UNDERWATER COLORIMETRY

ATTENUATION & BACKSCATTER

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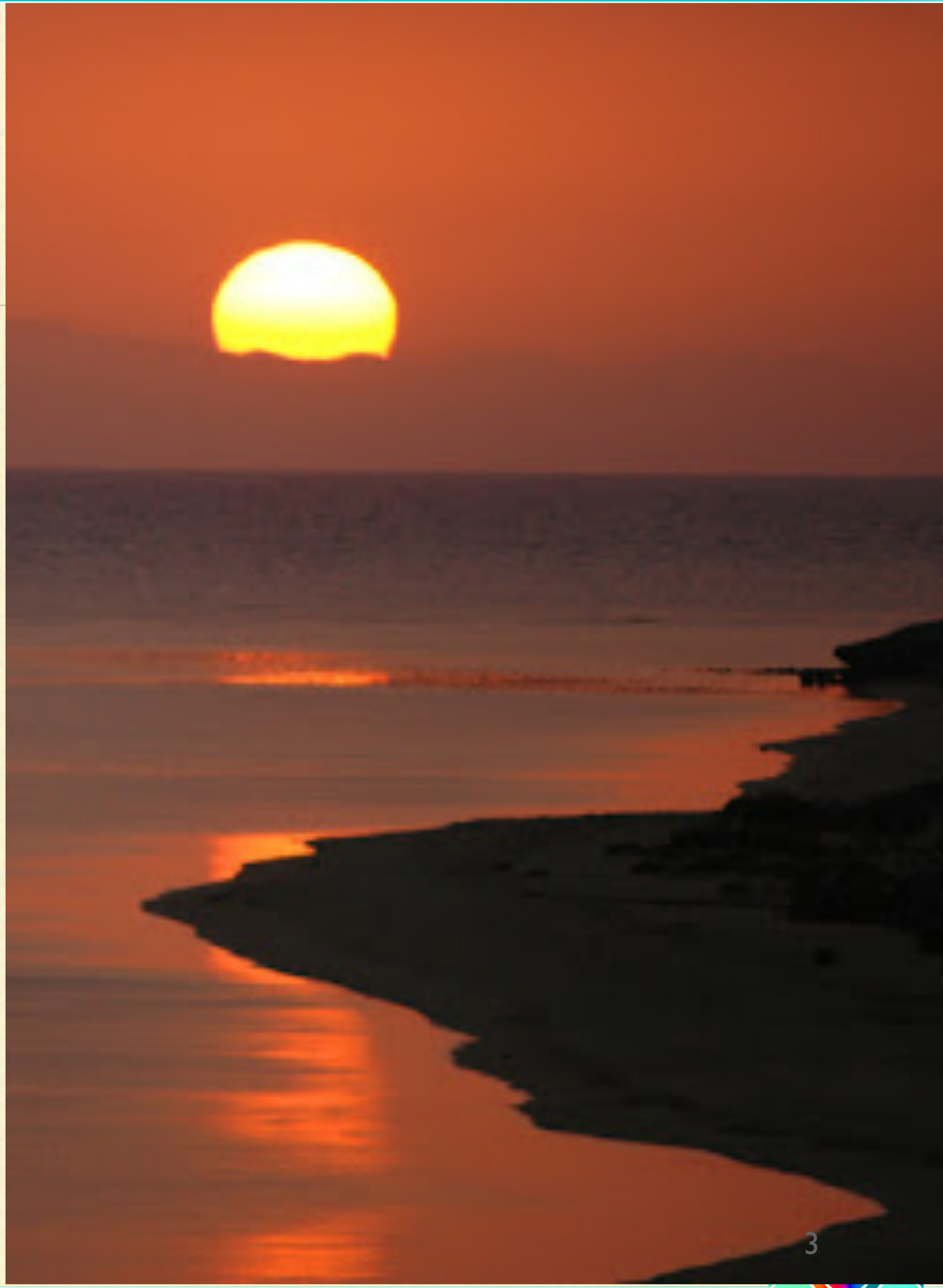
SCHEDULE AT-A-GLANCE

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SAT	SUNDAY
Lectures	Lectures	Lectures	Lectures	Cruise	Mt. Sfahot hike (optional)		Project/ Presentation preparations
Lunch	Lunch	Snorkel/scuba	Snorkel/scuba		Review		Project presentations
Snorkel/scuba	Lab	Lunch	Lunch	Observatory tour			Evaluations
Lab		Lab	Lab				
	Night snorkeling (optional)	Lectures	Lectures	Lab (Pizza & Project Lottery)			

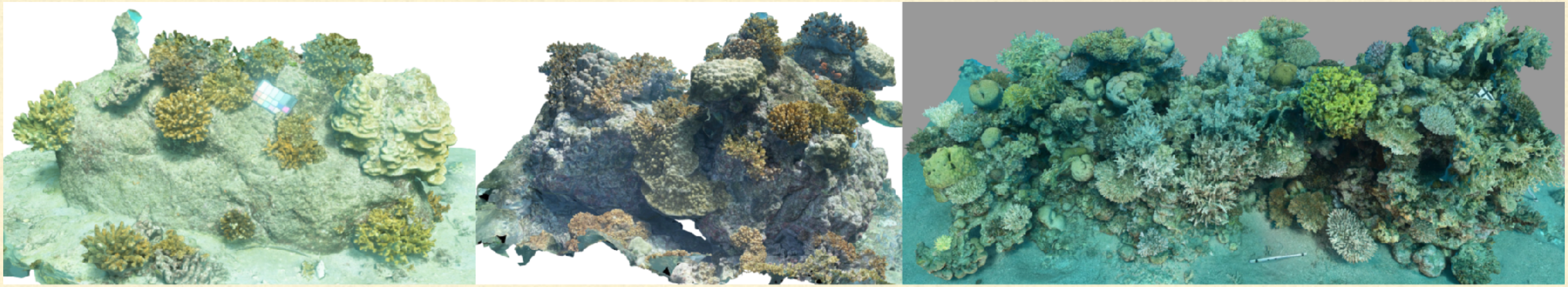
LAB: Underwater Photogrammetry
POSTMORTEM

- Today, you can make your models with JPGs.
- If you are comfortable with programming, white balance your PNGs and and use those for the model.



Structure-From-Motion: Emerging Underwater Use

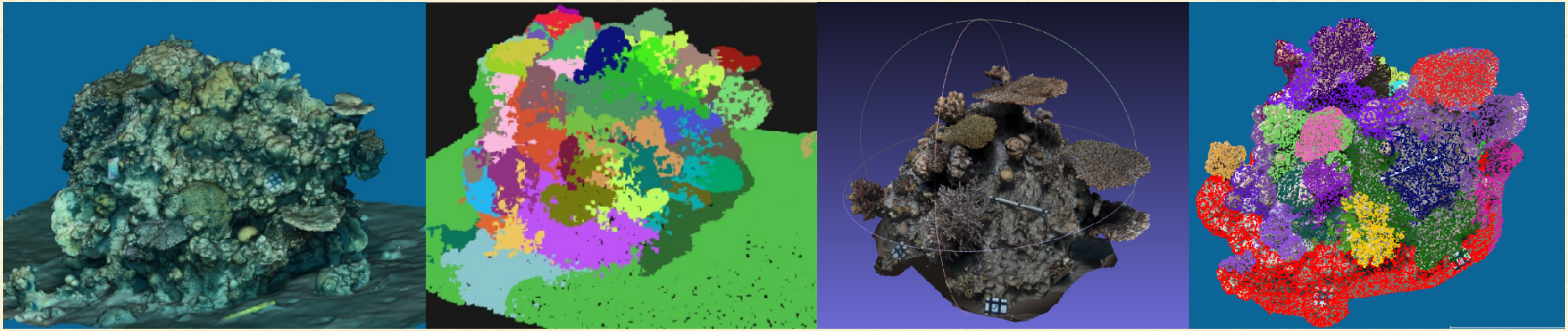
Increase in structural complexity and biodiversity of coral reefs



Slide courtesy of **Matan Yuval** from Marine Imaging Lab at the University of Haifa

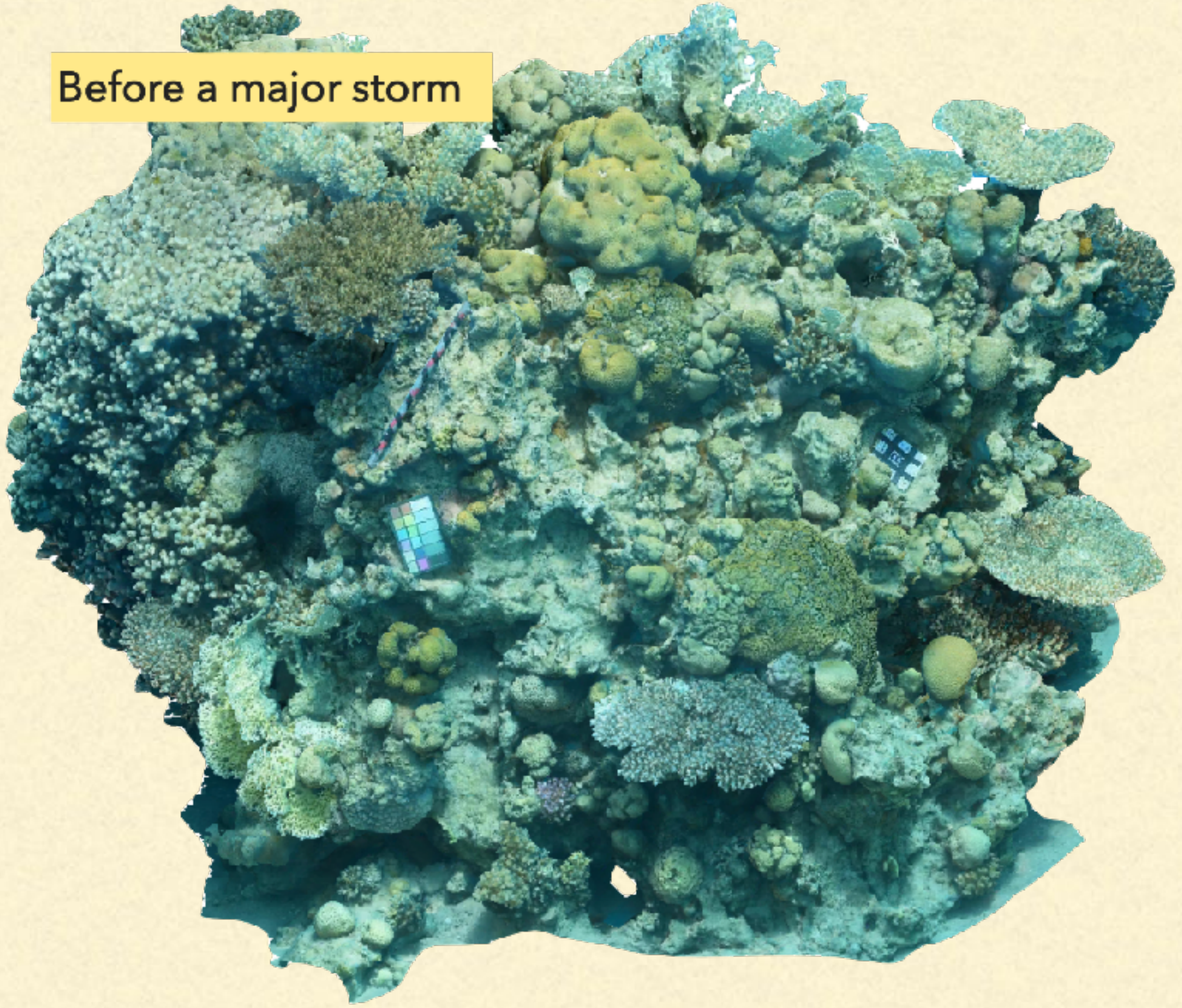
Structure-From-Motion: Emerging Underwater Use

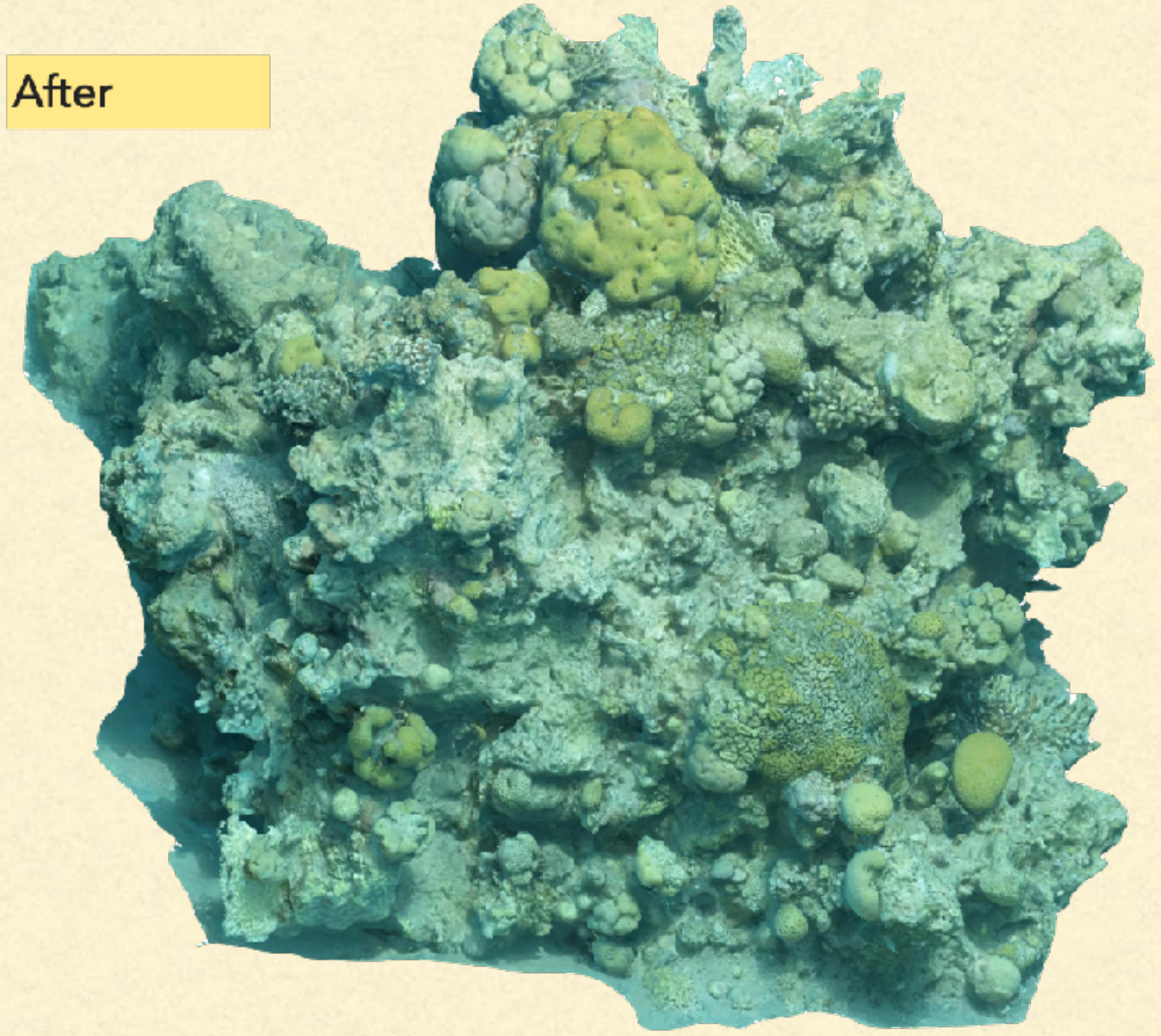
Quantifying the diversity of coral reefs



Slide courtesy of **Matan Yuval** from Marine Imaging Lab at the University of Haifa

Structure-From-Motion: Emerging Underwater Use





Slide courtesy of **Matan Yuval** from Marine Imaging Lab at the University of Haifa

What Will I Learn in This Lecture?

- Attenuation
- Path radiance (Backscatter)
- Physical attenuation coefficients
- RGB (Wideband) attenuation coefficients

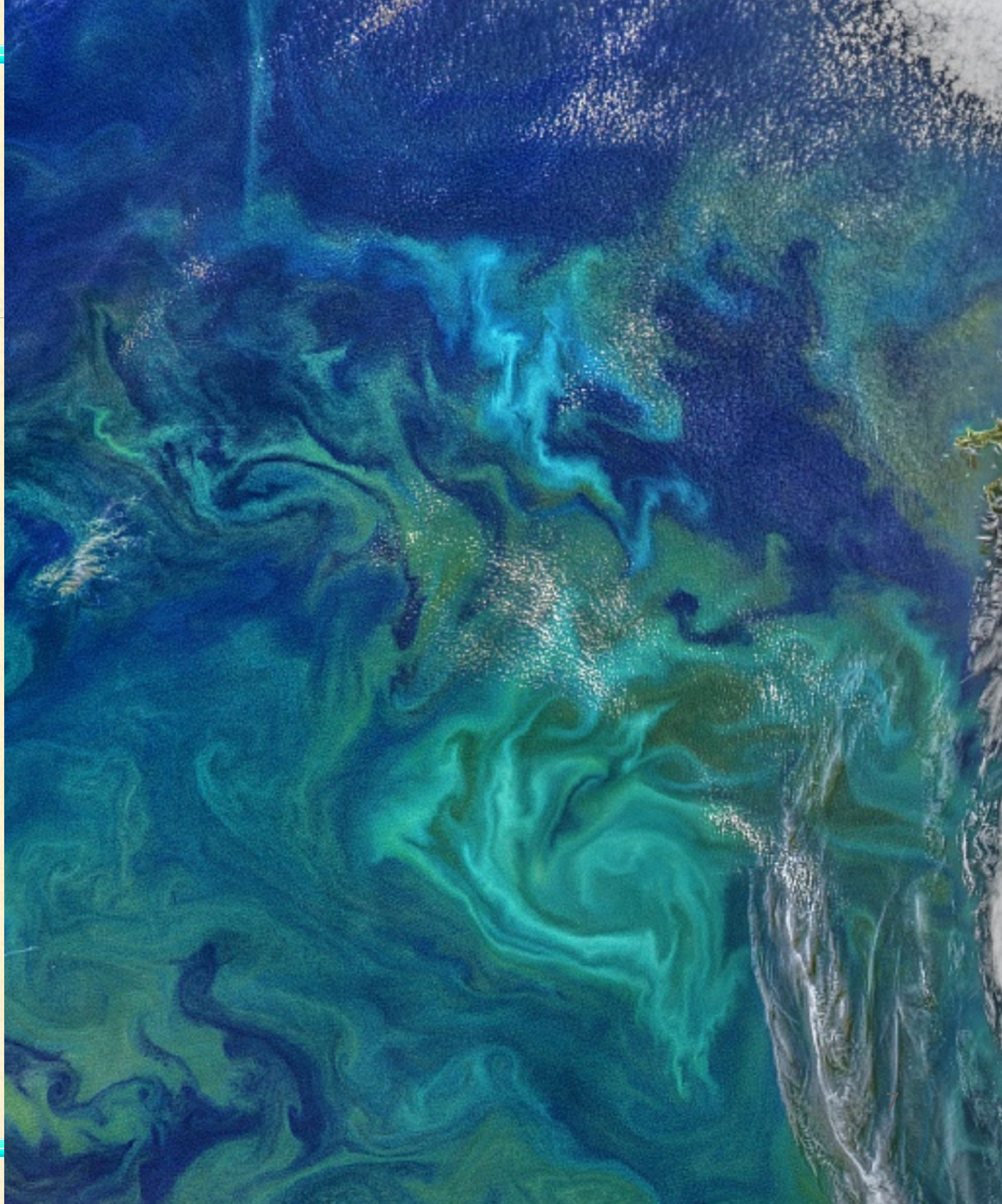
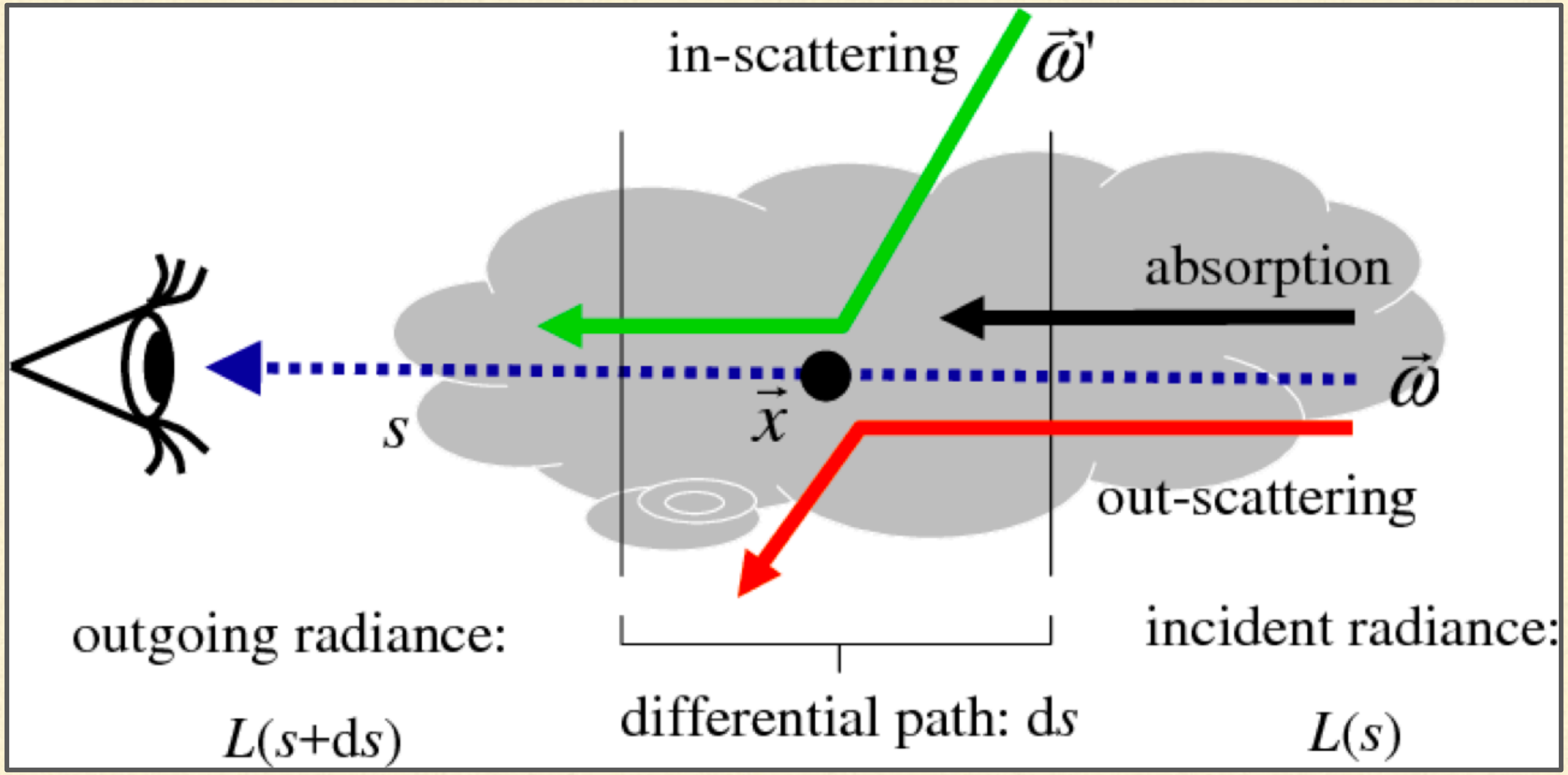
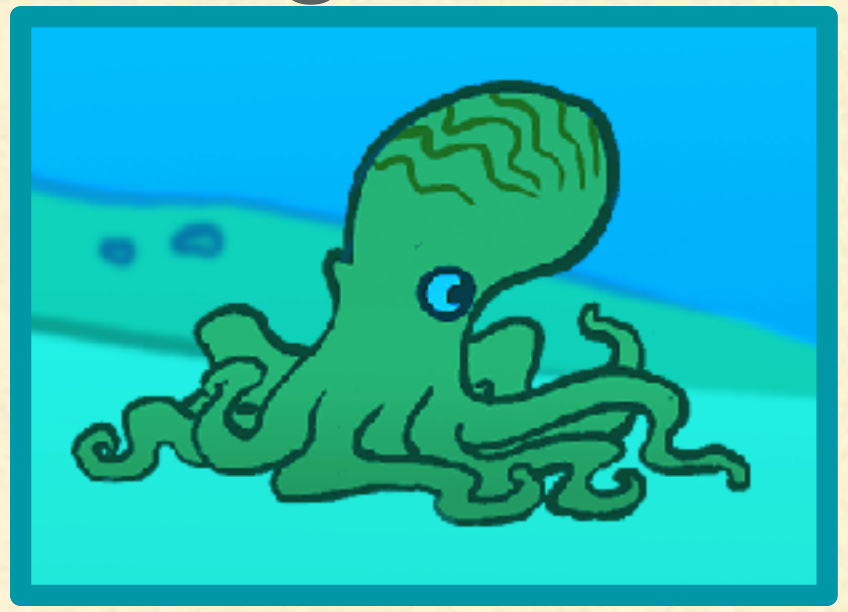


Image formation

What Happens to Light in the Water?

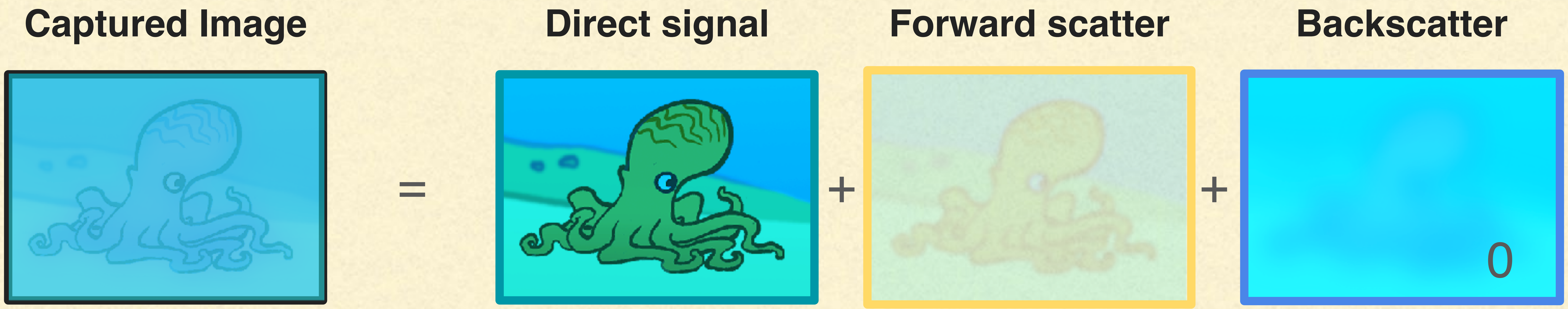


Absorption + (out)-scattering = Attenuation



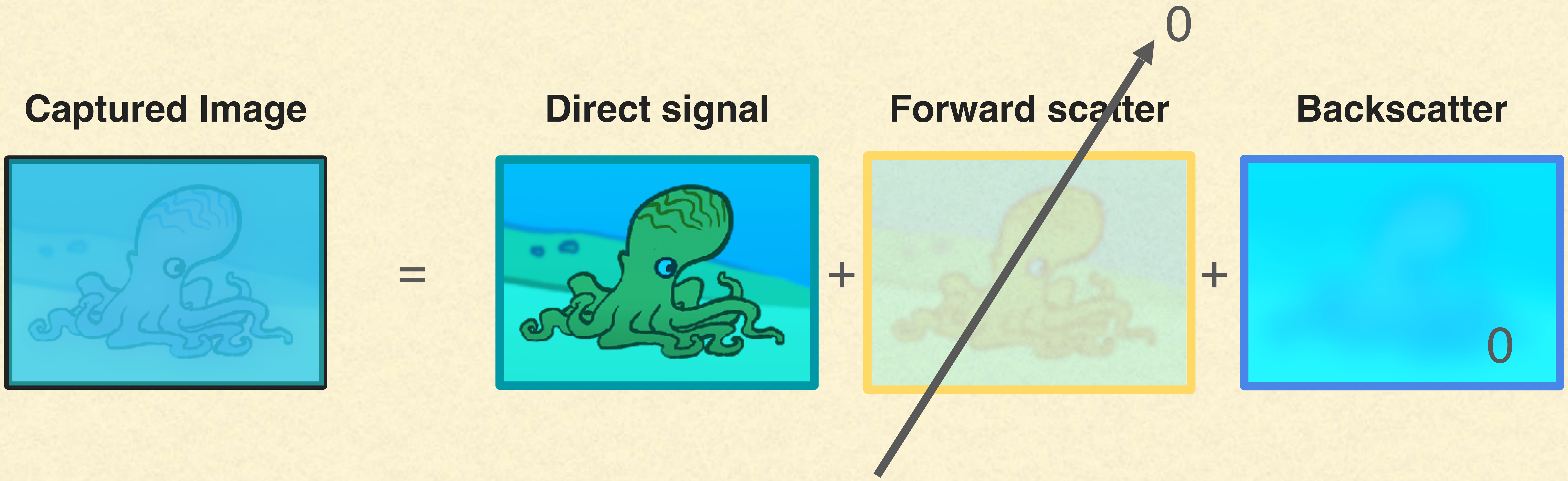
(In)-scattering = Backscatter

General Form Image Formation in any Medium



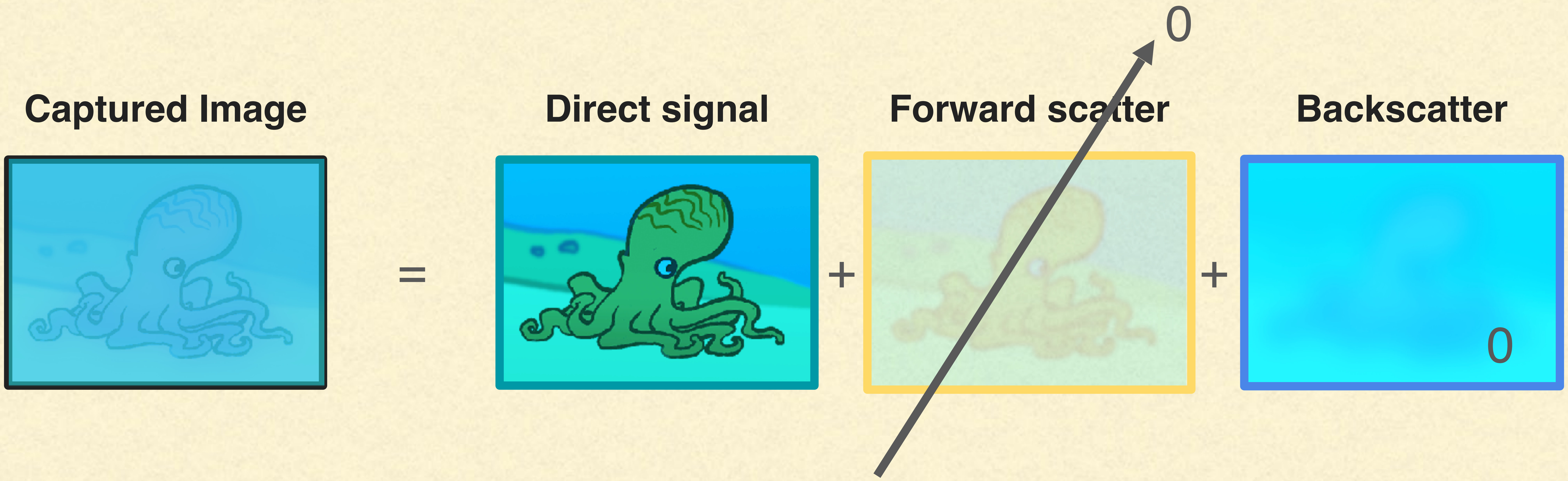
$$\boxed{I_c = D_c + F_c + B_c}$$

General Form Image Formation in any Medium



$$\boxed{I_c = D_c + F_c + B_c}$$

General Form Image Formation in any Medium



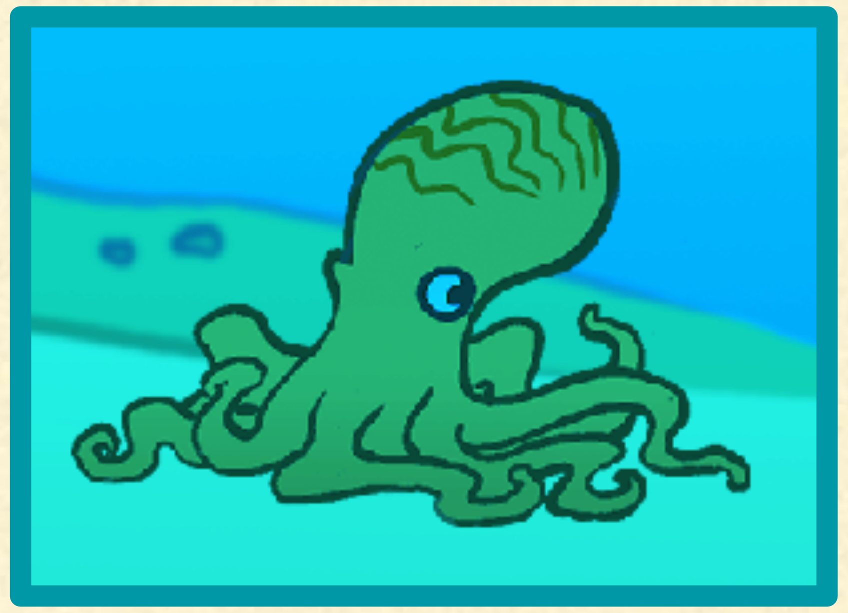
$$I_c = D_c + \cancel{F_c} + B_c$$

Simplified Version We Will Use

Captured Image (I_c)

=

Direct signal (D_c)



+

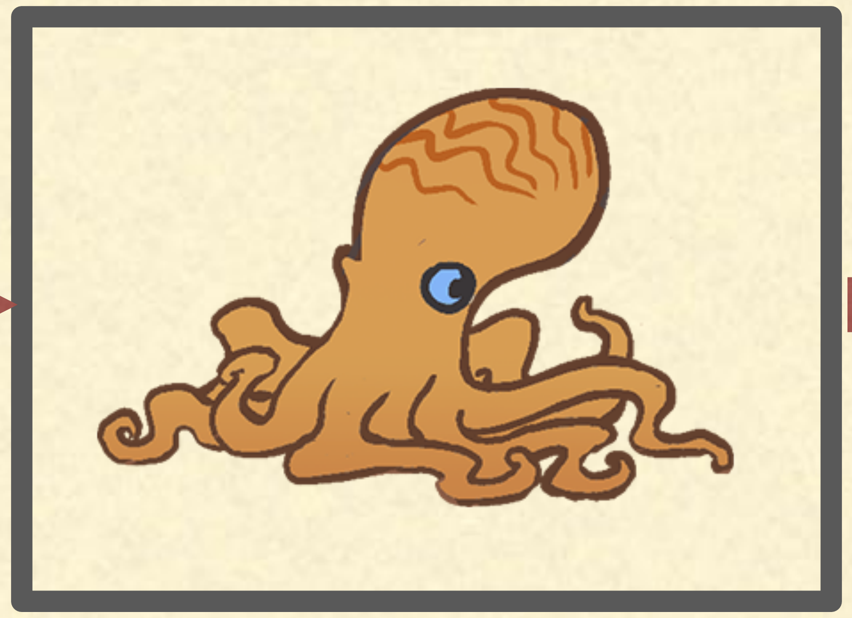
Backscatter (B_c)

$$\boxed{I_c = D_c + B_c}$$

Underwater Colorimetry

In-water image

Remove the water



Convert to XYZ space

Apply Standard Colorimetry

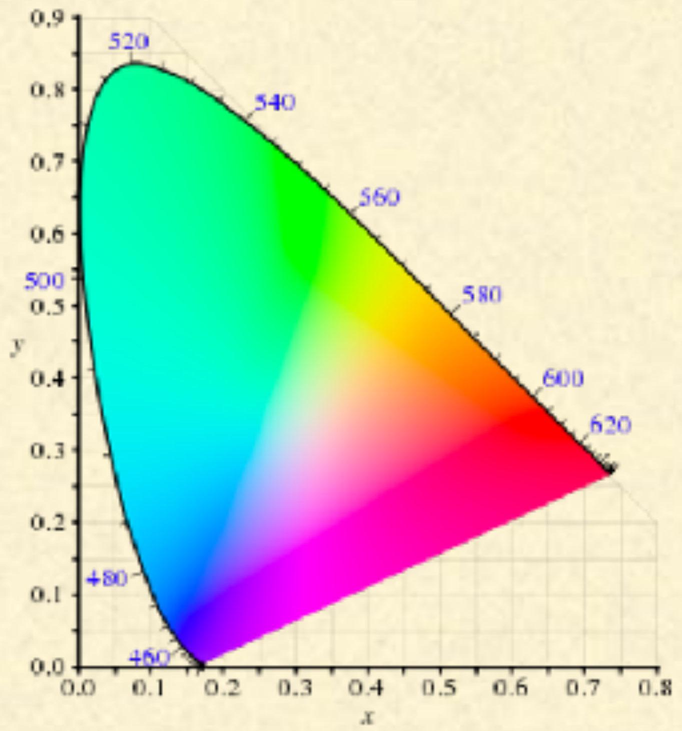
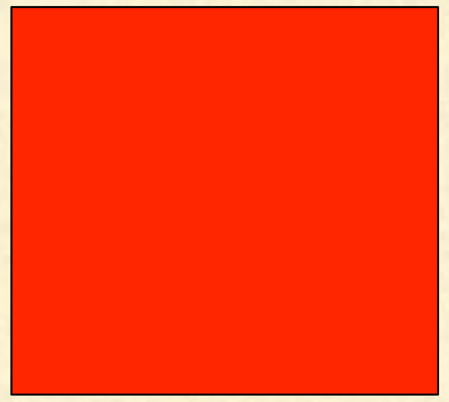


Image Formation (Clear Air)

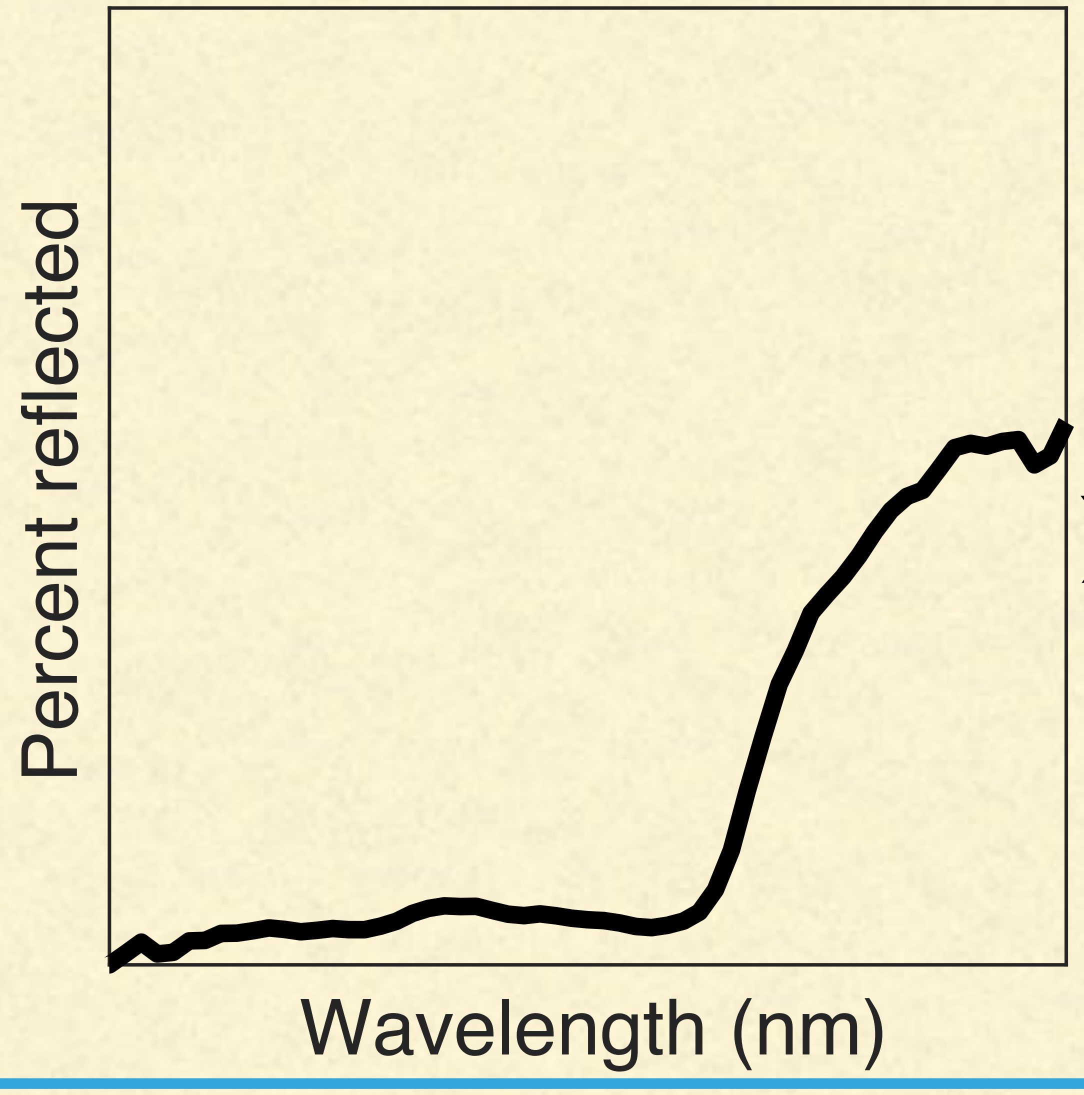
$$\boxed{Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)d\lambda}$$

κ: exposure-related constant

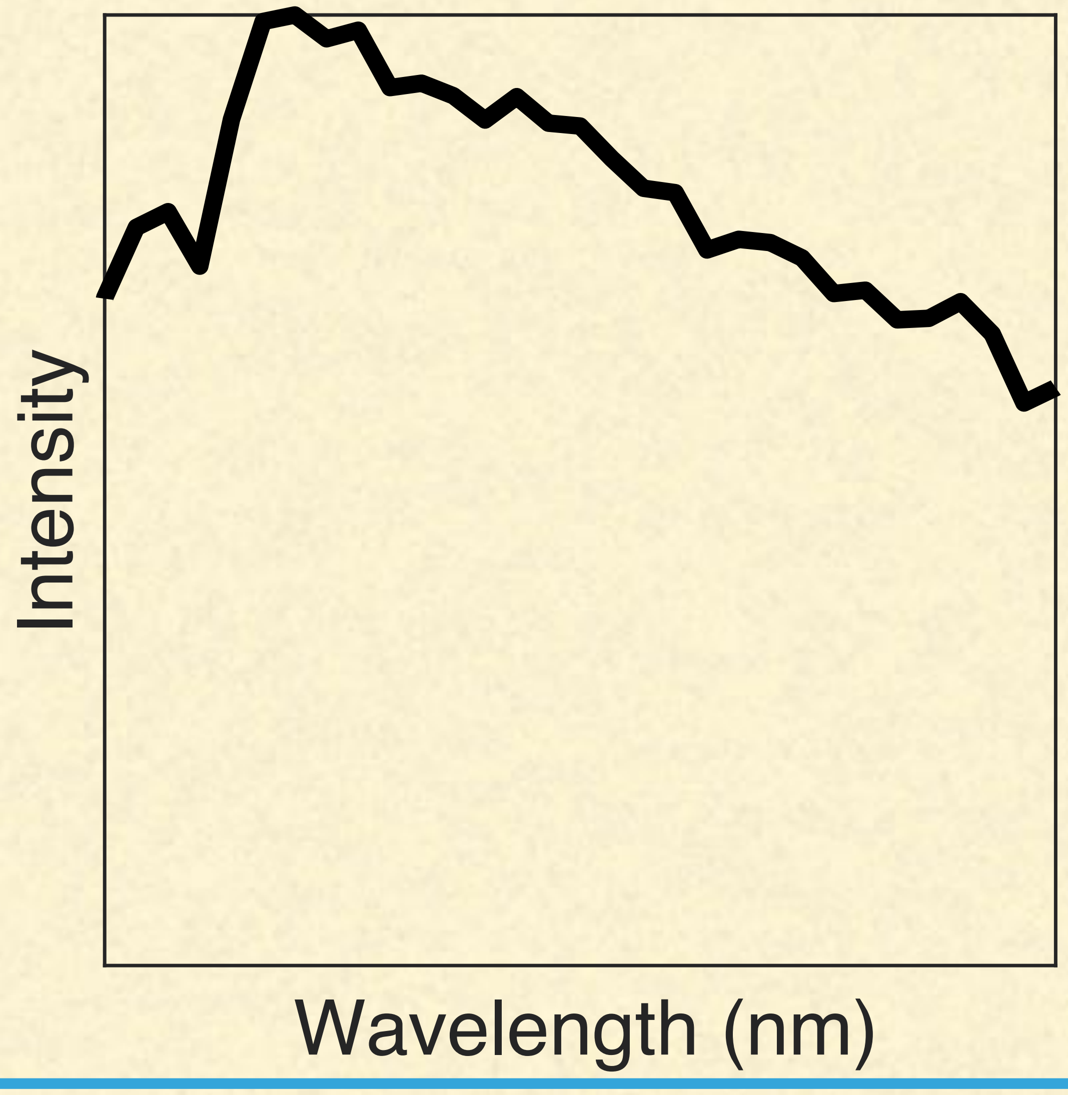
Color	Reflectance	Light	Observer
	$\rho(\lambda)$	$E(\lambda)$	$S(\lambda)$



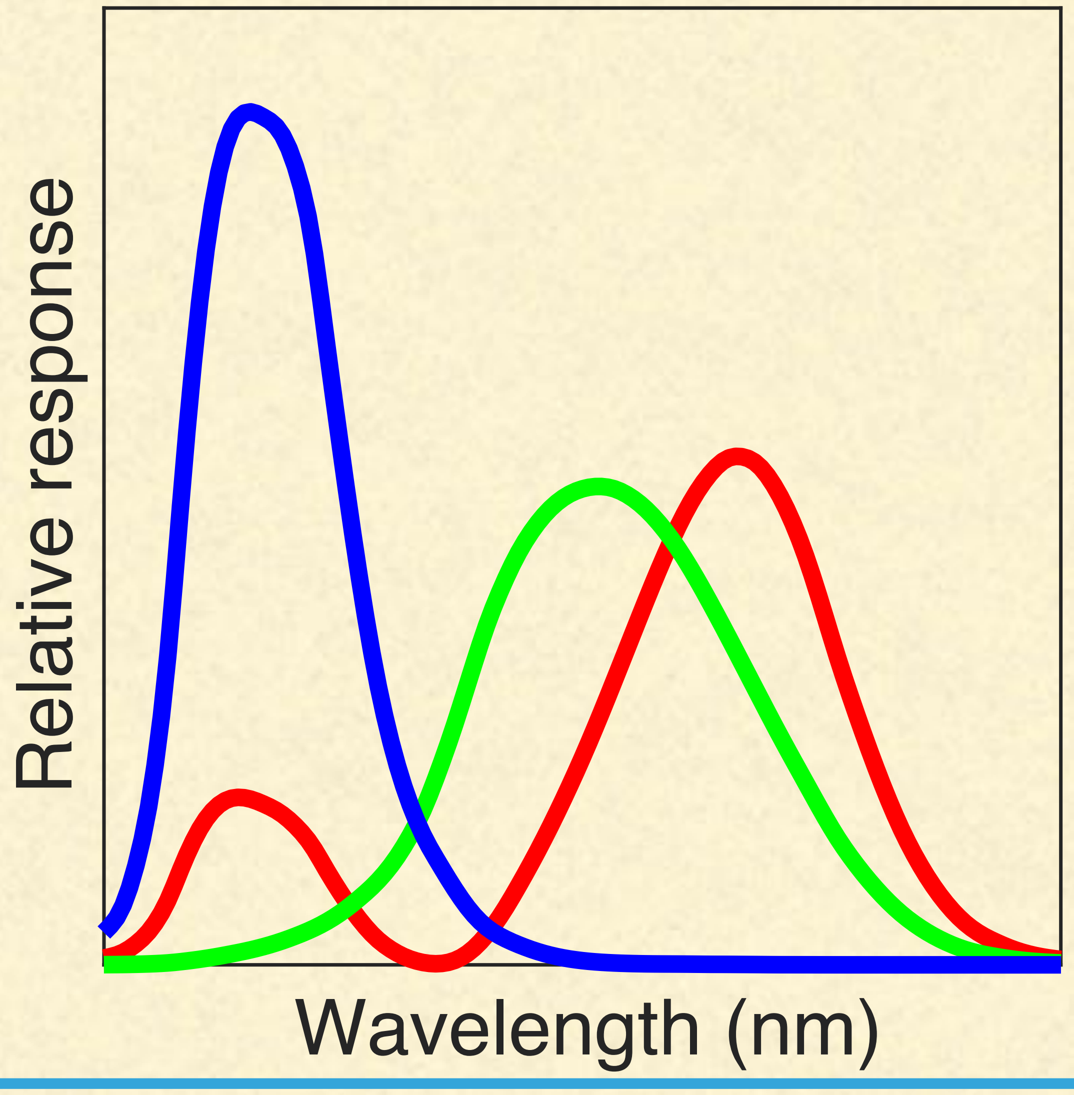
=



X



X



In clear air, there is no light attenuation:

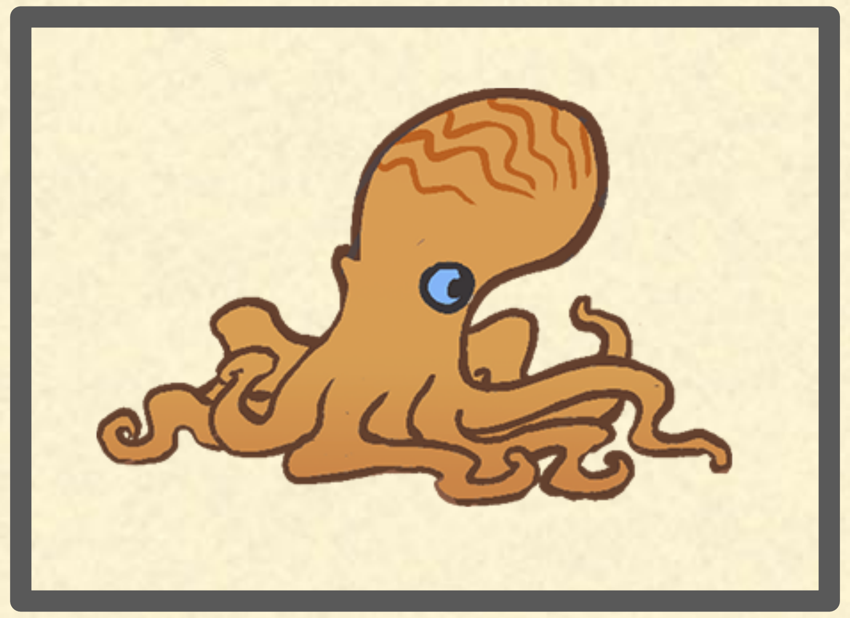
Captured Image (I_c) = Direct signal (D_c)

Image Formation (Clear Air)

In clear air, there is no light attenuation:

Captured Image (I_c) = Direct signal (D_c) + 0

Captured Image (I_c)



=

Direct signal (D_c)

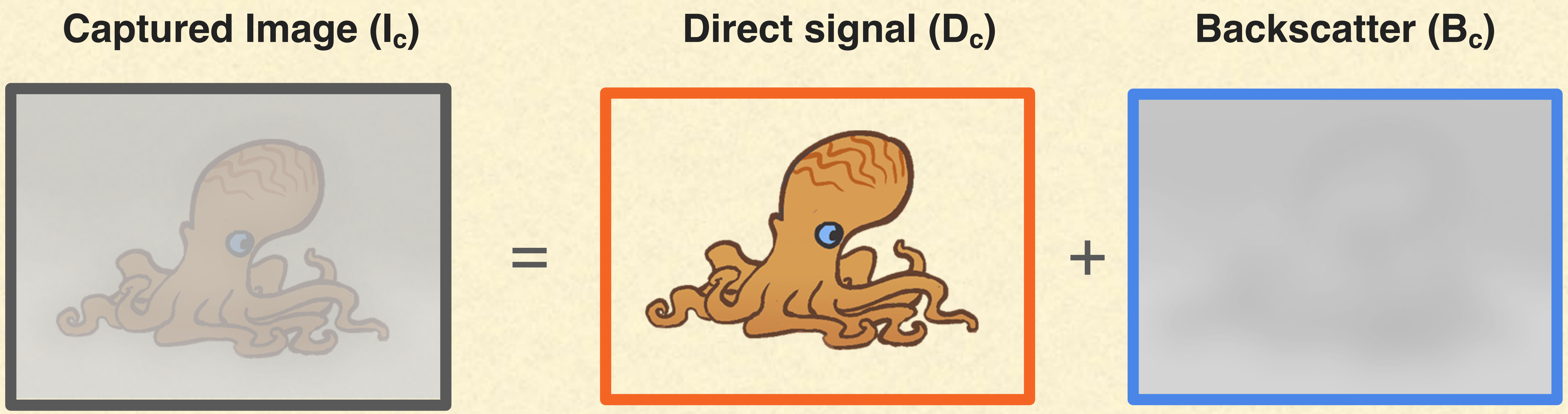
$+ \mathbf{0}$

$$\boxed{Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)d\lambda}$$

Image Formation (in Atmospheric Fog)

In fog, there *is* light attenuation:

Captured Image (I_c) = Direct signal (D_c) + Backscatter (B_c)

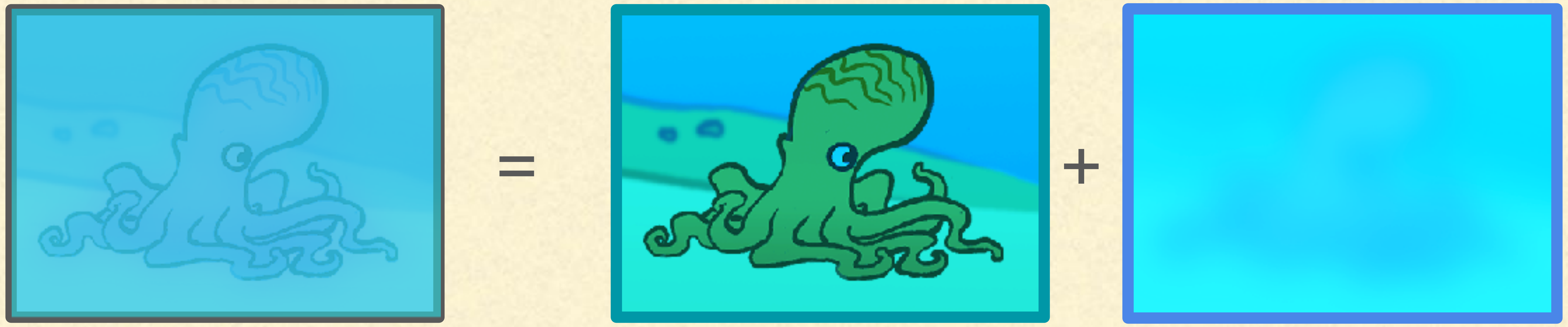


Remember that backscatter carries no information about the scene!
It is just fog!

Subscript *c* refers to a color channel of a camera (i.e., R,G, or B).

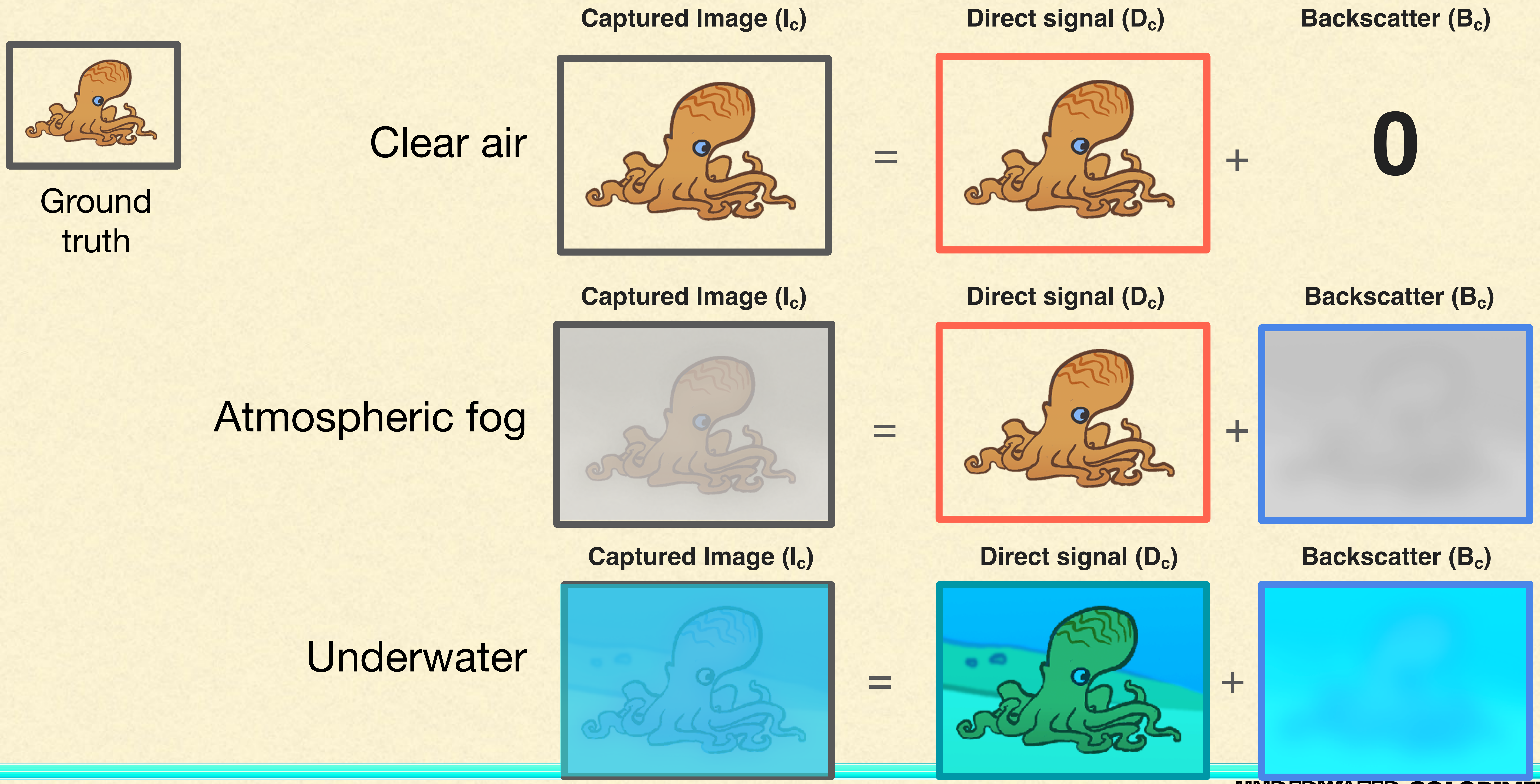
Image Formation (Underwater)

Captured Image (I_c) **Direct signal (D_c)** **Backscatter (B_c)**



Remember that backscatter carries no information about the scene!
It is just colored fog!

Cheat Sheet



Ground truth
Clear air
Captured Image (I_c)
=
Direct signal (D_c)
+
Backscatter (B_c)
0
Atmospheric fog
Captured Image (I_c)
=
Direct signal (D_c)
+
Backscatter (B_c)
Underwater
Captured Image (I_c)
=
Direct signal (D_c)
+
Backscatter (B_c)

Color underwater

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \ +$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

K_d: diffuse downwelling attenuation coefficient

b = beam scattering coefficient

c: beam attenuation coefficient

z: distance along line-of-sight

Akkaynak & Treibitz CVPR 2018

Physical attenuation coefficients

E_0

K_d: diffuse downwelling attenuation coefficient
c: beam attenuation coefficient
z: distance along line-of-sight

Physical attenuation coefficients

K_d: diffuse downwelling attenuation coefficient
c: beam attenuation coefficient
z: distance along line-of-sight

$$E_d(\lambda) = E_0(\lambda)e^{-K_d(\lambda)d}$$

(Beer-Lambert law)

Physical attenuation coefficients

K_d: diffuse downwelling attenuation coefficient
c: beam attenuation coefficient
z: distance along line-of-sight

Physical attenuation coefficients

K_d: diffuse downwelling attenuation coefficient
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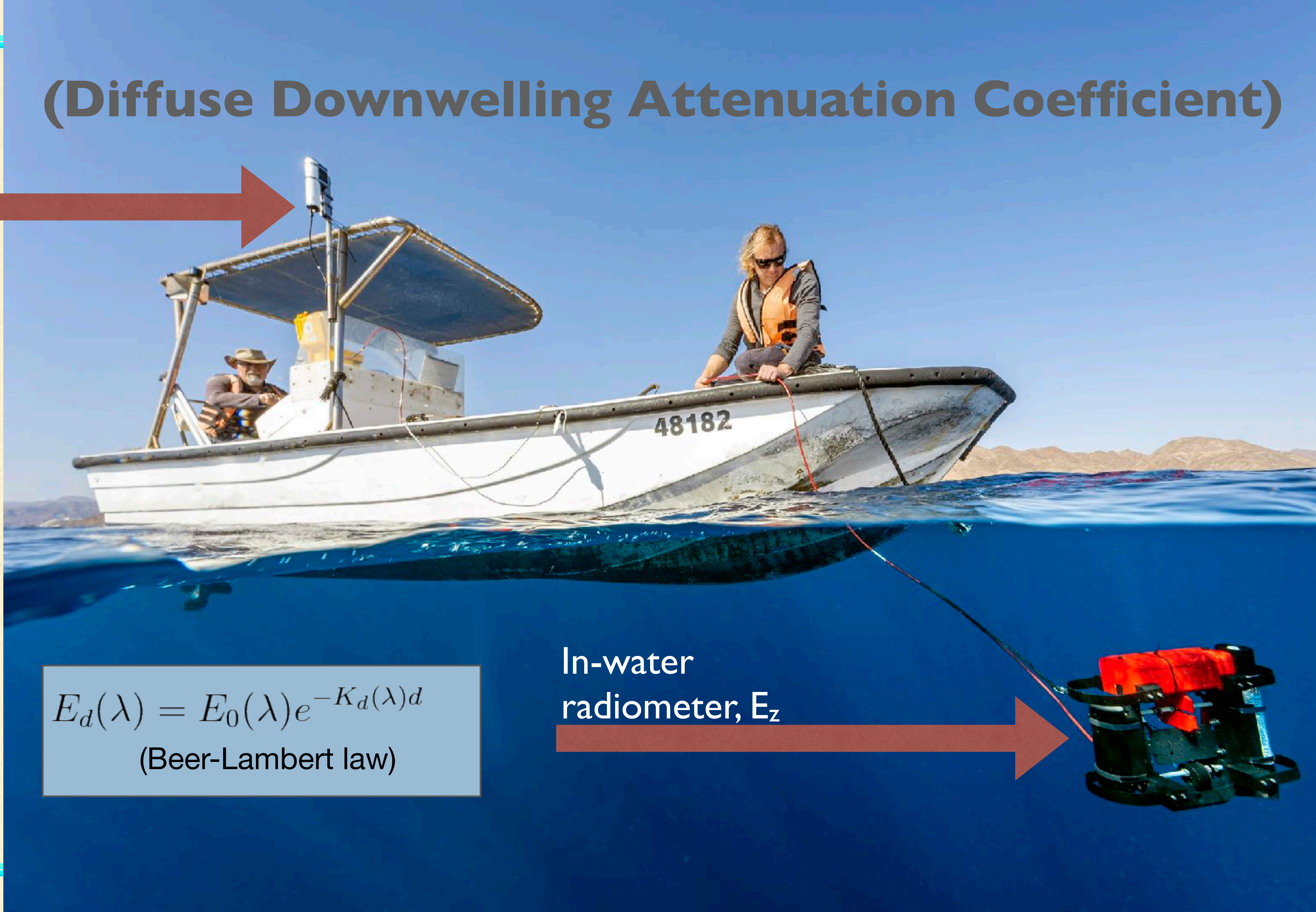
$$E_d(\lambda) = E_0(\lambda)e^{-K_d(\lambda)d}$$

(Beer-Lambert law)

Measuring K_d (Diffuse Downwelling Attenuation Coefficient)

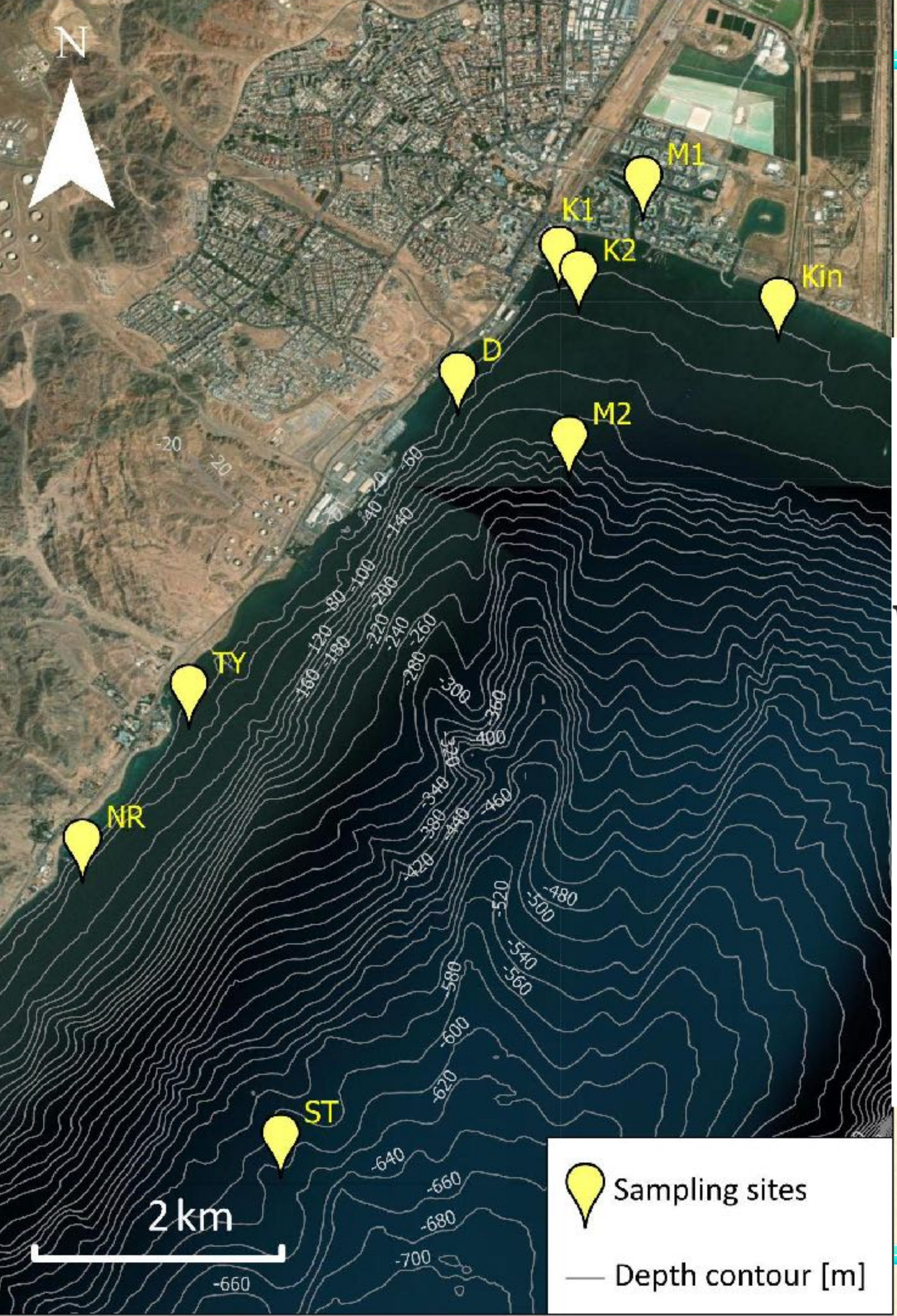
Surface radiometer, E_0

Measure light spectrum E at different depths & solve for Kd

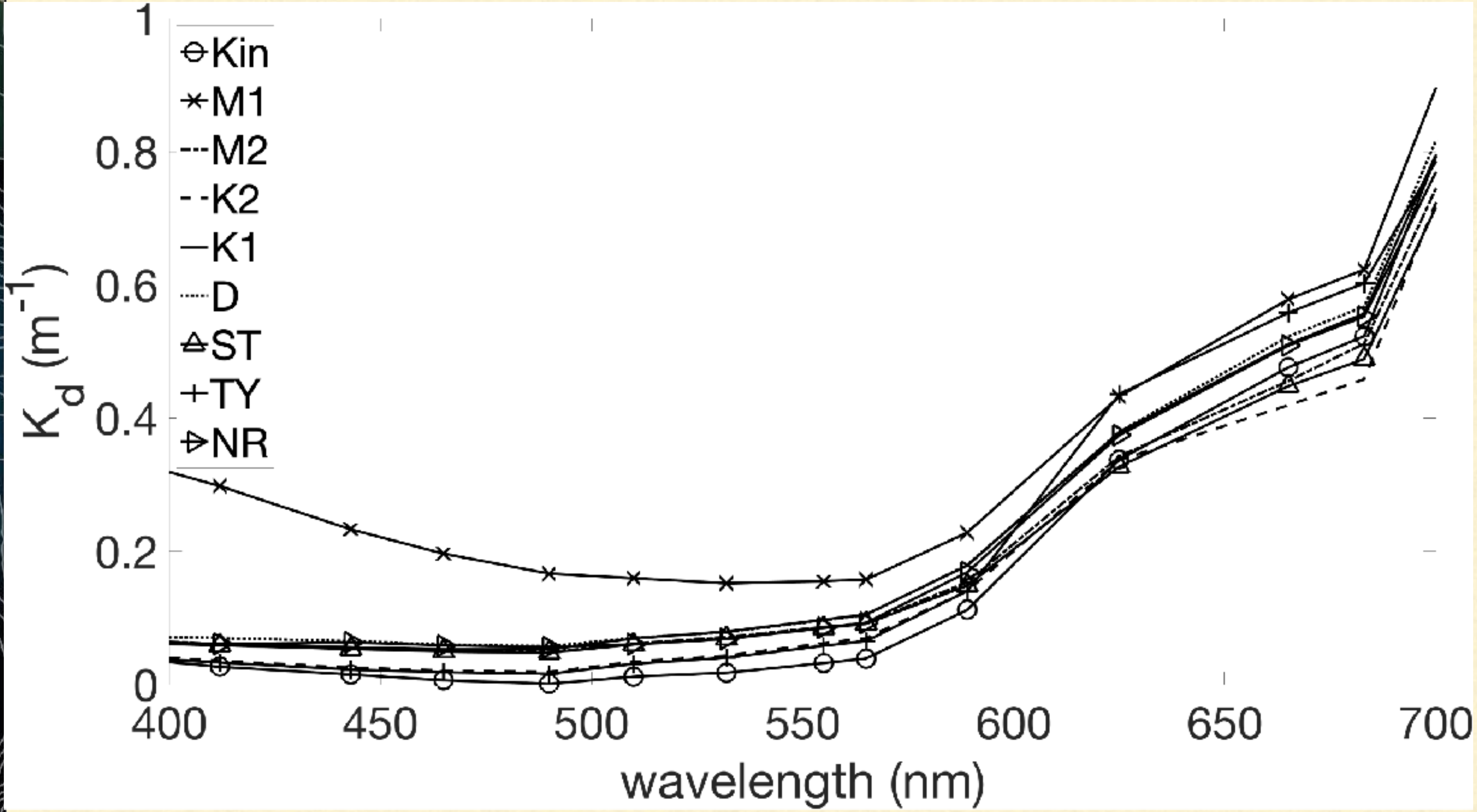


$$E_d(\lambda) = E_0(\lambda)e^{-K_d(\lambda)d}$$

(Beer-Lambert law)



Measuring K_d



Underwater Image formation - Forward Model

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \;+$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2}\frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

Underwater Image formation - Forward Model

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \ +$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

Underwater Image formation - Inverse Model

We work with RGB images, and rarely know the physical coefficients (even if we did, they wouldn't be helpful without additional information).

Thus, we need a new formula for image formation that is specific for RGB images.

Captured Image (I_c)

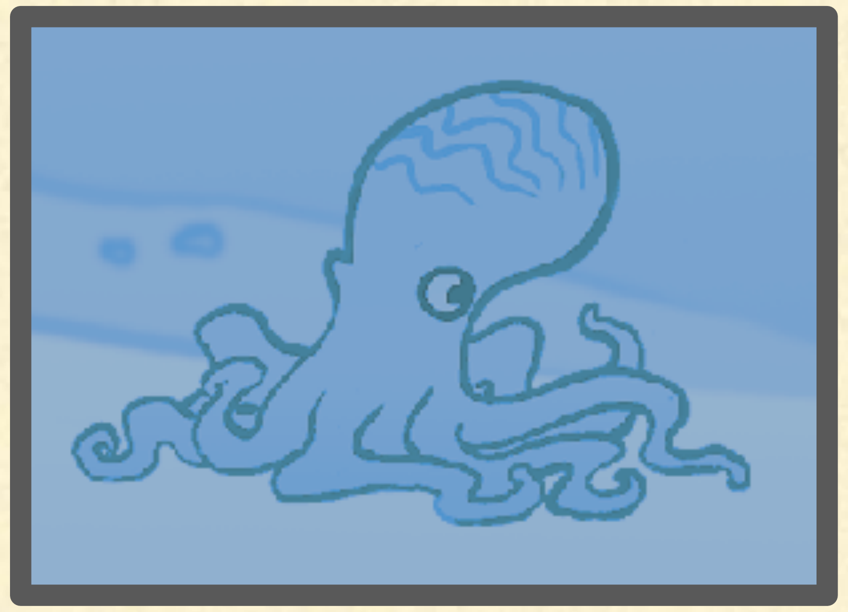
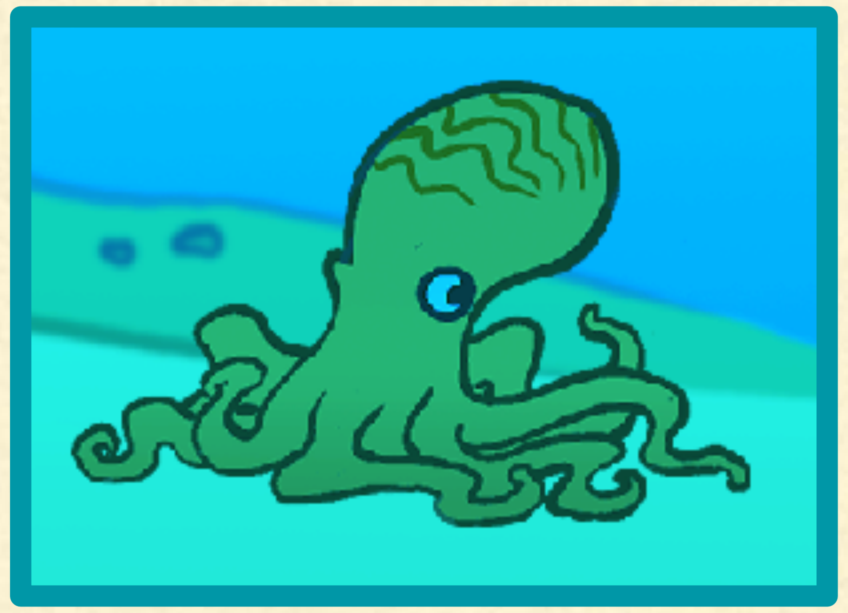


Image we want to recover (J_c)

Underwater Image formation - Inverse Model

$$I_c = \underbrace{J_c e^{-\beta_c^D(\mathbf{v_D})z}}_{D_c} + \underbrace{B_c^\infty\left(1 - e^{-\beta_c^B(\mathbf{v_B})z}\right)}_{B_c}$$



Akkaynak et al. CVPR 2017 & Akkaynak & Treibitz CVPR 2018

Underwater Image formation - Inverse Model

Direct signal coefficient OR (Wideband) attenuation coefficient

Backscatter signal coefficient OR (Wideband) backscatter coefficient

$$I_c = J_c e^{-\boxed{\beta_c^D(\mathbf{v_D})} z} + B_c^{\infty}(1 - e^{-\boxed{\beta_c^B(\mathbf{v_B})} z})$$

$\mathrm{v_{D}}, \mathrm{v_B}$ = dependencies of the wideband coefficients

$$\mathbf{v}_D = \{z, \rho, E, S_c, \beta\} \qquad \mathbf{v}_B = \{E, S_c, b, \beta\}$$

Akkaynak et al. IEEE CVPR 2017 & Akkaynak & Treibitz IEEE CVPR 2018

Physical

Underwater Image formation - Forward

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \;+$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

RGB

Direct signal coefficient OR (Wideband) attenuation coefficient

Backscatter signal coefficient OR (Wideband) backscatter coefficient

$$I_c = J_c e^{-\boxed{\beta_c^D(\mathbf{v_D})}z} + B_c^{\infty}(1 - e^{-\boxed{\beta_c^B(\mathbf{v_B})}z})$$

Two different coefficients with different (weird) dependencies

Akkaynak et al. IEEE CVPR 2017 & Akkaynak & Treibitz IEEE CVPR 2018

What Do the Dependencies Mean?

Direct signal coefficient OR (Wideband) attenuation coefficient

Backscatter signal coefficient OR (Wideband) backscatter coefficient

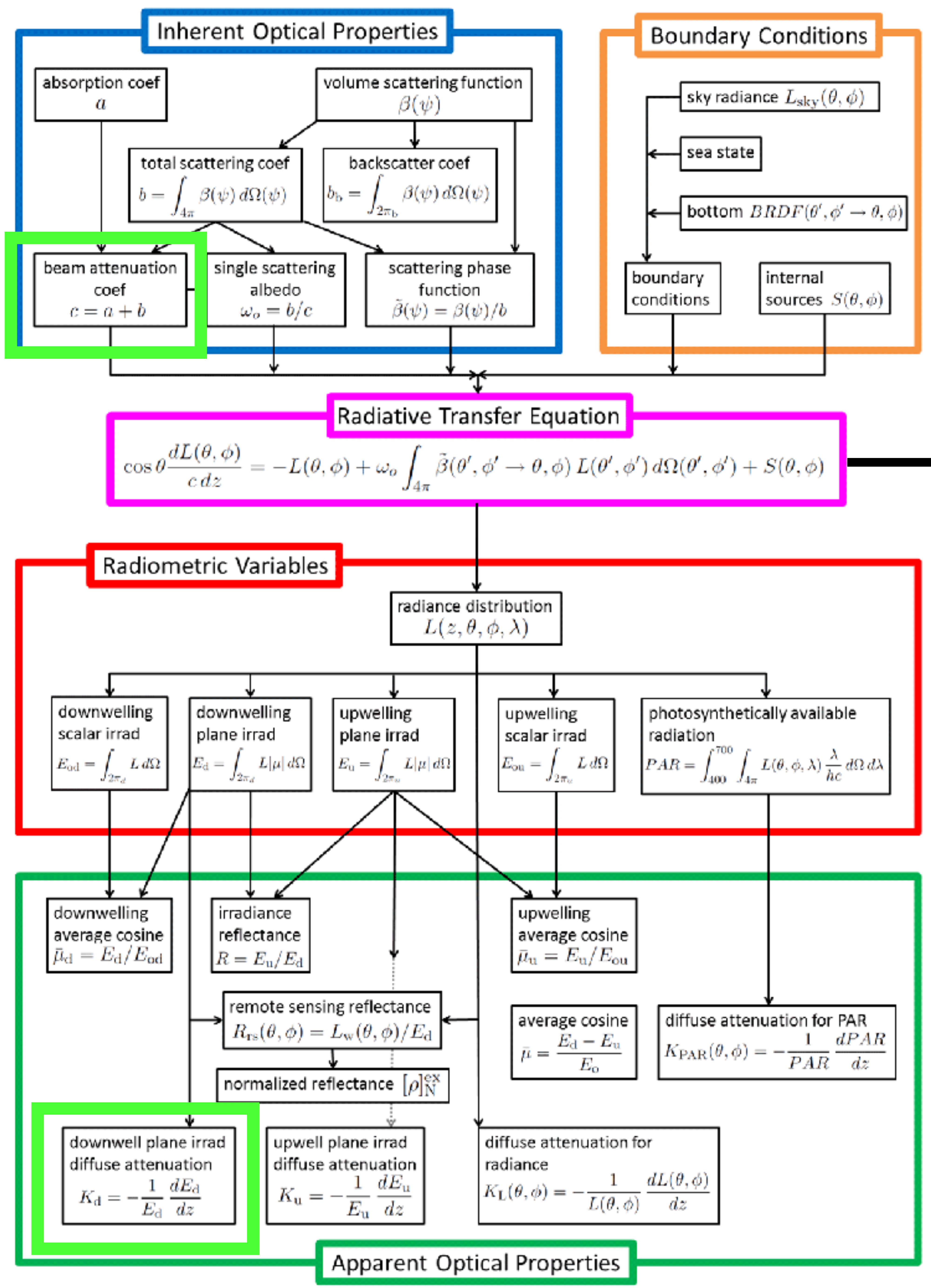
$$I_c = J_c e^{-\boxed{\beta_c^D(\mathbf{v_D})} z} + B_c^\infty (1 - e^{-\boxed{\beta_c^B(\mathbf{v_B})} z})$$

v_D, v_B = dependencies of the wideband coefficients

$$\mathbf{v}_D = \{z, \rho, E, S_c, \beta\} \qquad \mathbf{v}_B = \{E, S_c, b, \beta\}$$

They mean that the coefficients are camera & scene specific; the coefficients you derived from your images for a given set of conditions are meaningless for someone else's imaging setup/conditions!

Akkaynak et al. IEEE CVPR 2017 & Akkaynak & Treibitz IEEE CVPR 2018



World of Ocean Optics

RGB Image Formation Models

$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty\left(1 - e^{-\beta_c^B(\mathbf{v_B})z}\right)$$

Radiative transfer in the ocean:

OCEAN OPTICS Web Book https://www.oceanopticsbook.info/

Radiative transfer in the atmosphere:

Carynelisa Haspel HUJI

Associate Professor

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Room 302 North | Google Scholar | ResearchGate | Research Group

RADIATIVE TRANSFER IN THE ATMOSPHERE - 82309

Ilan Koren WIZ

The Koren Lab
Cloud Physics

Cheat Sheet

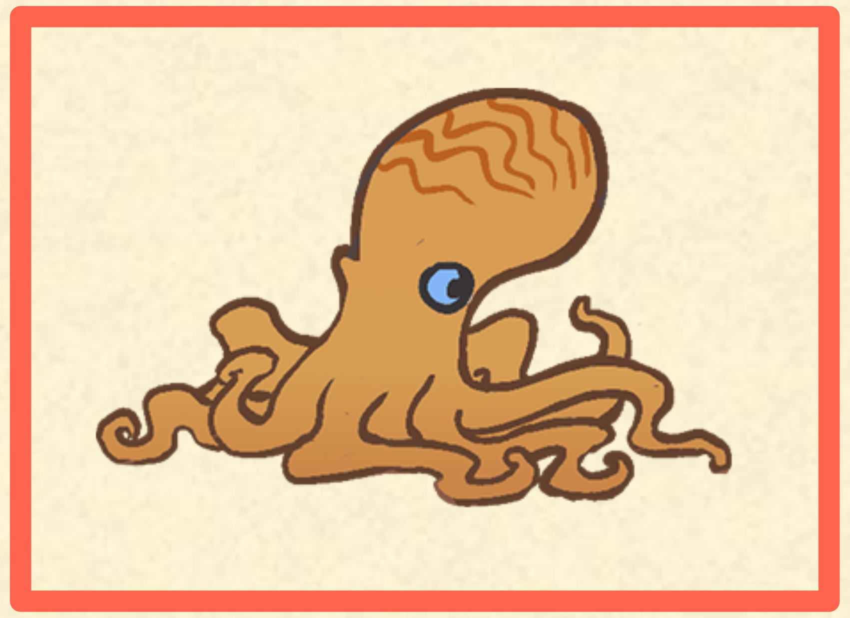
Ground truth

Clear air

Captured Image (I_c)

=

Direct signal (D_c)



+

Backscatter (B_c)

0

Atmospheric fog

Captured Image (I_c)

=

Direct signal (D_c)

+

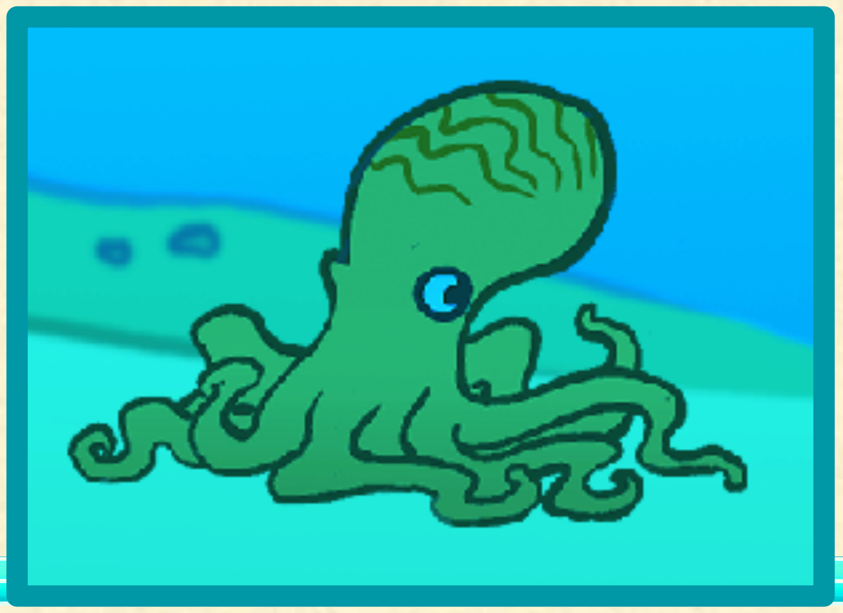
Backscatter (B_c)

Underwater

Captured Image (I_c)

=

Direct signal (D_c)



+

Backscatter (B_c)

IMAGE FORMATION IN CLEAR AIR

$$J_c = \rho E S_c$$

CHEAT SHEET

Basic Image Formation

$$I_c = D_c + B_c$$

IMAGE FORMATION IN FOG/HAZE

Nayar & Narasimhan 1999

$$I_c = J_c e^{-\boxed{\beta_c z}} + B_c^{\infty}(1 - e^{-\boxed{\beta_c z}})$$

Attenuation Coefficient

IMAGE FORMATION IN THE OCEAN

Akkaynak & Treibitz 2018

$$I_c = J_c e^{-\boxed{\beta_c^D(\mathbf{v}_D)}z} + B_c^{\infty}(1 - e^{-\boxed{\beta_c^B(\mathbf{v}_B)}z})$$

$\boxed{\mathbf{v}_D = z, \rho, E, S_c, \beta}$

$\boxed{\mathbf{v}_B = E, S_c, b, \beta}$

dependencies

Attenuation Coefficient

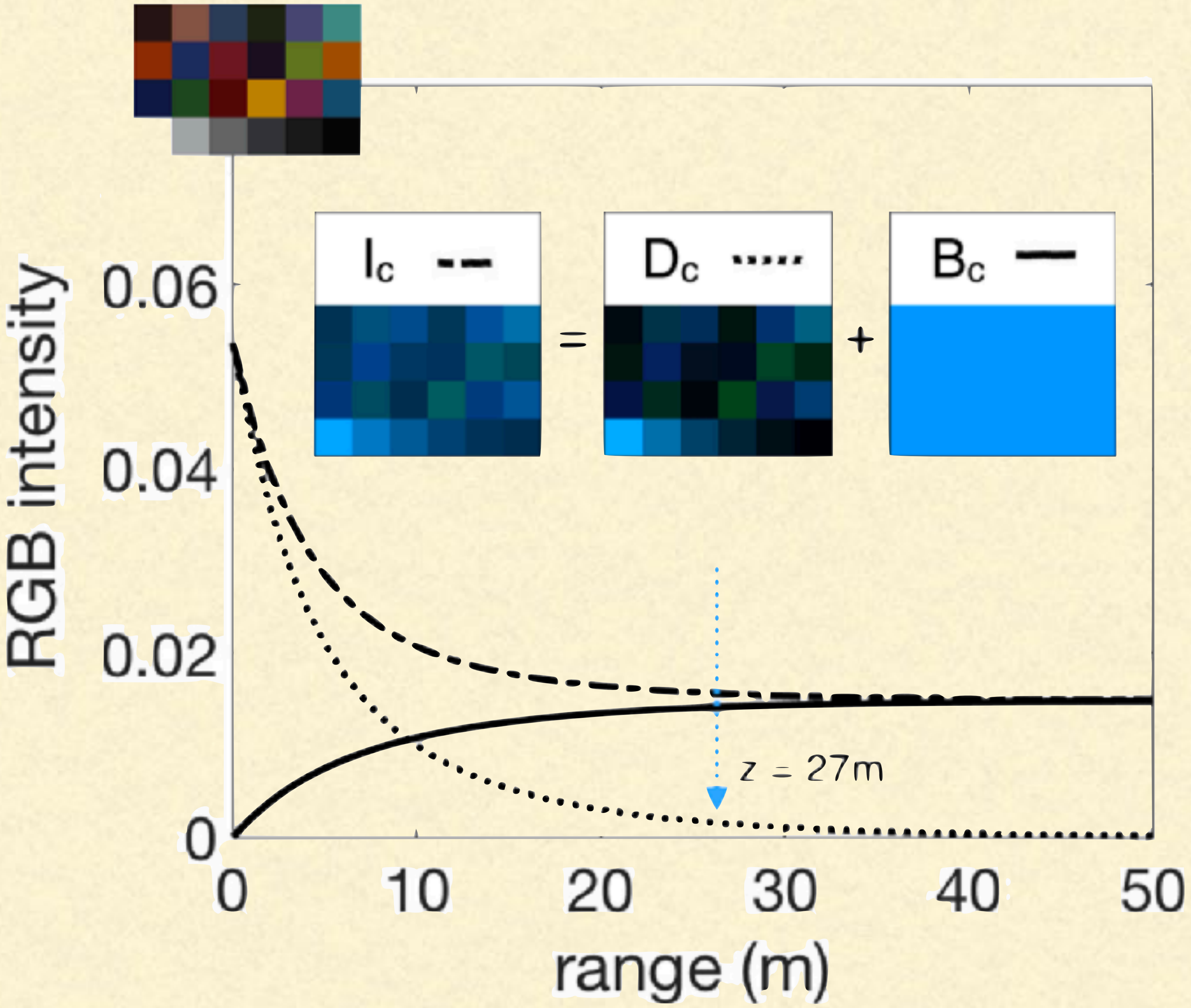
Backscatter Coefficient

Why Is Distance So Important?

All degradations get exponentially worse with distance.

$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

- Backscatter ("fog") grows exponentially with distance!
- Colors are lost exponentially with distance!
- Everything gets worse with increasing distance!



When $z \rightarrow 0$, Image Formation Is Greatly Simplified

When z→0, Image Formation Is Greatly Simplified

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \; +$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

When z→0, Image Formation Is Greatly Simplified

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}\,\overset{1}{e^{-c(\lambda)z}}\,d\lambda \; +$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})\,d\lambda$$

When z→0, Image Formation Is Greatly Simplified

$$Color = \frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)S(\lambda)e^{-K_d(\lambda)d}e^{-c(\lambda)z}d\lambda \; +$$

$$\frac{1}{\kappa}\int_{\lambda_1}^{\lambda_2}\frac{b(\lambda)E(\lambda)e^{-K_d(\lambda)d}}{c(\lambda)}S(\lambda)(1-e^{-c(\lambda)z})d\lambda$$

1

1

When z→0, Image Formation Is Greatly Simplified

Remember: image formation model for clear air?

$$\left[Color = \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S_c(\lambda) d\lambda \right]$$

We can use simple white balancing!

Simplified underwater image formation model (z→0):

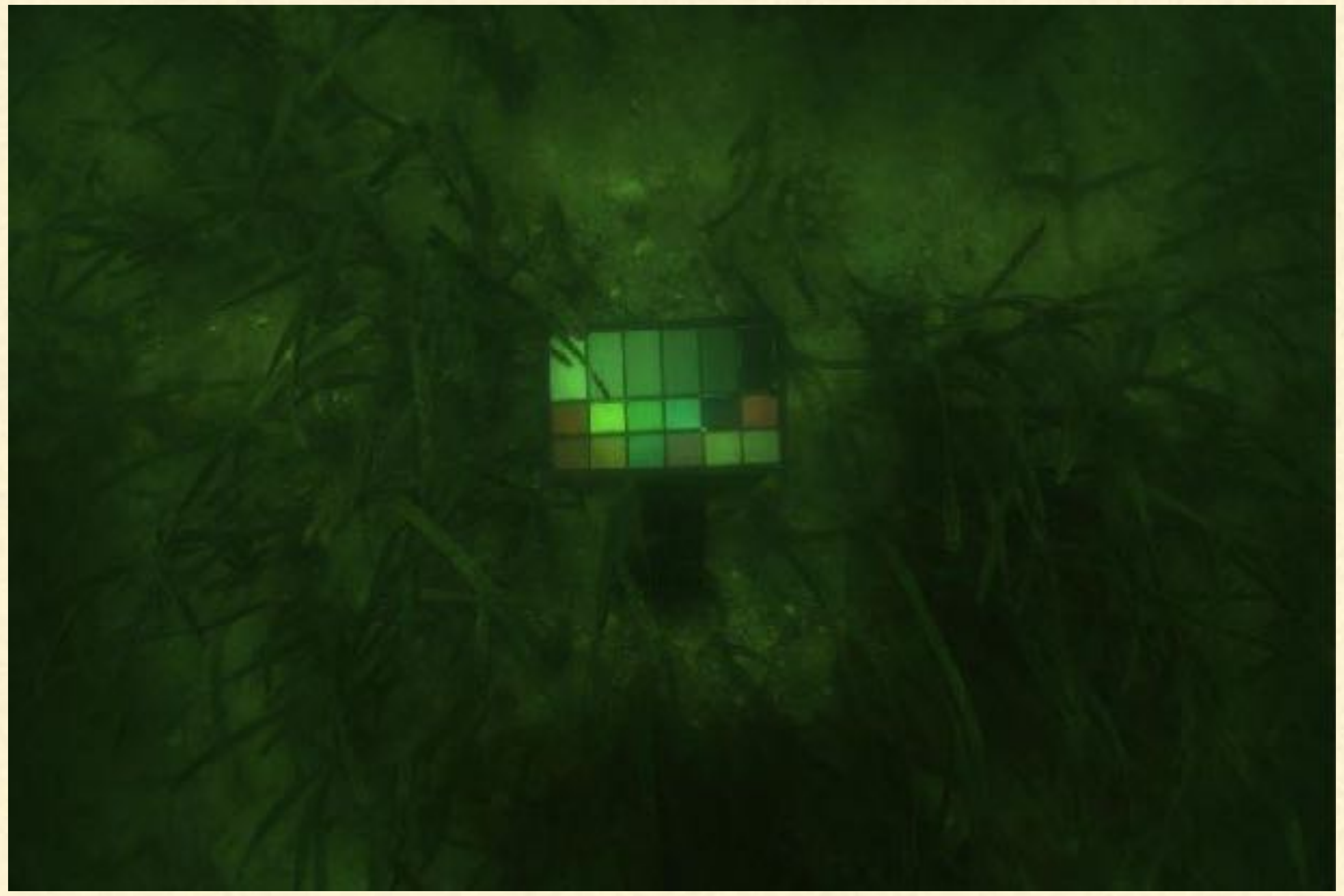
$$Color = \int_{\lambda_1}^{\lambda_2} \rho(\lambda)[E(\lambda)e^{-K_d d}]S_c(\lambda)d\lambda$$

Example: Z→0

Simplified underwater image formation model (z→0):

$$Color = \int_{\lambda_1}^{\lambda_2} \rho(\lambda)[E(\lambda)e^{-K_d d}]S_c(\lambda)d\lambda$$

I_c : Raw image (linear tiff, camera RGB color space)



I_{JPG} : Camera JPG (sRGB color space)

1. Because z→0, we have $I_c \rightarrow D_c$.
2. Chart has 18 patches. XYZ values are known for D65, i.e., $Chart_{XYZ}$ is 18 x 3.
3. White balance the image I_c using one of the achromatic patches.
4. Build camera (white balanced) RGB → (white balanced) XYZ transformation M.
5. Apply the transformation M to convert image into XYZ space, i.e., get I_{XYZ}
6. Convert I_{XYZ} to sRGB color space using standard transform T, i.e.,get I_{srgb}
7. For ground-truthing, convert chart XYZ into sRGB values, i.e., $Chart_{sRGB}$, also 18 x 3.
8. Calculate angular error between the patches of I_{srgb} and with $Chart_{sRGB}$ (ground truth).
9. Calculate angular error between the patches of I_{JPG} and with $Chart_{sRGB}$ (ground truth).
10. Compare the magnitudes of errors from #8 and #9. Which makes more sense?

Color Differences

1) **Delta E (CIE 2000)** Based on the human visual system

The color difference, or ΔE, between a sample color (L_2, a_2, b_2) and a reference color (L_1, a_1, b_1) is:

$$\Delta E = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)}$$

where

$$\bar{L}' = (L_1 + L_2)/2$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\bar{C} = (C_1 + C_2)/2$$

$$G = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$a_1' = a_1(1+G)$$

$$a_2' = a_2(1+G)$$

$$C_1' = \sqrt{a_1'^2 + b_1^2}$$

$$C_2' = \sqrt{a_2'^2 + b_2^2}$$

$$\bar{C}' = (C_1' + C_2')/2$$

$$h_1' = \begin{cases} \arctan(b_1/a_1') & \text{if } \arctan(b_1/a_1') \geq 0 \\ \arctan(b_1/a_1') + 360^\circ & \text{otherwise} \end{cases}$$

$$h_2' = \begin{cases} \arctan(b_2/a_2') & \text{if } \arctan(b_2/a_2') \geq 0 \\ \arctan(b_2/a_2') + 360^\circ & \text{otherwise} \end{cases}$$

$$\bar{H}' = \begin{cases} (h_1' + h_2' + 360^\circ)/2 & \text{if } |h_1' - h_2'| > 180^\circ \\ (h_1' + h_2')/2 & \text{otherwise} \end{cases}$$

$$T = 1 - 0.17\cos(\bar{H}' - 30^\circ) + 0.24\cos(2\bar{H}') + 0.32\cos(3\bar{H}' + 6^\circ) - 0.20\cos(4\bar{H}' - 63^\circ)$$

$$\Delta h' = \begin{cases} h_2' - h_1' & \text{if } |h_2' - h_1'| \leq 180^\circ \\ h_2' - h_1' + 360^\circ & \text{else if } |h_2' - h_1'| > 180^\circ \text{and } h_2' \leq h_1' \\ h_2' - h_1' - 360^\circ & \text{otherwise} \end{cases}$$

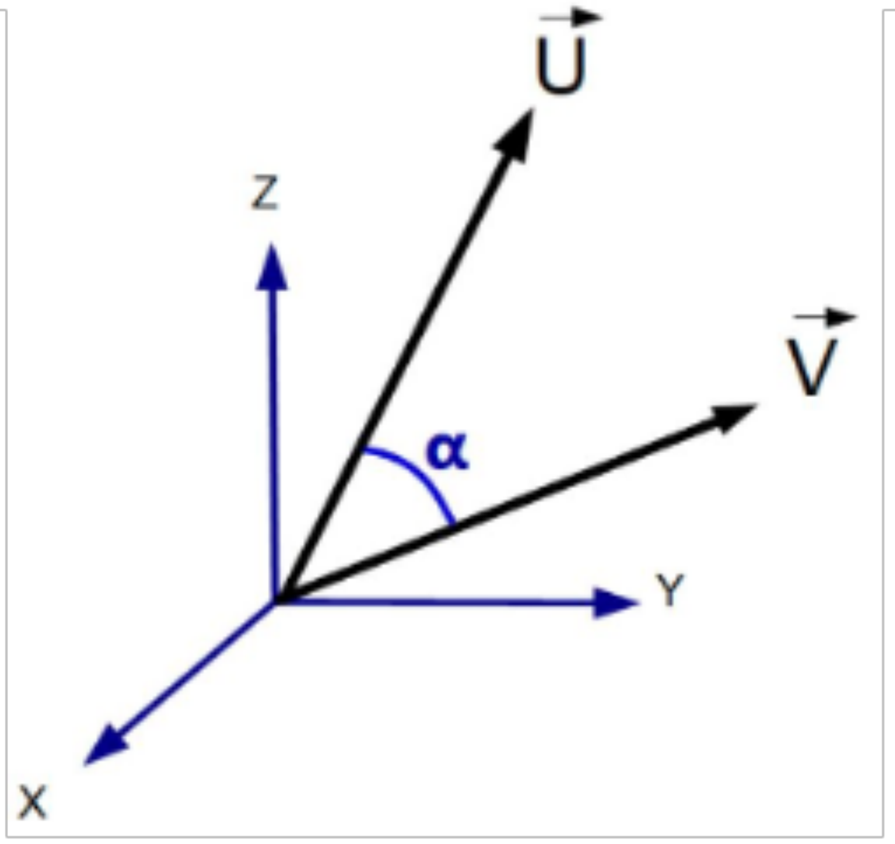
Δ = difference

Empfindung = sensation

And the formula goes on!

2) Angular error (mathematical)

$$D(\mathbf{U}, \mathbf{V}) = \angle(\mathbf{U}, \mathbf{V}) \triangleq \arccos\left(\frac{\mathbf{U} \cdot \mathbf{V}}{\|\mathbf{U}\|_2 \|\mathbf{V}\|_2}\right)$$



3) Non-human animal vision (DeltaS and DeltaL)

Receptor noise as a determinant of colour thresholds

Misha Vorobyev[1*] and D. Osorio[2]

[1]*Institut für Neurobiologie, Freie Universität Berlin, Königin-Luise-Strasse 28–30, 14195 Berlin, Germany*
[2]*School of Biological Sciences, University of Sussex, Brighton BN1 9QG, UK*

for trichromatic vision,

$$(\Delta S^t)^2 = \frac{e_1^2(\Delta q_3 - \Delta q_2)^2 + e_2^2(\Delta q_3 - \Delta q_1)^2 + e_3^2(\Delta q_1 - q_2)^2}{(e_1 e_2)^2 + (e_1 e_3)^2 + (e_2 e_3)^2} \tag{4}$$

and for tetrachromatic vision,

$$\begin{aligned}(\Delta S^t)^2 = &((e_1 e_2)^2(\Delta q_4 - \Delta q_3)^2 + (e_1 e_3)^2(\Delta q_4 - \Delta q_2)^2 + \\ &(e_1 e_4)^2(\Delta q_3 - \Delta q_2)^2 + (e_2 e_3)^2(\Delta q_4 - \Delta q_1)^2 + \\ &(e_2 e_4)^2(\Delta q_3 - \Delta q_1)^2 + (e_3 e_4)^2(\Delta q_2 - \Delta q_1)^2) / \\ &((e_1 e_2 e_3)^2 + (e_1 e_2 e_4)^2 + (e_1 e_3 e_4)^2 + (e_2 e_3 e_4)^2).\end{aligned} \tag{5}$$

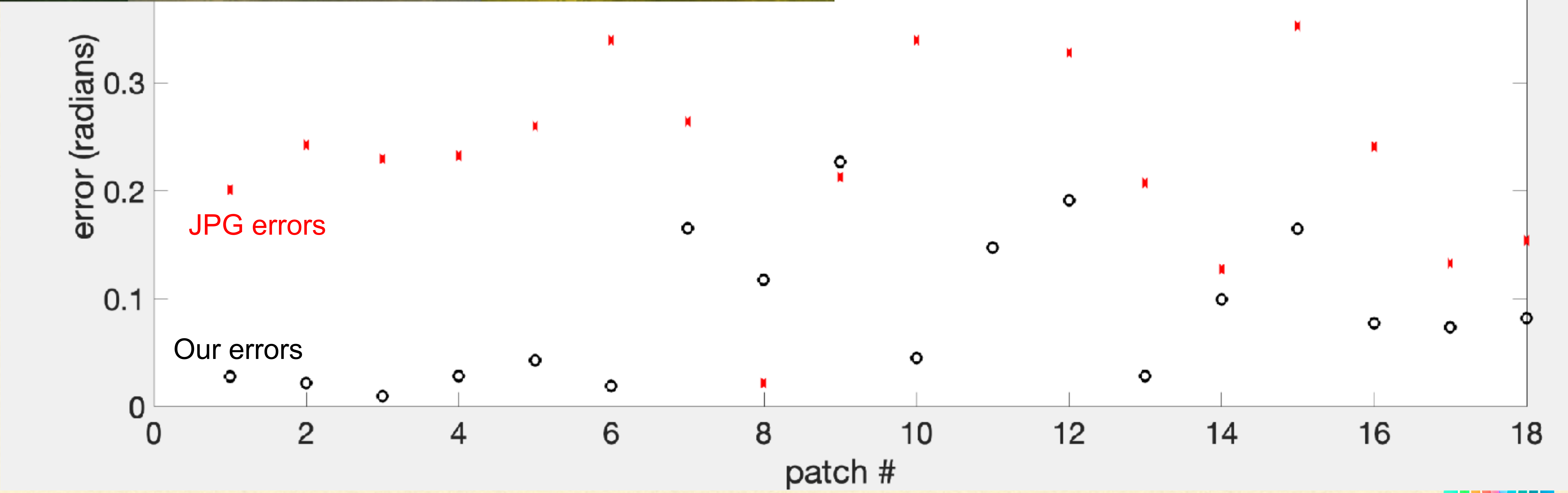
The spectral sensitivity is the inverse of threshold intensity, $I^t(\lambda)$, i.e. of the minimum intensity of monochromatic light of wavelength, λ, detectable over an adapting background. The difference in the quantum catch between background and stimulus is given (see equation (1)) by

$$\Delta q_i = k_i R_i(\lambda) I^t(\lambda). \tag{6}$$

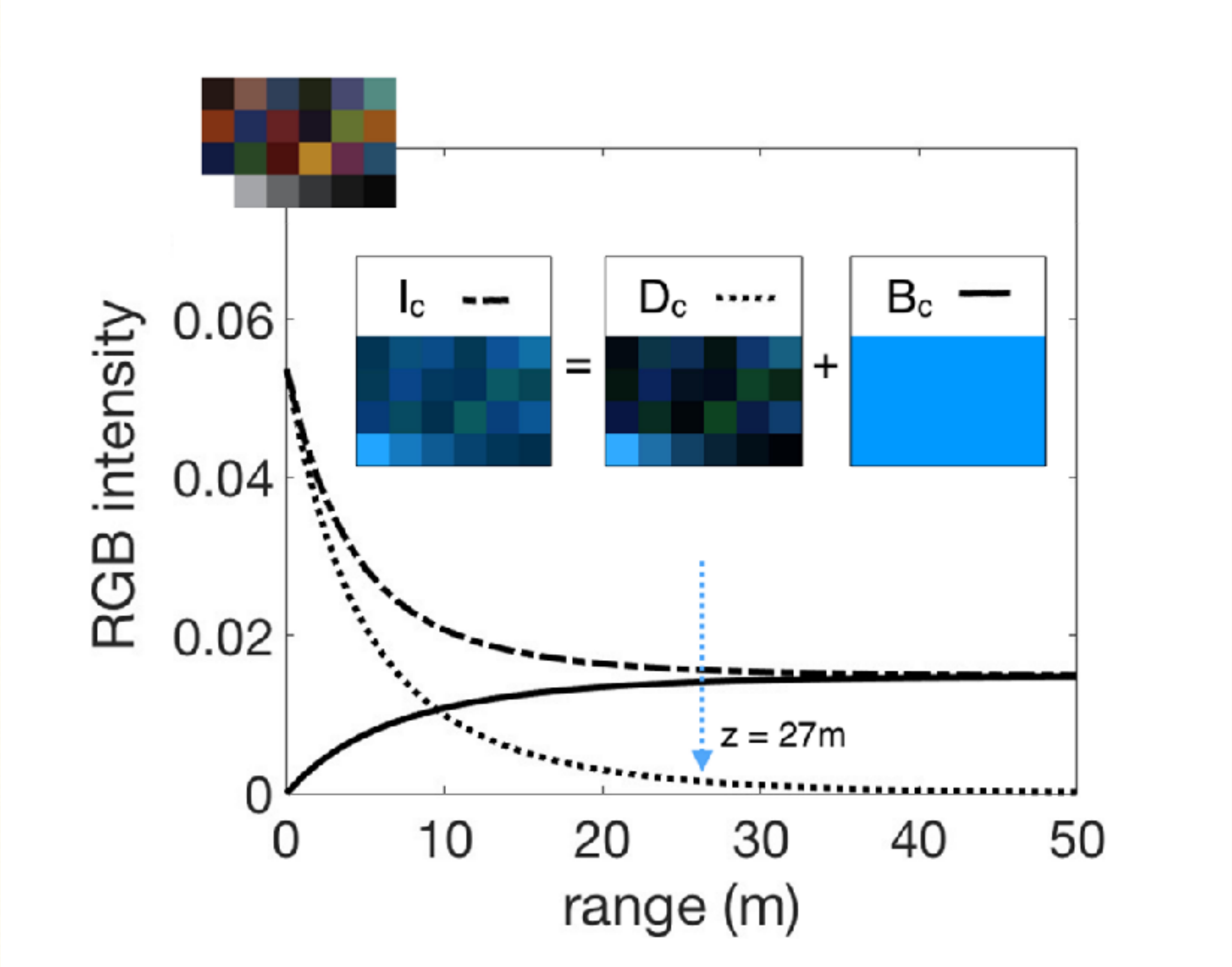
Color Errors

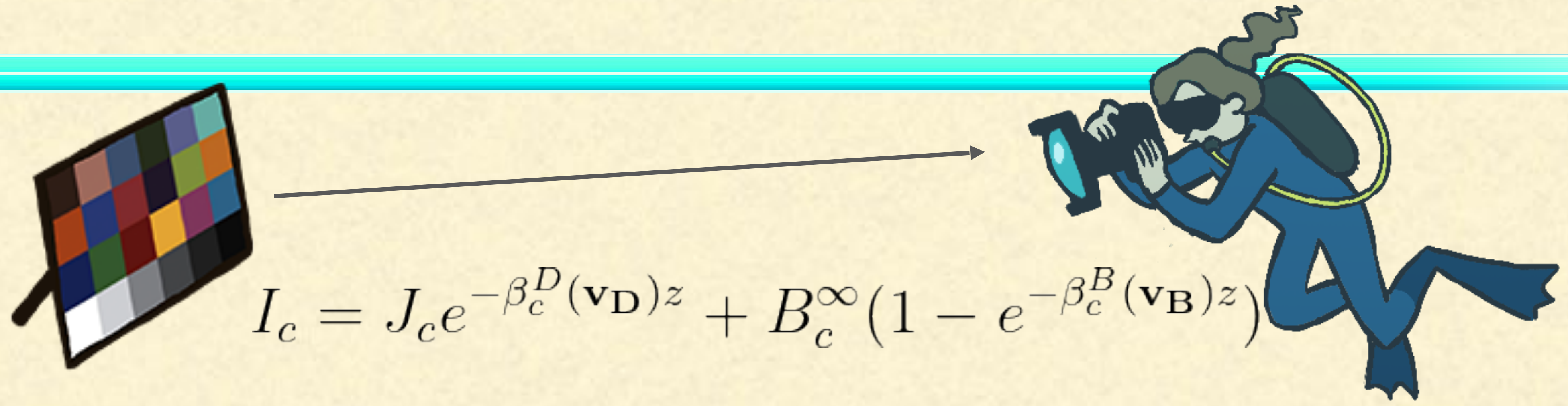
Simplified underwater image formation model (z→0):

$$Color = \int_{\lambda_1}^{\lambda_2} \rho(\lambda)[E(\lambda)e^{-K_d d}]S_c(\lambda)d\lambda$$



Example: z≠0

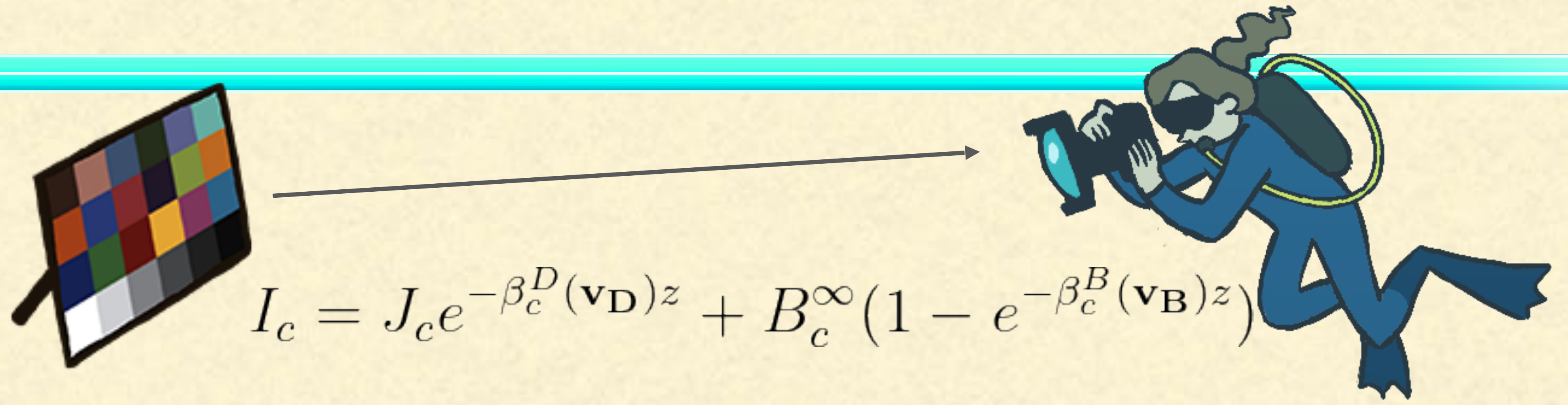


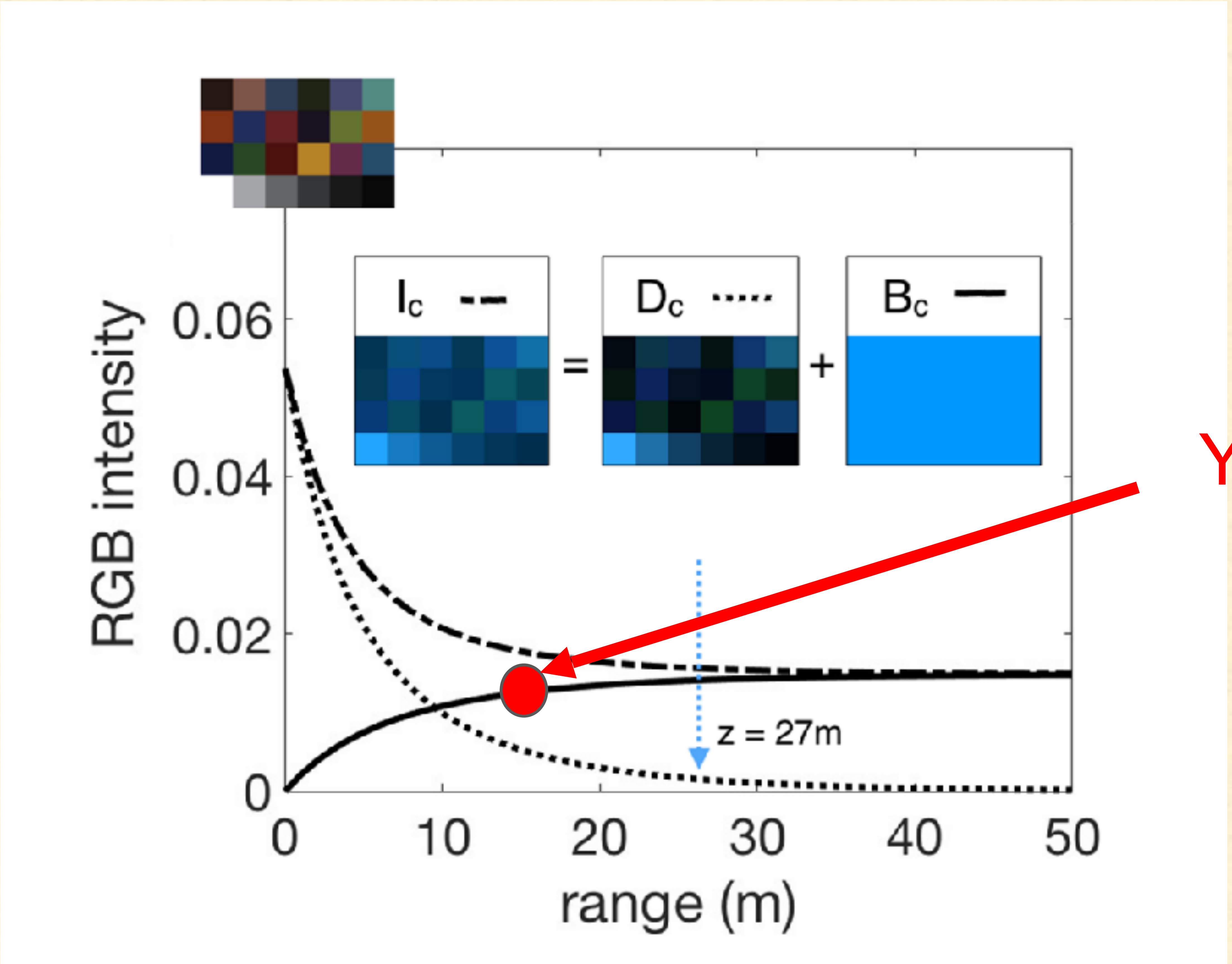


$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

Also: all your calculations will only be valid for distance z.

Example: z≠0

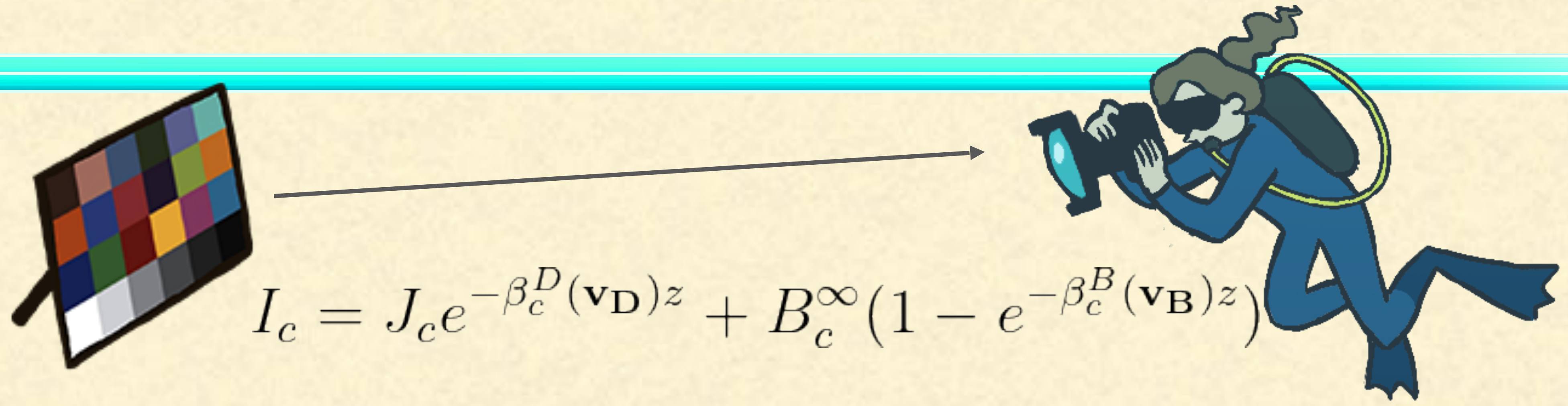




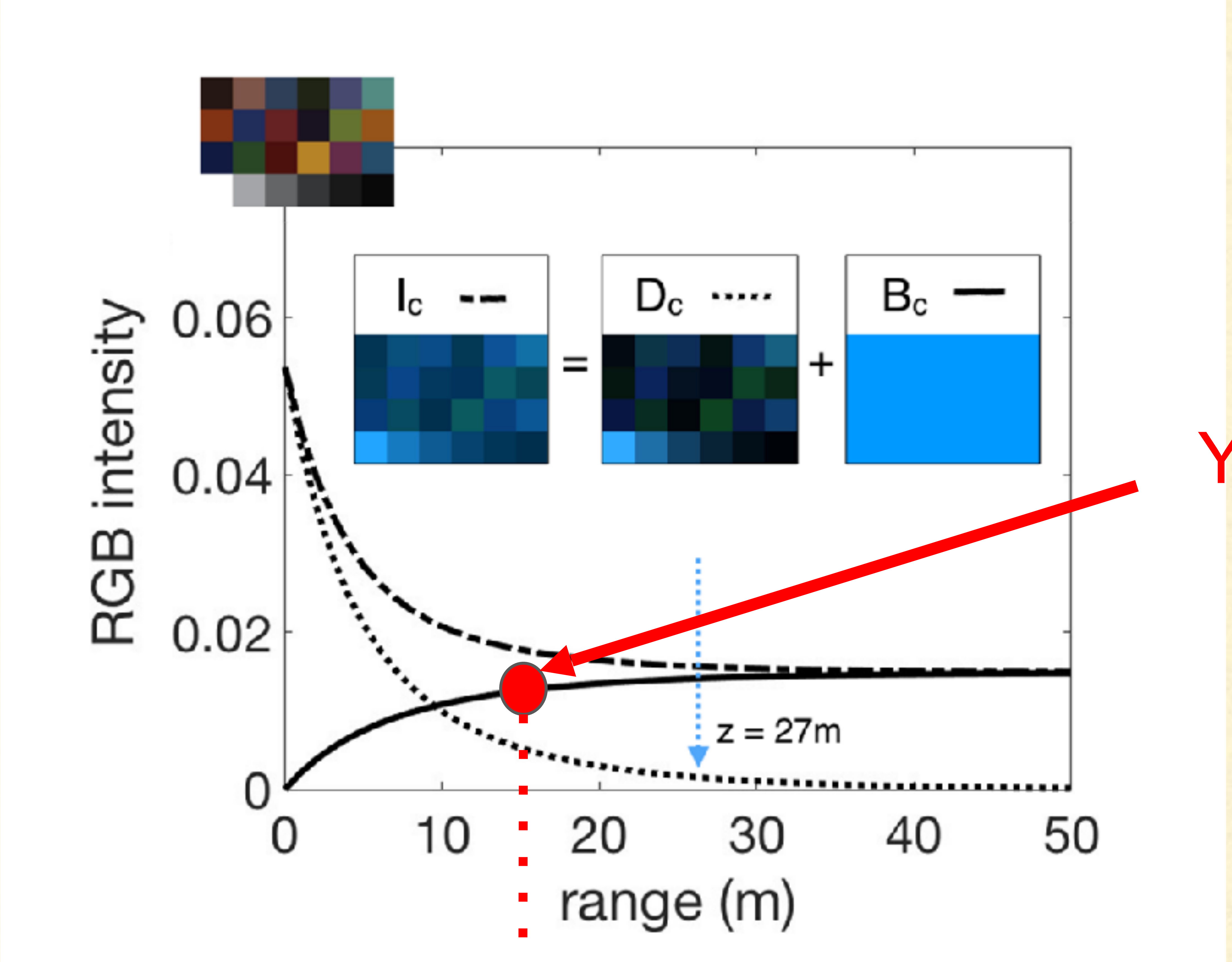
You are here!

Also: all your calculations will only be valid for distance z.

Example: z≠0



$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

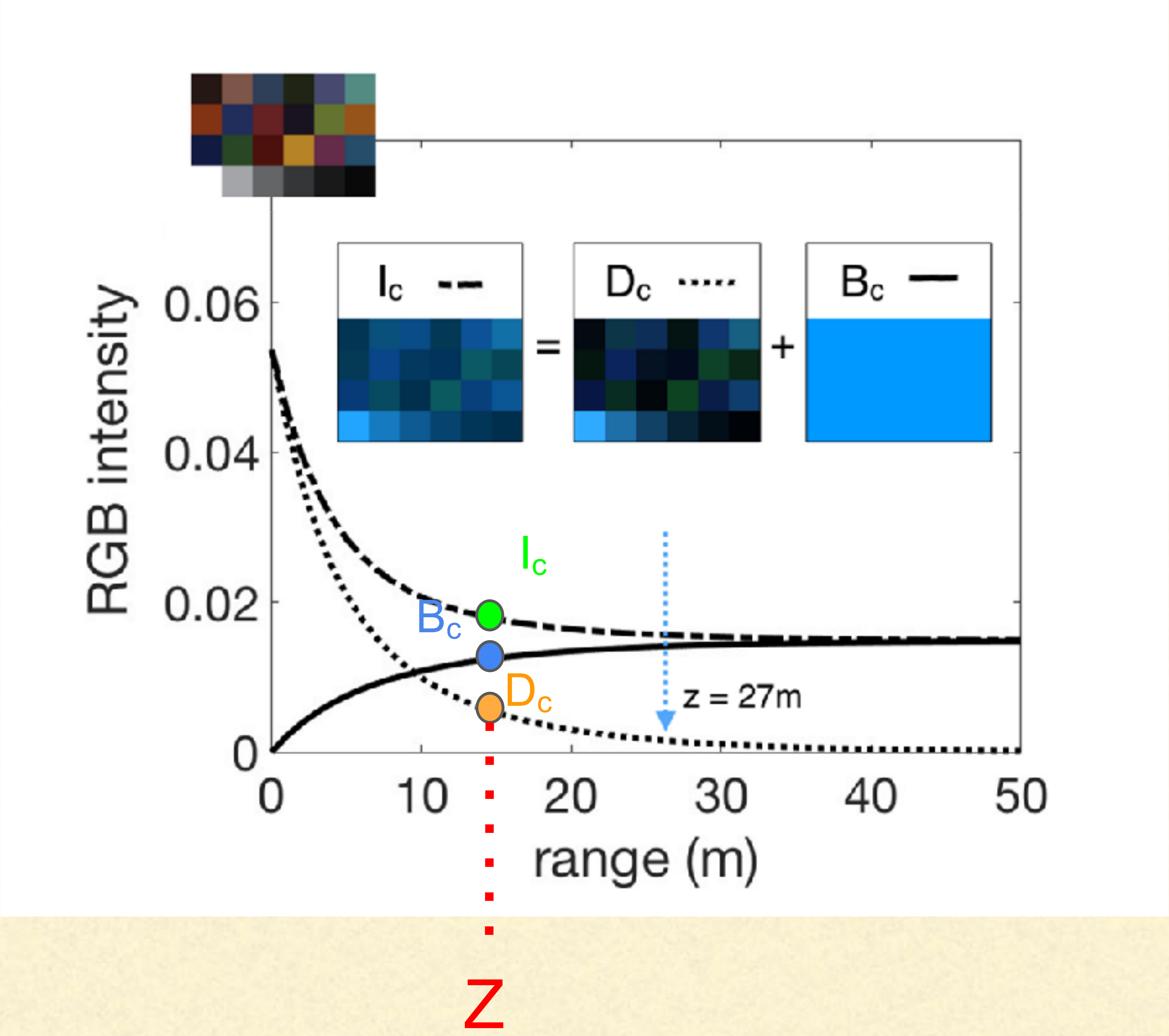


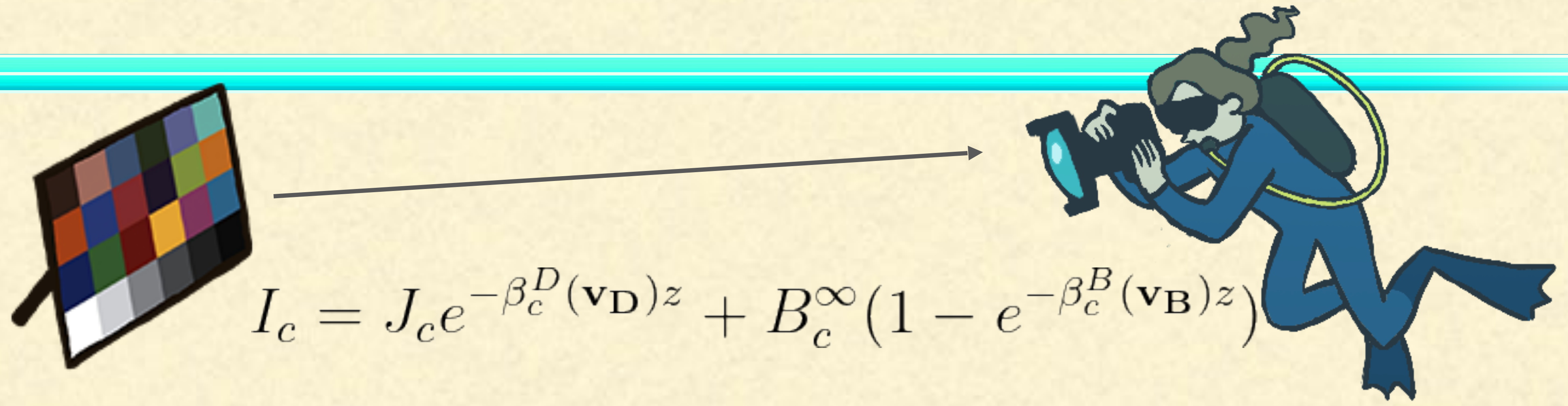
You are here!

Also: all your calculations will only be valid for distance z.

Z You need to know z, so you must take multiple images and do SFM to get a depth map. No escape!

Example: z≠0





$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

I_c = D_c + B_c

1. Calculate and subtract backscatter. Then you have:

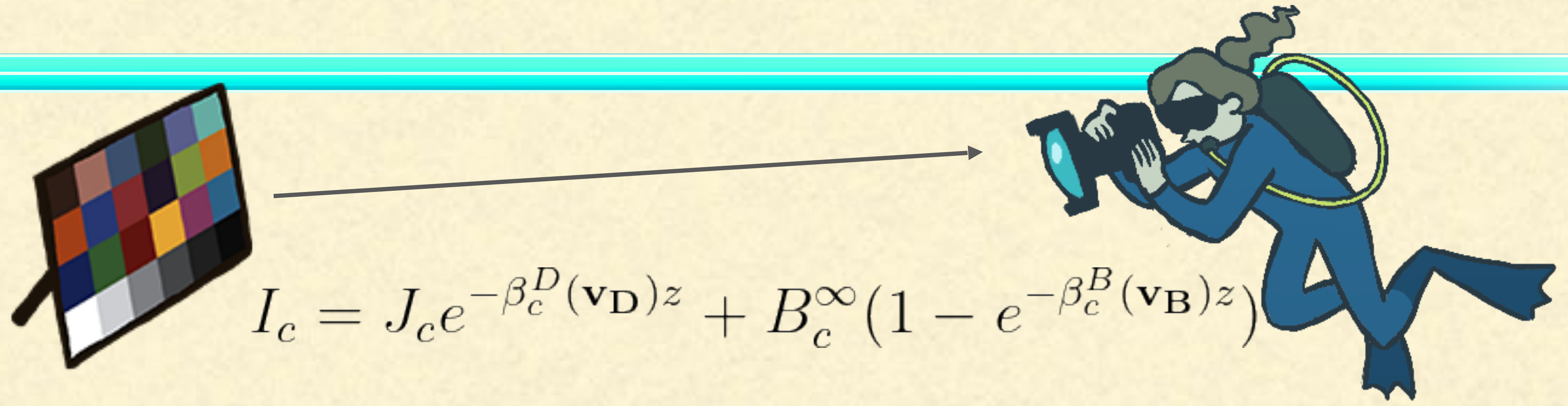
$$D_c = J_c e^{-\beta_c^D z}$$

2. Your goal is to recover:

$$J_c = D_c e^{\beta_c^D z}$$

How to calculate backscatter at z

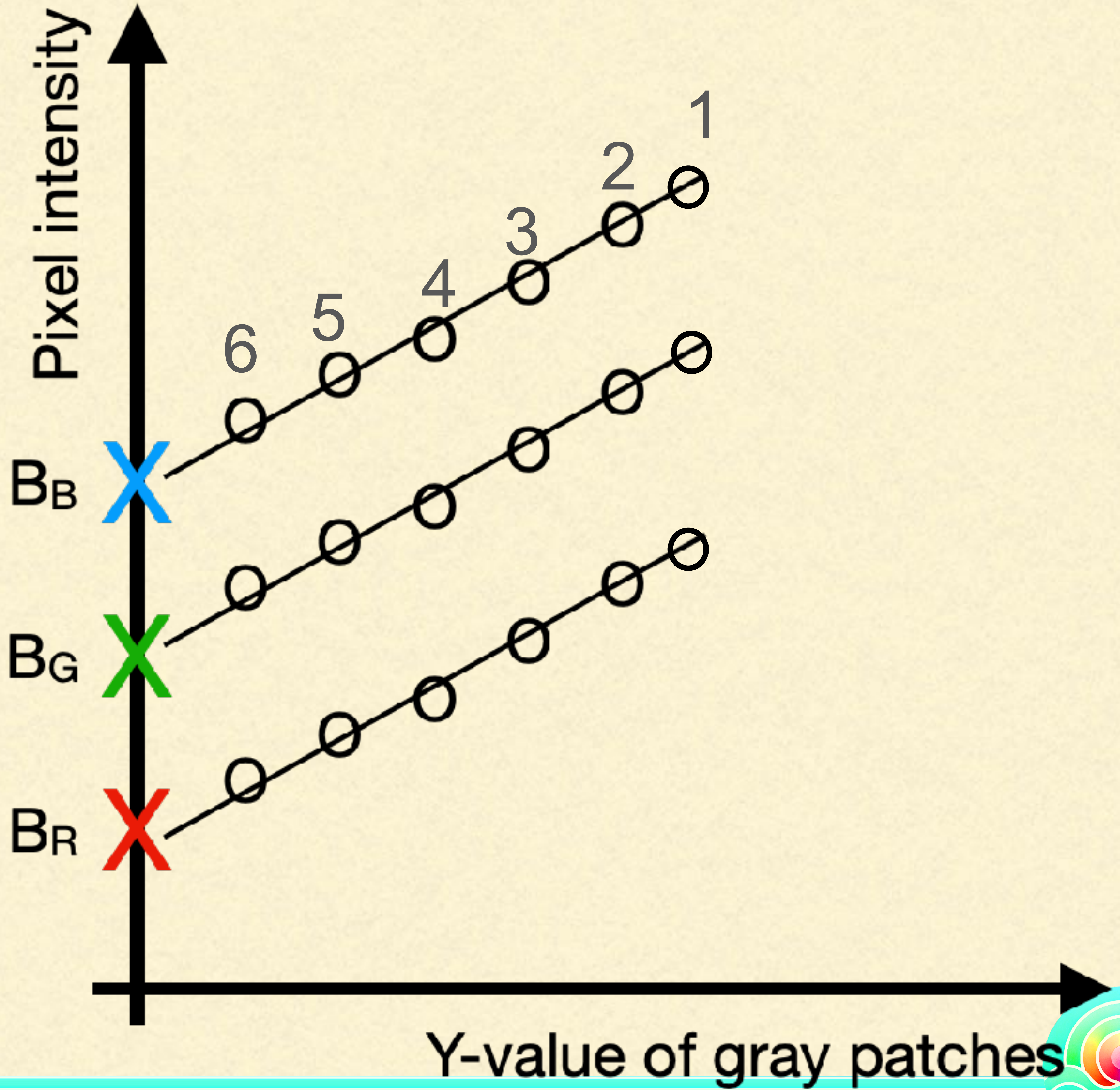
$$B_c^{\infty}(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$



$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^{\infty}(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

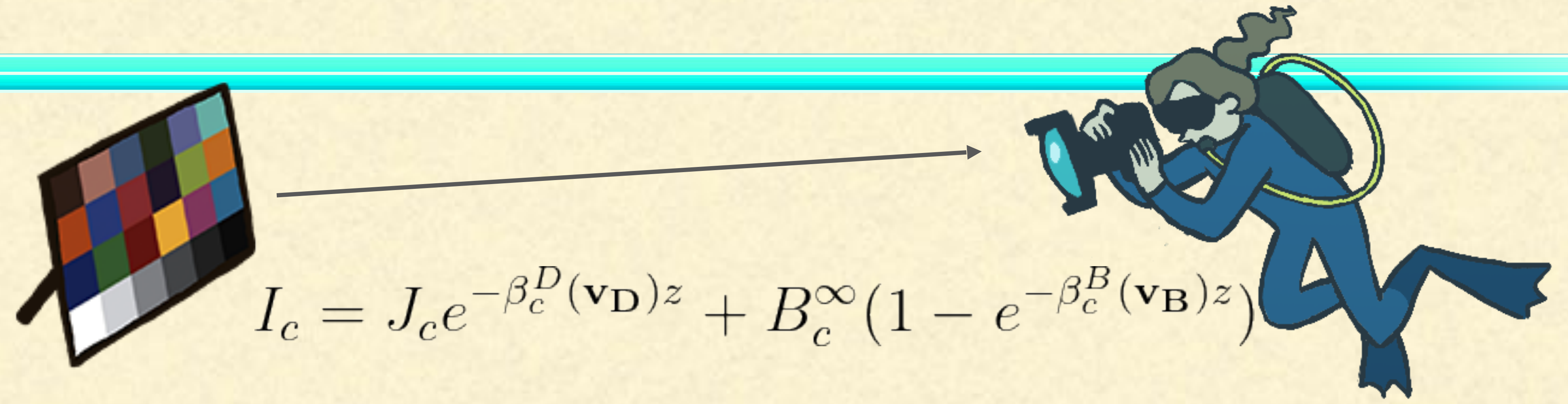
How to calculate backscatter using a color chart:

(because we don't have Vantablack)



!!! With this method, you can only calculate backscatter (B_c) at the z where the chart is, not the backscatter coefficients. You need to two charts at different distances to be able to calculate the coefficients.

How to calculate attenuation at z



This is what is left after subtracting B_c:

$$D_c = J_c e^{-\beta_c^D z}$$

Now need to calculate β_c^D to be able to recover J_c

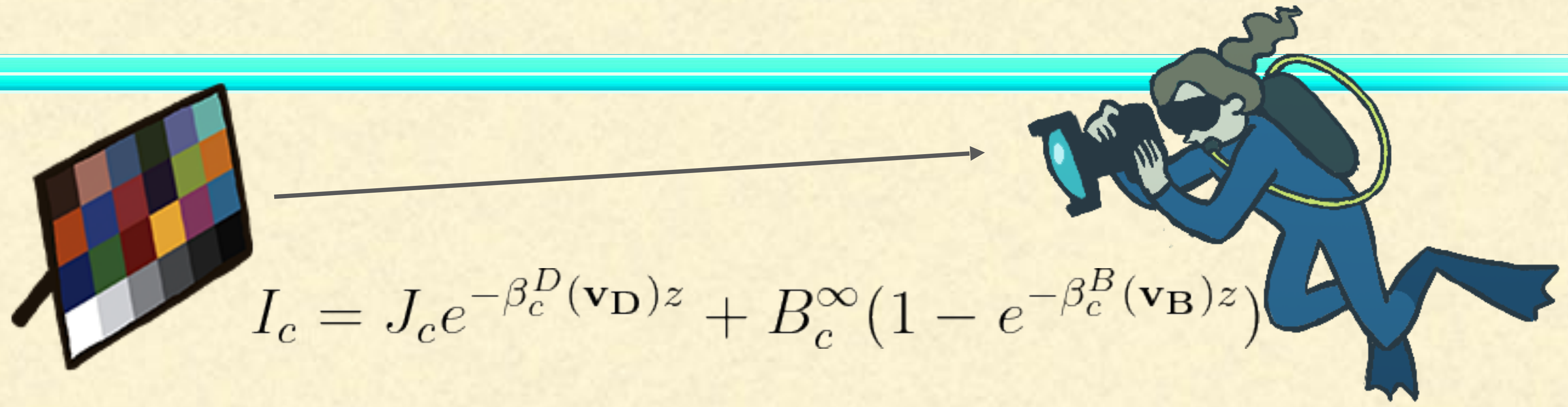
$$J_c = D_c e^{\beta_c^D z}$$

$$\beta_c^D = \ln \frac{D_c(z)}{D_c(z + \Delta z)} / \Delta z$$

You need two color charts, at distances z and z + Δz

Akkaynak et al. "What is the space of attenuation coefficients in underwater computer vision?." *IEEE CVPR* 2017.

Remember the dependencies?



$$I_c = J_c e^{-\boxed{\beta_c^D(\mathbf{v_D})}z} + B_c^\infty(1 - e^{-\boxed{\beta_c^B(\mathbf{v_B})}z})$$

v_D, v_B = dependencies of the wideband coefficients

$$\mathbf{v}_D = \{z, \rho, E, S_c, \beta\} \qquad \mathbf{v}_B = \{E, S_c, b, \beta\}$$

There is a different β_c^D
for each reflectance!!!! (but we will ignore that)

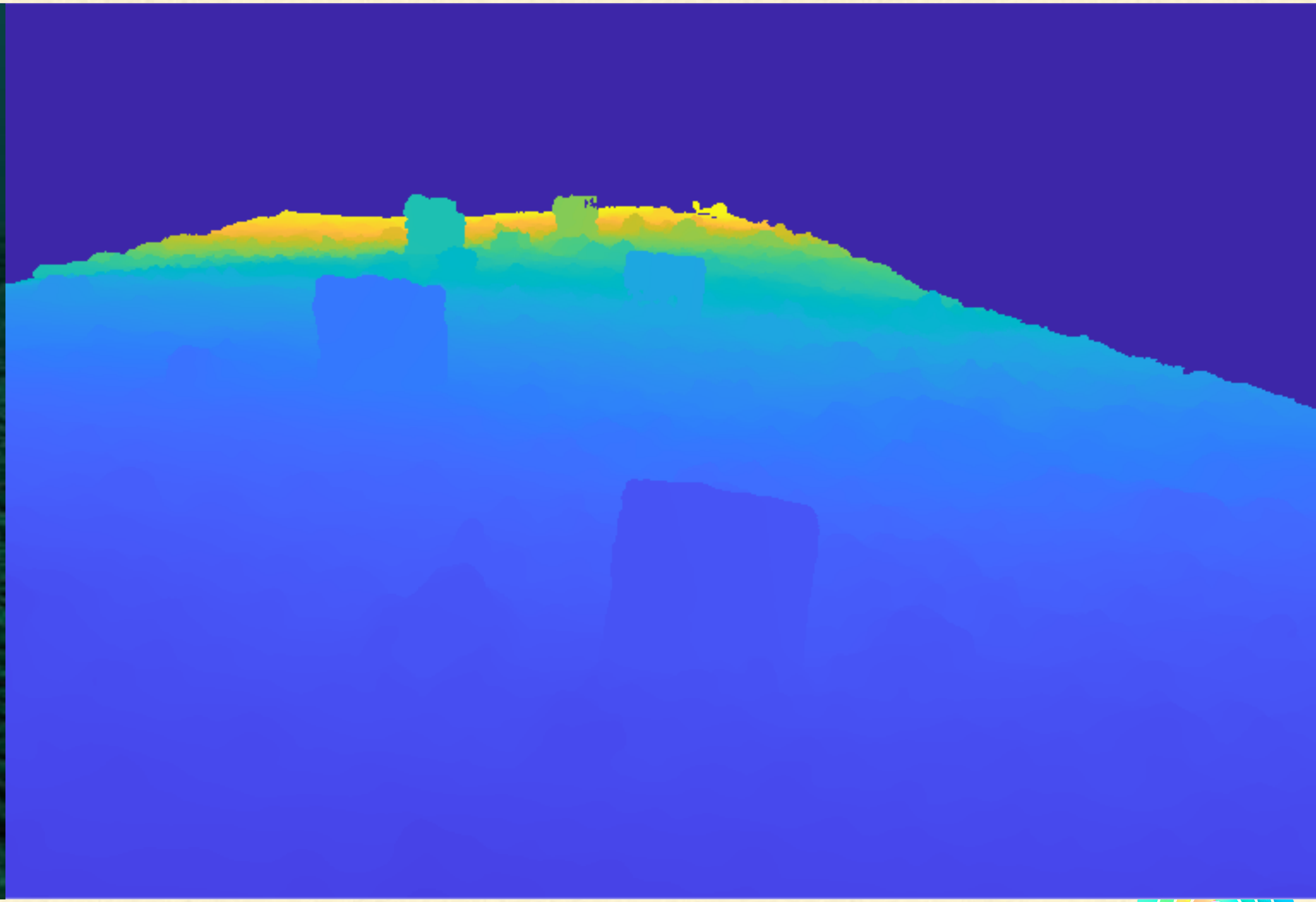
There is a different β_c^D
for each range!!!! (and we CANNOT ignore that)

How to calculate attenuation at z

$$I_c = J_c e^{-\beta_c^D(\mathbf{v}_\mathbf{D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v}_\mathbf{B})z})$$

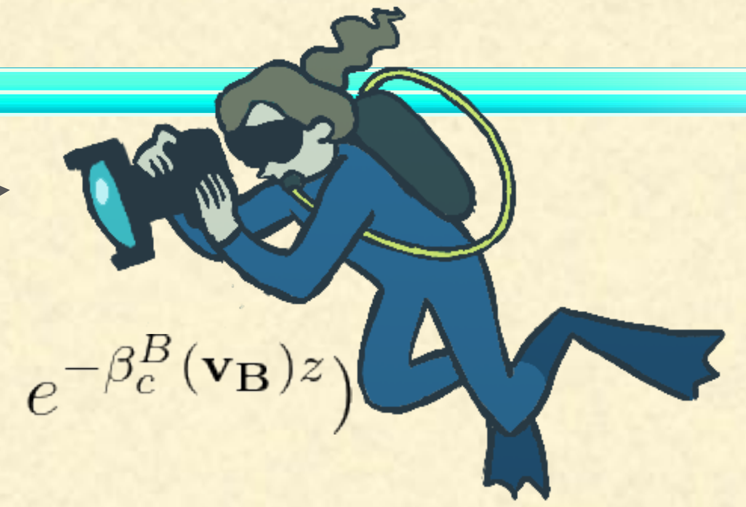
RGB image with ≥ 2 color charts

Corresponding scaled depth map



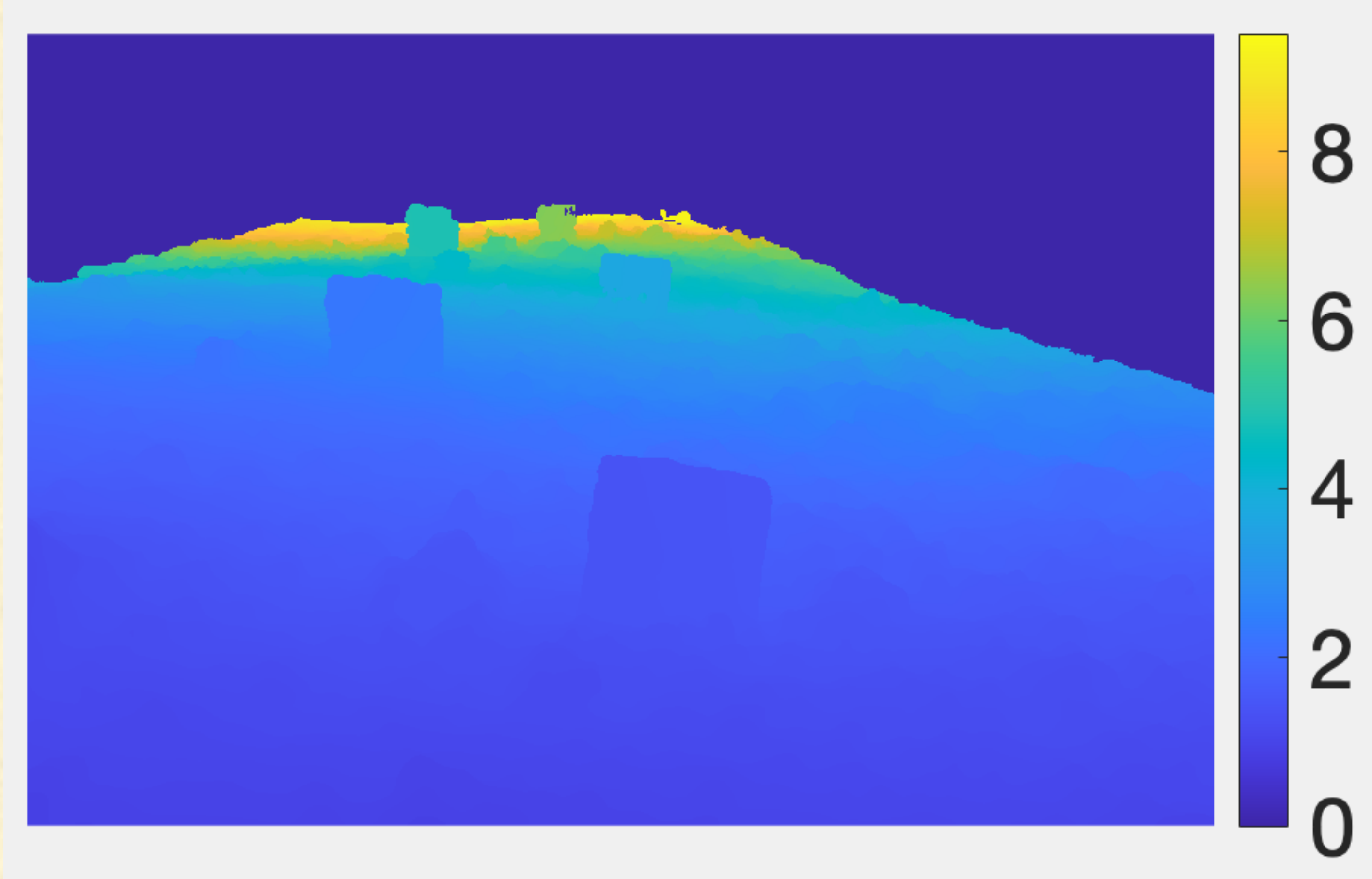
How to calculate attenuation at z

$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$



RGB image with ≥ 2 color charts

Corresponding scaled D image

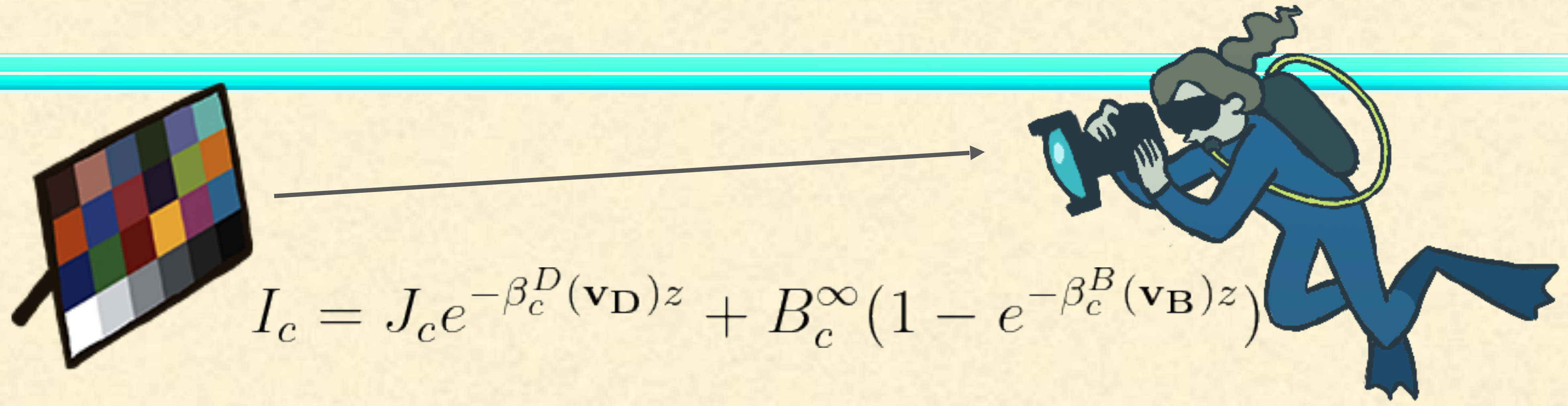


1. From the linear tiff (or PNG) image, extract RGB values for each patch, for each chart. Our underwater charts have 18 patches, so you will have 18 x 3 matrices <u>for each chart</u>.
2. Using the "D" (distance/range) image, extract the z value for each chart. (Here, we do not expect variation per patch because all patches of a given chart is approximately the same distance from the camera.)
3. Calculate and remove backscatter from each chart, as previously described, to obtain Dc value at each chart. (Here, remember that we are ignoring color dependency of β_c^D so we are assuming each chart has one Dc value).
4. Plot Dc versus z, and look at the data. It's always good to inspect your data.
5. Compute the attenuation coefficient using two charts at different z's. Try as many combinations as possible, sometimes data can be noisy and not every pair works.
6. Obtain J_c!

$$J_c = D_c e^{\beta_c^D z}$$

$$\beta_c^D = \ln \frac{D_c(z)}{D_c(z + \Delta z)} / \Delta z$$

Are we done?



Almost - two last things!

1.Thus far, you compensated for the effects of z. So there is no more backscatter and attenuation due to the distance between the camera and the scene.

But there is still the color cast due to the effect of depth d.

Lucky for us, at this point, that's a simple, global, white balancing operation. Remember:

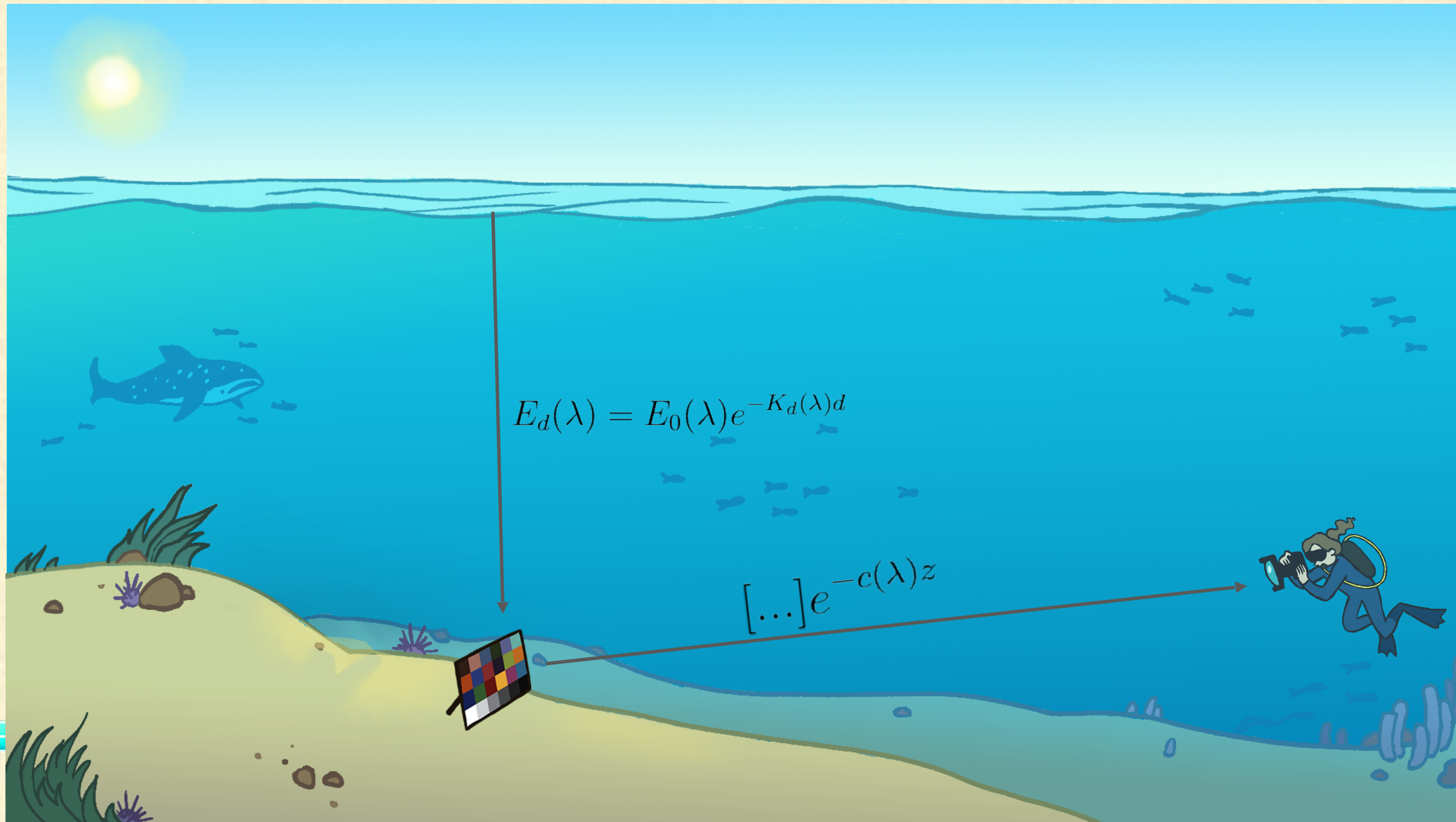
Simplified underwater image formation model (z→0):

$$Color = \int_{\lambda_1}^{\lambda_2} \rho(\lambda)[E(\lambda)e^{-K_d d}]S_c(\lambda)d\lambda$$

Use any gray patch on any chart and white balance!

2. Your results are still in the camera RGB color space. Build and apply an RGB→ XYZ transformation, and from there, go to sRGB color space, as we learned before.

Congrats! Colors in your images (for objects that were located next to your color charts) are under a standard light, in a standard color space, and are reproducible!



When publishing:

$$I_c = J_c e^{-\beta_c^D(\mathbf{v_D})z} + B_c^\infty(1 - e^{-\beta_c^B(\mathbf{v_B})z})$$

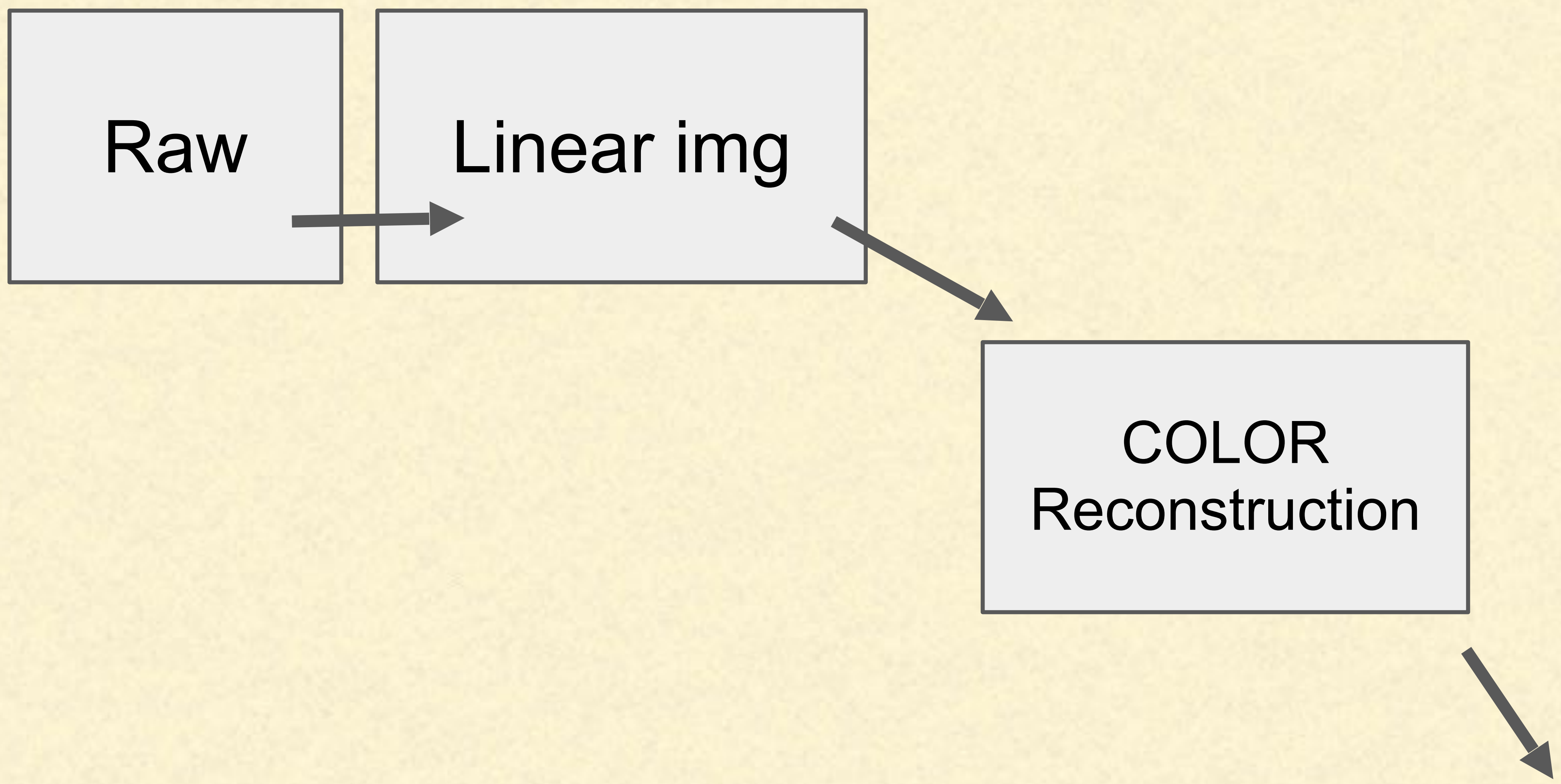
- Always shoot RAW; publish & archive your RAW data.
- Always verify sensor linearity, and mention in your paper.
- Invest in high-quality color charts and take good care of them.
- You need to know the reflectances and XYZ values (generally under D65). If possible, don't trust manufacturer data and measure its reflectances yourself. Repeat periodically!
- When possible, measure light with a radiometer whenever you are doing experiments. If not, report what light profile you assumed (for most cases, you can assume D65 but be aware of what it means).
- Obtain the curves of your camera. Ideally, derive them with a monochromator. Even if you may not directly use them (we didn't need them in these examples), they will be handy for debugging and validation.
- Always report the name & properties of the patch with which you white balance.
- Report which standard observer curves you used.
- Report whether you performed a chromatic adaptation transform at any point, if so, with which method.
- Report which final RGB color space your data are in.

Course summary:

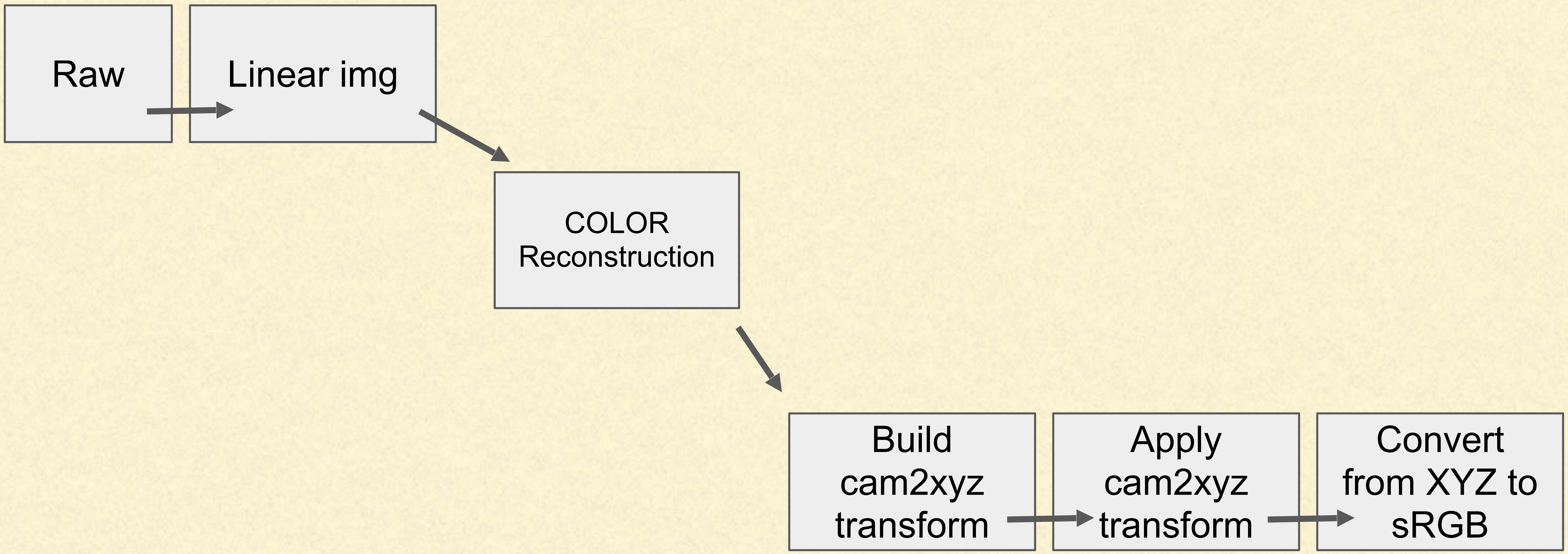
Course summary:

Raw → Linear img

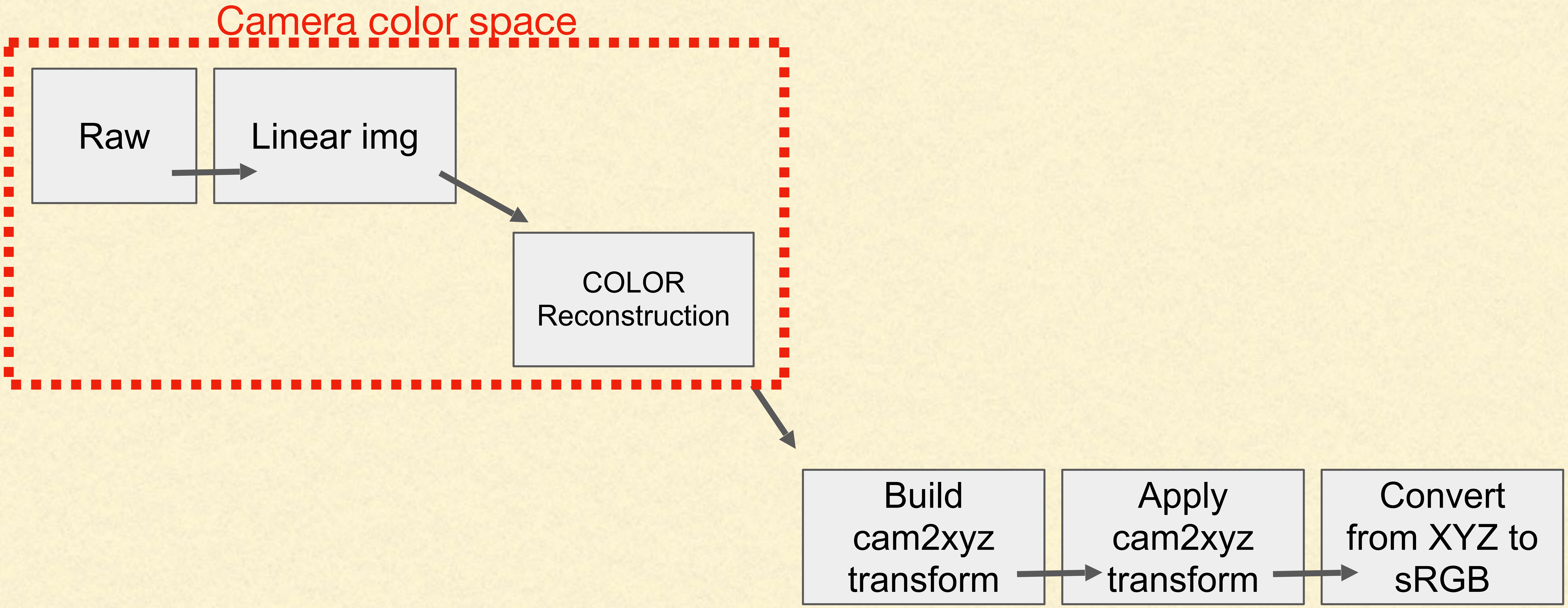
Course summary:



Course summary:



Course summary:



Course summary: