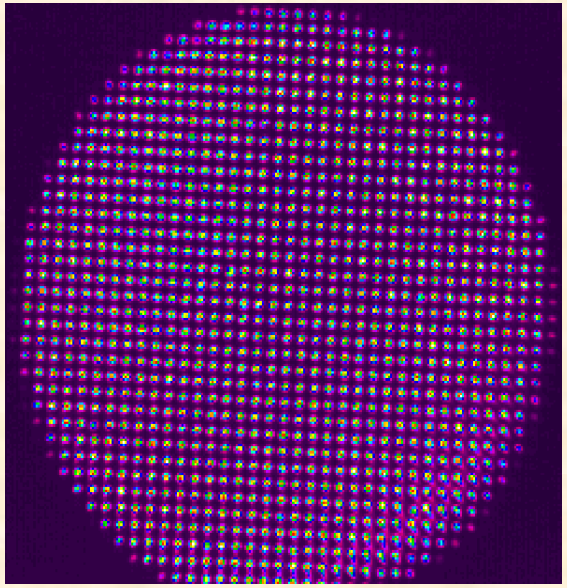
Simulating spins (in imaginary time) with coupled lasers

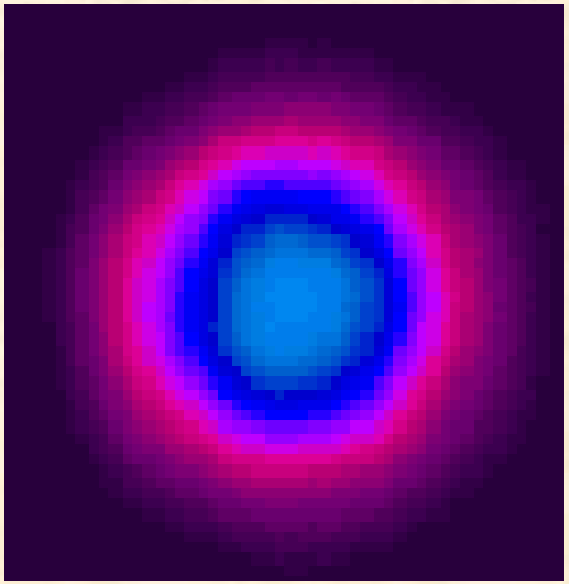
Nir Davidson

Weizmann Institute of Science

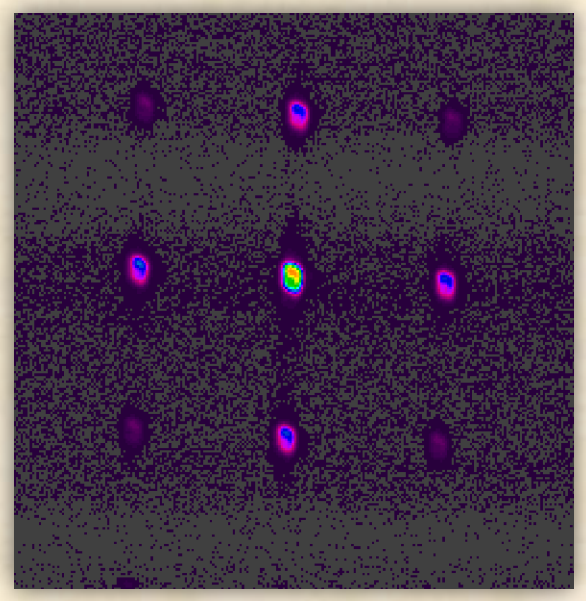
Near Field



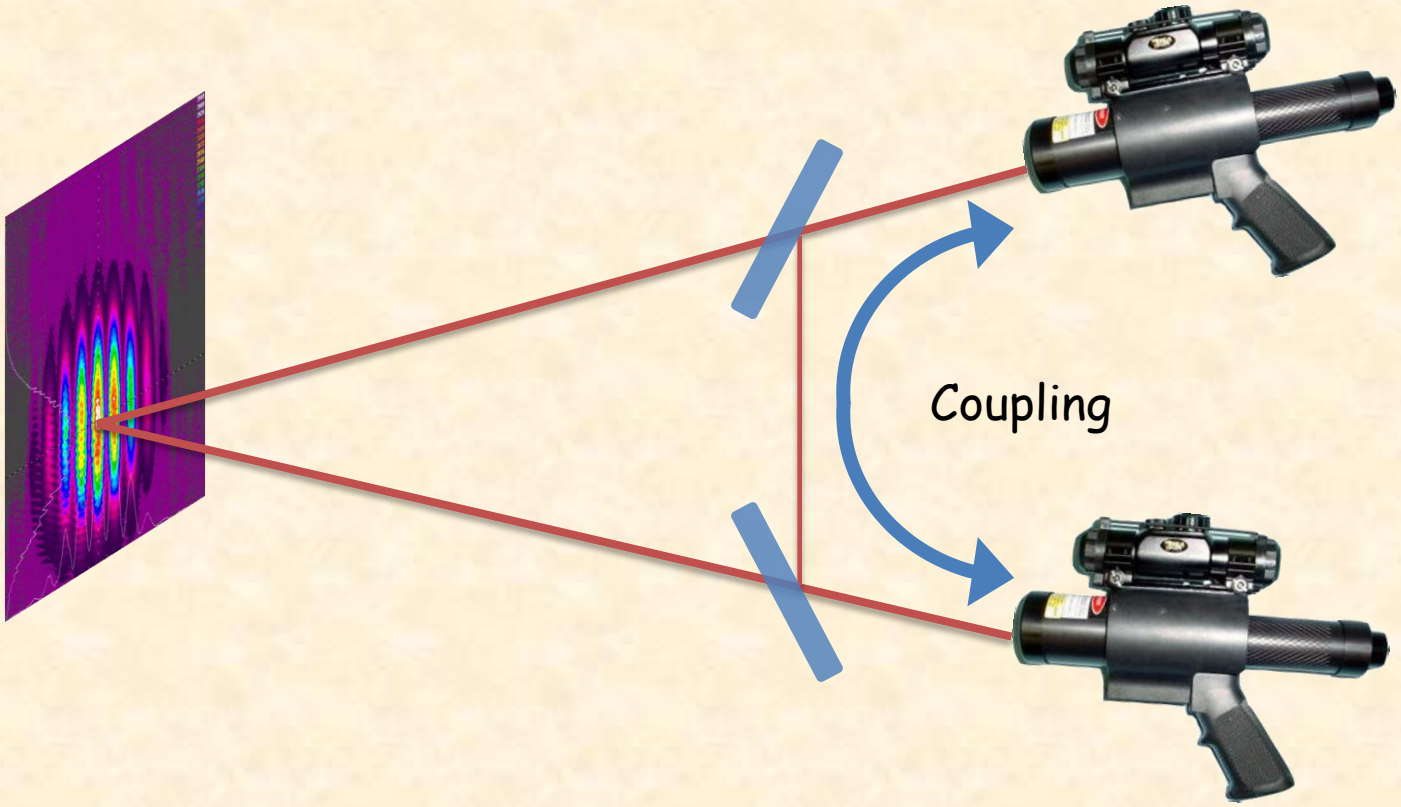
Far Field
No coupling



Far Field
with coupling

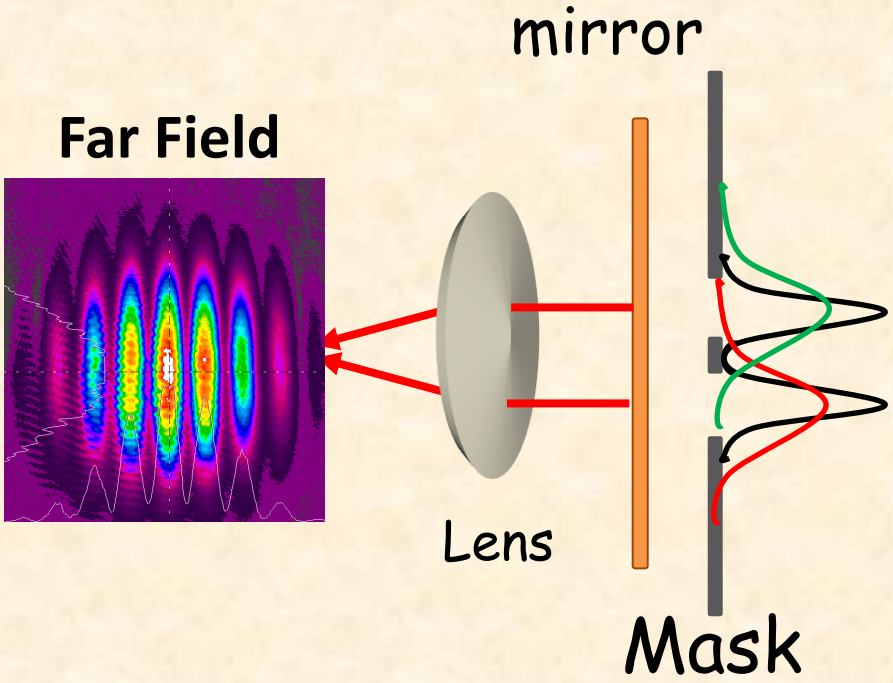


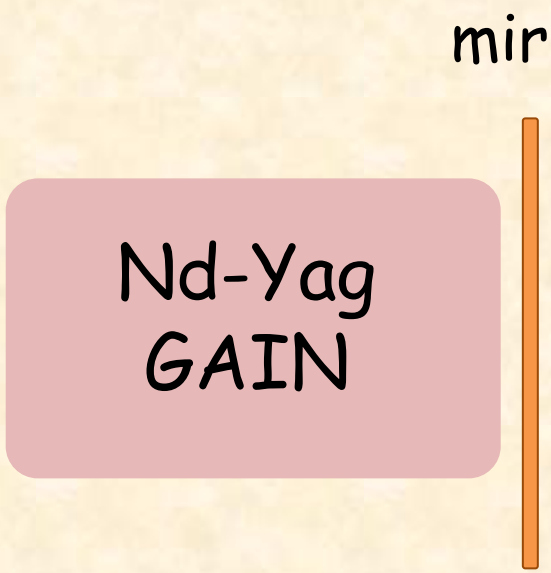
What is phase locking ?



$$\Delta\varphi(t) = \varphi_2(t) - \varphi_1(t) = const$$

Diffractive coupling

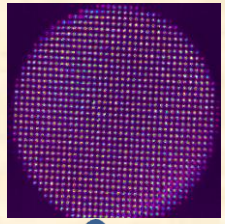




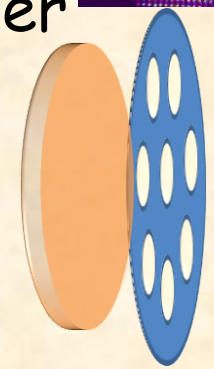
Short range coupling $\kappa_{ij} = \left\langle E_i \middle| E_j \right\rangle \cong e^{-\alpha(i-j)^2}$

Dissipative coupling: minimizes losses

Degenerate cavity: square array



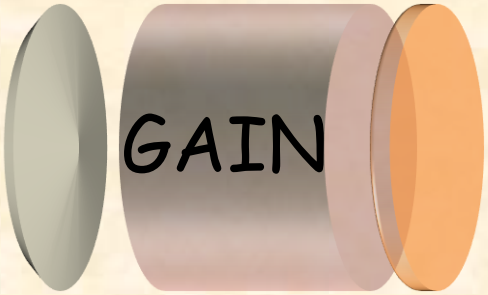
Output coupler



Lens

Lens

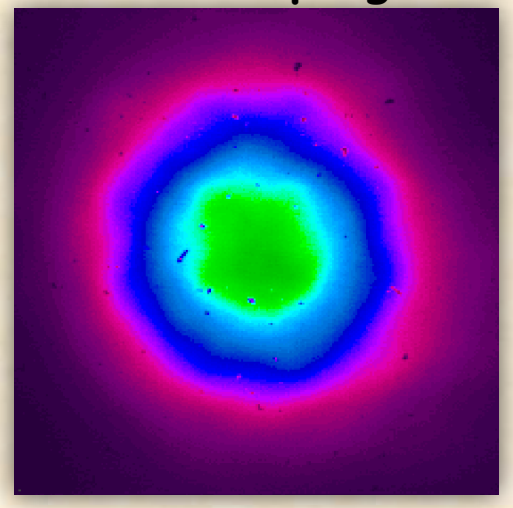
Mirror

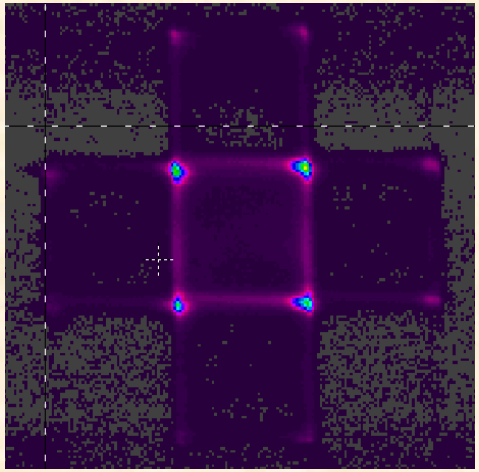


No coupling

Negative coupling

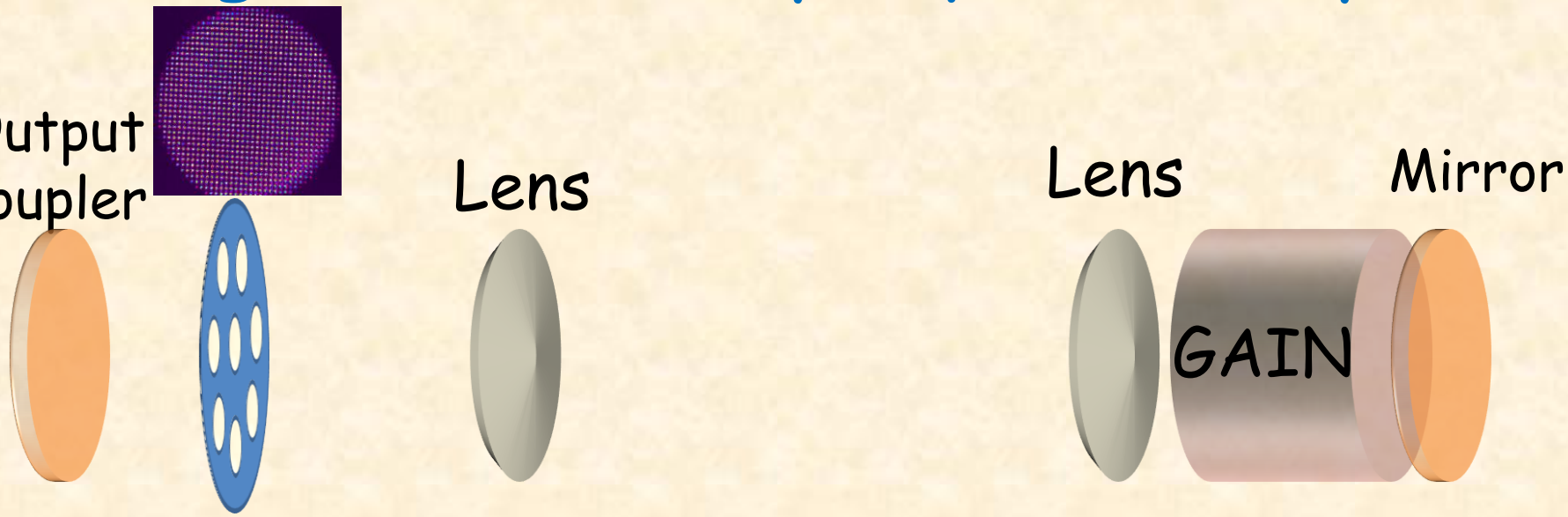
Far Field

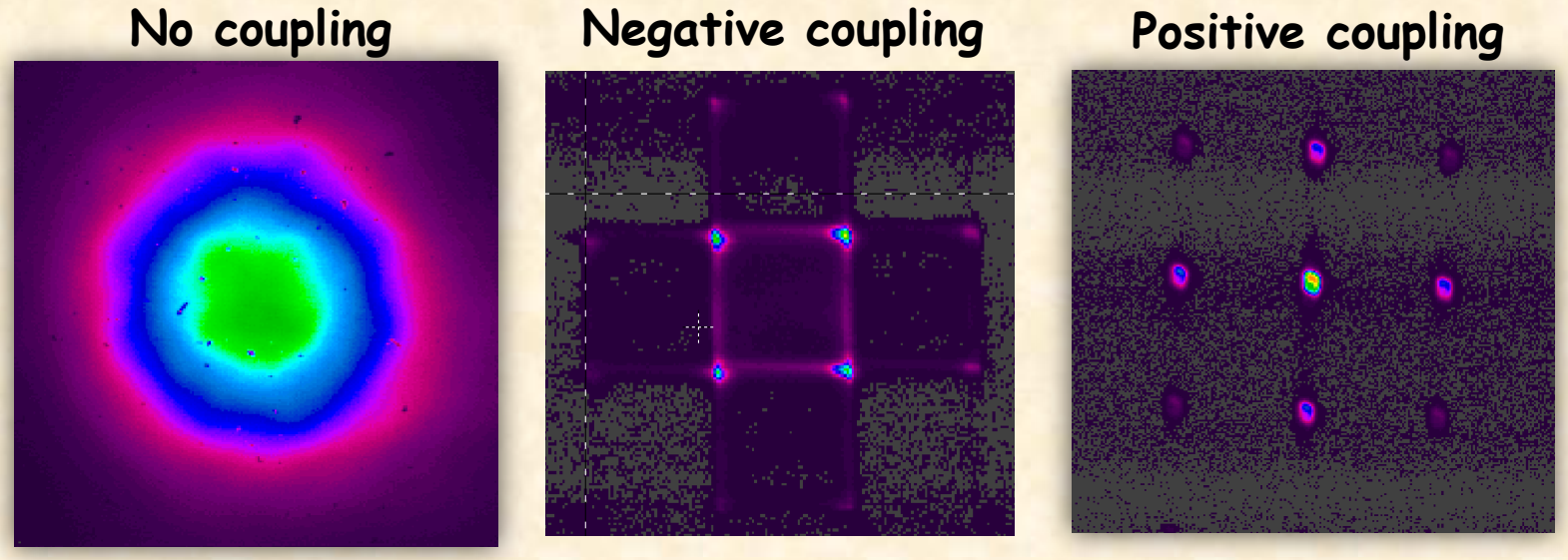




M. Nixon et. al., PRL 106, 223901 (2011); PRL 108, 214101 (2012)

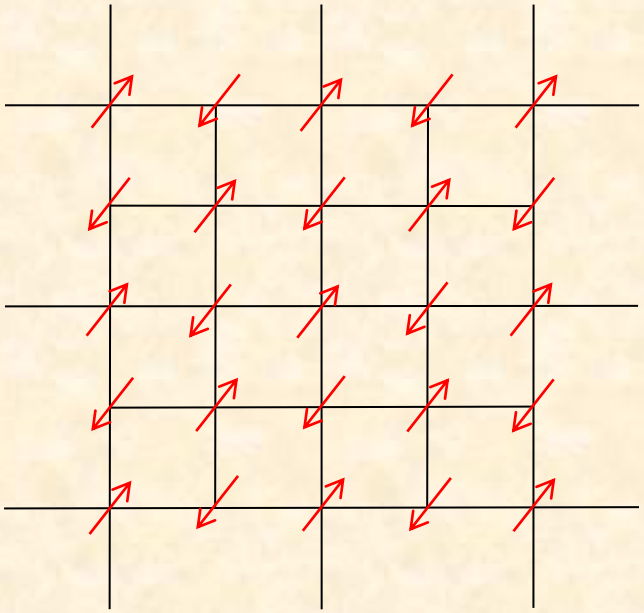
Degenerate cavity: square array





M. Nixon et. al., PRL 106, 223901 (2011); PRL 108, 214101 (2012)

Lasers ⟷ Spins



$$\dot{\theta}_i = \Sigma \kappa_{ij} \sin(\theta_j - \theta_i)$$

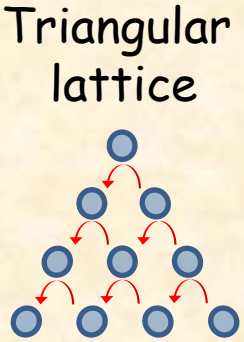
Kuramoto Model

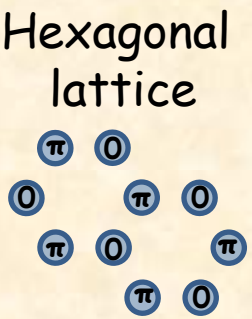
$$\mathrm{H} = J \sum_{i \neq j}^{n} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

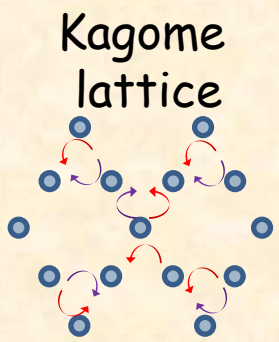
Classical XY model

M. Nixon et. al., PRL 110, 184102 (2013)

Very large arrays (NN coupling)

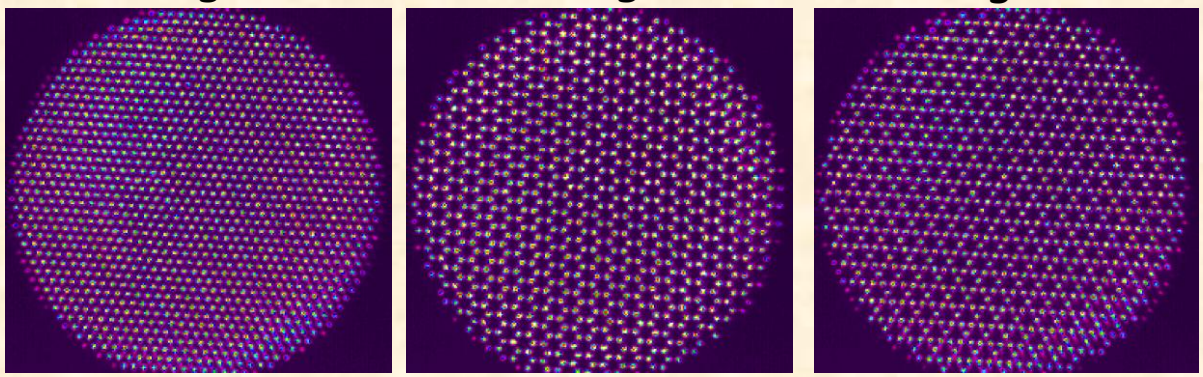




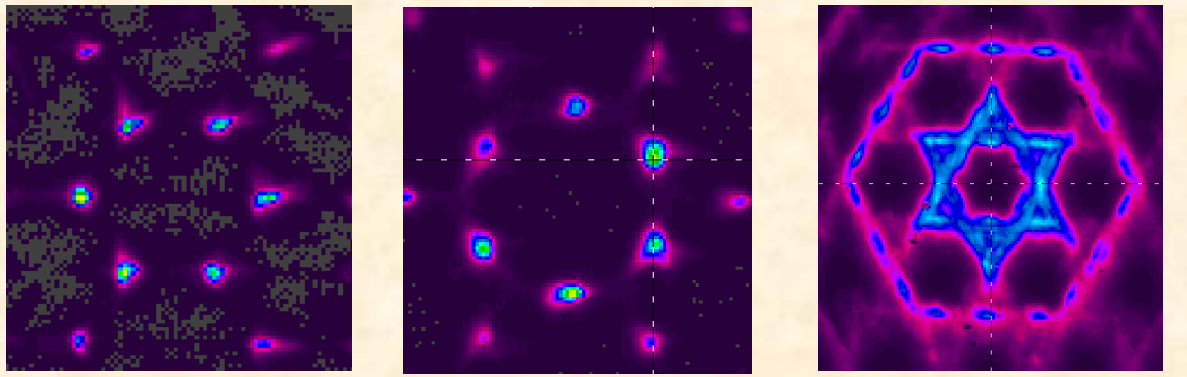


Triangular Hexagon Kagome

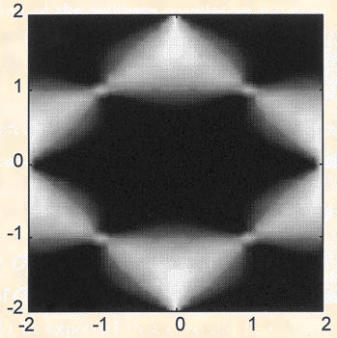
Near Fields



Far Fields

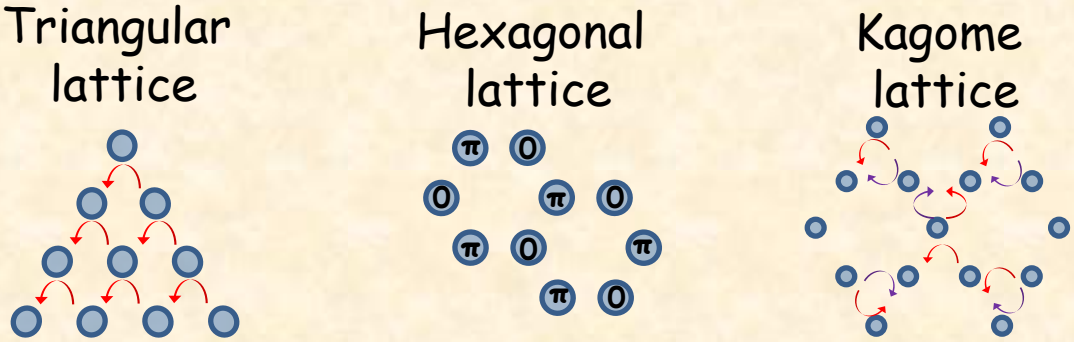


Moessner and Chalker
PRB **58** 12049 (1998)



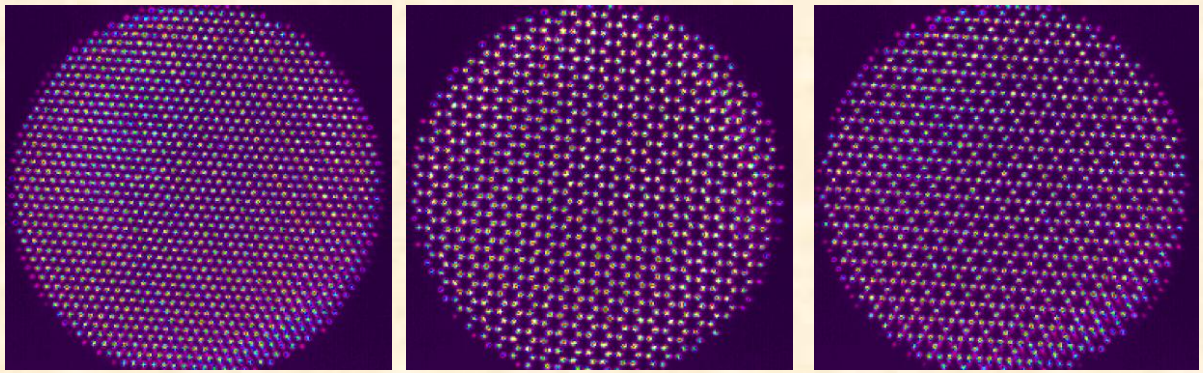
M. Nixon et. al., PRL 110, 184102 (2013)

Very large arrays (NN coupling)

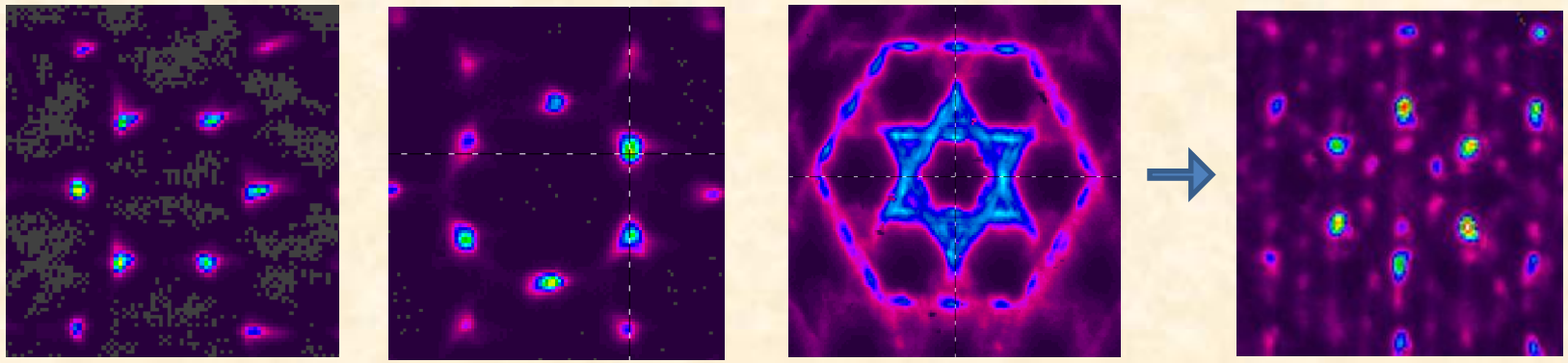


Triangular | Hexagon | Kagome

Near Fields



Far Fields

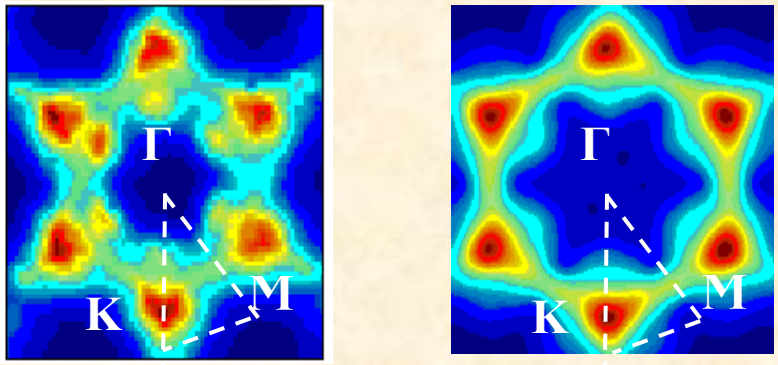


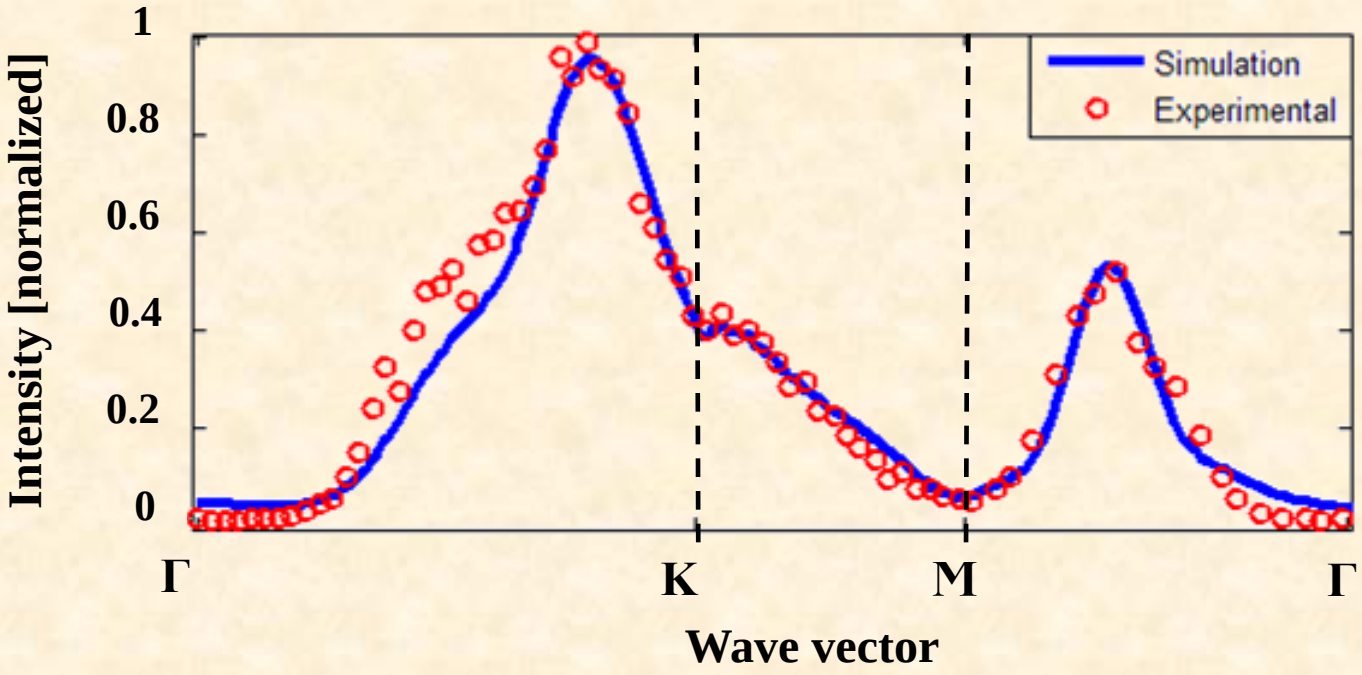
NNN coupling

M. Nixon et. al., PRL 110, 184102 (2013)

Is it a true "ground state"?

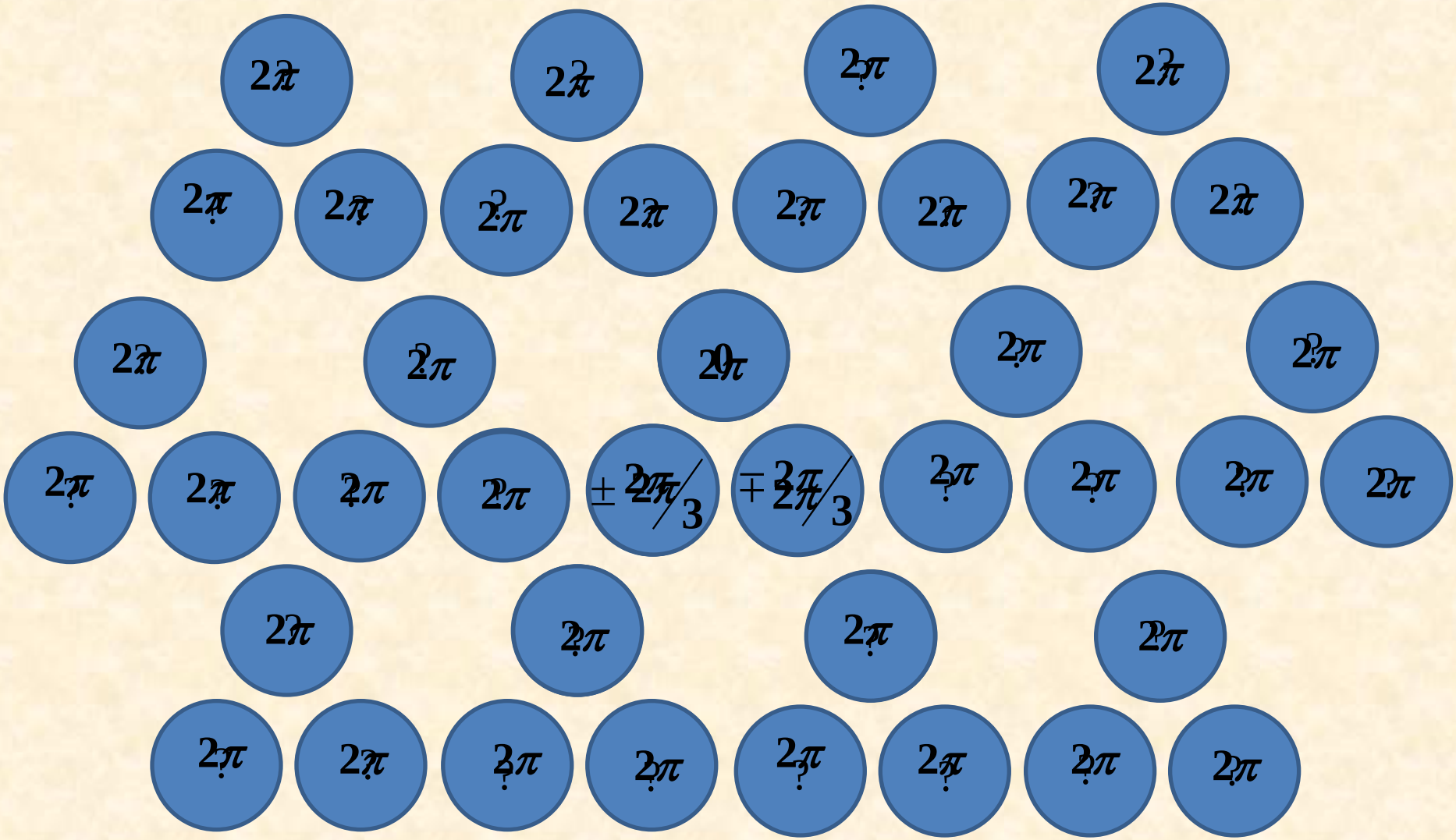
Experimental **Simulation**



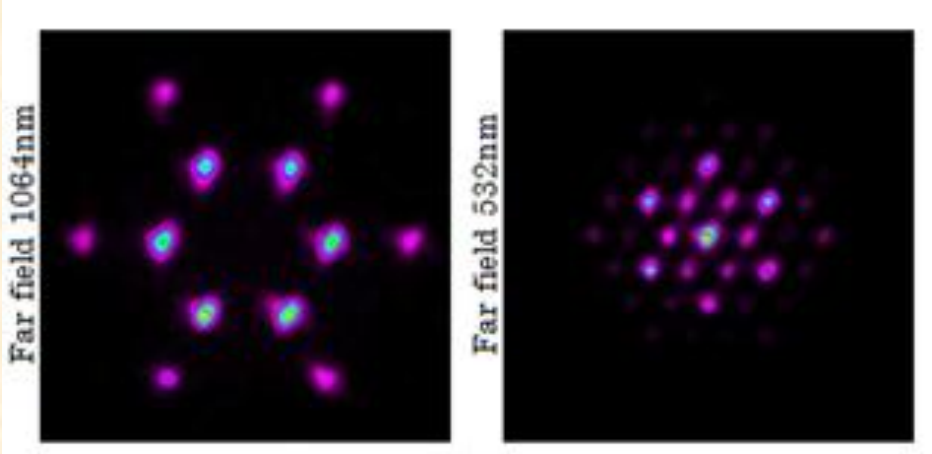


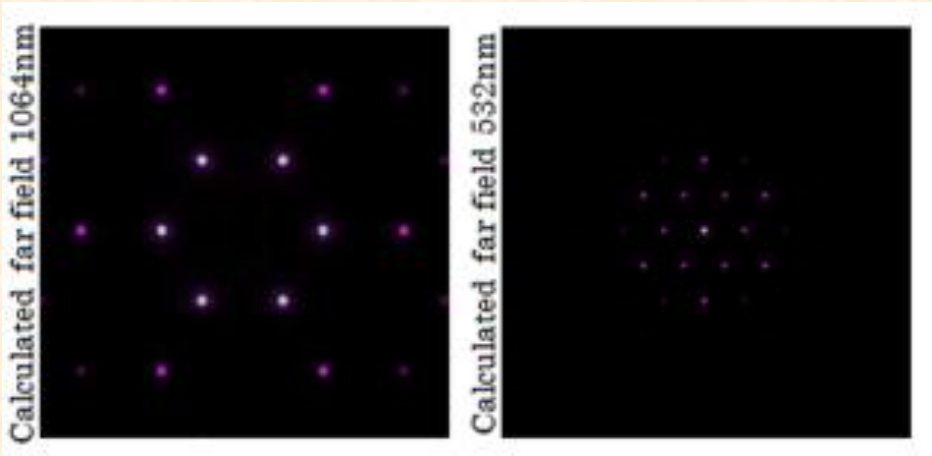
M. Nixon et. al., PRL 110, 184102 (2013)

No 3φ phase ordering !



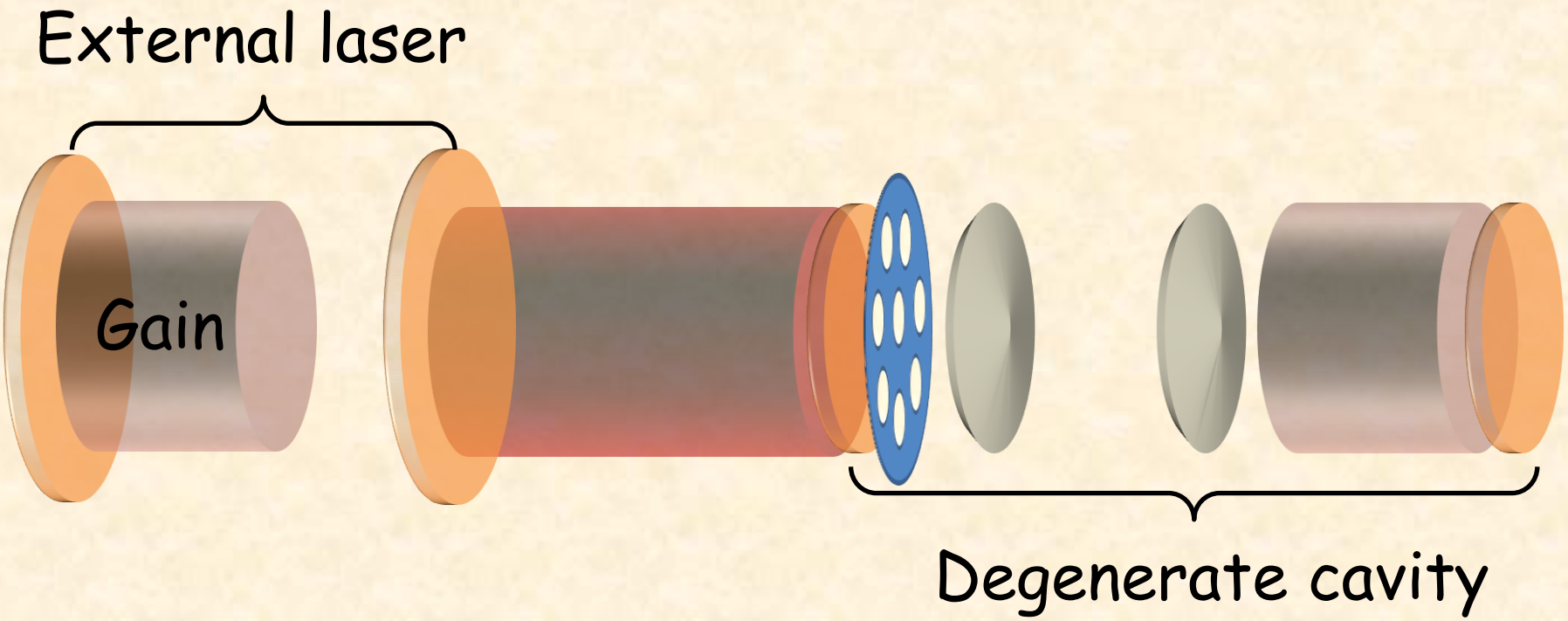
Second harmonics doubles the phase

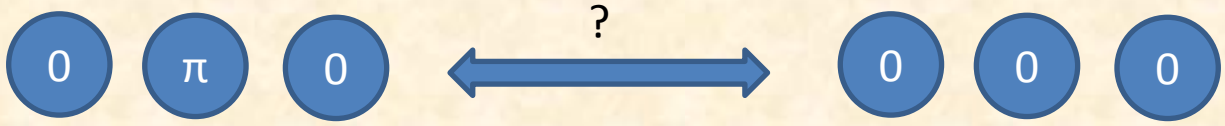




C. Tradensky et. al., submitted

External "magnetic field"

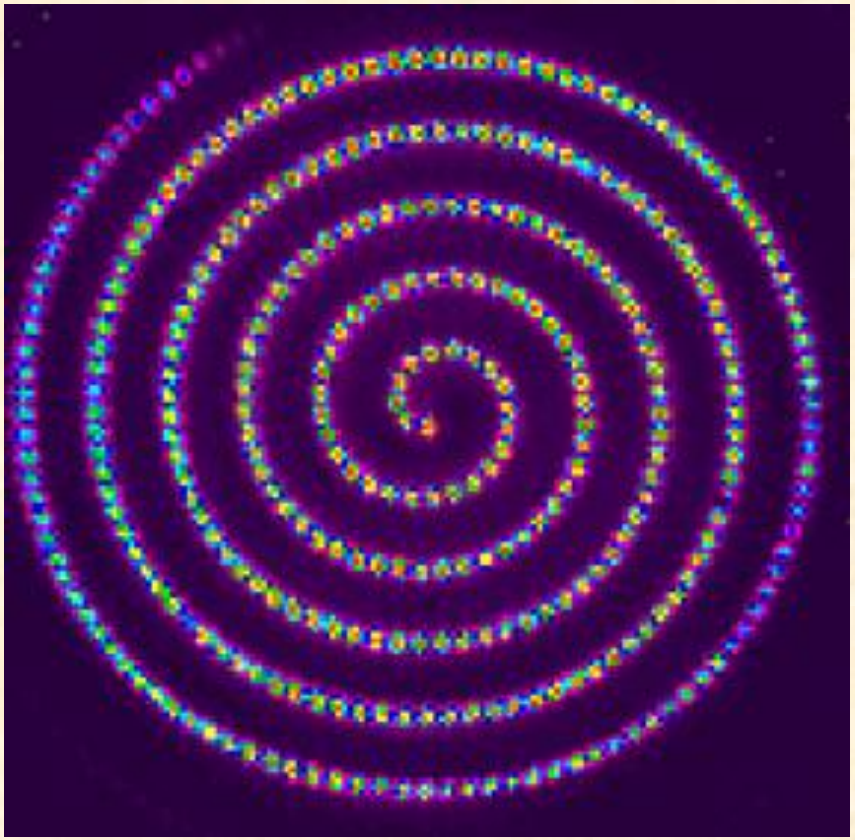




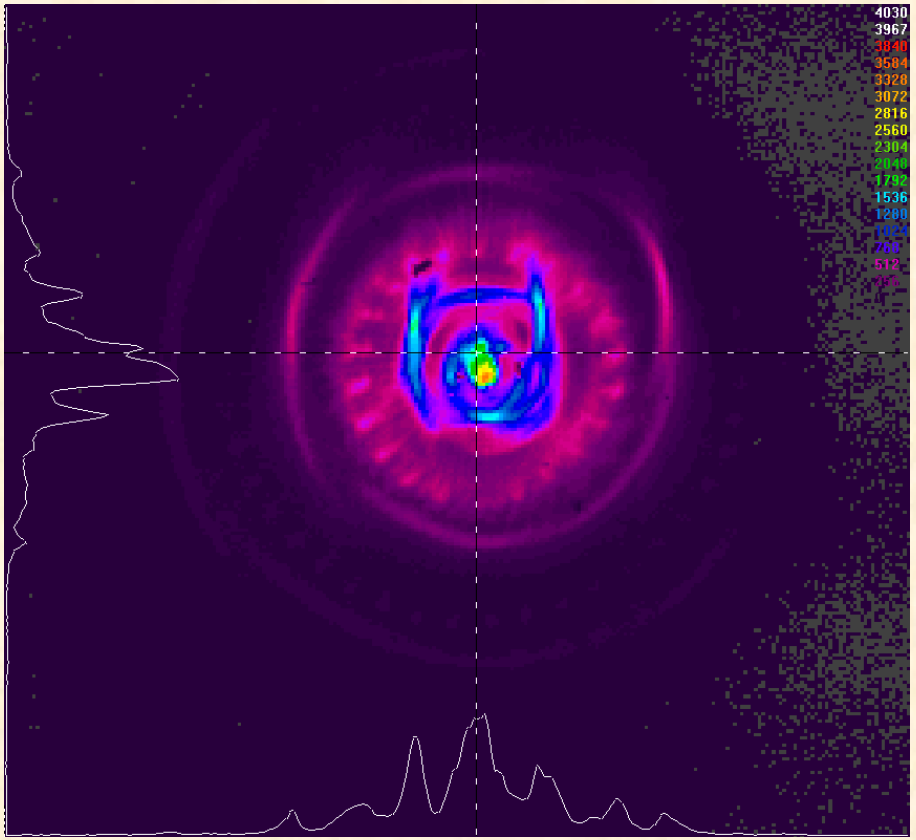
E. Ronen et. al., unpublished

External Field for 1D

Near field spiral



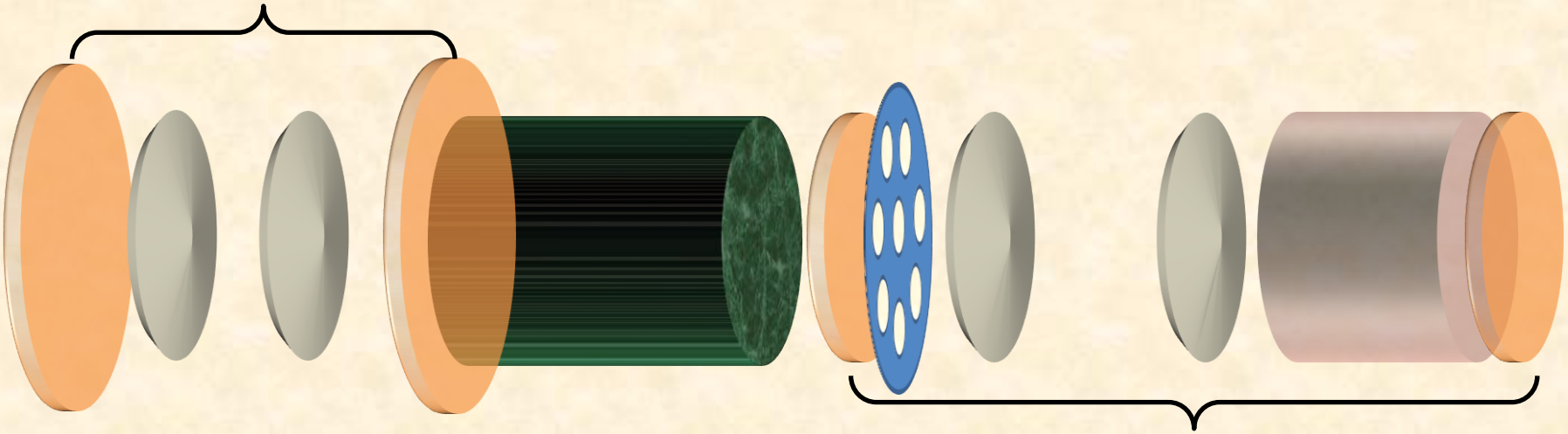
Far field



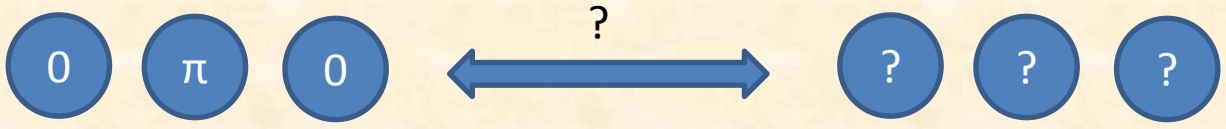
E. Ronen et. al., unpublished

External disordered field

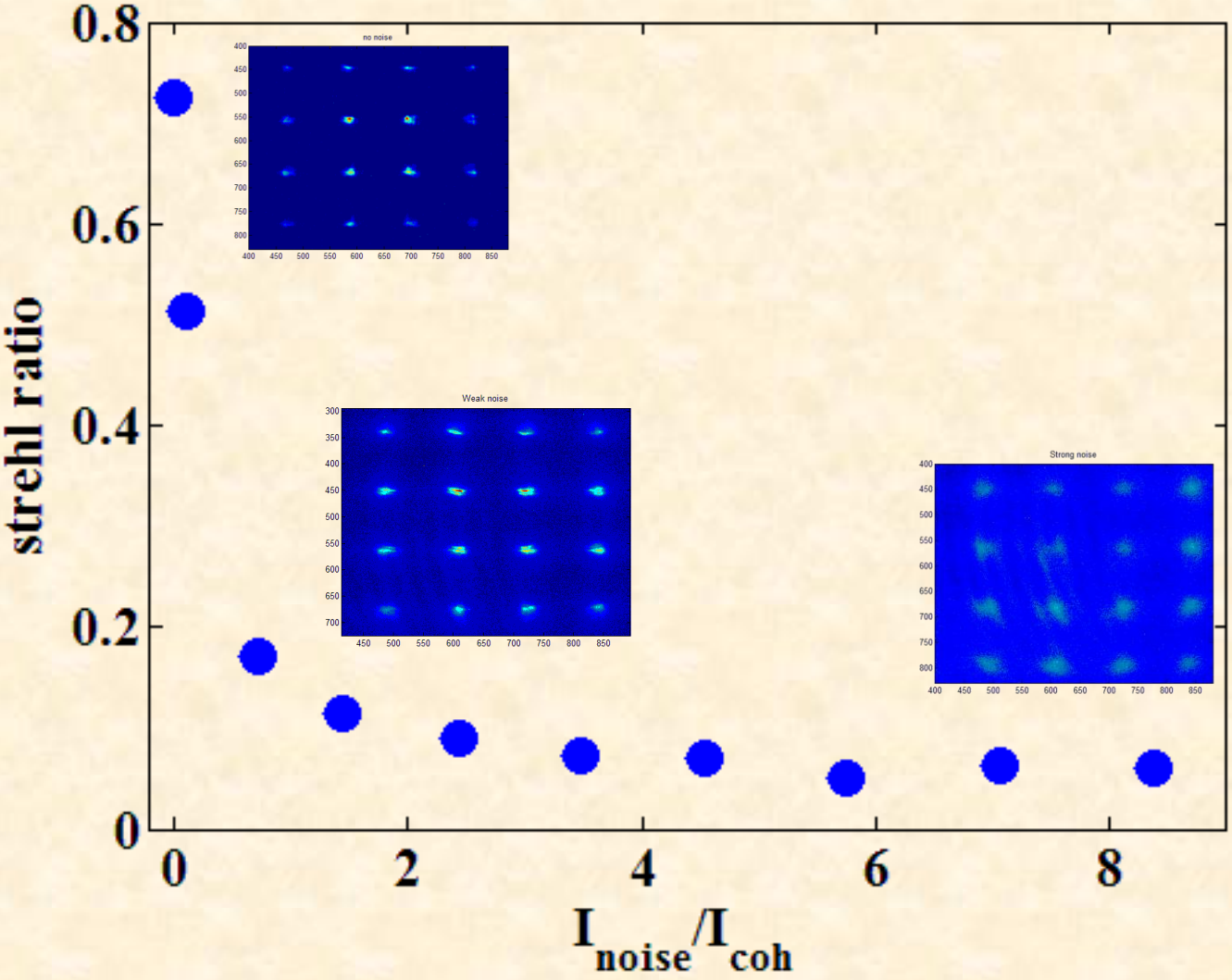
External degenerate laser cavity



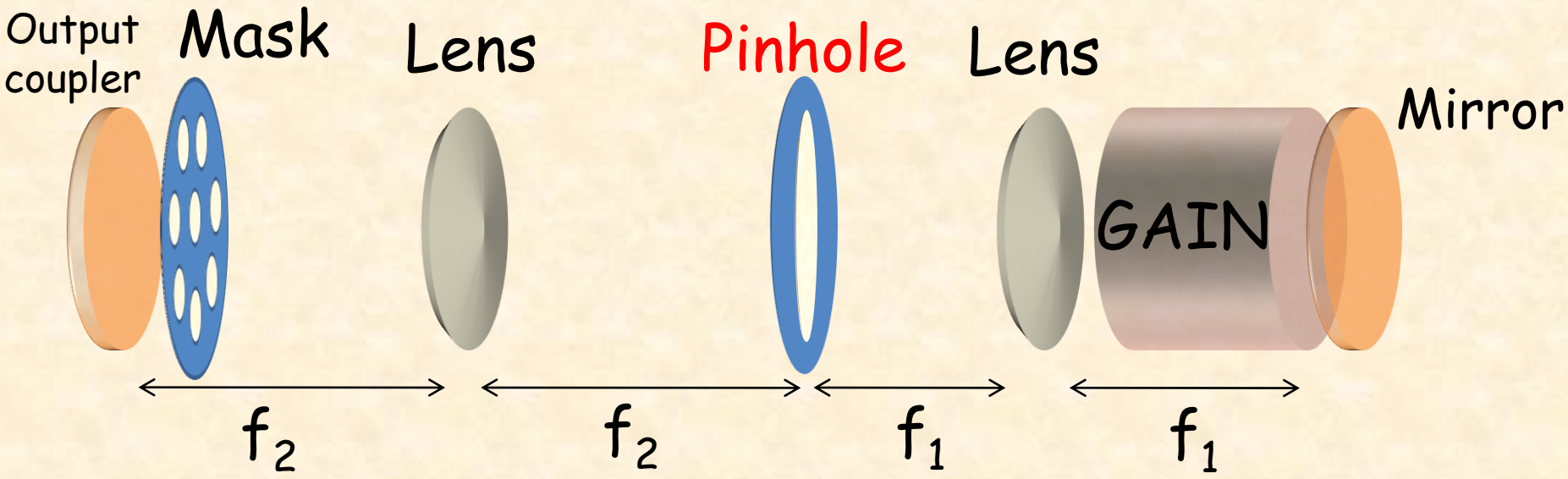
Degenerate cavity

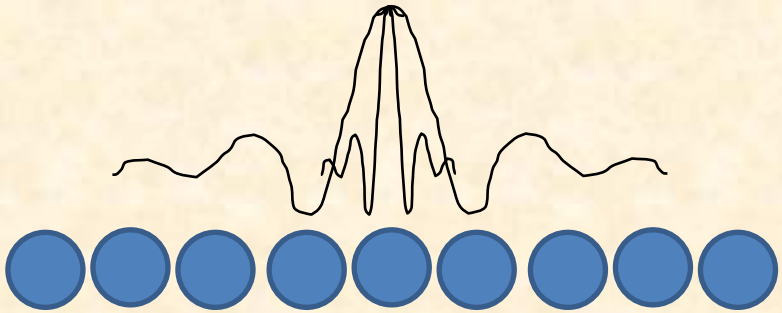


Effects of finite "temperature"



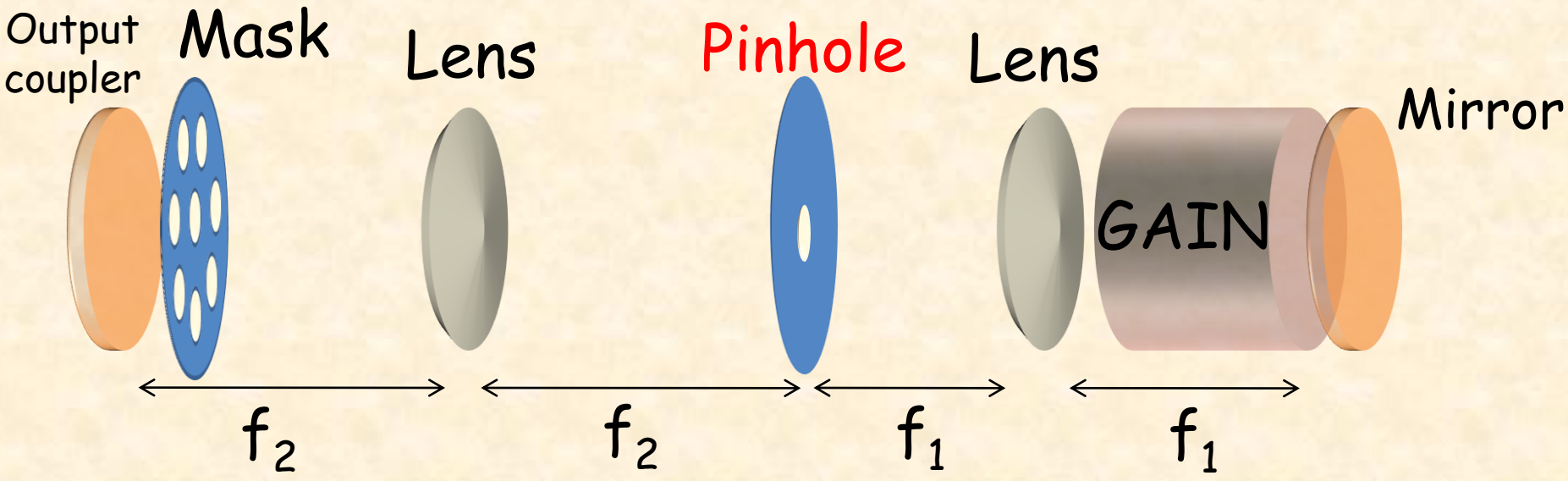
Long range coupling



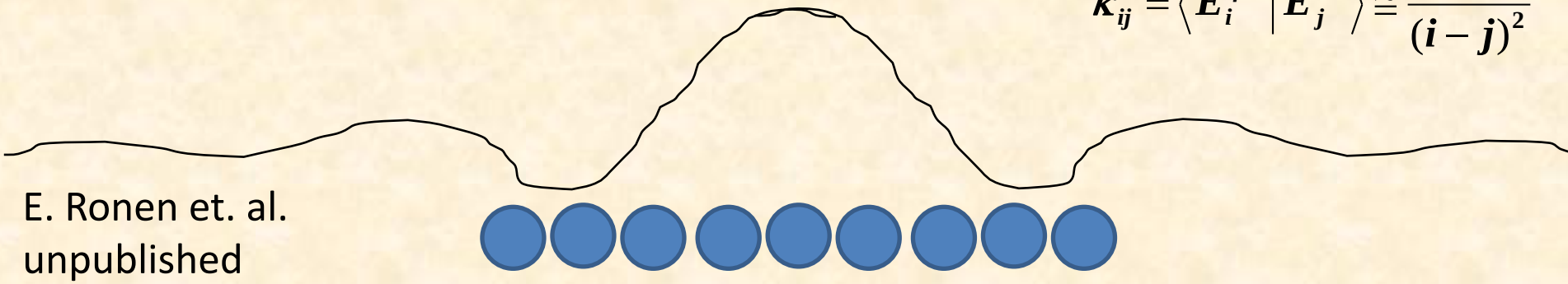


E. Ronen et. al.
unpublished

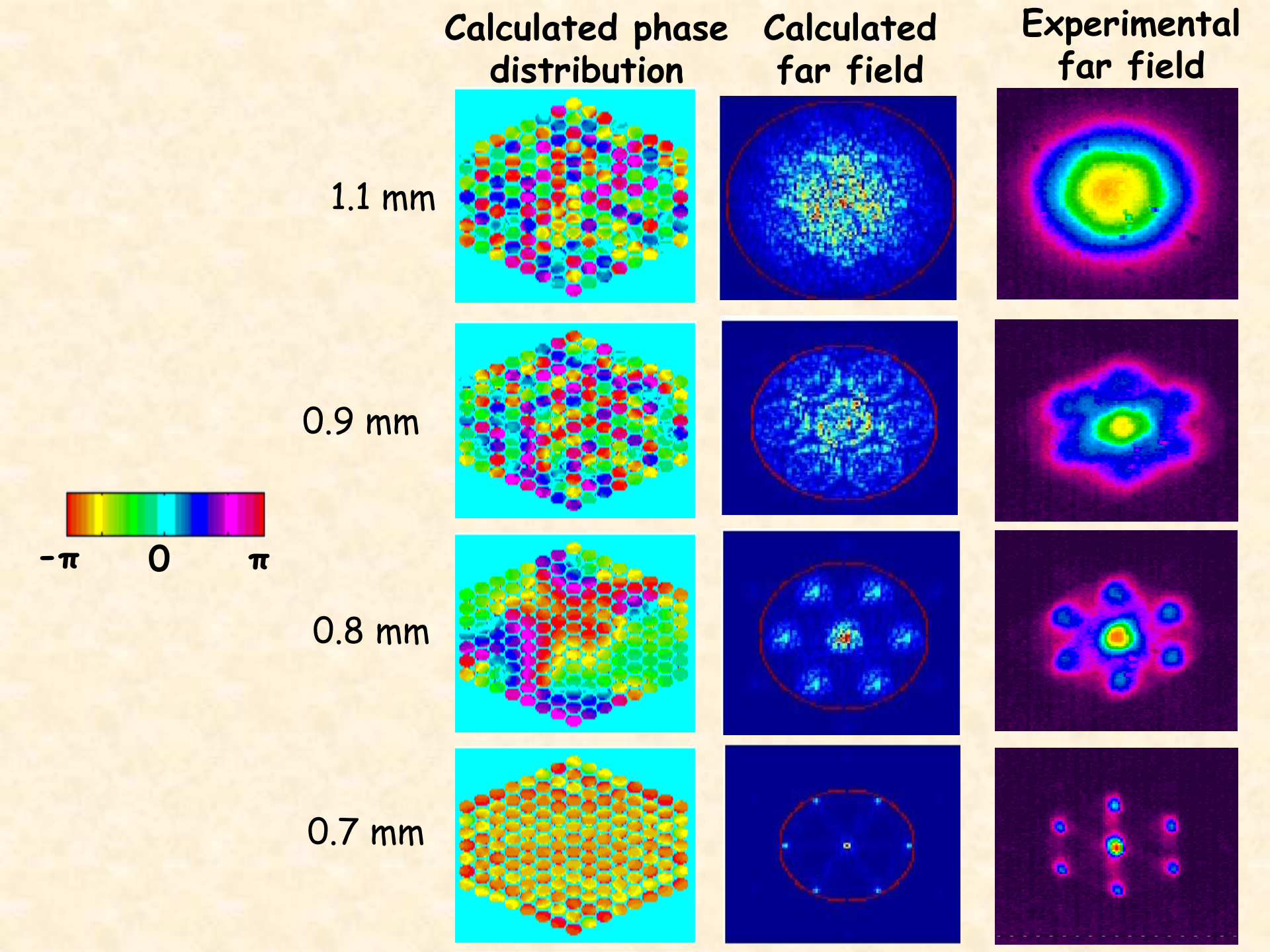
Long range coupling



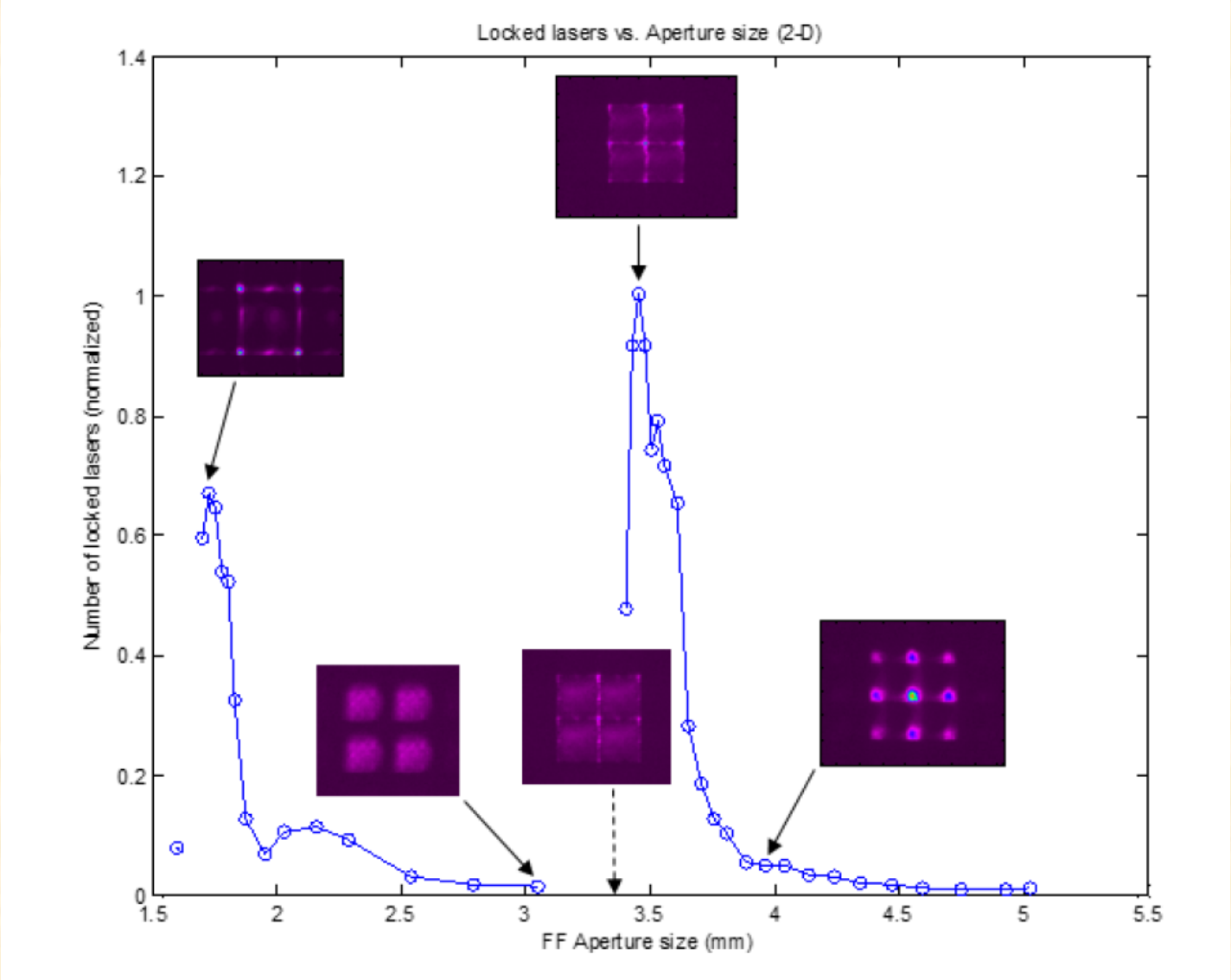
$$\kappa_{ij} = \left\langle E_i^{fin} \middle| E_j^{ini} \right\rangle \cong \frac{1}{(i-j)^2}$$



E. Ronen et. al.
unpublished

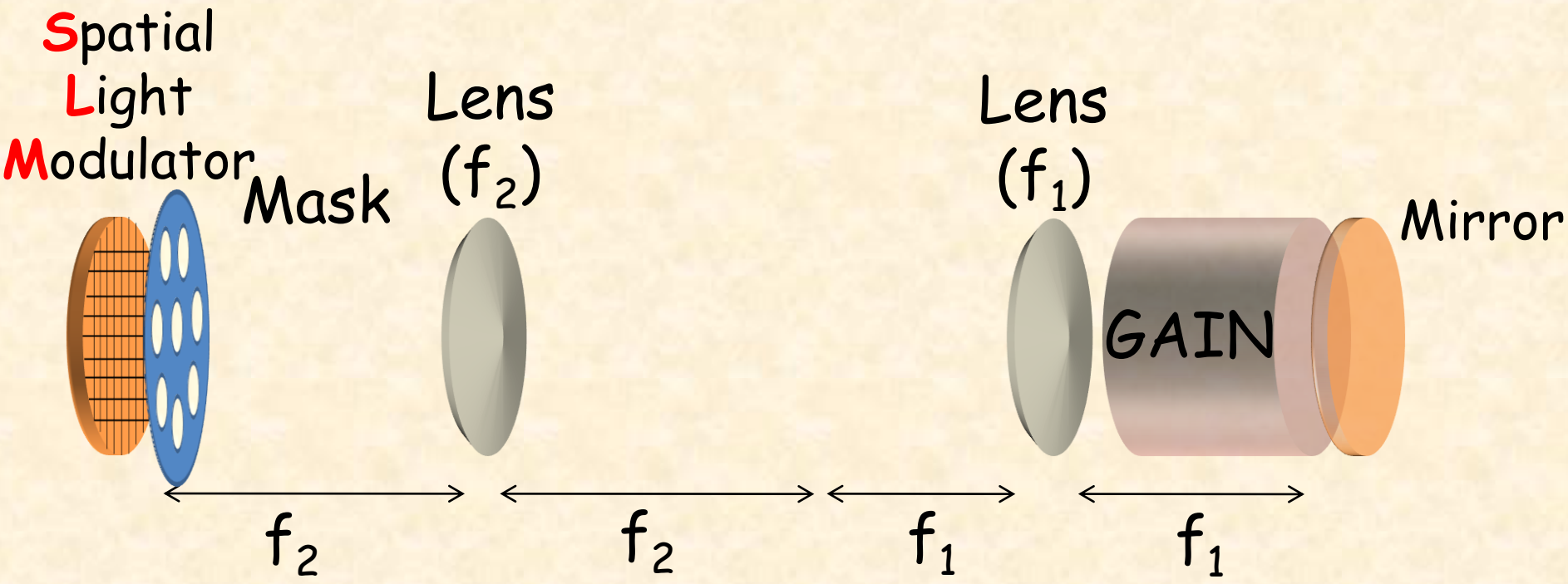

Calculated phase distribution
Calculated far field
Experimental far field
1.1 mm
0.9 mm
0.8 mm
0.7 mm
-π
0
π

Sharp phase transitions and "spin glasses"



G. Barach et. al.
unpublished

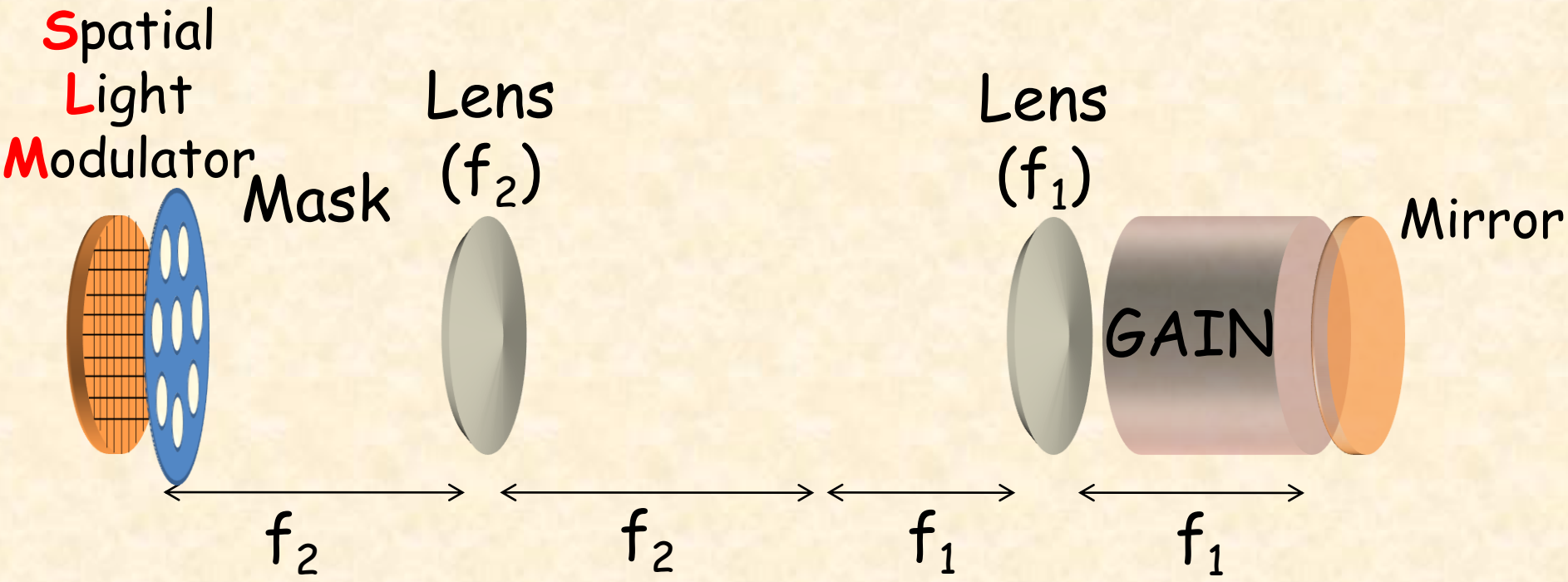
Adding disorder



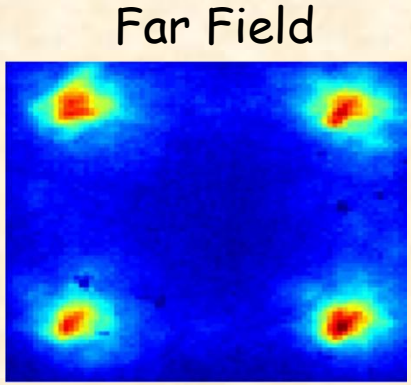
$$\dot{\theta}_i = \Omega_i + \Sigma \kappa_{ij} \sin(\theta_j - \theta_i)$$

E. Ronen et. al.
unpublished

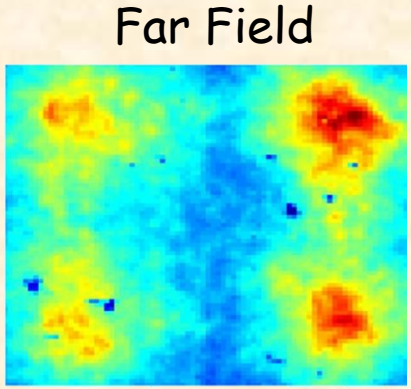
Adding disorder



$\langle\varphi\rangle_{rms} = 0$



$\langle\varphi\rangle_{rms} = \frac{\pi}{10}$

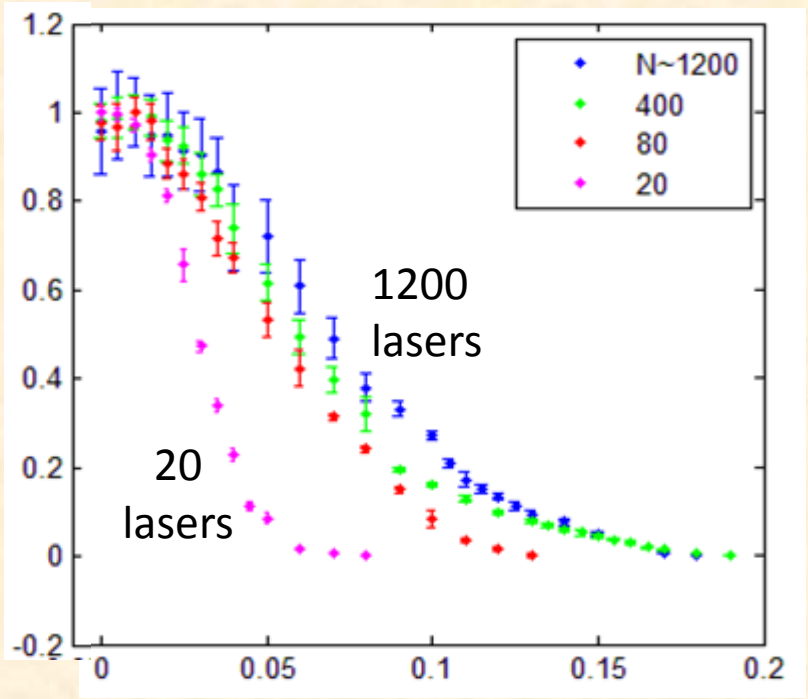


$\langle\varphi\rangle_{rms} = \frac{\pi}{5}$

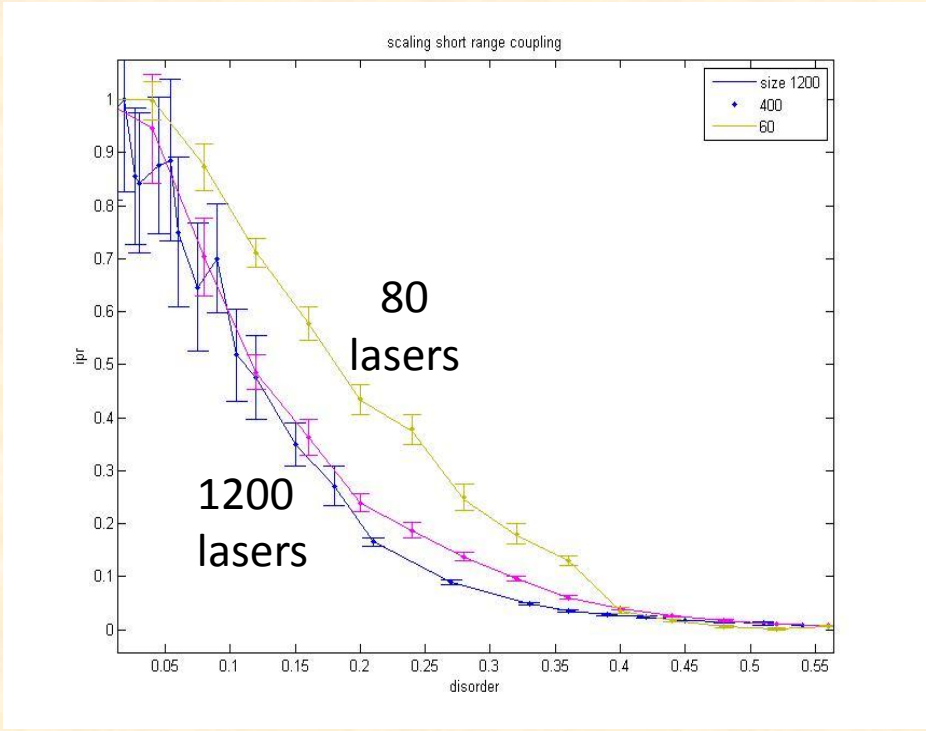
E. Ronen et. al.
unpublished

Long Vs. short range coupling
scaling system size

Long

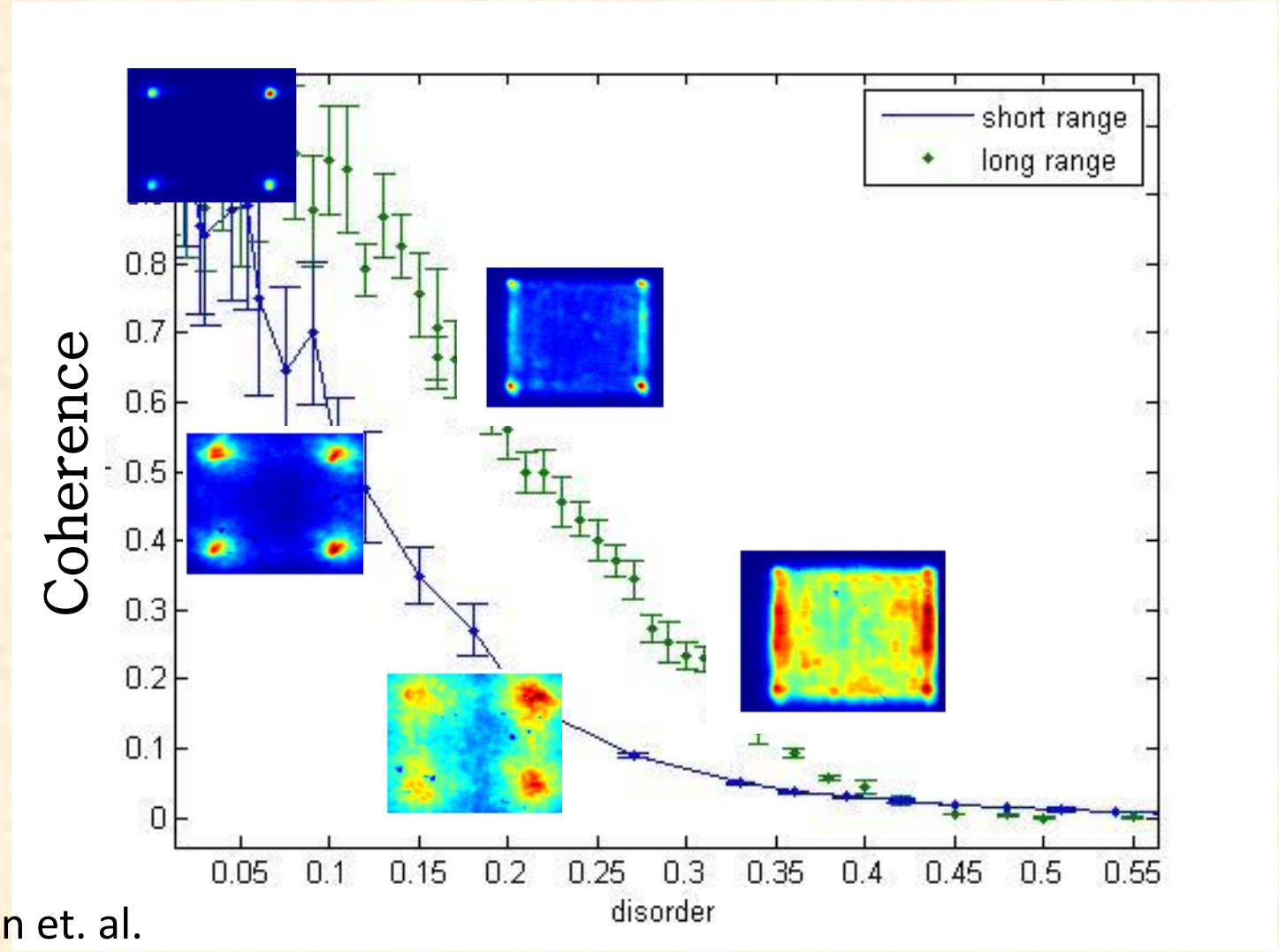


Short



E. Ronen et. al.
unpublished

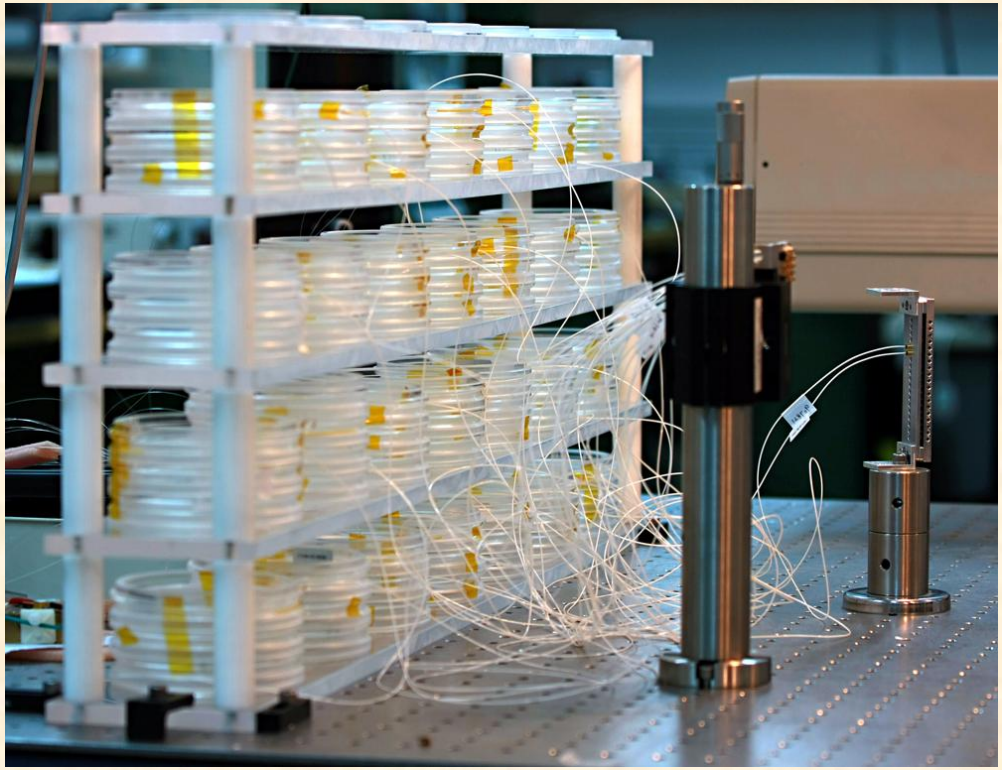
Long Vs. short range coupling

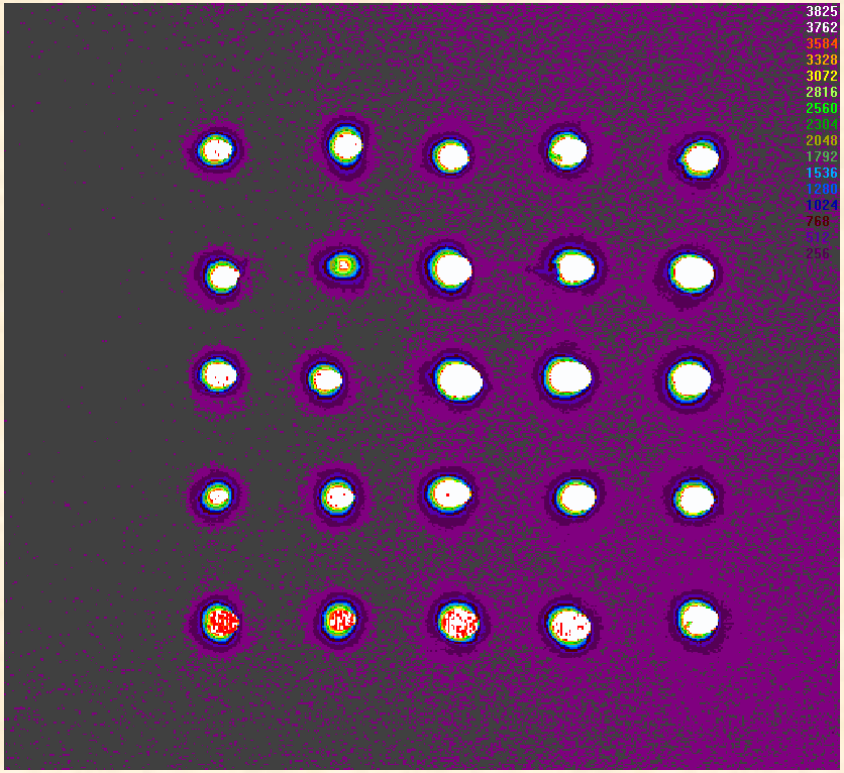


E. Ronen et. al.
unpublished

Phase locking of 25 fiber lasers

System with “infinite” disorder

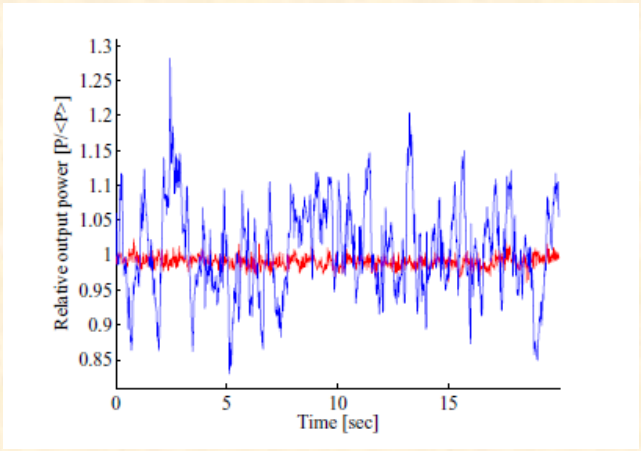


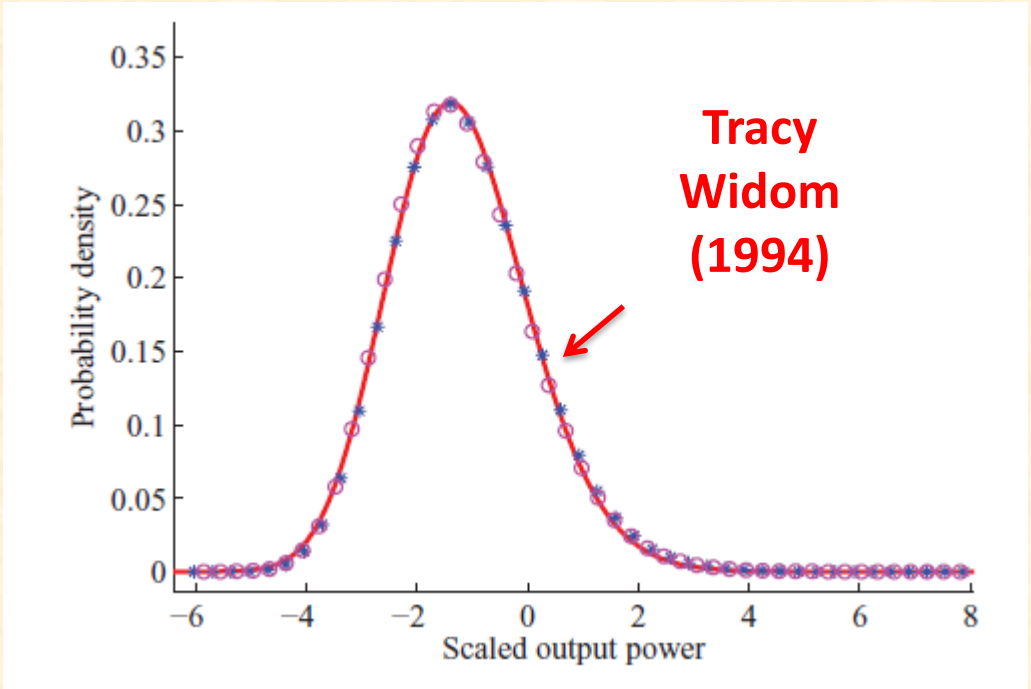


M. Fridman et. al., Opt. Lett. 35, 1434 (2010)

Power fluctuations

Extreme eigenvalue statistics of Wihsart random matrices

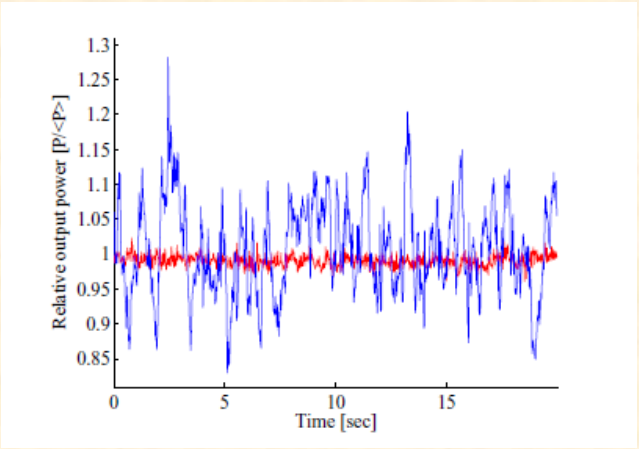


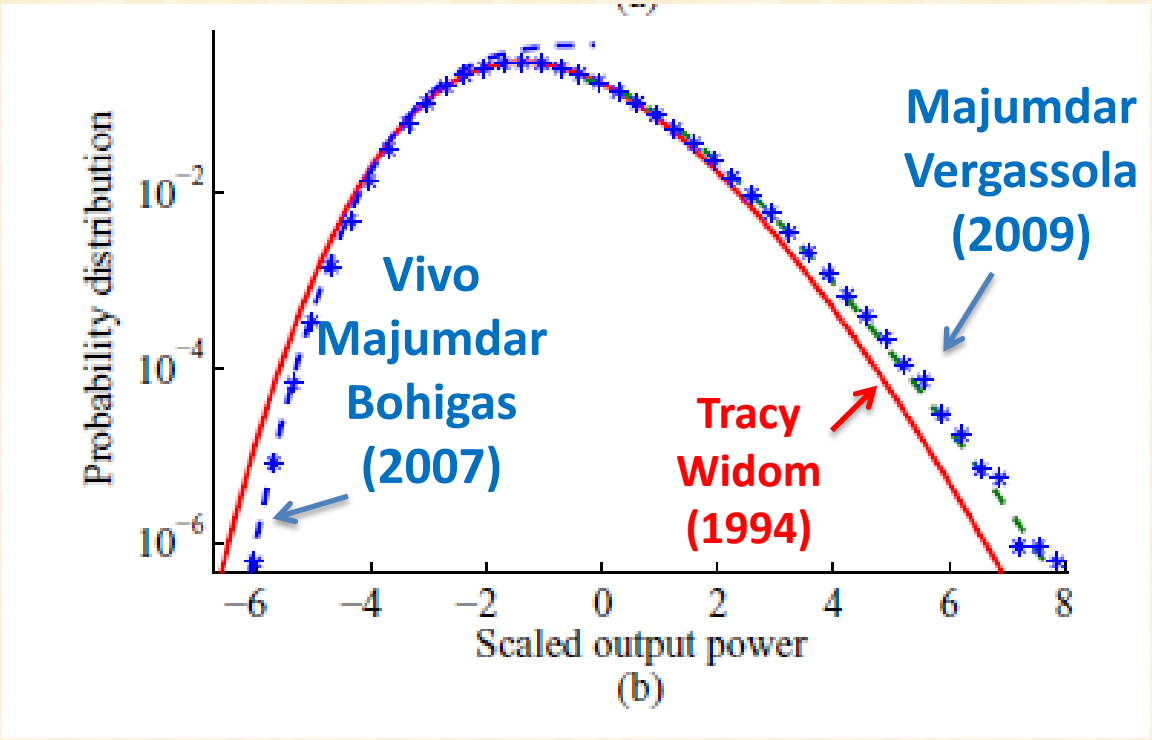


M. Fridman et. al., PRE R85, 020101 (2012)

Power fluctuations

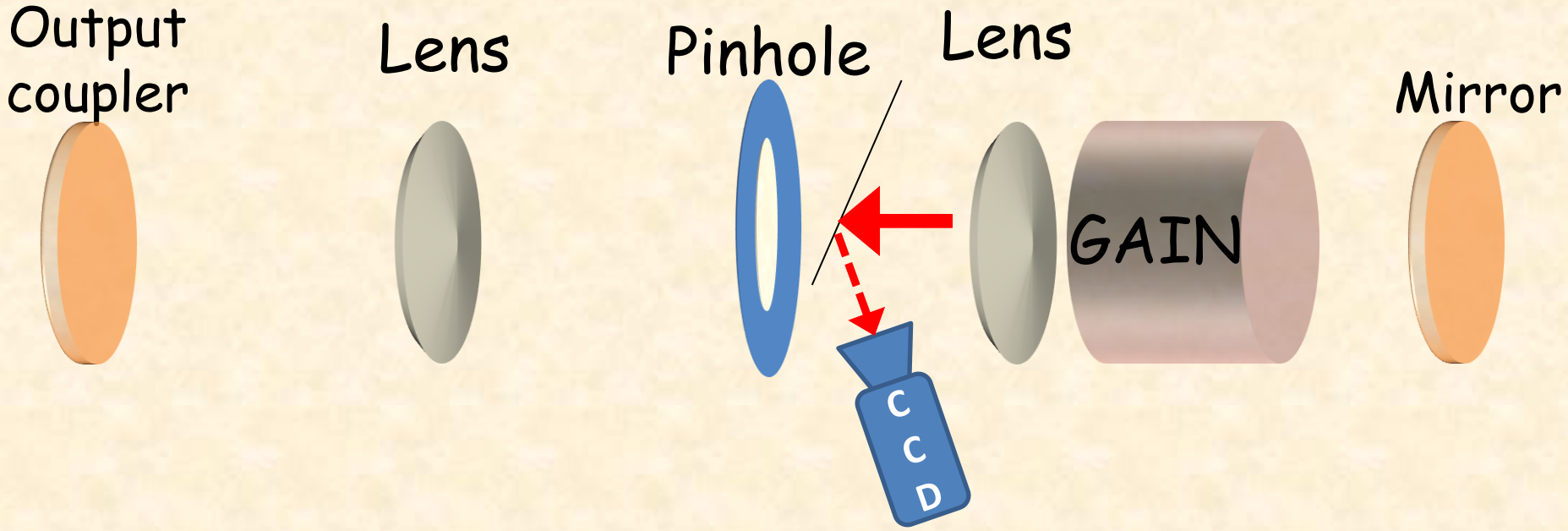
Extreme eigenvalue statistics of Wihsart random matrices

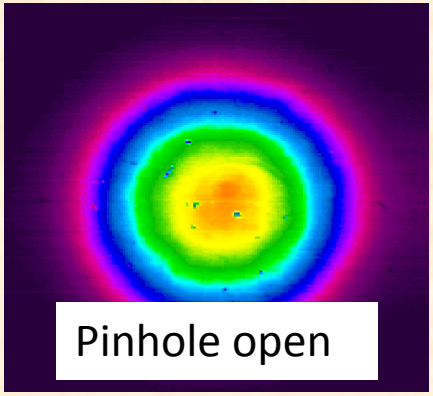




M. Fridman et. al., PRE R85, 020101 (2012)

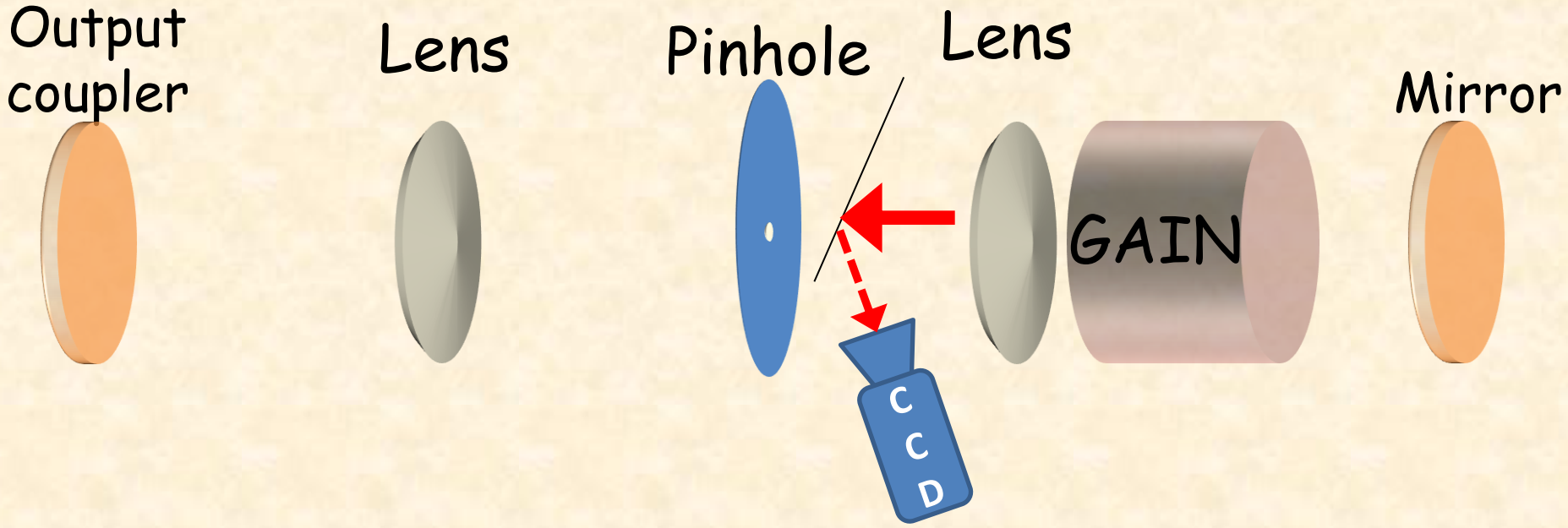
Lasing through a pinhole

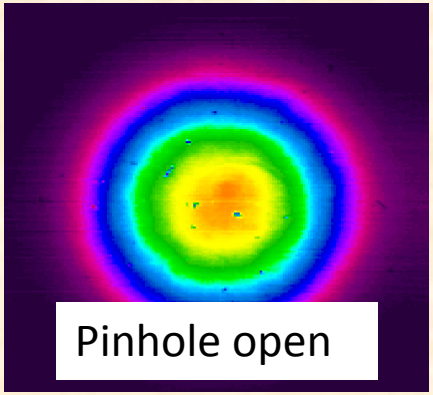


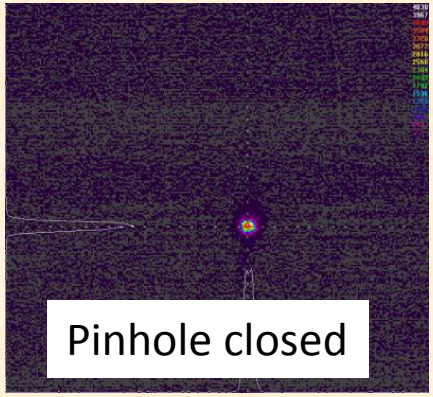


M. Nixon et. al., Opt. Lett. (2013)

Lasing through a pinhole

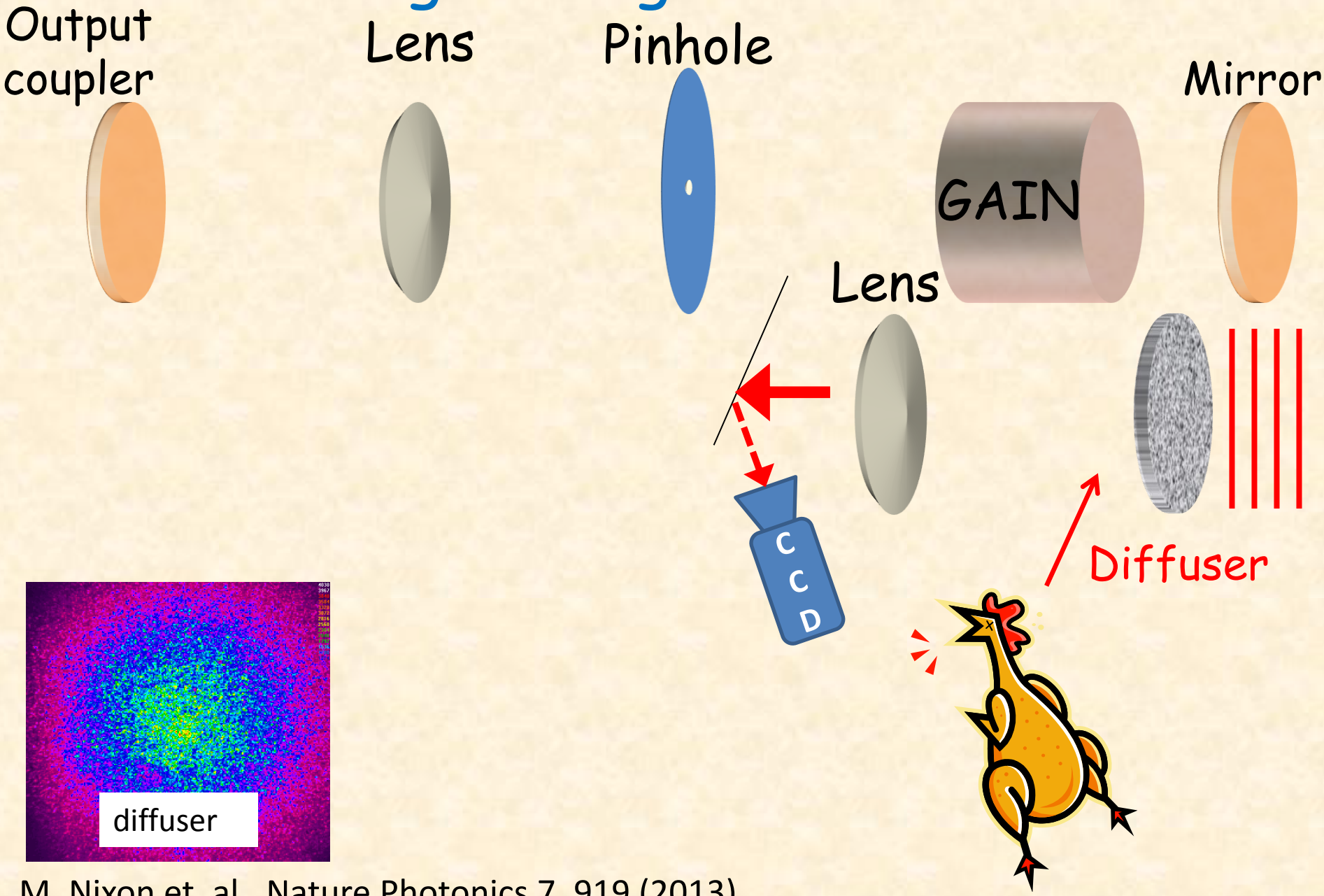






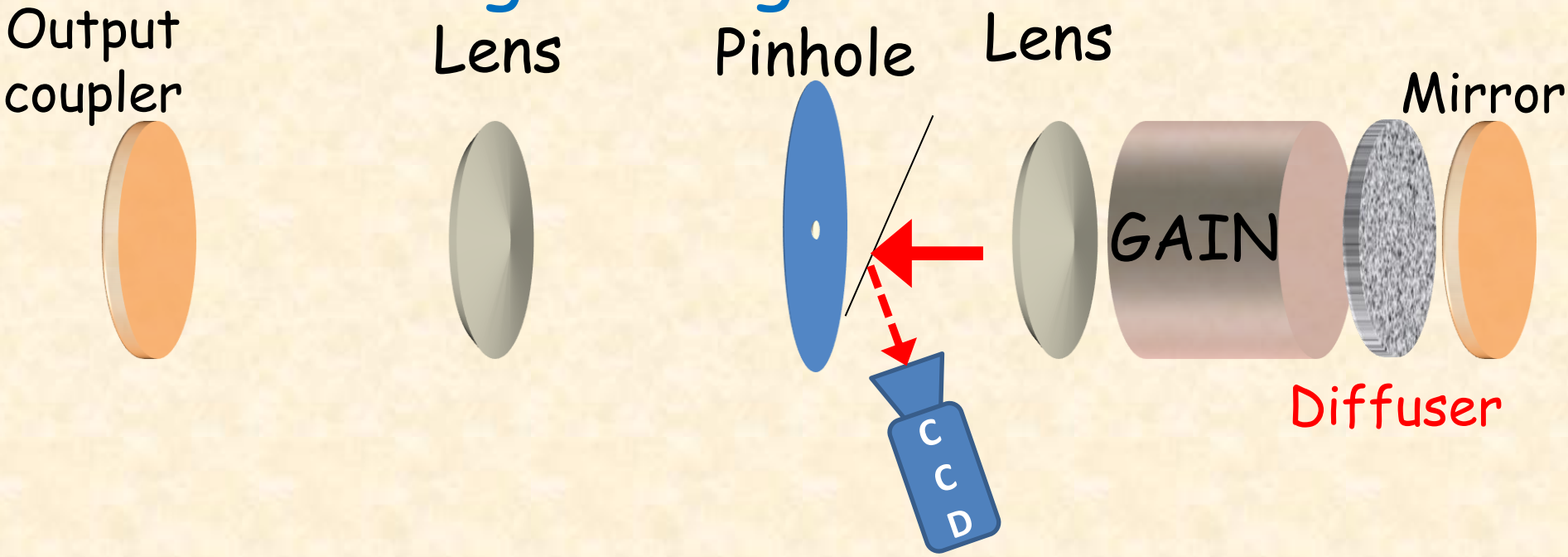
M. Nixon et. al., Opt. Lett. (2013)

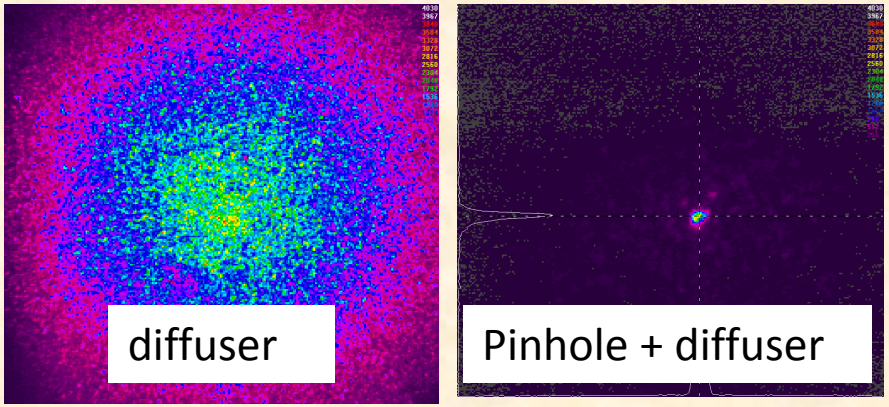
Lasing through a Diffuser



M. Nixon et. al., Nature Photonics 7, 919 (2013)

Lasing through a Diffuser



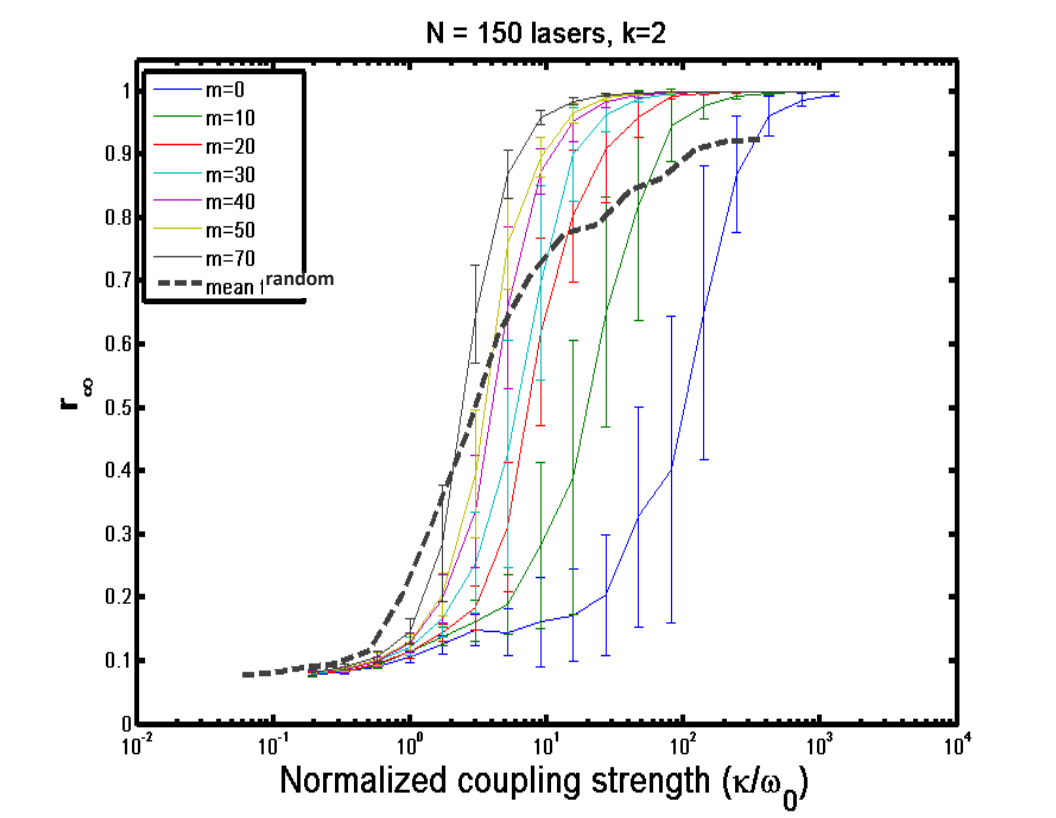


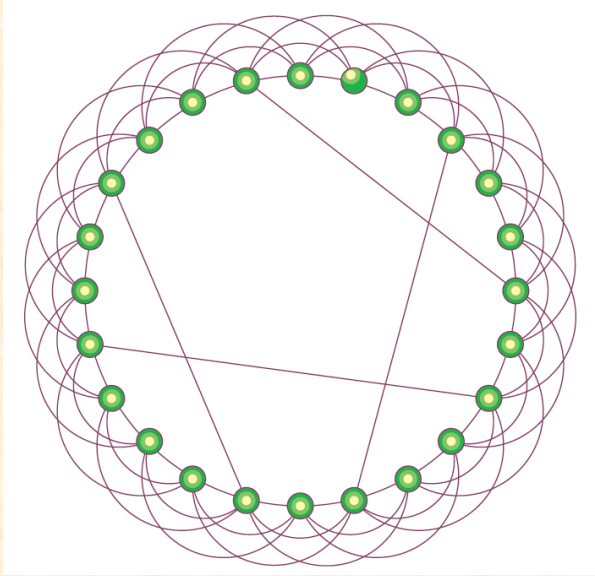
M. Nixon et. al., Nature Photonics 7, 919 (2013)

Coupled laser on "small world networks"

Collective dynamics of 'small-world' networks

Duncan J. Watts* & Steven H. Strogatz





R. Shriki et. al., unpublished

nature photonics

LETTERS

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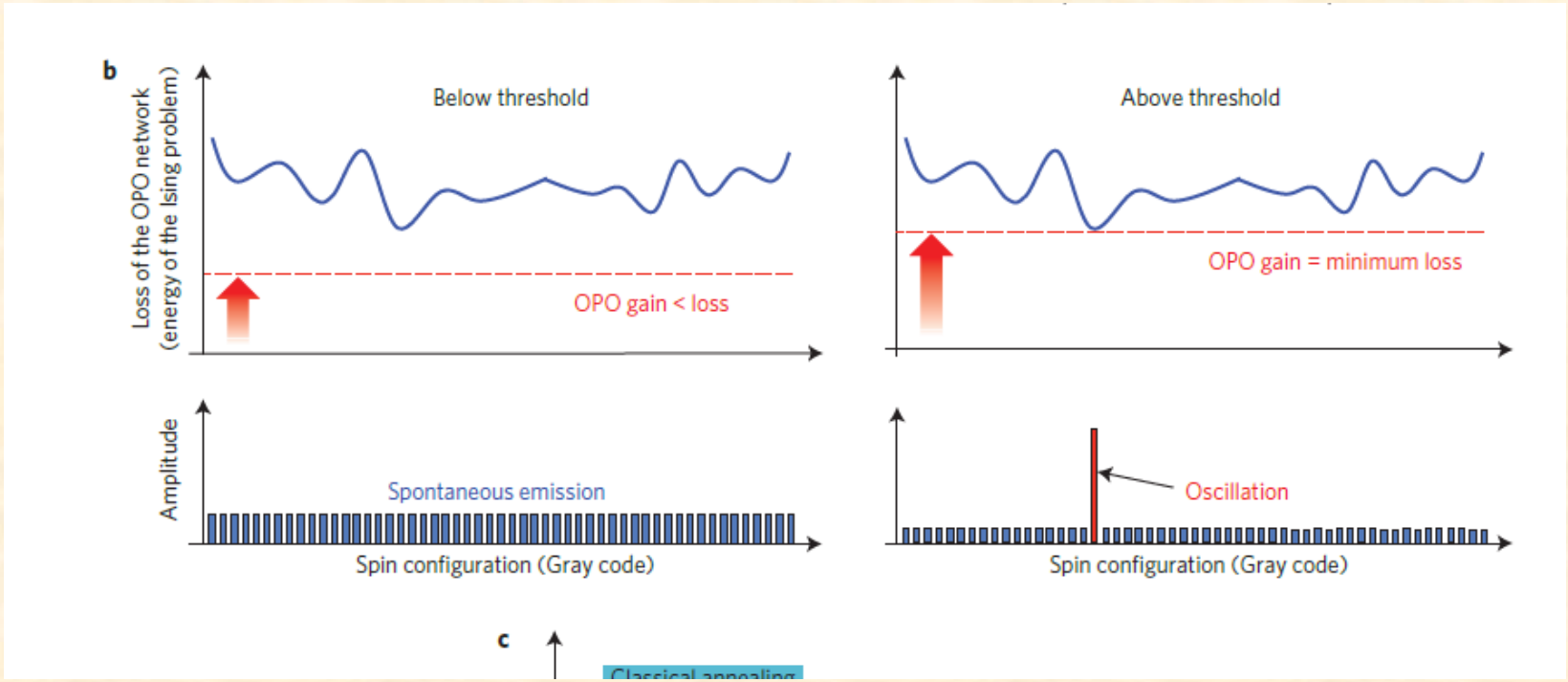
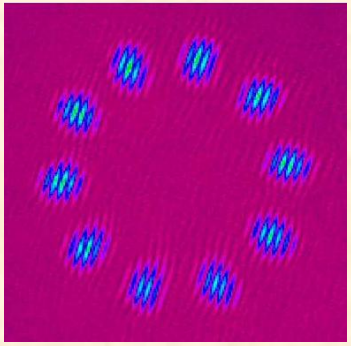
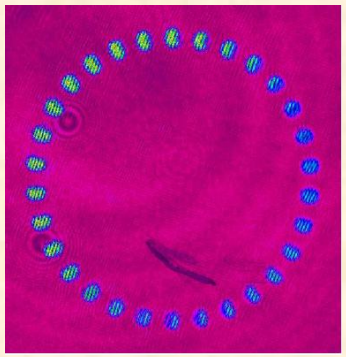
Network of time-multiplexed optical parametric oscillators as a coherent Ising machine

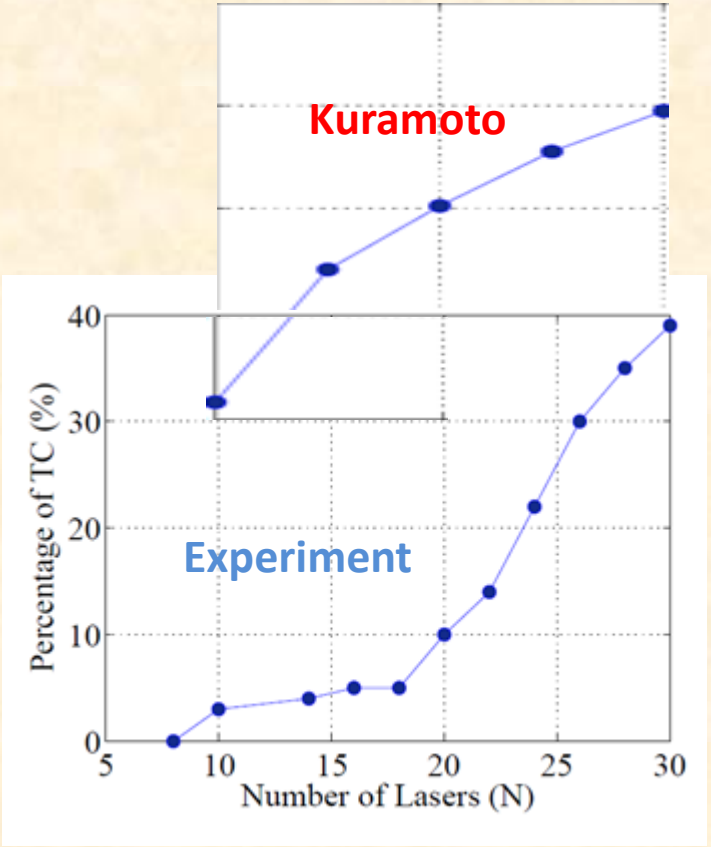
Alireza Marandi[1,2*], Zhe Wang[1], Kenta Takata[2,3], Robert L. Byer[1] and Yoshihisa Yamamoto[1,2,3]



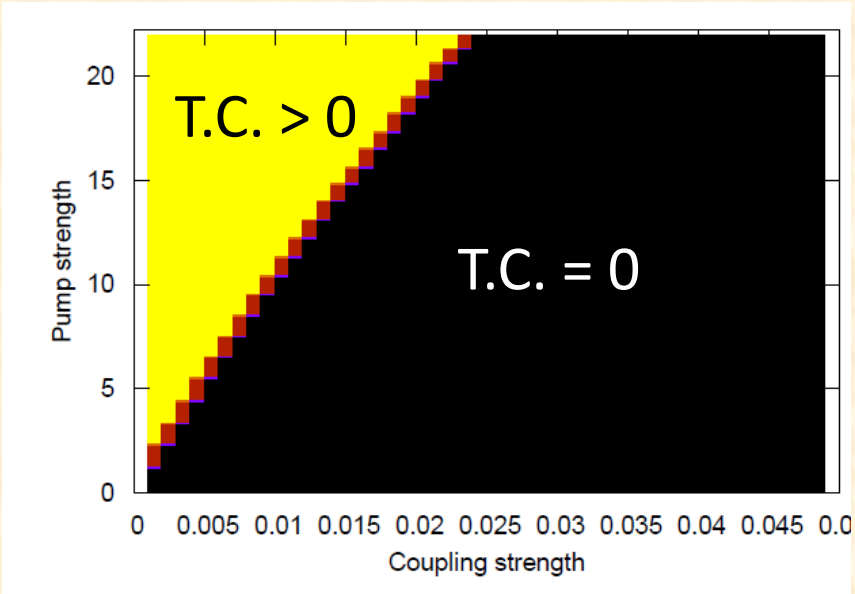
Beyond Kuramoto: how to avoid getting "stuck"





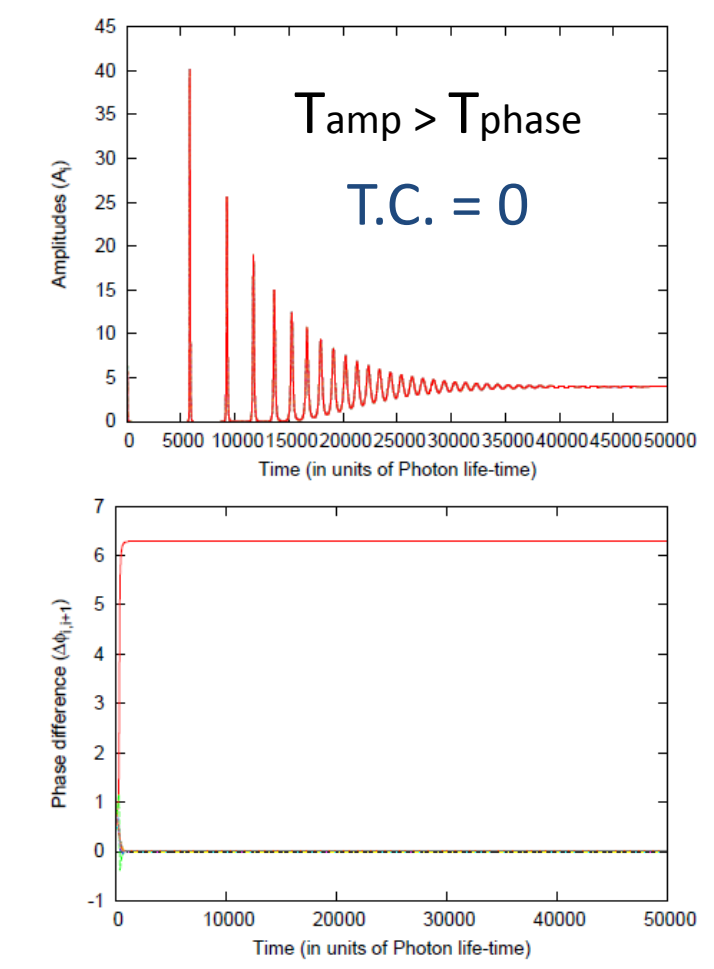


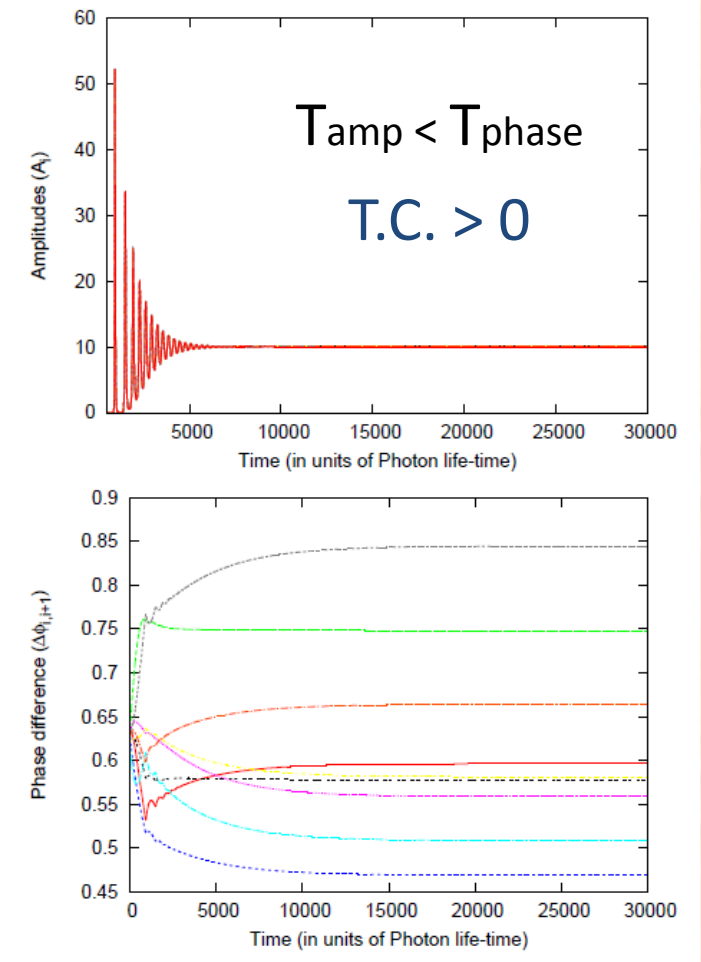
Full laser rate equations



Beyond Kuramoto: how to avoid getting "stuck"

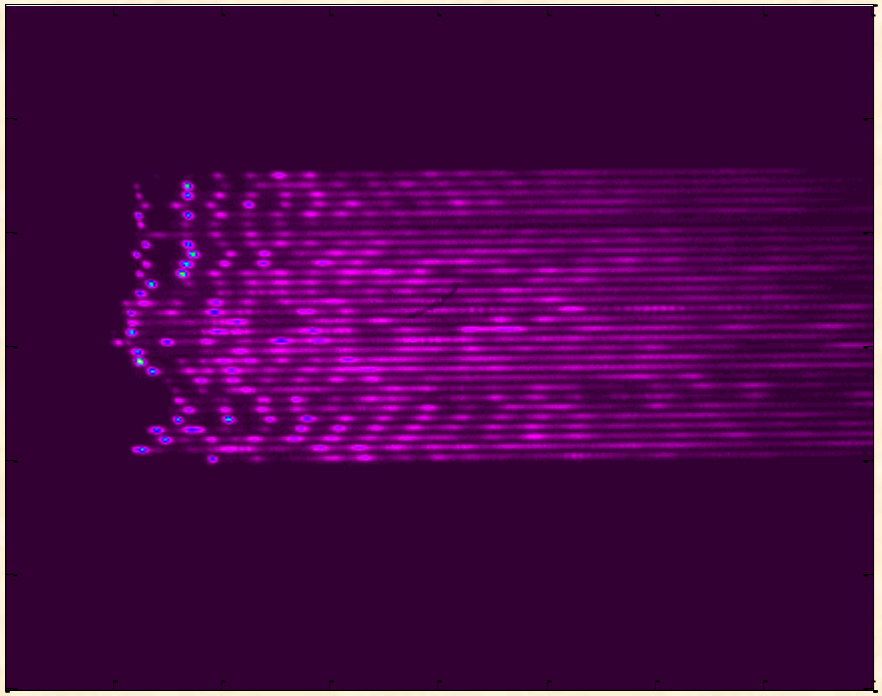
Relation to Kibble-Zurek mechanism





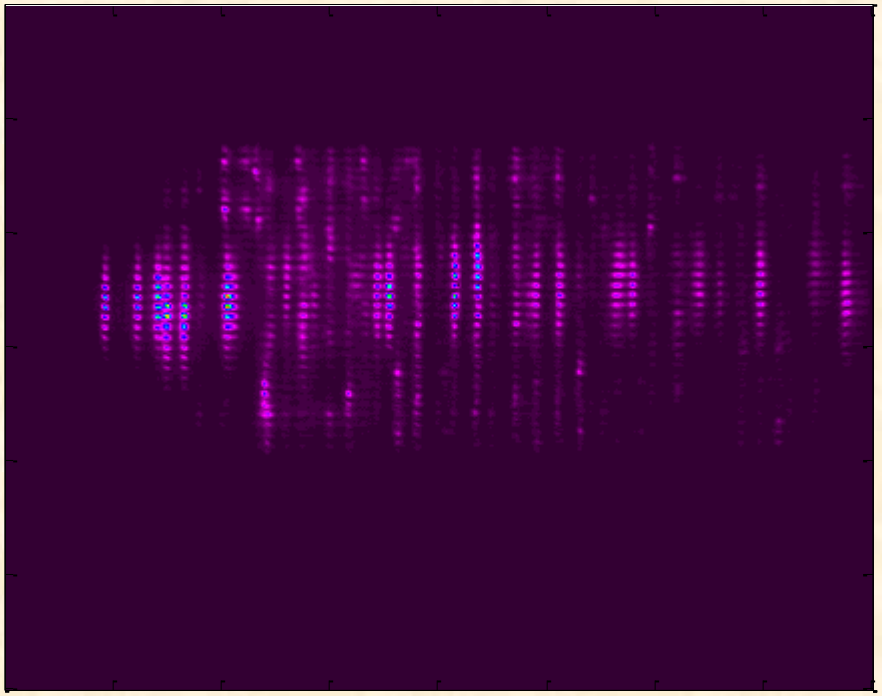
Beyond Kuramoto: Intensity (chaos) synchronization

Uncoupled lasers



time

Coupled lasers



time

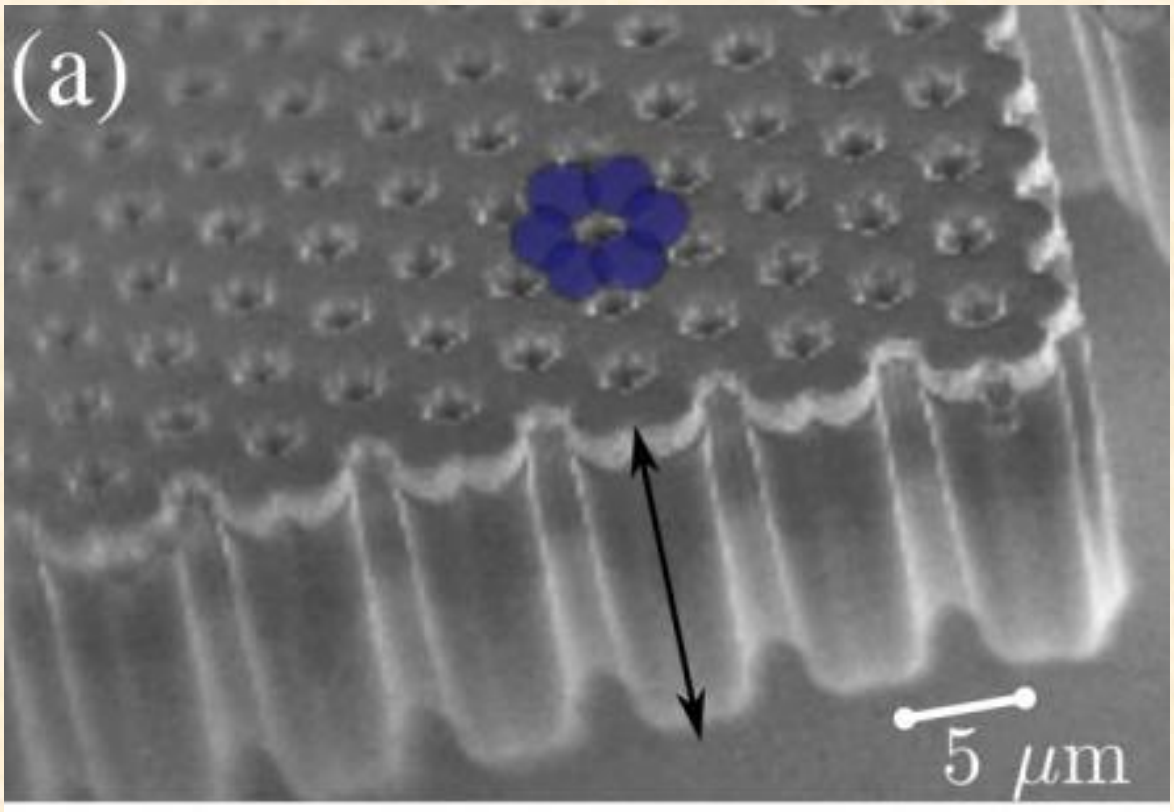
C. Tradensky et. al., unpublished

Long range coupling of polaritons ?

PRL **112,** 116402 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

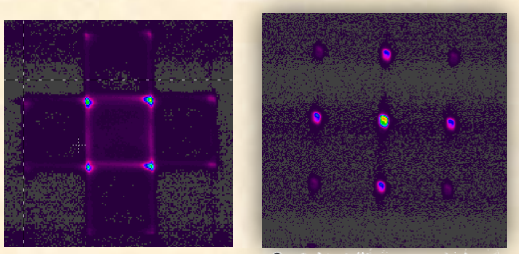
Direct Observation of Dirac Cones and a Flatband in a Honeycomb Lattice for Polaritons

T. Jacqmin,[1] I. Carusotto,[2] I. Sagnes,[1] M. Abbarchi,[1,*] D. D. Solnyshkov,[3] G. Malpuech,[3] E. Galopin,[1] A. Lemaître,[1] J. Bloch,[1] and A. Amo[1]

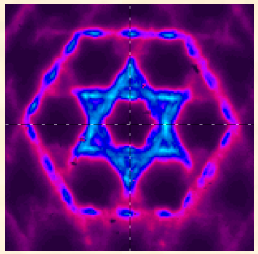


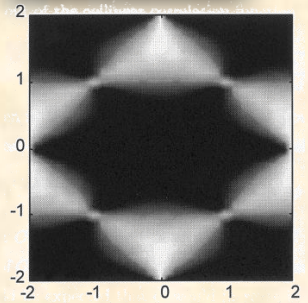
Summary

Phase lock >2000 laser with arbitrary coupling strength, range and sign

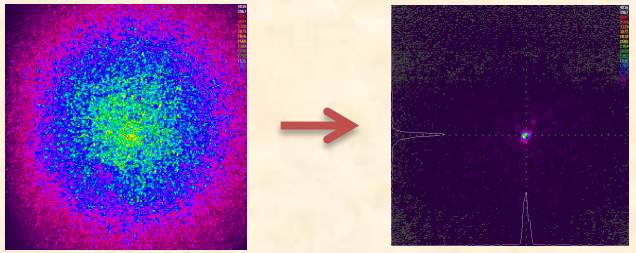


Geometric frustration (and its removal)

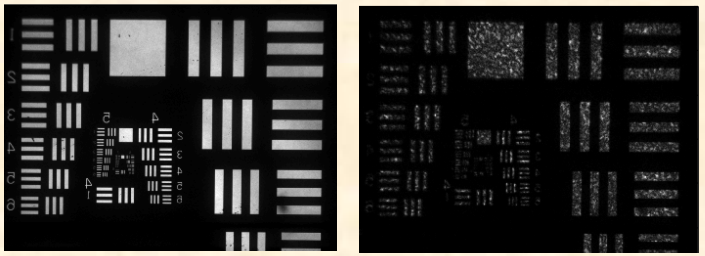




x80 better focussing for intra-cavity Diffuser (also biological tissue) faster than 600 nsec



High brightness laser illumination for speckle-free imaging.



Extreme Value Statistics