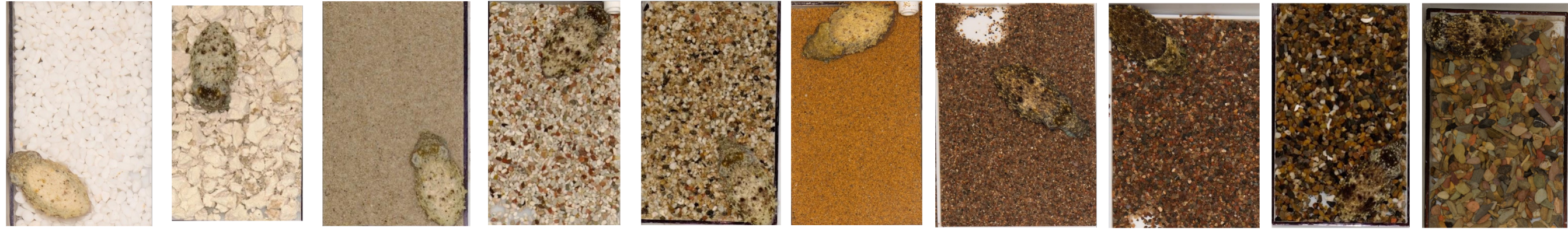
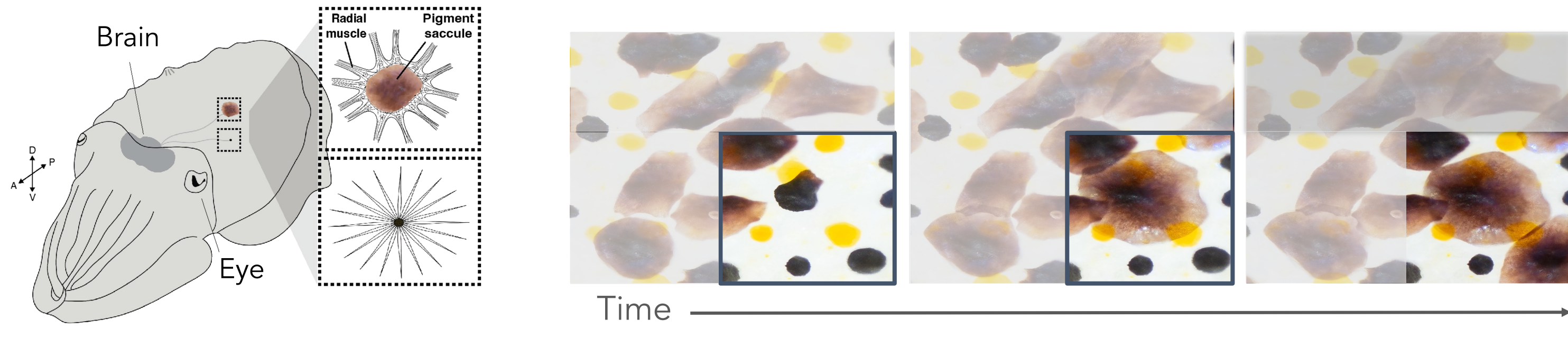


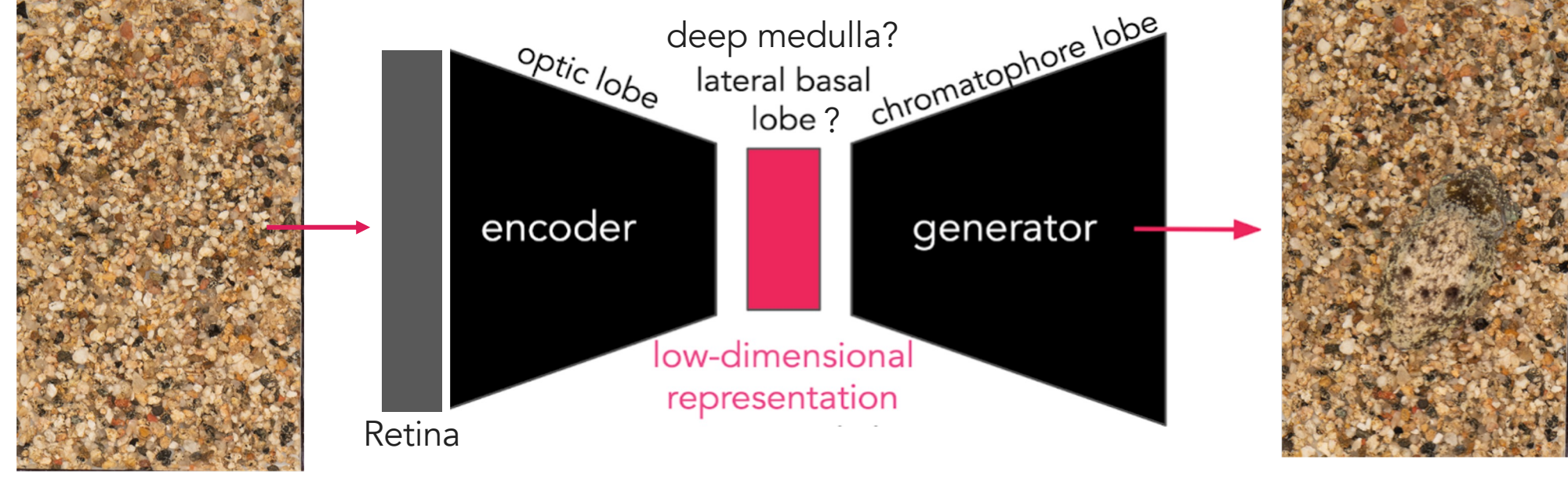
Cuttlefish change color & pattern of skin to evade detection.



This is accomplished by expanding pigment-filled sacs, known as chromatophores.

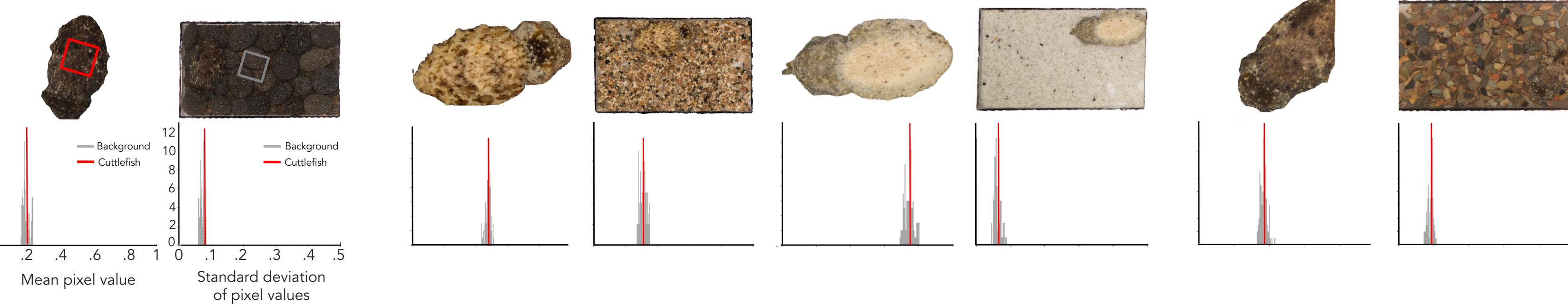


The computational problem



Hypothesis: Cuttlefish computes a set of statistics of their visual environment, and then generates a skin pattern that matches these statistics.

Cuttlefish match mean and variance



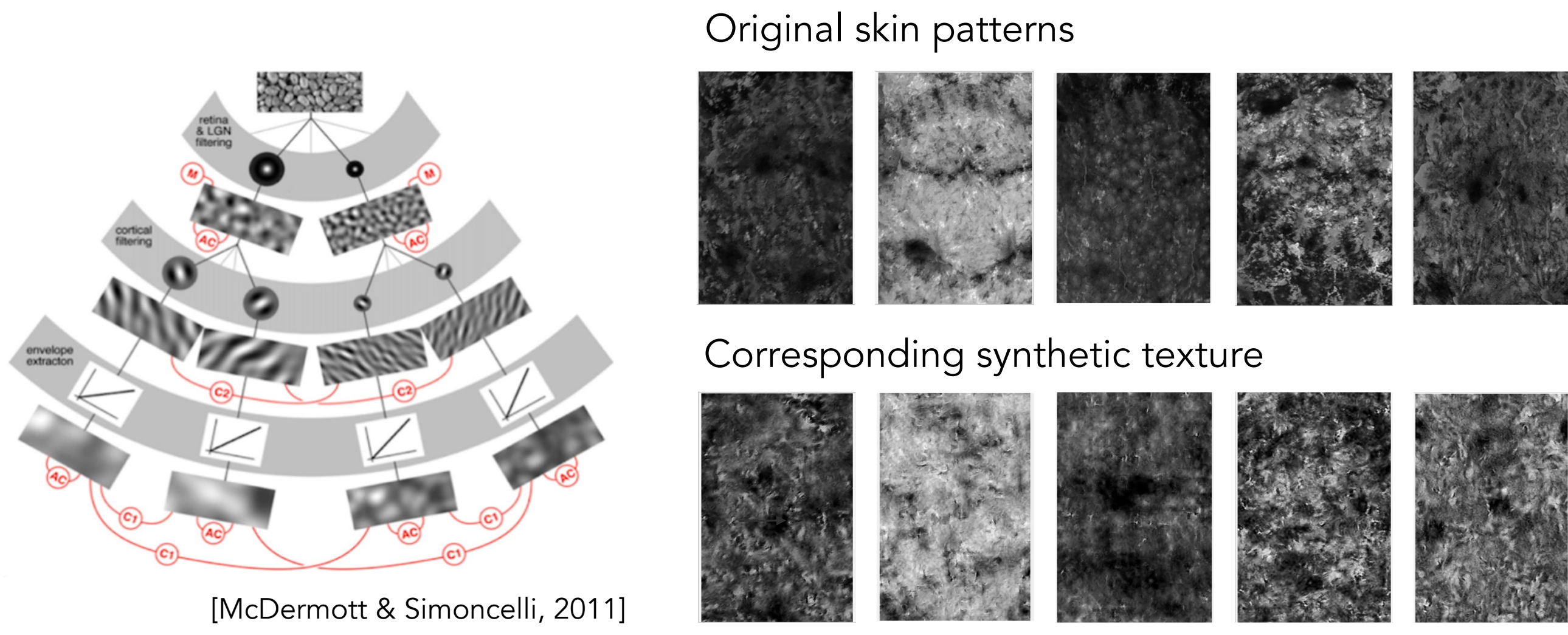
What other statistics might they be matching?



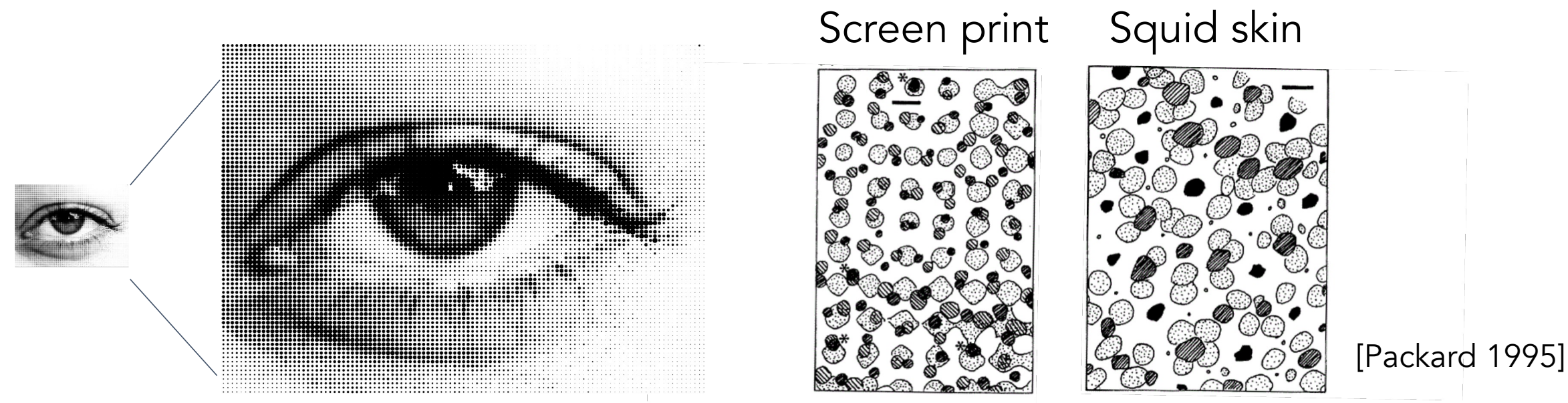
Visual Texture is common in a cuttlefish's natural environment.

Visual texture = Images that are spatially homogeneous, containing repeated structures, typically with some random variation (Portilla & Simoncelli, 2000).

Portilla and Simoncelli texture statistics capture cuttlefish skin appearance.



Using chromatophores to produce images is reminiscent of halftone printing.

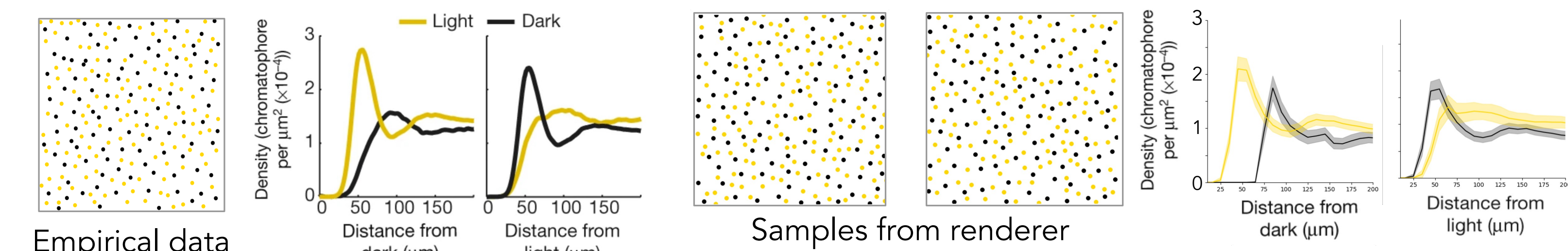


This chromatophore halftone process is going to constrain the patterns the animal can make. To test this, we built a cuttlefish skin renderer based on known biological properties.

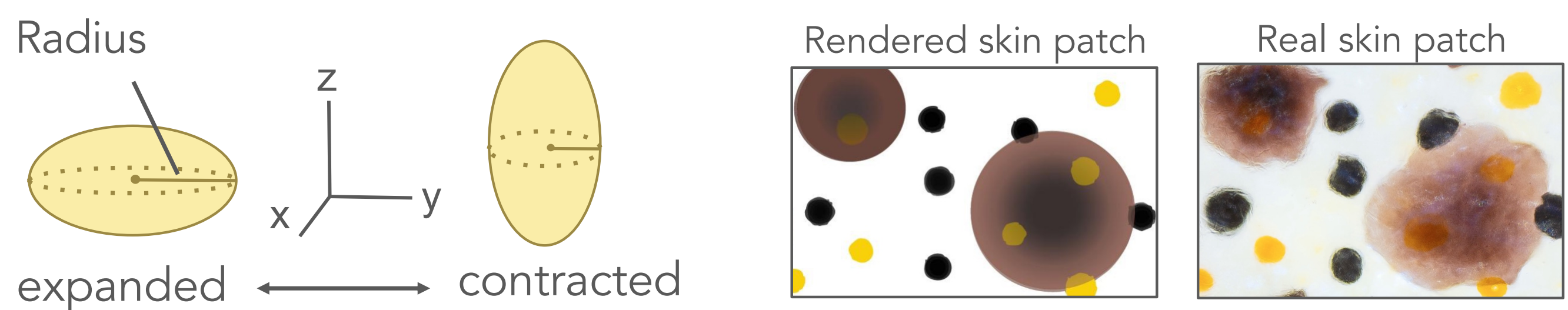
## Building a cuttlefish skin renderer

Modeling spatial distribution of chromatophores:

- 1: Place dark chromatophores using Poisson disk sampling.
- 2: Place light chromatophores using rejection sampling based on distance to nearest dark.



Modeling light absorption of chromatophores:



Model density of pigment as an ellipsoidal "sac of ink":

$$D(\vec{x}; r_k, \vec{l}_k) = \begin{cases} D_0 \sqrt{1 - \frac{\|\vec{x} - \vec{l}_k\|^2}{r_k^2}}, & \text{if } \|\vec{x} - \vec{l}_k\| < r_k \\ 0, & \text{otherwise} \end{cases} \quad D_0 = \frac{V_0}{\frac{4}{3} \pi r_k^2}$$

$\vec{x}$  = location of pixel in image       $r_k$  = radius of chromatophore  $k$   
 $\vec{l}_k$  = location of chromatophore  $k$        $V_0$  = total number of pigment molecules

Reflectance of chromatophores is computed by:

$$C(\lambda, \vec{x}; \vec{r}, L) = 1 - e^{-(a_Y(\lambda) * \sum_{k \in Y} D(\vec{x}; r_k, \vec{l}_k) + a_B(\lambda) * \sum_{k \in B} D(\vec{x}; r_k, \vec{l}_k))}$$

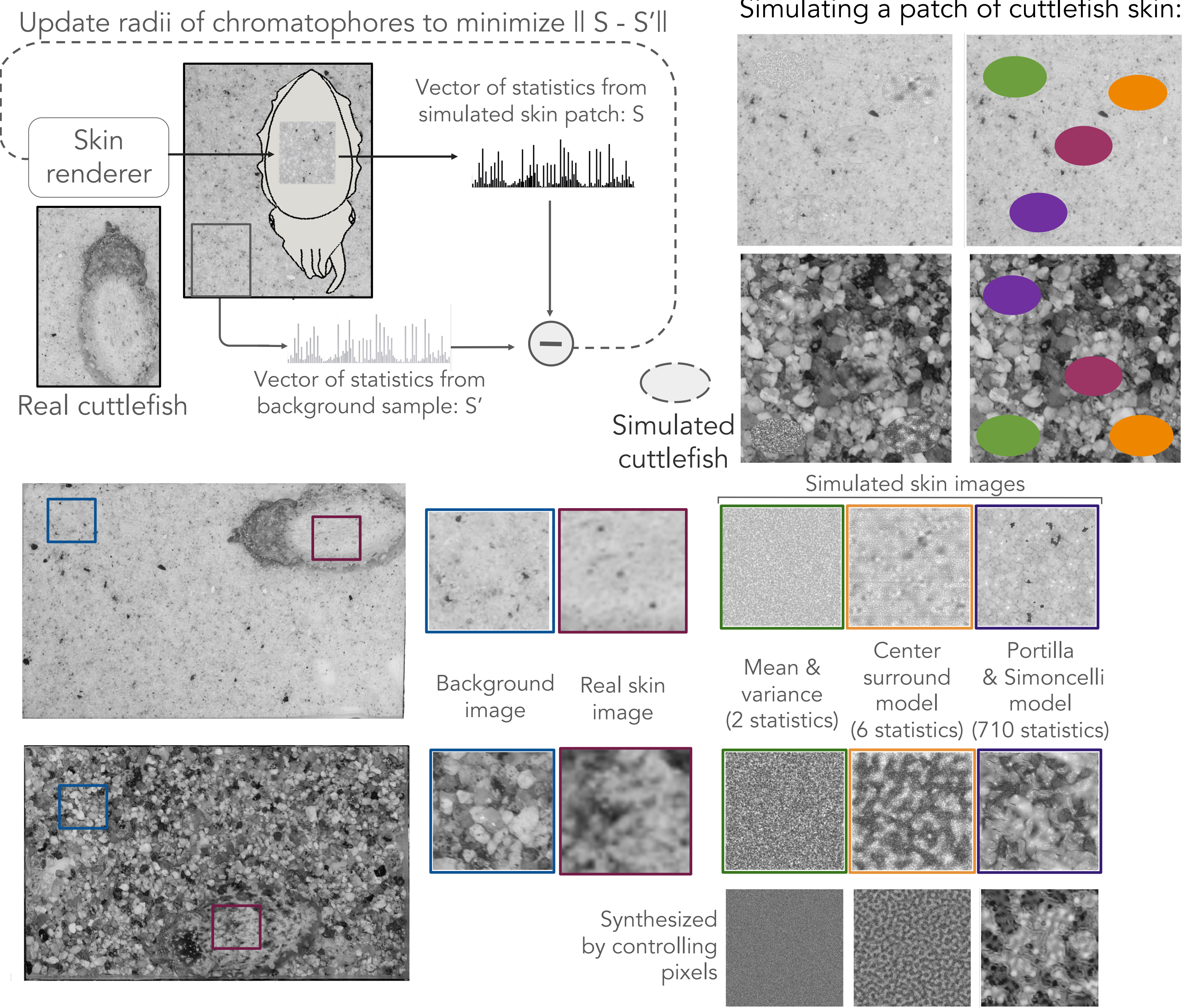
$Y$  = set of indices of yellow chromatophores       $a_Y(\lambda)$  = absorbance of yellow pigment  
 $B$  = set of indices of black chromatophores       $a_B(\lambda)$  = absorbance of black pigment

Rendering image:

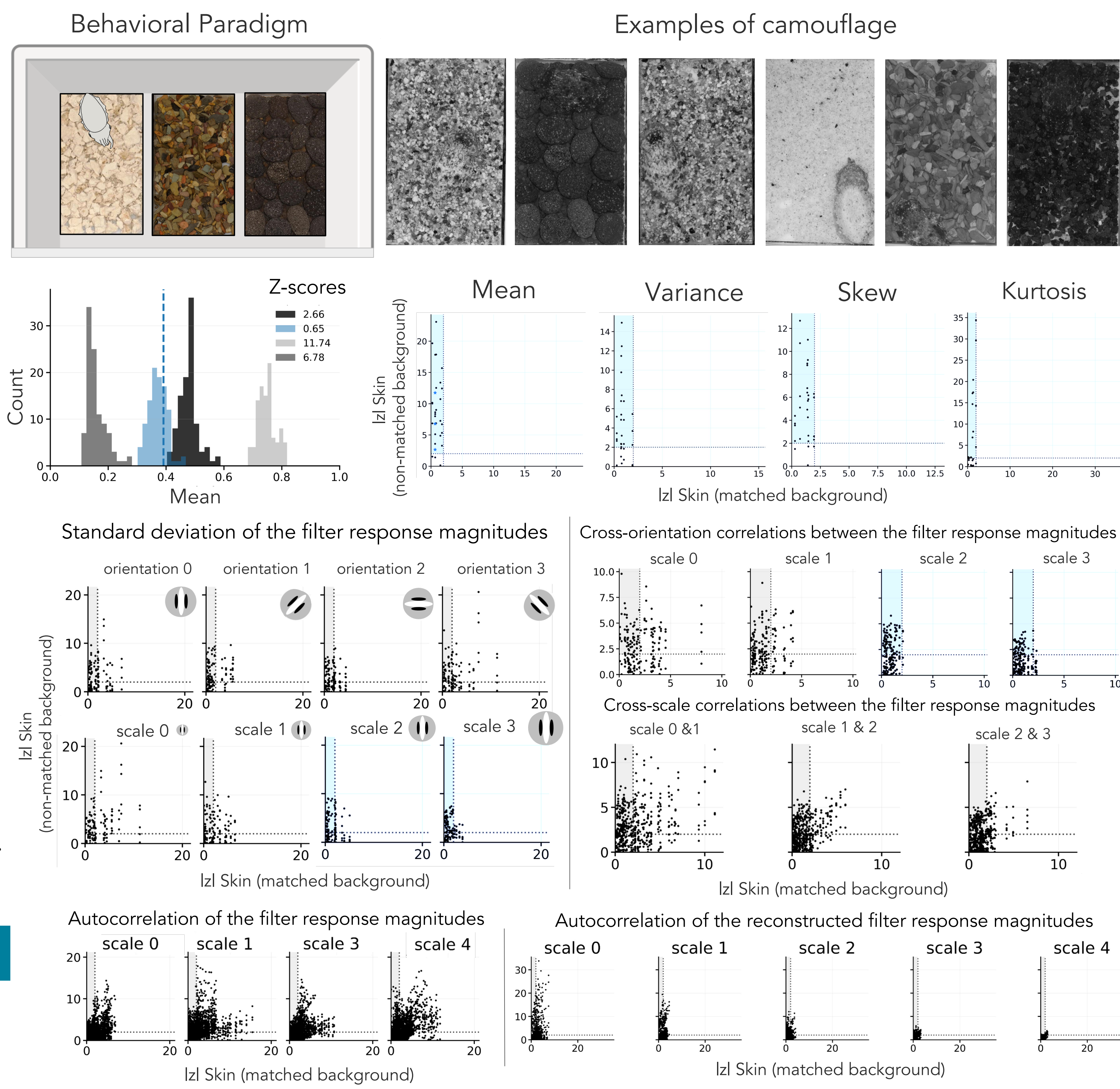
$$m(\vec{x}; \vec{r}, L) = \int_{\lambda} S(\lambda) I(\lambda) C(\lambda, \vec{x}; \vec{r}, L) d\lambda$$

$S(\lambda)$  = sensor spectrum       $\vec{r}$  = vector of chromatophore radii  
 $I(\lambda)$  = illumination       $L$  = Matrix of chromatophore locations

## Optimization: What statistics are cuttlefish matching?

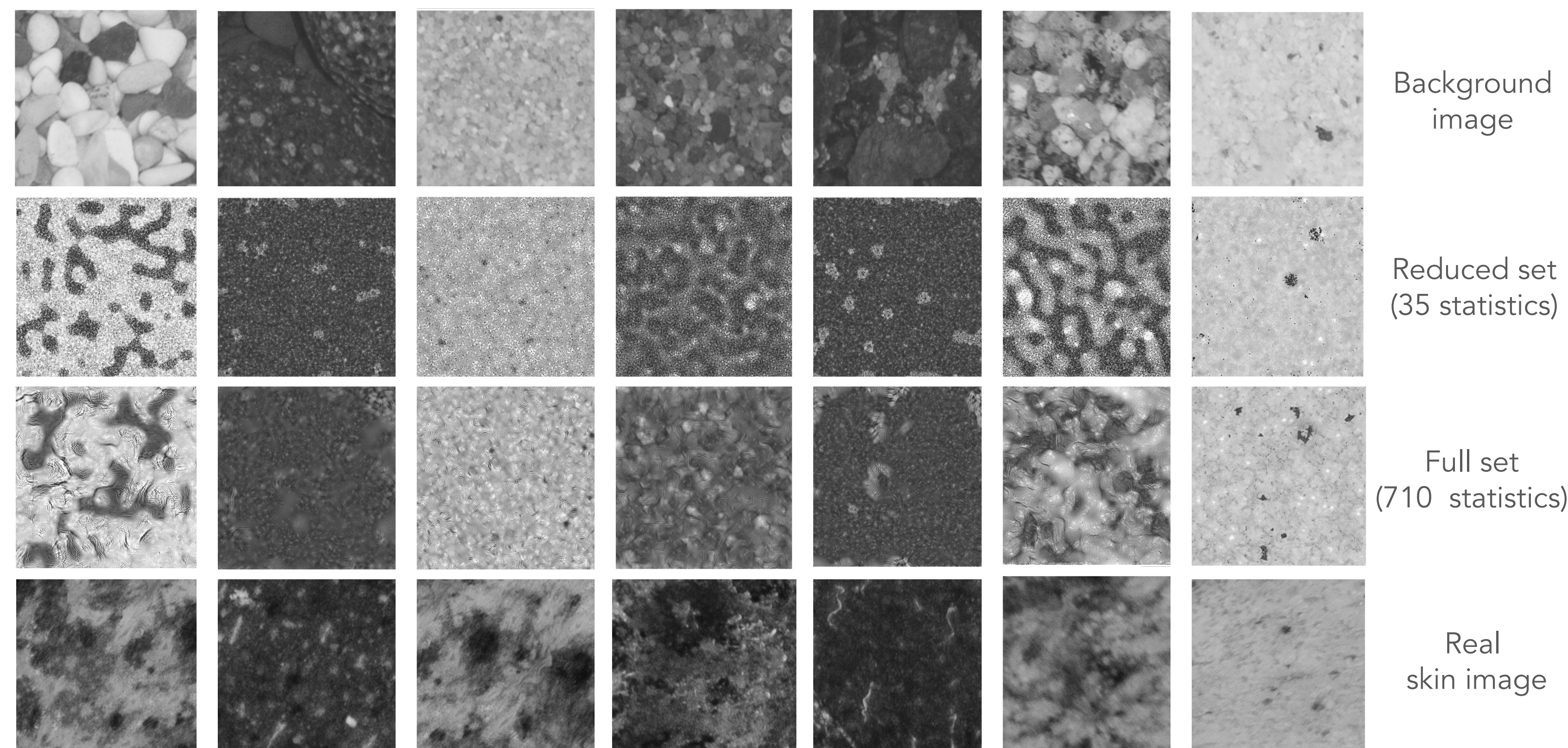


## Do cuttlefish match Portilla & Simoncelli texture statistics?



## A reduced set of Portilla & Simoncelli statistics

Reduced set of statistics



Simulating cuttlefish:

