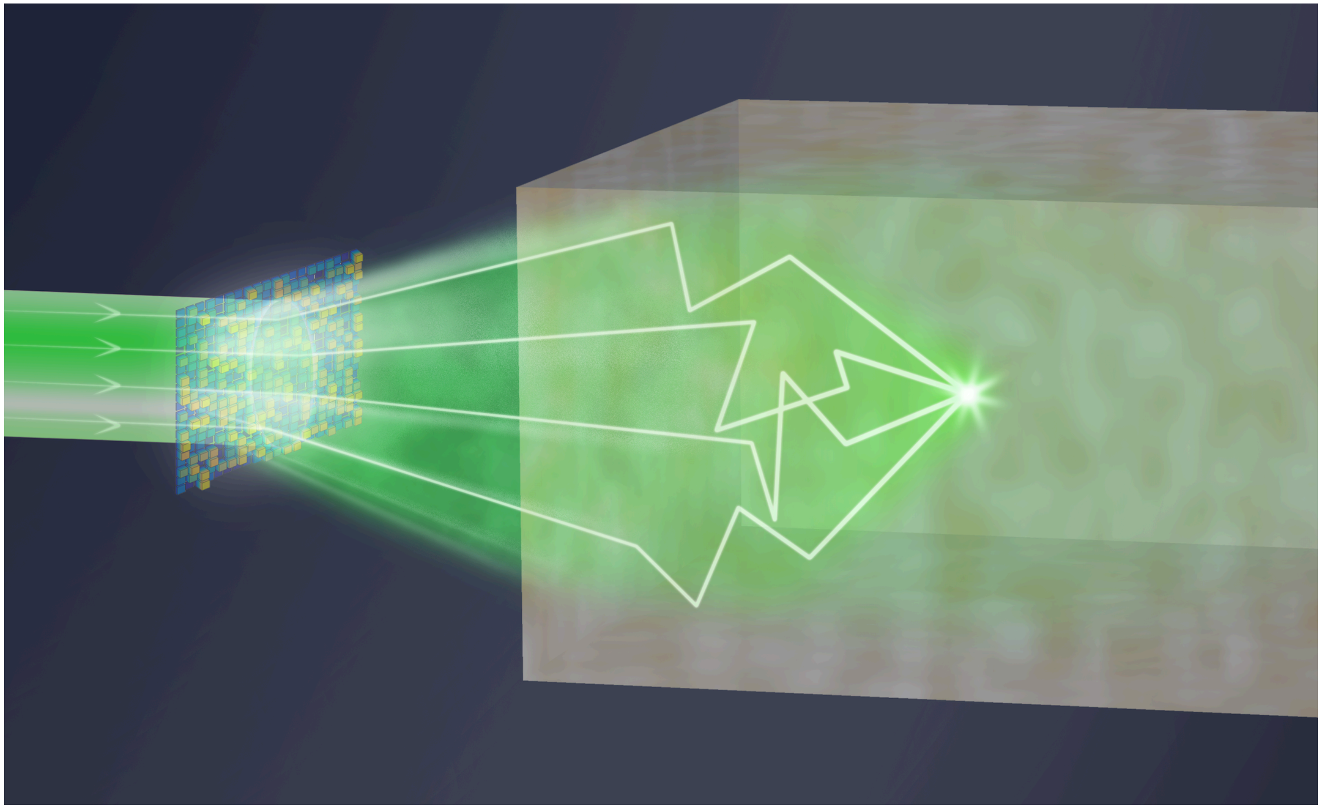
Memory effect correlations in random scattering media over space, angle and time



Roarke Horstmeyer

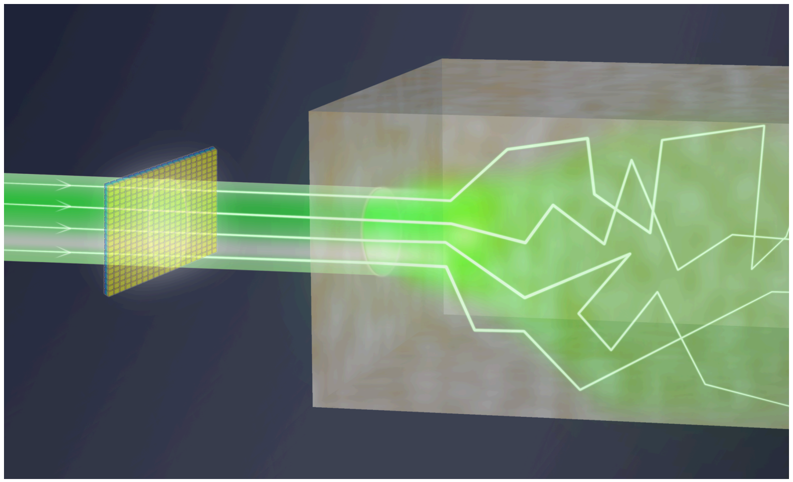
Charité Medical School, Humboldt University of Berlin

ICERM Waves and Imaging in Random Media

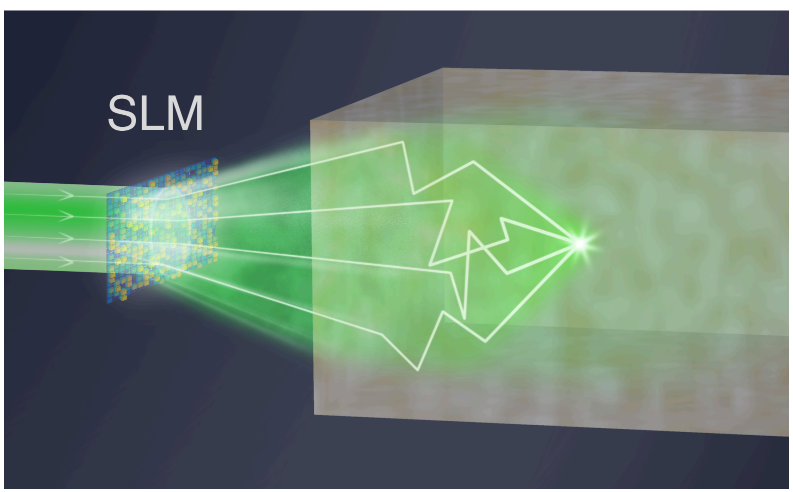
September 26, 2017

Challenge: controlling light deep within tissue

Light randomly scatters within tissue



Wavefront-shaping: "undo" scattering



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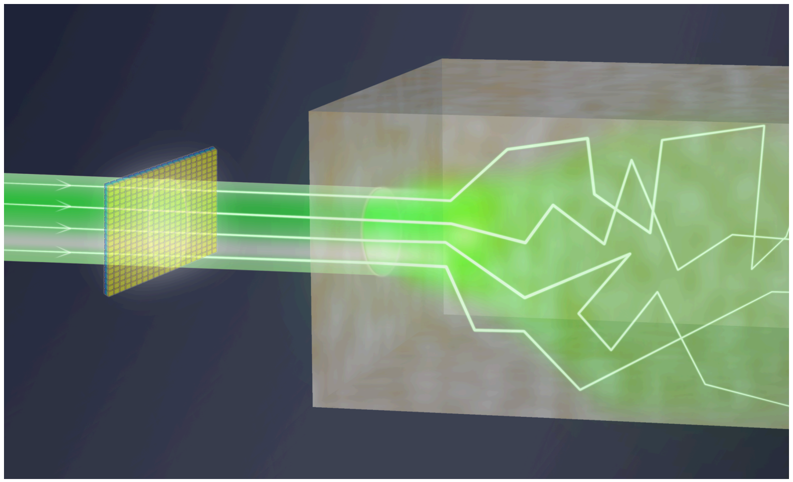

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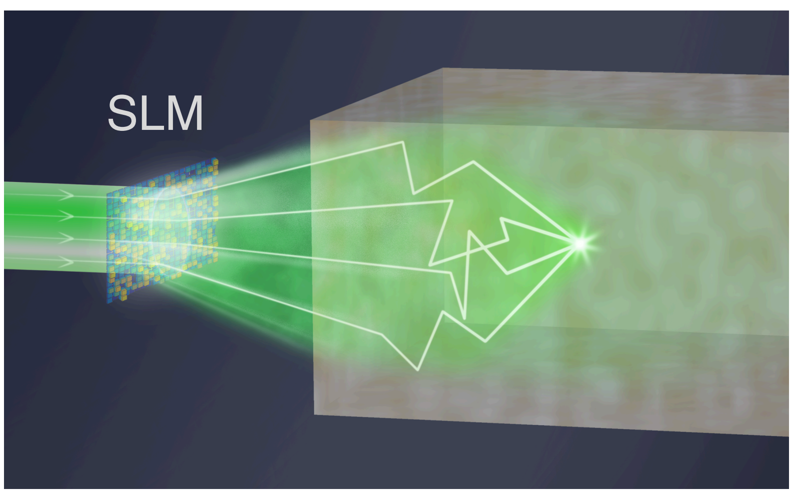
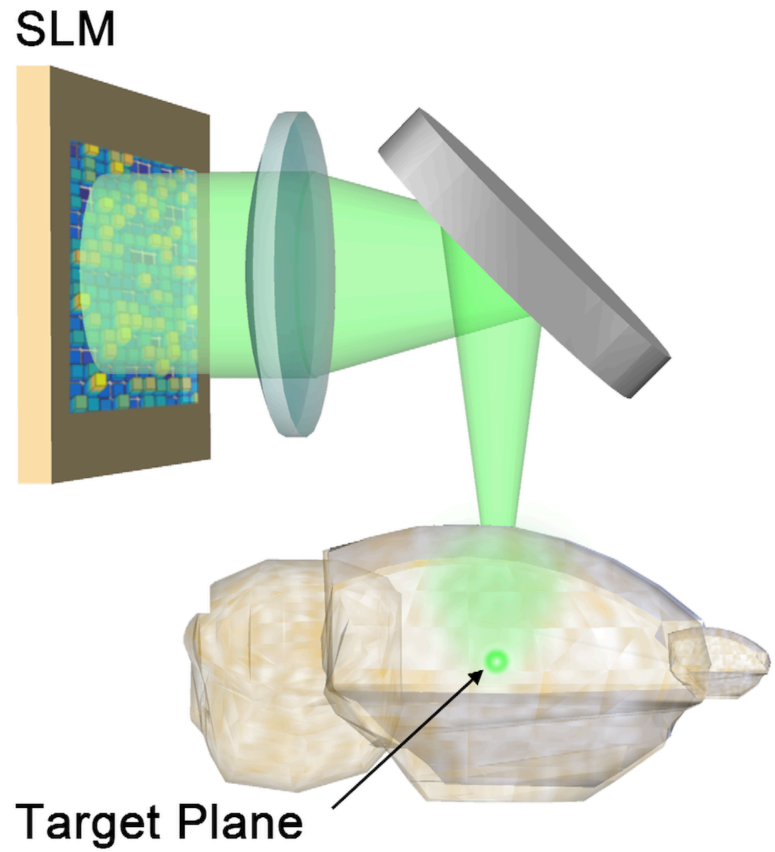
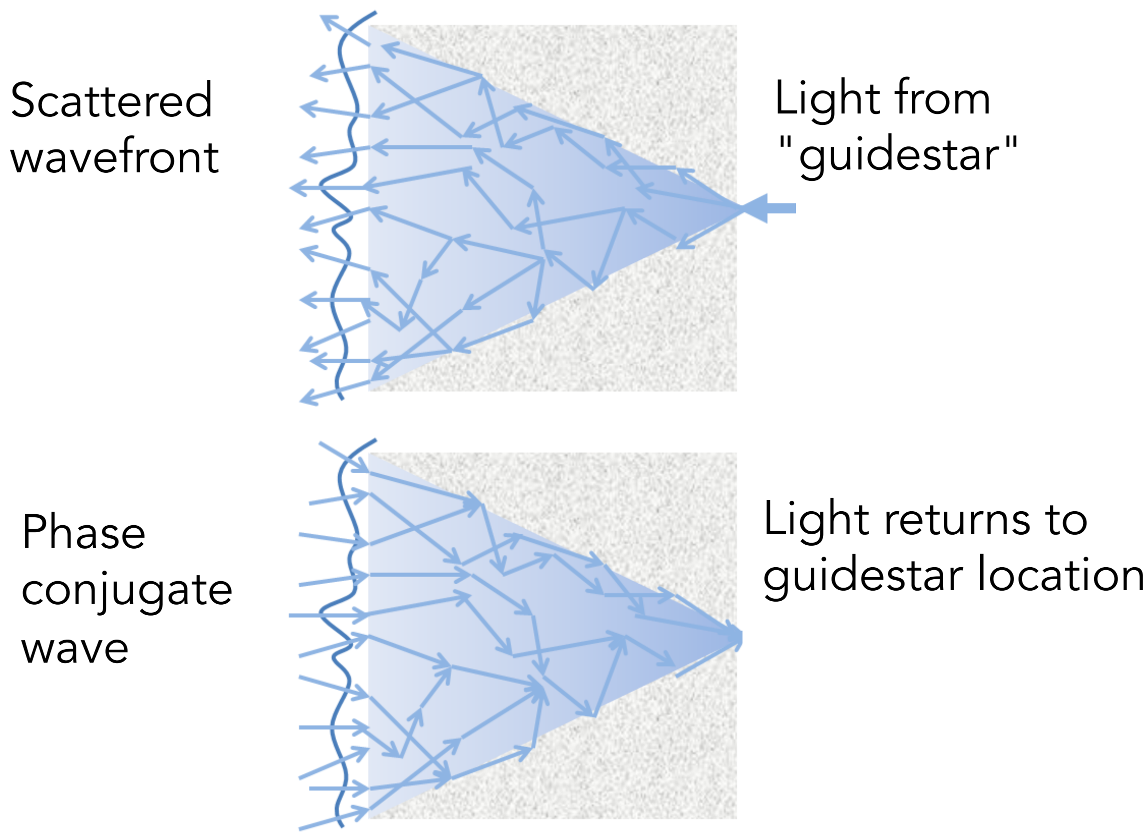
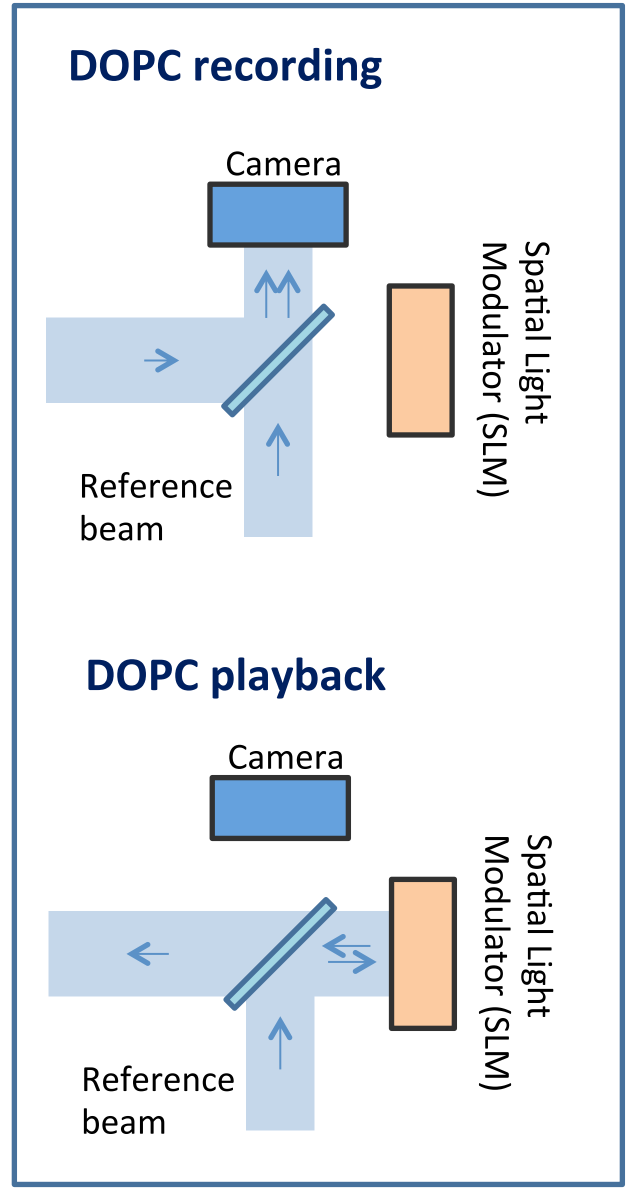




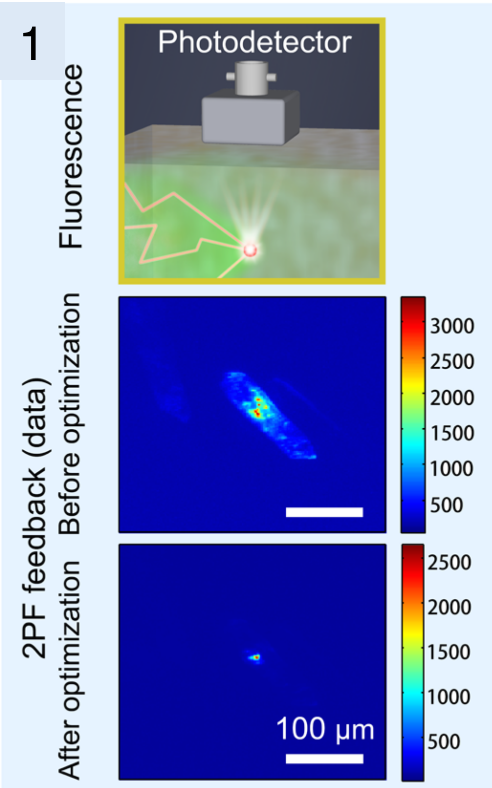
How do we form a focus deep within tissue?

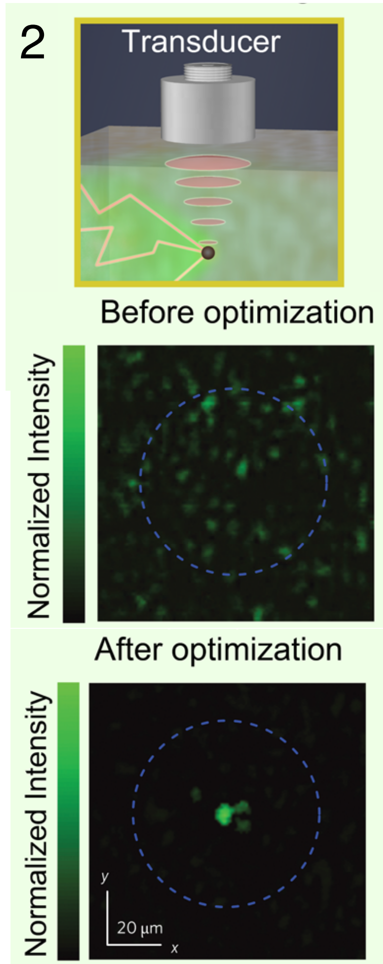
Technique #1: Optical Phase Conjugation

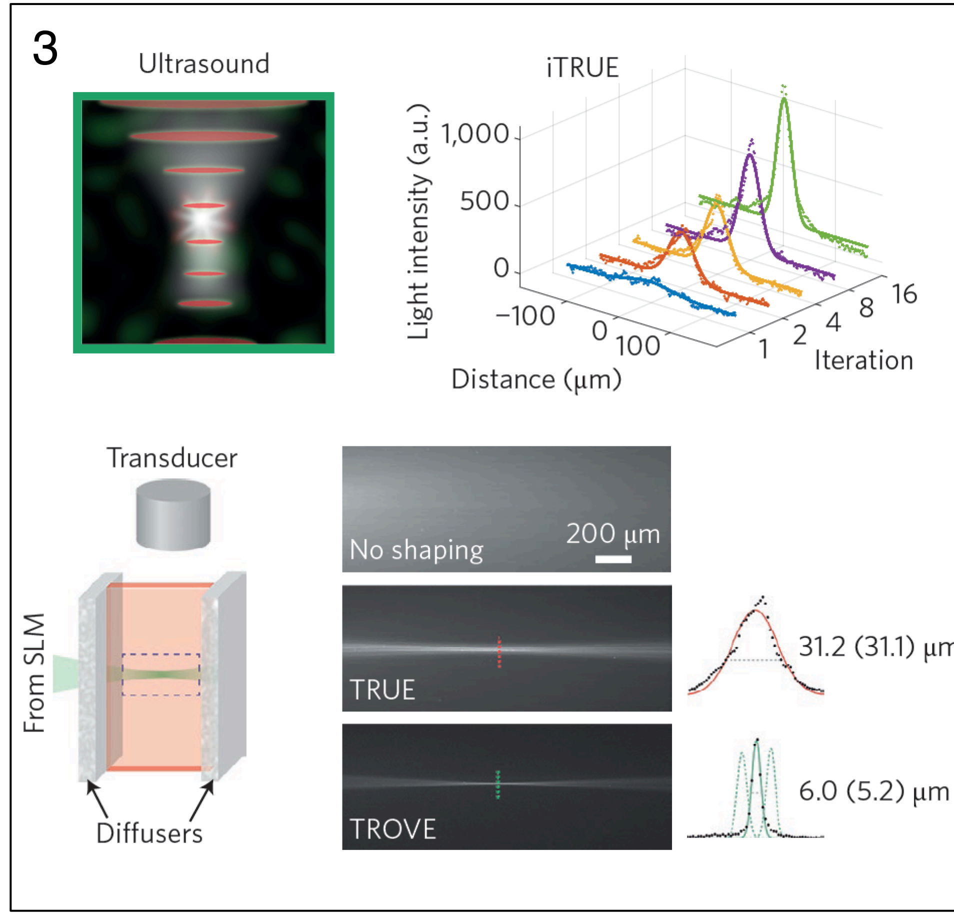


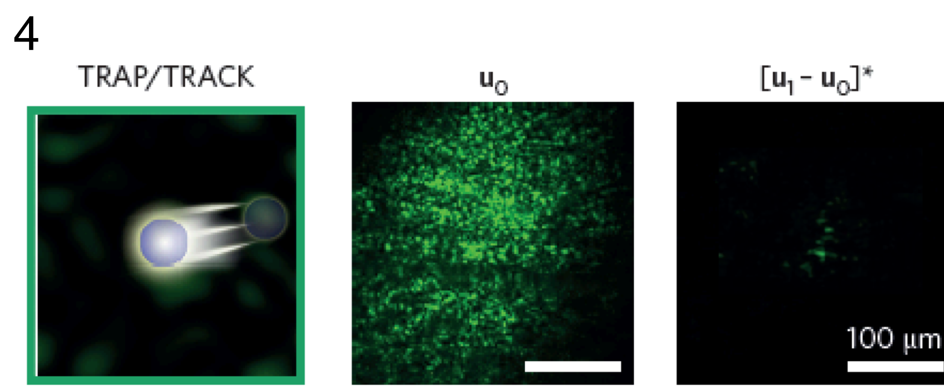


Guidestar examples



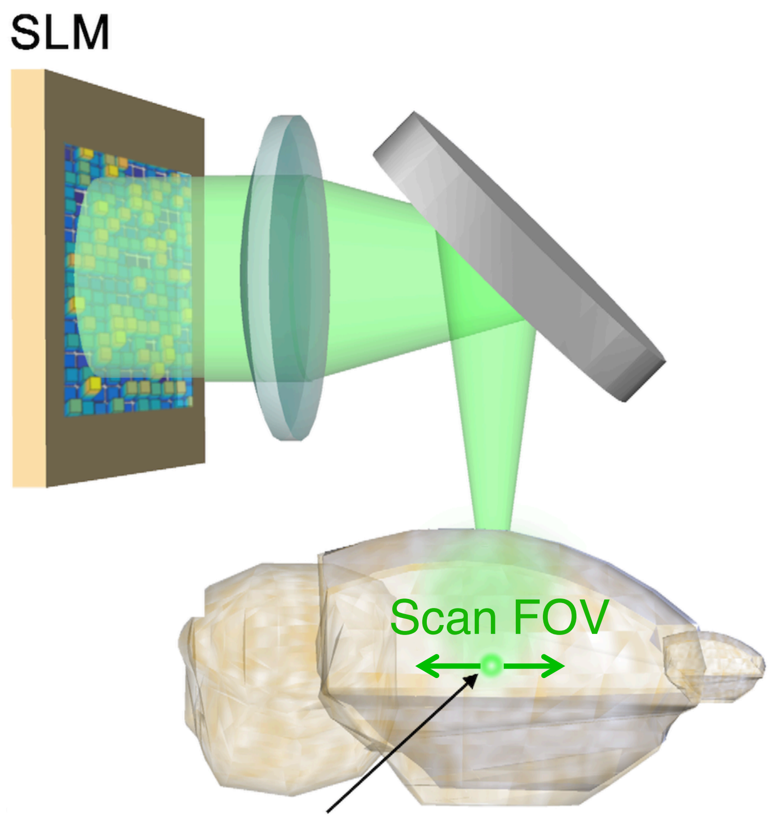






R. Horstmeyer et al., "Guidestar-assisted wavefront-shaping methods for focusing light into biological tissue", Nature Photon. (2015)

This talk: *efficiently scanning* focused light deep within tissue



Goal: want to scan focus around

Equivalent: maximize FOV of imaging with adaptive optics

Talk Outline

1. The optical memory effect

2. The "shift/shift" memory effect

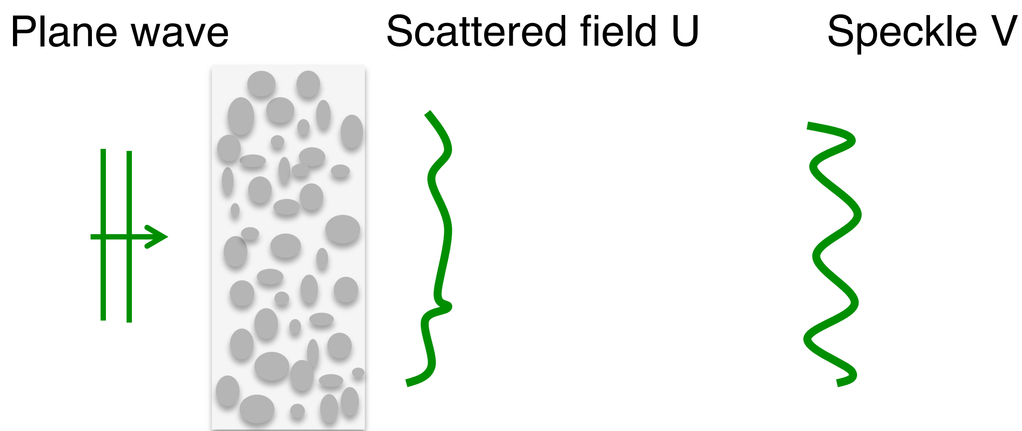
3. The generalized memory effect

4. Experimental demo of maximized scanning

5. Scanning further with time-gated light

The optical memory effect

- Well-known scattering correlation
- Speckle at a distance shifts around but does not change shape



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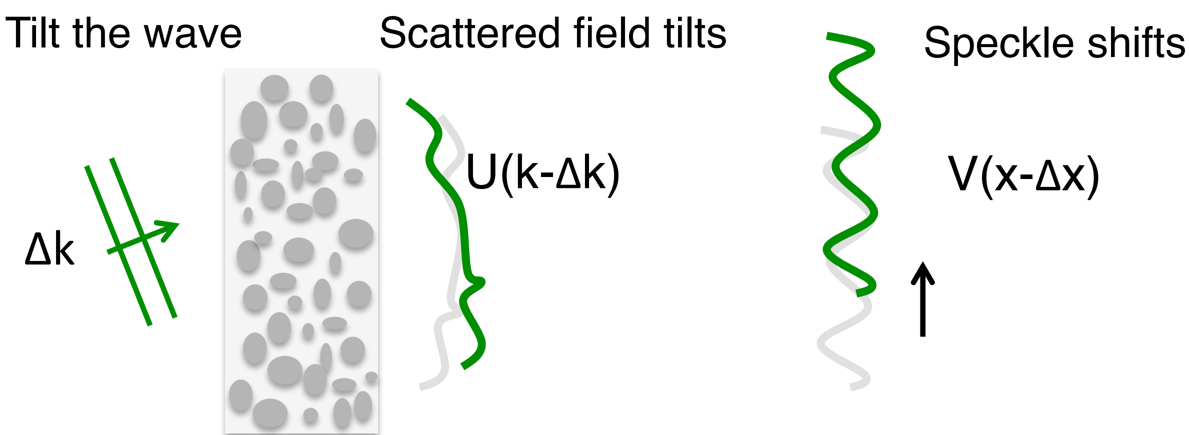


Application: Imaging "through" thin scattering layers

- J. Bertolotti et al., "Noninvasive imaging through opaque scattering layers," Nature (2012)
- O. Katz et al., "Noninvasive single shot imaging through opaque scattering layers and around corners," Nature Photon. (2014)
- X. Yang et al., "Imaging blood cells through scattering tissue using speckle scanning," Opt. Express (2014)

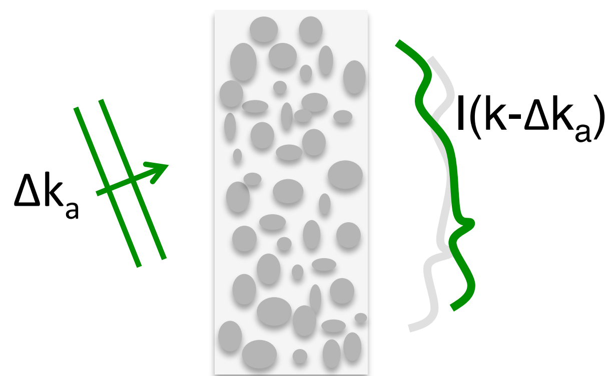
The optical memory effect

- Original approach[1] interested in *intensity-intensity* correlations:

$$C_I^{aba'b'} = \underbrace{C_I^{(1)}}_{\text{"Memory effect"}} + C_I^{(2)} + C_I^{(3)}$$

$$\downarrow$$

$$C_I^{(1)}(\Delta k) \propto (\Delta k L)^2 / \sinh^2(\Delta k L), \quad \Delta k_a = \Delta k_b$$



[1] S. Feng, C. Kane, P. A. Lee, and A. D. Stone, Phys. Rev. Lett. 61, 834 (1988).

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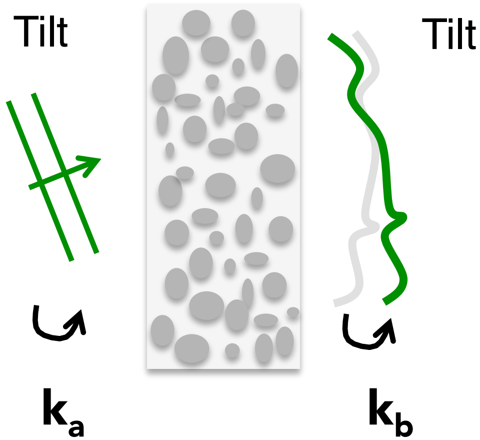
- We will work with *field-field* correlations[2], the square root of $C_I^{(1)}$:

$$C_I^{(1)}(\mathbf{k}) = |\langle \underbrace{E(\mathbf{k}) E^*(\mathbf{k})}_{\text{Our primary interest}} \rangle|^2 = |\underbrace{C(\mathbf{k})}|^2$$

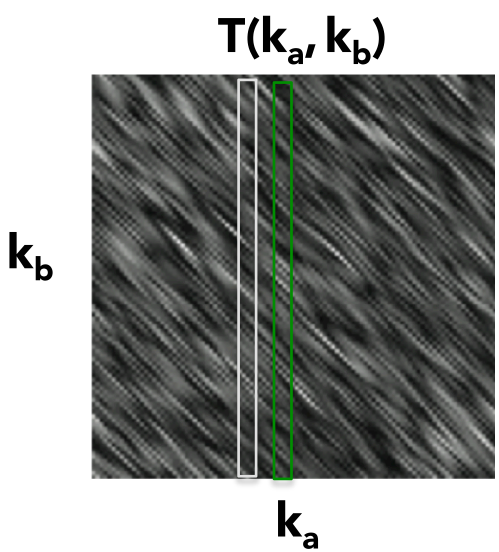
[1] S. Feng, C. Kane, P. A. Lee, and A. D. Stone, Phys. Rev. Lett. 61, 834 (1988).

[2] R. Berkovits, M. Kaveh and S. Feng, Phys. Rev. B 40, 737 (1989).

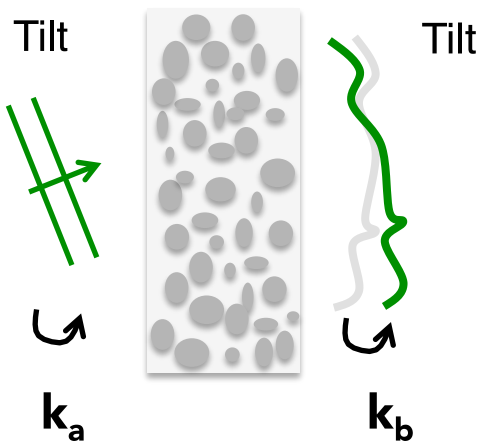
The optical memory effect

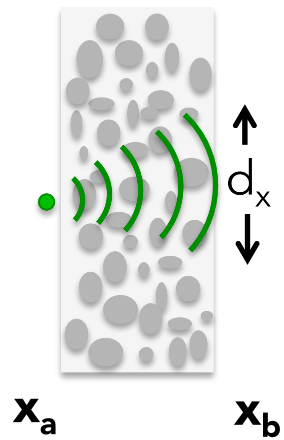


What does the memory effect look like within the transmission matrix?



The optical memory effect

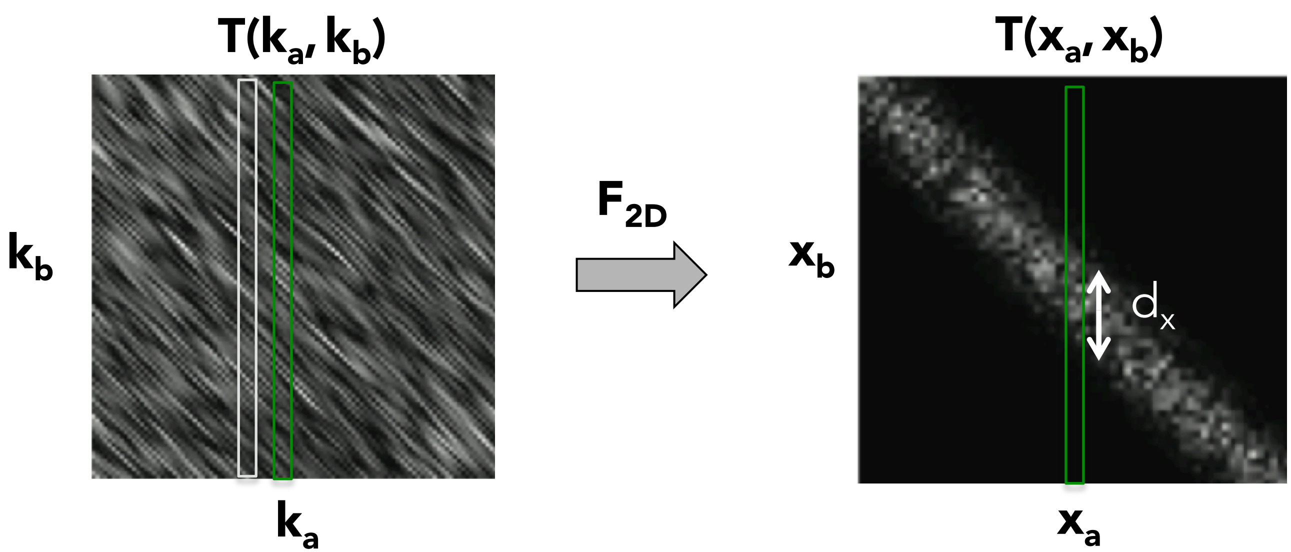




Scattering response to a point source:

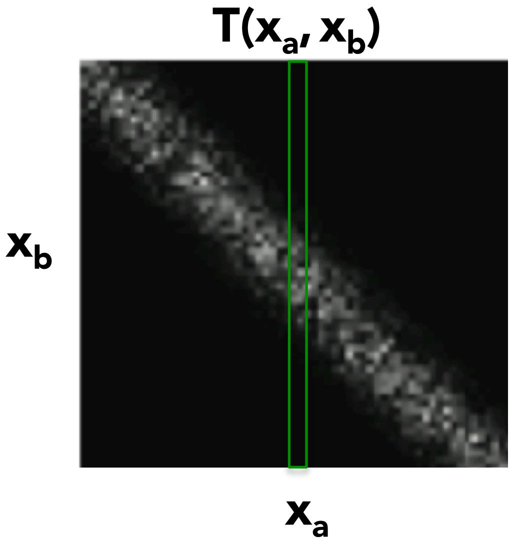
"Intensity propagator"

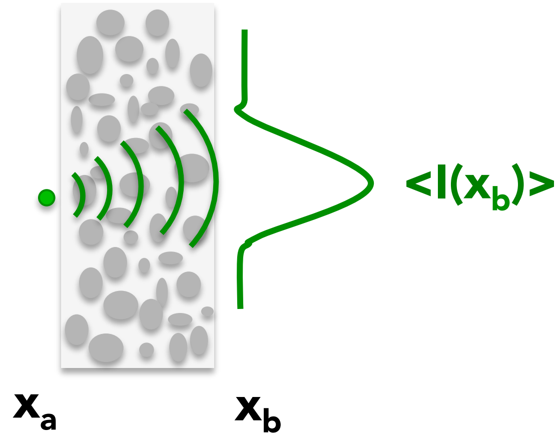
Visualization of the optical memory effect possible in k and x:



Banded structure in T_x

The optical memory effect: a simple derivation





Assume we know the average magnitude of transmission matrix:

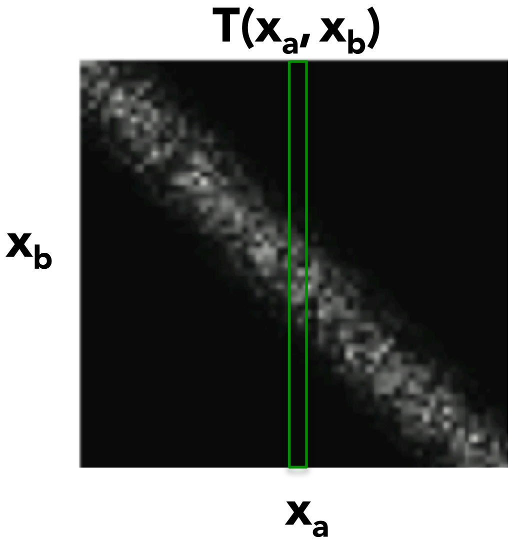
$$I(x_a, x_b) = \langle |T(x_a, x_b)|^2 \rangle$$

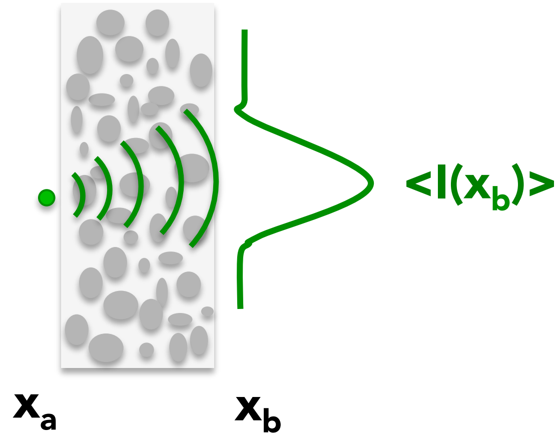
$$\mathcal{F}_{2D}\left[I(x_a, x_b)\right] = \sum_{k_a, k_b} \langle T(k_a, k_b) T^*(k_a - \Delta k_a, k_b - \Delta k_b) \rangle \propto C(\Delta k_a, \Delta k_b)$$

Assume average intensity response to point source is shift-invariant:

$$C(\Delta k_a - \Delta k_b) = C(\Delta k) \propto \mathcal{F}^{x_b \to \Delta k}\left[\langle I(x_b) \rangle\right]$$

The optical memory effect: a simple derivation

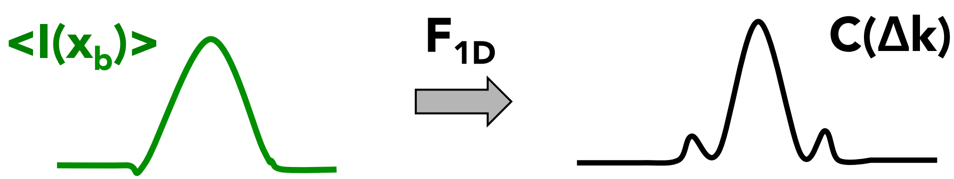




Recipe to measure the optical memory effect:

1. Put point source on input surface
2. Measure average intensity at output surface, $\langle I(x_b) \rangle$
3. Take Fourier transform to get $C(\Delta k)$

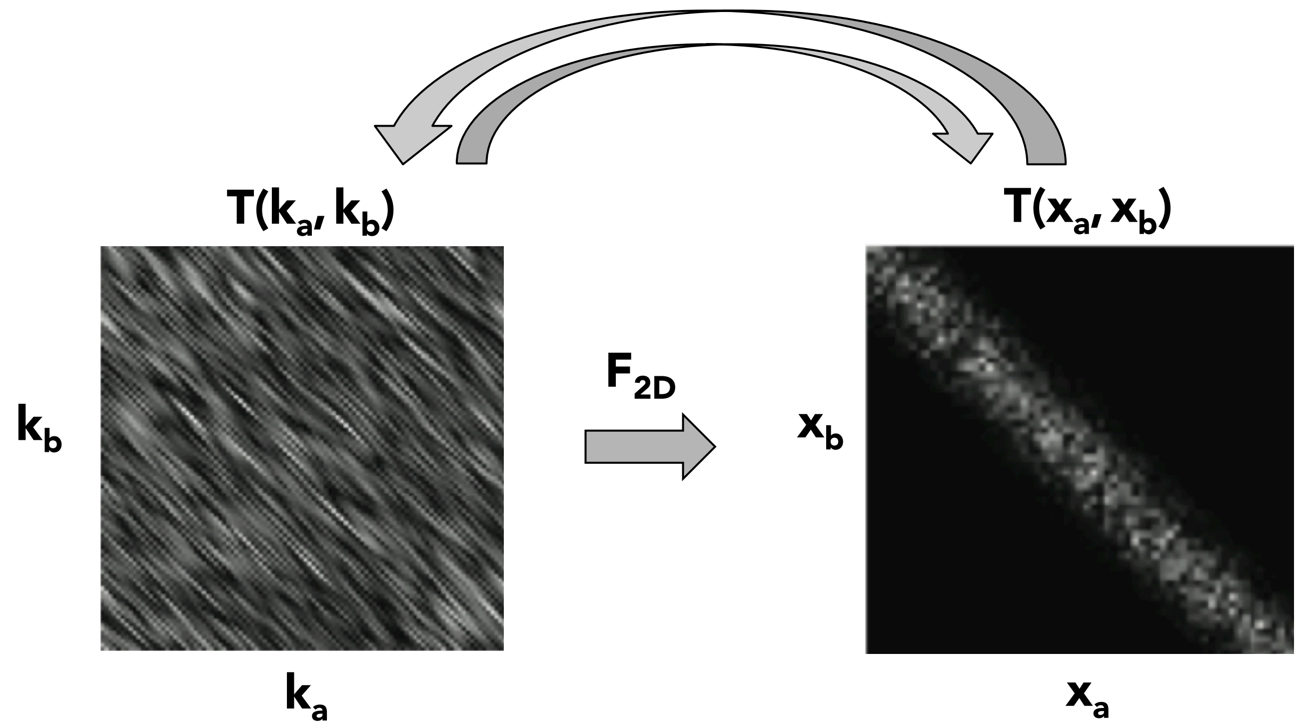
Intensity propagator



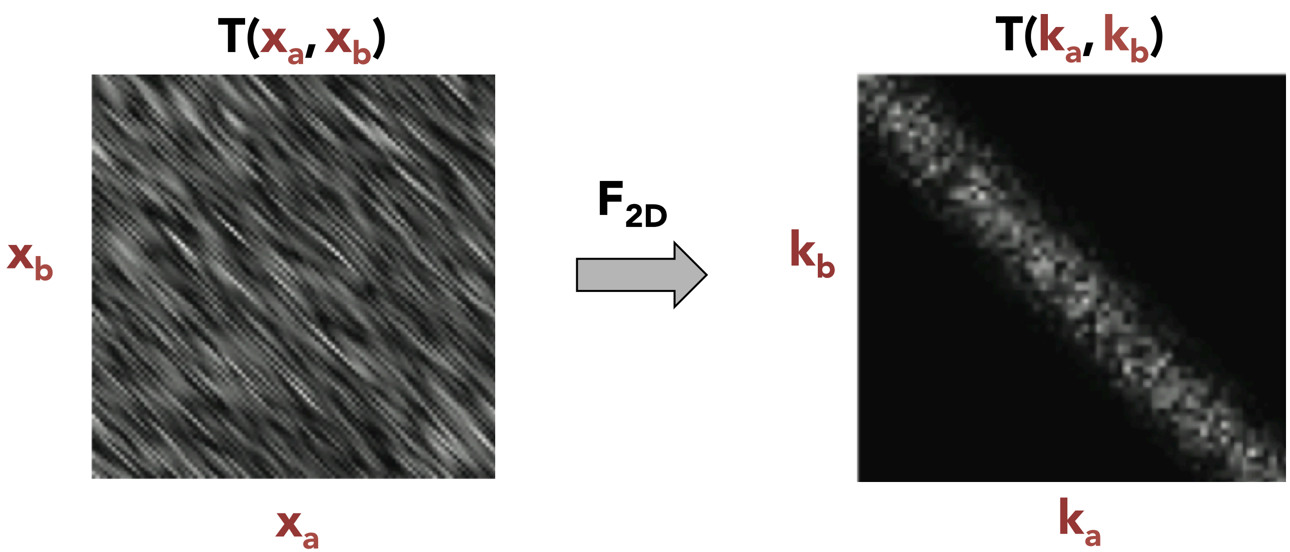
Optical memory effect

The shift/shift memory effect

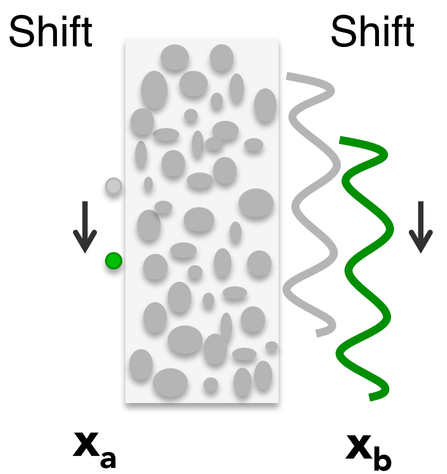
What happens if we switch x's and k's?

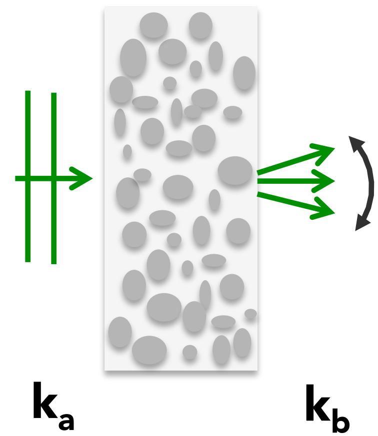


The shift/shift memory effect



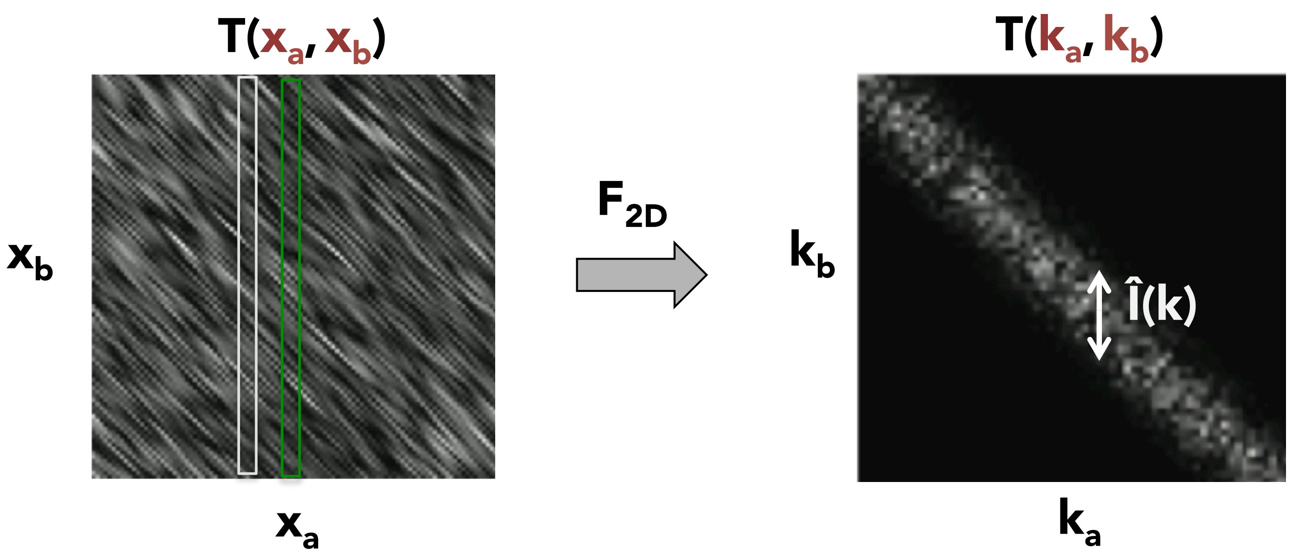
The shift/shift memory effect: the Fourier dual





Wavevector response to a plane wave:

"k-space intensity propagator"
<$\hat{I}(k_a,k_b)$>



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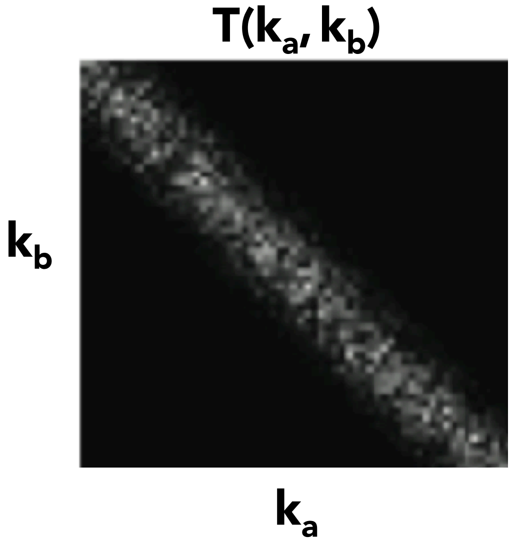
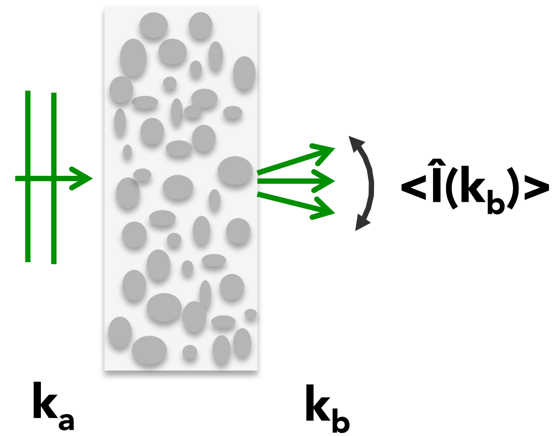
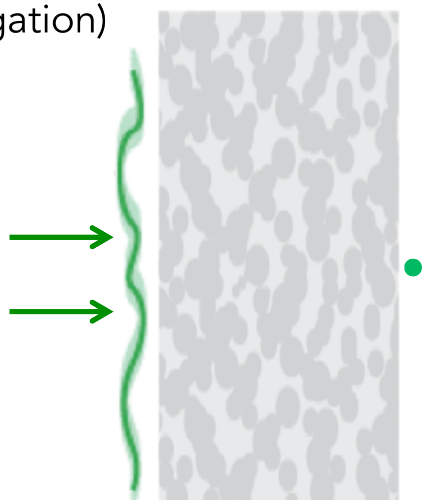


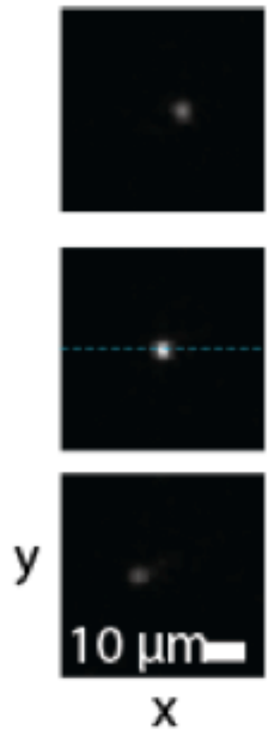


- Identical derivation, x's and k's swapped
- Recipe to measure the shift/shift memory effect:
    1. Shine plane wave on input surface
    2. Measure average wavevector spread at output
    3. Take its Fourier transform to get spatial correlation $C(\Delta x)$
- Focus and scan within anisotropic material (e.g., tissue g ~ 0.92-0.98)

Experimental demo of shift/shift memory effect

Light from SLM
(optical phase
conjugation)





B. Judkewitz, R. Horstmeyer et al., "Translation correlations in anisotropically scattering media," Nature Physics (2015)

Experimental demo of shift/shift memory effect

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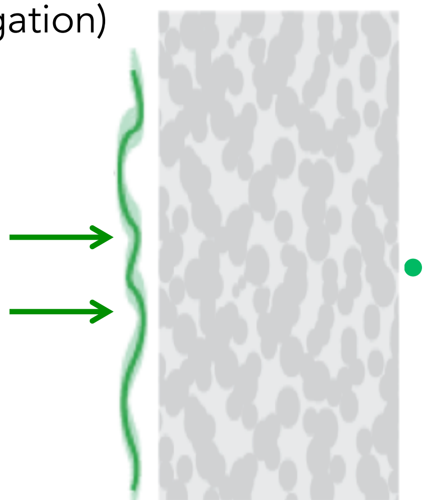
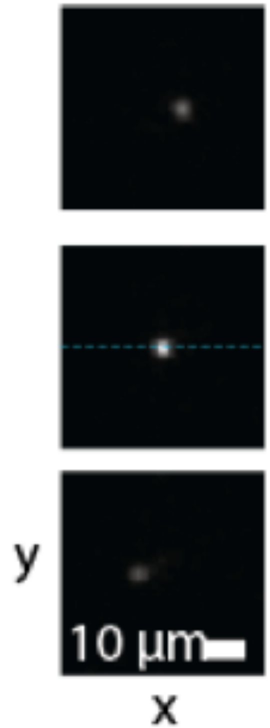
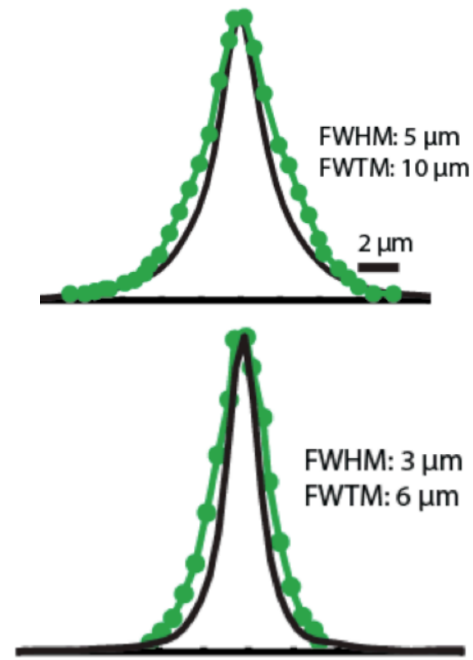




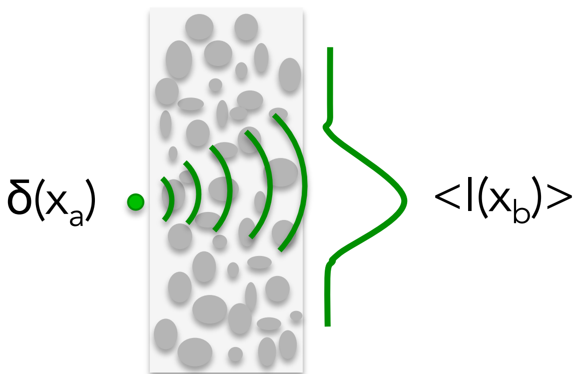


Green curve: focus intensity
Black curve: FT plane wave response

B. Judkewitz, R. Horstmeyer et al., "Translation correlations in anisotropically scattering media," Nature Physics (2015)

The tilt/tilt and shift/shift memory effects

Tilt/tilt correlation

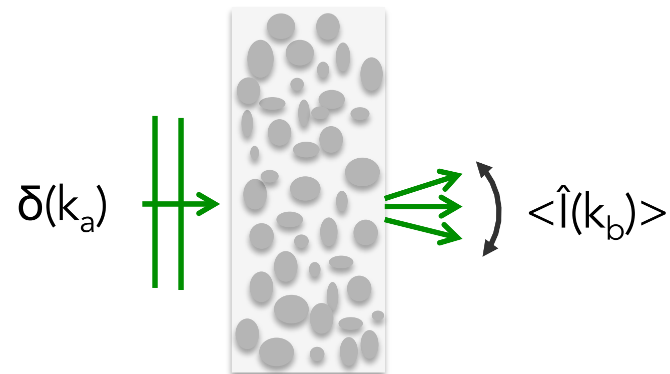


Spatial impulse response

$\downarrow$

Scanning in k

Shift/shift correlation



k-space impulse response

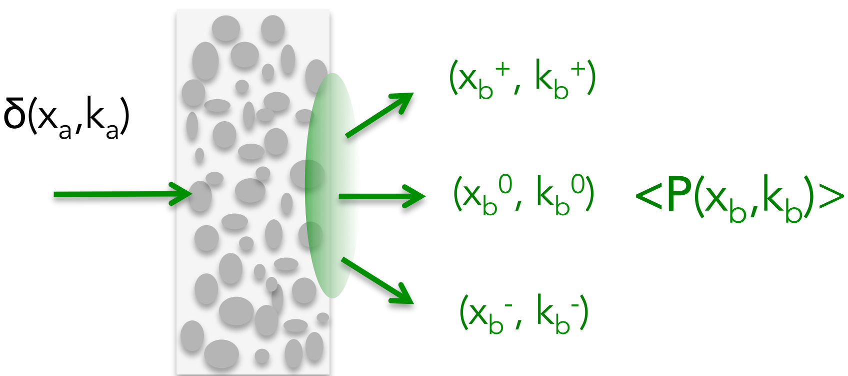
$\downarrow$

Scanning in x

How are these two effects connected?

The generalized memory effect: combining tilts and shifts

New input: "single ray"*



*Actually defined via the Wigner distribution, paper has math details:

G. Osnabrugge, R. Horstmeyer et al, "The generalized optical memory effect," Optica (2017)

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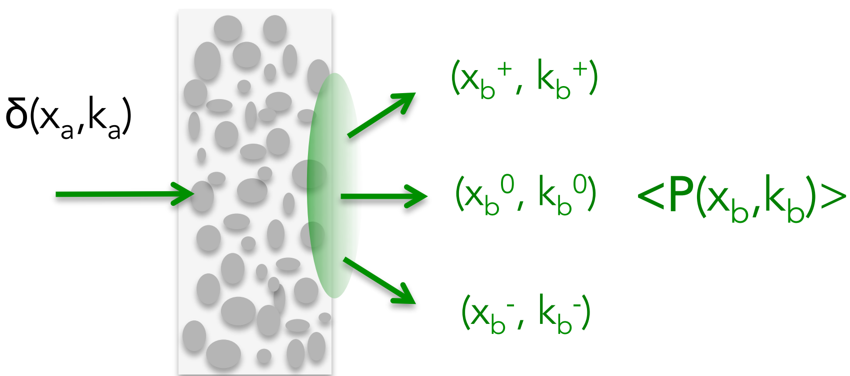
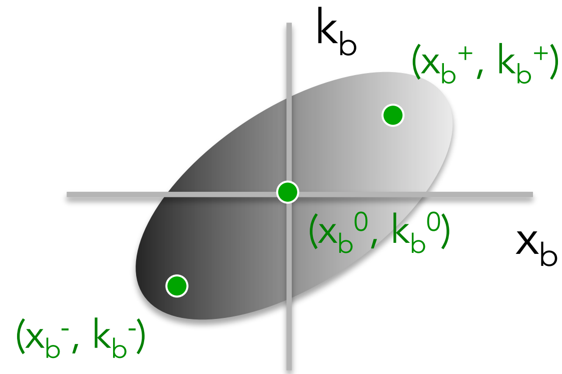


Space-angle response $<P(x_b,k_b)>$



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The generalized memory effect: combining tilts and shifts

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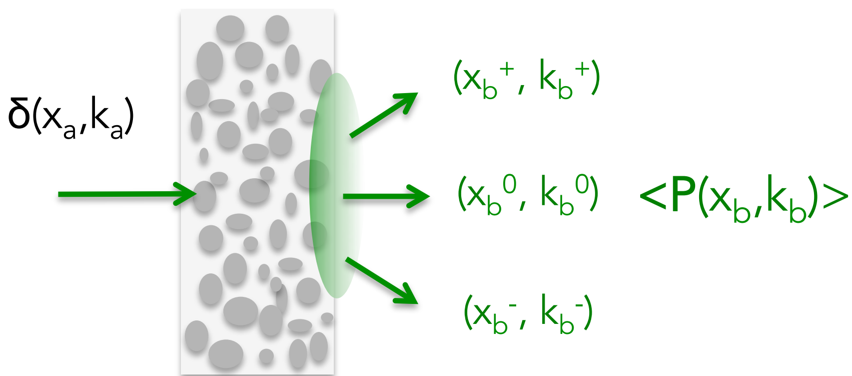

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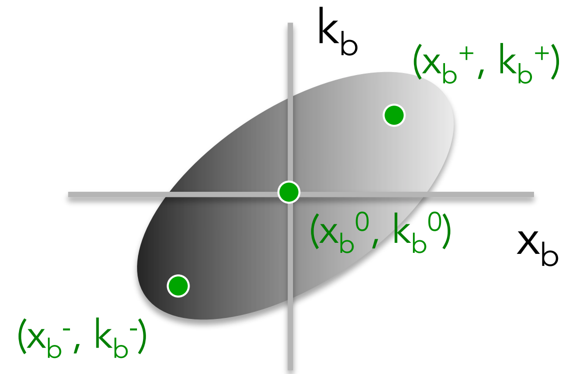


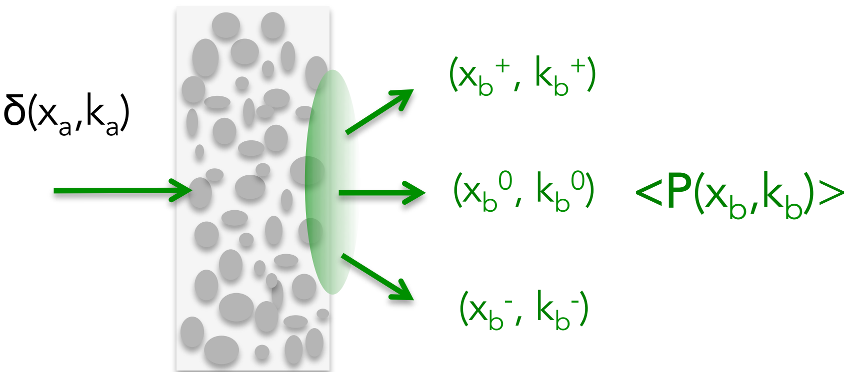
2D Fourier transform of space-angle response gives tilt/shift correlation:

$$\mathcal{F}_{2D}\left[\langle P(x_b, k_b)\rangle\right] \propto C(\Delta k, \Delta x)$$

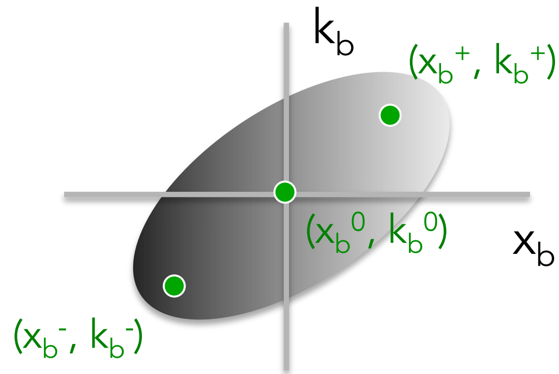
G. Osnabrugge, R. Horstmeyer et al, "The generalized optical memory effect," Optica (2017)

The generalized memory effect: combining tilts and shifts

New input: "single ray"



Space-angle response $\langle P(x_b,k_b)\rangle$



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$$\mathcal{F}_{2D}\left[\langle P(x_b,k_b)\rangle\right] \propto C(\Delta k, \Delta x)$$

4D Fourier transform used when scattering is not tilt/shift invariant:

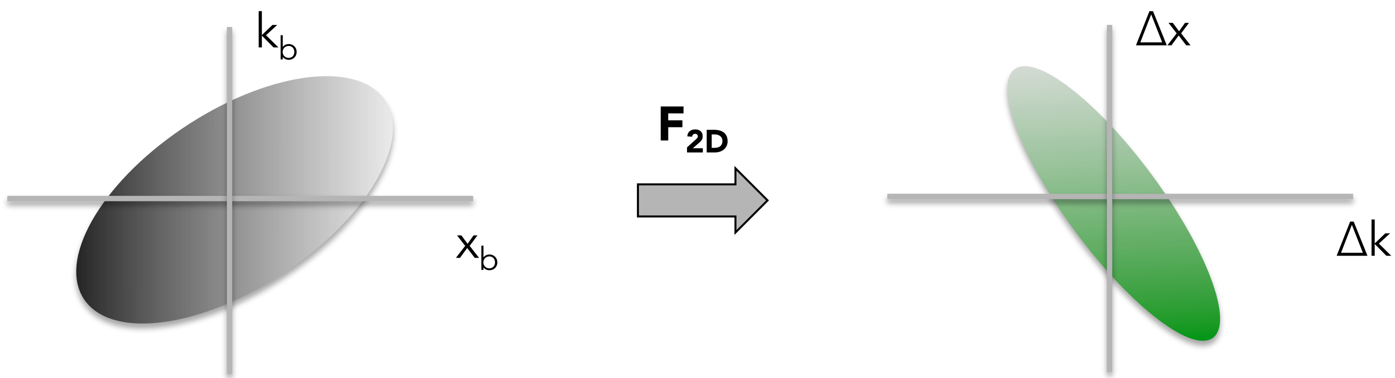
$$\mathcal{F}_{4D}\left[\langle P(x_a,k_a,x_b,k_b)\rangle\right] \propto C(\Delta k_a, \Delta x_a, \Delta k_b, \Delta x_b)$$

G. Osnabrugge, R. Horstmeyer et al, "The generalized optical memory effect," Optica (2017)

The generalized memory effect: is it important?

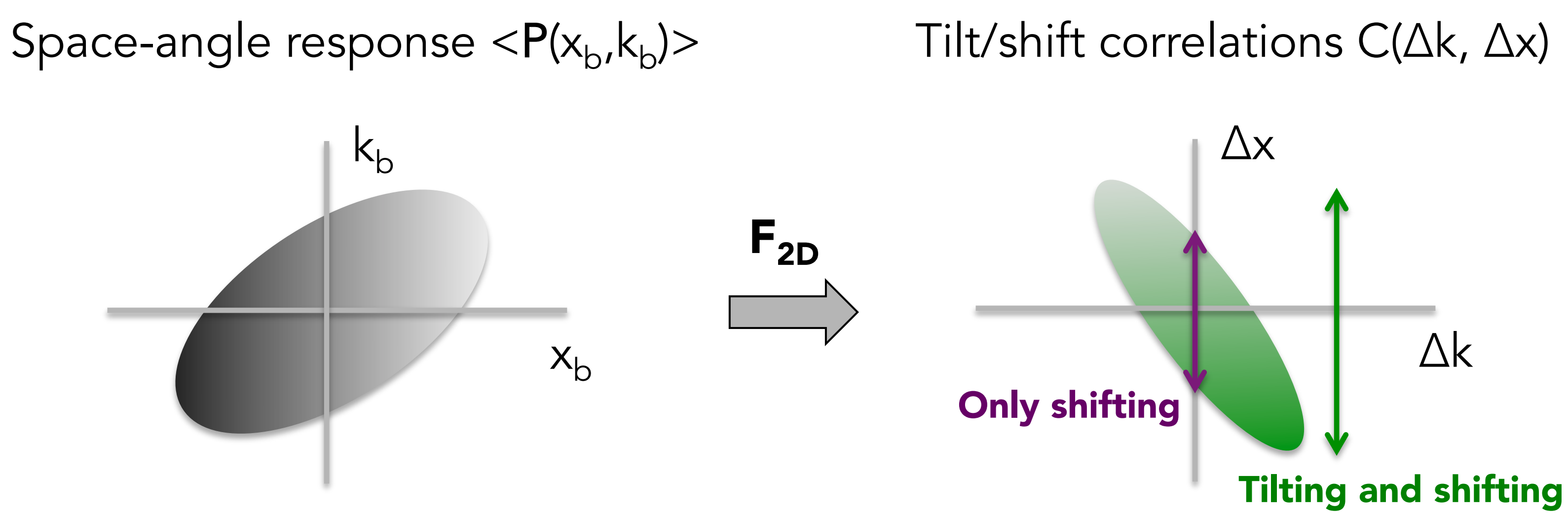
Space-angle response $<\mathbf{P}(x_b,k_b)>$

Tilt/shift correlations $C(\Delta k, \Delta x)$



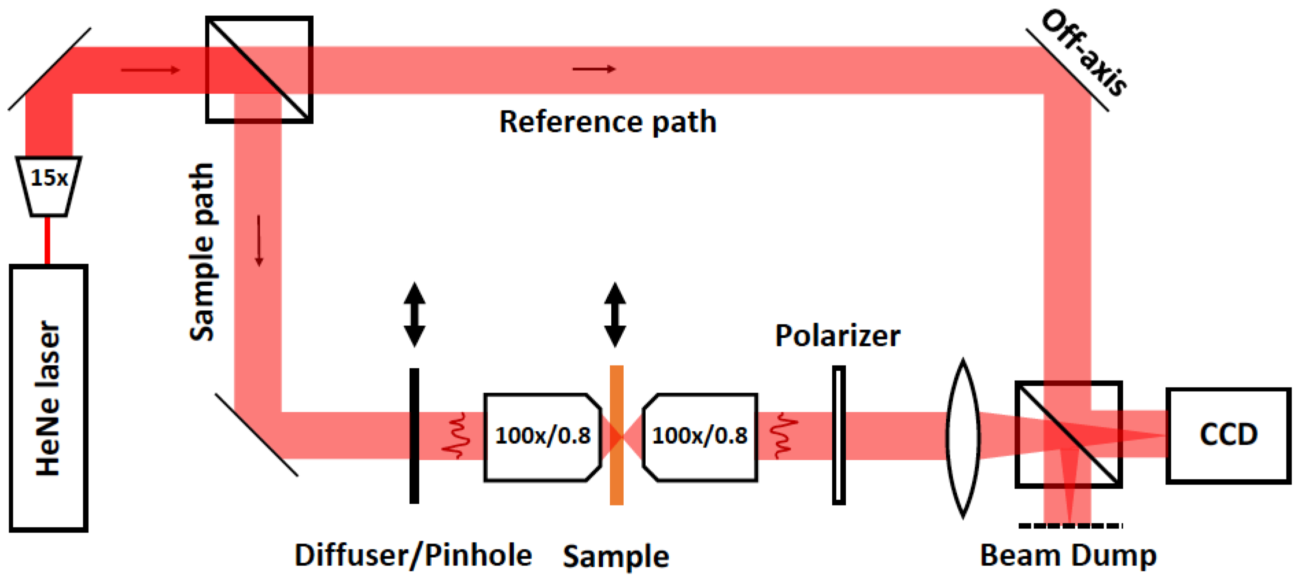
- Tilting and shifting correlations generally not independent

The generalized memory effect: is it important?



- Tilting and shifting correlations generally not independent
- Optimal tilt and shift combo can achieve larger scan range

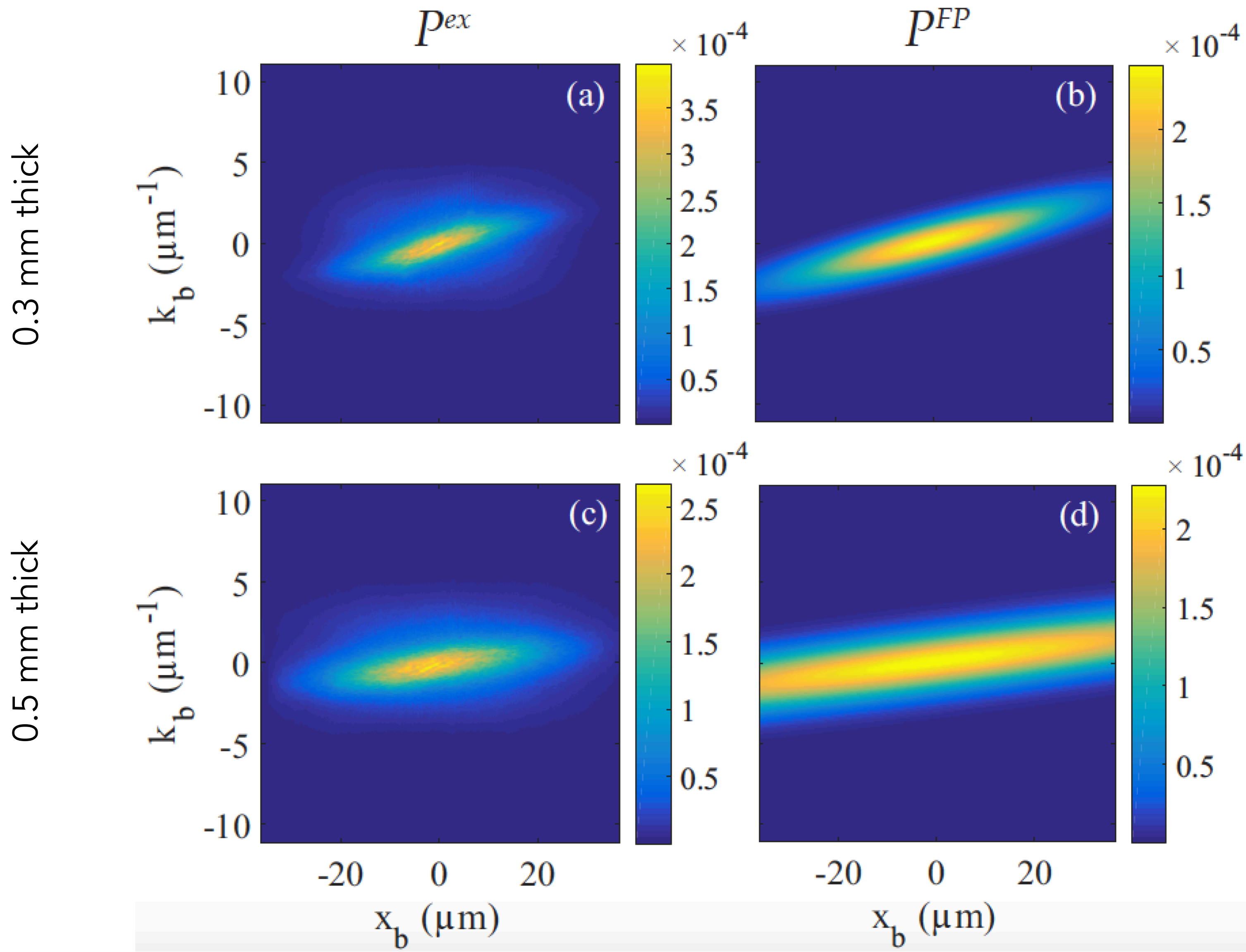
Experimental setup



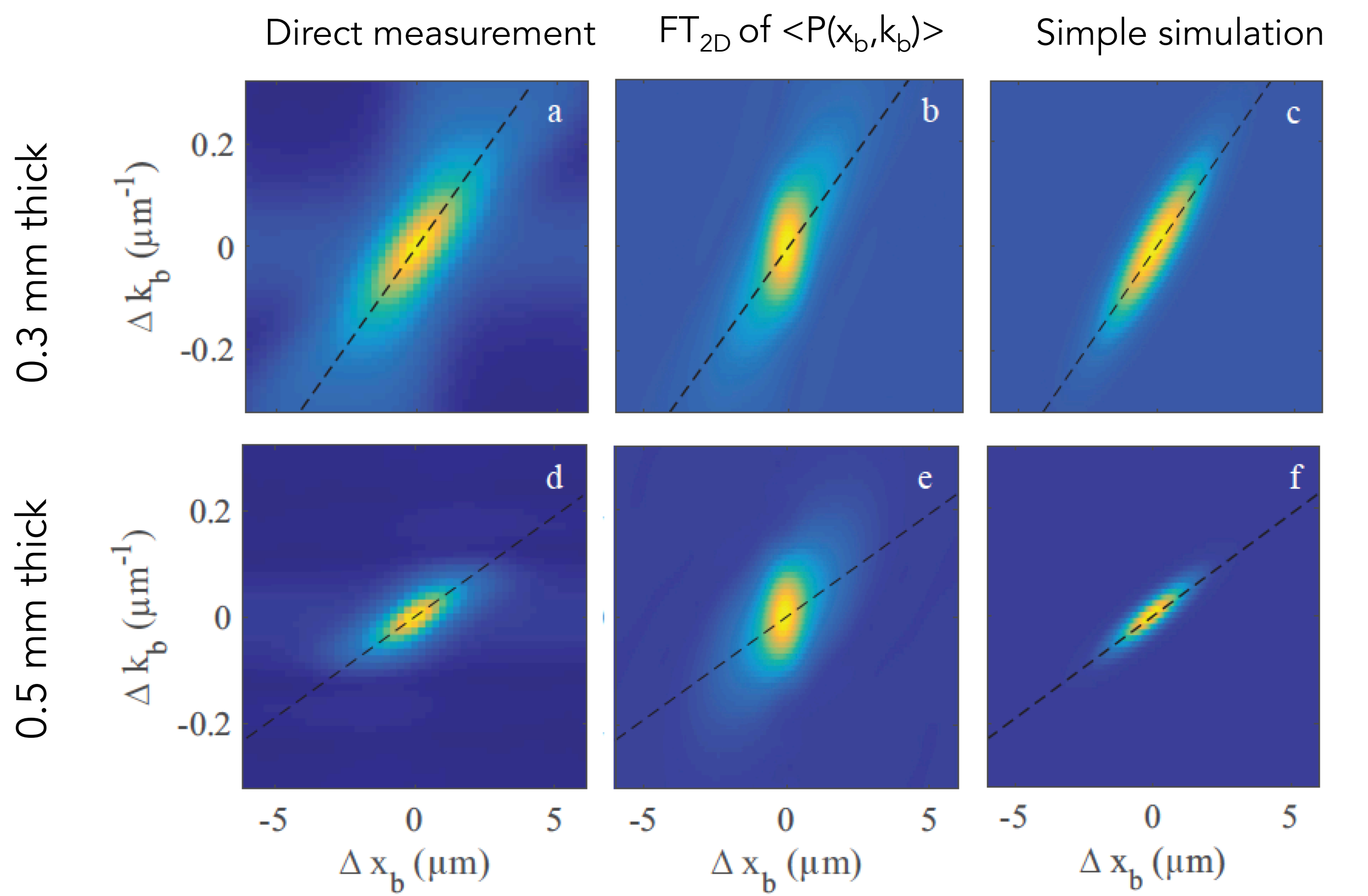
- Two experiments:
  1. Pencil beam response, $\langle P(x_b,k_b) \rangle$
  2. Shift/tilt correlation function (shift both diffuser & sample)

- Tissue phantom samples (5 μm spheres in agar, g=0.97, 0.3 mm – 1 mm thick)

Average space-angle scattering response to pencil beam



Directly measured shift/tilt correlations



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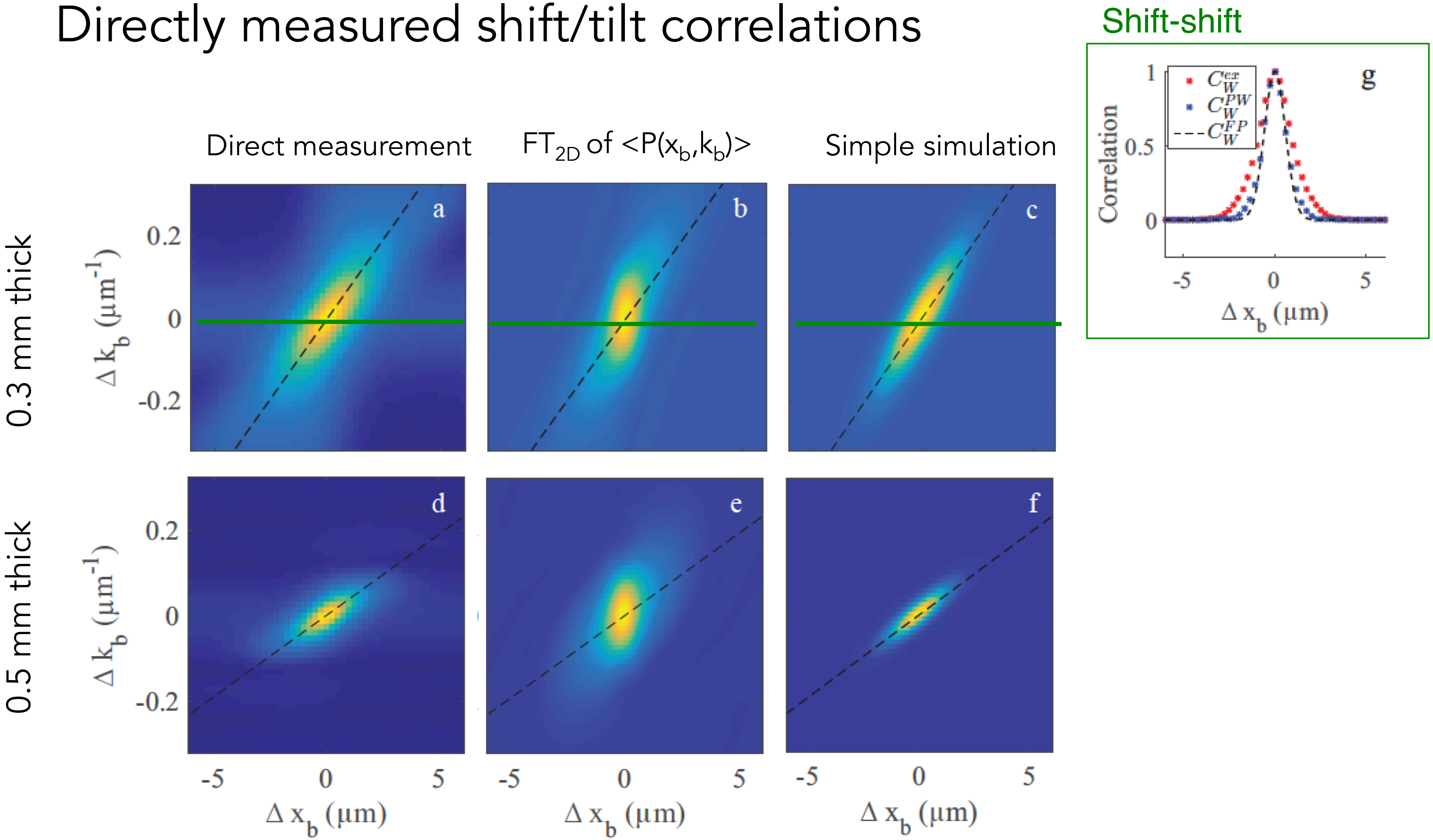

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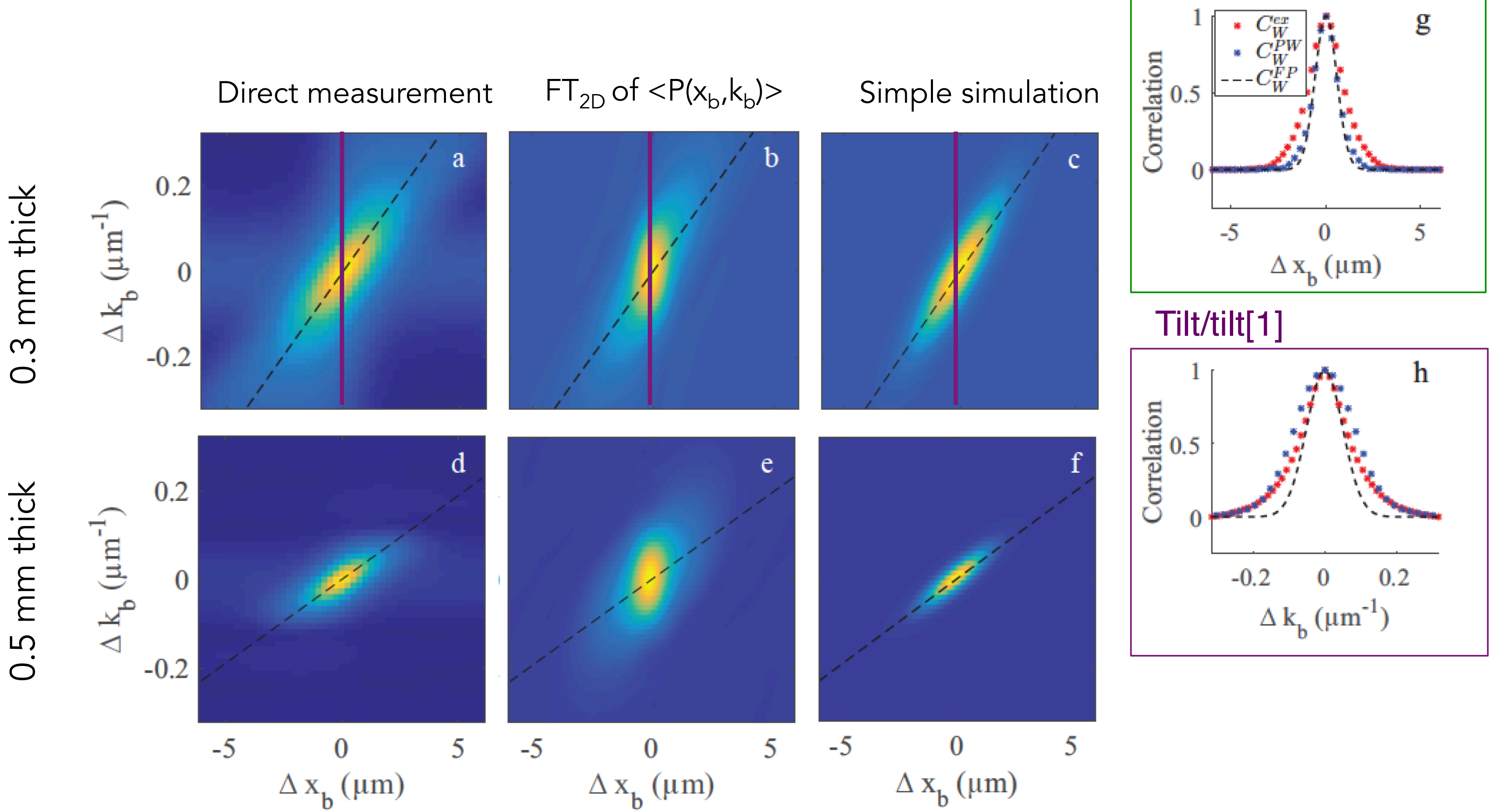


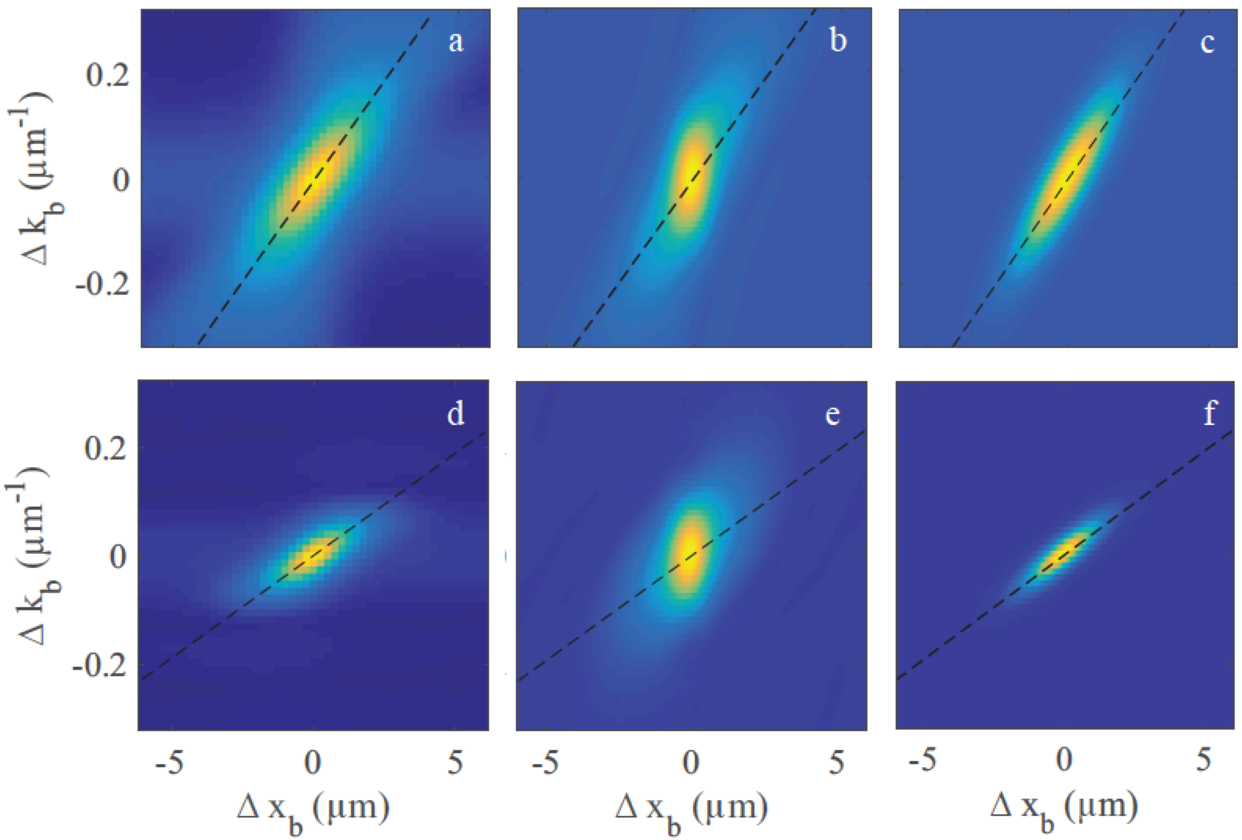
[1] S. Schott et al., "Characterization of the angular memory effect of scattered light in biological tissue," Opt. Express (2015)

Directly measured shift/tilt correlations

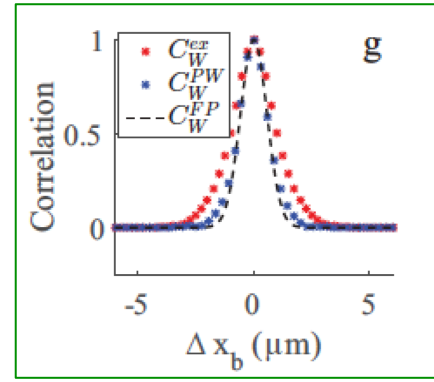
Direct measurement | FT$_{2D}$ of $\langle P(x_b,k_b)\rangle$ | Simple simulation

0.3 mm thick

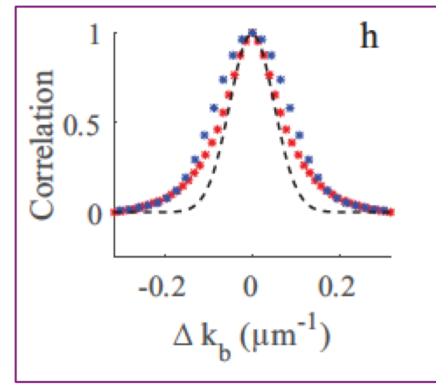
0.5 mm thick



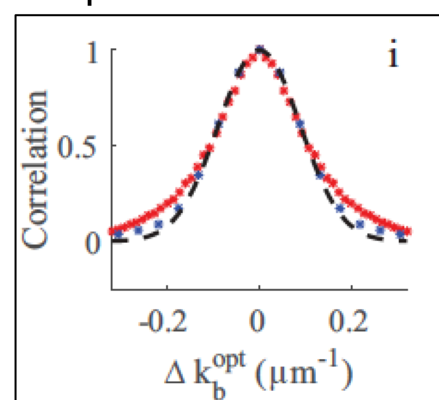
Shift-shift



Tilt/tilt[1]

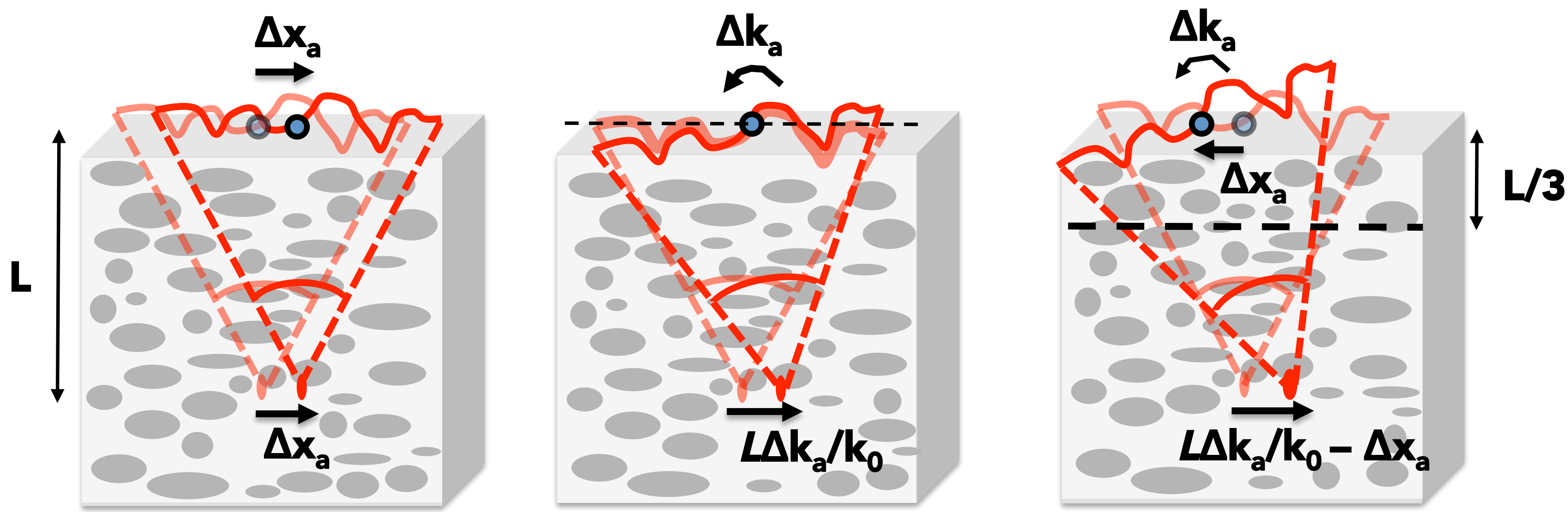


Optimal shift/tilt



[1] S. Schott et al., "Characterization of the angular memory effect of scattered light in biological tissue," Opt. Express (2015)

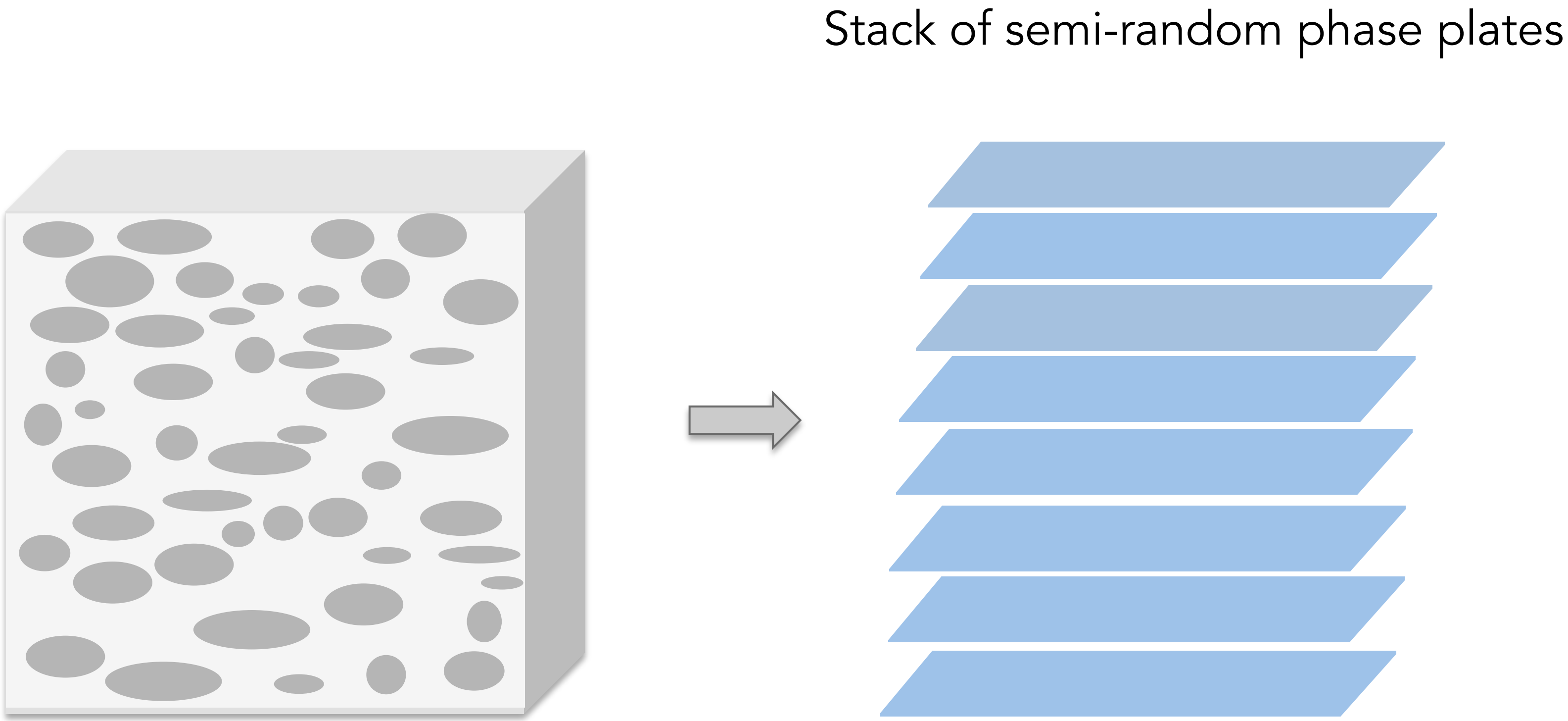
Scanning distances and the optimal rotation plane



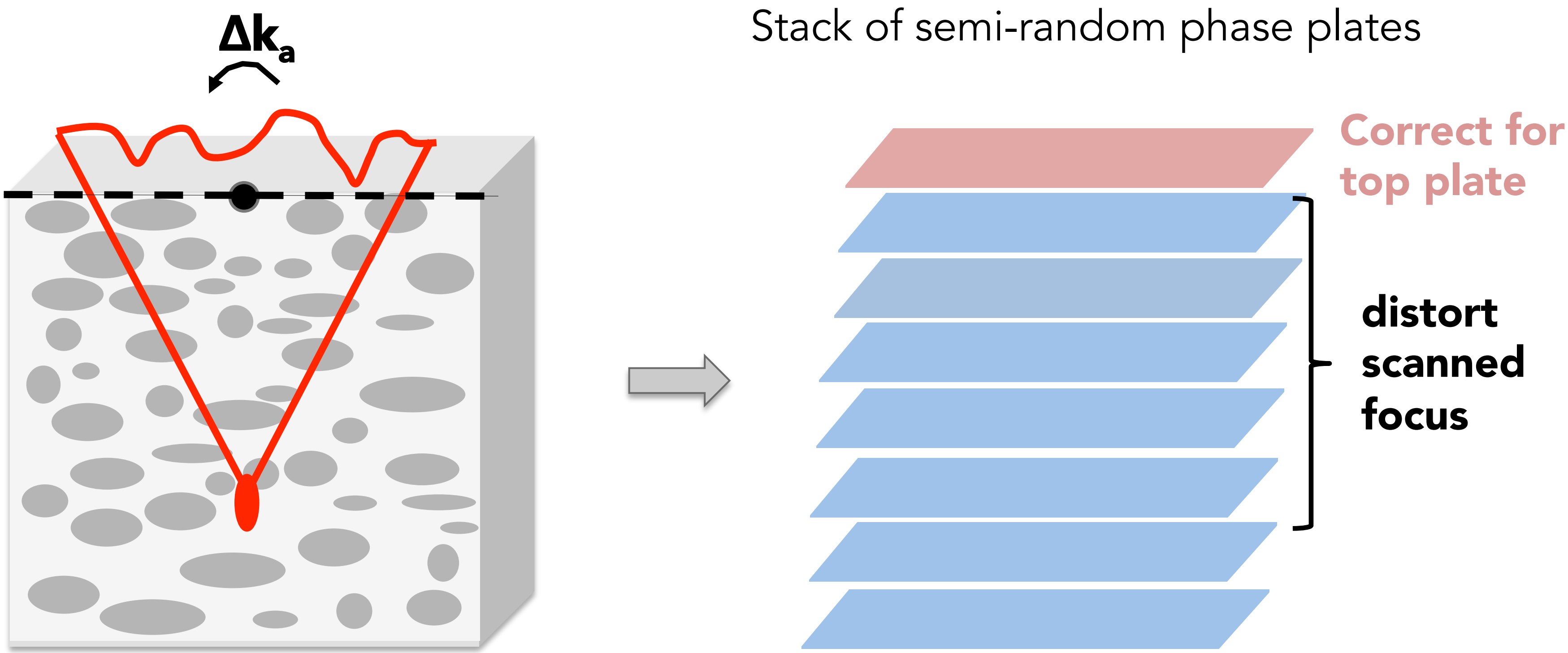
Optimally tilt and shift =
Tilt around plane **L/3** deep

Memory effect	Adaptive Optics	Tilt plane	Scan range
Shift	Pupil	$-\infty$	$\sqrt{2\ell_{tr}/k_0^2 L}$
Tilt	Surface Conjugate	0	$\sqrt{6\ell_{tr}/k_0^2 L}$
Generalized	Sample Conjugate	$L/3$	$\sqrt{8\ell_{tr}/k_0^2 L}$

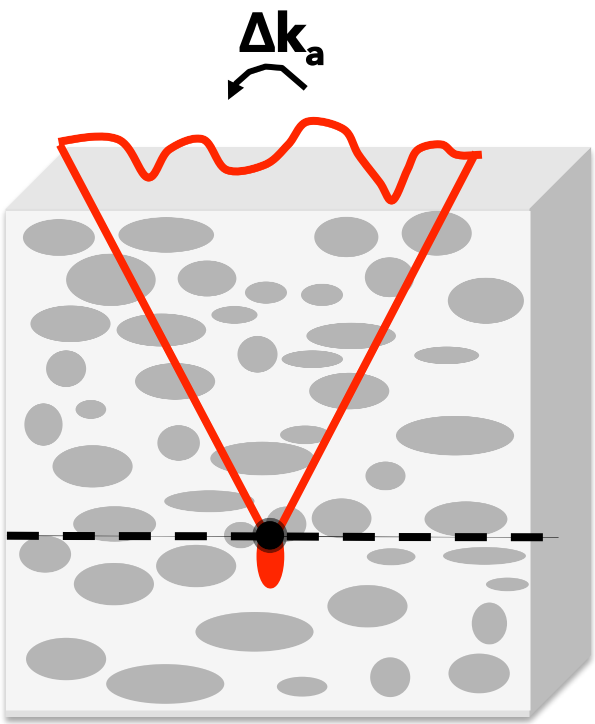
Why is L/3 optimal? An intuitive picture

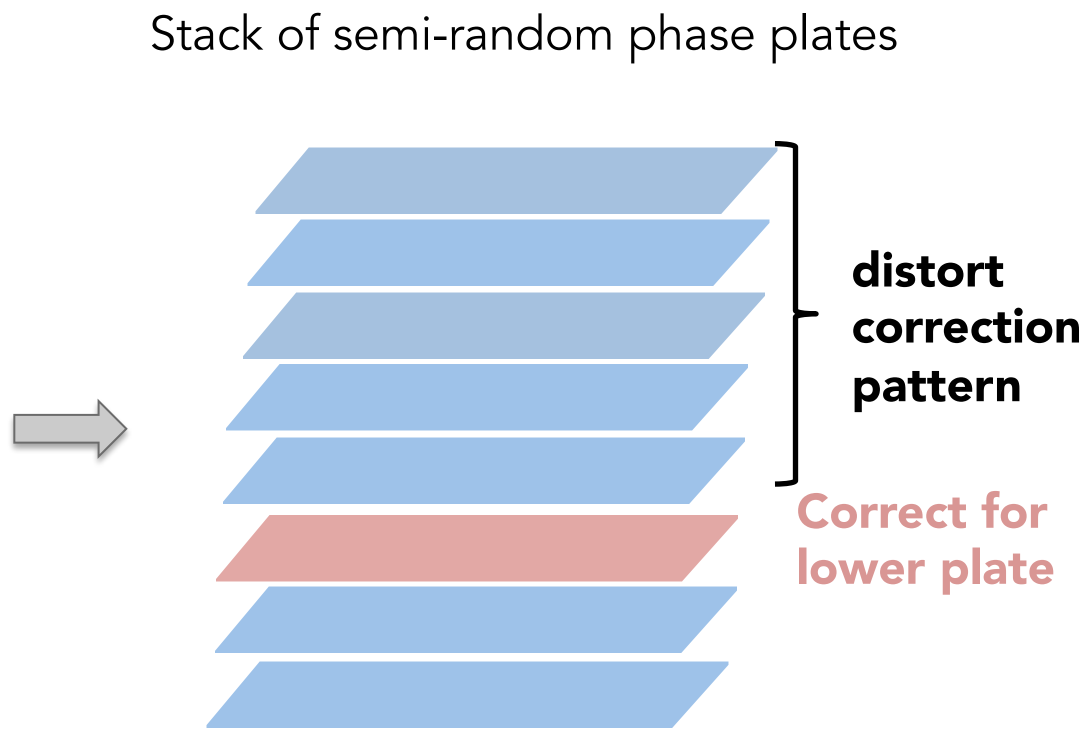


Why is L/3 optimal? An intuitive picture

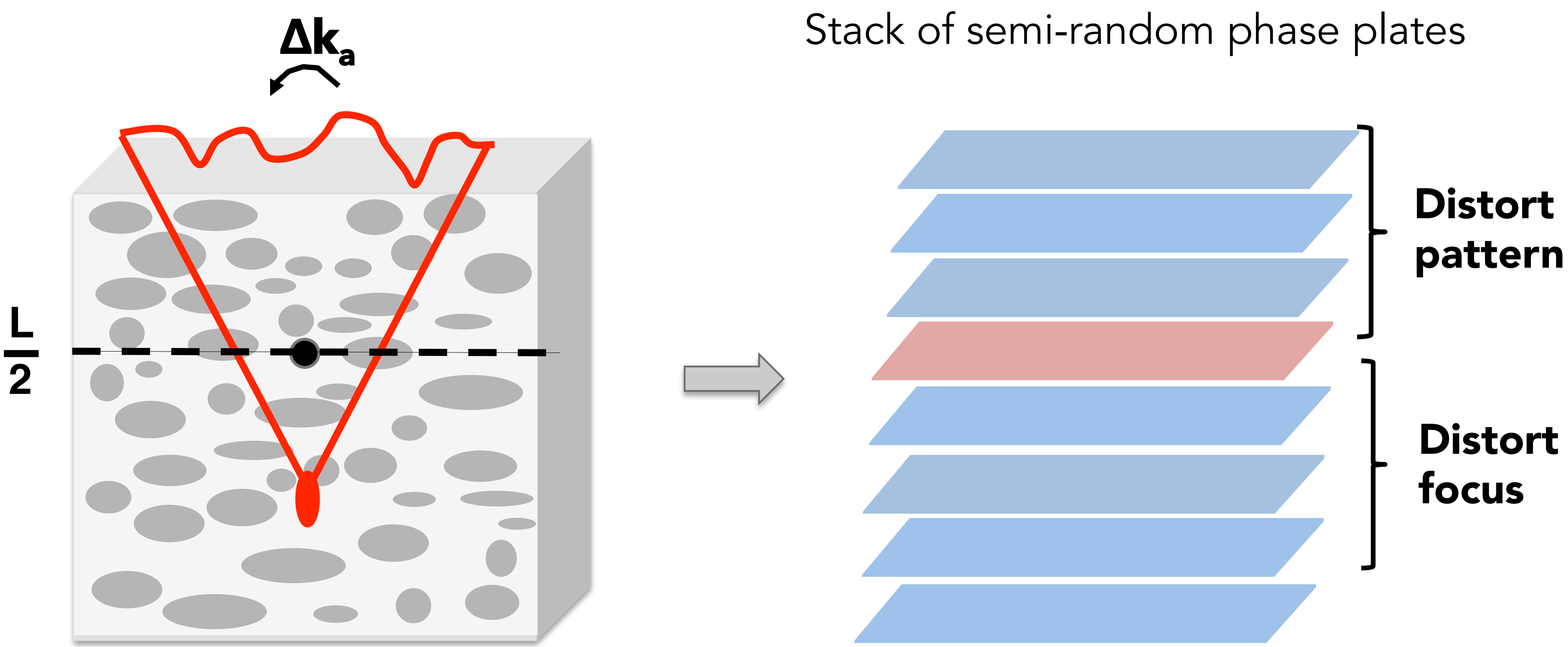


Why is L/3 optimal? An intuitive picture

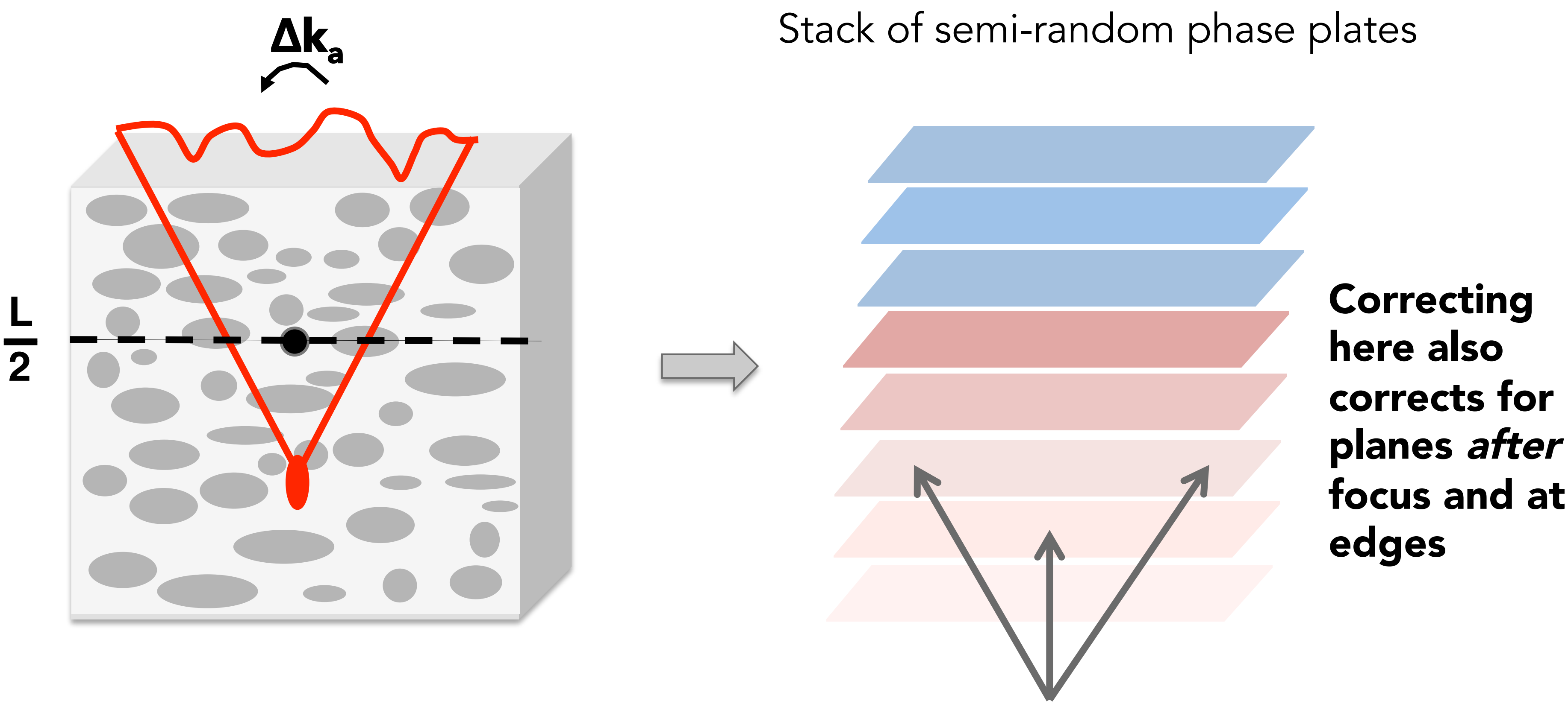




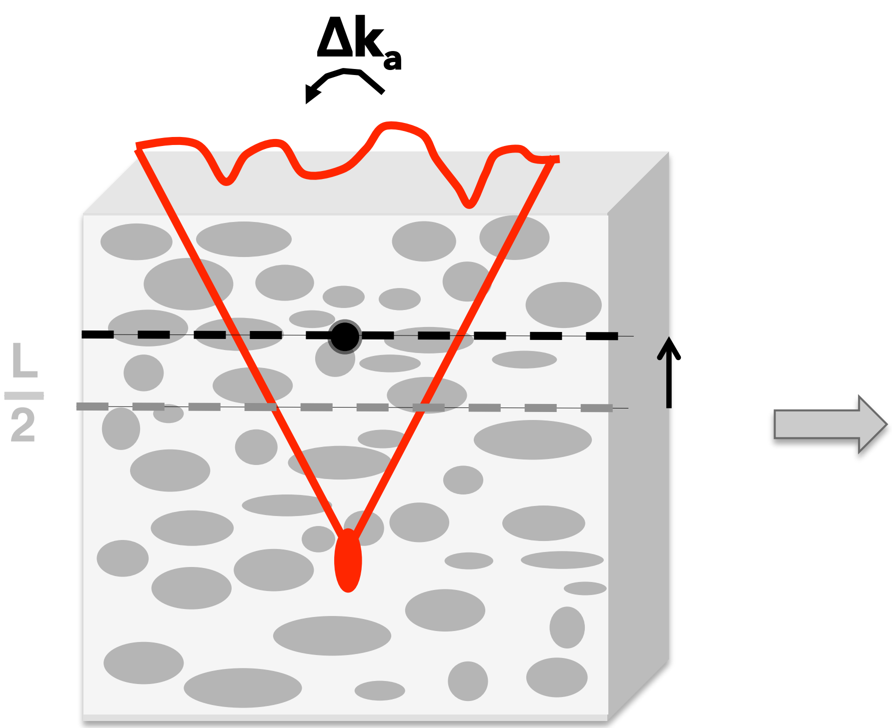
Why is L/3 optimal? An intuitive picture



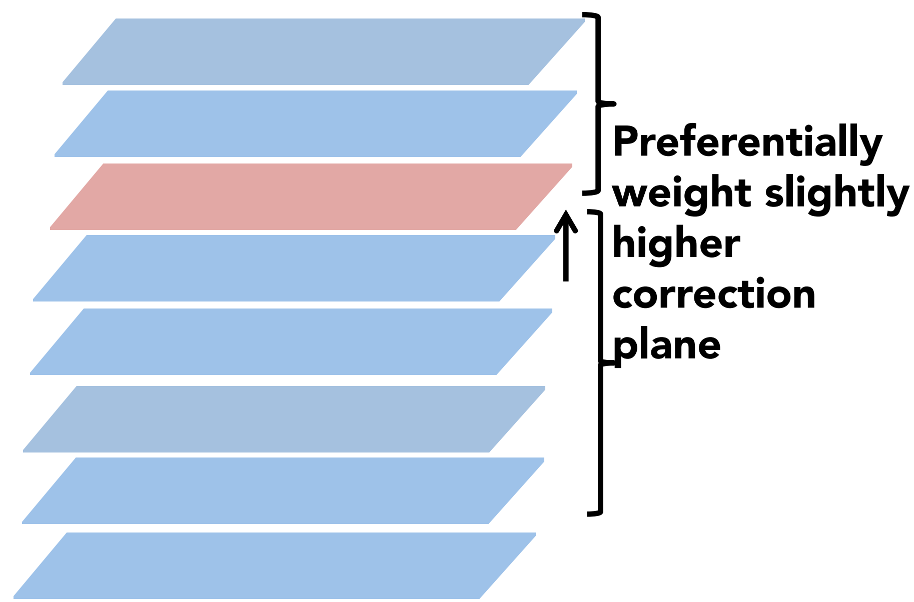
Why is L/3 optimal? An intuitive picture



Why is L/3 optimal? An intuitive picture

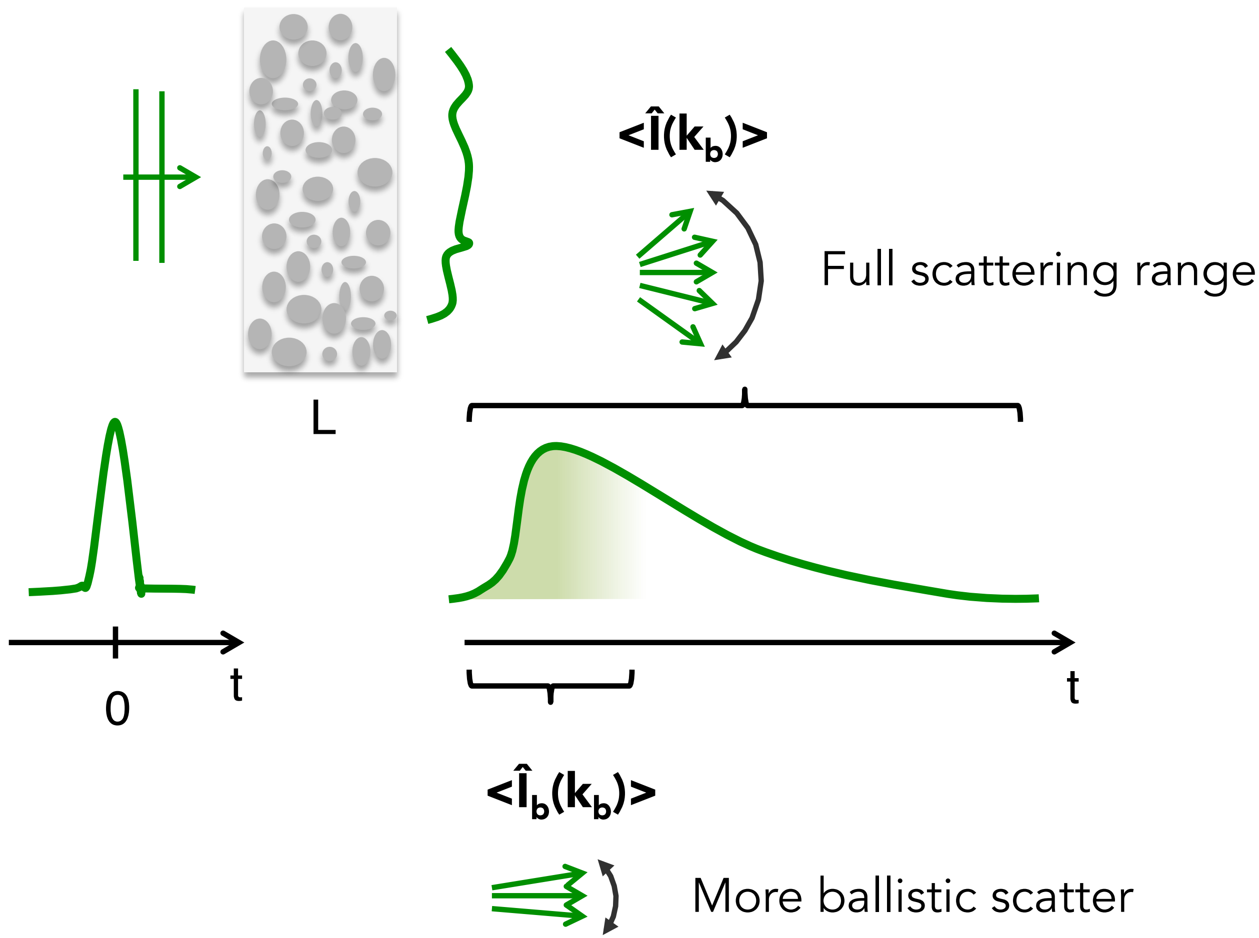


Stack of semi-random phase plates



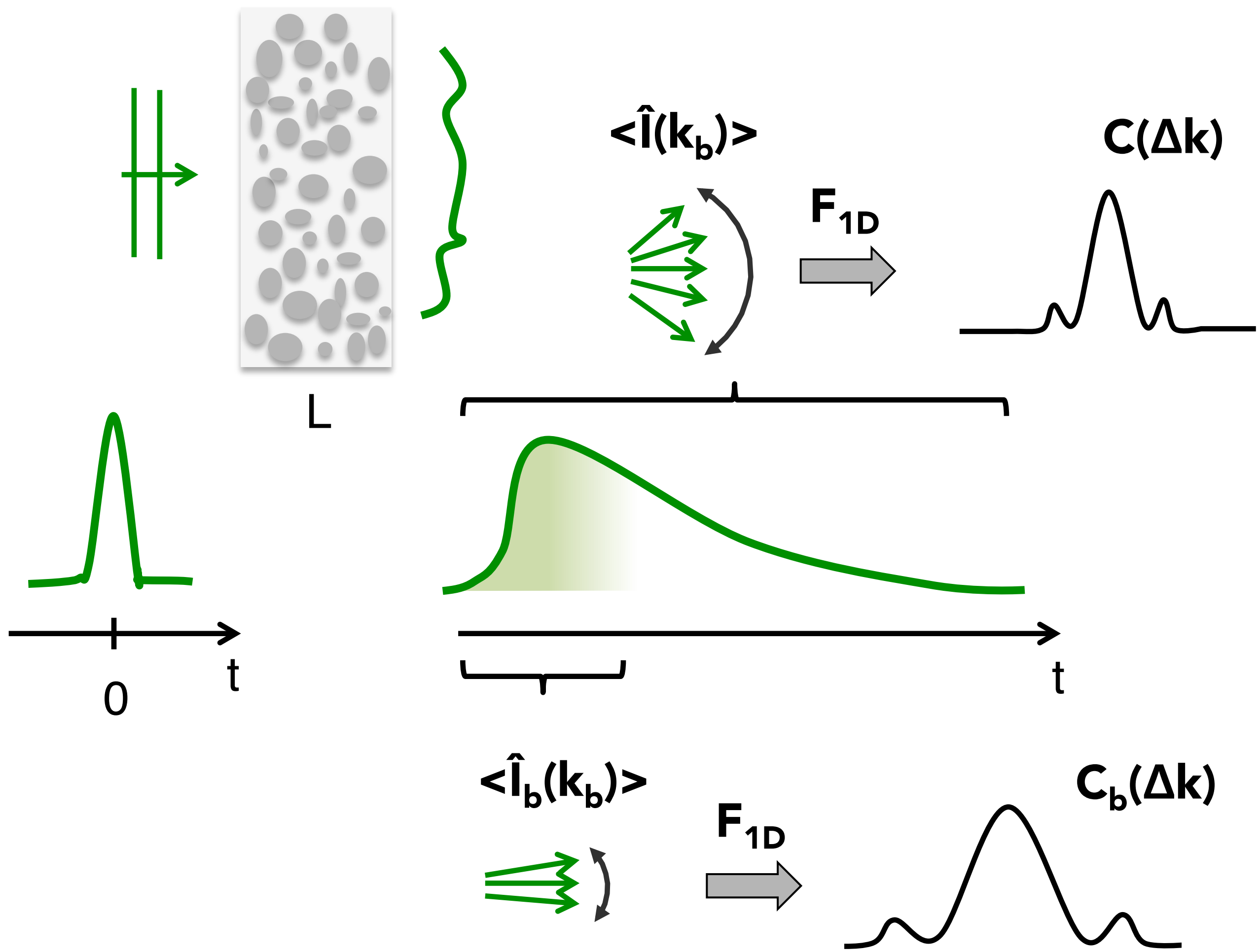
Towards a larger memory effect with time gating

- Goal: select early arriving "snake" photons for scanning

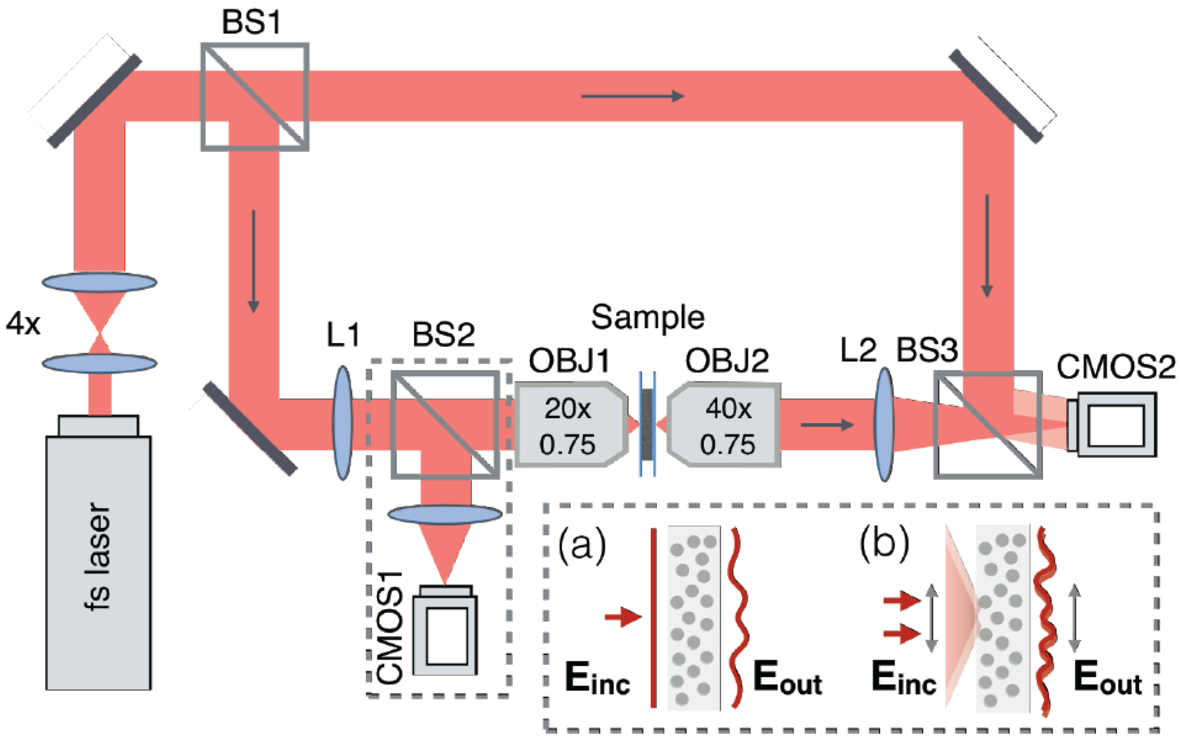


Towards a larger memory effect with time gating

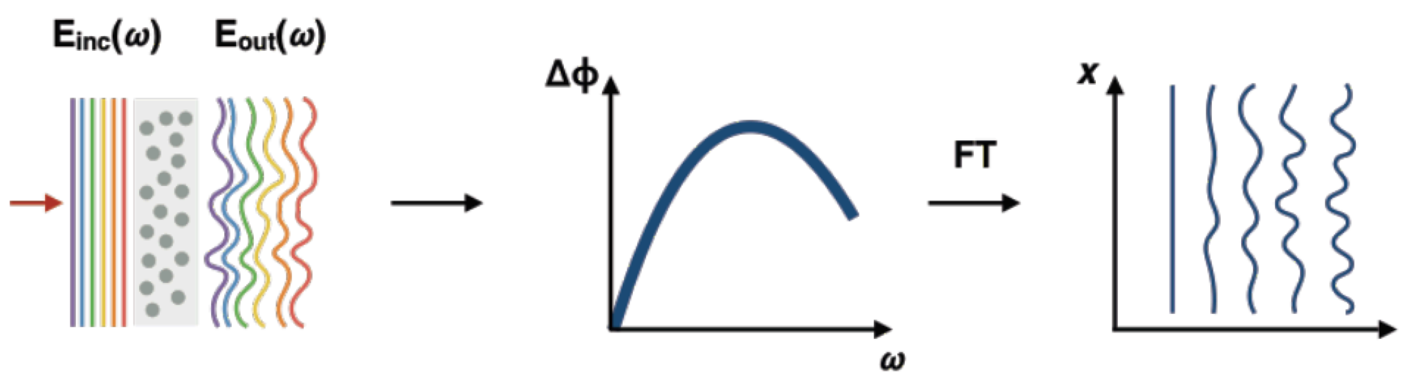
- Hypothesis: early arriving snake photons offer larger scan range



Experimental setup

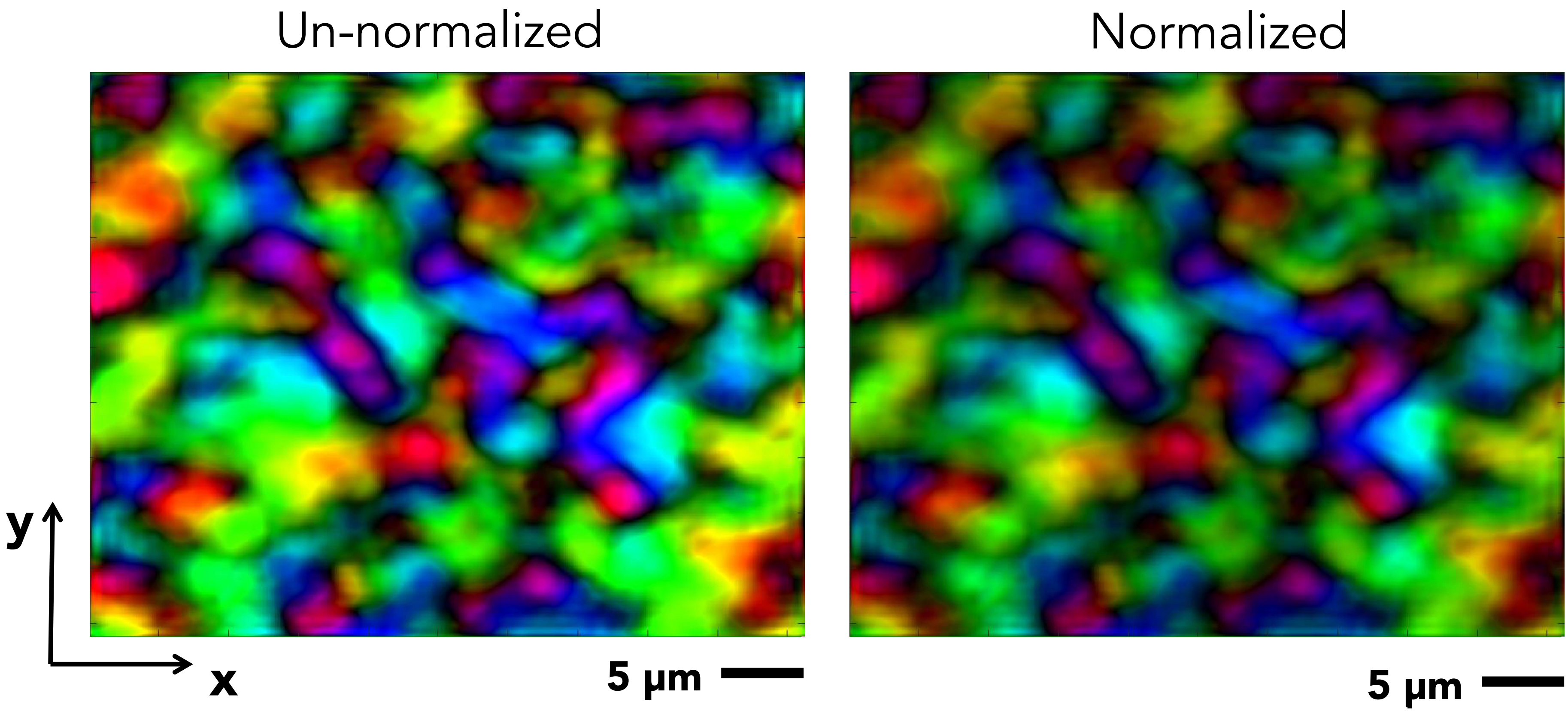


- Eventually obtained gating measurements in the spectral domain:



M. Kadobianskyi et al., "Scattering correlations of time-gated light," ArXiv 1707.06896 (2017)

Ultrafast speckle evolution over space



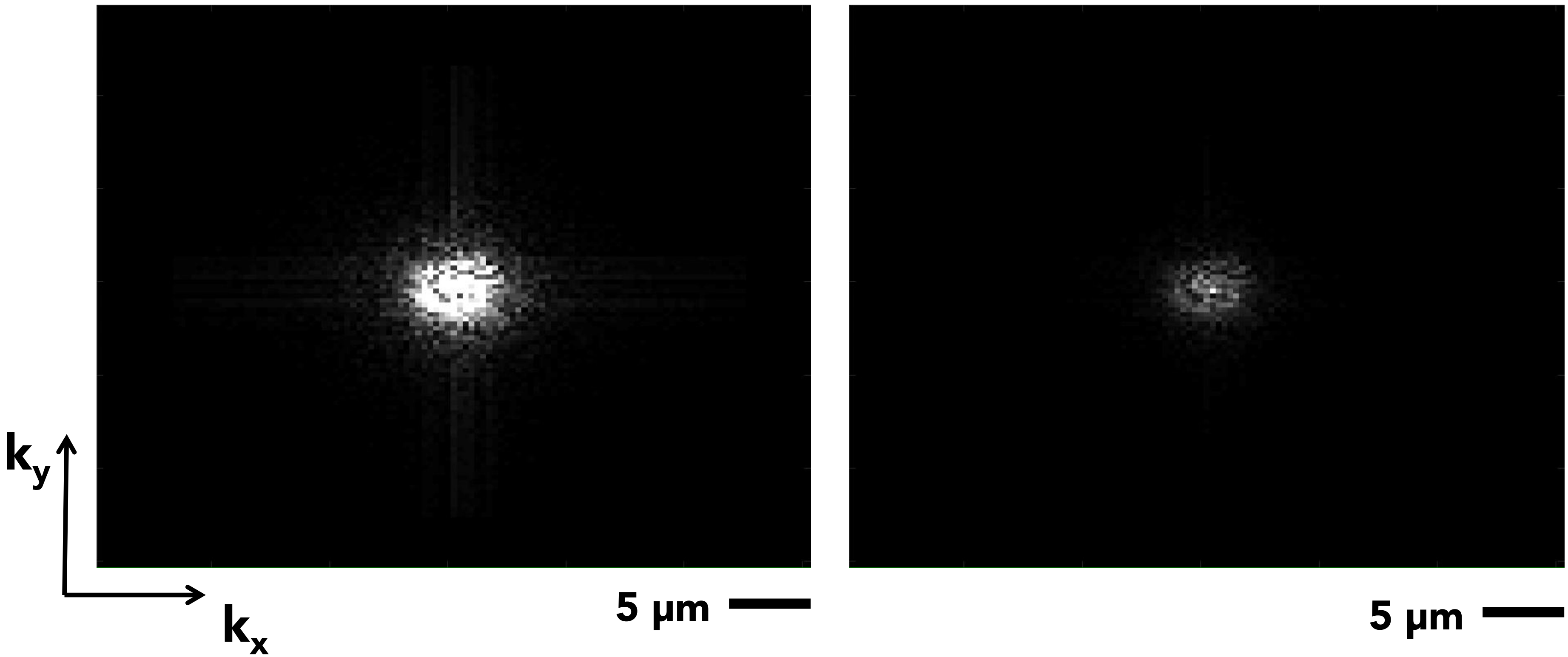
- Time step per frame: 8.5 femtoseconds
- 360 μm thick tissue phantom

M. Kadobianskyi et al., "Scattering correlations of time-gated light," ArXiv 1707.06896 (2017)

Ultrafast speckle evolution over wavevector

k-space, un-normalized

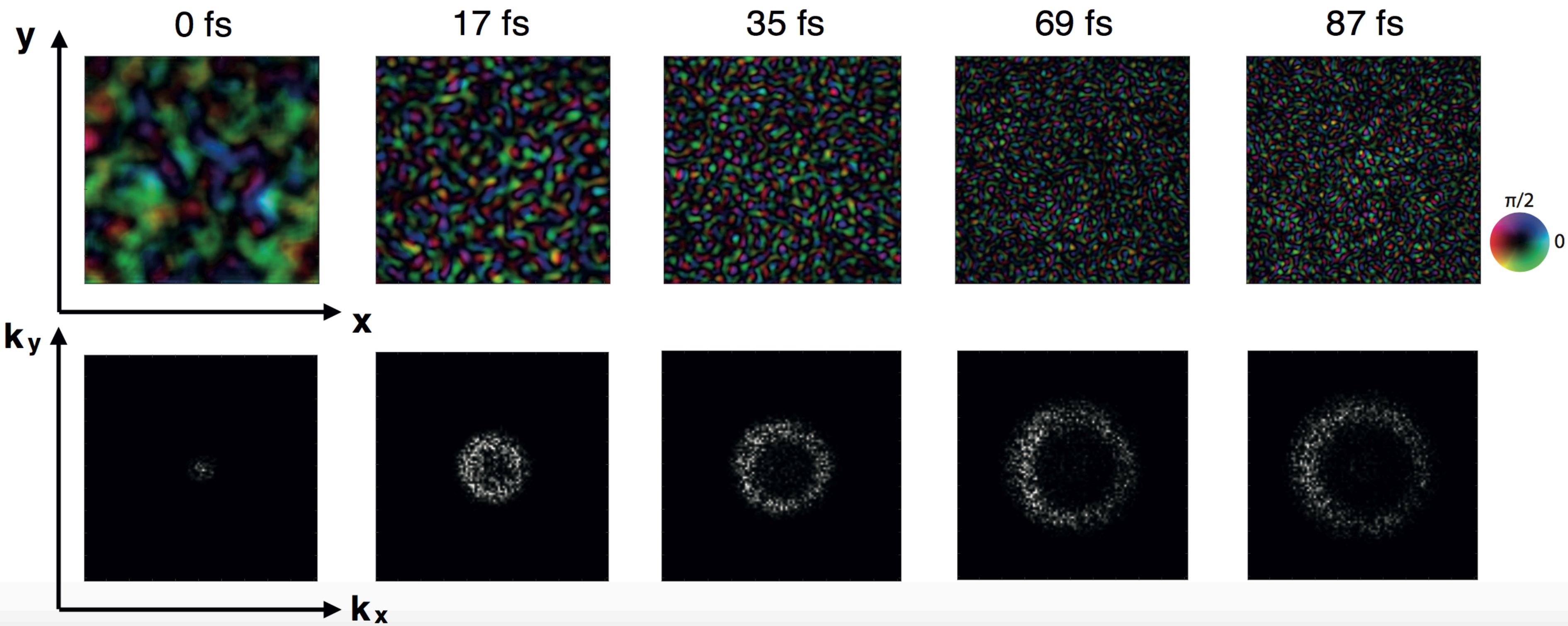
k-space, normalized



- Time step per frame: 8.5 femtoseconds
- 360 µm thick tissue phantom

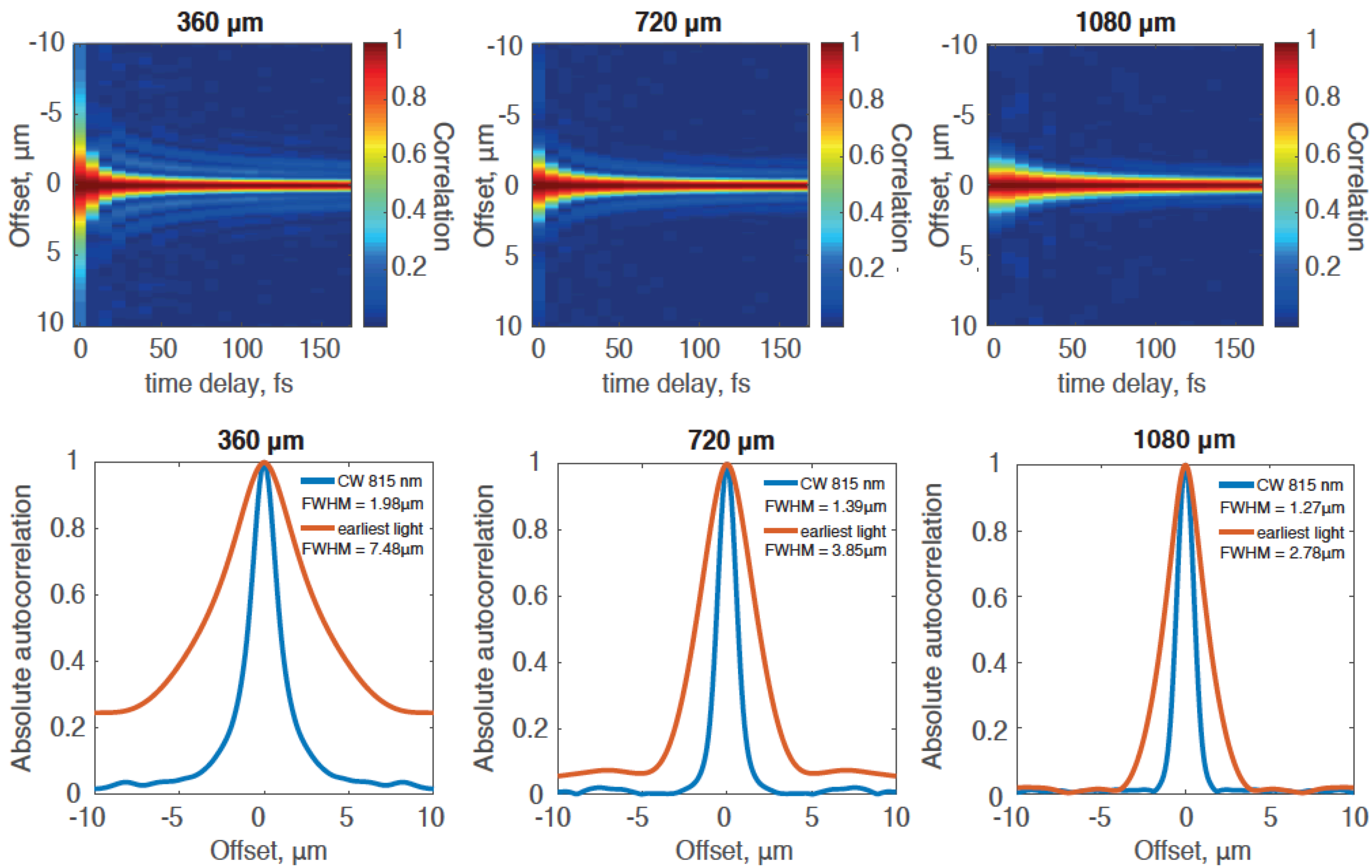
M. Kadobianskyi et al., "Scattering correlations of time-gated light," ArXiv 1707.06896 (2017)

Ultrafast speckle evolution over space and wavevector



M. Kadobianskyi et al., "Scattering correlations of time-gated light," ArXiv 1707.06896 (2017)

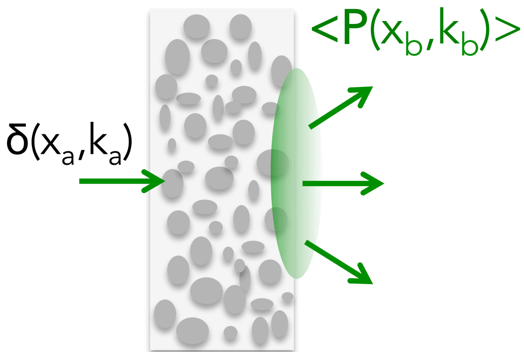
Time gating extends the shift-shift memory effect 3-4X



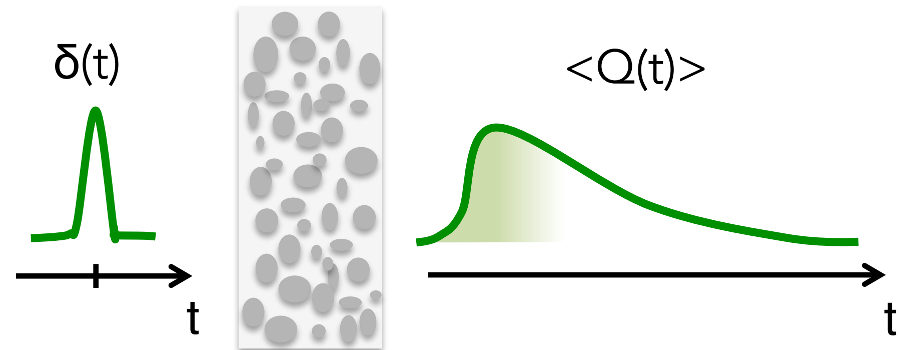
M. Kadobianskyi et al., "Scattering correlations of time-gated light," ArXiv 1707.06896 (2017)

To do: Put all of this together

Shift/tilt memory effect



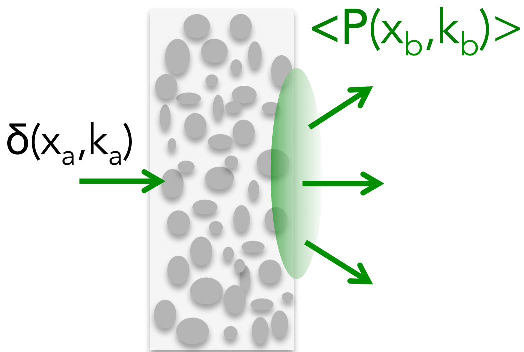
Time gating



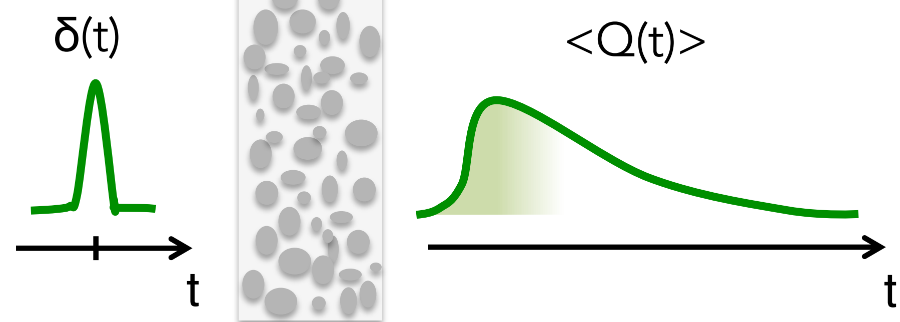
<u>1. Combine above</u>: $\mathcal{F}\left[\langle P(x_b.k_b, t_b, \omega_b)\rangle\right] \rightarrow C(\Delta k, \Delta x, \Delta\omega, \Delta t)$?

To do: Put all of this together

Shift/tilt memory effect

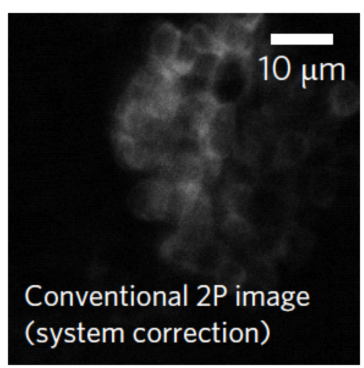


Time gating

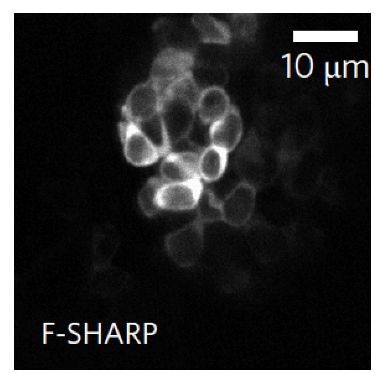


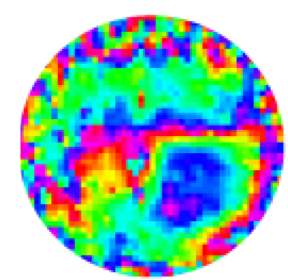
1. Combine above: $\mathcal{F}\left[\langle P(x_b.k_b, t_b, \omega_b)\rangle\right] \rightarrow C(\Delta k, \Delta x, \Delta \omega, \Delta t)$?

2. Implement with F-Sharp[1]



→

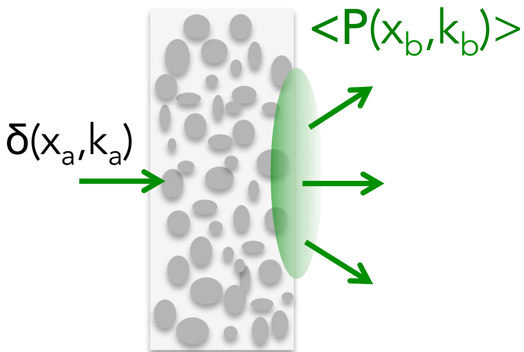




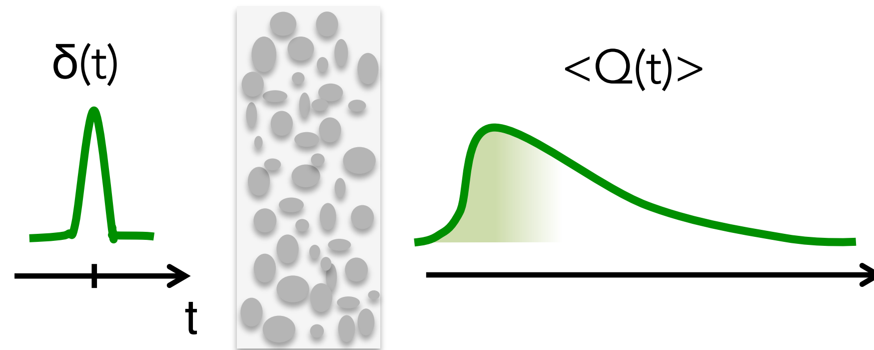
[1] I. N. Papadopoulos et al., "Scattering compensation by focus scanning holographic aberration probing (F-SHARP)," Nature Photon. 2016

To do: Put all of this together

Shift/tilt memory effect

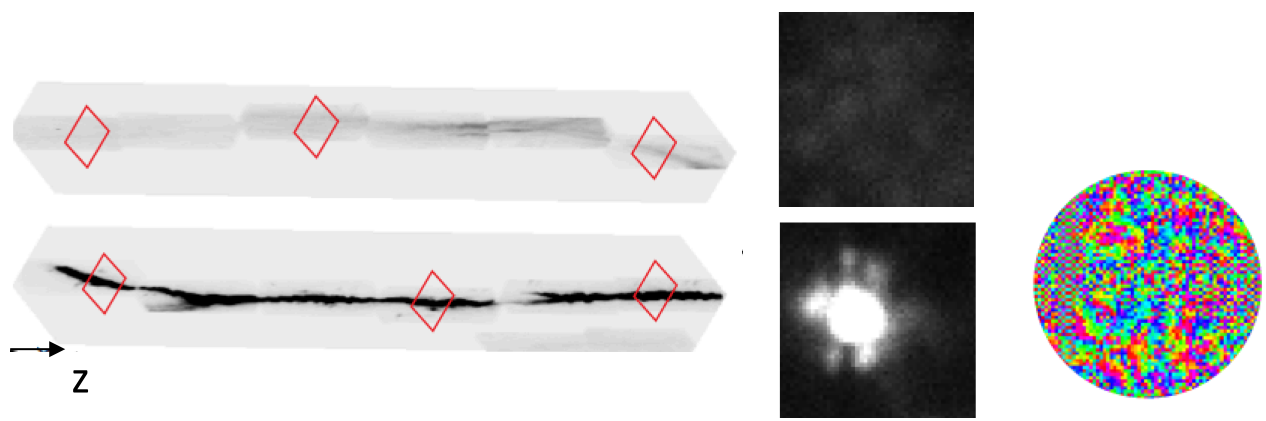


Time gating



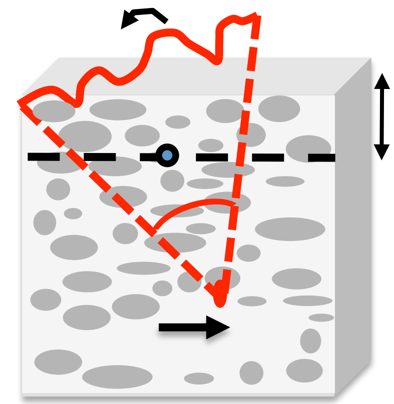
<u>1. Combine above</u>: $\mathcal{F}\left[\langle P(x_b.k_b, t_b, \omega_b)\rangle\right] \rightarrow C(\Delta k, \Delta x, \Delta\omega, \Delta t)$?

<u>2. Implement with F-Sharp[1]</u>



[1] I. N. Papadopoulos et al., "Scattering compensation by focus scanning holographic aberration probing (F-SHARP)," Nature Photon. 2016

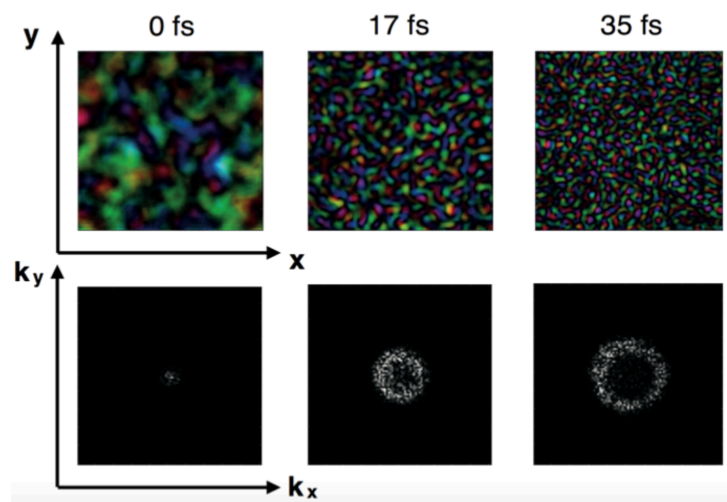
Thank you!



Joint work with:

<u>University of Twente:</u>
Gerwin Osnabrugge
Ivo M. Vellekoop

<u>Charité Medical School:</u>
Yiannis Papadopoulos
Nick Kadobianskyi
Benjamin Judkewitz



2018: starting as an assistant professor in Duke University's Biomedical Engineering Department, contact me if you'd like to chat!

Quick derivation of L/3 depth:

Fokker-Plank model for correlation in anisotropic scatterer:

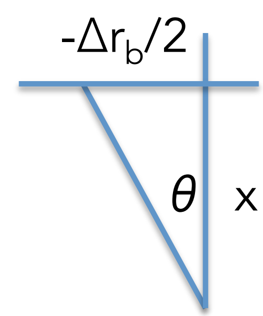
$$C_W^{FP}(\Delta\mathbf{r}_b, \Delta\mathbf{k}_b) = \exp\left(-\frac{L^3 k_0^2}{2\ell_{tr}}\left[\frac{|\Delta\mathbf{k}_b|^2}{3k_0^2} - \frac{\Delta\mathbf{k}_b \cdot \Delta\mathbf{r}_b}{k_0 L} + \frac{|\Delta\mathbf{r}_b|^2}{L^2}\right]\right). \quad (10)$$

Find optimal Δk_b: take derivative w.r.t. Δk_b and set to 0:

$$\Delta\mathbf{k}_b^{opt} = \frac{3k_0\Delta\mathbf{r}_b}{2L}.$$

Use $\Delta k_a = \Delta k_b$ and $\Delta r_b = \Delta r_a + \Delta k_a k_0/L$:

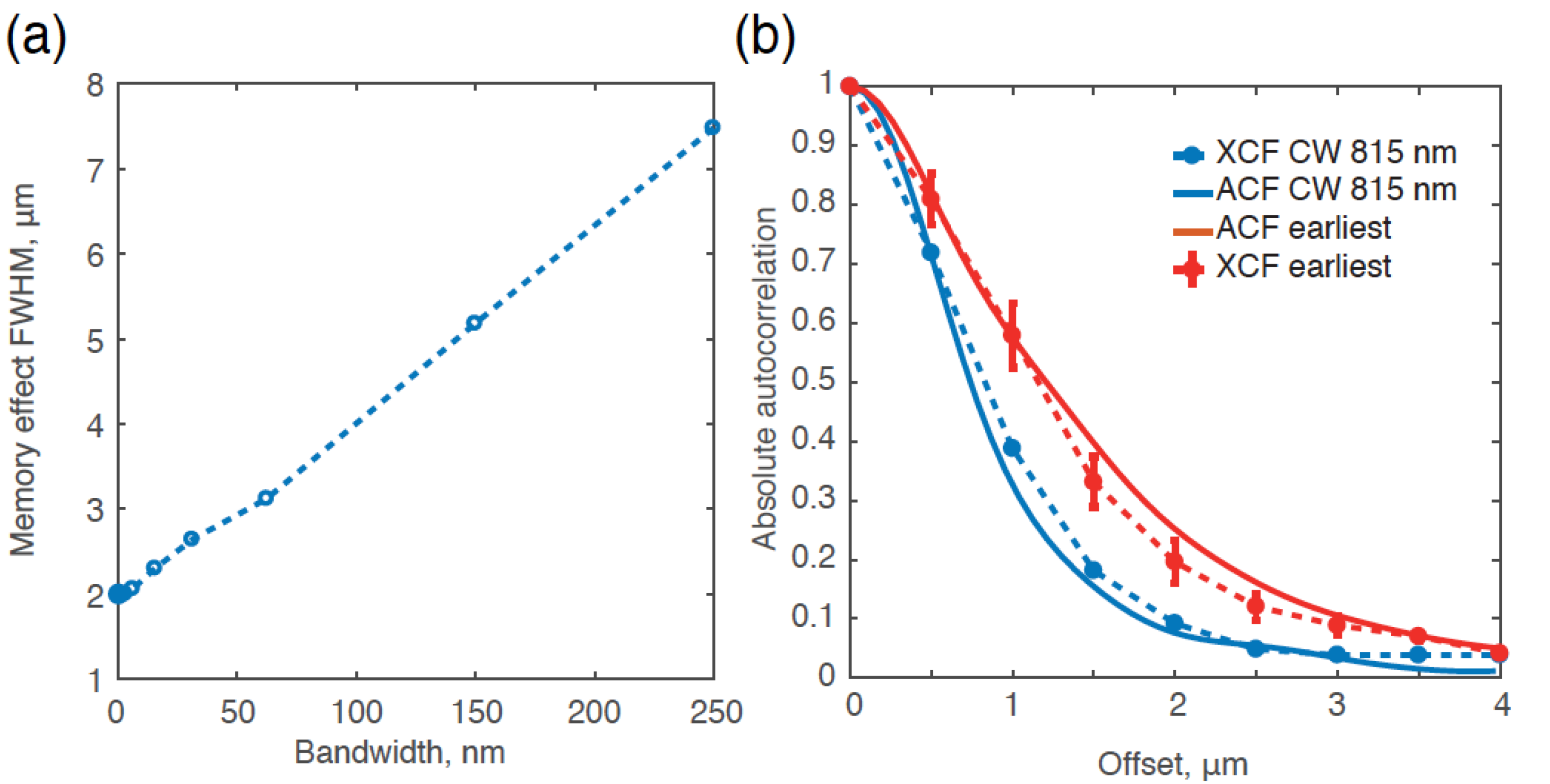
$$\Delta\mathbf{k}_a^{opt} = \frac{3k_0\Delta\mathbf{r}_b}{2L} \text{ and } \Delta\mathbf{r}_a^{opt} = -\Delta\mathbf{r}_b/2$$



$\mathrm{Tan}(\theta) \sim \theta = (1/k_0) * 3k_0\Delta r_b/2L = \Delta r_b/2x$

$x = \Delta r_b/2 * 2L/3\Delta r_b = L/3$

Time gating shift/shift correlations with physical shifting



Principle of F-Sharp