Thermodynamic temperature determination with absolutely calibrated filter radiometers in the temperature range from 419 °C to 962 °C

D. R. Taubert, K. Anhalt, B. Gutschwager, J. Hartmann,
N. Noulkhow, P. Meindl, C. Monte, L. Werner, J. Hollandt

Physikalisch-Technische Bundesanstalt

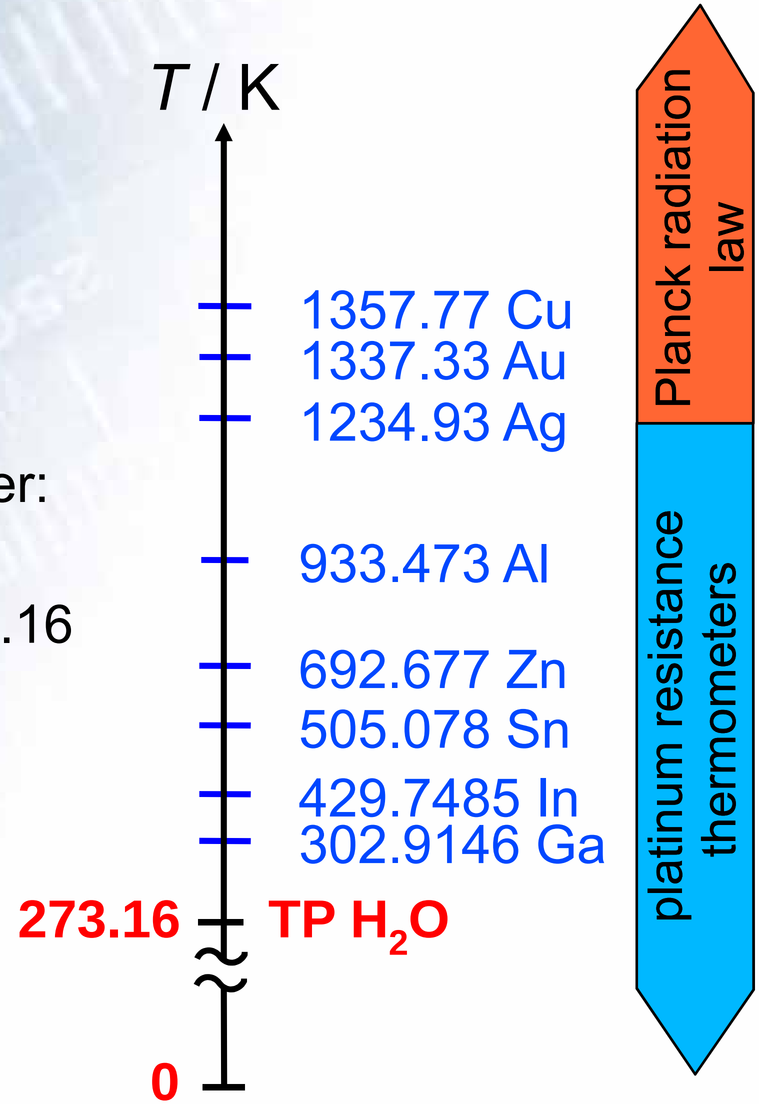
Contents

- Introduction / motivation
- Principle / instrumentation for thermodynamic temperature determination
- Filter radiometer calibration scheme and instrumentation
- Results for T-T_{90}
- NIR InGaAs-photodiode filter radiometer
- Results for T-T_{90} with NIR filter radiometer
- Summary

Introduction: Temperature scales

Thermodynamic Temperature Scale

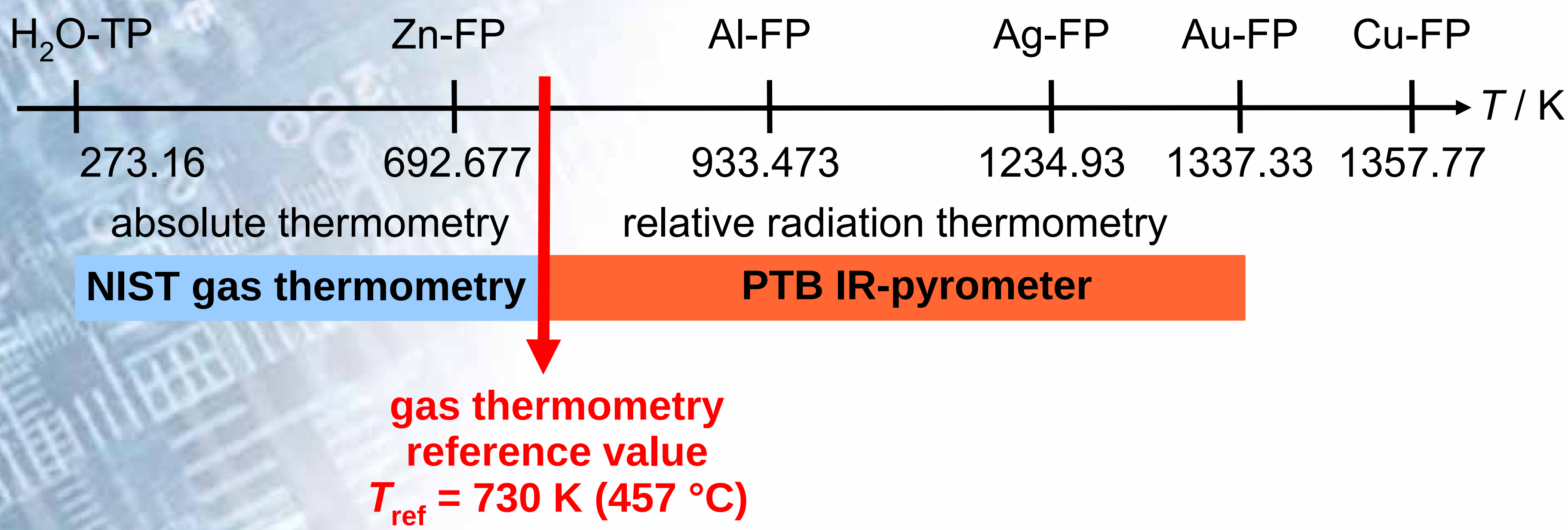
- Absolute Zero
- Triple Point of Water: **273.16 K** exact
- Unit: fraction 1/273.16 of H_2O-TP



The International Temperature Scale of 1990 (ITS-90)

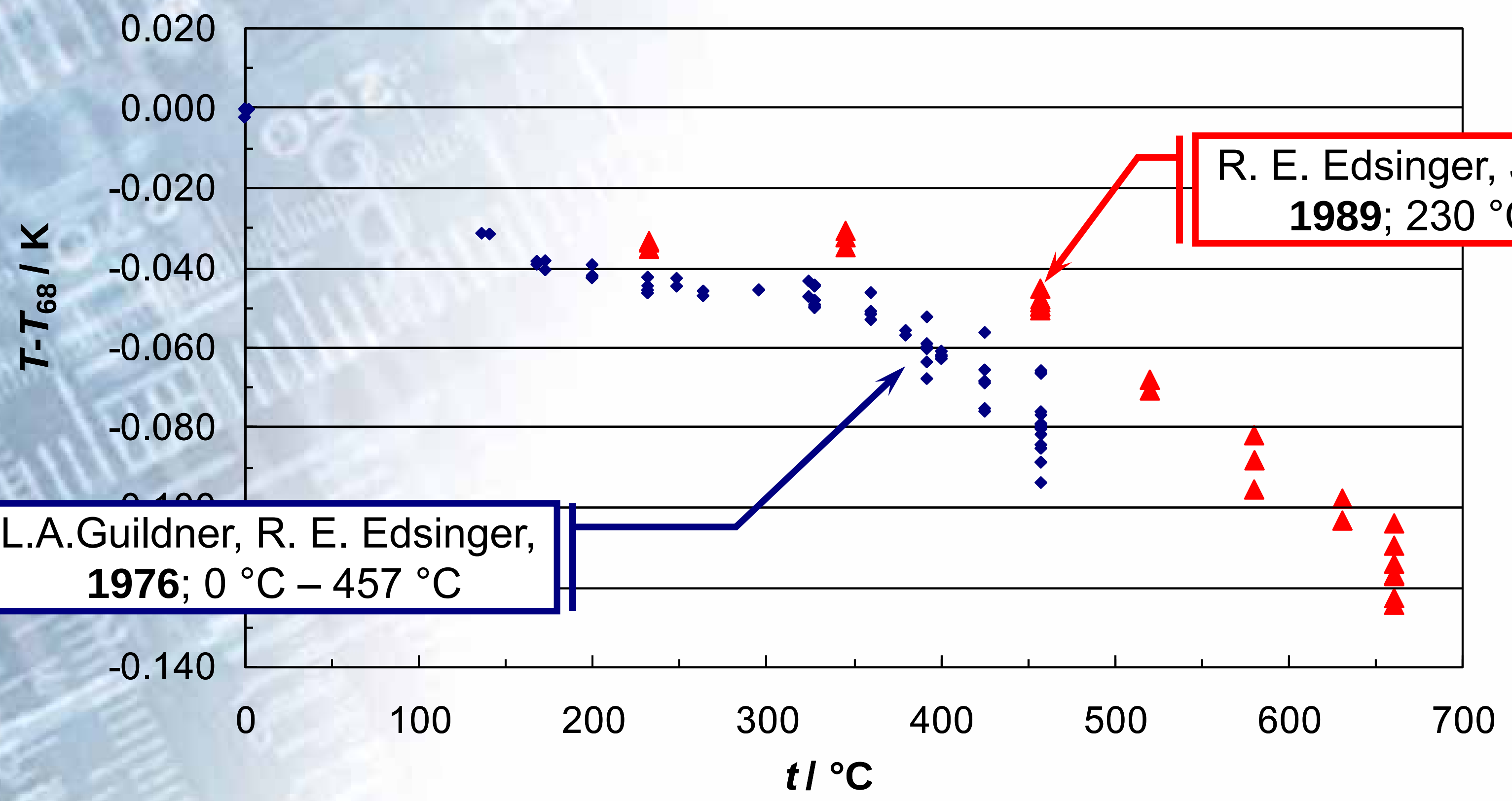
- Defining Fixed Points
- Interpolation Instruments

Introduction: Thermodynamic Basis of the ITS-90



Introduction: Thermodynamic Basis of the ITS-90

- Preparatory Thermodynamic Temperature Measurements for the ITS-90: Constant Volume Gas Thermometry (CVGT) at NIST
- Two, <u>independent</u> data sets for the intermediate temperature range

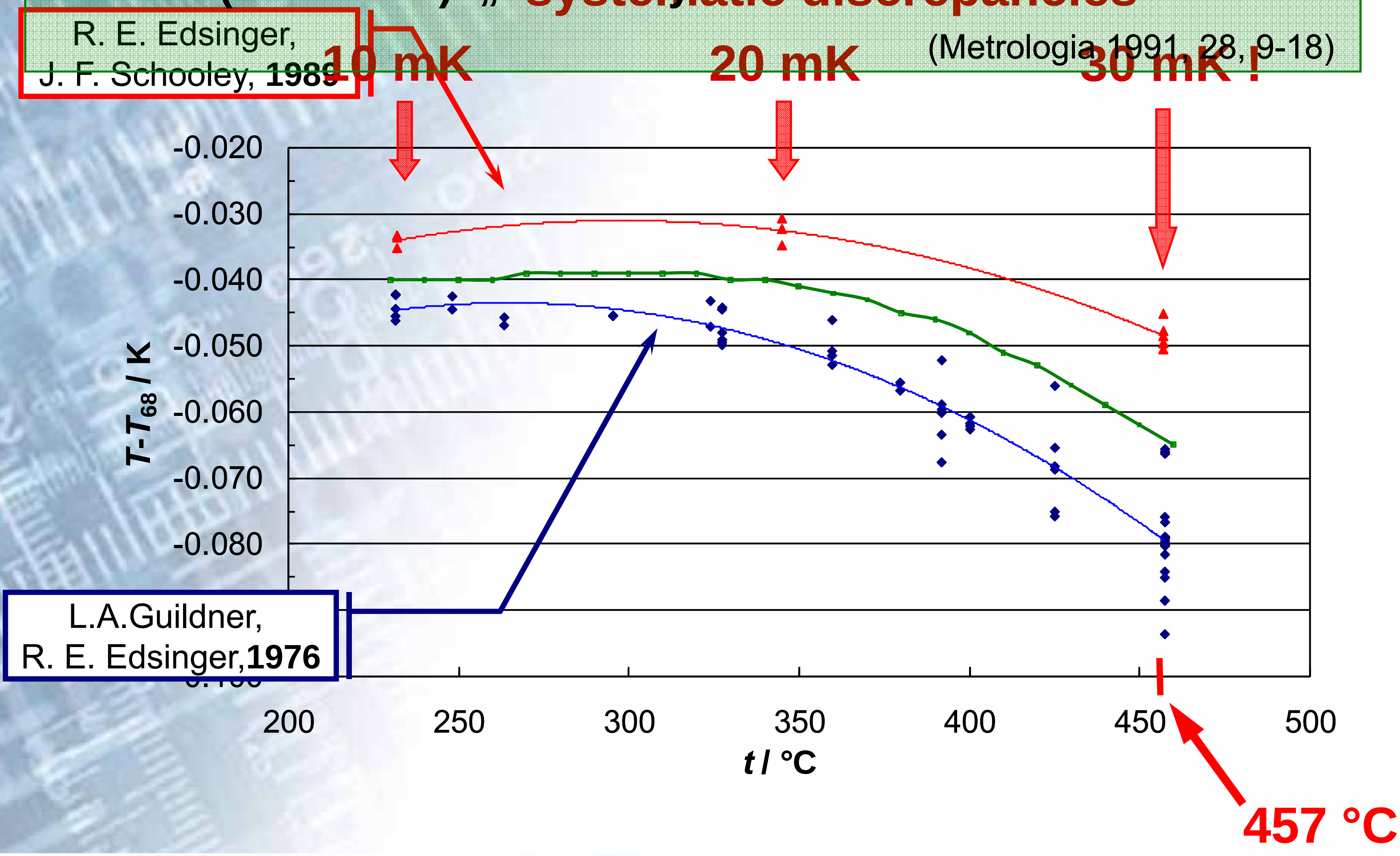


Introduction: Thermodynamic Basis of the ITS-90

Solution (CCT WG 4): „...mid-way between the two sets of results“

systematic discrepancies

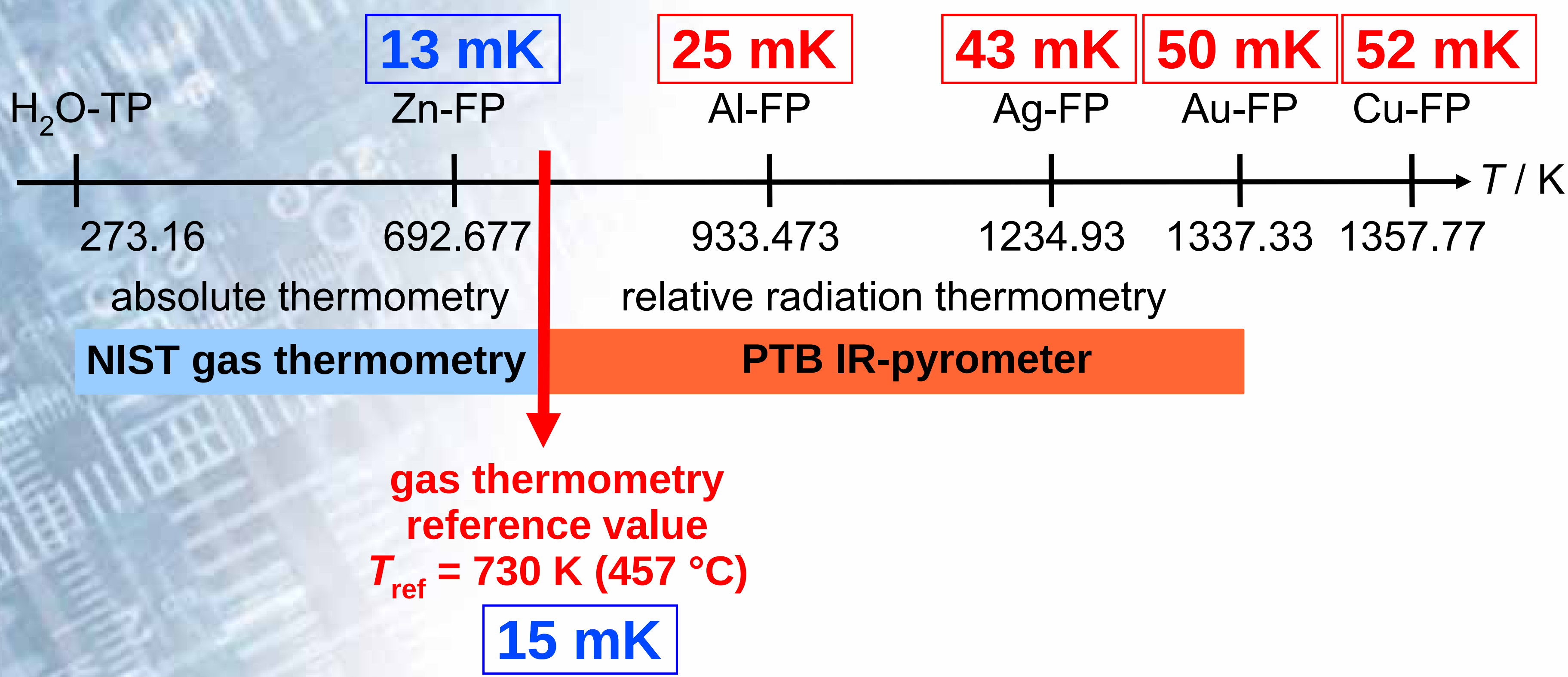
(Metrologia 1991, 28, 9-18)



Introduction: Thermodynamic Basis of the ITS-90

thermodynamic uncertainty of the ITS-90 fixed points

quadratic error propagation



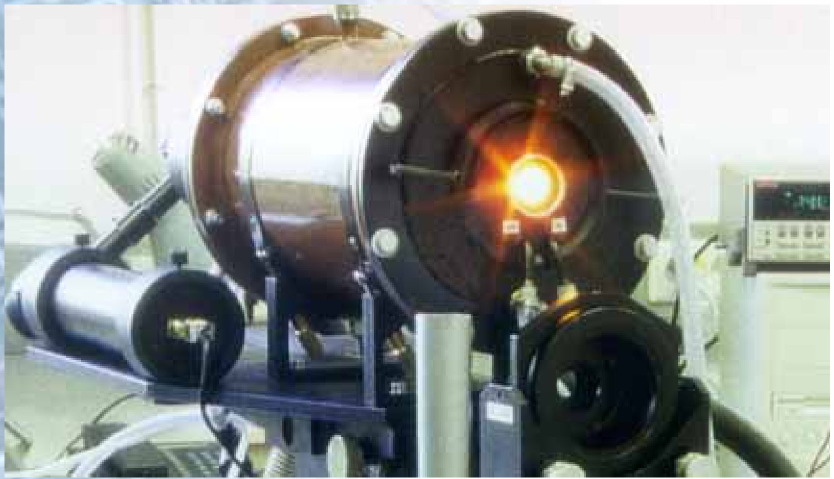
Introduction: Thermodynamic Basis of the ITS-90

Problem:

- increased thermodynamic uncertainty of the ITS-90 high temperature fixed points

Au-FP: $u(T_{\text{Au-FP}}) = 0.050$ K

Application: High temperature blackbodies (HTBB) as primary standards for the UV-precision radiometry



$T_{\text{HTBB}} = 3500$ K

→ $u(T_{\text{HTBB}}) \approx 0.345$ K

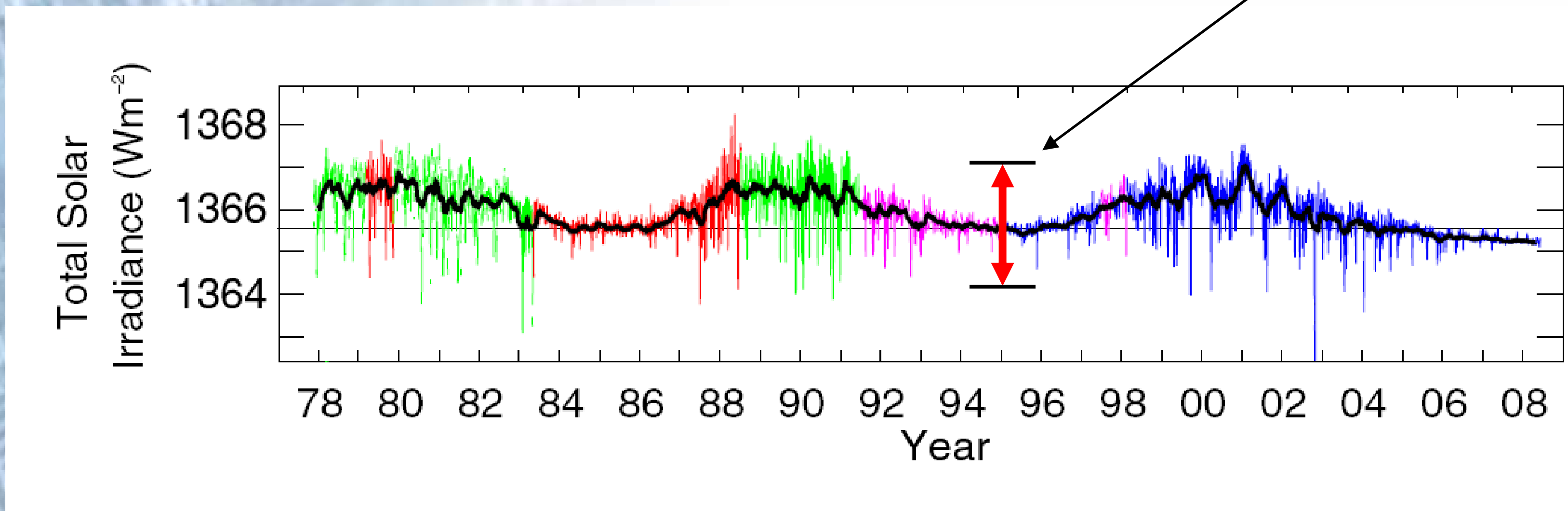
- relative uncertainty of the realized spectral irradiance

$$\frac{\Delta E_\lambda}{E_\lambda} = 0.2\,\% \quad \lambda = 200\,\text{nm}$$

Introduction: Thermodynamic Basis of the ITS-90

- Measurement of the Total Solar Irradiance
  critical factor in climate prediction

0.2% !



Source: Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center (PMOD/WRC)

Motivation

Decision: Which of the two NIST gas thermometry series is closer to the thermodynamic temperature ?

PTB approach:

- Absolute radiometric determination of thermodynamic temperatures of blackbodies with lowest possible uncertainties and comparison with the ITS-90 **?**
- **Instrumentation:** Absolutely calibrated filter radiometers

Task: 15 mK @ 730 K

$$\frac{\Delta L}{L} = \frac{c_2}{\lambda \cdot T^2} \cdot \Delta T \quad \xrightarrow{\lambda = 1000\ \text{nm}} \quad \frac{\Delta L}{L} \approx 4 \cdot 10^{-4} \ \mathbf{!}$$

Thermodynamic temperature determination

- Schematic experimental setup

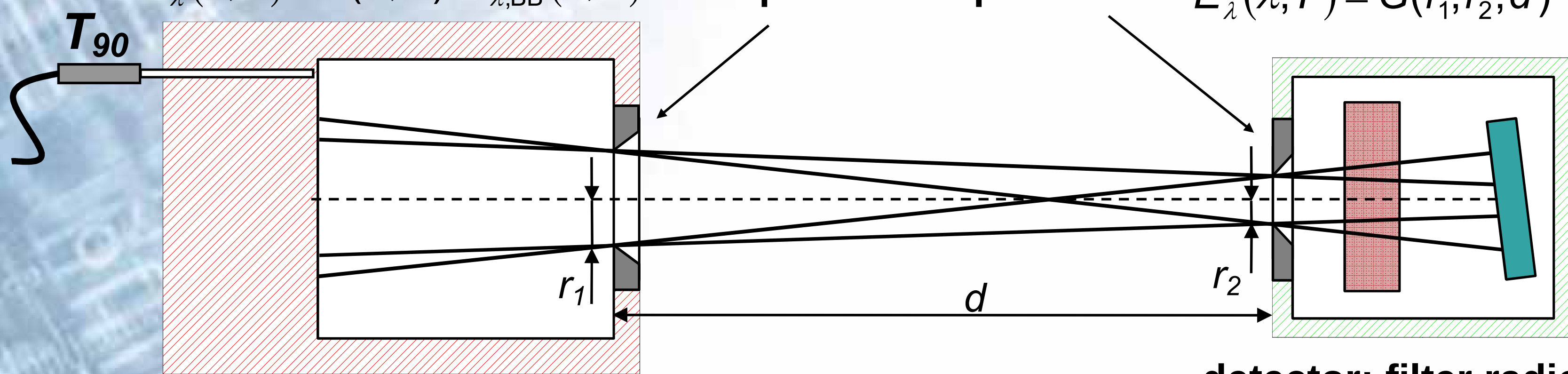
source output:
spectral radiance

$$L_\lambda(\lambda,T) = \varepsilon(\lambda,T)\cdot L_{\lambda,\mathrm{BB}}(\lambda,T)$$

precision apertures

detector input:
spectral irradiance

$$E_\lambda(\lambda,T) = G(r_1,r_2,d)\cdot L_\lambda(\lambda,T)$$



source: **blackbody,**
thermodynamic temperature T,
emissivity $\varepsilon(\lambda,T)$

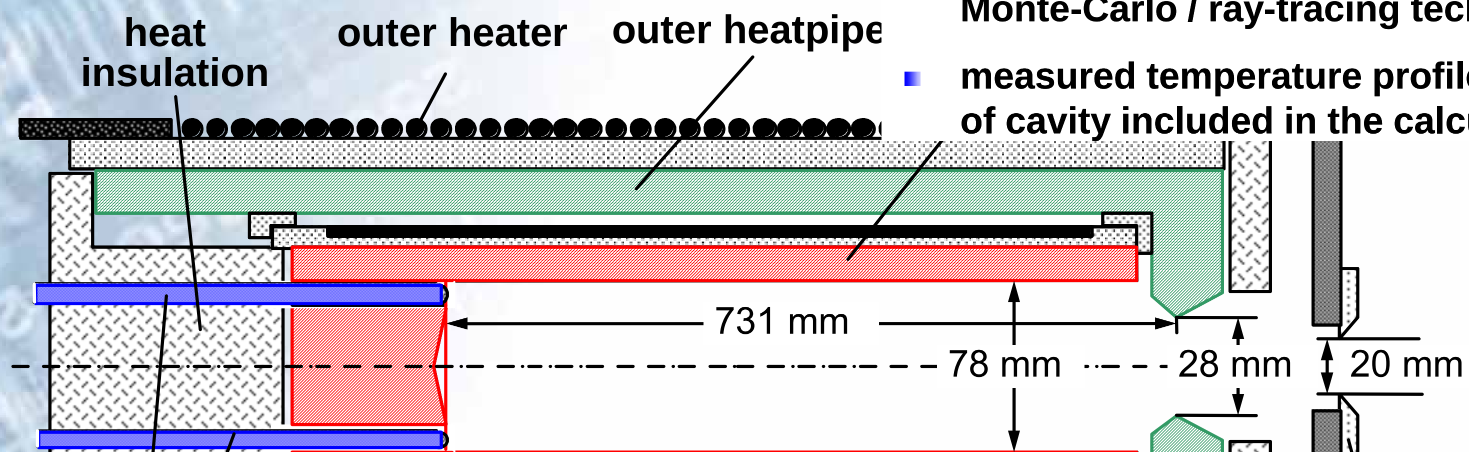
detector: **filter radiometer,**
spectral irradiance
responsivity $s_E(\lambda)$

detector output:
photocurrent

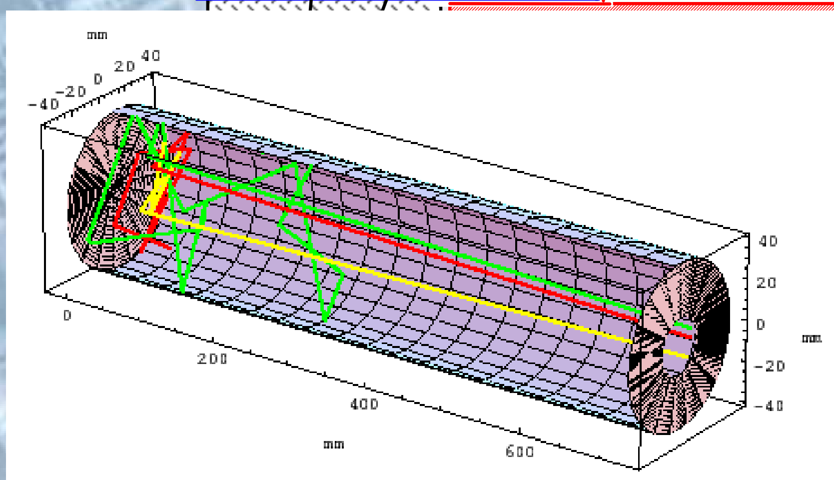
$$I_{\mathrm{photo}}(G,T) = \int E_\lambda(\lambda,T)\cdot s_E(\lambda)\,d\lambda =$$

$$= G(r_1,r_2,d)\int \varepsilon(\lambda,T)\cdot L_{\lambda,BB}(\lambda,T)\cdot s_E(\lambda)\,d\lambda$$

Large area blackbody (LABB) – schematic view

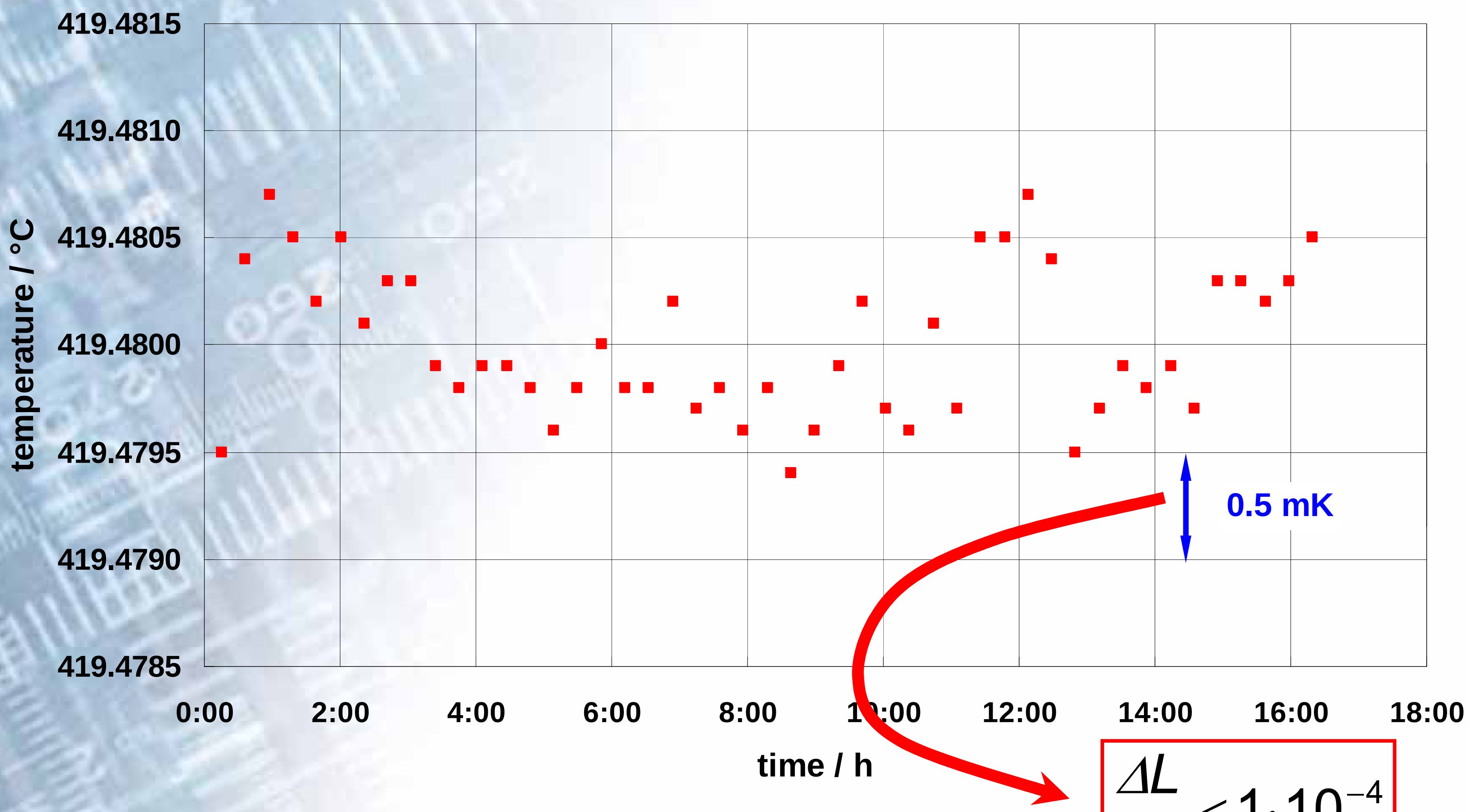


- emissivity calculation with Monte-Carlo / ray-tracing technique
- measured temperature profile of cavity included in the calculation



t_{LABB} /°C	ε isothermal	ε non-isothermal
415	0.99990	0.99959
450	0.99991	0.99987
480	0.99990	0.99989
510	0.99991	0.99988

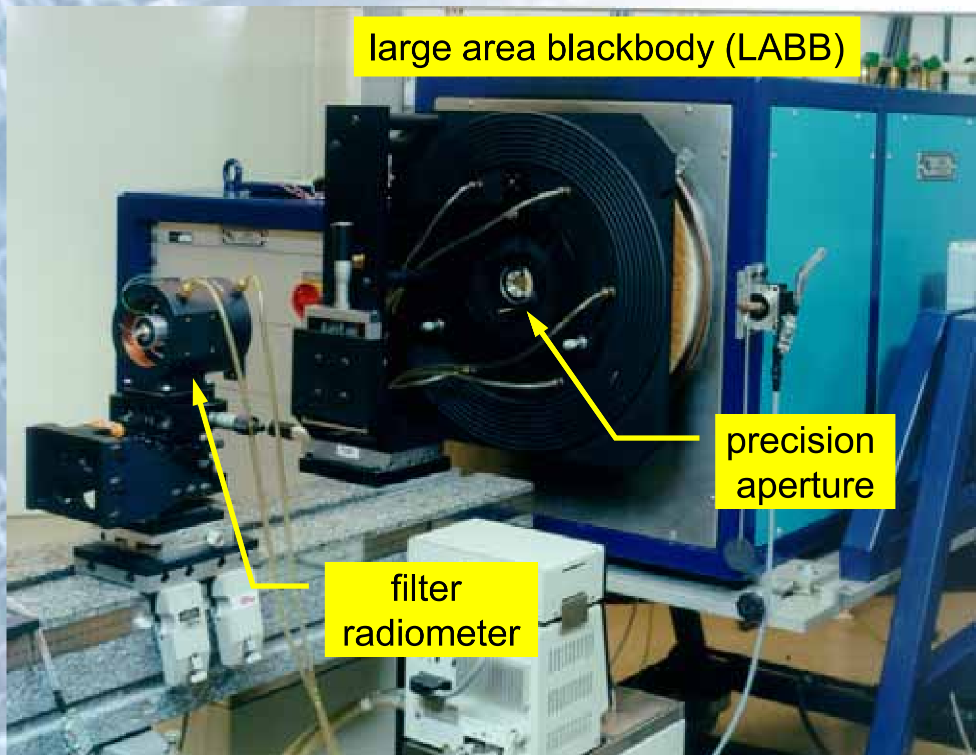
LABB - Temperature stability

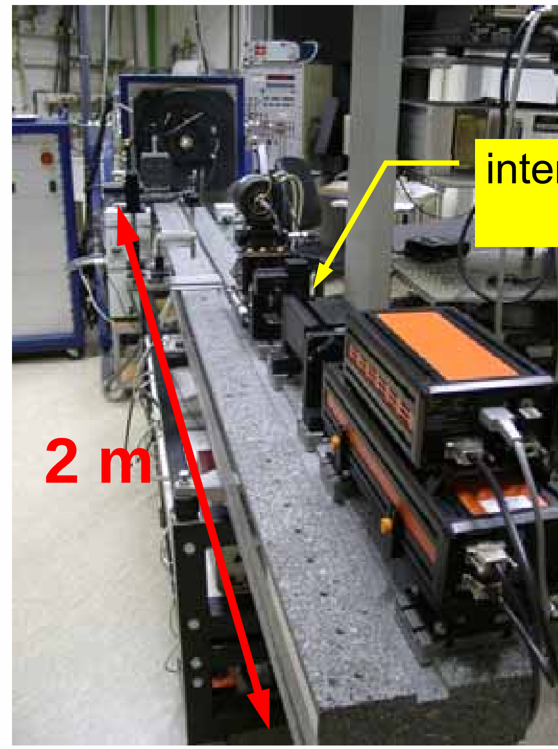


$$\frac{\Delta L}{L} < 1 \cdot 10^{-4}$$

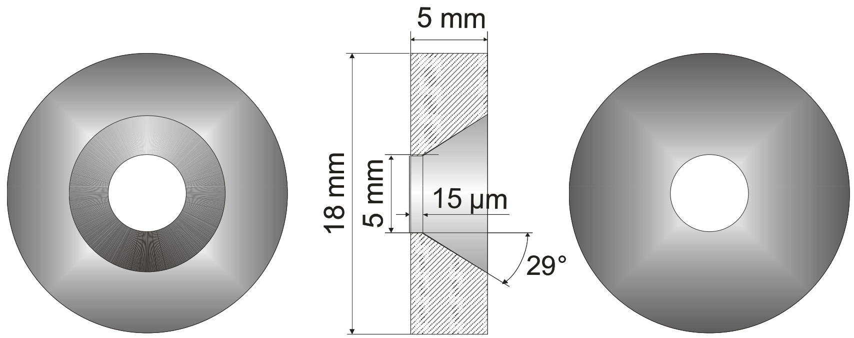
Thermodynamic temperature determination

- **PTB experimental setup**
  - thermodynamic accuracy of ITS-90 (T-T_{90})
  - temperature range: Zn-FP (419.527 °C) to Ag-FP (961.78 °C)

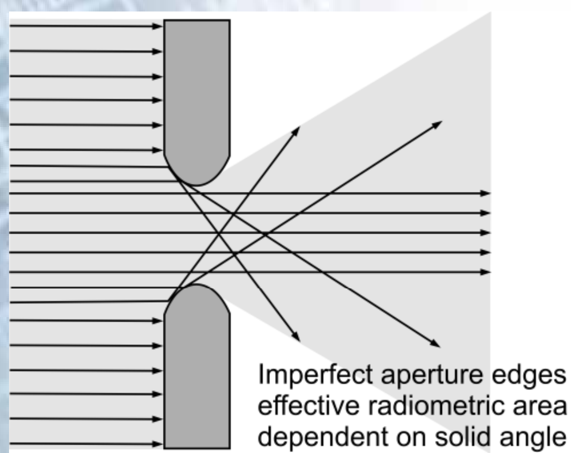


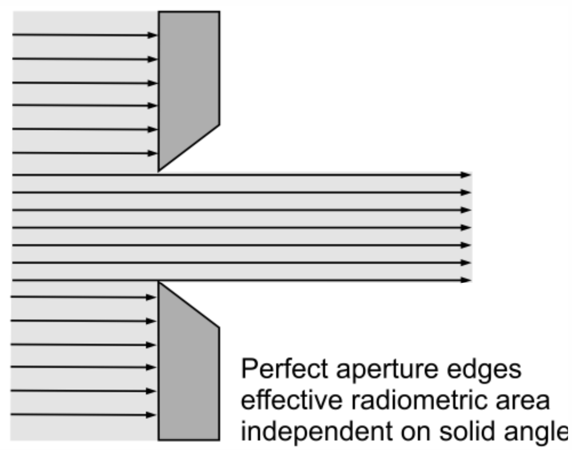


Precision apertures



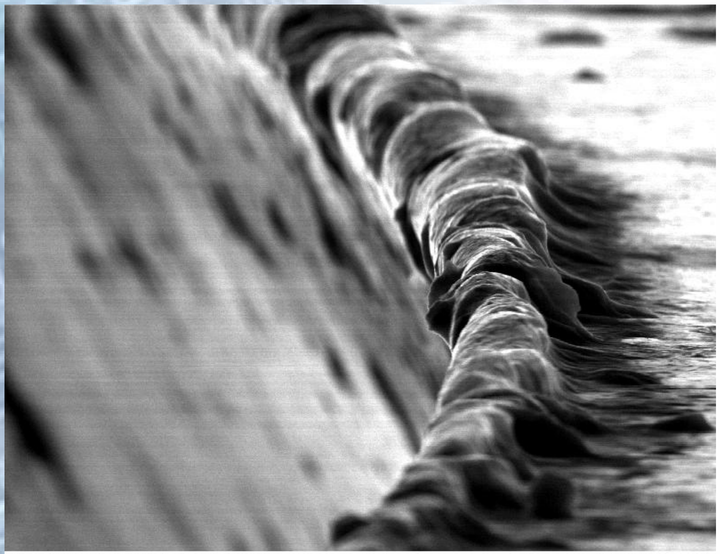
- diamond turned (Al, Cu)
- thin, „knife like"-edges
- non-contact measurement of the aperture diameter
- absolute uncertainty (*k*=1): < 0.5 µm





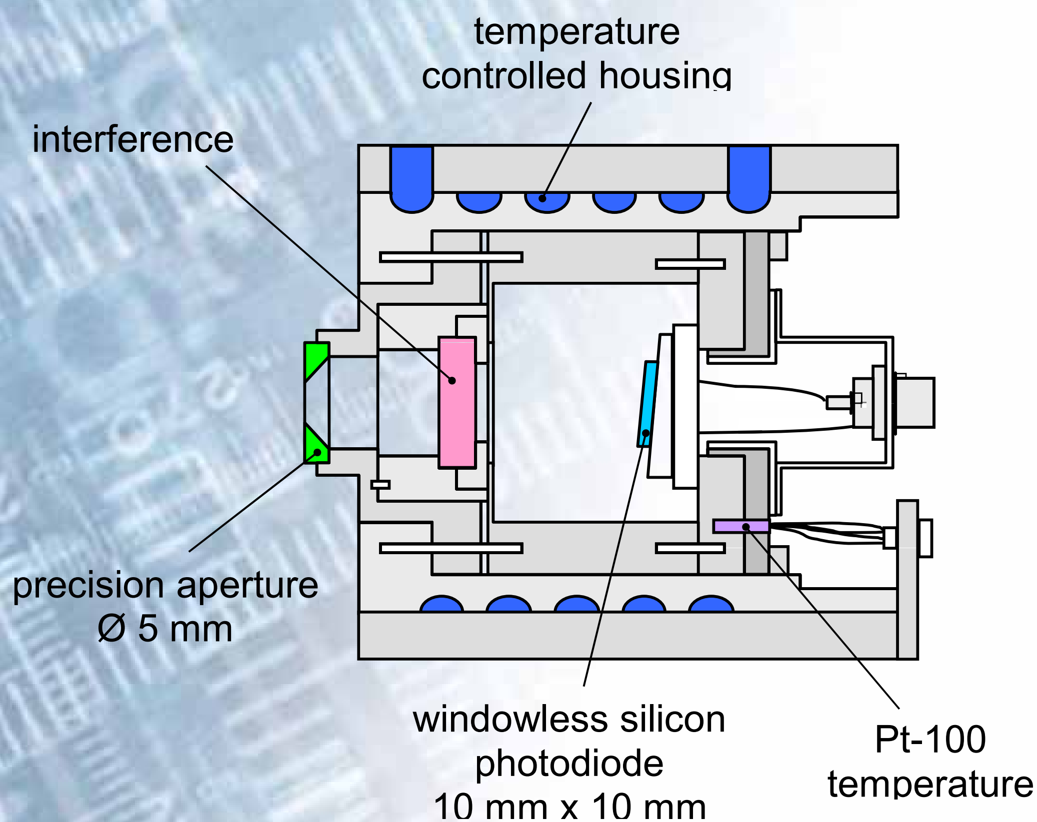
Precision apertures

Al9, 85°gekippt, seitliche Sicht ⊢ 10 µm ⊣



AlZn2; 85° gekippt; seitl. Sicht ⊢ 10 µm ⊣

Filter Radiometer – schematic view

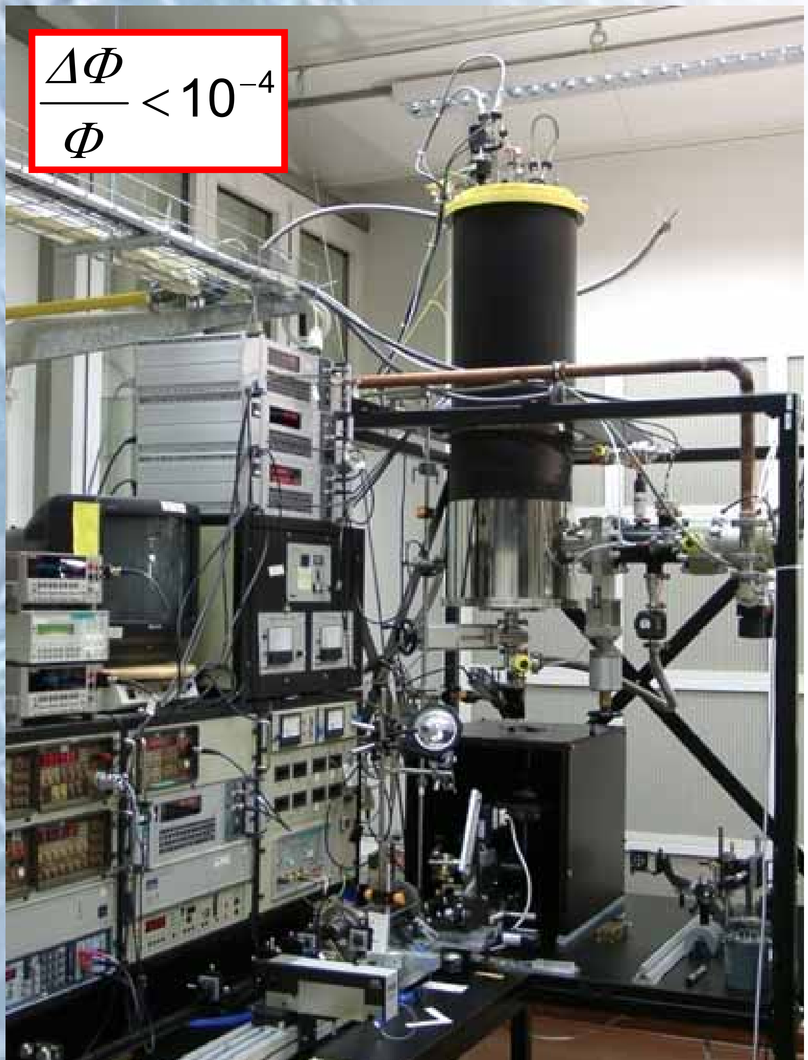


Absolute calibration

- **spectral irradiance responsivity**
- relative standard uncertainty: ~10^{-4}
- primary detector standard: **cryogenic radiometer**
- two step procedure

Filter radiometer absolute calibration: step 1

$$\frac{\Delta\Phi}{\Phi} < 10^{-4}$$



cryogenic radiometer RTCR
PTB detector primary standard
optical power Φ [W]

⇕

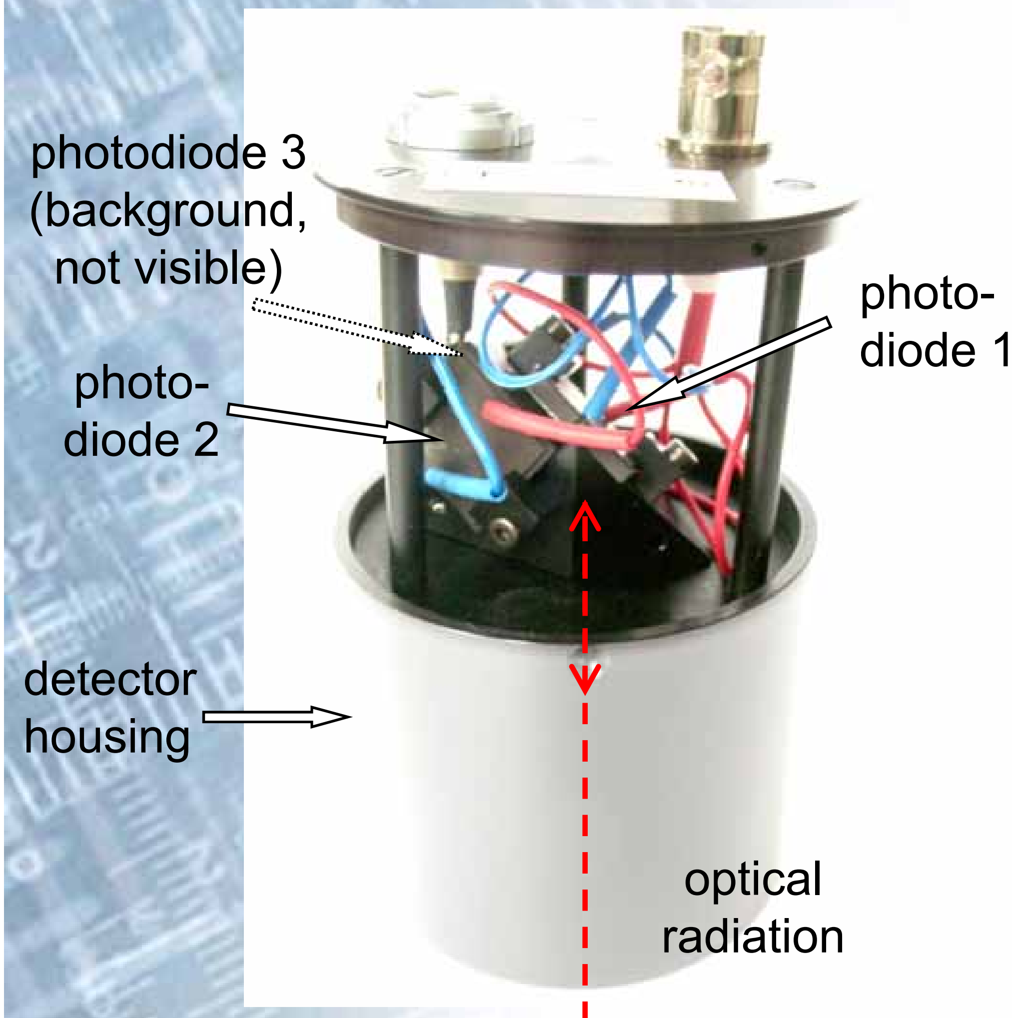
calibration at discrete laser lines

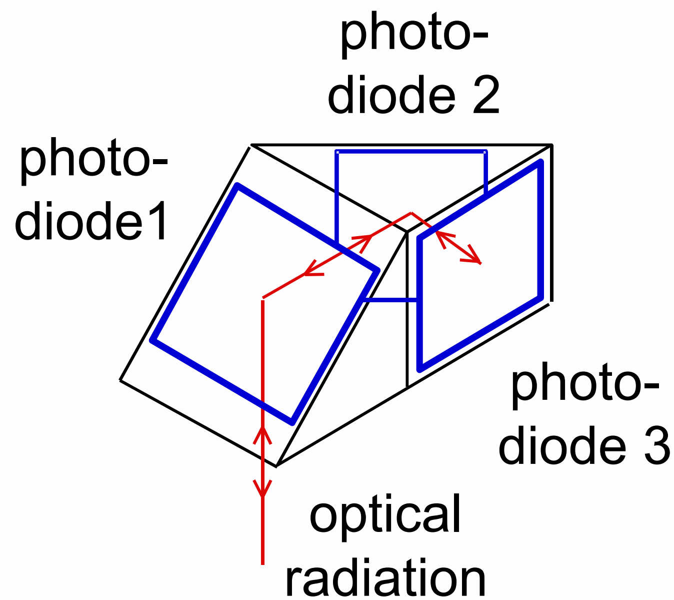
transfer standard
spectral responsivity $s(\lambda)$ [$A \cdot W^{-1}$]

⇑

silicon photodiode based
trap detector

Spectral responsivity transfer standard: trap detector

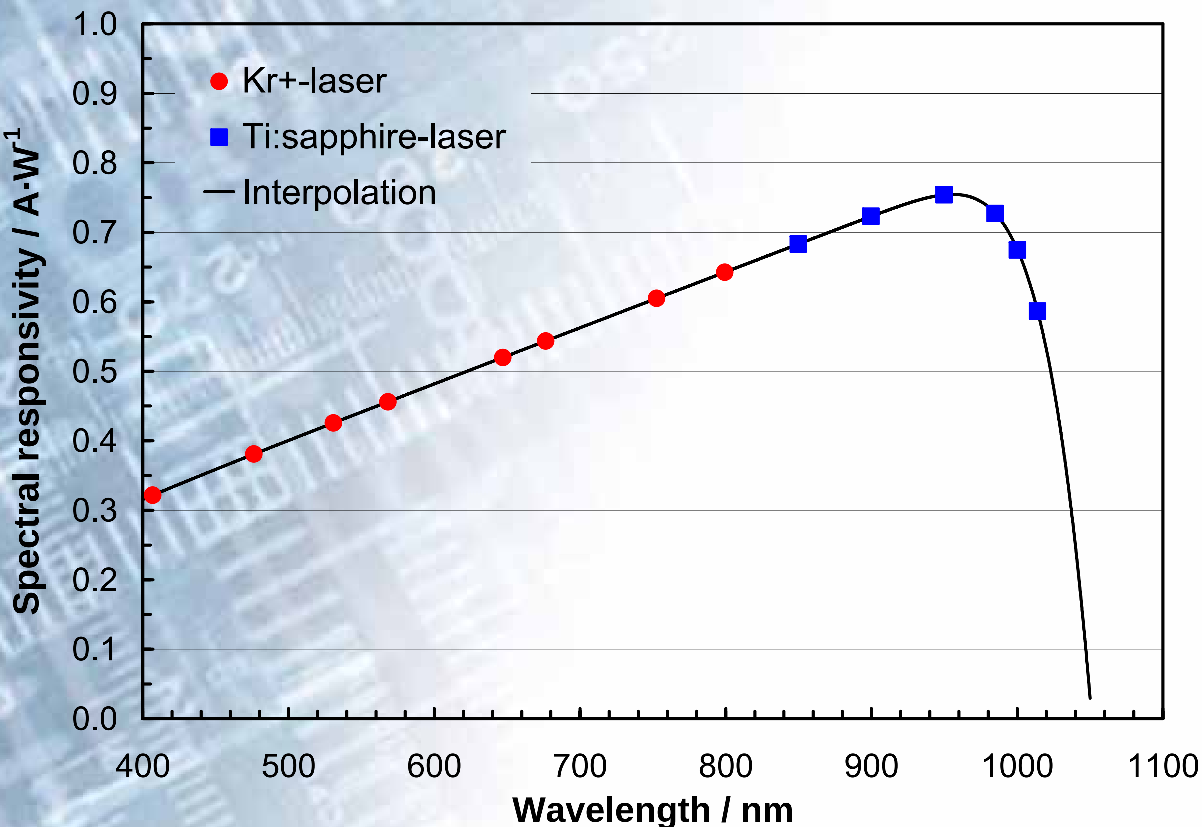




- high stability
- low reflectivity
- polarization insensitive
- homogenous responsivity

Trap detector: spectral responsivity

- **calibration at 14 laser lines**
- **interpolation with a physical model**

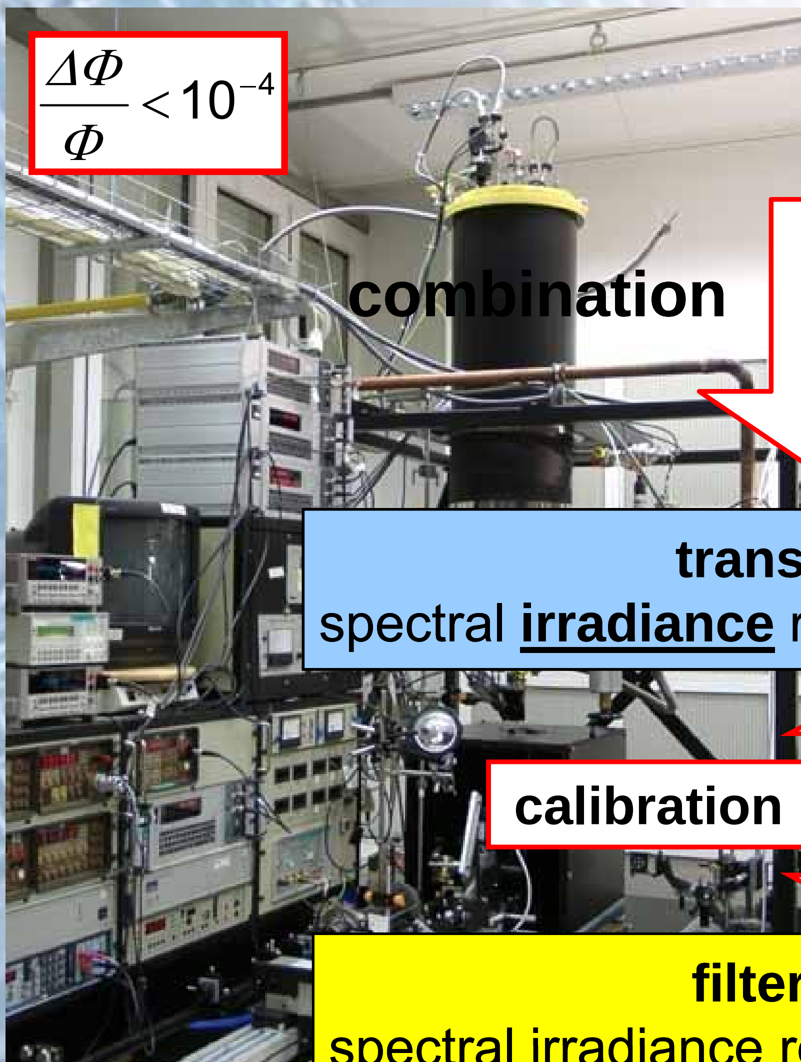


Werner et al., *Metrologia,* 2000, **37**, 279-284

relative uncertainty (*k*=1)
(400 nm to 950 nm)

- $1 \cdot 10^{-4}$ at the laser lines
- $2 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ continuous scale

Filter radiometer absolute calibration: step 2



$$\frac{\Delta\Phi}{\Phi} < 10^{-4}$$

combination

cryogenic radiometer RTCR
trap detector
PTB detector primary standard
optical power Φ [W]

precision aperture

calibration at discrete laser lines

transfer standard
spectral **irradiance** responsivity $s_E(\lambda)$ [A·W^{-1}·m^2]

...ard
spectral responsivity $s(\lambda)$ [A·W^{-1}]

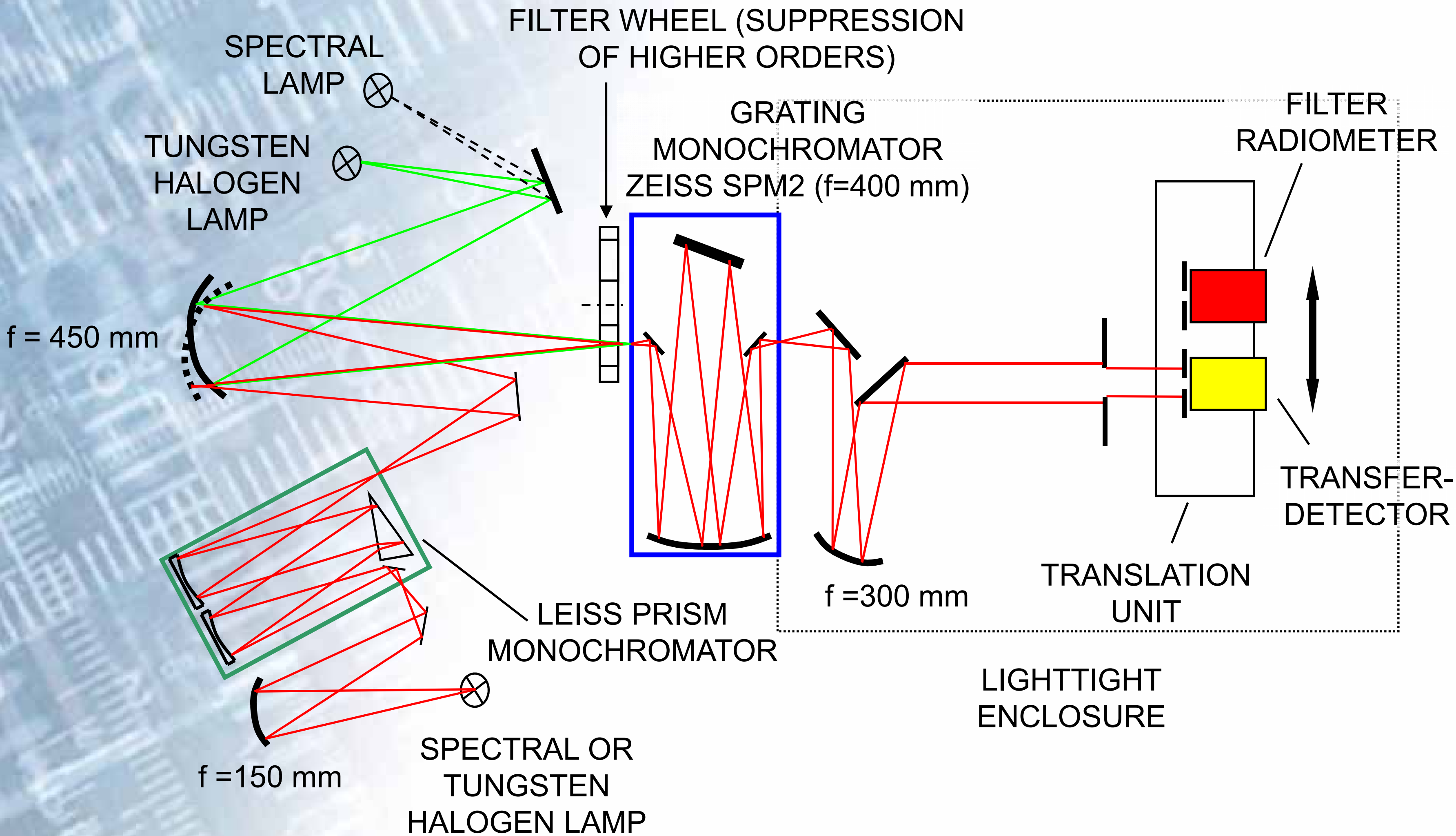
PTB Spectral Comparator Facility

calibration by comparison

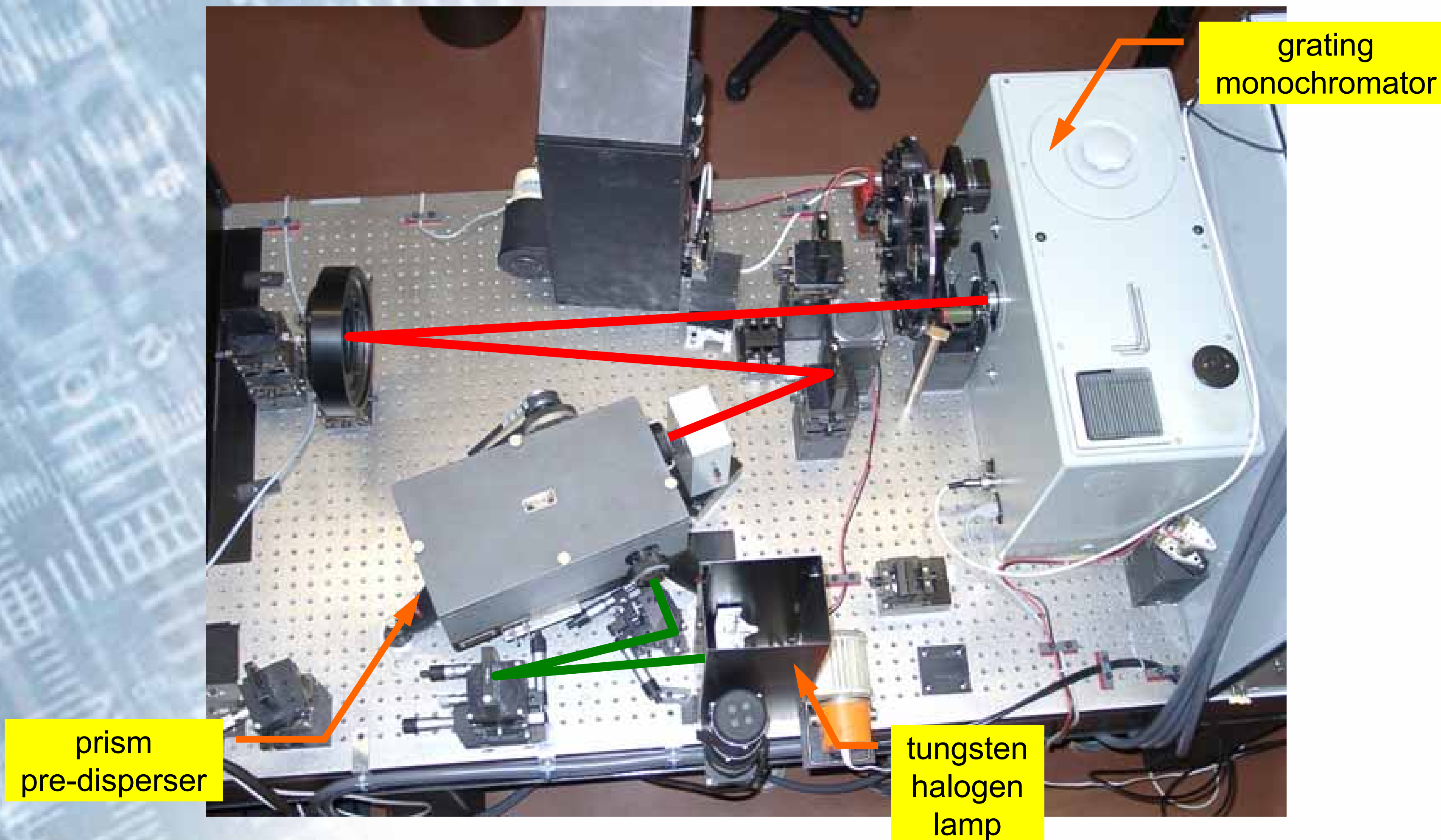
silicon photodiode based
...r

filter radiometer
spectral irradiance responsivity $s_E(\lambda)$ [A·W^{-1}·m^2]

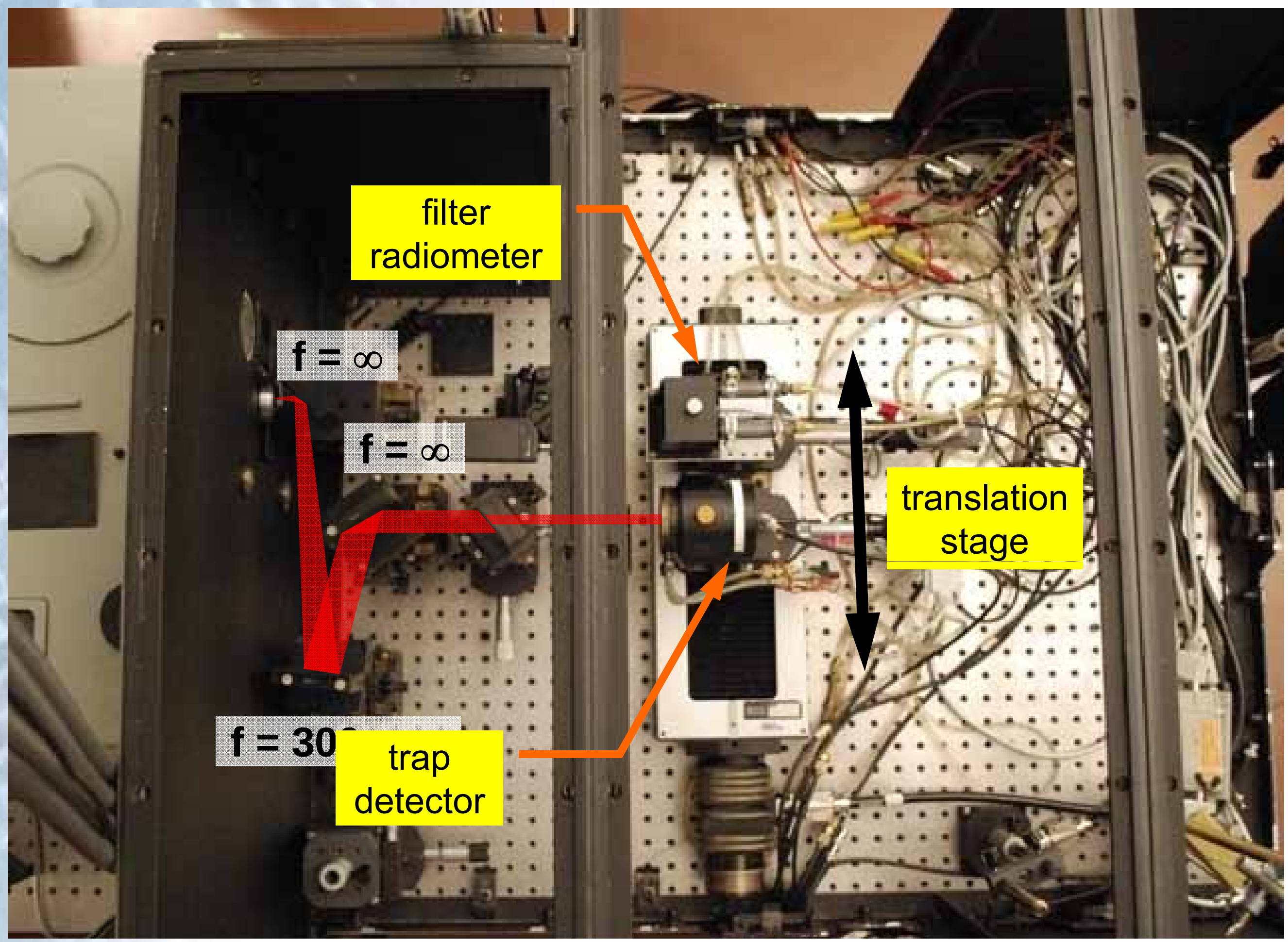
Spectral comparator facility — schematic view



Spectral comparator facility

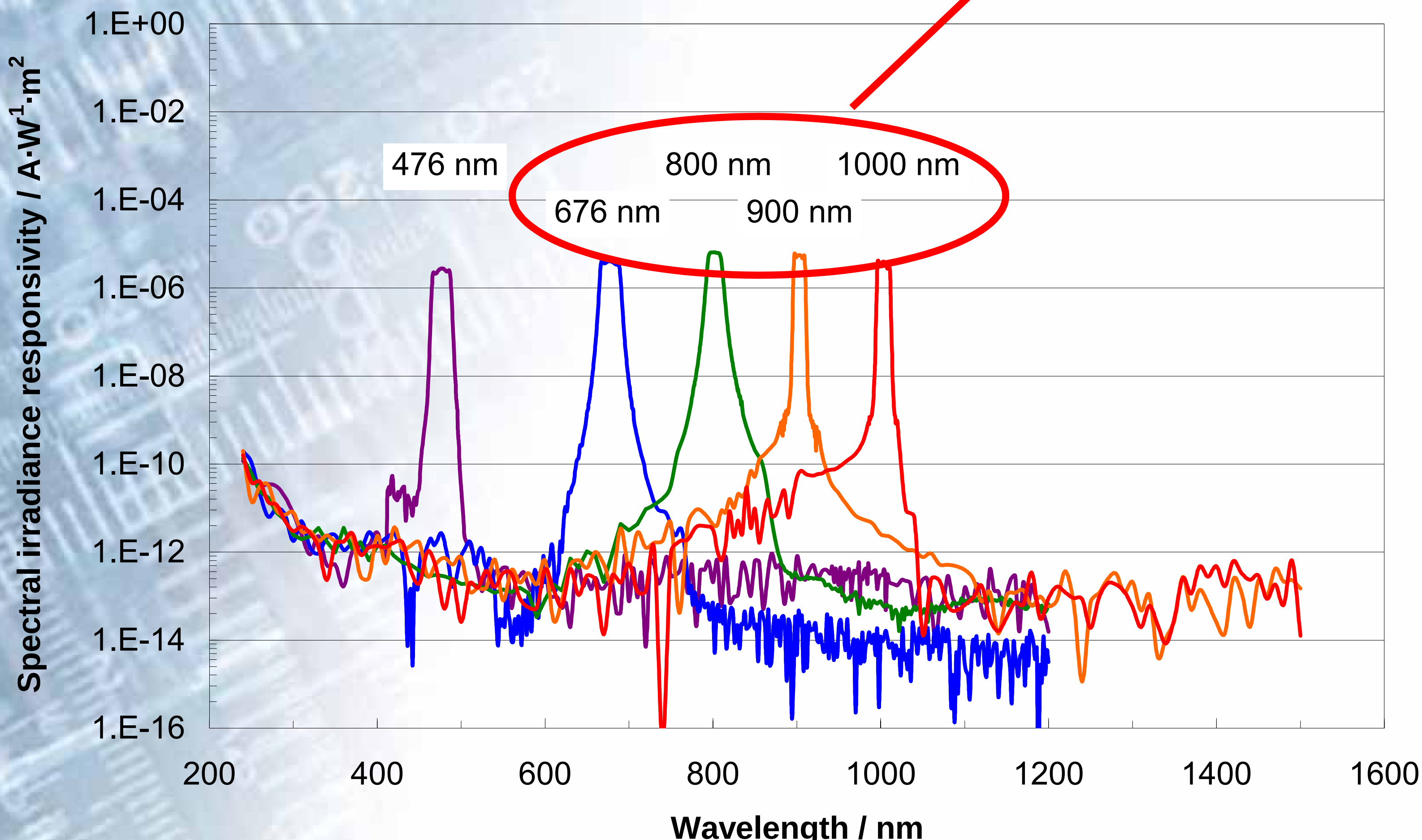


Spectral comparator facility

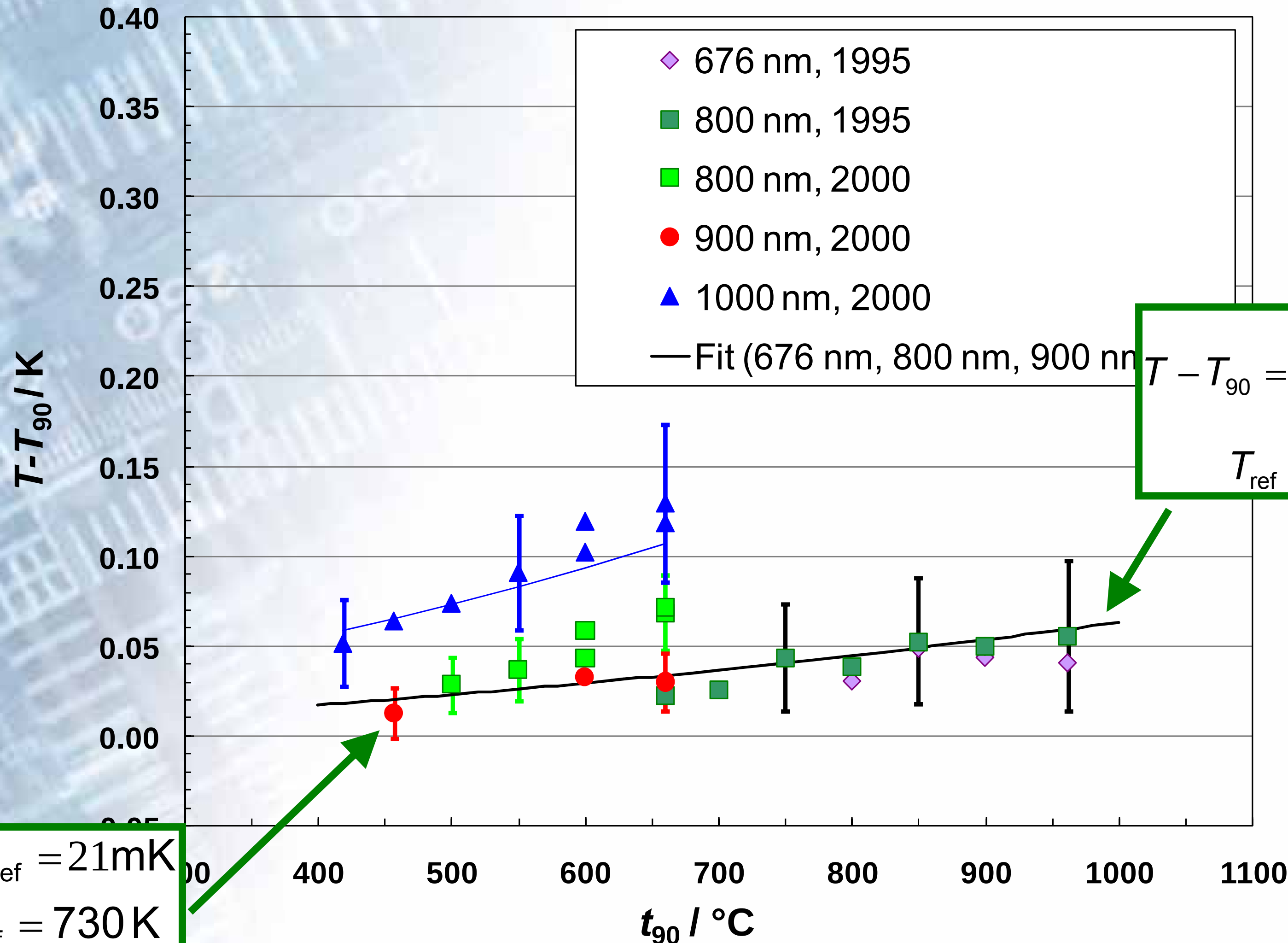


Filter radiometer calibration - results

investigation of the thermodynamic accuracy of the ITS-90 from 419 °C to 962 °C !



Results for T-T_{90} (Si filter radiometer)



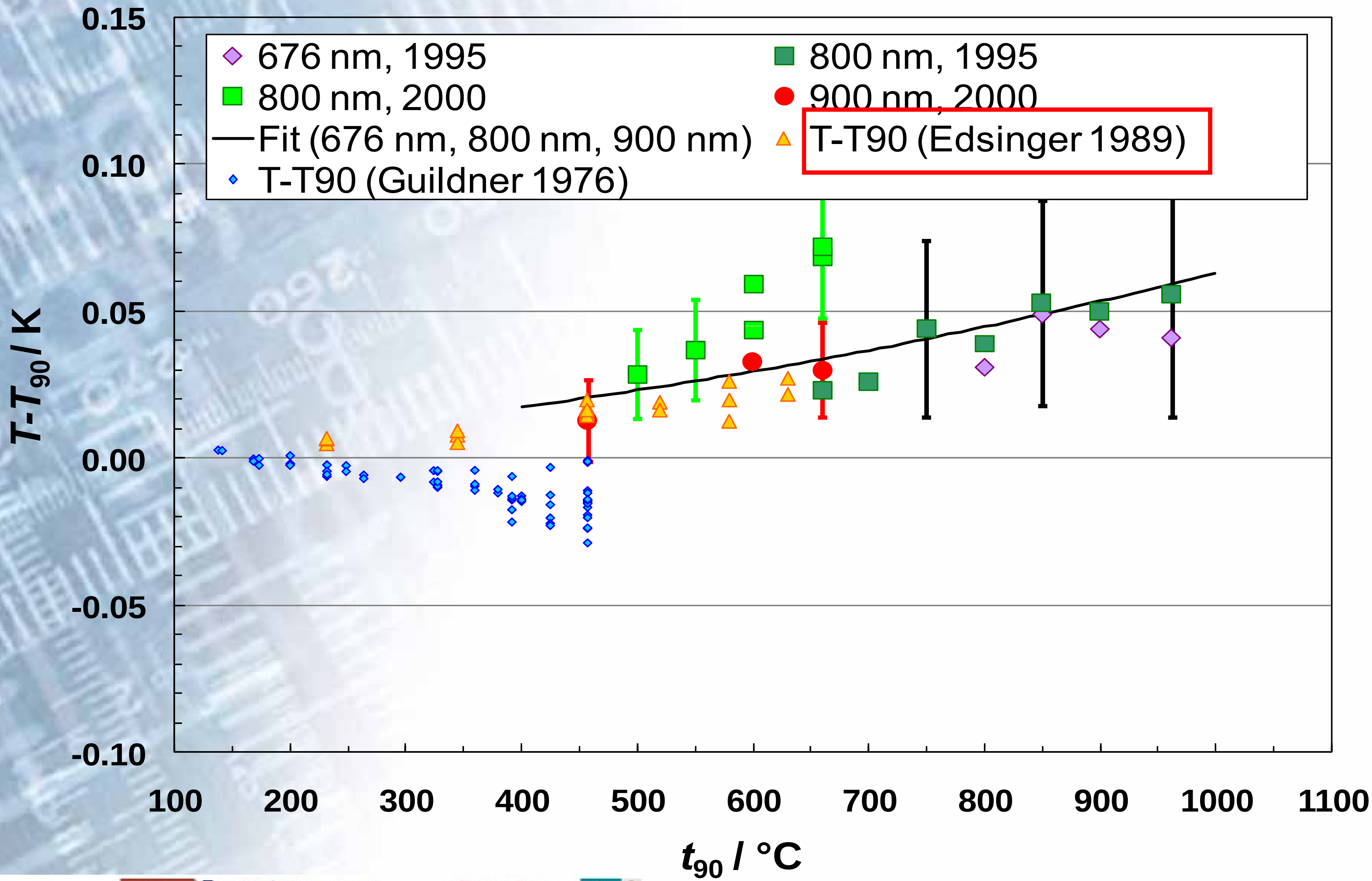
$$T - T_{90} = \left(\frac{T}{T_{\text{ref}}}\right)^2 \cdot \Delta T_{\text{ref}}$$

$$T_{\text{ref}} = 730\,\text{K}$$

$$\Delta T_{\text{ref}} = 21\text{mK}$$

$$T_{\text{ref}} = 730\,\text{K}$$

Results for $T\text{-}T_{90}$ – comparison with gas thermometry



Results for T-T_{90} – uncertainty

	filter radiometer					
	800 nm		900 nm		1000 nm	
	500 °C	660 °C	450 °C	660 °C	419 °C	660 °C
geometry						
area aperture LABB	0.4	0.4	0.4	0.4	0.4	0.4
thermal expansion aperture LABB	0.3	0.3	0.3	0.3	0.3	0.3
diffraction correction	1.6	1.6	1.8	1.8	2.0	2.0
aperture distance (50 µm @ 1000 mm)	0.5	0.5	0.5	0.5	0.5	0.5
total	**1.7**	**1.7**	**1.9**	**1.9**	**2.1**	**2.1**
ITS 90						
realization ITS 90 (9.9 mK @ 660 °C)	2.4	1.6	2.3	1.8	1.9	1.6
temperature stability LABB (± 2 mK)	0.6	0.4	0.6	0.4	0.6	0.3
total	**2.5**	**1.7**	**2.4**	**1.9**	**2.0**	**1.7**
measurement of *T*						
photo current I_{photo}	0.5	0.5	0.5	0.5	0.5	0.5
calibration *I/U*-converter	1.0	1.0	1.0	1.0	1.0	1.0
calibration digital voltmeter	0.2	0.2	0.2	0.2	0.2	0.2
numerical integration photocurr. integral	0.5	0.5	0.5	0.5	0.5	0.5
n refraction index air	0.3	0.3	0.3	0.3	0.3	0.3
k Boltzman constant (CODATA 1998)	0.4	0.3	0.4	0.3	0.4	0.3
emissivity LABB (0.99994 ± 0.00008)	0.8	0.8	0.8	0.8	1.2	0.8
total	**1.6**	**1.5**	**1.6**	**1.5**	**1.8**	**1.5**

- **in units of 10^{-4}**

Results for T-T_{90} – uncertainty

	filter radiometer					
	800 nm		900 nm		1000 nm	
	500 °C	660 °C	450 °C	660 °C	419 °C	660 °C
geometry						
total	**1.7**	**1.7**	**1.9**	**1.9**	**2.1**	**2.1**
ITS 90						
total	**2.5**	**1.7**	**2.4**	**1.9**	**2.0**	**1.7**
measurement of *T*						
total	**1.6**	**1.5**	**1.6**	**1.5**	**1.8**	**1.5**
filter radiometer calibration						
calibration spectral comparator	2.0	2.0	2.3	2.3	5.3	5.3
diffraction correction	0.5	0.5	0.5	0.5	0.5	0.5
central wavelength	2.3	1.8	1.9	1.3	1.0	1.0
total	**3.1**	**2.7**	**3.0**	**2.7**	**5.4**	**5.4**
total uncertainty	**4.6**	**4.0**	**4.6**	**4.1**	**6.4**	**6.2**
temperature equivalent (mK)	**15**	**19**	**15**	**22**	**21**	**38**

- **in units of 10^{-4}**

NIR InGaAs photodiode filter radiometer

Si photodiode
based filter radiometer

↓

InGaAs photodiode
based filter radiometer

↓

- thermodynamic temperature determination of blackbodies
- 419 °C up to 3000 °C
- below 500 °C a difficult task, even at λ_c=1000 nm

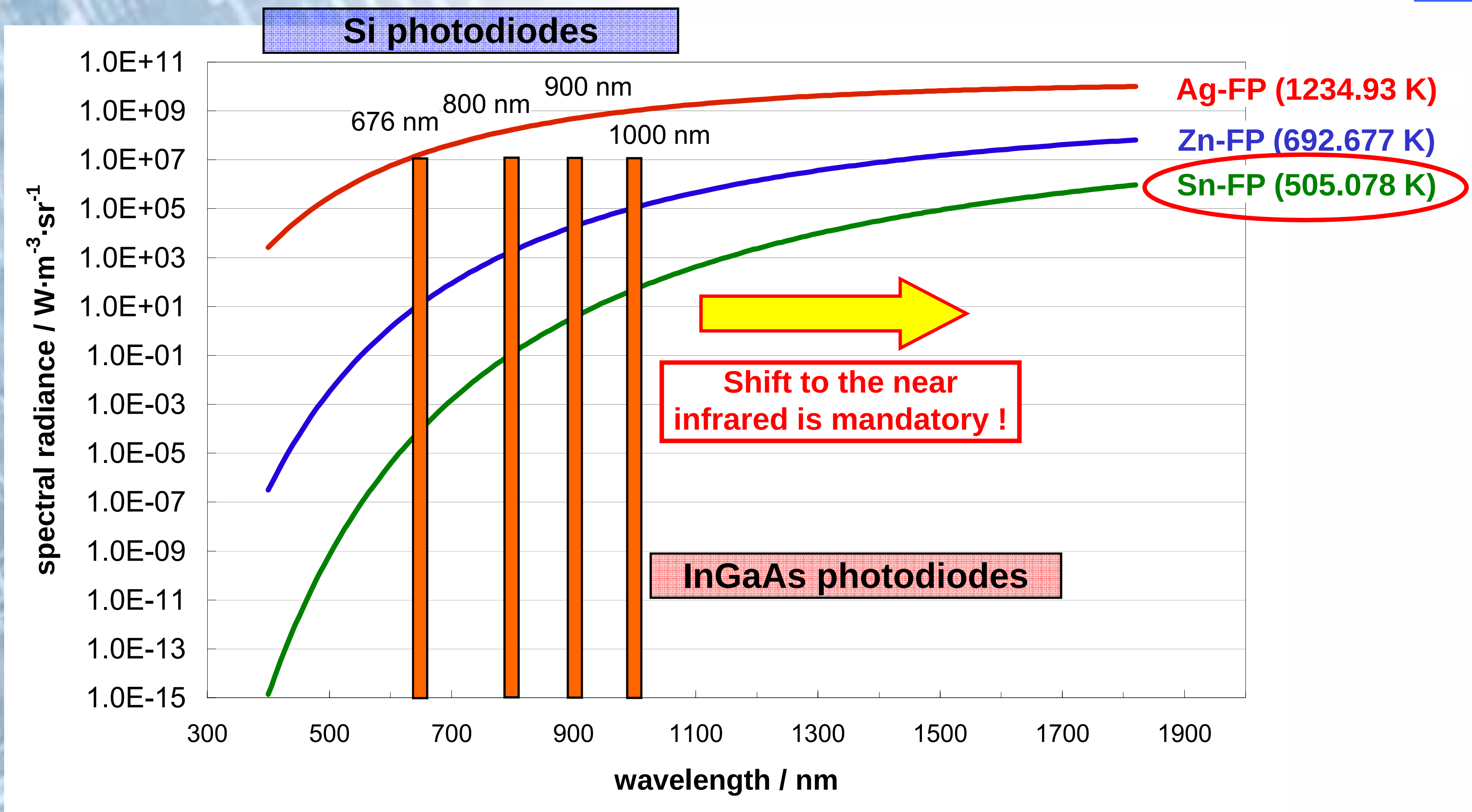
- centre wavelength: 1595 nm
- spectral bandwidth (FWHM): 100 nm

thermodynamic temperature determination in the range 419 °C – 660 °C

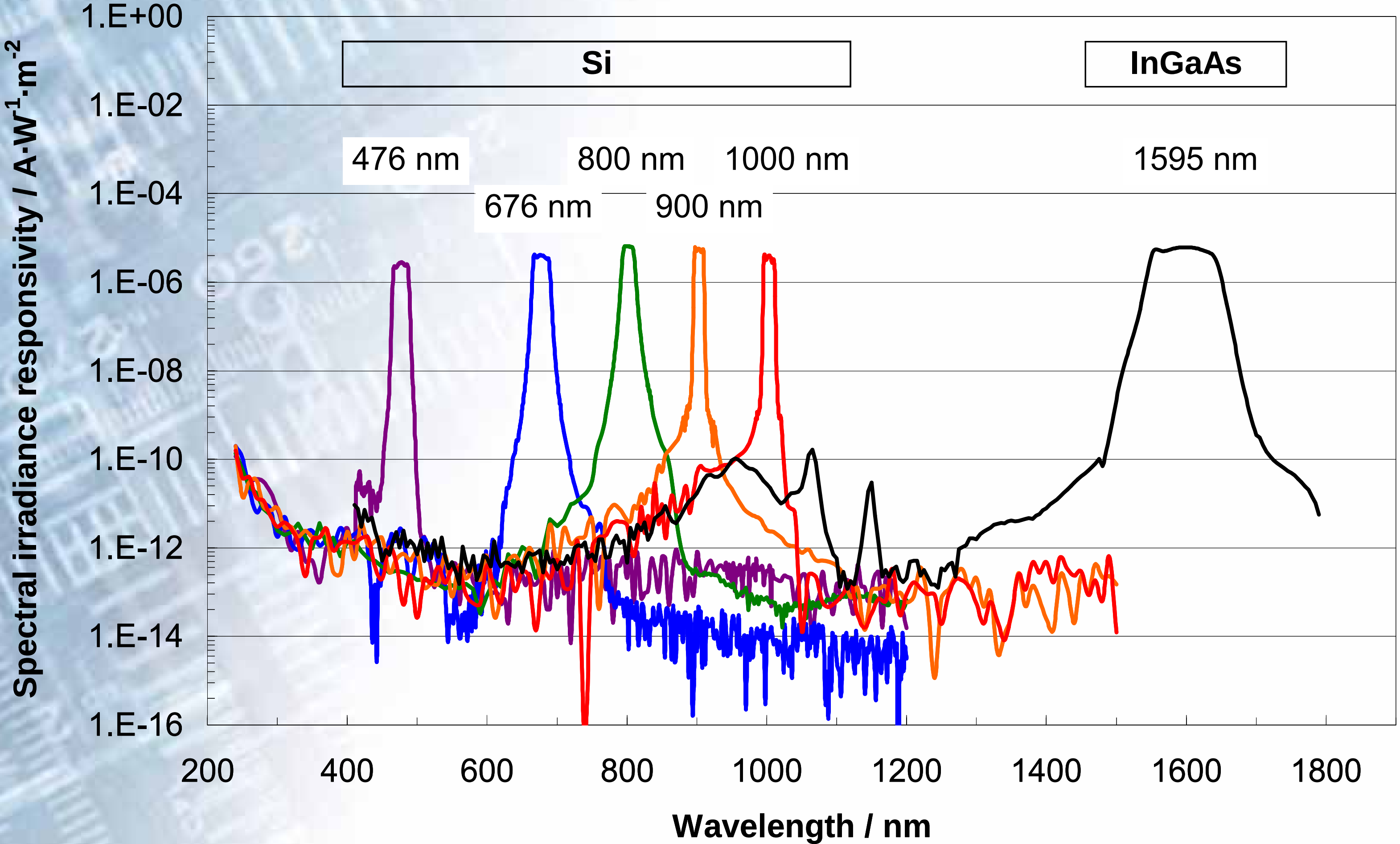
uncertainty: 100 mK @ 457 °C !

main contribution: uncertainty of the
spectral responsivity in the
NIR wavelength range (0.95 µm – 1.65 µm)

NIR InGaAs photodiode filter radiometer



NIR InGaAs photodiode filter radiometer – PTB first approach



NIR InGaAs photodiode filter radiometer

PTB objective : improvement of thermodynamic temperature determinations in the Zn-FP (419 °C) temperature range / extension down to Sn-FP (232 °C)

- improvement of the spectral responsivity scale in the near infrared

Si trap detectors: $u_{rel}(s) \approx 0.02$ % (500 nm – 850 nm)

one order of magnitude !

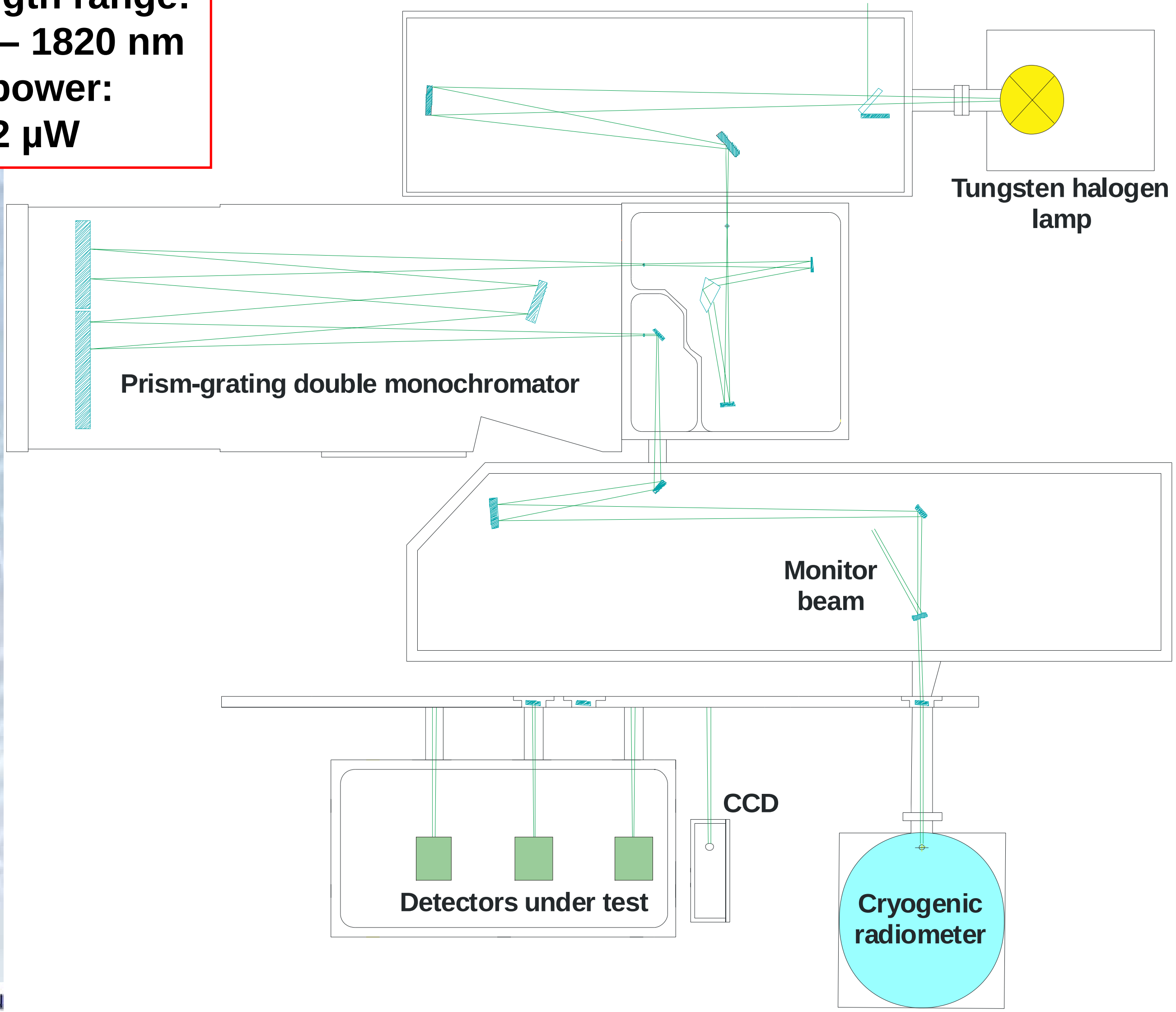
InGaAs photodiodes: $u_{rel}(s) \approx 0.17$ % (0.95 µm – 1.65 µm)

Establishment of a new, cryogenic radiometer facility for the high accuracy calibration of InGaAs transfer detectors

- design and calibration of new InGaAs-photodiode based filter radiometer

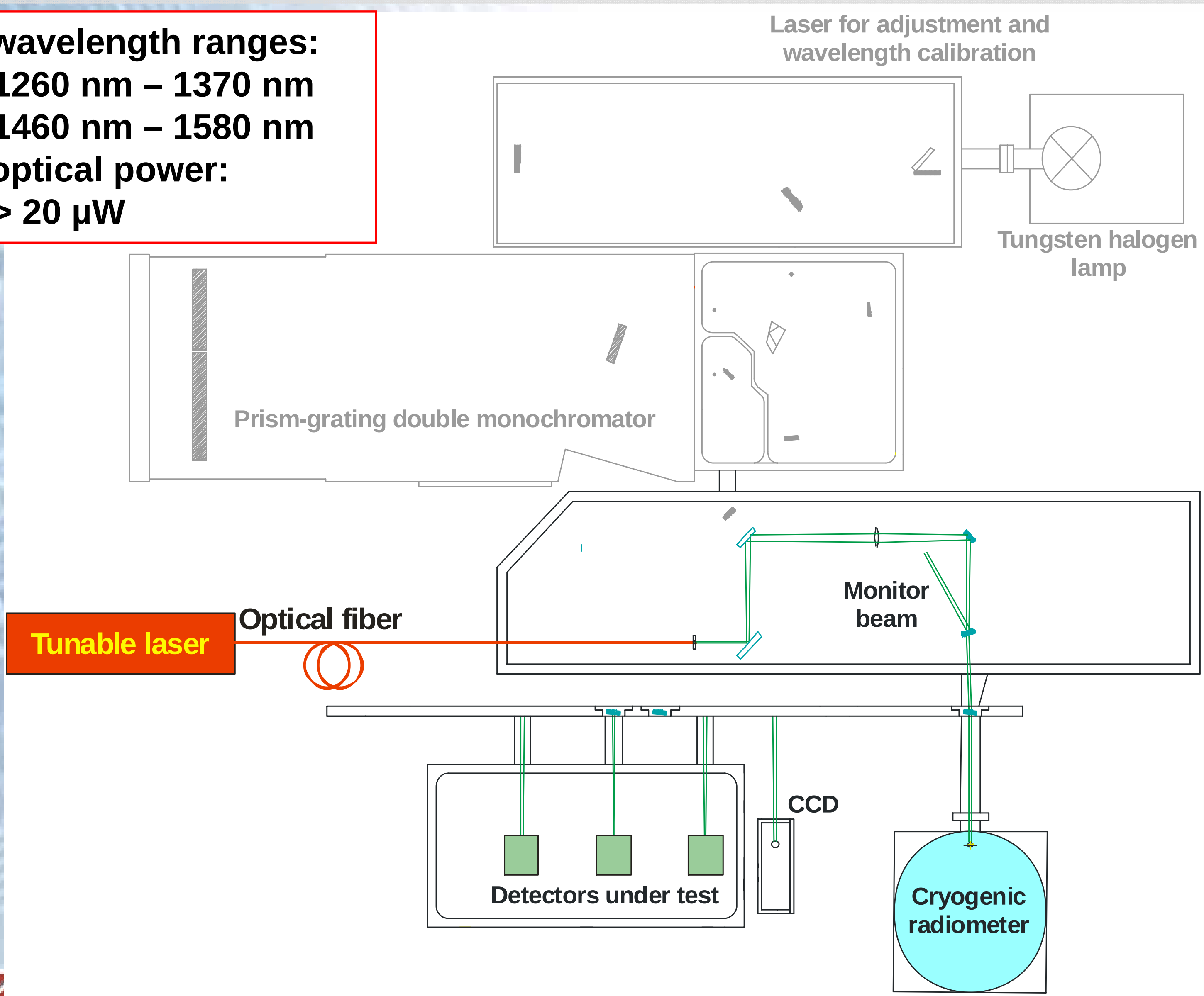
NIR-Detector calibration facility: monochromator source

- wavelength range: 900 nm – 1820 nm
- optical power: 1 µW – 2 µW

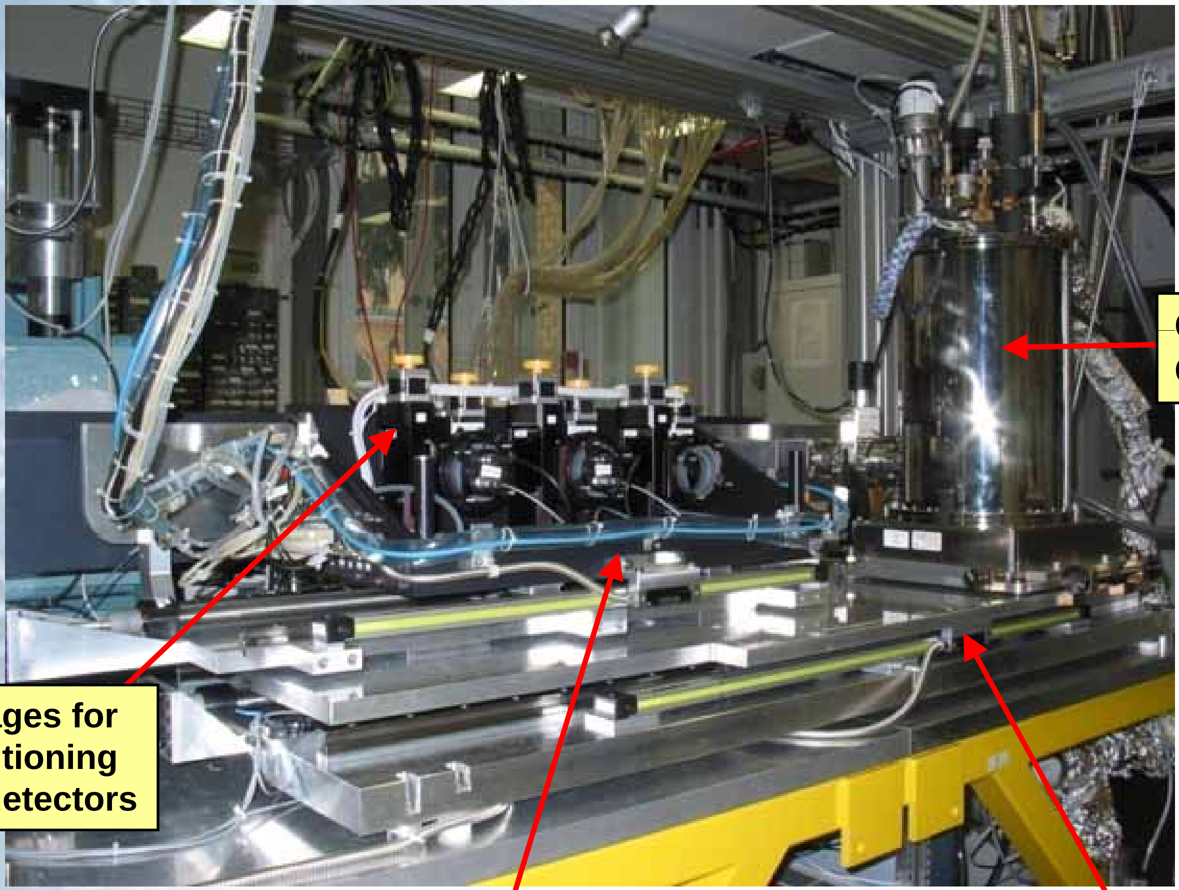


NIR-Detector calibration facility: tunable laser source

- **wavelength ranges:**
  1260 nm – 1370 nm
  1460 nm – 1580 nm
- **optical power:**
  > 20 µW



NIR-Detector calibration facility



Cryogenic radiometer
CRI, CryoRad II

Motorized stages for
• vertical positioning
• rotation of detectors

Motorized stage 2

Motorized stage 2

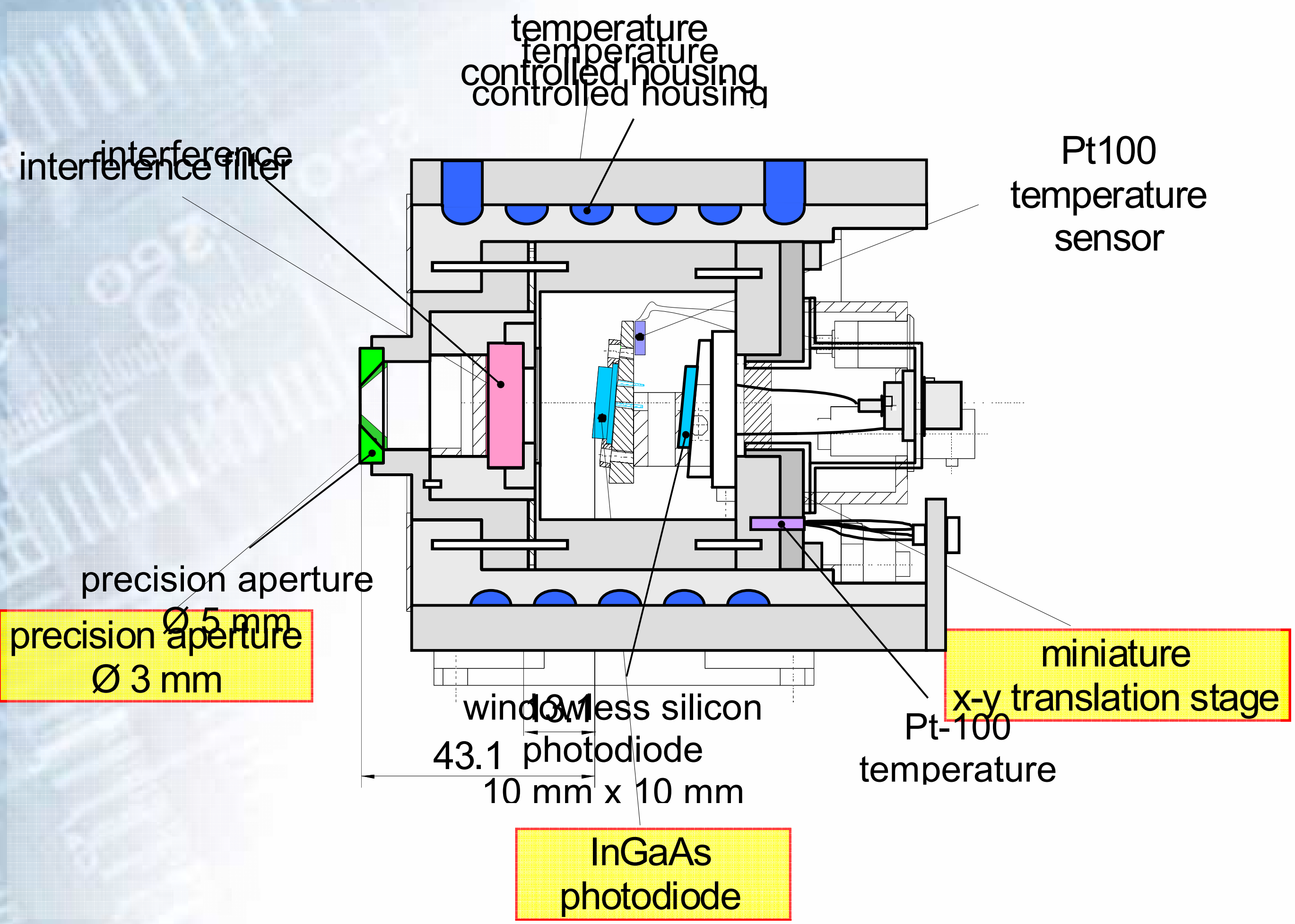
Uncertainty budget: NIR spectral responsivity

Source of uncertainty	Radiation source: Tungsten halogen lamp	Radiation source: Tuneable diode laser
Instability of cryogenic radiometer (noise, drift)	0.075%	0.011%
Uncertainty in wavelength	0.030%	0.001%
Window transmittance	0.030%	0.010%
Uncertainty of electric power measurement	0.015%	0.015%
Detector temperature	0.005%	0.005%
Cavity absorptance and nonequivalence of power measurement	0.003%	0.003%
Stray light	0.002%	0.002%
Combined relative standard uncertainty of spectral responsivity at beam position	**0.088%**	**0.022%**
Typical contribution of the nonuniformity of the transfer detector	0.030%	0.020%
Combined relative standard uncertainty of spectral responsivity	**0.093%**	**0.030%**

factor 5 improvement

NIR filter radiometer – schematic view

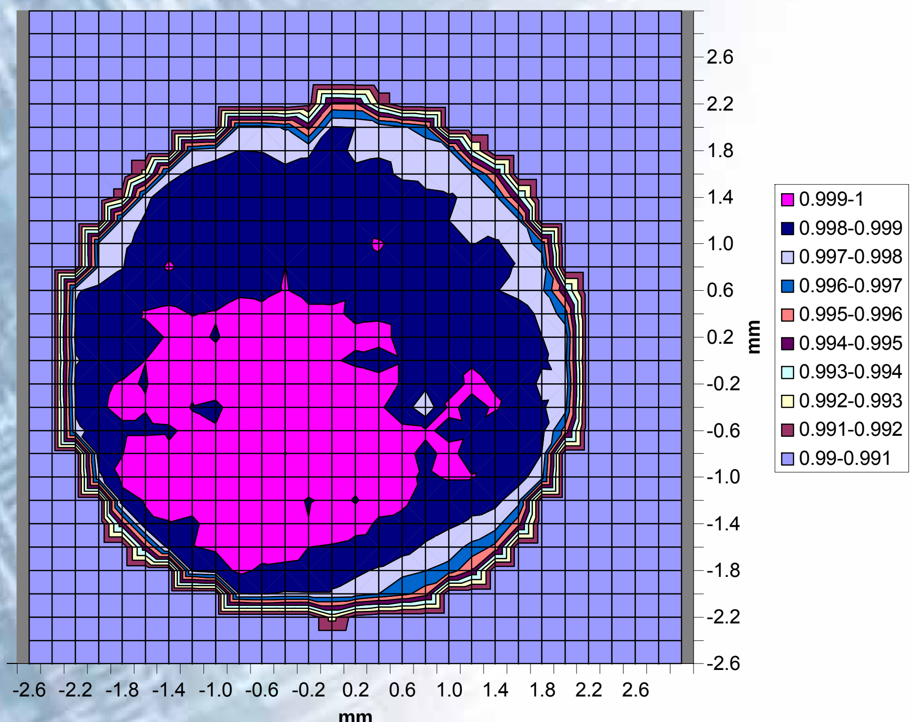
New design

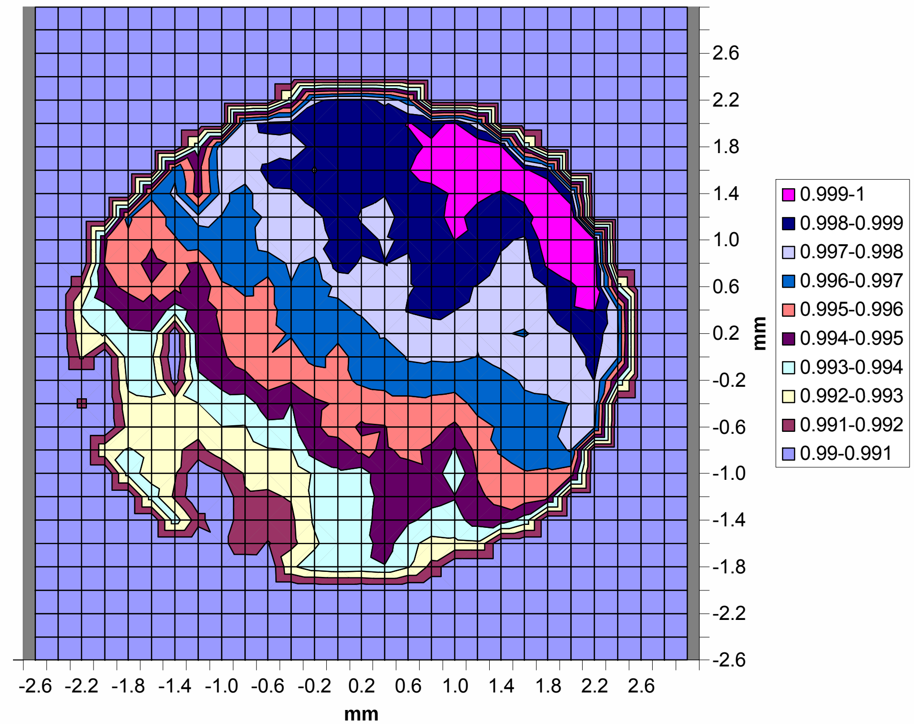


NIR filter radiometer

NIR filter radiometer: Detector homogeneity characterization

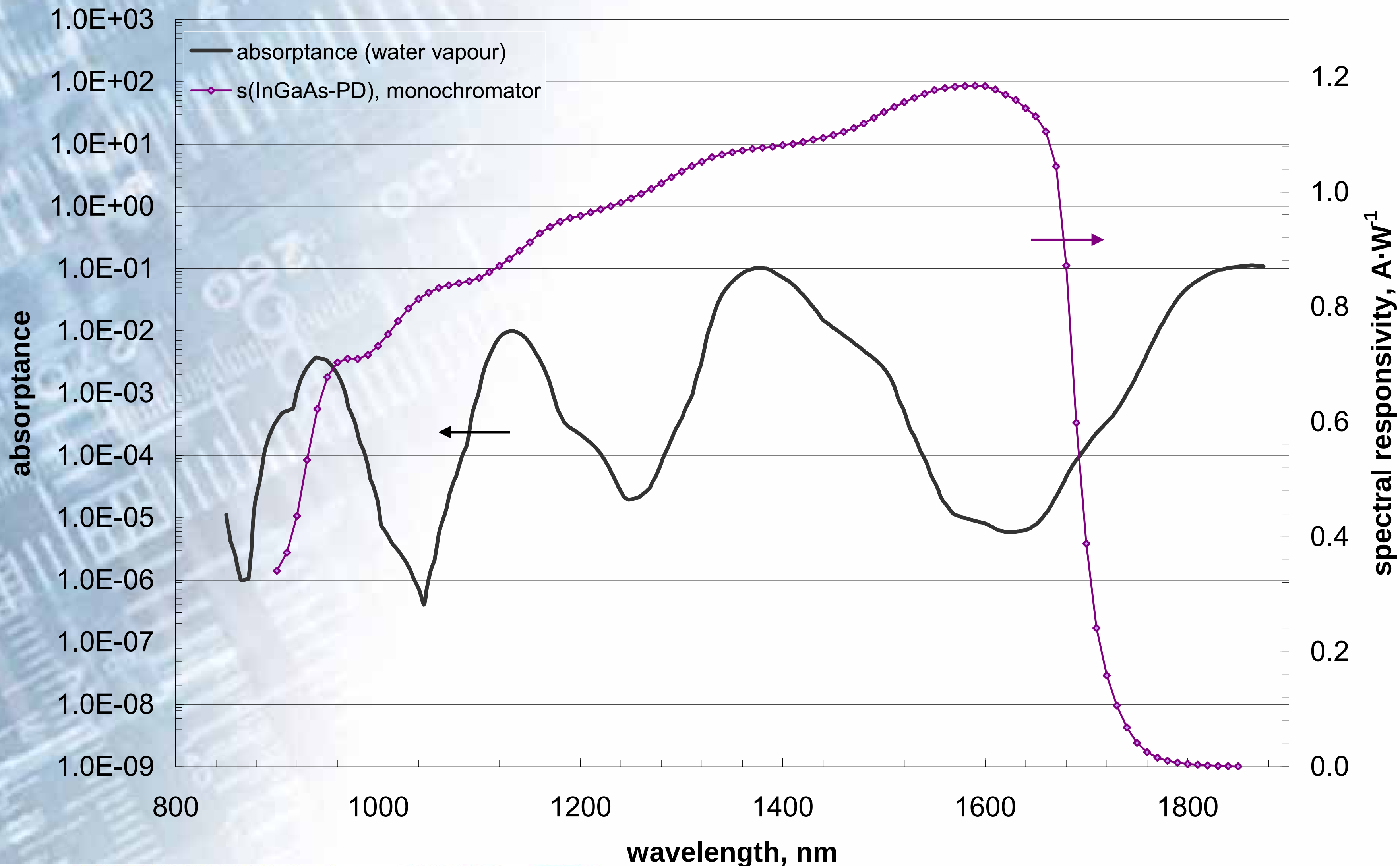
- InGaAs photodiode: Ø = 5 mm; high shunt resistance, typ. > 20 MΩ
- λ = 1300 nm
- Measurement spot size: Ø = 0.3 mm



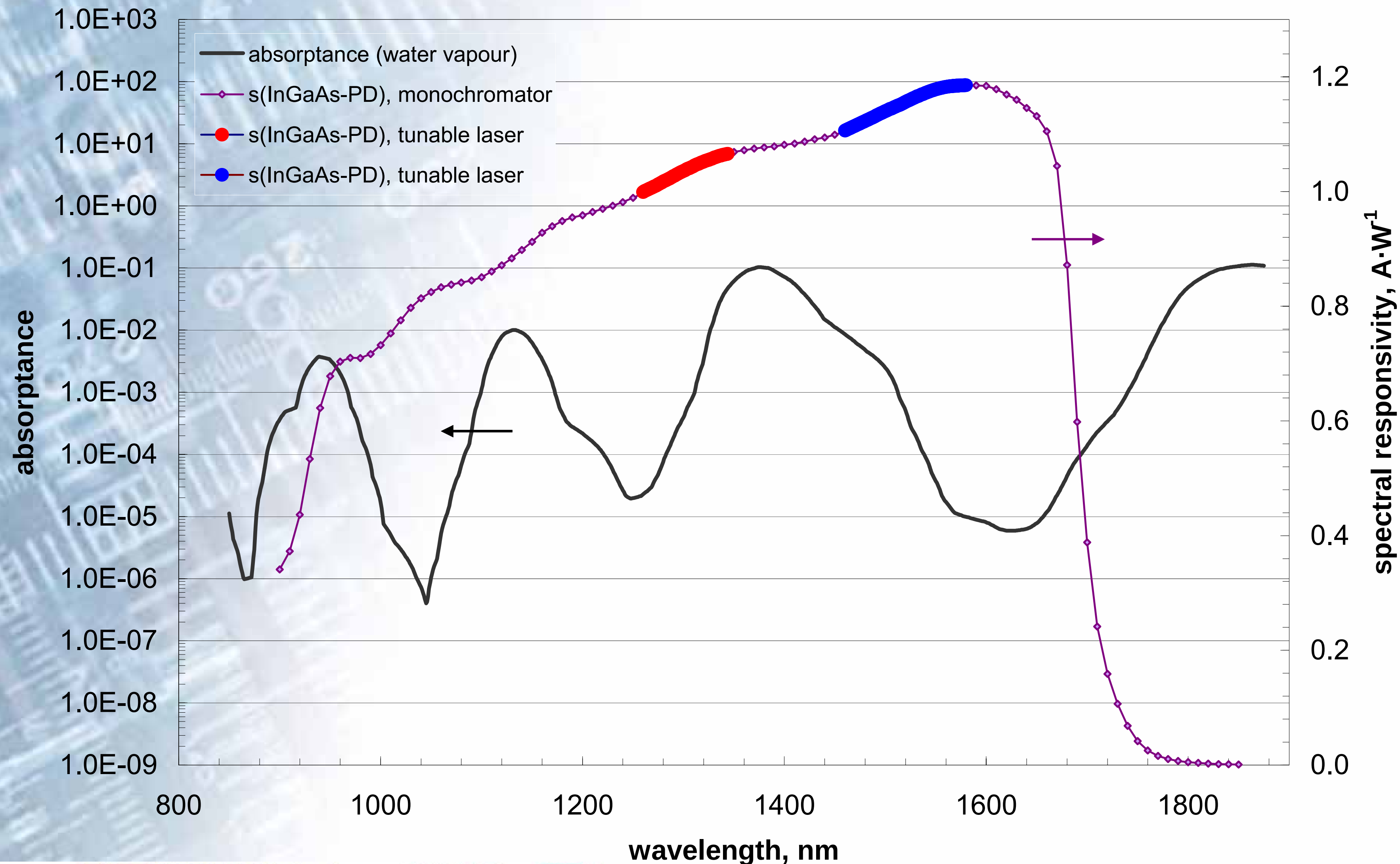


One colour change: $\Delta s/s = 1 \cdot 10^{-3}$

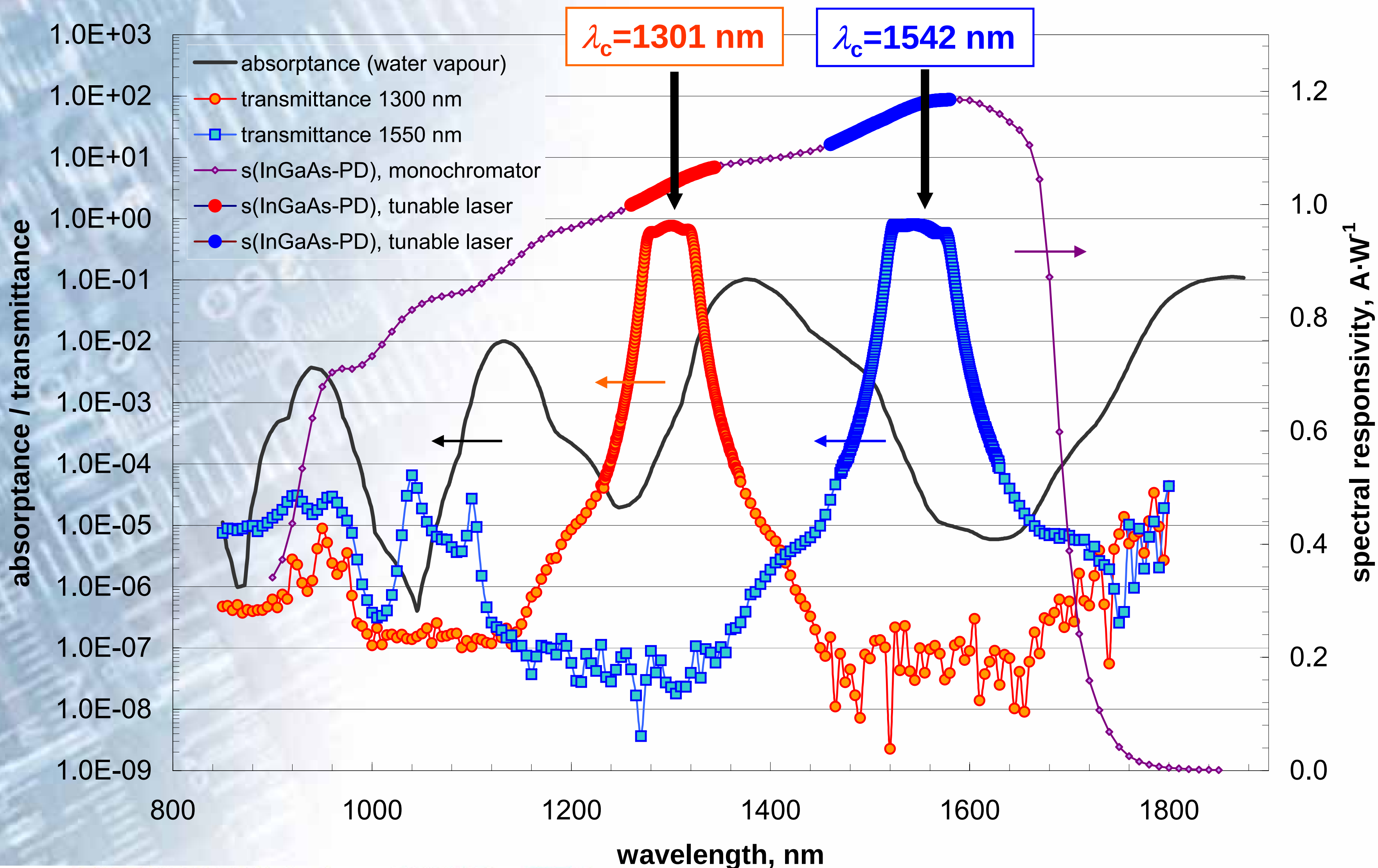
NIR filter radiometer: interference filters



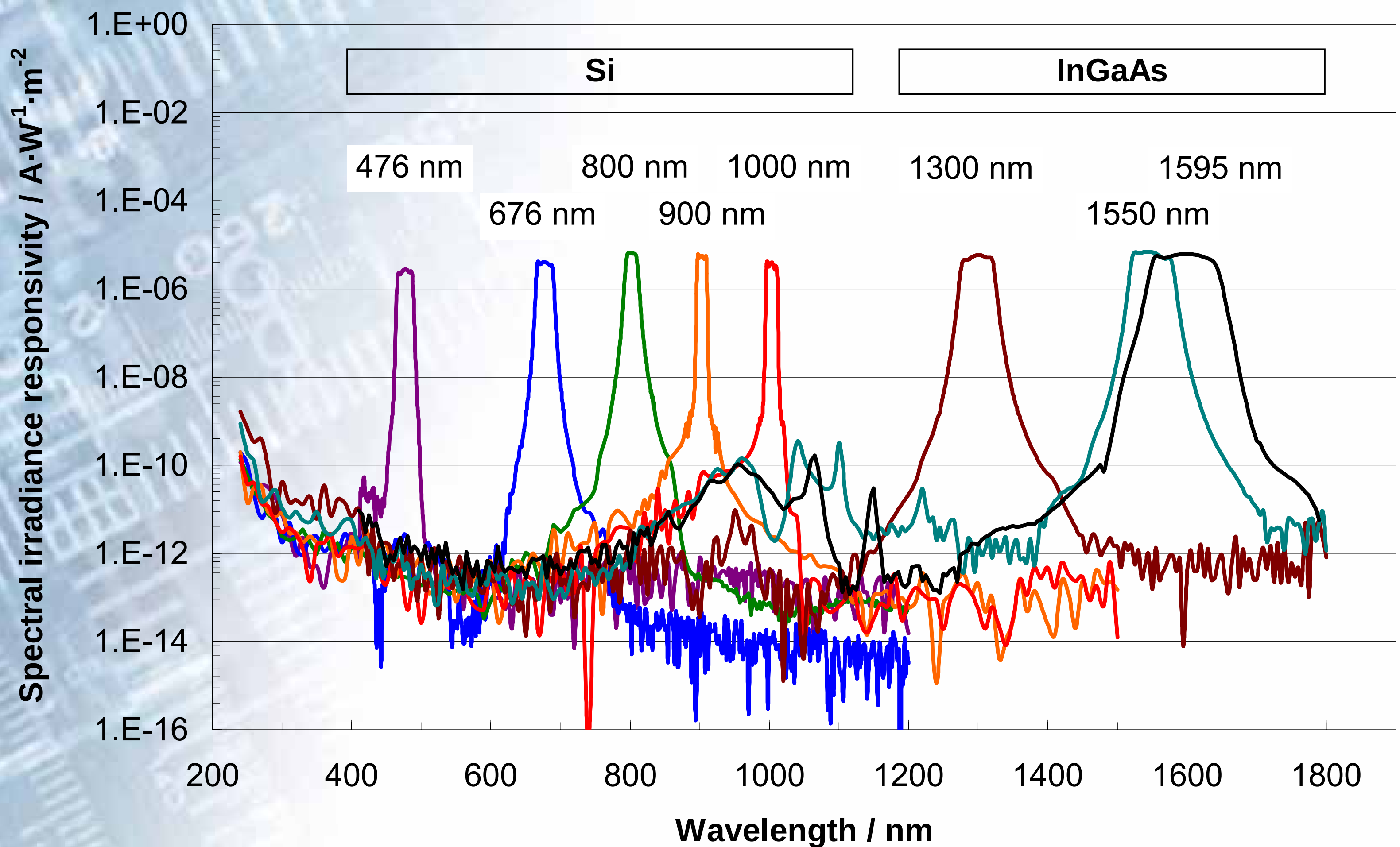
NIR filter radiometer: interference filters



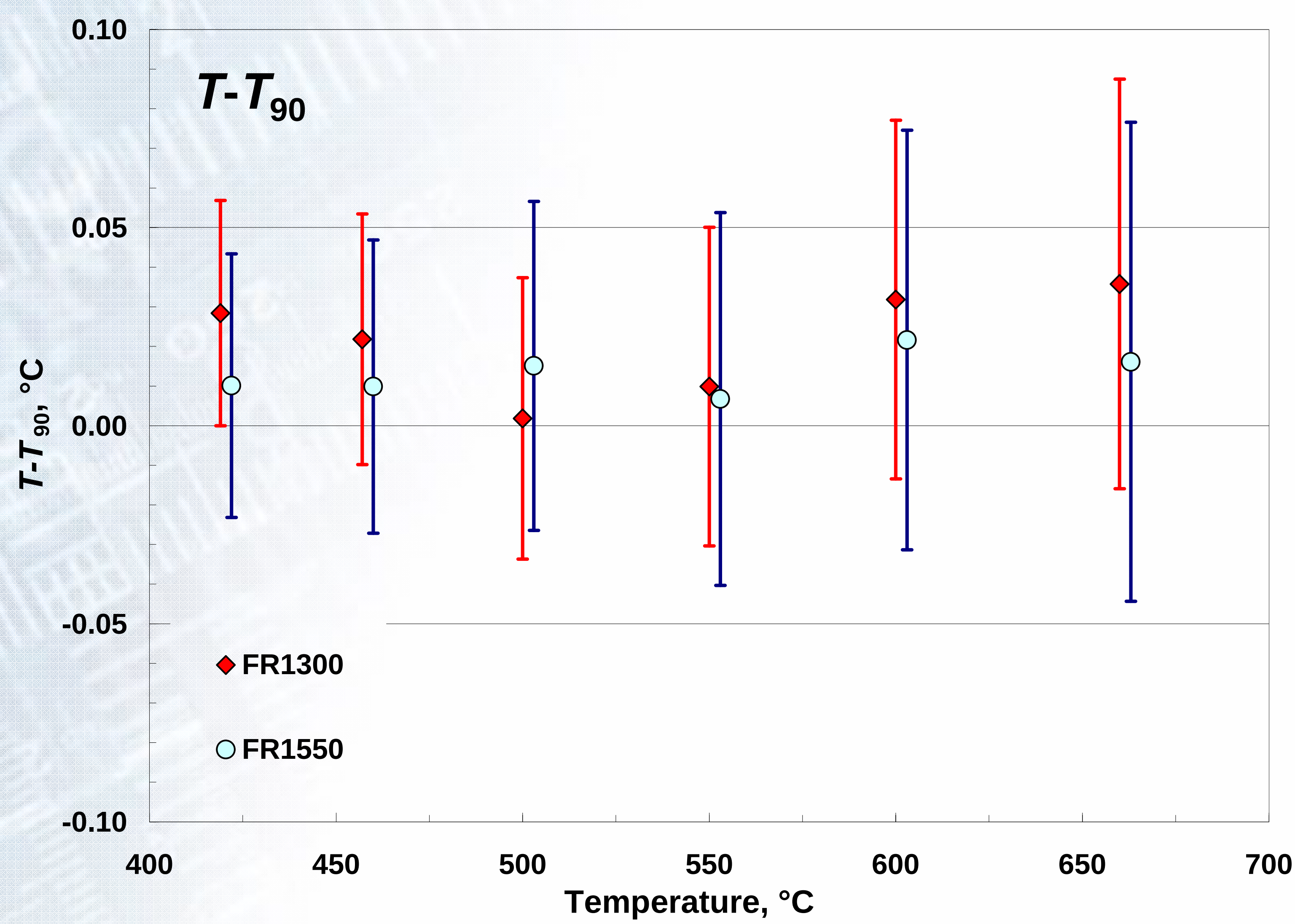
NIR filter radiometer: interference filters



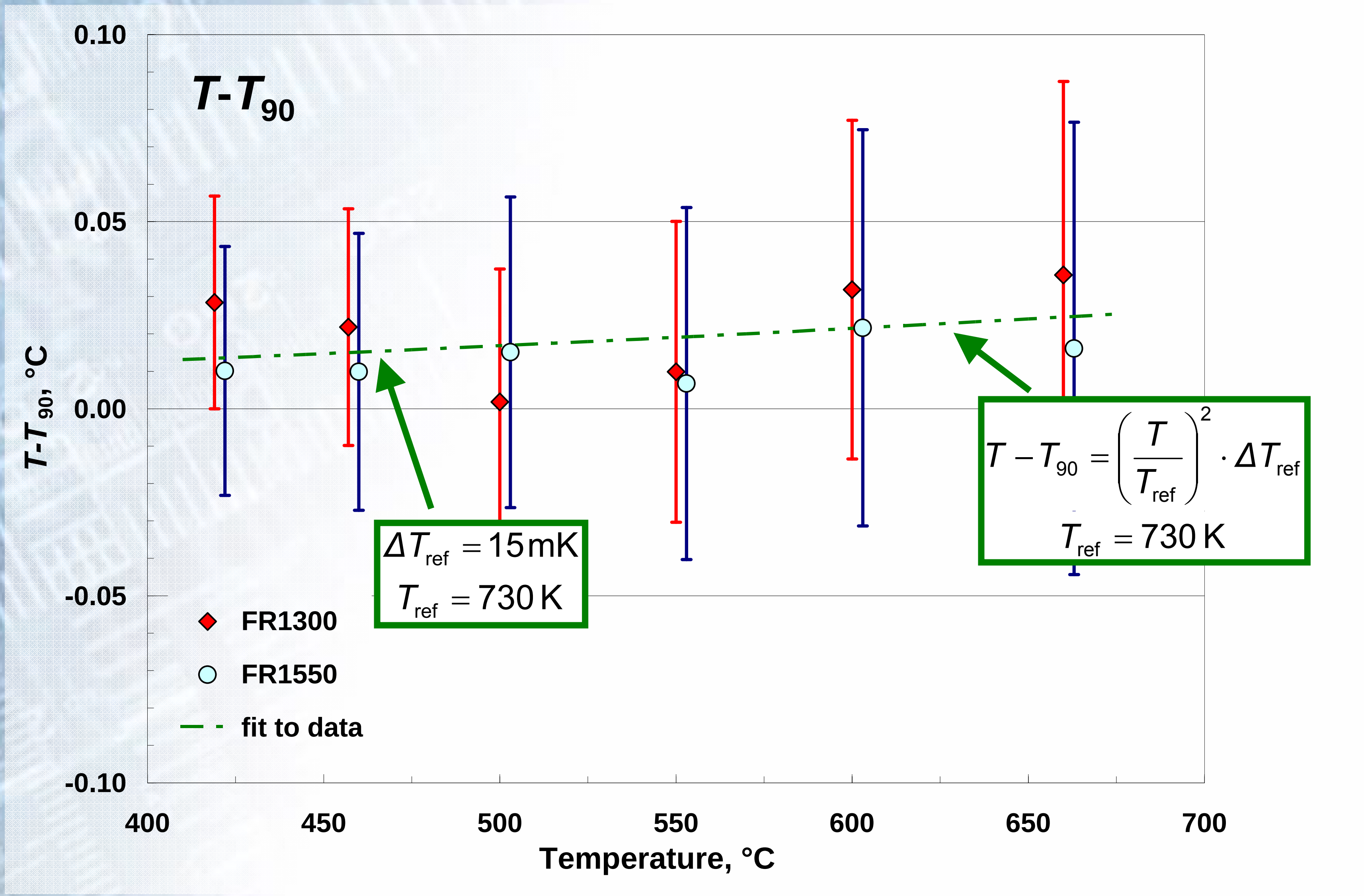
NIR filter radiometer: spectral irradiance responsivity



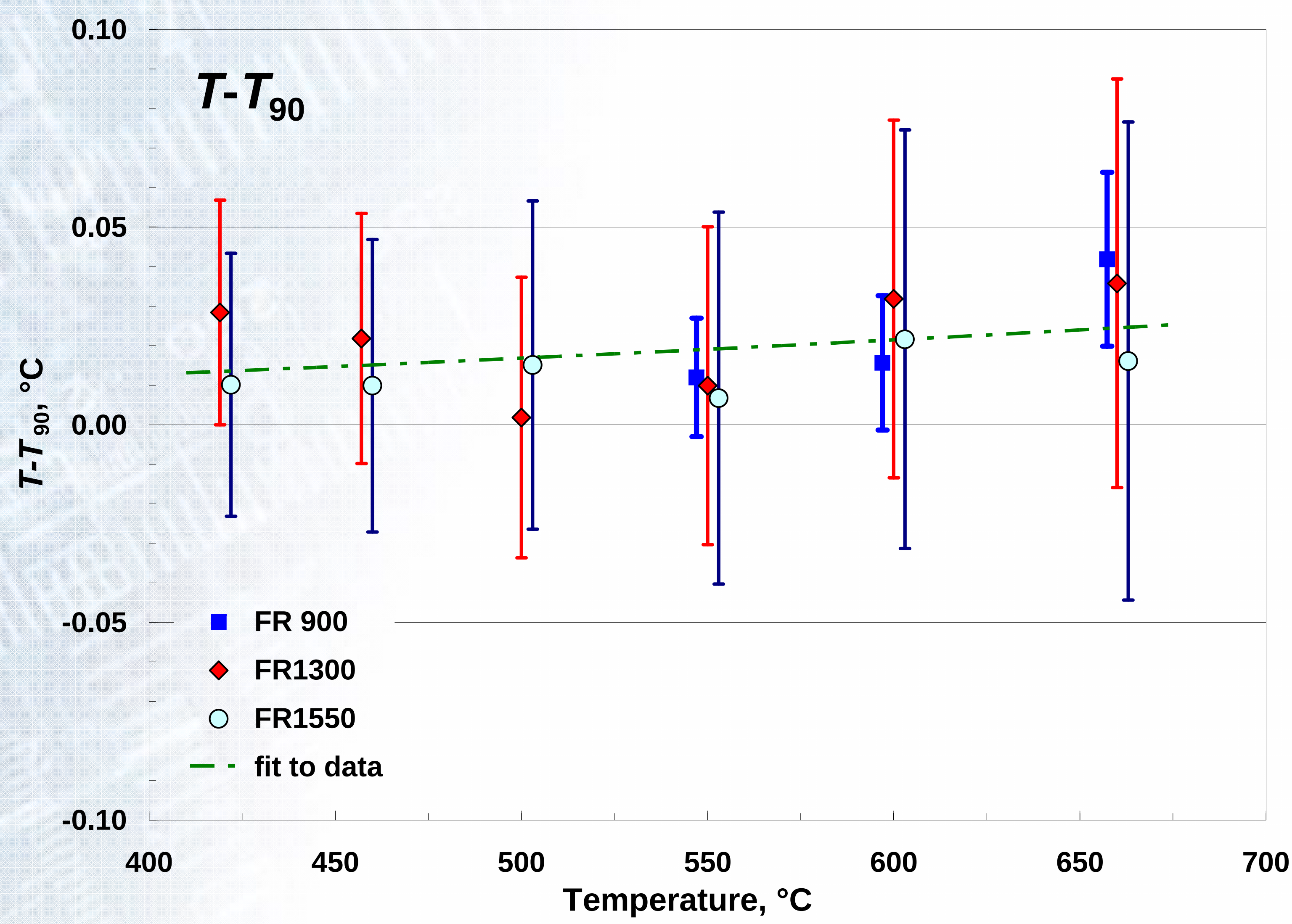
Thermodynamic temperature determination: results



Thermodynamic temperature determination: results



Thermodynamic temperature determination: results



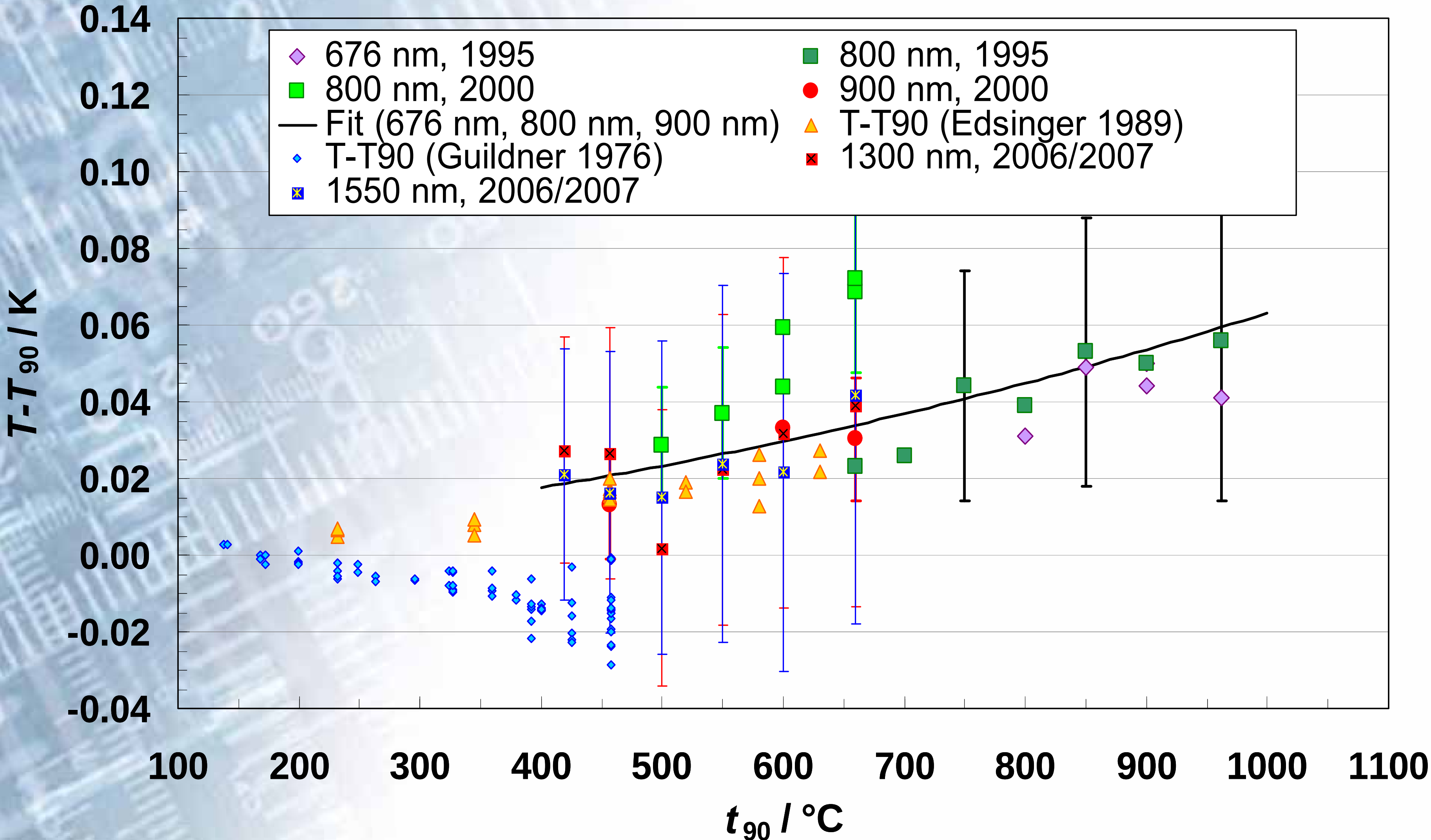
Thermodynamic temperature determination: uncertainty

Source of uncertainty	Filter radiometer FR1300	Filter radiometer FR1550	Filter radiometer FR1595
	$\Delta s_E / s_E$ ($\times 10^4$)		
Geometry			
Aperture area	0.4	0.4	0.4
Thermal expansion aperture	0.3	0.3	0.3
Distance of the apertures	1.0	1.0	1.0
Diffraction correction	1.0	1.0	1.0
Measurement of *T*			
Photocurrent noise	0.5	0.5	0.5
Calibration feedback resistors	1.0	1.0	1.0
Calibration DVM	0.2	0.2	0.2
Refractive index n	0.3	0.3	0.3
Boltzmann constant k	0.2	0.2	0.2
Numerical integration	0.5	0.5	0.5
Emissivity LABB	0.8	0.8	0.8
Homogeneity LABB	2.0	2.0	2.0
Filter radiometer calibration			
Calibration spectral comparator	5.8	5.5	13.5
Diffraction correction	1.0	1.0	1.0
Combined relative standard uncertainty	**6.6**	**6.3**	**13.9**

Thermodynamic temperature determination: uncertainty

Source of uncertainty	Filter radiometer FR1300	FR1550	FR1595
	$\Delta s_E/s_E$ (×10[4])		
Combined relative standard uncertainty	**6.6**	**6.3**	**13.9**
Temperature equivalent	$u(T)$ / mK		
419 °C	29	32	74
660 °C	52	59	134
Measurement of T_{90}	$u(T_{90})$ / mK		
419 °C	7	7	7
660 °C	10	10	10
$u(T - T_{90})$ / mK, k=1			
419 °C	**29**	**33**	**74**
660 °C	**53**	**60**	**134**

Results for T-T_{90} (Si and InGaAs filter radiometer)



Summary and Outlook

- PTB operates laser and monochromator based cryogenic radiometer calibration facilities
- Standard uncertainty (*k*=1) of the spectral responsivity:
  dissemination with Si trap detectors: 0.02 % to 0.1 %
  dissemination with InGaAs photodiodes: 0.03 % to 0.1%
- Absolute calibration of filter radiometers at the Spectral Comparator Facility;
  standard uncertainty (*k*=1)of the spectral irradiance responsivity:
  Si photodiode filter radiometer: 0.03 % to 0.06 %
  InGaAs-photodiode filter radiometer: 0.07 % to 0.14%

Summary and Outlook

- Systematic $T\text{-}T_{90}$ determinations with Si-/ InGaAs-photodiode filter radiometers in conjunction with a high accuracy sodium heat pipe blackbody in the temperature range from the Zn-FP (419 °C) to the Ag-FP (962 °C)
- Results for $T\text{-}T_{90}$ of all applied filter radiometers are consistent within their uncertainties
- Results strongly indicate that the ITS-90 reference from gas thermometry value has been chosen about **15 mK to low**
- Near future: $T\text{-}T_{90}$ determinations down to the Sn-FP (232 °C); source: cesium heat pipe blackbody

Muster