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Disorder-Enhanced Transport in Photonic Quasi-Crystals: Anderson Localization and Delocalization

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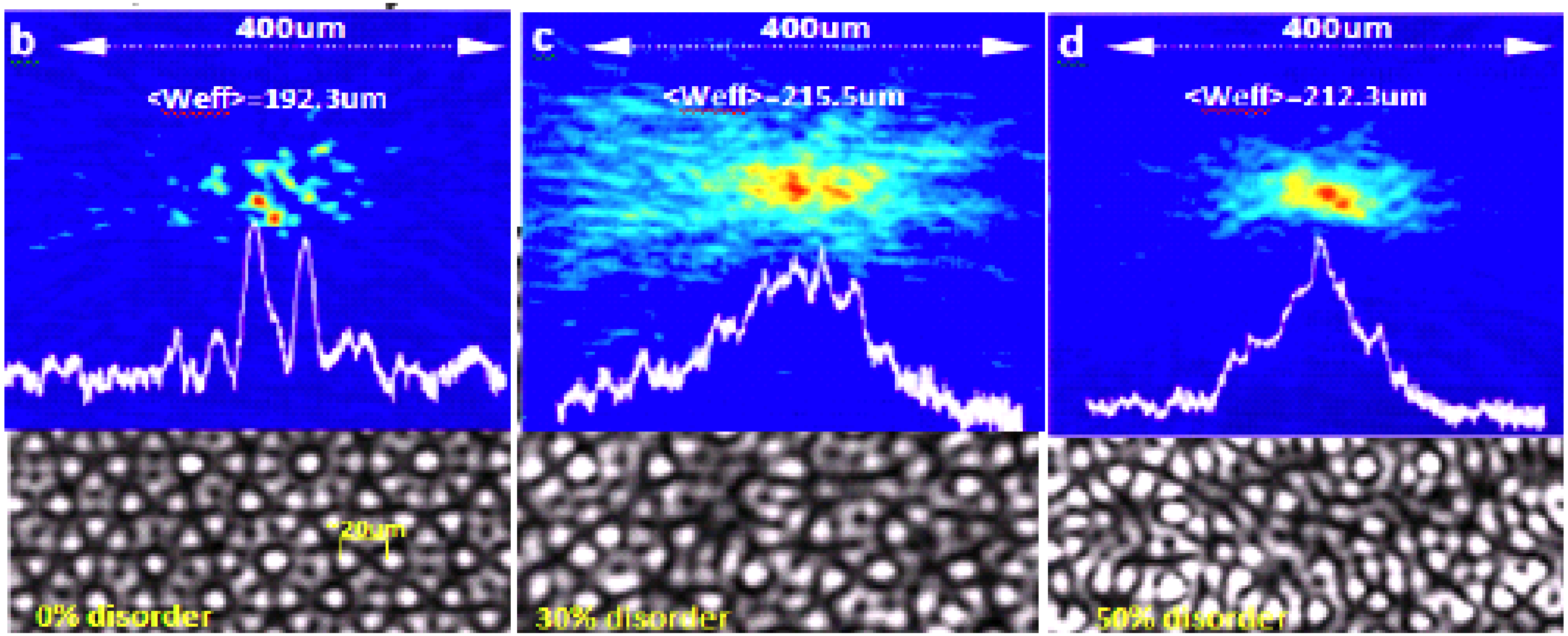

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What is this short talk about ?

Short Introduction:

What is Anderson Localization ?

What are Quasi-Crystals (QC)?

and then…

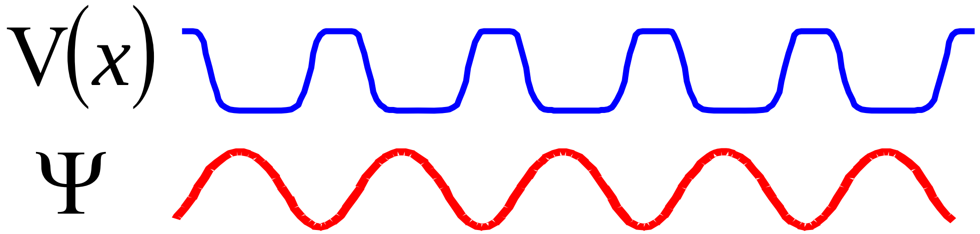
Utilizing optics, We will show a first direct observation of Delocalization due to disorder (enhanced transport) in QCs structures, and explain the underlying mechanism for it.

What is Anderson Localization ?

$$i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+V(\vec{r})\Psi$$

Periodic Potential:

Bloch waves (extended states)

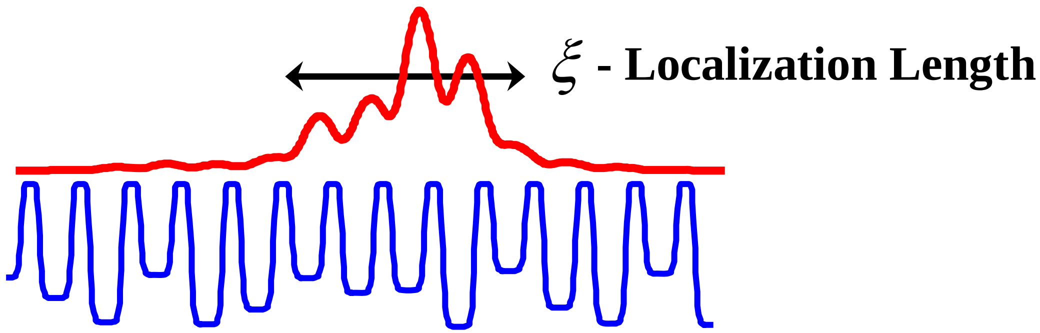


A wave packet propagating freely through the medium exhibits Ballistic Transport/Diffraction

Disordered Potential:

Localized States

Typical scale ξ



The wave remains confined in some region of the potential

Philip W. Anderson, 1958 (Nobel Prize 1977)

Why use Optics for demonstrating localization?

Anderson Model assumes:

$$i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+V(\vec{r},\not{t})\Psi$$

1. Constant potential with no time variations.
2. Single particle dynamics = no interaction.

In solids…

1. <u>Phonons</u> –
cause the potential to vary in time and in uncontrollable manner.
In optics, a frozen potential can be achieved relatively easy.

2. <u>Many-body interactions</u> –
interactions are inherent because electrons always interact.
in optics, it is easy to “switch” off interactions (nonlinearity).

Transverse Localization of Light

Wave Equation

$$\nabla^2 \vec{E} - \mu_0 \varepsilon(\vec{r}) \frac{\partial^2}{\partial t^2} \vec{E} = 0$$

\+

- **Scalar and Time harmonic**
- **slow variations of index of refraction**
- **slowly varying amplitude solution**

$$\lambda \frac{\partial^2 A}{\partial z^2} << \frac{\partial A}{\partial z}$$

$$\vec{E}(x,y,z) = A(x,y,z) e^{i(kz-wt)} \hat{x}$$

Optics

$$i\frac{\partial A}{\partial z} = -\frac{1}{2k}\nabla_\perp^2 A - \frac{k}{n_0}\Delta n(x,y,\not{z}) A$$

$$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

z-invariant refractive index

$$A = \alpha_n(x,y) e^{i(k_x x + k_y y - \beta_n z)}$$

Quantum Mechanics

$$i\frac{\partial \Psi}{\partial t} = -\frac{1}{2m}\nabla^2 \Psi + V(\vec{r},\not{t})\Psi$$

$\hbar = 1$

$$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

Time-invariant potential

$$\Psi = \varphi_n(x,y) e^{i(p_x x + p_y y - \frac{E_n}{\hbar} t)}$$

Correspondence

$A \leftrightarrow \Psi$

$z \leftrightarrow t$

$k\,\Delta n / n_0 \leftrightarrow -V$

$|k| \leftrightarrow m$ $\quad k_x, k_y \leftrightarrow p_x, p_y$

$\beta_n(\vec{k}_\perp) \leftrightarrow E_n(\vec{p})$

Optics

$$i\frac{\partial A}{\partial z} = -\frac{1}{2k}\nabla_{\perp}^{2} A - \frac{k\Delta n(x,y)}{n_0} A$$

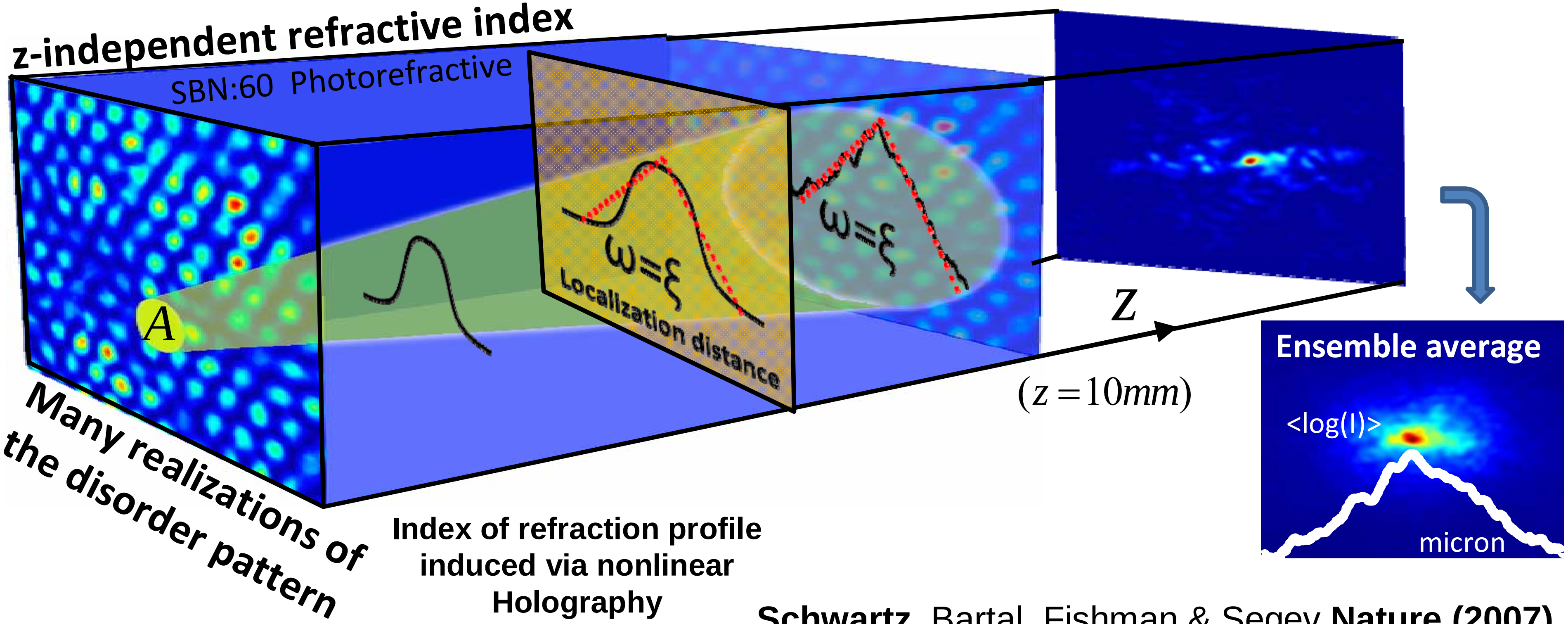
⟷

Quantum Mechanics

$$i\hbar\frac{\partial \Psi(\vec{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V(\vec{r})\Psi$$

Localization = disorder in a time-invariant potential, eliminates ballistic broadening of a wave packet	**Localization = disorder in a z-invariant refractive index, eliminates diffraction of a wave packet** Raedt, Lagendijk & de Vries, Phys Rev Lett (1989).

Localization Dynamics [order+disorder] (Optics)



Index of refraction profile induced via nonlinear Holography

Schwartz, Bartal, Fishman & Segev **Nature (2007)**

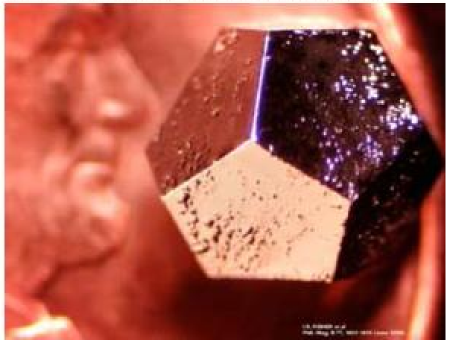
What are Quasi-Crystals ?

- **Up until 1982 it was believed that all solids in nature…**
  - ***Fully periodic structure***
  - **Rotational symmetry of orders 2,3,4,6 only.**

  In 1982: QC discovery by Shechtman; crystal redefined.

  Theory: Levine & Steinhardt, 1984

Al-Mn alloy-Quasi Crystal



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Quasi-crystals = Non-periodic structure with infinite correlations:

- **Long-range order**
- **No invariance under space translations or rotations**
- **No "unit cell"**
- **Fractal band structure –**

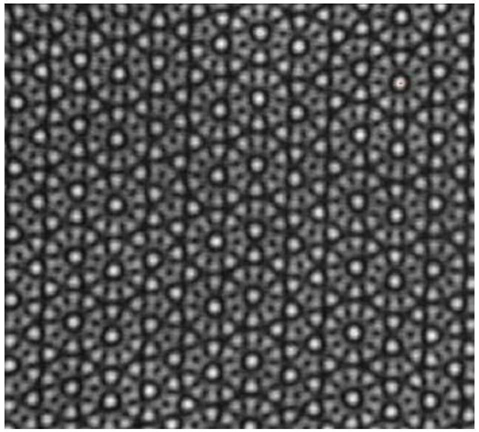
  with No Band Gaps ; Only "Pseudo gaps"
- **Eigen modes are critical states –** $r^{-\alpha}$

  polynomially decaying tails

  (in contrast with extended states in crystals

  and with Anderson-Localized modes in disordered media)

Penrose tiling



Freedman et al Nature (2006).

Anderson Localization and Delocalization in Quasi-Crystals

Motivation: several indirect measurements [Mayou et al. Phys. Rev. Lett. 1993 and reference there in] have shown that In Quasi-crystals disorder is able to enhance transport in contrast with periodic media where transport is reduced up to elimination (Anderson Localization)

1. The first direct experimental observation of enhanced transport in QCs.

2. Question 1 : Why ? What is the underlying mechanism?

   Question 2 : Is there Anderson Localization in QCs ?

   At which range of parameters will the addition of disorder lead to increased transport ?

   Question 3 : What is the difference between the dynamics in periodic structure and QC ?

Thus far… Quasicrystals in Solid State Physics

Kohmoto & Kadanoff Localization Problem in One Dimension Mapping and Escape *PRL* (1983).

Kohmoto et al. Critical wave functions and a Cantor-set spectrum of a one-dimensional quasicrystal model PRB (1987)

Passaro et al. Anomalous diffusion and conductivity in octagonal tiling models. *Phys. Rev. B* (1992).

Fujiwara, & Yamamoto Band structure effects of transport properties in icosahedral quasicrystals. *PRL* (1993).

Mayou, Evidence for Unconventional Electronic Transport in Quasicrystals. *PRL* (1993).

Roche & Mayou, Conductivity in Quasiperiodic Systems: A Numerical Study. *PRL* (1997)

Roche et al. Electronic Transport Properties of Quasicrystals. *J. Math. Phys*. (1997) **exp**

and more…

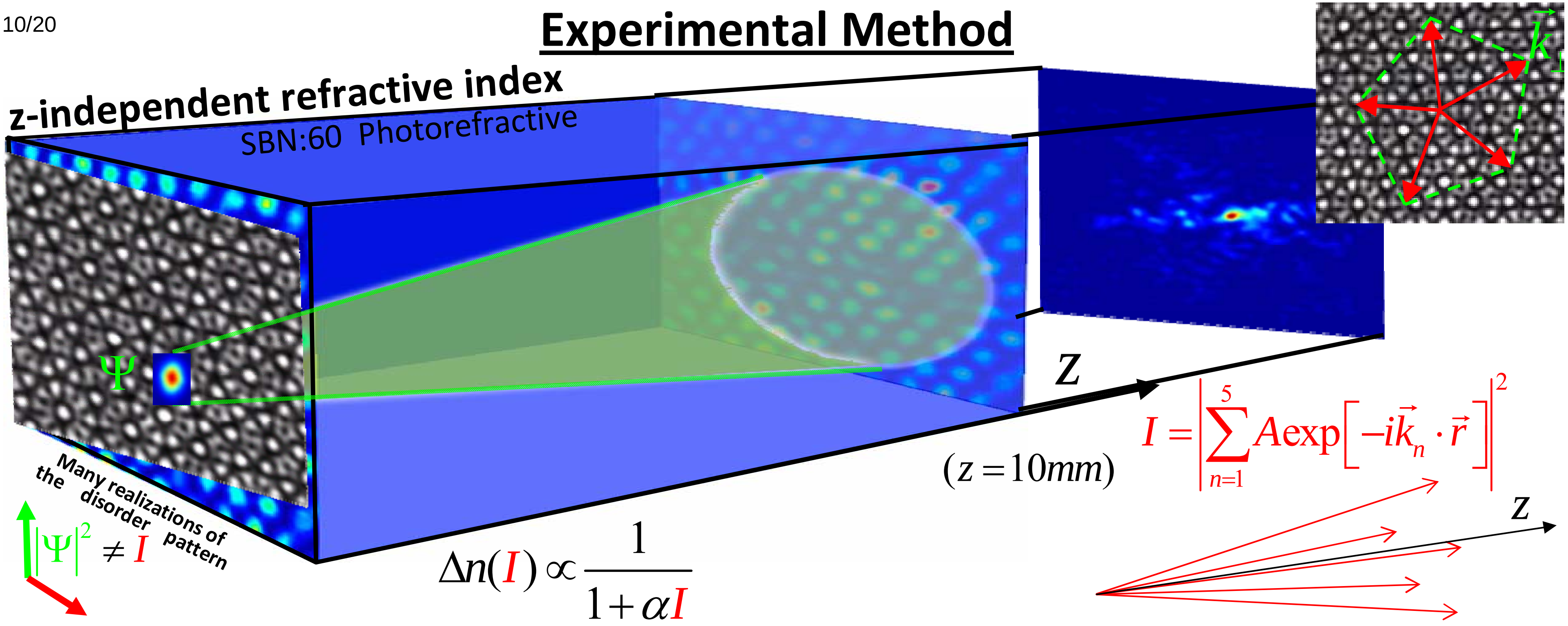
… Via Optics

Kohmoto et al. Localization of optics: Quasiperiodic media. PRL (1987)

Gellermann & Khomoto Localization of Light Waves in Fibonacci Dielectric Multilayers PRL (1994) **exp**

Lahini et al Observation of a Localization Transition in Quasiperiodic Photonic Lattices PRL (2009) (based on Aubry & Andre´, Ann. Isr. Phys. Soc. (1980)) **exp**

Experimental Method



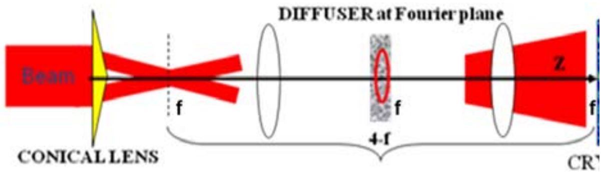
The Experimental challenge of demonstrating optical Localization

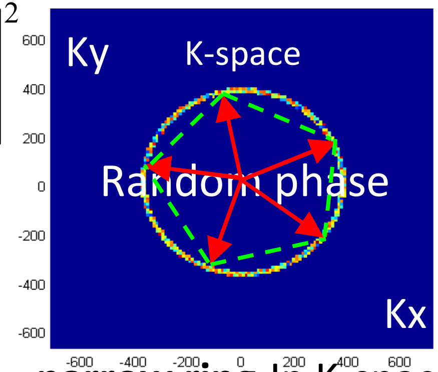
The Anderson model requires a frozen potential.

Eliminating diffraction of the speckle patterns (disorder) = **Propagation invariant disorder**

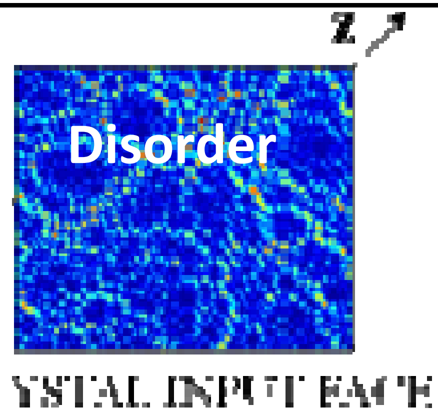
DIFFUSER at Fourier plane

$$I = \left| \sum_{n=1}^{N} C \exp\left[-i\vec{k}_{\perp,n} \cdot \vec{r} - k_{//} z + \phi_n^{rand} \right] \right|^2$$

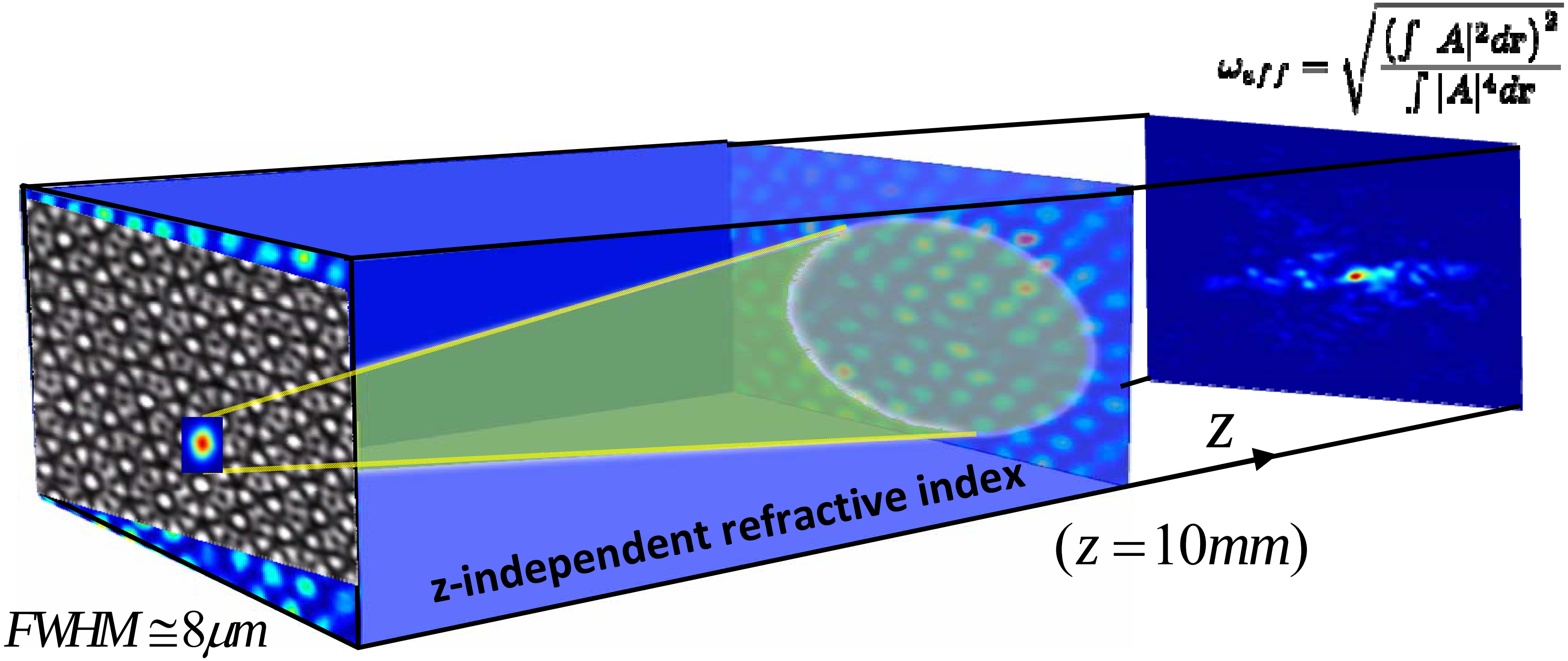




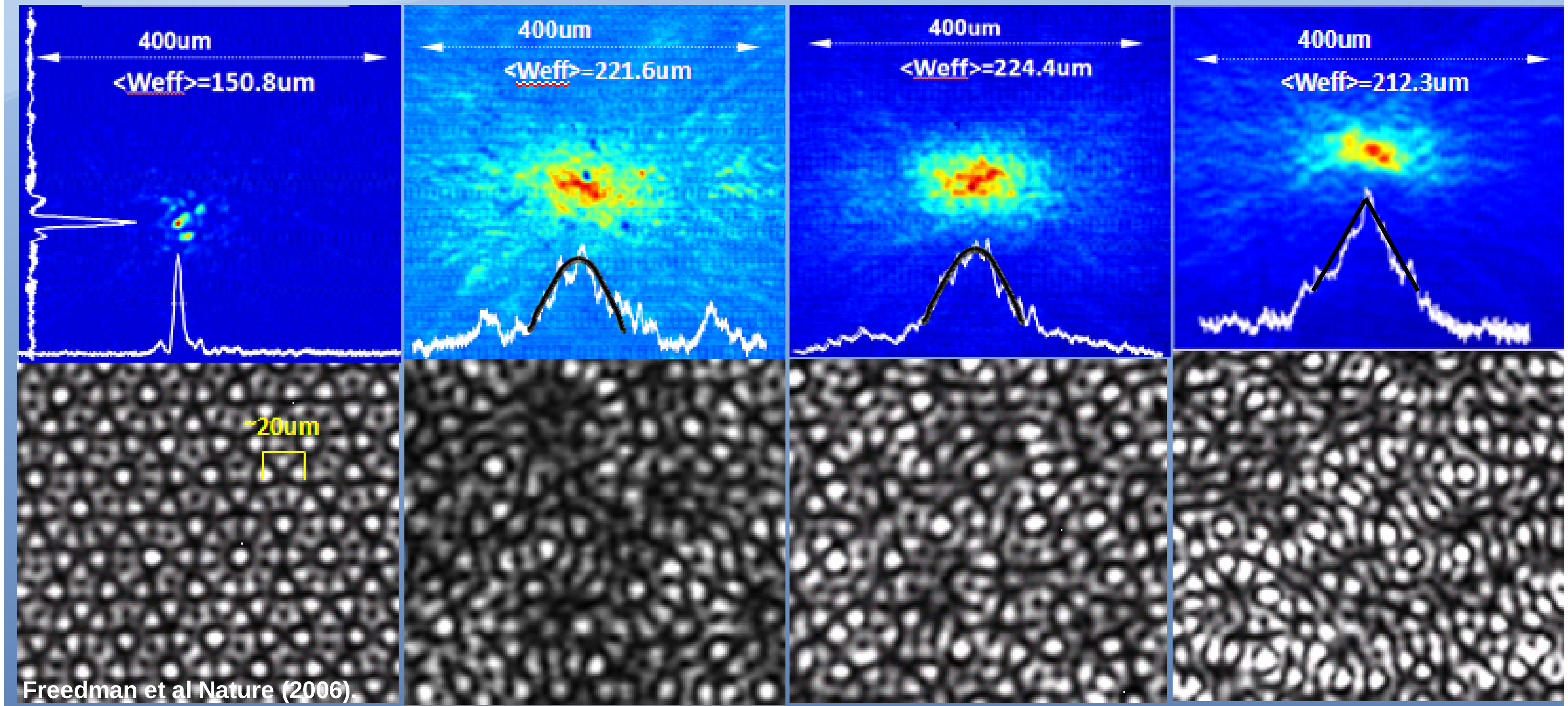
narrow ring In K-space



Experimental results



Experimental results



0% disorder
Transport via critical states

10% disorder
Disorder-enhanced transport;

Diffusion-like ?

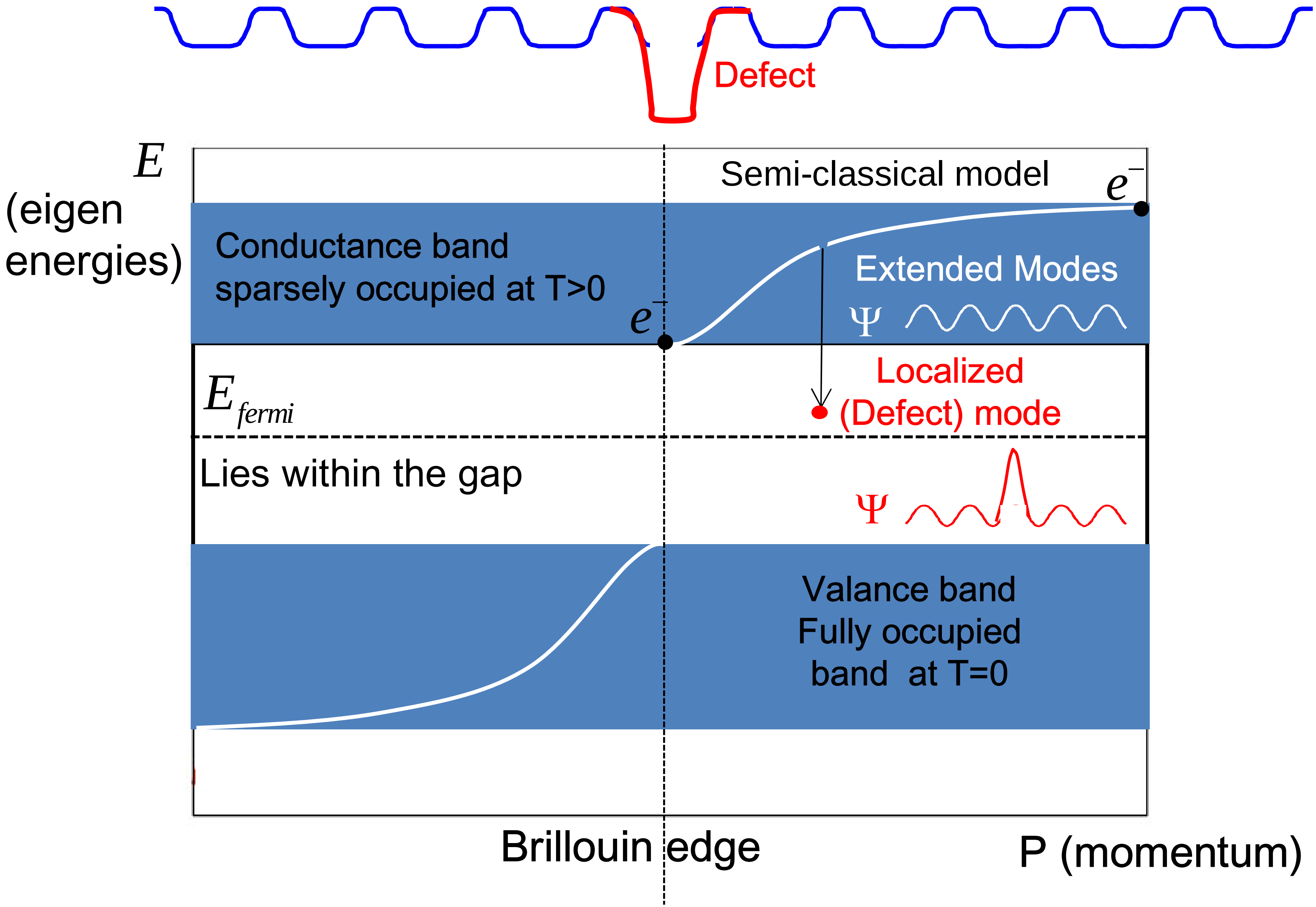
30% disorder
Disorder-enhanced transport;

Diffusion-like ?

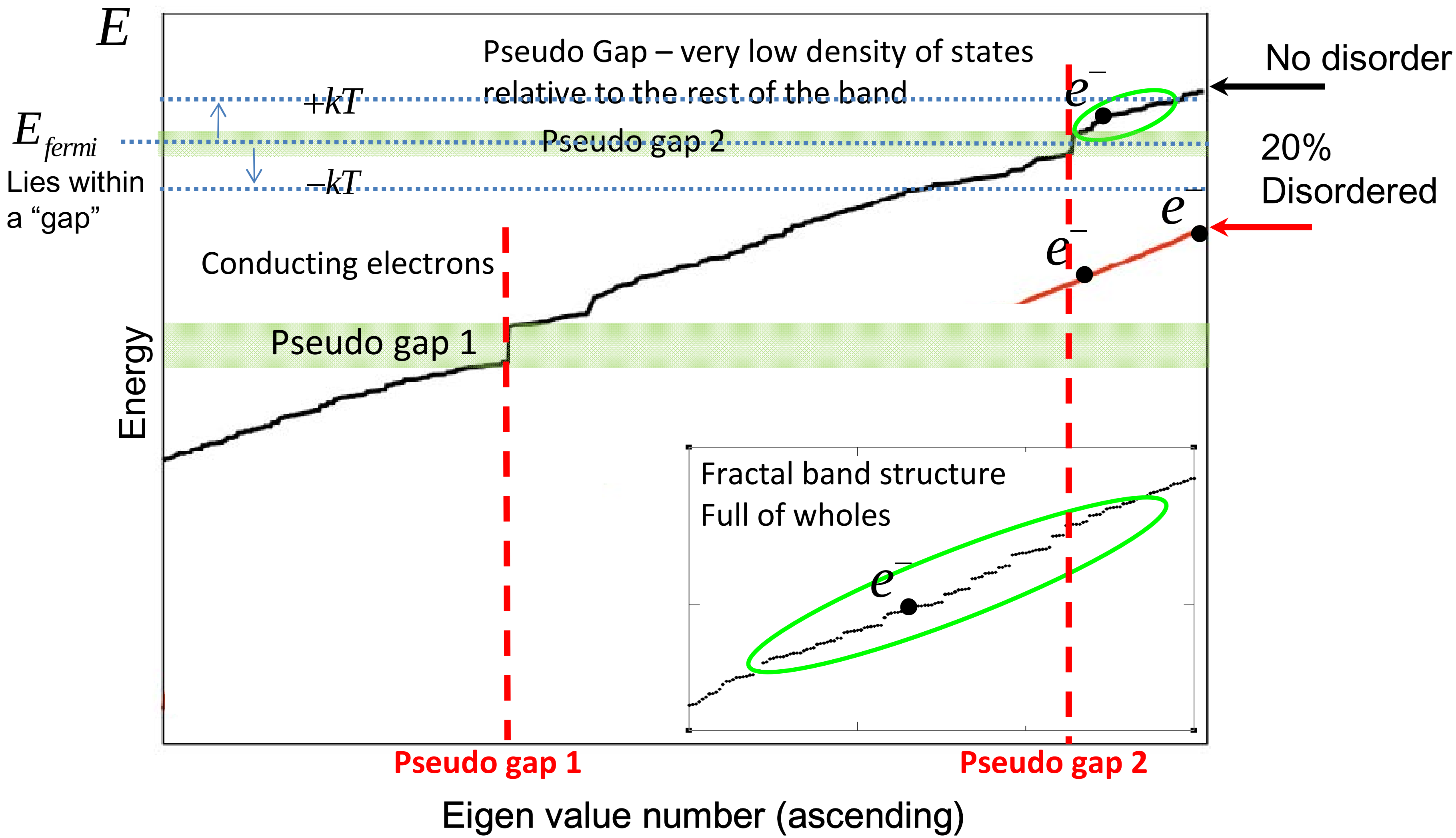
50% disorder
Anderson-localized

What is the underlying mechanism?

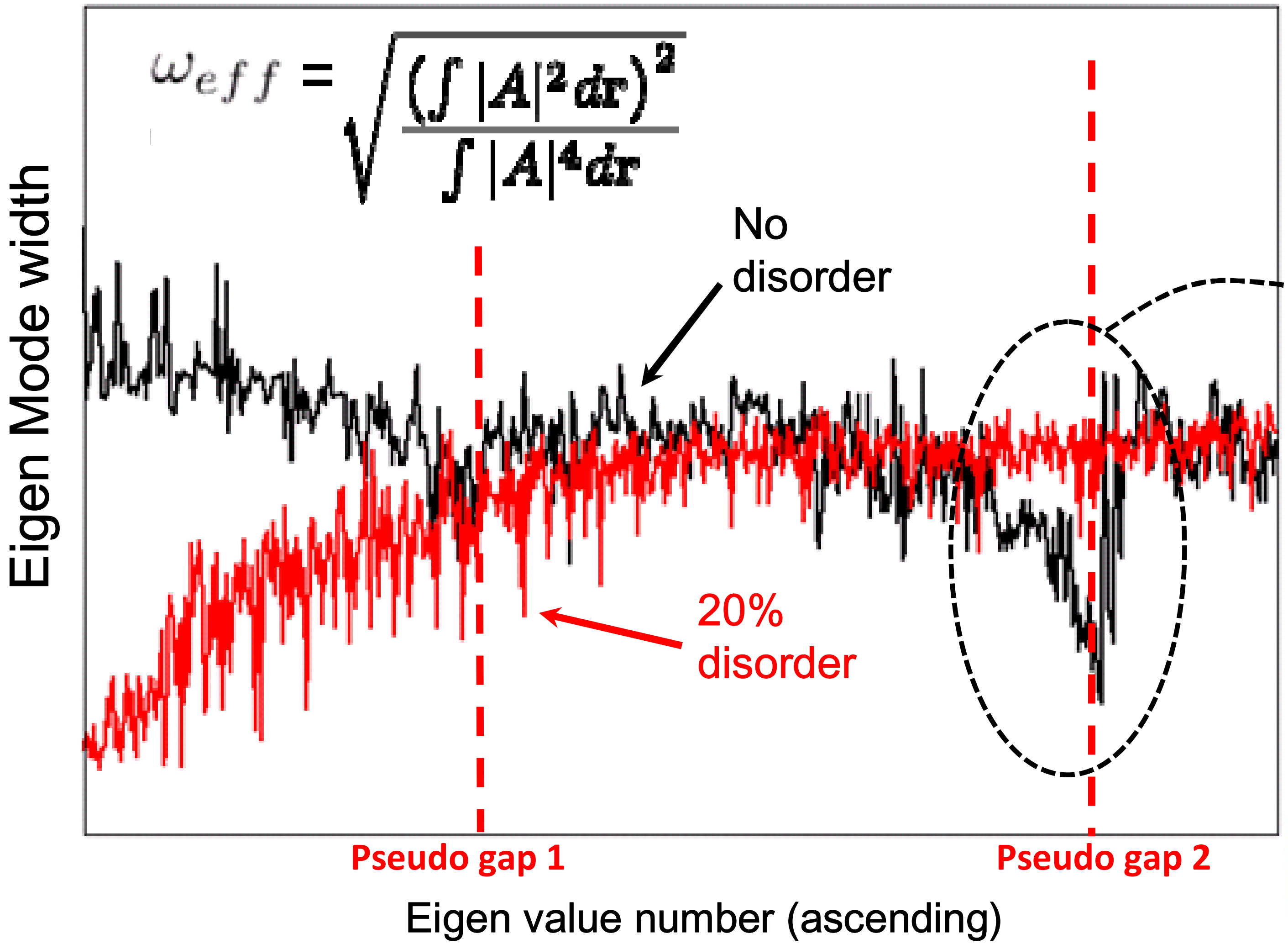
Eigen value spectra: Pure-crystal

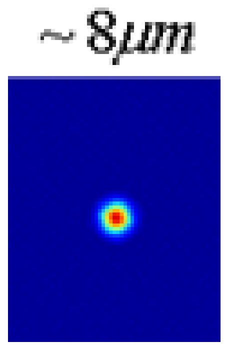


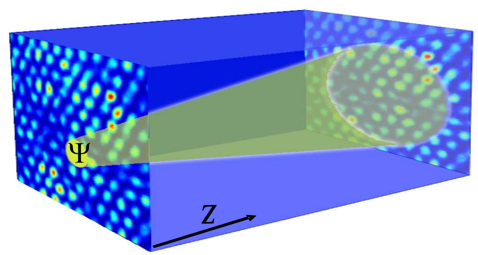
Eigen value spectra: Quasi-Crystal with and without disorder



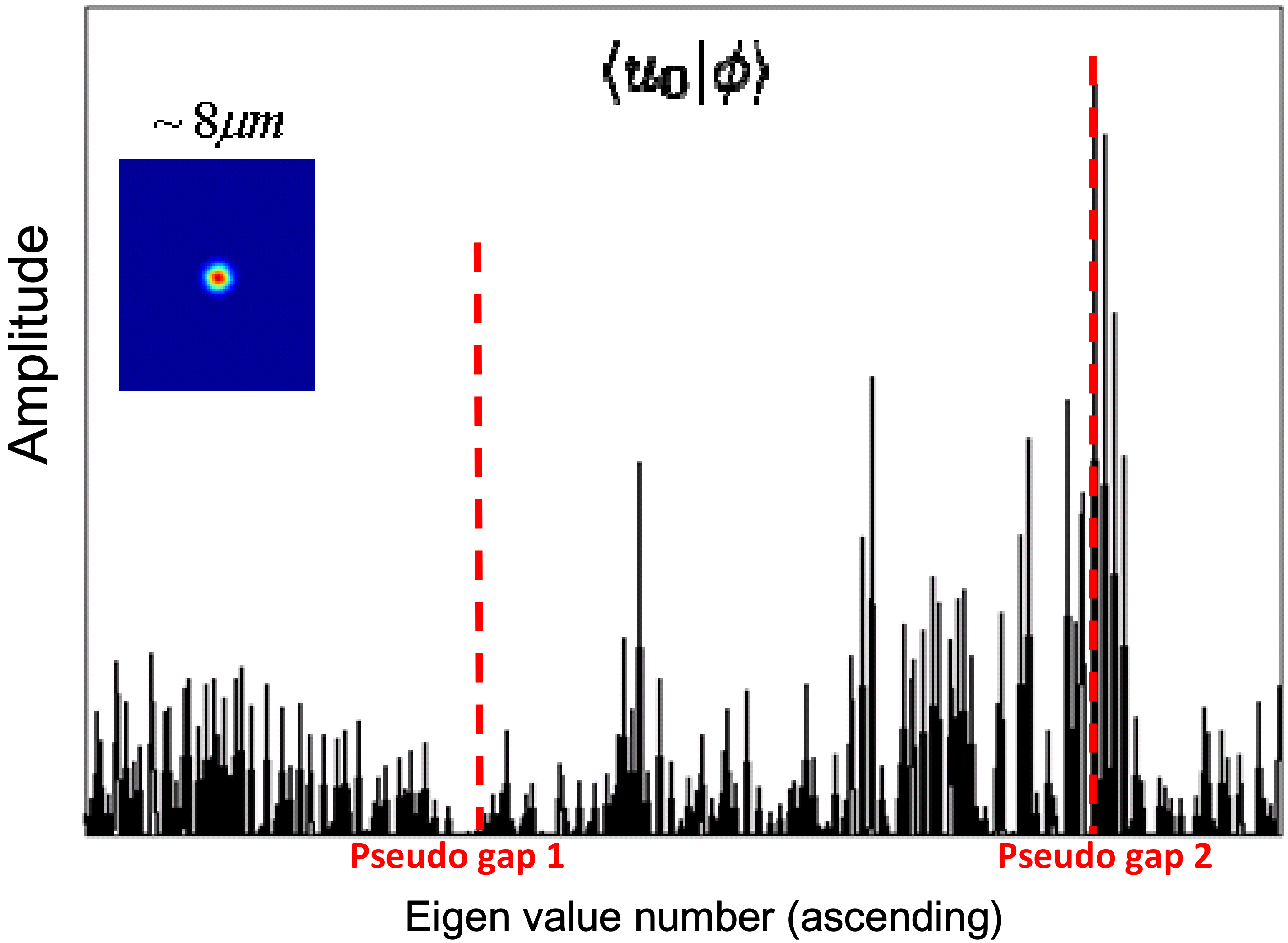
Eigen states width – some are extended some are not…



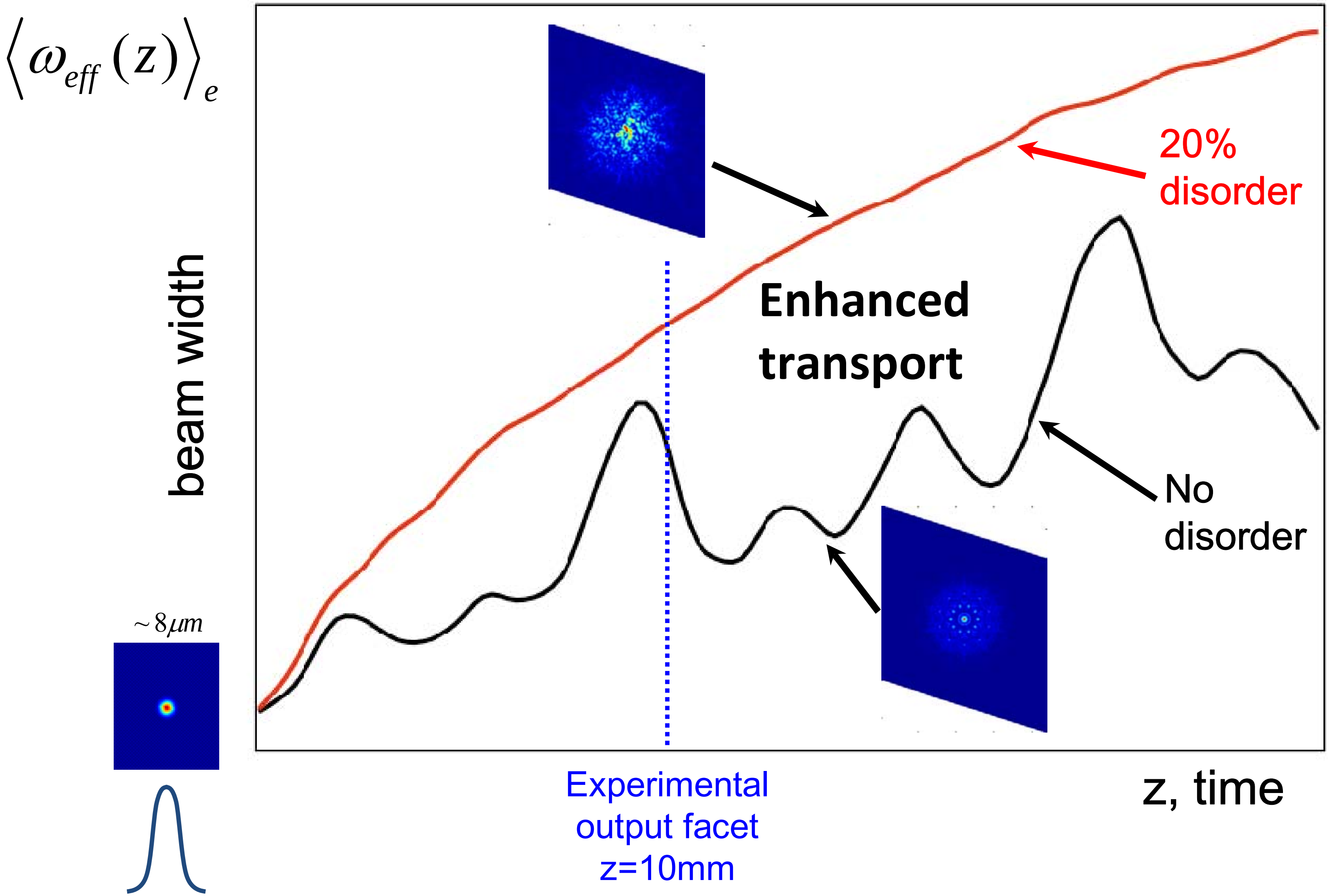




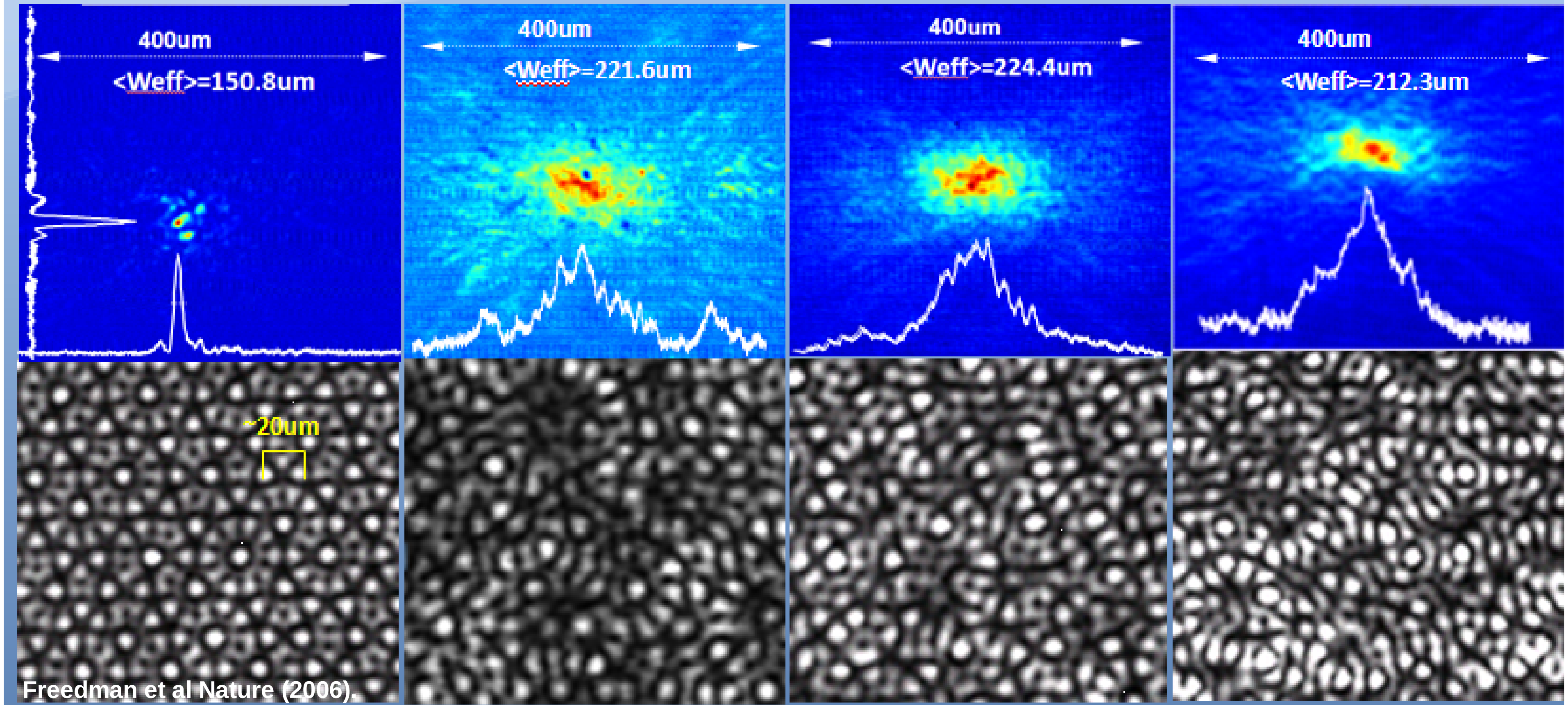
Constructing the initial wavepacket as "conduction electron"



Time evolution (Expansion) of initial beam: quasi-crystal with and without disorder



Experimental results



0% disorder	10% disorder	30% disorder	50% disorder
Transport via critical states	Disorder-enhanced transport; Diffusion-like ?	Disorder-enhanced transport; Diffusion-like ?	Anderson-localized

Conclusions:

1. First direct observation of disorder-enhanced transport in Quasi-Crystals.

2. We find that disorder-enhanced transport occurs only for states residing at the vicinity of pseudo-gaps

3. Pseudo-gap states correspond to conduction electrons in Quasi-Crystal solids, residing within a stripe of kT around Fermi energy

4. This sheds light on the long-debated issue of Anderson (anti-) localization in Quasi-Crystals