SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace

Atomic sensors metrology for long term and trustable monitoring of climate change Key Geodetic Parameters

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https://syrte.obspm.fr/spip/science/iaci/

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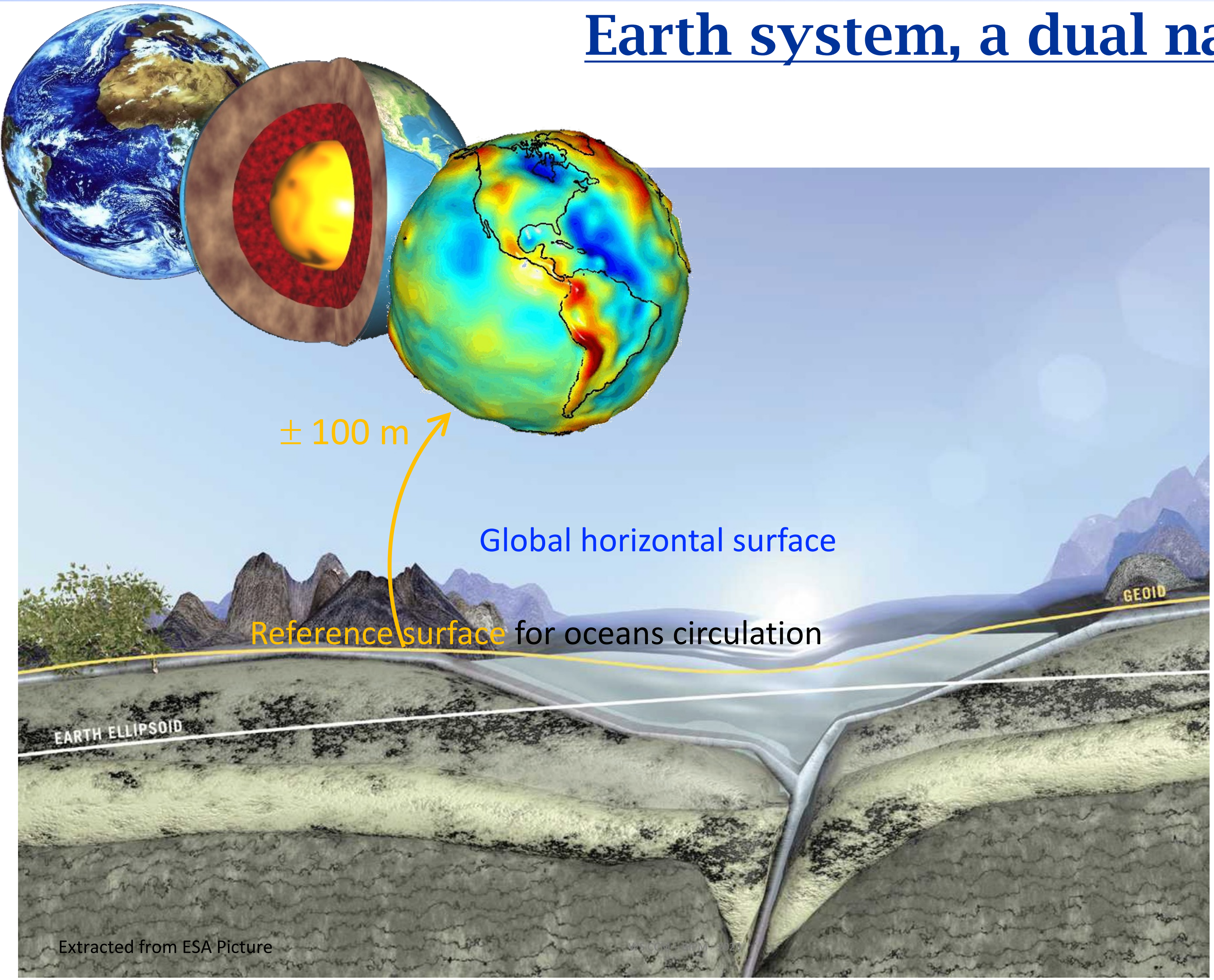
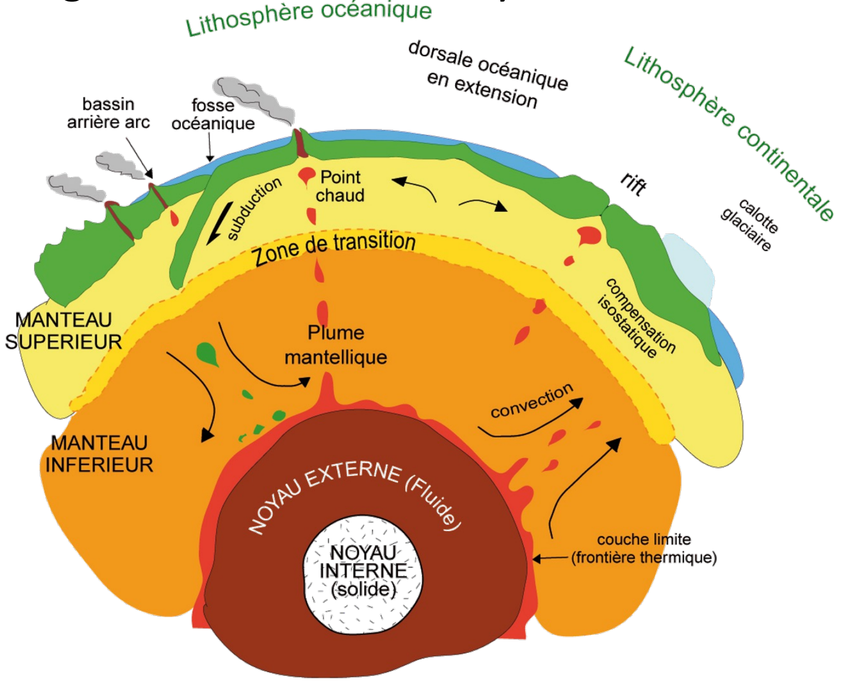
Earth system, a dual nature



Integrated view on Earth system masses



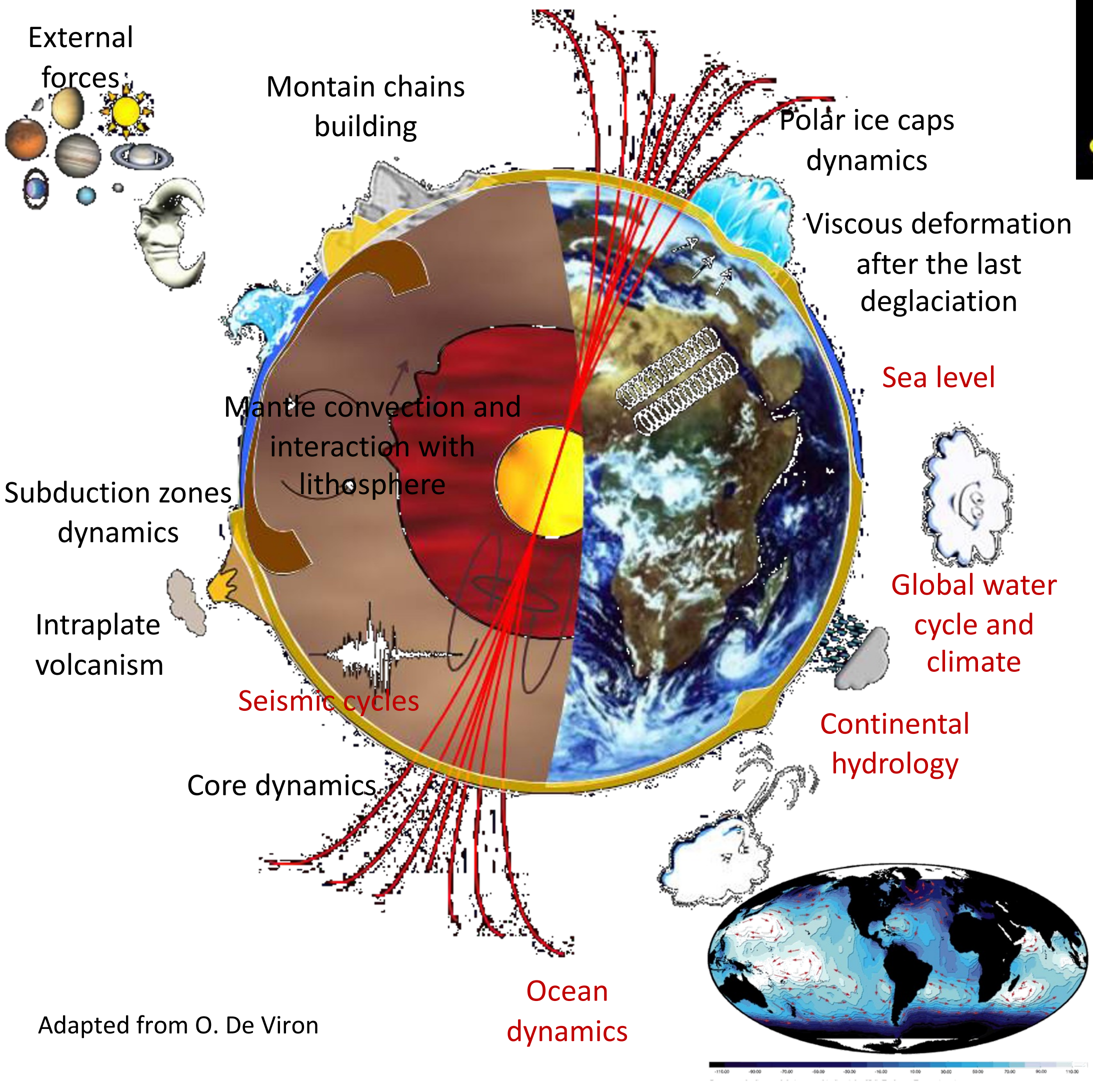
A nearly closed system

- Total **mass** conserved
- Exchange of energy with the outer space: primarily from solar heating

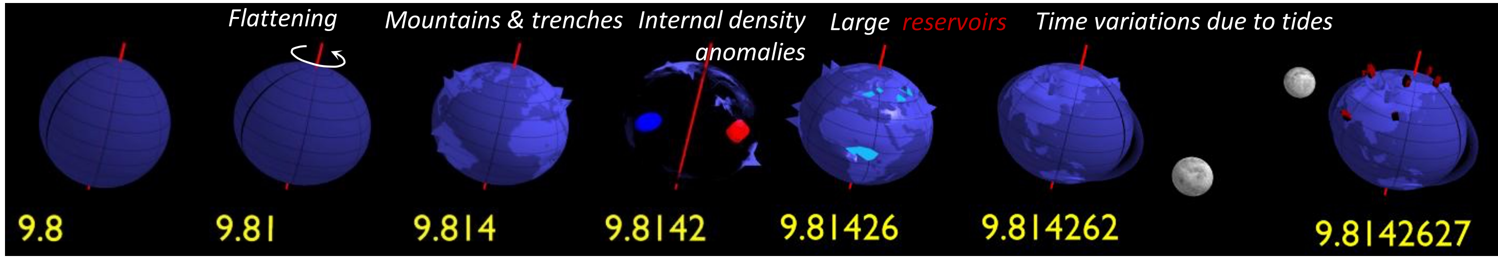
$$\vec{P} = m\vec{g}$$

Geophysics, Geodesy
… Metrology domain

Earth sciences, gravimetry



Adapted from O. De Viron



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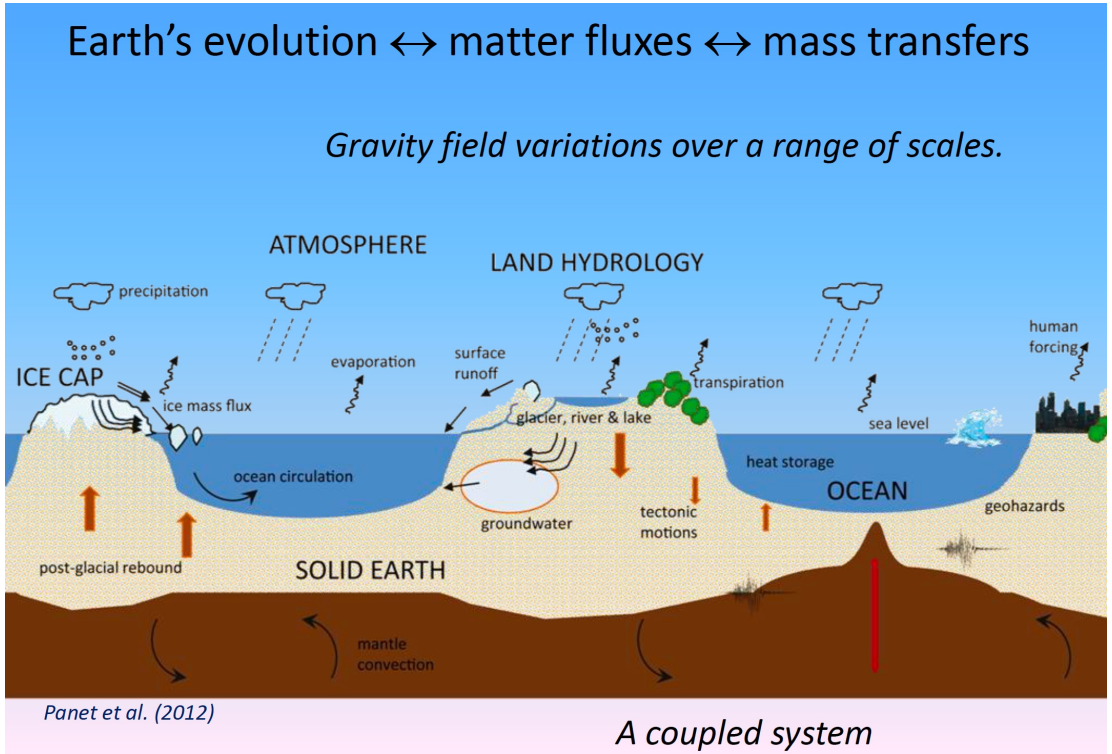


Energy, mass, geophysics and gravimetry domain

Needs for references (geoid) and trustables accurate measurements

Needs of Earth references

The United Nation resolution A/RE/69/266 “A Global Geodetic Reference Frame for sustainable development” (https://undocs.org/en/A/RES/69/266) calls for the **establishment of an improved Global Geodetic Reference Frame** (GGRF) which is essential for reliable determination of changes in the Earth system, for natural disaster management, for monitoring sea-level rise and climate change, and for providing **accurate** informations for decision-makers.

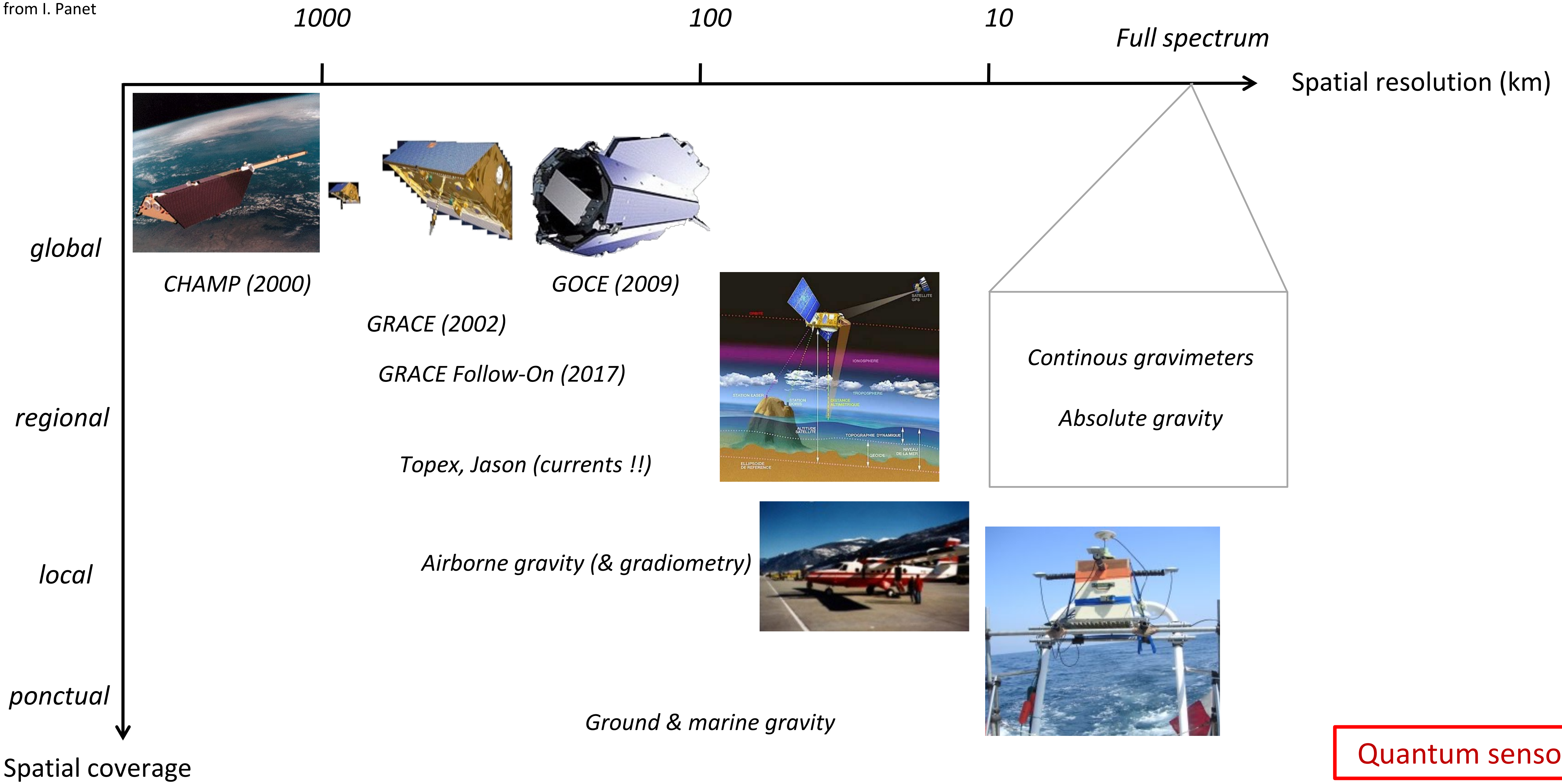
The United Nations proclaimed a Decade of Ocean Science for Sustainable Development, to be held from 2021 to 2030. With the Global Ocean Observing System (GOOS) (https://www.goosocean.org/), a program executed by the Intergovernmental Oceanographic Commission (IOC) of the UNESCO, the pursued goals can be summarized as follows : *(i)* assess the cumulative impacts of climate change and *(ii)* observe, understand in order to anticipate, inform and adapt.

Survey of gravity evolution. Science based on long term observations.

Instruments based on quantum technologies offer decisive advantages due to their intrinsic properties: accuracy, SI traceability, stability, which will revolutionize the measurement practices in geodesy.

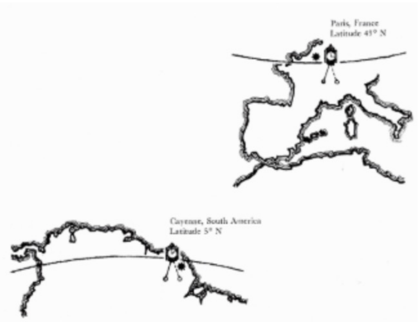
Measurements (up to now)

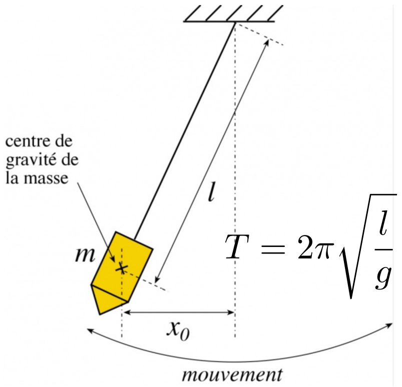
Adapted from I. Panet

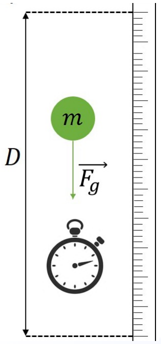


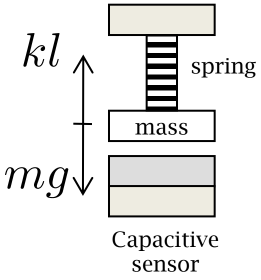
Quantum sensors ?

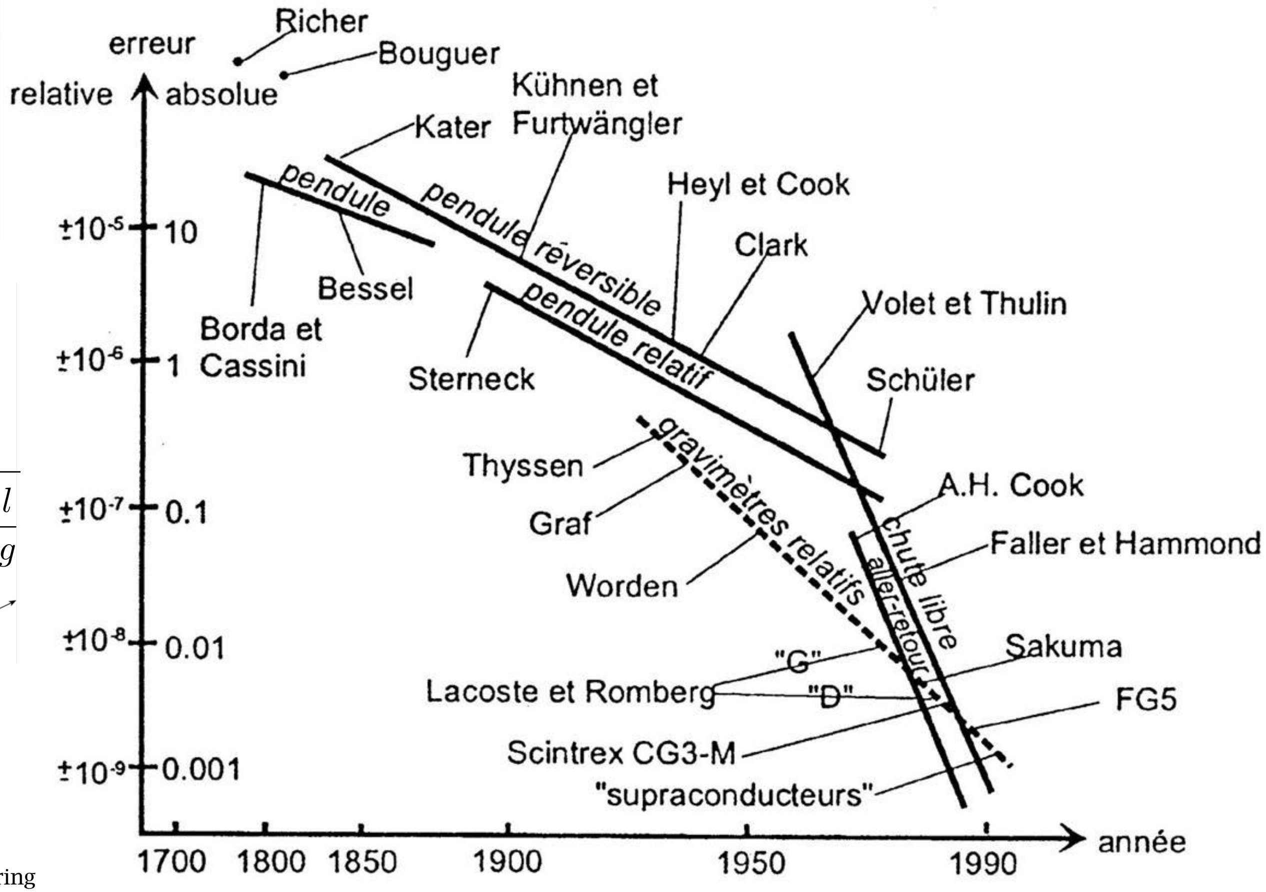
Instruments





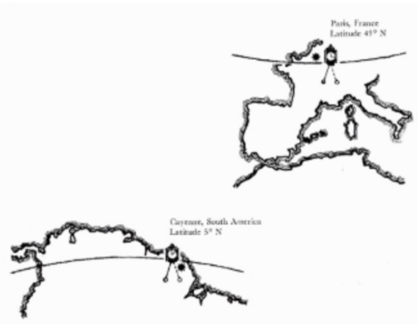


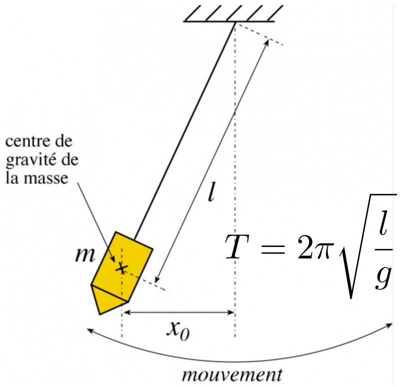


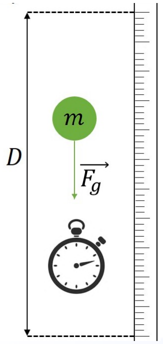


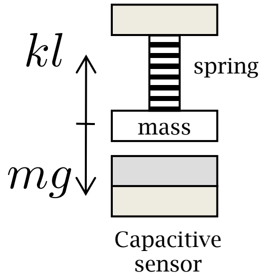
Adapted from W. Torge

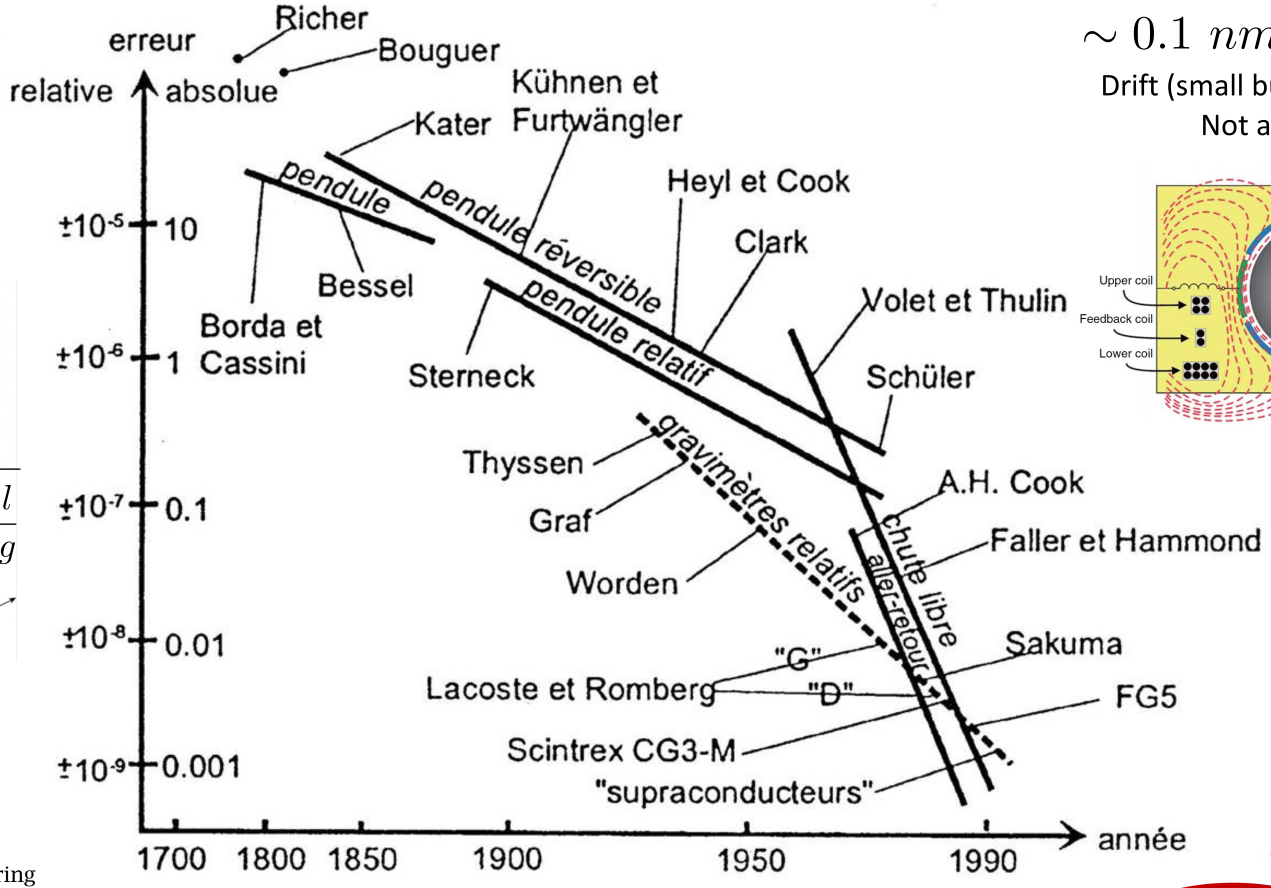
Instruments











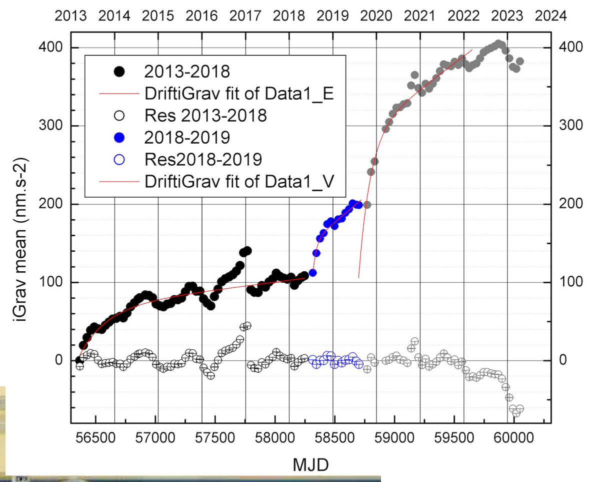
Adapted from W. Torge

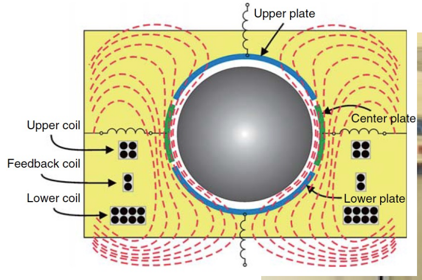
Continuous (1 Hz averaged)

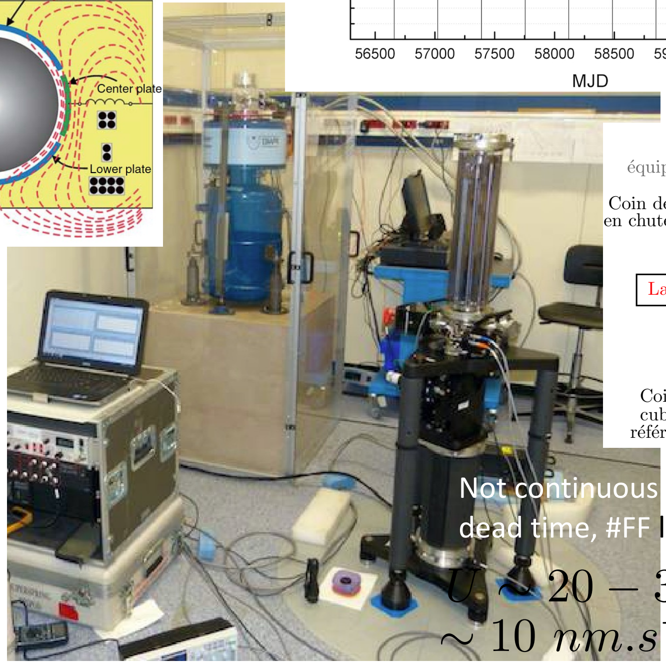
$\sim 0.1\ nm.s^{-2}$ in $1\ 000\ s$

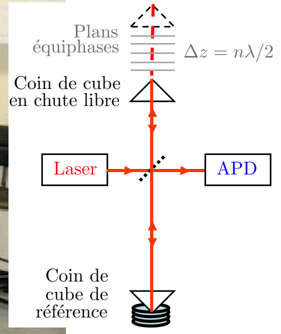
Drift (small but NL in the 2 first years)

Not accurate, to be calibrated









Not continuous (0.3 Hz)
dead time, #FF limited

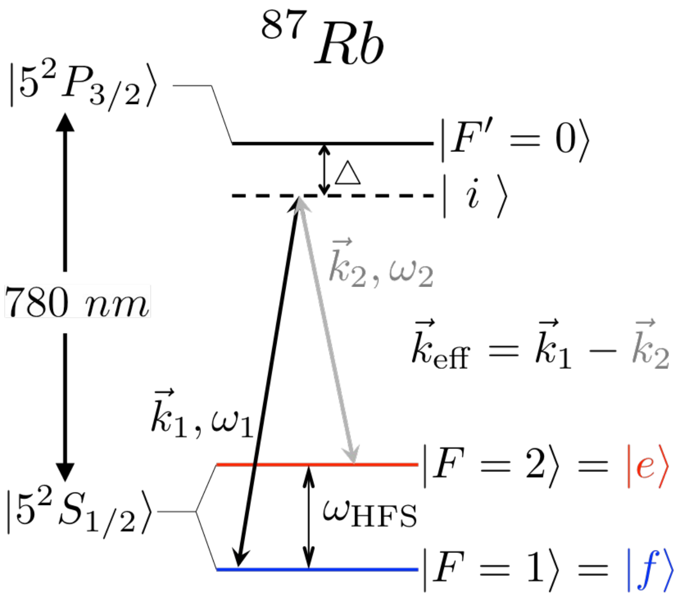
$U \sim 20 - 30\ nm.s^{-2}$

$\sim 10\ nm.s^{-2}$ in $90\ s$

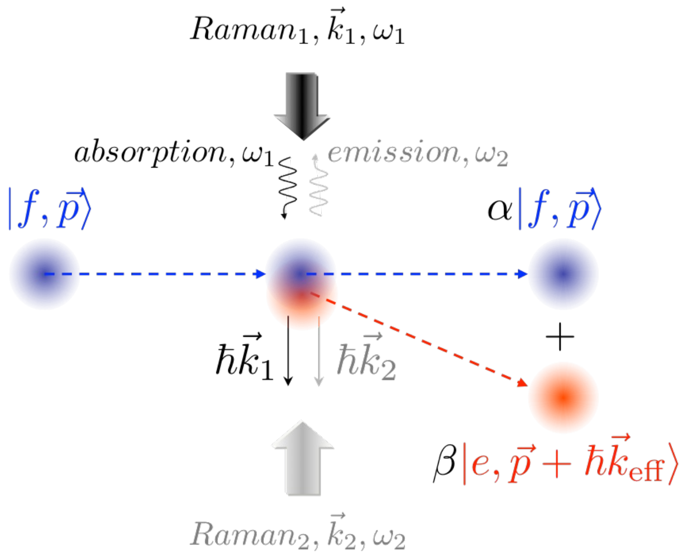
Needs of accurate and continous sensors, new sensors, new ideas
Quantum Technologies ?

Atom Interferometer, principle

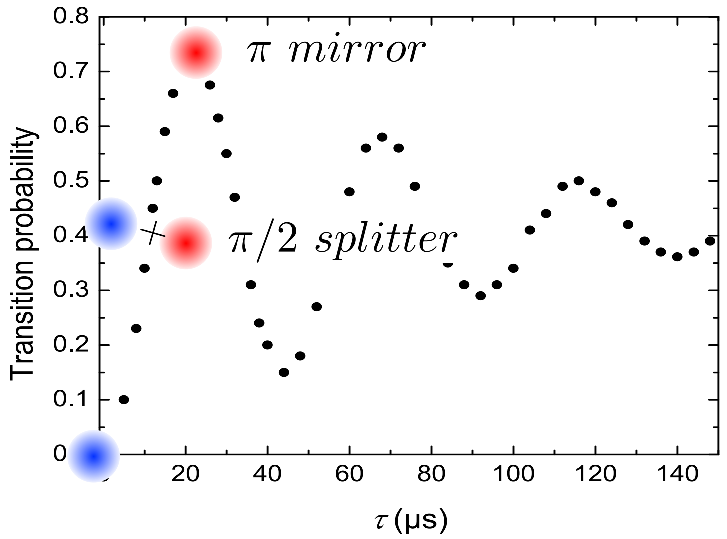
3 level atom



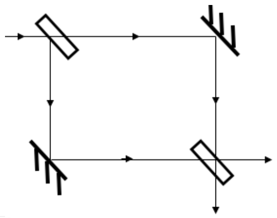
Two photon transition coupling $|f\rangle$ and $|e\rangle$



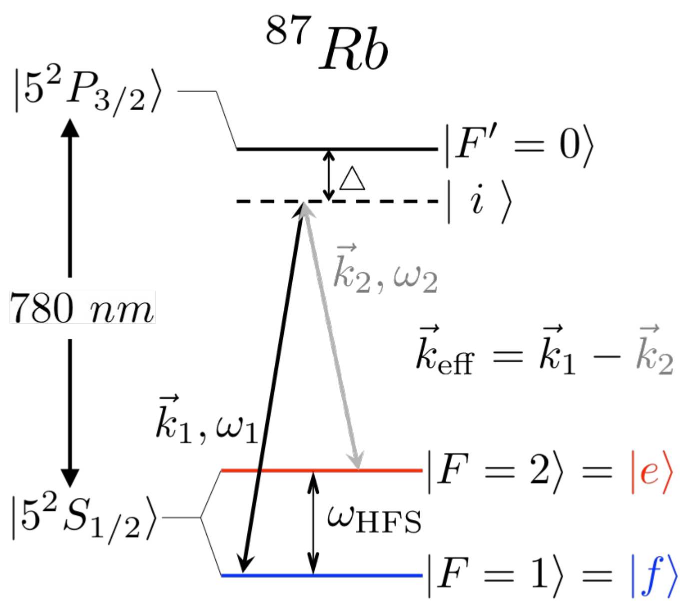
$$\phi(t) = \omega_{\text{eff}}t - \vec{k}_{\text{eff}}\vec{z}(t) + \varphi_{\text{eff}}(t)$$



Atom Interferometer, principle



3 level atom



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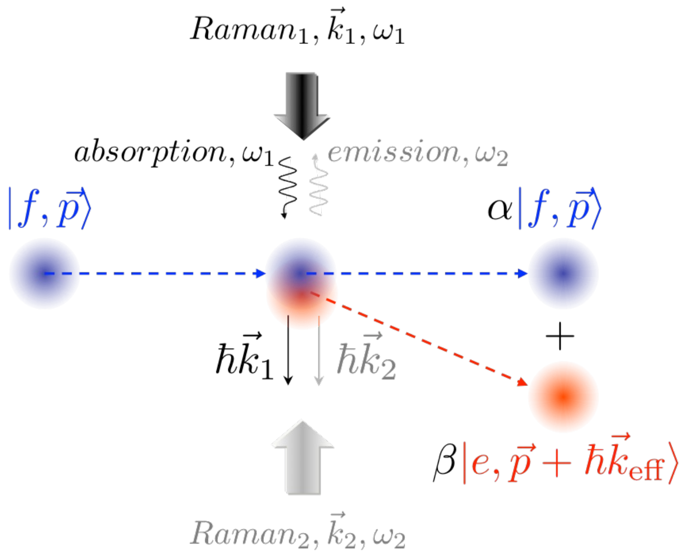
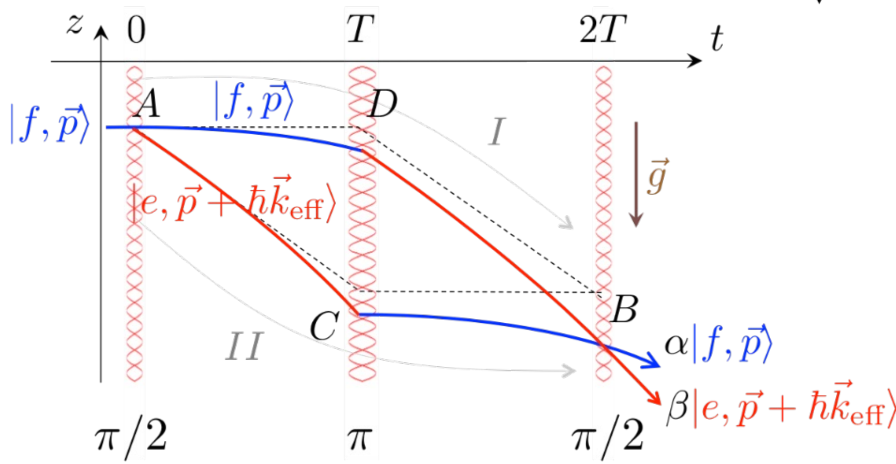
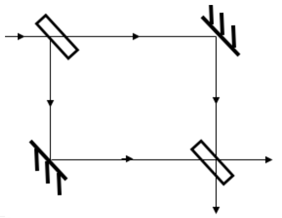


$$\phi(t) = \omega_{\text{eff}} t - \vec{k}_{\text{eff}} \vec{z}(t) + \varphi_{\text{eff}}(t)$$

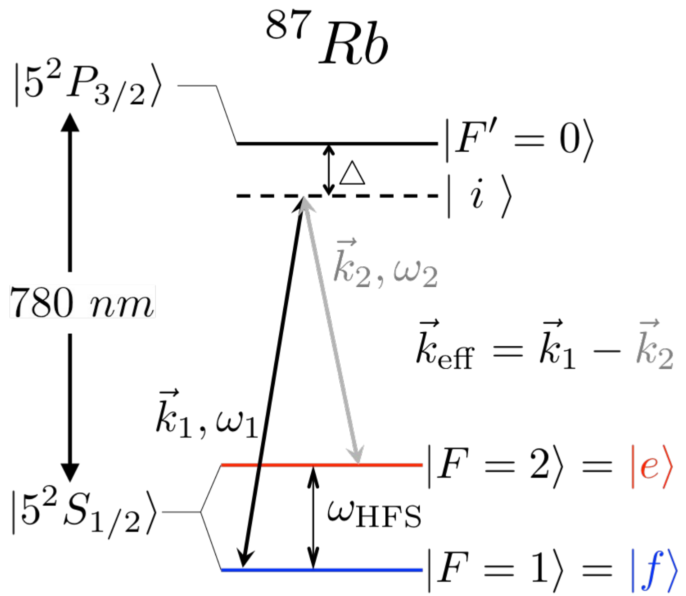


$$P_{|\vec{p}\rangle \to |\vec{p} + \hbar\vec{k}_{\text{eff}}\rangle} = \frac{1}{2}(1 - C cos \Delta\Phi)$$

Atom Interferometer, principle



3 level atom



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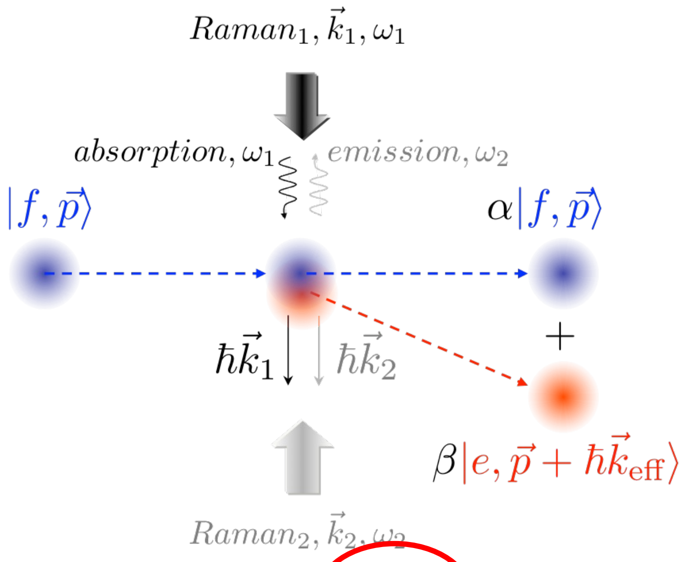
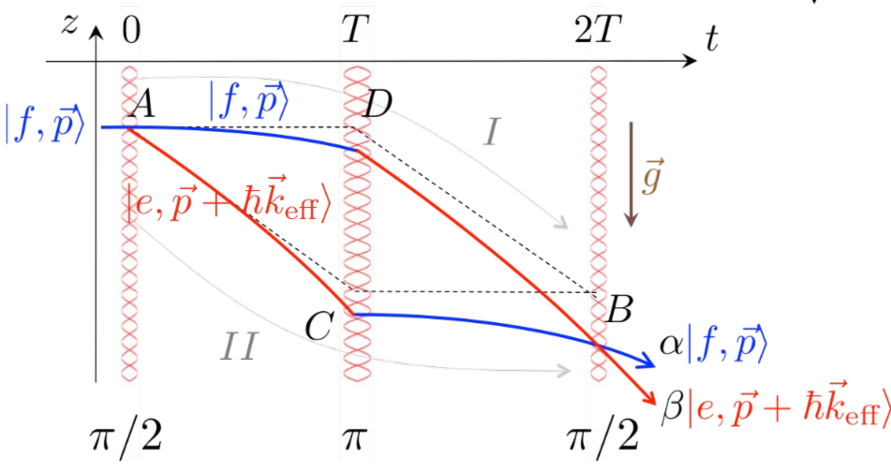


$$\phi(t) = \omega_{\text{eff}} t - \vec{k}_{\text{eff}} \vec{z}(t) + \varphi_{\text{eff}}(t)$$

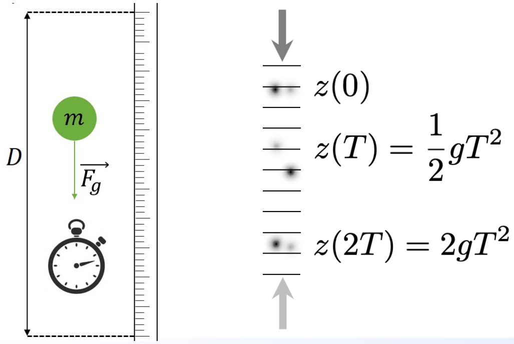
$$z = \frac{1}{2} g t^2$$



$$P_{|\vec{p}\rangle \to |\vec{p}+\hbar\vec{k}_{\text{eff}}\rangle} = \frac{1}{2}(1 - C\cos\Delta\Phi)$$

$$\begin{aligned} \triangle\Phi &= \Phi_{II} - \Phi_I \\ &= (\phi_A - \phi_C)\text{-}(\phi_D - \phi_B) \\ &= \phi(0) - 2\phi(T) + \phi(2T) \end{aligned}$$

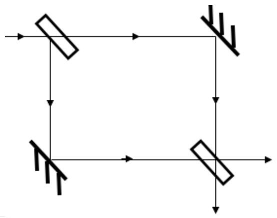
Sampling of the positions at the 3 pulses



$$\triangle\Phi = -\vec{k}_{\text{eff}} \vec{g} T^2 + \delta\Phi_{\text{noise}} + \delta\Phi_{\text{syst}}$$

Scales as T^2, benefits of cold atoms

Atom Interferometer, principle



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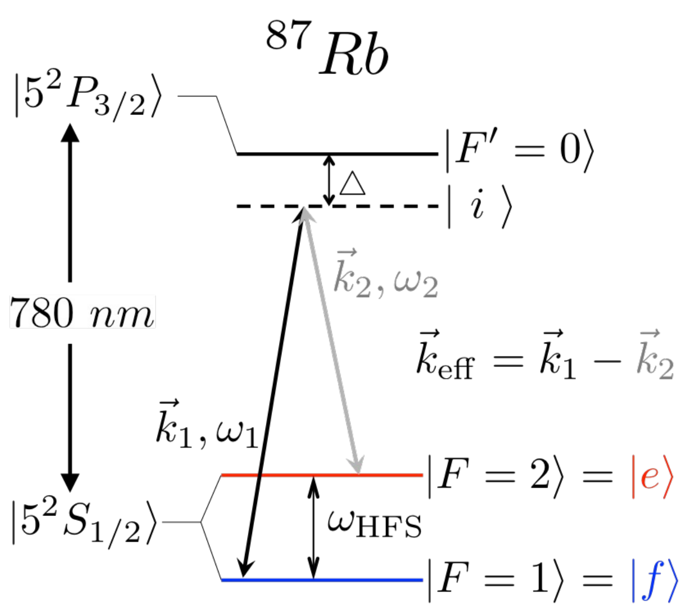

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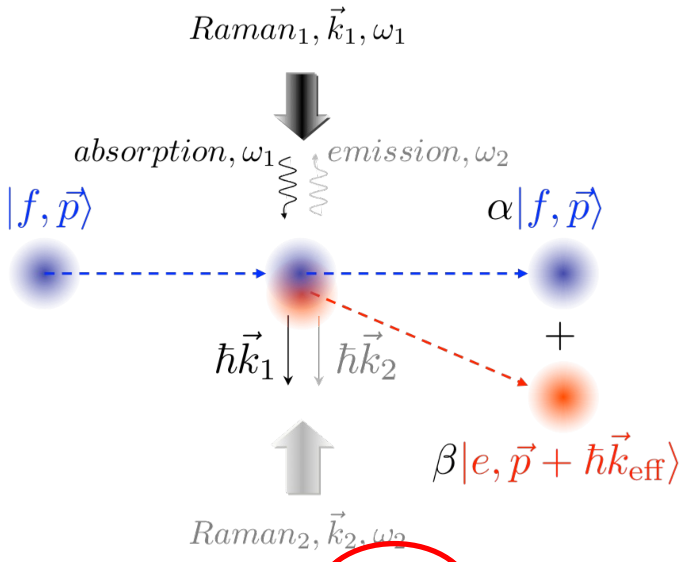
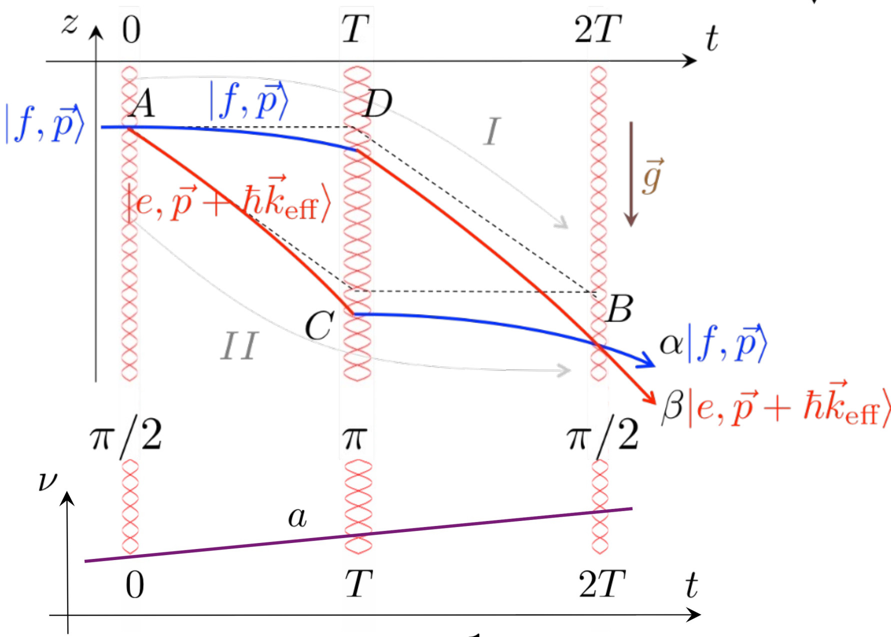


$$\phi(t) = \omega_{\text{eff}}t - \vec{k}_{\text{eff}}\vec{z}(t) + \varphi_{\text{eff}}(t)$$

$$\omega_1 - \omega_2 = \omega_e - \omega_f + \vec{k}_{\text{eff}}\vec{v}(t) + \frac{\hbar k_{\text{eff}}^2}{2m}$$



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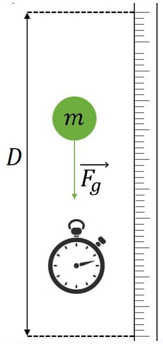
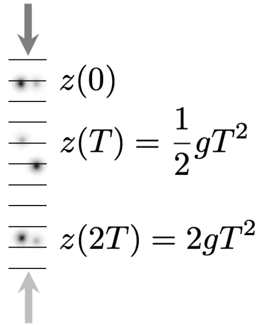
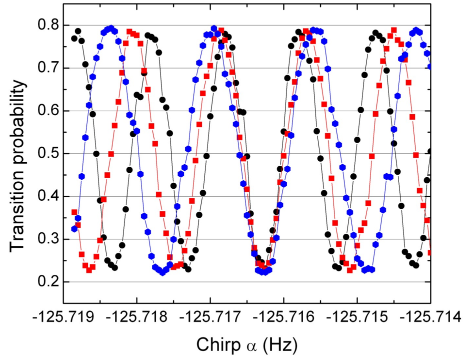




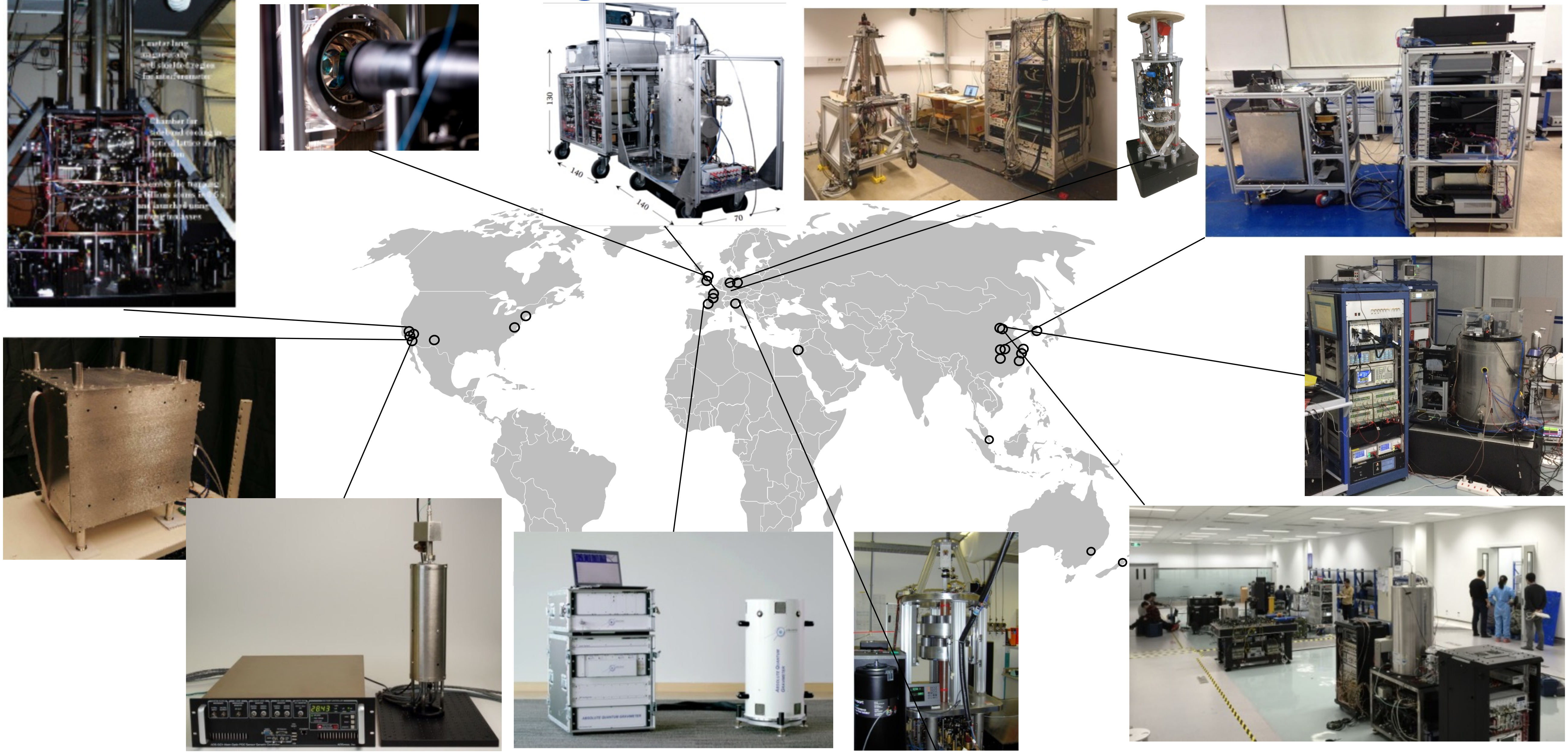
$$\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2 + aT^2$$

Gravity is a frequency measurement

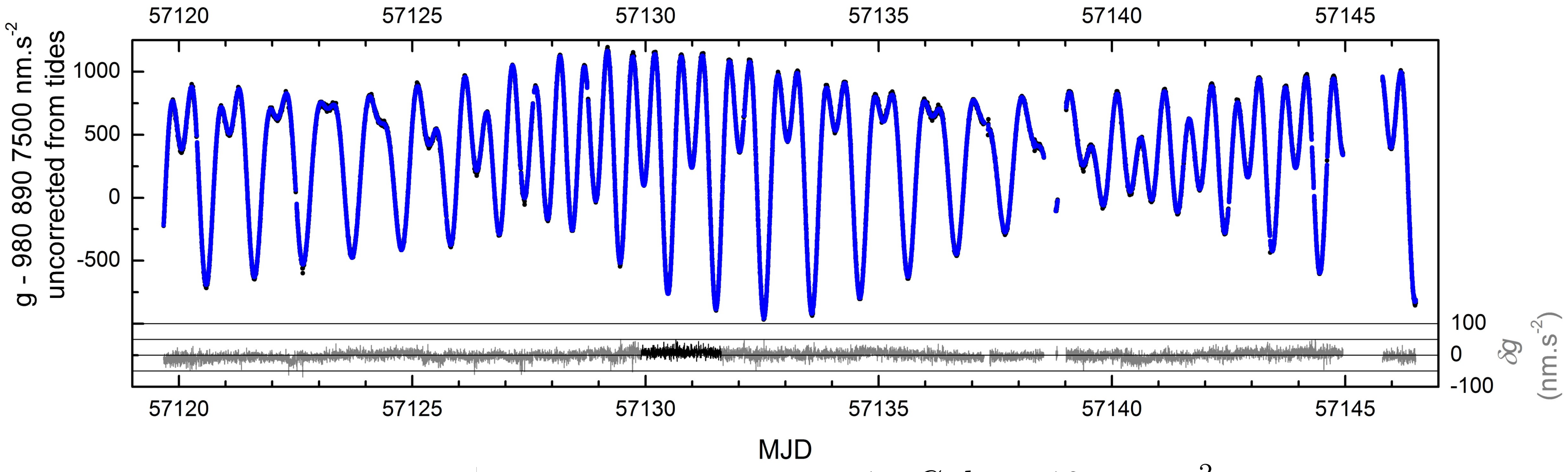
$$g = a/k_{\text{eff}}$$

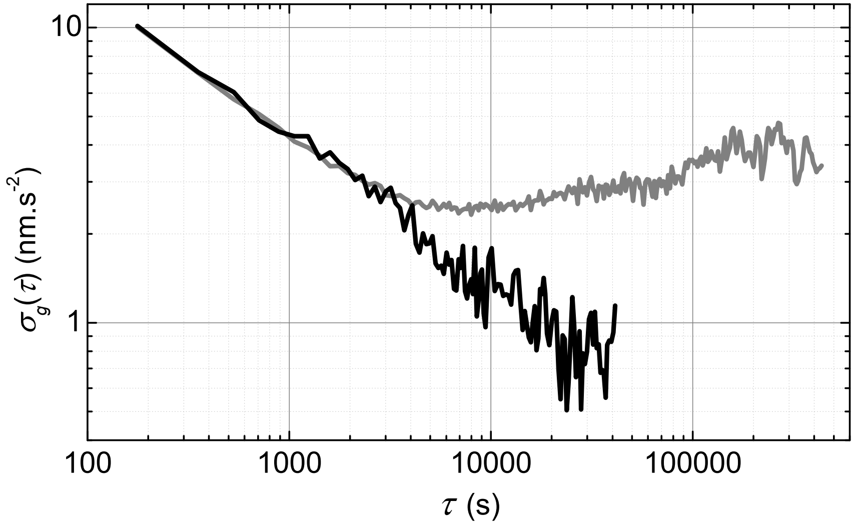


Huge worldwide activity

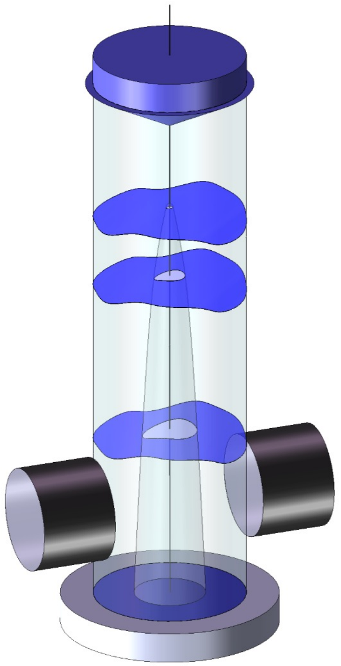


LNE-SYRTE sensor

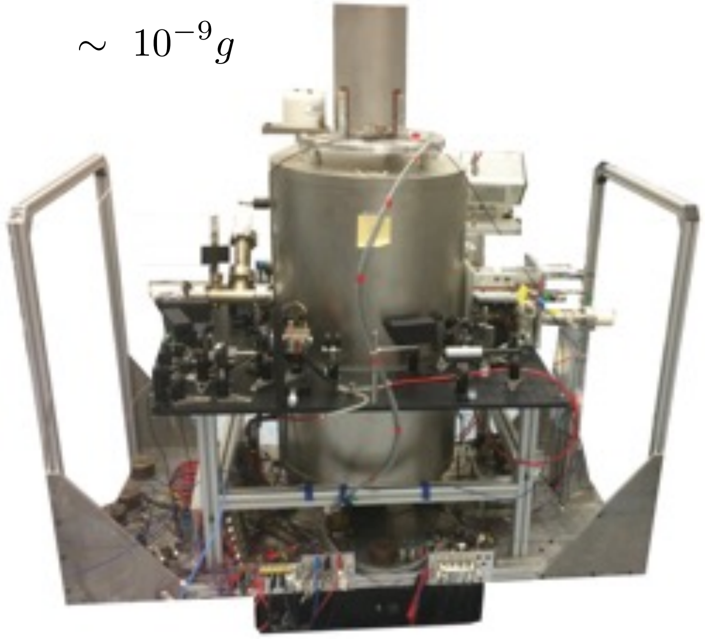


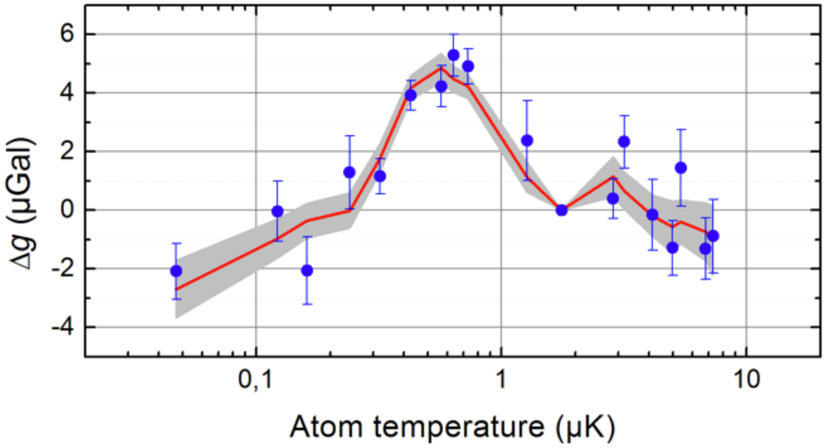


$$1\ \mu Gal = 10\ nm.s^{-2}$$
$$\sim 10^{-9} g$$



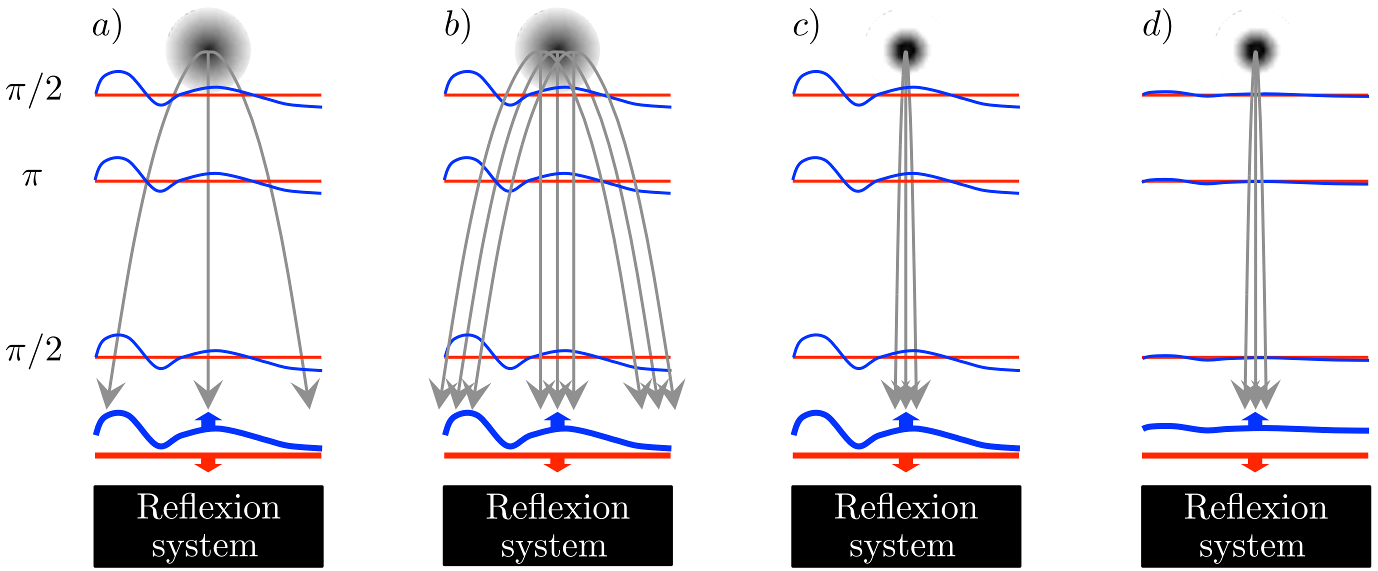
Effect	Bias µGal	u µGal
Alignments	0.3	0.5
Frequency reference	0.5	<0.1
RF phase shift	0.0	<0.1
vgg	-13.4	<0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	0.8
Wavefront aberrations	-5.6	1.3
LS1	0.0	<0.1
Zeeman	0.0	<0.1
LS2	-3.6	0.8
Detection offset	0.0	0.5
Optical power	0.0	0.5
Cloud indice	0.4	<0.1
Cold collisions	<0.1	<0.1
CPT	0.0	<0.1
Raman α LS	0.3	<0.1
Finite Speed of Light	0.0	<0.1
TOTAL	**-28.5**	**2.0**

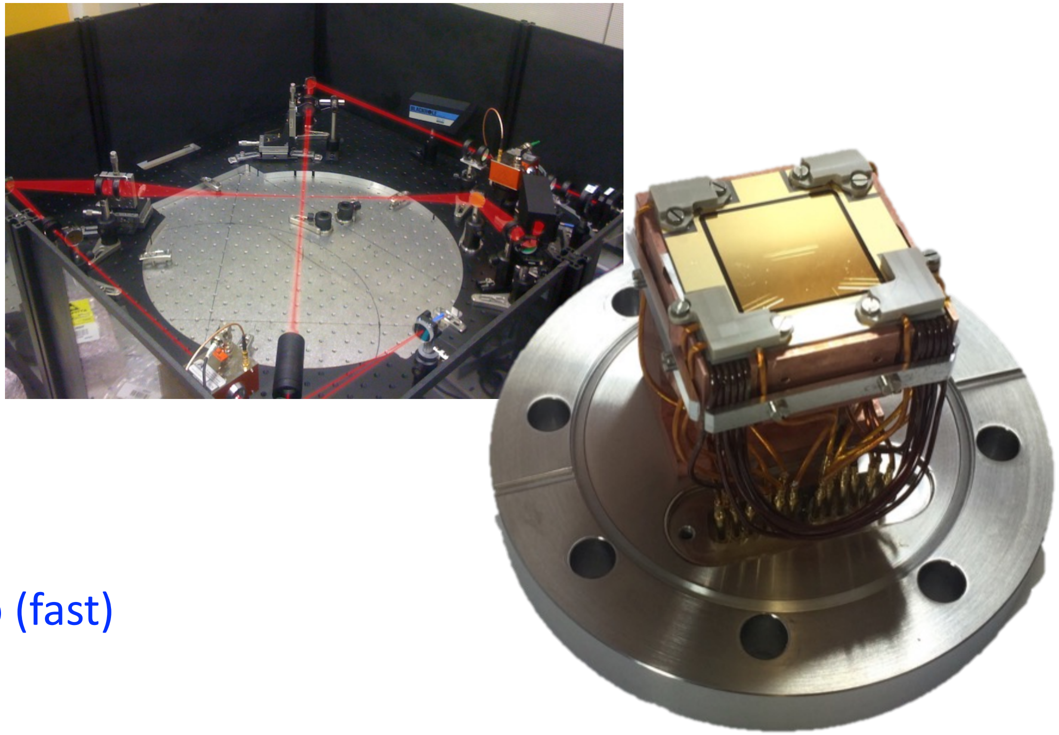




Several teams at similar level
Comparison needed. How to go further ?

Evolution, improvement



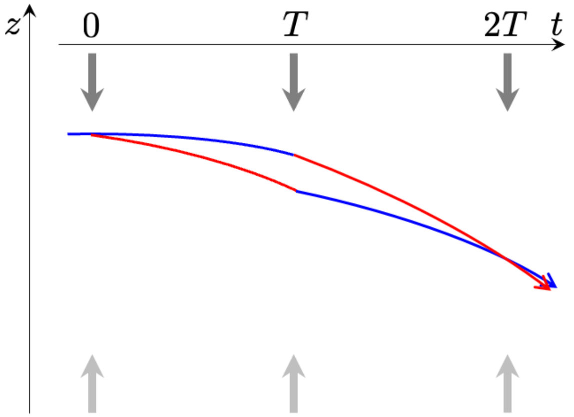


From cold (µK) to ultra-cold (nK) atomic source : optical or magnetic trap (fast)

→ Metrological tool to investigate wavefront bias : accuracy
→ Stabilize the atom source point : long term sensitivity

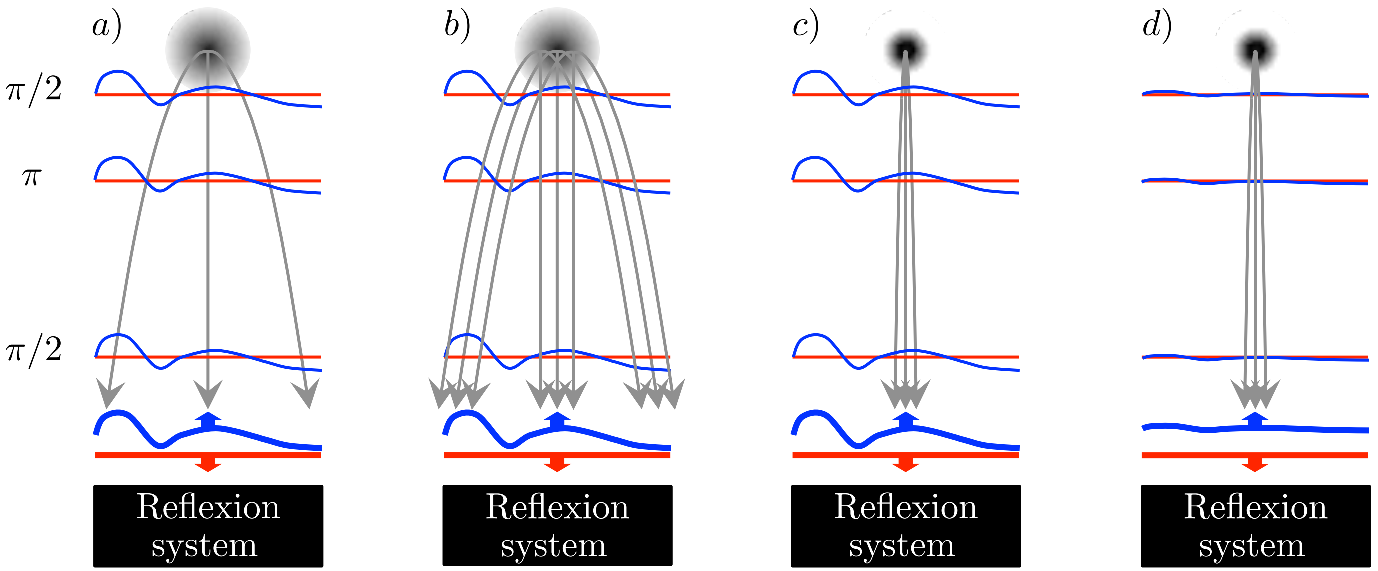
From 2 to 2×N photon transitions : LMT, Bragg
(and *T*)
→ Improve the scale factor, so sensitivity

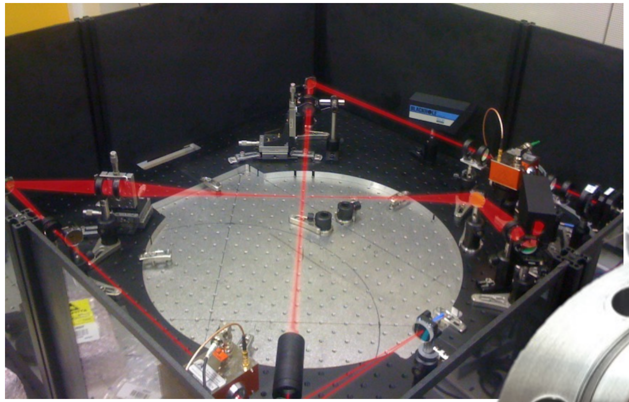
$$\triangle\Phi = \vec{k}_{\text{eff}}\vec{g}T^2$$

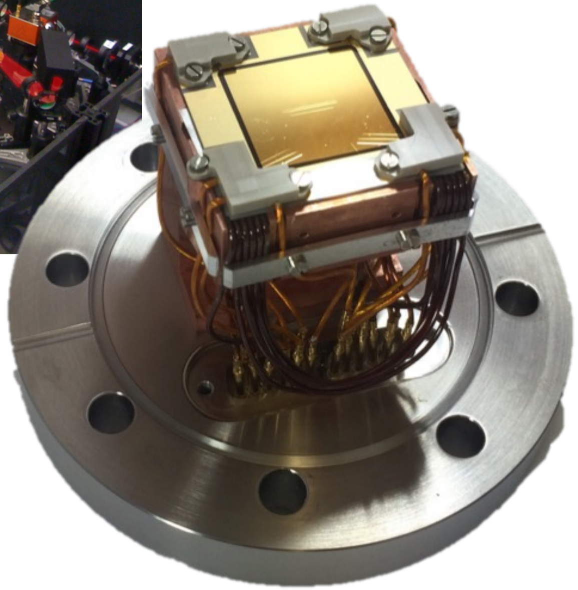


$2\hbar k$

Evolution, improvement







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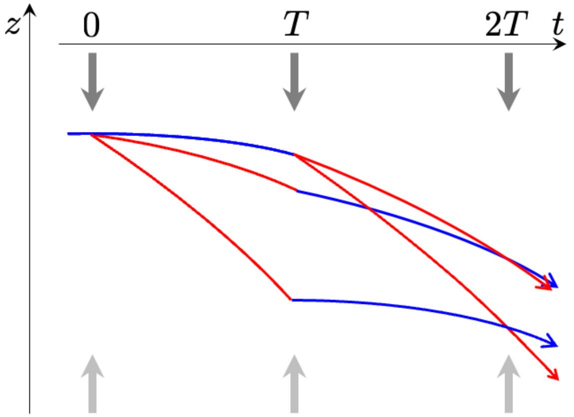
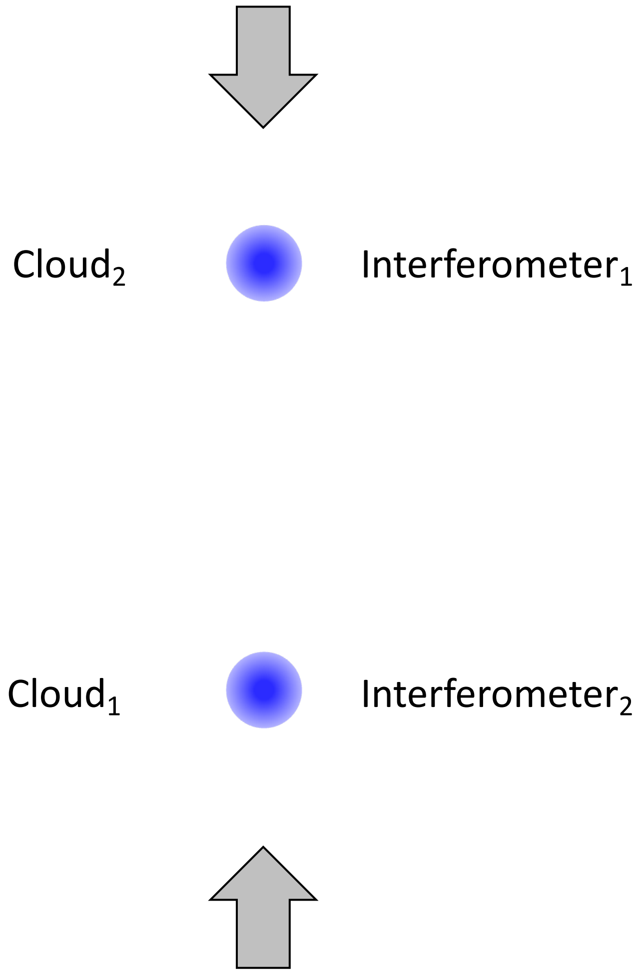


$2\hbar k$

$2N\hbar k$

New sensors, with improvements



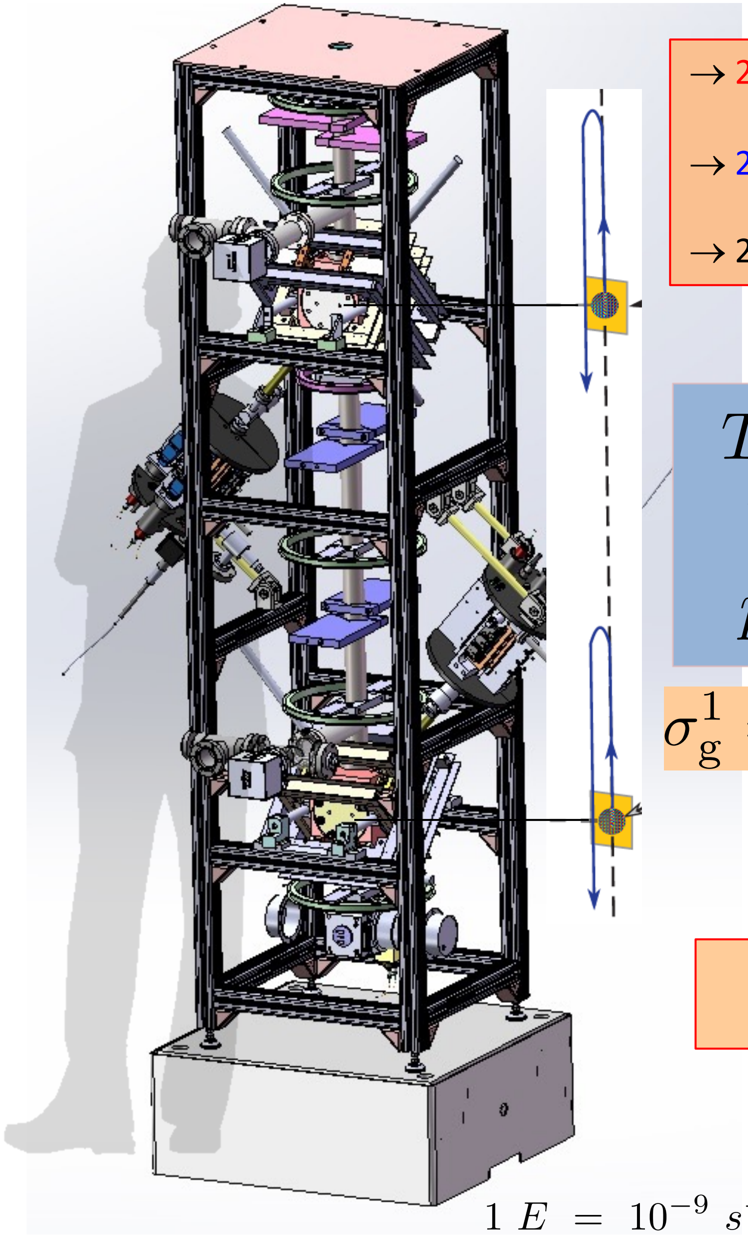
$g_1, \; g_2, \; g_1 - g_2$

- Simultaneous interferometers on two cold atom clouds with common lasers
- Differential measurement allows for extracting the acceleration difference (and thus the Earth gravity gradient)
- **Suppression of common mode noise**, and in particular of the vibration noise
- Adapted for onboard measurements
- *g* and *Δg*: resolve ambiguities in determination of mass and position

With the new tools

- High order Bragg diffraction LMBS with up to N photons
- Ultracold atoms Fast generation on atom chip

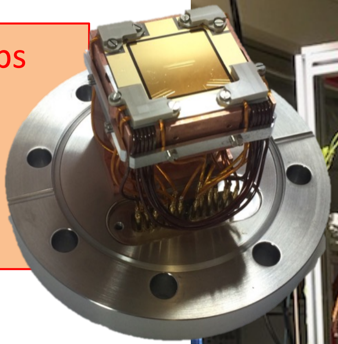
Quantum dual gravi-gradio meter



→ 2 ultracold Rb clouds obtained on 2 chips

→ 2 clouds launched with elevator

→ 2 Interferometers drived by LMTB



Targeted parameters

$$T_c = 2s \quad N_{\text{atoms}} = 5.10^5$$
$$T_{emp} = 10 - 100nK$$
$$p = 100\hbar k \quad 2T = 0.5s$$

$$\sigma_{\text{g}}^1 = 9 \times 10^{-11} m.s^{-2}.Hz^{-1/2}$$

If limitated by QNP

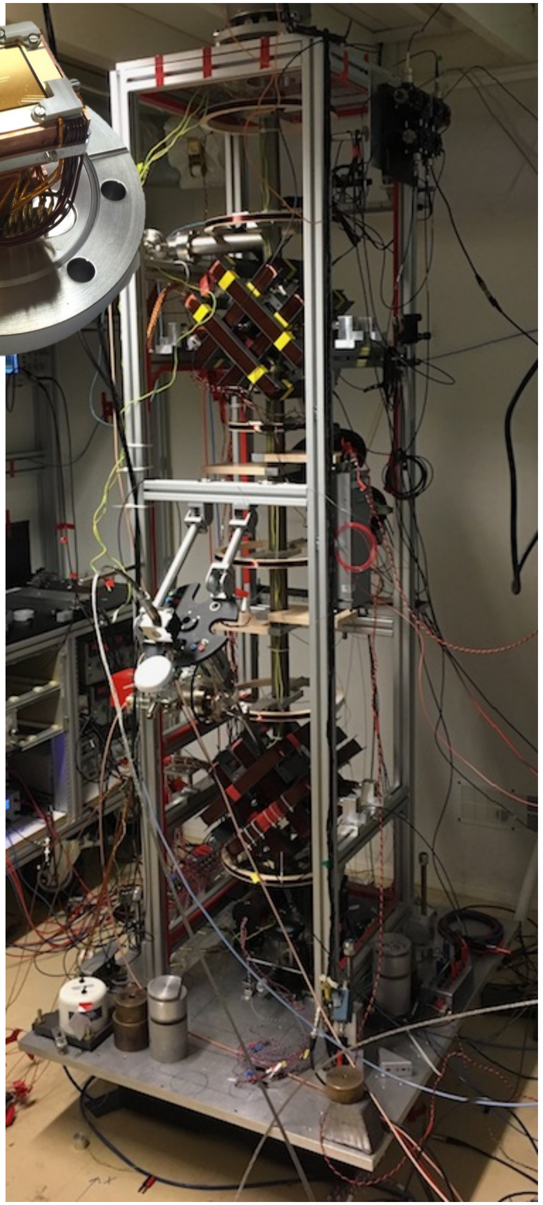
$$\Delta z = 1m$$

$$\sigma_{\text{gradg}} = 126\ mE\ @1s$$

More than one order of magnitude better than state of the art

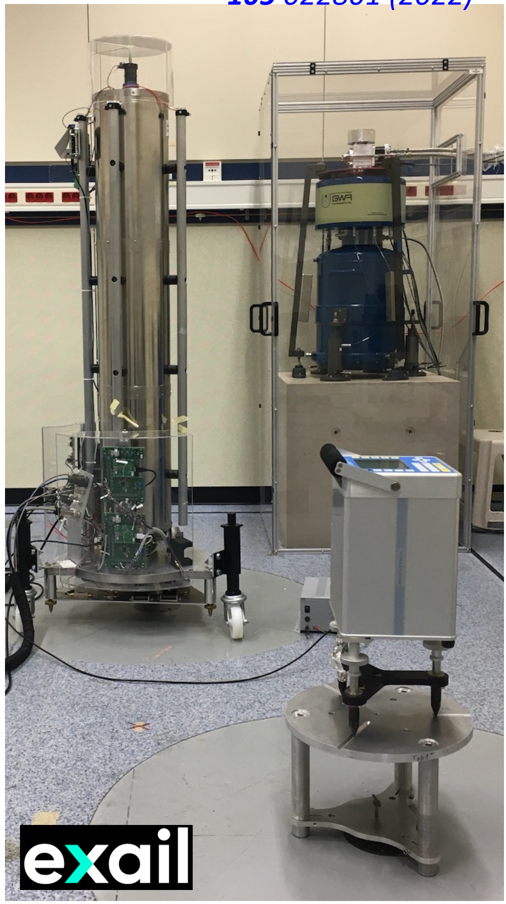
$$1\ E\ =\ 10^{-9}\ s^{-2}\ =\ 0.1\ \mu\ Gal.m^{-1}$$

R. Caldani et al., Phys. Rev. A ***99*** *033601 (2019)*



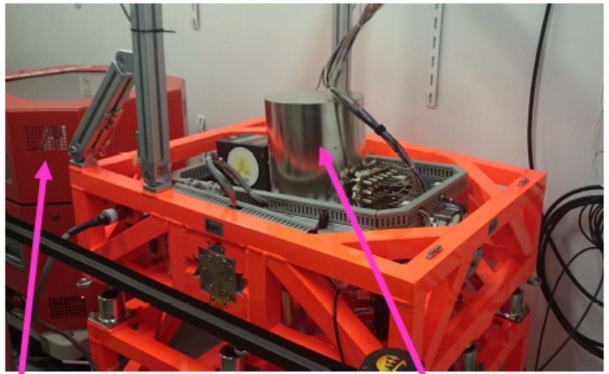
Method of dual measurement transfered in frame of a collaboration.

C. Janvier et al., Phys. Rev. A ***105*** *022801 (2022)*



Mobile sensors : more than transportable, onboard measurements

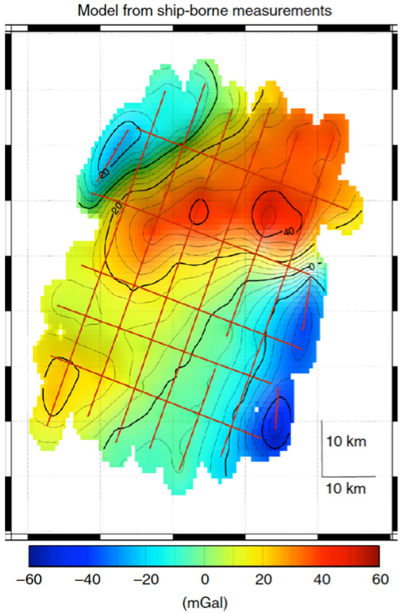
ONERA compact gravimeter for marine gravimetry cartography



Y. Bidel et al Nat Commun. 9, 627 (2018)

KSS32 relative Marine Gravimeter (Bodenseewerk)

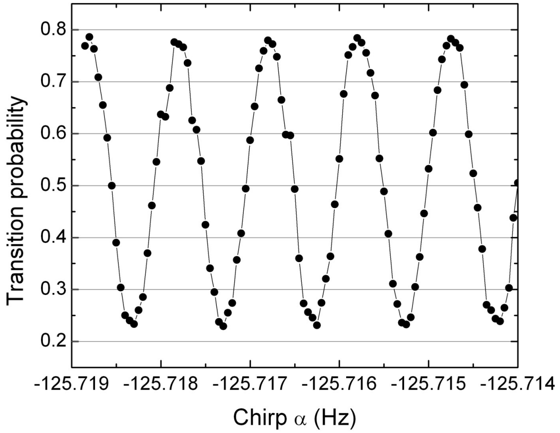
Cold Atom Gravimeter (Onera)

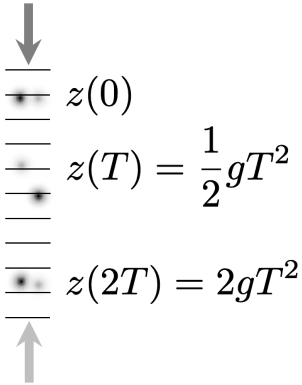


With a gyrostabilised platform. Better performance of Girafe2 absolute sensor: suppression of errors due to initial calibration and drift of relative sensor. Gain : factor 2-3

+ flying campaign

Y. Bidel et al J. Geod. 94, 20 (2020)



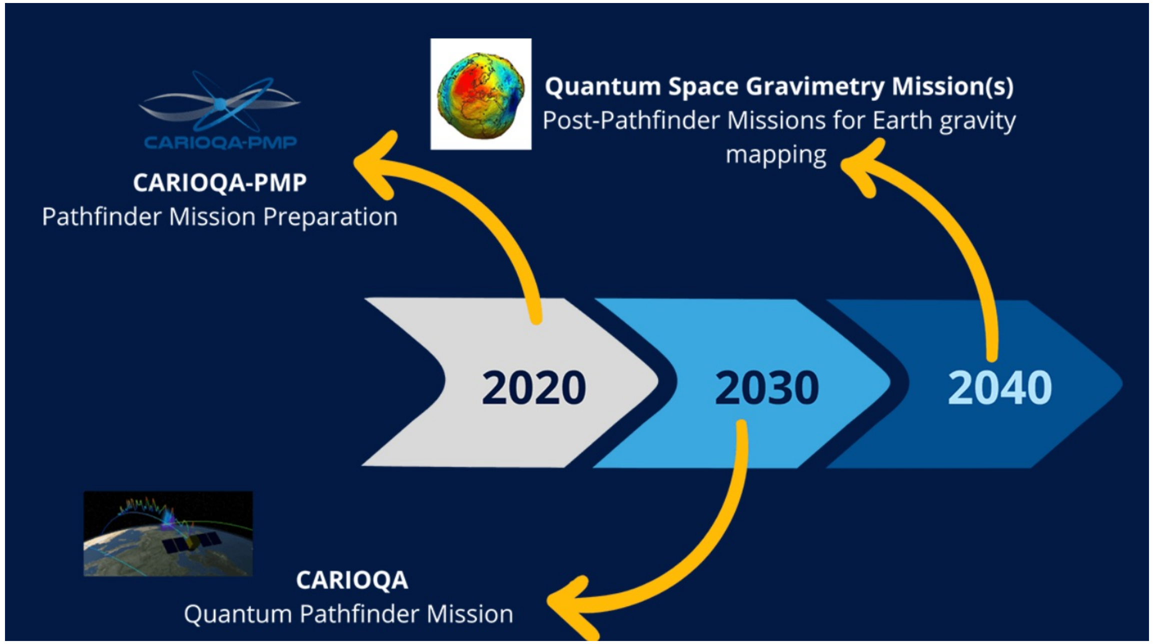


ADEQUADE (Advanced, Disruptive and Emerging QUAntum technologies for Defense) European Defence Fund lead by THALES with ONERA

Strap down sensor: so franges problem, atom in the beam ? control optimal, tip tilt, top hat

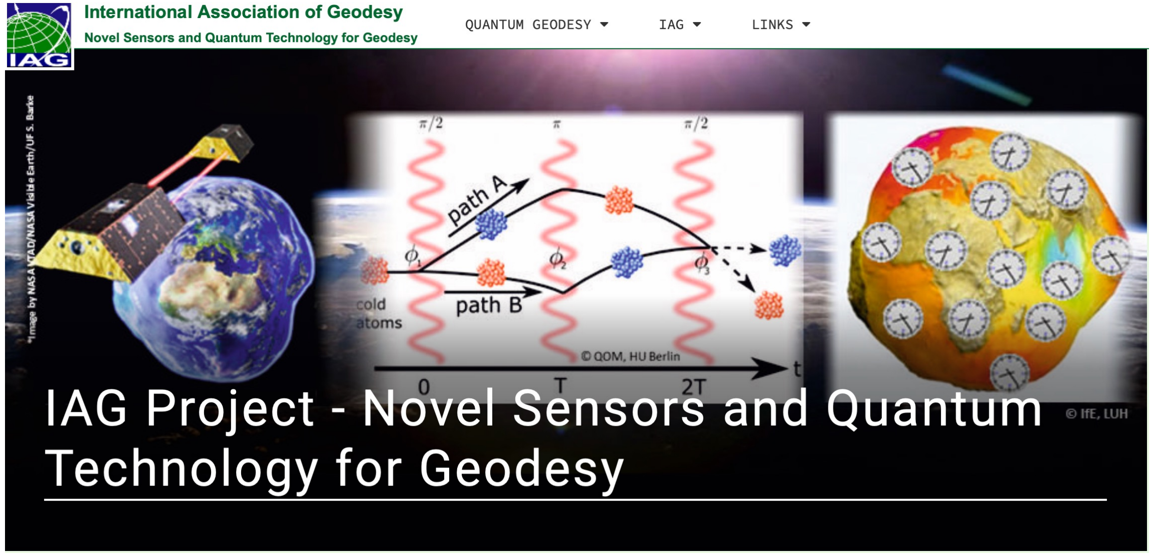
Going farer ? Space

Space



https://carioqa-quantumpathfinder.eu

https://quge.iag-aig.org

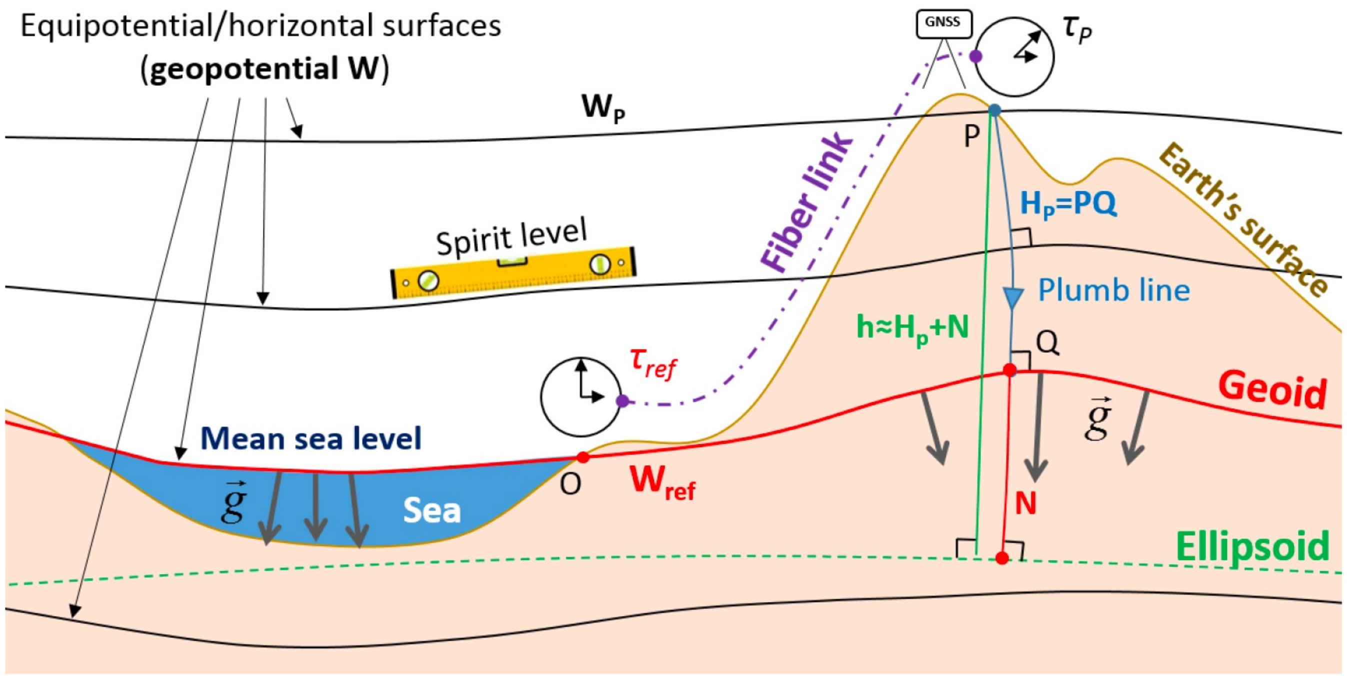


WG Q.1: Quantum gravimetry in space and on ground

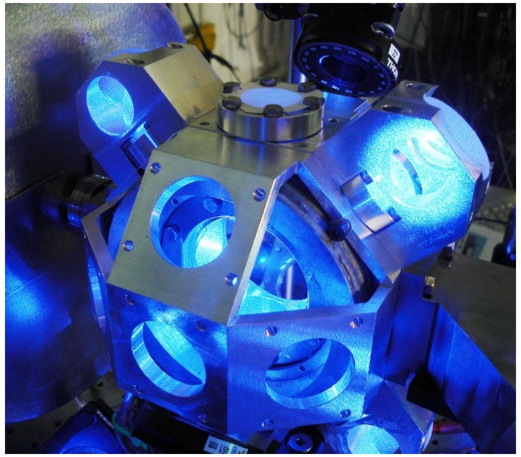
WG Q.2: Laser interferometry for gravity missions

WG Q.3: Relativistic geodesy with clocks

Clocks

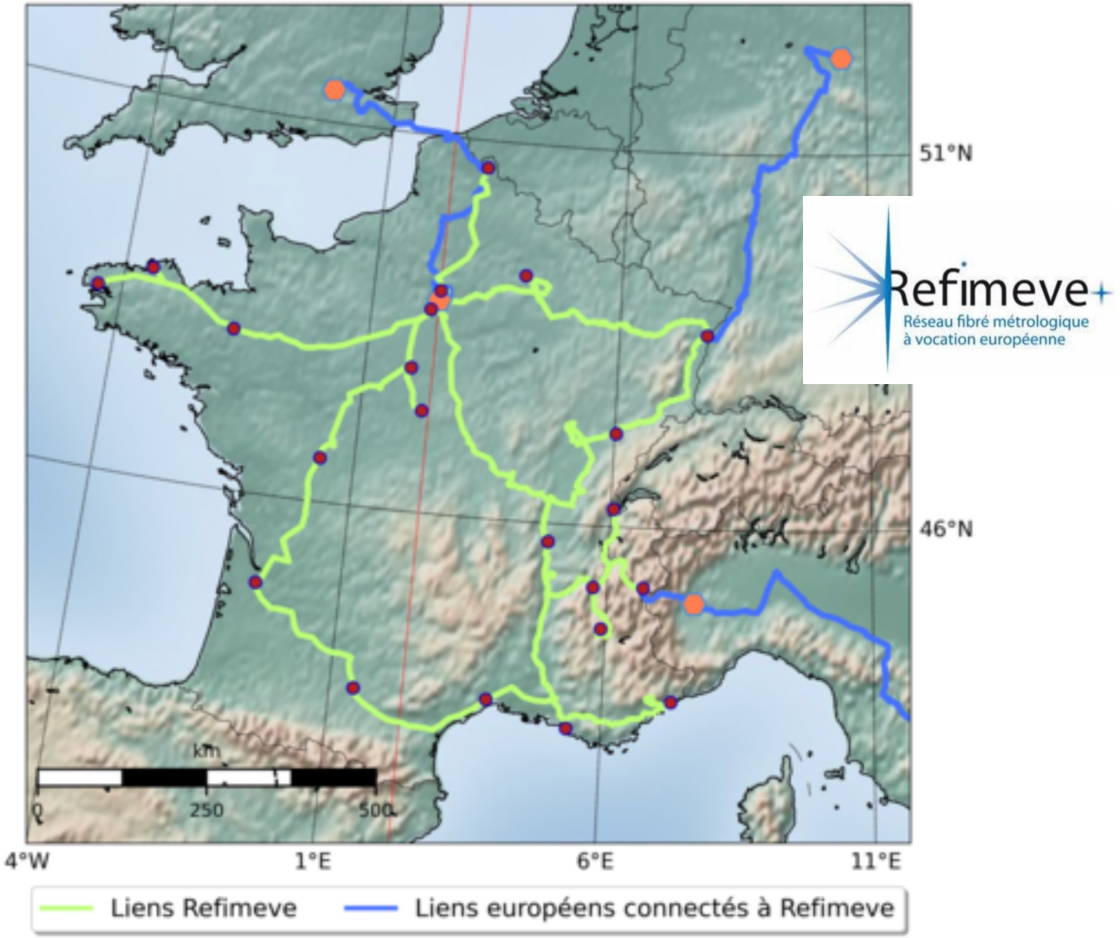


$$1cm \rightarrow 10^{-18}$$



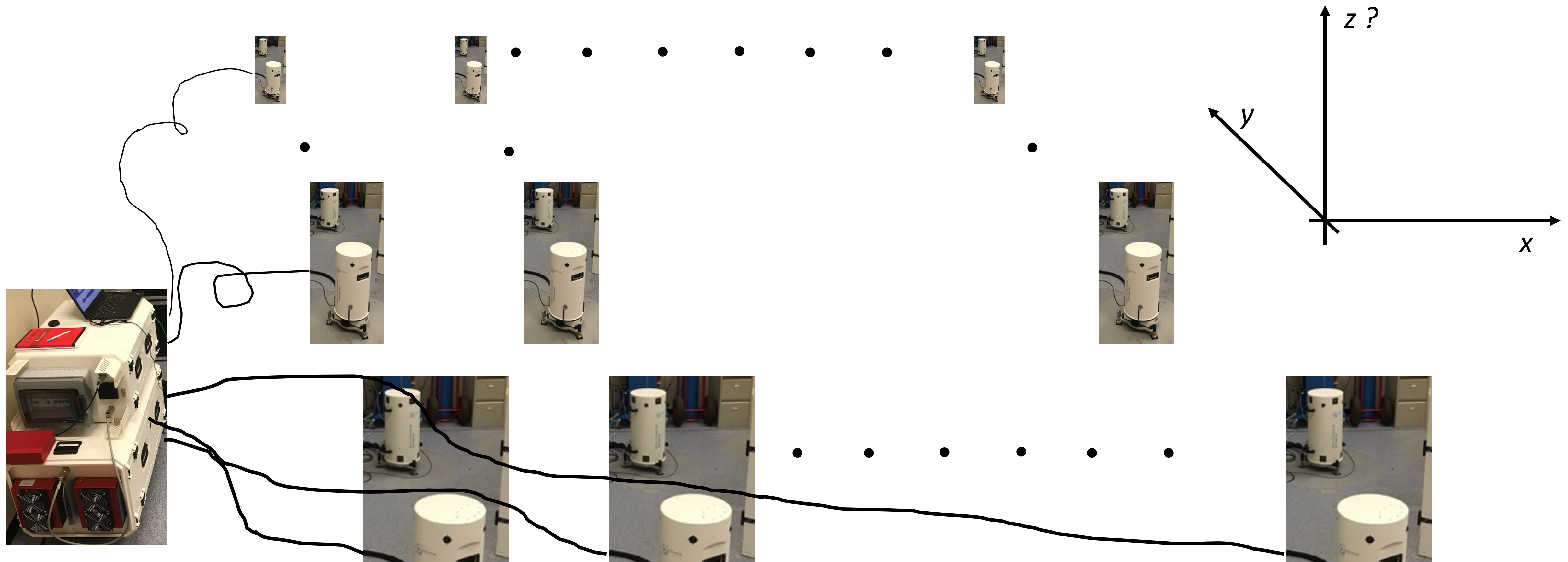
Fixed lab clocks
Movable clocks

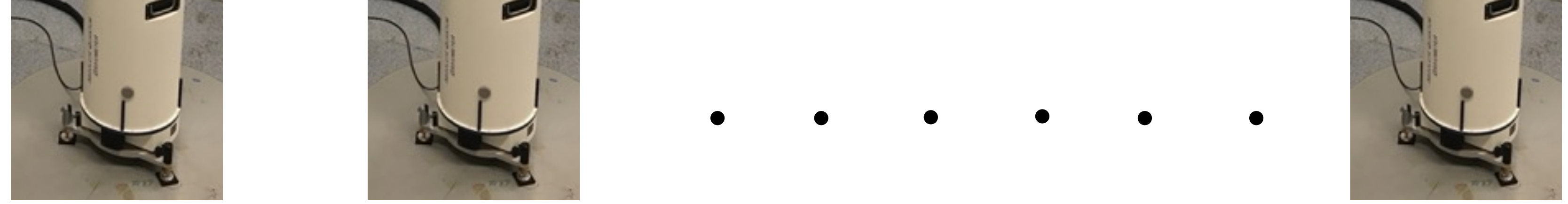
https://www.refimeve.fr



Why not using this network to, not only connect clocks, but also gravi-gradio-meters ? Altogether.

Arrays





Common laser source
Clocks, gravimeters, gradiometers, fibered linked

Conclusion

Atomic sensors (gravimeters, gradiometers, dual gravi-gradiometers, gyroscopes, clocks, arrays of quantic sensors) are promissing devices to establish references.

Because they are metrologicaly studied, absolute, no drift, limits not identified.

All scales, from ponctual to space, we will need nodes stations for continuous measurements, and satellites for global ones.

Need of several sensors at top level, in agreement, metrological.

Many countries involved. Many domain involved.

Industrial transferts (fiabilisation, automatisation).

Establishing and maintaining a long term geodetic reference system is of key importance for climate monitoring and Earth observation systems. This long standing objective of the geoscience community is well supported by relevant international organisations. The need of better monitoring of critical parameters, such as ocean level, demands an improved accuracy of the ***global reference system down to the mm level****, which constitutes the challenge to meet to evaluate accurately the cumulative impact of climate changes.*

State of the art

$1\ \mu Gal = 10\ nm.s^{-2} \sim 10^{-9} g$

Type	Techno	Institut / Company	Name	ν_c Hz	u μGal	u_{wfab} μGal	σ_g μGal	τ s	Rq
Abs	FFCC	Micro-g	FG5X	0.3	2.0	.	~ 1.0	~ 100	dead time,
		Lacoste		0.1	.	.	1.0	~ 700	wearing
Rel	Supra	GWR	iGrav	1.0	.	.	0.01	600	drift
Abs	Atom	SYRTE	CAG	2.8	2.0	1.3	5.7	1	T=80ms
					.	.	1.0	36	dropped atoms
					.	.	0.06	20 000	
Abs	Atom	HUB	GAIN	0.7	3.2	2.2	9.6	1	T=260ms
					.	.	1.0	100	launched atoms
					.	.	0.05	100 000	
Abs	Atom	HUST		0.5	5.0	.	4.2	1	T=300ms
					.	.	1.0	18	launched atoms
					.	.	0.3	200	
Abs	Atom	muquans	AQG		.	.	59.4	1	
					.	.	1.0	4000	dropped atoms
					.	.	0.3	200 000	
Abs	Atom	AOSense			.	.	.		
Abs	Atom	M Squared			.	.	.		

$$\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2$$

2T difference, not correlated with better performances

Motivation for the development of compact gravimeters (2T ≈ 100 ms, h ≈ 5 cm)