The OSA NonImaging Optical Design Technical Group Welcomes You

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Technical Group at a Glance

- ## Focus
  - Design and characterization of illumination systems using modeling techniques.
  - Non-sequential design techniques, including both software and tailoring methods provide the tools to design efficient optical components that provide the desired distribution at the target.
  - Typical applications include solar energy, lighting, and displays.
  - ## Mission
  - To benefit *YOU* and to strengthen *OUR* community
  - Webinars, podcasts, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.
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Today's Webinar

What is etendue, and why is it important?

Julius Muschaweck

CEO, JMO GmbH
julius@jmoptics.de

JMO
Illumination Optics

Speaker's Short Bio:
Julius Muschaweck, a German physicist, has been working on optical design for illumination for over twenty years. After a stay as Visiting Scholar at the University of Chicago with Prof. Roland Winston (well known as the originator of Nonimaging Optics), he was co-founder and CEO of OEC, an optical engineering service which pioneered freeform optics. Later, at OSRAM, where he held the position of Senior Principal Key Expert (the highest rank in the OSRAM/Siemens expert career), he coordinated the over 100 optical designers within OSRAM world-wide. He then joined ARRI, the leading movie camera and lamp head maker, as Principal Optical Scientist. Julius Muschaweck now works as an independent consultant, providing illumination optics solutions to industry clients, teaching courses on illumination optics, and writing about the subject.

Illumination Optics

Étendue

What is it? And why is it so useful?

Julius Muschaweck

OSA Webinar, July 17th, 2019

What is étendue?

A French word:

étendue

[etɑ̃dy]

FEMININE NOUN

1. *[d'eau, sable]* stretch ♦ expanse

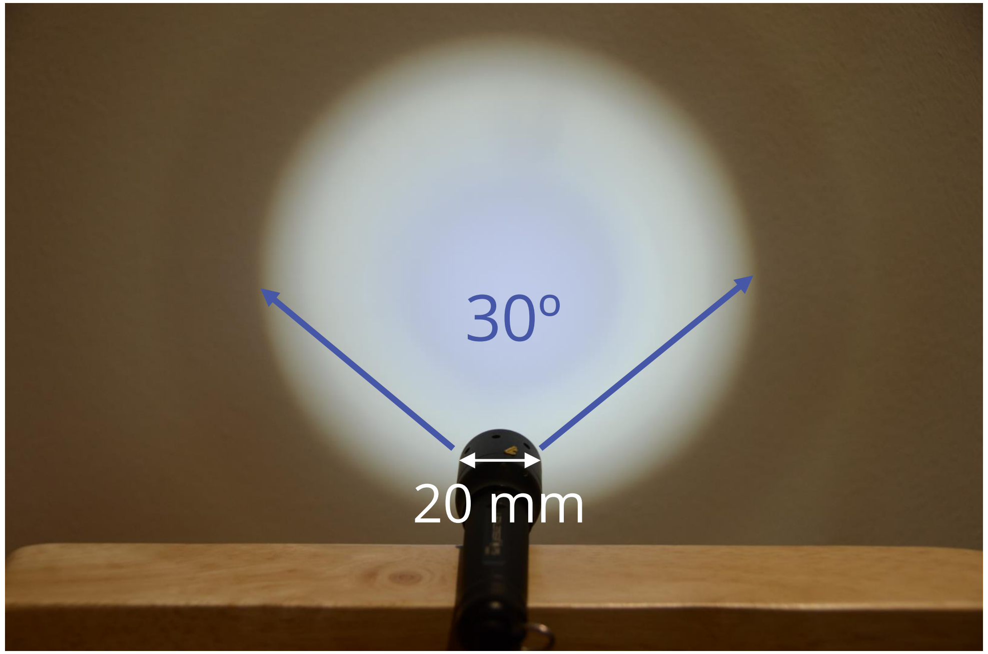
2. *[de problème]* extent

Source: Harper Collins

What is étendue?

Illumination Optics

- A purely geometric quantity
- The expanse, extent of a beam of light
- „Large“ beam ⇔ large cross section area
  ⇔ large angular spread
- Étendue = something like (area × solid angle)

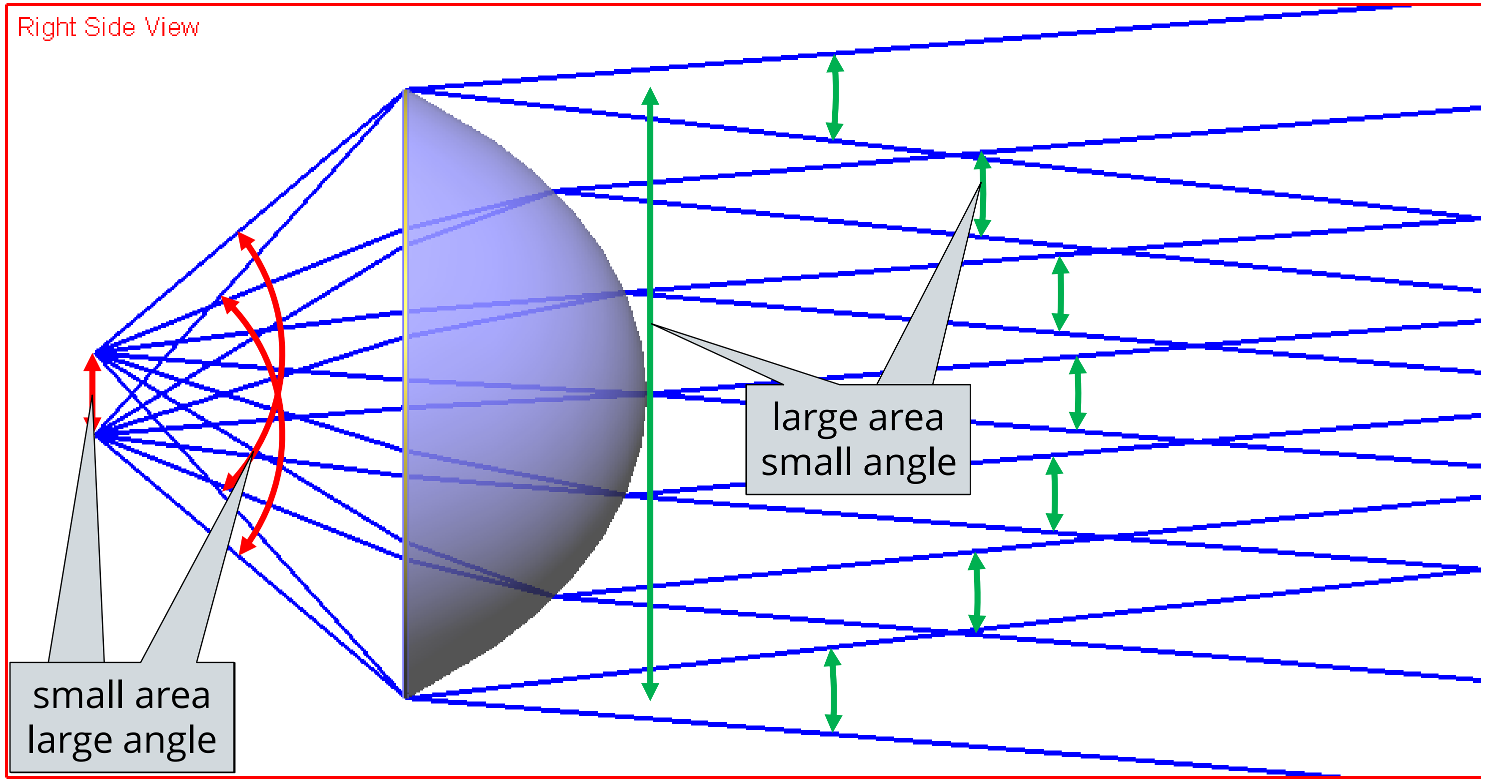


What is special about étendue?

„Étendue is conserved“

That‘s what some people say.

And it‘s true, in a sense...



A riddle

Xenon flash tube

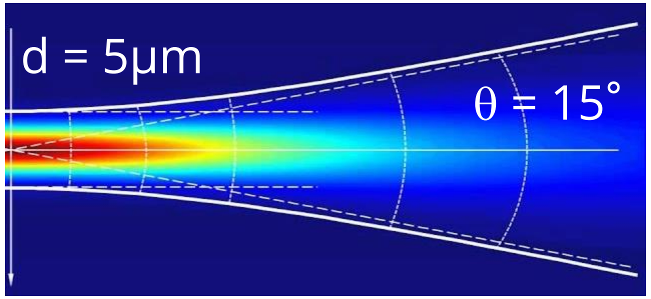
cylinder surface area = 1320 mm²
beam angle ± 90°

+

Lenses, mirrors, prisms, beam splitters

=

Narrow (Gaussian) beam
Optical effiency > 20%



area = 0.00002 mm²
beam angle ± 7.5°

Source: dhgate.com, Edmund Optics, RWTH Aachen, canstockphoto

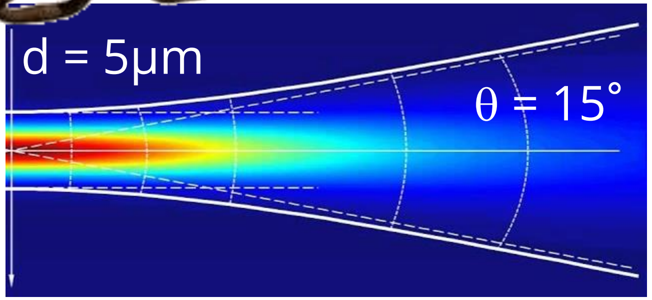
A riddle

Xenon flash tube

cylinder surface area = 1320 mm²
beam angle ± 90°

Lenses, mirrors,
prisms, beam splitters

Narrow (Gaussian beam)
Optical efficiency > 20%



area = 0.00002 mm²
beam angle ± 7.5°

Source: dhgate.com, Edmund Optics, RWTH Aachen, canstockphoto

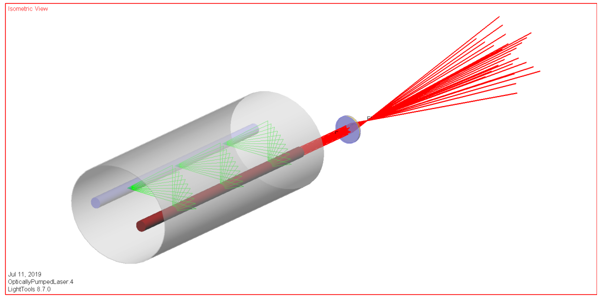
A riddle

Xenon flash tube

cylinder surface area = 1320 mm²
beam angle ± 90º

\+

Elliptical mirror,
Nd-YAG rod, lens



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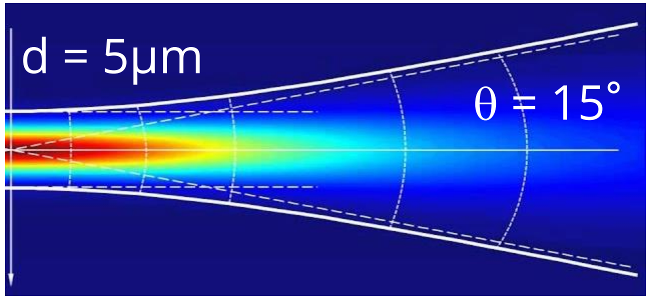
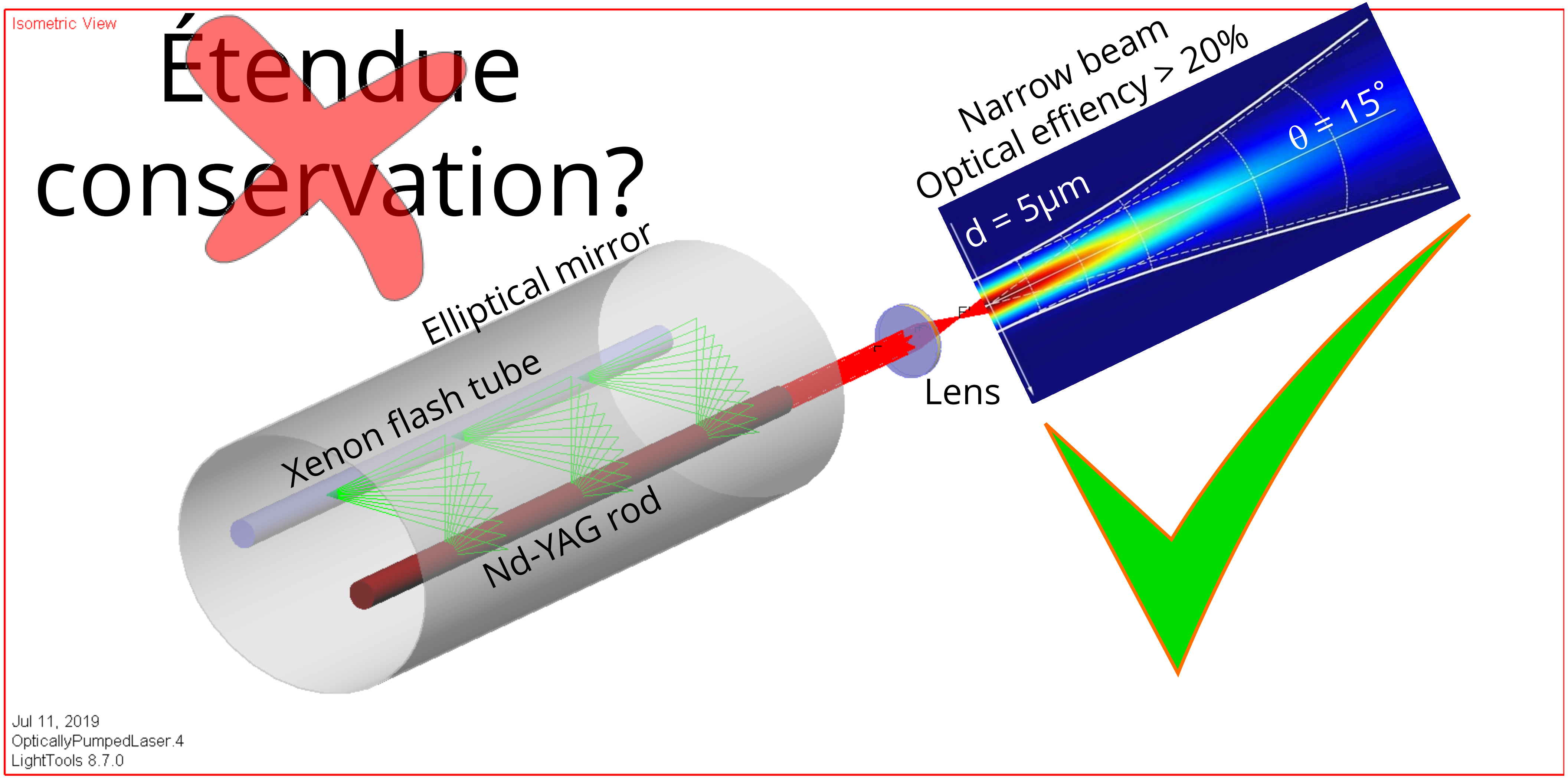
Narrow beam
Optical effiency > 20%



area = 0.00002 mm²
beam angle ± 7.5º

Source: dhgate.com, Edmund Optics,
RWTH Aachen, canstockphoto

A riddle

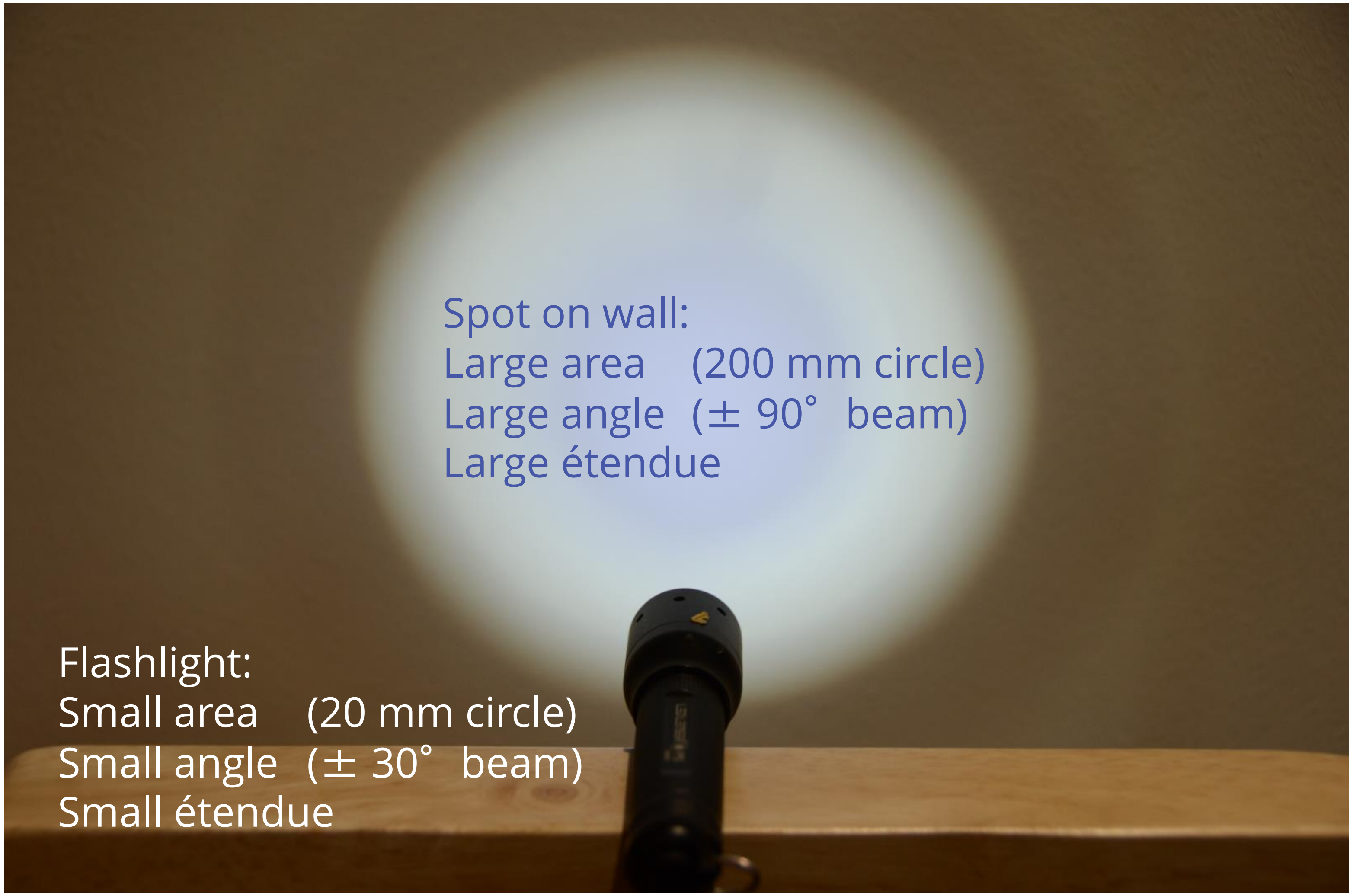


Source: dhgate.com, Edmund Optics, RWTH Aachen, canstockphoto

Another riddle

Just a flashlight and a wall

Étendue conservation?



A third riddle

At X-Prism:

Three sides input (R,G,B)

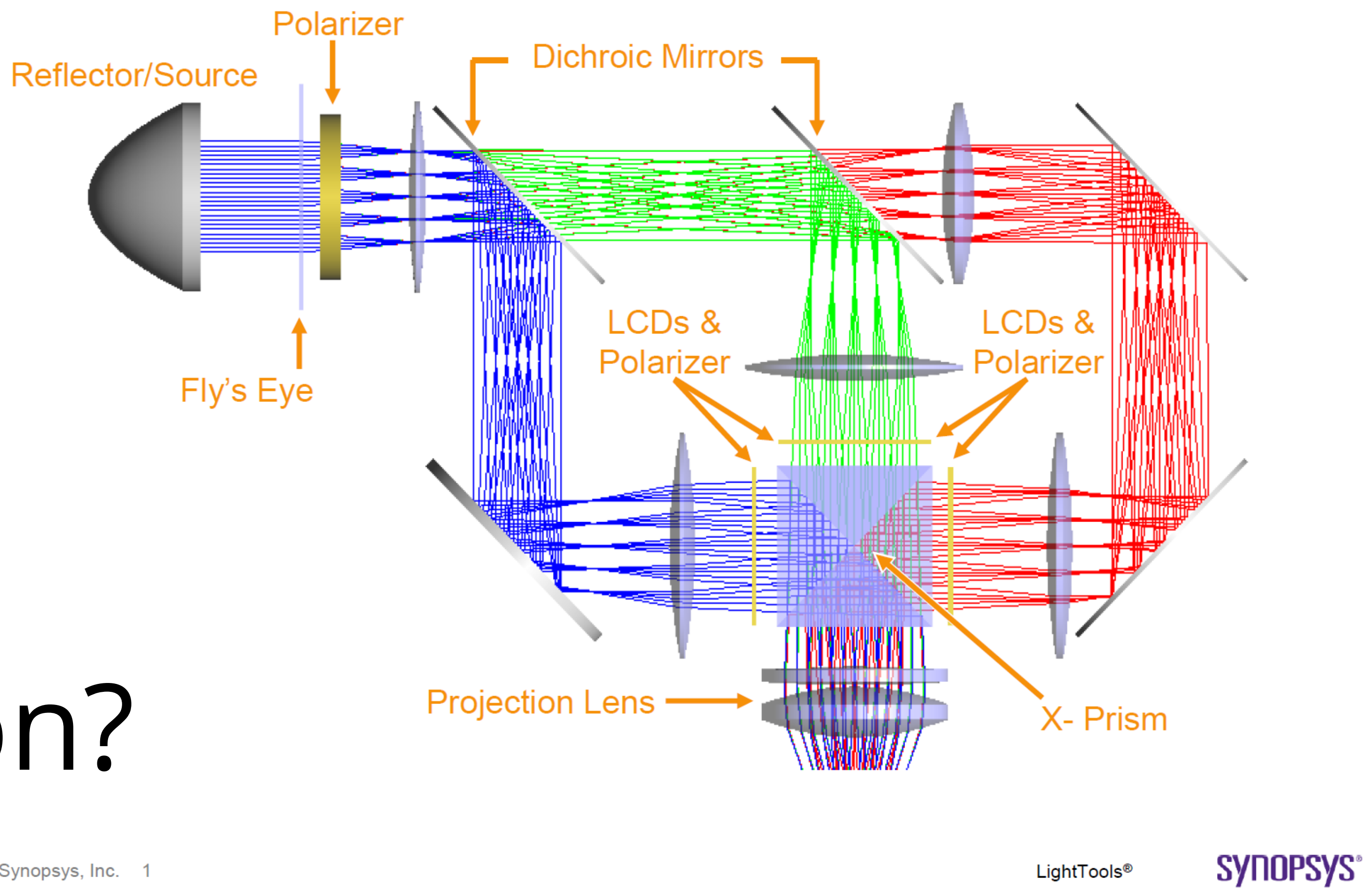
One side output (white)

All four areas equal

All beam

Étendue(

Étendue conservation?



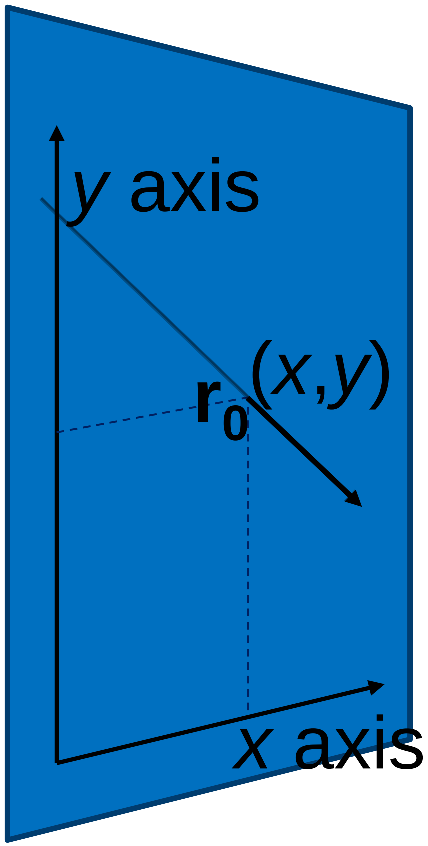
So what's the story about étendue?

Ray coordinates: Starting point

Starting point in space:

Global coordinates

Three numbers: $\boldsymbol{r_0} = (x_g, y_g, z_g)$



Starting point on screen:

Local surface coordinates

Two numbers (x, y)

Ray coordinates: Starting point

Starting point in space:

Global coordinates

Three numbers: $\boldsymbol{r_0} = (x,y,z)$

Starting point on surface:

Local surface coordinates

Two numbers (x,y)

For location:

Two numbers,

x, y

Ray coordinates: Direction vector

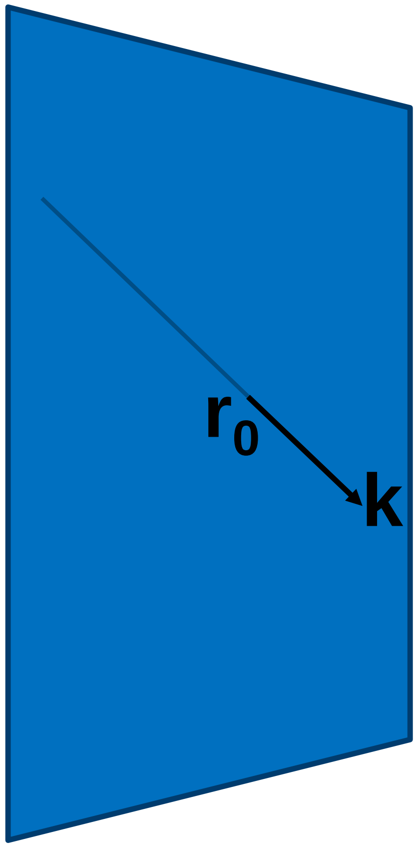
Direction vector in space:

Global coordinates

Three numbers: $\boldsymbol{k} = (k_x, k_y, k_z)$

Two should suffice!

But which two?



Normalized direction vector, local surface coordinates

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Normalization by refractive index:

$|\mathbf{k}| = n$ in material $\Rightarrow$ $|\mathbf{k}| = 1$ in vacuum

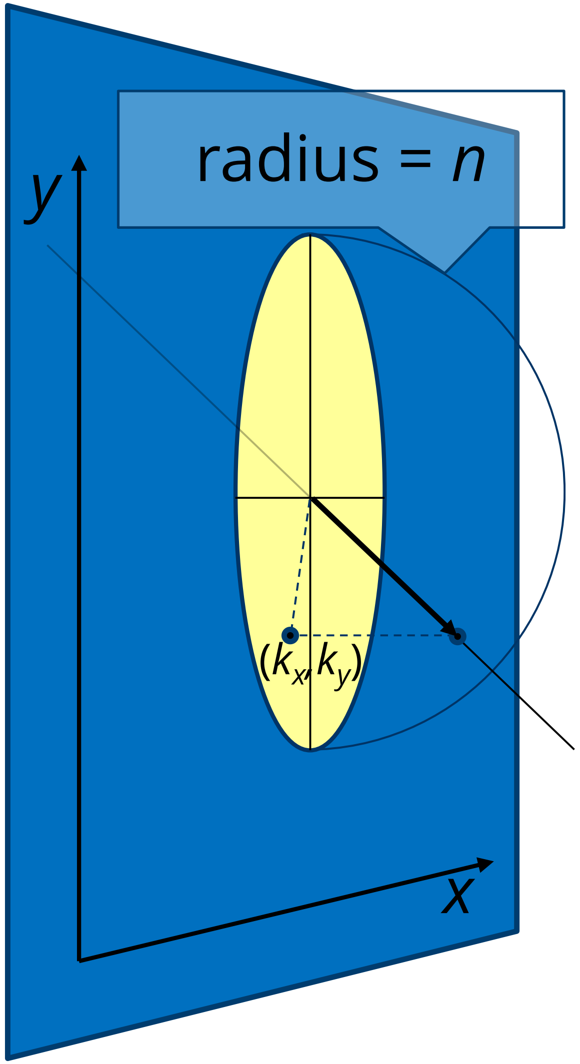
Local surface coordinates:

$k_x \| x \qquad k_x \| y \qquad k_z \| z$

No need for $k_z = \pm\sqrt{n^2 - k_x^2 - k_y^2}$

with **oriented** surface ($k_z > 0$)

$k_x,\ k_y$ sufficient!



Normalized direction vector, local surface coordinates

Normalization:

$|\mathbf{k}| = 1$ in vacuum $\Rightarrow$ $|\mathbf{k}| = n$ in material

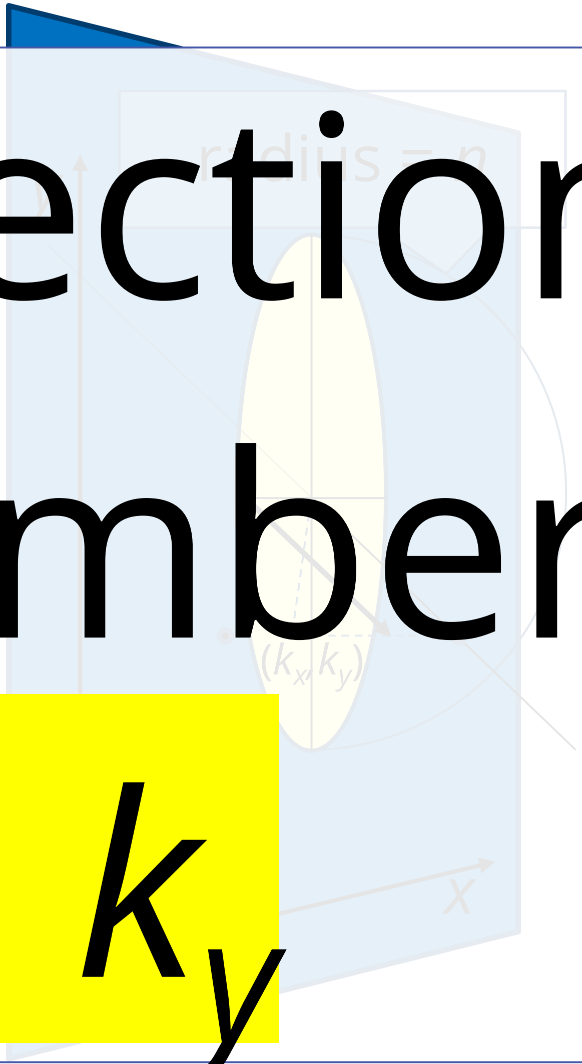
Local surface coordinates:

$k_x \| x \quad k_x \| y \quad k_z \| z$

No need for $k_z = \pm\sqrt{n^2 - k_x^2 - k_y^2}$

with oriented surface

$\Rightarrow k_x, k_y$ sufficient



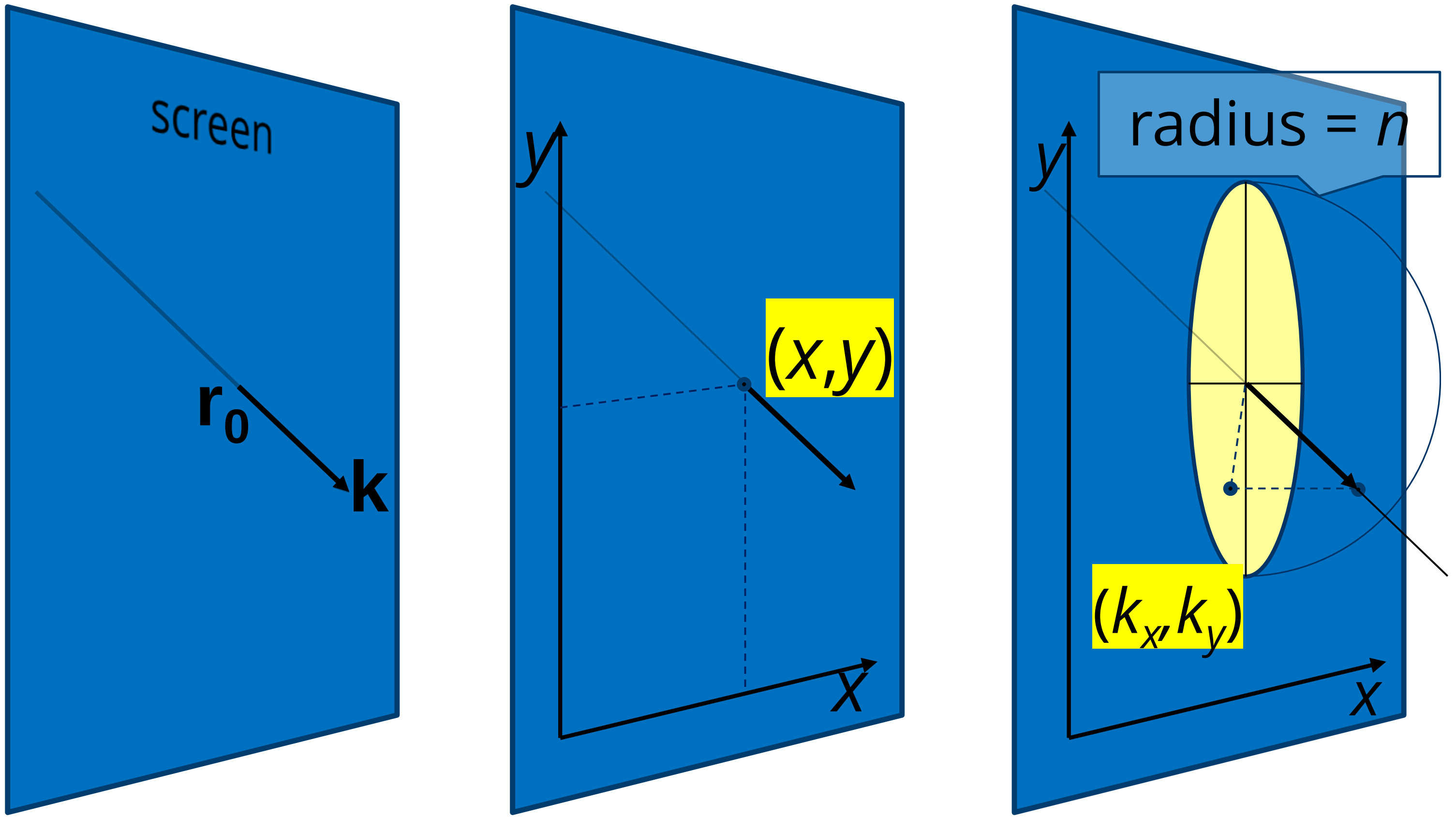
For direction:

Two numbers,

$k_x, \ k_y$

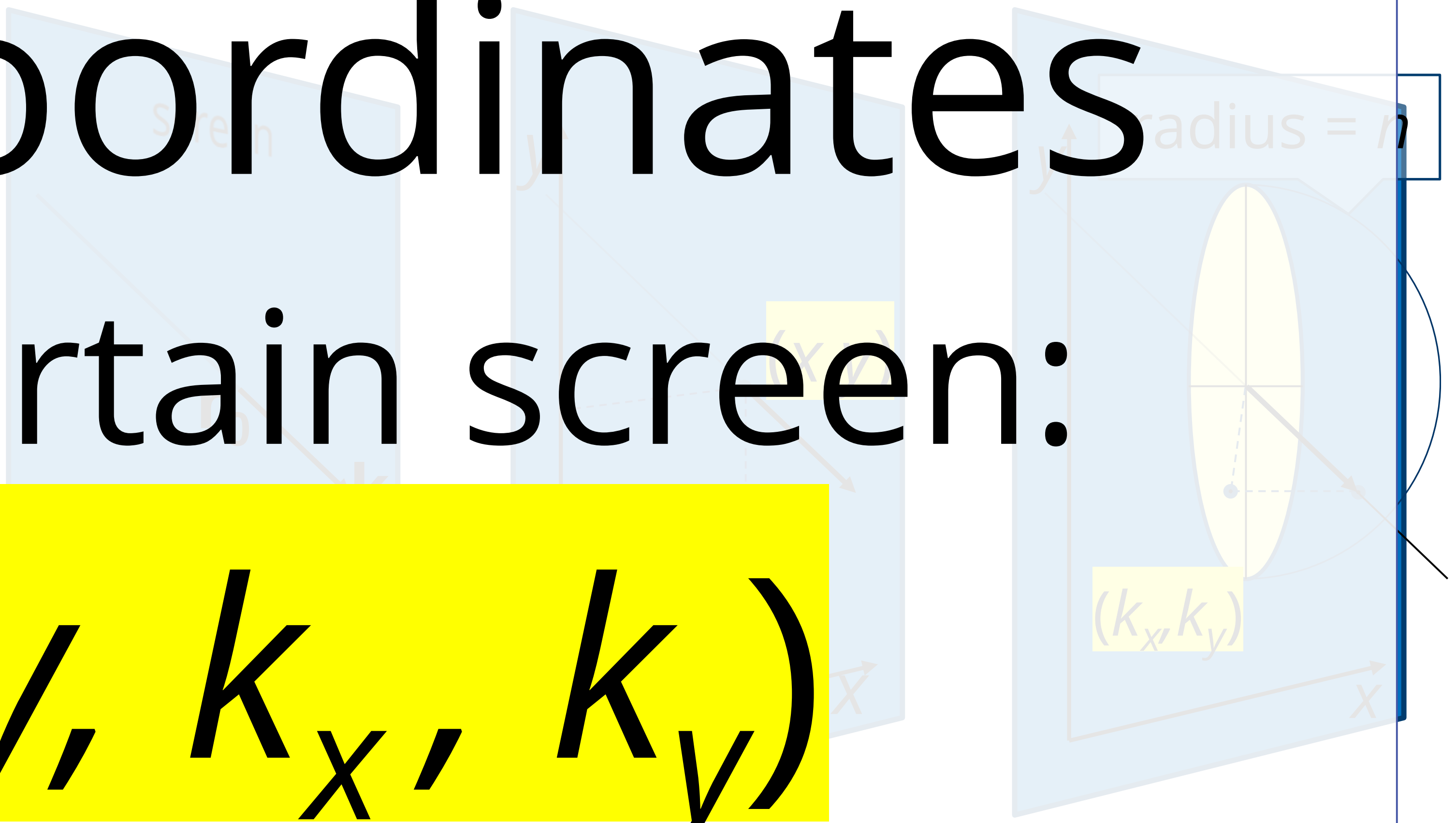
From 3D ray to 4D ray coordinates

1. Select screen
2. Define x-y coordinate system
3. Use (x,y) of ray intersection as location coordinates
4. Attach tangent hemisphere, radius n
5. Define k vector, $k = (k_x, k_y, k_z), \quad |k| = n$ by intersecting hemisphere
6. Obtain (k_x, k_y) by projection, use as direction coordinates
7. Voilà: Ray coordinates: (x, y, k_x, k_y)



From 3D ray to 4D ray coordinates

1. Select screen
2. Define x-y coordinate system
3. Use (x,y) of ray intersection as location coordinates
4. Attach tangent disk, radius n
5. Define k vector, $k = (k_x, k_y, k_z)$, by intersecting hemisph…
6. Use (k_x, k_y), by projectio… as direction coordinate…
7. Voilà: Ray coordinates: (x, y, k_x, k_y)

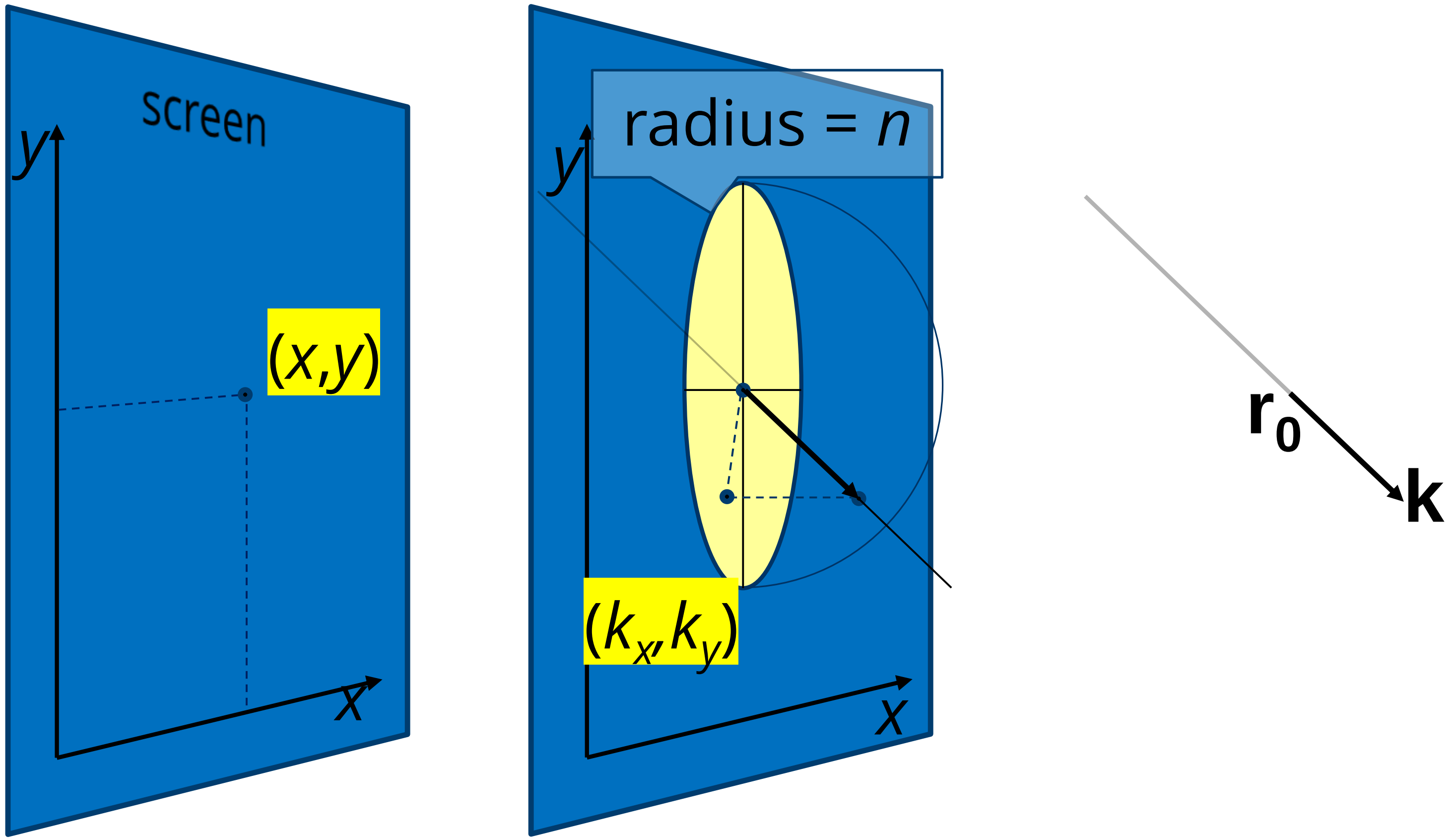


Ray coordinates on a certain screen:

$$(x, y, k_x, k_y)$$

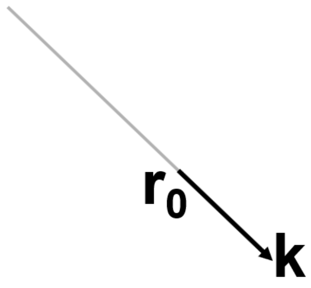
From 4D ray coordinates to 3D ray

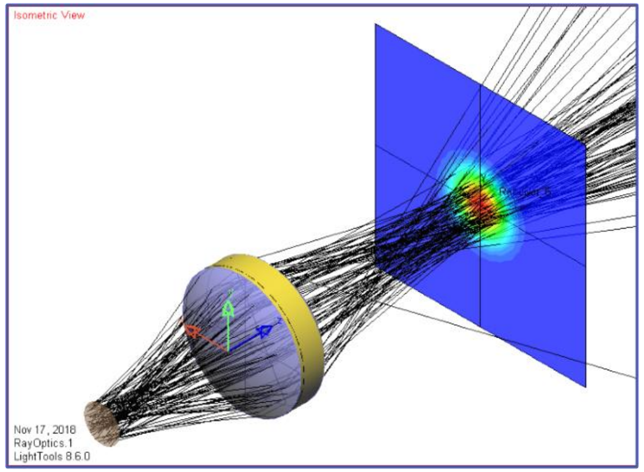
1. A ray is given by a screen and ray coordinates (x, y, k_x, k_y)
2. Determine starting point $\mathbf{r_0}$ from surface geometry, coordinate system and (x,y)
3. Attach tangent disk at $\mathbf{r_0}$, radius=n
4. Find point on disk with (k_x, k_y)
5. Raise this point up to hemisphere to find $\mathbf{k}$
6. 3D Ray:
   $\mathbf{r} = \mathbf{r}_0 + \mu\, \mathbf{k} \quad (\mu \in \mathbb{R}, \mu \geq 0)$



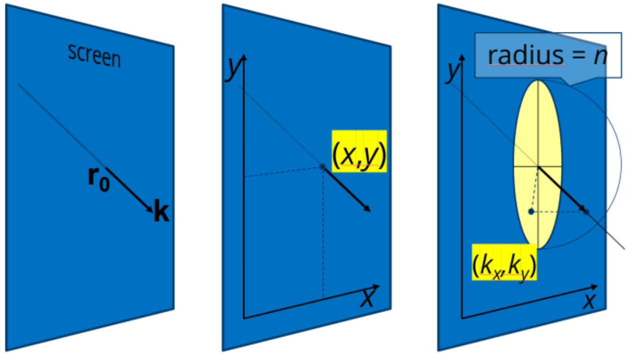
The bridge

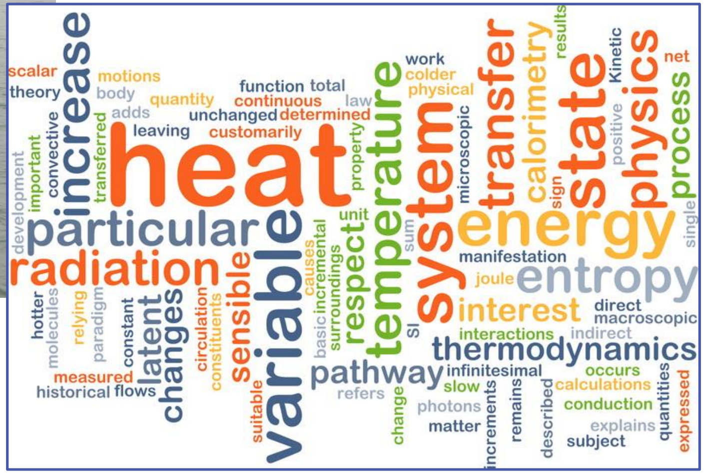
3D real world





4D phase space





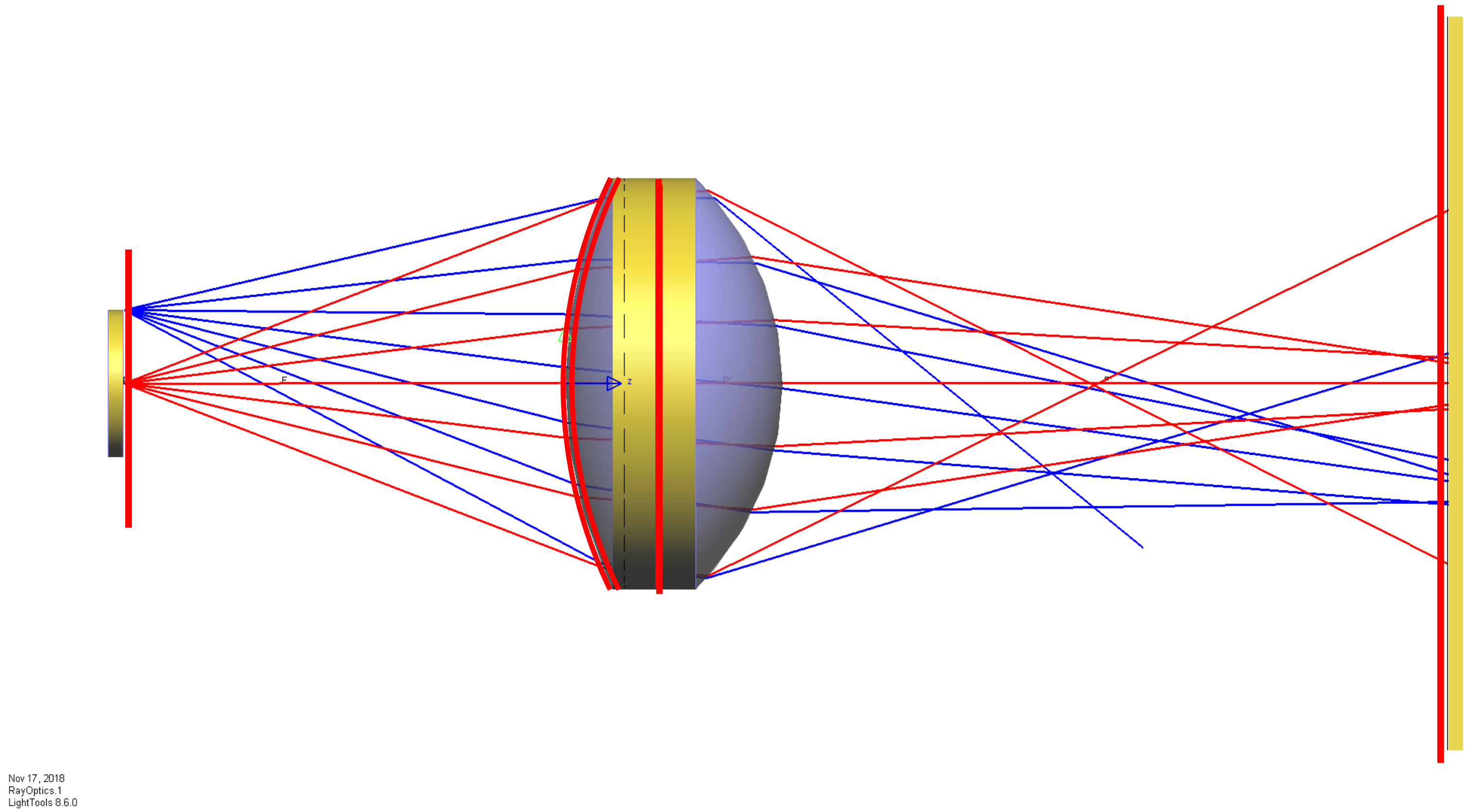
A closer look at screens

Screen ≠ optical surface (!!)

Choose freely, choose wisely

As many as you like

Not necessarily planar



What is phase space?

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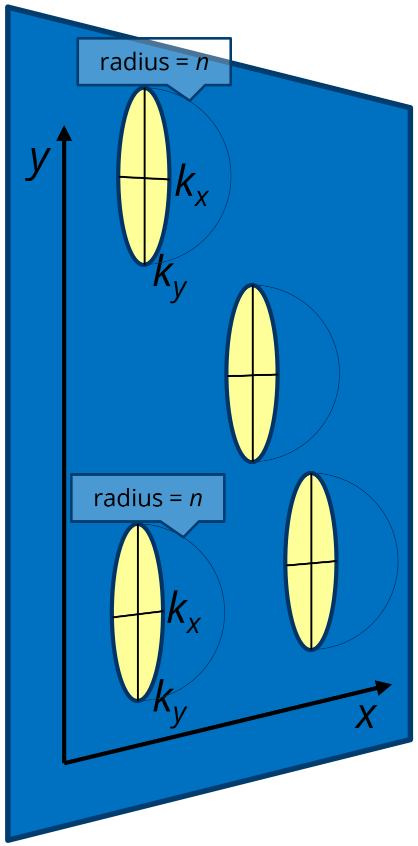
- Choose screen
- Define coordinate system for x, y, k_x, k_y
- „Allowed“ values:

  x, y such that (x,y) within surface boundary

  k_x, k_y such that $\sqrt{k_x^2 + k_y^2} < n$ i.e. within disk

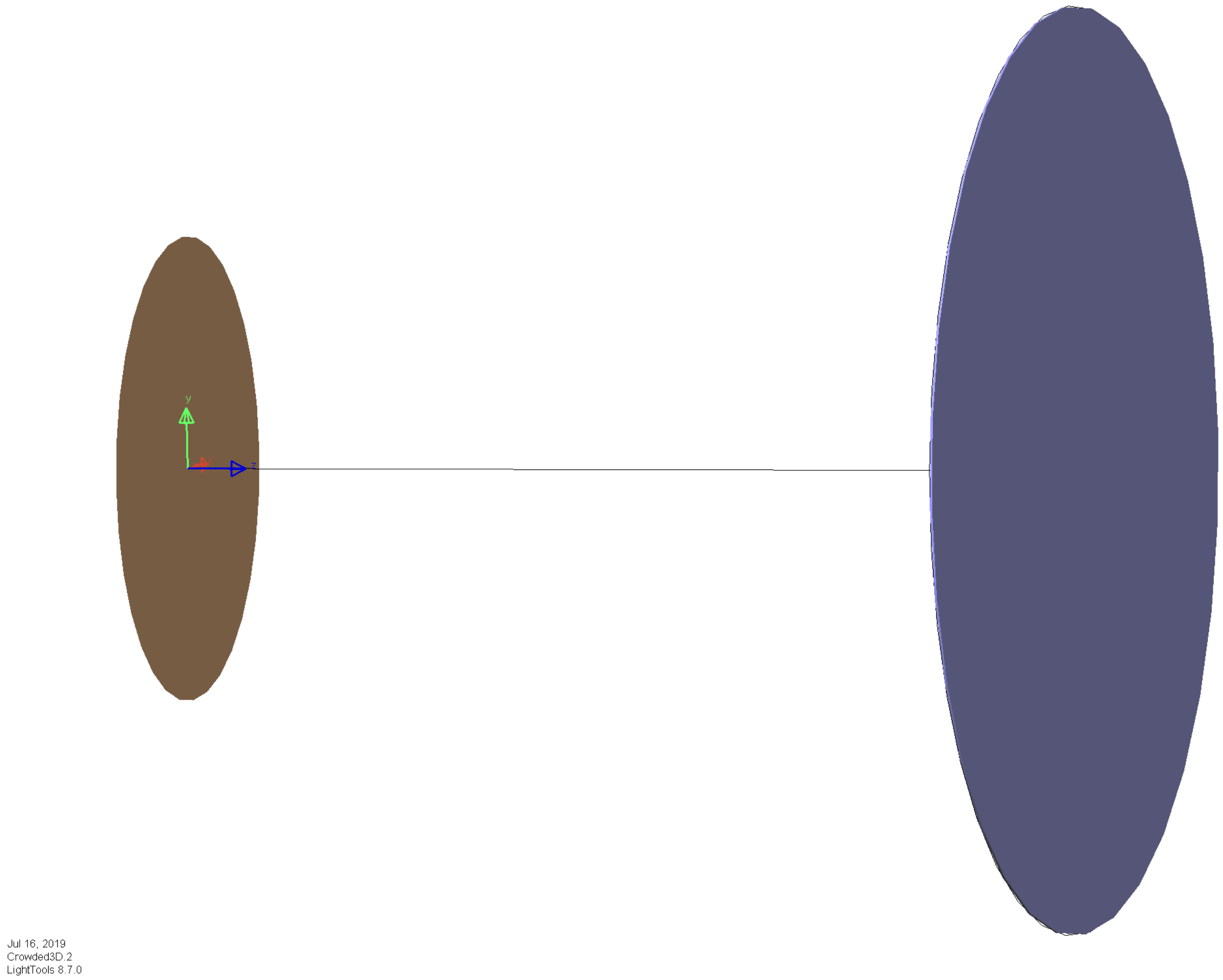


All allowed (x, y, k_x, k_y) naturally form a 4D space

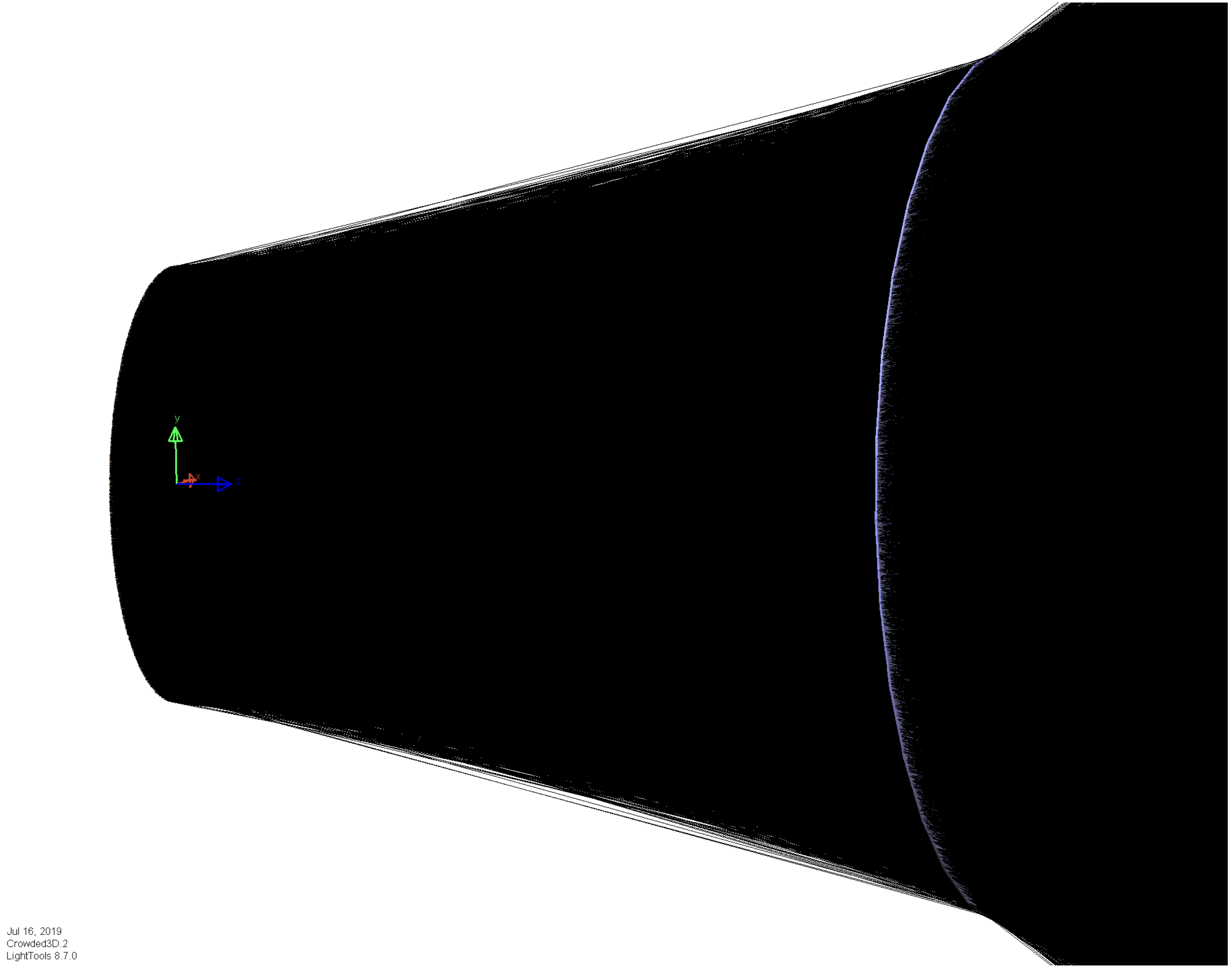
Each allowed (x, y, k_x, k_y) corresponds to a 3D ray

3D rays are points in 4D phase space

3D space: pretty crowded

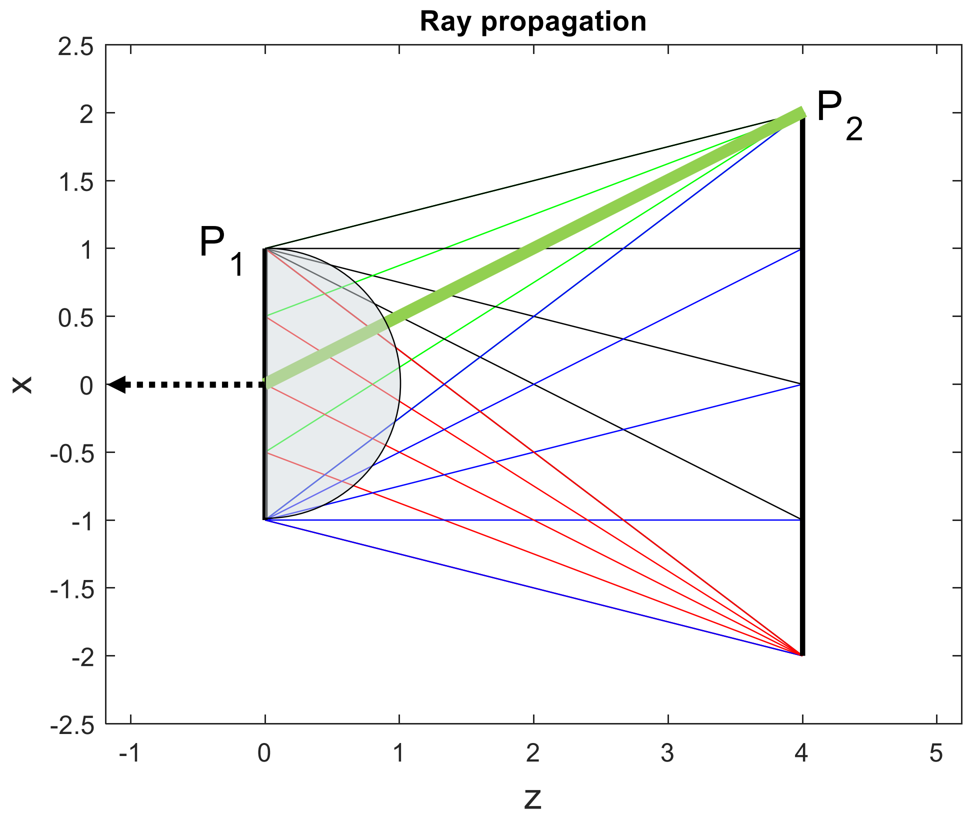


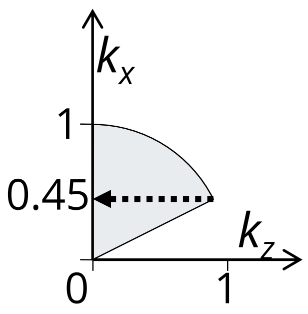
3D space: pretty crowded

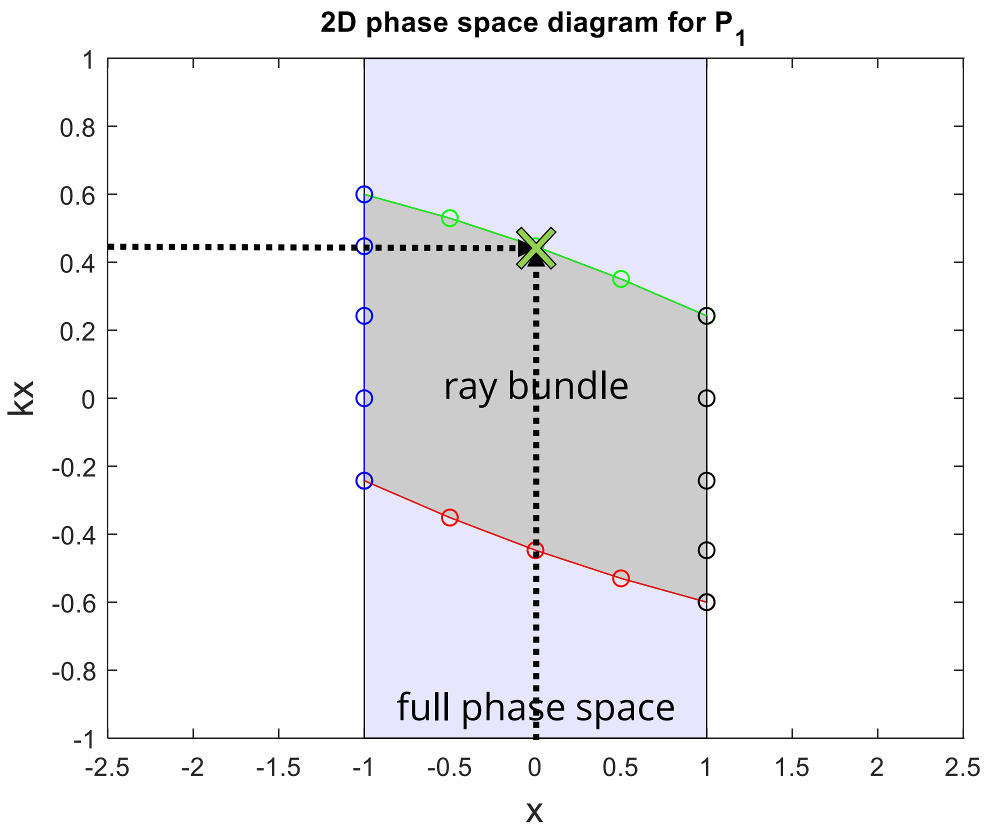


Visualizing 4D: 2D phase space diagrams

Illumination Optics



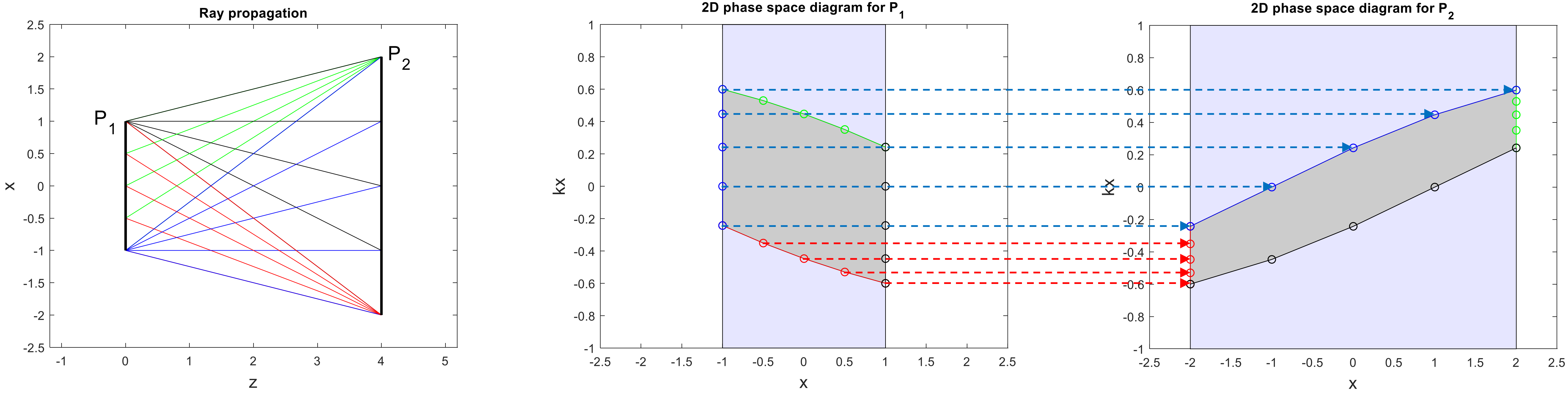




Ray bundles: Nonzero volume regions of phase space

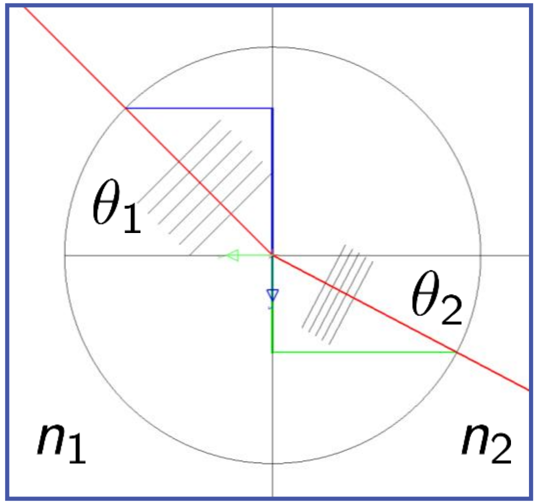
2D phase space diagrams: propagation

Free propagation in 3D = **shear** in 2D / 4D



2D area: conserved under free propagation

Refraction in phase space

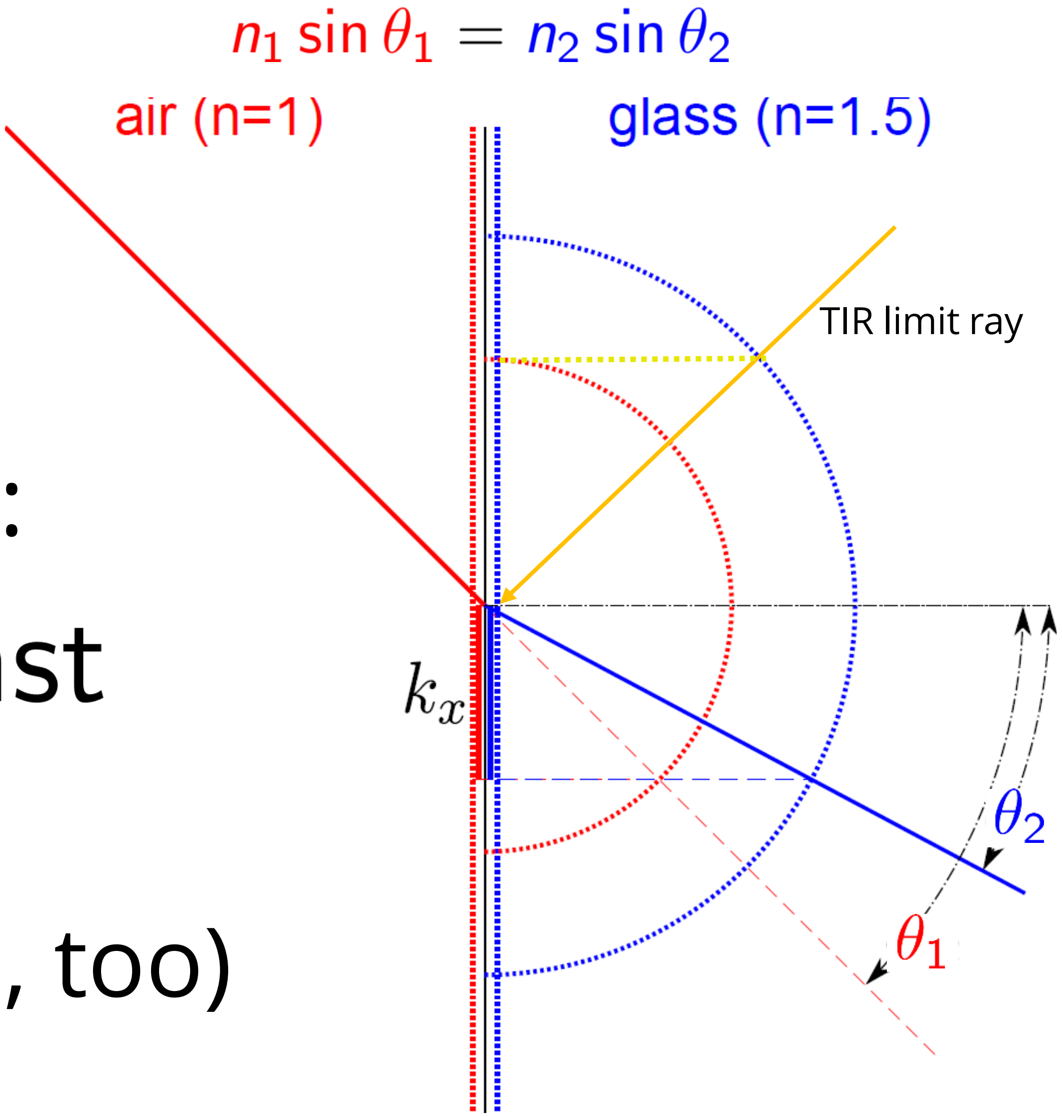


$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Under refraction:

$$(k_x, k_y) = \text{const}$$

(under reflection, too)



Refraction: 2D phase space diagram

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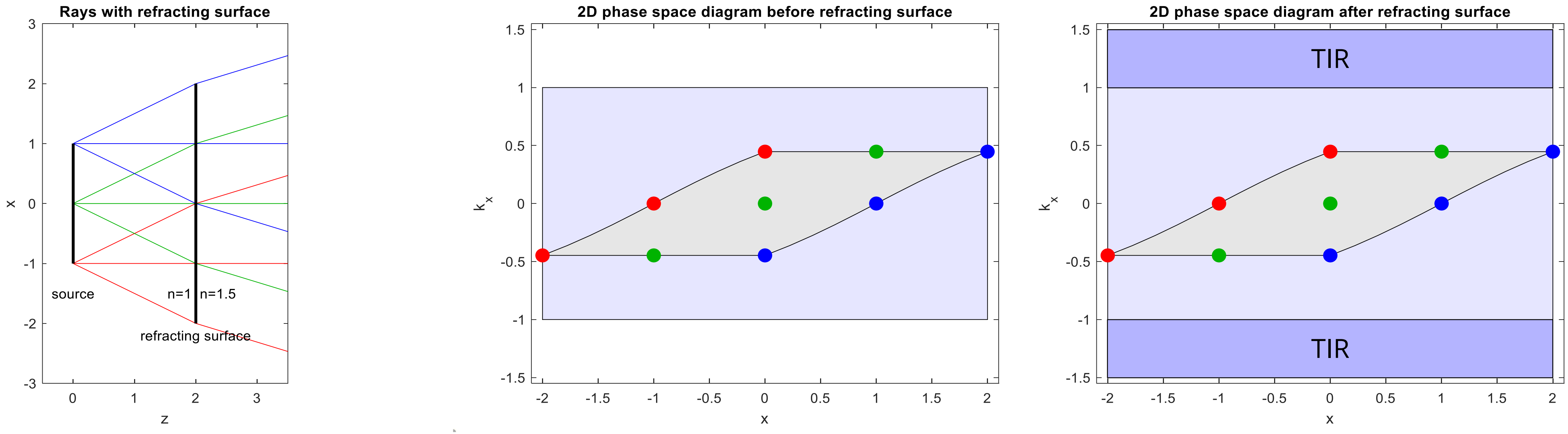
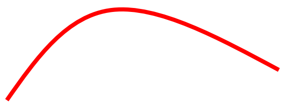
No change of ray coordinates in phase space ⇒ identical ray bundles

Ray directions change, k_x values change not!

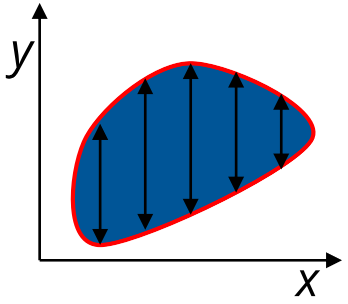
Total phase space volume changes, ray bundle volume changes not!



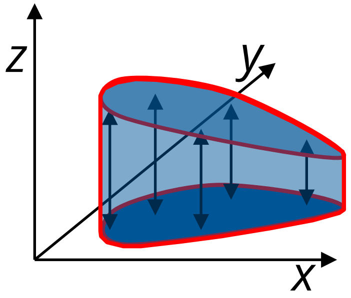
Volumes in 1D, 2D, 3D, ...



$$V_{1D} = \text{path length} = \int dl$$

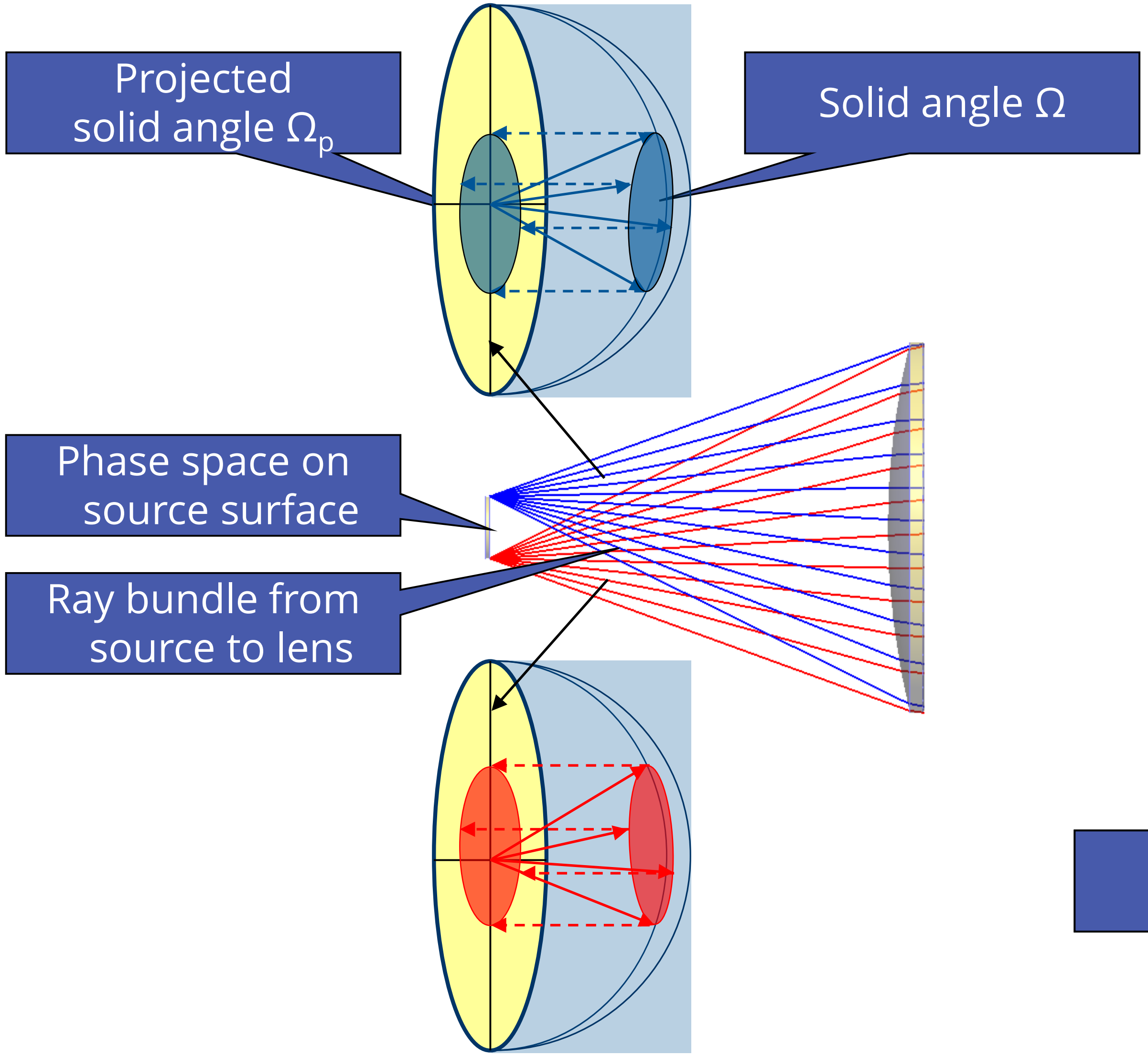


$$V_{2D} = \text{area} = \iint dA = \iint dx\,dy = \int h(x)dx$$

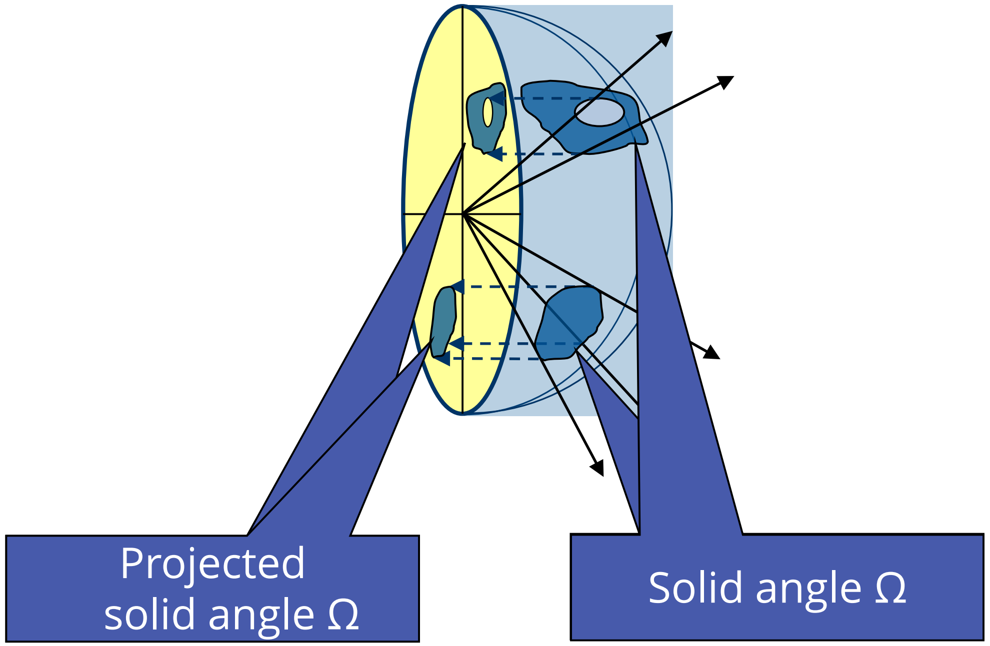


$$V_{3D} = \text{volume} = \iiint dV = \iint h(x,y)dA$$

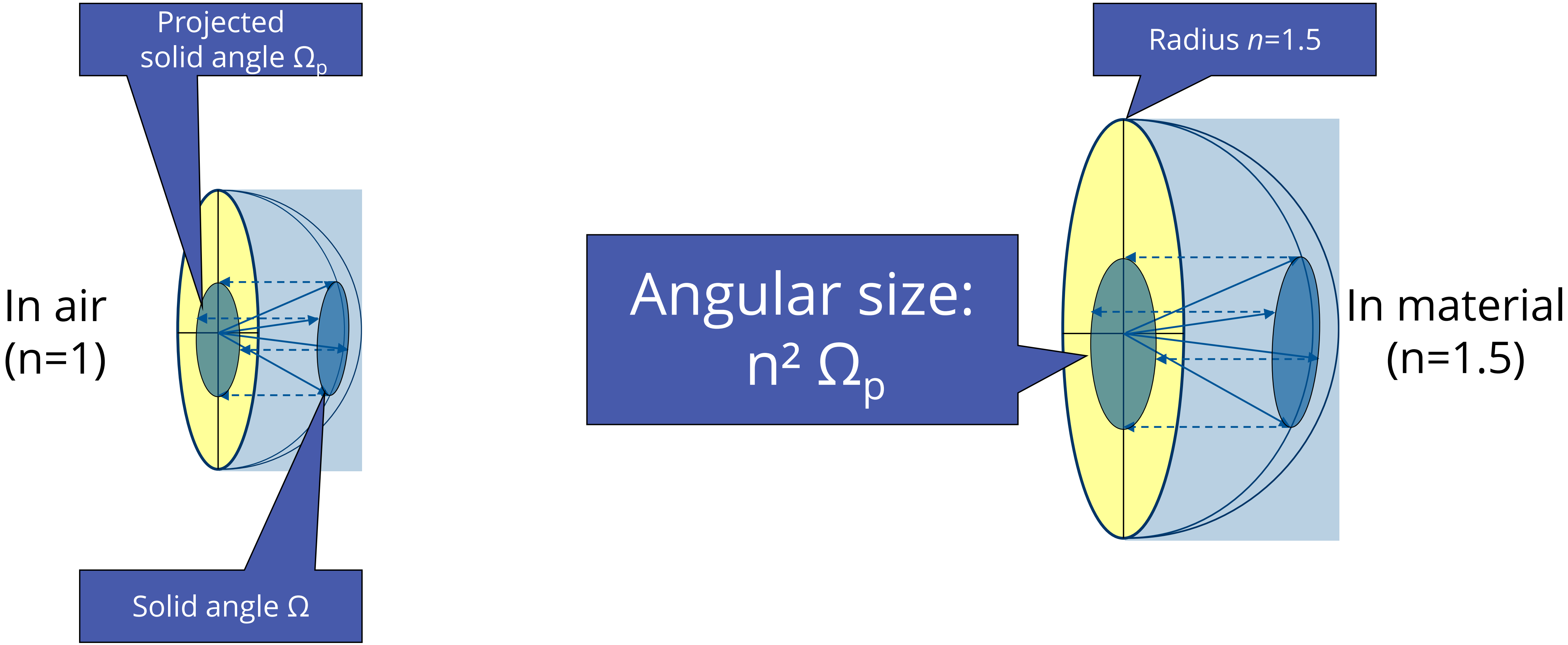
From 2D to 4D: Projected solid angle Ω_p



In general: anything

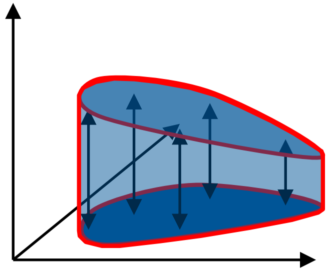


From 2D to 4D: Refractive index



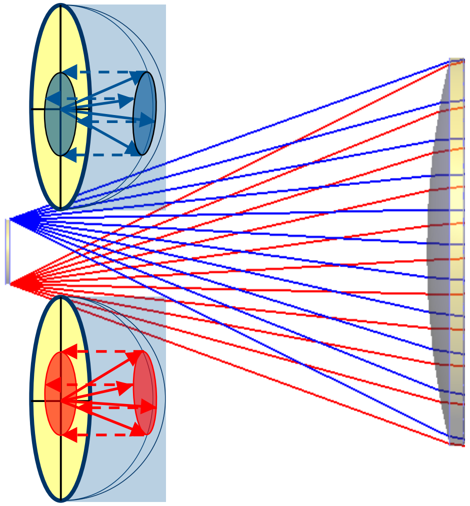
Volume in 4D

Classical volume in 3D: Integrate **height *h*(*x,y*)** over area



$$V_{3D} = \text{volume} = \iiint \mathrm{d}V = \iint h(x,y)\mathrm{d}A = \iiint \mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z$$

Phase space volume in 4D: Integrate **angular size n^2 Ω_p(*x,y*)** over area



$$V_{4D} = \iiiint \mathrm{d}U = \iint n(x,y)^2\Omega_p(x,y)\mathrm{d}A = \iiiint \mathrm{d}x\,\mathrm{d}y\,\mathrm{d}k_x\,\mathrm{d}k_y$$

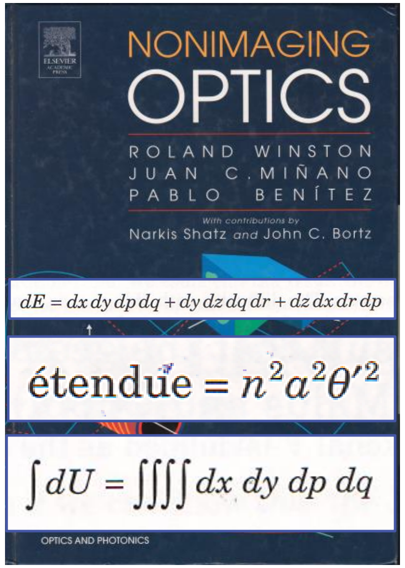
Étendue

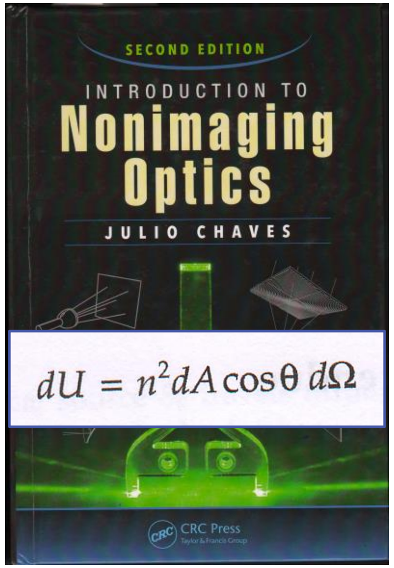
The name of this 4D volume: Étendue

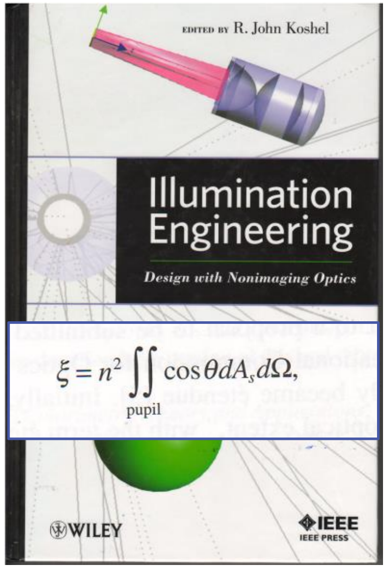
Physical units: m^2 sr or mm^2 sr

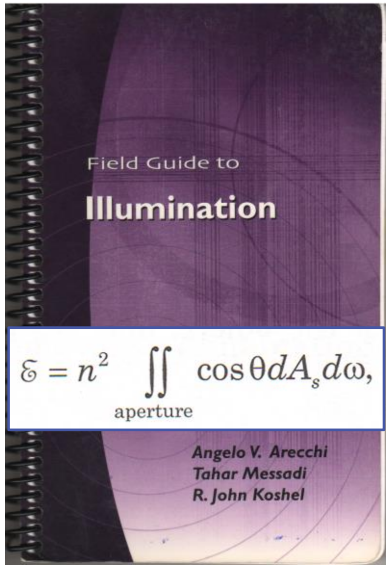
The symbol?

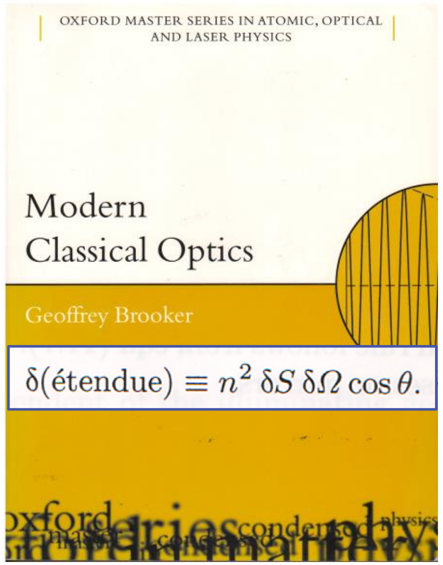
U







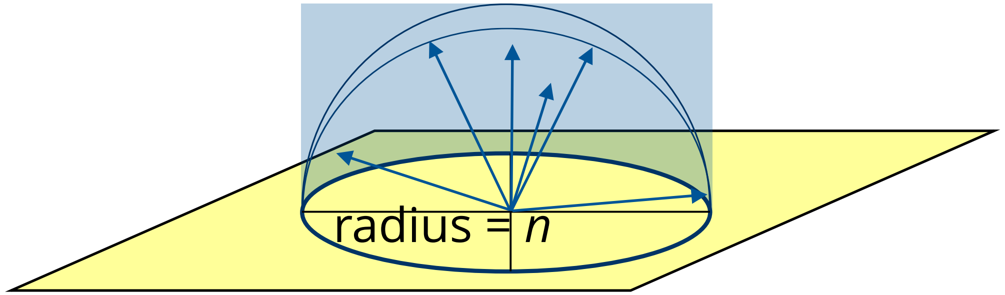




Étendue in simple cases: constant angular range

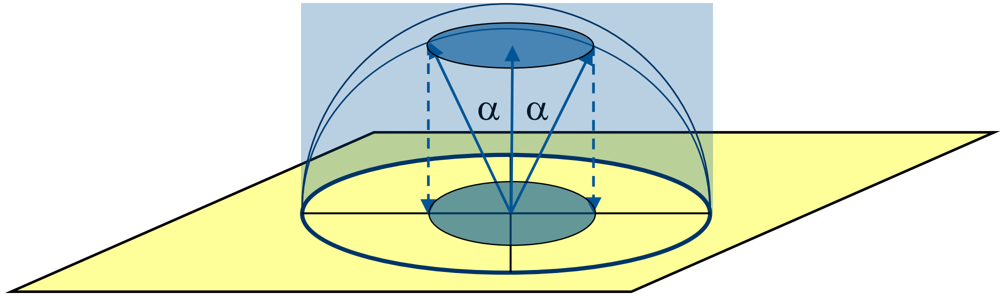
The full phase space volume
(from screen into full hemisphere)

$$U = \pi n^2 A$$



Far field collimator: From screen
into cone with half opening angle α

$$U = \pi (n \sin \alpha)^2 A$$



NB: „into cone with ± α" applies to **each screen point individually**

Example: A zoomable flashlight

Question: What LED size is ok?

Answer:

1. Compute beam étendue
   (large area, small angle)
2. Assume equal LED étendue
3. Assume ± 90° LED emission
4. Compute LED area

Example: A zoomable flashlight: flood mode

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Étendue of beam

```
d_Beam = 20; % mm
alpha_Beam = 30 * pi/180 % radians
```

```
alpha_Beam = 0.5236
```

```
A_Beam = (d_Beam/2)^2 * pi % mm²
```

```
A_Beam = 314.1593
```

```
n_Beam = 1; % refractive index
angularRange_Beam = (n_Beam * sin(alpha_Beam))^2 * pi;
U_Beam = A_Beam * angularRange_Beam % mm² sr
```

```
U_Beam = 246.7401
```

Max. LED size:
10 mm circle

Area of LED

Assume LED and beam have equal étendue

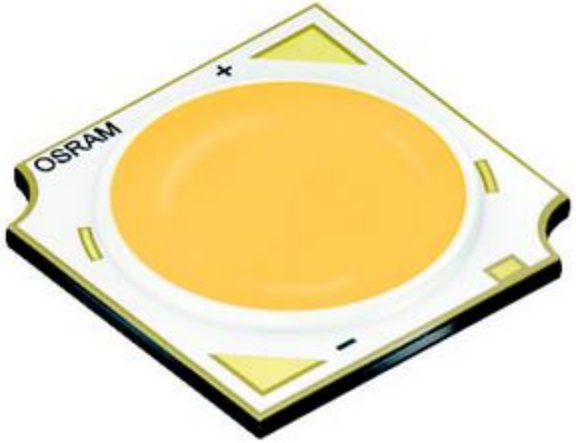
Assume LED has chip in air

```
n_LED = 1; % refractive index
angularRange_LED = n_LED^2*pi; % sr
U_LED = U_Beam;
A_LED = U_LED / angularRange_LED % mm²
```

```
A_LED = 78.5398
```

```
d_LED = 2 * sqrt(A_LED/pi) % mm diameter of circular LED
```

```
d_LED = 10
```



Source: OSRAM Opto Semiconductors

Example: A zoomable flashlight: spot mode

JMO Illumination Optics

Étendue of beam

```
d_Beam = 20; % mm
alpha_Beam = 5 * pi/180 % radians
```

```
alpha_Beam = 0.0873
```

```
A_Beam = (d_Beam/2)^2 * pi % mm²
```

```
A_Beam = 314.1593
```

```
n_Beam = 1; % refractive index
angularRange_Beam = (n_Beam * sin(alpha_Beam))^2 * pi;
U_Beam = A_Beam * angularRange_Beam % mm² sr
```

```
U_Beam = 7.4971
```

Area of LED

Assume LED and beam have equal étendue

Assume LED has chip in air

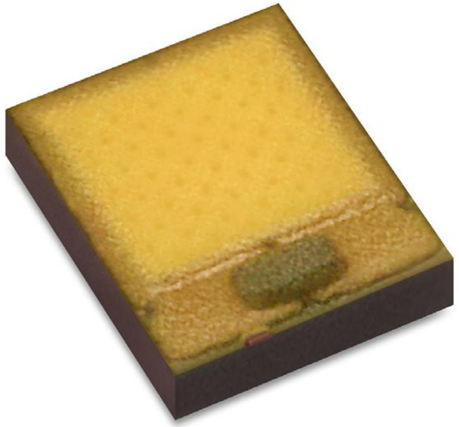
```
n_LED = 1; % refractive index
angularRange_LED = n_LED^2*pi; % sr
U_LED = U_Beam;
A_LED = U_LED / angularRange_LED % mm²
```

```
A_LED = 2.3864
```

```
d_LED = sqrt(A_LED) % mm edge length of square LED
```

```
d_LED = 1.5448
```

Max. LED size:
1.55 mm square



Source: Lumileds

Example: A zoomable flashlight: LED with dome

JMO Illumination Optics

Étendue of beam

```
d_Beam = 20; % mm
alpha_Beam = 5 * pi/180 % radians
```

```
alpha_Beam = 0.0873
```

```
A_Beam = (d_Beam/2)^2 * pi % mm²
```

```
A_Beam = 314.1593
```

```
n_Beam = 1; % refractive index
angularRange_Beam = (n_Beam * sin(alpha_Beam))^2 * pi;
U_Beam = A_Beam * angularRange_Beam % mm² sr
```

```
U_Beam = 7.4971
```

Max. LED size:
1.1 mm square

Area of LED

Assume LED and beam have equal étendue

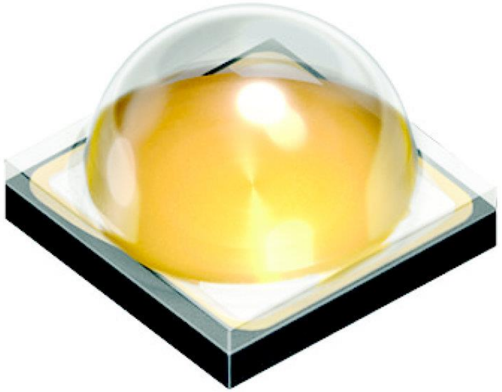
Assume LED has chip in silicone dome

```
n_LED = 1.41; % refractive index
angularRange_LED = n_LED^2*pi; % sr
U_LED = U_Beam;
A_LED = U_LED / angularRange_LED % mm²
```

```
A_LED = 1.2003
```

```
d_LED = sqrt(A_LED) % mm edge length of square LED
```

```
d_LED = 1.0956
```



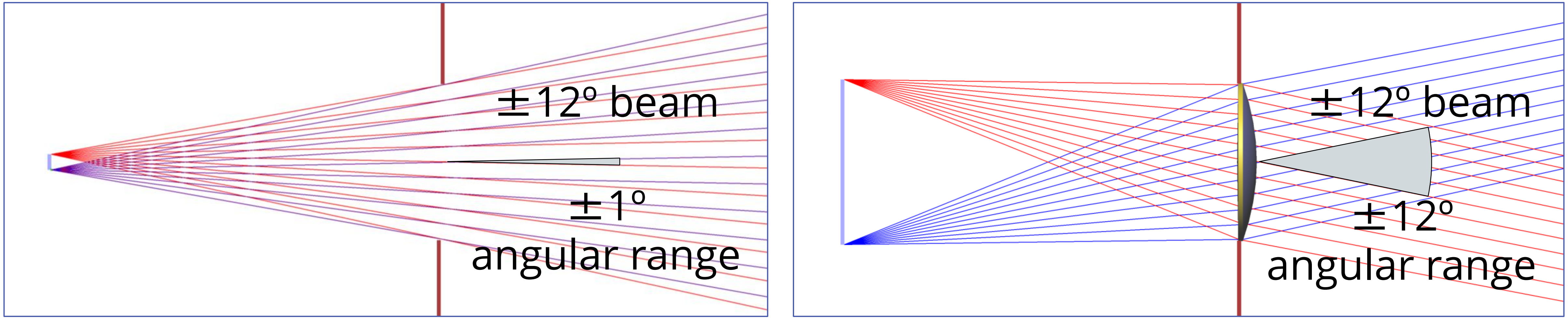
Source: Lumileds

The actual LED choice

Look at angular range at each point – not overall

Small étendue

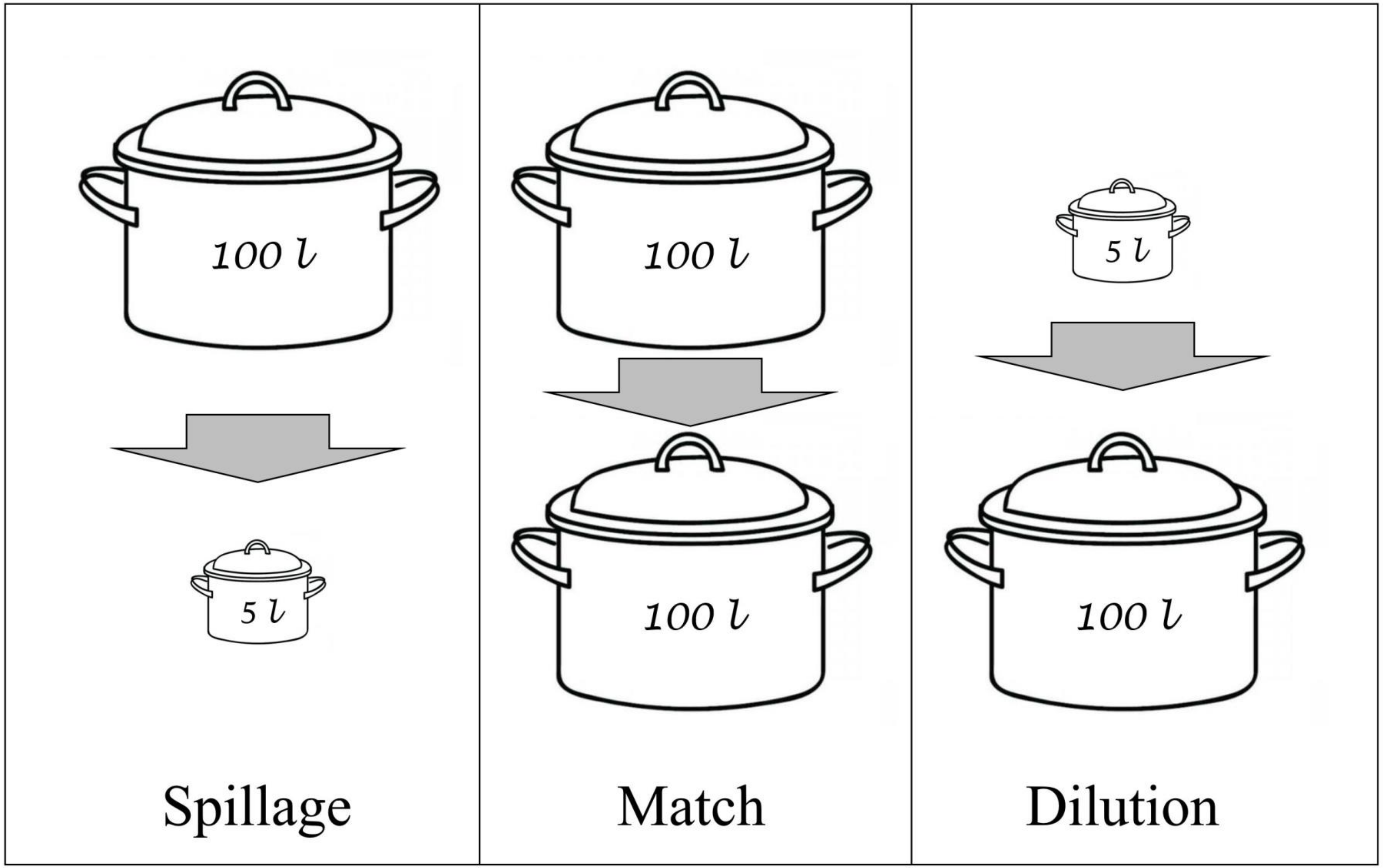
Large étendue



Spillage, match and dilution

Source

Target



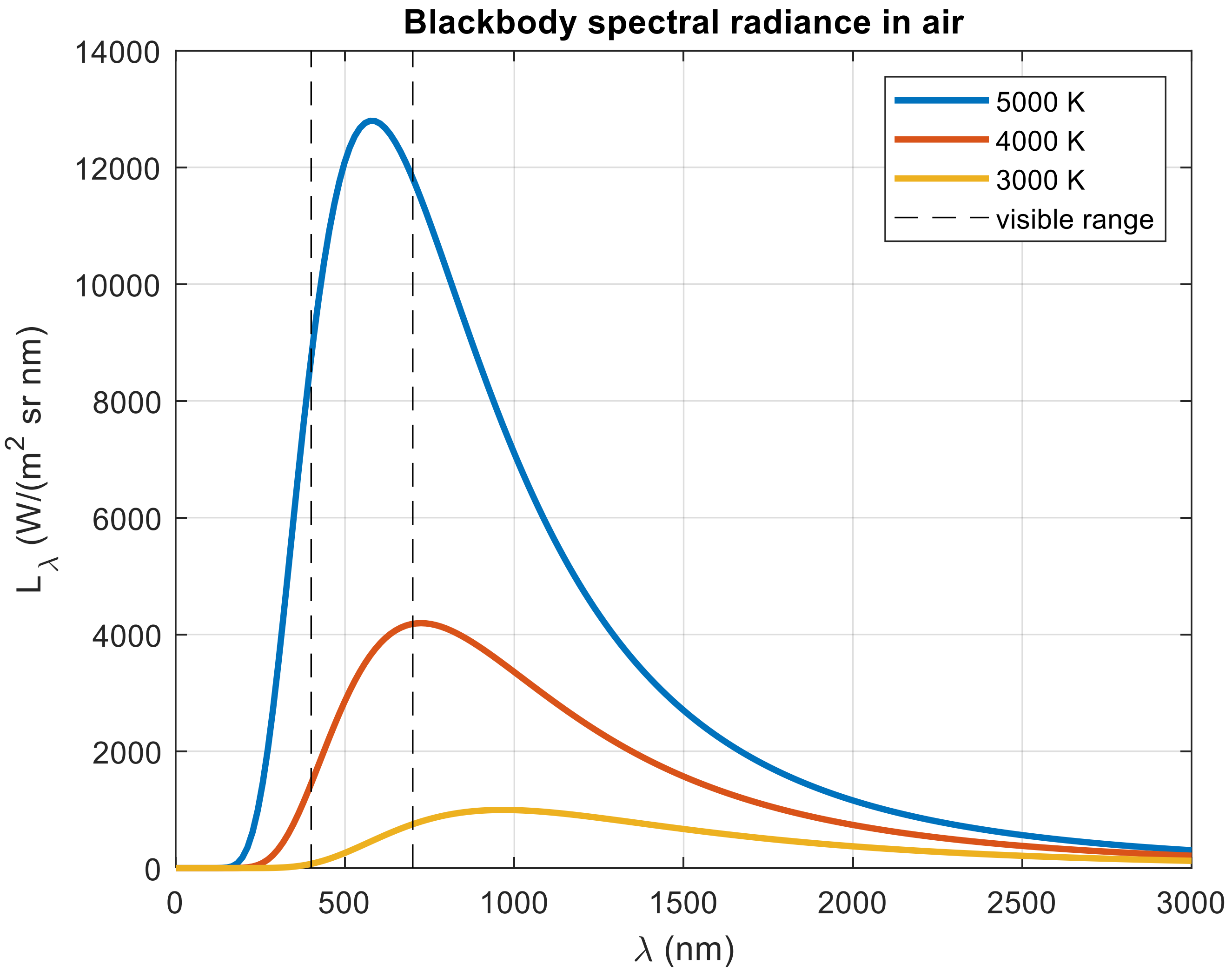
Planck's blackbody spectrum

Planck: Spectral radiance

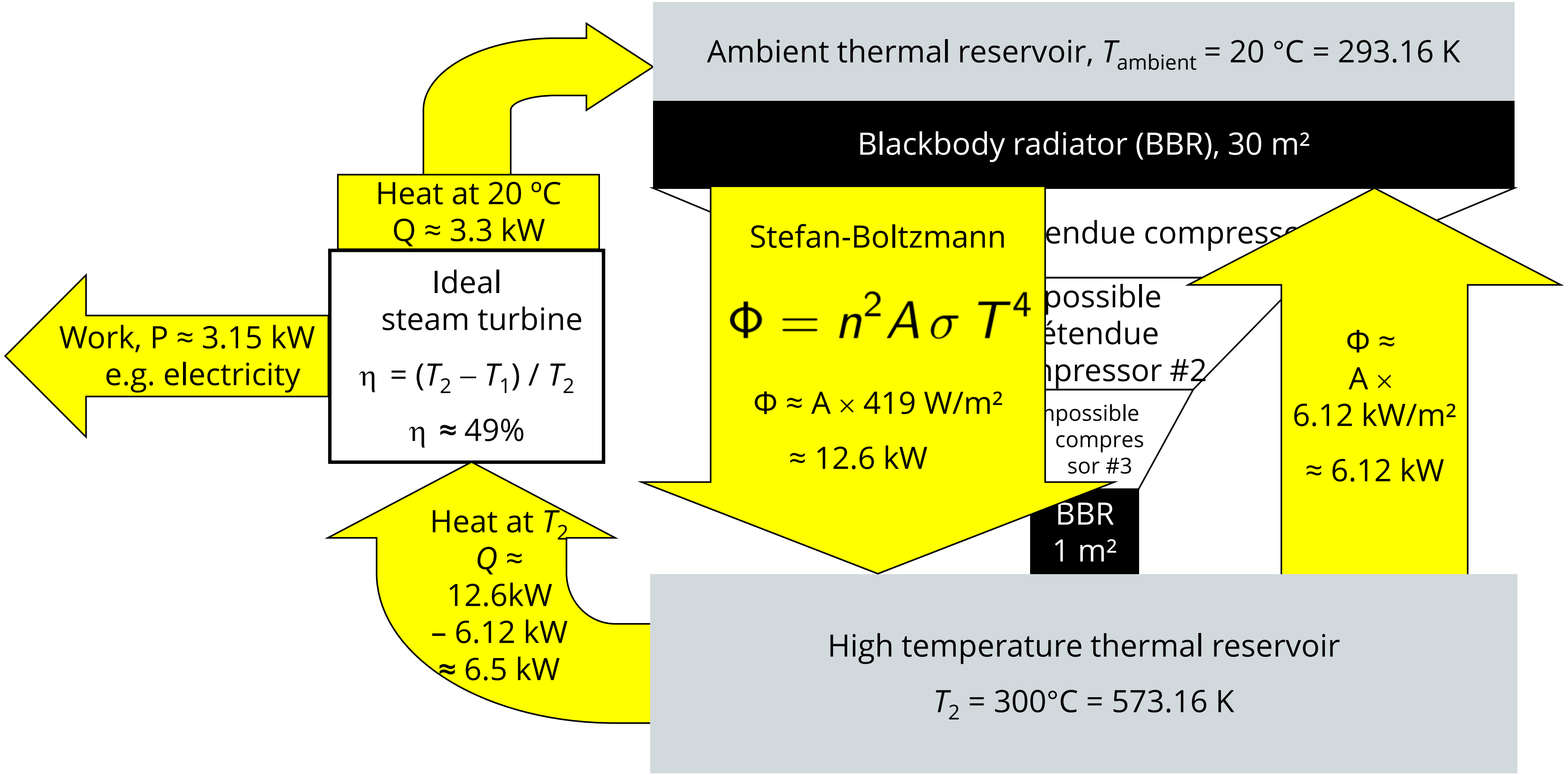
$$L_\lambda(\lambda, T)$$

Units: W / (m² sr nm)

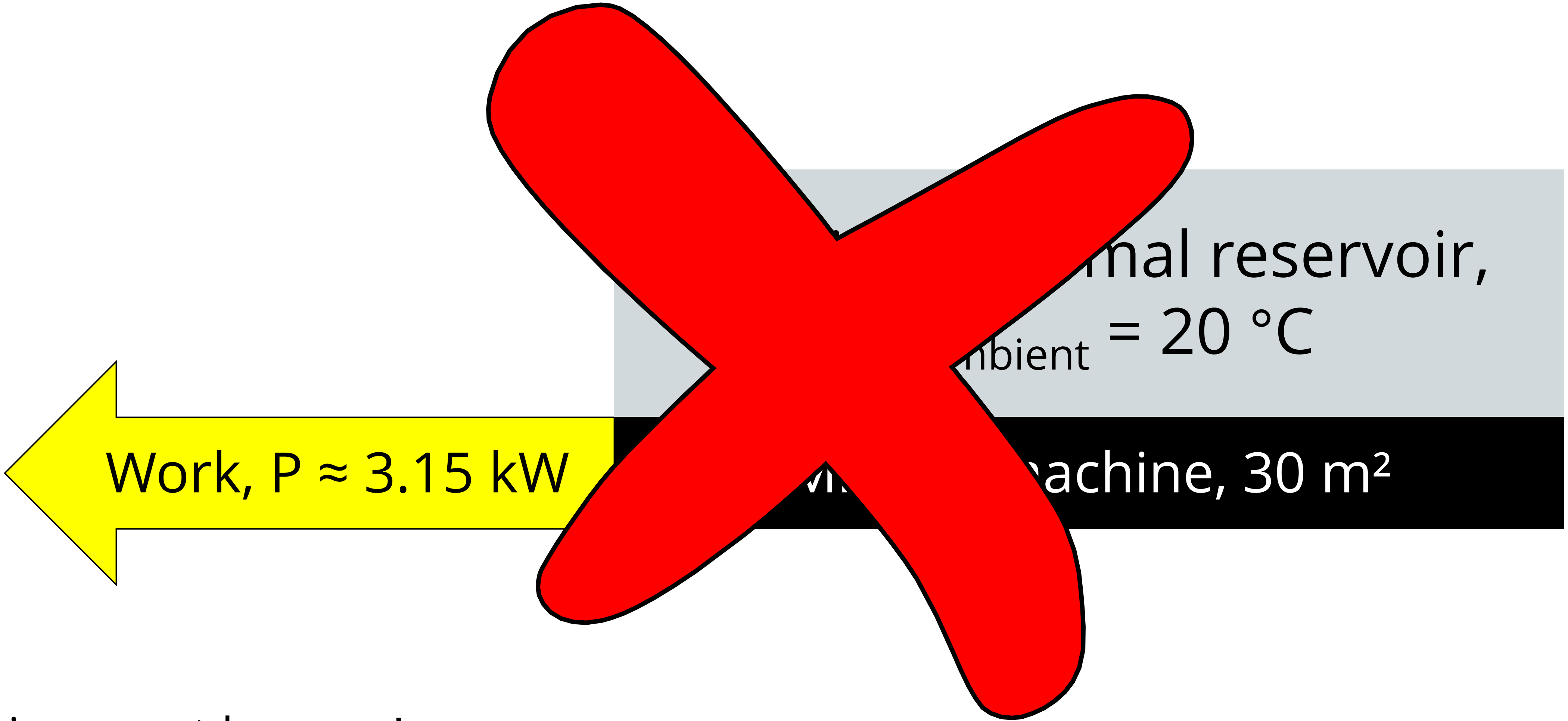
Flux per wavelength per étendue



Étendue conservation and the Second Law



Etendue conservation and the Second Law



This cannot happen!

For more details, see e.g. www.nature.com/articles/s41598-017-01622-6 www.entropyofradiation.com

The Second Law of Thermodynamics

„Spectral radiance cannot increase in passive systems“

Definition of passive system:
Anything that does not (re-)emit photons

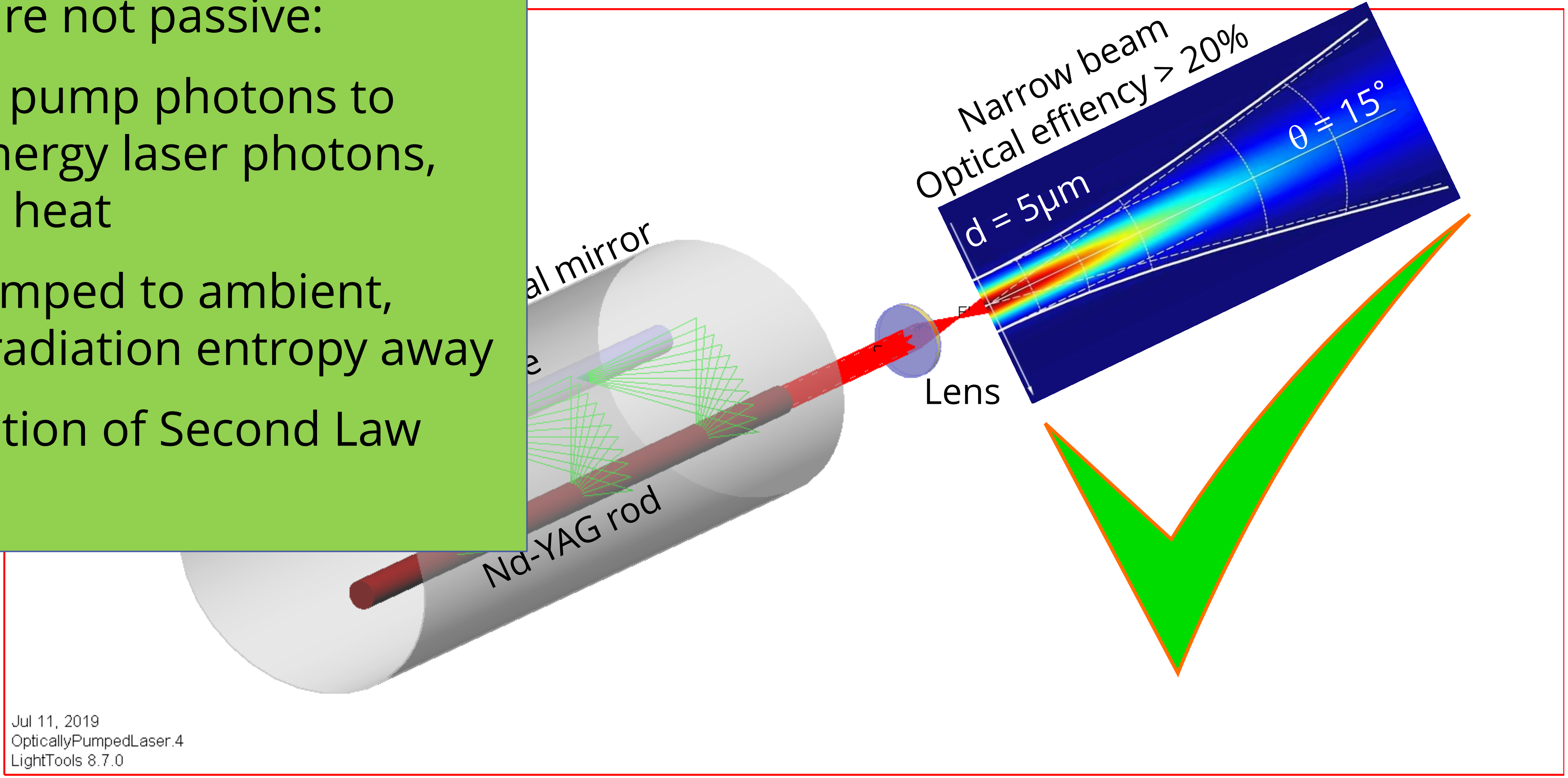
Solving riddle #1

Lasers are not passive:

Convert pump photons to lower energy laser photons, creating heat

Heat dumped to ambient, carries radiation entropy away

No violation of Second Law



Source: dhgate.com, Edmund Optics, RWTH Aachen, canstockphoto

Solving riddle #2

Illumination Optics

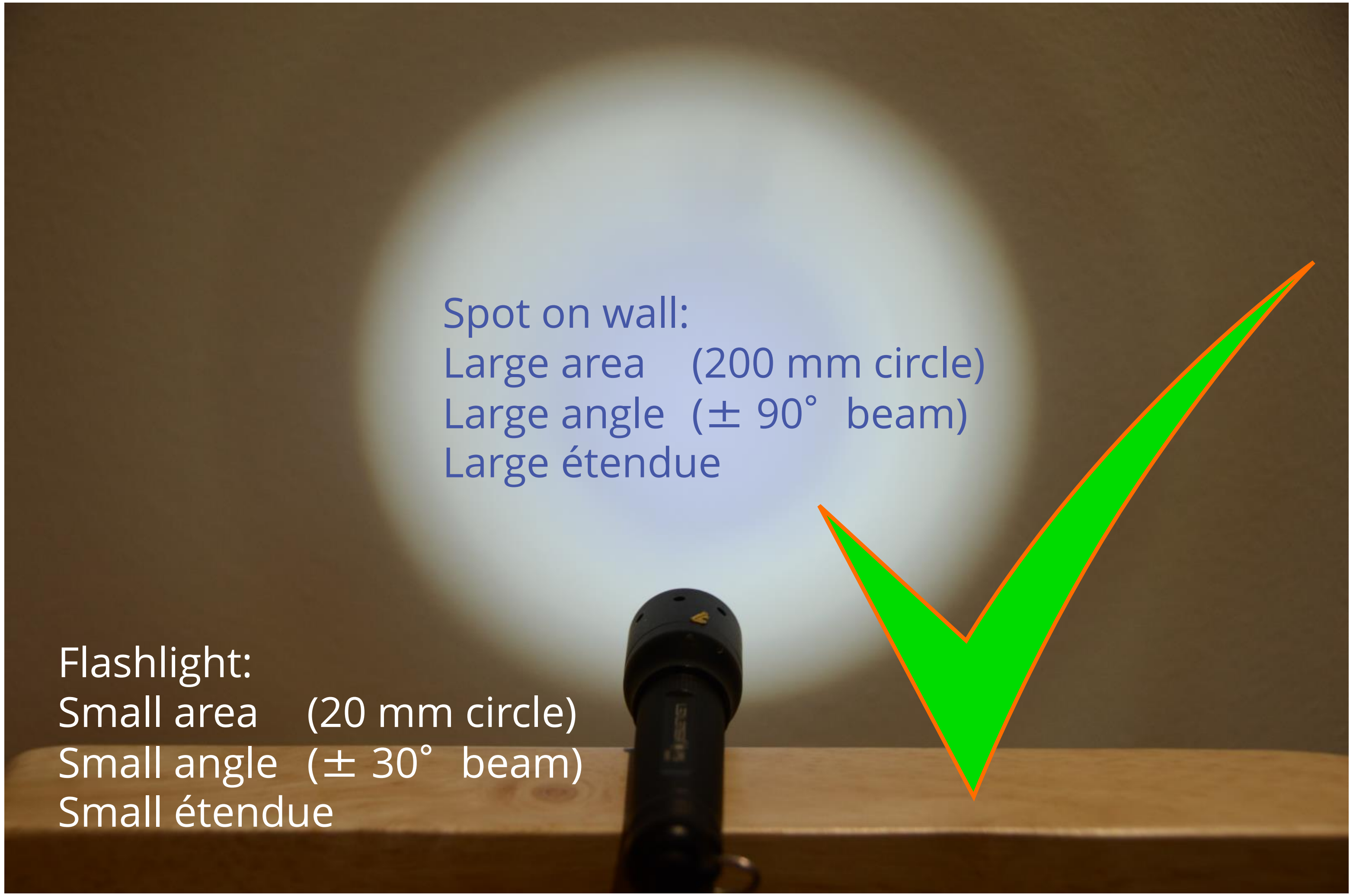
Just a flashlight and a wall

Radiation diluted at wall by scattering into previously (nearly) empty phase space

Spectral radiance decreases

Entropy is generated

No violation of Second Law



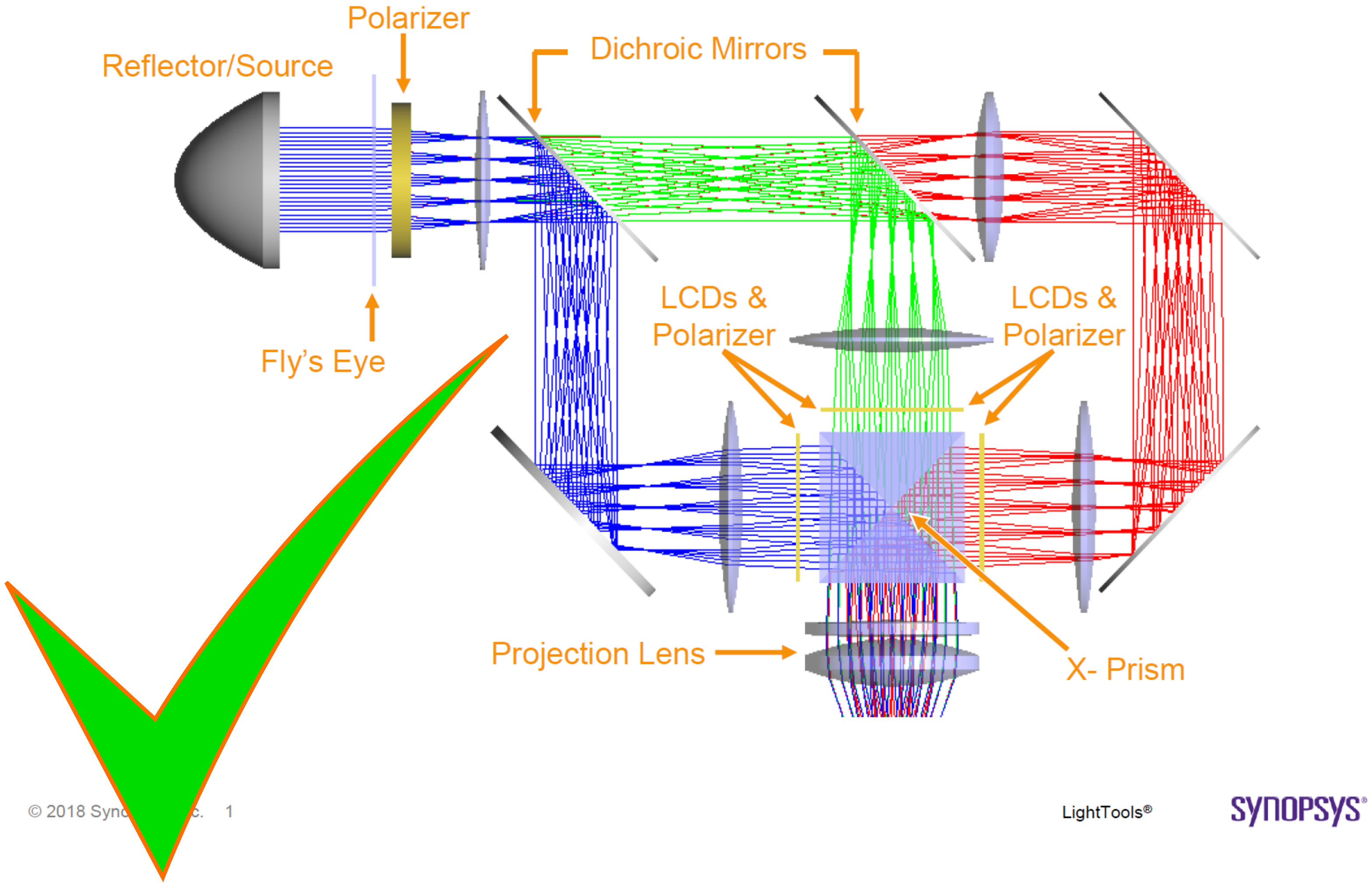
Solving riddle # 3

At X-Prism:
Three sides input (R,G,B)
One side output (white)

Light with **different** wavelength combined into same phase space

No increase of **spectral** radiance

No violation of Second Law



Étendue conservation spelled out

Consider a ray bundle passing through an optical system with

- refraction/reflection at smooth surfaces and free propagation only
- no scattering, no splitting of rays (consider one of the two splitted rays lost)
- no active components
- partial absorption allowed.

Place screens anywhere into the ray path, with exactly one intersection per ray

Determine étendues of ray bundle at each screen.

Étendue conservation: All these étendues are the same

When in doubt, ask yourself: Could I increase spectral radiance?

Using étendue

Illumination Optics

- Étendue conservation applicable to many optical systems
- Now you know when, and when not
- If applicable, then étendue conservation is supremely useful
- Compute hard, fundamental laws of nature based limits on
  aperture sizes, beam angles, source sizes, efficiencies…
  in just a few lines of Matlab, Excel, or in your head
- If you'd like to learn more
  (like about luminance, illuminance, intensity, design patterns, color):
  - Read the books, read my papers,
  - attend one of my courses (dates, locations and more on my LinkedIn profile)
  - just ask me

Thank you for your attention