Imaging and tracking objects beyond strongly scattering media

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22 July 2020

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Context

D. Psaltis: doi.org/10.1038/491197a

- A lot of opaque media are opaque due to scattering, not absorption.
- Scattering allows light to go through, but scrambles its information content.

<u>Goal</u>: extract as much information as possible about an hidden object (as non-invasively as possible).

Not all scattering is created equal

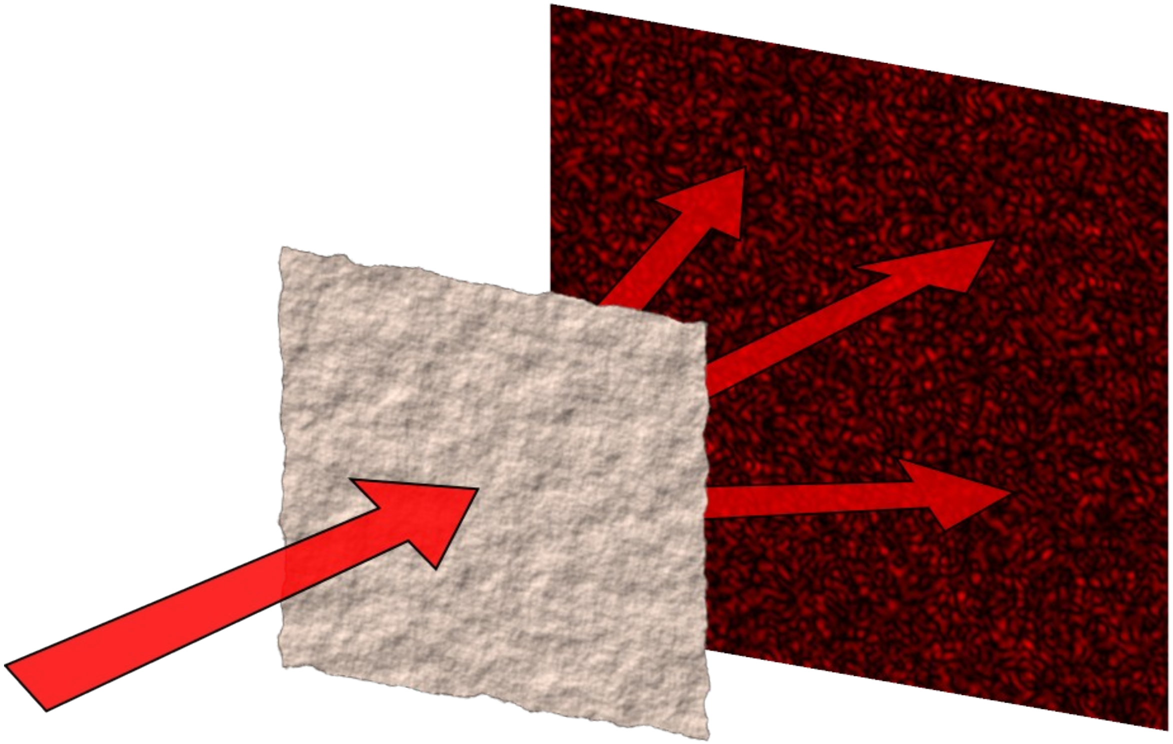
commons.wikimedia.org/wiki/
File:GGB_reflection_in_raindrops.jpg

Light is aberrated → adaptive optics.

Miroslav Prochazka (pixabay)

Weak scattering (e.g. mist/haze)
→ gated techniques (e.g. OCT, Lidar etc)

Strong scattering

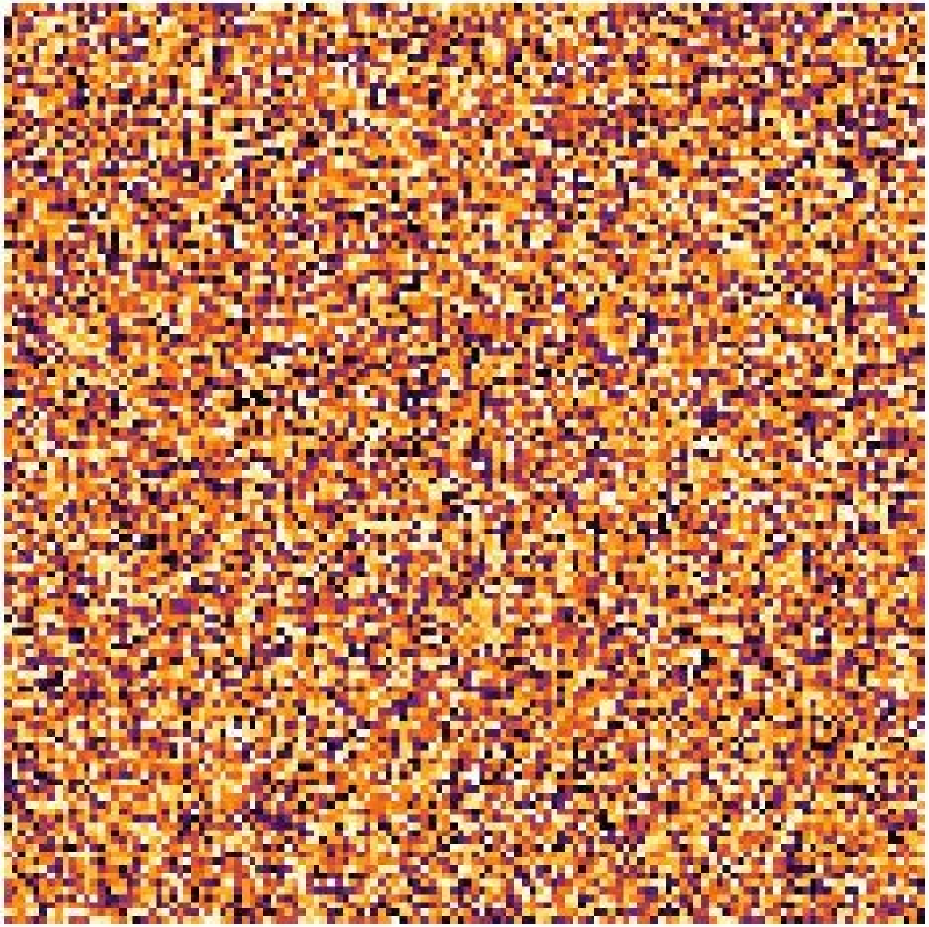


- All light is scattered.
- Information is scrambled beyond recognition.

Elastic scattering preserve coherence → laser light is converted into a speckle pattern.

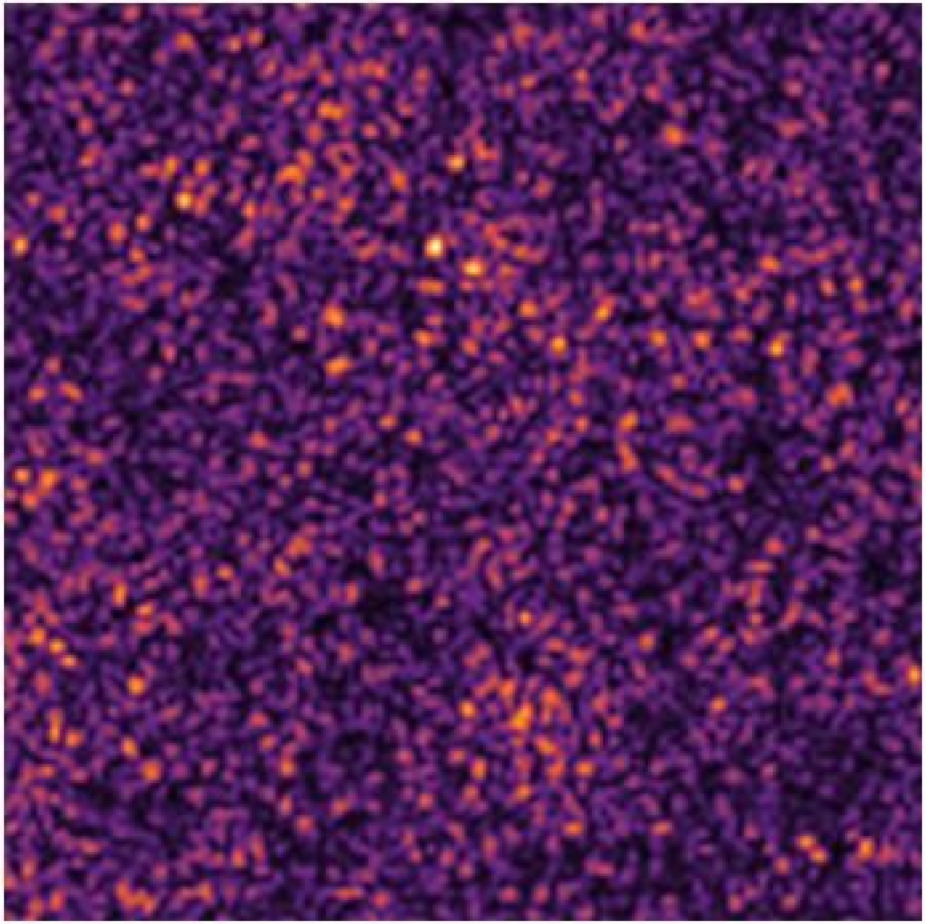
Speckle is not really random

White Noise



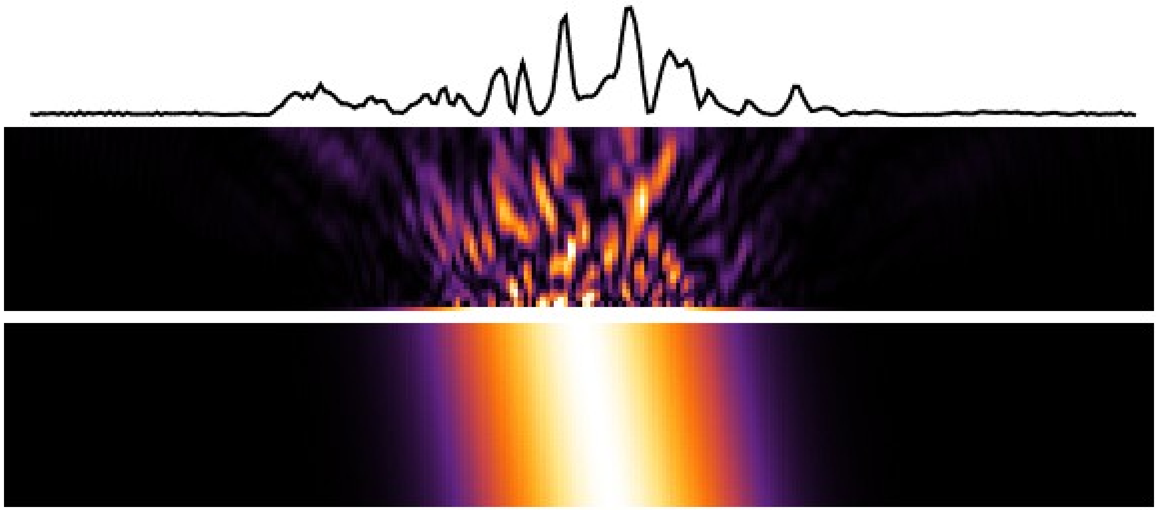
(Random)

Speckle



(Random???)

Optical Memory effect

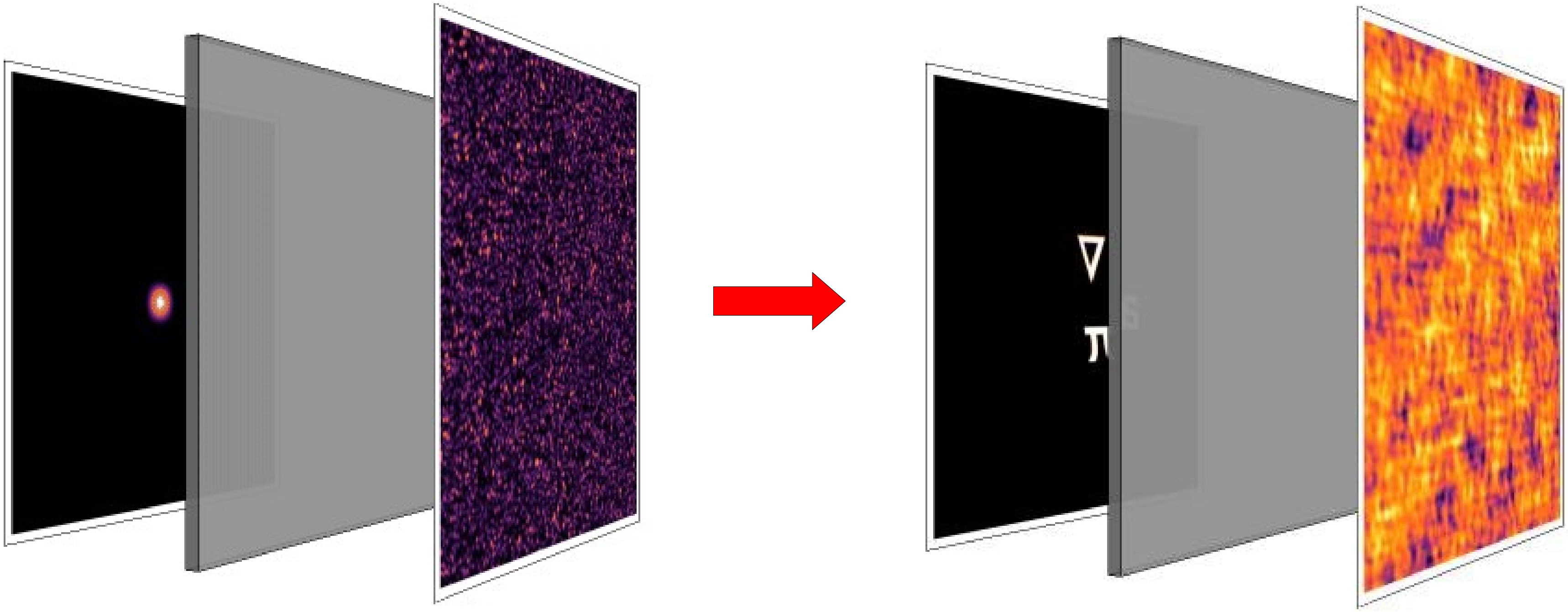


An incident laser beam is converted to speckle, whose pattern is effectively unpredictable.

BUT if the beam is tilted, to the first order the speckle is also tilted by the same angle (and changes slowly with the angle).

The available angle range depends on the sample thickness, but not on the scattering strength.

Optical Memory effect

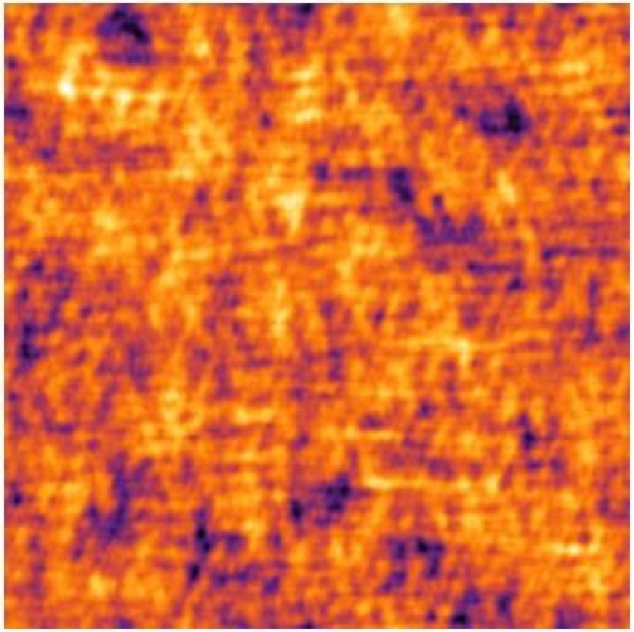


We don't know what the hidden object is, but the light coming from each point will produce essentially the same speckle pattern, just shifted.
→ The whole object will produce a pattern given by:

$$\int O(x_1)\,S(x-x_1)\,dx_1 = O * S \quad \text{(convolution product)}$$

→ We can measure the convolution

$O*S$

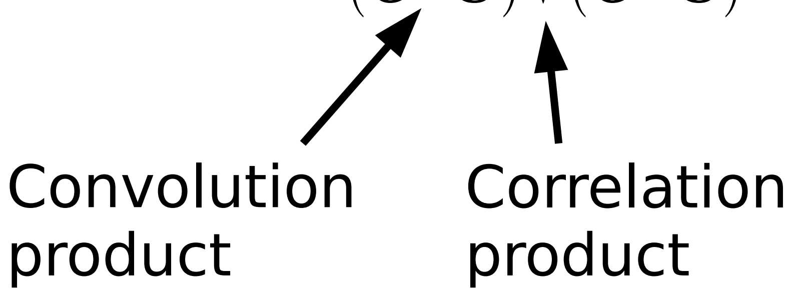


Can sort of guess a pattern.

But both O and S are unknown
→ can't invert the convolution.

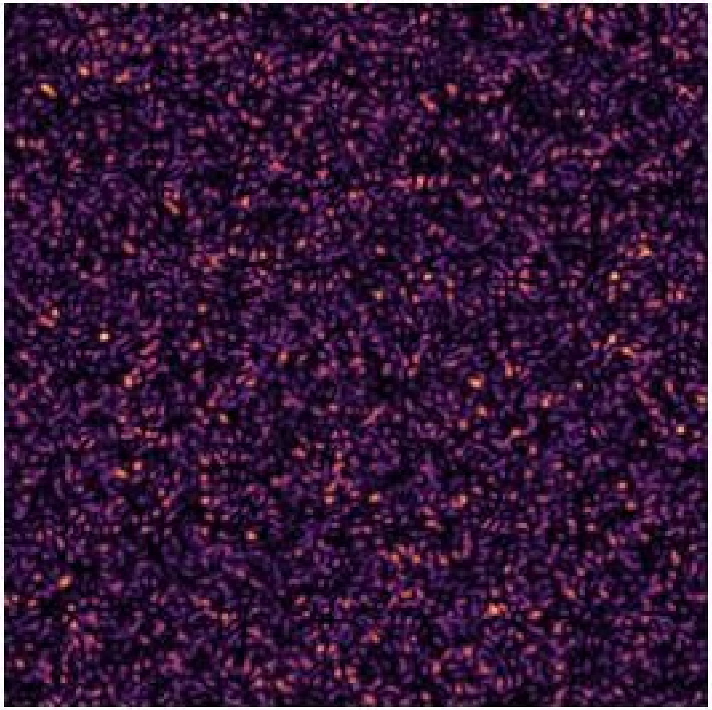
The shape of the object is there, but hidden in the correlations.
→ to highlight it we perform an autocorrelation of the pattern:

$$(O*S)\star(O*S)=(O\star O)*(S\star S)$$

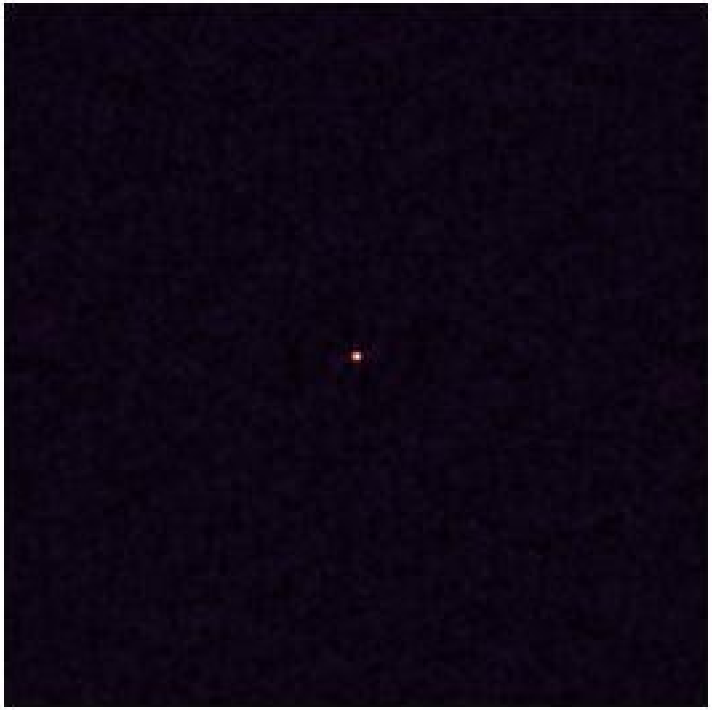


Speckle autocorrelation

S



$S \star S$

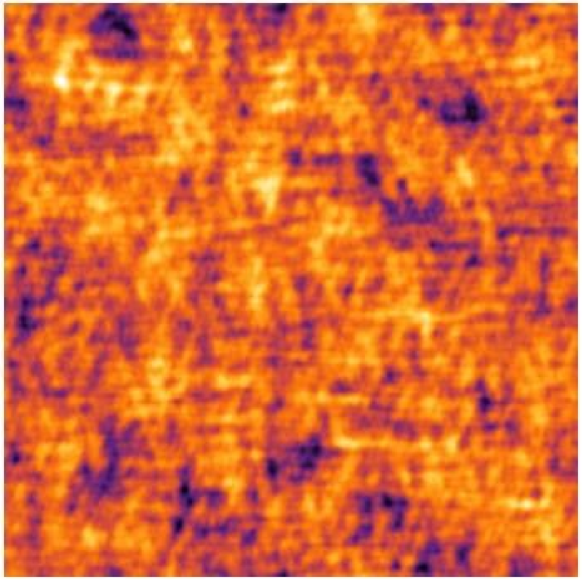


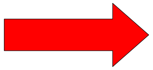
A speckle pattern is effectively random.
But its autocorrelation is not!

$$S \star S = \frac{J_1(k|\Delta\theta|W)}{k|\Delta\theta|W} \simeq \delta(\Delta\theta) \qquad (W \text{ is the illumination width.})$$

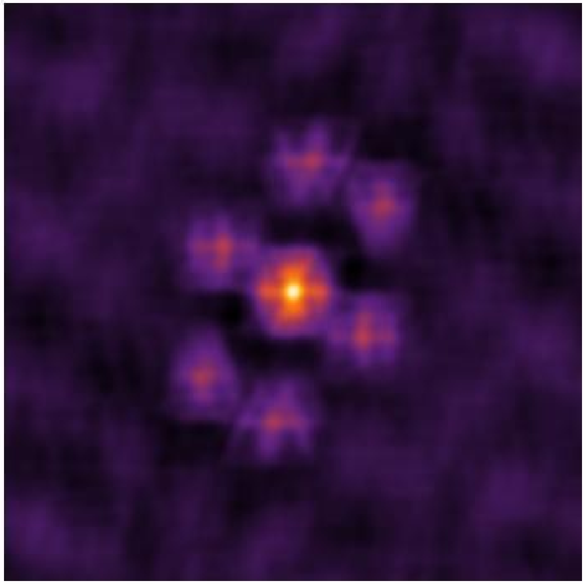
Object autocorrelation

$O * S$





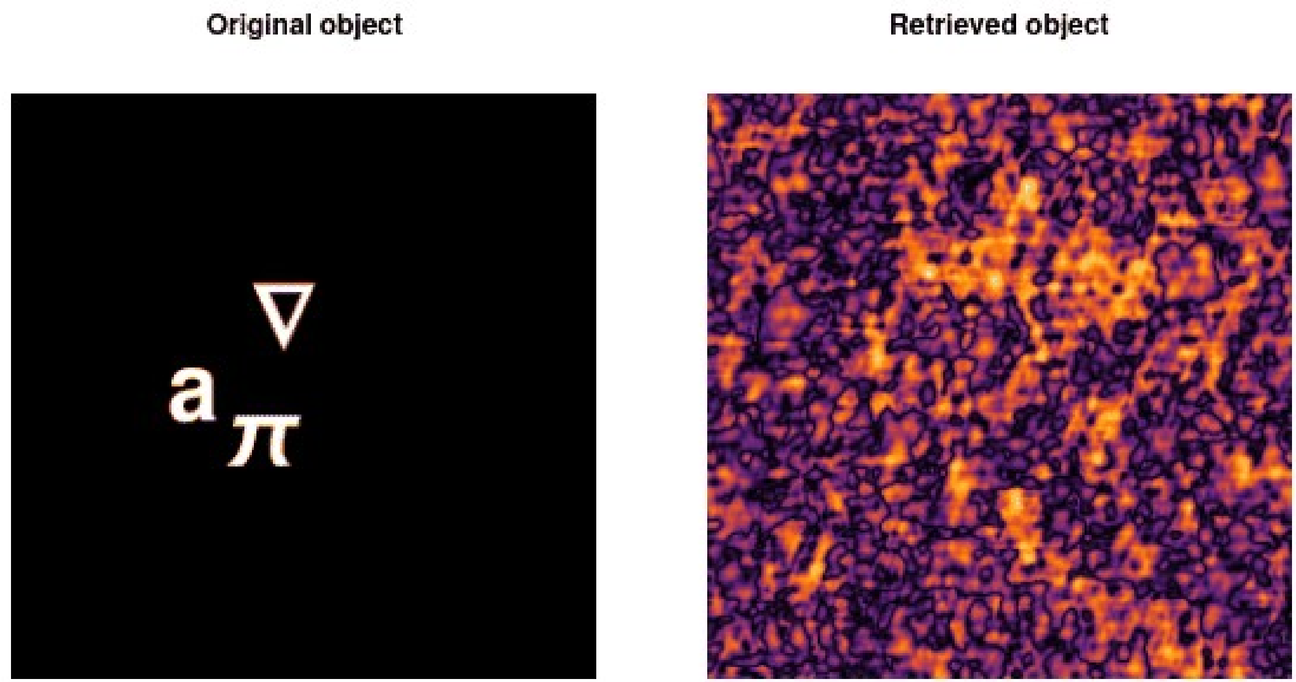
$(O \star O) * (S \star S) \simeq O \star O$



→ We can measure the object autocorrelation!

Problem: an autocorrelation contains less information than the original object → we need to rely on an iterative (approximated) approach.

Autocorrelation inversion

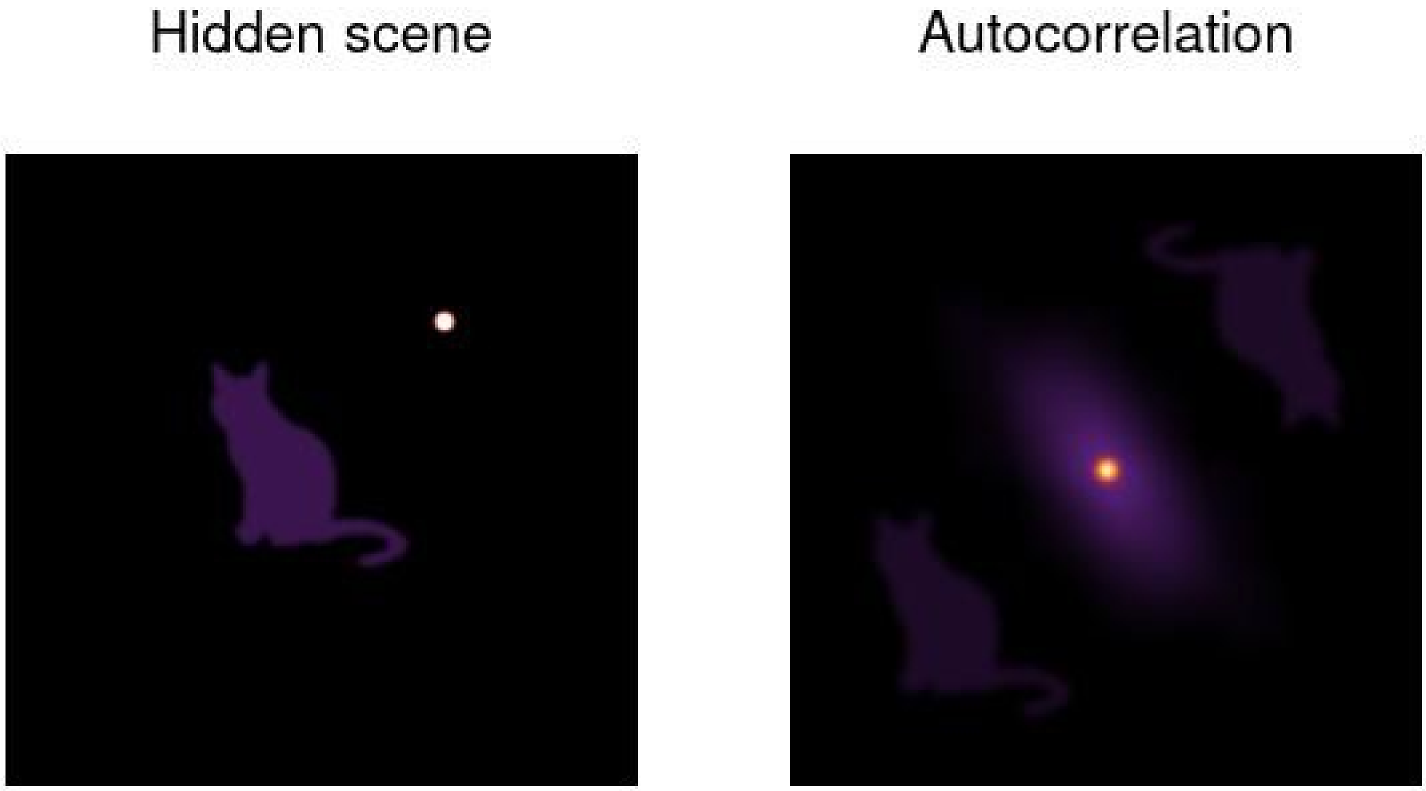


Fienup, *Appl. Opt.* **21**, 2758 (1982)
Dainty, *Laser Speckle & related phenomena* (1984)
Miao, Charalambous, Kirz & Sayre, *Nature* **400**, 342 (1999)
Abbey et al., *Nat. Photon*. **5**, 420 (2011)

External illumination

If the object is not self-luminous, the same can be done with an illumination on the other side of the scattering screen.

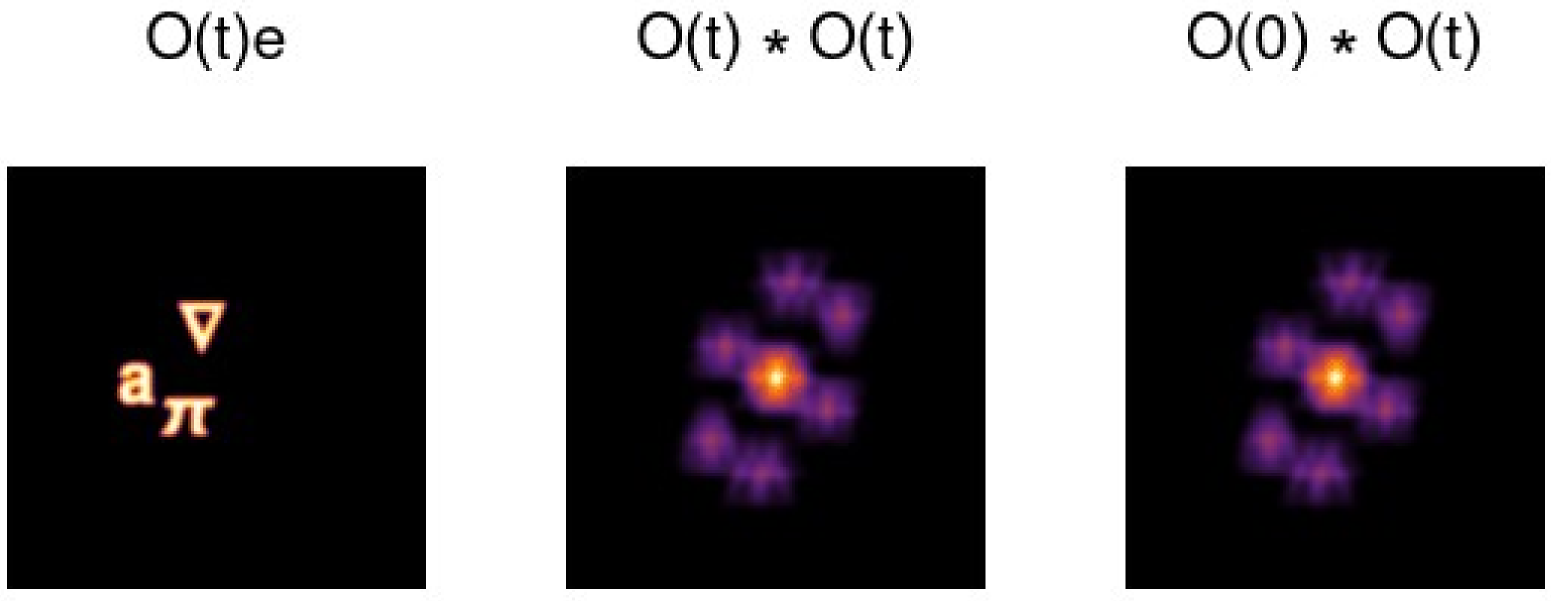
The presence of an external light source can actually make things much simpler.



What about moving objects?

If the objects in the scene move we can:

1) Take the measurement quickly and make an autocorrelation.
2) Take the measurement quickly and correlate it with the measurement at a previous time.

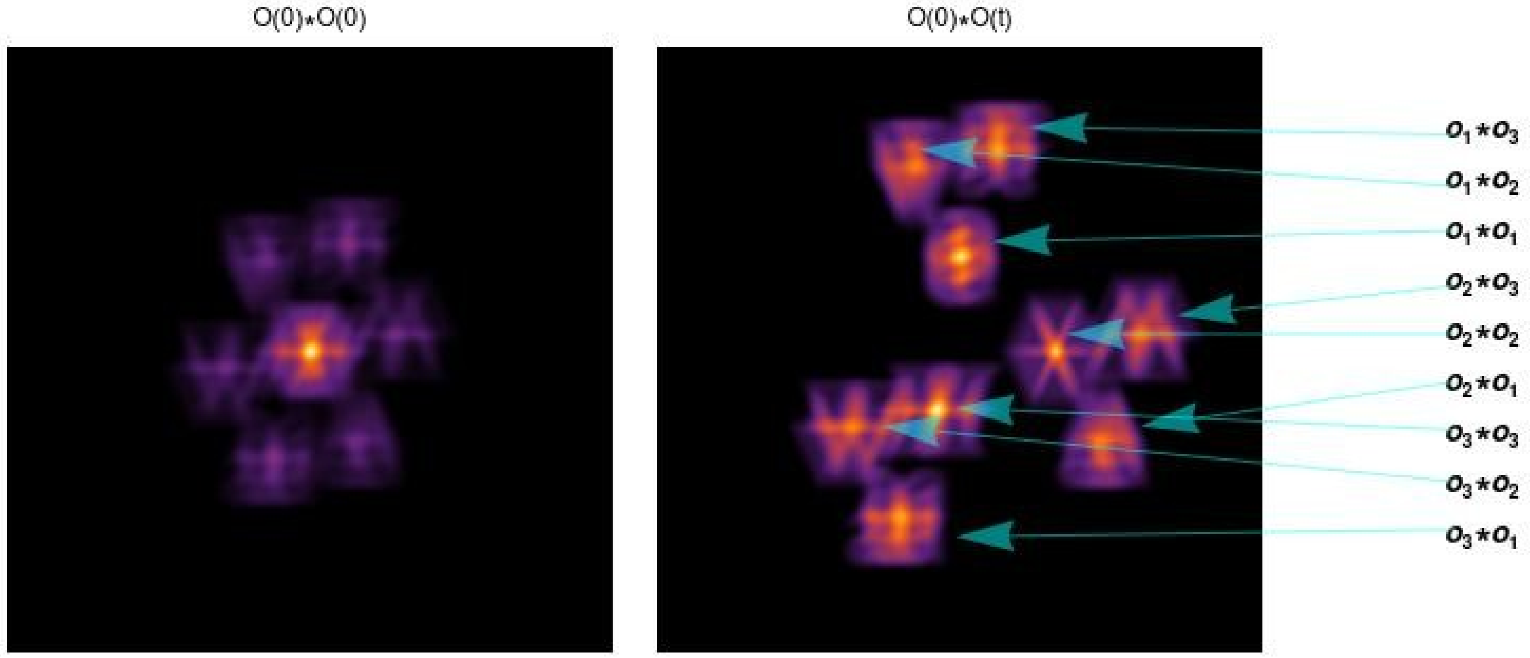


What can we learn?

3 objects → 3 clusters of 3 objects moving around.

Each cluster moves following one of the original objects.

Each cluster is composed by the correlation of an object with all the objects present (including itself).



Practicalities

- The memory effect works only in a limited range, which decreases with the screen’s thickness.
  → Field of view is limited.

- If the objects are moving, one needs to make a measurement before any object moves more than a memory range.
  → Need fast measurements (i.e. potentially low S/N)

- If enough range is available, the autocorrelation of many objects breaks up into simpler terms.
  → Easier to reconstruct the object’s shape.

- If objects not only move but change shape, it is less clear how to factor the correlations.
  → The reconstruction at t_1 can be used as a starting point for the reconstruction at t_2 to ensure a fast convergence.

Conclusions

- Strong scattering is a big problem for imaging, but it doesn’t have to an insurmountable one
- Knowledge of speckle correlations holds the key to novel approaches to imaging through scattering media.
- The optical memory effect tells us something about what the image looks like behind the scattering media.
- Can be used to reconstruct images and/or to track the movement of a group of objects.

Thank You!