Post-Detection of Dark Matter using Gravimetry and GNSS

Michal Cuadrat-Grzybowski (25/10/2022)

TU Delft — Royal Observatory of Belgium — ULB

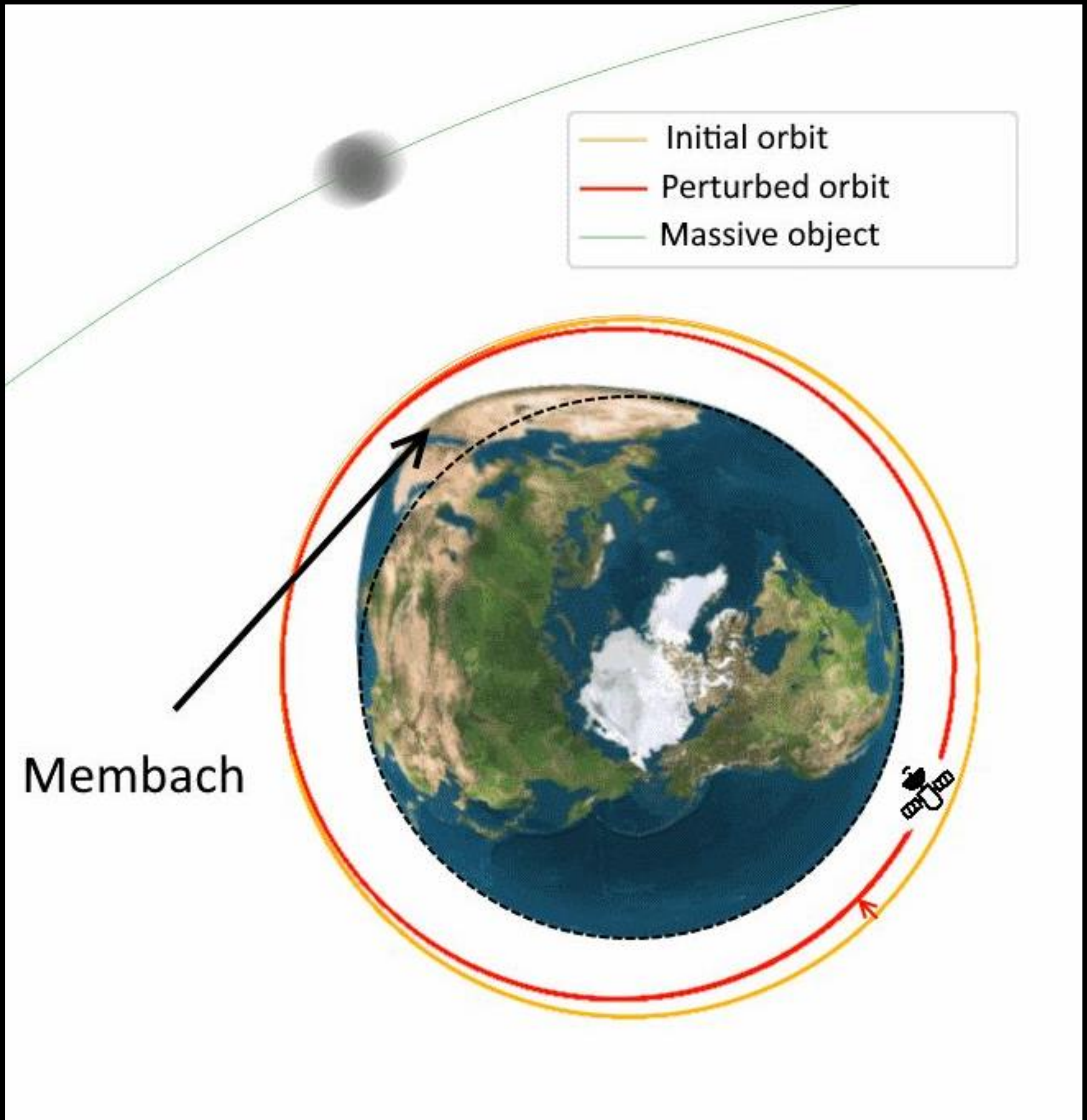


Image: O. Welcomme for ROB

What are the Different Scales of Dark Matter?

10^{-15} m

Particles

1 m

10^{7} m

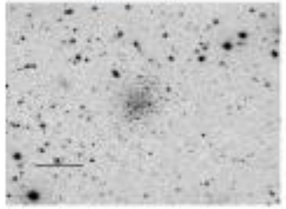
Earth

10^{13} m

Solar System

10^{17} m

UFD

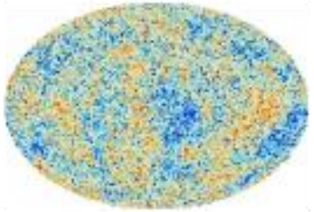


10^{21} m

Milky Way

10^{25} m

CMB



Weakly interacting fundamental dark matter particles (WIMPs)?

Dark Matter still has not been revealed at these scales…

Detected consequences of Dark Matter on Galaxy rotation rates (= gravitation based)

Photo: JeffGraphy

Photo: Nasa

Image: Nasa

Sand et al., 2022

Jet Propulsion Laboratory

ESA & Planck Collaboration

Courtesy for slide: Bruno Bertrand (ROB)

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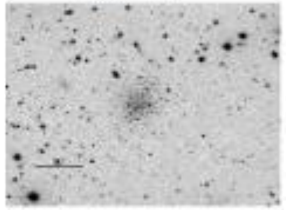

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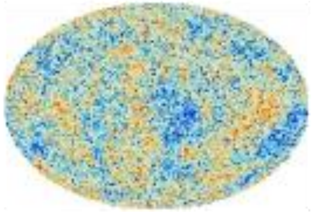

Unfortunately after 40 years of research still no fundamental particle found…

We may have not looked everywhere we could!

Detected consequences of Dark Matter on Galaxy rotation rates

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Photo: JeffGraphy

Photo: Nasa

Image: Nasa

Sand et al., 2022

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How to detect Dark Matter in the Solar System?

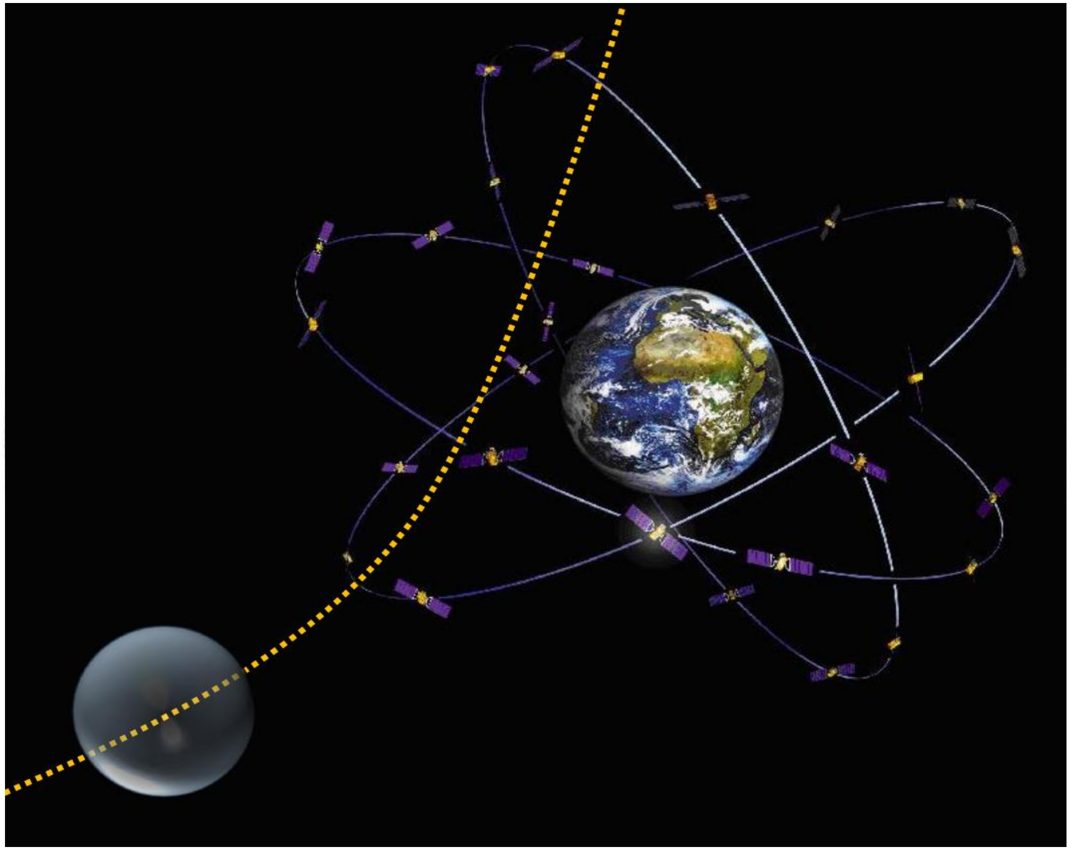
- Dark Matter clumps or PBH gravitationally attracted by Solar System (or even Earth)

- Potential of detection of Dark Matter clump fly-bys near Earth!

- Major Assumption:

  Dark Matter only interacts gravitationally with normal matter

- For this we have:
  - GNSS (Global Navigation Satellite System) constellations
  - Network of Superconducting Gravimeters
  - Two Earth-sized detectors with 20 years of data = FREE



Credit: Bruno Bertrand

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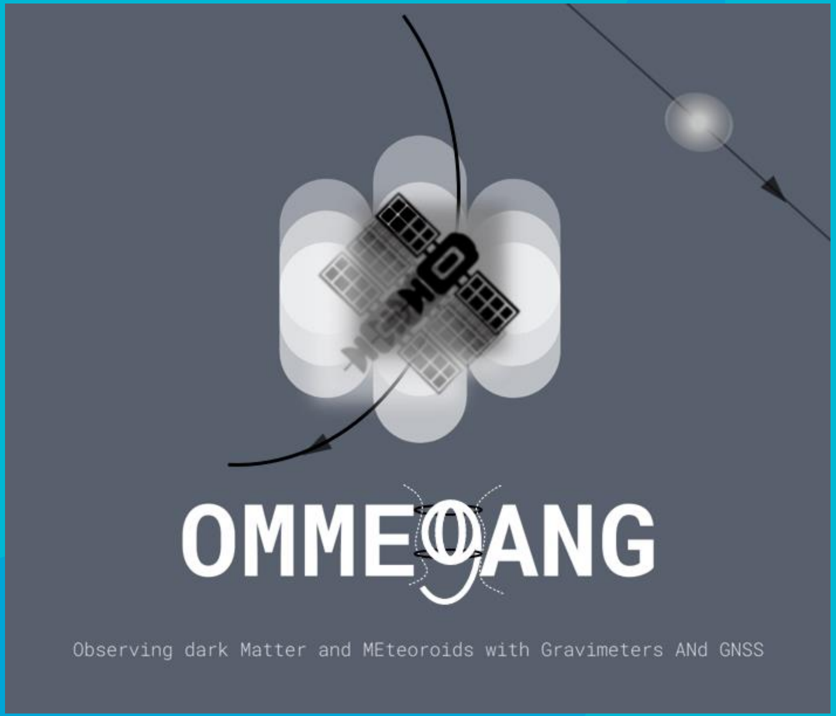
How can we use GNSS and gravimetry data to post-detect Dark Matter Signals?



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How can we use GNSS and gravimetry data to post-detect Dark Matter Signals?

- **Research Question 1**: What is the possible abundance, velocity and number of fly-bys of Dark Matter in the Solar System and in the Earth's vicinity?
- **Research Question 2**: How can a Dark Matter gravitational signal be modelled and translated to known observables?
- **Research Question 3**: What is the detection sensitivity related to relevant Dark Matter characteristics?

This presentation

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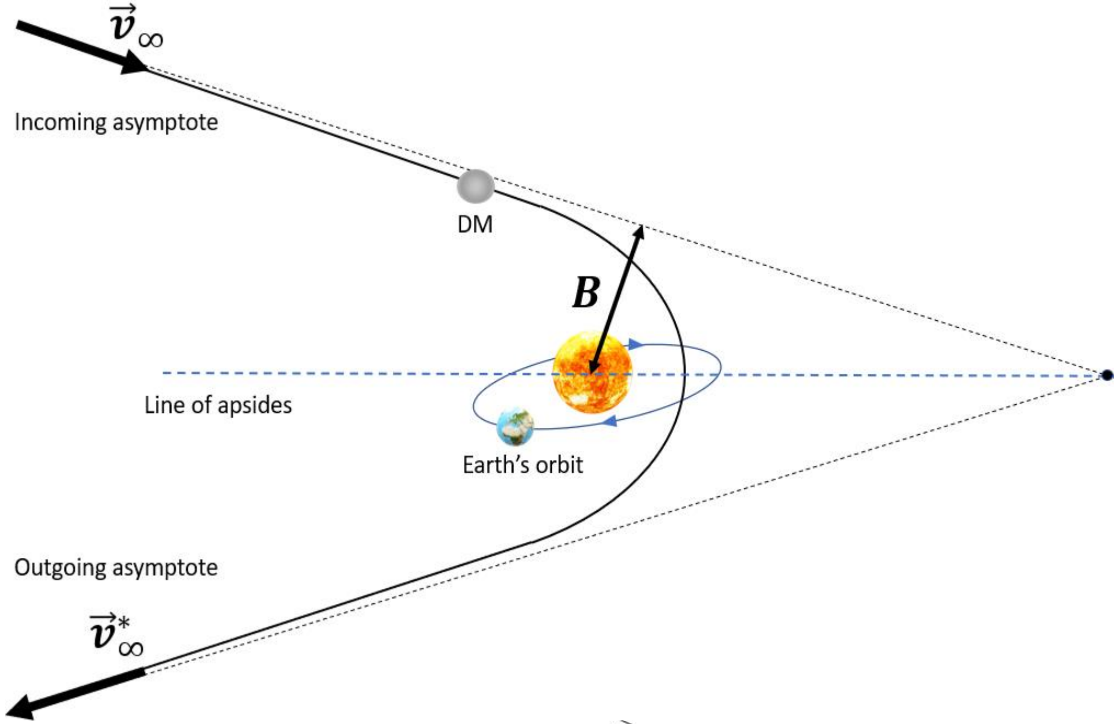
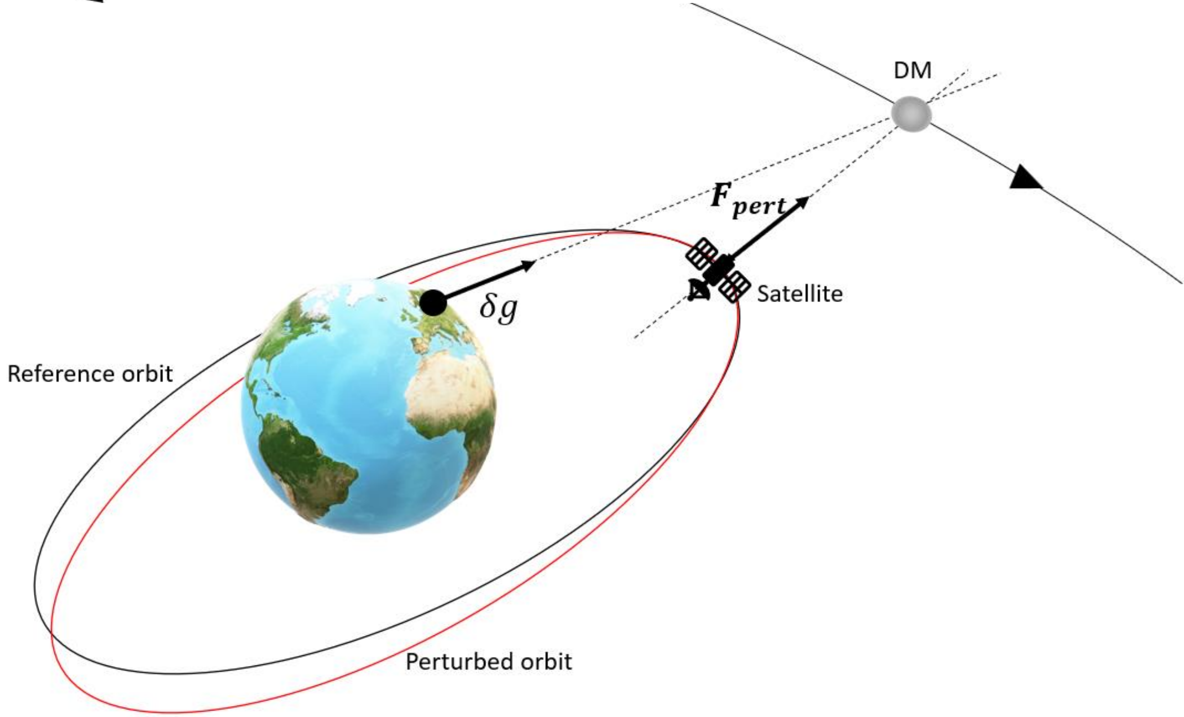
Modelling Tools Dark Matter Signals

- Characteristics of a DM clump orbit:
  - Keplerian Hyperbolic Orbit,
  - DM clump mass independent,
  - Impact parameter $\boldsymbol{B}$, excess hyperbolic velocity $\boldsymbol{v}_{\infty}$ and Keplerian angles.



- Signal obtained from 3rd –Body perturbation:
  - DM clump mass dependent!
  - GNSS: orbital deviation
  - Gravimeters: gravity residual



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I) What is the possible abundance, velocity and number of fly-bys of Dark Matter in the Solar System and in the Earth’s vicinity?

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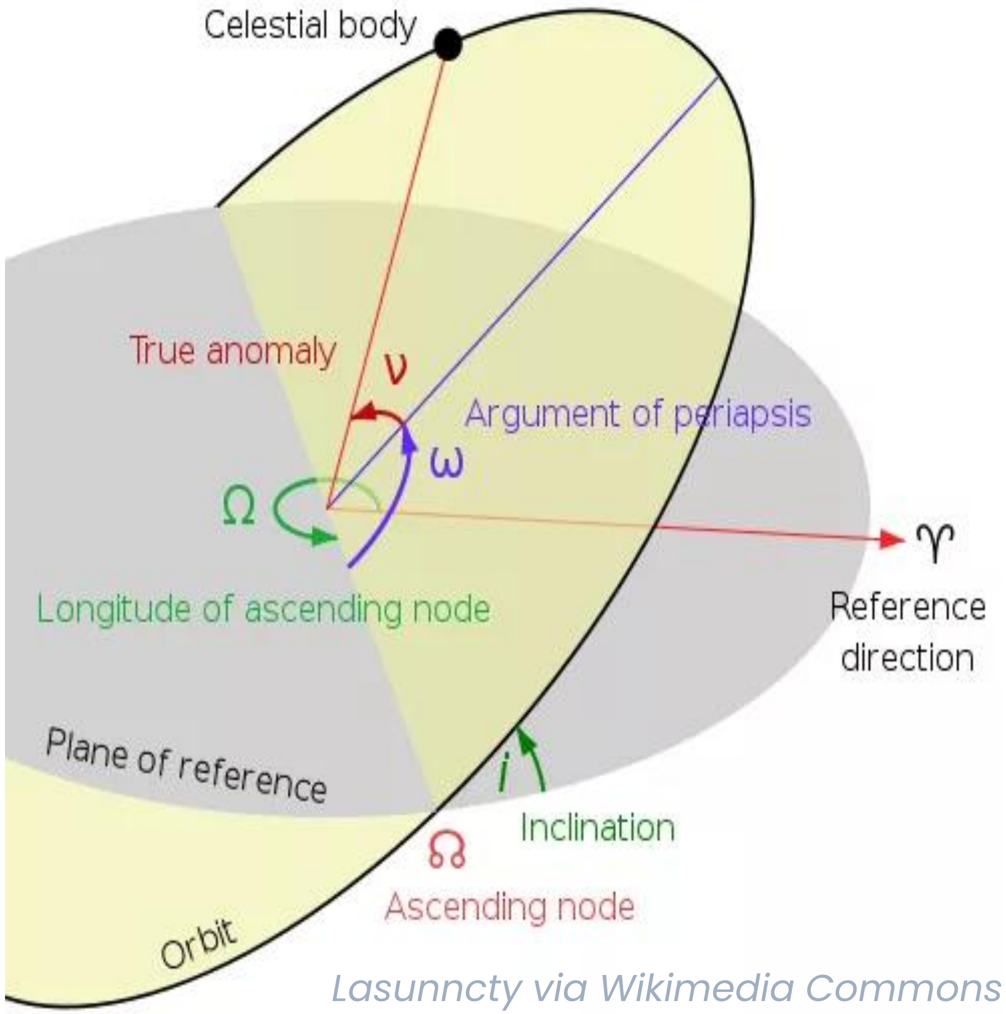
Orbital Elements Intermezzo

- Characteristics of a Keplerian orbit:
  - *a*: semi-major axis,
  - *e*: eccentricity,
  - *i*: inclination angle,
  - Ω: RAAN (Right Ascension of Ascending Node),
  - ω: Argument of periapsis (→ defines pericentre),
  - ν: True anomaly (actual dynamic element)*



Lasunncty via Wikimedia Commons

*: Sometimes the mean anomaly is used.

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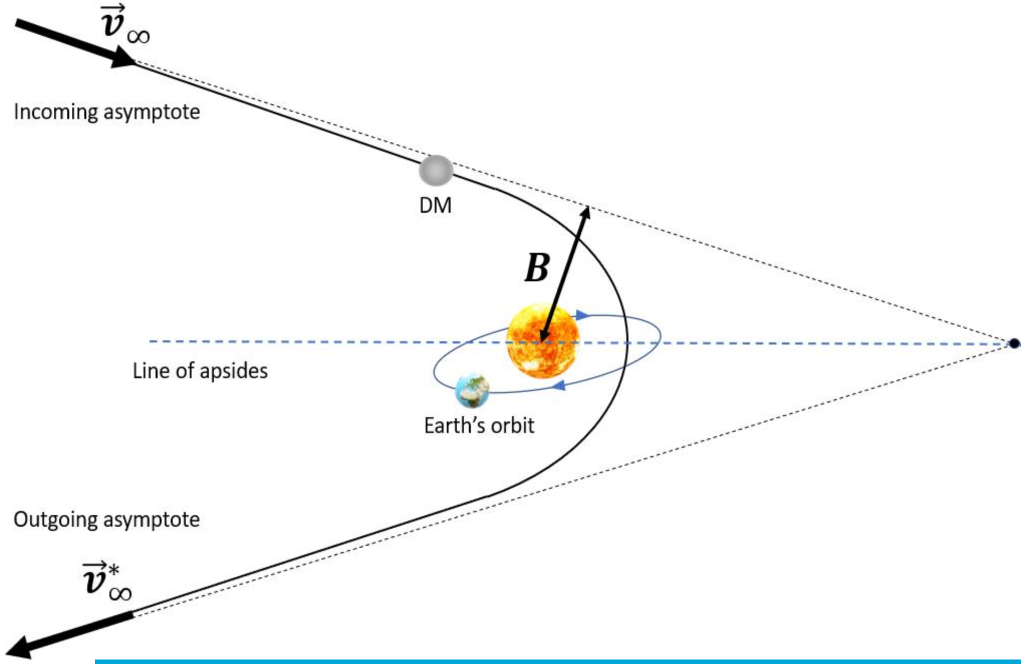
Estimating flux/density of DM (1)

- Fly-by flux:
  - d: closest approach distance to Earth,
  - $V_{DM/Earth}$: DM velocity (w.r.t Earth) at distance d,
  - F_g : gravitational focus factor of Earth.

$$\rho_{DM} = 0.009 \frac{M_\odot}{\mathrm{pc}^3}$$

V_∞: Maxwellian Distribution

B: Uniform distribution



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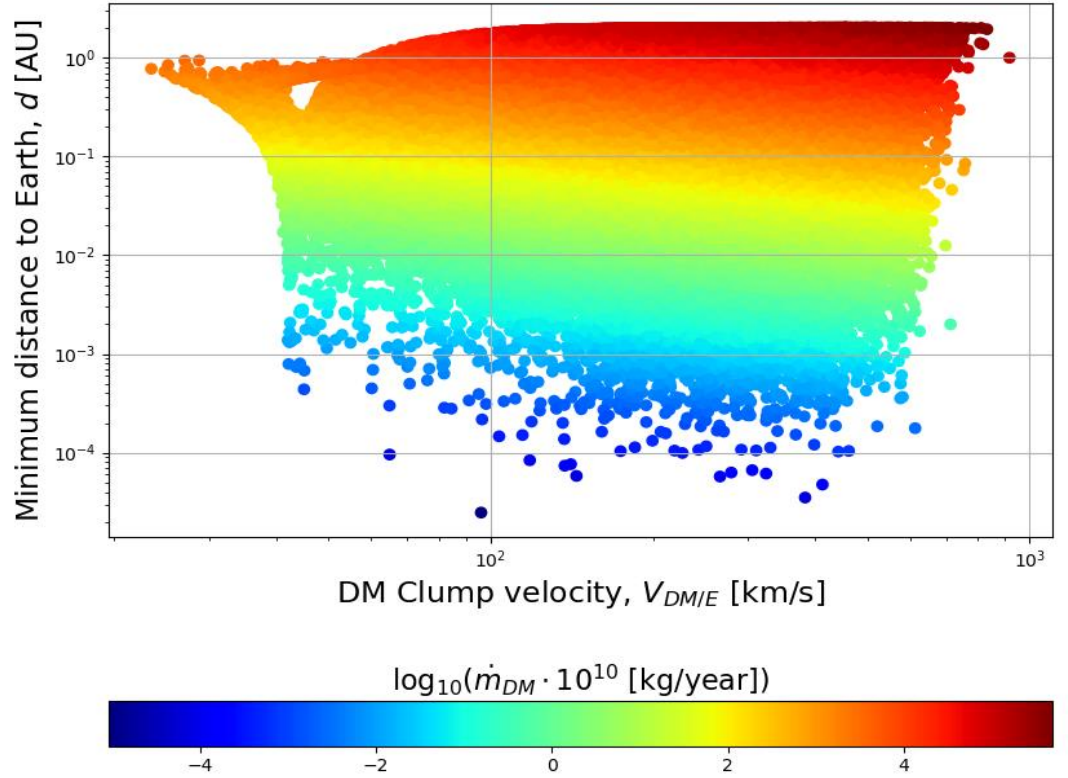

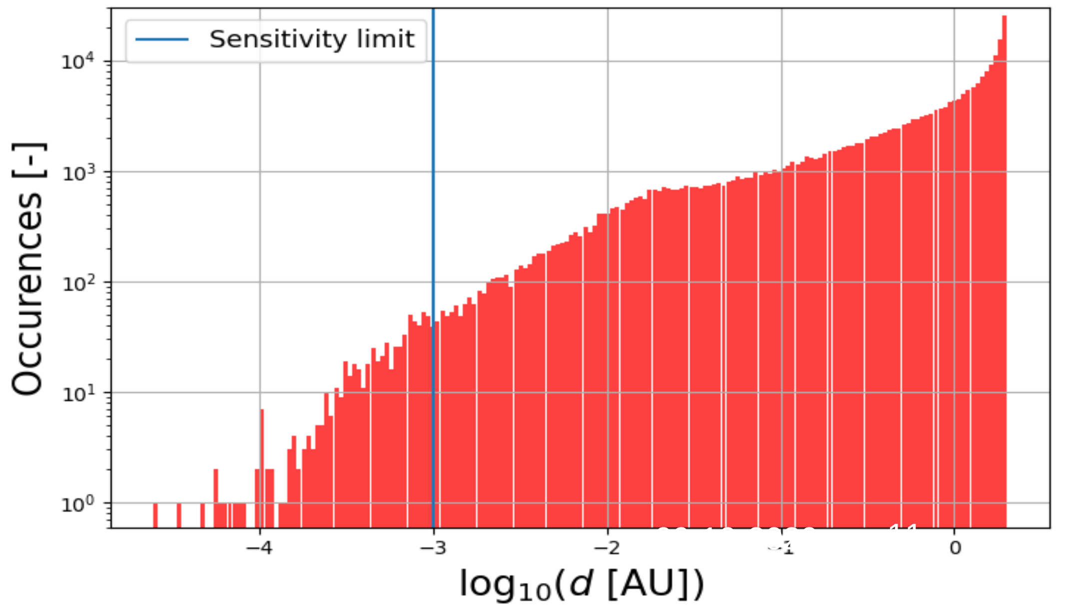

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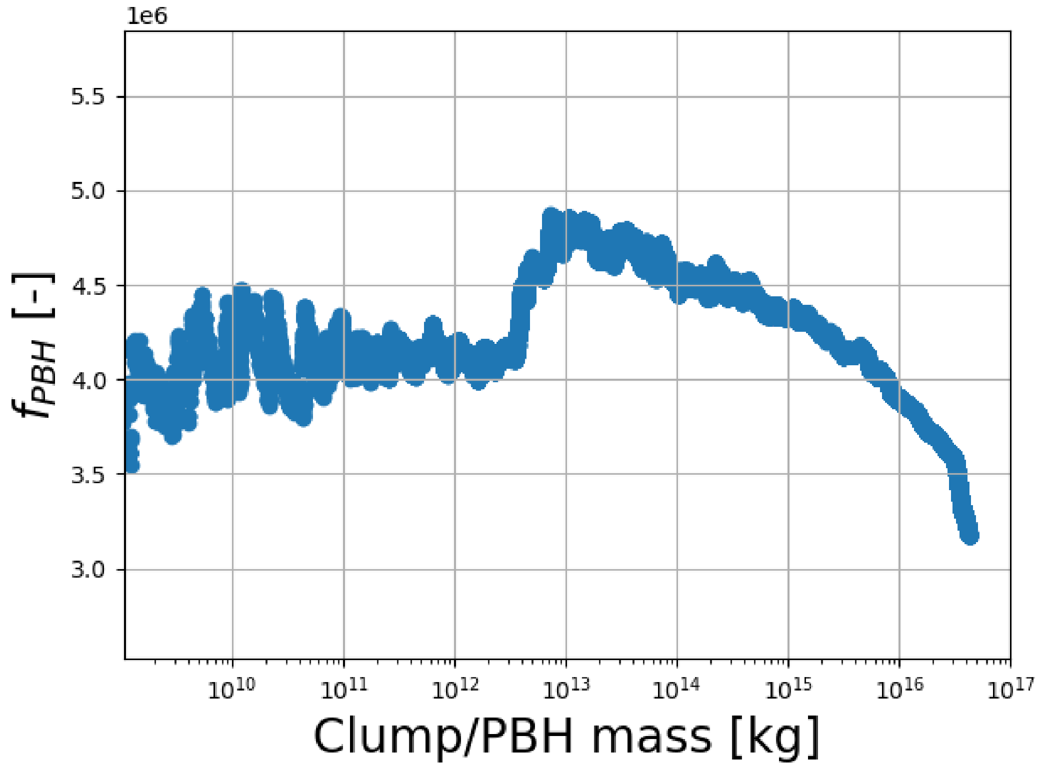

$$f_{PBH} \propto \left(\frac{d}{d_{sens}}\right)^2$$

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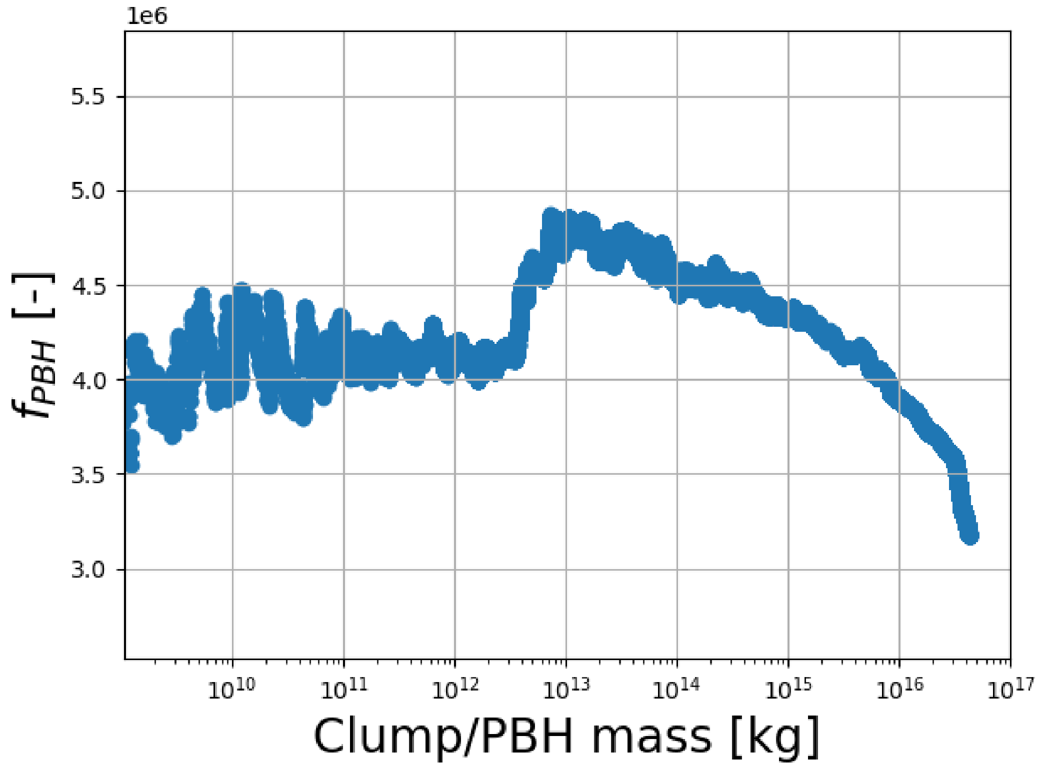

$$f_{PBH} \propto \left(\frac{d}{d_{sens}}\right)^2$$

- Captured and ejection flux (three-body capture):
  - Steady-state mass ~ 10^{13} kg → double increase in density

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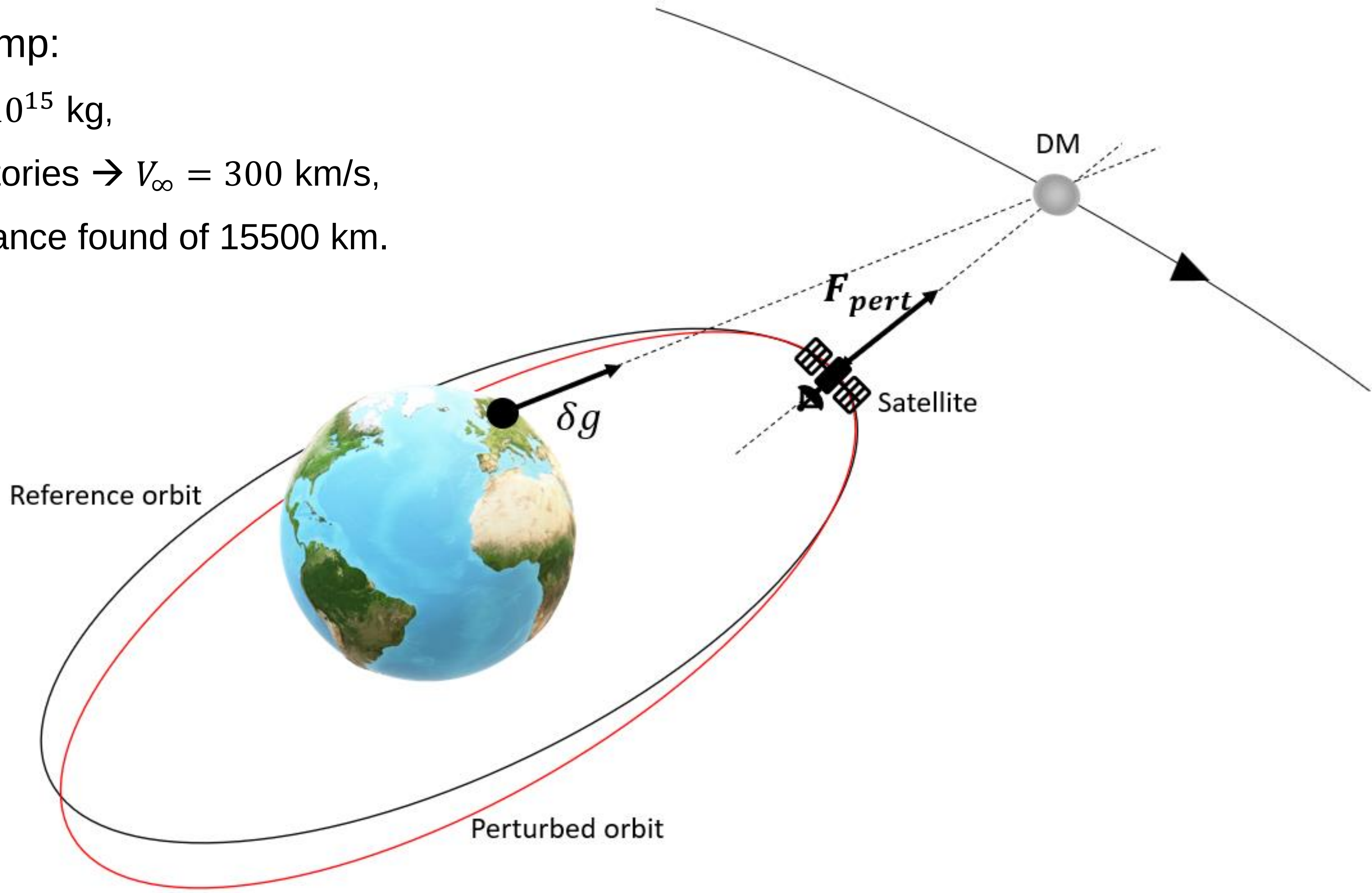
II) How can a Dark Matter gravitational signal be modelled and translated to known observables?

Case scenario to be investigated

Characteristics of DM clump:

- Clump Mass: $m_{DM} = 10^{15}$ kg,
- Highly energetic trajectories → $V_\infty = 300$ km/s,
- Minimum possible distance found of 15500 km.



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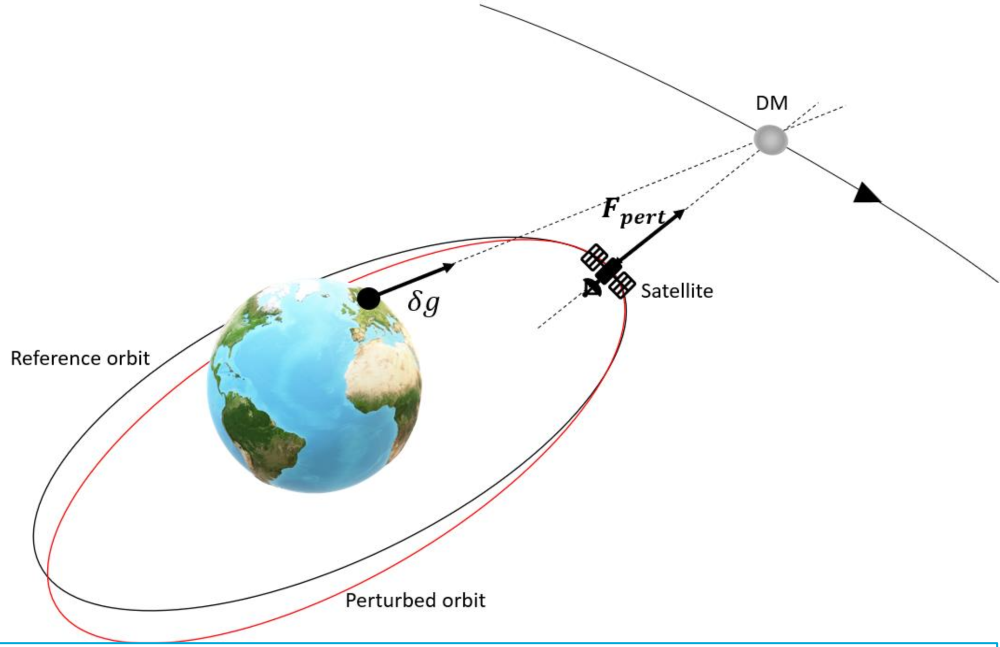
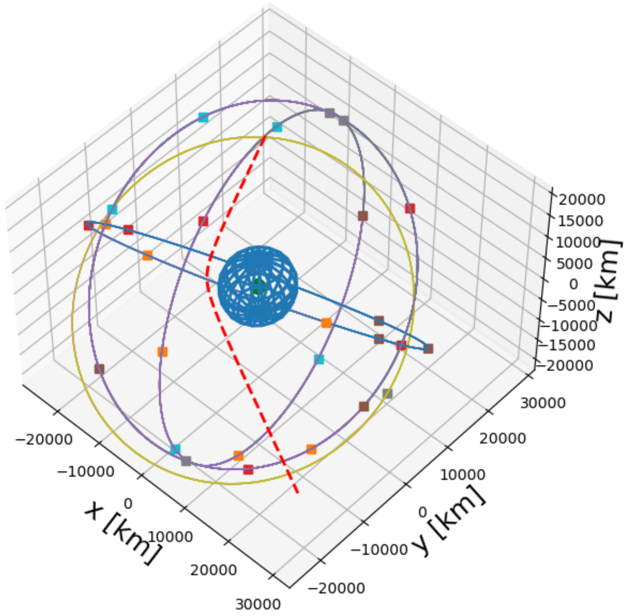
GNSS Signals - Results

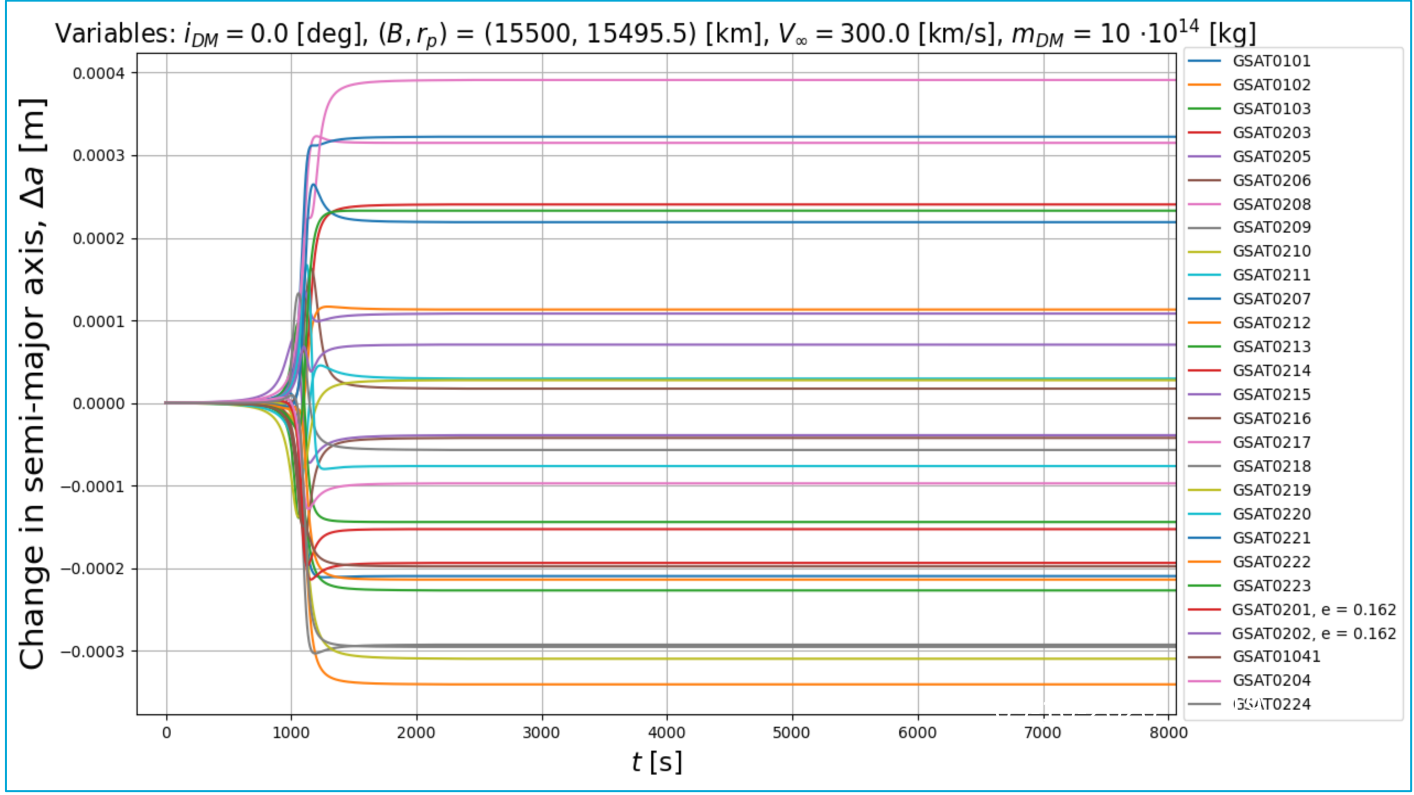
From an acceleration profile to observables:

- Compute third-body perturbation,
- Translate satellite reaction into orbital elements (= observables).



Preliminary investigation: semi-major axis

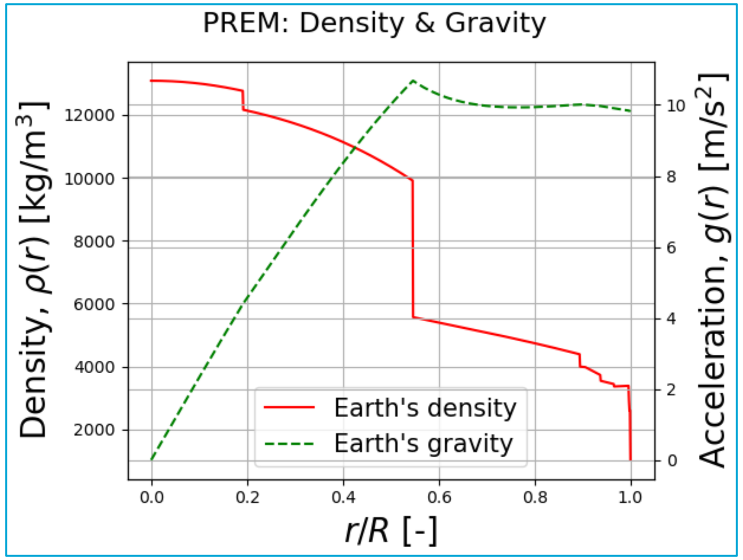


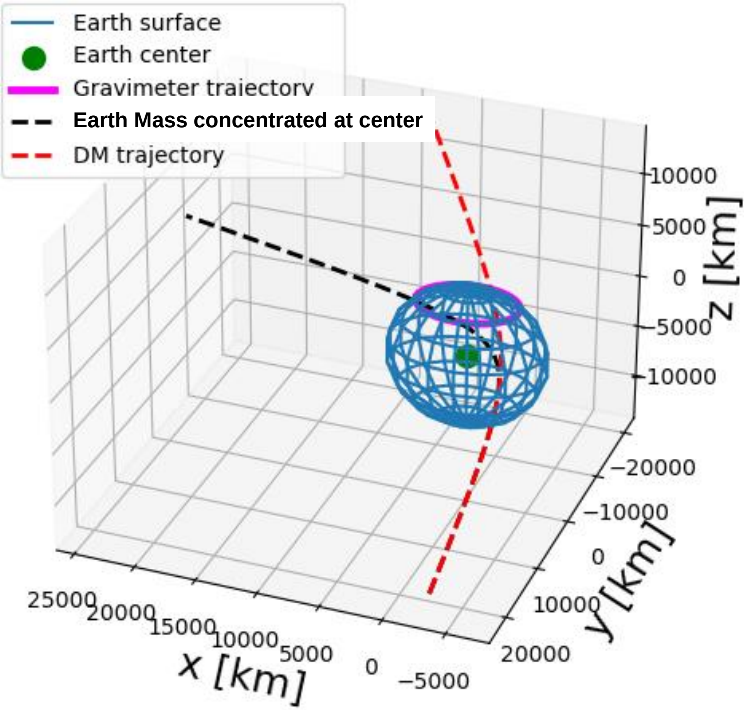


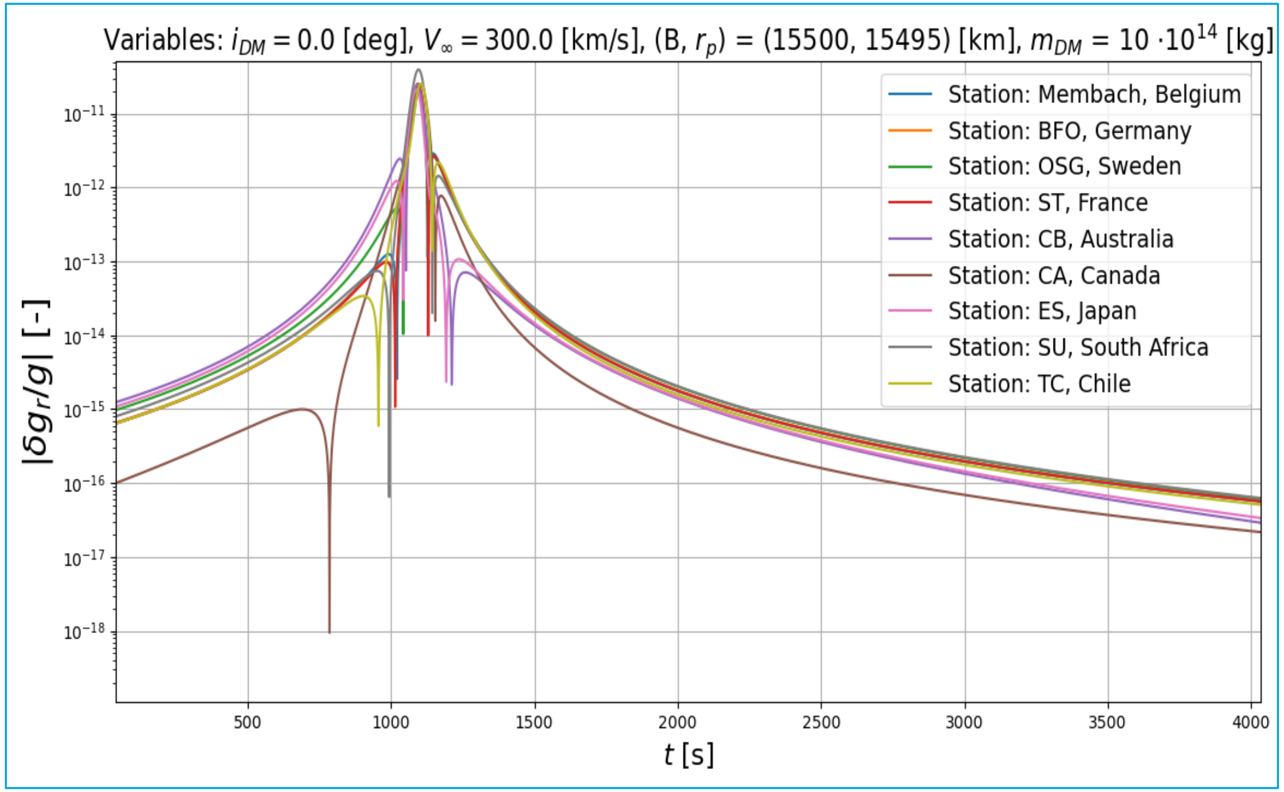
Gravimeter Signals - Results

Characteristics of acceleration profiles:

- Maximum occurs near pericentre,
- Maximum and duration of signal dependency on impact parameter, excess velocity, station location and DM mass.
- High sensitivity to DM orbit relative orientation (one order of magnitude difference).







Conclusions

- Minimum possible distance of 15000 km, with a majority mainly around 0.01 AU (→ problematic for detection).

- Signal successfully modelled and provides a clear pattern for future data analysis:
  - GNSS signal very characteristic = step-like,
  - SG network signal = peak AND highly dependent on the orbital relative orientation (not the case for GNSS),

- Similar sensitivity obtained with min. mass of $\sim 10^{15}$ kg at 15500 km for both gravimeters ($\sim 10^{-10}$ m/s^2) and GNSS (~ 1 cm).

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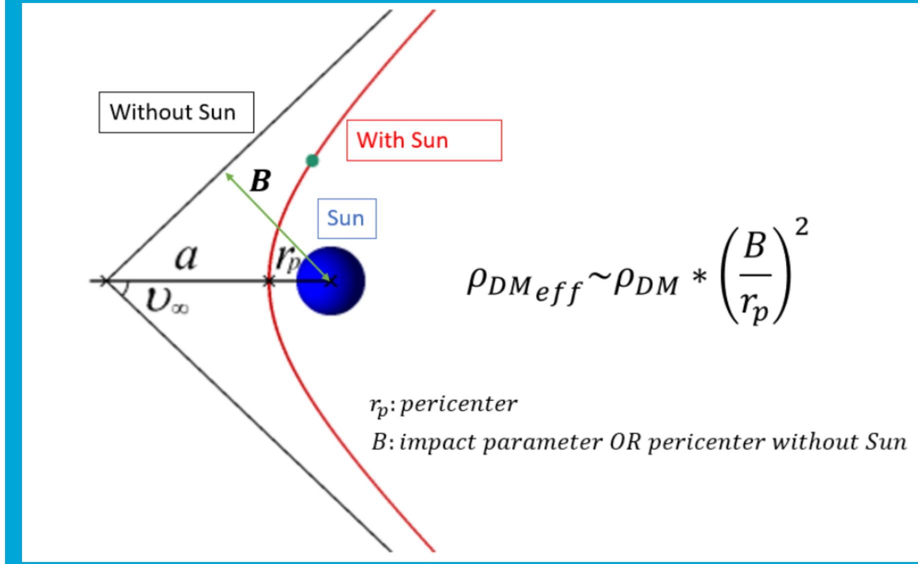
Future Work

- Further Model Development & Analysis:
  - Improvement of orbital models, inclusion of perturbations (=Moon, …)
  - Local enhancement of dark matter density
  - Detailed literature study on DM and PBH models.
- Improved characterisation and use of GNSS orbital data.
- Preliminary data analysis → template matching using sensitivity
- LISA, GOCE ($\sim 10^{-12}$ m/s^2) and gravimeters on the Moon (reduced noise)



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Thank you for listening!

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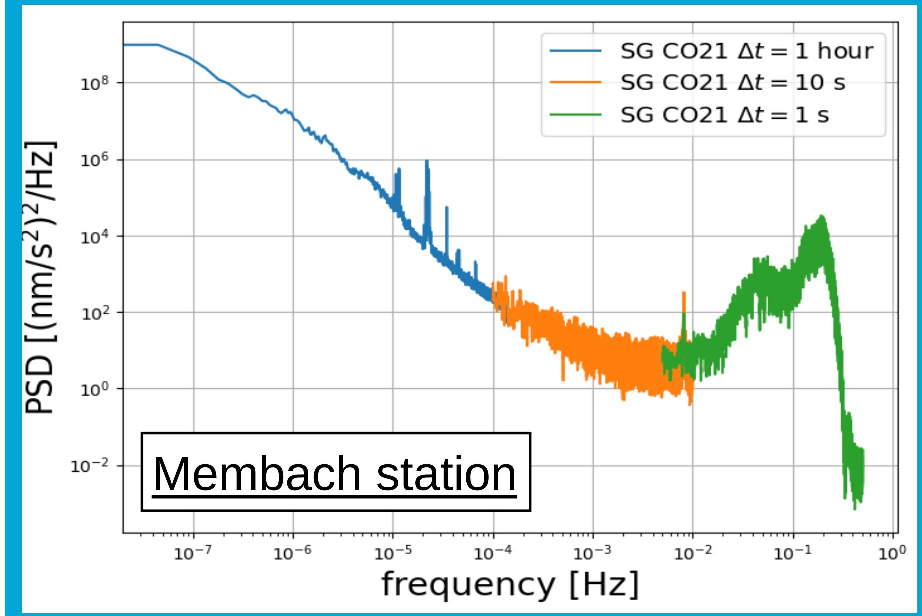

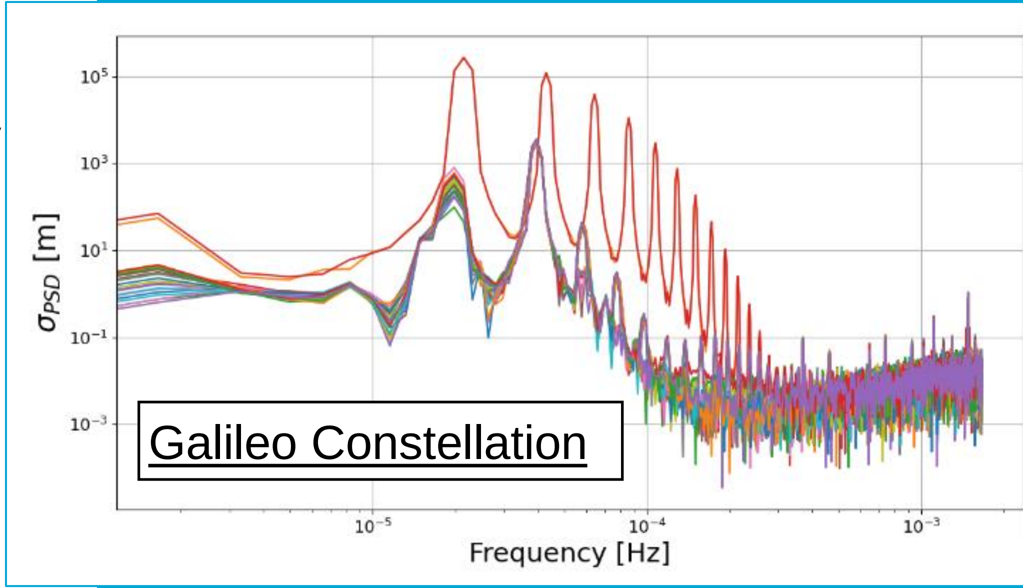

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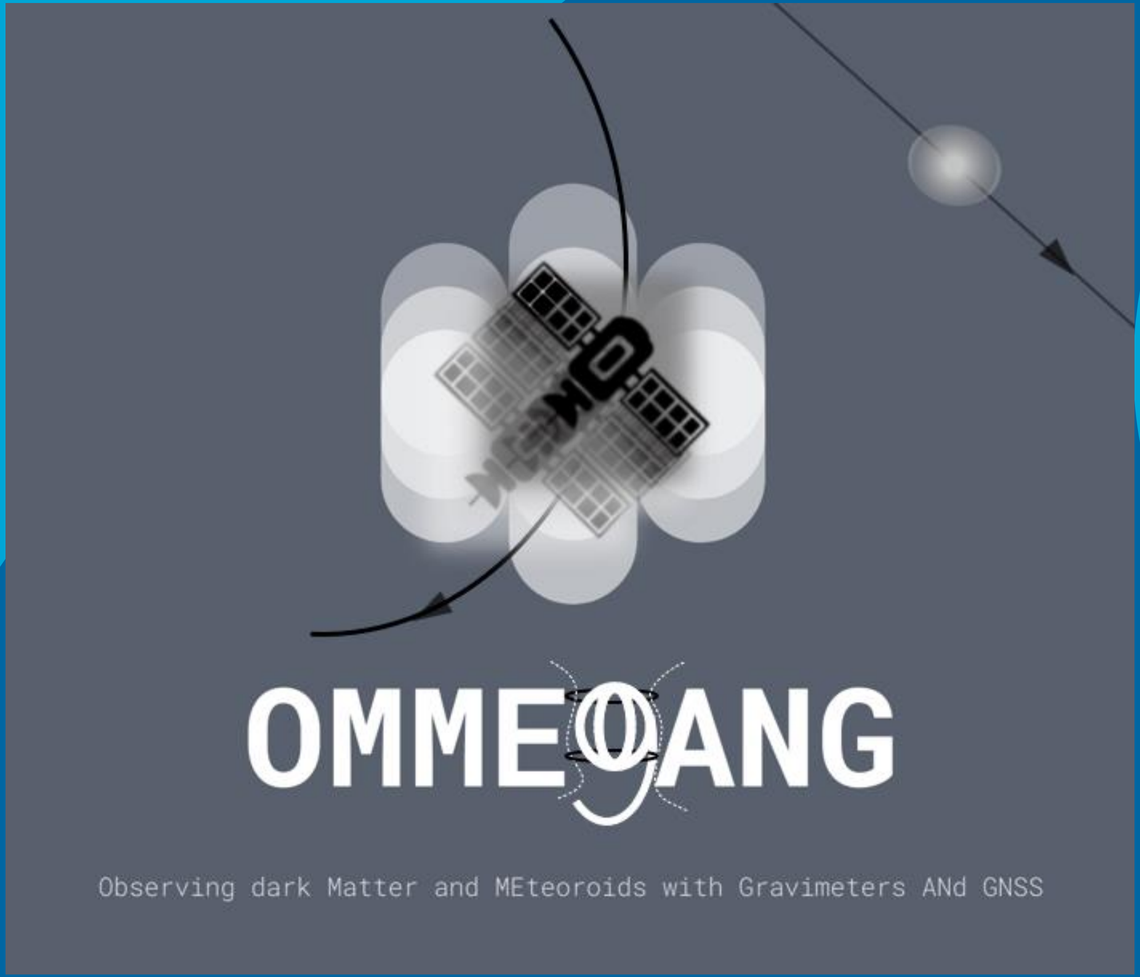

Questions?

Thank you for listening!

Michal Cuadrat-Grzybowski

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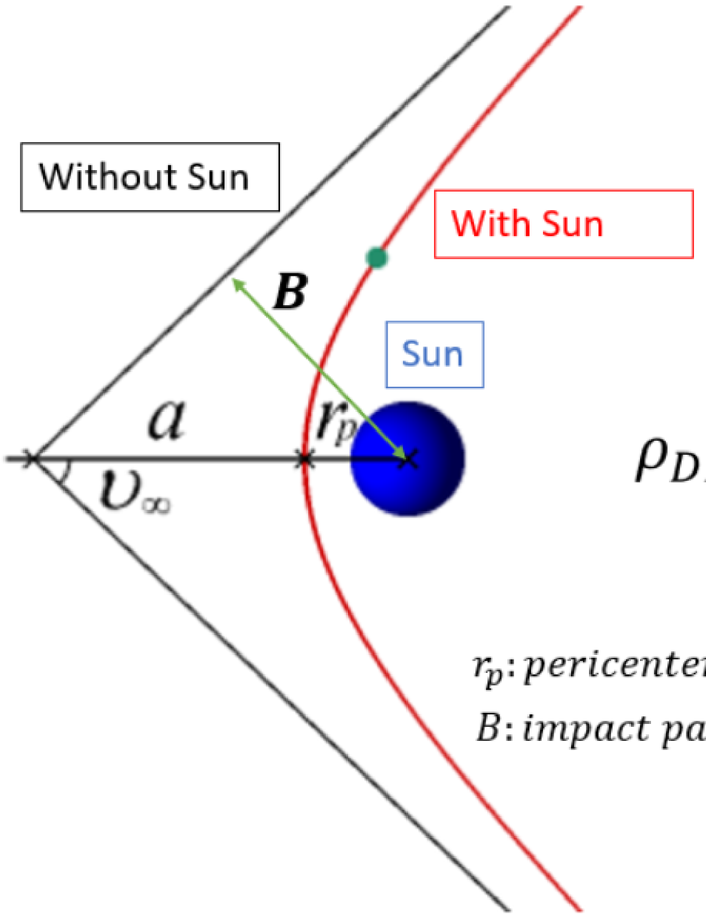
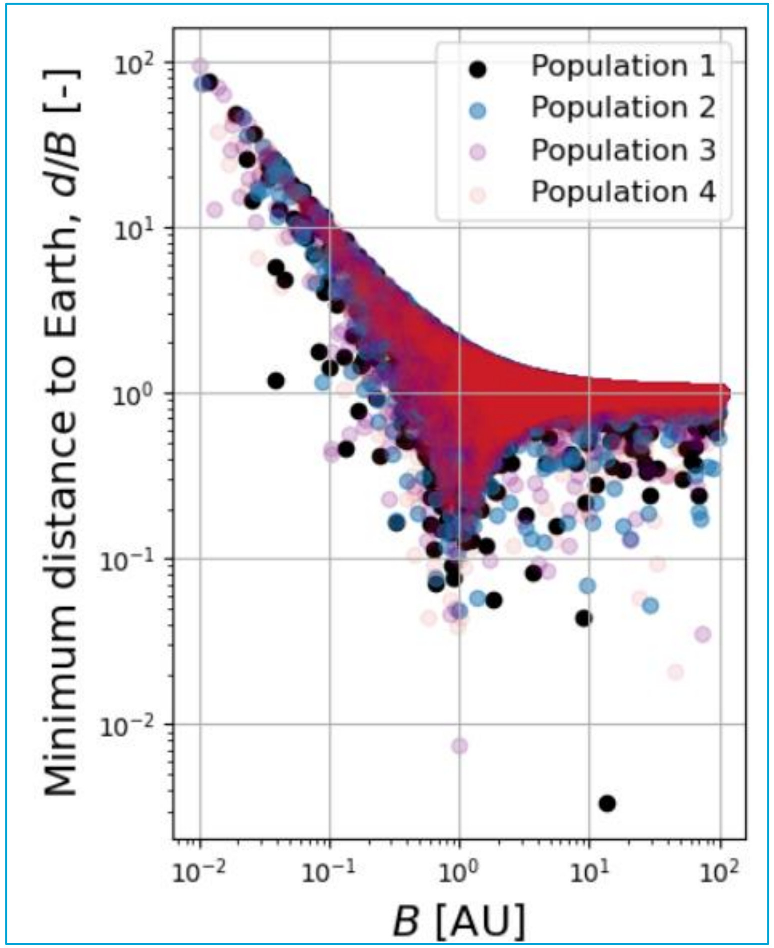
Density local enhancement



$$\rho_{DM_{eff}} \sim \rho_{DM} * \left(\frac{B}{r_p}\right)^2$$

r_p: *pericenter*

B: *impact parameter OR pericenter without Sun*



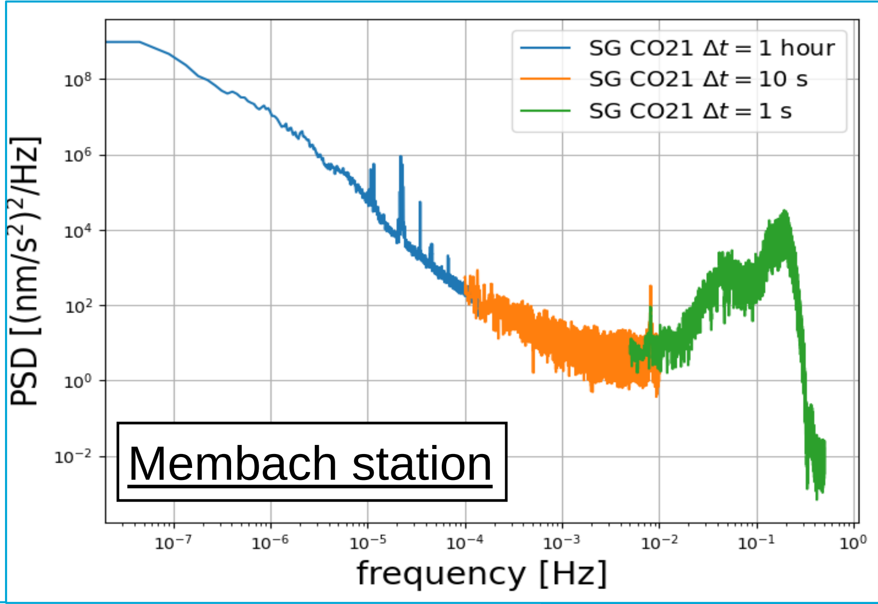
Conclusions

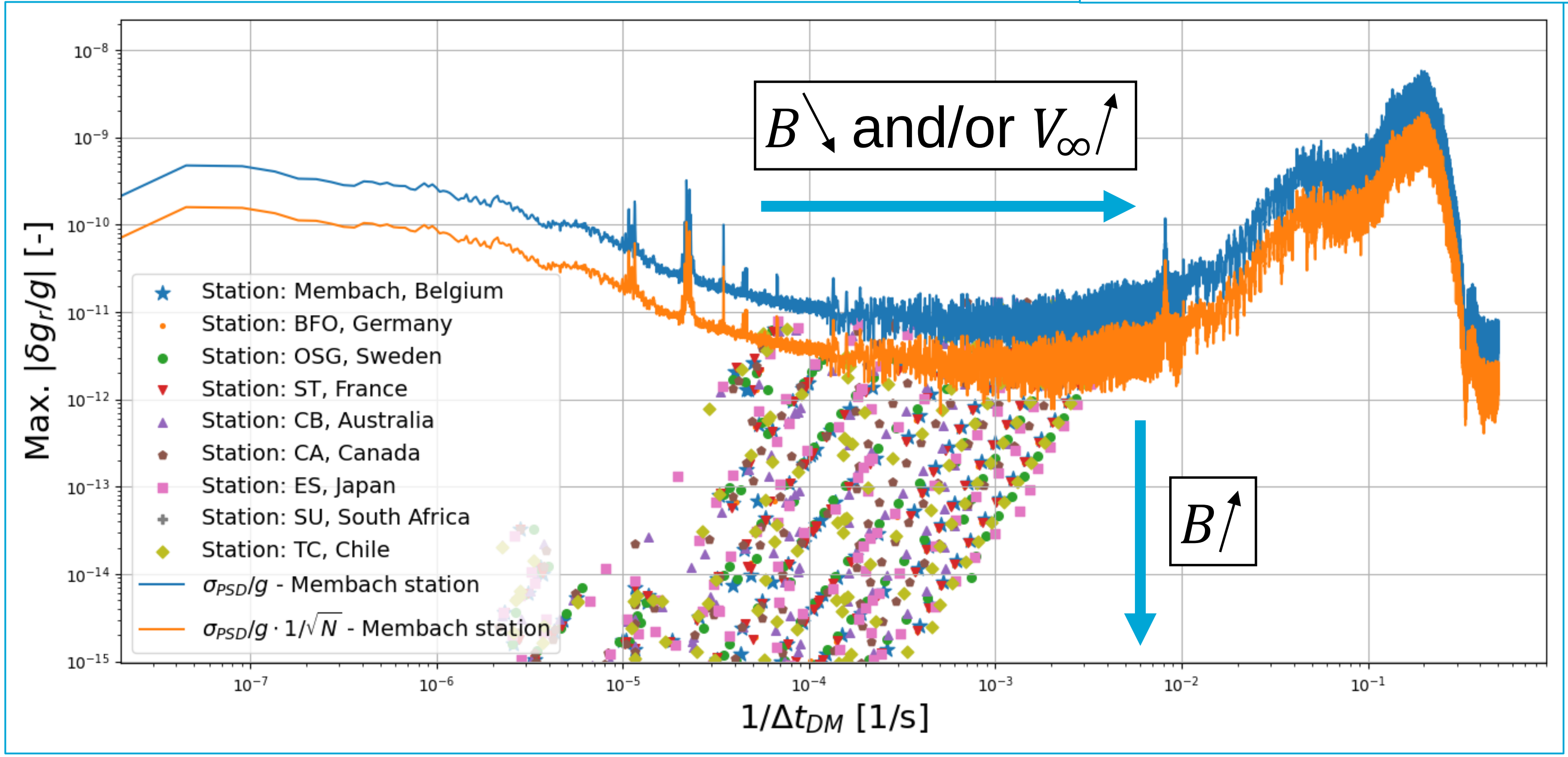
- Capture process seems to be insignificant for abundance estimations,
- Minimum possible distance of 15000 km, with a majority mainly around 0.01 AU (→ problematic for detection).
- Signal successfully modelled and provides a clear pattern for future data analysis:
  - GNSS signal very characteristic = step-like,
  - SG network signal = peak AND highly dependent on the orbital relative orientation (not the case for GNSS),
- Similar sensitivity obtained with min. mass of $\sim 10^{15}$ kg at 15500 km for both gravimeters ($\sim 10^{-10}$ m/s^2) and GNSS (~ 1 cm).

Gravimeter Signals & Sensitivity - Results

Characteristics of sensitivity limits:

- Absolute maximum governed by $\mathbf{GM}/r_{min}^2 \cos(\alpha_{r_{min}})$,
- Minimum mass of $\sim 10^{15}$ kg (at a distance of 15000 km).
- Signal shape essential as a basis for future *template matching*.





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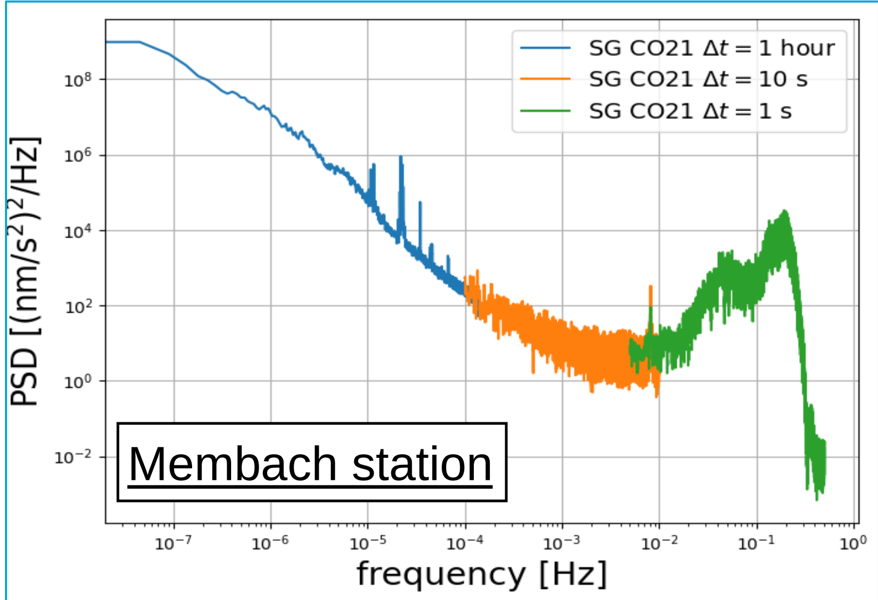
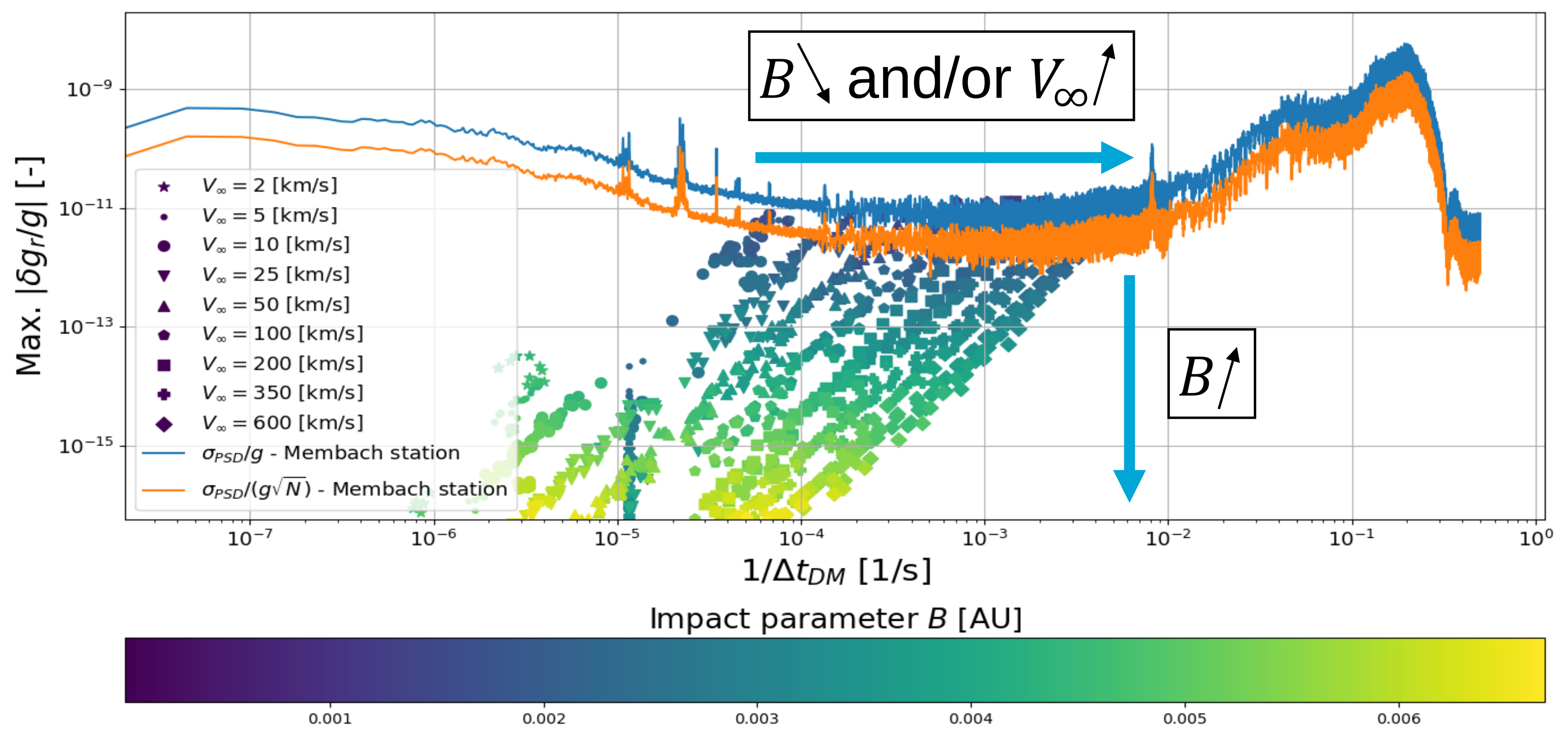
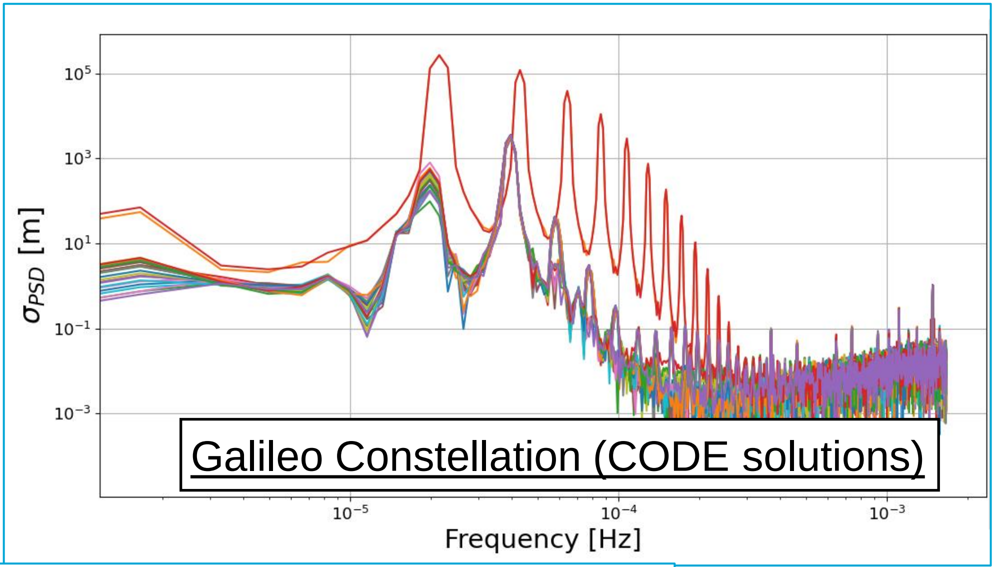


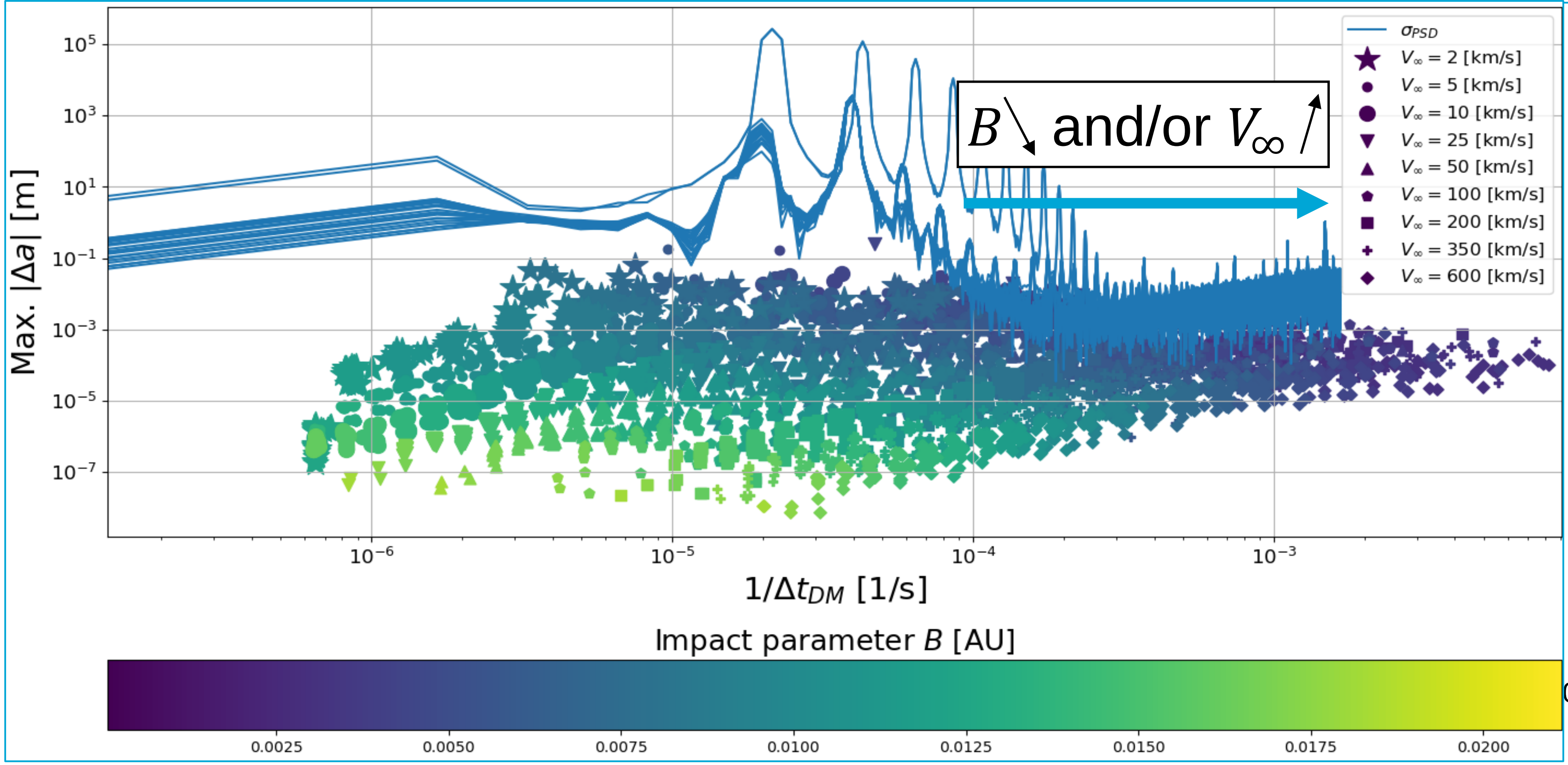


GNSS Signals & Sensitivity - Results

Characteristics of sensitivity limits:

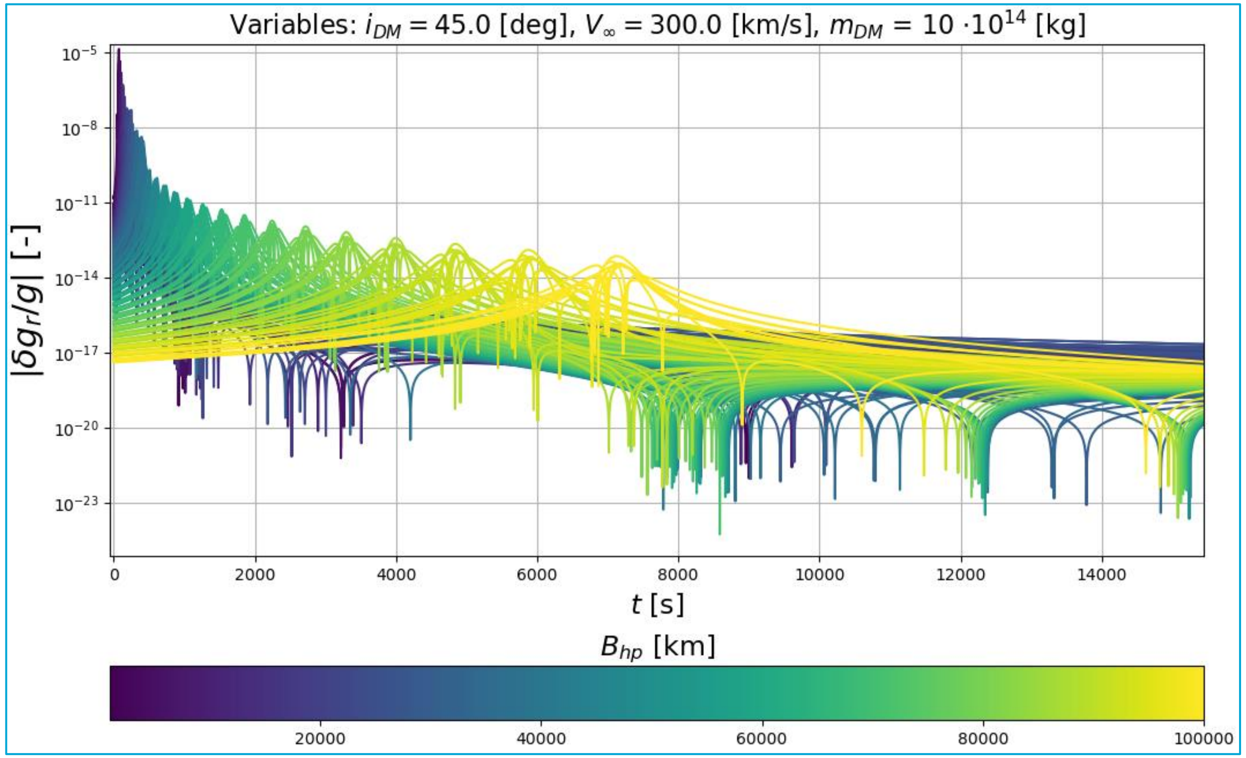
- Absolute maximum governed by $\mathbf{GM}/r_{min}^2$,
- Minimum mass of $\sim 10^{15}$ kg (at a distance of 15000-20000 km).
- Signal shape essential as a basis for future *template matching*.

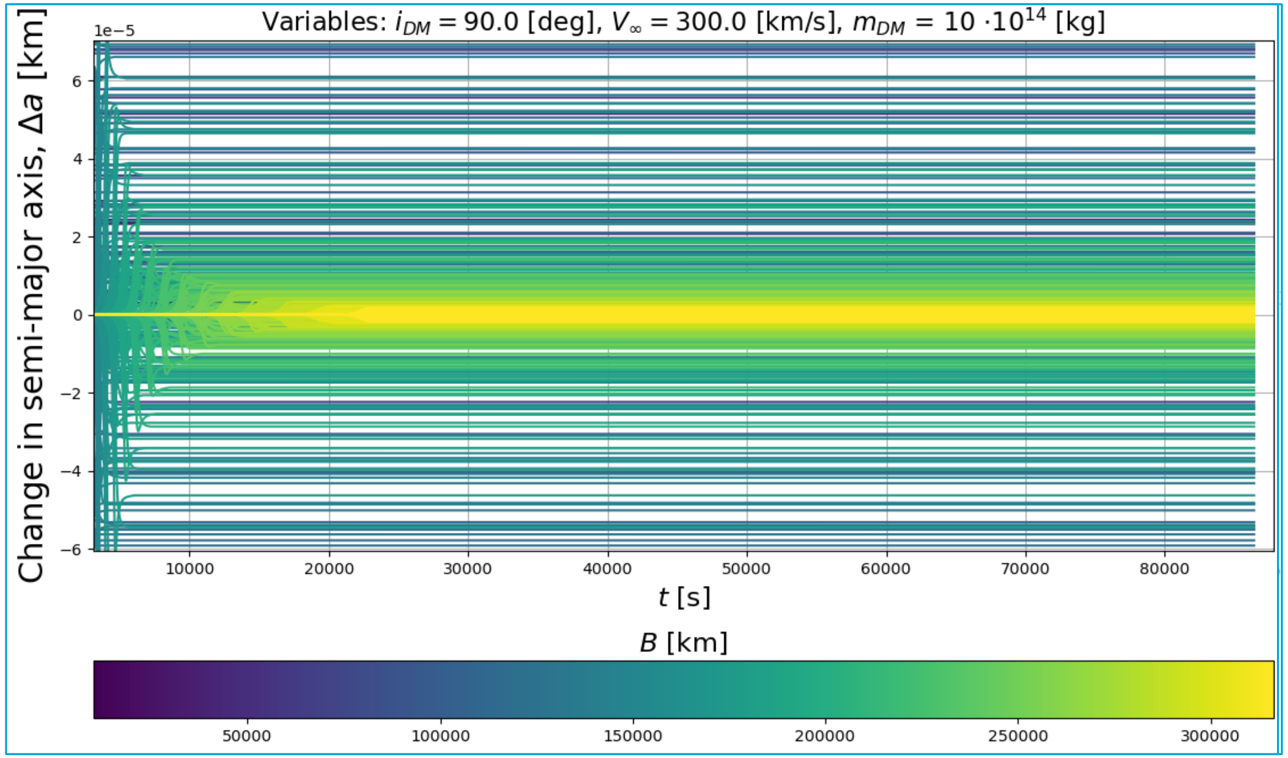




Signals Results Sensitivity

- Effects of B: change in signal duration and maximum
- Effects of V_∞: theoretically changes only signal duration → initial condition problems

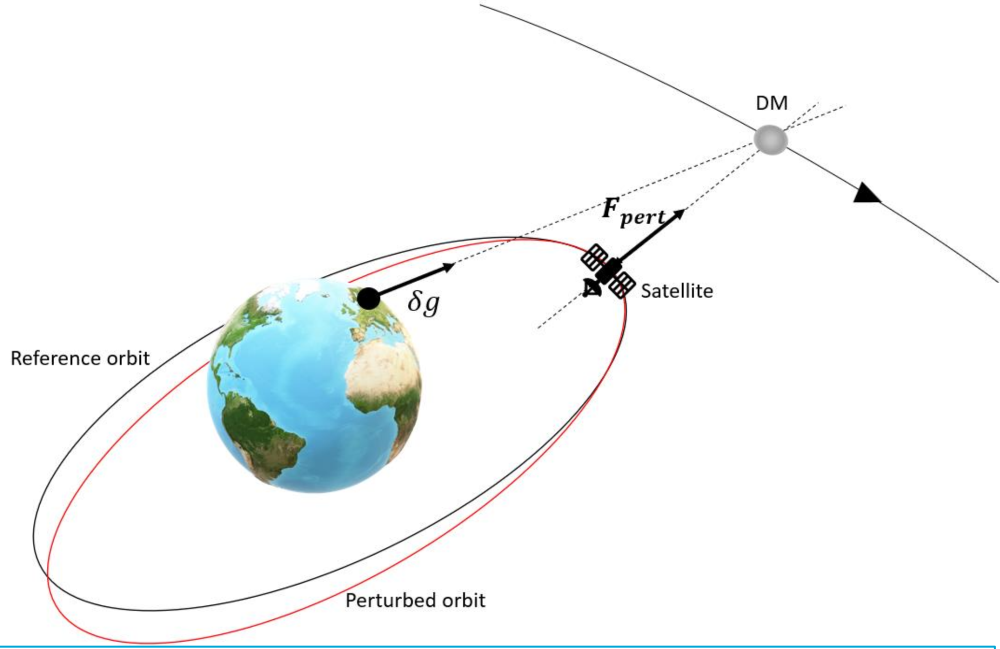




GNSS Signals

From an acceleration profile to observables:

- GNSS orbit assumed as Keplerian,
- Compute third-body perturbation,
- Translate satellite reaction into orbital elements (= observables).



$$\frac{\delta \boldsymbol{a}(t)}{g(t)} = -\frac{1}{g(t)} \cdot \mu_{DM} \cdot \left(\frac{\boldsymbol{r} - \boldsymbol{r}_{DM}}{||\boldsymbol{r} - \boldsymbol{r}_{DM}||^3} + \frac{\boldsymbol{r}_{DM}}{||\boldsymbol{r}_{DM}||^3} \right)$$

$$\frac{da}{dt} = \frac{2 \cdot a^2}{\sqrt{\mu p}} \cdot \left[e \sin(\theta) \cdot a_r + p/r_0 \cdot a_\theta \right],$$

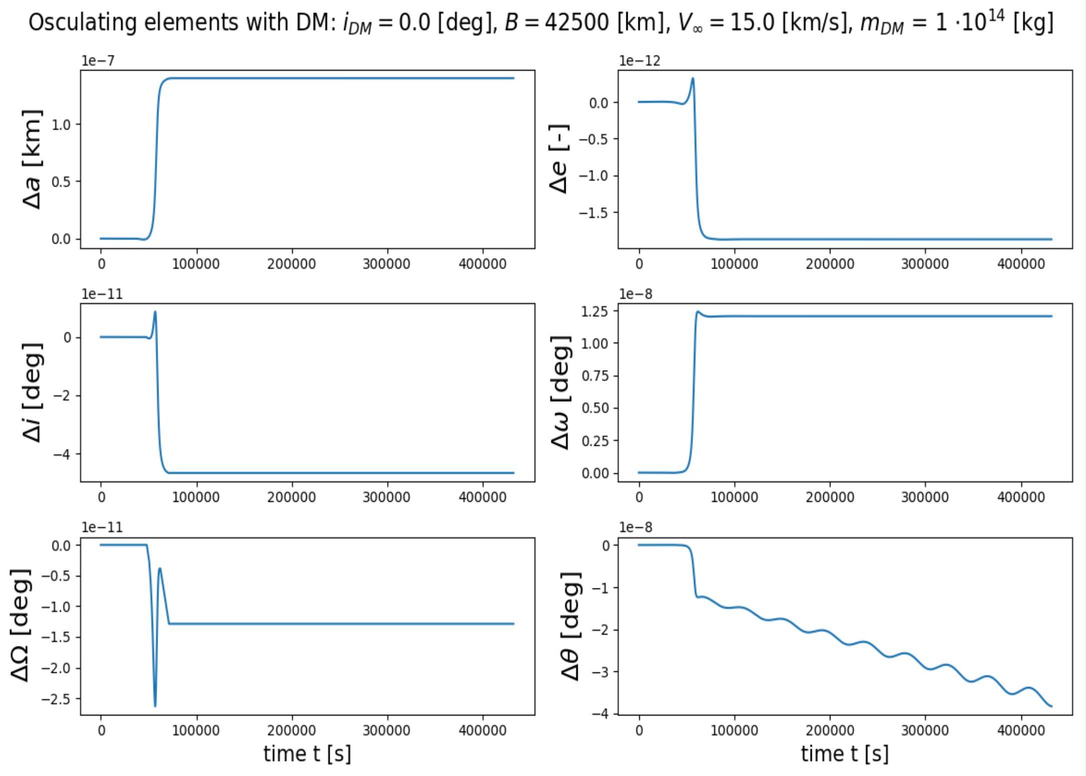
$$\frac{de}{dt} = \sqrt{\frac{p}{\mu}} \cdot \left[a_r \sin(\theta) + a_\theta \cdot \left(\frac{e r_0}{p} + (1 + \frac{r_0}{p}) \cos(\theta) \right) \right],$$

$$\frac{d\theta}{dt} = \frac{\sqrt{\mu \cdot p}}{r_0^2} - \frac{1}{e} \sqrt{\frac{p}{\mu}} \left(-a_r \cos(\theta) + a_\theta (1 + \frac{r_0}{p}) \sin(\theta) \right),$$

$$\frac{di}{dt} = a_z \cdot \frac{r_0}{\sqrt{\mu p}} \cdot \cos(\theta + \omega),$$

$$\frac{d\omega}{dt} = -\frac{d\theta}{dt} + \frac{\sqrt{\mu \cdot p}}{r_0^2} - a_z \frac{r_0}{\sqrt{\mu p}} \cot(i) \sin(\theta + \omega),$$

$$\frac{d\Omega}{dt} = a_z \cdot \frac{r_0}{\sqrt{\mu p}} \cdot \sin(\theta + \omega)/\sin(i),$$



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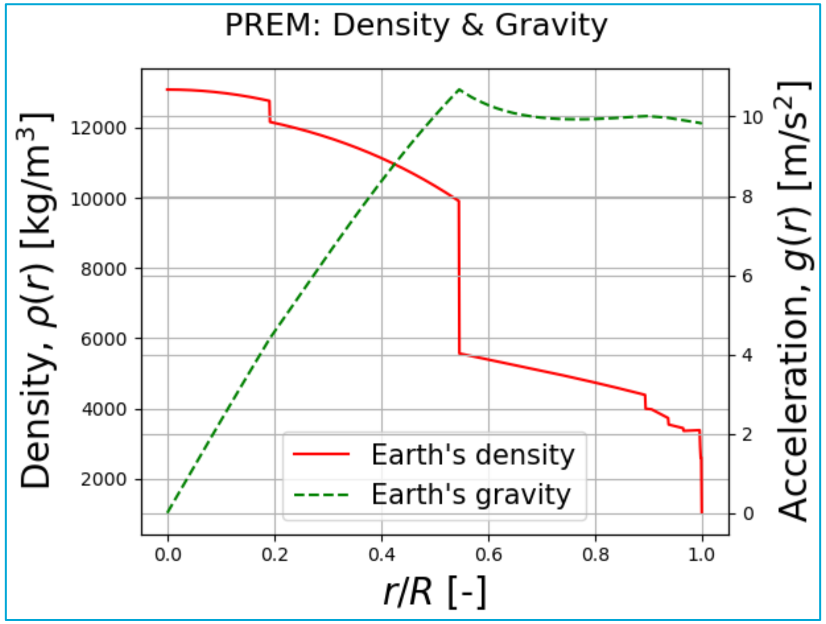
Gravimeter Signals

Characteristics of acceleration profiles:

- Orbits can be inside of Earth → PREM Density model,
- Simulate updated equation of motion from integrated density model,
- Compute signal from gravimeter station and DM positions.
- Radial direction!



$$\frac{d^2 \boldsymbol{r}_{DM}}{dt^2} = -\frac{G(M_{enc}(r_{DM}) + m_{DM})}{r_{DM}^3} \cdot \boldsymbol{r}_{DM}$$

$$\frac{\delta g(t)}{g} = -\frac{1}{g} \cdot \mu_{DM} \cdot \left(\frac{\boldsymbol{r}_g - \boldsymbol{r}_{DM}}{||\boldsymbol{r}_g - \boldsymbol{r}_{DM}||^3} + \frac{\boldsymbol{r}_{DM}}{||\boldsymbol{r}_{DM}||^3} \right) \cdot \frac{\boldsymbol{r}_g}{||\boldsymbol{r}_g||}$$