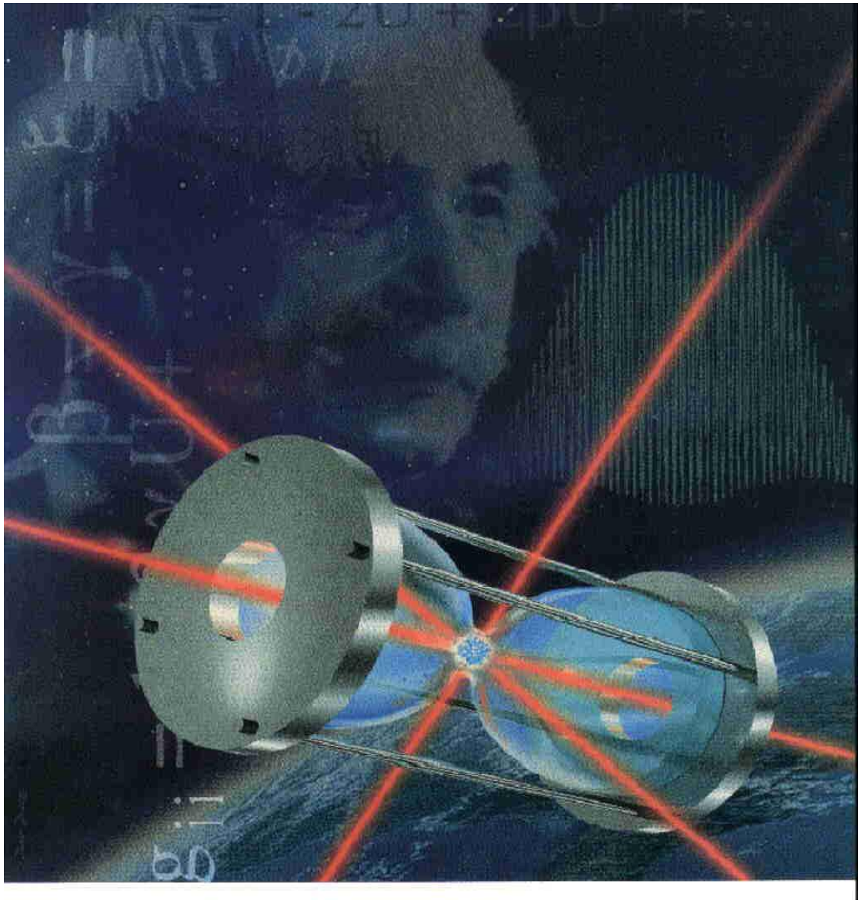
ACES Science



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

Paris Observatory, October 28, 2019

Cold atoms in space

Nearly unperturbed environment: long interaction time

Parabolic flights: 1991, 1997,…2018

Cold atom clocks: Laurent et al. 1997

Atom interferometers:

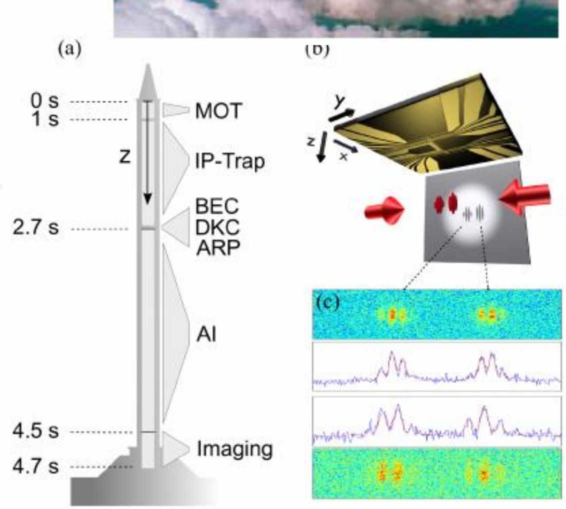
ICE project. R. Geiger et al. Nature Comm., 2011

EP test: ^{87}Rb-^{39}K Nature Comm., 2016

Drop tower:

BEC: Van Zoest et al. Science 2010

Matter wave interferometer, 2015



Sounding rocket: BEC in 2017

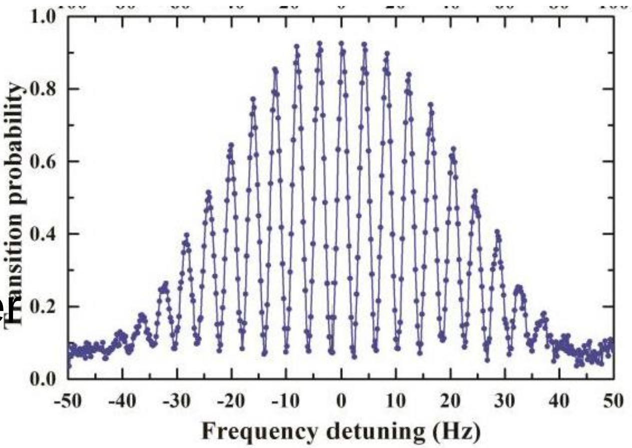
CAL on ISS: Rb BEC in 2018

Frequency combs

Satellite:

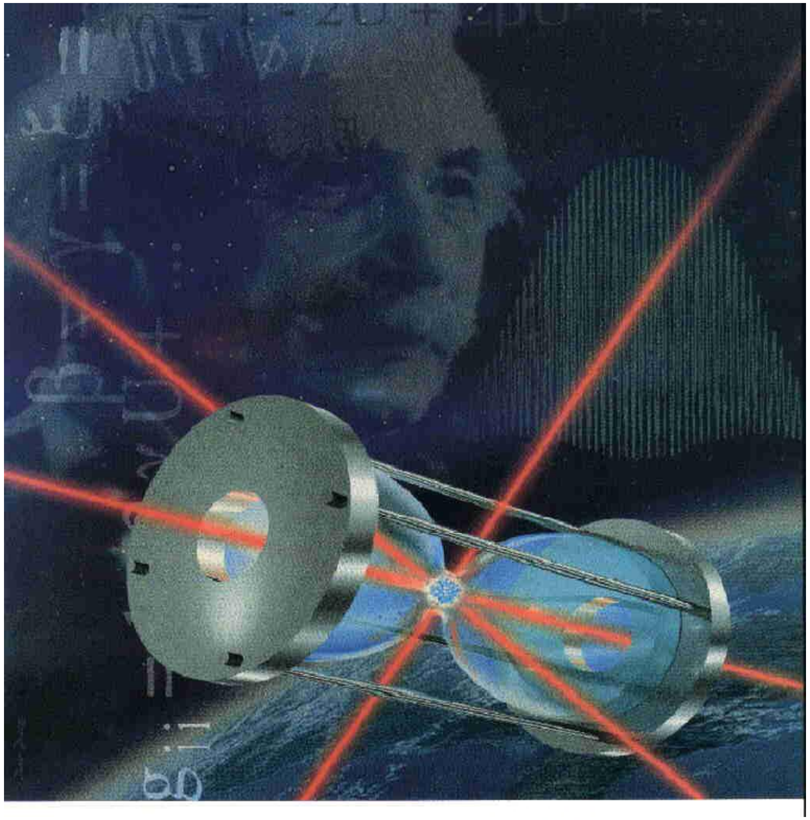
Rb clock in Chinese Tiangong 2: 2017. But linewidth 1.8 Hz is not narrower than in Earth-based fountains

Liu et al., Nat Comm' 2018



The space clock mission ACES

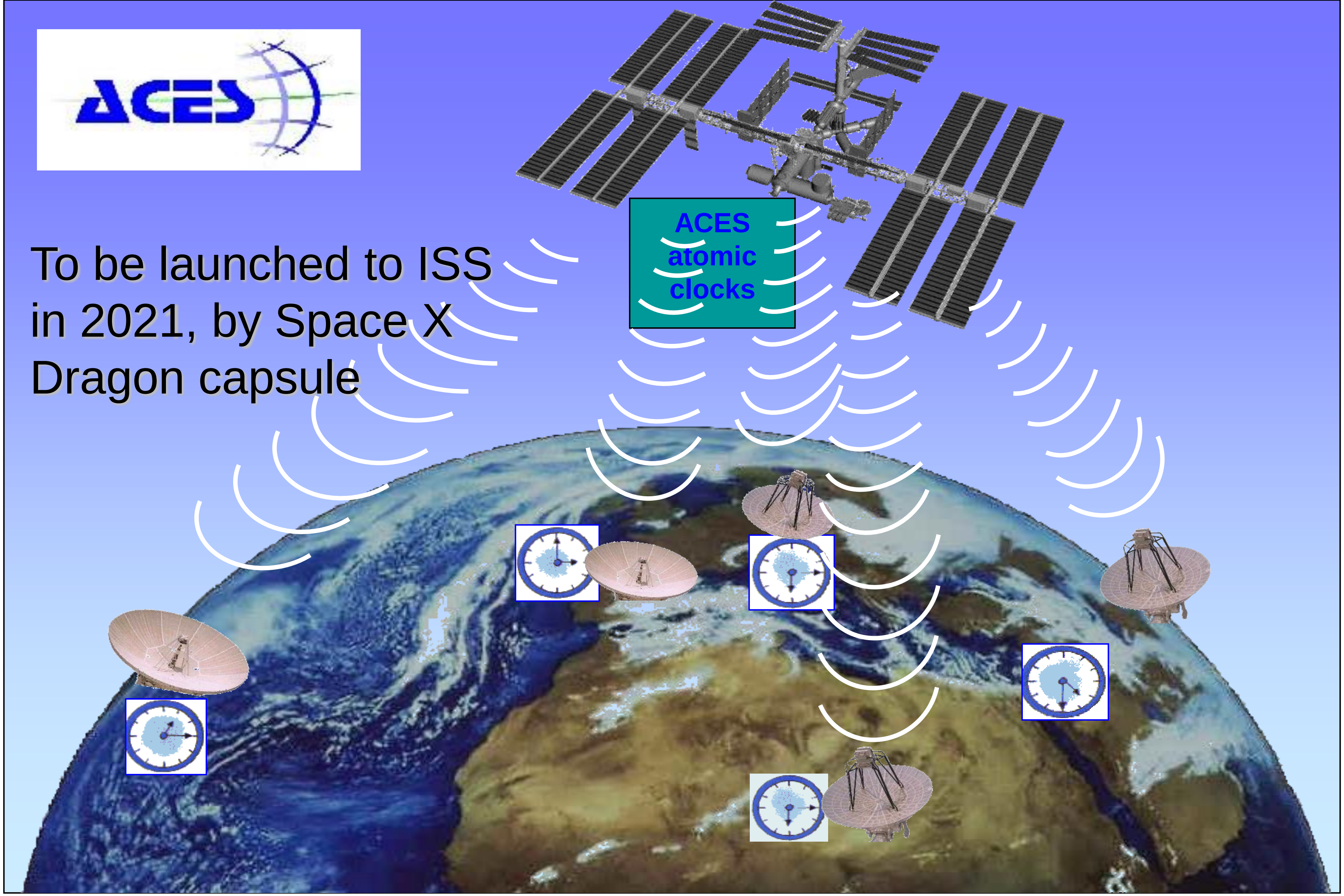
1997



2021

CENTRE NATIONAL D'ETUDES SPATIALES

P. Laurent, D. Massonnet, L. Cacciapuoti, C. Salomon, Comptes-Rendus Acad. Sciences, Paris, **16**, 540 (2015), The ACES /PHARAO Space Mission.



To be launched to ISS in 2021, by Space X Dragon capsule

- **A cold atom Cesium clock in space**
- **Fundamental physics tests**
- **Worldwide access**

esa

cnes
CENTRE NATIONAL D'ETUDES SPATIALES

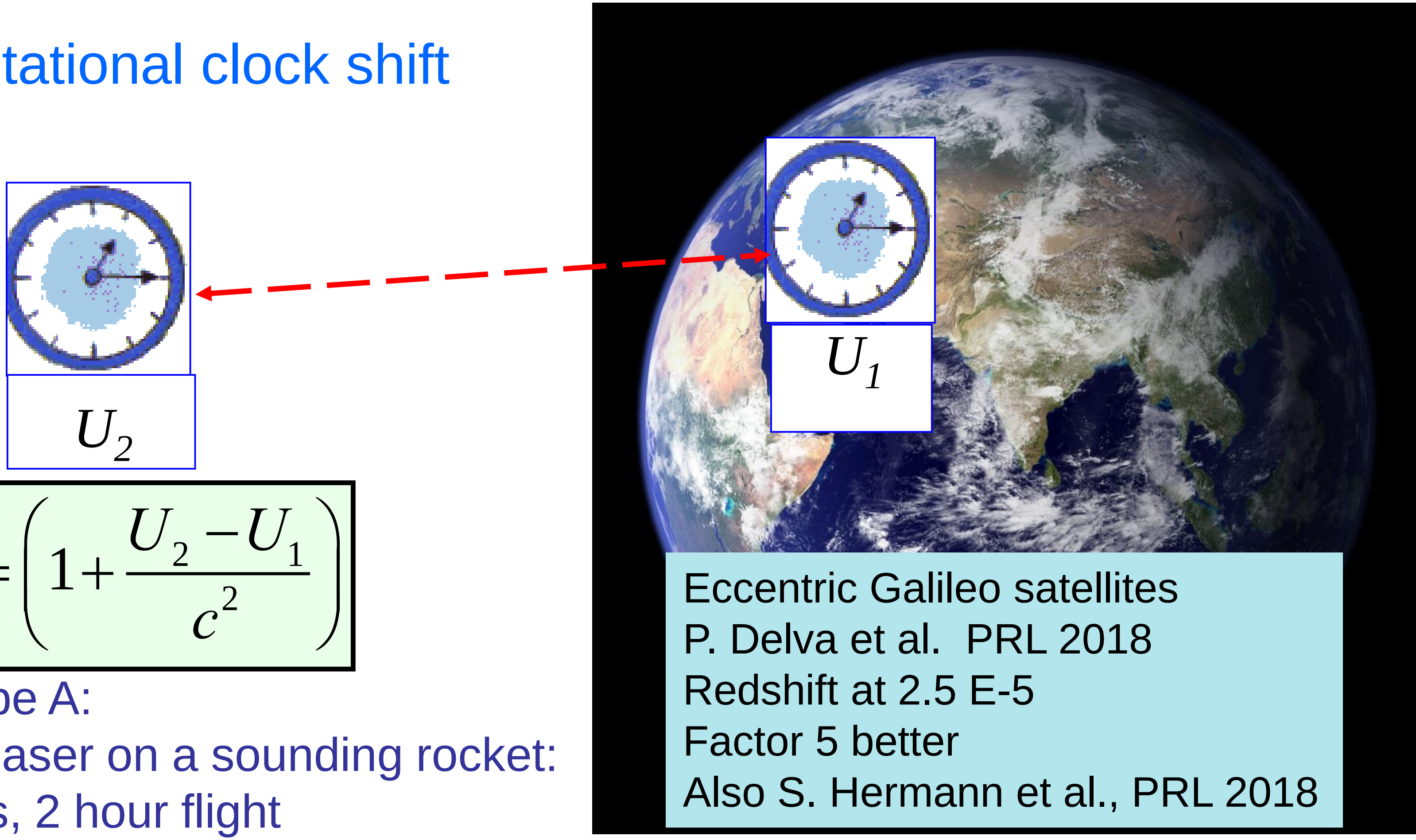
ACES ON COLUMBUS EXTERNAL PLATFORM on ISS

ACES

Current launch date : 2021
Mission duration : 18 months to 3 years

A Prediction of General Relativity

The gravitational clock shift



$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

Gravity- probe A:
- Space H maser on a sounding rocket: 10 000 kms, 2 hour flight
- Ground maser
- orbit determination by radio station tracking

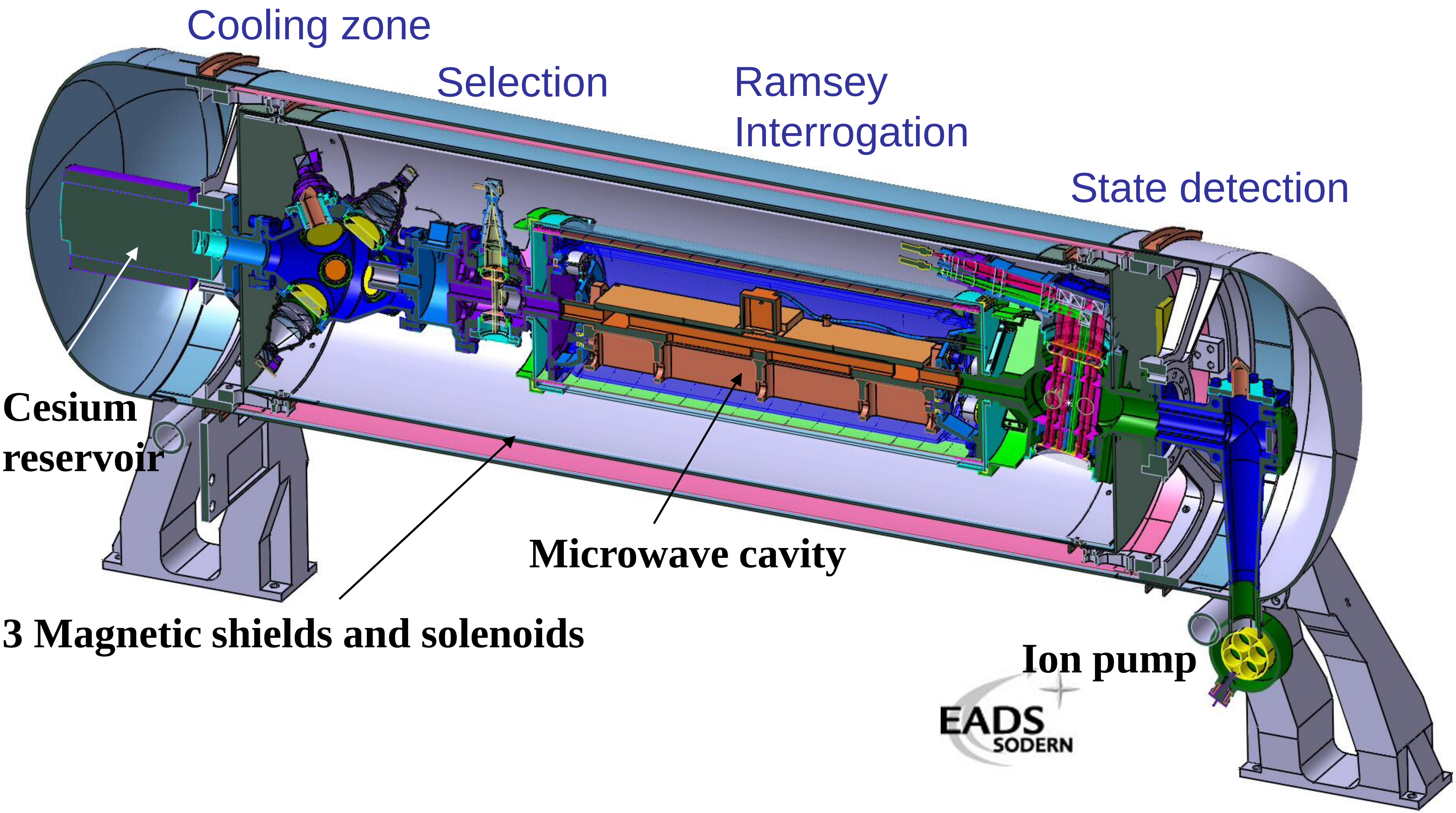
Also seen in lab with optical clocks !

C. W. Chou et al., Science 329, 1630, 2010

Eccentric Galileo satellites
P. Delva et al. PRL 2018
Redshift at 2.5 E-5
Factor 5 better
Also S. Hermann et al., PRL 2018

Gravitational Redshift
+ Time dilation
tested at 1.4 10^{-4}

PHARAO cold atom clock



Cooling zone

Selection

Ramsey
Interrogation

State detection

**Cesium
reservoir**

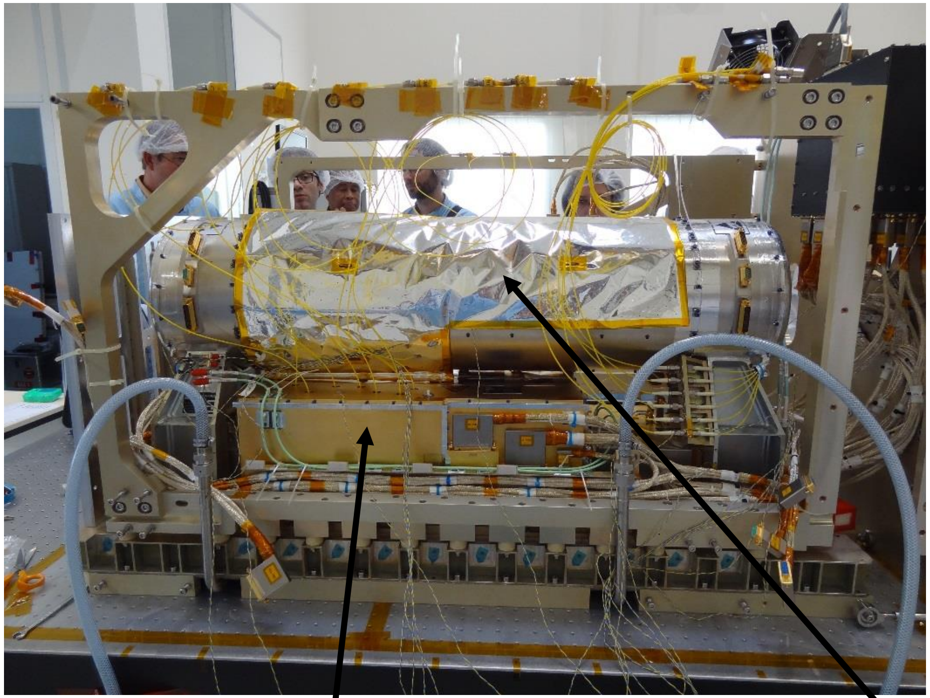
Microwave cavity

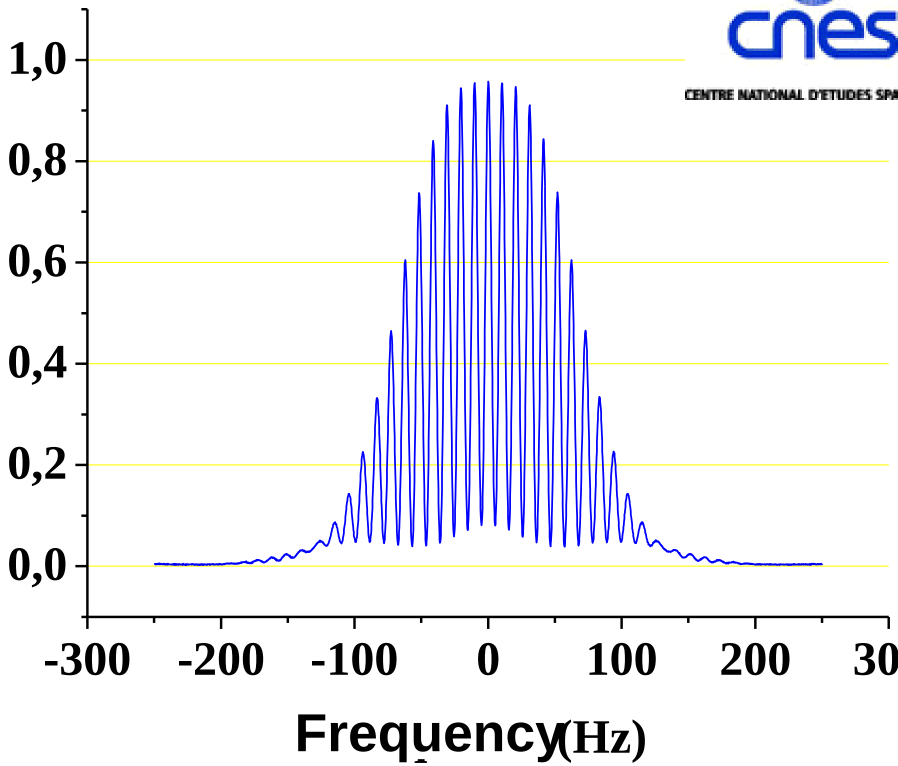
3 Magnetic shields and solenoids

Ion pump

Accuracy goal: 10^{-16} in space

PHARAO cold atom Space Clock





Laser source

Cesium tube

Flight model tests completed in Toulouse

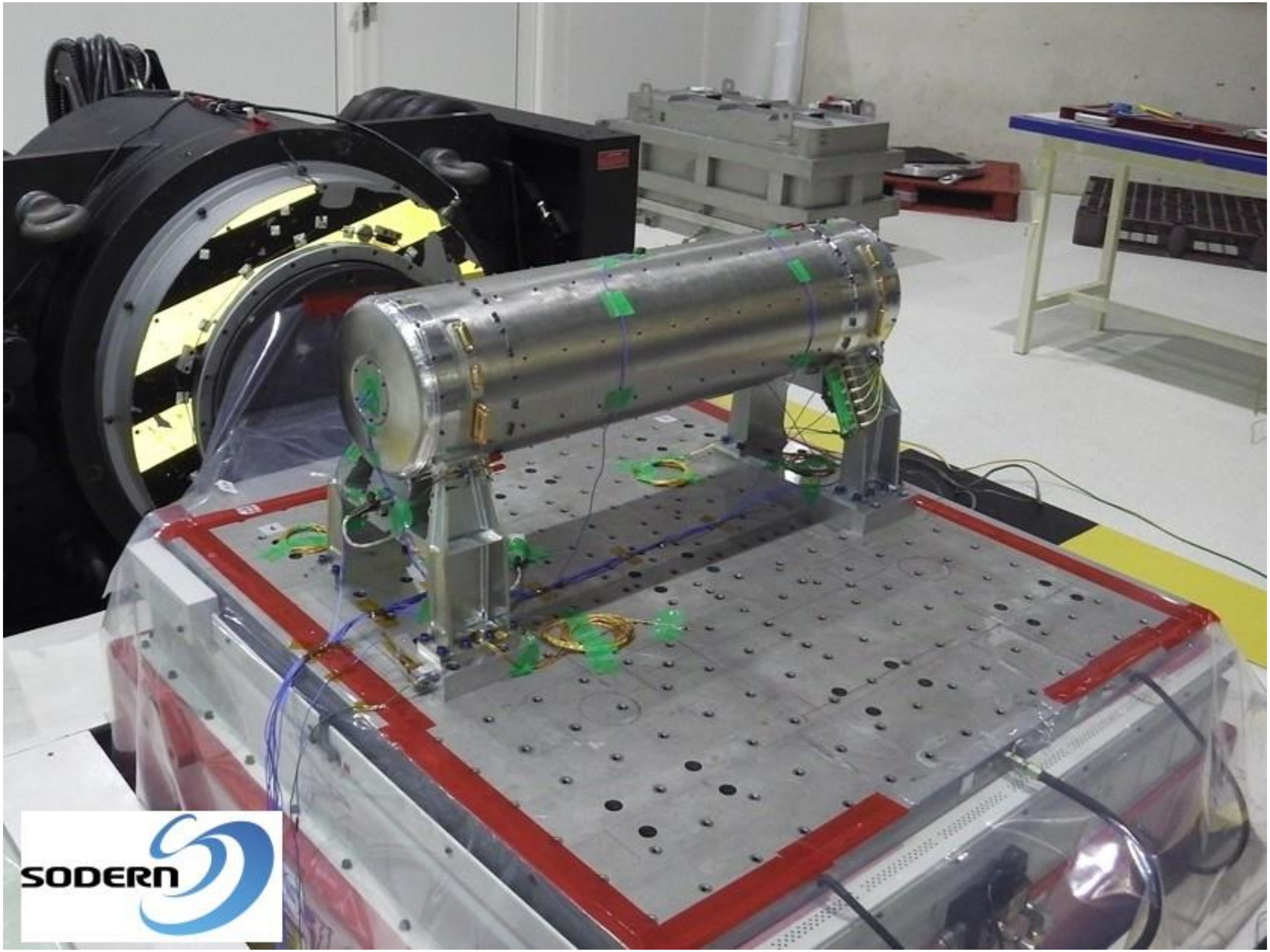
Expected accuracy and stability:10^{-16} in space

Delivery to ESA: July 2014

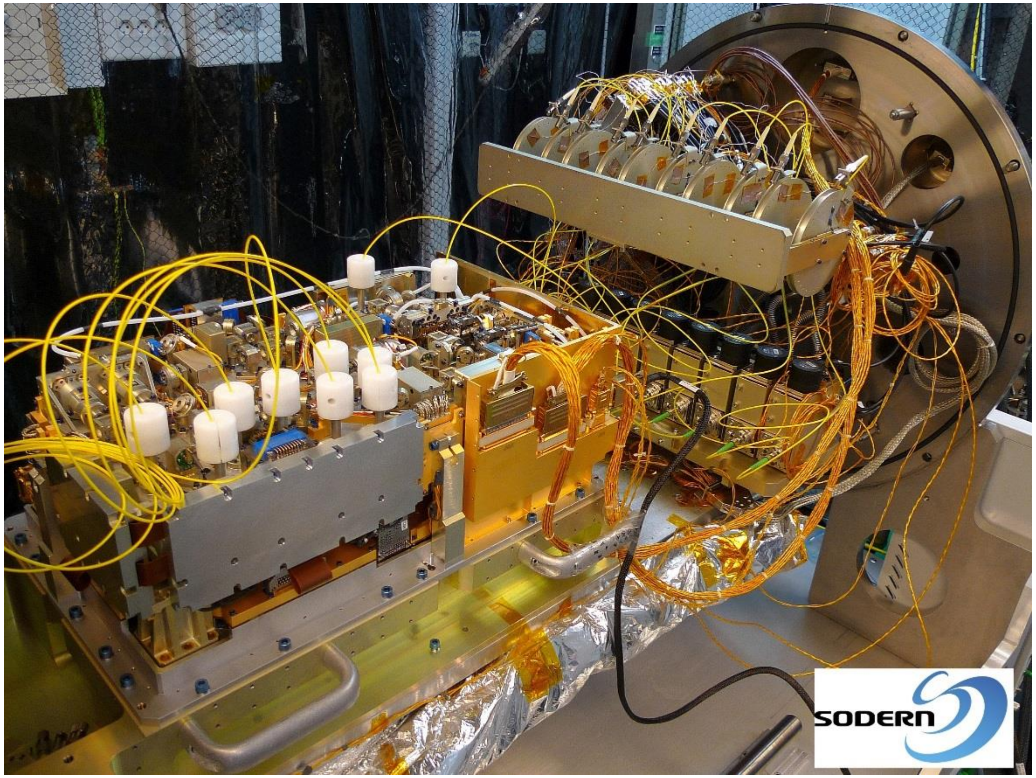
Test of Einstein effect at 2 ppm

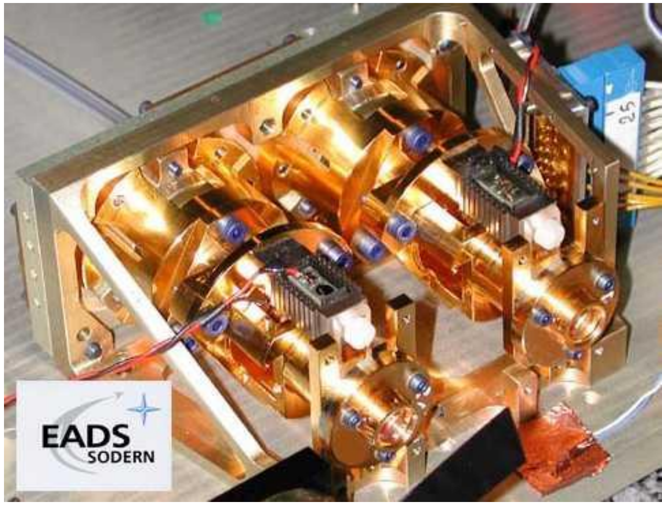
PHARAO Team in Toulouse

PHARAO Cesium Tube on the Shaker



PHARAO Laser Source





Extende cavity lasers
Autolock on cesium saturated absorption lines

Mass: 21 Kg, Vol: 17 liters, Power: 35 W
Flight model assembly: January 2014

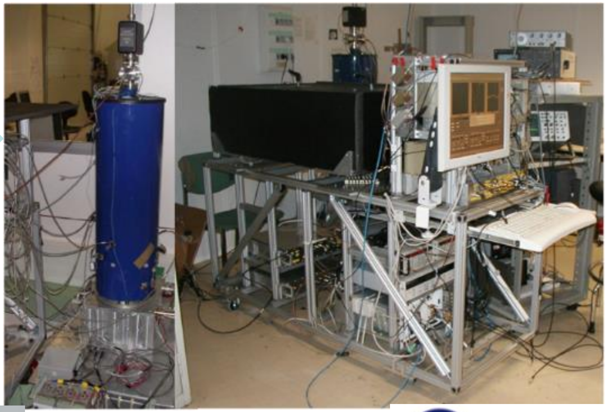
PHARAO Flight Model Performance Tests

Cryo-oscillator

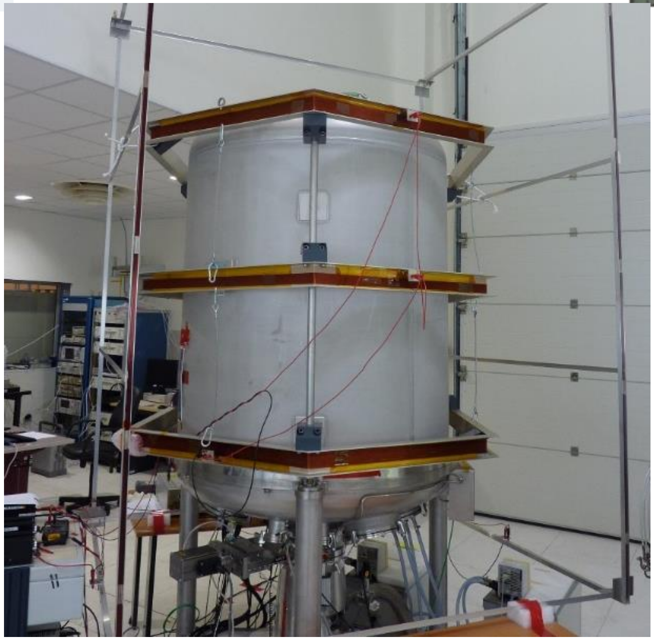
+ CNES H-MASER frequency stability

100MHz

Mobile Fountain FOM



Frequency comparison accuracy



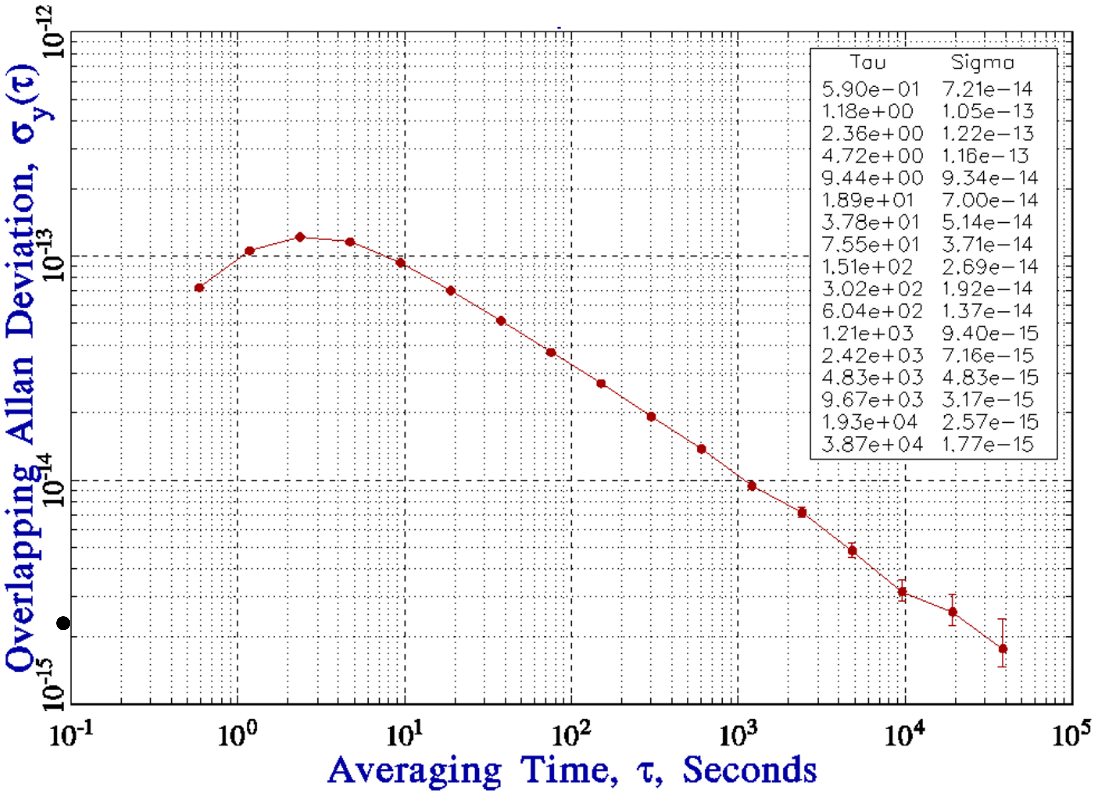
Ground Commands

- Orbital simulations in vacuum
- Temperature and Magnetism

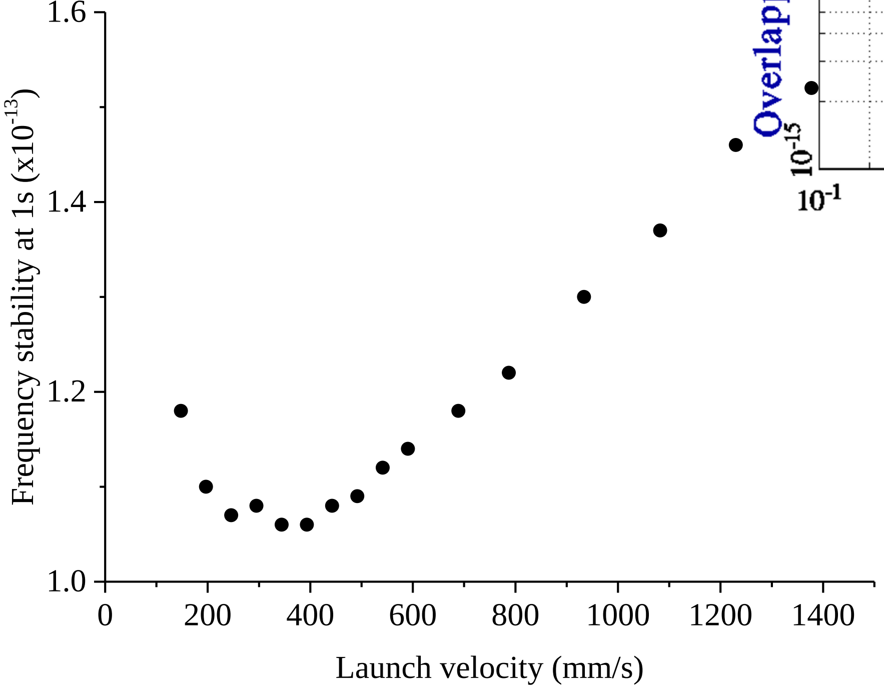
PHARAO Frequency Stability

$$\sigma_y(\tau) = 3.3\ 10^{-13}\ \ \tau^{-1/2}$$

With ultra-stable Quartz
Limited by gravity !



Tau	Sigma
5.90e−01	7.21e−14
1.18e+00	1.05e−13
2.36e+00	1.22e−13
4.72e+00	1.16e−13
9.44e+00	9.34e−14
1.89e+01	7.00e−14
3.78e+01	5.14e−14
7.55e+01	3.71e−14
1.51e+02	2.69e−14
3.02e+02	1.92e−14
6.04e+02	1.37e−14
1.21e+03	9.40e−15
2.42e+03	7.16e−15
4.83e+03	4.83e−15
9.67e+03	3.17e−15
1.93e+04	2.57e−15
3.87e+04	1.77e−15



Will enable 1.05 $10^{-13}\ \tau^{-1/2}$
in space with narrower line

PHARAO Frequency Accuracy

Crucial for the redshift test

Frequency comparison PHARAO- FOM = 7 10^{-16} + - 15 10^{-16} stat.

Accuracy evaluation : currently 1.8 10^{-15} on the ground

Main contributors:
- distributed cavity phase shift
- Cold Collisions

Will be evaluated in space by tuning the launch velocity over one order of magnitude

See work by P. Laurent and Kurt Gibble

Should enable 10^{-16} in space

ACES General View

Earth ↑

Mass: 227 kg,
Power: 450 W

Challenges: thermo-mechanical stability, three year operation

Famous ACES Visitors at ADS Friedrichshafen

Claude Cohen-Tannoudji Ted Hänsch

ACES TIME Transfer

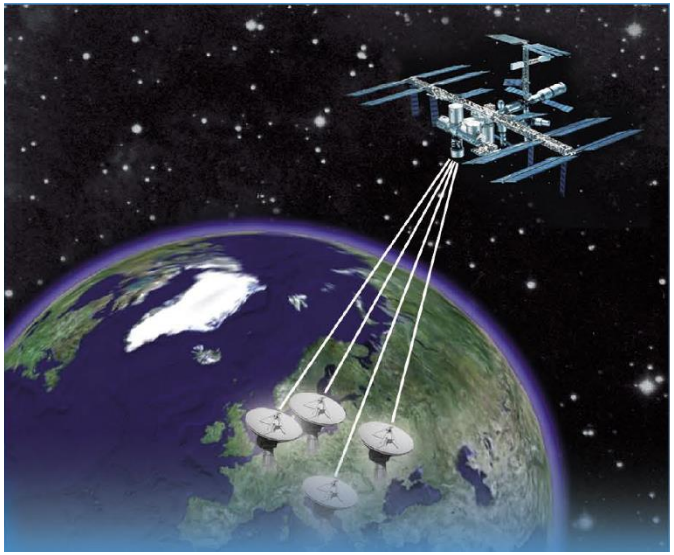
Ultra-stable frequency comparisons on a worldwide basis :

Ground Clock comparisons@ 10^{-17} over one week

Contribution to TAI

See talk by Wolfgang Schäfer

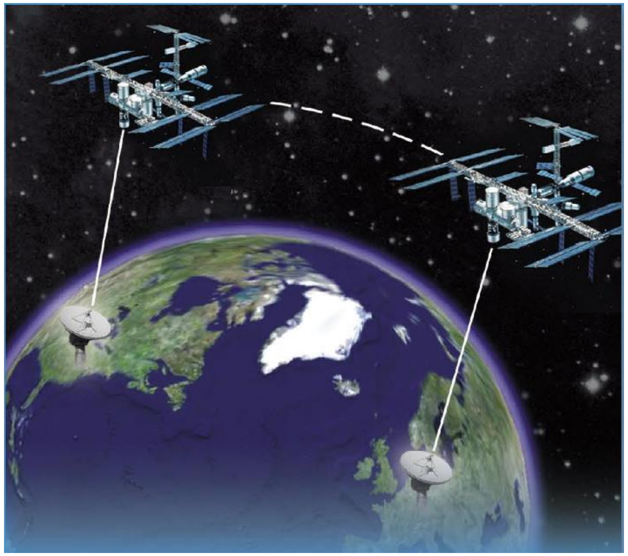
Common view



Error < 0.3ps over 300 s

To be checked by fiber-link

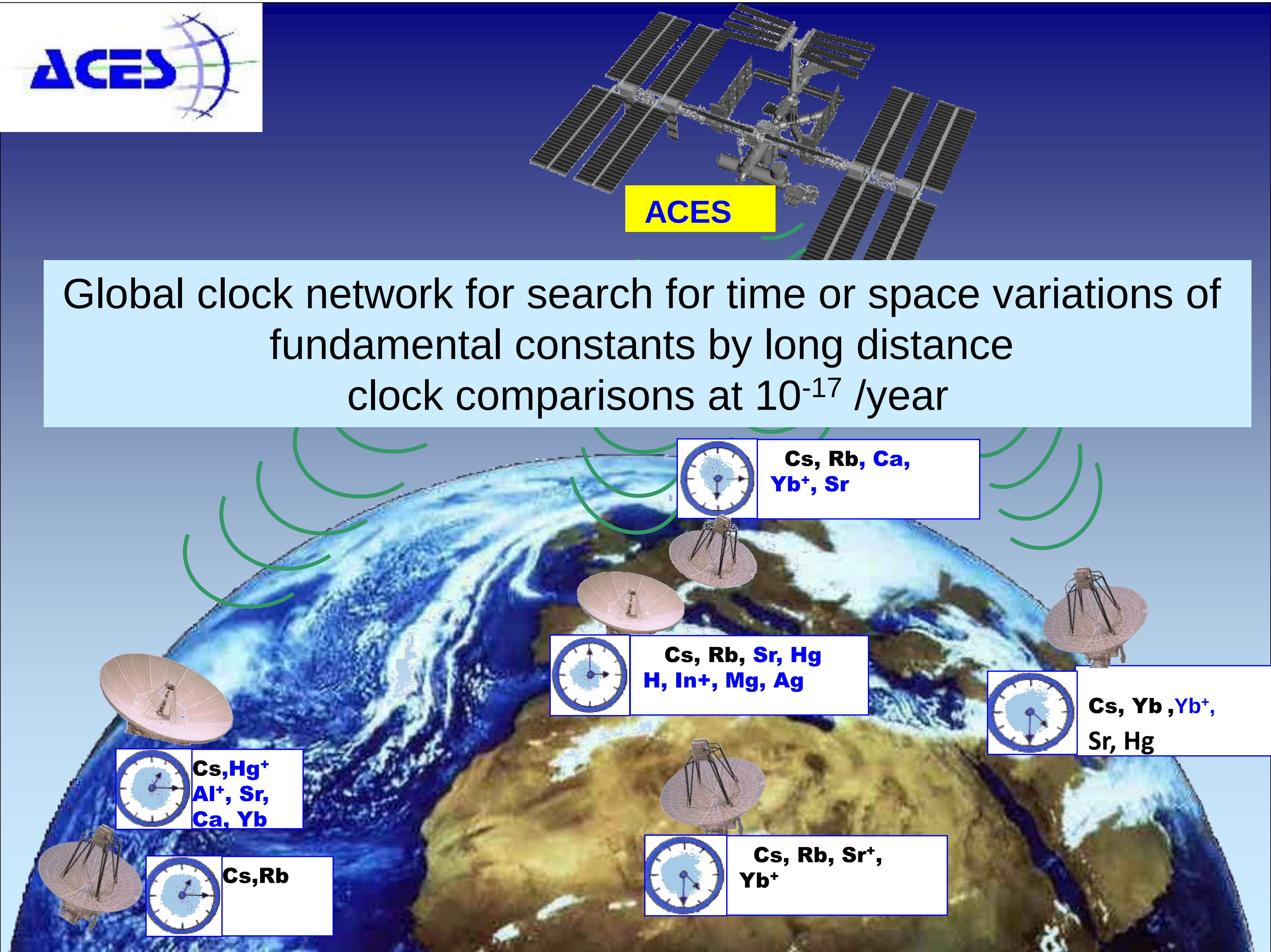
non common view



Error < 3ps over 3000 s

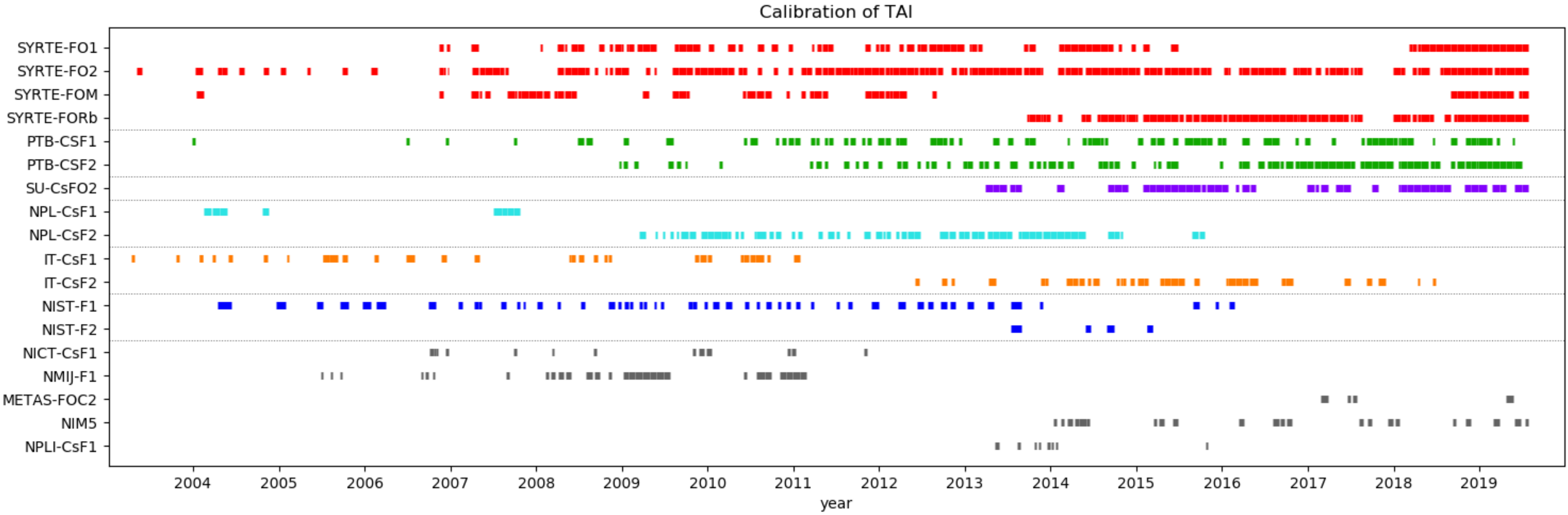
Frequency comparisons at 10^{-17} over 4-5 days

Global clock network for search for time or space variations of fundamental constants by long distance clock comparisons at 10^{-17} /year



Need for operating microwave and optical clock over extended periods

15 years of TAI calibration



The ACES data will have a similar structure and will require Continuous operation of microwave and optical clocks over several 20 day long sequences

Slide courtesy of B. Fang

Current Network of Ground Institutes

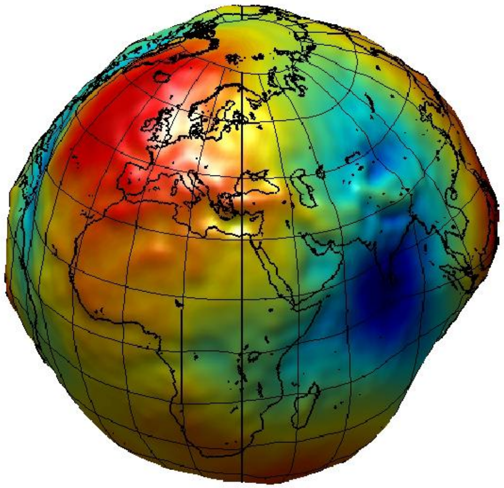
\+ 1 transportable MWL GT for other European institutes

+ 1 transportable MWL GT for calibration/troubleshooting purposes METAS, INRIM,…

Delivery of first MWL GT unit to PTB: end of 2015

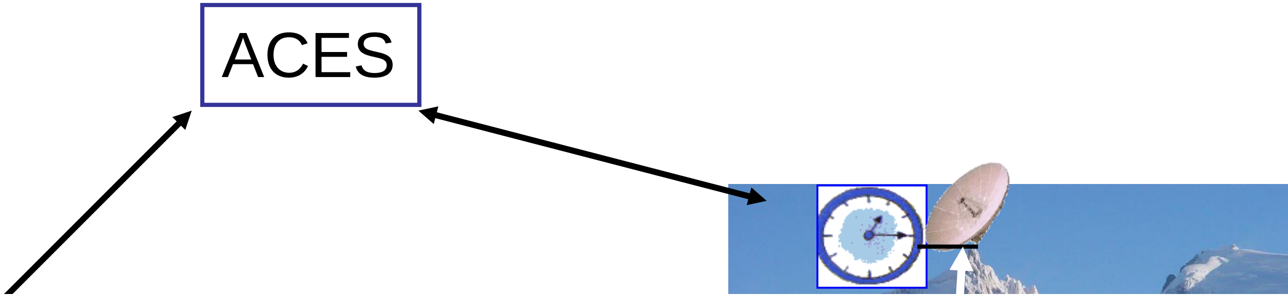
Relativistic Geodesy

The clock frequency depends on
the Earth gravitational potential
10^{-16} per meter
Best ground clocks have accuracy
of 1.4 10^{-18} and will improve !



Competitive with satellite + levelling techniques at ~ 20 cm level

Possibility to measure the **potential difference**
between the two clock locations at 10^{-17} level ie 10 cm
and 10^{-18} ie 1cm
with fiber link.



ACES

Atomic clock performance enabling geodesy below the centimetre level

NIST, Nature December 2018

W. F. McGrew[1,2], X. Zhang[1,3], R. J. Fasano[1,2], S. A. Schäffer[1,4], K. Beloy[1], D. Nicolodi[1,2], R. C. Brown[1,8], N. Hinkley[1,2,9], G. Milani[1,5,6], M. Schioppo[1,10], T. H. Yoon[1,7] & A. D. Ludlow[1,2*]

ACES publication policy

Mission Management Plan : prior access to data for one year
Paper authorship

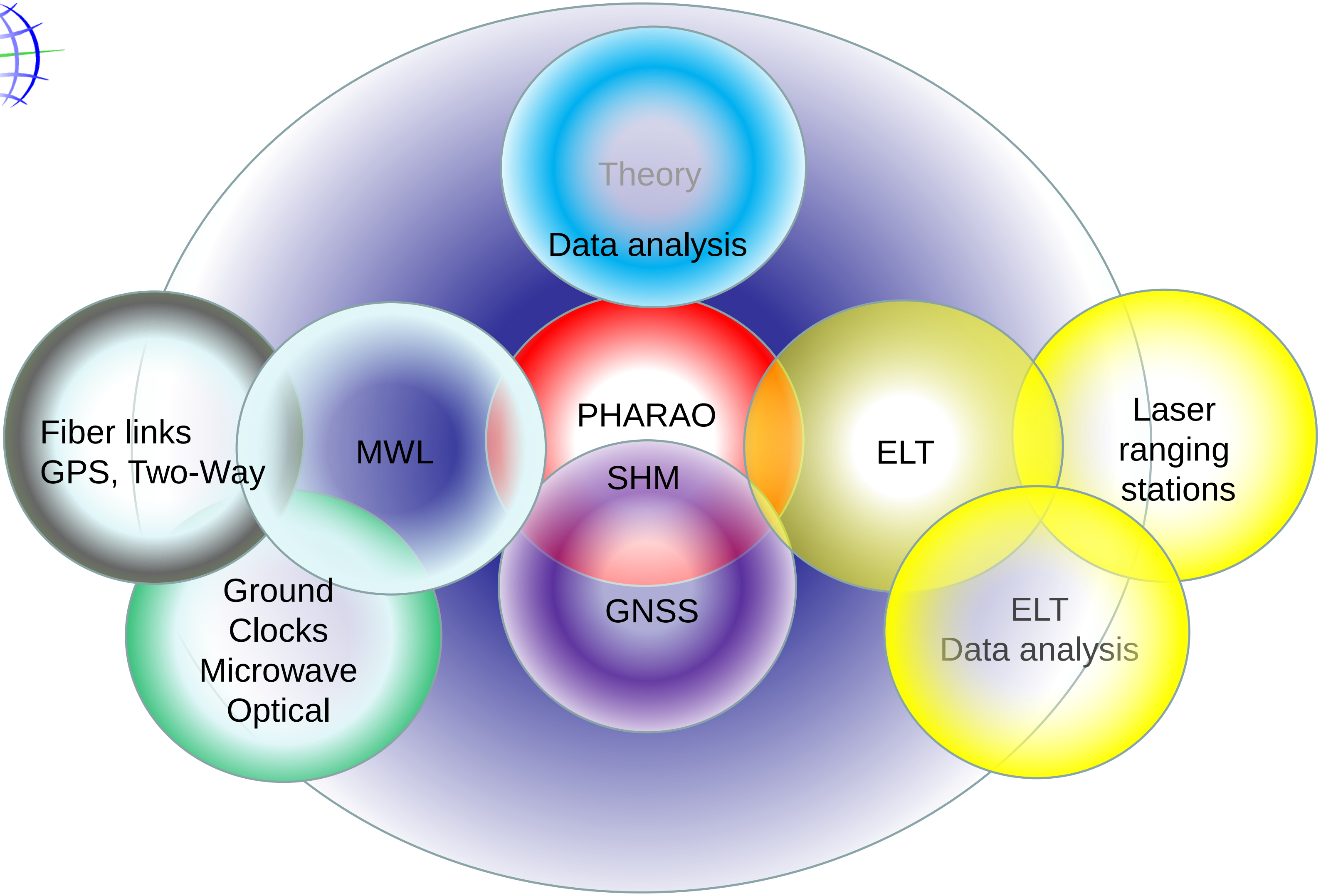
Actual trend:

LIGO-VIRGO model: members of the collaboration apply to the Ligo Science Collaboration with a research program. Once accepted by LSC (more than 2/3 of votes) they are automatically authors of the all the collaboration papers.

Planck Model
A core team. Scientific projects developped by subgroups but also authored by all members of the collaboration.

ACES model to be discussed

ACES Science


Theory

Data analysis

Fiber links
GPS, Two-Way

MWL

PHARAO

SHM

GNSS

ELT

Laser
ranging
stations

Ground
Clocks
Microwave
Optical

ELT
Data analysis

Proposal

- Each member of IWG is responsible for the team that He is representing within IWG
- For each experiment He proposes a list of people who are involved in the experiment
- This list is discussed in IWG and agreed (or not) by IWG (2/3 of votes)
- Each member of IWG signs all papers where ACES is involved
- As described in ACES Mission Science Management Plan, papers involving ACES are submitted first to an Editorial Board composed of ACES IWG members for approval.

Participants

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C. Guerlin, S. Reynaud