2nd Asteroid Science Intersections with In-Space Mine Engineering – ASIME 2018
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# Efficient Massively Parallel Prospection for ISRU by Multiple Near-Earth Asteroid Rendezvous using Near-Term Solar Sails and 'Now-Term' Small Spacecraft Solutions

**Jan Thimo Grundmann[(1)*], Waldemar Bauer[(1)], Jens Biele[(2)], Ralf Boden[(3)], Matteo Ceriotti[(4)], Federico Cordero[(5)], Bernd Dachwald[(6)], Etienne Dumont[(1)], Christian D. Grimm[(1)], David Herčík[(7)], Alain Herique[(16)], Tra-Mi Ho[(1)], Rico Jahnke[(1)], Aaron D. Koch[(1)], Wlodek Kofman[(17)], Alexander Koncz[(8)], Christian Krause[(2)], Caroline Lange[(1)], Roy Lichtenheldt[(9)], Volker Maiwald[(1)],Tobias Mikschl[(10)], Eugen Mikulz[(1)], Sergio Montenegro[(10)], Ivanka Pelivan[(8)(15)], Alessandro Peloni[(4)], Dirk Plettemeier[(17)], Dominik Quantius[(1)], Siebo Reershemius[(1)], Thomas Renger[(1)], Johannes Riemann[(1)], Michael Ruffer[(10)], Kaname Sasaki[(1)], Nicole Schmitz[(8)], Wolfgang Seboldt[(11)], Patric Seefeldt[(1)], Peter Spietz[(1)], Tom Spröwitz[(1)], Maciej Sznajder[(1)(12)], Simon Tardivel[(13)], Norbert Tóth[(1)], Elisabet Wejmo[(1)], Friederike Wolff[(9)], Christian Ziach[(14)]**

*[(1)]DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany – [*]+49-(0)421-24420-1107, jan.grundmann@dlr.de – [(2)]DLR German Aerospace Center, Space Operations and Astronaut Training – MUSC, 51147 Köln, Germany – [(3)]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Solar Power Sail ISAS Pre-Project, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210, Japan – [(4)]University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom – [(5)]Telespazio-VEGA, Darmstadt, Germany – [(6)]Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany – [(7)]Institute for Geophysics and Extraterrestrial Physics, Technical University Braunschweig, Germany – [(8)]DLR German Aerospace Center, Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin, Germany – [(9)]DLR German Aerospace Center, Robotics and Mechatronics Center, 82234 Wessling, Germany – [(10)]Informatik 8, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany – [(11)]Consultant to DLR Institute of Space Systems – [(12)]Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-069 Zielona Góra, Poland – [(13)]CNES, Future Missions Flight Dynamics, 18 avenue E. Belin, 31401 Toulouse cedex 9, France – [(14)] High-Tech Gründerfonds Management GmbH, Schlegelstraße 2, 53113 Bonn, Germany – [(15)] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany – [(16)]Univ. Grenoble Alpes, IPAG, Grenoble, France – [(17)] Space Research Centre, PAS, 00--001 Warsaw, Poland – [(18)] Dresden University of Technology, Chair for RF Engineering, Dresden, Germany*


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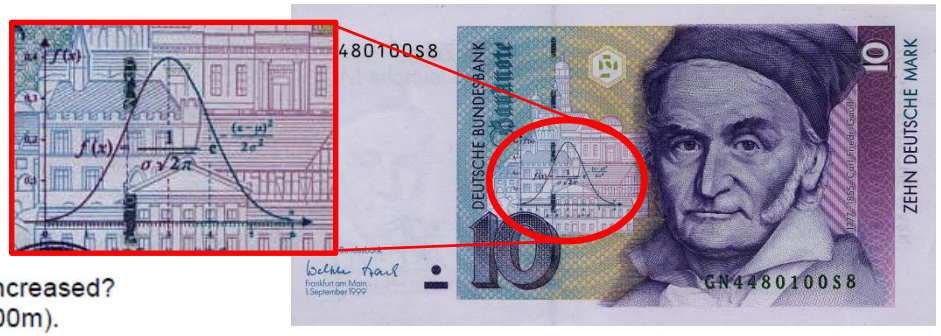
# the problem & the questions:




2. [revisit] How can the rate of spectral characterisation of NEOs be increased? It lags far behind discovery rate, especially at smaller sizes (D < 300m).

4. *Technically*, and *scientifically*, how does spectroscopy of an asteroid at short (km range) distances differ from spectroscopy with ground-based telescopes?

9. [revisit] Is there any evidence that the shape of an asteroid provides information on its composition?

5. [revisit] How can the water absorption feature at 3.1$\mu$m be best used as an indicator of hydrated minerals on carbonaceous asteroids? What additional measurement would further increase the quality or fidelity of the measurement?

8. What instrumentation should an exploration probe carry in order to establish with 100% confidence that water and/or hydrated minerals are present on an asteroid, and what further instrumentation, if any, would be required to ascertain how much water there is?

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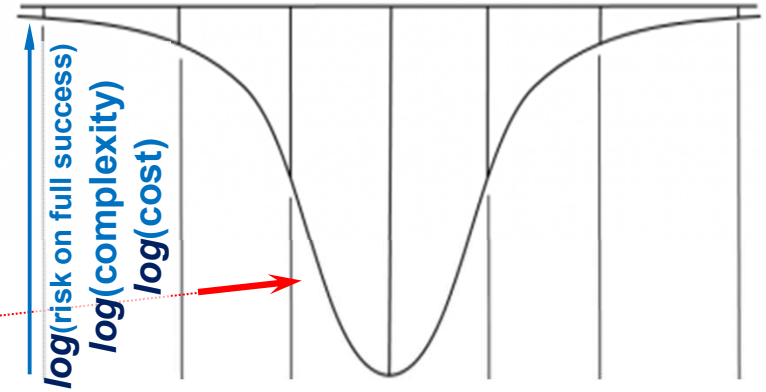
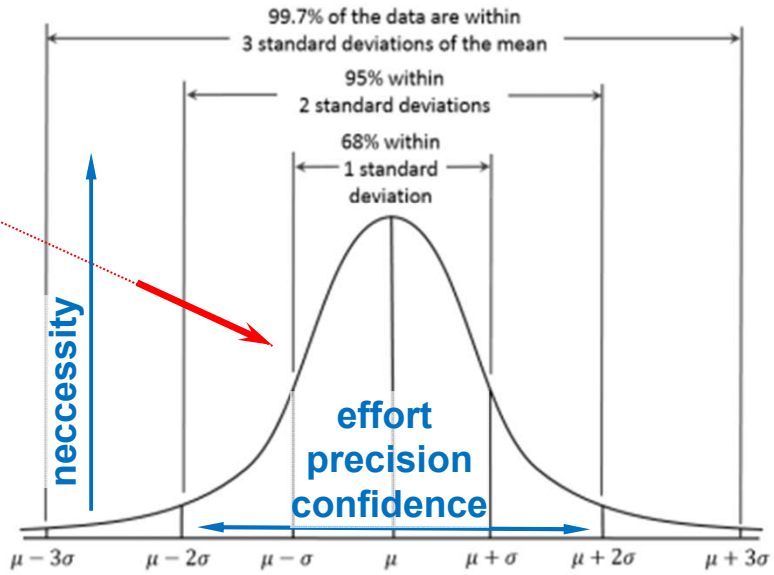
15. [revisit] How well understood are the processes of space weathering, and can we tell what the original state of the surface was, based on the current state?

22. What is the state of the art regarding matching meteorite spectra to asteroid spectra, and matching artificially weathered meteorite spectra to asteroid spectra?

23. Is anyone working on software that models how weathering affects meteorite spectra, to then attempt to match asteroid spectra to this modelled weathered meteorite spectra?

11. [revisit] What highest value telescopic composition/characterisation studies are not being pursued for lack of funding or perceived low priority from space agencies?






*clip-ins: ASIME2018 abstracts book (final), wikipedia/Bundesbank*

# "When you've seen one asteroid,… …or comet…
# …you've seen *one* asteroid. …or comet.

*so far, every asteroid visited looks different from all the others*

- approaches to classification:
  - spectral information → taxonomy ← ? → composition
  - shape & topography ← ? → interior structure → porosity
  - families ← orbital dynamics ← Yarkovsky → YORP ← ? ↖
- …*but*: each sees a little light at the end of the tunnel
  - *taxonomy*: obvious patterns but composition inferred (cf. 'TC$_3$)
  - *shapes*: radar (poor man's flyby) shows >1 "top-like", "cigar",…
  - *orbits*: long-term monitoring makes small Y*-effects quantifiable
- …*corollary*: all these dots & models still need to be connected

**➔ need to study many more asteroids – close-up, soon, affordable**

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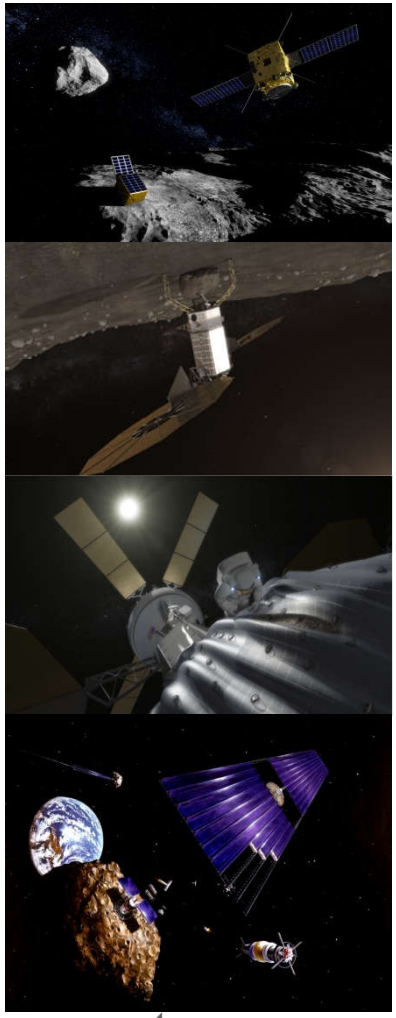
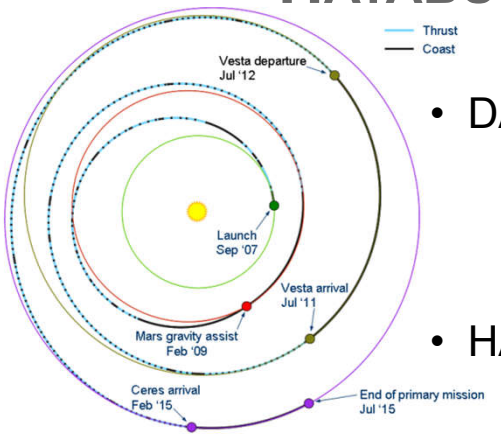
# pick target by ‘scope, get ground truth by probe

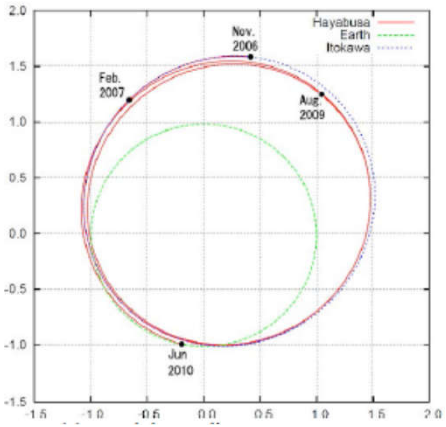


- even if the questions 1,3,5-10,15-17,21 can be answered “ with 100% confidence ” – at some point before starting to dig for real you’ll have to 1st go & check.
- proof-sampling ⇔ sample-return
- non-sampling in-situ observations
  - create multi-scale **context chain soil ⇔ telescope**
  - **landing site** panorama, **thermal** properties & **conditions**
  - local conditions of space weathering ⇔ spectra validity
- ‘deep’ sounding extends context chain via *and* to the interior
  - collisional & orbital history – hidden fluff & rock remnants
  - sub-surface sampling, tomography
- in-situ resource utilization specifics
  - staking claims – be there, stay there
  - prospection = area mapping of volatiles & minerals
- *note*: current & future small solar system bodies science missions *all* require sample in-situ analysis and/or return

images: J.R.C. Garry for ISAS, ESA/DLR, JAXA, , NASA/GSFC/LM

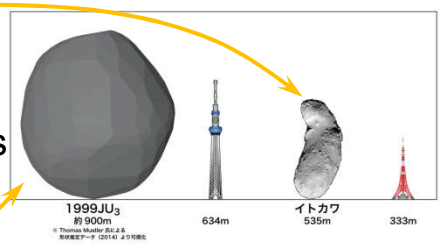
# state of the art: DAWN – 2-asteroid rendezvous
# HAYABUSA &HAYABUSA2 – 1-asteroid sample-return



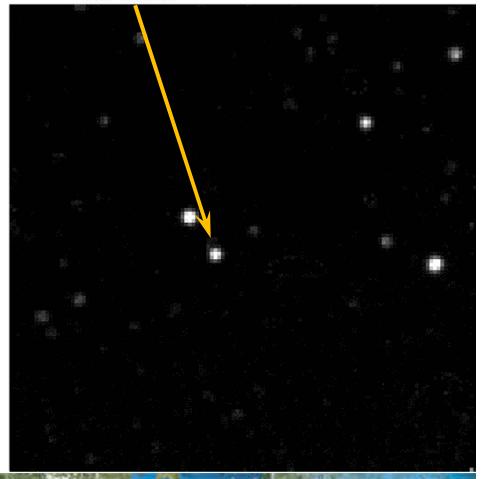




- DAWN orbited (4) Vesta & orbits (1) Ceres
  - **Δv capability ≈ 13 km/s** from 275 kg Xe propellant
  - fly-by at (2) Pallas suggested but too marginal, possible fly-by of (145) Adeona not accepted


- HAYABUSA returned samples from (25143) Itokawa
  - **Δv capability ≈ 4.0 km/s** from 66 kg Xe propellant
  - total Δv ≈ 0.4 km/s from 67 kg bipropellant
  - **≈ 40 kg** used for SEP during mission, yielding 2.2 km/s




- HAYABUSA2 is currently at <1 LD approaching carbonaceous NEA (162173) Ryugu
  - **Δv capability ≈ 3.2 km/s** from 66 kg Xe propellant
  - **up to ≈ 3.5 km/s** if filled up to 73 kg Xe capacity



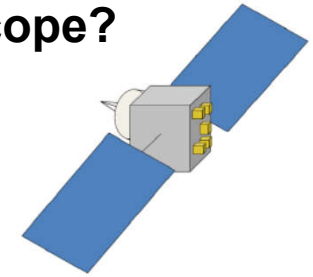
*<u>common feature</u>*:

high-performance electric propulsion

*figures: Kuninaka et al., 2009, Nishiyama et al., 2015, ASIME/NASA/DLR, JAXA*

# “if we keep it to a few basic questions, can we use what we already have to go to more asteroids at a time?”

- DAWN spent some Δv to move between various mapping orbits, the HAYABUSAs to return samples
  - **what‘s science payload to descope?**
  - **what‘s there to repurpose?**
  - **where are the limits?**



SESAME (Maiwald & Marchand, 2016)

- science payload 33 kg (orbiter) + 5* 4.3 kg (landers)
- **launch mass 1571 kg**
  - **~3x** HAYABUSA2, though only moderately larger than DAWN
- payload fraction <3.5 %: ≈ no gain by descoping (*sic!*)
- GTOC-5-like trajectory to **5 NEAs** of ≈200 candidate targets
- ***primarily*** **astrodynamic target selection**
- targets tied to launch date

➔ **possible, but…**

| Property | Value |
|---|---|
| Departure Date from Earth | 21 March 2023 |
| Arrival @ 5th target | 26 February 2030 |
| Total Δv | 16.6 km/s |
| Wet mass | 1,571 kg |
| Xenon fuel mass | 451 kg |
| Bi-propellant mass | 125 kg |

Table 7: Mission parameters of SESAME

| Target Body Data | Absolute Magnitude (H) | Orbit Condition Code (OCC) | Observation opportunities prior launch |
|---|---|---|---|
| $2001QJ_{142}$ | 23.4 | 6 | 2012 |
| $2000SG_{344}$ | 24.8 | 2 | none |
| $2009OS_5$ | 23.6 | 5 | 2014-2020 |
| 2007YF | 24.8 | 5 | 2021 |
| $1999AO_{10}$ | 23.9 | 6 | 2018, 2026 |

Table 8: Mission target data

| Body | Arrival Date | Departure Date | Time of Flight (d) | Duration of Stay (d) |
|---|---|---|---|---|
| Earth | - | 21 Mar 2023 | 316 | - |
| $2001QJ_{142}$ | 31 Jan 2024 | 22 Jul 2024 | 444 | 173 |
| $2000SG_{344}$ | 9 Oct 2025 | 8 Mar 2026 | 384 | 150 |
| $2009OS_5$ | 27 Mar 2027 | 28 Sep 2027 | 445 | 185 |
| 2007YF | 16 Dec 2028 | 19 May 2029 | 283 | 154 |
| $1999AO_{10}$ | 26 Feb 2030 | 4 Sep 2030 | 314 | 190 |

Table 9: Trajectory data.

*figures: Maiwald & Marchand, 2016*

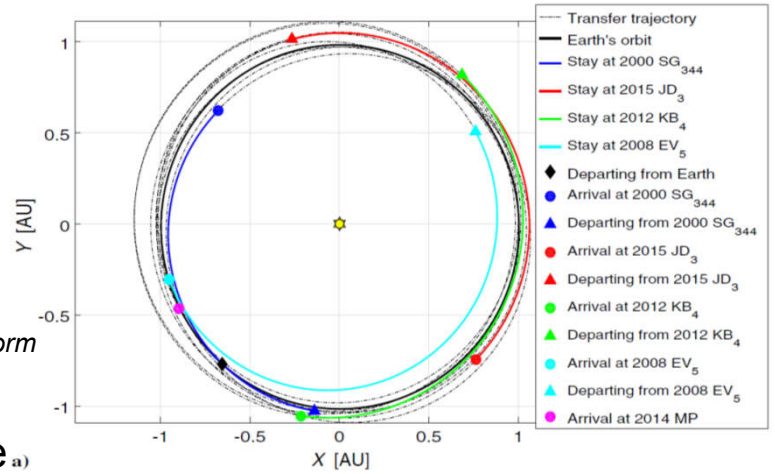
# *disrupt!* …the fuel tank: Multiple NEA Rendezvous by Solar Sail

- solar sailing provides propulsion *not* limited by the amount of fuel carried

*– then what's the next limit? –*

how well it is designed, built, tested, flown & fixed

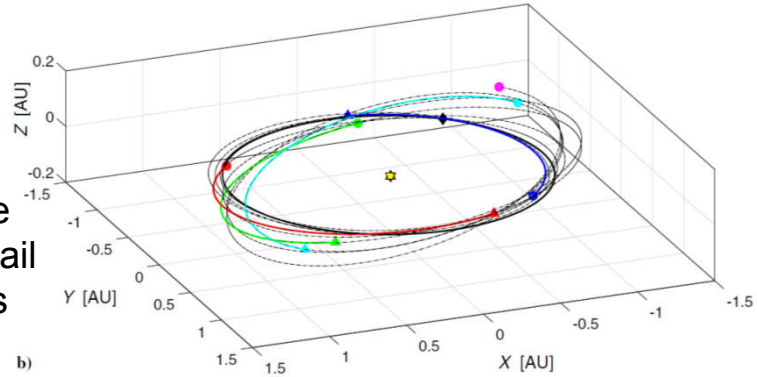
*mechanisms have been fixed in space w/o astronauts around: e.g. Voyager 1 scan platform*




- recent studies (Peloni et al., 2016-2018) demonstrate
  - 5 NEA stays for ≥100 days, each, in 10 years
  - accumulated **Δv >50 km/s** @ $a_c$ = 0.2 mm/s²

  ➔ asteroid-oriented target selection is feasible

  ➔ at-launch & in-flight target change capability




- target-flexible Multiple NEA Rendezvous for planetary science was identified as a mission type uniquely feasible with solar sail already by the GOSSAMER Roadmap Science Working Groups

*figures: Peloni, Ceriotti, Dachwald, 2016*

# “okay, low-thrust to so many targets in a row… – is this even a robust mission type or just a one-off?”

*even restricted to PHA & NHATS targets, only,…*

- there are 100’s of possible NEA sequences for each launch date
- targets can be changed any time while in cruise or rendezvous
- now available sail technology is sufficient

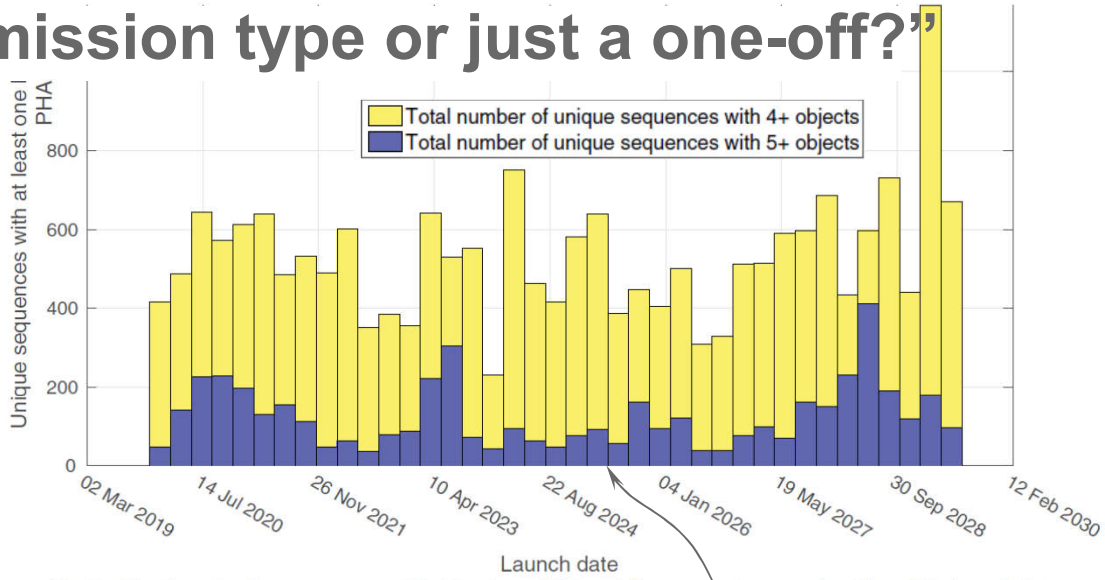



**Fig. 7** Number of unique sequences with at least one PHA and four encounters as a function of the launch date.

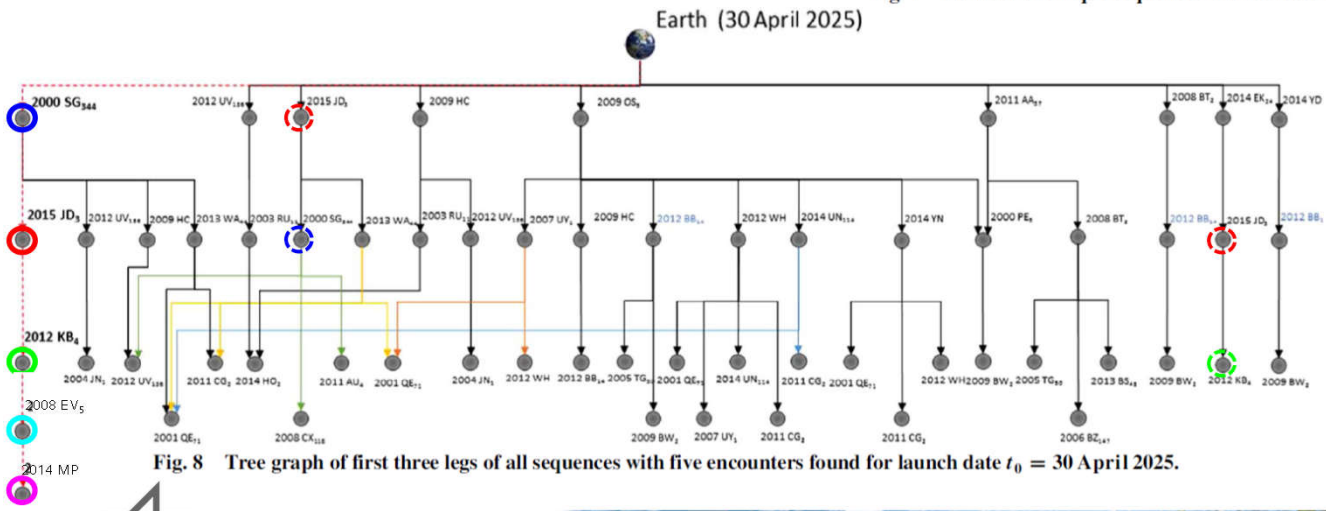



**Fig. 8** Tree graph of first three legs of all sequences with five encounters found for launch date $t_0 = 30$ April 2025.

| Object | Stay time [days] | Start | End | Time of flight [days] |
|---|---|---|---|---|
| Earth | // | 10 May 2025 | 26 Feb 2027 | 657 |
| 2000 $SG_{344}$ | 123 | 29 Jun 2027 | 06 Sep 2028 | 436 |
| 2015 $JD_3$ | 164 | 18 Feb 2029 | 24 Sep 2030 | 584 |
| 2012 $KB_4$ | 160 | 04 Mar 2031 | 29 Sep 2032 | 576 |
| 2008 $EV_5$ | 171 | 20 Mar 2033 | 30 Sep 2034 | 560 |
| 2014 MP | // | | | |

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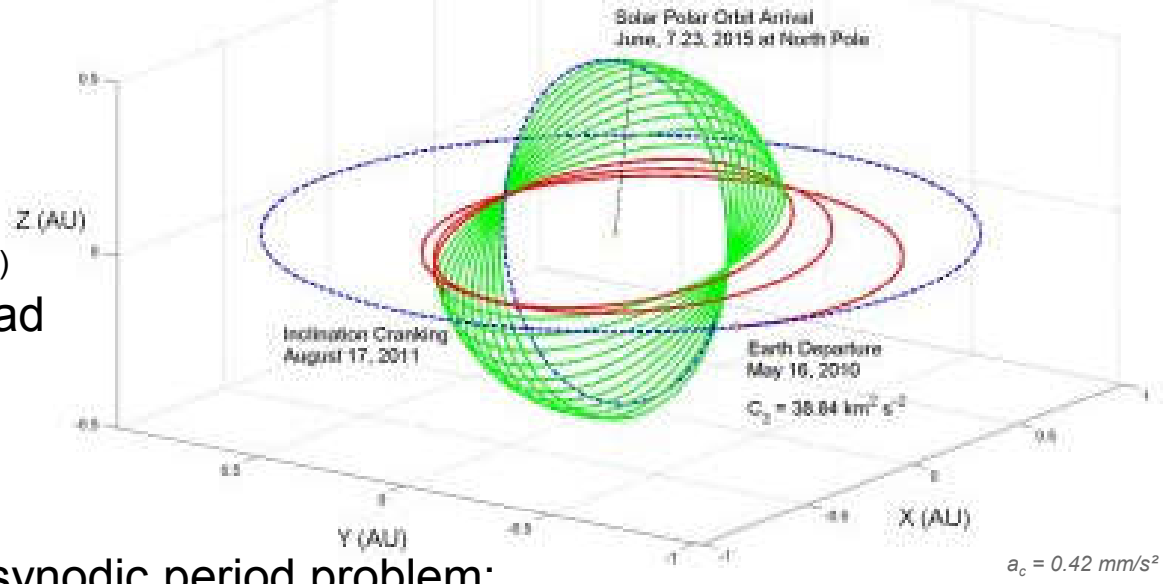
*figures & table: Peloni, Ceriotti, Dachwald, 2016*

# the other GOSSAMER Science Working Group studies: Displaced $L_1$ (DL1) & Solar Polar Orbiter (SPO)

- $DL_1$ – the 'low end' extreme: Earth co-orbiting trajectory, 'any' sail, @ e~0, i~0
- SPO – go to 75…90° inclination (heliocentric)

- SPO working principle:
  - get close to the Sun
  - crank up inclination
  - move out again (if necessary)
  - drop solar science payload




$a_c$ = 0.42 mm/s²

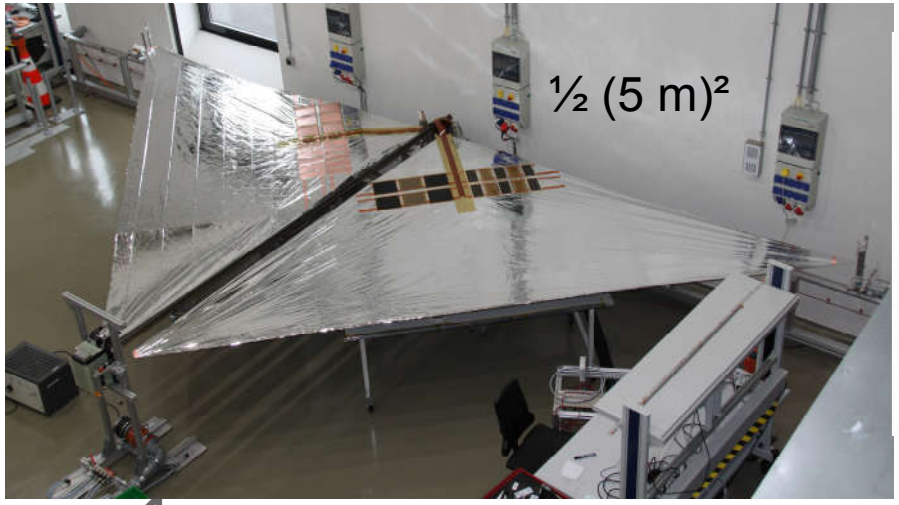
*<u>for asteroid work</u>*:

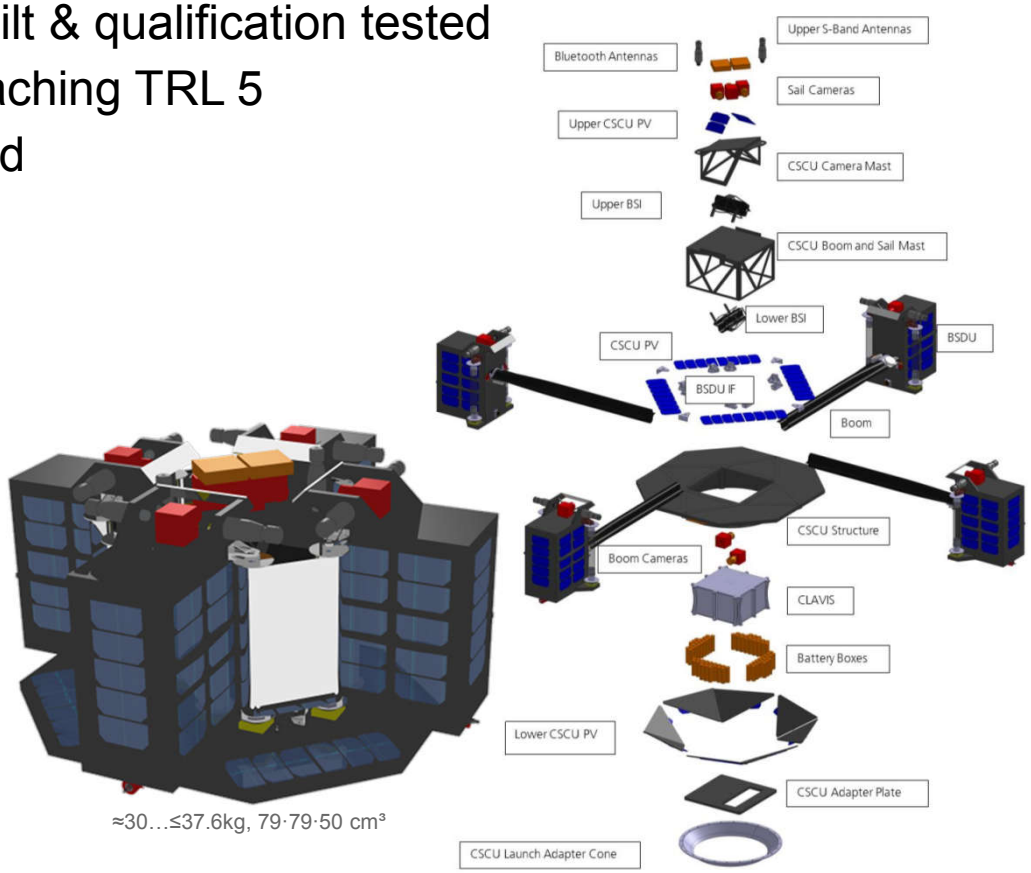
- get to inclination & get rid of synodic period problem:
  - go on a 'depressed trajectory' to phase with any target
    - *<u>note</u>*: a depressed trajectory will actually make you happy!
- looking-out opposition survey on the way possible (cf. „Earthguard")

*image: ESA SRE-PAM*
*Falkner et al 2004*

# GOSSAMER solar sail technology development (qualified)

- the 3-step DLR-ESTEC GOSSAMER Roadmap to Solar Sailing was set up in 2009 to develop key technolgies for science missions
- 1st step: GOSSAMER-1 EQM was built & qualification tested
- development was stopped after reaching TRL 5
- a PFM design was ready to proceed
- a launch opportunity was available
- all-launchers load envelope

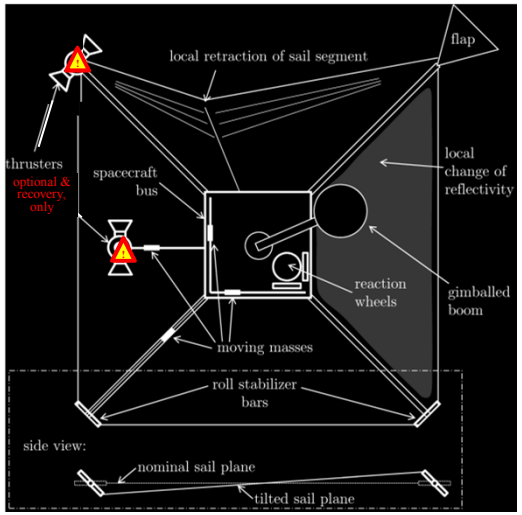




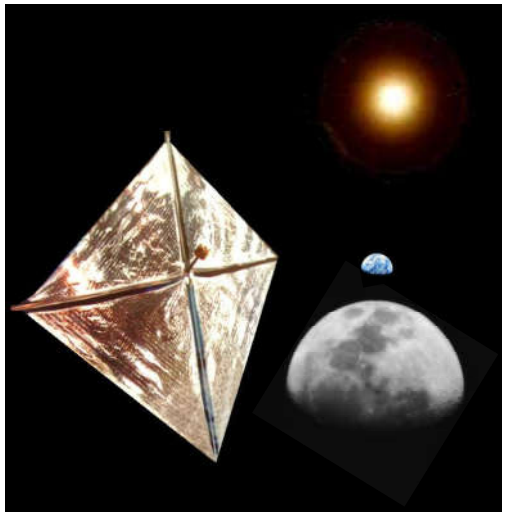

*figures: Seefeldt et al., 2016/2017*

# “okay, so you can deploy a membrane in a clean room – and how do you fly it?”




***the GOSSAMER Roadmap:***
***step 2 – control***
***step 3 – proving the principle***
***…***
*…that <u>was</u> the idea…*

(↑2009 – ↓2014)



***GOSSAMER-2 – high-orbit attitude & thrust vector control eval***

- (20…25 m)² sail area
- orbit where solar radiation pressure is dominant – high LEO, MEO, GTO, >GEO
- implementation of several to “all” control methods *and* <u>all</u> relevant mechanisms
- **find out what’s the best …**

***GOSSAMER-3 – all-up proof test & science mission readiness demonstrator***

- (50 m)² sail area
- initial orbit high enough to spiral out (sail up)
- applies best control method(s) of GOSSAMER-2
- **prove that sails can operate science missions**
  - imager & *maybe* a *<u>tiny</u>* science-like payload, e.g. sail-environment interaction (~1kg total)

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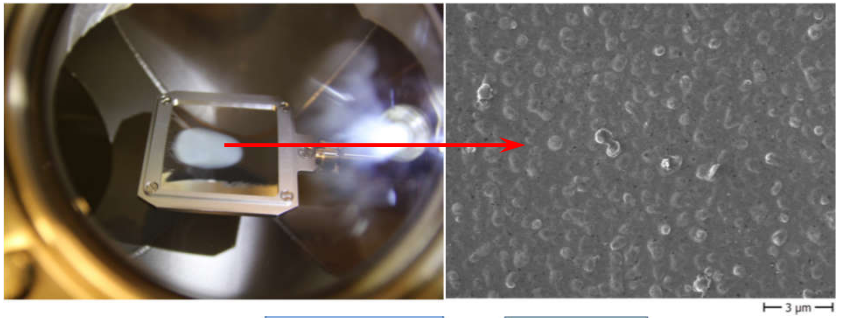
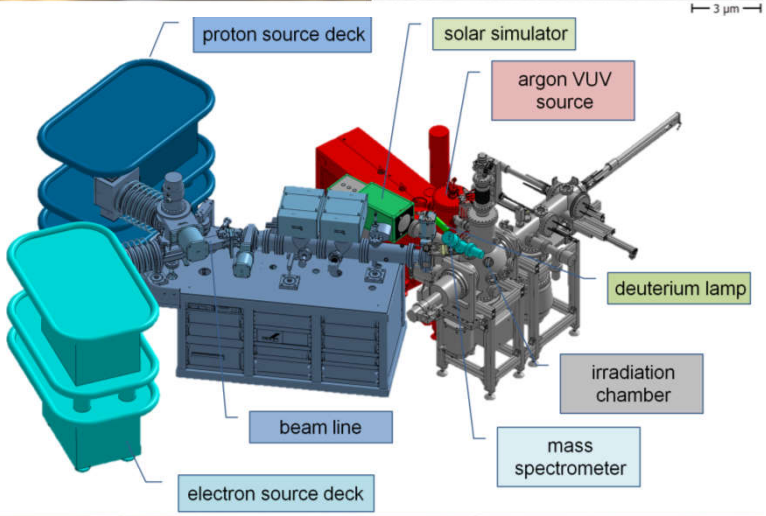
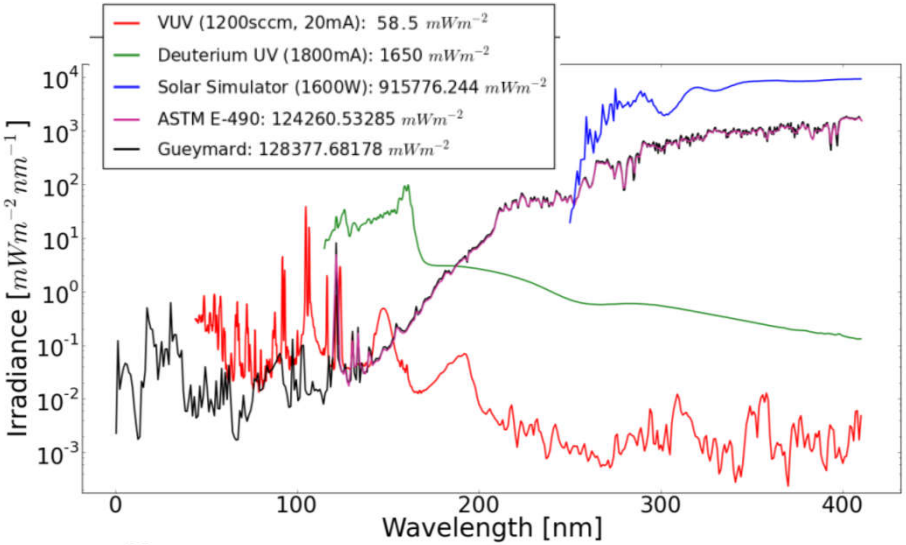
*images adapted from Dachwald et al. & ENEAS study*
*additional images: Moon: Jérôme Salez (wiki), Earth: Bill Anders, Apollo 8, NASA*

# …and will it last?

- Complex Irradiation Facility
- unique materials testing conditions for space weathering of surfaces
  - ultra-high vacuum ~$10^{-10}$ mbar
  - $p^+$ & $e^-$ @ 1…100 keV, 1 nA…100 µA
  - UV/vis/NIR 40…2500 nm
  - sample @ -193…+450°C



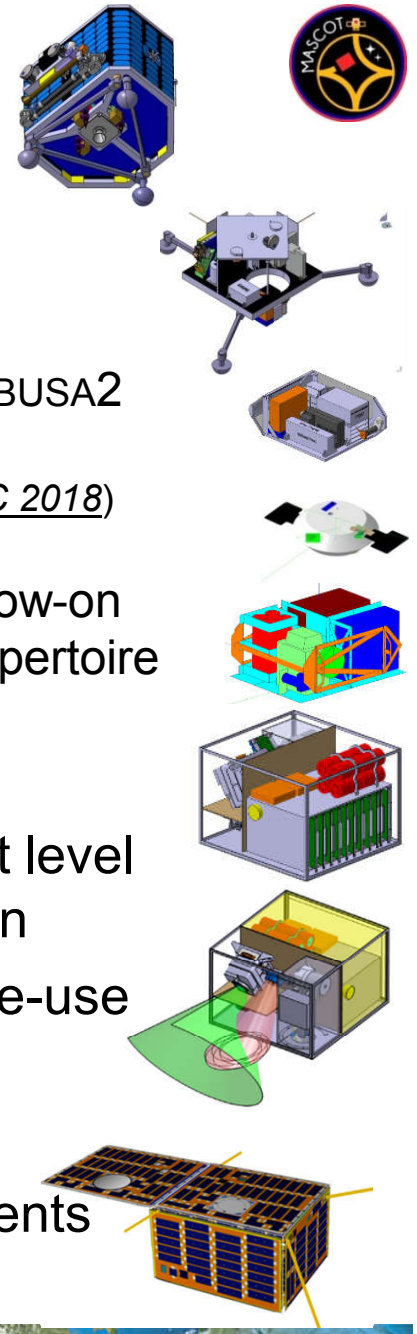




*Sznajder et al, 2017*

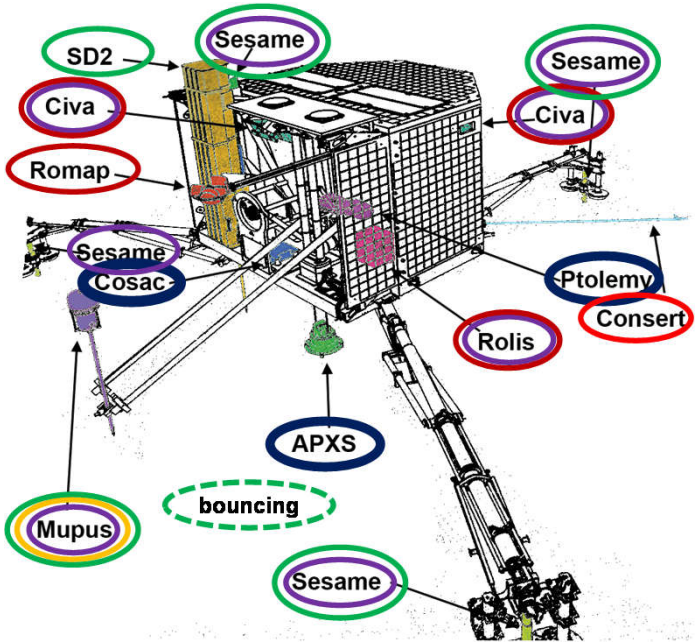
# MASCOT – Mobile Asteroid Surface Scout(s)


- *now* <300000 km from (162173) Ryugu, on HAYABUSA2
- landing expected October 1st…4th, 2018 (*during IAC 2018*)
- with precursor studies, e.g. MARCOPOLO, and follow-on studies, e.g. MASCOT2 for AIM, a ready-to-go repertoire for many missions has already been created

- lander at the instrument level of a mainstream mission
- high degree of design re-use
- high-density design
- serves 4 full planetary science quality instruments



# “okay, so… compared to a real spacecraft… – can a 10 kg shoe-box address all topics?”

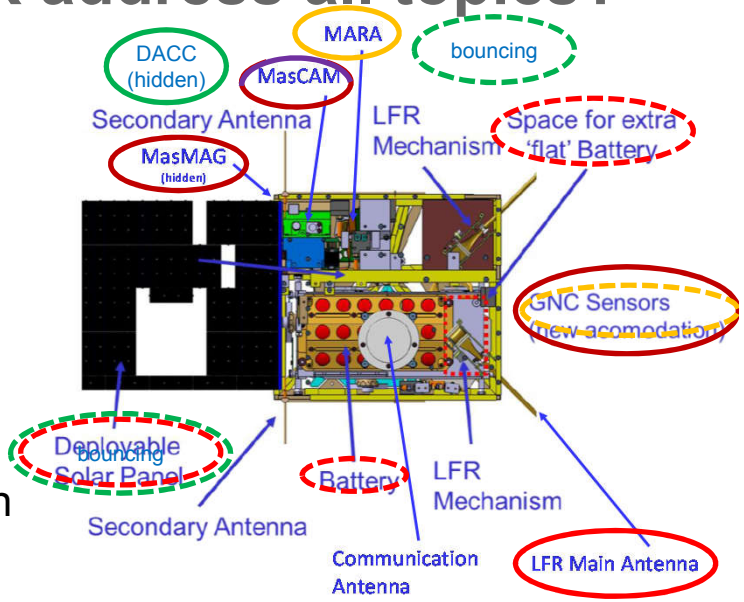



*target body properties addressed…*

- surface structure
- composition
- mechanical properties
- thermal properties
- interior structure
- spacecraft orientation

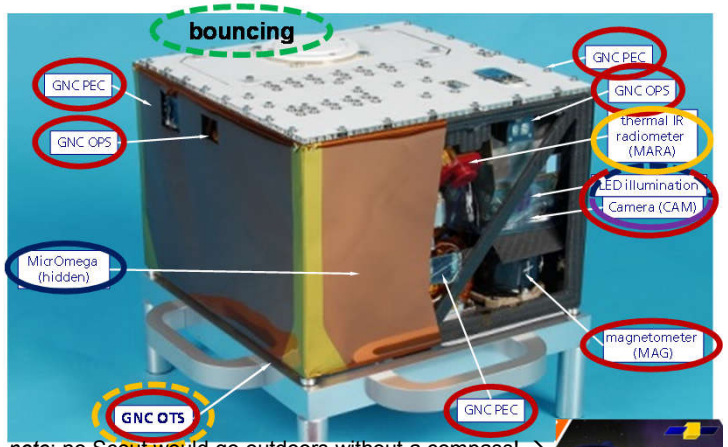
*heritage landers*:

- cover all fields
- medium-integrated design concept
- separate instrument interfaces ‘as usual‘
- requirements-driven design, drives mission

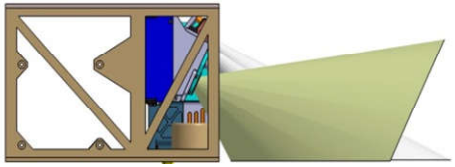


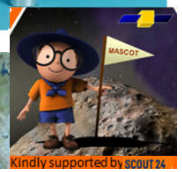

*MASCOTs*:

- focus on key topics
- organically integrated design
- across unit border optimized interfaces
- constraints-driven design

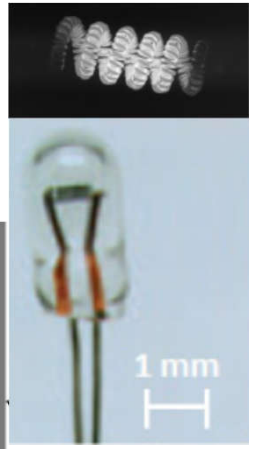


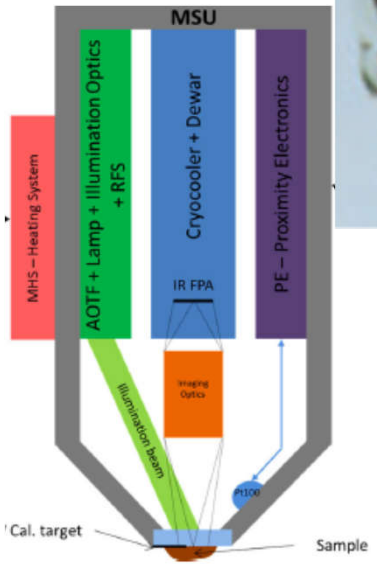

*note*: no Scout would go outdoors without a compass! →





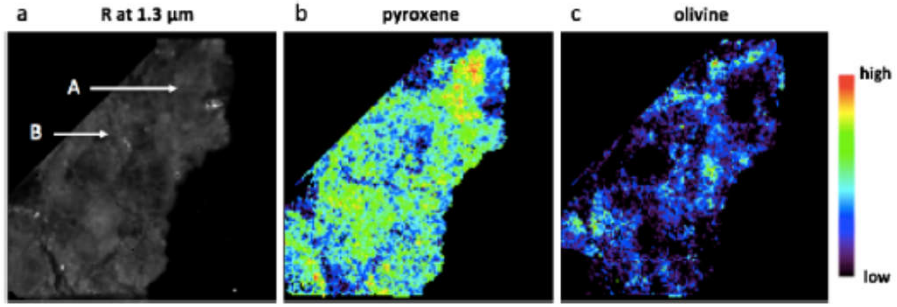
# MASCOT MicrOmega – composition by near-IR

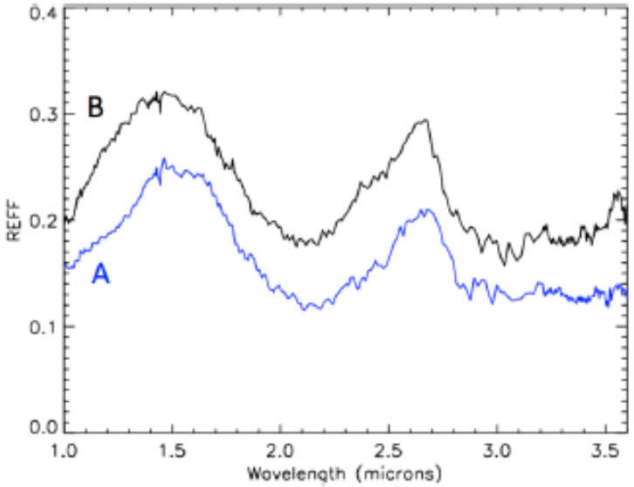


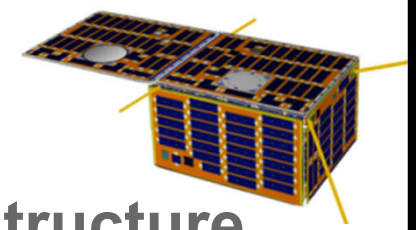

- MicrOmega hyperspectral NIR microscope
  - spectral range 0.99…3.65 µm
  - spectral resolution ~20 $cm^{-1}$
  - field of view (3.2 mm)²
  - spatial sampling 25 µm
- provided by IAS, Orsay, France

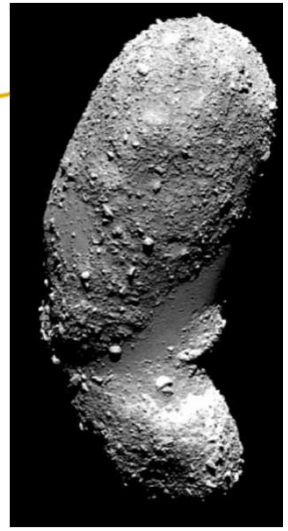
Shergotty – MicrOmega FM




*Bibring et al 2017;*
*Riu et al, 2018 & 2016;*
*Pilorget, 2012*

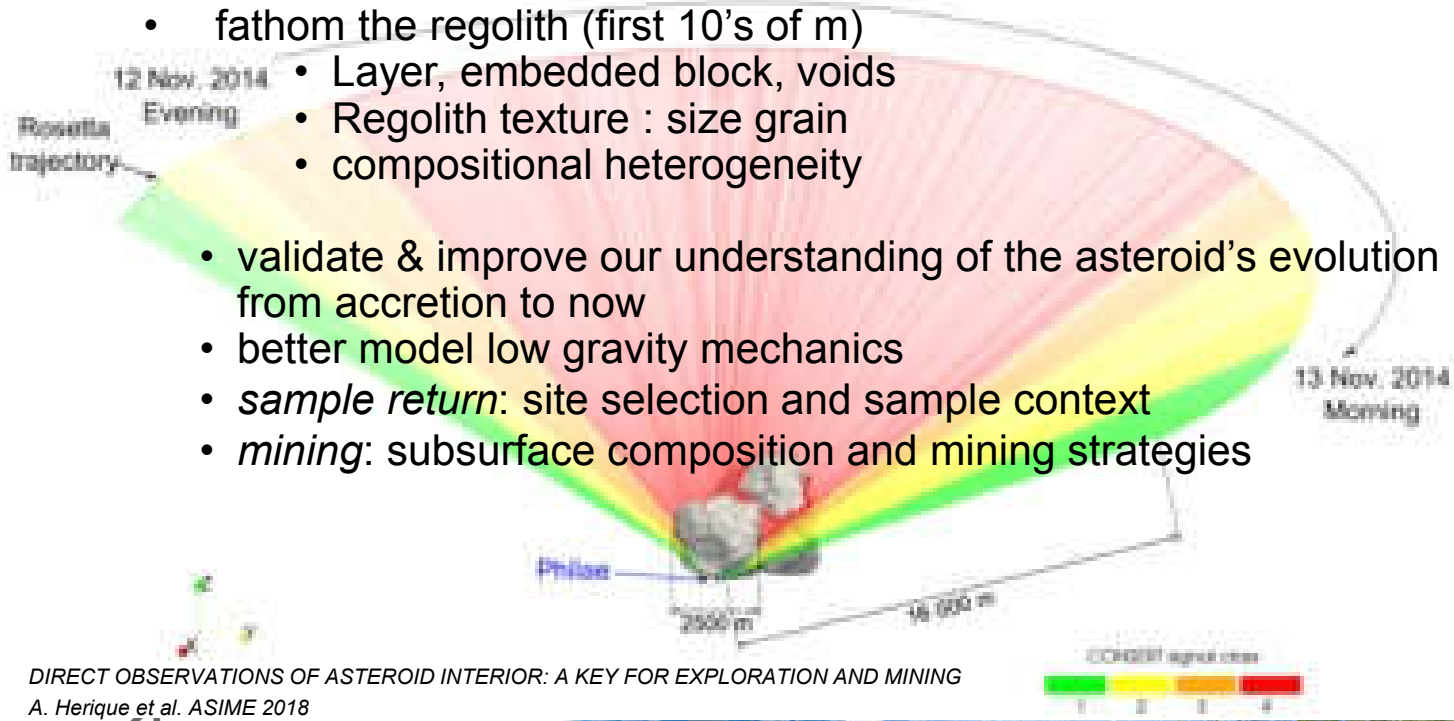




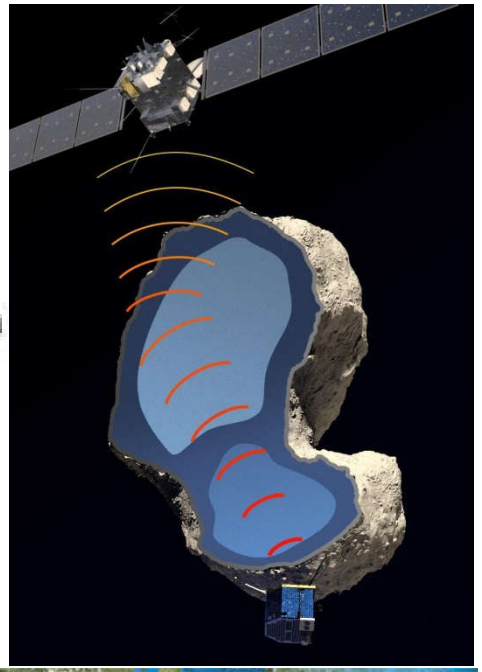
# MASCOT2 Low Frequency Radar – the key to the interior structure

- **Deep Interior Radar : LFR –** Low Frequency Bistatic Radar
- *with lander* (CONSERT-like) for tomography of the deep interior:
  - size of blocks
  - compositional heterogeneity

- **Shallow Subsurface Radar : HFR –** Higher Frequency Radar
- fathom the regolith (first 10's of m)
  - Layer, embedded block, voids
  - Regolith texture : size grain
  - compositional heterogeneity



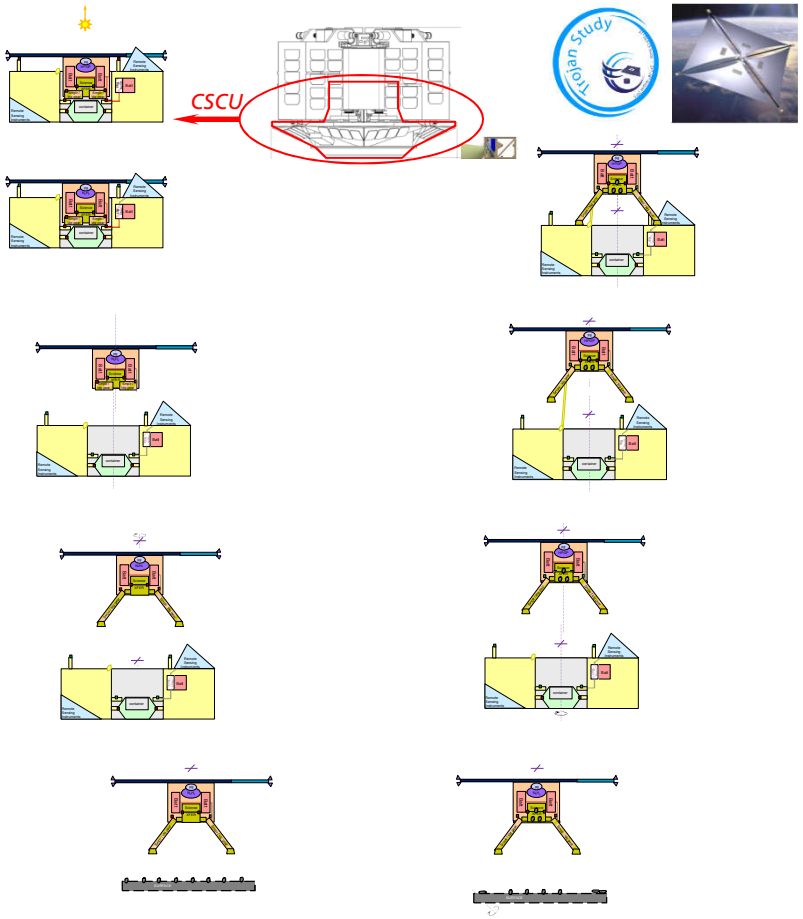

- validate & improve our understanding of the asteroid's evolution from accretion to now
- better model low gravity mechanics
- *sample return*: site selection and sample context
- *mining*: subsurface composition and mining strategies



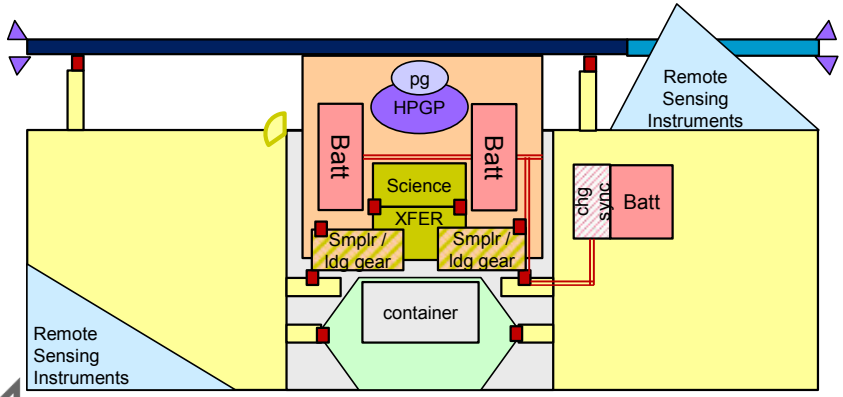


*images: ESA, JAXA, DLR*

# …and returning them to the Earth




- sample return requires propulsion
  - pre-deployment propulsion capability can be useful for large sails
  - propulsion entirely on lander, control divided
- propulsion power drives lander battery & photovoltaics
  - the core sailcraft needs pre-deployment photovoltaics (PV)
- battery shared, mostly on lander
- rigid PV completely on lander



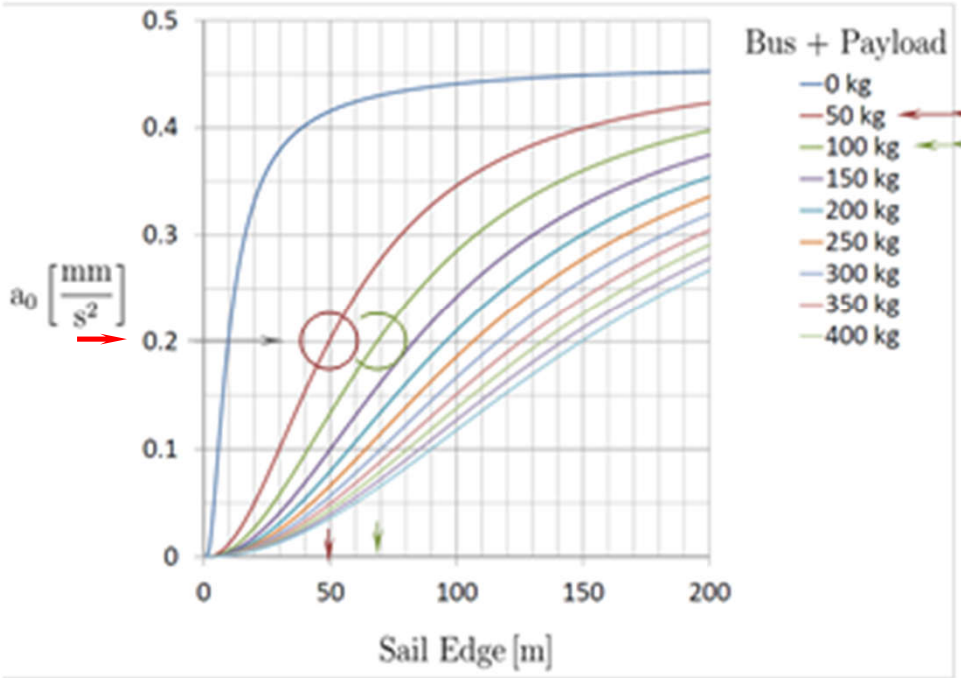

| Object | Stay time [days] | Start | End | Time of flight [days] |
|---|---|---|---|---|
| Earth | // | | | |
| 2000 $SG_{344}$ | 123 | 10 May 2025 | 26 Feb 2027 | 657 |
| 2015 $JD_3$ | 164 | 29 Jun 2027 | 06 Sep 2028 | 436 |
| 2012 $KB_4$ | 160 | 18 Feb 2029 | 24 Sep 2030 | 584 |
| 2008 $EV_5$ | *160* | 04 Mar 2031 | 29 Sep 2032 | 576 |
| *Earth* | ∞ | *18 Mar 2033* | *22 May 2036* | *1161* |

# performance: the magic MNR & lander(s) numbers

- GOSSAMER-1 technology based
  - 0.2 mm/s² & 50 kg bus & payload → (50 m)² membrane
  - 0.2 mm/s² & 100 kg bus & payload → (70 m)² membrane
  - 0.2 mm/s² & 150 kg bus & payload → (85 m)² membrane

➔ ESPA* / ASAP** compatible micro-spacecraft range ( * ≤181 kg, 61·61·96 cm³ / ** ≤200 kg , 80·80·100 cm³)

- start from GTO and upper stage disposal orbits of GEO & NavSat



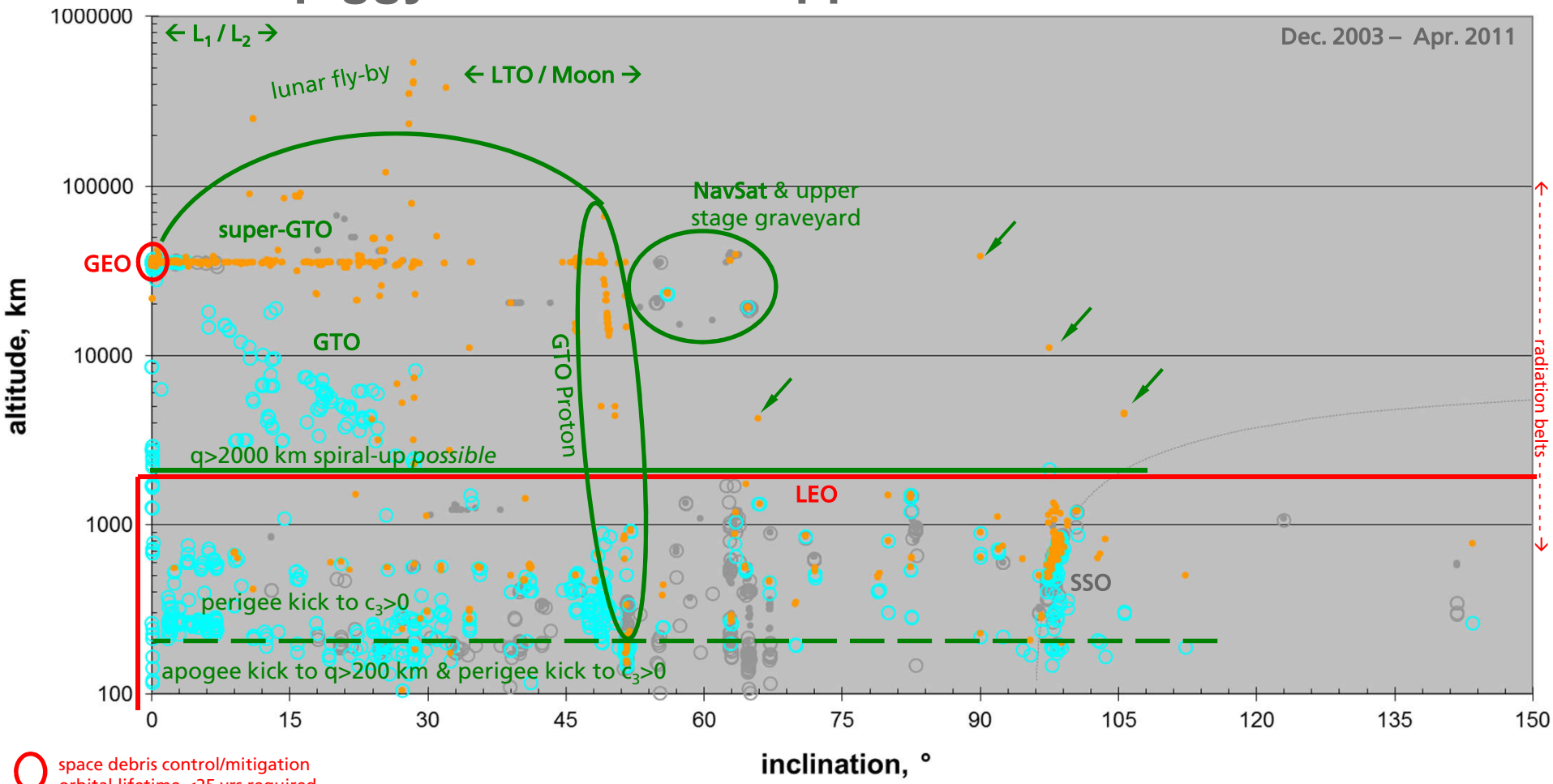

| | |
|---|---|
| Bus (Gos-1 + X-Band) | ≈ 30 kg |
| Mother Spacecraft Science Instruments | ≈ 10 kg |

| Lander | |
|---|---|
| PHILAE | 98 kg |
| SPS Lander | 100kg |
| 1 MASCOT | 10 kg |
| 5 MASCOTs | 50 kg +10 kg support equipment |



*figures : Seefeldt et al., 2016*

# where to start from?
## – piggy-back launch opportunities for solar sails




space debris control/mitigation
orbital lifetime <25 yrs required


# recap & bottom line:

2. [revisit] How can the rate of spectral characterisation of NEOs be increased? It lags far behind discovery rate, especially at smaller sizes (D < 300m).

4. *Technically*, and *scientifically*, how does spectroscopy of an asteroid at short (km range) distances differ from spectroscopy with ground-based telescopes?
9. [revisit] Is there any evidence that the shape of an asteroid provides information on its composition?

5. [revisit] How can the water absorption feature at 3.1$\mu$m be best used as an indicator of hydrated minerals on carbonaceous asteroids? What additional measurement would further increase the quality or fidelity of the measurement?
8. What instrumentation should an exploration probe carry in order to establish with 100% confidence that water and/or hydrated minerals are present on an asteroid, and what further instrumentation, if any, would be required to ascertain how much water there is?
1. [revisit] What instrumentation should an exploration probe carry in order to establish with 100% confidence that water and/or hydrated minerals are present on an asteroid, and what further instrumentation, if any, would be required to ascertain how much water there is?

15. [revisit] How well understood are the processes of space weathering, and can we tell what the original state of the surface was, based on the current state?
22. What is the state of the art regarding matching meteorite spectra to asteroid spectra, and matching artificially weathered meteorite spectra to asteroid spectra?
23. Is anyone working on software that models how weathering affects meteorite spectra, to then attempt to match asteroid spectra to this modelled weathered meteorite spectra?

11. [revisit] What highest value ~~telescopic~~ composition/characterisation studies are not being pursued for lack of funding or perceived low priority from space agencies?

☑ can even be improved in-situ, with mapping & particularly for small NEAs because they dominate catalogs

☑ go there & find out for many NEAs & for several classes

☑ remove shape model uncertainty by close look, and get definite composition by in-situ analysis & sample return

☑ in-situ, e.g. MicrOmega on the spot & at mineral grain scale (3.1µm); on small areas: MARA w/ filters for >5 µm bands, CAM with tuned LED illumination for <1 µm bands

☑ Low Frequency Radar can show the interior structure

☑ the information gained from spectroscopic instruments at the surface or from 'orbit' can be compared to in-situ analysis & sample return

☑ …and it is of course possible to [revisit] with another sailcraft that has a better suited MASCOT still aboard or carries a shuttling sample-return lander & capsule

☑ MASCOTs can likely scrape the surface to expose fresher materials in the mm…cm depth range (TBC in Oct)

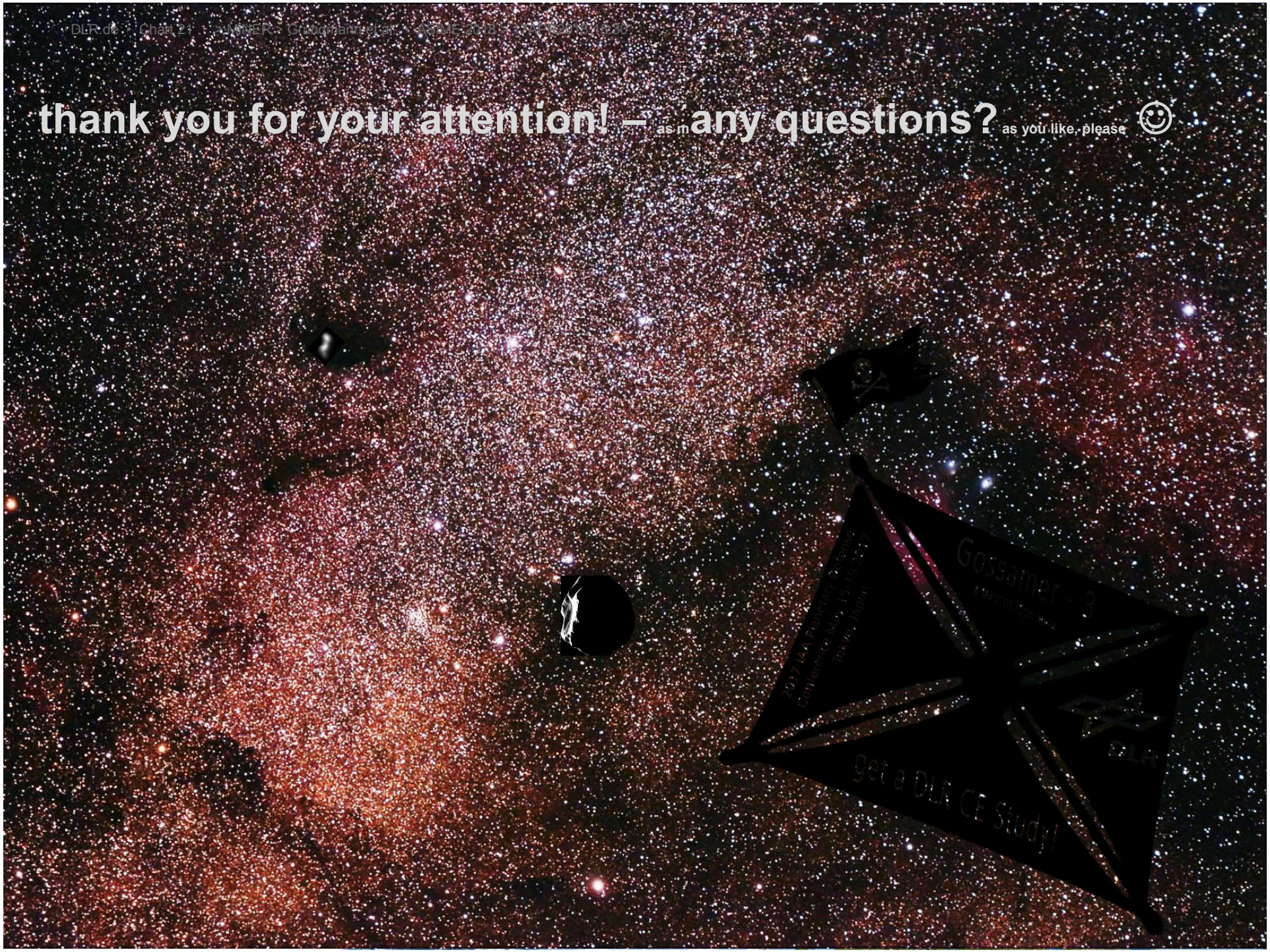
☑ Sample-return lander instruments considered include subsurface sampling devices (JAXA OKEANOS ldr study)

☑ on-ground studies in DLR Complex Irradiation Facility possible on dry materials (ultra-high vacuum environment)

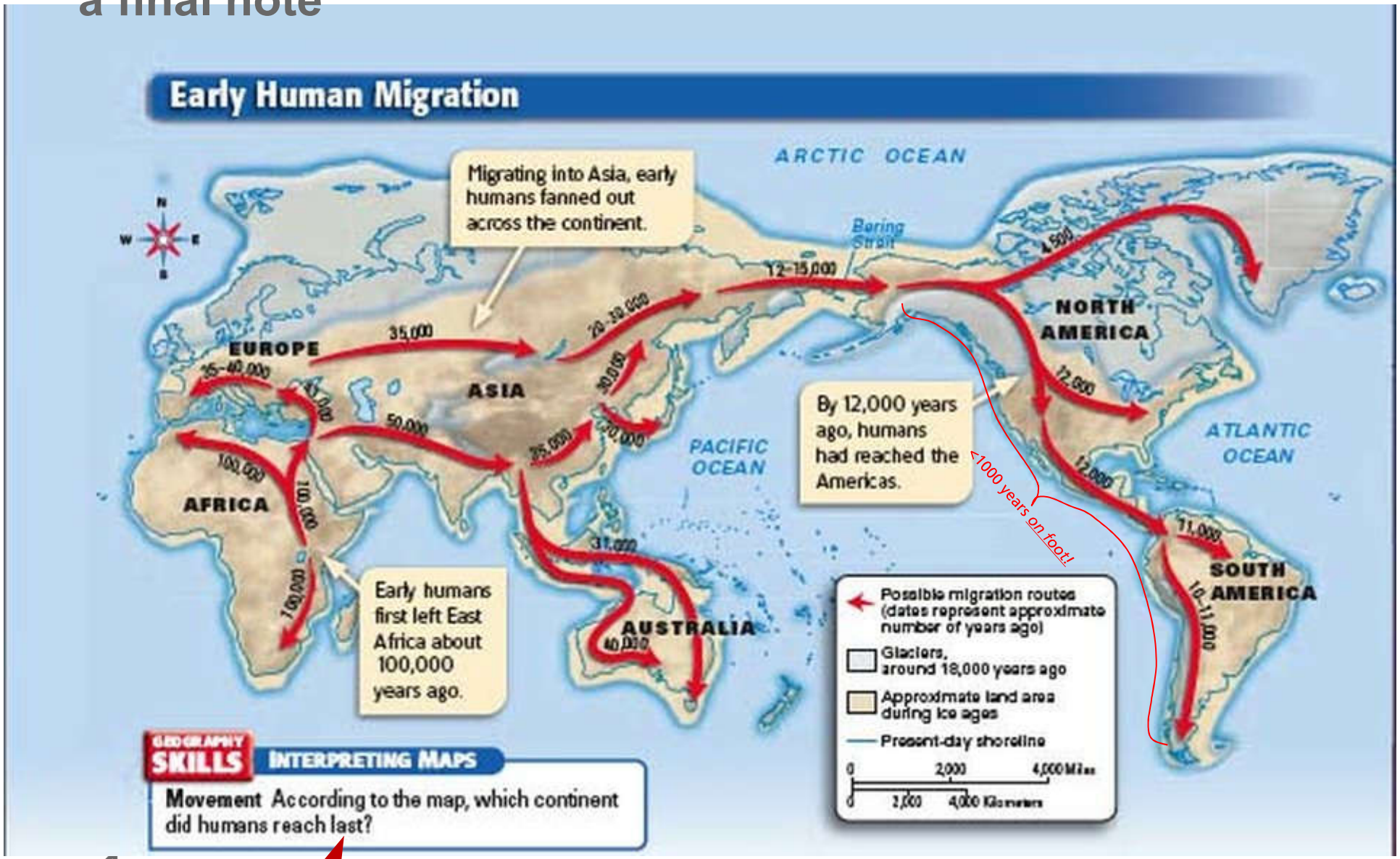
☑ solar sailing (e.g. GOSSAMER type), suitable nanolanders (e.g. MASCOT type), and specific MNR trajectory studies



# thank you for your attention! – as many questions? as you like, please ☺

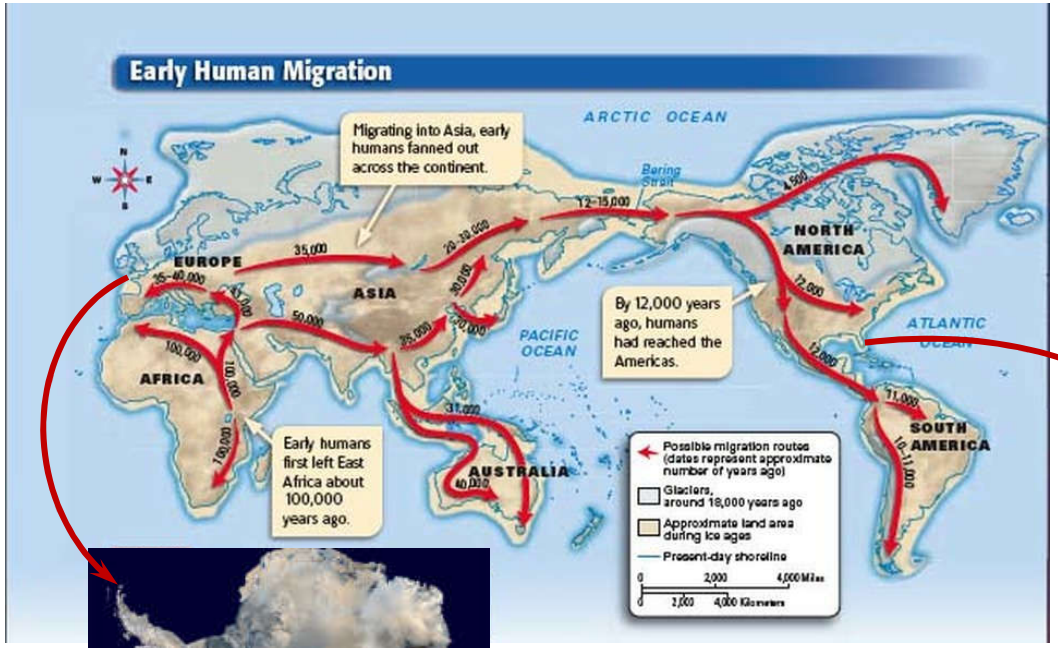


# a final note



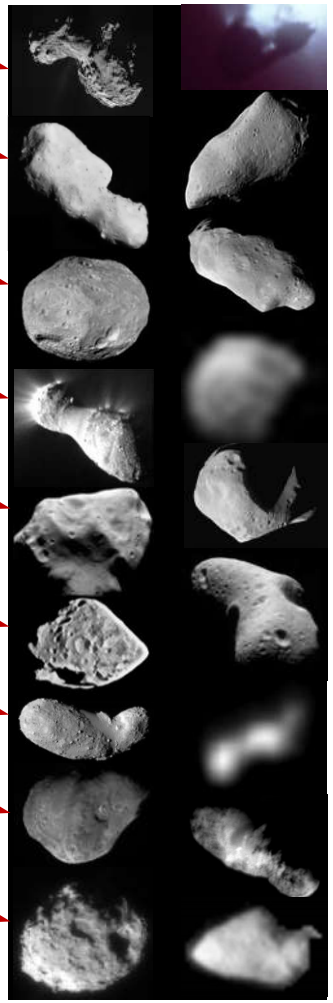

DLR

clip-ins: TesTeack / Wasvick's via google



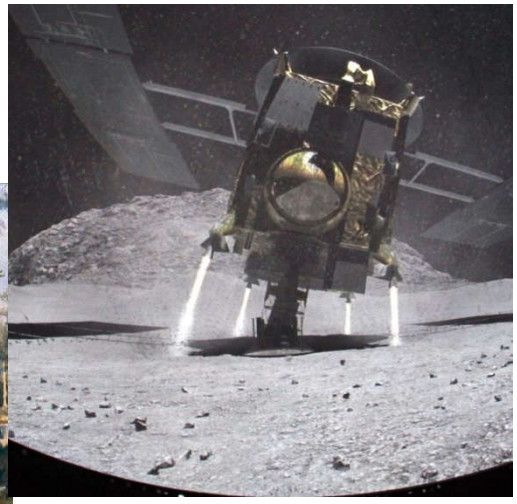



„only rocks“
…and gravity

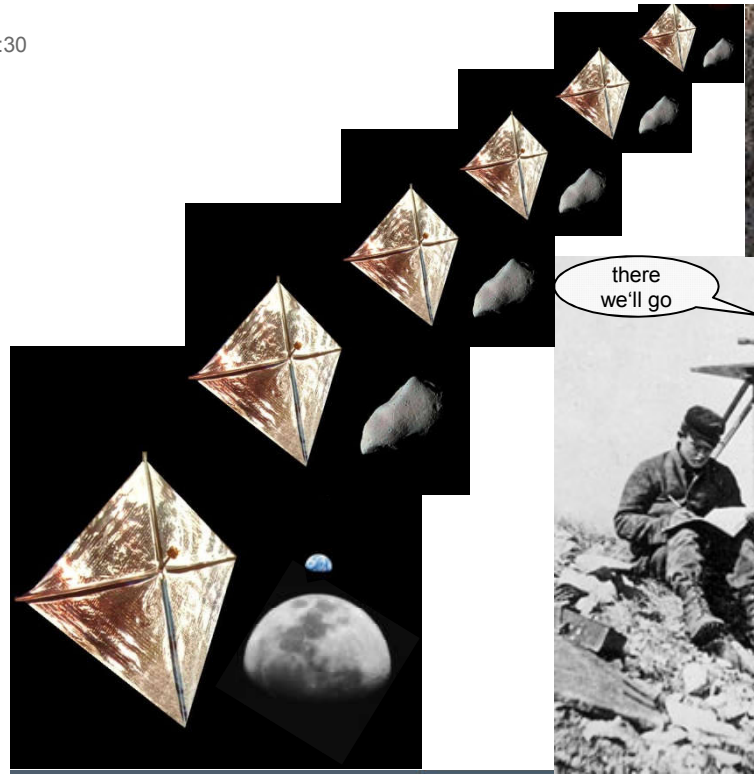


many rocks
a little water
all close to the surface
little gravity – but some

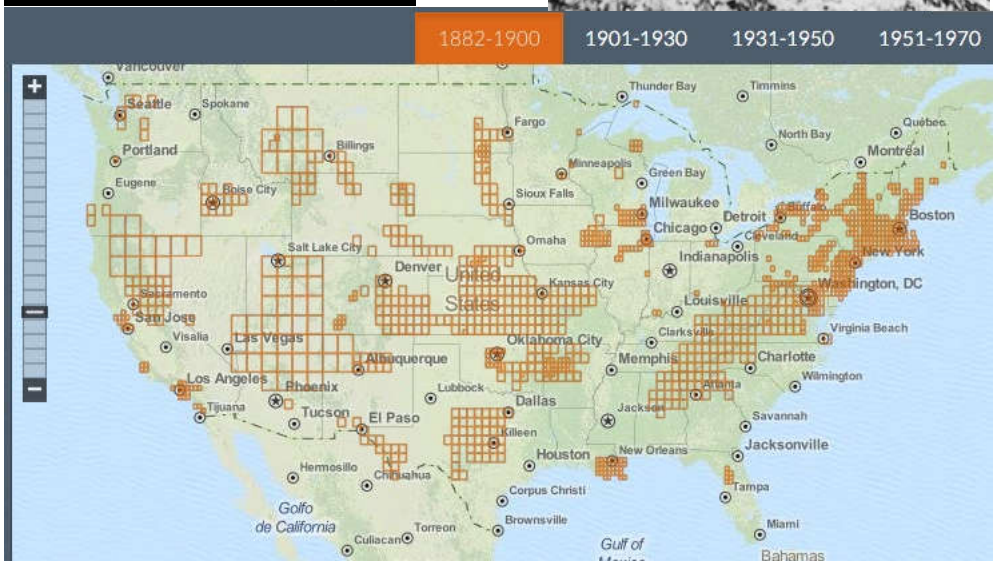
Life ?
…the next Antarctica ?
=‘look don’t touch’ ?
if so, then will need supplies
‘*from above*’!


Lewis and Clark Expedition Routes and Control of Lands





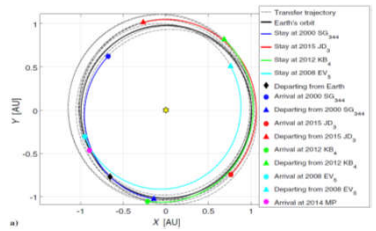



*Smithsonian Magazine*
*wanderwest, welt.de, duffjohnson,*
*waymarking, via google*

# spare slides

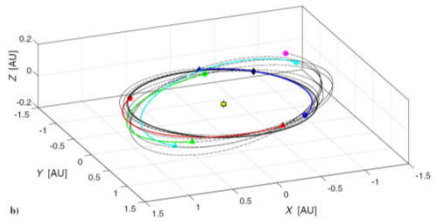
- MNR studies – performance development of optimizers & expanded NEA databases
- GOSSAMER-style integration of landers & samplers
- PDC'17 exercise
    - exactly 11 moths ago – JST
- diverting asteroids using small solar sails & impactors (~SPO)

# MNR by Solar Sail: performance development



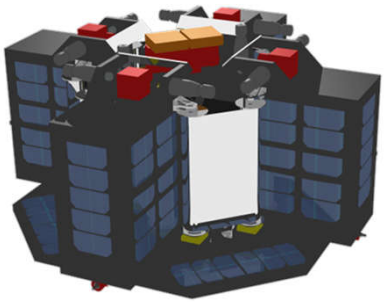

- in the past 20 years,…
  - low-thrust trajectory optimization was greatly improved
  - many more NEAs discovered to pick targets from
  - sailcraft designs matured, were tested & flown
  - better understanding of near-term sail performance

- DLR ENEAS study (2000) – 2 fast flybys & 1 rendezvous in 5 years – 0.14 mm/s²
- ENEAS-SR (2005) – 1 sample return & 117 days in 10 years – 0.10 mm/s²
- ENEAS+ / ENEAS+SR (2005) – 3 rendezvous/sample return in 10 years – 0.22 mm/s²
- GOSSAMER NEO reference (2011) – 3 very slow flyby-rendezvous >1 rotation in 10 years
- Johnson et al (2012) – 3 rendezvous of ~30 days in 6 years – 0.35 mm/s²
- GOSSAMER NEO reference (2014) – 3 rendezvous of ~100 days in 10 years – 0.20 mm/s²
- Peloni et al. (2016) – **5 rendezvous of >100 days in 10 years** – 0.20 mm/s²

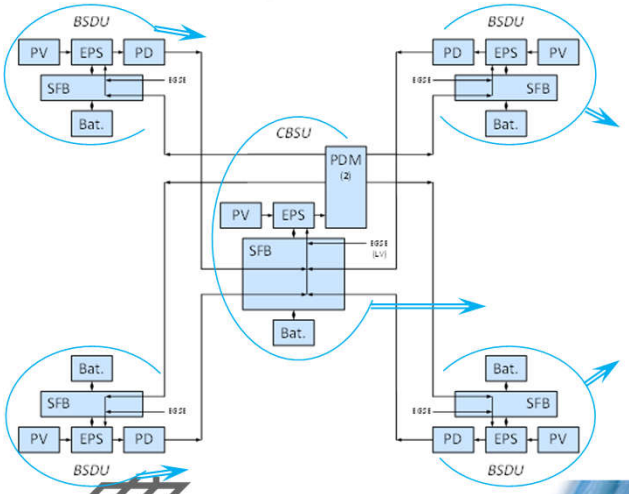


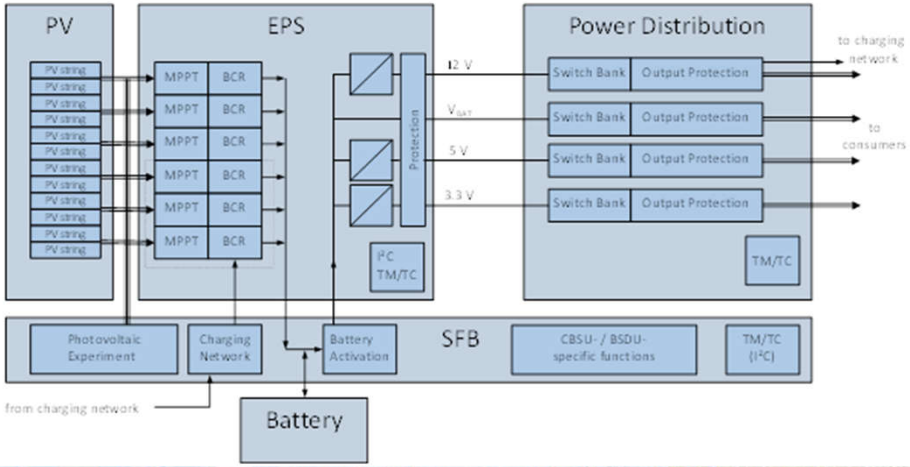

*figures: Peloni, Ceriotti, Dachwald, 2016*

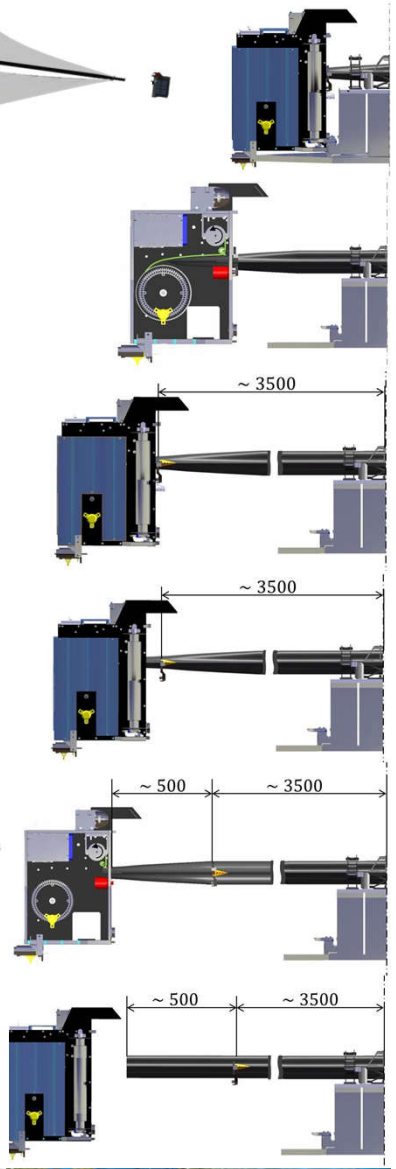
# integrating all that: GOSSAMER 1st



- a GOSSAMER sailcraft at launch consists of 5 independent spacecraft connected to act as one
- electrical – thermal – mechanical face-to-face interfaces enable energy transfer all through, end to end



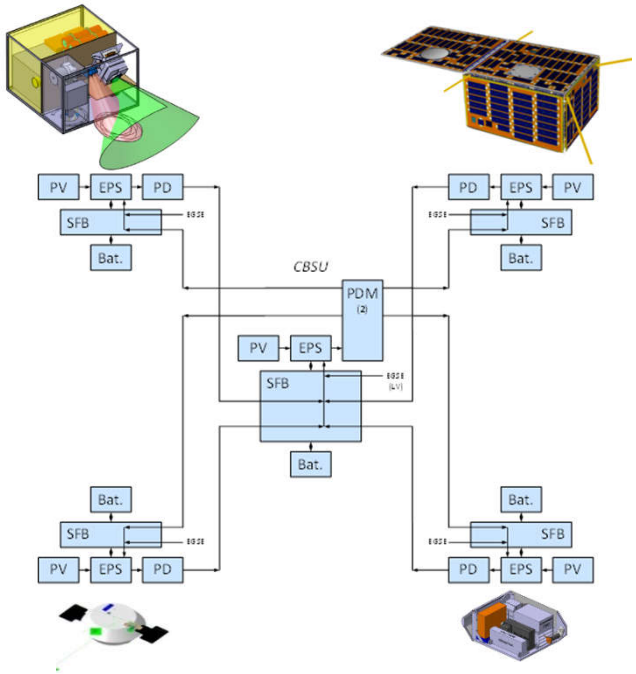



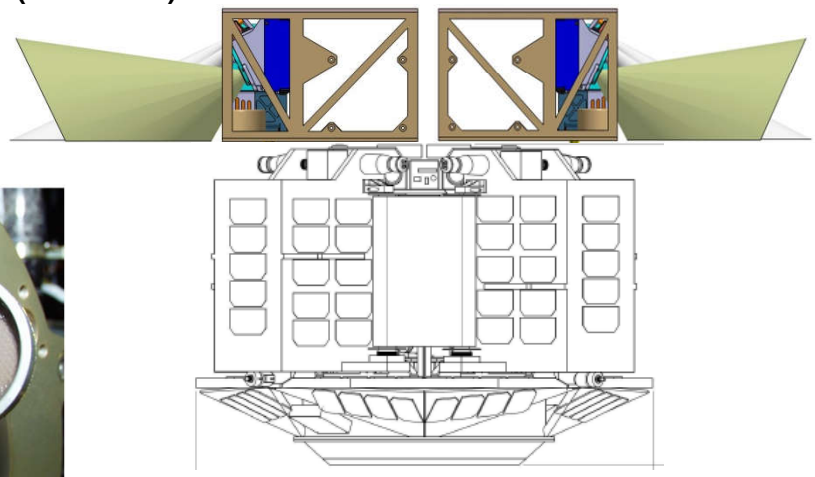

DLR

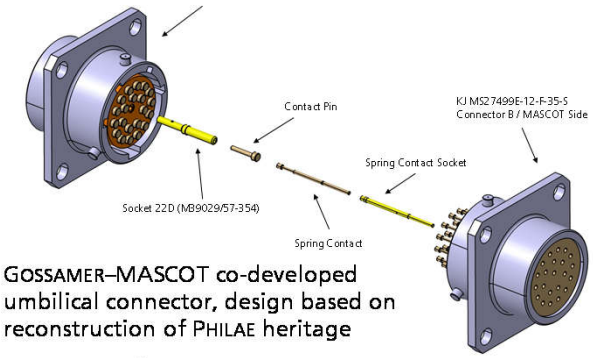
*figures : Seefeldt et al., 2016*

# integrating all that: …and landers




- an additional plane of interfaces is implemented on the ‘payload’ side of the Central Sailcraft Unit (CSCU)
- interfaces between the CSCU and the 4 Boom Sail Deployment Units (BSDU) already use elements also present in MASCOT, e.g. Umbilical
- MASCOT already has suitable interfaces to its carrying structure (MESS)

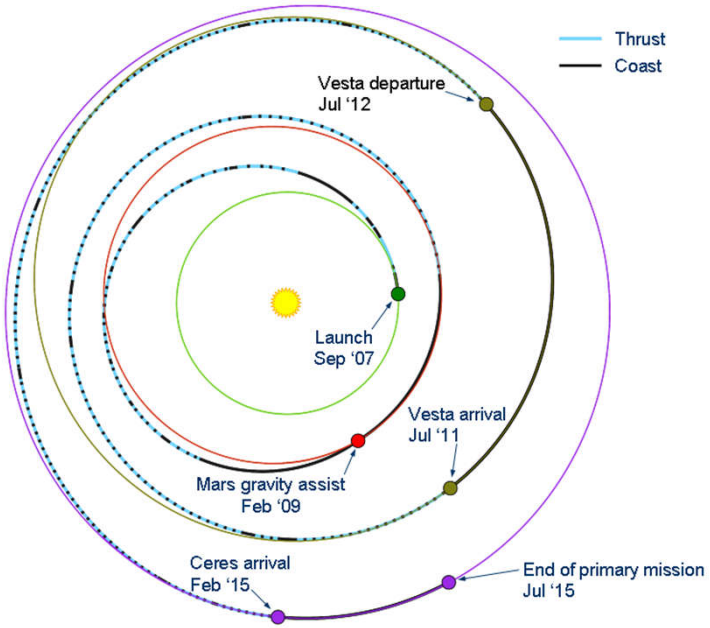


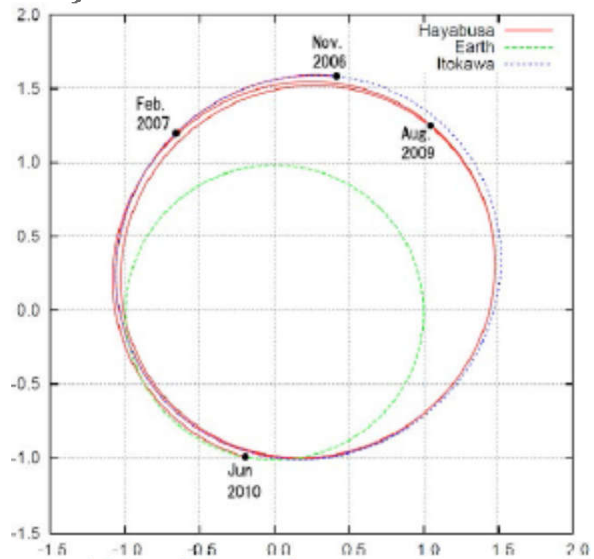


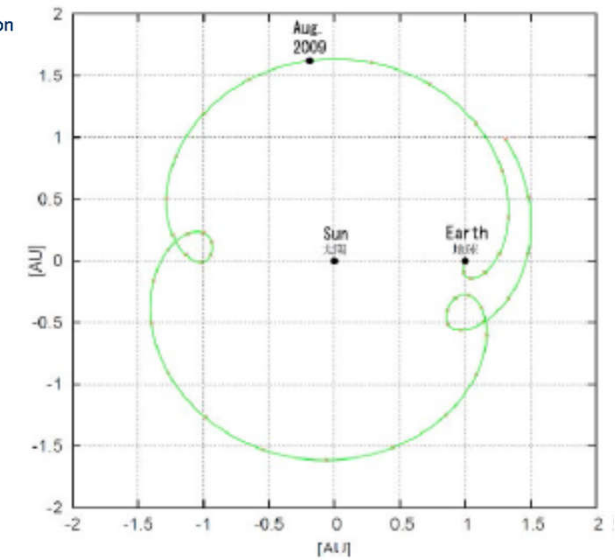

GOSSAMER–MASCOT co-developed umbilical connector, design based on reconstruction of PHILAE heritage

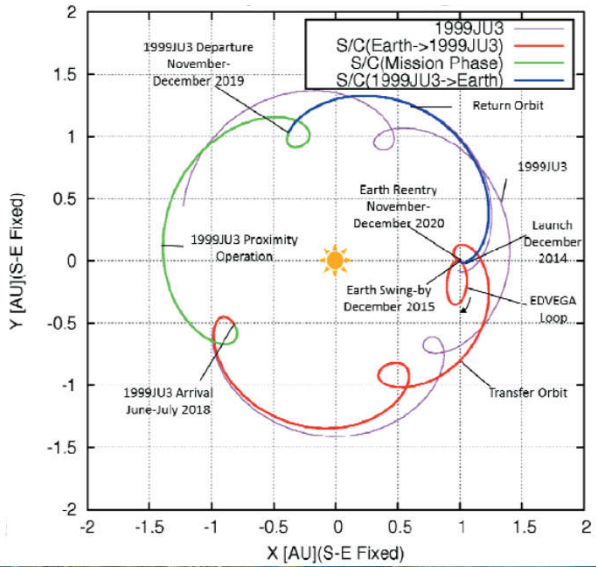

*figures adapted from: Seefeldt et al., 2016, Ksenik*

# SEP trajectories: DAWN, HAYABUSA & HAYABUSA2



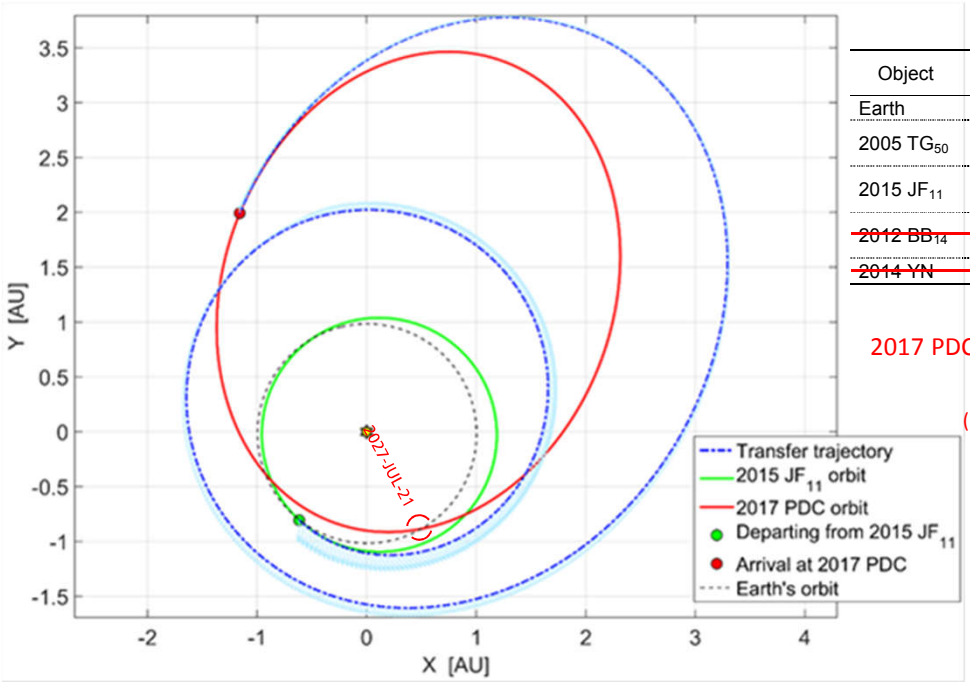

*figures: Kuninaka et al., 2009, Nishiyama et al., 2015 , NASA via wikipedia*

# EXERCISE – EXERCISE – EXERCISE – EXERCISE

NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT

## divert to PDC 2017 for rendezvous

- chasing 2017 PDC – too little ($a_c$celeration), too late (arrival)
- hits on July 21st, 2027 – fully optimized launch in 2025 can't be diverted in time
- a sequence launching in 2020 can divert and reach 2017 PDC but >3 years too late
- requires *substantial* $a_c$ rise: 0.2 → 0.73 mm/s² (!!!)




original sequence

| Object | Stay time [days] | Start | End | Time of flight [days] |
|---|---|---|---|---|
| Earth | // | 13 Aug 2020 | 26 Apr 2022 | 621 |
| 2005 $TG_{50}$ | 128 | 02 Sep 2022 | 13 Jan 2024 | 498 |
| 2015 $JF_{11}$ | 104 | 25 Apr 2024 | ~~10 Jun 2026~~ | ~~776~~ |
| ~~2012 $BB_{14}$~~ | ~~139~~ | ~~28 Oct 2026~~ | ~~02 Aug 2028~~ | ~~644~~ |
| ~~2014 YN~~ | ~~//~~ | | | |
| 2017 PDC | // | 21 Aug 2030 | >2000 | |

divert after 2nd leg to fly to 2017 PDC

($a_c$: 0.2 → 0.73 mm/s²) ← !

(1127 days = 3 years, 1 month ***after*** Earth impact or close fly-by of 2017 PDC)

| Object | 2017 PDC |
|---|---|
| Semi-major axis [AU] | 2.24 |
| Eccentricity | 0.607 |
| Inclination [deg] | 6.297 |
| Right ascension of the ascending node [deg] | 298 |
| Argument of periapsis [deg] | 312 |
| Mean anomaly [deg] | 332 |
| Epoch [MJD] | 57940 |
| Absolute magnitude [mag] | 21.9 |
| Estimated size [m] | 110 – 240 |

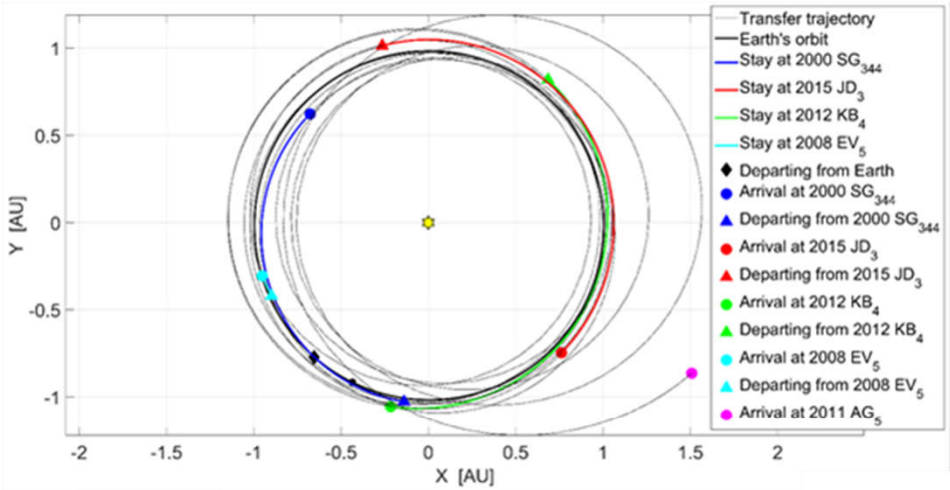
*figures & tables extended from: Peloni, Ceriotti, Dachwald, 2016*

# EXERCISE – EXERCISE – EXERCISE – EXERCISE

**NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT – NOT A REAL WORLD EVENT**

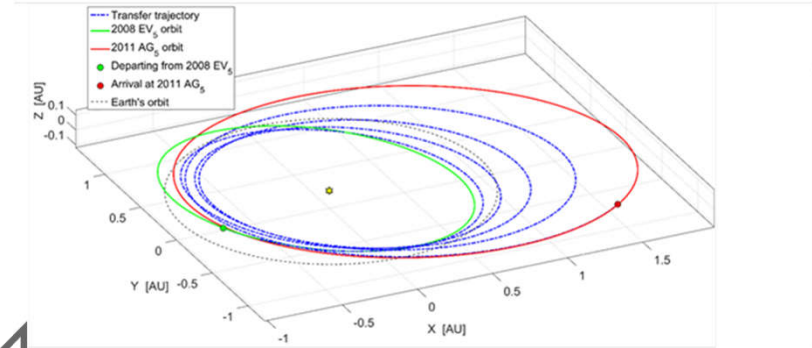
# divert to PDC 2013 for rendezvous

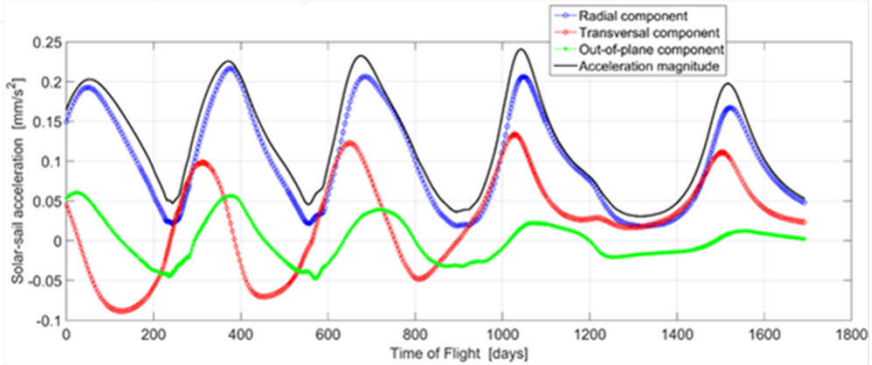
- 2011 $AG_5$ – the PDC 2013 Exercise impactor, hits February 3rd, 2040
- fully optimized launch in 2025 *can* be diverted to rendezvous 2011 $AG_5$ in time
- optimized trajectory: diverting from an ongoing MNR mission feasible at $a_c$ = 0.2 mm/s²




| Object | Stay time [days] | | Start | End | Time of flight [days] |
|---|---|---|---|---|---|
| Earth | // | | 10 May 2025 | 26 Feb 2027 | 657 |
| 2000 $SG_{344}$ | 123 | | 29 Jun 2027 | 06 Sep 2028 | 436 |
| 2015 $JD_3$ | 164 | | 18 Feb 2029 | 24 Sep 2030 | 584 |
| 2012 $KB_4$ | 160 | | 04 Mar 2031 | 29 Sep 2032 | 576 |
| 2008 $EV_5$ | 7.5 | | 07 Oct 2032 | 25 May 2037 | 1691 |
| *2011 $AG_5$* | *987 to ⊕* | | | | |

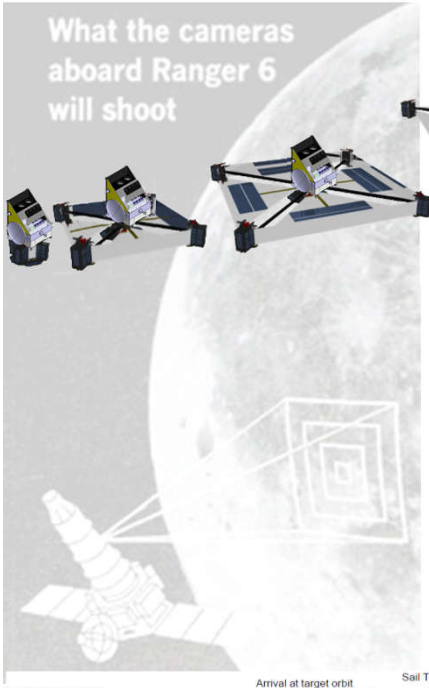
| Object | 2000 $SG_{344}$ | 2015 $JD_3$ | 2012 $KB_4$ | 2008 $EV_5$ | 2011 $AG_5$ |
|---|---|---|---|---|---|
| Orbital type | Aten | Amor | Amor | Aten | Apollo |
| Semi-major axis [AU] | 0.977 | 1.058 | 1.093 | 0.958 | 1.431 |
| Eccentricity | 0.067 | 0.009 | 0.061 | 0.083 | 0.390 |
| Inclination [deg] | 0.111 | 2.730 | 6.328 | 7.437 | 3.681 |
| Absolute magnitude [mag] | 24.7 | 25.6 | 25.3 | 20 | 21.8 |
| Estimated size [m] | 35 – 75 | 20 – 50 | 20 – 50 | 260 – 590 | 110– 240 |
| EMOID [AU] | 0.0008 | 0.054 | 0.073 | 0.014 | 0.0002 |
| PHA | no | no | no | yes | yes |
| NHATS | yes | yes | yes | yes | no |

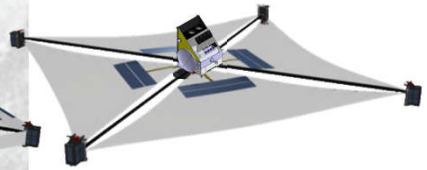


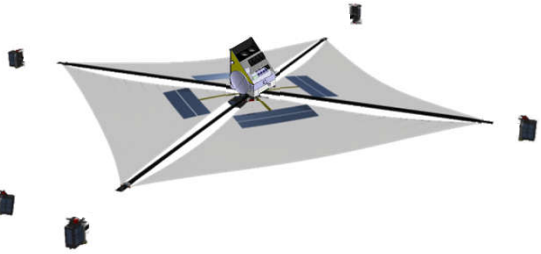



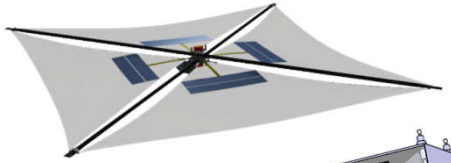

*figures & tables extended from: Peloni, Ceriotti, Dachwald, 2016*

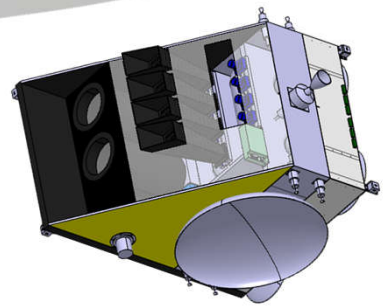
# landing… faster, harder, … head-on





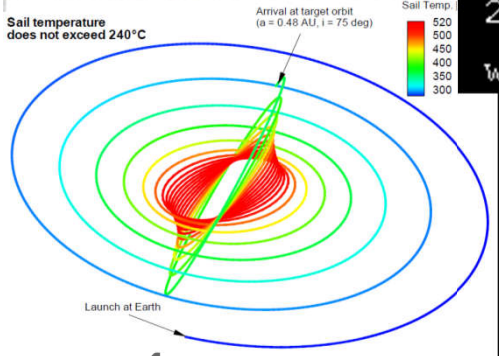




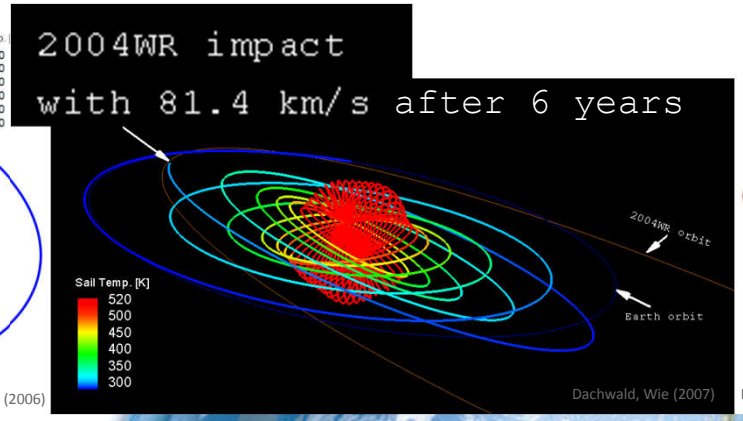
***an exercise of synergy***

- one of solar sails' unique capabilities: orbit cranking to *i* >>60°
- GOSSAMER solar sails are based on small separating sub-spacecraft
- payload-drop missions have been studied, e.g. Solar Polar Orbiter / Imager
- Kinetic Energy Impactors don't care what they are made of
- fast $e^-$-multiplied CCD ASTEROIDFINDER camera tech is good at tracking NEAs
- … add terminal guidance & propulsion
- … develop sails to $\mathbf{a_c}$ **~0.5 mm/s²**

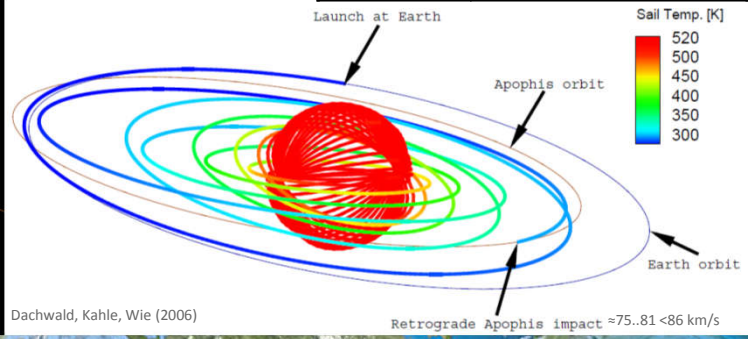
| | |
|---|---|
| Dimension | 1m x 0,78m x 0,7m |
| Sunshield | 50 degree |
| Mass | 179kg |
| Payload | 2 x High Resolution Cameras<br>4 x Middle Range Camera<br>4 x Webcam |
| Communication | 1 x Ka-band antenna<br>2 x X-band antenna<br>4 x Interlink antenna |
| ACS | Propulsion (8 x 1N thrusters,<br>1x 400N thruster) |




Dachwald, Ohndorf, Wie (2006)




Dachwald, Wie (2007)




Dachwald, Kahle, Wie (2006)

DLR

*Dachwald, Wie et al, 200x*
*background image:*
*NASA/JPL J.D. Burke et al.*

# references

*this presentation is based on the article*

Capabilities of Gossamer-1 derived small spacecraft solar sails carrying MASCOT-derived nanolanders for in-situ surveying of NEAs

***Acta Astronautica***
accepted manuscript **available online**: 17-MAR-2018
article reference: AA6761
**DOI: 10.1016/j.actaastro.2018.03.019**

*and references therein!* ☺