ETH zürich

Major Research Infrastructures for 21th century Geophysics

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Geo-INQUIRE seminar

29.1.2026

Main drivers for seismology:

- Monitoring & alert
- Seismic hazard & risk
- Exploration
- Discrimination
- Research

Major efforts required to:

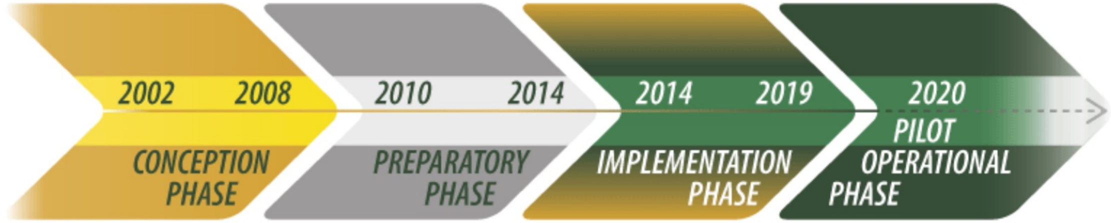
- harmonize standards and formats
- procure and install RIs
- provide virtual and physical access to data and RIs
- bypass boundaries and create an integrated regional infrastructure
- develop the tools to analyse data

Complex cooperation framework for seismology in Europe:

- European Seismological Commission
- Organizations & Research Facilities for European Seismology
- European-Mediterranean Seismic Center
- European Facility for Earthquake Hazard & Risk
- EU
- European Plate Observing System
- National seismic agencies
- European Geosciences Union
- Global framework: IASPEI, ISC, GEM, FDSN …

EU

- It influences what to fund, the relevant themes, how it should be done. Not all get funding, but all get the benefits. EU project provide vital funding to ensure cooperation and high standards.
- Until FP5, seismology was awarded only small projects, 1-2ME; difficult to ensure continuity.
- With FP6 (2002), the EU started the INFRA projects, including Networking Activities (NA), Joint Research Activities (JRA), Virtual Access (VA) and Transnational Access (TA) to RI and data.
- We decided to try a combination of INFRA + Marie Curie Networks (training PhDs, PDs) + ENV (thematic) + ERC (excellence).
- Two successive large INFRA projects (10+ milEuro) were funded in seismology
  - ✓ *NERIES: Network of Research Infrastructures for European Seismology*, 2006-2010
  - ✓ *NERA: Network of European RI for Earthquake Risk Assessment and Mitigation*, 2010-2014
- Earthquake engineering followed with *SERIES: Seismic Engineering RI for European Synergies*, 2009-13
- By now the EU considered seismology and earthquake engineering as a single advanced community and opened a new call for the two communities together. We won with *SERA: Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe*, 2017-2020



FP7
EPOS-PP

H2020
EPOS-IP

Horizon Europe
EPOS-SP

- In 2006, we decided to apply to ESFRI (European Strategy Forum on RI), a new framework just started by the EU for large RI
- We were successful on the first attempt in 2008 with *EPOS: European Plate Observing System*
- EPOS was envisioned to integrate existing and future advanced European facilities, into a unique, distributed, sustainable research infrastructure (RI), taking full advantage of new e-science opportunities
- EPOS is pan-European, with >150 research organisations, >250 RIs, all EU countries involved for data provision, 5 international organisations involved
- Multi-disciplinary data and products: >10'000 seismic stations, >3000 GNSS receivers, >120 labs, all volcano observatories, satellite data, 100 Petabyte data volume
- Operational services to society: anthropogenic hazards, hazard & risk services (seismic, volcanoes, tsunamis)

History and heritage

Framework programmes

- 2002-2006: Sixth Framework Programme
- 2007-2013: Seventh Framework Programme
- 2014-2020: Horizon 2020
- 2021-2027

INFRA projects

- NERIES
- SERIES
- NERA – Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
- SERA – Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe

ENV or EU projects

- SAFER – Seismic eArly warning For EuRope
- SHARE
- SYNER-G
- STREST
- REAKT
- MATRIX
- DESTRESS
- RISE – Real-time earthquake risk reduction for a reSilient Europe
- DT-GEO
- Geo-INQUIRE

EPOS – European Plate Observing System

2006: Design and planning

2008: entry in ESFRI roadmap

2010: EPOS-PP (Preparatory)

2016: EPOS-IP (Implementation)

2018: landmark

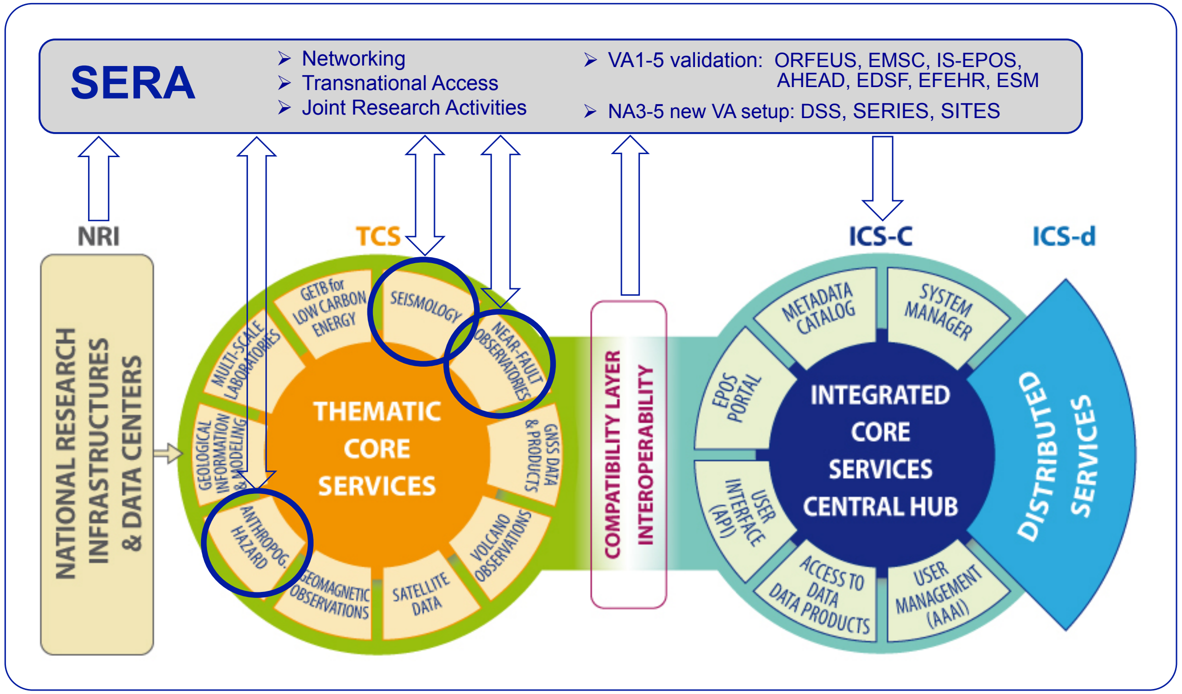
2018: ERIC signed

2020: EPOS-SP (Sustainability)

2024: EPOS-ON
(Optimization & evolutioN)

History and heritage

	neries	NERA	SERIES	SERA	EPOS
Waveforms data & products	NA, JRA	NA, JRA TA, VA		NA, JRA TA, VA	NA VA
Seismicity data & products	NA, JRA	NA, JRA VA		VA	NA VA
Earthquake hazard & risk assessment	SHARE	JRA		JRA	NA
Access to hazard & risk data & products		JRA VA		NA VA	NA VA
Shakemaps & Early Warning	JRA	TA		JRA	NA VA
Access to earthquake engineering RIs			NA, JRA TA	NA, JRA TA	TA, VA
Geotechnical site characterization	JRA	JRA	JRA	NA TA	VA
Vulnerability inventories		NA		NA, JRA VA	VA
Anthropogenic hazards				JRA VA	NA TA, VA

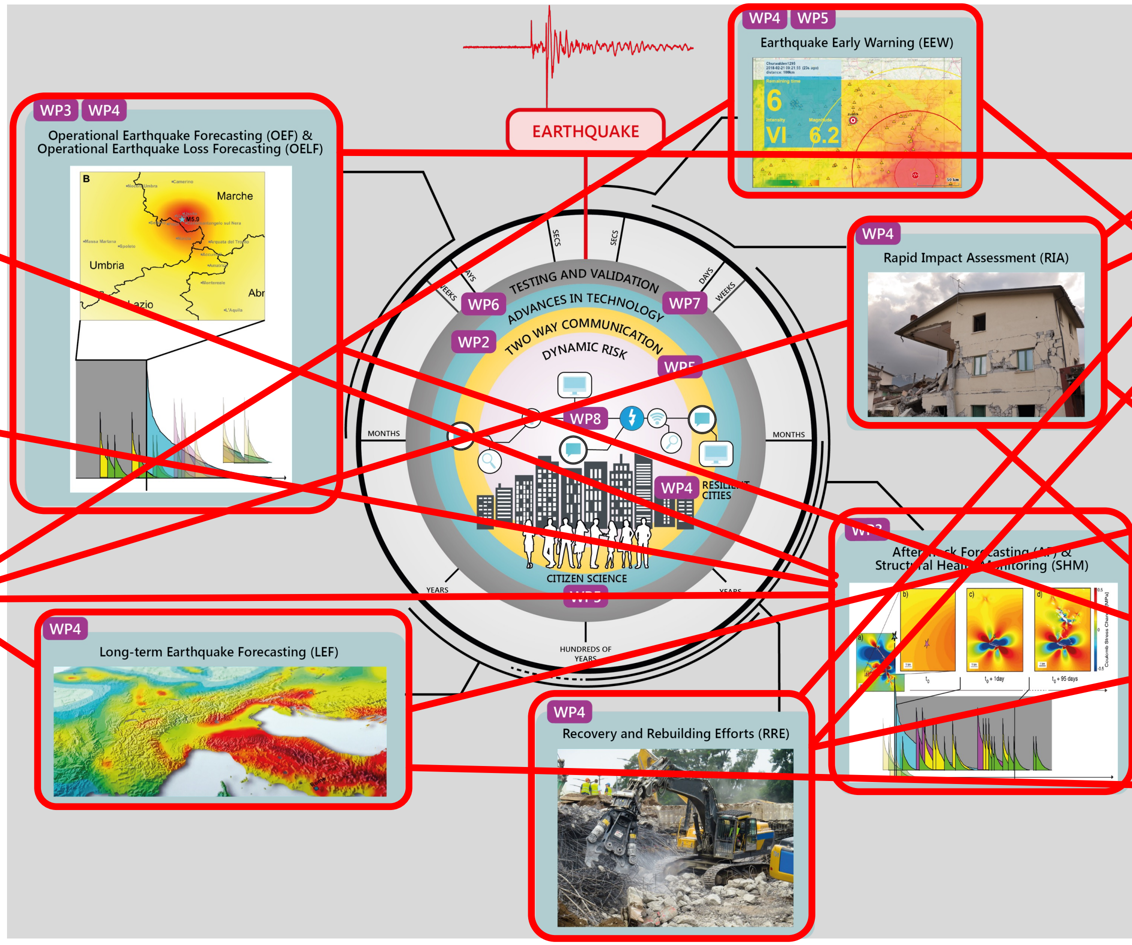


The workflow integration between SERA and EPOS included:

- ✓ further development of 3 EPOS TCS
- ✓ the incorporation of the EPOS interoperability layer to SERA
- ✓ validation of TA/VA services for future inclusion in EPOS

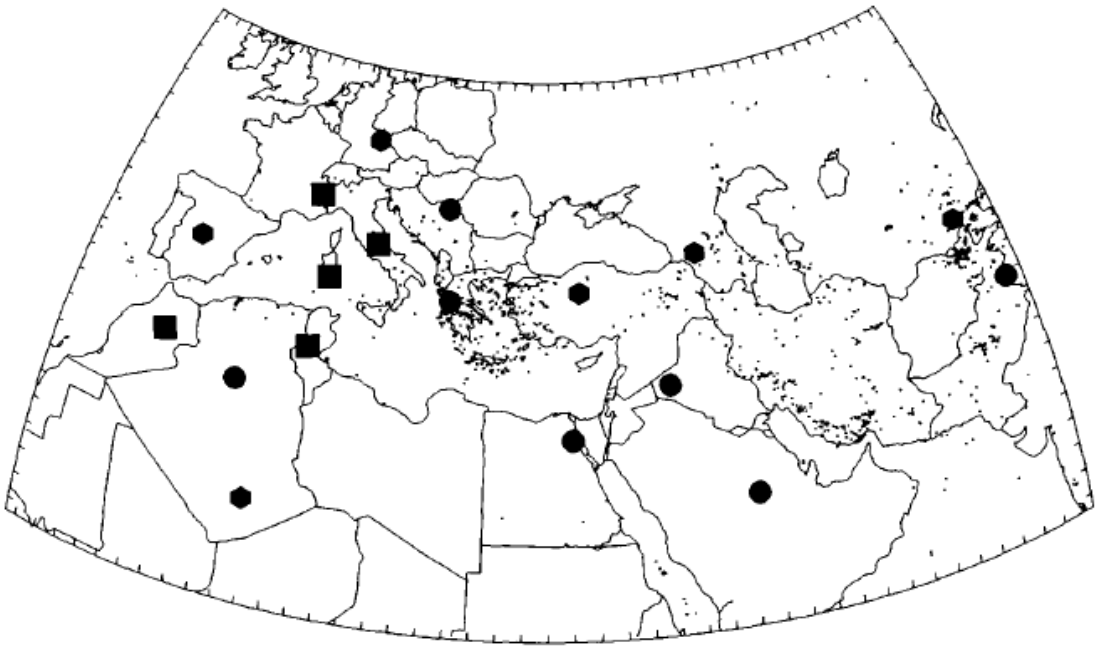
RISE

neries
NERA
SERIES
SERA
Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe
EPOS
EUROPEANPLATEOBSERVINGSYSTEM

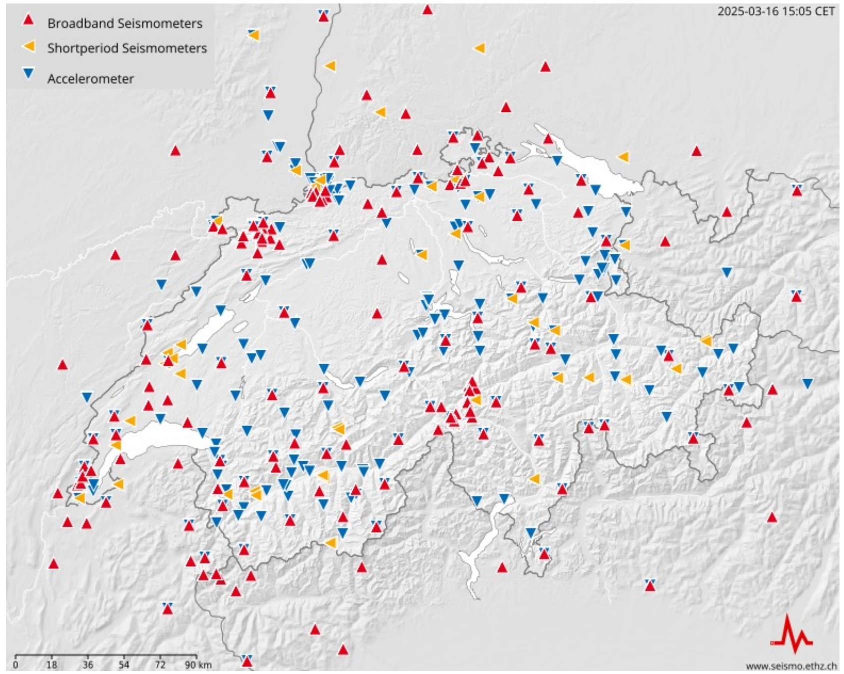


REAKT
SYNER-G
SAFER
Seismic eArly warning For EuRope
MATRIX
STREST
SHARE

Networks then and today

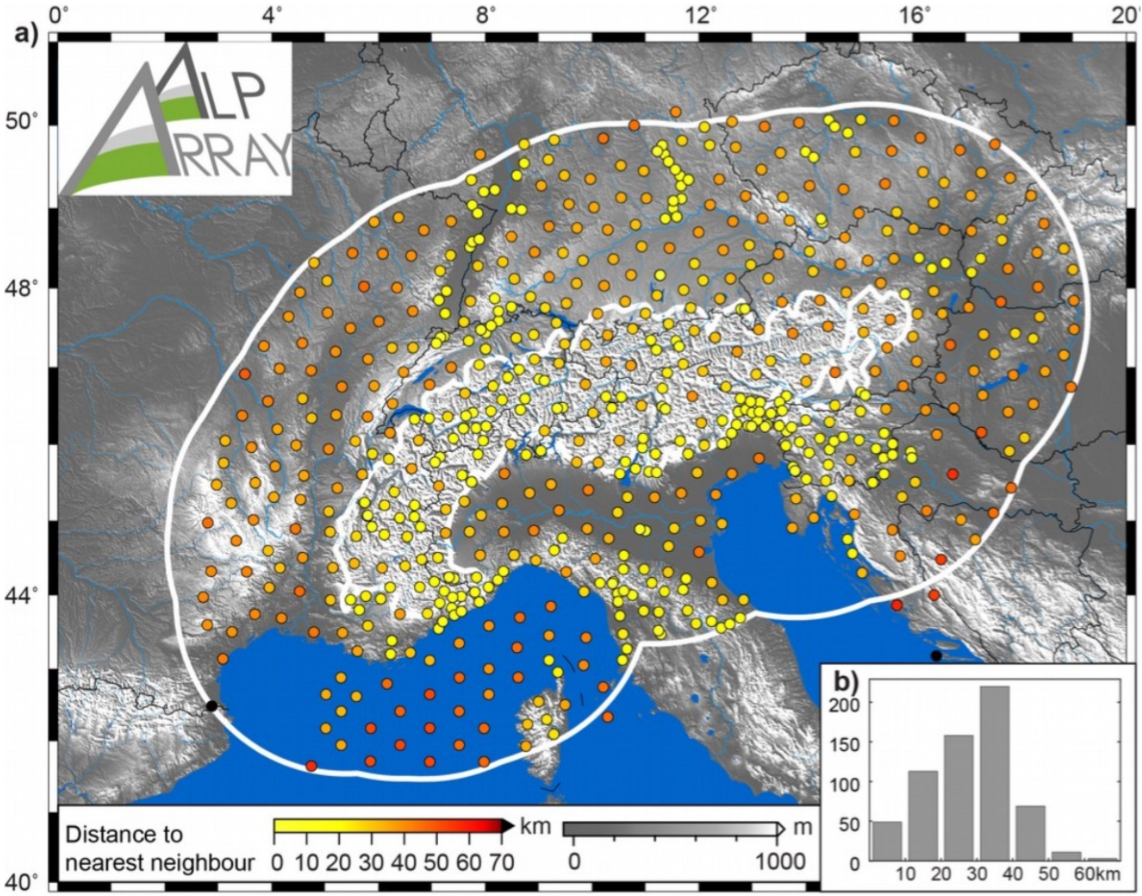


MedNet 1989-1992
First digital BB network in Europe-Med



Swiss National Networks, today

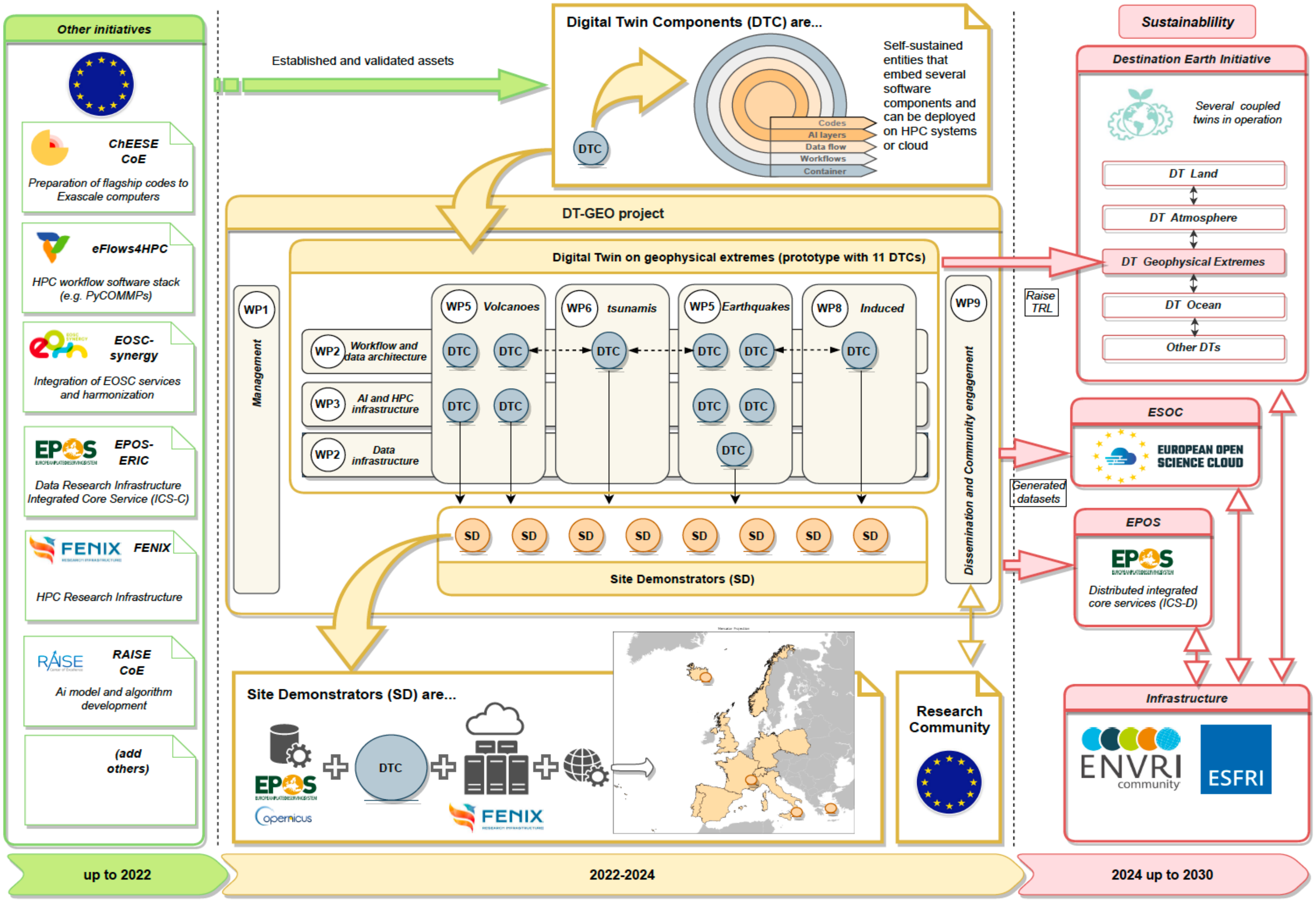
AlpArray



- 700 BB and OBS seismic stations
- Largest and densest portable/temporary array ever deployed worldwide
- Scientific goal: explore the deep structure and geodynamics of the Alps
- Operating until 2020 → moved to AdriaArray
- 8 participating countries
- Long-term legacy
- Challenges: logistics, funding, equipment, coordination, different scientific expectations, local politics, …

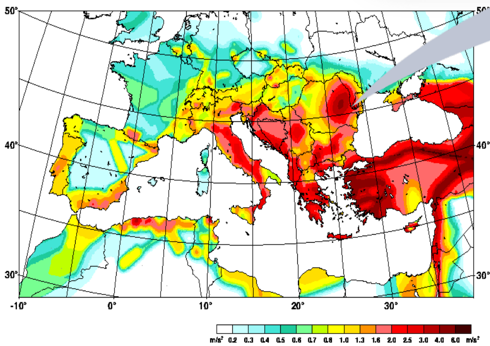
With Horizon Europe, the EU changed priority to use of the data → a real shift.

Two successful projects for *DT-GEO: Digital Twin for Geophysical Extremes*, 2022-2025, and in parallel *Geo-INQUIRE* to develop advanced services for EPOS.

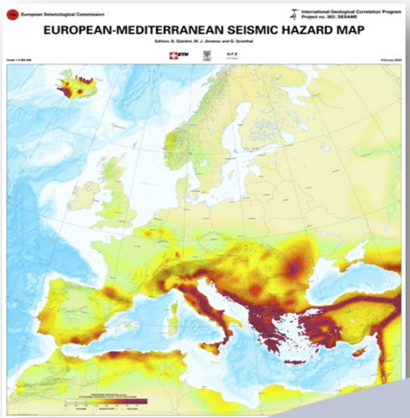


European Seismic Hazard Model

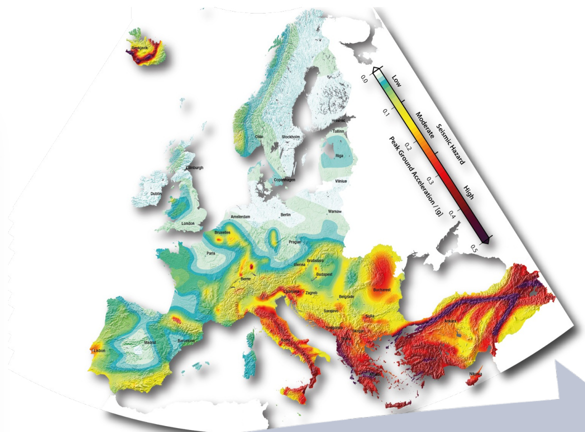
GSHAP 1999



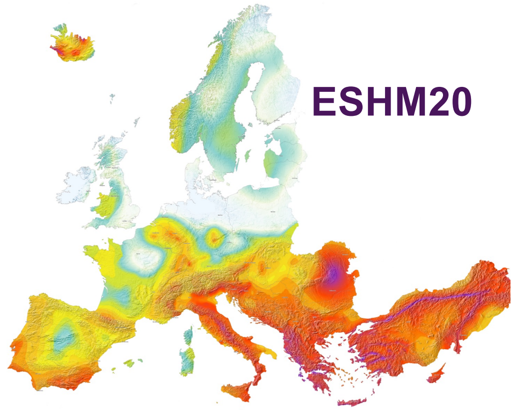
SESAME 2003



SHARE 2013



ESHM20



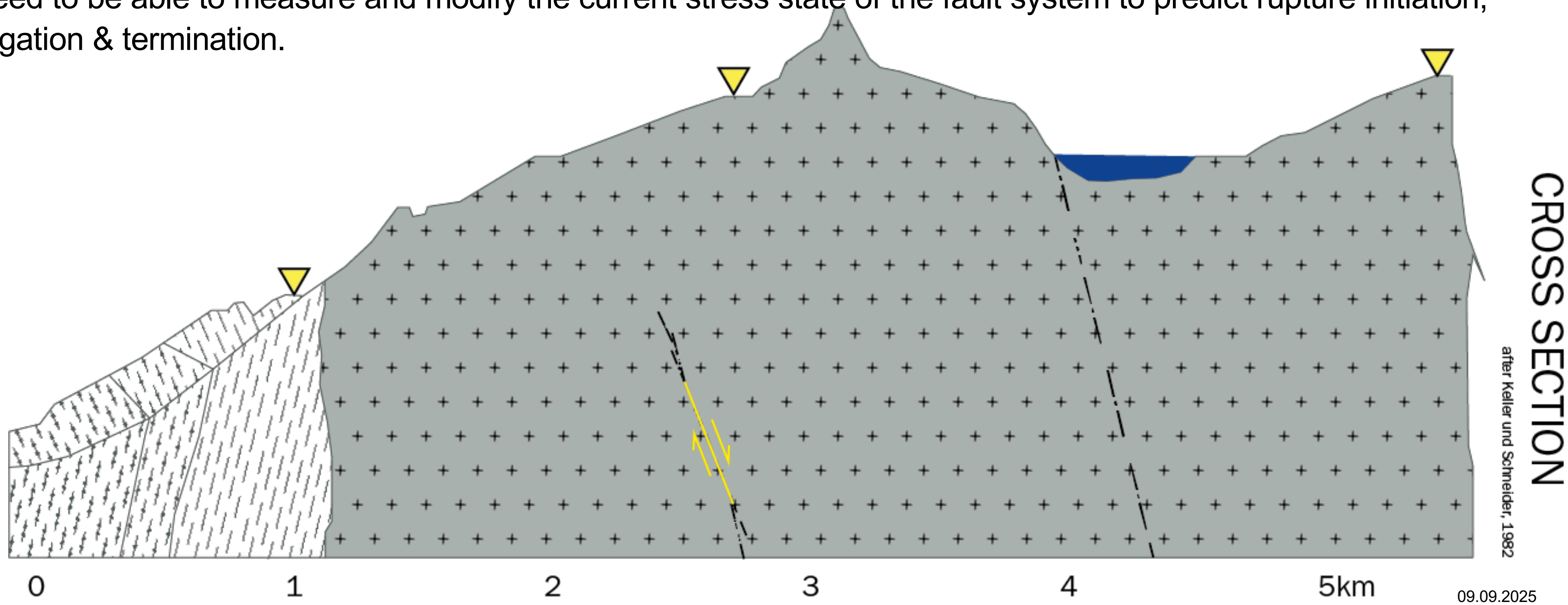
- ✓ Progress in PSHA goes hand-in-hand with progress in instrumentation and data products.
- ✓ A 30 years effort !
- ✓ Over 500 collaborators from all over Europe and all disciplines!

Technical Annex in the 2024 EuroCode8 revision


The Bedretto Underground Laboratory
for Geosciences and Geoenergies

We need to get our instruments closer to the quakes

- We do not know beforehand when and where the next big earthquake will happen, and most earthquake occur at 5-15 km depth → so we cannot be right there with multi-parameter instrumentation.
- We need to repeat experiments (i.e., ‘earthquakes’) under controlled conditions.
- We need to reconcile seismological investigations, physical models, geological observations and laboratory experiments.
- We need to be able to measure and modify the current stress state of the fault system to predict rupture initiation, propagation & termination.



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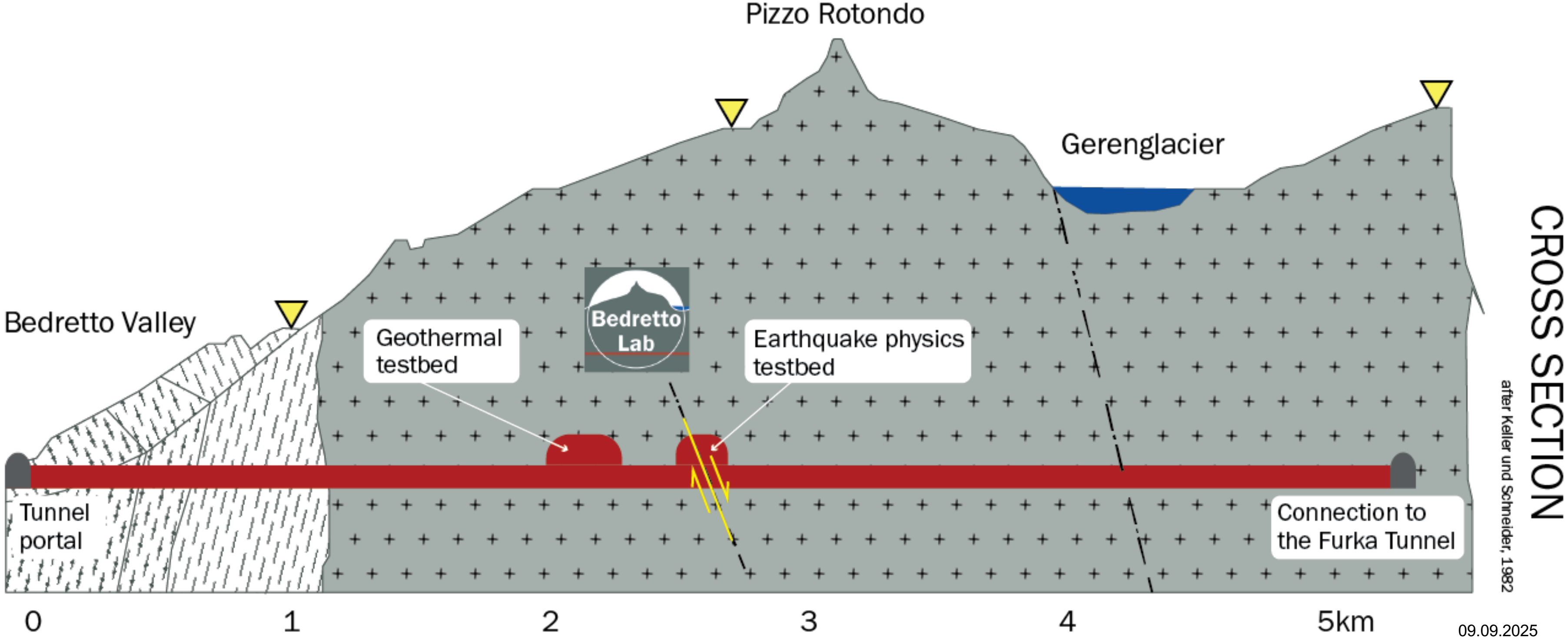
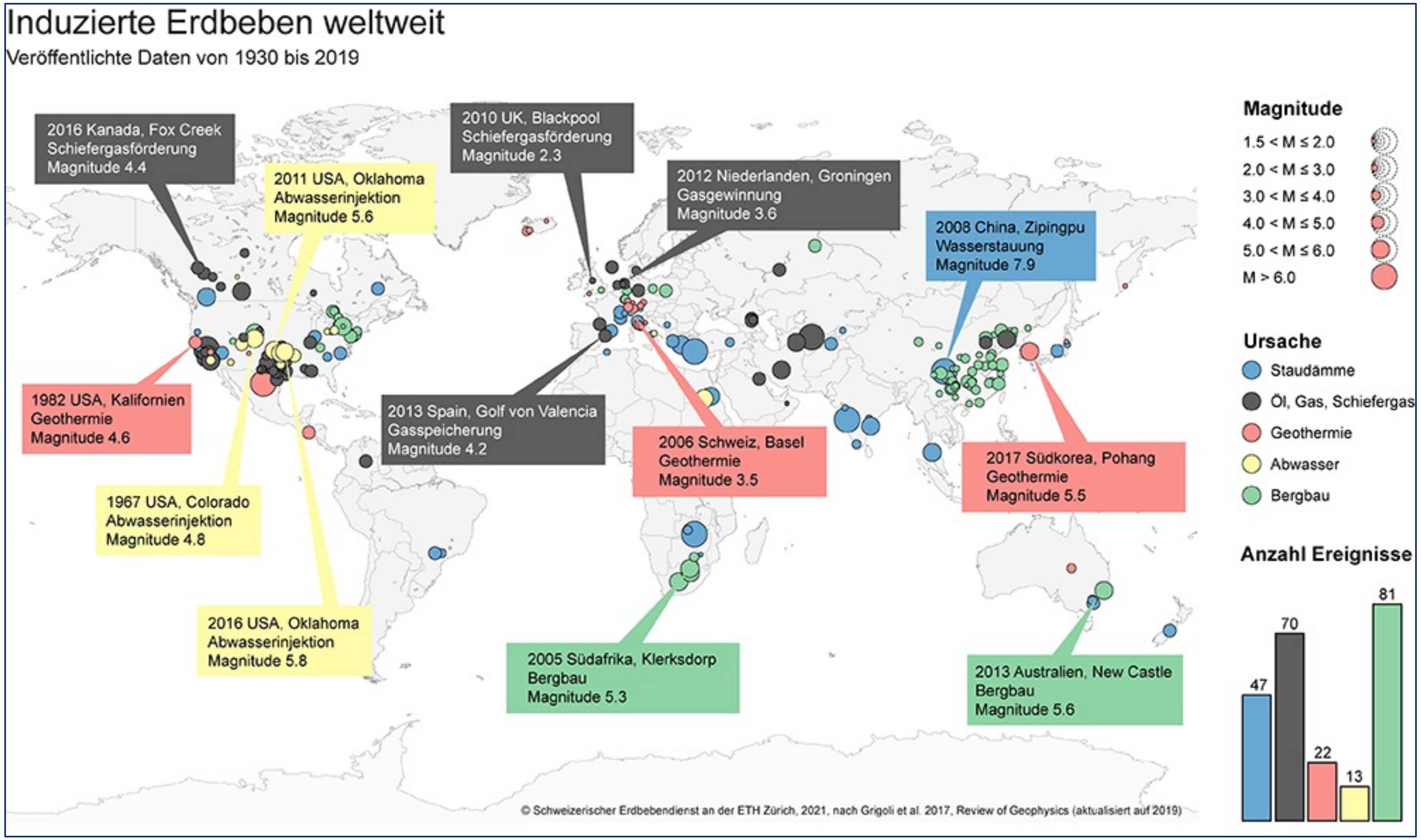


A global challenge: induced seismicity

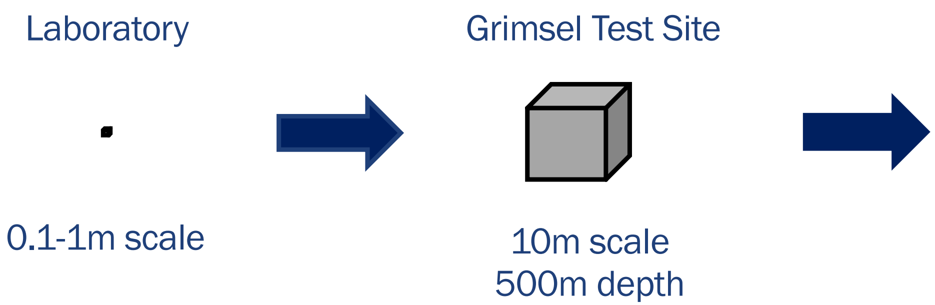
Induced seismicity is commonly observed in anthropogenic activities altering significantly the underground conditions of stress in the vicinity of seismogenic faults.

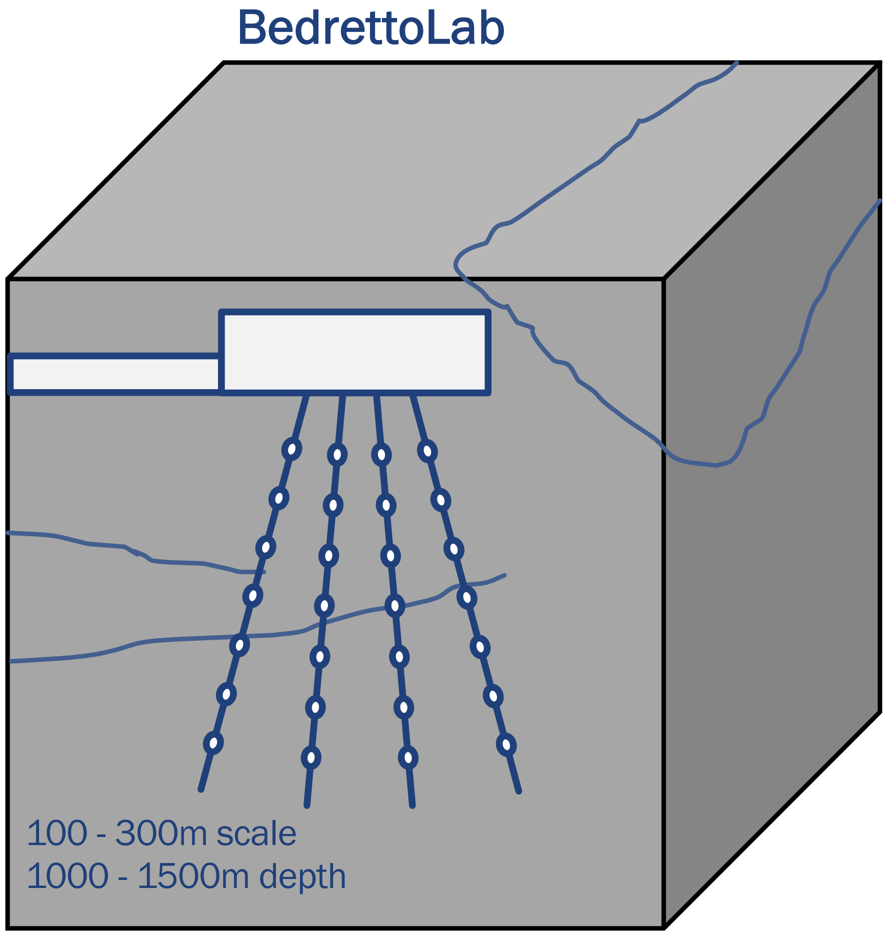
Induced seismicity provides a great chance to study earthquake physics, because if they are produced under controlled conditions, we know where and when they will be.



The overall experimental approach

- Reach relevant depths, rock types and rock volumes
- Build experimental testbeds designed for specific scientific targets (geothermal energy, earthquake physics), cementing hundreds of sensors in deep boreholes to measure all physical and chemical parameters, and transforming the target rock volume in a large sensing environment
- Install On-Fault Observatories
- Condition stress conditions on faults
- Move faults and induce quakes





BedrettoLab in a Nutshell

Pioneering research

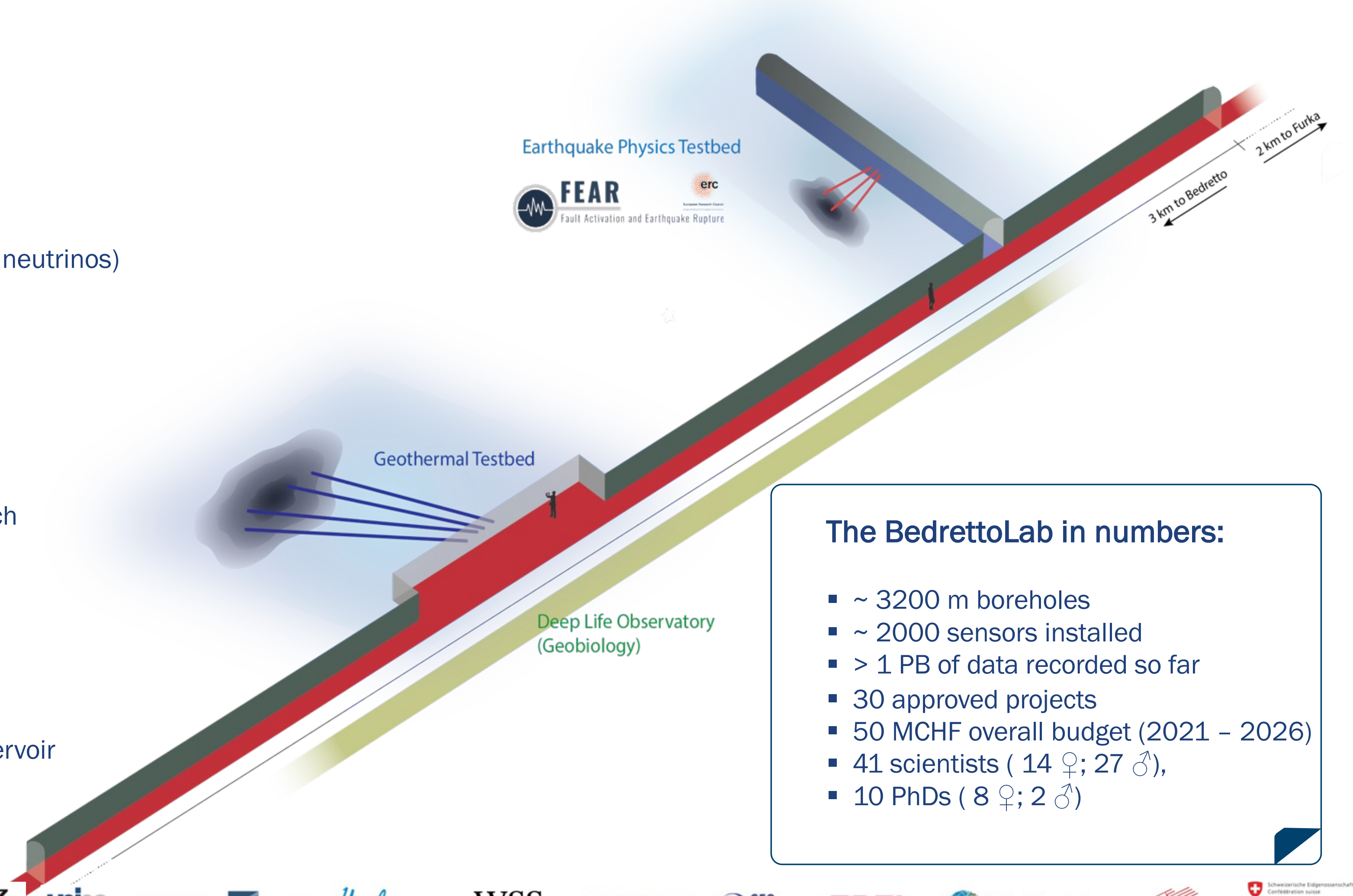
Earthquake Physics
Hydromechanics
Geobiology
High-energy physics (dark matter, neutrinos)

Areas of Societal Relevance

Geoenergy
Earthquake risk
Origin and prevalence of life
Nuclear repository related research

Technology development

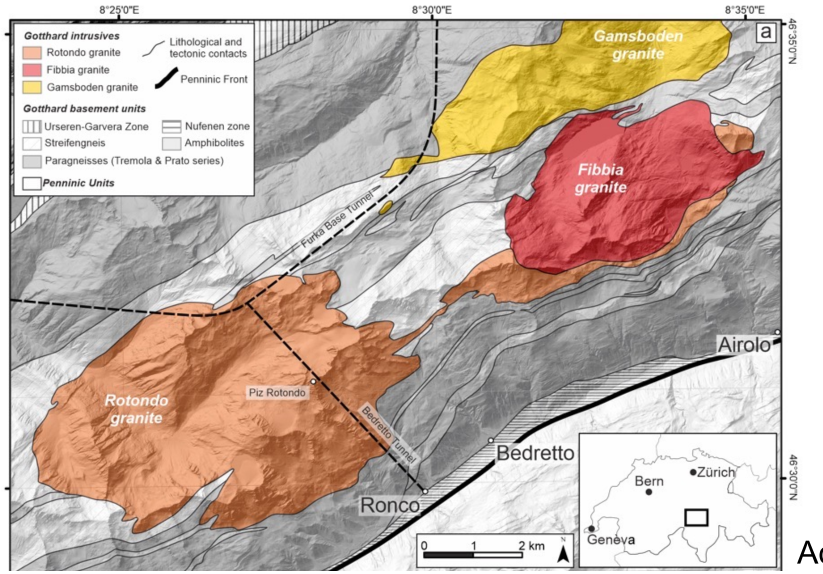
New instruments for underground exploration and monitoring
300 m scale fully engineered reservoir



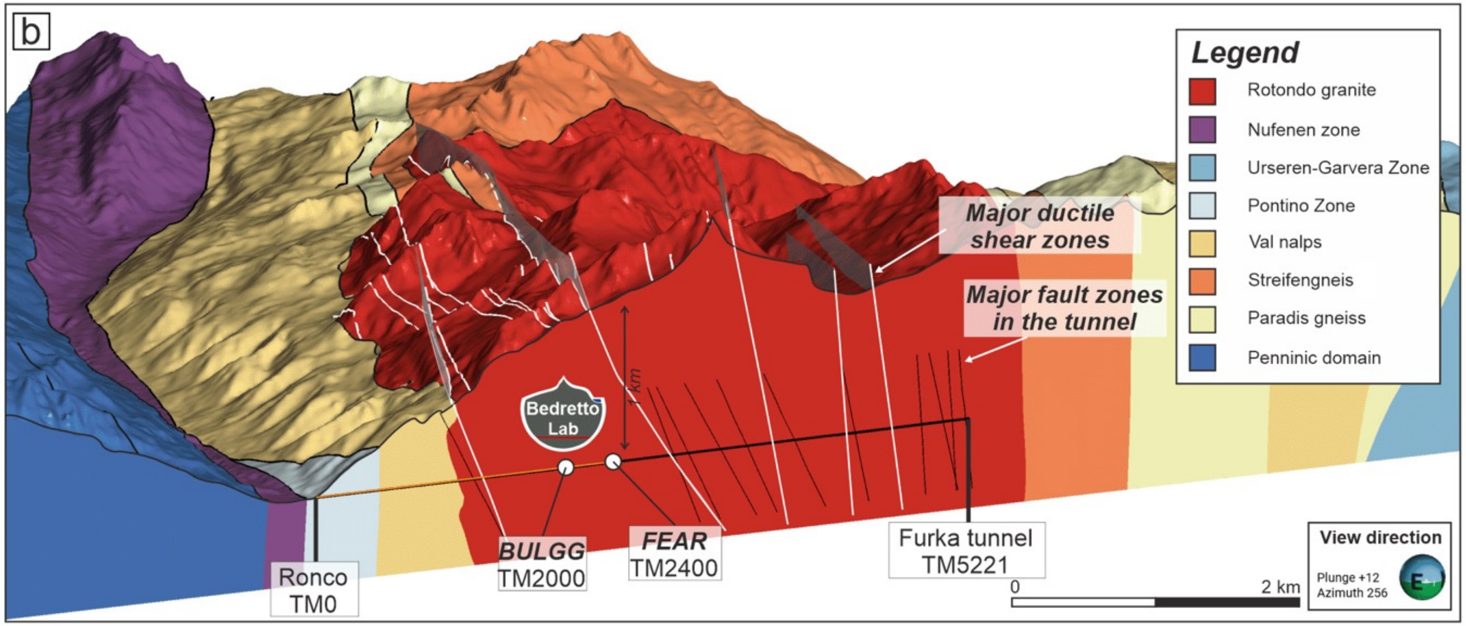
The BedrettoLab in numbers:

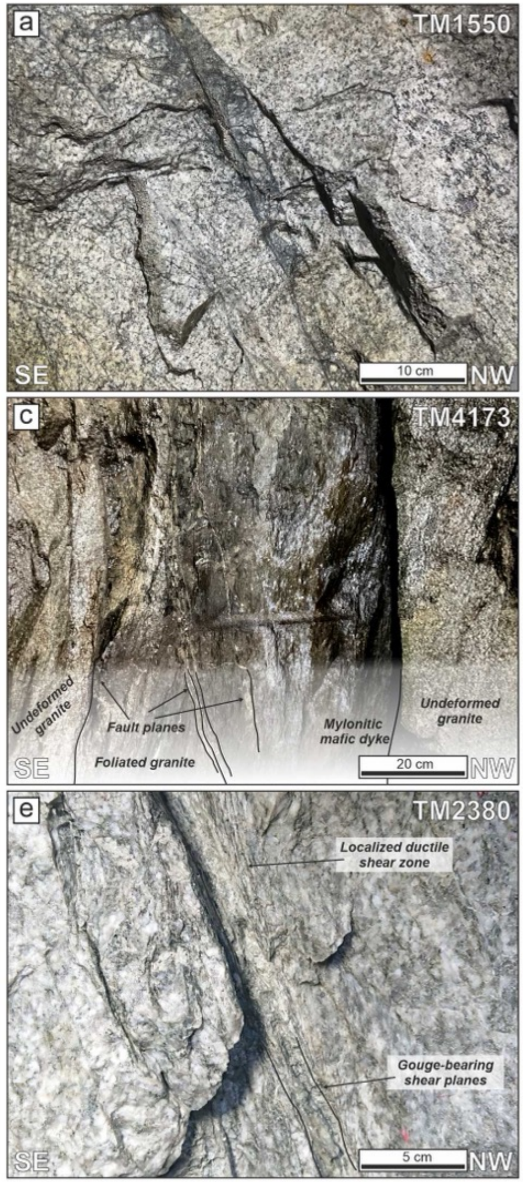
- ~ 3200 m boreholes
- ~ 2000 sensors installed
- > 1 PB of data recorded so far
- 30 approved projects
- 50 MCHF overall budget (2021 – 2026)
- 41 scientists (14 ♀; 27 ♂),
- 10 PhDs (8 ♀; 2 ♂)

Geological characterization



Achzinger et al., 2024

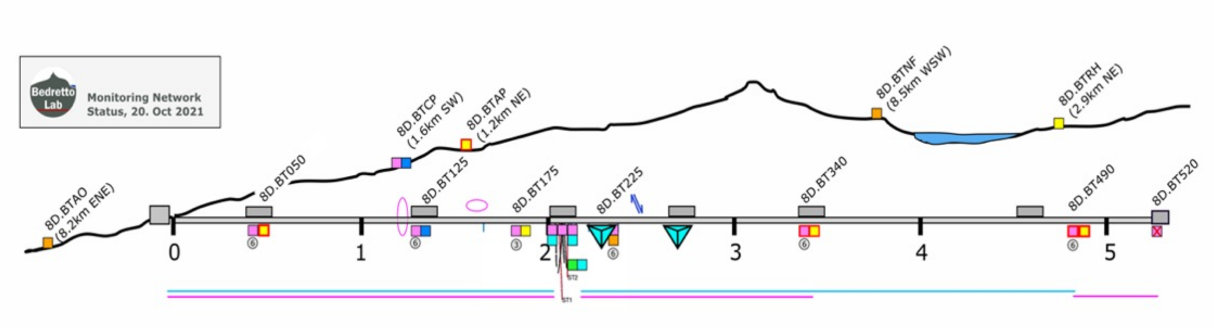




Seismic background monitoring

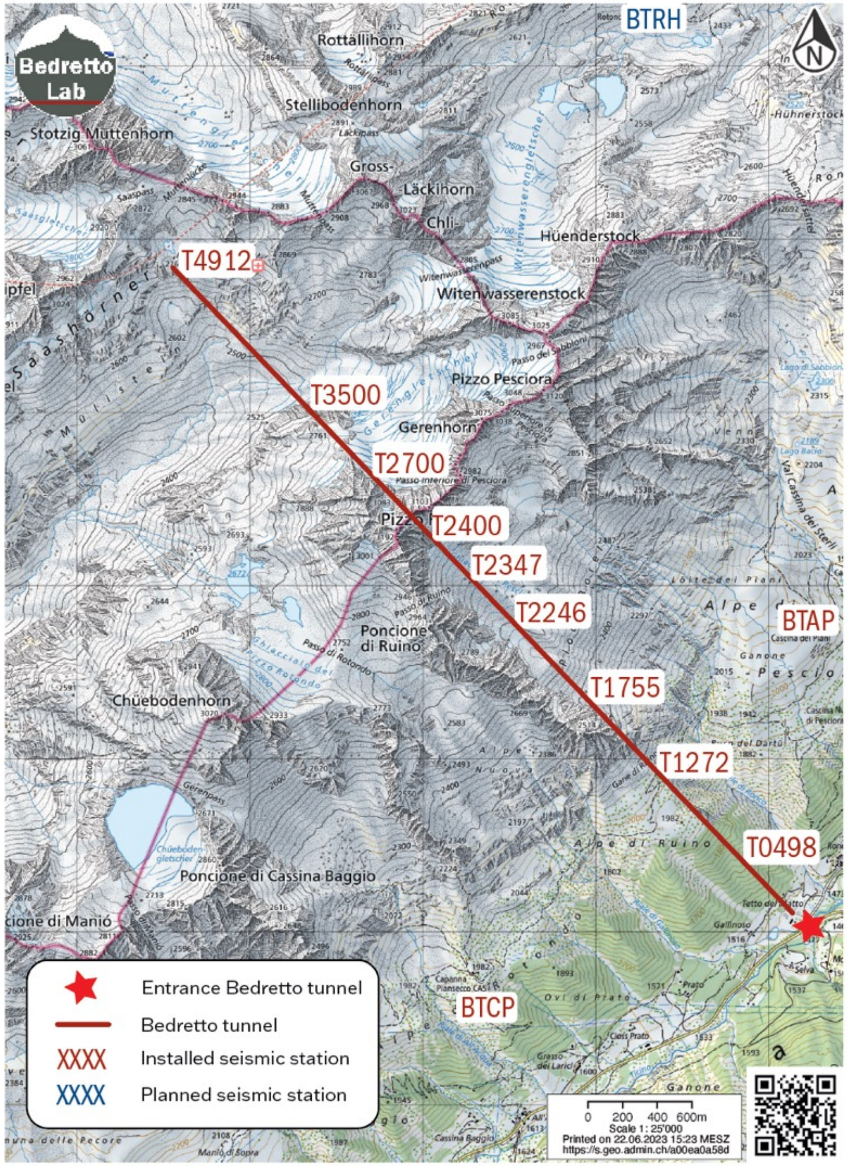
A dense, real-time, multi-sensor seismic array installed in the tunnel and on the surface…

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service



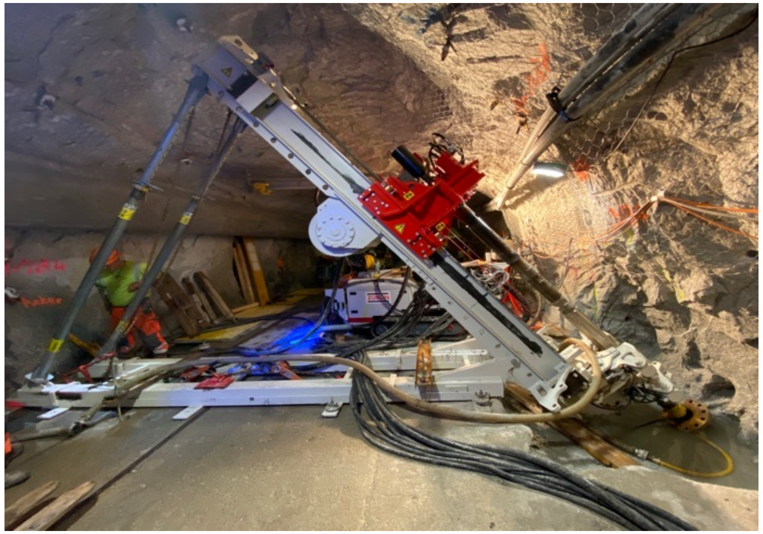
	Green (less than)		Yellow (greater equal)		Orange (greater equal)		Red (greater equal)	
	Mw	Ml	Mw	Ml	Mw	Ml	Mw	Ml
>50 m	-1	-2.75	-1	-2.75	0	-1.25	1	0.25
>100 m	-0.5	-2	-0.5	-2	0.5	-0.5	1.5	1
>150 m	-0.15	-1.5	-0.15	-1.5	0.85	0	2	1.75

Strict traffic light protocols.



Building the lab

We identified the target volume 100 – 400 m below the tunnel and drilled 8 monitoring boreholes and 2 injection boreholes (up to 400m long), to install the full monitoring system and engineer the reservoir for injection experiments and long-term seasonal energy exchange and storage.

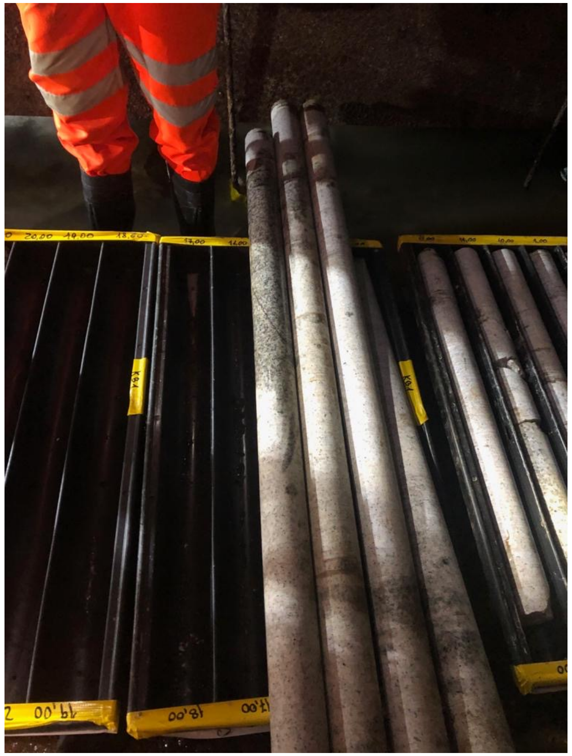


Building the lab

Kilometers of cores

A new storage facility built in Forch/Zääjuten,

All cores are scanned and fully characterized for the identification of faults



Data mountains also ...

- 800 MB of continuous data per day are sent from the acoustic emission sensors in the BedrettoLab to the servers in Zurich, using a dedicated 10 Gb line
- In addition, up to 1 TB per day is collected during experiments, measured by sensors such as fiber optics interrogators, geophones, temperature, pressure and strain meters
- Raw and processed data are archived in the dedicated mass storage facility of 2 PB capacity now installed at ID@ETHZ
- BedrettoLab is now a test area for the implementation of the EU Digital Twin on Geophysical Extremes (DT-GEO) for the real-time assimilation of data and modelling

DT-GEO

Building the Earthquake Physics Testbed

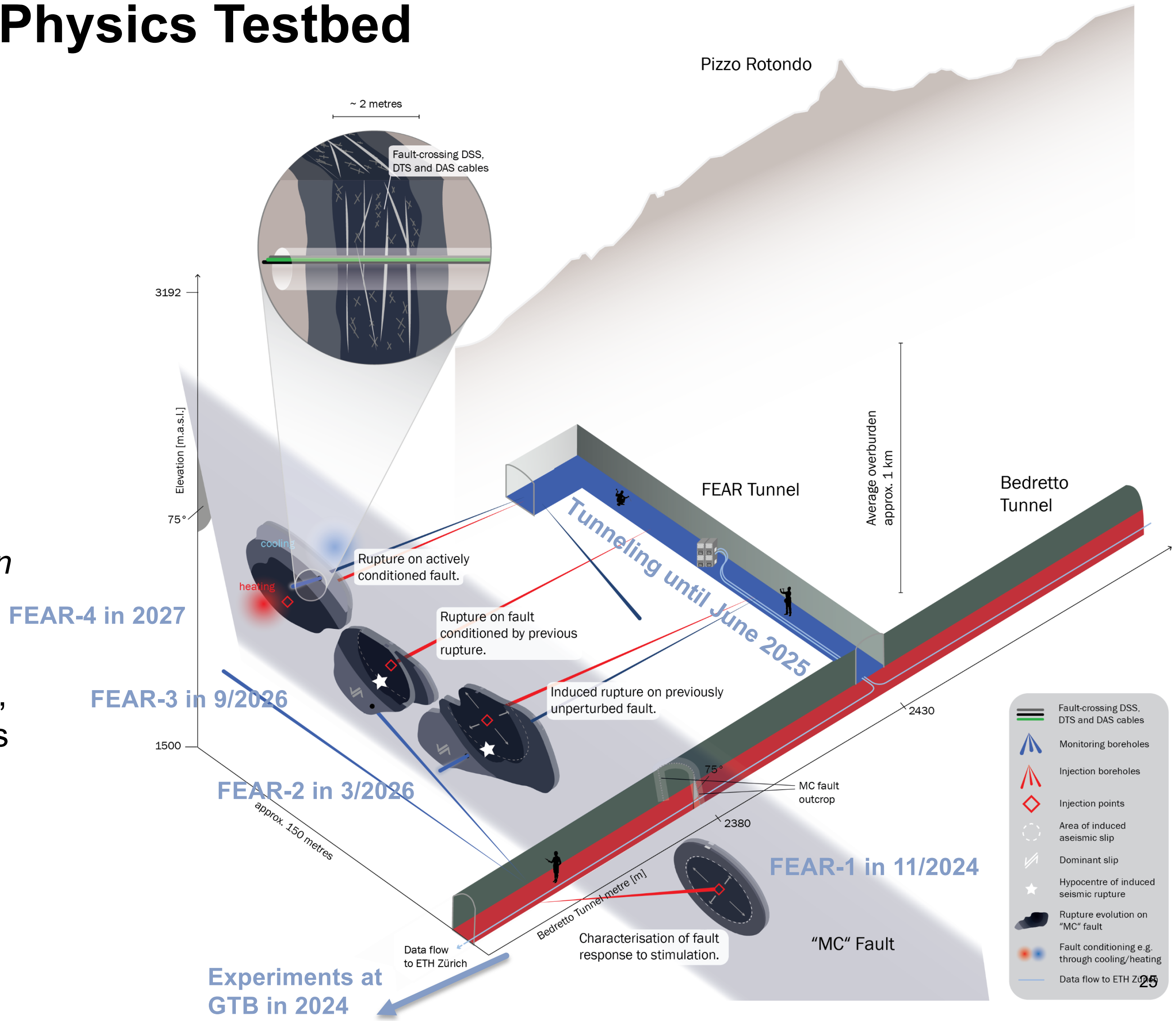
Build 130m long access tunnel, parallel to the fault

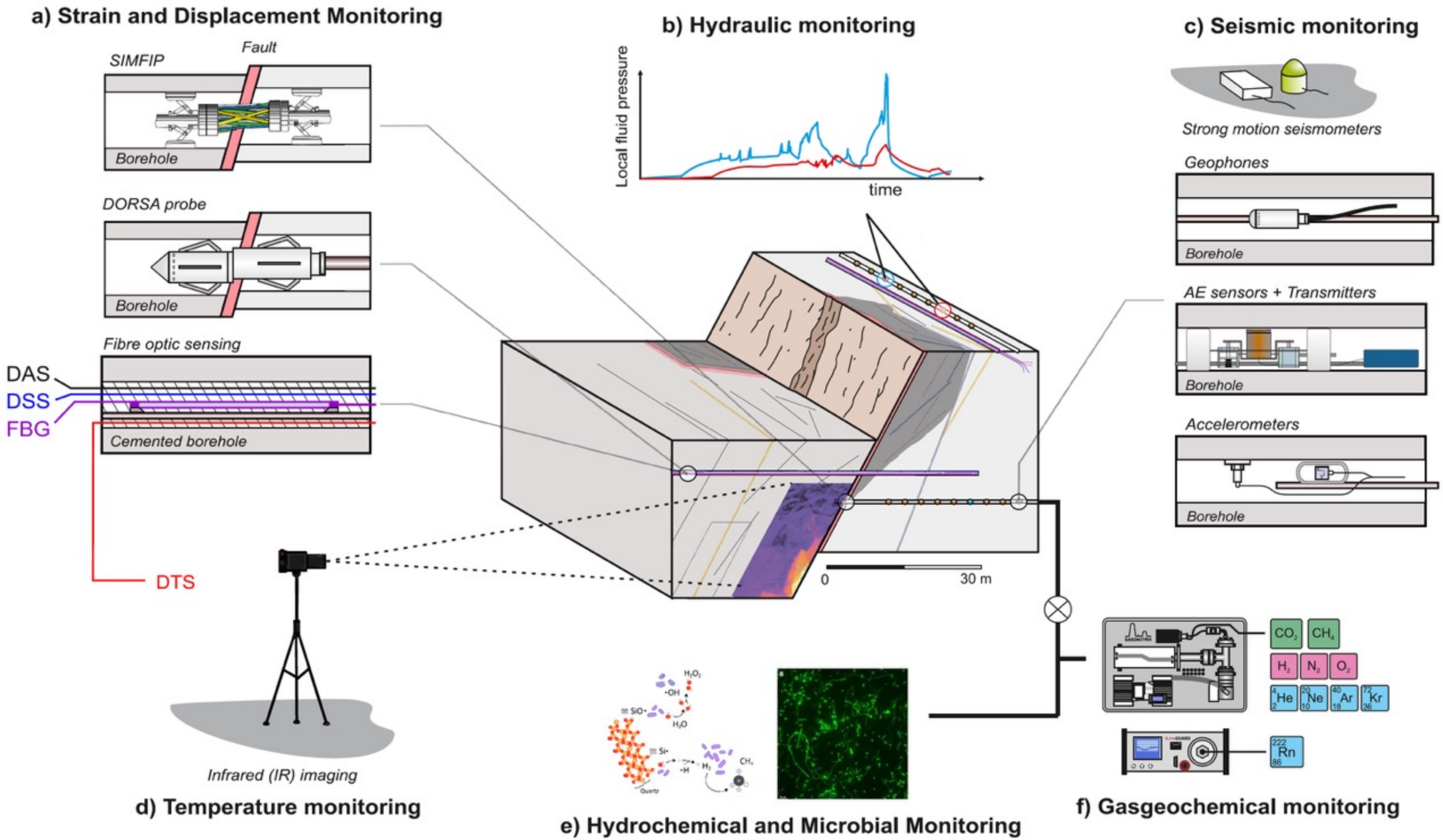
From there, place sensors to monitor

- slow and fast rock deformation
- fluid pressure
- temperature
- hydro-bio-chemistry

We place monitoring equipment directly *on* the fault → First On-Fault Observatory

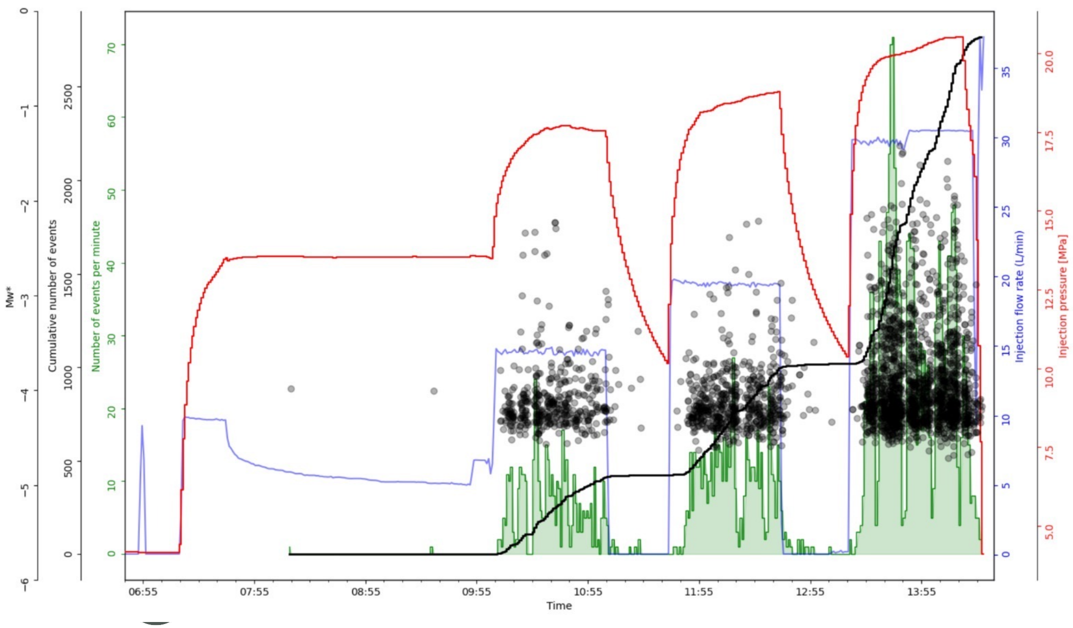
And then make earthquakes "on demand", with fluid injections, where our instruments are.



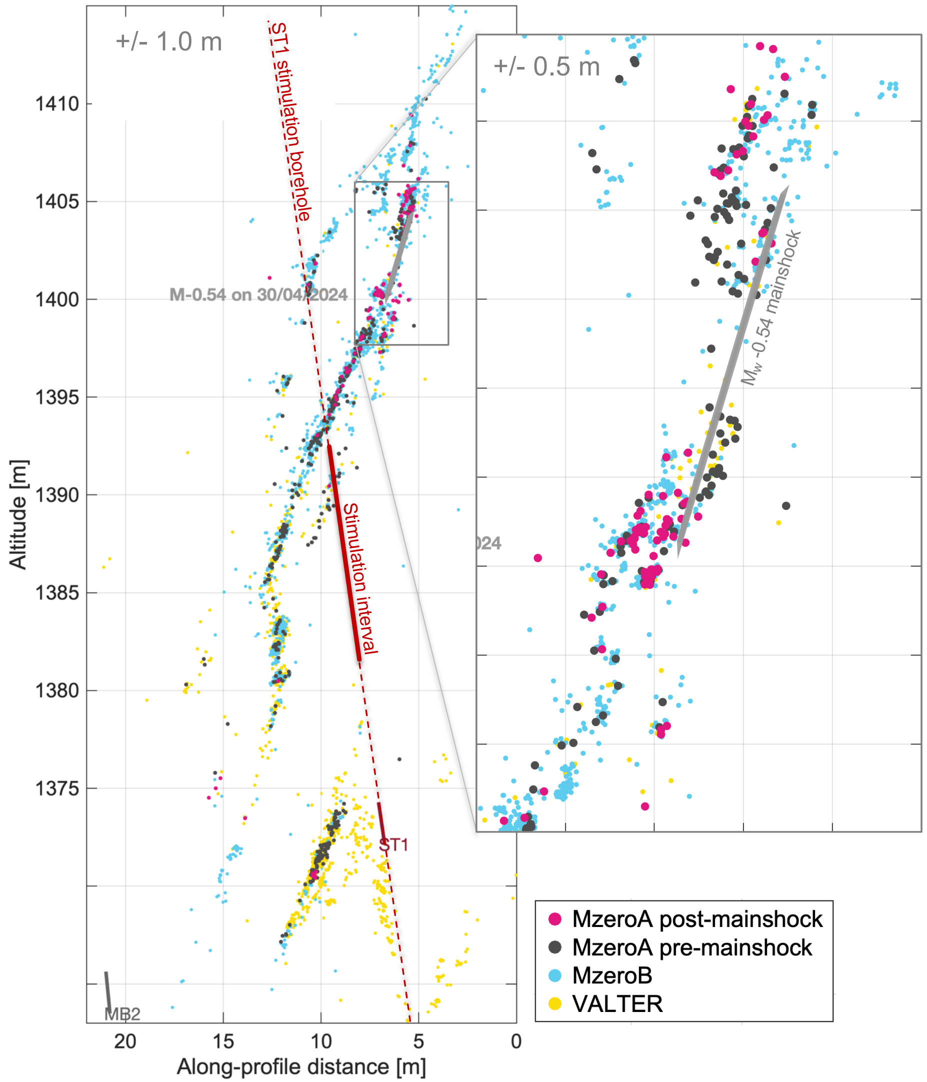

a) Strain and Displacement Monitoring
SIMFIP
Fault
Borehole
DORSA probe
Borehole
Fibre optic sensing
DAS
DSS
FBG
Cemented borehole
DTS
b) Hydraulic monitoring
Local fluid pressure
time
c) Seismic monitoring
Strong motion seismometers
Geophones
Borehole
AE sensors + Transmitters
Borehole
Accelerometers
Borehole
0
30 m
Infrared (IR) imaging
d) Temperature monitoring
e) Hydrochemical and Microbial Monitoring
CO2
CH4
H2
N2
O2
He
Ne
Ar
Kr
Rn
f) Gasgeochemical monitoring

Stimulation and induced seismicity

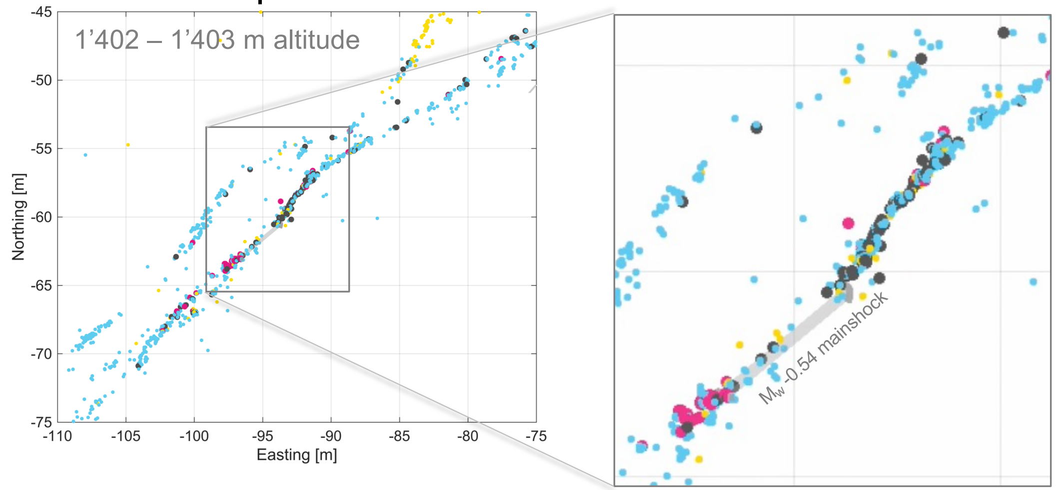
- We control microseismicity in repeated injections, steering injections parameters with the size and rate of induced seismicity
- We do not frack the rock nor we produce new faults, we change the conditions on the existing faults so that the stresses already active in the Alps will move the faults through micro and small earthquakes
- All operations controlled remotely and conducted over several weeks



Vertical profile



Horizontal profile

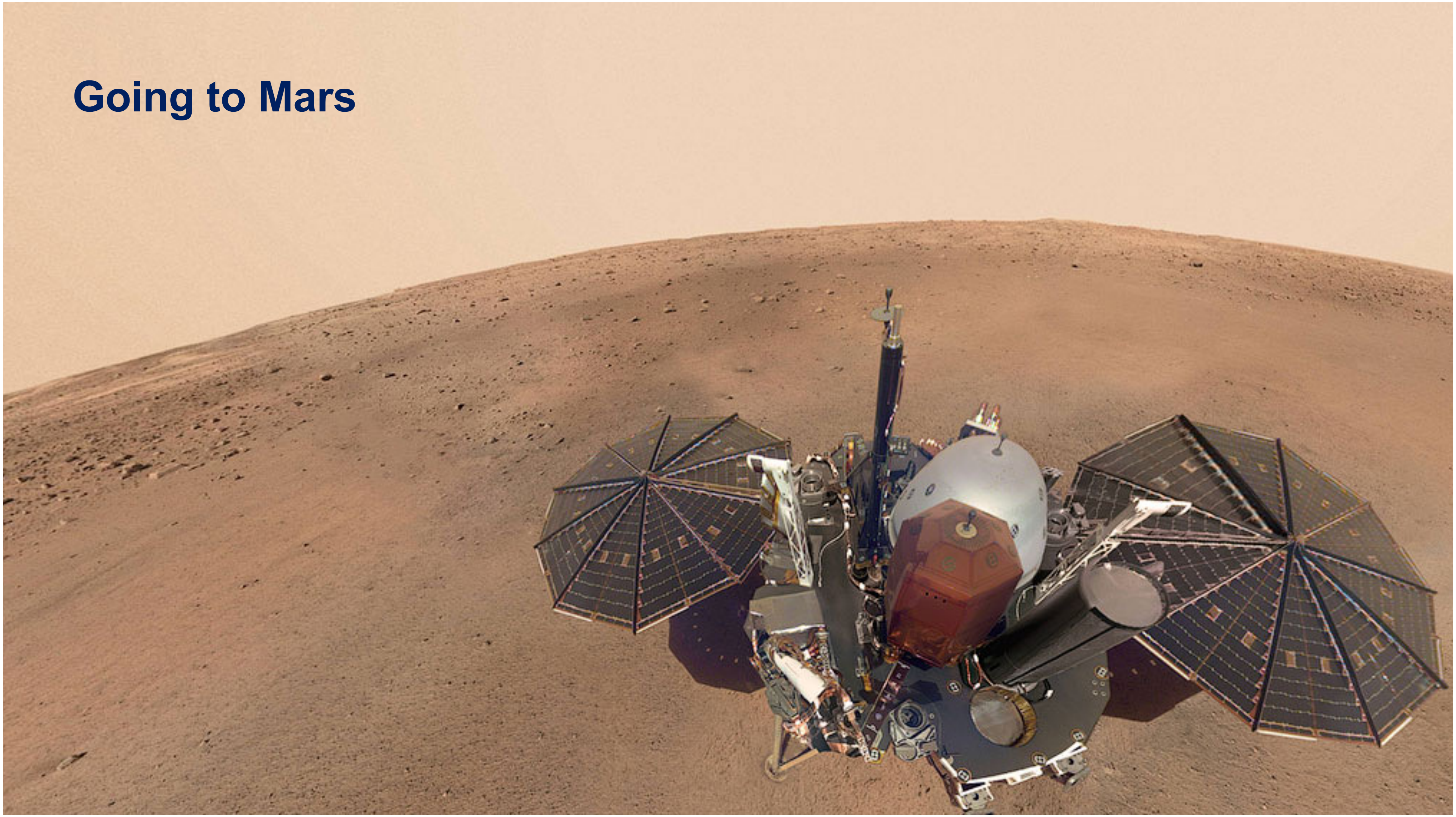


First injections

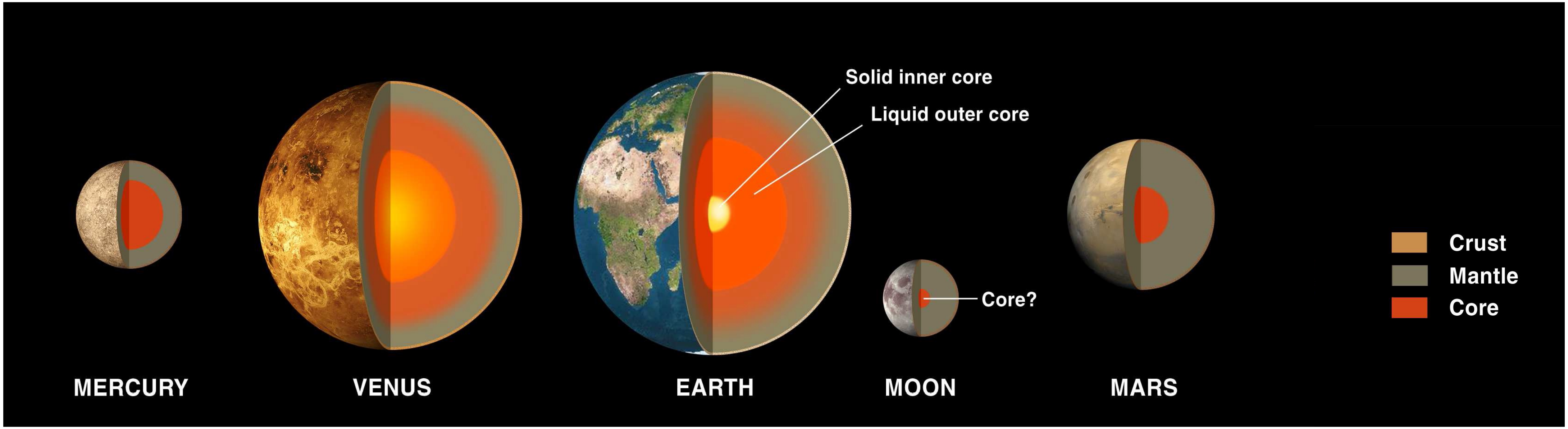
Remote controlled dual-point injection with up to 30MPa @ 270 l/min

Total injected volume > 1'000 m^3

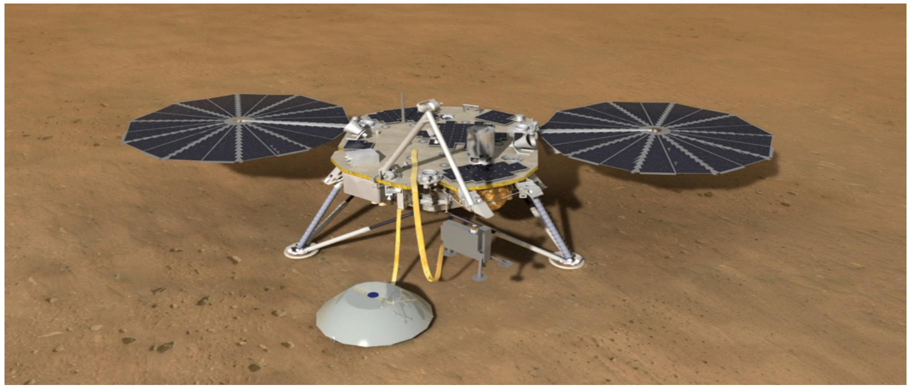
Going to Mars



- “Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as providing context for the history and processes of our own planet.” 2011 Decadal Review, NASA
- Key targets: internal structure and differentiation (crust, mantle, core), start and ending of the magnetic field, surface geology, water, atmosphere, past life, habitability

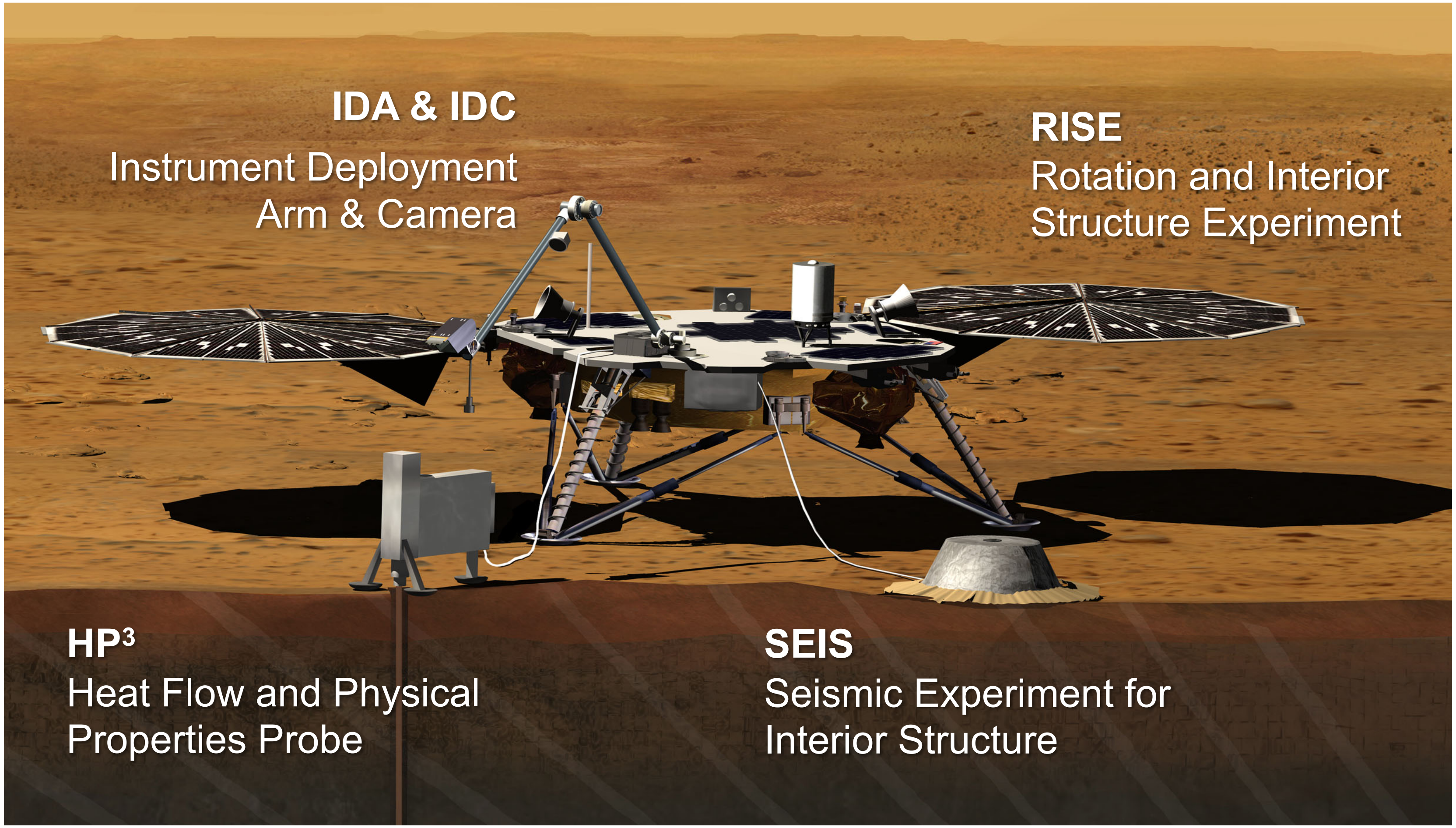


One chance every 20 years to install a seismometer on Mars

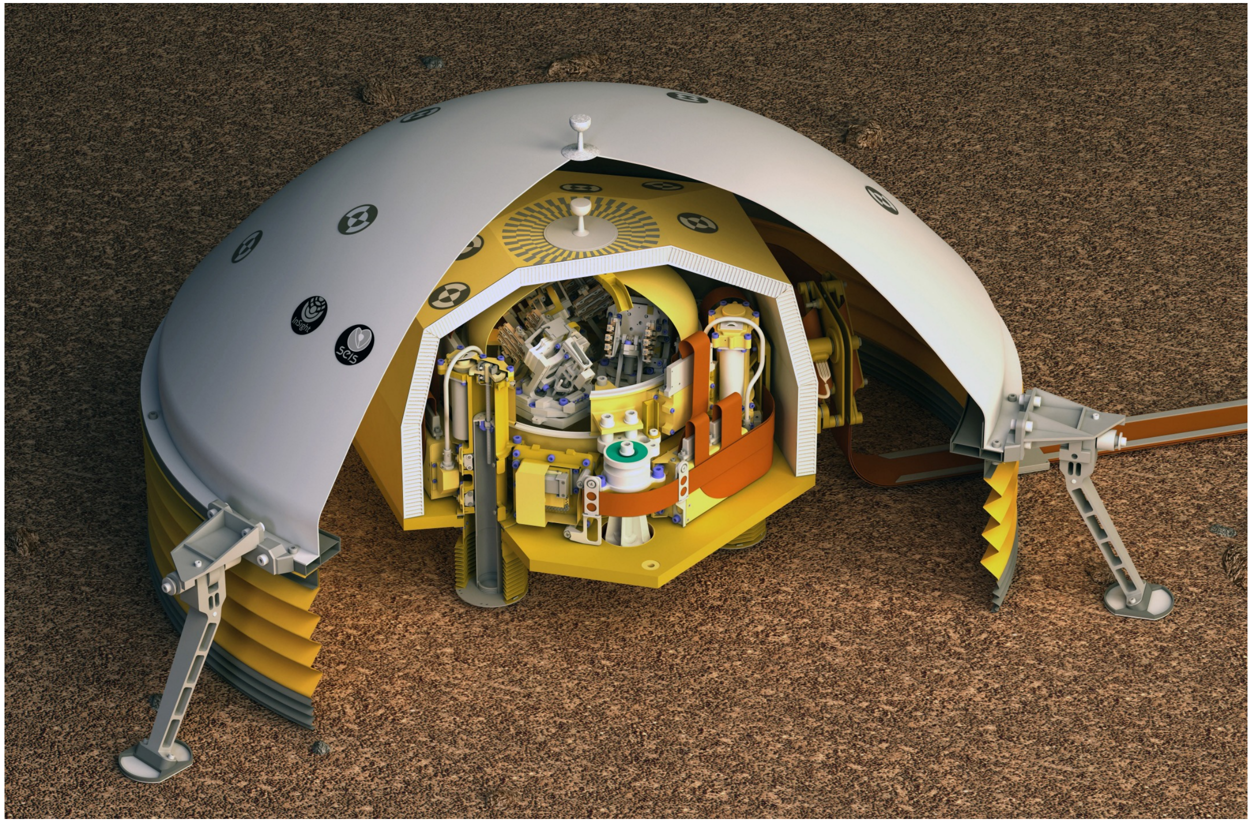


- 1975: the two Viking exobiology landers carry a seismometer on deck → one suspect signal, we know today that it could not be a marsquake signal
- 1996: Mars96, a Russian mission carrying two French seismometers, explodes after launch
- After several proposals and projects with ESA (Netlander, Exomars, …) NASA selected a geophysical package for a Mars mission for the 2016 Discovery selection
- We missed the 2016 launch window and we launched in 2018

InSight: Interior Exploration using Seismic Investigations, Geodesy and Heat Transport



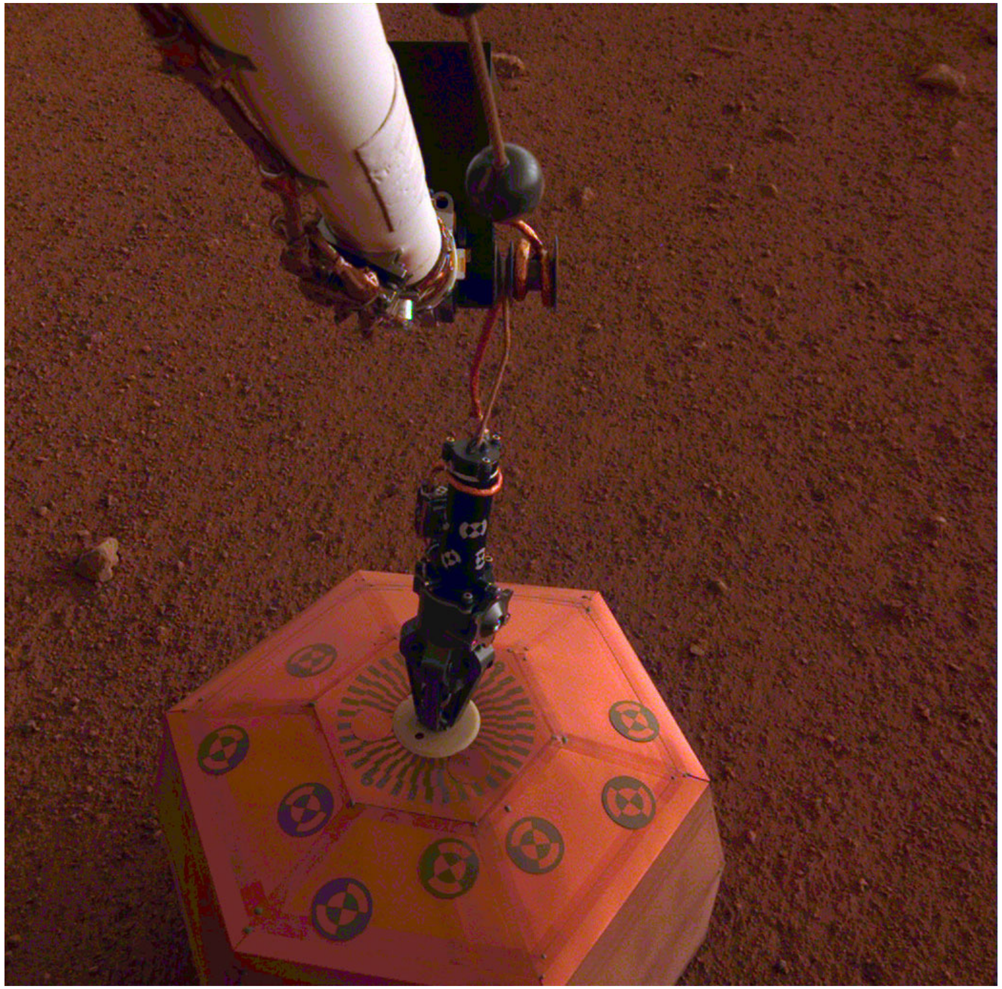
SEIS

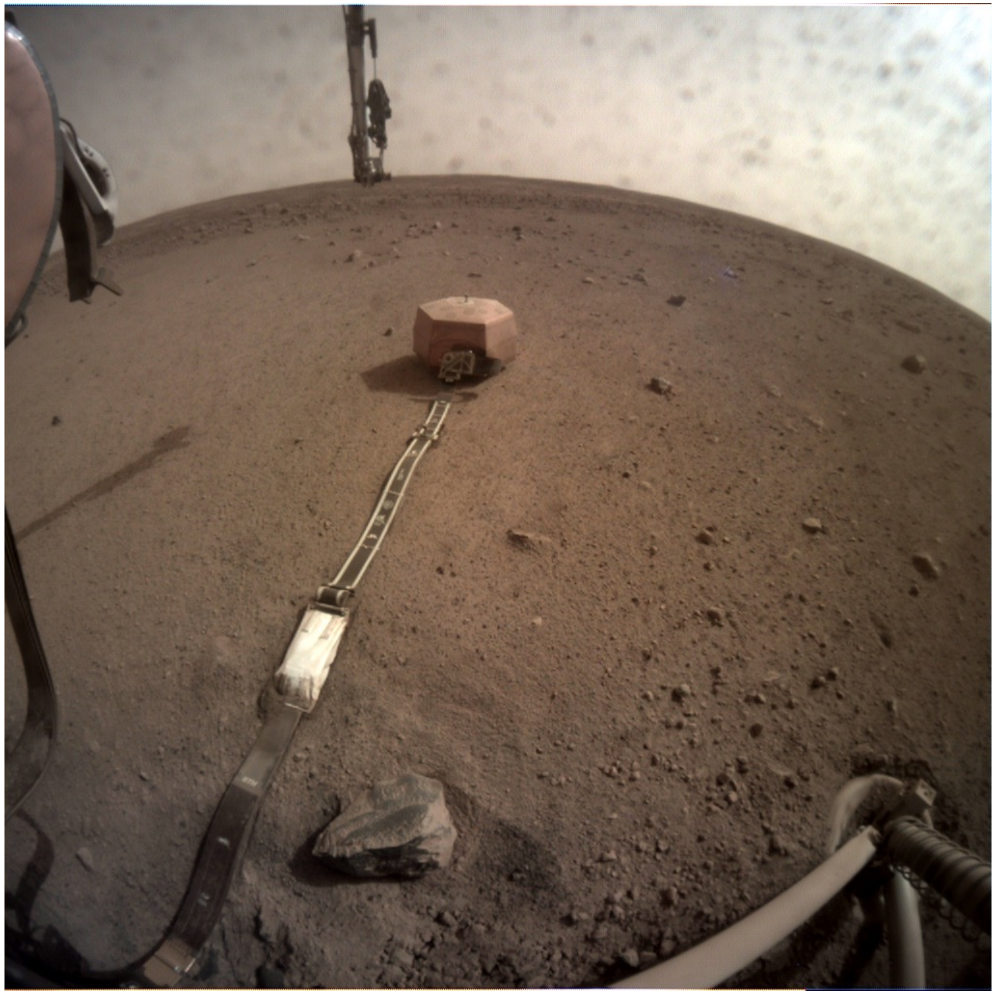


- SEIS includes a 3C VBB contained inside a vacuum sphere (IPGP, Sodern) and a 3C SP on the sides (ICL, U.Oxford)
- The levelling system (LVL) ensures that the seismometer is perfectly horizontal (MPS)
- The Wind and Thermal Shield (WTS) protects the sensor from external influence (Spain)
- SEIS and WTS are installed on the ground by a robotic arm (US)

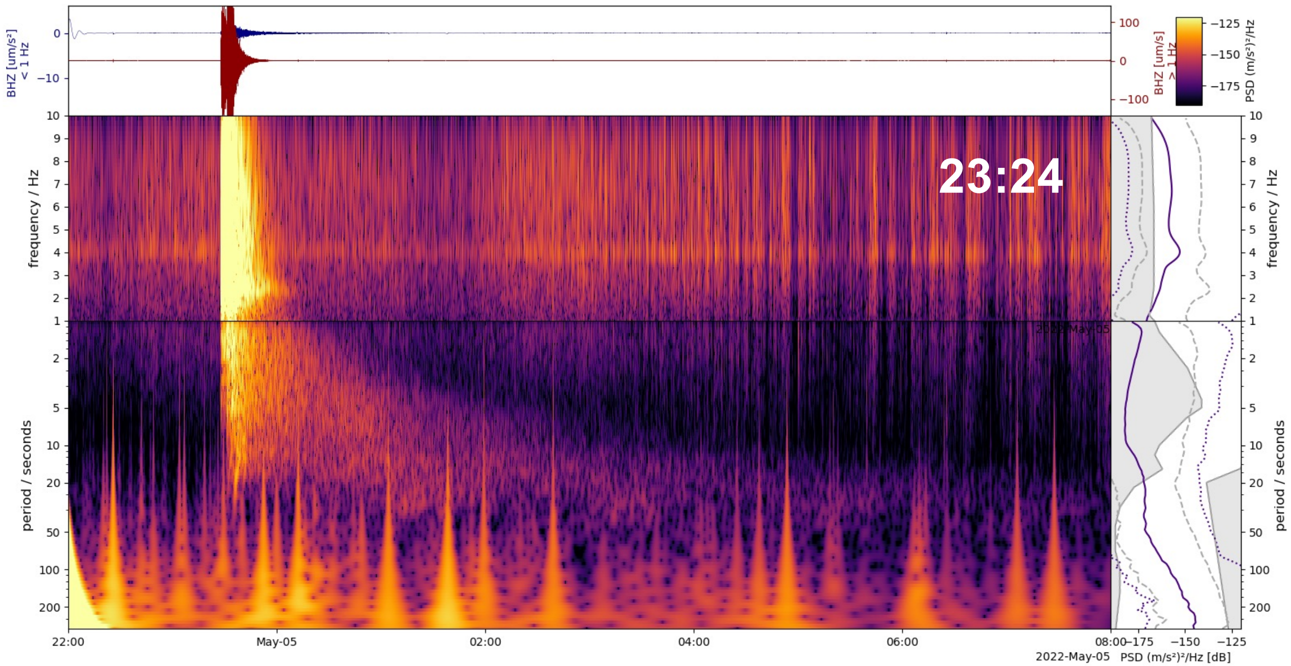

May 5, 2018: lift-off !

SEIS on the ground!



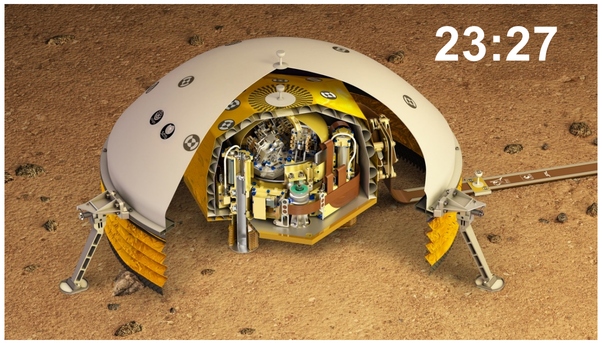


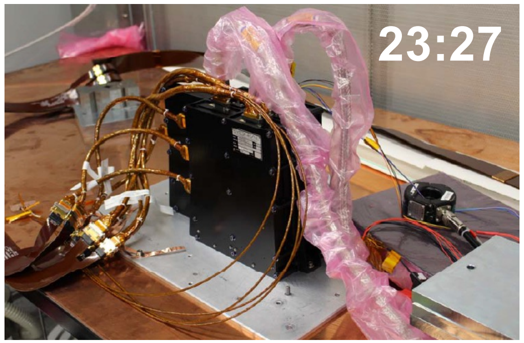
Running the MarsQuake Service

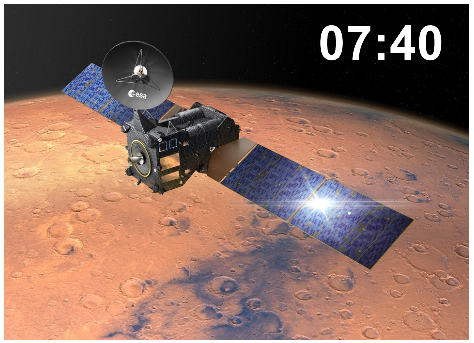


13:12: detection, localization and magnitude assessment by the MarsQuake Service @ ETH Zurich, with a distance accuracy of about 50km

QA, signal control, timing control, multi-channel correlation by JPL and CNES



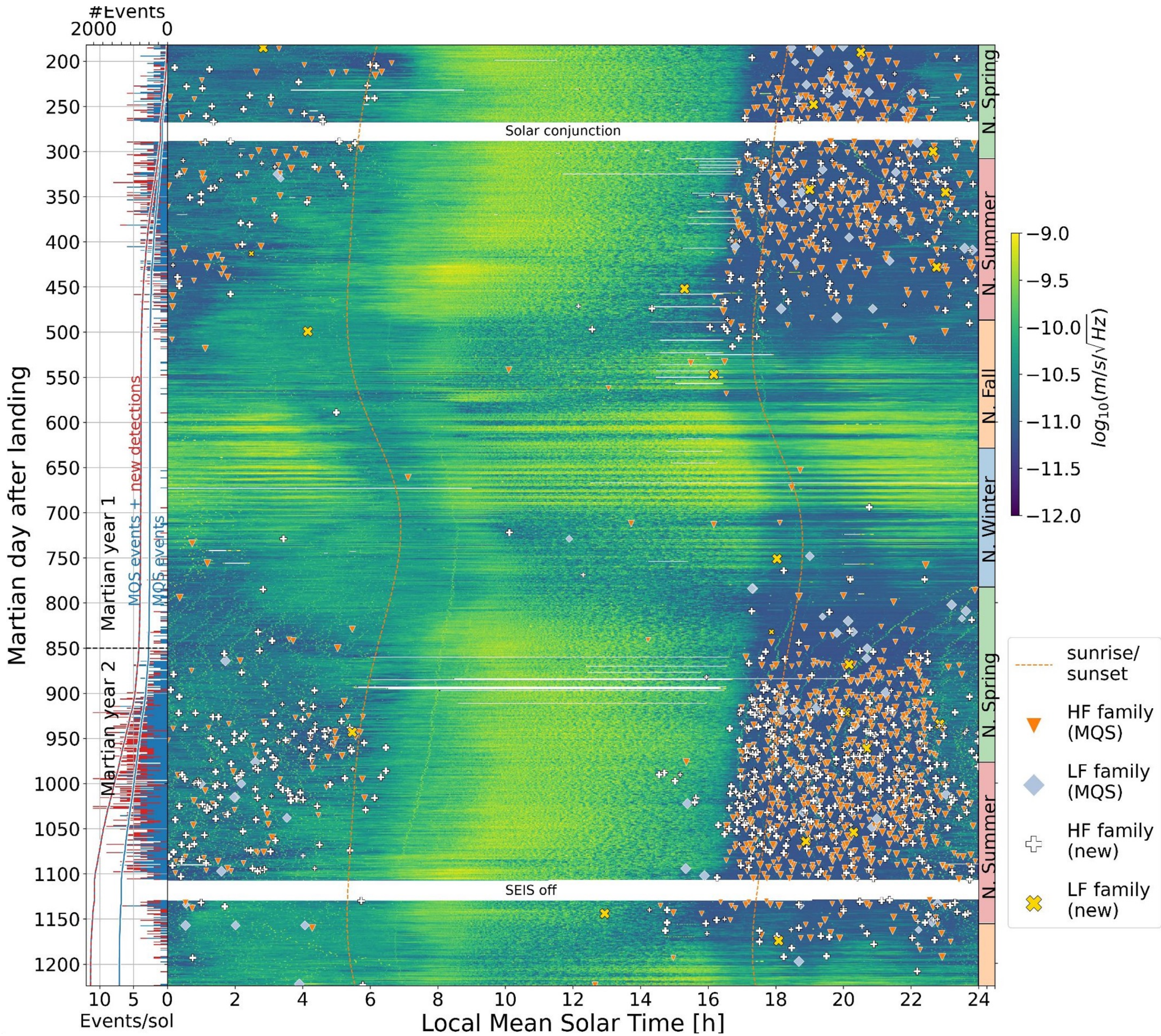




Running the MarsQuake Service

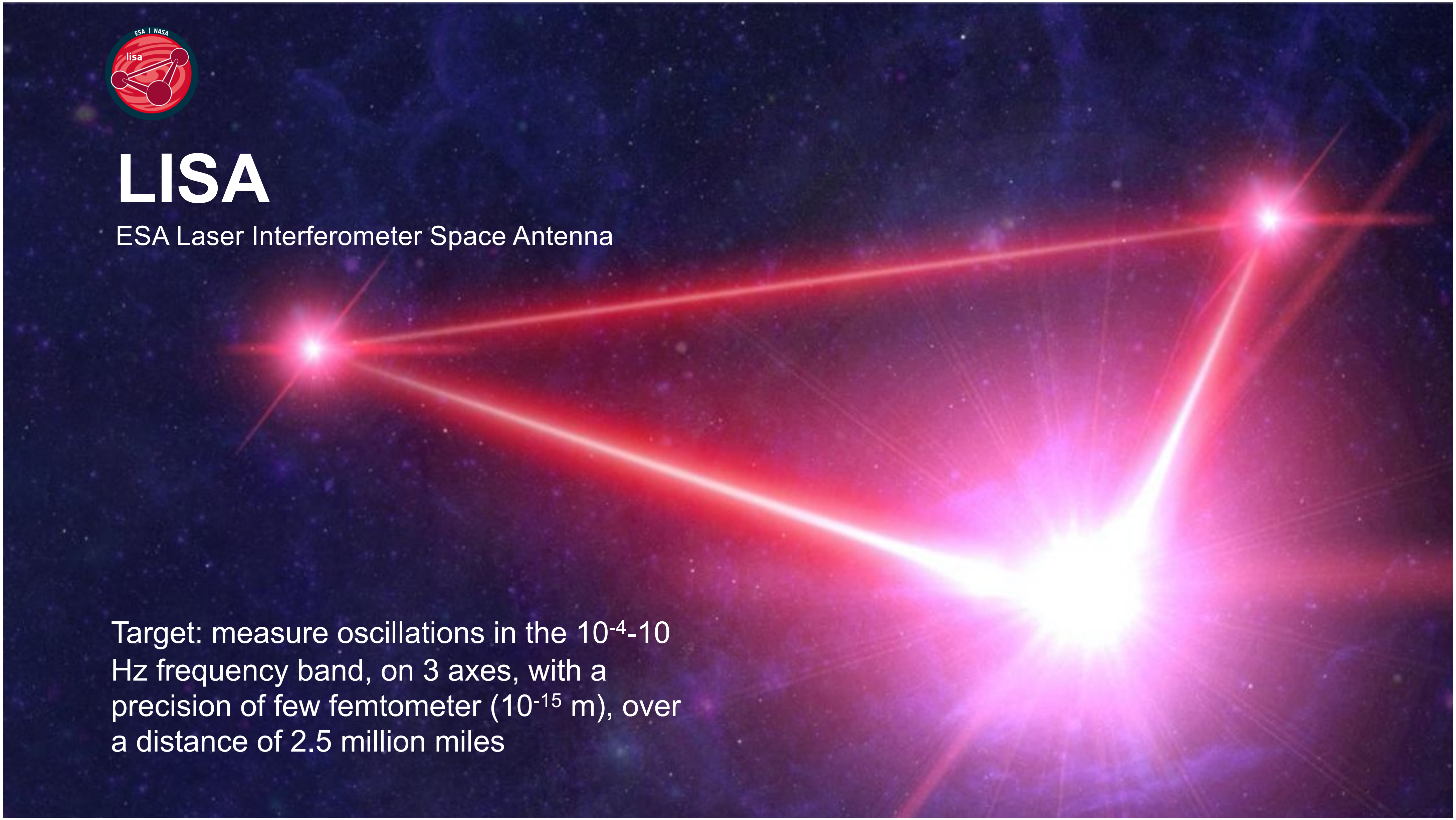
To ensure the successful analysis of data from Mars, we duplicated the procedures normally used on Earth, adapting from network to single-station.

Every day would stream from Mars, and it was an exhilarating process of understanding small events in a noisy environment and at the same time unraveling the internal structure of the red planet.



And then, a real treasure hunt!

- Shallow structure from surface resonances
- Crust from receiver functions and Pg-Sg
- Mantle velocities from multiply reflected body-waves
- Core radius from ScS, SKS, Pdiff phases
- Lower-mantle molten layer
- On-going extensional tectonics in Cerberus Fossae
- Seismic activity rates
- Detection and discrimination of meteoritic impacts, as ground-truth events
- Detection of water-ice at shallow depths ejected by meteoritic impacts



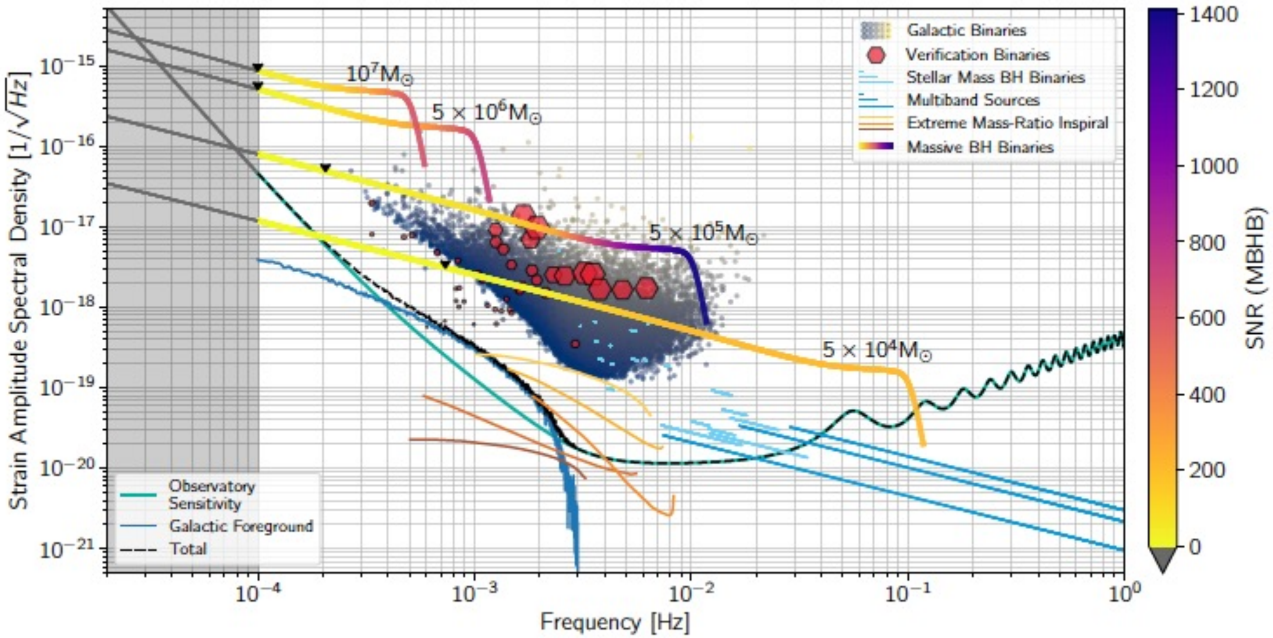
LISA

ESA Laser Interferometer Space Antenna

Target: measure oscillations in the 10^{-4}-10 Hz frequency band, on 3 axes, with a precision of few femtometer (10^{-15} m), over a distance of 2.5 million miles

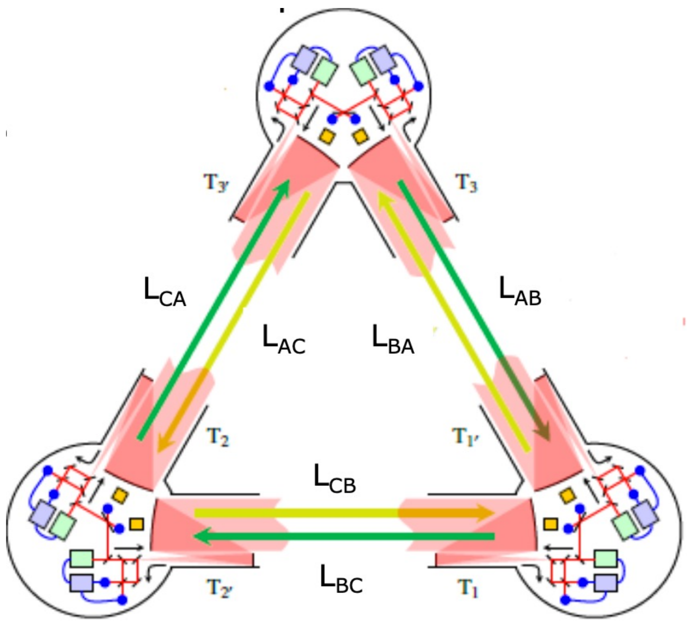
LISA targets

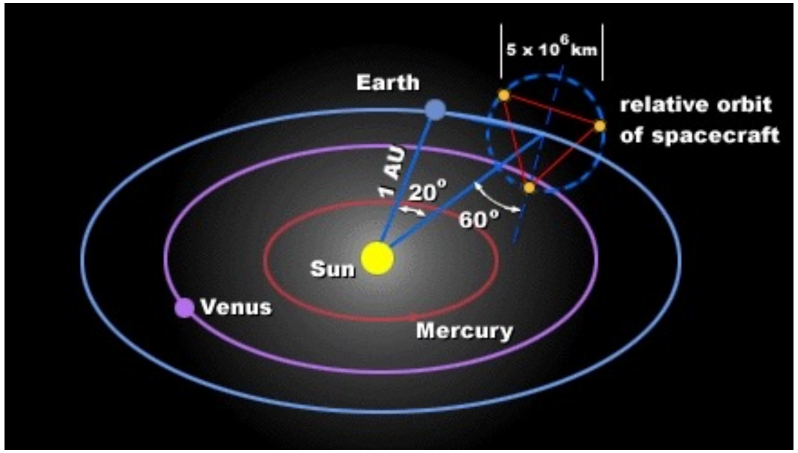
- Galactic Binaries (GB), 30 mil
- Stellar BHB (sBHB) or Stellar-Origin Binary Black Hole (SBBH), 10-100/yr
- Massive Black Hole Binaries (MBHB) or Super-Massive BHB (SMBHB), 10-1000/yr
- Intermediate Mass Black Hole Binaries (IMBHB), ?
- Extreme Mass Ratio Inspiral (EMRI), 1-1000/yr
- Intermediate Mass Ratio Inspiral (IMRI) ?
- Stochastic GW Backgrounds, ?
- Dark matter & dark energy ?

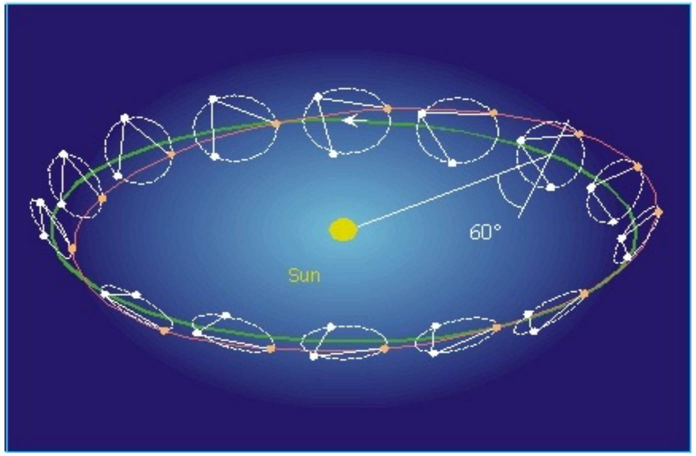


LISA Constellation

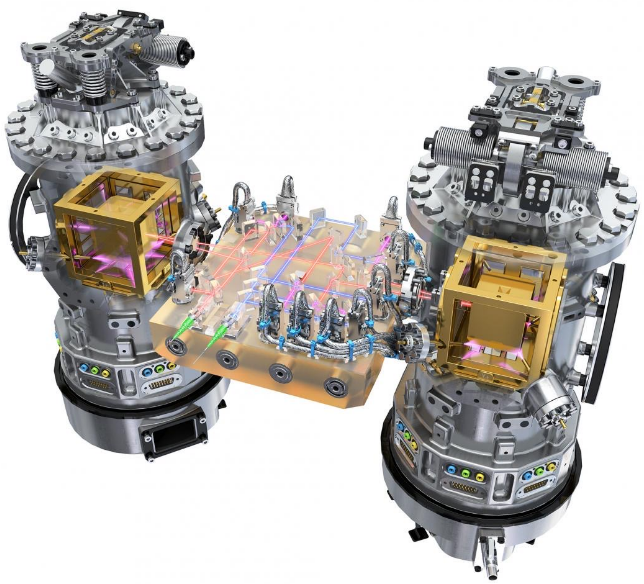
- 3 spacecrafts with 2 masses each
- Triangular configuration
- Earth-like orbit around the Sun, with a rotation which enables mapping the whole sky
- 2 key measures: (i) distance between the masses and (ii) mass position inside the spacecraft
- The mass is contained in a sensing box → a seismometer!

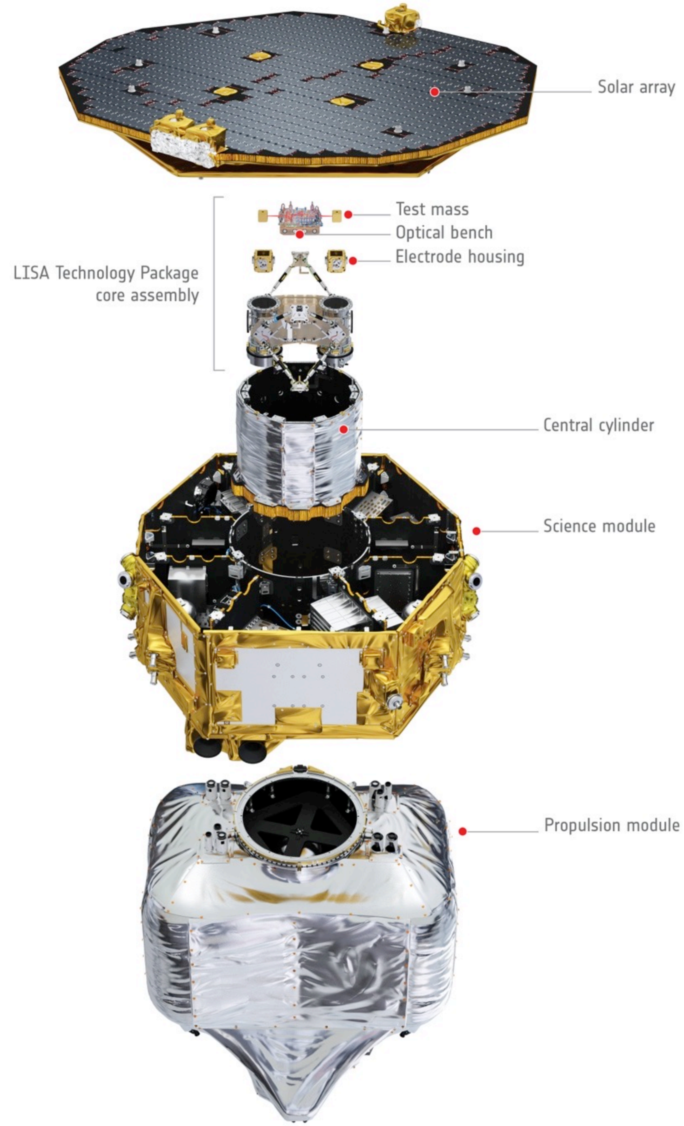






LISA PathFinder





LISA timescale

- First ideas and proposals in 1980'
- LISA PathFinder flew in 2015-2016
- LISA adopted by ESA and NASA in Jan 2024
- Flight & commissioning 2035-37
- Mission life-time until 2048

Conclusions

- RIs provide the main backbone for scientific progress
- Geophysics is well positioned, but needs to plan and install the RIs for the next generations
- The lifecycle of large RIs, from original ideas to selection, construction, installation, commissioning and scientific exploitation, require long efforts, often across generations
- Efficient trans-national cooperation is crucial to attract funding and advance availability of, access to and usage of RIs
- Large research instutions are called to provide the required critical mass, expertise and long-term engagement, but the whole scientific community is called to make the right choices and lobby to secure the installation of future RIs