Eye Evolution: Physics meets Biology

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Physics

Biology

Simon Laughlin- KITP 4/9/08

Eyes:
Structures, Molecules & Origins

1) Constraints on eyes, diversity of eyes, history of thinking about eye evolution;

2) Diversity vs. specialization of eyes: Clues for evolution?

3) Evidence about eye origins: What can we use?
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   d) How fast could an eye evolve?

4) Speculation

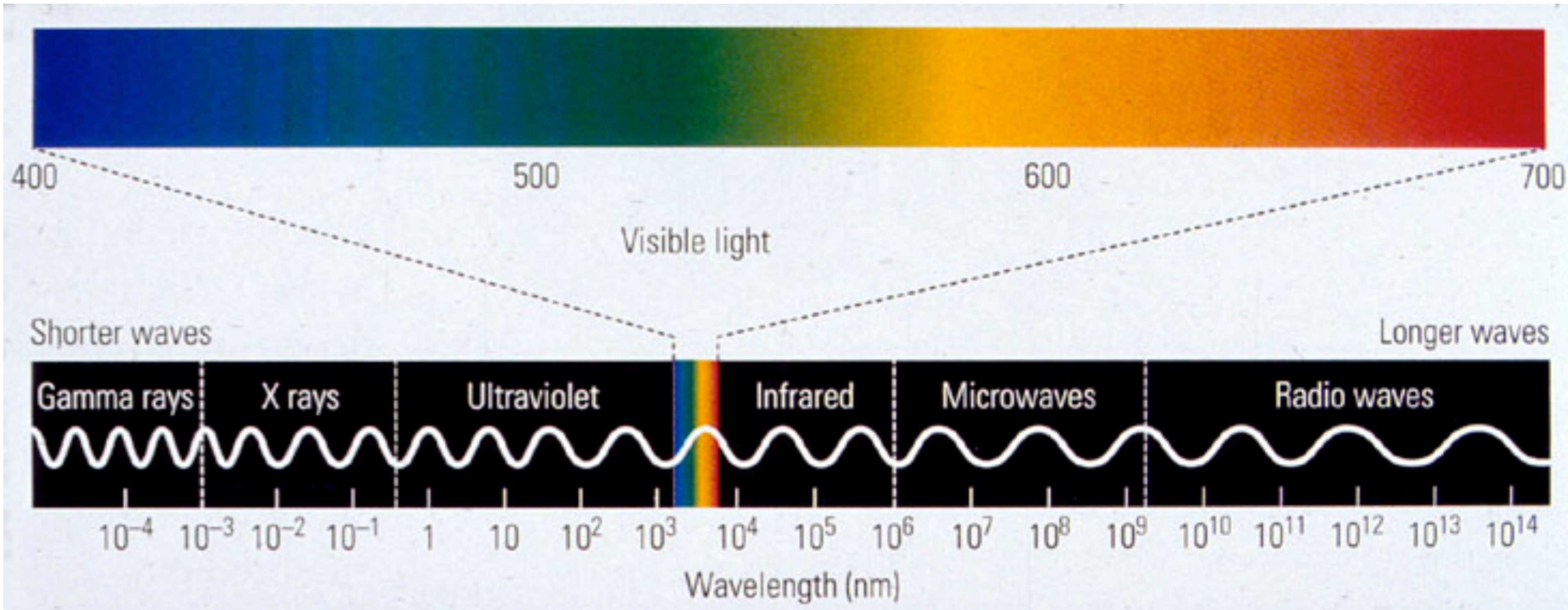
5) Alternate universe

Of 30 animal phyla, 1/3 have eyes, 1/3 have some light detection, 1/3 have no specialization for detecting light (the first group are most successful!)

Light is the premier selective force on the planet

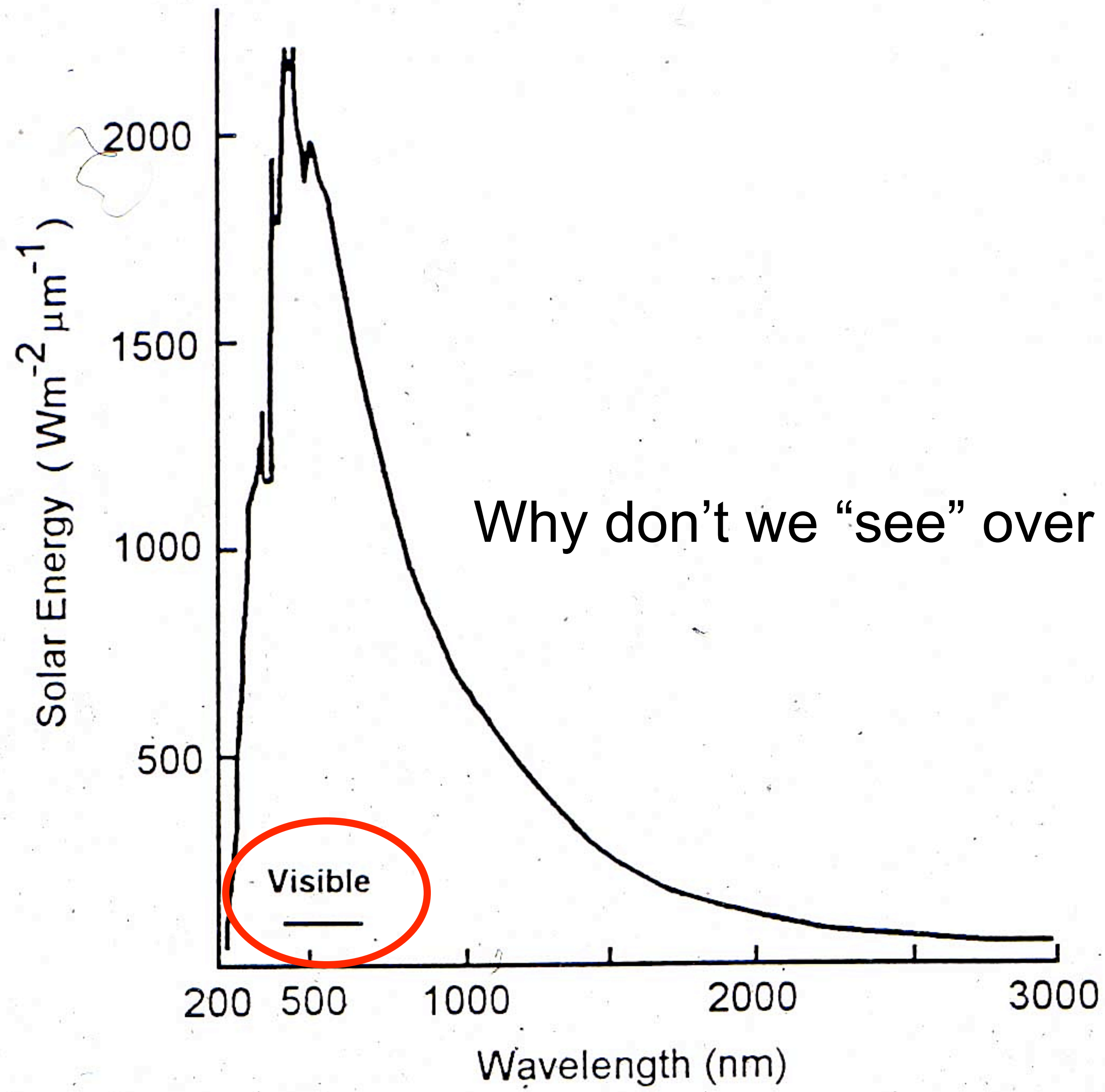
Light carries energy and information
~10^{15} sunrises/sunsets since the big bang;

We see only a small fraction of the EM spectrum



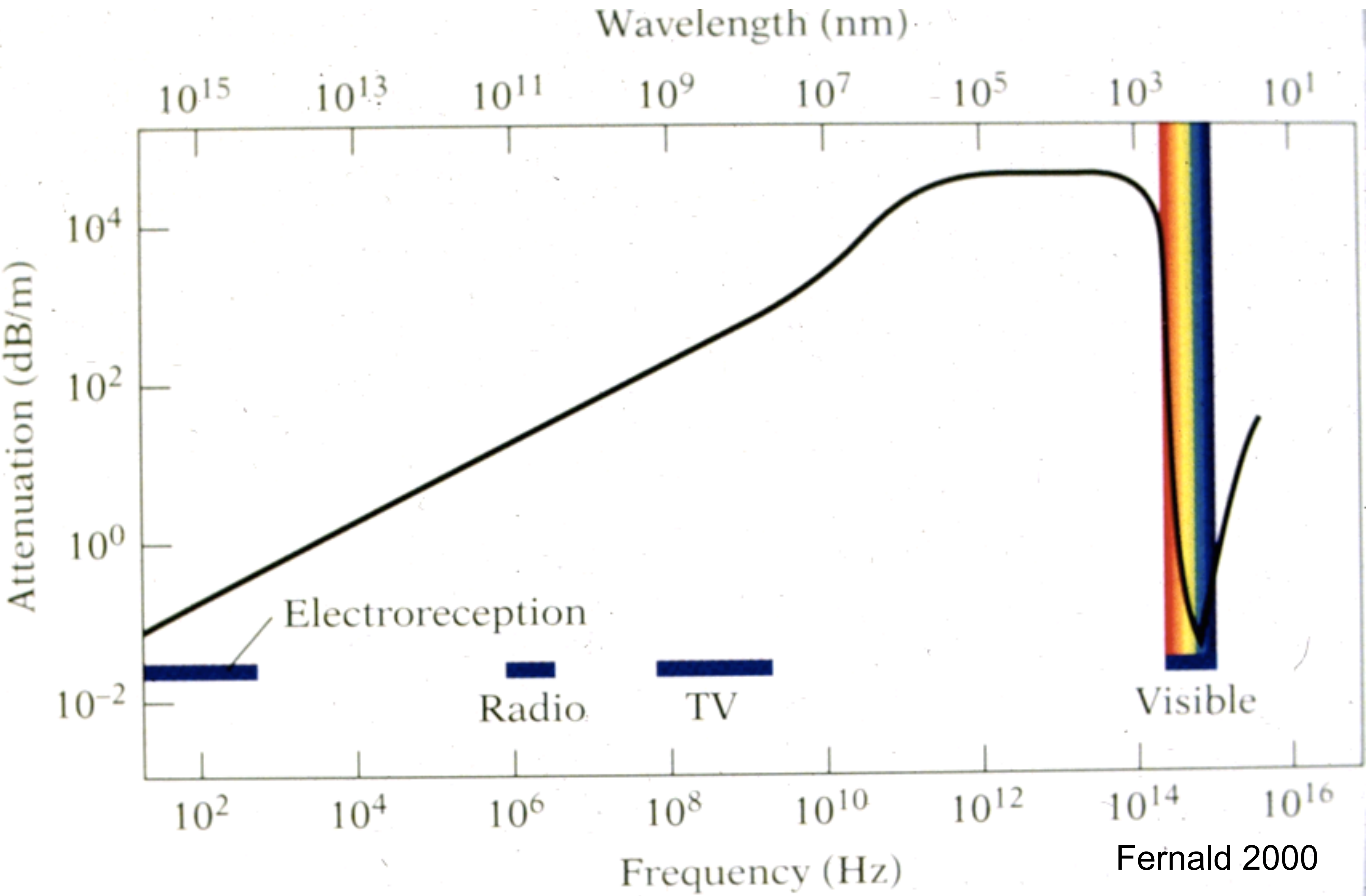
Why?

Consider the spectrum of sunlight



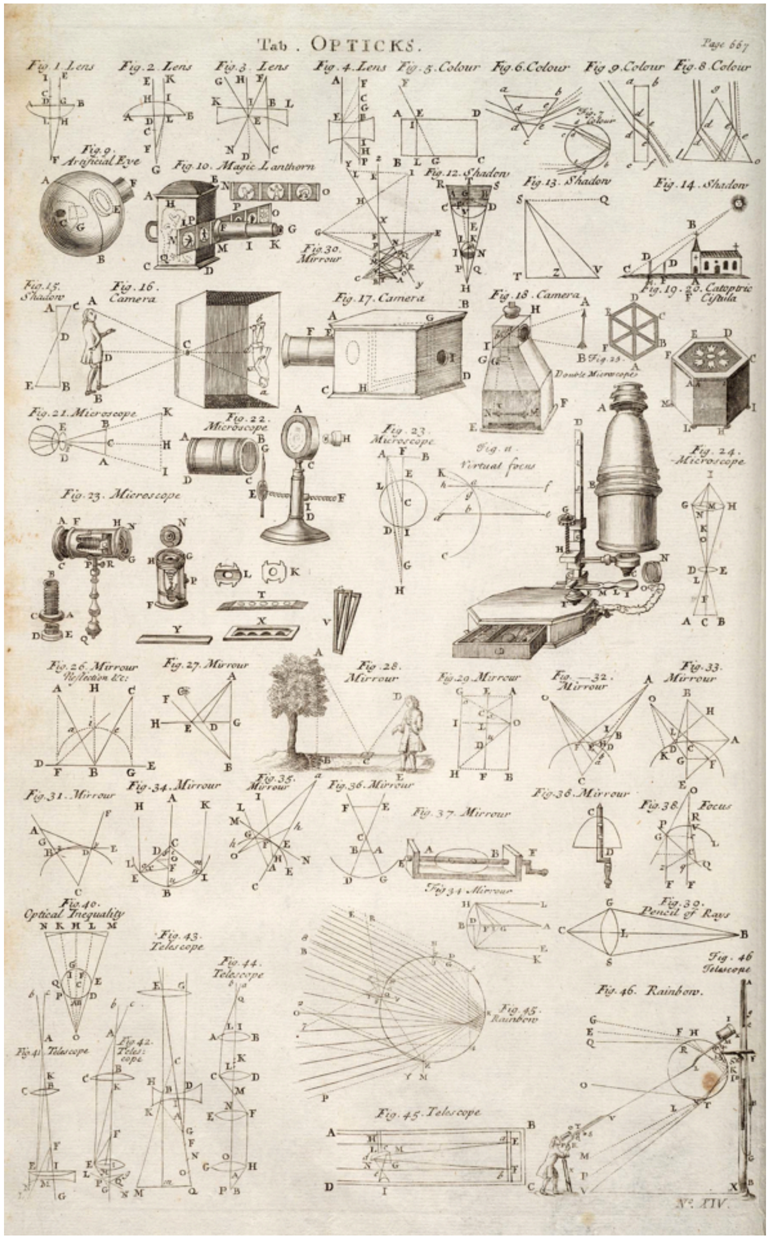
Why don’t we “see” over a wider range?

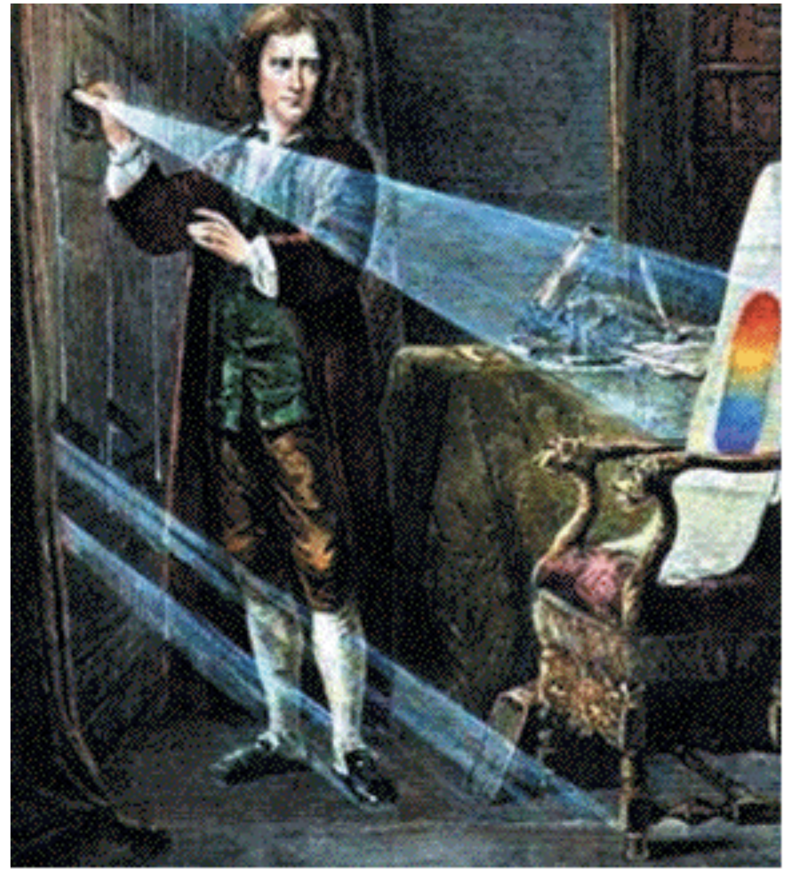
Because life (and eyes) began in the sea



Fernald 2000

Properties of light severely constrain eye structures

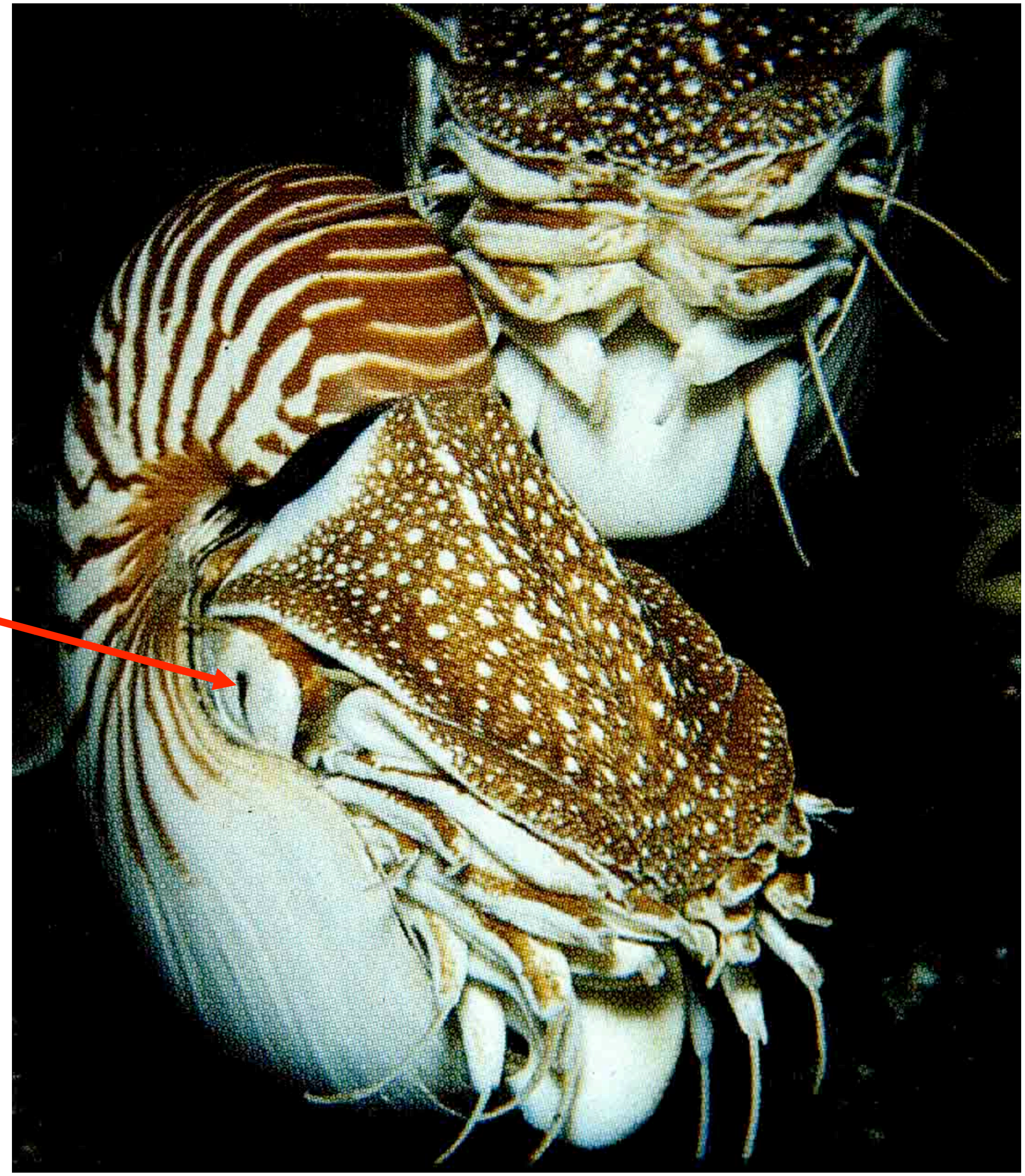


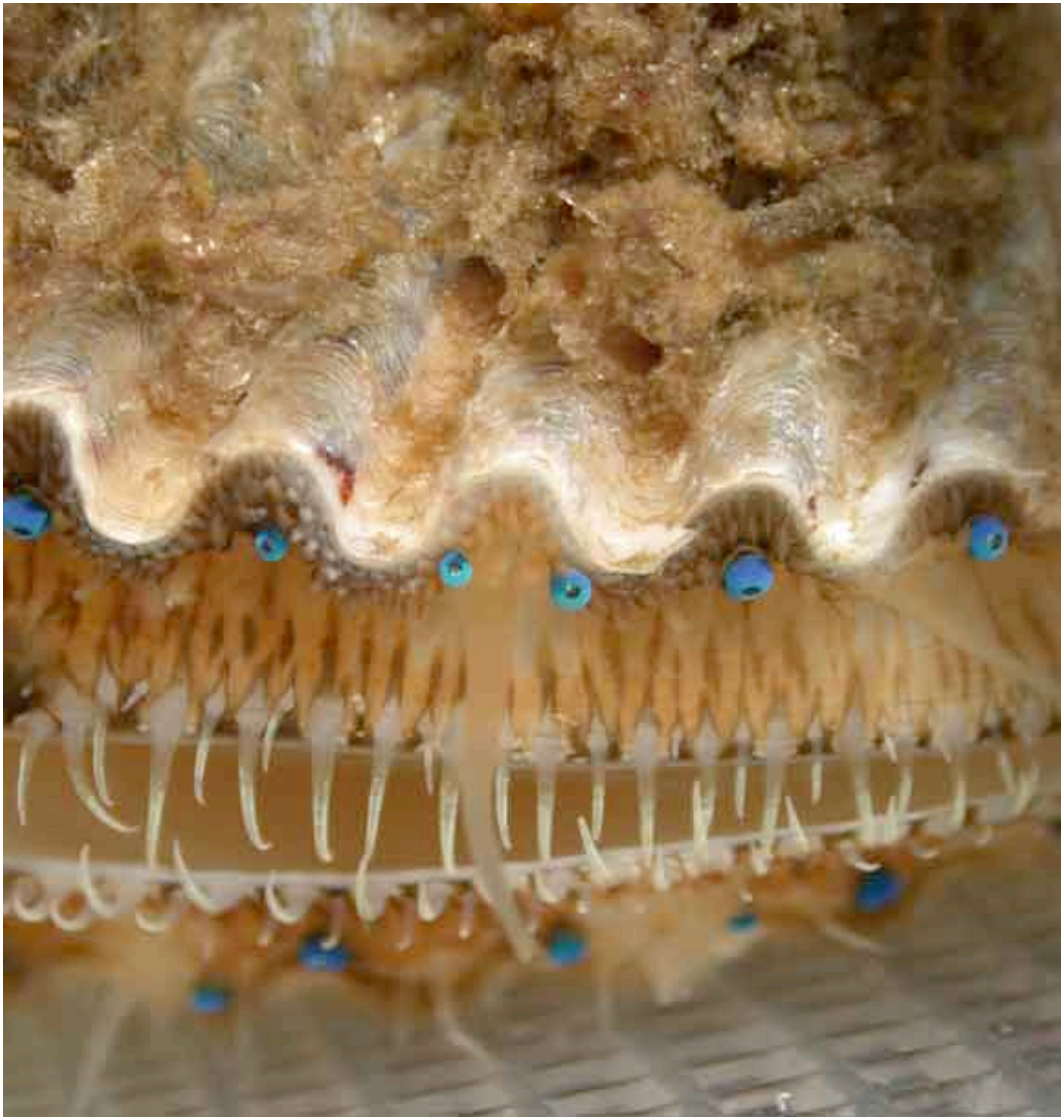


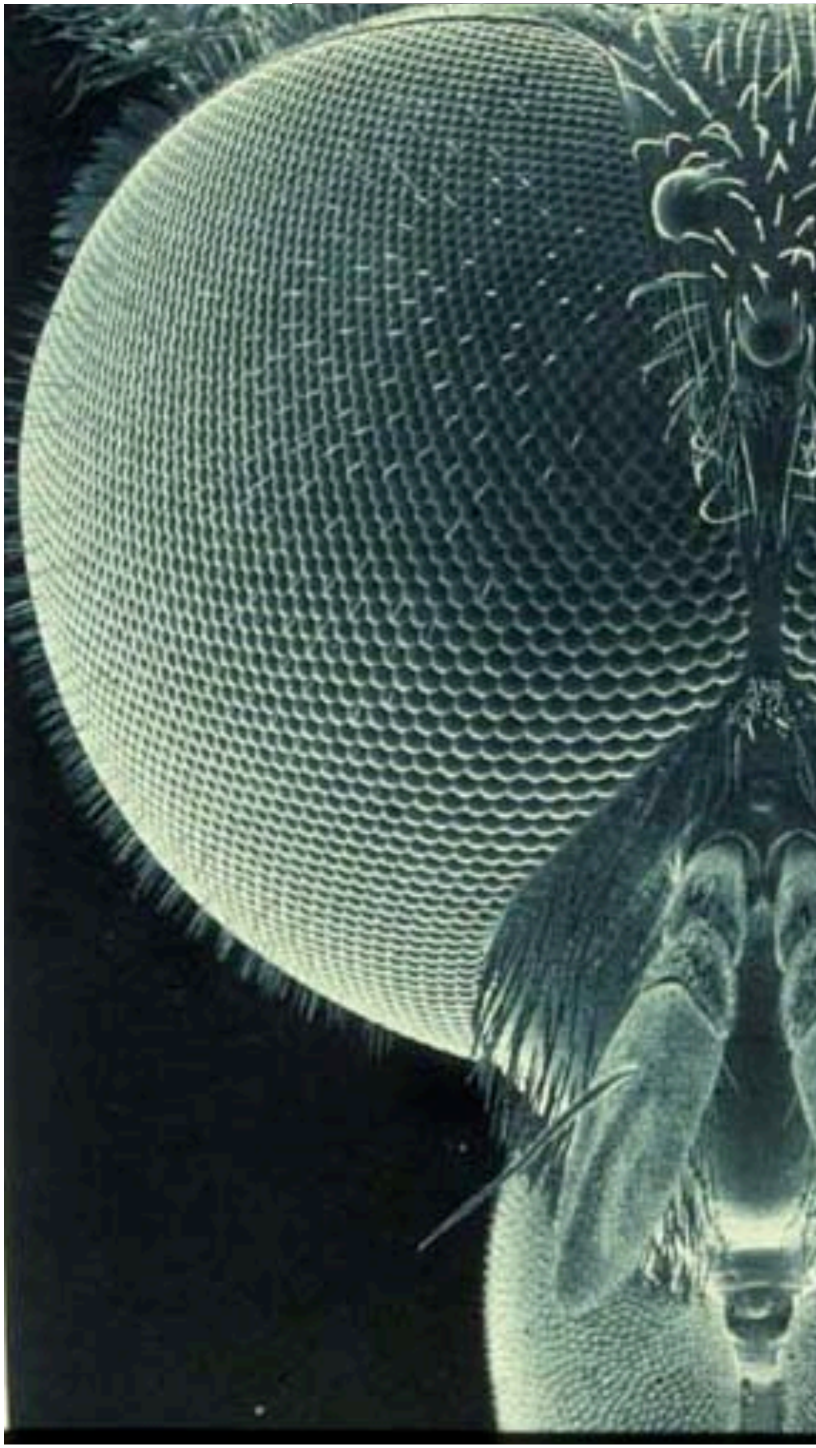
1) Light travels in straight lines, reflects, refracts, is spectral, and can be polarized
2) In the best cases, eyes can extract information about where & what an object is.

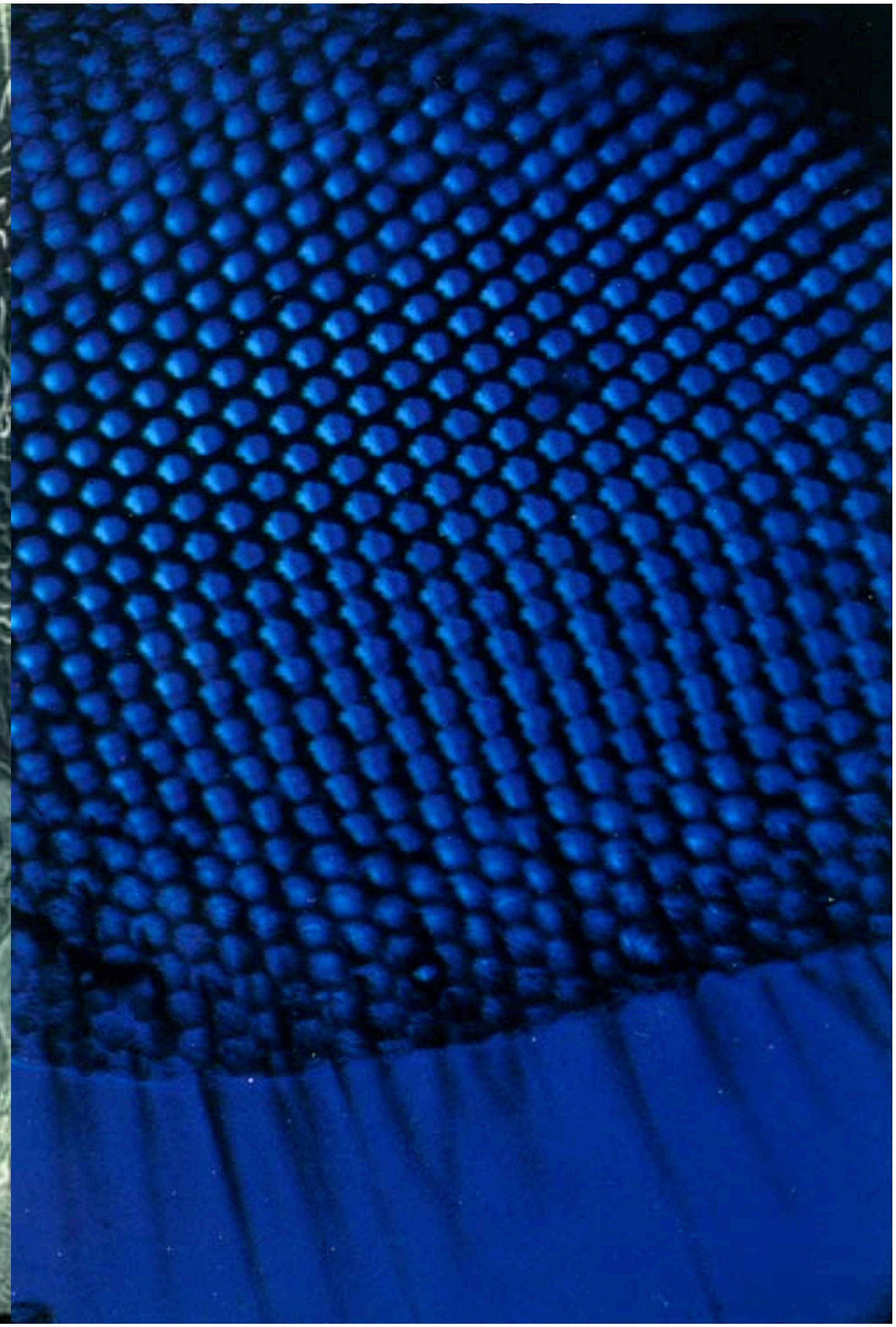
Yet, eyes appear quite diverse

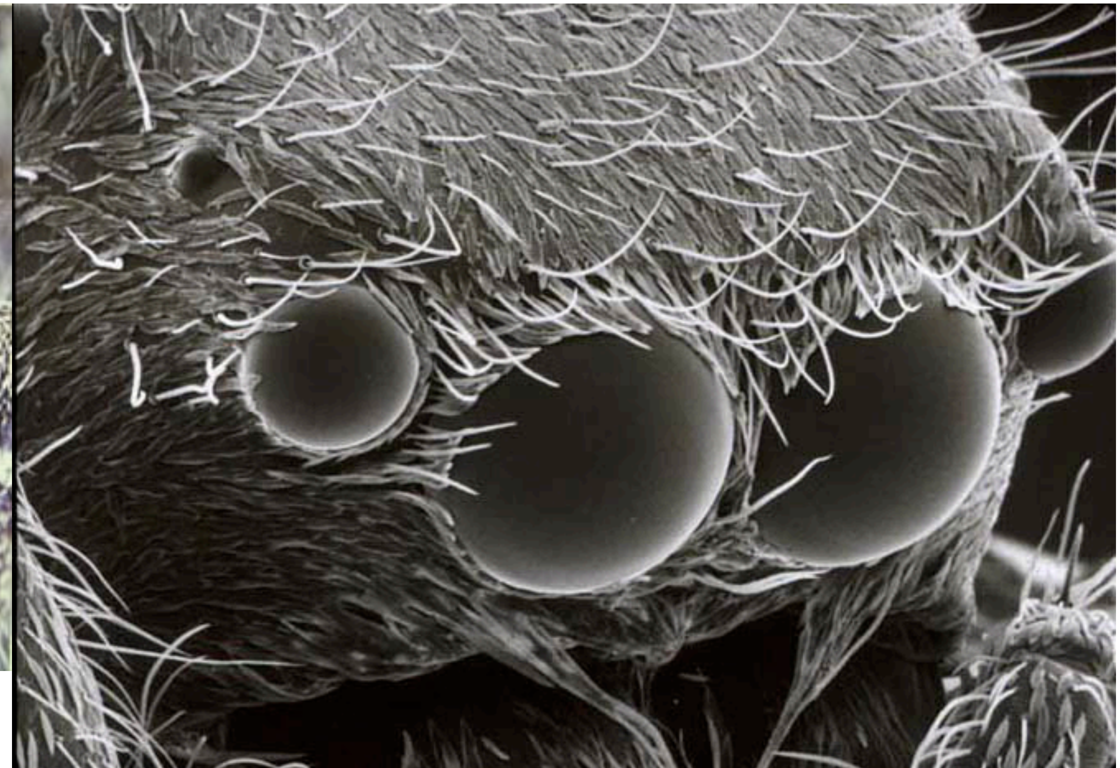
“pinhole camera” eye







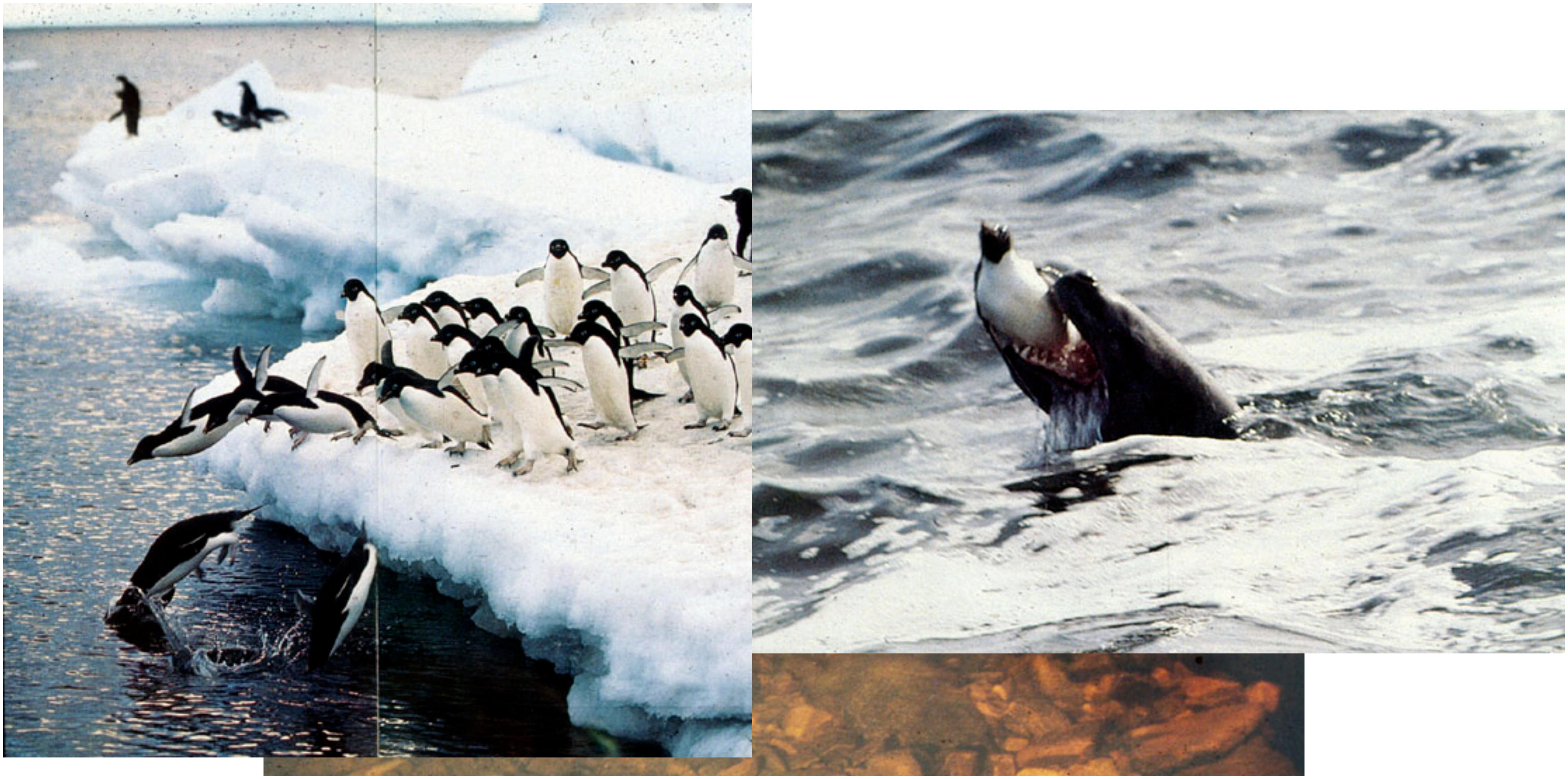




Habronattus americanus

Eyes have remarkable adaptations

Seeing in air and water

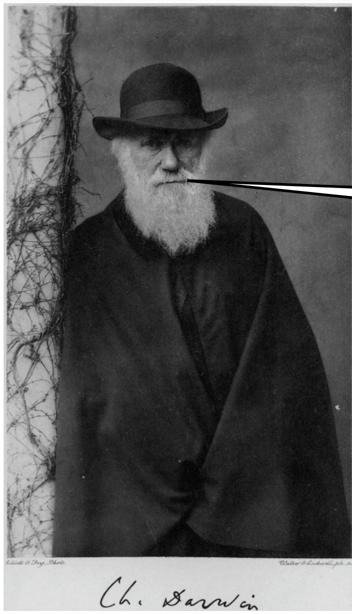


Seeing in the ultraviolet range

normal

ultraviolet

Short history of thoughts on Eye Evolution



~ “This is a tough problem” Darwin 1860

1977- There were multiple (40-65) eye origins (morphology, Salvini-Plawin/Mayr)

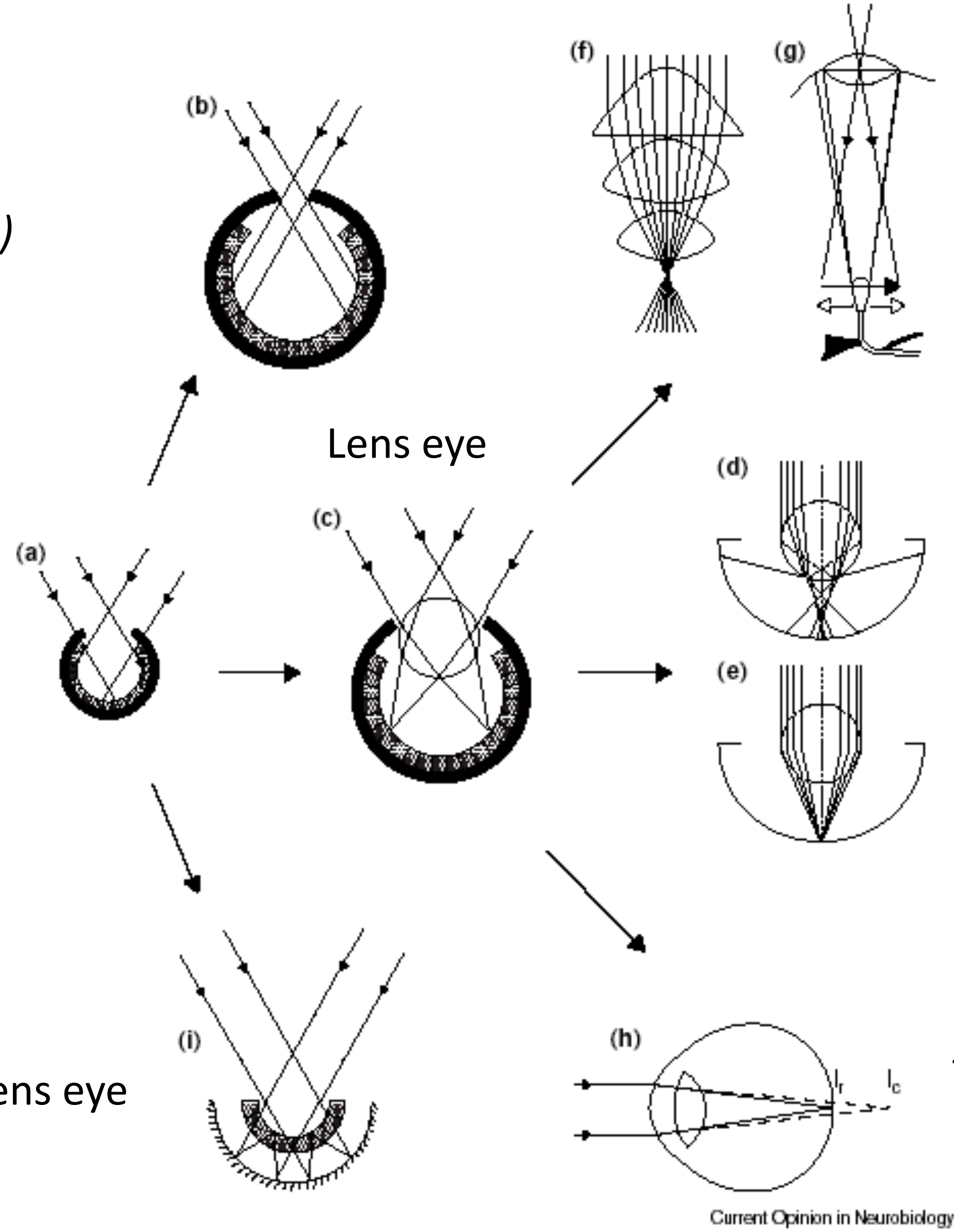
1979- There was probably a single origin (opsin family; Autrum)

1992- Probably multiple origins (opsin evolved <u>before eyes</u>; Land & Fernald)

1996- Single origin, master gene hypothesis (*Pax 6* can induce eyes*;* Gehring)

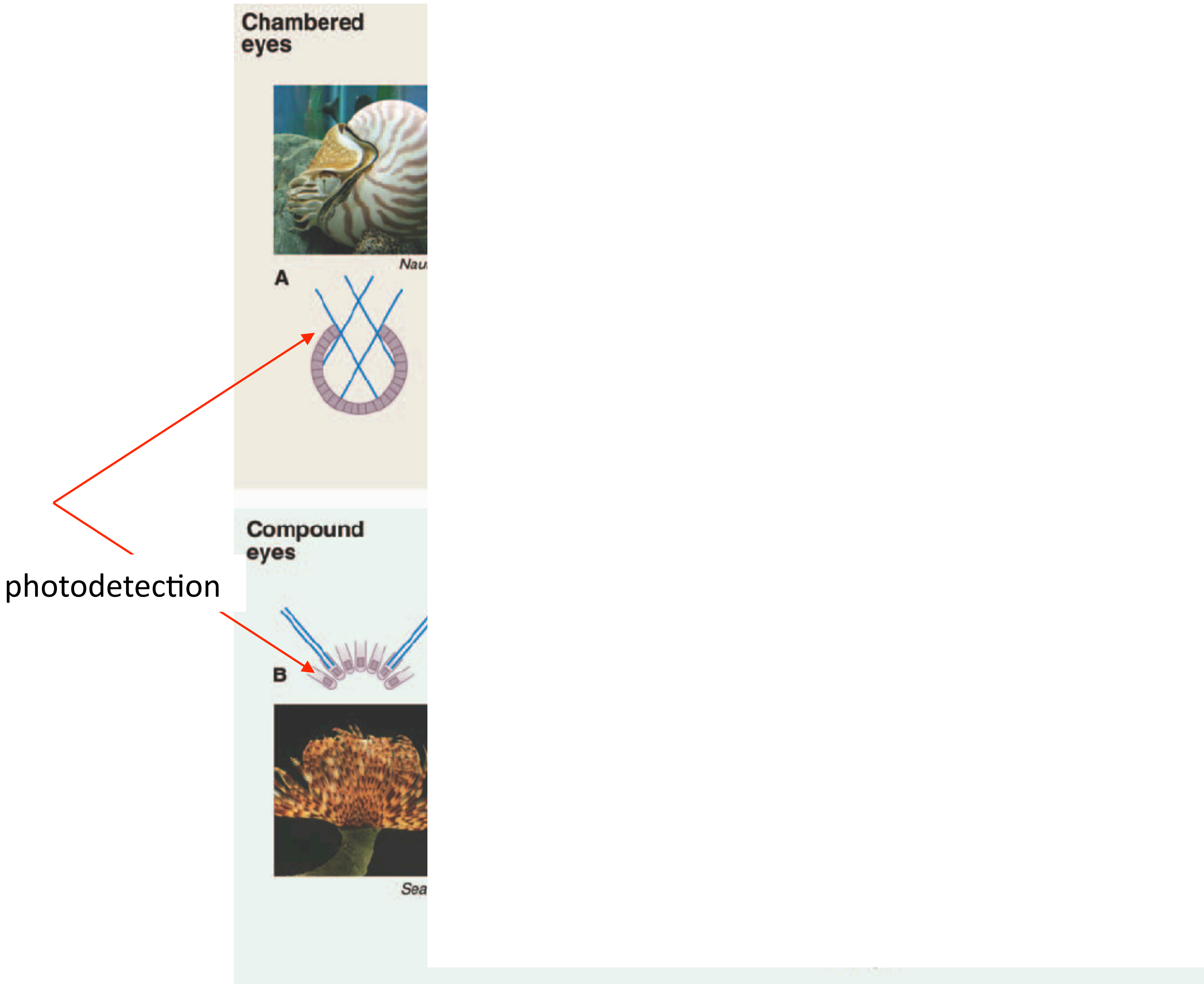
2004-2006 Multiple origins (“eyes” preceded bilateria; Fernald; Nilsson)

Eye optical systems are not that diverse, actually

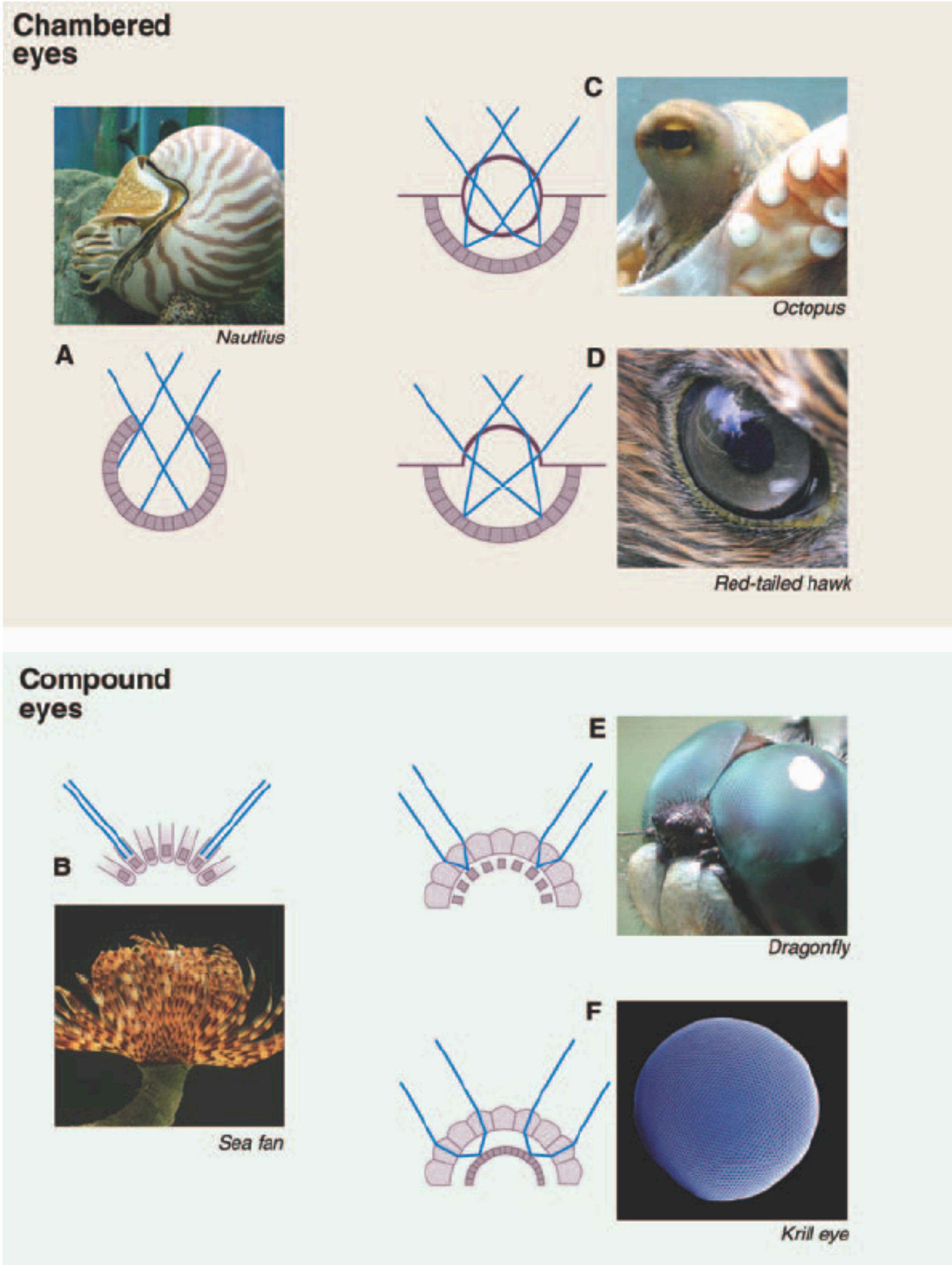


Fernald 2000

Eight eye types have evolved in 500myr



Fernald *Science* (2006)



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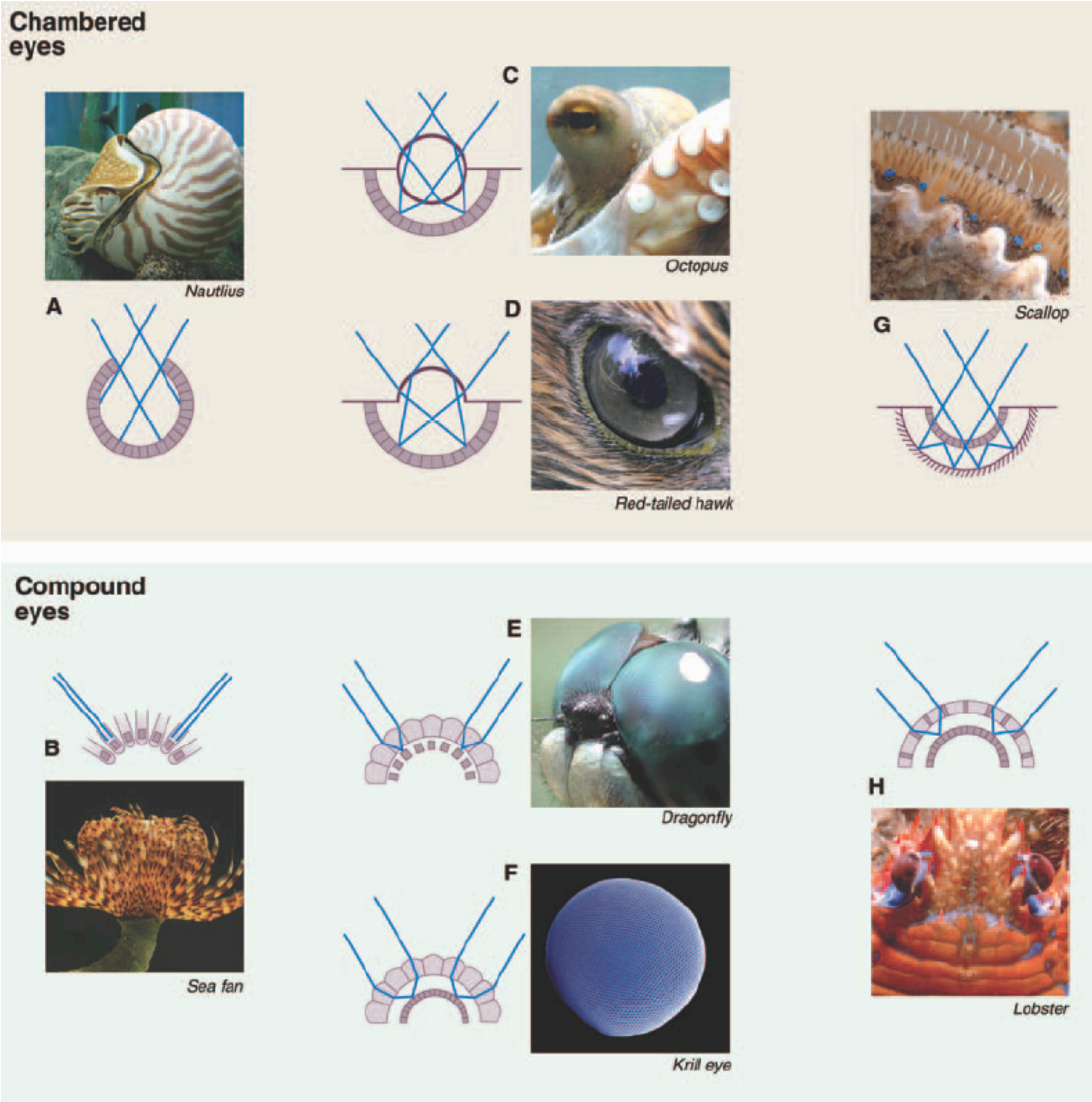

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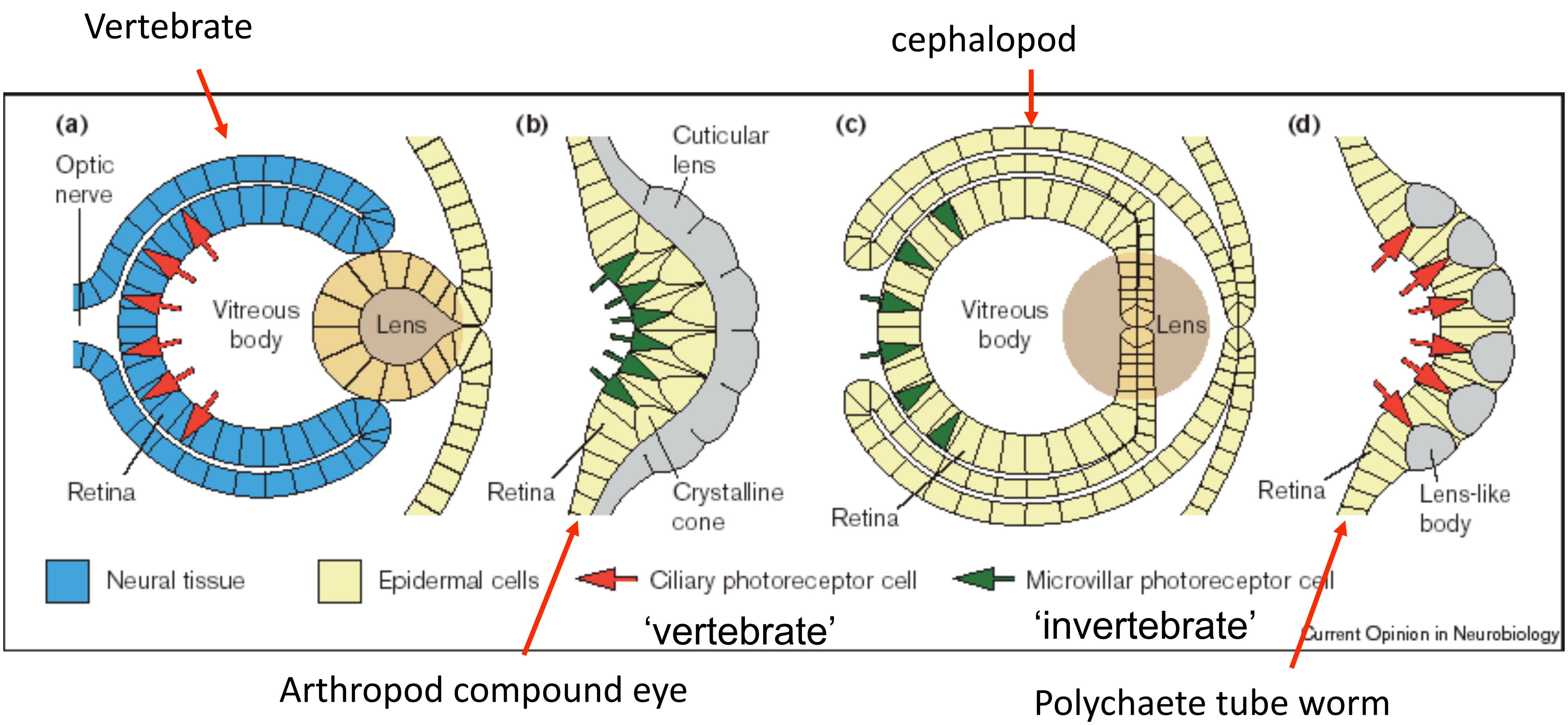
Eye tissues have distinct issue origins and developmental stages



Strongly suggests independent origin

Nilsson, CON

Are developmental molecules (genes) for eyes conserved?

1) *Pax6* is (a paired domain and homeodomain) a factor that has been found in the regulatory cascades of developing eyes in many animals, including *Drosophila* where it is called *eyeless (ey);*

2) *Pax6* homologues are proposed to share conserved functions across all phyla;

3) Does having common genes recruited for functional purpose allow one to conclude that eyes are monophyletic?

Many genes are essential for eye development

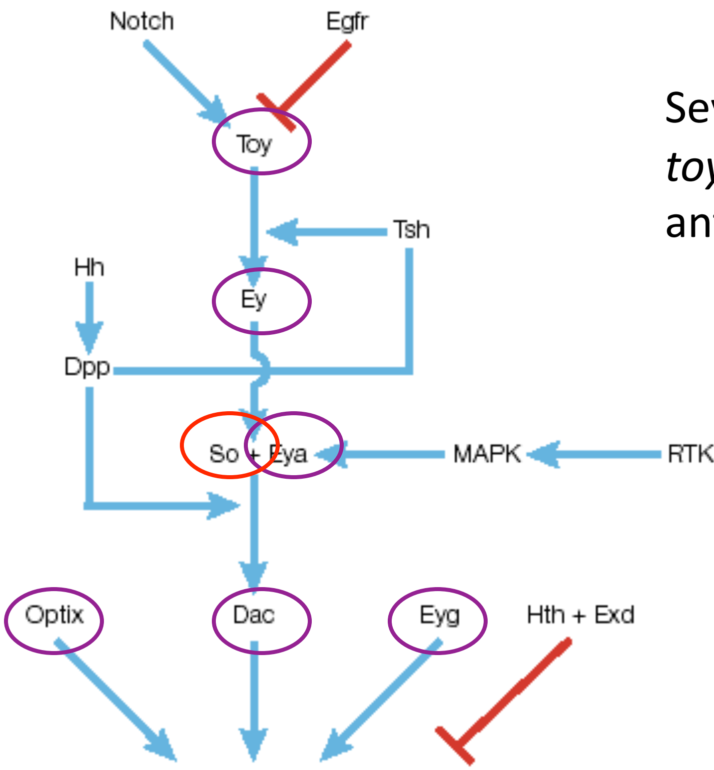


Figure 1 | **Genetic control of eye specification in *Drosophila*.** A set of nuclear proteins, patterning pathways and signal-transduction cascades form a complicated regulatory network and are together required to specify the compound eye in *Drosophila*. The arrows in this diagram indicate the direction of the genetic, molecular and biochemical relationships. Dac, Dachshund; Dpp, Decapentaplegic; Egfr, Epidermal growth factor receptor; Exd, Extradenticle; Ey, Eyeless; Eya, Eyes absent; Eyg, Eye gone; Hh, Hedgehog; Hth, Homothorax; MAPK, Mitogen-activated protein kinase; RTK, receptor tyrosine kinase; So, Sine oculis; Toy, Twin of eyeless; Tsh, Teashirt.

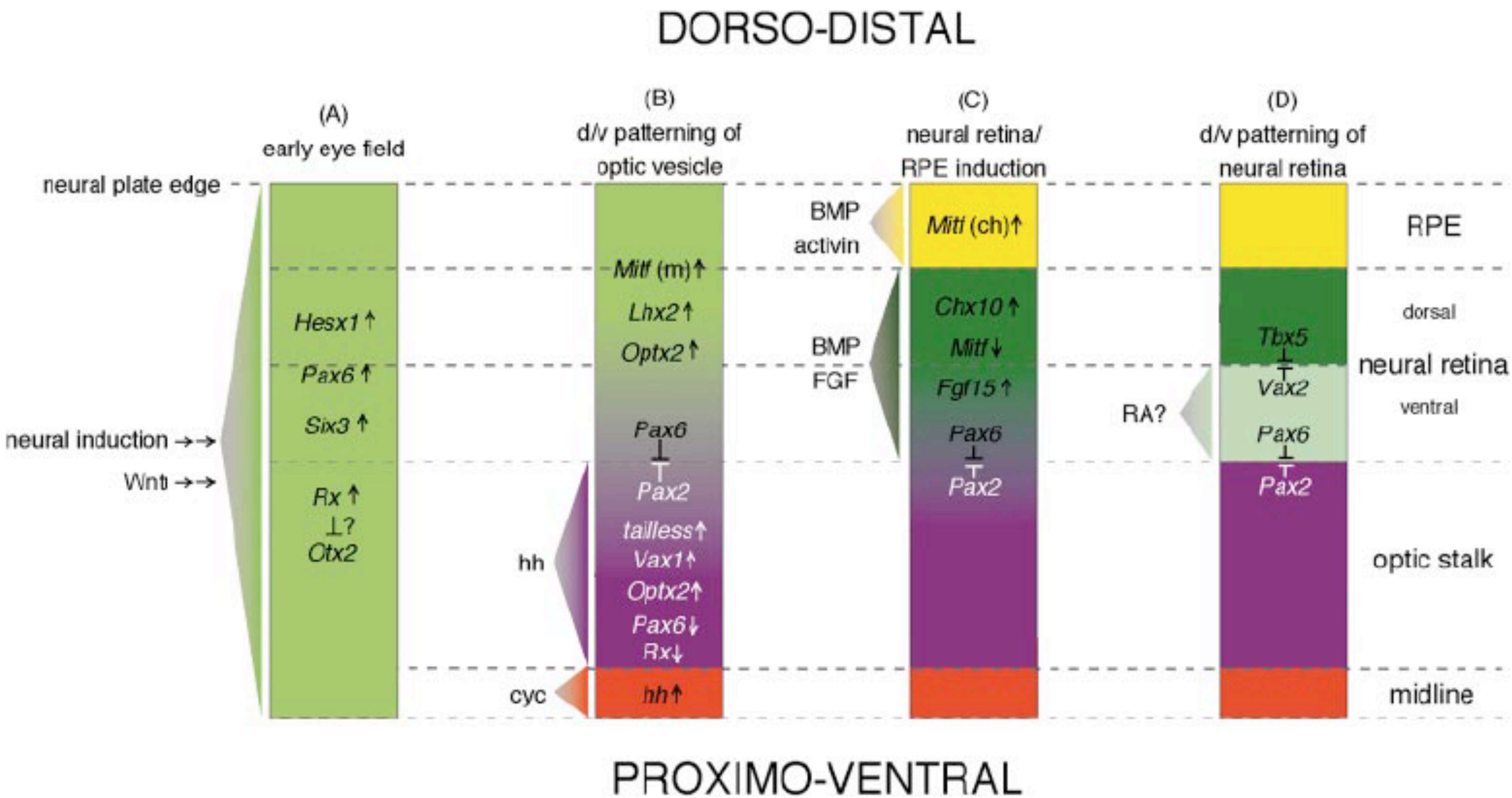
Several genes are capable of causing ectopic eye formation: *toy, ey, eya, so, optix, Dac, Eyg* (within a limited set of antennal disks).

Essential for eye formation:
Toy, ey, eya, so, optix, Dac, Eyg
(if any one absent, no eyes)

ey is *pax6* homologue

Kumar, 2002

Many genes are essential for eye development



Patterning /inductive events in the developing vertebrate eye

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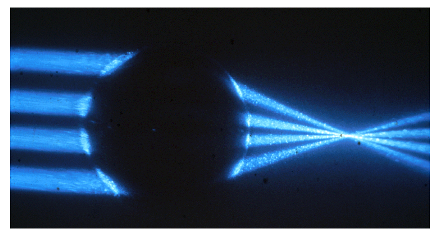
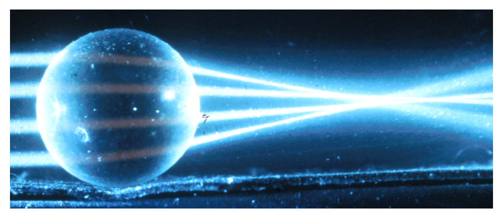


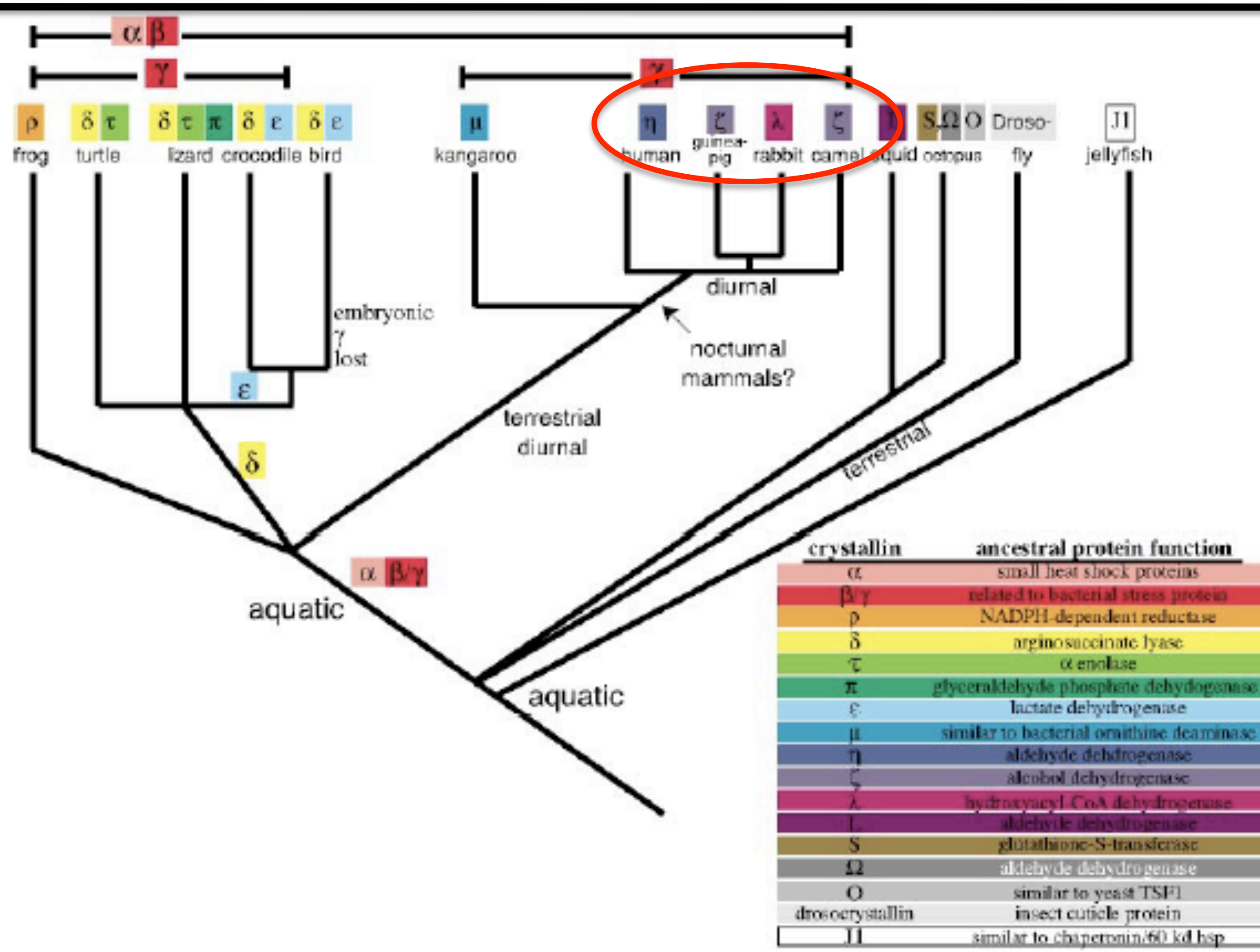


Eye lens proteins are diverse: enzymes, stress proteins etc.

Crystallin	Distribution	[Related] or **Identical**
Ubiquitous stress crystallins		
α	All vertebrates	**Small heat shock proteins** (αB) [*Schistosoma mansoni* antigen]
β γ	All vertebrates (embryonic γ not in birds)	[*Myxococcus xanthus* Protein S] [*Physarum polycephalum* spherulin 3a]
Taxon-specific enzyme crystallins	"Gene sharing"	
δ	Most birds, reptiles	**Argininosuccinate lyase** (δ2)
ε	Crocodiles, some birds	**Lactate dehydrogenase B**
ζ	Guinea-pig, degu rock cavy, camel, llama	**NADPH:quinone oxidoreductase**
η	Elephant shrews	**Aldehyde dehydrogenase I**
λ	Rabbits, hares	[Hydroxyacyl CoA dehydrogenase]
μ	Kangaroos, quoll	[Ornithine cyclodeaminase]
ρ	Frogs *Rana*	[NAPDH-dependent reductases]
τ	Lamprey, turtle; moderately	α-Enolase

From Wistow TIBS 1993

Eye lens proteins are diverse: enzymes, stress proteins etc.



crystallin	ancestral protein function
α	small heat shock proteins
β/γ	related to bacterial stress protein
ρ	NADPH-dependent reductase
δ	argininosuccinate lyase
τ	α enolase
π	glyceraldehyde phosphate dehydrogenase
ε	lactate dehydrogenase
μ	similar to bacterial ornithine deaminase
η	aldehyde dehydrogenase
ζ	alcohol dehydrogenase
λ	hydroxyacyl CoA dehydrogenase
ι	aldehyde dehydrogenase
S	glutathione-S-transferase
Ω	aldehyde dehydrogenase
O	similar to yeast TSF1
drosocrystallin	insect cuticle protein
J1	similar to chaperonin/60 kd hsp

Figure 2 Animal lens crystallin diversity. For ubiquitous vertebrate crystallins (α, β, γ), bars across top indicate distribution (embryonic γ crystallin expression is absent in birds). Taxon-specific crystallins are shown only for the taxa in which they have been found and their complete distributions are not necessarily indicated. Two novel crystallins, J2 and J3, have also been found in jellyfish (Tomarev & Piatigorsky 1996). Figure adapted from Wistow 1993, with further information from Tomarev & Piatigorsky 1996 and Janssens & Gehring 1999.

True & Carroll, Annu.Rev.Cell. Dev. Bio.**18**:53 (2002)

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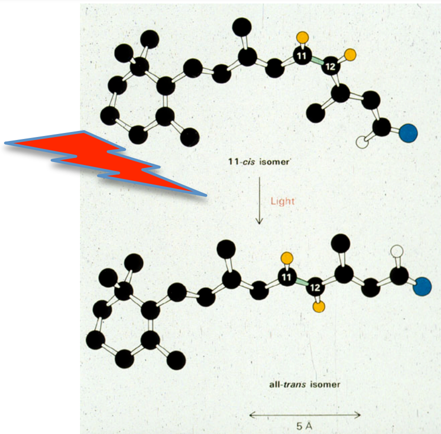
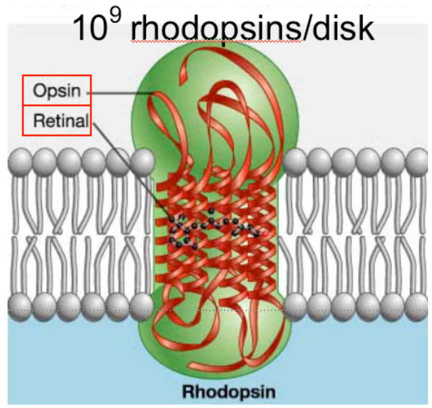
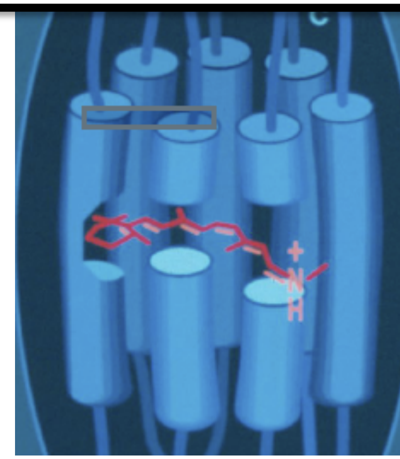
There are two main pathways for transducing light in animals



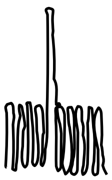




hν

VERTEBRATE: c-opsin → G_t → PDE → cGMP → Na channels close → membrane potential

ciliary

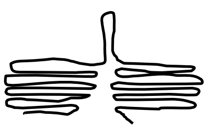


retinal activation — ***signal amplification*** *phototransduction* — ***current decrease*** — ***hyperpolarize***

hν

INVERTEBRATE: r-opsin → G_q → PIP_2 → DAG → TRP channels open → membrane potential

rhabdomeric

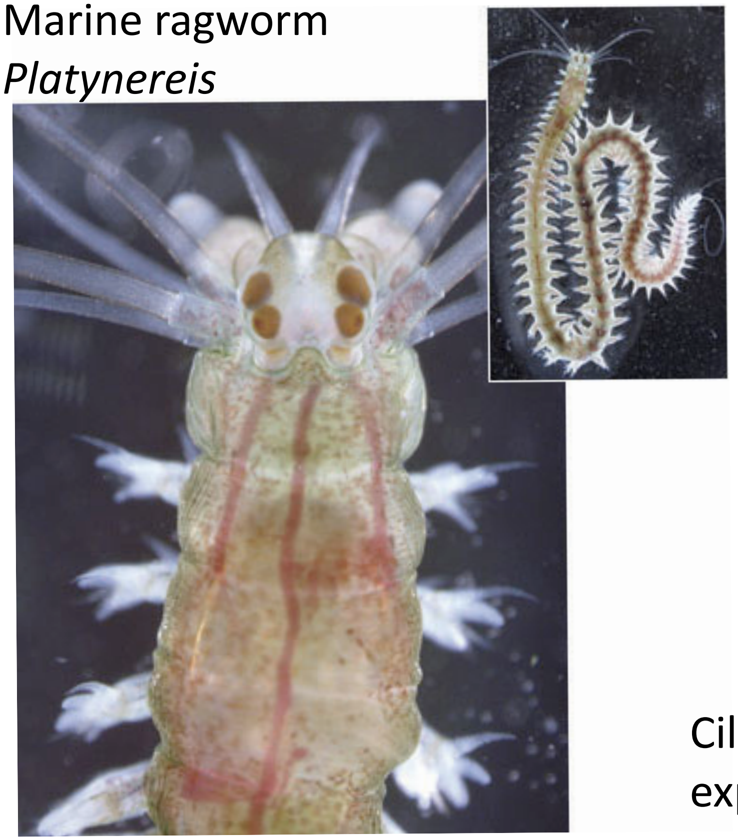


retinal activation — *phototransduction* — ***signal amplification*** ***current increase*** — ***depolarize***

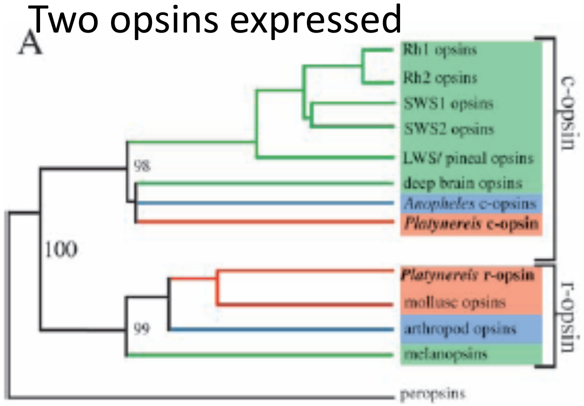
Fernald *Science* (2006)

Both pathways are in invertebrates

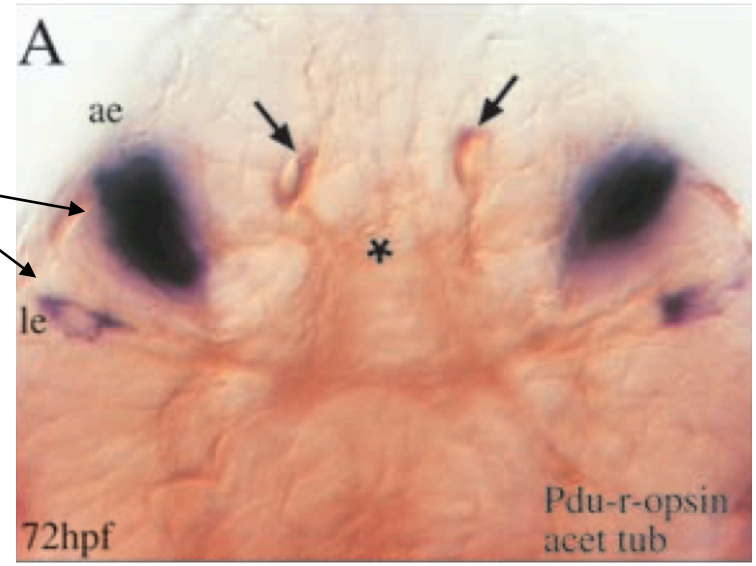
Marine ragworm
Platynereis



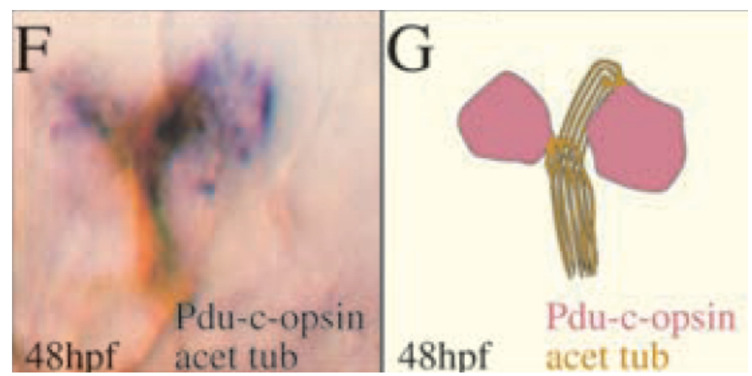
Two opsins expressed



Rhabdomeric eyes

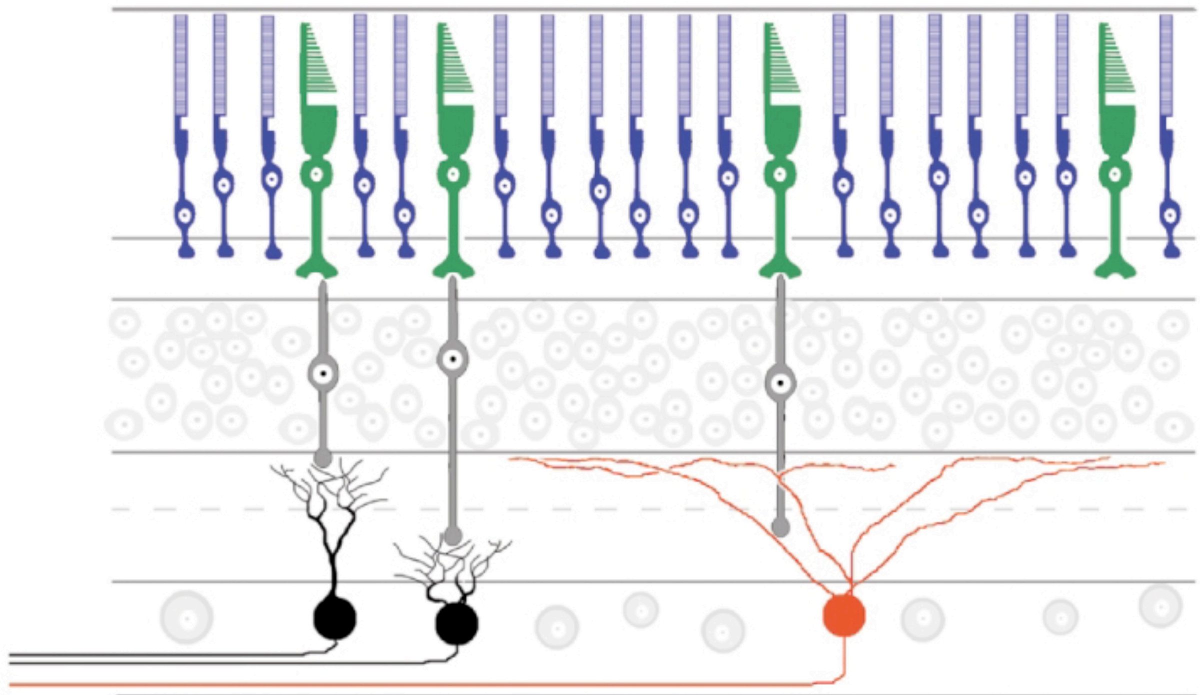


Ciliary opsins expressed in 'brain'

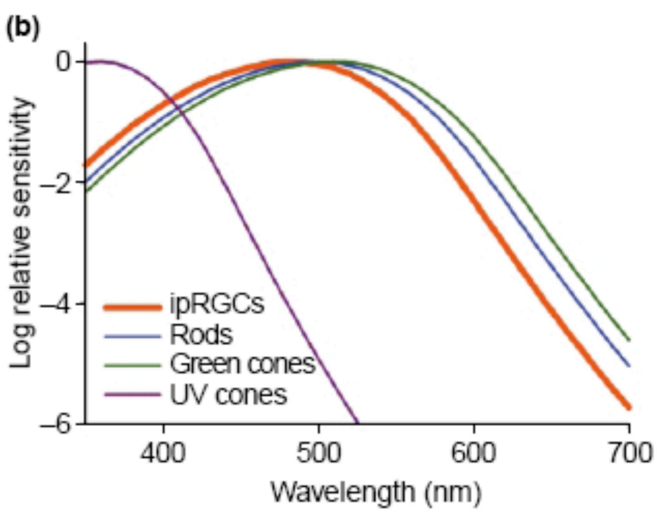


Arendt et al., 2004

Both pathways are ALSO in vertebrates



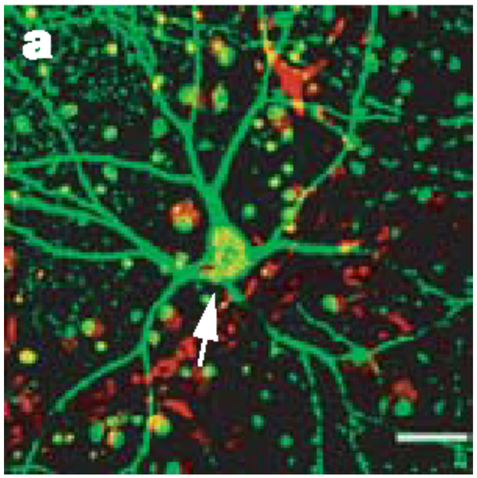
Melanopsin, a photopigment typical of invertebrates is found in the inner retina of mammals.

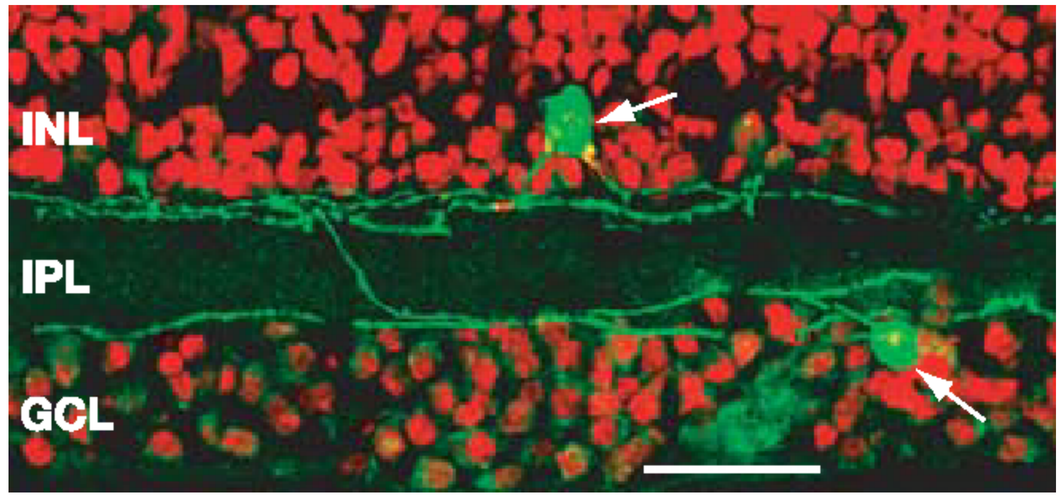


Light-activated melanopsin preferentially activates the Gq/G11 class of G proteins, followed by activation of PLC-b, similar to that used by invertebrates

Panda et al., 2005

Including human retinas



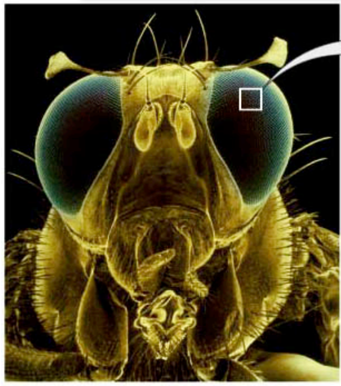


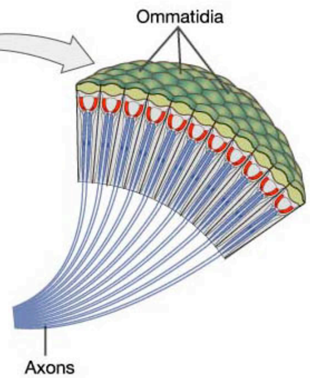
Human retina- melanopsin containing ganglion cells (~0.2%)

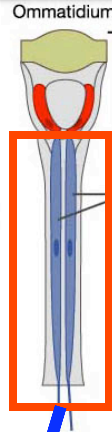
1) Project to the brain (LGN, SCN);
2) Respond to illumination and color;

Dacey et al., Nature **433**:749 (2004)

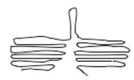
You have some fruitfly eye bits in your eye!







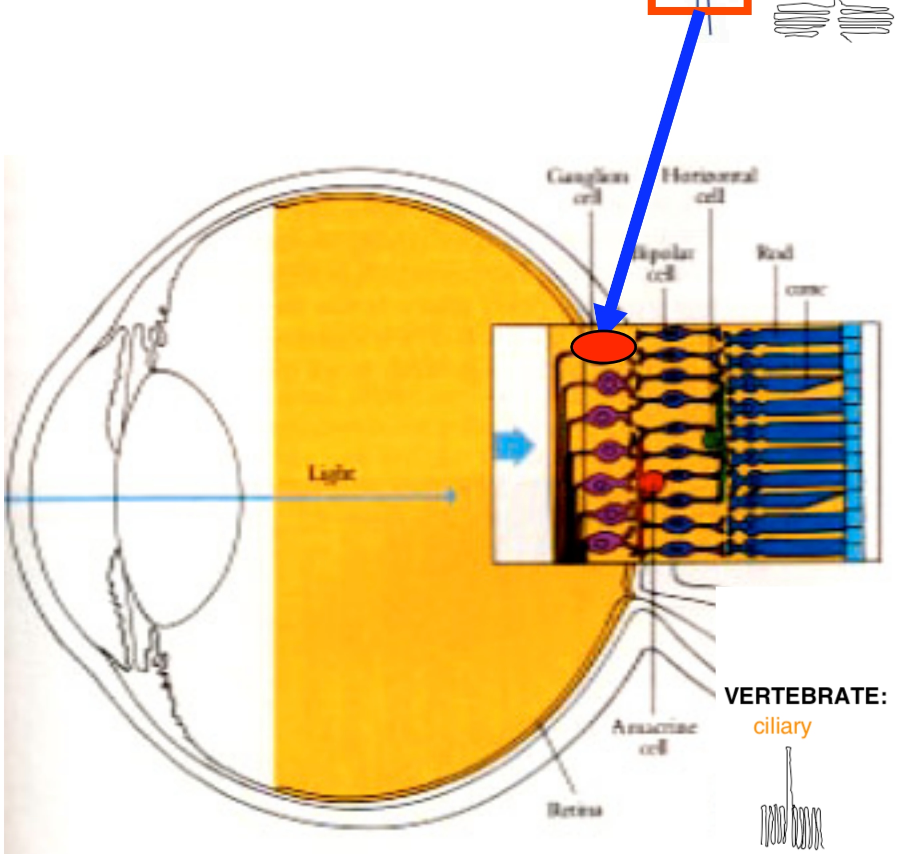
INVERTEBRATE: rhabdomeric



hν

r-opsin → G_q → PIP_2 → DAG → TRP channels open → membrane potential

retinal activation — *phototransduction* — ***signal amplification*** ***current increase*** — ***depolarize***



VERTEBRATE: ciliary

hν

c-opsin → G_t → PDE → cGMP → Na channels close → membrane potential

retinal activation — ***signal amplification*** *phototransduction* — ***current decrease*** — ***hyperpolarize***

Unexpectedly, ‘eye’ types collaborate to produce “vision”

The competition we associate with evolutionary selective pressure is often thought to produce a single outcome.

In both invertebrates and vertebrates, both canonical eye types collaborate to harvest and deliver information from photons to the brain.

What to think about repeated use of similar genes in eye evolution?

1) The primitive ancestral source of photodetection may have been produced by *Pax6* interacting with opsin to activate its expression;
2) With increasing eye complexity, *Pax6* began to be confined to photoreceptors;
3) The details of the regulation of conserved genes and networks support the idea they have been recruited independently (cephalopods!);
4) Interlinked genetic pathways (hh, EGFR, etc.) regulate complex developmental events;
5) BUT similar strategies do NOT imply common ancestries but reflect:
   a) Reuse of efficient mechanisms evolved for similar tasks (biology!);
   b) The consequences of a small genome.

6) Gene interactions are like an improvisational acting troupe: get together, act out a scene, if it works, keep it

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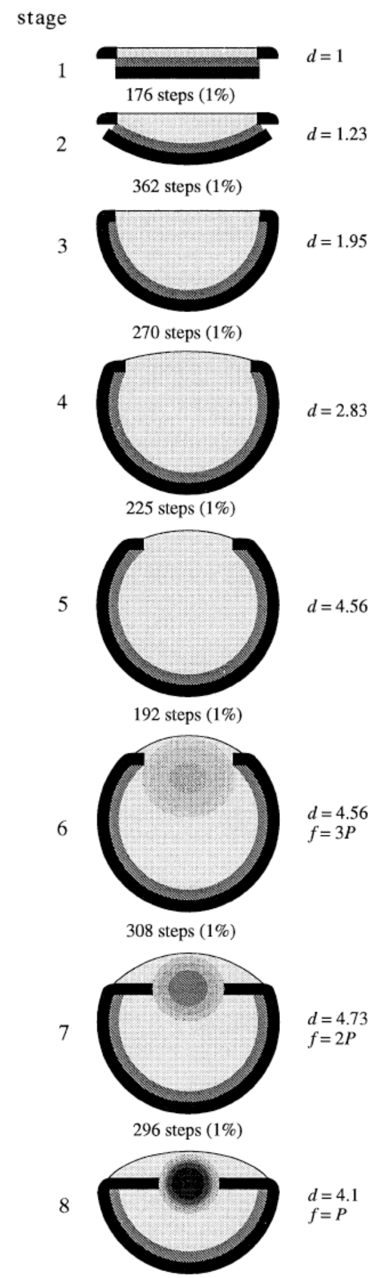
Modeling suggests eyes can evolve rapidly

Start with a flat photosensitive pigment spot and you can get a Vertebrate eye in 2000 sequential changes of 1% in length, width or protein density.

If each change took ~ 1year, this would mean an “eye” in < 0.5 myr



Generations
35,000
72,000
54,000
45,000
38,000
61,000
59,000

Nilsson & Pelger, 1994

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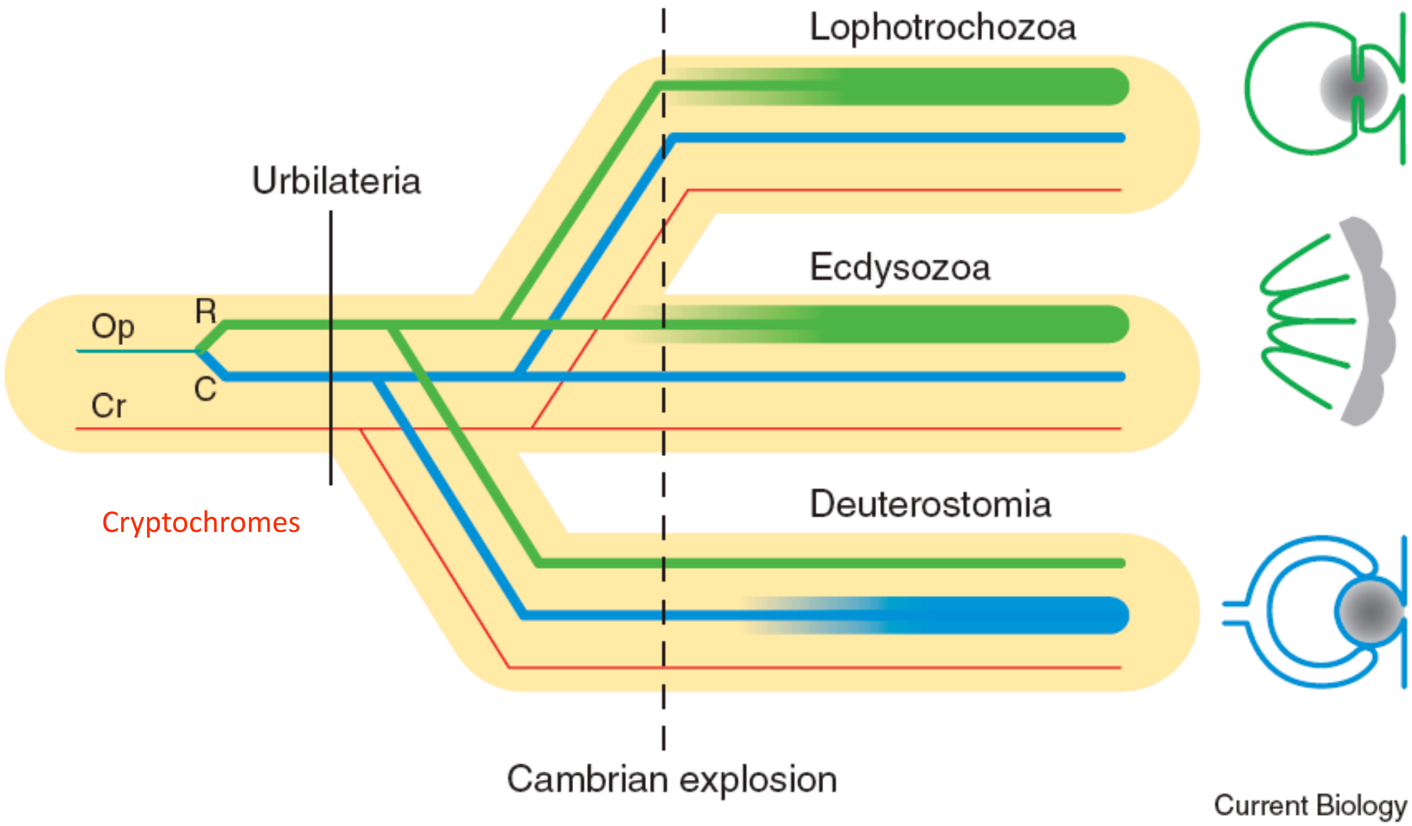
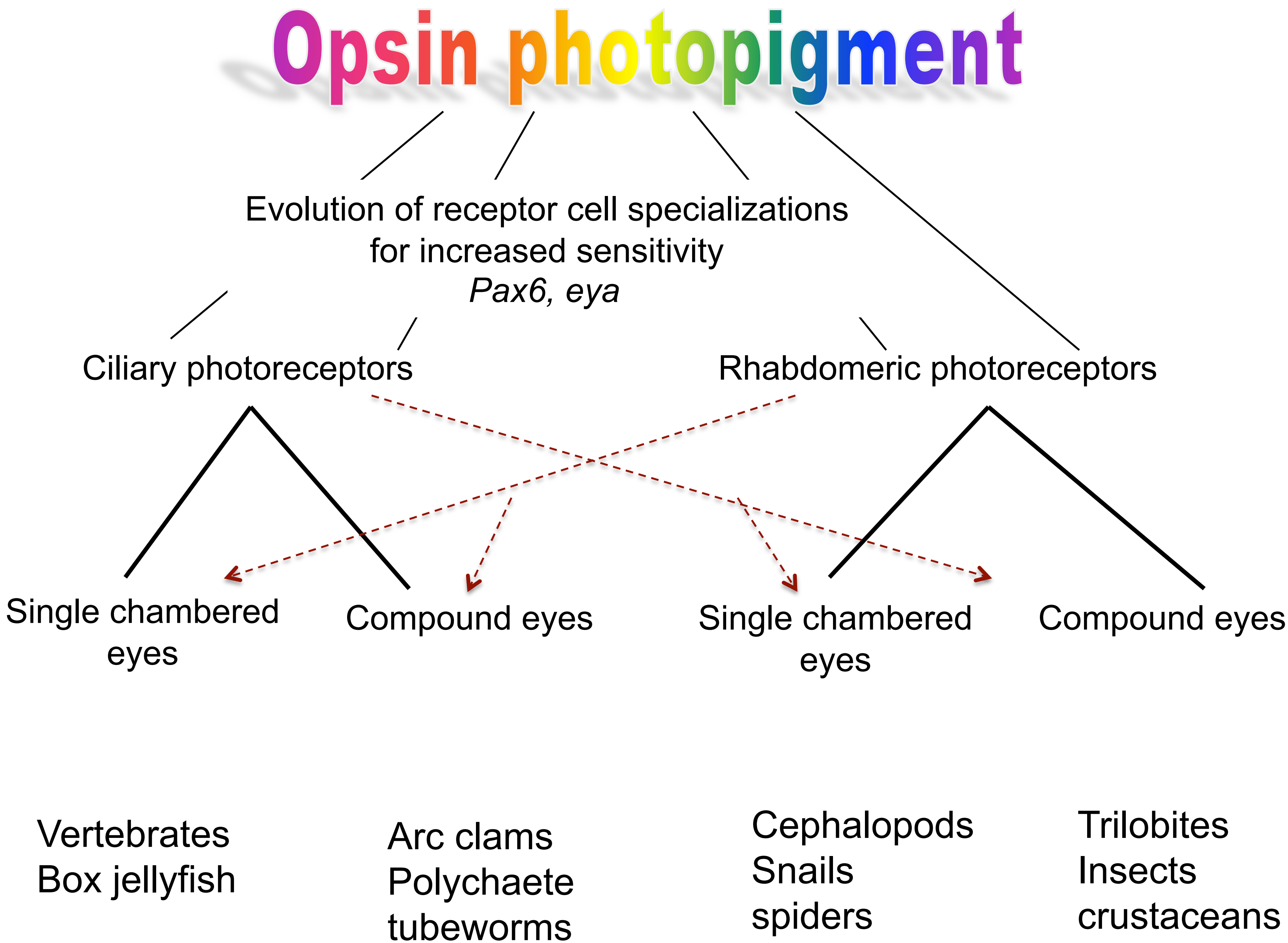
Both eye types had to exist prior to the rise of bilateria

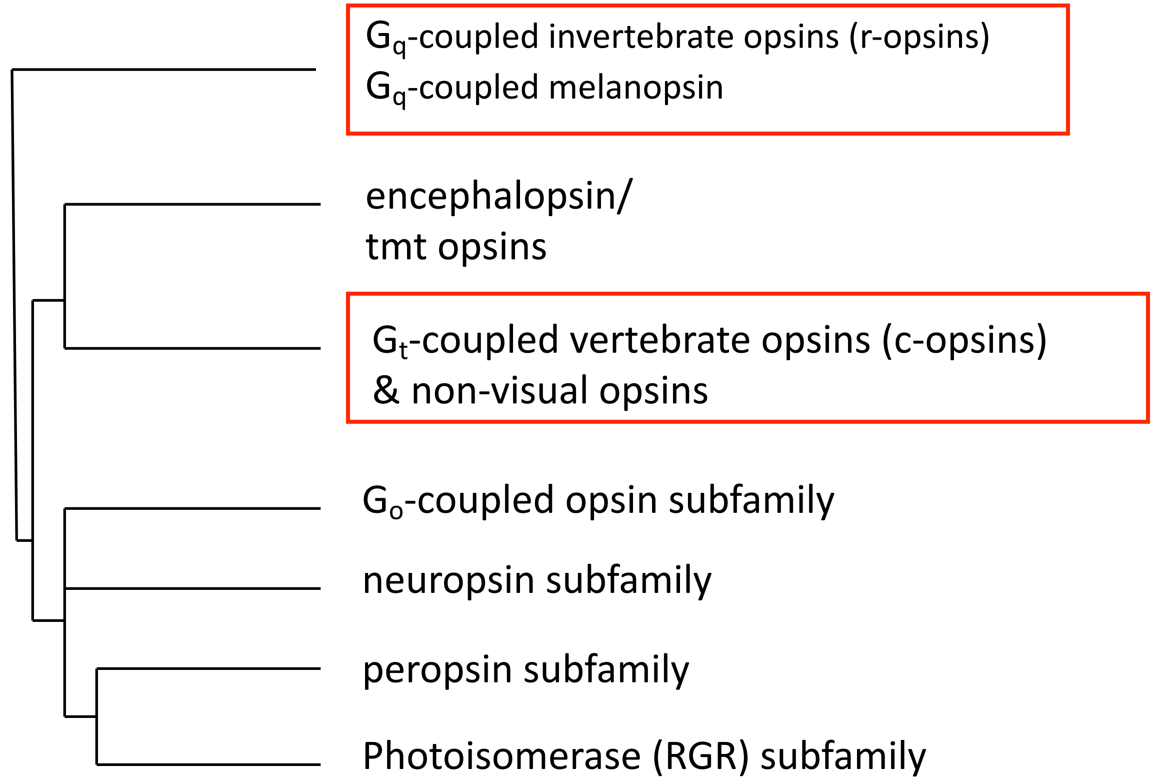


Nilsson, 2005



Opsin photopigment
Evolution of receptor cell specializations for increased sensitivity
Pax6, eya
Ciliary photoreceptors
Rhabdomeric photoreceptors
Single chambered eyes
Compound eyes
Single chambered eyes
Compound eyes
Vertebrates
Box jellyfish
Arc clams
Polychaete
tubeworms
Cephalopods
Snails
spiders
Trilobites
Insects
crustaceans

And the story isn't over



There are more opsin types found in humans and other vertebrates whose functions are not known.

Fernald *Science* (2006)

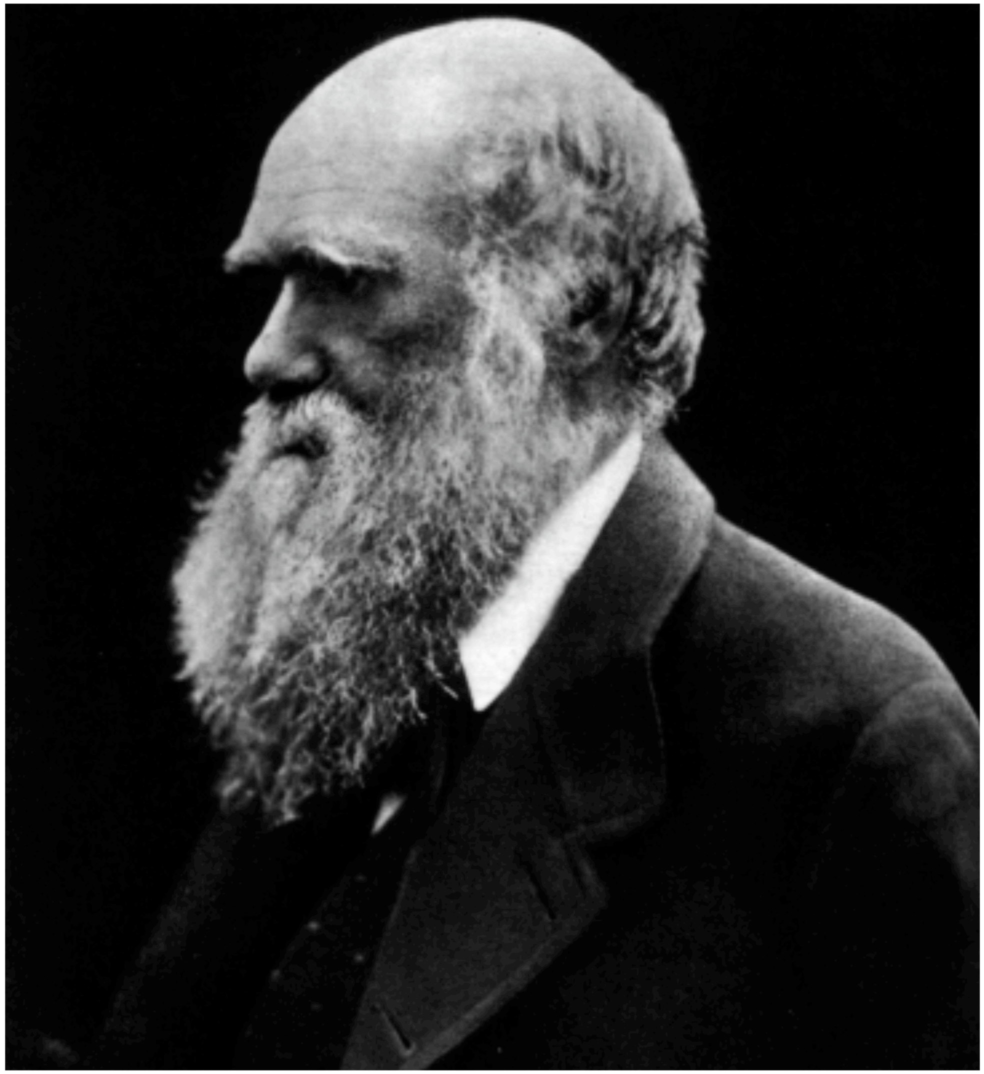
Eyes have evolved many (hundreds?) of times

1) It seems clear that eyes as we know them evolved at least twice since there are *at least* two types of "eye" in many extant organisms.

2) These two eye types were present before bilateral organisms and thus must have both existed prior to that time.

3) There may be more types of photoreception when we learn how the rest (5) of the opsin types and cryptochrome function.

4) The excitement about 'conservation' of genes used in eye development may be a red herring, reflecting instead gene improvisation in solution of developmental problems.



“Eyes arose many times
and the evidence is in our eyes”

Eyes:
Structures, Molecules & Origins

1) Constraints on eyes, diversity of eyes, history of thinking about eye evolution;

2) Diversity vs. specialization of eyes: Clues for evolution?

3) Evidence about eye origins: What can we use?
   a) Eye development?
   b) Lenses?
   c) Phototransduction: opsins and their transduction cascades;
   d) How fast could an eye evolve?

4) Speculation

5) Alternate universe

There is another opsin in the world

Animals all use “type 2” opsins, what about “type 1” opsins?

1) Present in all three domains of life;

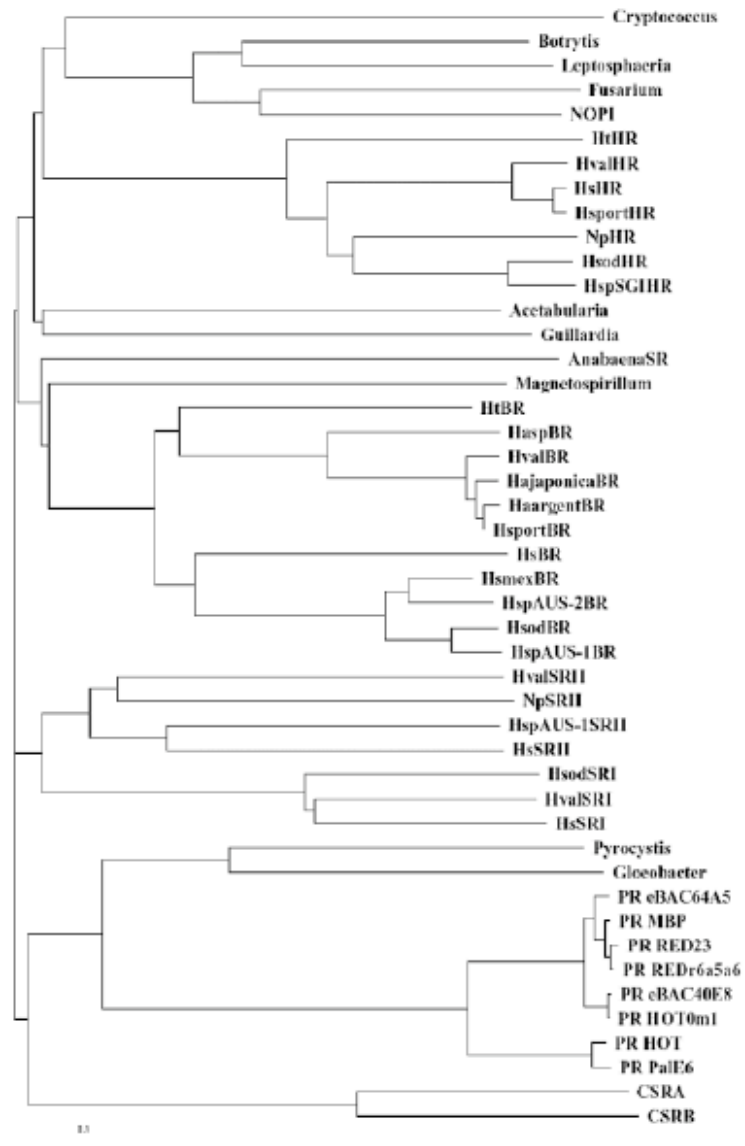
2) Progenitors of these proteins may have existed in early evolution before the divergence of archaea, eubacteria, and eukaryotes.

In 1999, four known examples, now ~800 (Venter et al., 2004; Sargasso sea)

Type 1 opsins are closely related to one another

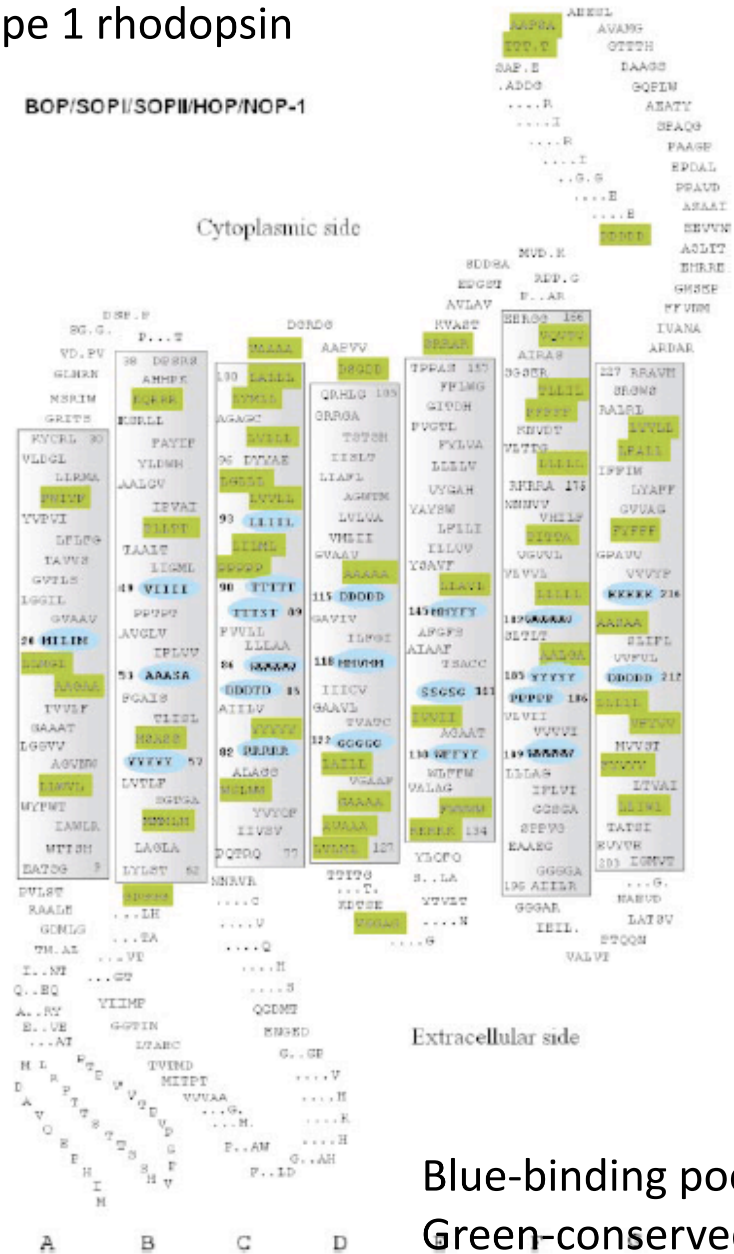
Phylogenetic tree of 46 microbial rhodopsins

No known relationship to rhodopsin 2

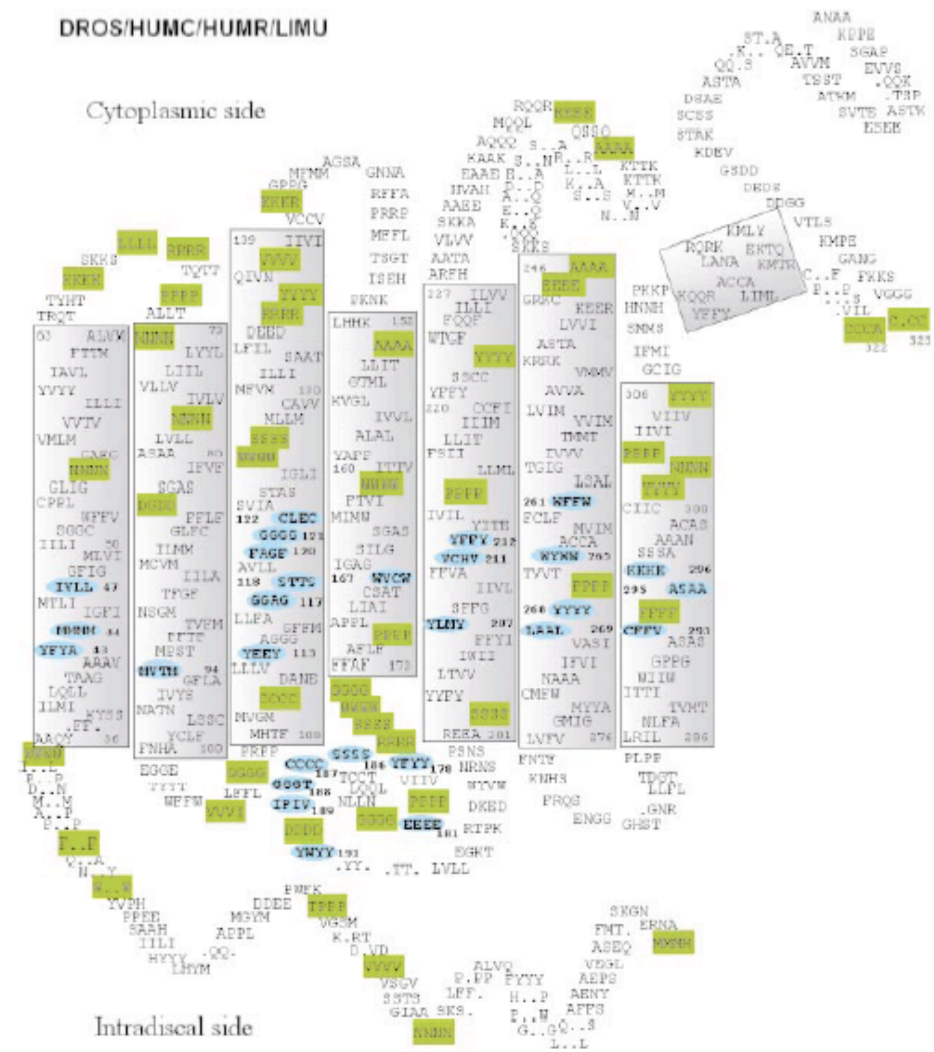


Spudich & Jung, 2005

Type 1 rhodopsin



Type 2 rhodopsin



Blue-binding pocket
Green-conserved within

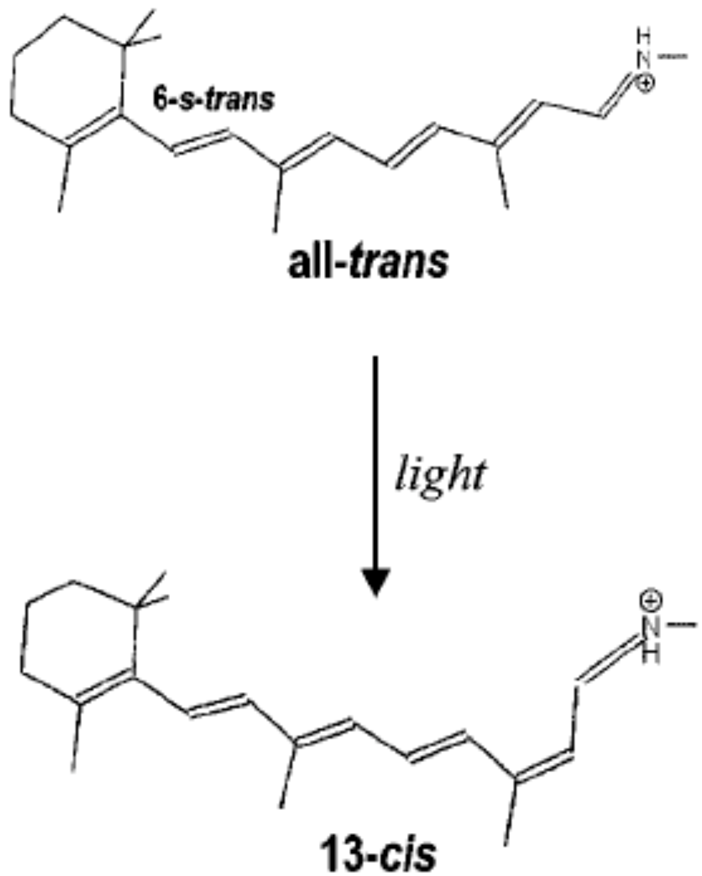
25-30 kDa

35 kDa

Type 1 opsins also use a form of retinal

Retinal photoisomerization in:

Archaea type 1 rhodopsins



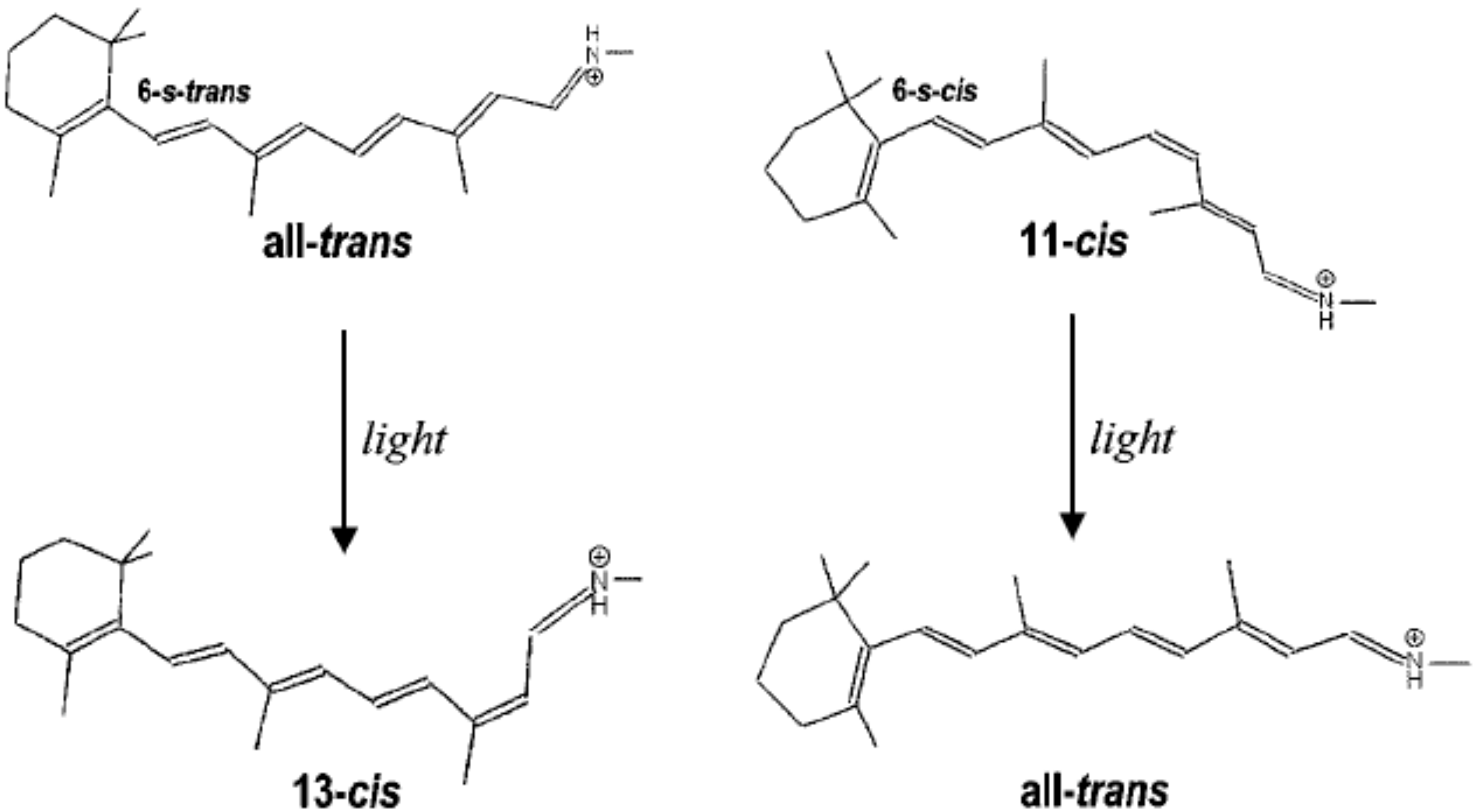
(Spudich et al., 2000)

But it shortens in response to light

Retinal photoisomerization in:

Archaea type 1 rhodopsins

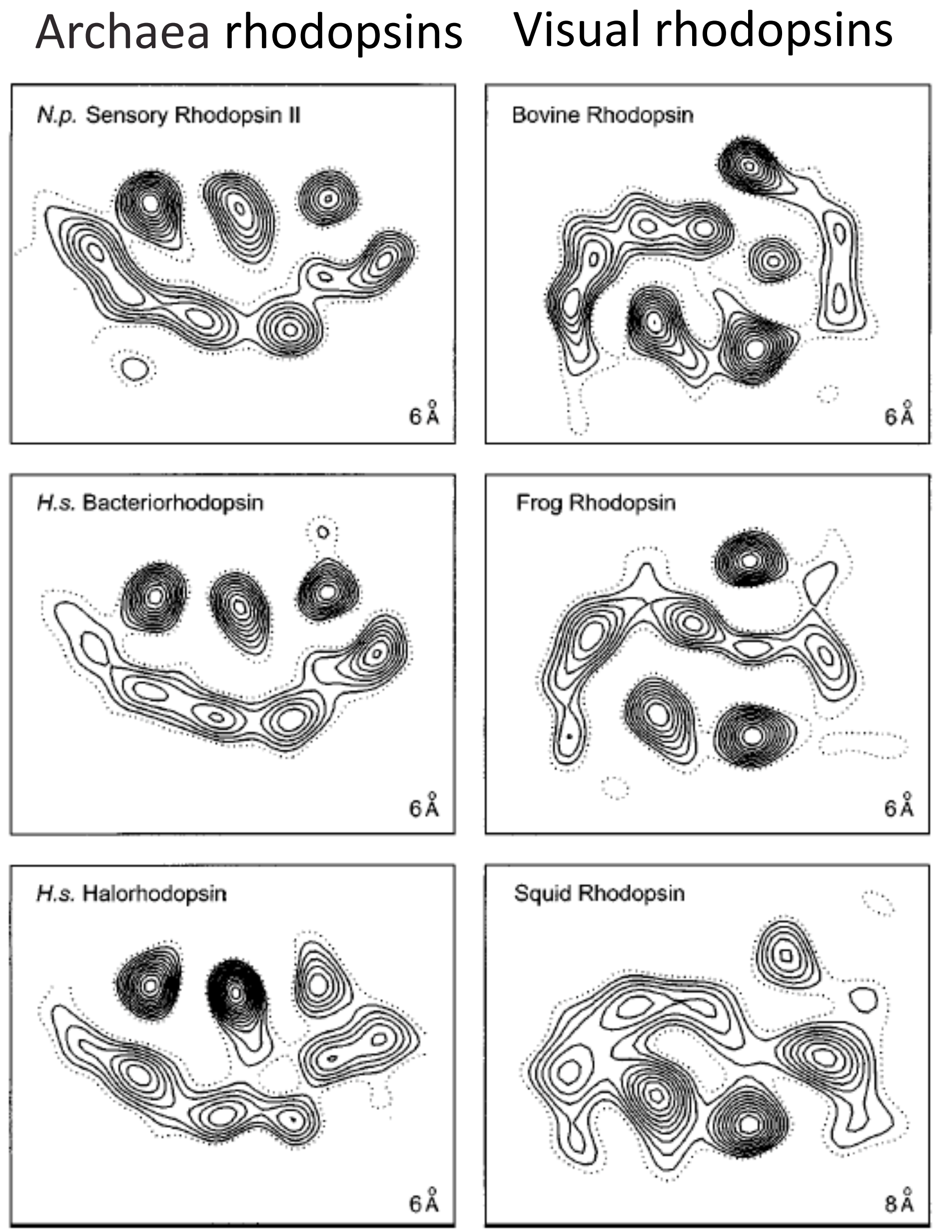
Visual pigments (type 2)



(Spudich et al., 2000)

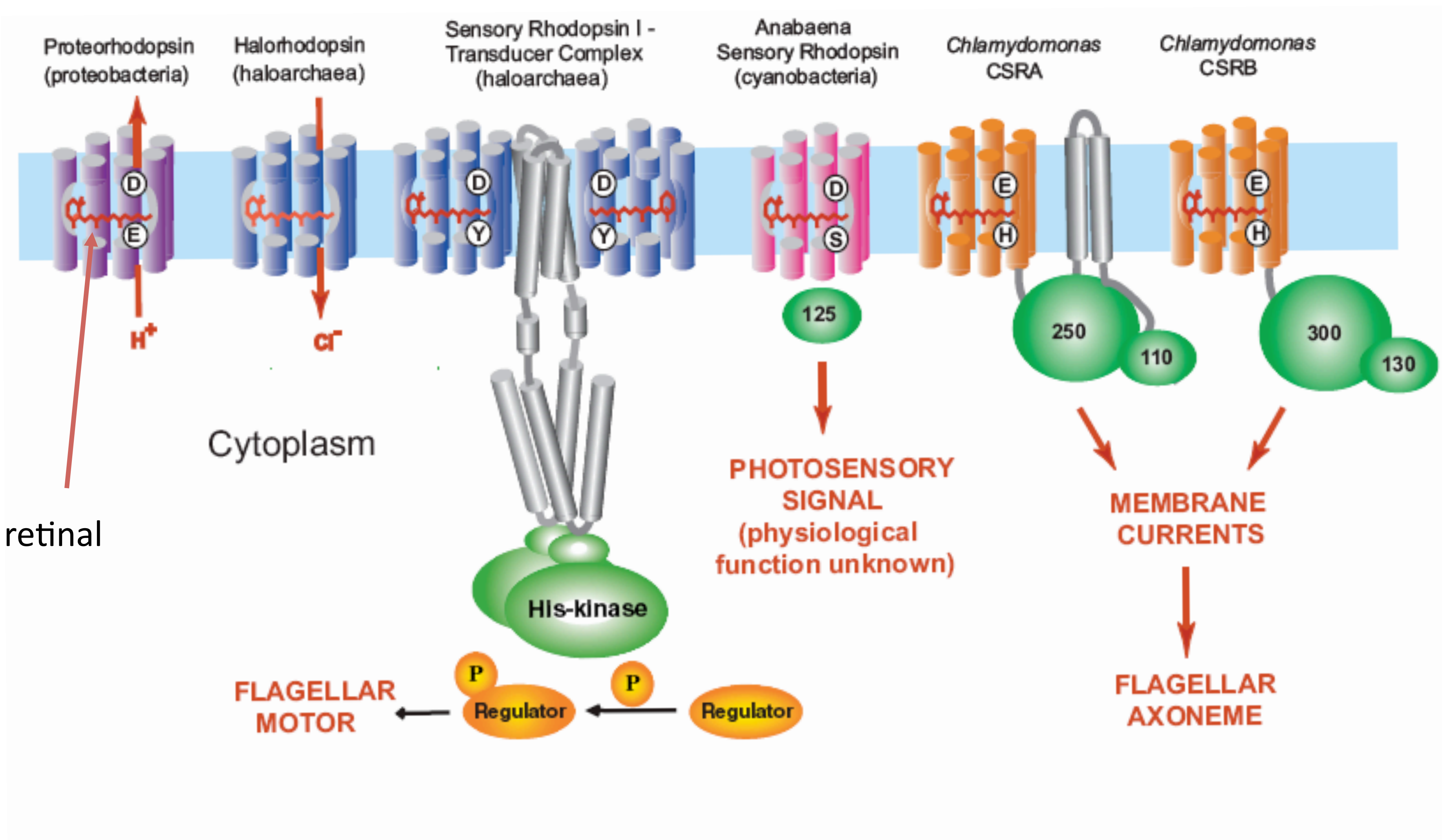
Opsins are positioned in membranes differently

Electron density projection maps (Spudich et al., 2000)



Type 1 opsins have very different outputs

Light response: Proton pumps, photon transduction



Solar to proton movement: Est. 10^{14} Watts

Spudich and Jung, 2005

Similarities and differences

Proteorhodopsin | Rhodopsin

Photoisomerization of retinal

Steric trigger-different sites on retinal

Schiff base proton transfer-
different acceptors

Helices C & F implicated in activation

Helix F most mobile

Protein-protein interaction->
signal transduction

Membrane embedded

Soluble factors (G proteins)

Alternate method of harvesting information

Gene sequence and three-dimensional structures suggest:

1) Evolution discovered retinal twice;

2) When solvated with 7-transmembrane protein it is useful for turning the energy of photons into other forms;

3) These remarkably similar mechanisms could result from “likely reinvention” that is due to the inherent properties of retinal as a chromophore;

4) Are there “eye-like” structures still to be discovered?

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