



Research in High Magnetic Fields

Peter Christianen

High Field Magnet Laboratory (HFML)

Radboud University, Nijmegen, the Netherlands

High Field Magnet Laboratory: Mission

1. Magnet Technology – generate the highest possible static magnetic fields

Magnetic fields up to 38 T; 45 T hybrid magnet under construction

2. User Facility – installation & instrumentation open for external users

National and European “large research infrastructure”

3. Excellent science in high magnetic fields

In-house research programme + user programme



Outline

- The global landscape of research in high magnetic fields
- Science enabled by high magnetic fields – examples from HFML
- Developments in instrumentation & magnet technology

The Global High Magnetic Field Landscape

Europe

Nijmegen (DC)

Grenoble (DC)

Toulouse (pulsed)

Dresden (pulsed)



USA

Tallahassee (DC)

Los Alamos (pulsed)

China

Hefei (DC)

Wuhan (pulsed)

Japan

Tsukuba (DC)

Sendai (DC)

Tokyo (pulsed)

European Magnetic Field Laboratory (EMFL)



EMFL Founded 2015

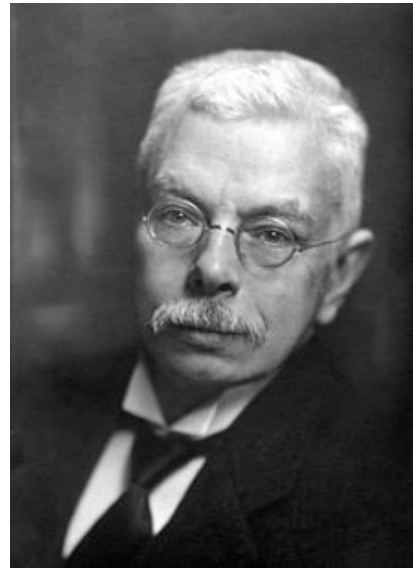
- HFML - Nijmegen
- HLD - Dresden
- LNCMI - Grenoble
- LNCMI - Toulouse

UK community joined EMFL in 2015

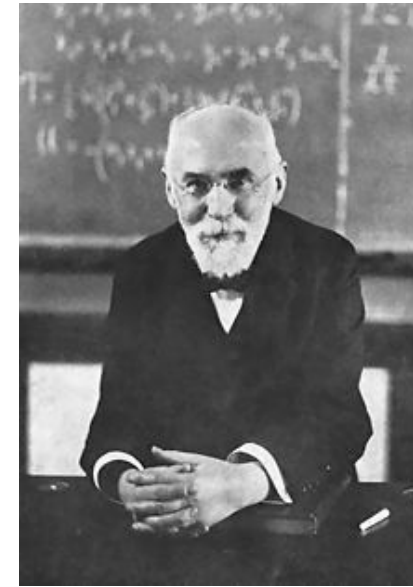
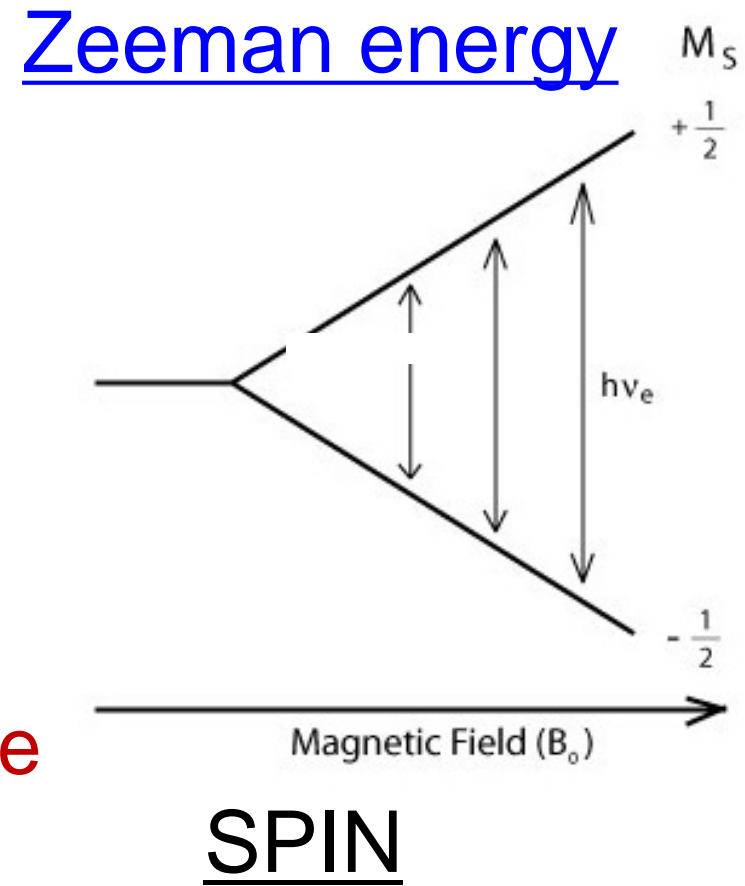


Landmark status 2016

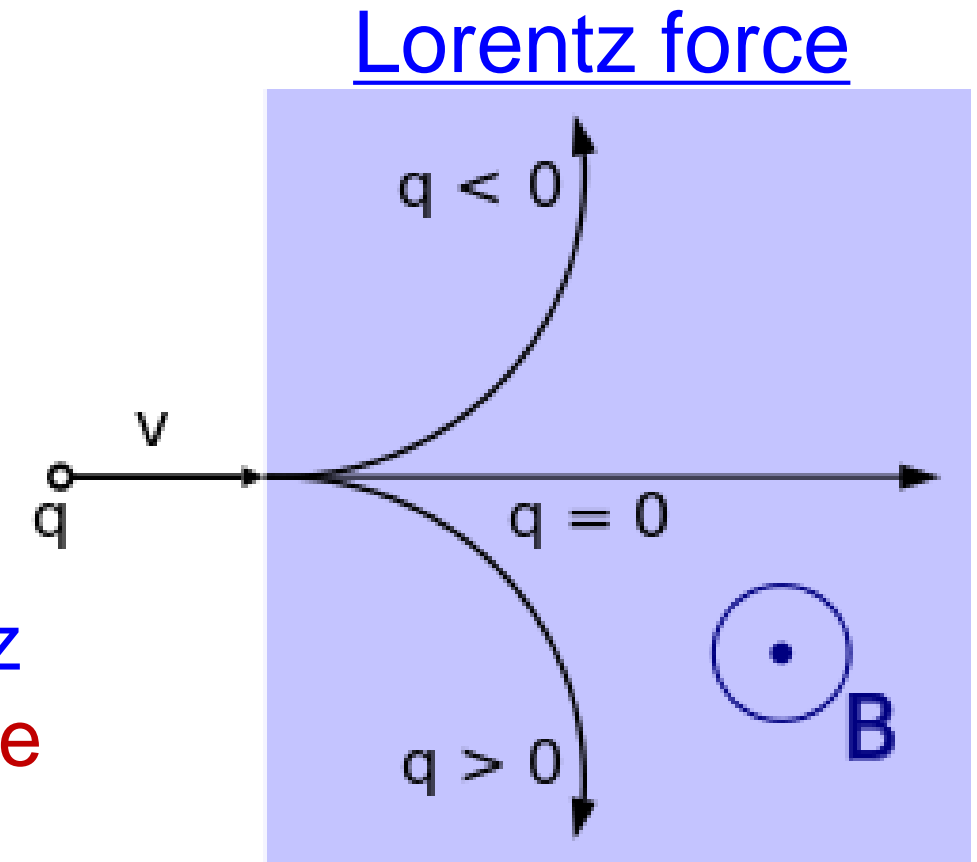
the Dutch tradition in Magnetism & Magnetic Fields



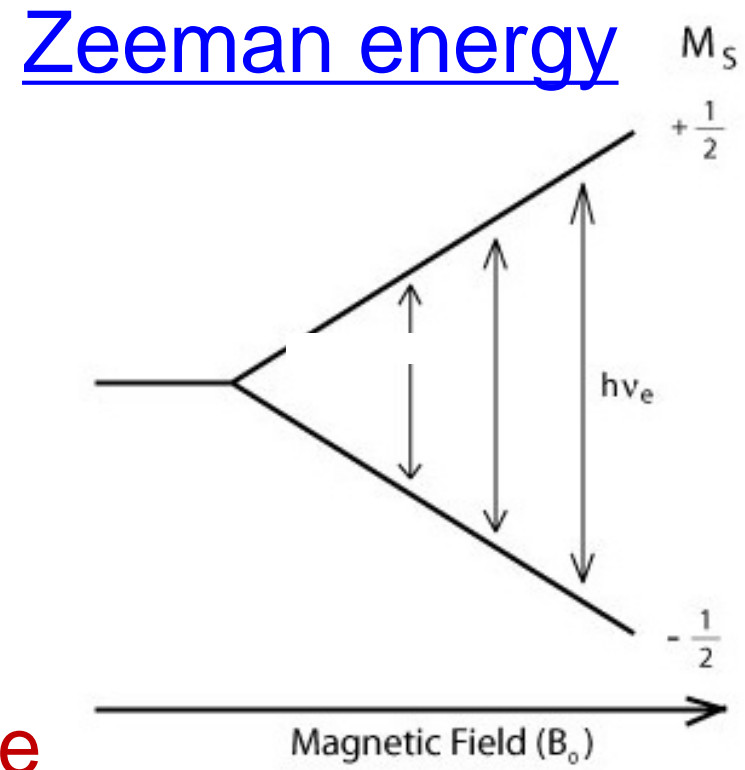
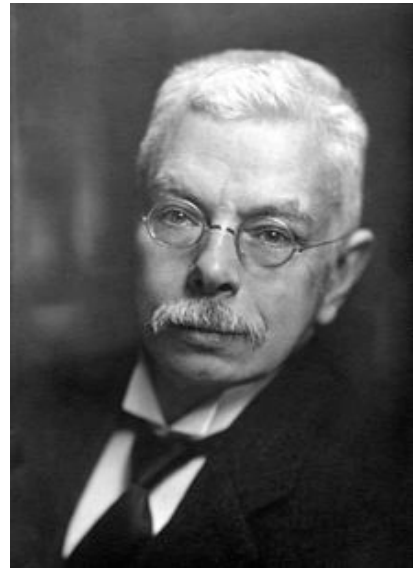
Pieter Zeeman
1902 Nobel prize



Hendrik Lorentz
1902 Nobel prize
CHARGE



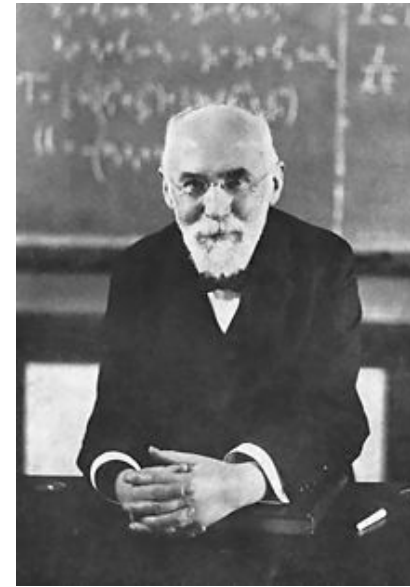
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Pieter Zeeman
1902 Nobel prize

SPIN

Concept of electron spin

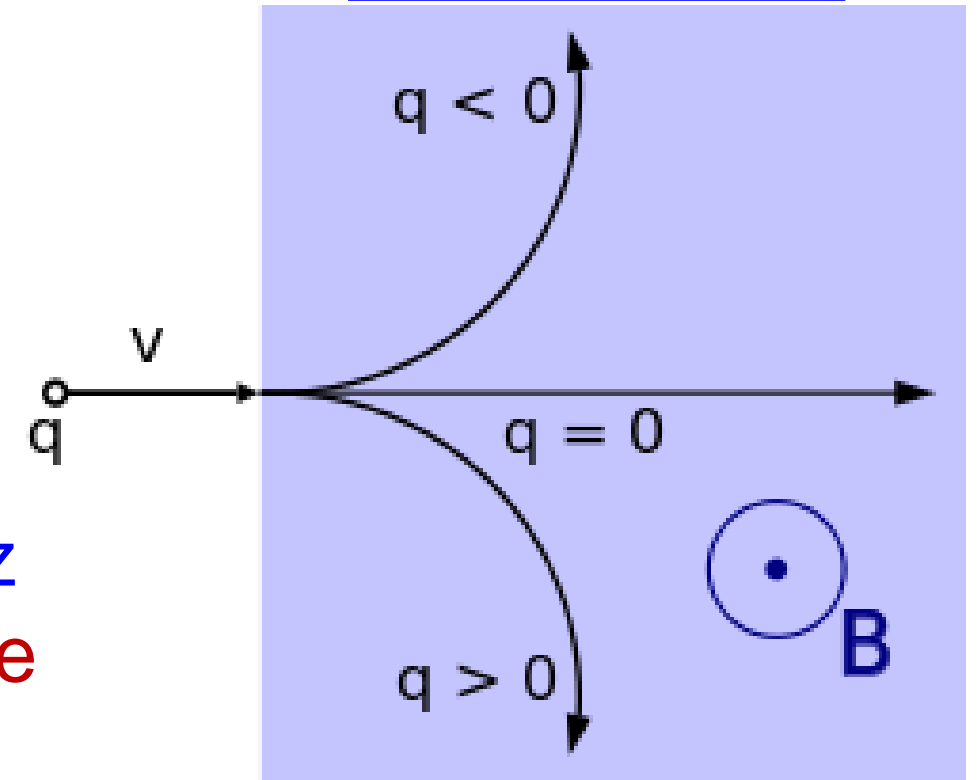


Hendrik Lorentz
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CHARGE

de Haas-van Alphen effect

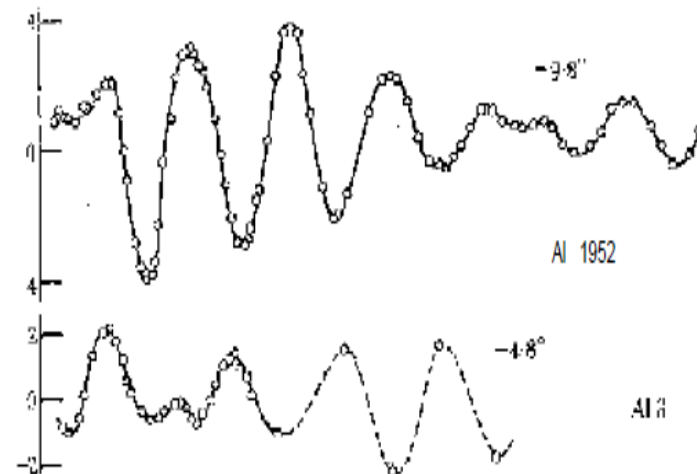
Lorentz force



Uhlenbeck



Goudsmit



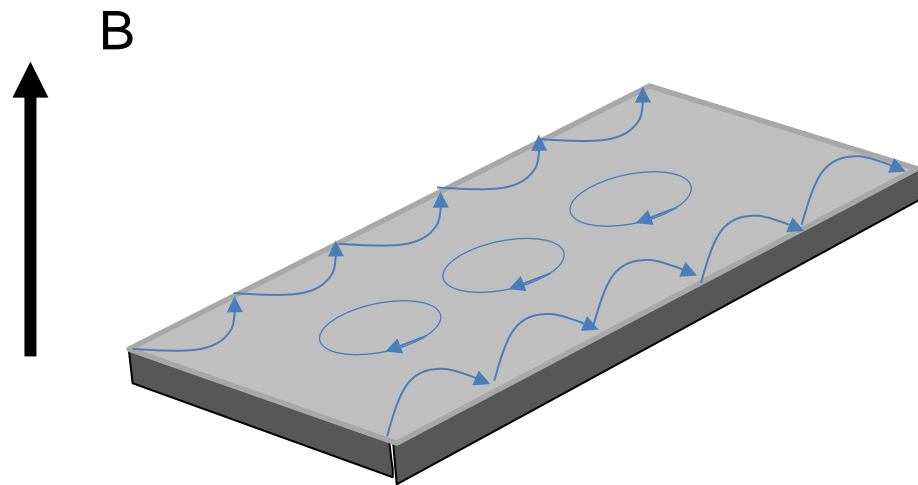
de Haas



van Alphen

Discovery of new states of matter !

Electrons in 2D + B

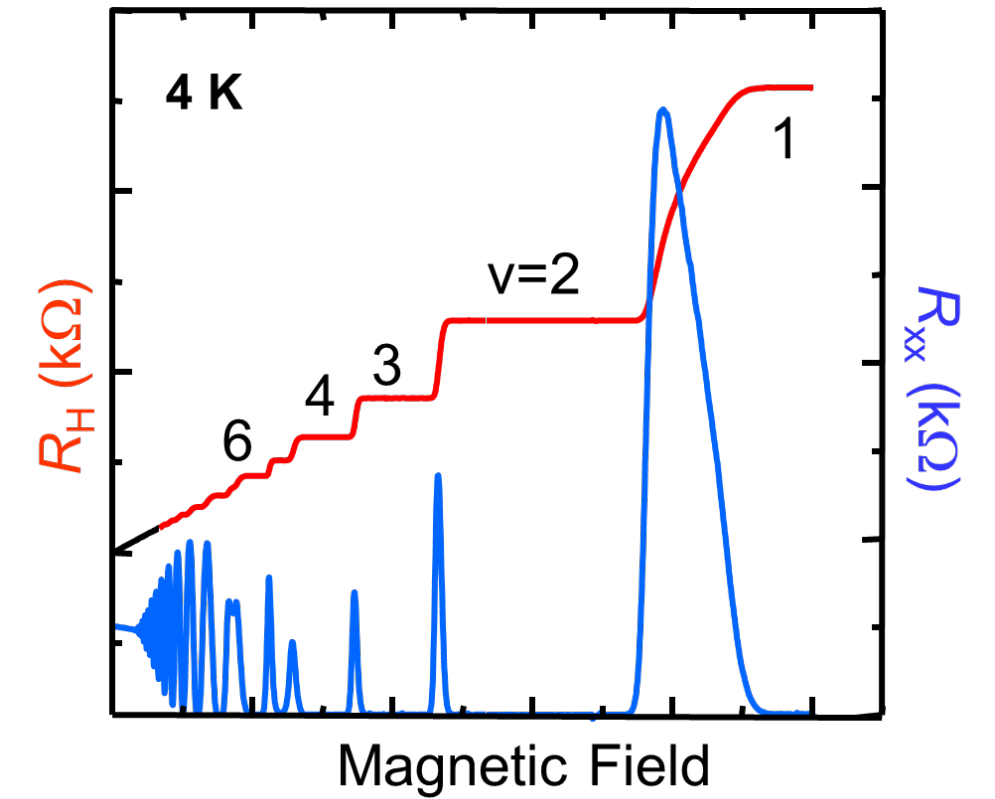


Quantum Hall effect (QHE)

[GHMFL, Grenoble, 1980]

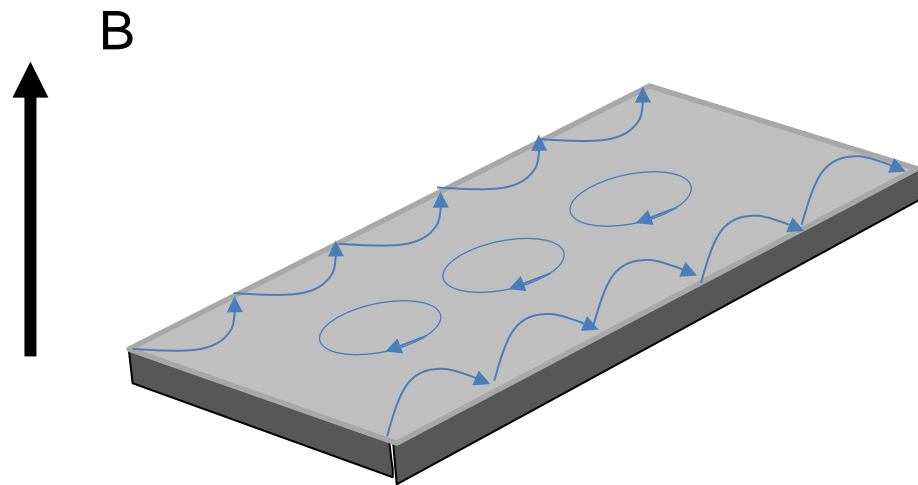


Klaus von Klitzing
1985 Nobel prize



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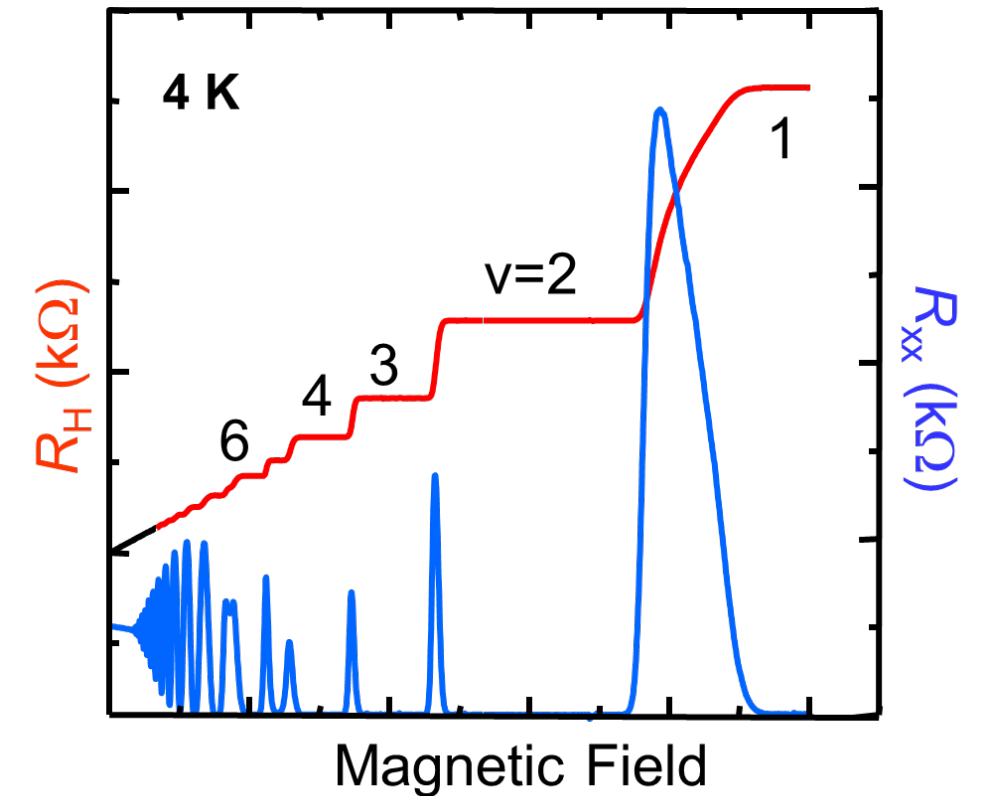


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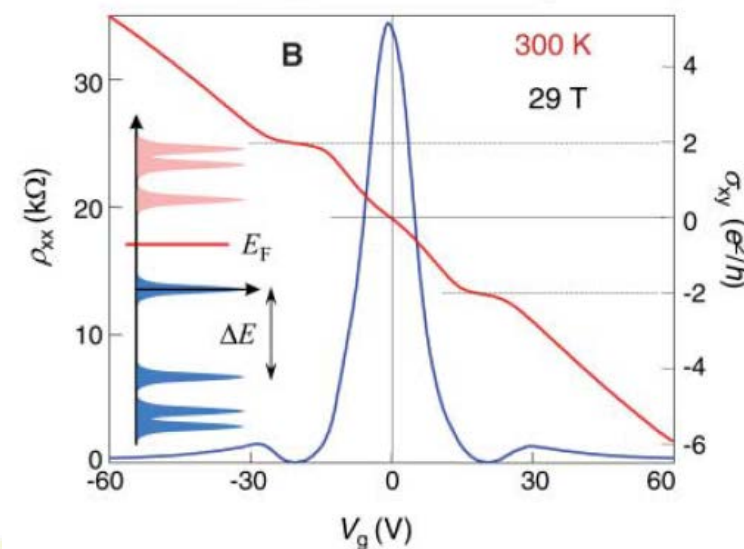
Fractional quantum Hall effect



[NBML, MIT, 1982]

Horst Störmer
Bob Laughlin
Dan Tsui
1998 Nobel prize

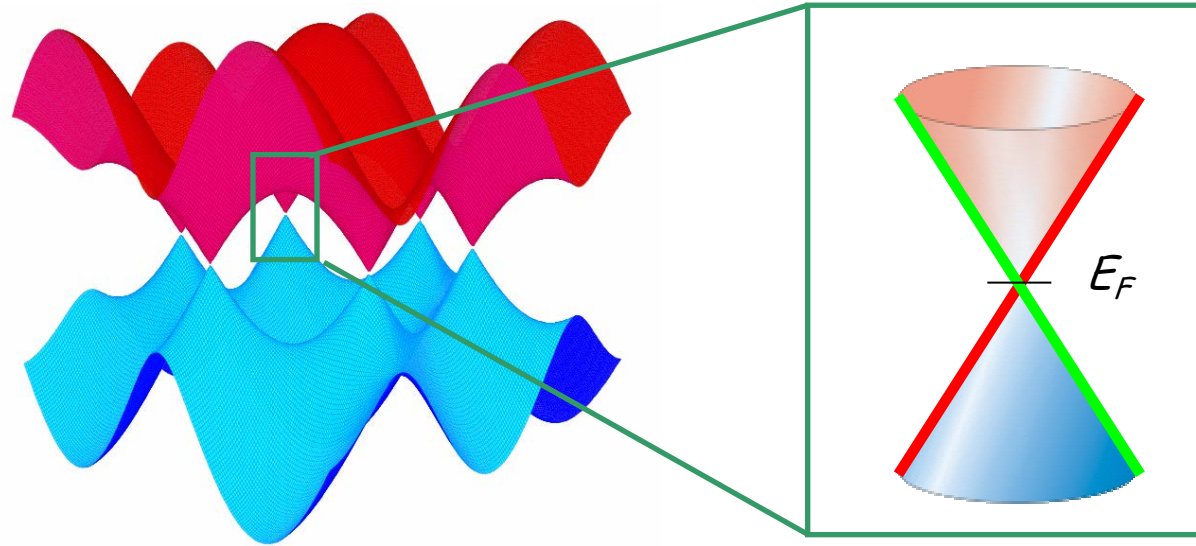
Room-temperature QHE in graphene [HFML, NHMFL, 2006]



Andre Geim
Kostya Novoselov
2010 Nobel prize



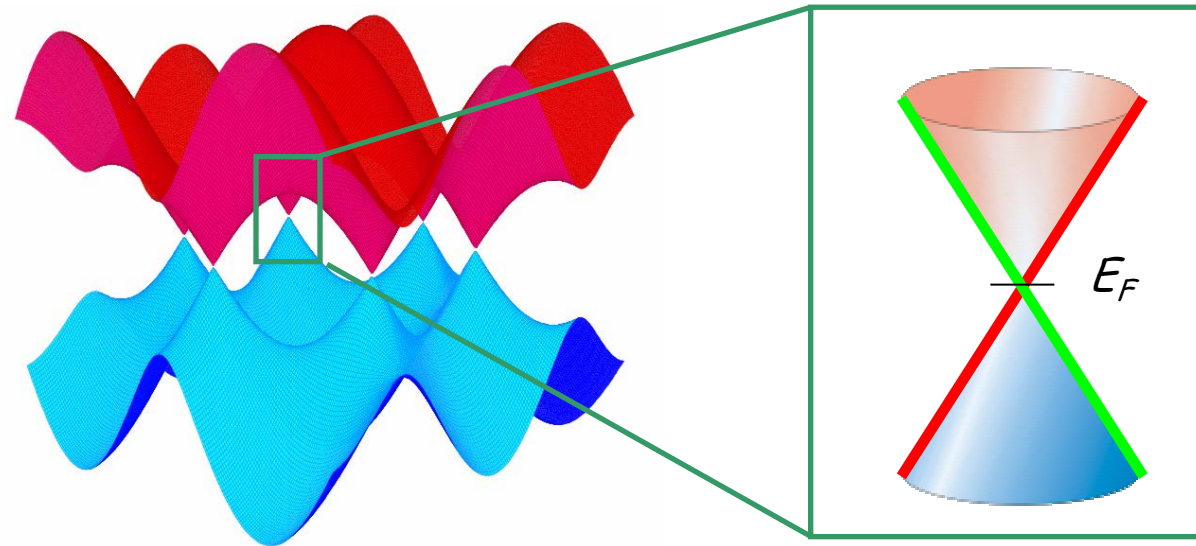
Graphene: inspiration for new materials



Linear Dispersion: Electrons behave photon-like
Degrees of freedom: Charge, Spin and Valley

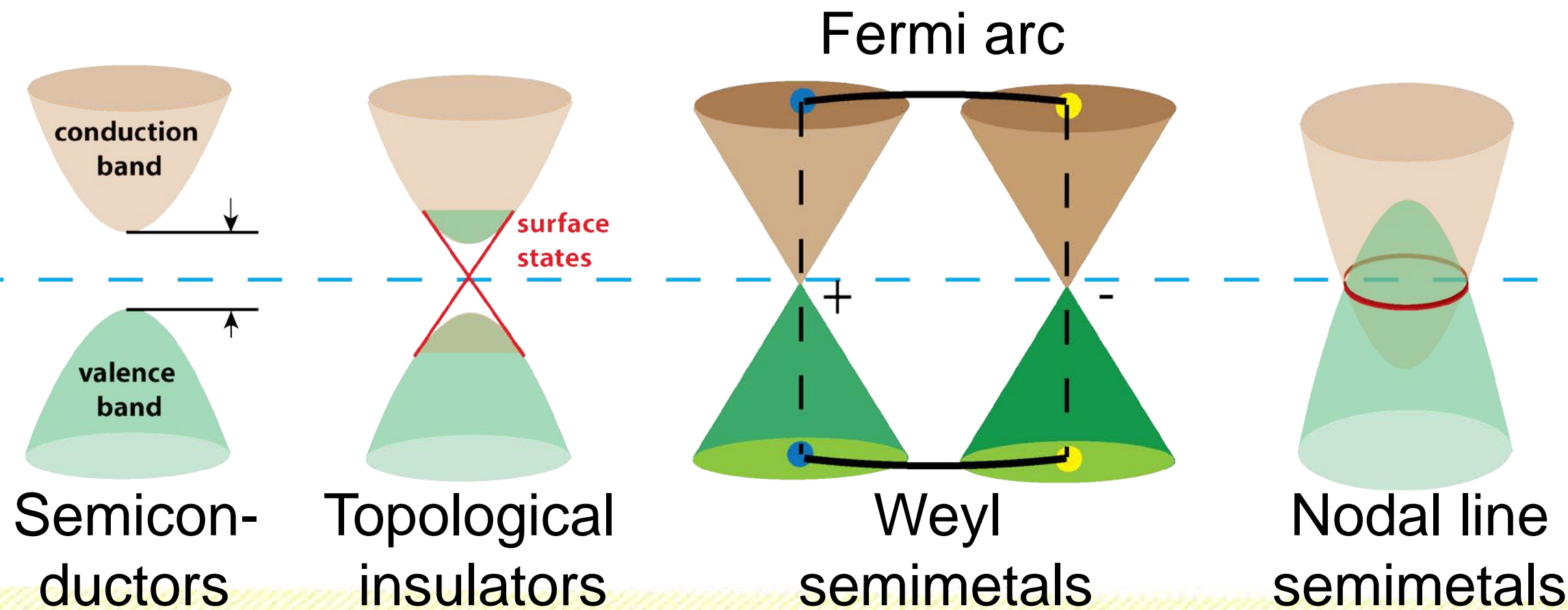
New physics through bandstructure

Graphene: inspiration for new materials

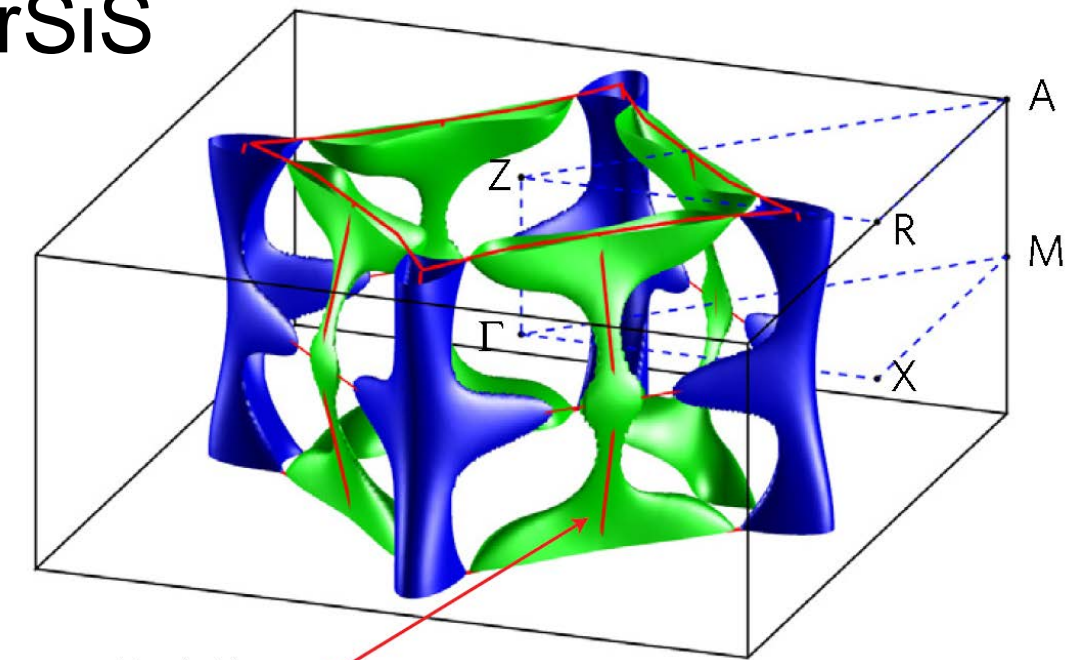


Linear Dispersion: Electrons behave photon-like
 Degrees of freedom: Charge, Spin and Valley

New physics through bandstructure



ZrSiS

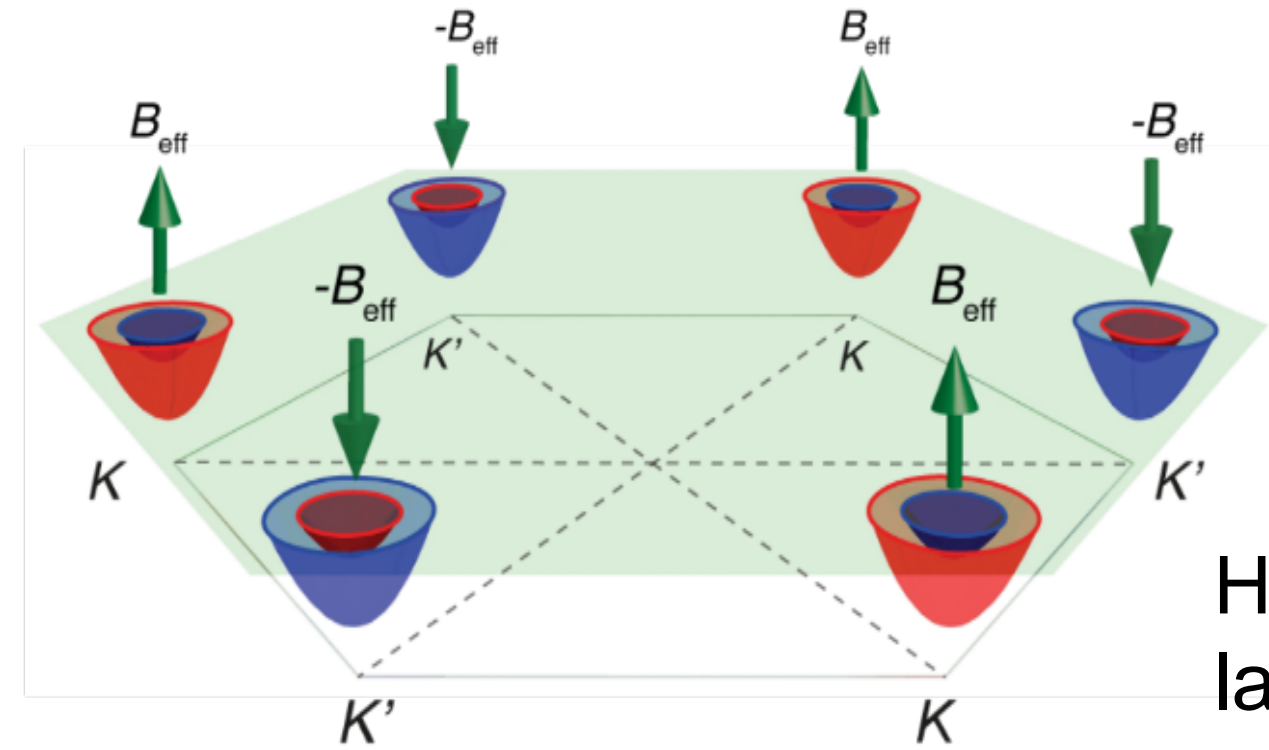
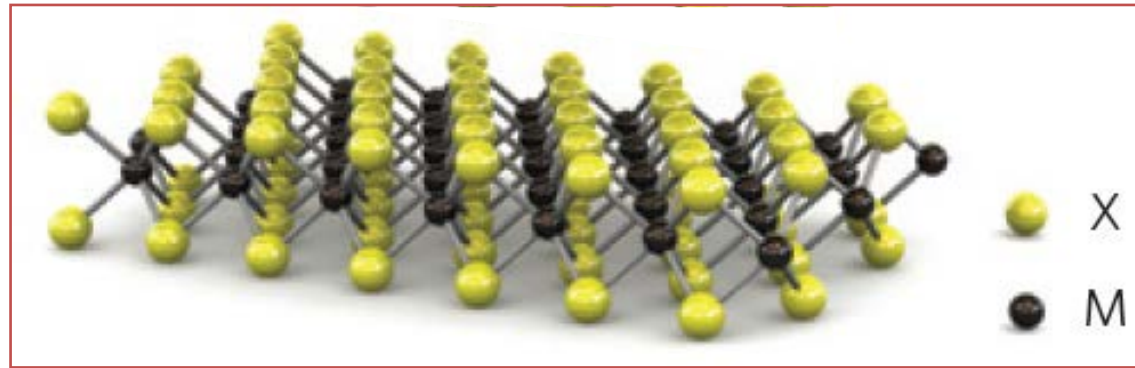


Nodal loop

Nature Phys. **14**, 178 (2018)

New 2D Semiconductors

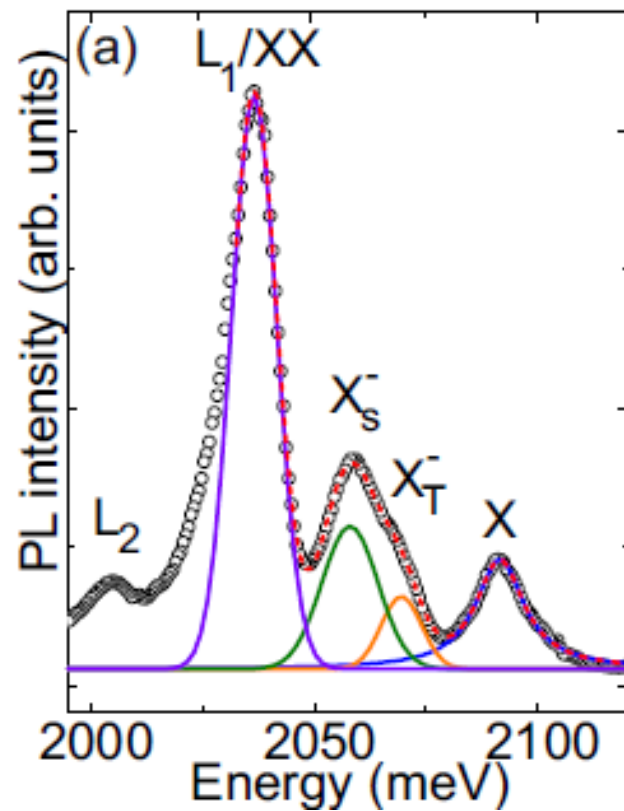
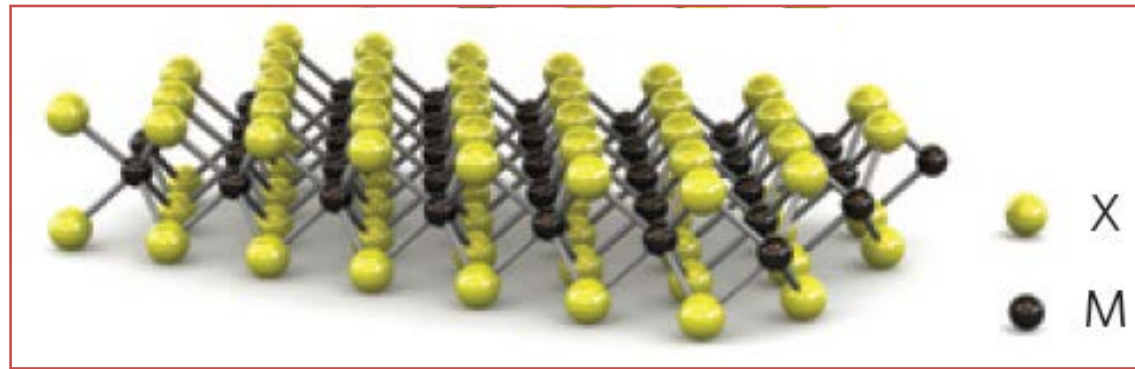
WSe_2 , WS_2 , MoSe_2 , MoS_2



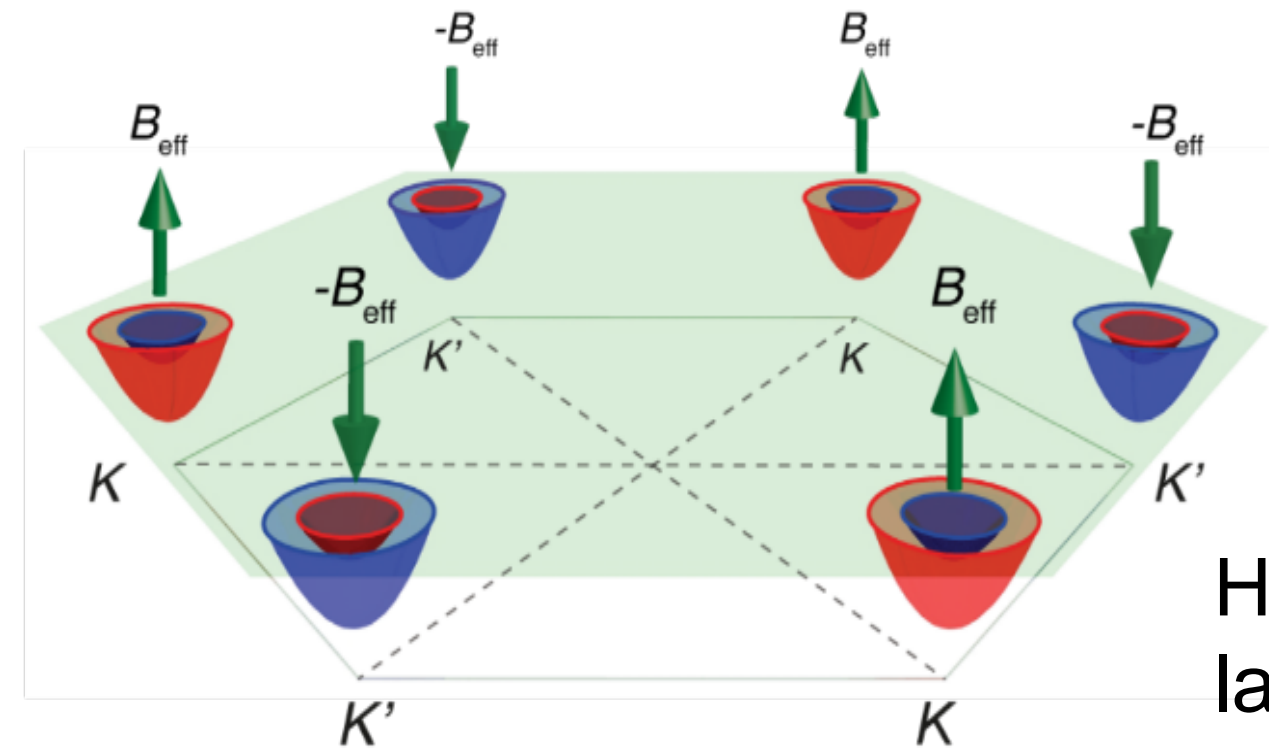
Honeycomb
lattice:
Valleys

New 2D Semiconductors

WSe_2 , WS_2 , MoSe_2 , MoS_2



Direct bandgap
semiconductors
with distinct
valley structure

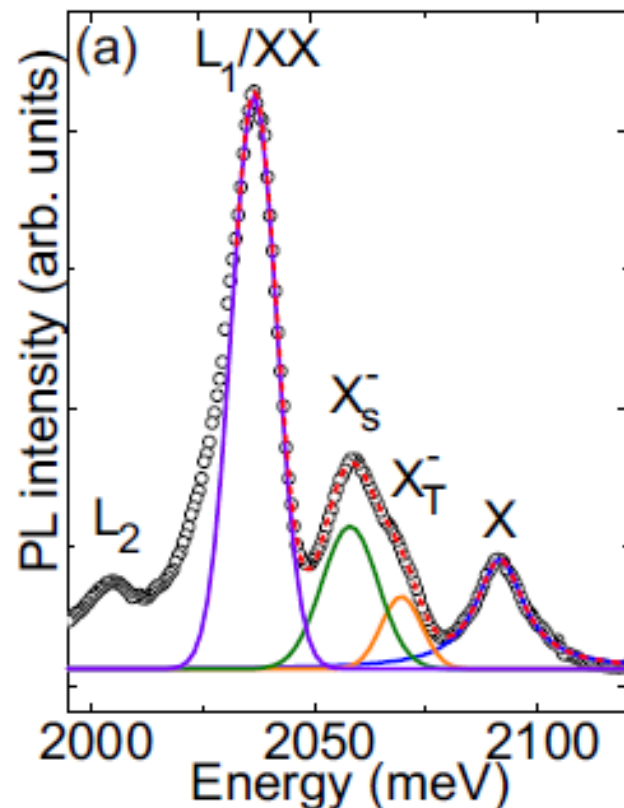
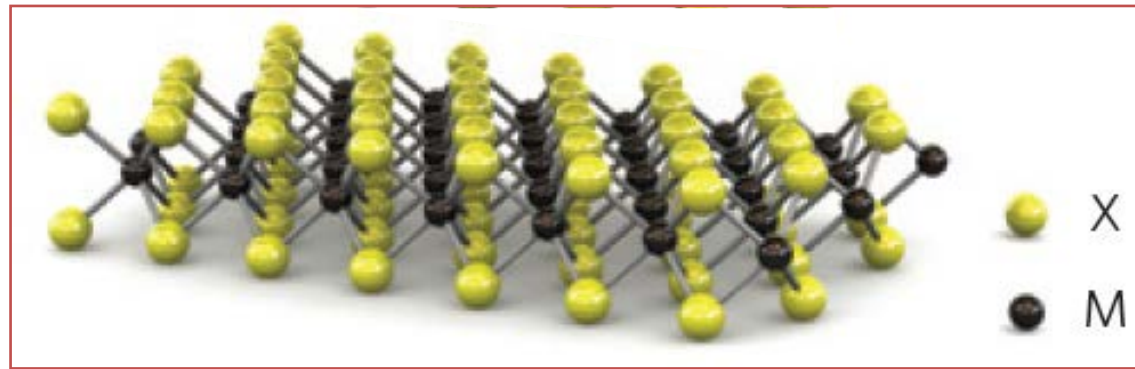


Honeycomb
lattice:
Valleys

Nature Comm. **7**, 12715 (2016)

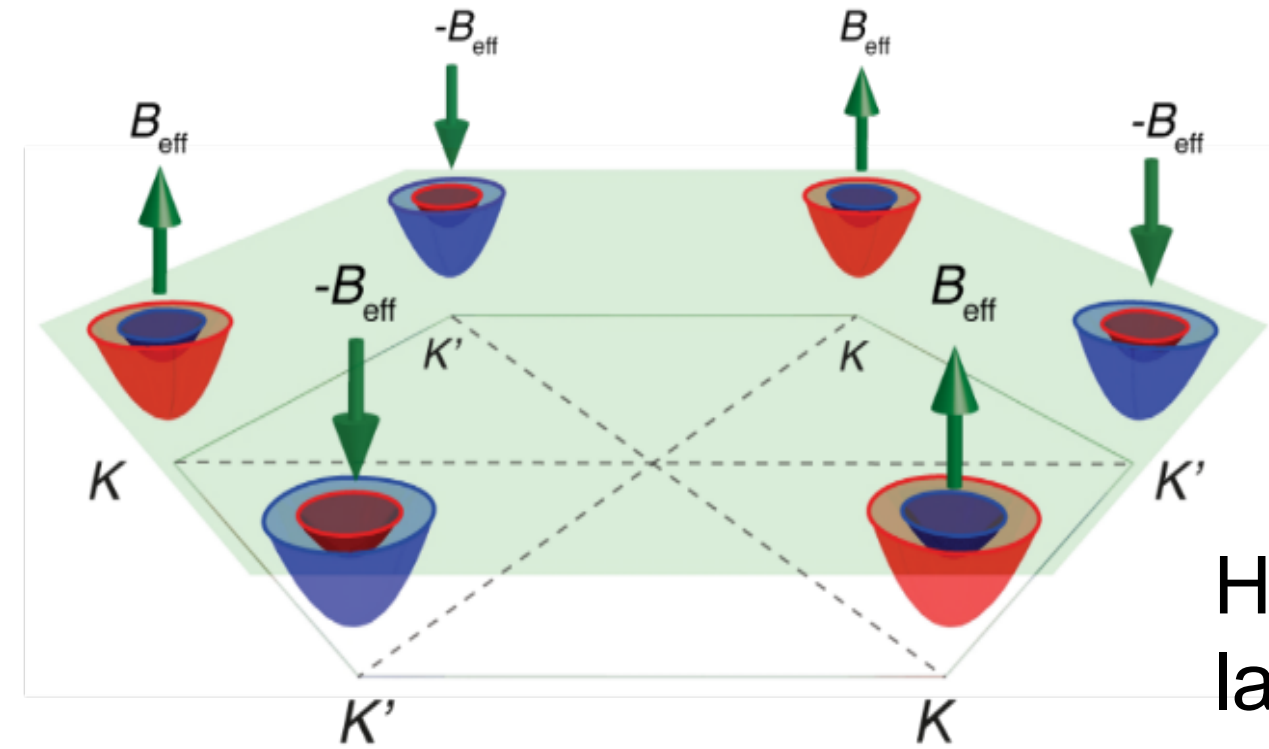
New 2D Semiconductors

WSe₂, WS₂, MoSe₂, MoS₂

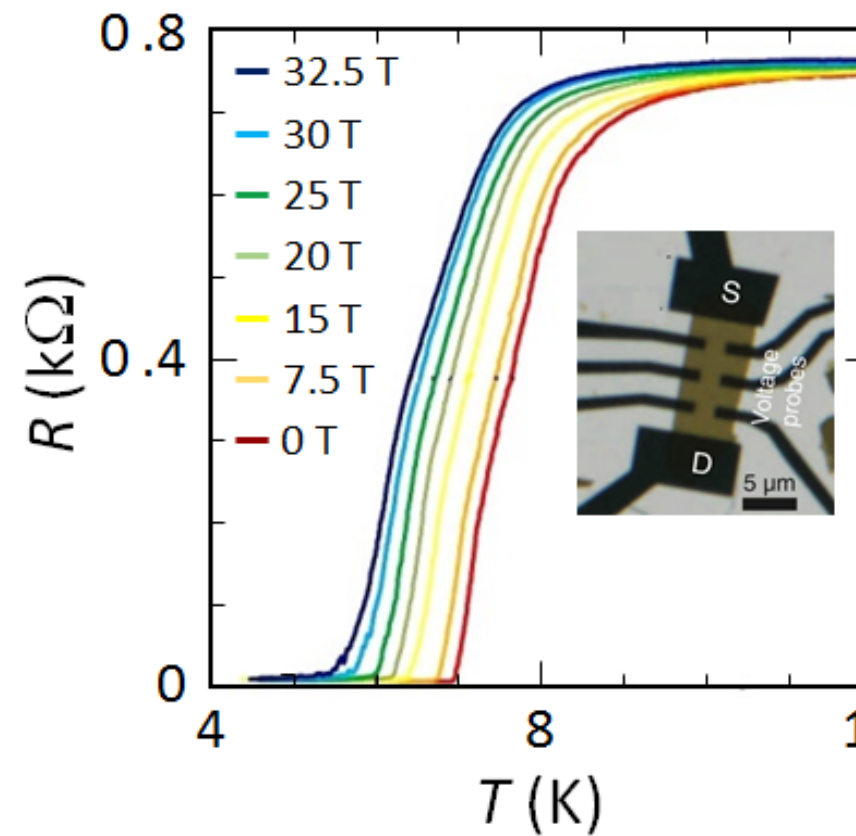


Direct bandgap
semiconductors
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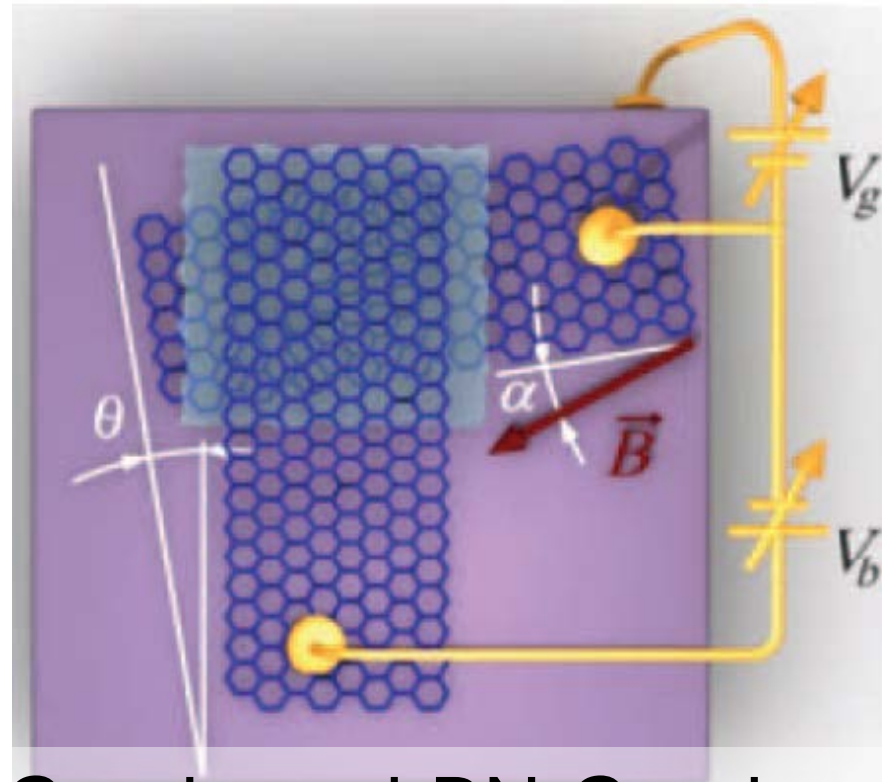
Honeycomb
lattice:
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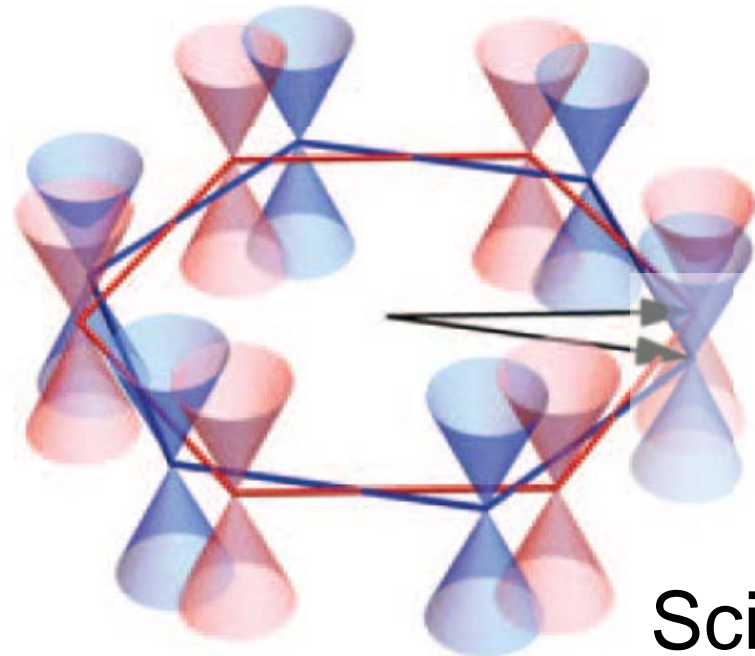
Gated MoS₂ structures:
superconductors that
resist high fields due to
strong spin-orbit coupling

Science **350**, 1353 (2015)

Van der Waals Heterostructures



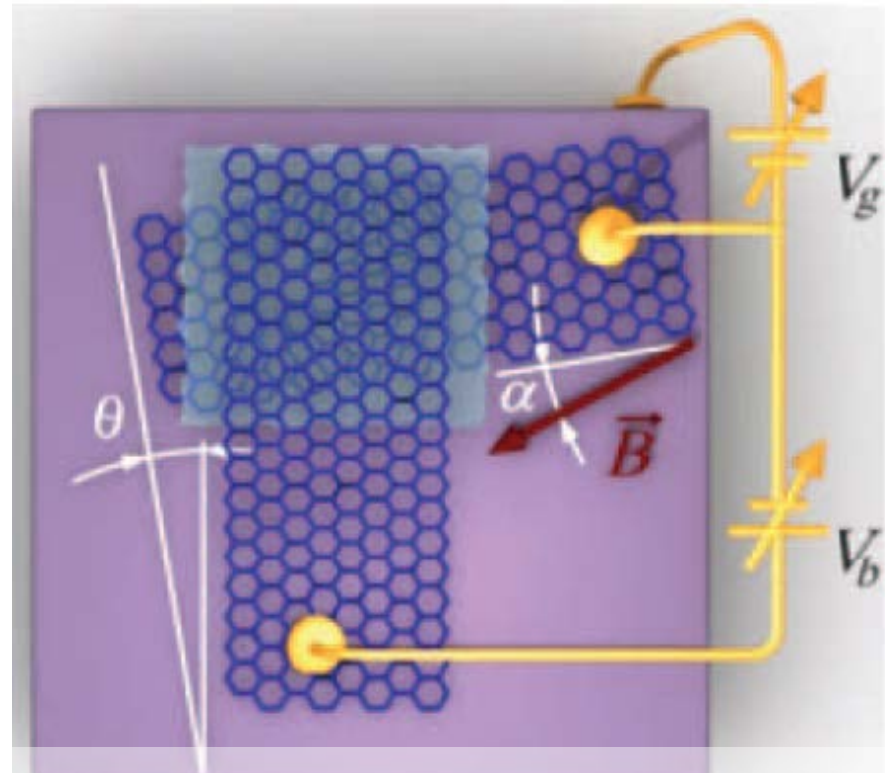
Graphene-hBN-Graphene



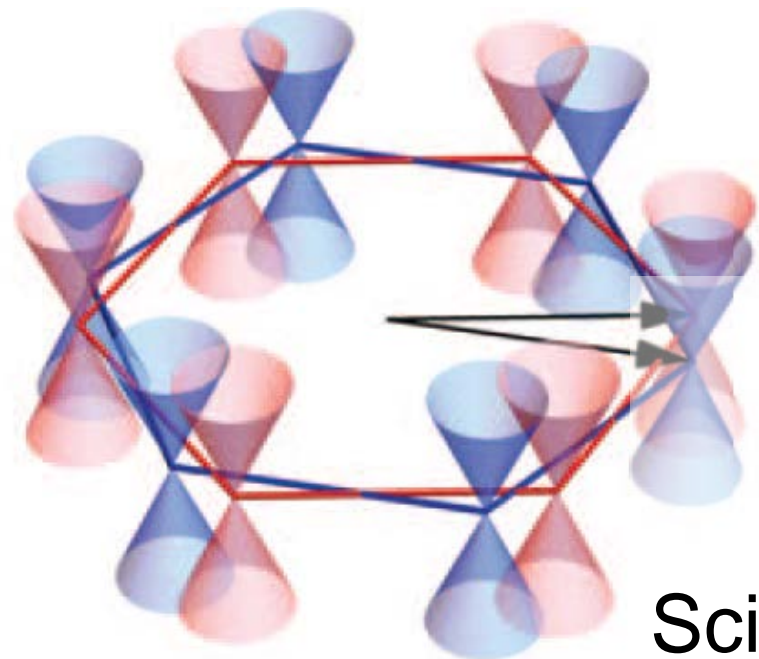
Chiral quantum states
of Dirac electrons

Science **353**, 6299 (2016)

Van der Waals Heterostructures

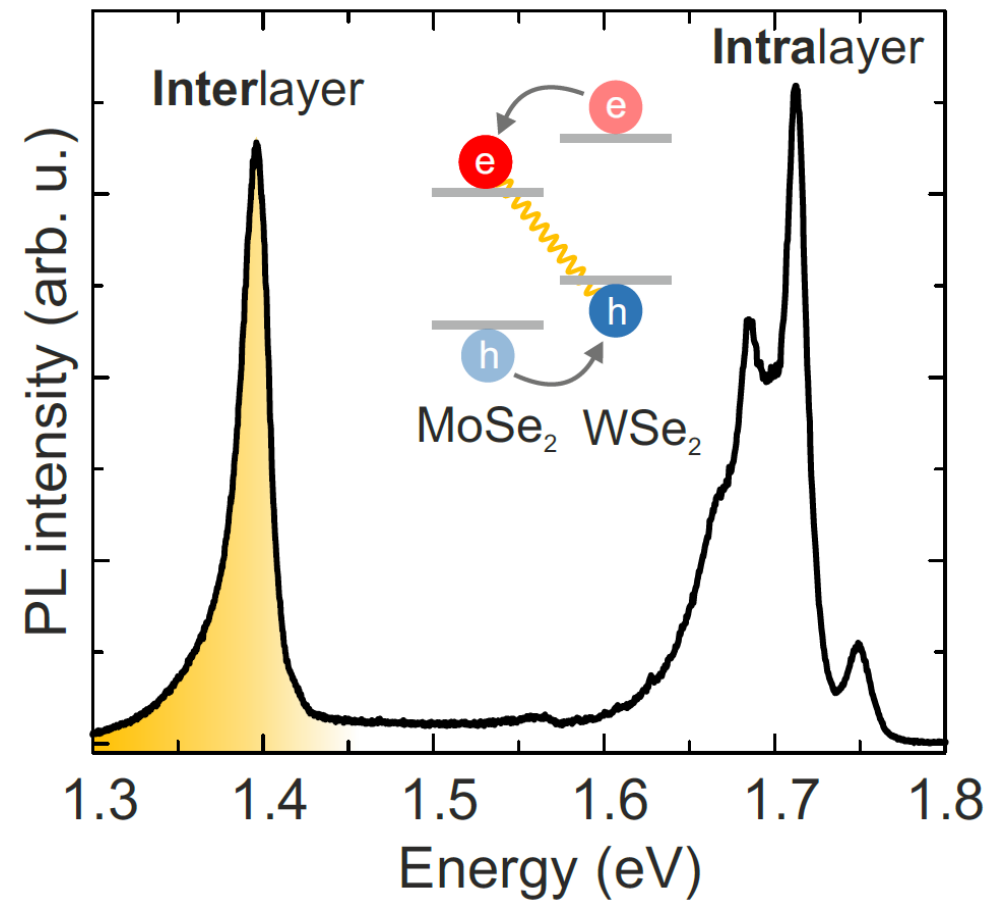


Graphene-hBN-Graphene



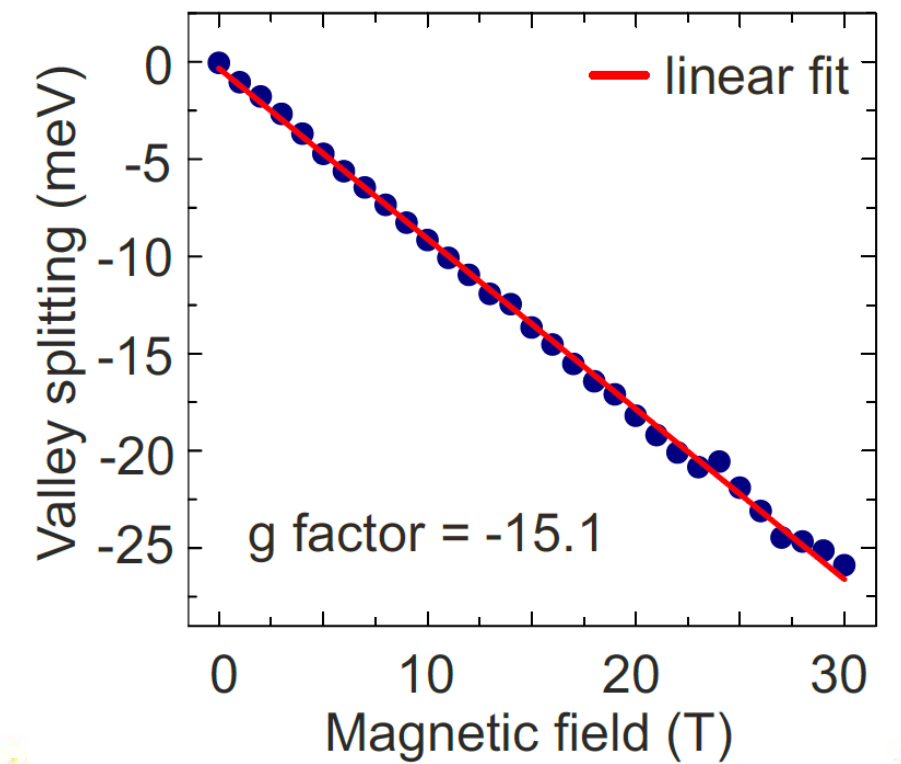
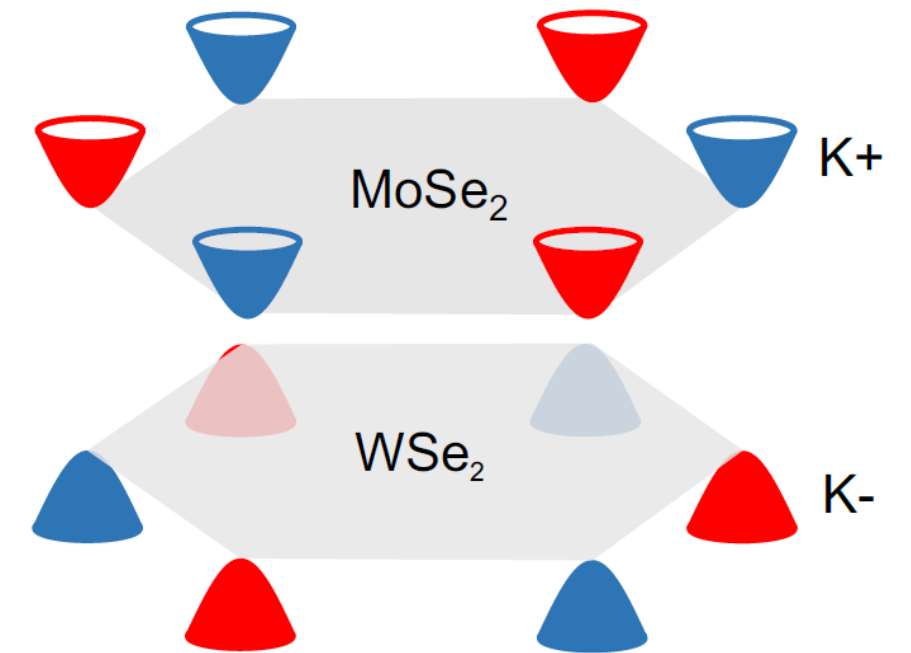
Chiral quantum states of Dirac Electrons

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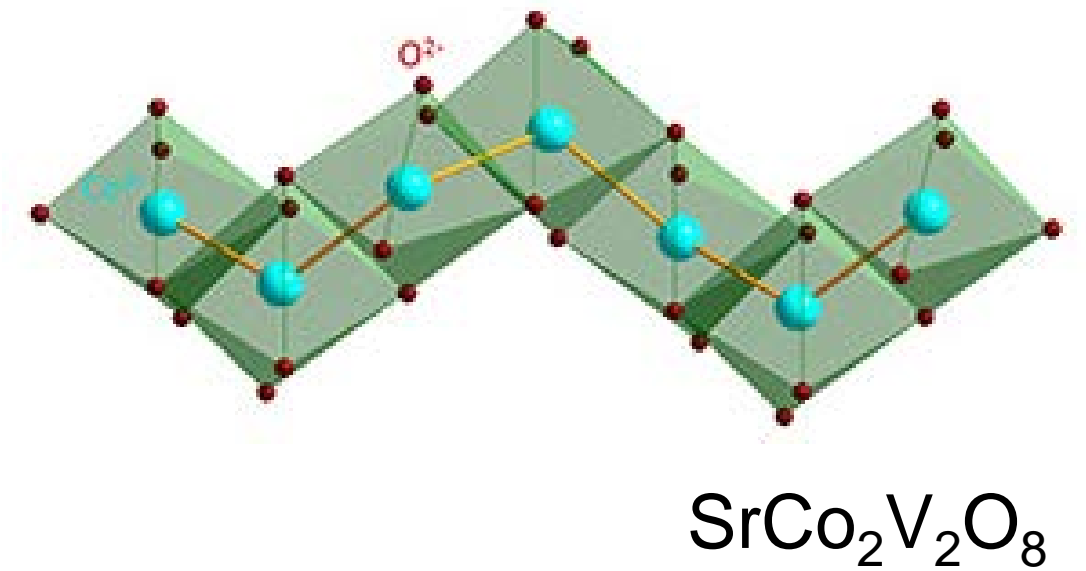
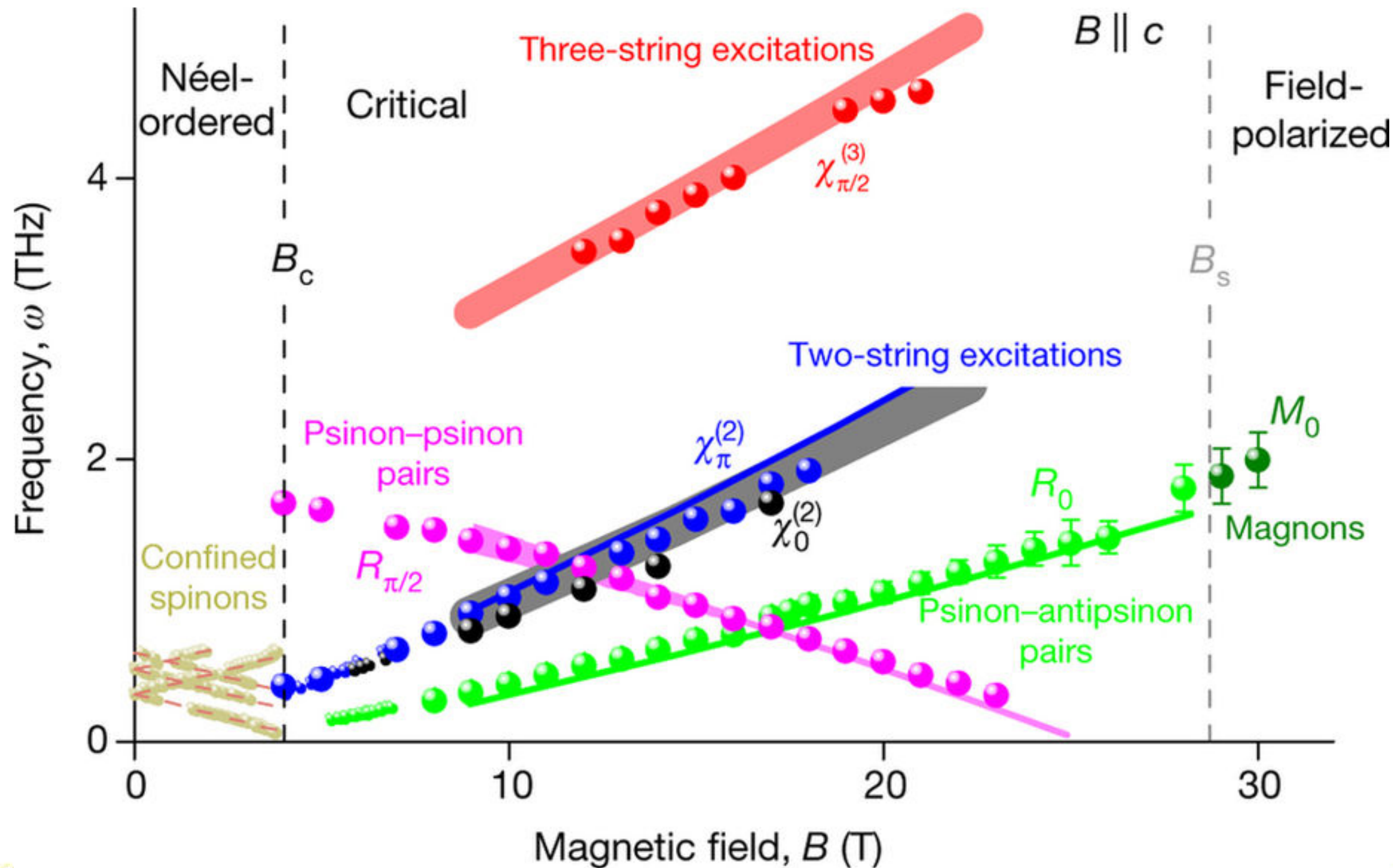


Giant Zeeman splitting due to specific valley-valley stacking

Nature Comm. **8**, 1551 (2017)



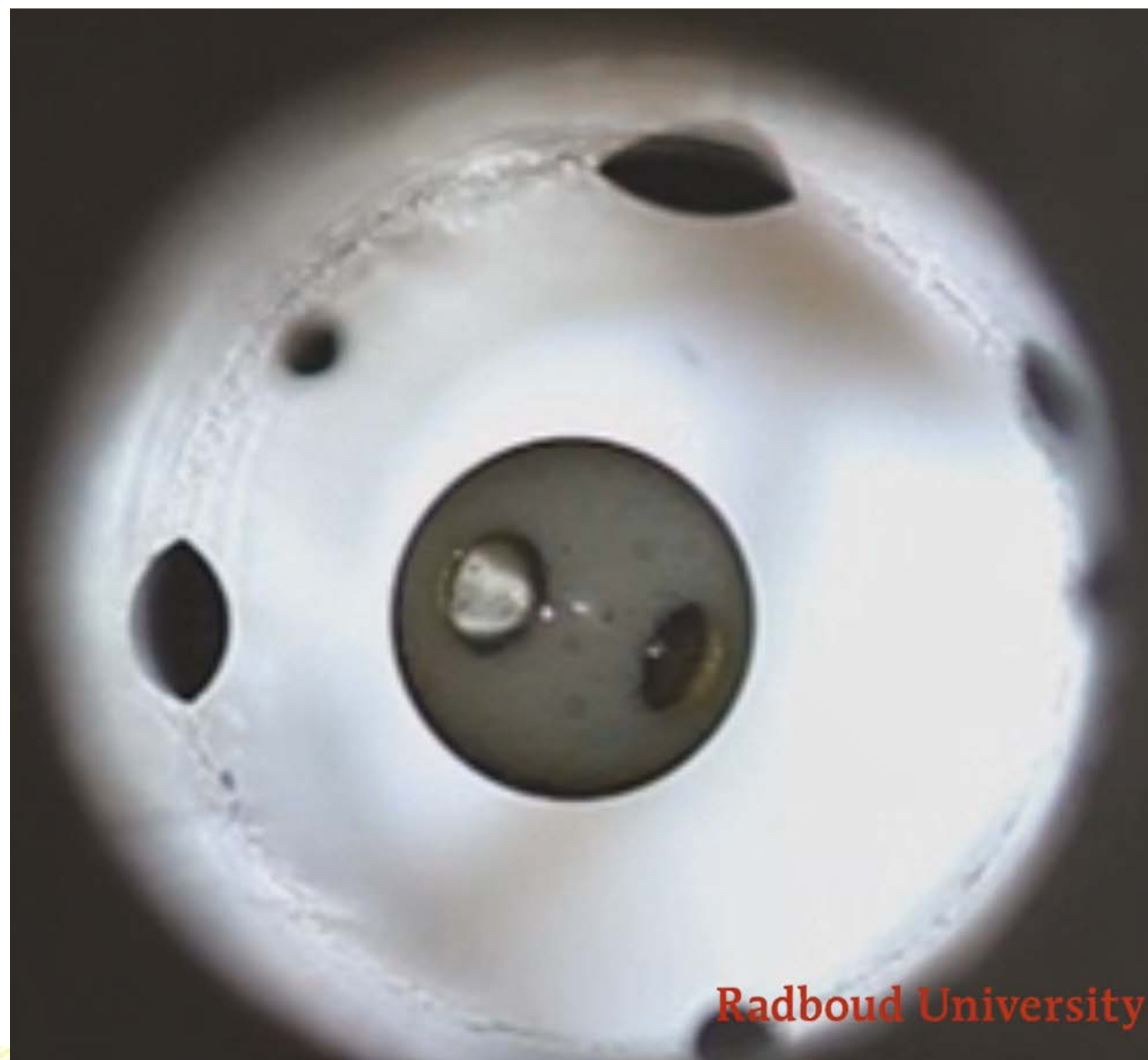
Magnetism: observation of Bethe strings



Nature **554**, 219 (2018)

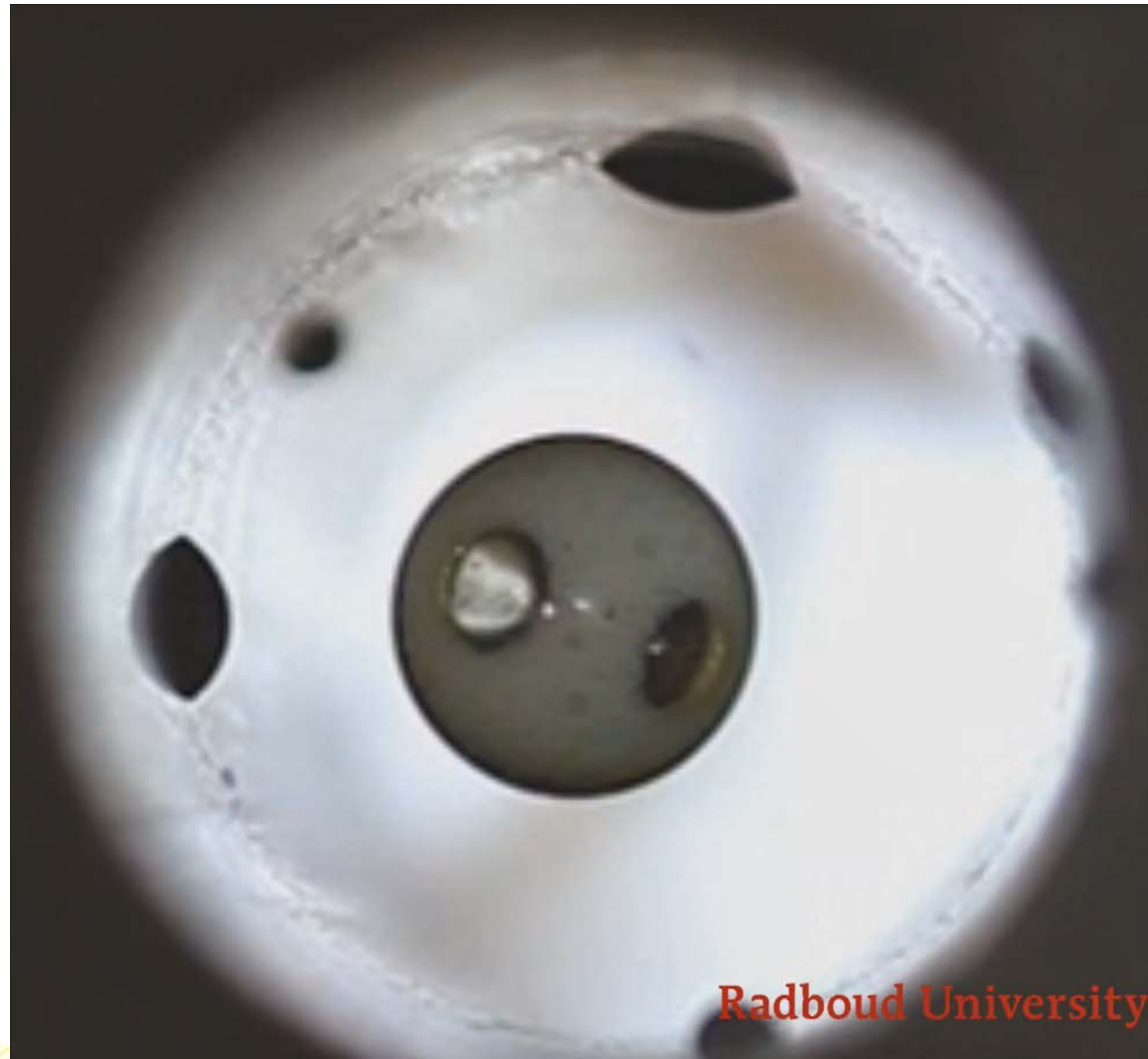
Everything is magnetic !

Magnetic Levitation

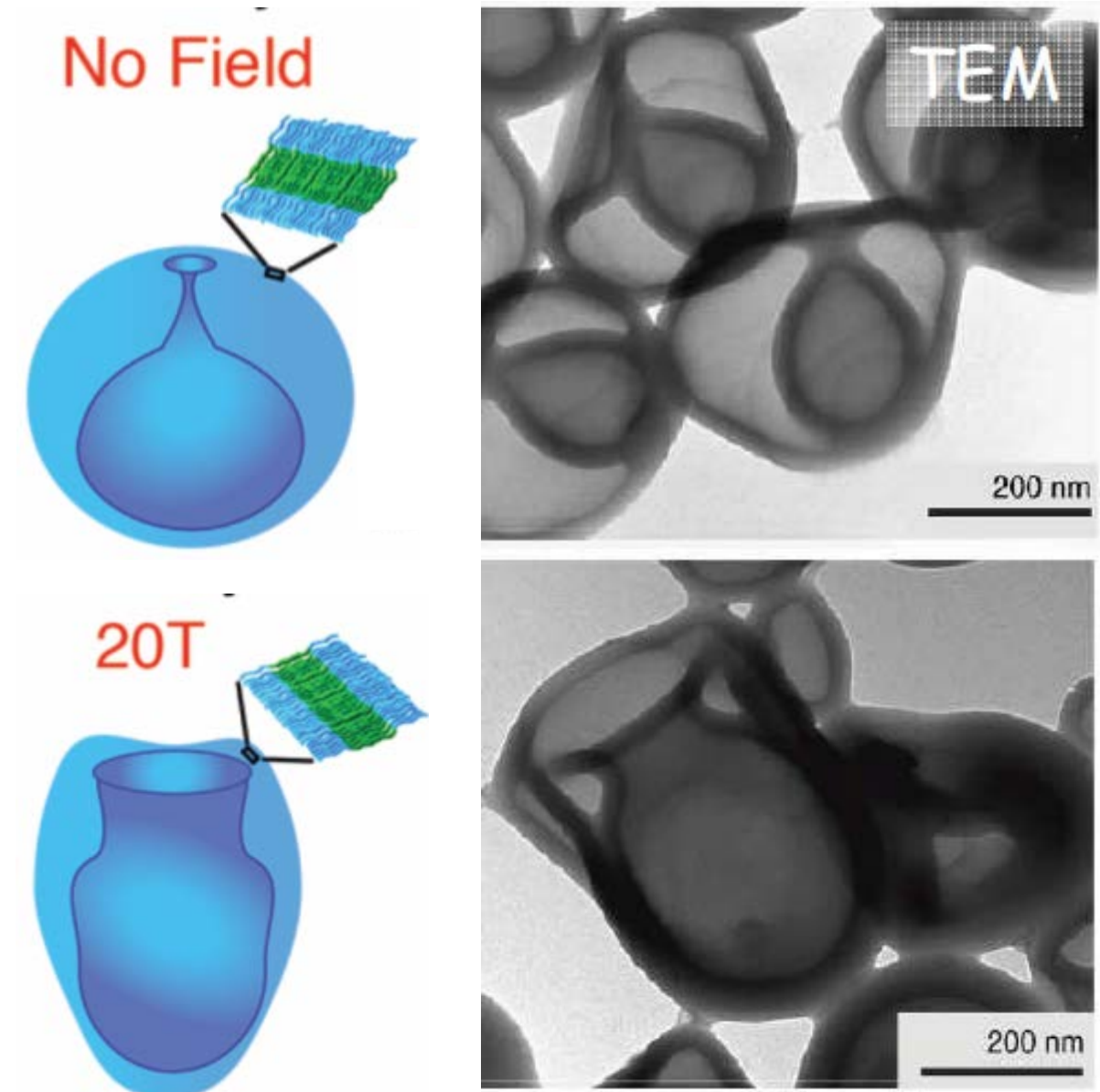


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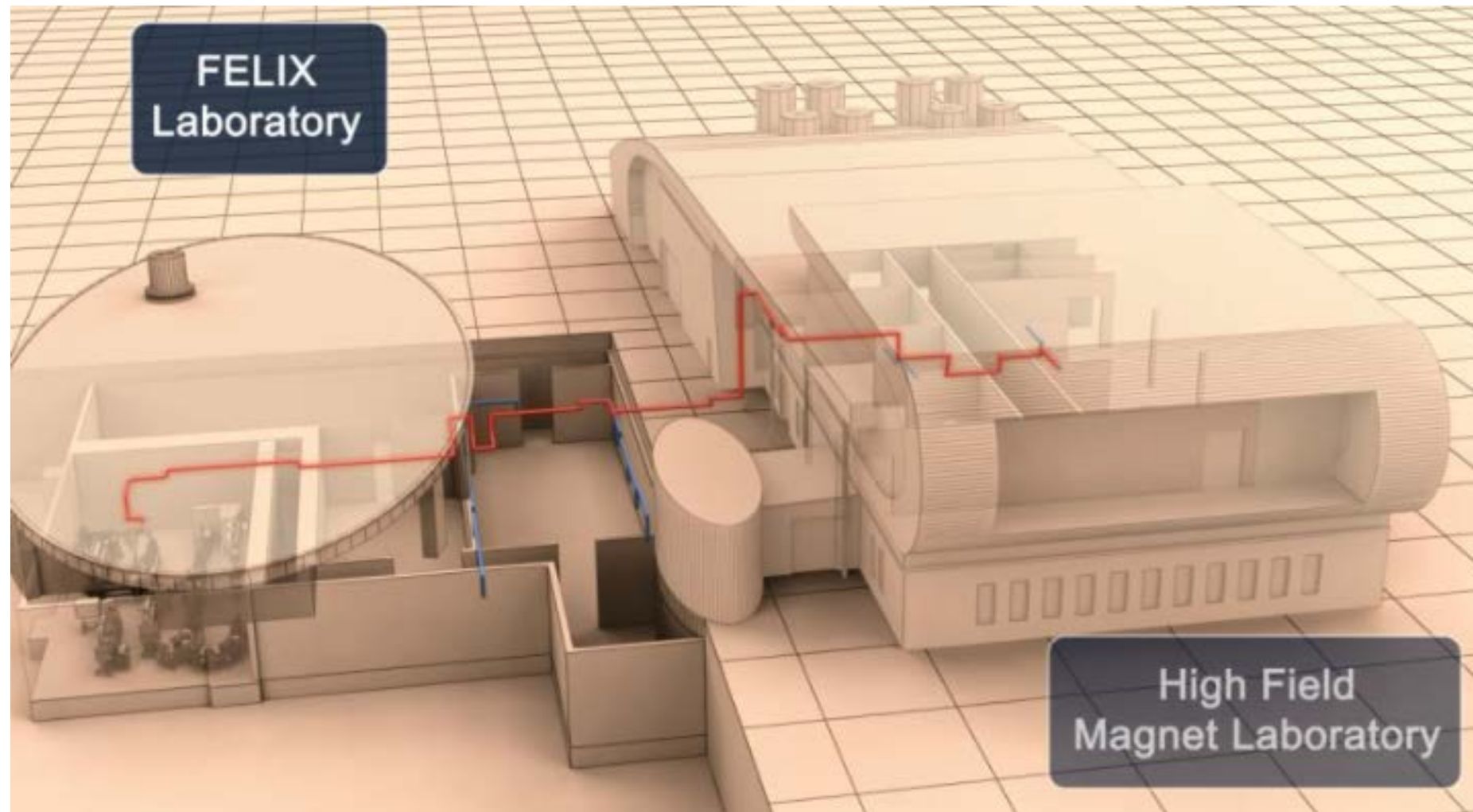
Magnetic Manipulation of Soft Matter



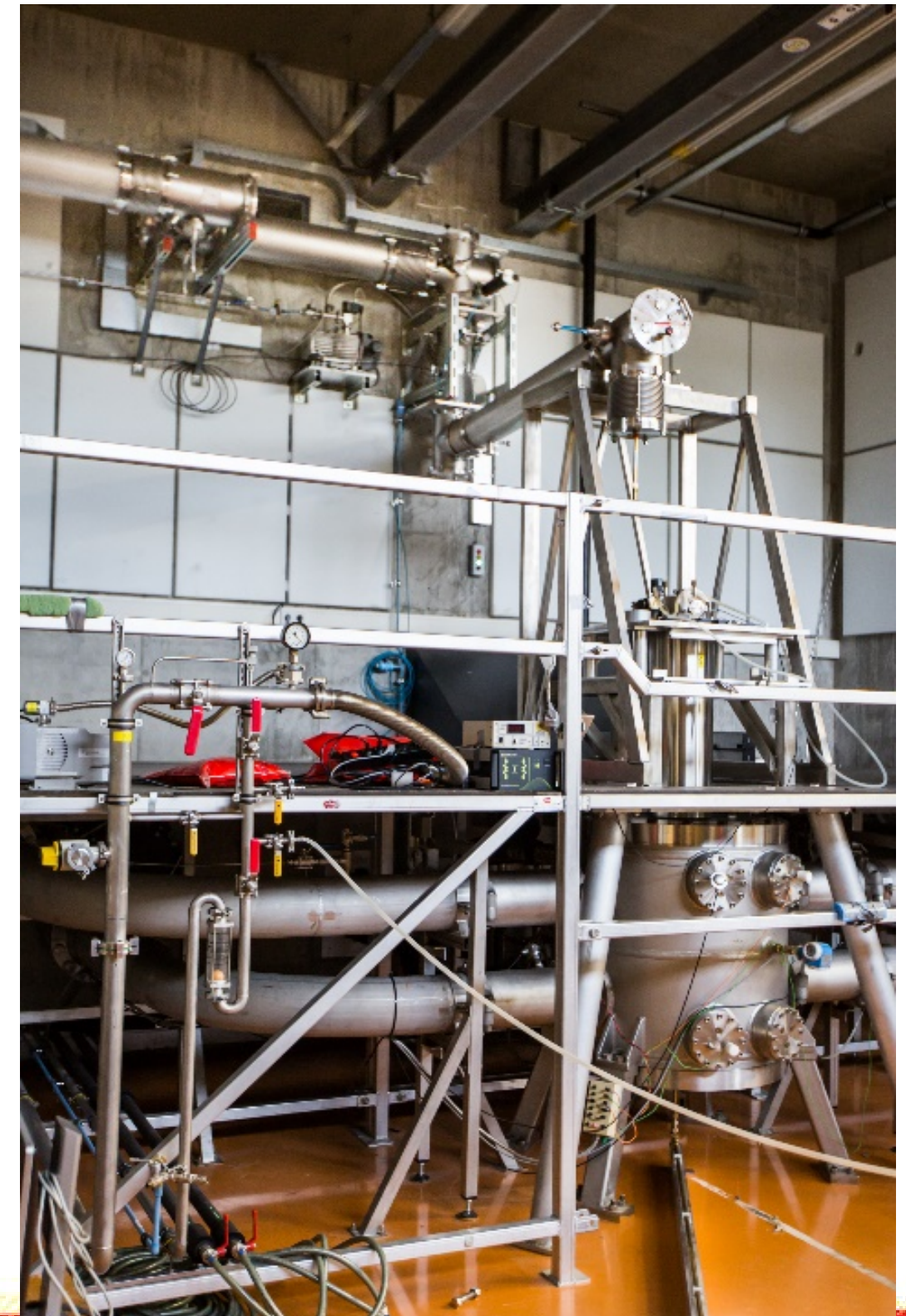
Nature Comm. **5**, 5010 (2014)

Nature Comm. **7**, 12606 (2016)

Combination with Free Electron Laser Radiation

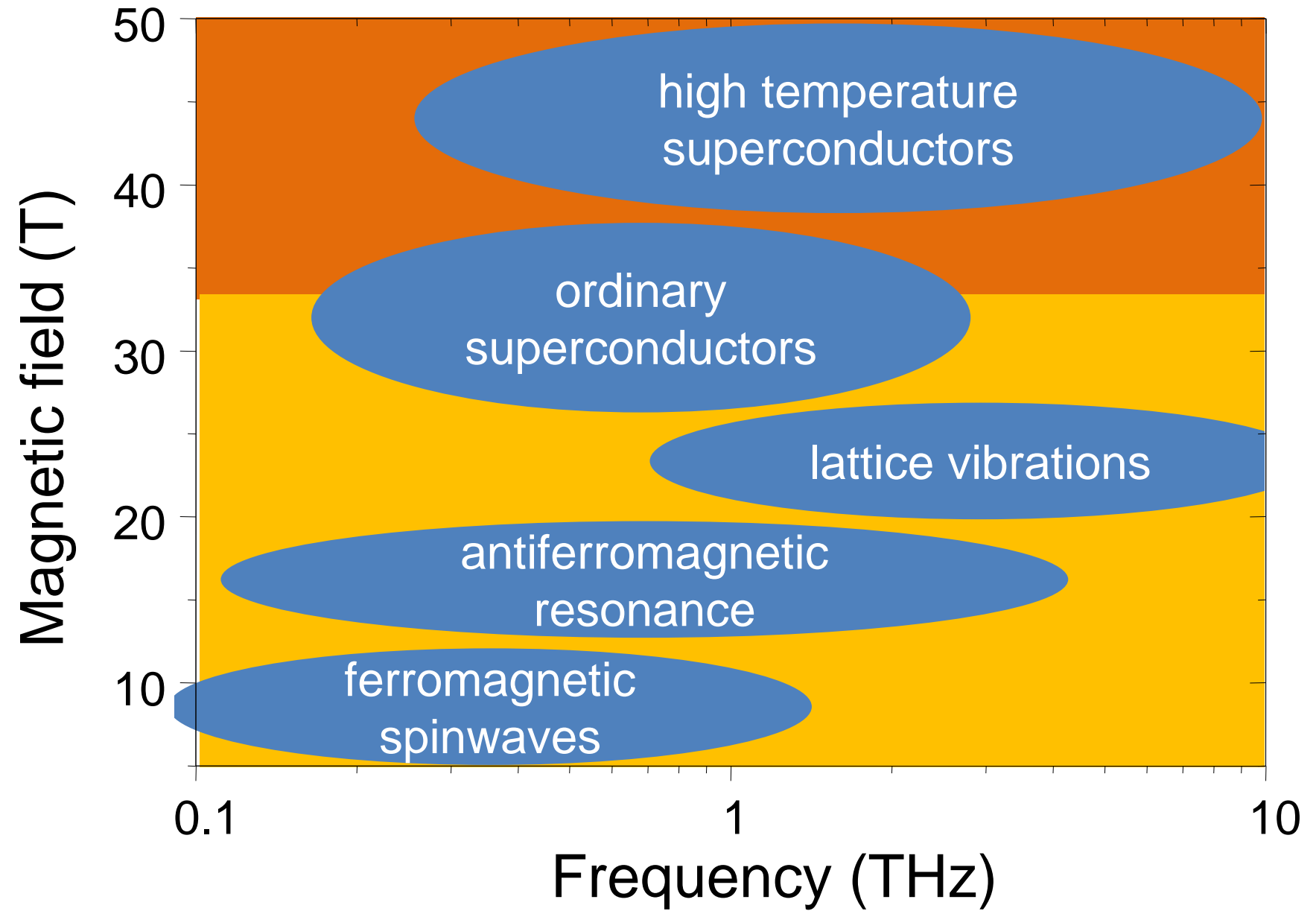
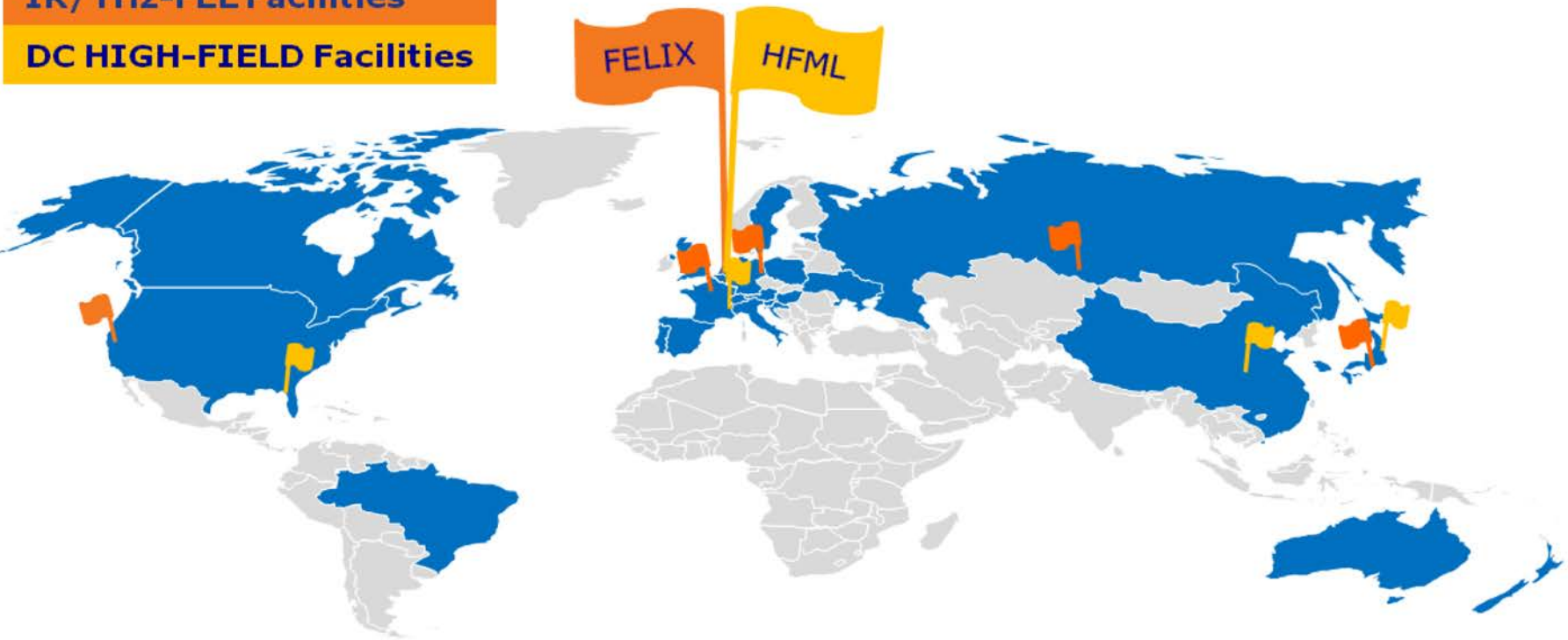


- 3 FELs (3 – 1500 μm) connected to 33 T magnet
- 90 m long beam line with 42 mirrors
- Combination in operation - open for external users
- Worldwide unique



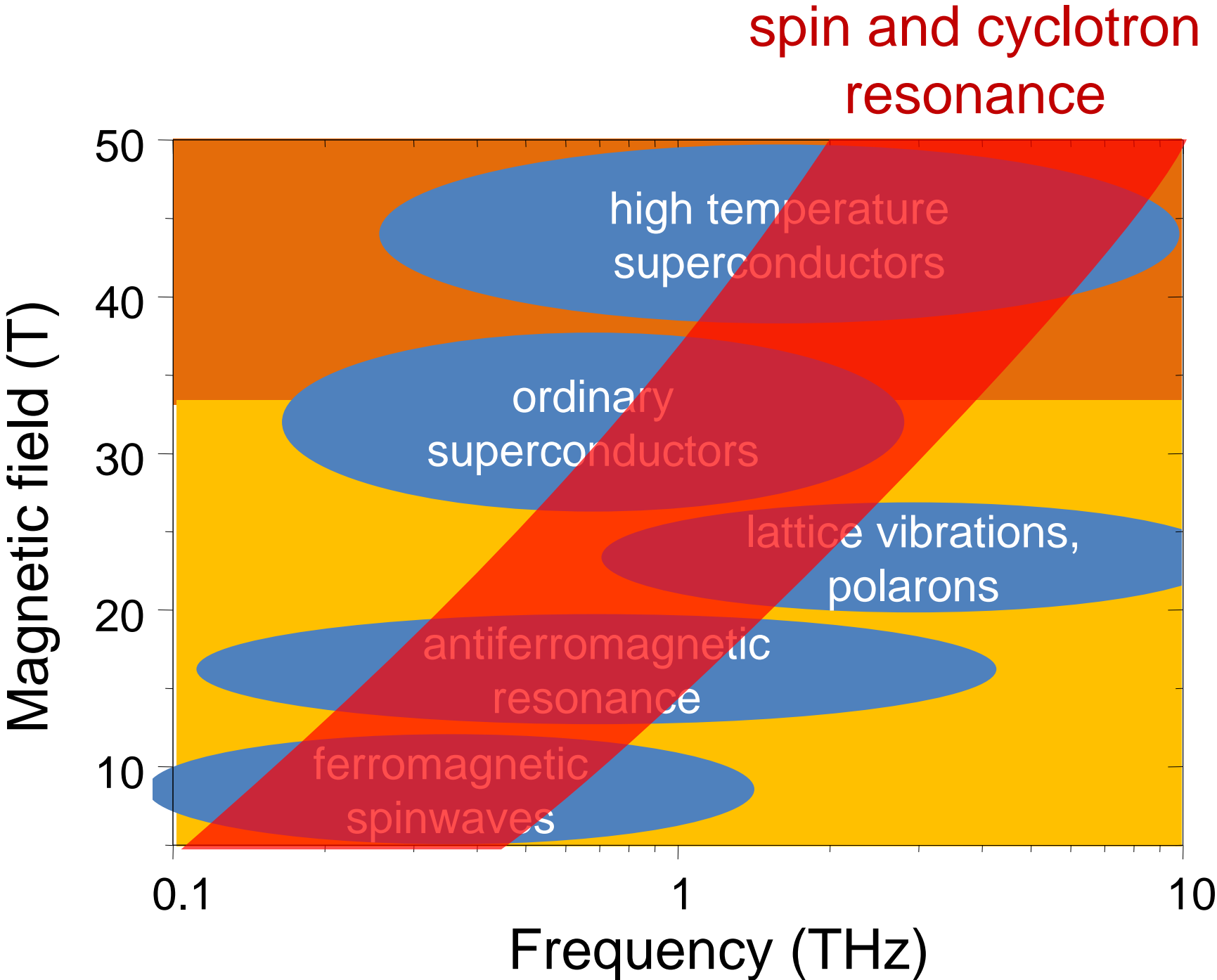
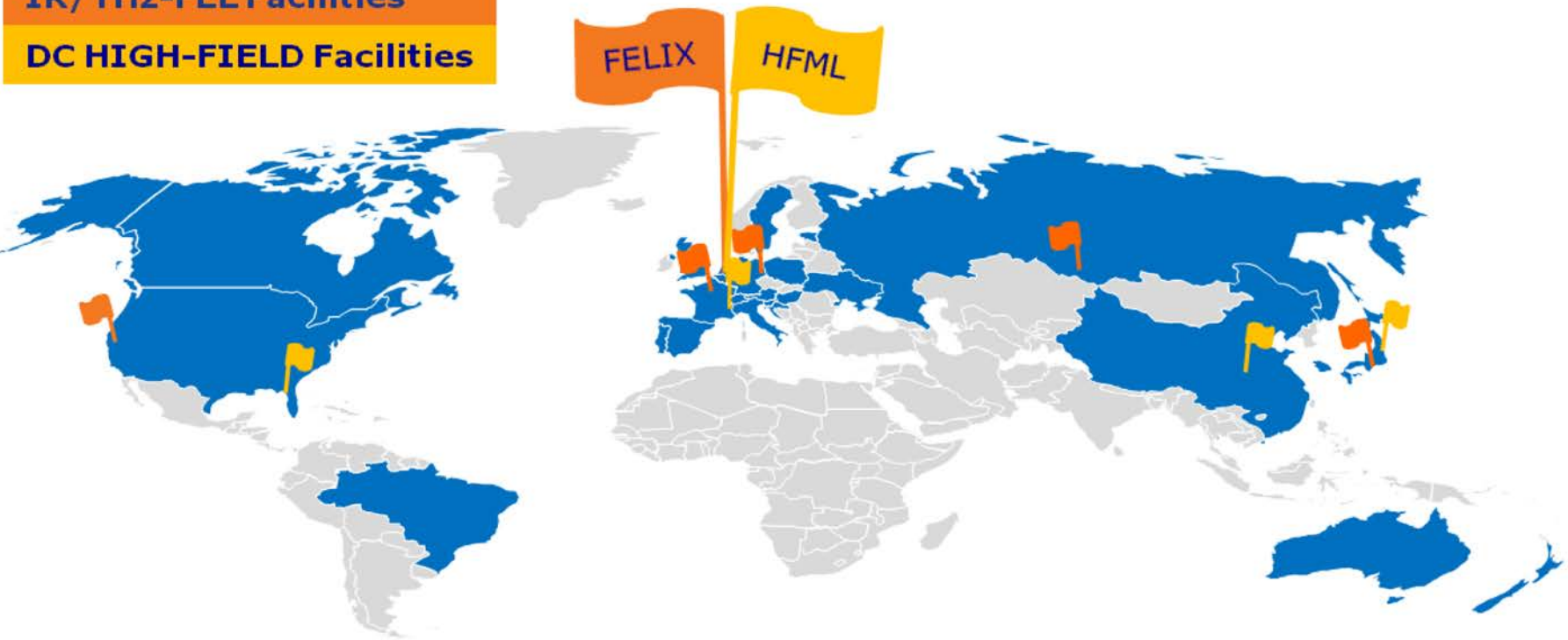
Unique combination for exploring new science

IR/THz-FEL Facilities
DC HIGH-FIELD Facilities

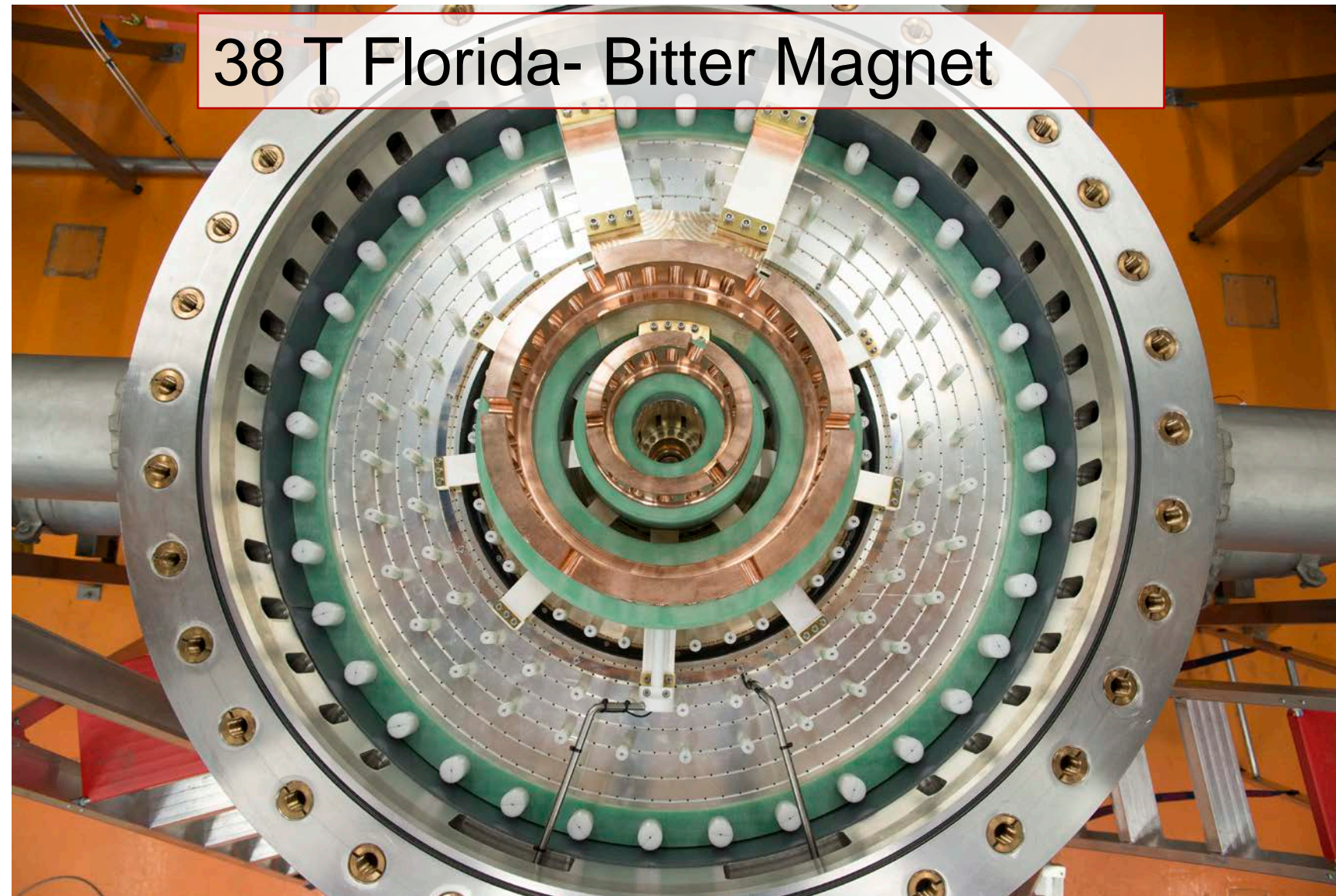


Unique combination for exploring new science

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Resistive magnets

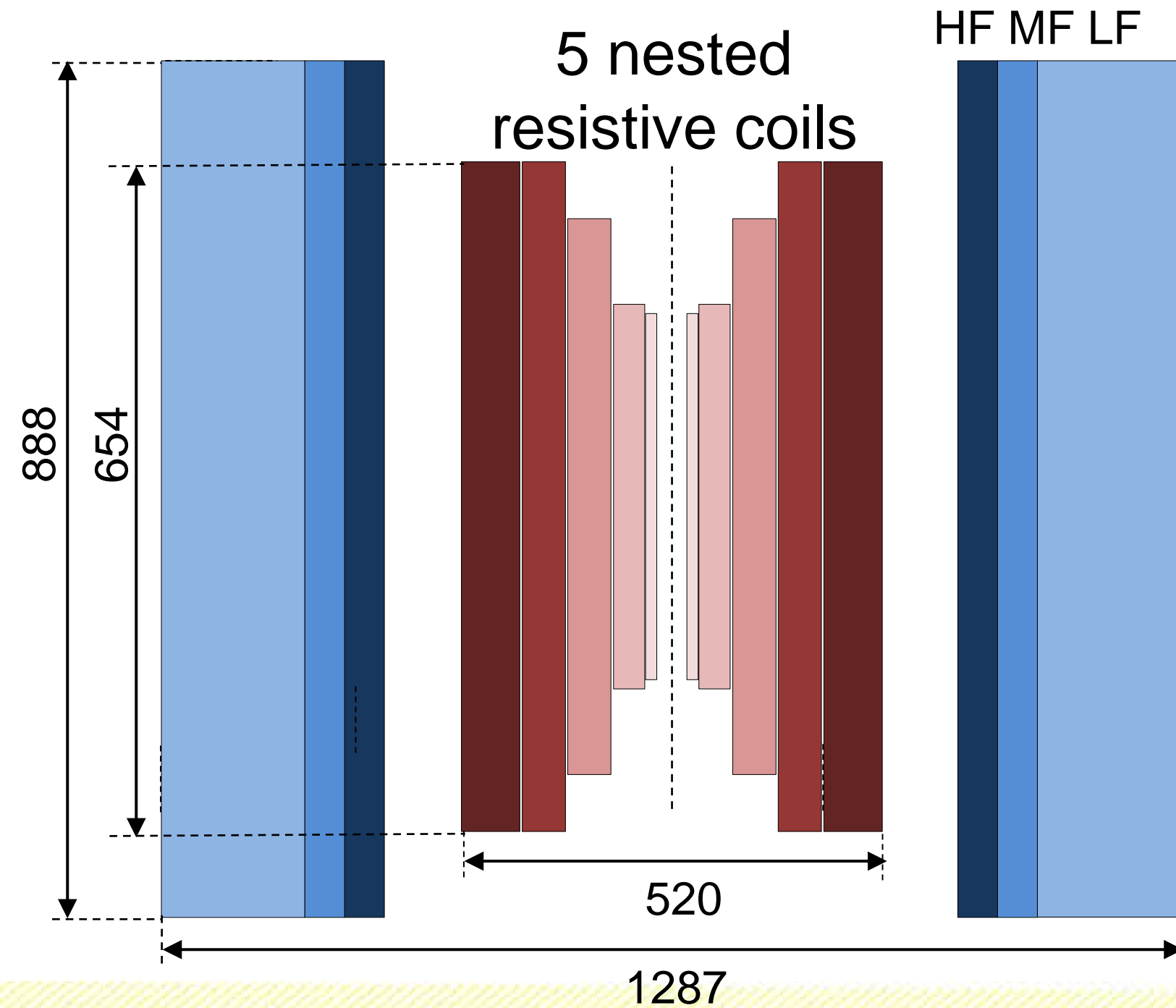


- Electrical Power: 22 MW
- Water cooled: 160 l/s
- Mechanical stress limited



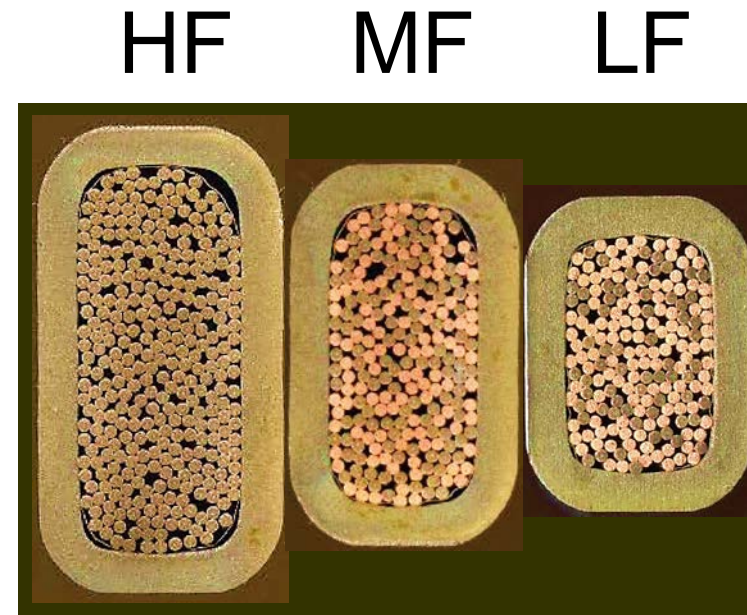
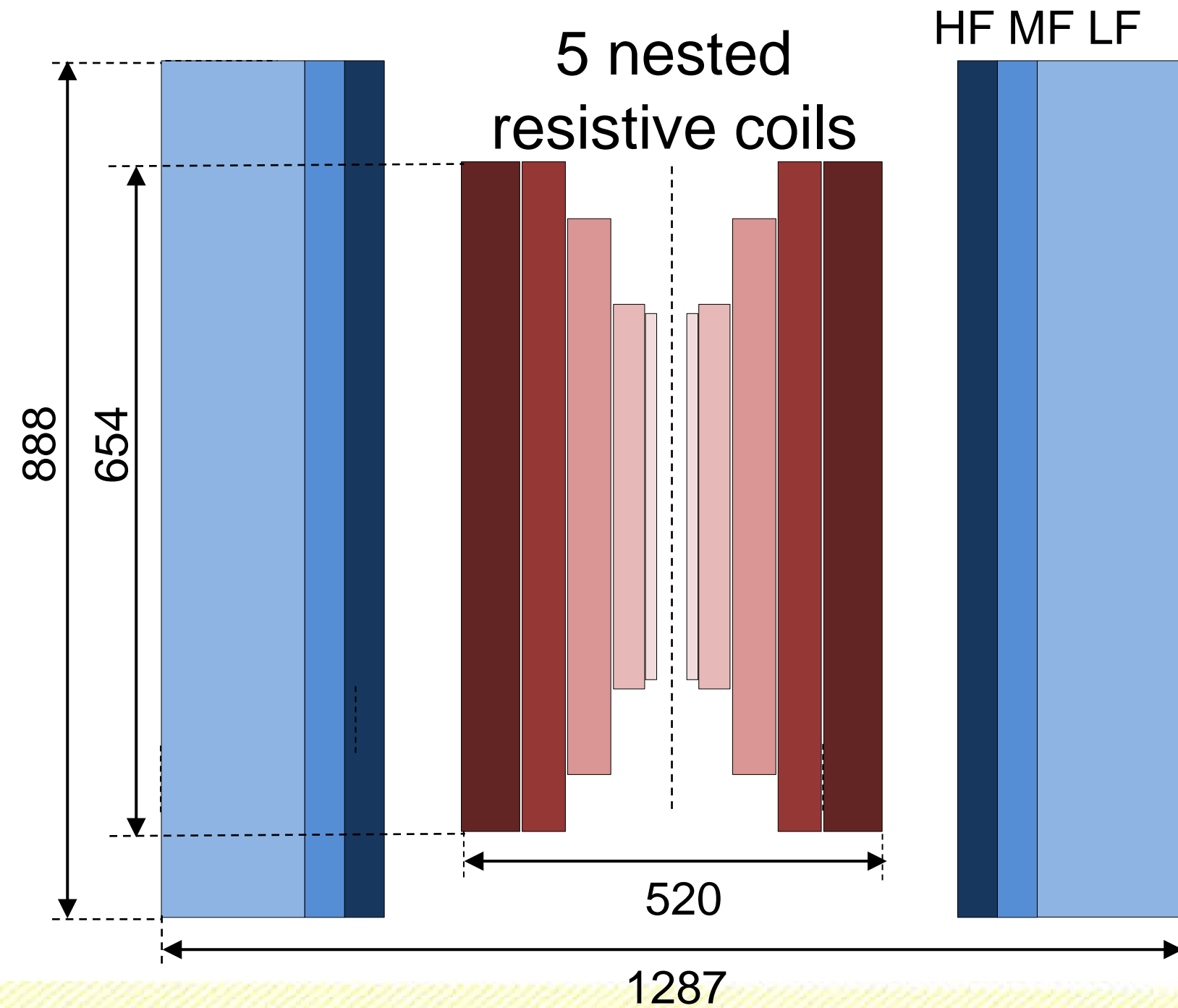
45 T Hybrid Magnet – under construction

3 nested SC coils



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3 nested SC coils



Nb₃Sn conductors,
manufactured by
ICAS (Italy)

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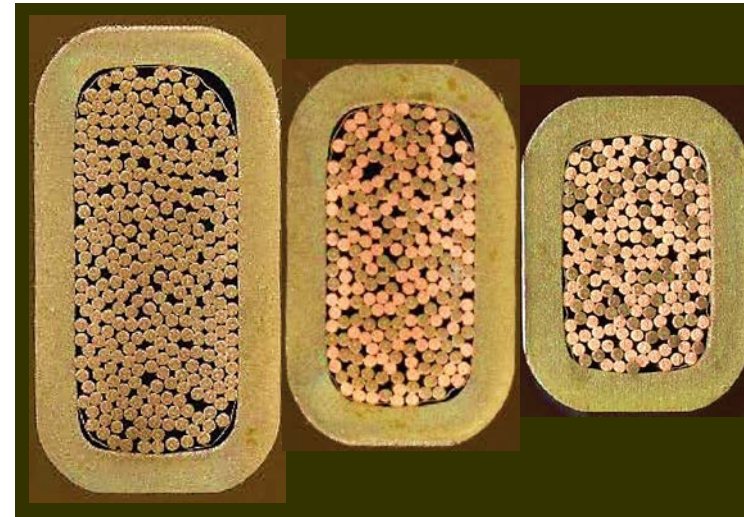
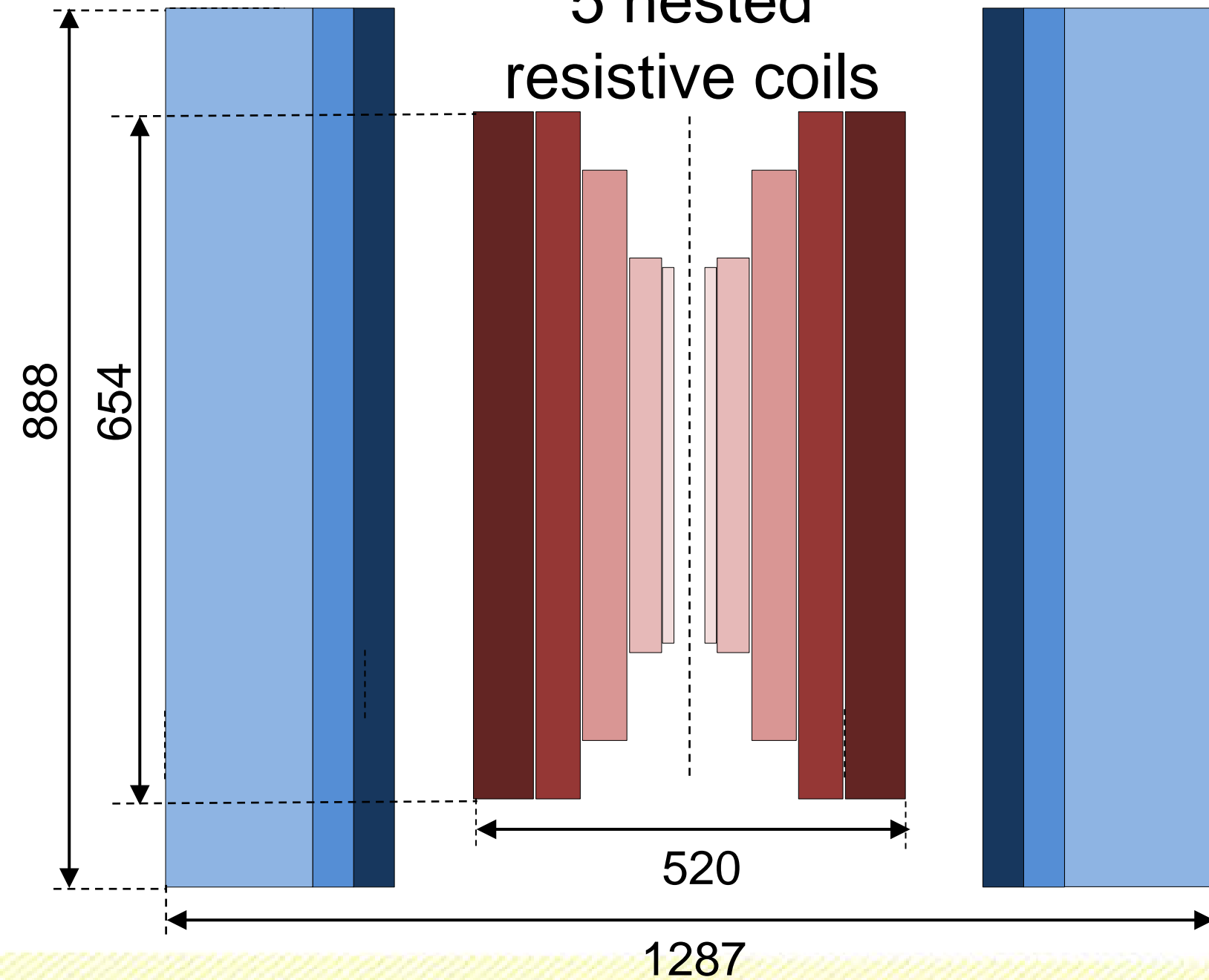
3 nested SC coils

5 nested resistive coils

HF MF LF

HF MF LF

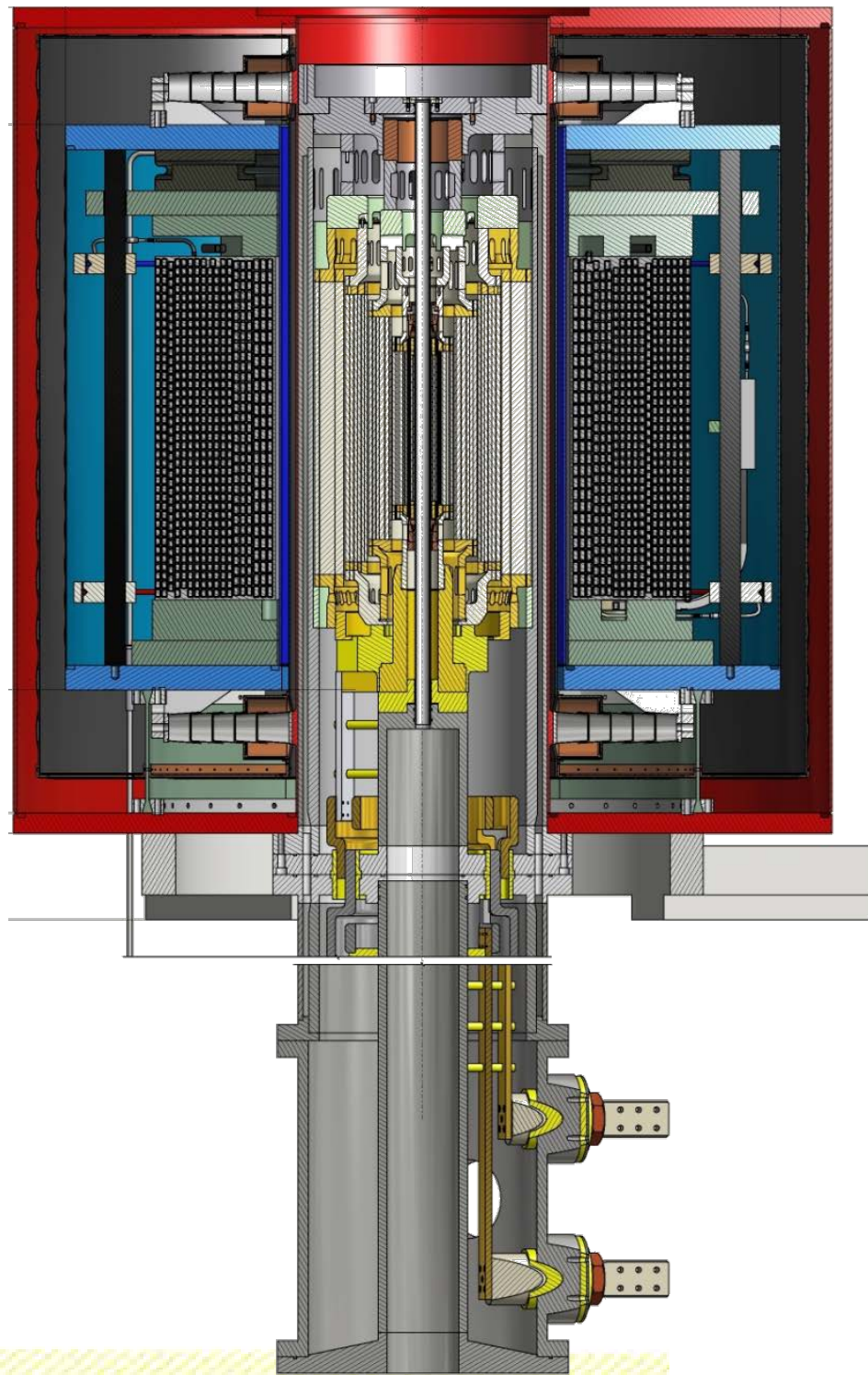
SC outsert



Nb₃Sn conductors, manufactured by ICAS (Italy)



45 T Hybrid Magnet – system



1000 W Stirling cooler
for radiation shields

20kA/10 V POC

20 kA current leads

Liquid helium plant

20 kA SC bus bars

DAQ, control & HMI

The hybrid magnet

Liquid nitrogen supply

A High Magnetic Field ...

... defines a frontier of scientific exploration
- a place where discovery happens

... is a vehicle for emergence, taking matter
to the extremes of uncharted phase space

... provides advanced innovative technologies

