COLLÈGE DE FRANCE 1530

Table Ronde SFP@150

`Les Grandes Questions Ouvertes et Enjeux Fondamentaux de la Physique'

Antoine Georges
Juillet 2023

Quantum Matter: Keys to Success

Experiments
Pushing the limits
New Instrumentation
New Techniques

Theory
Simple concepts
and basic mechanisms
Quantitative methods

The magic
Square

Devices and Control
Nanoscale devices
e.g gating
Atomic-scale synthesis
e.g. oxide MBE
`Synthetic materials'
e.g. TBLG/Twisted TMOs
Control by light:
Laser control, Cavities,…

Materials Science and Chemistry
New materials, bulk or `artificial'
High quality samples
New elaboration methods

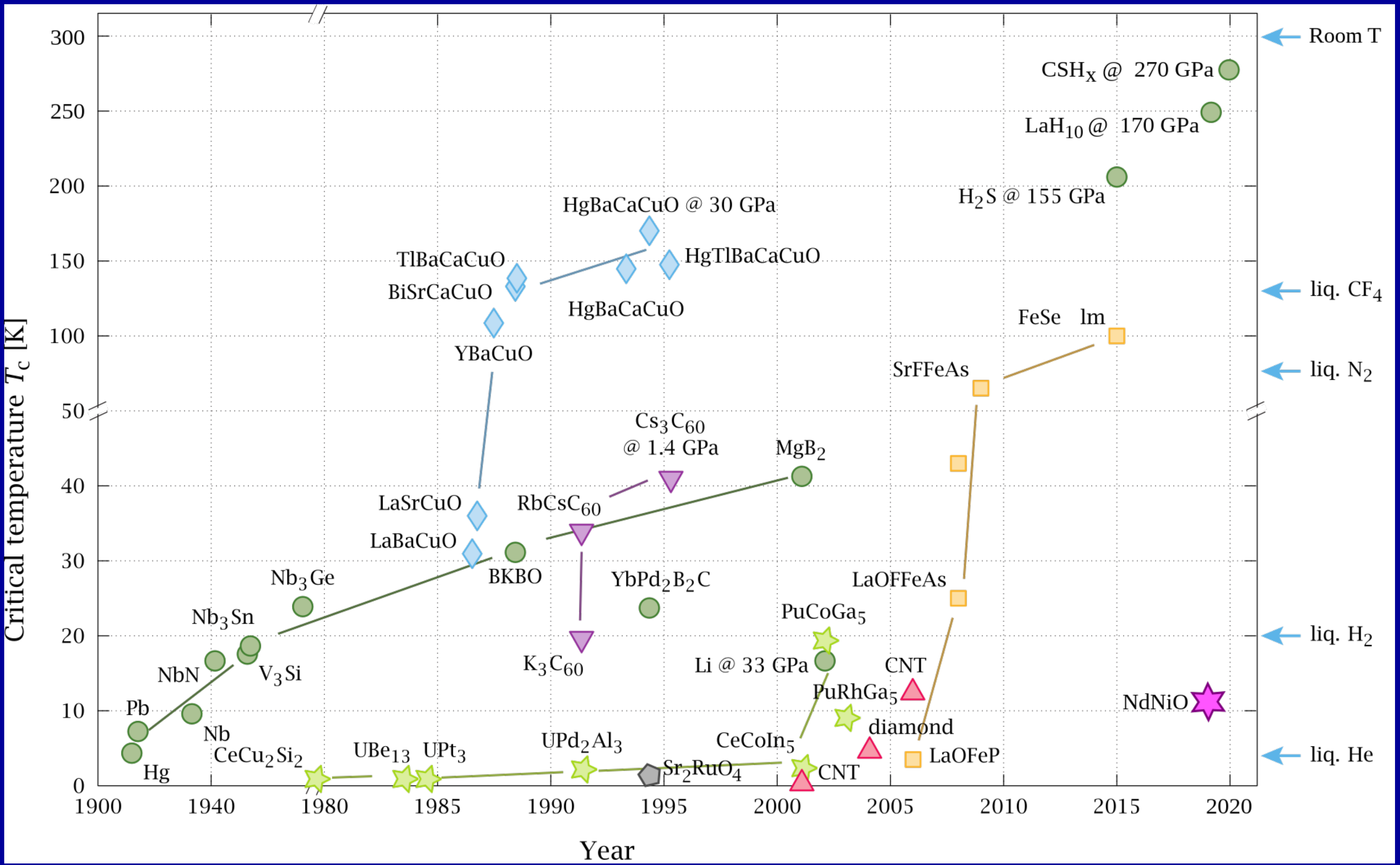
Materials Discovery

(A never-ending story that keeps us alive and busy)

1930-1950	• Classic correlated materials: TMs, Oxides/TMOs
	• Organic conductors (1D, 2D)
1980's	• Heavy fermions
1986	• Cuprates
	• Renewal of interest in TMOs: Sr_2RuO_4, $RNiO_3$, Manganites, Iridates, and many many others…
2002	• Mott to superfluid transition of cold atomic gases in optical lattices
2005	• Topological Insulators
2007	• Oxide heterostructures, SC in LAO/STO
2008	• Fe-based superconductors
	→ `Hund metals' (<u>New route to strong correlations</u>)
2015	SC in pressurized H_2S 155GPa → other hydrides
2018	• SC in twisted bilayer graphene
	• Twisted TMDCs
	• → <u>Interplay of correlations and topology/Flat bands</u>
	• → <u>Strong coupling to light, excitonic physics</u>
2019	• SC in infinite-layer $RNiO_2$
	• Low density metals (STO), kagome metals

AND SO ON…

Timeline of Superconductor Discoveries (Wikipedia)



Novel Materials

- `Semi-synthetic’
- Devices

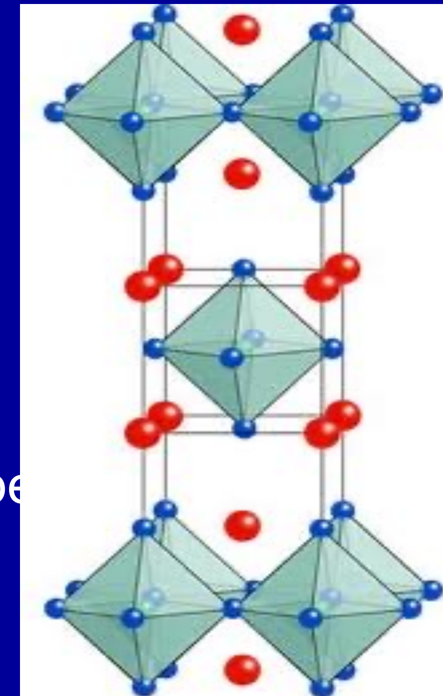
Novel forms of Quantum Matter:

- Cold atoms in optical lattices
- Arrays of trapped Rydberg atoms

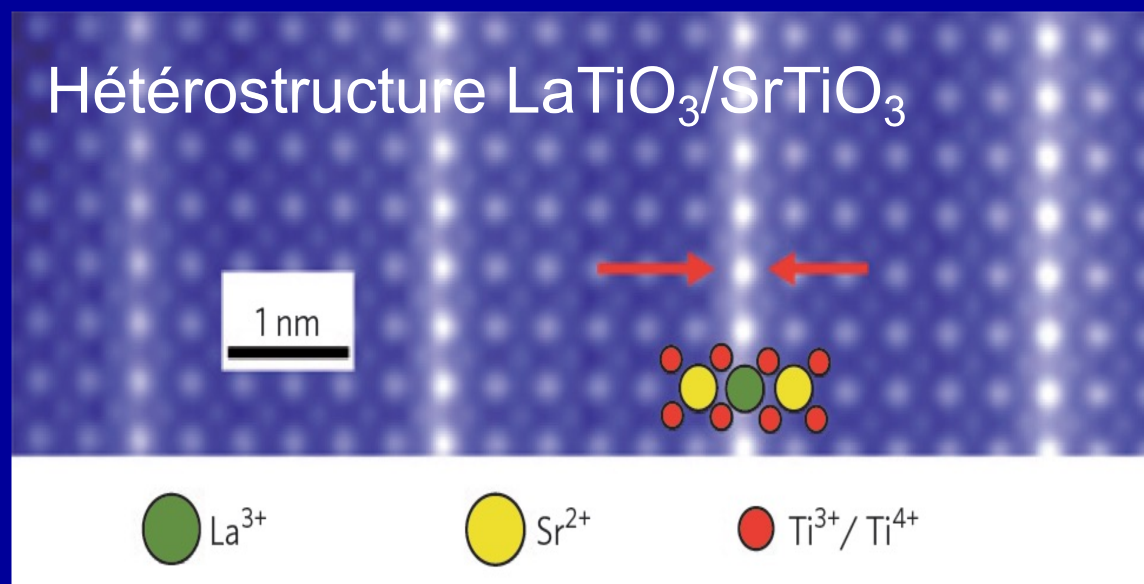
OXIDES: Old and New

Rust: oxyde/hydroxide. (wikipe

$La_{2-x}Sr_xCuO_4$



« Artificial materials »
MBE allows for synthesis one atomic layer at a time



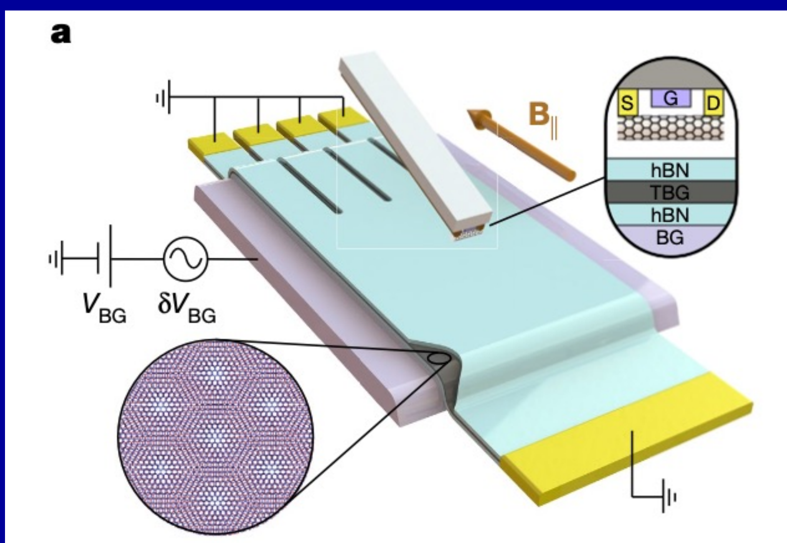
Example: Measurement of Electronic Compressibility

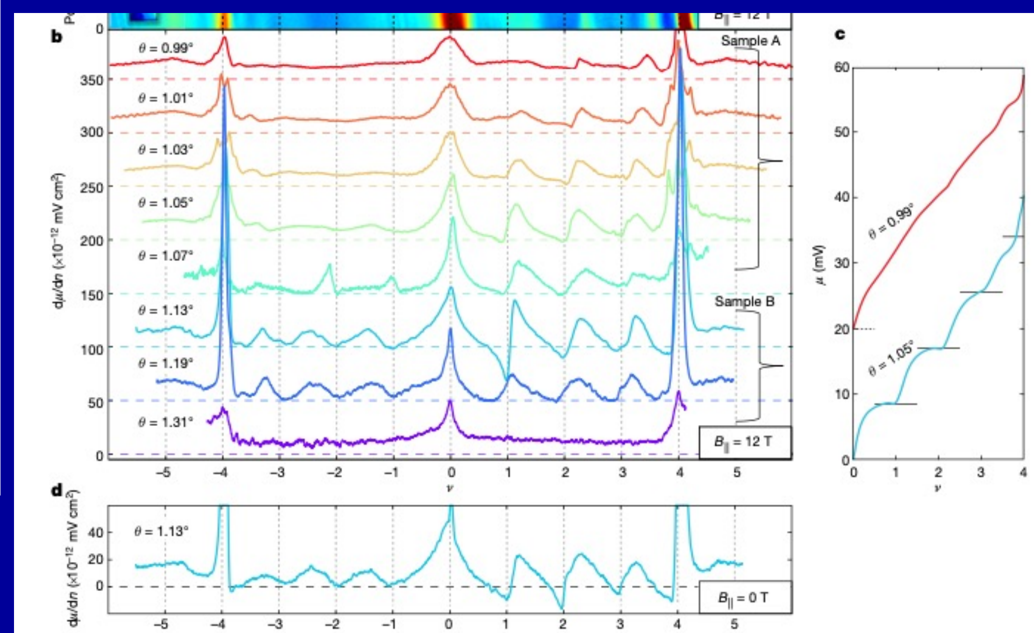
Article

Cascade of phase transitions and Dirac revivals in magic-angle graphene

https://doi.org/10.1038/s41586-020-2373-y
Received: 25 November 2019

U. Zondiner[1,5], A. Rozen[1,5], D. Rodan-Legrain[2,5], Y. Cao[2], R. Queiroz[1], T. Taniguchi[3], K. Watanabe[3], Y. Oreg[1], F. von Oppen[4], Ady Stern[1], E. Berg[1], P. Jarillo-Herrero[2] & S. Ilani[1]





`Twistronics'

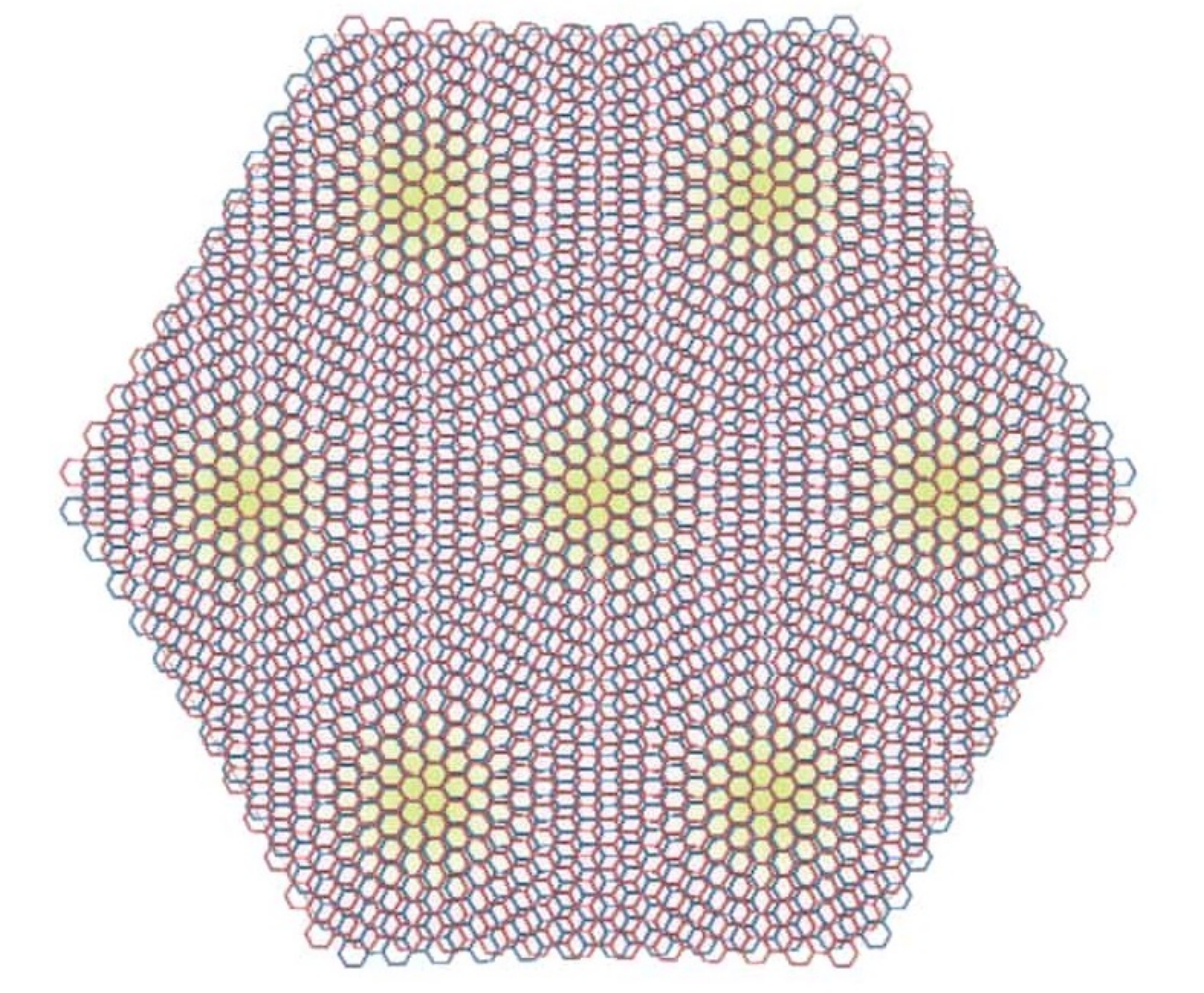


Image courtesy Pablo Jarillo-Herrero

nature physics

REVIEW ARTICLE

https://doi.org/10.1038/s41567-020-01154-3

Check for updates

Moiré heterostructures as a condensed-matter quantum simulator

Dante M. Kennes[1,2,12] ✉, Martin Claassen[3,4,12], Lede Xian[2,5,12], Antoine Georges[3,6,7,8], Andrew J. Millis[3,9], James Hone[10], Cory R. Dean[9], D. N. Basov[9], Abhay N. Pasupathy[9] ✉ and Angel Rubio[2,3,11] ✉

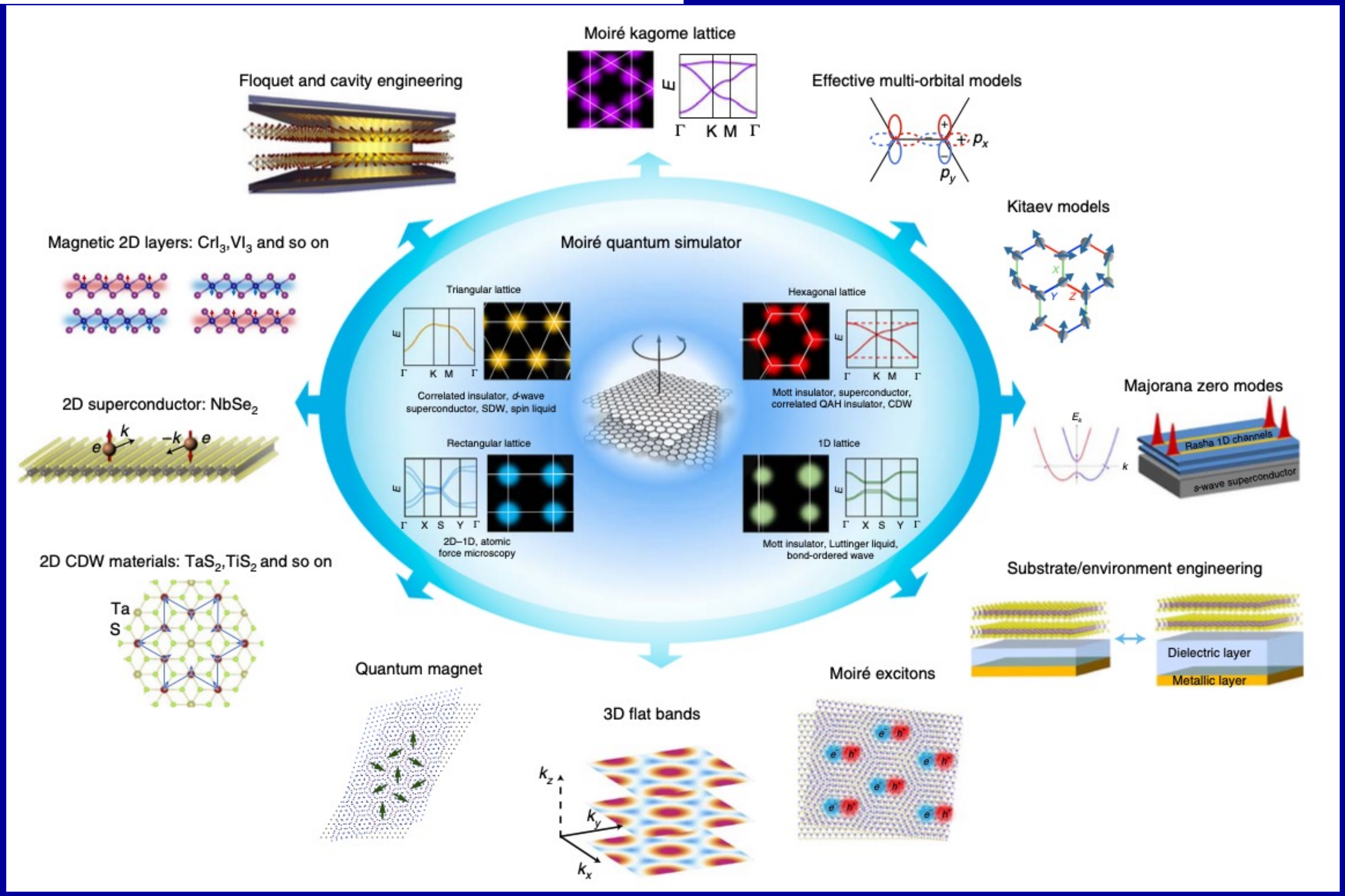
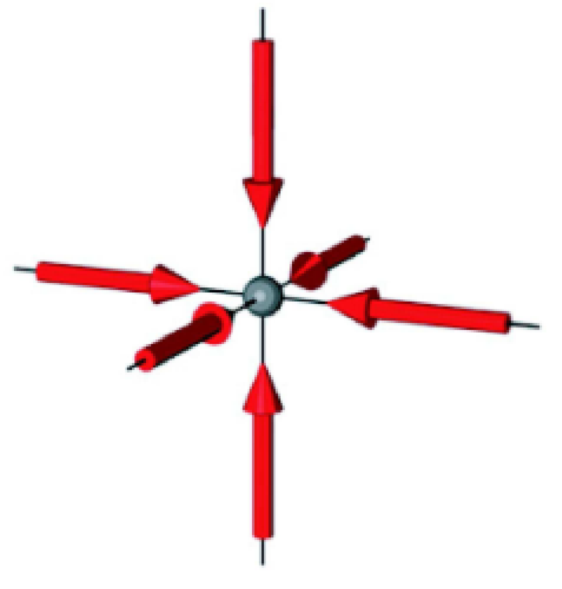


Table 1 | Overview of possible quantum Hamiltonians, materials realizations and phases in twisted moiré heterostructures

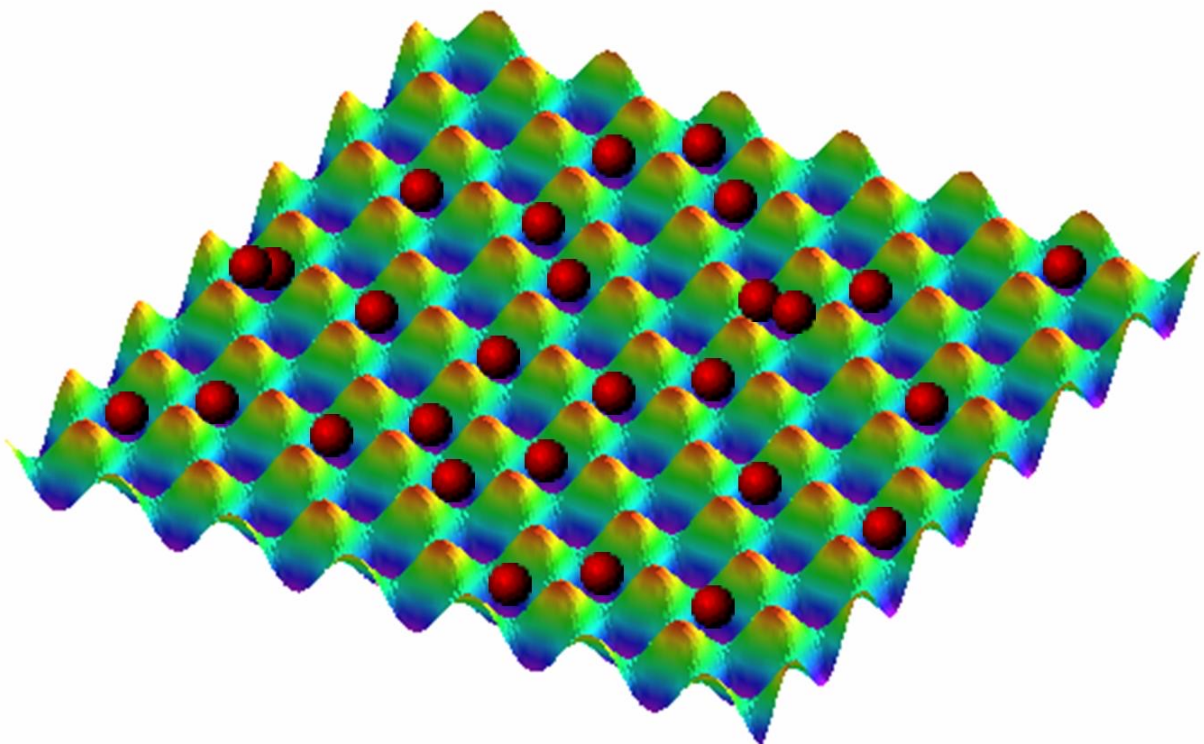
Lattice	Model	Possible materials realizations	Correlated phases
Twisted heterostructures of weakly correlated van der Waals monolayers			
Honeycomb	Two-orbital extended Hubbard model[18]; fragile topological insulator[107]	TBG (BN substrate, with/without twist)	Mott insulation[8]; superconductivity[7]; correlated QAH insulator[22,23]
	Two-orbital extended Hubbard model	Twisted double bilayer graphene	Ferromagnetic insulator superconductivity[12,13]; triplet pairing[108]
	Asymmetric p_x–p_y Hubbard model[29,30]	Twisted bilayer MoS_2, $MoSe_2$	Nematic (anti)ferromagnets[29]
	Domain wall networks	Small-angle TBG with domain reconstruction[57,58,66,109]	
Triangular	Hubbard model (with/without strong SOC)	Twisted bilayer WS_2, WSe_2 (ref. [34]); twisted WS_2/WSe_2 heterostructures[35,36]; twisted double bilayers of WSe_2 (ref. [110])	Correlated insulator[34]; superconductivity?; Wigner crystals[35]
	Doped multi-orbital Hubbard models	Twisted heterostructures of MoS_2, WS_2, WSe_2	Moiré excitons[100,101,111]
	Multi-orbital Kanamori models	Twisted bilayer BN	SDW; *d*-wave superconductivity[32]
Rectangular	1D ionic Hubbard model 1D–2D crossover	Twisted bilayer GeSe	Luttinger liquid; Mott insulator; bond density waves[43]
	Inverted band insulator, strong SOC	Twisted bilayer WTe_2	Quantum spin Hall insulator, fractional Chern/topological insulator
Any	Hofstaedter models	TBG or TMDs in strong magnetic fields	Fractional Chern insulator[112]
Kagome	Kagome Heisenberg model	TBD	Z_2 QSL; U(1) QSL; quantum chiral spin liquid; valence bond crystal
Decorated kagome	Hubbard model (putative)	Twisted bilayer MoS_2, $MoSe_2$	TBD
3D	Flat-band Hubbard–Kanamori models	Twisted multilayer 'staircase'	TBD
Proximity effects			
Honeycomb, triangular	Proximity-induced Rashba SOC	TBG on WS_2, WSe_2 substrate[113]	Correlated QSH insulator
Rectangular	Proximity-induced superconductivity	Superconductor, twisted bilayer GeSe, TMD 'sandwich' heterostructure	1D Kitaev superconductor; Majorana bound states
Twisted heterostructures of correlated monolayers			
	Moiré ferromagnet[70]	Twisted odd-multilayer CrI_3	Moiré domain wall; ferromagnets
	Moiré Kitaev model	Twisted multilayer α-$RuCl_3$	Kitaev QSL; stripe order; Majorana fermions
	TBD	Twisted bilayer $TaSe_2$	TBD
	TBD	Twisted bilayer $NbSe_2$	TBD

TBD, to be discovered; QSL, quantum spin liquid; SOC, spin–orbit coupling.

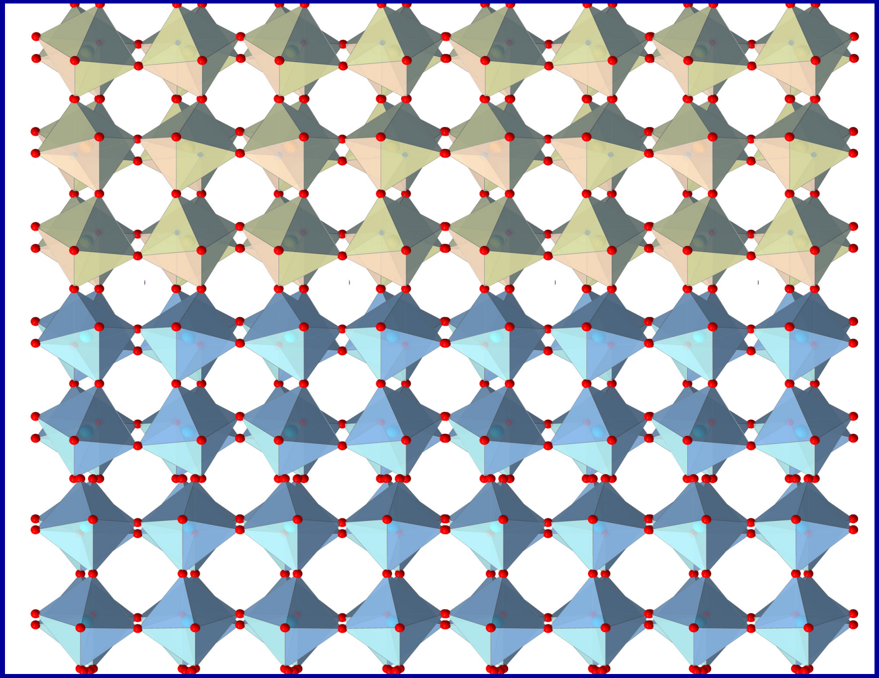
Crystals of Light and Atoms: cold atomic gases in optical lattices



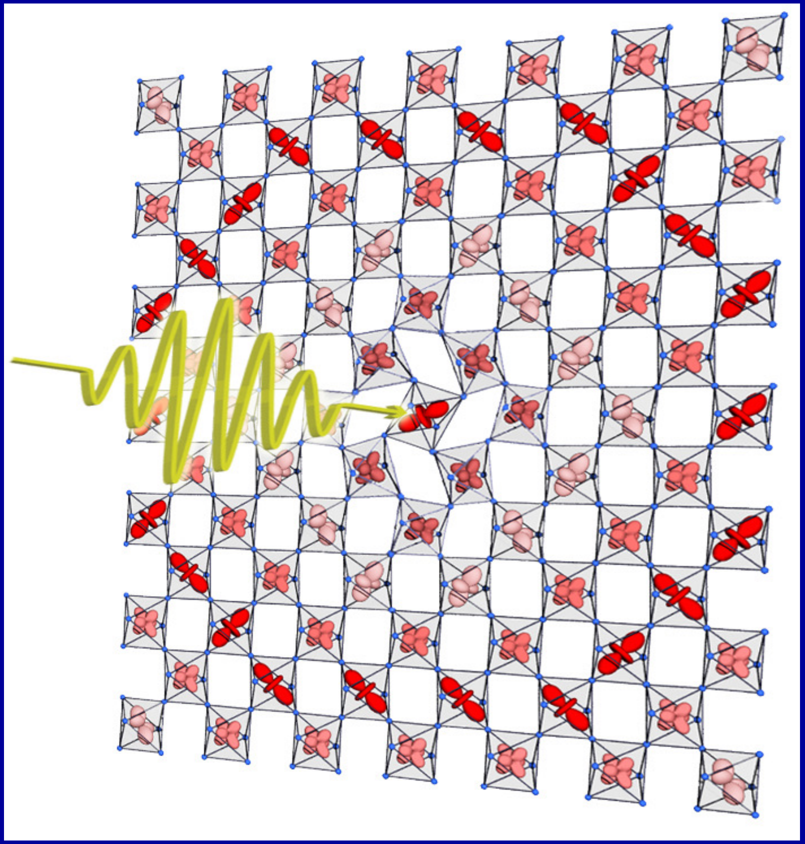
At the frontier
of condensed matter physics
and quantum optics…



Two novel routes to Control



Selective control with LIGHT



Artificial Materials:
Strained films and
Heterostructures
“Oxytronics/Mottronics”

CONTROL: Traditional and Novel routes

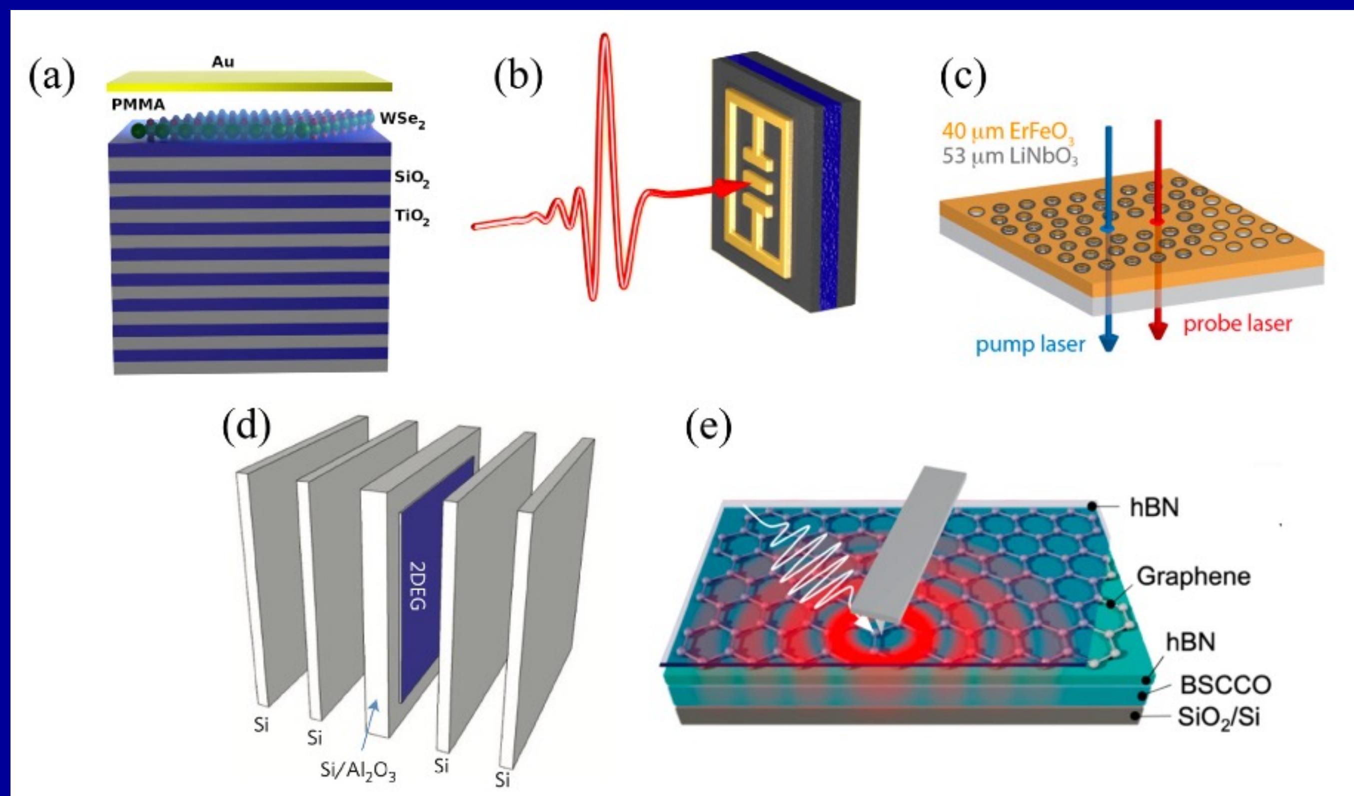
Bandwidth	Pressure Size of rare-earth Distortion Tolerance factor 3d,4d,5d metal	Strained thin films and heterostructures Light/non-linear phononics
Crystal field, Orbital degeneracy	Size of rare-earth Distortion Tolerance factor	- Same -
Filling of shell	Chemistry	Ionic liquids Gating
Doping	$Sr,Ca^{2+} \rightarrow La, R^{3+}$	
Interaction strength	3d,4d,5d metal	Tunable dielectric gating ? Light ?
Charge-Transfer	Change apical oxygen distance Change ligand: $O \rightarrow S, Se\ldots$	Light ?

Applied Physics Reviews

Cavity quantum materials

Cite as: Appl. Phys. Rev. **9**, 011312 (2022); doi: 10.1063/5.0083825
Submitted: 30 December 2021 · Accepted: 31 January 2022 ·
Published Online: 25 February 2022

F. Schlawin,[1,2] D. M. Kennes,[1,3] and M. A. Sentef[1,a)]



What About Theory?

- Up to the late 1980's our understanding of strong correlations was quite poor…
- Huge progress in 30 year!
- The raise of computational methods: theorists now have a right and a left hand (analytical/numerical)!
- Currently: very exciting times/recent developments in computational methods
- Merging of quantum many-body methods with realistic electronic structure → theory can be realistic (at last!)

Paul Dirac, 1929
``Quantum Mechanics of Many-Electron Systems’ ’

``The general theory of quantum mechanics is now almost complete (…). The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble."

P. A. M. Dirac, "Quantum Mechanics of Many-Electron Systems“,
Proceedings of the Royal Society of London, Series A, Vol.123,
April 1929, pp 714.

Quantum Mechanics of 10^{21} interacting particles !

$$H = -\frac{\hbar^2}{2m}\sum_i \nabla_i^2 + \sum_i v_{ion}(\vec{r}_i) +$$

$$+\frac{1}{2}\sum_{i,j}\frac{e^2}{4\pi\varepsilon_0|r_i - r_j|}$$

$$H\Psi(r_1, \cdots, r_N) = E\Psi(r_1, \cdots, r_N)$$

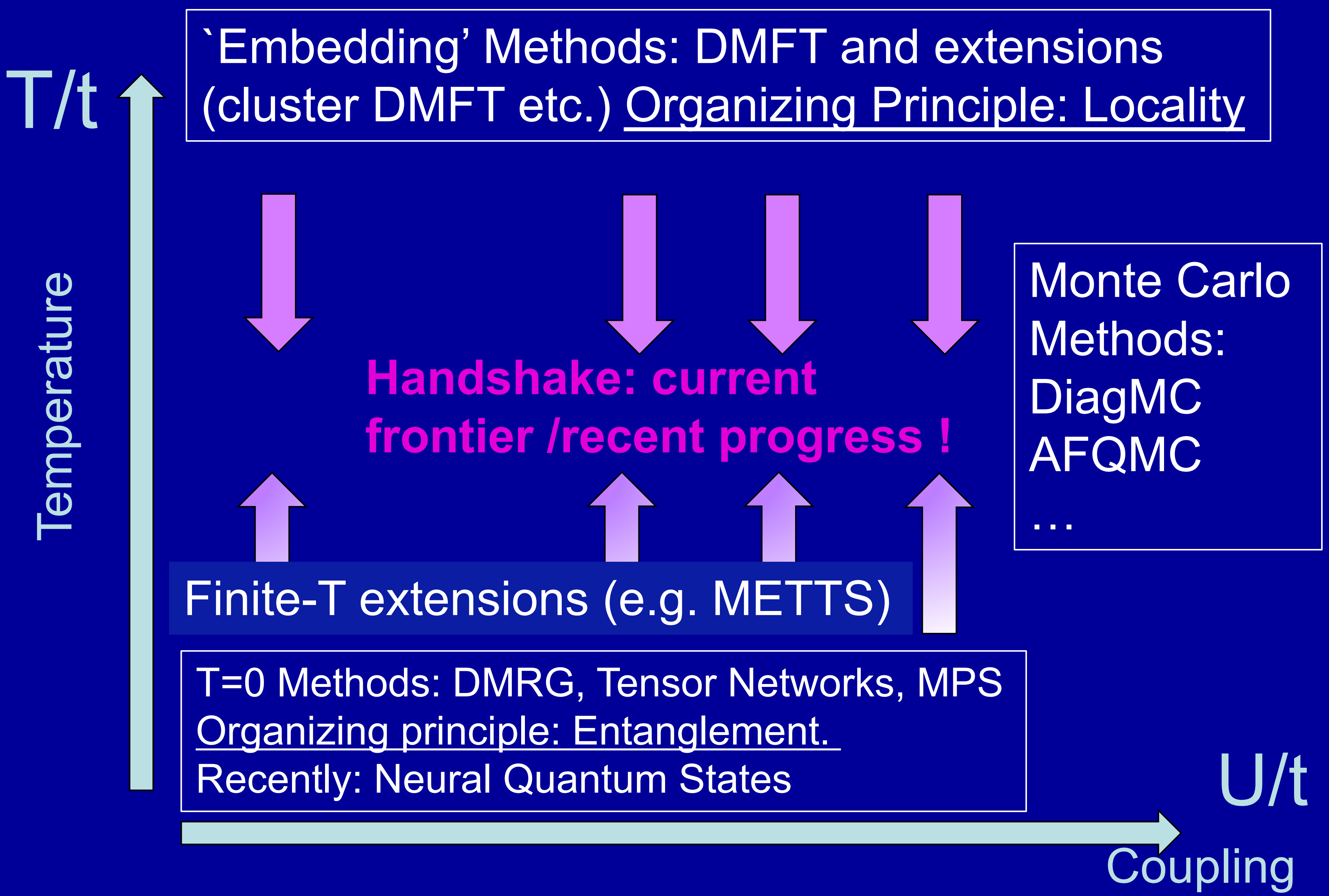
Eigenstates (wave-functions)
and Eigenvalues (Energy spectrum)

`Dirac's program' (same 1929 article):

`` It therefore becomes desirable that approximate practical methods of applying quantum mechanics should be developed, which can lead to an explanation of the main features of complex atomic systems without too much computation.''

Dirac's program is not yet fully implemented
but great progress is being made
→ we can hope that this will be
a major success of the 21st century!
[Note that ``*without too much computation*'' has an entirely different meaning now than in the 1930's ☺]

Computational Methods: Handshake!



Looking Immediately Ahead:

- Flat band physics
- Interplay of topology and correlations?
- Twisted layered oxides
- Light/Cavity control
- Finalize understanding of `simple’ models
- Pushing the combination of electronic structure + many body methods to the next step: predictive/design
- Can we reach predictive ability for e..g superconductivity in strongly correlated materials

Two Big Challenges for the 21st Century

- The Dirac program: computational solution of the `quantum many body problem'
- Materials by Design (Solid-State and Molecules)