Clustronics on quantum many-body architecture

Mack Kira

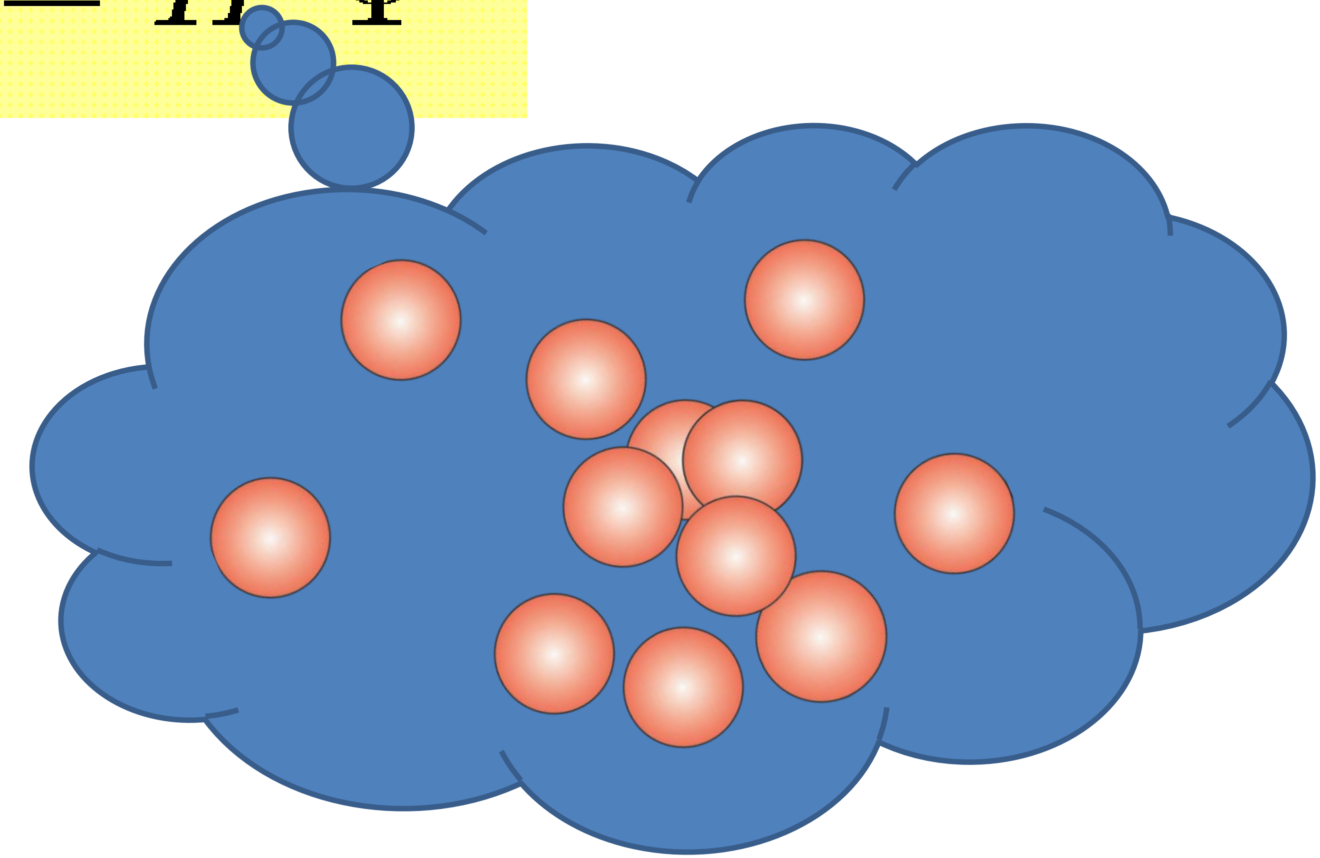
Quantum Science Theory Lab

M | ECE ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

M | LSA PHYSICS
UNIVERSITY OF MICHIGAN

Many-body physics dream

$$i\hbar \frac{\partial}{\partial t}\Psi = \hat{H}\,\Psi$$



Propagate quantum processes to macroscopic world despite and because of many-body interactions.

Many-body architecture

Bit $\xrightarrow{\text{Quantization}}$ Ψ(all possible states of a particle)

$$\text{Info}\left[\Psi(N\ \text{ples})\right] = (\#\ \text{of elements})^N$$

Information content grows exponentially with particle number!!!

Interactions couple/scramble possibilities

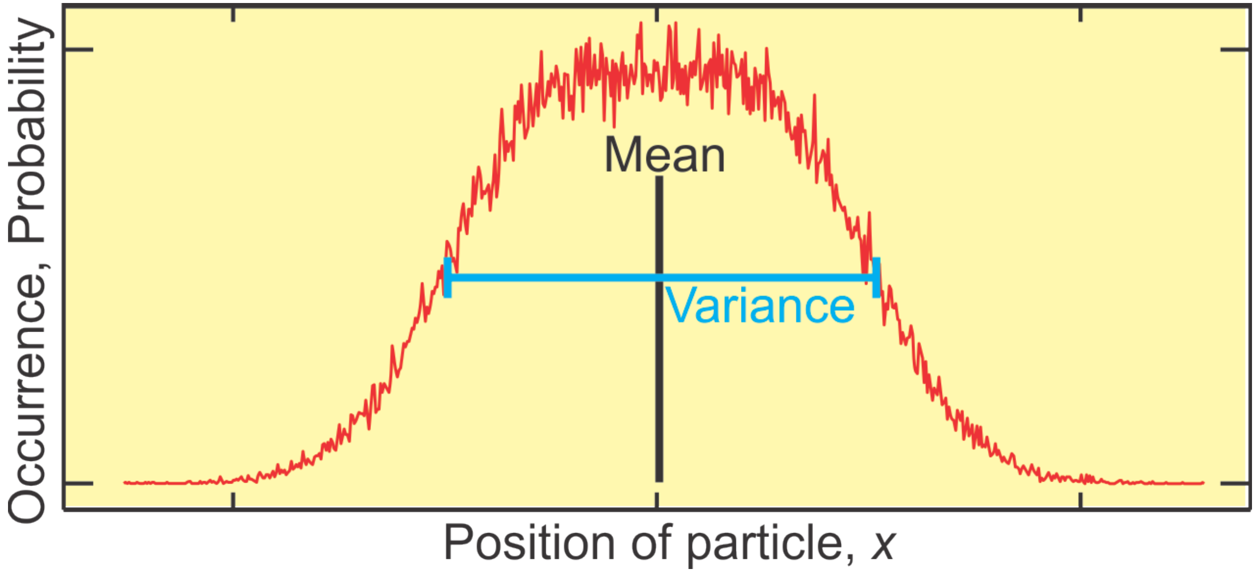
Correlations/entanglement yield hierarchy problem

MB & QO interactions → major-league scrambling

> 3-body problem not exactly solvable in full Ψ architecture…

Structure in quantum architecture?

Measurement in quantum architecture ➡ distribution of outcomes



Ever increasing information using cumulants (Thorvald N. Thiele, 1889):

1) Mean $\langle x \rangle$, **2)** Variance $\Delta\langle x^2\rangle \equiv \langle x^2\rangle - \langle x\rangle\langle x\rangle$,…

C) Cumulant *C* $\Delta\langle x^C\rangle \equiv \langle x^C\rangle - \text{all factorizations}$

All cumulants = full information of distribution

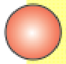
Cluster-expansion approach

MB field operators: $\hat{\Psi}(\mathbf{r}) \quad \& \quad \hat{\Psi}^\dagger(\mathbf{r})$

Clusters:

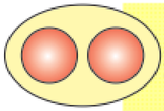
$$\Delta\langle C\rangle = \langle \hat{\Psi}_1^\dagger \cdots \hat{\Psi}_C^\dagger \hat{\Psi}_C \cdots \hat{\Psi}_1\rangle - \text{all factorizations}$$

Terminology:



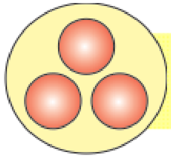
$\equiv \langle 1\rangle = \langle \hat{\Psi}^\dagger \hat{\Psi}\rangle$

Singlets



$\equiv \Delta\langle 2\rangle = \Delta\langle \hat{\Psi}^\dagger \hat{\Psi}^\dagger \hat{\Psi} \hat{\Psi}\rangle$

Doublets

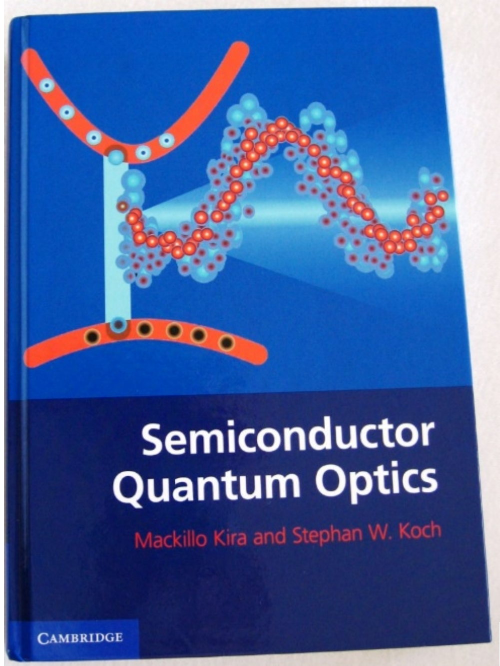


$\equiv \Delta\langle 3\rangle$

Triplets, etc…

Quasiparticles = Δ<C>

1st-principles with cluster expansion



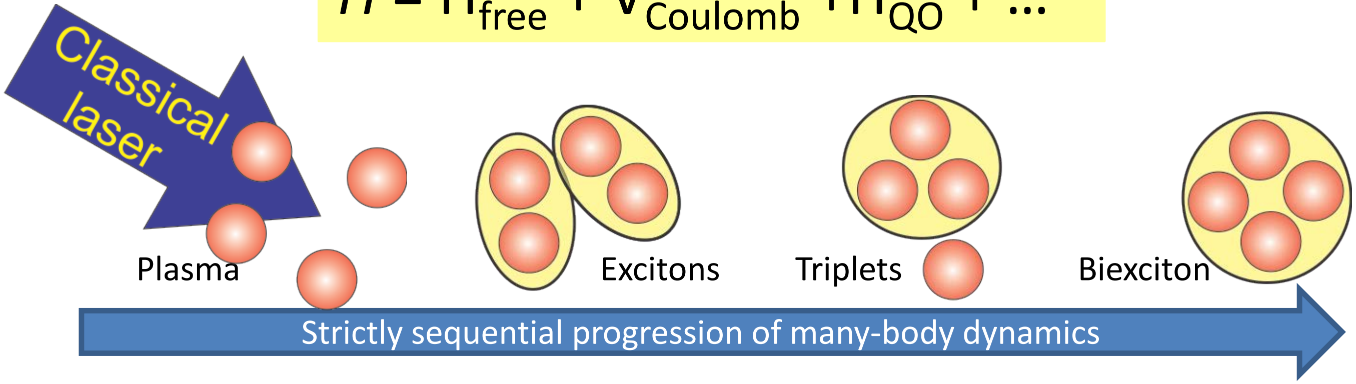
Semiconductor Quantum Optics

Mackillo Kira and Stephan W. Koch

CAMBRIDGE

1) MB+QO Hamiltonian

$$H = \mathrm{H}_{\mathrm{free}} + \mathrm{V}_{\mathrm{Coulomb}} + \mathrm{H}_{\mathrm{QO}} + \ldots$$



2) Cluster kinetics [Ann. Phys. **356**, 185 (2015)]:

$$i\hbar\frac{\partial}{\partial t}\Delta\langle C\rangle = \mathrm{F}_{\mathrm{1ple}}[\Delta\langle C\rangle] + \underbrace{S[\langle 1\rangle, \Delta\langle 2\rangle, \cdots, \Delta\langle C\rangle]}_{\text{Sequential source}} + \mathrm{V}[\Delta\langle C+1\rangle]$$

- exactly solvable & nonperturbative until Δ<C+1> cluster is formed

3) Ideal approach for following quasiparticle formation & dynamics

Clustronics = follow/control many-body processes through cluster kinetics

General proof of sequential clustronics

Q.E.D.

+ Interactions → Sequence of processes = simple → complex

Clustronics=

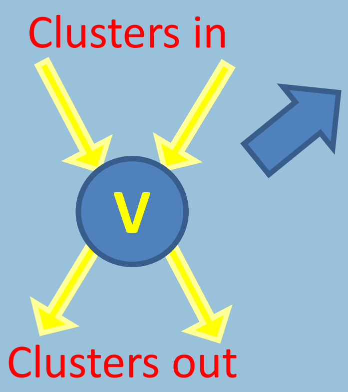
Natural & 1st-principles description of quantum processes

Typical 1st-principles cluster dynamics

$$S^{\mathbf{k}',\mathbf{k}}_{0,3} \equiv \frac{V_{\mathbf{k}}}{2}\left(\sqrt{N_{\mathrm{C}}}\,(1+f_{\mathbf{k}}+s_{\mathbf{k}})(s_{\mathbf{k}'}+s_{\mathbf{k}+\mathbf{k}'}) + \sqrt{N_{\mathrm{C}}}\,f_{\mathbf{k}'}\,s^{\star}_{\mathbf{k}+\mathbf{k}'} + \sqrt{N_{\mathrm{C}}}\,f_{\mathbf{k}+\mathbf{k}'}\,s^{\star}_{\mathbf{k}'}\right). \tag{C.5}$$

The full correlation dynamics becomes

$$\begin{aligned}
i\hbar\frac{\partial}{\partial t}T^{\mathbf{k}',\mathbf{k}}_{0,3} = {} & \left(E^{\mathrm{ren}}_{\mathbf{k}} + E^{\mathrm{ren}}_{\mathbf{k}'} + E^{\mathrm{ren}}_{\mathbf{k}+\mathbf{k}'}\right) T^{\mathbf{k}',\mathbf{k}}_{0,3} + \Delta^{\mathrm{ren}}_{\mathbf{k}}\,T^{\mathbf{k}',-\mathbf{k}-\mathbf{k}'}_{2,1} + \Delta^{\mathrm{ren}}_{\mathbf{k}'}\,T^{-\mathbf{k}-\mathbf{k}',\mathbf{k}}_{2,1} - \Delta^{\mathrm{ren}}_{\mathbf{k}+\mathbf{k}'}\,T^{\mathbf{k}',\mathbf{k}}_{2,1} \\
& + S^{\mathbf{k}',\mathbf{k}}_{0,3} + S^{\mathbf{k}',\mathbf{k}}_{0,3} + S^{\mathbf{k}',-\mathbf{k}-\mathbf{k}'}_{0,3} + (1+f_{\mathbf{k}}+f_{\mathbf{k}+\mathbf{k}'})\sum_{\mathbf{l}} V_{\mathbf{l}-\mathbf{k}}\,T^{\mathbf{k}',\mathbf{l}}_{0,3} \\
& + (1+f_{\mathbf{k}'}+f_{\mathbf{k}+\mathbf{k}'})\sum_{\mathbf{l}} V_{\mathbf{l}-\mathbf{k}'}\,T^{\mathbf{l},\mathbf{k}'}_{0,3} + (1+f_{\mathbf{k}}+f_{\mathbf{k}'})\sum_{\mathbf{l}} V_{\mathbf{l}}\,T^{\mathbf{k}'+\mathbf{l},\mathbf{k}-\mathbf{l}}_{0,3} \\
& + s_{\mathbf{k}}\sum_{\mathbf{l}}\left[V_{\mathbf{l}+\mathbf{k}+\mathbf{k}'}\,T^{\mathbf{k}',\mathbf{l}'}_{1,2} + V_{\mathbf{l}-\mathbf{k}'}\,T^{-\mathbf{k}-\mathbf{k}',\mathbf{l}}_{1,2}\right] + s_{\mathbf{k}'}\sum_{\mathbf{l}}\left[V_{\mathbf{l}+\mathbf{k}+\mathbf{k}'}\,T^{\mathbf{l},\mathbf{k}}_{1,2}\right. \\
& \left. + V_{\mathbf{l}-\mathbf{k}}\,T^{-\mathbf{k}-\mathbf{k}',\mathbf{l}}_{1,2}\right] + s_{\mathbf{k}+\mathbf{k}'}\sum_{\mathbf{l}}\left[V_{\mathbf{l}-\mathbf{k}}\,T^{\mathbf{k}',\mathbf{l}}_{1,2} + V_{\mathbf{l}-\mathbf{k}'}\,T^{\mathbf{l},\mathbf{k}}_{1,2}\right] \\
& + V_{\mathbf{k}}\,(s_{\mathbf{k}'}+s_{\mathbf{k}+\mathbf{k}'})\sum_{\mathbf{l}} T^{\mathbf{l},\mathbf{k}}_{1,2} + V_{\mathbf{k}'}\,(s_{\mathbf{k}}+s_{\mathbf{k}+\mathbf{k}'})\sum_{\mathbf{l}} T^{\mathbf{k}',\mathbf{l}}_{1,2} \\
& + V_{\mathbf{k}+\mathbf{k}'}\,(s_{\mathbf{k}}+s_{\mathbf{k}'})\sum_{\mathbf{l}} T^{-\mathbf{k}-\mathbf{k}',\mathbf{l}}_{1,2} + \mathrm{Hi}^{\mathbf{k}',\mathbf{k}}_{0,3} + \mathrm{Hi}^{\mathbf{k},\mathbf{k}'}_{0,3} + \mathrm{Hi}^{\mathbf{k}',-\mathbf{k}-\mathbf{k}'}_{0,3},
\end{aligned} \tag{C.6}$$


Clusters in

Clusters out

Integro, Non-perturbative

Ann. Phys. **356**, 185 (2015)

Contents

Clustronics = follow/control many-body processes through cluster kinetics

Clustronics in 4 diverse theory-experiment examples:
[1] Quantum-optical spectroscopy
[2] Ultrafast quantum electronics
[3] Quasiparticle collisions
[4] Bose-Einstein condensates

[1] Quantum-optical spectroscopy


nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

DROPLETONS

Quantum droplets created by light — meet the new quasiparticle

PAGE 471

OPEN SCIENCE
WISDOM OF THE CROWD
Mathemati
strength in
PAGE

PARTICLE PHYSICS
ACCENTUATE THE NEGATIVE

PALAEONTOLOGY
PREHISTORY IN COLOUR

NATURE.COM/NATURE
27 February 2014

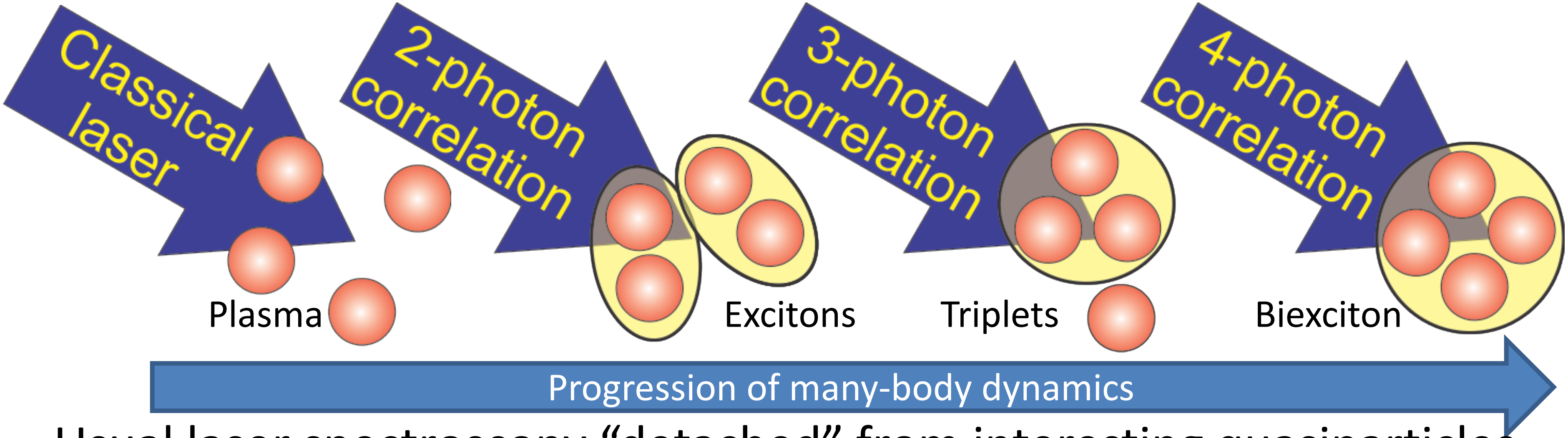
$10.00US $12.99CAN

Discovery of dropleton

EXP: Steven Cundiff group.

Quantum-optical spectroscopy

PRA **73**, 013813 (2006): Cluster-expansion analysis of quantum-optical excitations

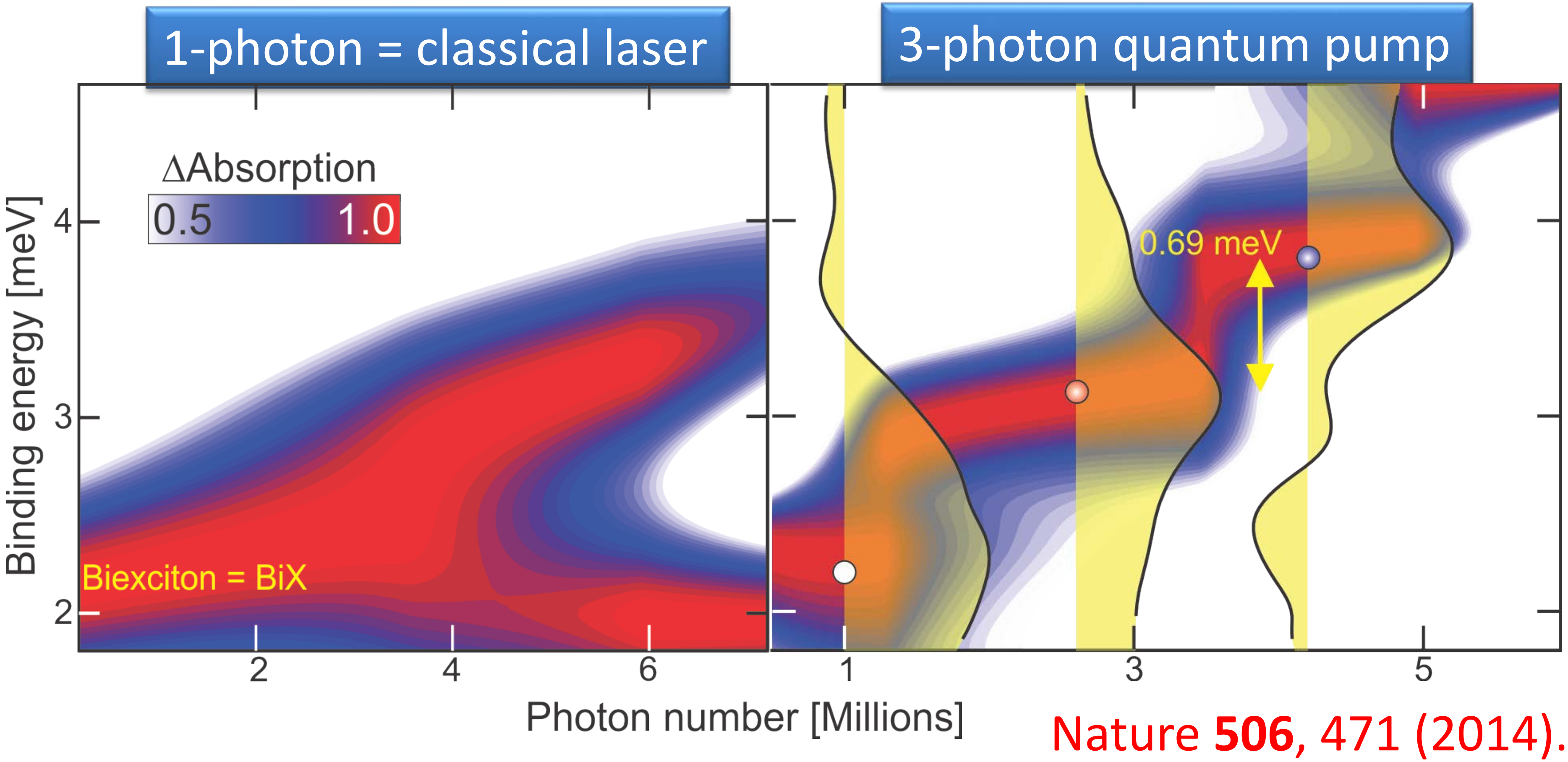


Usual laser spectroscopy “detached” from interesting quasiparticles

Quantum spectroscopy = excite (detect) quasiparticles **DIRECTLY** with quantum light (quantum-light emission)

New quasiparticle resonances

- Δabsorption via typical pump-probe **measurement** in GaAs QW
- Change pump-photon correlations: $\text{Binding} \equiv E_{1s} - \hbar\omega_{\text{probe}}$



Nature **506**, 471 (2014).

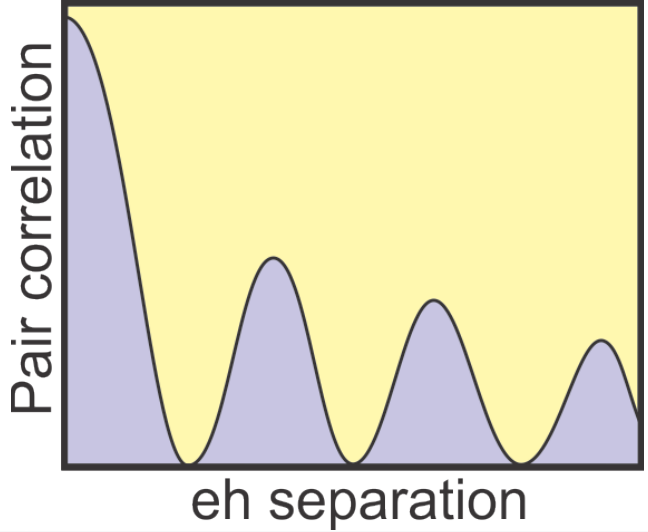
Quantum pump resolves NEW discrete resonances below BiX

What did we see?

Exact energy $E = E[\Delta g]$ as functional of pair correlation $\Delta g = \text{doublet}$

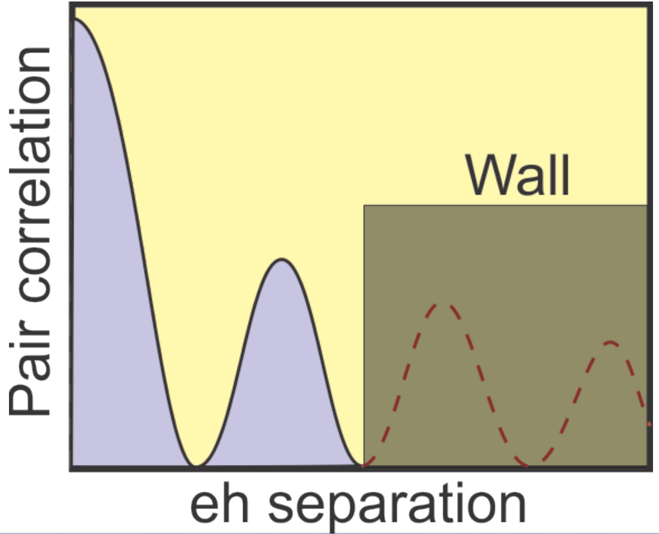
New J. Phys. **15**, 093040 (2013).

1) Energy lowering



- Liquid rings ⇨ *E* < BiX

2) Energy quantization



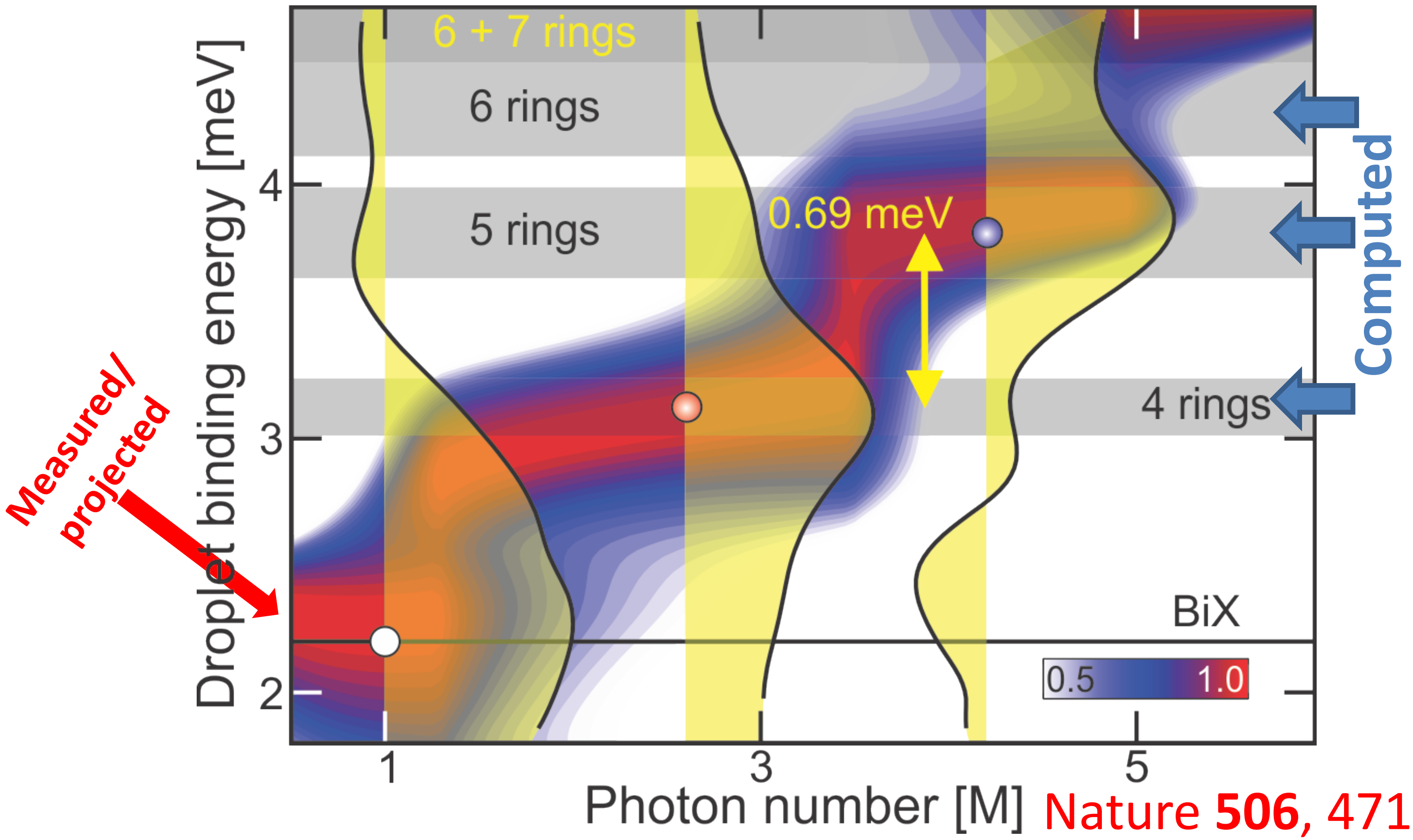
- quantum confinement ⇨ droplet
- 2meV wall height is enough!!!

Supplement to Nature **506**, 471 (2014)

3) Dropleton = tiny *correlation bubble of eh pairs in liquid-phase.*

- 3, 4, 5, rings… = 3, 4, 5… eh pairs

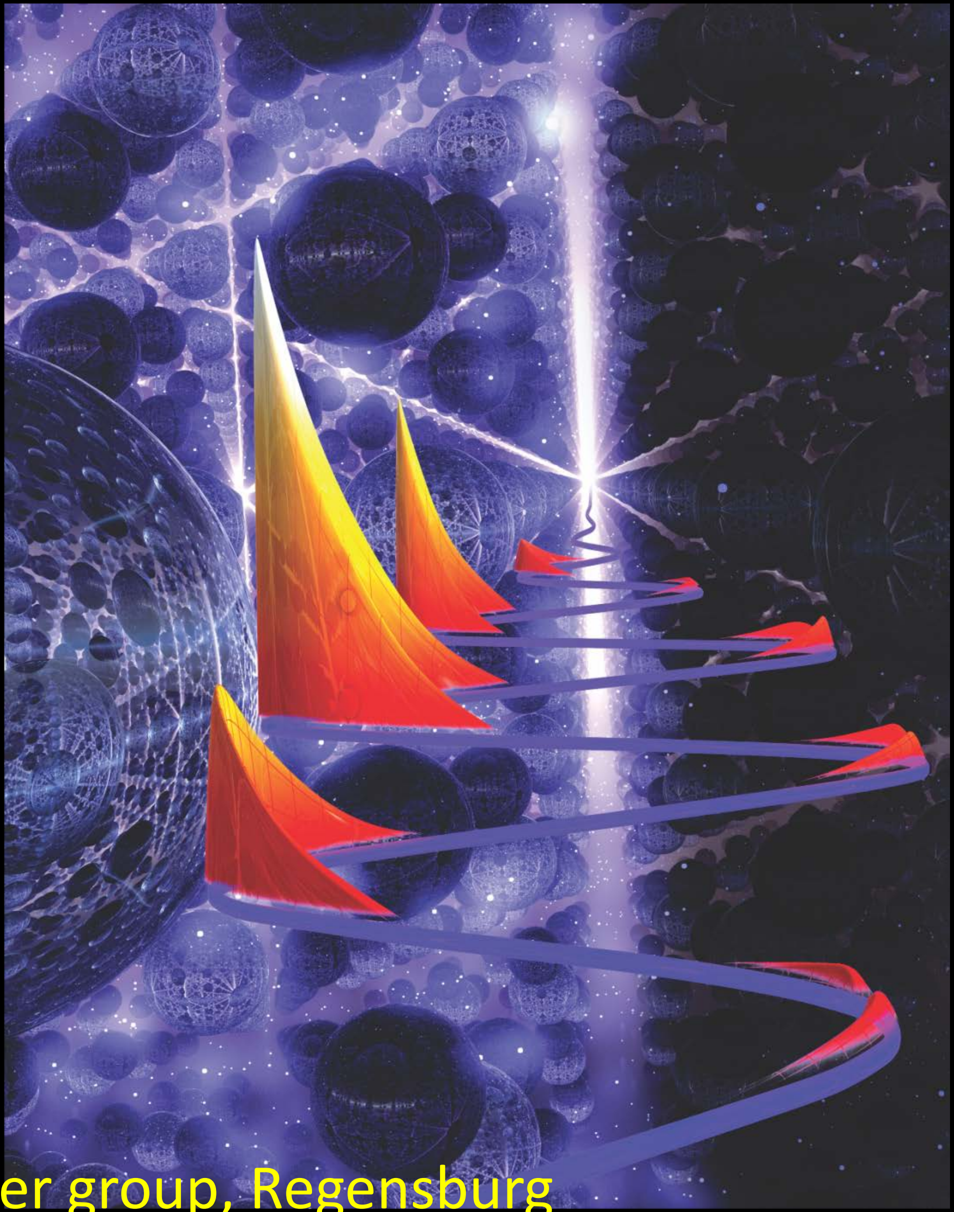
Positive dropleton ID



Nature **506**, 471 (2014).

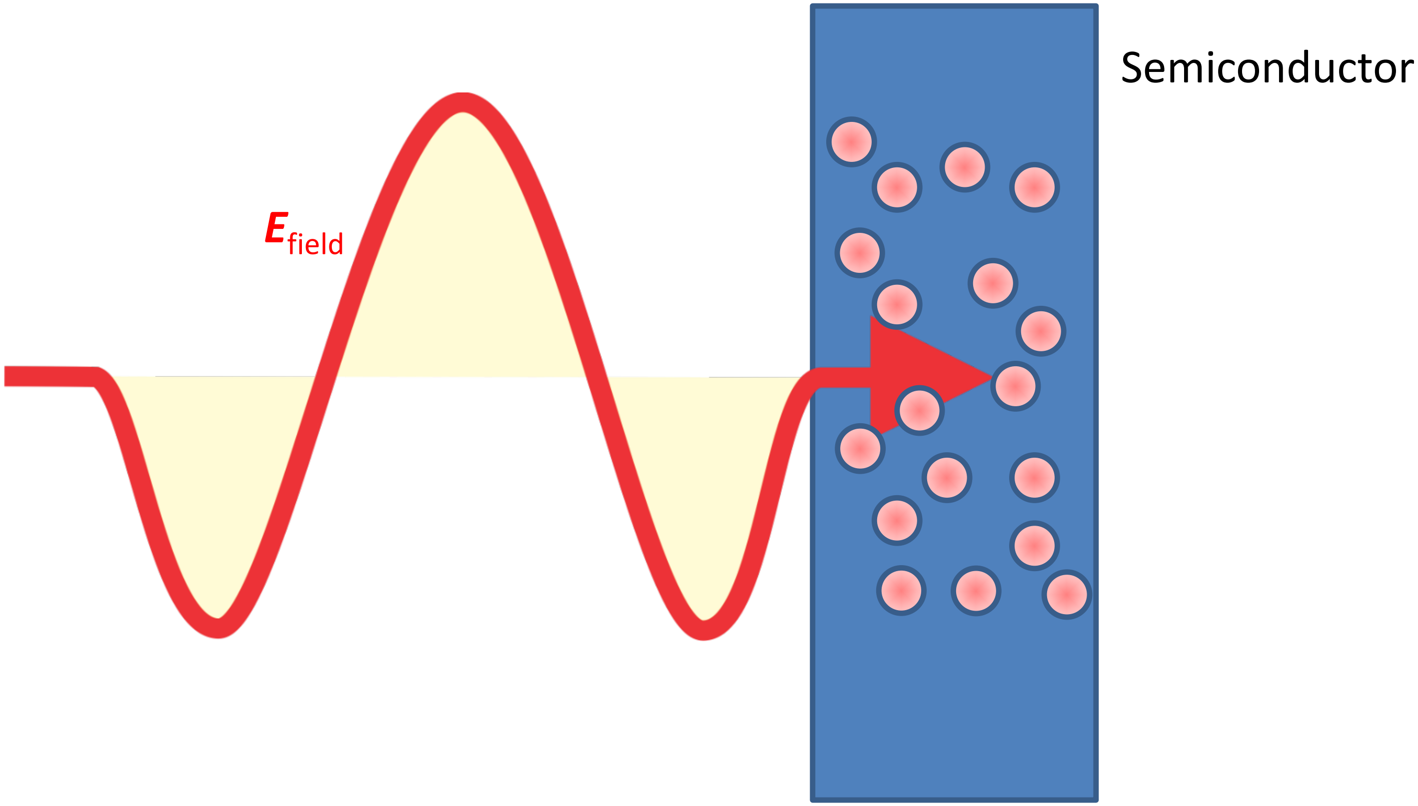
Dropletons explain measured energy structure

[2] ultrafast quantum electronics



Exp.: Rupert Huber group, Regensburg

Goal – realize lightwave electronics



Light creates & moves electrons, holes, and quasiparticles faster than scattering ⇨ quantum coherent effects

Strong-field physics

Strong nonresonant pumping

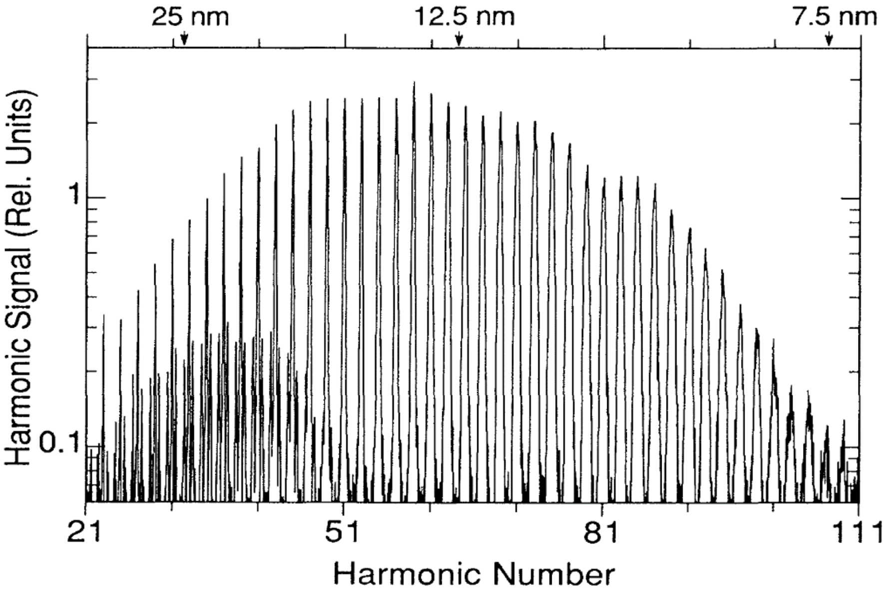
Ionization-acceleration-recollision

3-steps produce odd harmonics

VOLUME 70, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1993

High-Order Harmonic Generation Using Intense Femtosecond Pulses

J. J. Macklin, J. D. Kmetec, and C. L. Gordon III
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
(Received 21 September 1992)



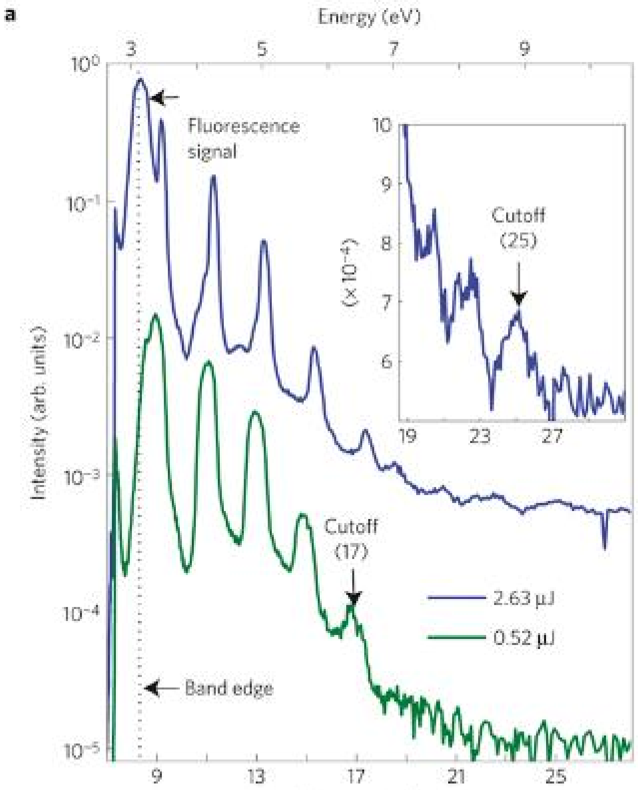
LETTERS
PUBLISHED ONLINE: 5 DECEMBER 2010 | DOI: 10.1038/NPHYS1847

2011

nature physics

Observation of high-order harmonic generation a bulk crystal

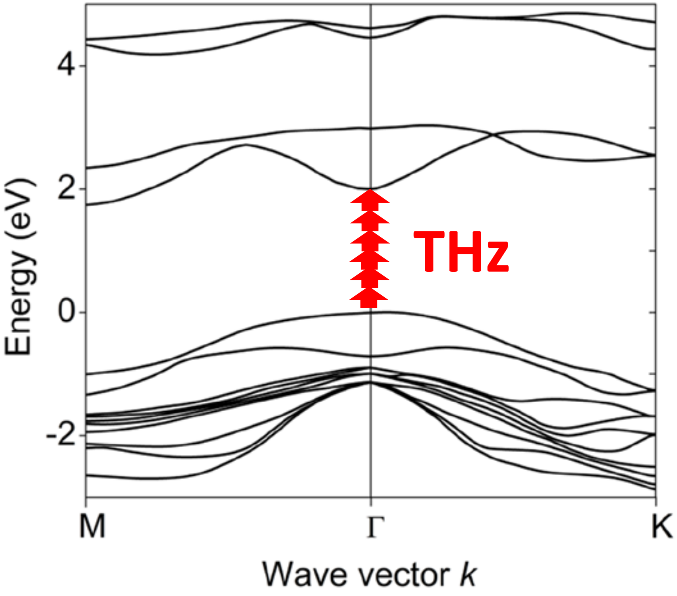
Shambhu Ghimire[1], Anthony D. DiChiara[2], Emily Sistrunk[2], Pierre Agostini[2], Louis F. DiMauro[2] and David A. Reis[1,3]*



Unique semiconductor physics?

Semiconductor excitations

Experiment: GaSe, gap=2eV = 16*30THz photons
100fs pulse with E > 100MV/cm, >1eV/Å, blasting e!!!!



PRB **13**, 3534 (1976)

Semiconductor Bloch equations

Coupled quantum kinetics of microscopic polarization:

$$P_{\mathbf{k}}^{\lambda,\nu} \equiv \langle a_{\lambda,\mathbf{k}}^{\dagger} a_{\nu,\mathbf{k}} \rangle$$

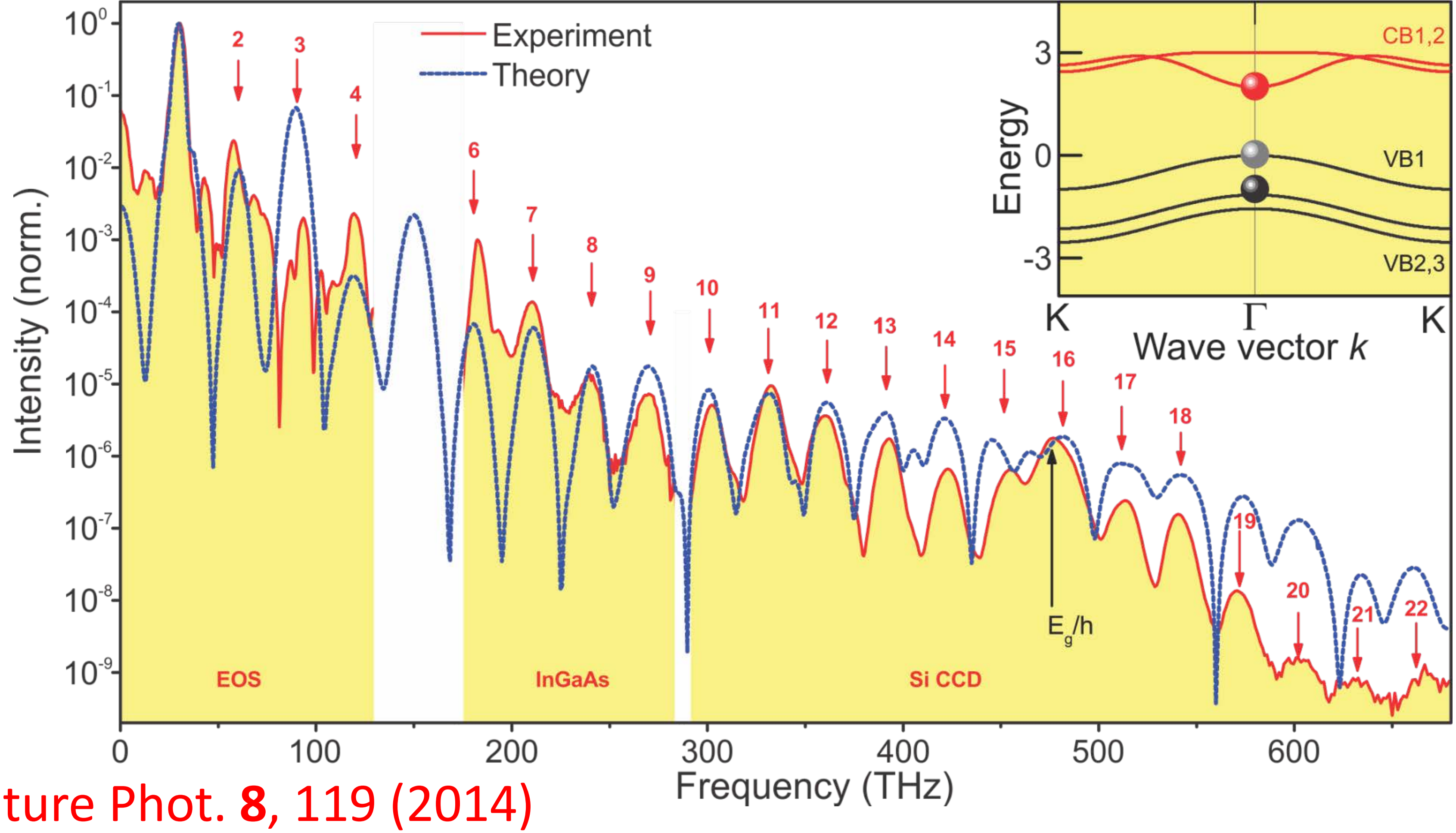
Microscopic density:

$$f_{\mathbf{k}}^{\lambda} = \langle a_{\lambda,\mathbf{k}}^{\dagger} a_{\lambda,\mathbf{k}} \rangle$$

phys. stat. sol. B **248**, 863 (2011).

High-harmonic generation (HHG)

THz peak field: 72MV/cm, **Theory:** 5-band model

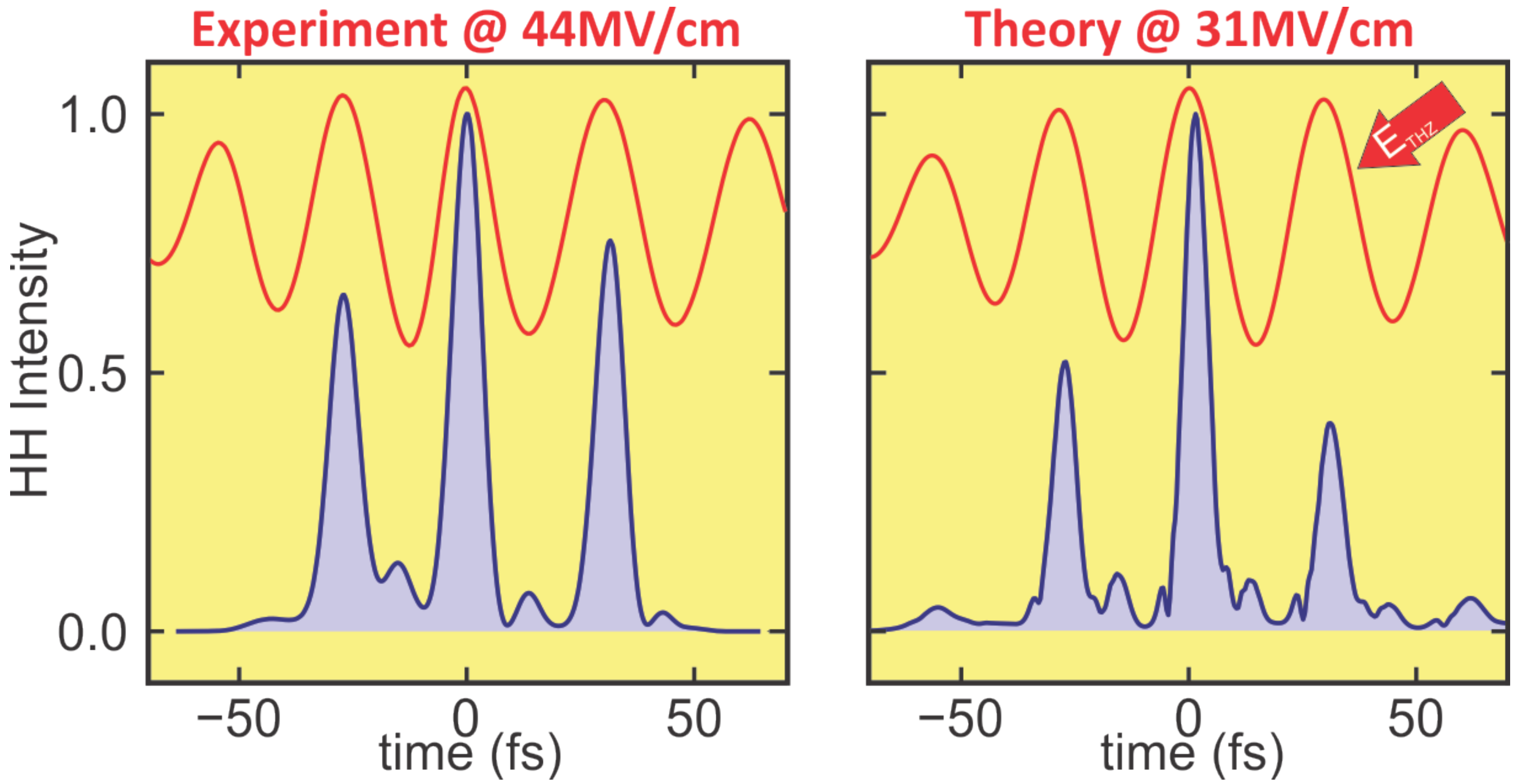


Nature Phot. **8**, 119 (2014)

22 harmonic orders, also even!!!

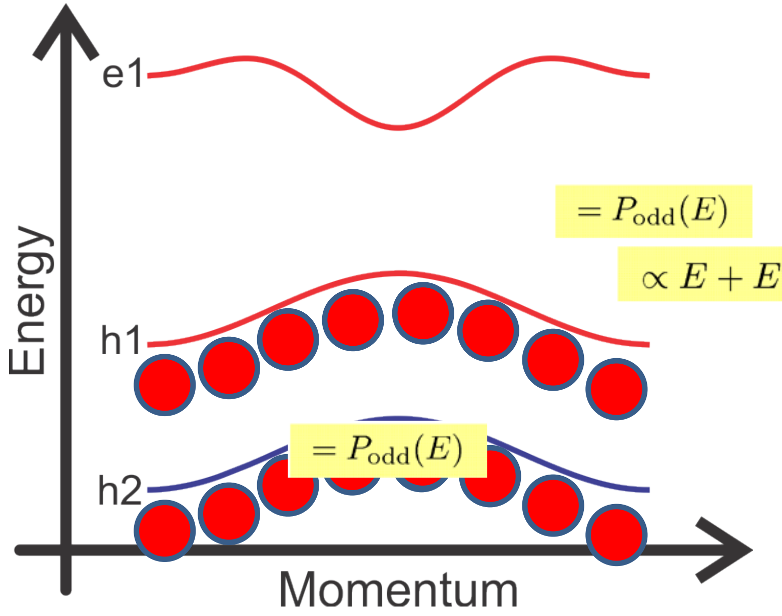
Time-resolved HH emission

- Measured time-resolved $I_{HH}(t)$ vs. $E_{THz}(t)$



- HHG bursts on at positive E_{THz} Nature **523**, 572 (2015).
- Why would positive and negative E_{THz} be so different?

Nonperturbative quantum interference

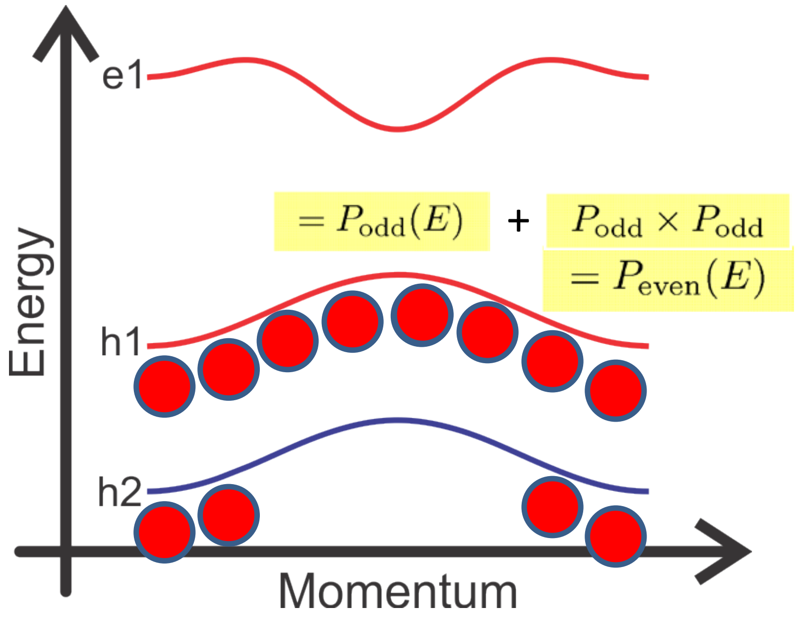


$= P_{\mathrm{odd}}(E)$

$\propto E + E^3 + \cdots$

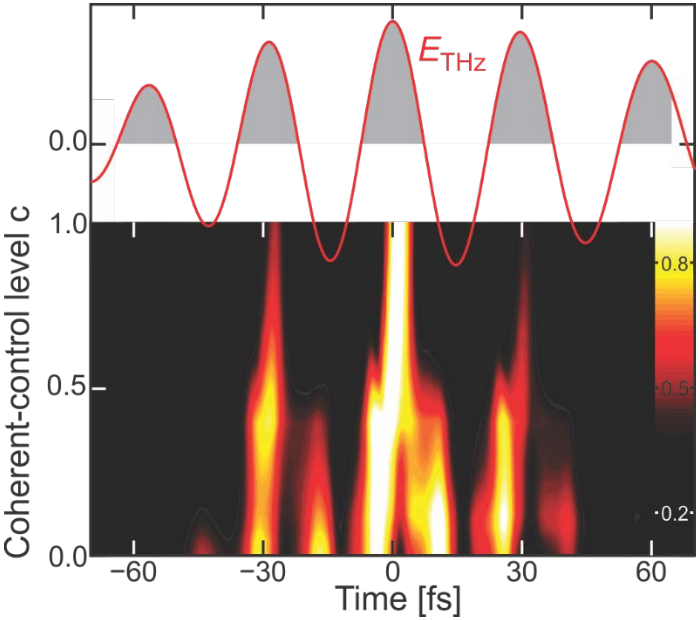
$= P_{\mathrm{odd}}(E)$

Nonperturbative quantum interference



$= P_{\mathrm{odd}}(E)$ + $P_{\mathrm{odd}} \times P_{\mathrm{odd}}$ $= P_{\mathrm{even}}(E)$

Include indirect path with a fraction *c*



Nature **523**, 572 (2015).

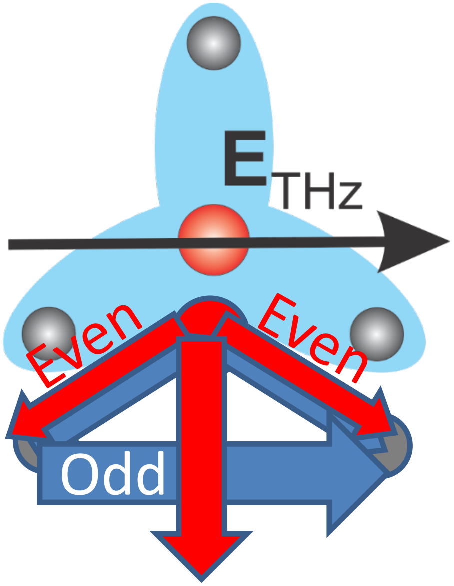
Paths 1 + 2 appear simultaneously → quantum interference

$$P^{\mathrm{h1,e}}_{\mathbf{k}} = P_{\mathrm{odd}}(E) + P_{\mathrm{even}}(E)$$ Constructive

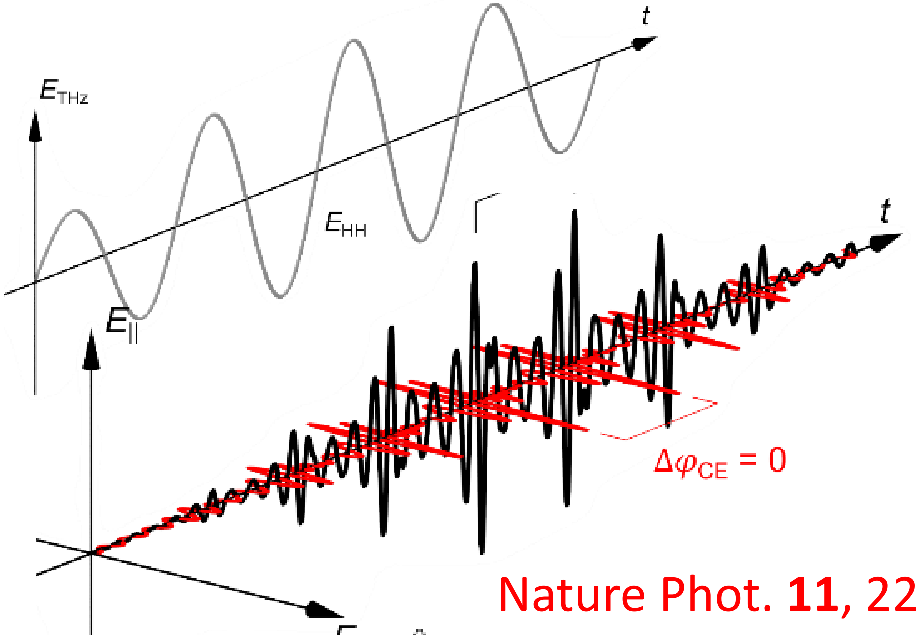
Sign flip, E to –E:

$$P_{\mathrm{odd}}(-E) + P_{\mathrm{even}}(-E) = -P_{\mathrm{odd}}(E) + P_{\mathrm{even}}(E)$$ Destructive!!!

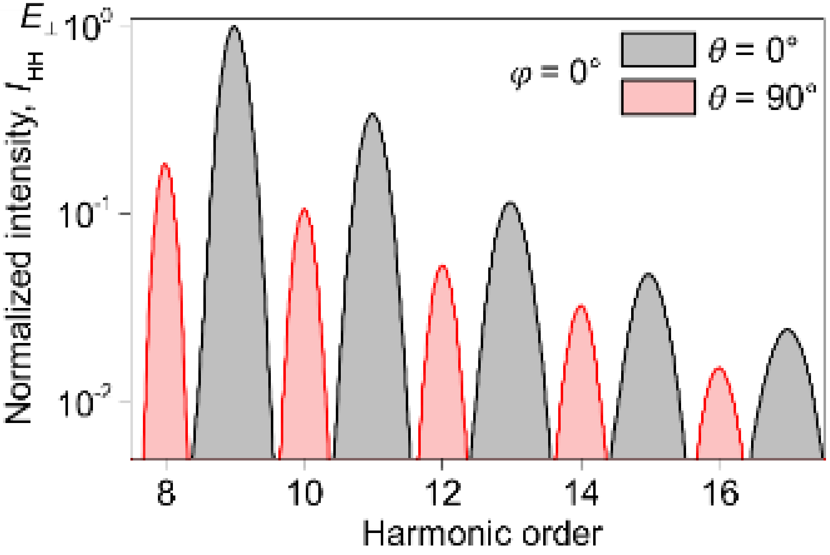
Crystallography with HHG



Even ⊥ Odd

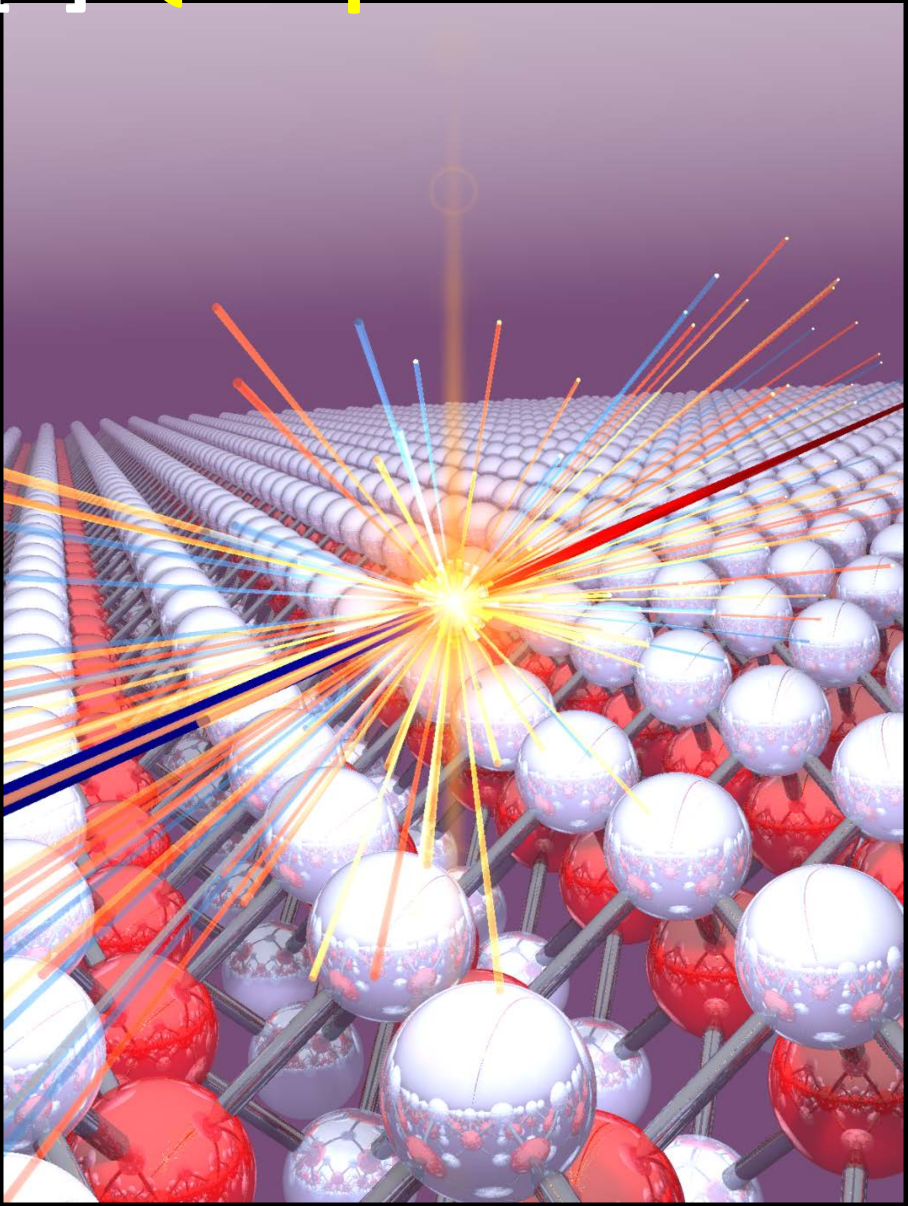


Nature Phot. **11**, 227 (2017).



- Even-order ⊥ odd-order HHG
- HHG at every field crest

[3] Quasiparticle collider

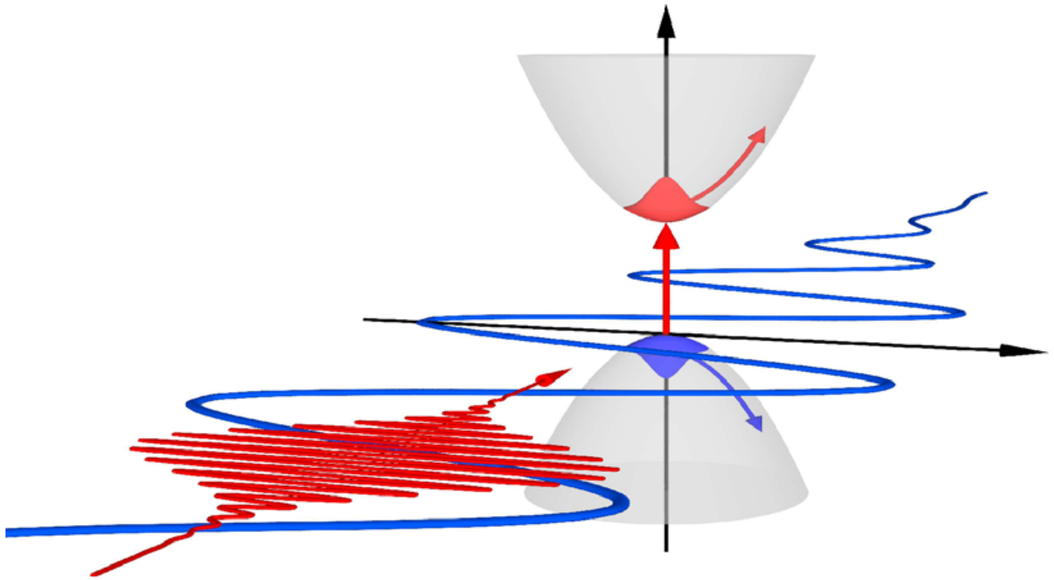


Exp.: Rupert Huber group, Regensburg + Sherwin, UC Santa Barbara

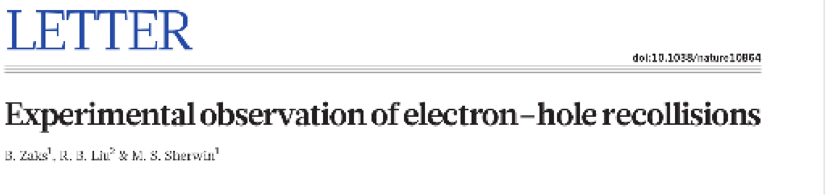
Harmonic sideband generation in solids

1) Excite coherent excitons optically

2) Accelerate/ionize electron-hole pairs



2012

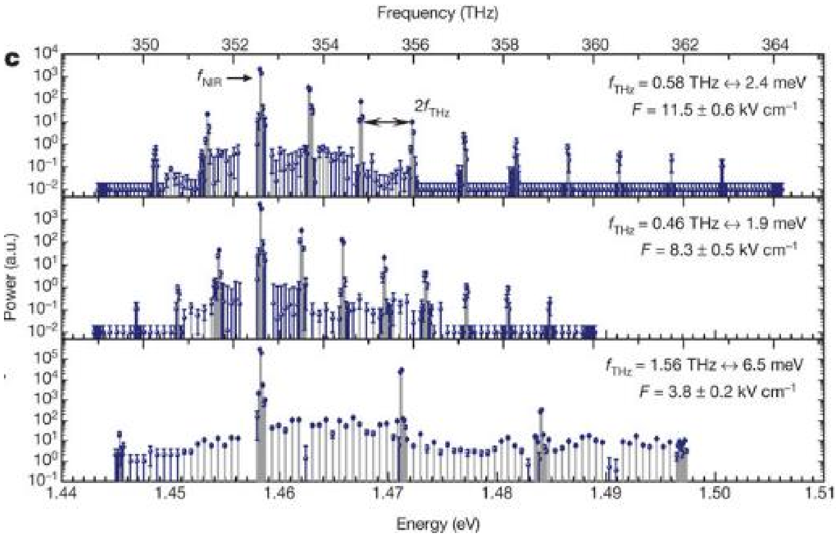


LETTER

doi:10.1038/nature10864

Experimental observation of electron–hole recollisions

B. Zaks[1], R. B. Liu[2] & M. S. Sherwin[1]



High-order sideband generation

3) Measure optical response

Pulsed HSG

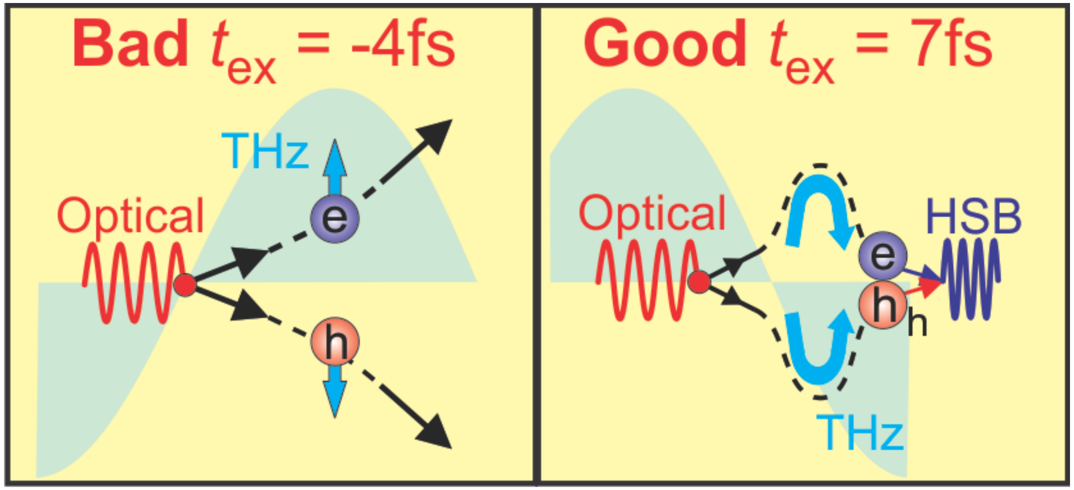
- 60nm thick WSe_2 with strong 1s X (60meV)
- 10fs optical pulse @1s X
- 100fs THz pulse, 17MV/cm
- E-h recollision

1. Creates coherent X/e-h- pairs
2. Ac/decelerates e-h separation
3. Photon emission as sidebands

Highly analogous to atomic 3-step model

- Will we detect the expected delay?

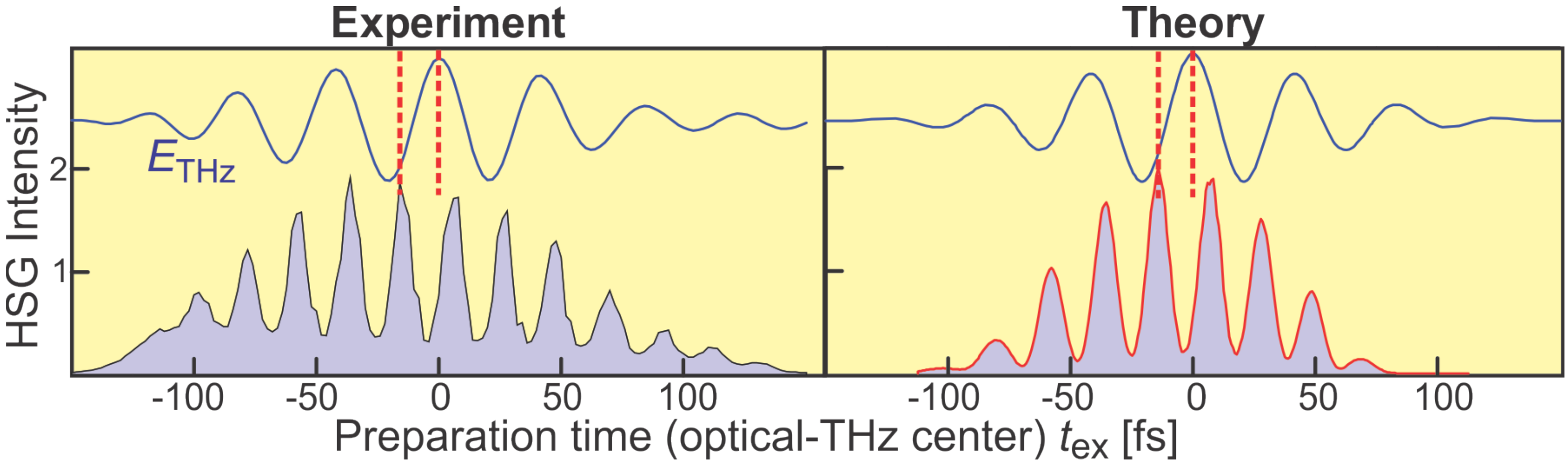
+ finite lifetime of coherences



Bad t_{ex} = -4fs **Good t_{ex} = 7fs**

Recollisions in time domain

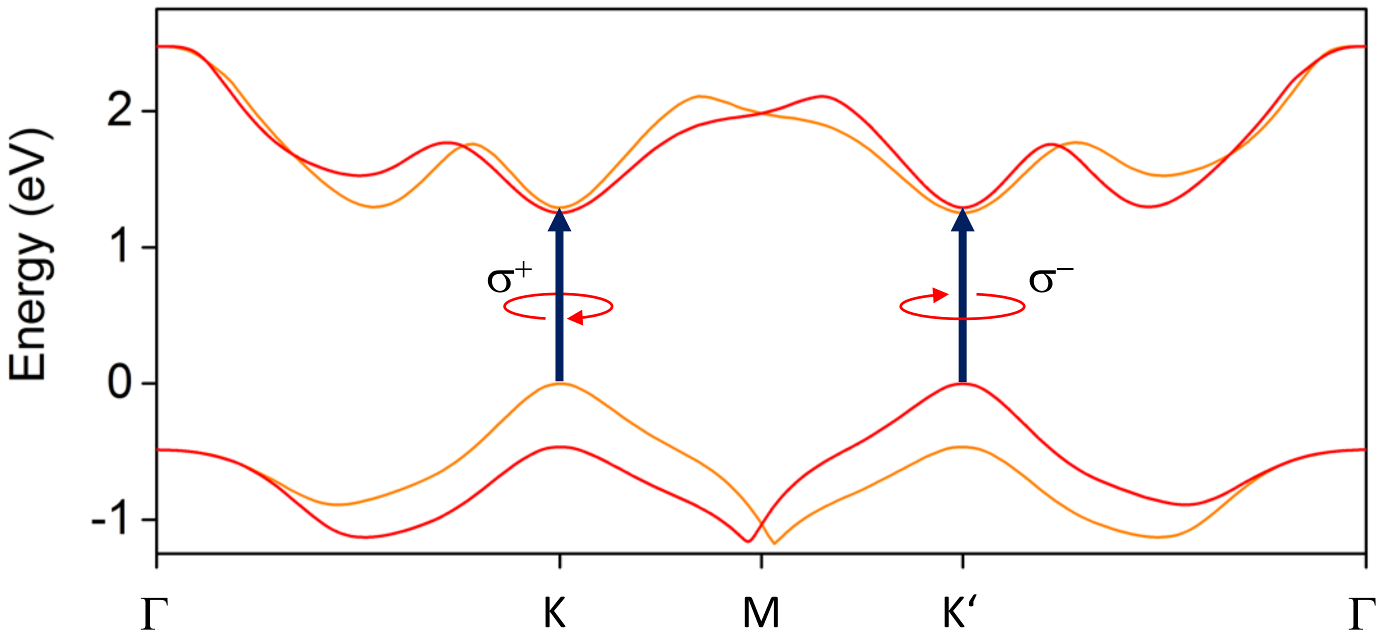
- 10fs optical pulse → Coh.X created << 50fs THz cycle
- Measure total HSG I vs. preparation time t_{ex}



Nature **533**, 225 (2016).

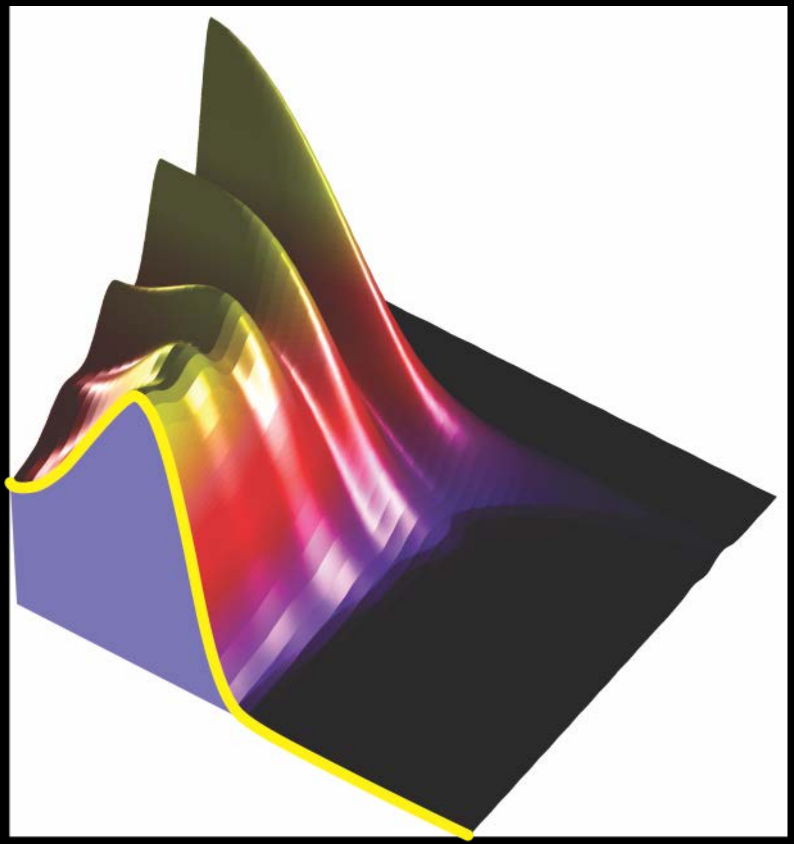
- Global delay = HSG emission delayed (as in 3-step model)
- Bad (low HSG) vs. good (high HSG) preparation times.

Lightwave valleytronics in WSe_2 monolayer

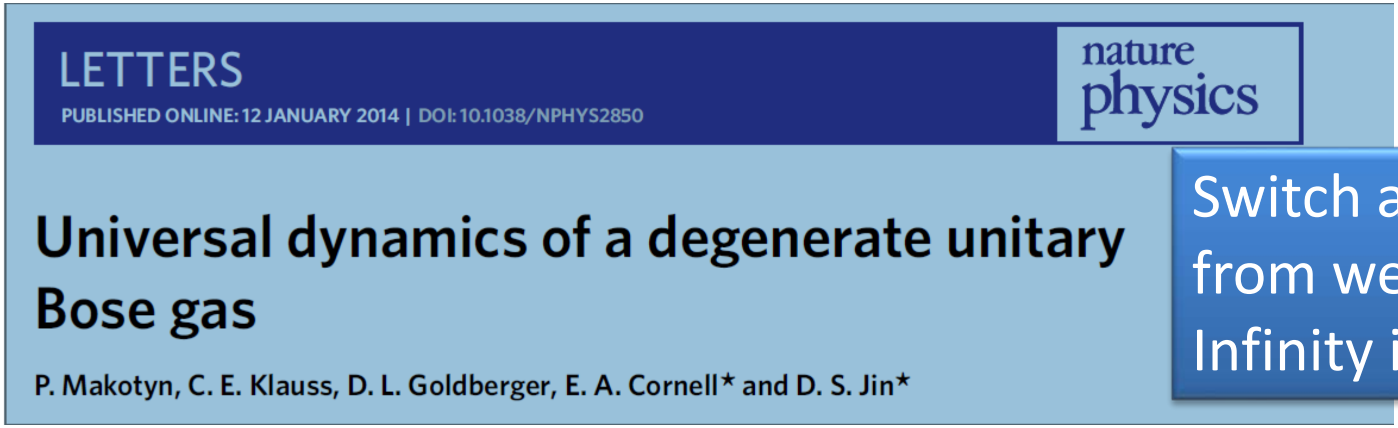


Valley physics!

[4] Atomic BECs with strong interactions



BECs with strong interactions



LETTERS

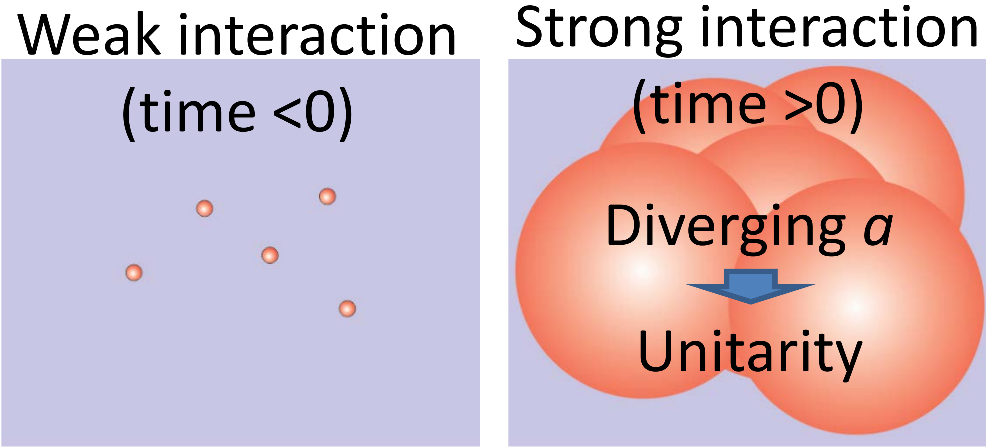
PUBLISHED ONLINE: 12 JANUARY 2014 | DOI: 10.1038/NPHYS2850

nature physics

Universal dynamics of a degenerate unitary Bose gas

P. Makotyn, C. E. Klauss, D. L. Goldberger, E. A. Cornell* and D. S. Jin*

Switch a BEC very fast from weak to Infinity interaction

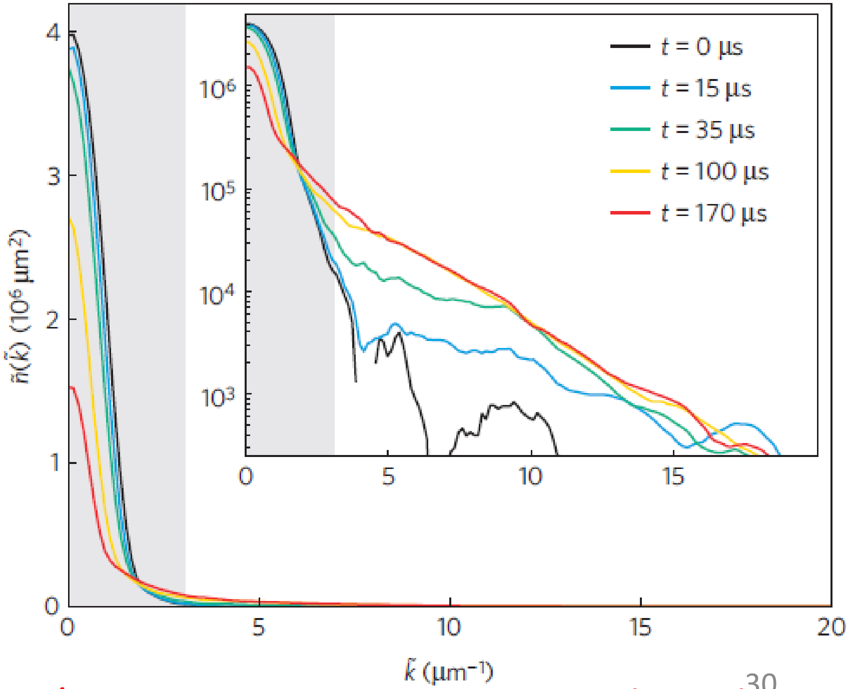


Weak interaction (time <0)

Strong interaction (time >0)

Diverging *a*

Unitarity

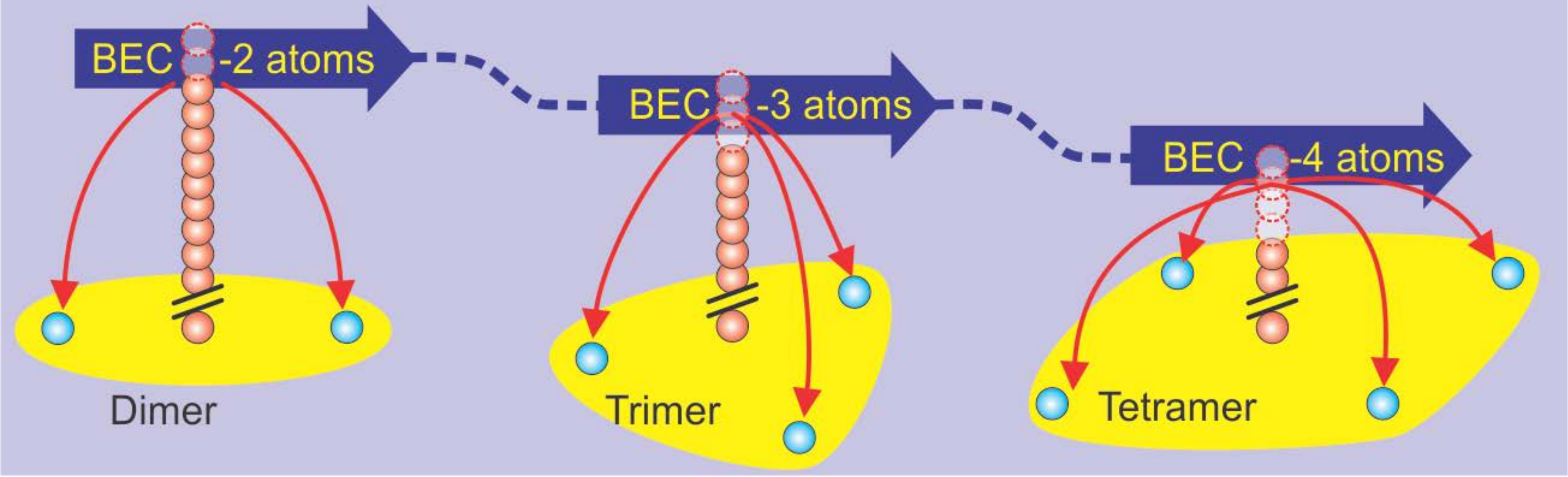


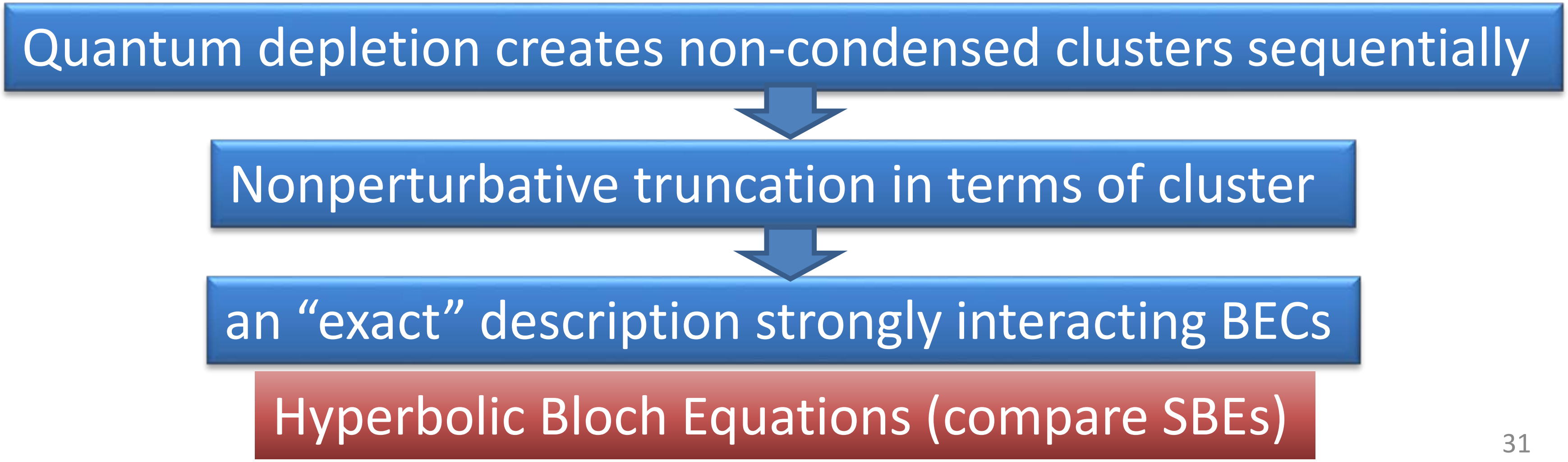
Need for a new theory!!!
Cluster-expansion based?

Cornell/Jin group, Nat. Phys. **10**, 116 (2014)

Cluster dynamics in excitation picture

58-pages of fun: Ann. Phys. **356**, 185 (2015)





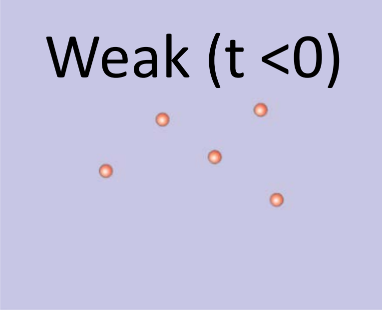
Quantum depletion creates non-condensed clusters sequentially

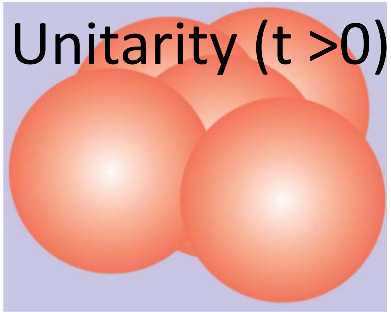
Nonperturbative truncation in terms of cluster

an “exact” description strongly interacting BECs

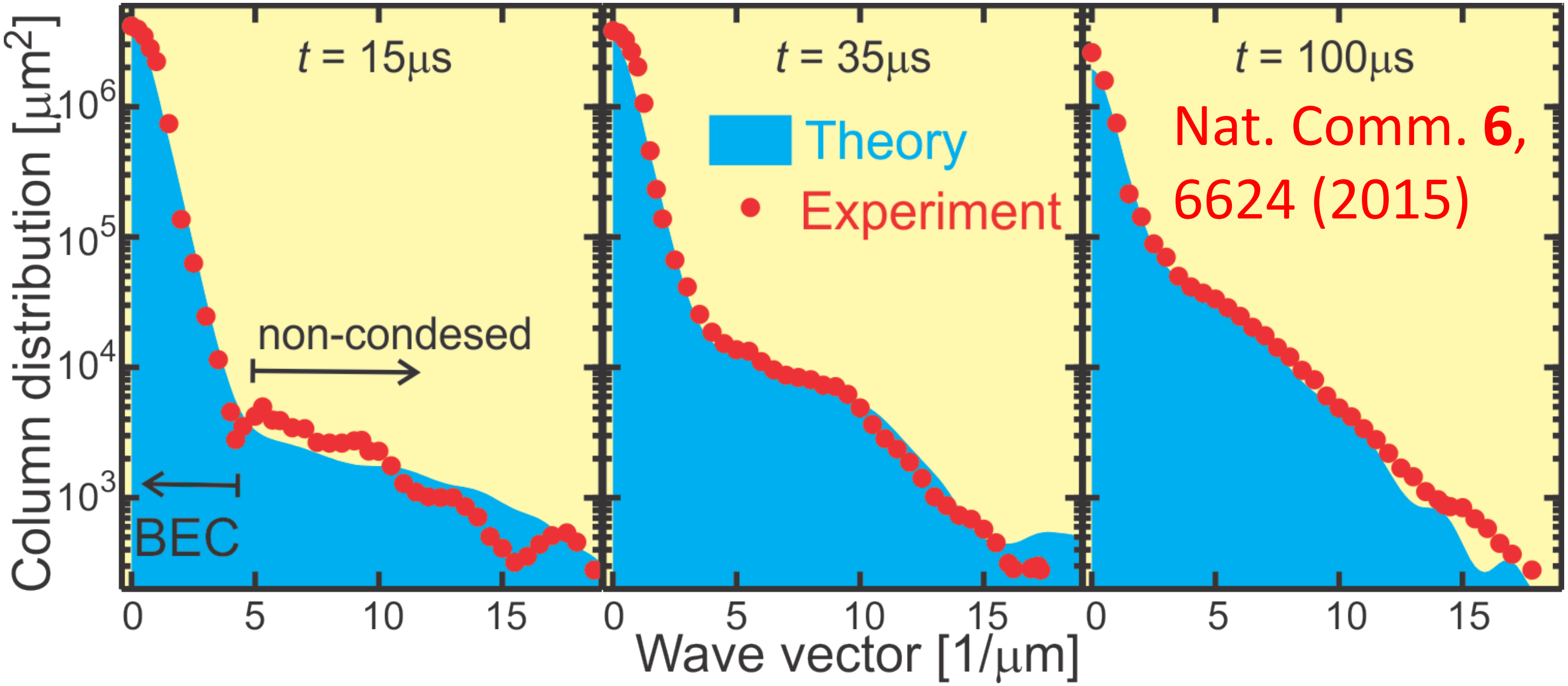
Hyperbolic Bloch Equations (compare SBEs)

HBEs get quantitative





Makotyn *et al. Experiment*
[Nat. Phys. **10**, 116 (2014)]
vs. HBE (column) distributions
in same absolute units!!!



Nat. Comm. **6**, 6624 (2015)

Switch to unitarity explained quantitatively by doublet HBEs

Doublets dominate until >100μs

Clustronics so far…

Theory insights:

- 1^{st} principles cluster kinetics from a known H.
- Interactions create clusters sequentially.
- Natural & exact description of quantum processes.
- Quantitative predictions for dynamic experiments/applications.

Use quantum spectroscopy, HHG, HSB, collider, BEC interactions:

➡ macroscopic quantum processes
(dropletons, multi BECs, Cooper pairs…)

➡ semiconductor-organic interface, organics, TMDCs…

➡ PHz electronics, UV/as sources, quantum information….

Clustronics team (since Sept. 2016)

Markus Borsch, excitonics
Ben Girodias, quantum & multi-D spectroscopy
Peter Hawkins, HHG, HSB
Weiwei Jiang, carbon nanotubes
Haiyi Liu, HHG, HSB
Claire Lu, many-body detection
Rachel Wooten, atomic BECs
Rodrigo Muniz, clustronics