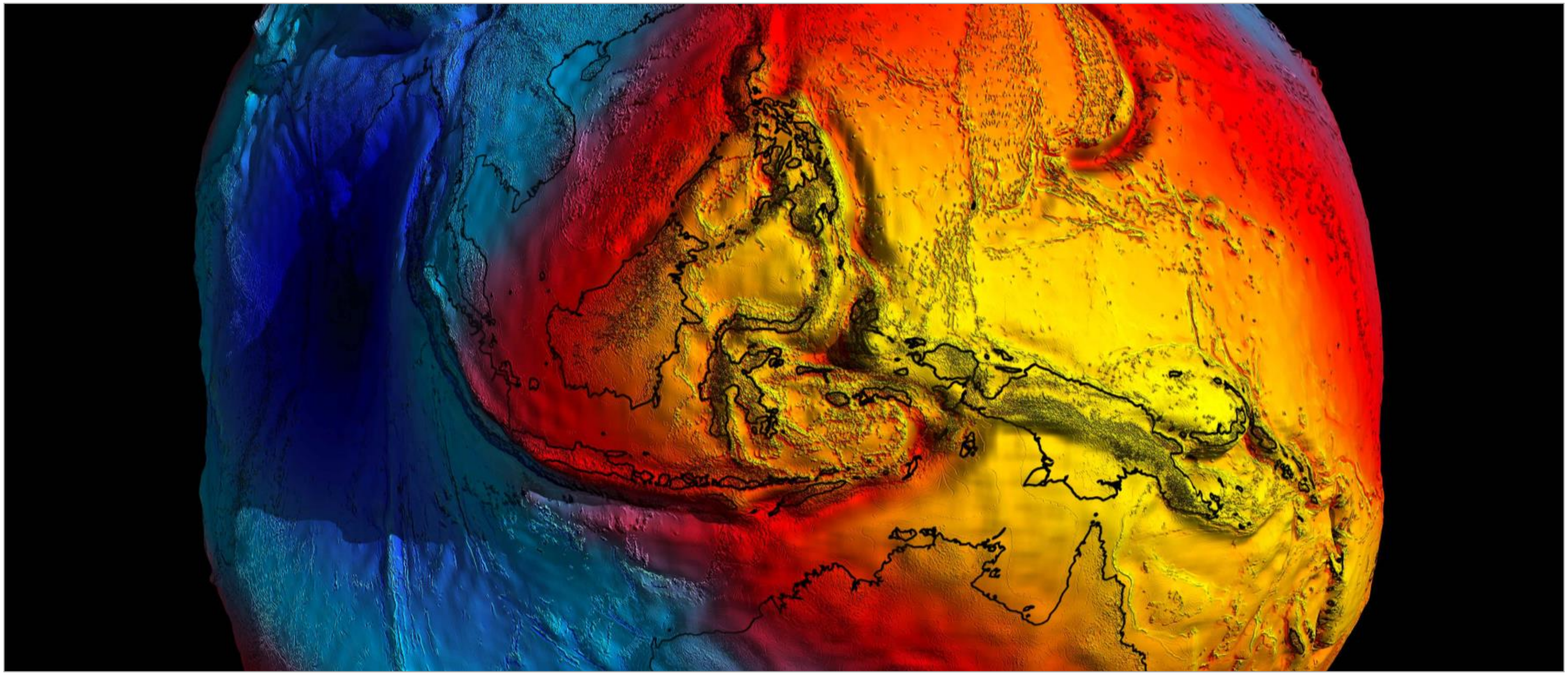
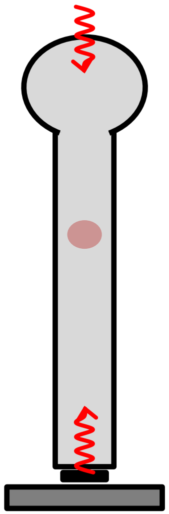
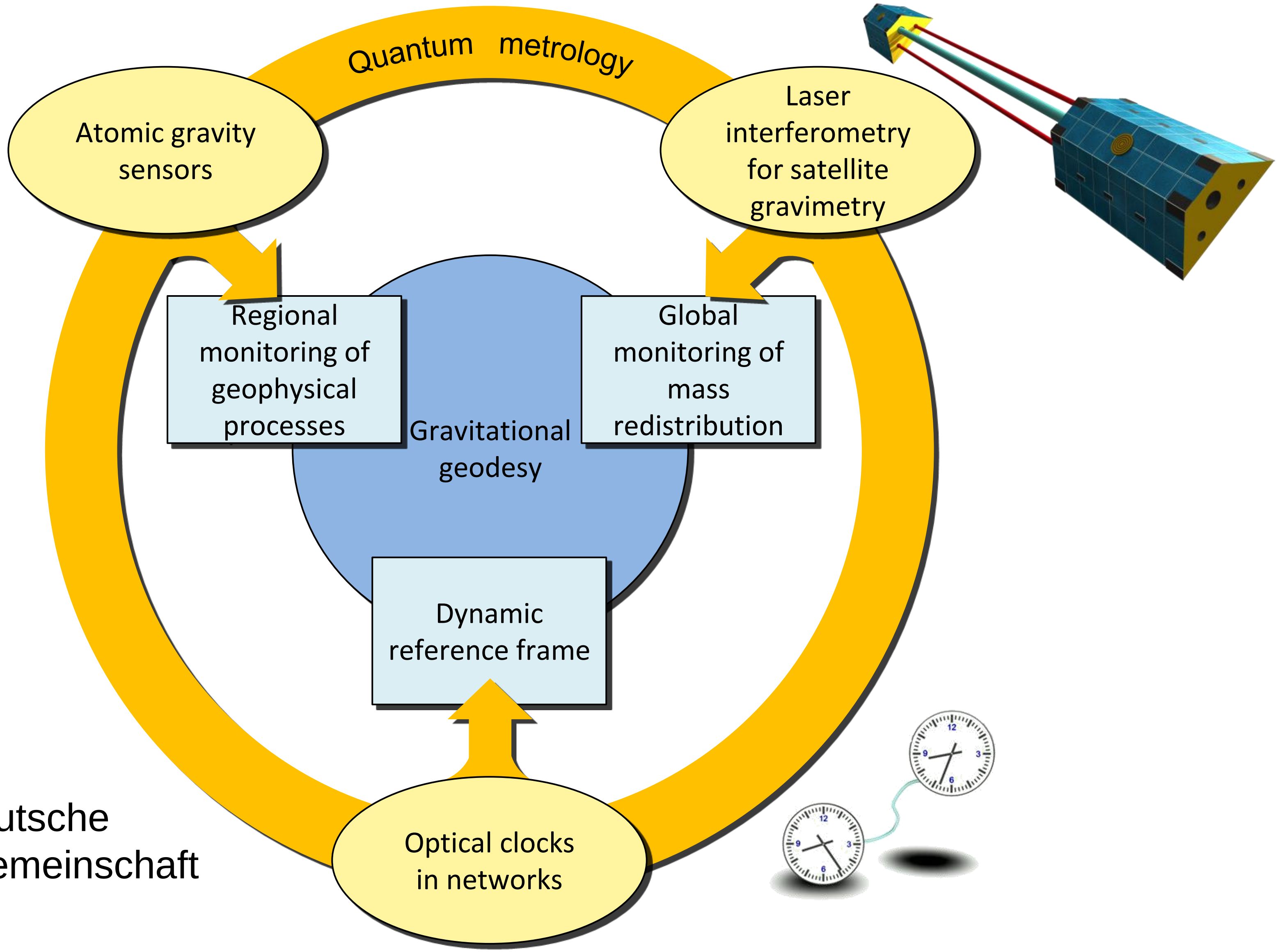
Relativistic Geodesy and Gravimetry with Quantum Sensors

Jakob Flury, Institut für Erdmessung (IfE) / Centre for Quantum Engineering and Space-Time Research (QUEST), Leibniz Universität Hannover



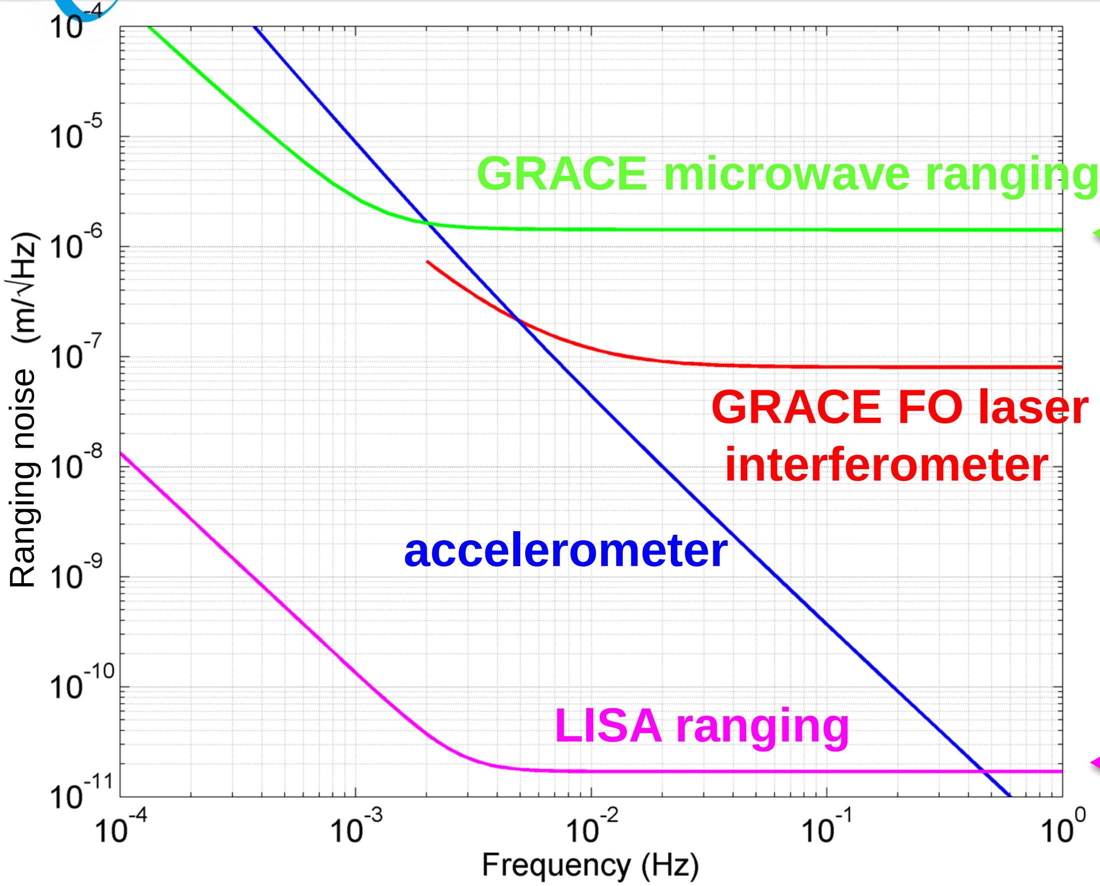
Collaborative Research Center SFB 1128 geo-Q

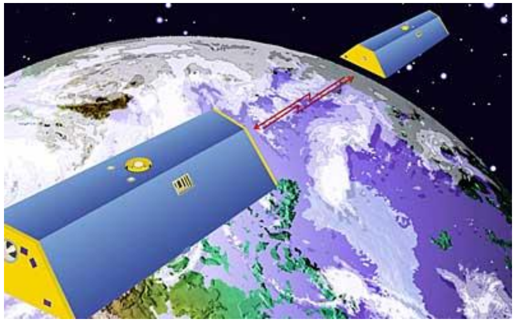




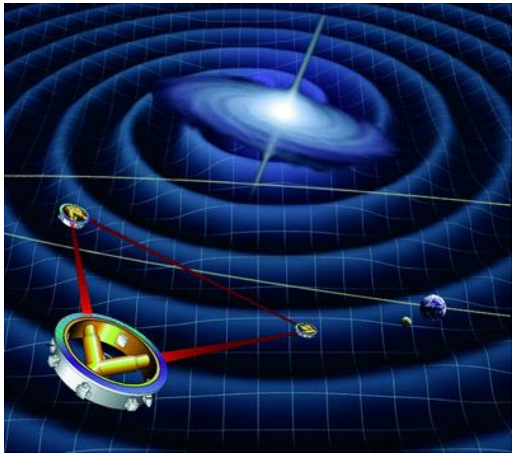
funded by Deutsche Forschungsgemeinschaft (DFG)

Laser interferometric ranging



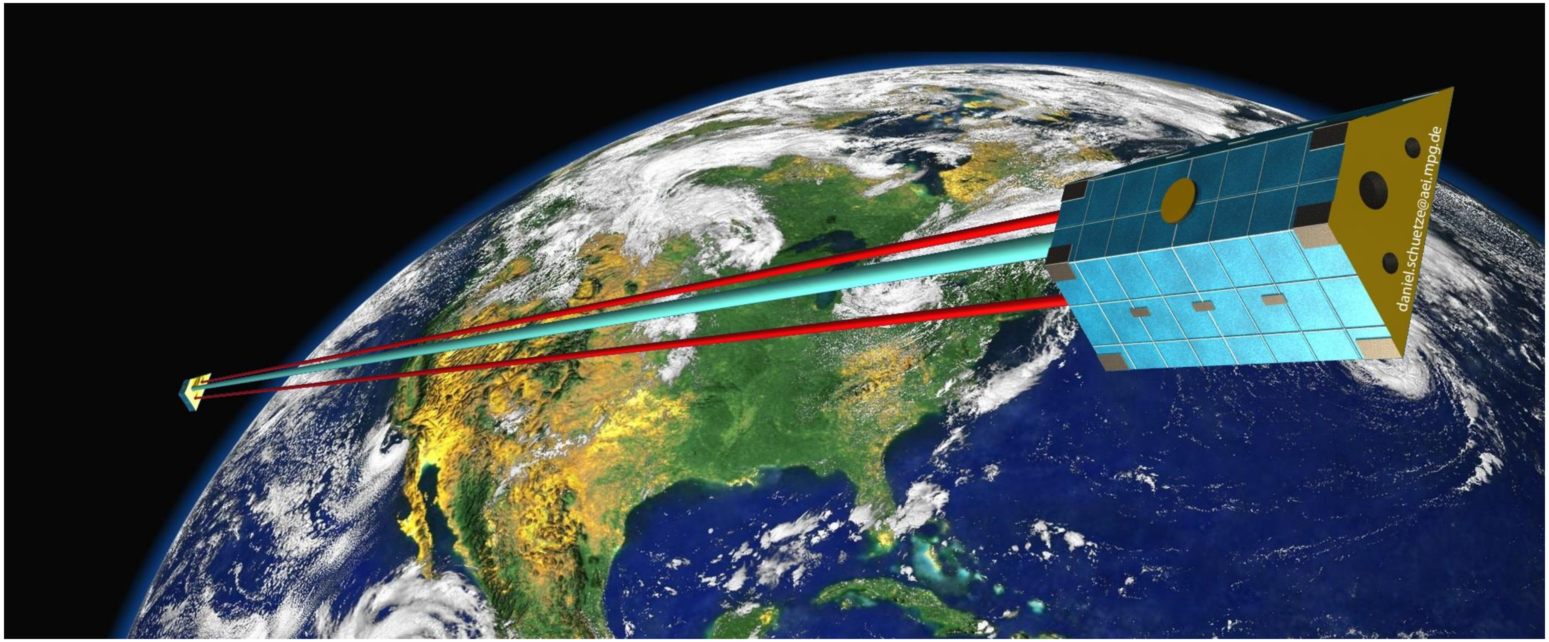


LISA



- very **low ranging noise** levels achievable in outer space
- **challenge: laser interferometry in Earth orbit**
- different environmental conditions, different target quantity: the **Earth gravitational field!**

First laser interferometer between Earth orbiters

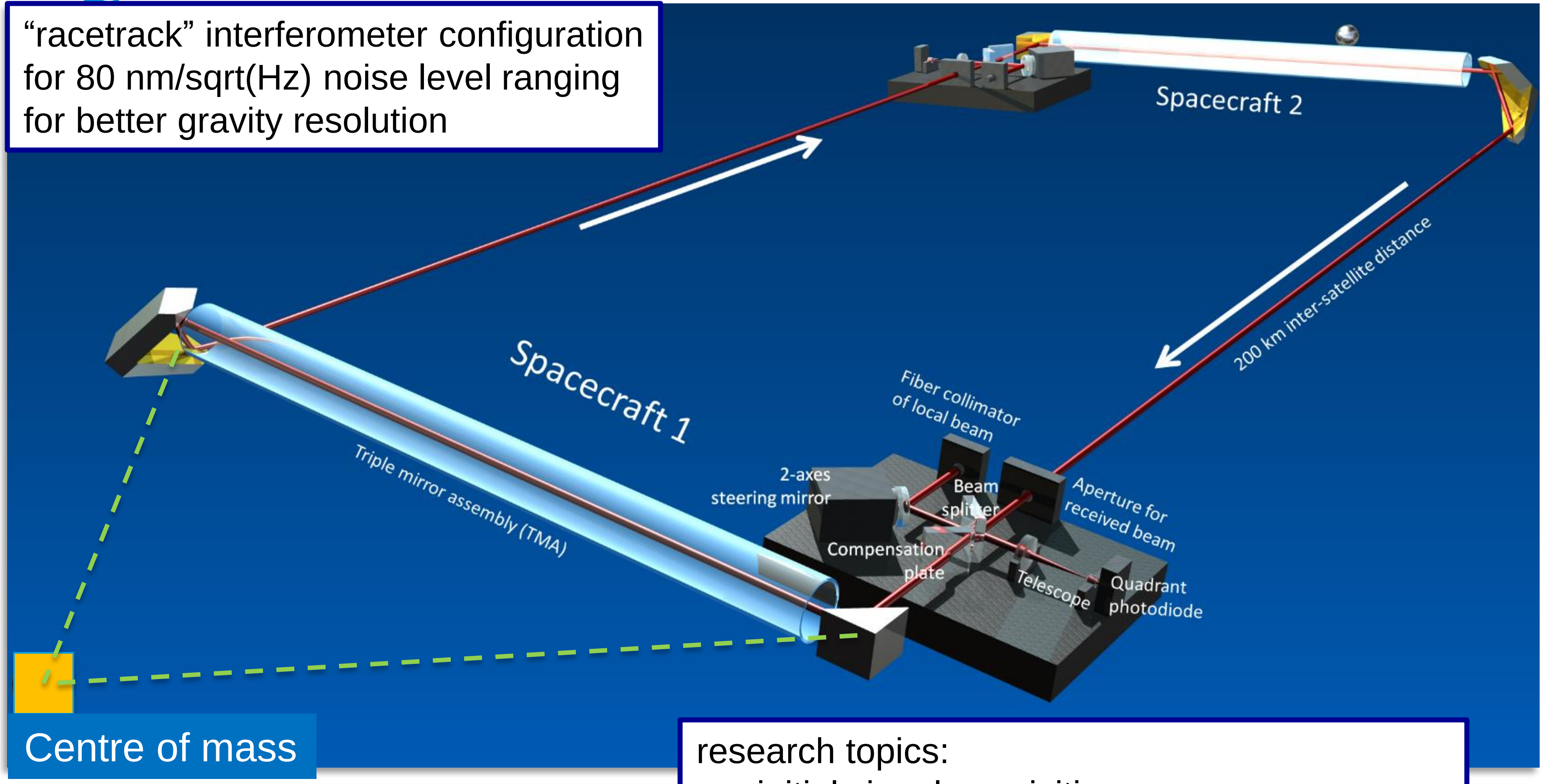


GRACE Follow-On mission 2017-2022

- experimental **demonstrator** on GRACE reflight
- design completed (NASA-JPL / AEI Hannover, group of Karsten Danzmann, Gerhard Heinzel)
- construction started
- **test case for exploring and understanding optical gravimetry in Earth orbit**

GRACE-FO Laser Ranging Interferometer (LRI)

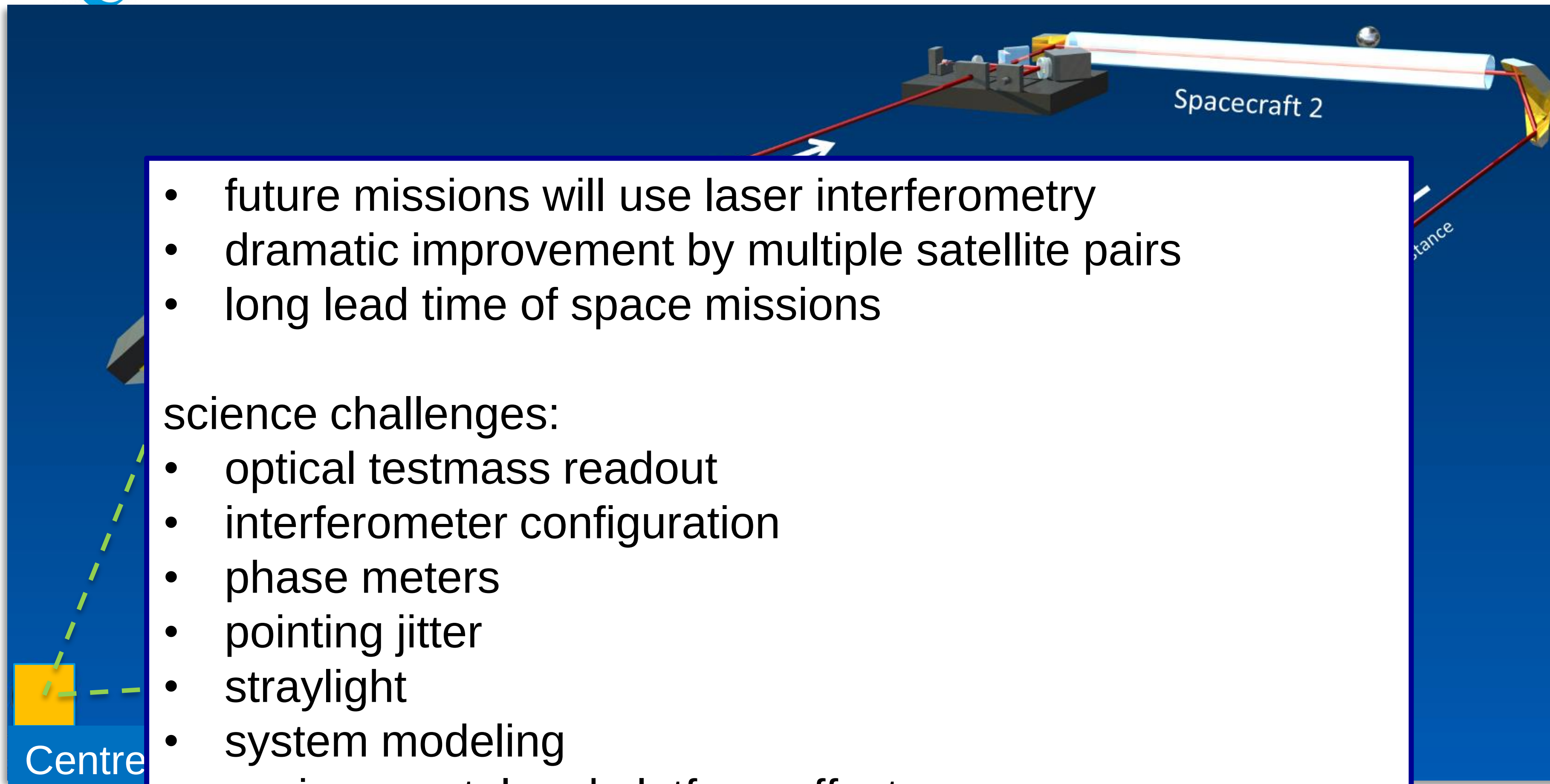
“racetrack” interferometer configuration for 80 nm/sqrt(Hz) noise level ranging for better gravity resolution



research topics:

- initial signal acquisition,
- differential waveform sensing,
- beam steering for better pointing control
- pointing jitter, optical pathlength
- combining µwave with LRI
- sensor fusion, data analysis

Beyond GRACE-FO



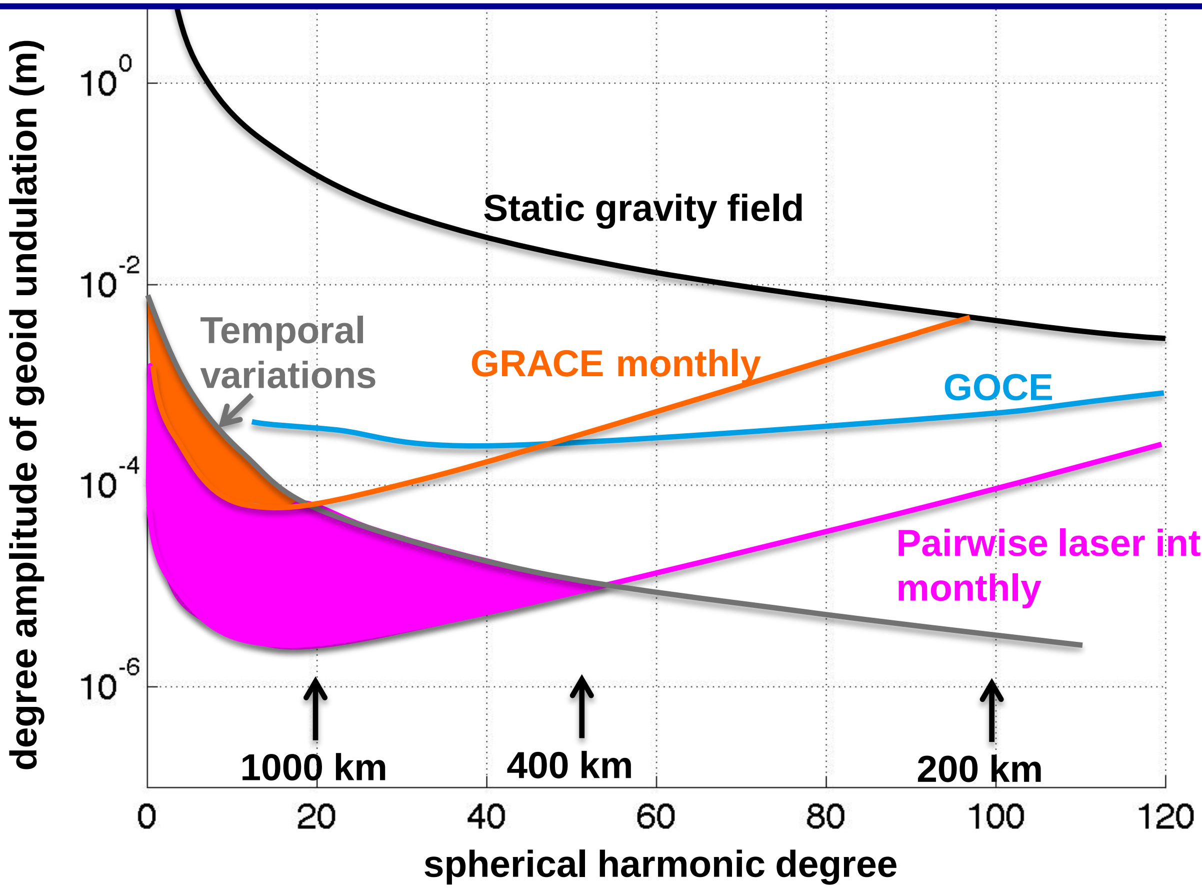
- future missions will use laser interferometry
- dramatic improvement by multiple satellite pairs
- long lead time of space missions

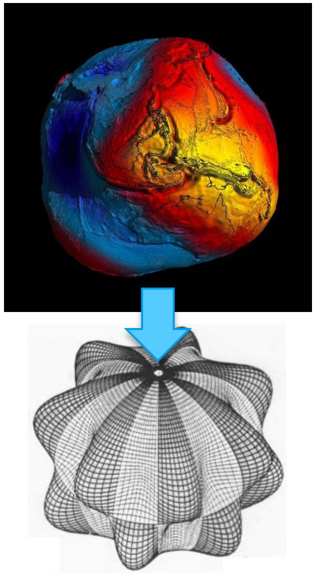
science challenges:

- optical testmass readout
- interferometer configuration
- phase meters
- pointing jitter
- straylight
- system modeling
- environmental and platform effects
- …

Enhanced resolution in gravity modeling

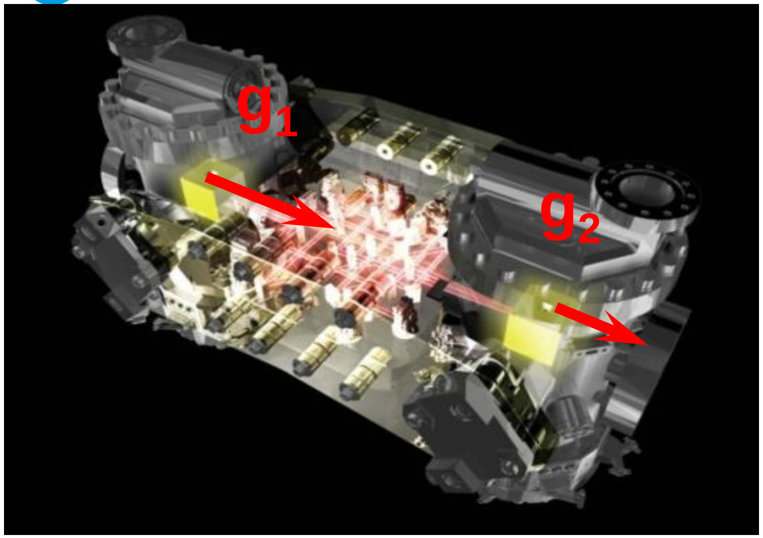
- **laser interferometry between satellites** is capable to recover temporal gravity and mass variations with significantly higher **spatial resolution**
- allows quantifying highly **relevant geophysical processes**



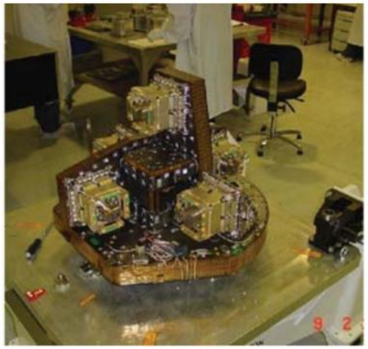


Laser interferometry scenario: Panet et al 2013

Optical gradiometry



LISA Pathfinder



GOCE

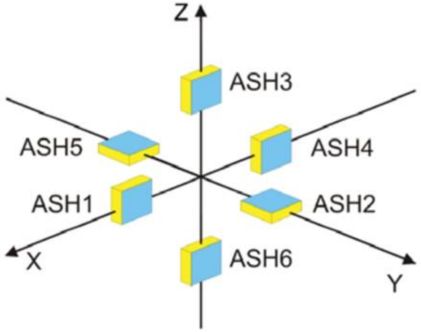
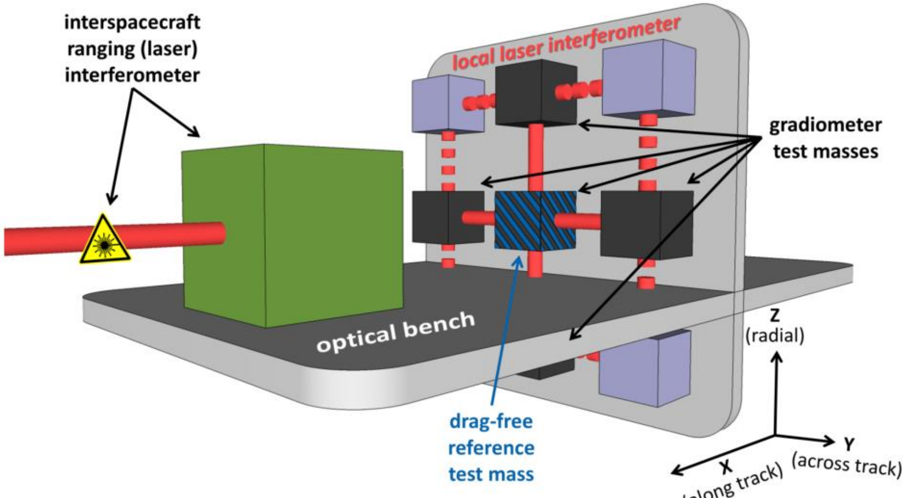
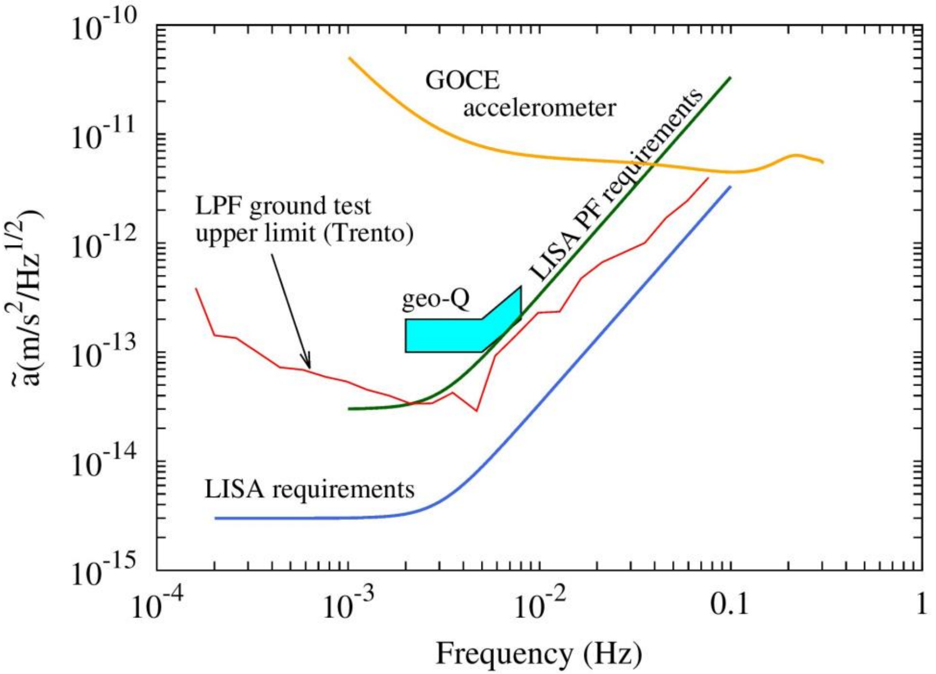


Image credit: ESA

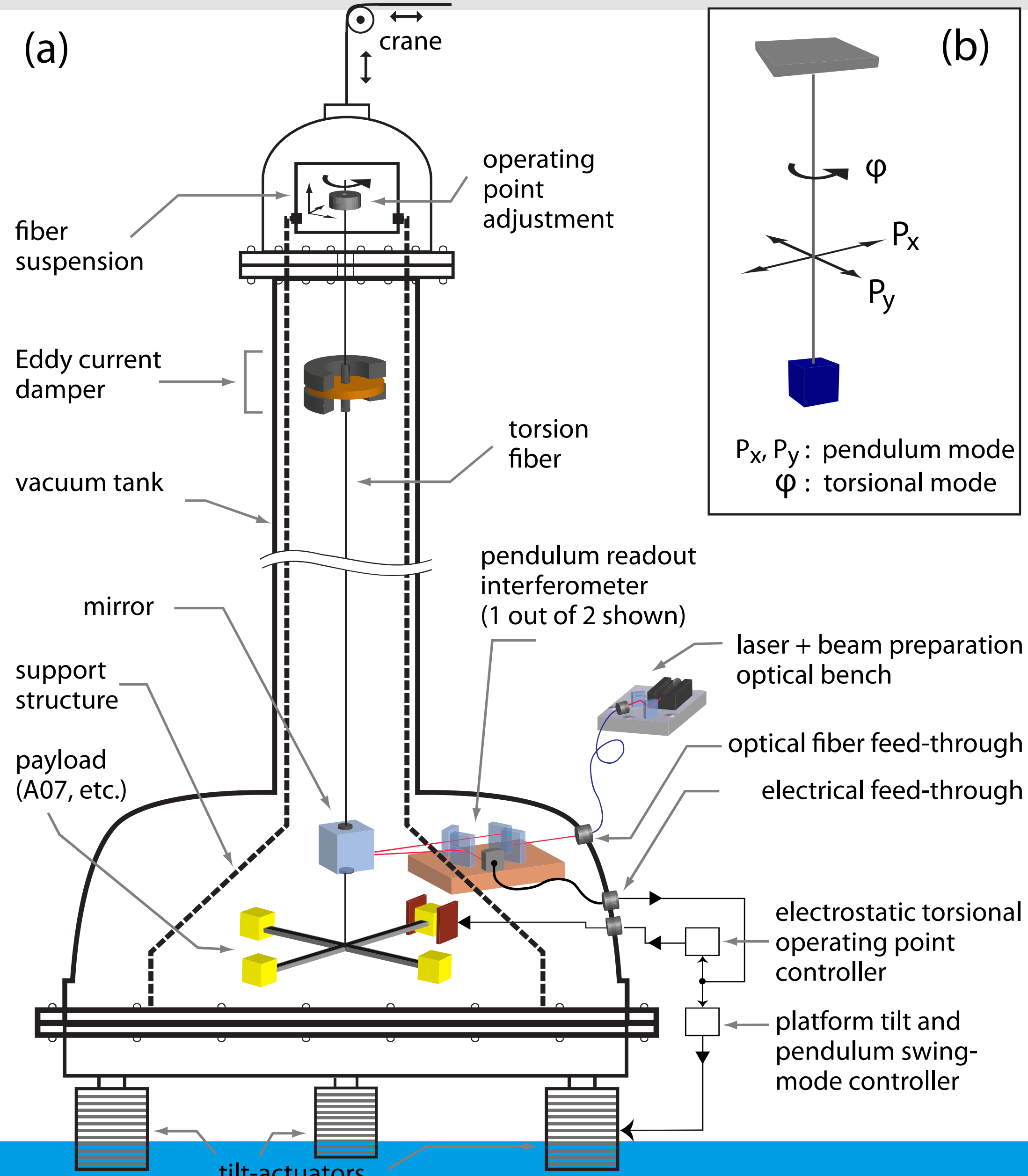




Multiple testmasses for optical gradiometry

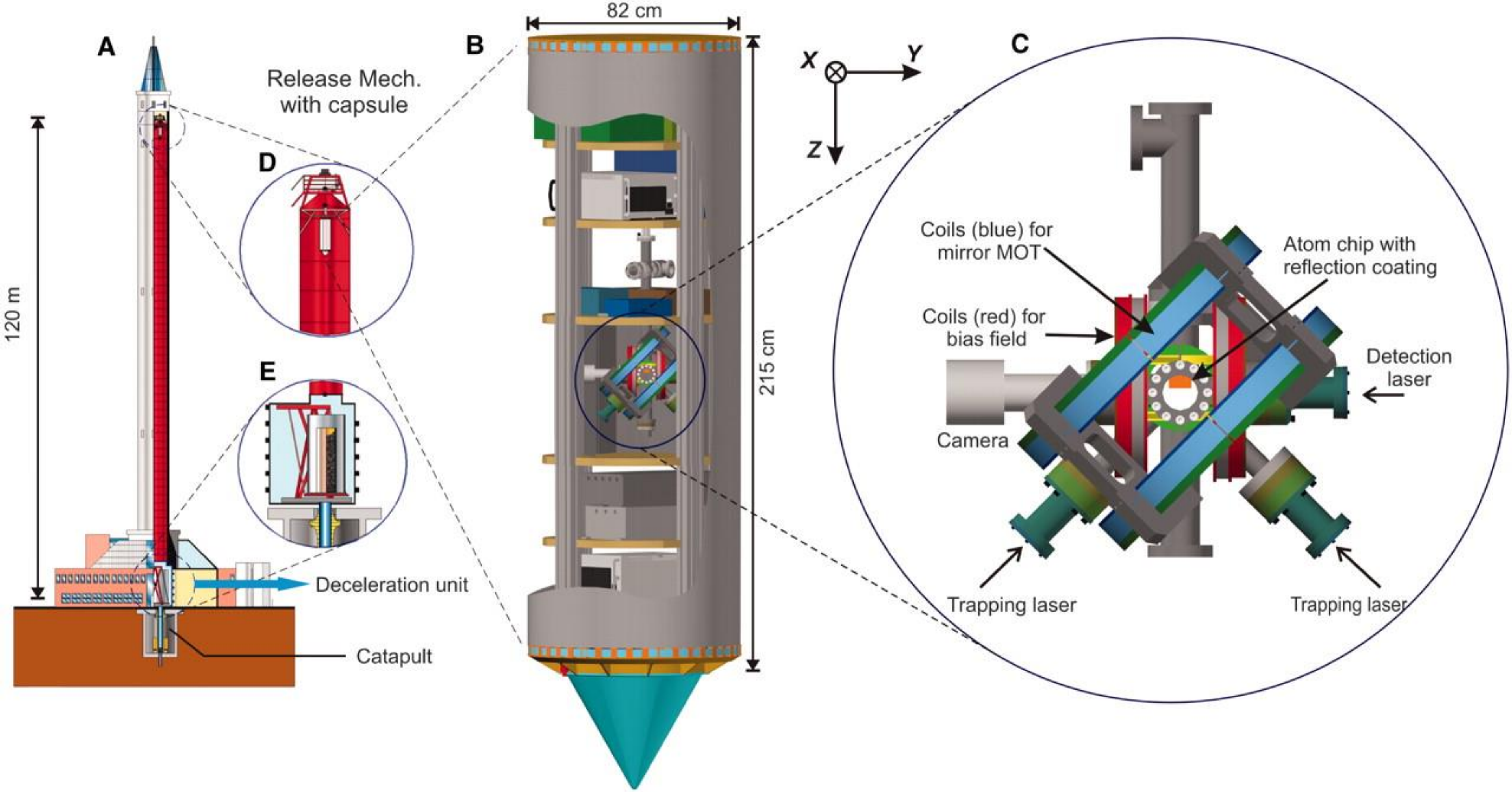
GOCE accelerometer performance using data from:
Stummer, Claudia S.: PhD Thesis, DGK, Reihe C, Heft 695
Torsion pendulum measurement data: courtesy of W.J. Weber, Trento

Torsion balance as test environment



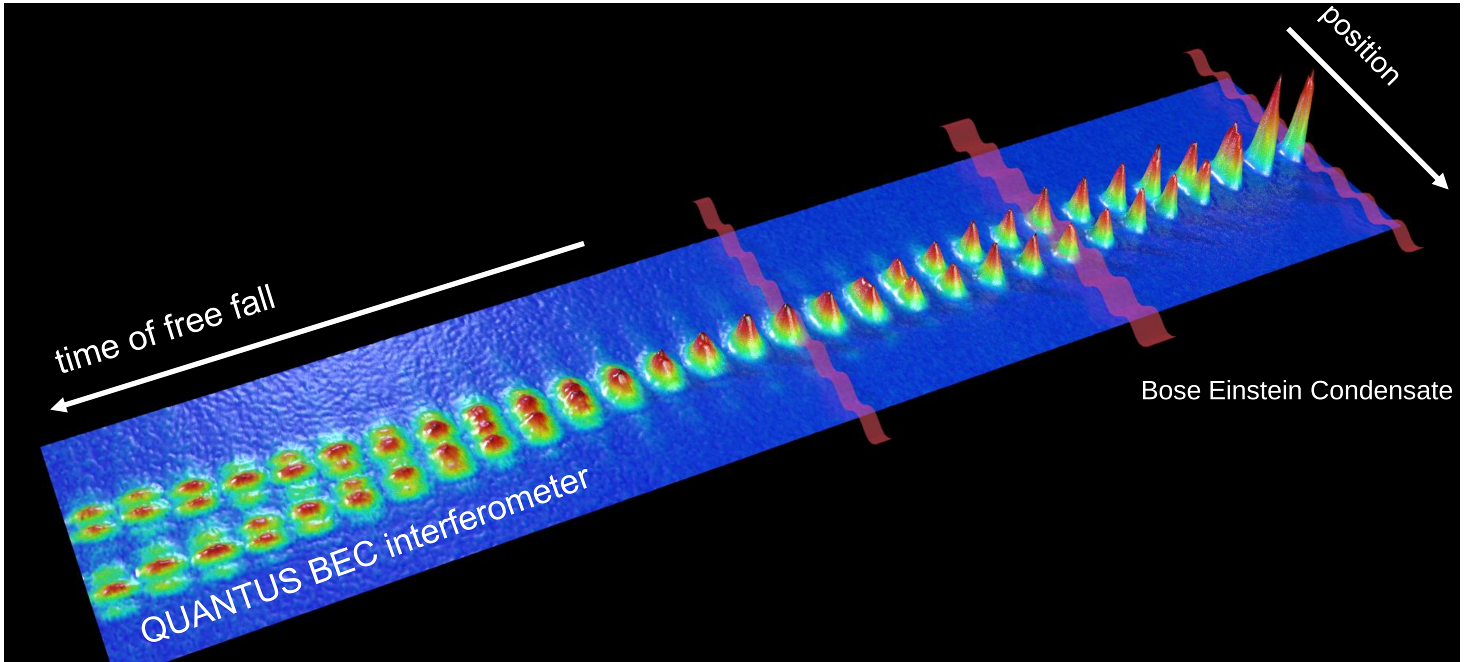
- test sensitivity to spurious forces
- test mass readout
- multi-testmass / multi-channel interferometry (> 20 degrees of freedom)

Atomic interferometry



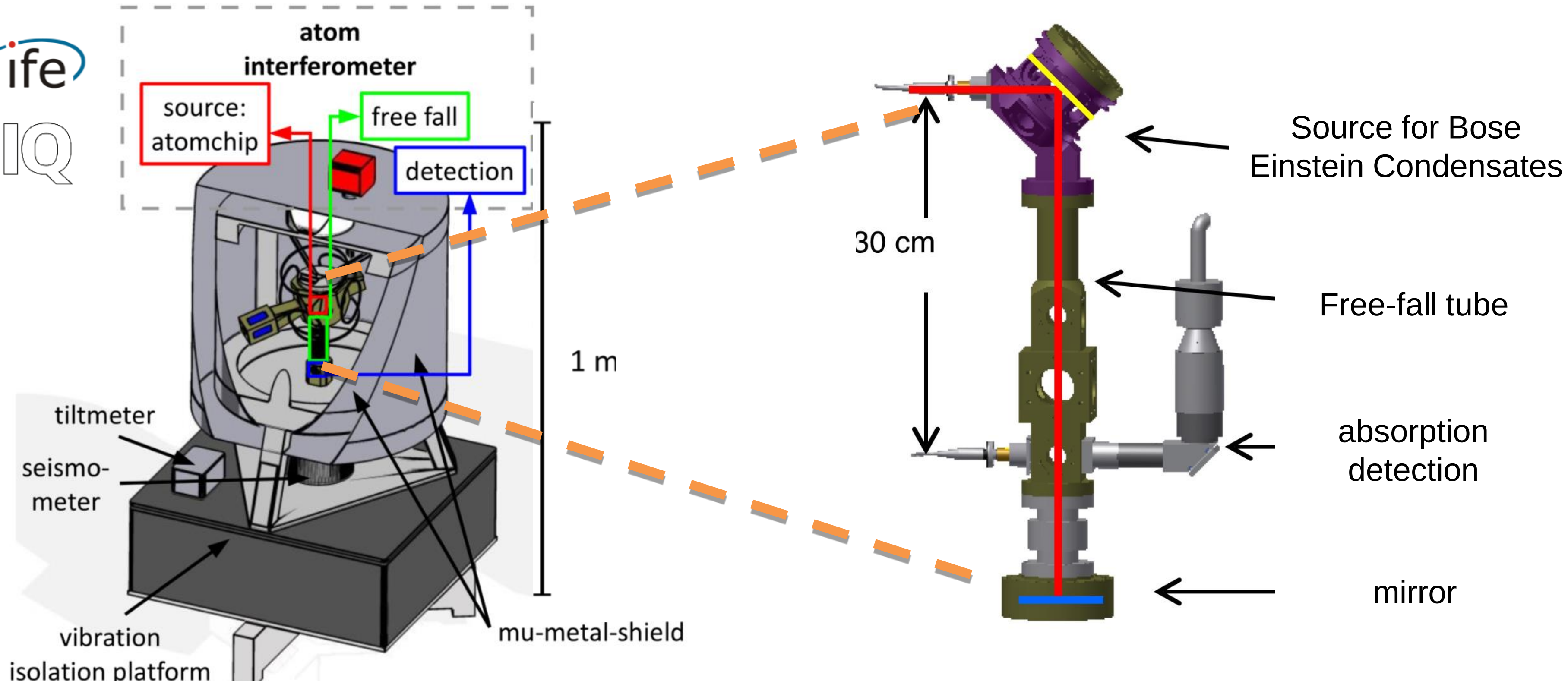
- QUANTUS experiments for quantum gases in microgravity
- DLR project in Bremen drop tower
- group of Ernst M. Rasel, Wolfgang Ertmer

Atomic interferometry



Müntinga et al., Phys. Rev. Lett. **110** 093602 (2013)

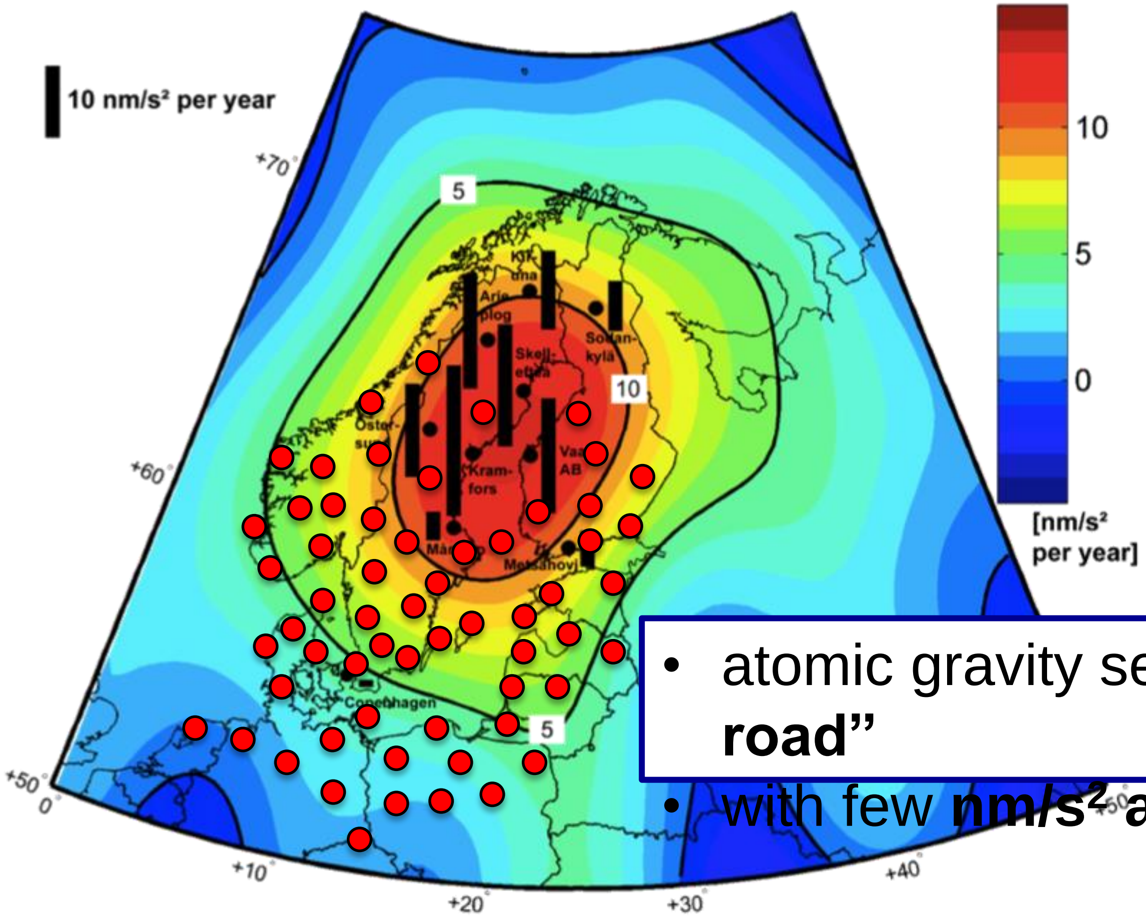
Transportable quantum gravimeter



Hannover approach:

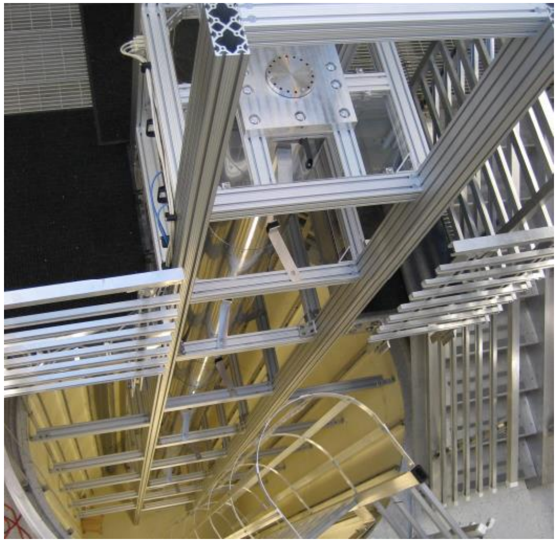
- chip atom source
- ultra-cold atoms in transportable setup, Bragg interferometry
- sub-µGal perspective for compact field devices

Compact sensors: long term perspective



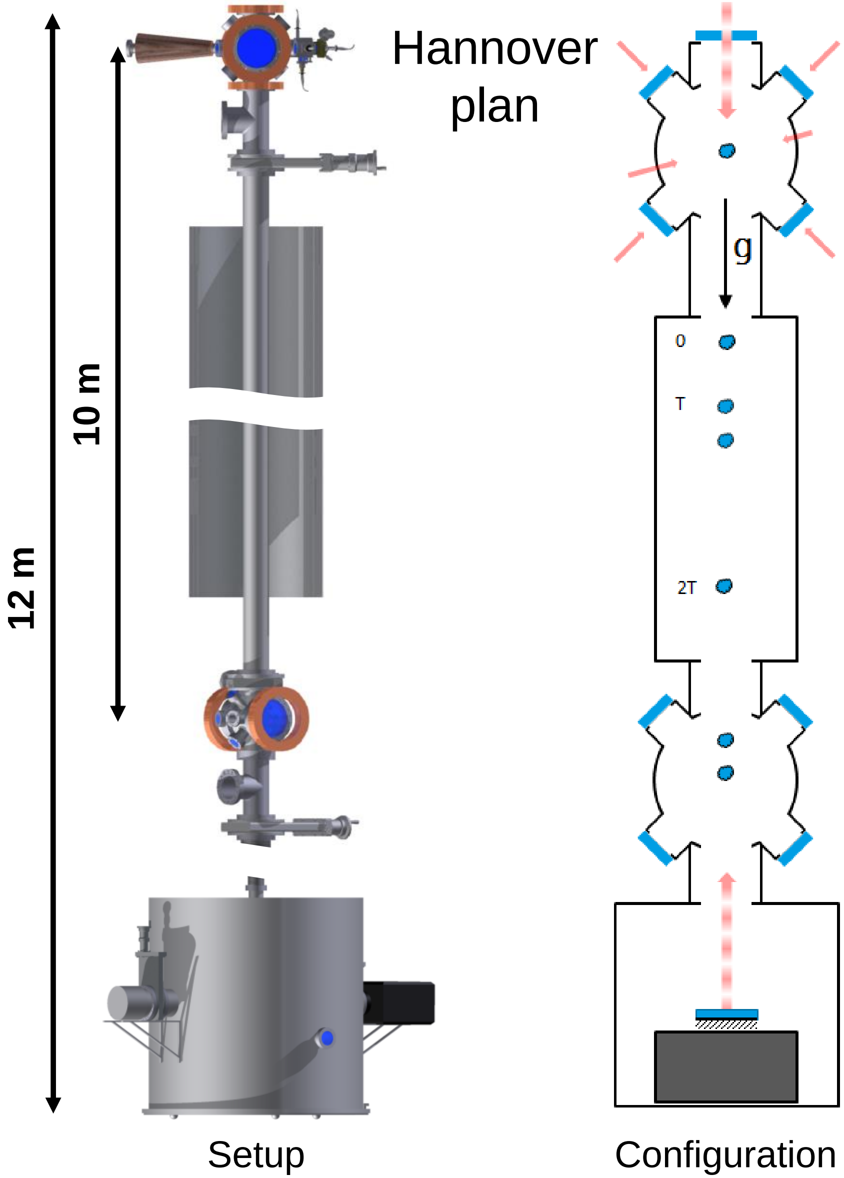
- atomic gravity sensors **“for the road”**
- with few **nm/s² accuracy**

Very long baseline atom interferometry (VLBAI)

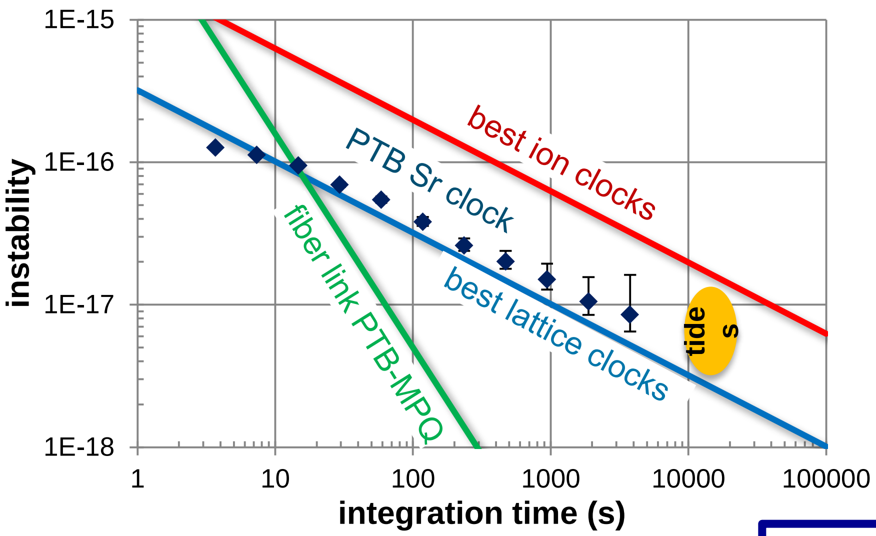


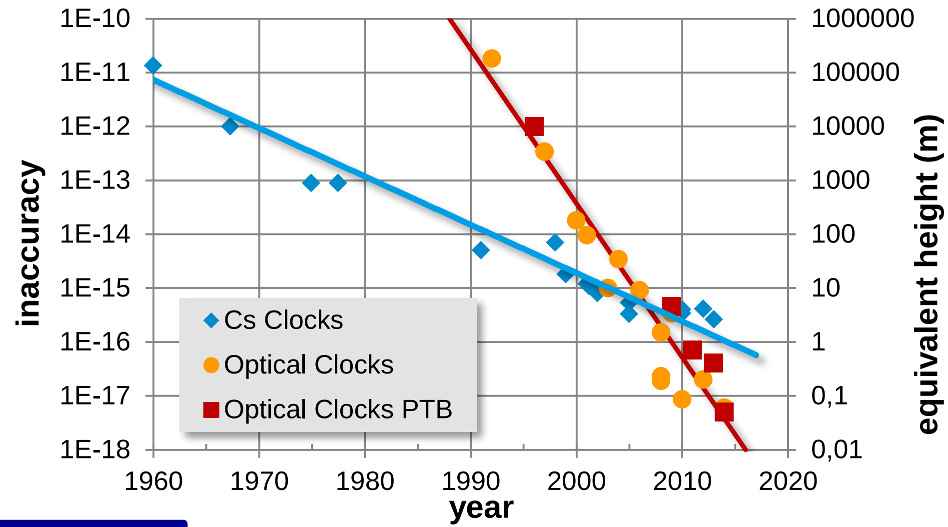
Stanford
10 m atom
fountain

- Stanford, MIGA
- sensitivity ~T^2
- 1 sec ~10^{-13} m/s^2
- challenges: VLBAI gravimetry, gradiometry and fundamental physics



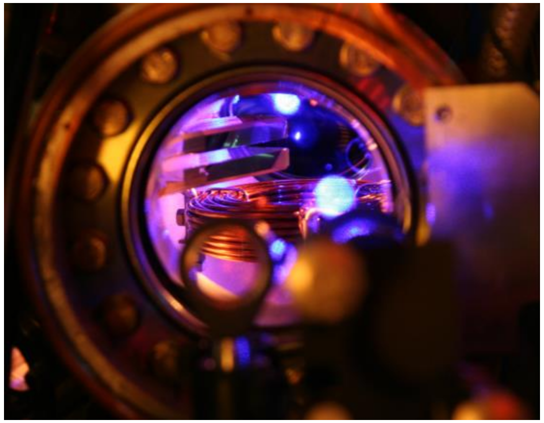
State of the art optical clocks



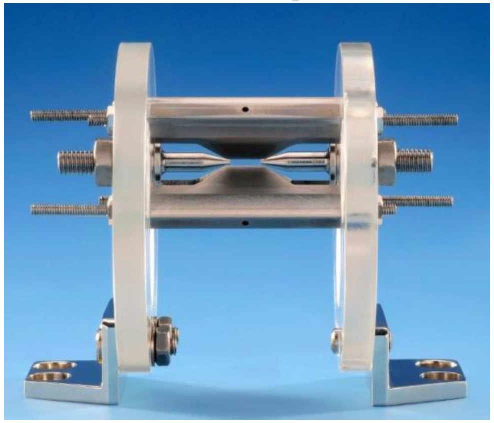


$$DW = \frac{Df}{f} c^2$$

Sr lattice clock: stable



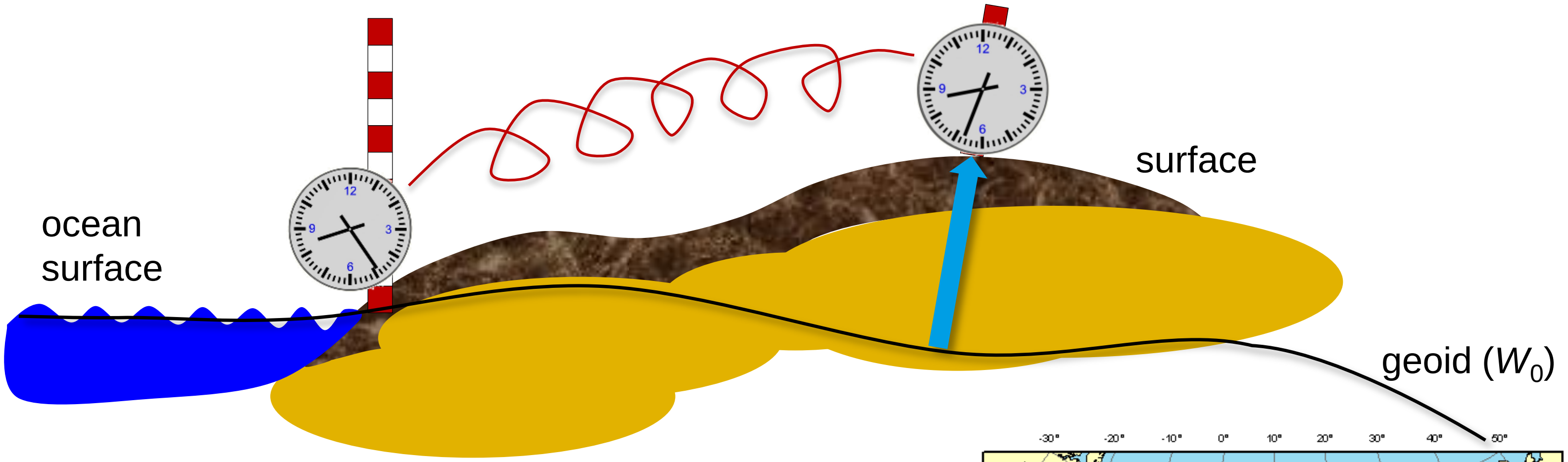
Al$^+$ clock: reproducible

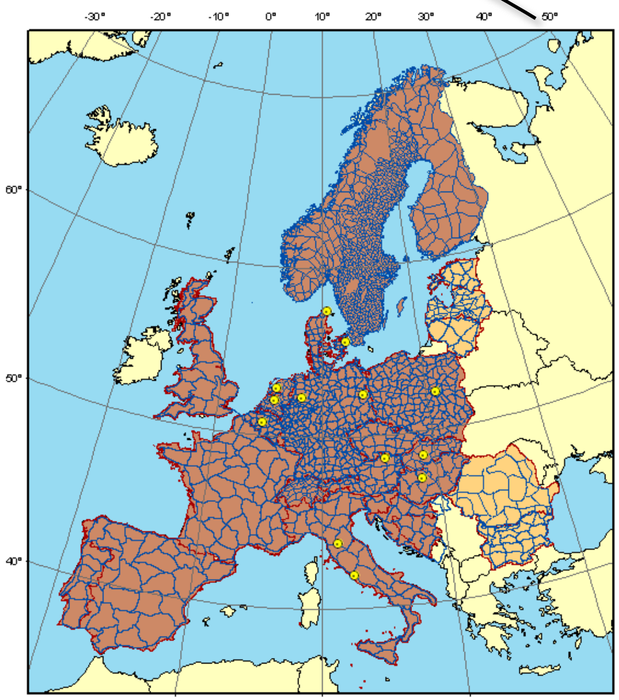


Hybrid Clock:
stable & reproducible

group of Piet Schmidt and Christian Lisdat

Chronometric leveling





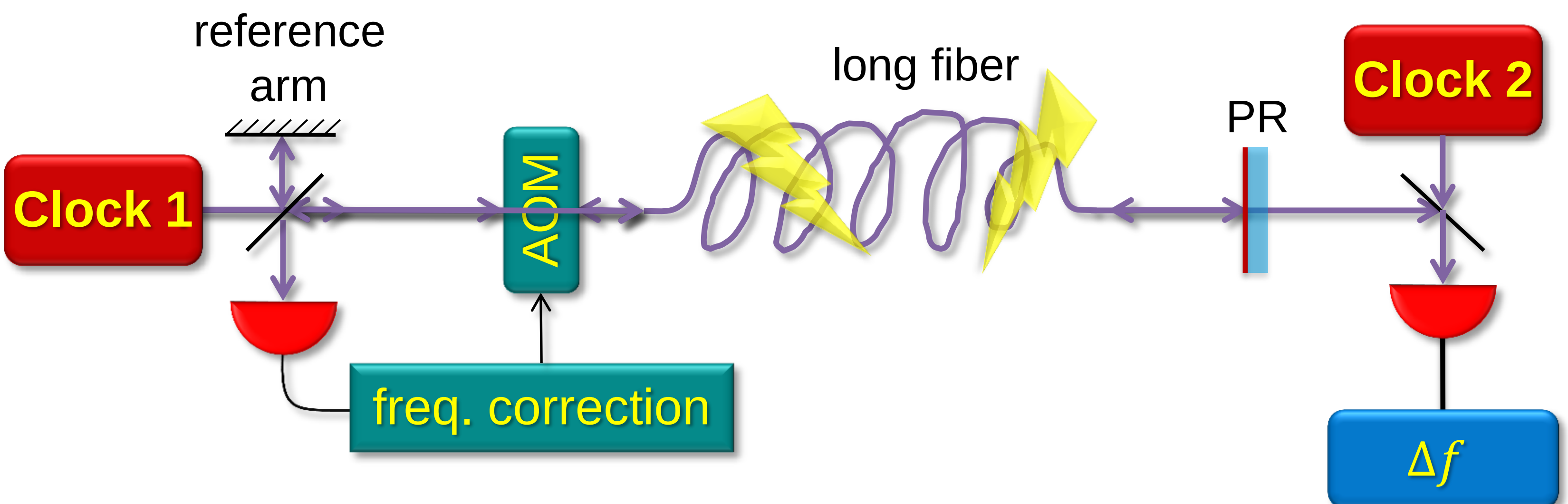
- frequency transfer through **optical fiber**
- frequency difference between remote clocks
- provides directly **potential differences** and **height differences** over very **large distances**

Steps towards chronometric leveling

existing and prospective fiber links

Clock comparison: phase-stabilized fibers

- Acoustic and thermal perturbations affect length of fiber
- frequency of transmitted light is Doppler-shifted
  ➔ active length stabilization of fiber required



➔ proof of principle experiments PTB–LUH/MPQ

1840 km loop link with $\delta f/f \sim 4\times10^{-19}$ @ 100 s

group of Harald Schnatz

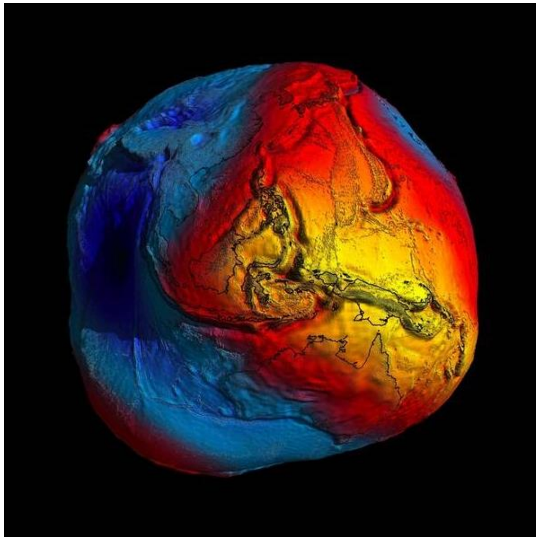
Steps towards chronometric leveling

- transportable clocks for side-by-side calibration
- to eliminate residual systematic errors
- connection F – D at University of Strasbourg Computing Centre

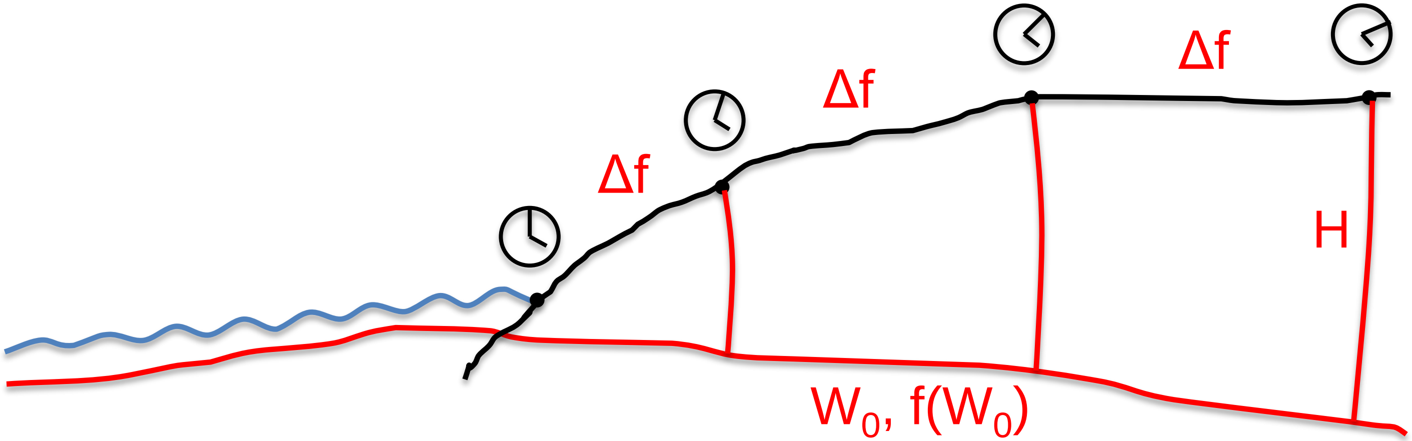
Relativistic geoid

- relativistic **geoid definition**: surface where clocks run with the same speed
- clock network: geoid **accessible** within continents
- well defined height reference
- very different from conventional height determination
- **challenge: develop the foundations for chronometric leveling and relativistic geoid**

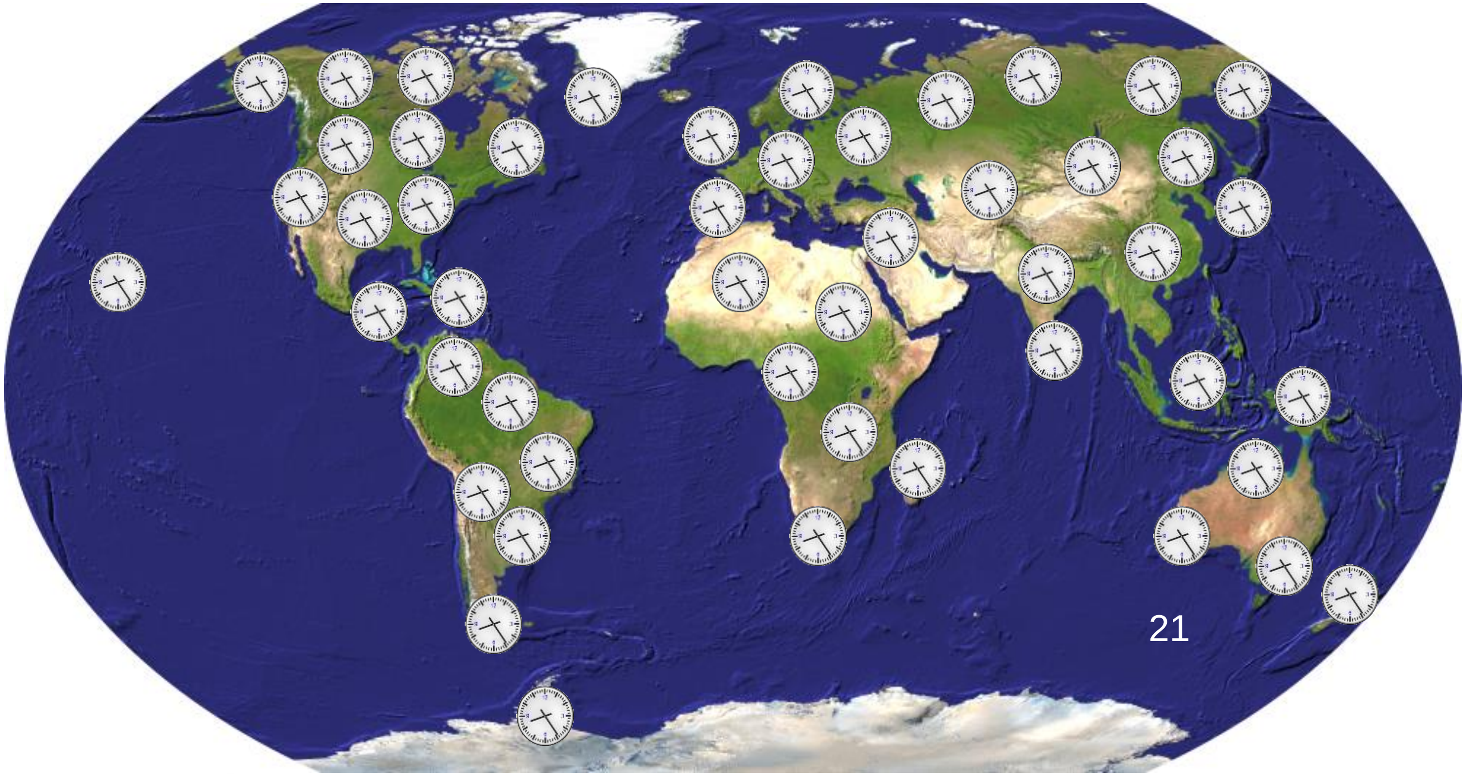
$$H = (W_0 - W_P) / \bar{g}$$



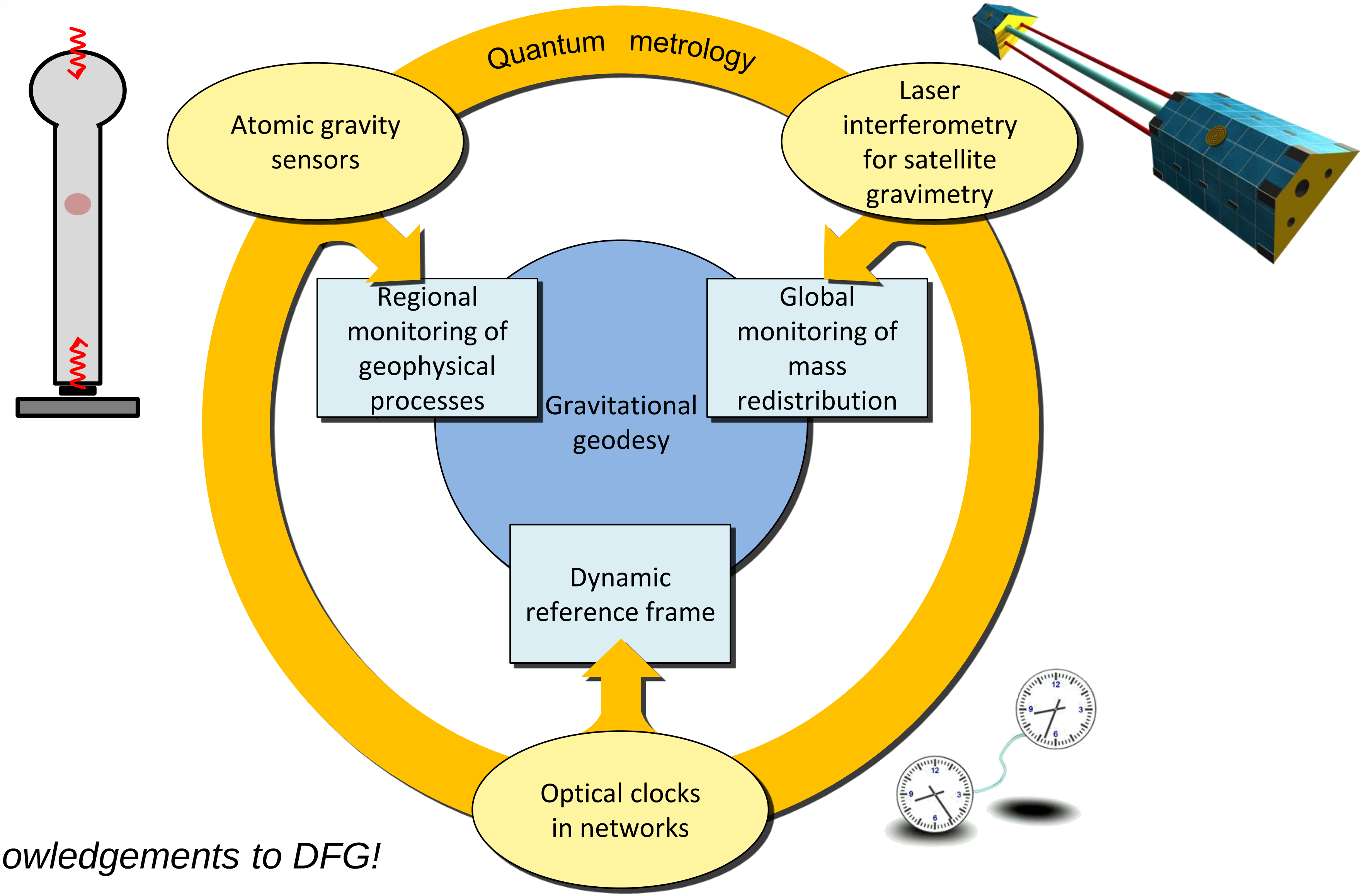
ESA



towards clock based gravity reference…

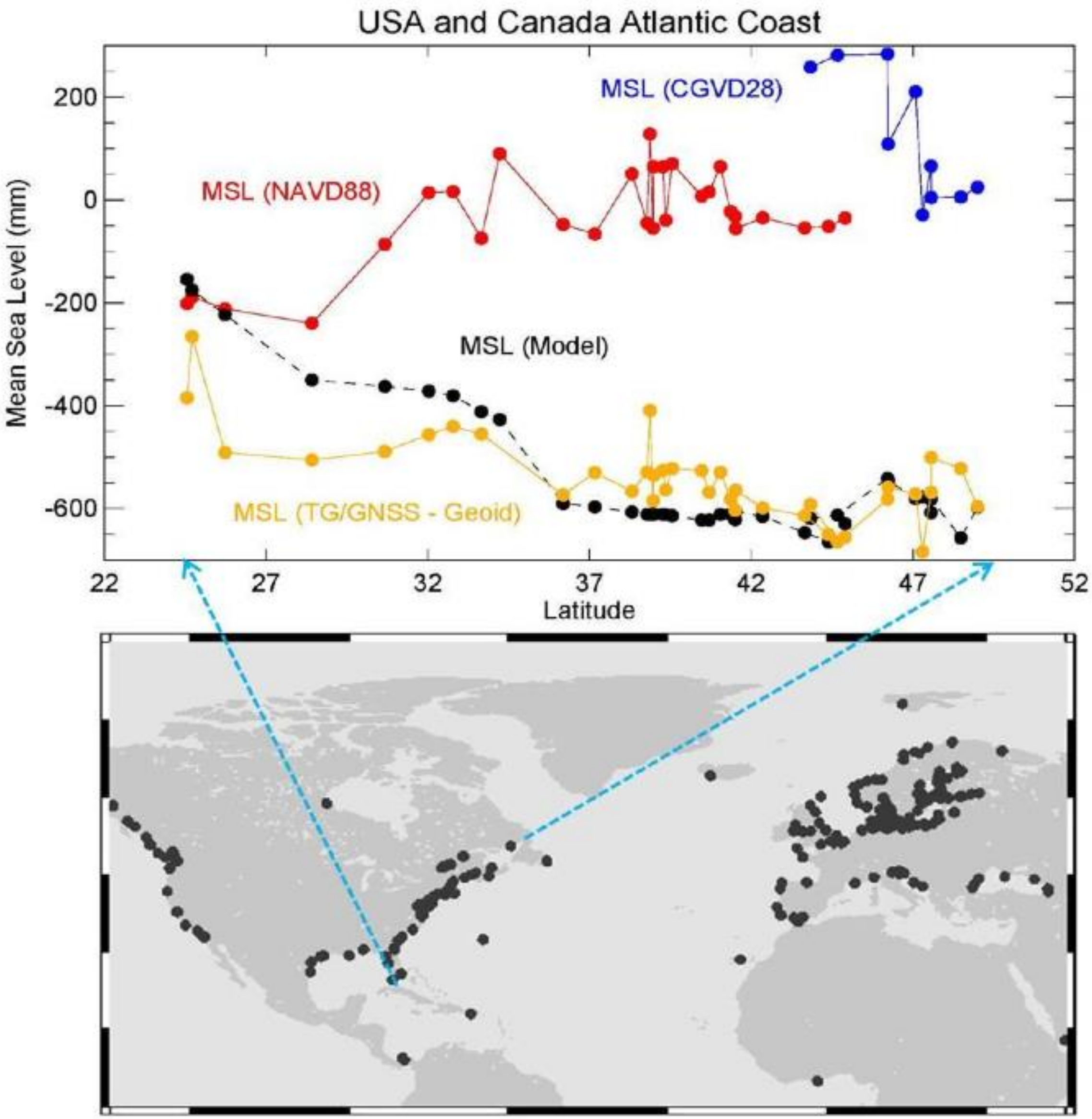


Summary



Acknowledgements to DFG!

Height inconsistencies

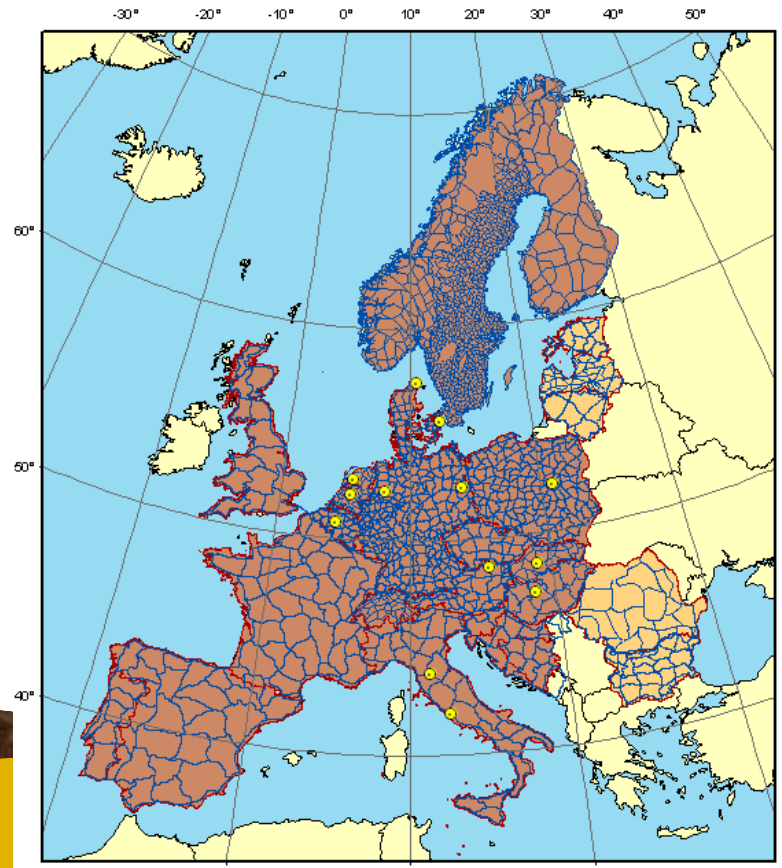


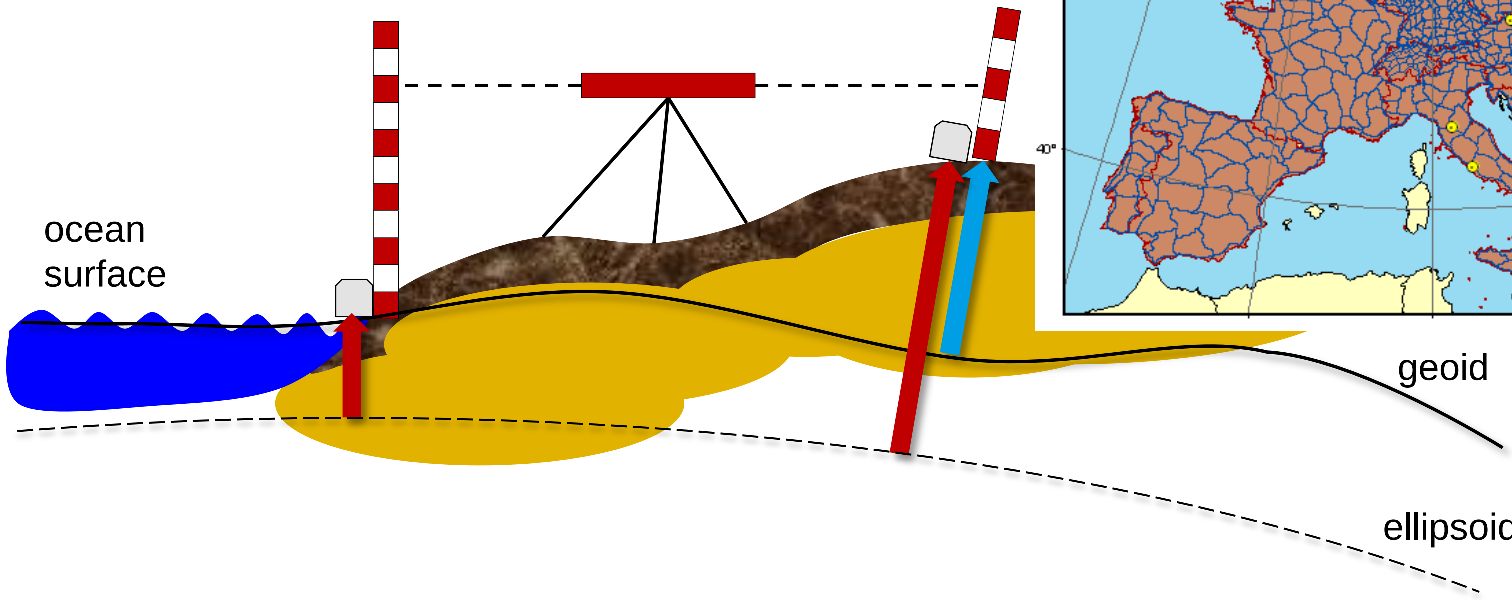
- decimeter inconsistencies
- hamper combination of tide gauges
- efforts for **height system modernization**
- **clocks** could provide **in-situ cm** accuracy referred to **well-defined W_0**

Sideris et al 2013 (GOCEplus study)

Classical leveling

- spirit leveling
- large effort
- **accumulation of errors** over large distances
- **tide gauges** as rather **arbitrary reference**

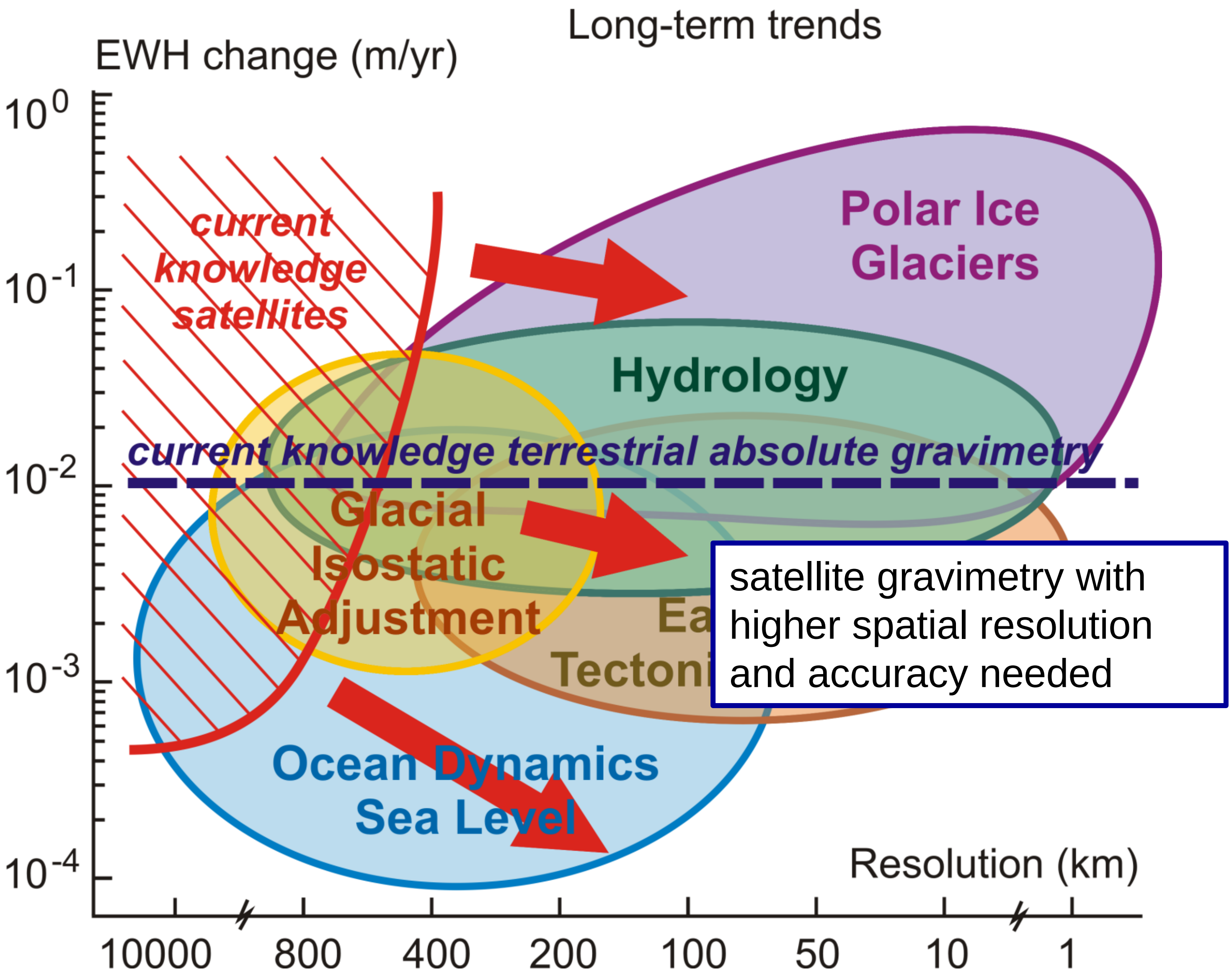




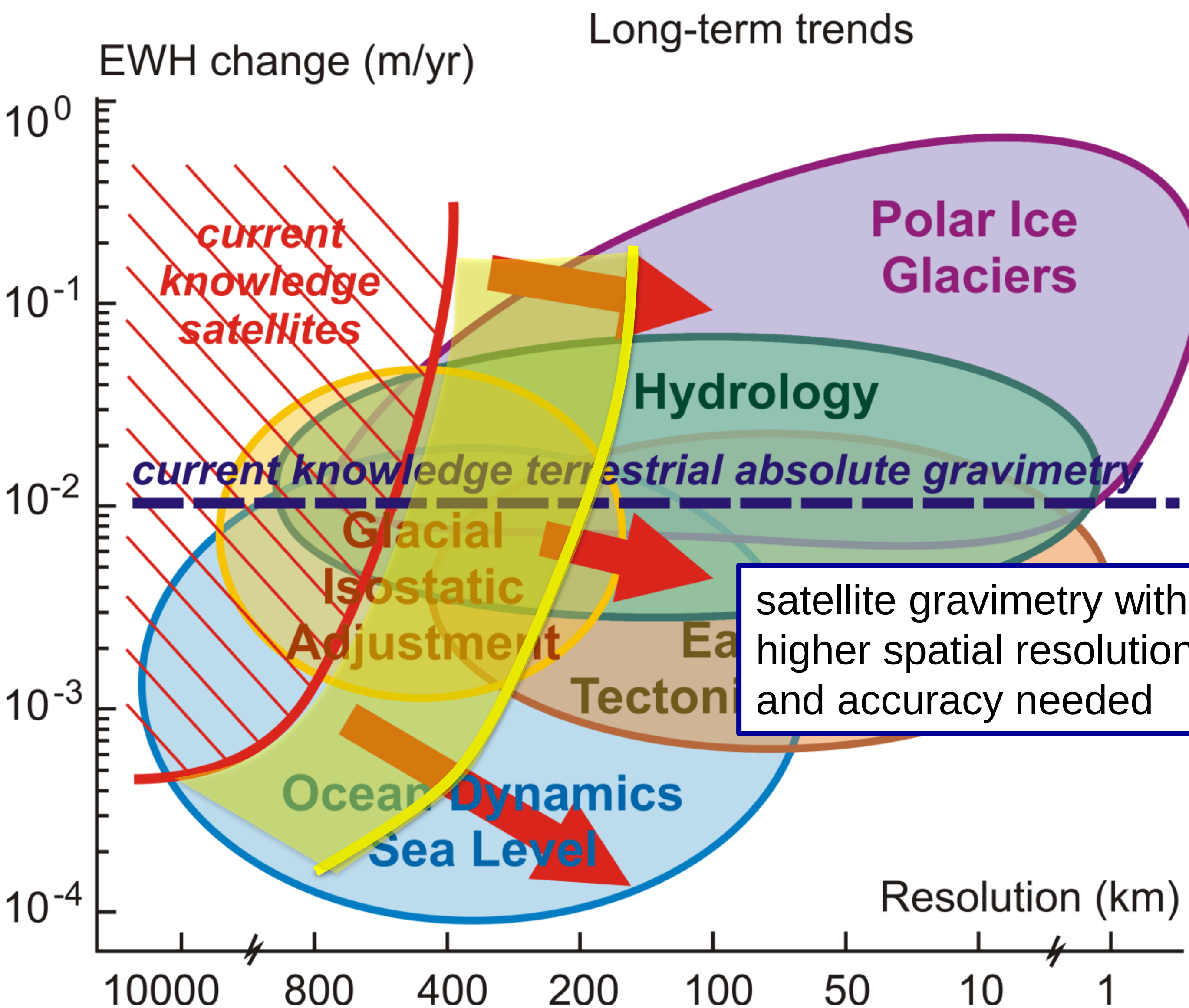
- Global change monitoring based on quantum measurement science
  - Multi-testmass interferometry in space as standard technique for sensing global mass variations
  - Quantum gravimeters rapidly and reliably monitoring sub-surface mass changes
  - Relativistic geodesy with clock networks establishing and distributing vertical reference
  - New class of gravity models integrating quantum sensor data with spatio-temporal zoom-in
- For everyday geo-applications & fundamental physics breakthroughs

J. Fraunhofer

Towards new geophysics

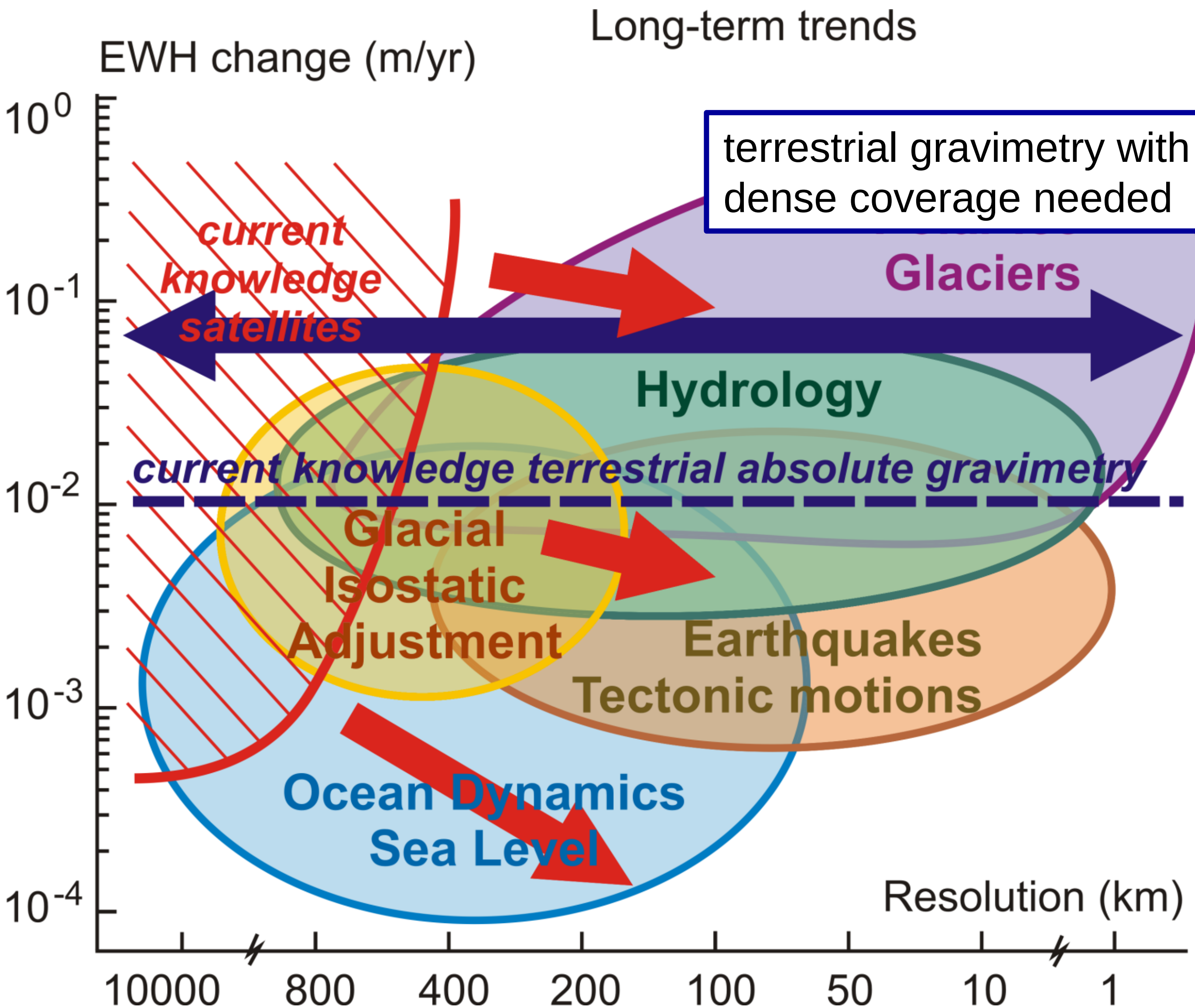


Towards new geophysics

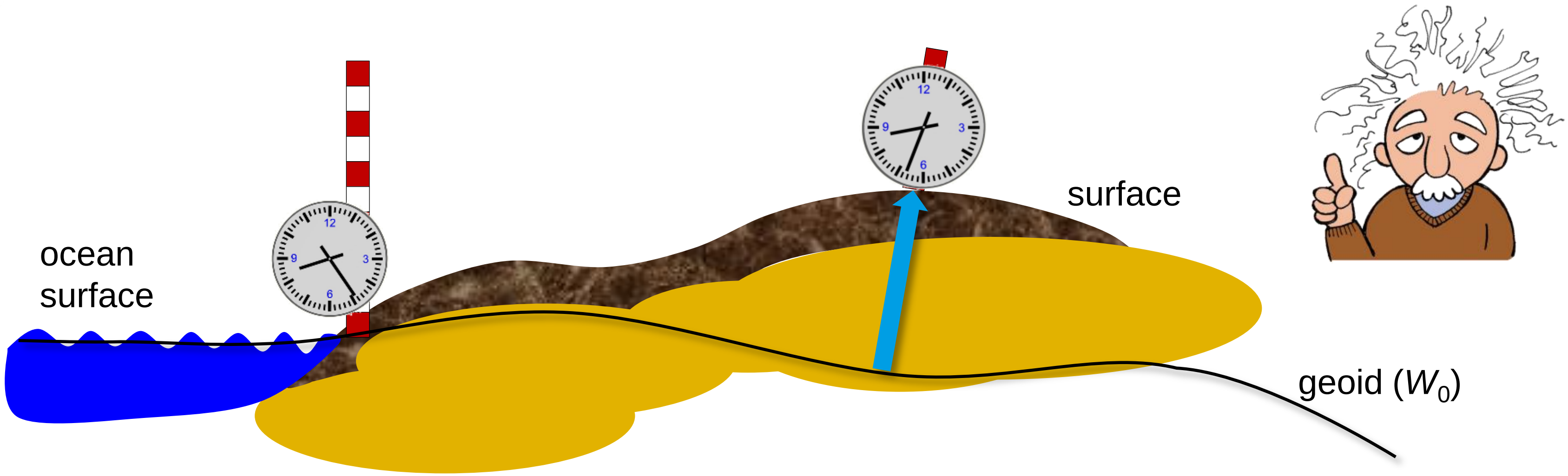


satellite gravimetry with higher spatial resolution and accuracy needed

Towards new geophysics



Relativistic geodesy with clocks

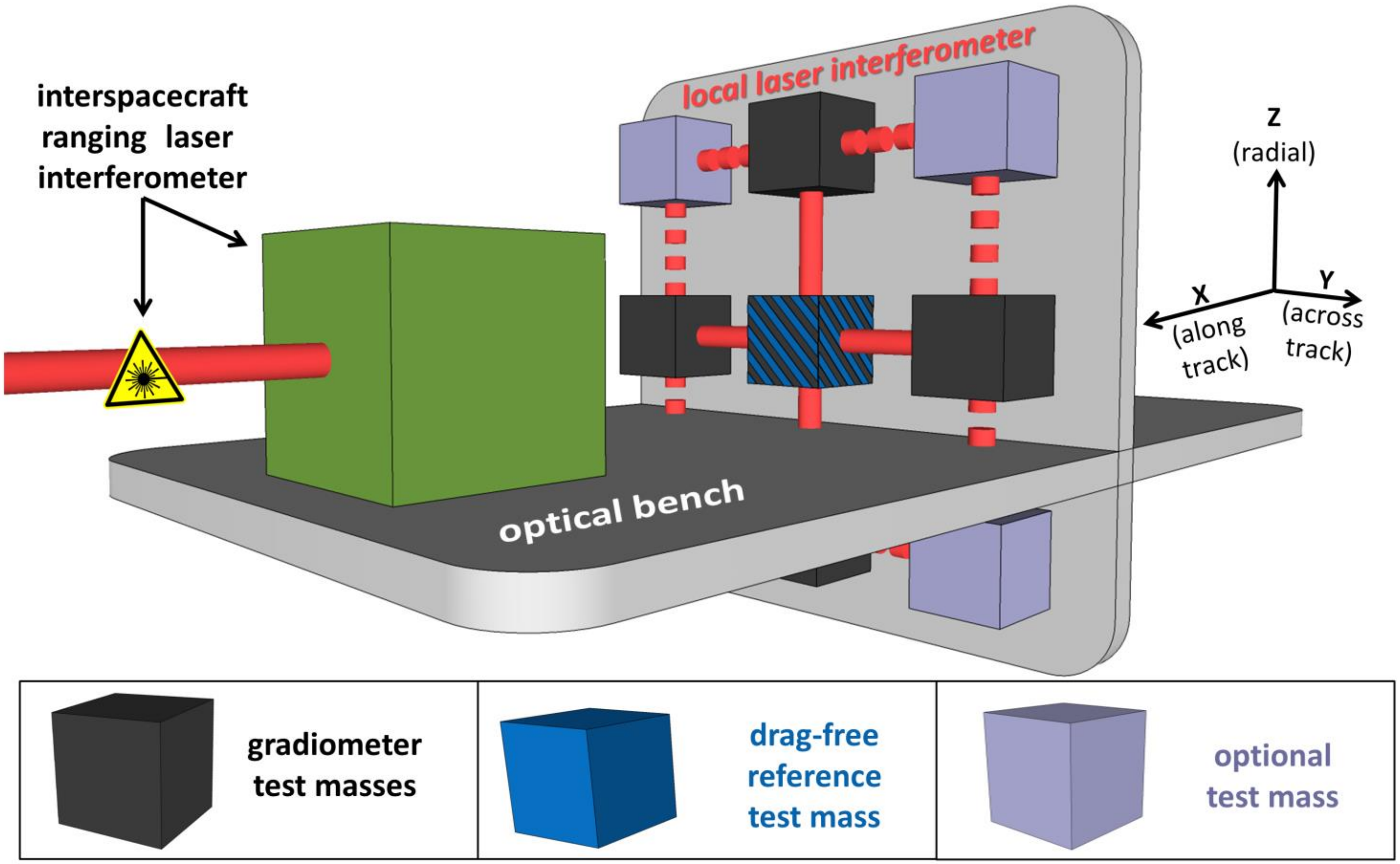


- fundamental relation **time / frequency – gravitation / height**

$$\Delta W = \frac{\Delta f}{f} c^2$$

- optical atomic clocks now approaching **10^{-18}** ⇔ 0.1 m^2/s^2 ⇔ 1 cm
- the **most accurate** physical measurement!
- towards cm precision height determination with frequency measurements
- curvature of **space-time** now relevant at the **cm level** on Earth surface!

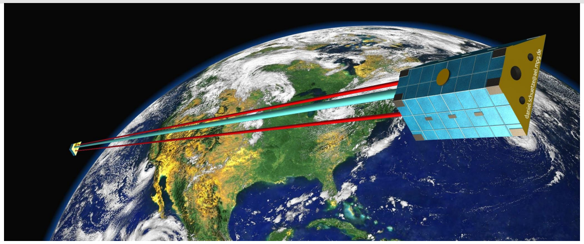
Optical gradiometry

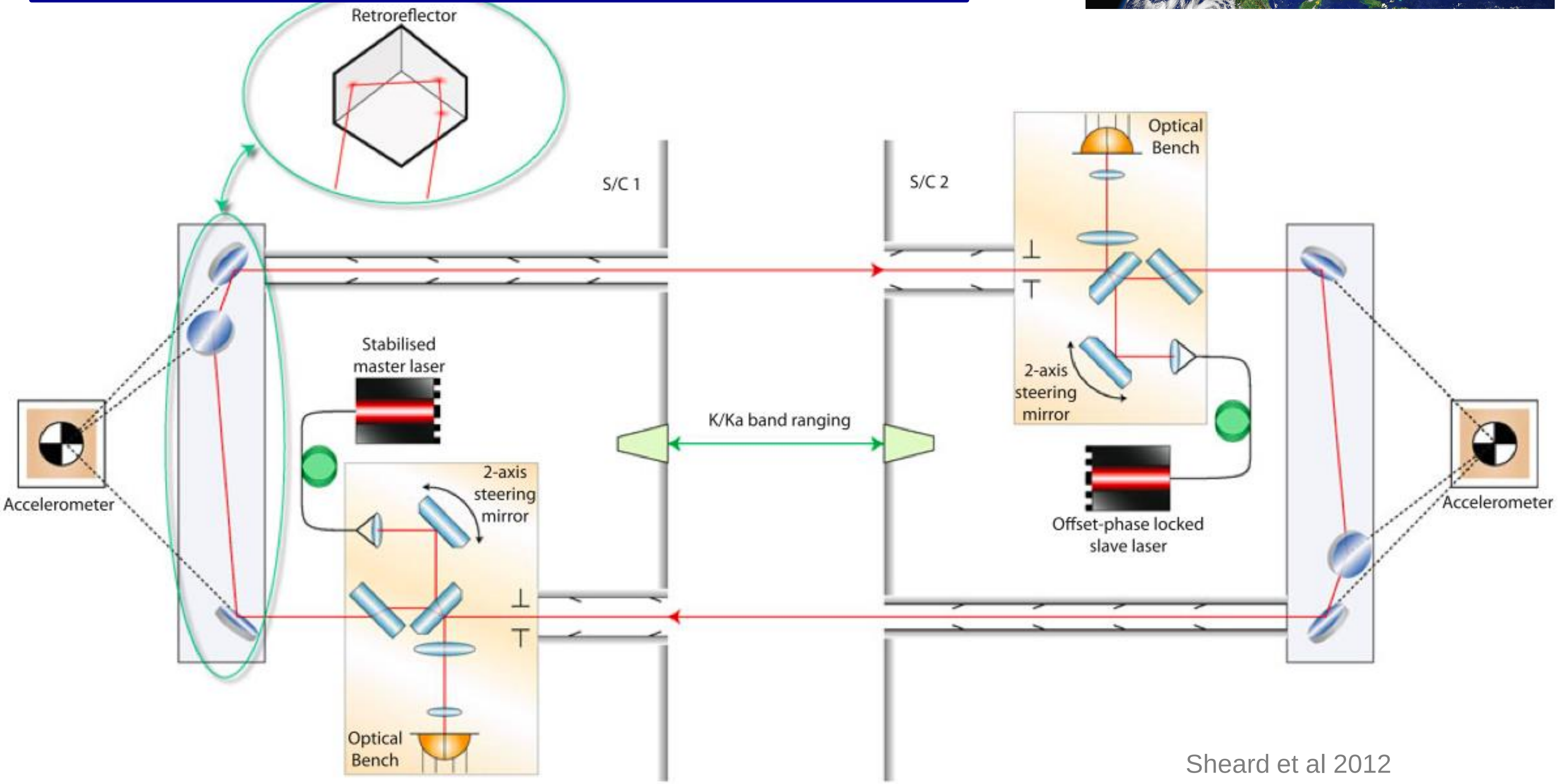


- **challenge: exploring the metrology of optical multi-testmass systems**
- pm/√Hz ranging
- multichannel optics, phasemeters, testmass control, …

First laser interferometer between Earth orbiters

- “racetrack” interferometer configuration
- beam steering for better pointing control
- nm ranging for better gravity resolution

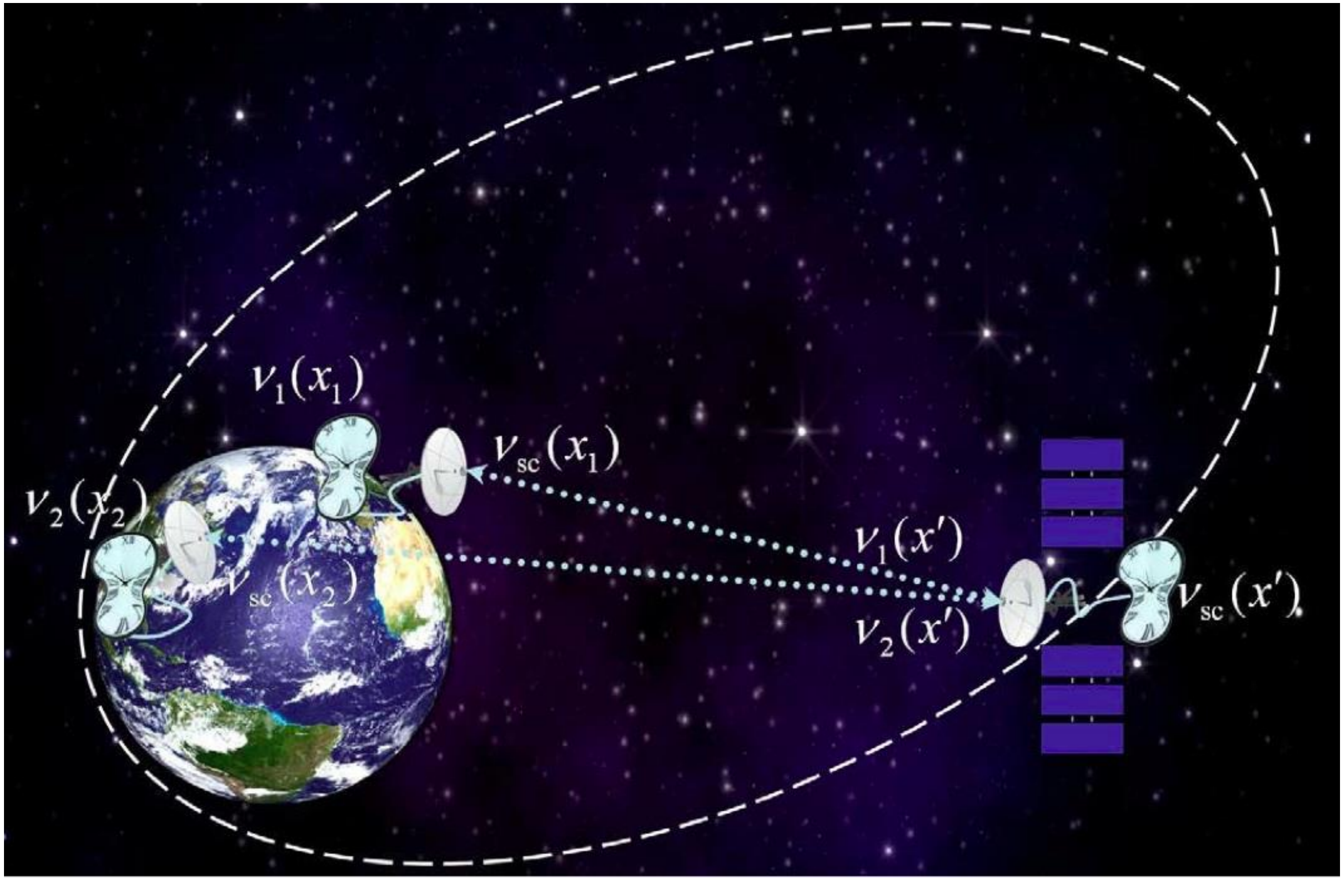




Sheard et al 2012

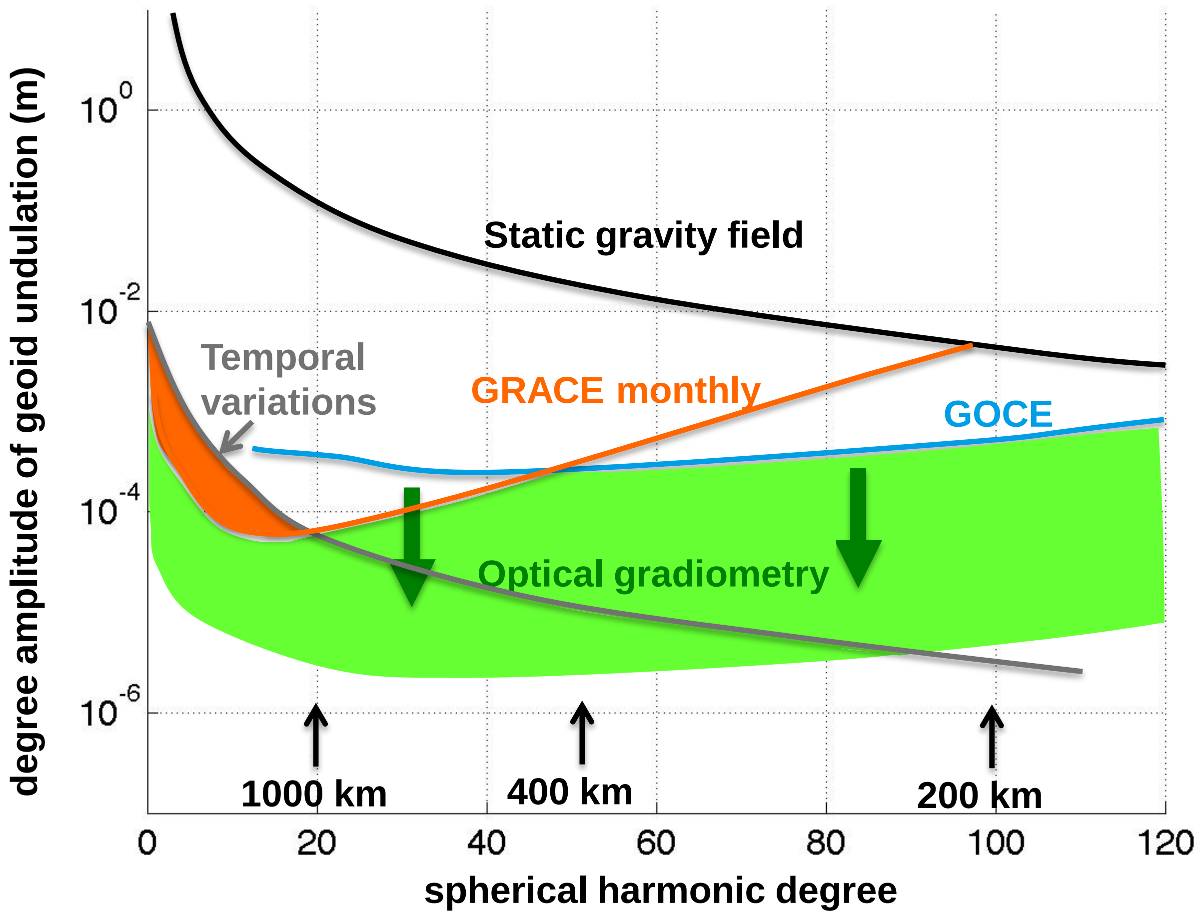
Future satellite gravimetry

- laser interferometric length measurements
- gravity gradiometry with atomic interferometry (ESA, NASA, …)
- gravitational redshift, clock network in space (STE-QUEST)

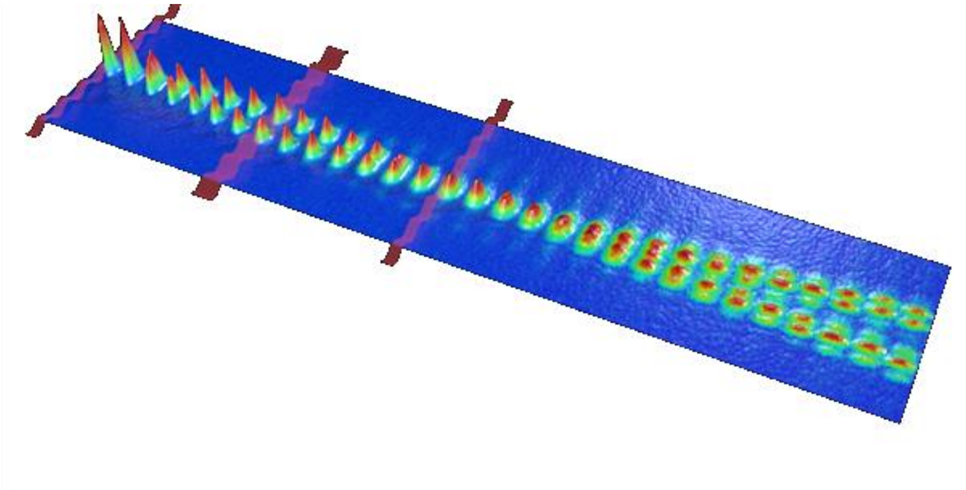


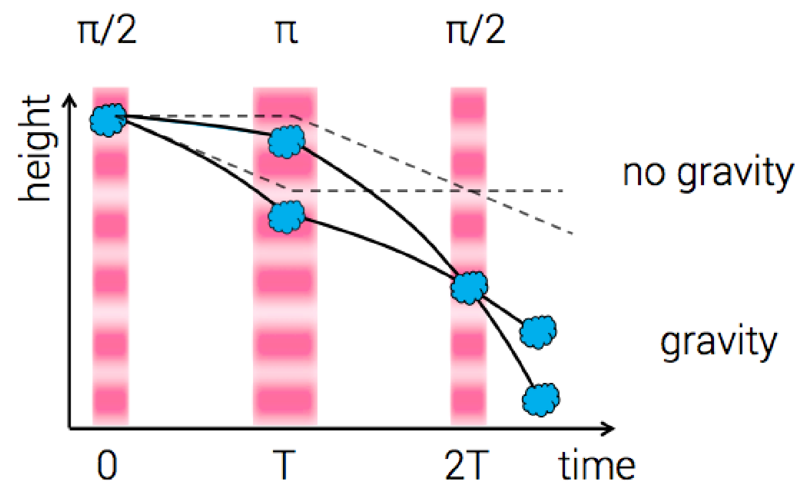
Enhanced resolution in gravity modeling

- future **gradiometry** in combination with ranging is very **promising for satellite gravimetry**



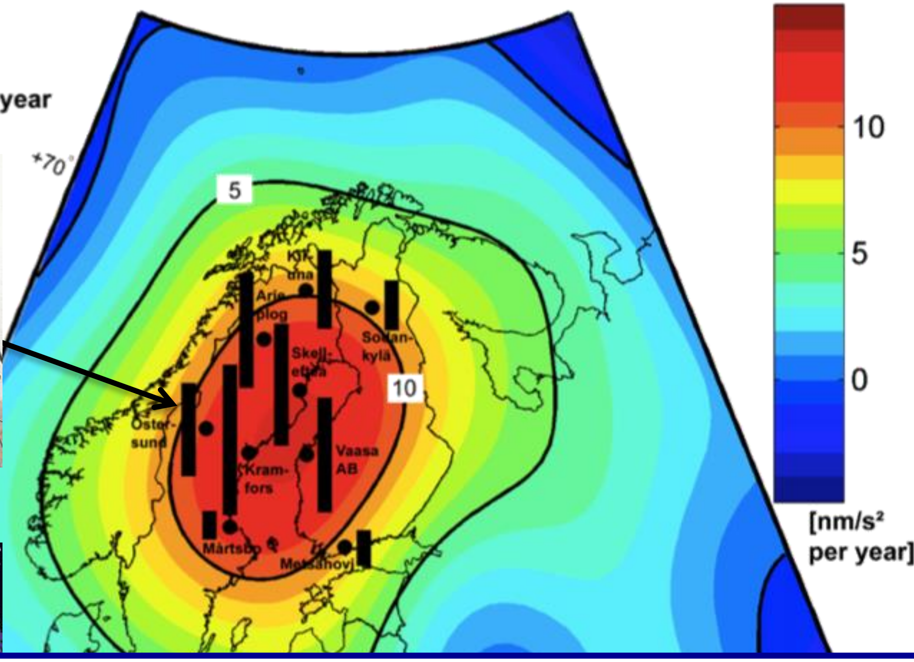
Gravity sensing with atom interferometry

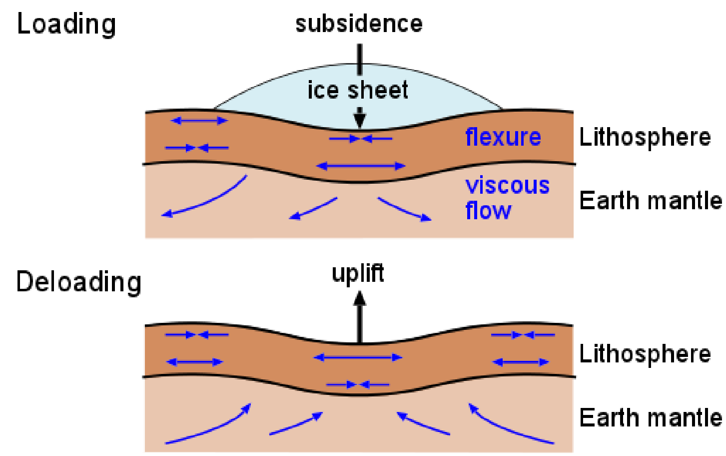




- **matter waves** of a **free-falling atom cloud** are coherently split, redirected and recombined with a pulsed light grating
- position information imprinted onto matter wave phase in each atom-light interaction
- measured through matter wave interferometer **phase readout**

Gravity signals: Glacial Isostatic Adjustment





V. Klemann

- uplift (up to 1 cm/y),
- viscous mass redistribution in

Glacial Isostatic Adjustement (GIA) is

- revealing **mass flux in Earth mantle** and mantle properties
- affecting whole Earth (mm/y-level), sea level change estimates
- affecting geodetic networks
- **measurement challenge, faster absolute gravimeters** needed to understand regional patterns