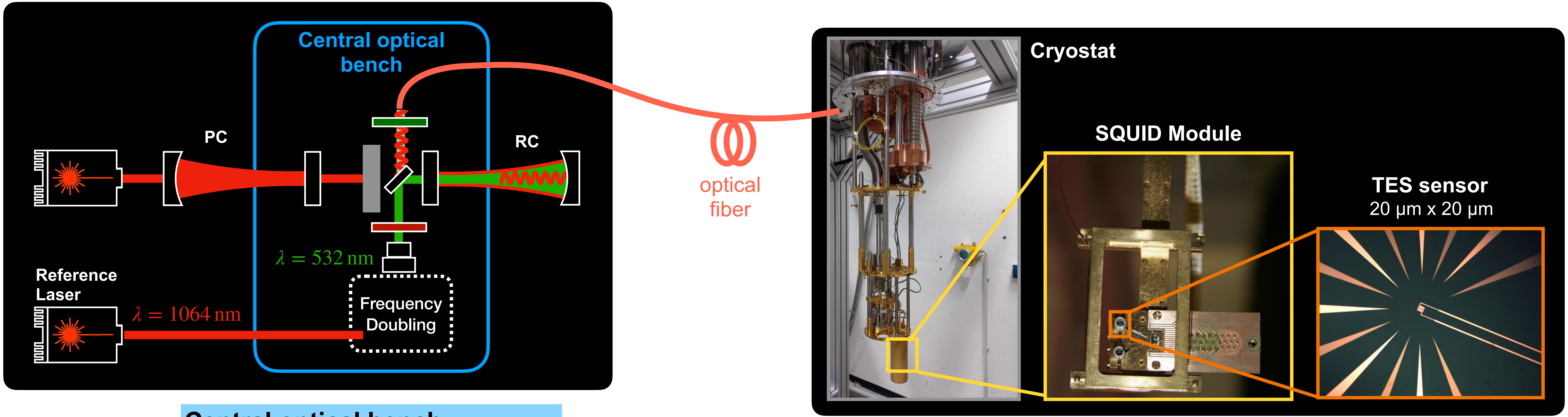
Optics for the TES Detector

Characterization and Interface Concepts

Overview

How many dark counts are there?

How (efficient) do we get the signal to the TES?



Central optical bench (COB)

- Dichroic filters before RC
- Effects in the RC + Signal
- Dichroic filters after RC
- Environmental light
- Fluorescence
- Open Shutter (Calibration Mode)
- …

Extrinsic Noise (fiber connected)

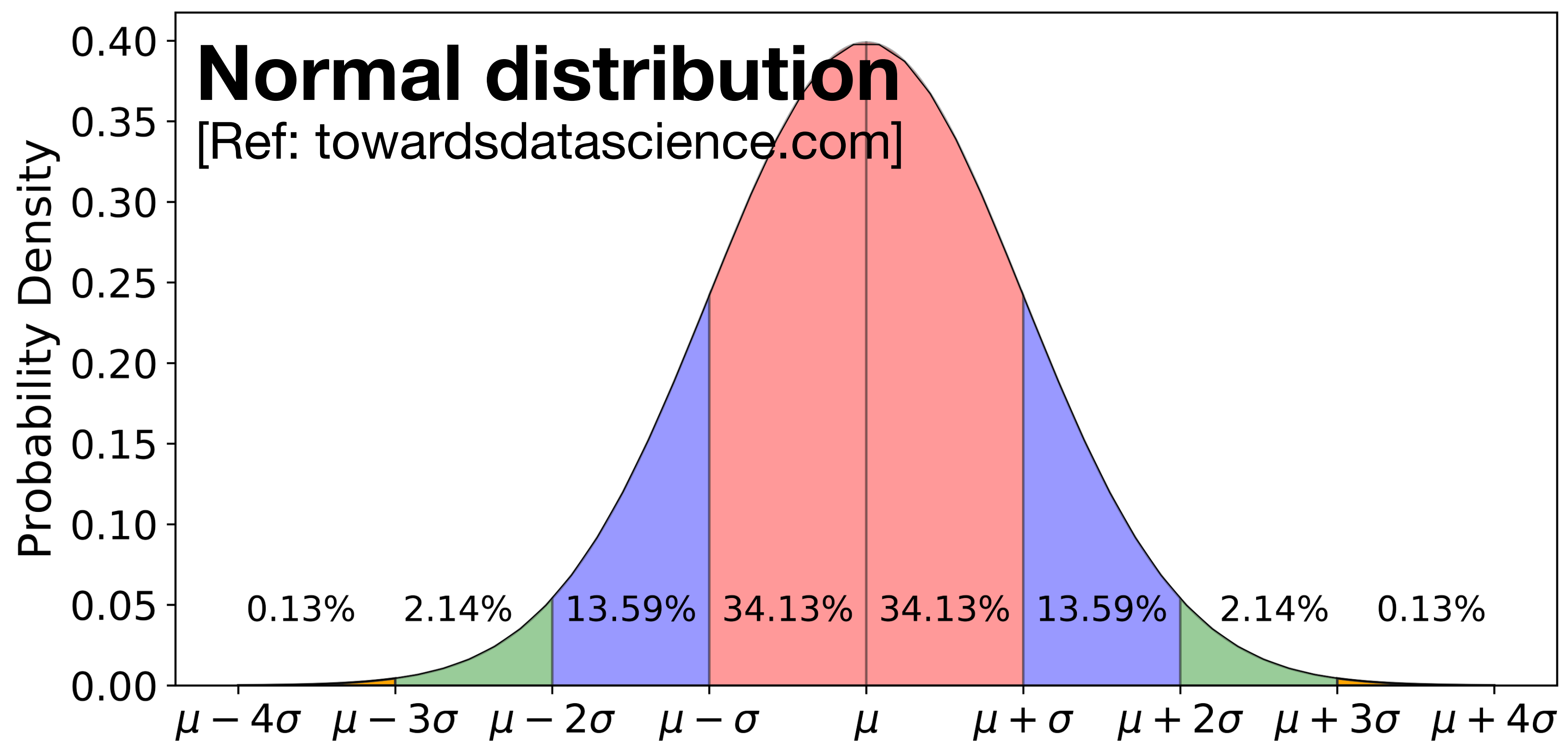
- Cosmic, radioactivity
- Environmental light
- Thermal fiber (& end)
- Fiber components
- Black body pile-ups
- … ?

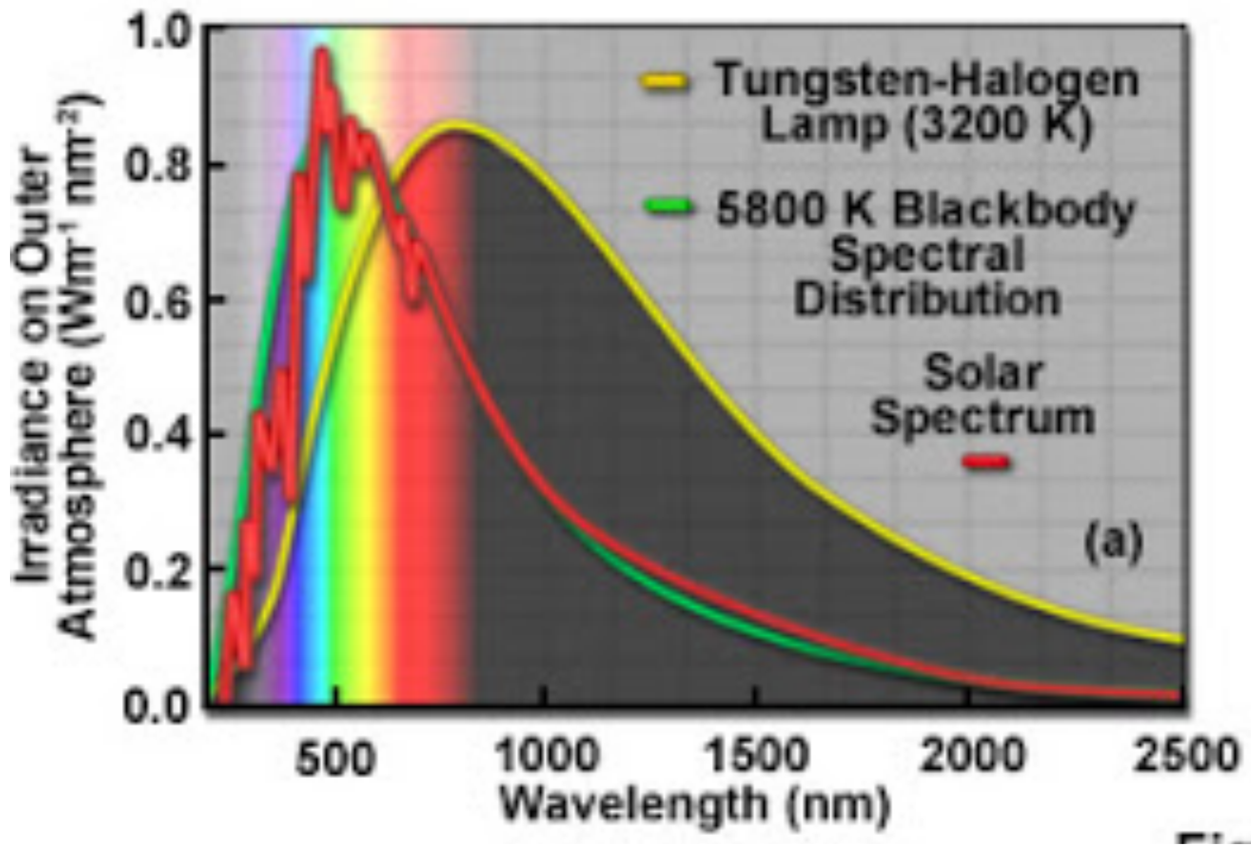
Intrinsic Noise (TES sensor only)

- Fit algorithm
- TES operation point
- Readout electronics
- Radioactivity
- Cosmic radiation
- EM interference
- … ?

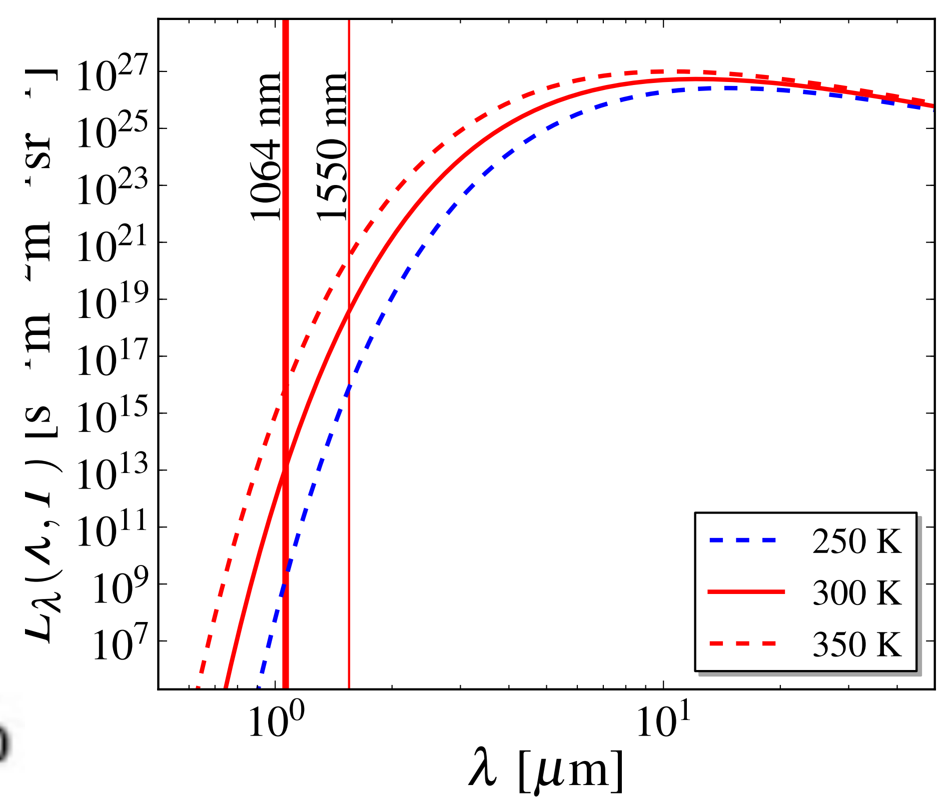
Detector Side

Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

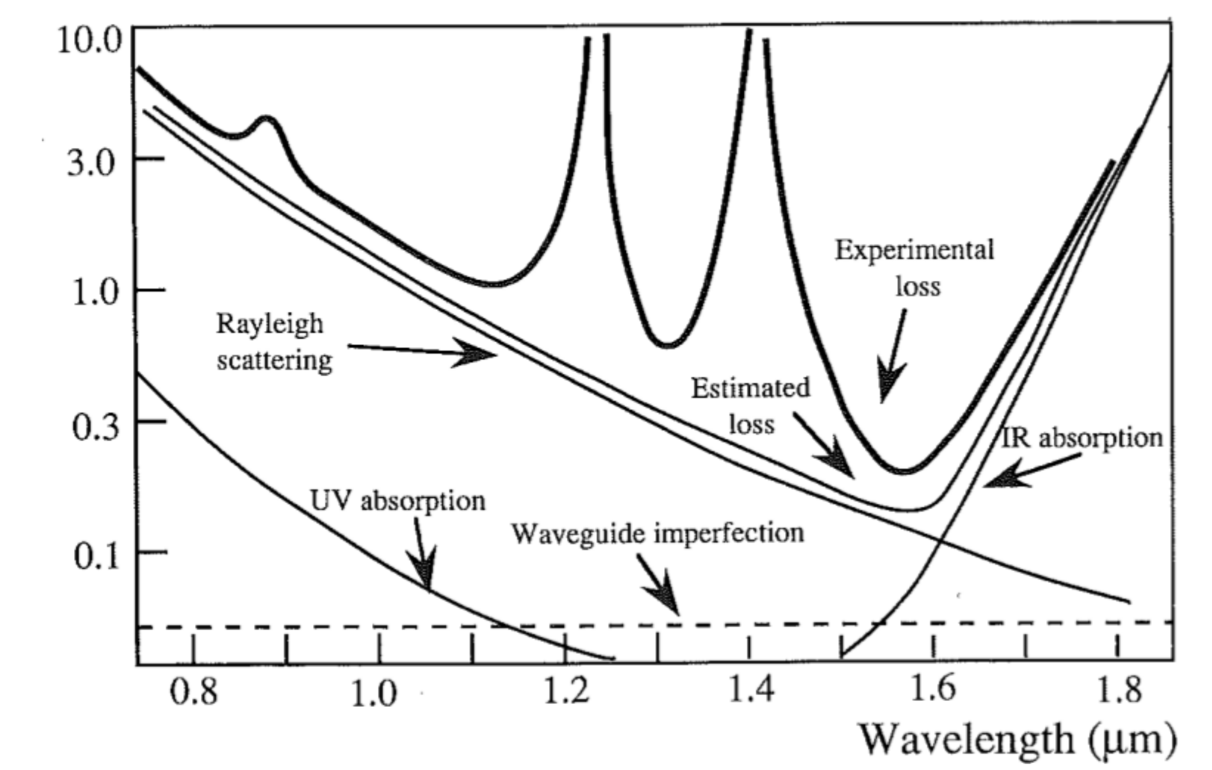




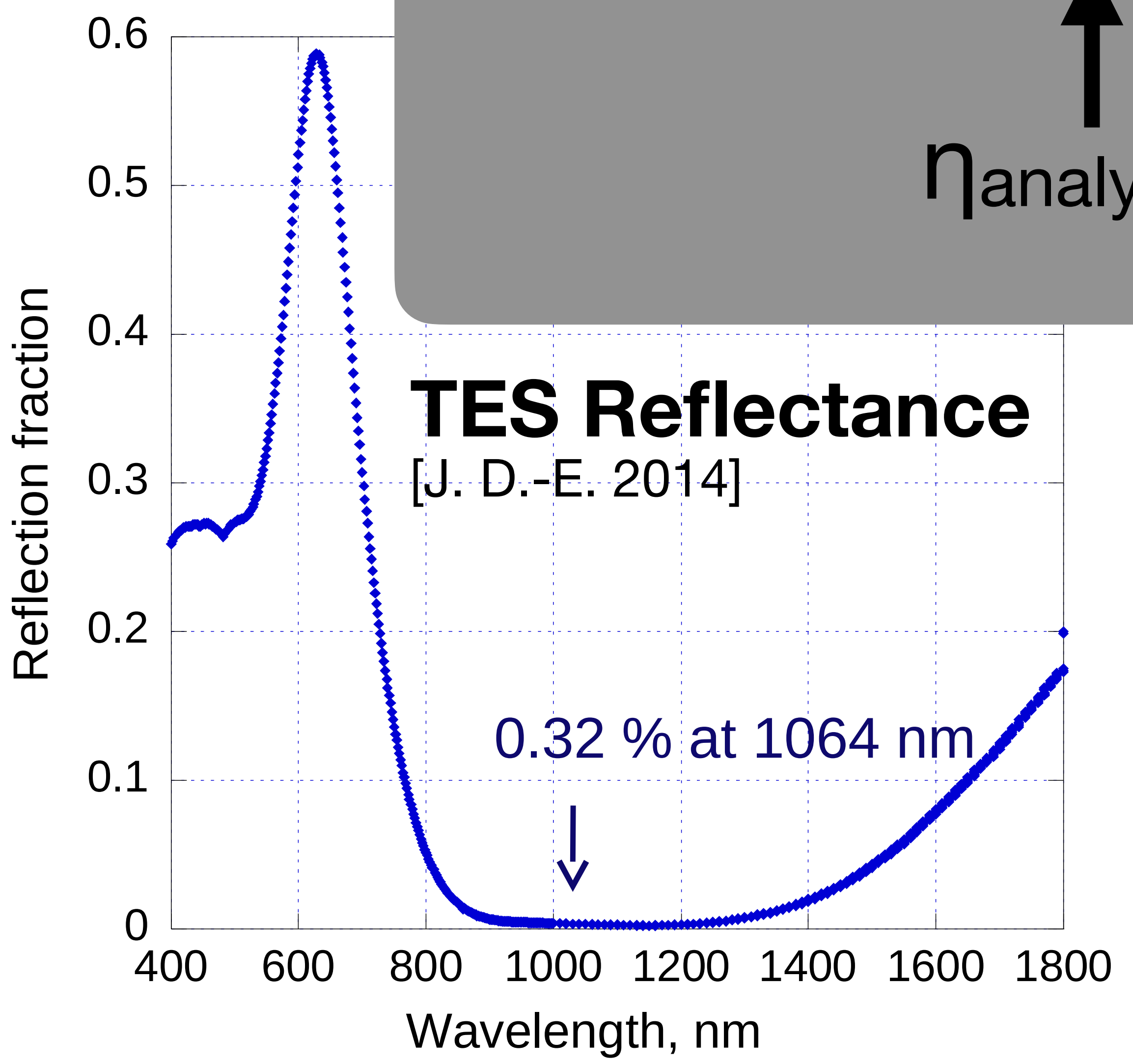
Environment light [Ref: google :P]



Black body [J. D.-E. 2014]



Losses in fiber [J. D.-E. 2014]

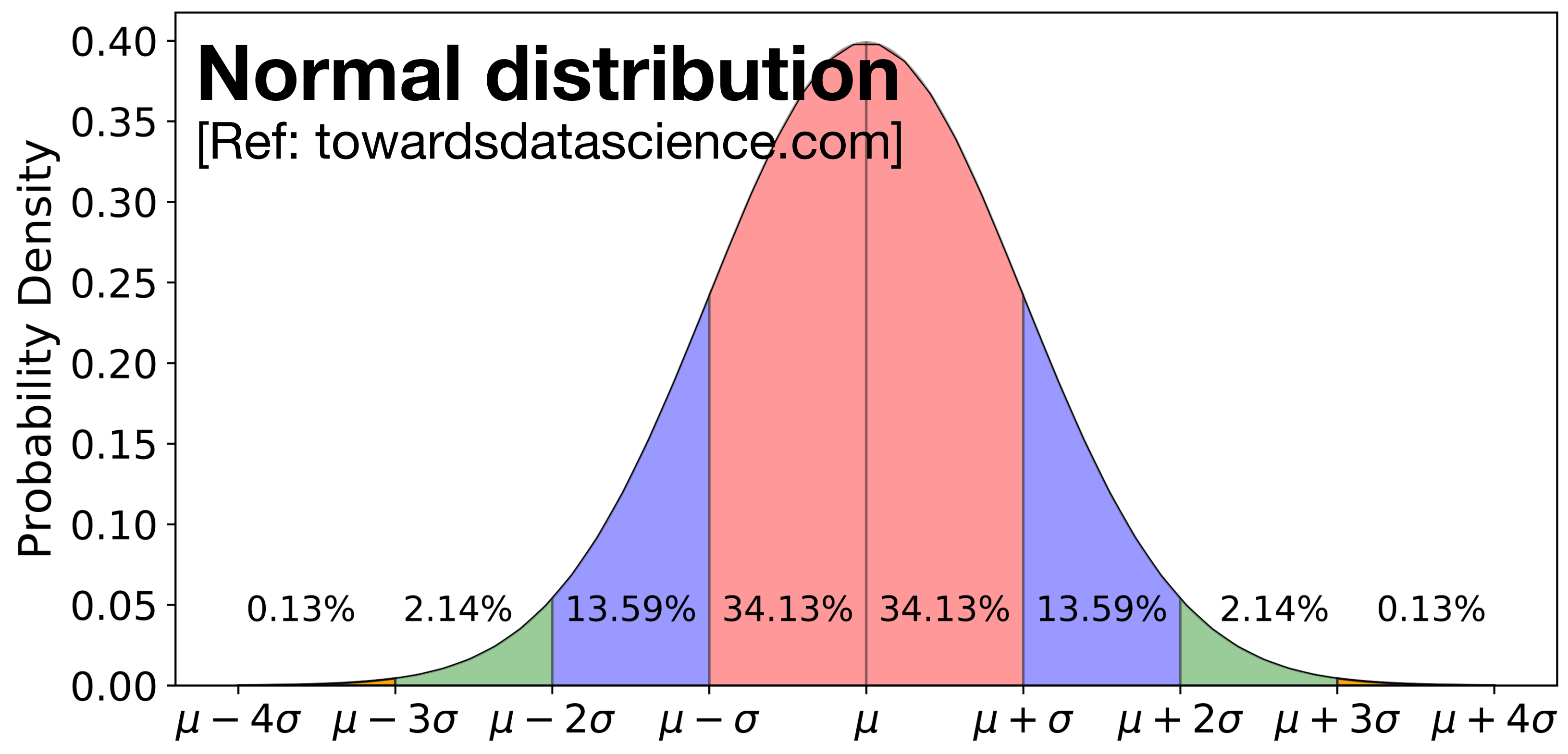


TES Reflectance [J. D.-E. 2014]

Detector Side

Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

Normal distribution [Ref: towardsdatascience.com]



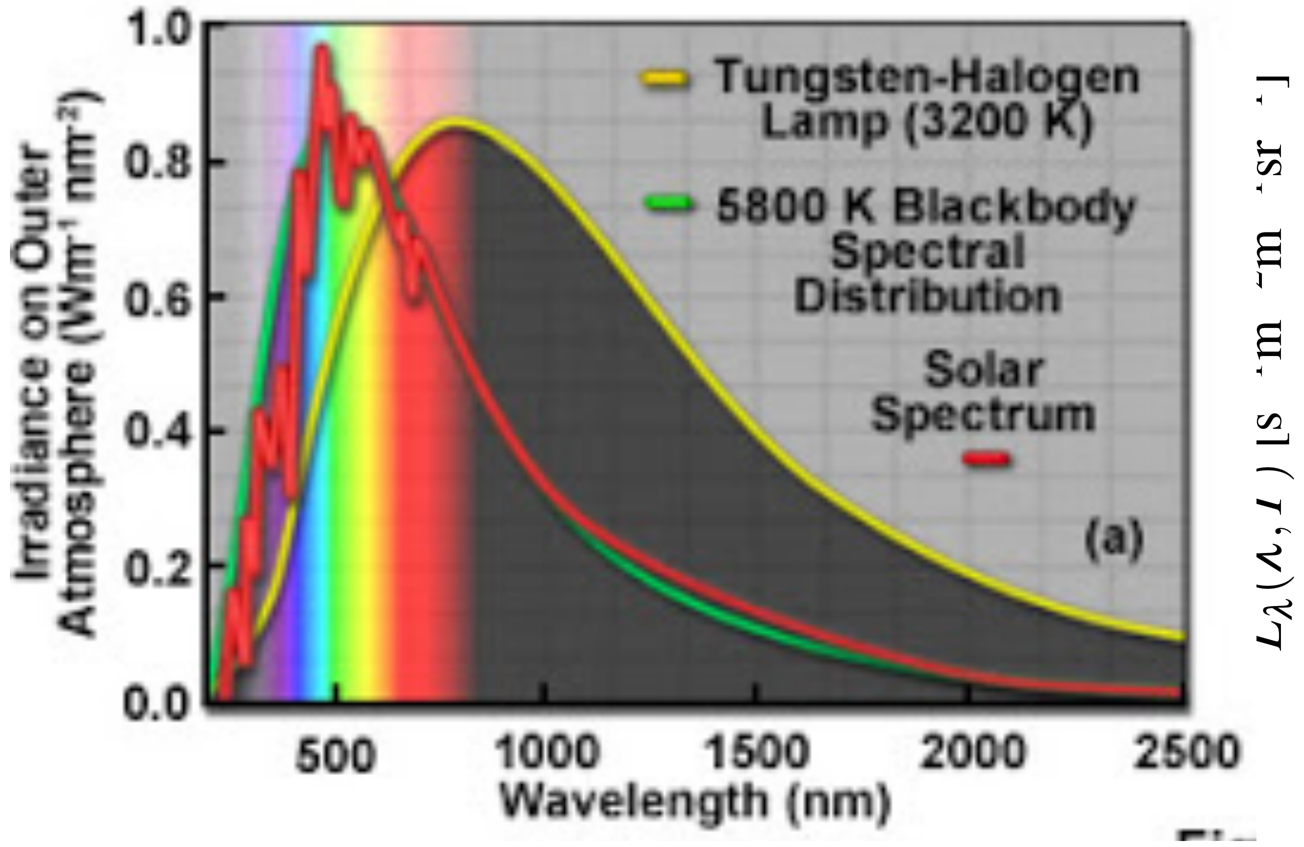
Photon numbers, $N^{(\varepsilon)}$ depend on energy, ε, (or wavelength)

Efficiencies, $\eta^{(\varepsilon)}$, („*transfer function*“) depend on energy, ε, (or wavelength)

Energy bandwidth! TES energy resolution ~10%

Intrinsic

Environment light [Ref: google :P]



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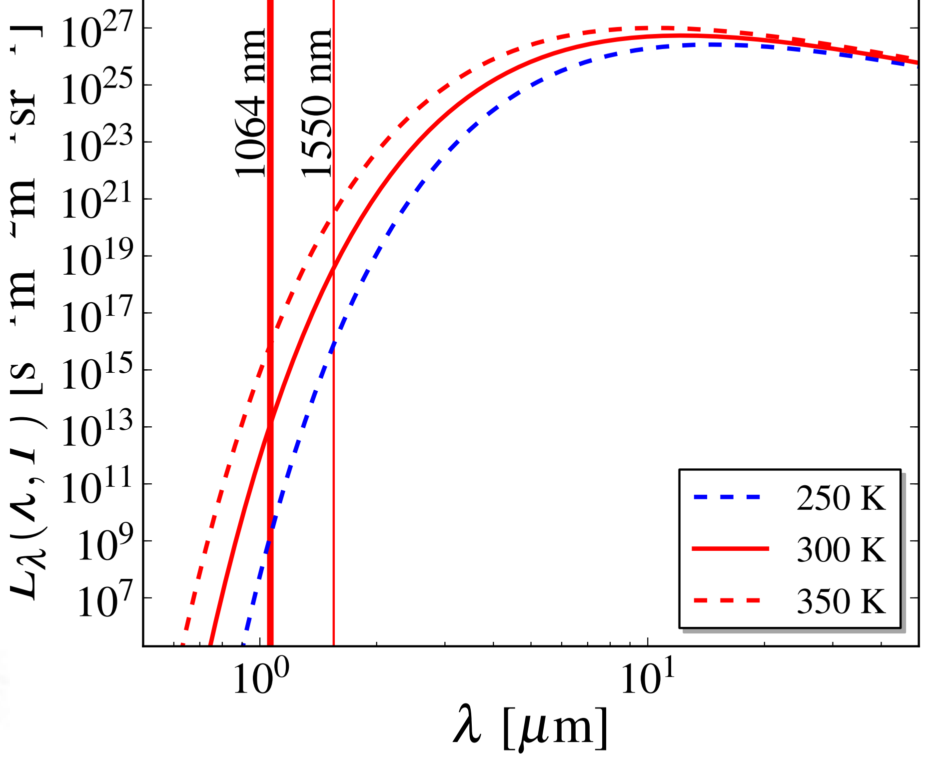

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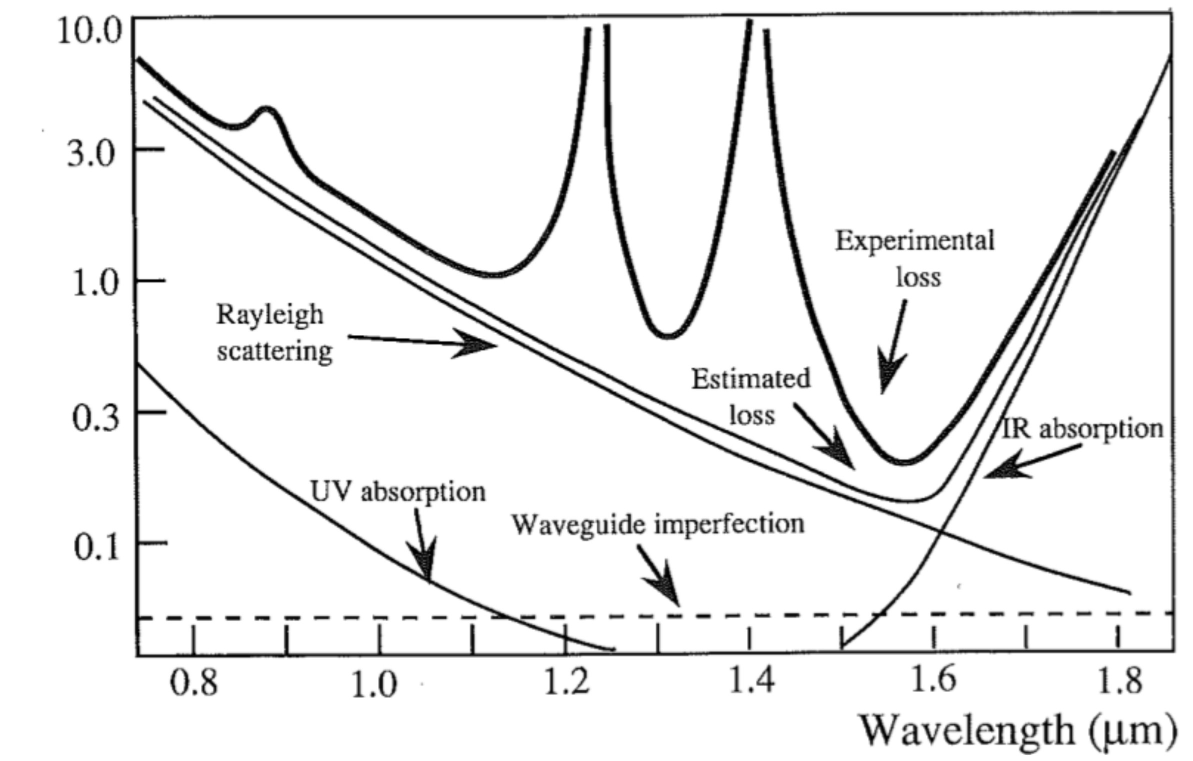
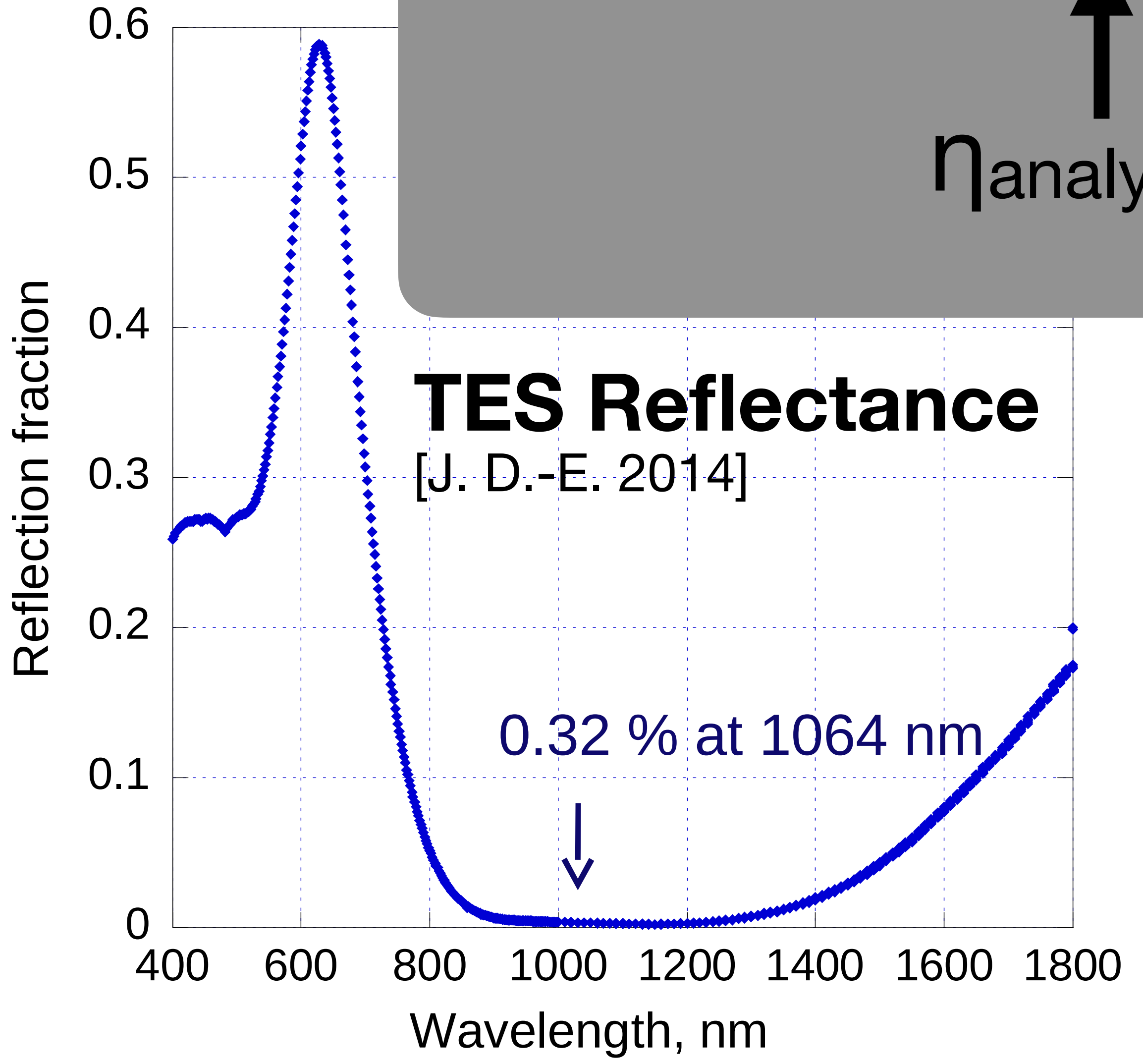


TES Reflectance [J. D.-E. 2014]



Detector Side

Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

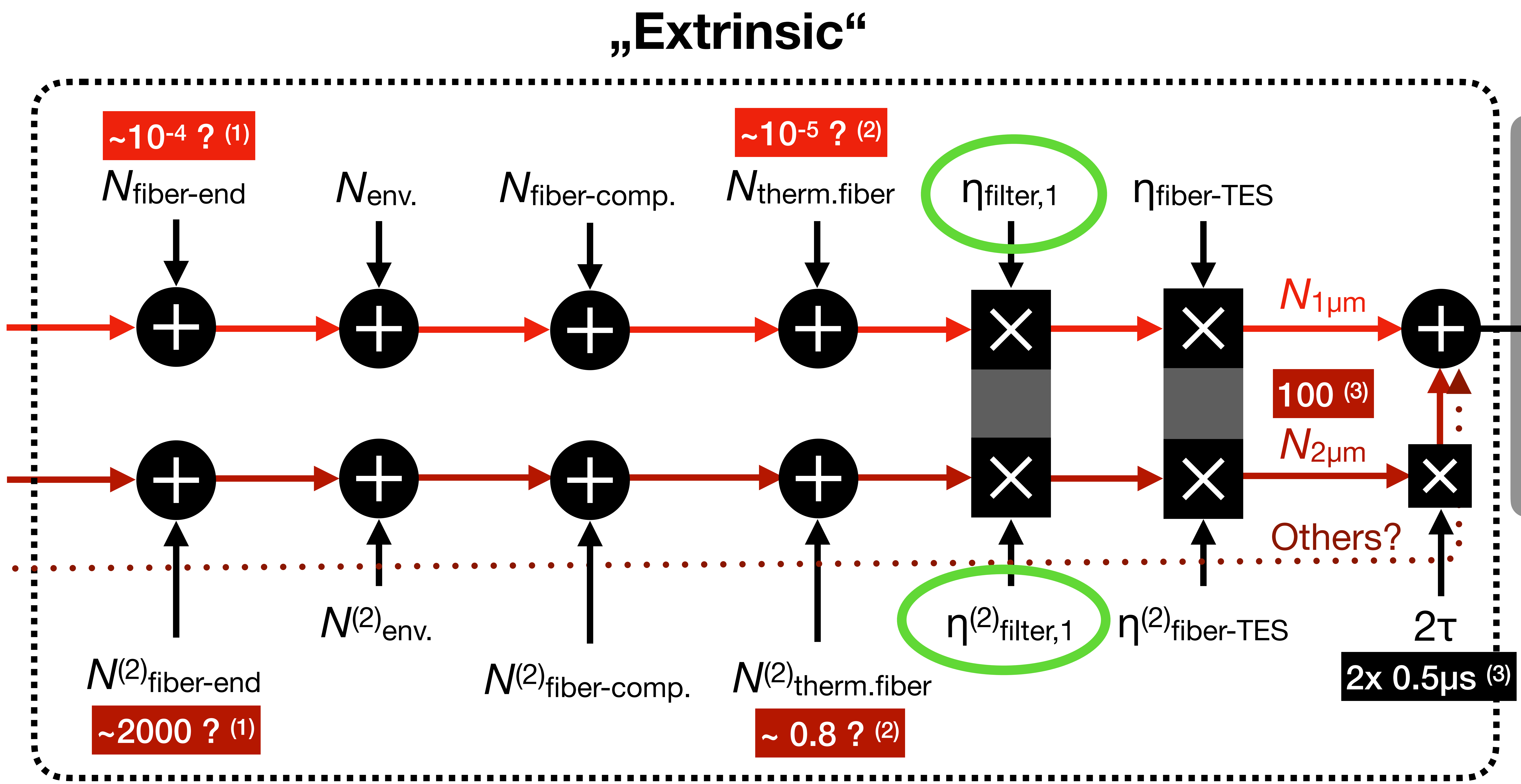
Detector Side

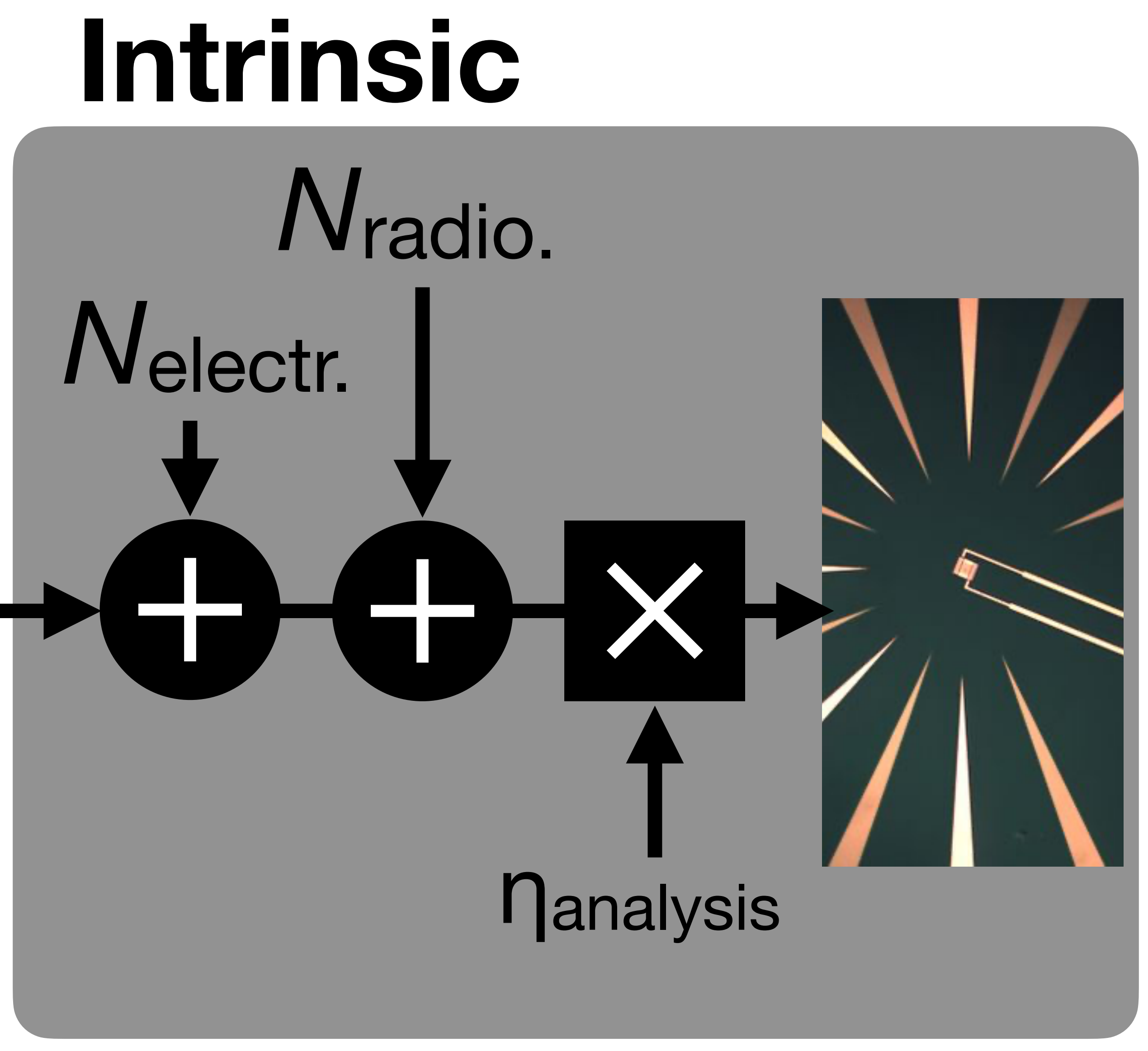
Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

(1) **Model**: fiber-coupled TES looking at a Black body, Miller et al. 2007, 100nm window, 300K
(2) **Model**: Black body photons (outside) coupling to the fiber core, Fuji et al. 2011, 10% window, 10m fiber, 300K
(3) **Measurement** [J. D.-E. 2014]: 2 energy regimes: 0.5eV and 0.7eV as mean values, each has 100 photons/s

Detector Side

Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$





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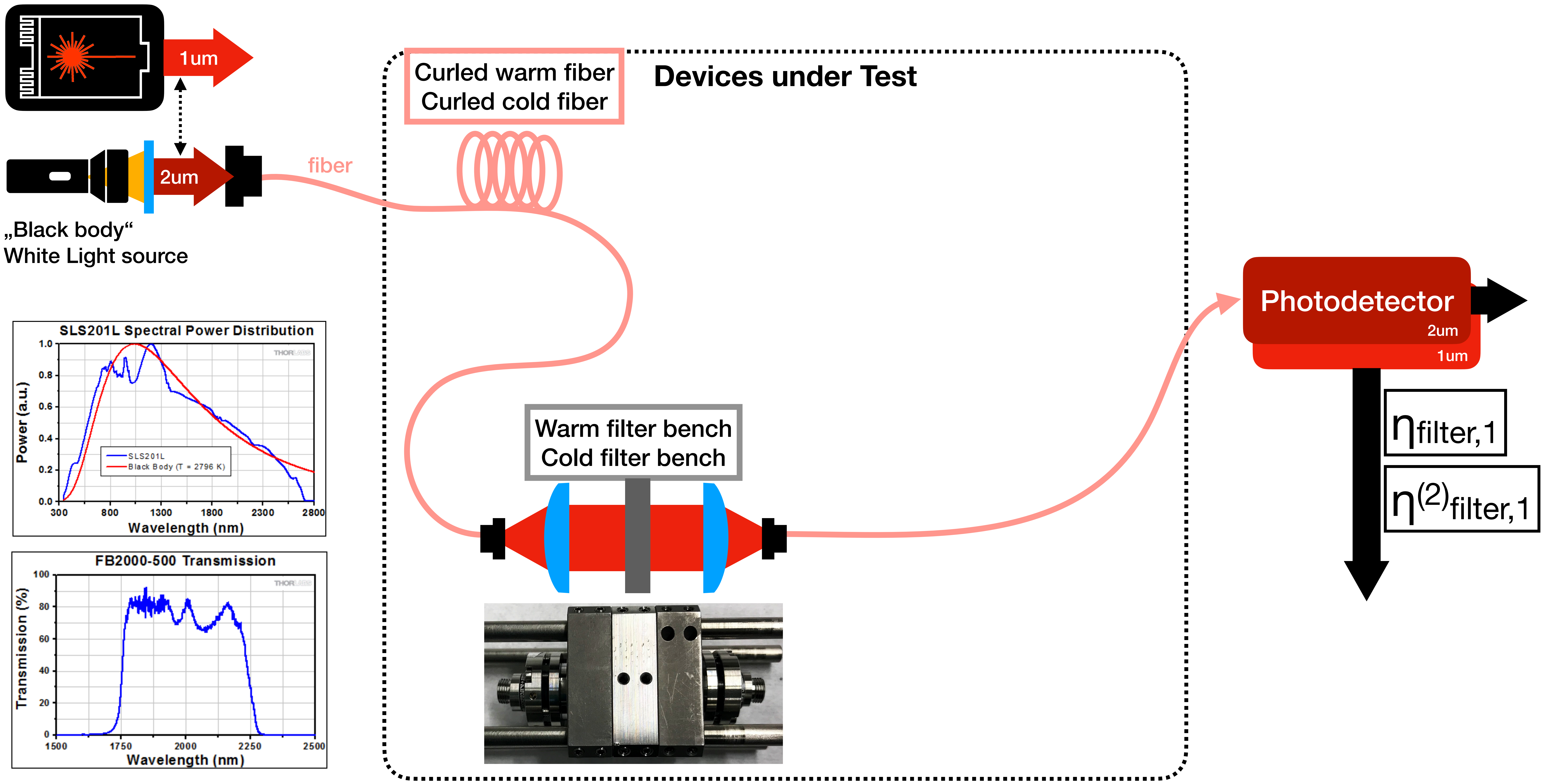
Independent efficiency measurement

Black-Body Pile-Up Strategy: Filter characterization

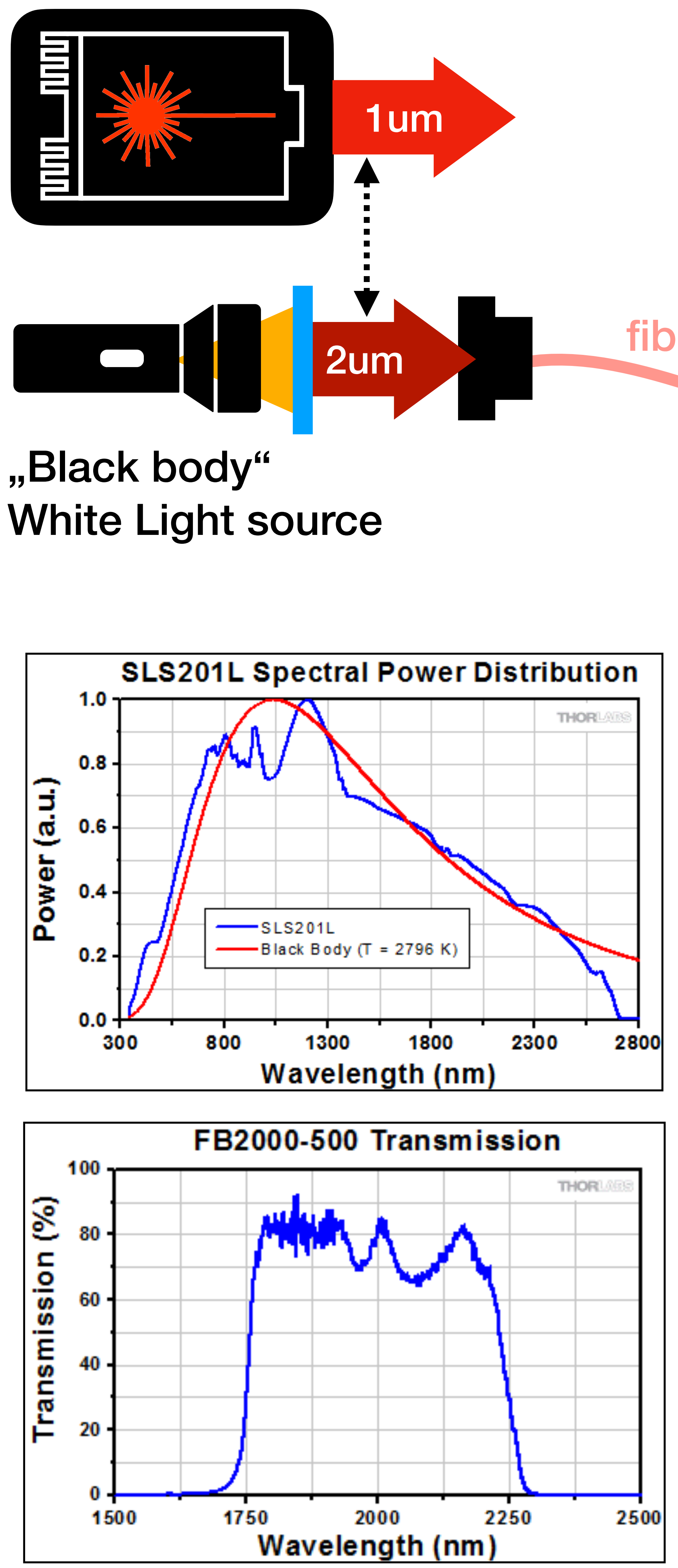


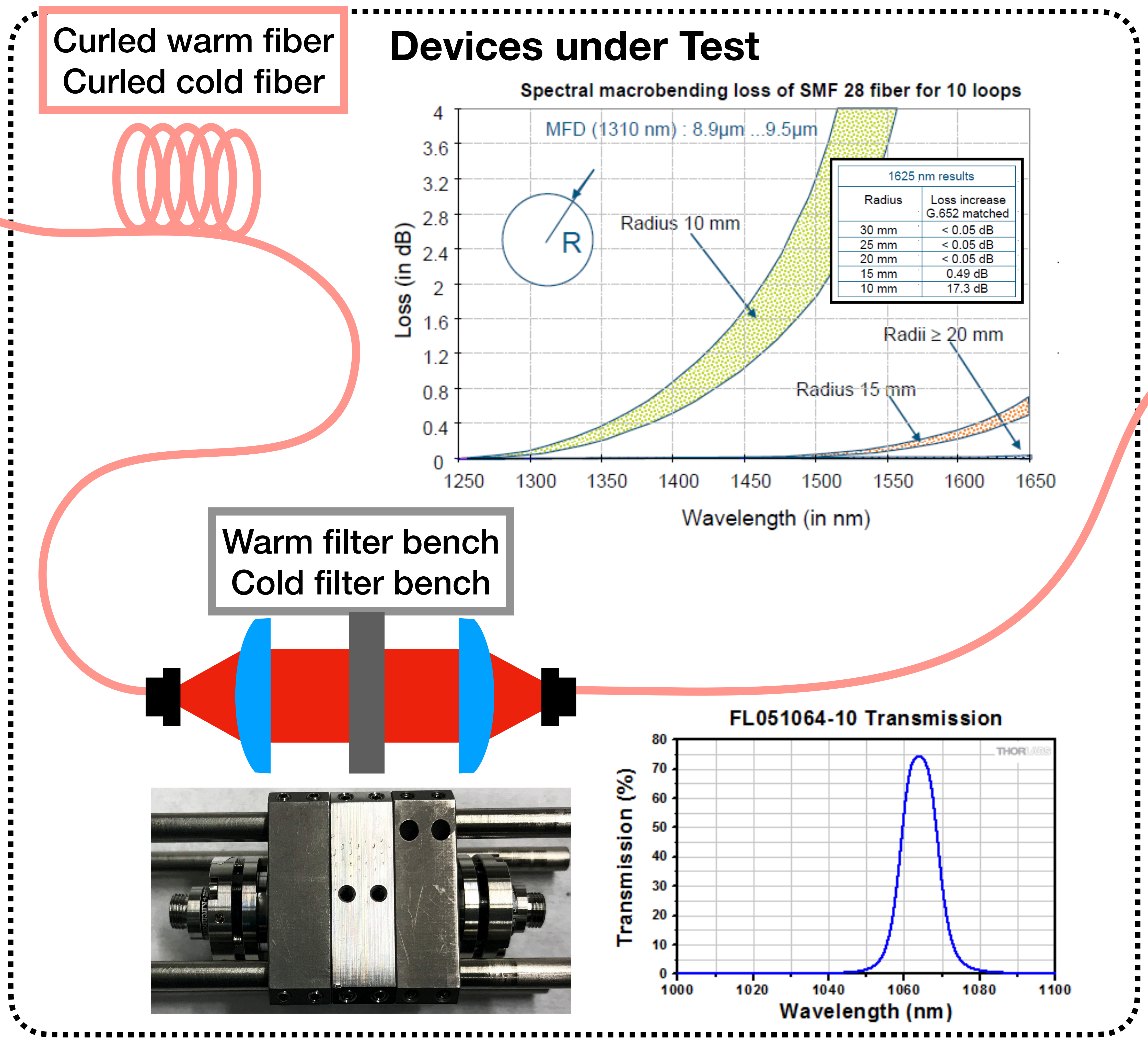
Fiber curling:
- Optimal radius
- Optimal number

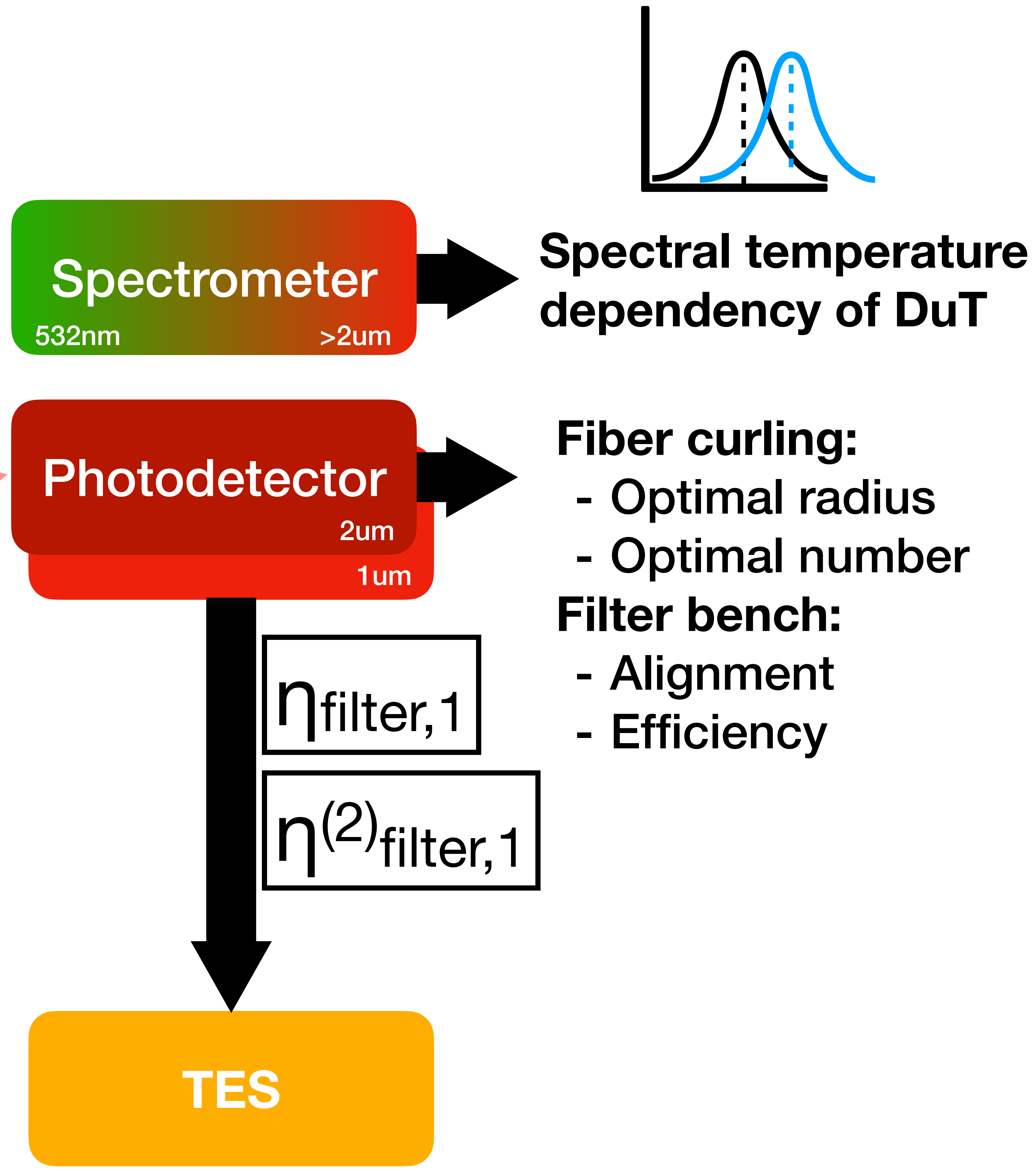
Filter bench:
- Alignment
- Efficiency

Independent efficiency measurement

Black-Body Pile-Up Strategy: Filter characterization







Are we limited by Black-Body Pile-Ups?
What is the „conversion-into-1µm"-coefficient?

Detector Side

Intrinsic and Extrinsic Noise: Photon numbers N^{ε} & Efficiency η^{ε}

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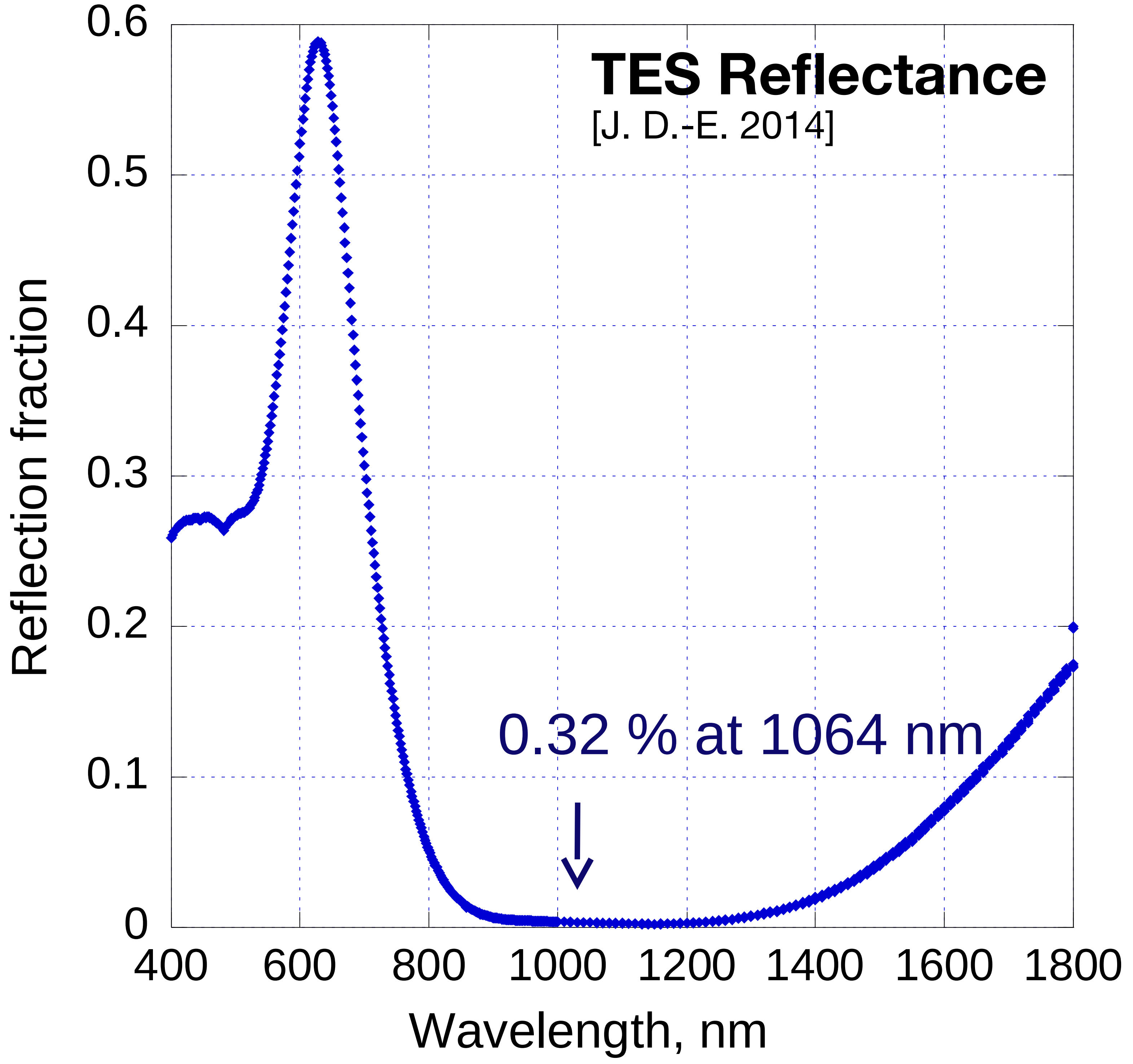
(3) **Measurement** (Jan's Diss.): 2 energy regimes: 0.5eV and 0.7eV as mean values, each has 100 photons/s

TES Spectral Response

Indirect Efficiency for other wavelengths

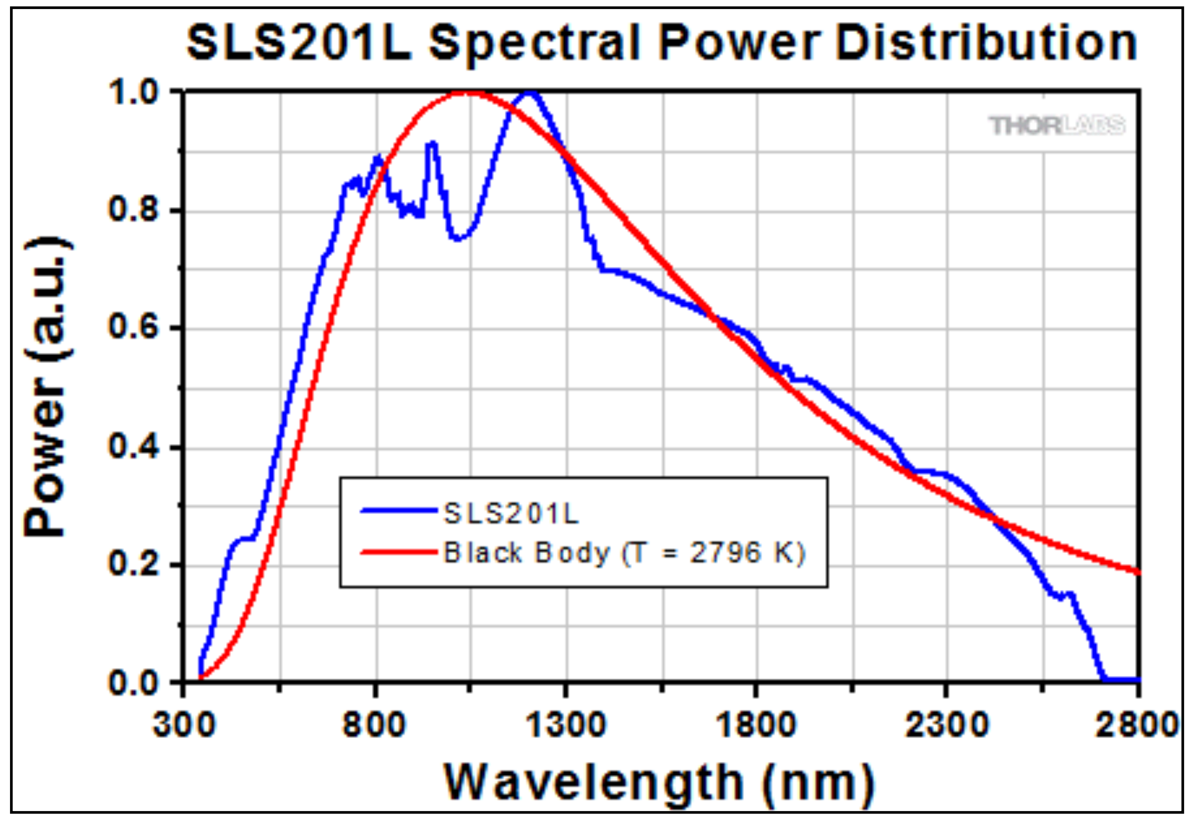
- Indirect measurement of fiber AR coating for other wavelengths in reflection
- Switch to TES detector + fiber attenuation for verification of TES reflectance

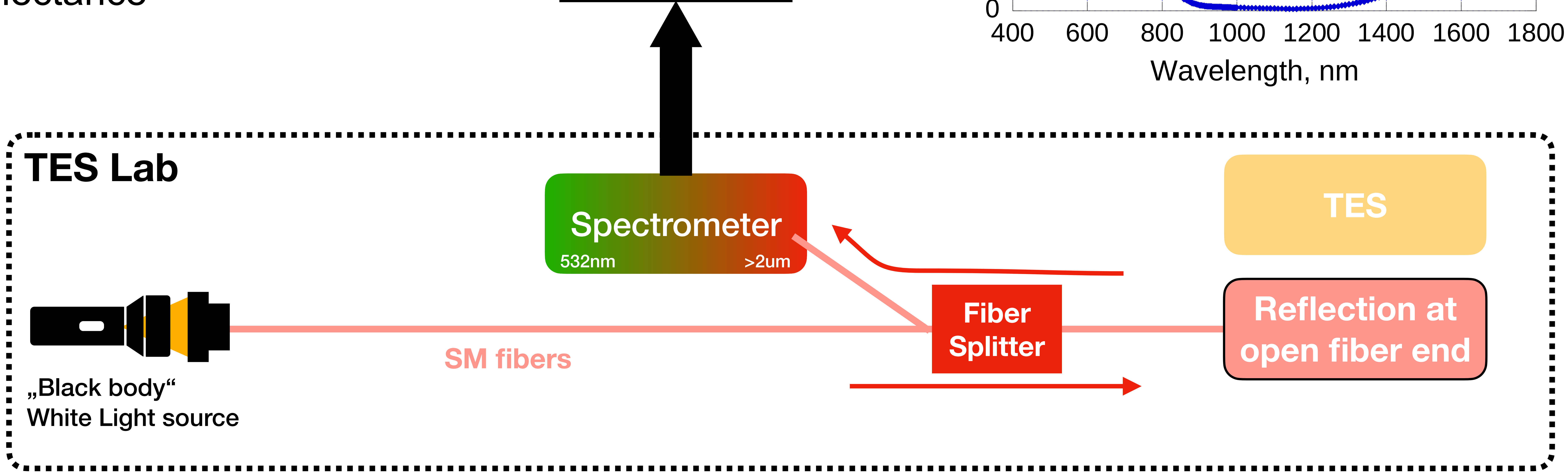


$\eta^{(0)}$fiber-TES

$\eta^{(3)}$fiber-TES

$\eta^{(2)}$fiber-TES





„Single-Photon Source“

Detection Efficiency: Calibrated optical power source

- Detection efficiency rely on calibrated optical power source
- Optical attenuators: individually measured before by a calibrated powermeter (6OoM)
- Dominant uncertainty: multiple of systematic errors in the calibration of the powermeter (done by PTB):
  1. Powermeter compared to transfer standard detector at certain λ and at a given power level
  2. Linearity of powermeter measured relative to calibration power level (series of additive power measurements)
- Option: Pulsed light source eliminate pile-up related counting errors, provide specific duty cycle measures, QE?

Detector Side

Intrinsic and Extrinsic Noise: Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

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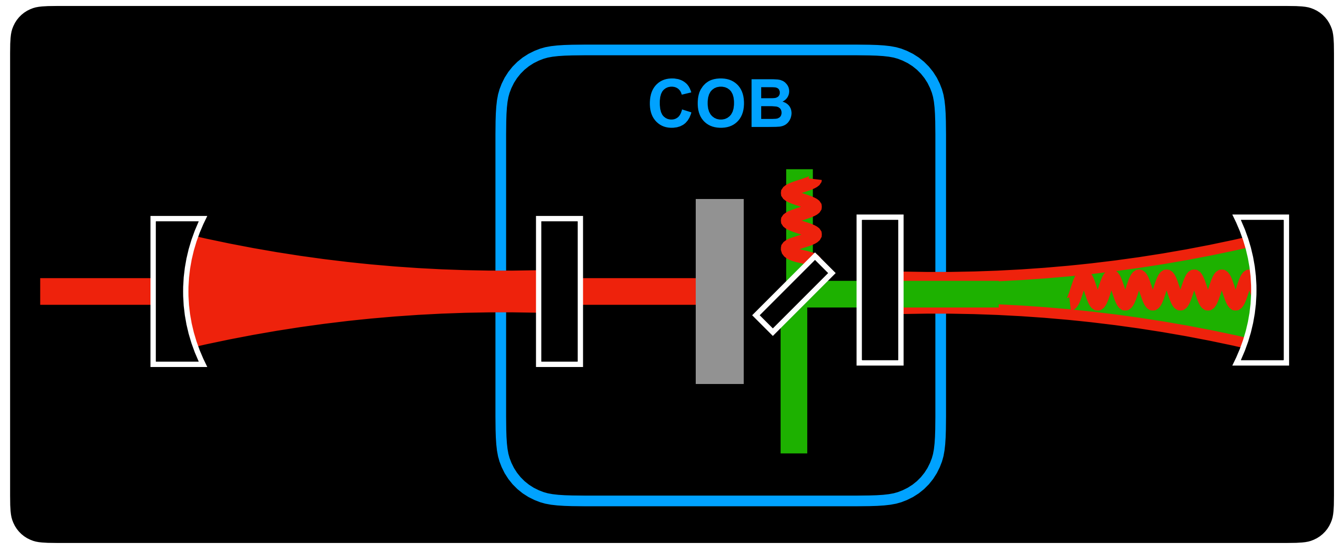
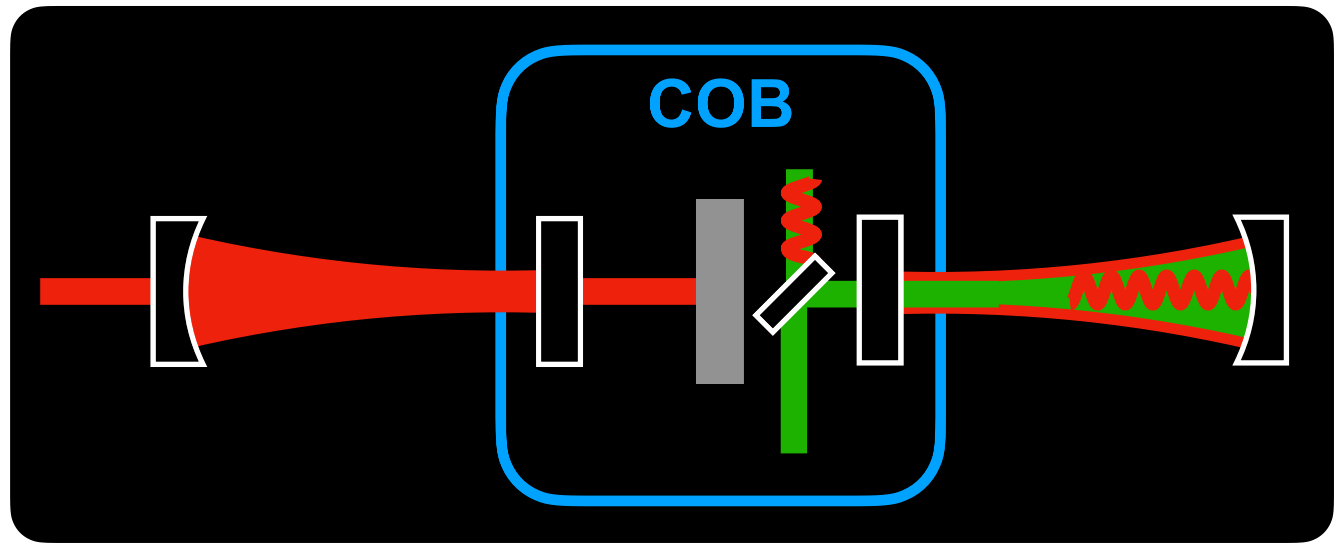
COB Side: Science Mode

Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$



COB Side: Science Mode

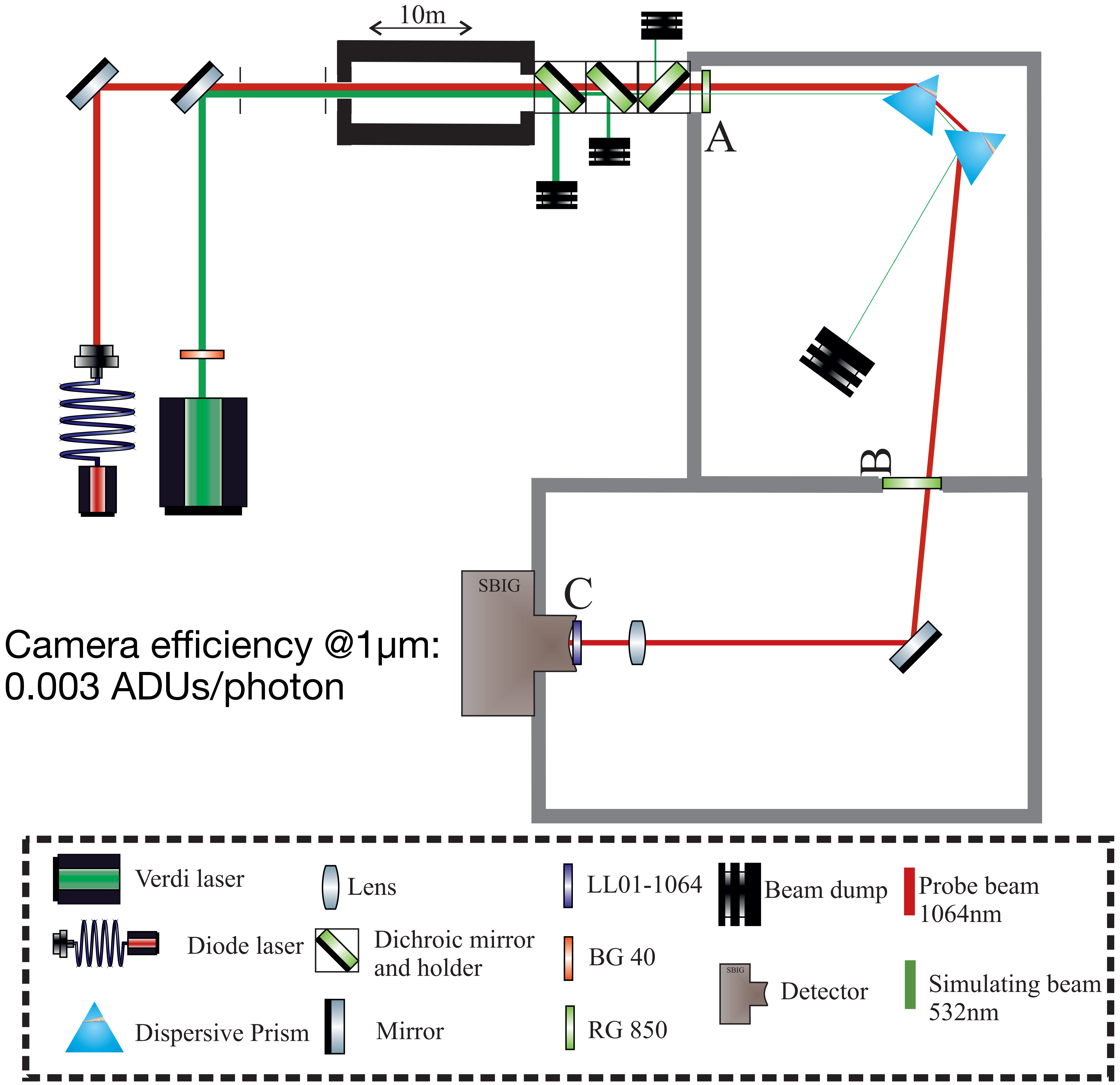


Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

(1) Reza (2014)

Dichroic Filter Results

Reza H. 2014 - Final Setup

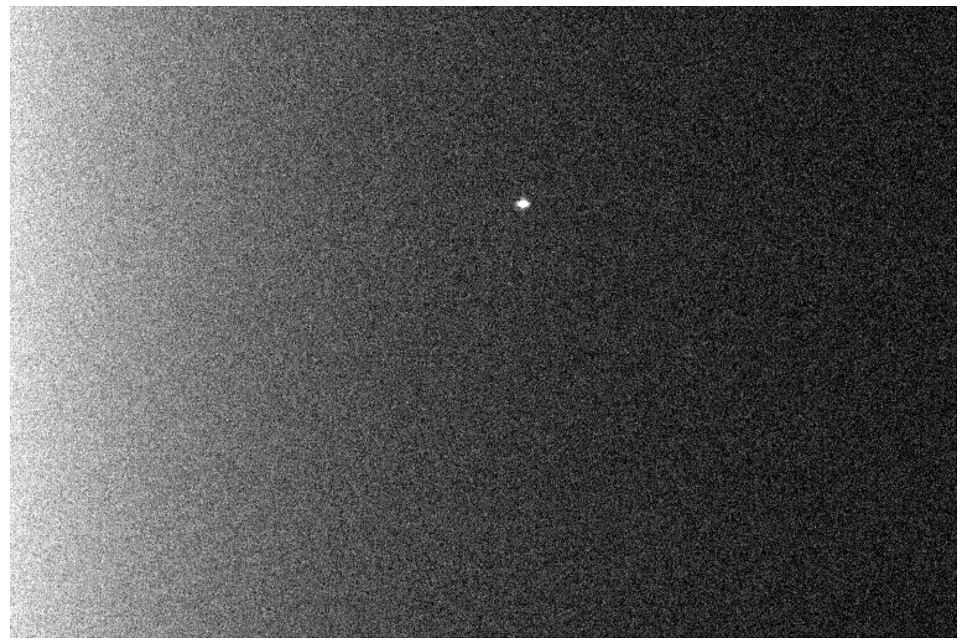


Camera efficiency @1μm:
0.003 ADUs/photon

Figure 5.17: Second setup with dispersive prisms and including a narrow band filter. The attenuation unit is placed in the lab with the SBIG detector. This setup is more similar to the proposed ALPS-II setup.

30mW green already produces Fluorescence!

1mW? probe beam, 100ms

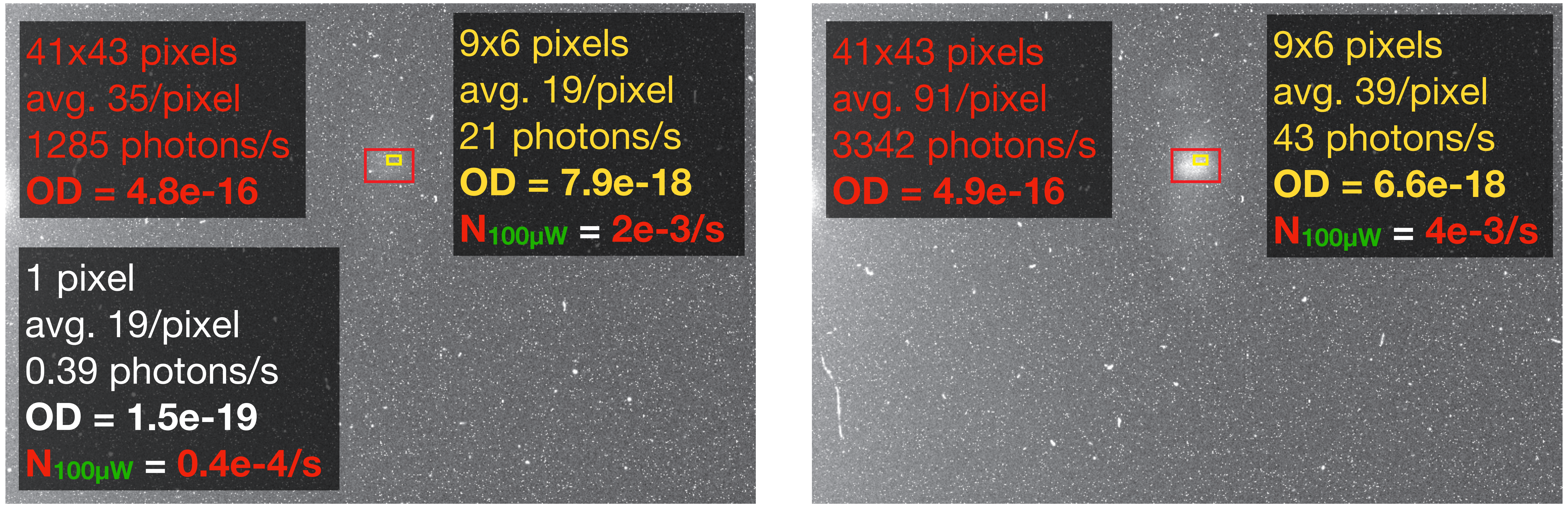


Residual Verdi IR, 100ms

Transmission IR: 85% [(400±20)μW → (343±18)μW]

1W = 2.7e18 photons/s, 3600s

2.5W = 6.7e18 photons/s, 3600s

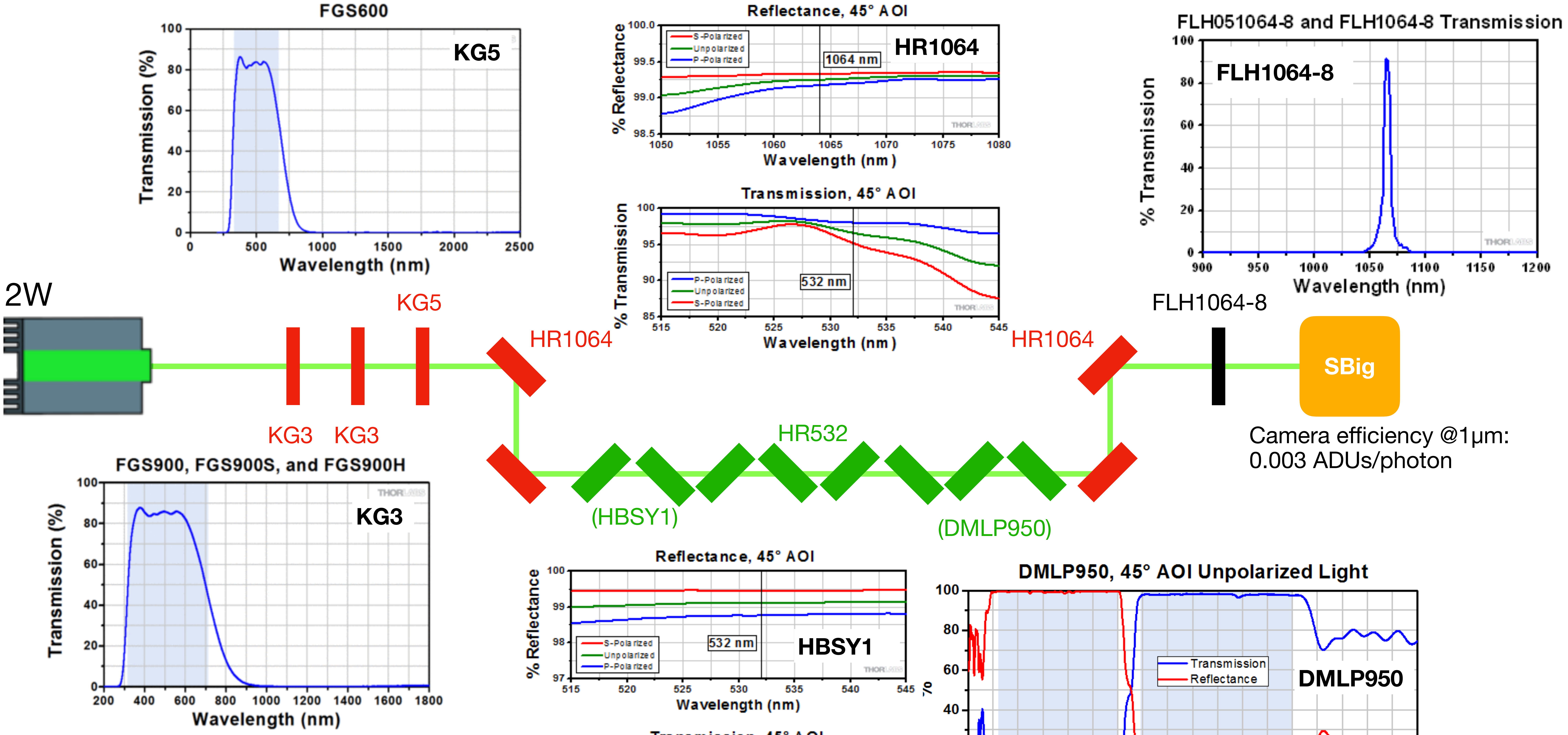


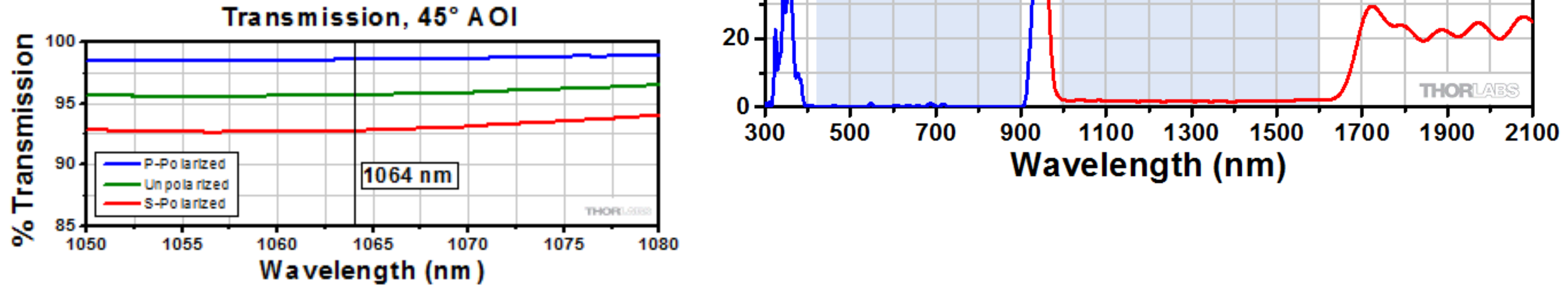
(a) (b)

Figure 5.19: Final pictures with an exposure time of 3600 s and 1 W of incoming light in picture (a) and 2.5 W respectively in picture (b).

Dichroic Filter

Misha (2018) DarkCosmos





New Calculation of the results (mistake online?)**:**

1. focus light to 25 pixels: 15 ADU/Pixel/2h, 2W green

15*25/2h/0.003/20000=**0.9e-4/s** (for 100uW green), **OD = 1.3e-19**

2. focus light to 1 pixel: ~50 ADU/Pixel/1h, 2.5W green

50*1/1h/0.003/25000 = **1.8e-4/s** (for 100uW green), **OD = 6.6e-19**

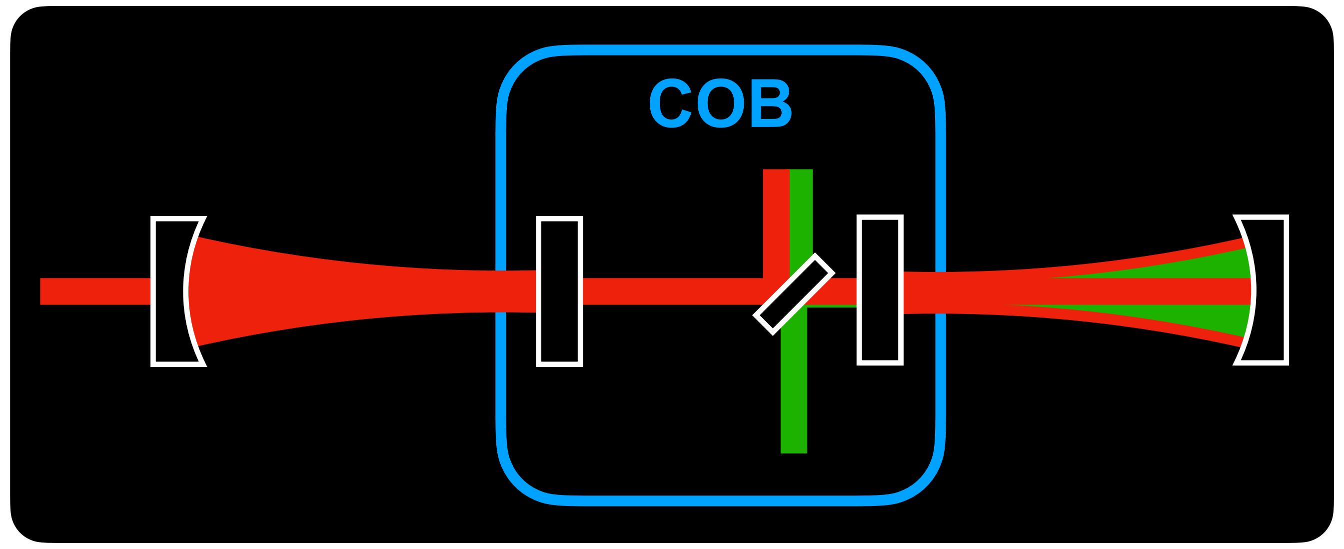
COB Side: Science Mode

Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

Attenuation 532nm: 10^{-19} (1)
Transmissivity for 1064nm: 85% (1)
Conversion effects: 10^{-4}/s ? (2)

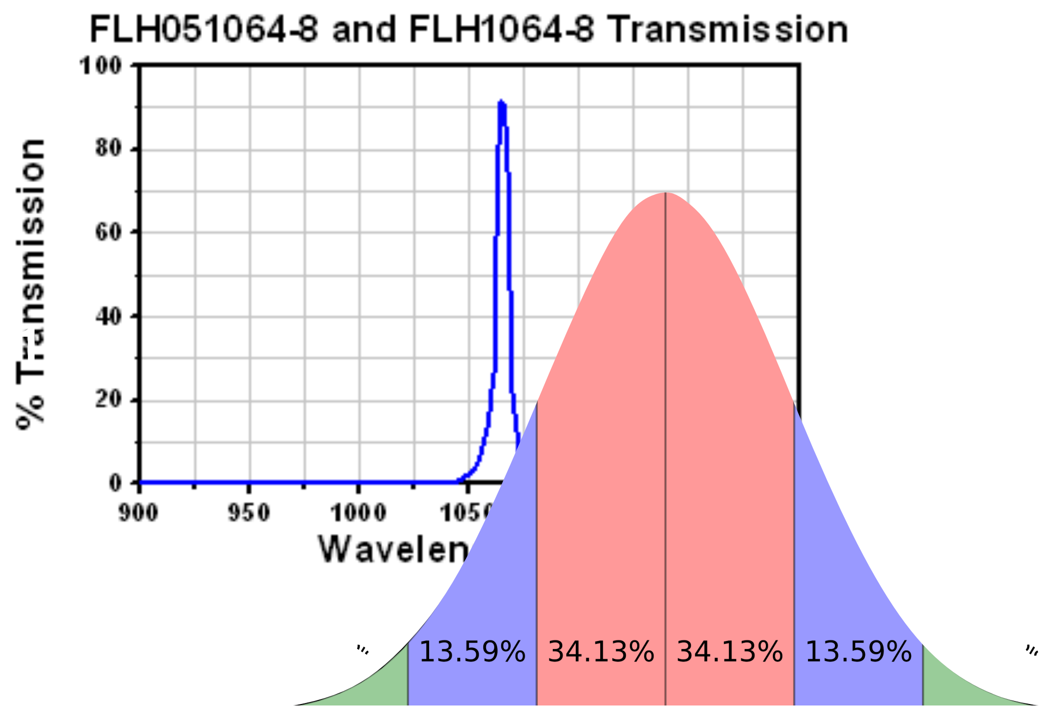
(1) Reza (2014)
(2) Misha (2018) DarkCosmos

COB Side: Calibration Mode

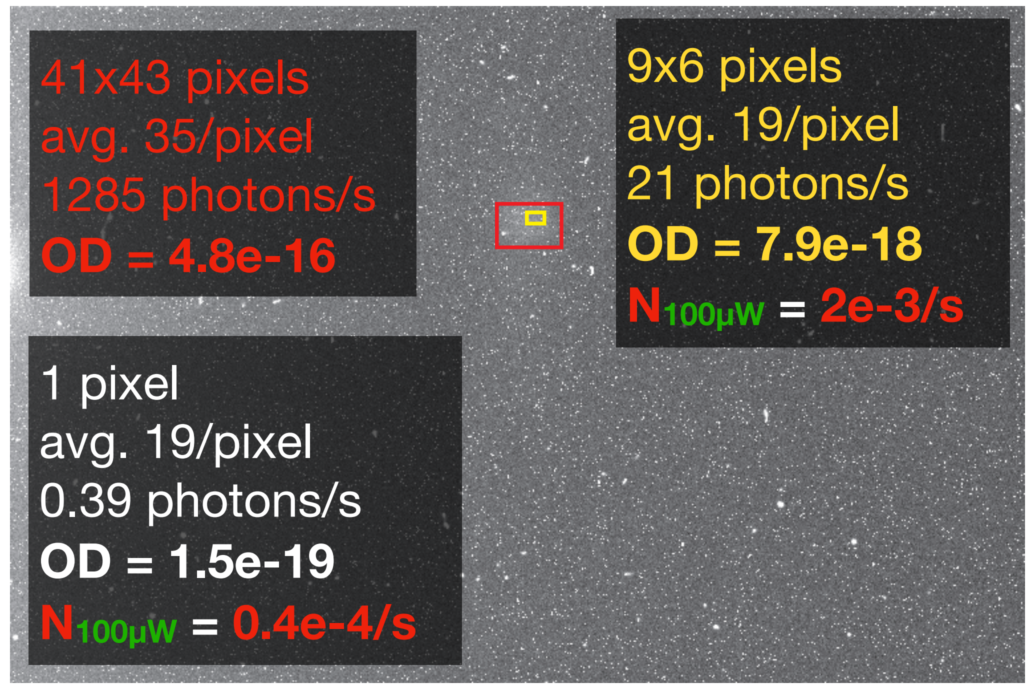


Photon numbers $N^{(\varepsilon)}$ & Efficiency $\eta^{(\varepsilon)}$

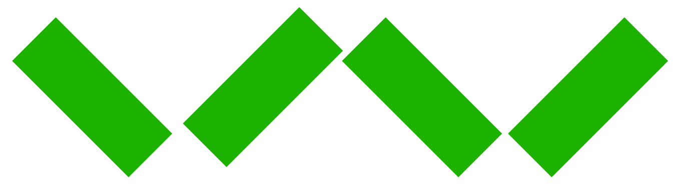
Summary / Discussion



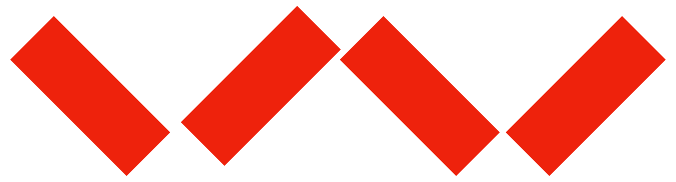
1W = 2.7e18 photons/s, 3600s



Dichroic



Dichroic



Detector characterization…

- Independent ***experimental*** investigations on extrinsic noise:
  - ✓ Exp.: What is the distribution of different photon noise sources?
  - ✓ Exp.: What is the „system transfer function“ in dependency on the energy?
  - ✓ Exp.: What is the energy resolution of the TES?
  - How does "signals“ look when folding it with a Gaussian distribution?

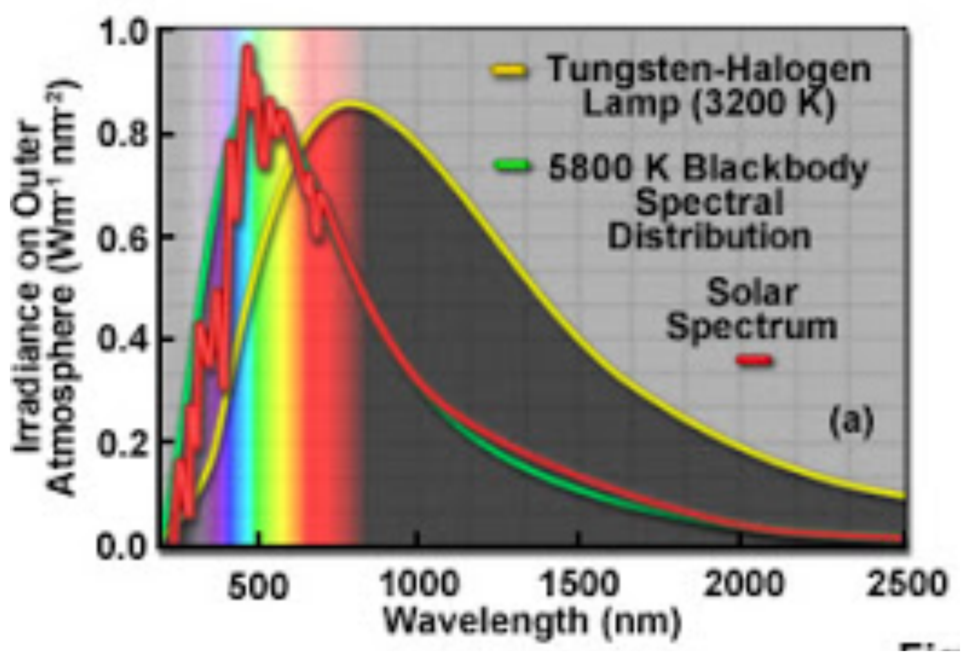
➡ Dark count rate estimations, predictions, verifications

Central optical bench…

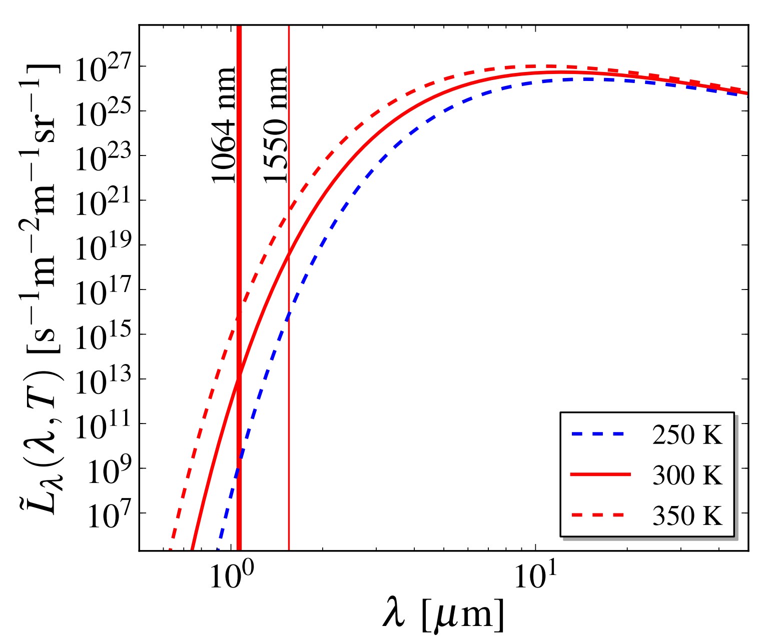
- Dichroic filters for Green:
  - Suppression of green is OD = <10^{-17}? Optimistic is OD ~10^{-19}?
  - 10^{-4} IR-photons/s for [1W,2.5W]. What do we expect for low-power green?
  - Spectral distribution of Fluorescence when using filters/coatings/…?
- Dichroic filters for Red:
  - Number of IR-photons of SHG in RC? What is the suppression here?
- Calibration Mode:
  - How and where do we attenuate the „calibration beam“?
  - How to preserve the fiber coupling? Usage of dichroic mirrors?
  - Is a calibrated power measurement required for the detection efficiency?
- What are the design power levels on the COB for green & IR for Science and Calibration Mode?
- …

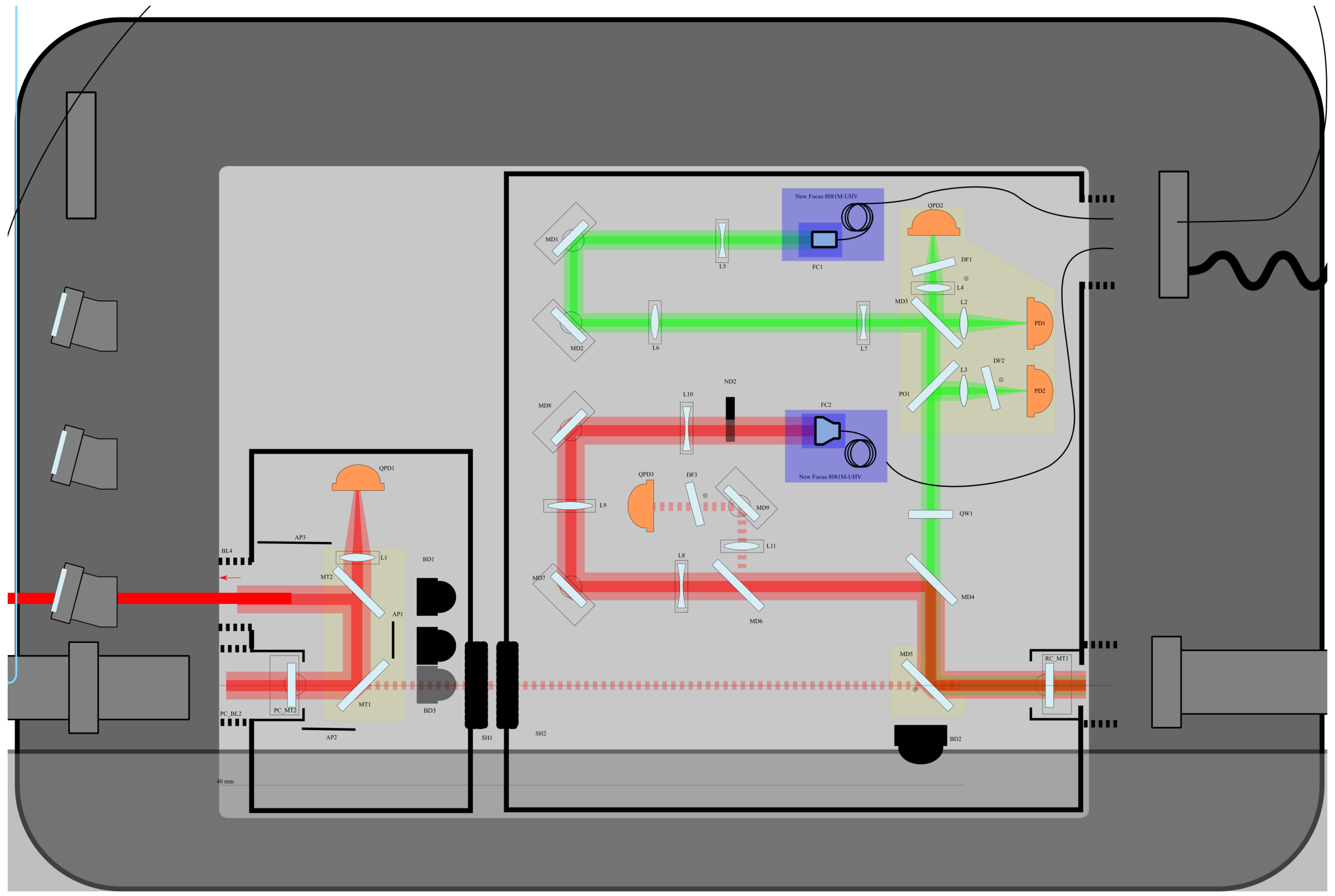
➡ „Prototype“ connecting to the TES?

Environment light [google :P]



Black body [J. D.-E. 2014]





Thank you!

Thank you!

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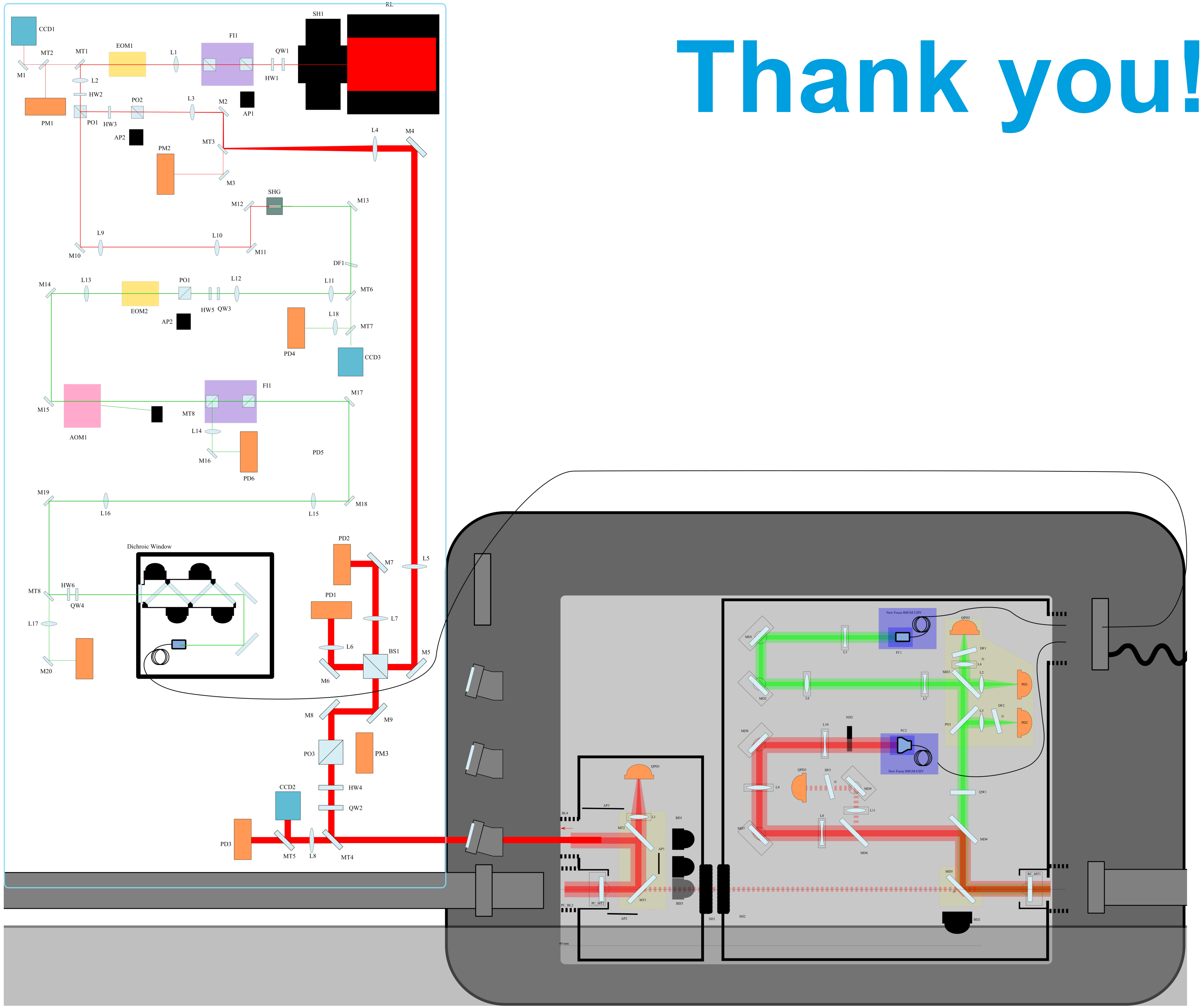
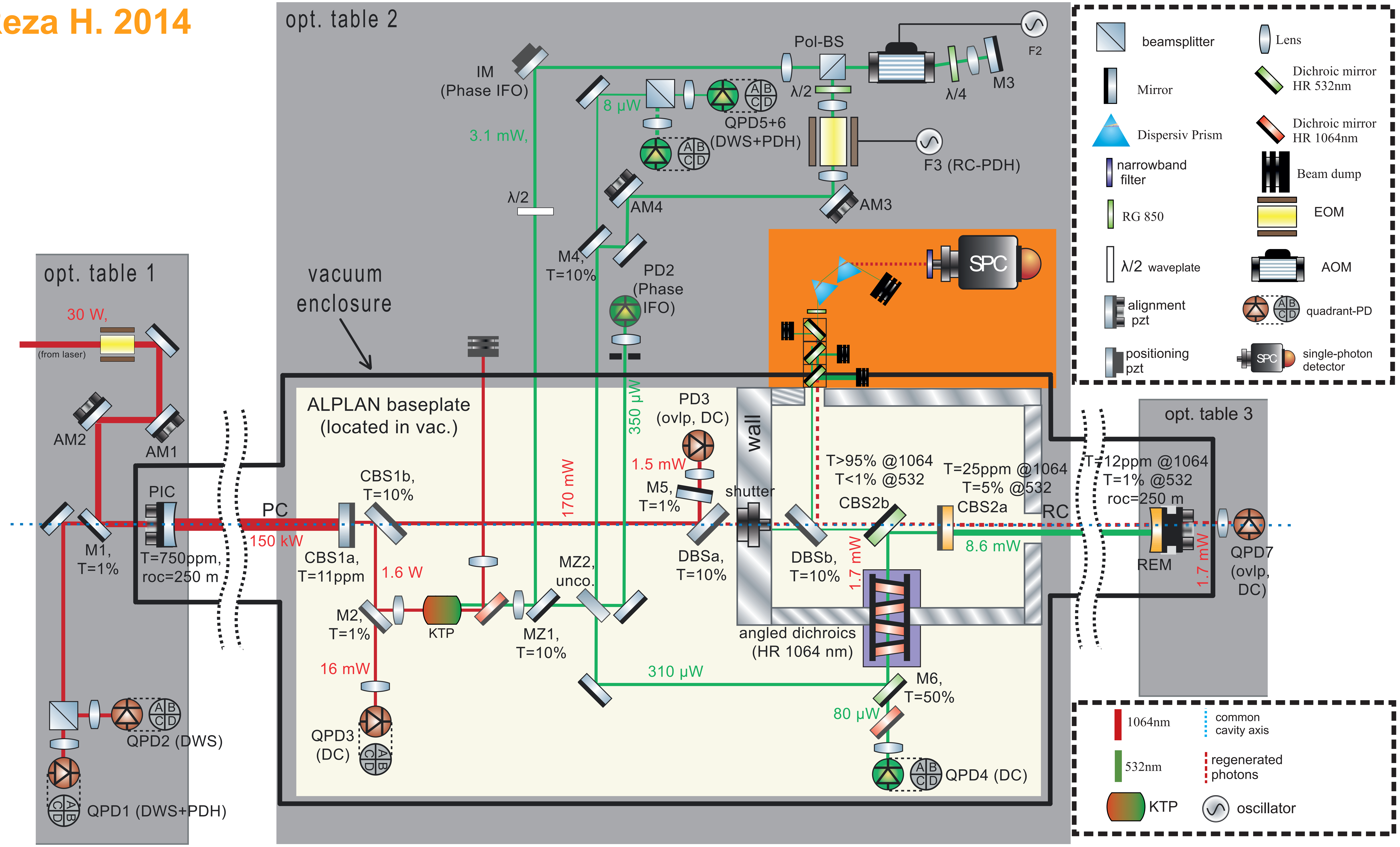


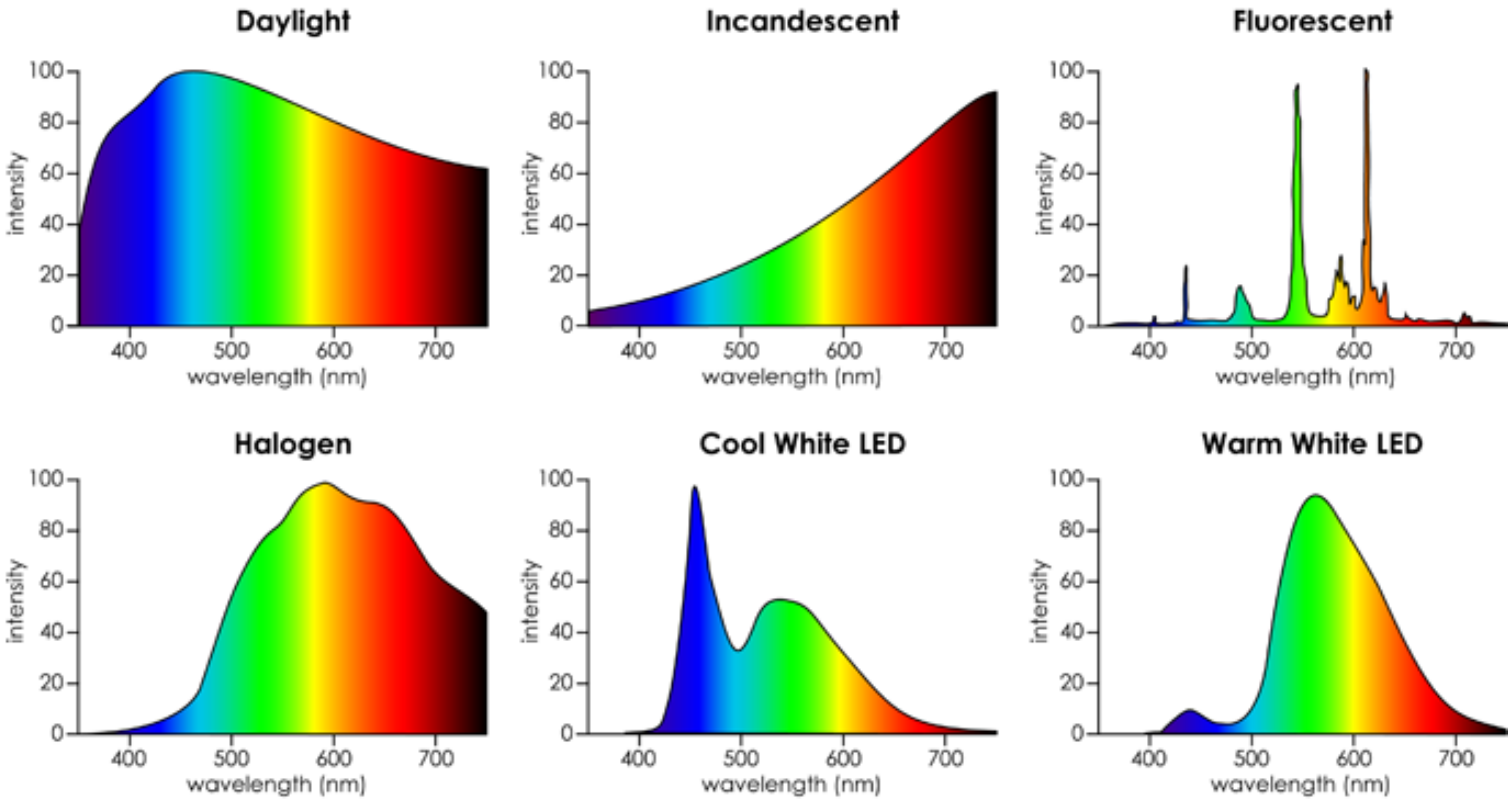
Optical scheme ALPS IIc TES

Design from Reza H. 2014



Bulb comparison

Go for cool LEDs in labs!



Dichroic Filter Results

Reza H. 2014

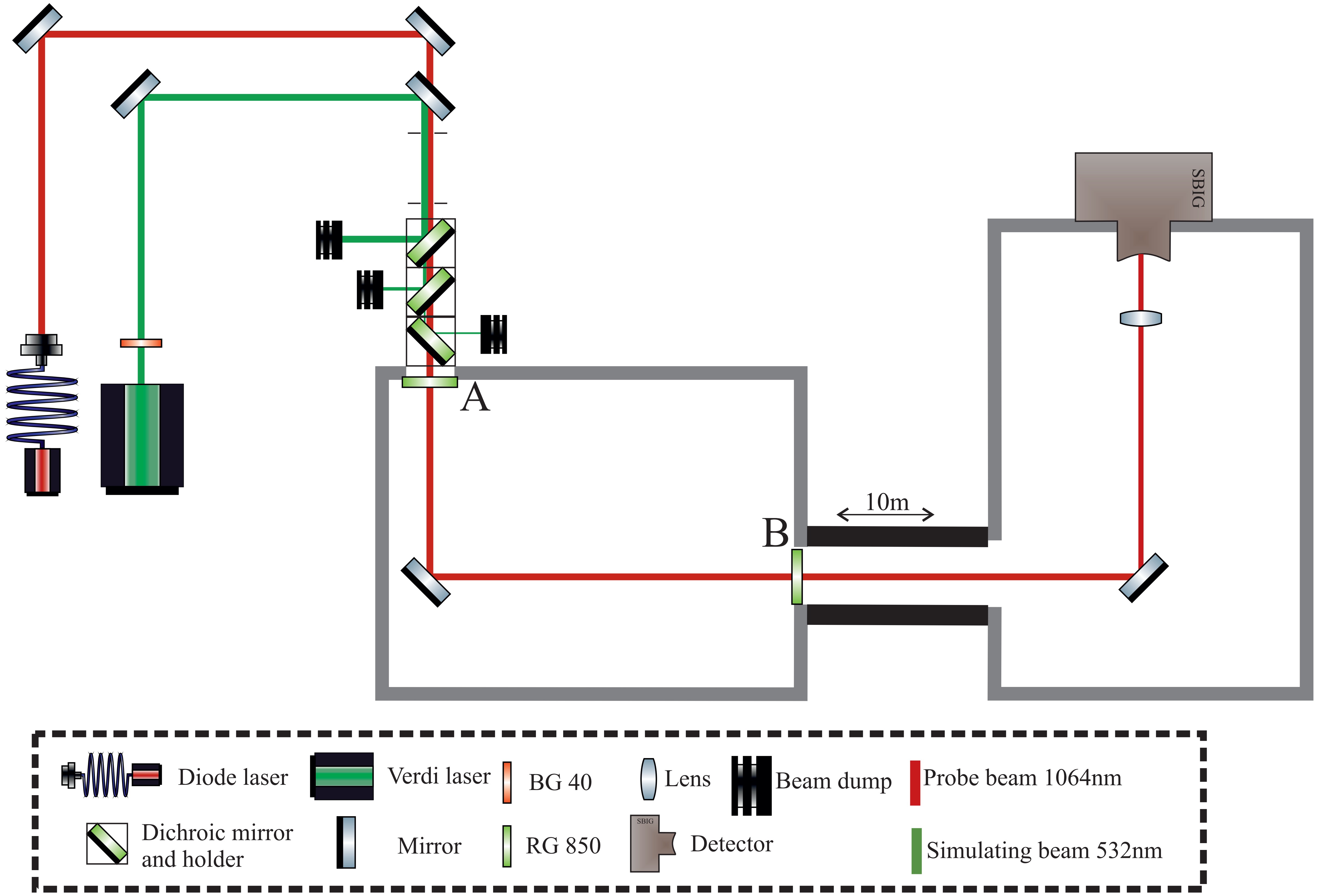
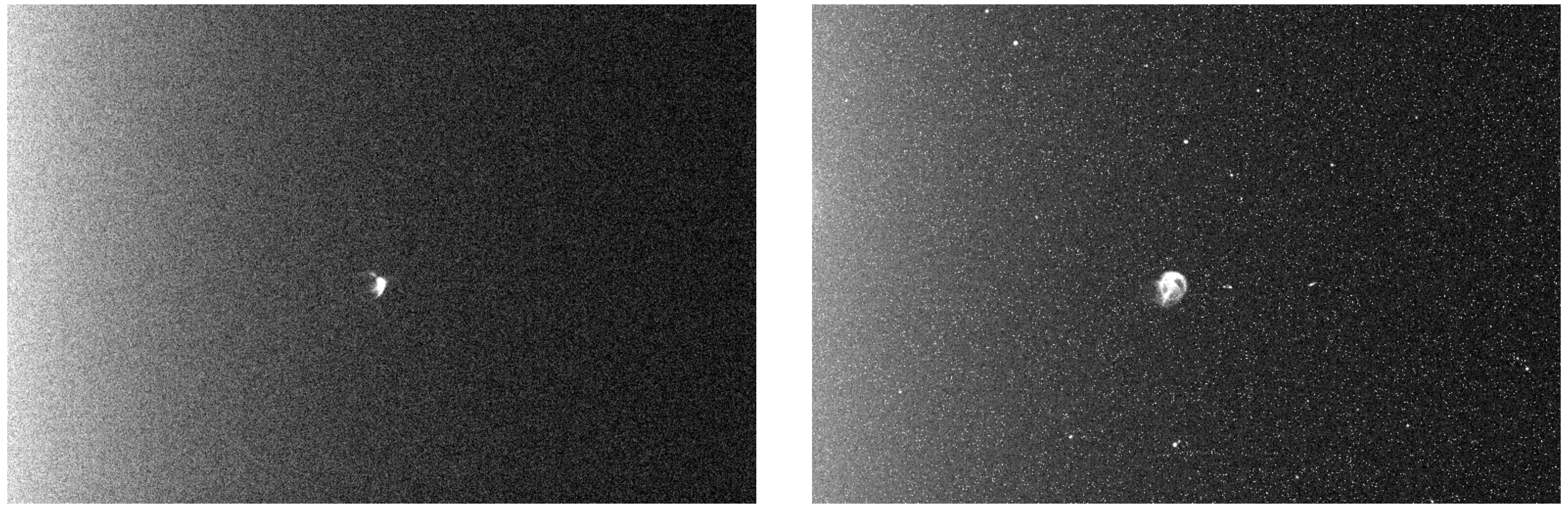


Figure 5.11: First setup in Hamburg with 10 m distance between the laser and the attenuation unit with the detector. The dichroic mirrors are used for attenuation.

1mW probe beam, 100ms

Residual Verdi IR, 600s

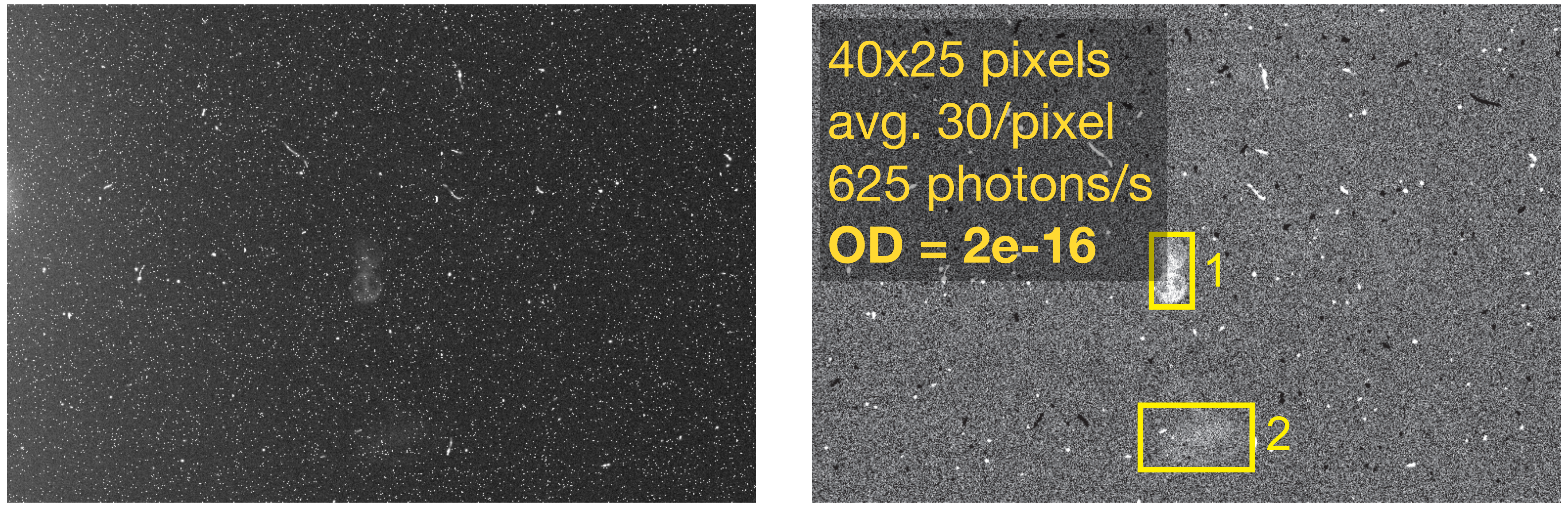


(a) (b)

Figure 5.13: Two possibilities for realizing a probe beam in the setup shown in Figure 5.11. Picture (a) shows the probe light of the test laser and picture (b) shows the residual infrared part of the Verdi laser.

1W, 3600s

1W, 3600s, BG Substraction



(a) (b)

Figure 5.14: First measurement in Hamburg with an exposure time of 3600 s. Both frames shown here are the from the same measurement. Picture (b) is with a subtracted dark frame.

Dichroic Filter Results

Reza H. 2014 - Fluorescence Test

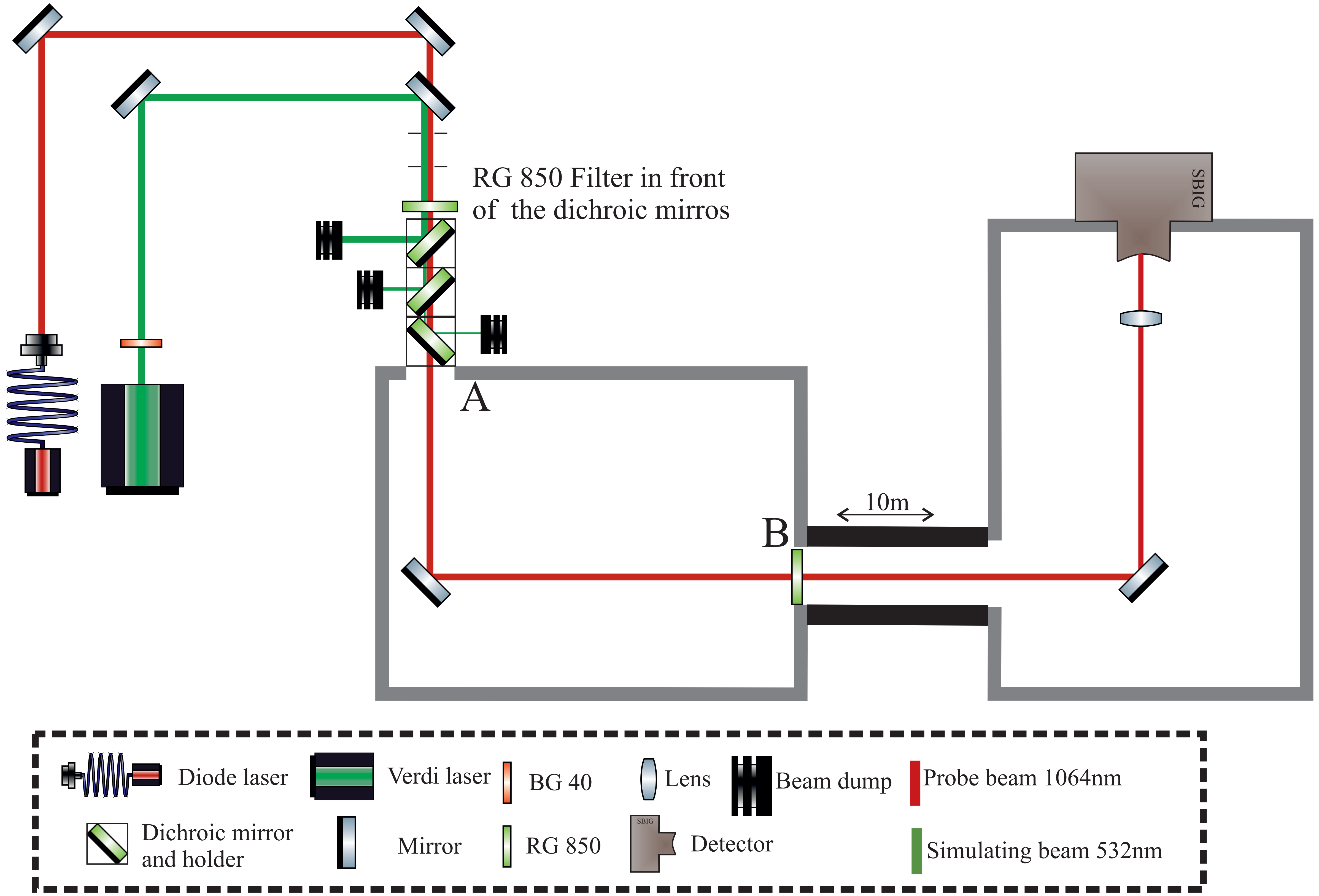
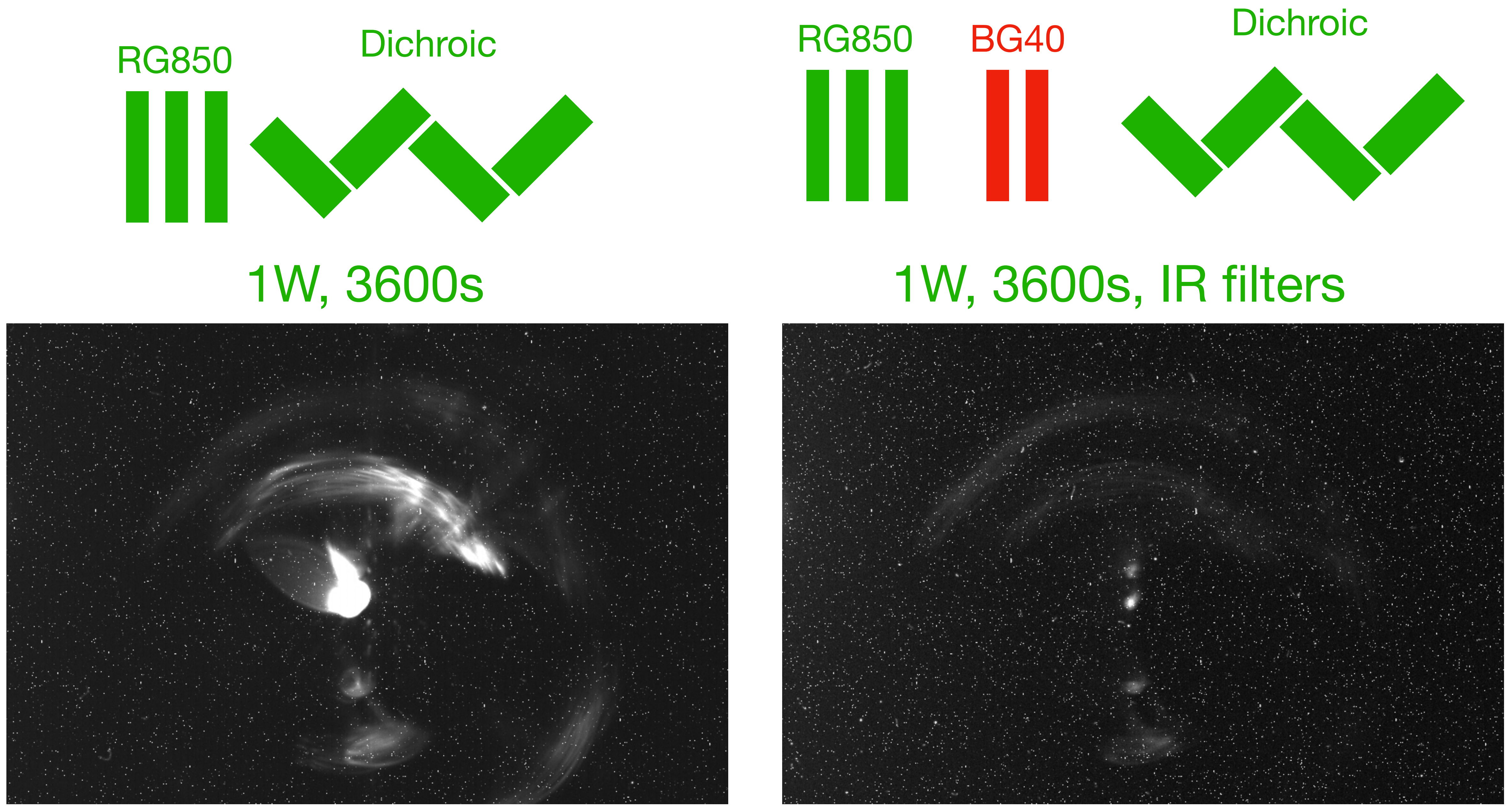


Figure 5.15: Position change of the absorbing filters compared to Figure 5.11 from being behind the dichroic mirrors to the in front of them. This setup shows its fluorescing abilities.



(a) (b)

Figure 5.16: Picture (a) was taken with the setup shown in figure 5.15 and shows the disturbing light produced by the RG850 filters. Picture (b) was taken with the same setup but with BG40 behind RG850 filters.

Filter Transmission Curves

Reza H. 2014

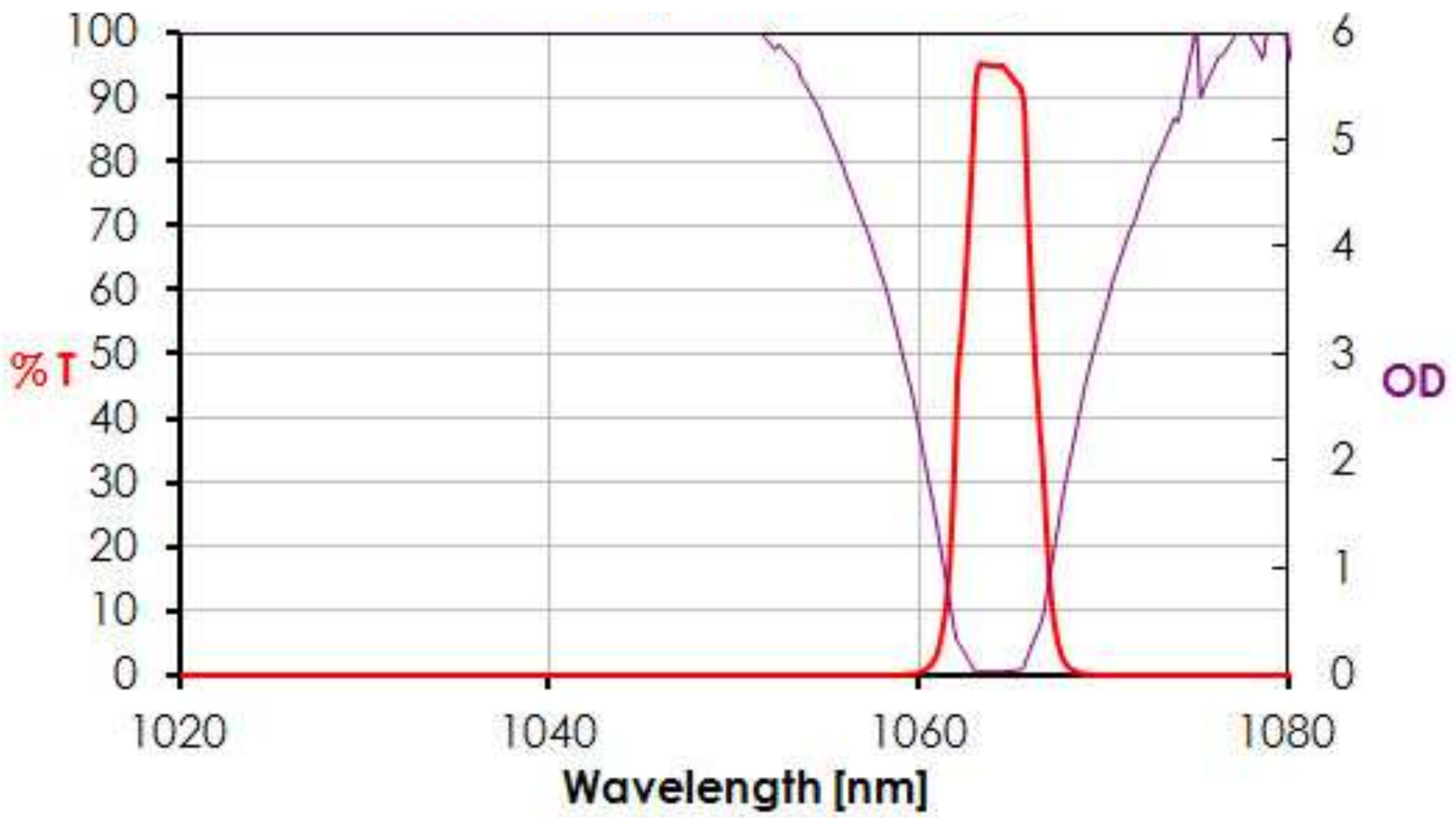
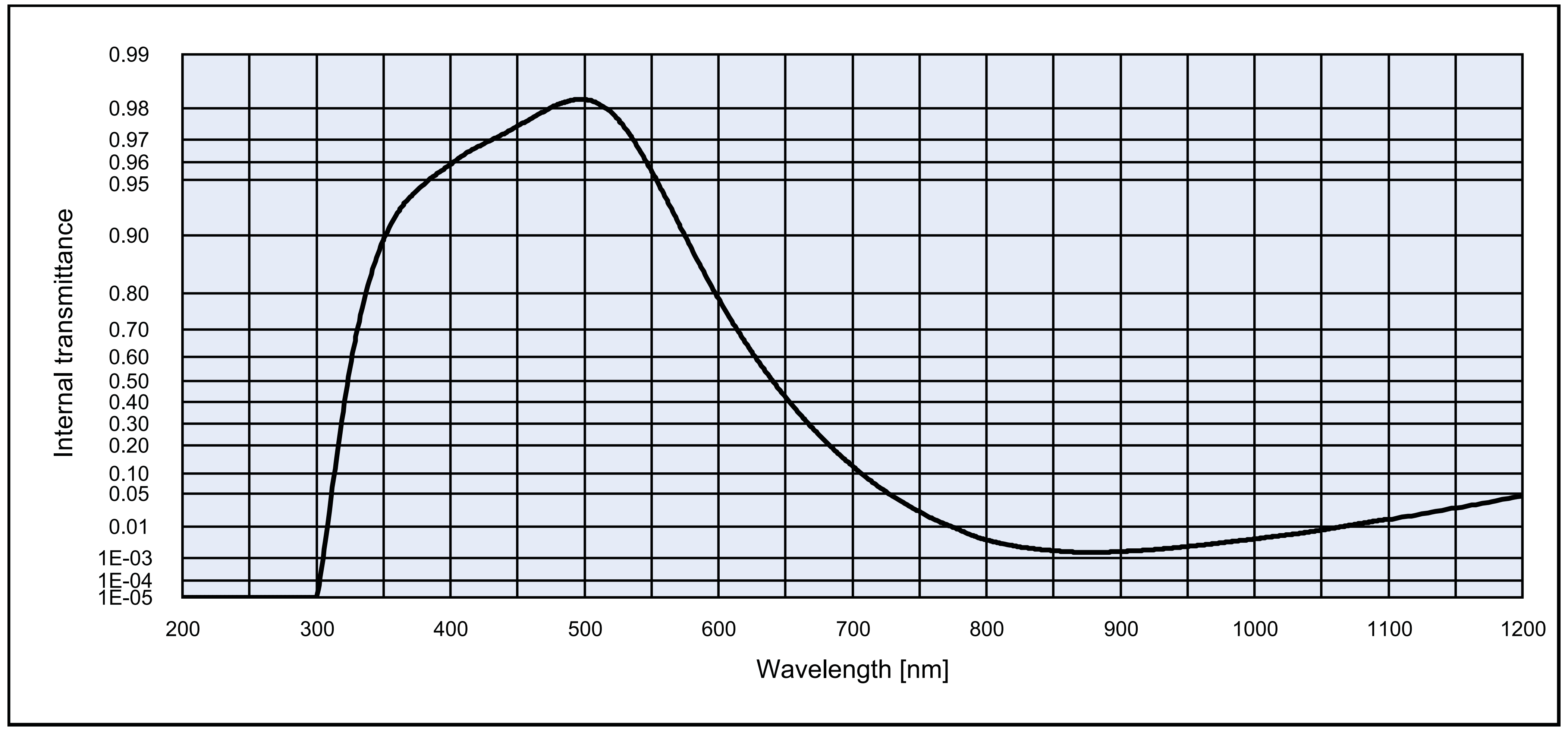
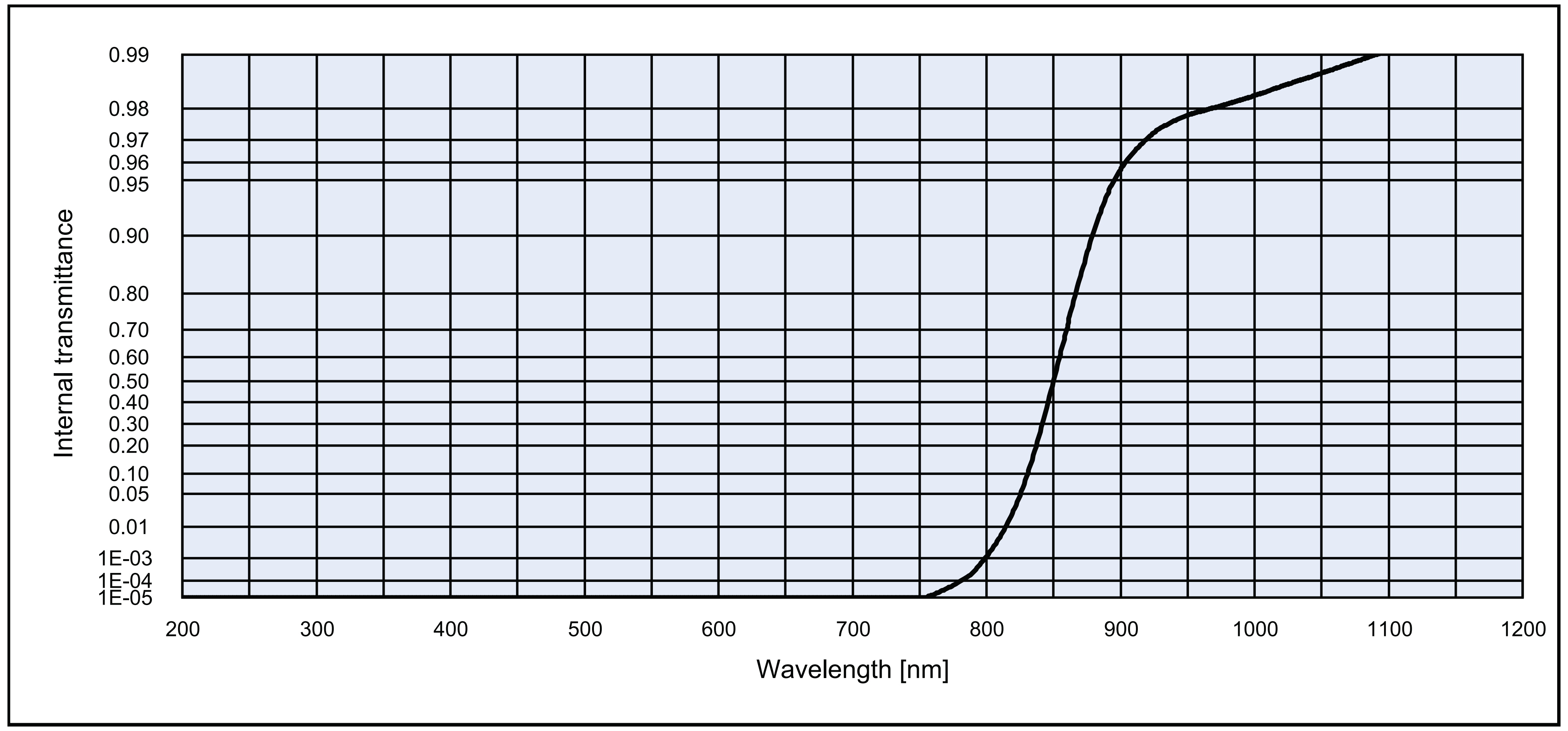


Figure A.3: The red line is the transmissivity of the narrow band absorption filter (LL01-1064).



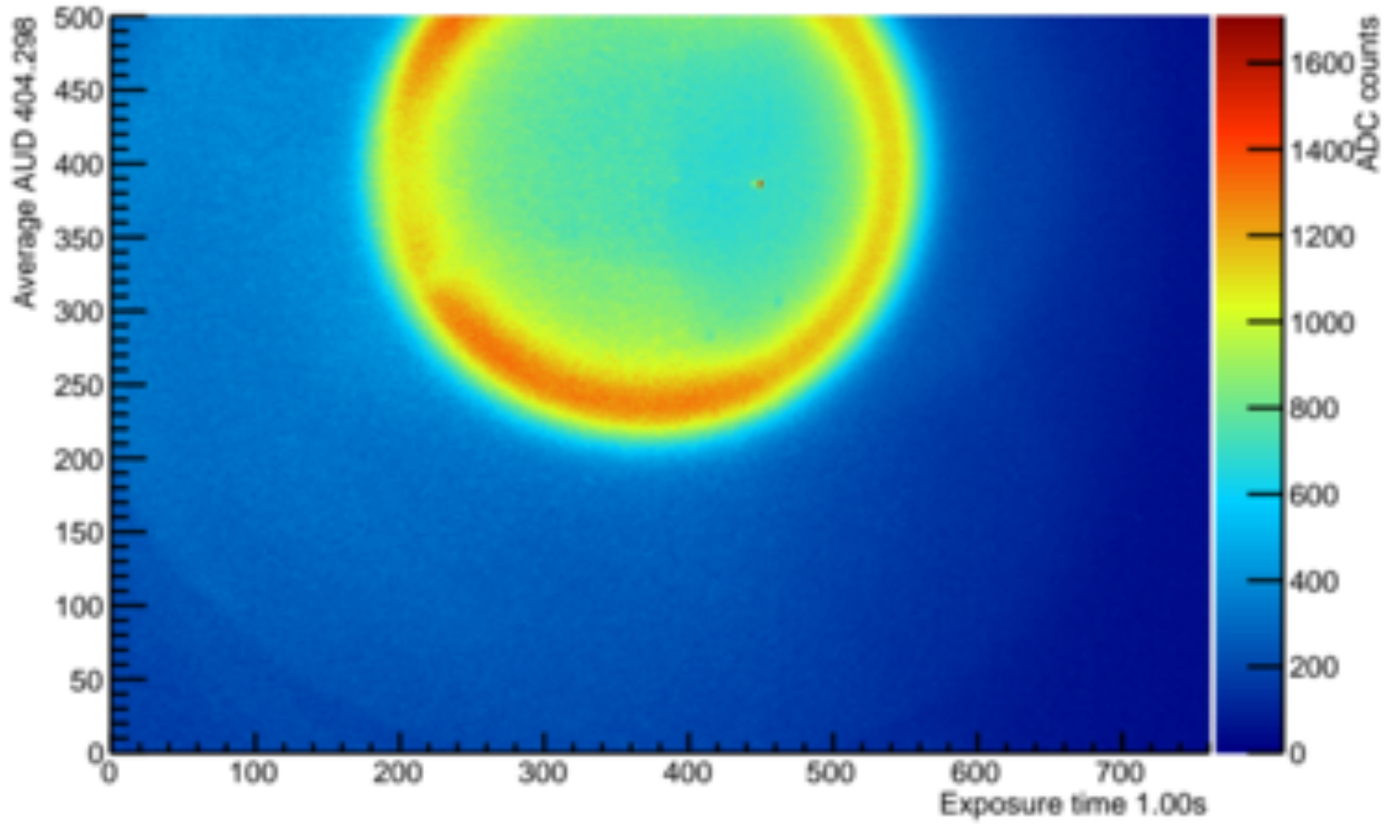
(a) BG40

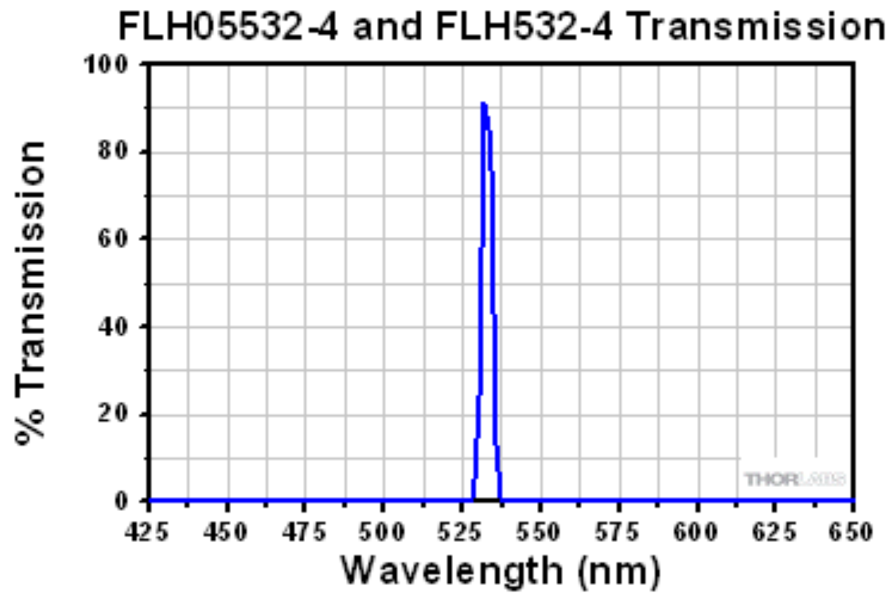


(b) RG850

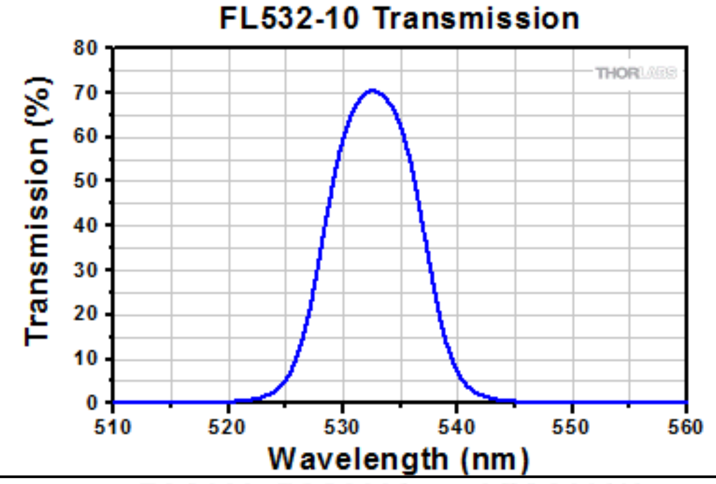
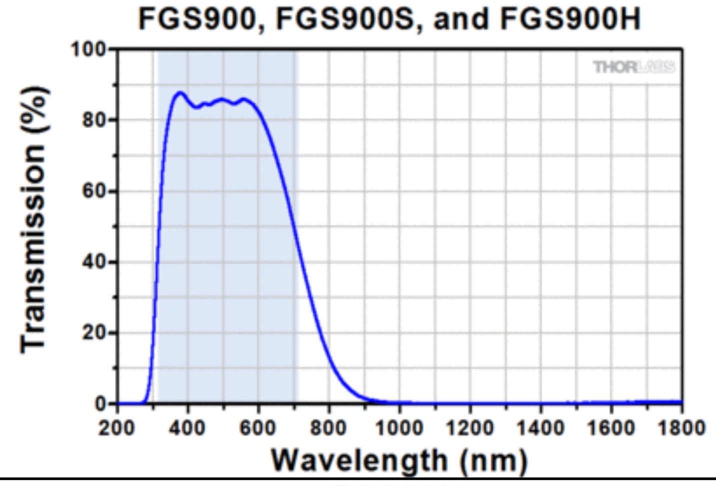
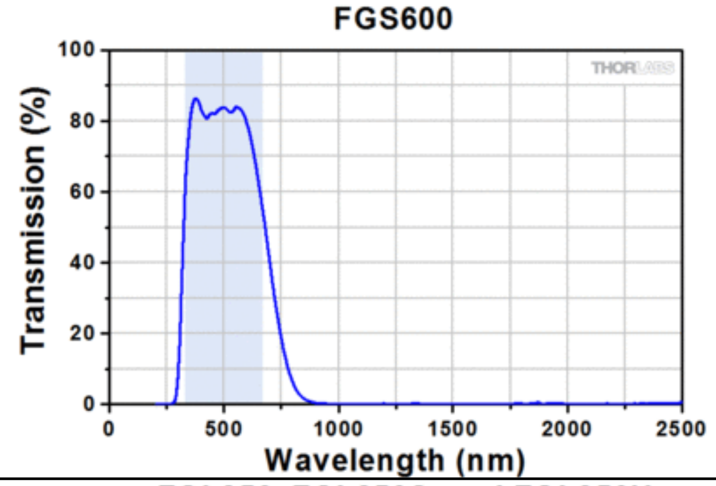
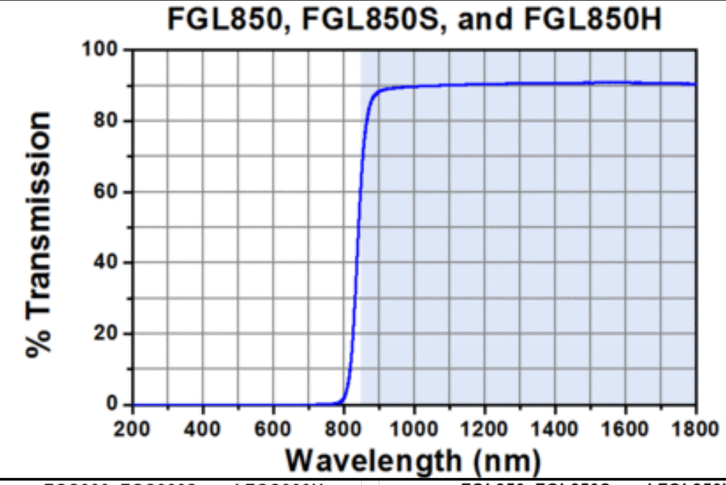
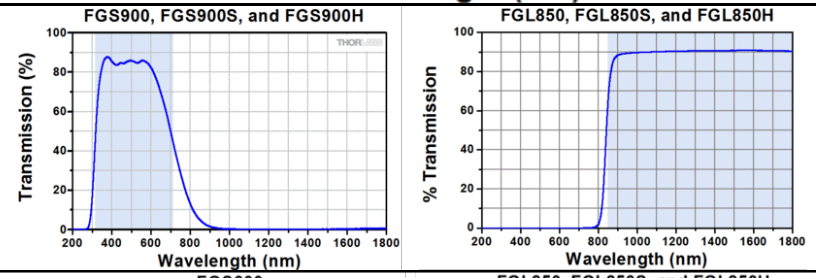
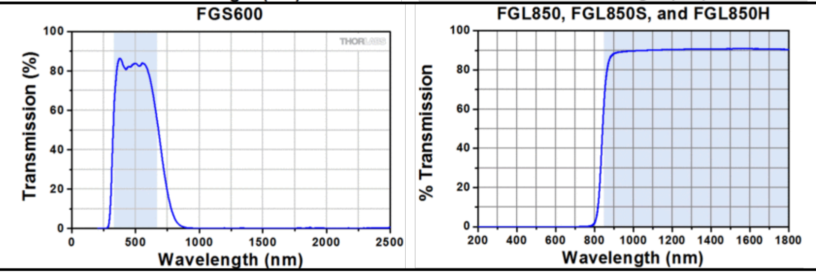
Spectrum Fluorescence

DarkCosmos 2017



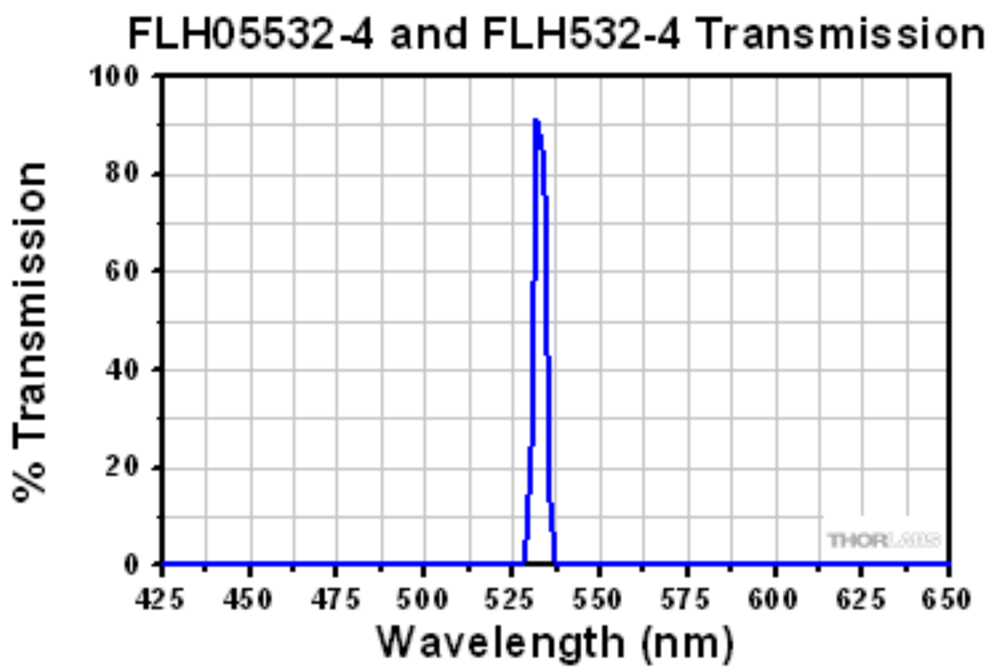


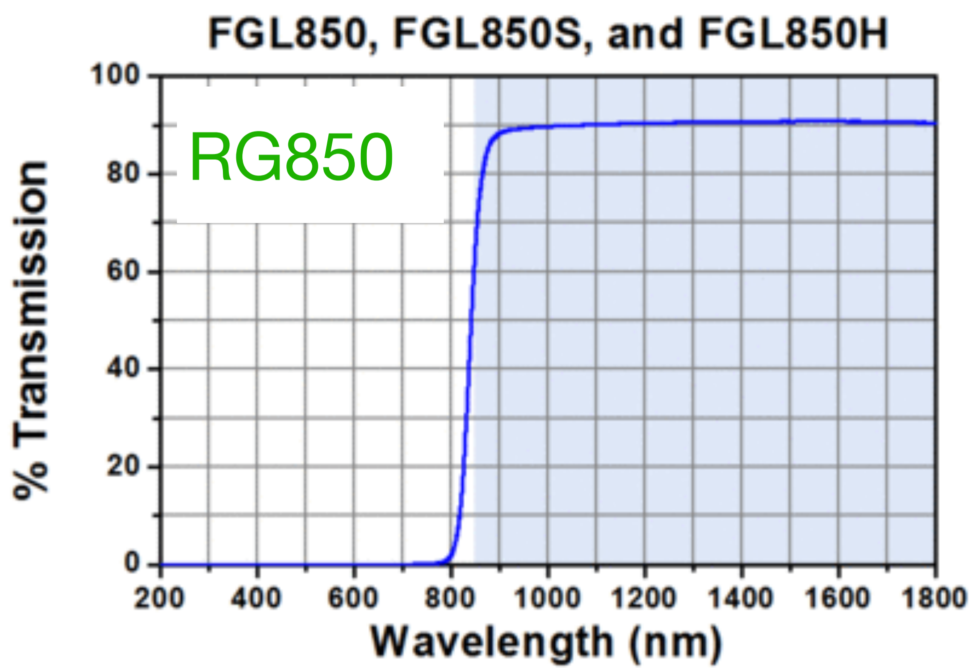
Spectrum of the fluorescence from FLH532-4 is rather falling from green to IR.

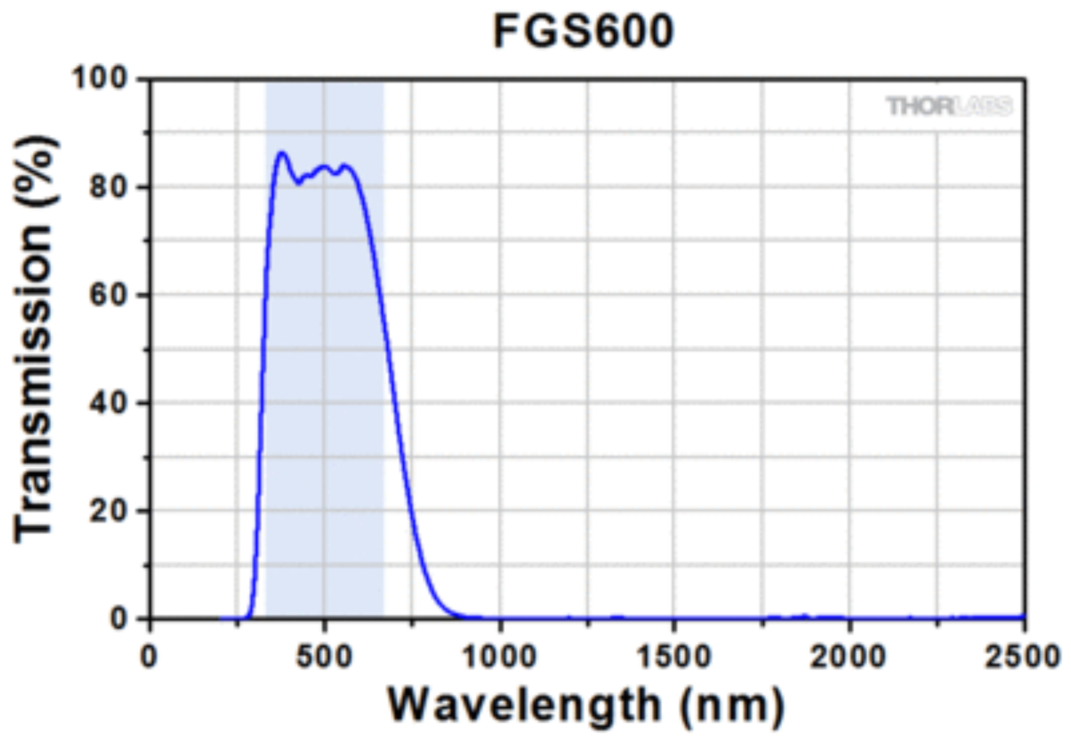
Filter	Filter Transmission	Avg. counts
No Filter		**404**
FL532-10		**84** *Remaining green*
KG3 (FGS900)		**272** *315nm-710nm*
KG5 (FGS600)		**170** *330nm-665nm*
RG850 (FGL850)		**2.44** *>850nm*
KG3 + RG850		**0.12** *315nm-710nm > 850nm*
KG5 + RG850		**<0.01** *330nm-665nm > 850nm*

Reducing Fluorescence

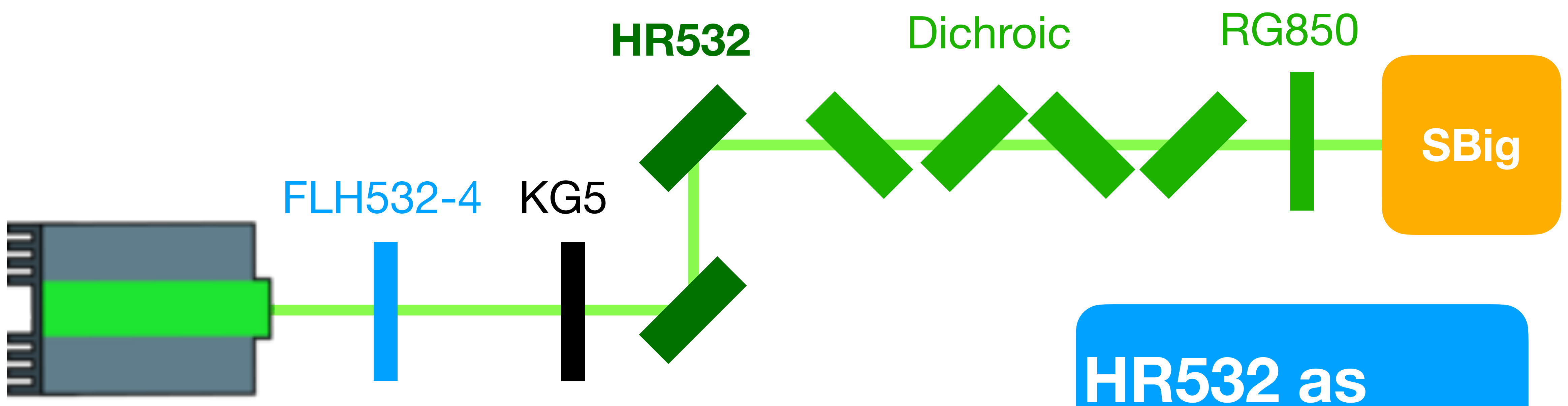
DarkCosmos 2017



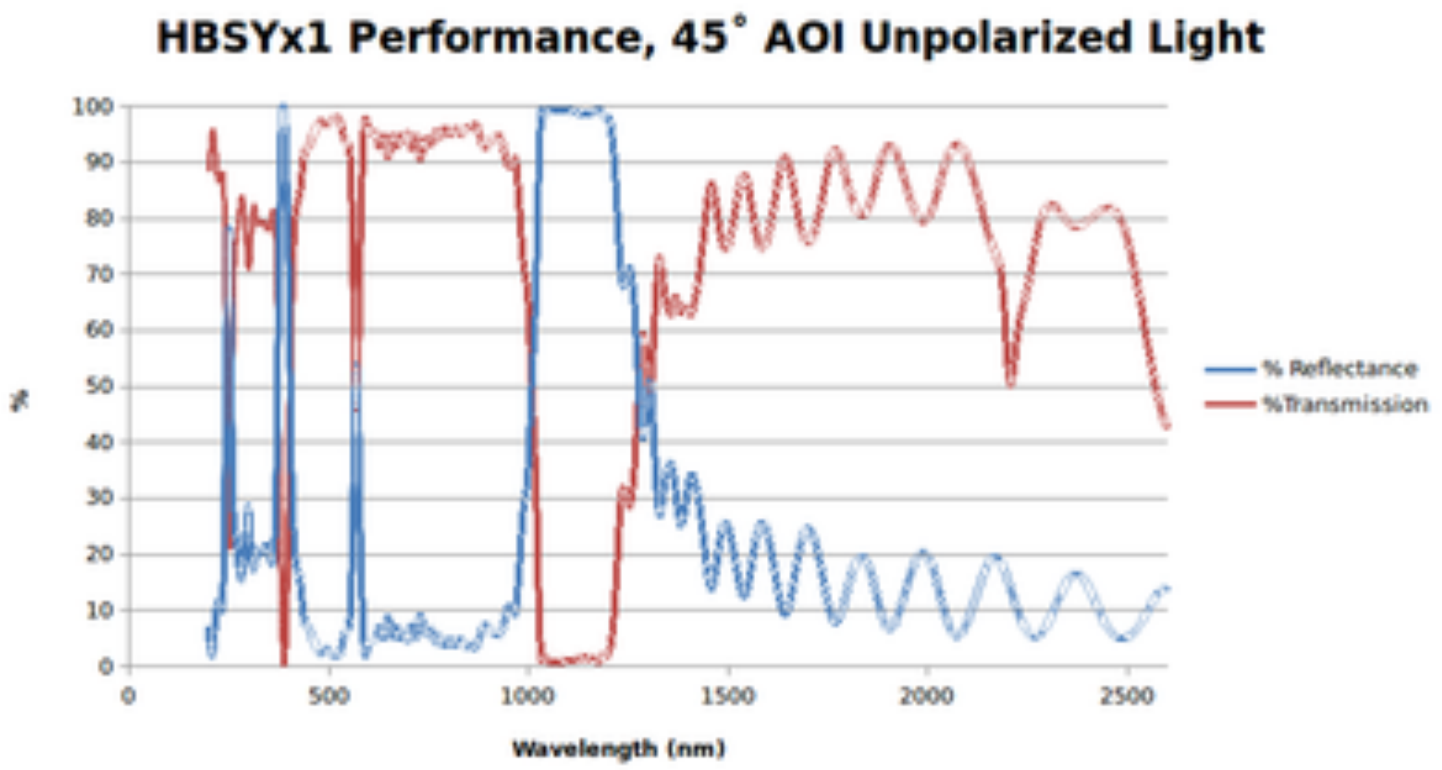


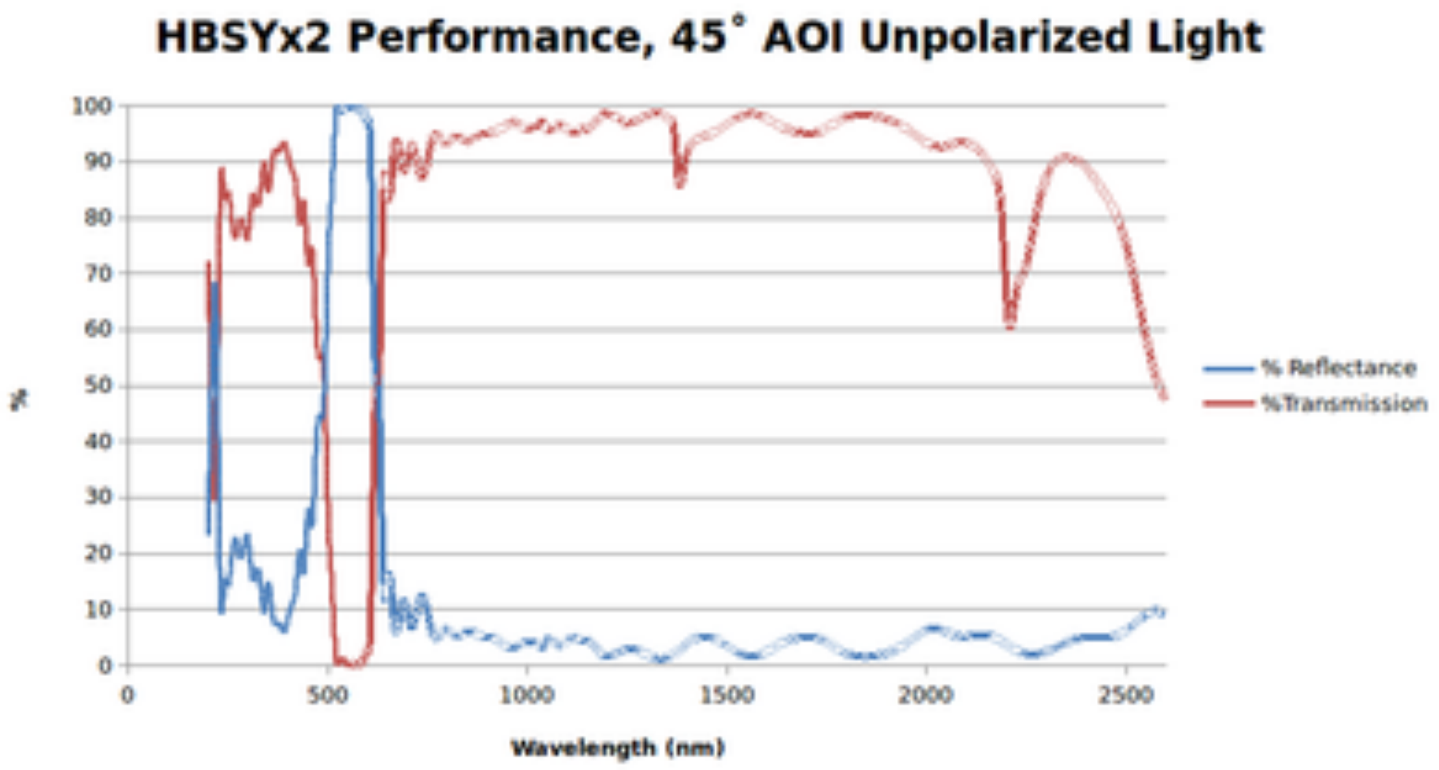


KG5 provides best results
- before „Dichroic“: 0.84
- after „Dichroic“: <0.01



HR532 as bandpass ?
- Without: 0.84
- With: 0.95





Dichroic Filter Results

Reza H. 2014 - Conclusion & Outlook

Attenuation experiment			
#	Source	Detector	Detectable attenuation
1	Verdi P= 1 W $n_{ph} \approx 10^{18}$	SBIG $Q_e \approx 1-2\%$ DC=$1\,\frac{\text{ph}}{\text{s}}$	10^{-18}
2	Verdi P= 1 W $n_{ph} \approx 10^{18}$	PIXIS $Q_e = 1,21\%$ DC=$1\cdot 10^{-3}\,\frac{\text{ph}}{\text{s}}$	10^{-21}
3	Verdi P= 1 W $n_{ph} \approx 10^{18}$	TES $Q_e \approx 60\%$ DC=$1\cdot 10^{-4}\,\frac{\text{ph}}{\text{s}}$	10^{-22}
4	Green Cavity $P_i = 1$ W PB=60 $n_{ph} \approx 10^{20}$	PIXIS $Q_e = 1,21\%$ DC=$1\cdot 10^{-3}\,\frac{\text{ph}}{\text{s}}$	10^{-23}

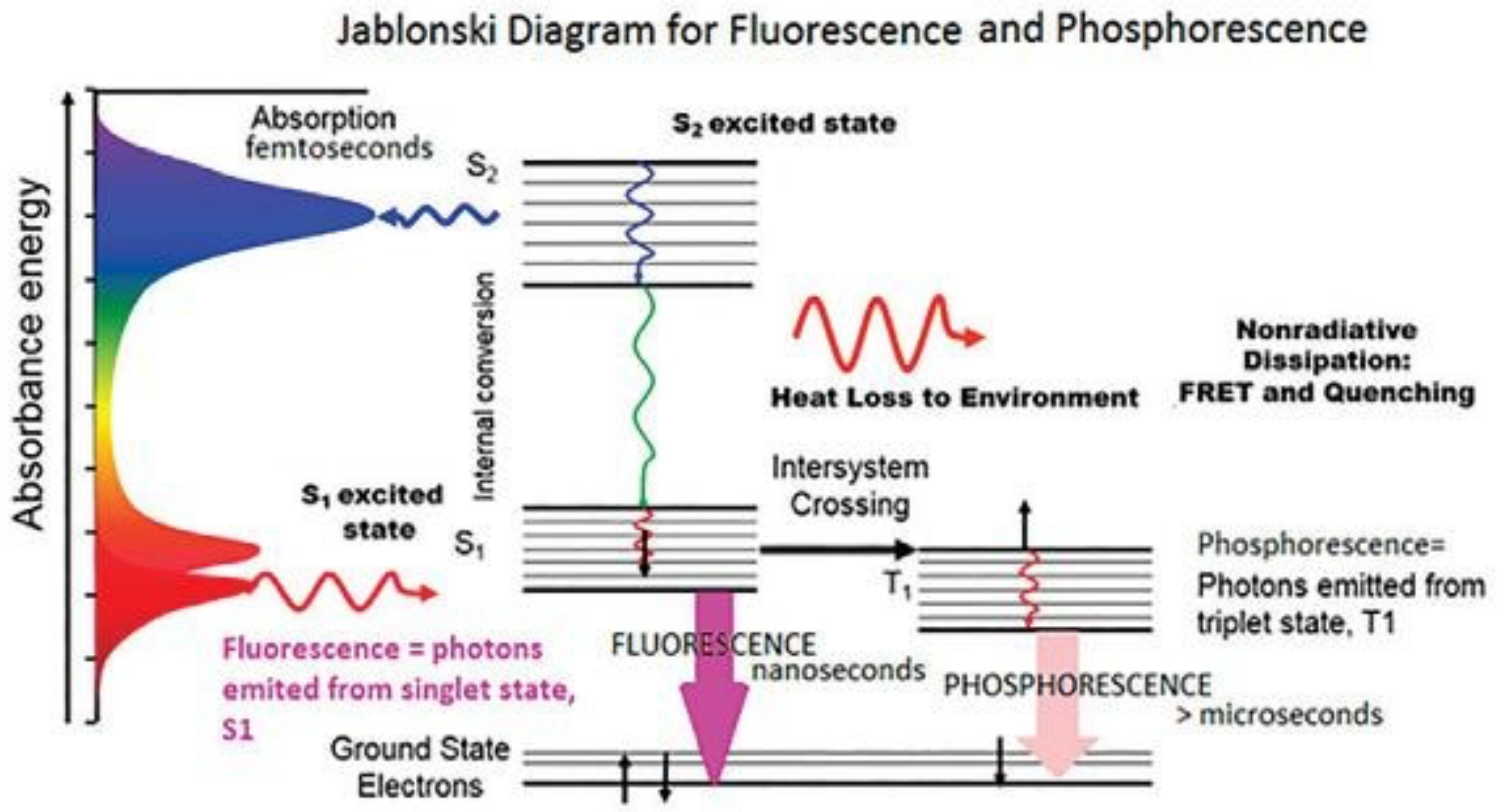
Table 5.1: Possible combinations of source and detector to increase the sensitivity of the attenuation experiment

ALPS-II comparability			
#	Source	Detector	Required attenuation
1	KTP P= 150 µW $n_{ph} \approx 4\cdot 10^{14}$	TES $Q_e \approx 60\%$ DC=$1\cdot 10^{-6}\,\frac{\text{ph}}{\text{s}}$	$2,5\cdot 10^{-21}$
2	KTP P= 150 µW $n_{ph} \approx 4\cdot 10^{14}$	TES $Q_e \approx 60\%$ DC=$1\cdot 10^{-6}\,\frac{\text{ph}}{\text{s}}$	$2,5\cdot 10^{-21}$
3	KTP P= 150 µW $n_{ph} \approx 4\cdot 10^{14}$	TES $Q_e \approx 60\%$ DC=$1\cdot 10^{-6}\,\frac{\text{ph}}{\text{s}}$	$2,5\cdot 10^{-21}$
4	RC for green $P_i = 150$ µW PB=60 $n_{ph} \approx 2\cdot 10^{16}$	TES $Q_e \approx 60\%$ DC=$1\cdot 10^{-6}\,\frac{\text{ph}}{\text{s}}$	$4\cdot 10^{-23}$

Table 5.2: Compared sensitivities in ALPS-II of the setup suggestions discussed above and shown in table 5.1.

Frequency down conversion types

- Fluorescence
- Phosphorescence
- Spontaneous parametric down conversion
- Two photon emission
- Black body radiation
- Roomlight



Dark count models

Fiber-coupled TES looking at a Black-Body:

- Modification for single mode blackbody cavity:
  - Cavity temperature, *T*, couples in: 1D, only allowed modes, each polarization
- Mean number of photons per unit length and single polarization $f(k)dk$ for a wave vector between k and $k + dk$
- There are $\frac{1}{2\pi}dk$ of these photon states per unit length of the cavity
- Typical mode population function gives mean photon number for one specific k:
  $$n = \frac{1}{e^{\hbar\omega/kT} - 1}$$
- Mean rate at which photons populate the cavity per unit time becomes:
  $$r(\omega)d\omega = \frac{\eta}{\pi}\frac{d\omega}{e^{\hbar\omega/kT} - 1}$$ with η being the non-unity cavity emissivity and DE

➡ 300K, $\eta = 1$, $\lambda = 1064\,\mathrm{nm}$, $d\lambda = 100\,\mathrm{nm}$: **1.4e-06 photons / second**

➡ 300K, $\eta = 1$, $\lambda = 2128\,\mathrm{nm}$, $d\lambda = 100\,\mathrm{nm}$: 2158.30 photons / second

SUPERCONDUCTING PHOTON NUMBER RESOLVING DETECTORS: PERFORMANCE AND PROMISE

Aaron J. Miller[1], Adriana Lita[2], Danna Rosenberg[3], Stephen Gruber[2], and Sae Woo Nam[2]

Black-Body from the outside to the fiber core:

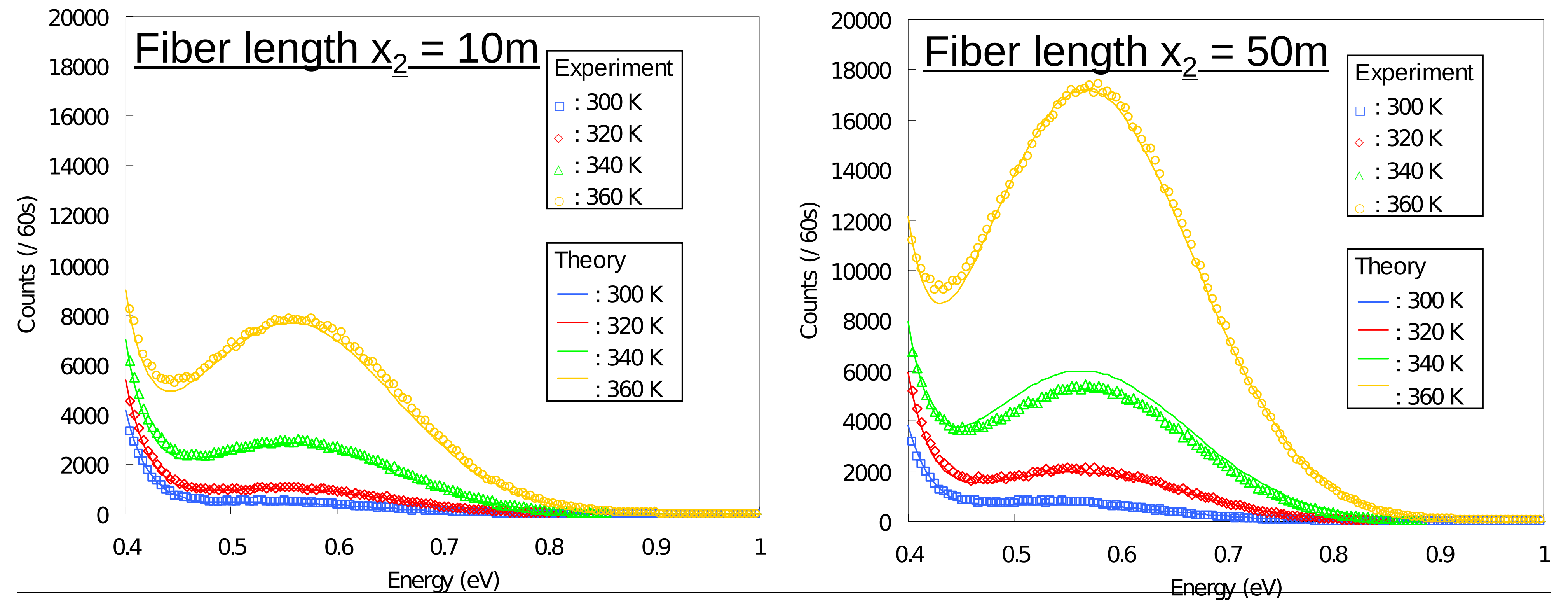


Figure 4.9.: Thermal photon rates of different temperatures and different fiber length: Fujii et al. (2011) measure the count rate of different fiber length, in different temperatures. With a model including Planck's law and the fiber transmittance, they fit the measurements (eqn. 4.14). This explains the peak shape: For lower photon energies, the transmittance of the fiber decreases (e.g. fig. C.4). [Taken from Fujii et al. (2011)]

- Fit curve: $f(E,T,x) \propto \int_0^\infty \frac{\mathrm{DE}(\epsilon)R(\epsilon,T,x)}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}\left(\frac{E-\epsilon}{\sigma}\right)^2} d\epsilon$

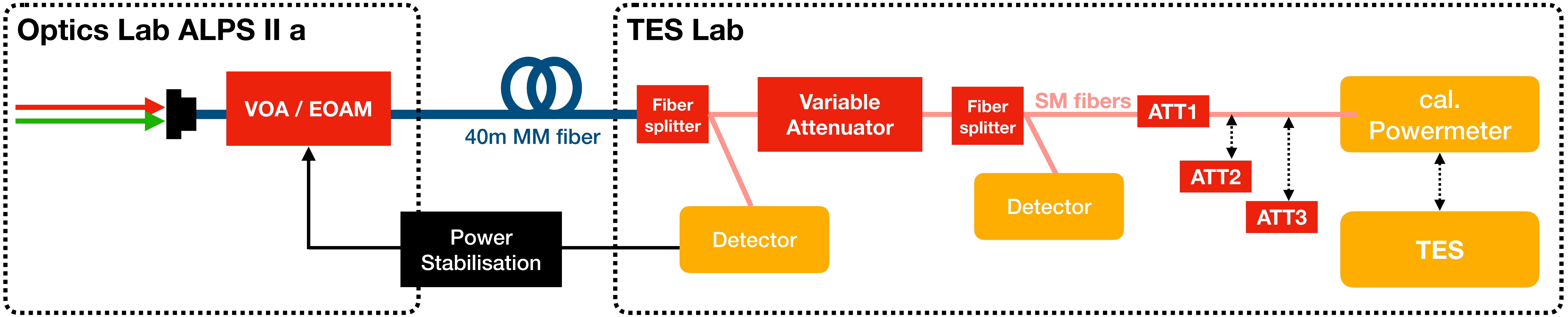
  With energy E, temperature T, fiber length x, rate R, detector energy resolution σ, detector efficiency DE
- R combined fiber transmittance and spectral BB distribution, fit parameter including also coupling efficiency of photons to fiber core
- Extrapolation & internal communication (Jan's thesis):

➡ 300K,1eV, 10m fiber: ~1e-4 photons / second / eV (log!)

➡ 300K,1eV, 10m fiber, 10% window: **~1e-5 photons / second** (log!)

Photon numbers & Efficiency

Detection Efficiency: Single photon source with calibrated filters



- System detection efficiency:

$$\eta_{\mathrm{system}} = \underbrace{\eta_{\mathrm{fiber}}}_{\text{Losses in fiber}} \underbrace{\eta_{\mathrm{cpl}}}_{\text{Overlap mode and detector}} \underbrace{\eta_{\mathrm{absorption}}}_{\text{Absorption on the TES}} \underbrace{\eta_{\mathrm{QE}}}_{\text{Absorption that results in electrical signal („pulse“)}} \underbrace{\eta_{\mathrm{trigger}}}_{\text{signals, that meet criteria}} \approx \eta_{\mathrm{cpl}}$$

for TES in optical cavity, high SNR, pustet operation, negligible losses in fibers