EL for Broadband Optical Radiation

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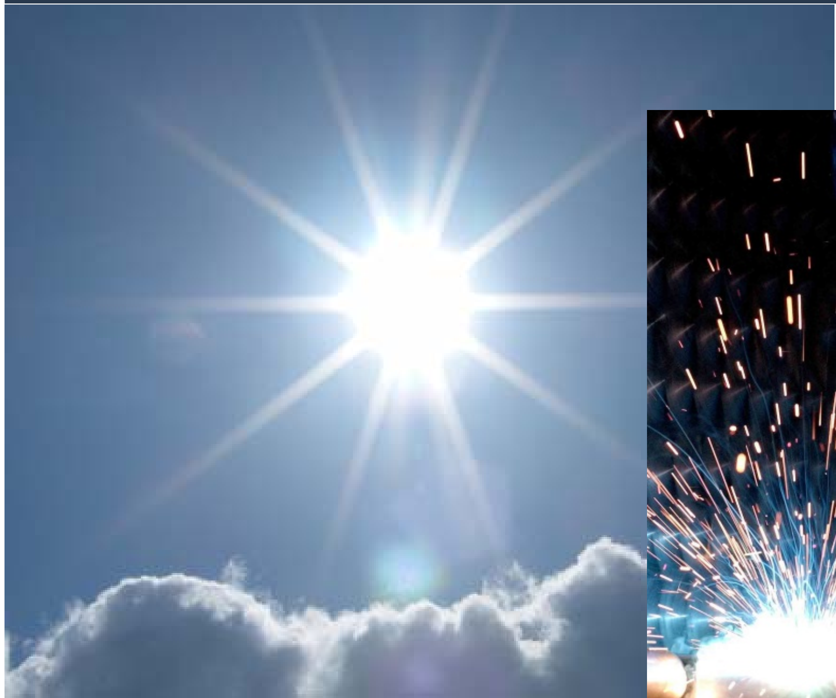
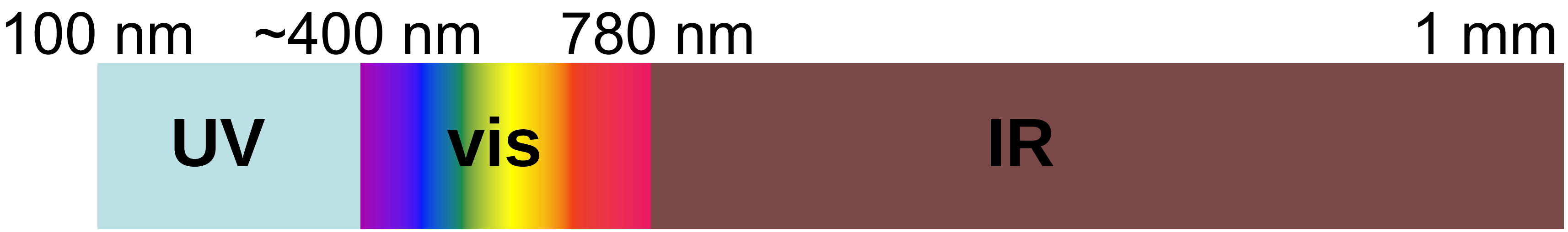
ICNIRP SC-IV Member

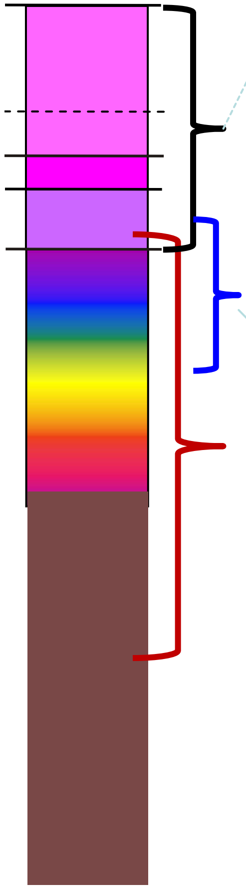
Seibersdorf Laboratories, Austria

SEIBERSDORF LABORATORIES

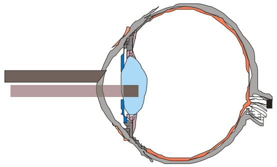



100 nm
~400 nm
780 nm
1 mm
UV
vis
IR

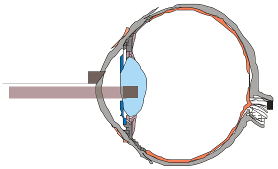
Exposure Limits



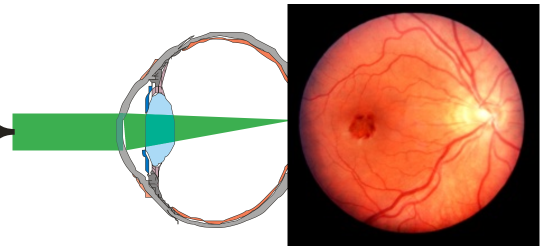
- UV – s(λ)



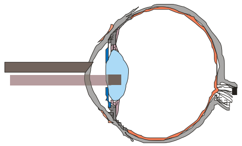
- UV-A



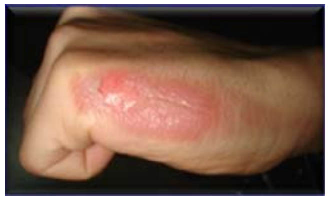

- Retina photochemical
- Retina thermal



- Infrared eye

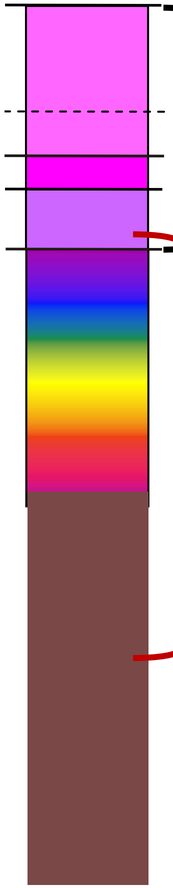



- Skin (vis. and IR)



Photographs courtesy of P Söderberg JP Cesarini and Univ. Michigan, Kellogg Eye Center

Exposure Limits



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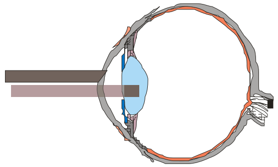
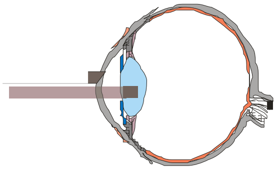


- UV-A



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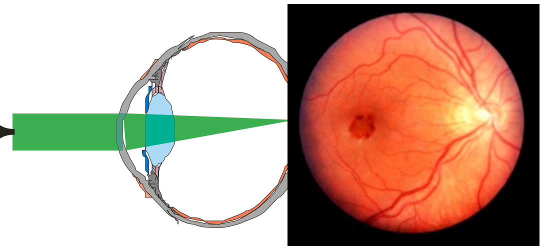

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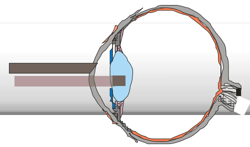

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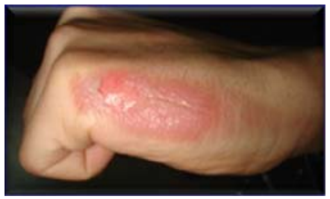


Current Guidelines:

ICNIRP Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38-3µm)

Health Phys. 73: 539-554; 1997

New Edition of Guidelines for visible and IR:

Open Consultation 2011

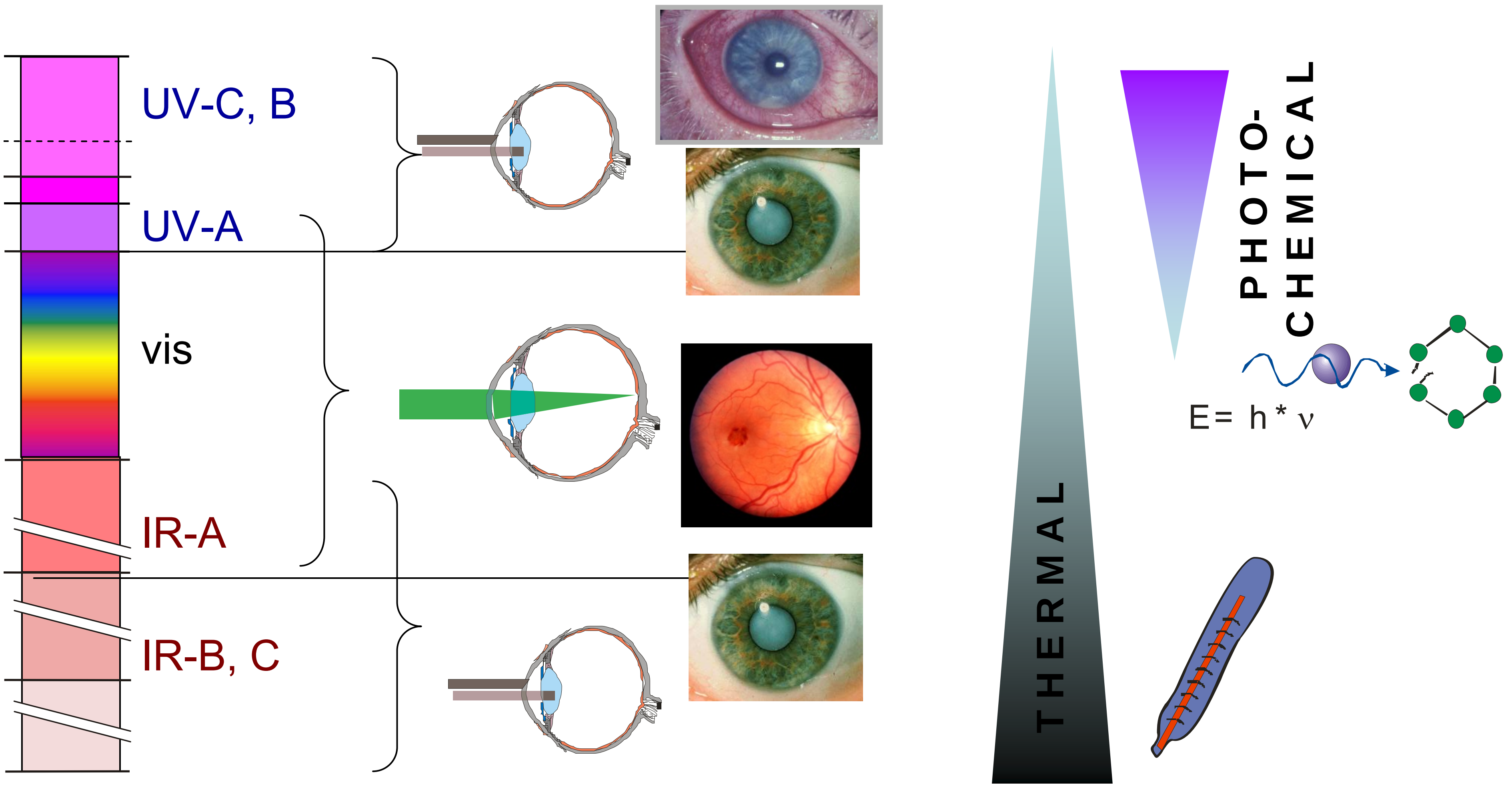
Health Physics Publication: End 2012/Beginning 2013

Product Standards updated in parallel:

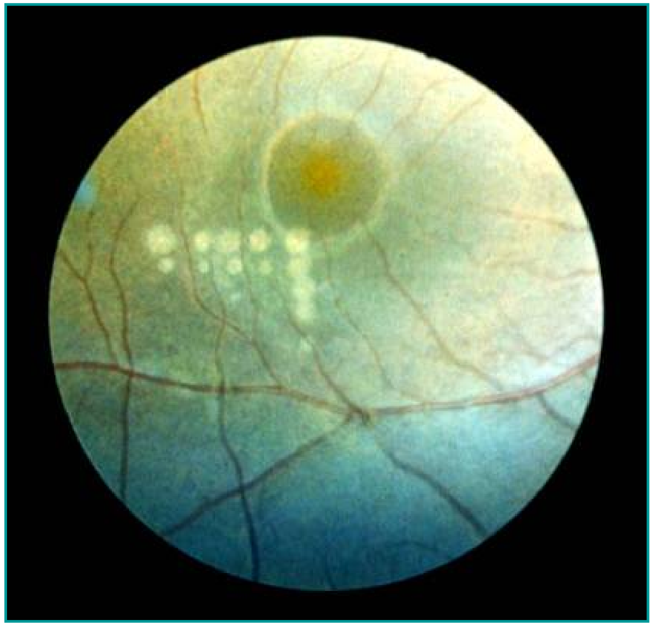
CIES009/ IEC 62471 (Lamp Product Safety Standard)

IEC 60825-1 (Laser Product Safety Standard)

Absorption location and mechanism overview



Changes in Guidelines



- Thermally induced retinal injury

- Near IR limit for cornea/lens

No changes:

- photochemically induced retinal injury „blue light hazard“ (but averaging FOV defined for t > 100 s)
- UV
- skin

Current EL - retinal thermal injury

Effective Exposure **Exposure Limit**

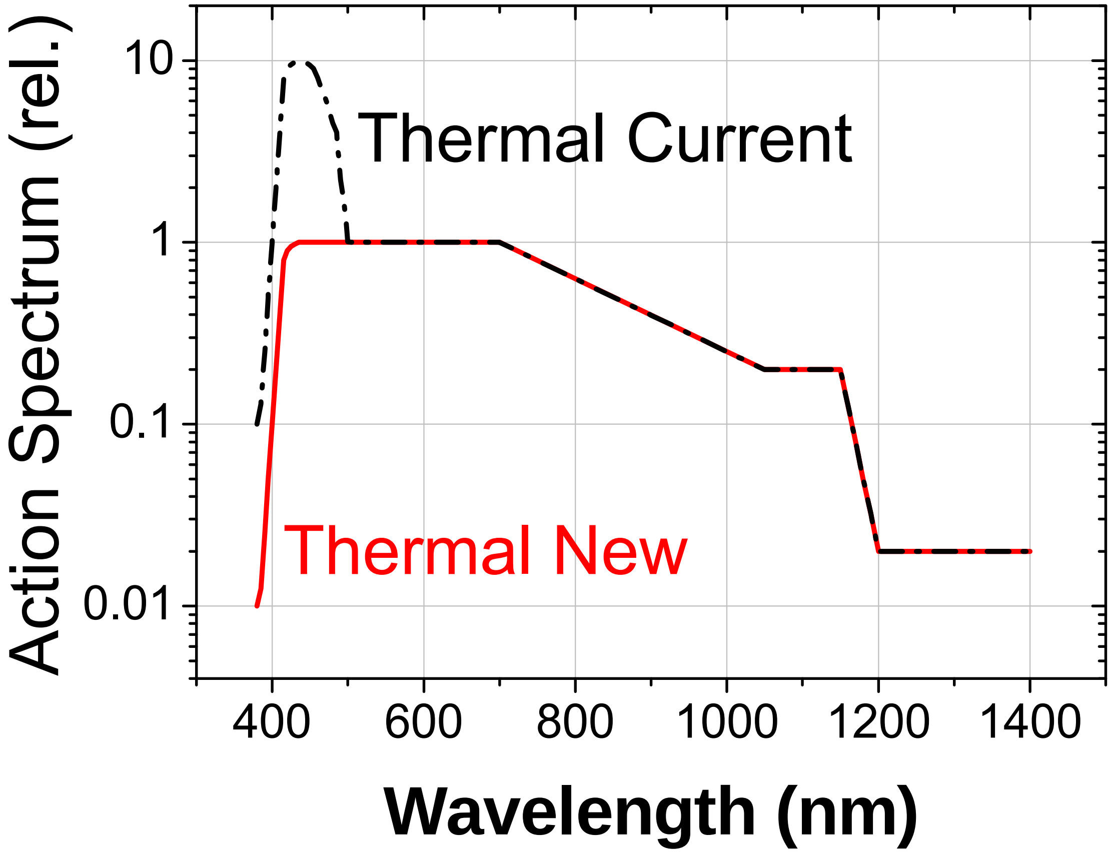
$$\sum L_\lambda \cdot R(\lambda)\Delta\lambda \leq 50 \cdot \alpha^{-1} \cdot t^{-0.25} \, kW \cdot m^{-2} \cdot sr^{-1}$$

α *in rad!*

For t < 10 s

- Wavelength dependence
- Base limit value
- Retinal spot size dependence
- Pulse duration dependence

R(λ) Wavelength Dependence

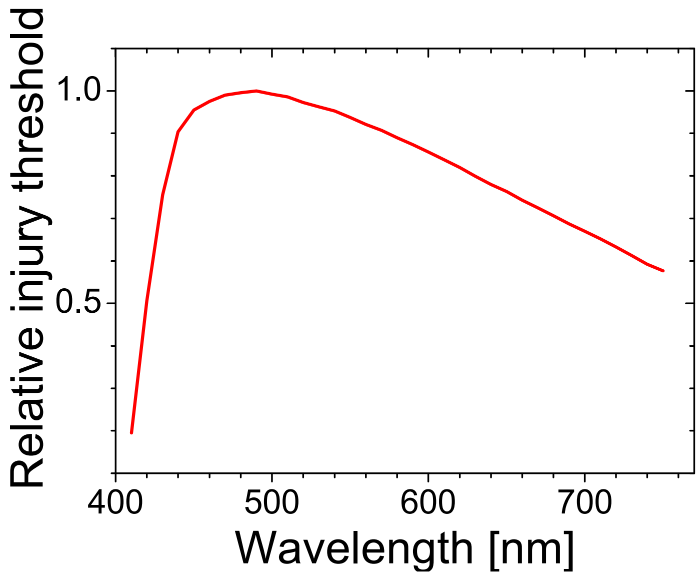


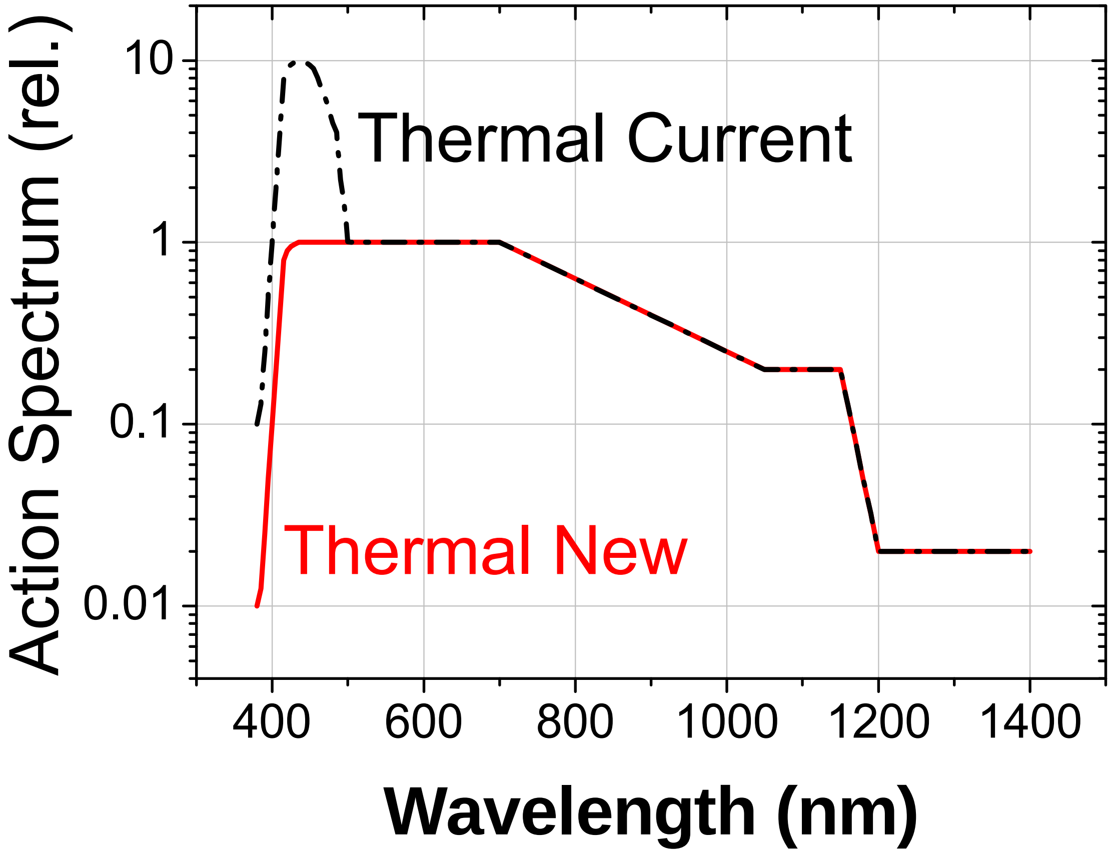
Lund DJ, BE Stuck, P Edsall

Retinal injury thresholds for blue wavelength lasers

Health Phys 90: 477-484; 2006

R(λ) Wavelength Dependence





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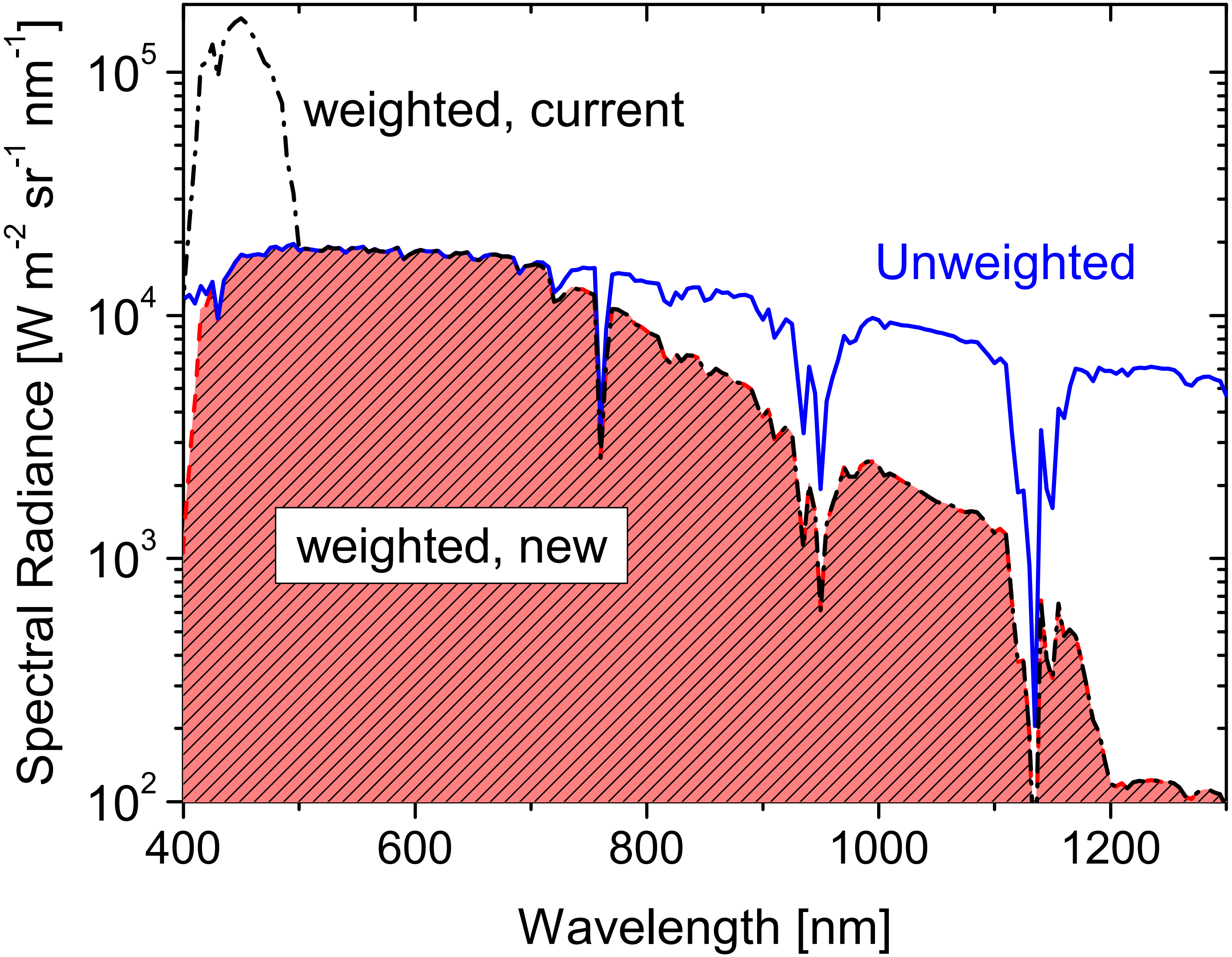
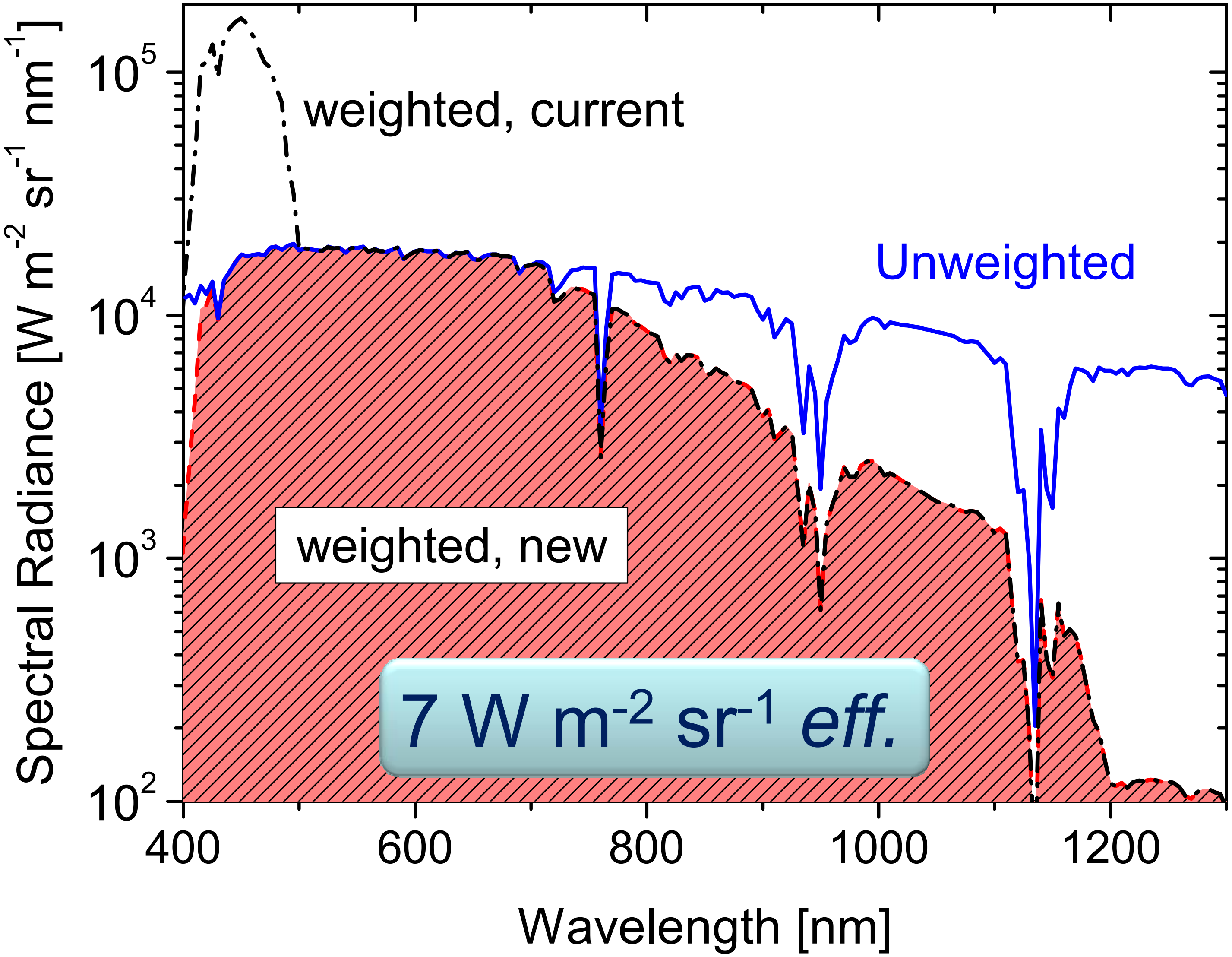
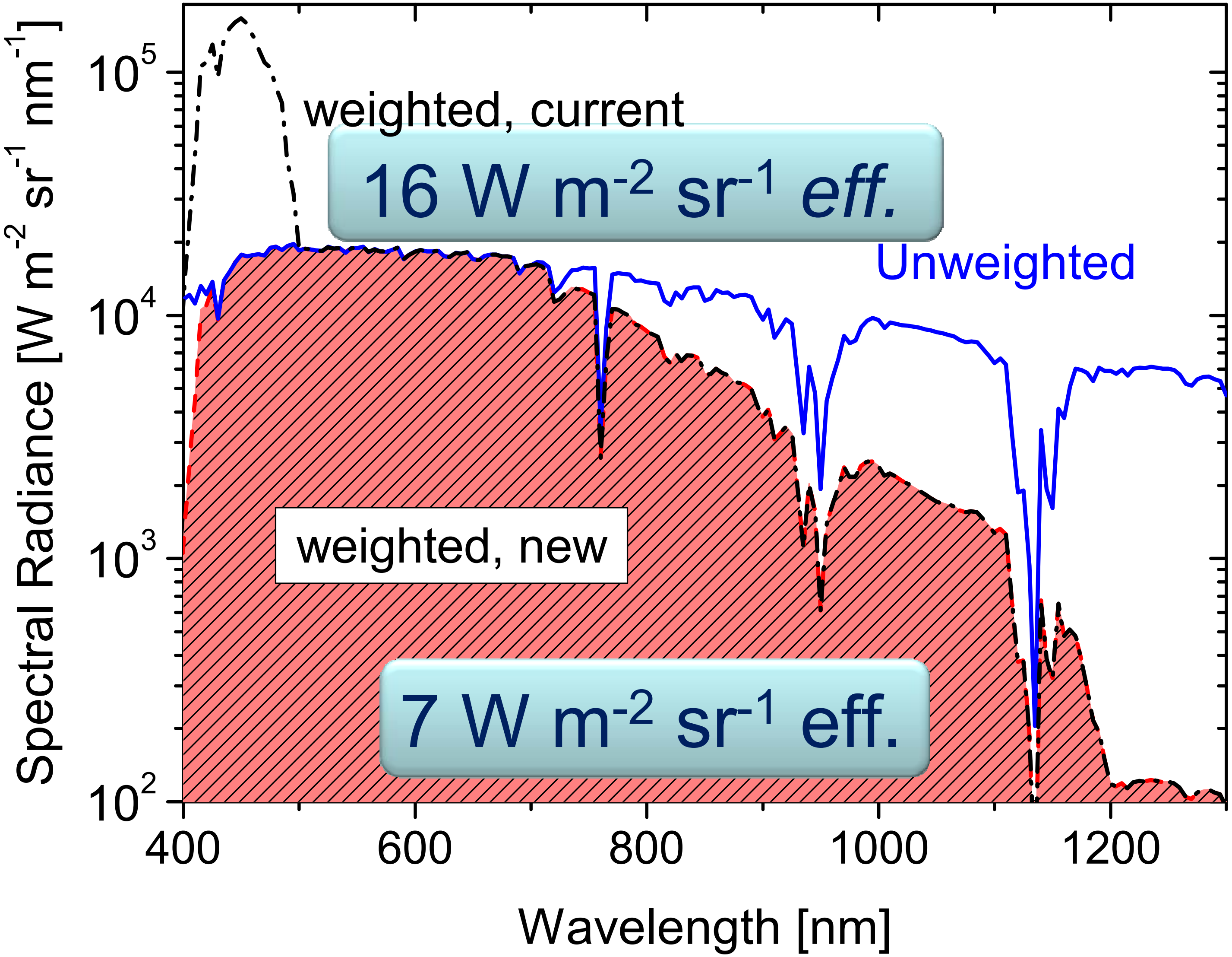
Sun


weighted, current
Unweighted
weighted, new
Spectral Radiance [W m^{-2} sr^{-1} nm^{-1}]
10^5
10^4
10^3
10^2
400
600
800
1000
1200
Wavelength [nm]

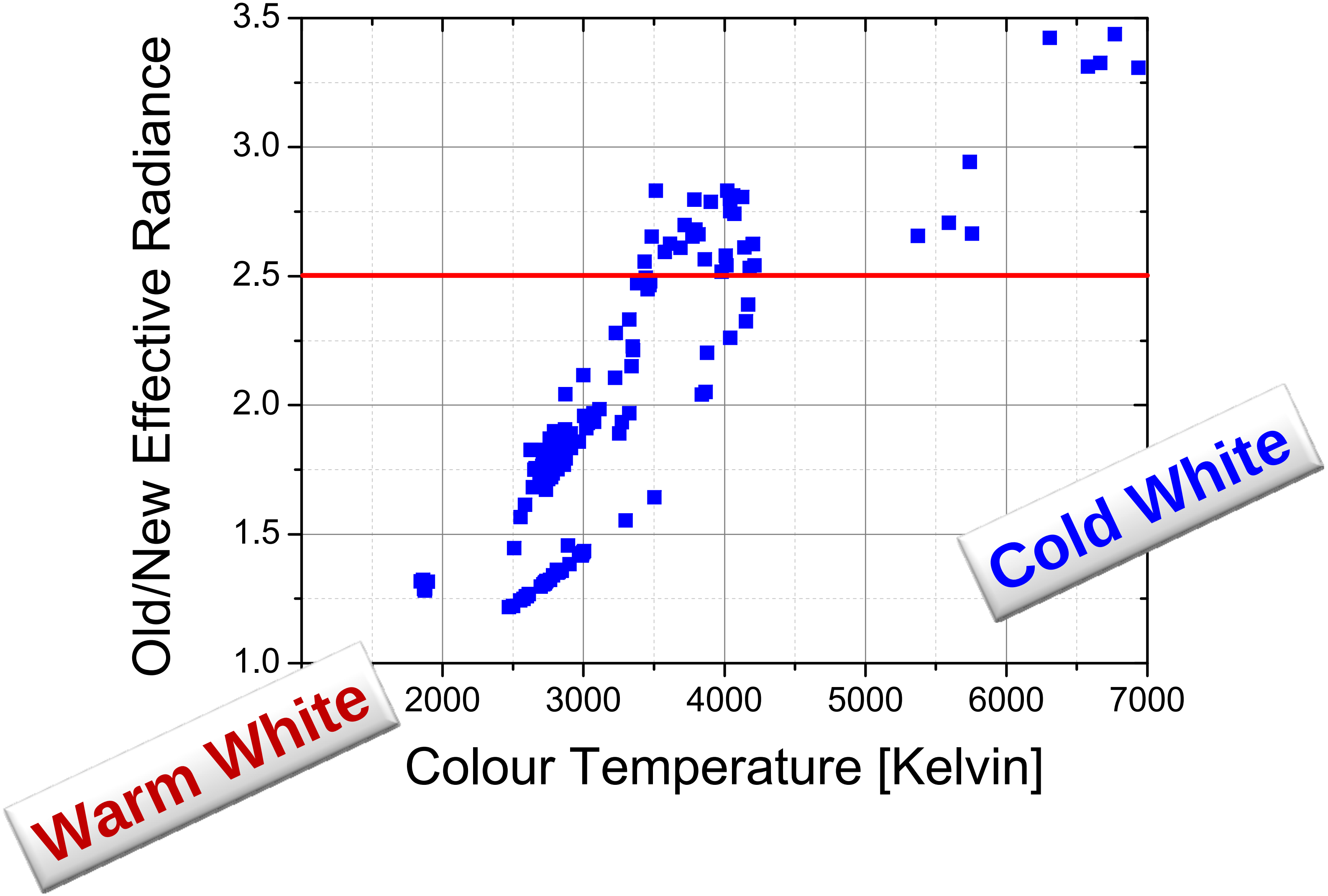
Sun


Spectral Radiance [W m-2 sr-1 nm-1]
10^5
10^4
10^3
10^2
400
600
800
1000
1200
Wavelength [nm]
weighted, current
Unweighted
weighted, new
7 W m-2 sr-1 eff.

Sun


weighted, current
16 W m-2 sr-1 eff.
Unweighted
weighted, new
7 W m-2 sr-1 eff.
Spectral Radiance [W m-2 sr-1 nm-1]
Wavelength [nm]
10^5
10^4
10^3
10^2
400
600
800
1000
1200

Wavelength Evaluation Less Restrictive



Current EL - retinal thermal injury

Radiance

Effective Exposure | **Exposure Limit**

$$\sum L_\lambda \cdot R(\lambda)\Delta\lambda \leq 50 \cdot \alpha^{-1} \cdot t^{-0.25}\, kW \cdot m^{-2} \cdot sr^{-1}$$

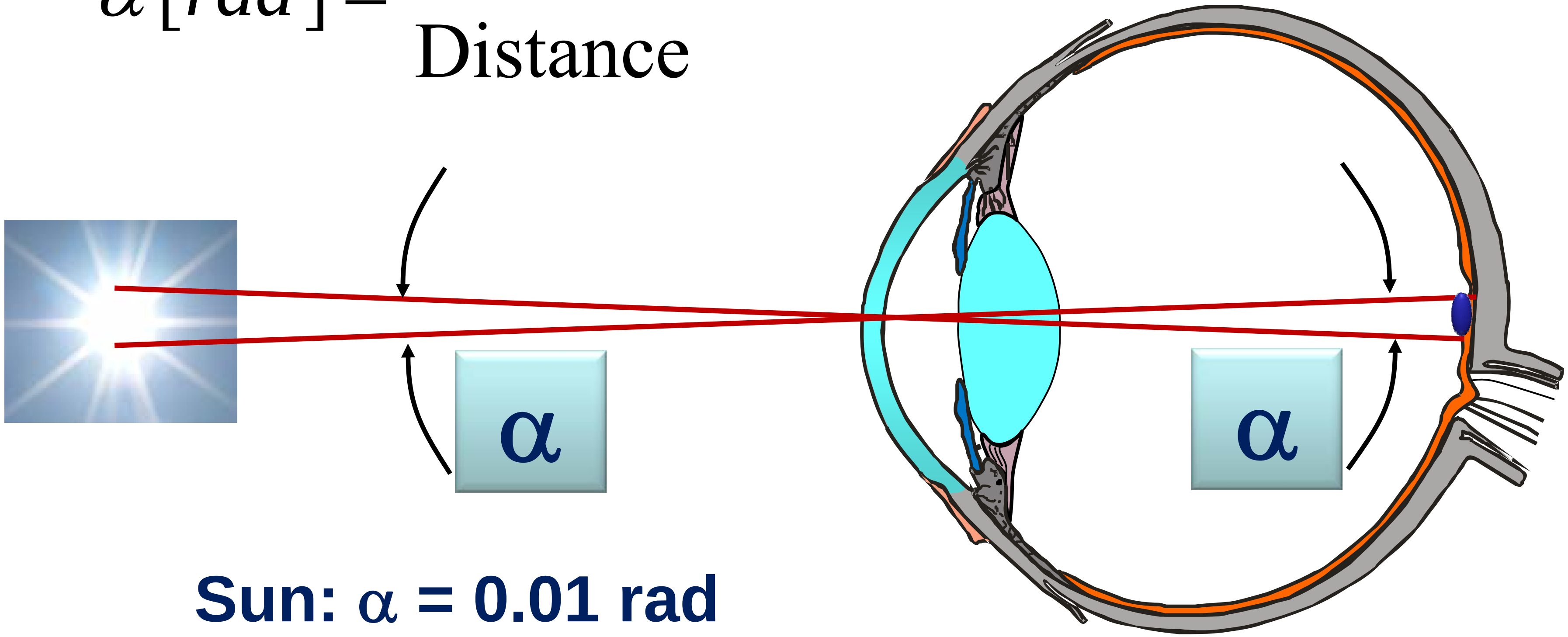
α in rad!

For t < 10 s

- Wavelength dependence
- Base limit value
- Retinal spot size dependence
- Pulse duration dependence

Angular Subtense of Source & Image

$$\alpha[rad] = \frac{\text{Diameter}}{\text{Distance}}$$

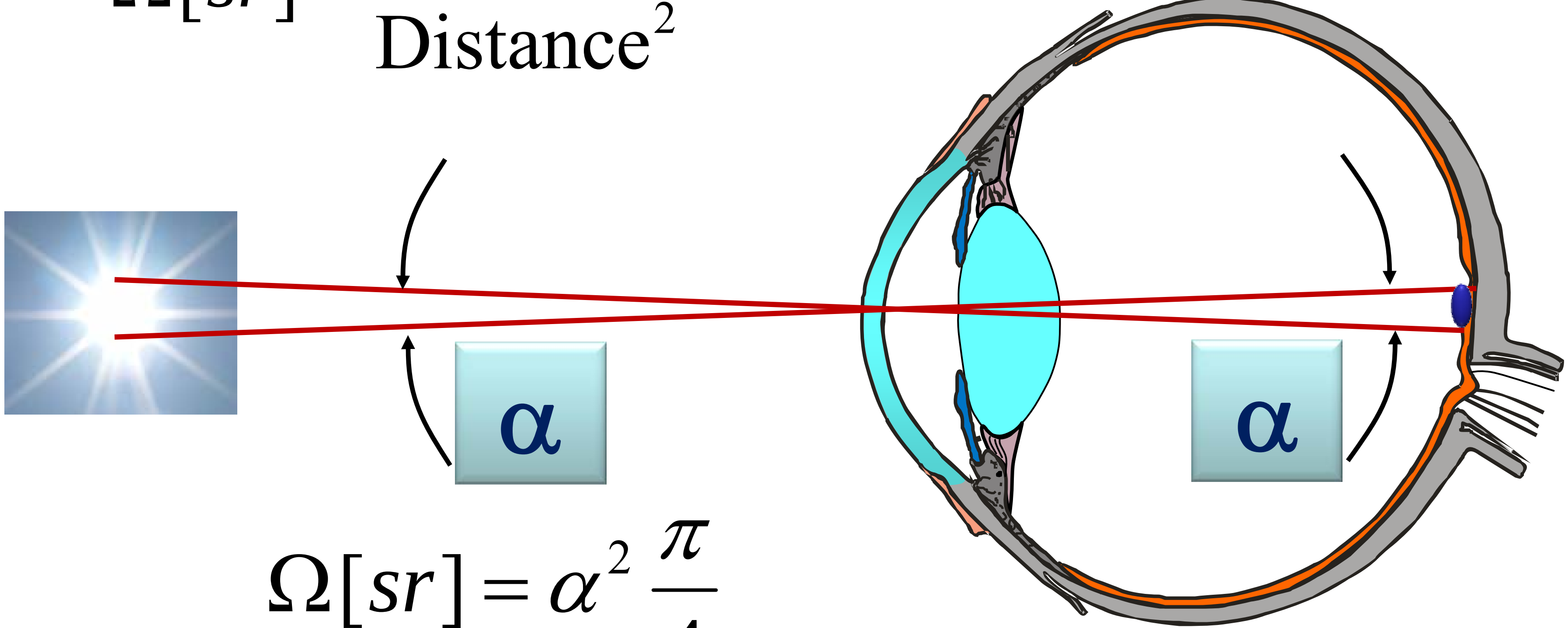


Sun: α = 0.01 rad

Image: 170 µm

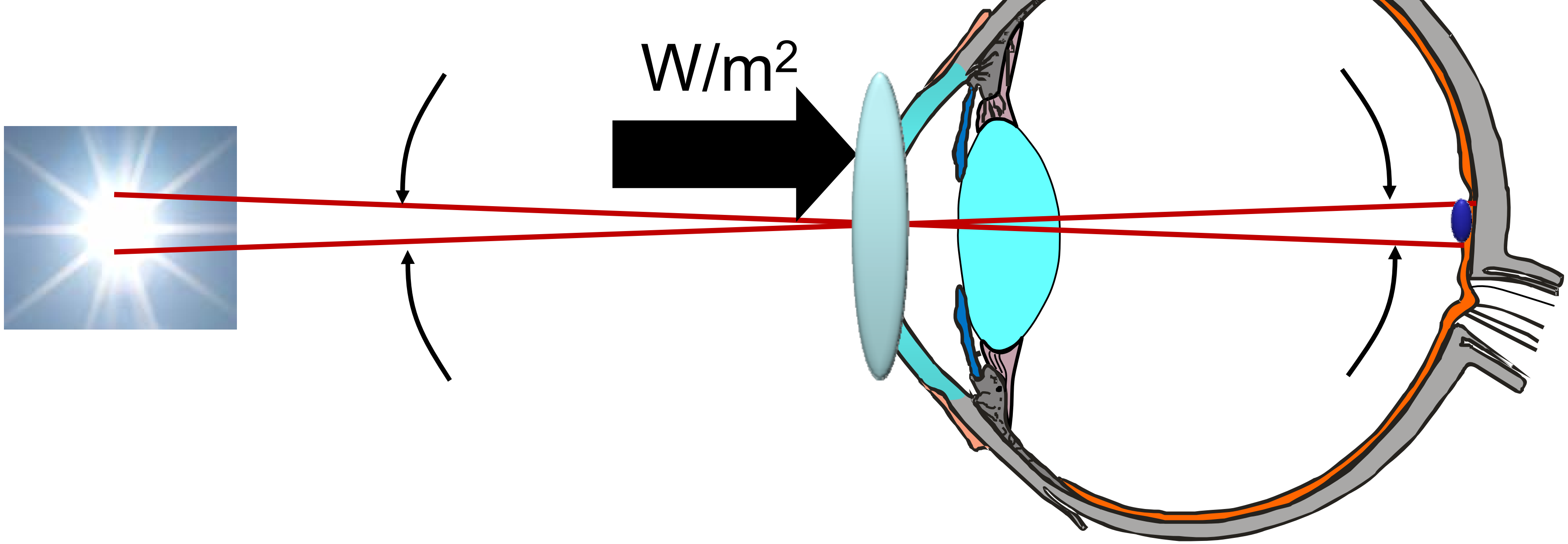
Solid Angle of Source & Image

$$\Omega[sr] = \frac{\text{Area}}{\text{Distance}^2}$$

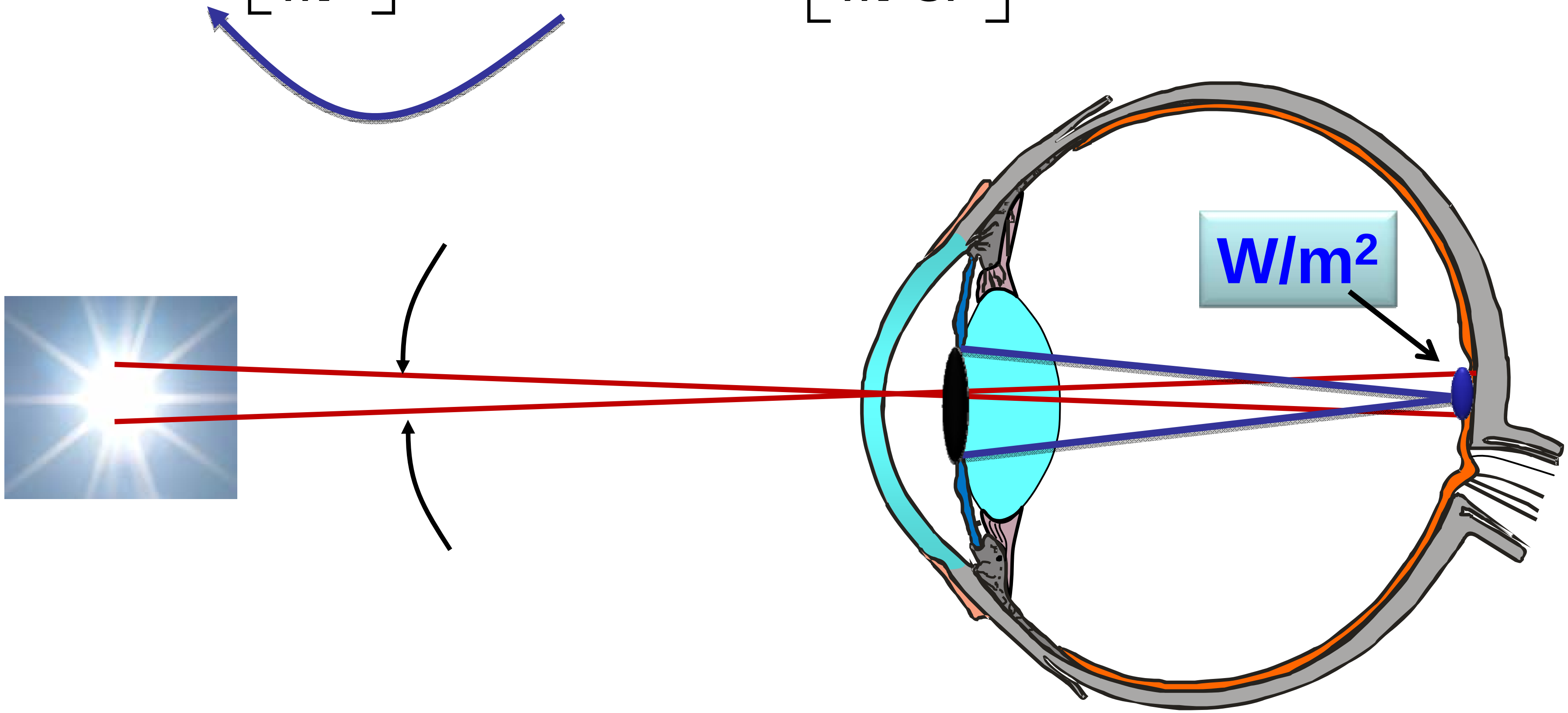


$$\Omega[sr] = \alpha^2 \frac{\pi}{4}$$

$$Radiance\left[\frac{W}{m^2 sr}\right] = \frac{Irradiance\left[\frac{W}{m^2}\right]}{Solid\ Angle[sr]}$$



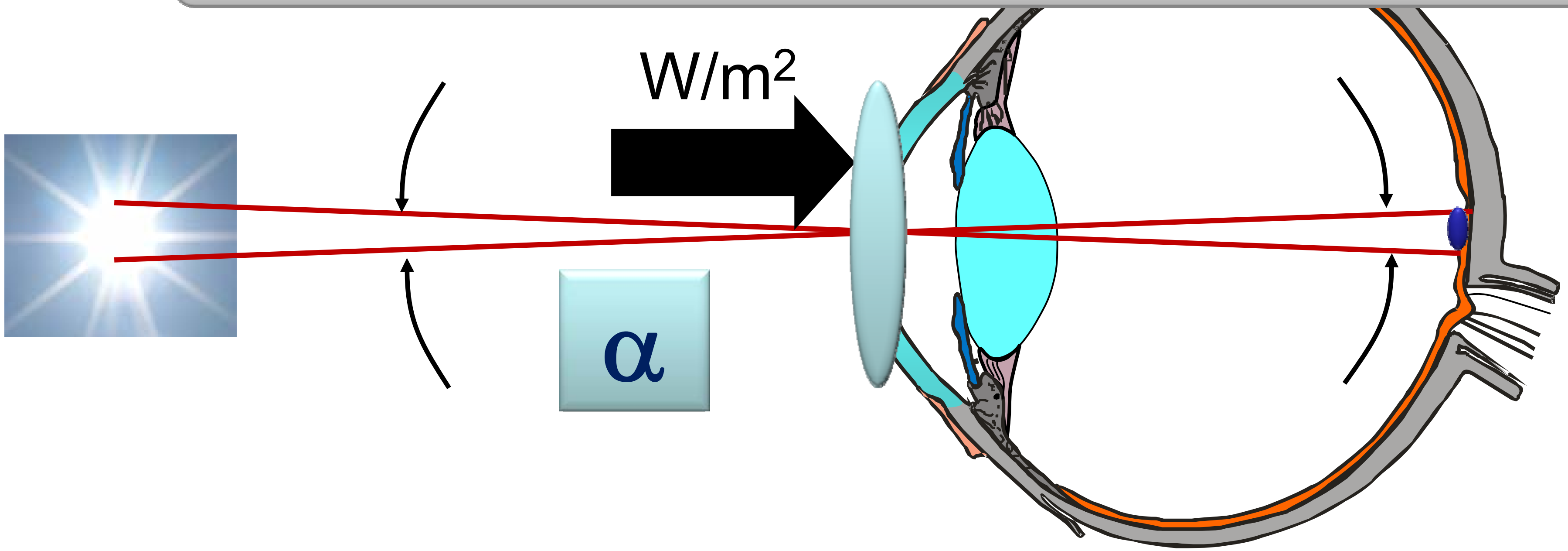
$$\text{Ret.Irrad.}\left[\frac{W}{m^2}\right] = T \cdot \text{Radiance}\left[\frac{W}{m^2 sr}\right] \times \text{Solid Angle Pupil}[sr]$$



Properties of Radiance

- Does not depend on distance

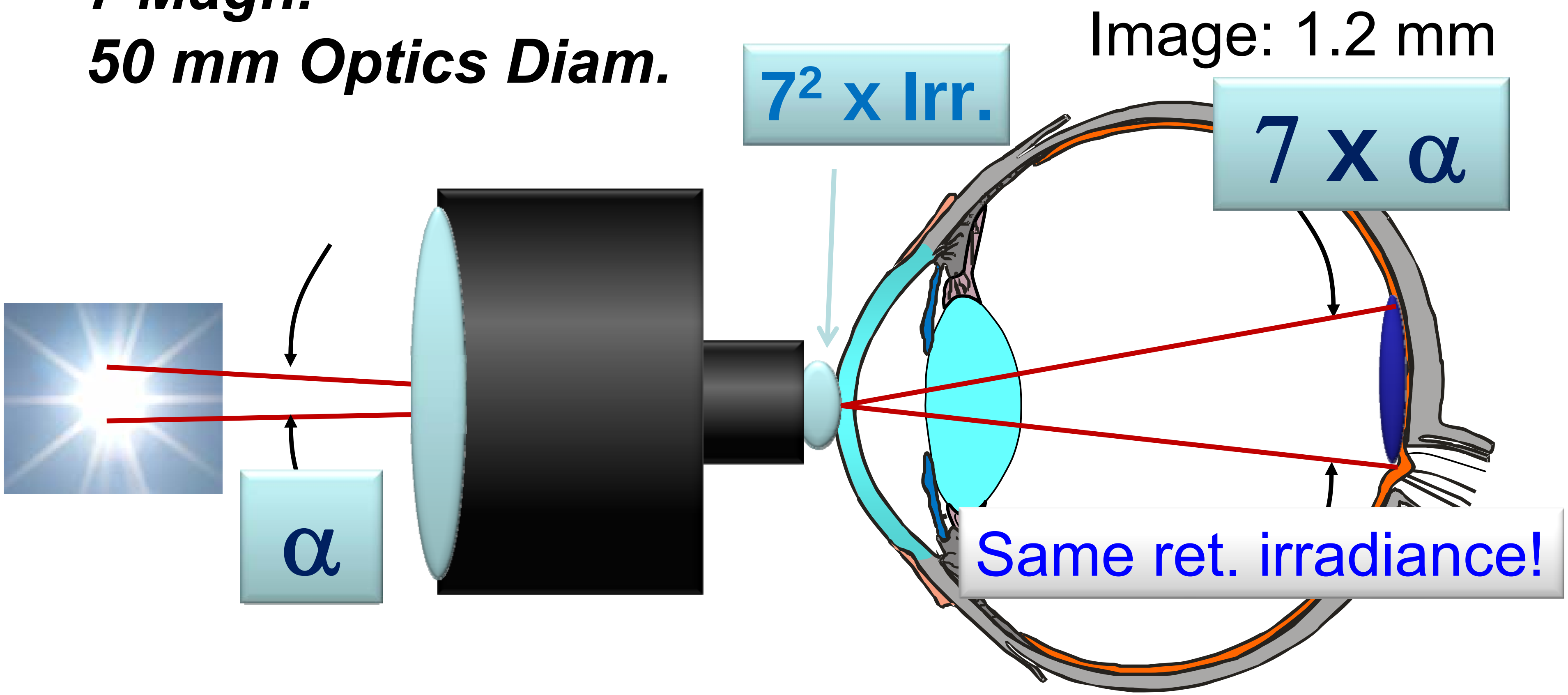
$$Radiance\left[\frac{W}{m^2 sr}\right] = \frac{Irradiance\left[\frac{W}{m^2}\right]}{Solid\ Angle[sr]}$$



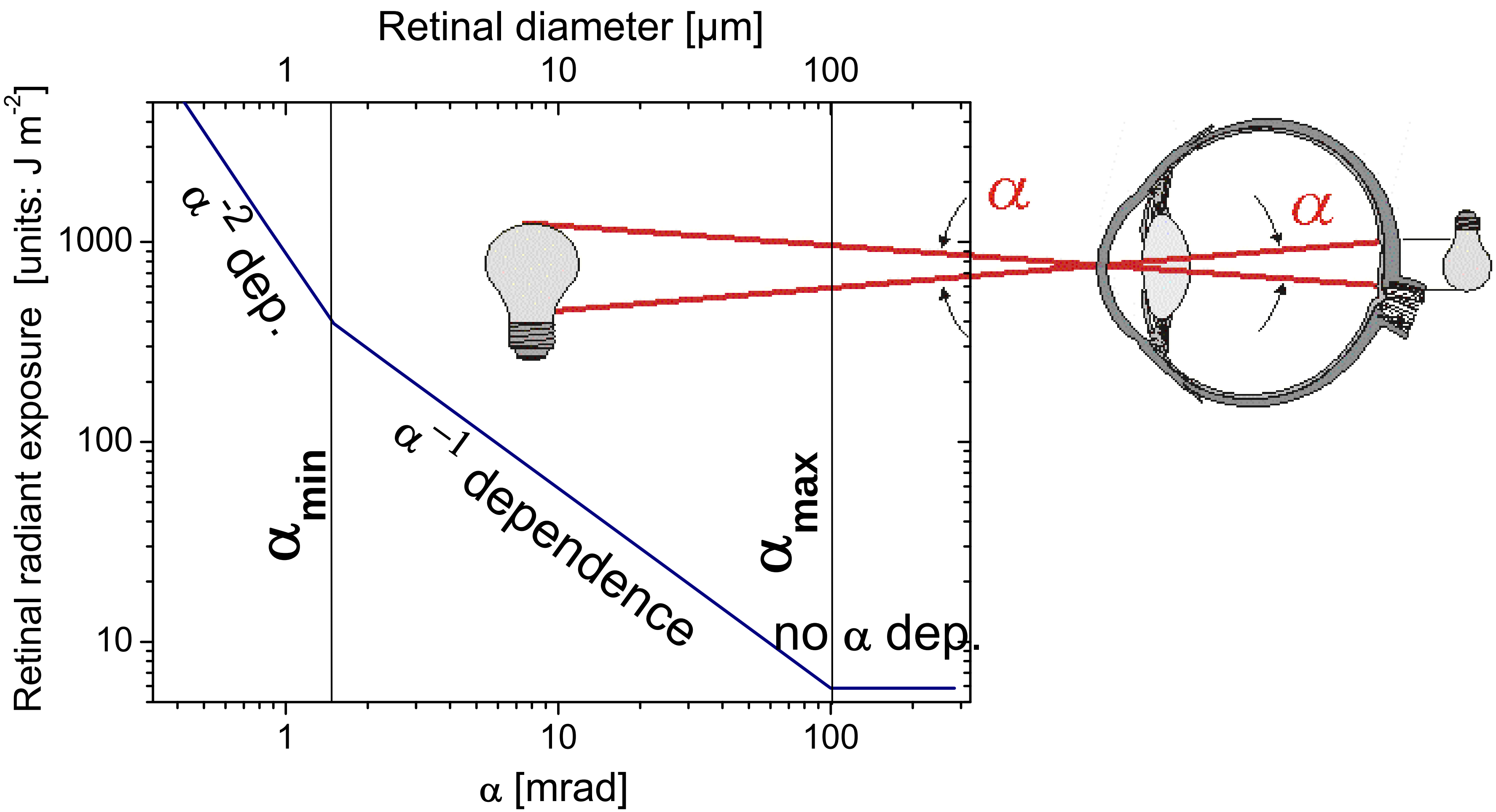
Properties of Radiance

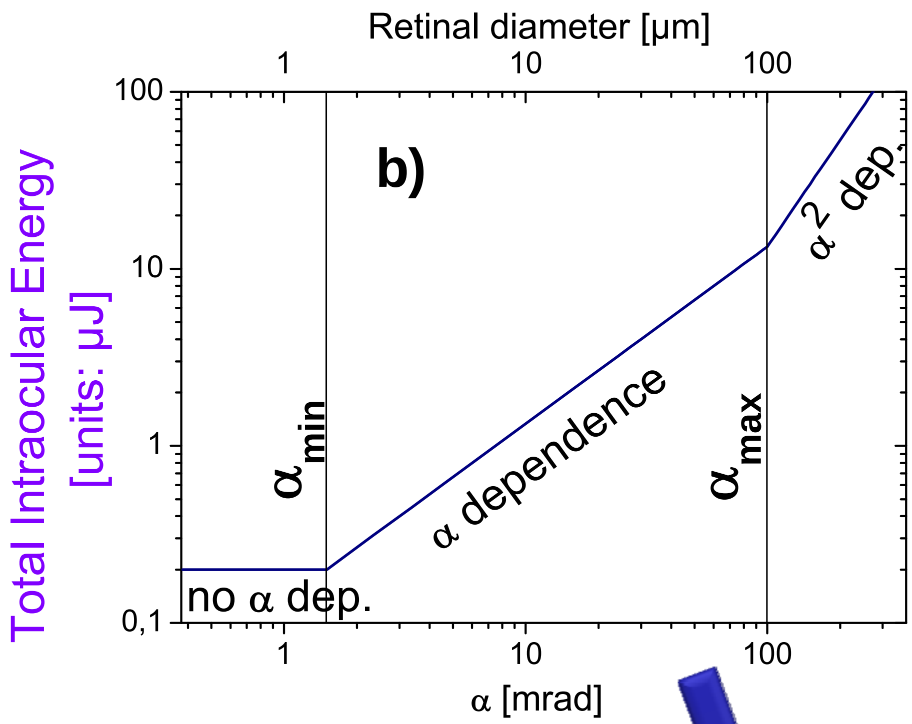
- Is not changed by optical intruments

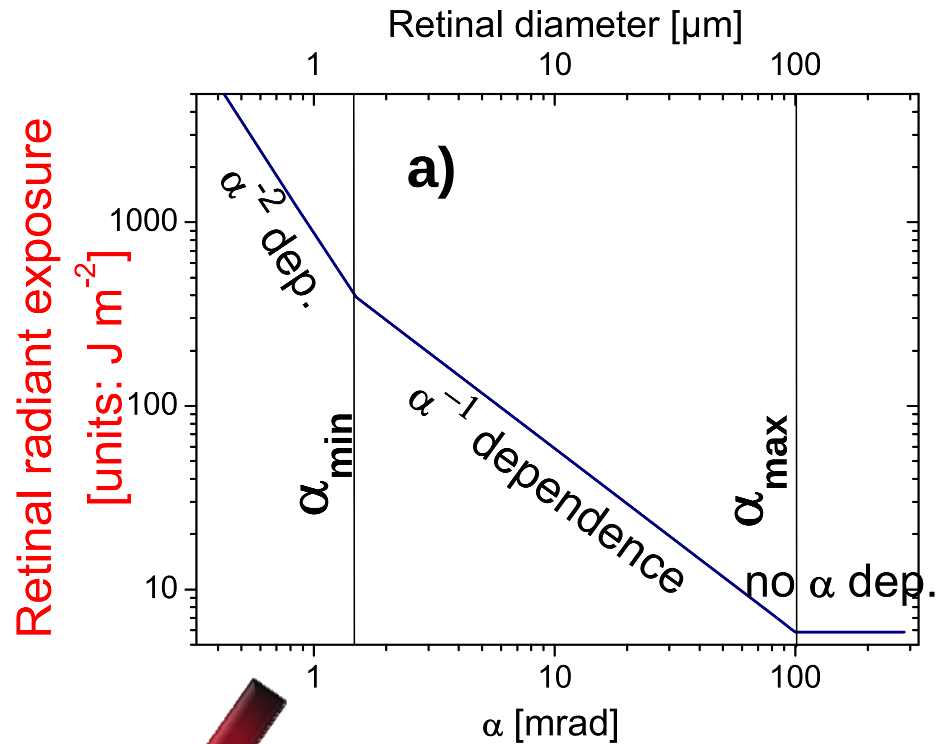
Telescope:
7 Magn.
50 mm Optics Diam.

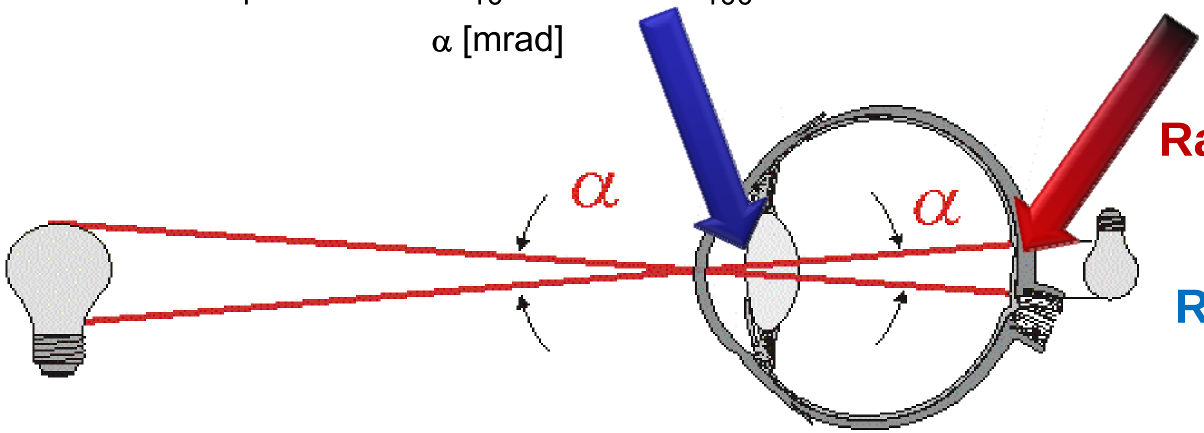


Spot Size Dependence







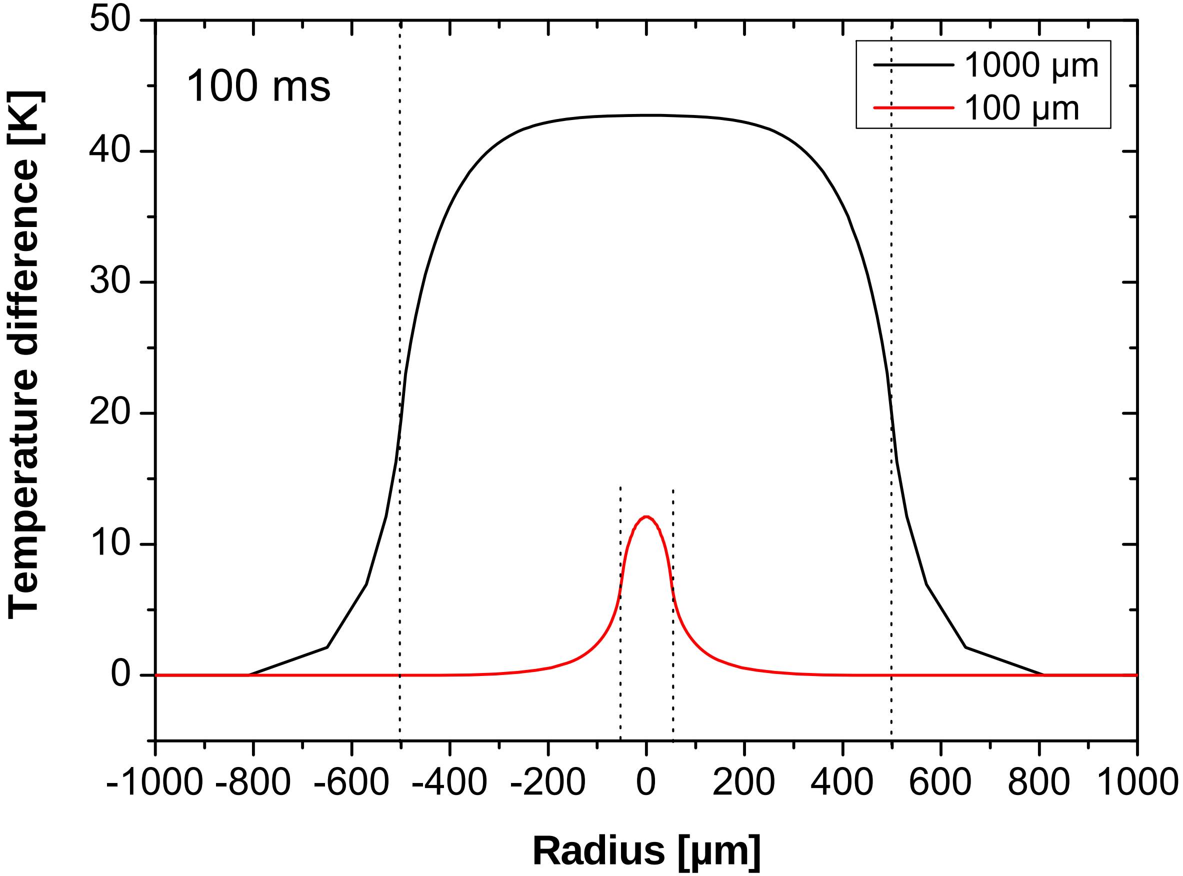


Radiance = Retinal Irradiance / Solid Angle of Pupil

Retinal Irradiance = IOP/Image Area

Larger Spot: Compromised Cooling

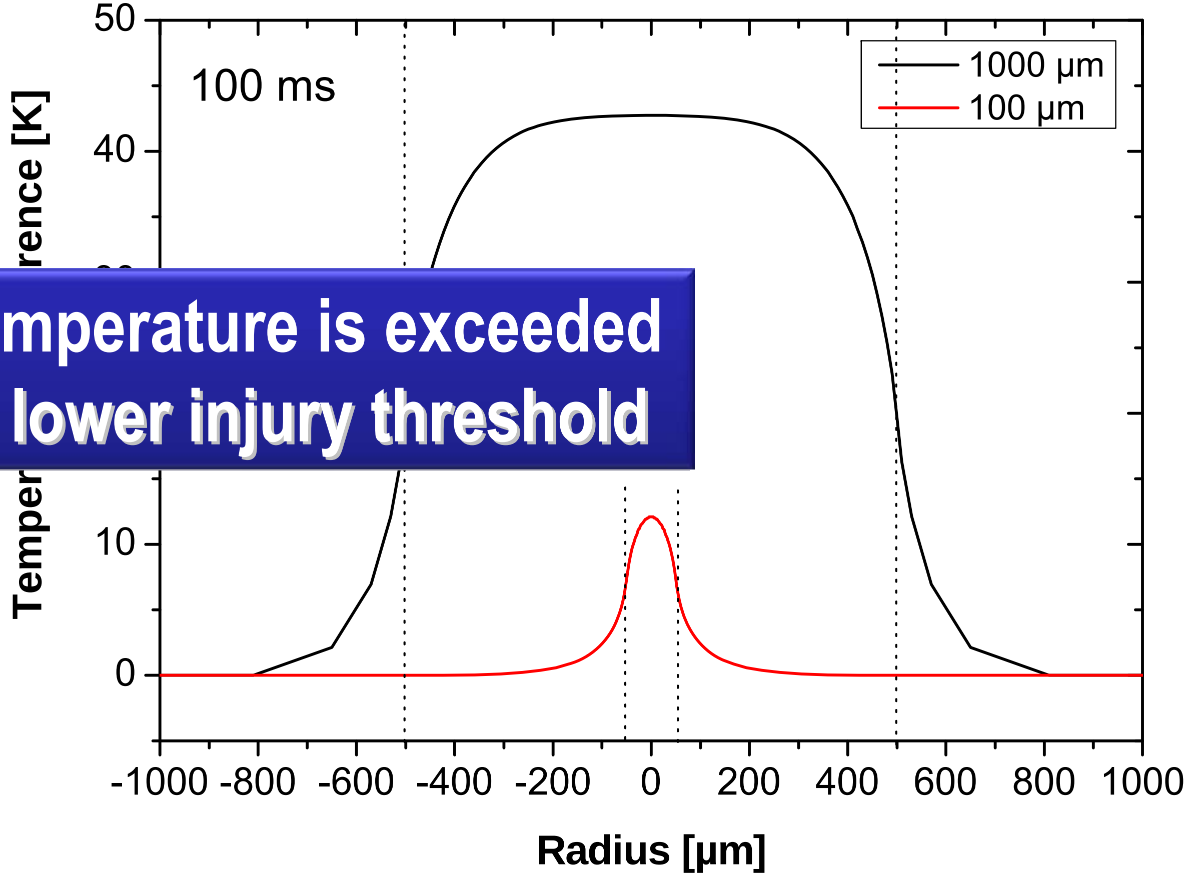
Temperature rise after 100 ms



For same retinal irradiance, larger spot higher temperature

Larger Spot: Compromised Cooling

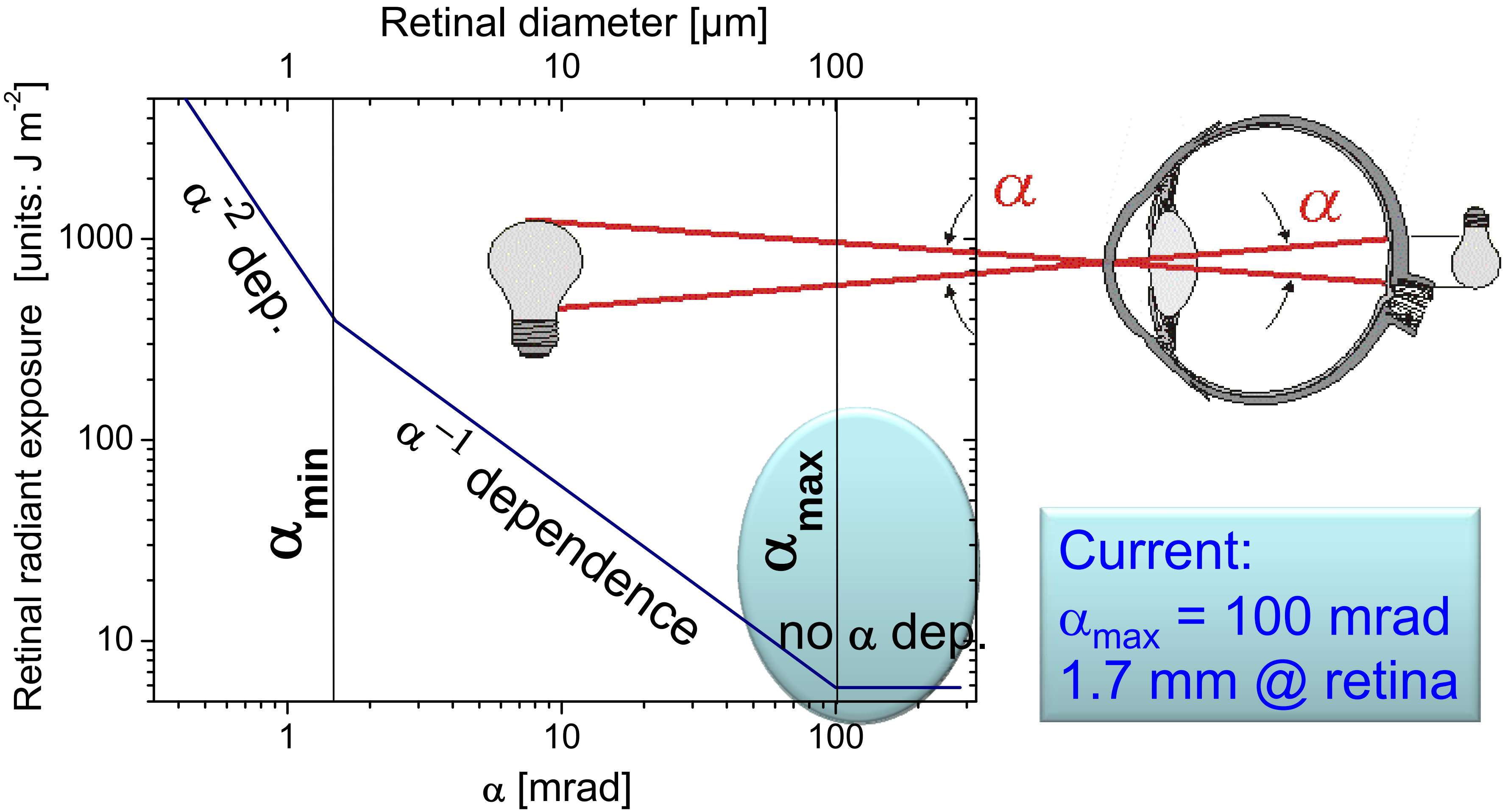
Temperature rise after 100 ms



Injury when critical temperature is exceeded
→ Larger spots have lower injury threshold

For same retinal irradiance, larger spot higher temperature

Spot Size Dependence

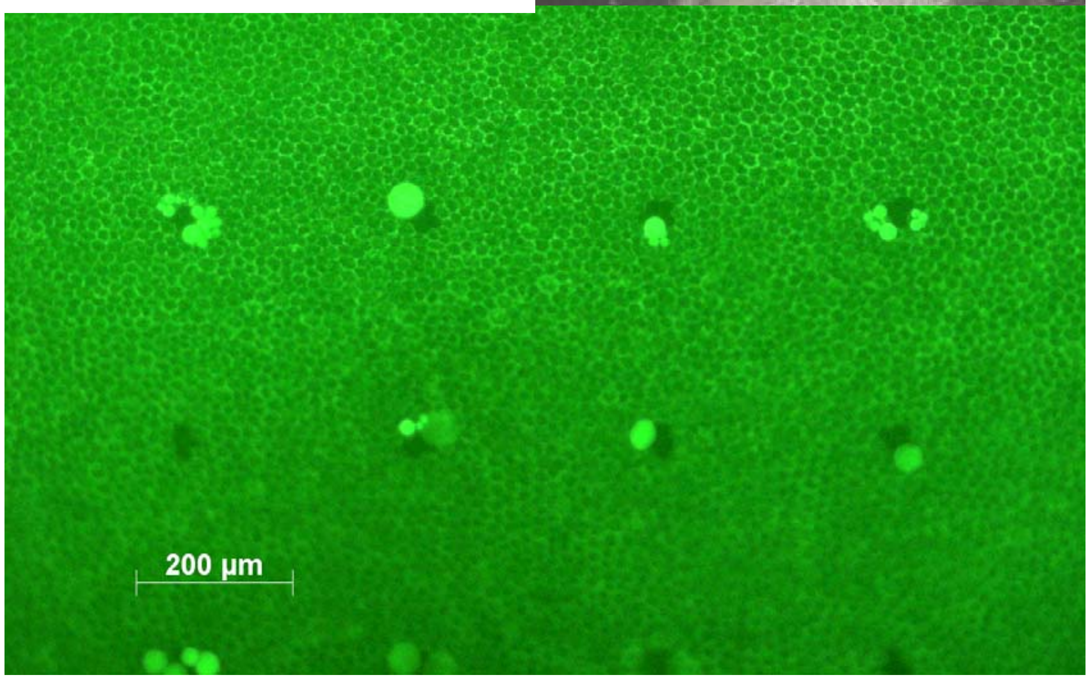


Current:
α_{max} = 100 mrad
1.7 mm @ retina

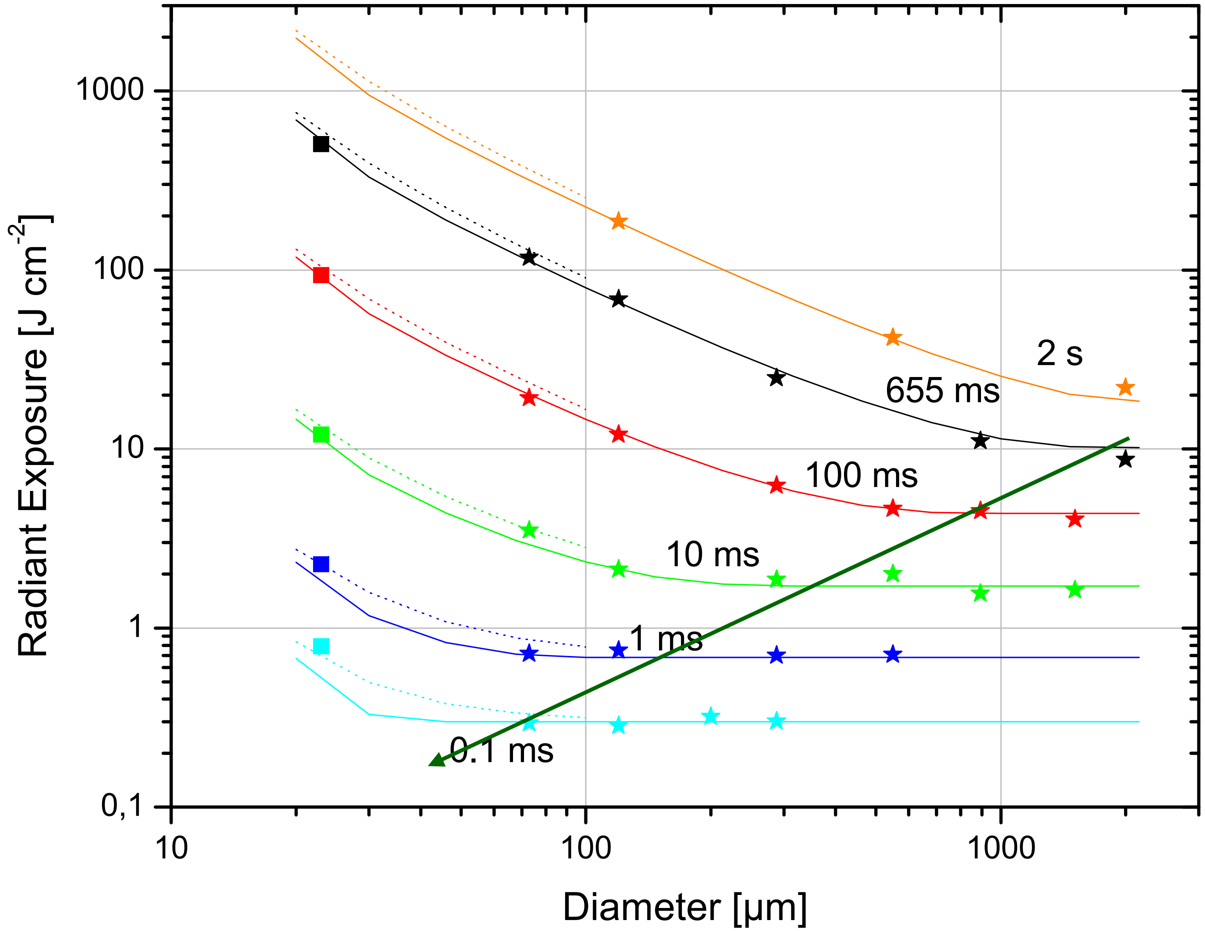
Spot Size Study

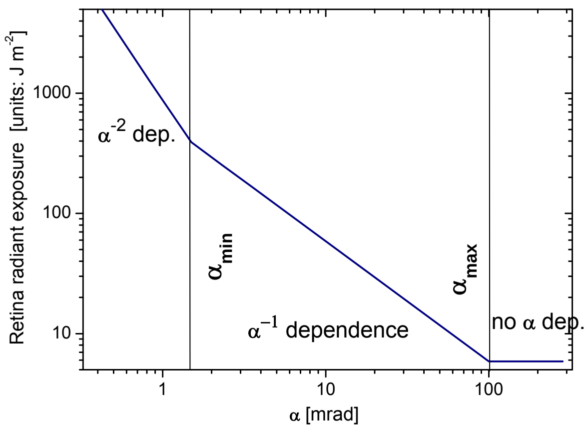
- 532 nm (green), 1090 nm (IR)
- Pulse durations 100 µs to 2 s
- Spot Size: 20 µm to 2 mm

532 nm:
31 thresholds
170 samples
5000 exposures



Spot Size Dependence



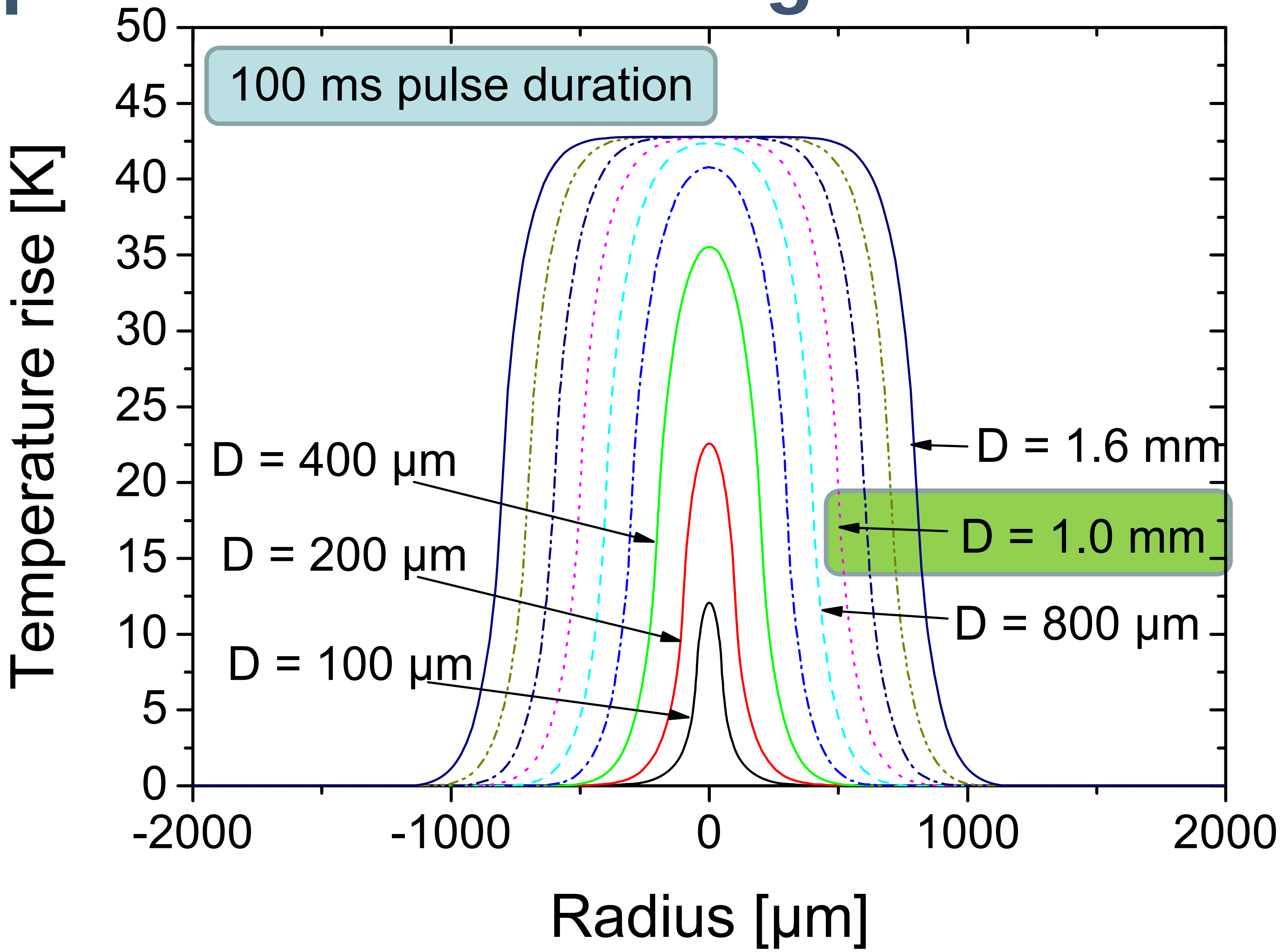


Diffusion length = $2\sqrt{(D_{th}\ t)}$

Ex-vivo and computer model study on retinal thermal laser induced damage in the visible wavelength range

K Schulmeister, et al J. Biomed. Optics 13, 054038 (2008)

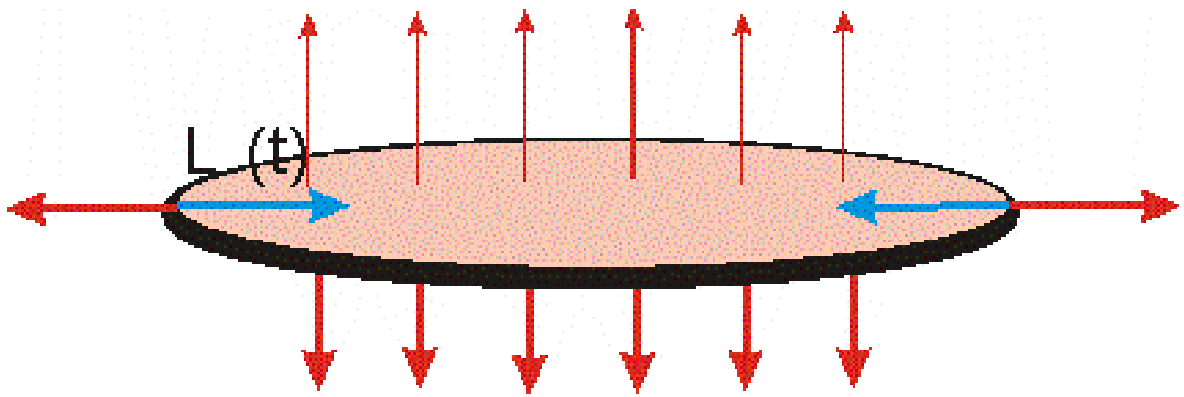
Impact of radial cooling



$\alpha > \alpha_{max}$

- Retinal spot so large, that (during pulse), <u>center is not affected by „cooling wave“</u>

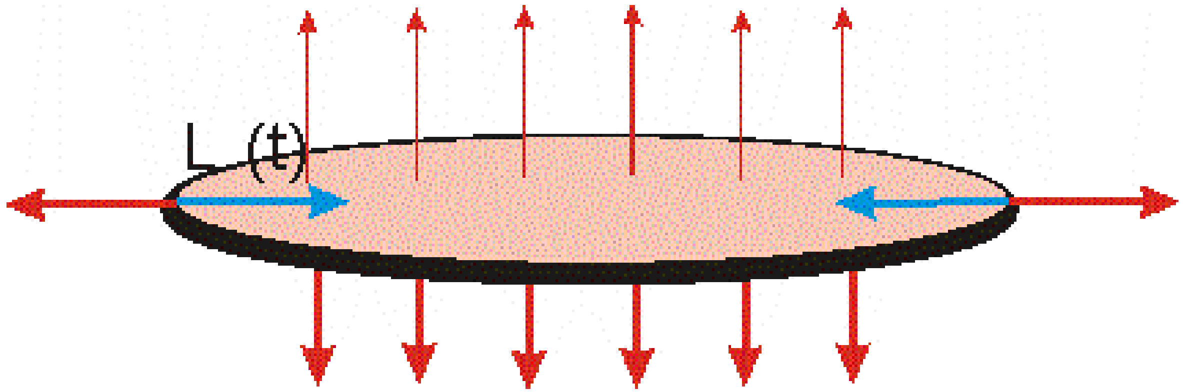
- Thermal diffusion length = 2 √(D_{th} t)



α_{max} depends on t

- The **longer pulse duration τ**
- the more time the cooling wave has to reach the center,
- the **larger image has to be** so that center is *not* cooled within τ

- Diffusion length = $2\sqrt{(D_{th}\ \tau)}$



Time dependent α_{max}

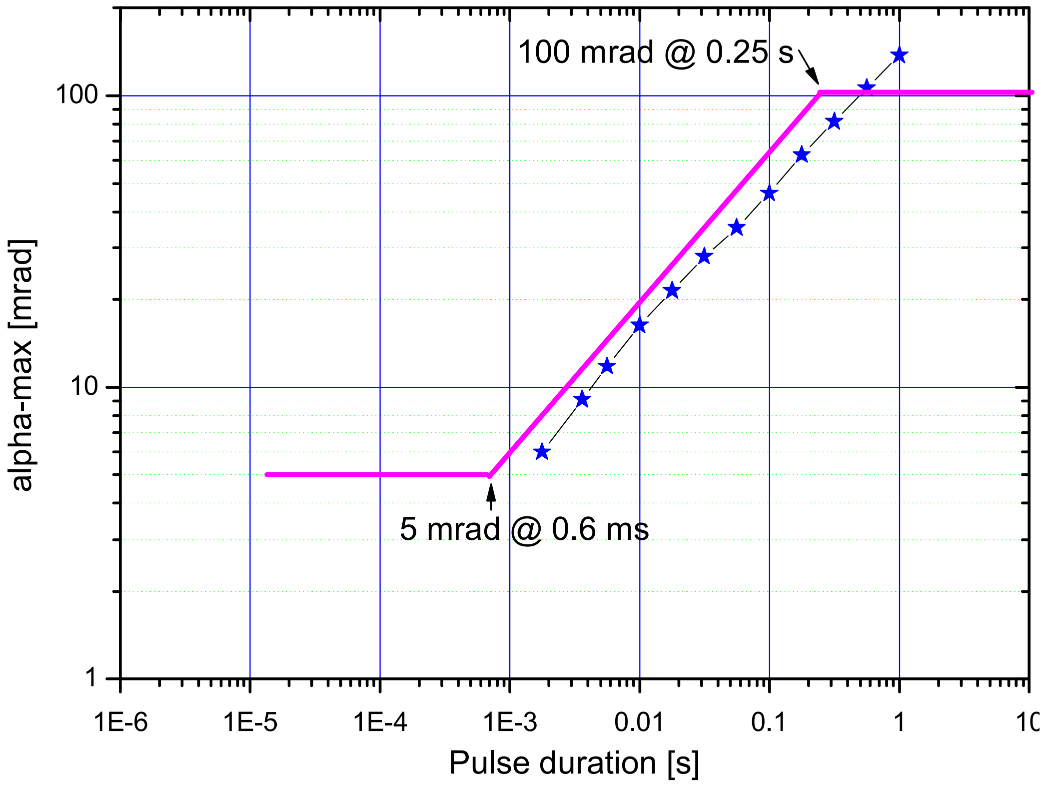
$\alpha_{max} = 200\ t^{0.5}$

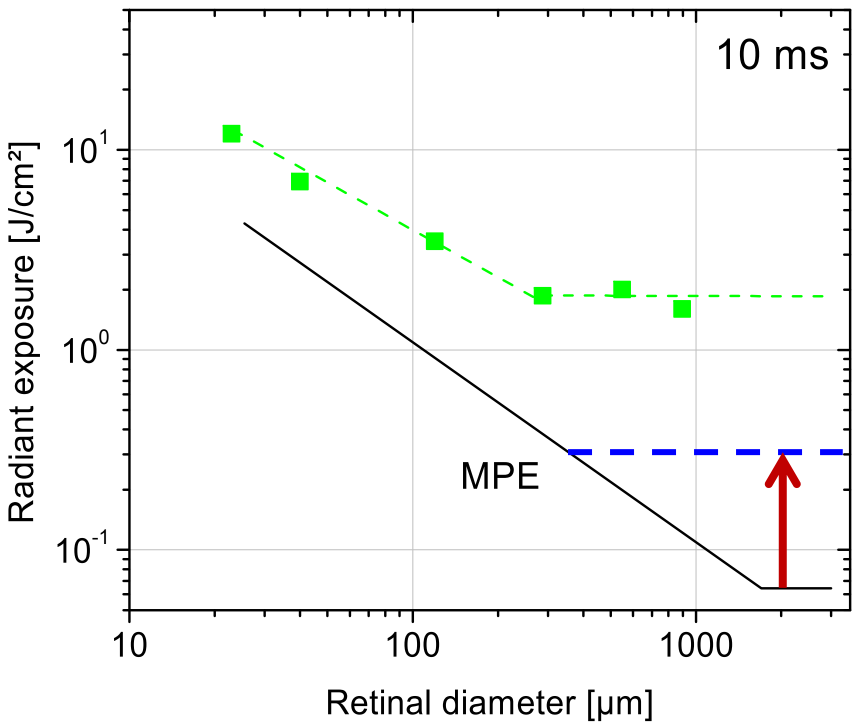
(for 625 µs < t < 0.25 s)

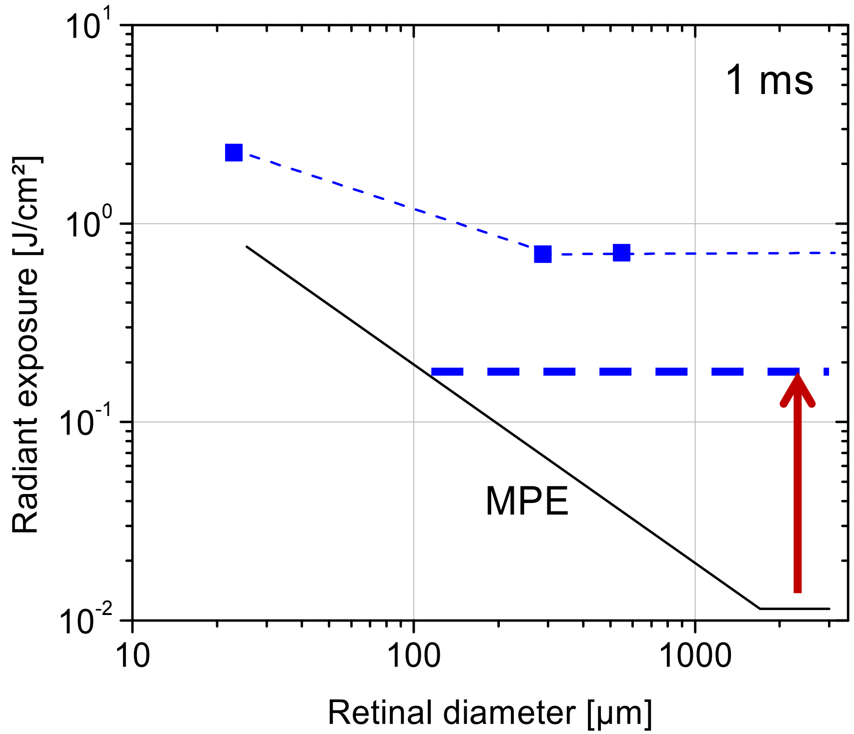
α_{max} = 5 mrad for t < 625 µs

α_{max} = 100 mrad for t > 0.25 s

(currently = 100 mrad for all t)





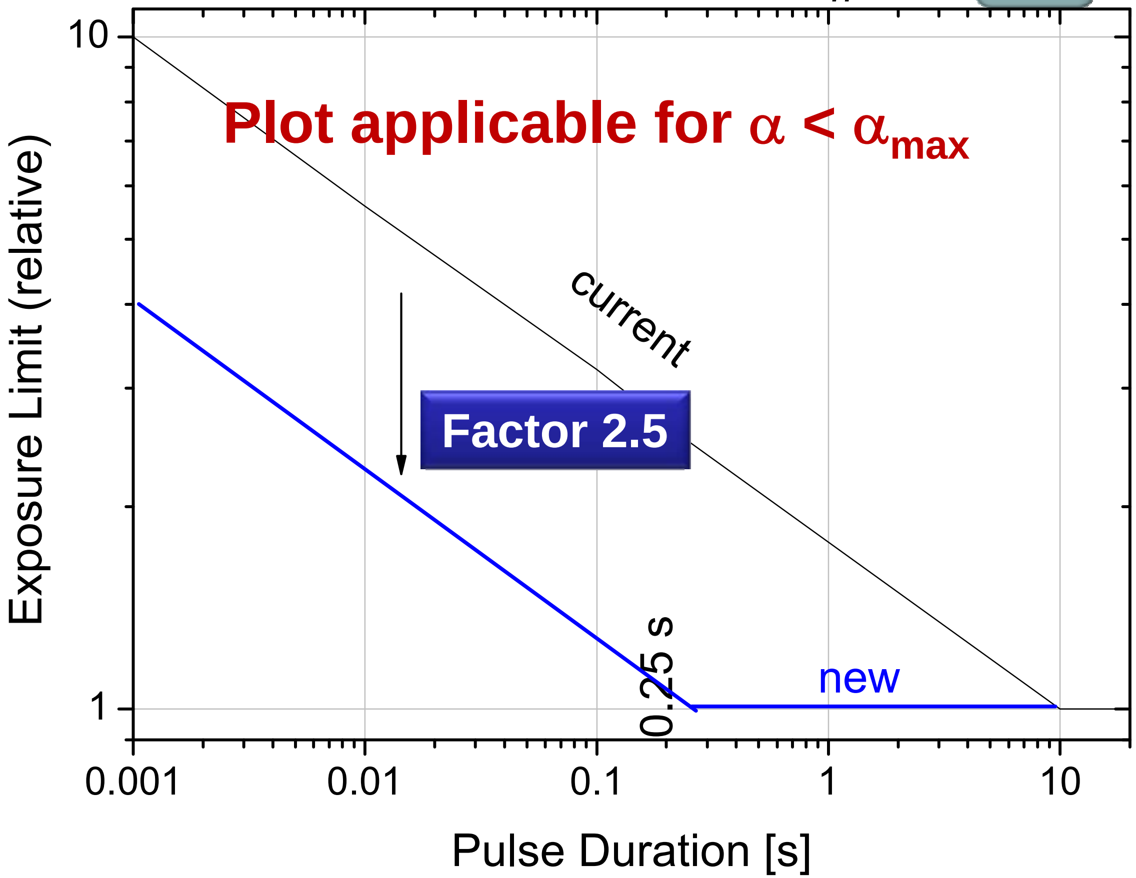


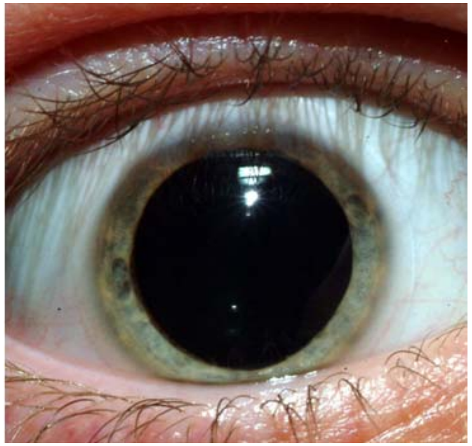
Maximum increase from change of α_{max}: factor 20

Time Dependence

Raise of limit due to time dependent α_{max}
→ lower base limit

$$L_{eff} \leq 20 \cdot \alpha^{-1} \cdot t^{-0.25} \; kW \cdot m^{-2} \cdot sr^{-1}$$





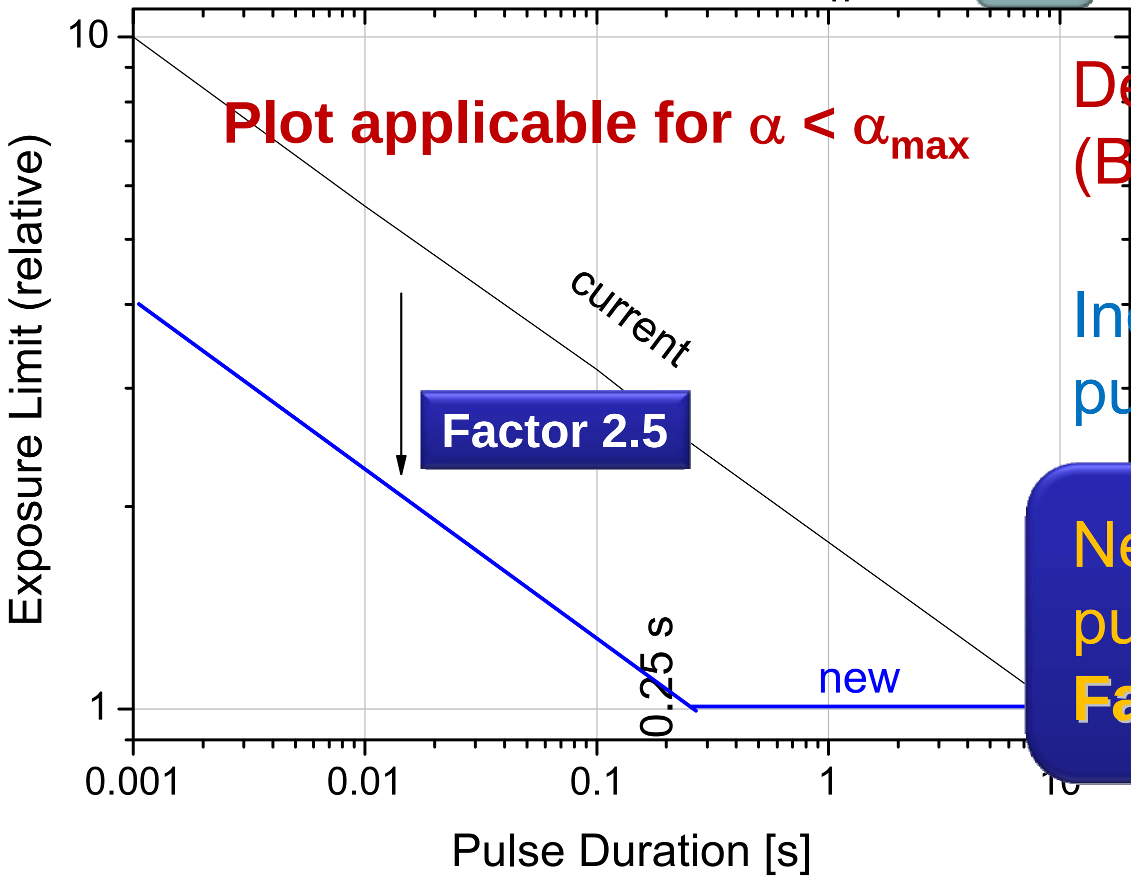
7 mm Pupil

***BUT*: keep it constant for t > 0.25 s (pupil constriction)**

Time Dependence

Raise of limit due to time dependent α_{max}
→ lower base limit

$$L_{eff} \leq 20 \cdot \alpha^{-1} \cdot t^{-0.25} \; kW \cdot m^{-2} \cdot sr^{-1}$$



Decrease 2.5
(Basic Limit)

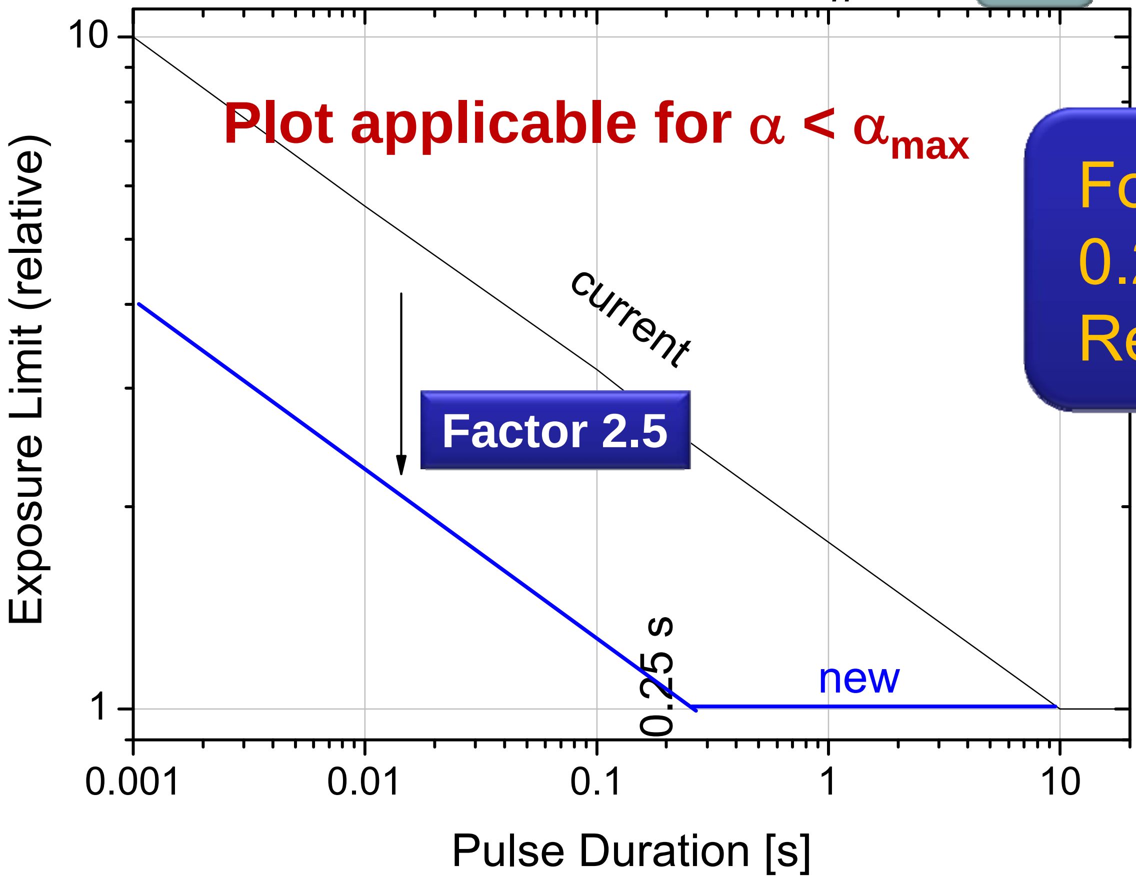
Increase x 20 for > 100 mrad pulsed sources

Net-Increase for large pulsed sources:
Factor 8

Time Dependence

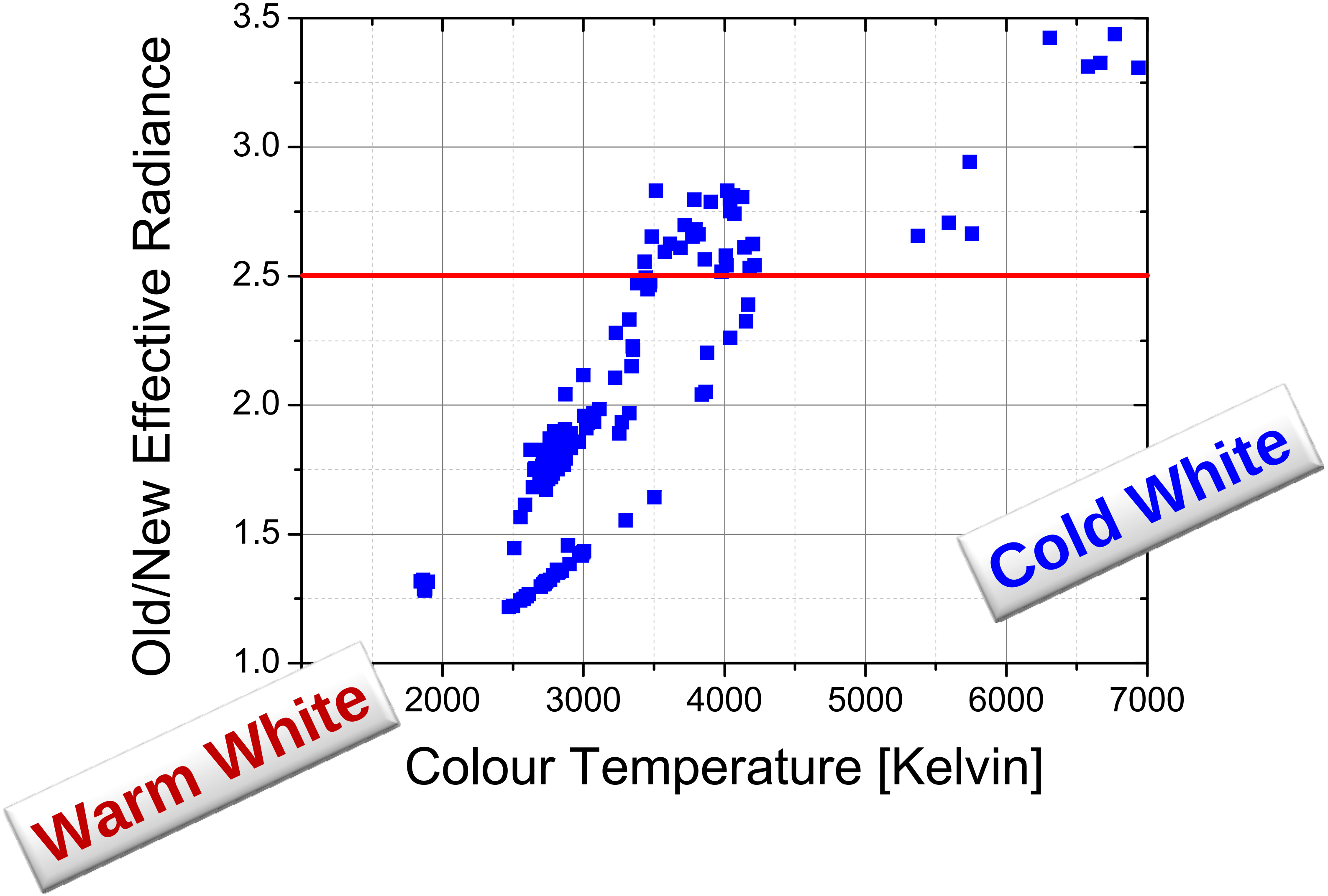
Raise of limit due to time dependent α_{max}
→ lower base limit

$$L_{eff} \leq 20 \cdot \alpha^{-1} \cdot t^{-0.25}\ kW \cdot m^{-2} \cdot sr^{-1}$$



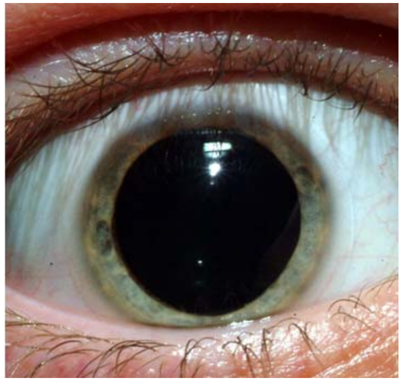
For continous sources,
0.25 s exposure duration:
Reduction factor 2.5

Wavelength Evaluation Less Restrictive

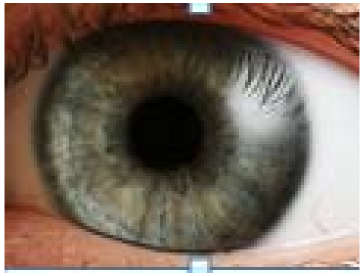


Sun

- Effective Radiance: 7 MW m^{-2} sr^{-1}



- EL for 0.25 s: 3 MW m^{-2} sr^{-1}
  (7 mm Pupil)



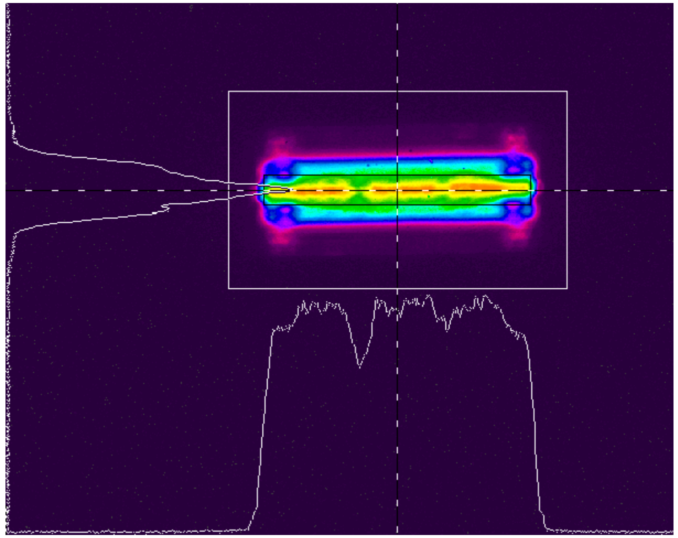
- „Safe“ Pupil: 4.5 mm

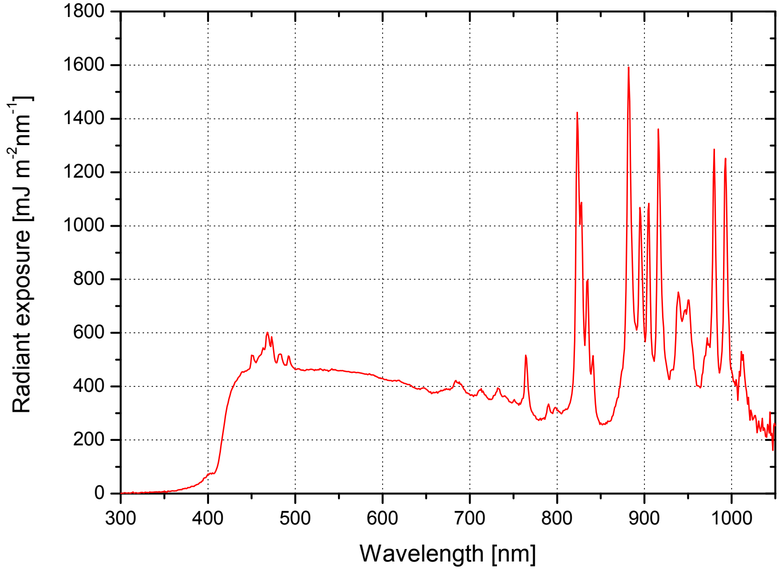
Relevance

- Flashlights, pulsed LEDs

Photoflash

- regular photoflash for semi-professional cameras





Pulse duration 2 ms

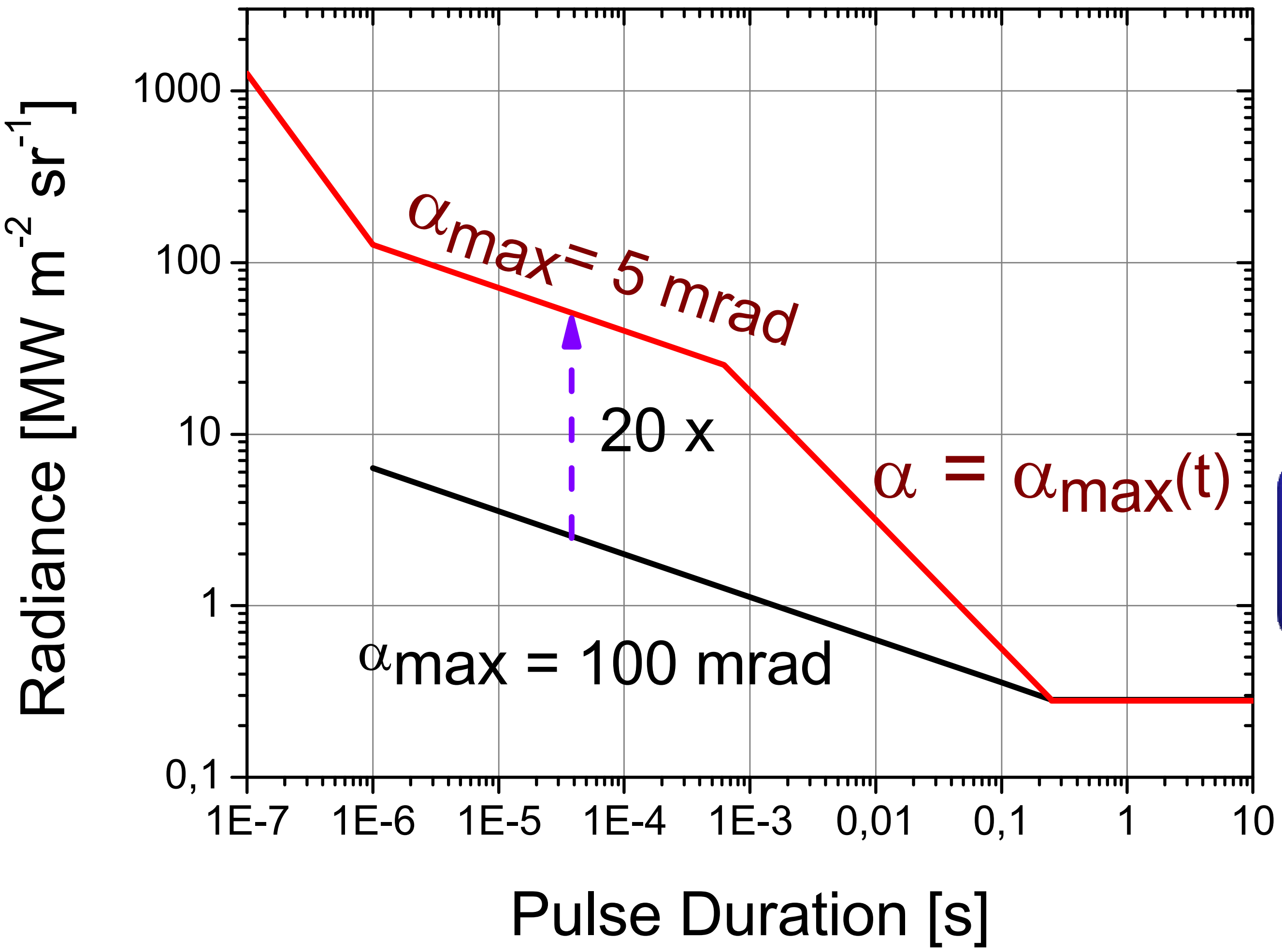
$t < 1\ \mu s$: $D_{eff} \leq 0.6\ \alpha^{-1}\ J\ m^{-2}\ sr^{-1}$

D… Time integrated radiance (L·t)

$1\ \mu s < t < 0.25\ s$: $L_{eff} \leq 20 \cdot \alpha^{-1} \cdot t^{-0.25}\ kW \cdot m^{-2} \cdot sr^{-1}$

$t > 0.25\ s$: $L_{eff} \leq 28\ \alpha^{-1}\ kW\ m^{-2}\ sr^{-1}$

Averaging FOV γ_{th}: cw: 11 mrad; Pulsed (t < 0.25 s): 5 mrad



Decrease 2.5
(Basic Limit)

Increase 20
(α_{max})

Net-Increase:
Factor 8

Multiple Pulses

$\alpha \leq 5$ mrad: $C_5 = 1$

$\alpha > 5$ mrad: $C_5 = N^{-0,25}$
with following max N numbers (max reductions):

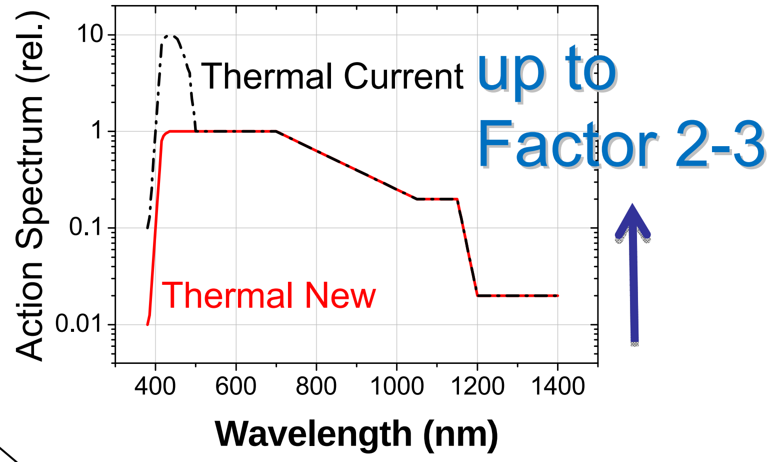
$\alpha \leq \alpha_{max}$: max-C_5 = 0.4 (max-N = 40)

$\alpha > \alpha_{max}$: max-C_5 = 0.2 (max-N = 625)

$\alpha > 100$ mrad: $C_5 = 1$

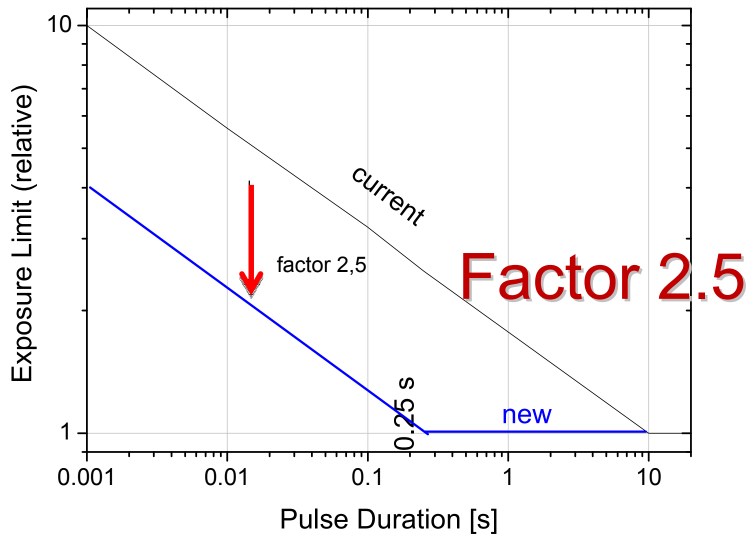
Summary

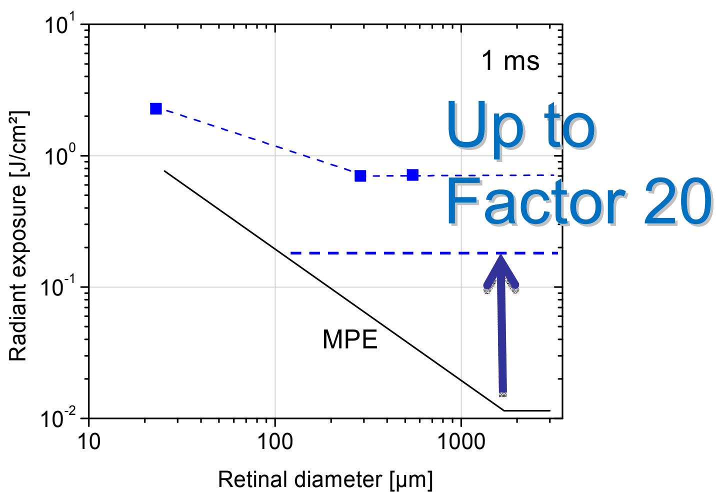
– Wavelength dependence



– Retinal spot size dependence

– Pulse duration dependence





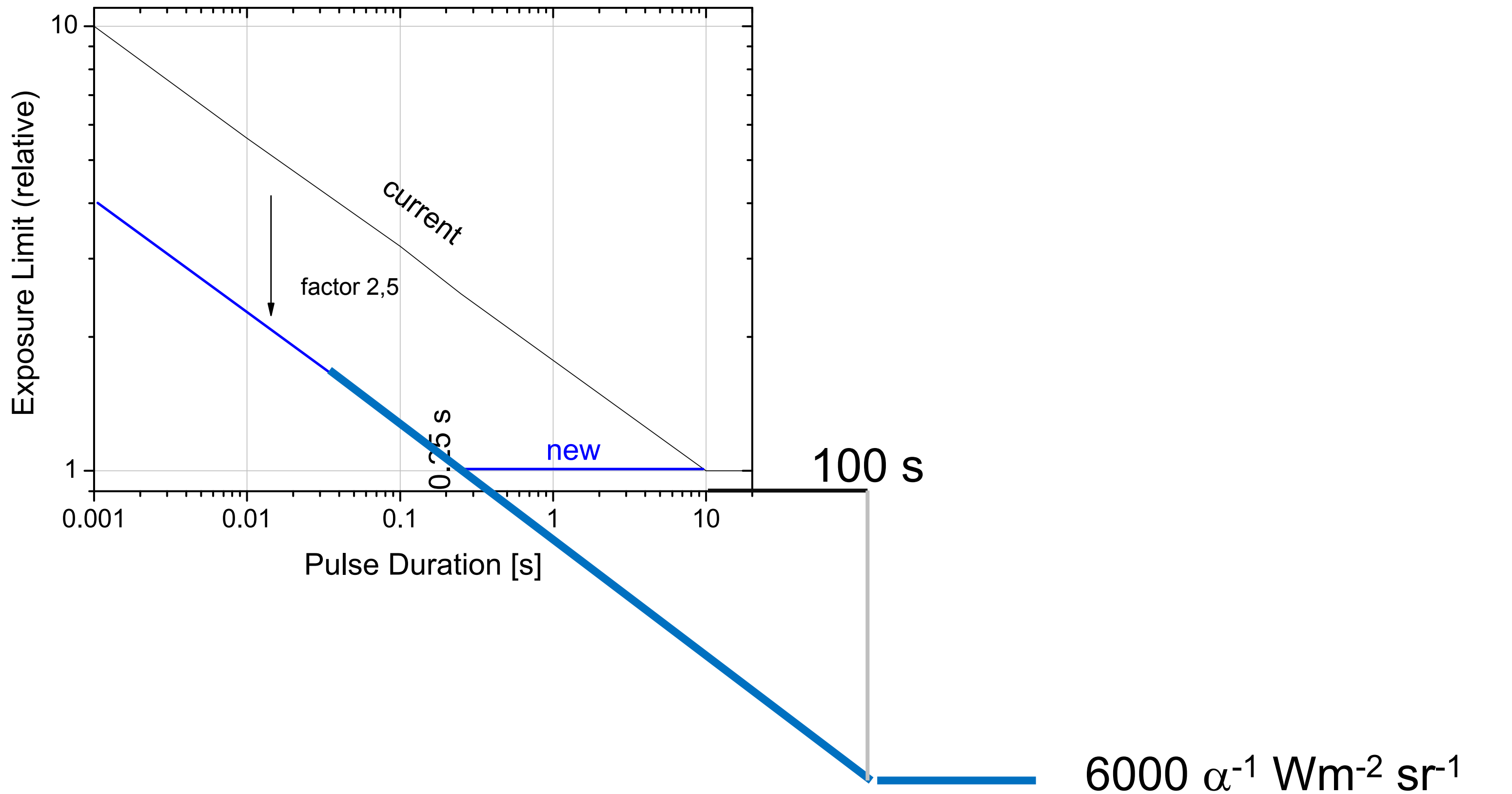
Low Visual Stimulus

Luminance < 10 cd m^{-2}

$$\sum_{780}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \leq 20\ \alpha^{-1}\ t^{-0.25}\ kW\ m^{-2}\ sr^{-1}\ (0.25\,s < t < 100\text{ s})$$

$$\sum_{780}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \leq 6000\ \alpha^{-1}\ W\ m^{-2}\ sr^{-1}\ (\,for\ t > 100\text{ s})$$

Low Visual Stimulus

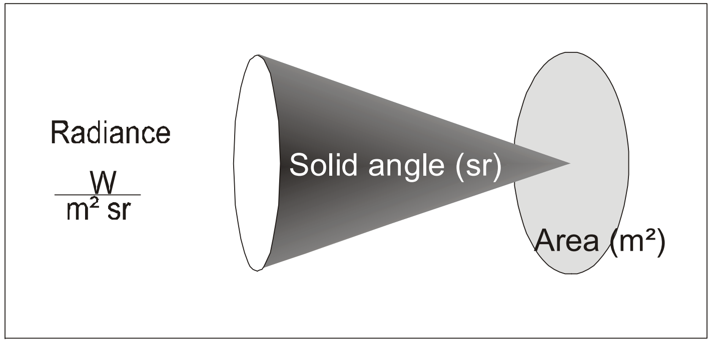


Photochemical Retinal

$$D_B \leq 10^6 \frac{J}{m^2\, sr}$$

10 s < t < 10 000 s

(Basic Limit)



	Averaging Field of View γ_{ph}		**„Small source limit“**
< 100 s	γ_{ph} = 11 mrad	$\Gamma = 10^{-4}$ sr →	100 J/m²
100 s – 10 000s	$\gamma_{ph} = 1.1\sqrt{t}$ mrad	$\Gamma = 10^{-6} \cdot t$ sr →	1 W/m²
t > 10 000 s	γ_{ph} = 110 mrad	$\Gamma = 10^{-2}$ sr →	1 W/m²

IR-Limit Cornea/Lens

$$E_{IR} = \sum_{780}^{1000} 0.5\, E_\lambda + \sum_{1000}^{3000} E_\lambda$$

„Action Spectrum“

$$E_{IR} \le 18 \cdot t^{-0.75}\ kW\ m^{-2}\ \ (for\ t < 1\,000\, s)$$

$t \geq 1000$ s: 100 W m^{-2} (10 mW cm^{-2})

High Irradiance Pulses:

courtesy of Tsutomu Okuno

Long Term Chronic: (Glass blowers cataract)

Thank You