

Atoms for Space

Wolf von Klitzing

QTSpace
29/03/2017



QTea ITN



QUESCA

MARIE SKŁODOWSKA-CURIE
INDIVIDUAL



MatterWave

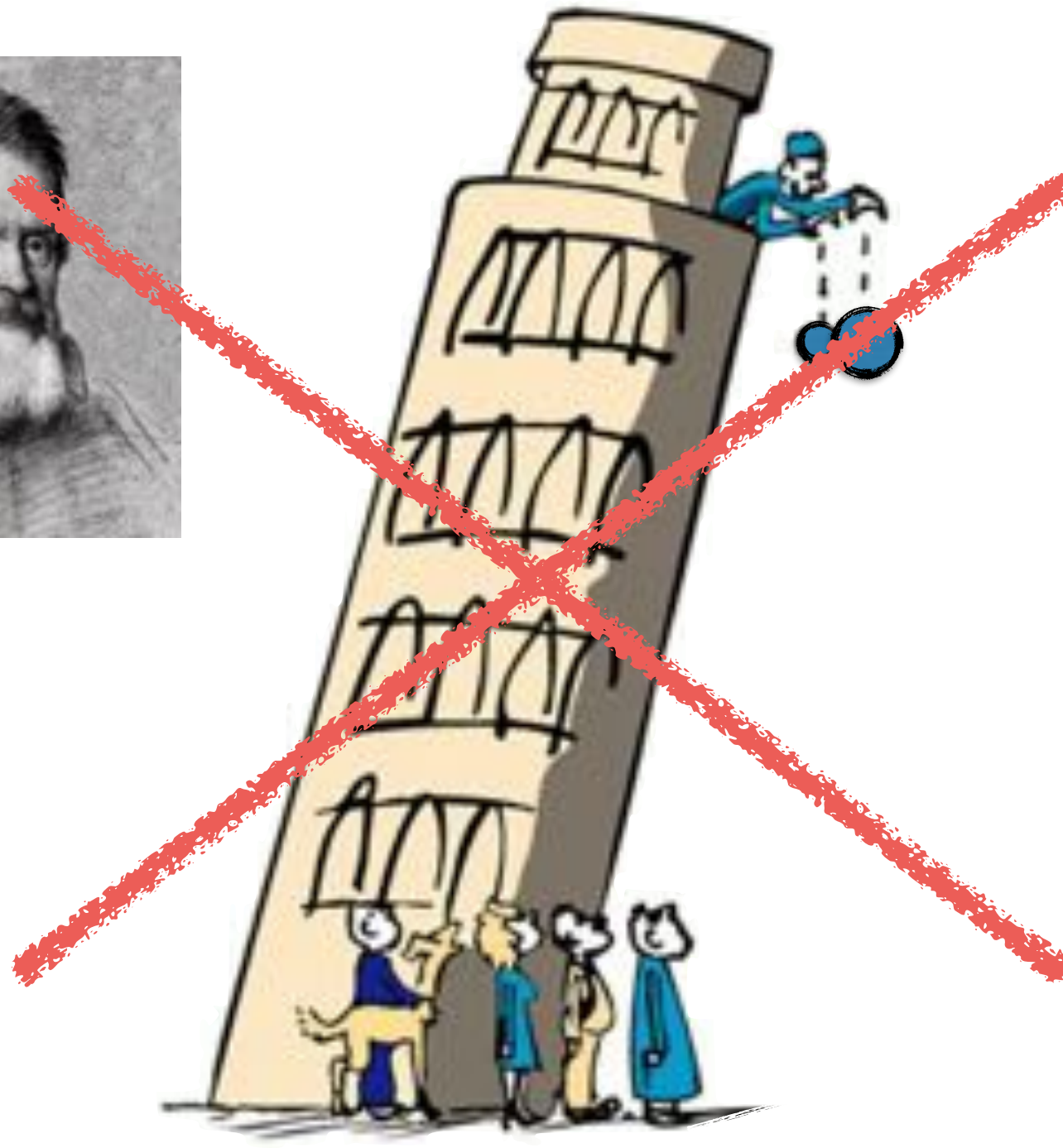


ESA-OBST

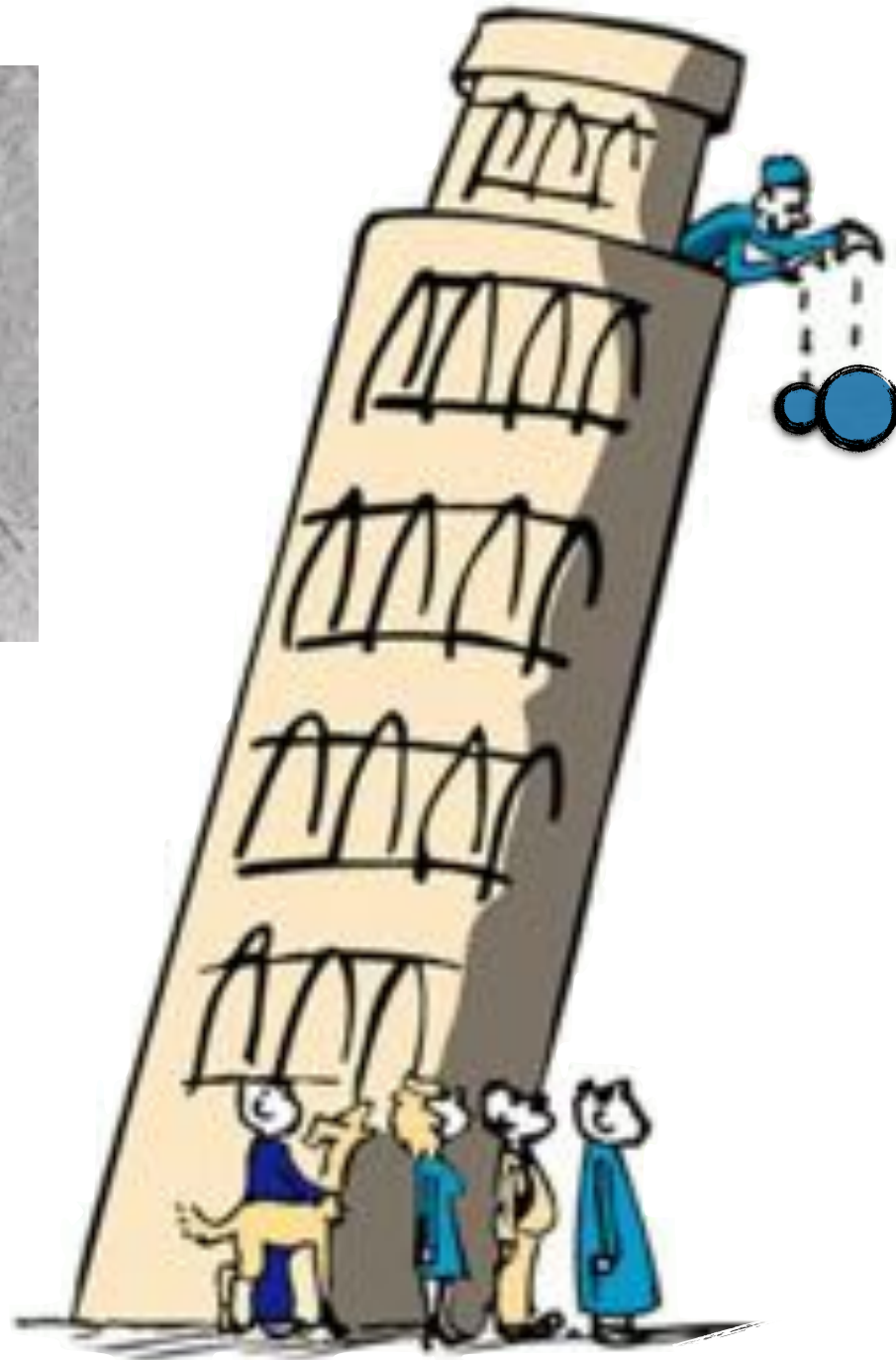


TRUMP TOWER

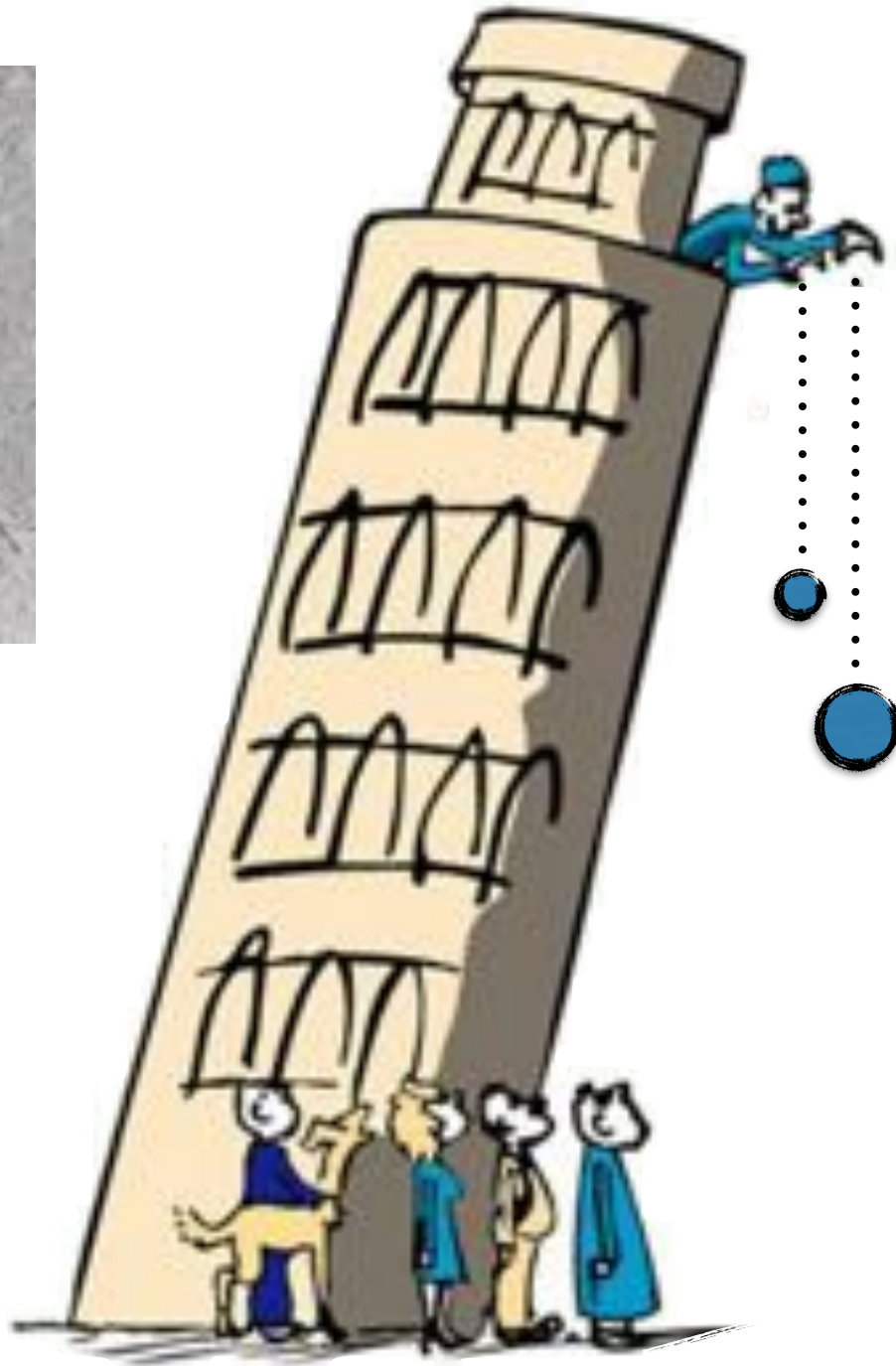
Why atoms ?



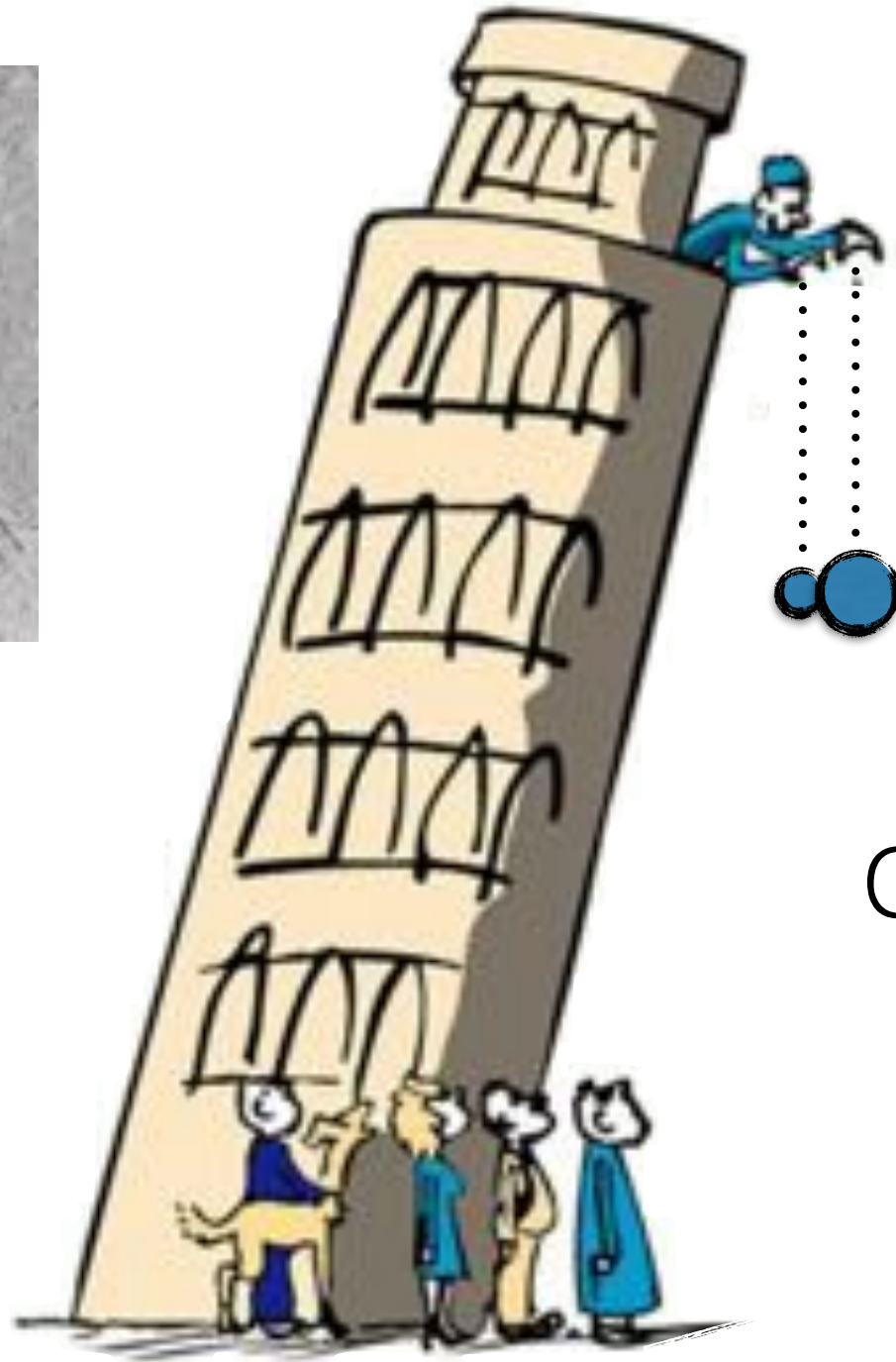




Overview:
Why Atoms ?
Why Space ?
An Example...



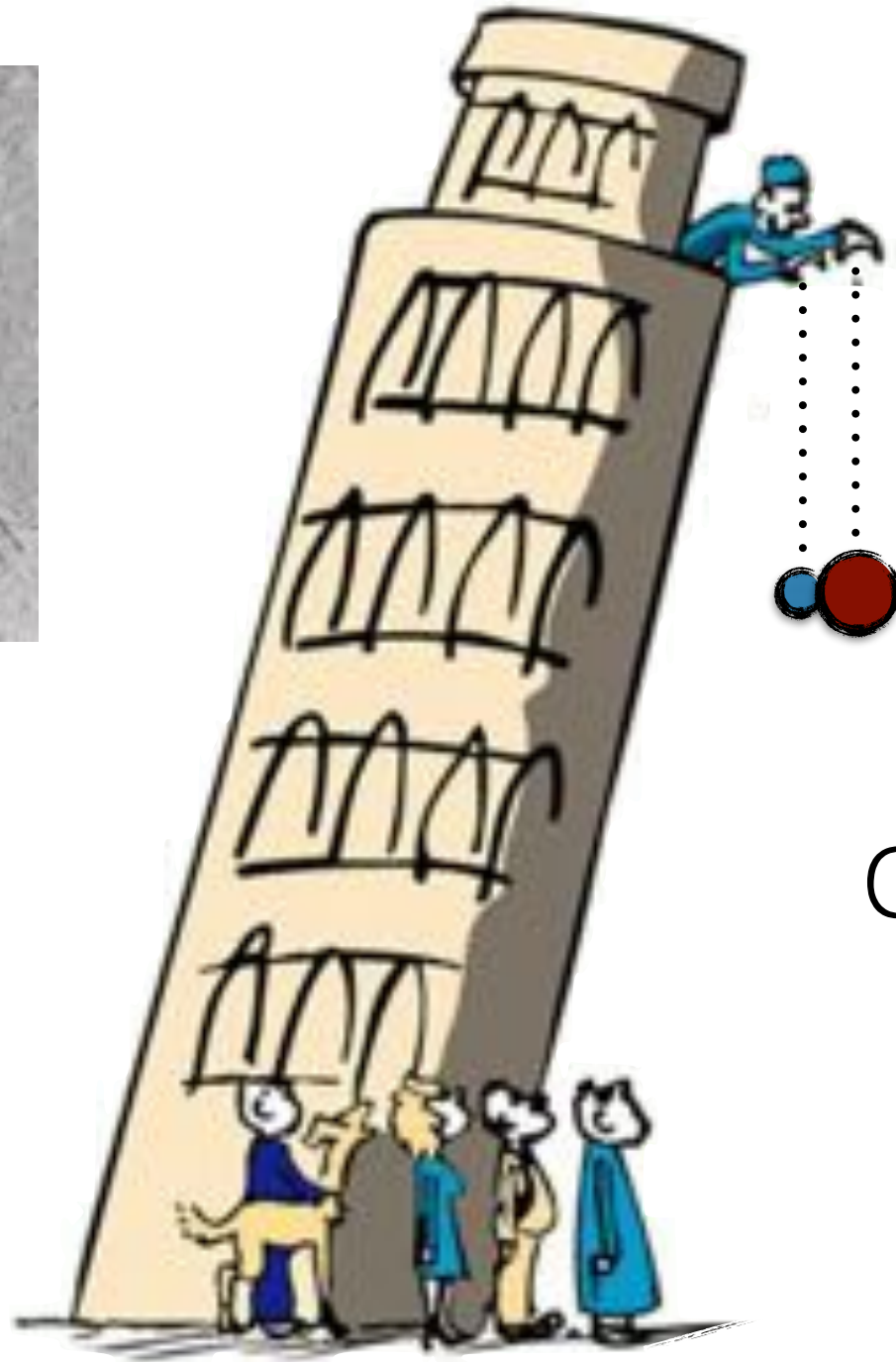
Why atoms ?



Inertial mass =
Gravitational mass

$$m_i = m_g$$

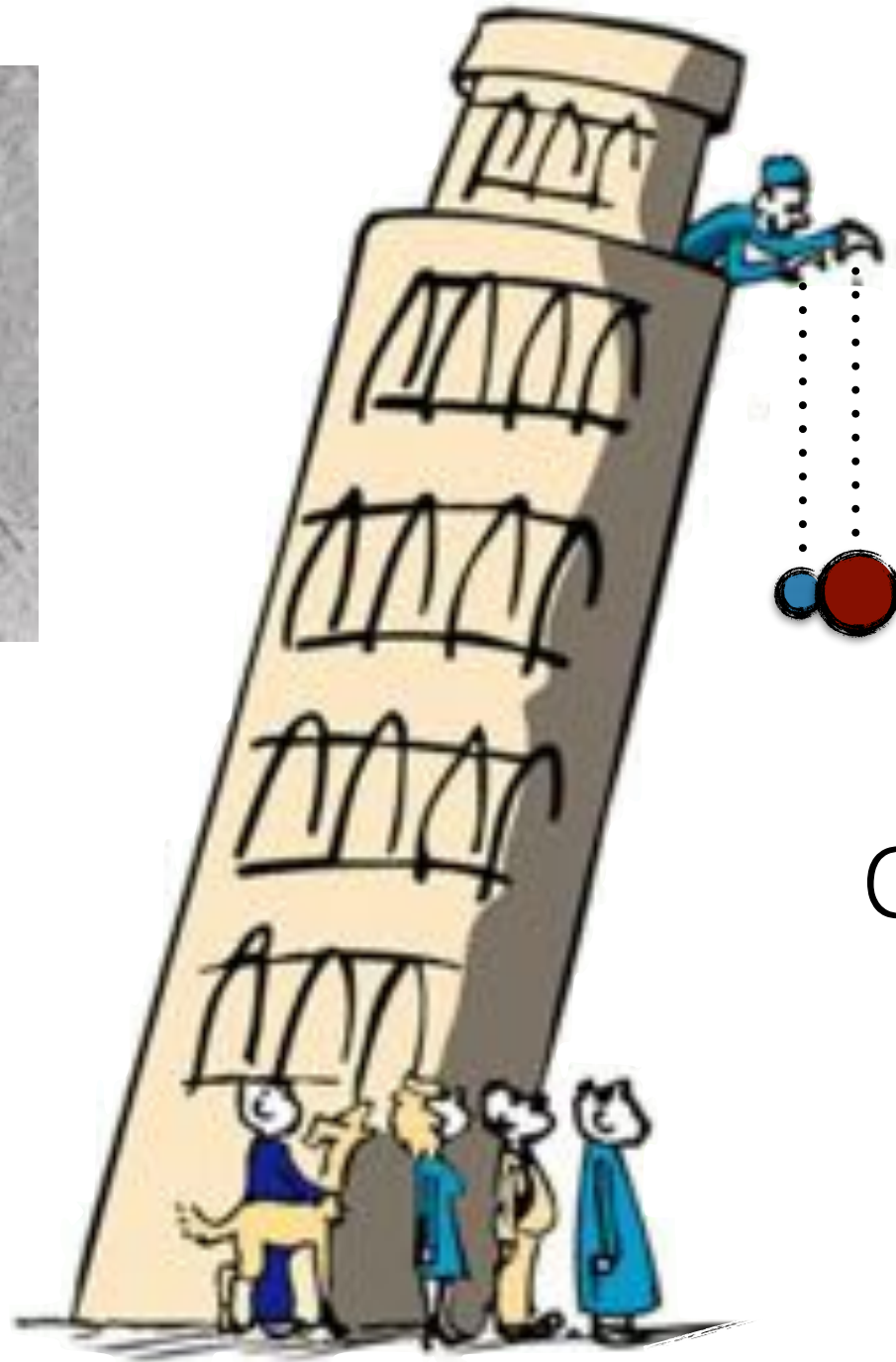
Why atoms ?



Inertial mass =
Gravitational mass

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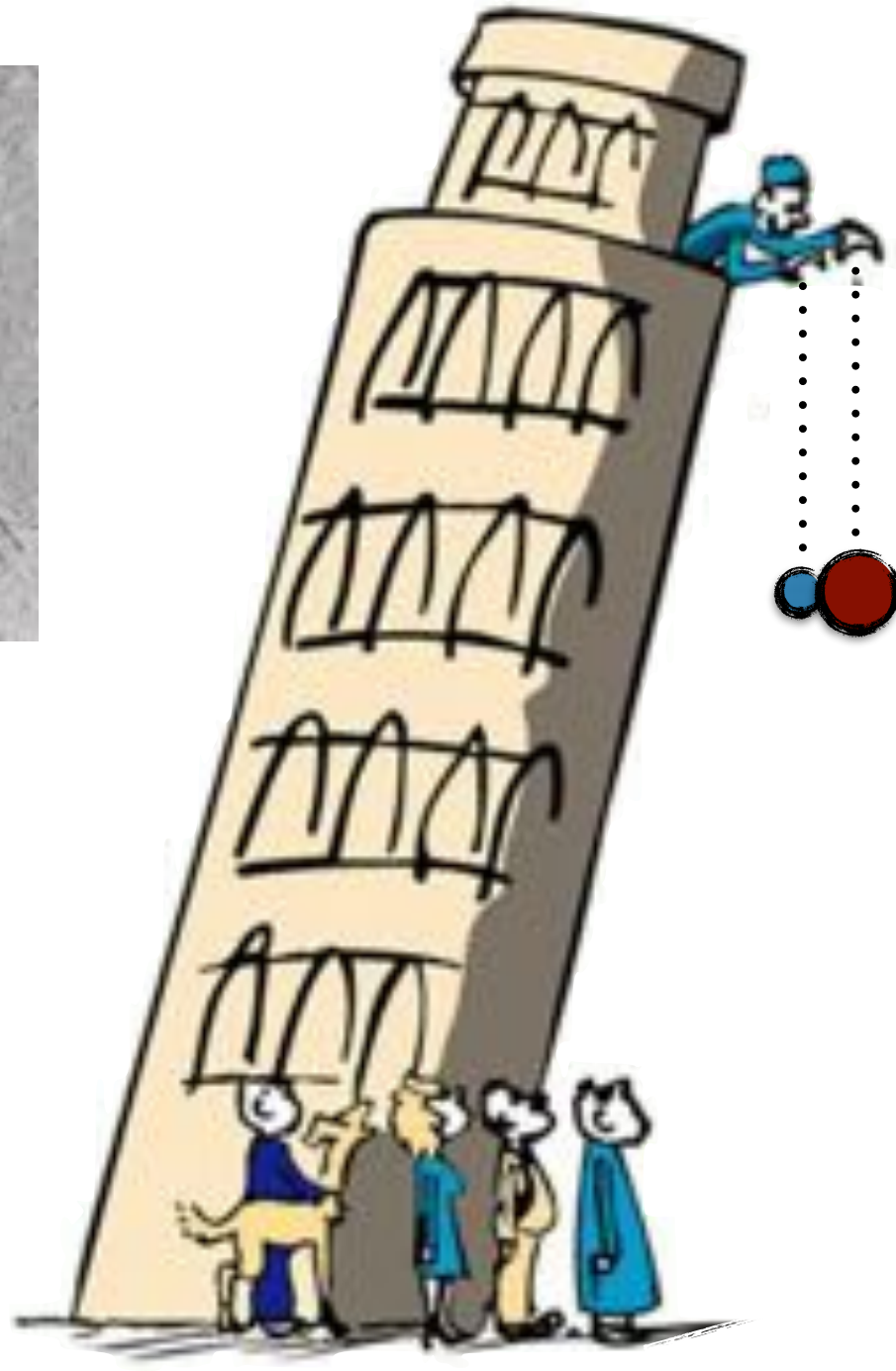
Why atoms ?



Inertial mass =
Gravitational mass

$$m_i = m_g$$

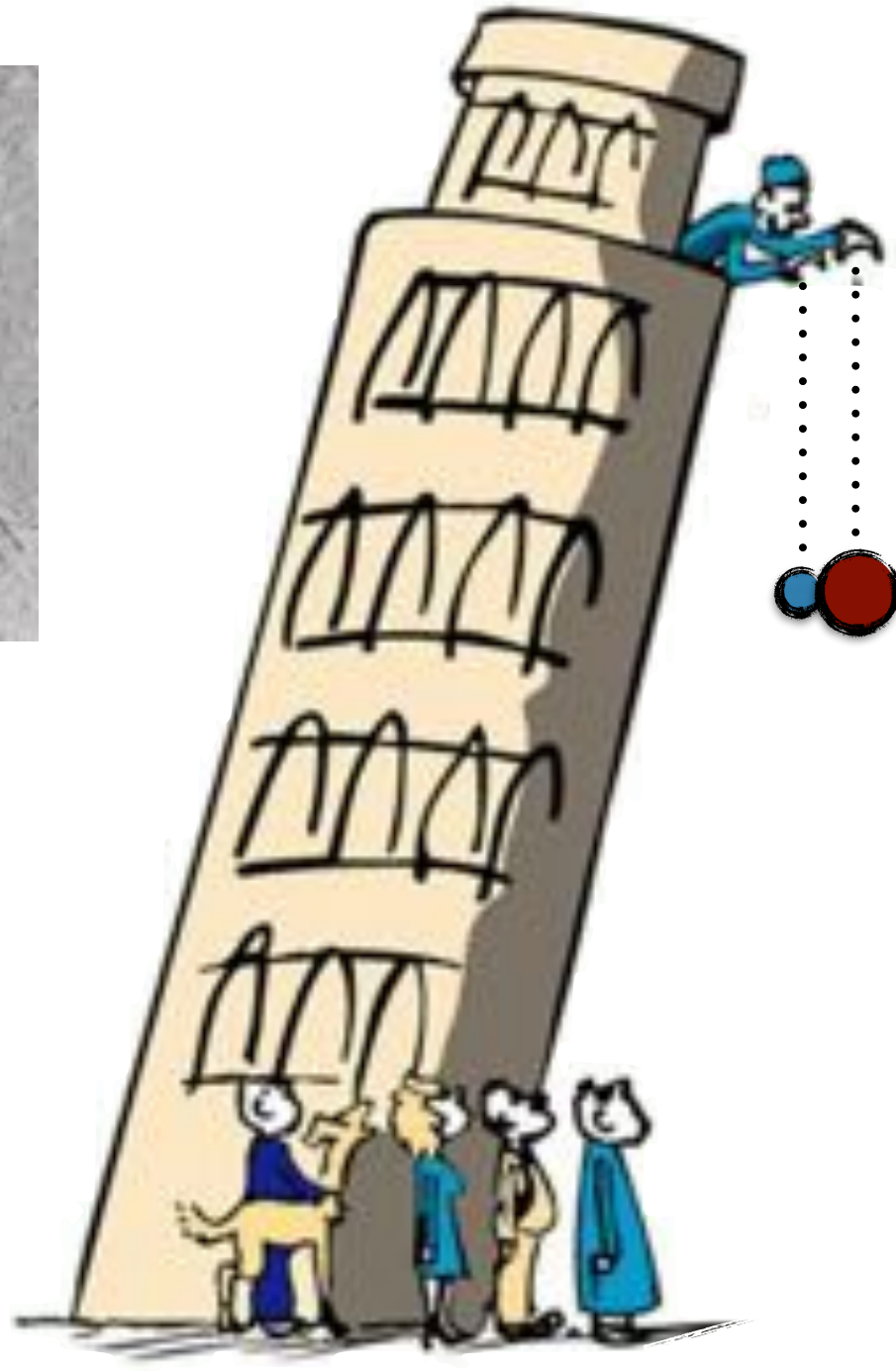
Why atoms ?



Inertial mass =
Gravitational mass

$$m_i = m_g$$

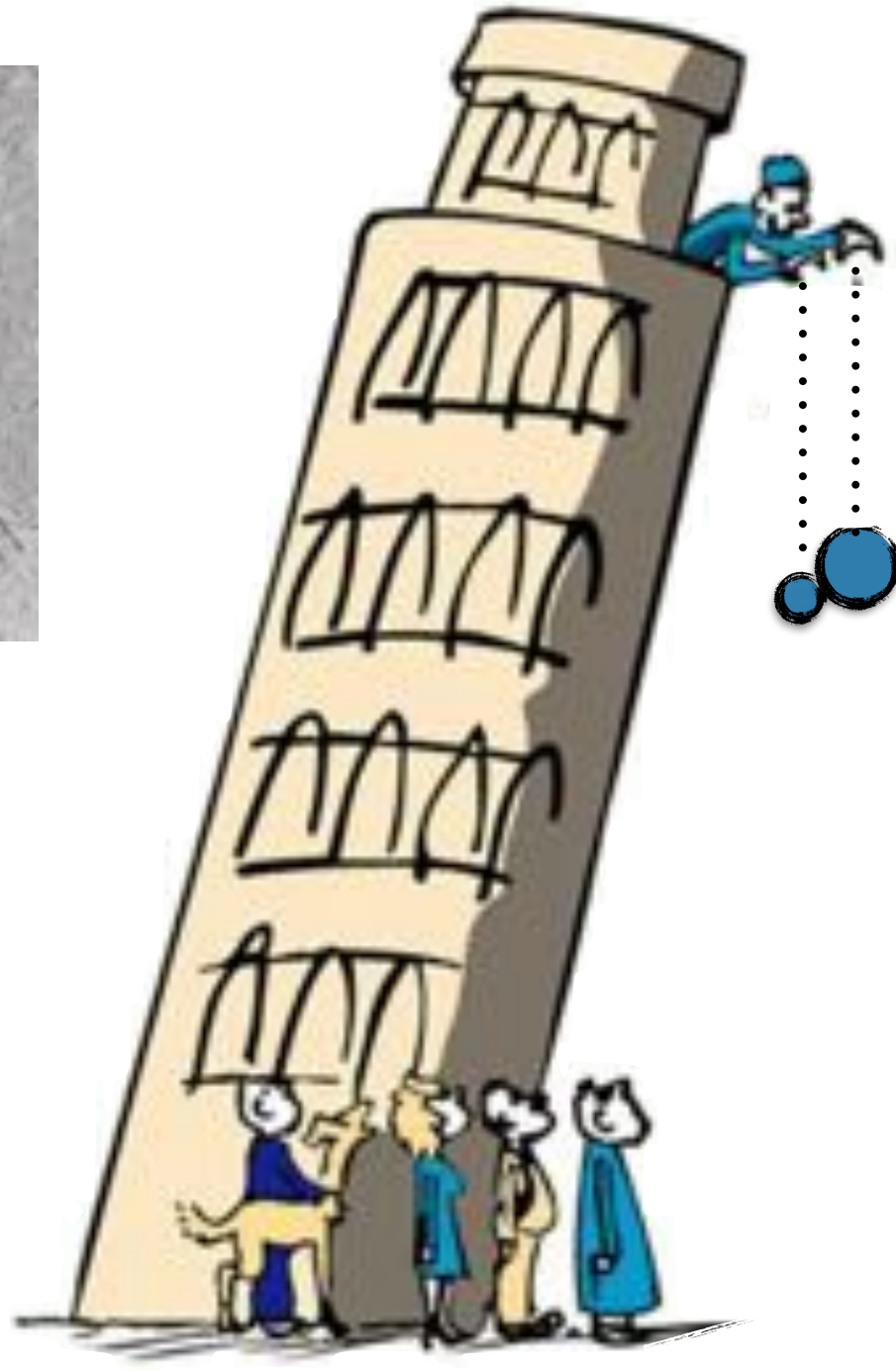
Why atoms ?



Inertial mass =
Gravitational mass ?

$$m_i = m_g ?$$

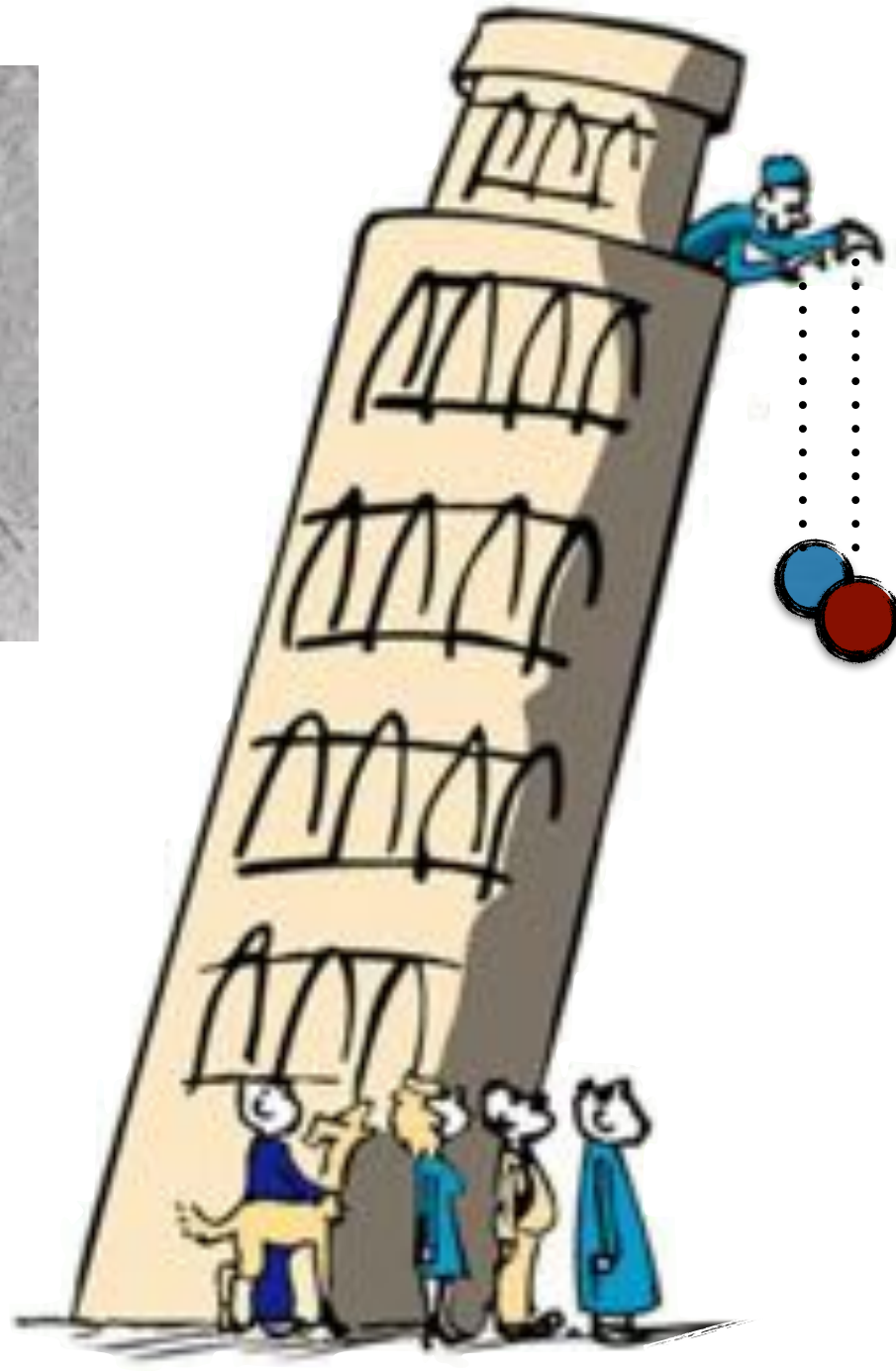
Why atoms ?



Inertial mass =
Gravitational mass ?

$$m_i = m_g ?$$

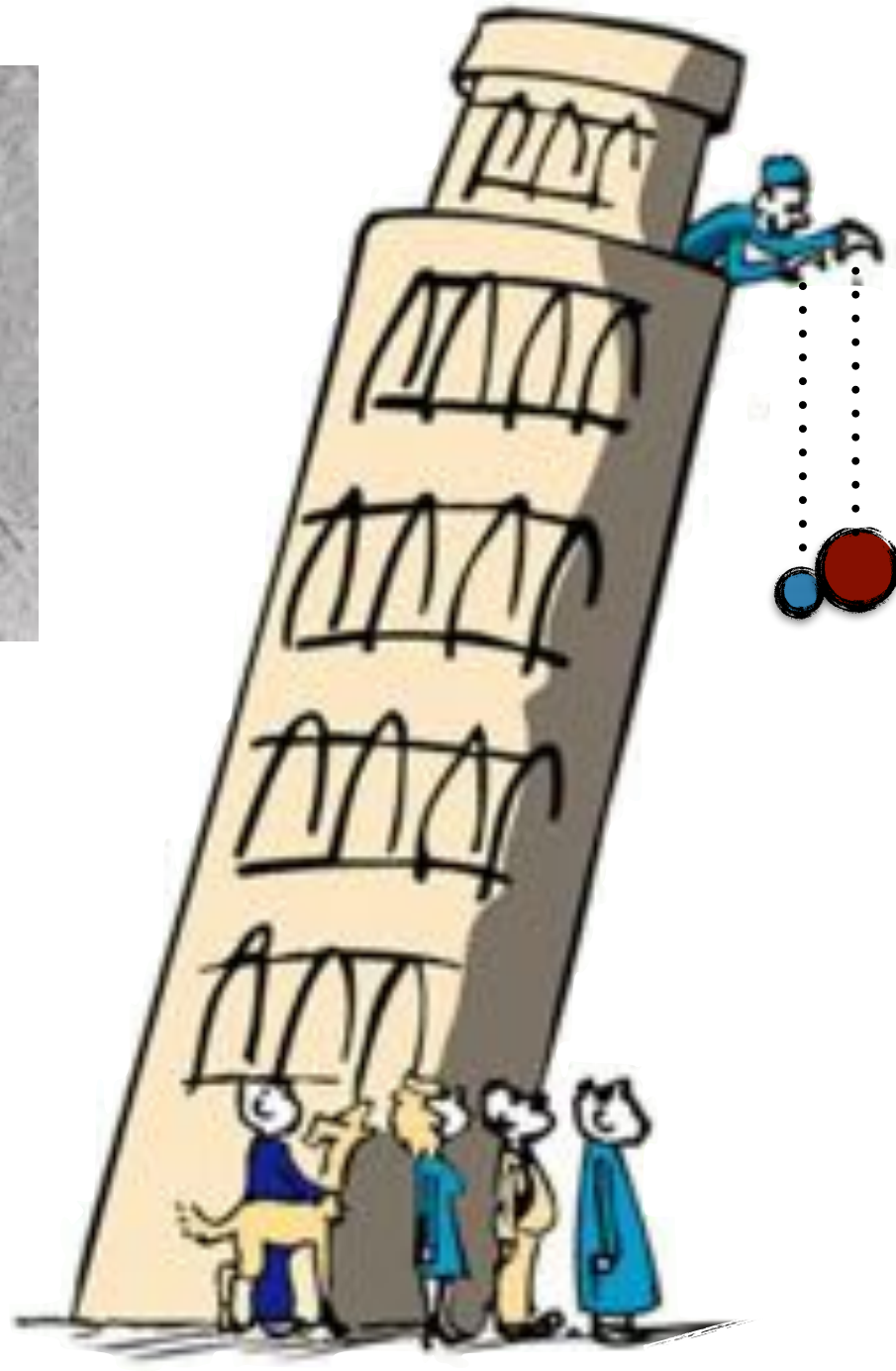
Why atoms ?



Inertial mass =
Gravitational mass ?

$$m_i = m_g ?$$

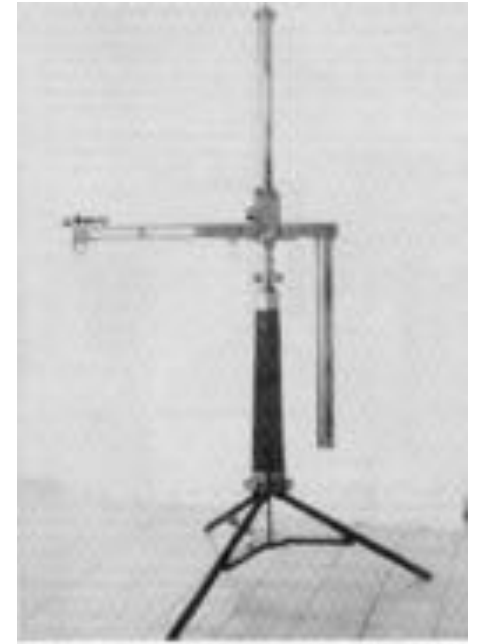
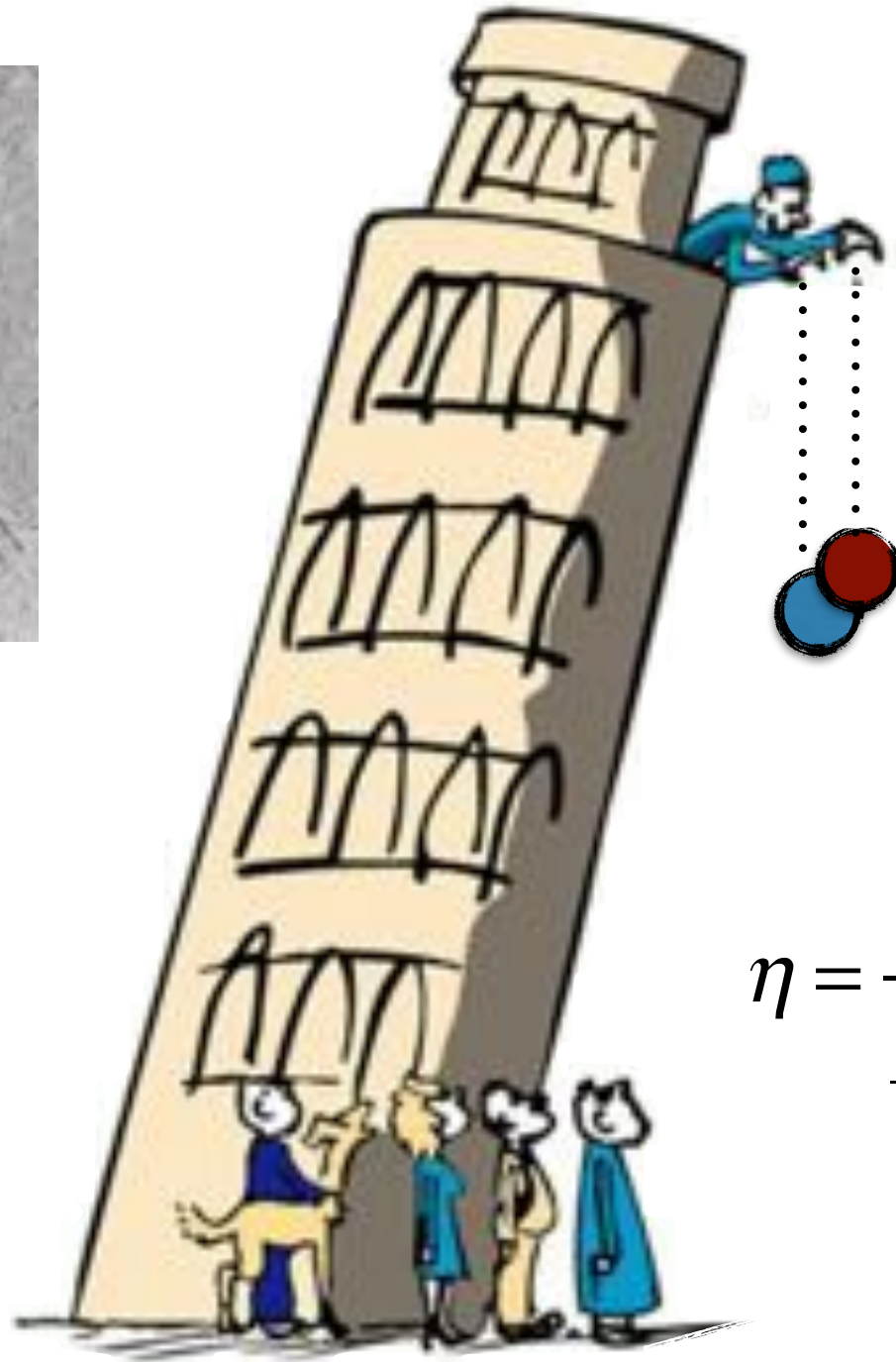
Why atoms ?



~~Inertial mass =~~
~~Gravitational mass~~

$$m_i \neq m_g$$

Why atoms ?

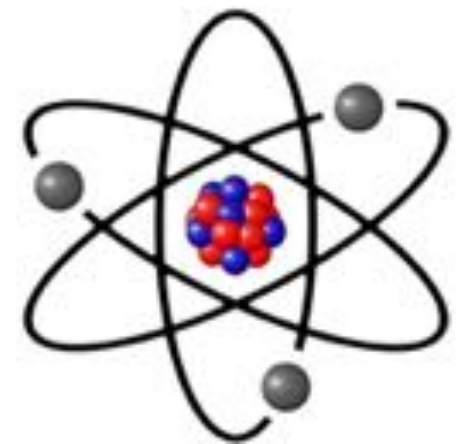
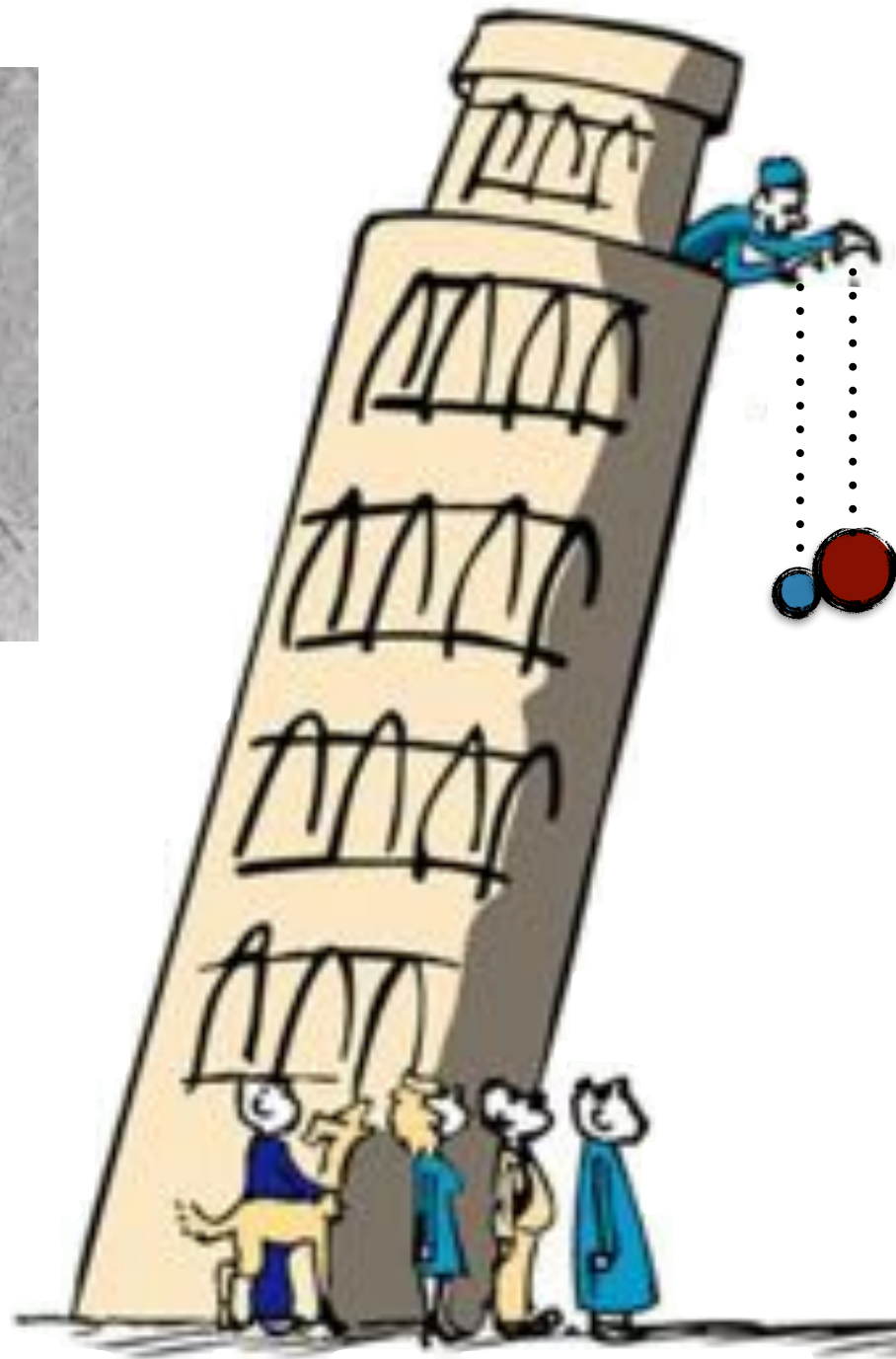


Eötvös ratio*

$$\eta = \frac{\left(m_g/m_i\right)_A - \left(m_g/m_i\right)_B}{\frac{1}{2} \left[\left(m_g/m_i\right)_A + \left(m_g/m_i\right)_B \right]}$$

* Eötvös 1885

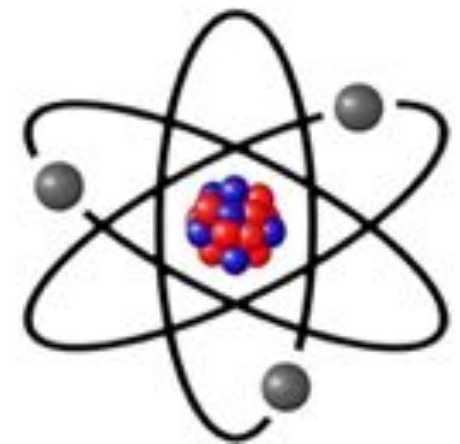
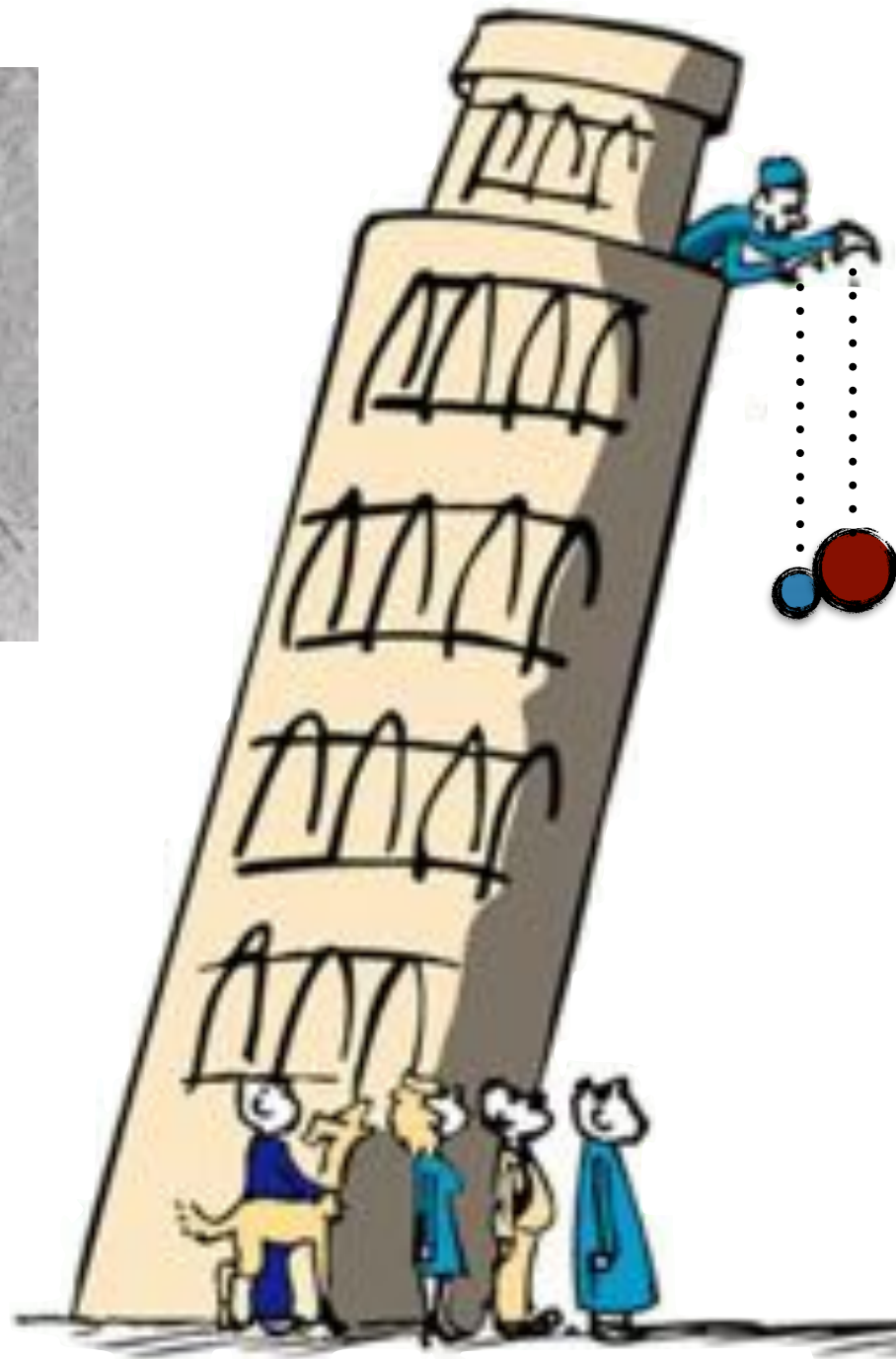
Why atoms ?



Systematics!

- Perfect Object
 - Identical
 - Properties
 - Interactions
- Perfect Tools
 - Wavelength
 - Frequency

HOW atoms ?



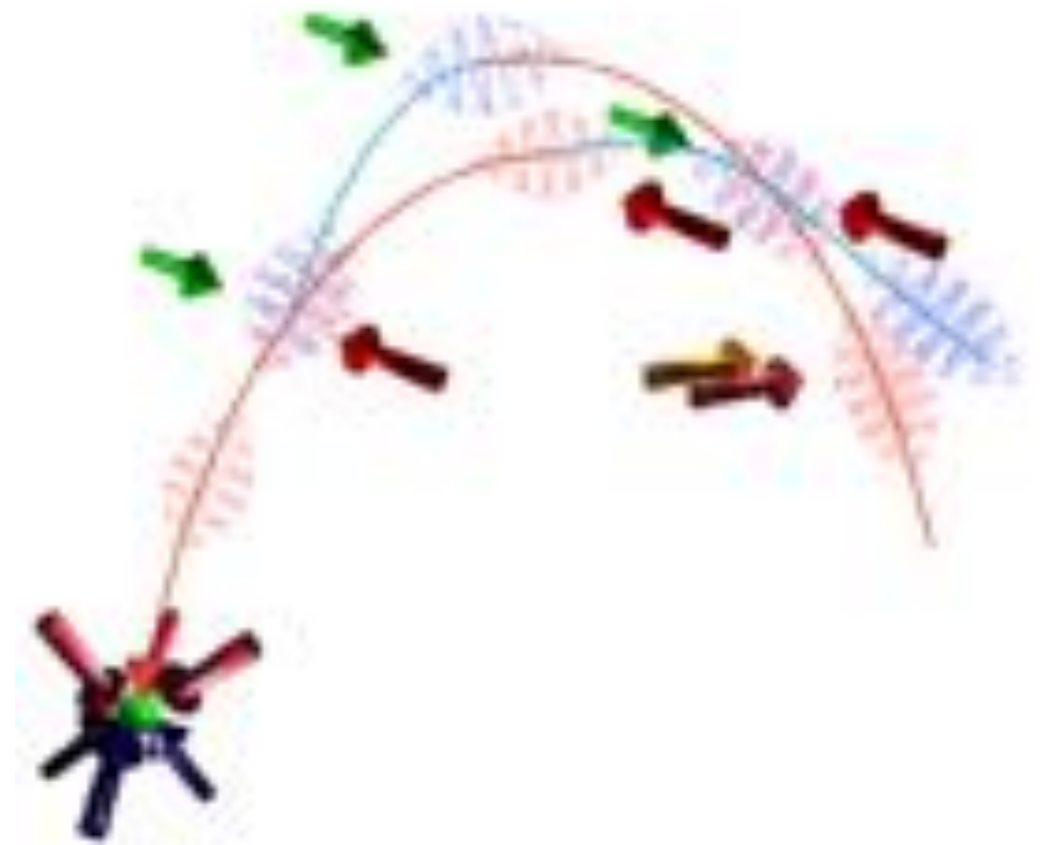
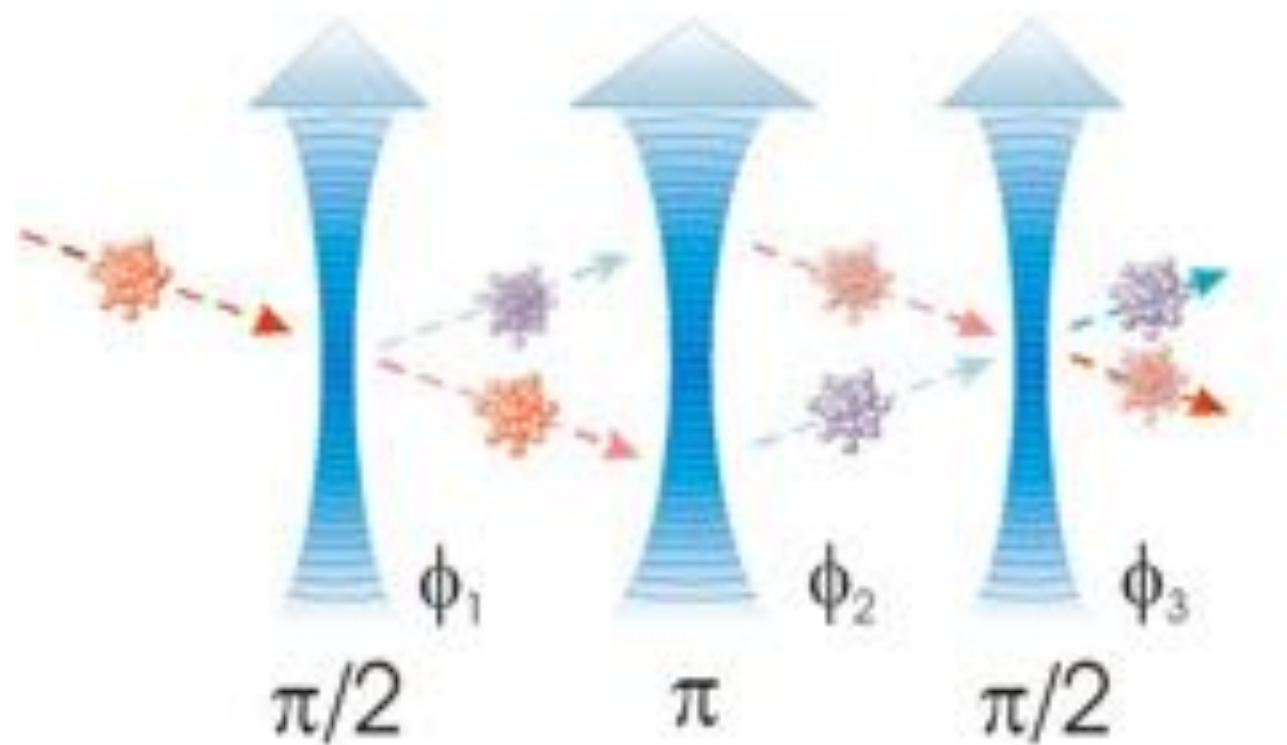
Systematics!

- Perfect Object
 - Identical
 - Properties
 - Interactions
- Perfect Tools
 - Wavelength
 - Frequency

MatterWave Interferometry

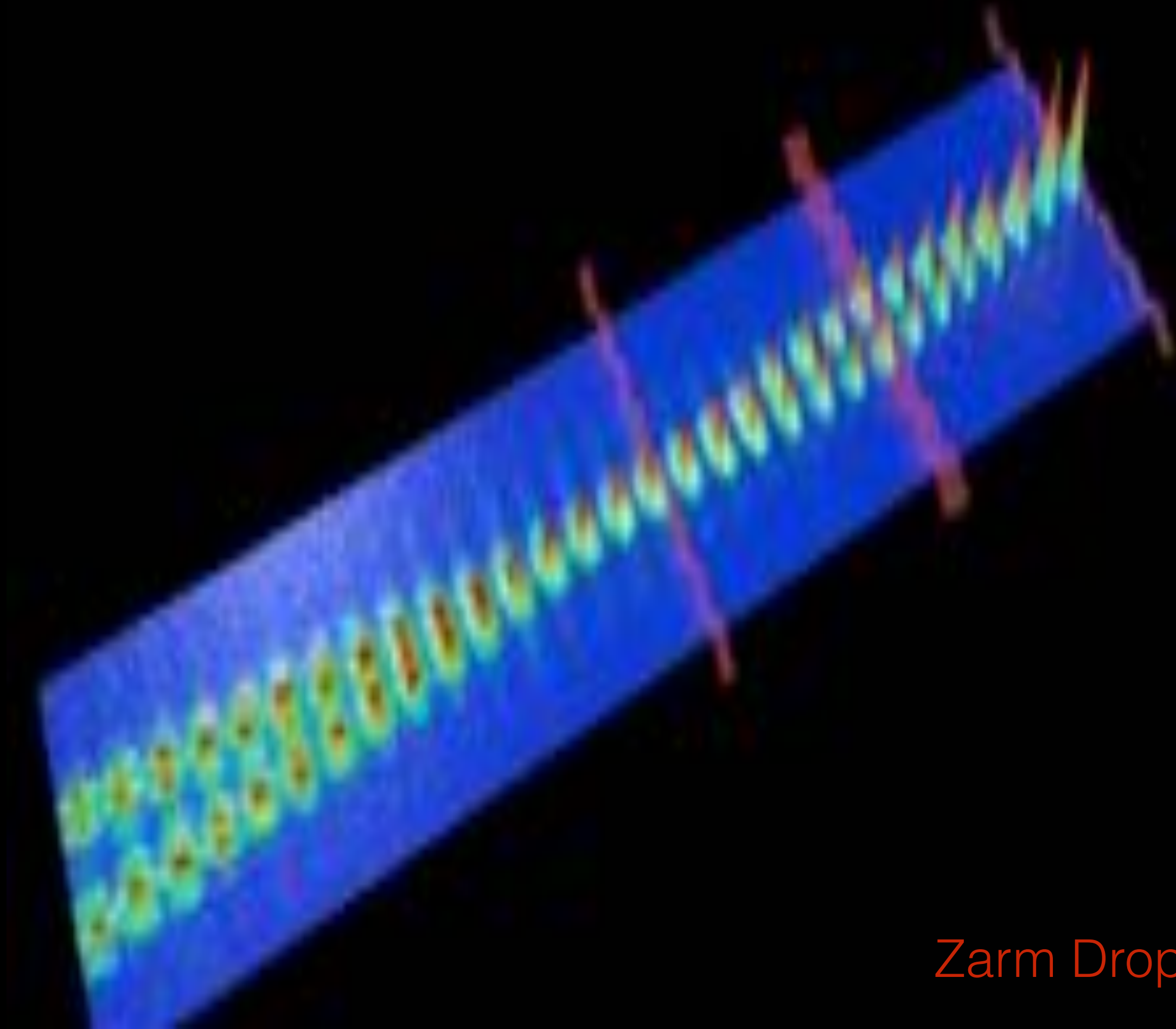
Measure

- Acceleration
- Gravity (incl. G-Waves)
- Rotation



A High Precision Mobile Atom Interferometer
M. Schmidt, et al.

<https://www.physik.hu-berlin.de/qom/research/ai>



Zarm Drop Tower

Matter-Wave Interferometry

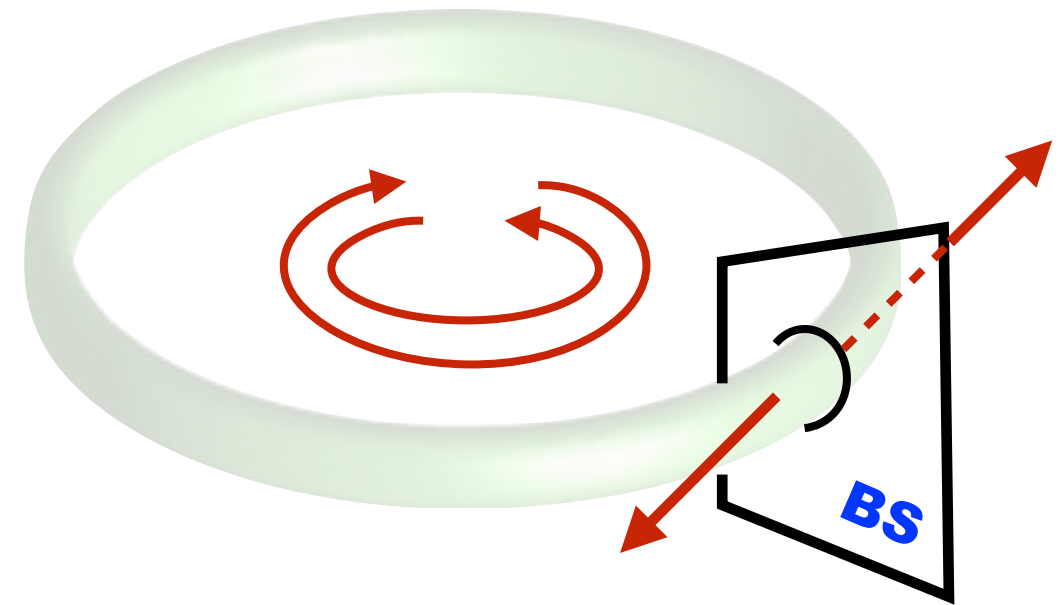
Why NOT ?



A Sagnac Gyroscope:

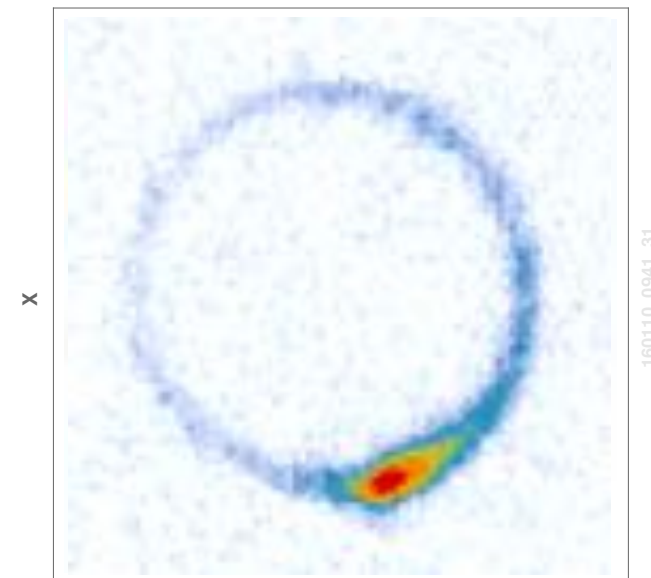
$$\Delta\phi = \frac{4\pi}{\lambda v} \Omega A$$

$$\frac{\Delta\phi_{\text{atom}}}{\Delta\phi_{\text{light}}} = \frac{\lambda_{\text{light}} c_0}{h/m} = \mathbf{5 \times 10^{10}}$$



Plus

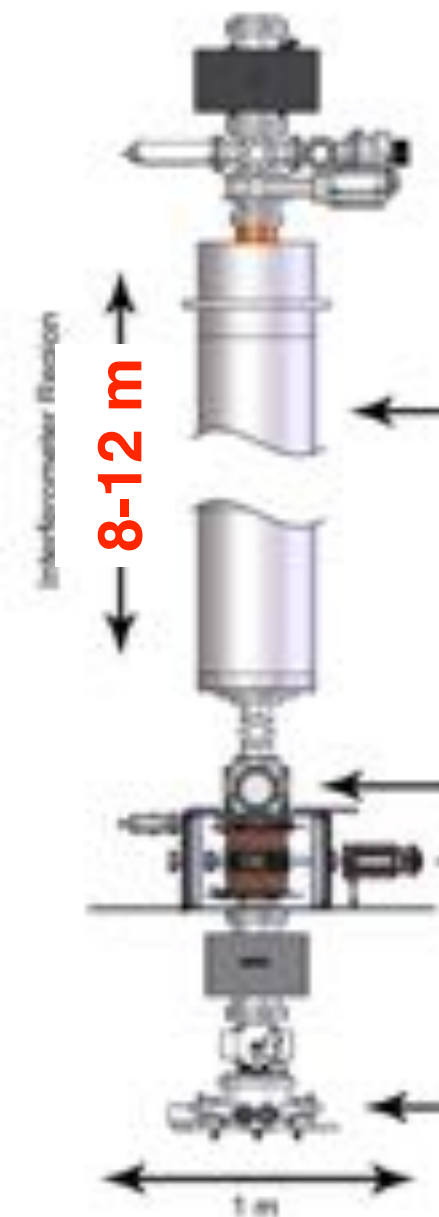
- + Internal States
 - + Gravitation (waves)
 - + Atom-Atom Interaction
- => Heisenberg Limited Detection



Why Space ?

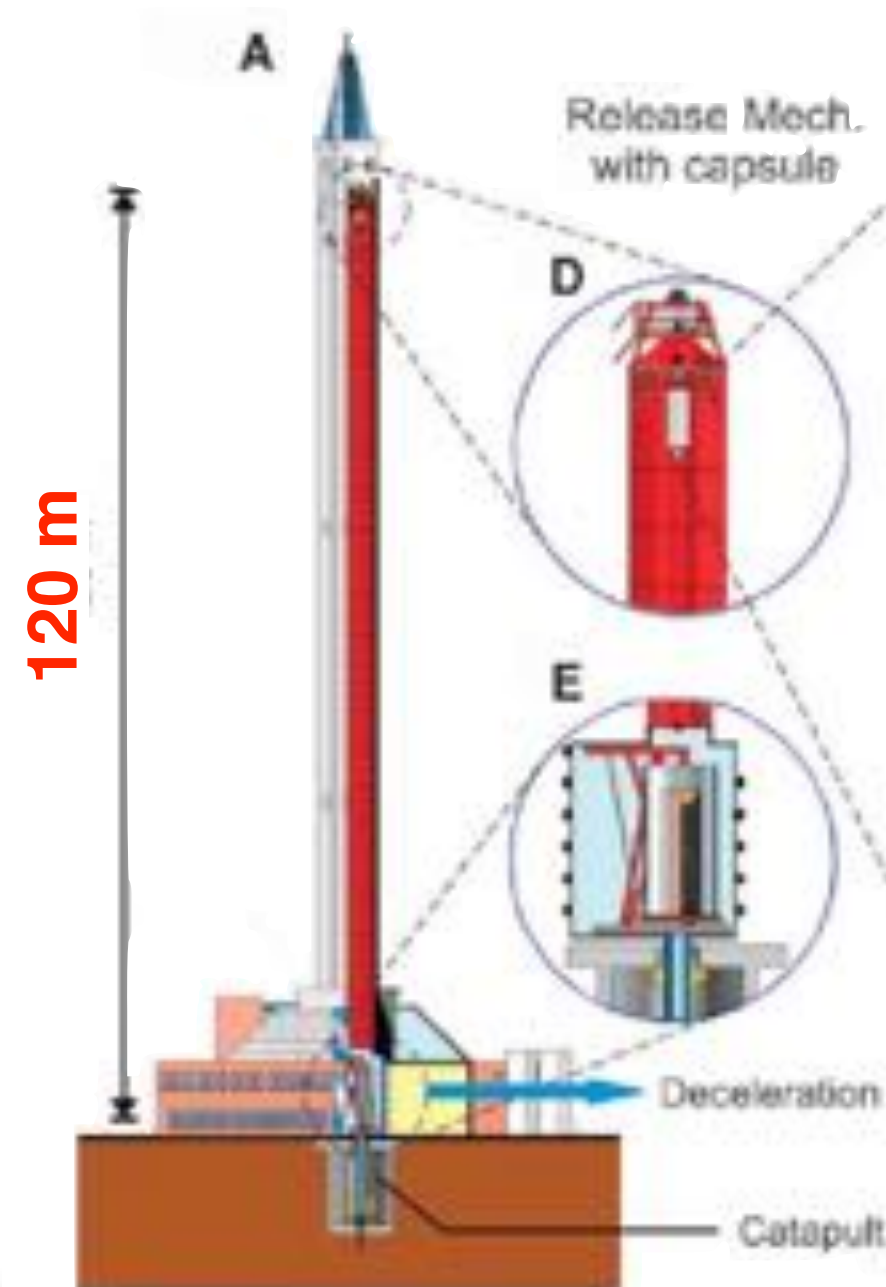
 t^2

Matter-Wave Interferometers



Stanford,
Wuhan,
Hannover

ZARM
drop Tower

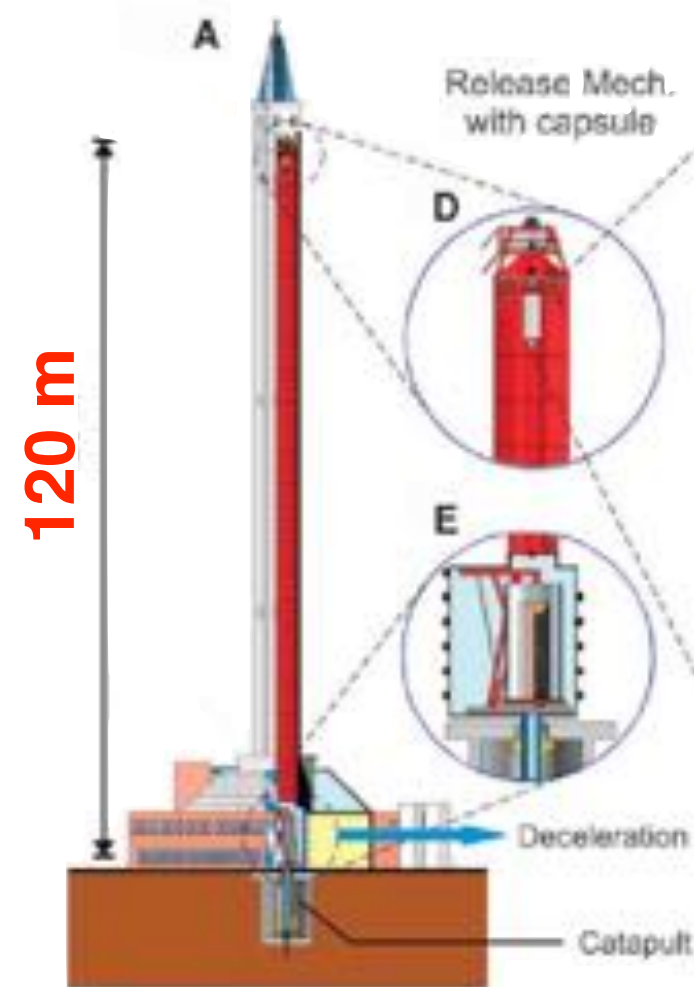
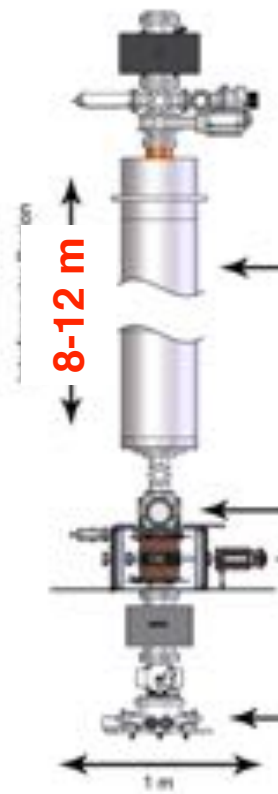


MIGA / ELGAR
10 km



Matter-Wave Interferometers

Free Space



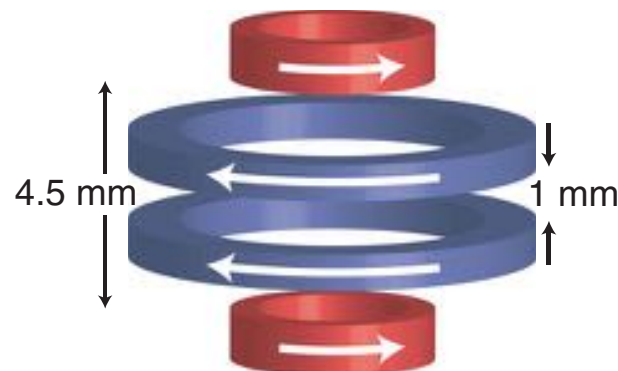
Atomtronics



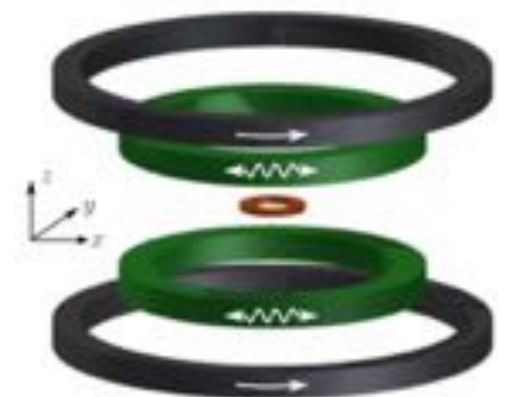
← 2cm →



← 5 μm - 2 cm →

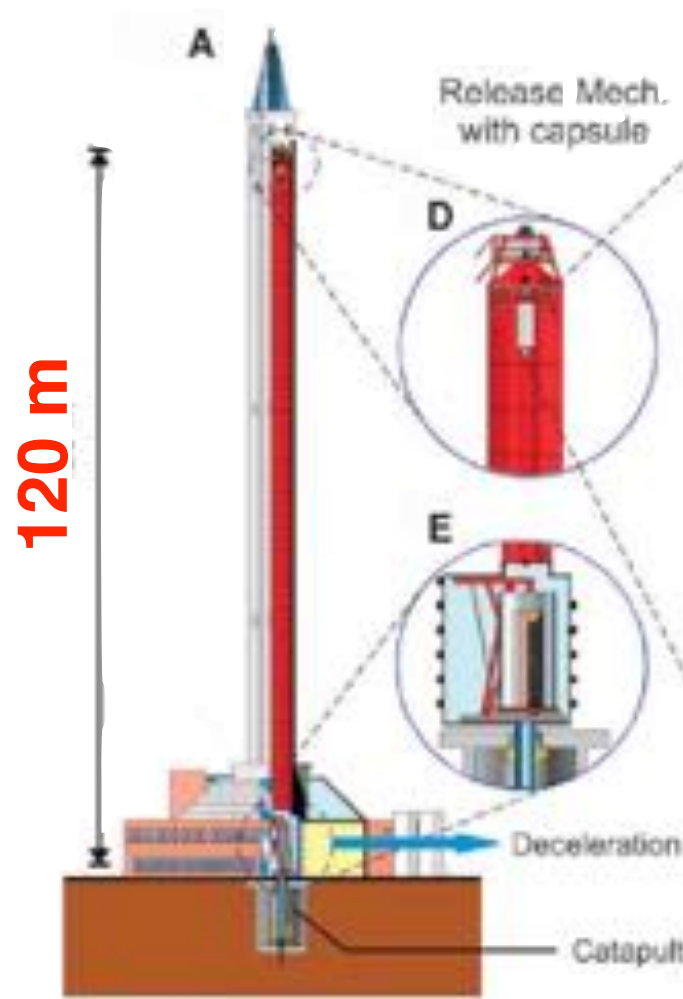
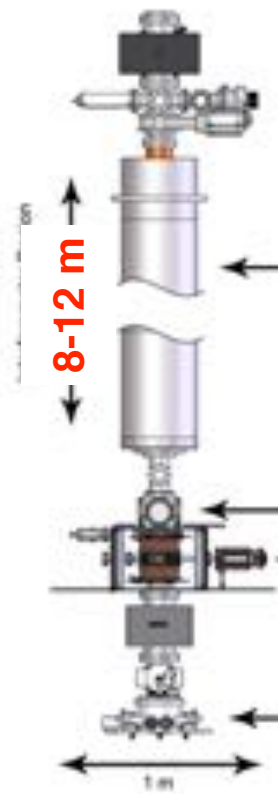


← 1-3 mm →

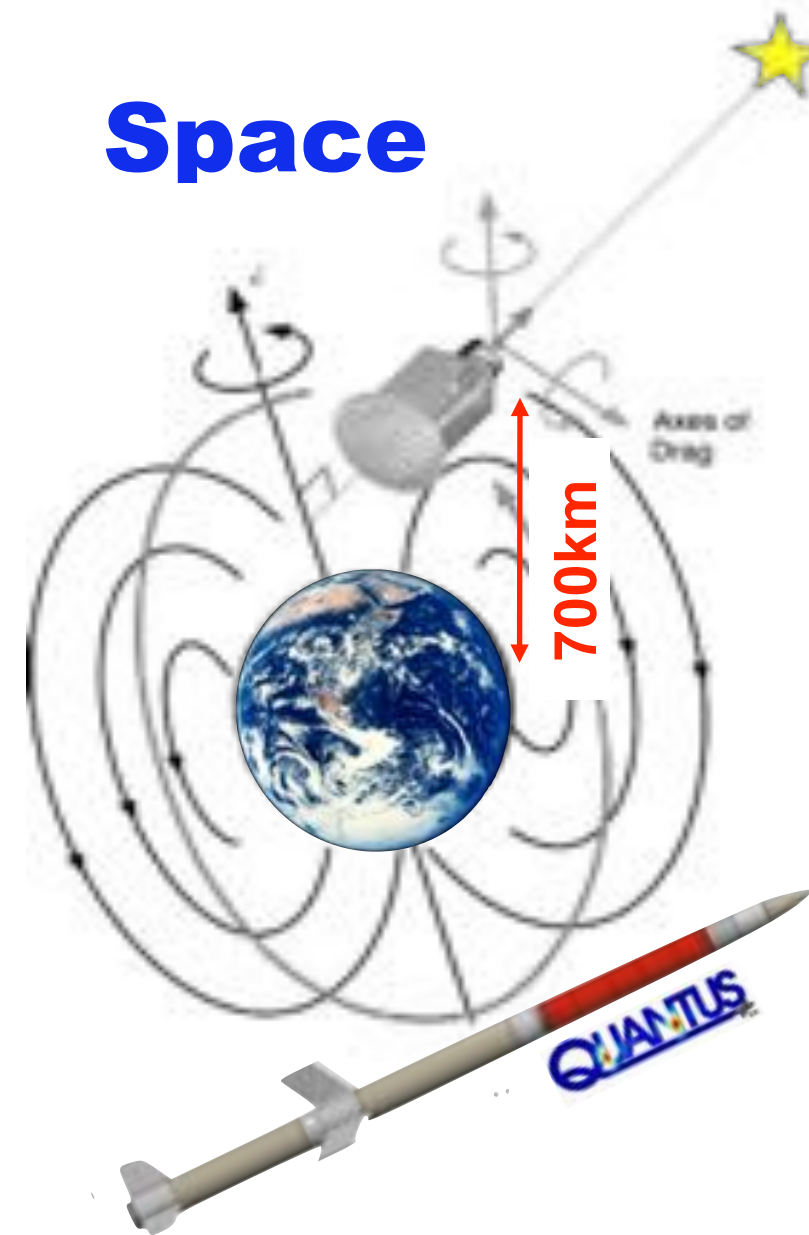


Matter-Wave Interferometers

Free Space



Space



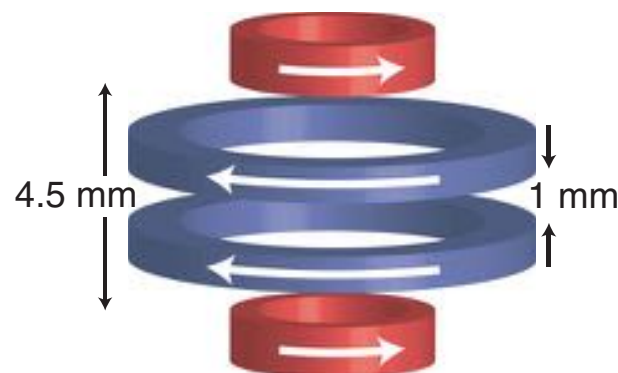
Atomtronics



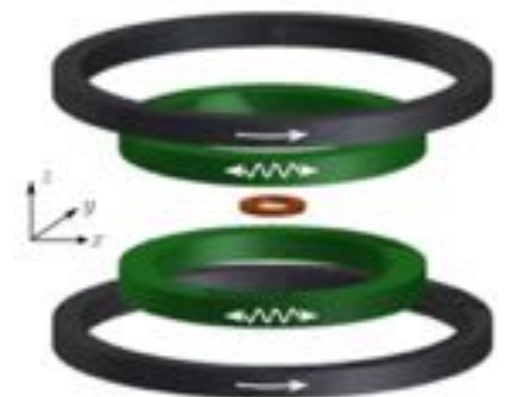
← 2cm →



← 5 μ m - 2 cm →



← 1-3 mm →



Why Atoms ?
Why Space ?

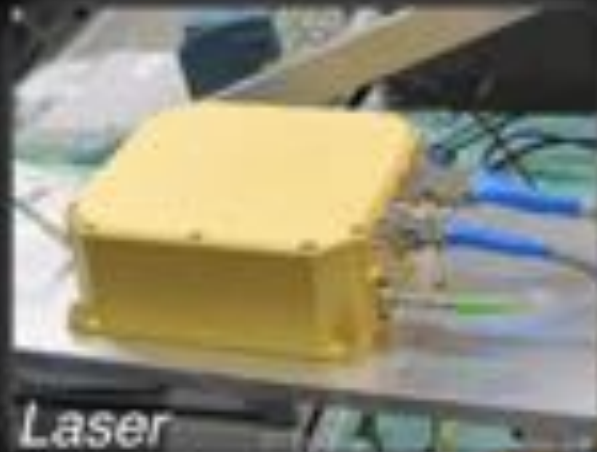
Systematics!
Sensitivity!

Why Not Space ?



Why Not Space ?

- complexity
- time
- money



Laser



Phase-meter



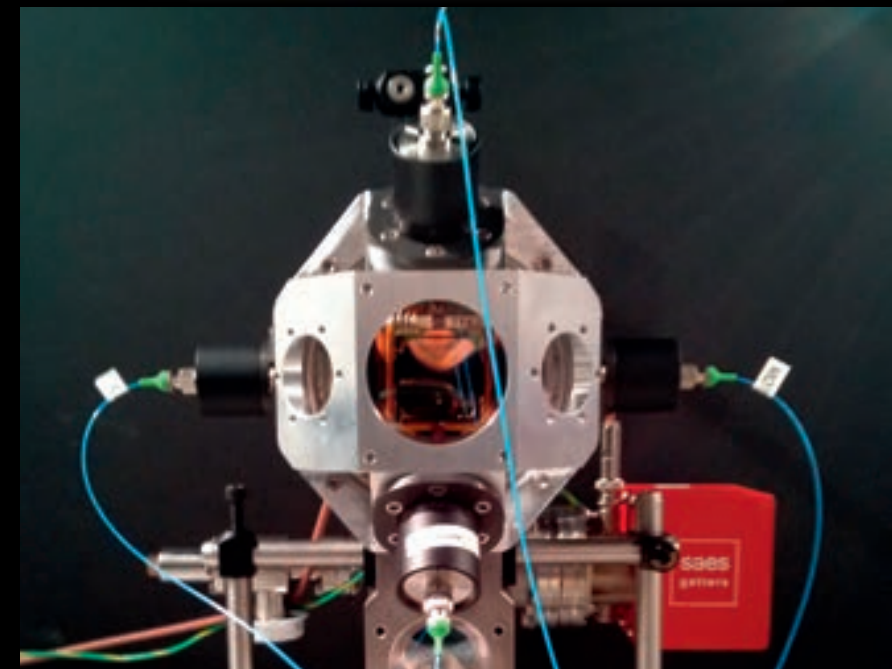
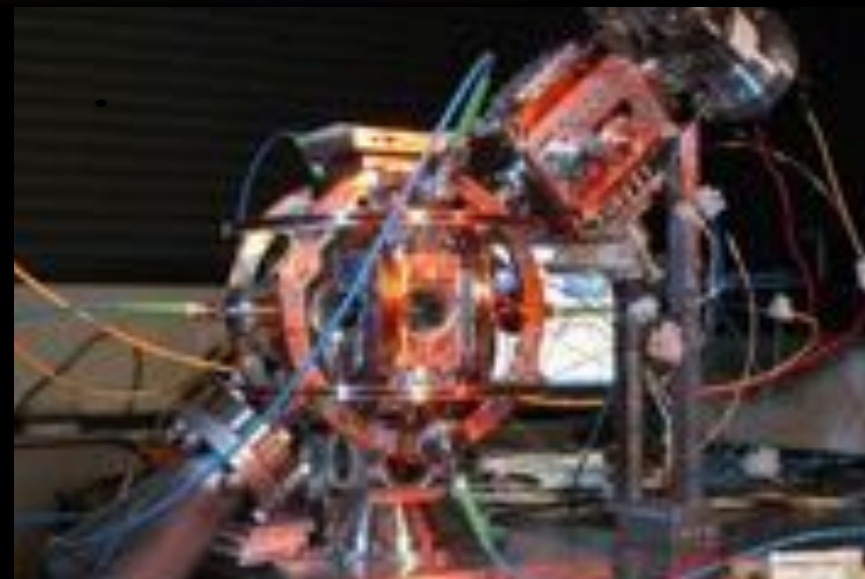
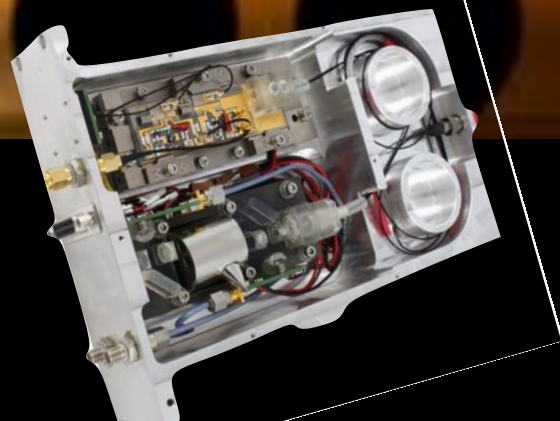
Optical Bench



Modulator



Data Management Unit





Vacuum &
Atom Chips



Laser System



Electronics

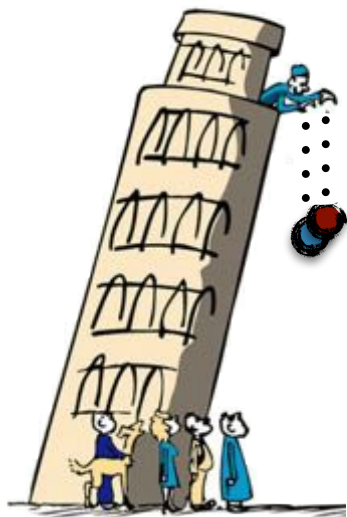


Batteries

Why Atoms ?
Why Space ?

Systematics!
Sensitivity!

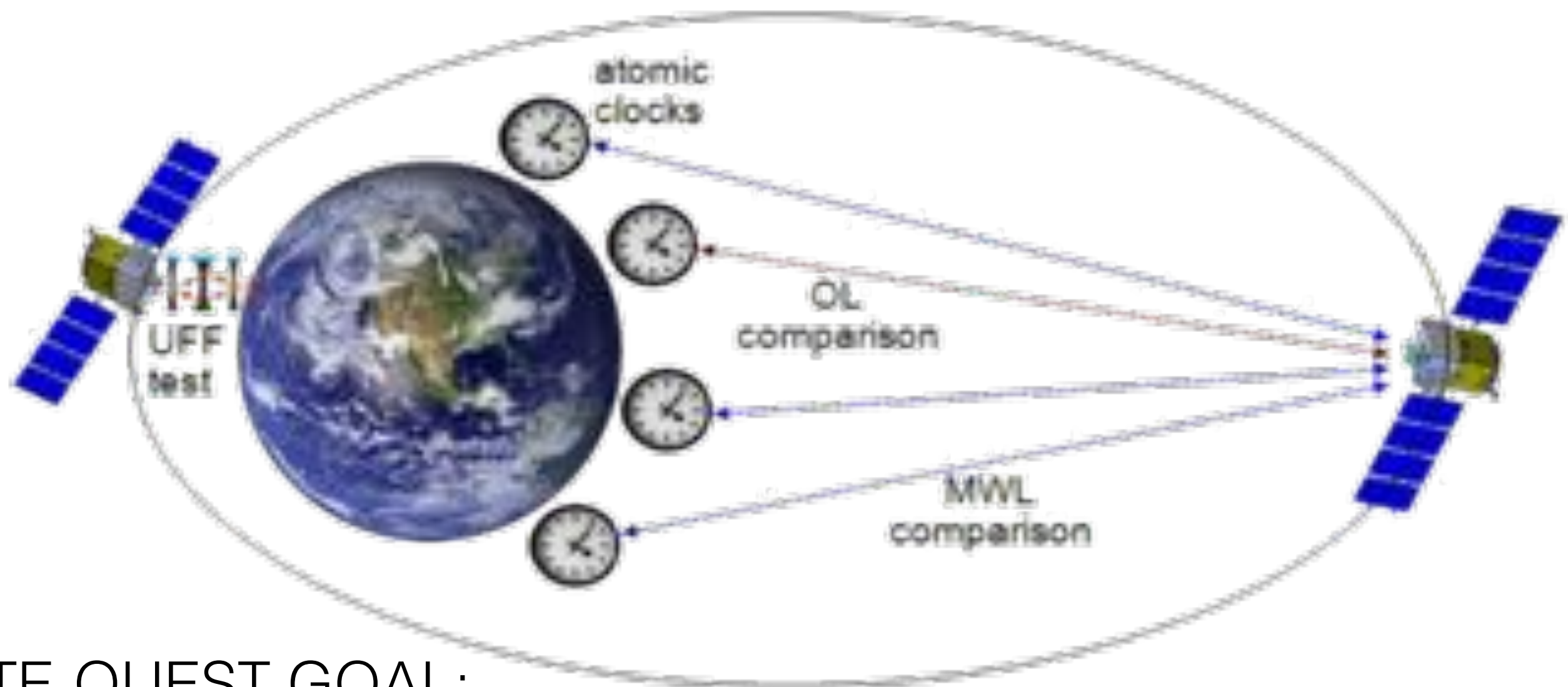
Experiments



- **QUANTUS—MAIUS (1,2)**
- ACES — PHARAO
- **Cold Atom Laboratory (CAL - ISS)**
- Cold Atomic Clock in Space (Cacs)
- BECCAL (ISS — NASA DLR)
- **STE-QUEST**
- QUANTUS (drop tower)
- SAGE

STE-QUEST

^{41}K vs ^{87}Rb



STE-QUEST GOAL:
measure η to 2×10^{-15}

Earth based Measurements of the Eötvös ratio

Class. Quantum Grav. **31** (2014) 115010

D N Aguilera *et al*

Table 1. Existing and planned UFF tests on ground.

Apparatus	Target precision for η	Species	Reference
Torsion balance ^c	$(0.3 \pm 1.8) \times 10^{-13}$	Ti, Be	[24]
Lunar laser ranging ^{b,c}	$(-0.8 \pm 1.8) \times 10^{-13}$	Moon, Earth	[25]
AI/FG5	$(7 \pm 7) \times 10^{-9}$	Cs, Glass	[26]
Dual AI (Garching)	$(1.2 \pm 1.7) \times 10^{-7}$	⁸⁵ Rb, ⁸⁷ Rb	[27]
Dual AI (ONERA)	$(1.2 \pm 3.2) \times 10^{-7}$	⁸⁵ Rb, ⁸⁷ Rb	[28]
Dual AI (Firenze)	7×10^{-7}	⁸⁷ Sr, ⁸⁸ Sr	[29]
Dual AI ^a (Hanover)	10^{-9}	⁸⁷ Rb, K	[30]
Dual AI ^a (Berkeley)	10^{-14}	⁶ Li, ⁷ Li	[31]
Dual AI tower initial/upgrade ^a (Stanford)	$10^{-15}/10^{-16}$	⁸⁵ Rb, ⁸⁷ Rb	[32]

^a Work in progress.

^b LLR references the differential acceleration between Moon and Earth to the gravitational field of the Sun. All other tests in this table are referenced to the gravitational field of Earth.

^c Macroscopic test masses.

Earth based Measurements of the Eötvös ratio

Table 2. Planned and proposed UFF tests in space and zero-g environments. All tests in this table are referenced to the gravitational field of Earth.

Apparatus	Target precision for η	Species	Reference
SAI ground based/in zero-g	$[10^{-7}/1.8 \times 10^{-10}]^b$	^{87}Rb	[33]
ICE	10^{-11}	^{87}Rb , K	[34]
QUANTUS	6.3×10^{-11}	^{87}Rb , K	[35]
MICROSCOPE ^a	10^{-15}	Pt, Ti	[36]
STEP ^a	10^{-18}	Pt, Ir, Nb, Be	[37]
GG ^a	10^{-17}	^c	[38]

^a Macroscopic test masses.

^b Single species experiment, sensitivity given in $\text{m s}^{-2} \text{ Hz}^{-1/2}$.

^c Not yet decided.

STE-QUEST 2×10^{-15}

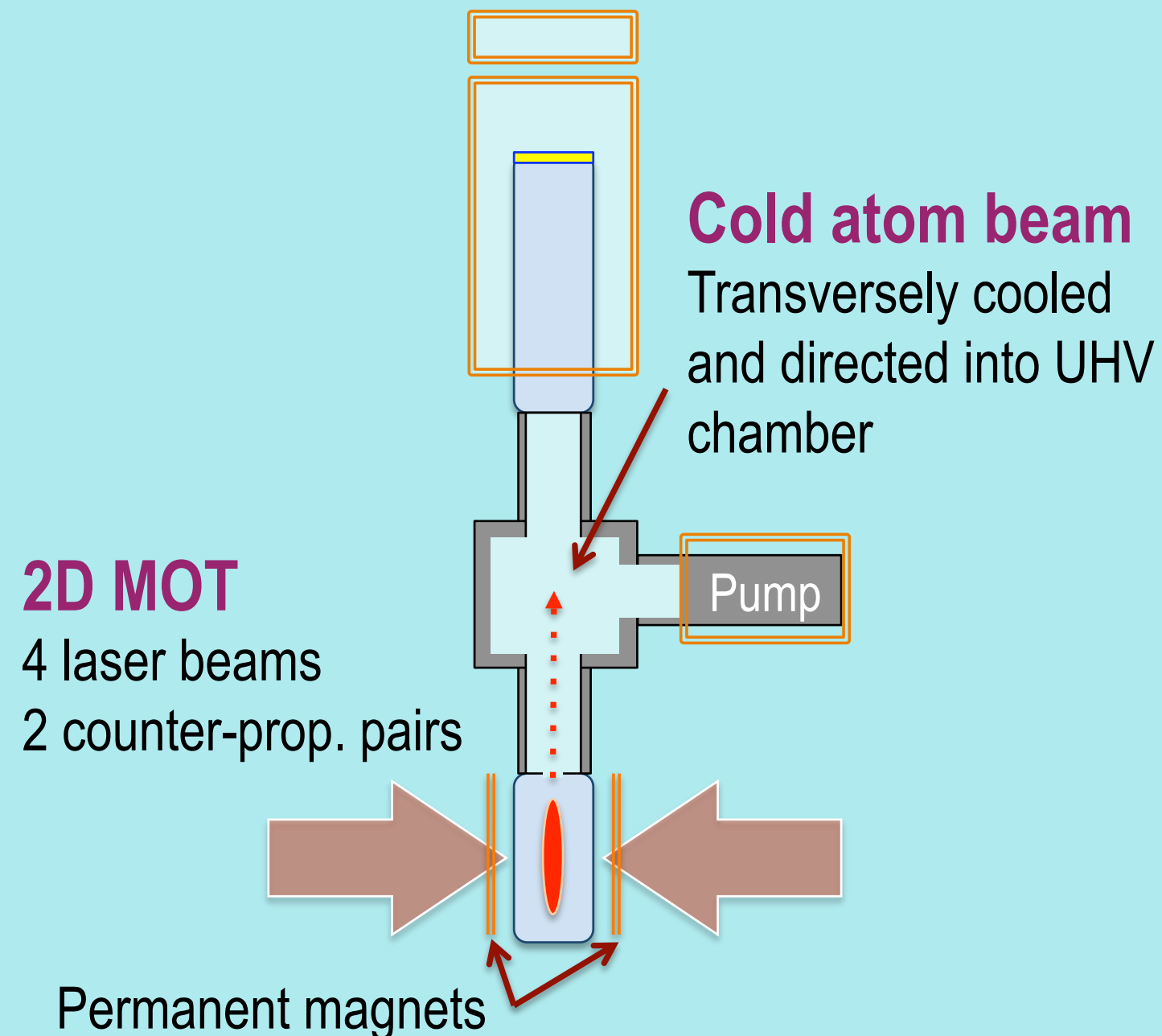
Cold Atom Laboratory (CAL) on the ISS





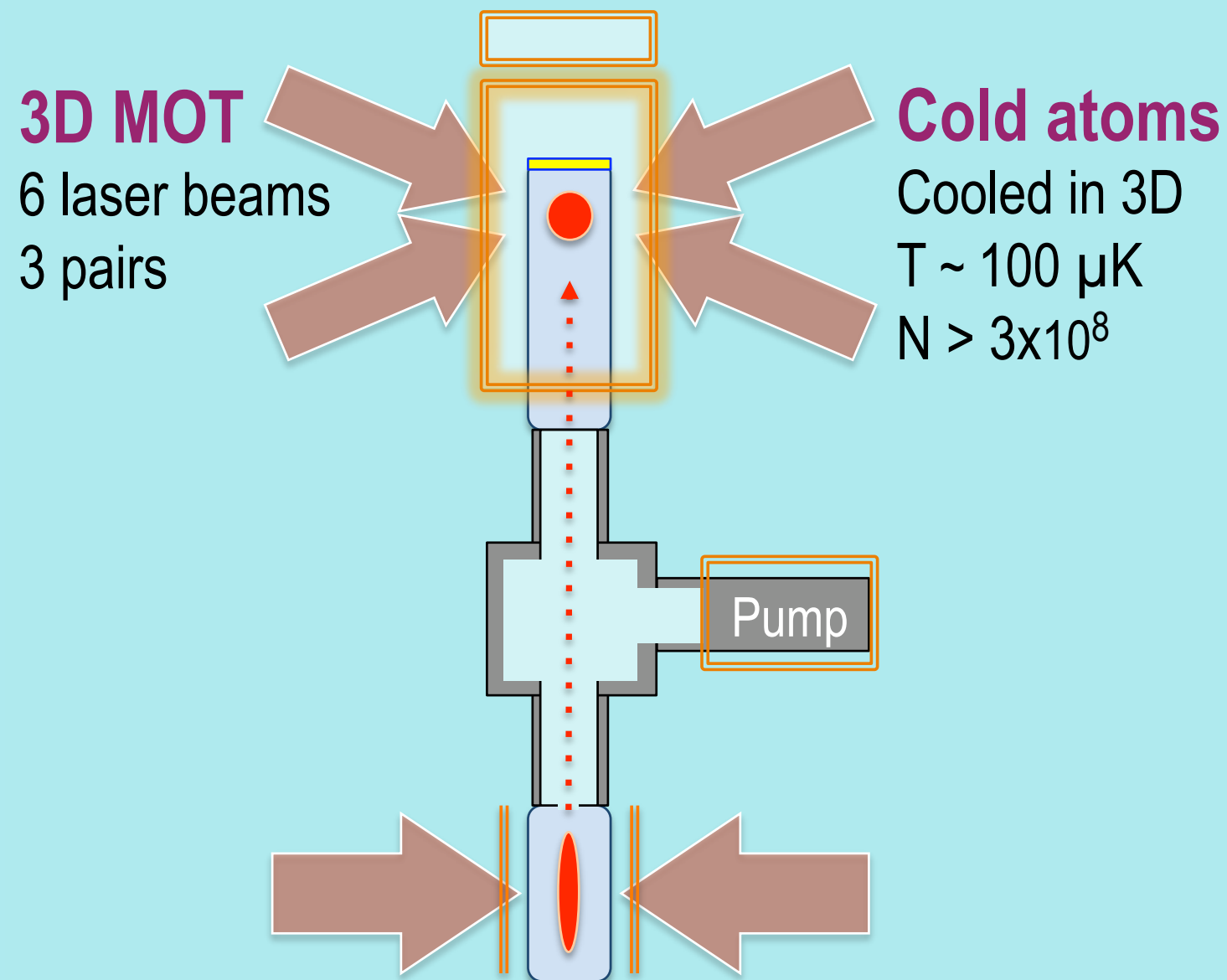
Cold Atom Laboratory (CAL) on the ISS

Atom Cooling Stages: 2D MOT Source



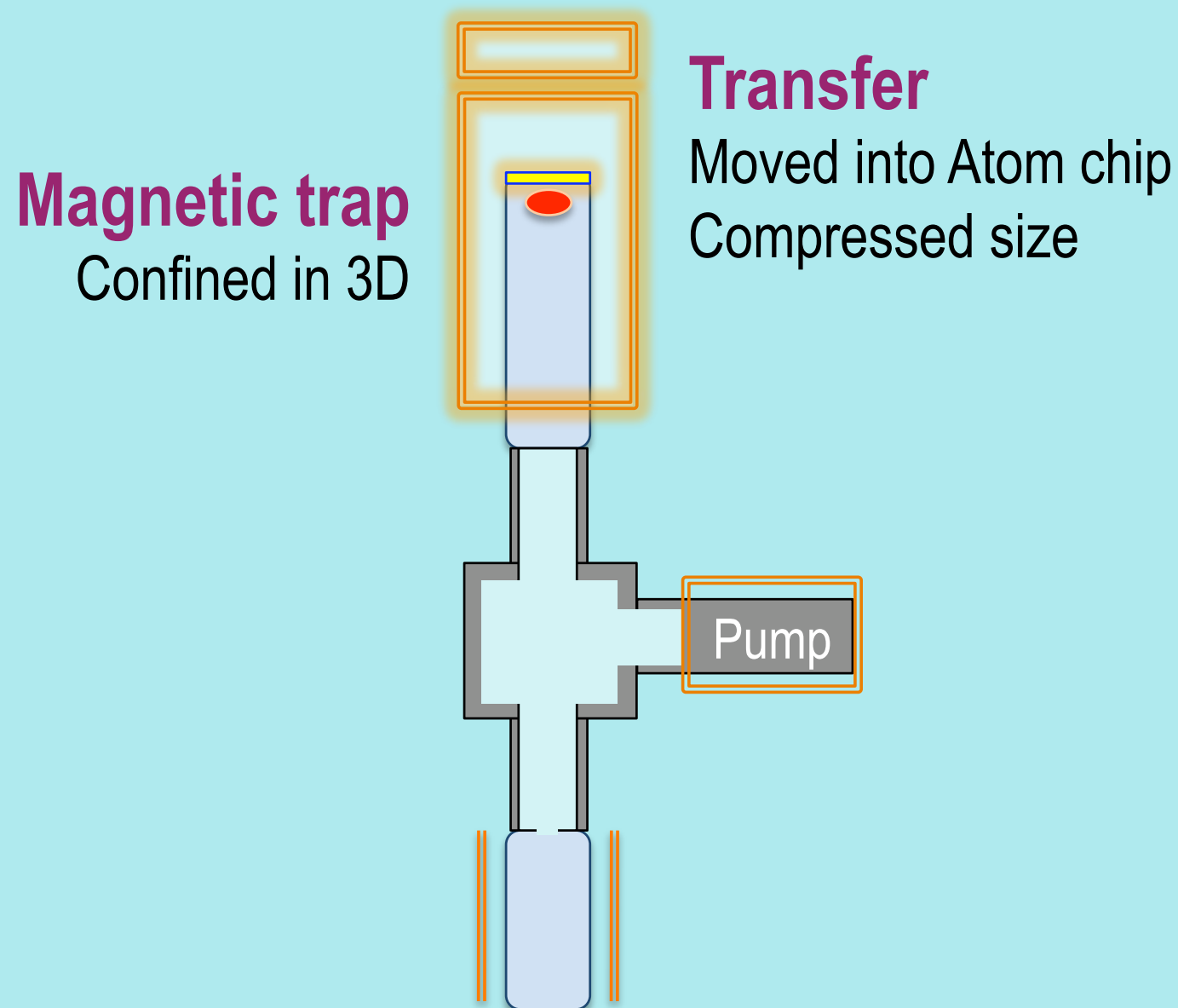
Cold Atom Laboratory (CAL) on the ISS

Collect 3D MOT



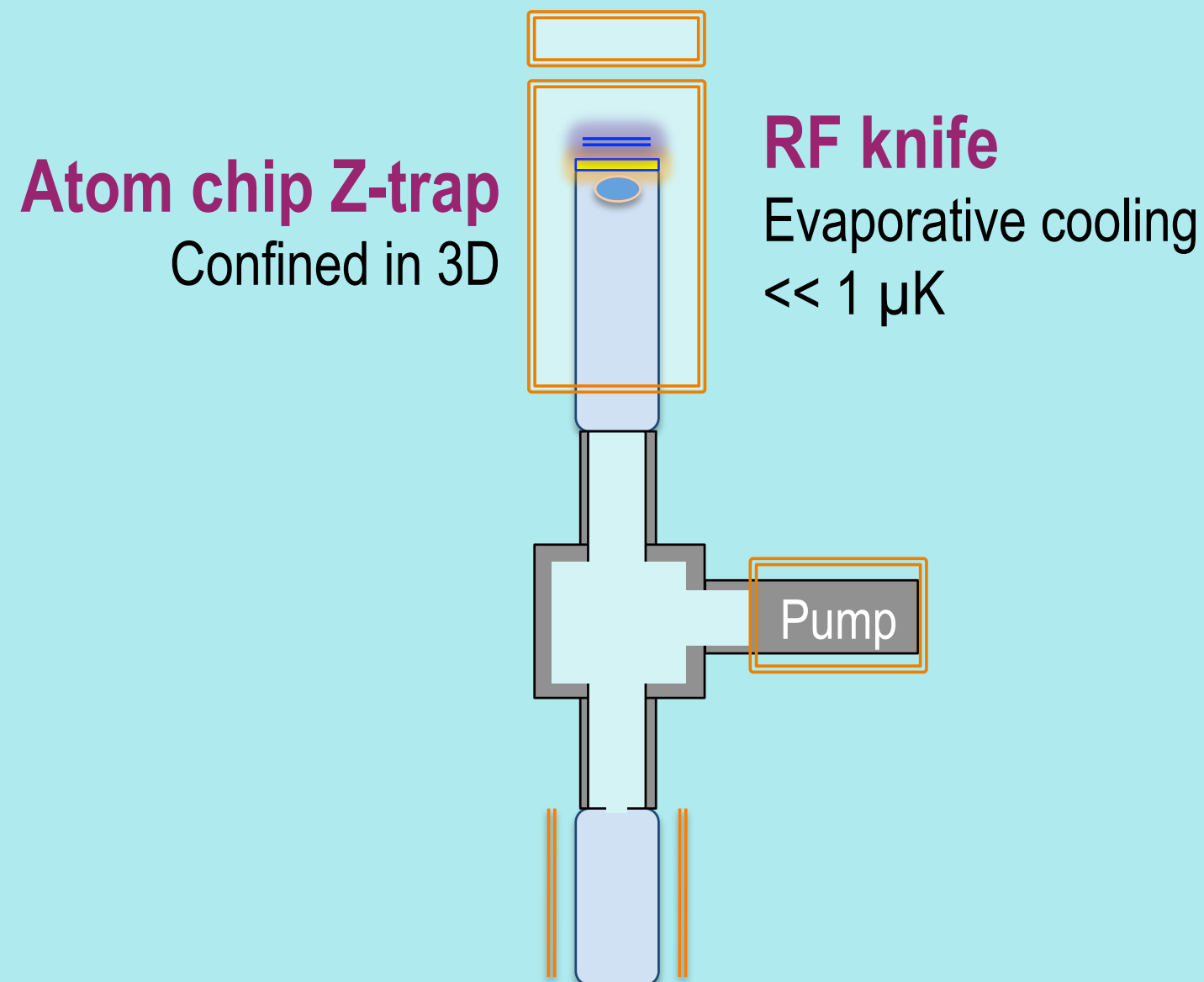
Cold Atom Laboratory (CAL) on the ISS

Transfer to Magnetic Trap



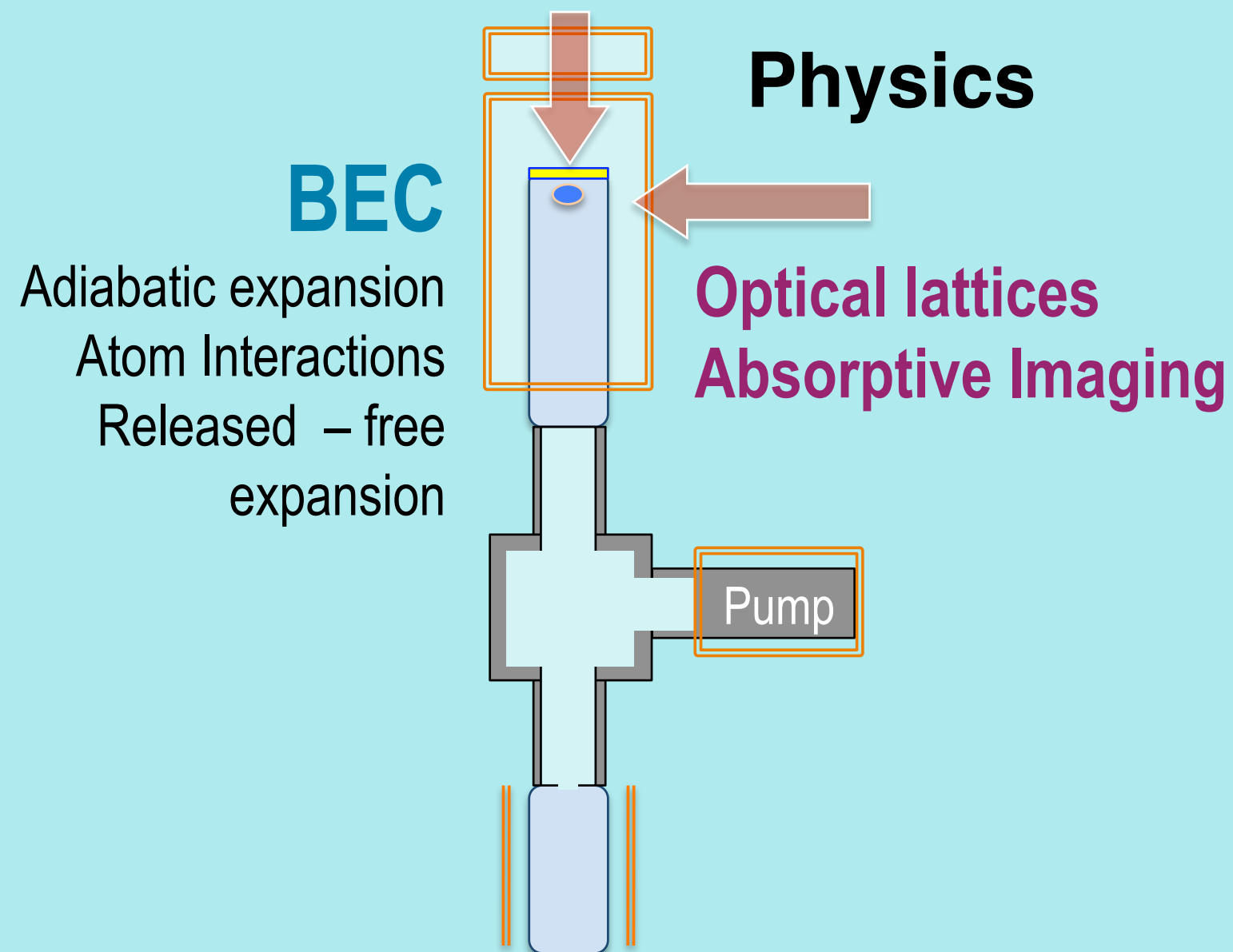
Cold Atom Laboratory (CAL) on the ISS

Evaporative Cooling



Cold Atom Laboratory (CAL) on the ISS

Condensate Formation





QUANTUS / MAIUS Cooperation

Atomic Quantum
Sensors



Atom-Chip



Robust & Compact Laser
Fermionic Source



Theory

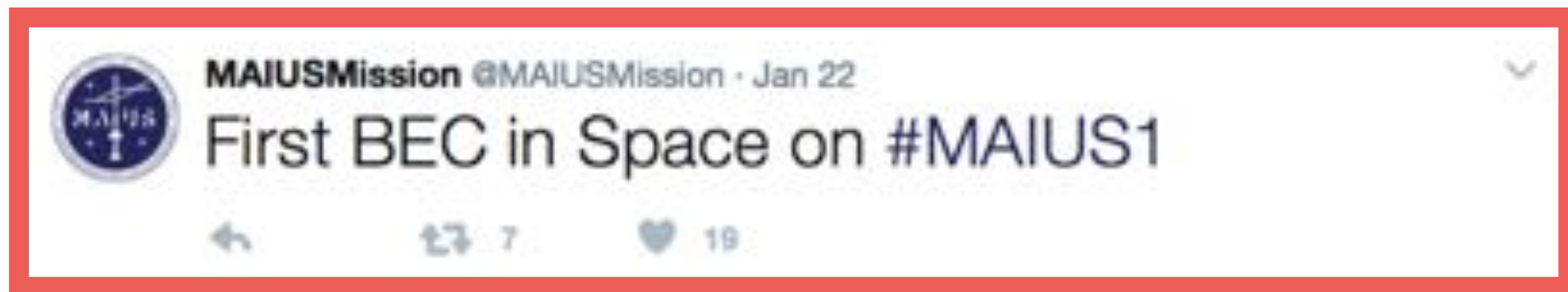


Drop Tower & Space
Integration



The Quantum-Space Age

03:31:47 23.Jan 2017
(on Twitter)



Conclusions

- Fundamental Physics needs Atoms and Space, but...
- Big steps have been taken recently