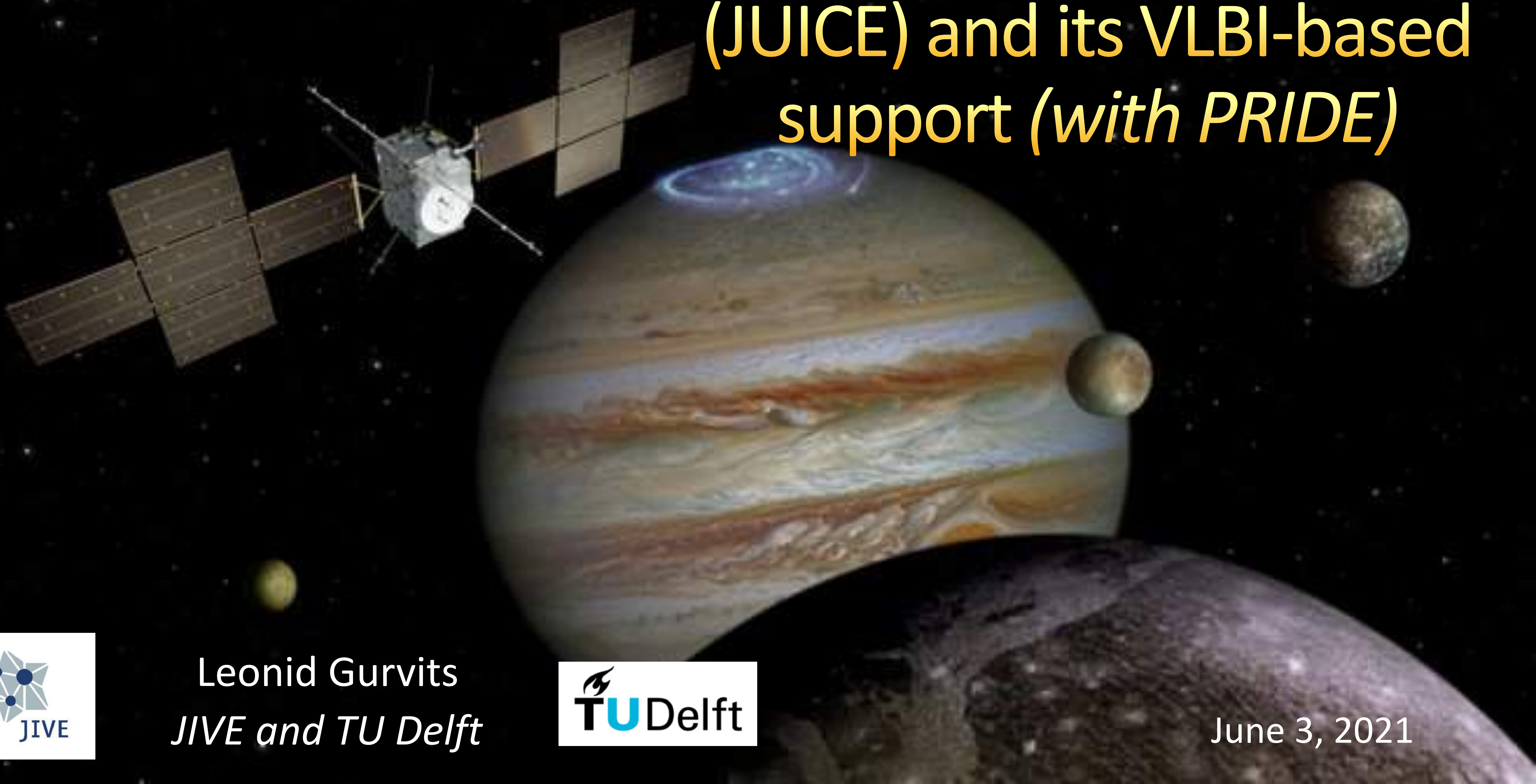
Jupiter Icy Moons Explorer (JUICE) and its VLBI-based support *(with PRIDE)*



Leonid Gurvits
JIVE and TU Delft

June 3, 2021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JUpiter ICy moons Explorer

Why a mission to Jupiter?

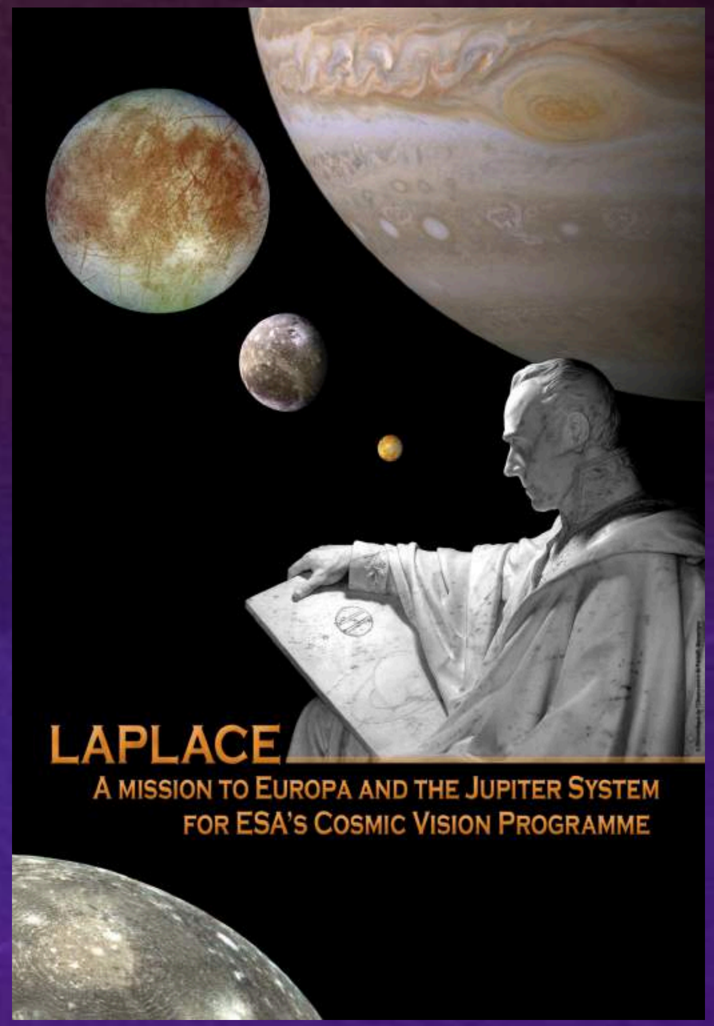
Bits of history

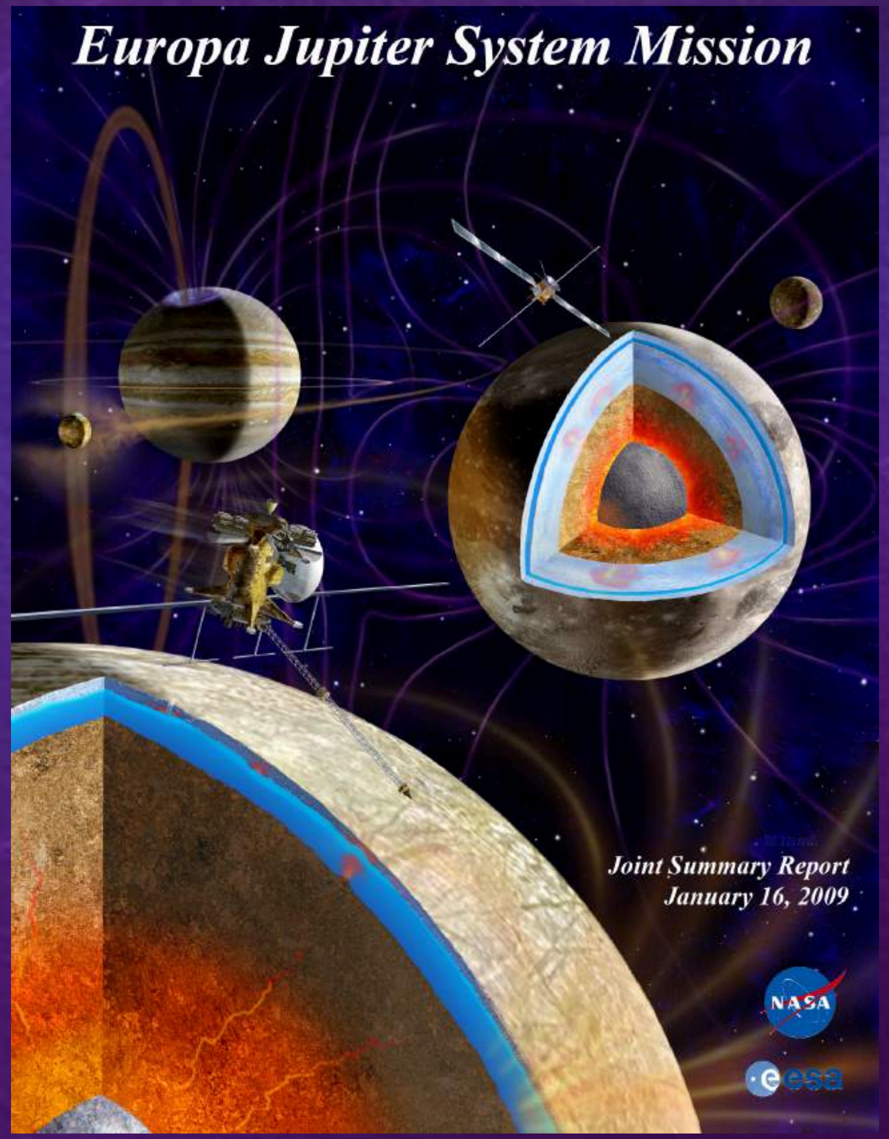
Mission challenges

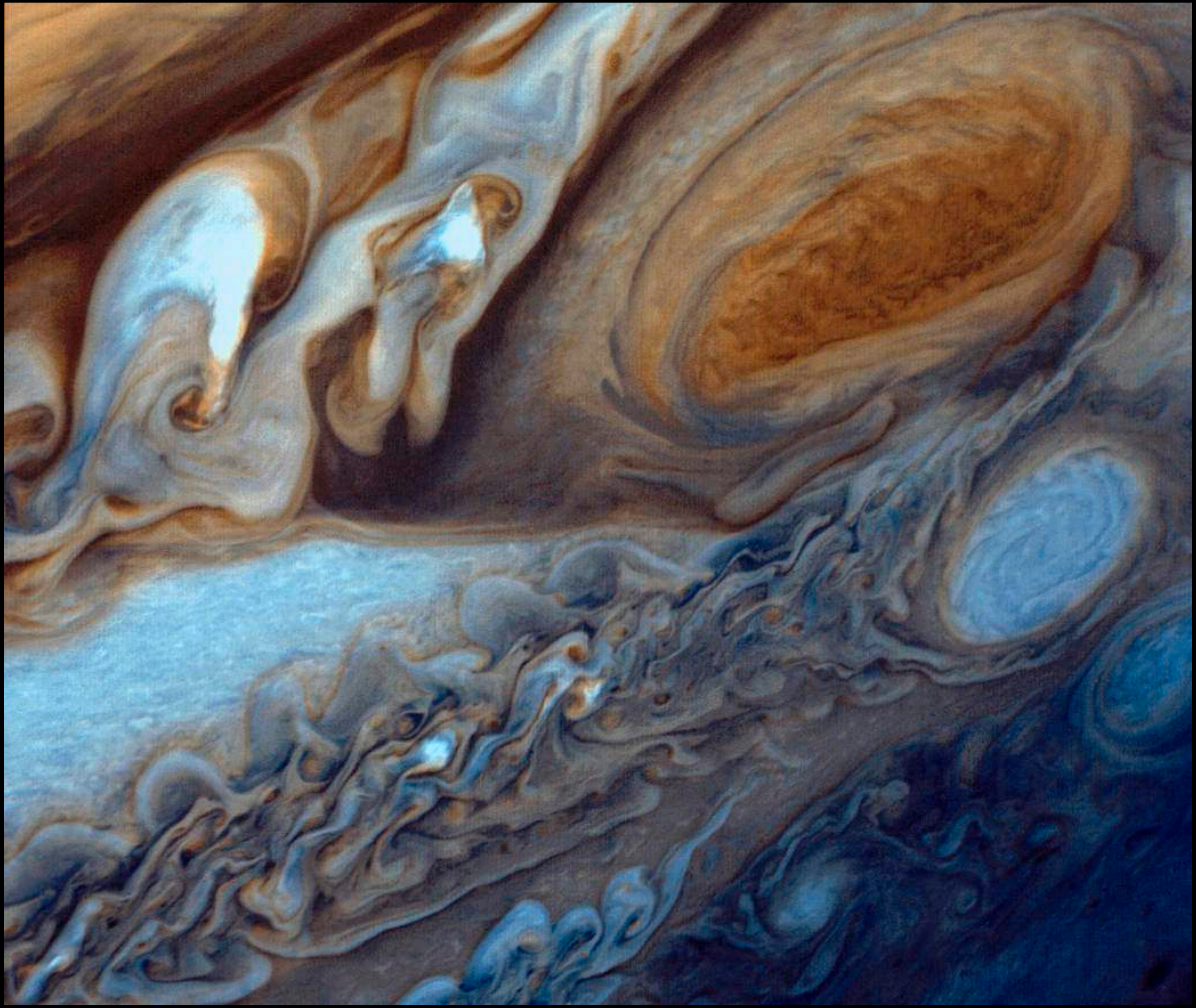
Where radio astronomy comes in

JUICE: bits of history

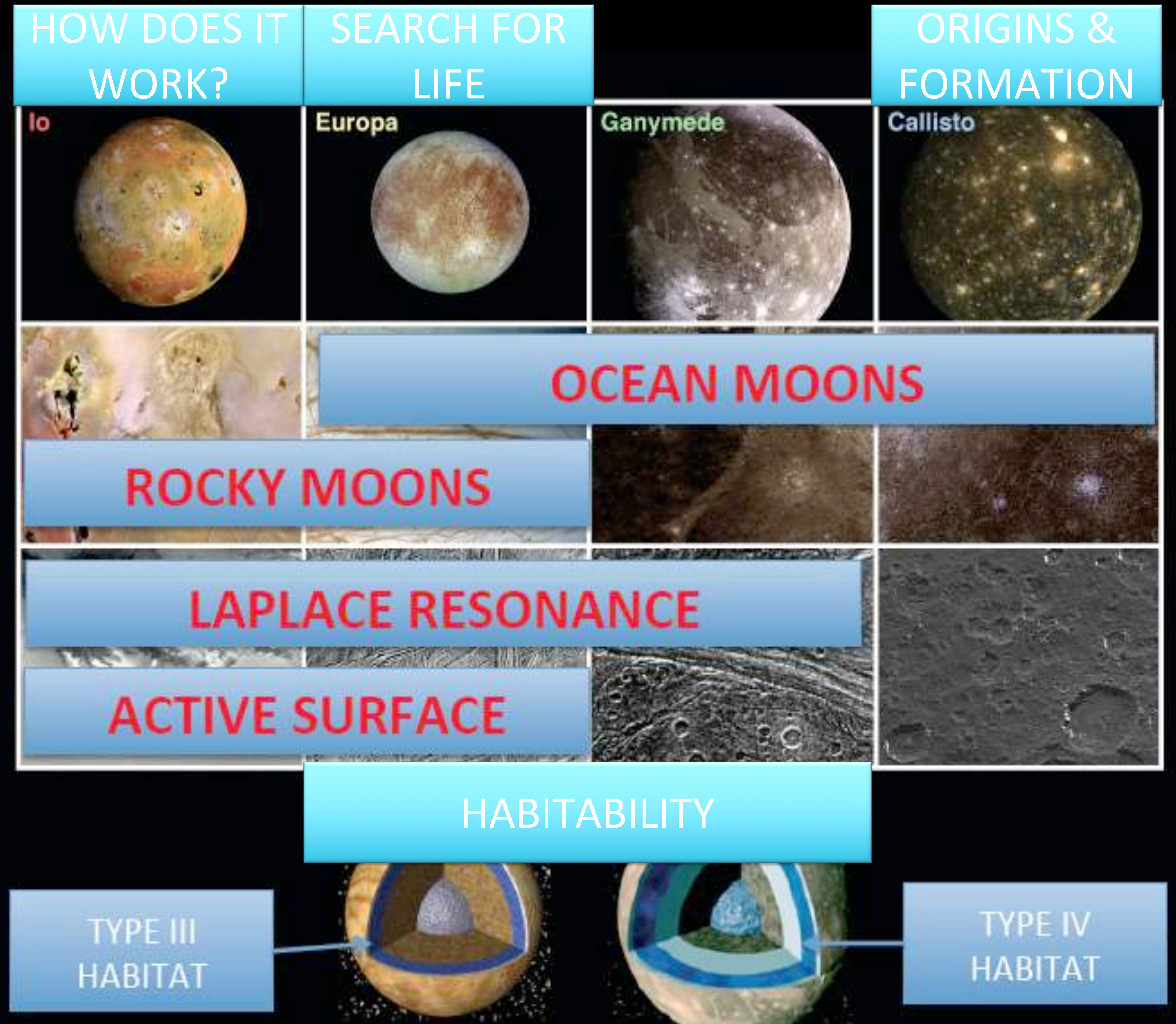
- ~2000–2005: success of Cassini and Huygens missions (NASA, ESA, ASI)
- 2006: Europlanet meeting in Berlin – “thinking aloud” on a Jovian mission
- 2008: ESA-NASA jointly exploring a mission to giant planets’ satellites
    - *ESA "Laplace" mission proposal (Blanc et al. 2009)*
    - *ESA Titan and Enceladus Mission (TandEM, Coustenis et al., 2009)*
    - *NASA Titan Explorer*
- 2009: two joint (ESA+NASA) concepts selected for further studies:
    - *Europa Jupiter System Mission (EJSM)*
    - *Titan Saturn System Mission (TSSM: Coustenis et al., 2009)*
- 2010: EJSM-Laplace selected, consisting of two spacecraft:
    - *ESA’s Jupiter Ganymede Orbiter (JGO)*
    - *NASA’s Jupiter Europa Orbiter (JEO)*
- 2012: NASA drops off; EJSM-Laplace/JGO becomes JUICE
- 2013: JUICE payload selection completed by ESA; JUICE becomes an L-class mission of ESA’s Vision 2015-2025
- 2015: NASA selects Europa Clipper mission (Pappalardo et al., 2013)







Voyager 1, 1979


HOW DOES IT WORK?
SEARCH FOR LIFE
ORIGINS & FORMATION
Io
Europa
Ganymede
Callisto
OCEAN MOONS
ROCKY MOONS
LAPLACE RESONANCE
ACTIVE SURFACE
HABITABILITY
TYPE III HABITAT
TYPE IV HABITAT

Overarching questions

JUICE Science Themes

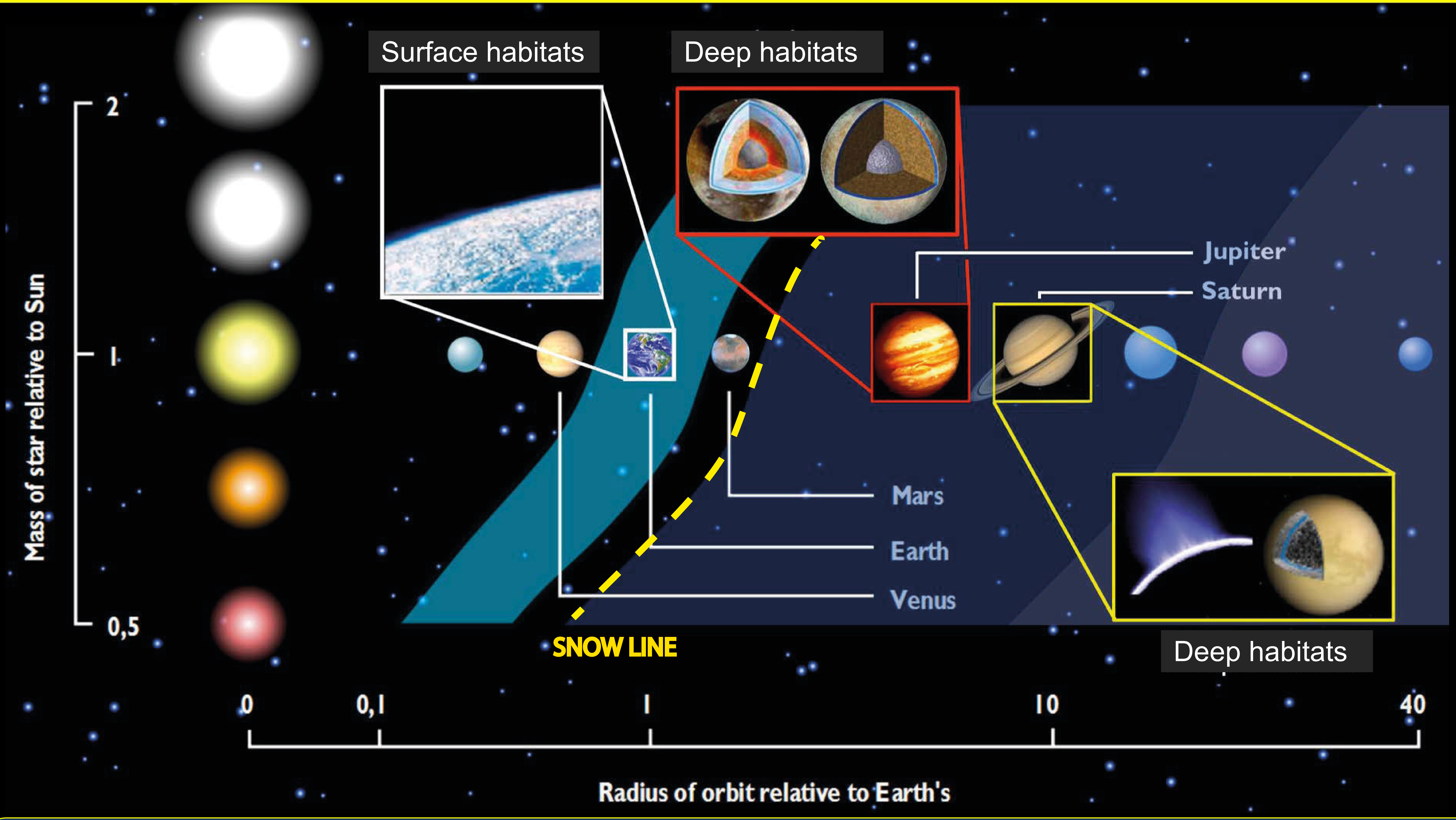
- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

JUICE concept

- *European-led mission to the Jovian system*
- *First orbiter of an icy moon*
- *JGO/Laplace scenario with two Europa flybys and moderate-inclination phase at Jupiter*
- *Science payload selected in Feb 2013, fully compatible with JUICE objectives*

From the Jupiter system to extrasolar planetary systems JUICE

Habitable worlds



Cosmic Vision: The quest for evidence of life in the Solar System must begin with an understanding of what makes a planet habitable

Ganymede and Europa are the archetypes of two classes of habitable worlds

Three large icy moons to explore

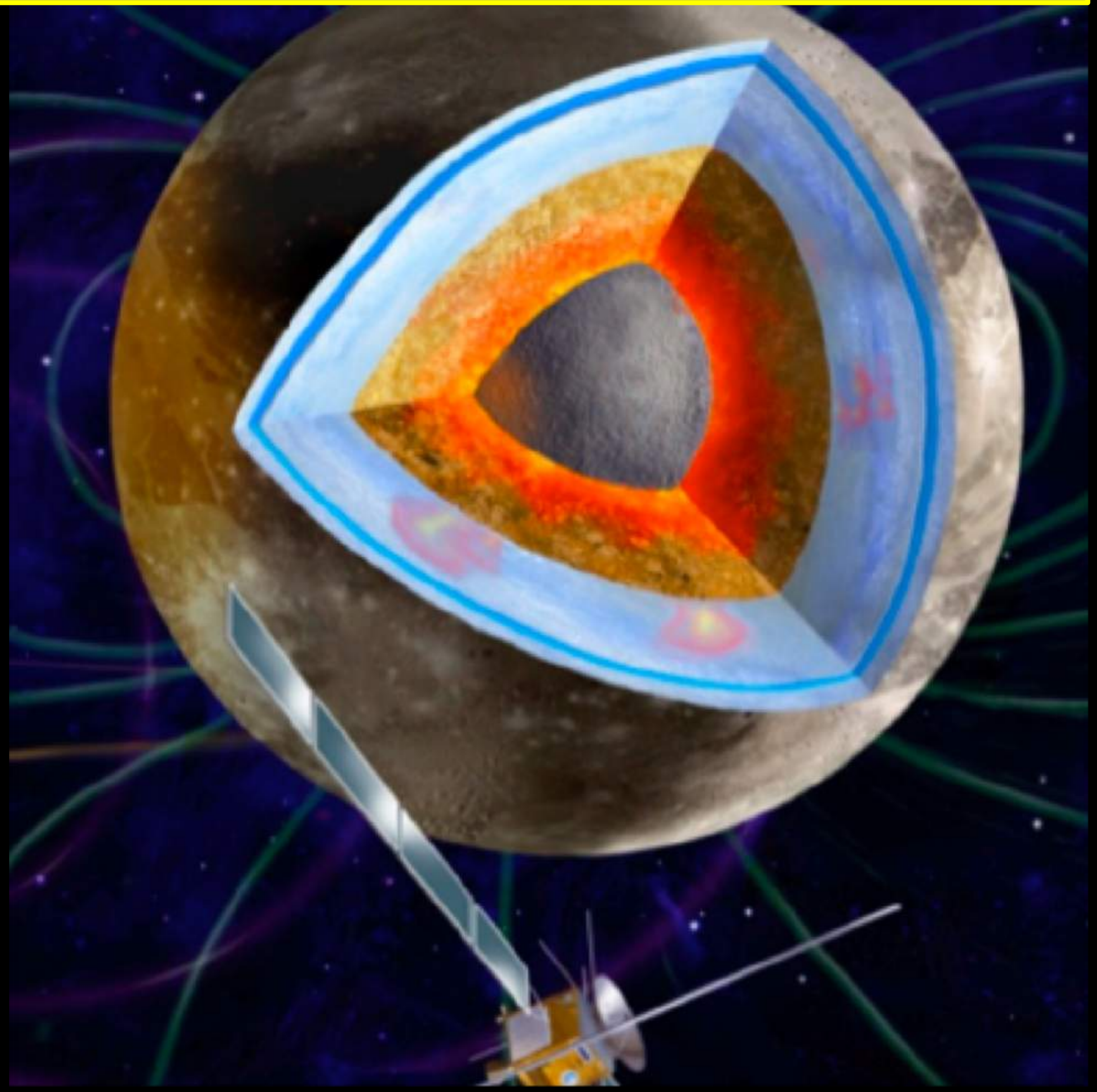
Ganymede
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

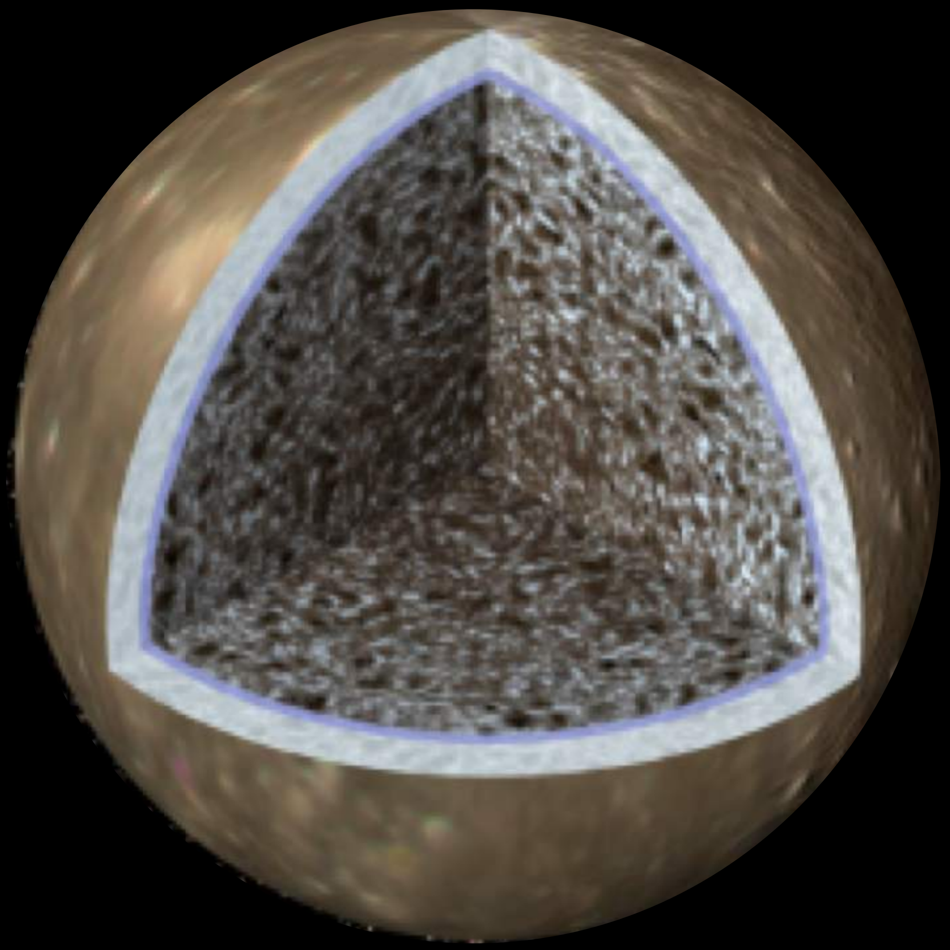
- Archetype of waterworlds
- Best example of liquid environment trapped between icy layers

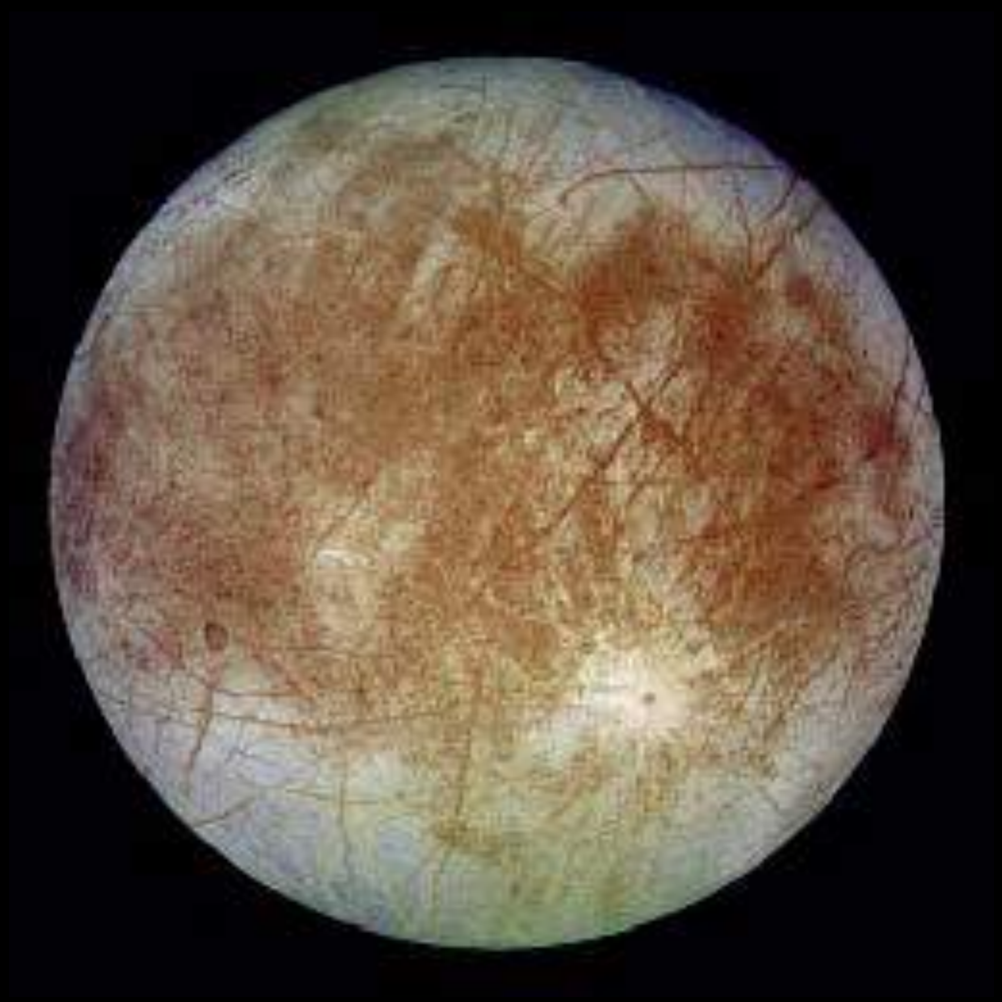
Callisto
- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages

Europa
- A deep ocean
- An active world?

- Best example of liquid environment in contact with silicates





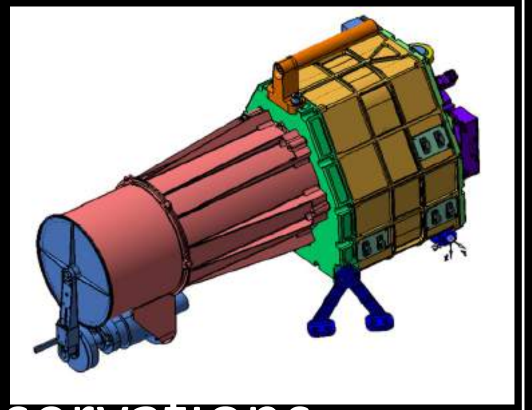


JUICE: The 'Firsts'

- Orbiter of an icy moon
- European-led mission to outer solar system
- Subsurface exploration of icy moons
- Opportunity to characterise the waterworlds class of planetary bodies
- Opportunity to completely explore Ganymede's unique combination of magnetic fields
- Prolonged study of mid-high latitudes of Jupiter's magnetosphere
- Direct measurements of atmospheric circulation in Jupiter's middle atmosphere

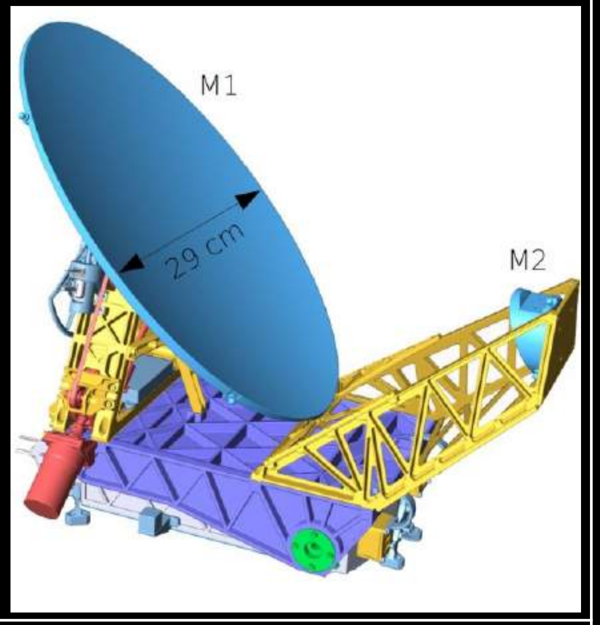
JUICE Science Payload

JANUS: Visible Camera System
PI: Pasquale Palumbo, Parthenope University, Italy.
Co-PI: Ralf Jaumann, DLR, Germany



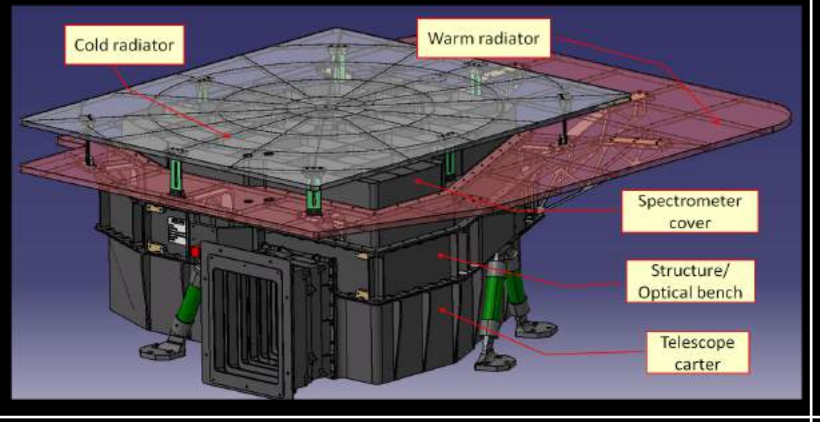
- ≥ 7.5 m/pixel (on Ganymede)
- Multiband imaging, 340 - 1080 nm
- Icy moons' geology
- Io activity monitoring and other moons observations
- Jovian atmosphere dynamics

SWI: Sub-mm Wave Instrument
PI: Paul Hartogh, MPS, Germany



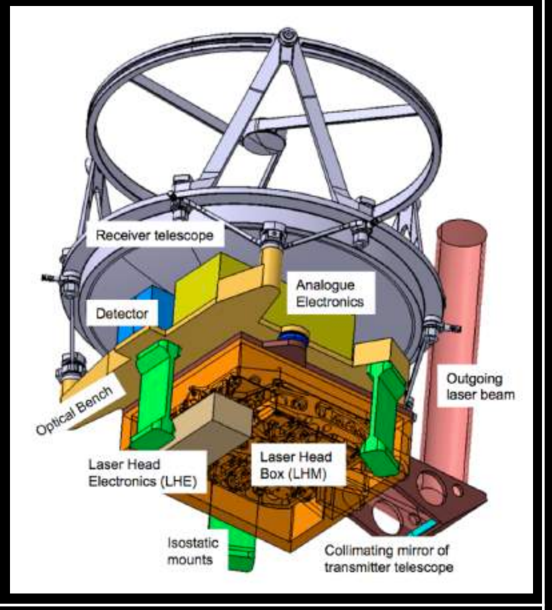
- 600 GHz
- Jovian Stratosphere
- Moon atmosphere
- Atmospheric isotopes

MAJIS: VIS-NIR/IR Imaging Spectrometer
PI: Yves Langevin, IAS, France
Co-PI: Guiseppe Piccioni, INAF, Italy



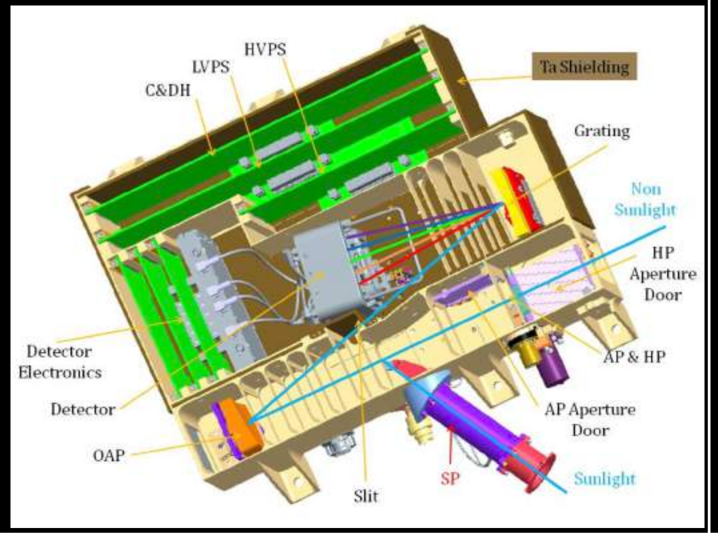
- Hyperspectral imaging in the range 0.5–5.54 µm
- ≥ 75 m/pixel (on Ganymede)
- Surface composition
- Jovian atmosphere

GALA: Laser Altimeter
PI: Hauke Hussmann, DLR, Germany



- ≥ 40 m spot size
- ≥ 0.1 m accuracy
- Shape and rotational state
- Tidal deformation
- Slopes, roughness, albedo

UVS: UV Imaging Spectrograph
PI: Randy Gladstone, SwRI, USA



- 55–210 nm
- 0.04˚x 0.16˚
- Aurora and Airglow
- Surface albedos
- Stellar and Solar Occultation

RIME: Ice Penetrating Radar
PI: Lorenzo Bruzzone, Trento, Italy
Co-PI: Jeff Plaut, JPL, USA

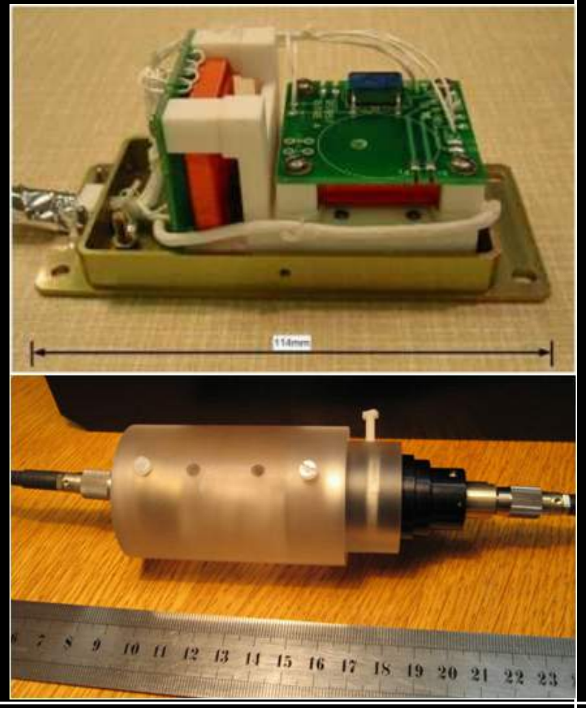
- 16 m-long boom
- 9 MHz
- Penetration ~9 km
- Vertical resolution 50 m
- Subsurface investigations

JUICE Science Payload

JMAG: JUICE Magnetometer

PI: Michele Dougherty, Imperial, UK

- Dual Fluxgate and Scalar mag
- ±8000 nT range, 0.2 nT accuracy
- Moon interior through induction
- Dynamical plasma processes

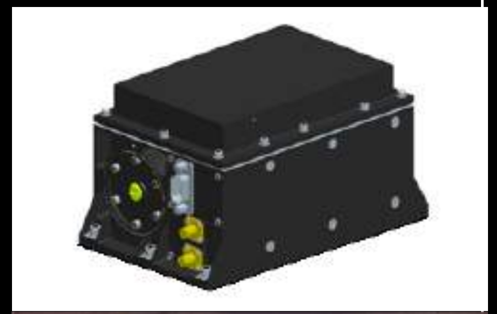


3GM: Gravity, Geophysics, Galilean Moons

PI: Luciano Iess, Rome, Italy

Co-PI: David J. Stevenson, CalTech, USA

- Ranging by radio tracking
- 2 µm/s range rate
- 20 cm range accuracy
- Gravity fields and tidal deformation



PEP: Particle Environment Package

PI: Stas Barabash, IRF-K, Sweden

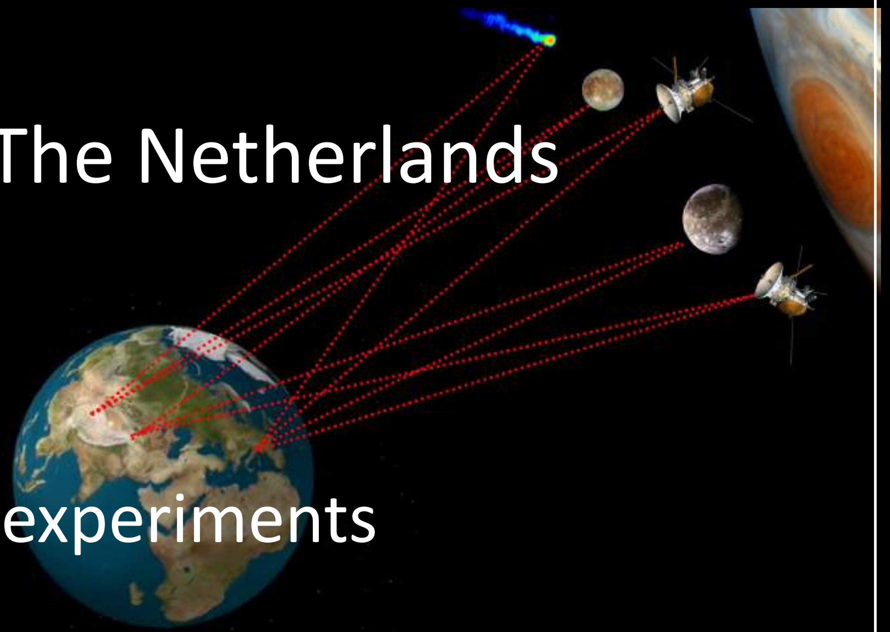
Co-PI: Peter Wurz, UBe, Switzerland

- Six sensor suite
- Ions, electrons, neutral gas (in-situ)
- Remote ENA imaging of plasma and torus

PRIDE: Planetary Radio Interferometer & Doppler Experiment

PI: Leonid Gurvits, JIVE, EU/The Netherlands

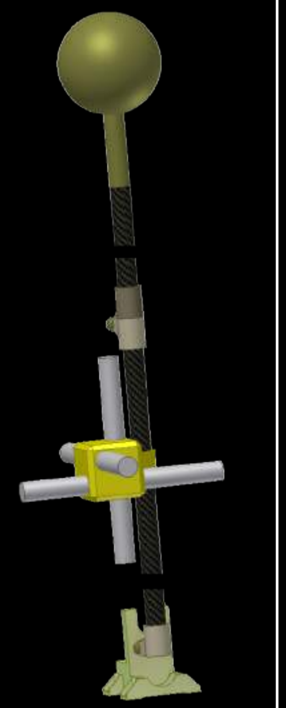
- S/C state vector
- Ephemerides
- bi-static and radio occultation experiments



RPWI: Radio and Plasma Wave Investigation

PI: Jan-Erik Wahlund, IRF-U, Sweden

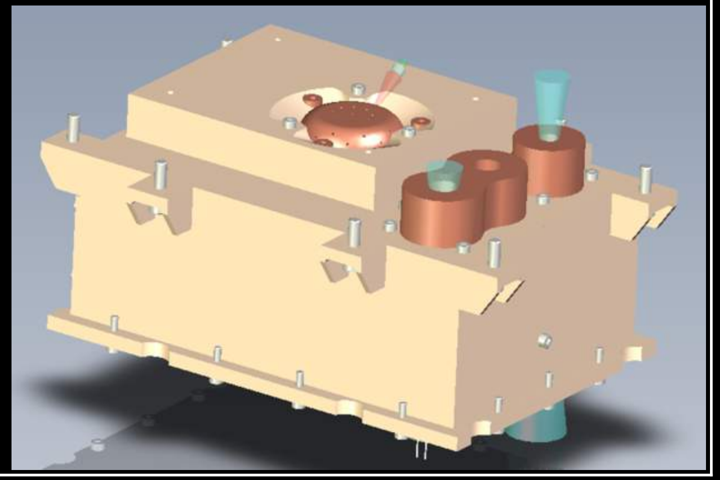
- Langmuir Probes
- Search Coil Magnetometer
- Tri-axial dipole antenna
- E and B-fields
- Ion, electron and charged dust parameters



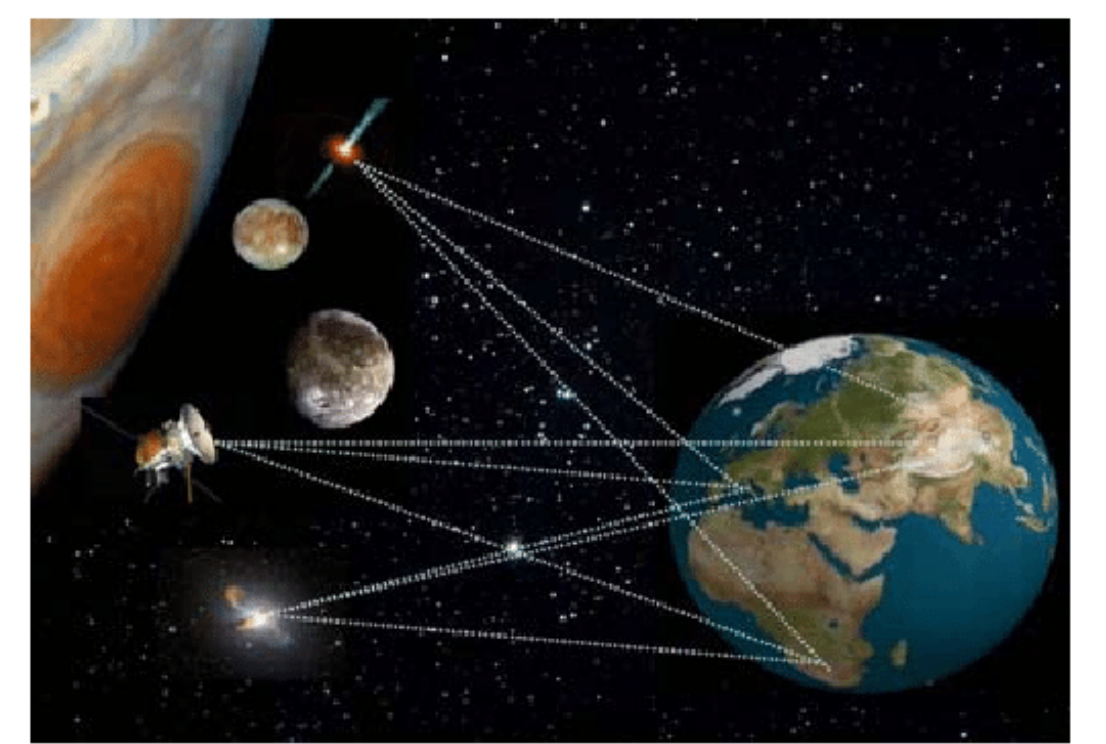
RADEM: Radiation Hard Electron Monitor

Paul Scheller Institute (CH), LIP (Portugal)

- Electrons: 0.3 – 40 MeV
- Protons: 5 – 250 MeV
- Ions (He, O): 0.1 – 10 MeV



JUICE: 12 experiments (11 instruments + ...)



Broad science and interdisciplinary

Mission description: https://www.cosmos.esa.int/web/juice/home

SWI, PEP, RPWI, J-MAG, MAJIS, UVS, 3GM, PRIDE

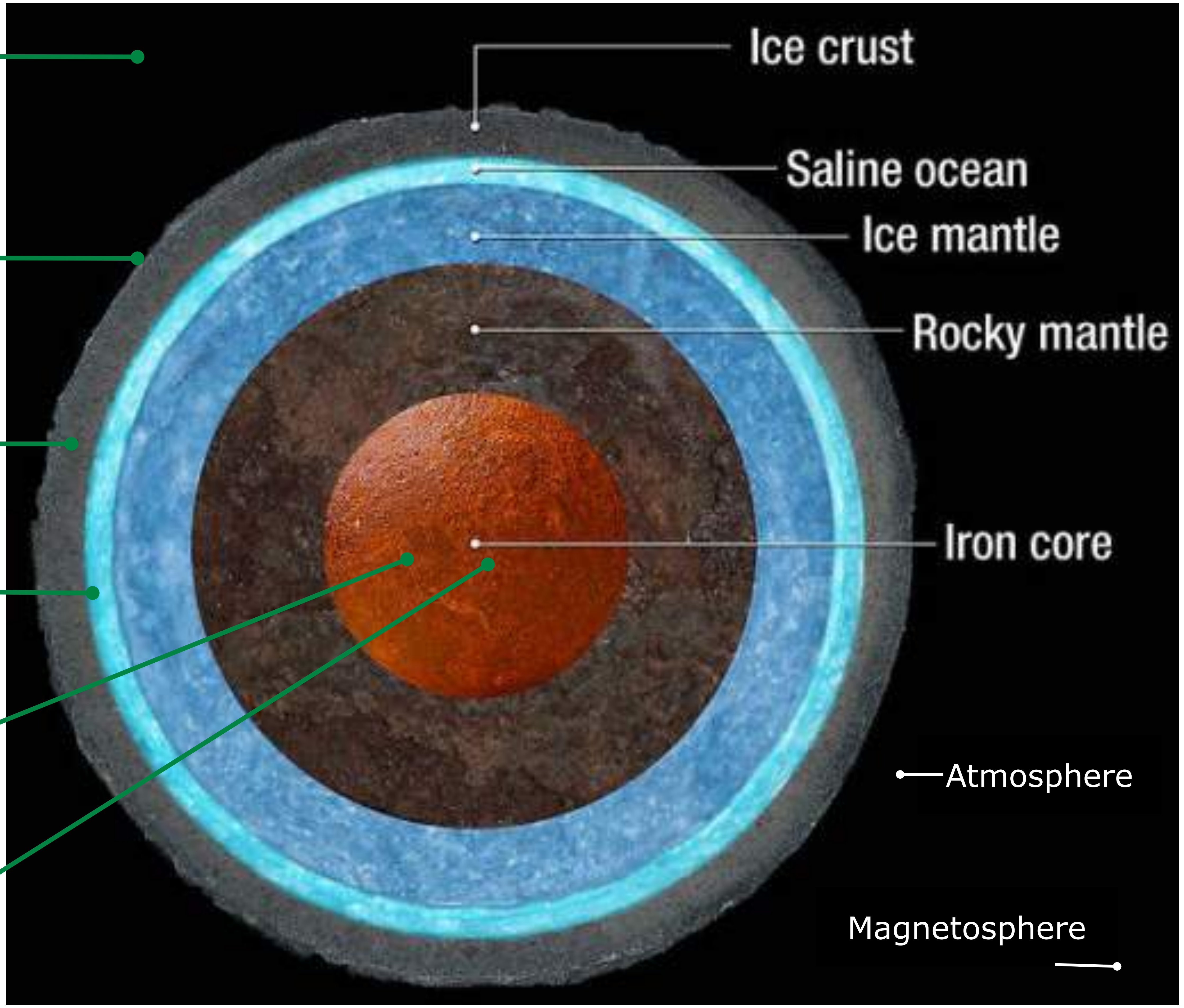
Remote sensing instruments, GALA, RIME

RIME, GALA

3GM, J-MAG, RPWI, GALA, passive radar?

3GM, J-MAG

3GM, PRIDE, JANUS



Spacecraft flight model: high gain antenna tested and mounted

JUICE @ Airbus Defence and Space, Friedrichshafen, Germany
April 2021

Credits: Airbus/TAS-I

Challenges

Technical:

Instrument + s/c development

Radiations

Thermal

Power

EMC

Operationals:

Navigation

Planetary protection

Power and data volume for the instruments

Programmatics:

Ariane 5 or 6?

"OTOCOQ"

Human challenges

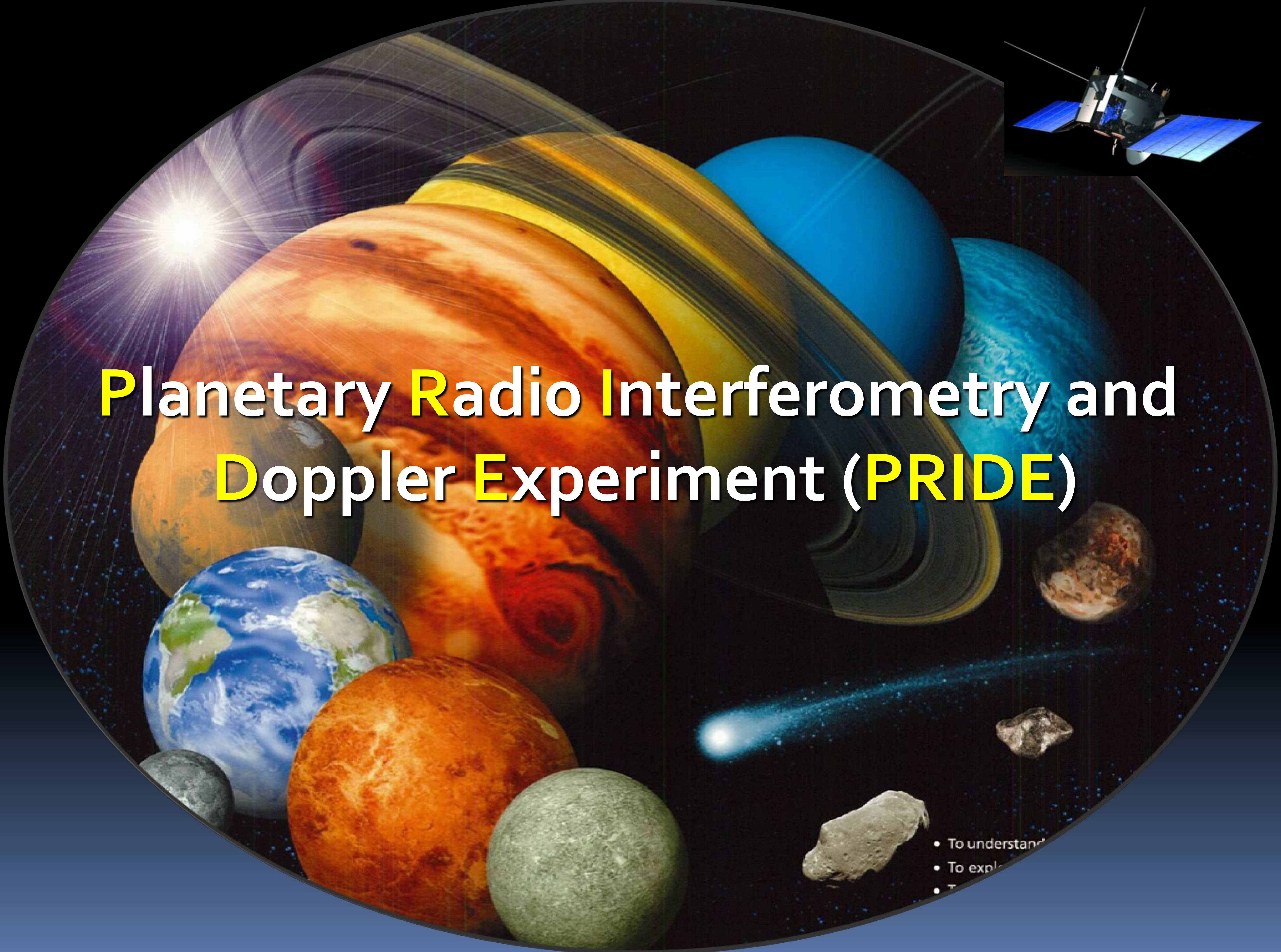
JUICE mission timetable

Events	Date
Launch	End of August/mid-Sept 2022
5 planetary flybys (Earth-Moon / Earth / Venus / Earth / Earth	September 2023-January 2029
Jupiter orbit insertion	July 2031
1st Ganymede flyby (400 km closest approach)	February 2032
1st Callisto flyby (3500 km closest approach)	June 2032
Two Europa flybys (400 km closest approach)	July 2032
Jupiter inclined phase (250 days spent above 25 degrees inclination)	October 2032- June 2033
Callisto 17 flybys season	July 2032-November 2033
Ganymede orbit insertion	December 2034
Ganymede 500 km circular orbit	May 2035
End of nominal mission	September 2035
Impact on Ganymede	October 2035

Stay tuned!


sci.esa.int/juice
cosmos.esa.int/juice
Twitter @ESA_JUICE
The Making of JUICE shorturl.at/rzY89

Planetary Radio Interferometry and Doppler Experiment (PRIDE)



Spacecraft as a celestial radio source

- Spacecraft tend to be radio loud… actually?
  - Transmitter power 1 W
  - Distance 5 AU (Jupiter)
  - On-board antenna gain 3 dB
  - Bandwidth 100 kHz

Flux density ≈ 0.5 mJy=0.5·10^{-29} Wm^{-2}Hz^{-1}

- Operate at frequencies radio astronomers love (or hate):

  UHF (400 and 800 MHz), S (2.3 GHz), X (8.4 GHz), Ka (32 GHz)

- Estimates of state-vectors of spacecraft:
  - Need for "higher-than-standard" accuracy in special cases
    - *Geodynamics and planetology*
    - *Trajectory measurements in close vicinity of Solar System bodies (e.g. landings)*
    - *Fundamental physics*
    - *Space-borne astrometry missions (e.g. Gaia)*

- Need for "eavesdropping" (sometimes, in desperation…)

VEGA balloons VLBI tracking, 1986

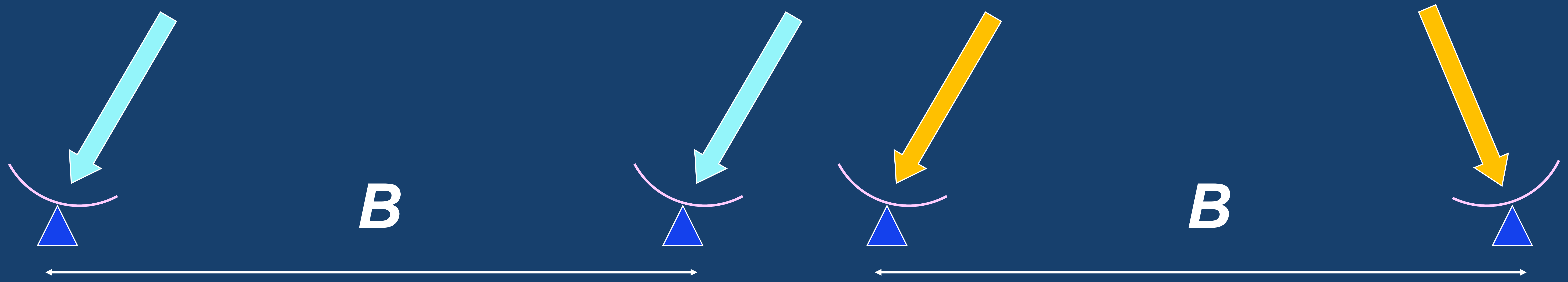
f = 1.6 GHz, Δf = 2 MHz, 20 radio telescopes

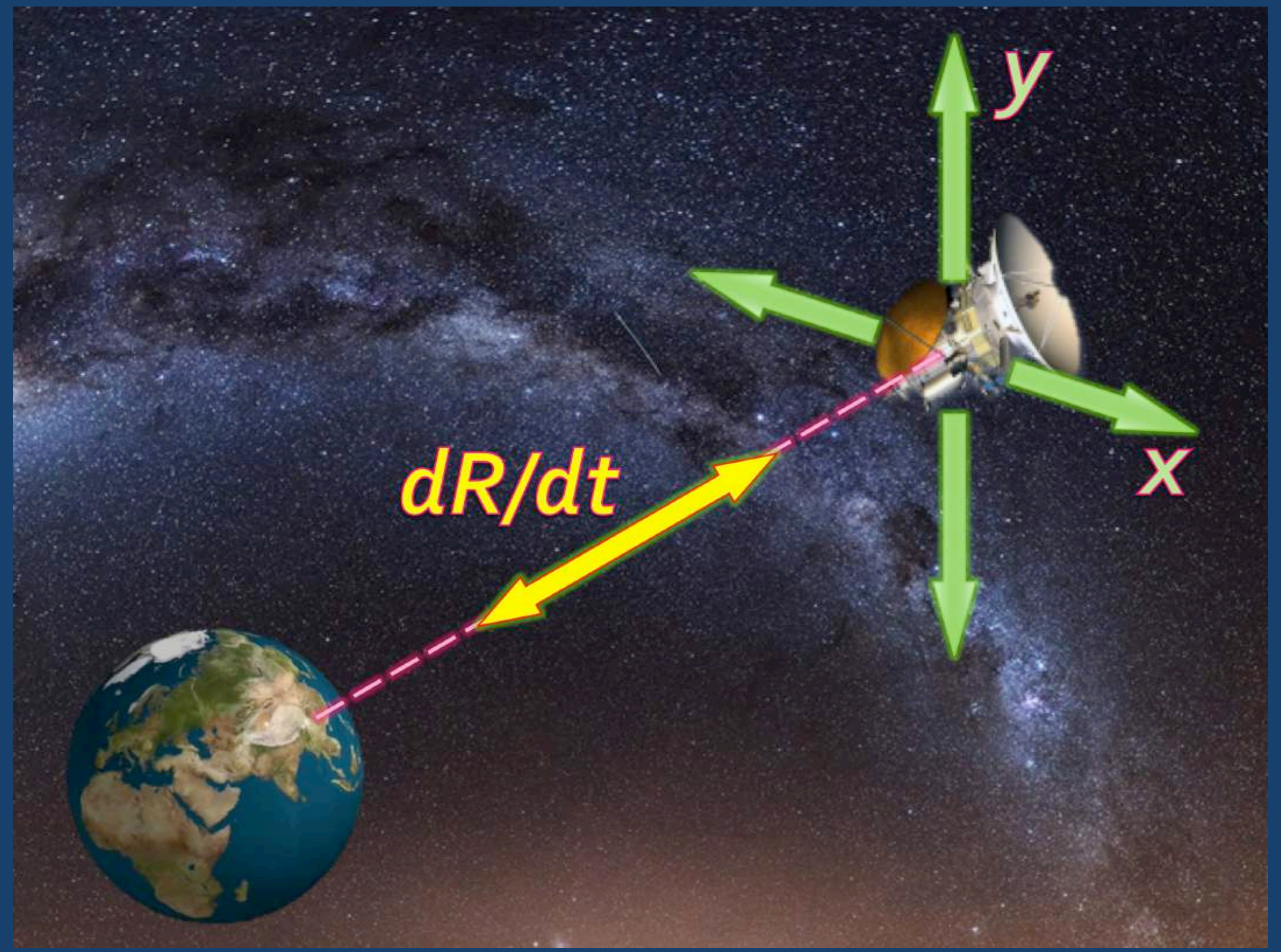
σ_x = 10 km
σ_v = 1 m/s

Preston et al. 1986, Science, 231, 1414

Near-field VLBI and other opportunistic exercises

Not only λ/B, but also $\boxed{R_{nf} \propto \frac{B^2}{\lambda}}$, Fraunhofer criterium

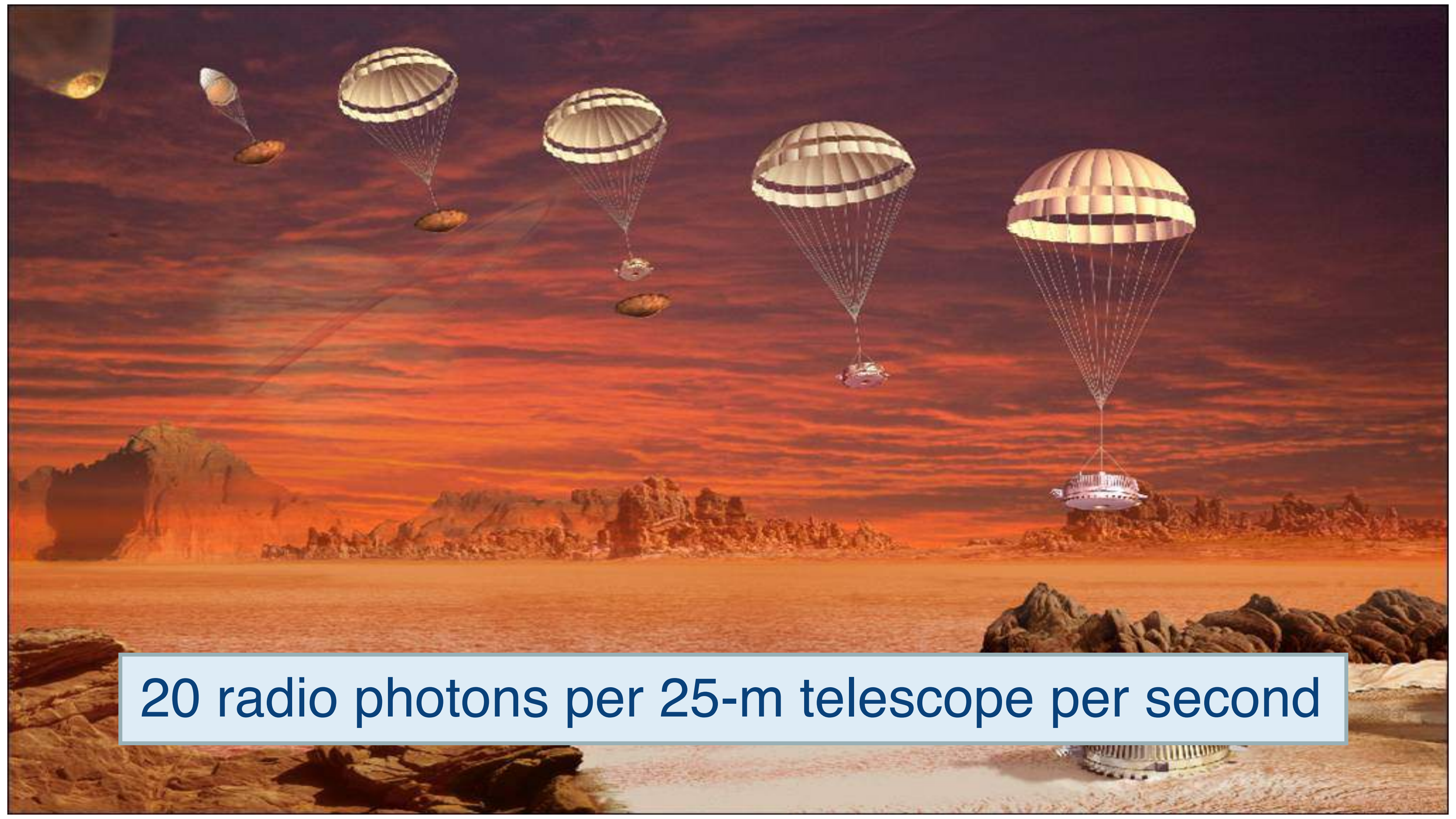


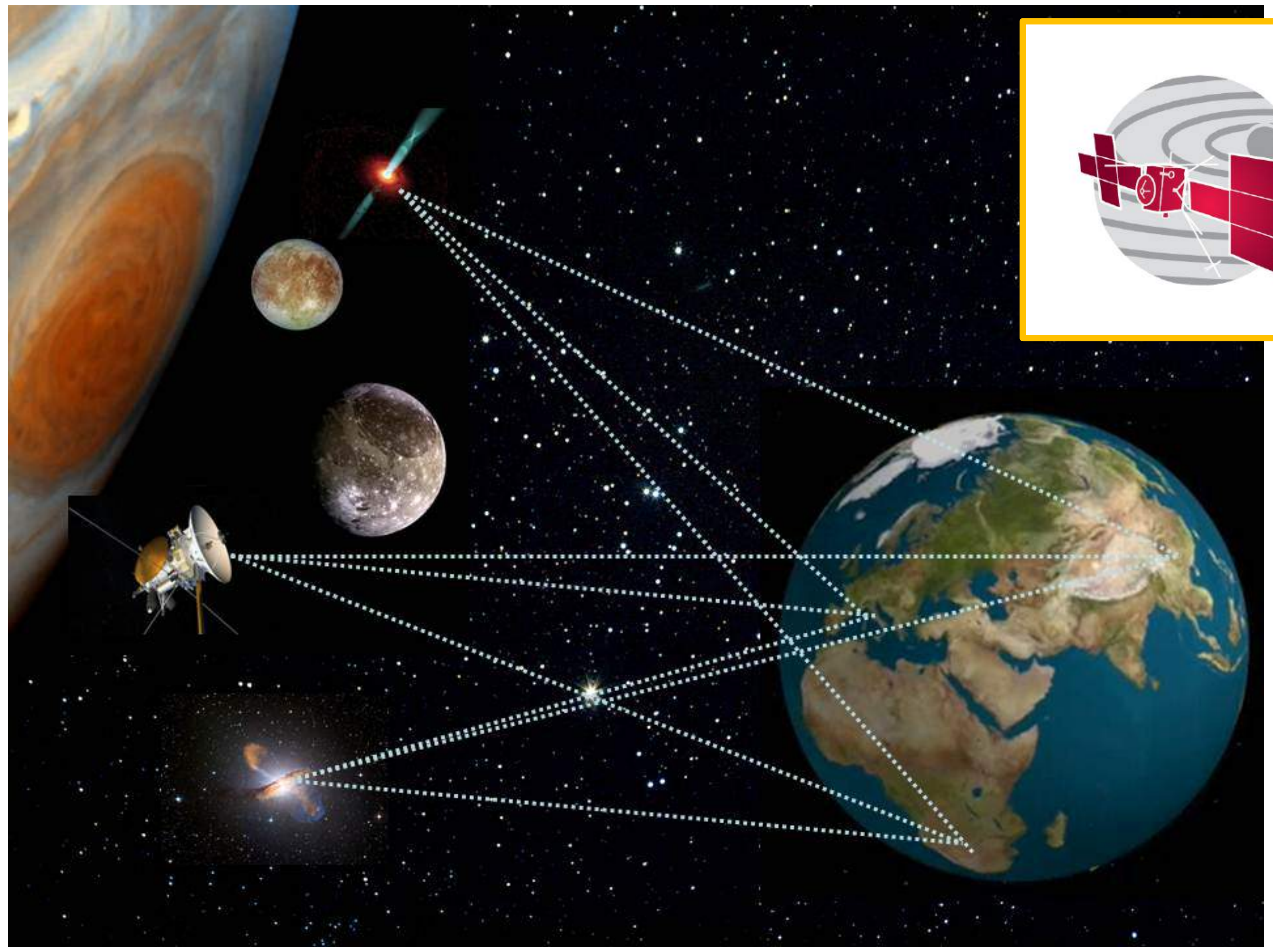


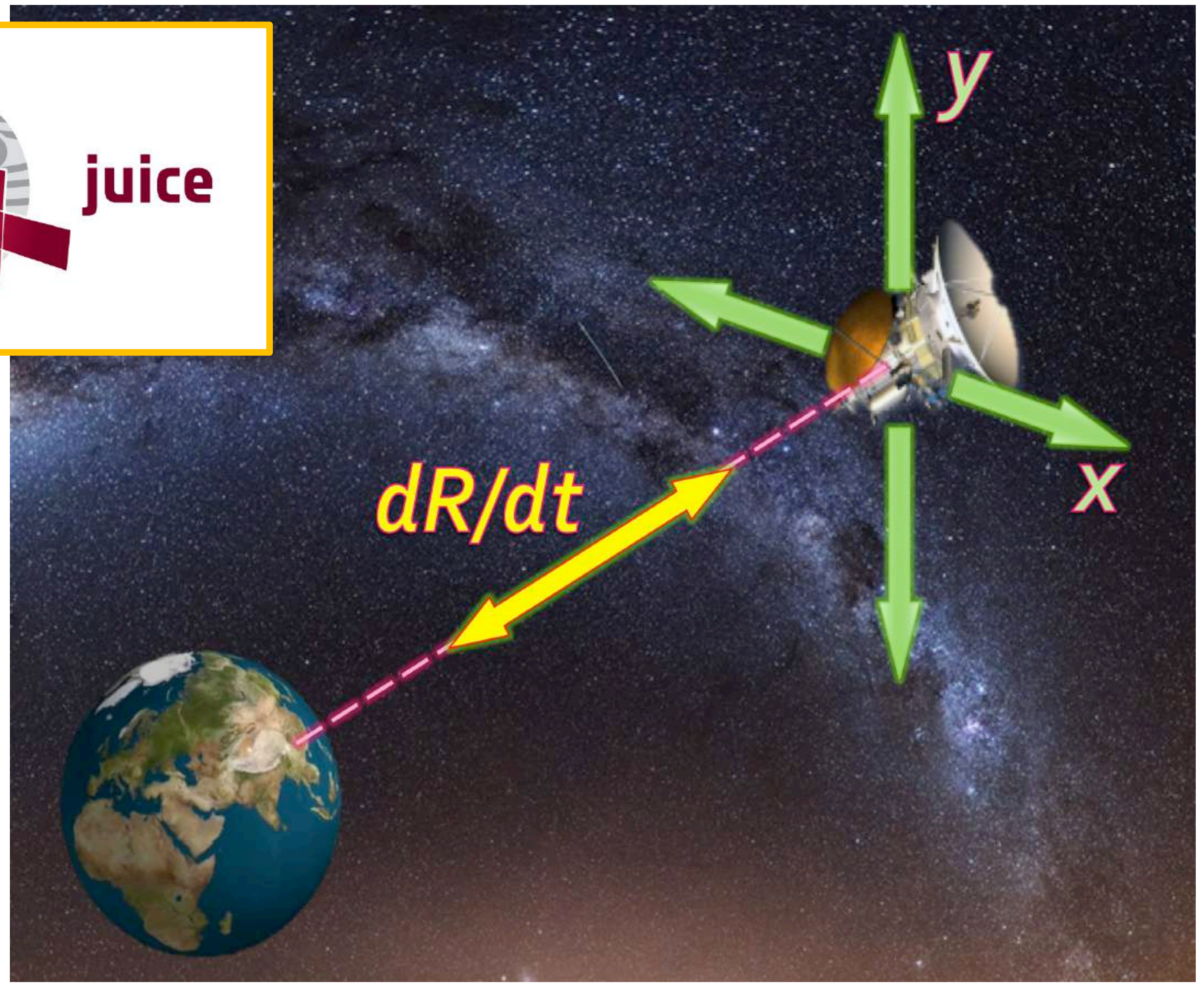
Baseline	**100 km**	**1000 km**	**10^4 km**
Facility	MERLIN	EVN_{WE}	EVN
λ = *3.6 cm X-band*	2 AU	200 AU	0.1 pc
λ = *1 cm* K_a*-band*	8 AU	750 AU	0.5 pc

Near-field VLBI (PRIDE) developments

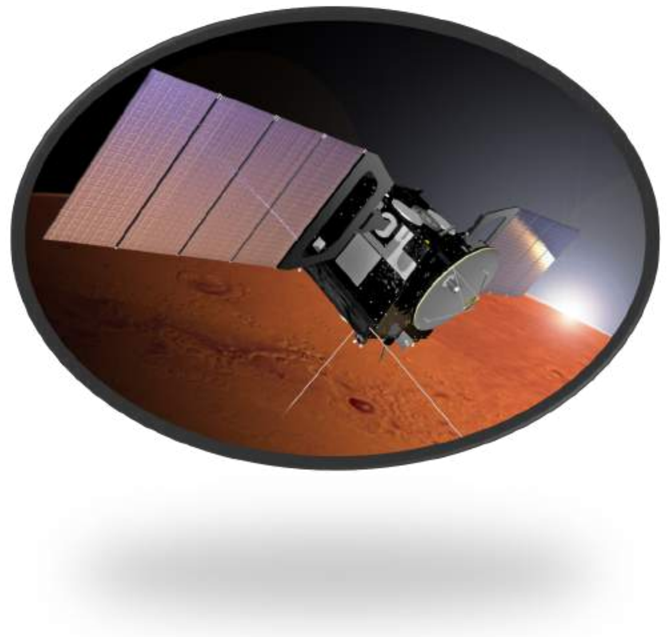
- Planetary Radio Interferometry and Doppler Experiment (PRIDE)
  - User-oriented "observing opportunity"
  - Based on the JIVE-developed know-how, supported by many EVN organisations
  - Concept PRIDE is based on know-how developed at JIVE in 2003–2012
- PRIDE adopted by ESA as one of 11 experiments of JUICE
  - Ramping-up preparatory activities started in 2012
  - (near-field) VLBI is mentioned as a desirable science support technique in >6 Voyage 2050 White Papers (October 2019)



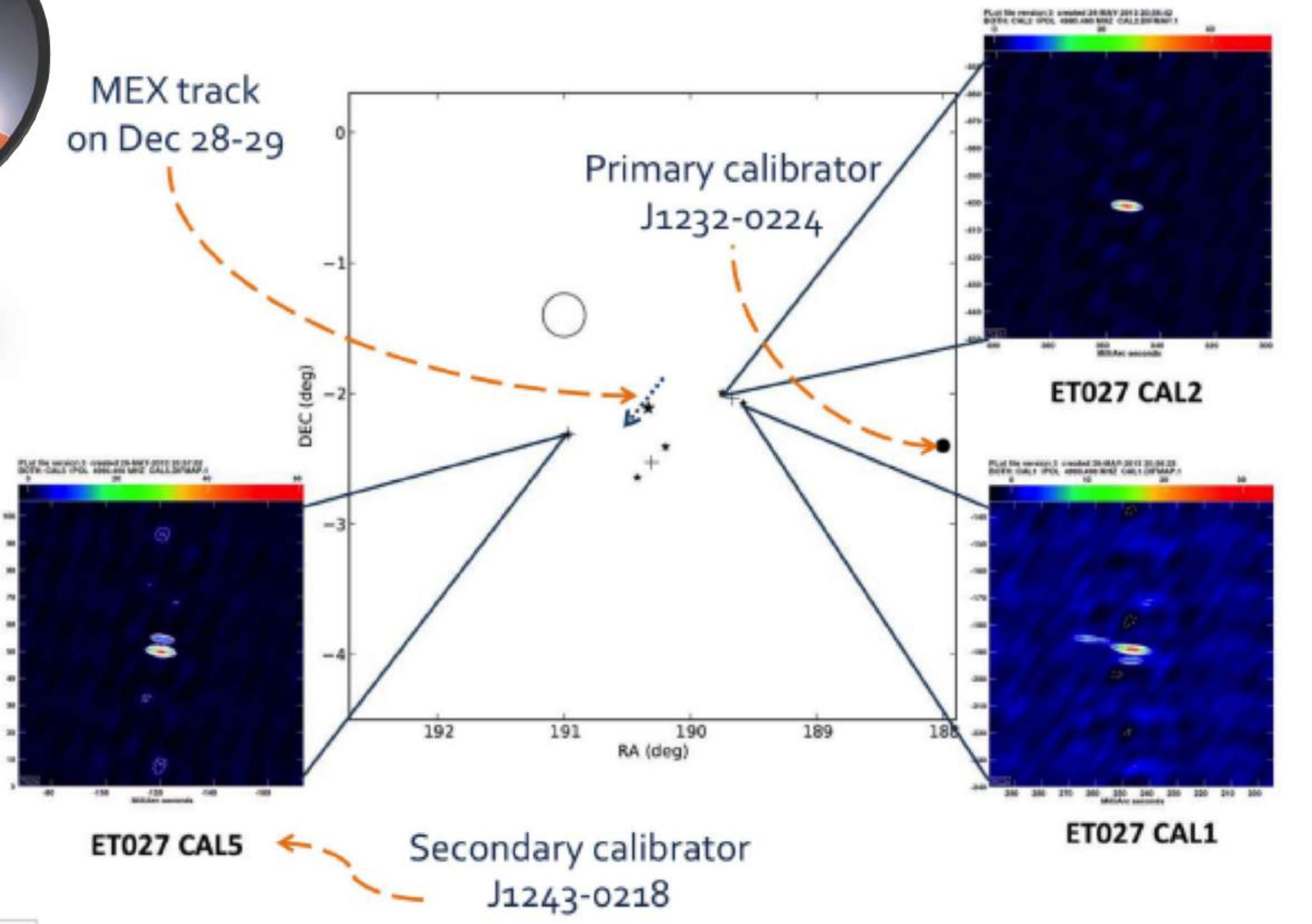


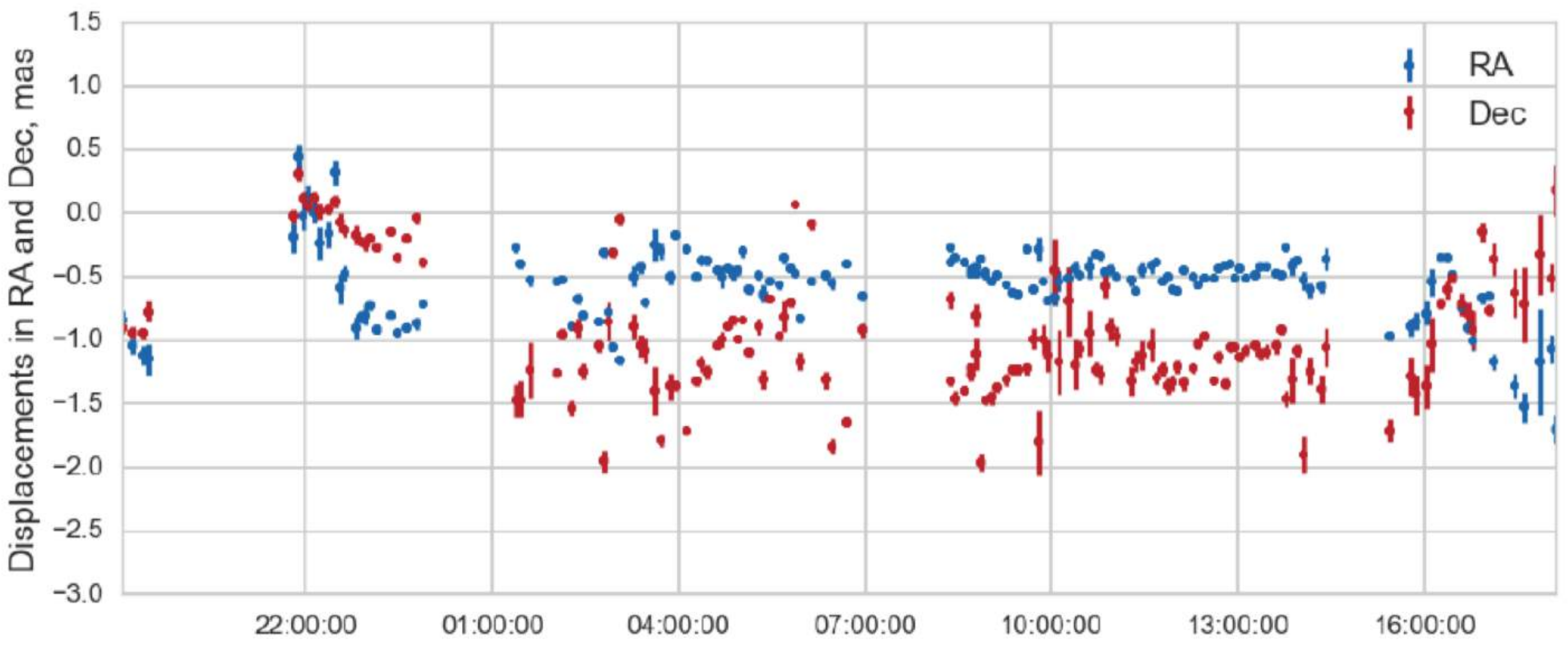


MarsExpress GR035 (Dec 2013) – test and show-case



- MEX/Phobos flyby, near-field VLBI tracking
  - User-led experiment, PI –P. Rosenblatt, Royal Observatory Belgium
  - Uniquely close (58 km) Phobos flyby by MEX
    - *29 December 2013 (Sunday)*
- Involved more than 30 radio telescopes globally
- Lasted for 26.5 hours continuously, ~3 MEX orbits
  - PRIDE data processing at JIVE with "operational" pipeline

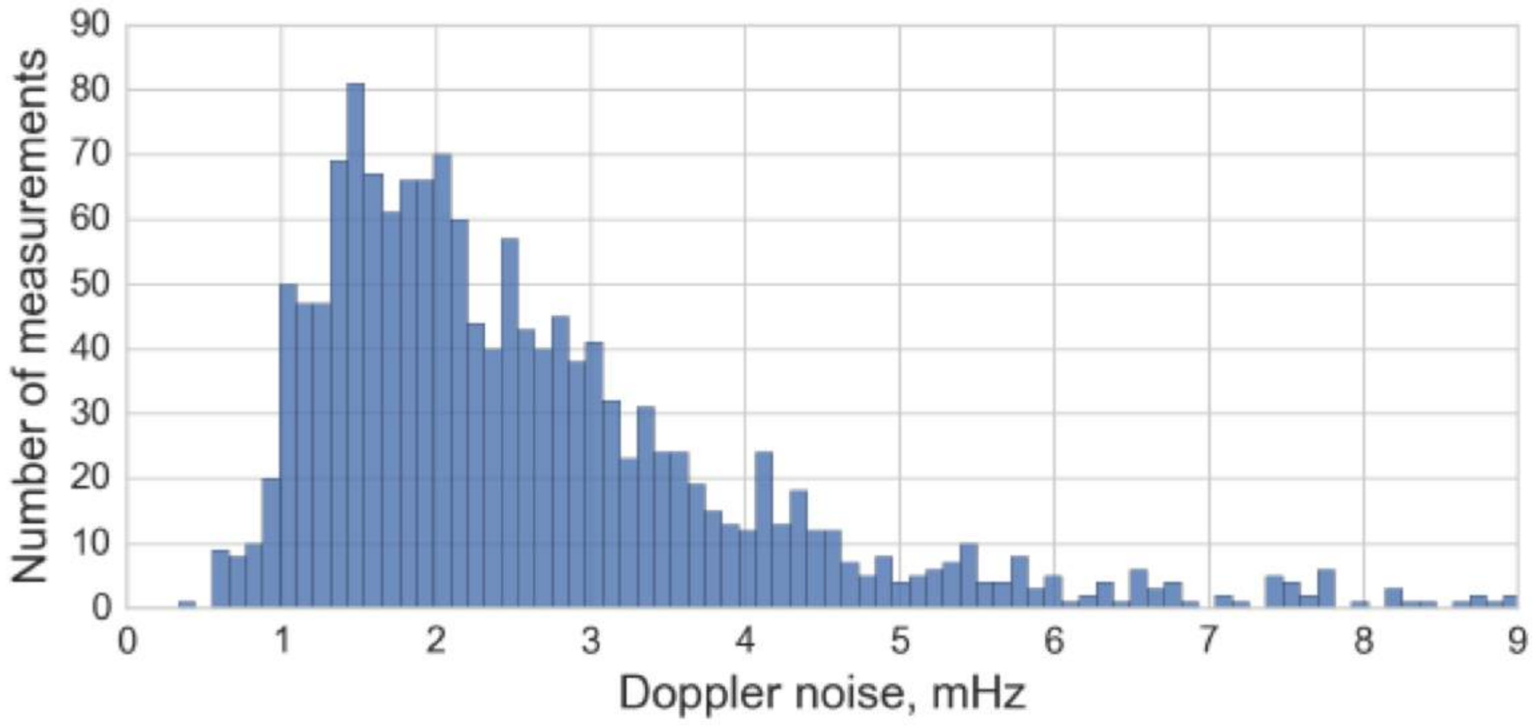




Displacement between measured and predicted MEX position, 2 min per point (imaging approach).

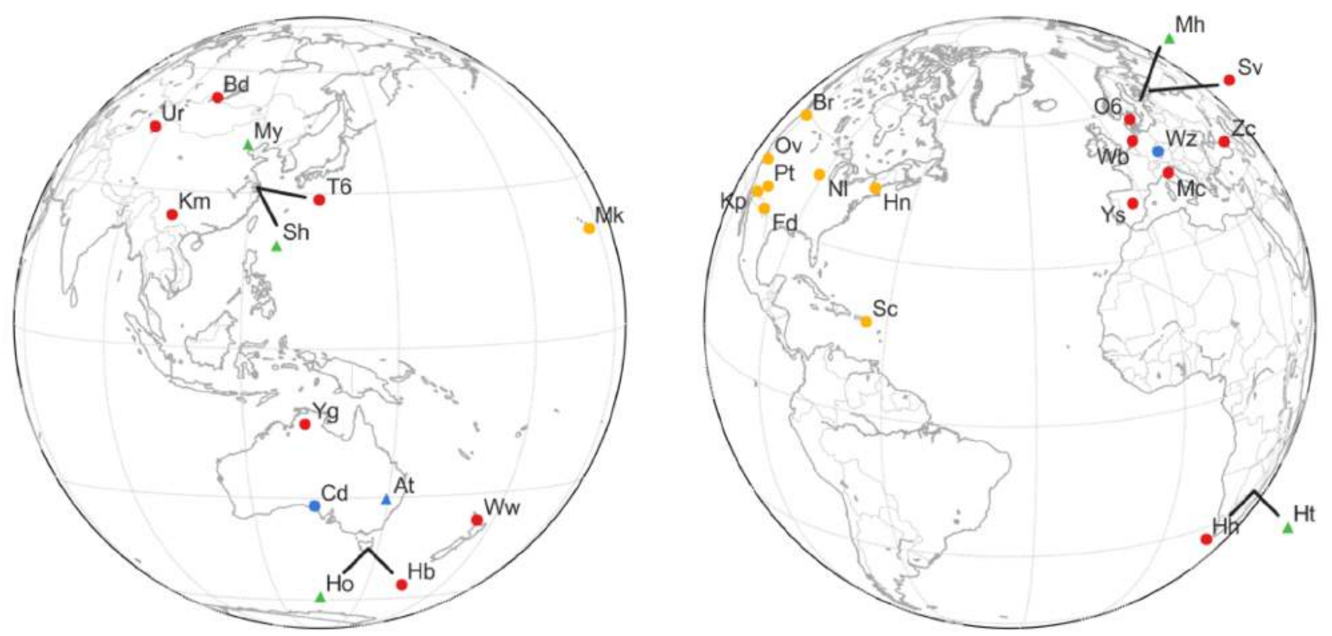
<u>**Formal precision (3σ):**</u>

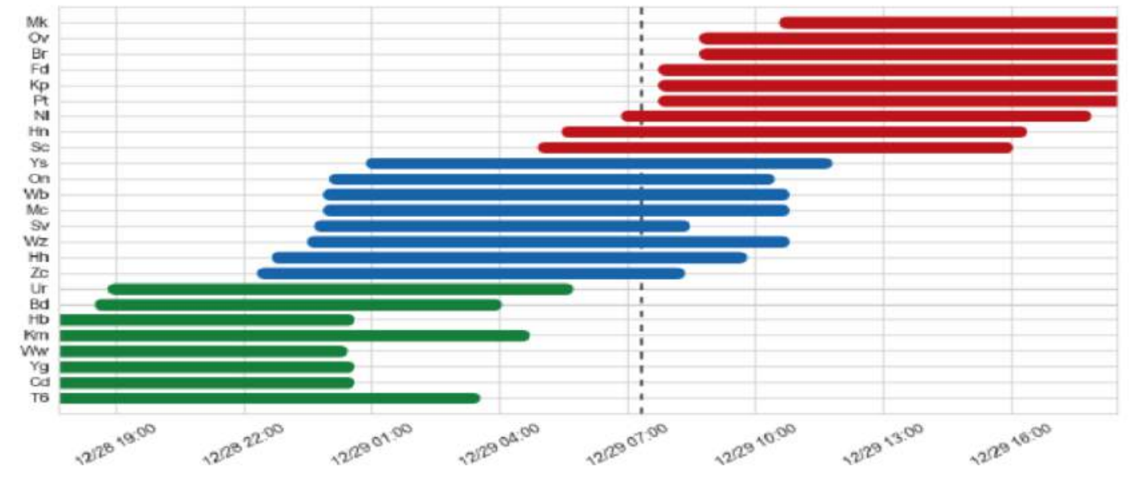
RA	**34 μas**	**35 m**	**~0.17 nrad**
Dec	**58 μas**	**60 m**	**~0.30 nrad**



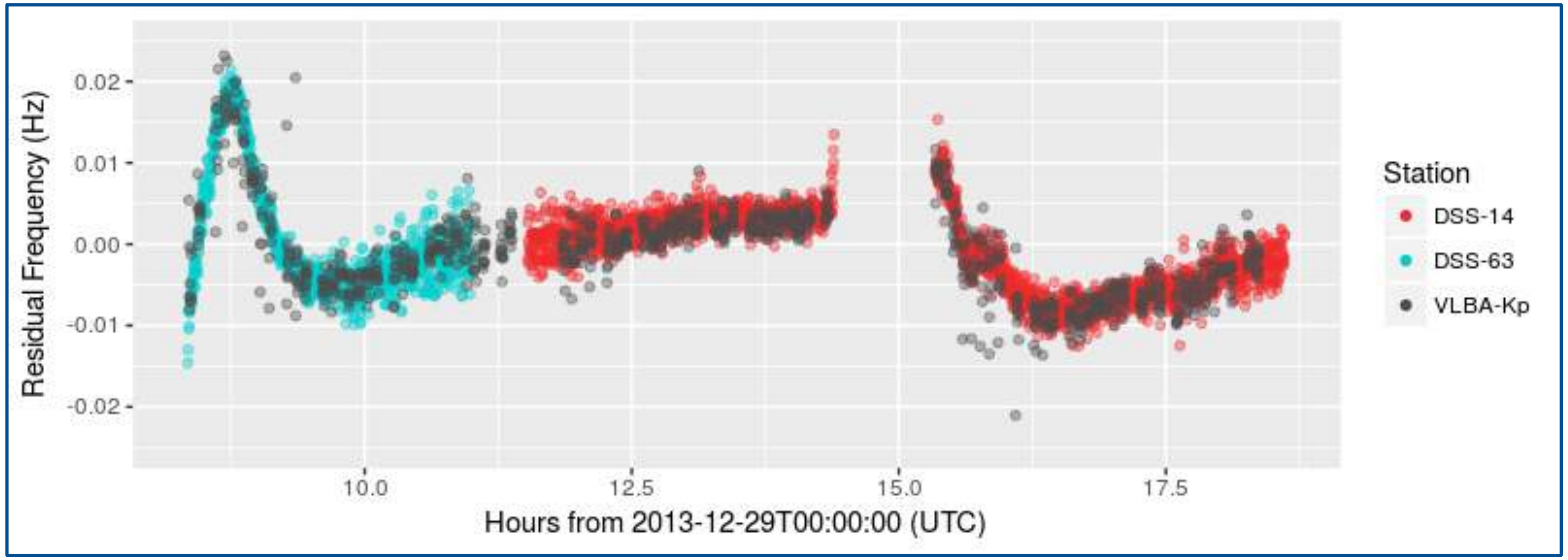
Doppler detection noise, 10 s integration:

- mean value 2.5 mHz
- median value 2.2 mHz
- **mod (maximum log-normal fit) value 1.7 mHz ➔ 30 μm/s**



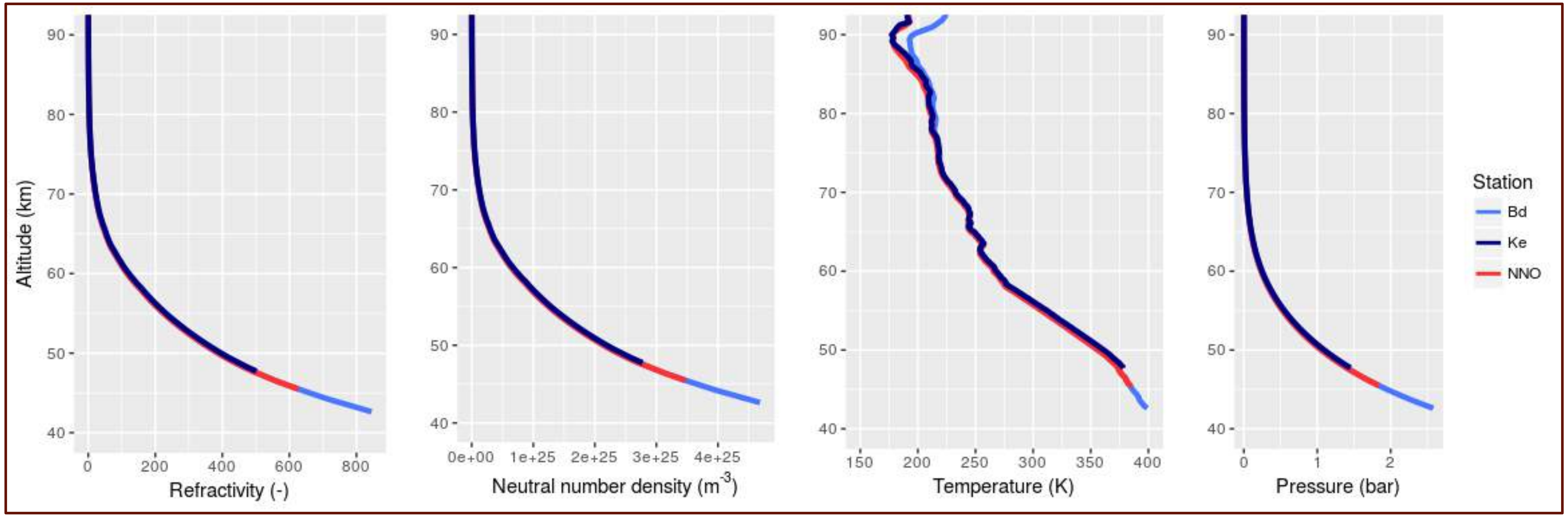


PRIDE: two current "bests"



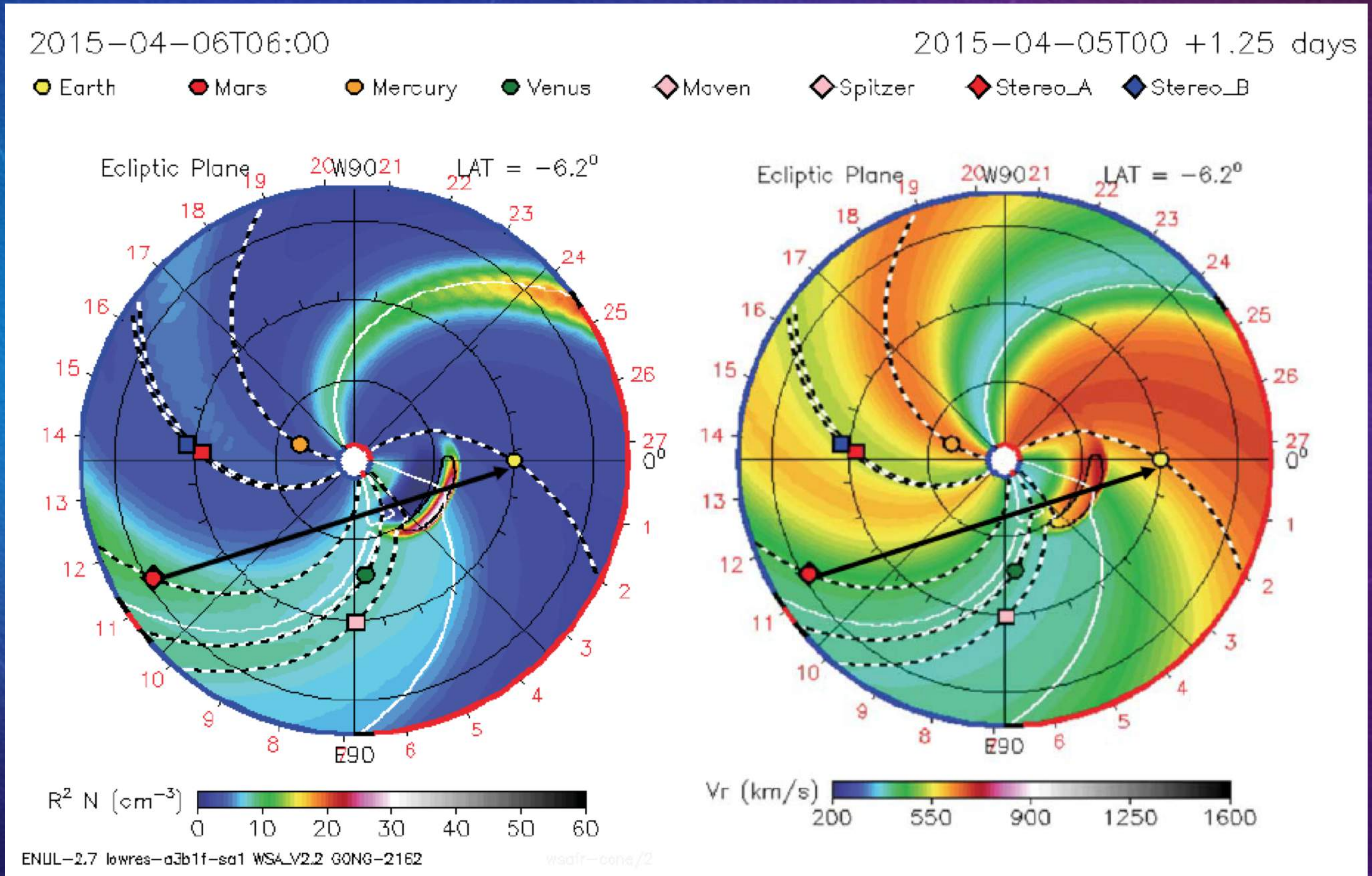
Record-precise PRIDE tracking of Mars Express, residual Doppler noise 1σ < 1 mHz; *Bocanegra Bahamón et al. 2018, A&A 609, A59*

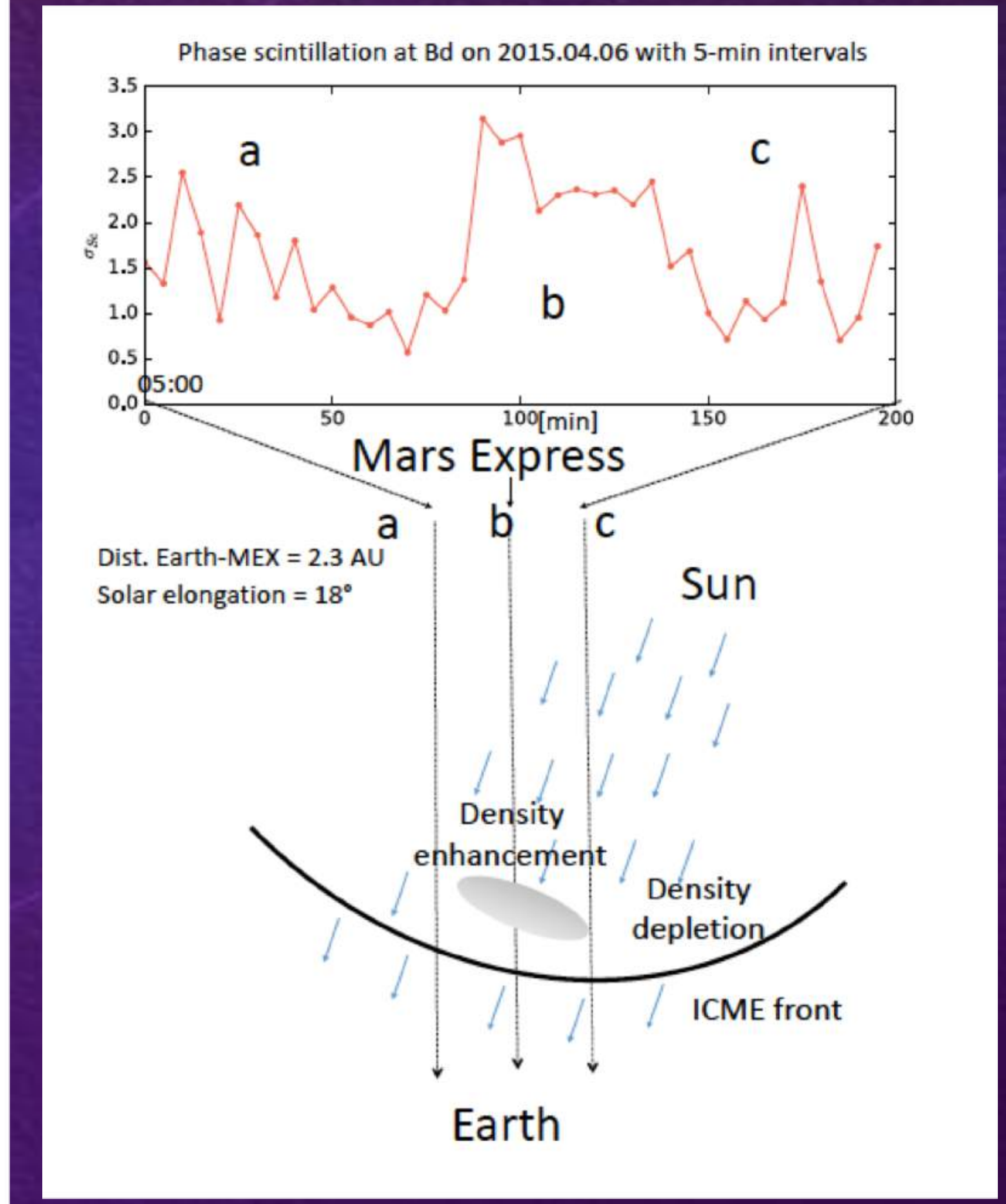
Record-deep penetration into Venus atmosphere (down to 41 km) by PRIDE Venus Express radio occultation experiment, *Bocanegra et al. 2019. A&A 624, A59*



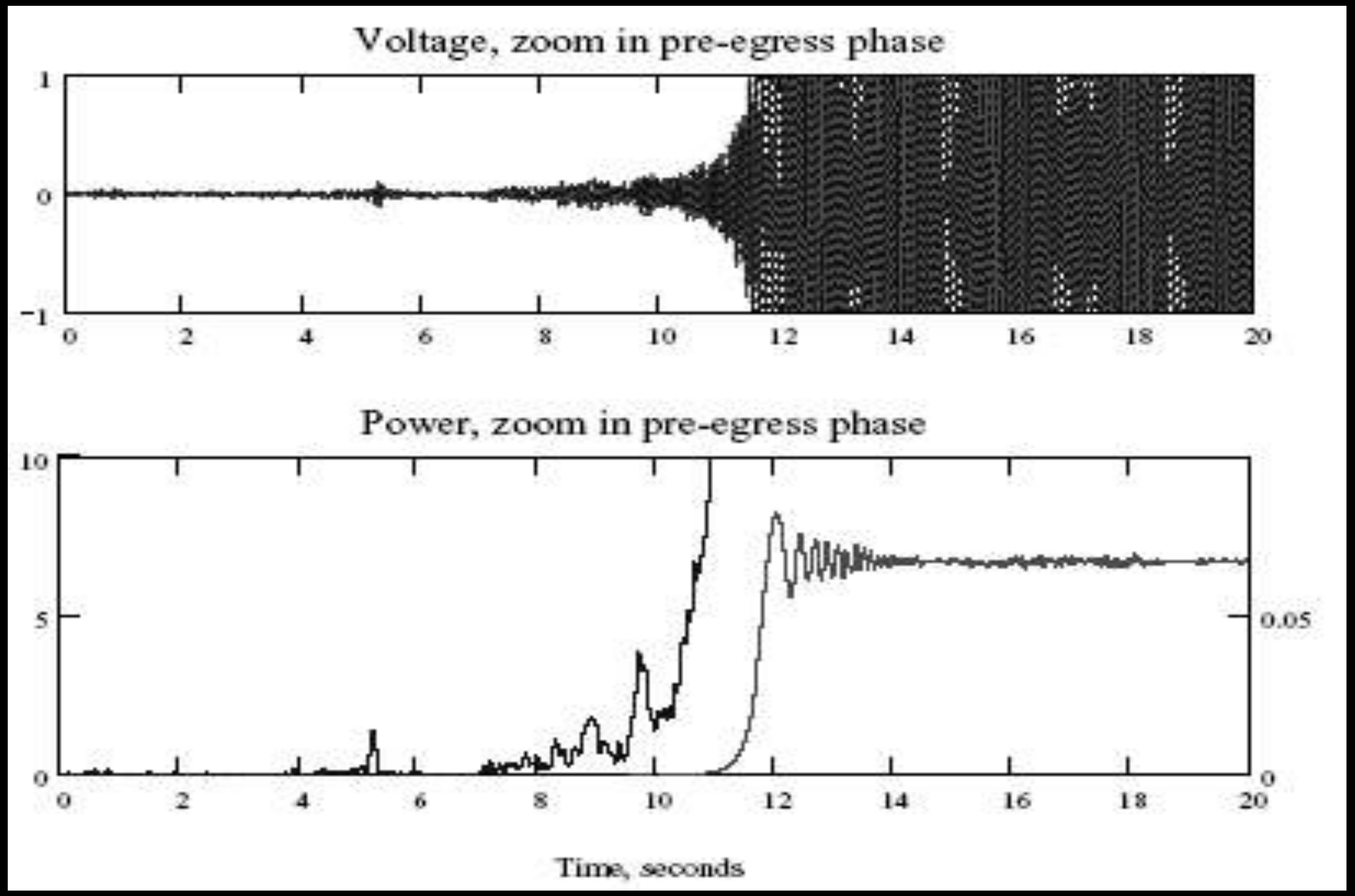
PRIDE serendipty: CME detection

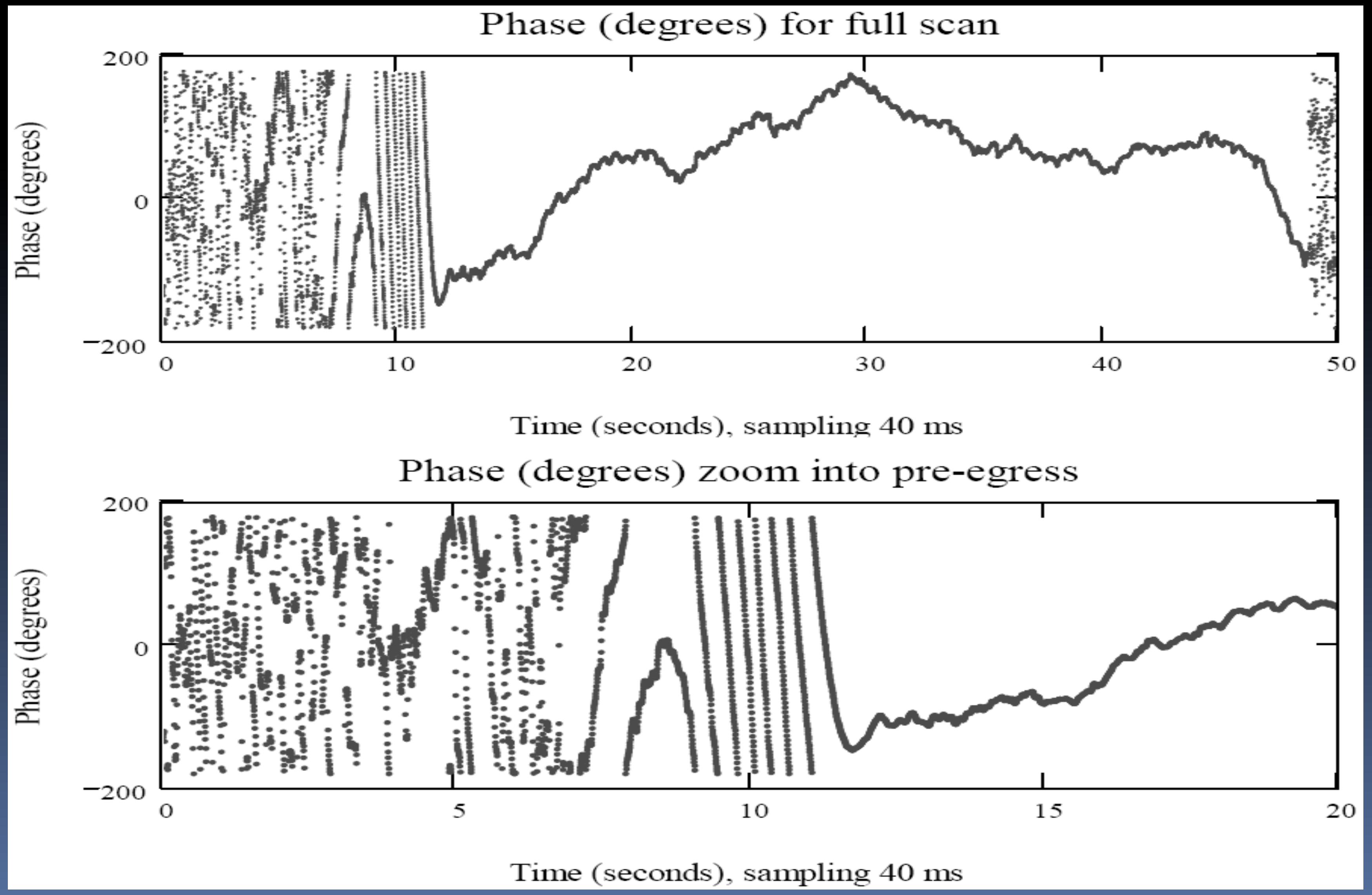
Analysis of an Interplanetary Coronal Mass Ejection 1 by a spacecraft radio signal
Molera Calves et al. 2018, Space Weather





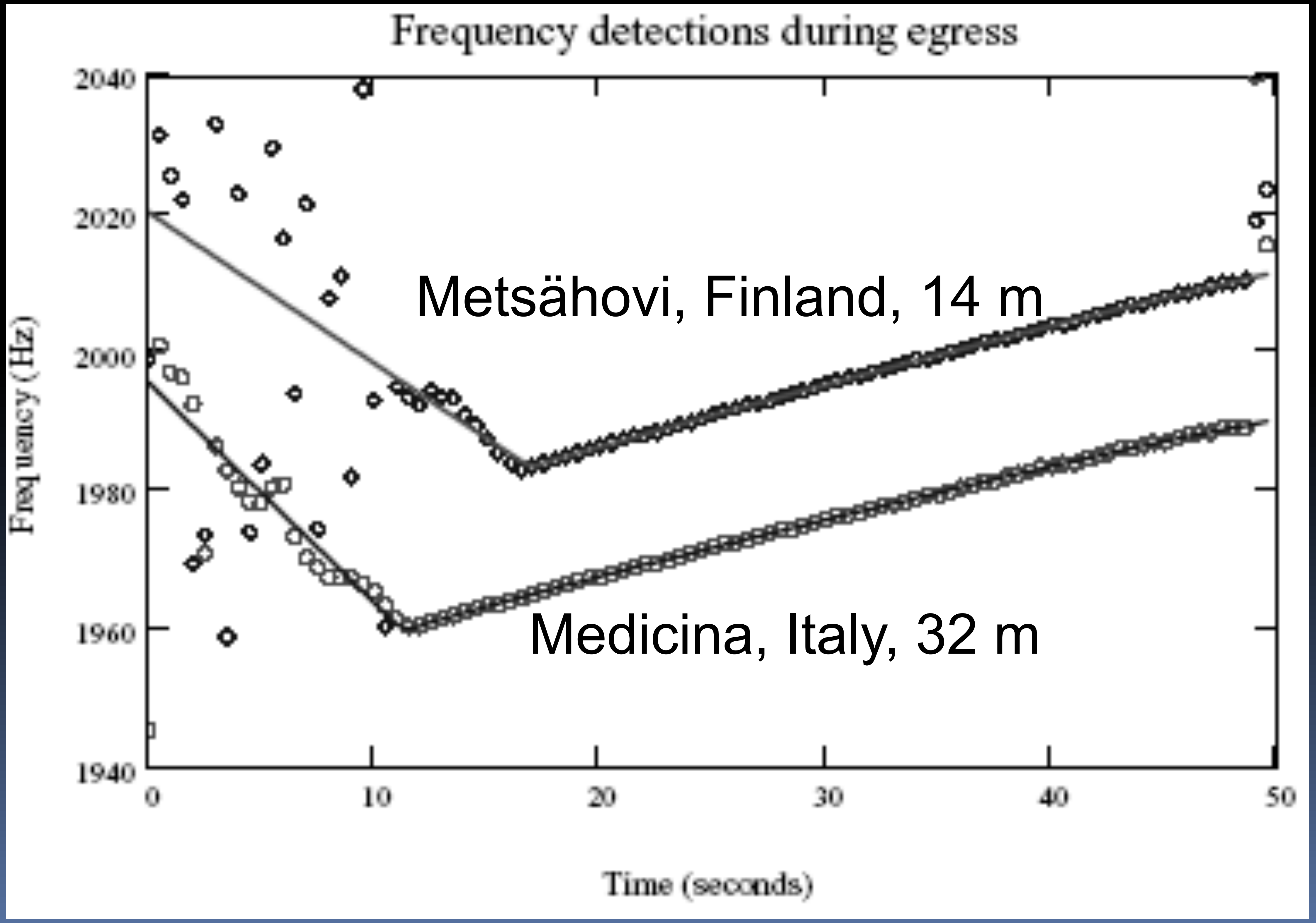
Radio occultation with PRIDE *(Smart-1, 2006)*



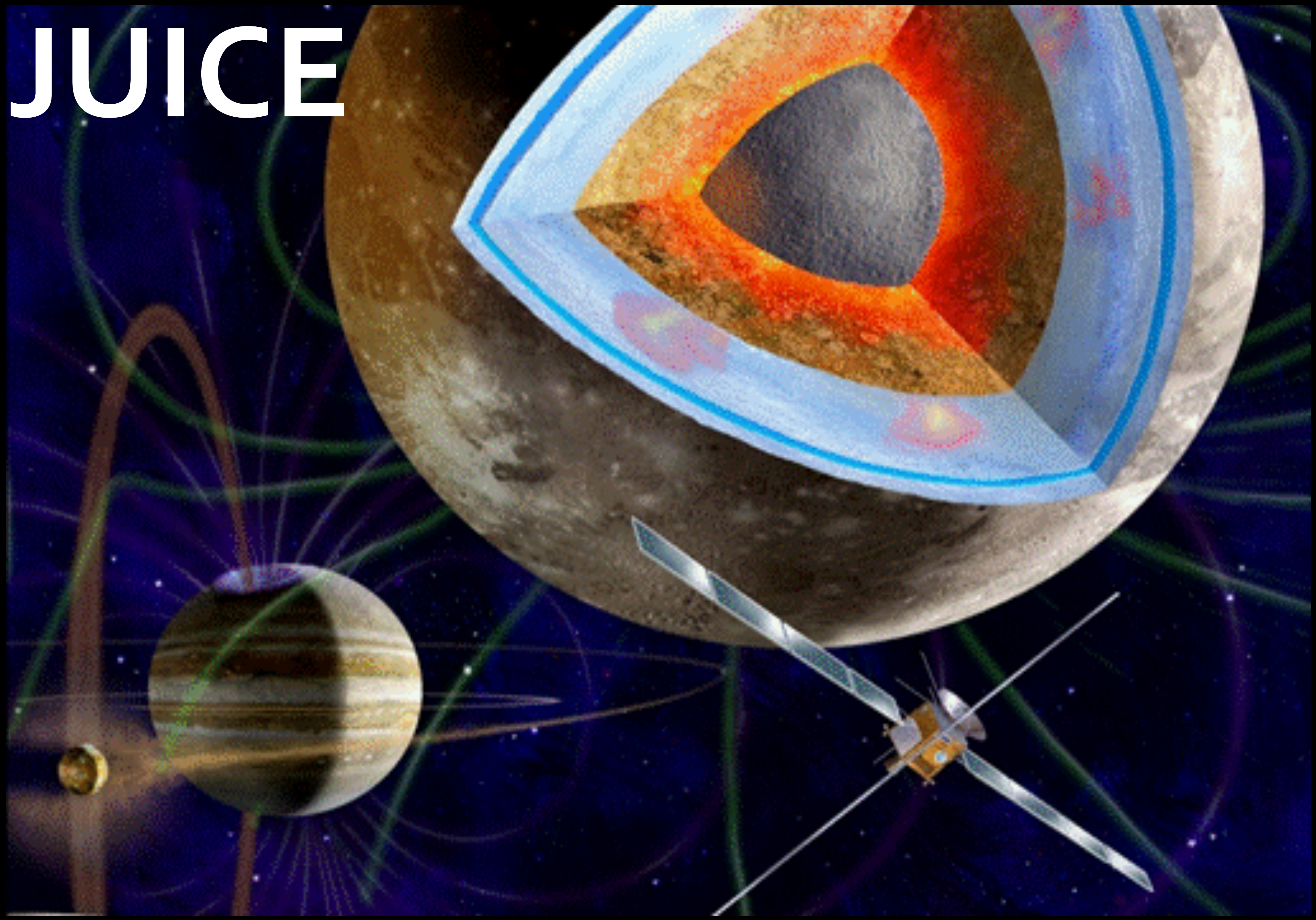


Smart-1 egress, 25.05.2006, S-band

Signal detected ~10 s before geometric egress (10 Fresnel zones below the Lunar limb);
Power level -50 dB of the post-egress level.



Probing Ganymede's interior from Geodesy



Geodesy from orbit (tides+librations)

Tide vertical Love number: h_2

- *From Laser altimeter (GaLa):*
  Cross-over data-points
  Vertical precision: 1 meter ($\Delta h2=0.01$)
  Lateral precision: (10 meters)

Tidal potential Love number: k_2

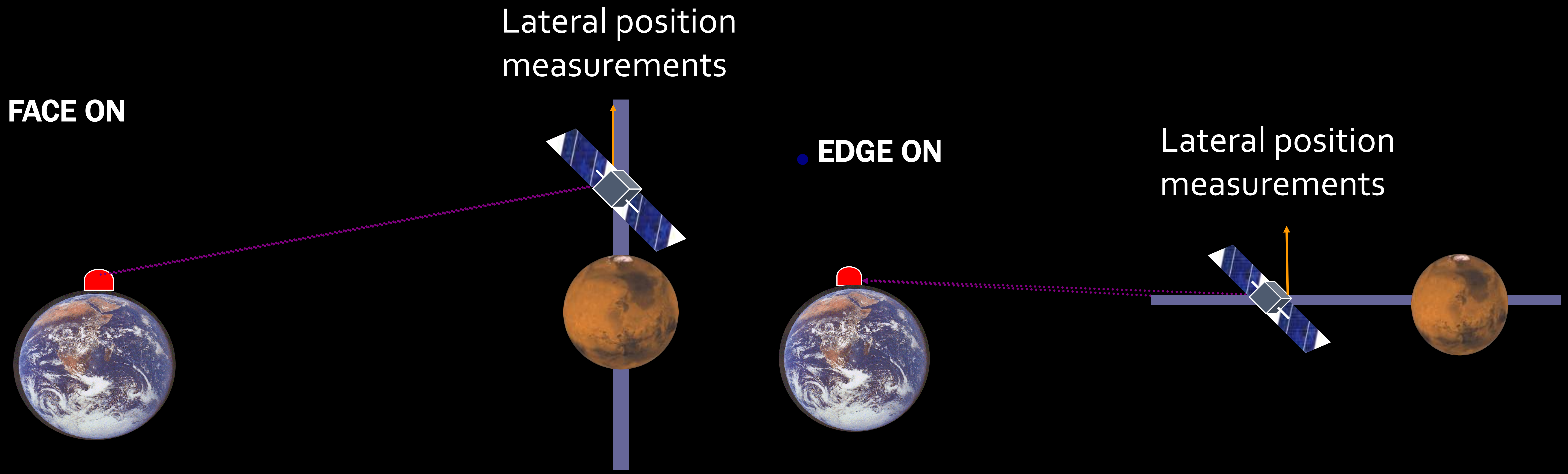
- *Tracking of orbiter (3GM + PRIDE):*
  Gravity field
  Precision:

Amplitude of librations

- *Tracking of orbiter (3GM + PRIDE)*
  (as done for Mars' LOD with DSN tracking)

- PRIDE will be used in addition to ESTRACK tracking data (Doppler and range) to help reaching the goals of the Geodesy experiment by performing:
- Precise Orbit Determination (POD) of the JUICE spacecraft orbiting Ganymede. Better constraints from PRIDE Doppler and lateral position measurements.

PRIDE: gravimetry, geodynamics, interior



- Complementarity of PRIDE tracking: Lateral position S/C Position perpendicular to Doppler-LoS direction
- Better constraints on orbital perturbations, thus on gravity field coefficients determination, depending on orbital plane geometry
- Thorough simulations to assess the improvement.

PRIDE-2021 vs Huygens VLBI tracking in 2005

Garmin accuracy anywhere in Solar System

Mission	Distance	Transmitter power/gain	Band	Time resolution	Delay	[illegible]teral)
	[AU]		*[GHz]*	[illegible]	*[illegible]ps]*	*[m]*
Huygens VLBI	8	3 W / 3 d[illegible]	[illegible]	500	15	1000
PRI[illegible]	[illegible]	10 w / 6 dBi	2.3 (S)	100	5	120
			8.4 (X)	10	3	70
			32 (Ka)	10	1	23

- **Conservative estimate, today's technology**
- **Minimal special requirements for the on-board instrumentation**
- **Helps to address the key science of JUICE (Solar System origins)**

What PRIDE brings for JUICE state-vector estimates

1. Uniform coverage on the global baselines, 10 or more telescopes at any session

2. More collecting area, improved SNR for both calibrators and S/C, based on densified calibrators data base

3. Wider bandwidth for calibrators enables use of weaker compact calibrators closer to the target, potentially reaching a calibration accuracy at the level of a few micro arc seconds for in-beam cases

   - Wider bandwidth helps to better model the dispersive components of interferometric delay (ionosphere and interplanetary plasma)

4. Multi-station Doppler and range measurements enable averaging of un-modeled dispersive and non-dispersive propagation effects and receiving station clock variations

5. Advanced broad band signal transfer and processing facilities

Near-field VLBI compendium (2021) – JIVE publications

General algorithms of PRIDE:

- Duev D.A. et al. 2012, A&A 541, A43 — *VLBI & Doppler algorithms*
- Bocanegra Bahamon T.M. et al. 2018, A&A 609, A59 — *Doppler analysis*
- Molera Calves G. et al. 2021, in preparation — *Software implementation*

PRIDE demonstrations:

- Duev D.A. et al. 2016, A&A 593, A34 — *Mars Express*
- Duev D.A. et al. 2015, A&A 573, A99 — *RadioAstron (really near-field…)*
- Bocanegra Bahamon T.M. et al. 2019, A&A 624 A59 — *Venus Express*

Diagnostics of interplanetary plasma (scintillations):

- Molera Calvés G. et al. 2014, A&A 564, A4 — *Mas Express*
- Molera Calvés G. et al. 2017, Space Weather 15, 1523-1534 — *Mars Express (Coronal Mass Ejection)*

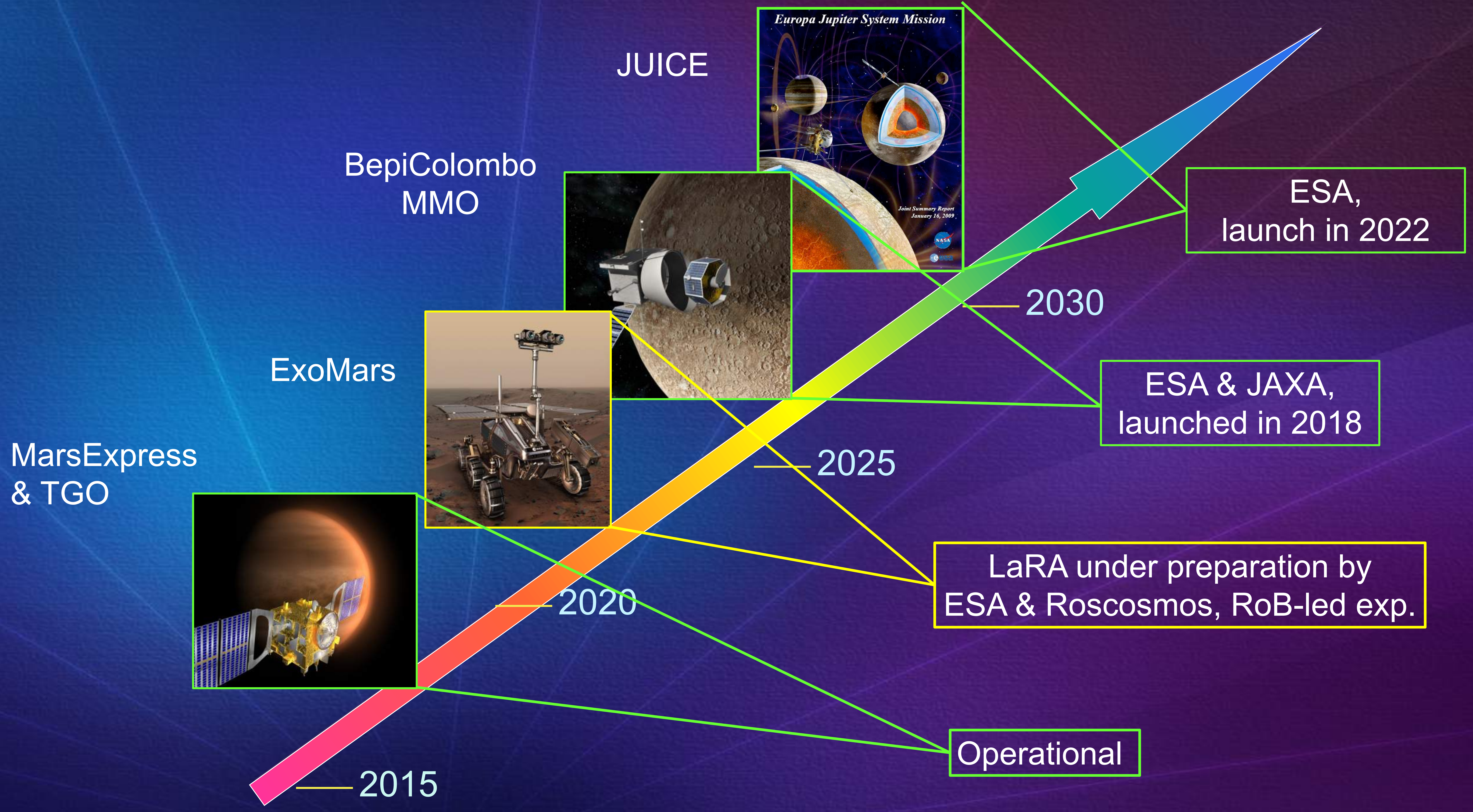
Forward look (JUICE and other prospective planetary missions):

- Dirkx D. et al. 2016, A&A 587, A156
- Dirkx D. et al. 2016, PSS 134, 82-95
- Dirkx D. et al. 2017, PSS 147, 14–27
- Dirkx D. et al. 2018, Journal of Geodesy, https://doi.org/10.1007/s00190-018-1171-x

Fundamental physics (Einstein Equivalence Principle):

- Litvinov D. et al. 2018, Phys. Letters A 382, 2192 — *RadioAstron*

Planetary science missions – near-field VLBI users



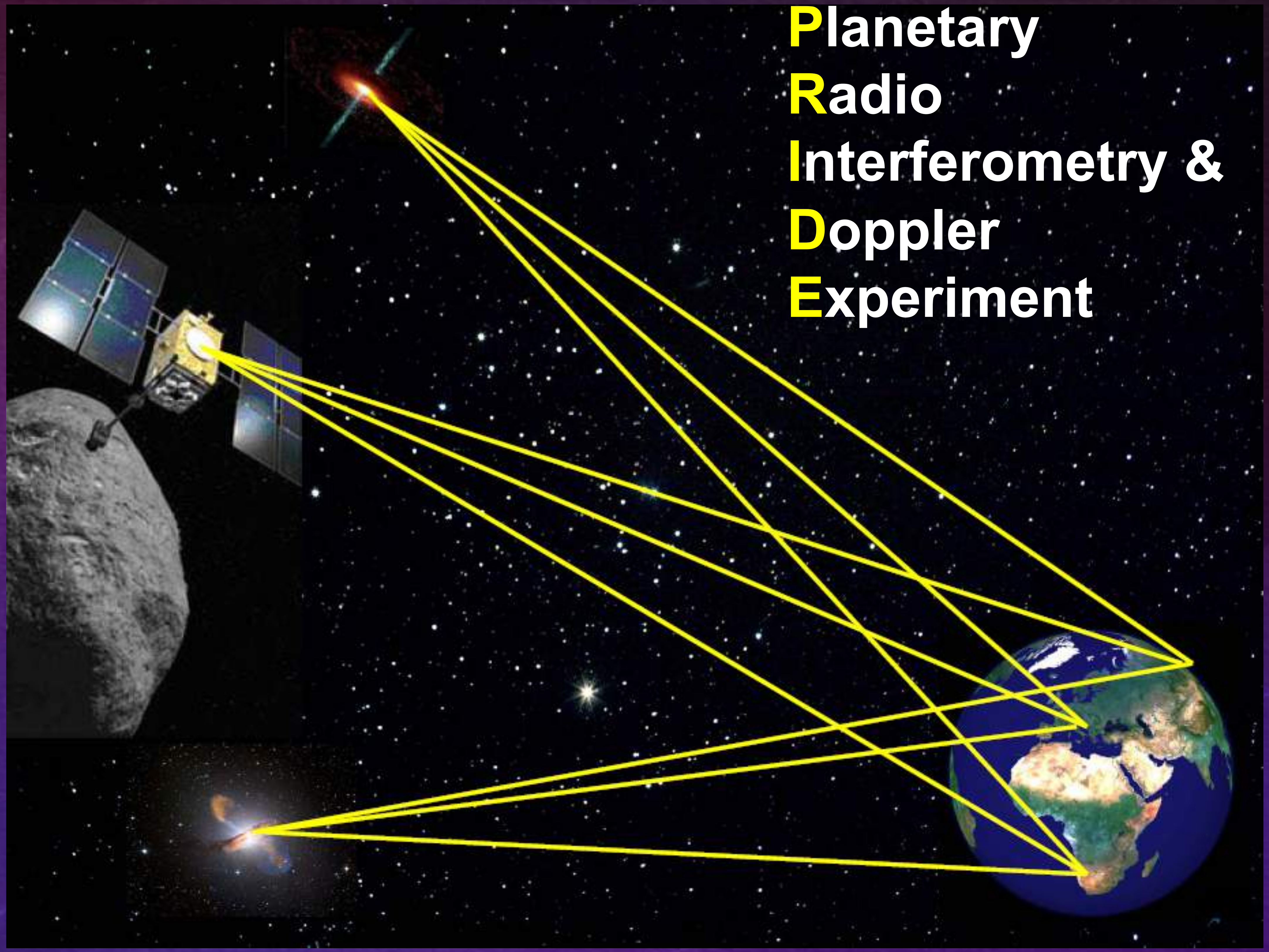
Near field VLBI (the dreams)

$$R \approx B^2/\lambda$$

3D astrometry of high T_B objects

$T_B > 10^{18}$ K?

Kardashev, Parijskij & Umarbaeva, 1973



Baseline	**100 km**	**1000 km**	**10^4 km**	**10^5 km**	**10^6 km**	**10^7 km**	**10^8 km**
Facility	MERLIN	EVN *WE*	EVN	RadioAstron	L2	-	~1 AU
λ = 3 cm	2 AU	200 AU	0.1 pc	10 pc	1 kpc	100 kpc	10 Mpc
λ= 30 cm	$3x10^7$km	20 AU	$2x10^3$AU	1 pc	100 pc	10 kpc	1 Mpc

Astrometry of extragalactic pulsars?