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Incoherent astronomy

Frantz Martinache

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Observational electromagnetic astronomy

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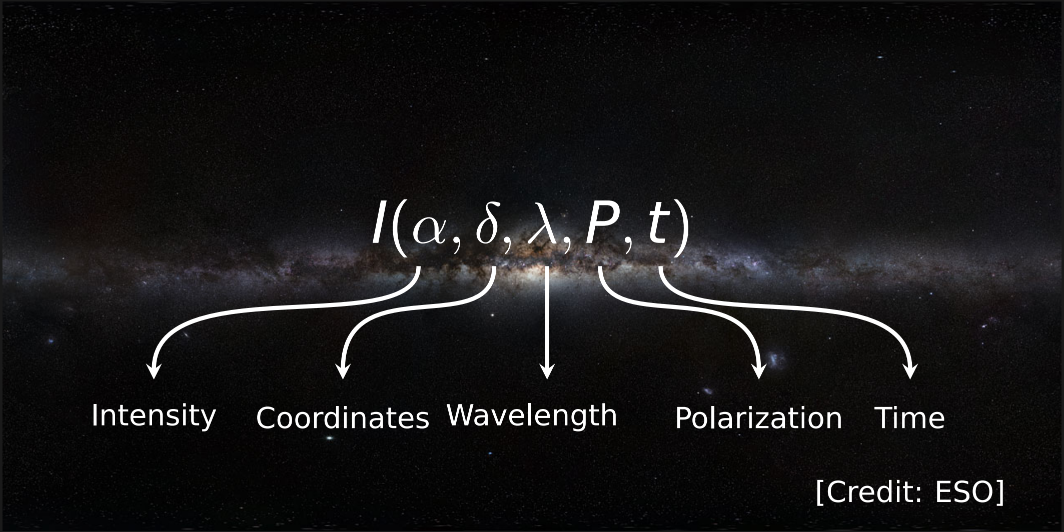
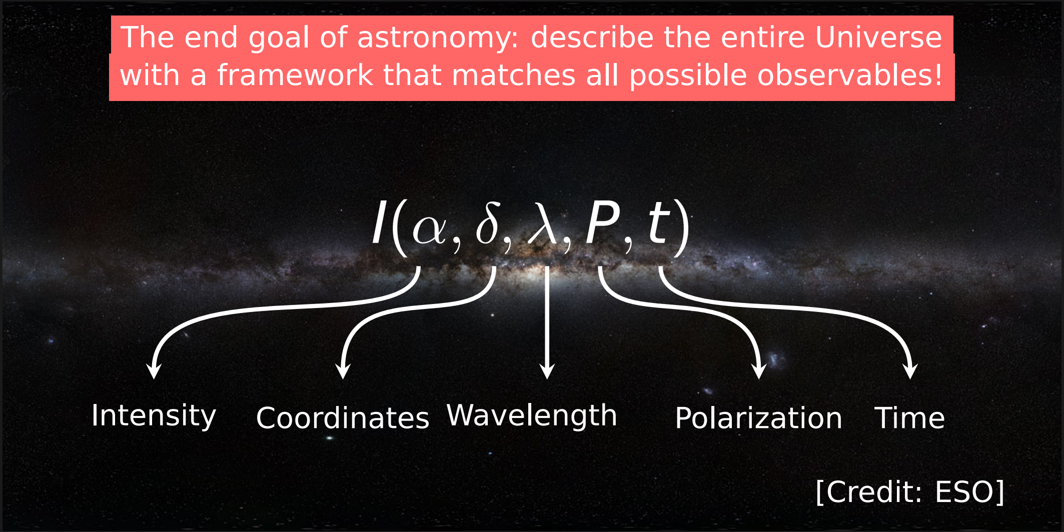
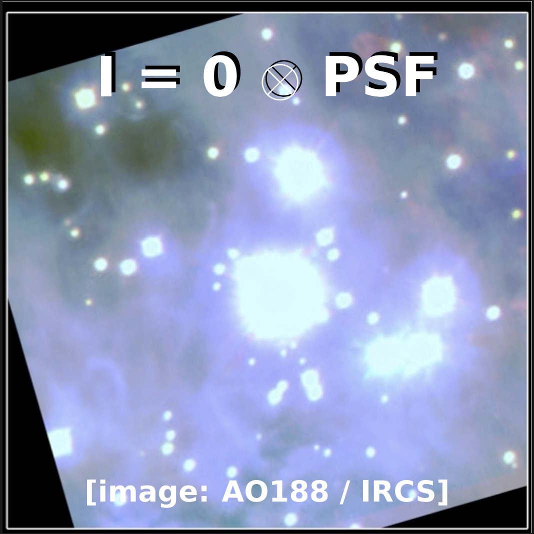


Observational electromagnetic astronomy



interpreting images is the game



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diffraction-dominated data

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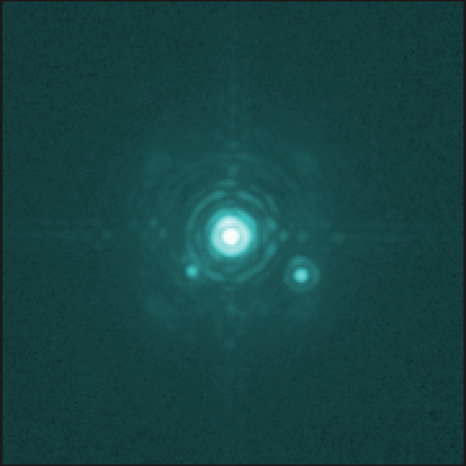
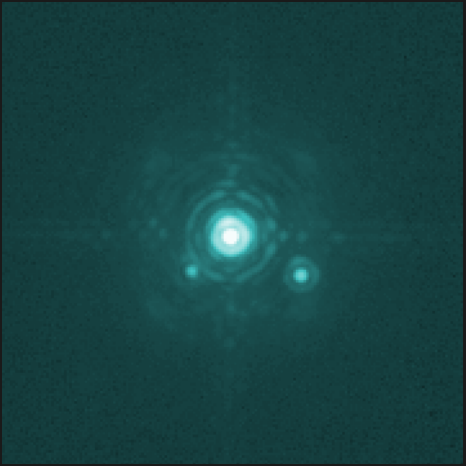
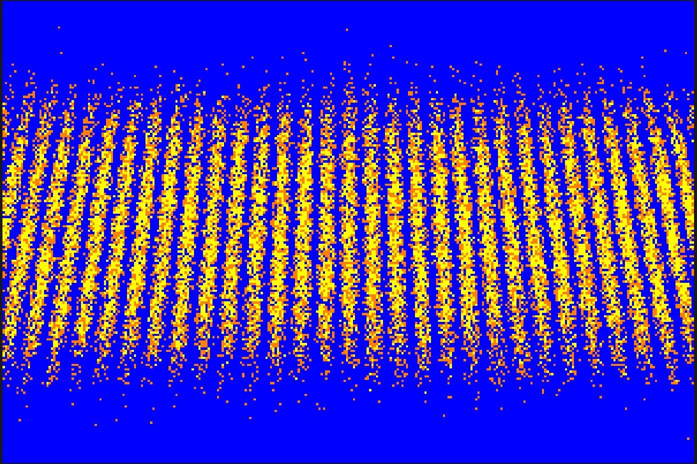


diffraction-dominated data





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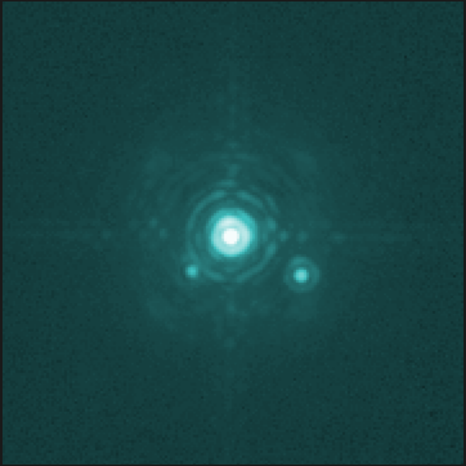
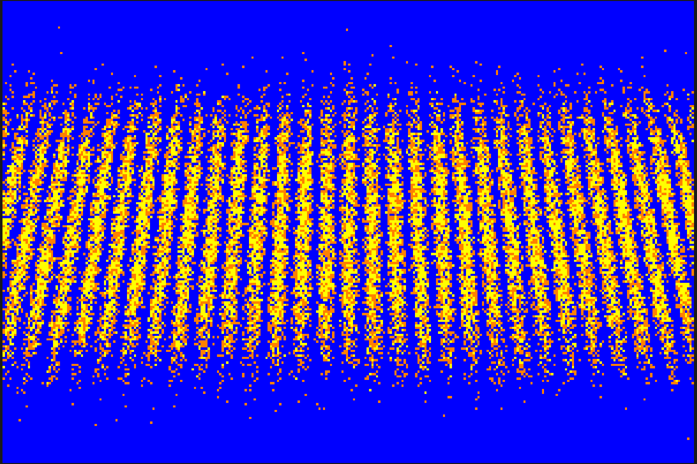
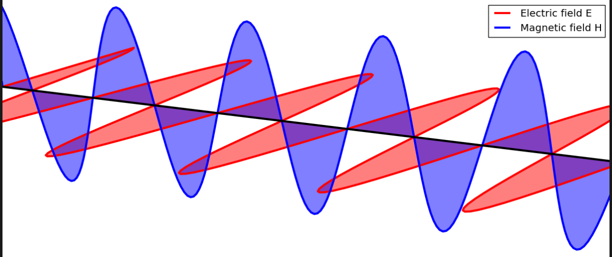




In both cases

The question is the same: am I looking at a point source, or something else?

electromagnetic waves

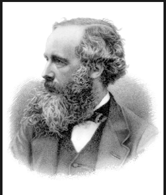


What we perceive as light is the result of an electromagnetic wave.
We need to keep track of the electric field **E**, that respects:

the wave (Helmoltz's) equation

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\ddot{\mathbf{E}} = 0,$$

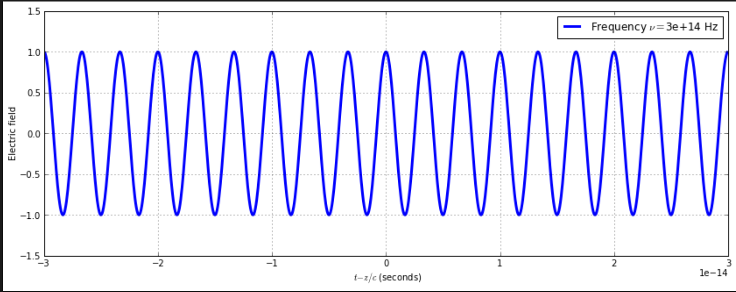
where c is the speed of light



the ideal wave solution

Natural solutions are oscillating functions with this form:

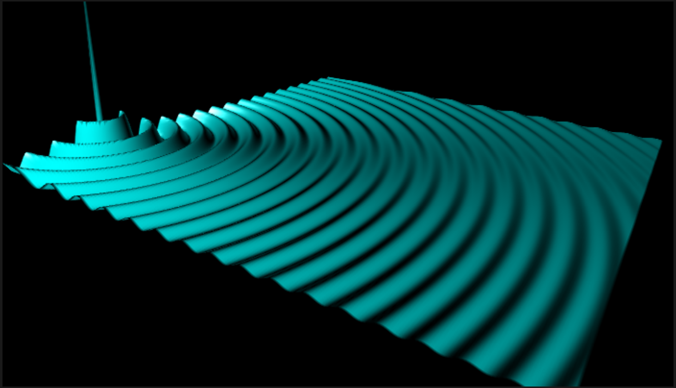
$$\mathrm{E}_\nu(t, x) = \mathrm{E}_0 e^{i(kx-\omega t)} = \mathrm{E}_0 e^{i2\pi(x/\lambda - \nu t)}.$$



the wavelength

$$\lambda = c/\nu$$

like ripples on water?



$$E_\nu(t, r) = (1/r)\, E_0 e^{i(kr-\omega t)}$$

The geometry of the situation matters...
but the oscillating characteristic is still there!

the "optical" regime

The complex exponential form of the oscillating solution conveniently allows to separate the time and space dependencies of the electric field. The spatial component gets a new name, the **complex amplitude** noted $\mathrm{A}(x)$ so that:

$$\mathrm{E}_{\nu}(t, x) = \mathrm{A}(x)\, e^{-i2\pi\nu t}$$

The “optical” is a regime of wavelength that covers:

- the visible ($\lambda \sim 0.4$ μm - 0.8 μm)
- the IR (up to $\lambda \sim 50$ μm)

Beyond the IR, it is customary to use the frequency, rather than the wavelength.

seeing these oscillations in the optical?

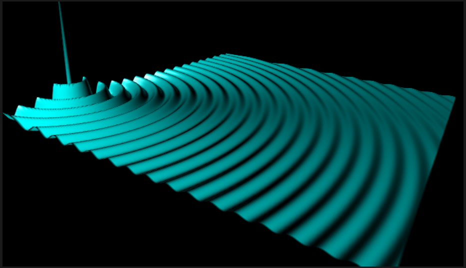
high frequency!

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{10^{-6}} = 3 \times 10^{14}\ \mathrm{Hz}$$

- Fast switching semi-conductors read/write access time t$\sim$ 1 ns.
- One switch: >10^5 complete oscillations of the E-field: too fast!
- Instead, one measures the time averaged energy, aka, the intensity:

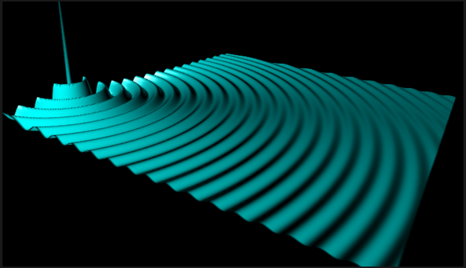
$$\begin{aligned} I \propto \langle|\mathrm{E}|^2\rangle &= \int_{t_0}^{t_0+\tau} \mathrm{E}(t)^2\, \mathrm{d}t \\ &= |\mathrm{A}|^2\ \ (\text{with } \tau >> 1/\nu). \end{aligned}$$

not like ripples on water



What is really happening (at high speed): Instant snapshot of the electric field

not like ripples on water



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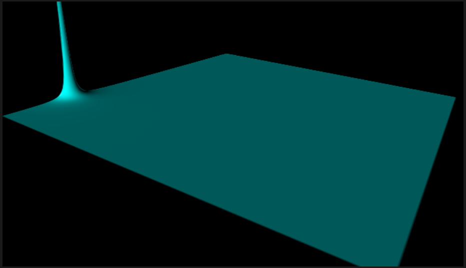

What we see in practice: Static, stable, time-averaged intensity

if we don’t see it, does it matter?

The oscillating nature becomes manifest, if more than one source is involved!

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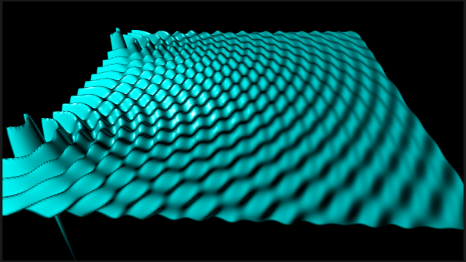

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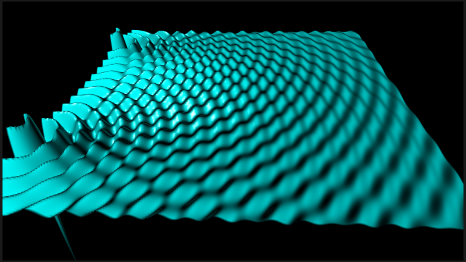

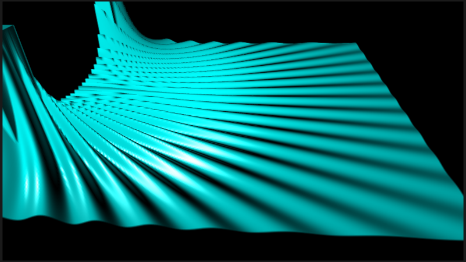

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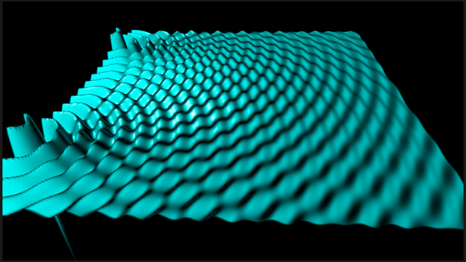
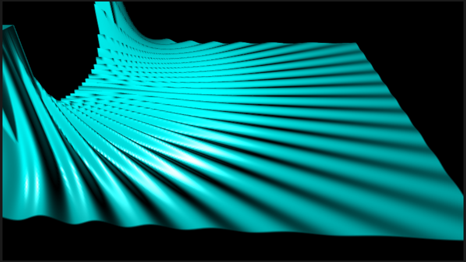


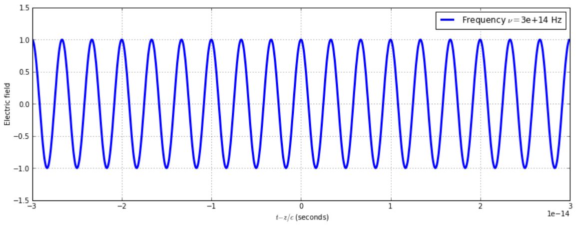


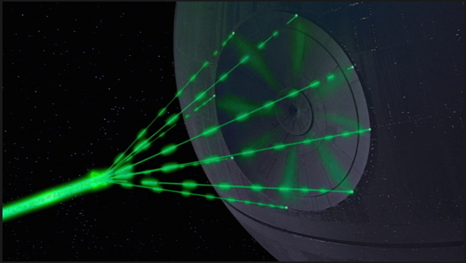
Really? If that were true, then...

where are my interferences?

If the physics I have described were true, then we should see interference fringes everywhere, yet clearly we don't. Is the physics wrong?

stars are not lasers!





[Credit: Starwars.com]

- Our model is only fairly suited to the description of a **laser beam**
- A laser is, by design, a **coherent** light source
- What is coherence?

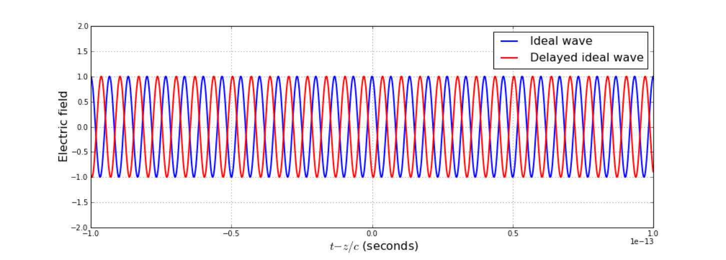
degree of coherence

Used to quantify how well correlated (how "look alike") two waves are, using a normalized cross-correlation function.

coherence #1: self-coherence

How well correlated is one wave... **with itself delayed in time**.

$$c(\tau) = \frac{< E^*(t) \times E(t+\tau) >}{< |E(t)|^2 >}$$

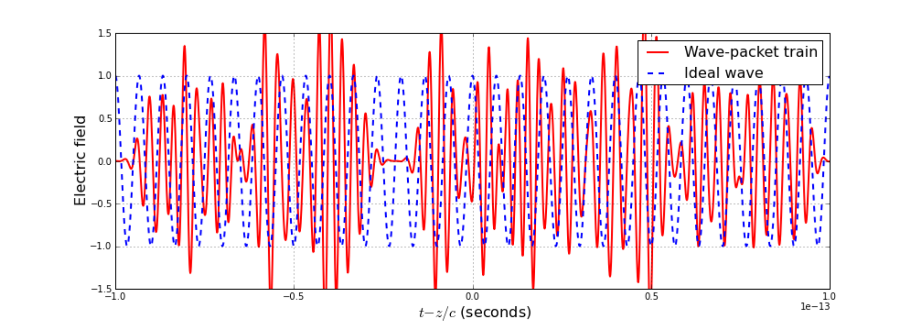


No matter the delay, the two are perfectly correlated:

$$|c(\tau)| = 1$$

ordinary light sources?

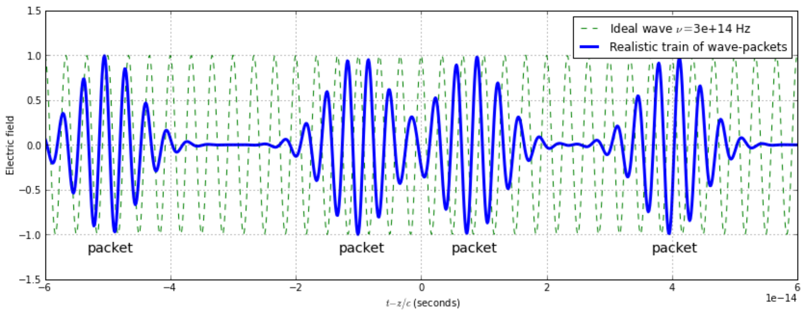
The light emitted by thermal sources like light bulbs... or stars originates from uncorrelated events (atomic transitions).



- resulting E-field: **fluctuations of amplitude and phase**
- this new field and the ideal wave are **not in sync**

a more appropriate model?

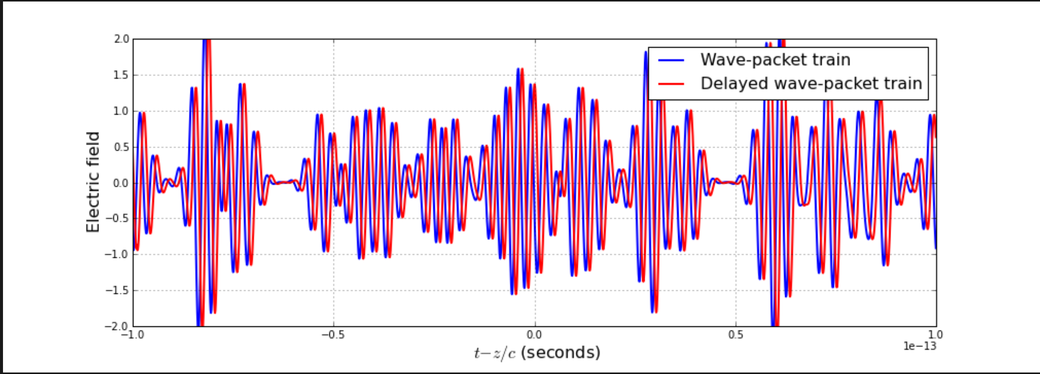
A series of damped oscillations (modulated by an envelope function) characterized by a random emission time t_k and random phase at origin Φ_k.



The E-field of each packet is of the form:

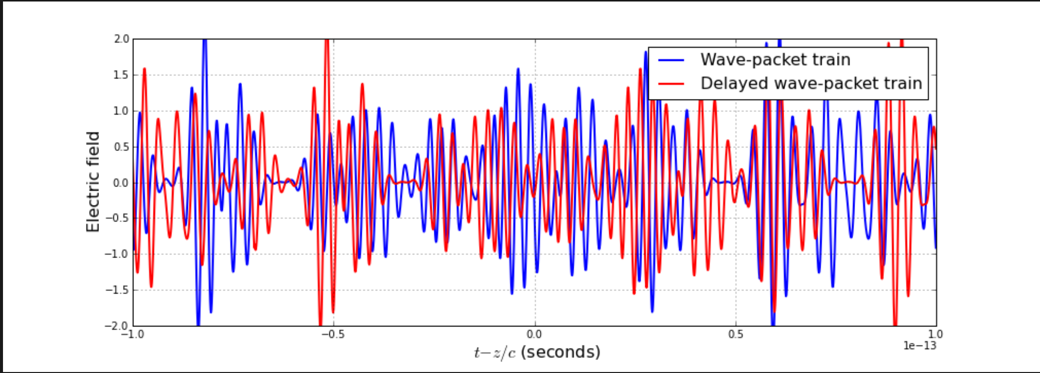
$$\mathrm{E_k}(r,t) = \mathrm{env}(t - t_k) \times e^{i2\pi(r/\lambda - \nu(t - t_k) + \Phi_k)}$$

self-coherence of an ordinary light source?



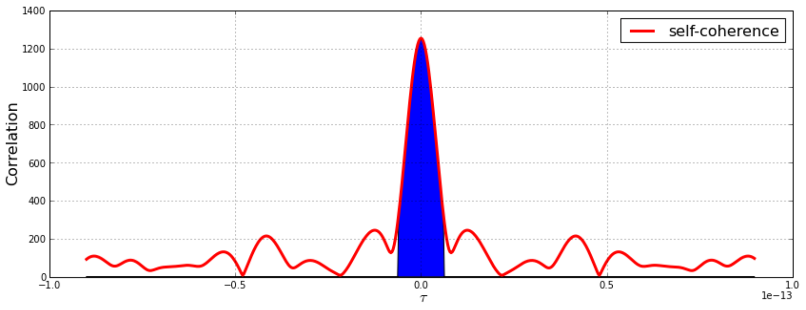
Small delay: the signal and its copy do look alike.

self-coherence of an ordinary light source?



With enough delay, the signals do not correlate anymore.

natural light sources are self-coherent



Only over a small range of time delay do we get a reasonably strong correlation between the two signals.

coherence time

There is a limit beyond which the signal and its copy do no longer look alike. This **time delay** τ_0 is called the **coherence time**.

coherence time - coherence length

- If wave packets are purely random: $\tau \leq 1/\nu$
- Specific theories exist for black bodies, showing $\tau \propto 1/T_{eff}$
- Within a spectral line, one expects longer coherence time
- The coherence time depends on the properties of the source
- The important thing to keep in mind: **it is not infinite**

the coherence length

The E-field propagating at the speed of light: to a coherence time τ, corresponds a coherence length Λ, such that:

$$\Lambda = c \times \tau$$

In most observing conditions, the coherence length is constrained by the filter used to select a given bandpass.

mutual coherence

- This time: mutual coherence between two distinct electric fields E_1 and E_2.

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- A normalized cross-correlation function of the two fields.

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The degree of mutual coherence

$$\gamma_{12}(\tau) = \frac{\langle E_1(t+\tau)E_2(t)^*\rangle}{\sqrt{I_1 I_2}} = \frac{\langle E_1(t+\tau)E_2(t)^*\rangle}{\sqrt{\langle|E_1(t)|^2\rangle\langle|E_2(t)|^2\rangle}} = \frac{1}{\sqrt{I_1 I_2}}\int_{\Delta t} E_1(t+\tau)E_2^*(t)\,\mathrm{d}t$$

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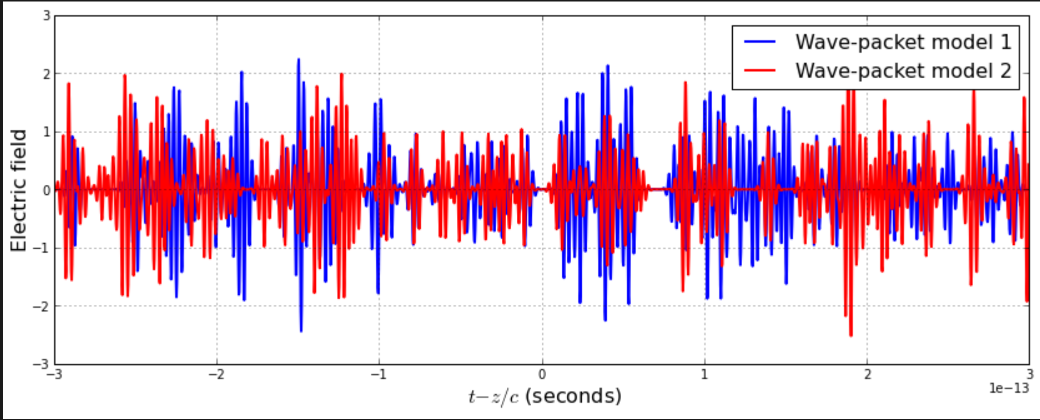
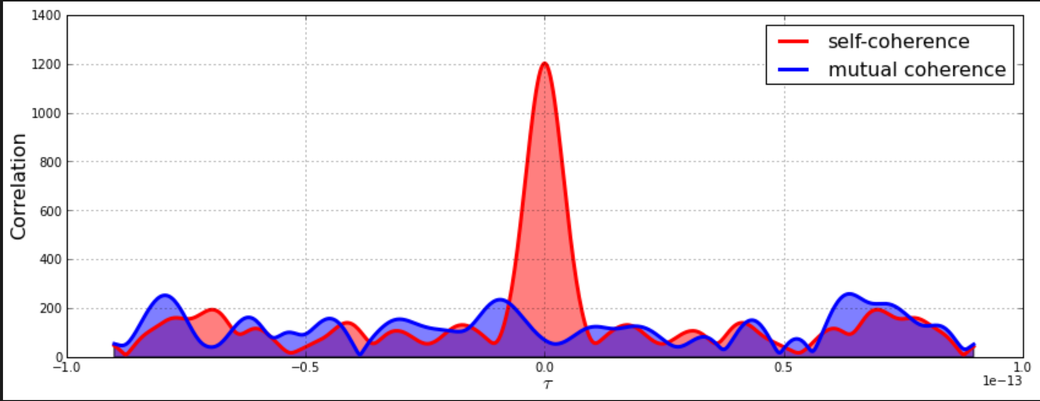
It is a complex number, of modulus $0 \leq \mu \leq 1$. It quantifies the capacity of a situation or an optical setup to produce interferences.

mutual coherence of two distinct sources



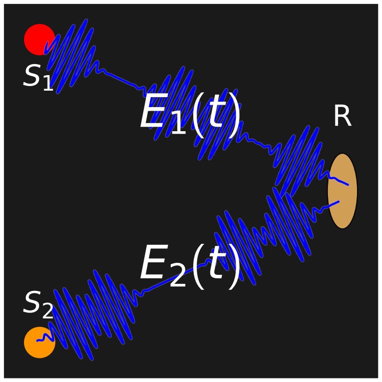
The E-fields do not look alike to start with!

self- vs mutual- coherence



Comparison of self-coherence and mutual-coherence curves.

spatial incoherence



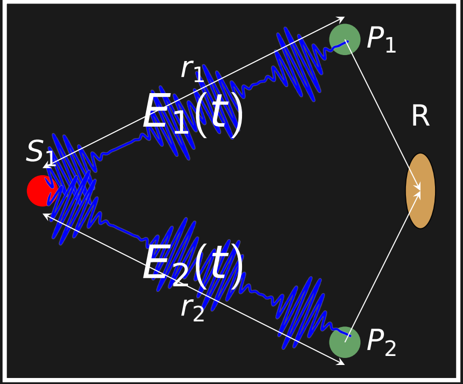
S_1 and S_2: the two sources
E_1 and E_2: the electric fields
R: mono-pixel quadratic detector

- The **events** in S_1 and S_2 giving birth to the wave packets of E_1 and E_2 have **no reason to be synchronized**!
- The degree of mutual coherence, ie. the average of a large sum random packets, is equal to 0.

important fact #1!

Distinct astronomical sources do not interferere. Sources are spatially incoherent.

self-coherence



S_1: the source
E_1 and E_2: the electric fields
P_1, P_2: the observing stations
R: mono-pixel quadratic detector

The field, emitted by one source, is collected by two stations, such that the distances r_1 and r_2 are covered within the coherence time.

Important fact #2!

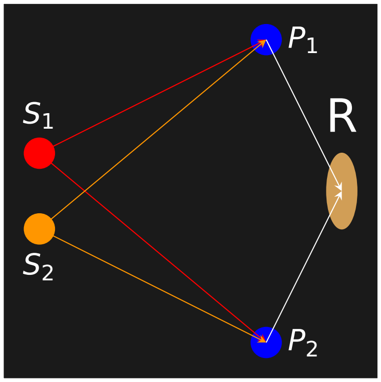
When well adjusted, the self-coherence will systematically differ from 0.

$$\gamma_{12} = \frac{\langle E_1 E_2^* \rangle}{\sqrt{(I_1 I_2)}} \neq 0$$

combine these ideas: interferometry

the important facts

1. **Sources are spatially incoherent**. Fields of distinct origins won't interfere.
2. **Point-sources are self-coherent**. Every point source will produce its own set of interferences.

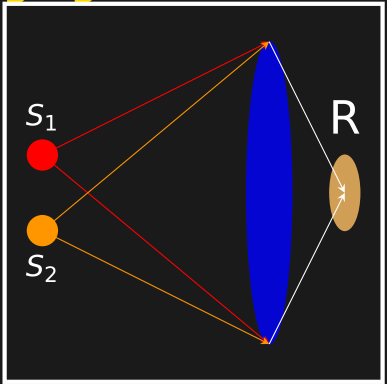


This pictures is for optical interferometry.
When looking at a complex source, with a mix of self- and mutual-coherence, one measures coherence of intermediate value.

combine these ideas: imaging

the important facts

1. **Sources are spatially incoherent**. Fields of distinct origins won't interfere.
2. **Point-sources are self-coherent**. Every point source will produce its own **point spread function**.



This pictures is for diffraction-dominated imaging.
When looking at a complex source, with a mix of self- and mutual-coherence, one measures coherence of intermediate value.

empty