Welcome to Today's Seminar!

About the Vision Technical Group

Our technical group focuses on optics of the eye and of ophthalmic lenses and devices, physiological optics, mechanisms of transduction, transmission, coding, detection, and analysis of visual information.

Our mission is to connect the 1000+ members of our community through technical events, webinars, networking events, and social media.

Share your ideas for technical group events or let us know if you're interested in presenting your research. Connect with us:

- Our website at www.osa.org/vv
- Email us at TGactivities@osa.org

Our First Speaker Today

Larry Thibos

School of Optometry, Indiana University

Short Bio:

- Professor Emeritus at the Indiana University School of Optometry
- Ph.D. degree in Physiological Optics (1975) at the University of California, Berkeley
- Joined the Visual Sciences faculty of the School of Optometry at Indiana University in 1983 where he taught vision science until his retirement in 2012
- Elected Fellow of the Optical Society (1996), serving as topical editor for Journal of the Optical Society of America (1993-1999), Chair of the Vision Division (1996-1998), and member of the OSA Executive Council (1996-1998).

Our Second Speaker Today

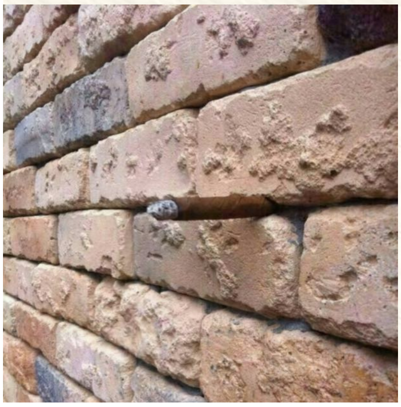
Michael Bach

University Medical Center Freiburg

Short Bio:

- Studied physics, computer science and psychology, then completed his PhD thesis recording from single units in monkey visual cortex
- Went on to work in the Eye Center of Freiburg university with patients suffering from eye diseases to arrive at early diagnosis
- With 300+ papers (H index 60), he is interested in all things vision from basic science to ophthalmological pathophysiology
- President of the International Society for Clinical Electrophysiology of Vision for 8 years

Optical illusions neither "trick the eye" nor "fool the brain"

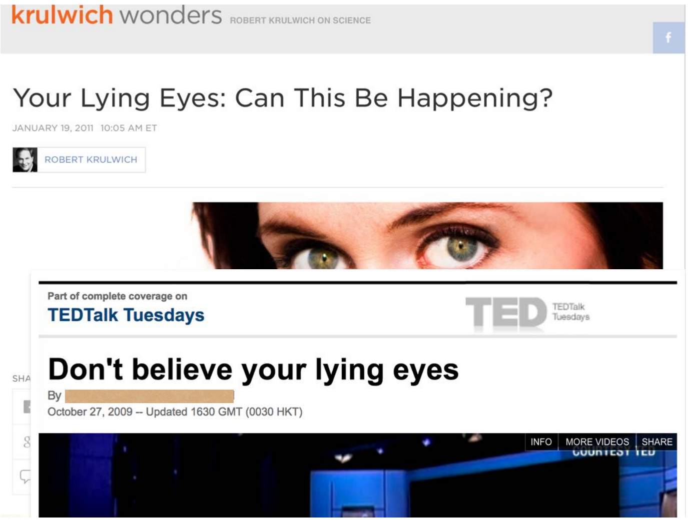


Section Visual Function
Vision Center, Freiburg University
Germany

UNIVERSITÄTS KLINIKUM FREIBURG

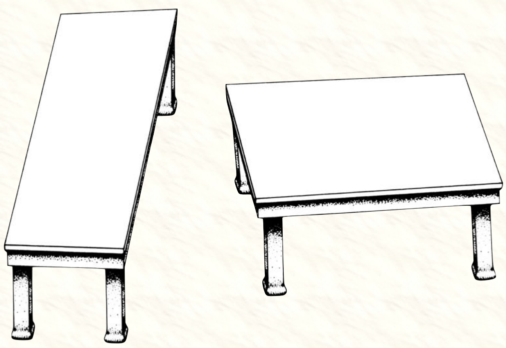
Outline

- Guiding Thoughts on "lying eyes"
- Examples
- Perception = Reconstruction
- Motion



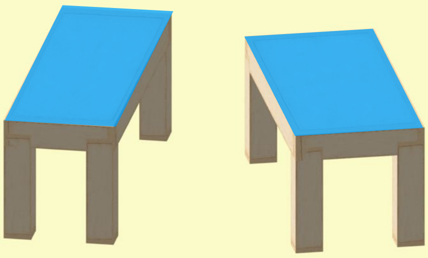
An (counter) example of a "brain error"

Roger Shepard (1981) "Turning the Tables"



→demo →demo

Roger Shepard (1981) “Turning the Tables”



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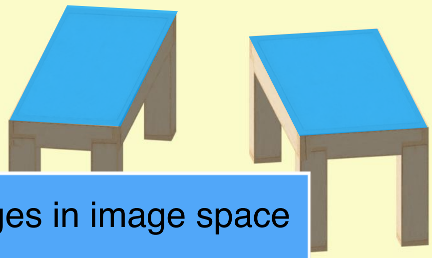
Roger Shepard (1981) “Turning the Tables”



changes in image space
≠
changes in object space

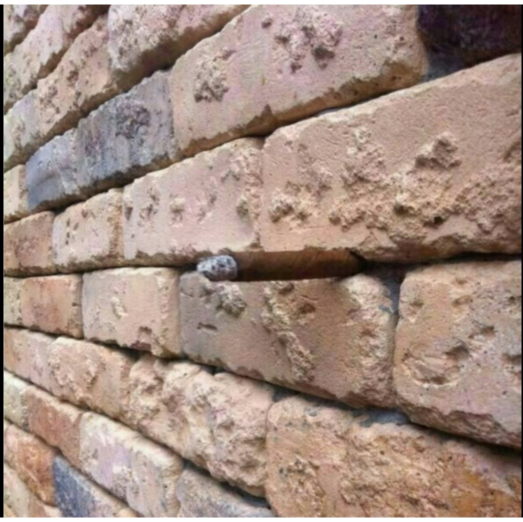
→demo →demo

Roger Shepard (1981) “Turning the Tables”

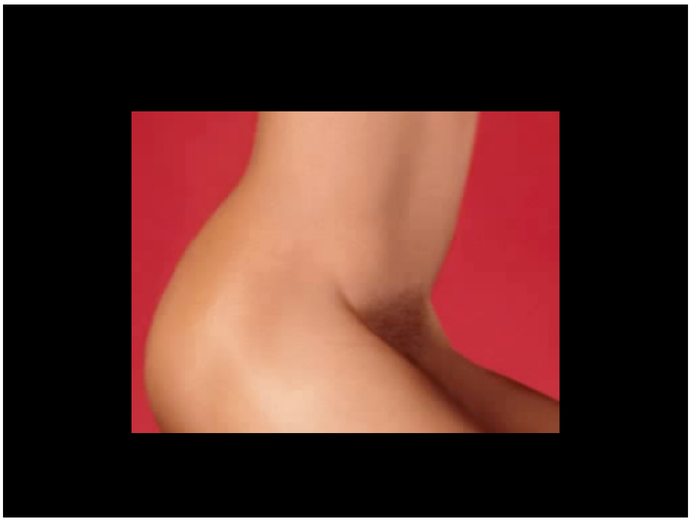
- This is not an “illusion” (whatever that is…)
- Transformations in image space ≠ transfs. in object space
- To put it nastily: This is a cheap trick
- Positively: It demonstrates that the brain is rather good at reconstructing the 3D scene, because in object space the tables *really* are different
- This applies to a number of illusions, e.g. Adelson’s checkerboard or the Color Cube
- → Illusions don’t always “trick the eye” nor “fool the brain”

Outline

- Guiding Thoughts
- **Examples**
- Perception = Reconstruction
- Motion



Nude Adrift, Melbourne,
Spencer Tunick ©2001

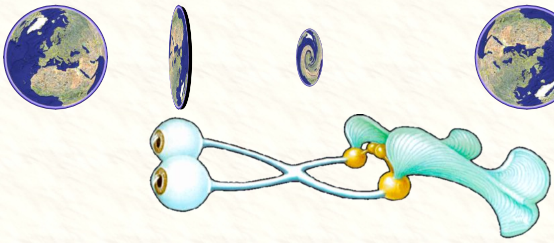


Agenda

- Guiding thoughts
- Examples
- **Perception = Reconstruction**
- Gestalt
- Motion

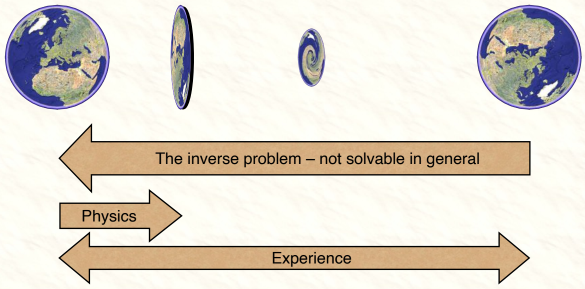
From the outer to the inner world

World / “scene” | flat retinal image | compressed along visual pathway | mental representation, e.g. for action planning



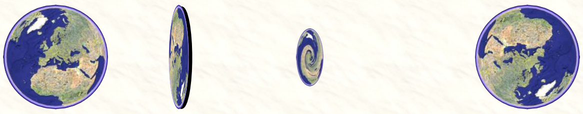
The Bayesian interpretation of perception

World scene | flat retinal image | compressed along visual pathway | mental representation, e.g. for action planning



The Bayesian interpretation of perception

World scene | flat retinal image | compressed along visual pathway | mental representation, e.g. for action planning

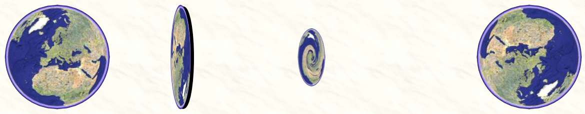


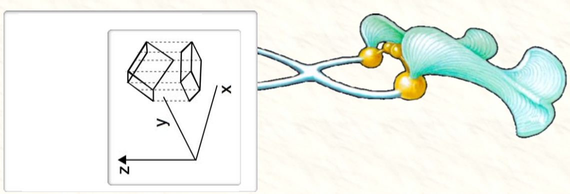
- Bayesian interpretation:
  P(**scene** | **image**) ~ P(**image** | **scene**) · P(**scene**)
  optics ⇑ ⇑ experience

$$P(H|DX) = \frac{P(H|X) \times P(D|HX)}{P(D|X)}$$

The Bayesian interpretation of perception

World scene | flat retinal image | compressed along visual pathway | mental representation, e.g. for “probehandeln”





Multiple interpretations of shadows

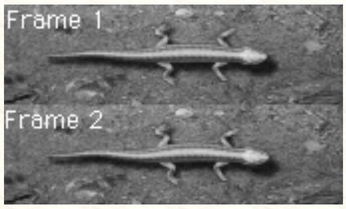
How NOT to explain perception

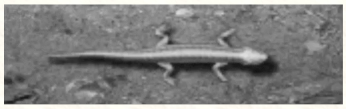
Agenda

- Guiding Thoughts
- Examples
- Perception = Reconstruction
- **Motion**

Marcel Duchamp (1912)
Nu descendent un escalier

Motion perception: An ecological advantage



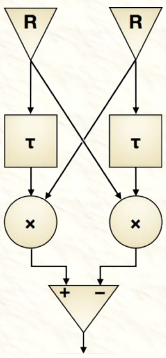


Apparent movement

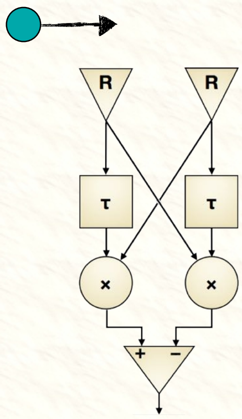
Motion Detector (Reichardt-Hassenstein)

Warning: Theory ahead

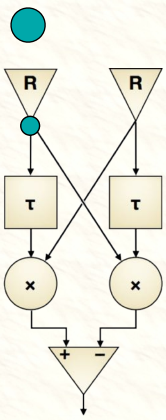
Reichardt 1986



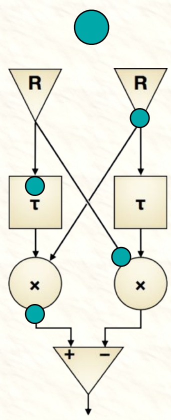
Motion Detector (Reichardt-Hassenstein)



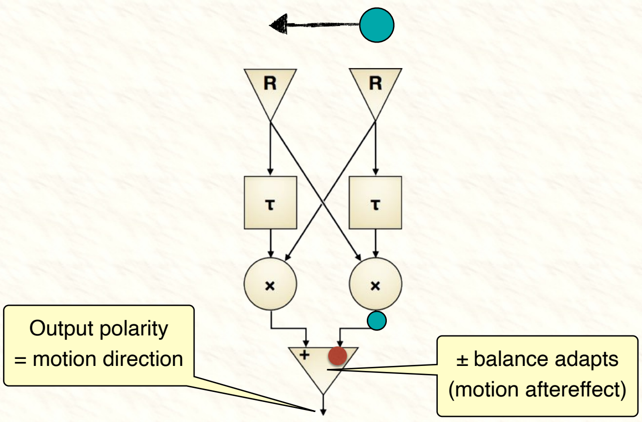
Motion Detector (Reichardt-Hassenstein)



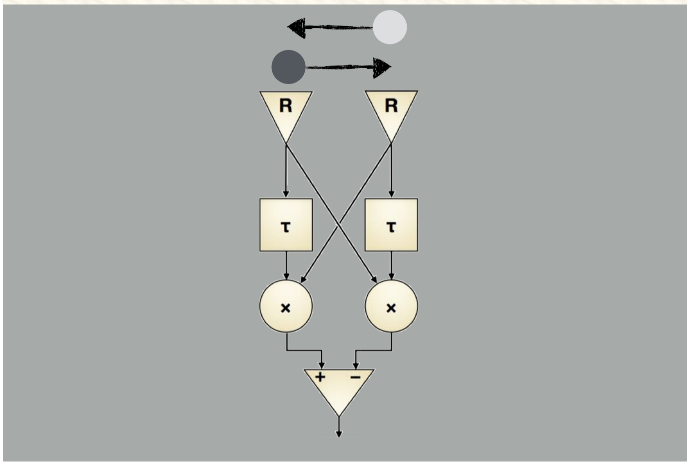
Motion Detector (Reichardt-Hassenstein)



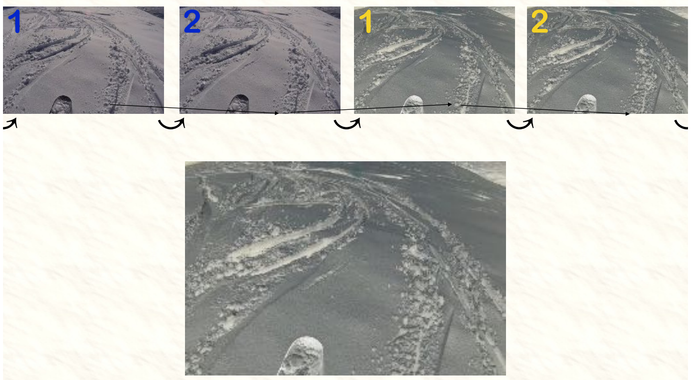
Motion Detector (Reichardt-Hassenstein)



Motion detector: Effect of contrast sign



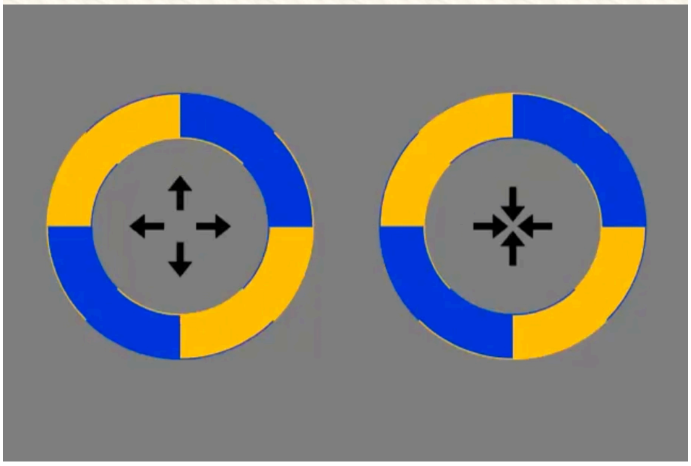
Sign-specific → "reverse phi"



Anstis & Rogers (1975) Vision Res 15:957–961

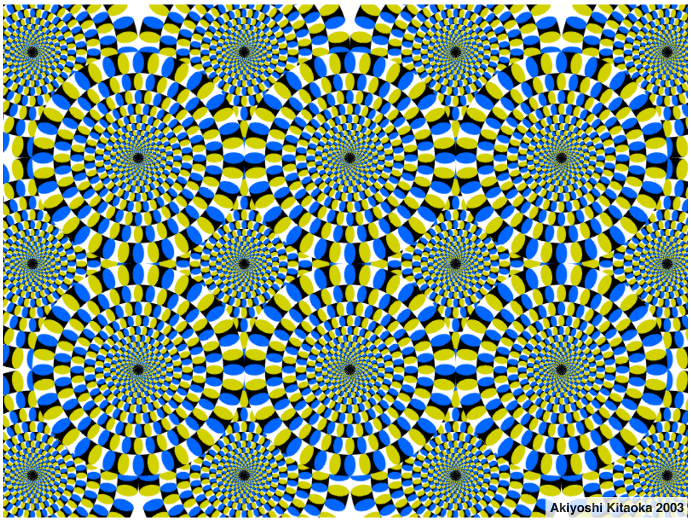
→demo →demo

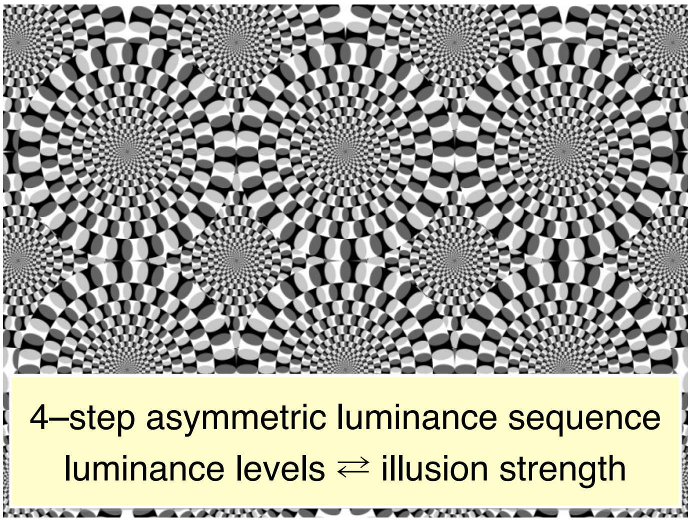
New "reverse phi" examples

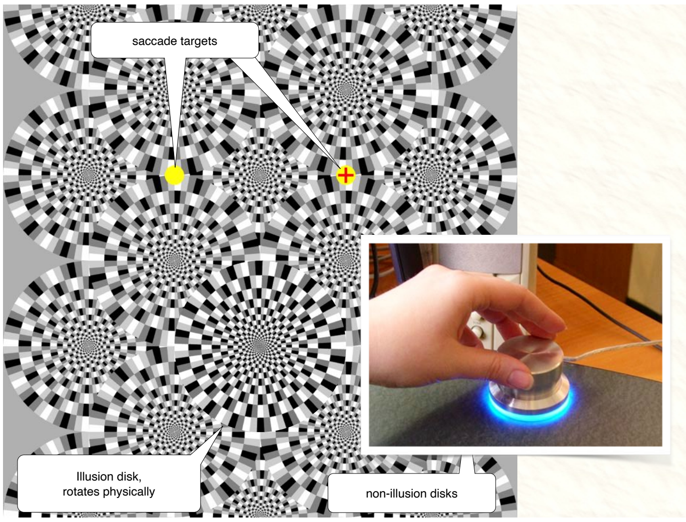


“Rotating Snakes” Motion Illusion

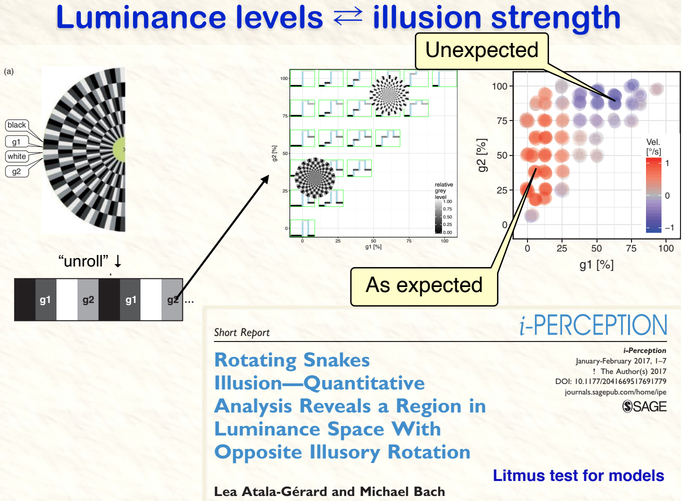
- Certain stationary visual patterns evoke illusory movement
  - Bülthoff & Götz (1979)
  - Fraser and Wilcox (1979)
  - Faubert and Herbert (1999): “peripheral drift illusion”
  - Optimised by Kitaoka (2003): “Rotating Snakes Illusion”



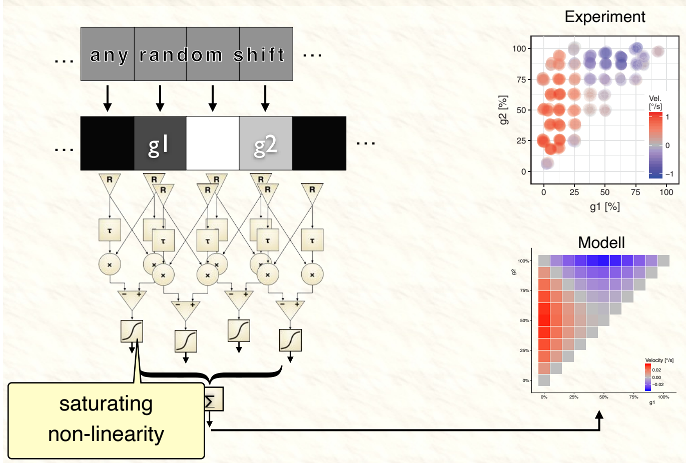




Luminance levels ⇄ illusion strength



Model: motion detectors look at “unrolled” snake



Short Report

i-PERCEPTION

i-Perception
2020, Vol. 11(5), 1–9

DOI: 10.1177/2041669520958025
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The Rotating Snakes Illusion Is a Straightforward Consequence of Nonlinearity in Arrays of Standard Motion Detectors

Michael Bach and Lea Atala-Gérard
Eye Center, Medical Center – University of Freiburg, Faculty of Medicine, University of Freiburg, Germany

Abstract
The Rotating Snakes illusion is a motion illusion based on repeating, asymmetric luminance patterns. Recently, we found certain gray-value conditions where a weak illusory motion occurs in the opposite direction. Of the four models for explaining the illusion, one also explains the unexpected perceived opposite direction. We here present a simple new model, without free parameters, based on an array of standard correlation-type motion detectors with a subsequent nonlinearity (e.g., saturation) before summing the detector outputs. The model predicts (a) the pattern-appearance motion illusion for steady fixation, (b) an illusion under the real-world situation of saccades across or near the pattern (pattern shift), (c) a relative maximum of illusory motion for the same gray values where it is found psychophysically, and (d) the opposite illusion for certain luminance values. We submit that the new model's sparseness of assumptions justifies adding a fifth model to explain this illusion.

The model successfully predicts

- With *steady fixation:* Illusion for pattern-appearance
- Illusion with real-world *saccades* across or near the pattern
- Maximum of illusory motion for the luminance levels where it is found psychophysically
- Opposite illusion for another luminance levels region

While just assuming standard motion detectors
+ saturating non-linearity (and some simplification)

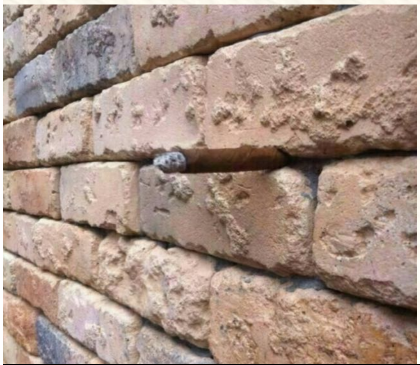
Still not the full story…

Final Thoughts

- “Optical illusions” are not an error in the design of the visual system
- Evolution + experience optimised our perceptual apparatus for typical visual environments
- Implemented as a set of probabilities

- → in **a**-typical visual environments: illusions can occur
- Illusions →
  neuronal mechanisms of our perceptual apparatus

Thank you for thinking along!



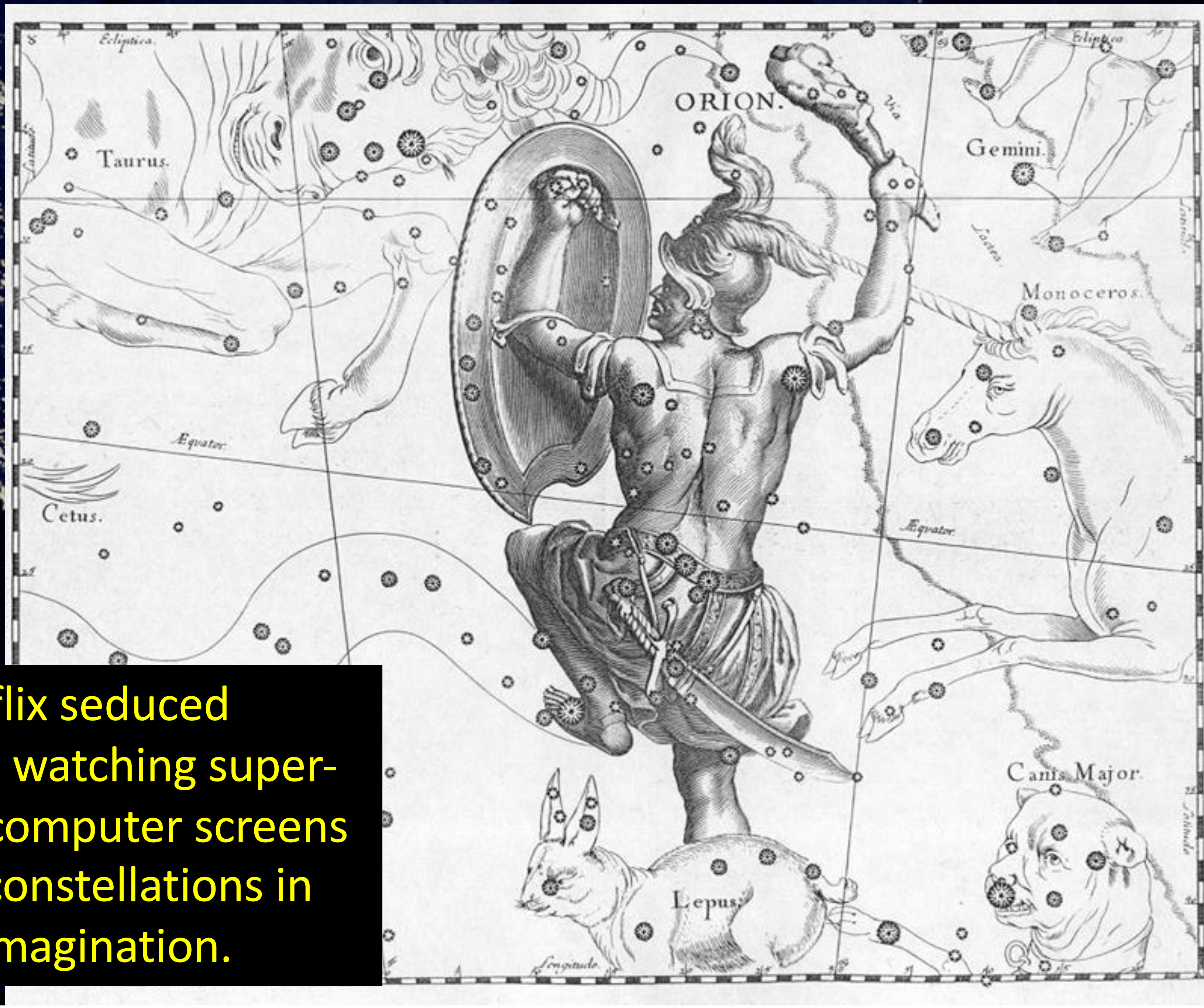
More:
http://michaelbach.de/ot/

Starbursts: their history, nature, origin and importance

Collaborators: Arthur Bradley, Renfeng Xu, Pete Kollbaum
Indiana University School of Optometry, USA

Norberto Lopez-Gil, Ivan Marin-Franch
Facultad de Óptica y Optometría. University of Murcia, Spain

In a time long, long ago, before Thomas Edison illuminated the night sky with his electric lights,



before Netflix seduced people into watching super-heroes on computer screens instead of constellations in our visual imagination.

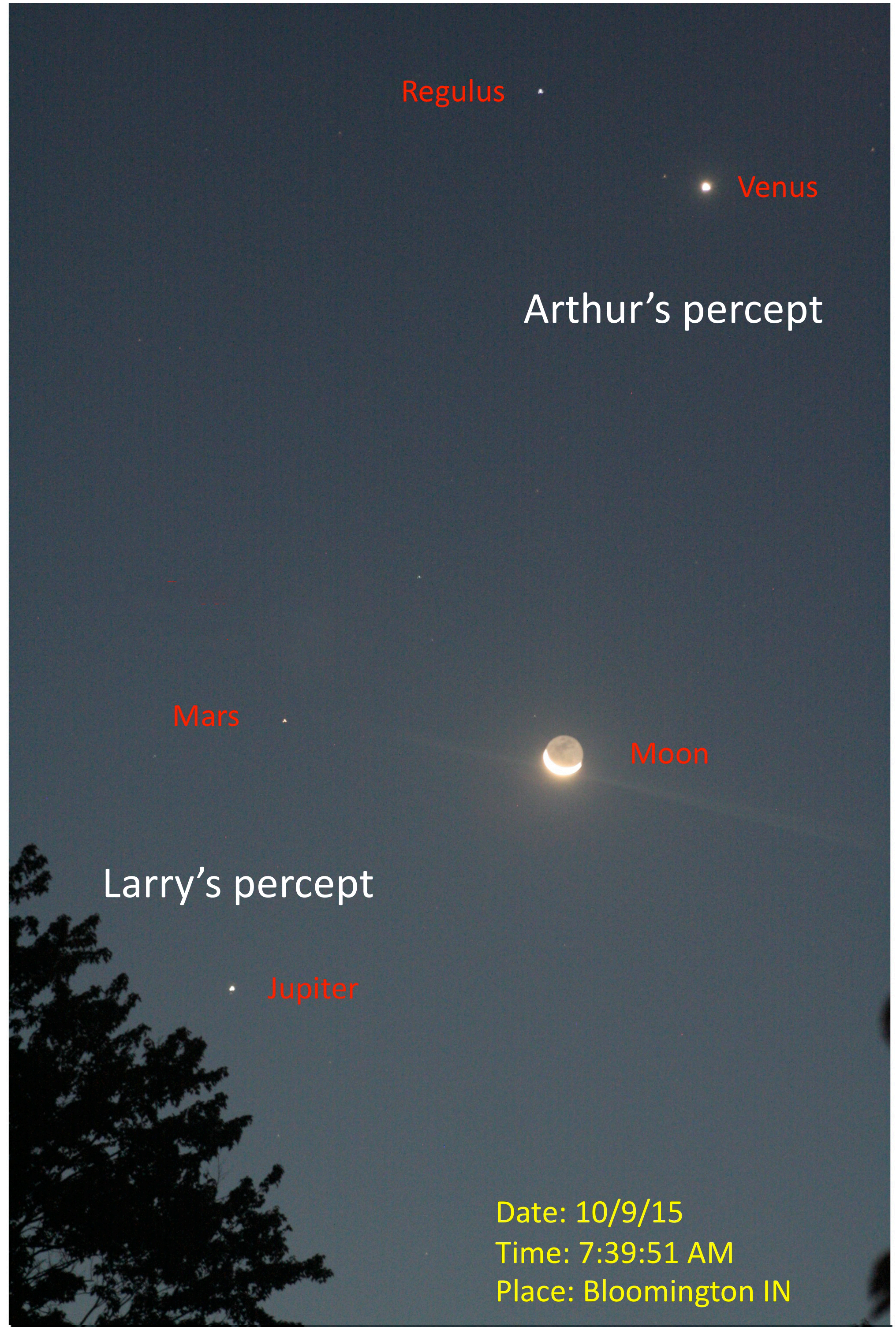
People gazed at the stars and planets, wondering about the origin of such wondrous sights.

Strangely, when the sky was very dark (and pupils dilated), stars and planets appeared as points of light with thin, dim lines radiating out to distances that could be larger than the diameter of the moon (0.5°)

What are these “starbursts”?

Where do they come from?

Why does each person see a unique starburst pattern?



Starburst History

- Art
- Religion
- Science

Ancient paintings and sculptures show that people have been seeing starbursts for thousands of years, in many countries and cultures.

Sopdet, the stellar goddess SIRIUS, from the 1300 BC tomb of Seti I.

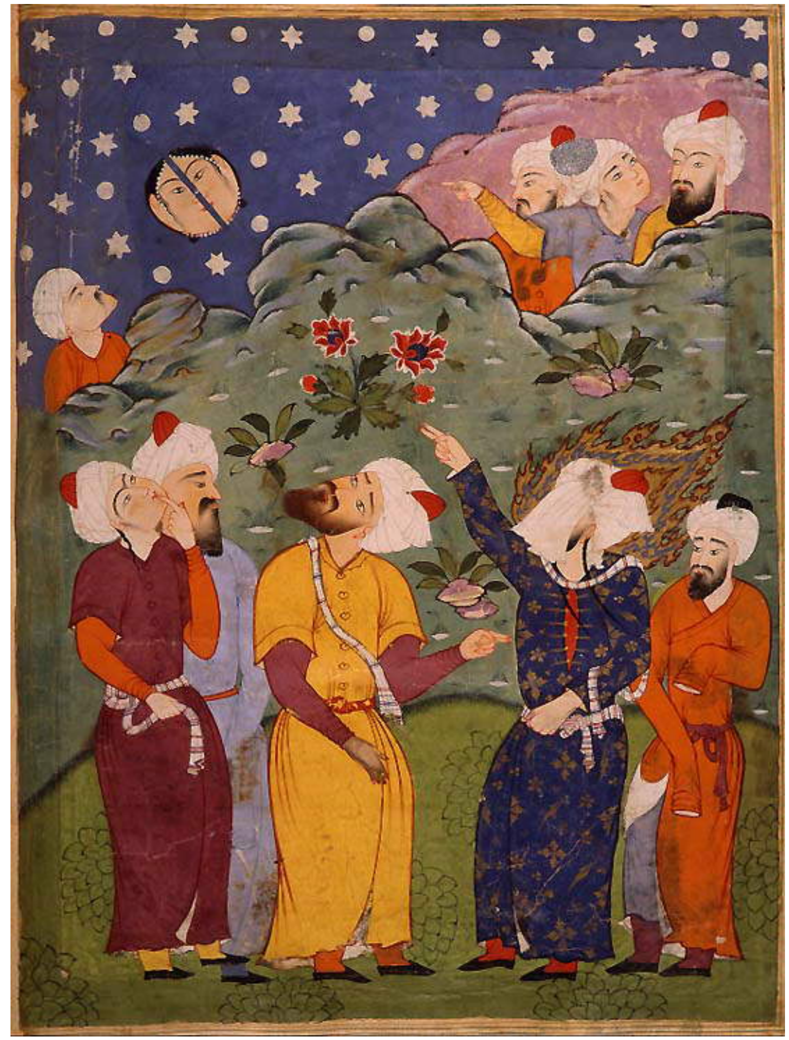
Journey of the Magi,
from St. Albans Psalter, ~ 1130

Ancient Roman mosaic shows the characteristic pattern of radiating lines, called “starbursts”.

Detail of nave mosaic depicting the Three Magi
~ 500 AD, Basilica of Sant' Apollinare Nuovo, Ravenna, Italy

Star images are universal yet individual.
Everyone sees the same star differently, yet their perceptions share a common feature of light radiating from a central core.

Starbursts in a 15th century French manuscript

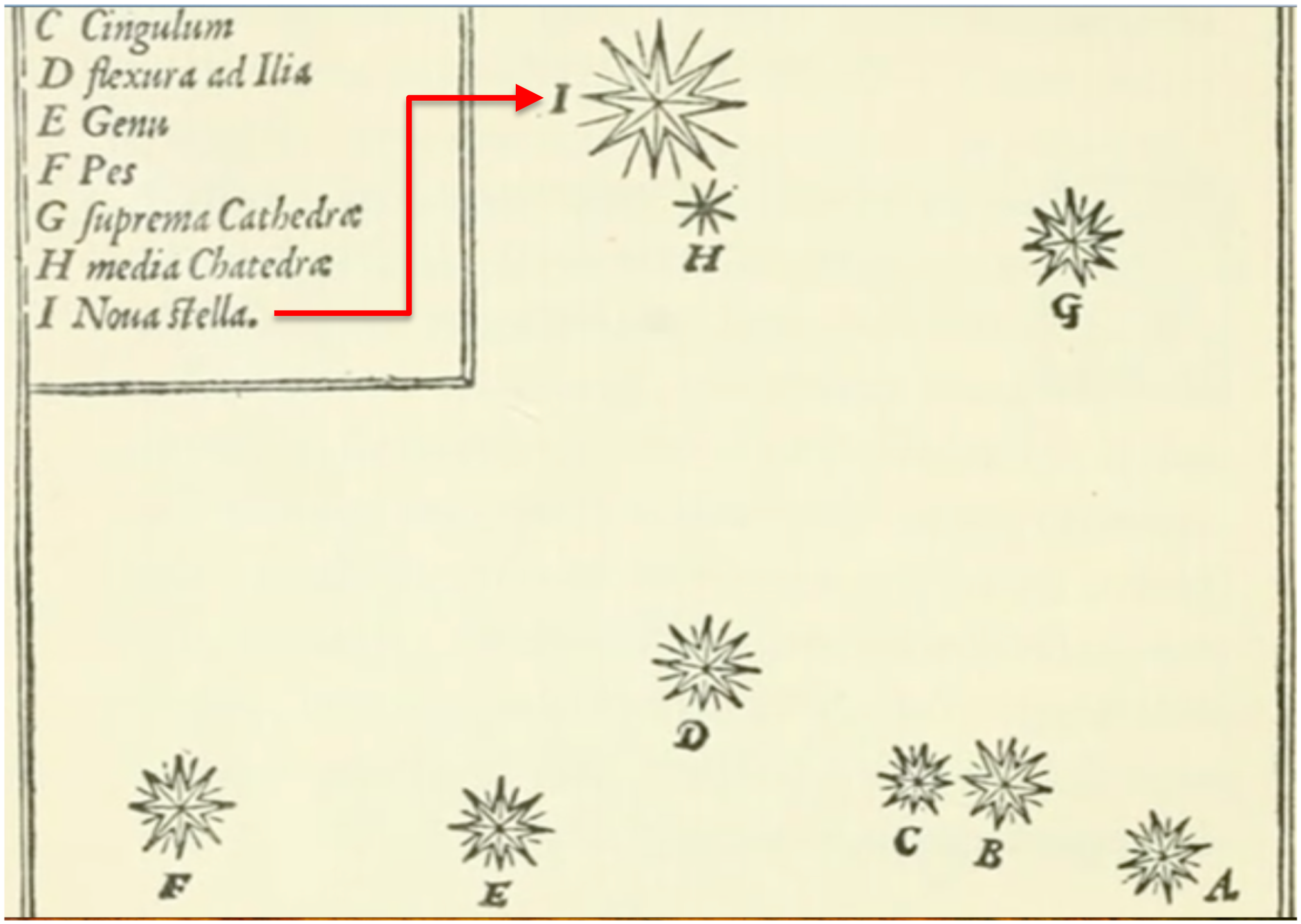


Mohammed splits the Moon
Persia 16th century

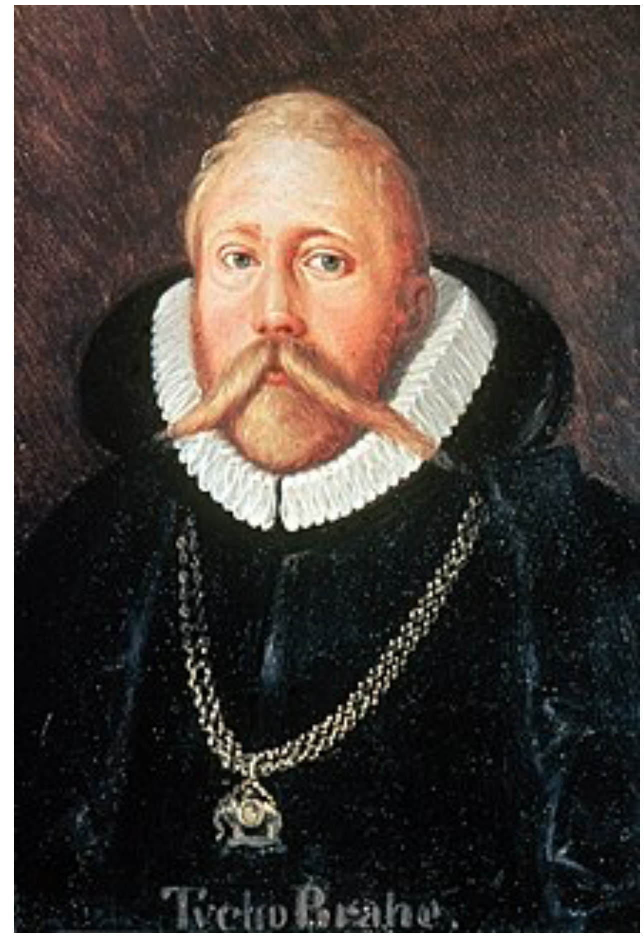
Celebrated astronomers recorded starbursts in their log books.

Tycho Brahe's (1572) drawings of stars in the constellation Cassiopeia and a new star (*Nova stella*)* are starbursts.

Tycho Brahe (1546-1601)



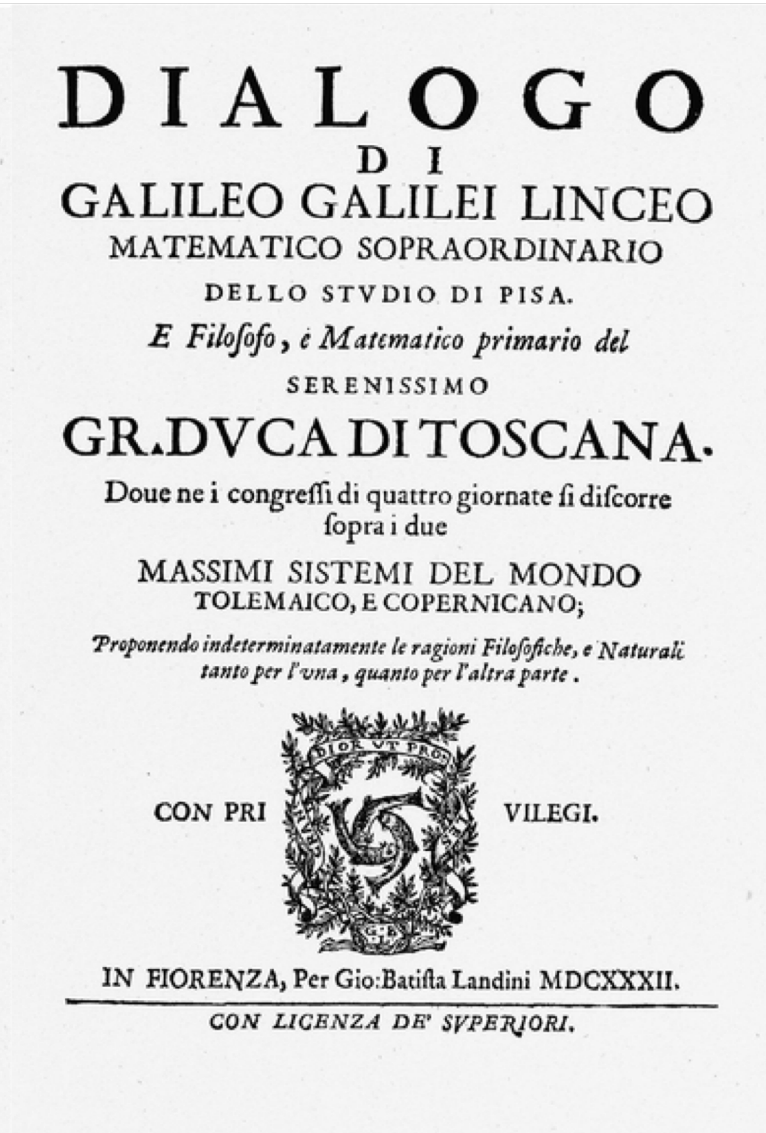
Star map of Cassiopeia from Tycho Brahe's *De Nova Stella.*



* Now believed to be a supernova explosion marking the death of a star.

The Nature of Starbursts

Modern discussion begins in 1632 with Galileo's analysis of his own observations



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filoſofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.
Doue ne i congreſſi di quattro giornate ſi diſcorre
ſopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali tanto per l'vna, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio: Batiſta Landini MDCXXXII.

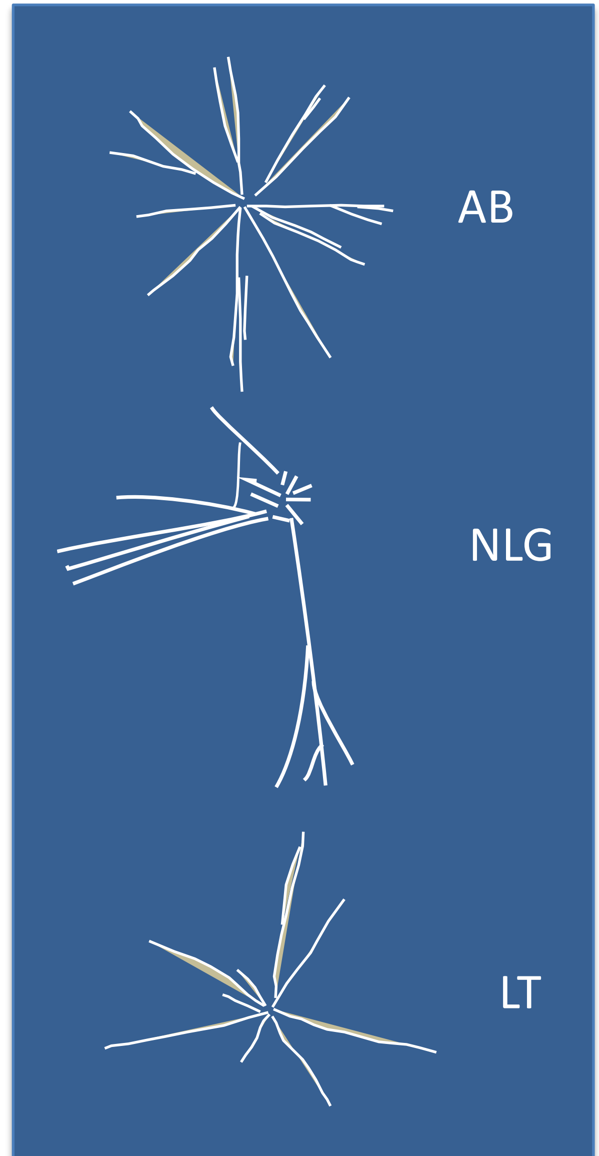
CON LICENZA DE' SVPERIORI.

Title: *Dialogue on the two major systems of the Ptolemaic and Copernican world*

Galileo (1632) recognized starbursts as artifacts of the eye, not inherent to celestial objects.

“Venus and Mars are perceived by simple natural vision, in which the **impediment of our eyes** (*l'impedimento del nostro occhio stesso*) plays a large part. Bright, distant objects are not represented to us as simple and plain, but are **festooned with adventitious* and alien rays (***inghirlandati di raggi avventizii e stranieri***) which are so long and dense** that the bare [celestial] bodies are shown as expanded ten, twenty, a hundred, or a thousand times as much as would appear to us if the little **radiant crown which is not theirs** were removed.”

Recent starburst drawings



To prove that this "radiant crown" of starbursts is made of "adventitious and alien rays", Galileo proposed an experiment using artificial pupils:

"This evening, when the sky is well darkened, let us look at Jupiter; we shall see it very radiant and large. Then let us cause our vision to pass through a tube, or even through a tiny opening which we may leave between palm of our hand and our fingers, clenching the fist and bringing it to the eye; or through a hole made by a fine needle in a card. **We shall see the disc of Jupiter deprived of rays** and so very small that we shall judge it to be less than 1/60 of the size it appeared previously like a great torch when viewed with the naked eye."

Two centuries later, Helmholtz (1867)* confirmed Galileo's observations, concluding that starbursts are a perceptual manifestation of the eye's optical aberrations. Starbursts are not inherent to the external stimulus, they are entoptic perceptions caused by anatomical structures inside the eye.

Helmholtz's observations of his own subjective perceptions:

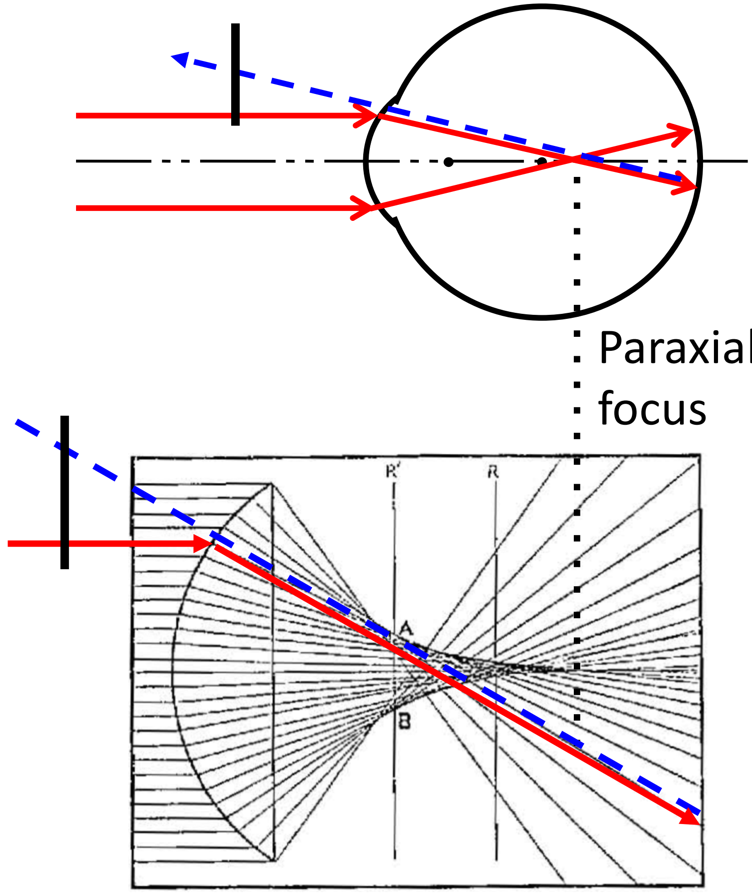
- For a point of light located beyond the far-point, what is seen is not a circular spot, as in a telescope out of focus, but a star-shaped pattern with four to eight irregular points or rays, which are different in the two eyes and different also for different individuals." Blocking the *top part* of the pupil makes the *top part* of the star image disappear.
- Placing the point source in front of the far-point has the opposite effect: Blocking the *top part* of the pupil makes the *bottom part* of the star image disappear.
- The perceived size of the starburst gets smaller as the point source is moved closer to the eye's far-point.
- The effect of blocking part of the pupil is very different from the "hair corona" phenomenon (i.e. ciliary corona) caused by diffraction by lens fibers.

*Helmholtz, H. von. (1867) Handbuch der physiologischen Optik, Volume 1

Helmholtz's pupil mapping experiment for a *myopic* eye

Geometrical optics says superior rays strike inferior retina, so are perceived in superior visual field.

Blocking superior rays eliminates superior part of entoptic percept.



Verhoff, 1900

Radiating starbursts are greatly amplified by ocular spherical aberration (SA).

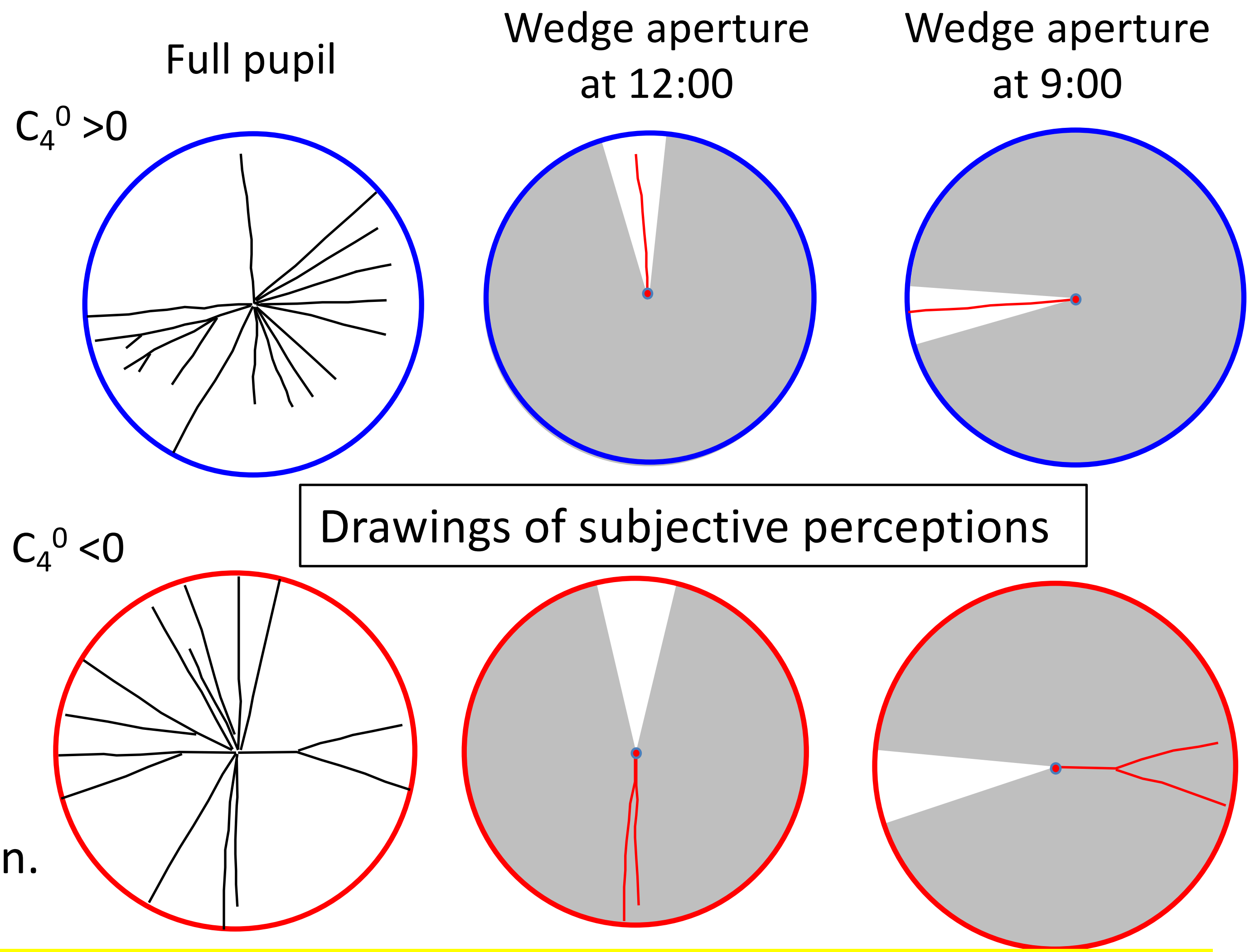
Pupil mapping for SA > 0 has the same sign as for myopic defocus: superior rays produce superior percepts.

This prediction can be confirmed empirically using a wedge aperture.

Wedge apertures dissect the entoptic percept *meridionally**

For positive spherical aberration, a wedge aperture isolates the starburst line in the *same* visual meridian.

For negative spherical aberration, a wedge aperture isolates the starburst line in the *opposite* visual meridian.



Conclusion: meridional mapping of pupil plane to entoptic perception is consistent with geometrical optics (ray-tracing).

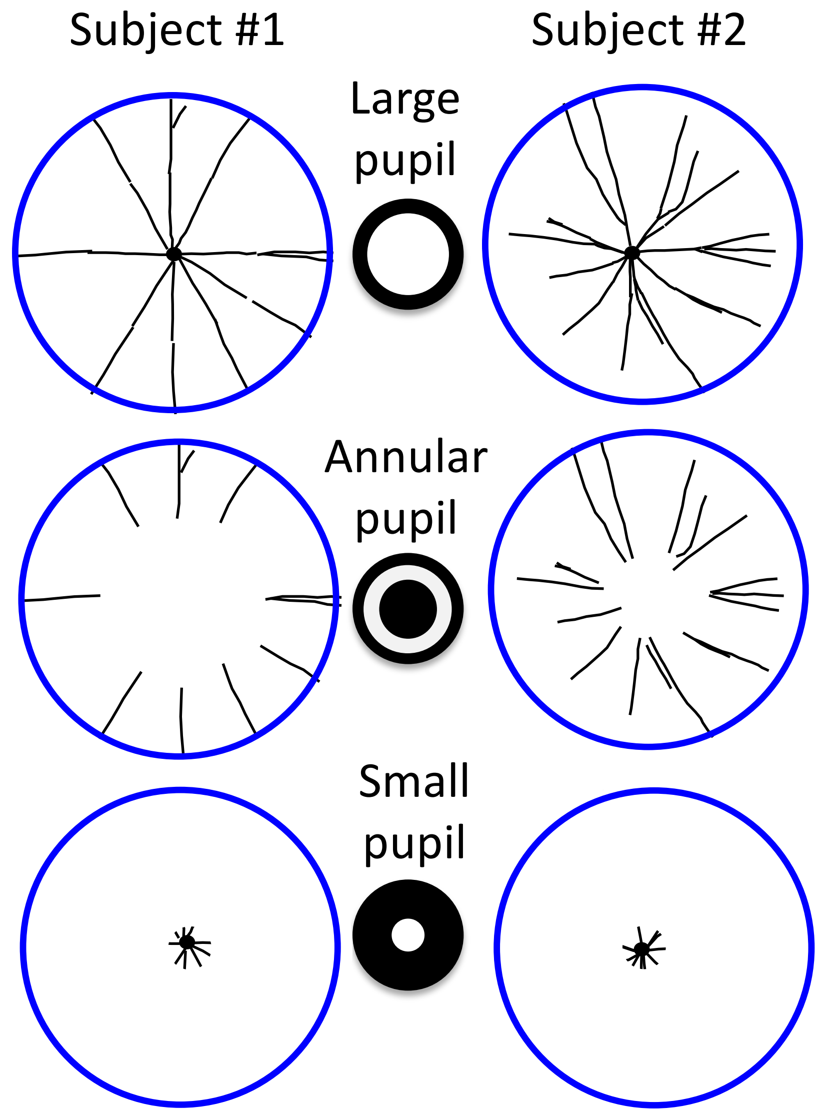
* Xu, Thibos, Lopez-Gil, Kollbaum, & Bradley (2019) J. Opt. Soc. Am. A **36**:B97-B102

Annular apertures dissect the entoptic percept *radially**

Dilated pupil reveals the full starburst with a central core and radiating lines.

Annular pupil reveals only the marginal portions of the radiating starburst lines.

Small central pupil reveals the central core and possibly very short radiating lines.



Conclusion: radial mapping of pupil plane to entoptic perception is consistent with geometrical optics (ray tracing).

* Xu, Thibos, Lopez-Gil, Kollbaum, & Bradley (2019) J. Opt. Soc. Am. A **36**:B97-B102

Additional observations about starbursts in the paraxially-focused eye*

1. Starbursts are typically absent for pupil diameter smaller than 3-4mm

   = > starbursts are due to marginal rays
2. Defocus & astigmatism alone do not produce starbursts in the focal plane

   = > starbursts are a manifestation of higher-order aberrations
3. Starburst size is proportional to the magnitude of spherical aberration

   = > starbursts are governed by the non-uniform distribution of refractive power over the eye's pupil
4. Entoptic starbursts are seen by pseudophakic patients

   = > the crystalline lens is <u>*not*</u> required to elicit starburst perceptions
5. Starbursts are also seen by post-LASIK patients

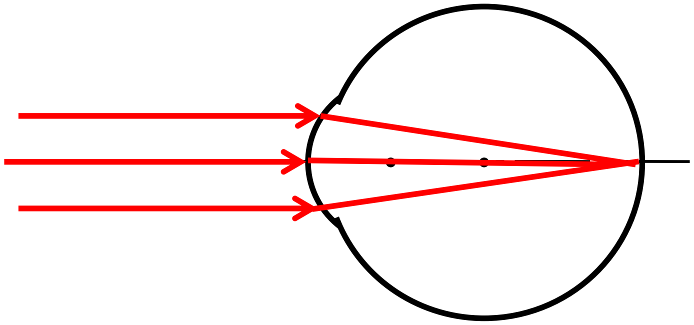
   = > corneal refractive surgery might exacerbate starburst perceptions
6. Starburst lines are exceptionally thin and dim compared to the central core

   = > starbursts are ***caustics*** produced when light is concentrated into small areas

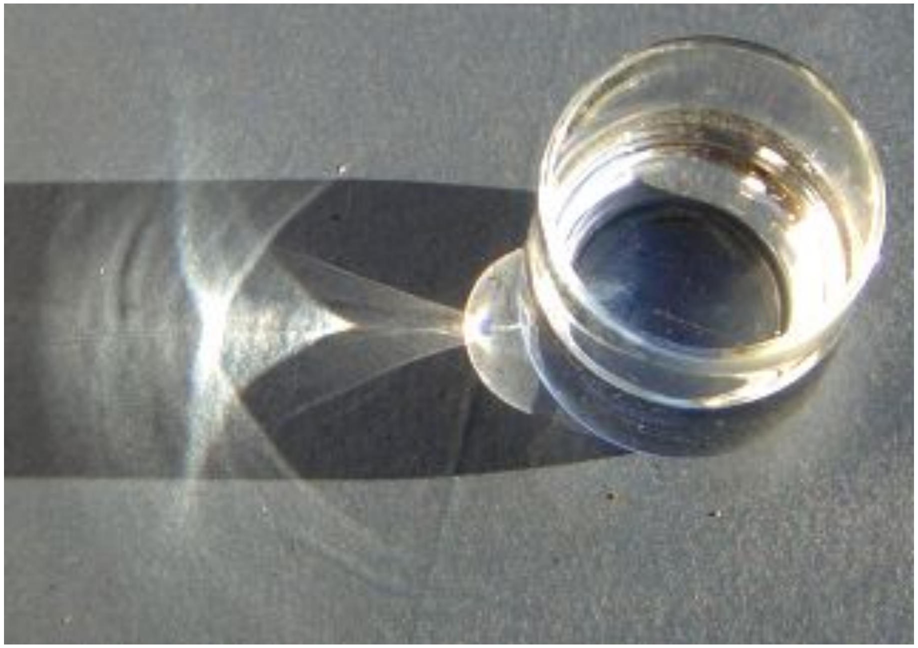
* Xu, Kollbaum, Thibos, Lopez-Gil & Bradley (2018). *Ophthalmic Physiol Opt* **38**(1): 26-36.
* Xu, Thibos, Lopez-Gil, Kollbaum, & Bradley (2019) *J. Opt. Soc. Am. A* **36**:B97-B102

Calculating Starbursts

An optically perfect eye produces a point-caustic in the focal plane.



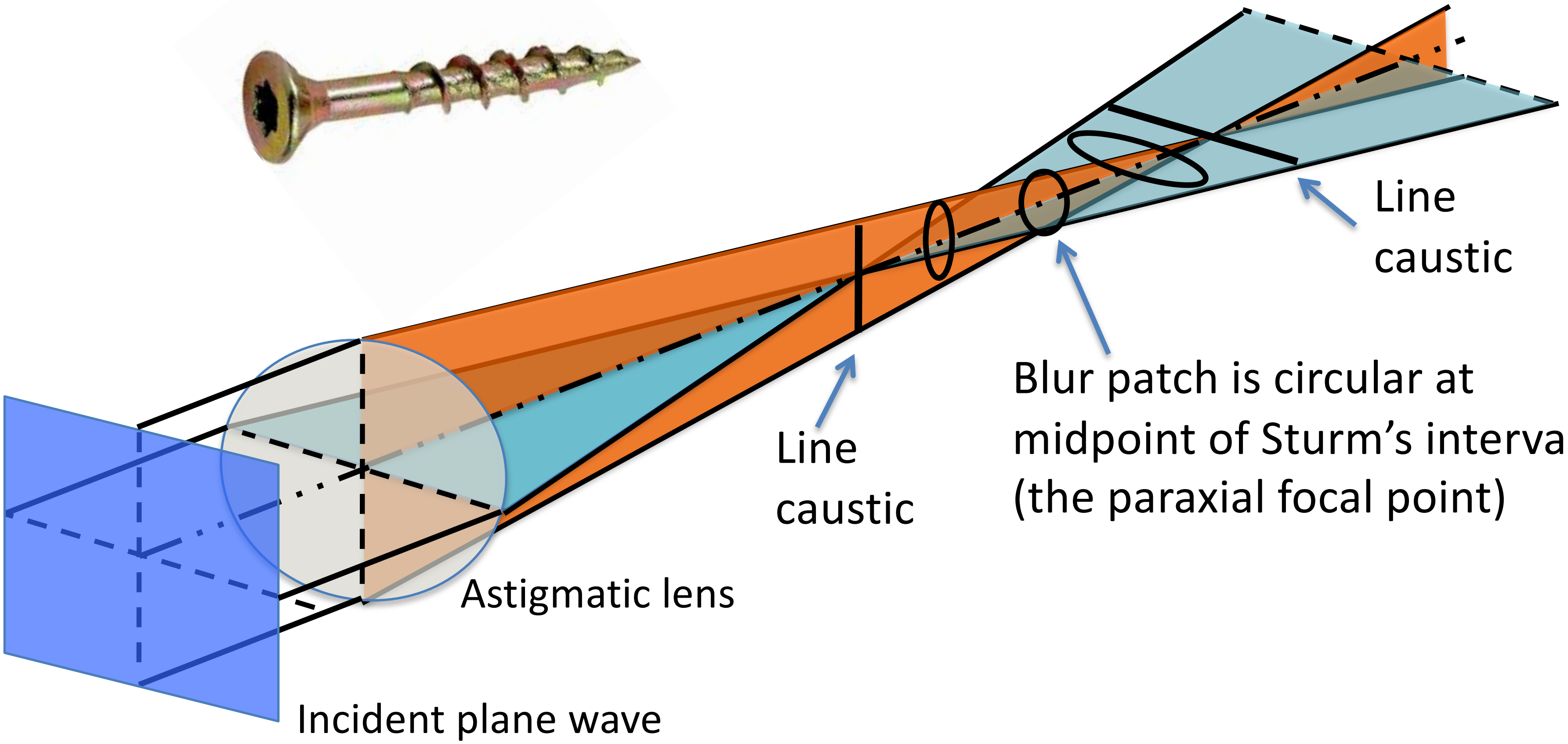
Water glass caustics are complicated by higher-order aberrations.



Caustics are locally bright areas where light flux density is very high. If starbursts are caustics on the retina, can they be calculated from an eye's wavefront aberrations using geometrical optics?

Astigmatism produces line caustics before & after focal point

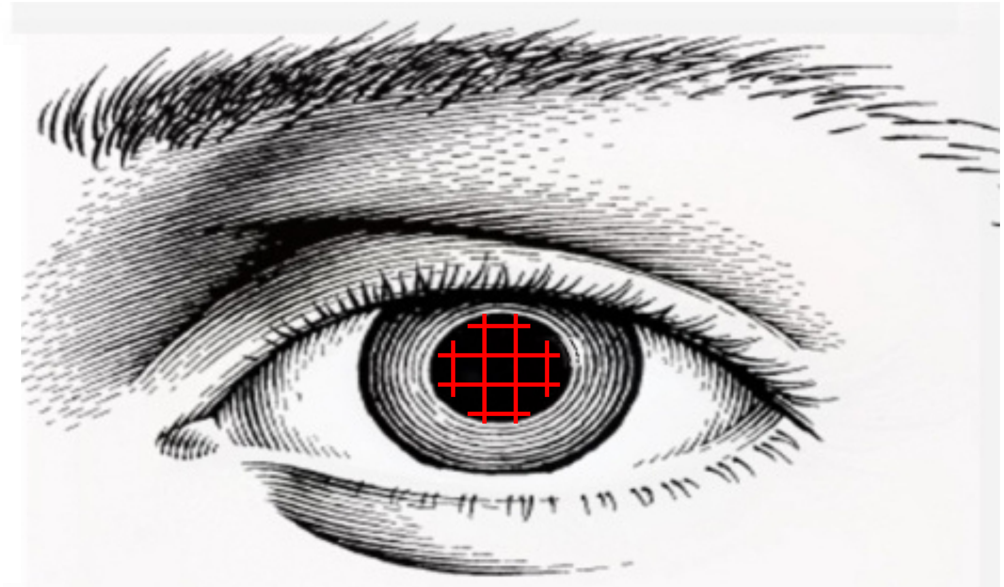
Textbook figures typically show refraction only in the principal meridians.
In other meridians, sheets of light twist (like a wood screw). Too hard to draw!!



Computer simulation of wavefront propagation: the perfect eye

Imagine a grid attached to a wavefront as light propagates from pupil to paraxial focal point.

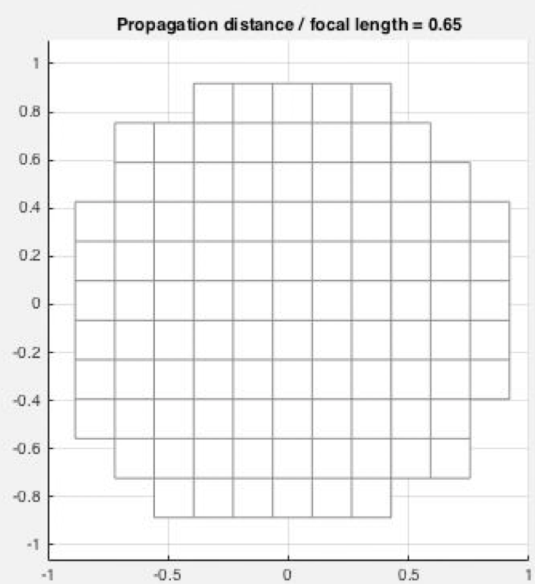
As light approaches the focal point, grid lines get closer together, flux density increases, & image brightens.



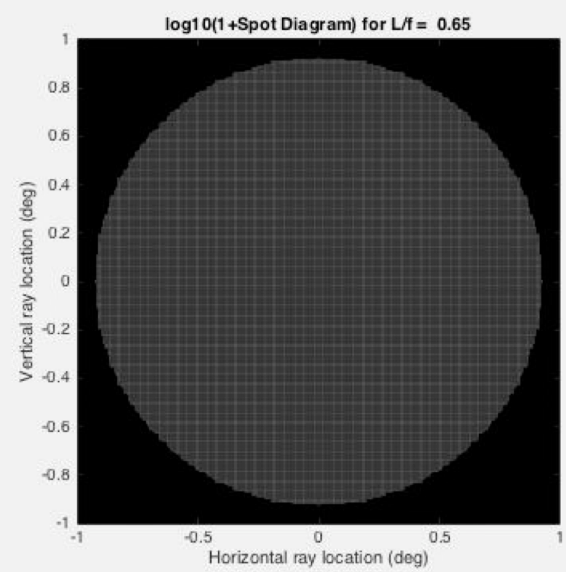
Higher-order aberrations distort the grid.

This is the principle of operation for Tscherning's aberroscope (1904)

Wavefront Grid



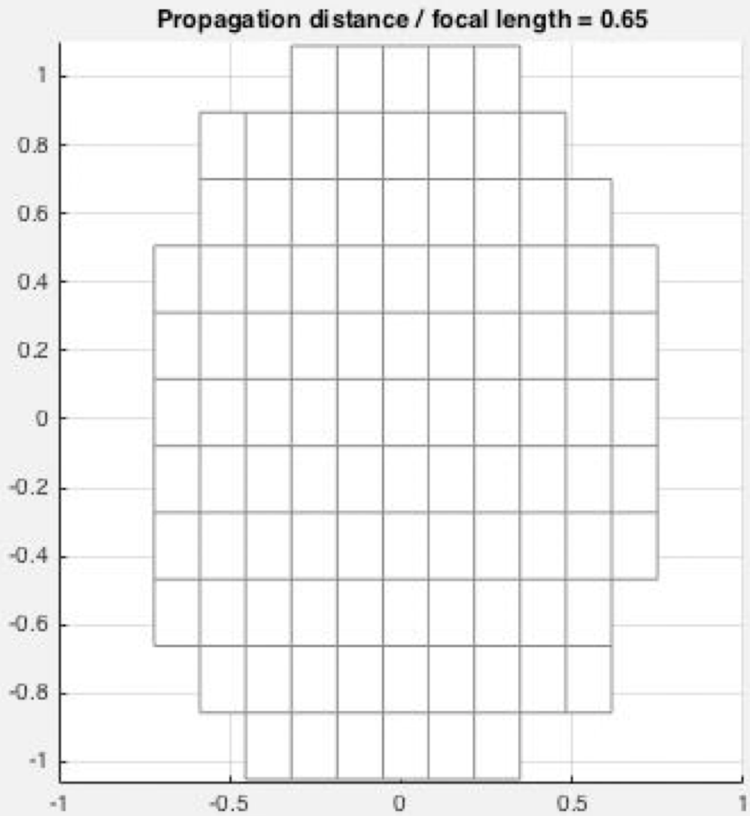
Irradiance Distribution



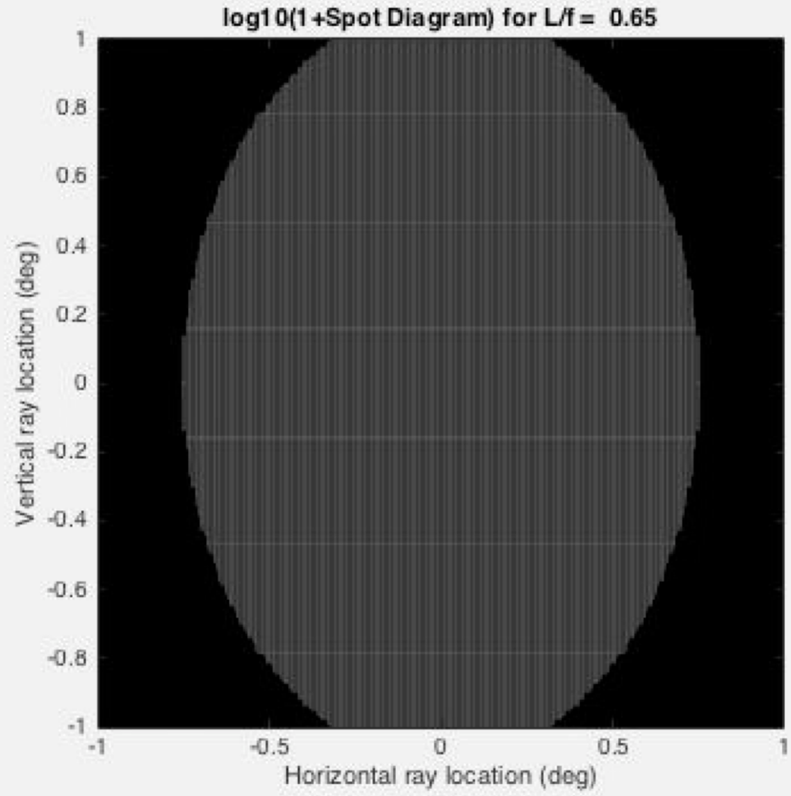
Perfect eye produces a uniform blur circle when defocused.

Computer simulation for an astigmatic eye: principle meridians 0°, 90°

Caustics occur when grid tiles collapse to zero area.



In the paraxial focal plane, the image is a uniform blur circle.

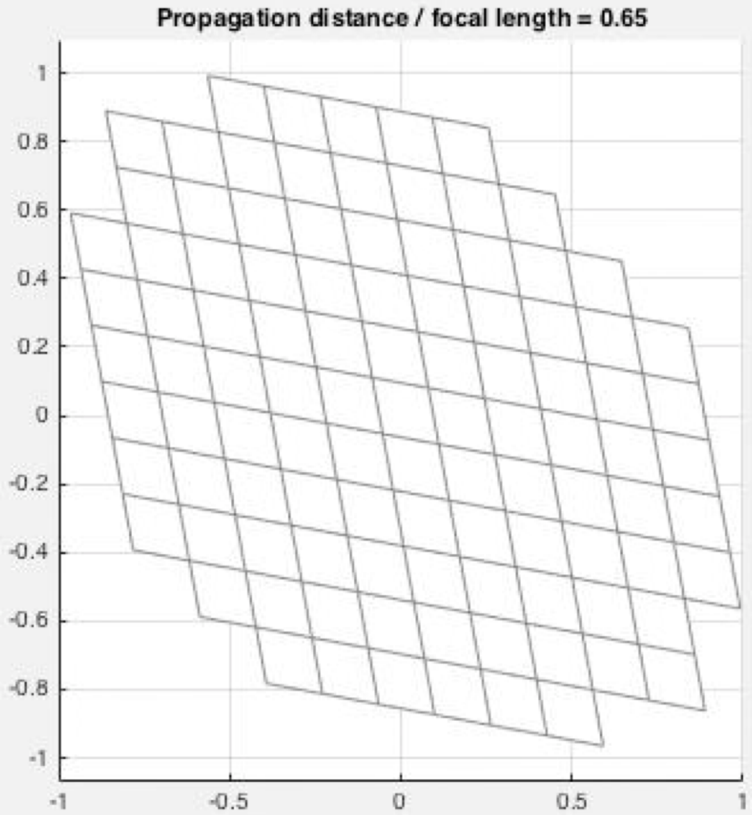


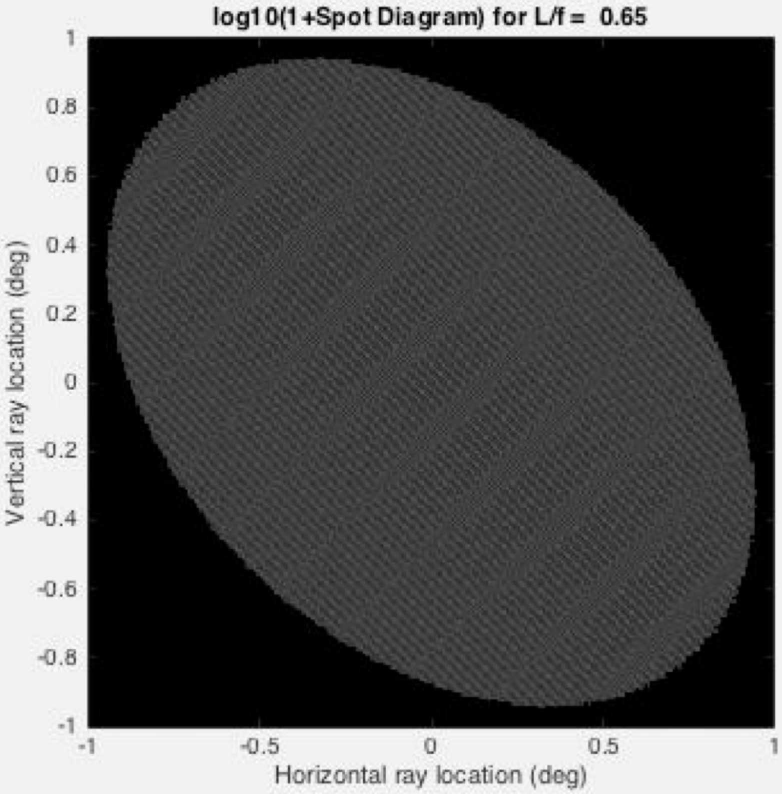
For an astigmatic eye with zero higher-order aberrations, ALL of the grid tiles collapse to zero area simultaneously. Result is a line-focus (a line caustic) before and after the paraxial (Gaussian) image plane.

Computer simulation for an astigmatic eye: principle meridians 45°, 135°

Twisting of the wavefront produces a 90° rotation of the grid.

In the paraxial focal plane, the image is a uniform blur circle.

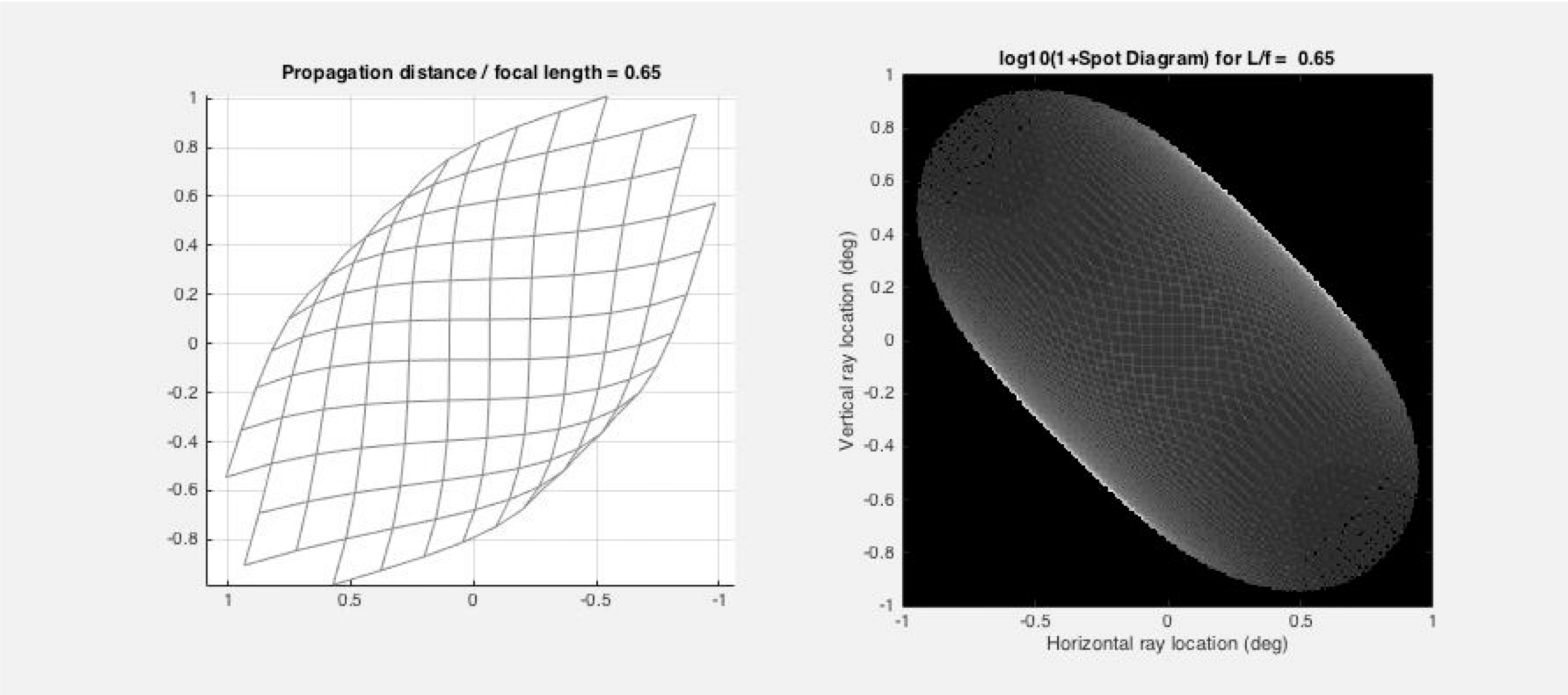




Grid distortion in the focal plane indicates higher-order aberrations.
This is the principle of the crossed-cylinder aberroscope.
[Howland & Howland (1976). Science **193**(13): 580-582.]

Computer simulation for eye with mixture of 4th-order aberrations

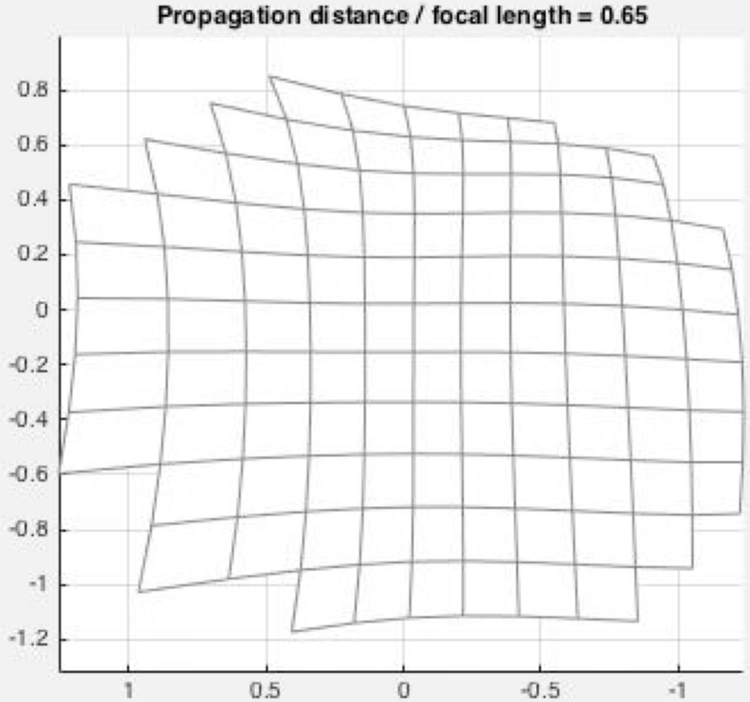
Spherical aberration + Oblique secondary astigmatism



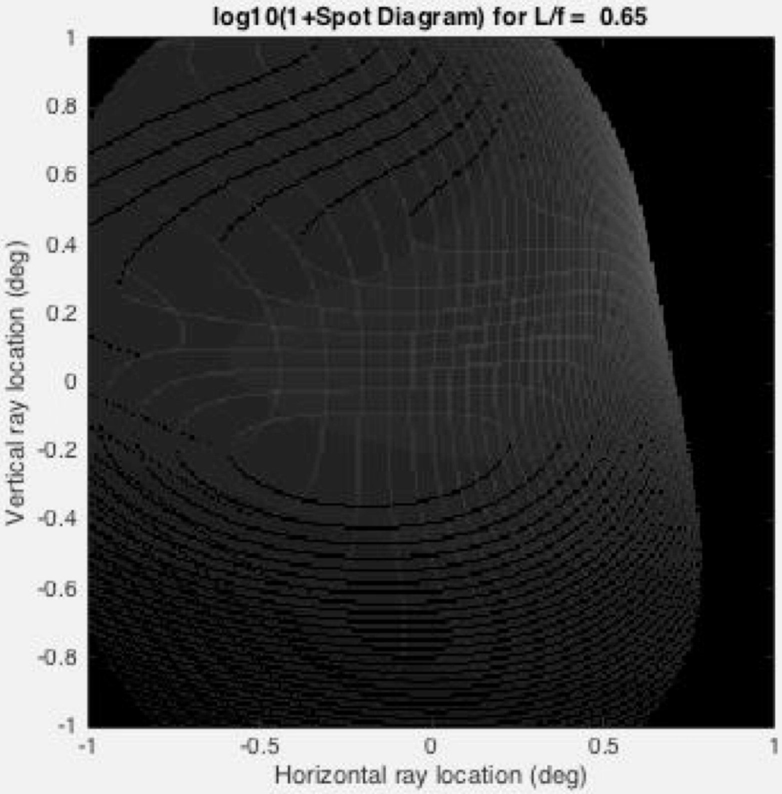
This is an example of a mathematical theorem proving that a mixture of aberrations of the same order always produces radial line caustics. [Rubinstein, J. (2019). *J. Opt. Soc. Amer. A* ***36****:B58-B64*

Computer simulation for aberrations of human observer with a full set of Zernike wavefront aberrations.

Wavefront Grid

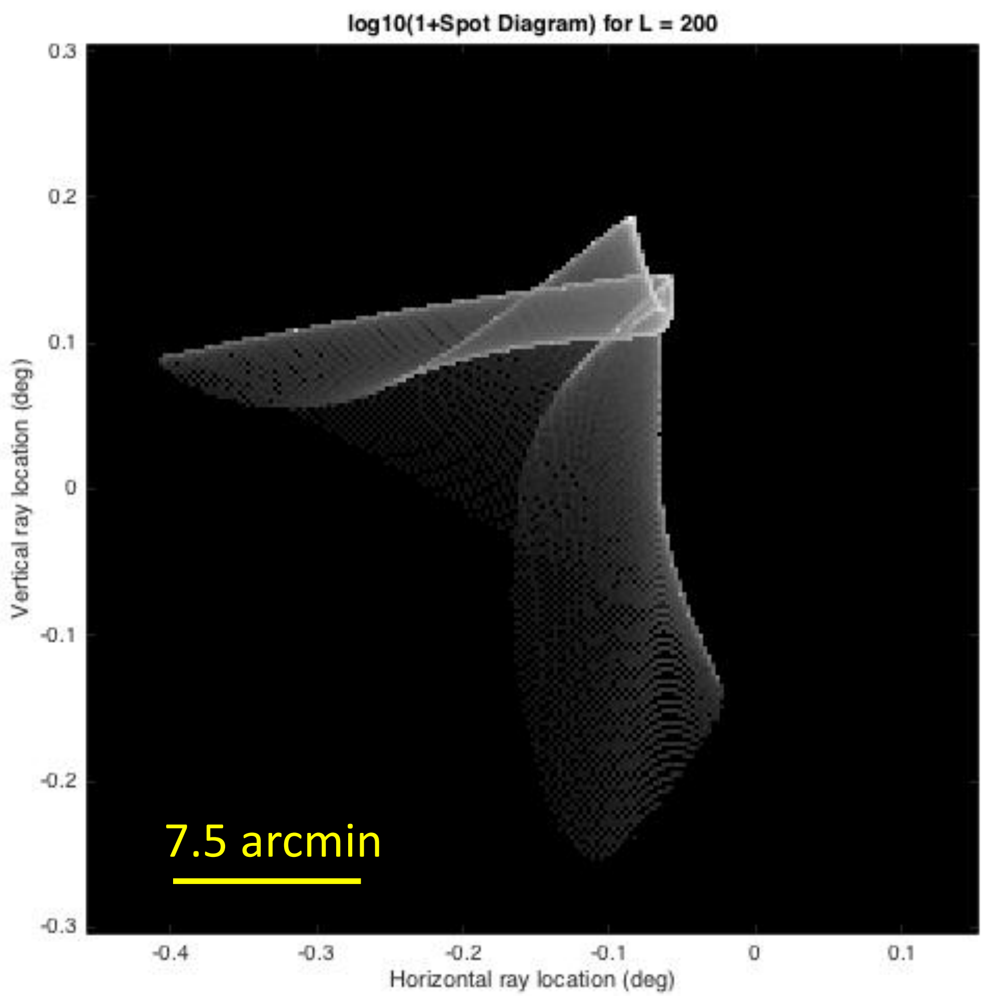


Irradiance Distribution

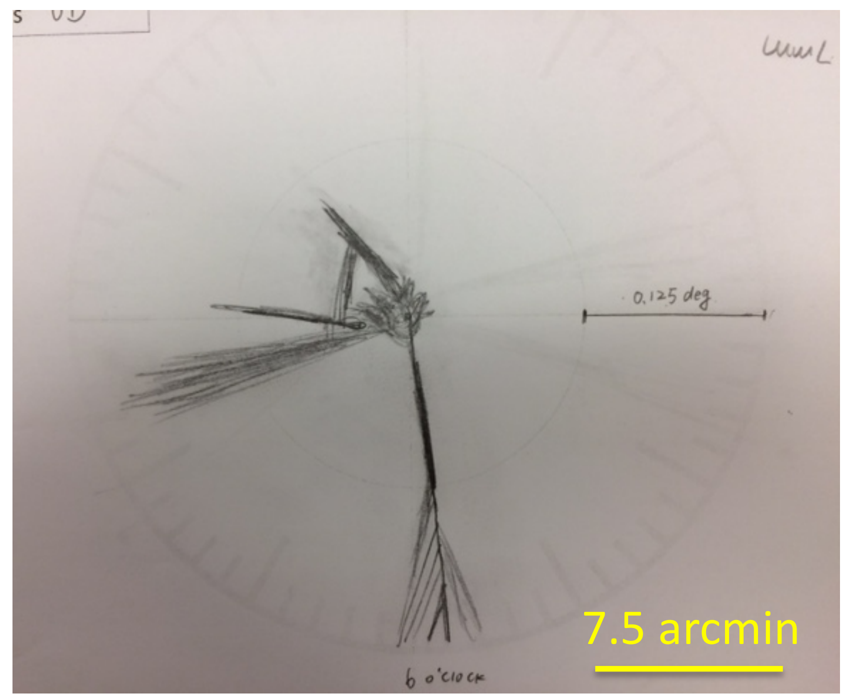


Entoptic drawing agrees with geometrical optics calculation displayed at same magnification for human subject (NLG).

Geometrical optics calculation of log(PSF)

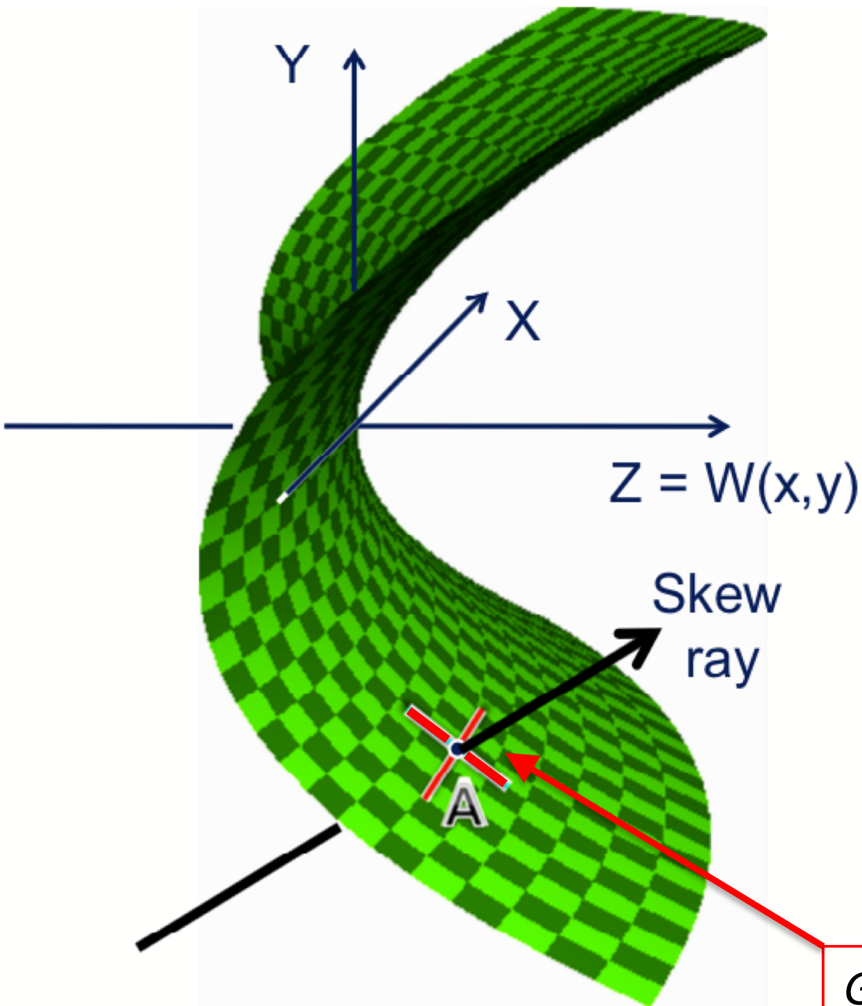


Subject's drawing of entoptic starbursts



No arbitrary scaling, flipping, flopping or rotating were used to draw this comparison.

Geometrical optics calculation of wavefront propagation, caustics, and point-spread functions is an extension of ordinary ray tracing*



Every traced ray is assigned an irradiance value that is inversely proportional to the *Gaussian curvature* of the wavefront error (WFE) function at the foot of the ray.

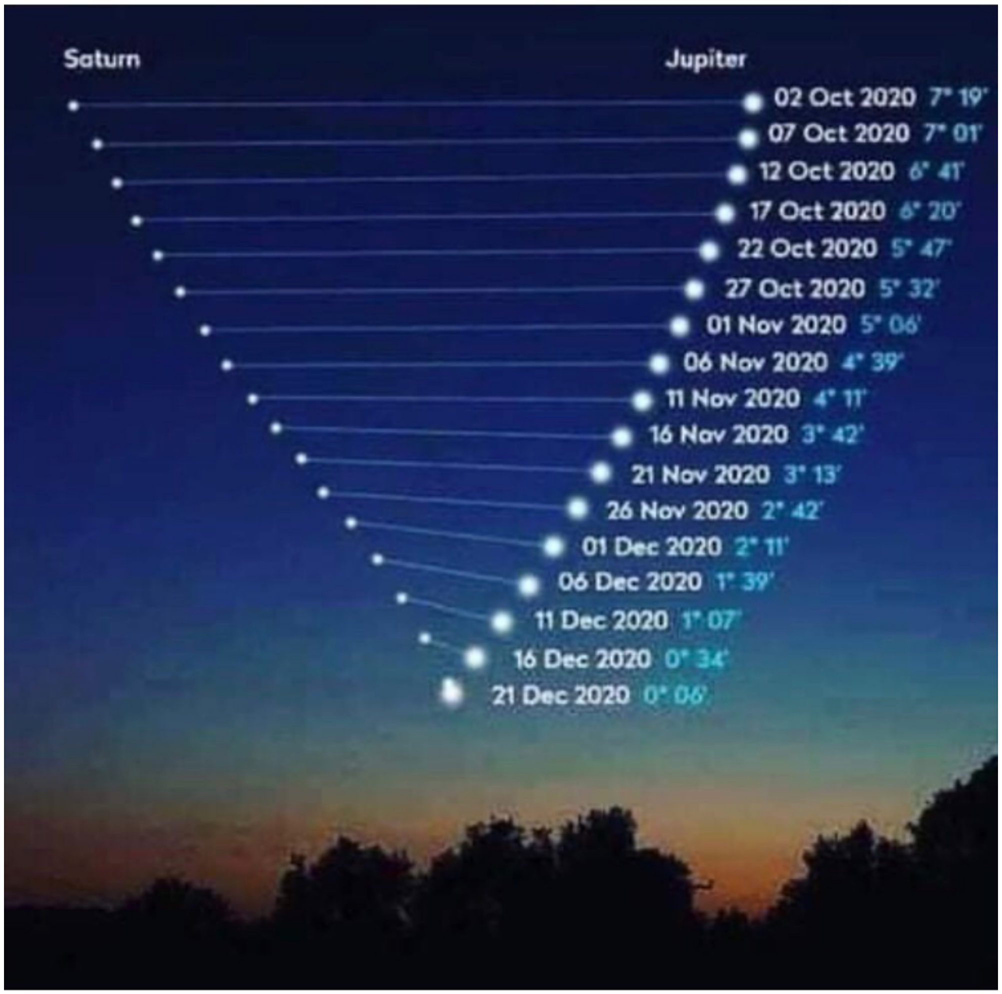
- High WFE curvature (positive or negative) indicates more blurring, so retinal irradiance is low.
- Low WFE curvature (positive or negative) indicates less blurring, so retinal irradiance is high.
- Caustics appear when one or both curvatures approaches zero (i.e. cylinder or plane locally)

Gaussian curvature of the WFE function at point A is the product of principal curvatures (i.e. max & min curvatures found locally in the principal meridians).

* Thibos, L. N. (2019). *Ophthalmic Physiol Opt, 39*(4), 232-244.

Importance of Starbursts

Astronomy: spatial resolution of stars & planets



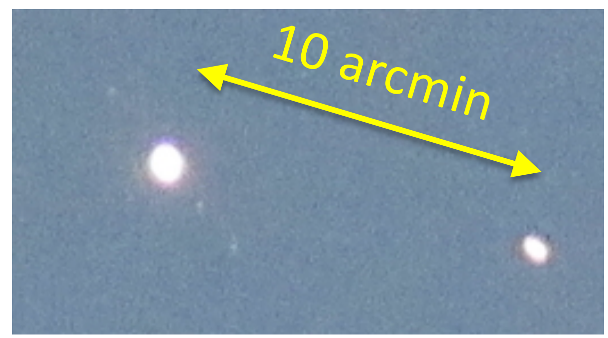
Conjunction of Saturn & Jupiter 21-Dec-2020

Amateur Astronomy Magazine 15 hrs ·

A visual experiment with natural stimuli: will starbursts prevent visual resolution of Jupiter & Saturn during conjunction?

Jupiter and 3 moons

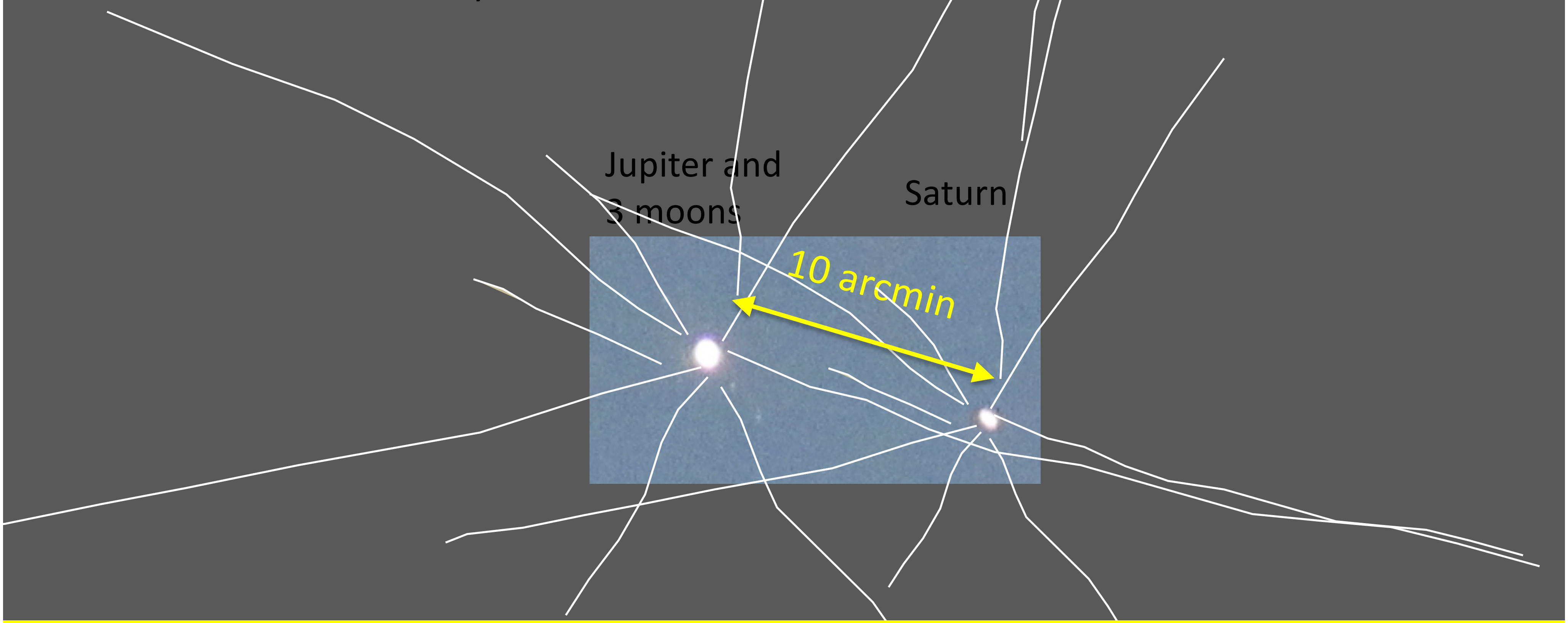
Saturn



Telescopic photo of conjunction.
Bloomington, Indiana, USA
(22-Dec-2021)

RESULTS: All four observers in Indiana and several more in Spain reported that Jupiter and Saturn were easily resolved when they first became visible against the twilight sky, but the task became more difficult as the sky darkened.

Starbursts centered on the two planets.

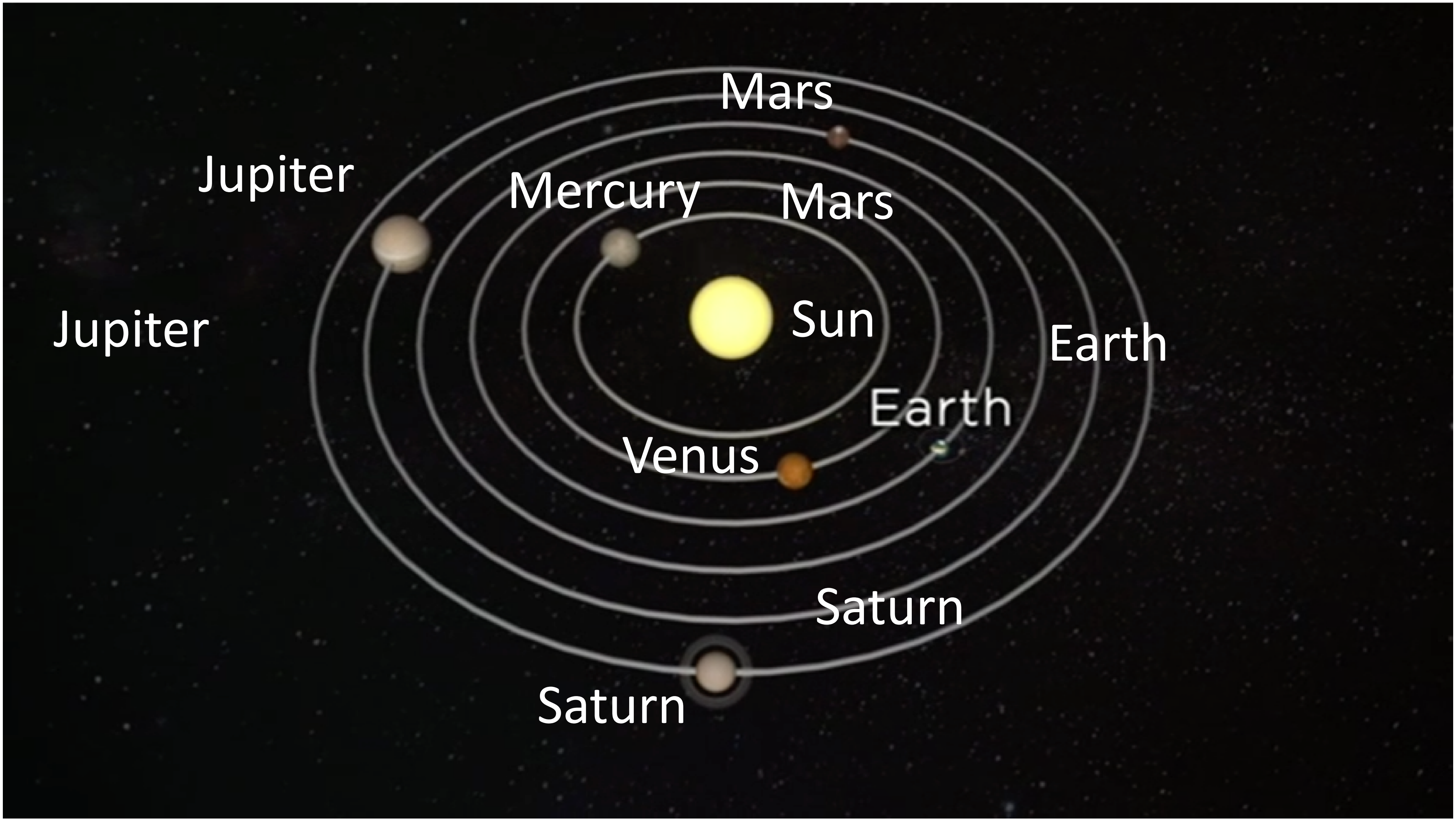


This experience makes sense: starbursts are less visible against the twilight sky (when the photo was taken) for two reasons: less contrast with the sky and smaller pupils.

Starbursts are a greater hindrance as the sky darkens because (1) increasing contrast increases visibility of the radiating lines and (2) pupils dilate, which lengthens the lines.

Starburst glory: Renaissance cosmology

In the Copernican model of the solar system, distances between planets vary greatly with time.



Galileo's rebuttal: blame starbursts!

Galileo argued that **starbursts cause our visual assessment of the size of planets to be unreliable.**

In the past, we have judged the size of stars and planets by simply looking at them, but **our eyes deceive us!** Our eyes show these bodies "festooned with adventitious and alien rays which make these bodies appear much larger than if the little radiant crown, which is not theirs, were removed."

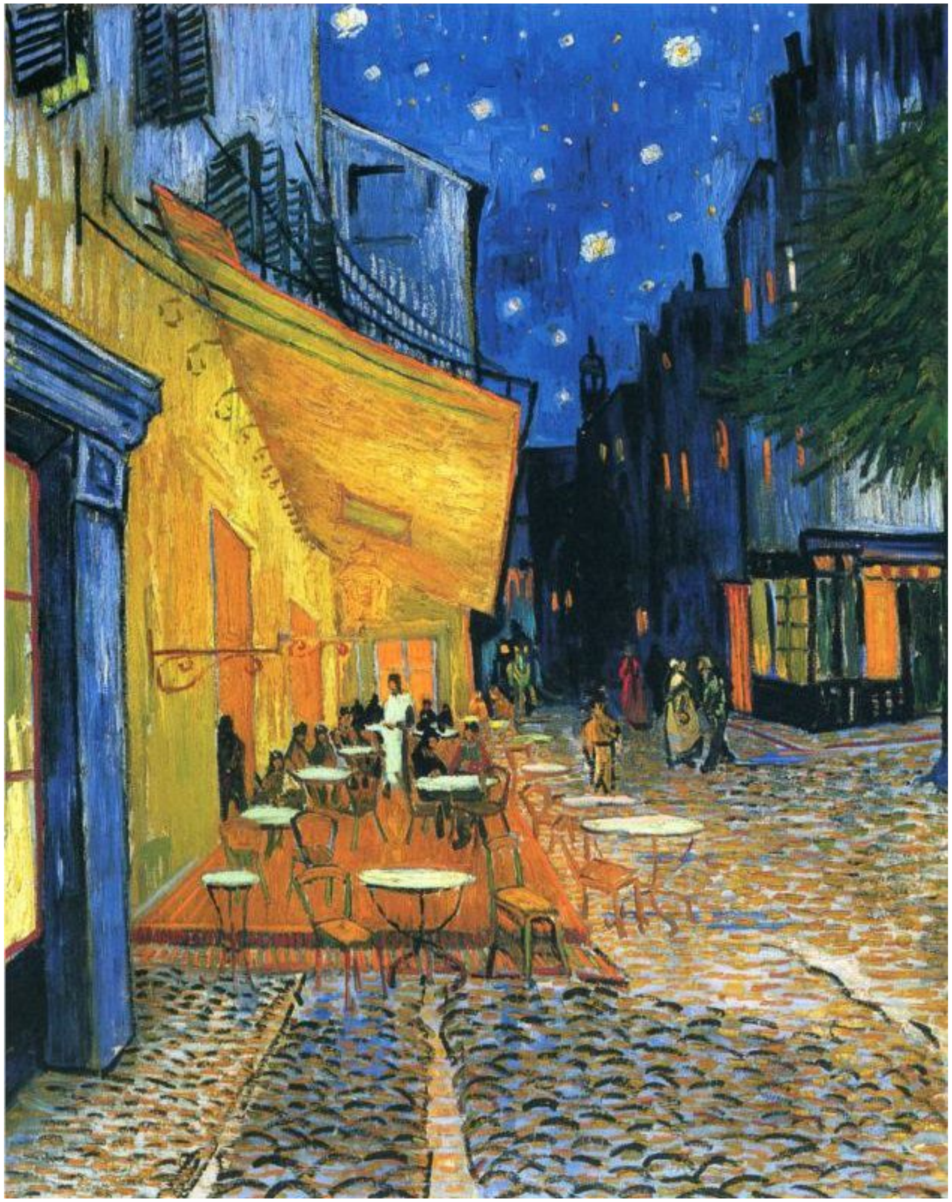
This artifactual "crown" is best removed by viewing through the newly invented telescope, which removes the adventitious rays for two reasons:

1. A telescope reduces the eye's effective pupil size, like looking through a narrow tube or a small hole, which shortens starbursts.
2. A telescope magnifies our view of the planets so their true size can be better appreciated.

When Galileo viewed Mars and Venus through his telescope, he observed a large variation in size that agreed with predictions based on changes in their distance from Earth as described by the Copernican model.

Eureka! Starbursts saved the Universe!

Conclusions:



Café Terrace at Night (1888) Vincent Van Gogh

Psychophysical observations show that each sub-region of the pupil contributes to unique features of the entoptic perception of starbursts generated by isolated points of light viewed against a black background.

Results of laboratory experiments are consistent with Helmholtz's explanation that ocular aberrations of the cornea and the crystalline lens cause starbursts.

Computed retinal images of point sources using geometrical optics reveals morphological similarities between light caustics in the retinal image and perceived entoptic starbursts, indicating a minor role for diffraction.

The end

Vision Research at

Indiana University School of Optometry

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Included below is the text of the questions asked to Larry Thibos and Michael Bach by attendees during the seminar. The majority of questions were answered verbally and can be viewed in the recording. Where a text answer was provided, it has been included below.

Hi Prof. Thibos, thank you for your interesting presentation. I'm wondering, based on the aberrations measured on a person's eye, is it able to exactly produce the shape of the 'star' perceived by that eye? Has this been achieved and experimentally verfied for both central and paracentral visual fields?
Prof. Thibos, great talk. How does the spectral properties of the stimuli affect starburst? Is there evidence to support the notion that violet and/or blue-blocking lenses disproportionately reduce strabust?
Do subjects report abruptly less starburst effects after having lens replacement surgery?
Prof Bach, thank you for your talk. Given the Bayes theory of perception you described, could this explain why very young children don't understand what's making a shadow? Response from Michael Bach: Wow, that's an interesting question. I did not know about this interesting observation. From that it follows that I cannot answer your question. I am not aware of any research on this fascinating topic. Anyone?
Hi Prof. Thibos, what's the relationship between PSF and the 'starburst' formed by caustics effects? If we want to obtain the distribution of light received on a certain position of the retina formed by a point object, is it the starburst obtained from geometrical optics or PSF obtained from the idea of diffraction?
To Michael Bach: why the visual system would 're-consruct the world' and not simply 'construct' the world?
Larry, It was not clear to me why the starbursts tend to be radial. Why not some in arcs? Is there a physical or mathematical explanation for that? Is it because spherical aberration dominates?
Larry, Michael: Most people do not realize the presence of their starburst until conciously trying to see them for the first time. After they have seen them once, they become plainly apparent. An example ofg Michaels 'cigar effect'?
Hi Prof. Bach, Can you please comment about theories of perception of transparency, reflections and the link to bayesian priors?
Larry Thibos: is there a relationship between starbursts and twinkling? Response from Salva Bará: Twinkling is the result of moving caustics at ground-level, due to wind-driven turbulent atmospheric refraction... not entoptic, but basically the same phenomenon.
Hi Michael, I manage to capture some film of my 3 year old son jumping around with surprise and delight when we pointed out his own shadow.
For Professor Michael Bach: A great deal of vision research today concerns computational neural networks. What relevance in your perceptual theories do these networks have?