

# Asteroid selection database for space mining mission analysis

Global Virtual Workshop I of the Stardust-R project  
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2. Asteroid selection database
3. SEMPy database tools
4. Conclusion and future work

# Introduction

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# ECOCEL

## Exploitation des Ressources des Corps Célestes

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First French interdisciplinary study on the space mining



Law and  
regulations



Engineering and  
Planetology



Economics

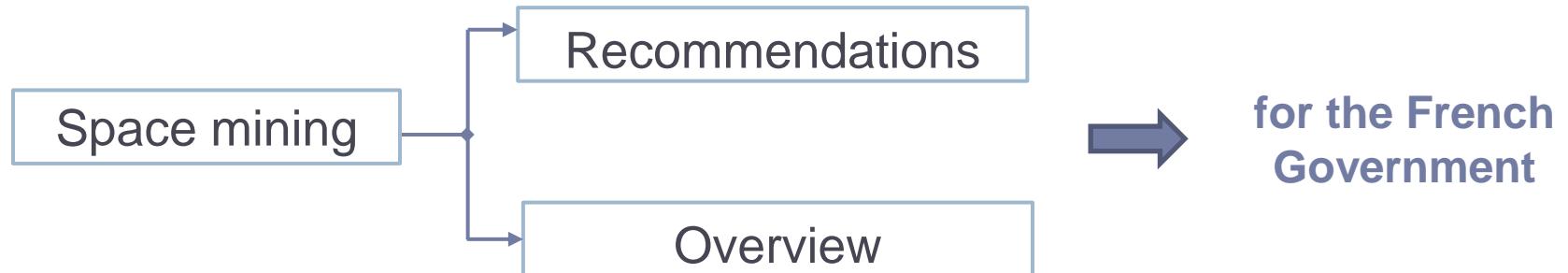


Geography



Political  
sciences

# ECOCEL Objectives



## Space Advanced Concepts Laboratory

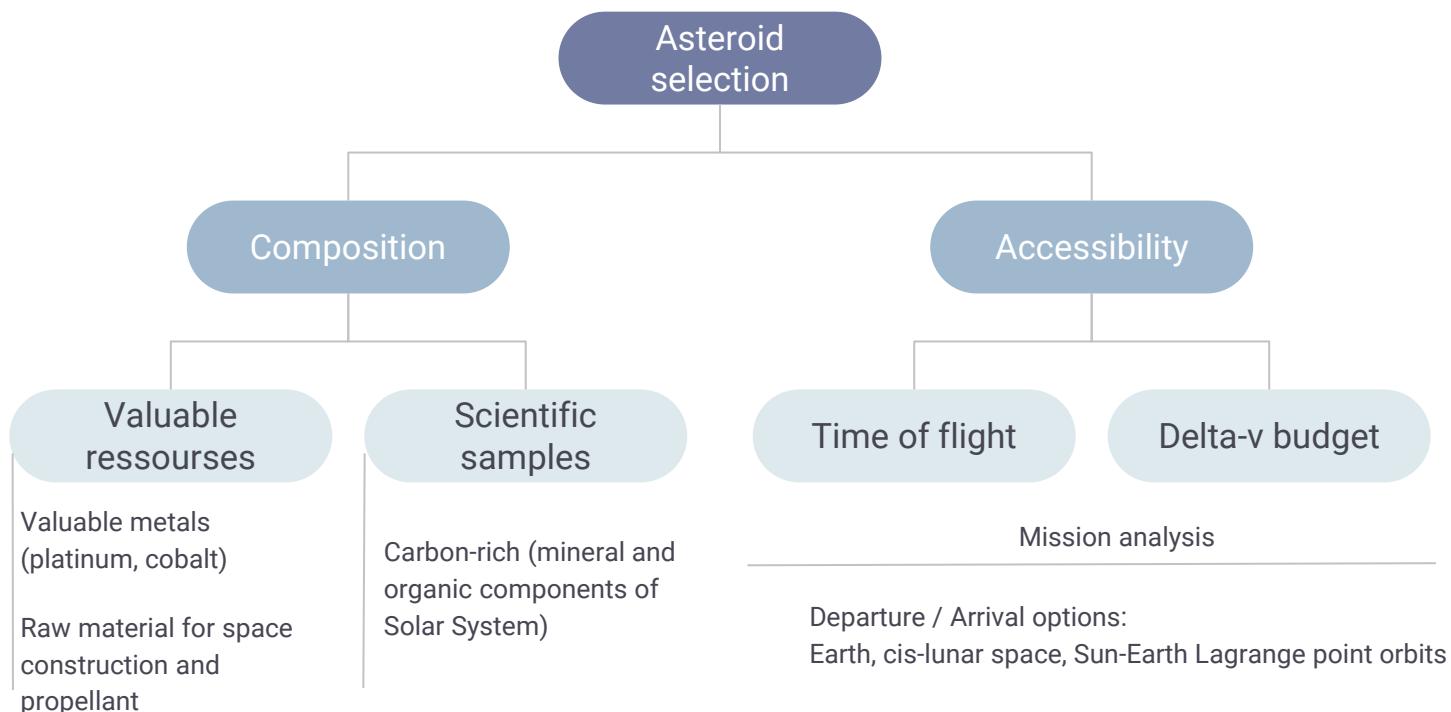
### SaCLaB study:

- *Ressources*
- *Accessible objects*
- *Technology*
- *Timeframe*

# Asteroid selection database

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# Database content



# Database creation

Step 1

Step 2

Step 3

## Collect available data

Basic orbital and physical parameters of near-Earth asteroids (NEAs) are collected from JPL Small-Body Database [1]

## Complete by composition data

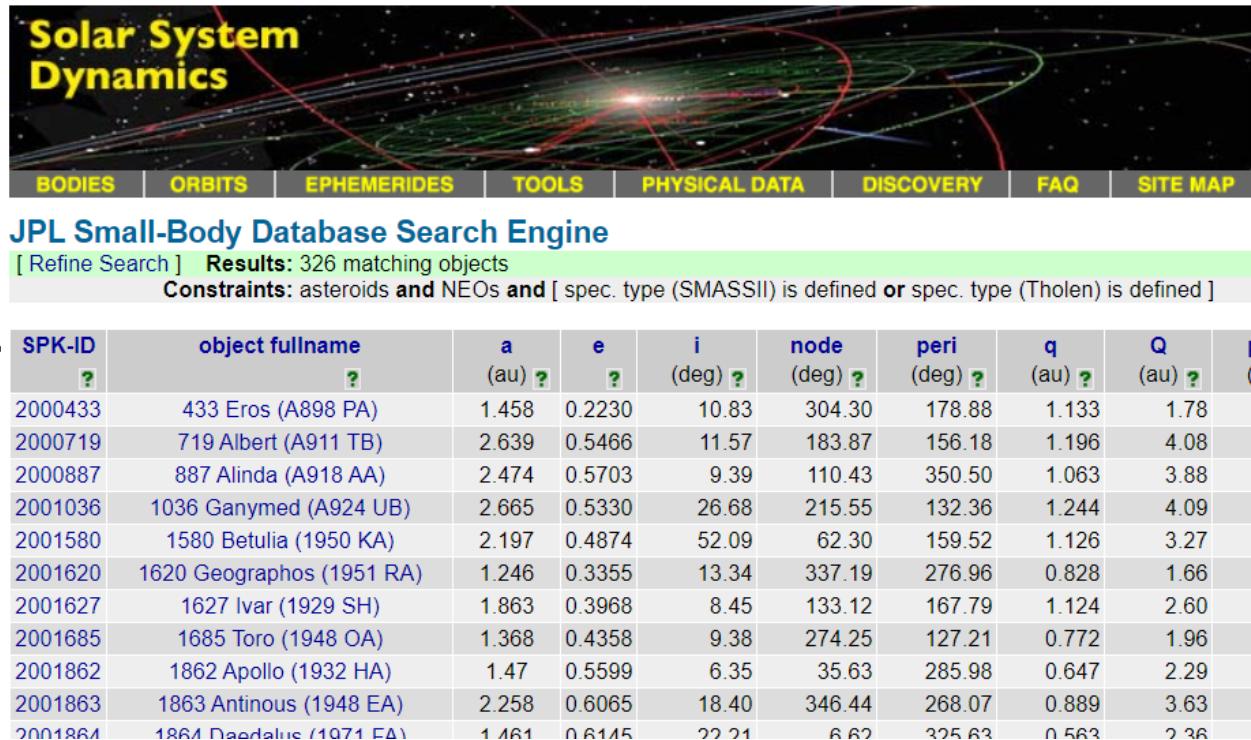
The composition is inferred from asteroid-meteorite samples link from literature.

## Compute mission opportunities

For each object in database we computed mission opportunities for one-way and round trip missions from Earth.

[1] <https://ssd.jpl.nasa.gov/sbdb.cgi>

# Step 1: data from JPL Small-Body Database



The screenshot shows the JPL Solar System Dynamics website with the title "Solar System Dynamics". Below it is a visualization of the solar system with various orbits. The main content area is titled "JPL Small-Body Database Search Engine". It displays search results for "326 matching objects" with constraints: asteroids and NEOs and [ spec. type (SMASSII) is defined or spec. type (Tholen) is defined ]. The results table includes columns for SPK-ID, object fullname, a (au), e, i (deg), node (deg), peri (deg), q (au), Q (au), and P (yr). The table lists 10 objects, including 433 Eros, 719 Albert, 887 Alinda, 1036 Ganymed, 1580 Betulia, 1620 Geographos, 1627 Ivar, 1685 Toro, 1862 Apollo, and 1863 Antinous.

SPK-ID	object fullname	a (au)	e	i (deg)	node (deg)	peri (deg)	q (au)	Q (au)	P (yr)
2000433	433 Eros (A898 PA)	1.458	0.2230	10.83	304.30	178.88	1.133	1.78	
2000719	719 Albert (A911 TB)	2.639	0.5466	11.57	183.87	156.18	1.196	4.08	
2000887	887 Alinda (A918 AA)	2.474	0.5703	9.39	110.43	350.50	1.063	3.88	
2001036	1036 Ganymed (A924 UB)	2.665	0.5330	26.68	215.55	132.36	1.244	4.09	
2001580	1580 Betulia (1950 KA)	2.197	0.4874	52.09	62.30	159.52	1.126	3.27	
2001620	1620 Geographos (1951 RA)	1.246	0.3355	13.34	337.19	276.96	0.828	1.66	
2001627	1627 Ivar (1929 SH)	1.863	0.3968	8.45	133.12	167.79	1.124	2.60	
2001685	1685 Toro (1948 OA)	1.368	0.4358	9.38	274.25	127.21	0.772	1.96	
2001862	1862 Apollo (1932 HA)	1.47	0.5599	6.35	35.63	285.98	0.647	2.29	
2001863	1863 Antinous (1948 EA)	2.258	0.6065	18.40	346.44	268.07	0.889	3.63	
2001864	1864 Daedalus (1971 FA)	1.161	0.6145	22.21	6.62	325.63	0.563	2.36	

[1] <https://ssd.jpl.nasa.gov/sbdb.cgi>

[2] Tholen, D. J. (1989)

[3] Bus, S. J., & Binzel, R. P. (2002)

# Step 2: Composition data

Meteorite samples



Asteroid's spectral type

- Spectroscopy technique for asteroid observations  
→ Classifications:  
Tholen [2] or SMASSII [3]
- Established asteroid–meteorite links [4]

Asteroid's composition

Chemical composition from [5]:

- |       |      |
|-------|------|
| • Fe  | • P  |
| • Ni  | • Ga |
| • Au  | • Ge |
| • Pb  | • Cd |
| • ls  | • Cu |
| • Rh  | • As |
| • Re  | • Sc |
| • Ge  | • In |
| • Si  | • Sb |
| • Al  | • Te |
| • H2O |      |

- Estimated surface composition  
→ Internal structure and composition are undefined

[4] Cloutis, E. A., Binzel, R. P., & Gaffey, M. J. (2014).

[5] McSween Jr, H. Y., & Huss, G. R. (2010). *Cosmochemistry*.

# Step 2: Composition data

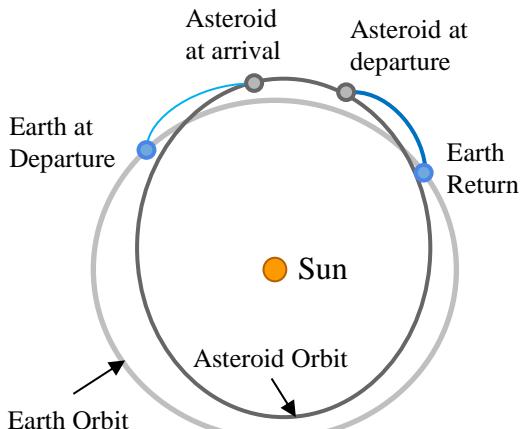
	spkid	name	chondrite_type	spec_b	spec_t	fe	ni	au	pt	si	al	ga	cd	cu	h2o
0	2000433	Eros	O	S	S	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00
1	2000719	Albert	O	S	NaN	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00
2	2000887	Alinda	O	NaN	S	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00
3	2001036	Ganymed	O	S	S	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00
4	2001580	Betulia	CM, CI	NaN	C	18.2	1.10	0.000014	0.000100	10.64	0.865	0.00098	0.000069	0.0125	18.18
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
321	3114075		M	X:	NaN	88.0	10.00	0.000000	0.000000	0.00	0.000	0.00000	0.000000	0.0000	0.00
322	3114077		O	Sq	NaN	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00
323	3114105		NaN	L	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
324	3114106		M	X:	NaN	88.0	10.00	0.000000	0.000000	0.00	0.000	0.00000	0.000000	0.0000	0.00
325	3448992		O	S	NaN	21.8	1.24	0.000016	0.000109	18.60	1.160	0.00054	0.000003	0.0090	0.00

# Step 3: Mission opportunities

Tools ○ SEMPy

Sun Earth Moon dynamics python package

Mission analysis ○ One-way mission  
○ Round-trip mission



Asteroid Rdv Mission Analysis x +  
file:///home/dcasa/i.kovalenko/sempy\_project/sempy/docs/build/html/asteroids/asteroid\_rdv\_mission\_analysis.html

Docs » Asteroids Subpackage » Asteroid Rdv Mission Analysis Module

## Asteroid Rdv Mission Analysis Module

Created on Tue Sep 10 10:03:33 2019

@author: Irina Kovalenko

```
class
src.asteroids.asteroid_rdv_mission_analysis.Asteroid_rdv_mission_analysis(asteroid_name,
departure_range, tof_range, step_dpr=10, step_tof=1, **kwargs)
```

Bases: object

Asteroid\_rdv\_mission\_analysis computes all impulsive mission options in a given range of launch dates from the Earth to an asteroid. The tool generates pork-chop plot (a time of flight vs launch date map) for total delta-V (sum of the departure and arrival V-infinities), or for V-infinities at departure or arrival, and enables to find optimal solution, minimizing total delta-V, or V-infinities at departure or arrival, or time of flight. Optionally, if departure is performed from a parking orbit, the total delta-V includes the Earth departure maneuver from a LEO parking orbit.

Parameters

- asteroid\_name (str) – Case-sensitive asteroid name (e.g. '2017 AP4'), or number, designation, MPC packed designation, or (SPK ID-2000000) number
- departure\_range (list of str) – Interval of departure dates, e.g. ['2020-01-01','2050-01-01']
- tof\_range (list of int) – Mission duration limit [days]
- step\_dpr (int, optional) – Departure date step [days]. Default 10 days.
- step\_tof (int, optional) – TOF step [days]. Default 1 day.
- \*\*kwargs –
- leo\_alt (float) – altitude of the parking Low Earth Orbit [km].

asteroid\_name

# SEMPy mission analysis tools

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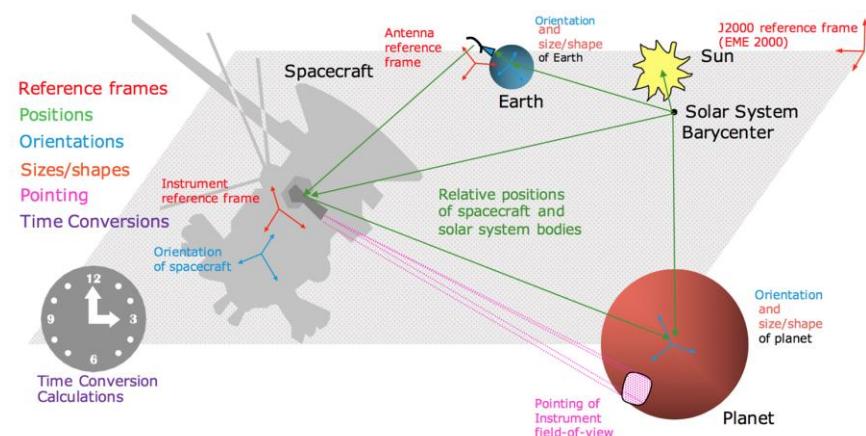
# SEMPy: mission analysis methods

## Ephemerides

Earth's and asteroids ephemerides from JPL Horizons system [9]

## SPICE Kernels

The screenshot shows the NAIF (Navigation and Ancillary Information Facility) website. At the top left is the NASA/JPL logo and the text "Jet Propulsion Laboratory California Institute of Technology". To the right is a link "+ View the NASA Portal". Below this is a large banner with the text "NAIF" in red and "The Navigation and Ancillary Information Facility" in white. On the left side of the main content area is a vertical sidebar with links: Home, Announcements, About SPICE, About NAIF, For New Projects, For the Public, Data Toolkit, Utilities, and WebGeocalc. The main content area has a title "SPICE Data (SPICE Kernels)" and a list of categories: PDS Archived SPICE Data Sets, Operational Flight Project Kernels and Other Non-archived Project Kernels, and Generic Kernels. A descriptive text follows: "As shown above, three categories of SPICE data, often referred to as kernels, are available from this website. You should carefully read about all three of these categories using the links below in order to find the data best suited to your needs." At the bottom, there is a note: "If you are not already familiar with how to use SPICE data, take a moment to".



Source: <https://www.cosmos.esa.int/web/spice> (c)

# SEMPy: mission analysis methods

Ephemerides

Lambert's problem

Earth's and asteroids ephemerides from JPL Horizons system [9]

Lambert's problem solutions for Earth → Asteroid and  
Asteroid → Earth (if round trip).



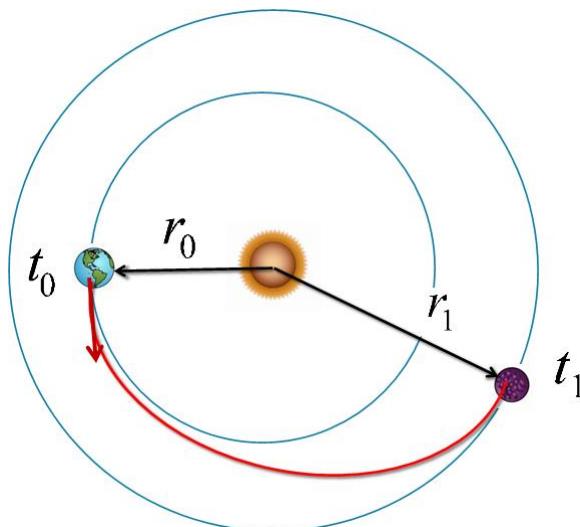
## Lambert's problem

Given:

- $r_0$  position at time  $t_0$
- $r_1$  position at time  $t_1$

Find:

a conic trajectory between  
two positions



# SEMPy: mission analysis methods

Ephemerides

Lambert's problem

Patched conic approximation

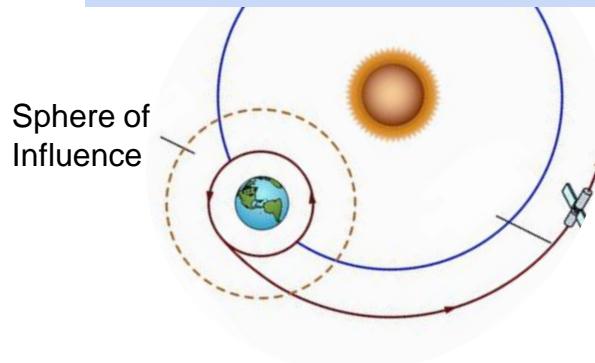
Earth's and asteroids ephemerides from JPL Horizons system [9]

Lambert's problem solutions for Earth → Asteroid and Asteroid → Earth (if round trip).

Two body approximation for departure from a low-Earth orbit (LEO).

**Delta-v:**

- the Earth departure maneuver from a circular parking orbit
- the maneuver to match the NEA's velocity at arrival
- the maneuver to depart the NEA (if round trip mission)



# SEMPy: mission analysis methods

Ephemerides

Earth's and asteroids ephemerides from JPL Horizons system [9]

Lambert's problem

Lambert's problem solutions for Earth → Asteroid and Asteroid → Earth (if round trip).

Patched conic approximation

Two body approximation for departure from a low-Earth orbit (LEO).

**Delta-v:**

- the Earth departure maneuver from a circular parking orbit
- the maneuver to match the NEA's velocity at arrival
- the maneuver to depart the NEA (if round trip mission)

SEMPy Tools: Constraints

Precomputed trajectories

- **launch interval** 2020-2050
- **mission duration** 450 days
- **stay at asteroid** at least 10 days (if round trip mission)

Output

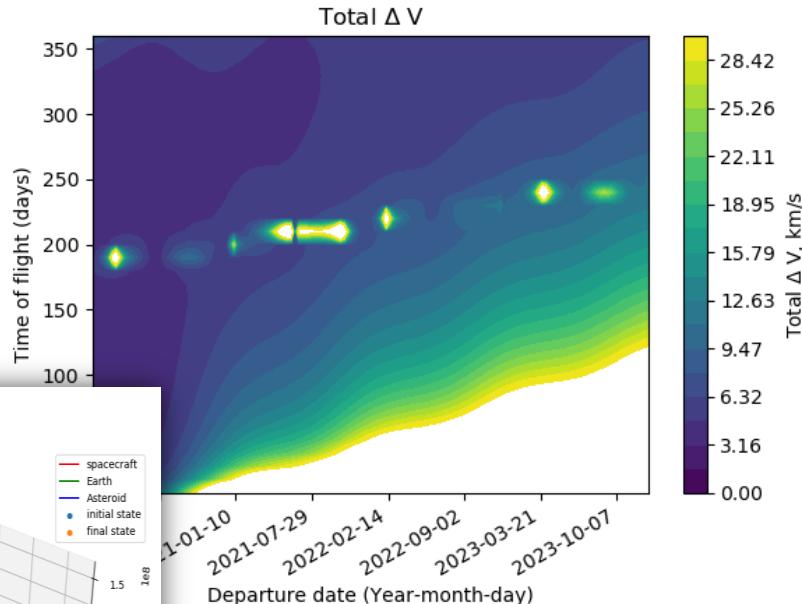
Optimal **delta-v** and **TOF** solutions

- + associated all the maneuvers and Lambert's solution values

# SEMPy: mission analysis methods

## Input: Constraints

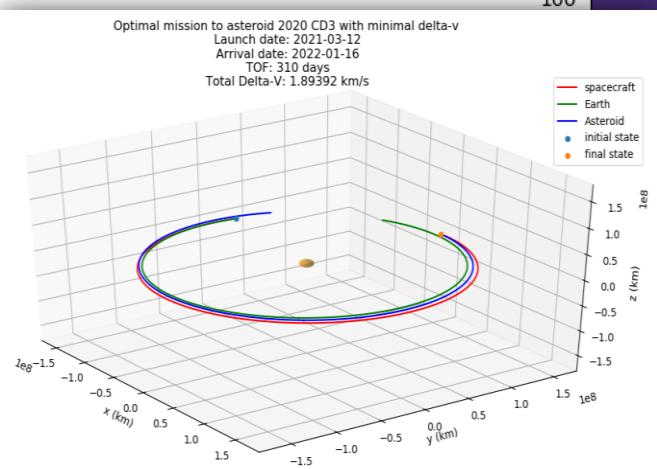
- **Launch interval** 2020-2050
- **Mission duration** 450 days
- **Stay at asteroid** at least 10 days (if round trip mission)
- **Departure LEO** (optional)



## Output

### Optimisation parameters choice:

- **Time of flight (TOF)**
- **Total delta-v**
- **Departure/arrival delta-v**
- **Hyperbolic excess velocity**



# SEMPy database tools

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# SEMPy database tools

## User interface



- Environment for **code** and **data**
- Consistent with Python methods in SEMPy
- Flexible for new functions, new data
- Open source

The screenshot shows the Jupyter Notebook interface with several open notebooks:

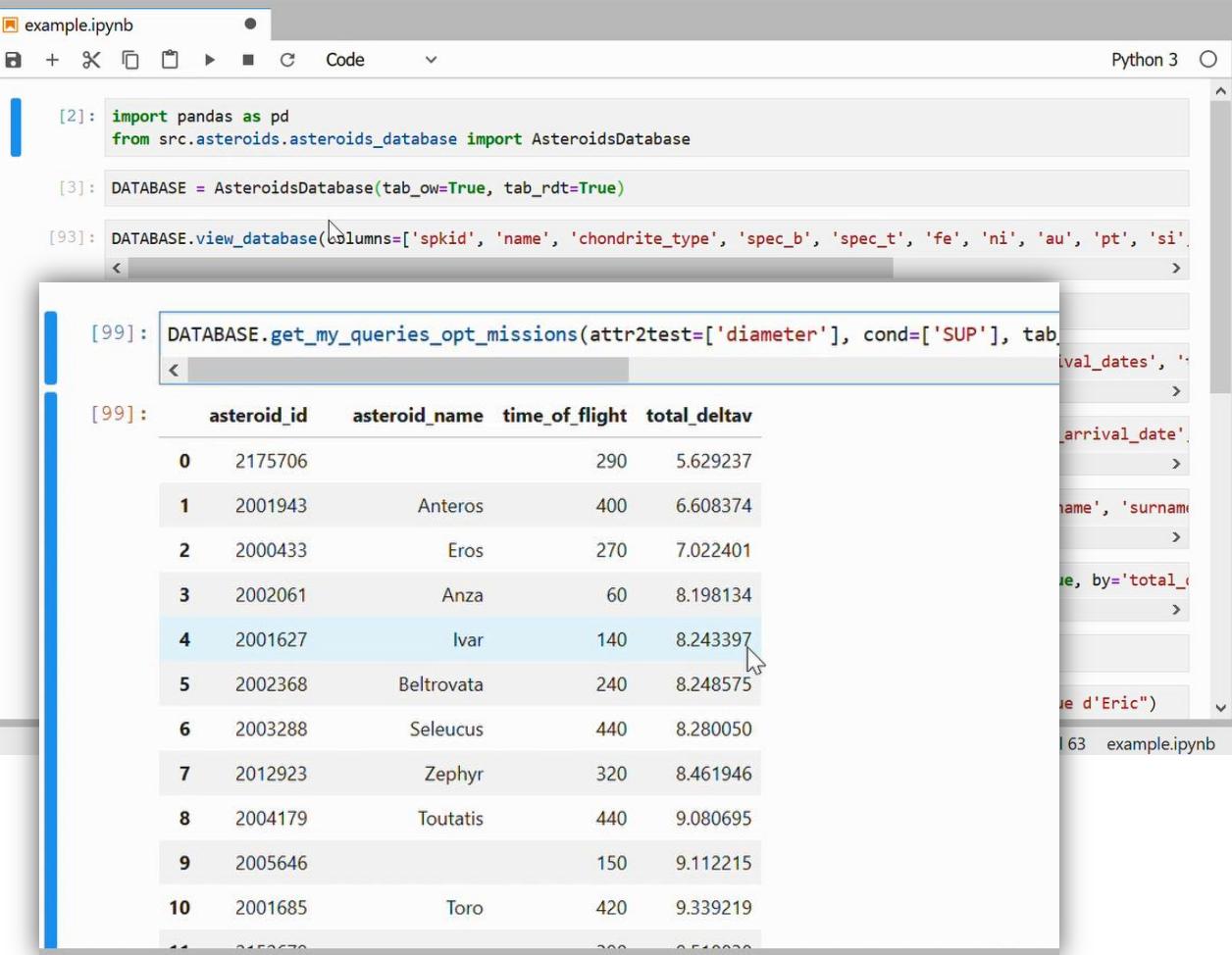
- Python 3 | iPython**: A file browser showing various Jupyter files like `Linear.ipynb`, `Bayes.ipynb`, etc.
- In Depth: Linear Regression**: A notebook titled "In Depth: Linear Regression" with code and text explaining linear regression models.
- Simple**: A notebook titled "Simple" containing a single cell with the code `print("Hello World")`.
- Julia | iPython**: A notebook titled "Julia" with code related to Lorenz attractors and eigenvalues.
- pythont notebook**: A notebook titled "pythont notebook" with code related to Lorenz attractors and eigenvalues.
- R**: A notebook titled "R" showing a scatter plot of Seattle Weather data from 2012-2015.

The interface includes tabs for "File", "Edit", "View", "Run", "Kernel", "Settings", "Help", and "Launcher". The "Launcher" panel shows icons for different kernels: Python 3, Julia 1.1.0, R, and others.

# SEMPy database tools

## Functionalities:

- Multicriteria target selection:
  - mission parameters (TOF, delta-v, ...)
  - composition
  - diameter
  - ...



The screenshot shows a Jupyter Notebook interface with the following code and output:

```
example.ipynb
```

```
[2]: import pandas as pd
from src.asteroids.asteroids_database import AsteroidsDatabase

[3]: DATABASE = AsteroidsDatabase(tab_ow=True, tab_rdt=True)

[93]: DATABASE.view_database(columns=['spkid', 'name', 'chondrite_type', 'spec_b', 'spec_t', 'fe', 'ni', 'au', 'pt', 'si'])

[99]: DATABASE.get_my_queries_opt_missions(attr2test=['diameter'], cond=['SUP'], tab_rdt=True)
```

The output of the last cell is a Pandas DataFrame:

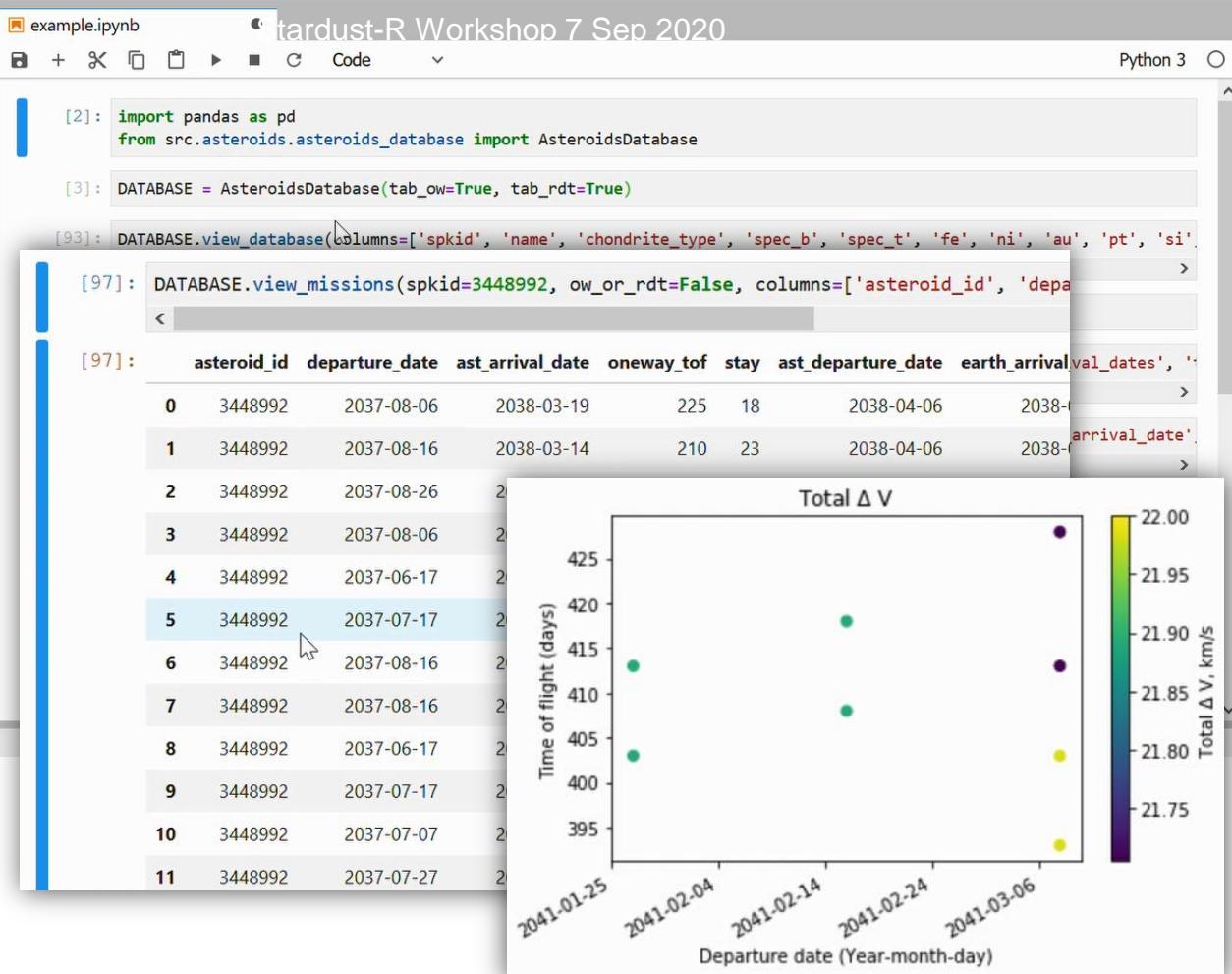
	asteroid_id	asteroid_name	time_of_flight	total_deltav
0	2175706		290	5.629237
1	2001943	Anteros	400	6.608374
2	2000433	Eros	270	7.022401
3	2002061	Anza	60	8.198134
4	2001627	Ivar	140	8.243397
5	2002368	Beltrovata	240	8.248575
6	2003288	Seleucus	440	8.280050
7	2012923	Zephyr	320	8.461946
8	2004179	Toutatis	440	9.080695
9	2005646		150	9.112215
10	2001685	Toro	420	9.339219
11	2150670		380	9.510030

# SEMPy

## database tools

### Functionalities:

- Multicriteria target selection:
  - mission parameters (TOF, delta-v, ...)
  - composition
  - diameter
  - ...
- **Mission opportunities for each object**
  - precomputed one-way
  - and round-trip

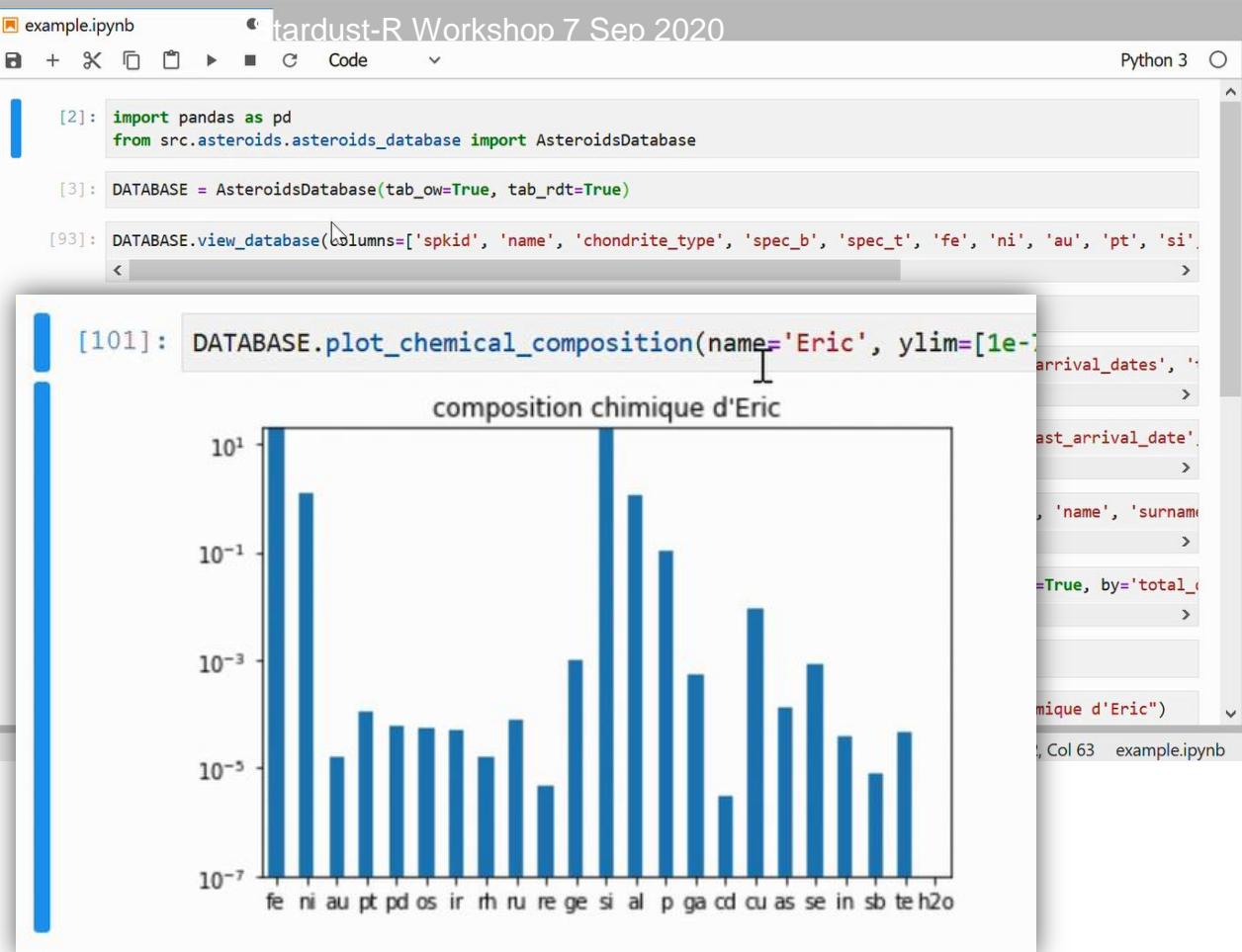


# SEMPy

## database tools

### Functionalities:

- Multicriteria target selection:
  - mission parameters (TOF, delta-v, ...)
  - composition
  - diameter
  - ...
- Mission opportunities for each object
  - precomputed one-way
  - and round-trip
- Data visualisation



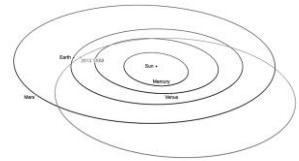
# Conclusion and future work

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# Comparison with other databases

	NASA Ames [6]	JPL MDT [7]	CNEOS [8]	ECOCEL
Asteroids type	NEAs	All	NHATS [12]	NEAs with Tholen/SMASSII class
Launch interval	2020-2045	2020-2040	2020-2040	2020-2050
Mission duration	10 years	2000 days	450 days	450/900 days
Delta-v limit	10 km/s		12 km/s	(optional)
Flyby authorized	✓	✗	✗	✗
One-way flight	✓	✓	✗	✓
Roundtrip flight	✓	✗	✓	✓
Parking orbit	200 km	✗	400 km	✓ (optional)
Composition	✗	✗	✗	✓

# Future work



Nov 2019

## Mission analysis tools

SEMPy preliminary mission analysis: Earth-Asteroid mission



June 2020

## Database creation

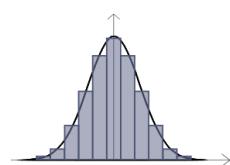
Composition: chemical elements, water  
Precomputed trajectories



Oct 2020

## Database extension

Lunar flyby opportunities  
Multiple targets mission



... 2020

## Data analysis

Data interpretation and visualisation  
Statistical analysis



2021

## ECOCEL Final report

Overview and recommendations for the French Government

# Thank you for your attention!

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Any questions?

Corresponding author [in](#)



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# References

- [1] JPL Nasa. Jpl small-body database search engine.
- [2] THOLEN, David J. Asteroid taxonomic classifications. In : Asteroids II. 1989. p. 1139-1150.
- [3] Bus, S. J., & Binzel, R. P. (2002). Phase II of the small main-belt asteroid spectroscopic survey: A feature-based taxonomy. *Icarus*, 158(1), 146-177.
- [4] Cloutis, E. A., Binzel, R. P., & Gaffey, M. J. (2014).
- [5] Harry Y McSween Jr and Gary R Huss. Cosmochemistry. Cambridge University Press, 2010.
- [5] Rivkin, A. S., Howell, E. S., Vilas, F., & Lebofsky, L. A. (2002). Hydrated minerals on asteroids: The astronomical record. *Asteroids III*, 1, 235-253.
- [6] Nasa Ames Research Center. Trajectory browser.
- [7] Nasa JPL. Jpl small-body mission-design tool.
- [8] Nasa Center for Near Earth Object studies. Accessible neas.
- [9] SPICE Kernels <https://naif.jpl.nasa.gov/naif/spiceconcept.html>