Green Quantum

Climate Change Observation with Quantum Technologies

Lisa Wörner

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Knowledge for Tomorrow

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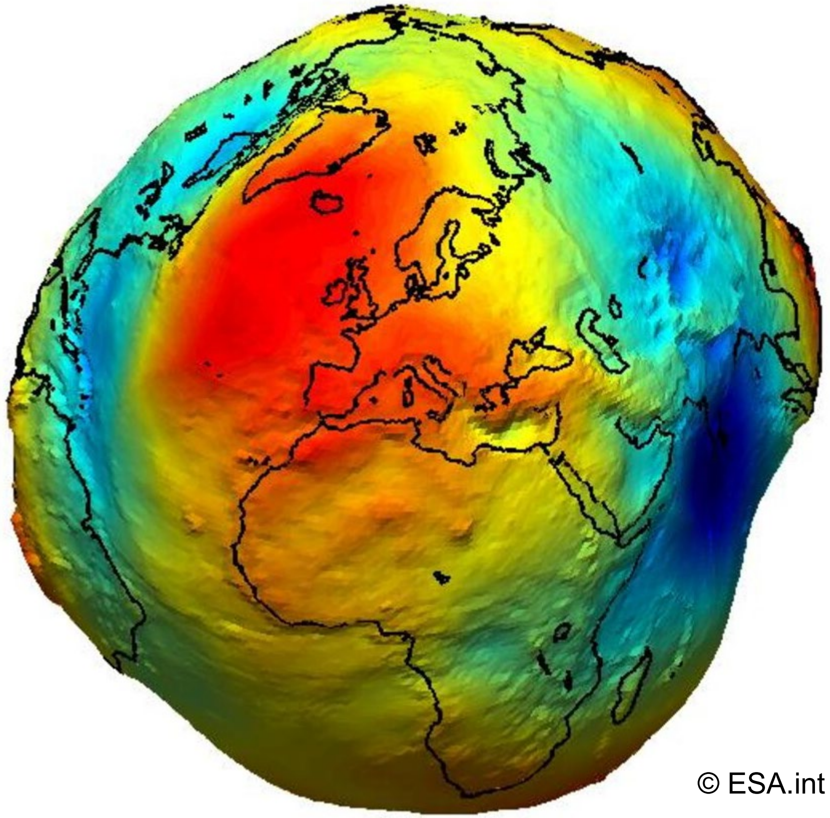
Knowledge for Tomorrow

Climate Change Observation
Global Surveillance

Gradiometry

‚GOCE' - type



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Gravimetry

‚GRACE' - type

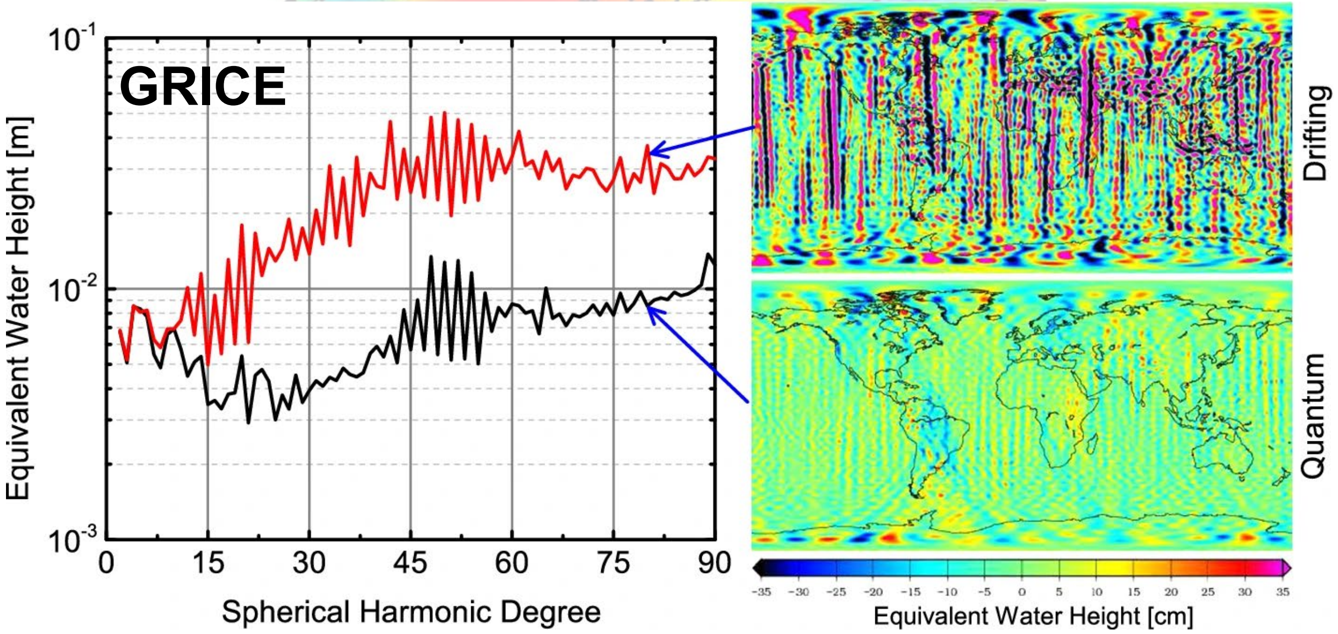
Climate Change Observation
Global Surveillance with Quantum Technologies

Gradiometry

‚GOCE' - type

Gravimetry

‚GRACE' - type



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Gradiometry

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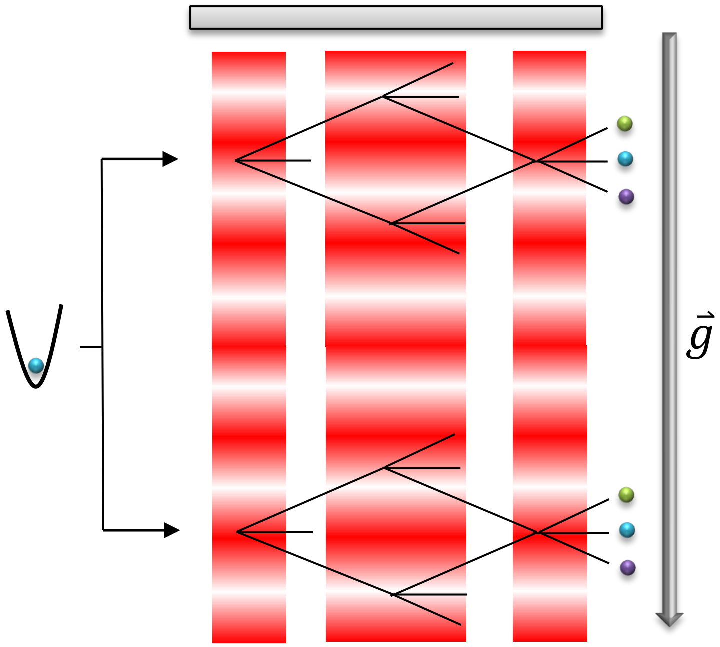

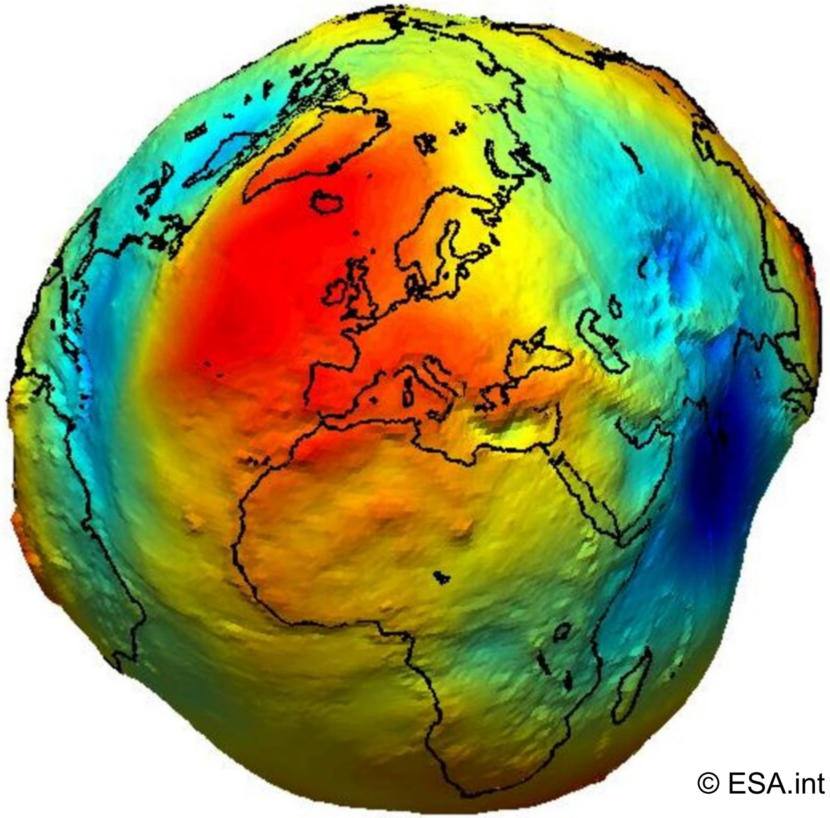

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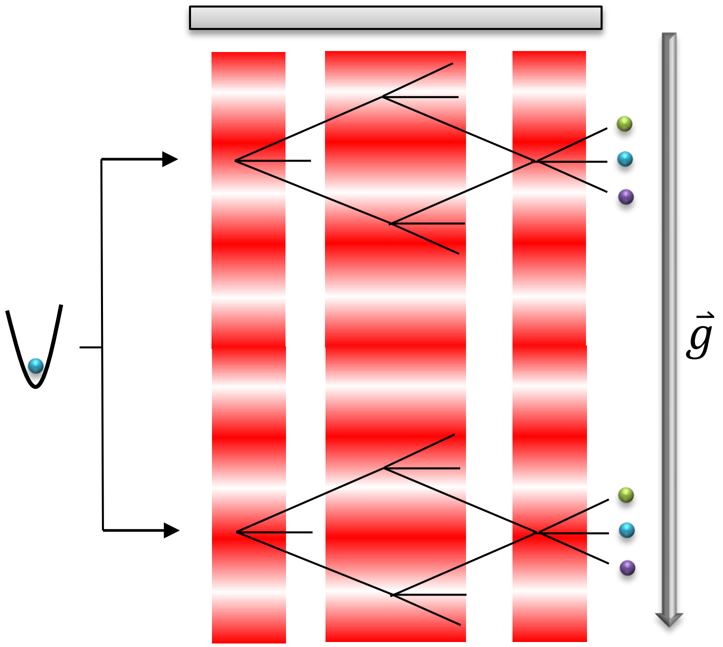

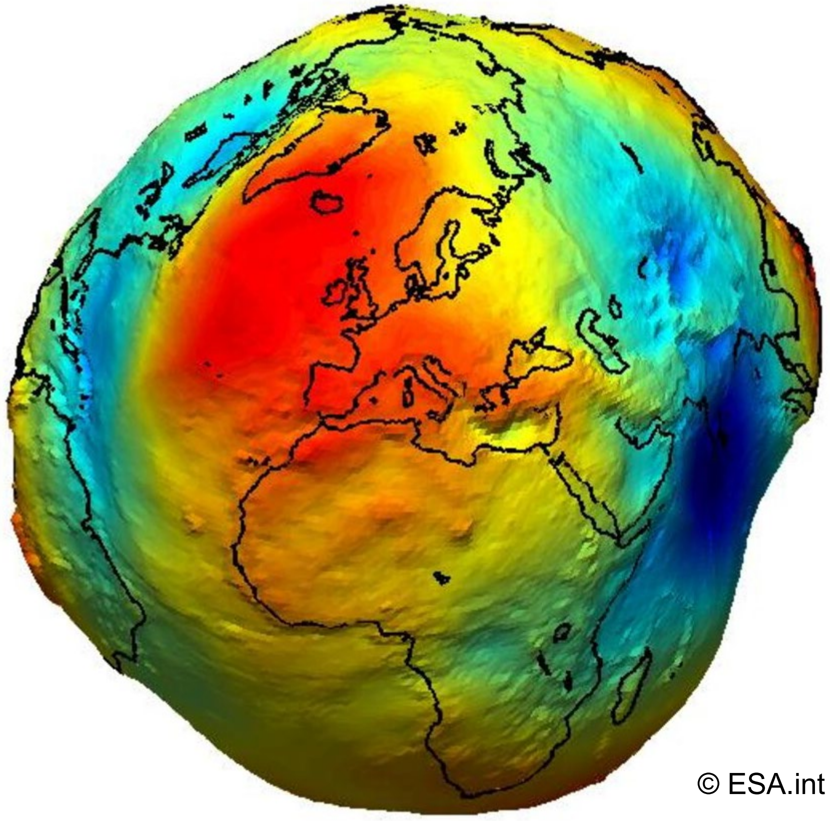

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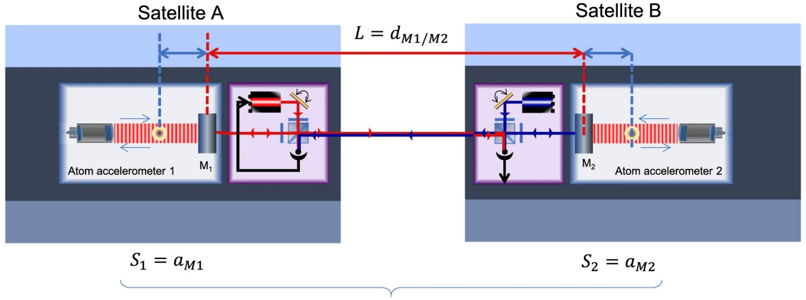
Gravimetry

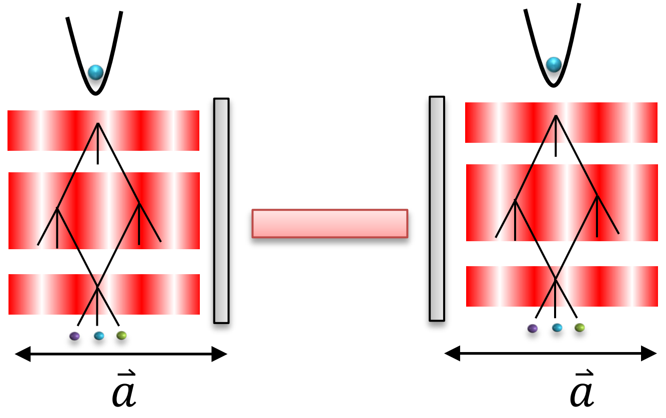
GRICE

‚GRACE‘ - type



$$\frac{\partial a_x}{\partial x} = \frac{1}{L}\left(S_1 - S_2 + \frac{d^2L}{dt^2}\right)$$

© T. Lévèque et al., J.Geod.**95**, 15 (2021)



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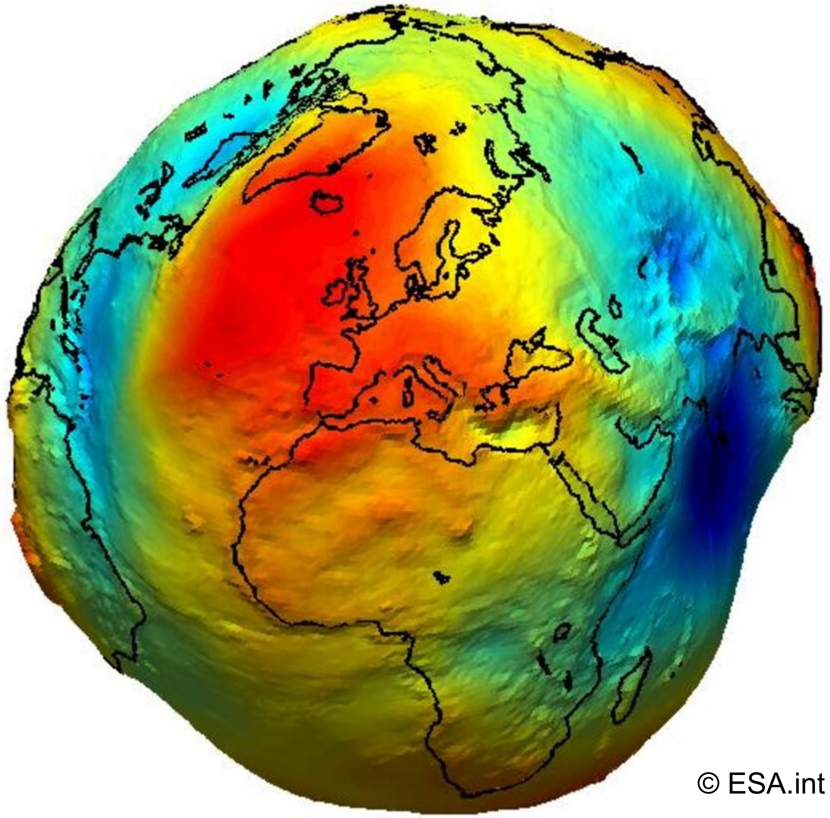
- Müller et al., JoG 94, 71 (2020)
- MOCASS: Migliaccio et al., SiG 40, 1029 (2019)

- GRACE – I (QGG)



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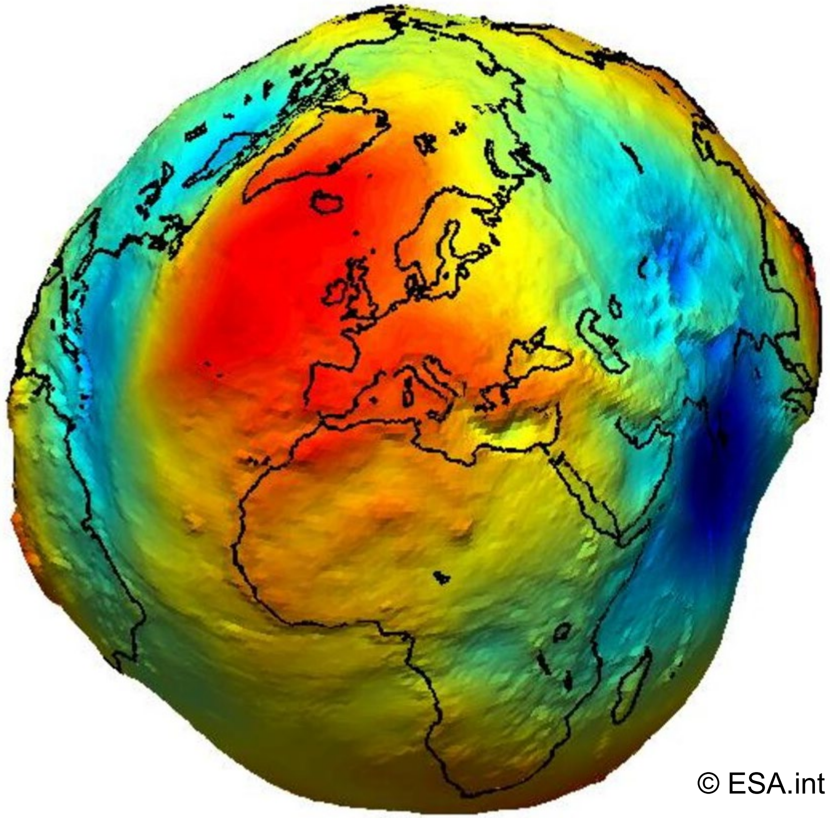

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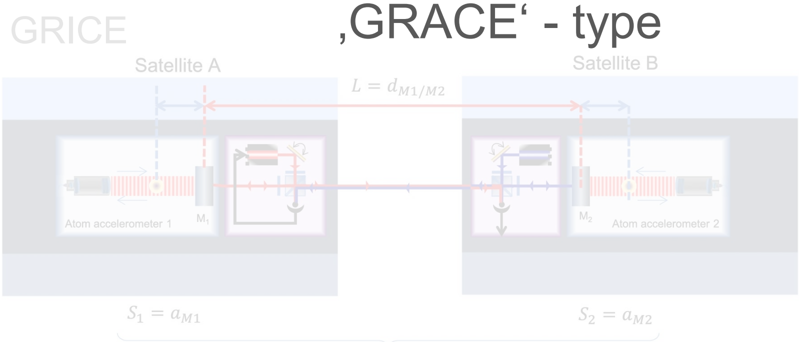

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- Chiow et al., PRA 92, 063613 (2015)
- PRAGRICE: Lévèque et al., JoG 95, 15 (2021)
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- MaQuIs: Wörner et al., in preparation

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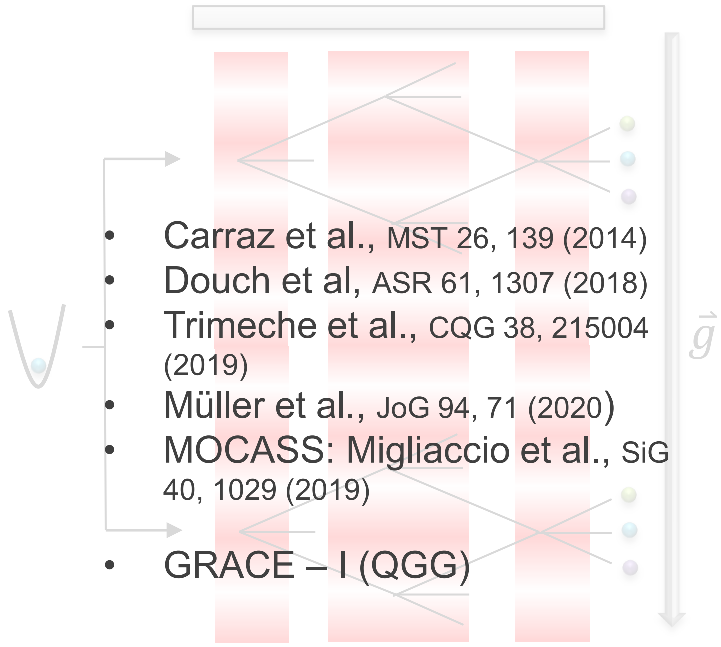

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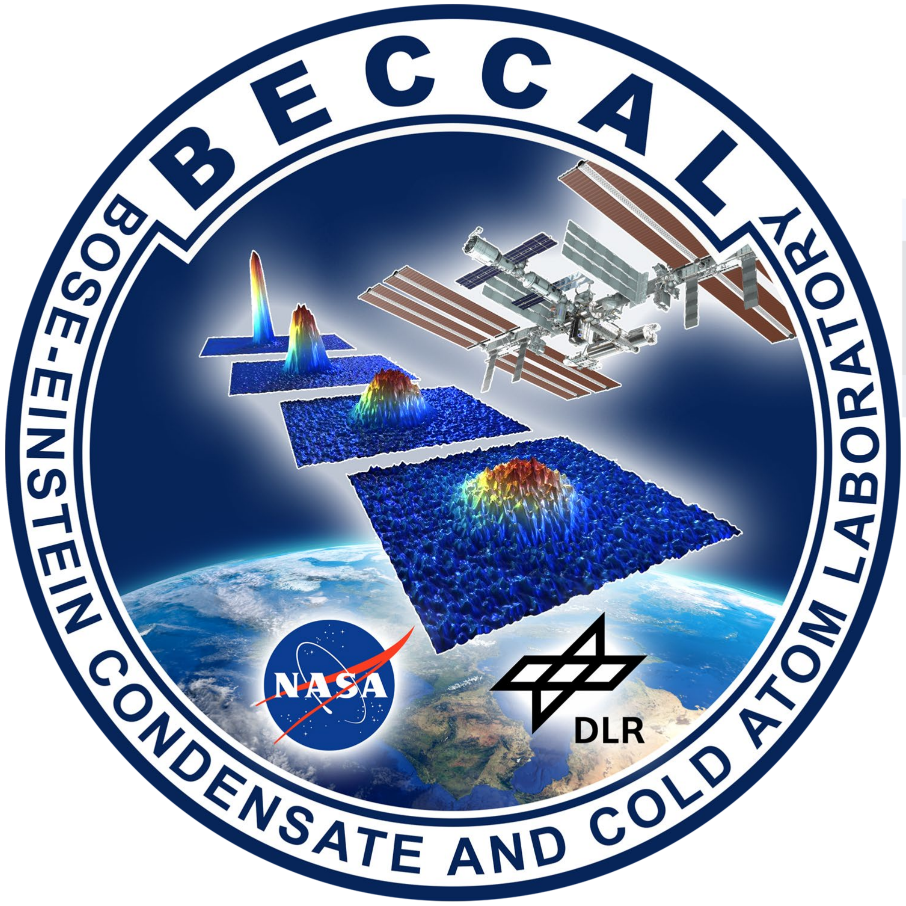

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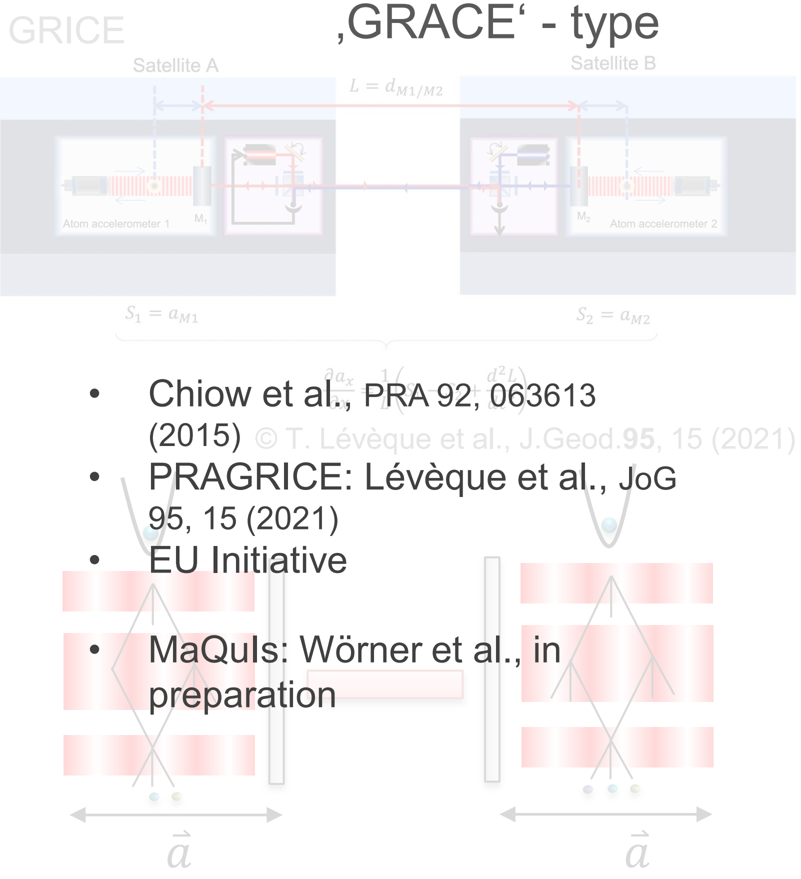

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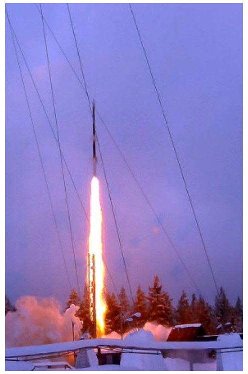
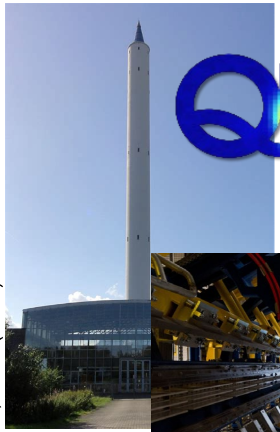
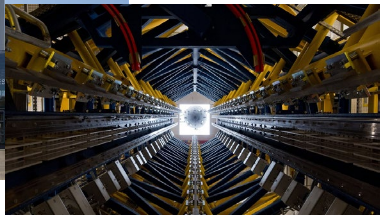


1.BEC im All
D.Becker, et al, Nature
562, 391 (2018)

MAIUS



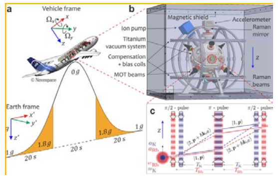


QUANTUS

1. BEC in Mikrogravitation
T. Van Zoest et al., Science
328, 1540 (2010)

BECCAL
BOSE-EINSTEIN CONDENSATE AND COLD ATOM LABORATORY

CAL



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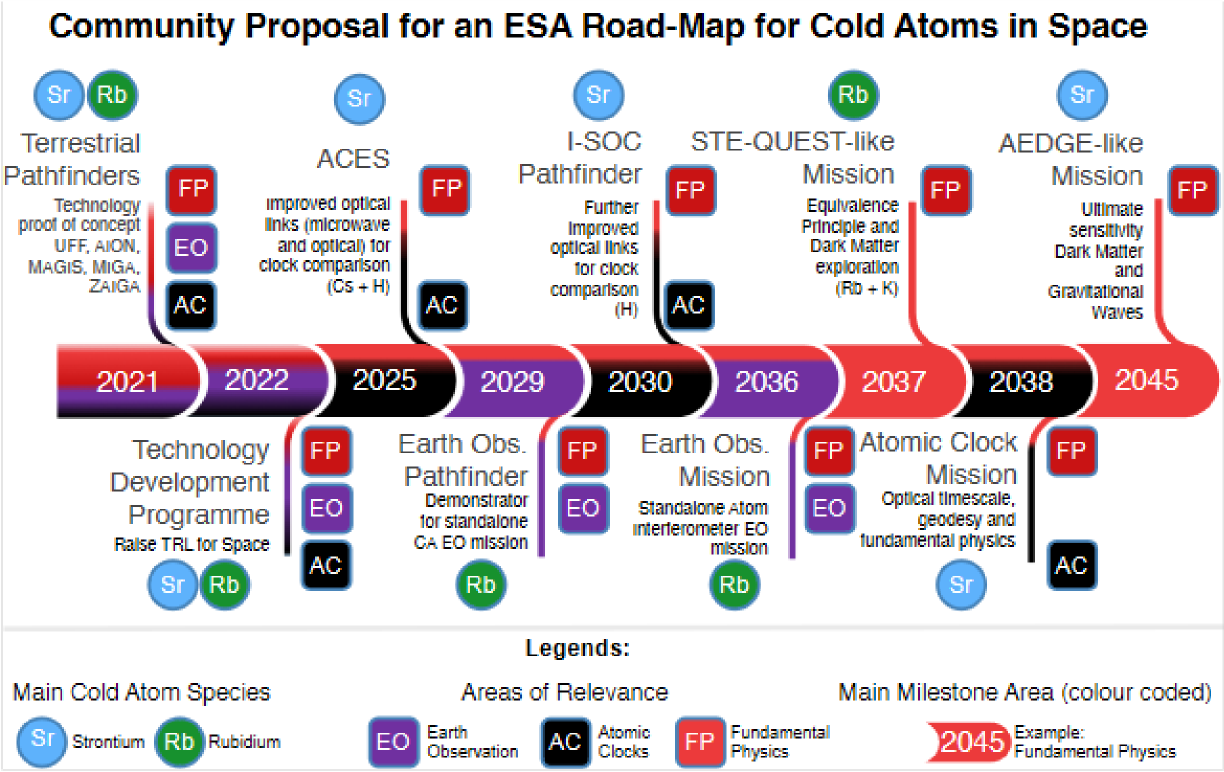

Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map

Ivan Alonso, Cristiano Alpigiani, Brett Altschul, Henrique Araujo, Gianluigi Arduini, Jan Arlt, Leonardo Badurina, Antun Balaz, Satvika Bandarupally, Barry C Barish Michele Barone, Michele Barsanti, Steven Bass, Angelo Bassi, Baptiste Battelier, Charles F. A. Baynham, Quentin Beaufils, Aleksandar Belic, Joel Berge, Jose Bernabeu, Andrea Bertoldi, Robert Bingham, Sebastien Bize, Diego Blas, Kai Bongs, Philippe Bouyer, Carla Braitenberg, Christian Brand, Claus Braxmaier, Alexandre Bresson, Oliver Buchmueller, Dmitry Budker, Luís Bugalho, Sergey Burdin, Luigi Cacciapuoti Simone Callegari, Xavier Calmet, Davide Calonico, Benjamin Canuel, Laurentiu-Ioan Caramete, Olivier Carraz, Donatella Cassettari, Pratik Chakraborty, Swapan Chattopadhyay, Upasna Chauhan, Xuzong Chen, Yu-Ao Chen, Maria Luisa Chiofalo, Jonathon Coleman, Robin Corgier, J. P. Cotter, A. Michael Cruise, Yanou Cui, Gavin Davies, Albert De Roeck, Marcel Demarteau, Andrei Derevianko, Marco Di Clemente, Goran S. Djordjevic, Sandro Donadi, Olivier Dore, Peter Dornan, Michael Doser, Giannis Drougakis, Jacob Dunningham, Sajan Easo, Joshua Eby, Gedminas Elertas, John Ellis, David Evans, Pandora Examilioti, Pavel Fadeev, Mattia Fanì, Farida Fassi, Marco Fattori, Michael A. Fedderke, Daniel Felea, Chen-Hao Feng, Jorge Ferreras, Robert Flack, Victor V. Flambaum, Rene Forsberg, Mark Fromhold, Naceur Gaaloul, Barry M. Garraway, Maria Georgousi, Andrew Geraci, Kurt Gibble, Valerie Gibson, Patrick Gill, Gian F. Giudice, Jon Goldwin, Oliver Gould, Oleg Grachov, Peter W. Graham, Dario Grasso, Paul F. Griffin, Christine Guerlin, Mustafa Gundogan, Ratnesh K Gupta, Martin Haehnelt, Ekim T. Hanımeli et al. (149 additional authors not shown)

We summarize the discussions at a virtual Community Workshop on Cold Atoms in Space concerning the status of cold atom technologies, the prospective scientific and societal opportunities offered by their deployment in space, and the developments needed before cold atoms could be operated in space. The cold atom technologies discussed include atomic clocks, quantum gravimeters and accelerometers, and atom interferometers. Prospective applications include metrology, geodesy and measurement of terrestrial mass change due to, e.g., climate change, and fundamental science experiments such as tests of the equivalence principle, searches for dark matter, measurements of gravitational waves and tests of quantum mechanics. We review the current status of cold atom technologies and outline the requirements for their space qualification, including the development paths and the corresponding technical milestones, and identifying possible pathfinder missions to pave the way for missions to exploit the full potential of cold atoms in space. Finally, we present a first draft of a possible road-map for achieving these goals, that we propose for discussion by the interested cold atom, Earth Observation, fundamental physics and other prospective scientific user communities, together with ESA and national space and research funding agencies.

https://arxiv.org/abs/2201.07789

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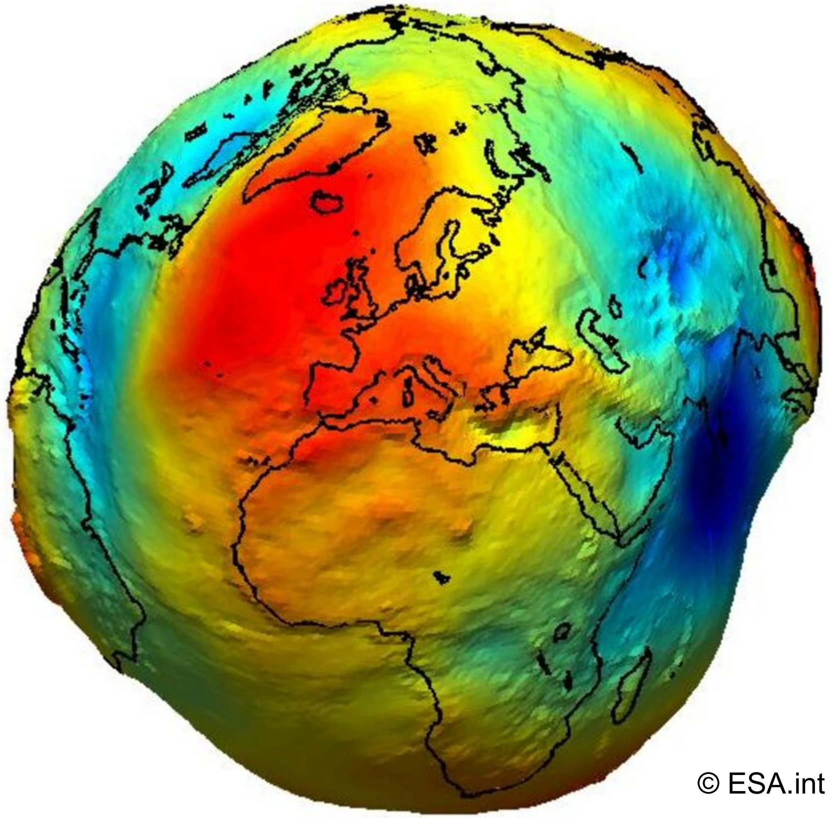

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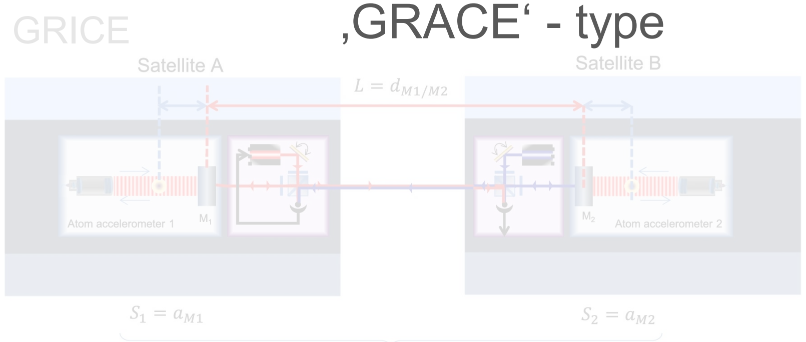

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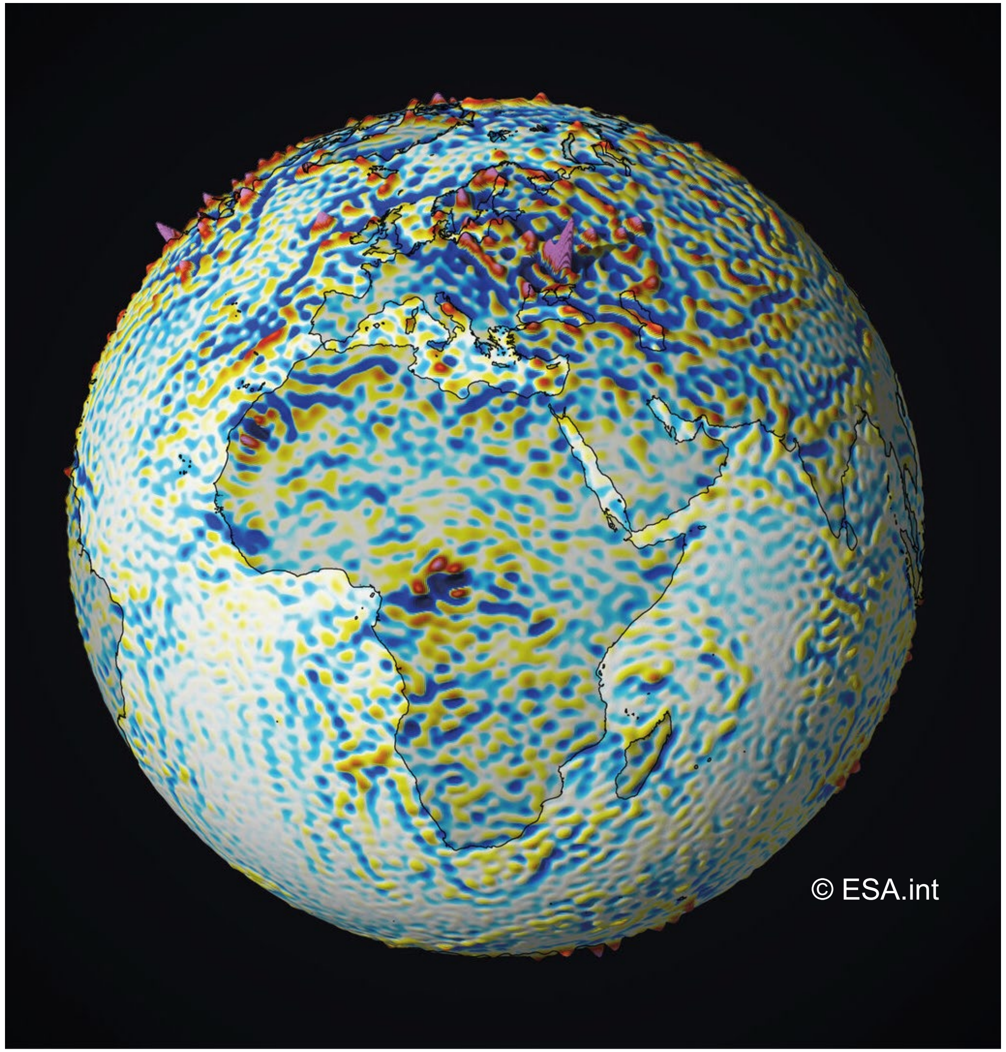

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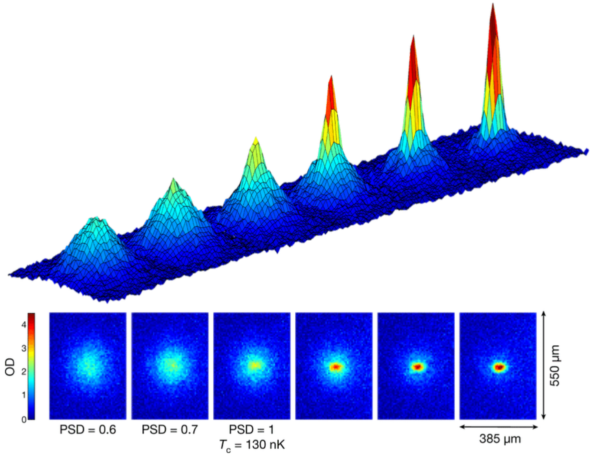

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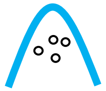

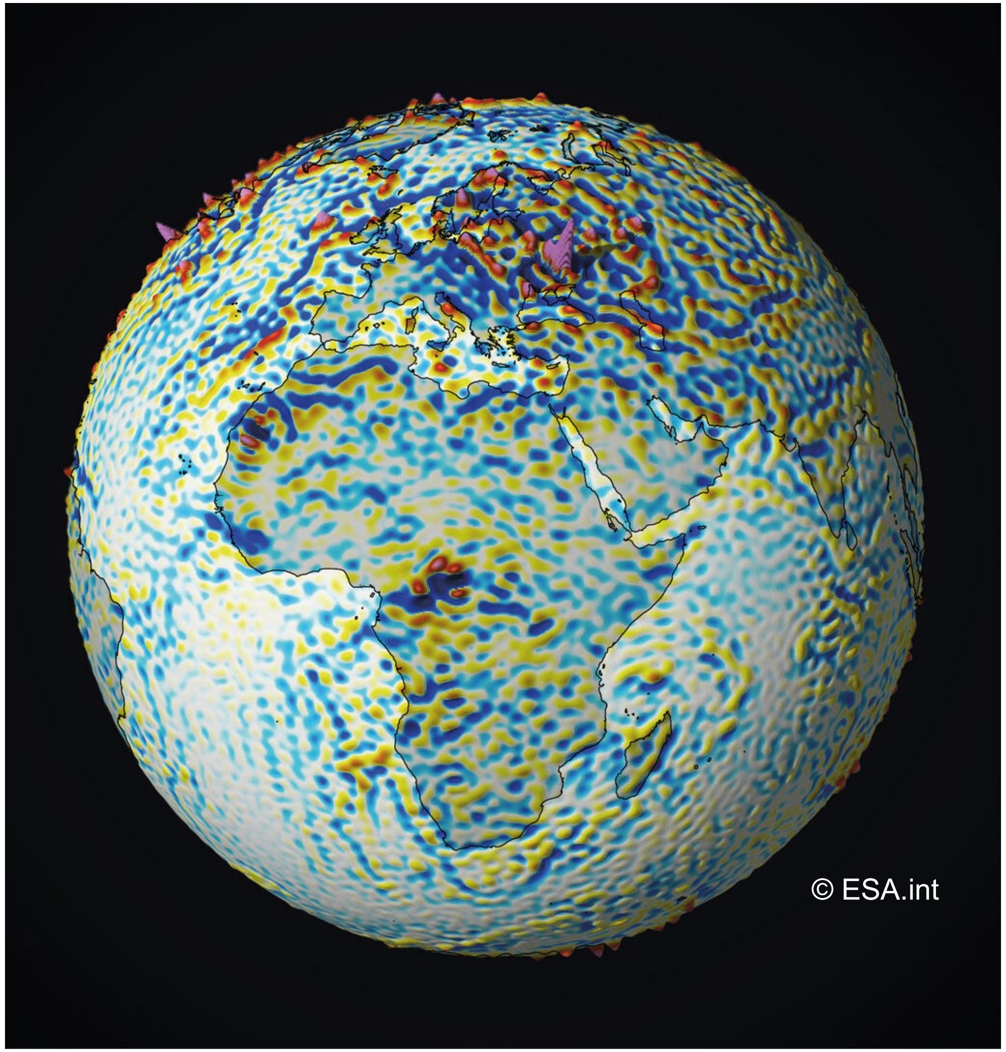

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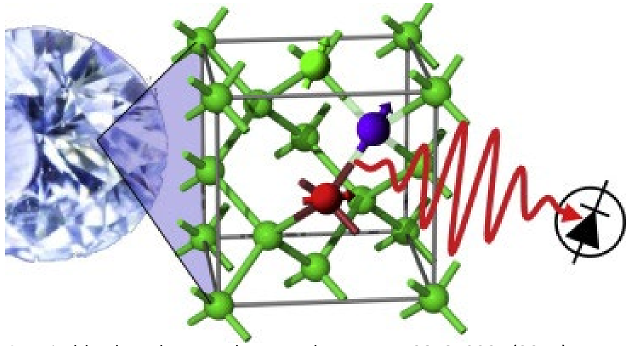

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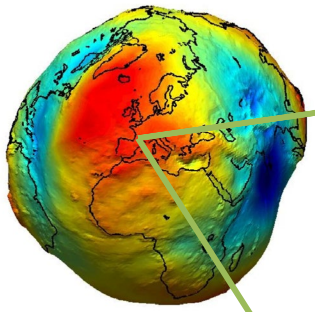

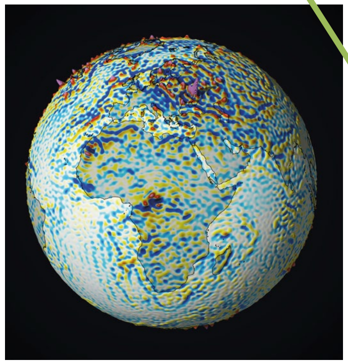

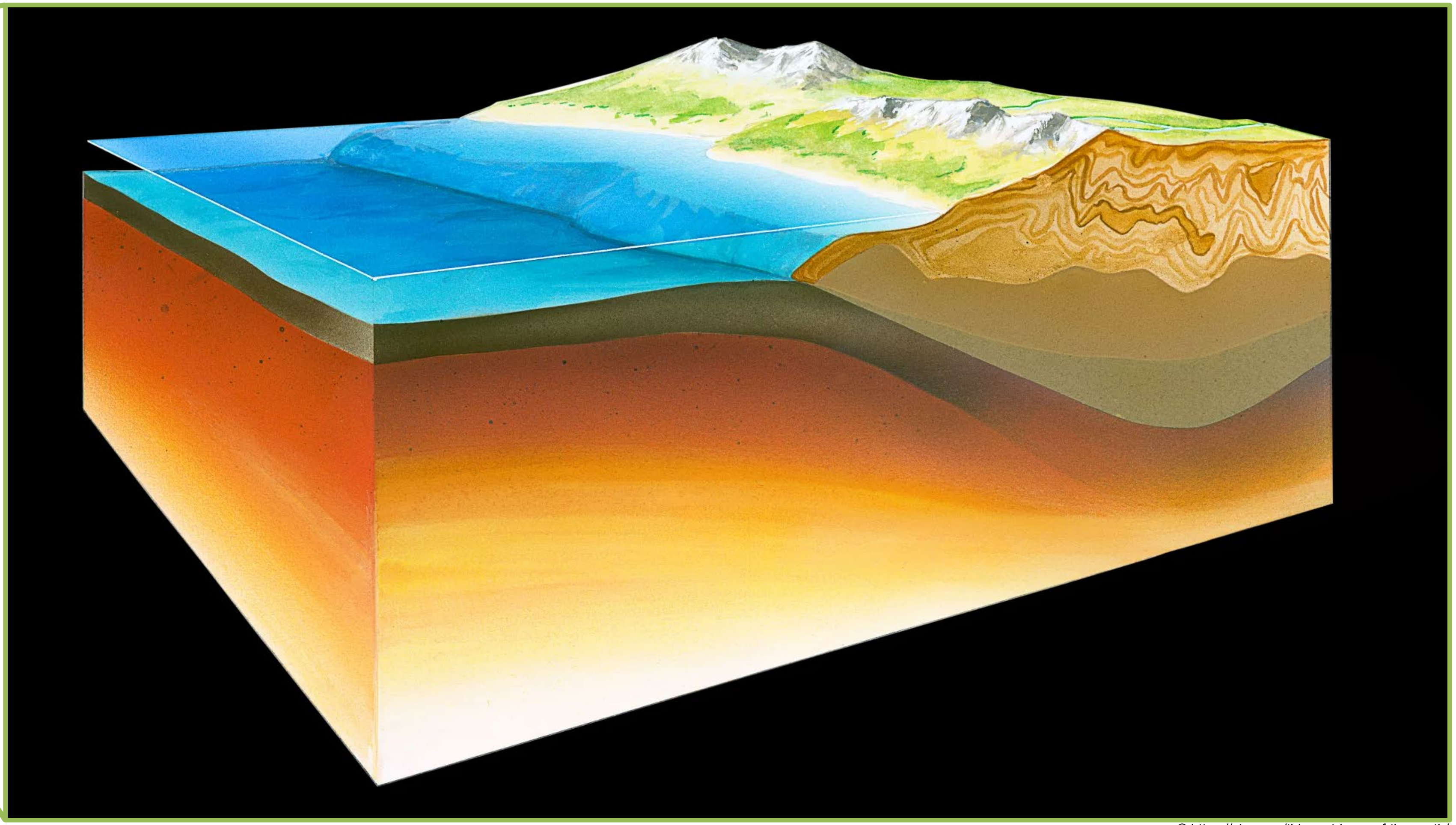

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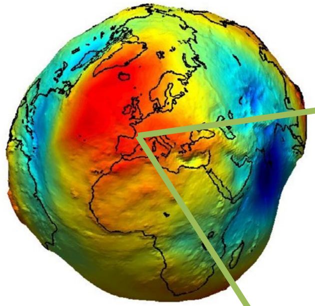

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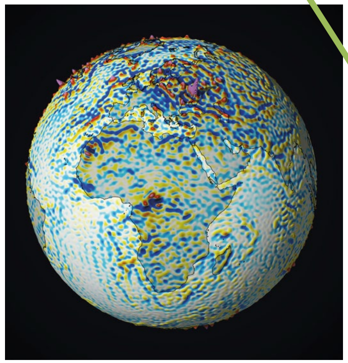

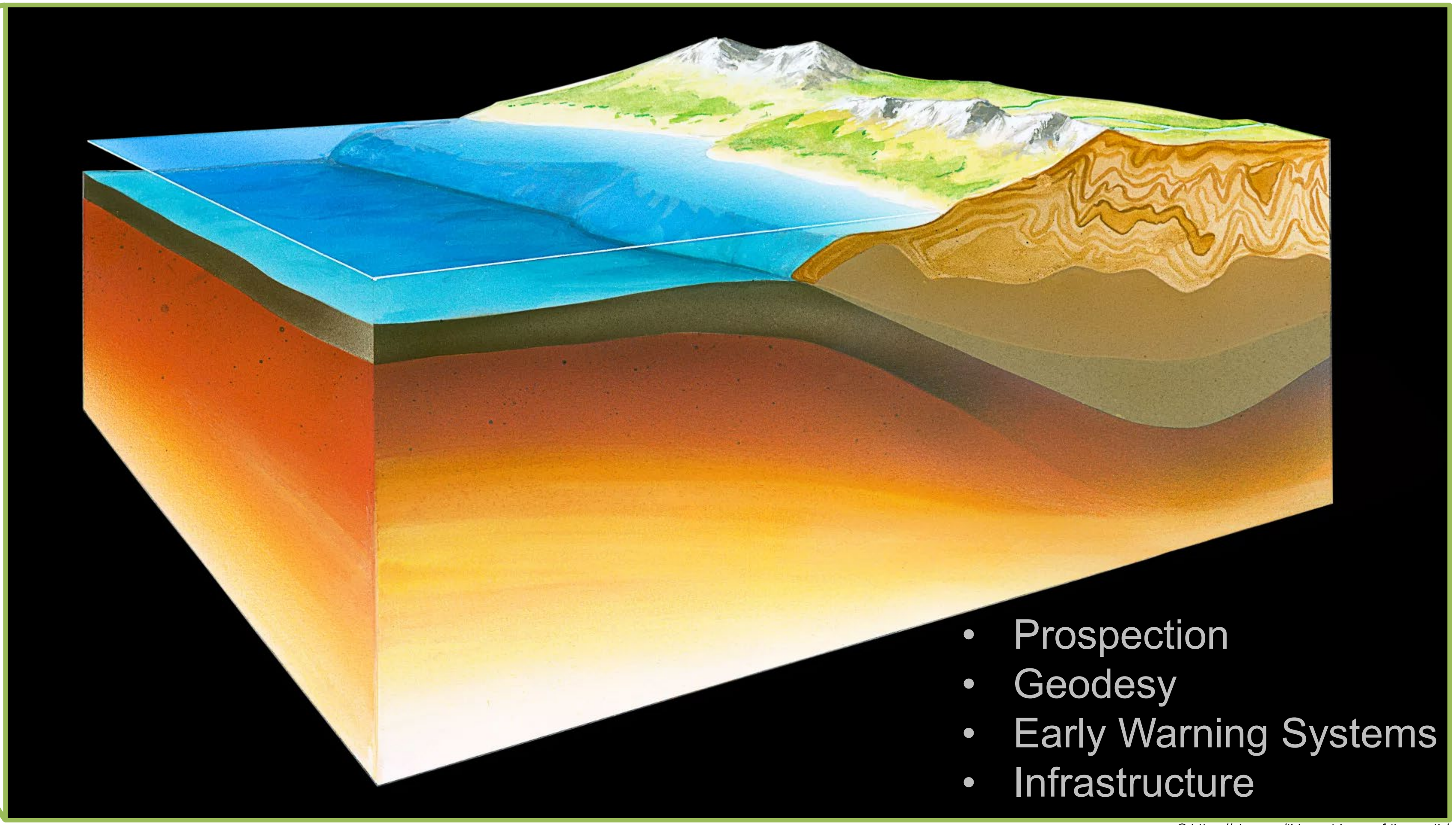

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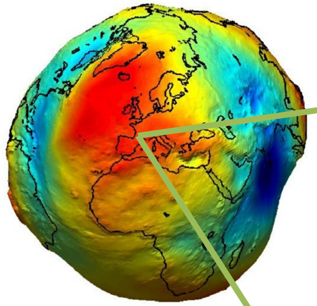
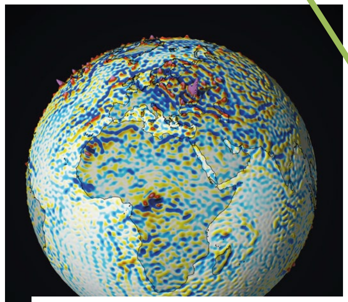
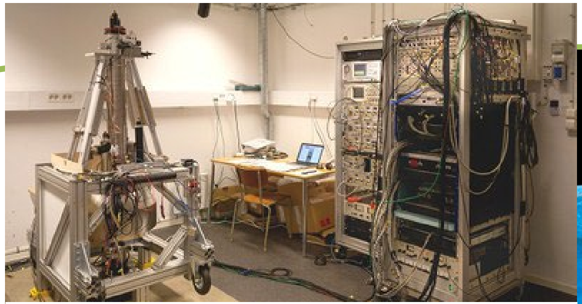




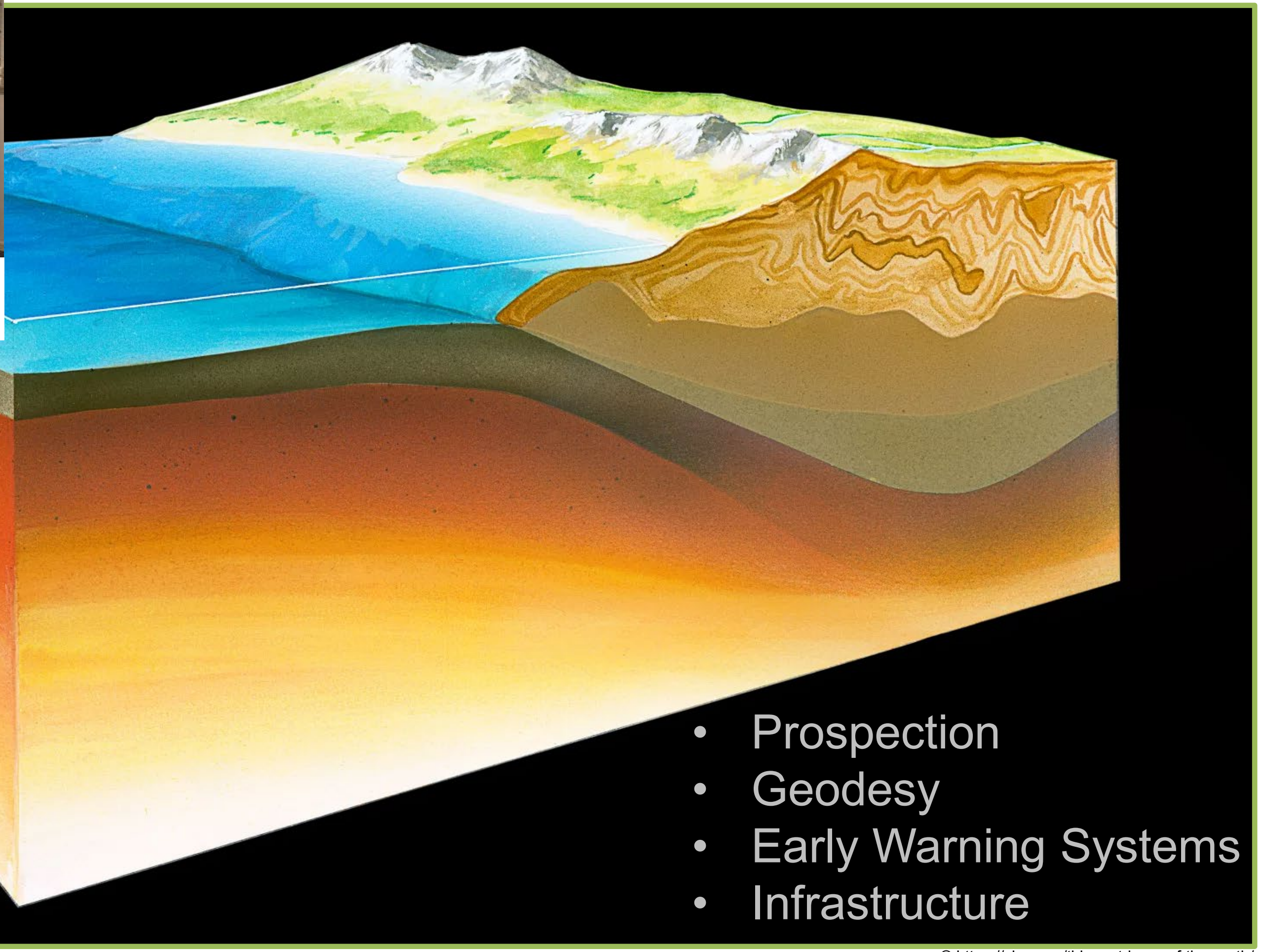
Specifications & Characteristics

Sensitivity:	50 µGal/√Hz at a quiet place
Measurement frequency:	2 Hz
Long-term stability:	< 1 µGal
Accuracy:	under evaluation
Dimensions :	Sensor head: h = 70 cm / D = 38 cm
Laser & electronics:	100 x 50 x 70 cm³
Mass Sensor head:	25 kg, control unit : 75 kg
Power consumption:	250 W typical



Gravimetric Atom Interferometer GAIN

B. Leykauf, H.Thaivalappil Sunilkumar, V. Schkolnik, and A. Peters



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Tackling Climate Change
with Quantum Technologies

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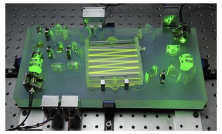

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- Improved Navigation

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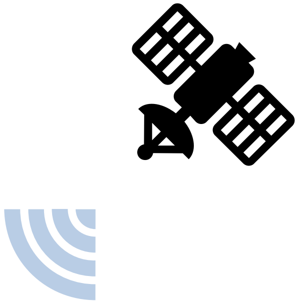

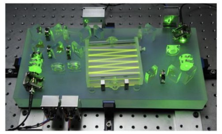

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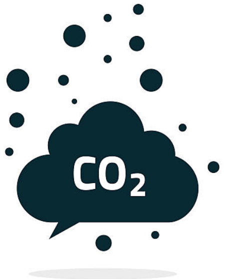
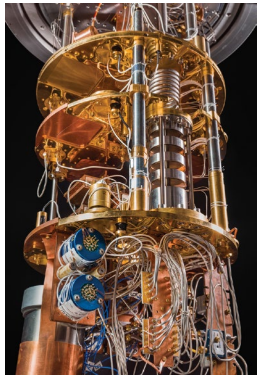


- Improved Navigation
- Traffic Jam Reduction



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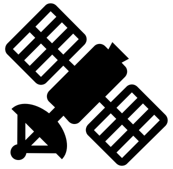

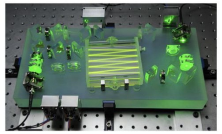

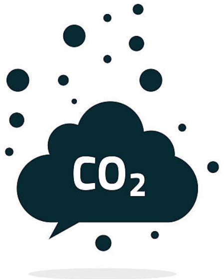

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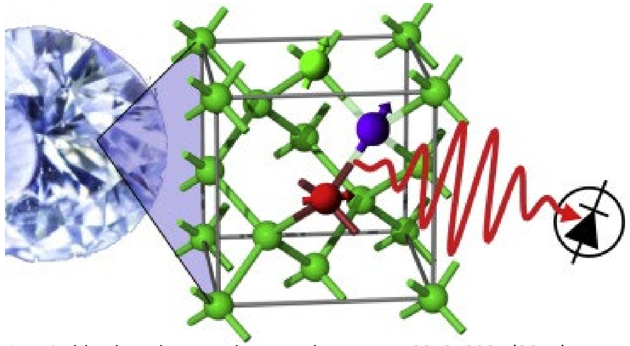

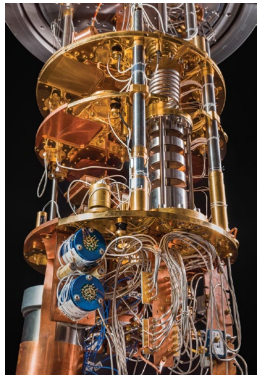

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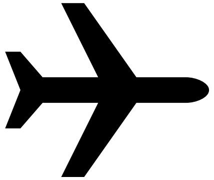
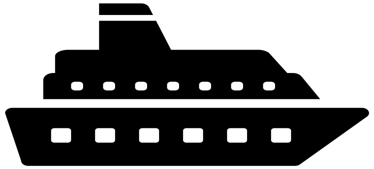
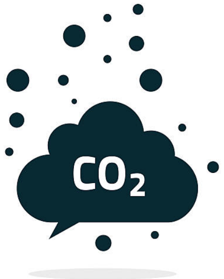
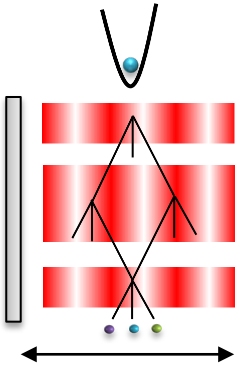
with Quantum Technologies



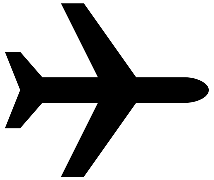




- Improved Navigation
- Traffic Jam Reduction
- Environmental Maps



Tackling Climate Change
with Quantum Technologies



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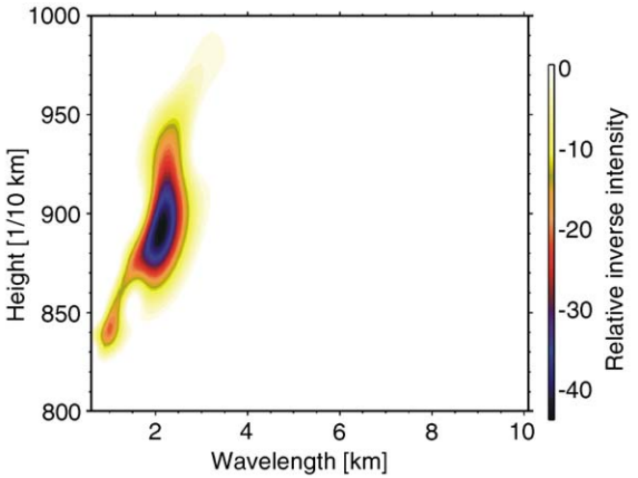

Fig. 5. Typical wavelet spectrogram showing the wavelengths plotted against the height for DBC13 (zonal component).

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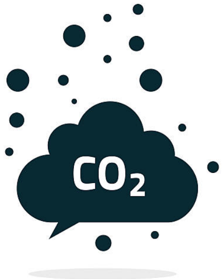

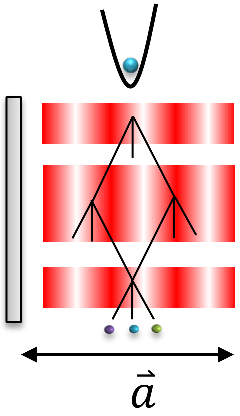

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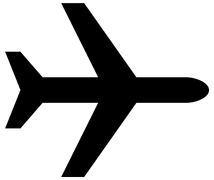
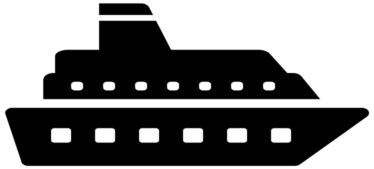
with Quantum Technologies





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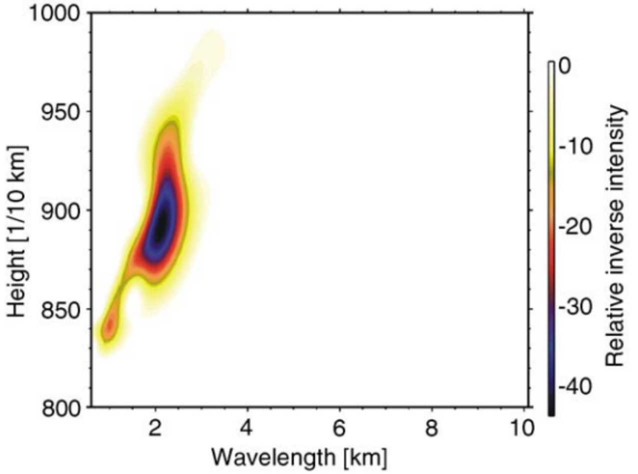

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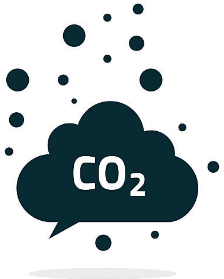

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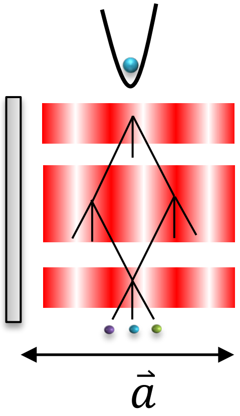

Tackling Climate Change
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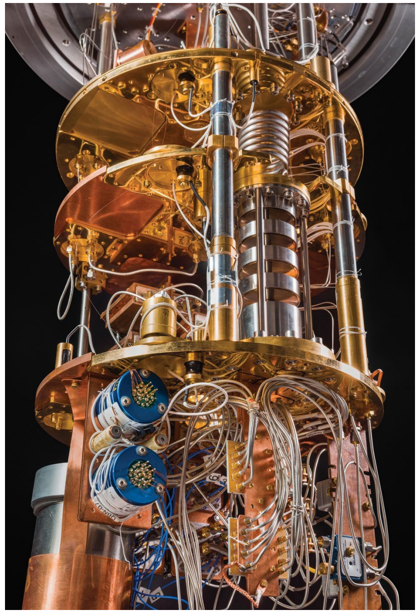

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- Scenario Assessment
- Predictions
- Recommendations

- Improved Navigation
- Traffic Jam Reduction
- Environmental Maps

Green Quantum

Climate Change Observation with Quantum Technologies

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Green Quantum

Climate Change Observation and Tackling with Quantum Technologies

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Climate Change Observation

Global Surveillance with Quantum Technologies

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Global Surveillance with Quantum Technologies

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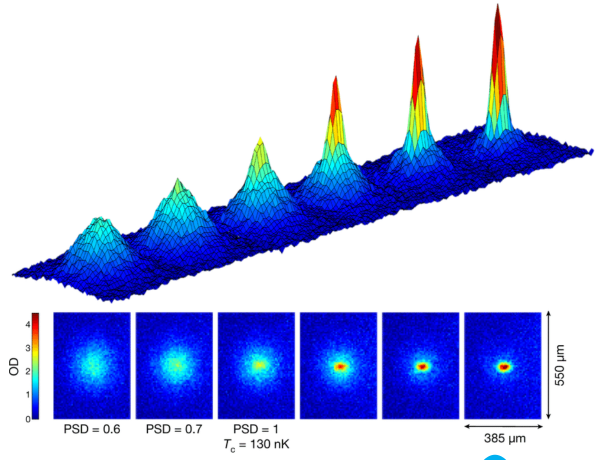

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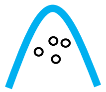

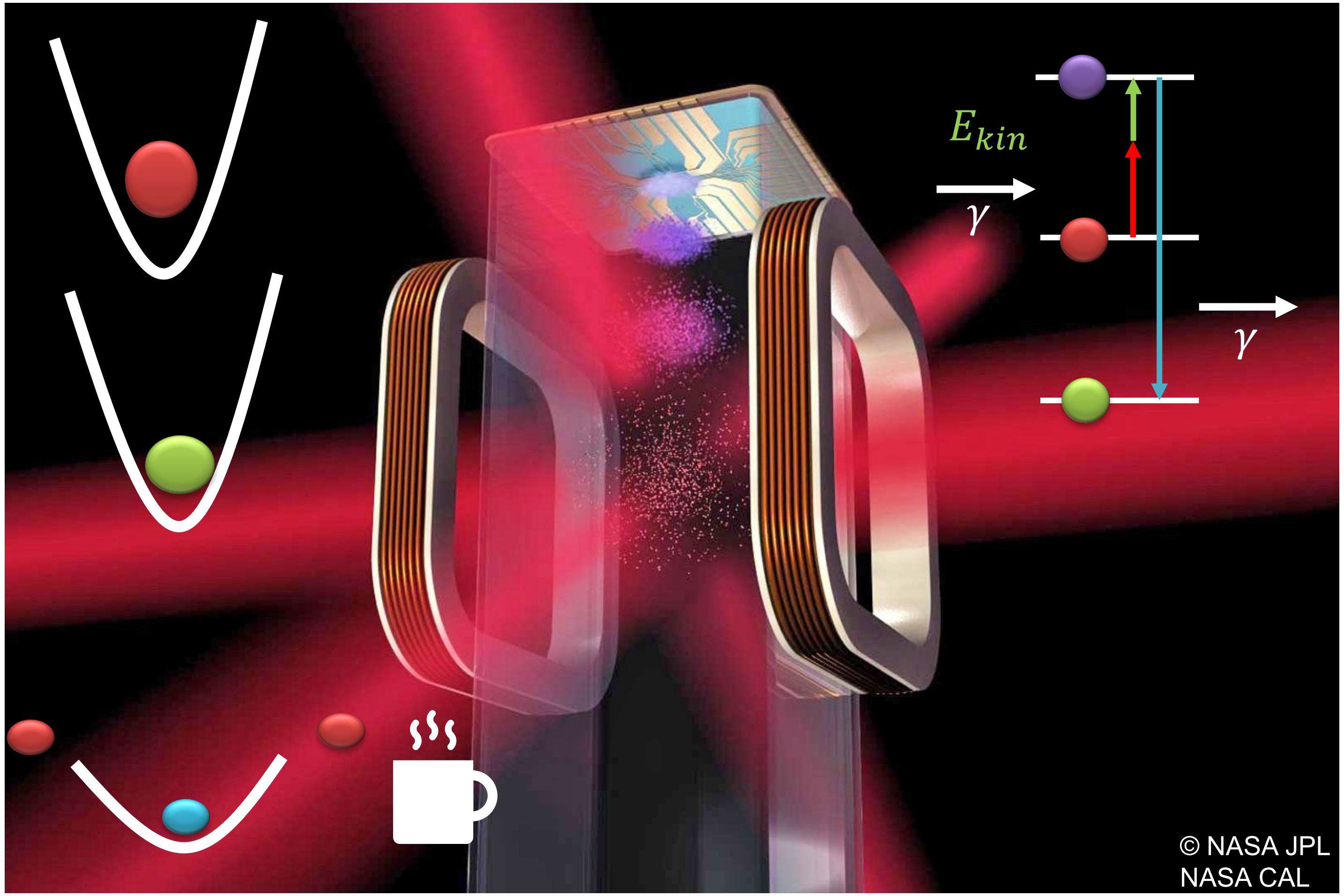

Climate Change Observation

Global Surveillance with Quantum Technologies

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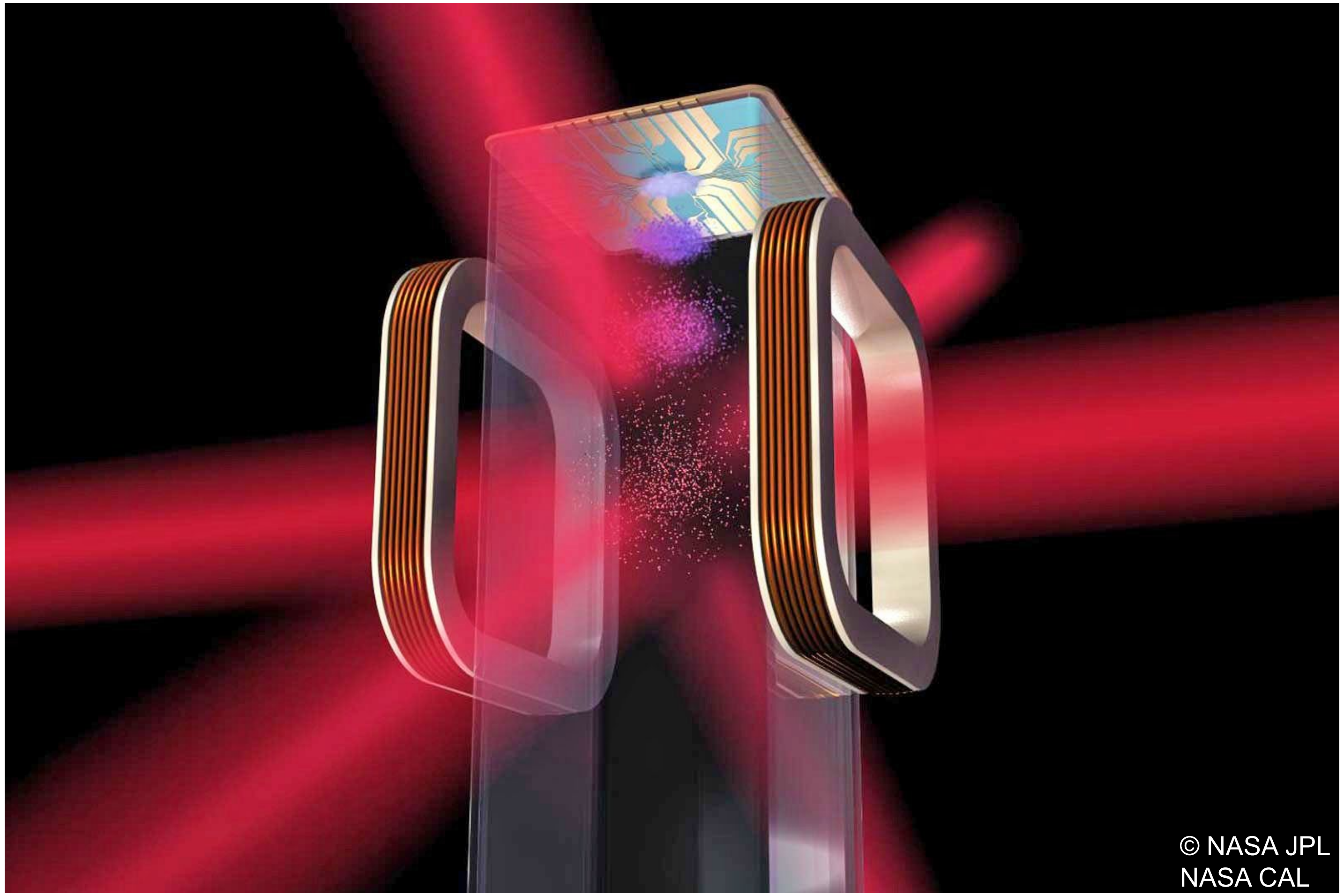

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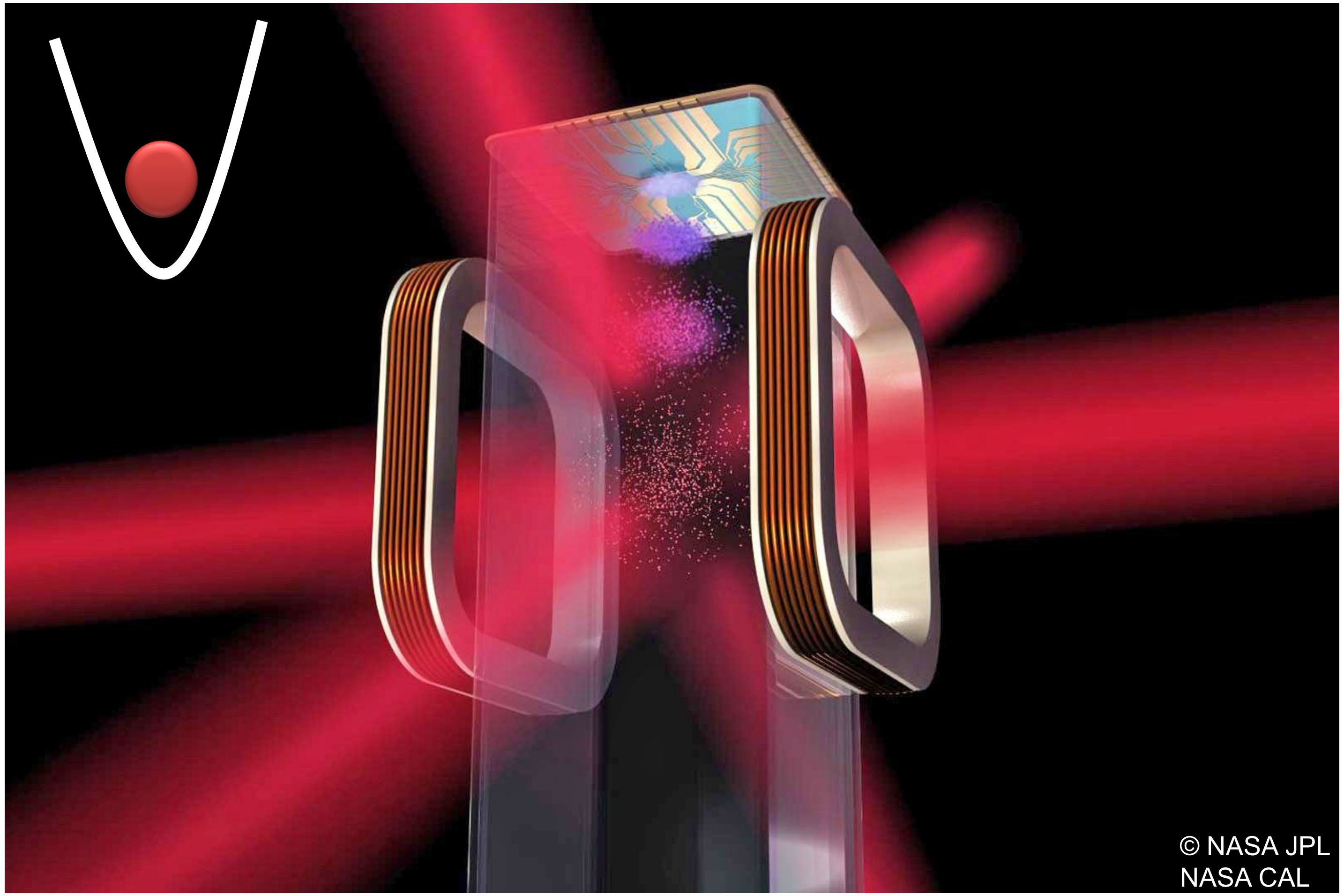

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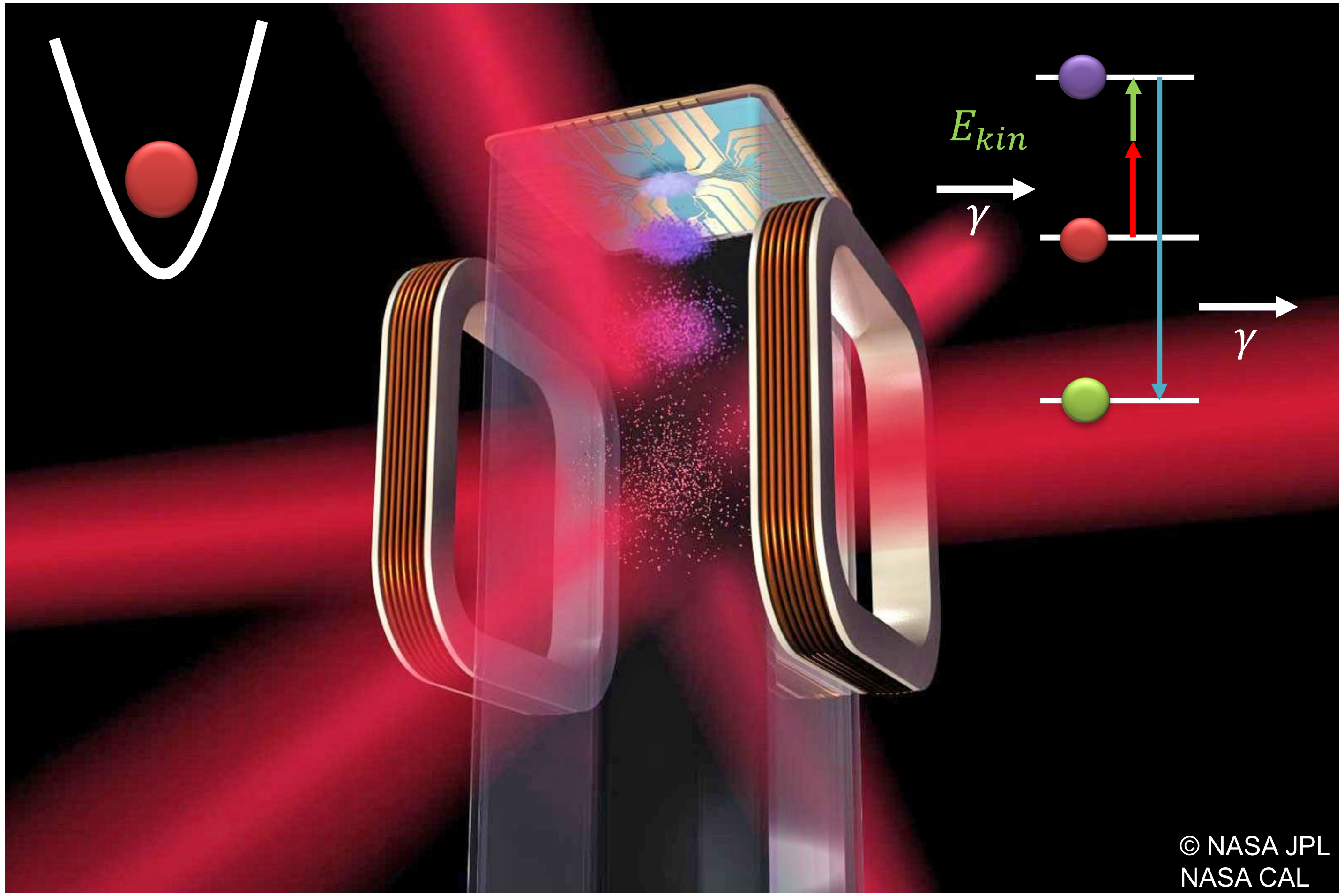

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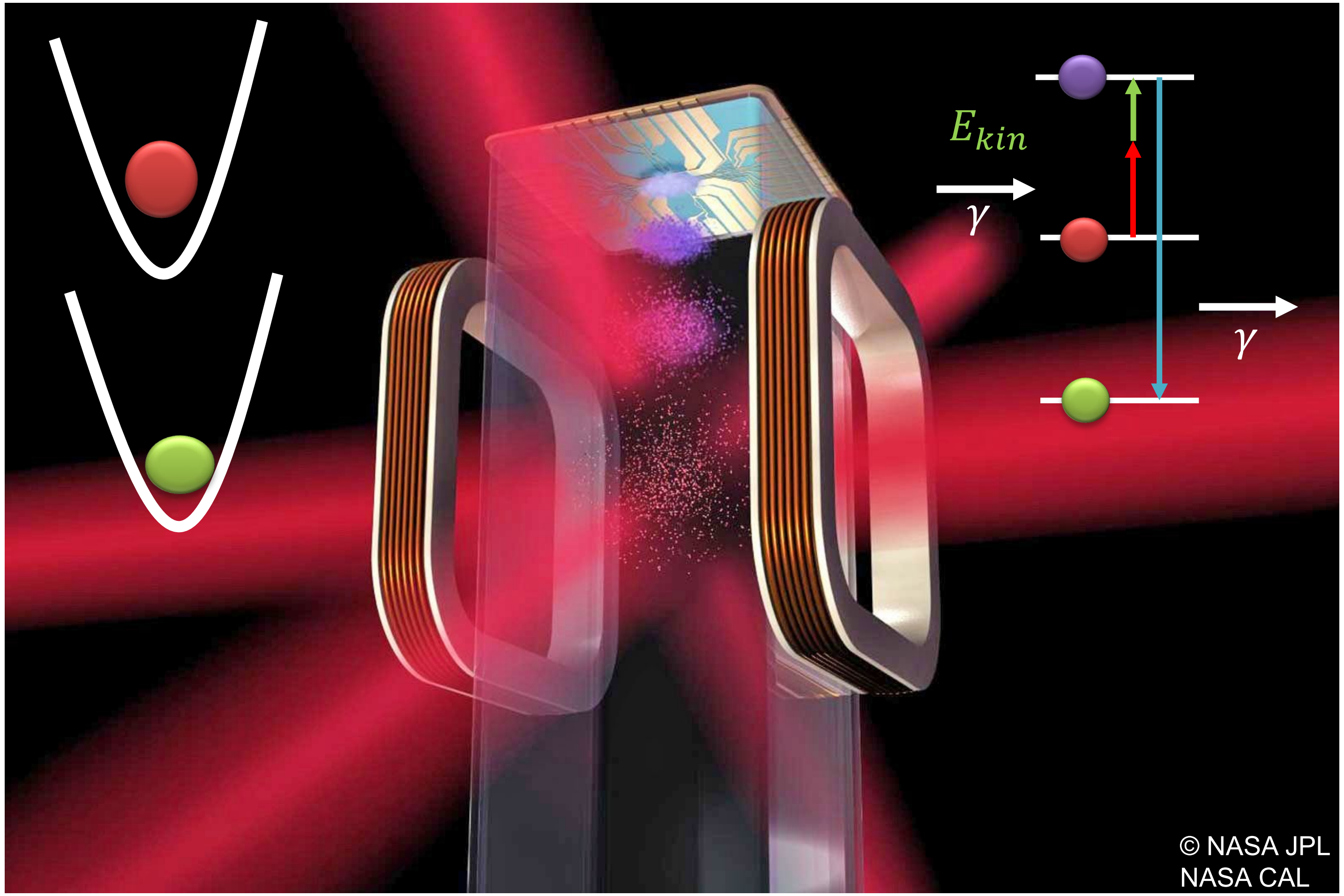

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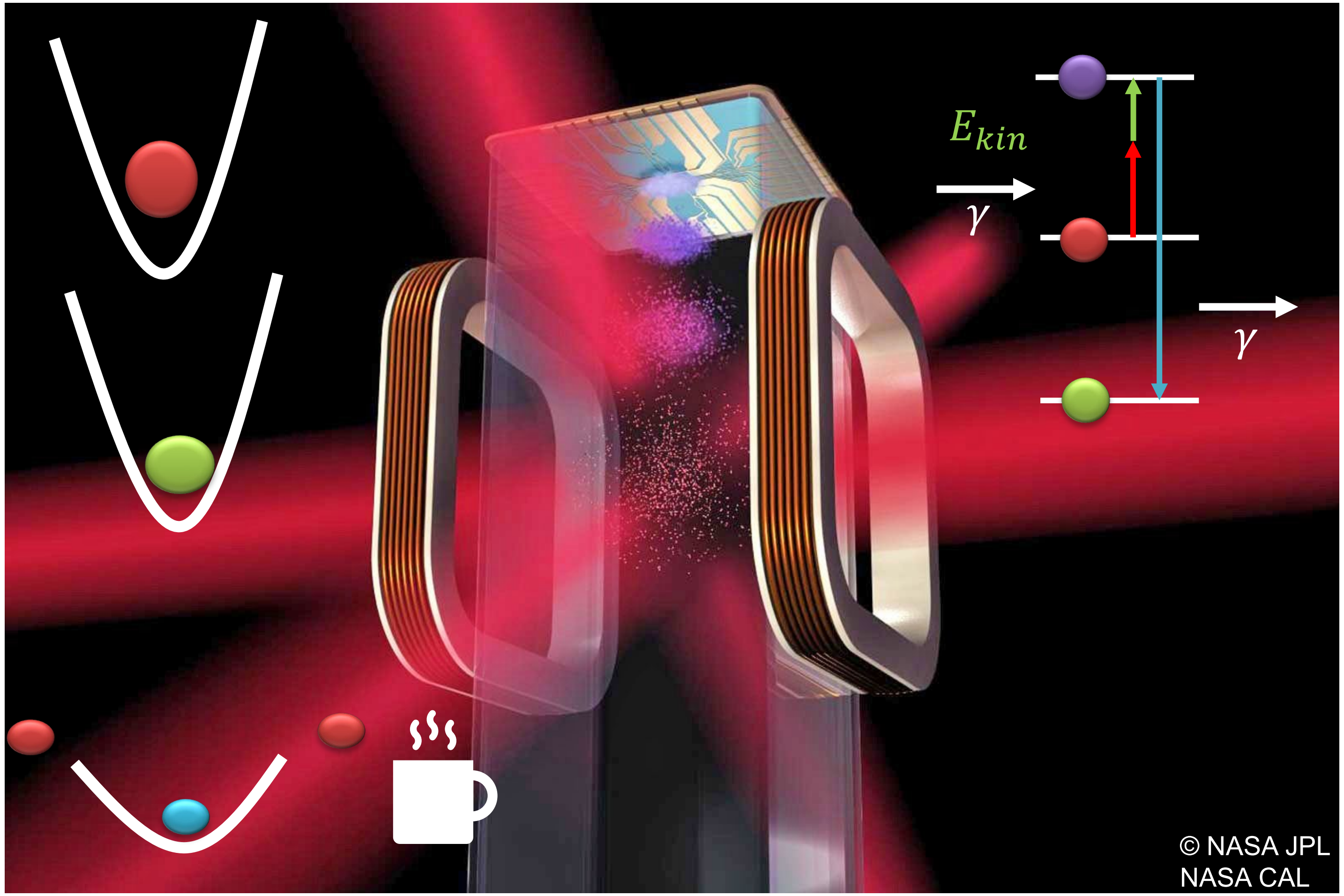

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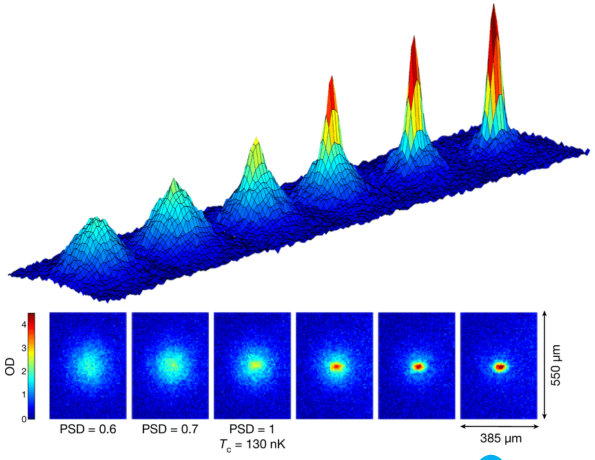

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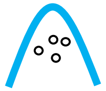

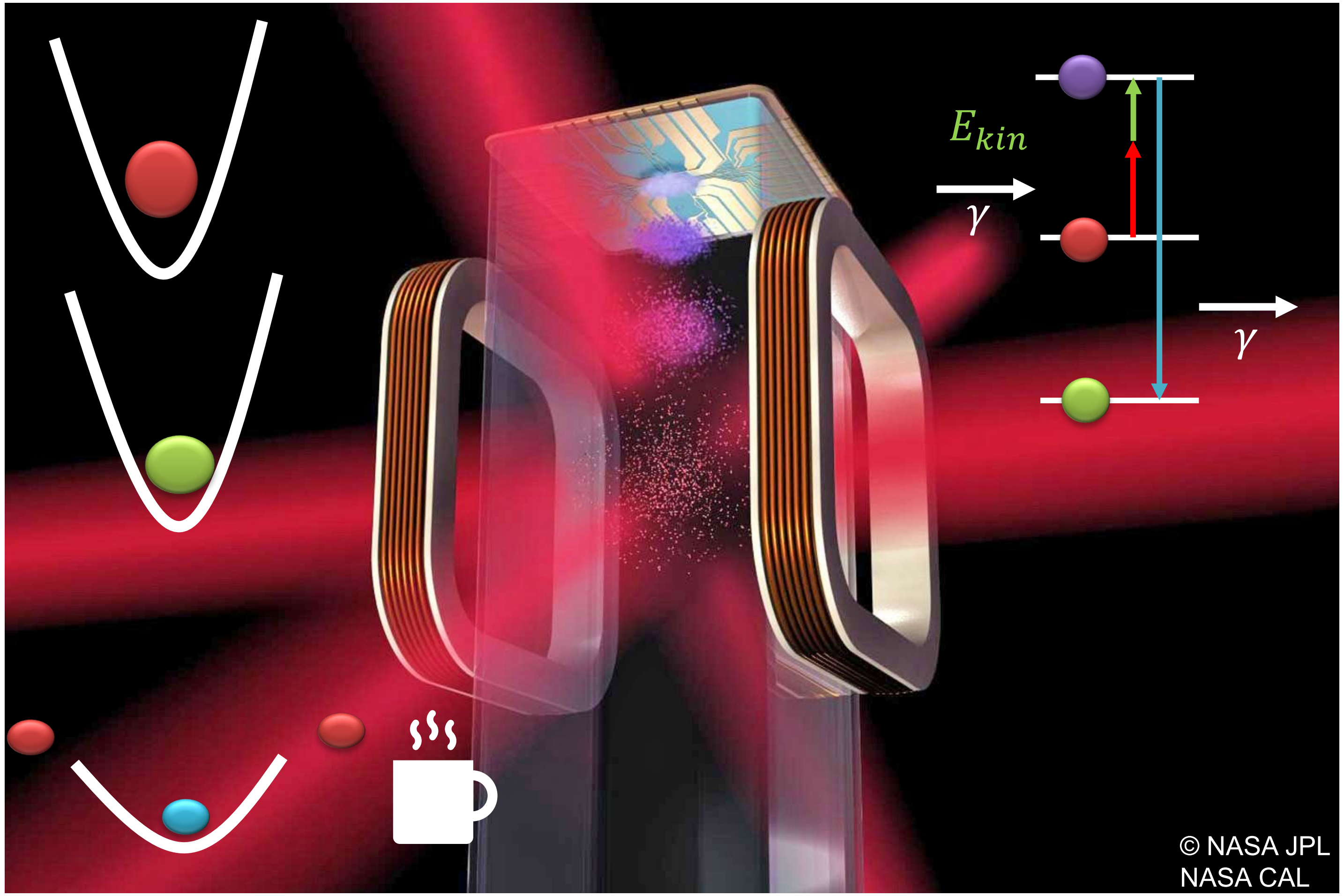

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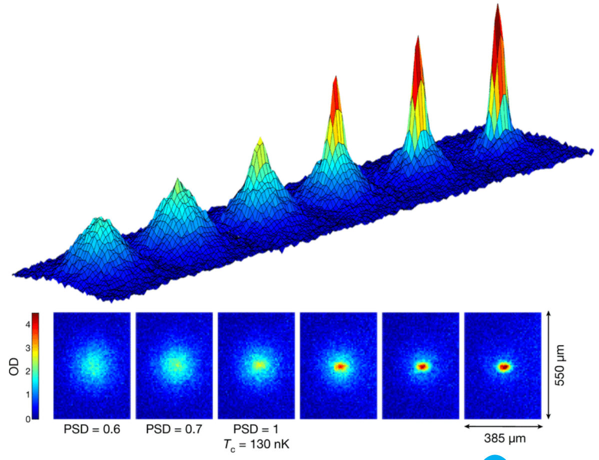

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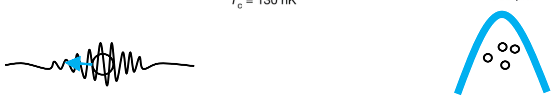

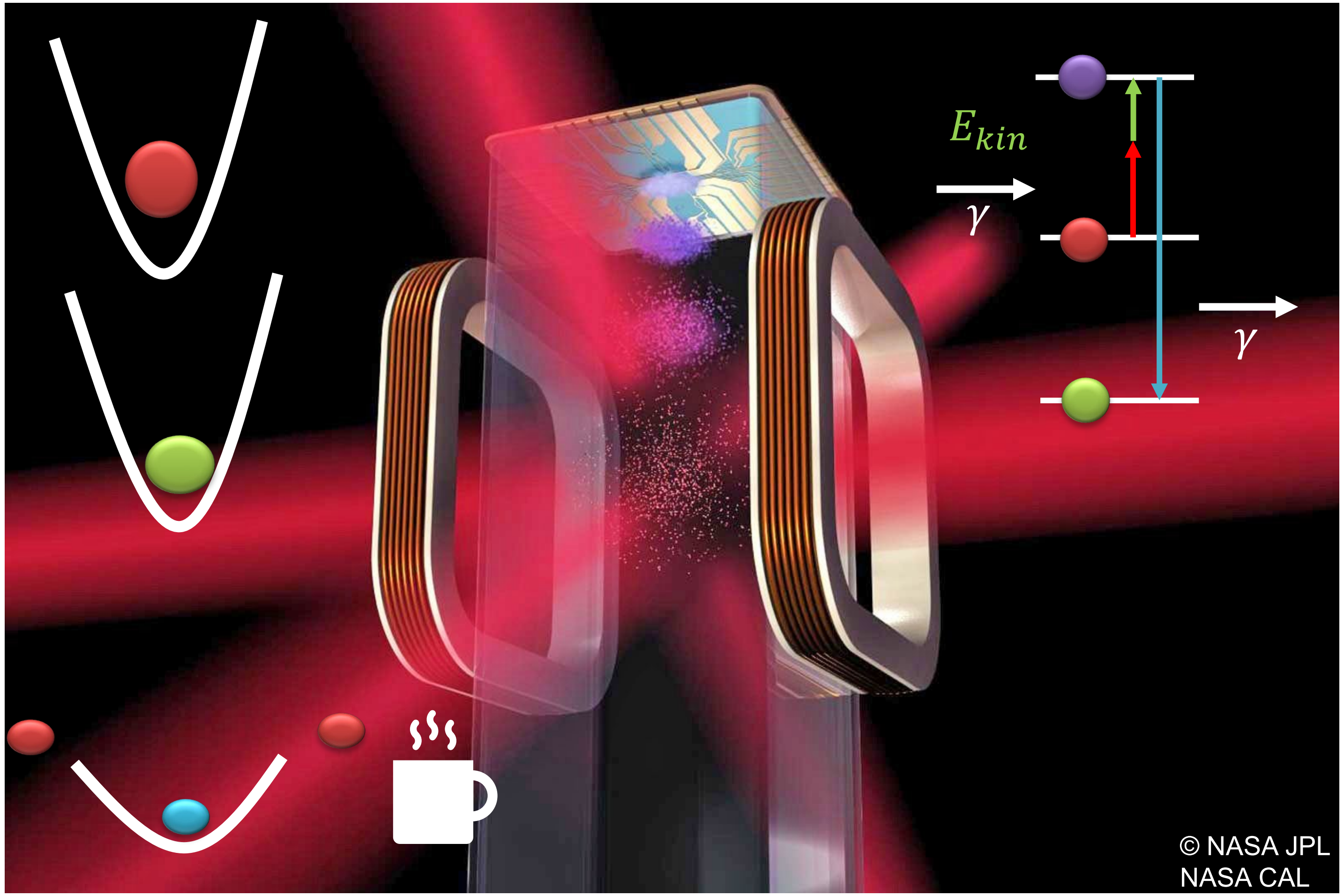

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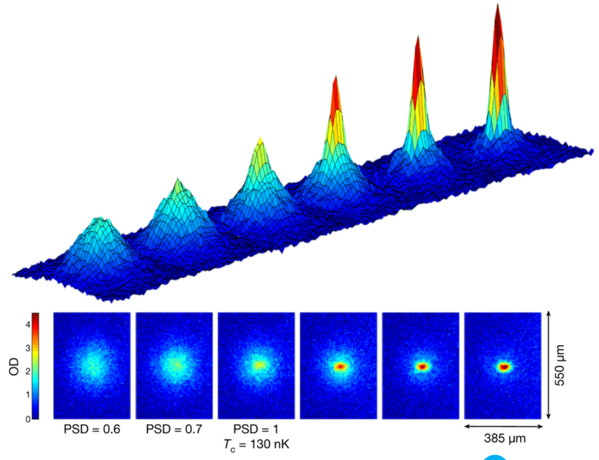

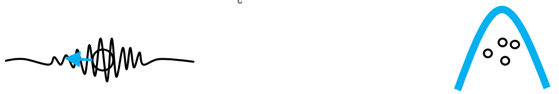

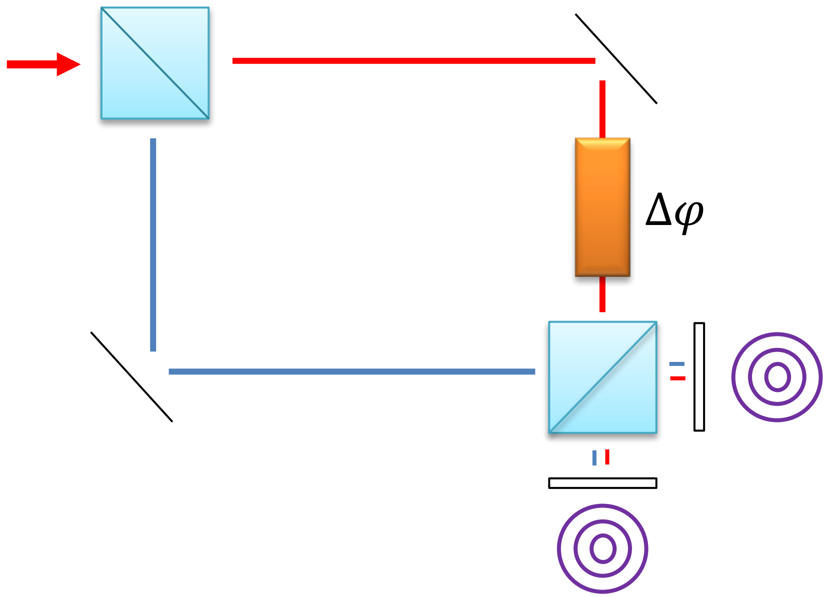

Climate Change Observation

Global Surveillance with Quantum Technologies

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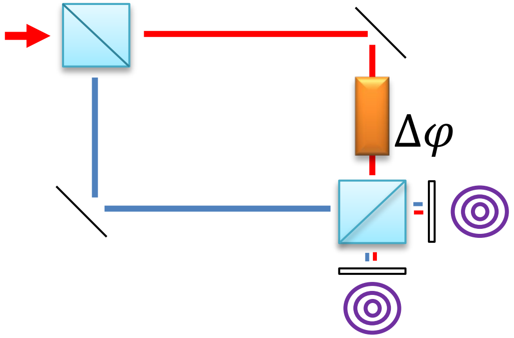
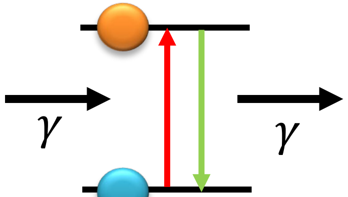
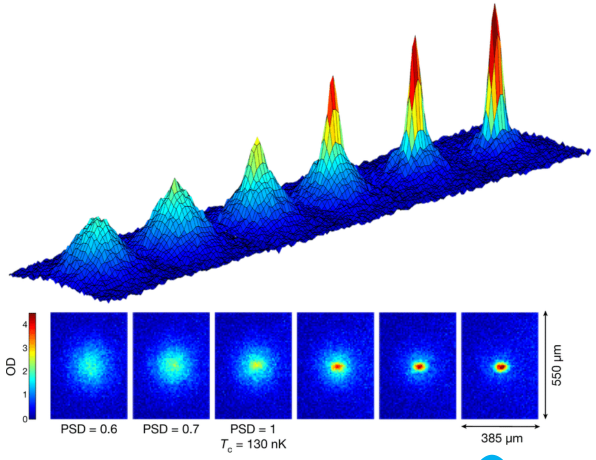
- **L**aser **R**anging **I**nterferometry







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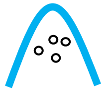

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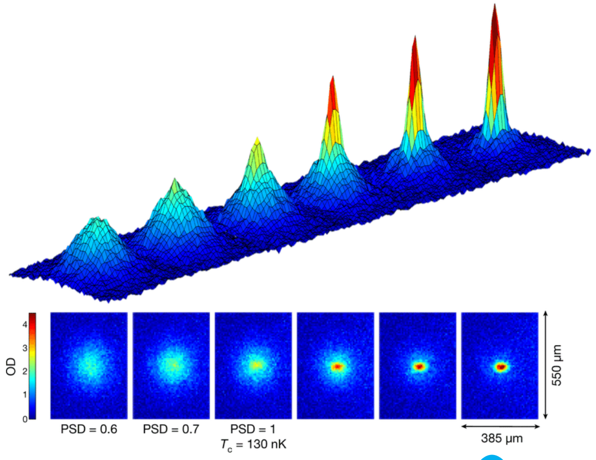

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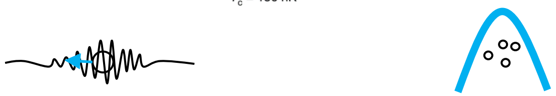

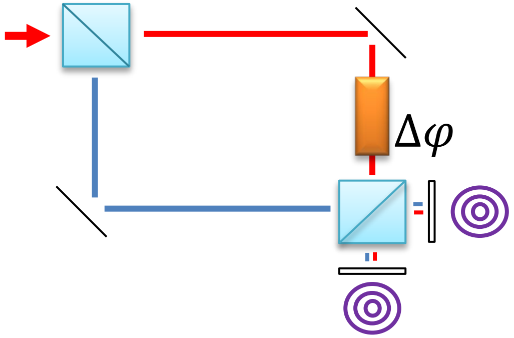

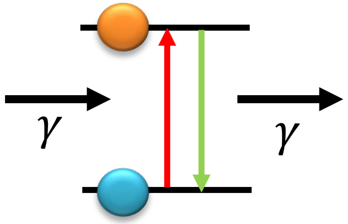

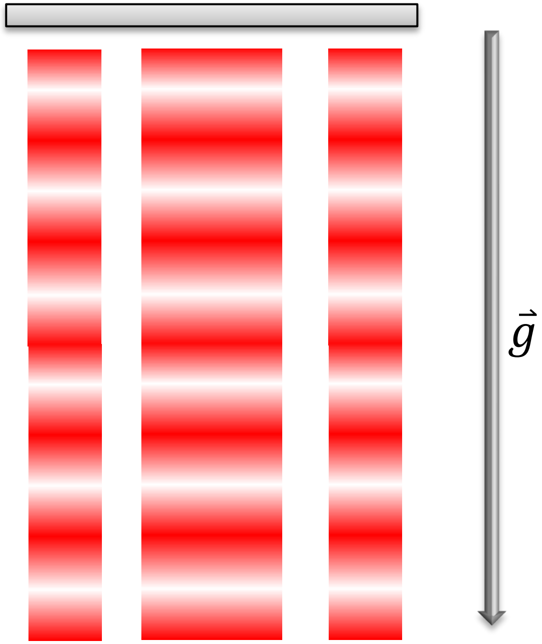

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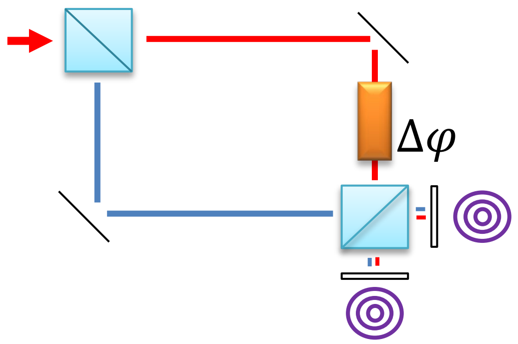

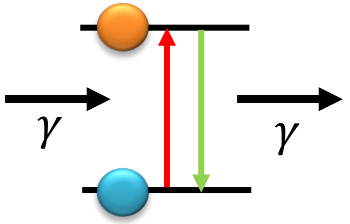

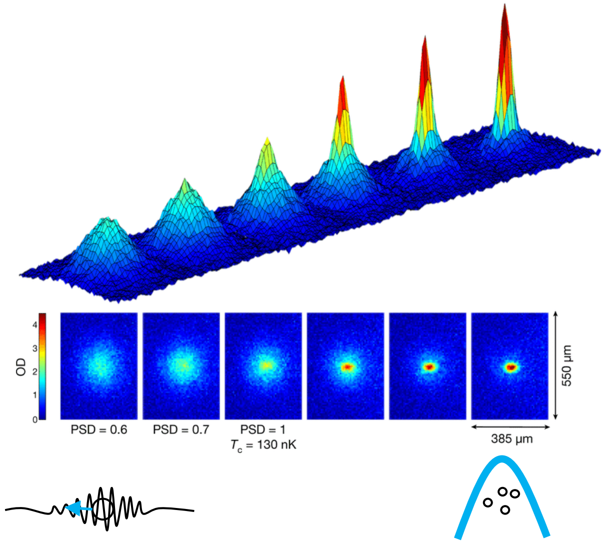

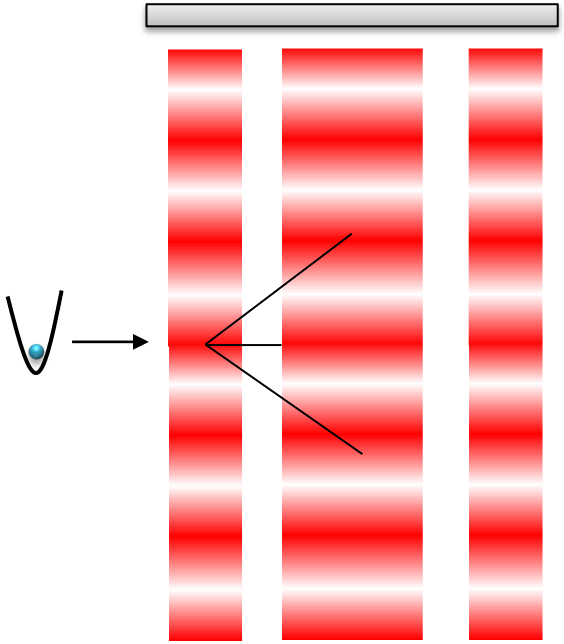

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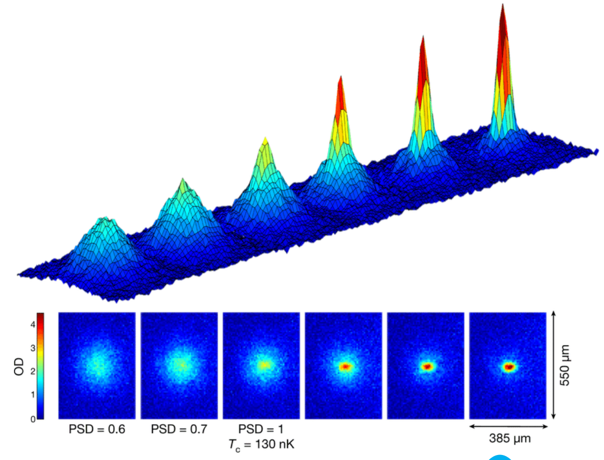

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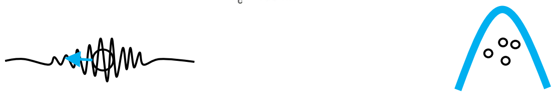

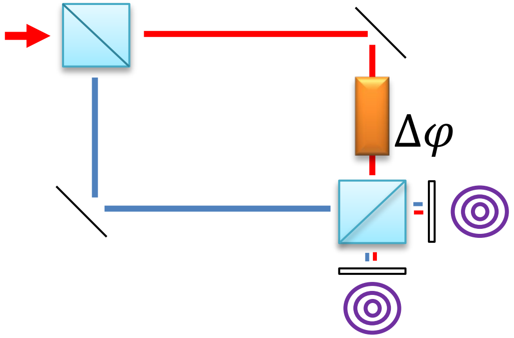

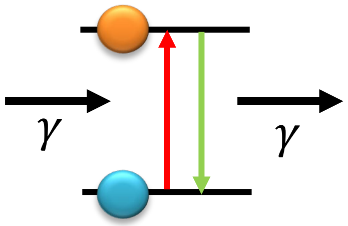

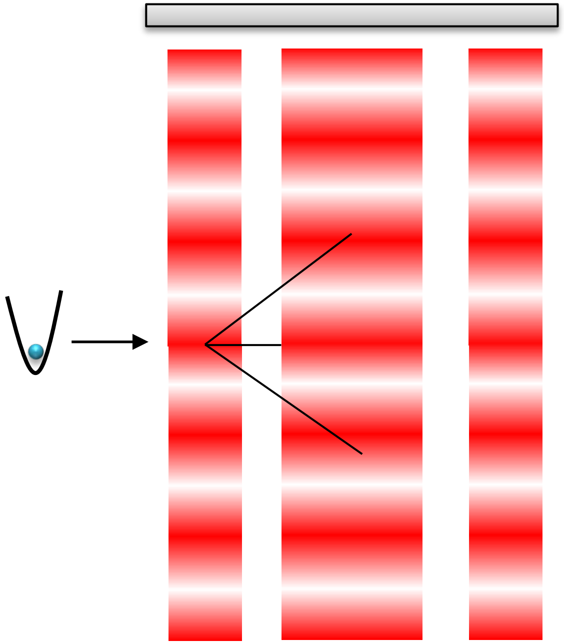

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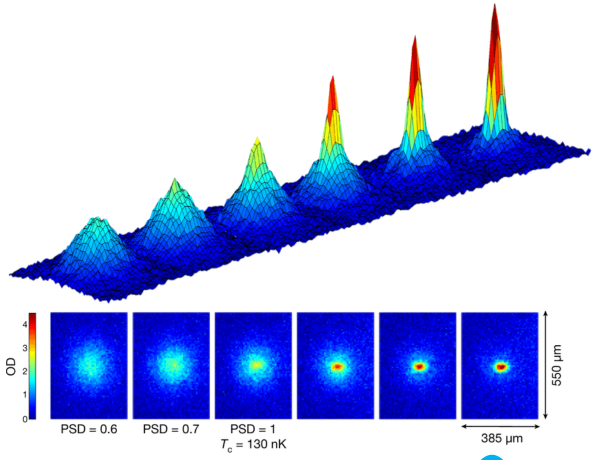

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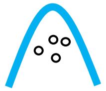

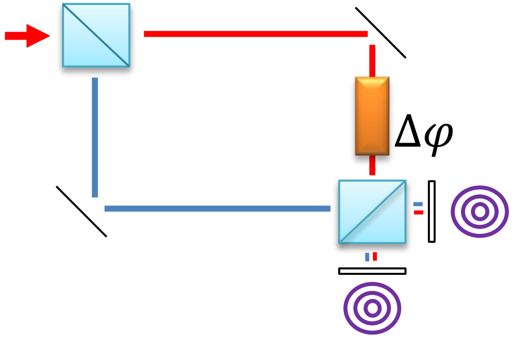

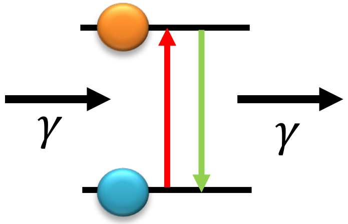

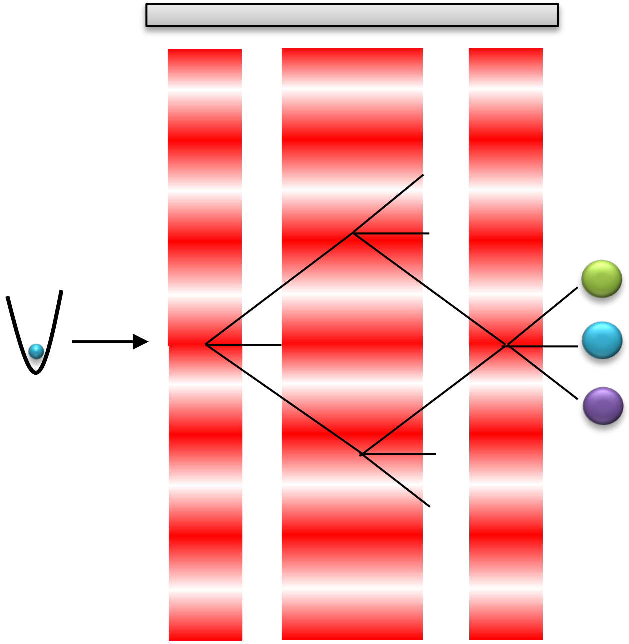

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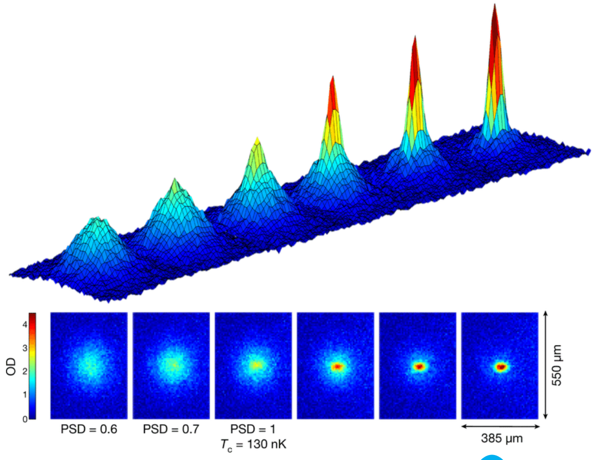

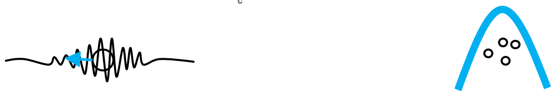

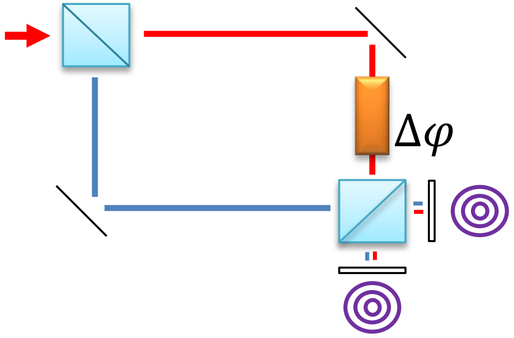

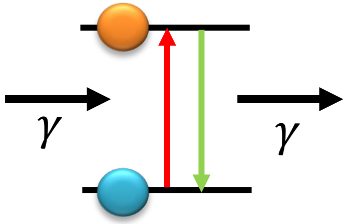

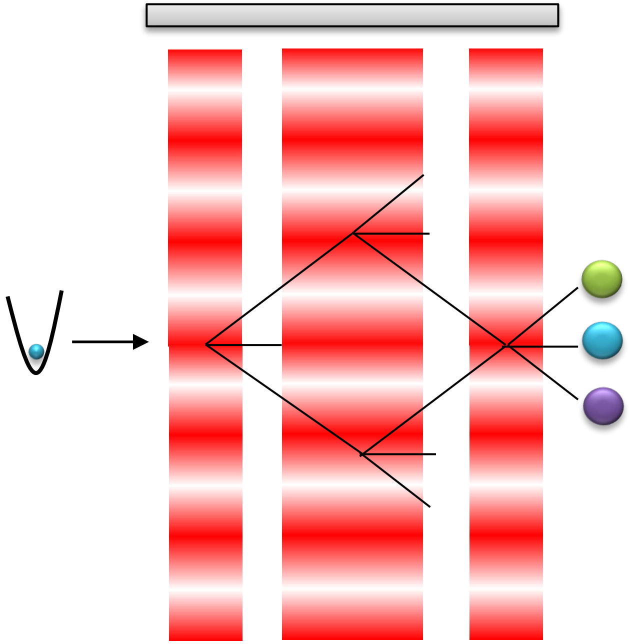

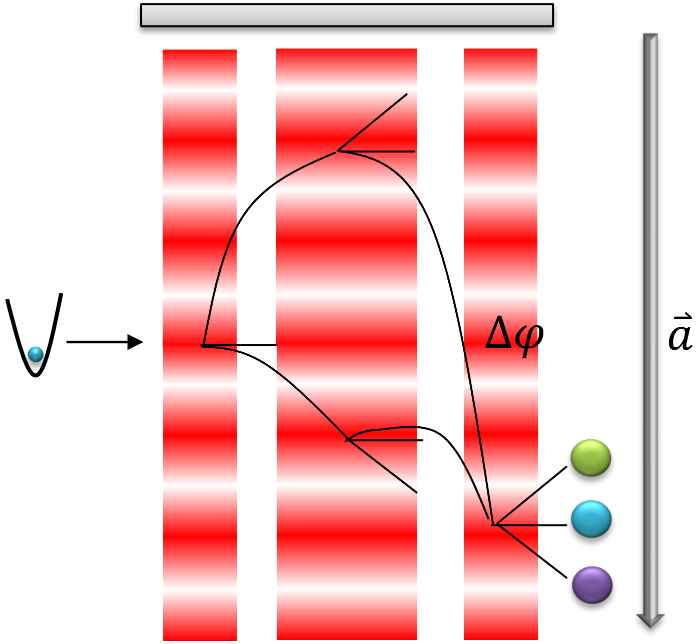

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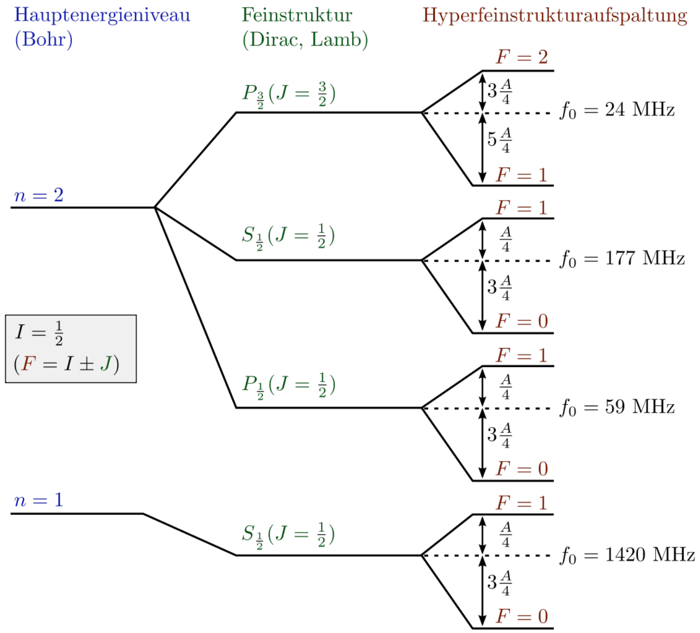

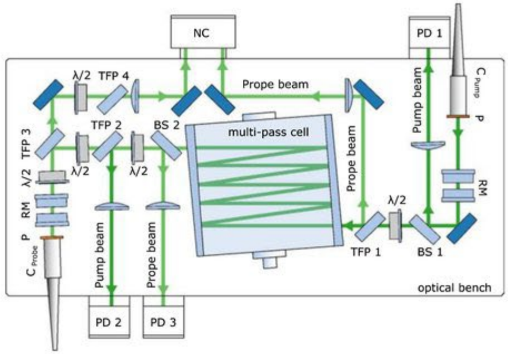

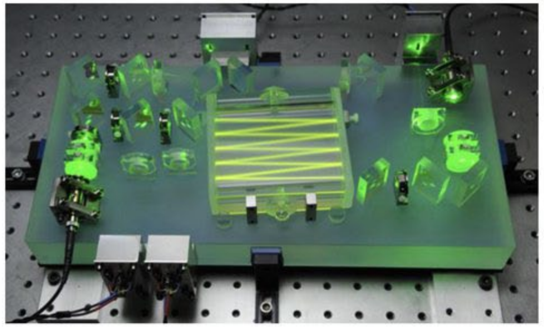

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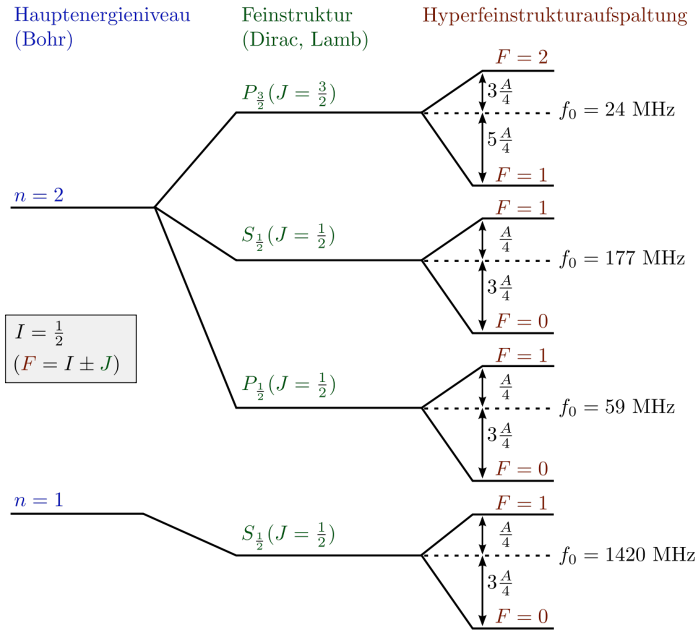

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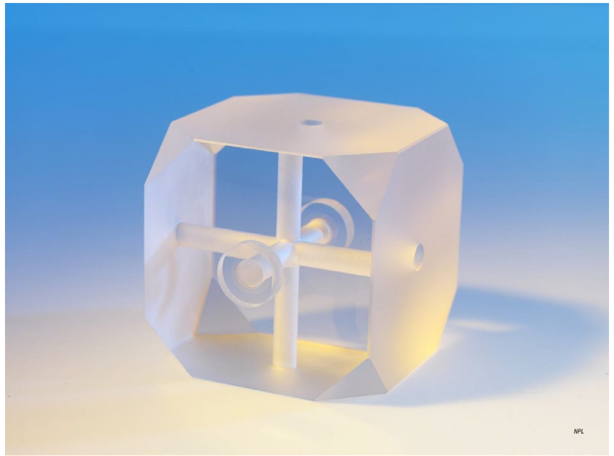

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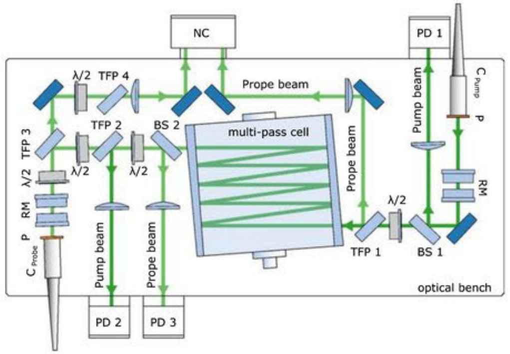

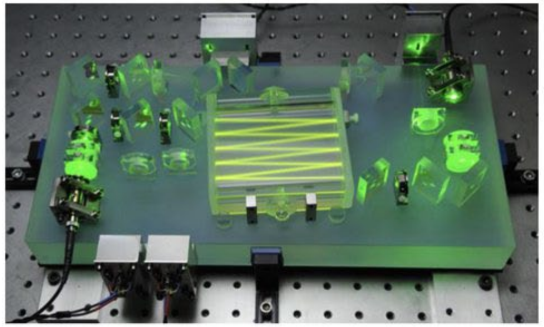

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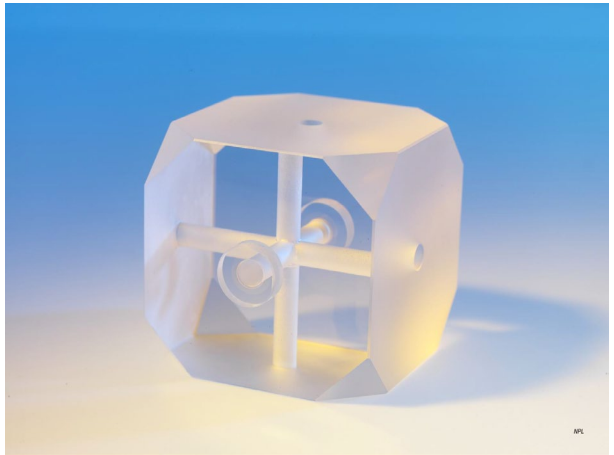
Climate Change Observation

Global Surveillance with Quantum Technologies

- Magneto Optical Trap
- Bose Einstein Condensate
- Cold Atom Interferometry
- Laser Stabilization
- Laser Ranging Interferometry



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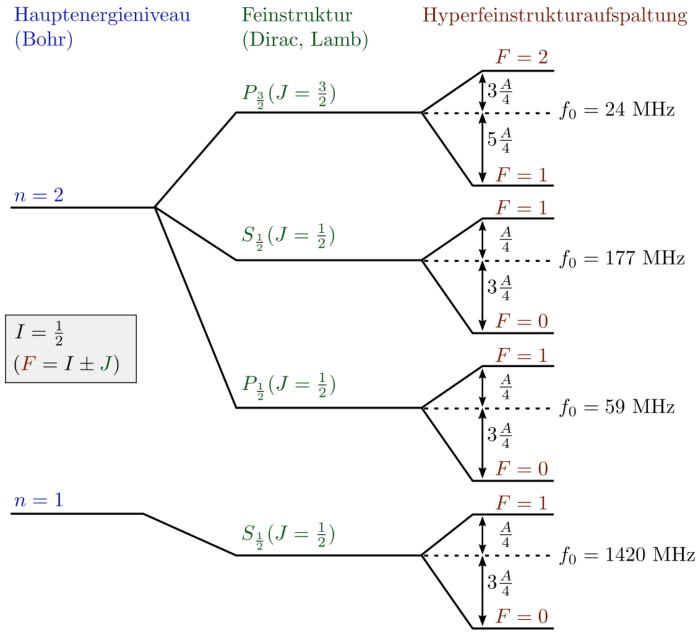

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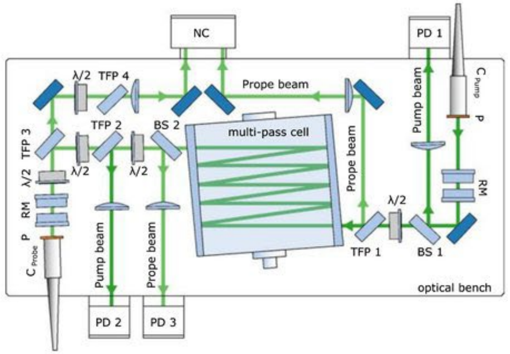

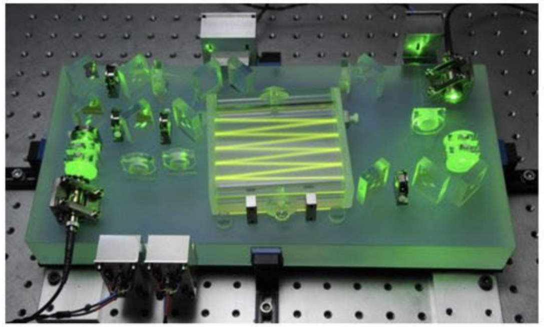

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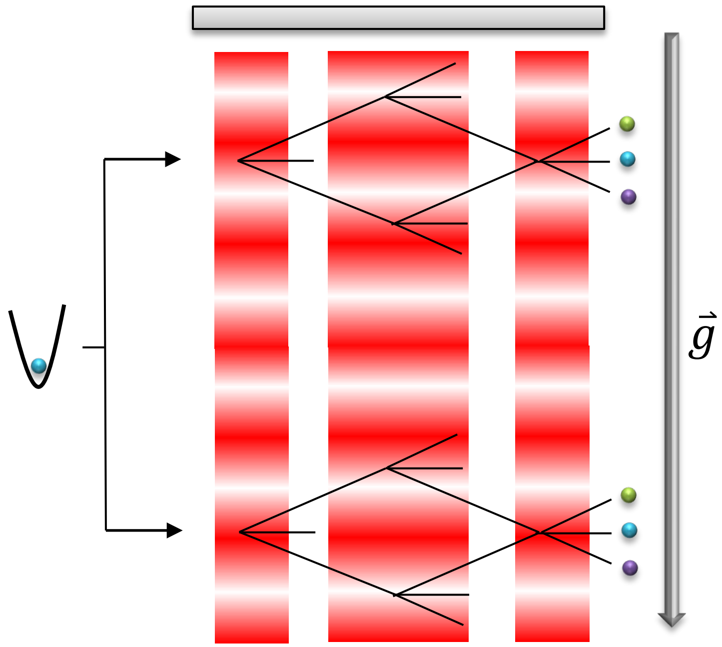
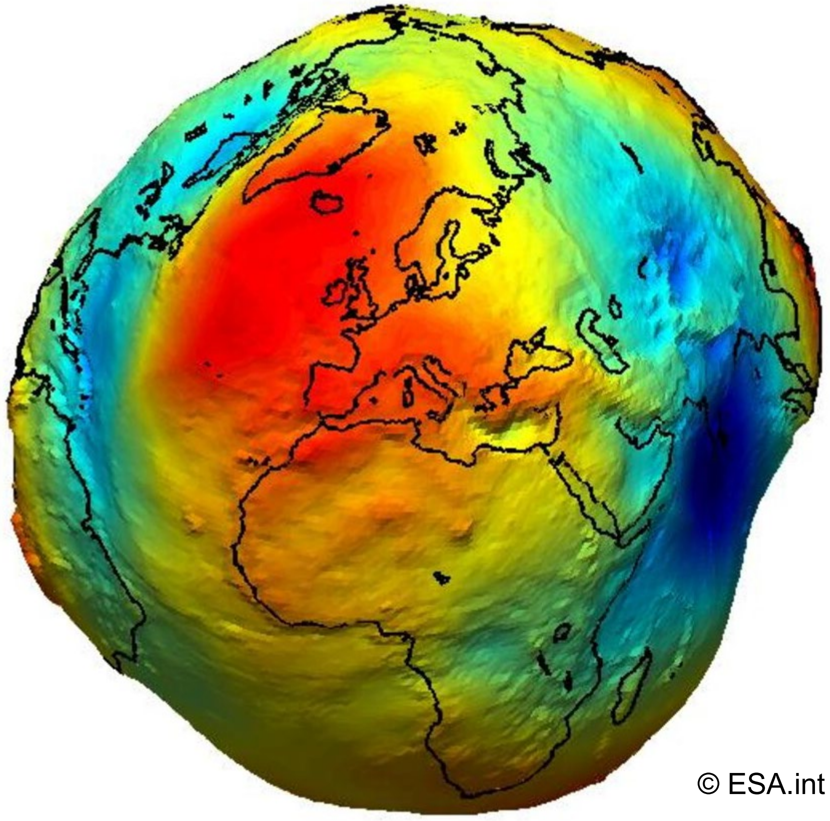
Climate Change Observation
Global Surveillance with Quantum Technologies

Gradiometry

‚GOCE' - type





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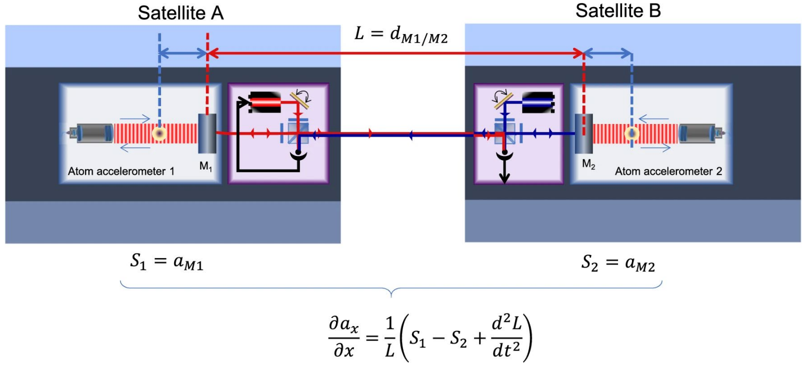
Gravimetry

GRICE ‚GRACE' - type



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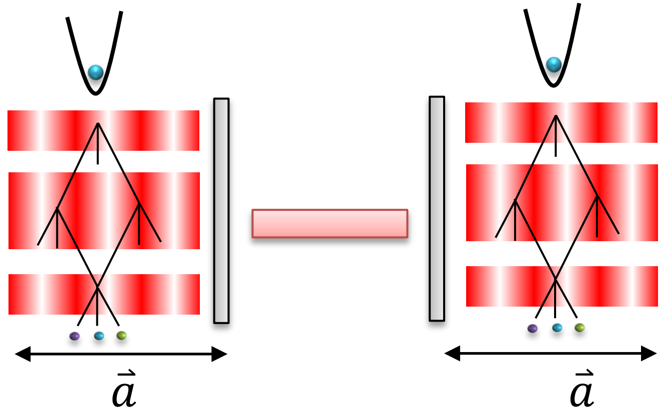

Climate Change Observation

Global Surveillance with Quantum Technologies

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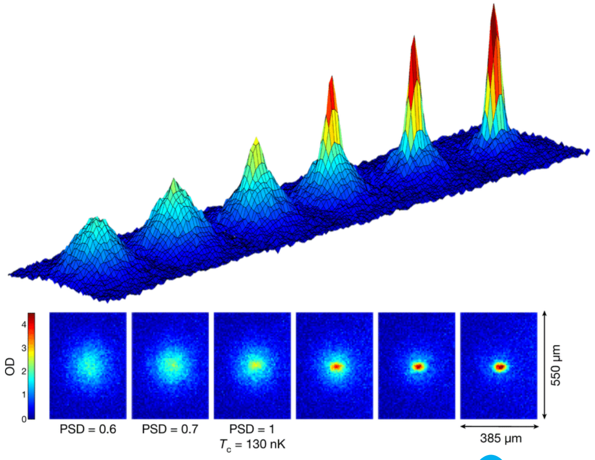

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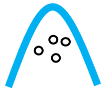
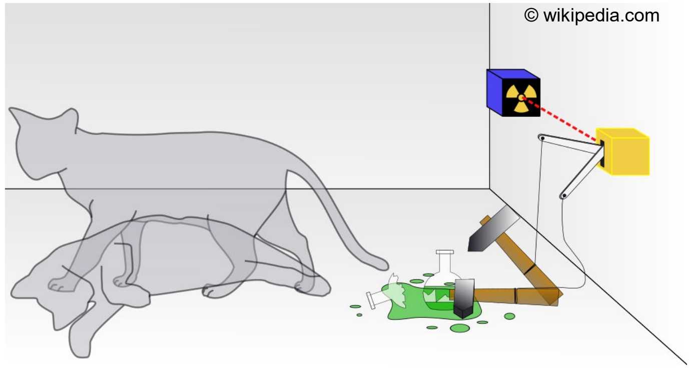
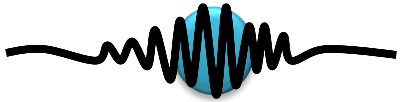


Quantum Mechanics

$$\left(-\frac{\hbar^2}{m}\Delta + E_{pot}\right)\Psi(x,y,z,t) = -i\hbar\,\frac{\partial}{\partial t}\Psi(x,y,z,t)$$

$$\Psi(x,t) = A\,e^{2\pi\,i\,(\nu t-\lambda x)} = \mathrm{A}\,e^{\frac{i}{\hbar}(Et\,-px)}$$





$$\lambda = \frac{h}{p} = \frac{h}{m\,v}$$

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Quantum Mechanics

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Quantum Techologies
Earth Observation

$$(-\frac{\hbar^2}{m}\Delta + E_{pot})\Psi(x,y,z,t) = -i\hbar\frac{\partial}{\partial t}\Psi(x,y,z,t)$$

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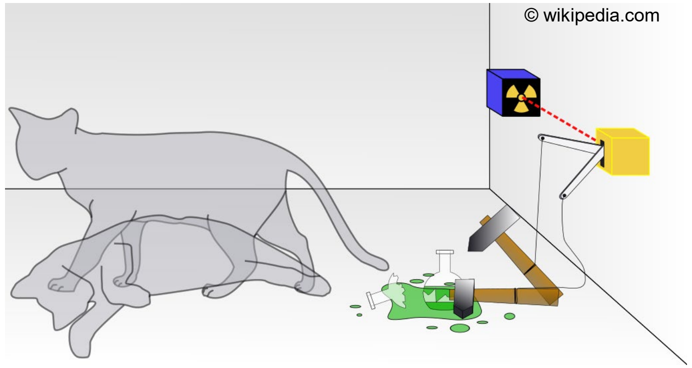

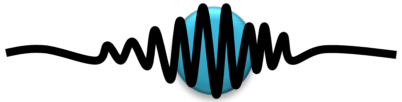

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Quantum Mechanics → Quantum Techologies Earth Observation

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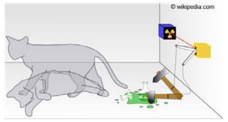

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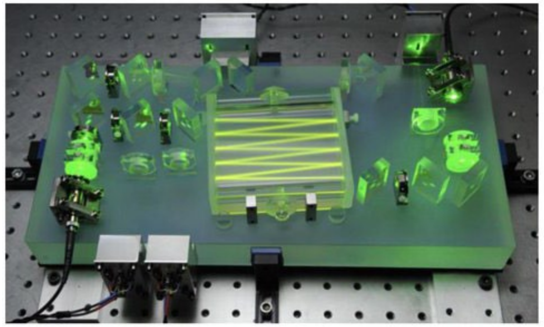

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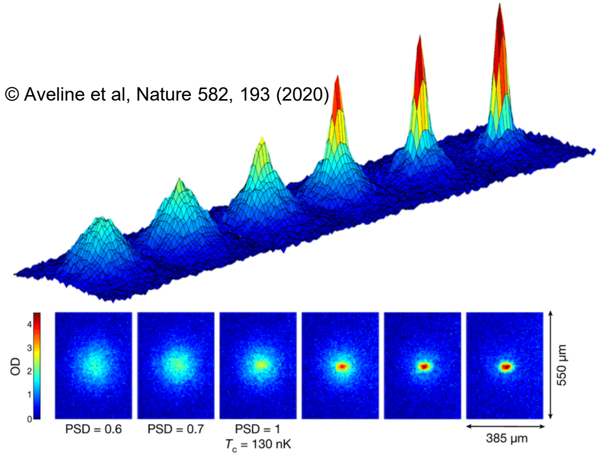

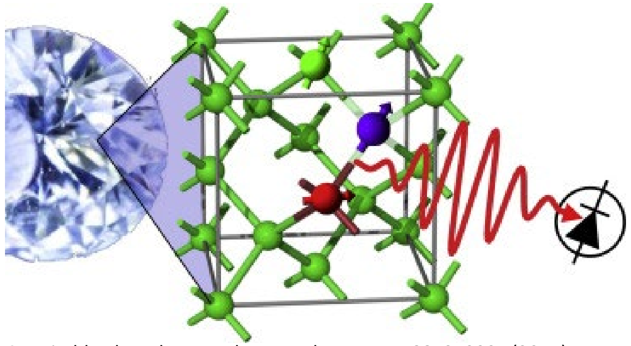

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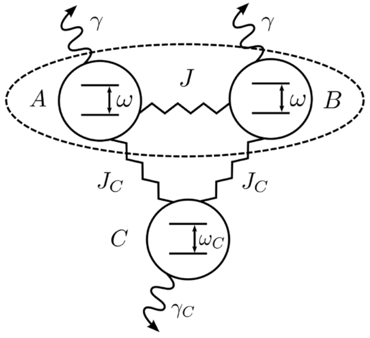

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Quantum Mechanics

Quantum Techologies
Earth Observation

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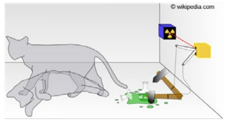

$$\lambda = \frac{h}{p} = \frac{h}{m\,v}$$

Quantum Technolgies

- **Sensing and Timing**
  - Inertial Sensing
  - Magnetic and Electric Fields
  - Precise Timing
  - Gravimetry and Gradiomentry
- **Entanglement**
  - Communication
  - Computing

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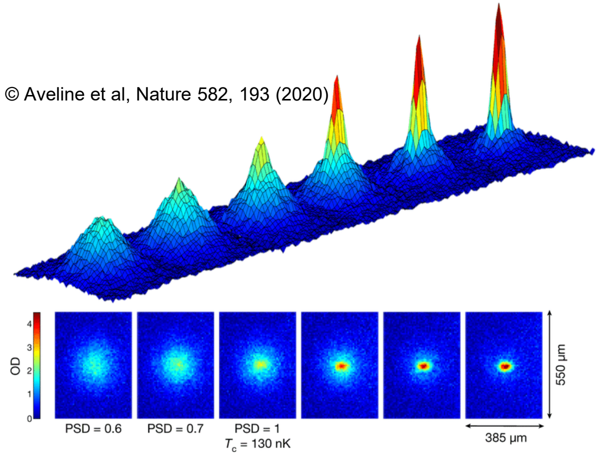

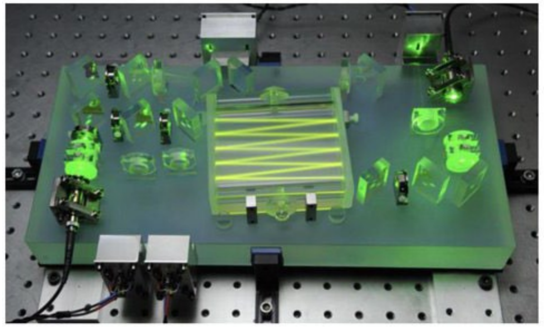

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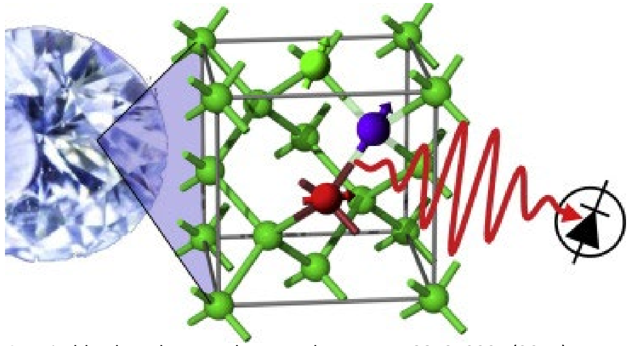

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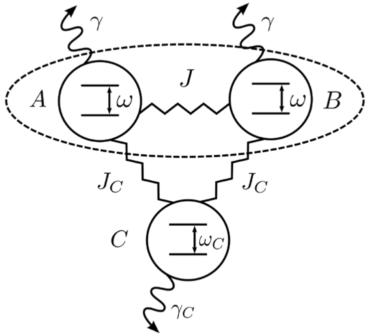

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Quantum Mechanics

Quantum Techologies Earth Observation

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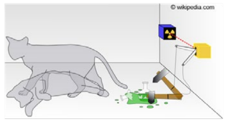

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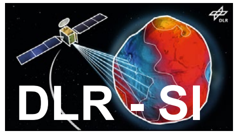

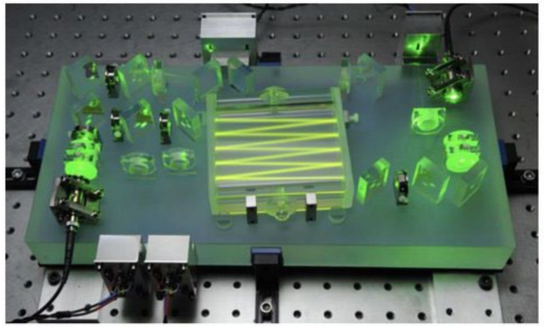

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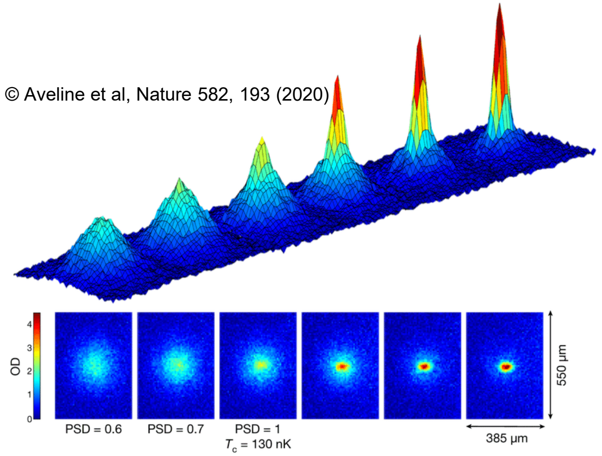

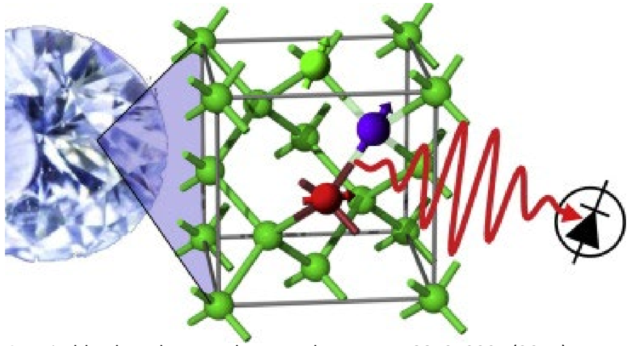

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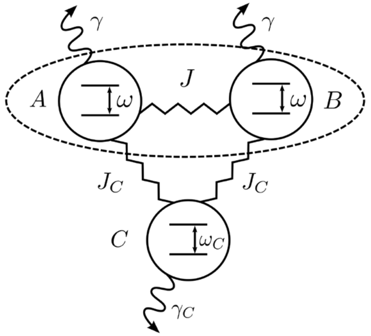

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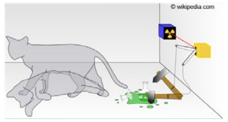

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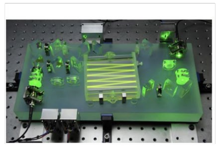

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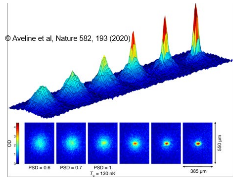

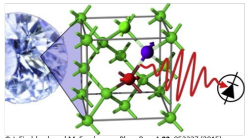

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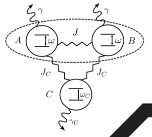

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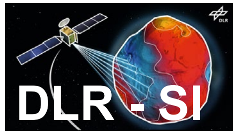

- Global Observation
  - GRACE – FO – like
  - GOCE – like
  - Magnetic Fields
- Early Warning Systems
  - Flooding
  - Earthquakes
- Prospection
- External Effects
  - Solar Winds
- Chaotic Effects
  - Weather Predictions
- Other (outside Earth Observation)
  - Exploration
  - Fundamental Physics