FOMO Lectures 2021

Matter Wave Interferometry in Space

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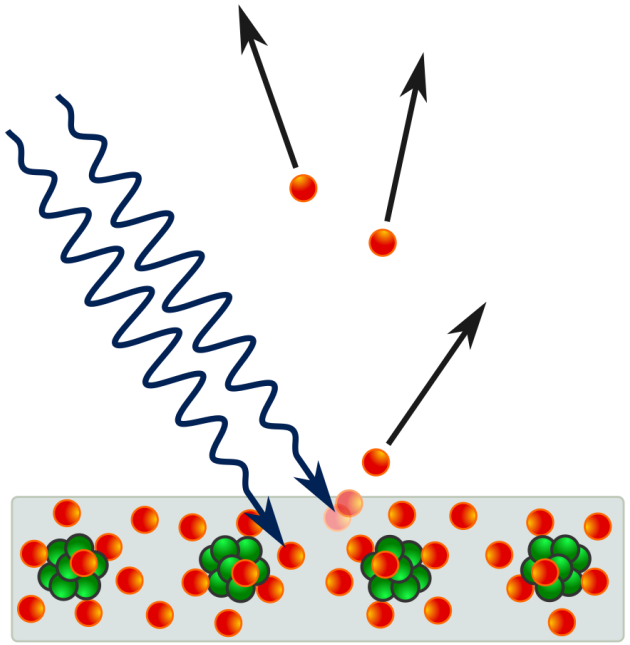
FOMO Lecture 2021

Matter Waves
Wave – Particle Duality

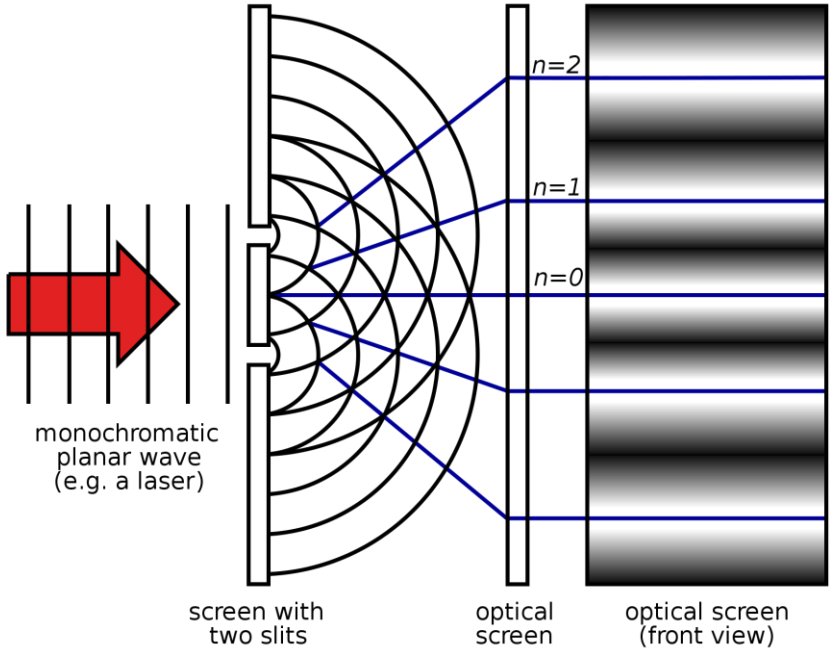
Particle – Like Behaviour

- Proof for Particle – Like Behavior:
  - Imaging
  - Photoelectric Effect



Wave – Like Behaviour

- Proof for Wave – Like Behaviour: Interferometry



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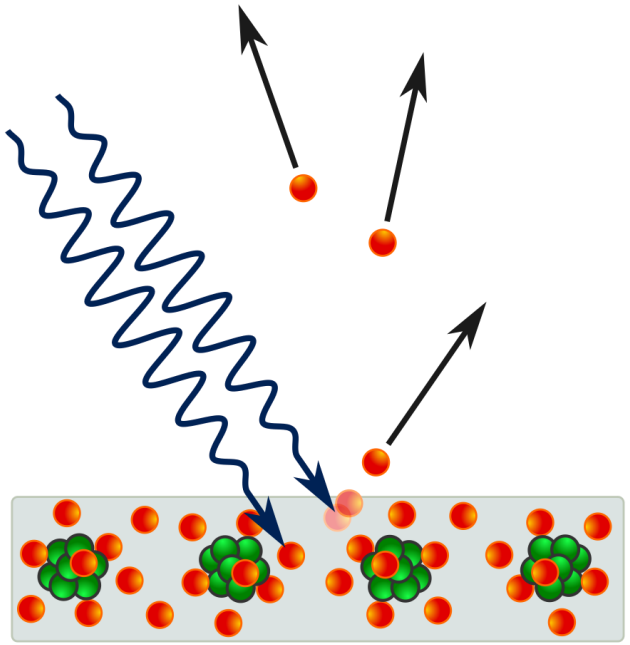
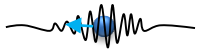


de Broglie Wavelength

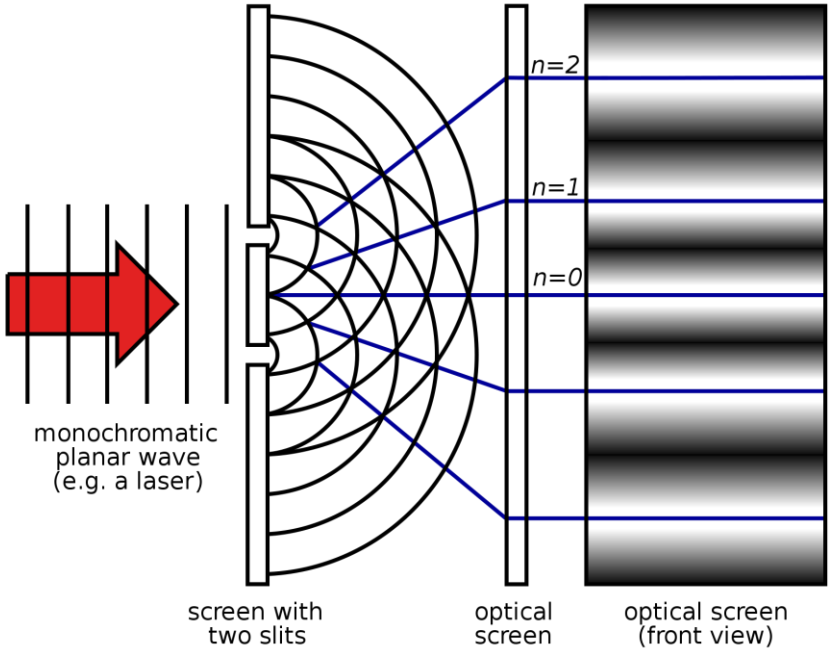
$$\lambda = \frac{h}{p} = \frac{h}{m\,v}$$



Mass m
Velocity v

Wave – Like Behaviour

- Proof for Wave – Like Behaviour: Interferometry



Matter Wave Interferometry

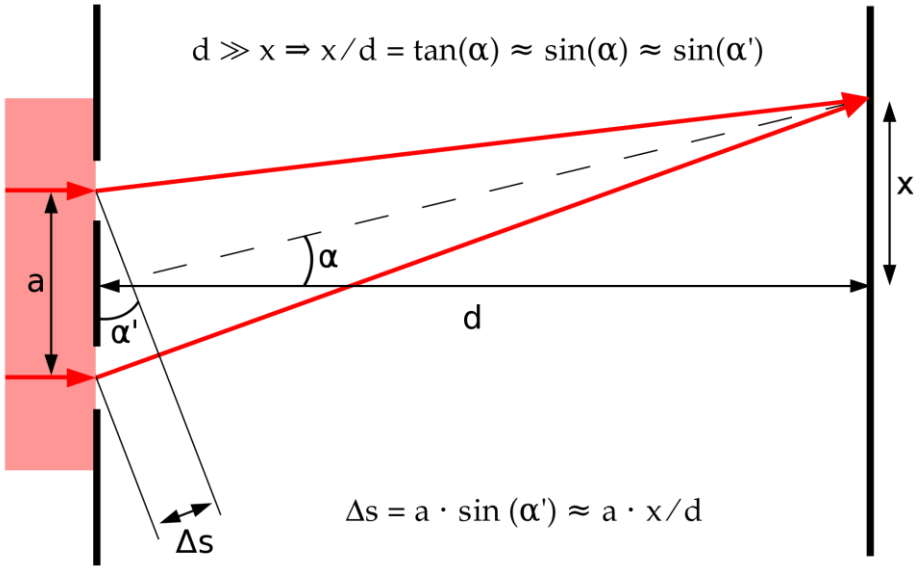
Matter Wave Interferometry

Double Slit / Grating Geometry

Mach Zehnder Geometry

Matter Wave Interferometry

Double Slit / Grating Geometry



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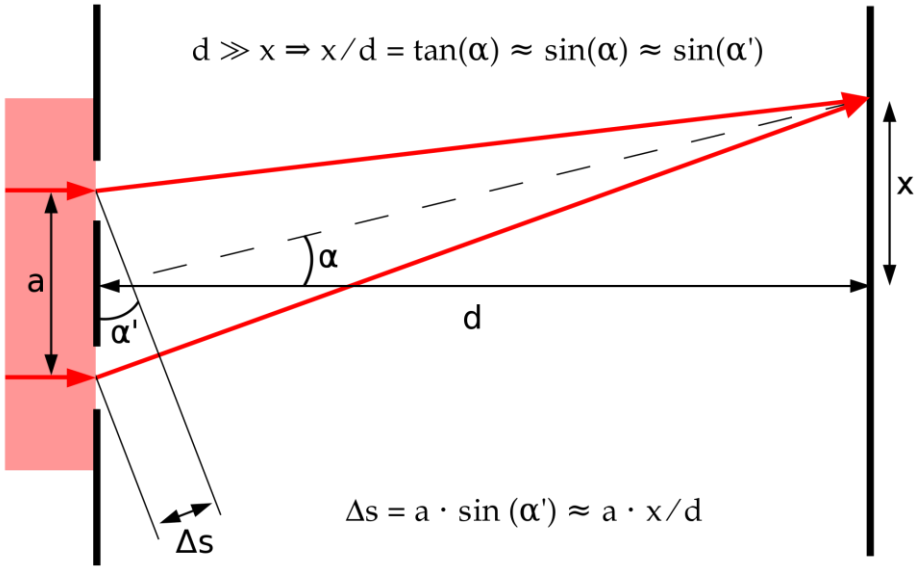

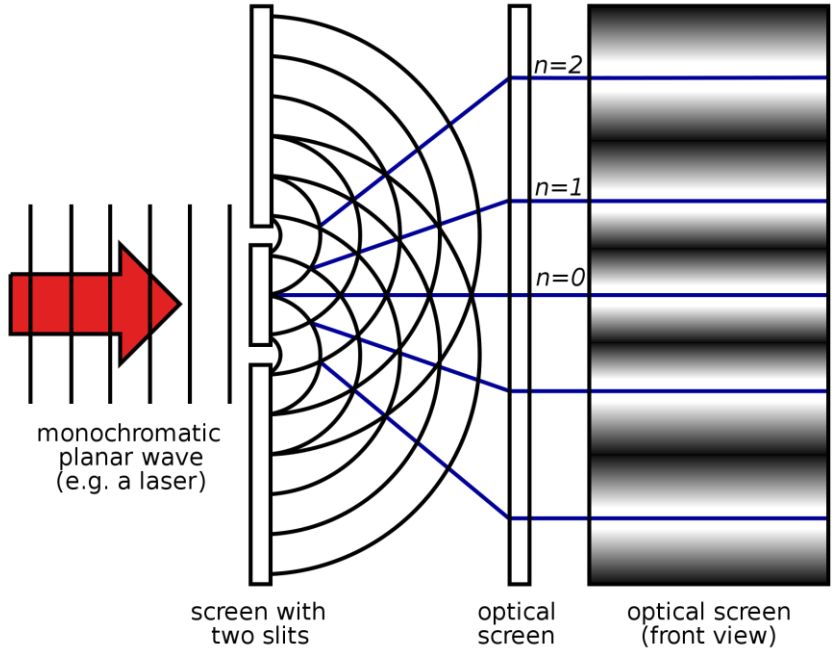

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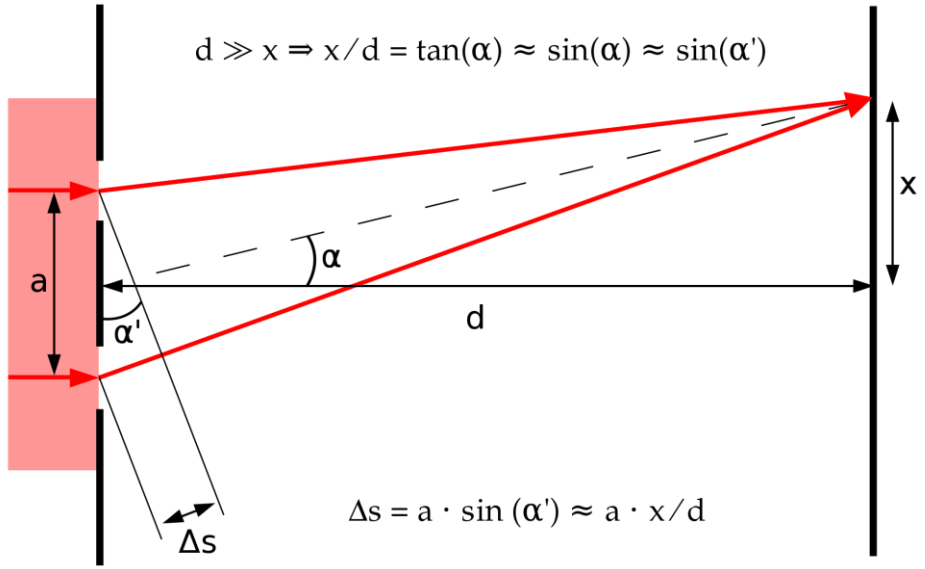
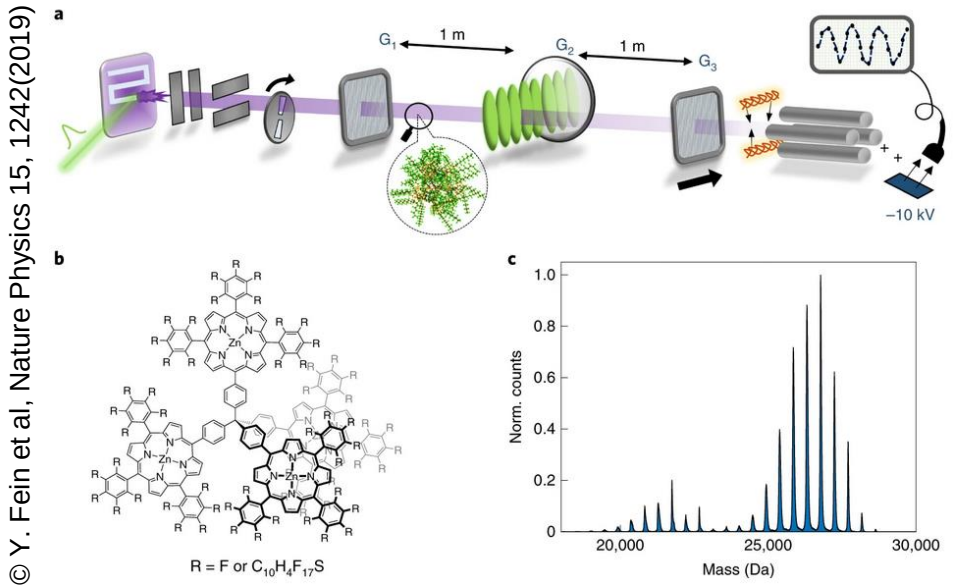


Experimental Proof:

- 1961 Electrons
  Clauss Jönsson et al.
- 1999 C_{60} Molecules
  Markus Arndt et al.
- 2019 Molecules containing 2000 Atoms
  Markus Arndt et al.



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Matter Wave Interferometry

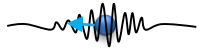
Matter Wave Interferometry

de Broglie Wavelength

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

Grating / Slit

Detection Screen



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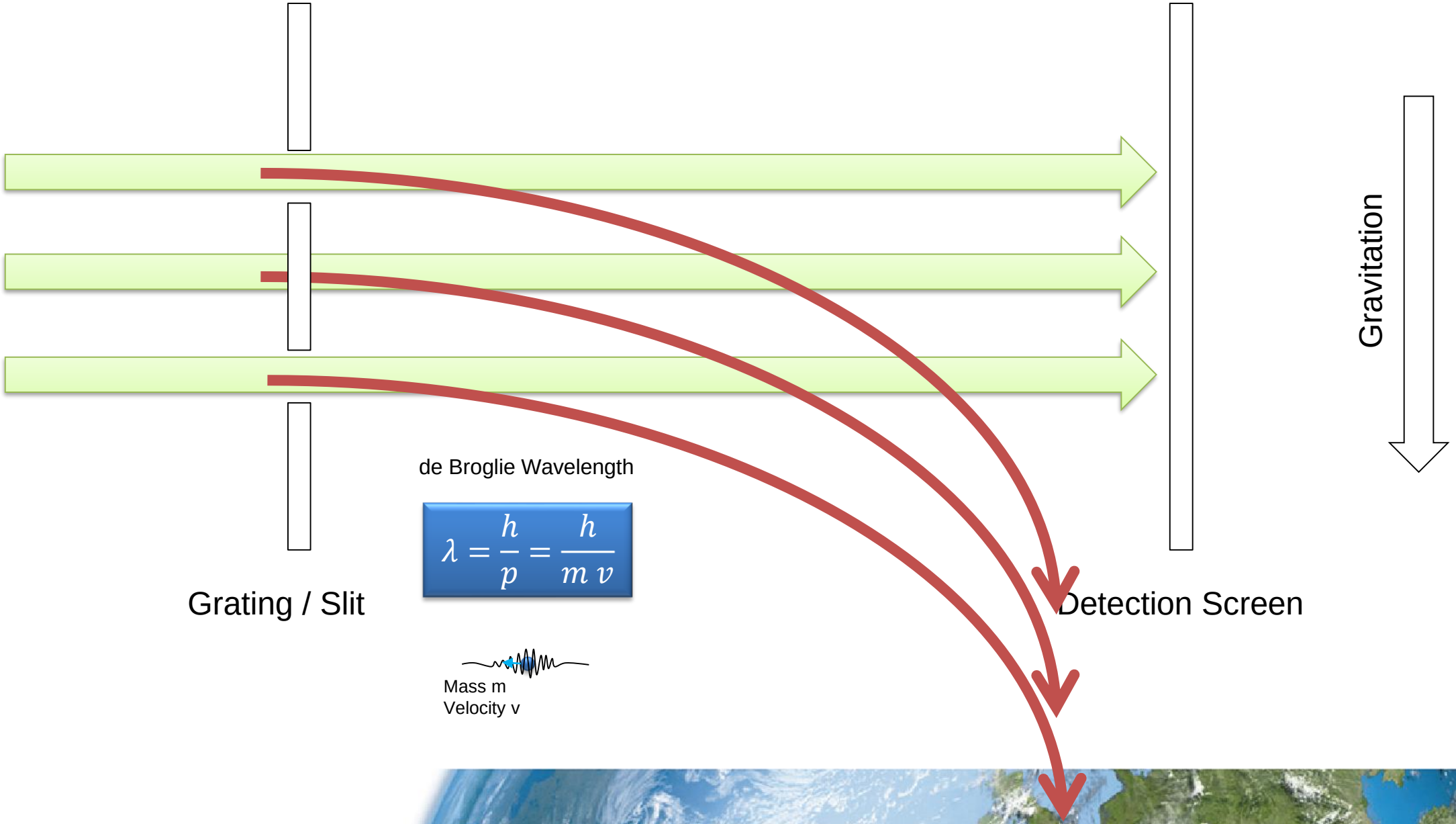
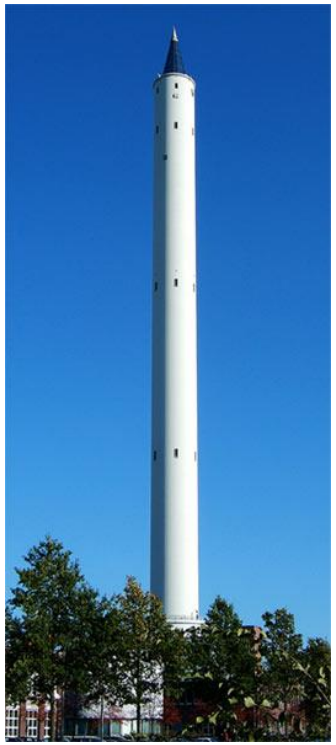
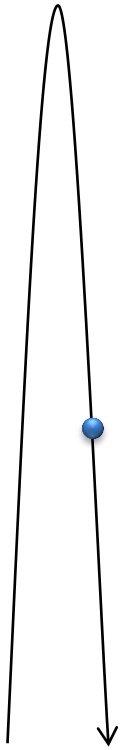
Matter Wave Interferometry



Matter Wave Interferometry

Free Falling Apperatus





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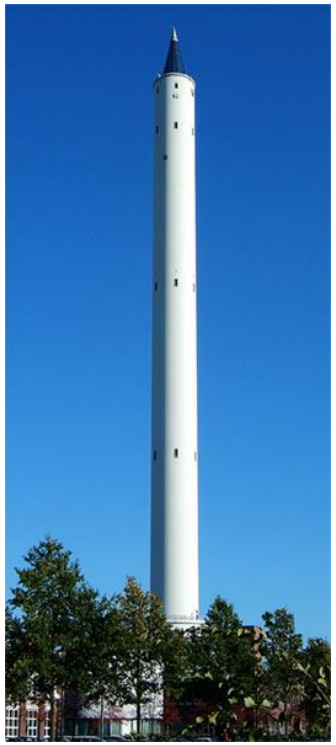
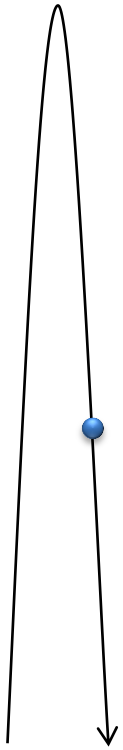




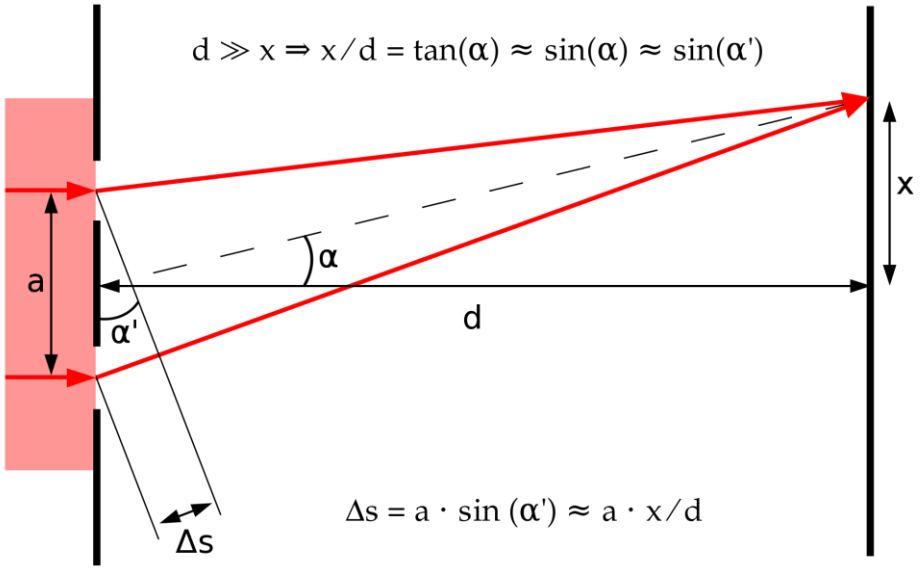
Space

MAQRO

R. Kaltenbaeck et al.
https://arxiv.org/abs/1503.02640

Matter Wave Interferometry

Double Slit / Grating Geometry



Mach Zehnder Geometry

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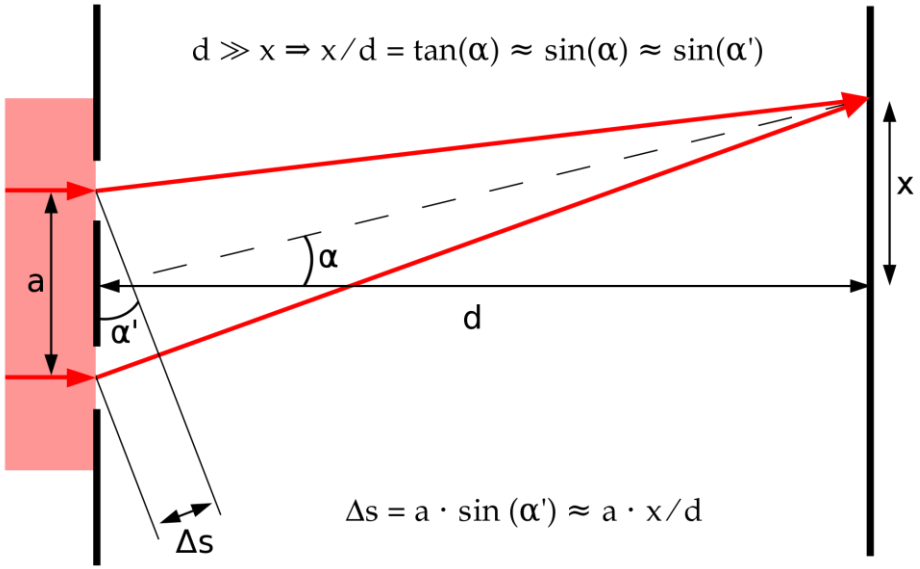

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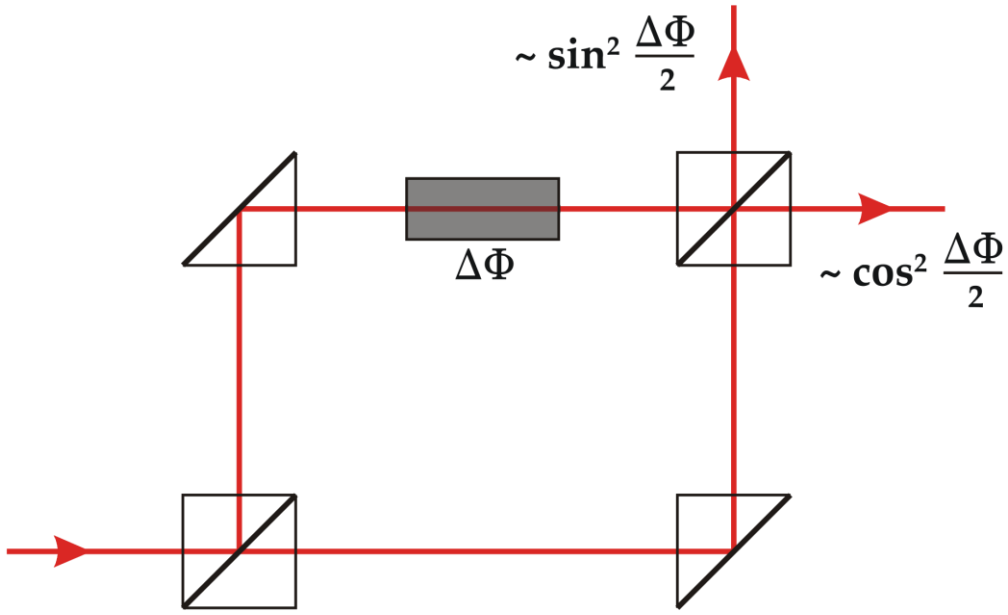

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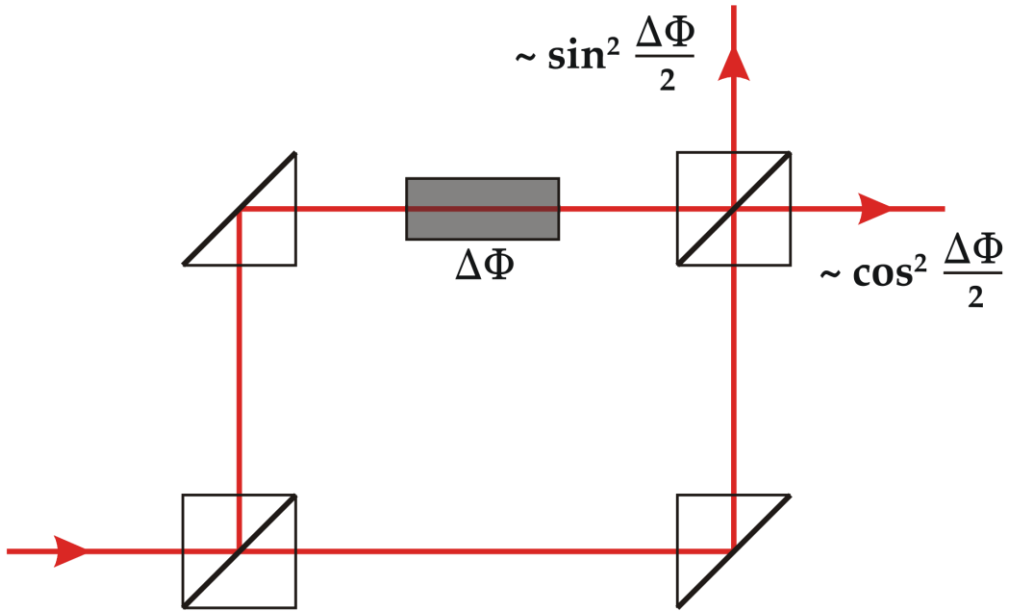

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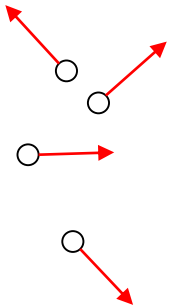
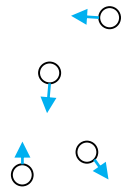
States of Matter and Condensation

Temperature / Motion

States of Matter and Condensation




Temperature / Motion

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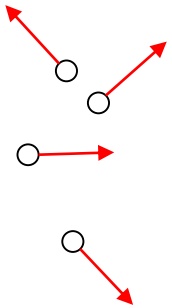

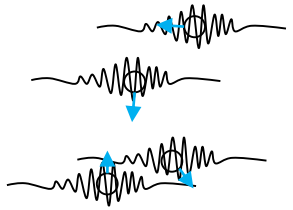

$$\lambda_{dB} = \frac{h}{p} = \frac{h}{m\,v}$$

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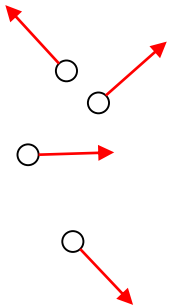

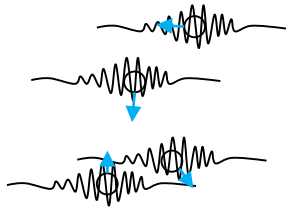

Further Cooling of Substance

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Fermions and Bosons

Fermions

- *Spin: n + ½ (n = 0,1,2,…)*

Bosons

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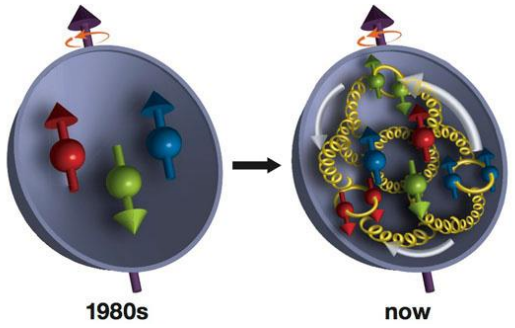
Fermions and Bosons

Fermions

- *Spin: n + ½ (n = 0,1,2,…)*
- Typical Examples:
- Leptons (Electron, Muon, Tau, Neutrinos)
- Quarks
- Baryons (Particle made from odd number of Quarks)
  - Proton (up, down, down)
  - Neutron (up, up, down)
  - …
  - Exotic: Pentaquarks



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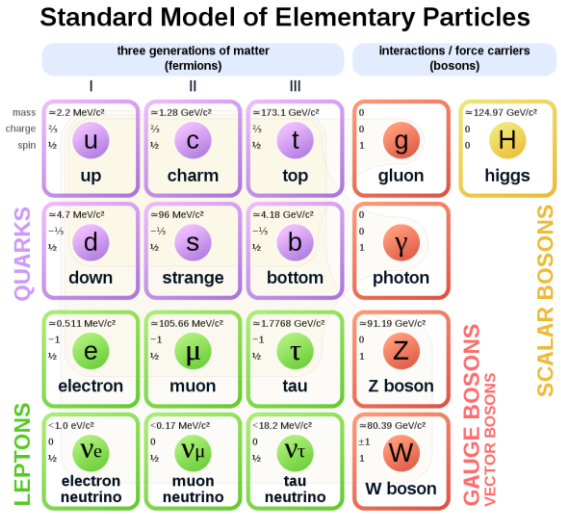
Bosons

- *Spin: n (n=1,2, …)*
- Typical Examples:
- Gauge Bosons (Gluon, Photon, Z, W)
- Higgs Boson
- Mesons (Particles made from even number of Quarks)



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Statistical Description

Fermi – Dirac Statistic

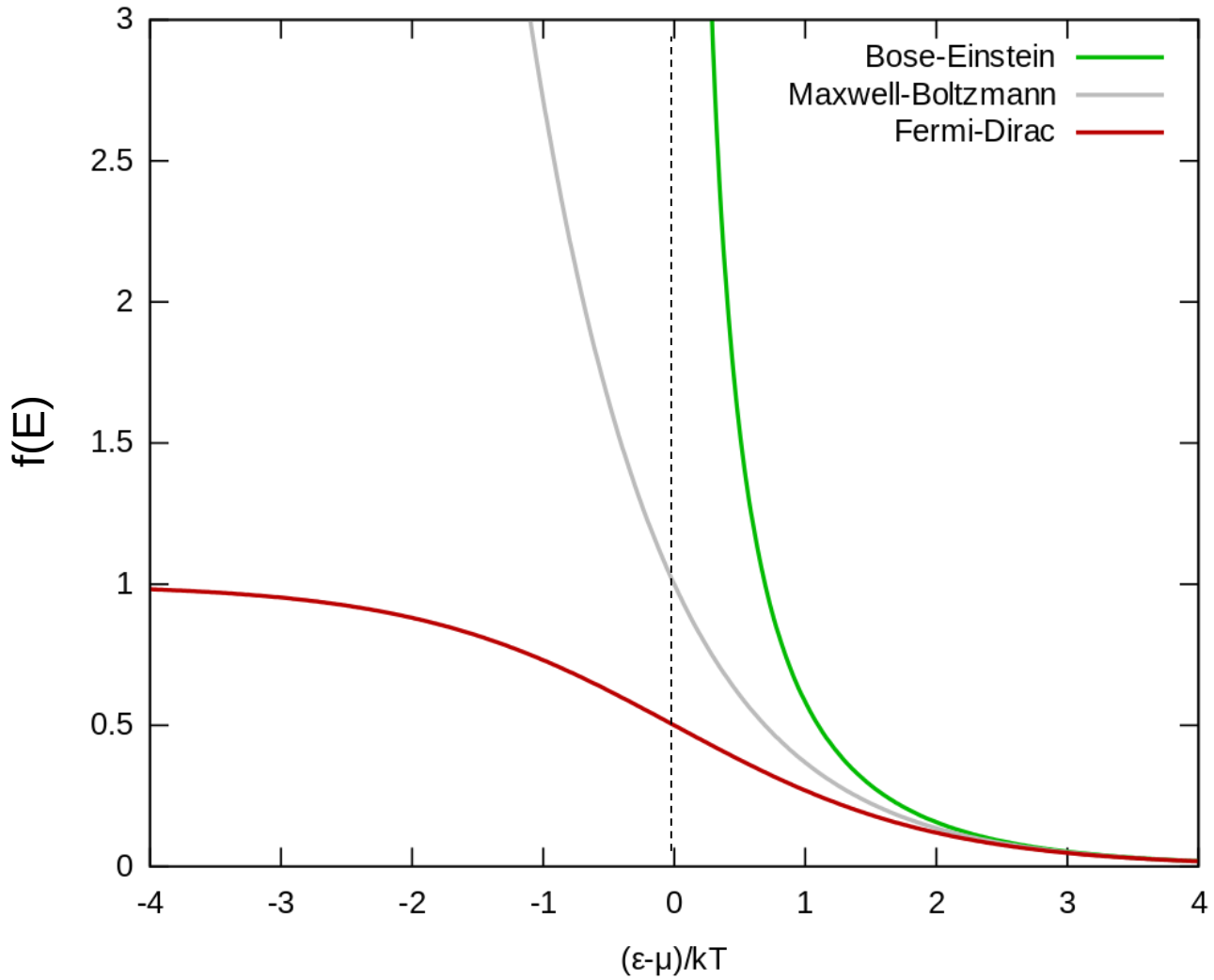
$$f(E) = \frac{1}{e^{(\frac{E-\mu}{k_B T})} + 1}$$

Bose – Einstein Statistic

$$f(E) = \frac{1}{e^{(\frac{E-\mu}{k_B T})} - 1}$$

Maxwell – Boltzmann Statistic
(classical limit for T >> 0K)

$$f(E) = \frac{g}{e^{(\frac{E-\mu}{k_B T})}}$$



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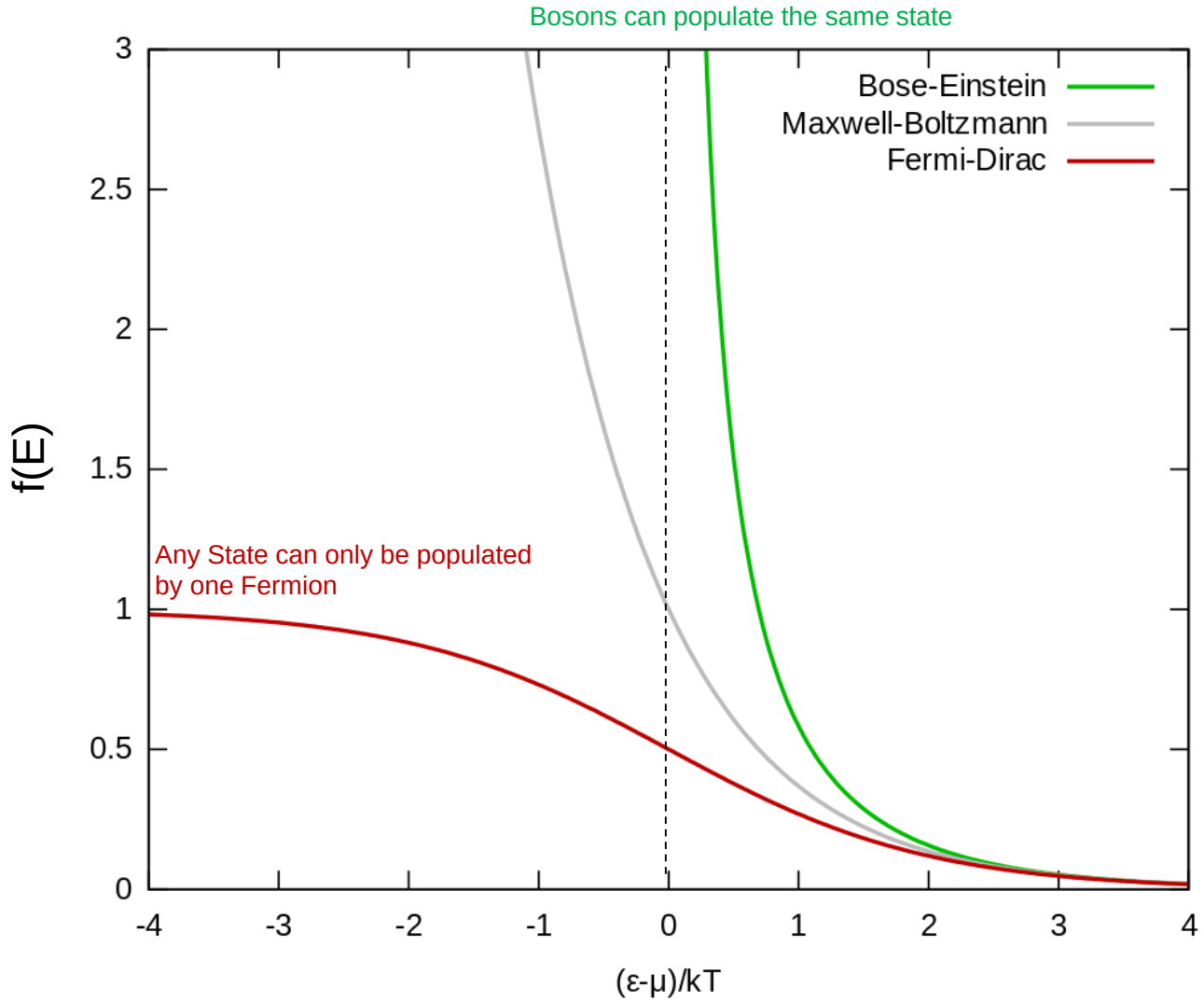

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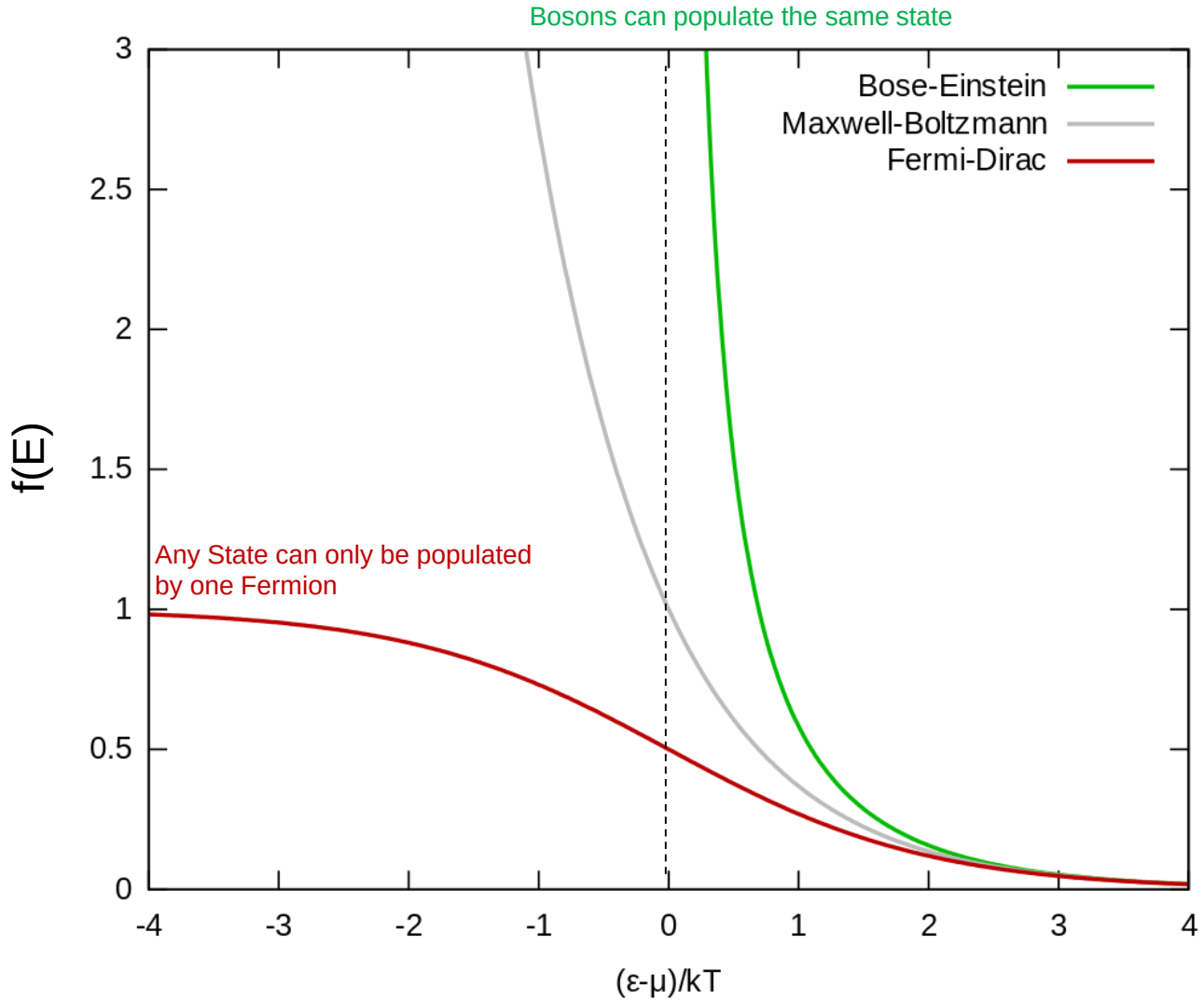

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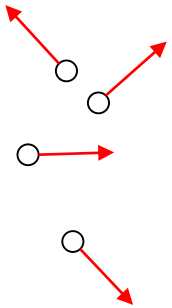
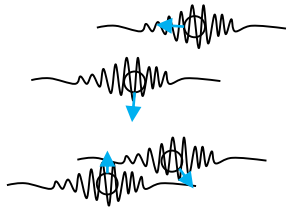
States of Matter and Condensation




Temperature / Motion





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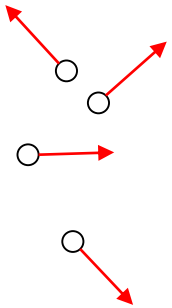

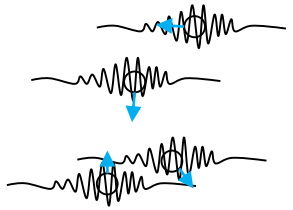

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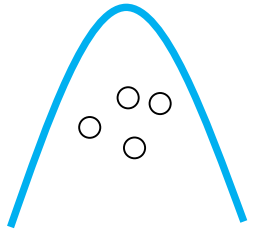
Bose Einstein Condensation



States of Matter and Condensation

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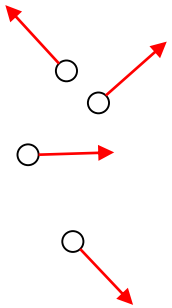
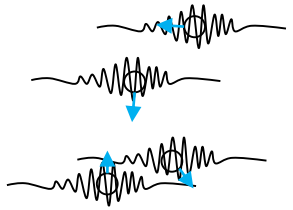




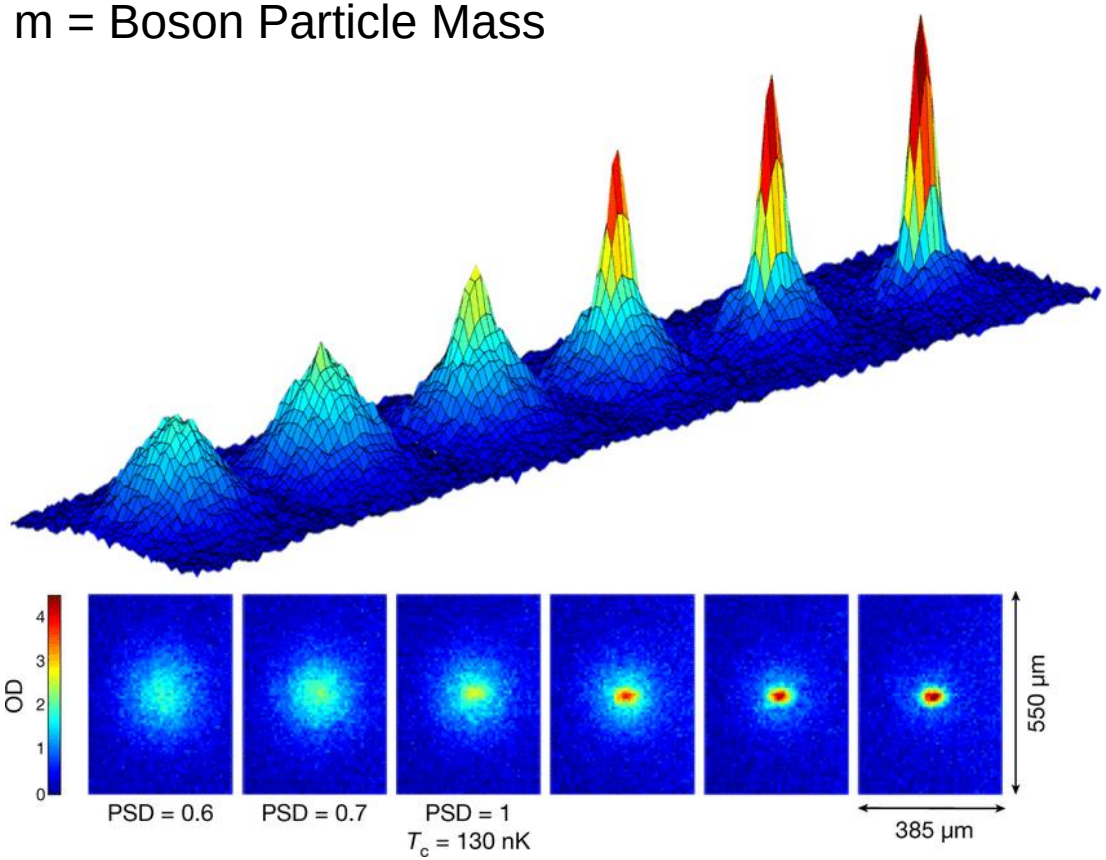
$$\lambda_{dB} = \frac{h}{p} = \frac{h}{m\,v}$$

T_C ‚critical temperature‘
$\Rightarrow$ At which condensation occurs

$$\Rightarrow T_C \sim 3.3\ \frac{\hbar^2 n^{2/3}}{m k_B}$$

with

- n = Particle Density
- m = Boson Particle Mass



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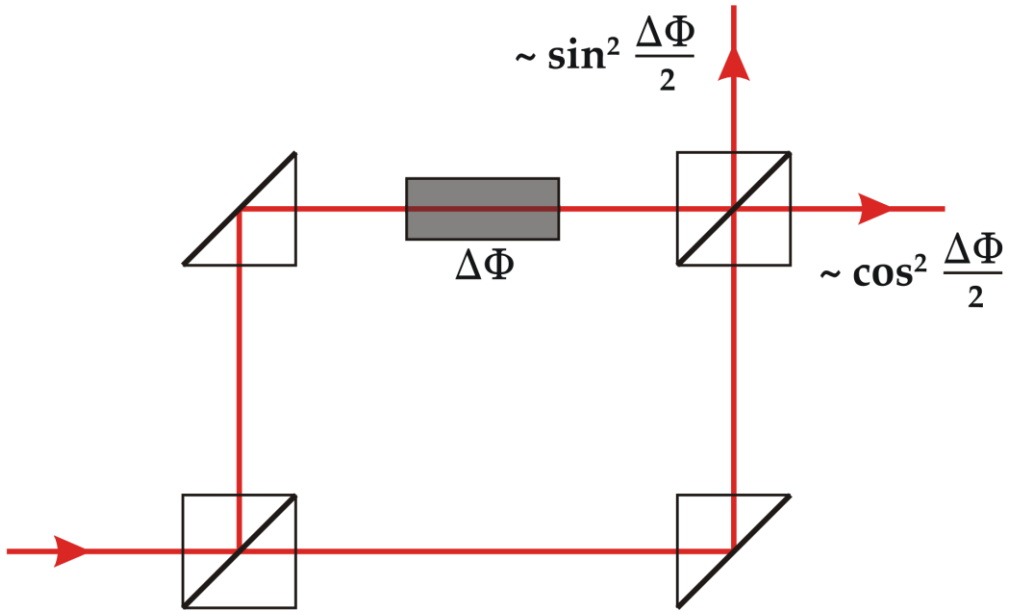
Matter Wave Interferometry

Mach Zehnder Geometry



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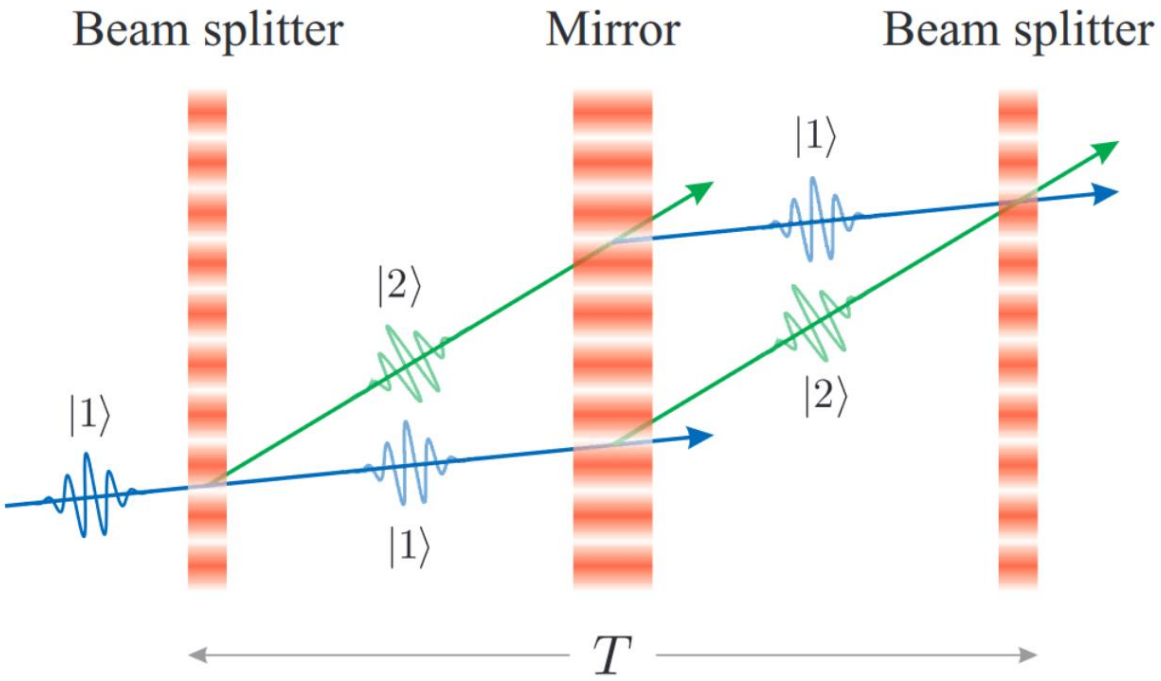

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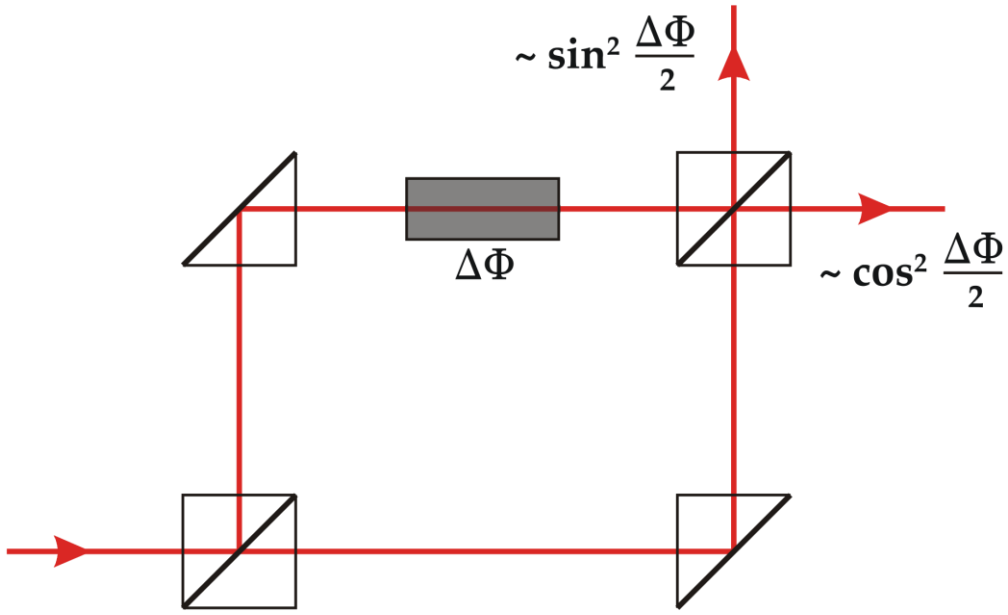

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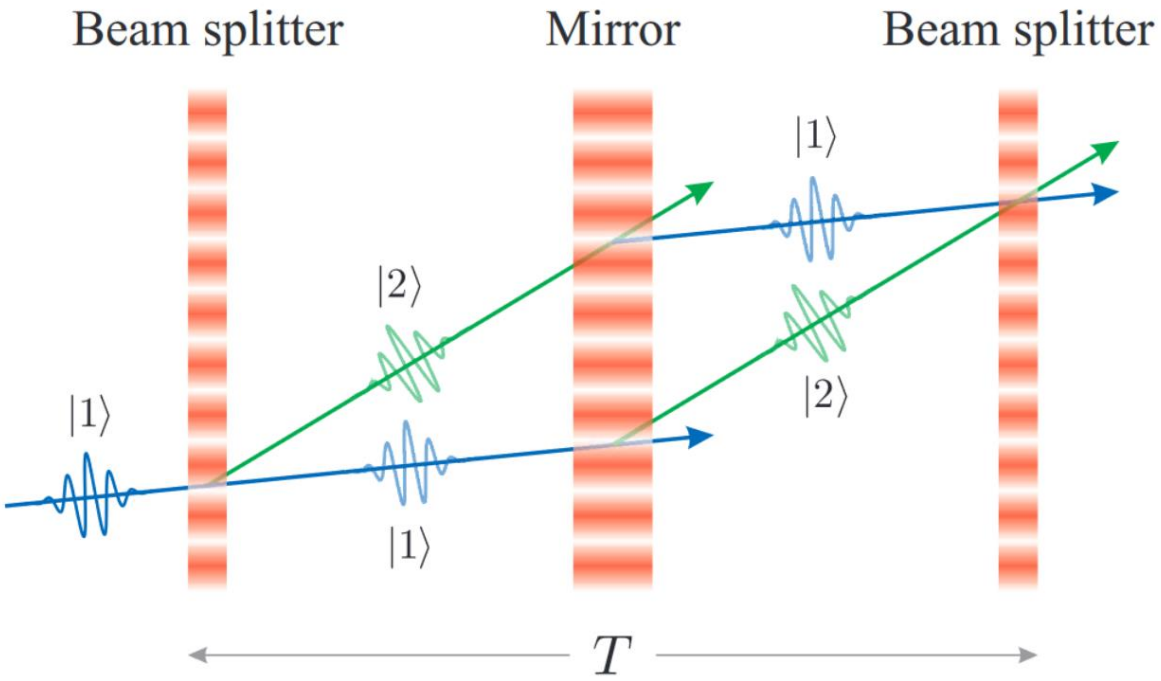

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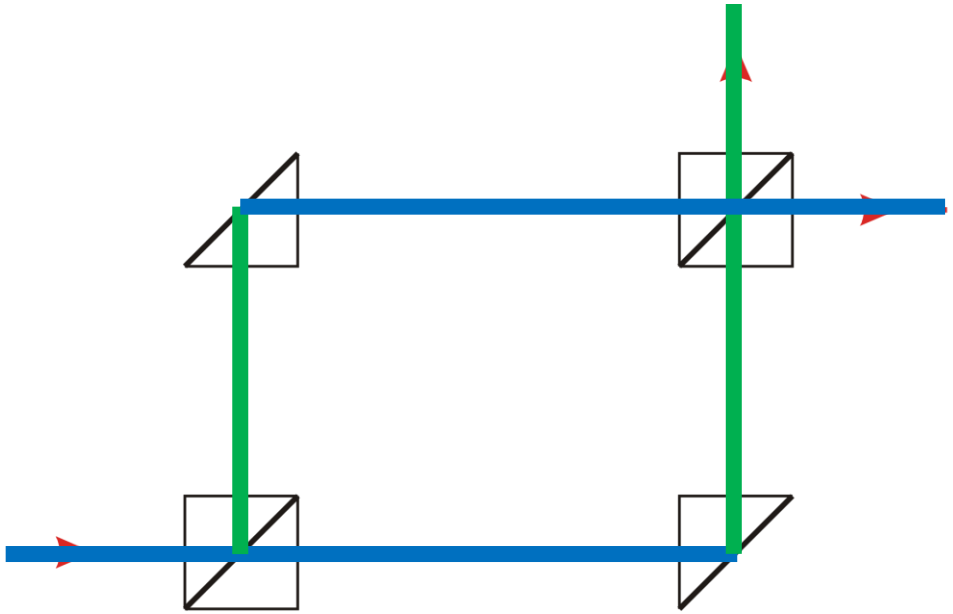

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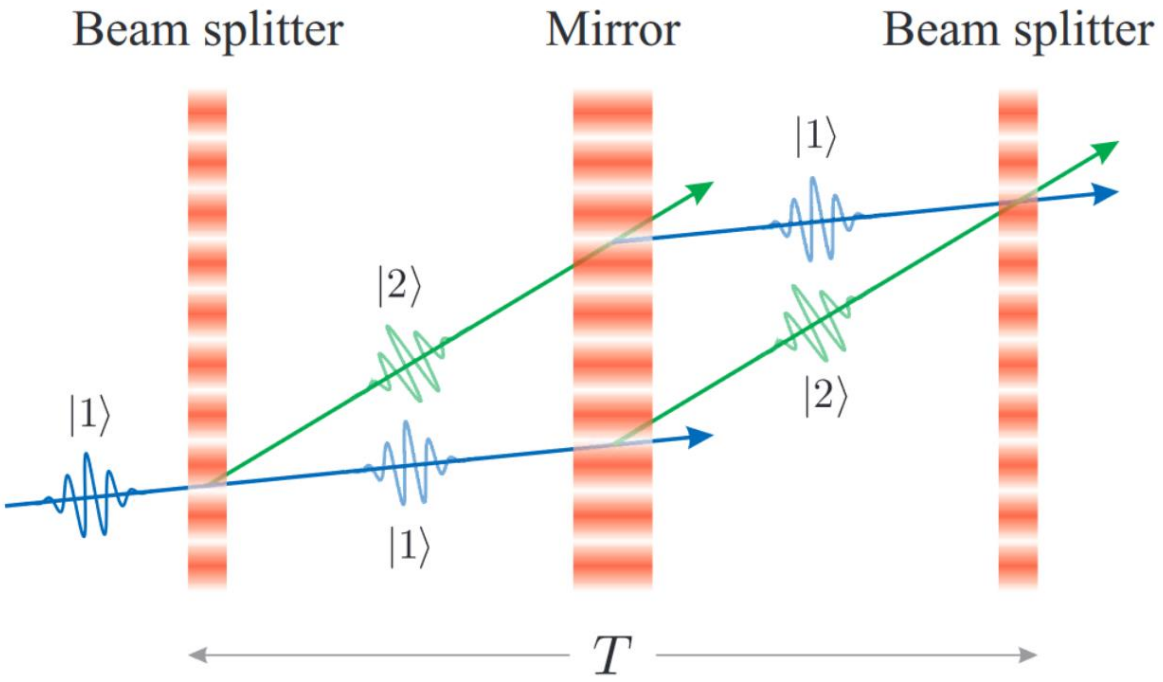

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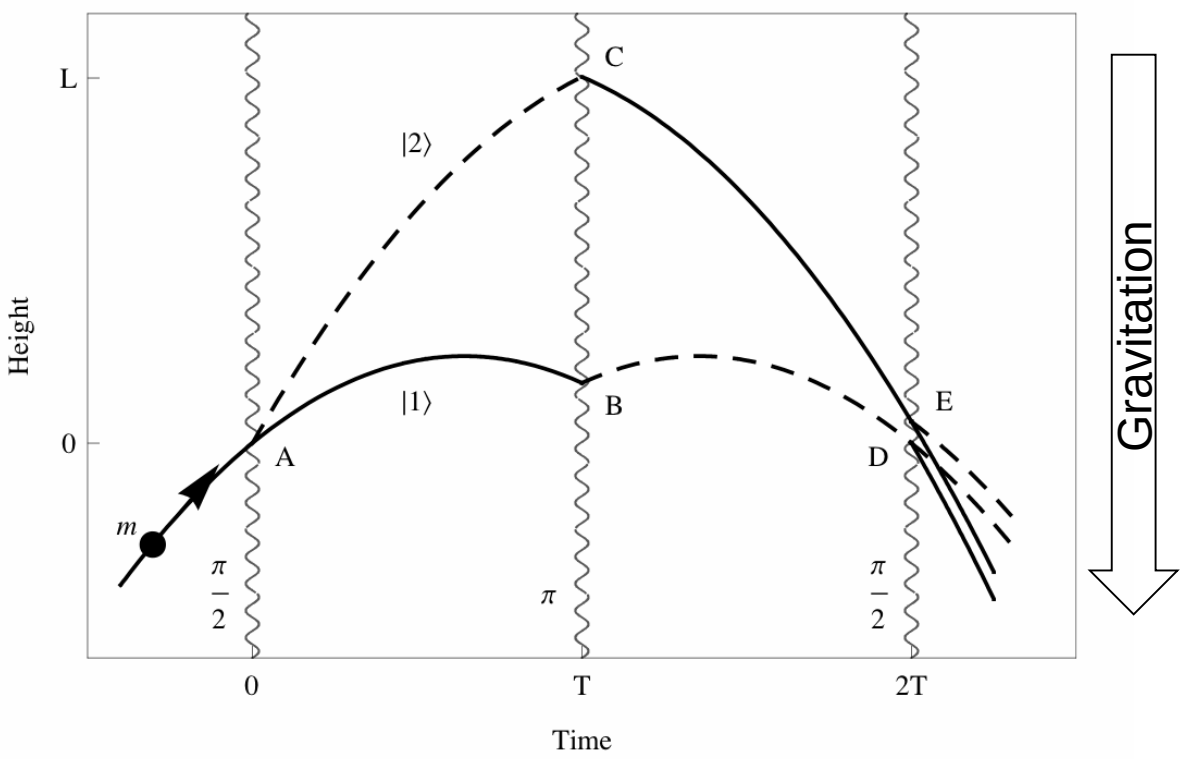

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Atom Interferometry in Space

Reminder:

- Interferometry is a precise tool to measure changes in a system
- Atom Interferometry is sensitive to Accelerations (such as Gravitation)

Atom Interferometry in Microgravity

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Atom Interferometry in Microgravity

- Fundamental Research on Atom Interferometry
- Equivalence Principle Tests
- Earth Observation
- Gravitational Wave Detection

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- Atom Interferometry is sensitive to Accelerations (such as Gravitation)

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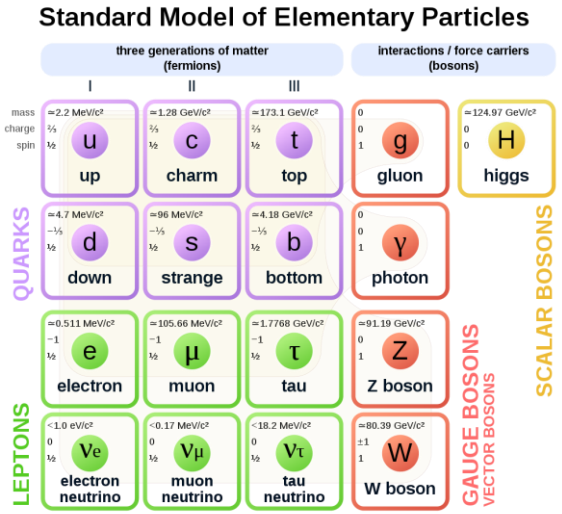
Equivalence Principle

Standard Model:

- Electromagnetic Force
- Weak Force
- Strong Force
- Gravitation



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Quantum Field Theory

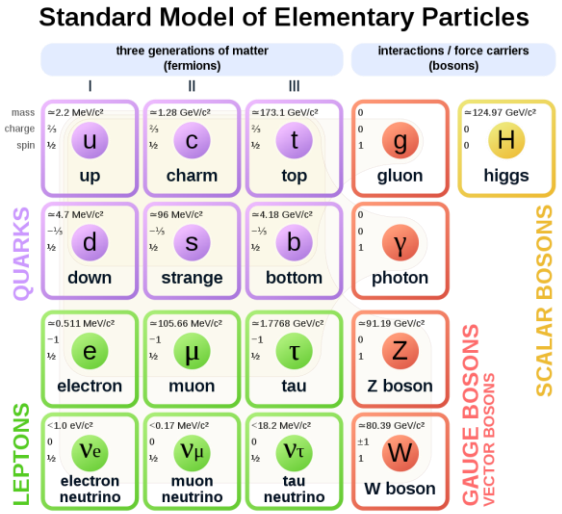
Equivalence Principle

Basis of Gravitational Theories:

1. *Weak Equivalence Principle*
2. *Local Lorentz Invariance*
3. *Local Position Invariance*

Standard Model:

- Electromagnetic Force
- Weak Force
- Strong Force
- Gravitation



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Quantum Field Theory

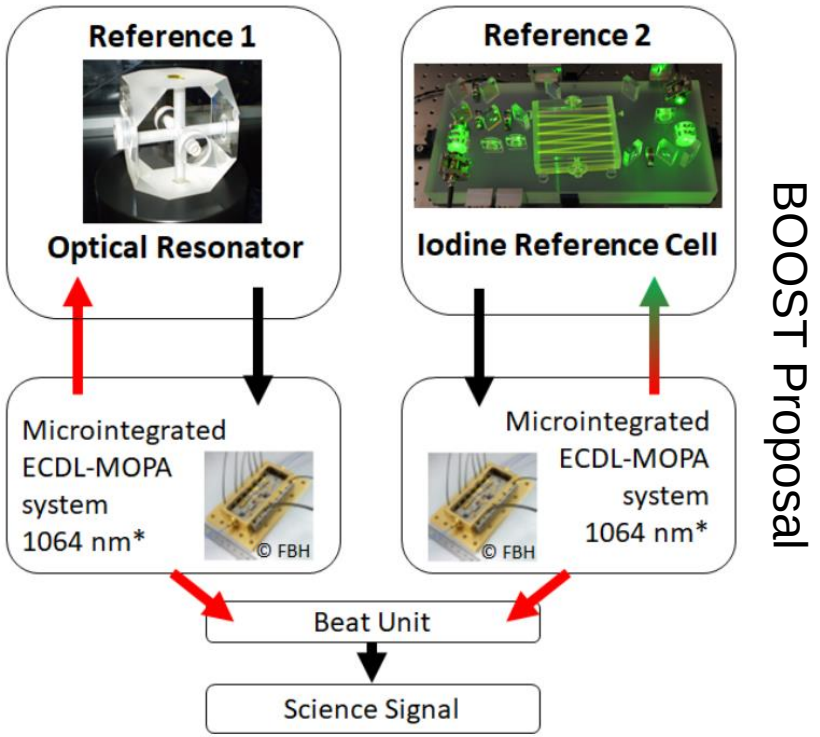
Equivalence Principle

Basis of Gravitational Theories:

1. *Weak Equivalence Principle*
2. *Local Lorentz Invariance*
3. *Local Position Invariance*

Local Lorentz Invariance

- Local Non-Graviational Test is independent of velocity and orientation of Experiment



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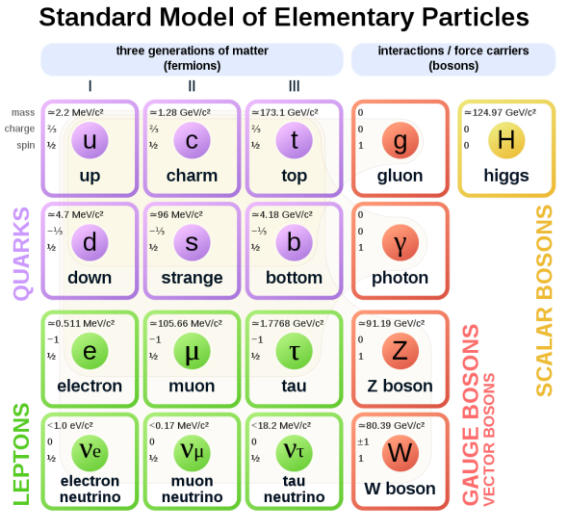

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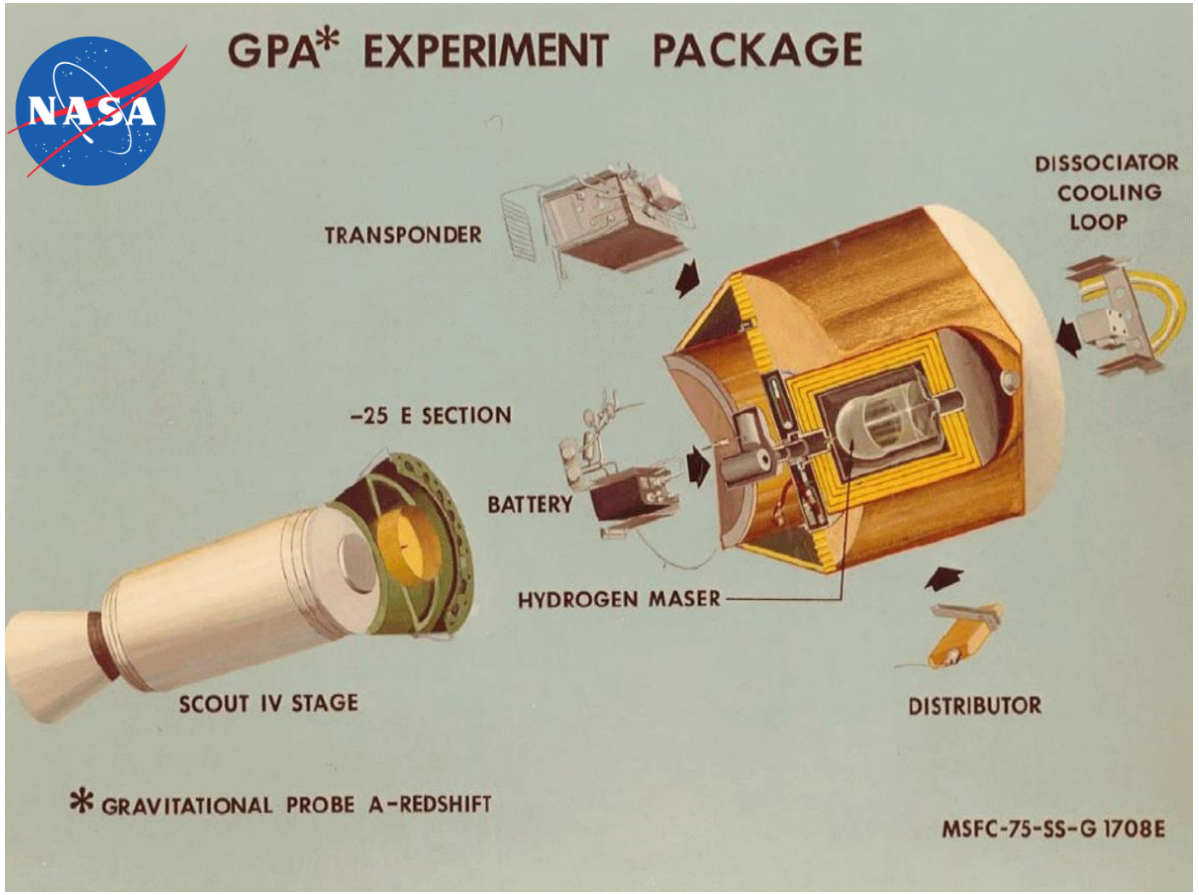
Quantum Field Theory

Local Position Invariance
Gravitational Redshift

Local Position Invariance
Gravitational Redshift

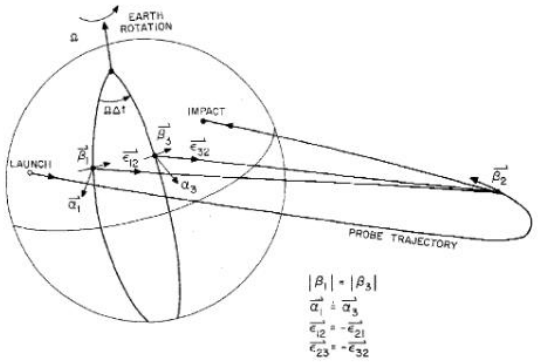
Gravity Probe A (B & C)



- Robert VESSOT & Martin LEVINE
- Hydrogen Maser in Flight and on Ground

- Launch 1967
- Parabola with 10 000km height

- Theoretical Predictions
  - Accuracy 0.02%

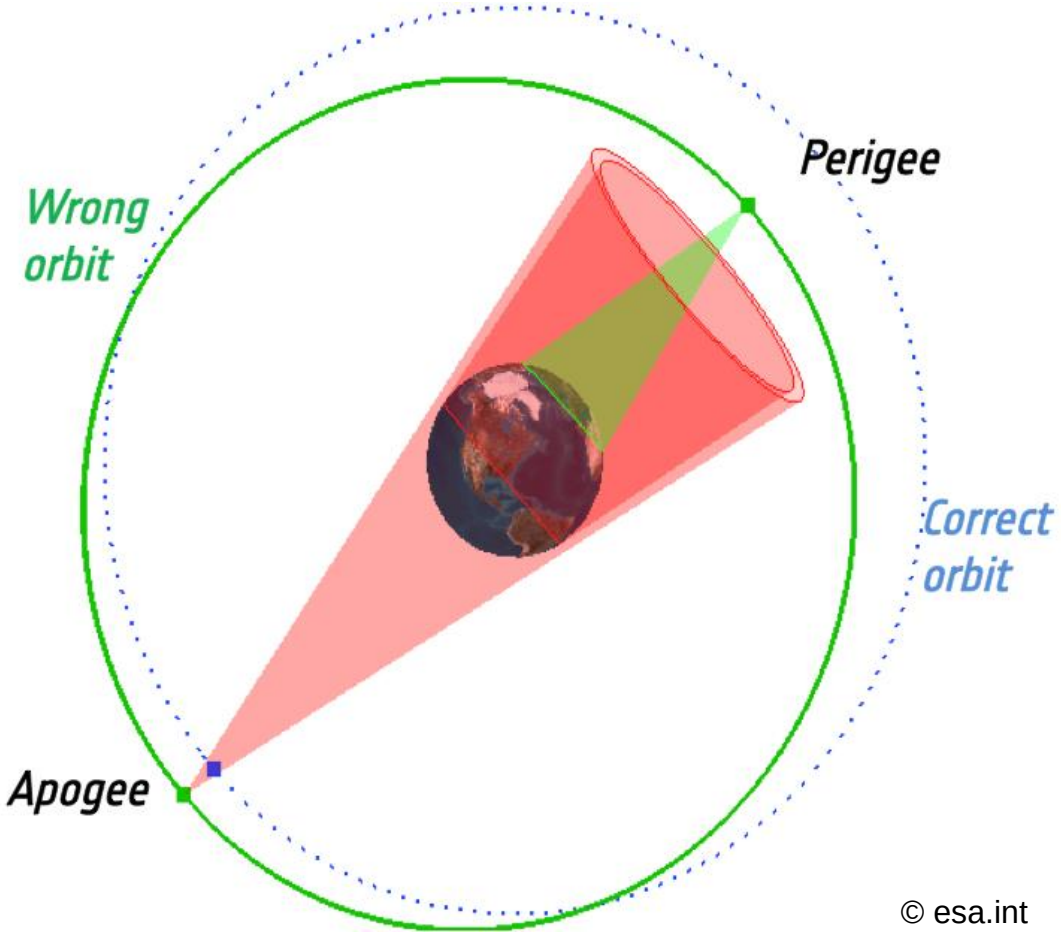


R. F. C. Vessot and M. V. Levine, *Gen. Relativ. Gravit.* **10**, 181 (1979)

DLR

Local Position Invariance
Gravitational Redshift

Galileo ‚Mishap‘



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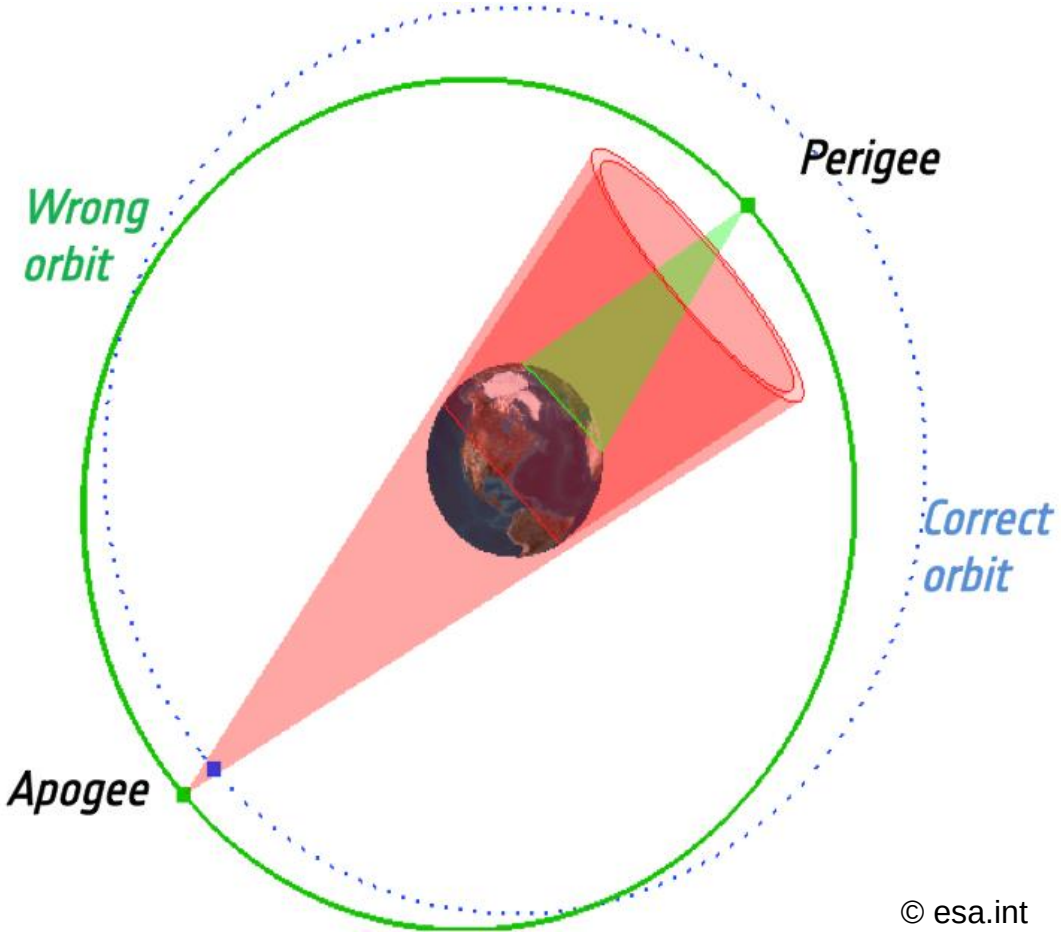
Local Position Invariance
Gravitational Redshift

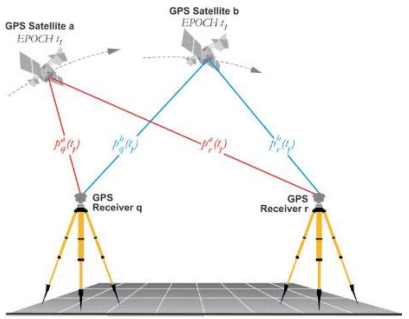
Galileo ‚Mishap‘



© esa.int

- Misplaced Galileo Satellites
  - Shift of 8 500 km twice per day

- Two Passive Hydrogen Masers
- Two Rubidium Frequency References
- Precise Tracking from Ground



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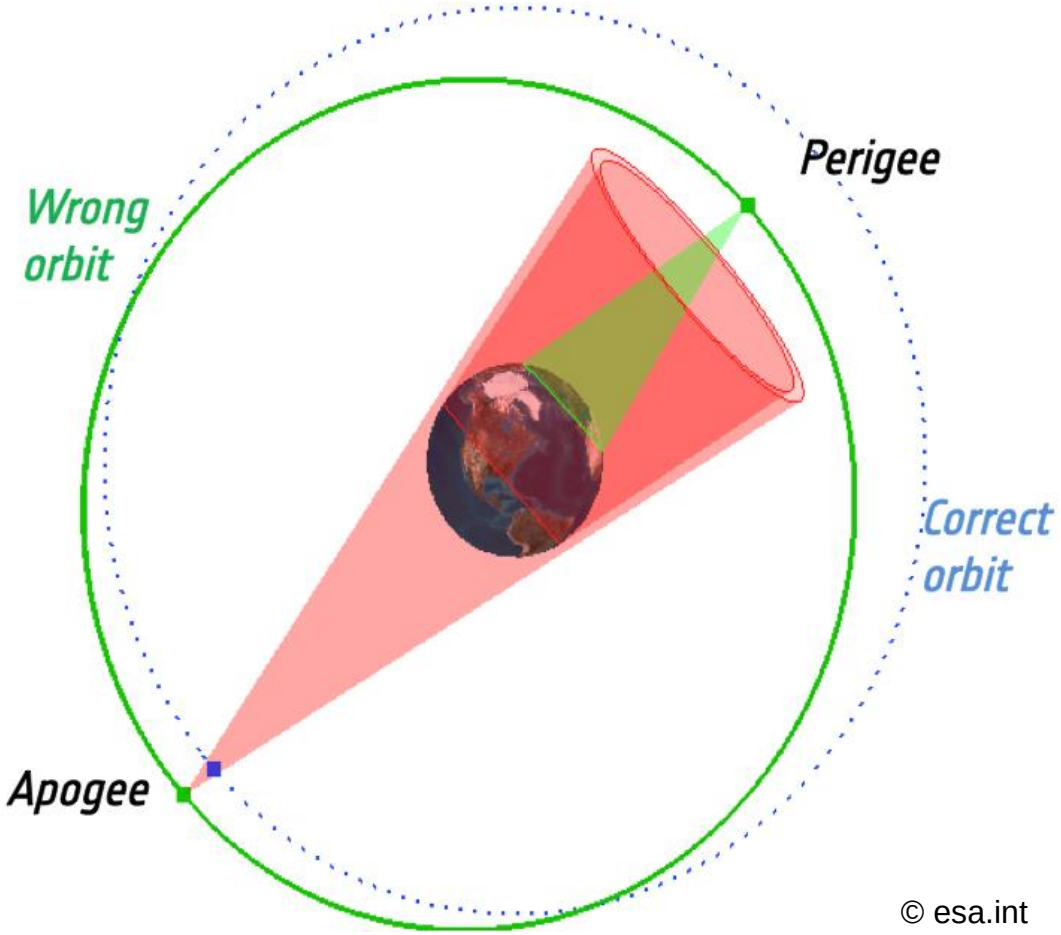
Local Position Invariance Gravitational Redshift

S. Herrmann et al. *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.231102
P. Delva et al. *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.231101

Galileo ‚Mishap‘



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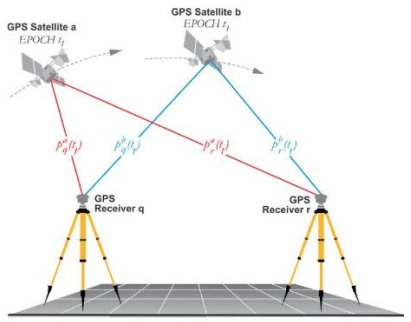
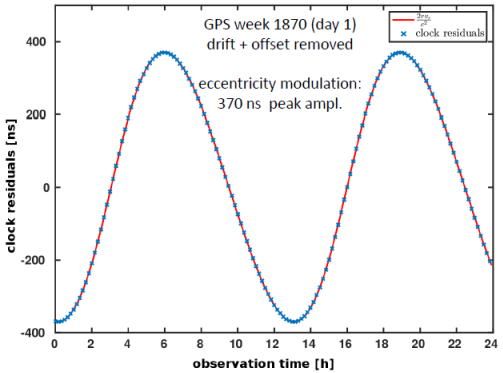
- Two Rubidium Frequency References
- Precise Tracking from Ground

- Pacome DELVA and Sven HERMANN





https://www.youtube.com/watch?v=aKwJayXTZUs

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Equivalence Principle

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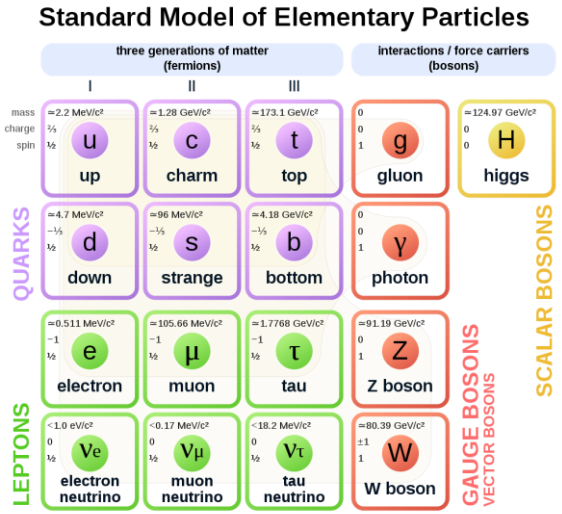

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Quantum Field Theory

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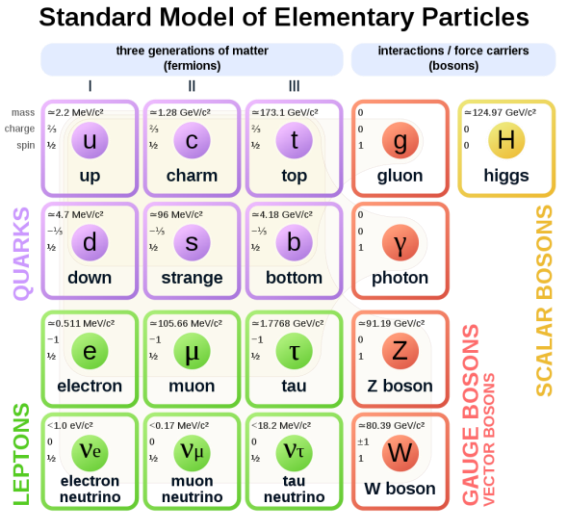

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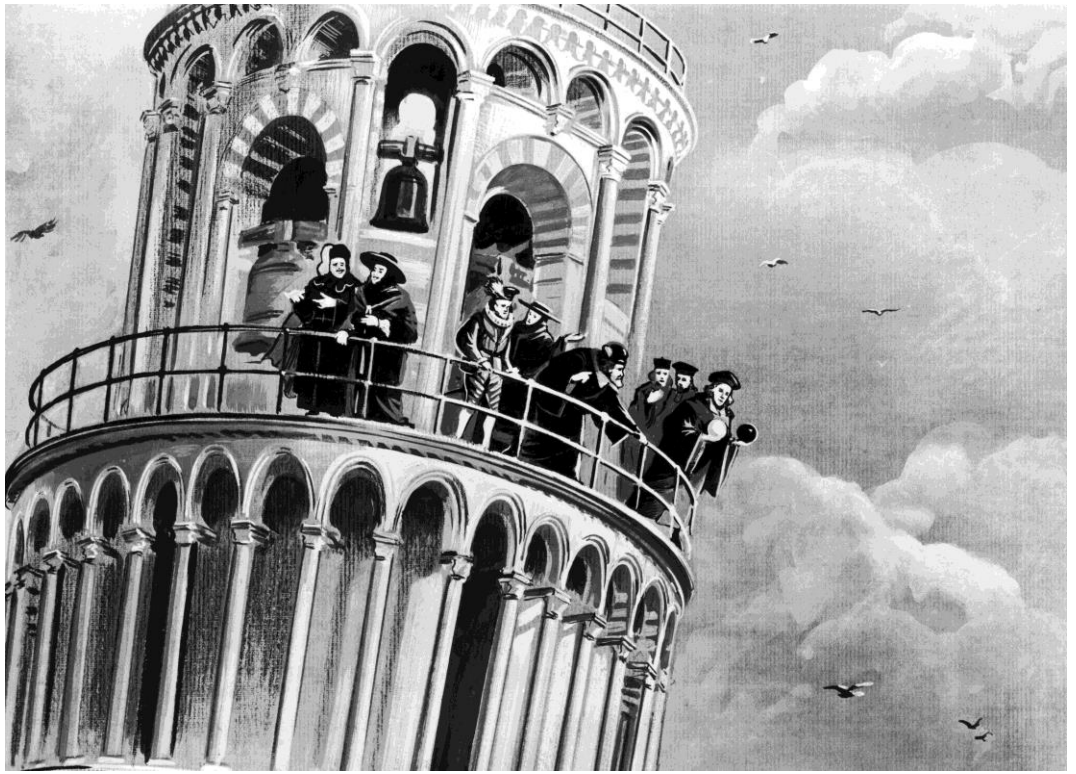
Quantum Field Theory

Weak Equivalence Principle
Universality of Free Fall

Weak Equivalence Principle
Universality of Free Fall

- Galileo using Pisa Tower



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Weak Equivalence Principle
Universality of Free Fall

- Galileo using Pisa Tower

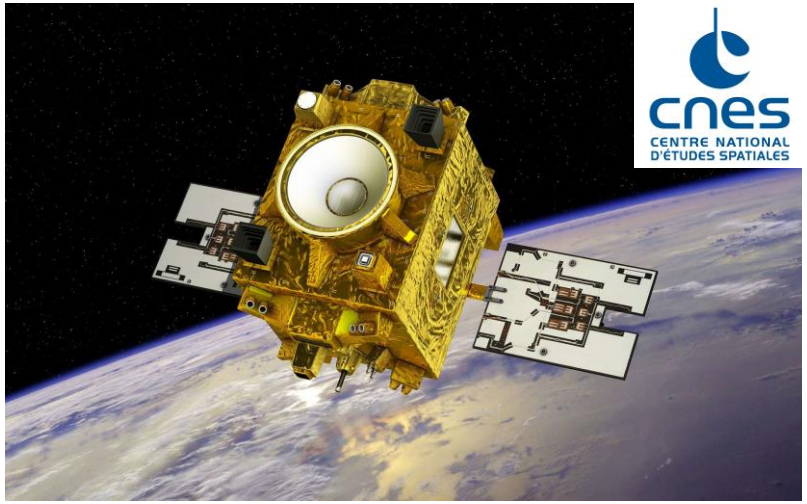
- Astronaut on Lunar Surface
- Hammer and Feather

https://www.youtube.com/watch?v=5C5_dOEyAfk

Weak Equivalence Principle
Universality of Free Fall

MICROSCOPE

https://microscope.cnes.fr/en/MICROSCOPE/



Weak Equivalence Principle
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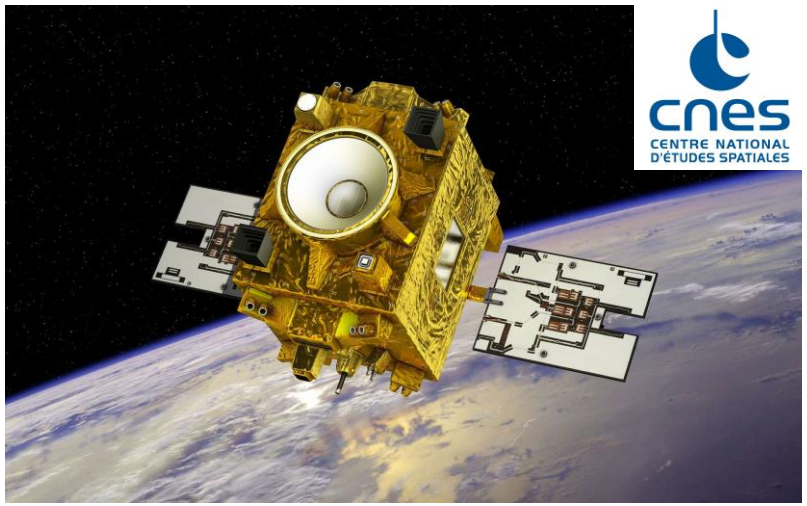

- Accelerometer
  - Reference: Two Platinum / Rhodium Masses
  - Measurement:
    - Platinum-Rhodium Alloy
    - Titanium-Aluminium-Vanadium Alloy
- Motionless with respect to Satellite
- Measurement in 10^{-14} Accuracy

Weak Equivalence Principle
Universality of Free Fall

- Galileo using Pisa Tower

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  https://www.youtube.com/watch?v=5C5_dOEyAfk

- MICROSCOPE Satellite

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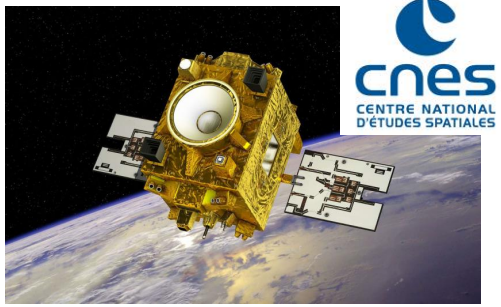

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Weak Equivalence Principle
Universality of Free Fall

Matter Wave Inferferometry (Atom Interferometry)

- Interferometry is very precise
- Atoms are suceptible to Accelerations (Gravitation)

- Galileo using Pisa Tower

- Astronaut on Lunar Surface
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  https://www.youtube.com/watch?v=5C5_dOEyAfk

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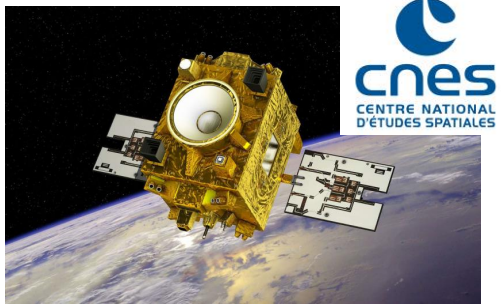
  https://microscope.cnes.fr/en/MICROSCOPE/



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Weak Equivalence Principle
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Perform Atom Interferometry, comparing two species

- Rubidium
- Potassium
- Strontium
- Ytterbium

- Galileo using Pisa Tower

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- Hammer and Feather
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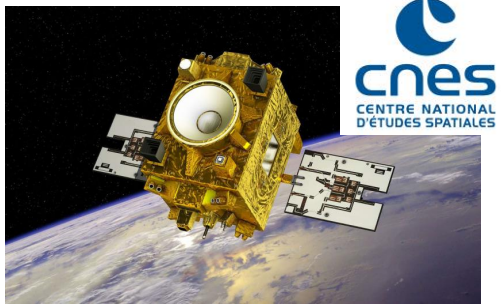

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Weak Equivalence Principle
Universality of Free Fall

Matter Wave Inferferometry (Atom Interferometry)

Voyage 2050 Proposal led by P. Wolf

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008 [57]	Torsion balance
	Pt - Ti	1×10^{-14}	2017 [1]	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2019+	MICROSCOPE full data
	$M_A - M_B$	10^{-17}	2035+	Adv. MICROSCOPE, macrsocopic masses M_i TBD
Hybrid	^{133}Cs - CC	7×10^{-9}	2001 [59]	AI and macroscopic corner cube (CC)
	^{87}Rb - CC	7×10^{-9}	2010 [60]	
	$At_A - M_B$	10^{-17}	2035+	Adv. MICROSCOPE, atomic species At_A TBD
Quantum	^{39}K - ^{87}Rb	5×10^{-7}	2014 [61]	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014 [62]	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015 [63]	same element, different isotopes
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+ [64]	$\geq$ 10 m towers
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+ [65]	
	^{41}K - ^{87}Rb	10^{-17}	2035+	Atom Interferometry mission
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2020+ [66, 67]	under construction at CERN

Weak Equivalence Principle
Universality of Free Fall

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© B. Battelier et al., arXiv1908:11785v3
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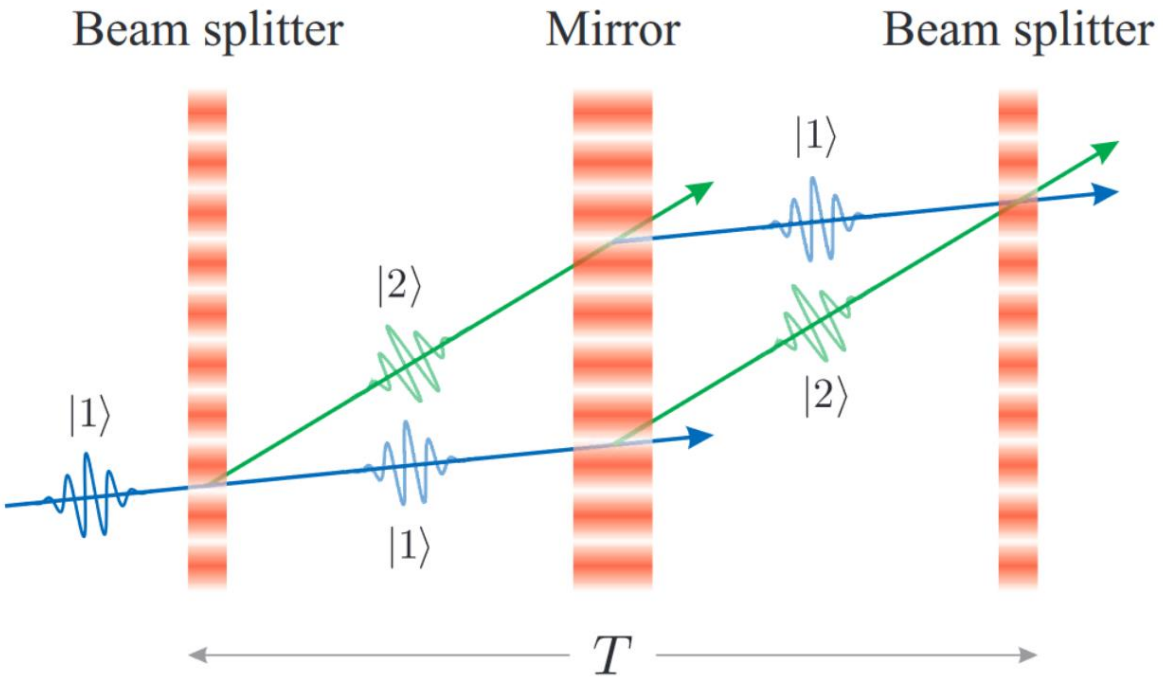
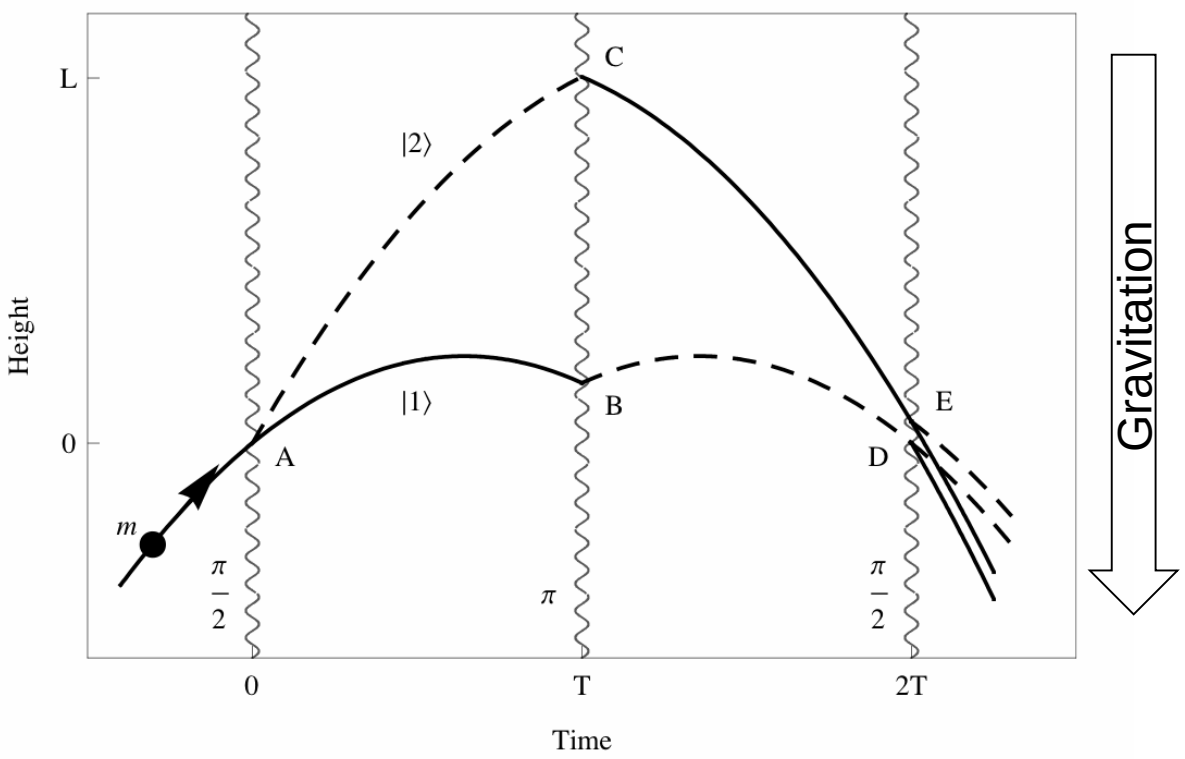
Matter Wave Interferometry



© P.Barett et al., https://arxiv.org/abs/1311.7033v1



© M. Kasevic, Stanford.edu

Atom Interferometry under Microgravity

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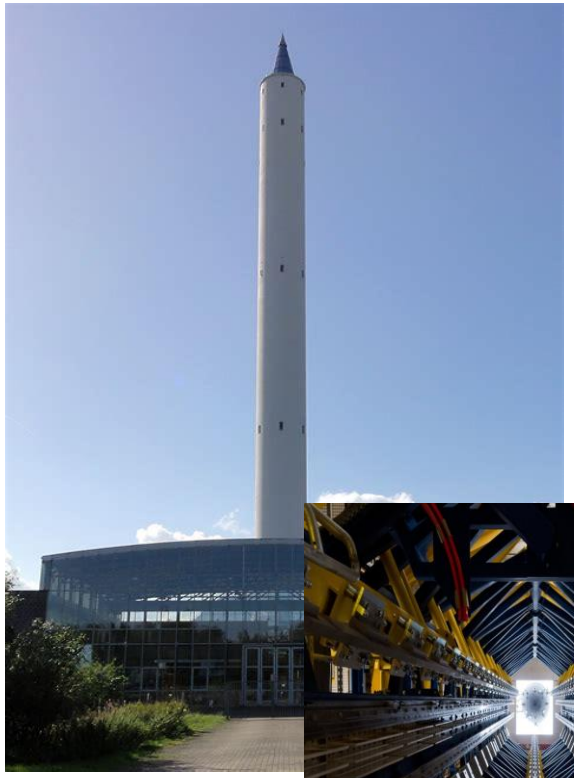

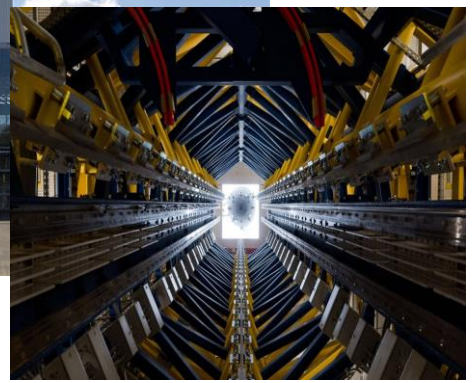

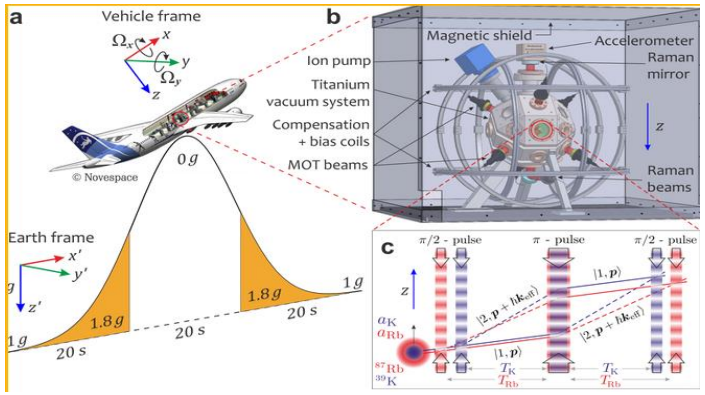

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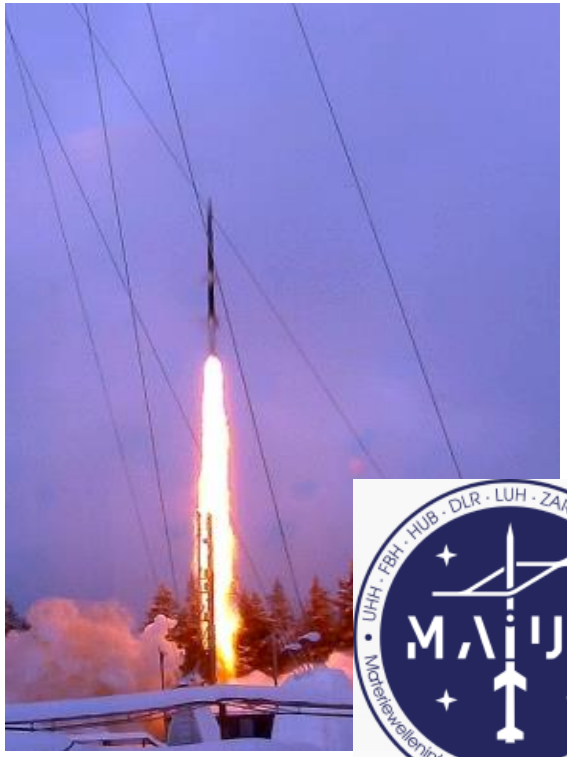

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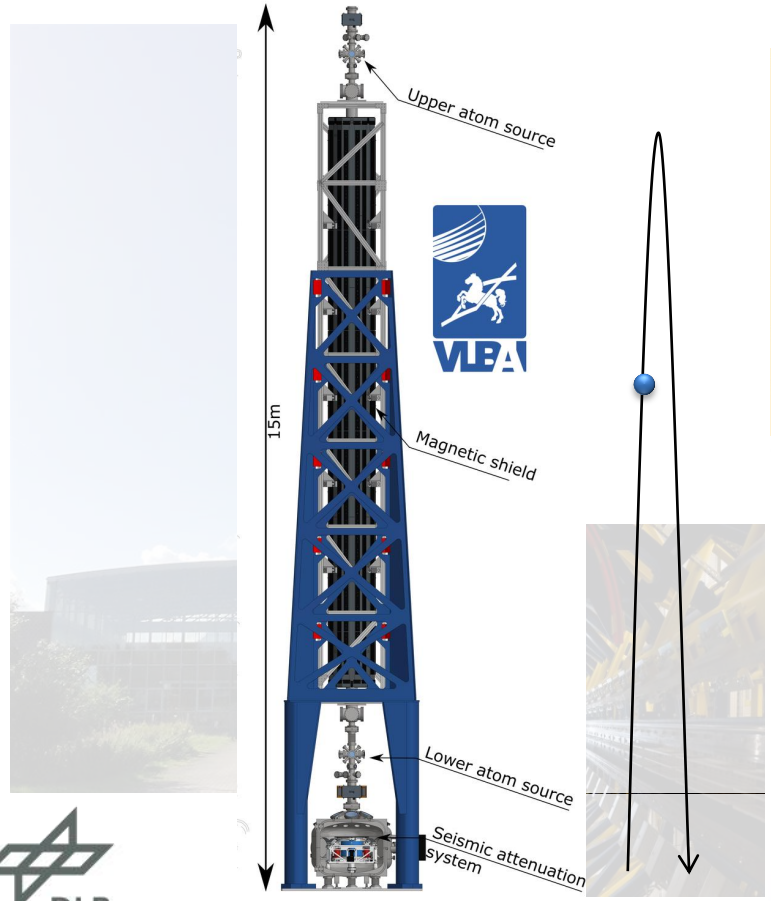
UHH · FBH · HUB · DLR · LUH · ZARM · UULM · TUDA

Materiewelleninterferometer unter Schwerelosigkeit

Prolonged Microgravity

DLR

Atom Interferometry under Microgravity



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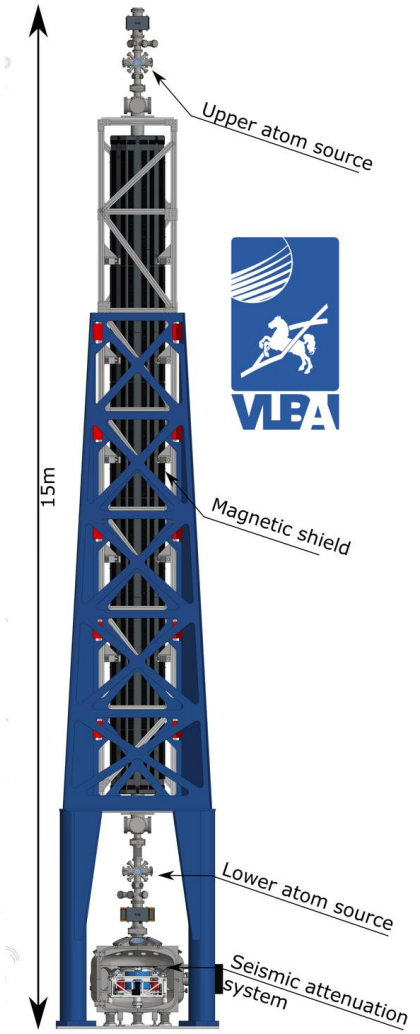
Prologned Microgravity

Weak Equivalence Principle
Universality of Free Fall

- Galileo using PISA Tower
- Astronauts on Lunar Surface
- MICROSCOPE Experiment

Weak Equivalence Principle
Universality of Free Fall

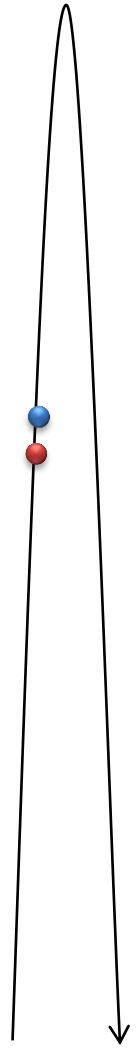


Schlippert Group

Kasevic Group

Weak Equivalence Principle
Universality of Free Fall

- Experiments with ^{85}Rb and ^{87}Rb
- Atomic Fountain

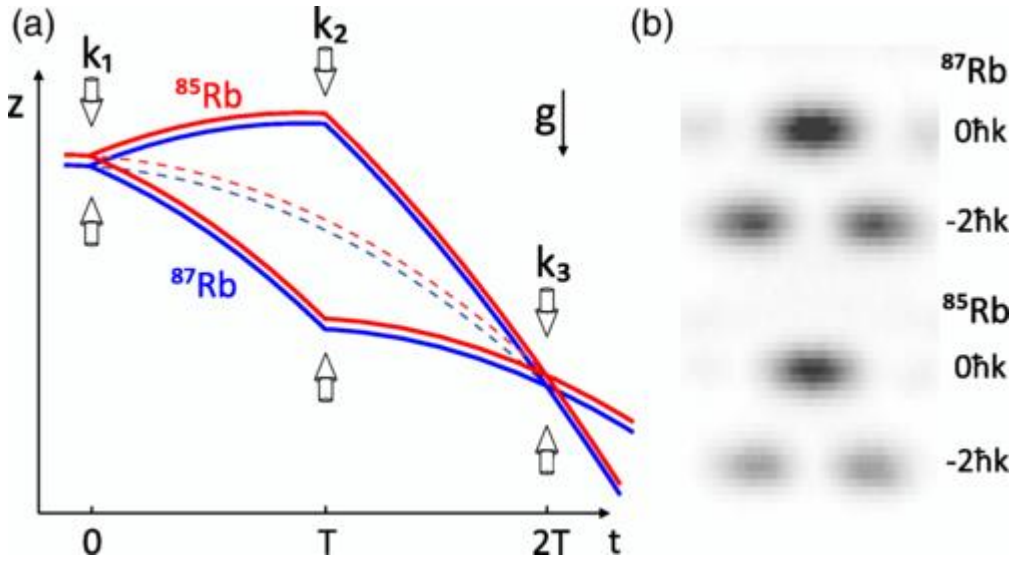


Kasevic Group

Weak Equivalence Principle
Universality of Free Fall

- Experiments with ^{85}Rb and ^{87}Rb
- Atomic Fountain

- Accuracy at 10^{-12} Level



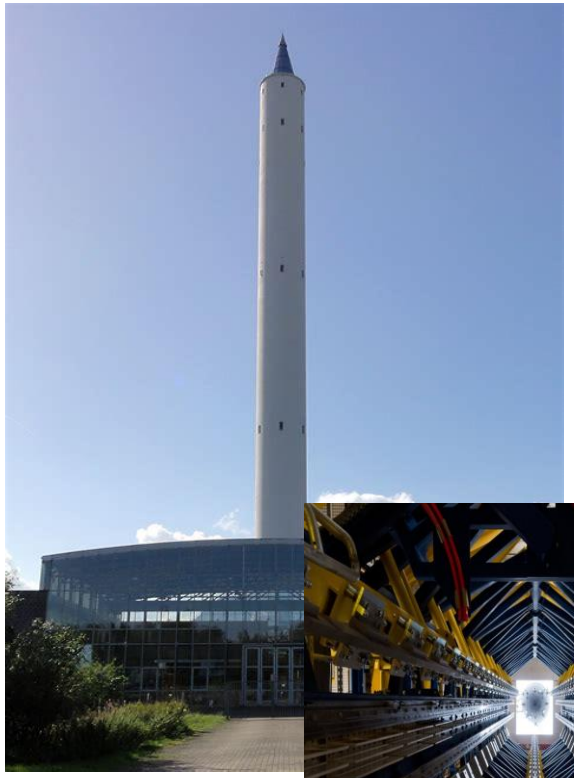
P. Asenbaum et al., Phys. Rev. Lett 25, 191101 (2020)

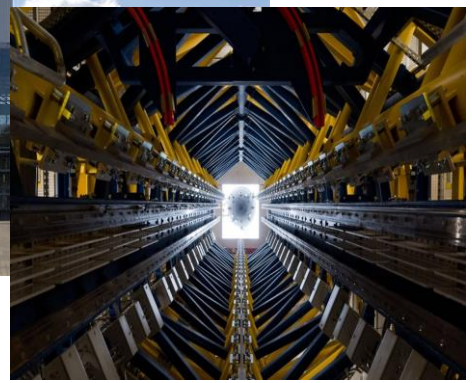
Kasevic Group

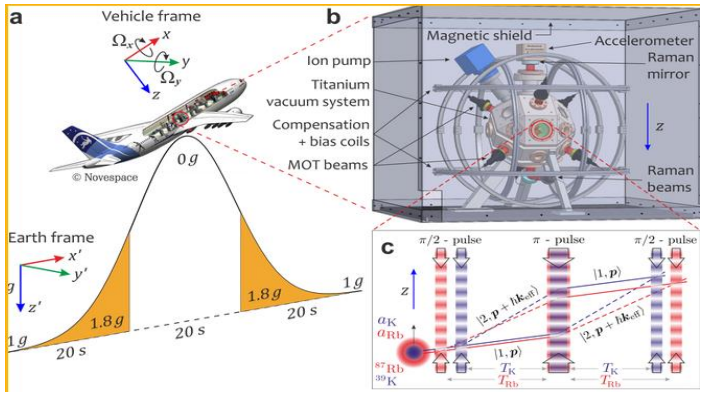
Atom Interferometry under Microgravity

QUANTUS

DLR







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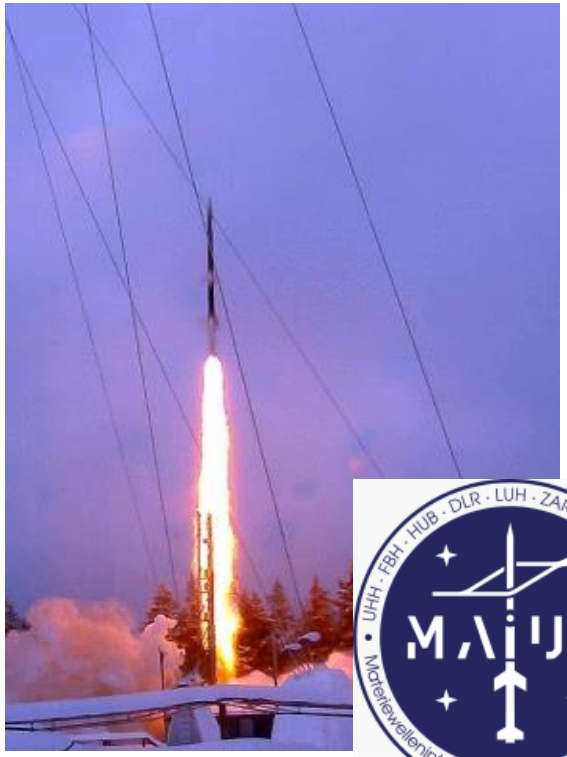

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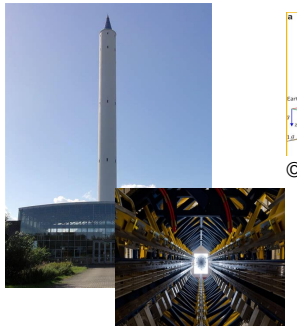

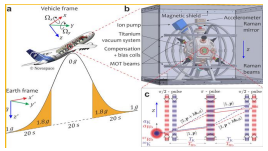

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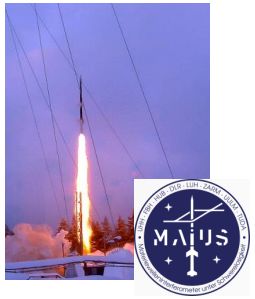

Prolonged Microgravity

BECCAL
Bose Einstein Condensate and Cold Atom Laboratory

Bose Einstein Condensate and Cold Atom Laboratory

- State-of-the-Art quantum mechanical Laboratory
- Operation in the Microgravity Environment of ISS
- Multi-User & Multi-Purpose Facility

Definition of the Payload

- Science Envelope Requirements Document (SERD)
- Science Definition Team
- Overview: K. Frye et al., EPJ QT 8, 1 (2021)

BECCAL
Bose Einstein Condensate and Cold Atom Laboratory

Scientific Areas:

1. Atom Interferometry
2. Coherent Atom Optics
3. Scalar Bose - Einstein Condensates
4. Spinor Bose - Einstein Condensates and Quantum Gas Mixtures
5. Strongly Interacting Gases and Molecules
6. Quantum Information

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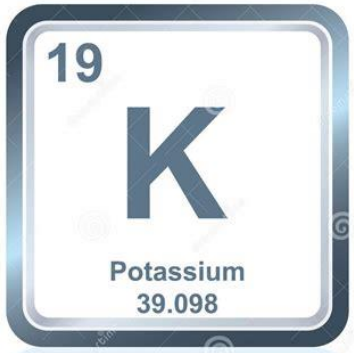
Kollaboration:

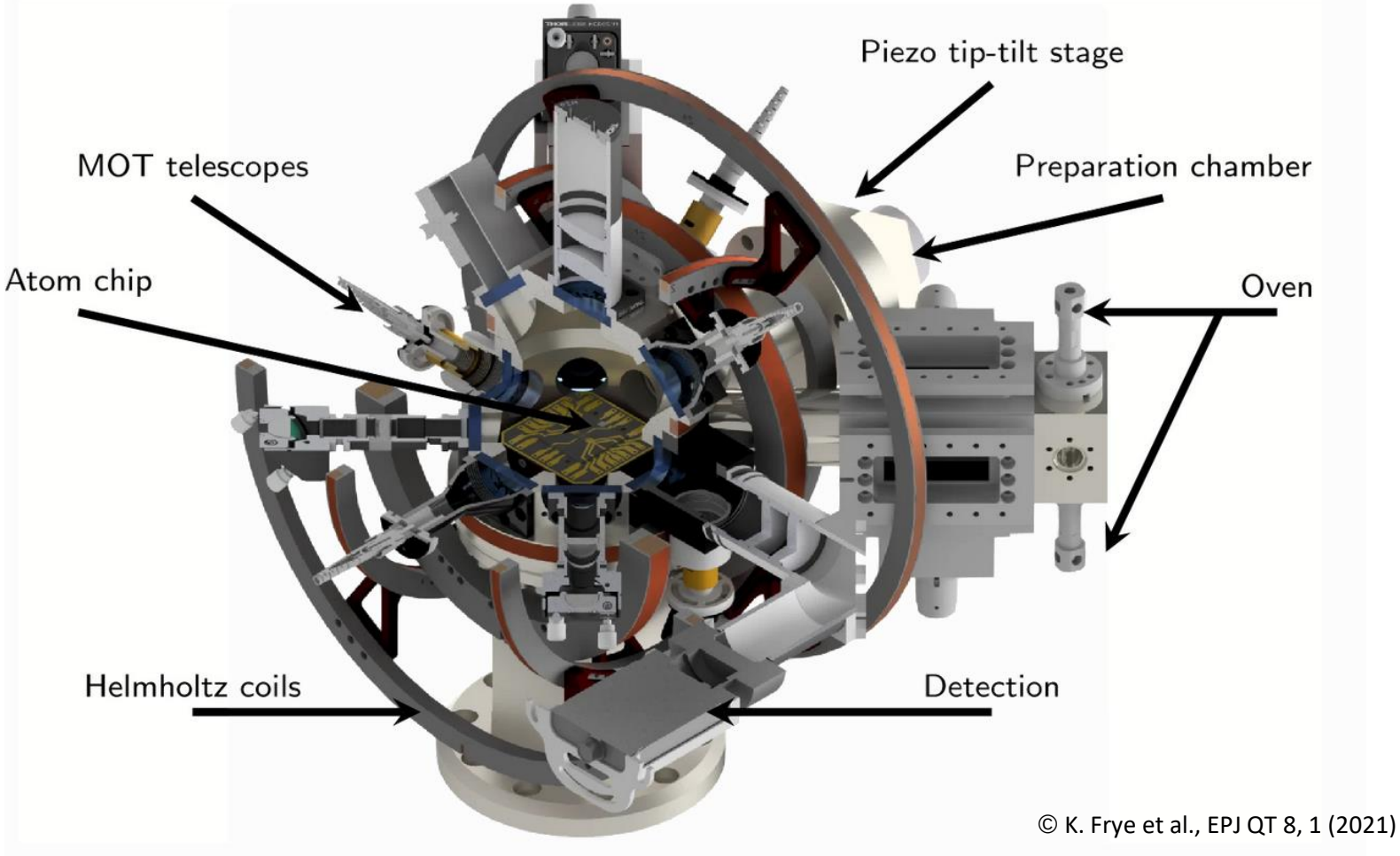
• NASA	Transport / ISS
• DLR RfA	Lasersystem
• DLR (SI, SC, QT)	Physics Package, Control Elektronics, Software, AIVT

BECCAL
Bose Einstein Condensate and Cold Atom Laboratory

Rubidium 85, 87



Potassium 39, 40, 41



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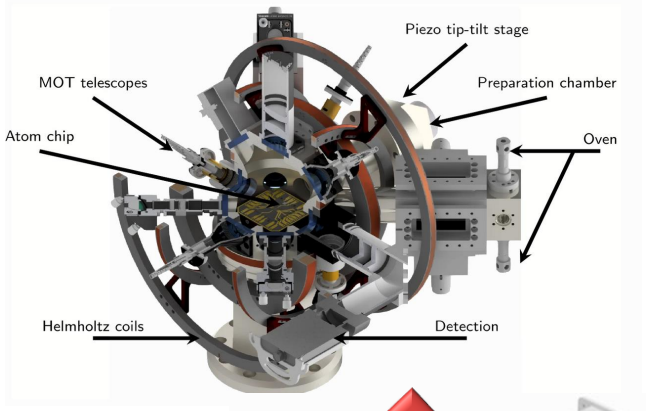
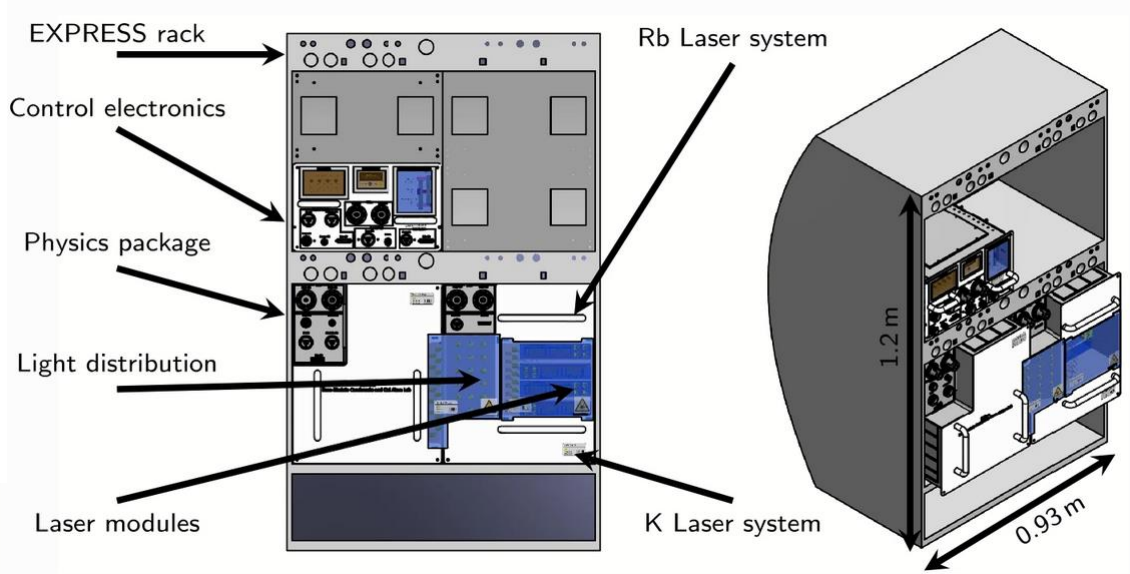
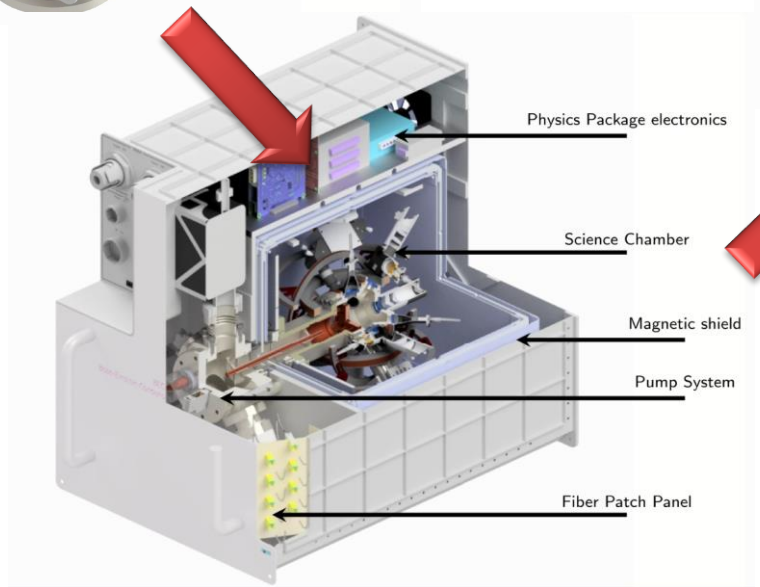
BECCAL
Bose Einstein Condensate and Cold Atom Laboratory







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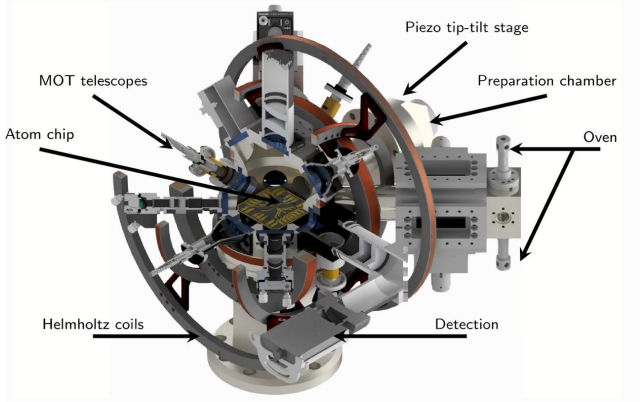
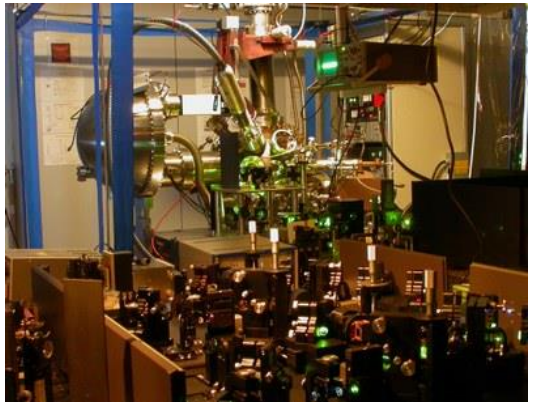


Scientific Areas:

1. Atom Interferometry
2. Coherent Atom Optics
3. Scalar Bose - Einstein Condensates
4. Spinor Bose - Einstein Condensates and Quantum Gas Mixtures
5. Strongly Interacting Gases and Molecules
6. Quantum Information



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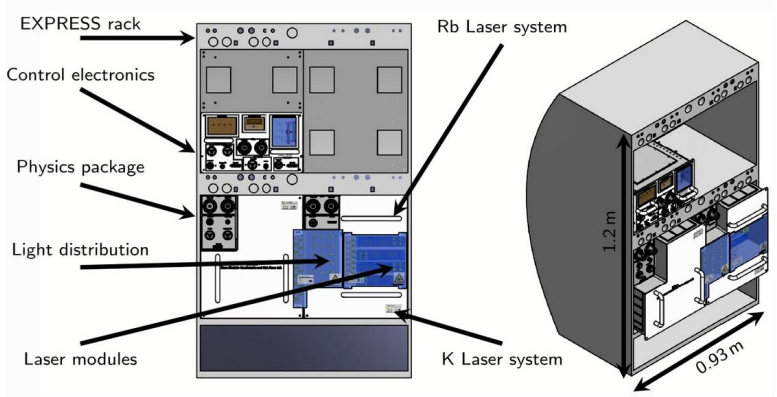

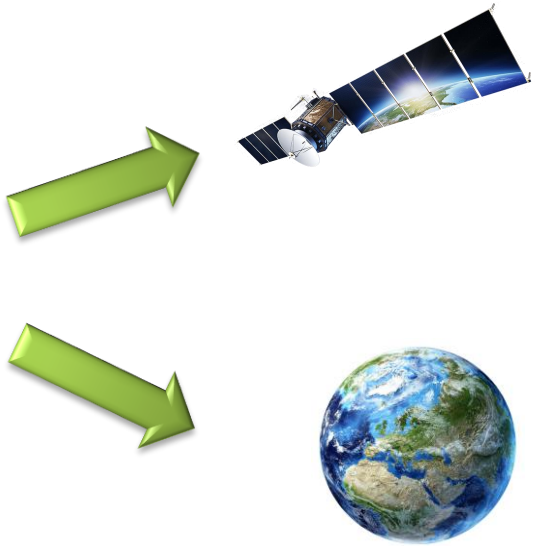

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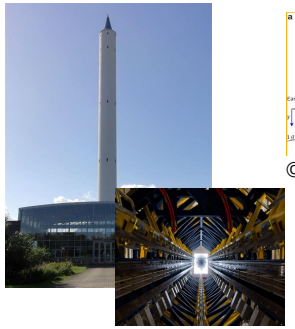
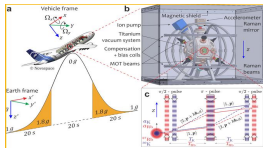
Atom Interferometry under Microgravity





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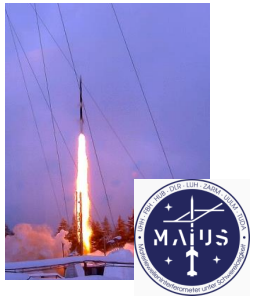

Prolonged Microgravity

e.g.
STE Quest
Aguilera et al., Class. Quant. Grav, 31, 159502 (2014)

Voyage 2050 Propsal
B. Battelier et al., arXiv1908:11785v3 (2020)

Atom Interferometry in Microgravity

Reminder:

- Interferometry is a precise tool to measure changes in a system
- Atom Interferometry is sensitive to Accelerations (such as Gravitation)

Atom Interferometry in Microgravity

- Fundamental Research on Atom Interferometry
- **Equivalence Principle Tests**
- Earth Observation
- Gravitational Wave Detection

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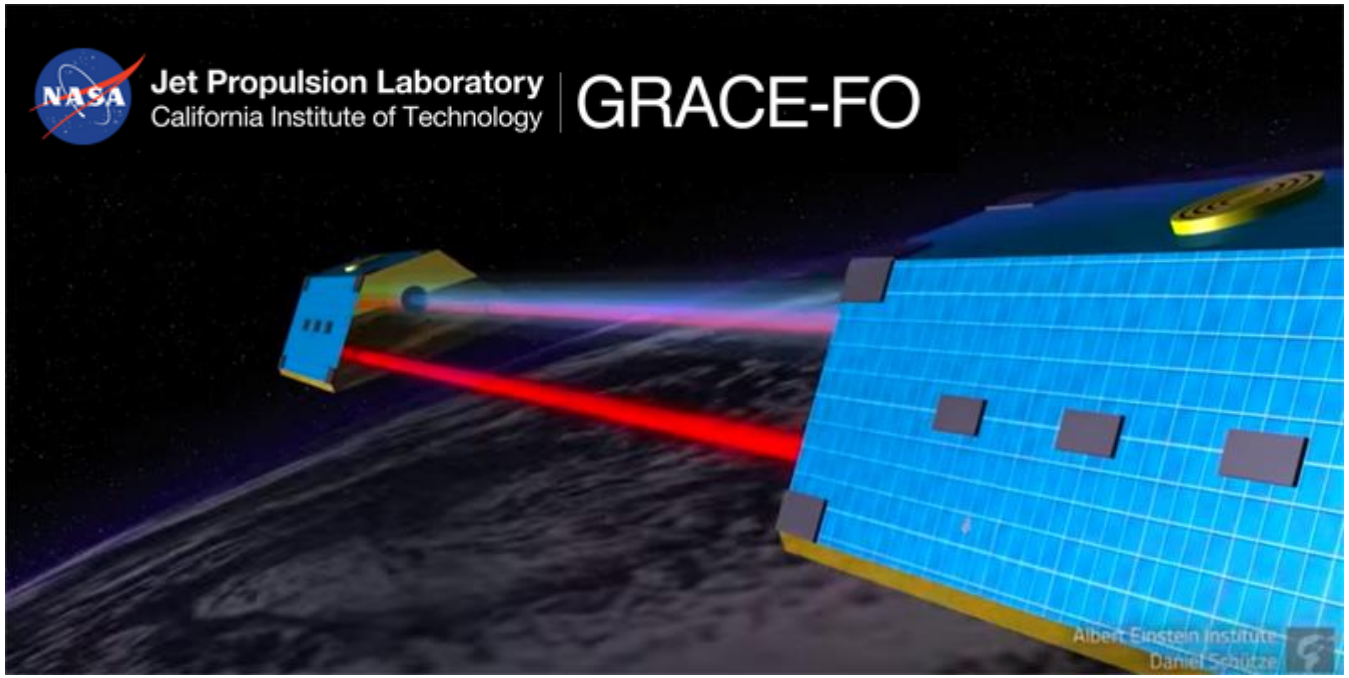
Earth Observation from Space

- GOCE Mission
  GOCE = Gravity Field and Steady-State Ocean Circulation Explorer

- GRACE and GRACE Follow on Mission
  Gravity Recovery and Climate Experiment

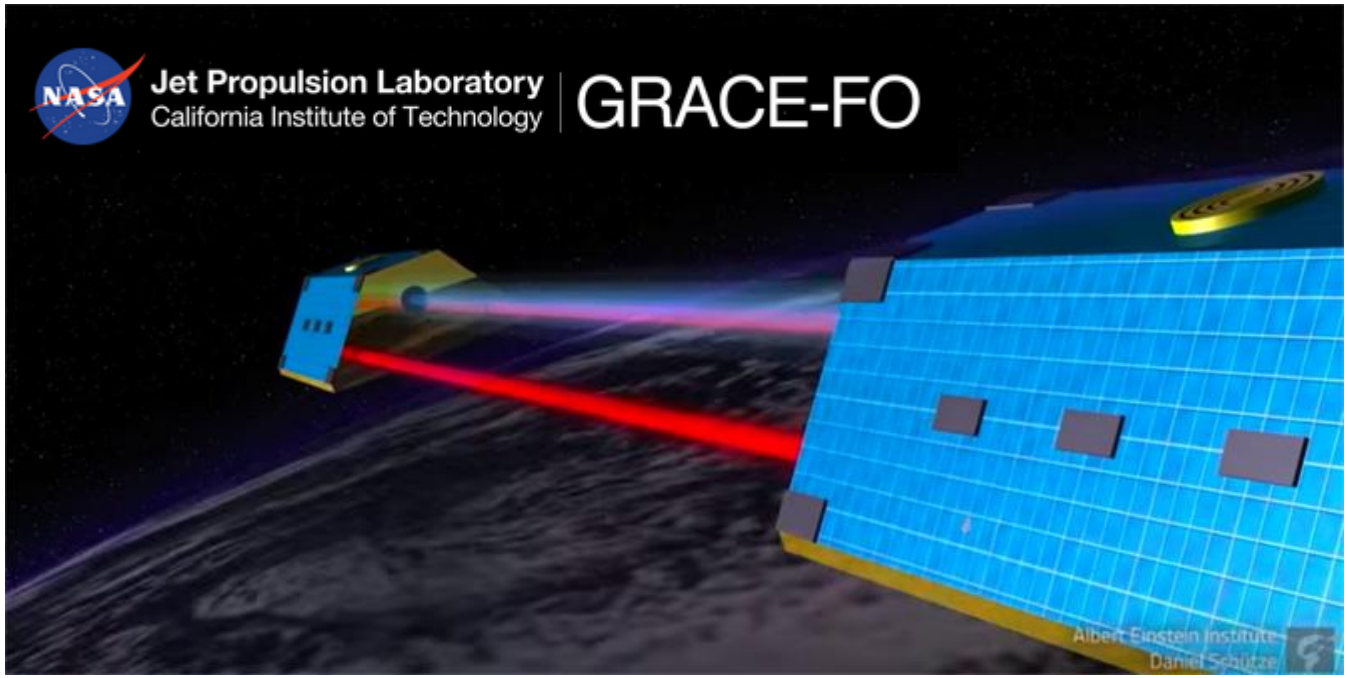


Earth Observation from Space

- GOCE Mission
  GOCE = Gravity Field and Steady-State Ocean Circulation Explorer

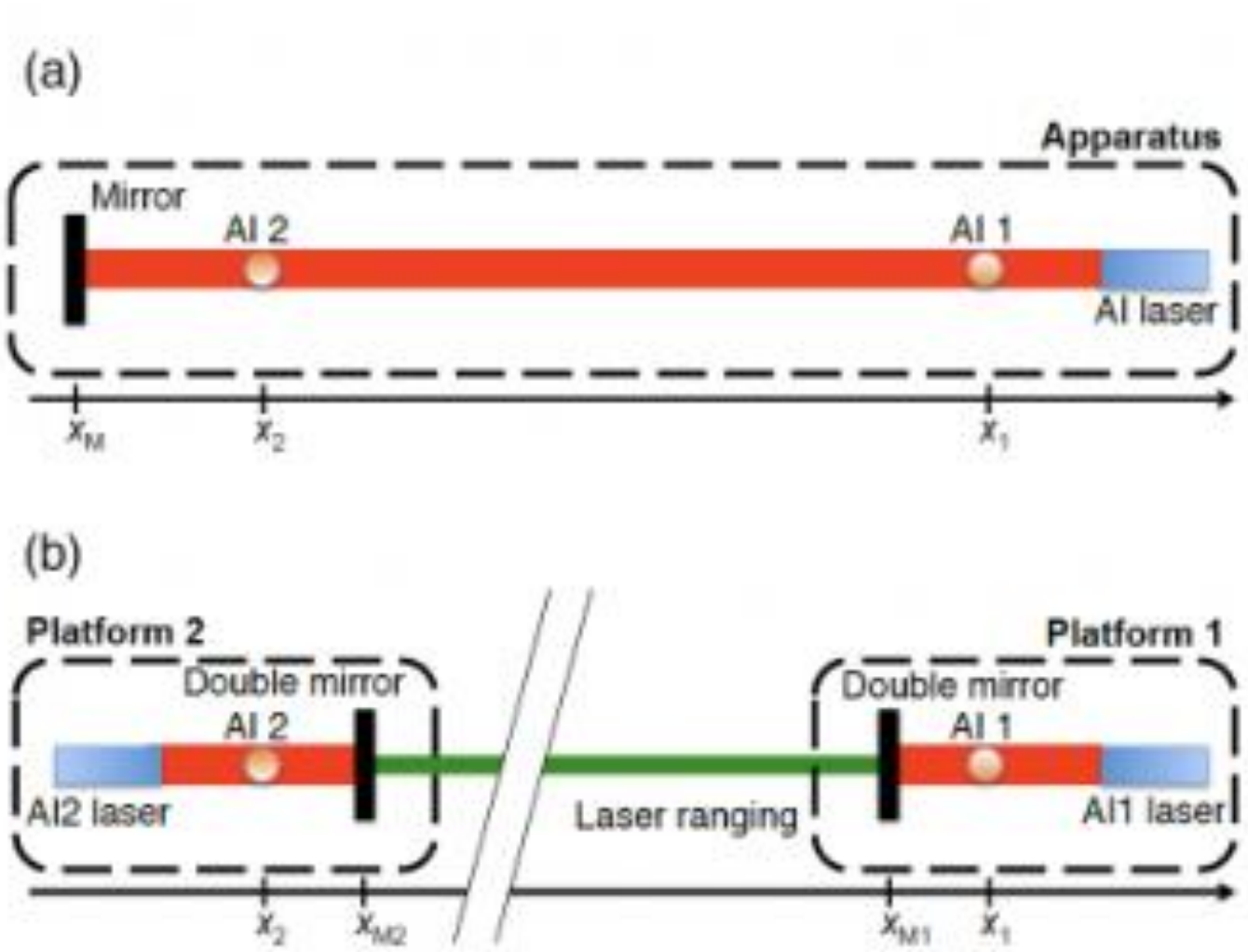
- GRACE and GRACE Follow on Mission
  Gravity Recovery and Climate Experiment

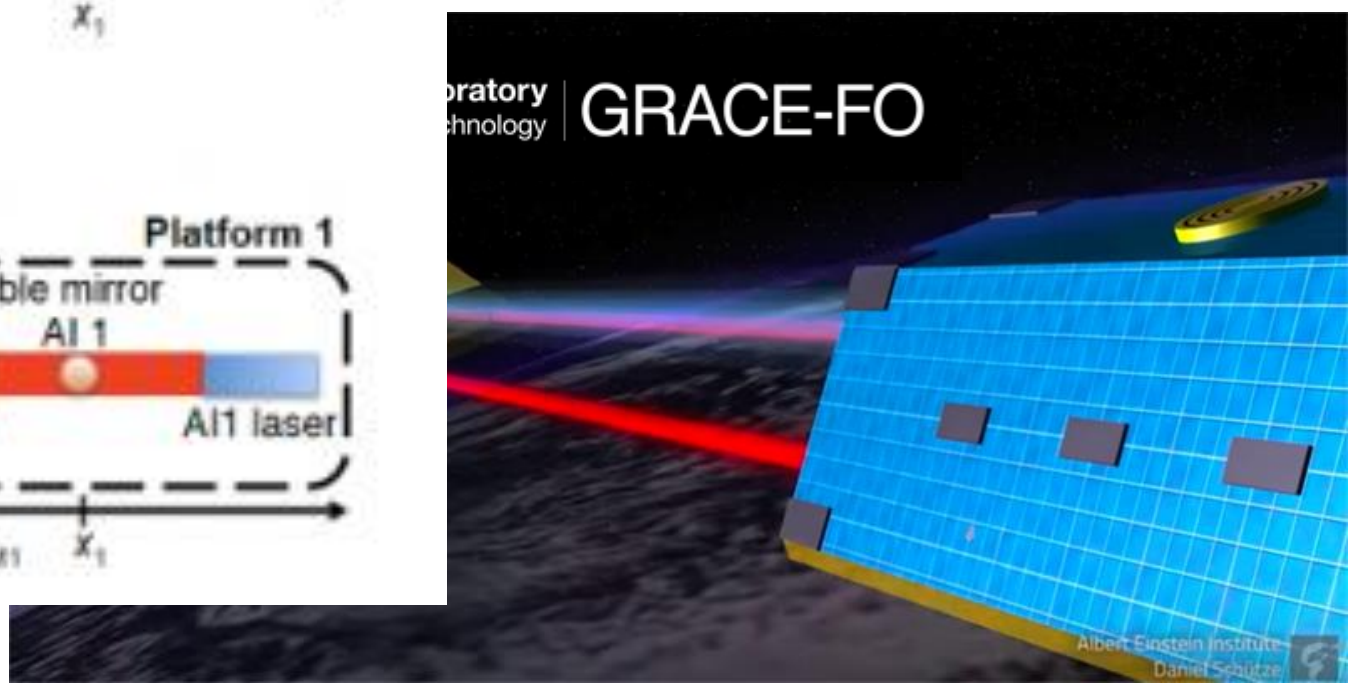
  - Measurement of Distance
  - Accelerometers on both satellites
  - Accuracy depending on the Accelerometer



DLR

Earth Observation from Space





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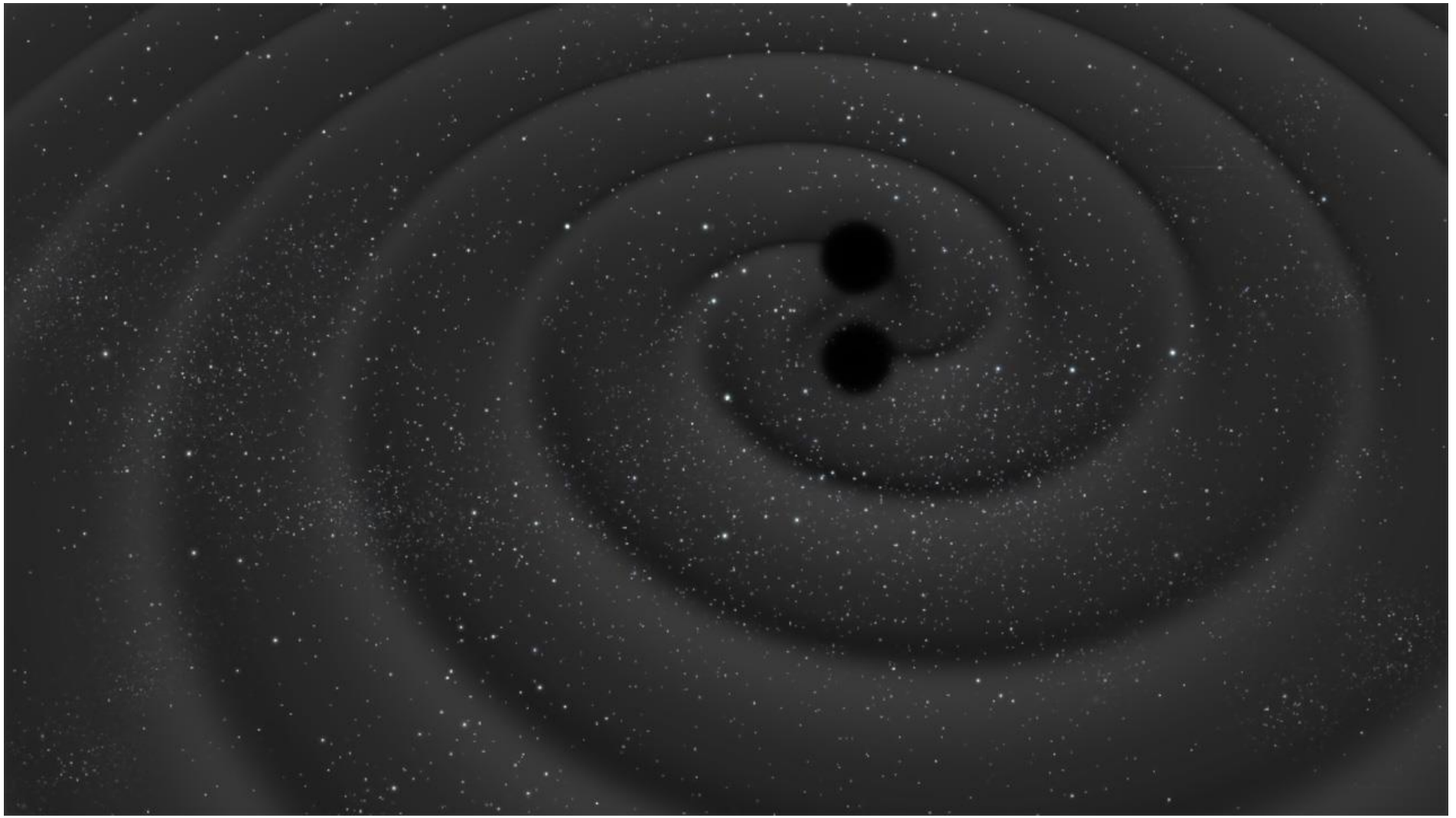
Atom Interferometry for Gravitational Wave Detection



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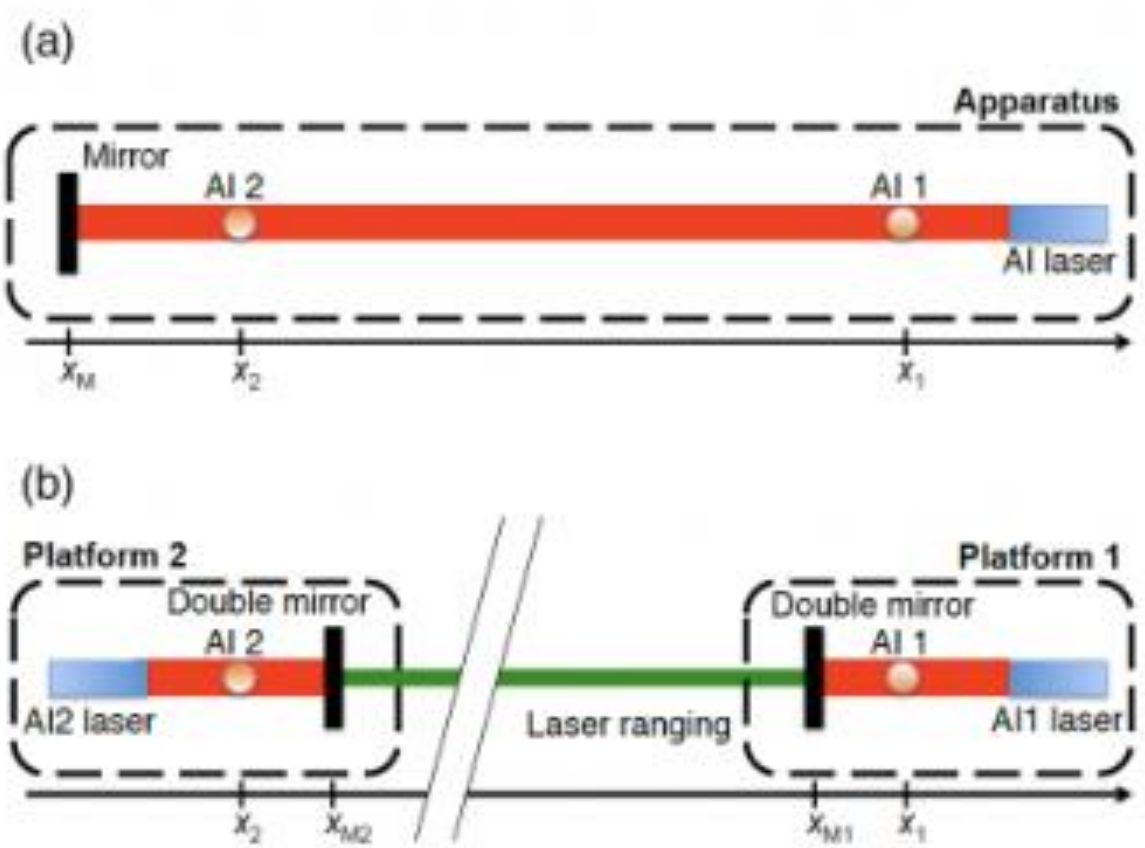
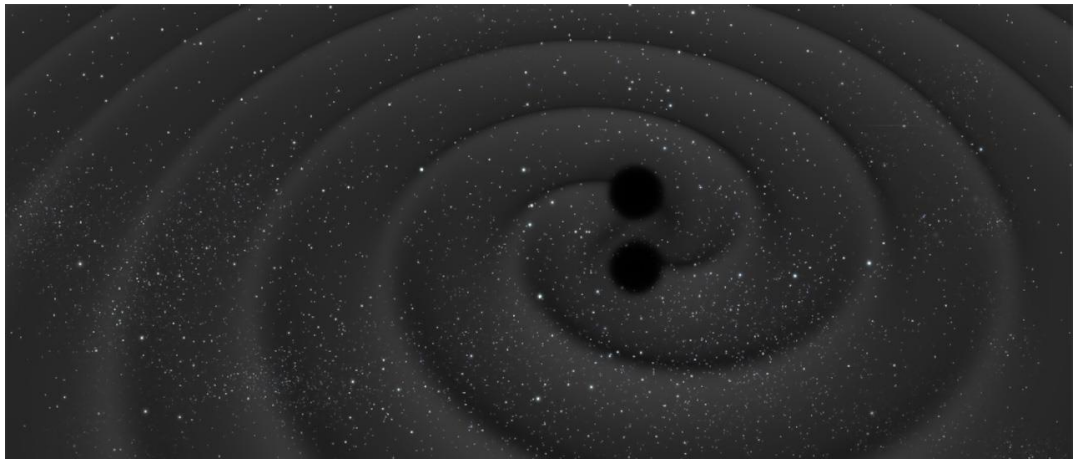
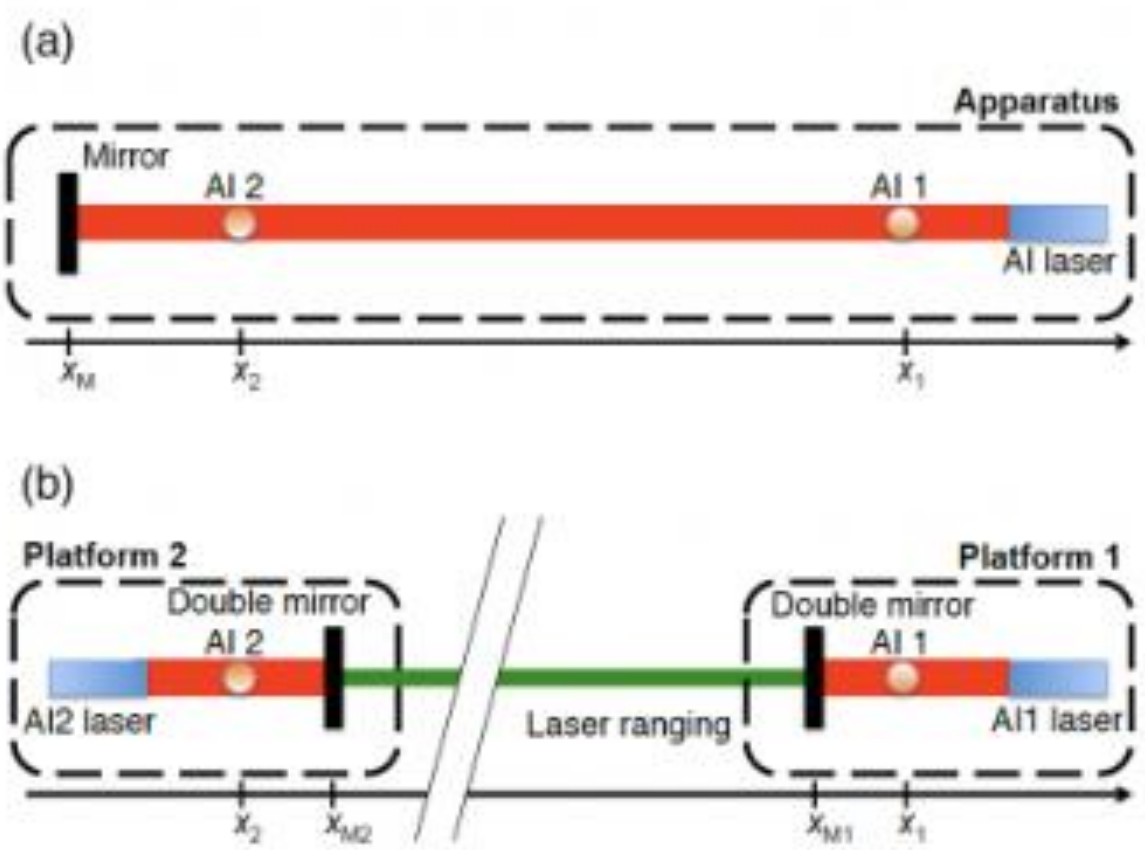
Atom Interferometry for Gravitational Wave Detection





Atom Interferometry for Gravitational Wave Detection



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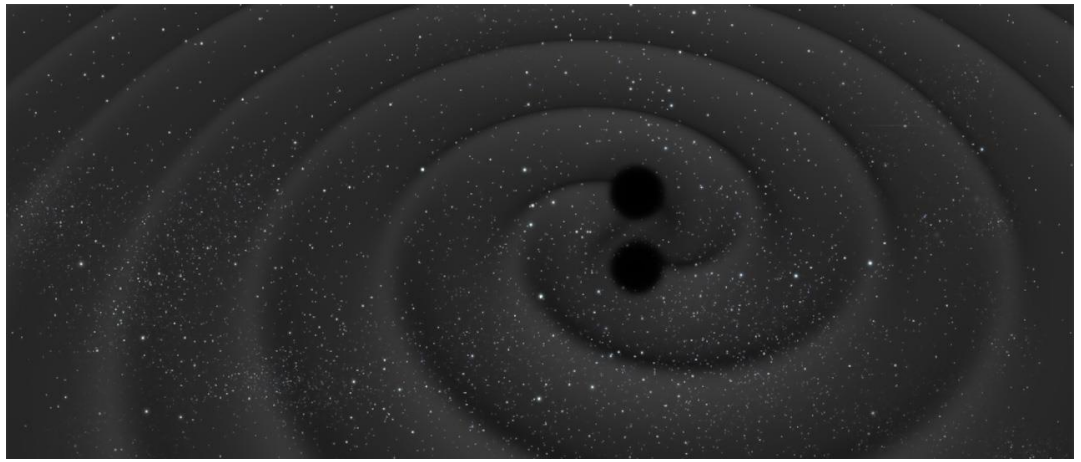
AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration

Contact person: **Oliver Buchmueller** *(other authors listed on back cover)*

High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, UK

E-mail: o.buchmueller@imperial.ac.uk

See also Talk by O. Buchmüller!



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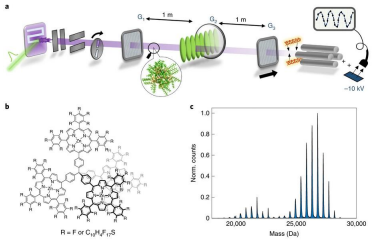
Matter Wave Interferometry in Space / Micorgravity

- Large Molecular Interferometry
  - Need for Microgravity / Long Baseline Experiments
  - Optomechanics being crucial to the newest Developments
- Bose Einstein Condensation
  - Involved Statistics
  - Description by an Encapsuling Wave
- Atom Interferometry in Microgravity / Space
  - Fundamental Physics
  - Equivalence Principle Tests
  - Earth Observation
  - Gravitational Wave Detection



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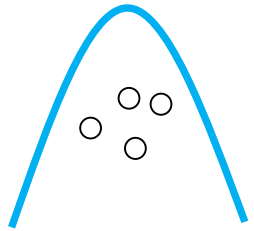

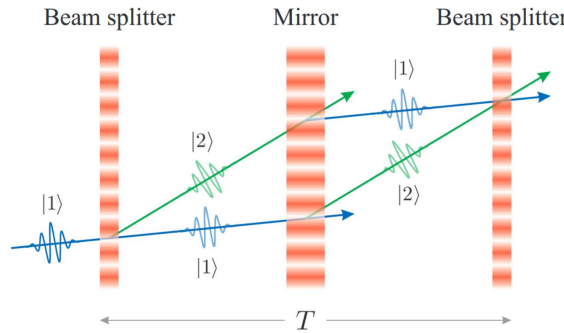

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