Pre-talk advertisements

LINDAU NOBEL LAUREATE MEETINGS

Sig

Path: >

Selection Criteria – please read through the selection criteria first to see if you are eligible to apply:

73nd Lindau Nobel Laureate Meeting (PDF)

Application

In which meeting do you wish to participate? — 73rd Lindau Nobel Laureate Meeting (Physics)

In which country is your main university or institution? — Uzbekistan

I have the nationality of this country — Uzbekistan

Info — You need to apply via the Open Application Process. Please be advised that if you enter false data and are not truly eligible to apply through the Open Application Process, your participation will not be considered.

Go to Open Application

deadline 26 Oct 2023

deadline 30 Sept 2023

New Journal of Physics

Early Career Award

The *New Journal of Physics* (NJP) Early Career Award recognises the talents of exceptional young researchers, who are making a significant contribution to their respective field of research.

Nominations for the 2023 ECR award are now open

Nominee criteria

The award is open to all researchers working in the physical sciences who meet the following criteria:

- Early-career scientist (less than five years since PhD qualification - i.e. defended in 2018 or thereafter - allowing for career breaks)
- Author of at least one article published in/accepted for publication in NJP in the 12 months prior to the award closing date of **30 September 2023**.

Making your nomination

Nominations should be submitted by a senior colleague e.g. department head, research group leader or principal investigator. Submissions must include the nominee's full name, contact email, institution/affiliation, the date that their PhD

Interference and wave-particle duality on the many-particle level

Andreas Buchleitner

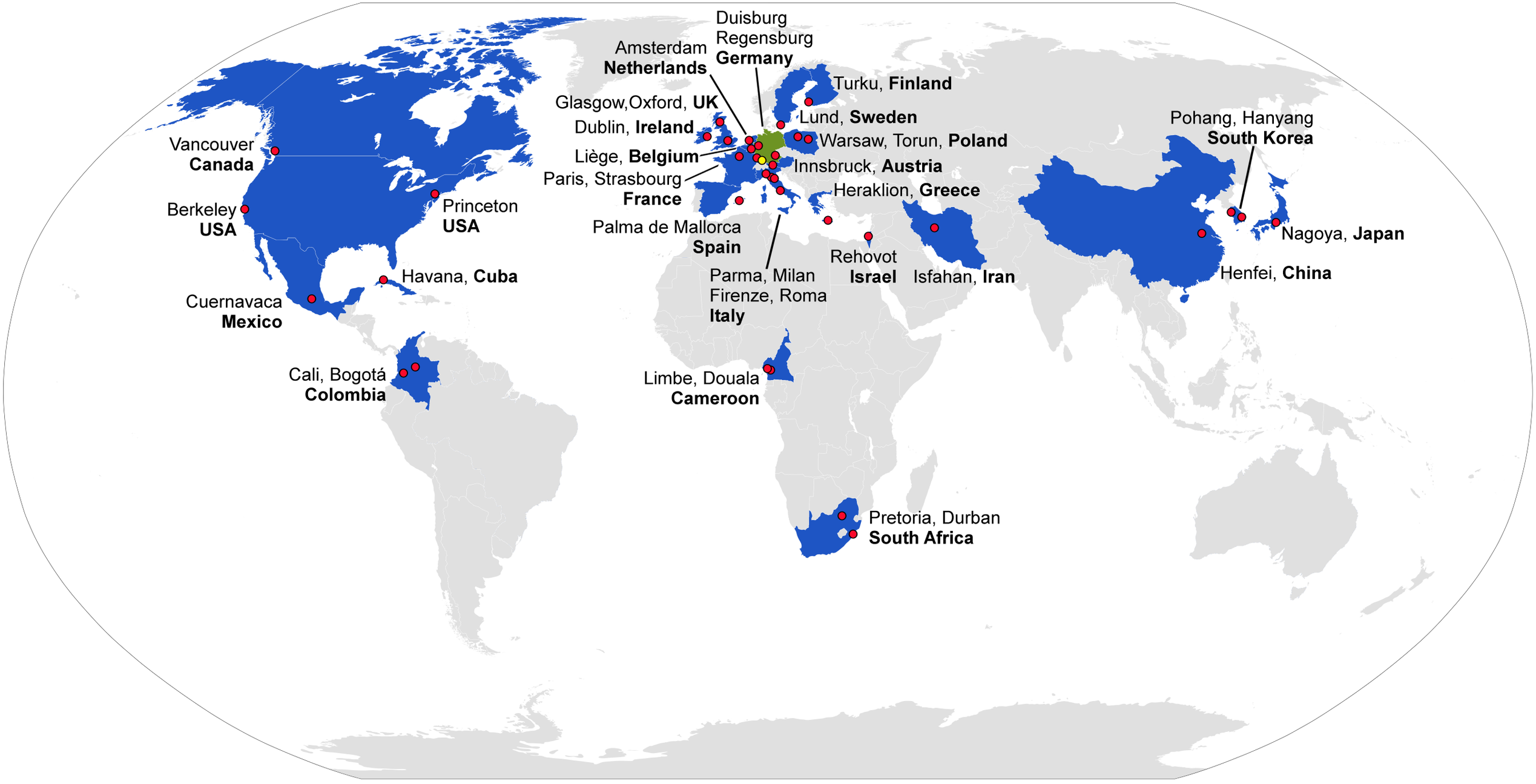
University of Bukhara, 28+29 September 2023

ICTP Summer School on New Trends in Modern Quantum Science

The Freiburg gang

People/Collaborations

M. Walschaers, M.C. Tichy, K. Mayer, F. Mintert, R. Keil, G. Weihs, Y.-S. Ra, Y.-H. Kim et al., J. Kuipers, J.-D. Urbina, K. Richter, F. Sciarrino et al.

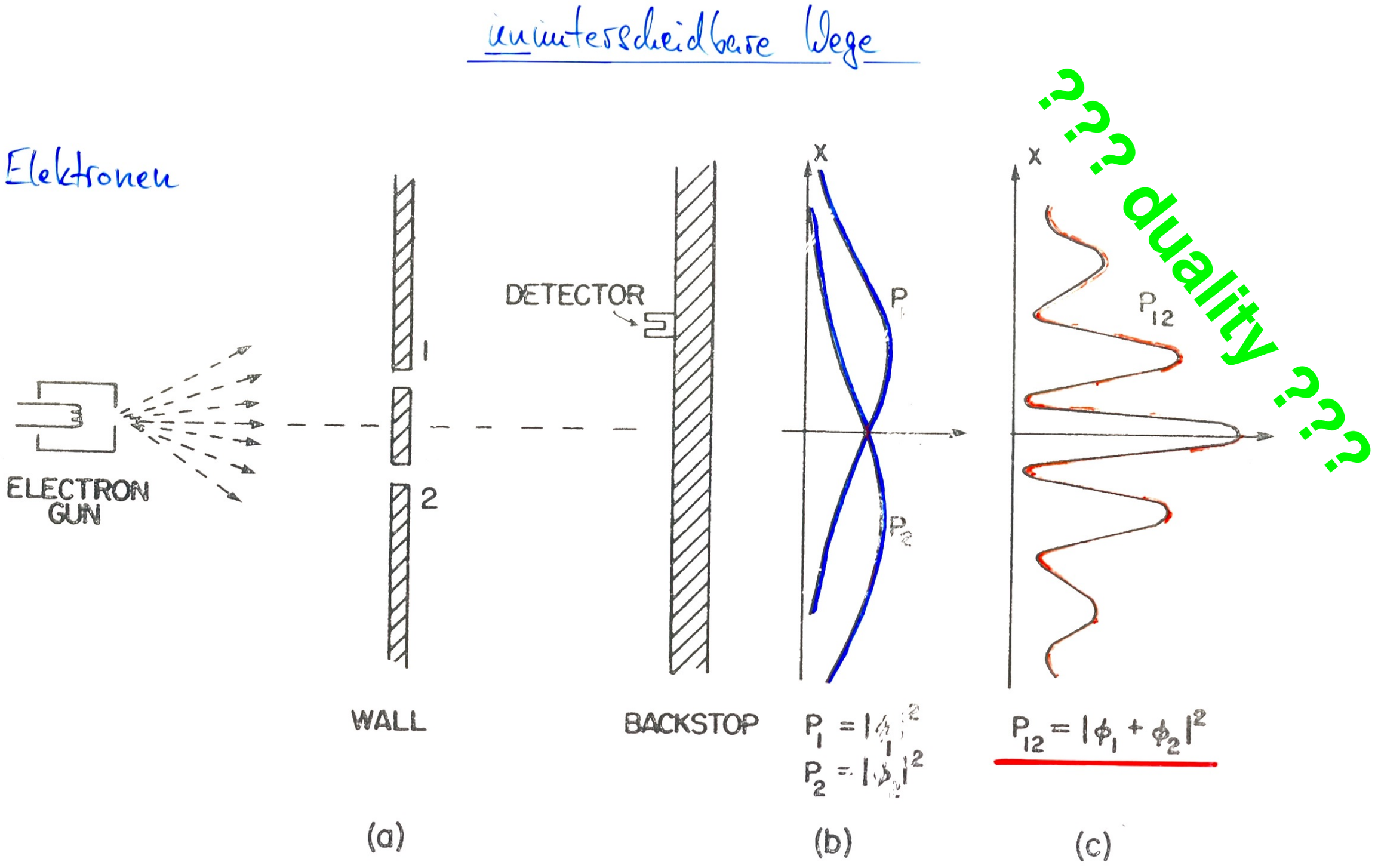


funded by

UFR, DFG, EU, Studienstiftung des deutschen Volkes, GH Endress foundation, State of Baden-Württemberg

Interference and (one-body) wave-particle duality

Single particle on a double slit



[Feynman, Lectures on Physics]

- interference of two single particle amplitudes -

Many-particle scenarios

larger (composite) particles

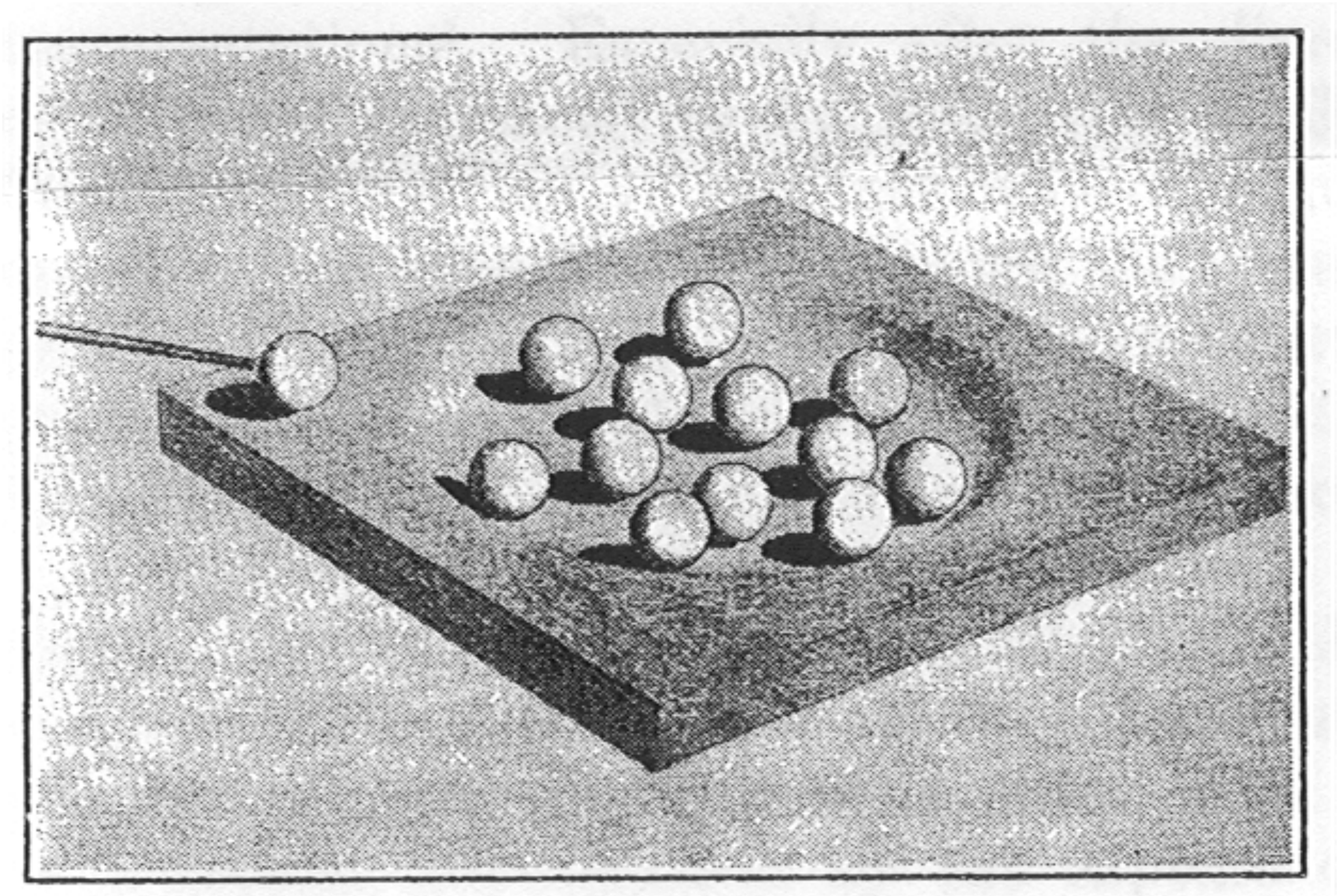
more particles

more modes/classically mutually exclusive alternatives/ways

How to deal with emerging complexity?
[in a panoply of physical settings]

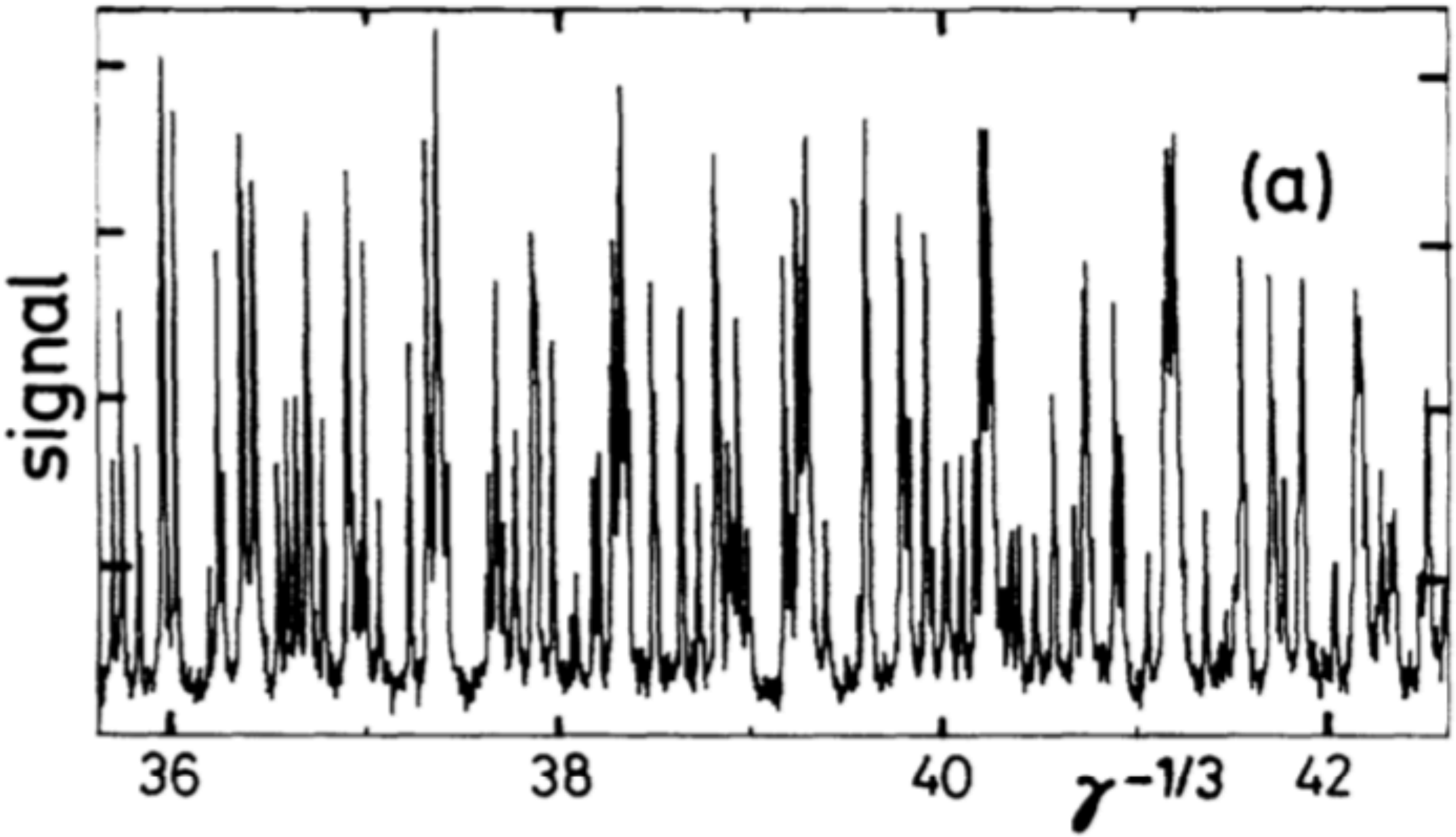
How to generalise (many-body) wave-particle duality?

Complex (interacting) many-particle dynamics



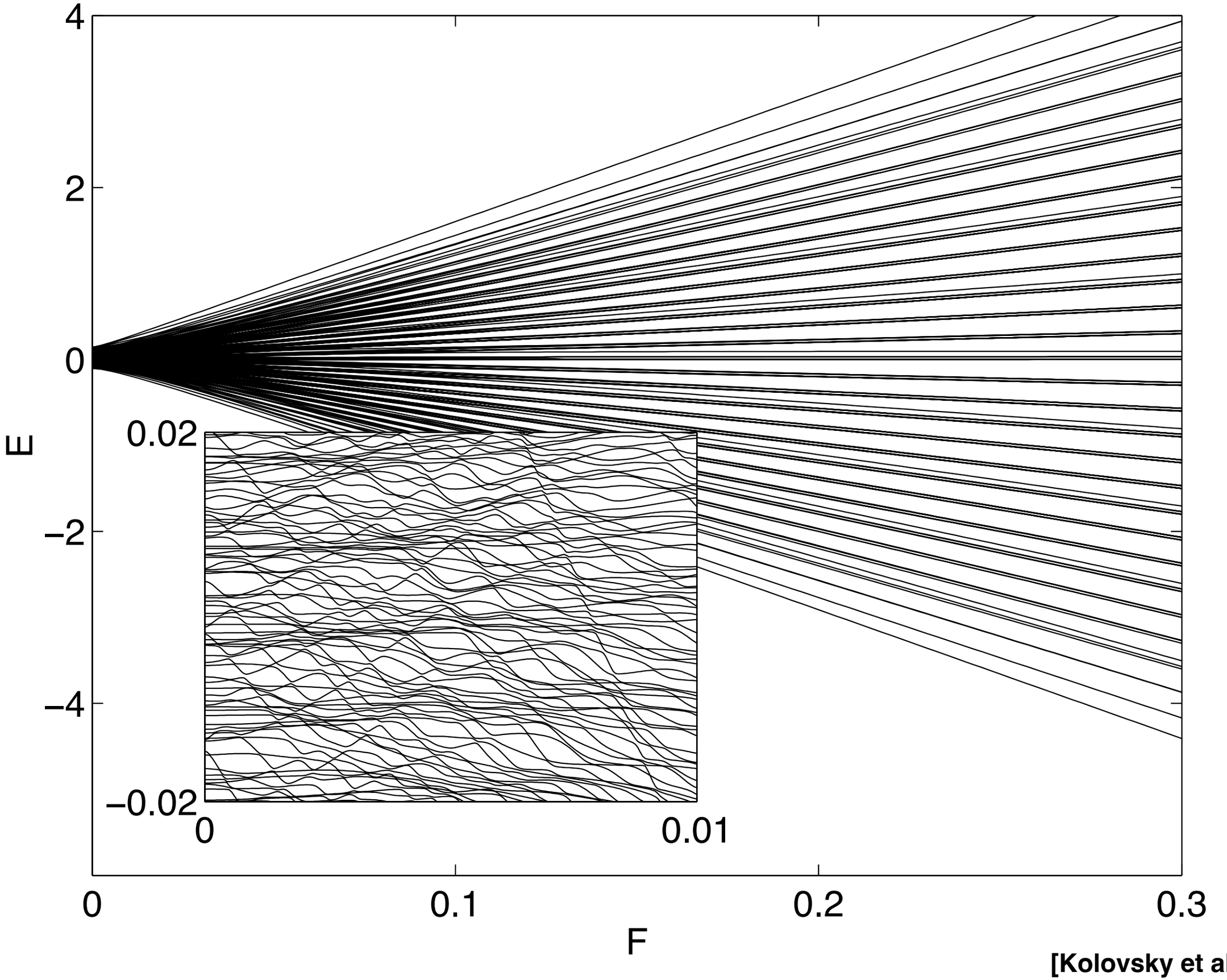
[Bohr 1936, incl. News and Views]

Complex cross sections



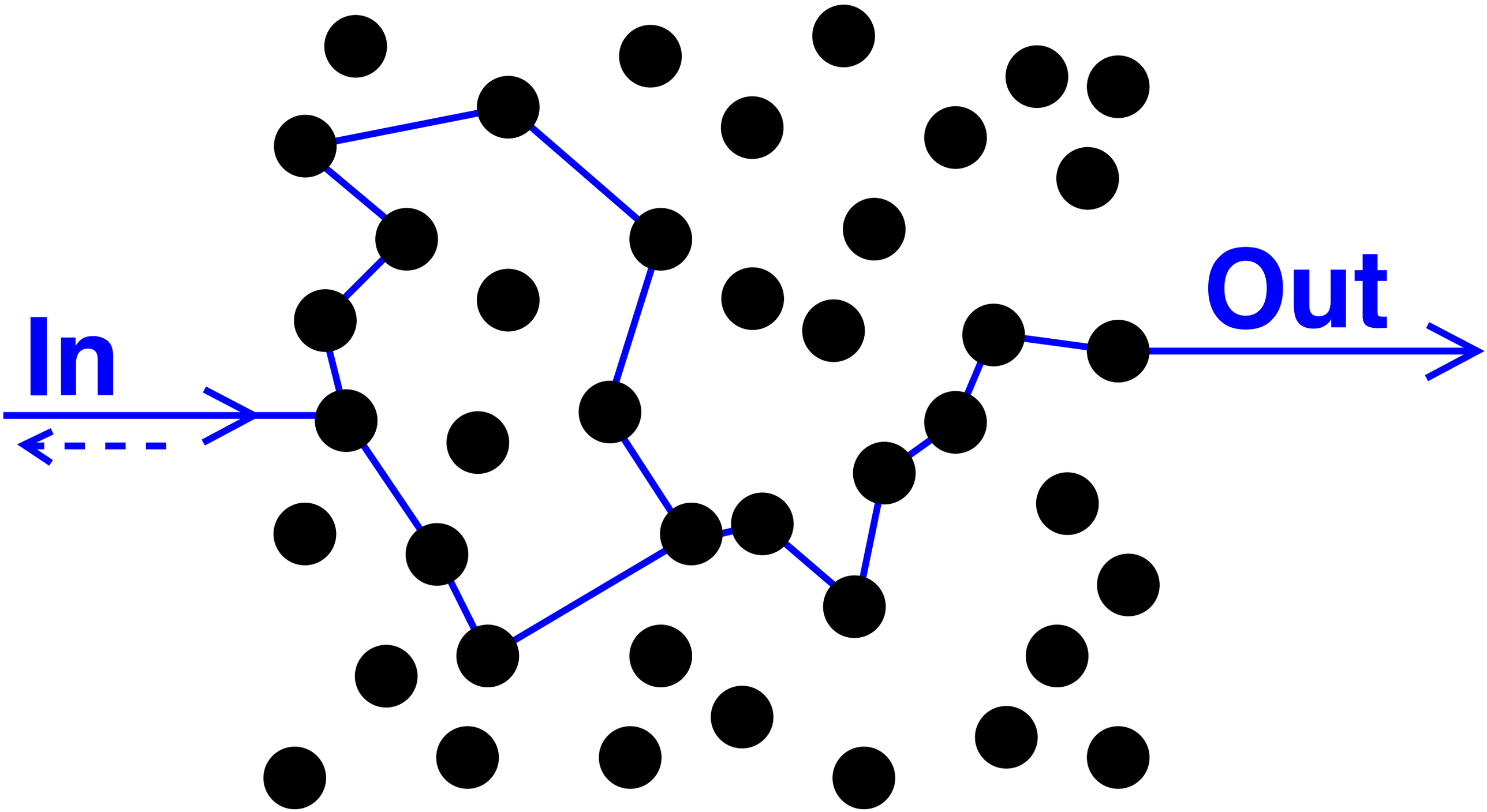
[Welge et al., 1988]

Complex spectra



[Kolovsky et al., 2003]

Complex transport



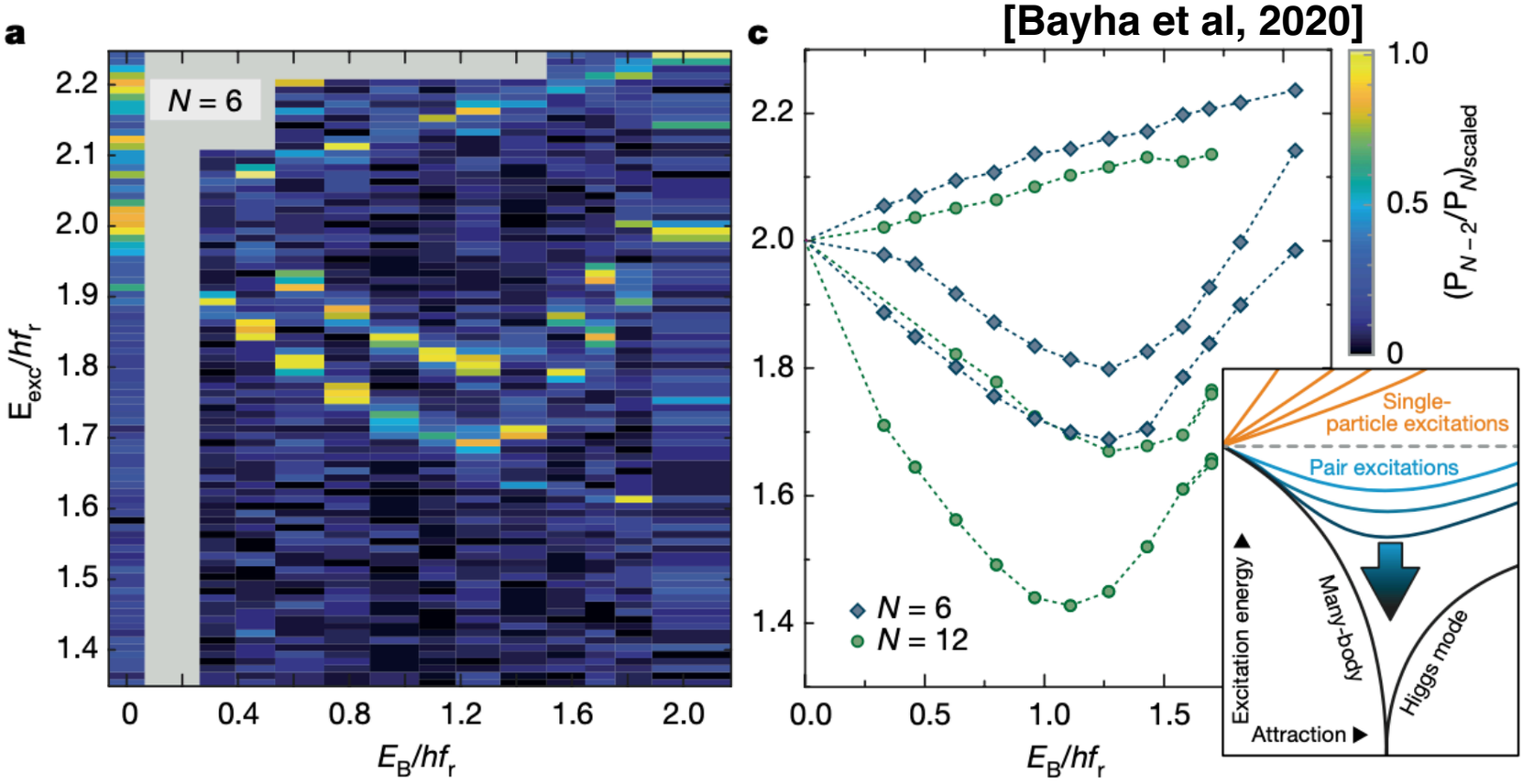
[Anderson 1958; Labeyrie et al., 1999; Tichy et al., 2010; Geiger et al., 2013; Jörder et al., 2014; Brünner et al, 2018]

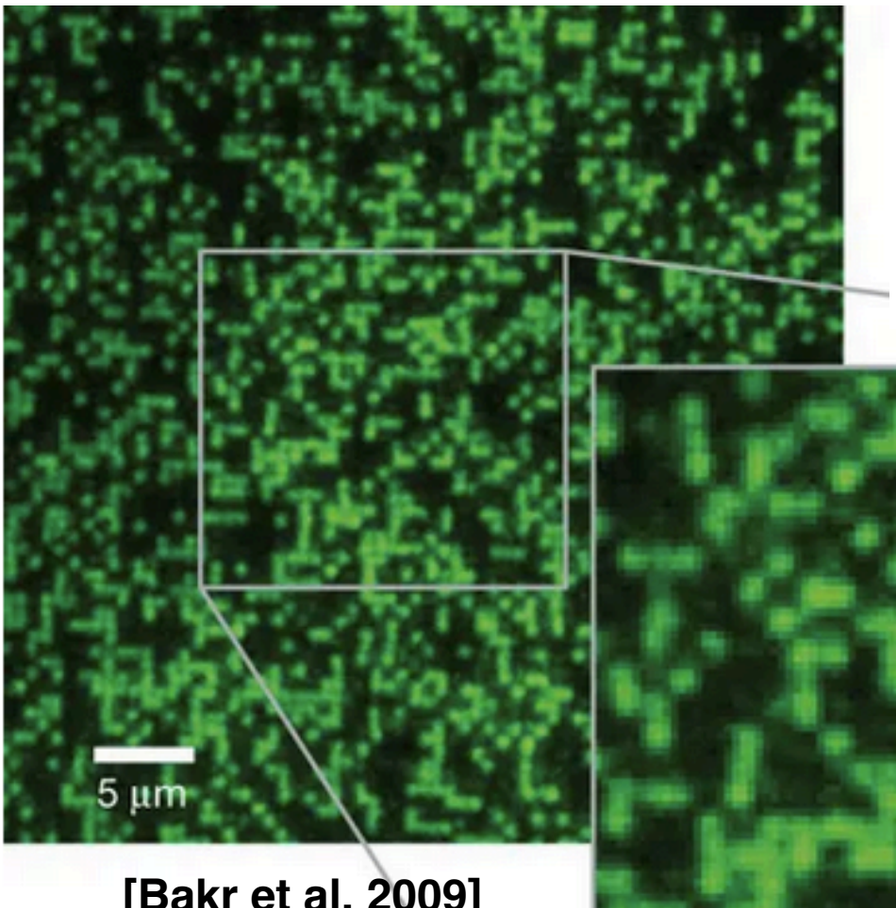
here: many particle scenario

Universality vs. (distinct) engineering perspective

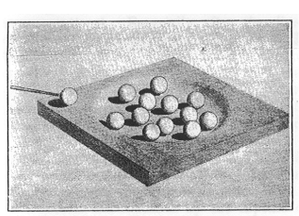
distinctive **rather than universal properties!?!**

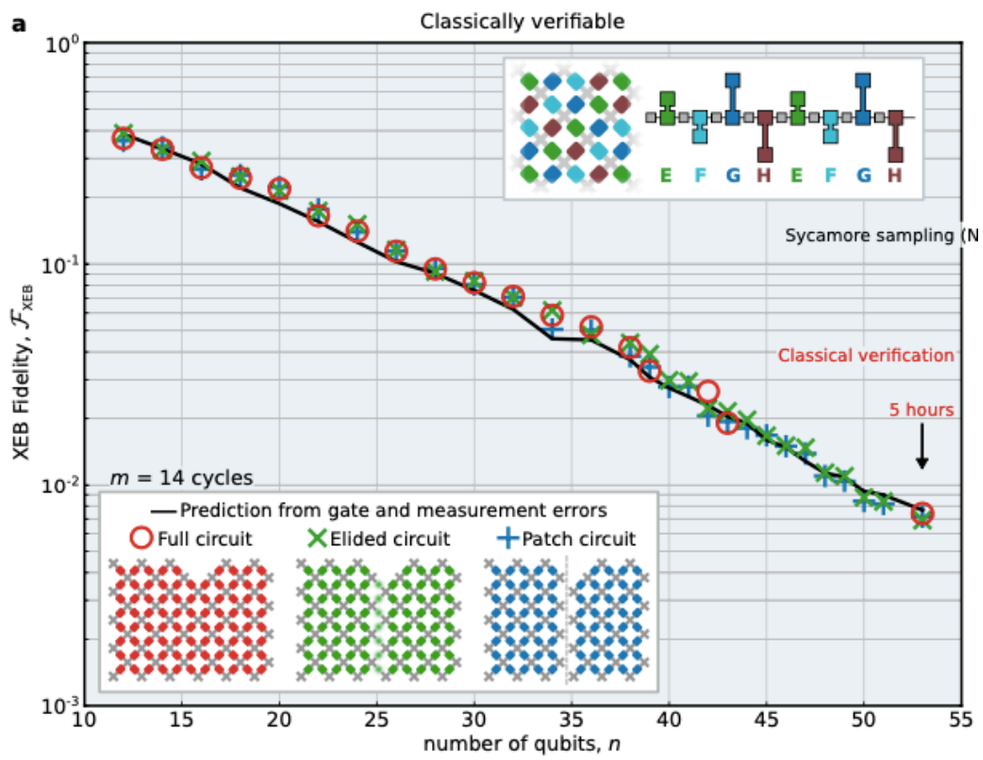
[Bayha et al, 2020]





[Bakr et al, 2009]

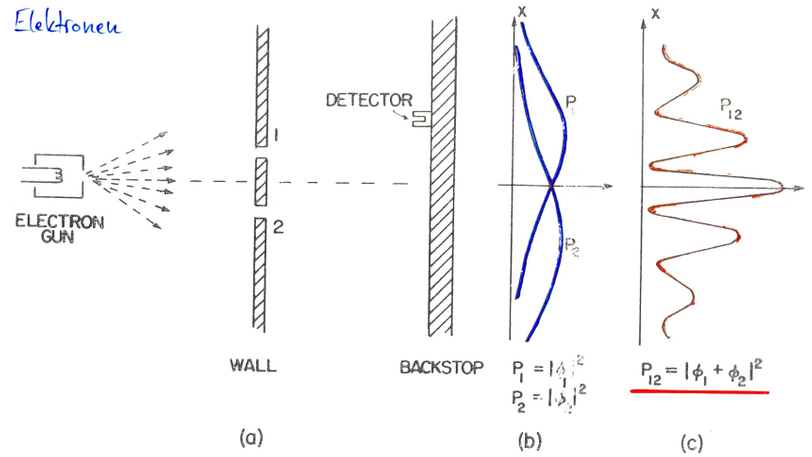




[NASA/TP-2019-220319, 2019]

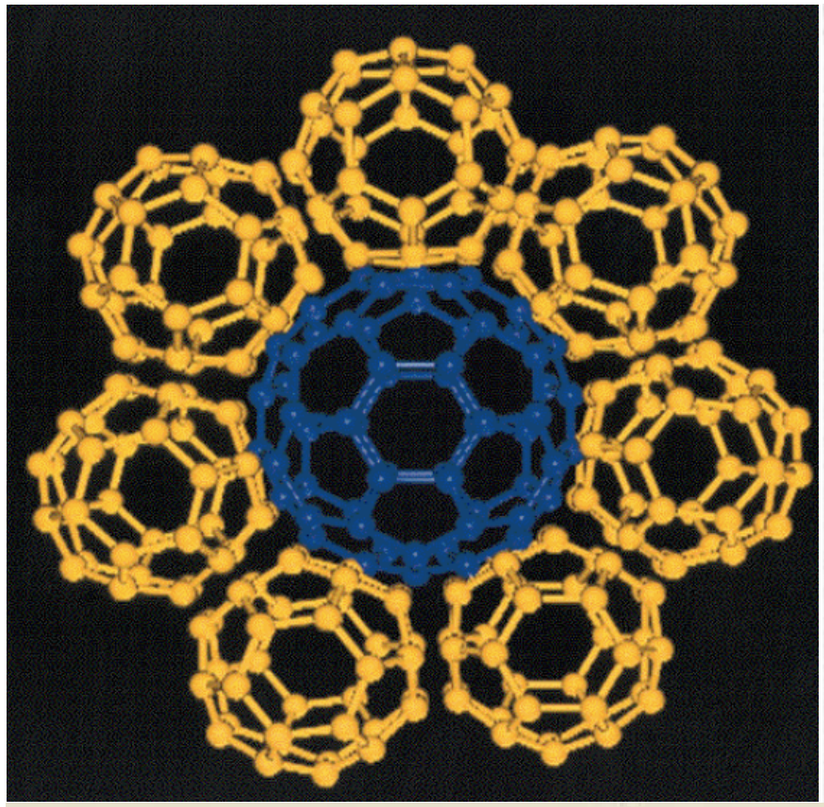
ununterscheidbare Wege

Elektronen



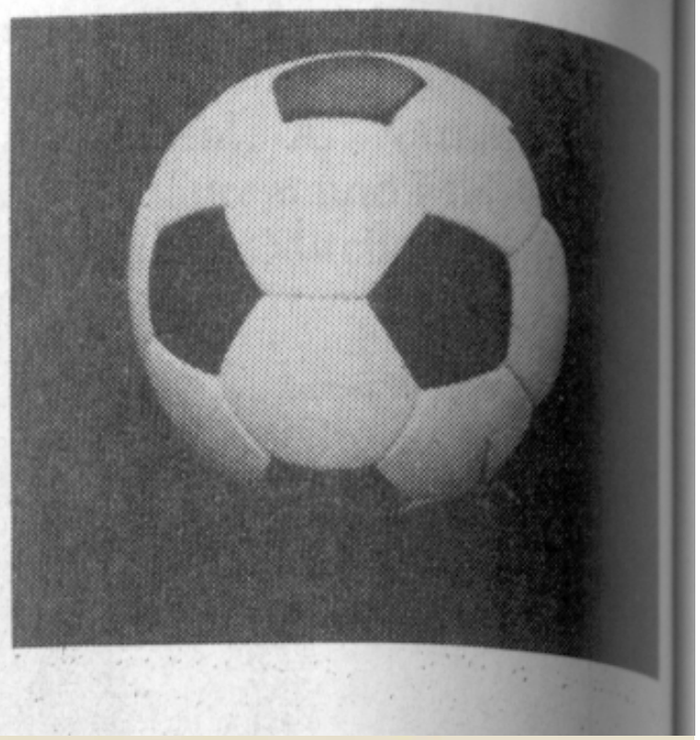
Larger (composite) particles

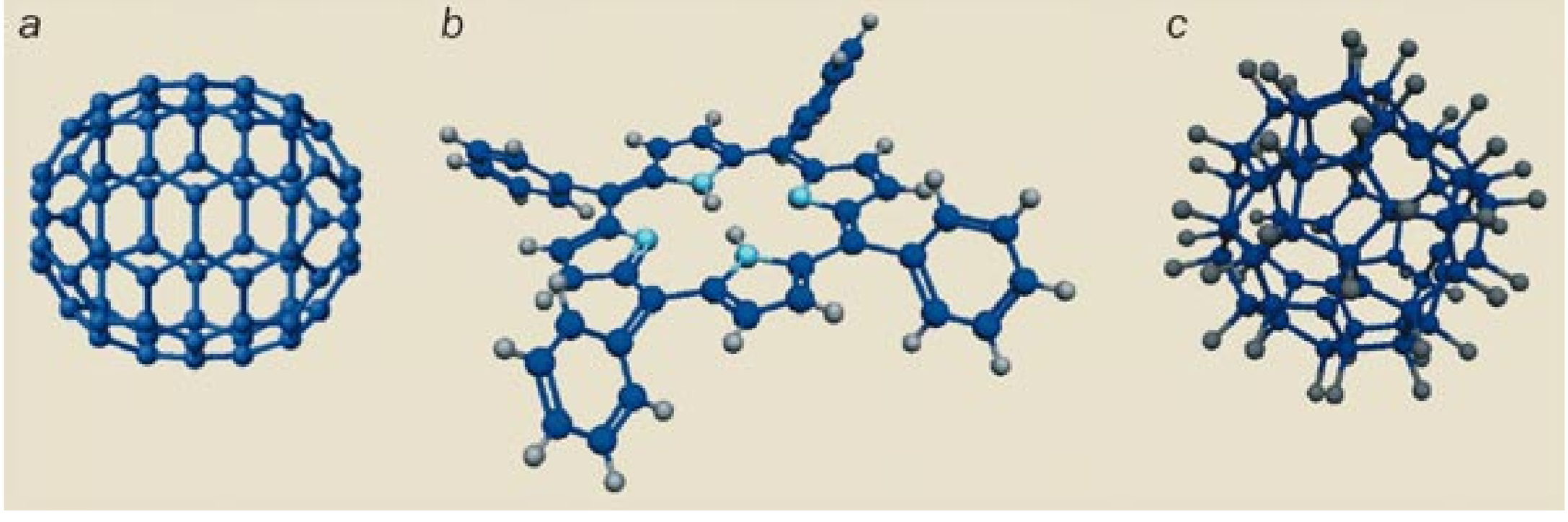
Molecular soccer balls (and relatives)



NATURE

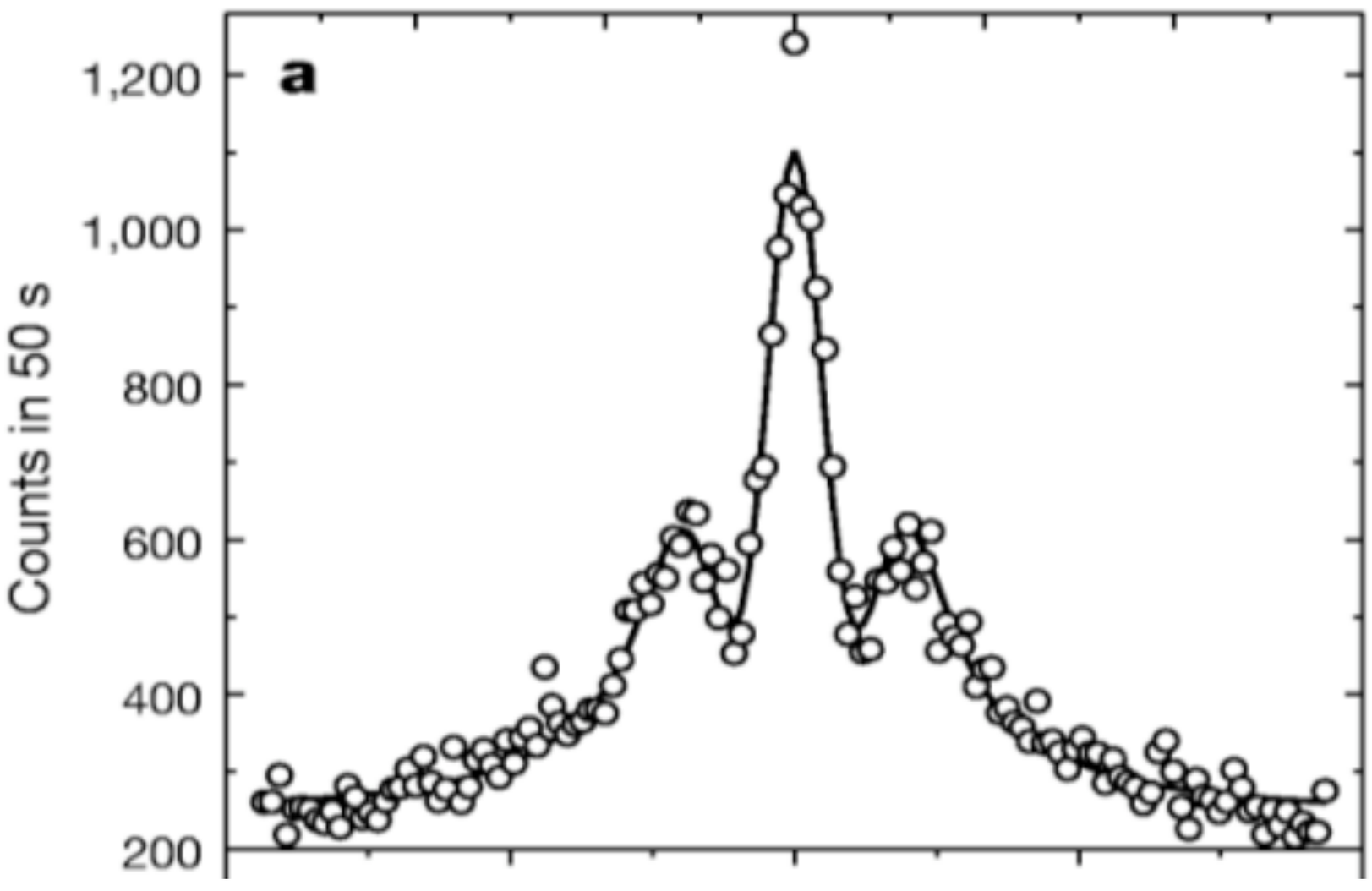
Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.





[Hornberger et al., 2005]

Interference of C60 molecules



[Arndt et al., 1999]

Interference despite …

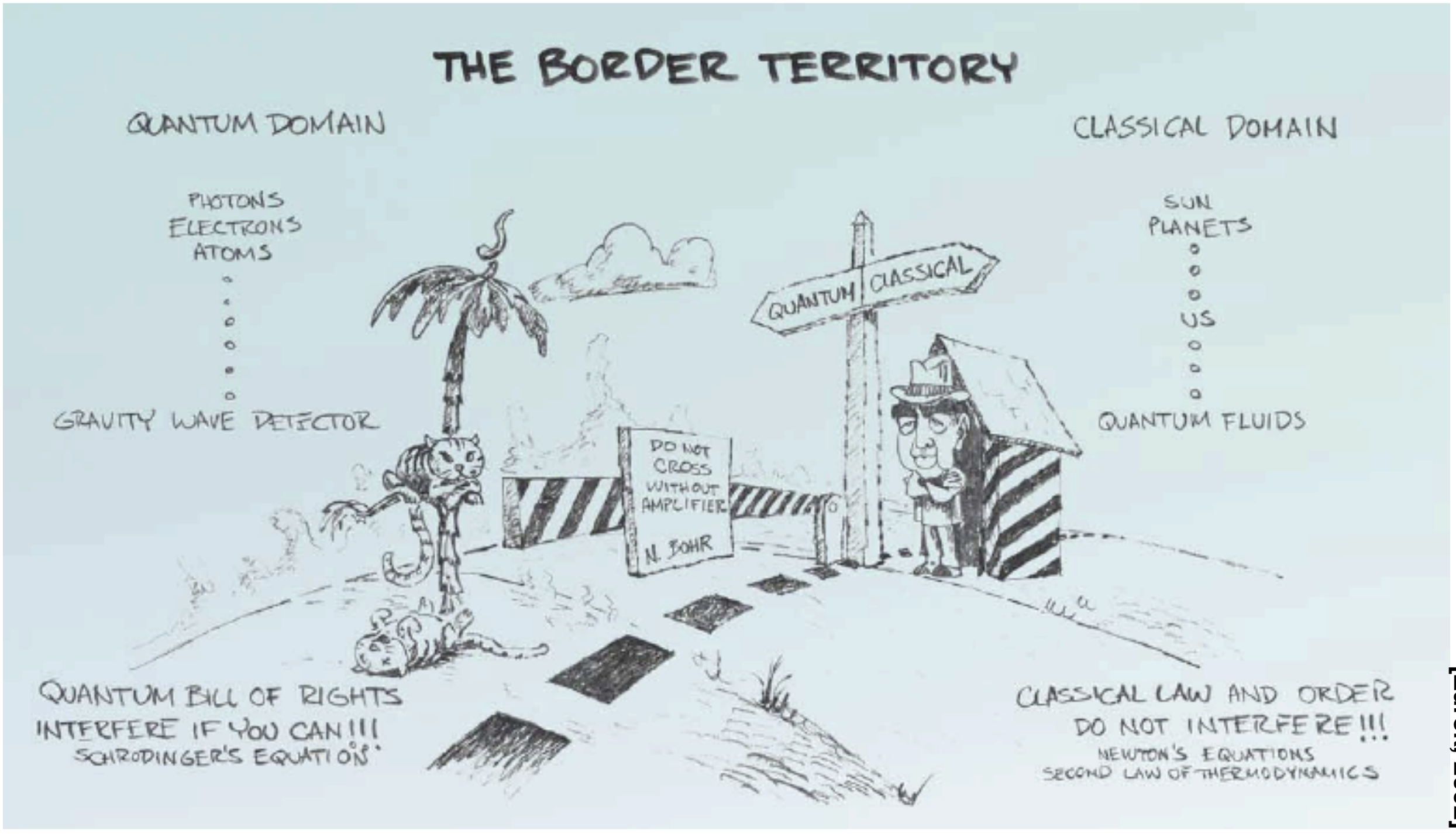
… internally hot (T≅900 K)

… de Broglie wavelength of C60 $\lambda \cong 2.5 \times 10^{-12}$ m

… smaller than molecular diameter, ca. 7×10^{-10} m

interrogation of CM degree of freedom alone

Demarcation line for quantum-classical transition?



[Żurek, 2002]

how large? **how many?** **how hot?**

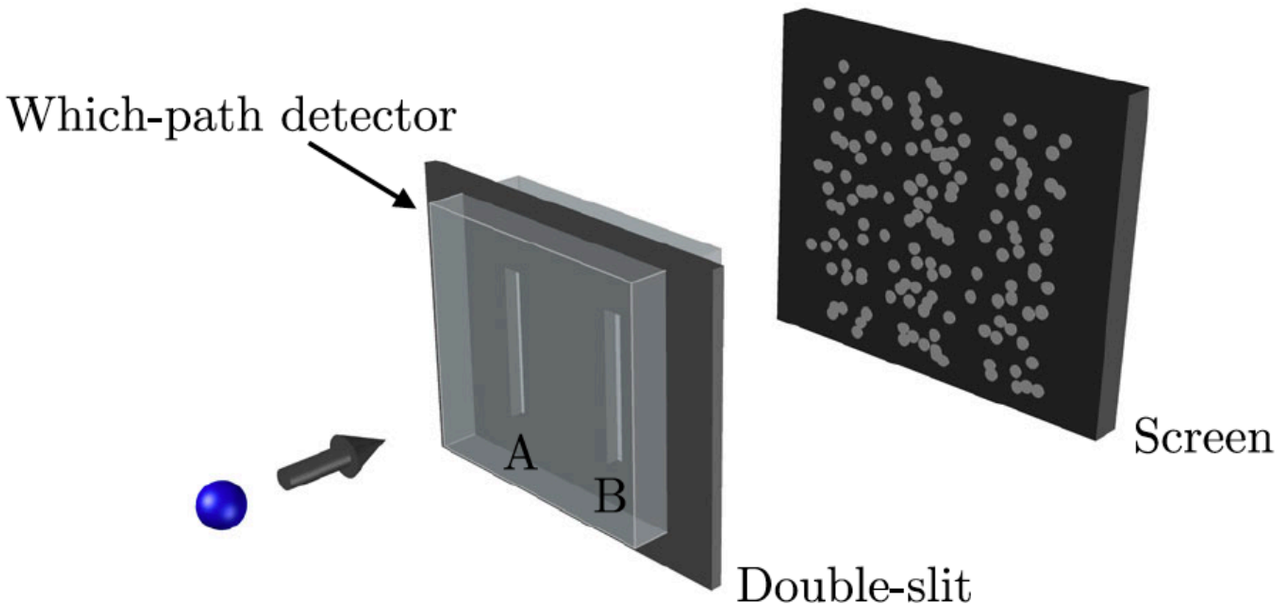
Interference visibility vs. particle character I

detector state

injected

$$\rho_{pd}^{\text{ini}} = |P_0\rangle\langle P_0| \otimes \sum_j q_j |D_0^{(j)}\rangle\langle D_0^{(j)}|$$

particle state



$$|P_0\rangle \otimes |D_0^{(j)}\rangle \mapsto \frac{1}{\sqrt{2}}\left(|P_A\rangle \otimes |D_A^{(j)}\rangle + |P_B\rangle \otimes |D_B^{(j)}\rangle\right)$$

transmitted

$$\rho_{pd} = \frac{1}{2} \sum_{J,K\in\{A,B\}} |P_J\rangle\langle P_K| \otimes \sum_j q_j |D_J^{(j)}\rangle\langle D_K^{(j)}|$$

Interference visibility vs. particle character II

particle state

$$\rho_p = \mathrm{Tr}_d(\rho_{pd}) = \sum_{J,K\in\{A,B\}} [\rho_p]_{J,K} |P_J\rangle\langle P_K|$$

$$[\rho_p]_{J,K} = \sum_j q_j \langle D_K^{(j)} | D_J^{(j)} \rangle / 2$$

$$\mathcal{V} = \sum_{\substack{J,K\in\{A,B\} \\ J\neq K}} |\langle P_J|\rho_p|P_K\rangle| = \left| \sum_j q_j \langle D_B^{(j)} | D_A^{(j)} \rangle \right|$$

visibility/ wave character

detector state

$$\rho_d = \mathrm{Tr}_p(\rho_{pd}) = \frac{1}{2} \sum_{J\in\{A,B\}} \rho_d^J$$

$$\rho_d^J = \sum_j q_j |D_J^{(j)}\rangle\langle D_J^{(j)}|$$

$$D(\rho,\sigma) = \mathrm{Tr}(|\rho-\sigma|)/2$$

$$\mathcal{P} = D(\rho_d^A, \rho_d^B)$$

particle character

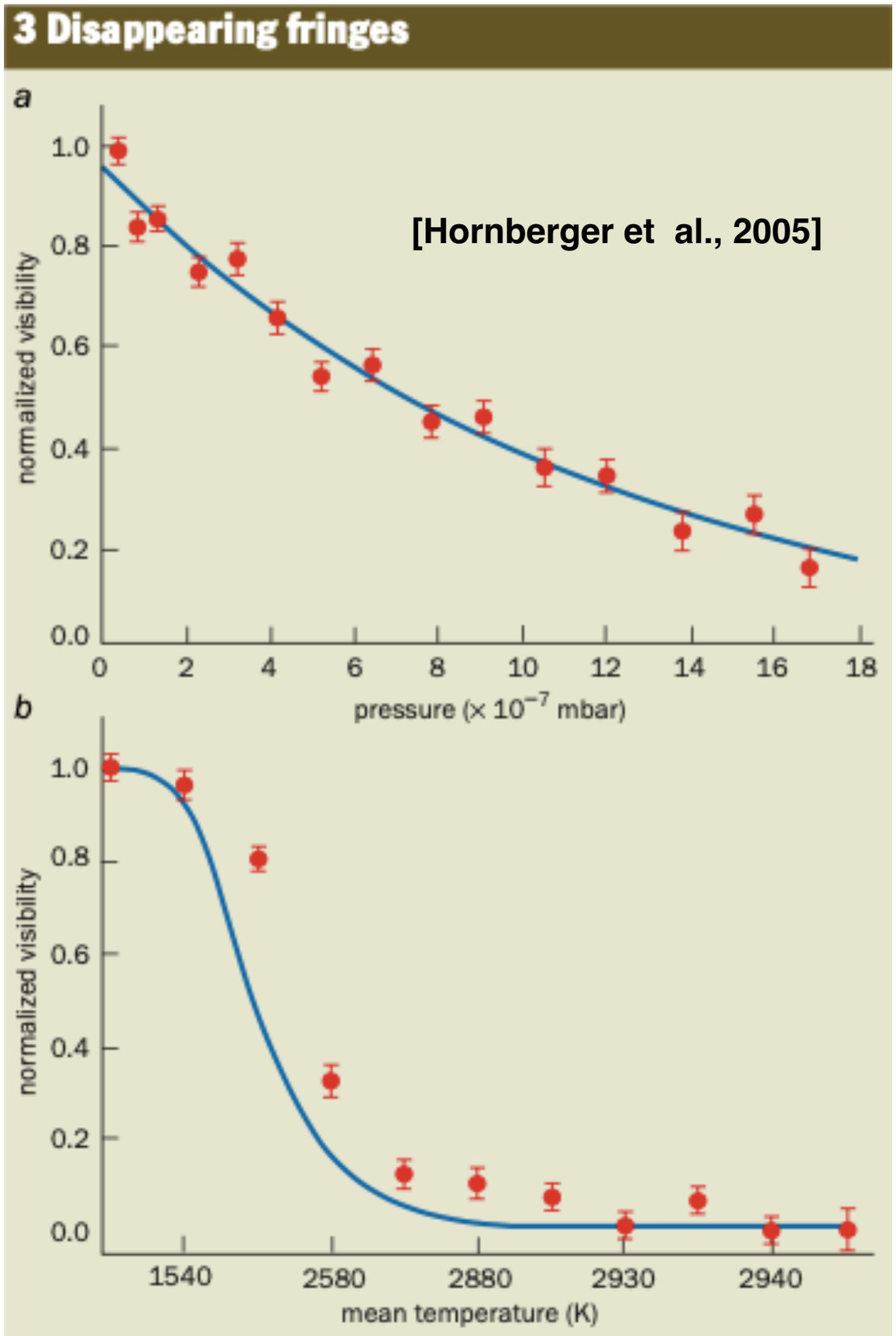
$$\mathcal{P}^2 + \mathcal{V}^2 \leq 1$$

wave-particle duality relation

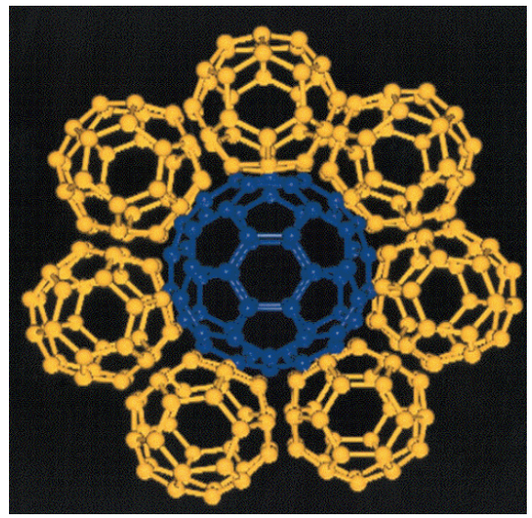
$0 \leq \mathcal{P}, \mathcal{V} \leq 1$

[Jaeger et al., 1995; Englert 1996]

Decoherence due to which-way information



[Hornberger et al., 2005]



Interference *fades away with*

available which-way information

mediated by

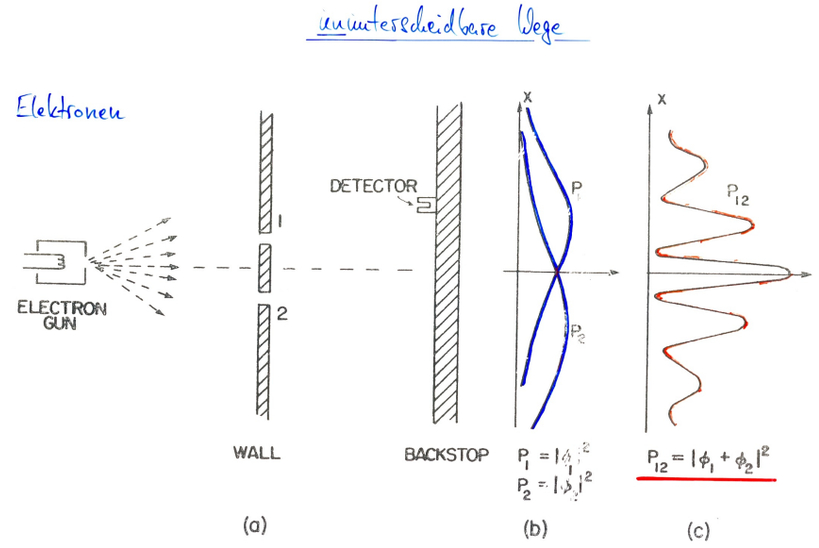
increasing rest gas pressure (top)

and

increasing temperature (bottom)

Single particle summary

(*single particle/CM of arbitrary mass/number of elementary constituents*)



dual character: **granular on detection, wave-like in propagation**

refinement: **trade-off between wave (visibility) and particle (which-way information) character, quantified by duality relation**

decoherence/quantum-classical transition: **due to entanglement with environment/ancilla/detector/which-way degree of freedom**

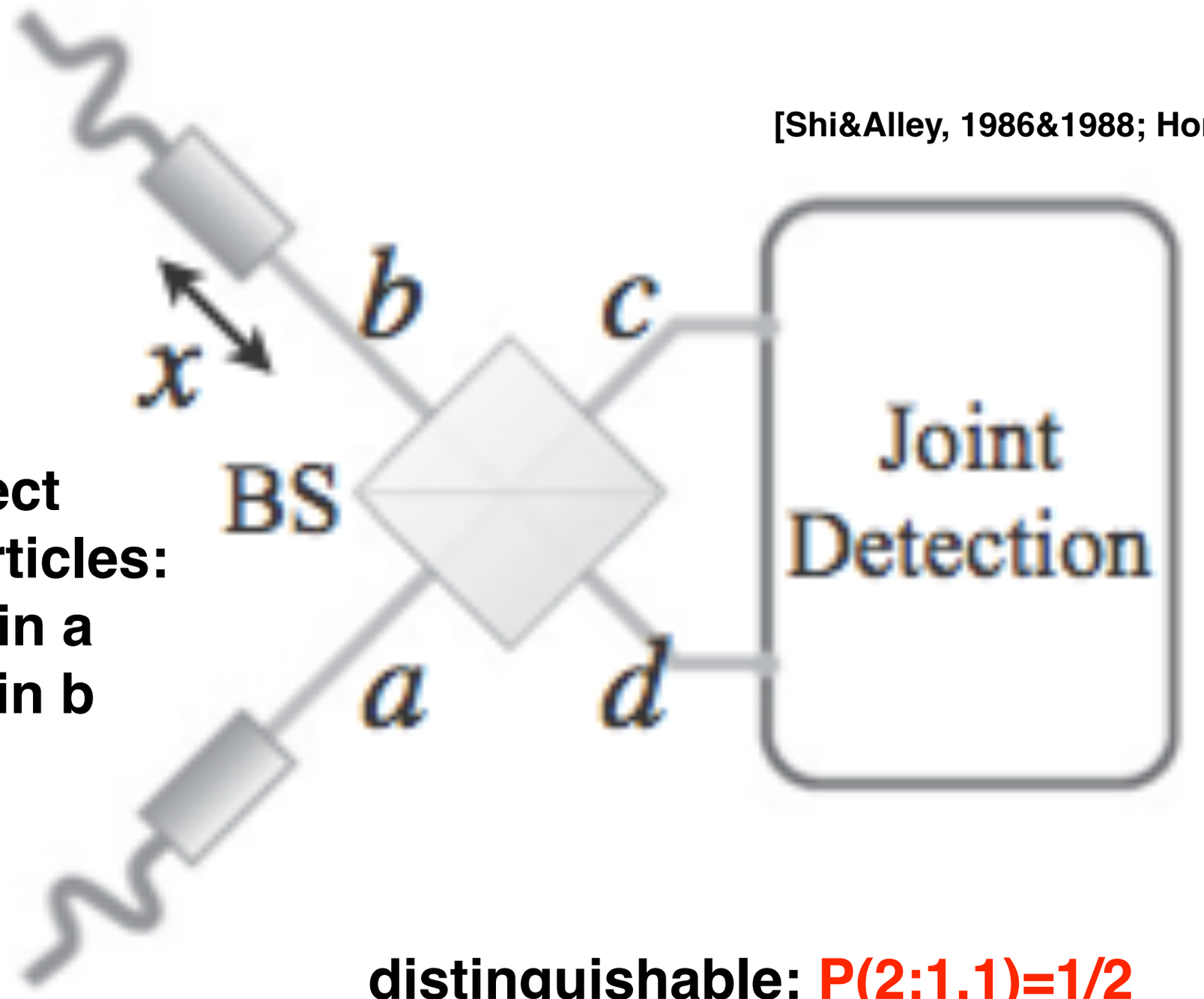
Homework

? How to map the GHZ-state onto a (bona fide) Schrödinger CAT state ?

Generalisation for two particles

Quantum optics: Hong-Ou-Mandel

[Shi&Alley, 1986&1988; Hong, Ou&Mandel 1987]



inject two particles: one in a one in b

single, coincident event

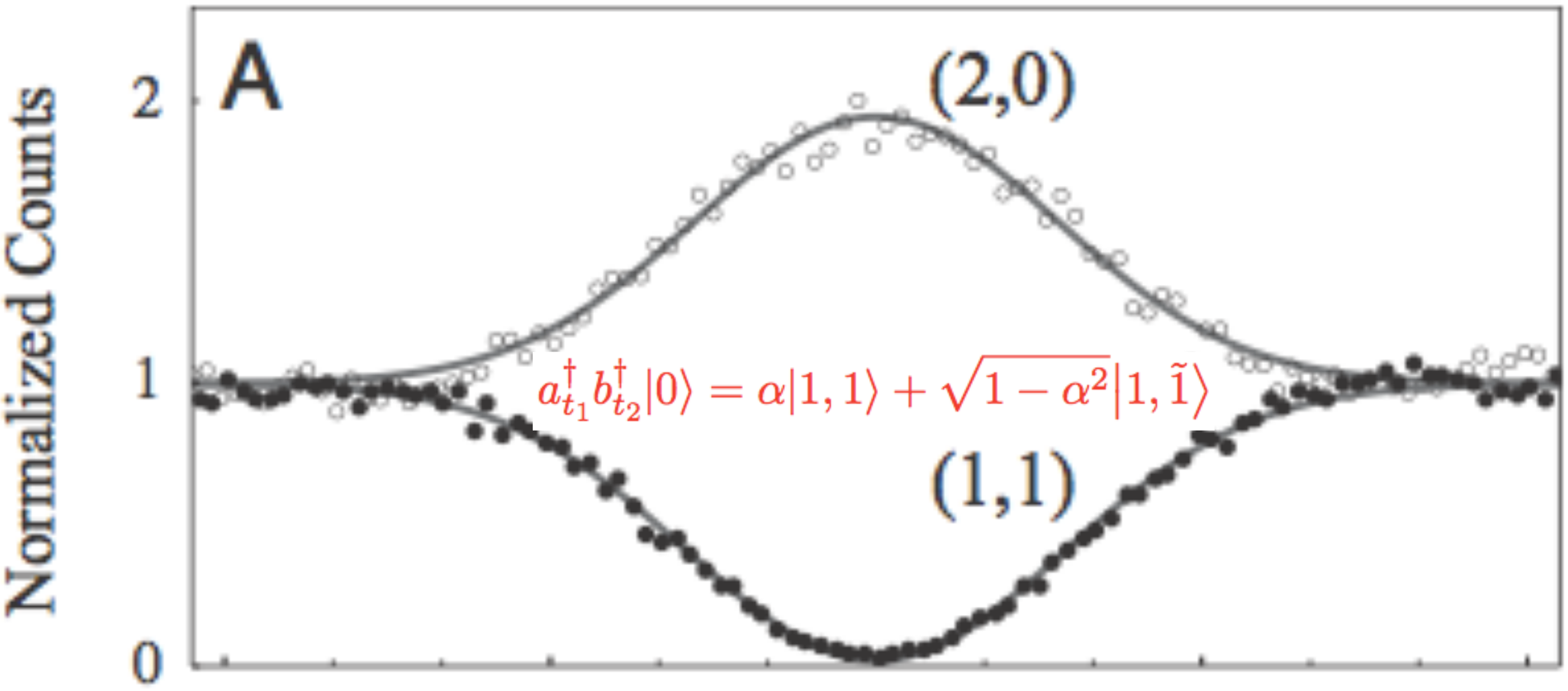
detect two particles: one in c one in d

distinguishable: P(2;1,1)=1/2

indistinguishable: P(2;1,1)=0

due to destructive two-particle interference

Two-body quantum-to-classical transition



[Ra et al., 2013]

two-particle interference certifies two-particle indistinguishability
≡ *absence* of two-particle which-way information (encoded by α)

More than two is different!

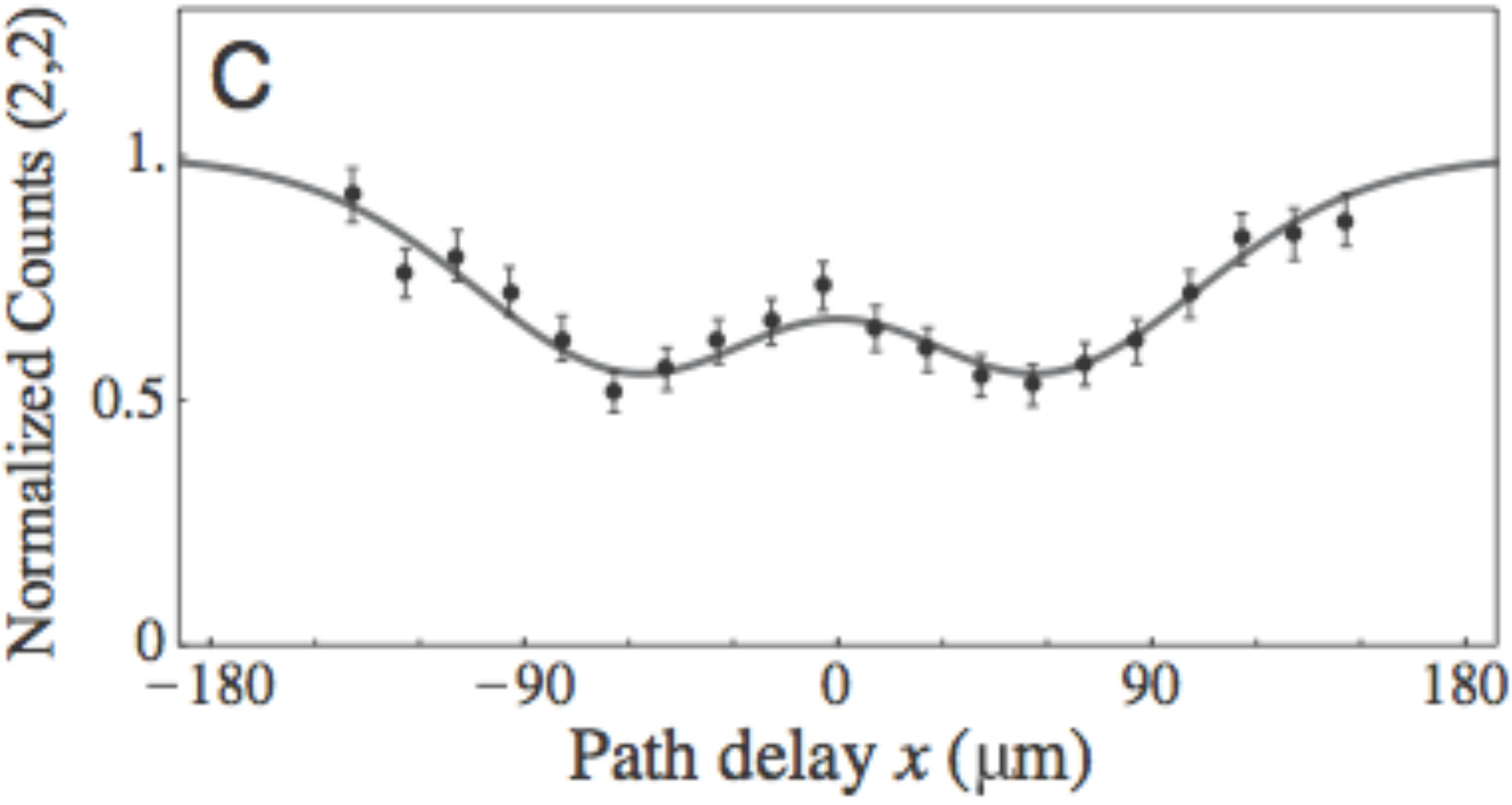
e.g., He vs. H, triple- vs. double-well Bose-Hubbard

“… Und nagelt mit Engelsmiene,
Beiden einen auf die Schiene …”

[R. Mey - *Bevor ich mit den Wölfen heule*]

Non-monotonic quantum-classical transition

$$\frac{1}{2}(a_{t_1}^\dagger)^2(b_{t_2}^\dagger)^2|0\rangle = \alpha^2|2,2\rangle + \sqrt{2}\alpha\sqrt{1-\alpha^2}\big|2,1,\tilde{1}\big\rangle + (1-\alpha^2)\big|2,\tilde{2}\big\rangle$$

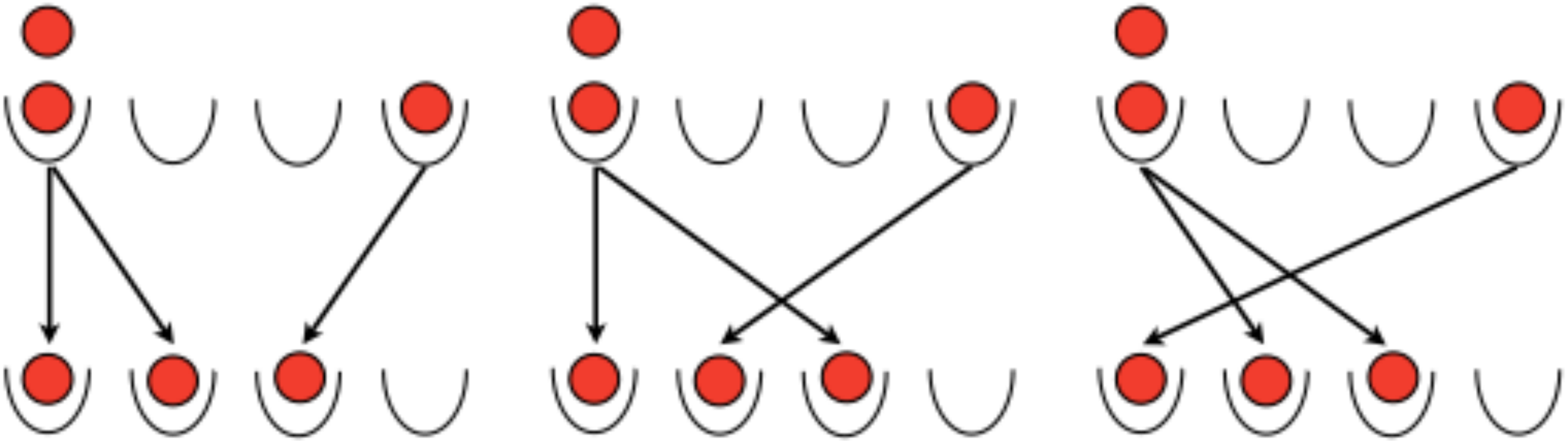


interference of four- and three-particle amplitudes

[Tichy et al., 2011; Ra et al., 2013]

Many particles in *many* modes
[inference of interference]

Mapping n-boson input on n-boson output



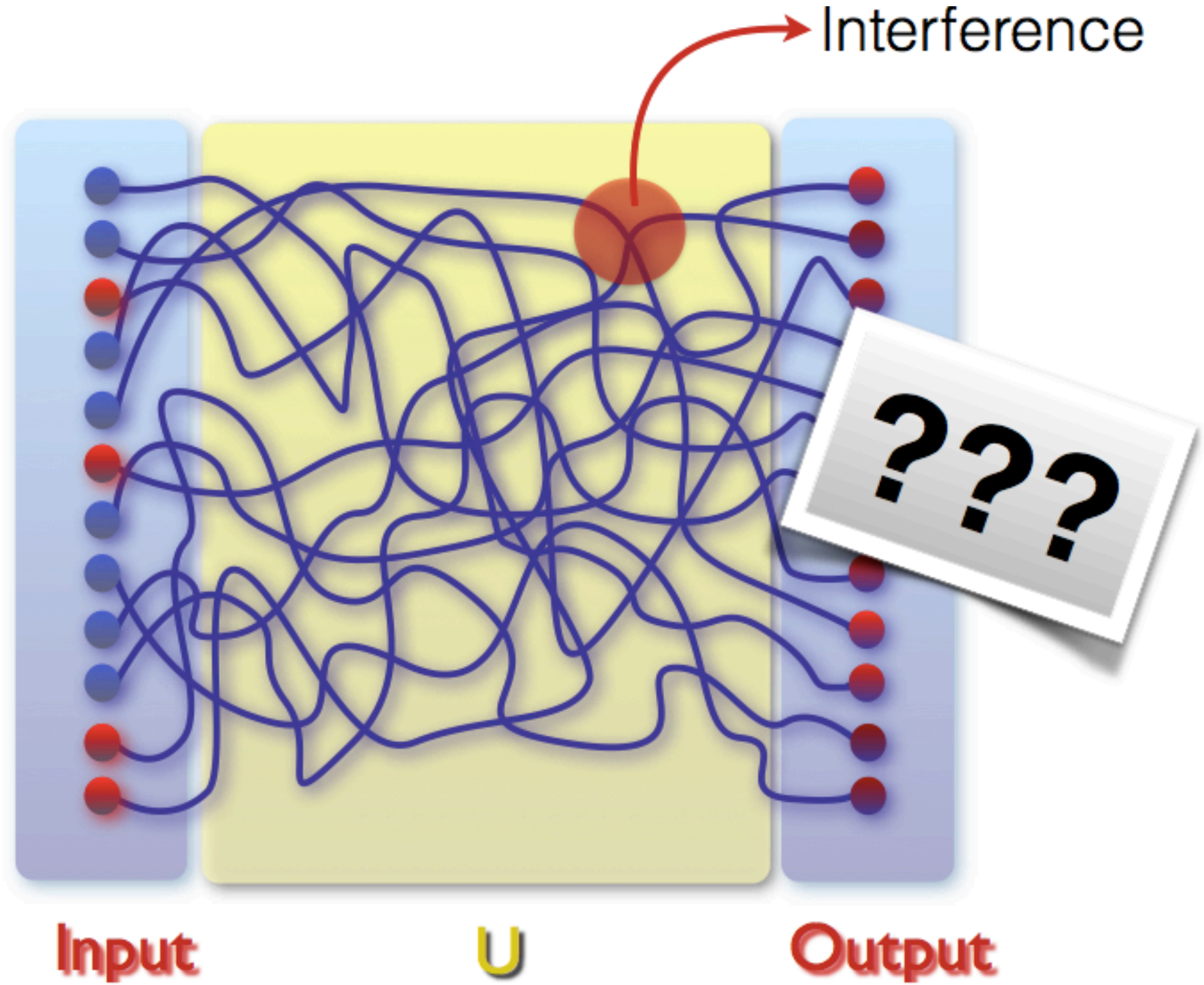
$$U_{1,1}U_{1,2}U_{4,3} \qquad U_{1,1}U_{1,3}U_{4,2} \qquad U_{1,2}U_{1,3}U_{4,1}$$

$$\sigma = (1,2,3) \qquad \sigma = (1,3,2) \qquad \sigma = (2,3,1)$$

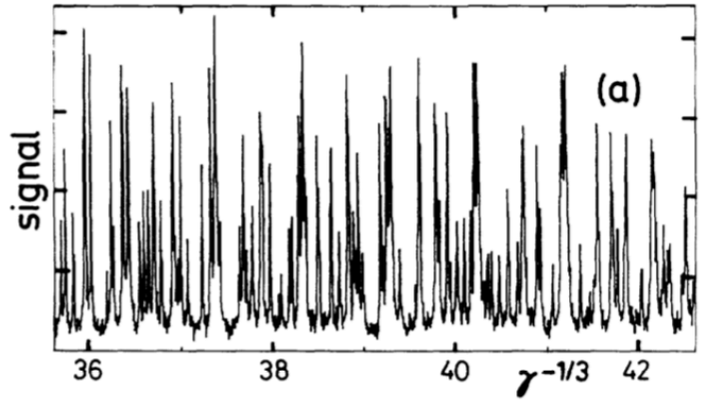
coherent sum of up to n! amplitudes — “computationally hard”

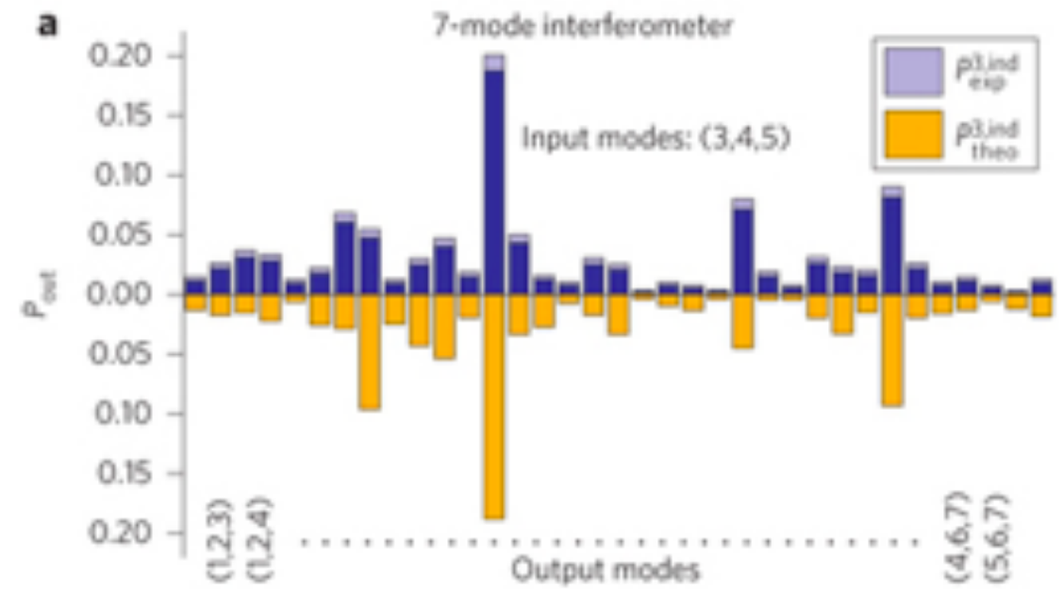
[Tichy, Tiersch et al., 2010]

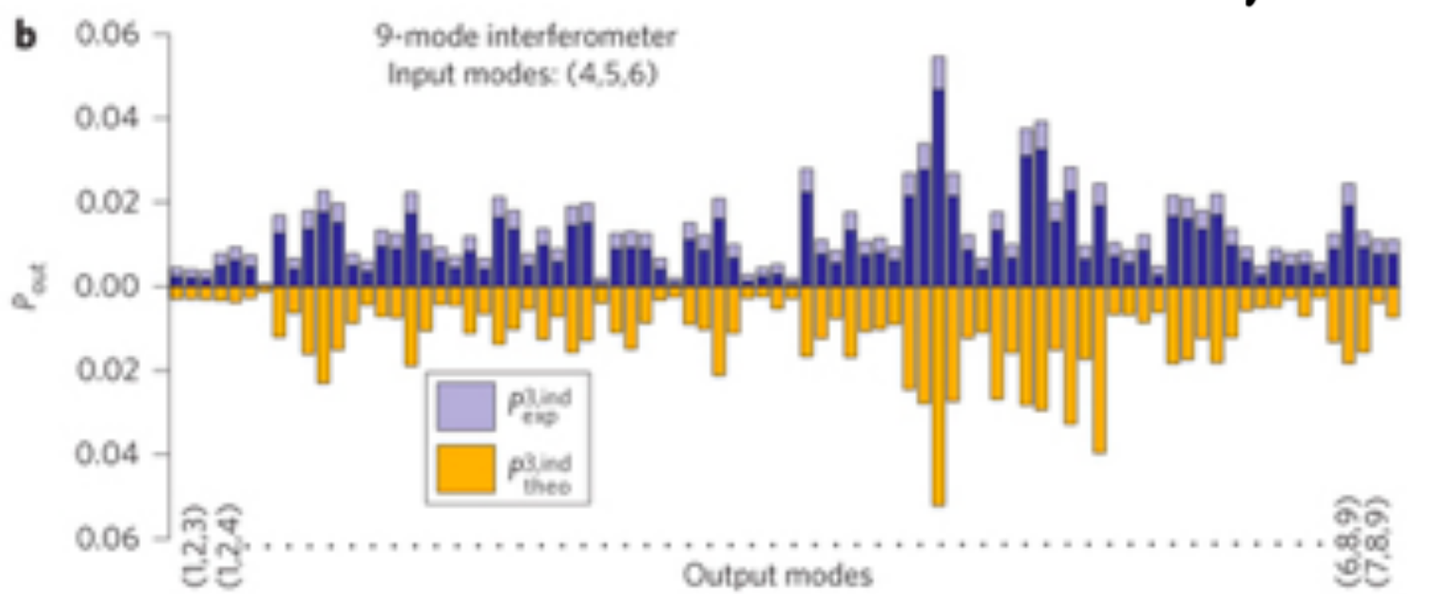
Transmission across a random unitary U

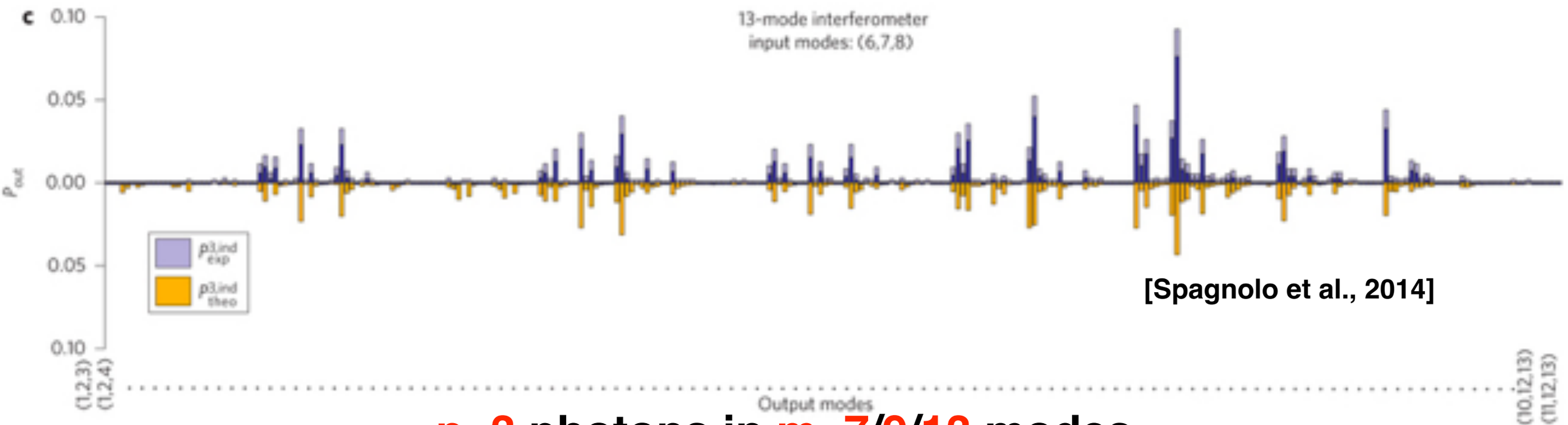


Complex counting statistics









[Spagnolo et al., 2014]

n=3 photons in m=7/9/13 modes

any features indicative of particle type(s) and dynamics?

Certification problems everywhere

New J. Phys. **18** (2016) 041001

New Journal of Physics

The open access journal at the forefront of physics

[Fraunhofer IAF & IBM]

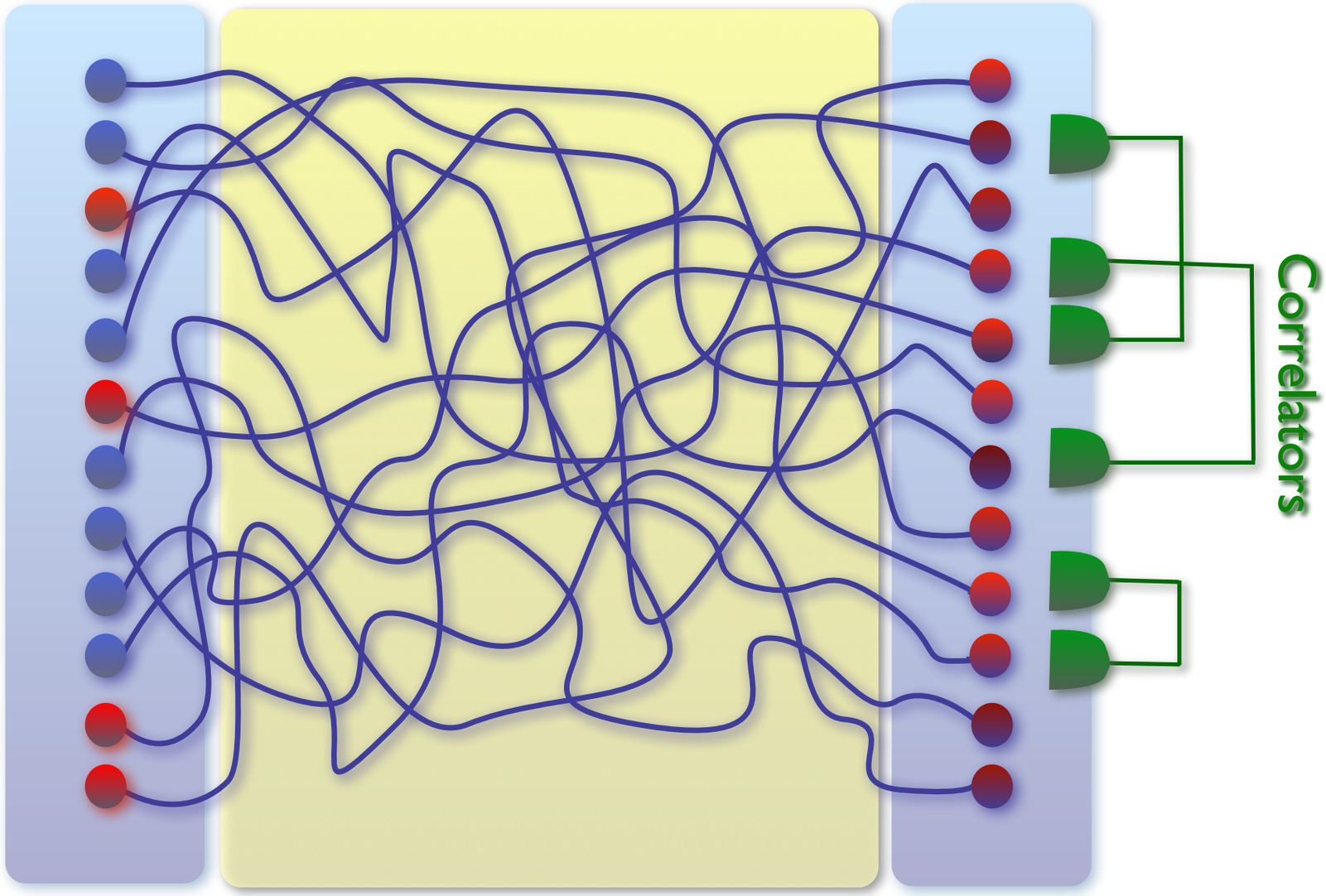
PERSPECTIVE

Is my boson sampler working?

Marco Bentivegna, Nicolò Spagnolo and Fabio Sciarrino

Distinctive statistical features

Statistical inference



$$C_{ij} = \langle N_i N_j \rangle - \langle N_i \rangle \langle N_j \rangle = t \sum_{k \neq l=1}^{n} U_{q_k,i} U_{q_l,j} U^*_{q_l,i} U^*_{q_k,j} - \sum_{k=1}^{n} U_{q_k,i} U_{q_k,j} U^*_{q_k,i} U^*_{q_k,j}$$

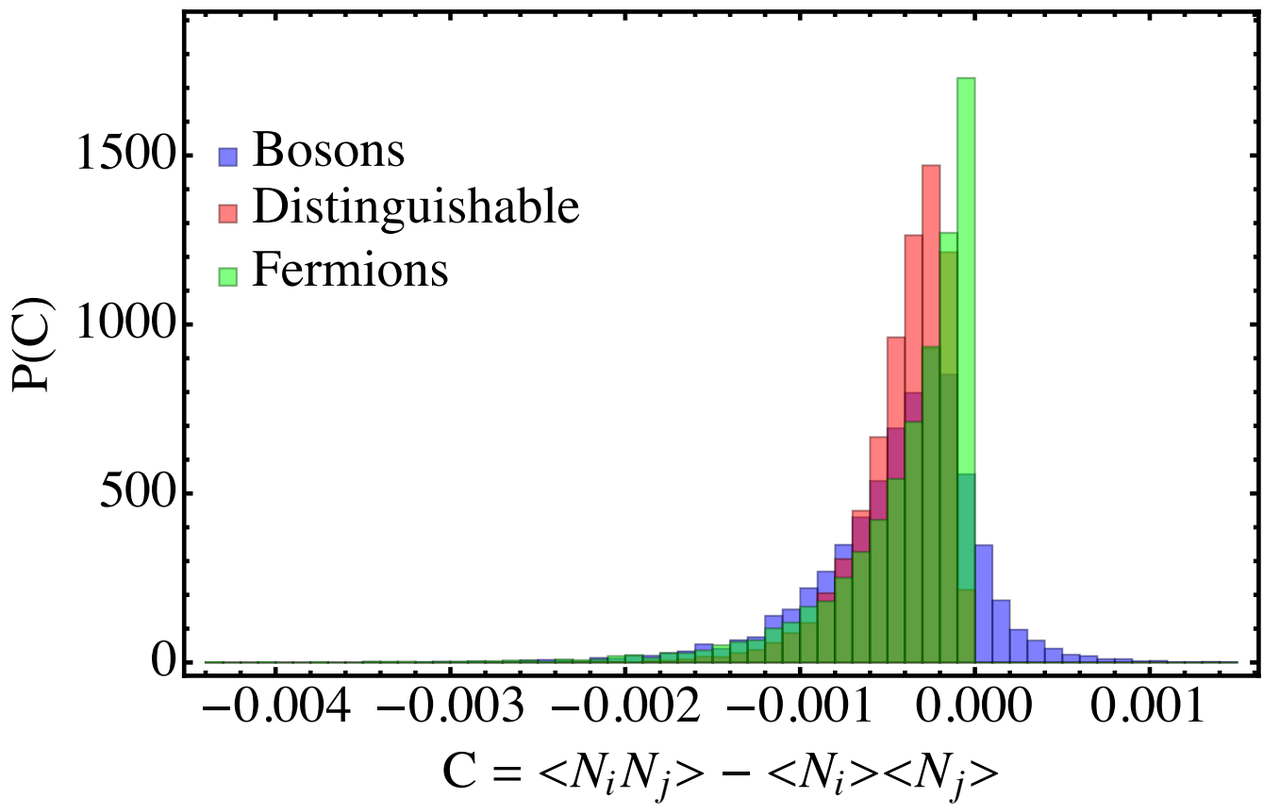
set of two-point correlations for all i,j defines the C-dataset

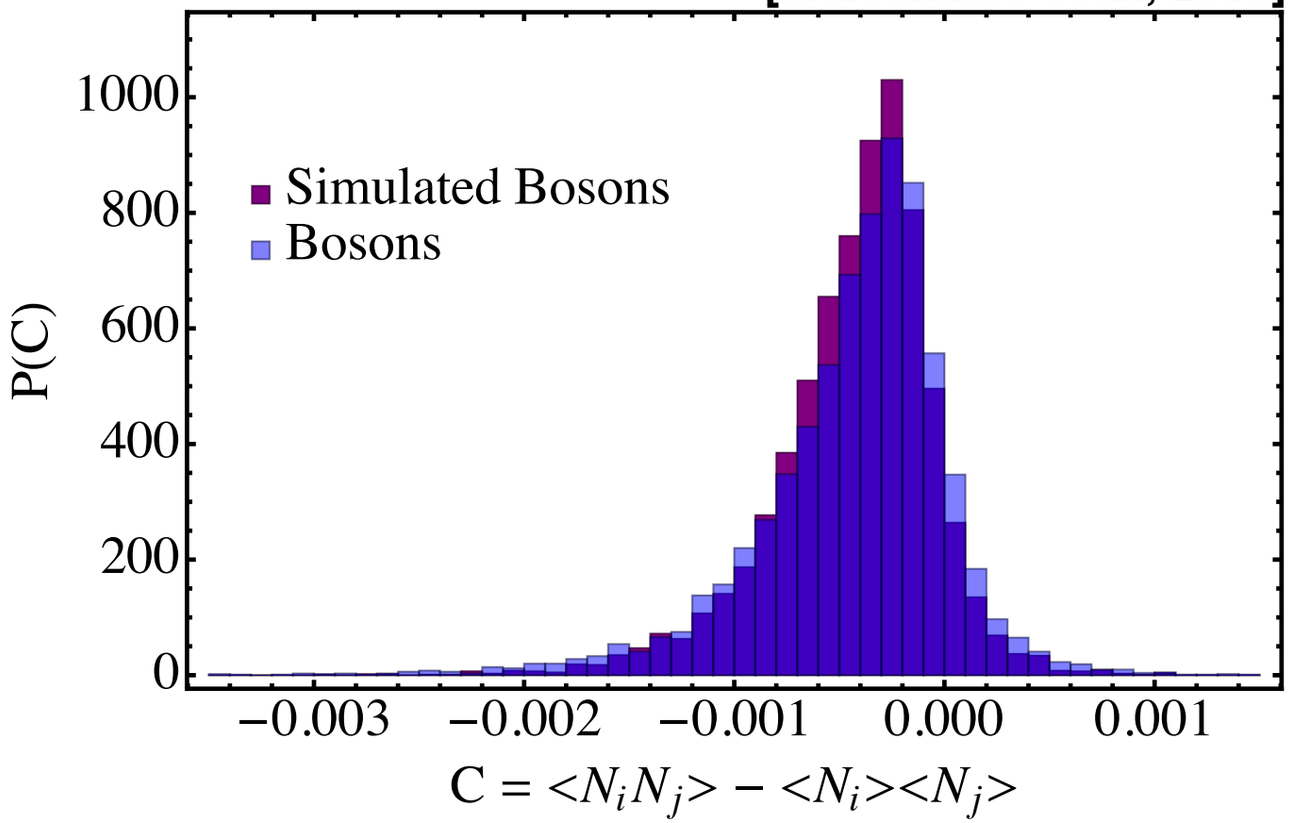
t=-1,0,+1 for fermions, distinguishables, bosons

C-dataset statistics

sampling $C_{i,j}$ over all i,j — the "C-dataset"

[Walschaers et al., 2016]

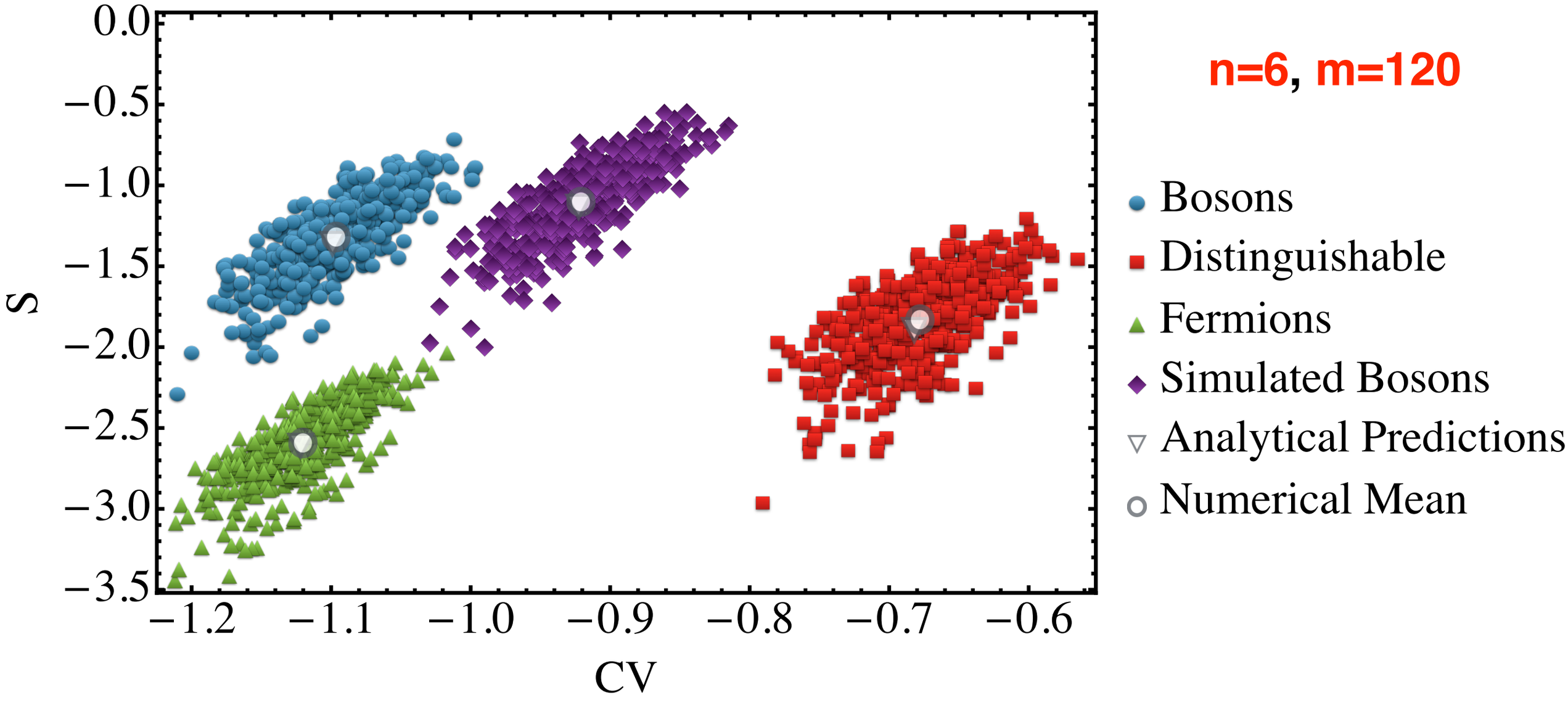




6 particles injected into 120 modes

"simulated bosons" — average over relative phases of interfering many-particle amplitudes, thus only keep bunching, kill interference terms

Statistical certification of many-particle interference (3rd vs. 2nd moment of C-dataset)



unambiguous distinction of all particle types certification accomplished!

excellent agreement with (analytical) RMT prediction!

[Walschaers et al., 2016]

Typical RMT result for C-dataset moments

$$\mathbb{E}_U(C_B) = -\frac{n(m+n-2)}{m(m^2-1)},$$

$$\mathbb{E}_U(C_B{}^2) = \frac{2n(m^2n + m^2 + 9\,mn - 11m + n^3 - 2n^2 + 5n - 4)}{m^2(m+2)(m+3)(m^2-1)},$$

$$\mathbb{E}_U(C_B^3) = -2n\left(\frac{m^3n^2 + 15\,m^3n + 2m^3 + 3\,m^2n^3 + 6\,m^2n^2 + 213\,m^2n - 222\,m^2 - 3\,mn^4}{m^2(m+1)(m+2)(m+3)(m+4)(m+5)(m^2-1)}\right.$$
$$\left. + \frac{45mn^3 + 32mn^2 + 372mn - 464m + 3n^5 - 6n^4 + 45n^3 + 78n^2 + 168n - 288}{m^2(m+1)(m+2)(m+3)(m+4)(m+5)(m^2-1)}\right),$$

[n photons in m modes — scalable protocol!]

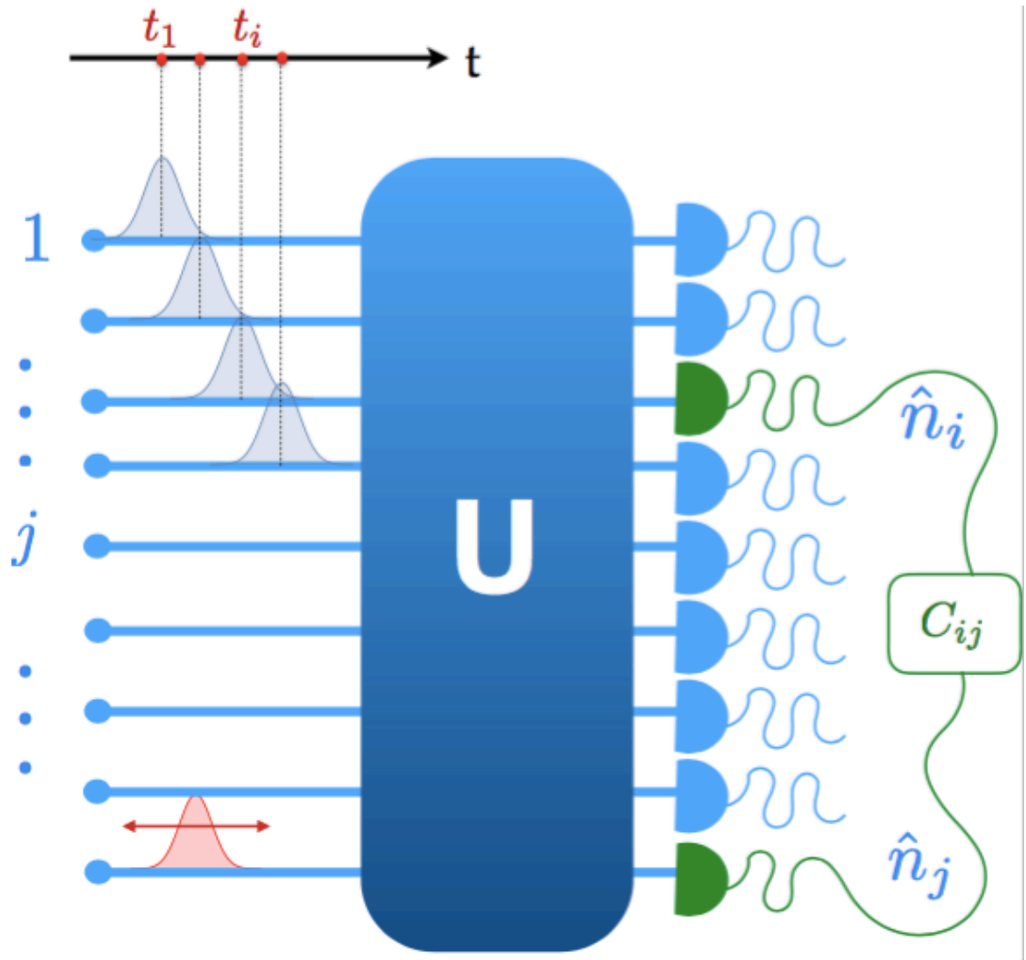
[Walschaers et al., 2014, 2016]

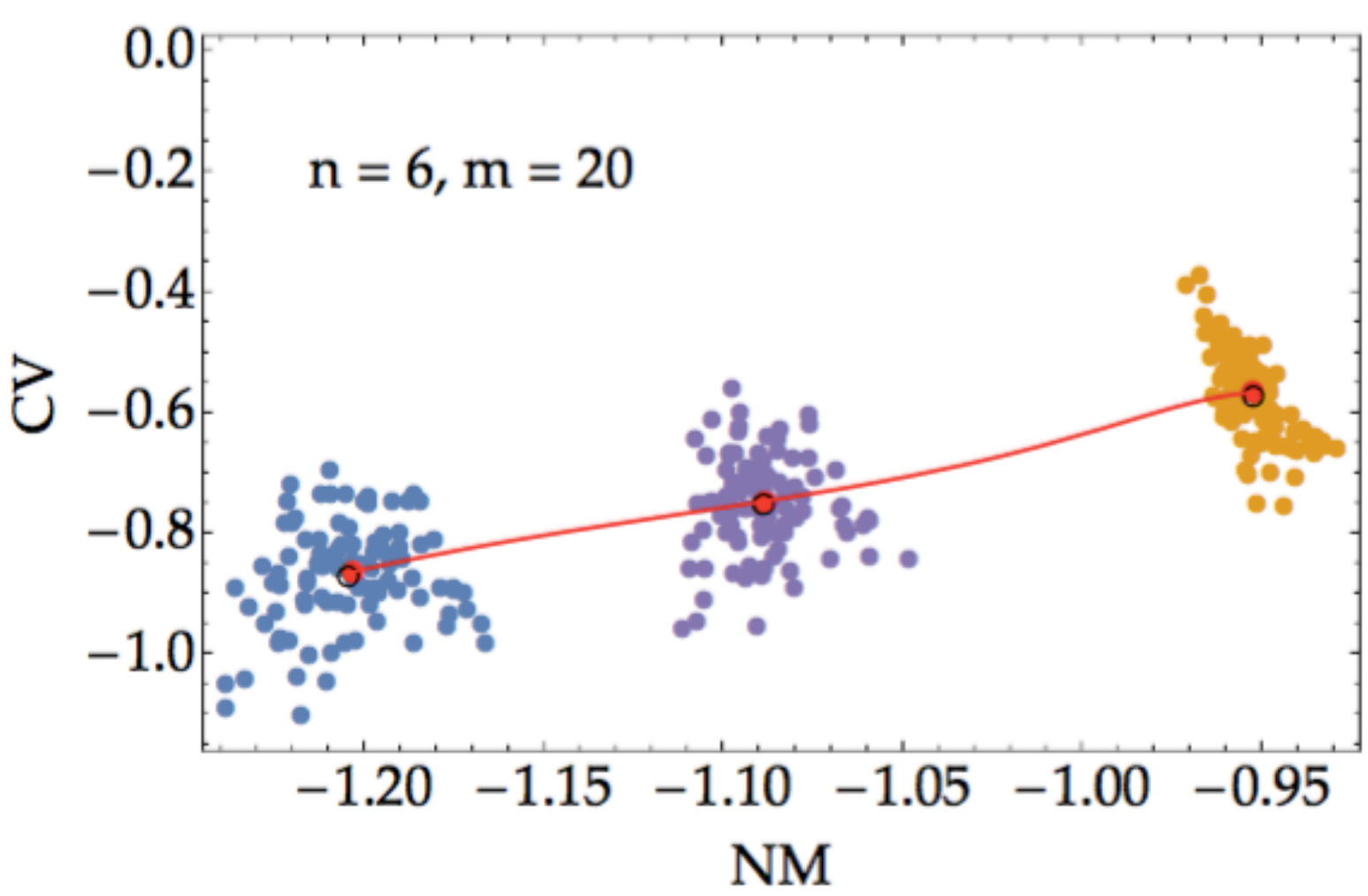
Partially distinguishable identical particles

Many-particle correlation spectroscopy

distinguishability-transition on the level of first and second moment of C-dataset

(rather than of single event in HOM)

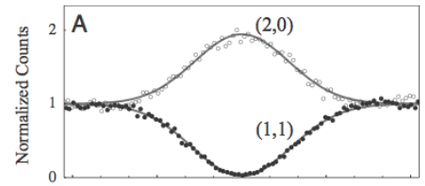




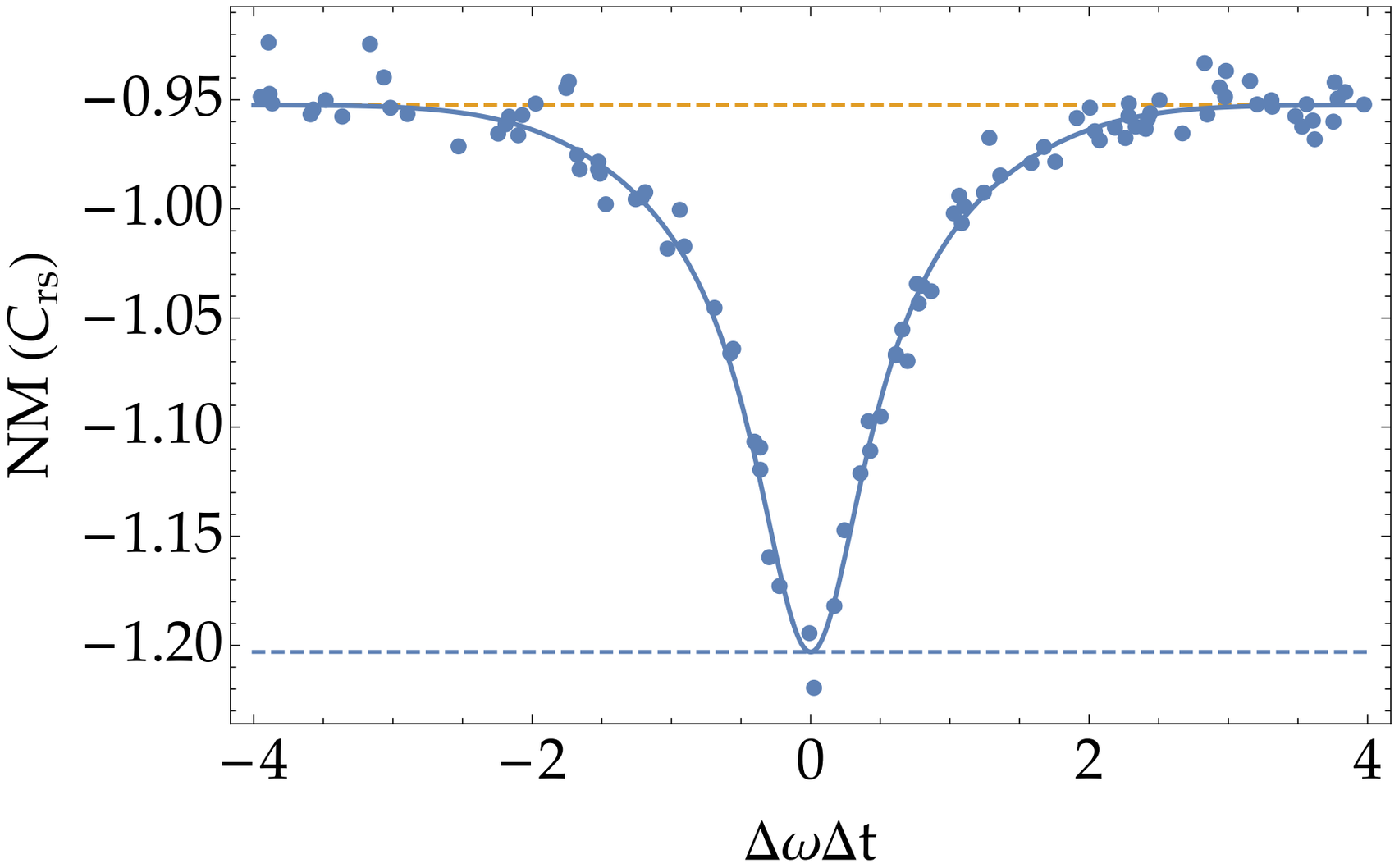
- Bosons
- Distinguishable
- $\Delta\omega\Delta t = 1/2$
- RMT Results
- Center of Cloud

[Walschaers et al., 2016]

The C-dataset dip à la HOM



ensemble average of two-point correlators as diagnostic tool



6 particles
20 modes

Bosons
Distinguishable
Partially Distinguishable

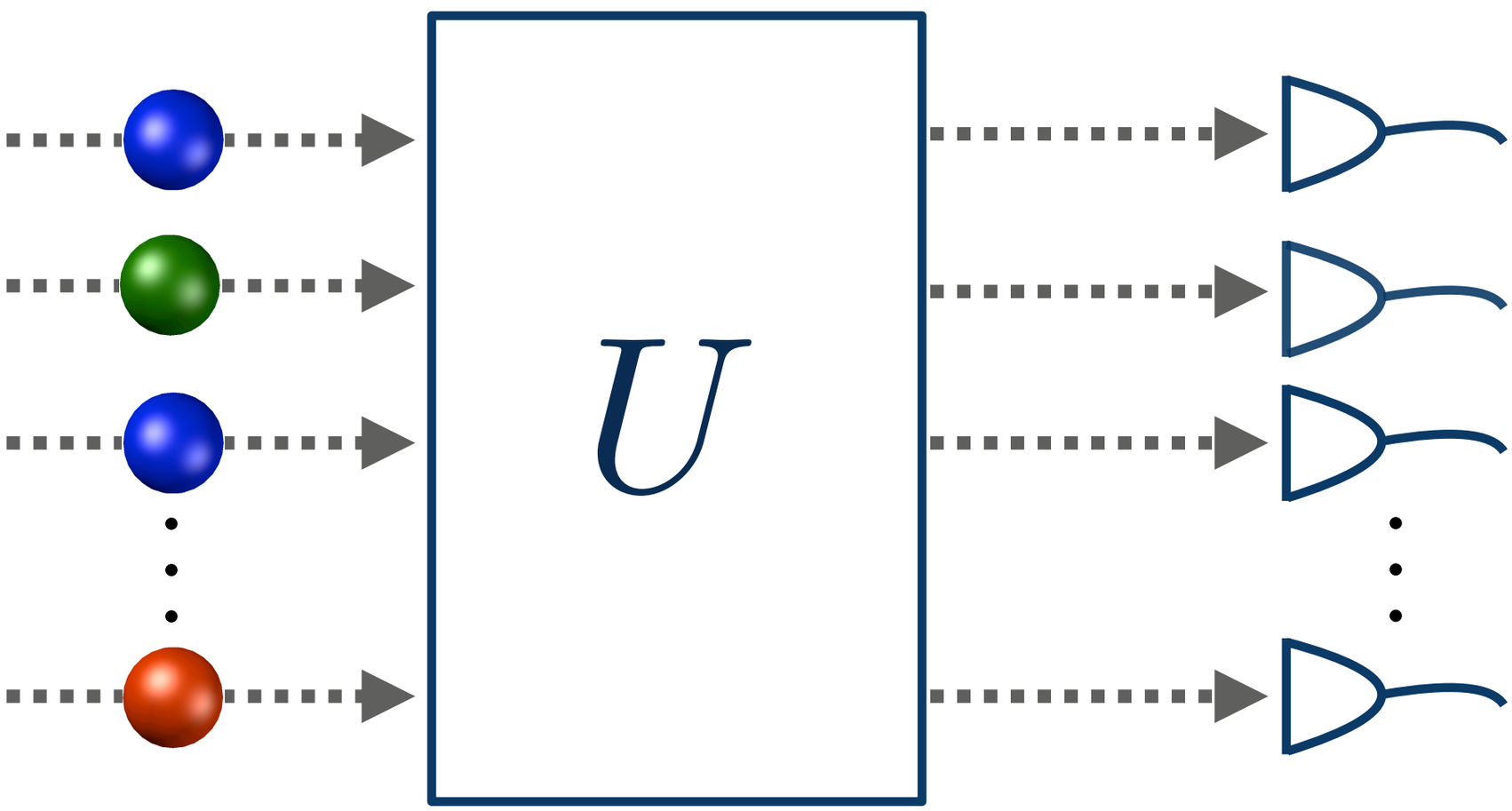
[Walschaers, 2016]

$$C_{ij} = \sum_{k \neq l = 1}^{n} |<\psi_k|\psi_l>|^2 U_{q_k,i} U_{q_l,j} U^*_{q_l,i} U^*_{q_k,j} - \sum_{k=1}^{n} U_{q_k,i} U_{q_k,j} U^*_{q_k,i} U^*_{q_k,j}$$

inference through *lowest order moment of C-dataset* (compare HOM!)

Many-body wave-particle duality

Distinguishability sets bounds on visibility



counting statistics (of events x)

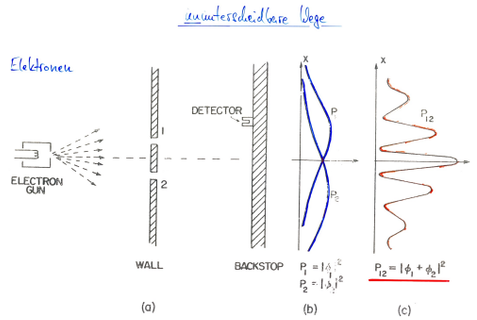
$$p_x = p_x^{\mathrm{D}} + I_x(\bullet, \bullet, \bullet, \dots)$$

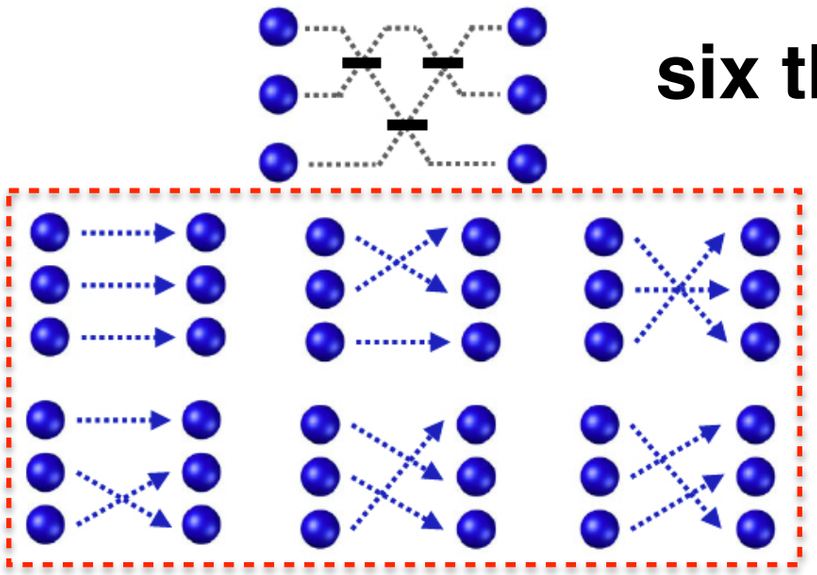
classical/D-istinguishable signal

many-particle interference correction

[Dittel, Dufour, et al., 2021]

Which many-particle way information

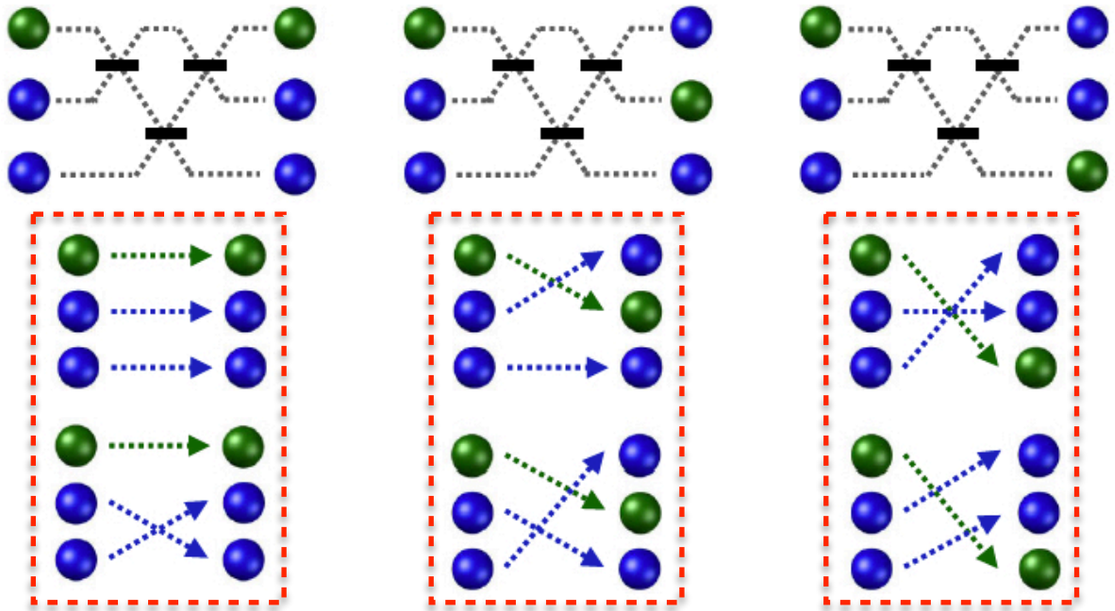




six three-particle amplitudes interfere

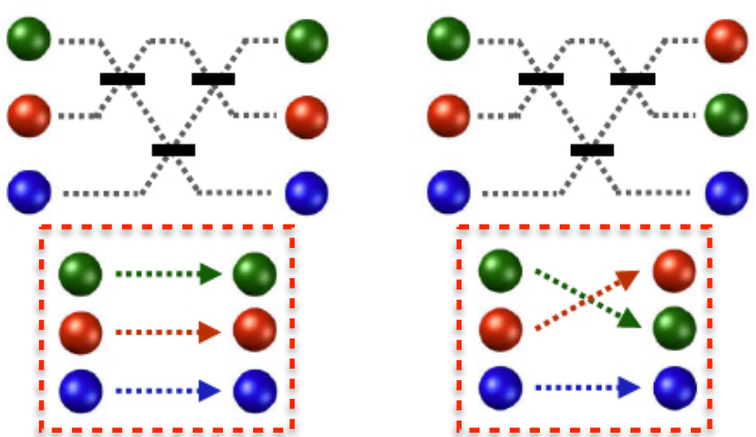
[Cohen-Tannoudji, Diu, Laloë, *Mécanique quantique II, 1973*]

pairs of three-particle amplitudes interfere



entanglement of internal (colour) with external (mode) dof

three particle amplitudes do not interfere



[Dittel, Dufour, et al., 2021]

(bosonic) Many-body state

$$\rho = S\left(|1,2,\ldots,N\rangle \otimes |\bullet,\bullet,\ldots,\bullet\rangle\right)$$

external state

$$\rho_{\mathrm{E}} = \mathrm{Tr}_{\mathrm{I}}(\rho)$$

internal state

$$\rho_{\mathrm{I}} = \mathrm{Tr}_{\mathrm{E}}(\rho) = \frac{1}{N!} \sum_{\pi \in \mathrm{S}_N} \rho_{\mathrm{I}}^{\pi}$$

$$\mathcal{W} = \sqrt{\frac{N!}{N!-1} \sum_{\pi \neq \pi'} \left|[\rho_{\mathrm{E}}]_{\pi,\pi'}\right|^2}$$

$$= \sqrt{\frac{N!}{N!-1}\left(\mathrm{Tr}(\rho_{\mathrm{E}}^2) - \frac{1}{N!}\right)}$$

wave character

$$\mathcal{W}^2 + \mathcal{P}^2 \leq 1$$

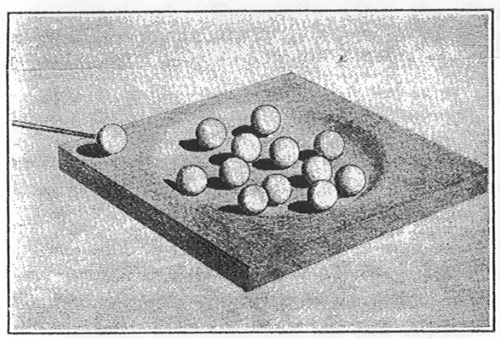
[Dittel, Dufour, et al., 2021]

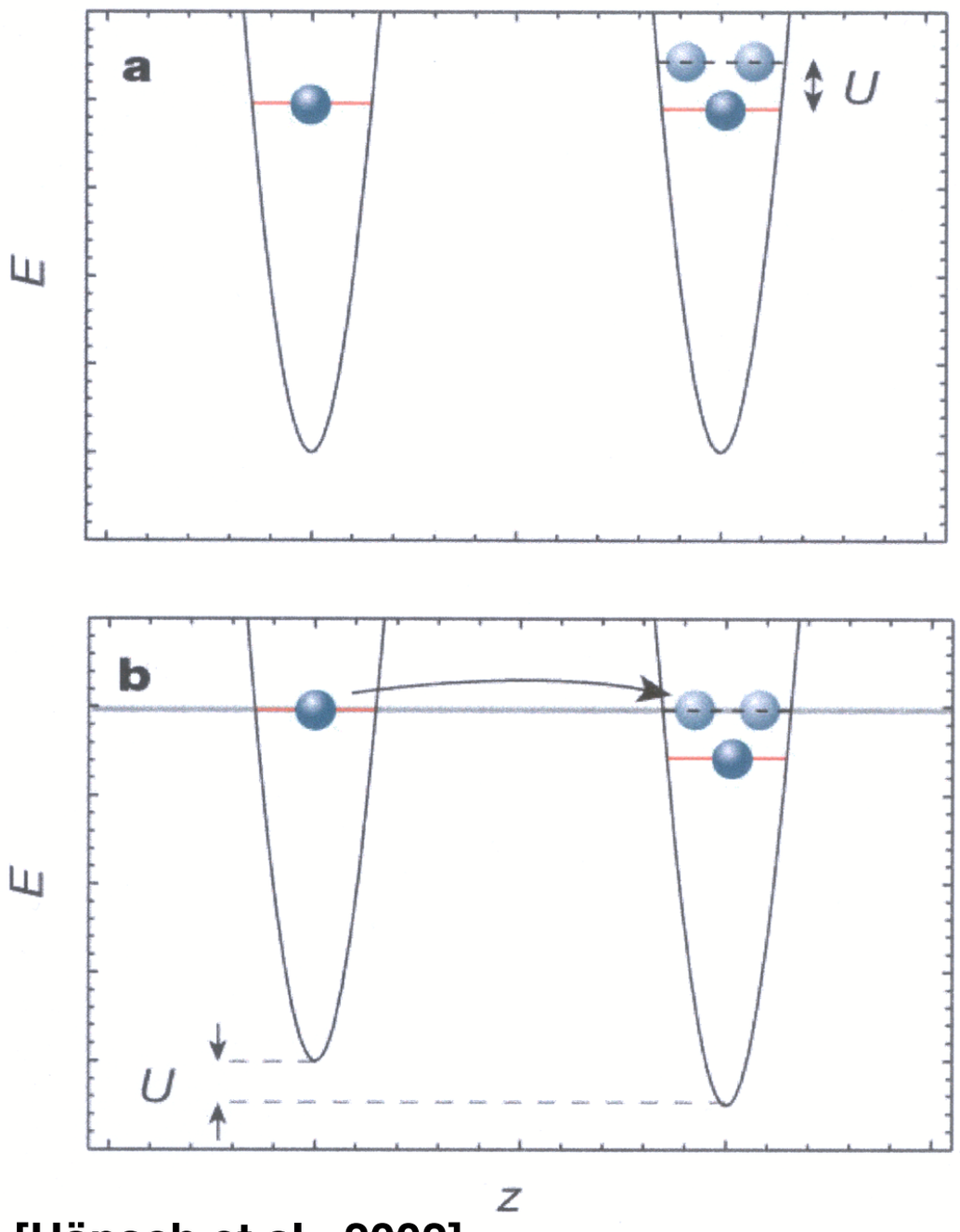
$$\mathcal{P} = \sqrt{1 - \frac{1}{N!(N!-1)} \sum_{\substack{\pi,\pi' \in \mathrm{S}_N \\ \pi \neq \pi'}} F^2(\rho_{\mathrm{I}}^{\pi}, \rho_{\mathrm{I}}^{\pi'})}$$

particle character

Application to an interacting model

Bose-Hubbard Hamiltonian





[Hänsch et al., 2002]

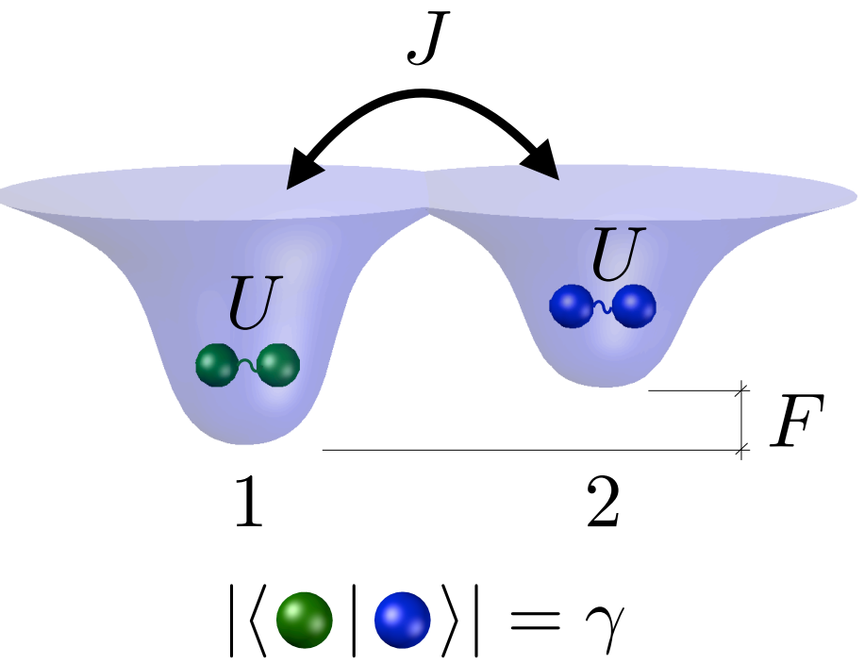
$$H = -J\sum_{j=1}^{L}\left(a_j^\dagger a_{j+1} + a_{j+1}^\dagger a_j\right) + \frac{U}{2}\sum_{j=1}^{L} n_j(n_j-1)$$

- N particles on L sites -

[picture: N=4, L=2]

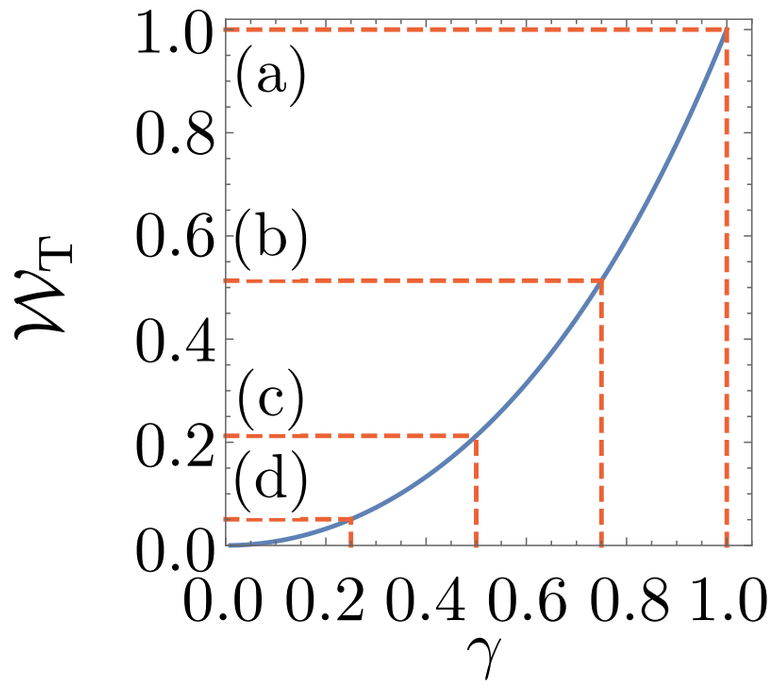
tunneling and interaction terms induce *incompatible* symmetries

Interacting Bose Hubbard dimer

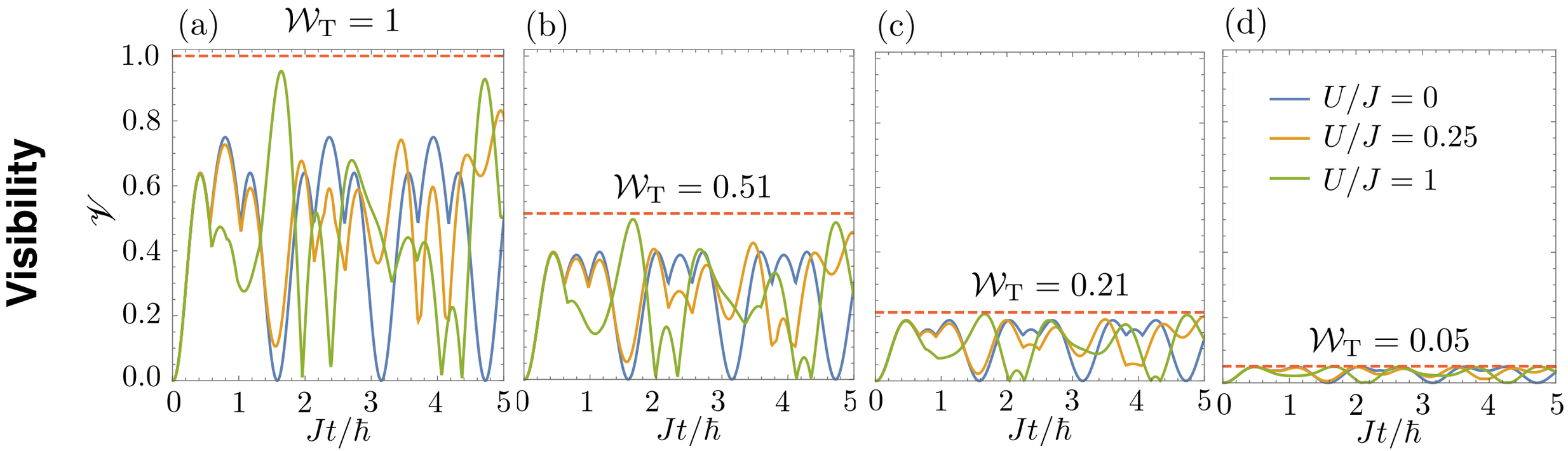


$$|\langle \bullet\bullet | \bullet\bullet \rangle| = \gamma$$

contrast of time dependent output mode occupation enhanced by many-particle interferences



$$\mathscr{V} \propto \sum_x |p_x - p_x^\mathrm{D}| = \sum_x |I_x(\bullet, \bullet, \bullet, \dots)| \leq \mathcal{W}_\mathrm{T}$$



[Dittel, Dufour, et al., 2021]

Take home

! wave-particle duality & decoherence
from single to many-body paths !

! lift HOM from two-mode deterministic to many-mode statistical inference via C-dataset of two-point correlators !

?!? resolve many-particle interaction vs. interference phenomena ?!?

?!? theory of open many-particle quantum systems ?!?

further reading

[incl. detailed bibliographies]

PhD Malte Tichy, diploma Klaus Mayer,
PhD Mattia Walschaers, PhD Tobias Brünner, B.Sc. Michael Minke,
M.Sc. Christian Haen, B.Sc. Niklas Neubrand, B.Sc. Katrina Wharam,
PhD Kabir Njoya, M.Sc./PhD Eric Brunner

& Annu. Rev. Condens. Matter Phys. 7, 223 (2016); NJP 22, 103006 (2020); PRX 11, 031041 (2021); PRR 4, 043101 (2022); PRL 130, 080401 (2023)

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