Testing Lorentz Invariance with Laser-Cooled Cesium Atomic Frequency Standards

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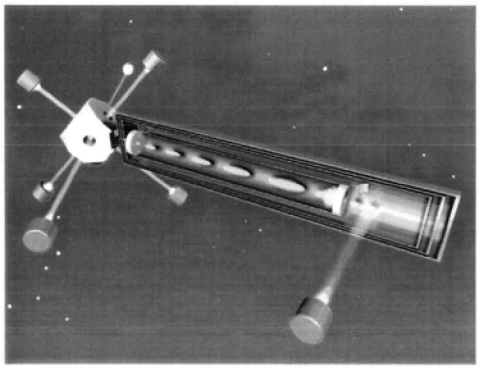
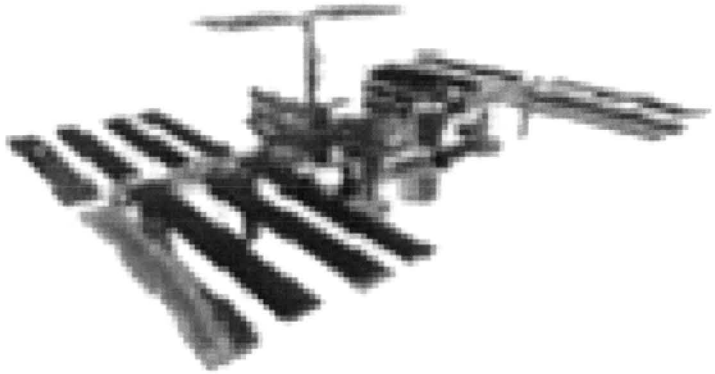
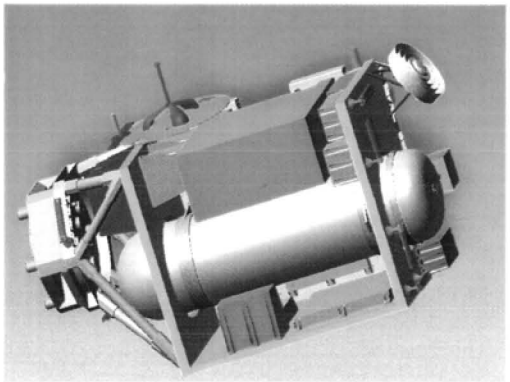


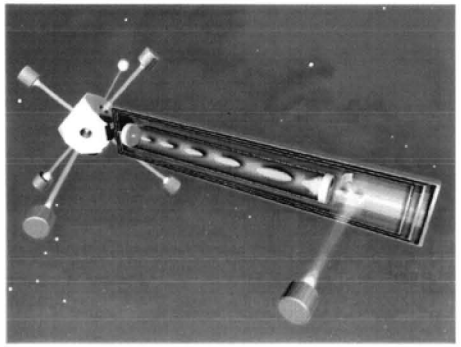




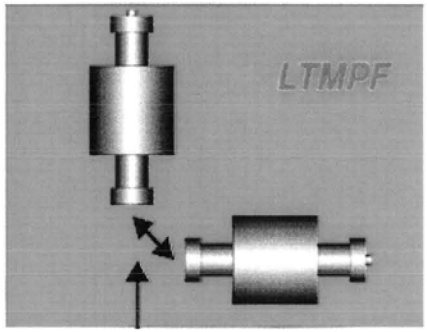
The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Fundamental Physics in Microgravity

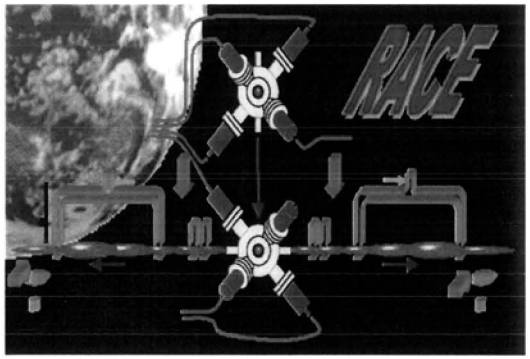
To be, or not to be….



PARCS
PI Don Sullivan
NIST



SUMO
PI John Lipa
Stanford



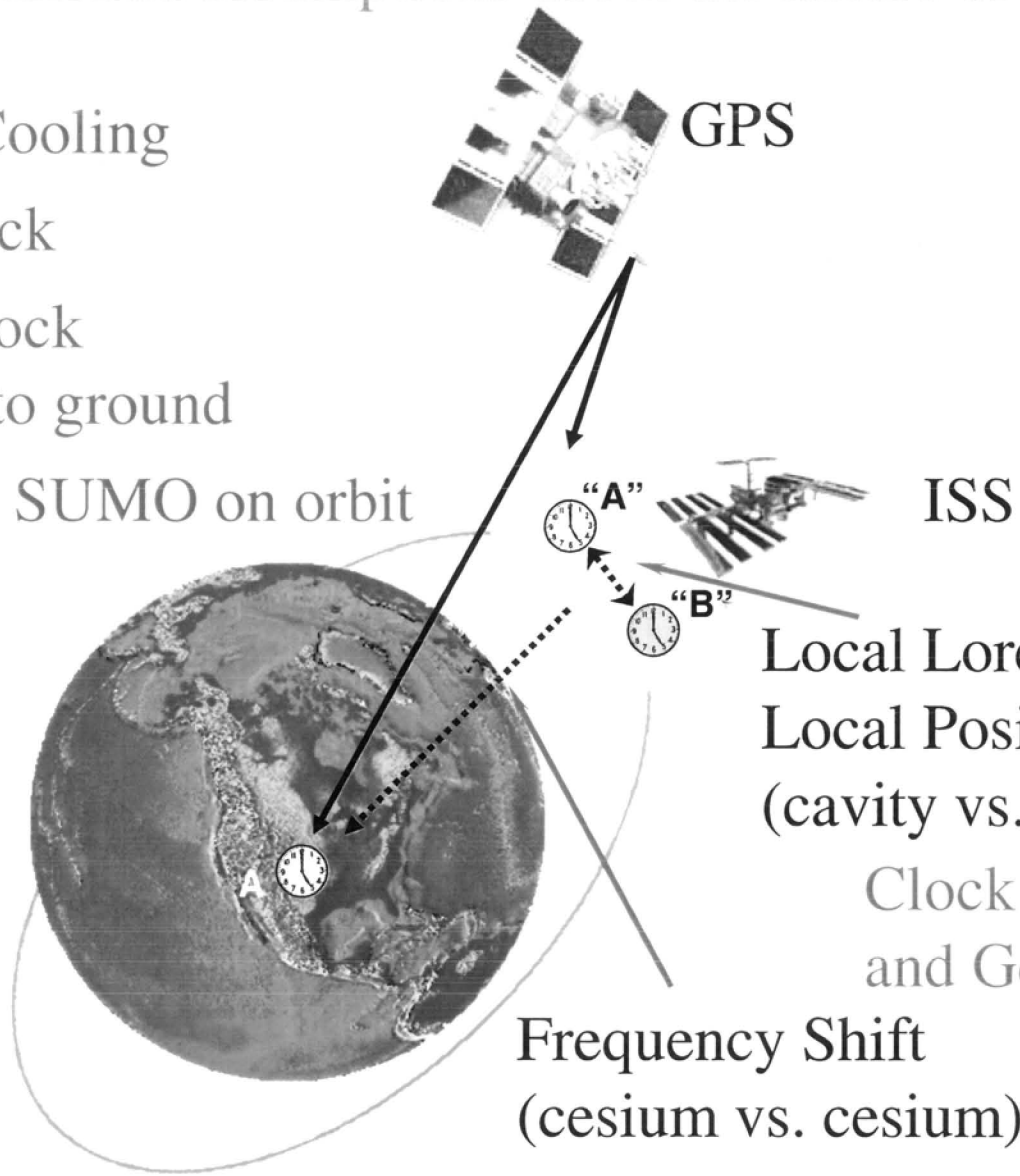
RACE
PI Kurt Gibble
Penn. State

Shuttle accident + Exploration Vision = Outrageous Fortune

PARCS Science Goals

Testing fundamental assumptions about the nature of space and time

1. Do Laser Cooling
2. Make a clock
3. Transfer clock performance to ground
4. compare to SUMO on orbit



Courtesy of The Archives, California Institute of Technology

Local Lorentz Invariance,
Local Position Invariance
(cavity vs. cesium)

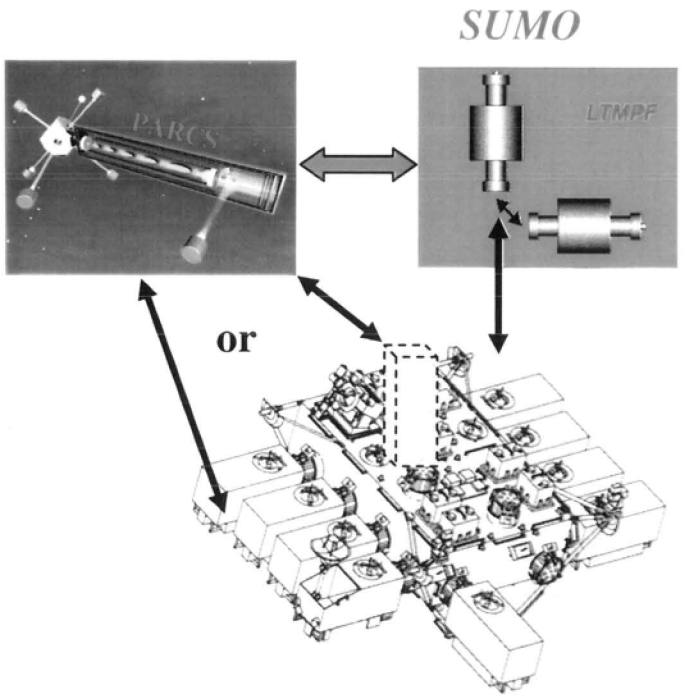
Clock tests of Special and General Relativity

Frequency Shift
(cesium vs. cesium)

Cesium to SUMO comparison

Requirements (from JPL D-19986, D-26697 and D-TBD link specification)

- Most Make a Frequency Standard Requirements (stability only, not accuracy) plus
- Link to SUMO: responsibility of LTMPF (John Dick, JPL)
  - Direct fiber connection
  - Free space optical
  - HRDL (JEM fiber)
  - Radiofrequency
- Phase lock for on-board USO
- Orbit info (coarse)



View of JEM-EF from top side (RAM direction is toward the left)

(Star crossed lovers. Oops, wrong play.)

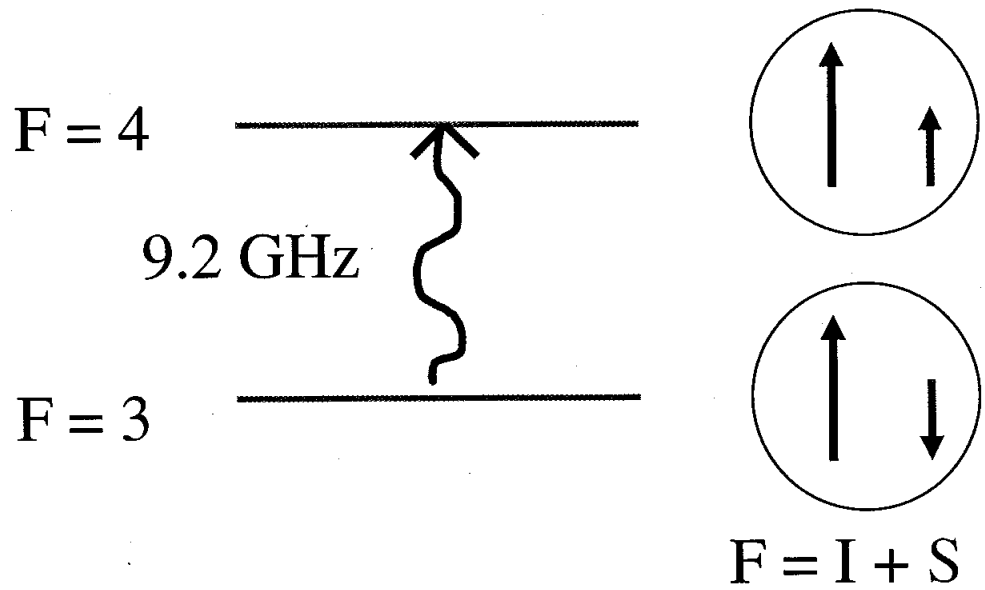
PARCS Science Goals from SRD

Performance Metric	Science Observable	Program Objective	Success Criterion	Success Weight
Laser-Cooling Pathfinder	Atom drift time	10 s	2 s	20 %
Most Accurate Space Clock	Realization of the Second, $\Delta f/f_{Cs}$	1×10^{-16}	3×10^{-15}	30 %
Frequency Difference between Orbiting and Ground Cesium Clocks	Net Frequency Shift, $\Delta f/f_{Rel}$	1.7×10^{-6}	1×10^{-5}	15 %
	Gravitational Freq. Shift, $\Delta f/f_{Grav}$	1.2×10^{-5}	7.2×10^{-5}	15 %
Cesium vs. SUMO Frequency Comparison*	Local Position Invariance, C_{AB}	4.4×10^{-5}	3×10^{-3}	5 %
	Local Lorentz Invariance, Kennedy -Thorndike Experiment, $\beta - \alpha - 1$	9×10^{-10}	9×10^{-8}	15%

*-(SUMO numbers replace H-maser comparison)

"Does anybody really know what time it is?..

The second is defined to be "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium atoms."



"atomic" time is:

universal (all cesium atoms are alike)

accurate (1 second every 30 million years)

"…Does anybody care?"

Global Positioning System (GPS)
Deep space navigation

navigation

Second
Volt
Meter
(mass)

standards

High performance frequency and time metrology

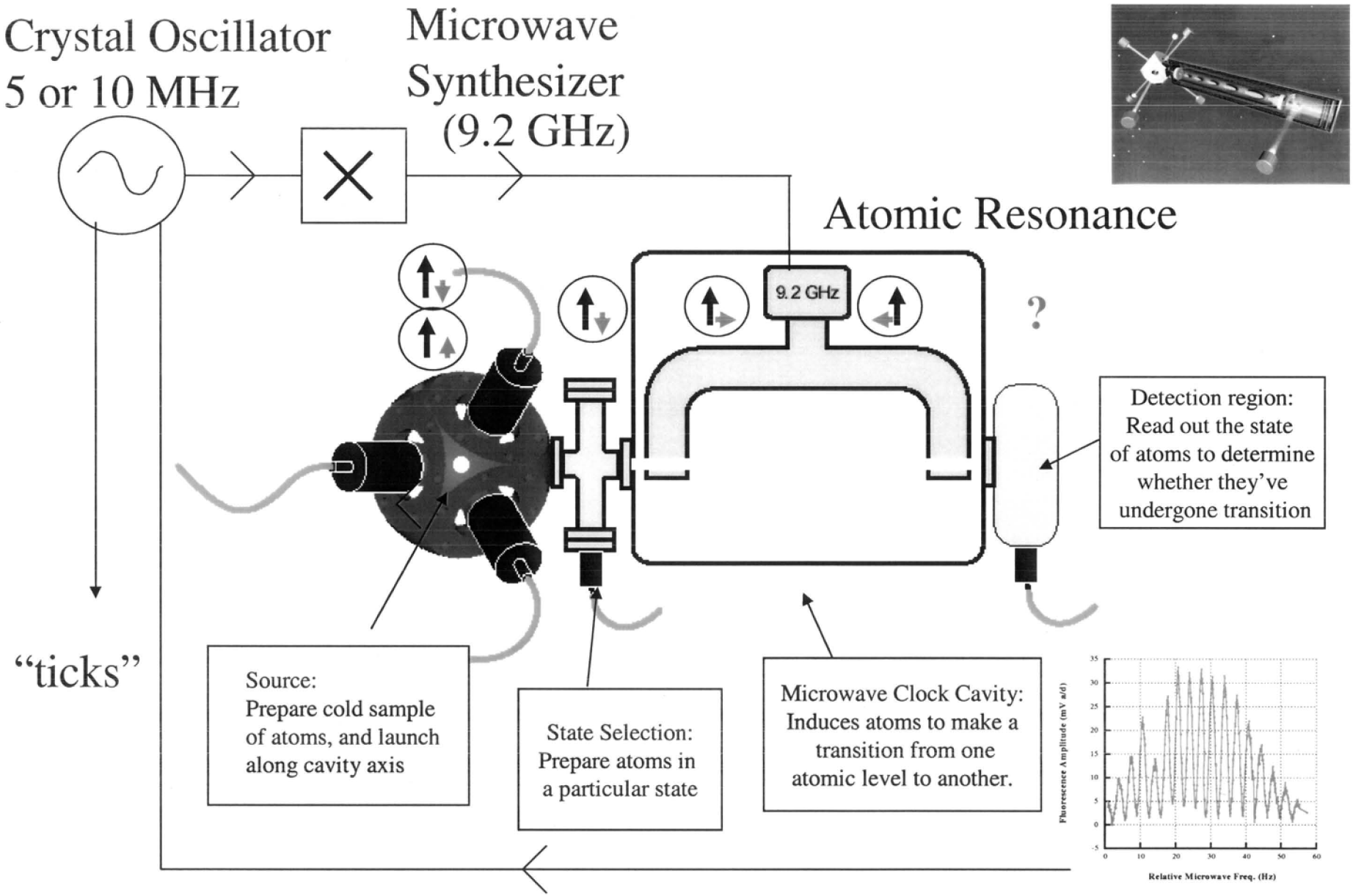
synchronization

Communication
Secure communications
Power grids
Stock market

Precision measurements

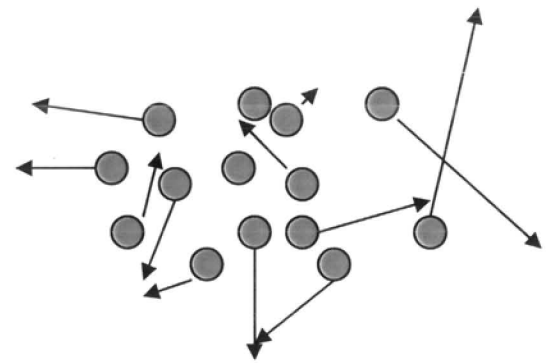
General relativity
Film thickness
Pressure

What is an atomic clock?



What is temperature?

The temperature of a gas of atoms is a measure of the spread of velocities

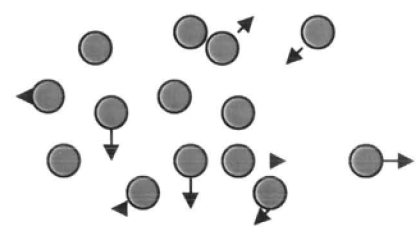


(at room temperature v ~ 200 m/s)

How cold does laser cooling get?

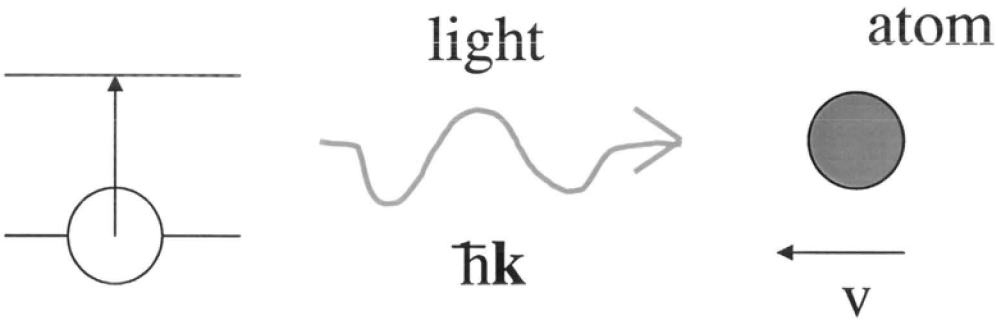
Laser cooled (cesium) atoms are cooled to 1 microKelvin

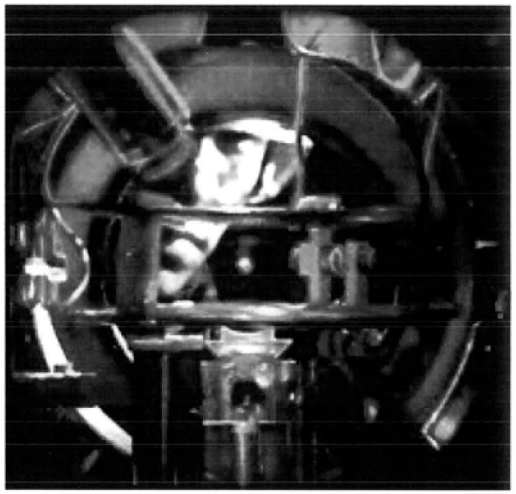
(v ~ 1 cm/s)



Laser Cooling Simplified

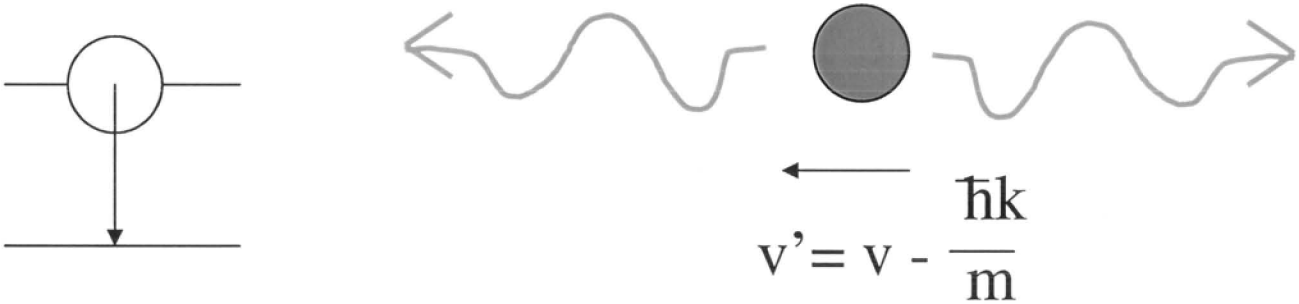
Atom absorbs the energy and momentum of a photon in excitation process:





Kris Helmerson at NIST viewing a sample of laser-cooled atoms (~100 million atoms)

Photon re-emitted in random direction during decay process

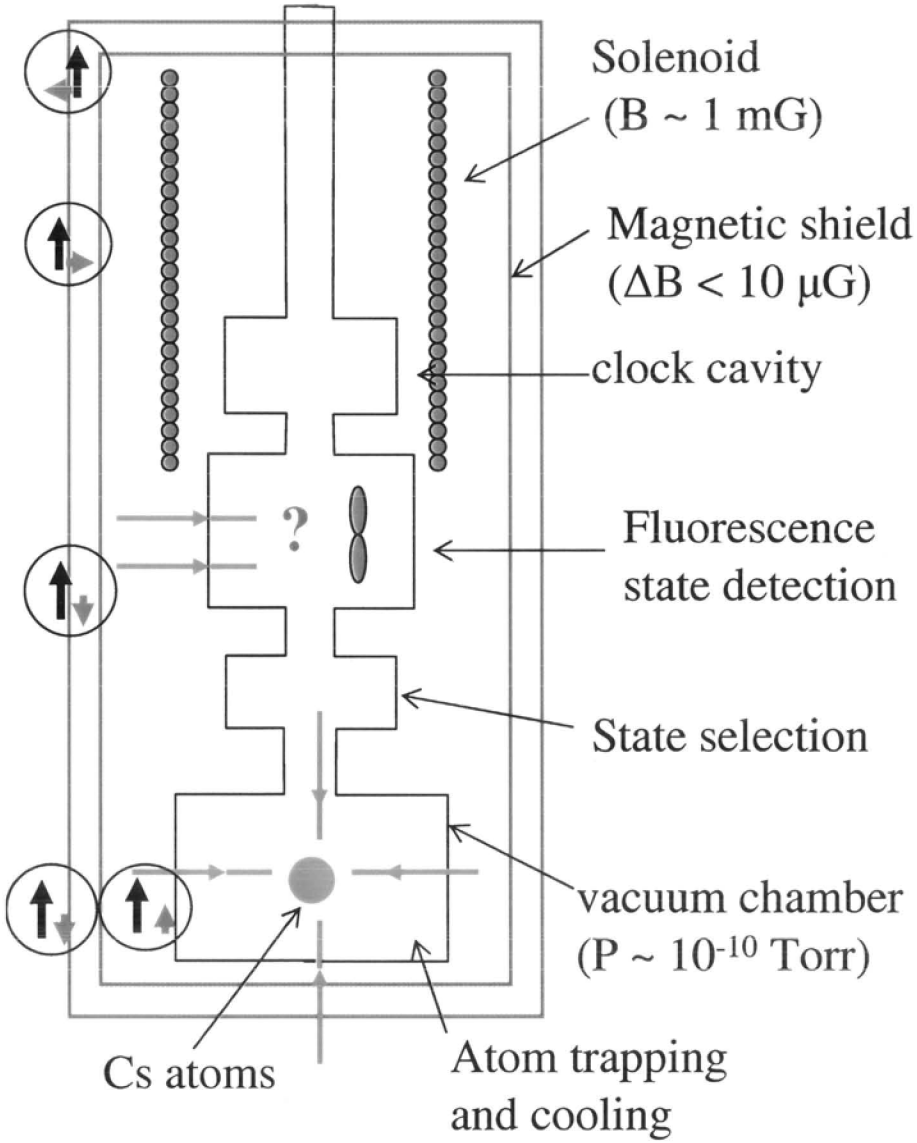


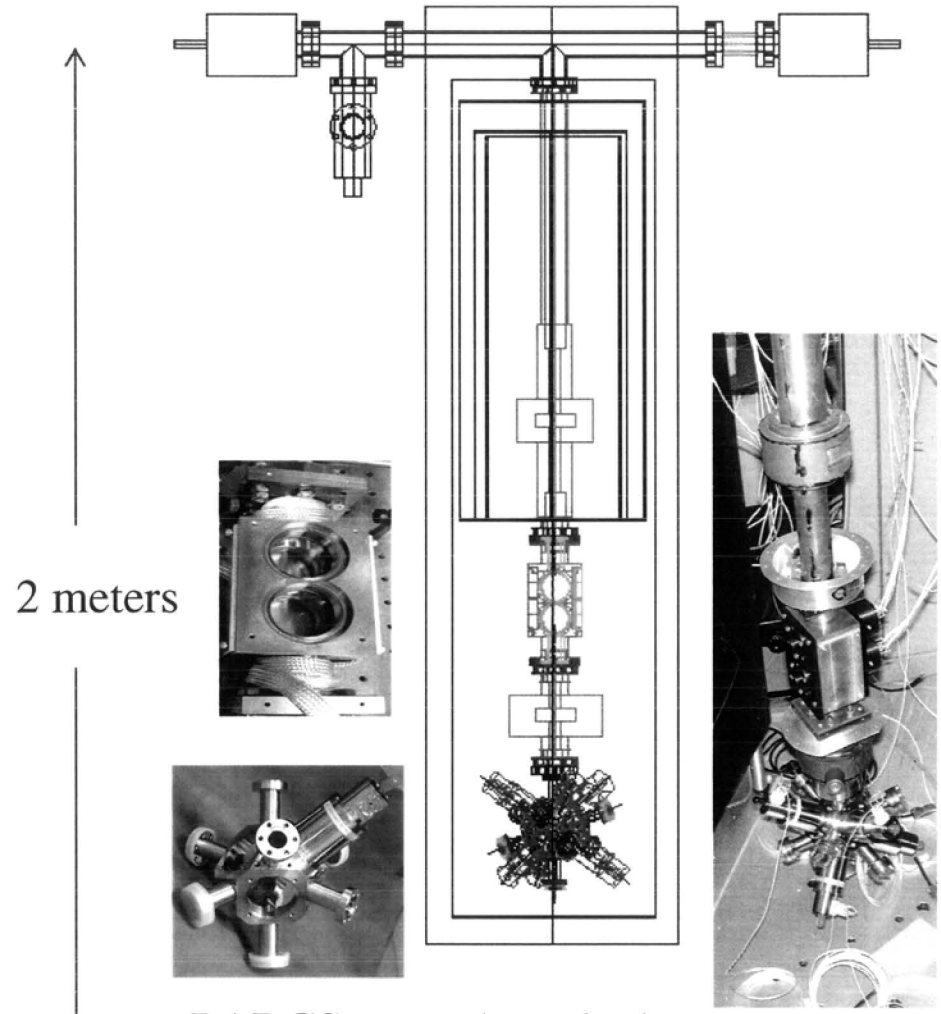
$\Delta v = 3.5$ mm/s

(deceleration ~ 6000 g!)

gravity

Application to Clocks





PARCS ground test bed

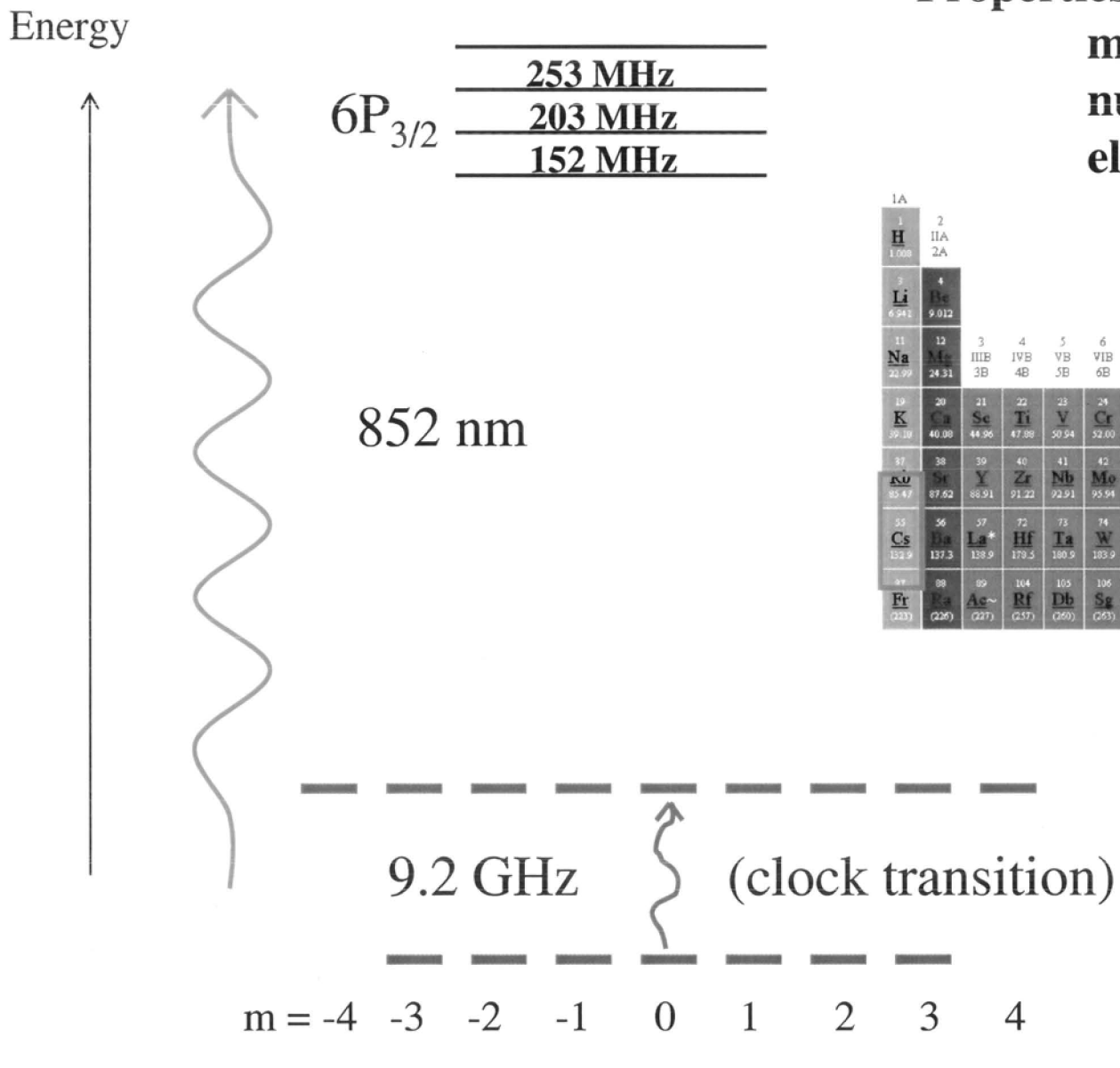
The Cesium Atom:

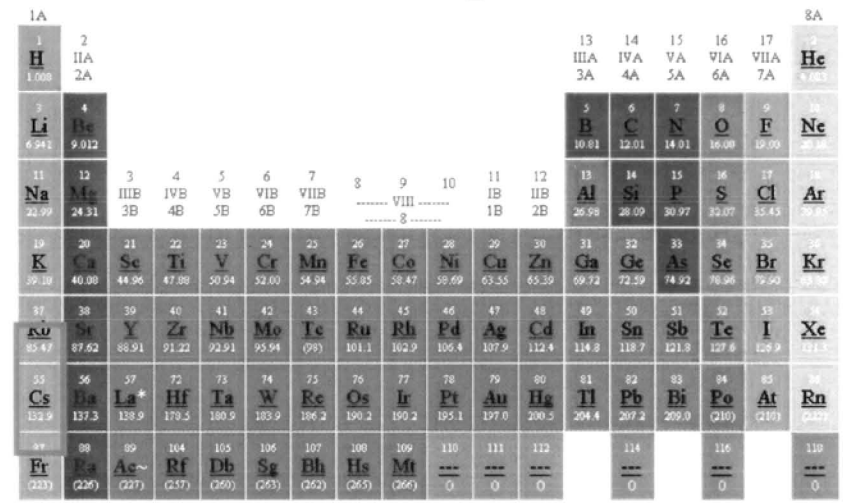
Properties:

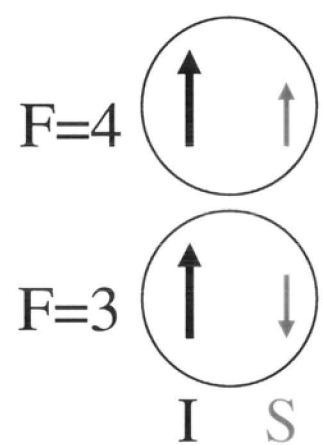
mass

nuclear spin I = 7/2

electron spin S = 1/2





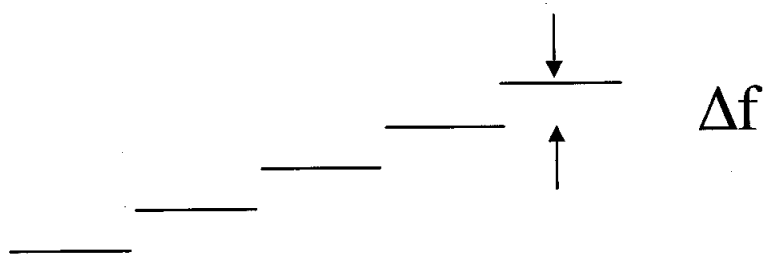


Features of experiments in space

- Pros:
  - High orbital velocity
  - Samples many different orbit projections
  - Short orbital period (90 minutes)
- Cons
  - Magnetic environment
  - Hard and expensive

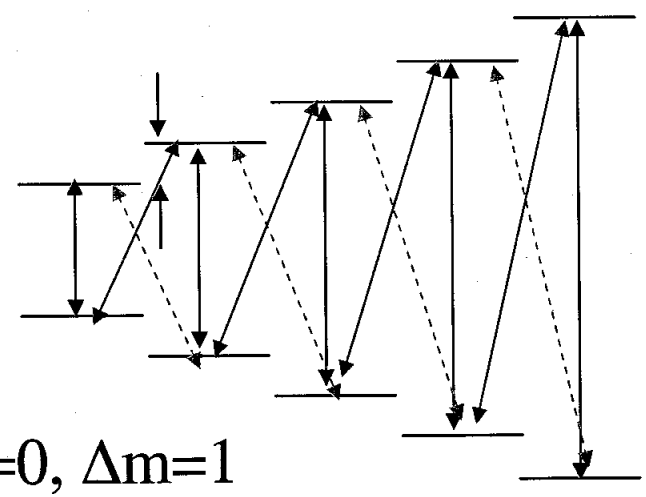
Zeeman vs. Microwave

Zeeman:
Excellent energy resolution, but
1 observable per atom



ΔF=0, Δm=1

Microwave:
Generally better Δf/f, also
many discrete transitions

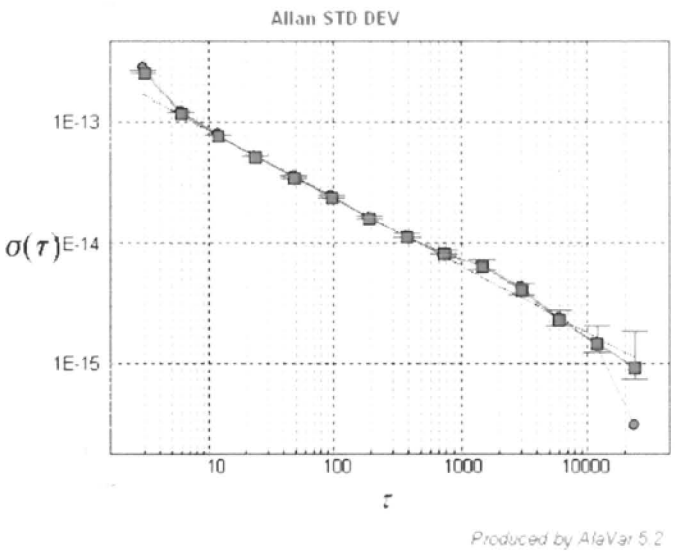


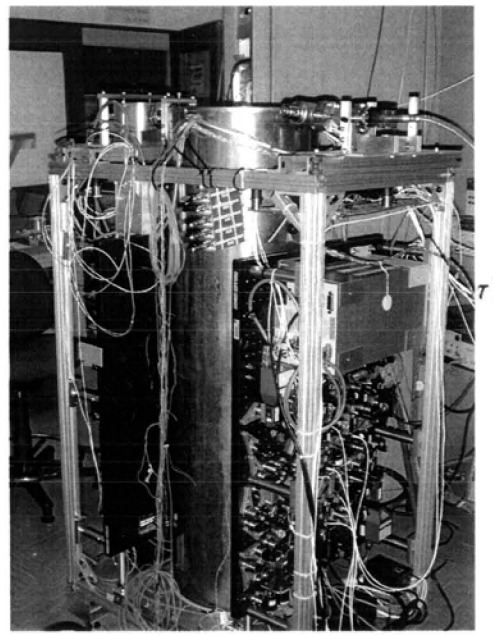
ΔF=0, Δm=1
ΔF=1, Δm=0
ΔF=1, Δm=1

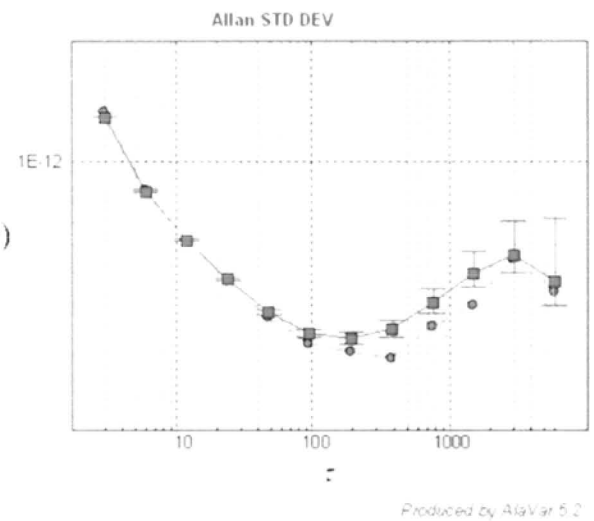
How well can we do?

Clock mode: depends on reference, but < 1 mHz at 1 s

Zeeman mode: limited by noise in magnetic field to ~10 mHz at 1 s





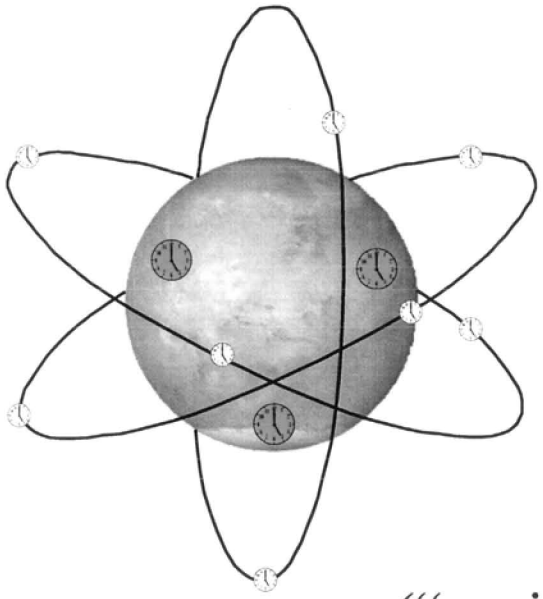


PARCS Ground Fountain

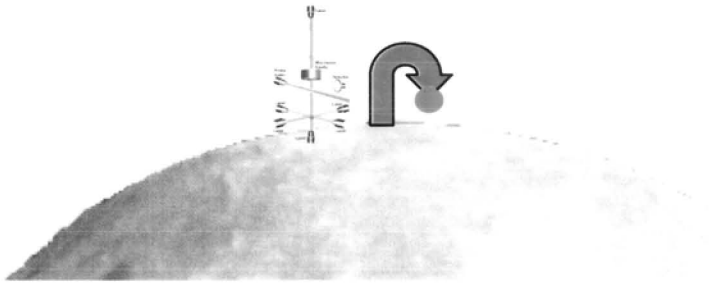
Vision for the Future

Clocks for Exploration/Clocks for Science

GPS around Mars



Fountain on the moon



("accidental" science)

"Perchance to dream"