Optical Radiation - Eye Protection

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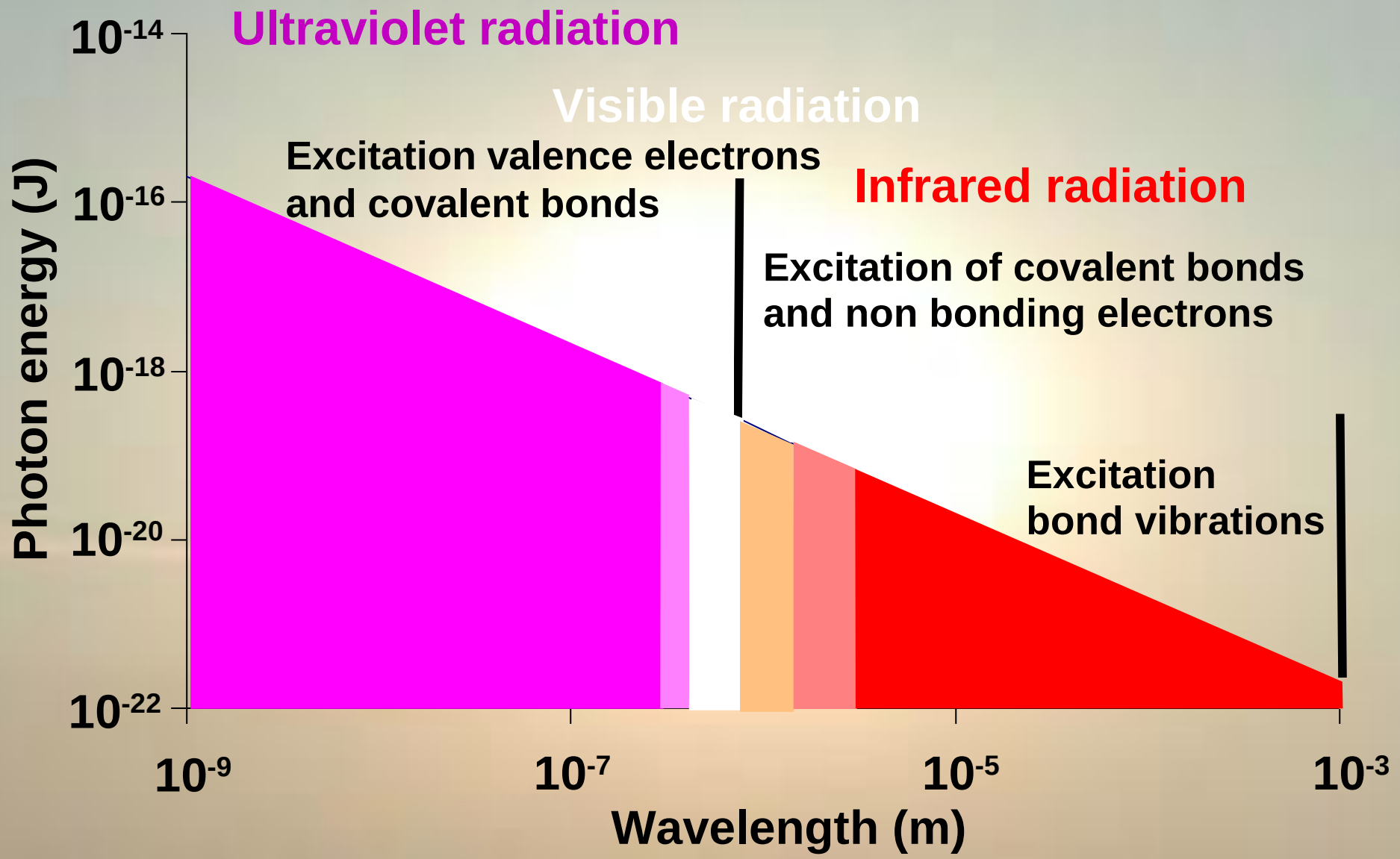
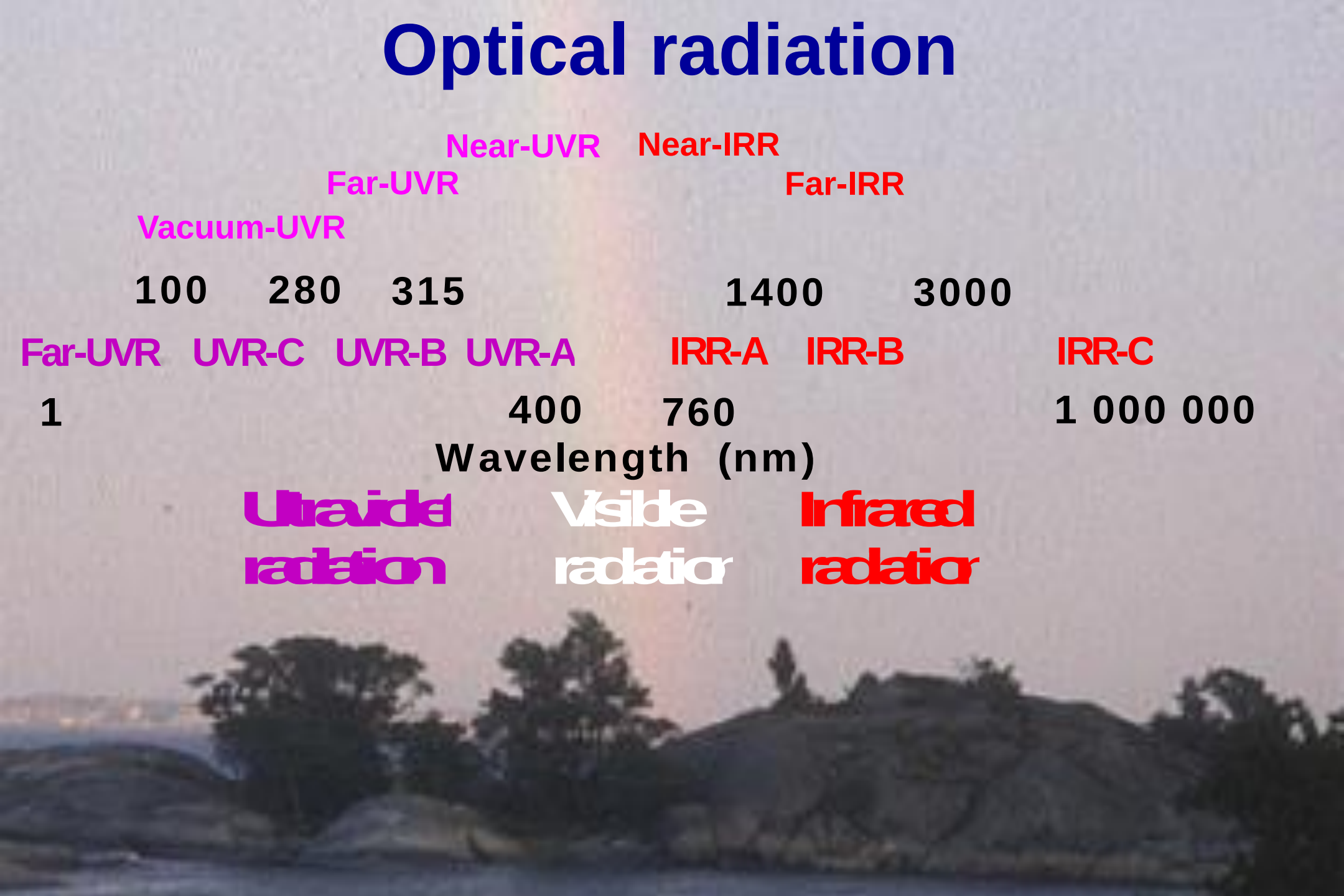
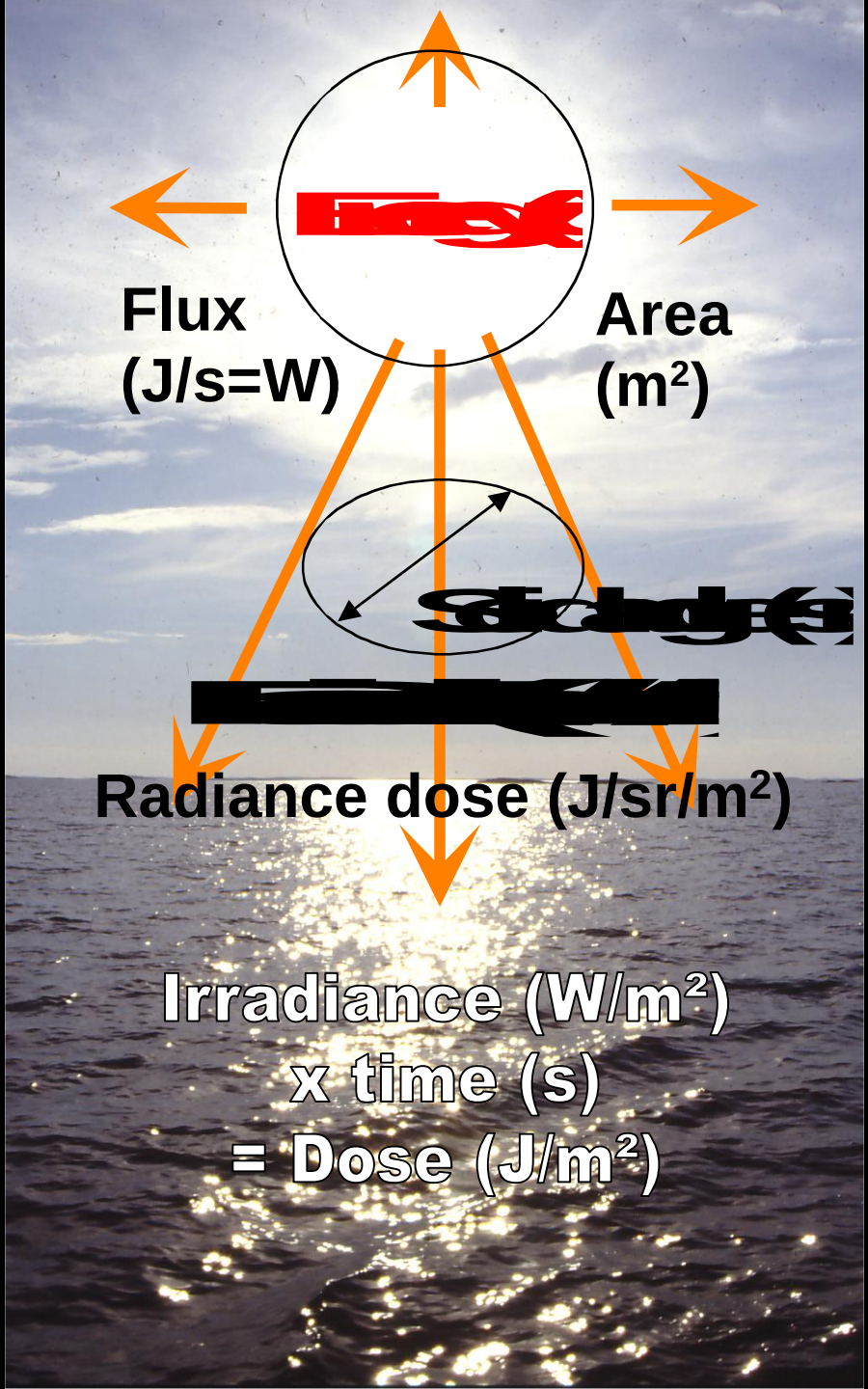

Ultraviolet radiation
Visible radiation
Infrared radiation
Excitation valence electrons and covalent bonds
Excitation of covalent bonds and non bonding electrons
Excitation bond vibrations
Photon energy (J)
10-14
10-16
10-18
10-20
10-22
10-9
10-7
10-5
10-3
Wavelength (m)

Optical radiation




Flux
(J/s=W)
Area
(m²)
Radiance dose (J/sr/m²)
Irradiance (W/m²)
x time (s)
= Dose (J/m²)

Exposure of ocular tissues, extended sources

Irradiance

E_C= Corneal irradiance (W m^{-2})

$E_L = \tau E_C$ E_L= Lens irradiance (W m^{-2})

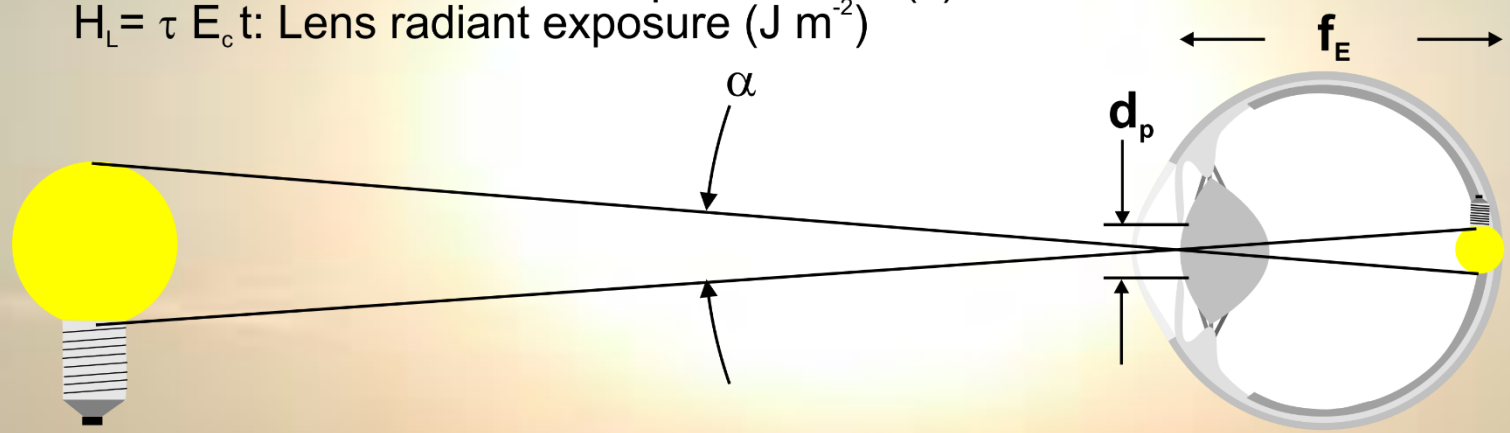
τ= Transmittance to (Rel.)

Radiant Exposure

$H_C = E_C\, t$:Corneal radiant exposure (J m^{-2})

t = Exposure time (s)

$H_L = \tau E_c t$: Lens radiant exposure (J m^{-2})



$\alpha < 20$ deg

Irradiance

$$E_R = \frac{\pi L_S \tau d_p^2}{4 f_E}$$

Radiant exposure

$$H_R = \frac{\pi L_S t \tau d_p^2}{4 f_E}$$

α = Angle subtended by the source (radians)

L_S= Source Radiance (W m^{-2} sr^{-1})

d_p= Diameter pupill (m): 7 mm

f_E= Effective focal length eye - air (m): 17 mm

$L_s t$= Source radiance dose (J m^{-2} sr^{-1})

Exposure of ocular tissues, laser, large spot size

Irradiance

E_C= Corneal irradiance (W m^{-2})

$E_L = \tau E_C$

E_L= Lens irradiance (W m^{-2})

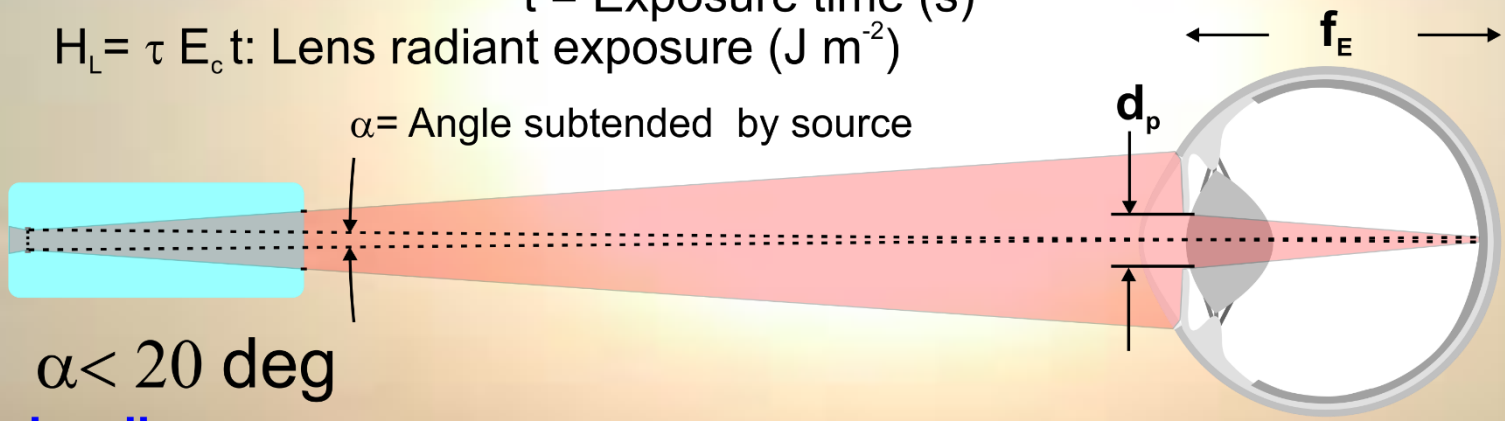
τ= Transmittance to (Rel.)

Radiant Exposure

$H_C = E_C\, t$:Corneal radiant exposure (J m^{-2})

t = Exposure time (s)

$H_L = \tau E_c t$: Lens radiant exposure (J m^{-2})



$\alpha < 20$ deg

Irradiance

$$E_R = \frac{\pi L_S \tau d_p^2}{4 f_E}$$

Radiant Exposure

$$H_R = \frac{\pi L_S t \tau d_p^2}{4 f_E}$$

α = Angle subtended by the source (radians)

L_S= Source radiance (W m^{-2} sr^{-1})

d_p= Diameter pupill (m): 7 mm

f_E= Effective focal length eye - air (m): 17 mm

$L_s t$ = Soure radiance dose (J m^{-2} sr^{-1})

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Exposure of ocular tissues, laser, point sources

Angle subtended by the source < 1.5 mradians

Power

E_C= Corneal irradiance (W m^{-2})

$E_L = \tau E_C$ E_L= Lens irradiance (W m^{-2})

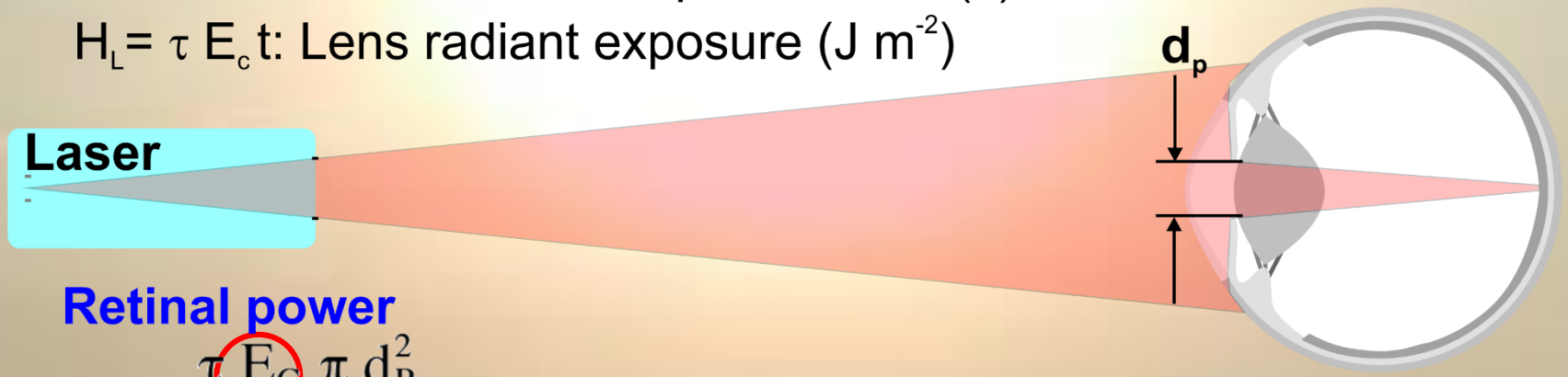
Energy

τ= Transmittance to (Rel.)

$H_C = E_C\, t$:Corneal radiant exposure (J m^{-2})

t = Exposure time (s)

$H_L = \tau E_c t$: Lens radiant exposure (J m^{-2})



Retinal power

$$\Phi_E = \frac{\tau E_C \pi d_P^2}{4} \text{ (W)}$$

d_p= Diameter pupill (m): 7 mm

Retinal energy

$$Q_E = \frac{\tau E_C \pi d_P^2 t}{4} \text{(J)}$$

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Intermediate spot sizes

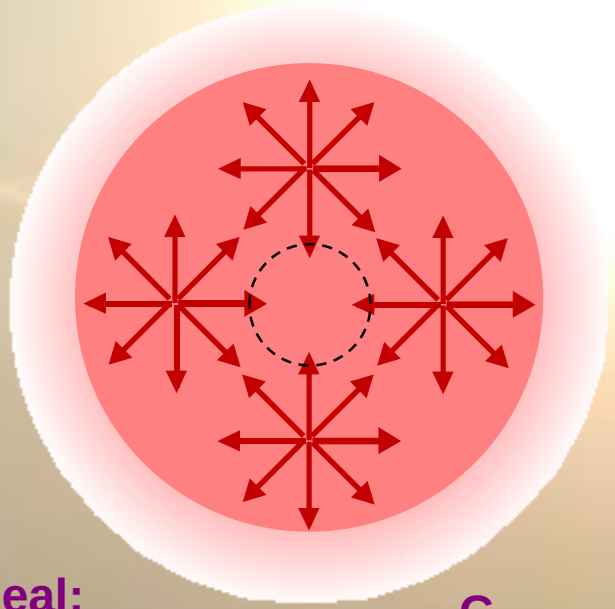
Retinal spot size, exposure time dependent

Point sources
< 1. 5 mrad

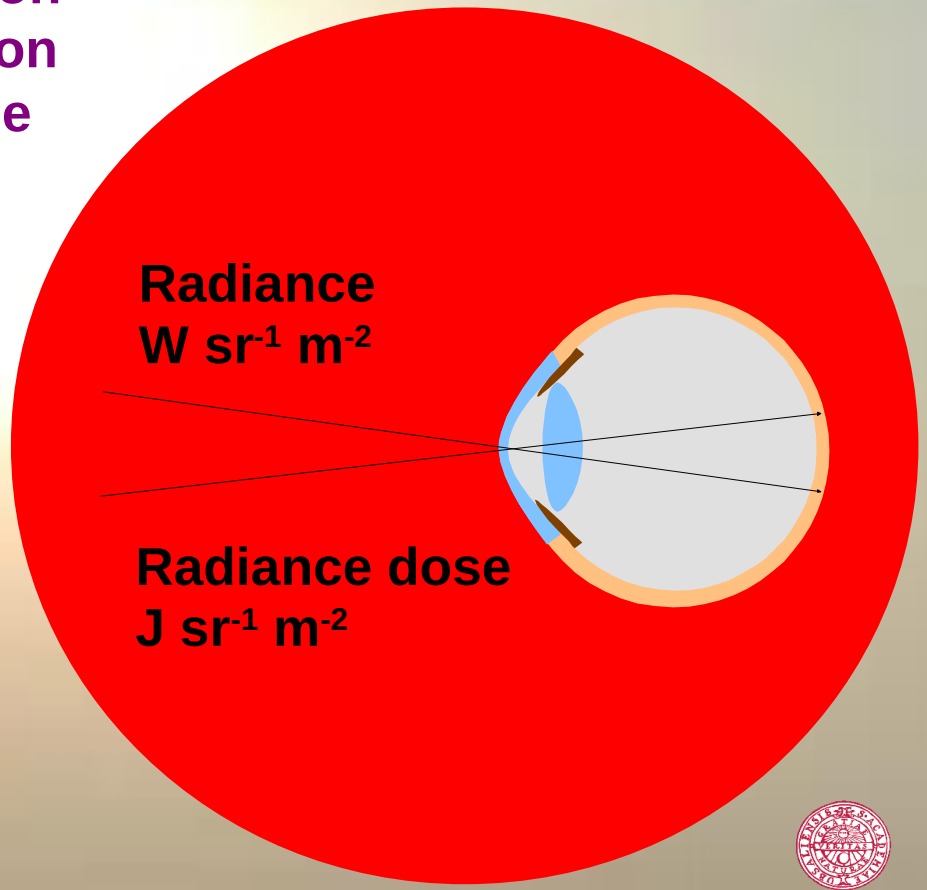
Intermediate
[1.5 mrad;100 mrad]

Point sources with correction
Transition to large depend on pulse duration and spot size

Large
>100 mrad

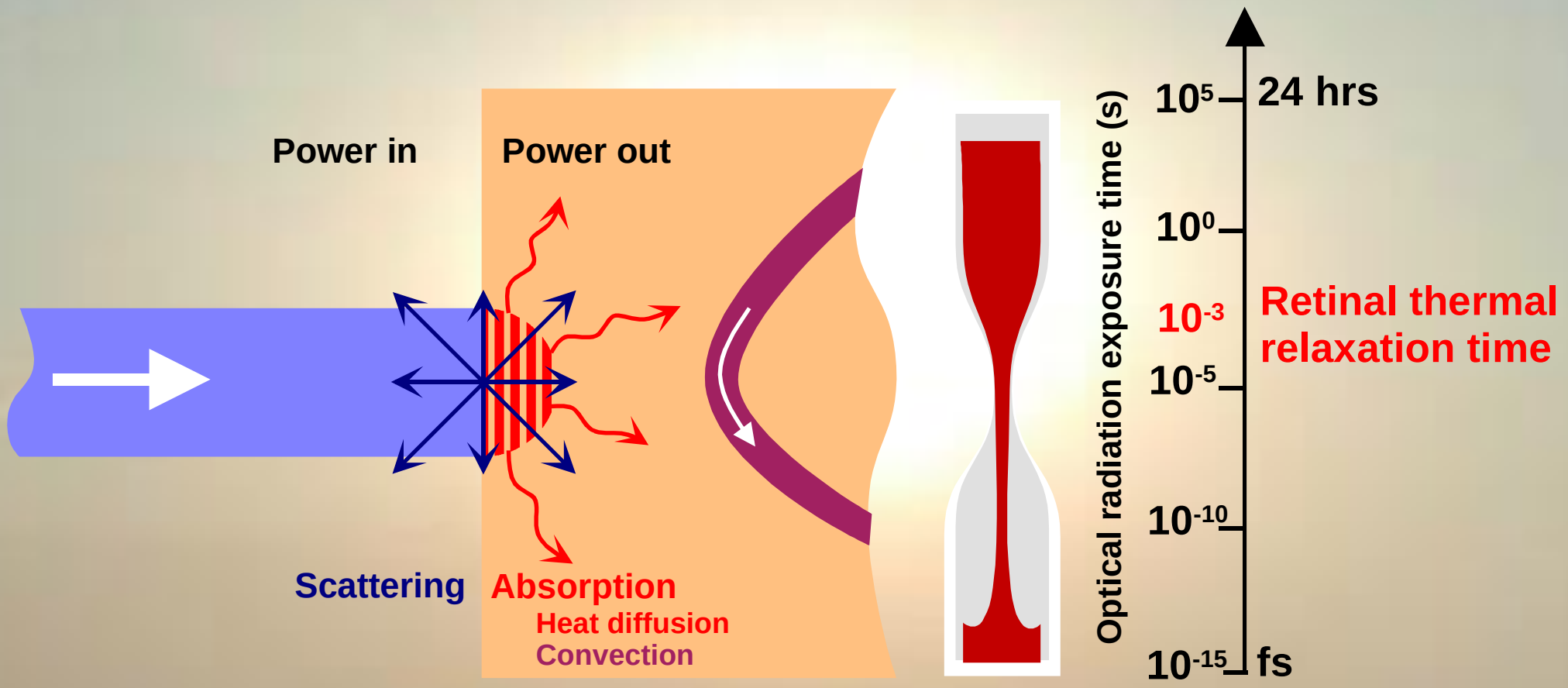


C_E



Exp. limit: Corneal:
Irradiance (W/m^2) or Power (W)
Energy (J)

Exposure time – radiation damage



Power in < Power Out

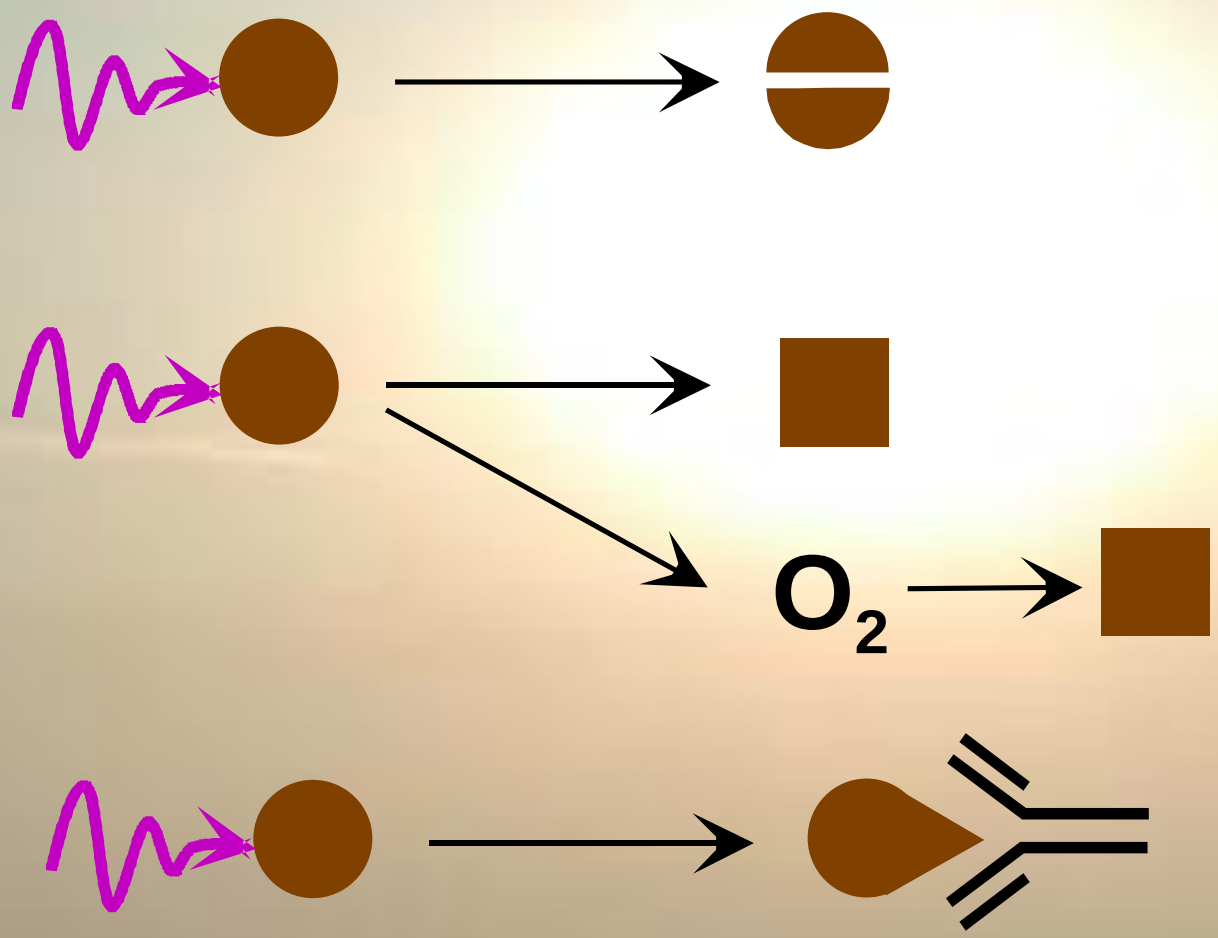
Photochemical damage

Radiant exposure/Dose/Radiant exposure dose, H (J/m2) =

Irradiance, E_e (W/m^2) x Exposure time, t (s)

Reciprocity condition

Power in < Power Out
Photochemical damage



Phototoxic

Photosensitized

Type I

Type II
(Photodynamic)

Photoallergic

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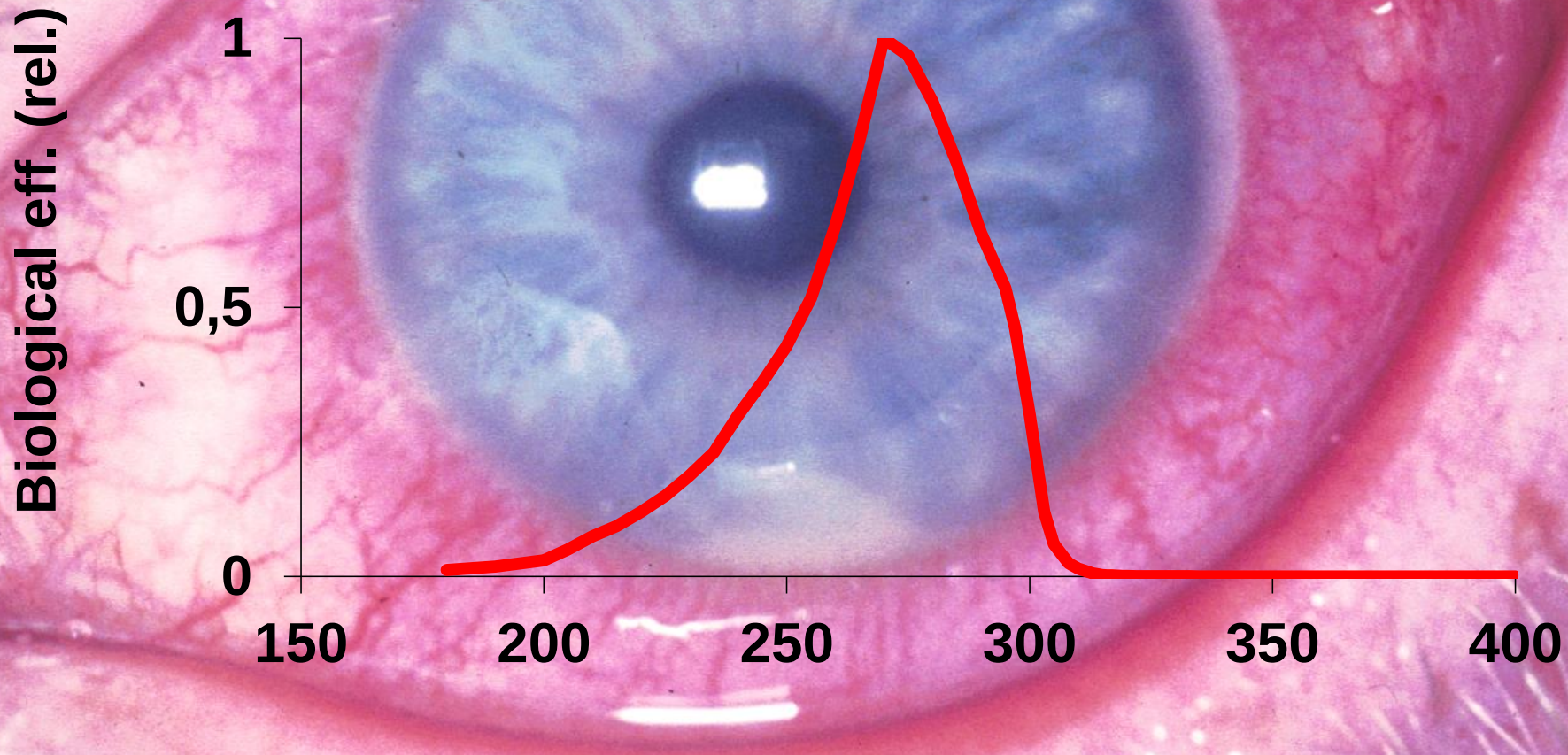
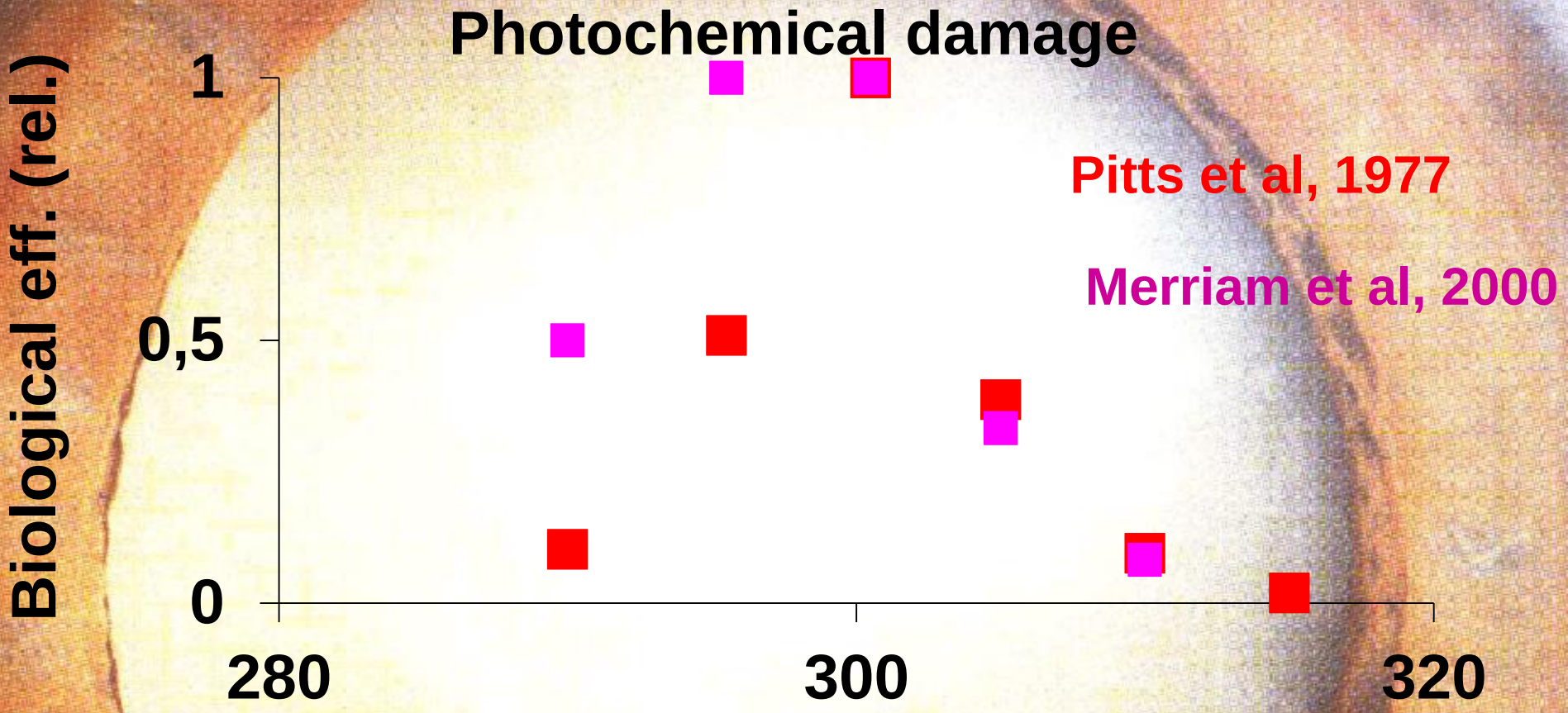
Power in < Power Out

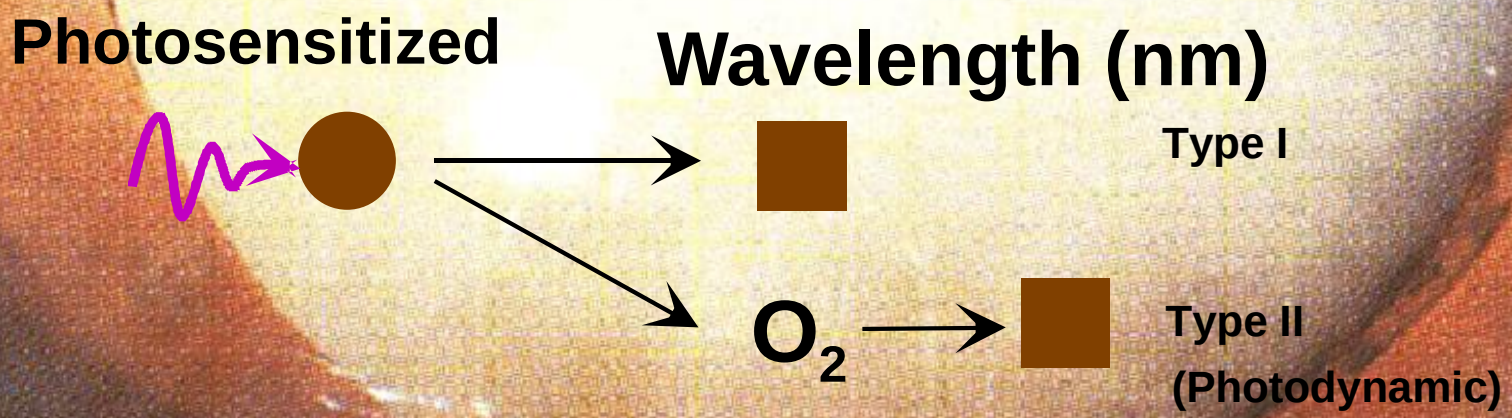
Photochemical damage



Phototoxic

Power in < Power Out

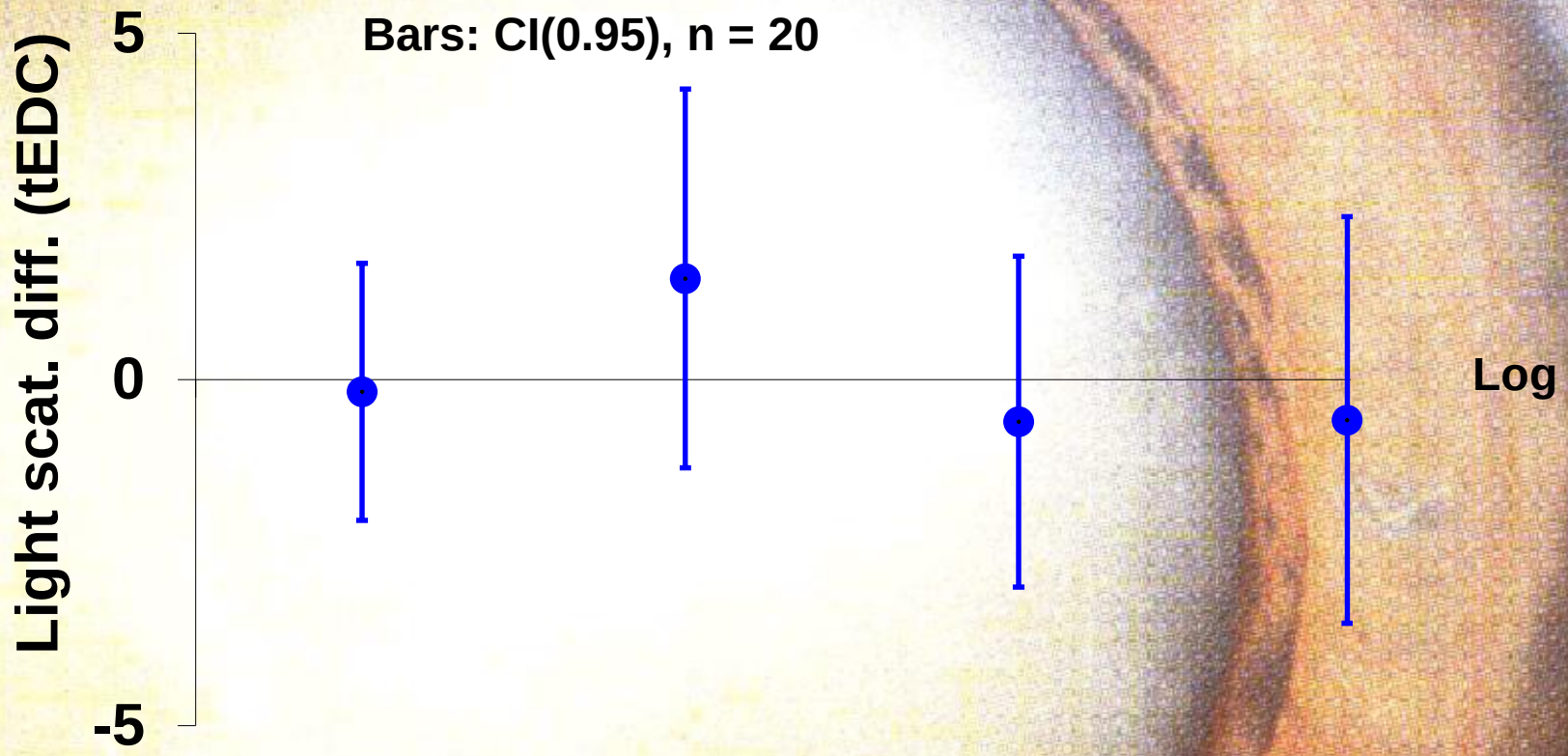




Power in < Power out: Near IRR

Photochemical damage ?

Sprague-Dawley rats, 6 w, 1090 nm 96 W cm^{-2} , within pupill, 1 w after exposure after exposure



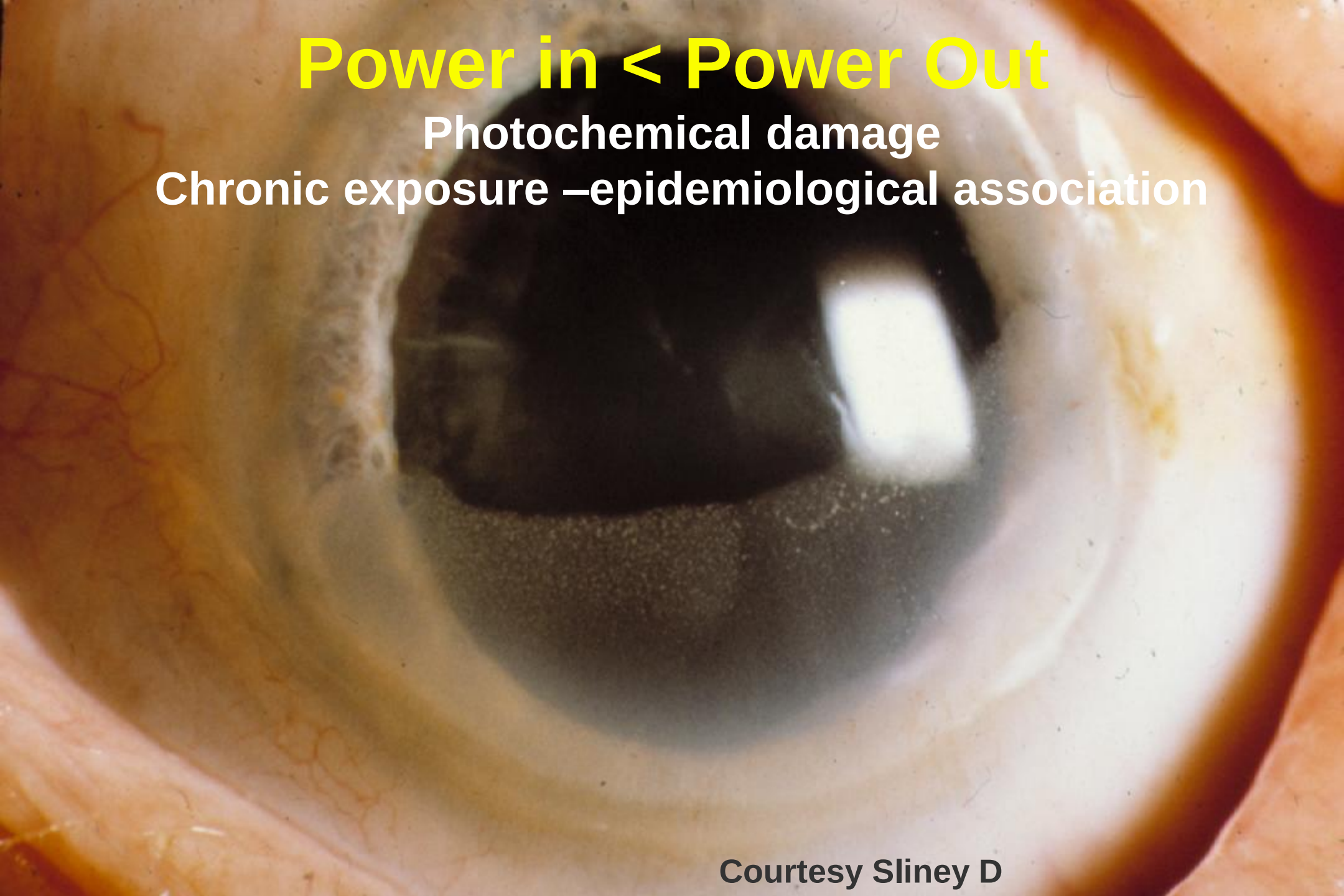
Radiant exposure (kJ cm^{-1})	57	103	198	344	Lin
Exposure time (Min.)	10	18	33	60	Lin

Yu et al, Epub, JBO 2015

Power in < Power Out

Photochemical damage

Chronic exposure –epidemiological association



Courtesy Sliney D

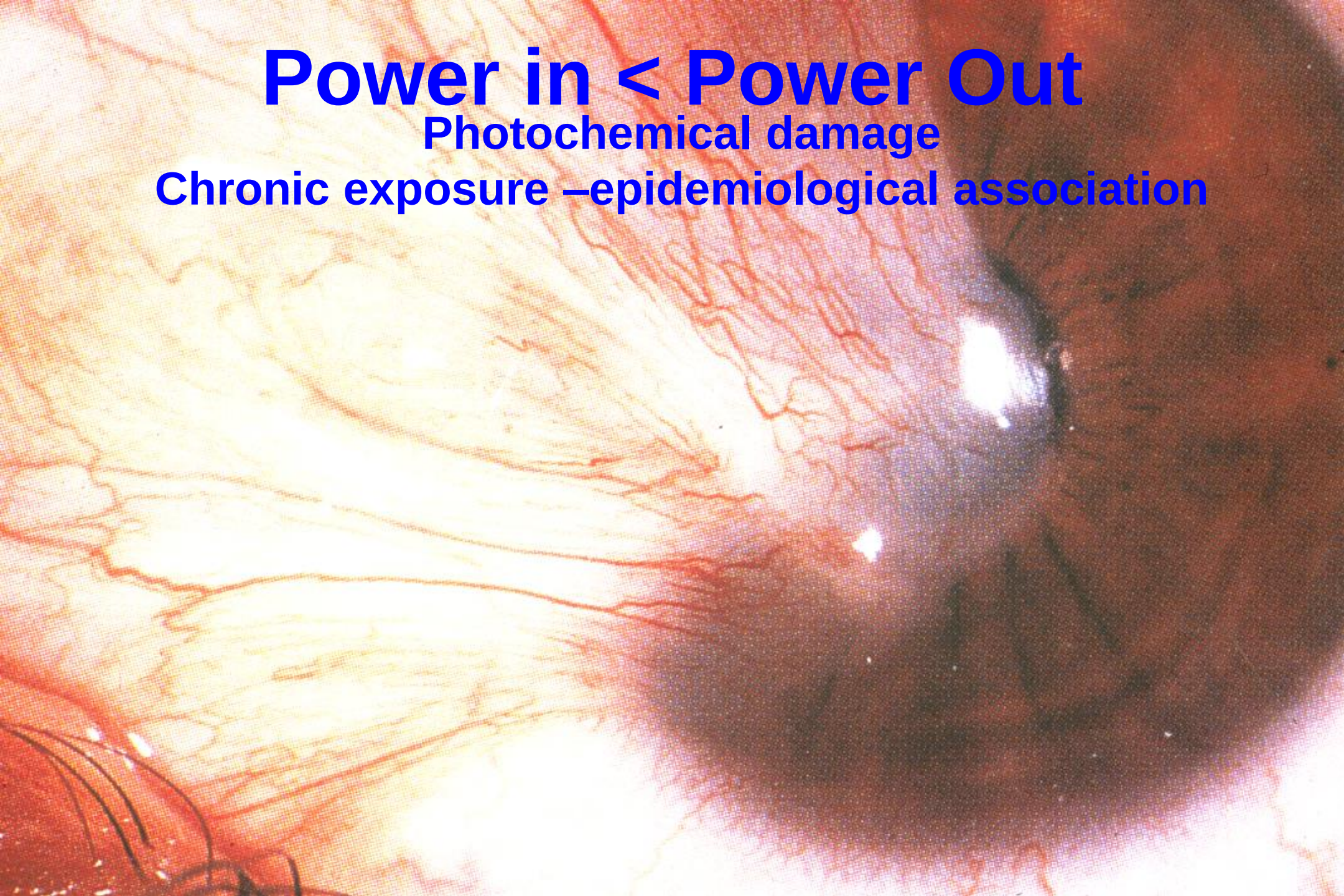
Power in < Power Out
Photochemical damage
Chronic exposure –epidemiological association

Power in < Power Out
Photochemical damage
Chronic exposure –epidemiological association

Power in < Power Out

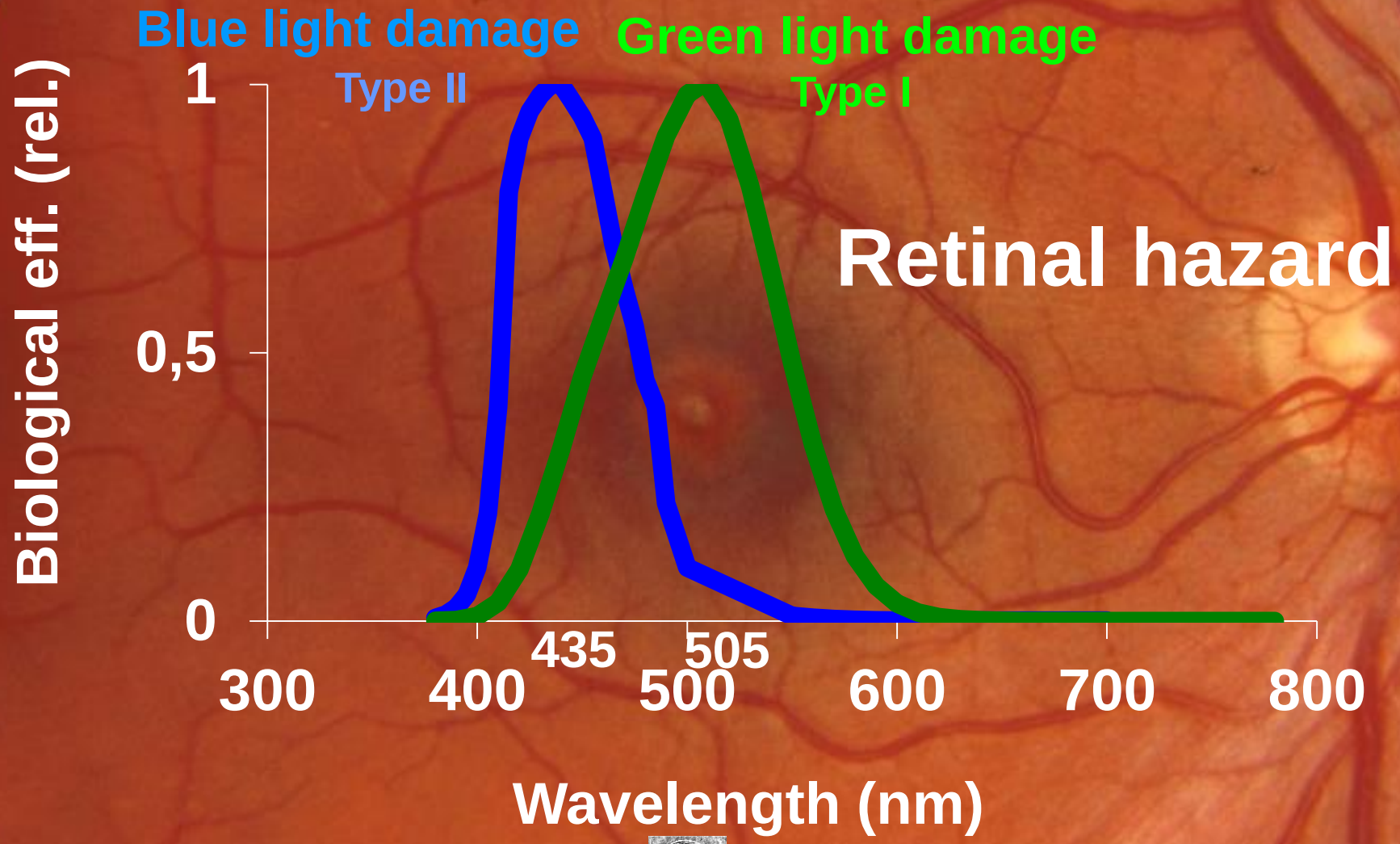
Photochemical damage

Chronic exposure –epidemiological association



Power in < Power Out

Photochemical damage



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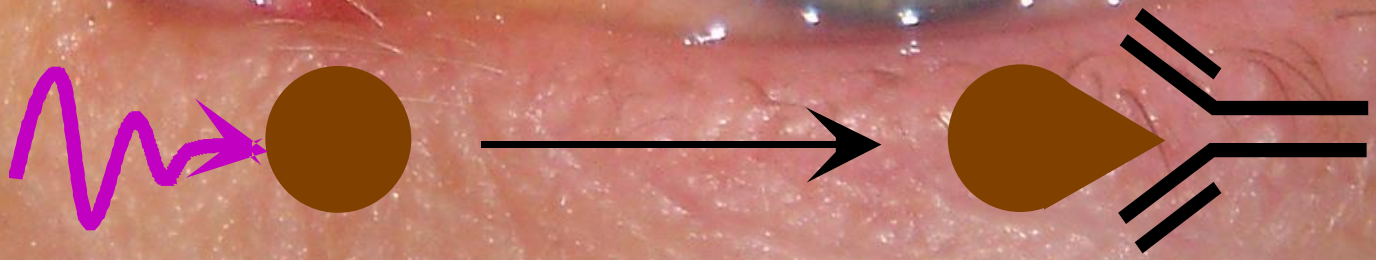
Power in < Power Out

Imunologically mediated
Photochemical damage



Photoallergic

Reaction without relationship to parameters of the radiant exposure
Determined by biological immune reaction

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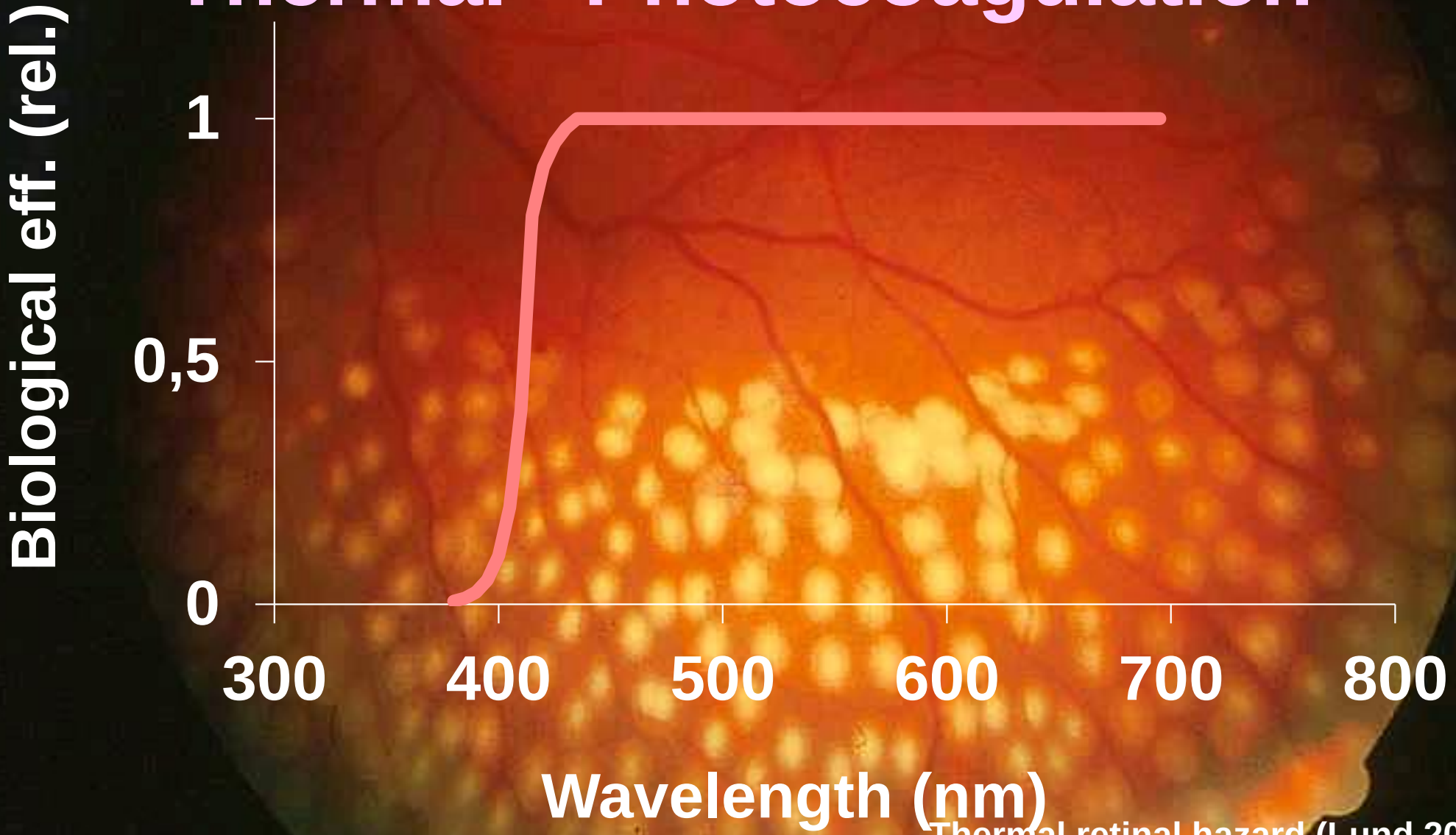
Power in > Power Out

Thermal - Photocoagulation



Thermal retinal hazard (Lund 2006)

Power in >> Power out, water

Thermal- Photovaporization

Typical parameters (Argon green: 514.5 nm)

- **Spot size: 100 μm**
- **Power on the eye: 0.6 W**
- **Iris irradiance: 6 kW/m^2**
- **Pulse duration: 0.1 s**
- **Radiant exposure: 0.6 kJ/m^2**

Power in >> Power out, no water

Thermal- Carbonization

Typical parameters (CO_2: 10.6 μm)

- **Spot size: 1 mm^2 (Diam. 0.6 mm)**
- **Power on the skin: 100 W**
- **Irradiance on the skin: $1x10^8$ W/m^2**
- **Pulse duration (CW): 1 s**
- **Radiant exposure: $1x\ 10^8$ J/m^2**

Power in >>> Power, expansion space

Thermal - Photoablation

Typical parameters (ArF: 193 nm)

Spot size: 0.2 mm^2 (Diam. 0.5 mm)

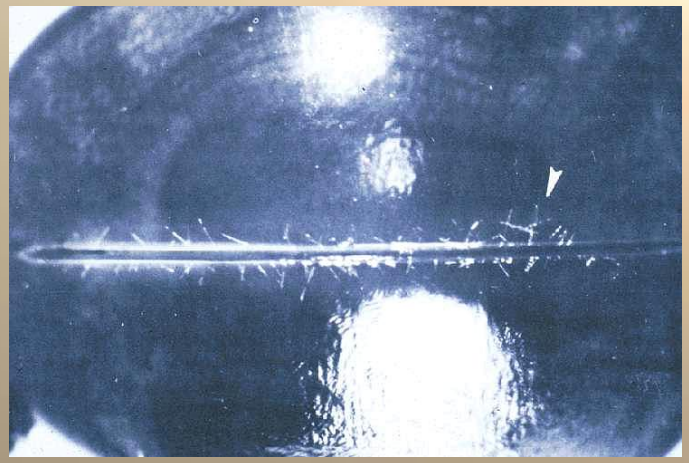
Irradiance: 1.3 $x10^{14}$ W/m^2

Pulse duration: 15 ns

Radiant exposure: 2 $x10^6$ J/m^2

Pulse energy: 400 mJ

1 puls = 0.2 μm ablation along the beam



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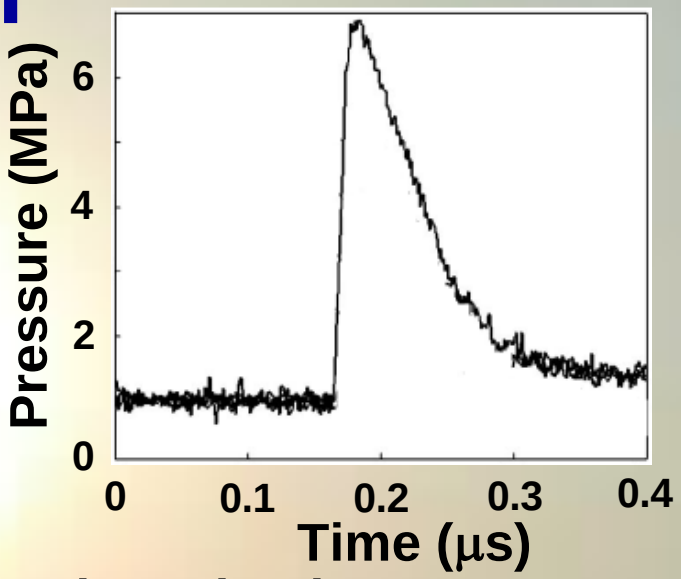
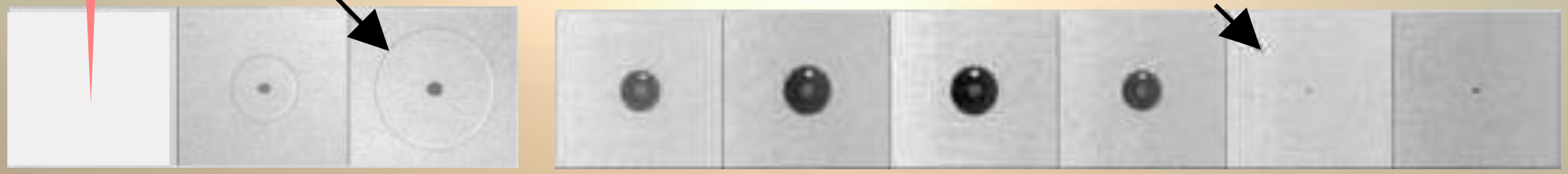
Power in >>>> Power out
Photodisruption

Typical parameters
- **Pulse width: 5 ns**
- **Spot size: 1 μm²**
- **Irradiance: 1 x10¹⁹ W/m²**
- Pulse energy: 50 mJ



Primary shockwawe

Secondary shockwawe



0 0.2 0.4 10 20 30 40 50 60

Post impact time (μs)

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Sankin (2008)

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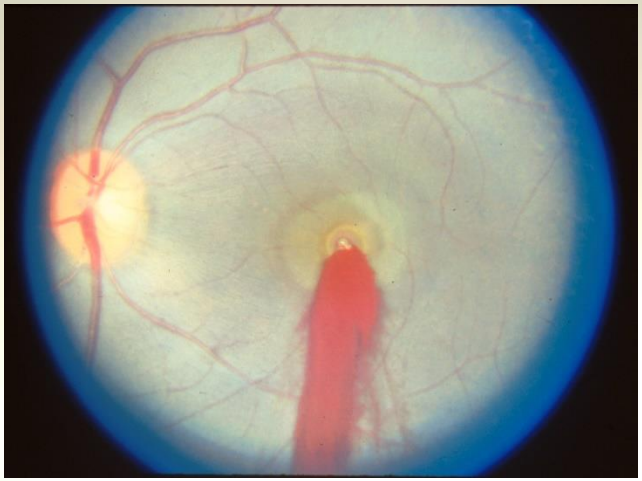
Photodisruption retina (Q-switched Nd:Yag)



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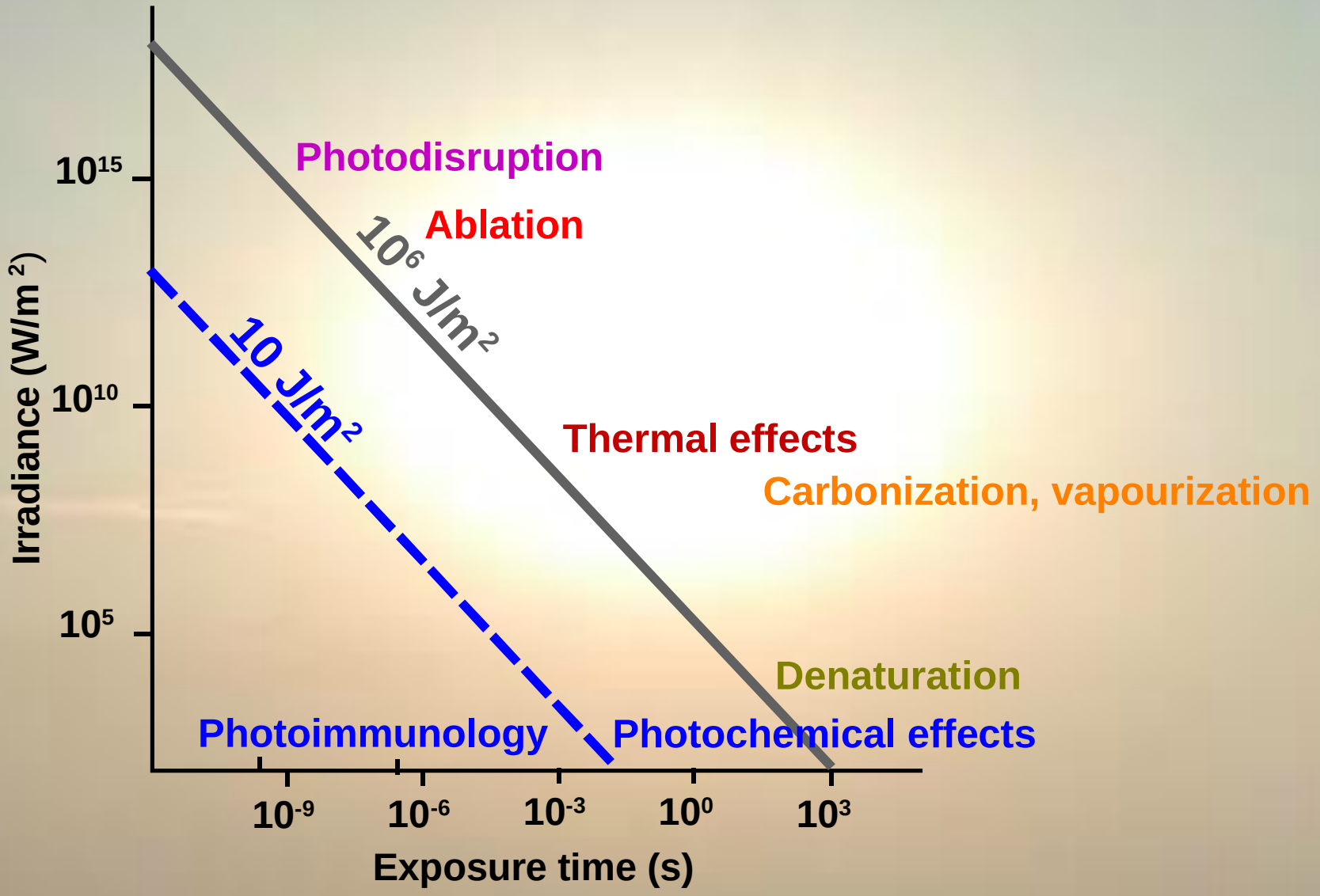
Courtesy: Bruce Stuck,
USAMRD - WRAIR, Brooks AFB, TX

Optical radiation tissue interaction



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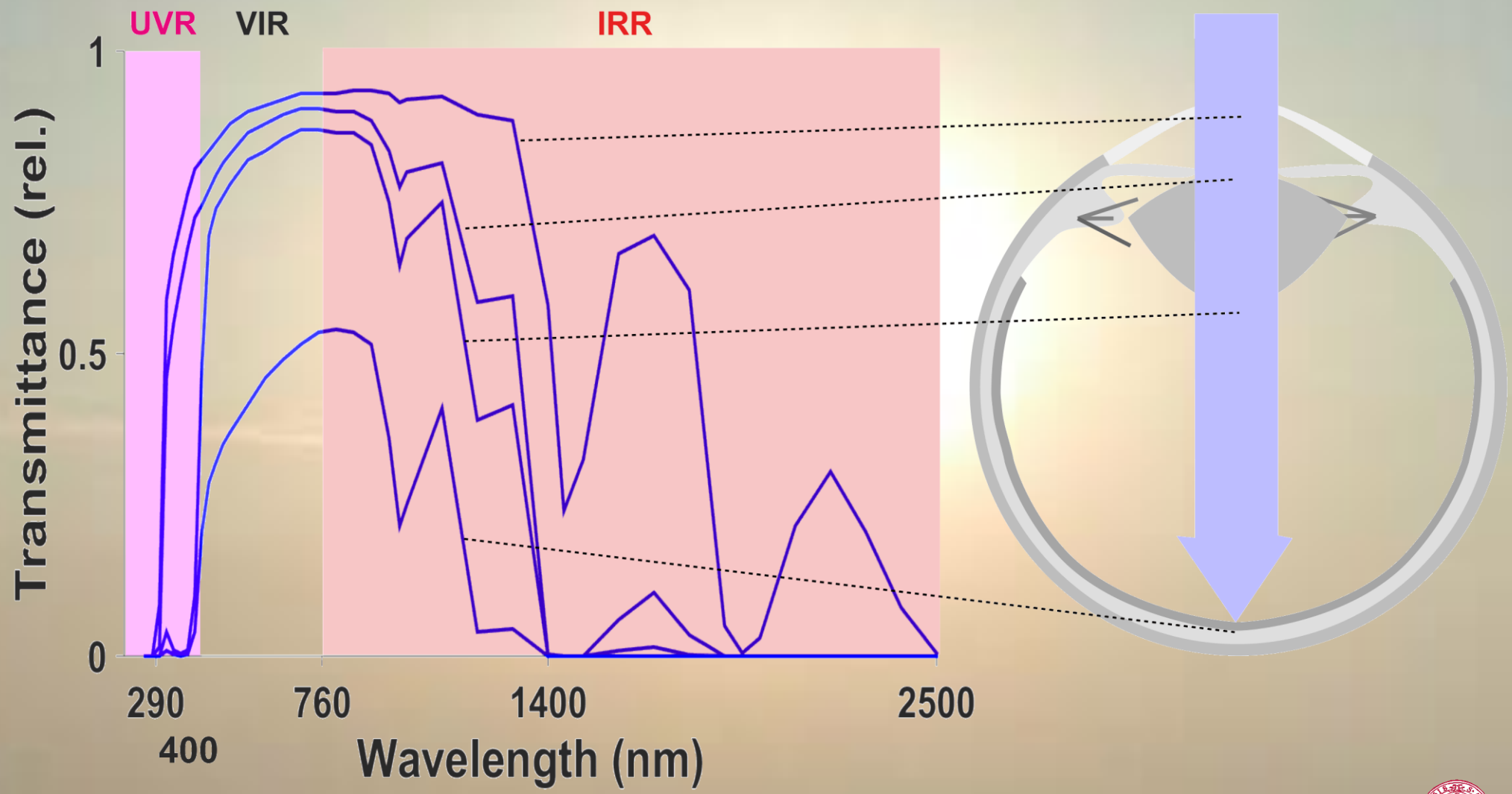
Transmittance of the eye



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Boettner et al., 1962

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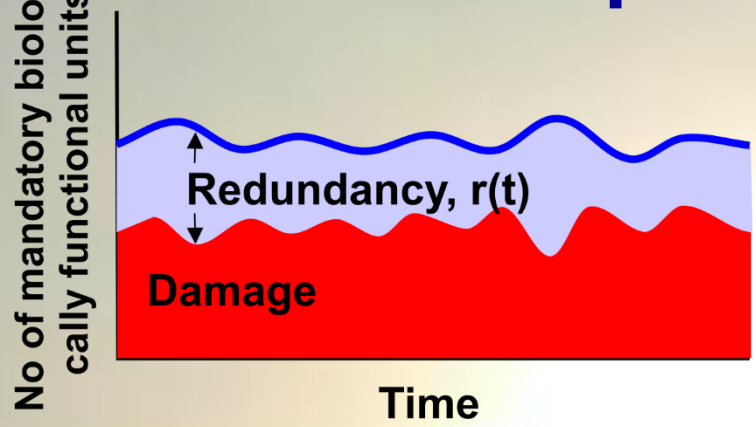
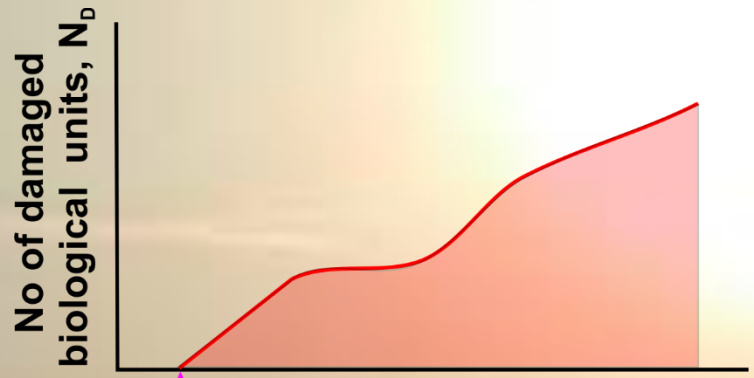
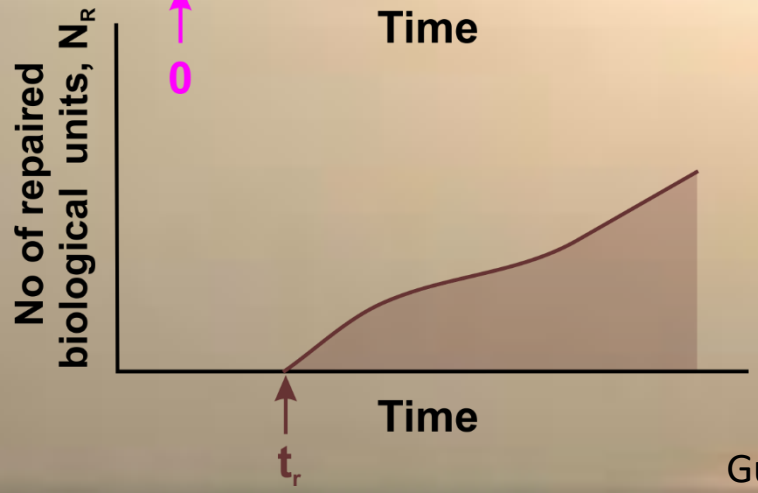
Model for photobiological damage





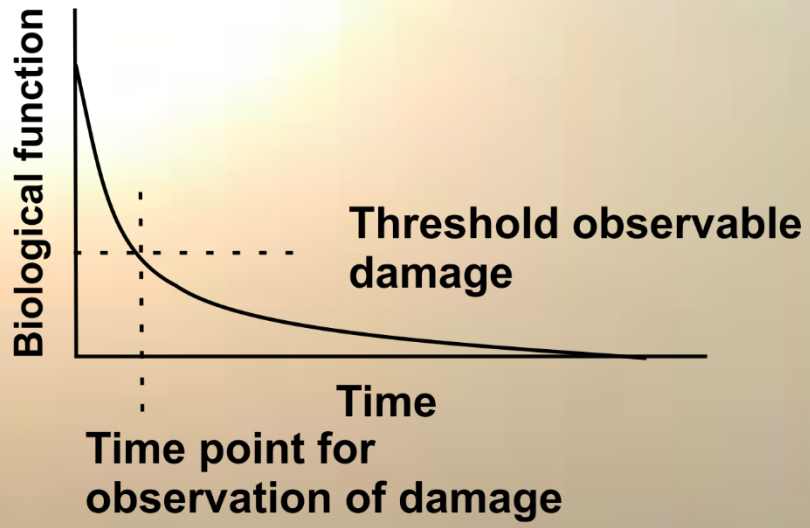


No damage

$$\int_0^t N_D\,dt - \int_0^t N_R\,dt \le r(t)$$

Damage

$$\int_0^t N_D\,dt - \int_0^t N_R\,dt > r(t)$$



1 month

Experiment **Epidemiology**

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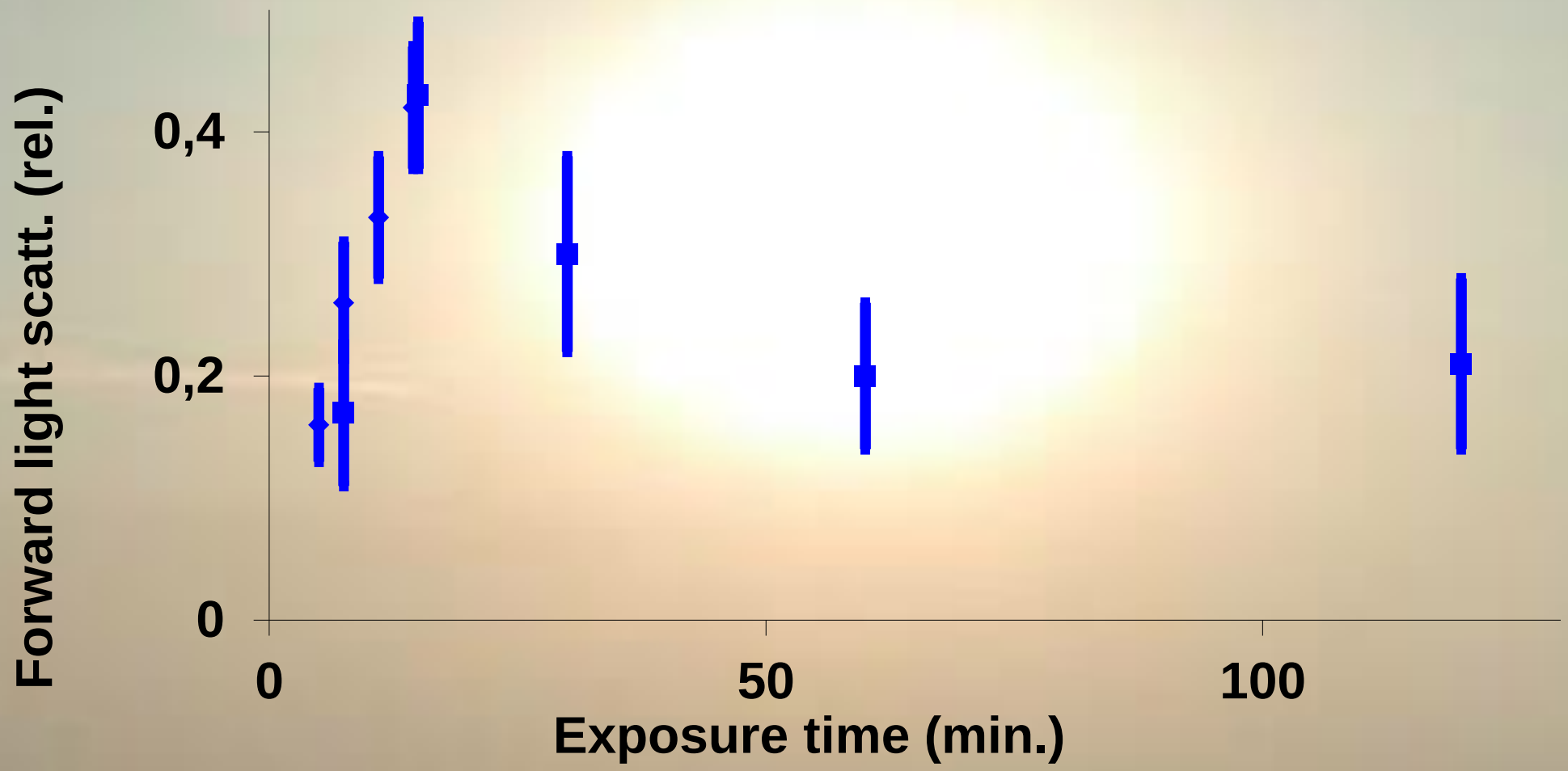
UVR Cataract, exposure time

Albino, SD, 6 weeks, 300 nm, 8 kJ/m^2, 1 week latency



Ayala, 2000

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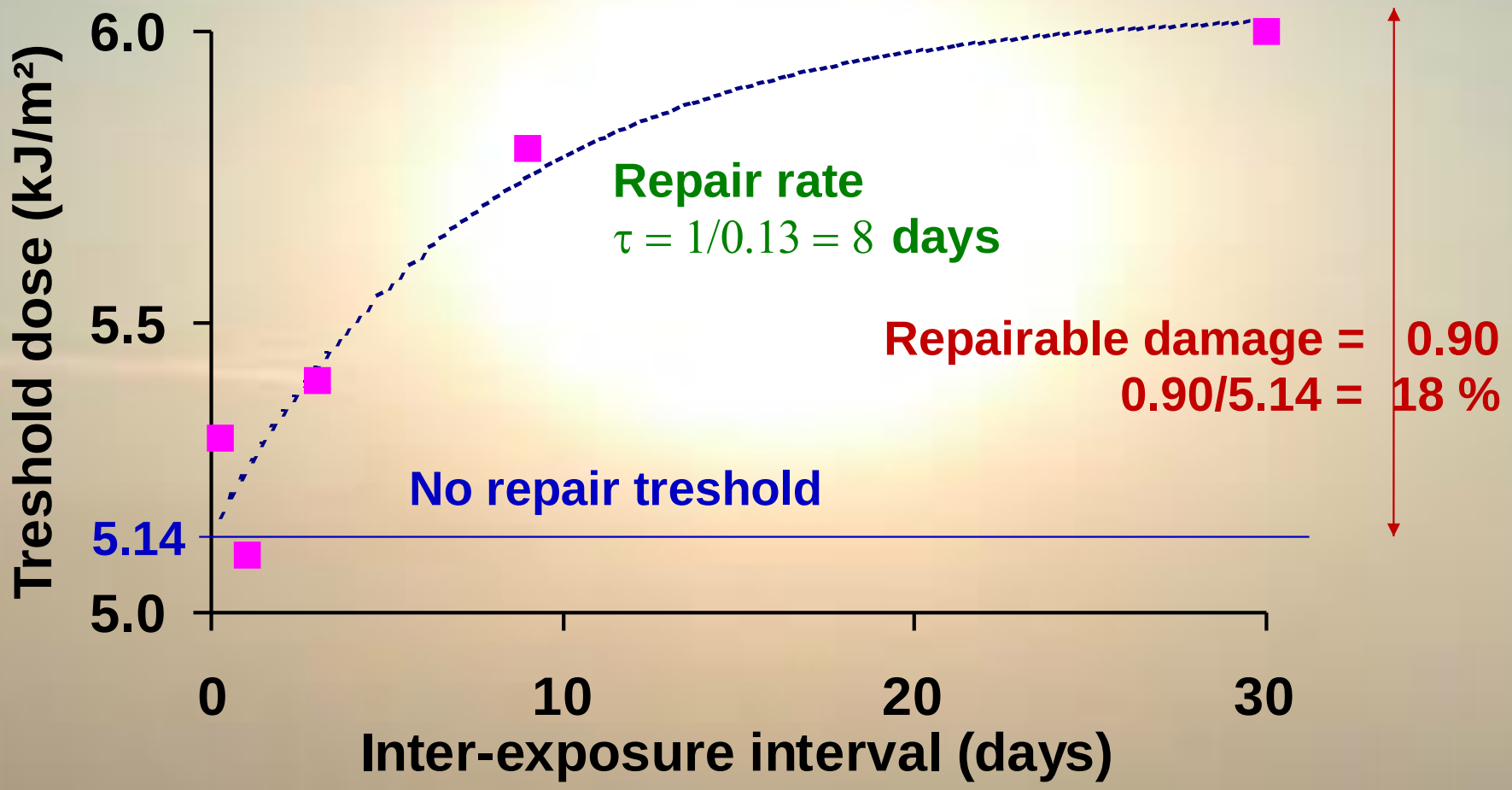
$MTD_{2.3:16}$ dependence on fractionation interval

SD rat, albino, 6 weeks, UVR 300 nm, latency 1 weeks

$$MTD_{2.3:16} = 5.14 + 0.90(1 - e^{-0.13 * IntExpInt})$$



Dong et al, 2006

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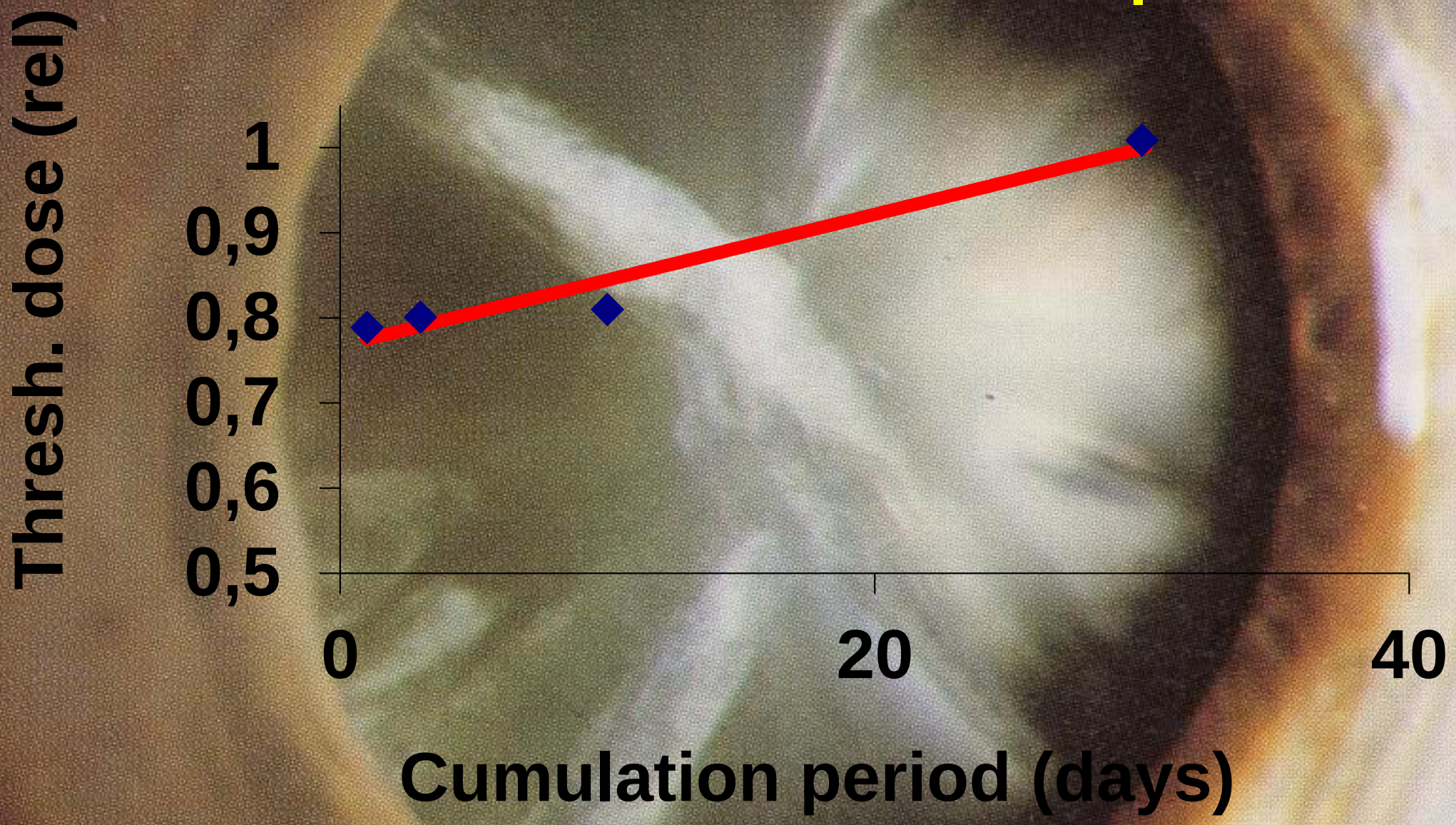
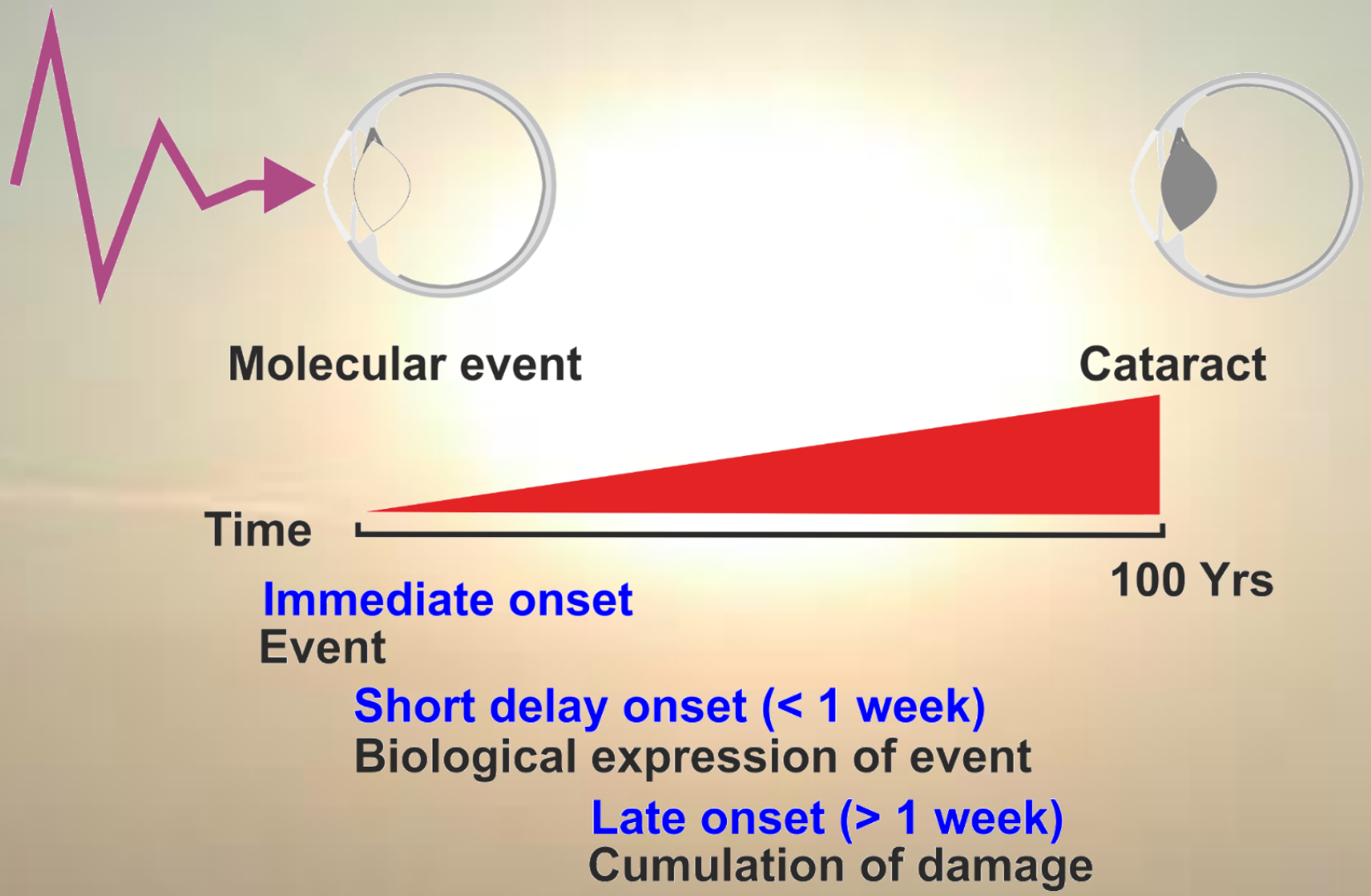
Threshold versus cumulation period



Gallichanin et al, 2014

Time delay between exposure to light and response in the lens



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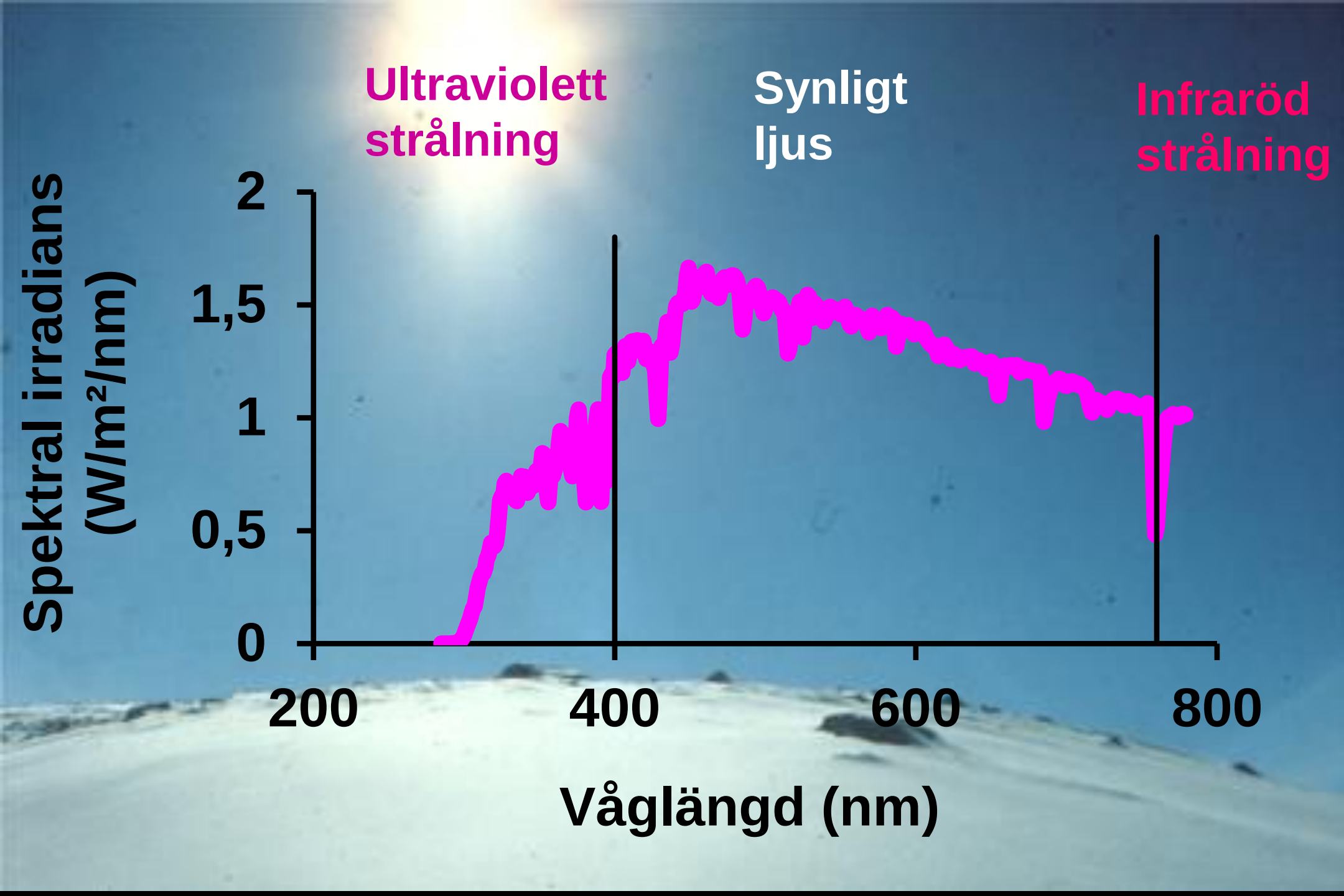

Ultraviolett strålning
Synligt ljus
Infraröd strålning
Spektral irradians (W/m²/nm)
2
1,5
1
0,5
0
200
400
600
800
Våglängd (nm)

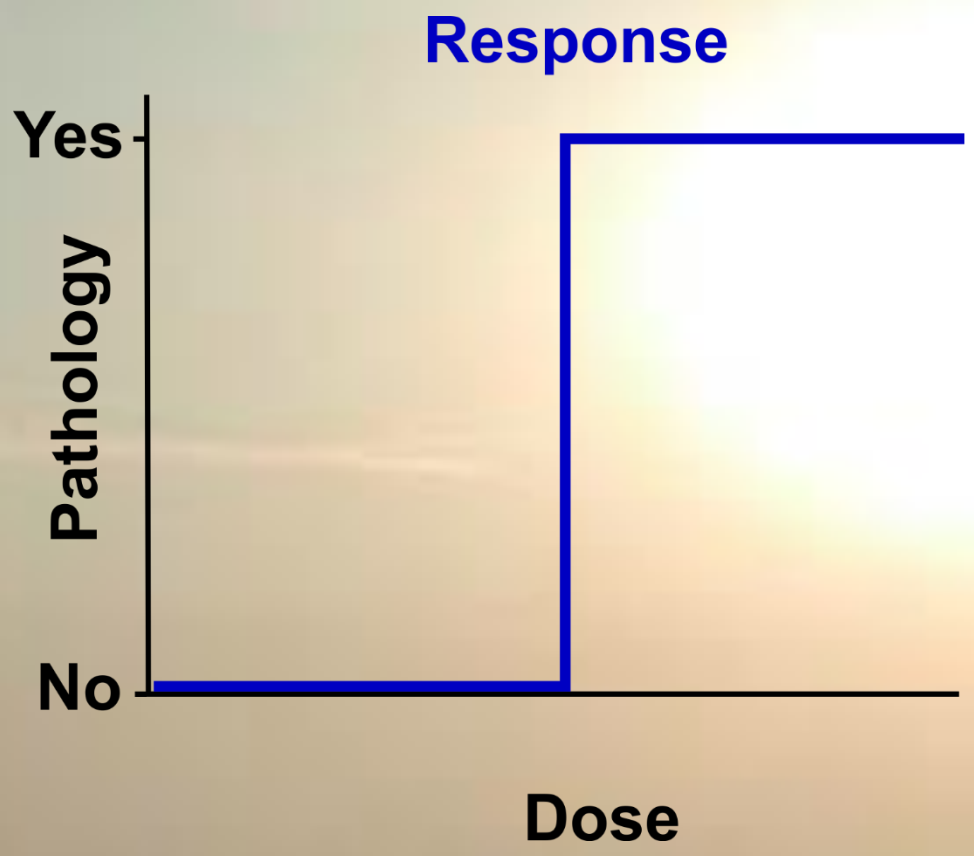
Treshold dose

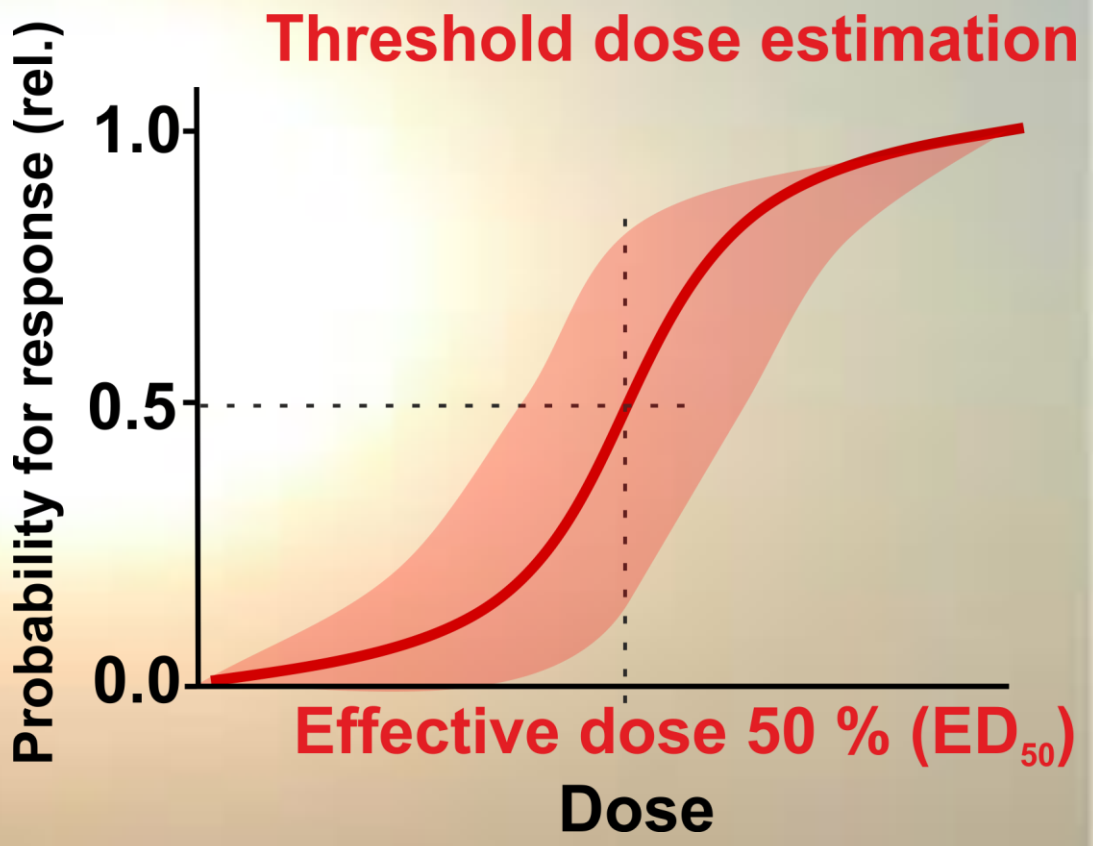
The least dose that evokes a defined damage

Action spectrum

Threshold dose as a function of wavelength

Threshold dose estimation, binary response variables

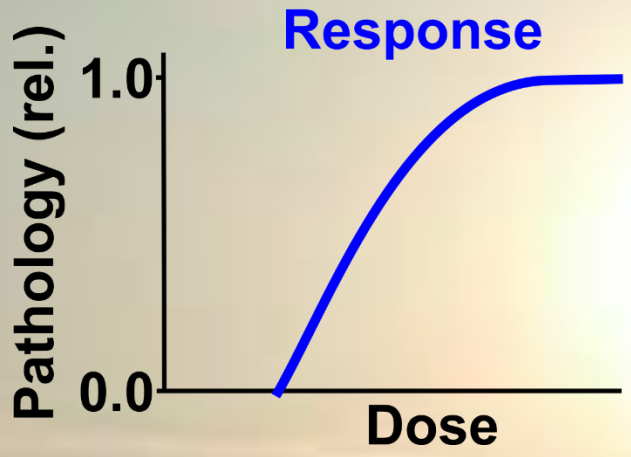


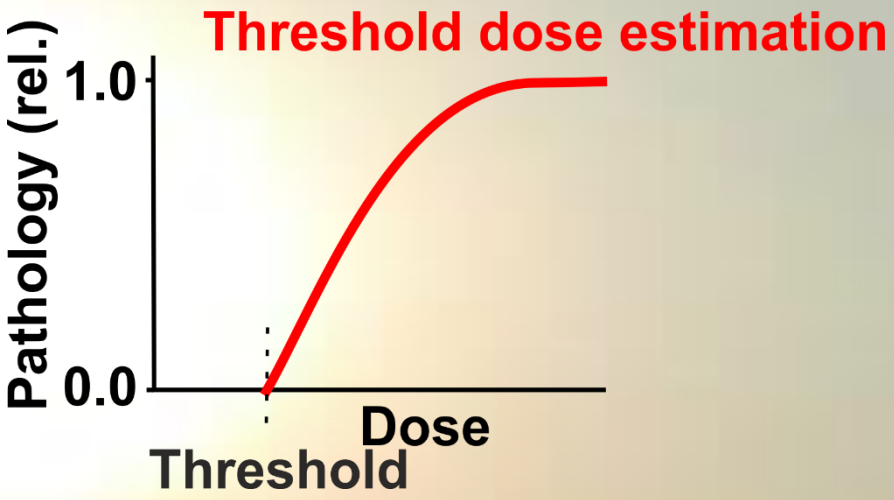


Finney, 1971

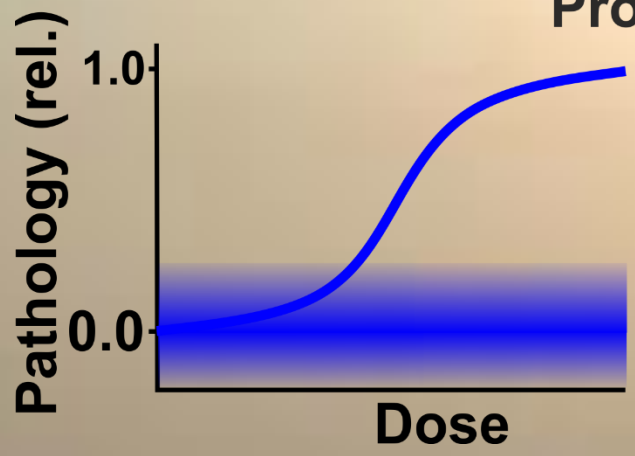
Threshold dose estimation, continuous response variables

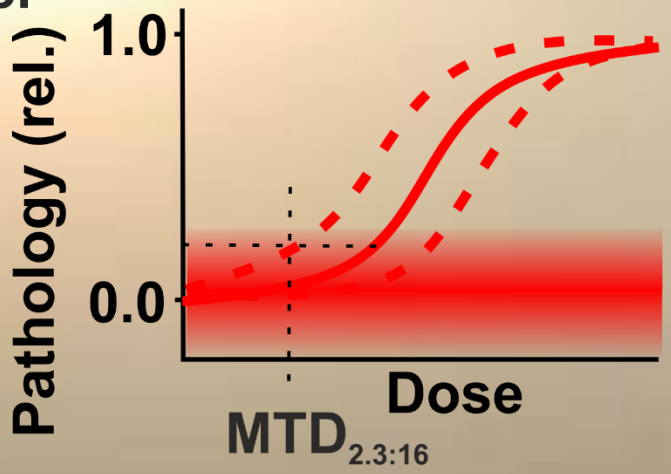
Deterministic model





Probabilistic model





Söderberg et al., 2001

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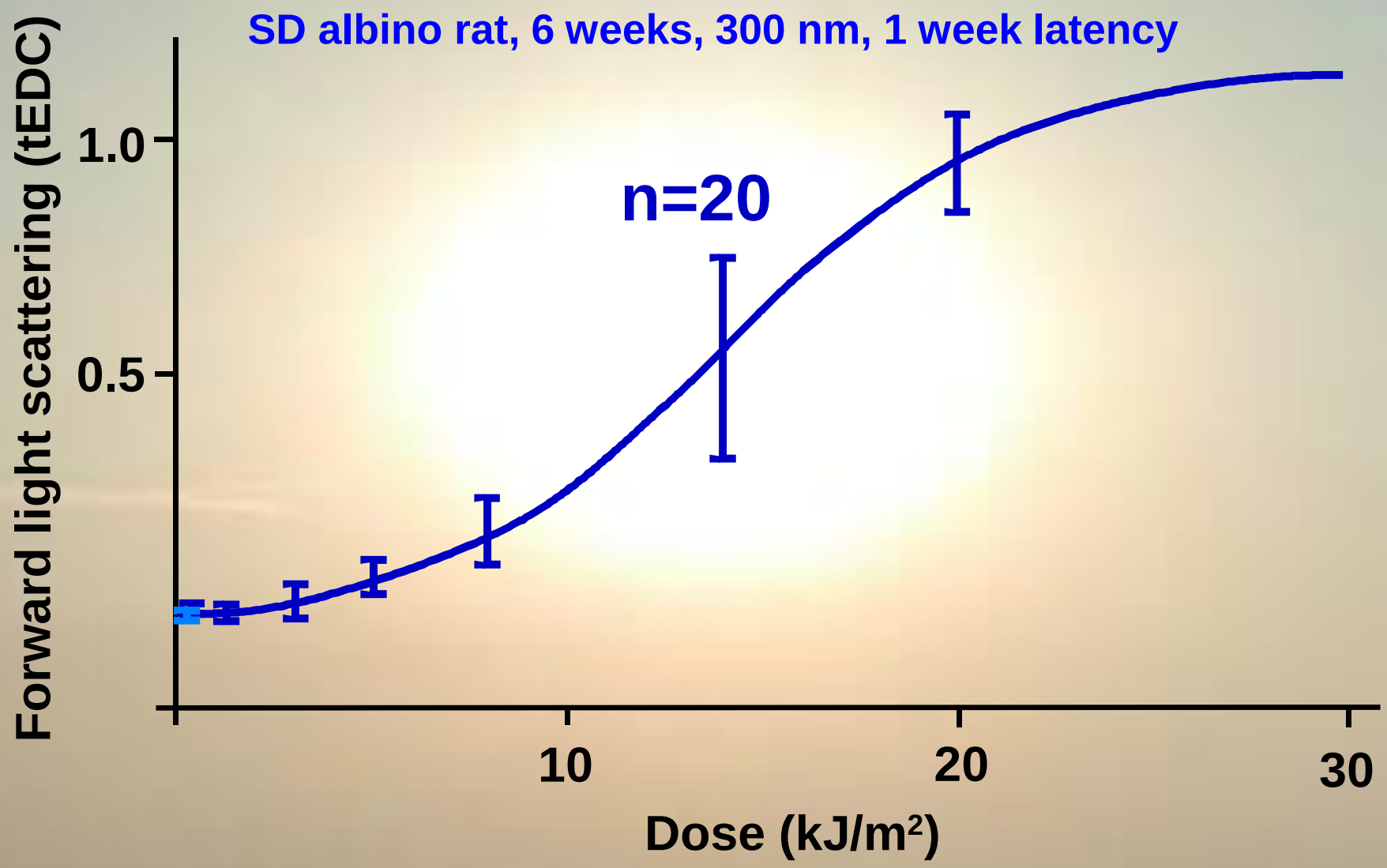
UVR-cataract, dose-response function



Söderberg et al., 2001

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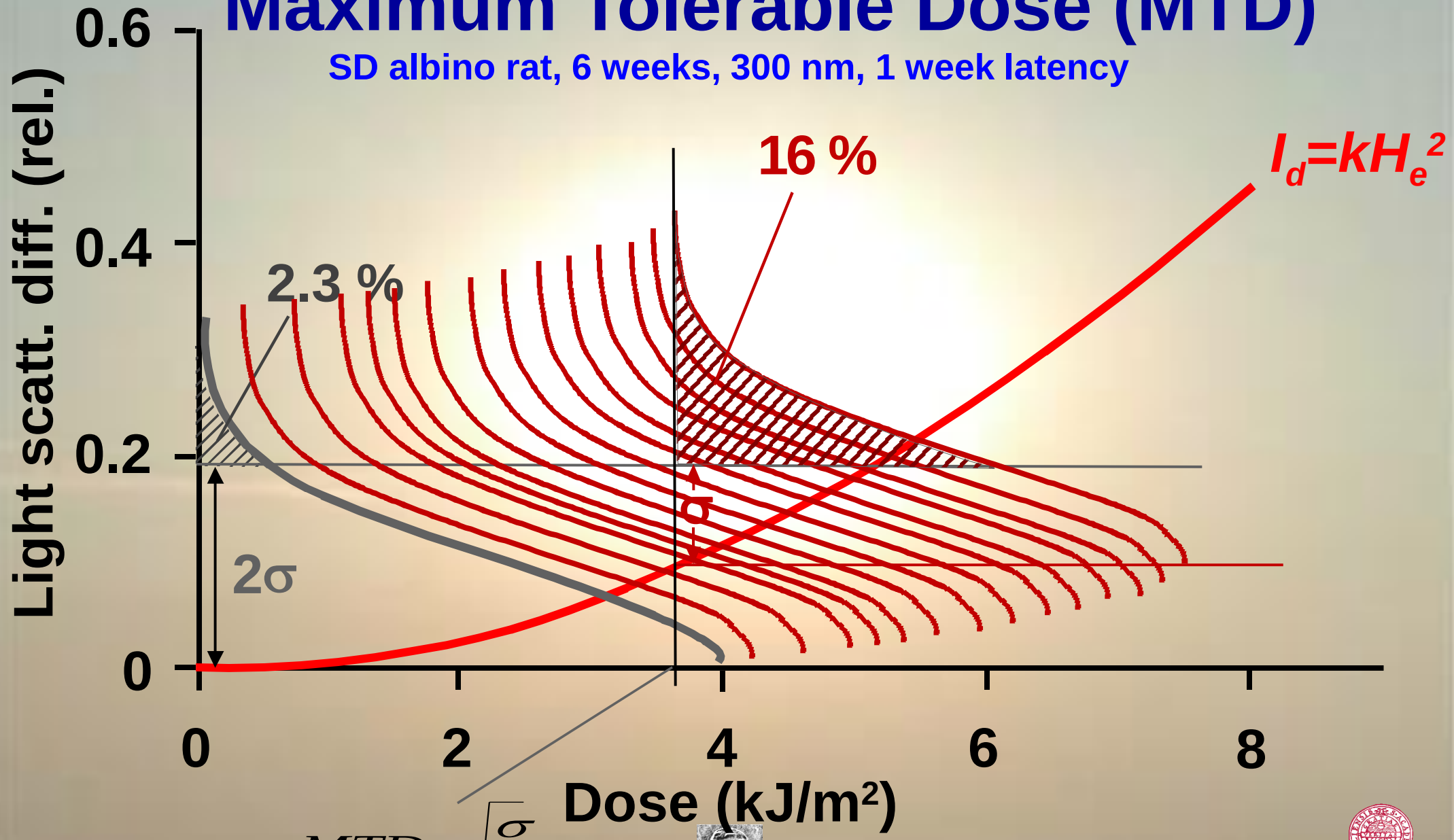
Maximum Tolerable Dose (MTD)

SD albino rat, 6 weeks, 300 nm, 1 week latency



$$MTD_{2,3;16} = \sqrt{\frac{\sigma}{k}}$$

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Söderberg et al., 2002

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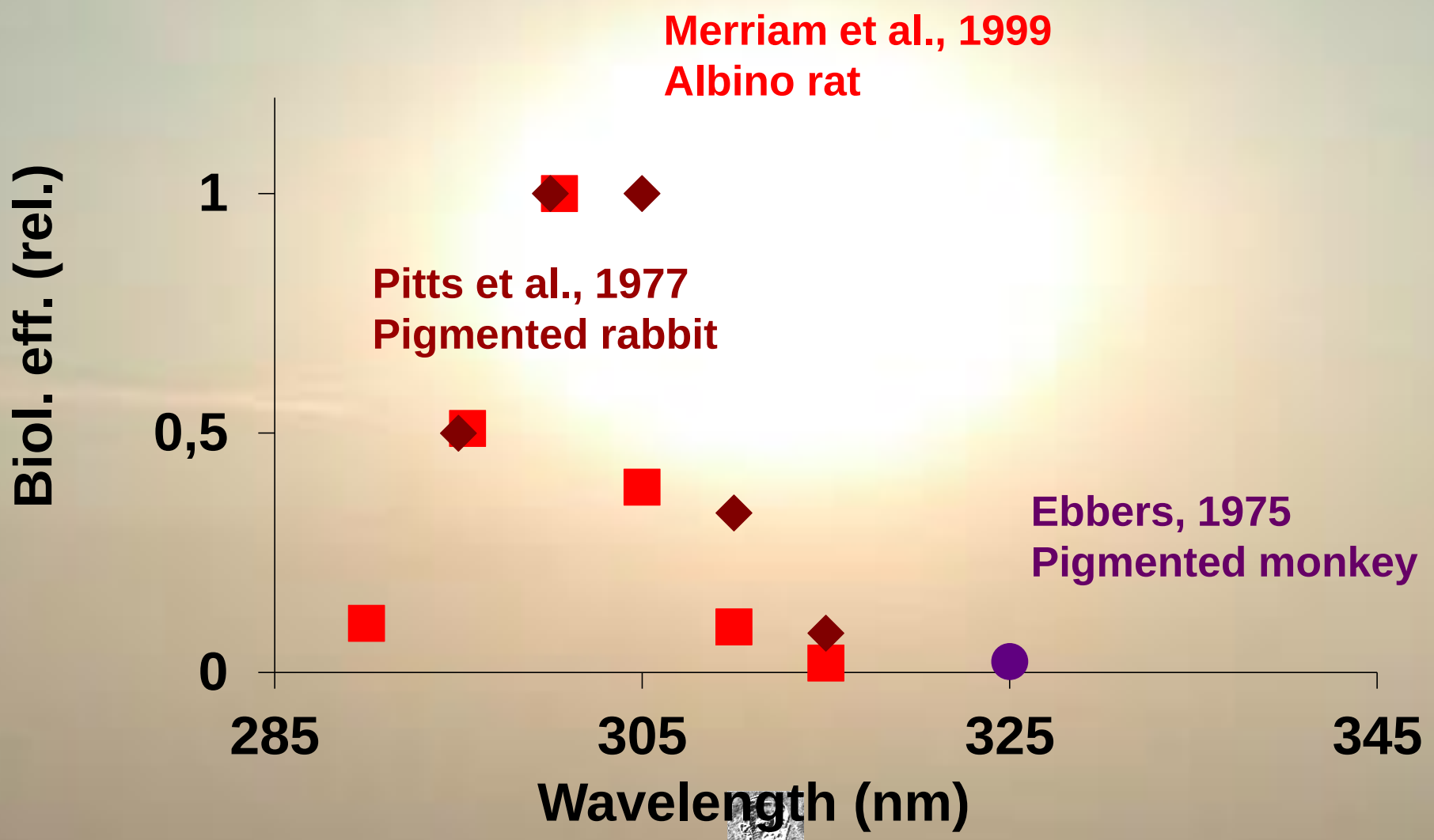
Action Spectrum UVR-induced cataract



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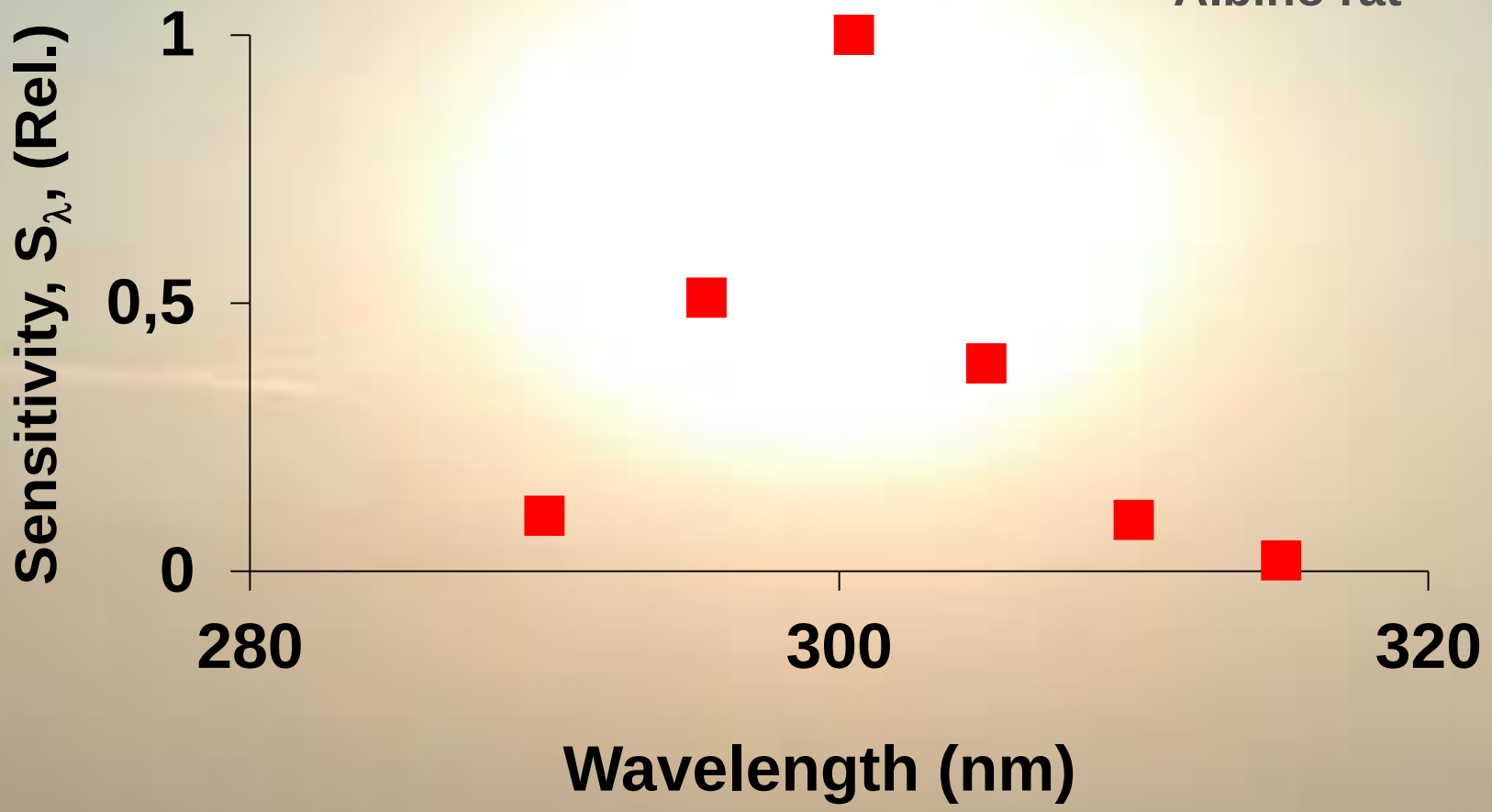
Spectral biological efficiency, UVR cataract

Merriam et al., 2000
Albino rat



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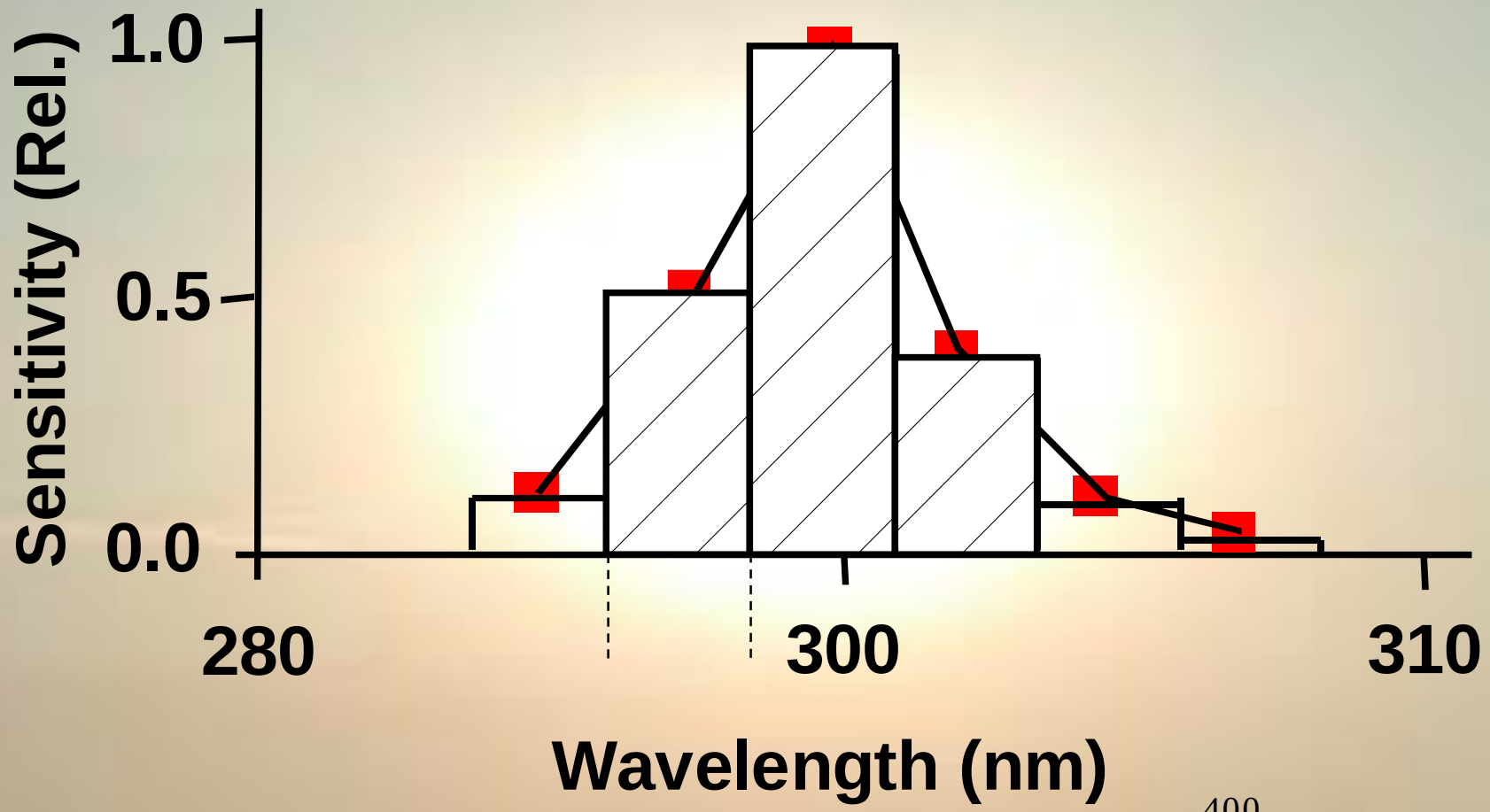
Exposure for broadband sources



$$Biol..eff.dose = t \cdot \sum_{290}^{400} (E_\lambda \cdot S_\lambda \cdot \Delta\lambda)$$

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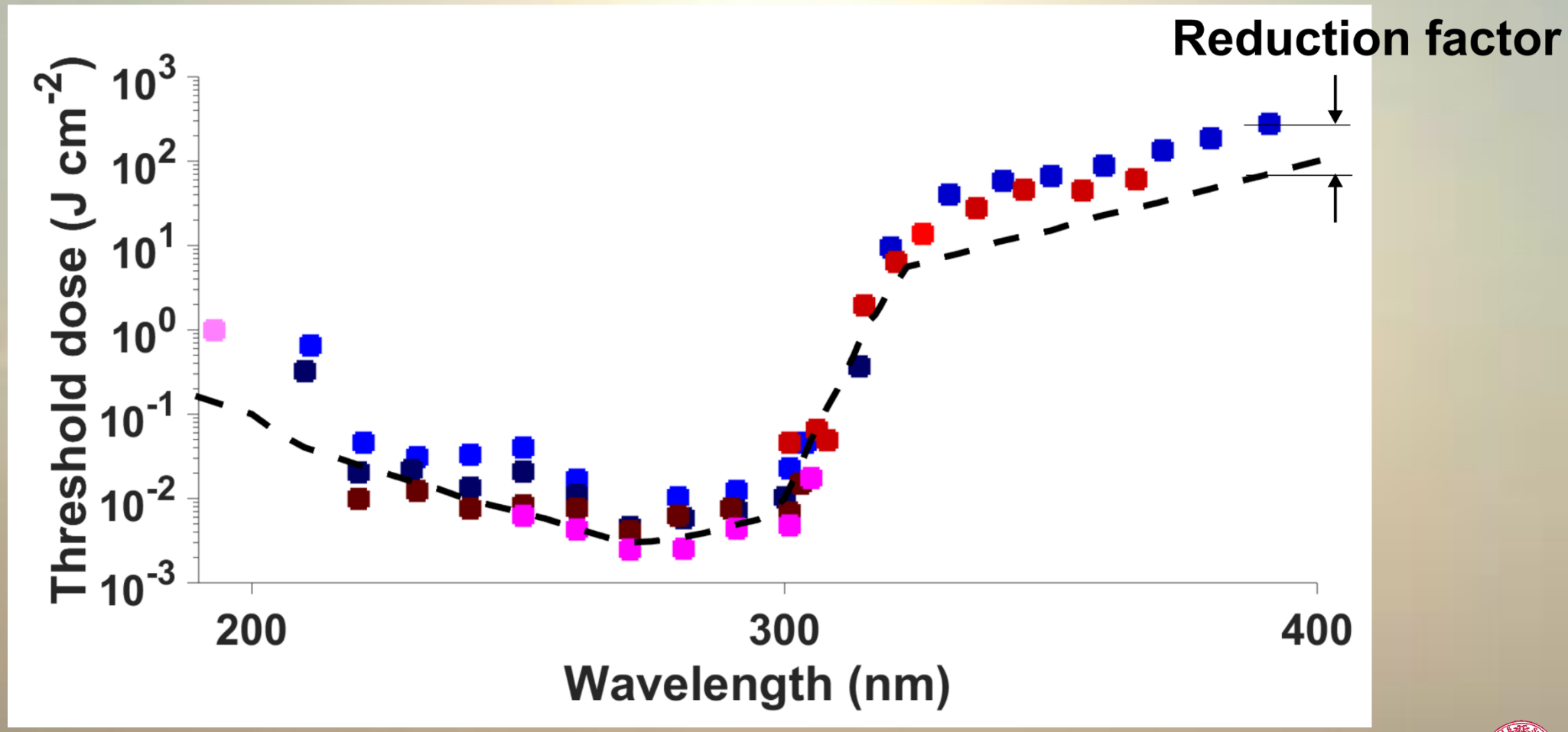
Exposure limits

Corneal action spectrum UVR



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Summary hazardous exposures

Damage mechanism	Critical tissue	Waveband	Exposure time	EL unit
Photochemical	Optical media and retina	UVR, Blue light	ms-days	$J\ m^{-2}$ $J\ sr^{-2}\ m^{-2}$ J
Photothermal	Optical media and retina	UVR, VIR, IRR	µs-ms	$W\ m^{-2}$ $W\ sr^{-2}\ m^{-2}$ W s radians
Photoablation	Cornea	UVR, IRR	ms-ns	$J\ m^{-2}$
Photodisruption	All media	VIR, near-IRR	ns-fs	J

Safe expsure: Lowest exposure limit wins

General protection – Source awareness

Laser classification

Class I: < 40 μW: Never hazaardous but glare

Class II: < 1 mW: Visible, aversion reflex (10-20 s) protects

Class IIIa: < 5 mW: Visible, blink reflex (0.25 s) protects

Class IIIb: < 500 mW: Direct exposure dangerous

Class IV: > 500 mW: Even reflexes dangerous

General protection - Laser safety goggles

Courtesy Pascal Rol

General protection - Sunglasses

EN 1836 (2005) Sunglasses and sunglare filters for general use

Filter categories

- 0: Non or very limited attenuation (T_v=80-100 %)
- 1: Light attenuation (T_v=43-80 %)
- 2: Moderate attenuation (T_v=18-43 %)
- 3: Substantial attenuation (T_v=8-18 %)
- 4: Expressed attenuation (T_v=3-8 %
  Unsuitable for driving

Protection for specific exposures

ICNIRP Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 100 nm and 400 nm (INCOHERENT OPTICAL RADIATION)

Health Physics 2004;87:171-186

ICNIRP Guidelines on limits of exposure to incoherent visible and infrared radiation

Health Physics 2013;105:74-91

(380 nm 1000 μm)

ICNIRP Guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1000 μm

Health Physics 2013;105:271-295