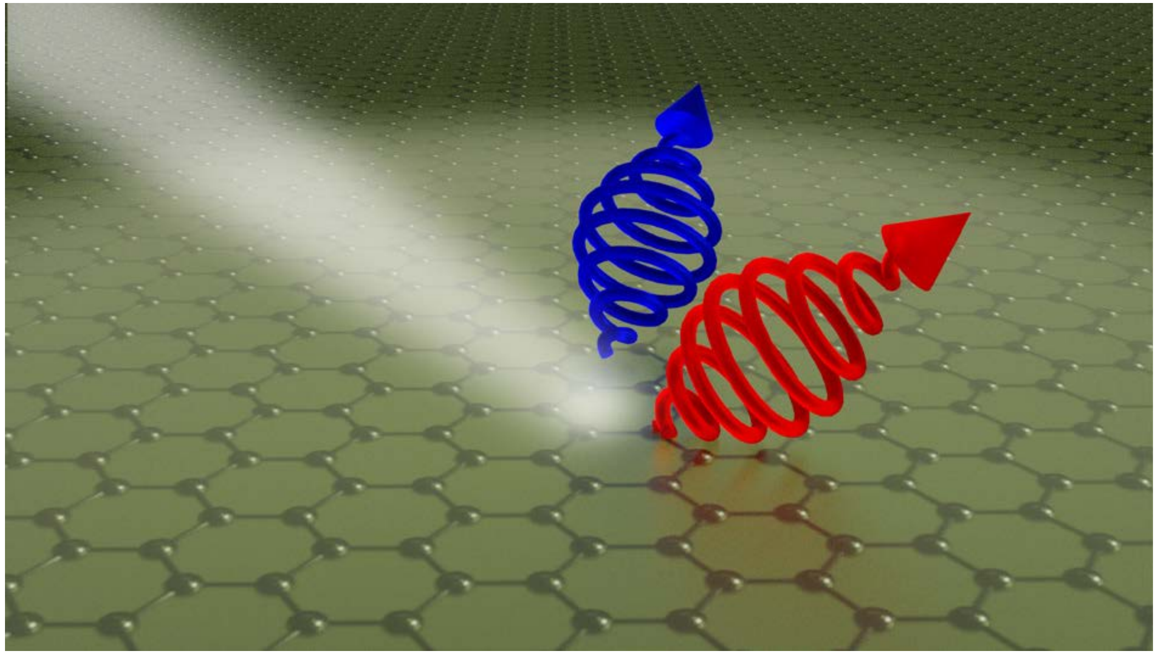
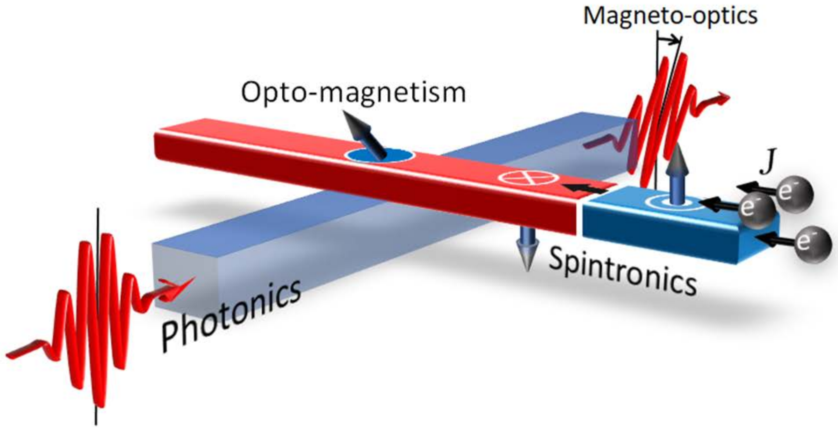
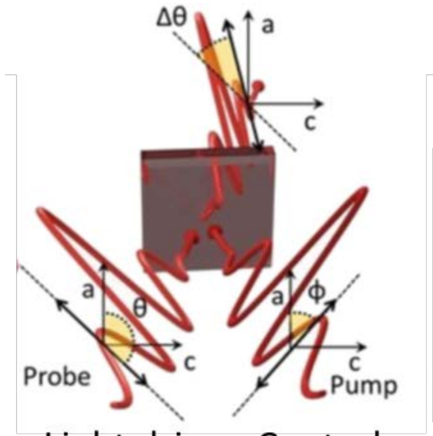
QuMat; Pillar 4



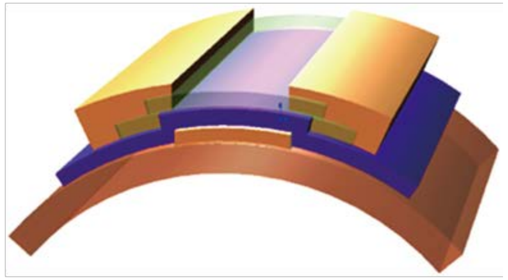
Topological light-matter interfaces

Pillar leaders: Kobus Kuipers (TUD) & Caspar van der Wal (RUG)





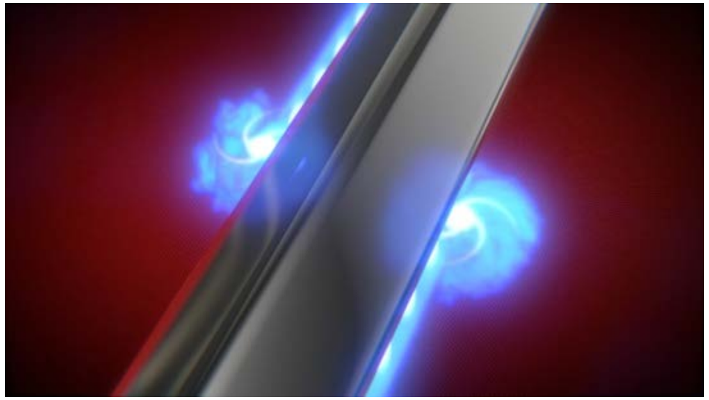
Light driven Control



Strain driven Control

Aim:

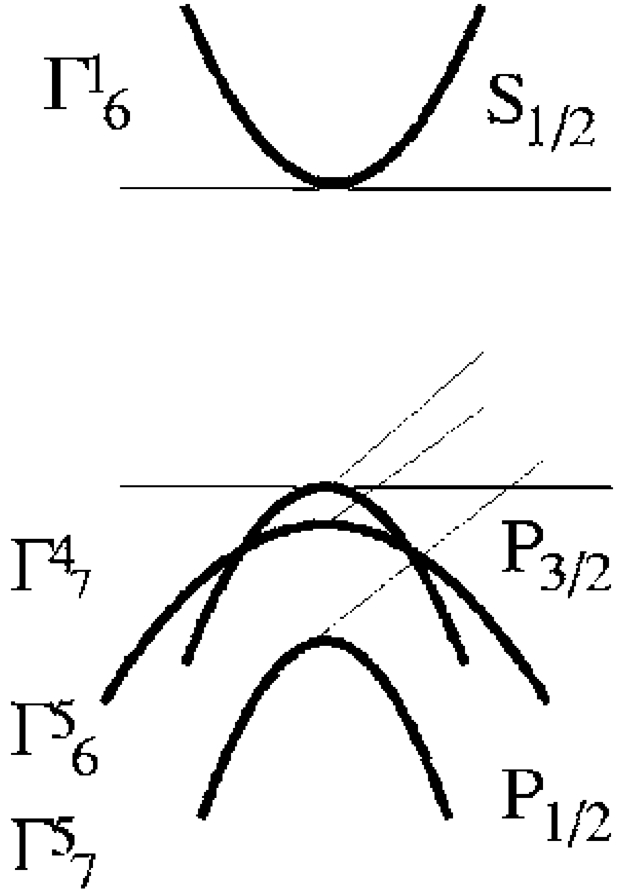
- Create efficient interfaces between topological quantum states & photons while retaining quantum information
- Investigate hybridization between topological quantum states & light

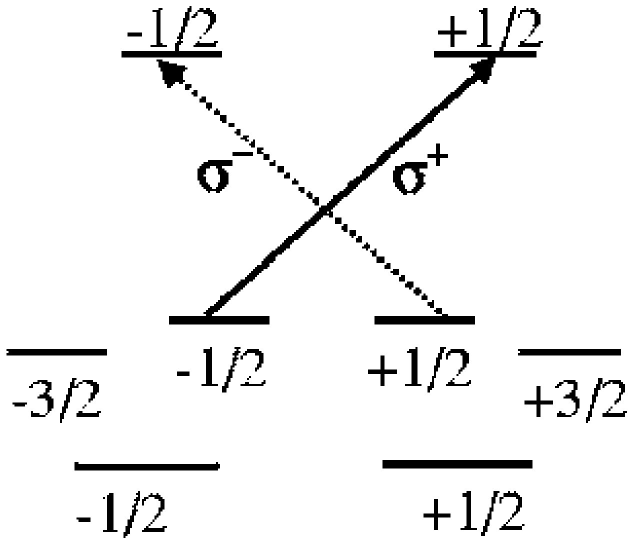


Concepts from conventional states of atoms, semiconductors

Light-matter quantum-state transfer

Famous examples: GaAs, Cs atoms

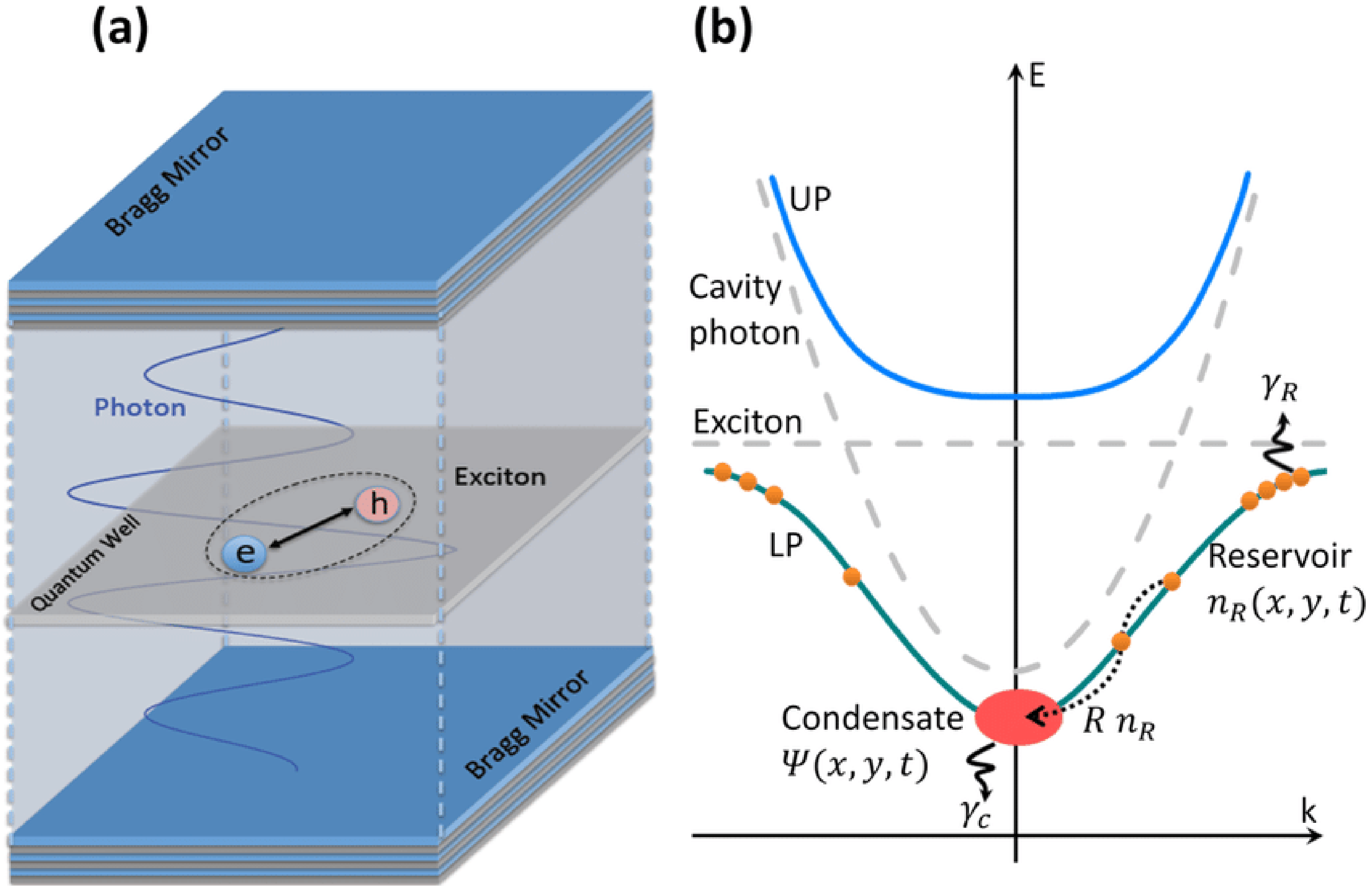




Concepts from conventional states of atoms, semiconductors

Light-matter hybridization

Famous examples: Polaritons

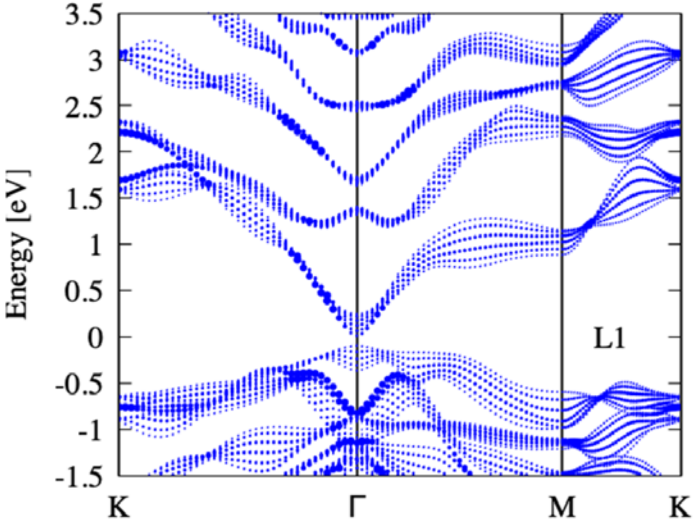


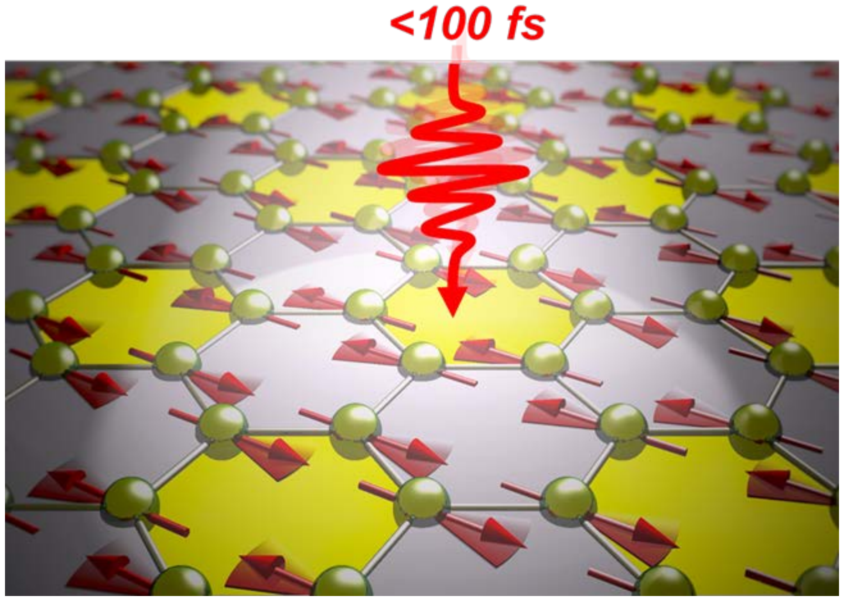
Phys. Rev. **94**, 043310 (2016)

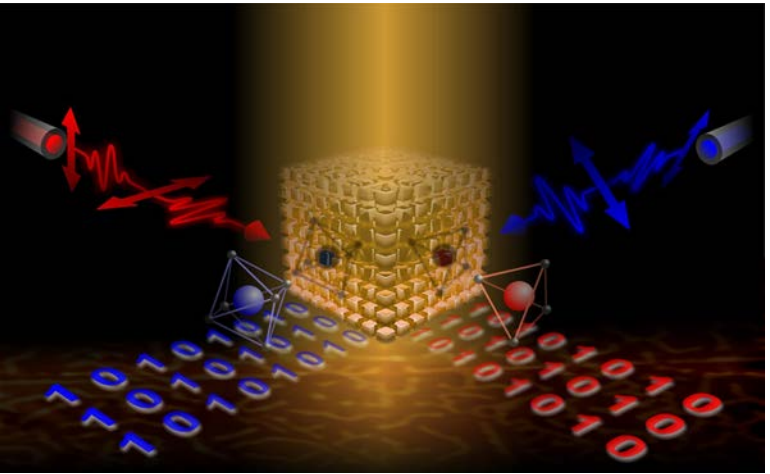
Background:

- Topological quantum states often hardly propagate or have an (ultra)short lifetime
- Light readily propagates
- Converting the quantum information of a topological state to a photon allows it to be transported of large distances
- ***However***: light, in general, interacts weakly with matter; transferring quantum information while retaining coherence is not trivial

→ Quantum information needs to be transferred to topology of light (spin or orbital angular momentum) through proper selection rules and light-matter interaction needs to be maximized







4.1 Topological light-matter interface based on hybrid Bi2Se3 2D heteronanocrystals

3 PhD students; UU, TUD, RUG, TU/e, RU

4.2. Spin-orbit opto-matter

2.5 PhD students; RU, TU/e, TUD, RUG

Mutations with respect to original proposal:

Andrea Caviglia (TUD) left to take up a beautiful position in Switzerland
Maz Ali (TUD) was added to the team
1 PD position moved from Pillar 4 to Pillar 2 (and now new lead: Jagoda Slawinska)

Todays presentations

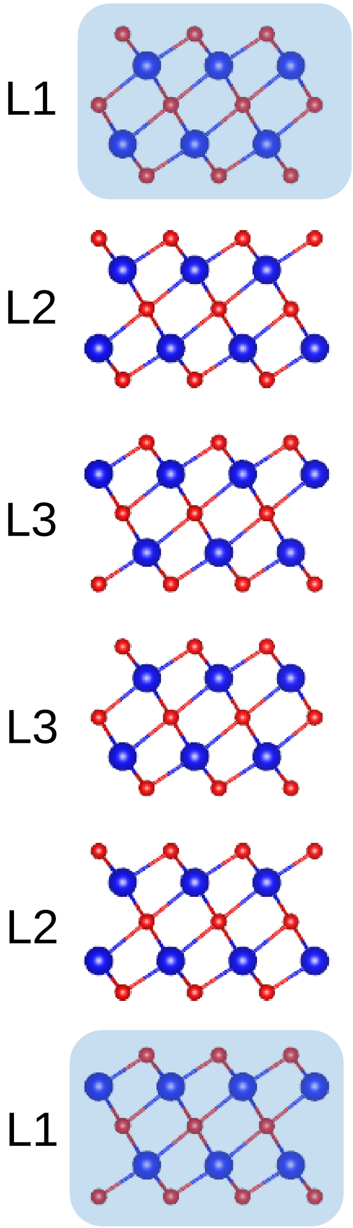
Theory of topological excitons	Pedro Campos de Melo
Optical sensing…protected states	Alexey Kimel
Coherent phono-magnetism	Maz Ali
Writing of magnetic bits	Dima Afanasiev

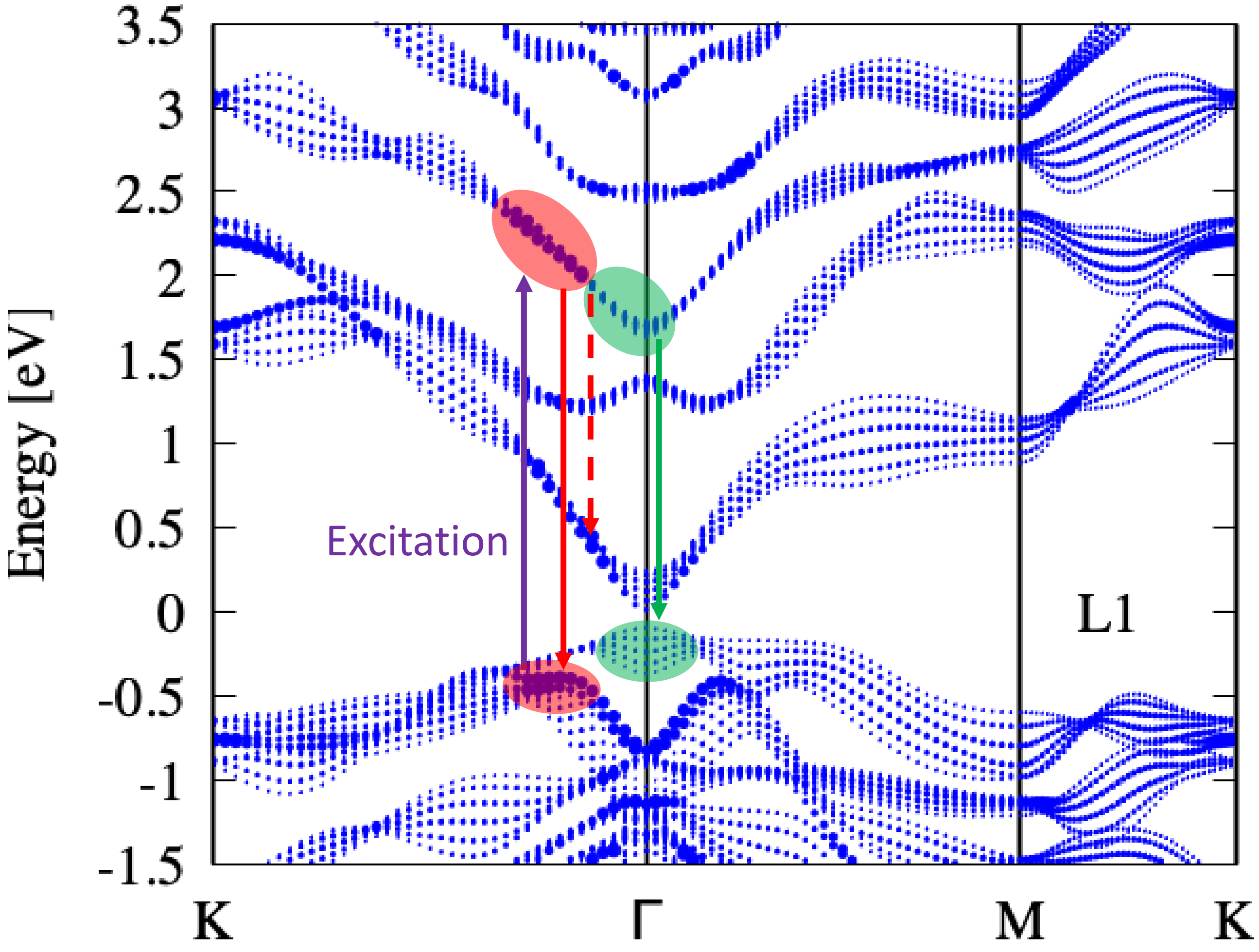
Followed by Q&A

Most PhD students haven't been hired

Bi_2Se_3 – luminescent surface states

Pedro Campos de Melo





Emission energies

Surface to surface-> strongest dipole

Interior to interior

Surface to interior transition must overcome vdW barrier

Most favorable radiative decay channel is between surface states

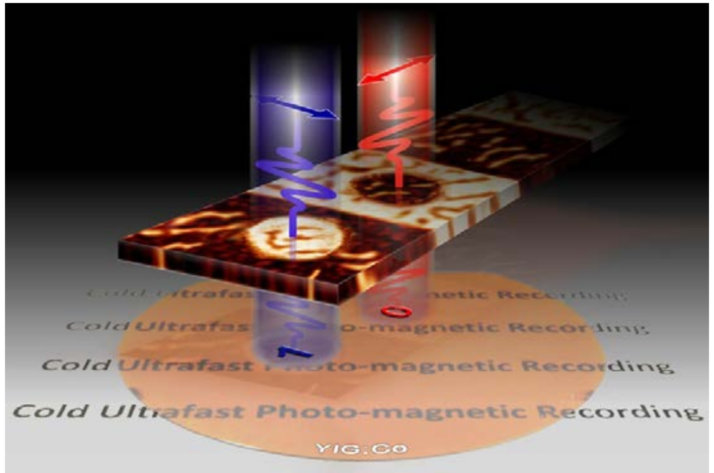
We should see excitons made of electrons/holes in surface states only!

Alexey Kimel

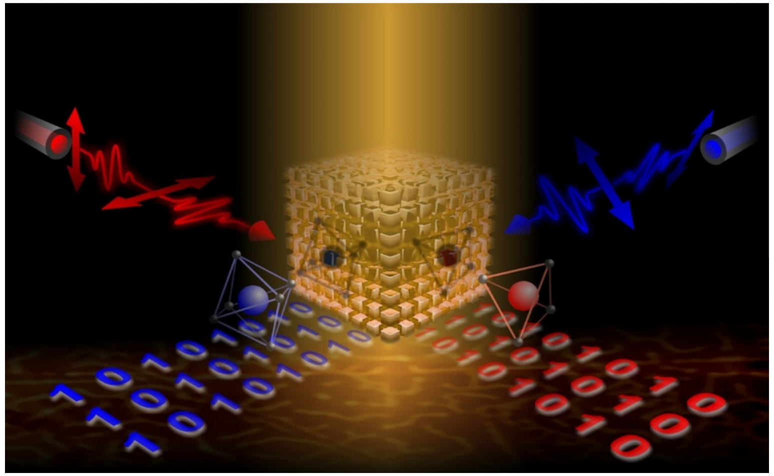
Goal: *Explore the emergence of complex magnetic order and the ways to manipulate the order.*

State of the art:

Ultrafast and least dissipative writing of magnetic bits in bulk magnets



A. Stupakiewicz et al, *Ultrafast nonthermal photo-magnetic recording in a transparent medium*, Nature **542** 7639 (2017).



A. Stupakiewicz et al, Selection rules for all-optical magnetic recording in iron garnet, *Nature Communications* **10**, 612 (2019).

Beyond the state-of-the-art:

Can we realize such a control in 2D magnets?
What are the mechanisms?

Maz Ali

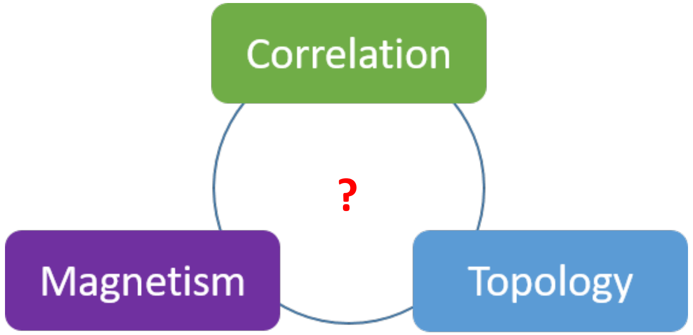
Coherent phono-magnetism: static and dynamical manipulation of magnetism via lattice degrees of freedom

Ali (TUD) & Kimel (RU)

Optics

- Kerr and Faraday Dynamical order effects
- Magnon excitations

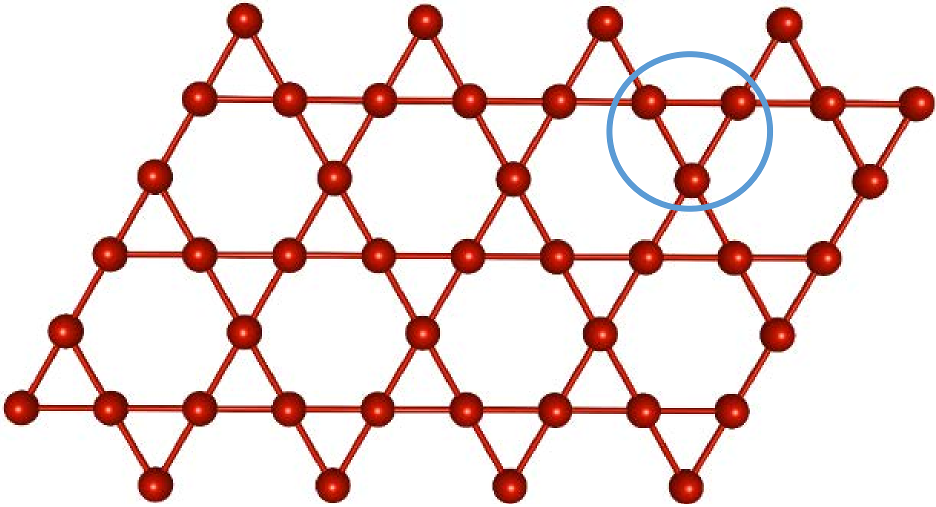
Kagome Quantum Materials

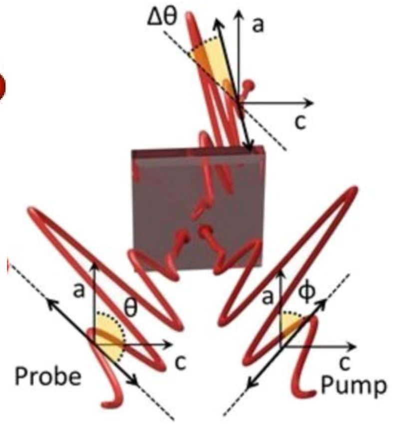


Van der Waals Heterostructures

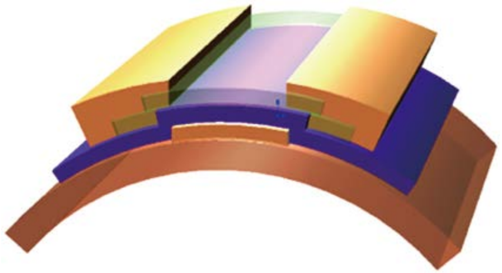
Electron Transport

- Hall Effects
- Magnetoresistance
- Static order effects
- Orbital loop current

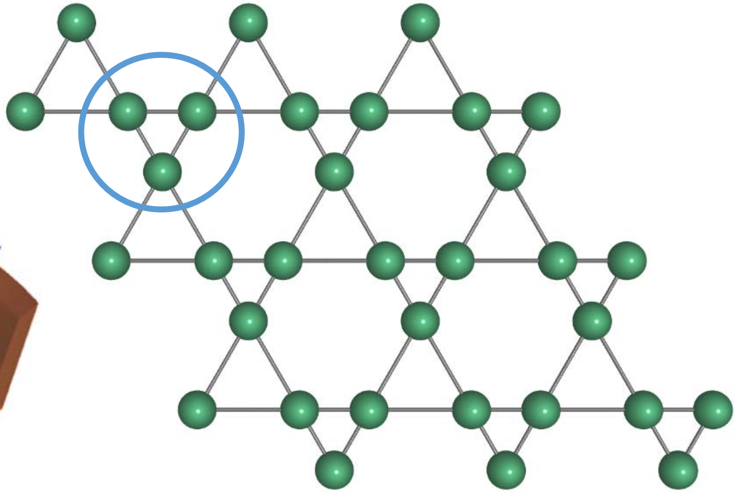




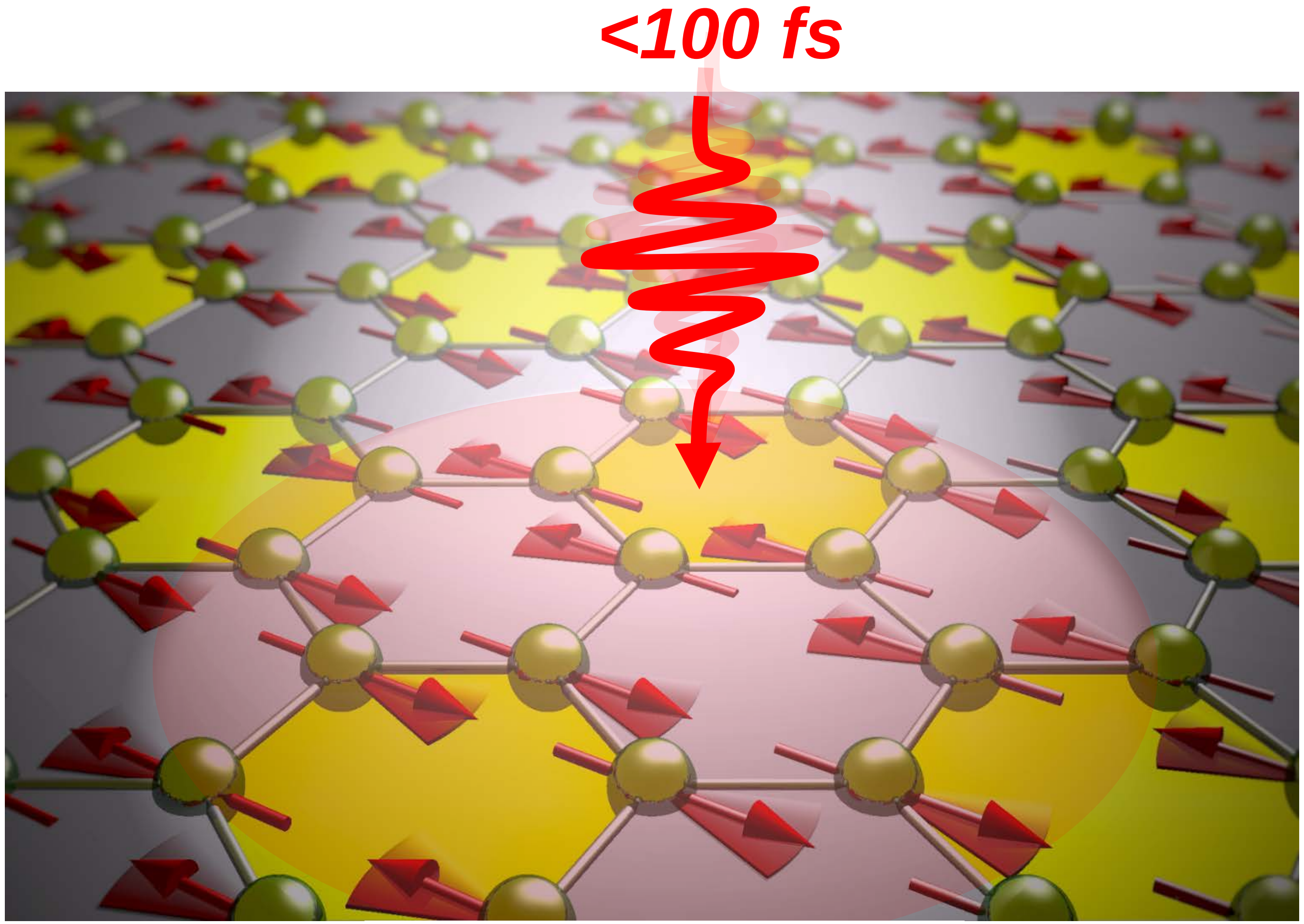
Light driven Control



Strain driven Control



Dima Afanasiev



Light-induced writing of magnetic bits in complex quantum materials

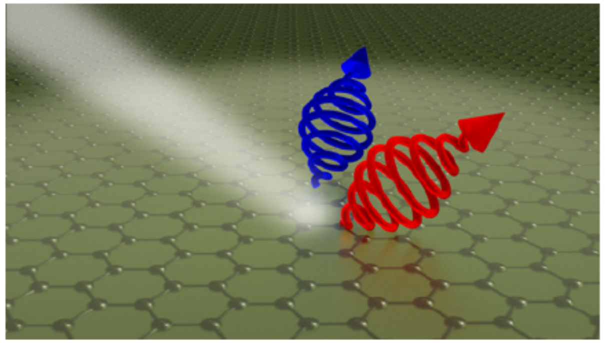
Light

- ***electronic orbitals***
- ***crystal lattice***
- ***spins***

Materials

- ***Van der Waals magnets***
- ***Frustrated magnets***
- ***Atomically thin oxide heterostructures***

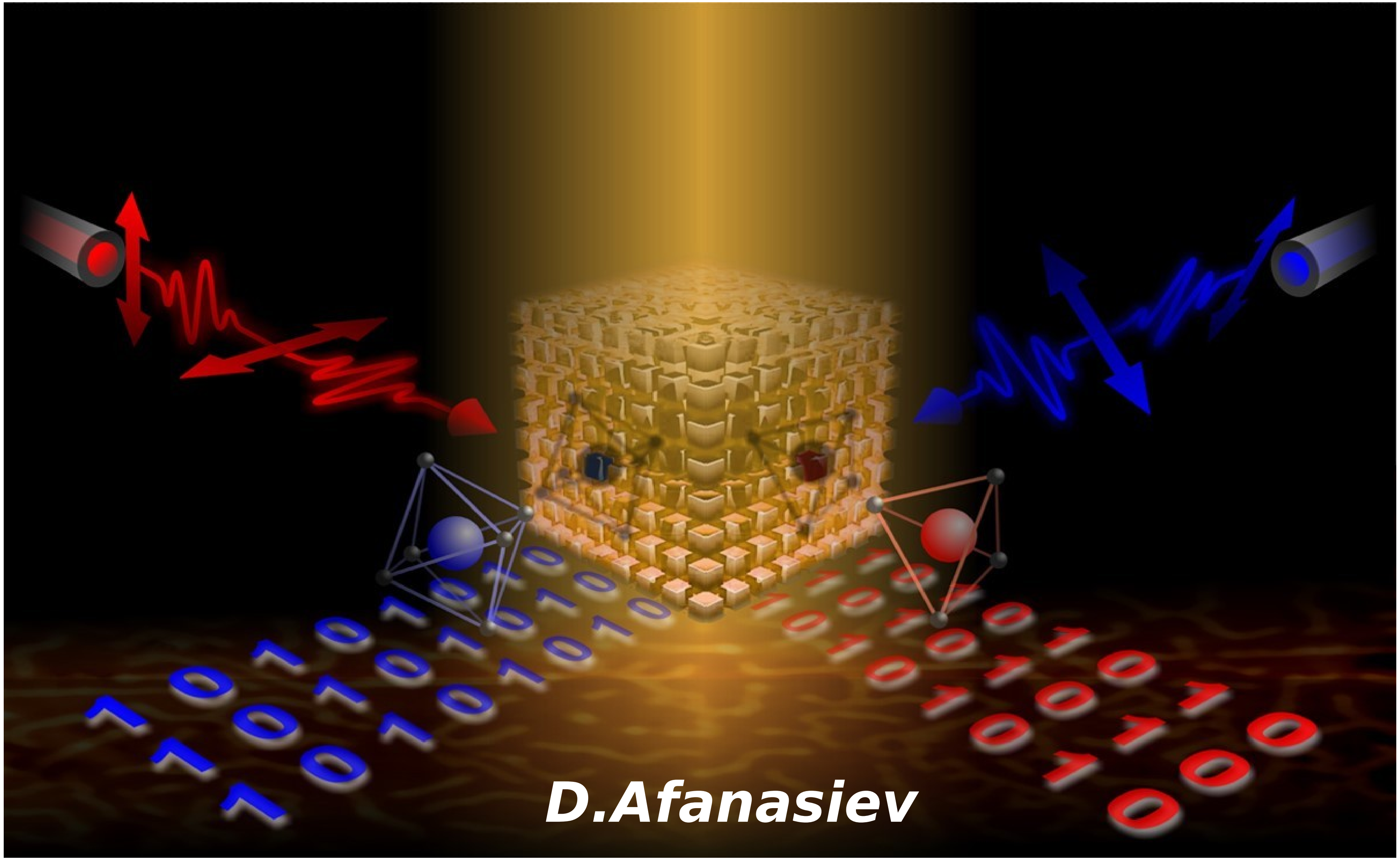
Pillar 4: Topological light-matter interfaces develops and studies the conversion of topological quantum states



(magnons, excitons) into (wave guide) photon states, and hybridization of topological quantum states with light. For topological exciton-light interfaces, we will start with 2D Bi_2Se_3 systems (project 1). The 2D magnetic materials of Pillar 2 form the basis for magnon/light interfaces (project 2). The physics of topological light-matter conversion must be fully understood and used to fabricate efficient interfaces between topological materials and wave guides.

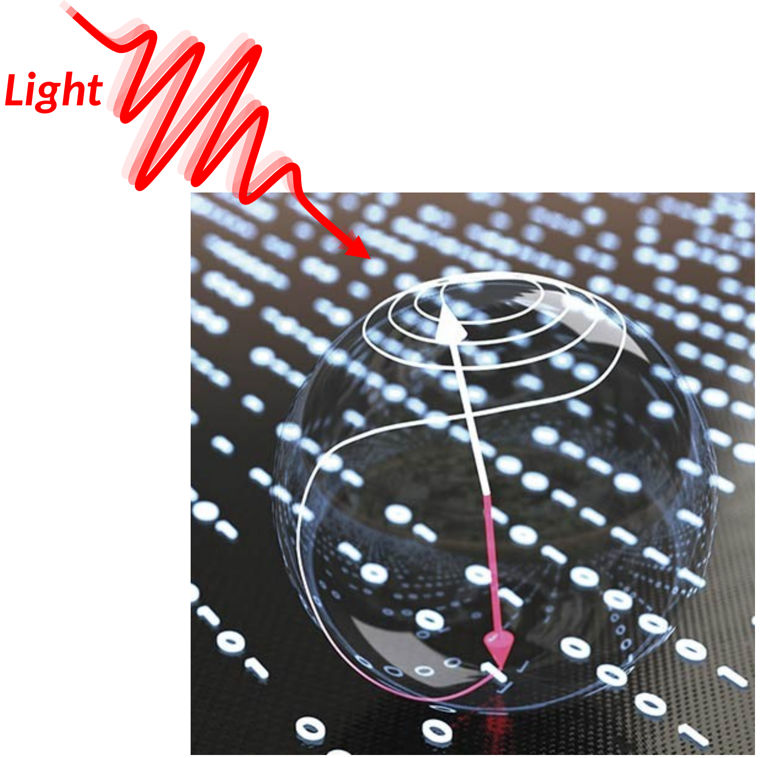
Highlight after first term: Controlled and efficient conversion of magnons into photons and vice versa

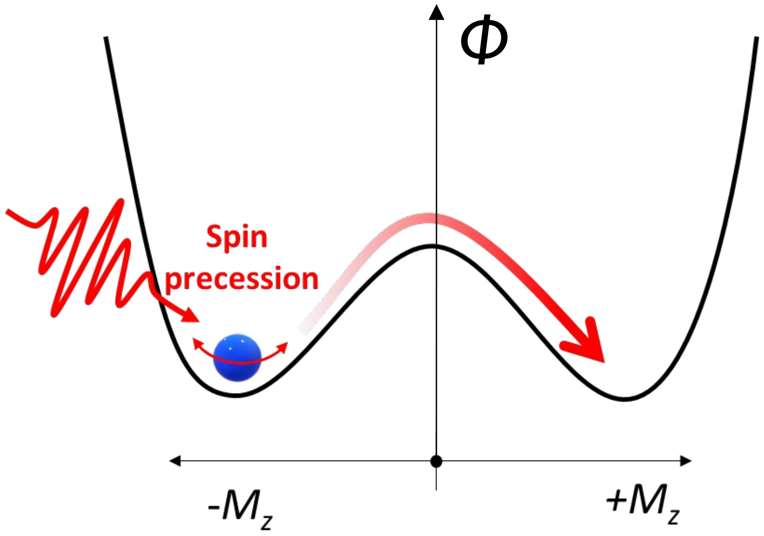
Pillar IV. Cold optical writing at the edge of time

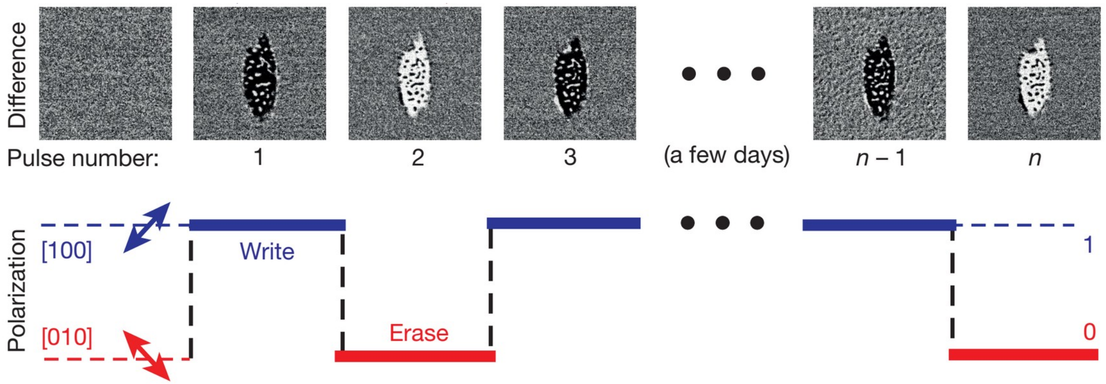


D.Afanasiev

State of the art:
Light-induced precessional switching of ordered spins







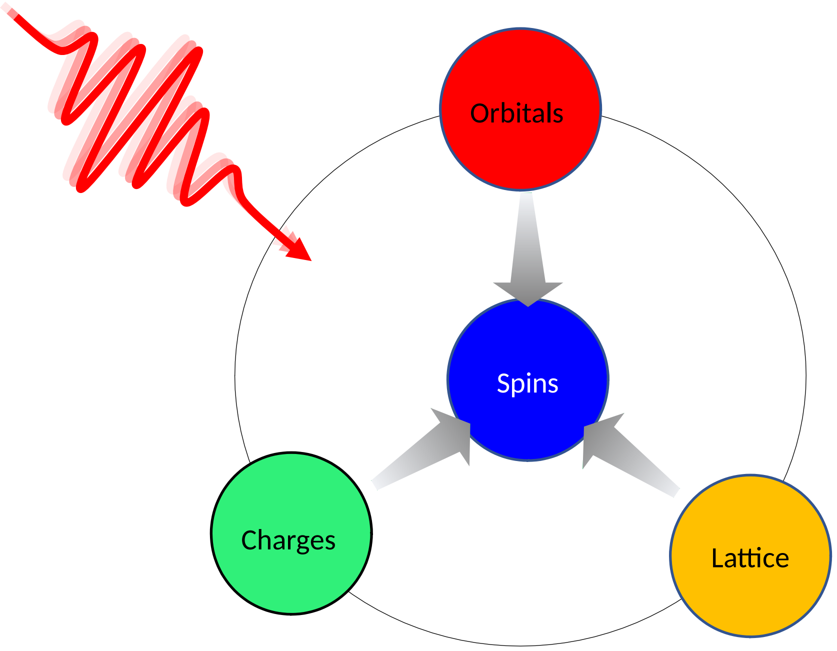
Precessional switching:

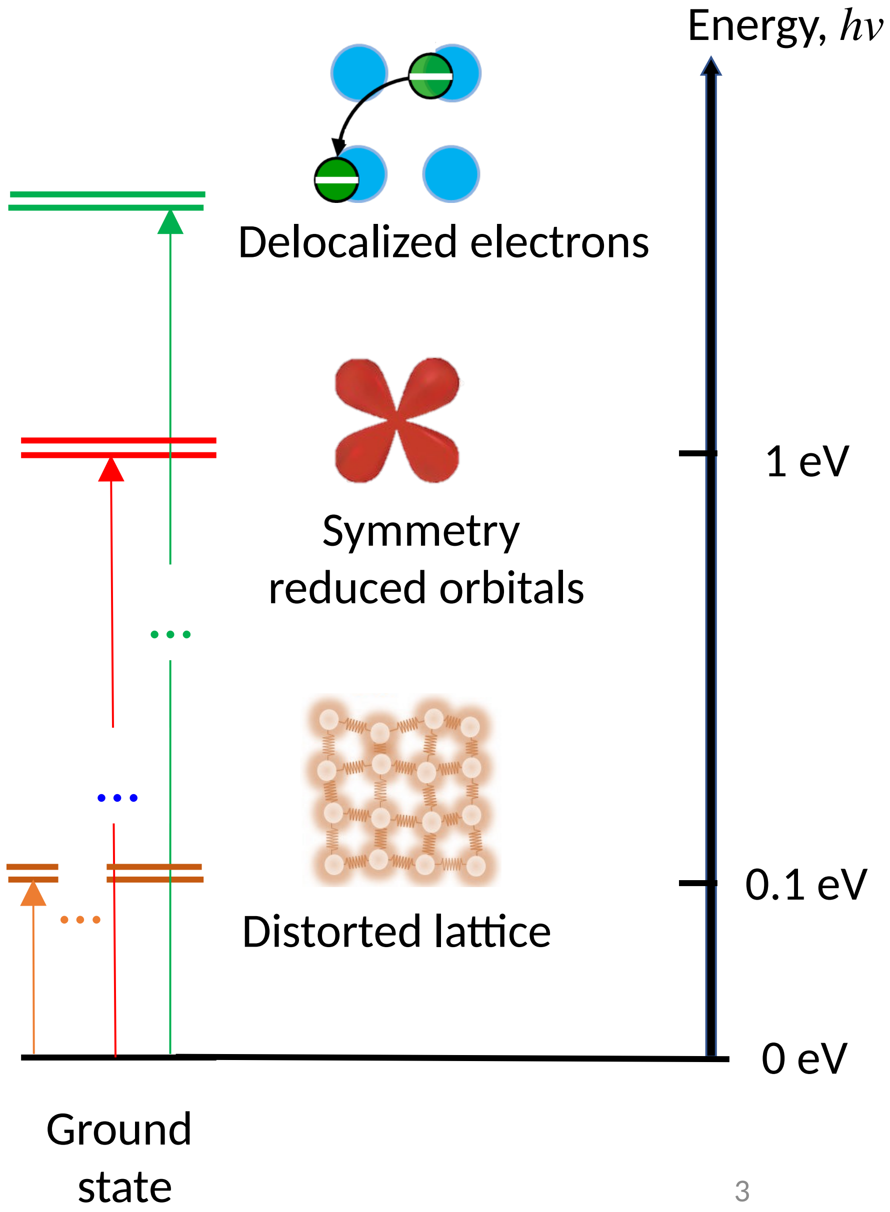
- ***Fast:*** Switching within a half-period of the precession
- ***Cold:*** The most energy efficient switching <u>~10^{-19} J/bit</u>

Switching in YIG:Co <u>within 20 ps</u>

Nature **542,** 71–74 (2017)

Selective excitation with light

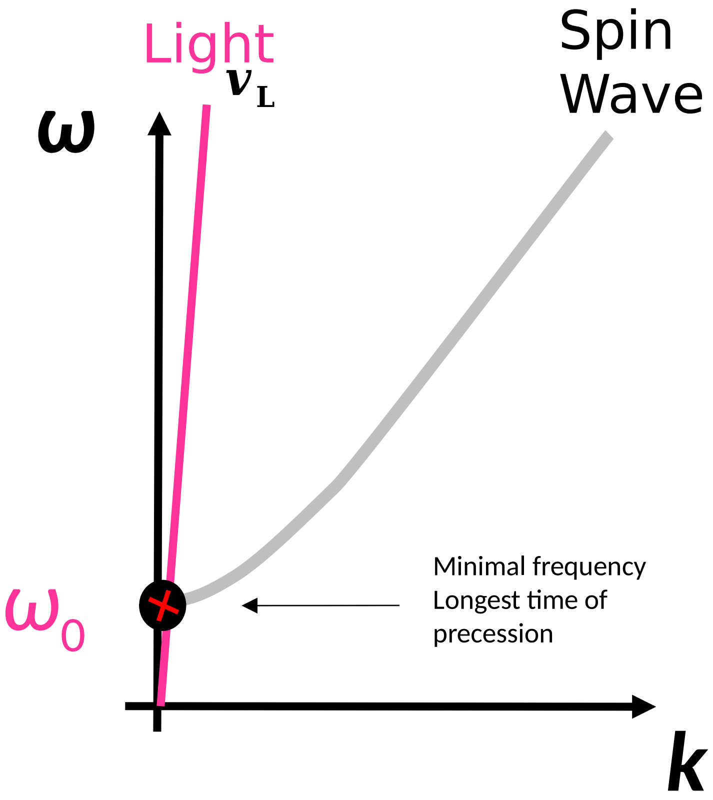


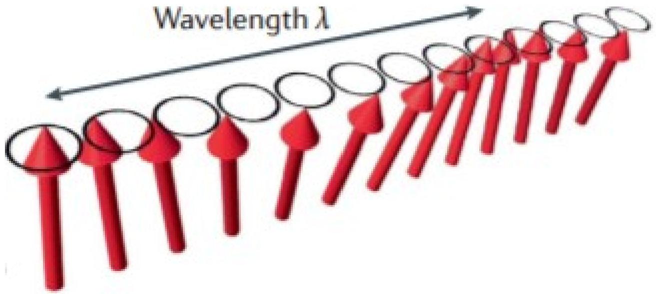


Excitation is **<u>non-thermal</u>**:
-effects of the heating are not dominant
Excitation is **<u>resonant</u>**:
-highly efficient
Excitation is **<u>selective</u>**:
-only specific degrees of freedom can be directly addressed

Beyond state of the art:

How to make it even faster?





Light can excite only homogeneous spin-precession

- Has the lowest frequency in the spin-wave spectrum
- No propagation occurs

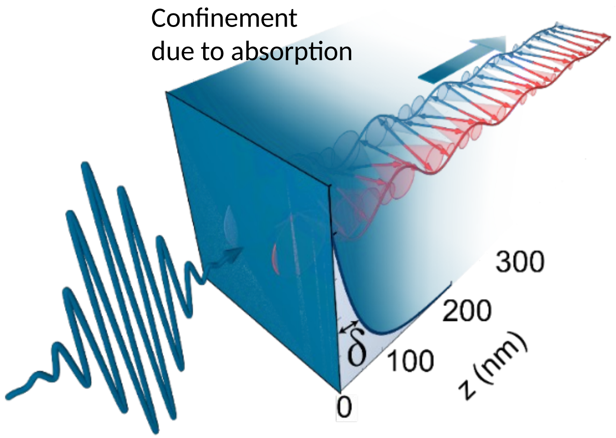
Advantages of finite *k*-spin waves:

- Higher-frequencies > 1 THz
- Non-zero velocity: nonlocal transport

Two possible strategies

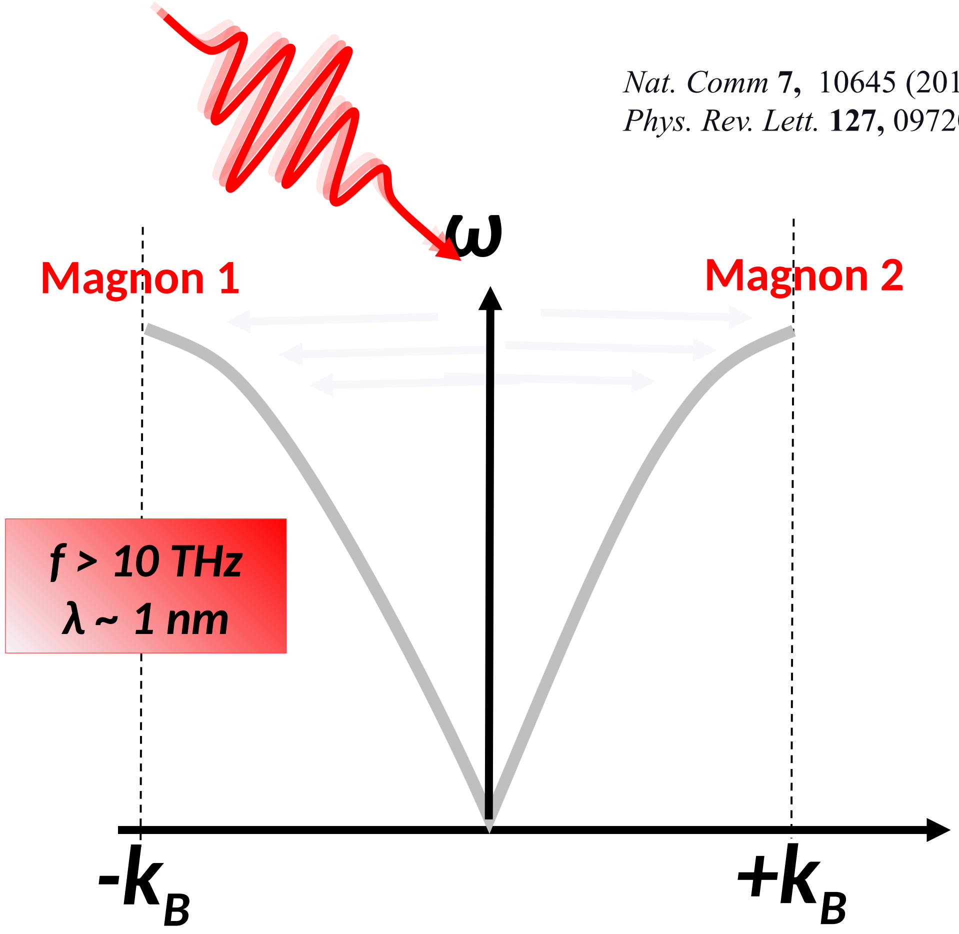
Nat. Phys. **20,** 607-611 (2021)

$f > 1$ THz
$\lambda \sim 10$ nm



Propagating spin-wave packets due to optical confinement

Nat. Comm **7,** 10645 (2016)
Phys. Rev. Lett. **127,** 097202 (2021)

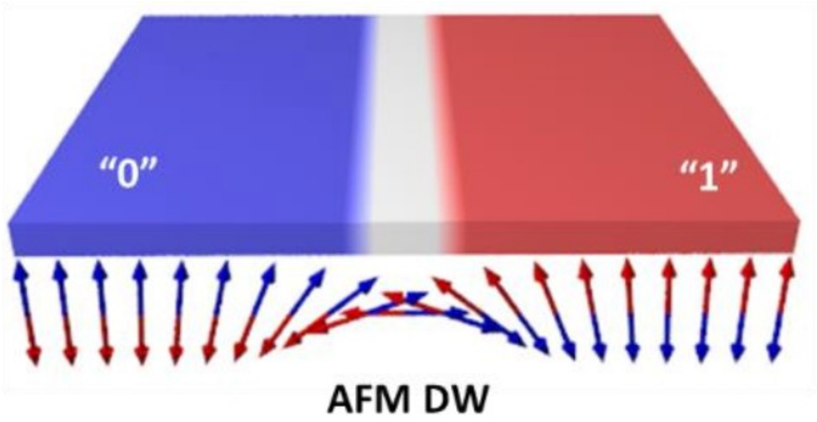


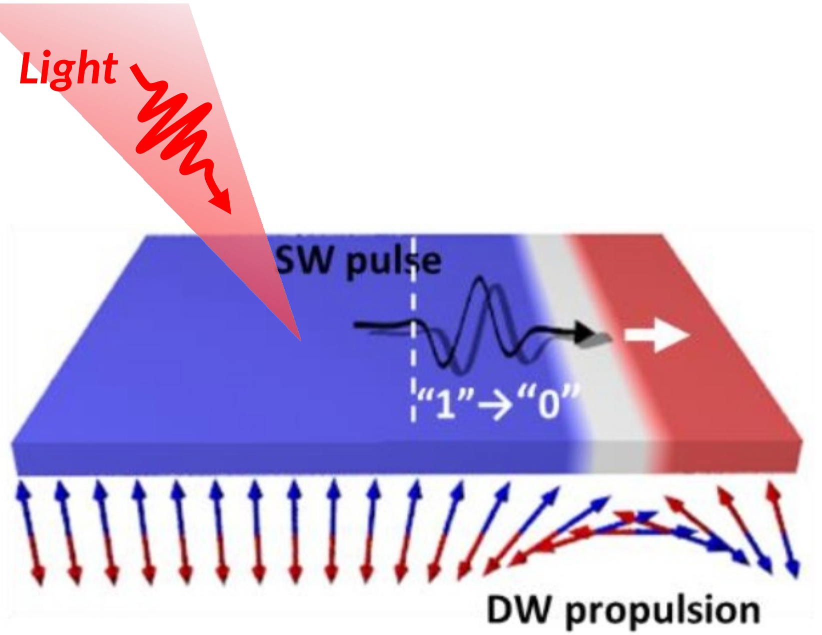
$f > 10$ THz
$\lambda \sim 1$ nm

Two-magnon line – excitation of a pair of counterpropagating magnons at the edge of the Brillouin zone

- Highest possible frequency
- Supermagnonic propagation

Novel scenarios for magnetic recording

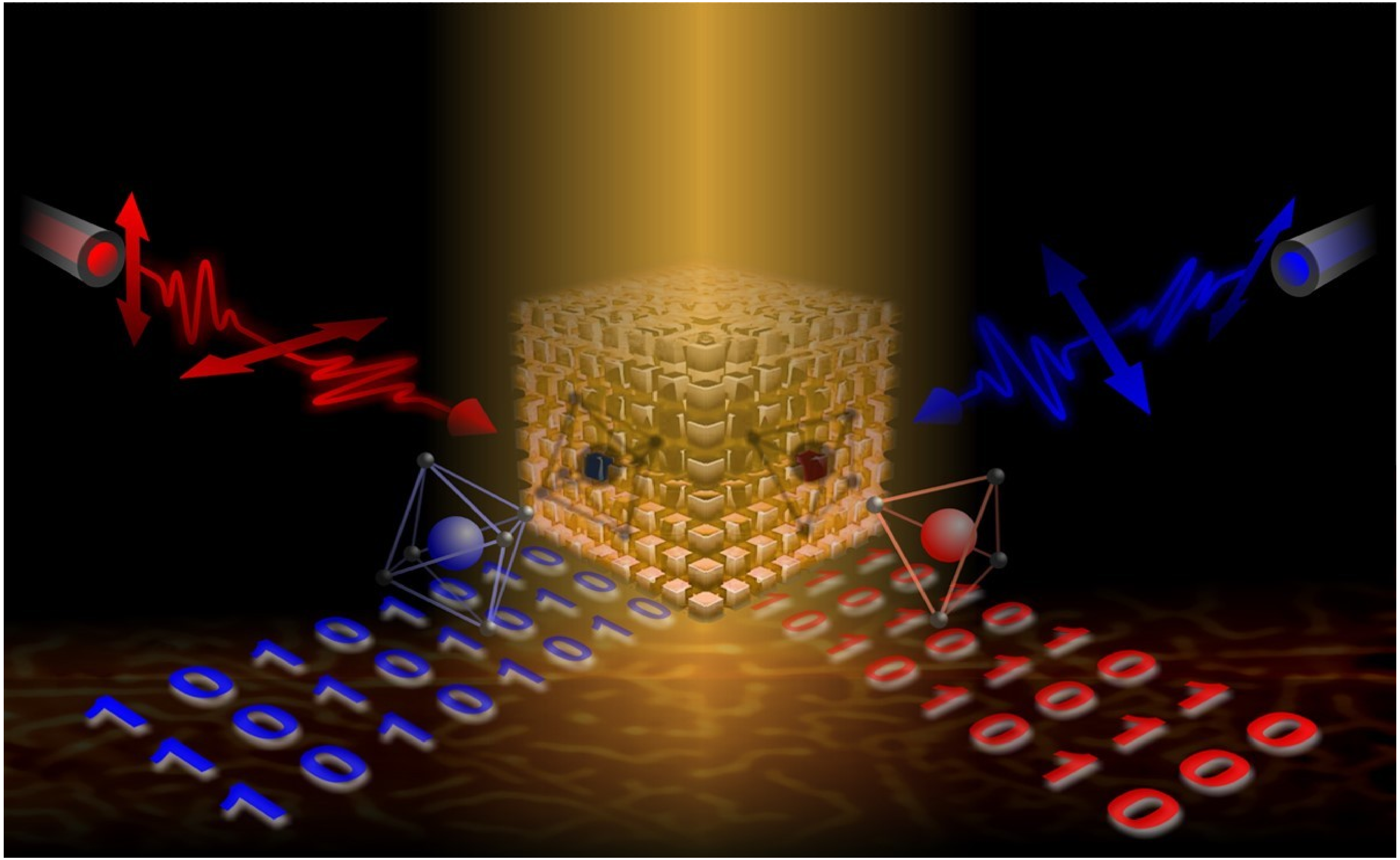


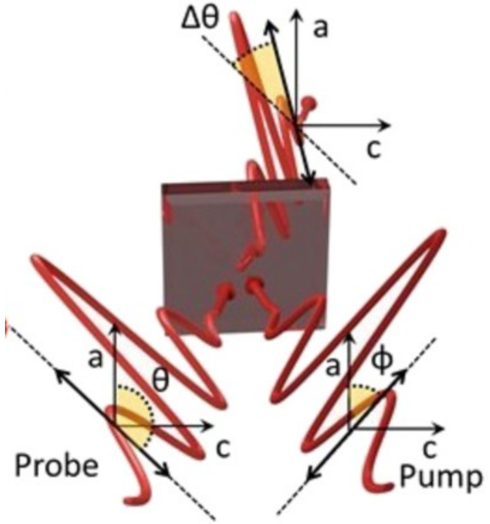


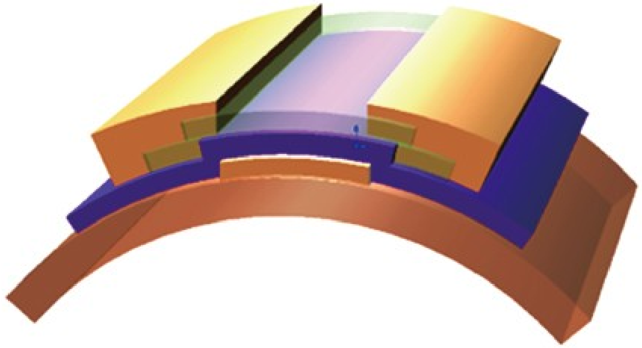
Novel Materials

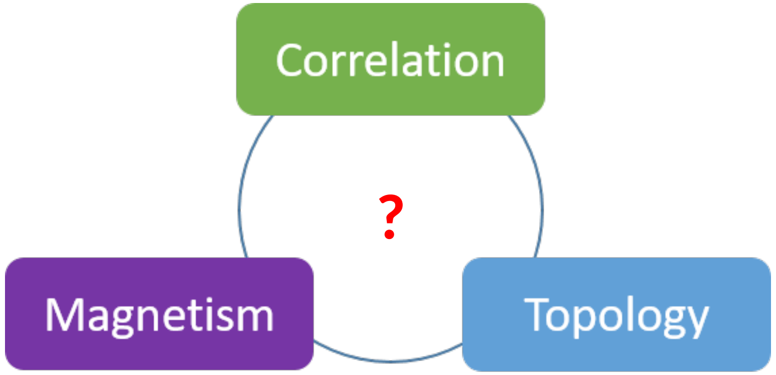
- ***Van der Waals magnets***
- ***Frustrated magnets***
- ***Atomically thin oxide heterostructures***

Thank you








Correlation

?

Magnetism

Topology

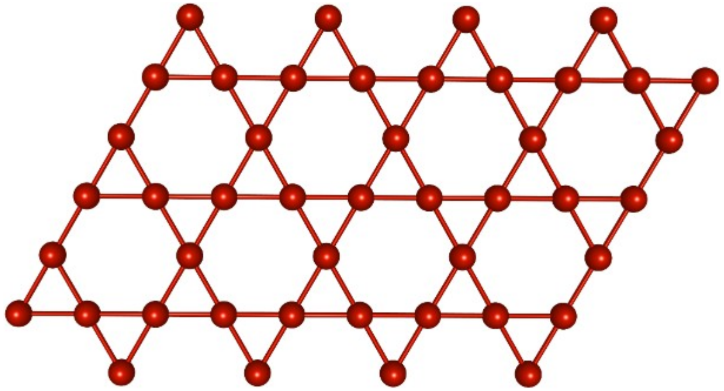
Coherent phono-magnetism: static and dynamical manipulation of magnetism via lattice degrees of freedom

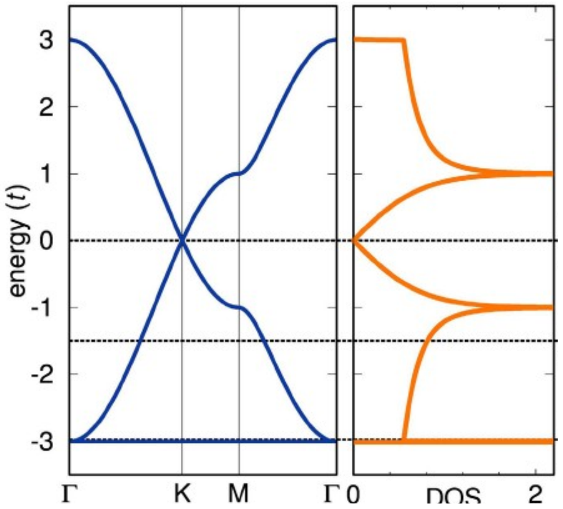
Mazhar Ali[1] & Aleksey Kimel[2]

QuMat Kick-off meeting, Utrecht, NL,
October 25th, 2022

[1]Delft University of Technology (TU Delft), Netherlands

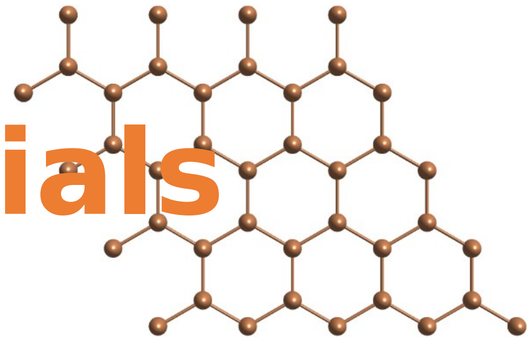
[2]Radbound University, Institute for Molecules and Materials, Nijmegen, The Netherlands

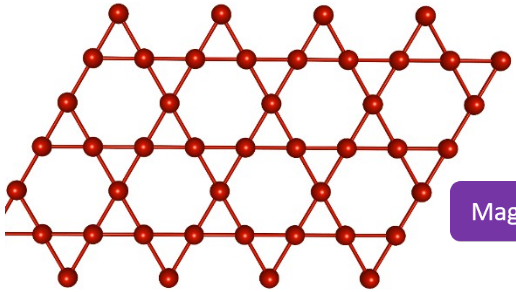


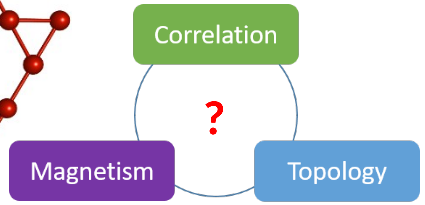


Quantum Materials

Rao, M. S. R., Bhallamudi, V. P., Hammel, C. P., Journal of Physics D: Applied, 51, 2020







Correlation

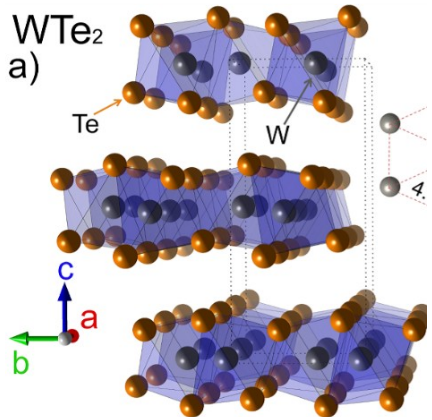
?

Magnetism

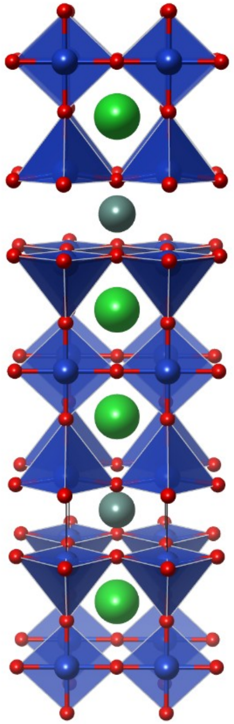
Topology

“The simplest of definition might be that a quantum material is a material whose electronic or magnetic properties are not best described using classical particles or calculations that do not take into account the full character of the system.”

- Topological materials
- Spin liquids
- Quantum Ferroelectrics
- Quantum Magnetoelectrics
- Non-collinear magnets
- Superconductors
- Many more classes



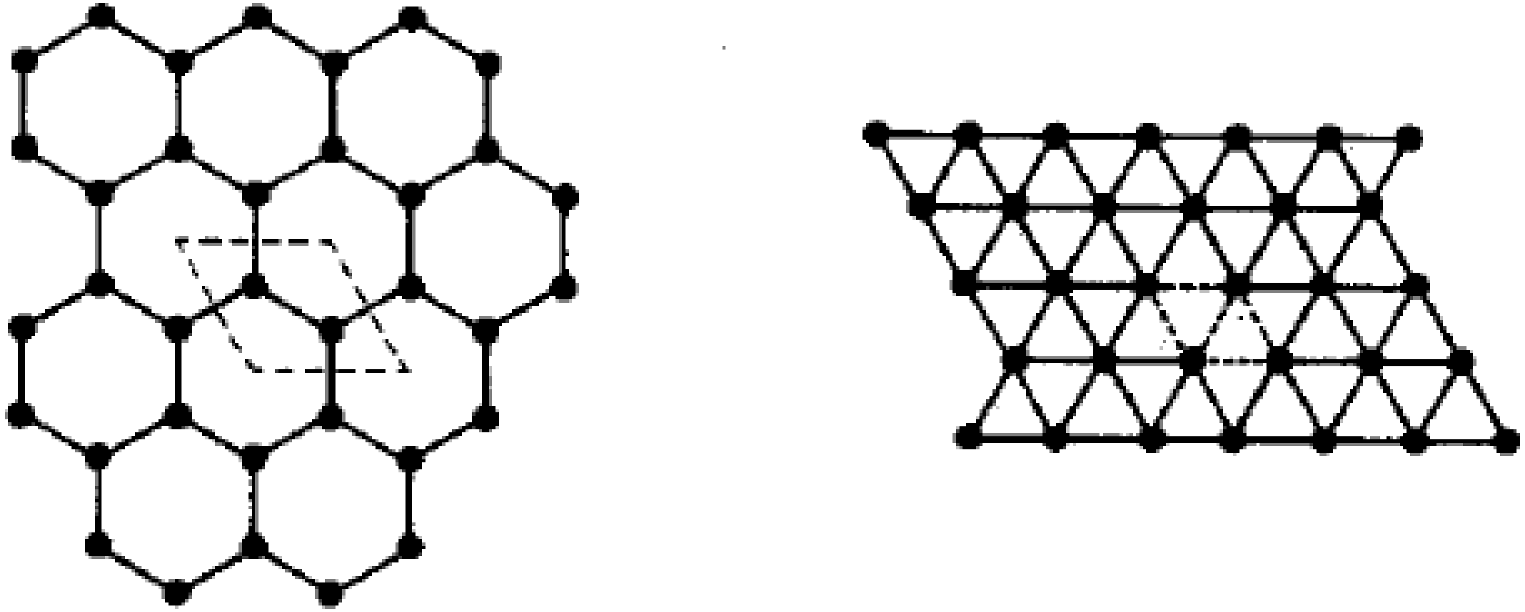
- **2D ones are especially fun: can easily be made into quantum devices!**



$YBa_2Cu_3O_{7-x}$

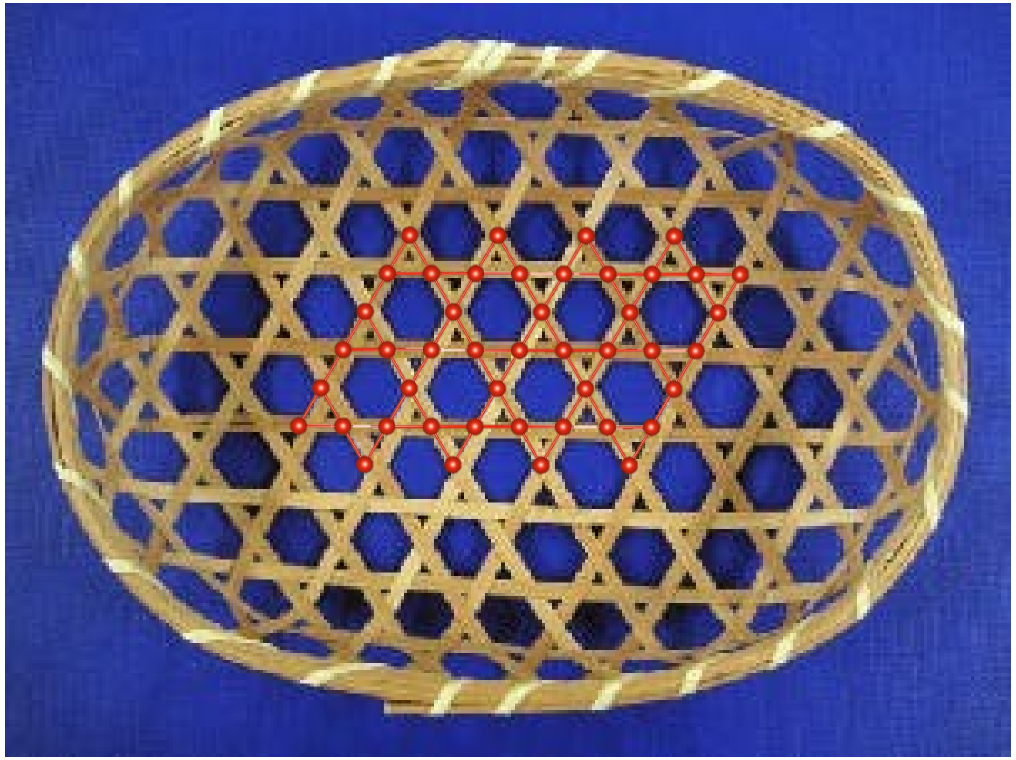
(YBCO)

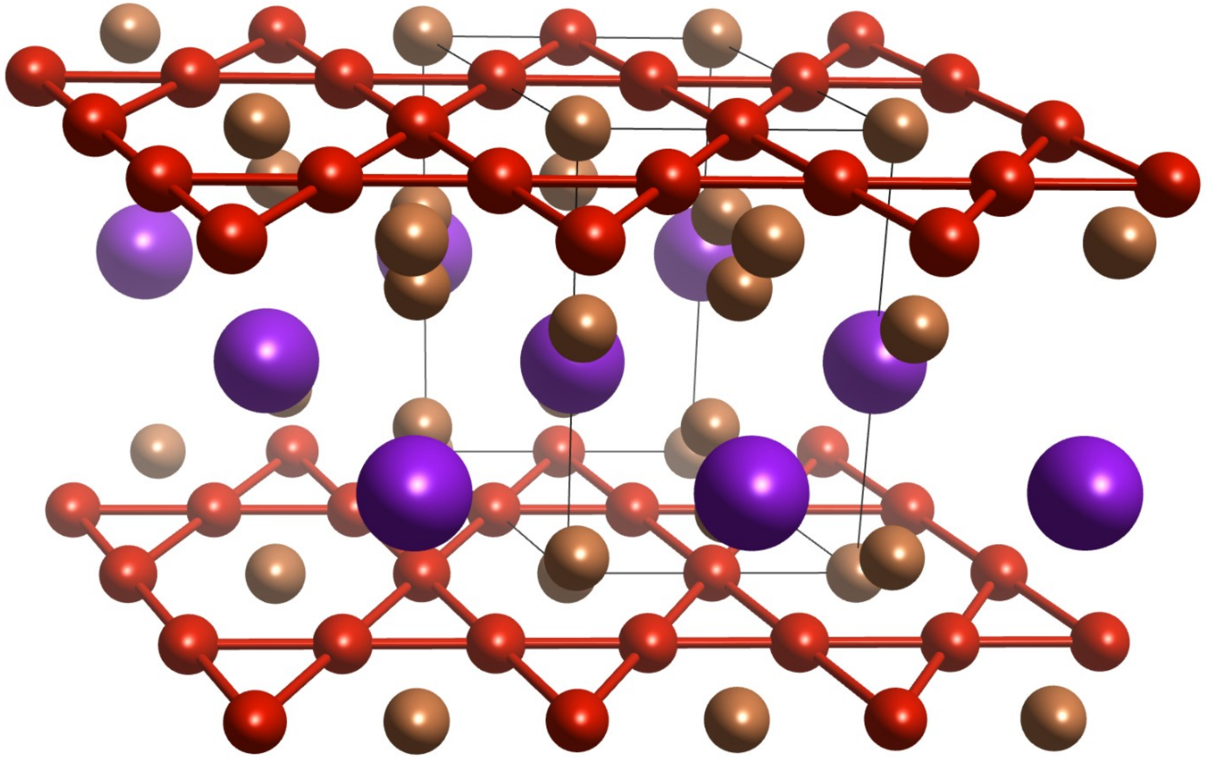
Graphitic vs Triangular Net



- Graphitic Net: Honeycomb -> hexagons
- Triangular Net: close-packed triangles
- Both are **3-connected: each vertex has 3 neighbours**

Kagome – “in a basket…eyes”

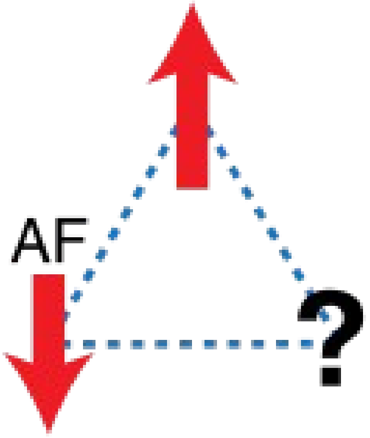




KV_3Sb_5

- Japanese Basket Weaving Pattern -> Real world solid state crystal structure
- “Trihexagonal Tiling” – **4 connected**: each vertex has 4 neighbours
- Hexagons + Triangles

Geometric Frustration



Imagine triangle of Ising spins…what do you do with the third one? Surprisingly not trivial…

Balancing act of coupling strengths of J1, J2, etc.

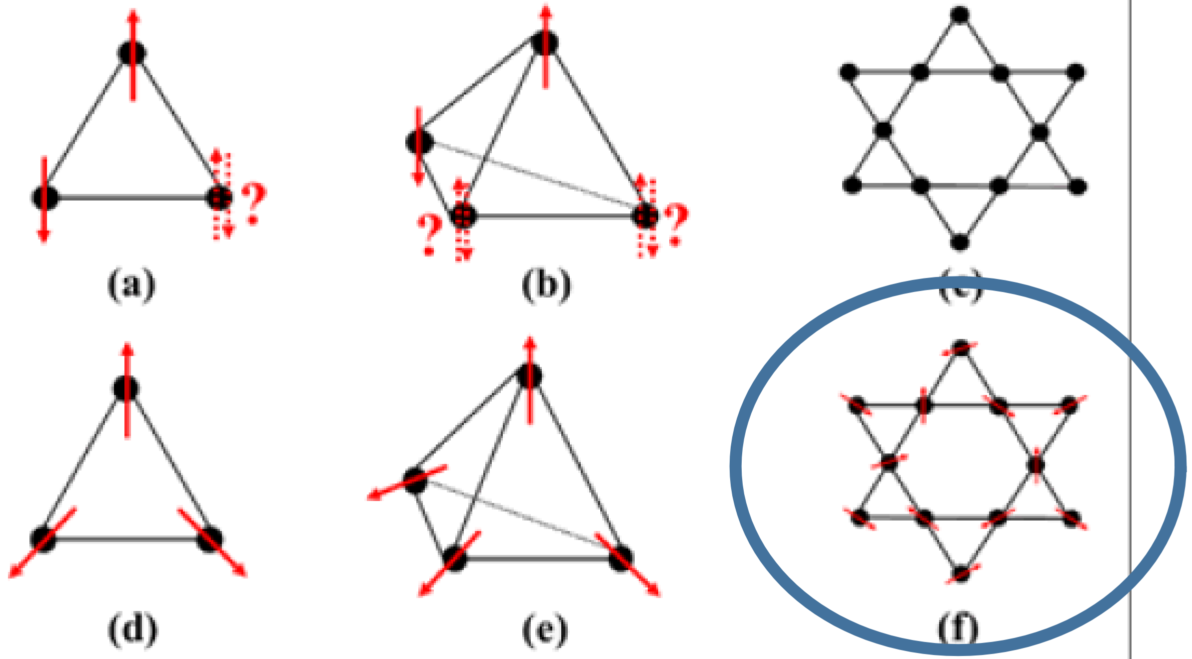
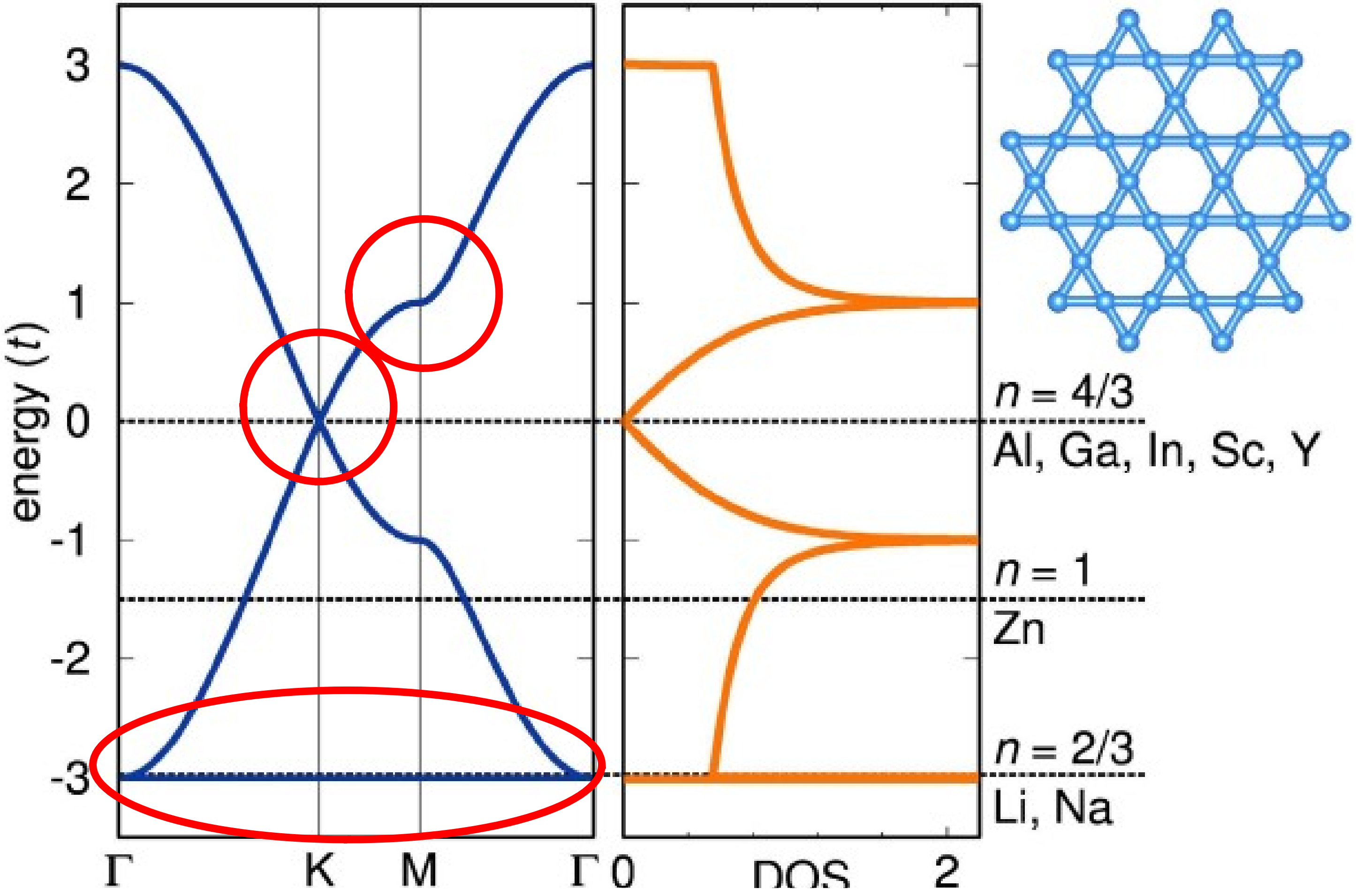


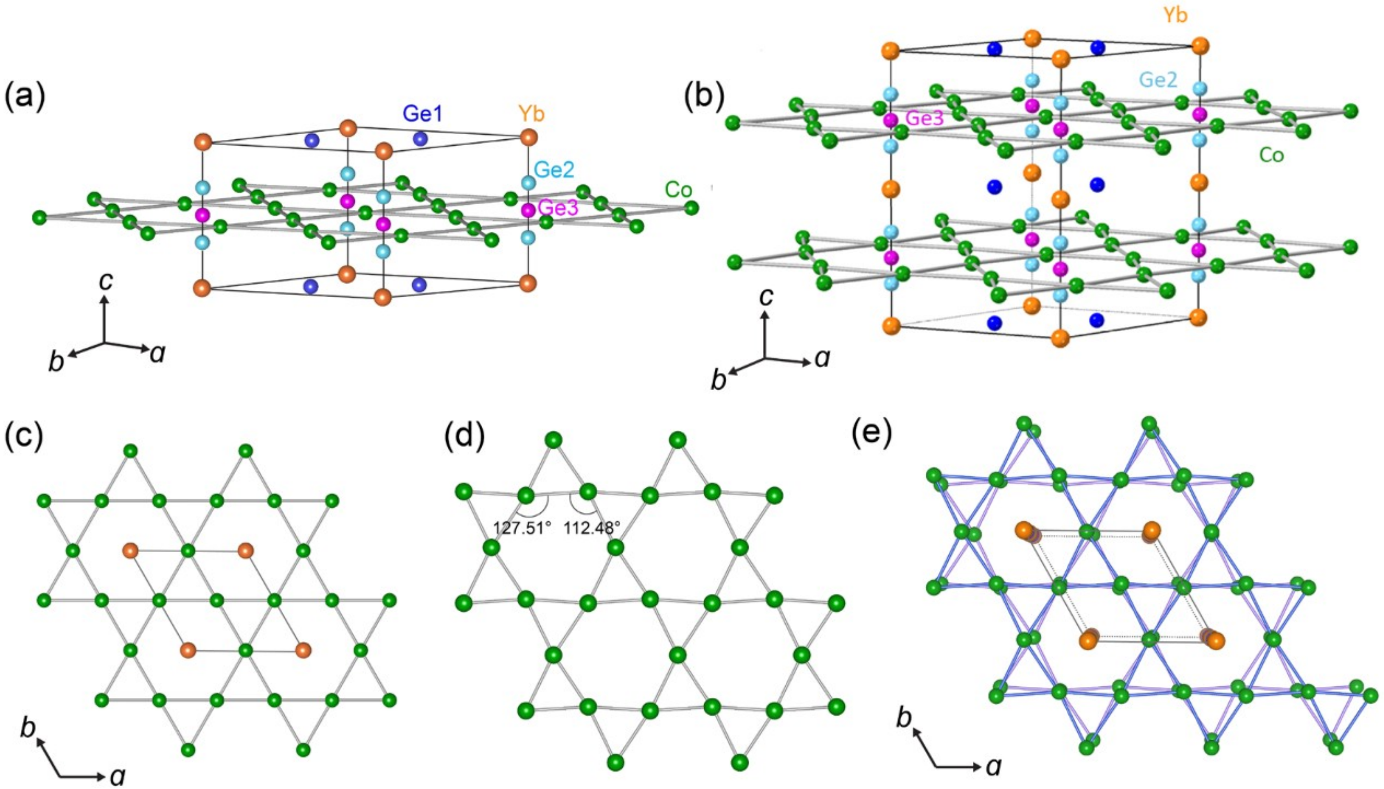
Figure 1: Examples of few spin frustrated magnetic lattices.

Kagome Band Structure Points of interest

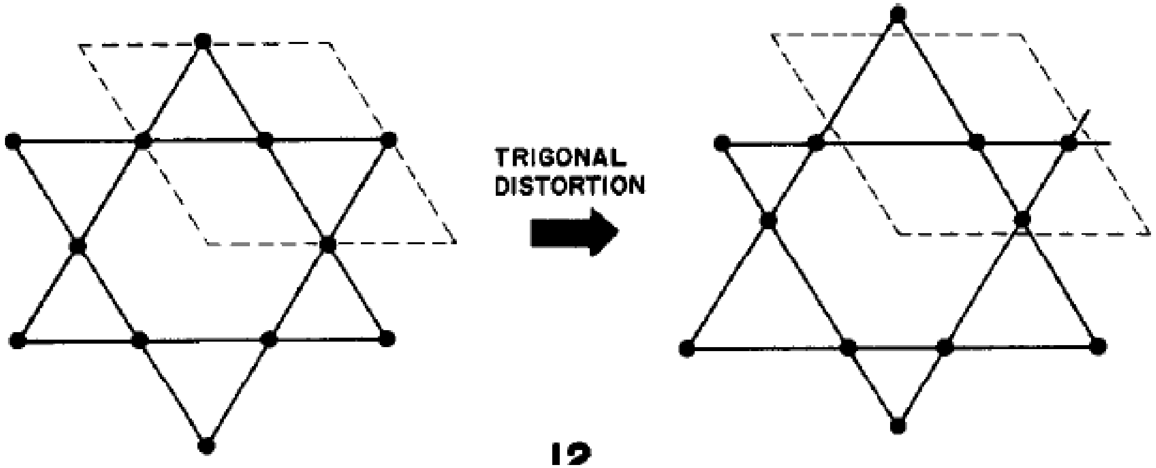


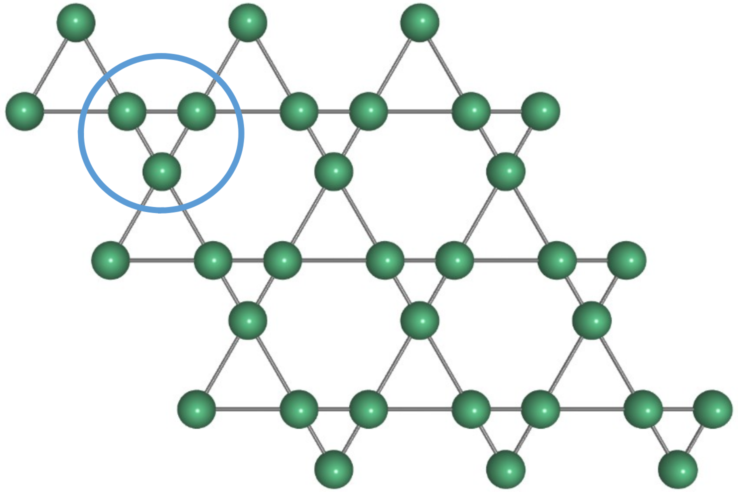
- Dirac Point at K
- Surface/edge states in SOC gap opening
- Van Hove Singularity
- Flat Band

Some examples of Kagome modes



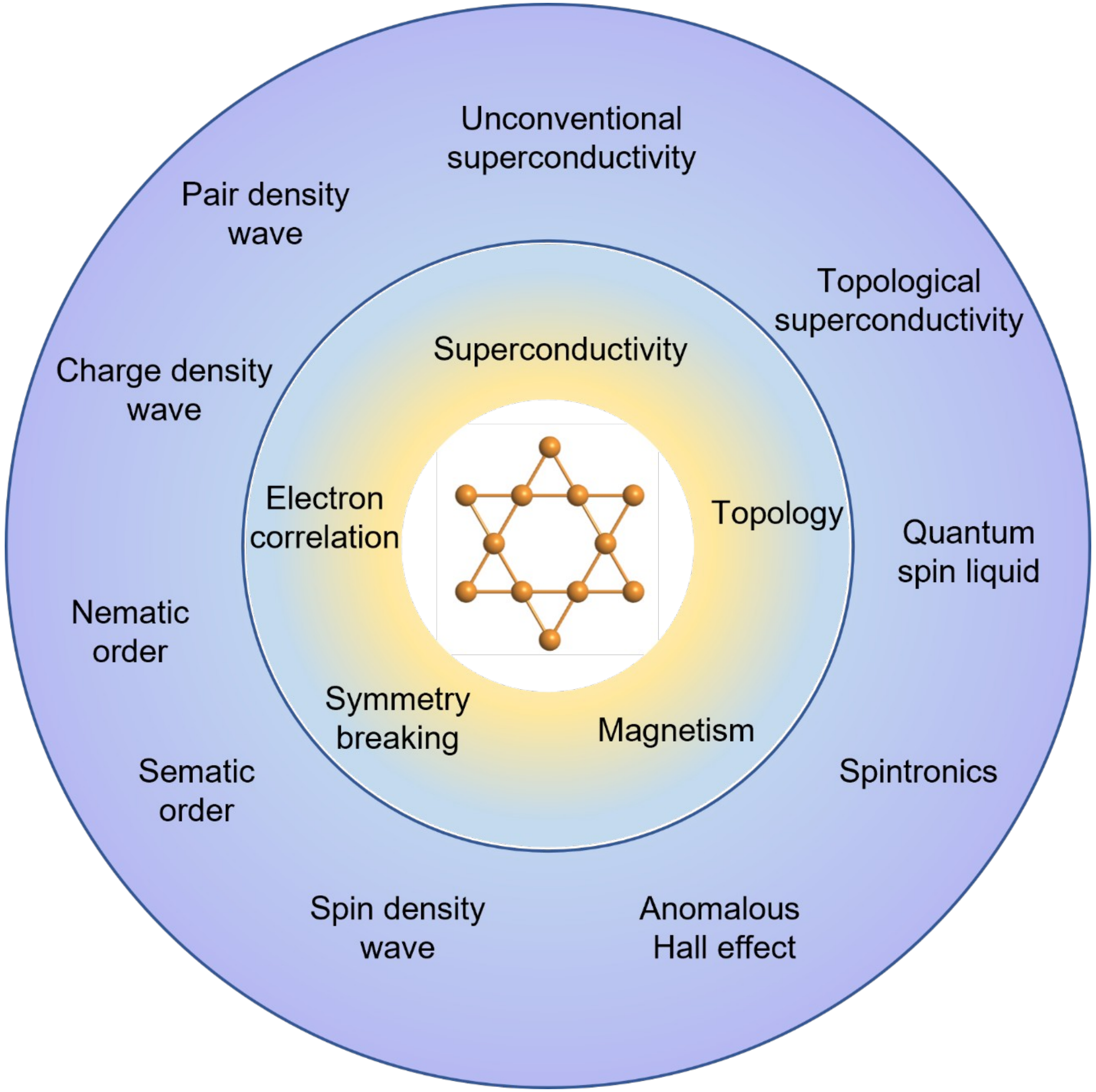
$Yb_{1/2}Co_3Ge_3$

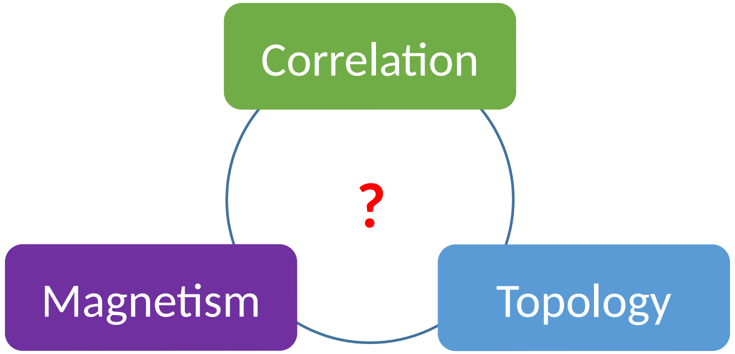




$Nb_3Cl_8/Br_8/I_8$

Kagome Lattice: Yes it can



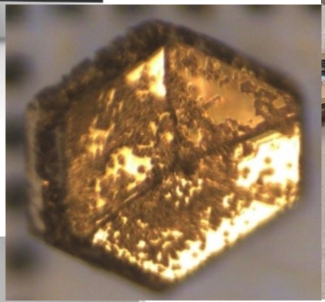


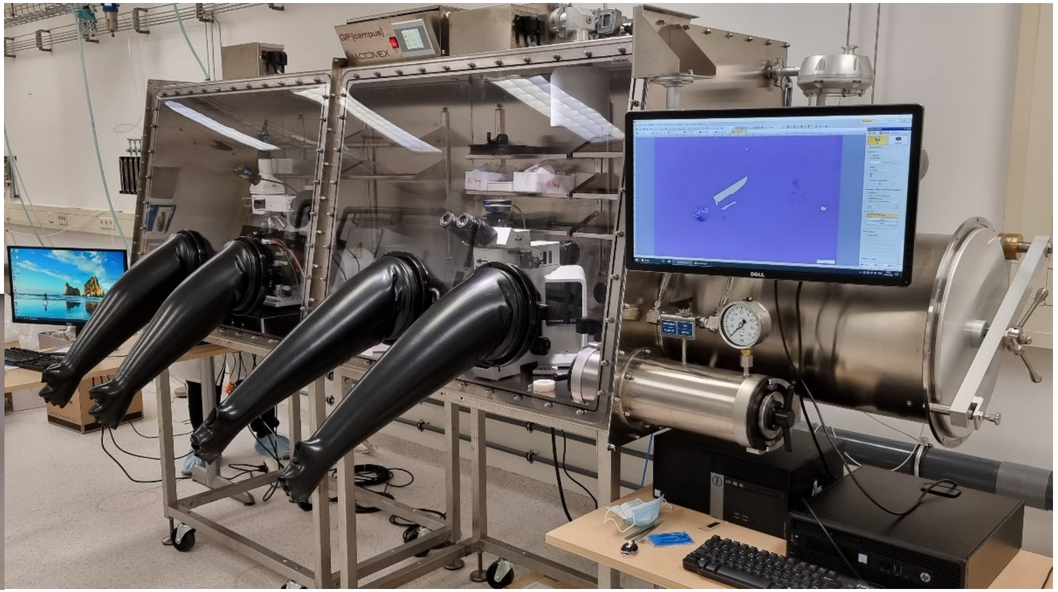
Can we move the arrow?

Tuning via strain and light interactions

S.Y. Yang, et al., under review Nature Physics (2022)

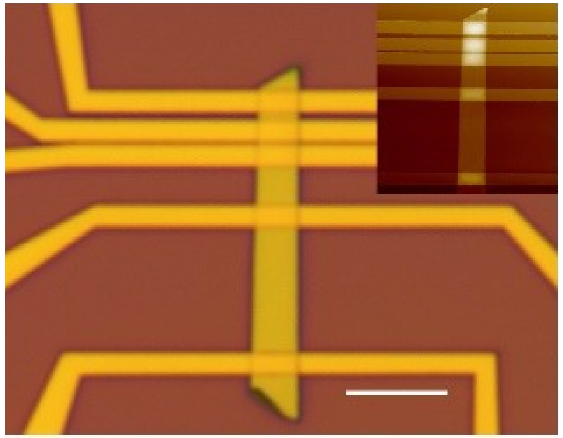
Synthesis -> 2D Devices -> Magnetotransport





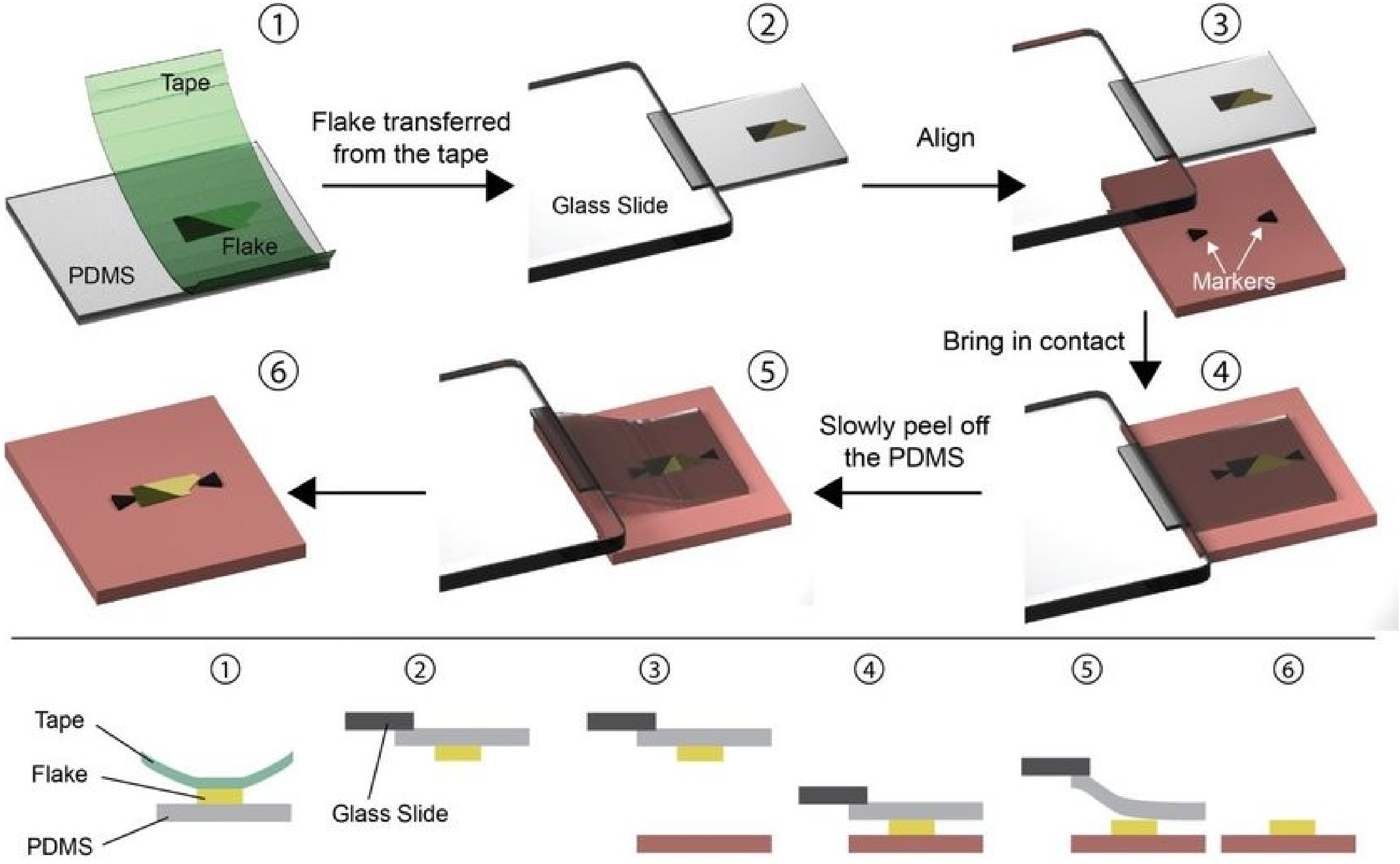
2D Fab Lab
Triple Inert Glovebox
HQ Graphene Transfer Stage
Olympus Microscope
In-situ AFM
Antivibration Stages

Solid State Synthesis Lab
~25 Furnaces
Up to 1800 C
Variable Gas Environment
pXRD
Inert atmo Glovebox
Elements 1-83* used

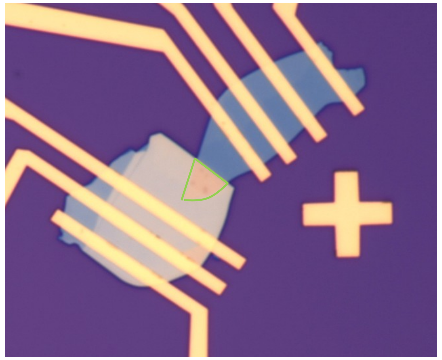


Magnetotransport Lab
Liquid He Cryos
Dual ADR Cryo (Kiutra)
6-14 T Magnetic Field
300K - ~30 mK range
DC Measurement electronics (insulators to superconductors)

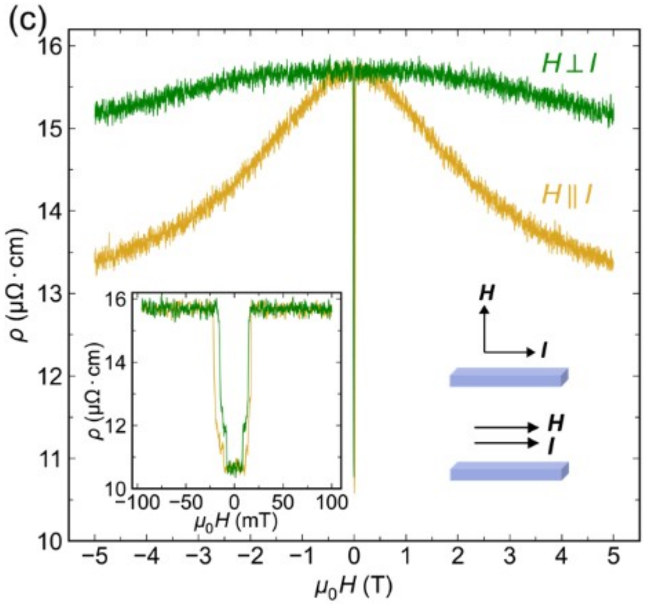
2D Quantum Materials can exfoliate/transfer

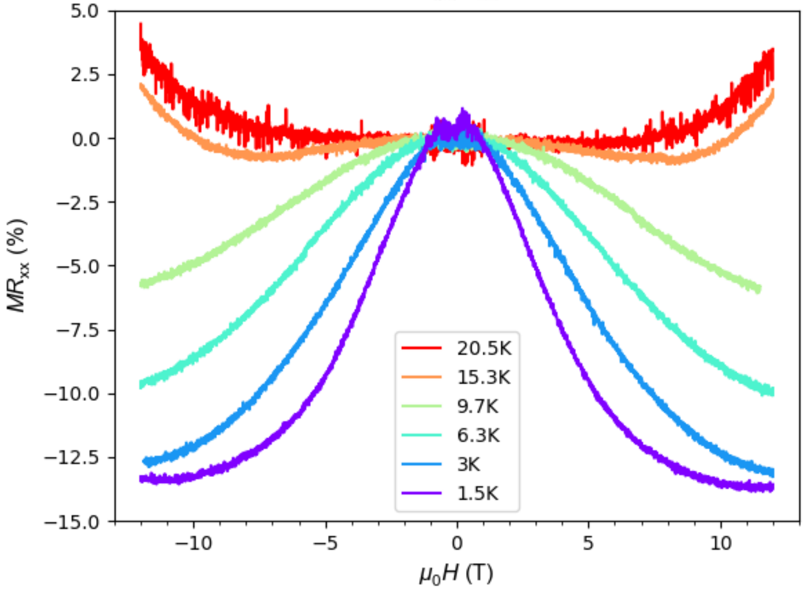


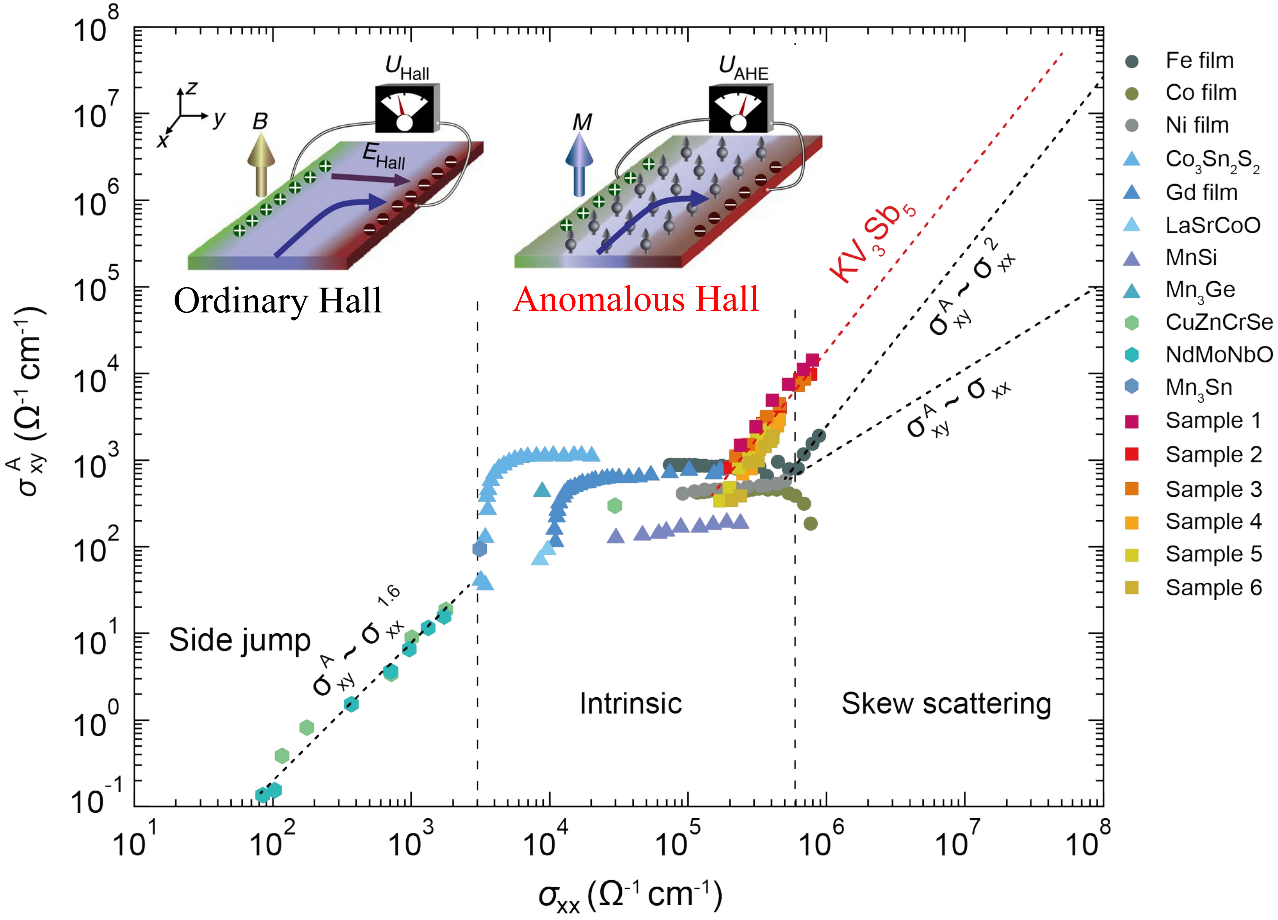
- Nearly layer by layer construction
  - 2D limit, finite size
- Can make novel heterostructures
  - Non-thermodynamic products
  - Access novel areas of materials phase space



Magnetotransport (modulated by strain)







S.Y. Yang, et al. Science Advances (2020): eabb6003

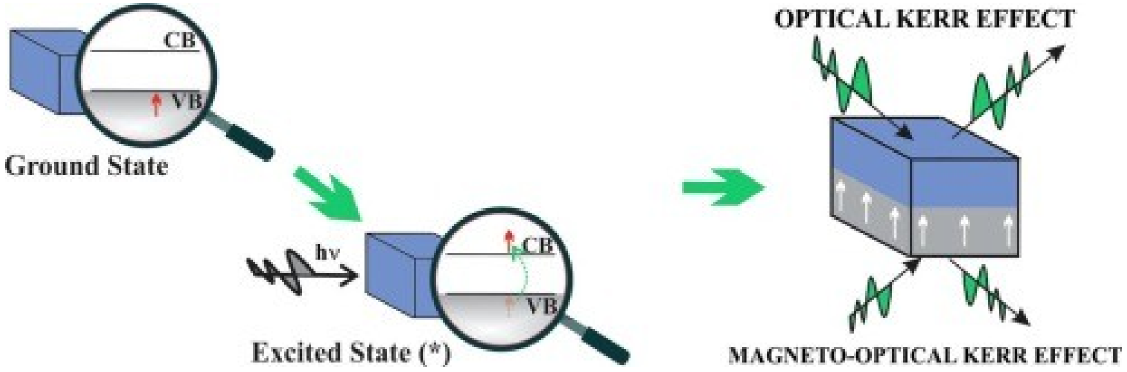
Y. Wang et al, *Nature Physics*, 17, 542, 2021

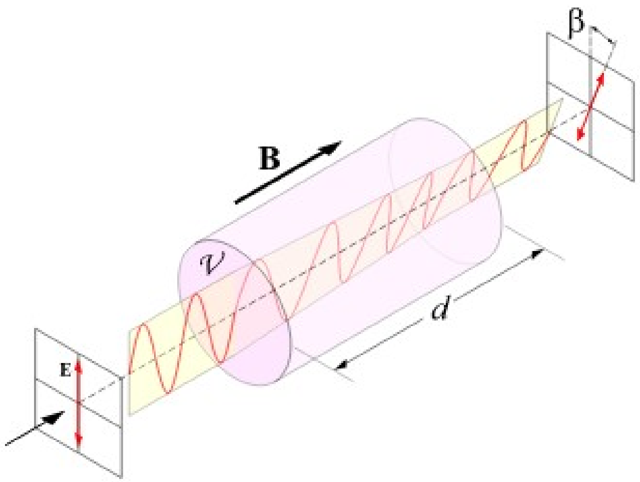
Wang, Y. et al, https://doi.org/10.1021/acs.chemmater.2c01309

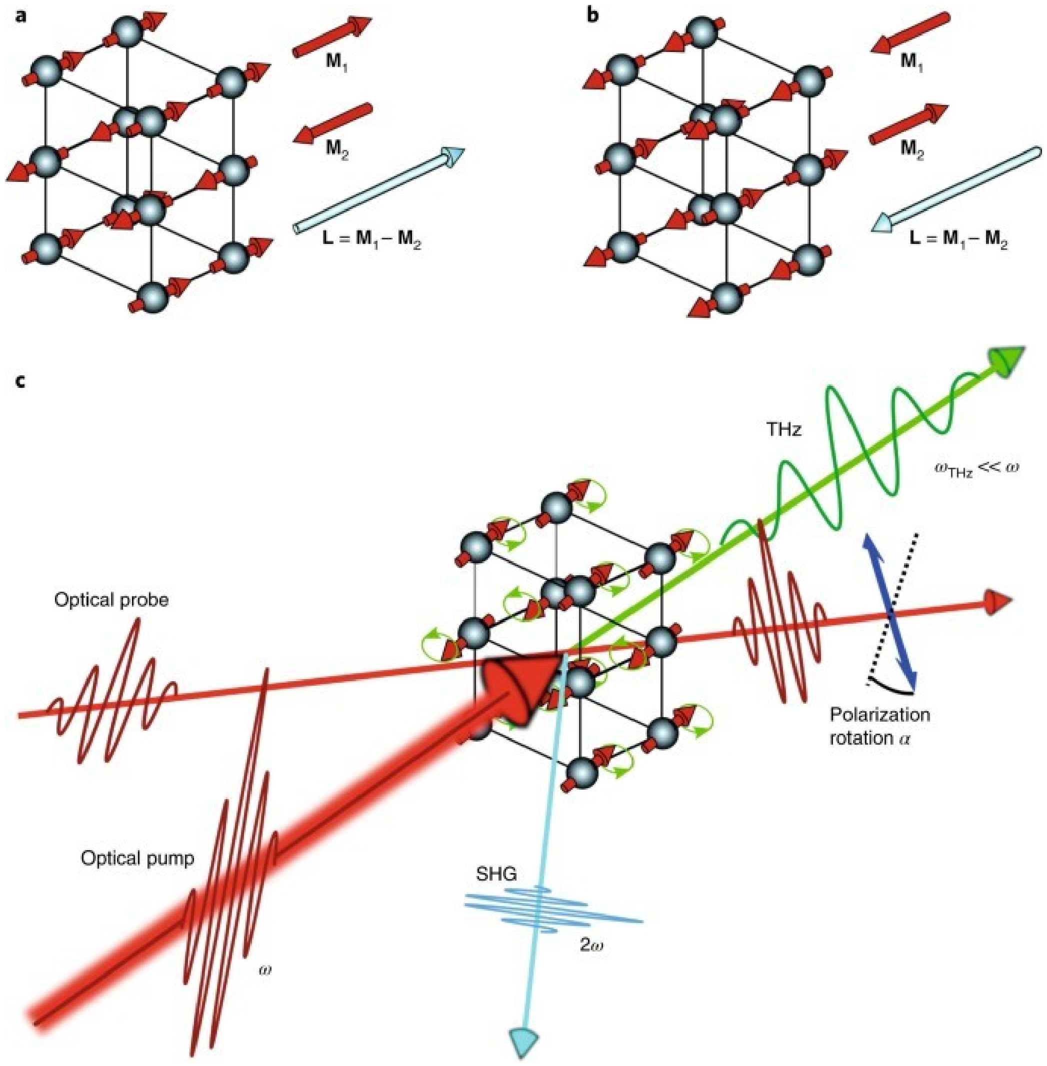
M. N. Ali et al, *Nature*, 514, 205, 2014

Magnetooptical Kerr and Faraday

modulated by strain

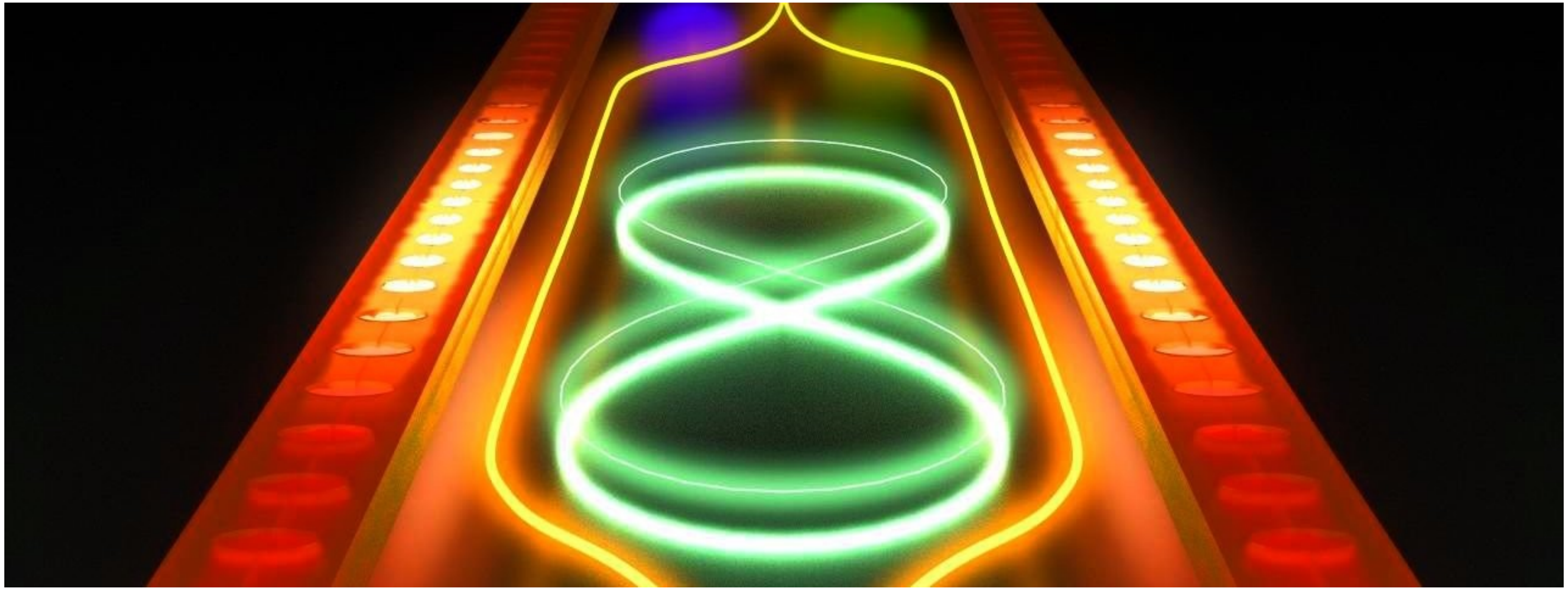






P. Nemec et al, *Nat. Phys.* 14, 229, (2018)

Potential Application: Transduction



- “Transduction” – Conversion of energy from one form into another
    - Think of a microphone – mechanical to electrical energy transducer
- Coherent phono-magnetism – opto-phono-magno transduction?

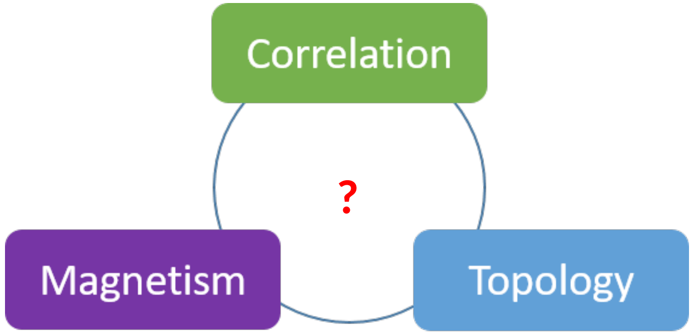
Coherent phono-magnetism: static and dynamical manipulation of magnetism via lattice degrees of freedom

Ali (TUD) & Kimel (RU)

Optics

- **Kerr and Faraday Dynamical order effects**
- **Magnon excitations**

Kagome Quantum Materials



Correlation

?

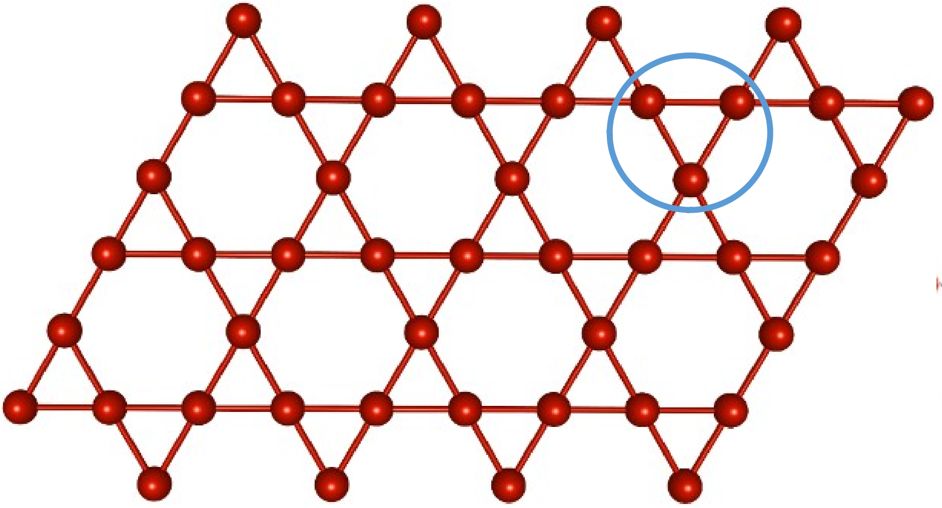
Magnetism

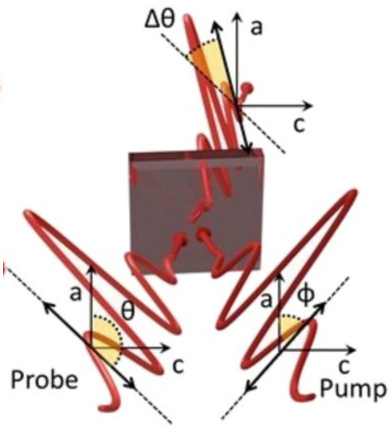
Topology

Van der Waals Heterostructures

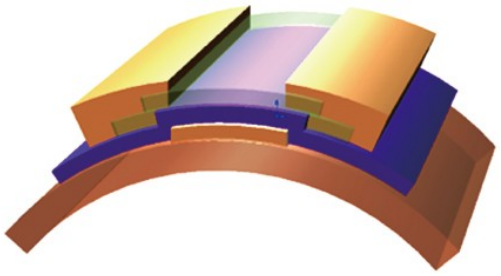
Electron Transport

- **Hall Effects**
- **Magnetoresistance**
- **Static order effects**
- **Orbital loop current**





Light driven Control



Strain driven Control