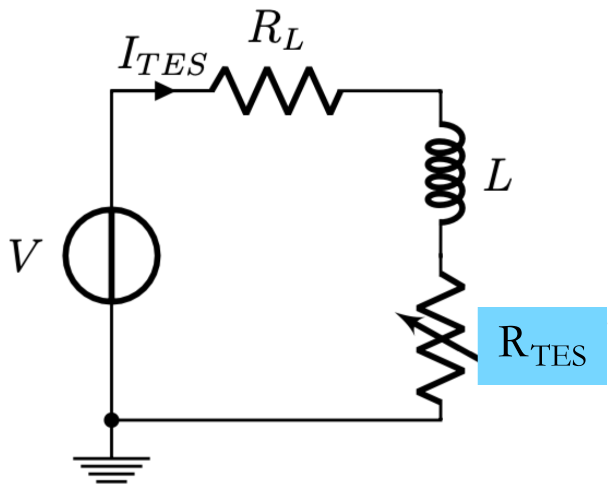
$$R(T,I) \approx R_0 + \alpha_I \frac{R_0}{T_0}\delta T + \beta_I \frac{R_0}{I_0}\delta I$$

$$\frac{\mathrm{d}\delta I}{\mathrm{d}t} = -\frac{R_L + R_0(1+\beta_I)}{L}\delta I - \frac{\mathscr{L}_I G}{I_0 L}\delta T$$

TES Design







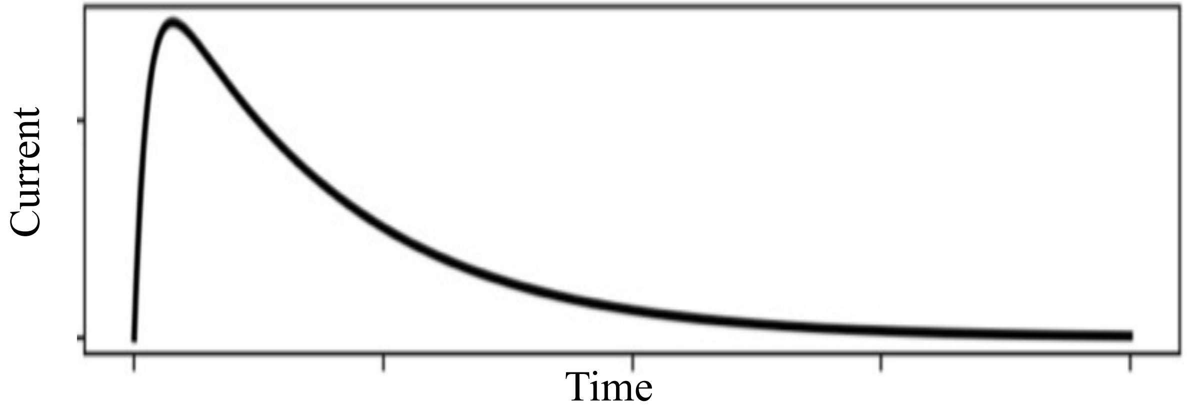
R(T, I) relation

Thermal bias ← - - - - → Electrical bias

$$\frac{\mathrm{d}\delta T}{\mathrm{d}t} = \frac{I_0 R_0 (2+\beta_I)}{C}\delta I - \frac{(1-\mathscr{L}_I)}{\tau}\delta T$$

$$R(T,I) \approx R_0 + \alpha_I \frac{R_0}{T_0}\delta T + \beta_I \frac{R_0}{I_0}\delta I$$

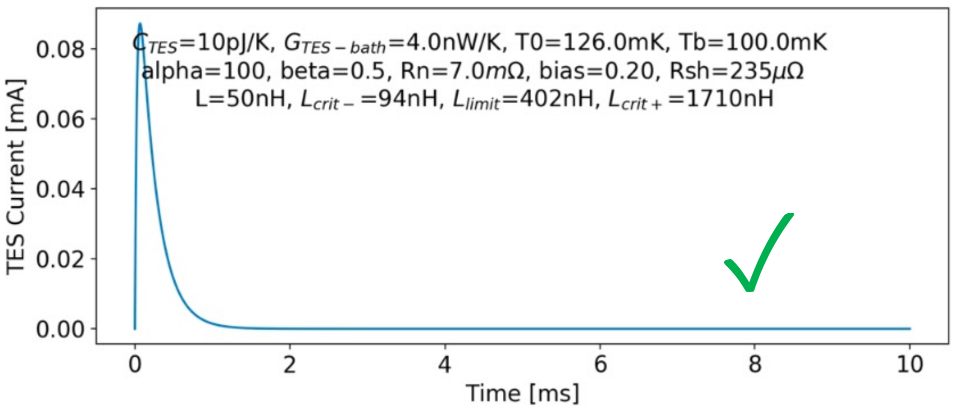
$$\frac{\mathrm{d}\delta I}{\mathrm{d}t} = -\frac{R_L + R_0(1+\beta_I)}{L}\delta I - \frac{\mathscr{L}_I G}{I_0 L}\delta T$$



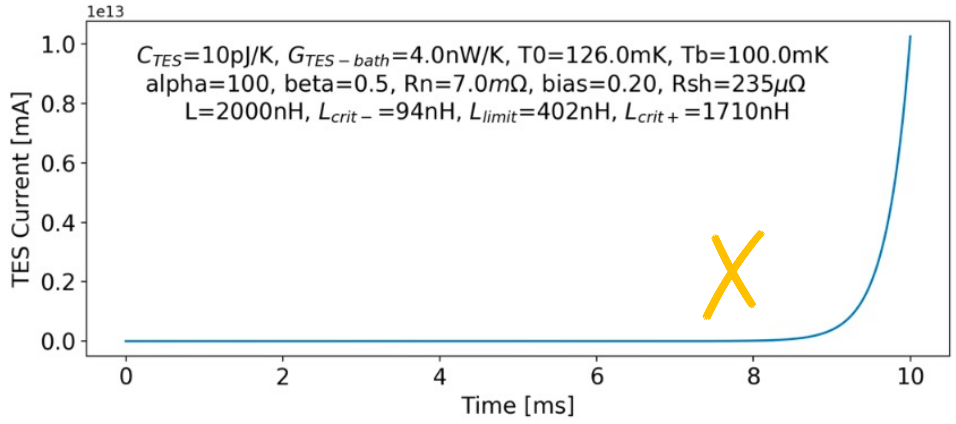
TES Design

Thermal and electrical parameters should be carefully chosen to produce stable signal response

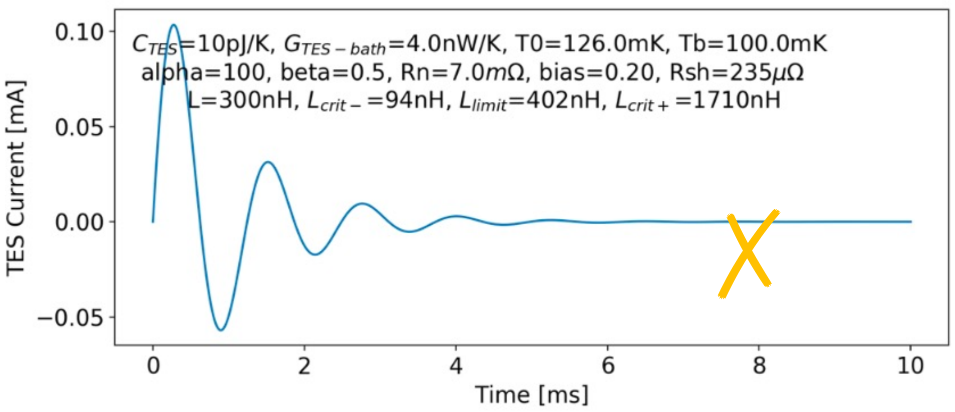
(a) $L < L_{crit-}$, overdamped, stable



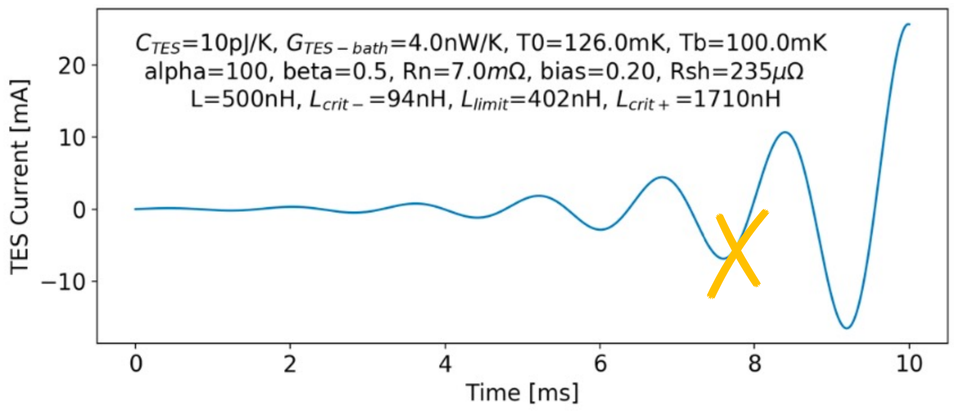
(c) $L > L_{crit+}$, overdamped, unstable



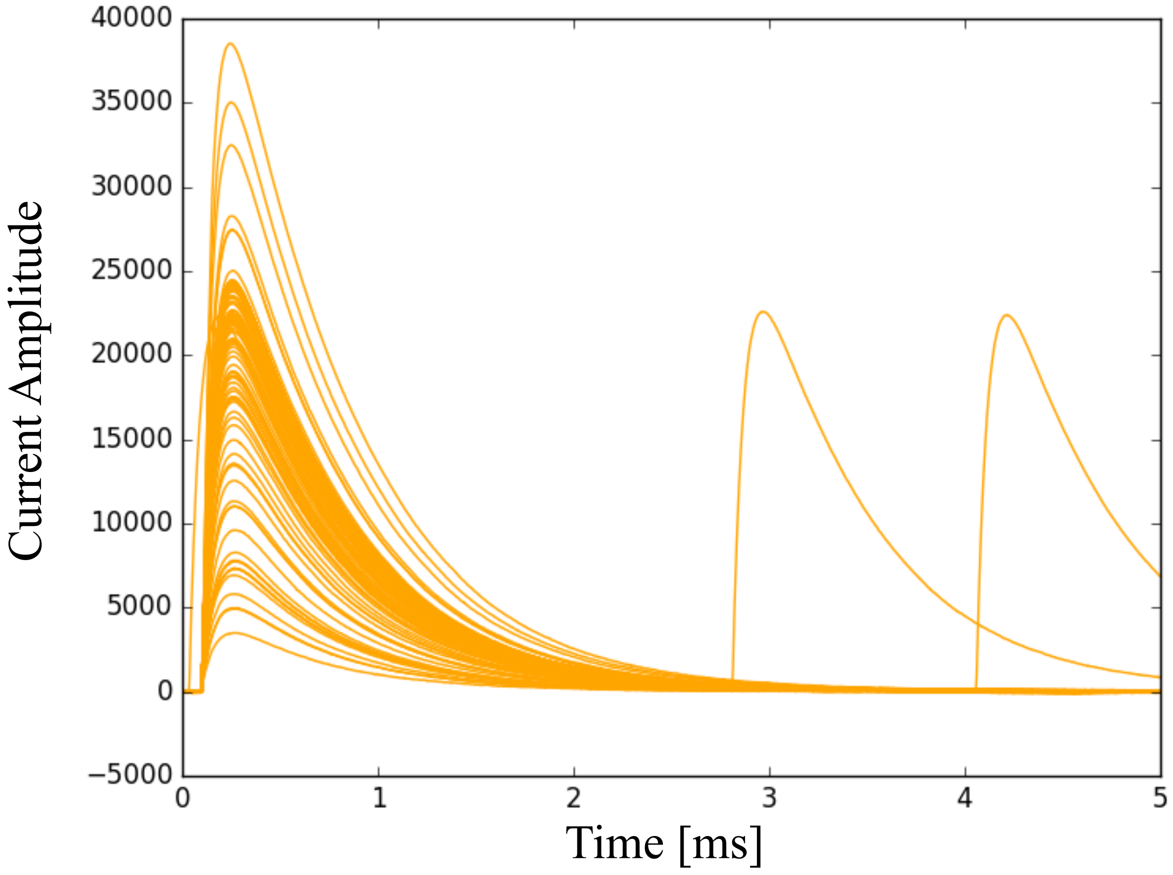
(b) $L_{crit-} < L < L_{limit}$, underdamped, stable



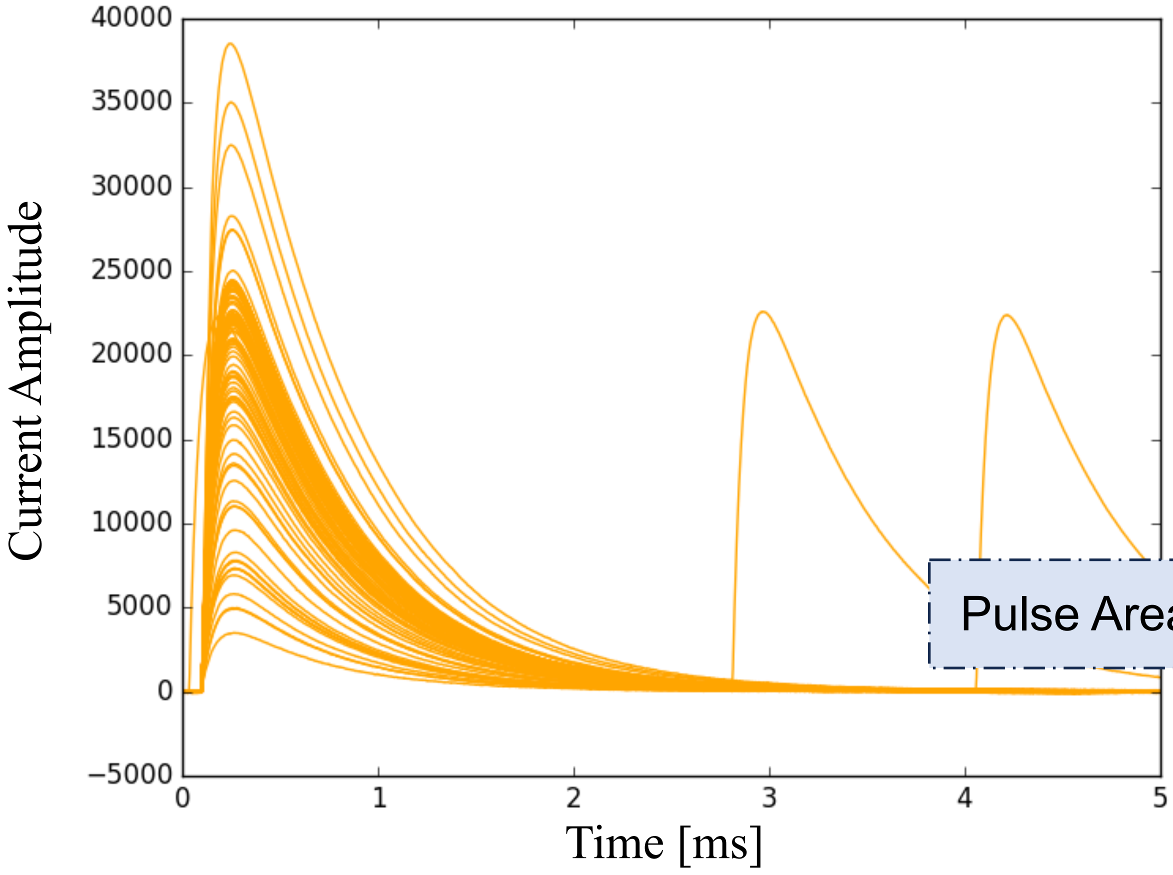
(d) $L_{limit} < L < L_{crit+}$, underdamped, unstable



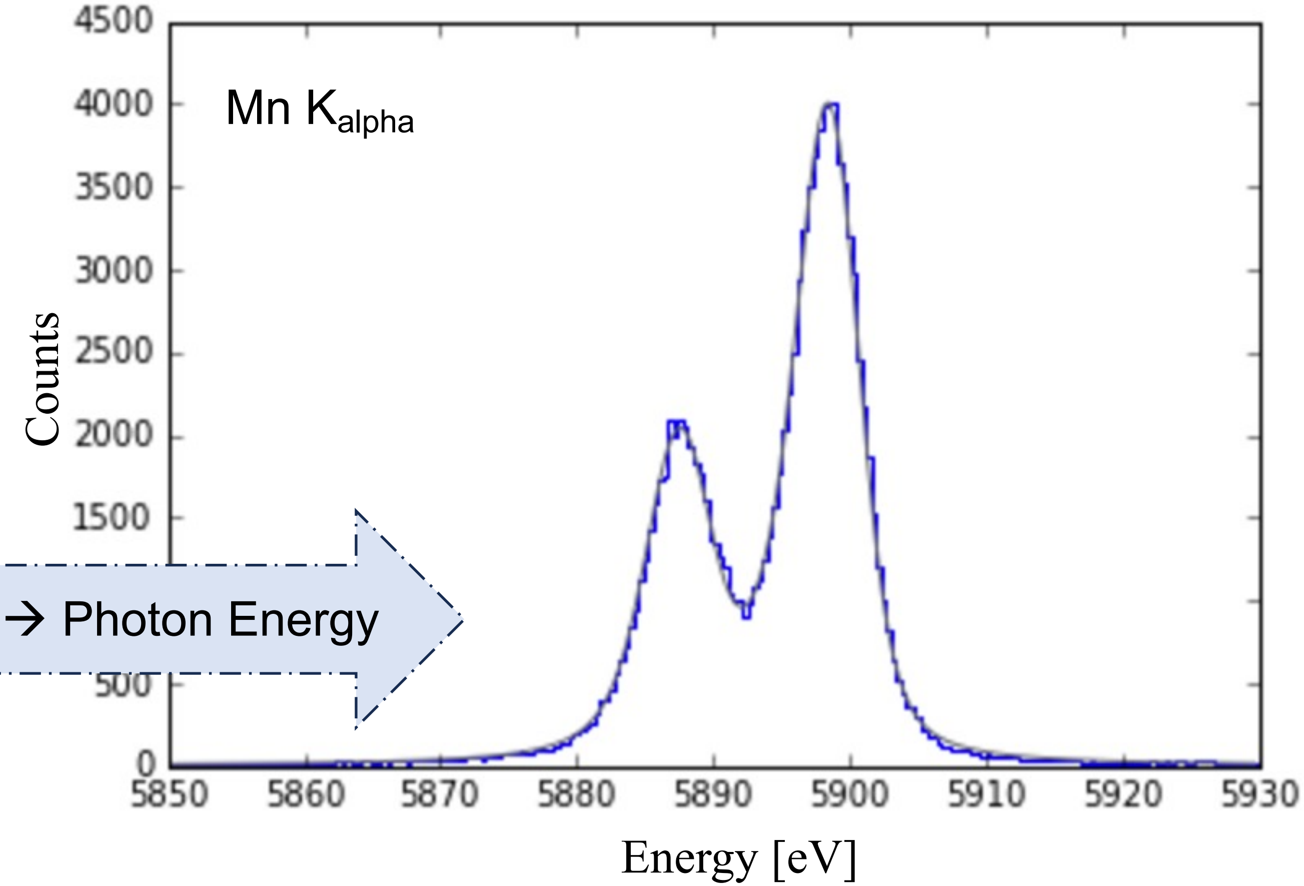
TES Design


40000
35000
30000
25000
20000
15000
10000
5000
0
−5000
0
1
2
3
4
5
Current Amplitude
Time [ms]

TES Design



Pulse Area → Photon Energy



Application I: X-ray Science

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

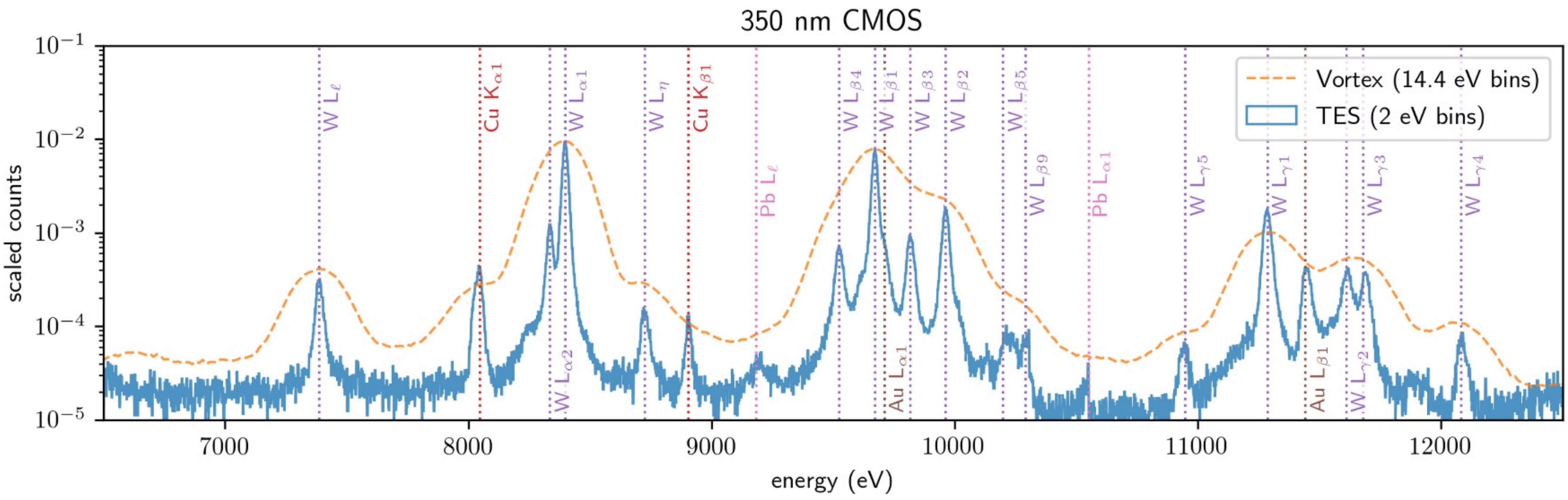


Fig. 3. Fluorescence spectra of a 350 nm CMOS integrated circuit chip, measured with a TES sensor (blue solid line) and a Vortex silicon-drift detector (orange dashed line). Prominent peaks are labeled with their corresponding element and line name.

Tejas Guruswamy et al. (2021)

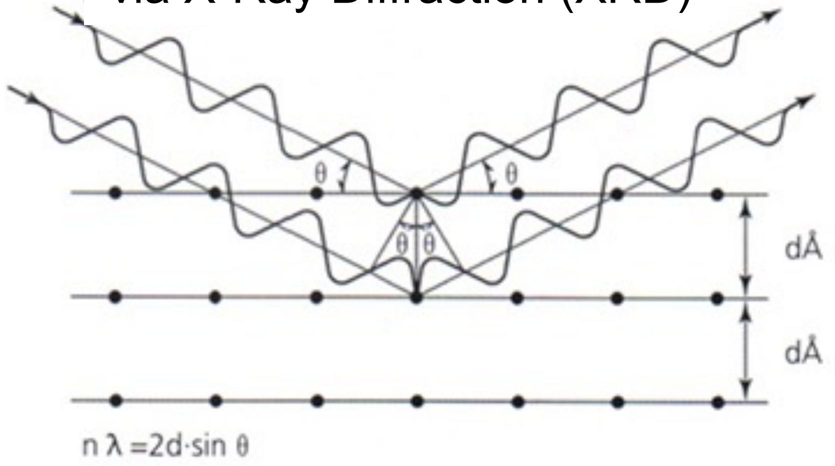
✓ neighboring spectral lines

✓ low content elements

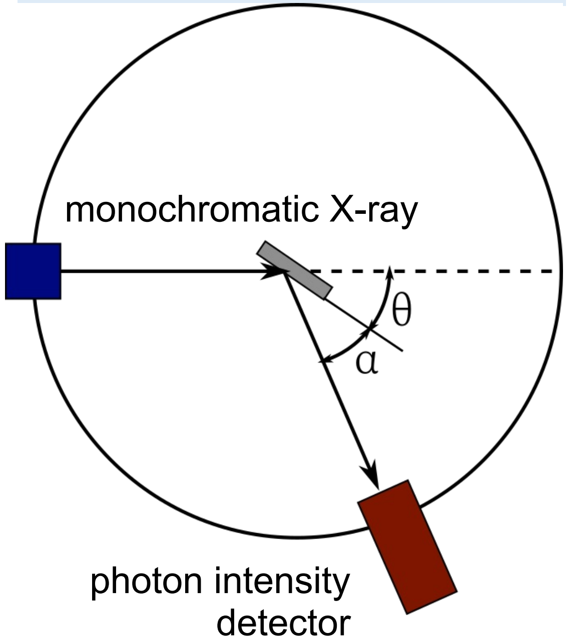
Application I: X-ray Science

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

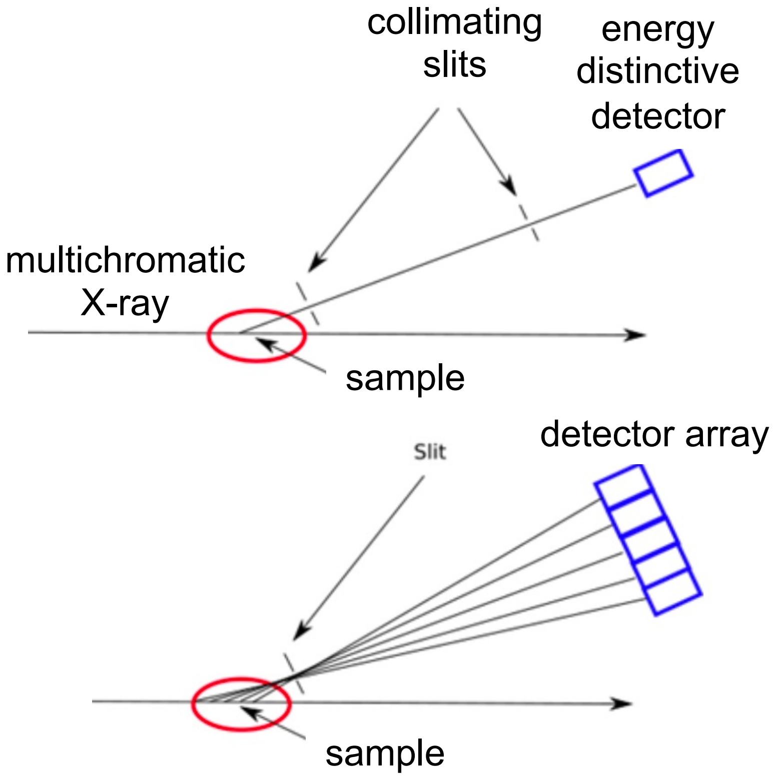
detect crystal structure
via X-Ray Diffraction (XRD)



angular dispersive XRD

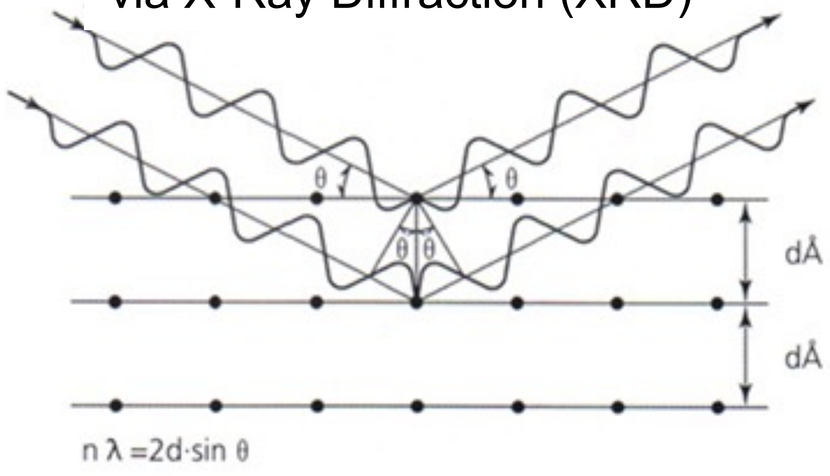


energy dispersive XRD

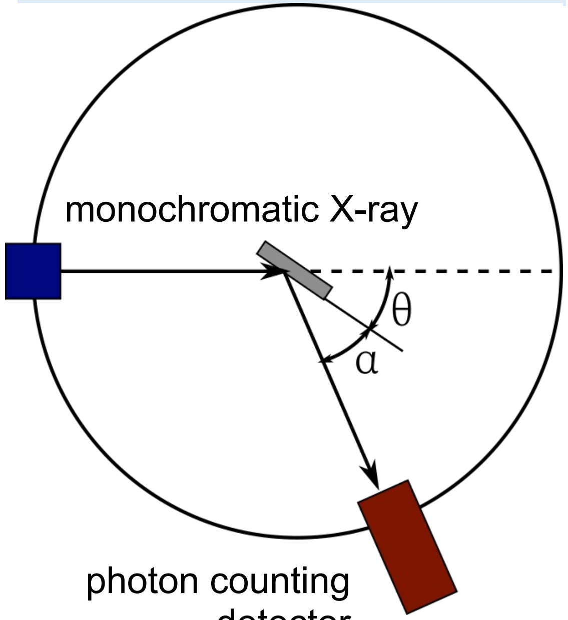


Application I: X-ray Science

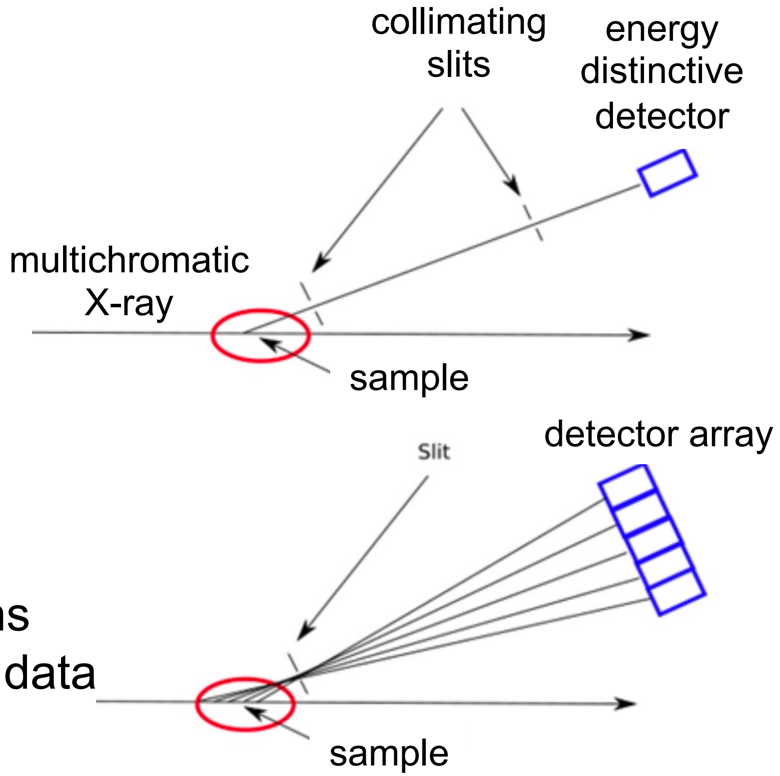
detect crystal structure
via X-Ray Diffraction (XRD)



angular dispersive XRD



energy dispersive XRD



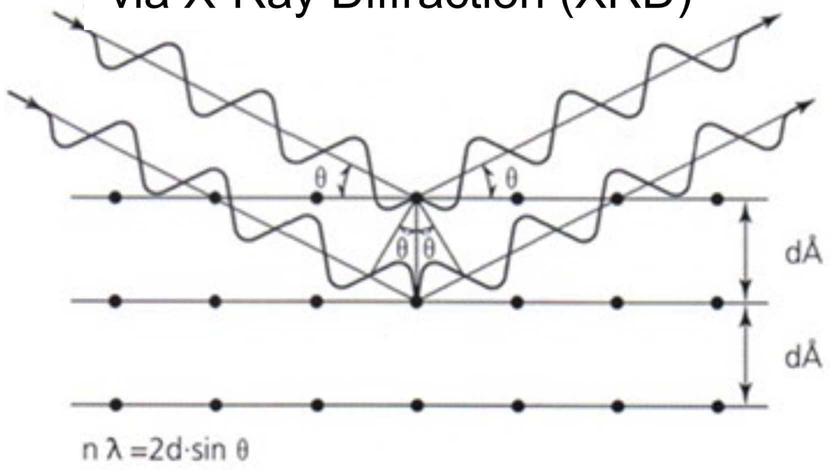
advantage of energy dispersive XRD:

- flexibility: fixed angle, convinient for experiments with extreme conditions
- 2 function in 1 shot: measures characteristic spectra while getting XRD data
- large volumn of interest

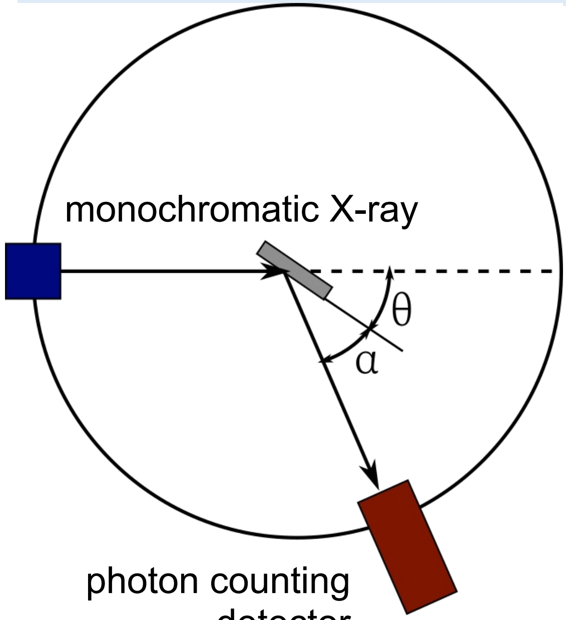
Application I: X-ray Science

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

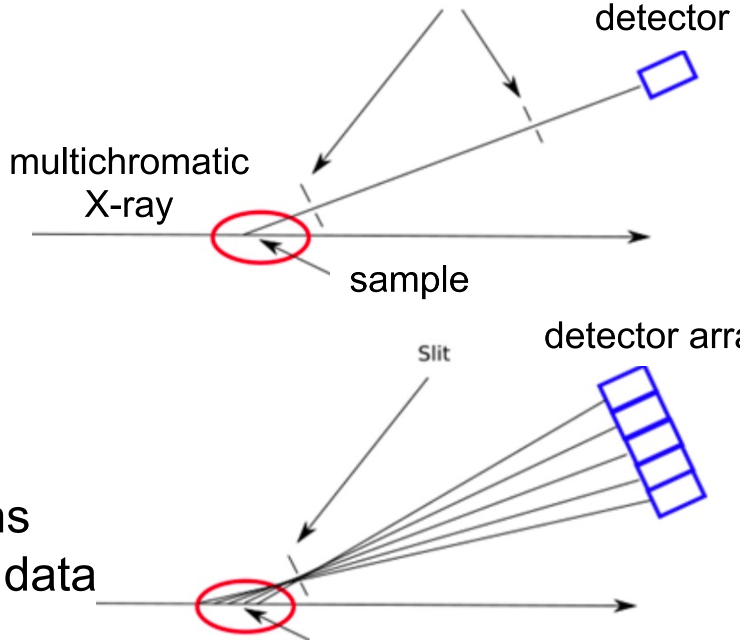
detect crystal structure
via X-Ray Diffraction (XRD)



angular dispersive XRD



energy dispersive XRD



advantage of energy dispersive XRD:

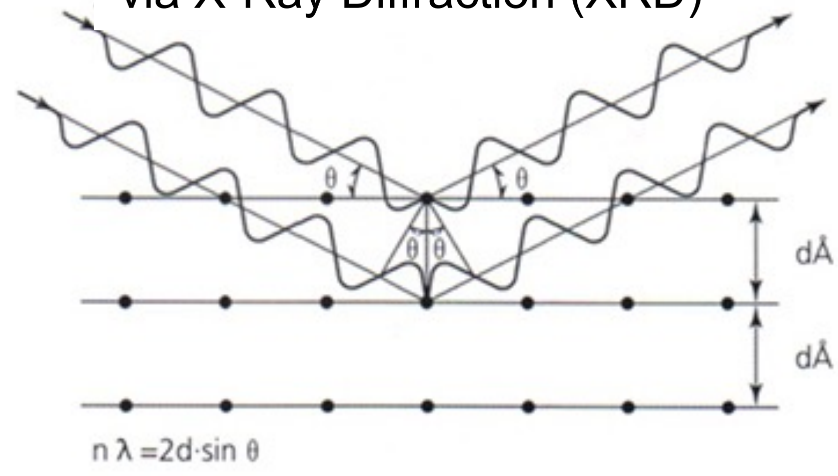
- flexibility: fixed angle, convinient for experiments with extreme conditions
- 2 function in 1 shot: measures characteristic spectra while getting XRD data
- large volumn of interest

disadvantage:

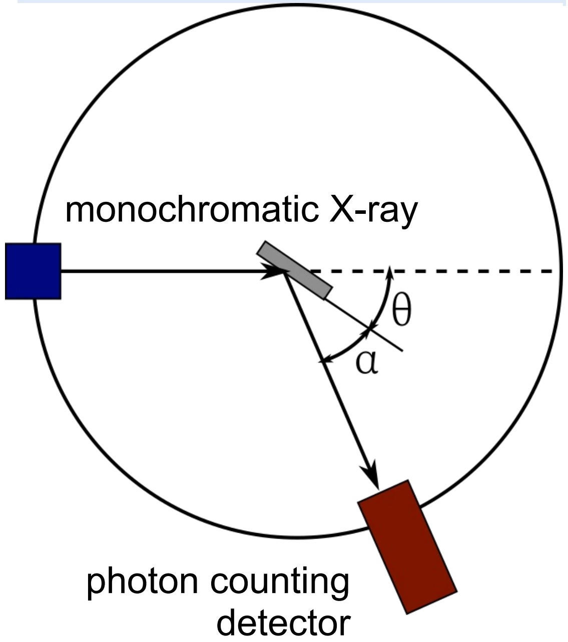
- resolution worse than angular dispersive XRD with semiconductor detectors (770 eV @ 112 keV)

Application I: X-ray Science

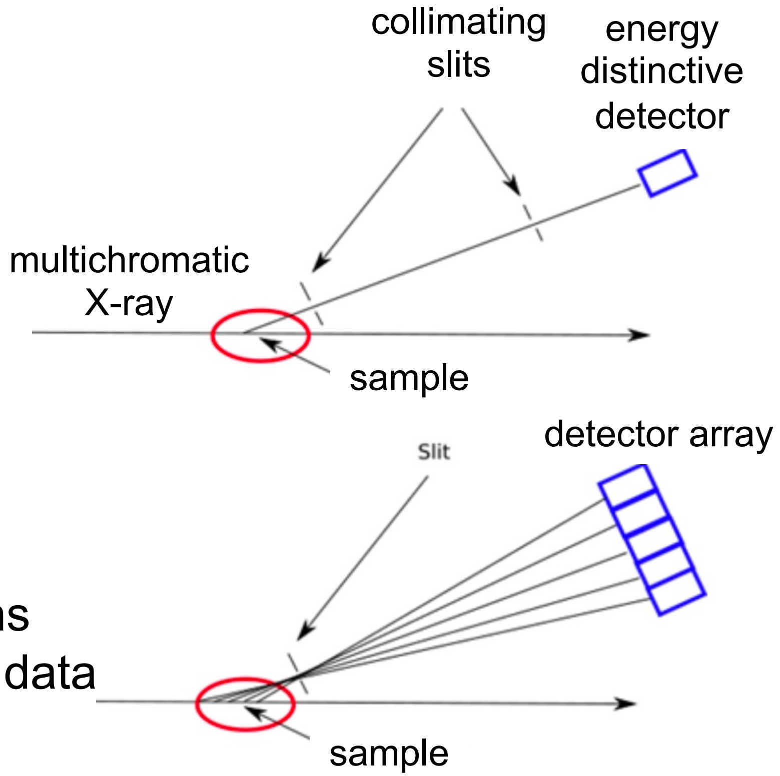
detect crystal structure
via X-Ray Diffraction (XRD)



angular dispersive XRD



energy dispersive XRD



advantage of energy dispersive XRD:

- flexibility: fixed angle, convinient for experiments with extreme conditions
- 2 function in 1 shot: measures characteristic spectra while getting XRD data
- large volumn of interest

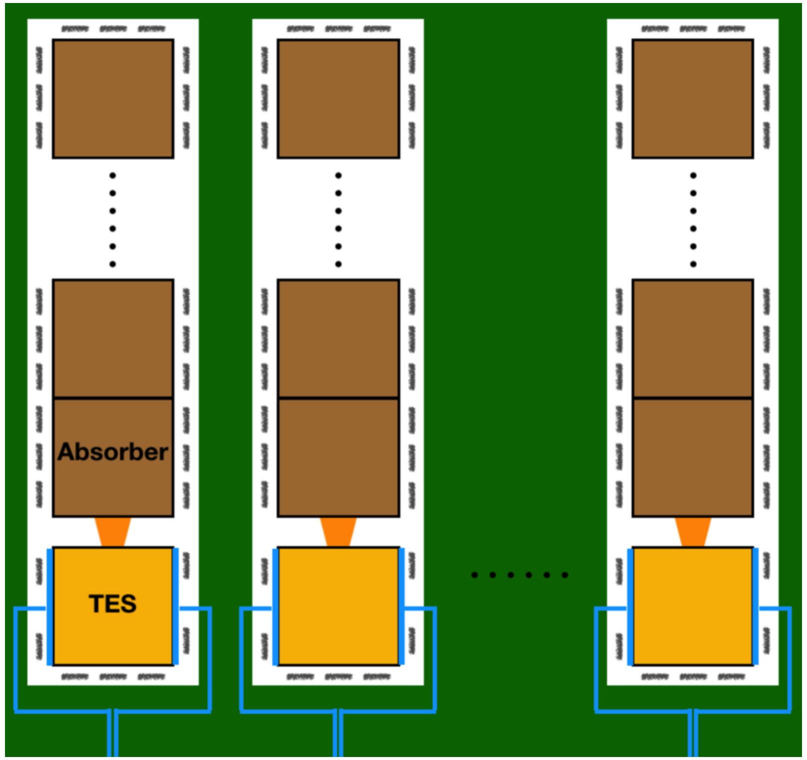
disadvantage:

- resolution worse than angular dispersive XRD with semiconductor detectors (770 eV @ 112 keV)

TES detector: 80 eV @ 100 keV, can compete with angular dispersive XRD

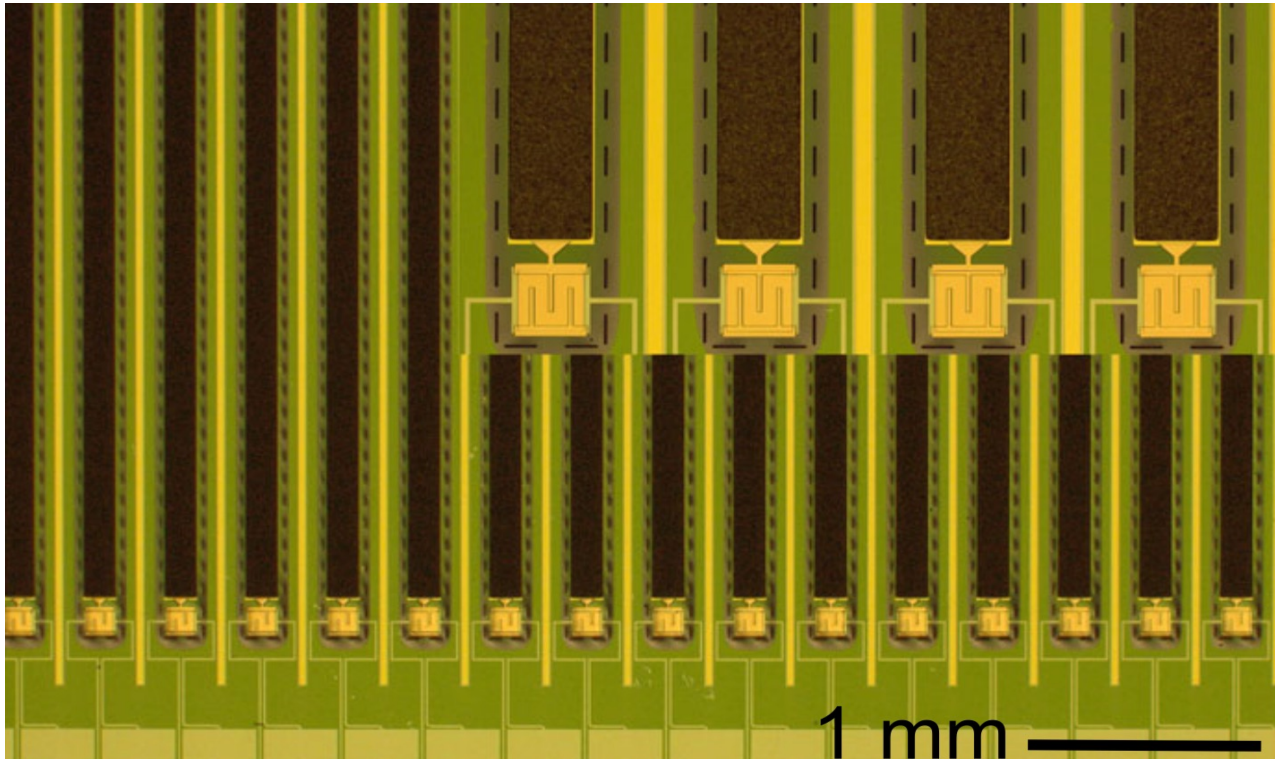
Application I: X-ray Science

design



Daikang Yan *et al. IEEE Trans. Appl. Supercond.* 29, 1–4 (2019)

1st version of fabrication



Umeshkumar Patel ... Daikang Yan .... *J. of Low Temp. Phys.* 199, 384–392 (2020)

Application II: QED

Muon: same charge as an electron, 200 times more massive

↓

Muonic atom Bohr radius: 200 times smaller

↓

Coulomb field: 40,000 times stronger

↓

Study QED (quantum electrodynamics) under extremely strong electric fields by **measuring the x-ray energy of muonic atom de-excitation**

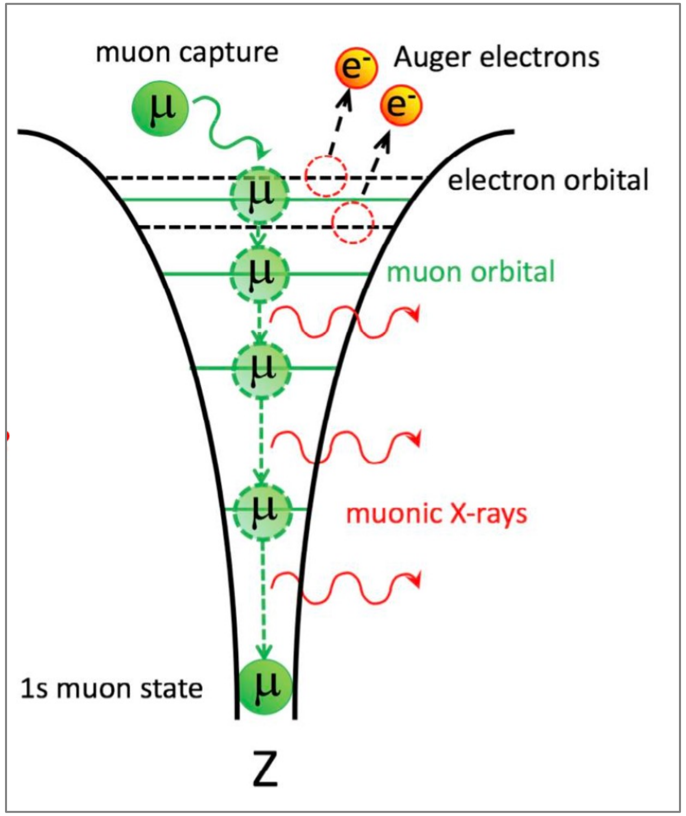
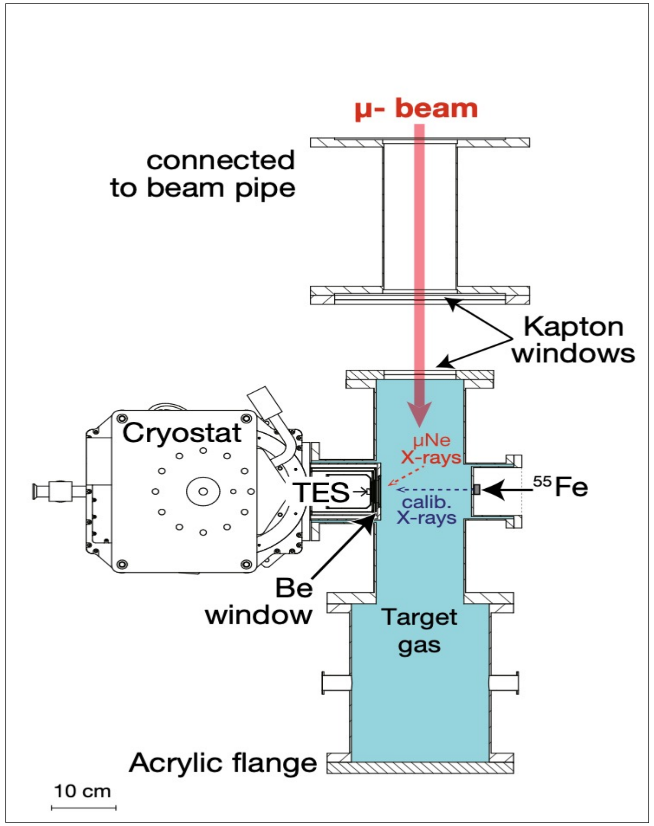


Figure credit: T. Okumura, RIKEN



S. Okada *et al*,. Journal of Low Temperature Physics (2020) 200:445–451

Application II: QED

Target μ-Ar energy: — 44.3 keV, predicted QED shift 99 eV
— 20.5 keV, predicted QED shift 23 eV

Measurement goal: measure absolute energy with accuracy of ~ 1eV

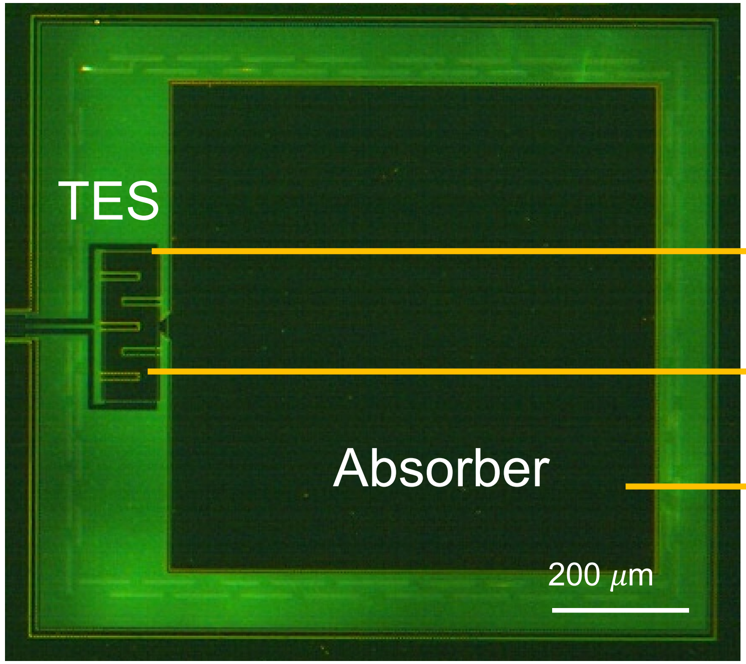
↓

Traditional semiconductor detectors does not have enough energy resolution (500 eV @ 45 keV).

TES is a good candidate for this application, the key design considerations are:

- good linearity under 45 keV → $E_{sat} \propto C/\alpha$
- good energy resolution → $\Delta E \propto \sqrt{C/\alpha}$
- high collecting efficiency → multiplexing, large absorber

Application II: QED

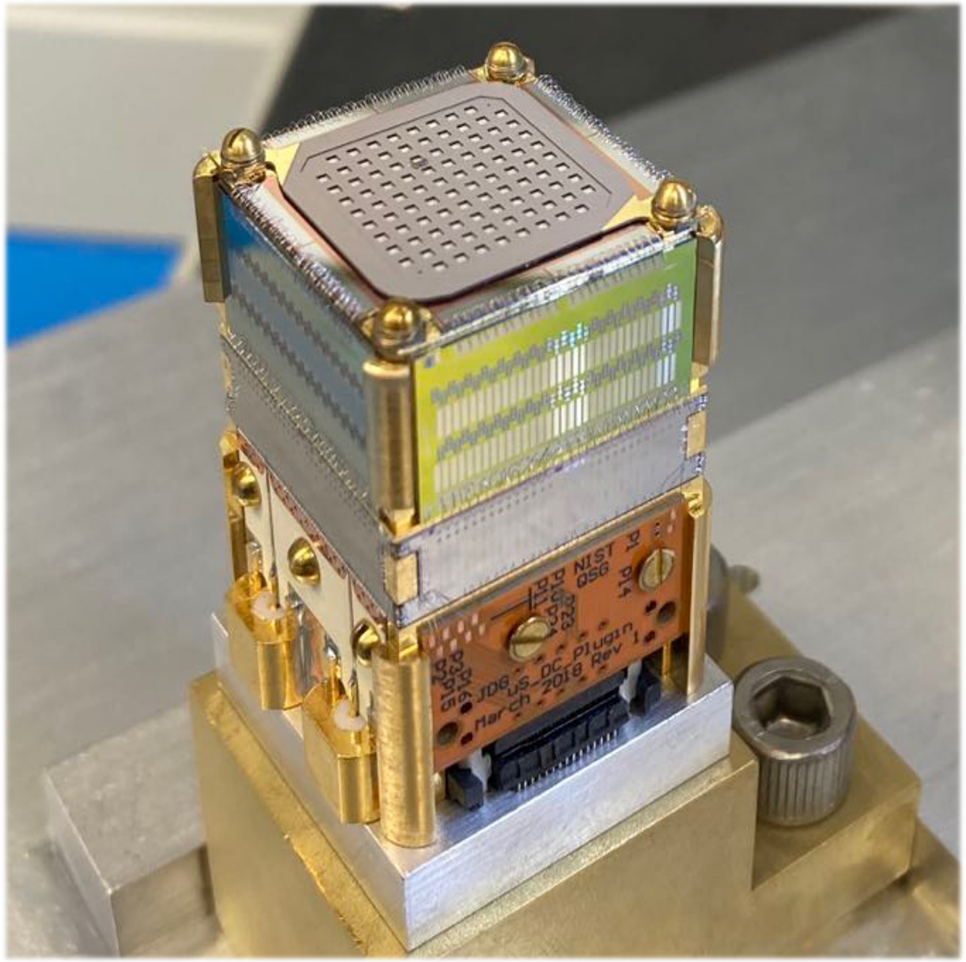


TES:
Mo/Au bilayer

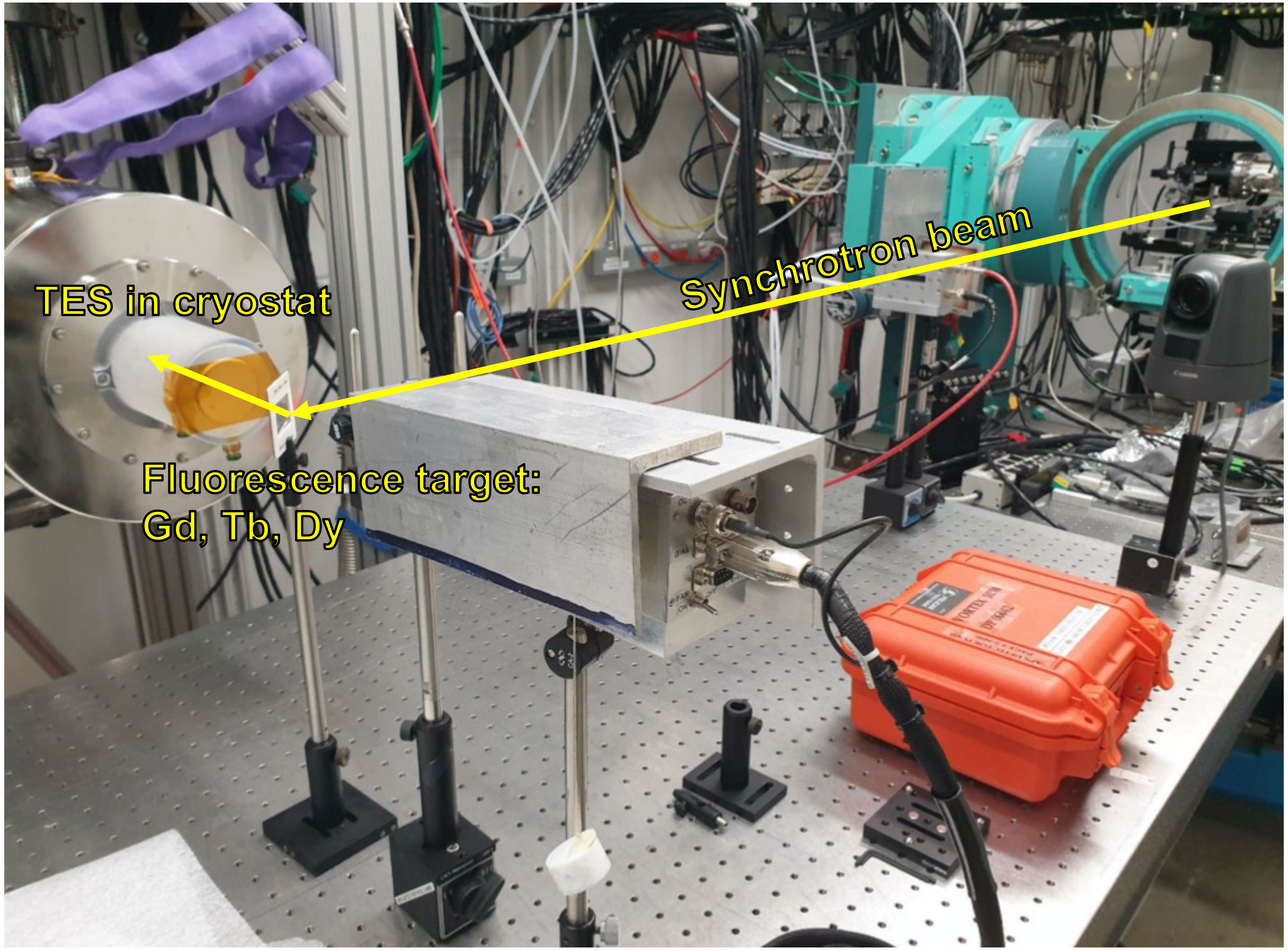
Au bars： suppress noise and adjust $\alpha = \frac{\partial logR}{\partial logT}$

Absorber:
Au： large specific heat, set the total *C*
Bi： small specific heat, thick plating to increase QE

Application II: QED

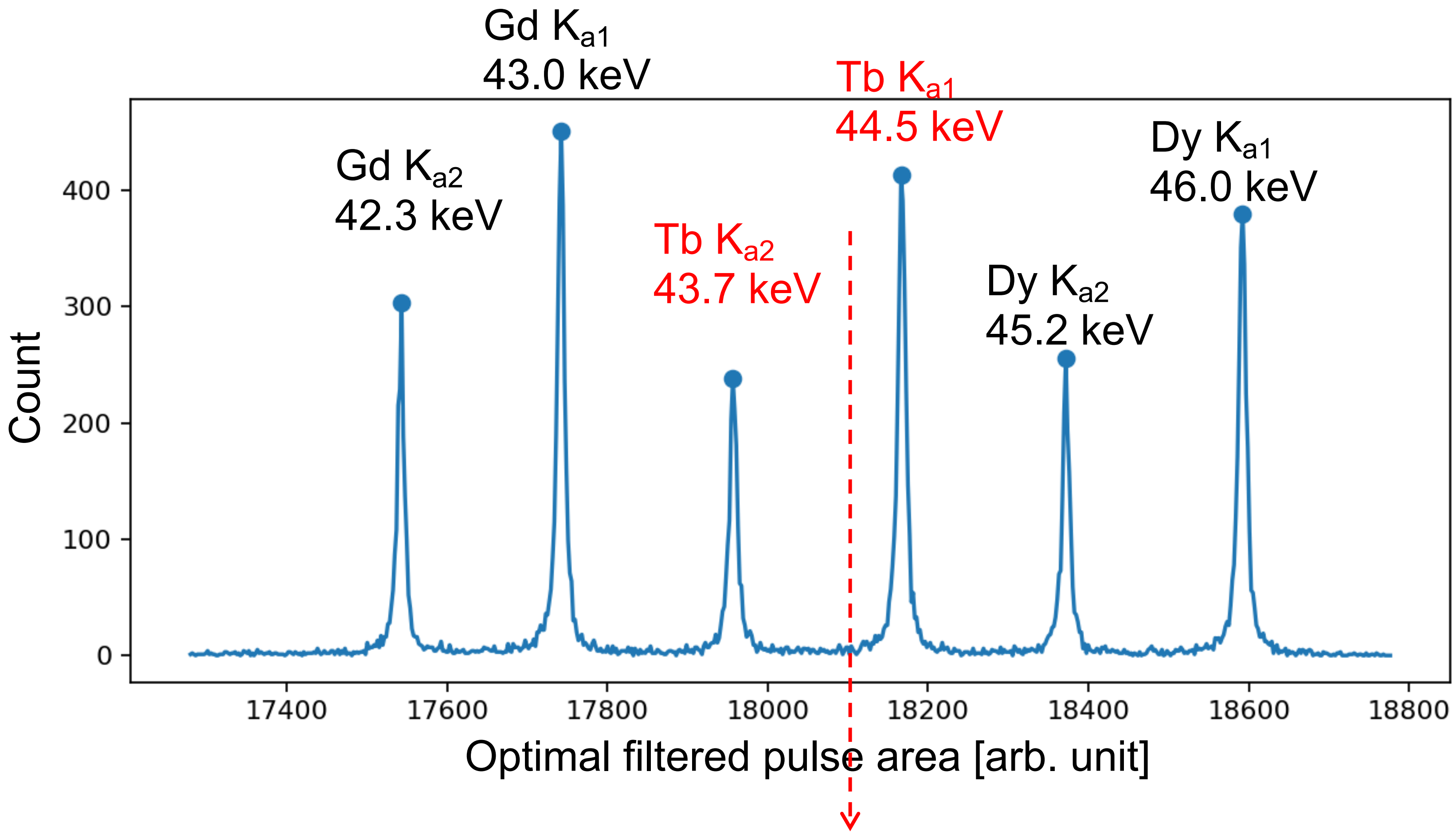


Application II: QED



Experiment conducted at Beamline-1BM-C, Advanced Photon Source, ANL, USA

Application II: QED



Line of interest is at 44.3 keV

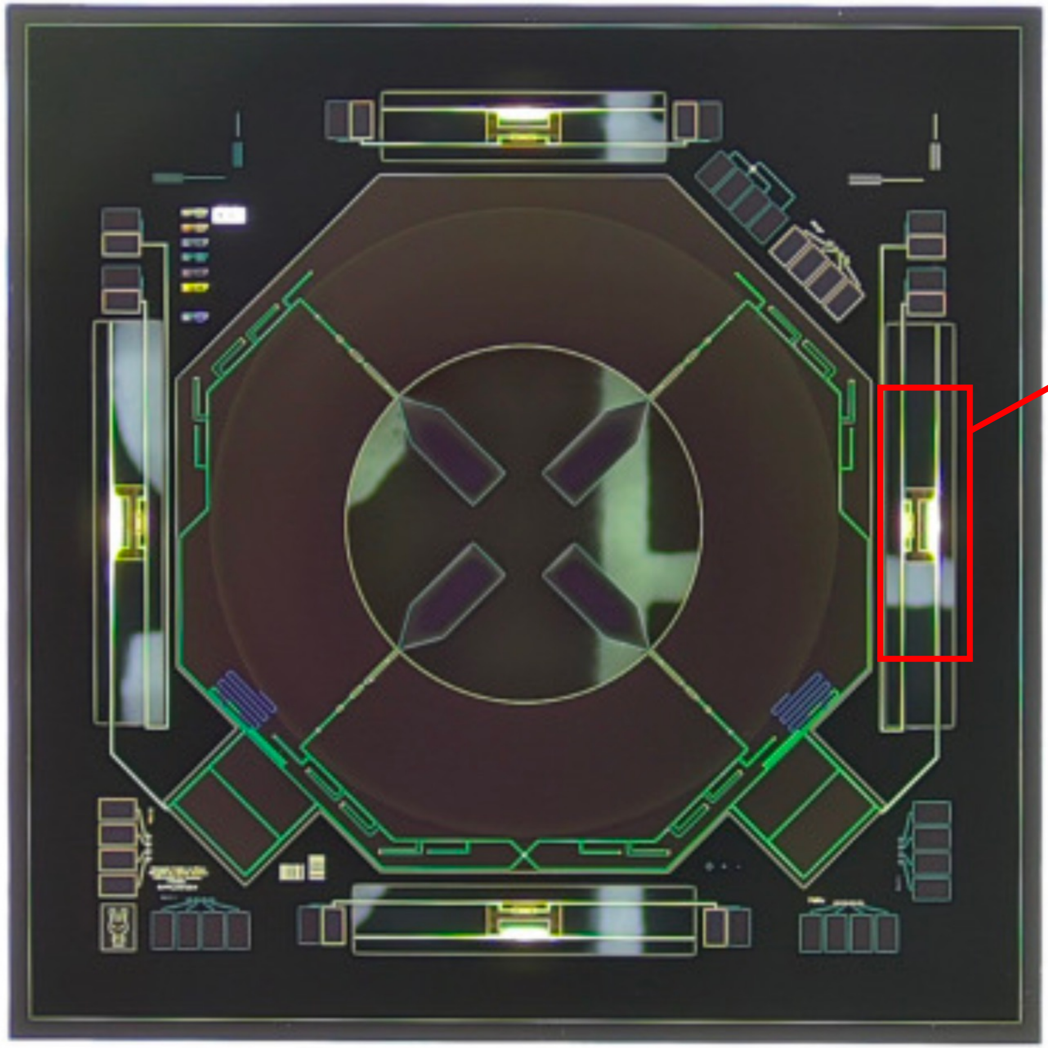
Application II: QED

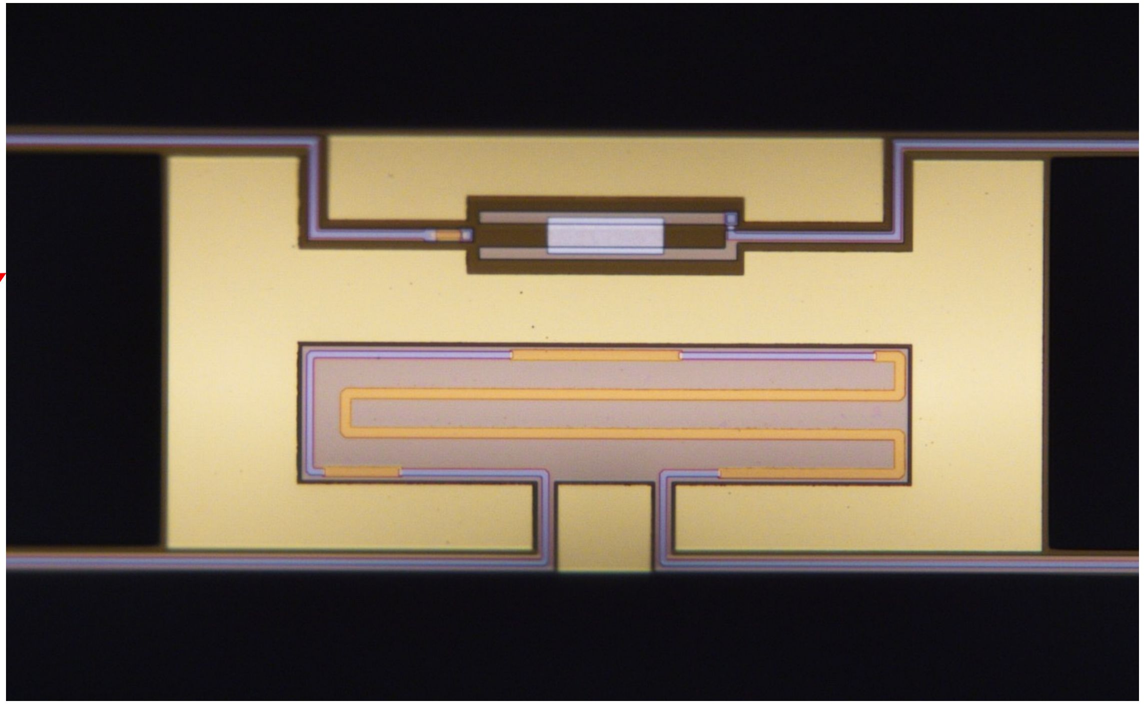
Energy deviation (eV)	Tb $K\alpha_1$ 44.5 keV	Tb $K\alpha_2$ 43.7 keV
5 pJ/K	2.11 (116)	1.00 (122)
6 pJ/K	0.38 (76)	0.13 (84)
7 pJ/K	0.01 (103)	0.24 (107)

Daikang Yan *et al.* (2022)

More results to come in 2024......

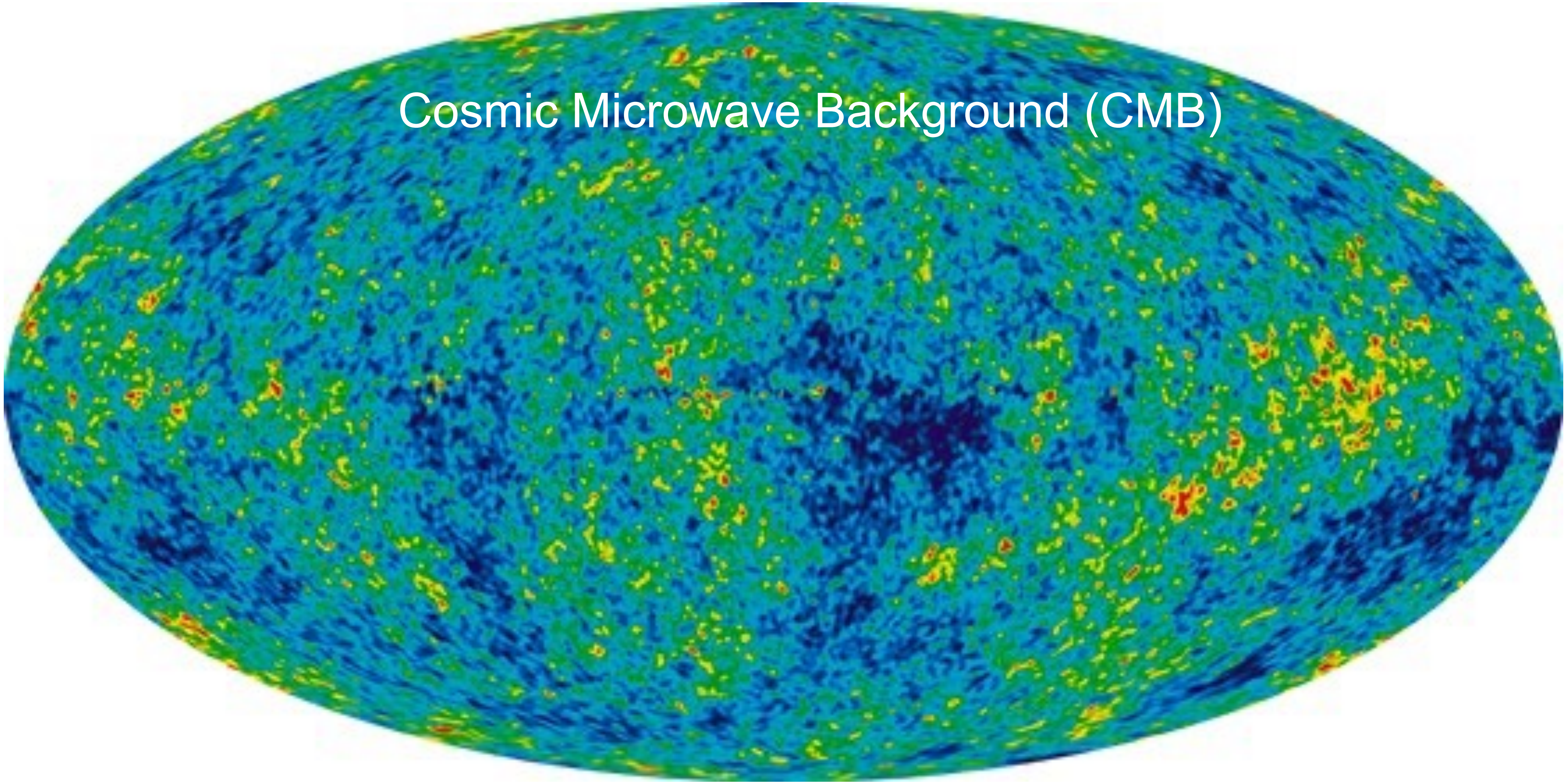
Application III: Cosmology





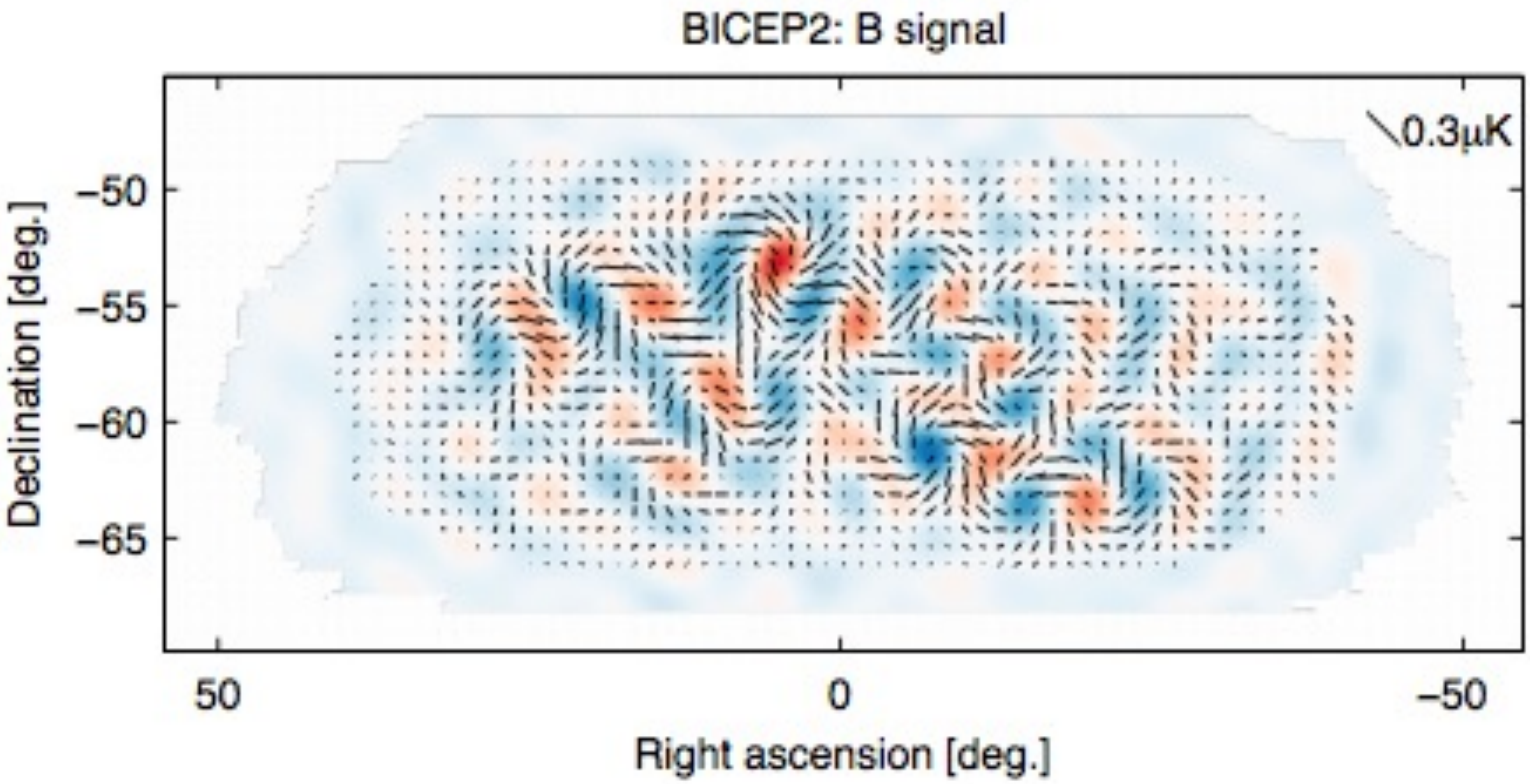
Application III: Cosmology

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences



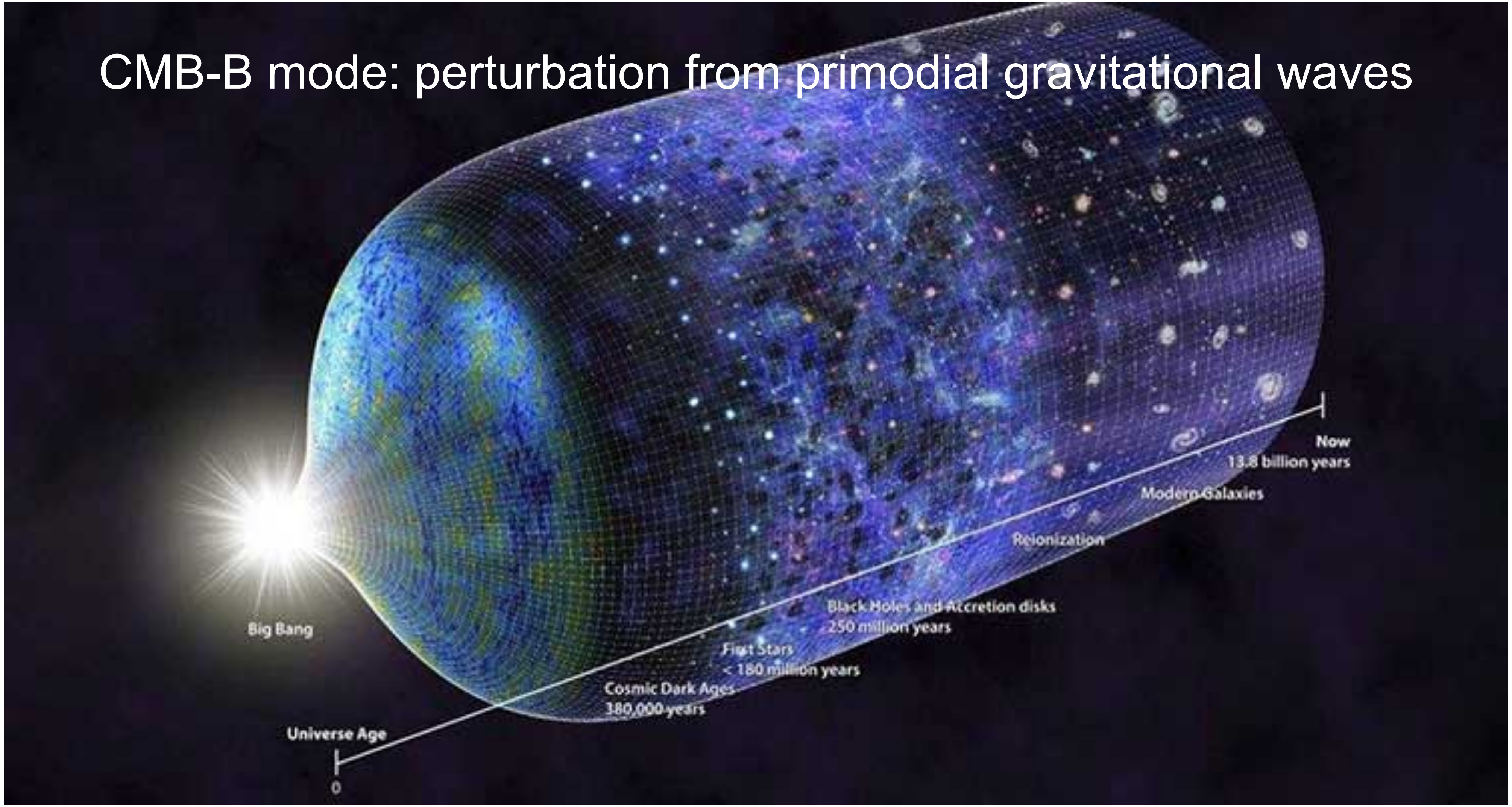
Picture credit: Herbert Huffner, “The Beginning of the World We Know”

Application III: Cosmology



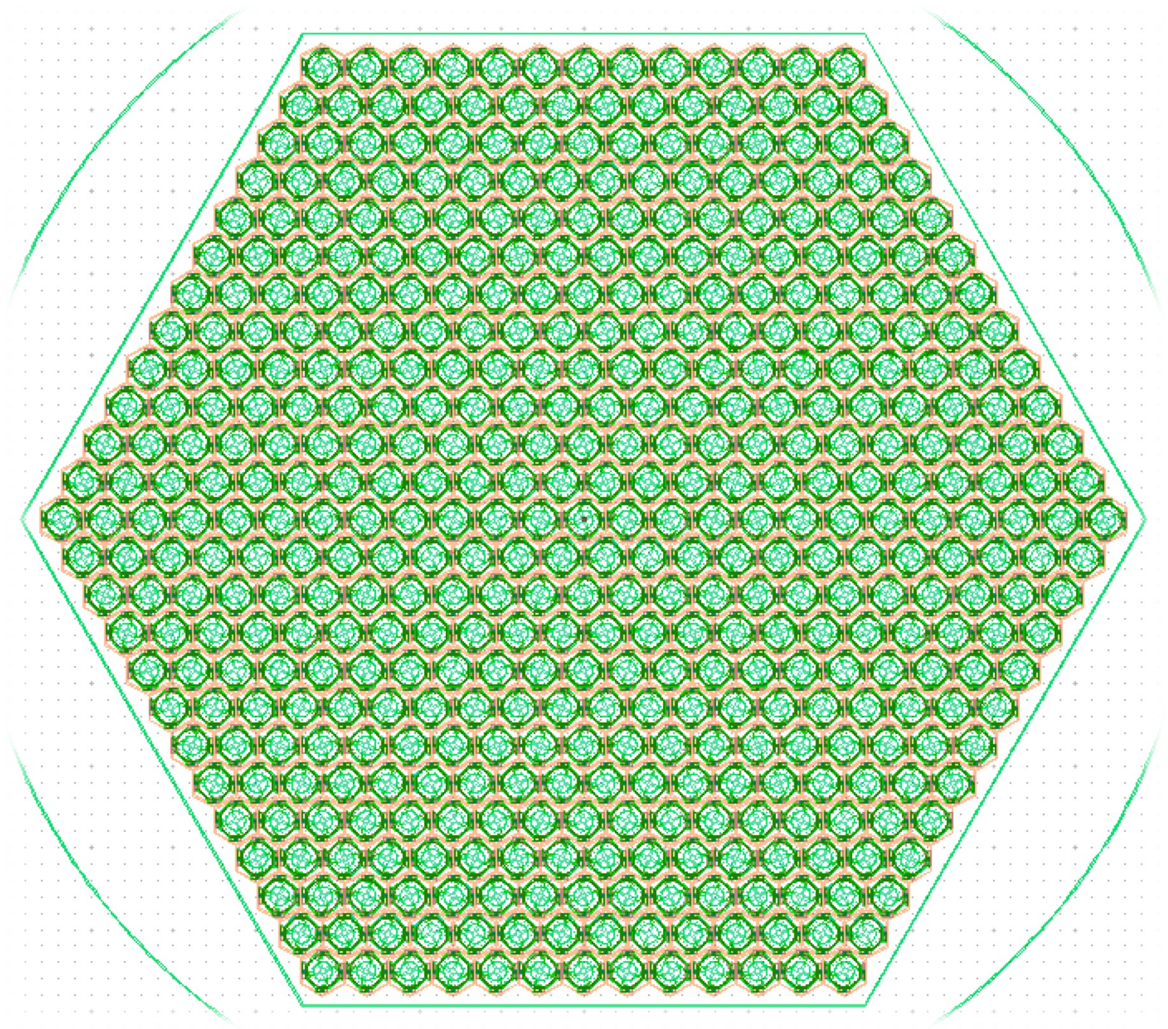
Picture credit: Victor Marin Felip, “The Search for Cosmic Inflation”

Application III: Cosmology

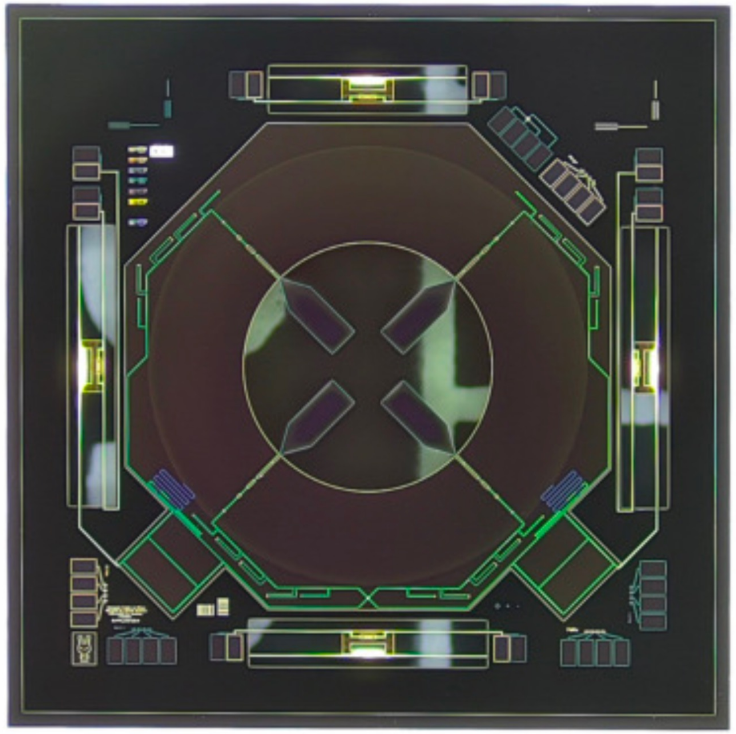


Picture credit: Herbert Huffner, "The Beginning of the World We Know"

Application III: Cosmology

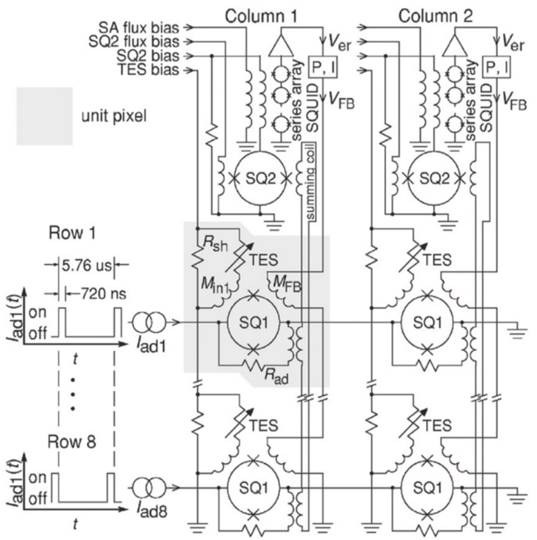


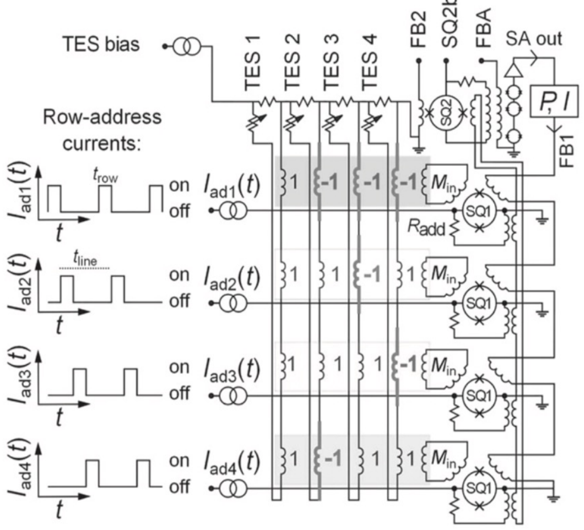
6-inch wafer
432 pixels per array
4 TESs per pixel

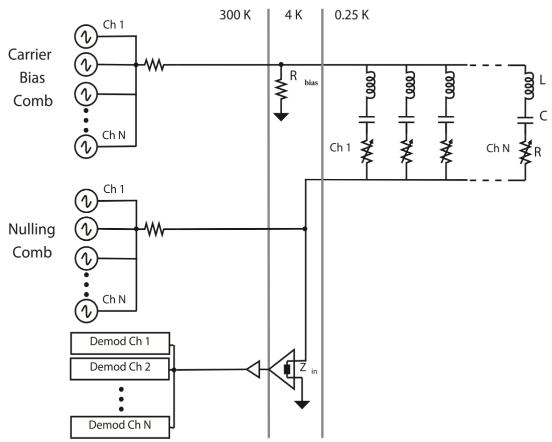


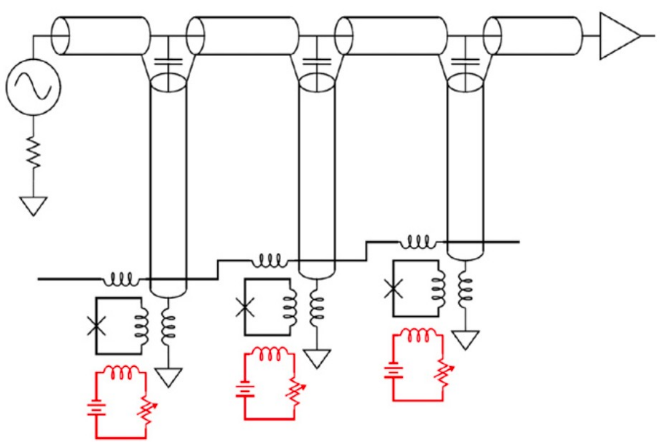
Low-Temperature Multiplex Readout

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences





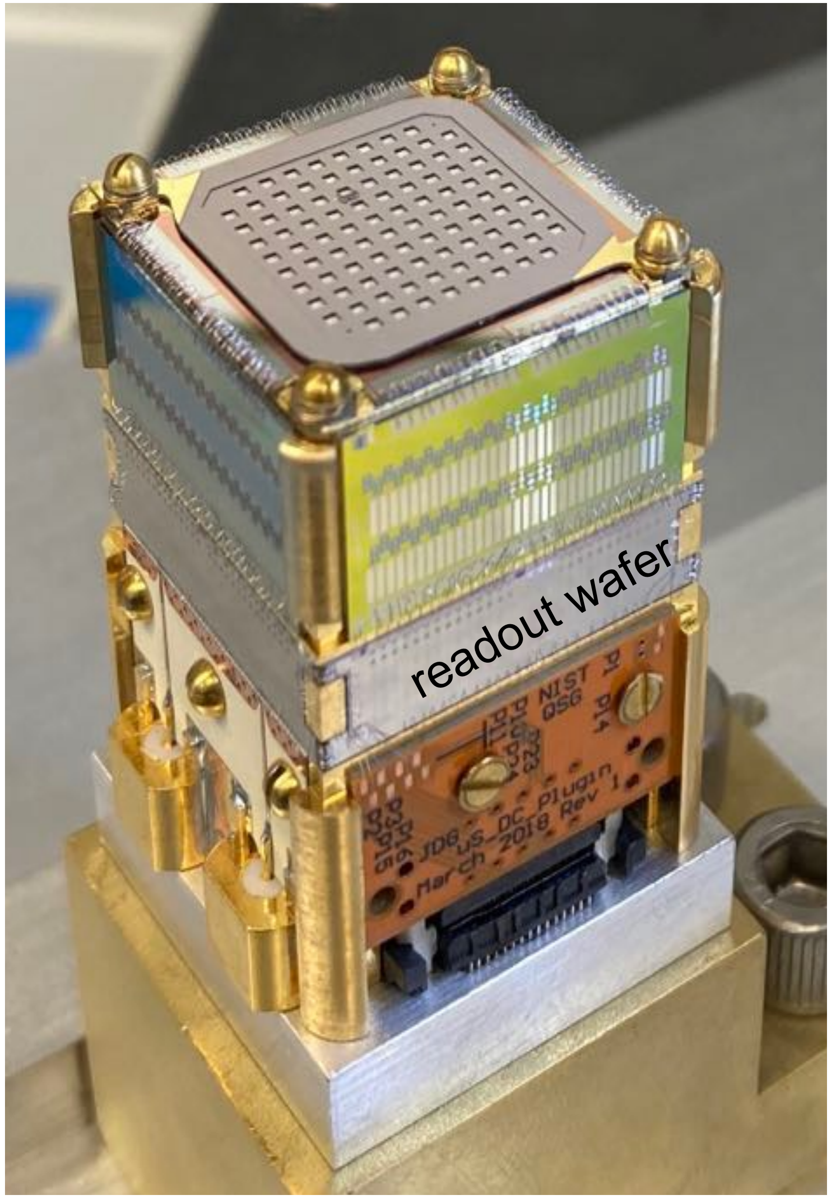


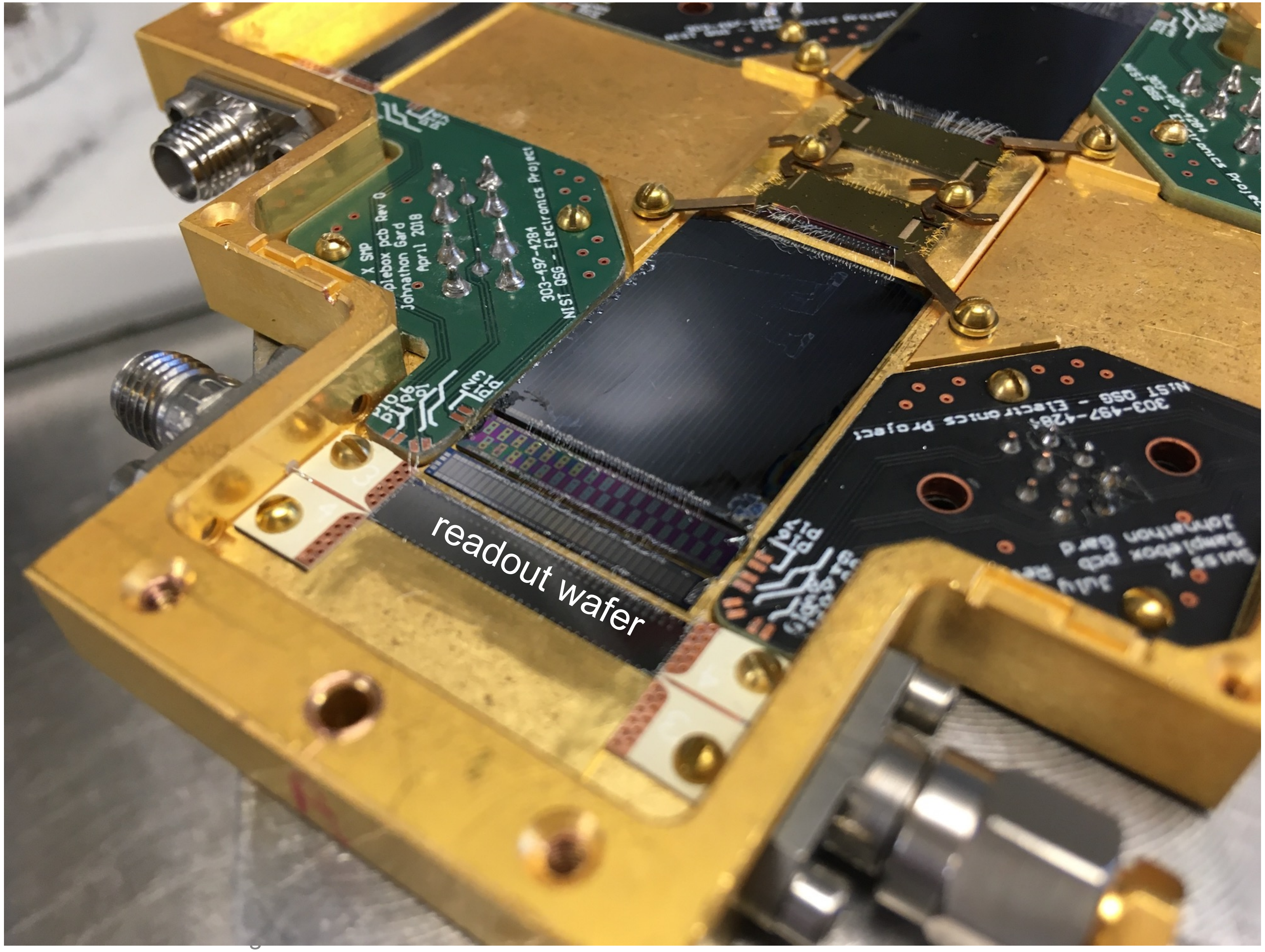


	time-division multiplexing	code-division multiplexing	frequency-division multiplexing	microwave-squid multiplexing
Machanism	pixels in the same column are read out in time series	signals from each pixel are encoded and read out	each pixel is biased in a unique LCR circuit, and detected in a unique frequency channel	TES signal coupled to rf-SQUID, then readout by microwave resonators
Advantage	well-developed technology	each pixel can be biased individually	each pixel can be biased individually	large readout bandwidth, only uses 3 pairs of cables for the whole detector module
Disadvantage	$\sqrt{N}$ sampling noise	one bad pixel kills a whole column	complicated matching between TESs and the readout electronics	pixels are not individually biased, subject to nonuniformity across large arrays

Detector Assembly

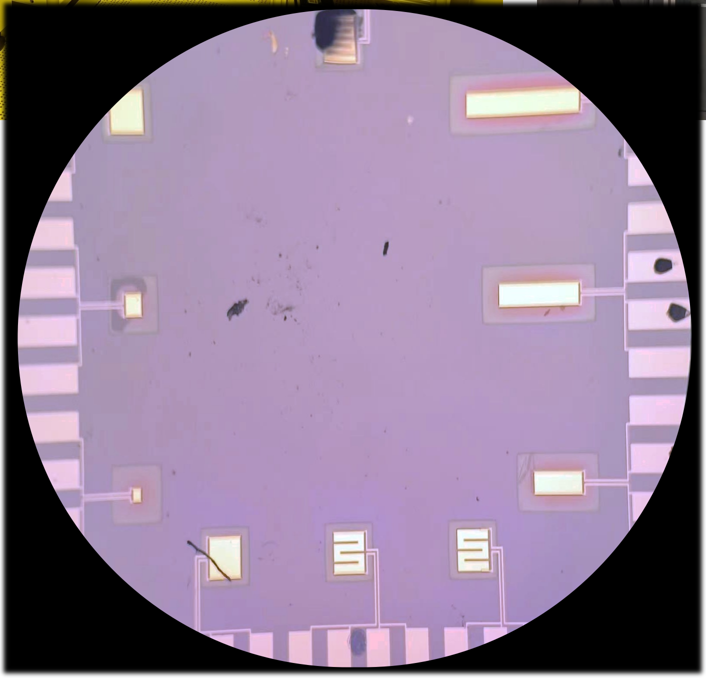
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

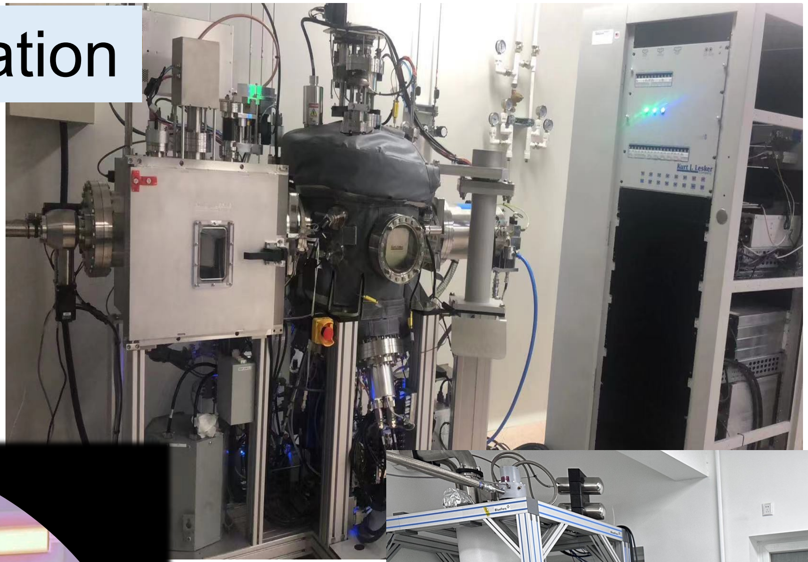




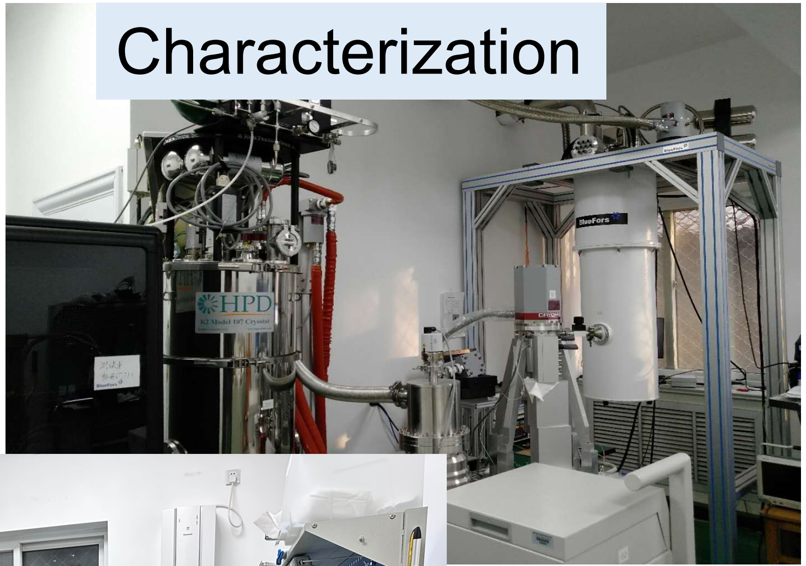
Research at IHEP: R&D

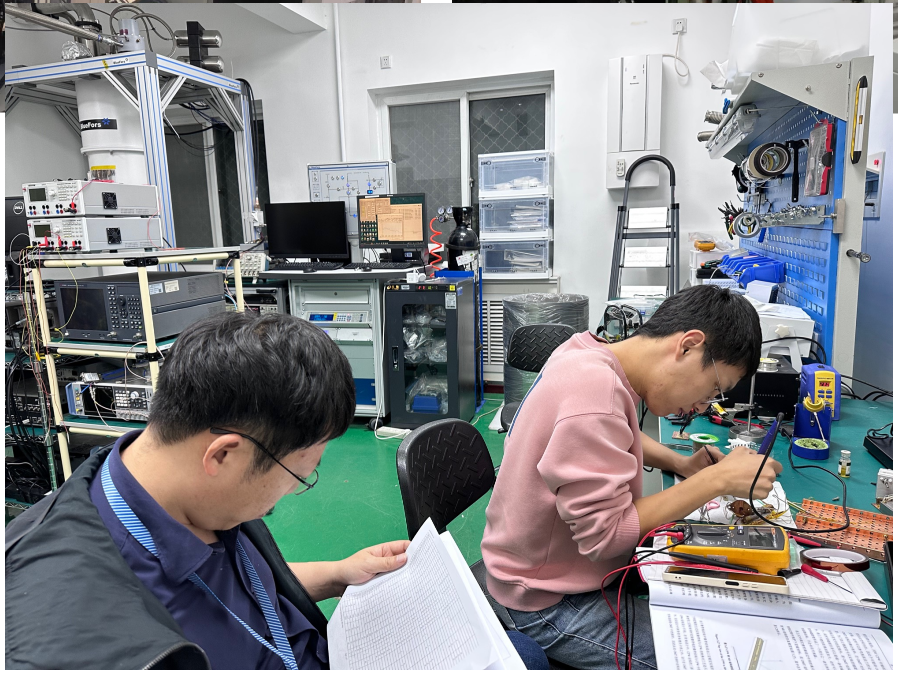
Fabrication





Characterization





Research at IHEP

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

What we do:

1. superconductor detector development (mainly TES, and for various applications)
    - overall design
    - device fabrication
    - detector characterization
2. low-temperature multipexing readout electronics (SQUID)
3. room-temperature detector control & data taking electronics
4. data processing
    - photon signal analysis and optimization

Research at IHEP

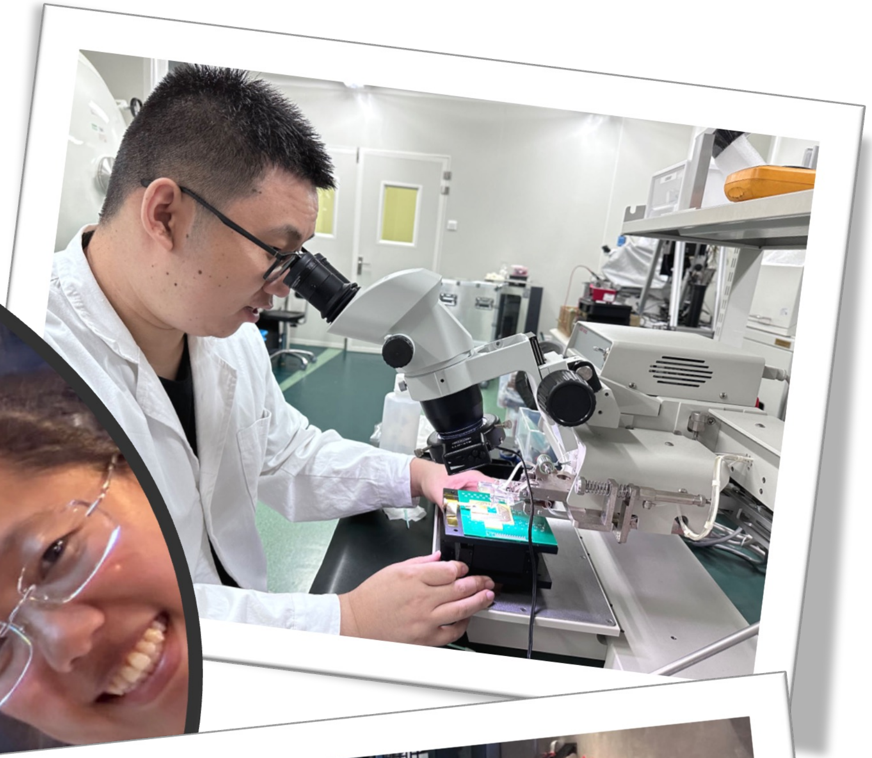
What we do:

1. superconductor detector development (mainly TES, and for various applications)
    - overall design
    - device fabrication
    - detector characterization
2. low-temperature multipexing readout electronics (SQUID)
3. room-temperature detector control & data taking electronics
4. data processing
    - photon signal analysis and optimization

We are looking for postdocs and students!

Daikang Yan (闫代康): yandk@ihep.ac.cn, yandaikang@gmail.com

Research at IHEP: Life



Research at IHEP: Life

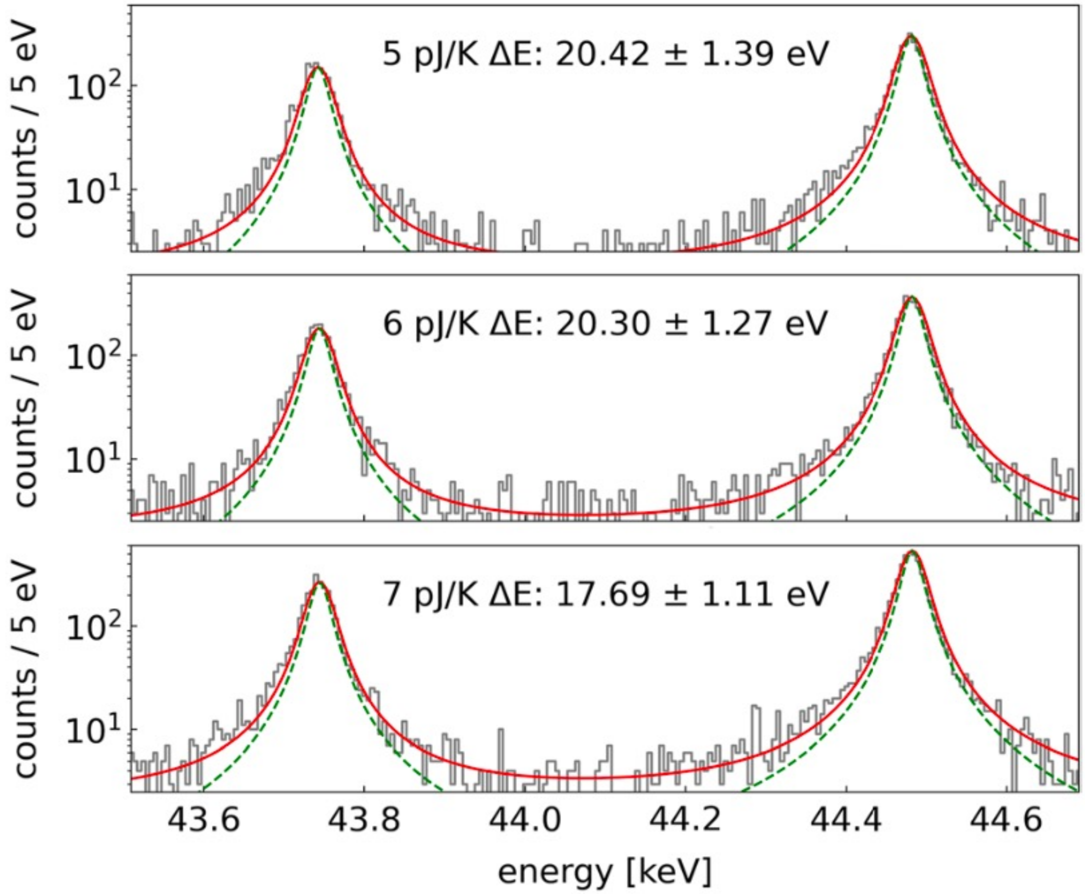
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Visit our superconducor device lab, start your low-resistance journey!

We are looking for postdocs and students!

Daikang Yan (闫代康): yandk@ihep.ac.cn, yandaikang@gmail.com

Application II: QED



More results to come in 2024......

Application II: QED

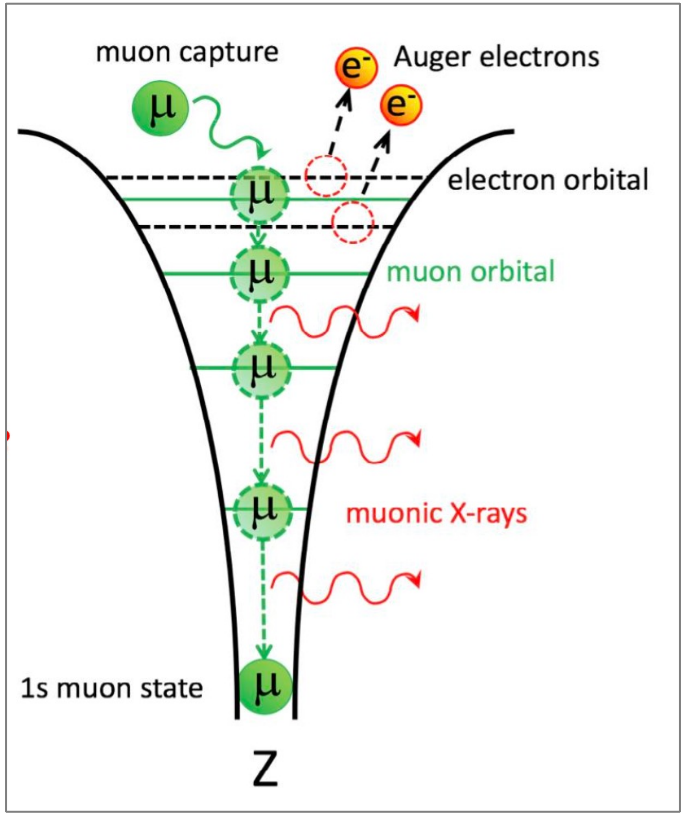
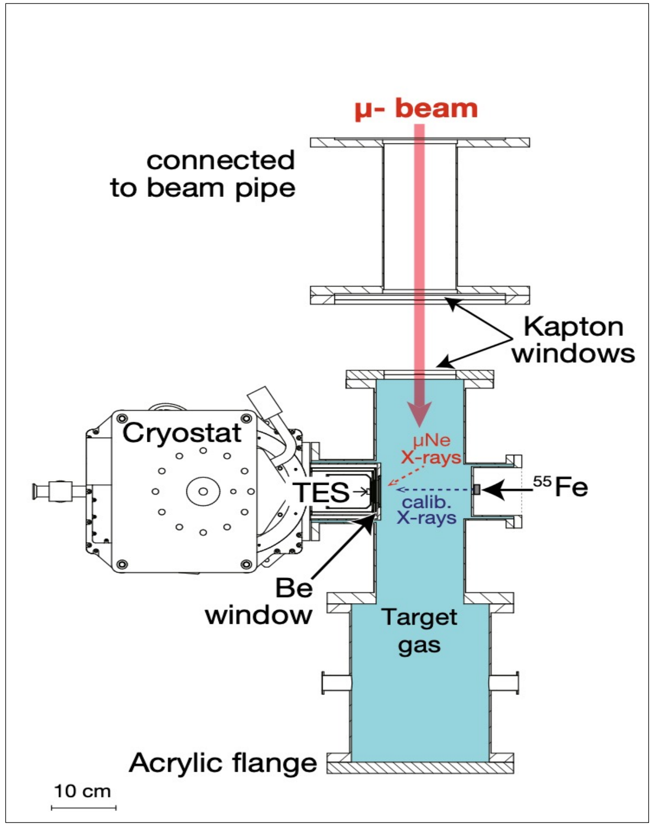


Figure credit: T. Okumura, RIKEN

Limitation/Requirement:

1) target atom low density

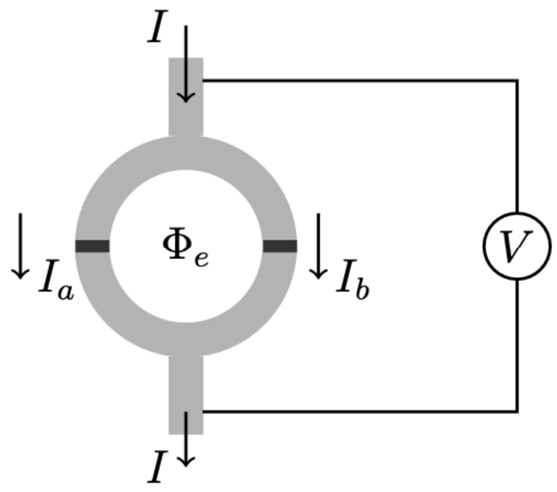
2) high energy resolution



S. Okada *et al*,. Journal of Low Temperature Physics (2020) 200:445–451

SQUID

DC-SQUID



RF-SQUID