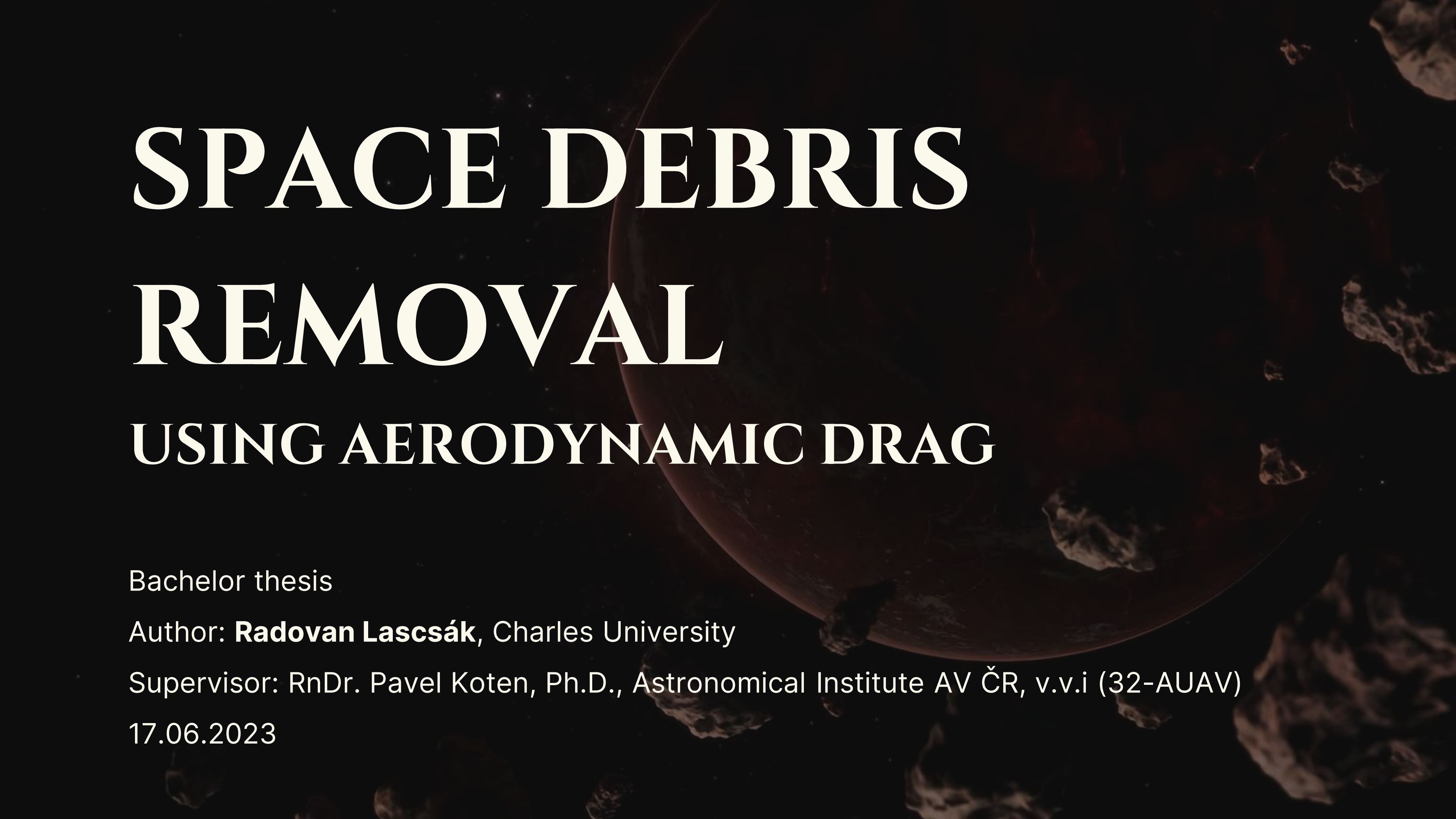


SPACE DEBRIS REMOVAL

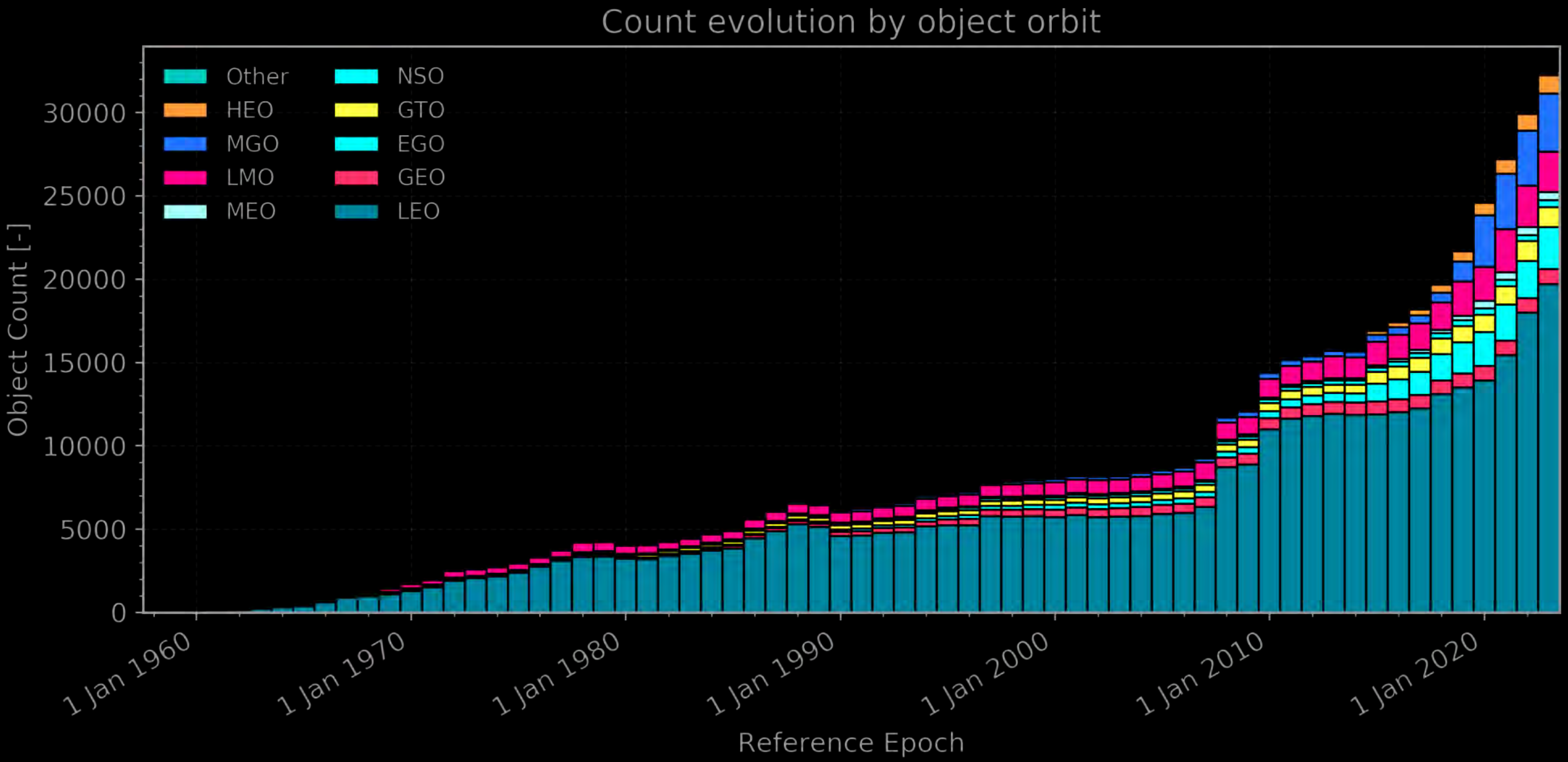
USING AERODYNAMIC DRAG

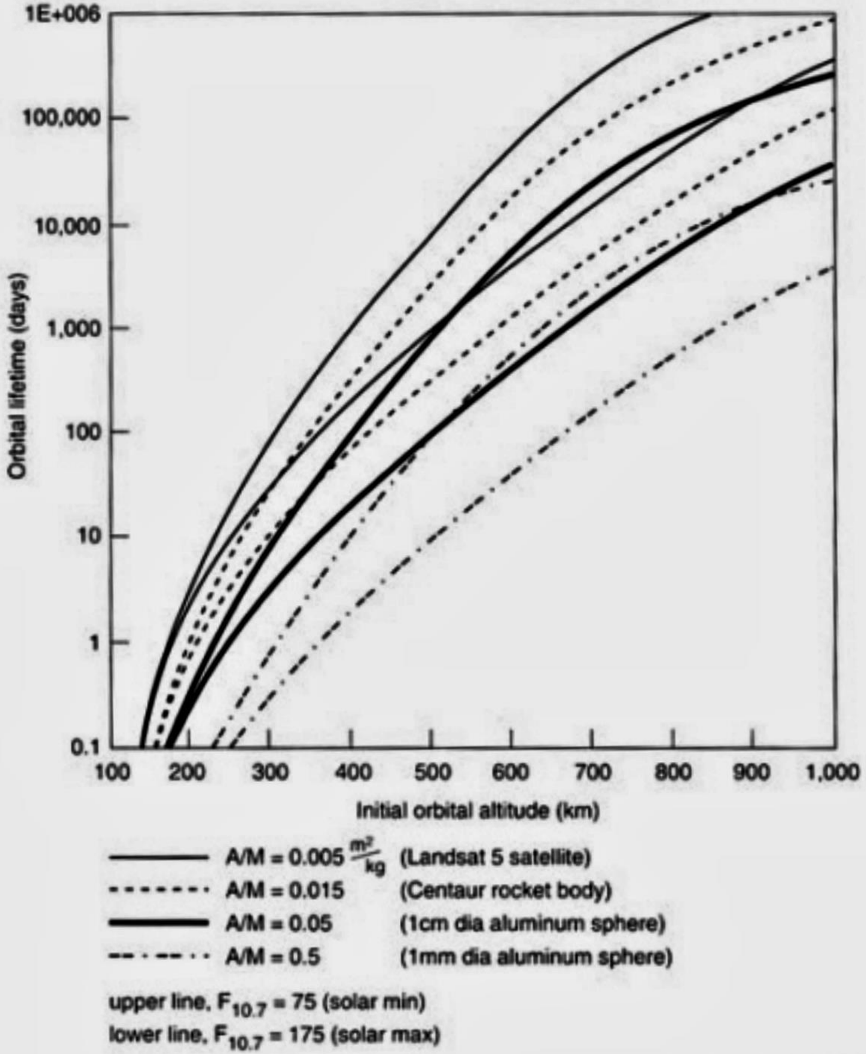
Bachelor thesis

Author: **Radovan Lascsák**, Charles University

Supervisor: RnDr. Pavel Koten, Ph.D., Astronomical Institute AV ČR, v.v.i (32-AUAV)

17.06.2023


Count evolution by object orbit
Other
HEO
MGO
LMO
MEO
NSO
GTO
EGO
GEO
LEO
Object Count [-]
30000
25000
20000
15000
10000
5000
0
1 Jan 1960
1 Jan 1970
1 Jan 1980
1 Jan 1990
1 Jan 2000
1 Jan 2010
1 Jan 2020
Reference Epoch


1E+006
100,000
10,000
1,000
100
10
1
0.1
Orbital lifetime (days)
100
200
300
400
500
600
700
800
900
1,000
Initial orbital altitude (km)
A/M = 0.005 $\frac{m^2}{kg}$ (Landsat 5 satellite)
A/M = 0.015 (Centaur rocket body)
A/M = 0.05 (1cm dia aluminum sphere)
A/M = 0.5 (1mm dia aluminum sphere)
upper line, $F_{10.7}$ = 75 (solar min)
lower line, $F_{10.7}$ = 175 (solar max)

CLASSIFICATION OF SPACE DEBRIS

	DIAMETER	COUNT	DAMAGE TO SPACECRAFT	PROBLEMATIC REGION
LARGE	> 10 cm	$> 30\,000$	Catastrophic breakup	> 650 km
MIDDLE	$0{,}1$ cm – 10 cm	$\sim 10^{7}$	Loss of spacecraft capability	> 750 km
SMALL	$< 0{,}1$ cm	$\sim 10^{12}$	Degradation of surface	> 1000 km

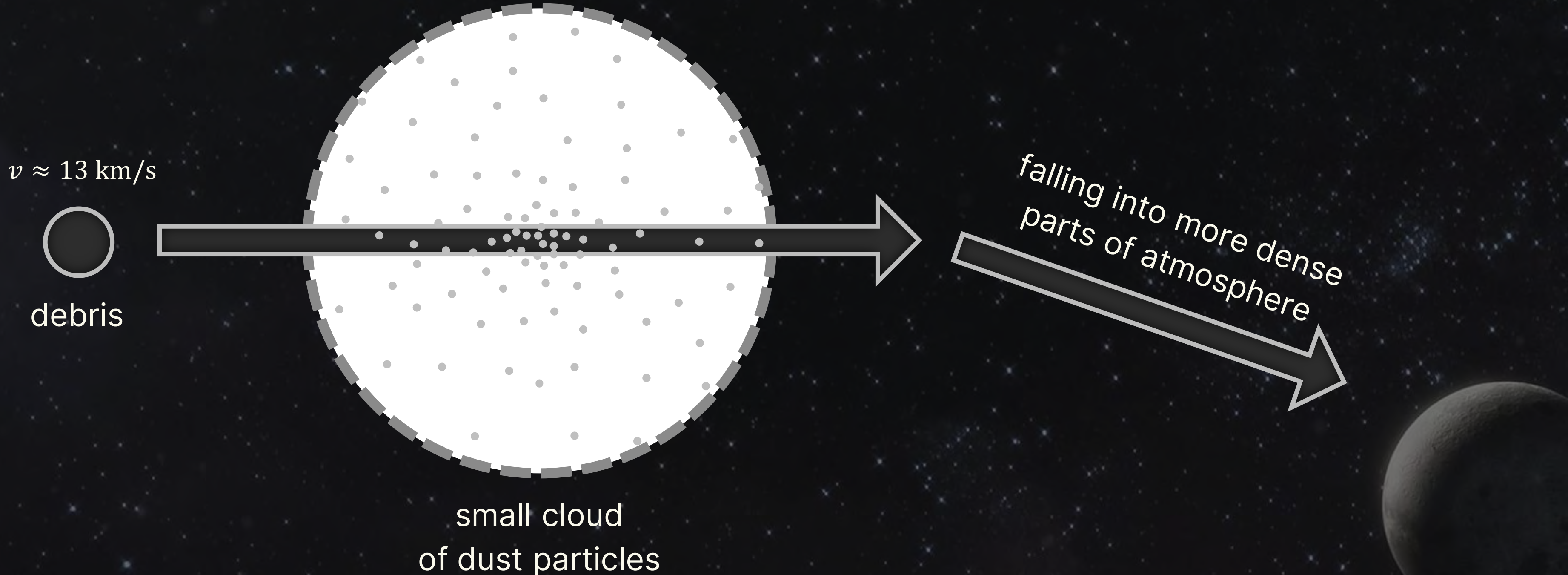
Method Of Local Aerodynamic Drag

(MOLAD)

MOLAD's FOCUS

- LEO ($\sim 1000\ \mathrm{km}$)
- Middle sized space debris ($\sim 1\ \mathrm{cm}$)
- High relative velocity ($\sim 13\ \mathrm{km/s}$)

MOLAD's FUNDAMENTALS



$v \approx 13\ \mathrm{km/s}$

debris

small cloud
of dust particles

falling into more dense
parts of atmosphere

PHASE 0

Intro

Orbital debris problem.
Introduction to
MOLAD.

PHASE 1

Cloud

Stability and density
distribution of
a cloud.

PHASE 2

Collision

Velocity reduction
during collision of
the cloud and debris

PHASE 3

Ablation

Orbital debris lifetime
before its ablation
in atmosphere

THEORETICAL 1D MODEL

EXPANSION OF CLOUD IN VACUUM

Volume of element

Pressure

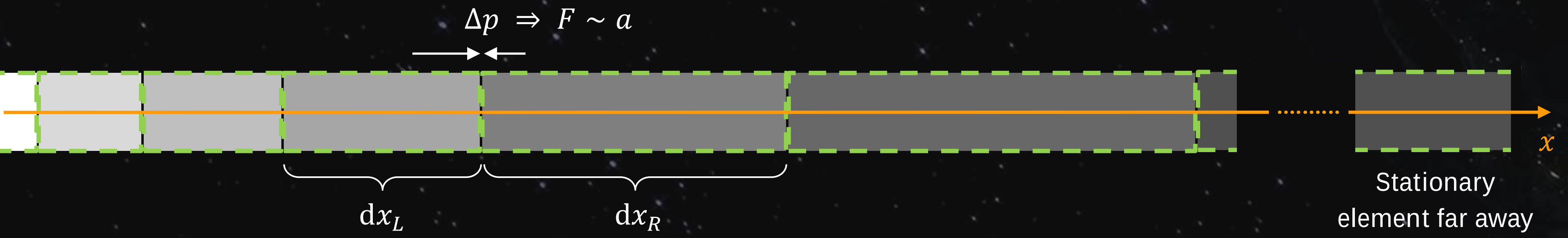
Boltzmann constant

Temperature

Number of particles
in element

$$p\mathrm{d}V = kT\mathrm{d}N$$

Local approximation by ideal gas



THEORETICAL 1D MODEL

EXPANSION OF CLOUD IN VACUUM

Volume of element

Pressure

Boltzmann constant

Temperature

Number of particles in element

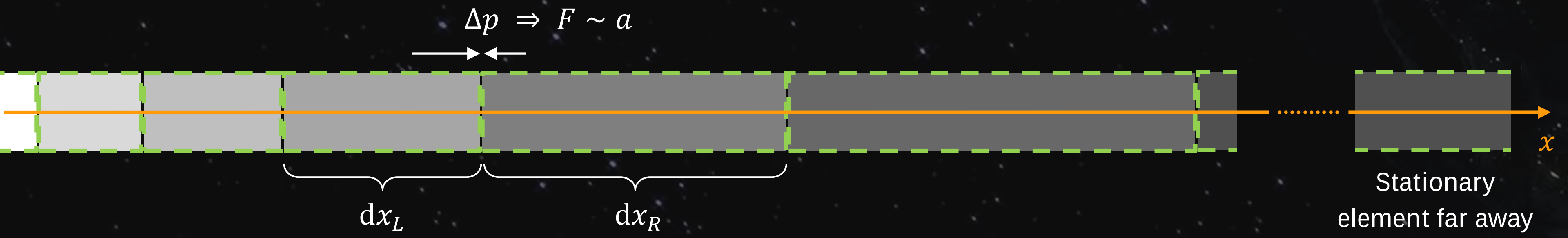
$$p\mathrm{d}V = kT\mathrm{d}N$$

Local approximation by ideal gas

Mass of particle

$$a = \frac{kT}{m_C}\left(\frac{1}{\mathrm{d}x_L} - \frac{1}{\mathrm{d}x_R}\right)$$

Acceleration



THEORETICAL 1D MODEL

EXPANSION OF CLOUD IN VACUUM

Pressure

Volume of element

Boltzmann constant

Temperature

Number of particles in element

$$pdV = kTdN$$

Local approximation by ideal gas

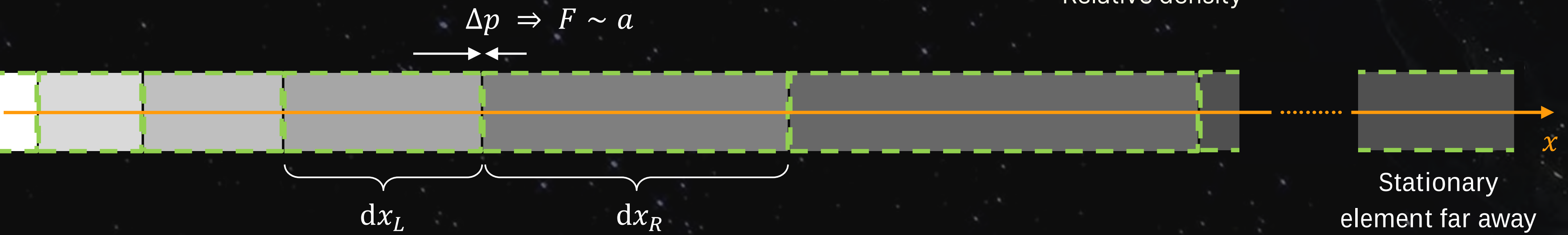
Mass of particle

$$a = \frac{kT}{m_C}\left(\frac{1}{dx_L} - \frac{1}{dx_R}\right)$$

Acceleration

$$\rho_r(t) = \frac{dx_L(t=0) + dx_R(t=0)}{dx_L(t) + dx_R(t)}$$

Relative density



Theoretical 1D model

Expansion of cloud in vacuum

Important parameters		Studied range	
m_C	Mass of particles	10^{-18} kg	10^{-9} kg
r	Radius of cloud at beginning	0,1 cm	50 cm
T	Temperature	50 K	350 K
t	Time of collision	10 s	

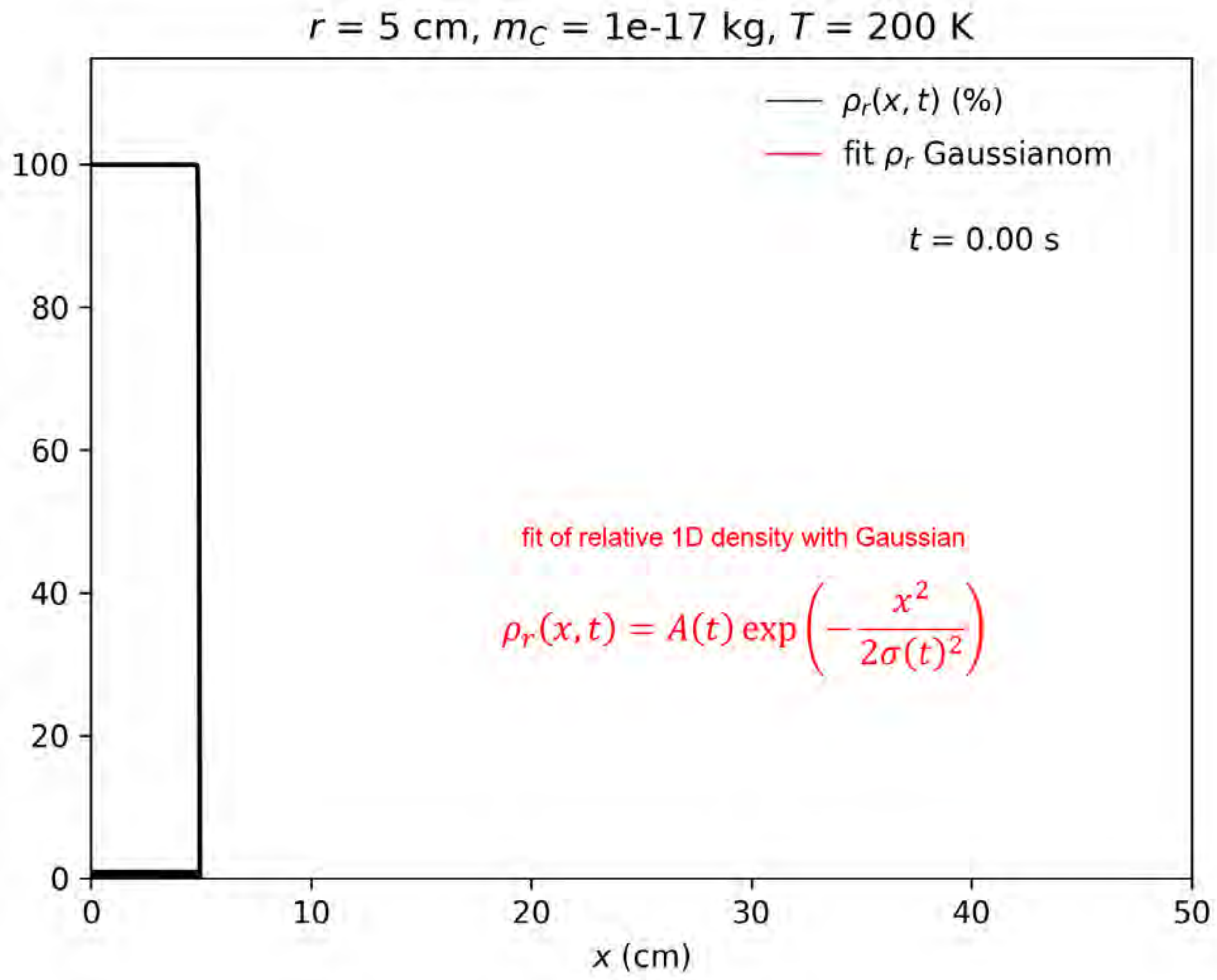
Mass of particle

$$a = \frac{kT}{m_C}\left(\frac{1}{\mathrm{d}x_L} - \frac{1}{\mathrm{d}x_R}\right)$$

Acceleration

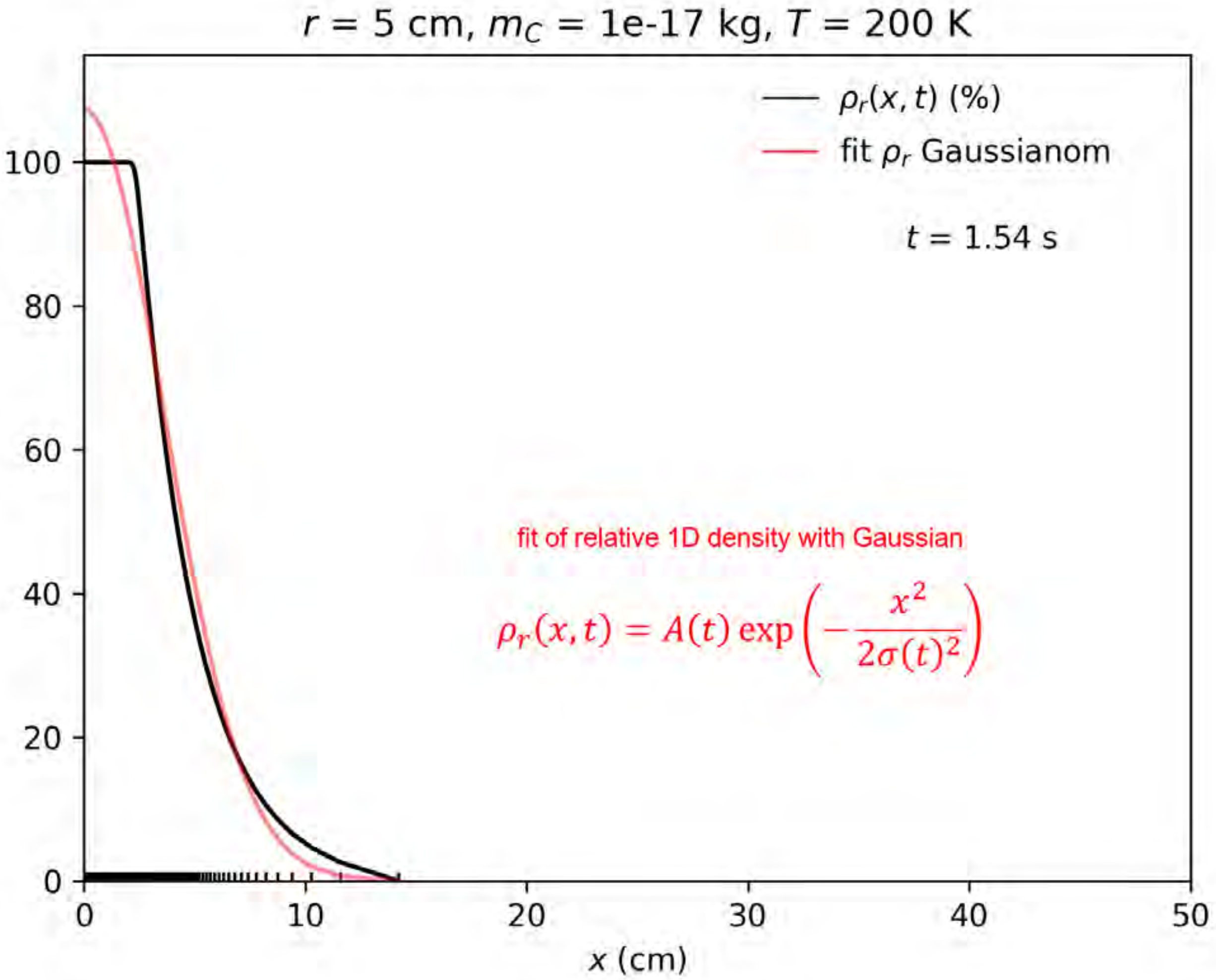
$$\rho_r(t) = \frac{\mathrm{d}x_L(t=0) + \mathrm{d}x_R(t=0)}{\mathrm{d}x_L(t) + \mathrm{d}x_R(t)}$$

Relative density



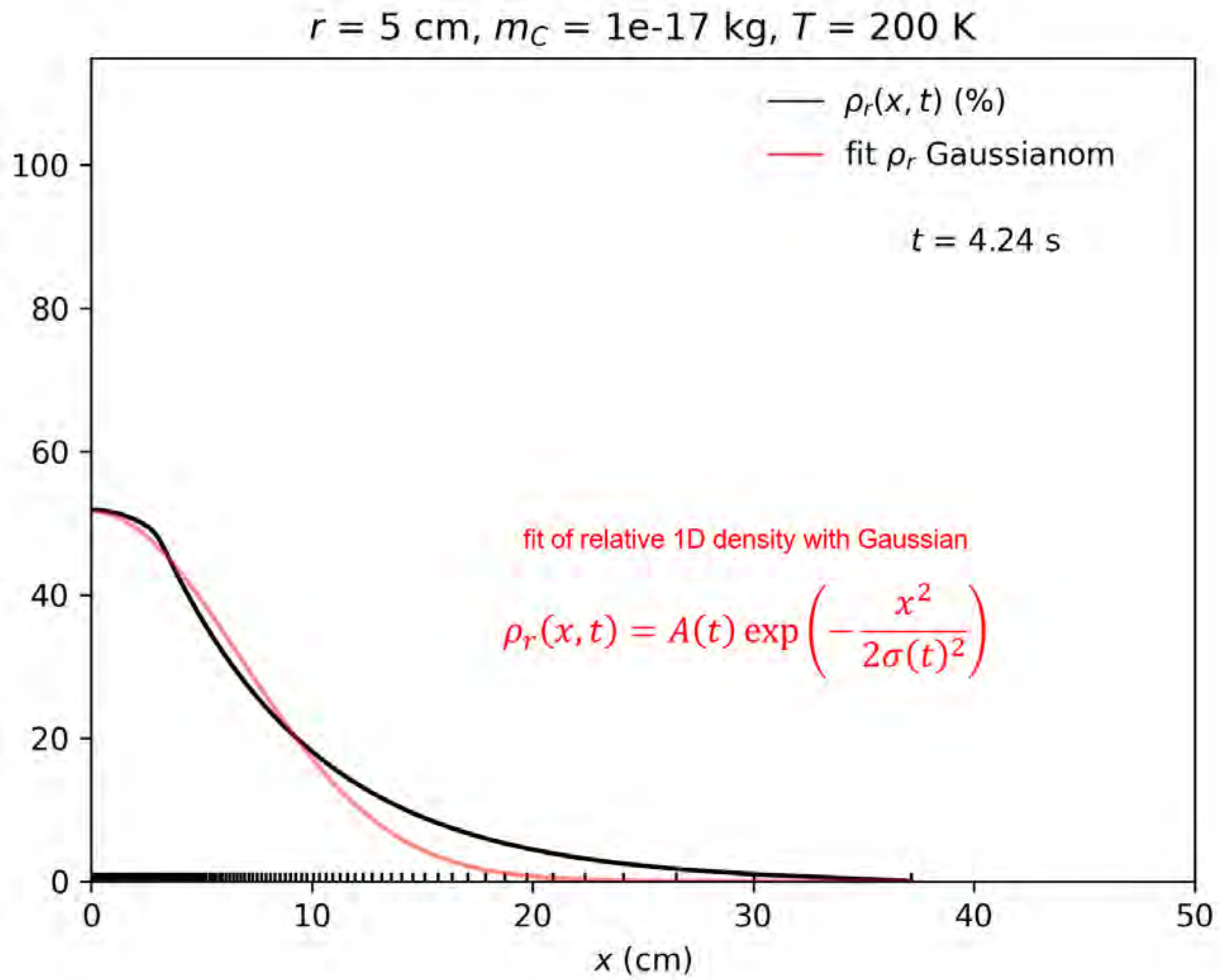
fit of relative 1D density with Gaussian

$$\rho_r(x,t) = A(t)\exp\left(-\frac{x^2}{2\sigma(t)^2}\right)$$



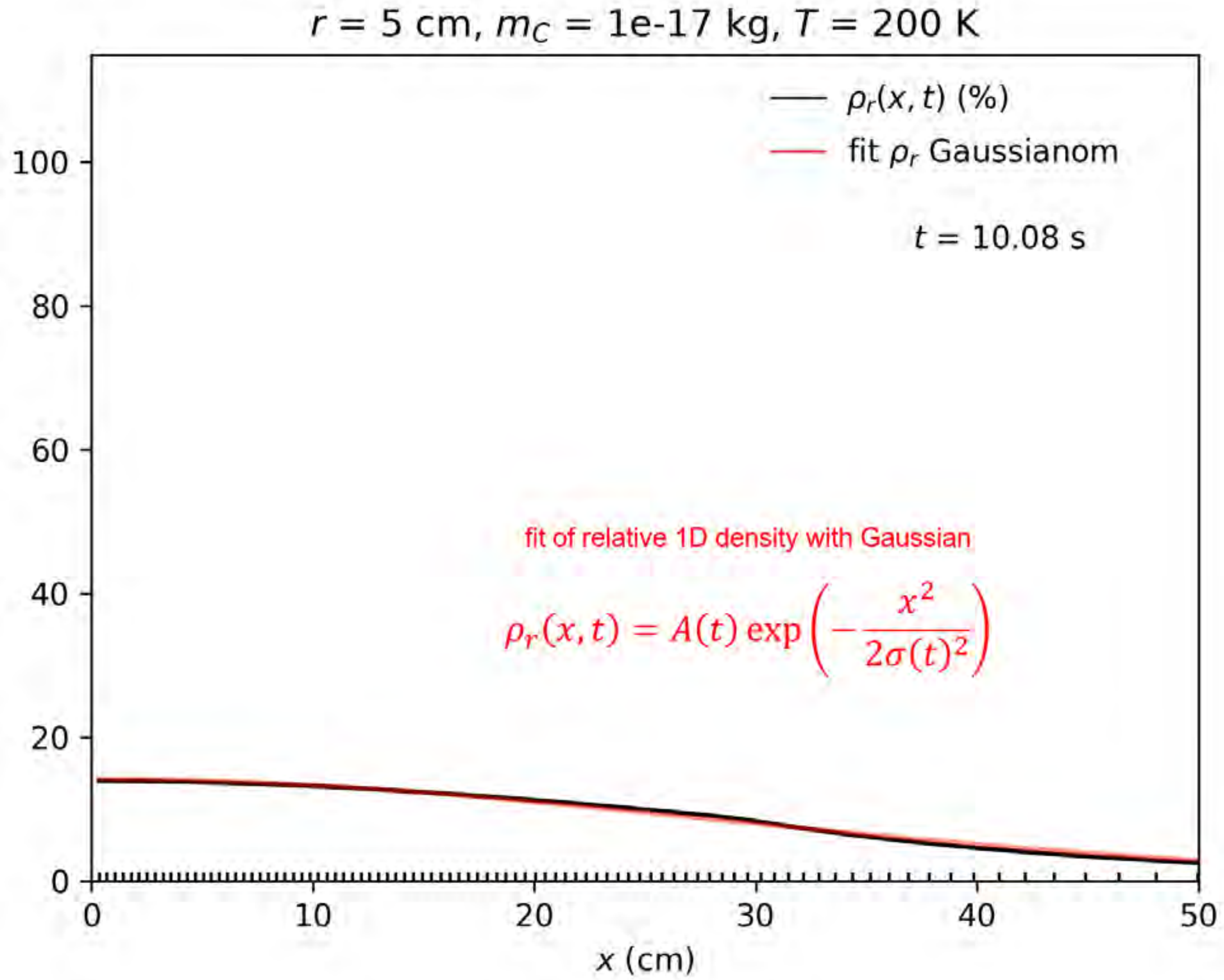
fit of relative 1D density with Gaussian

$$\rho_r(x,t) = A(t)\exp\left(-\frac{x^2}{2\sigma(t)^2}\right)$$



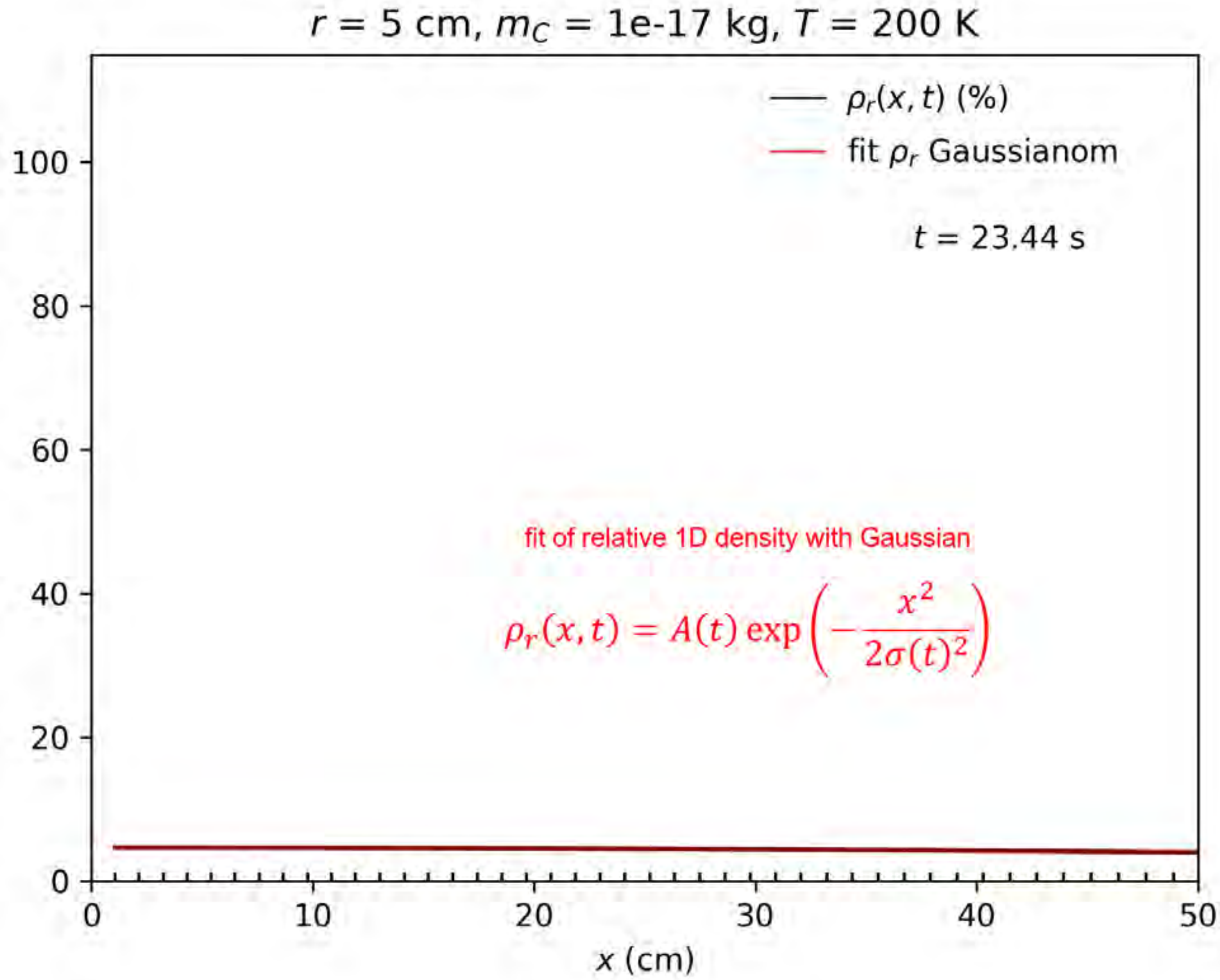
fit of relative 1D density with Gaussian

$$\rho_r(x,t) = A(t)\exp\left(-\frac{x^2}{2\sigma(t)^2}\right)$$



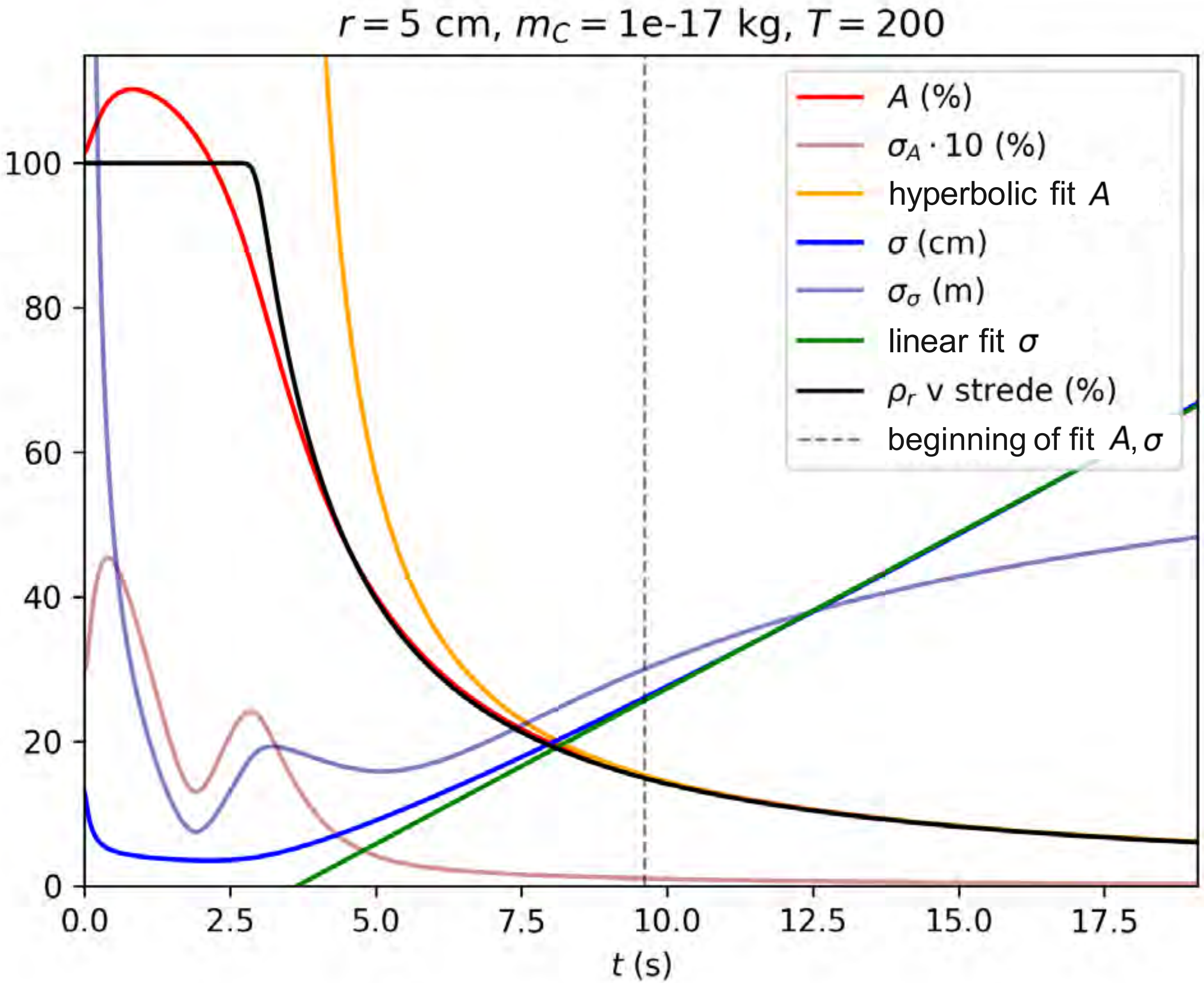
fit of relative 1D density with Gaussian

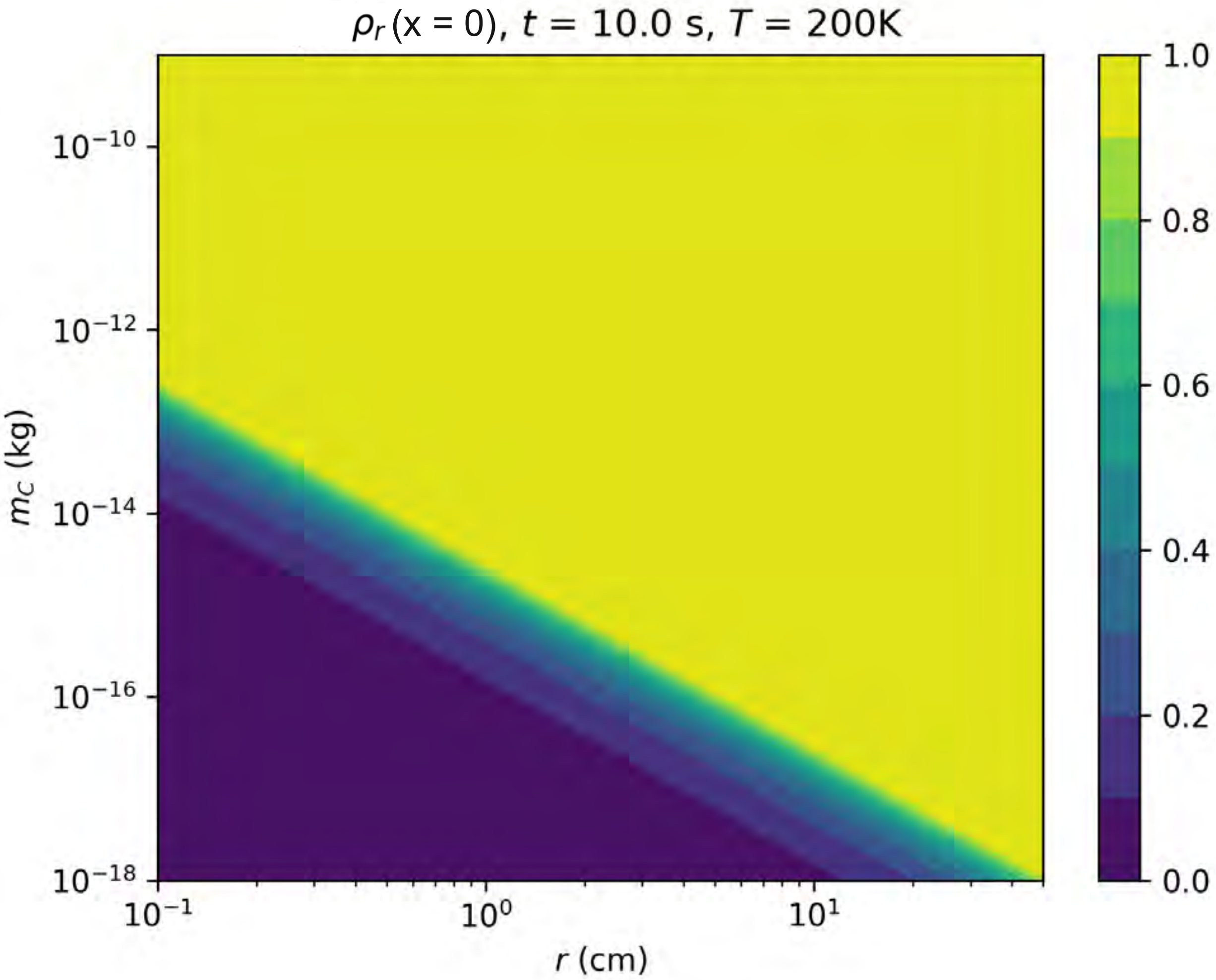
$$\rho_r(x,t) = A(t)\exp\left(-\frac{x^2}{2\sigma(t)^2}\right)$$

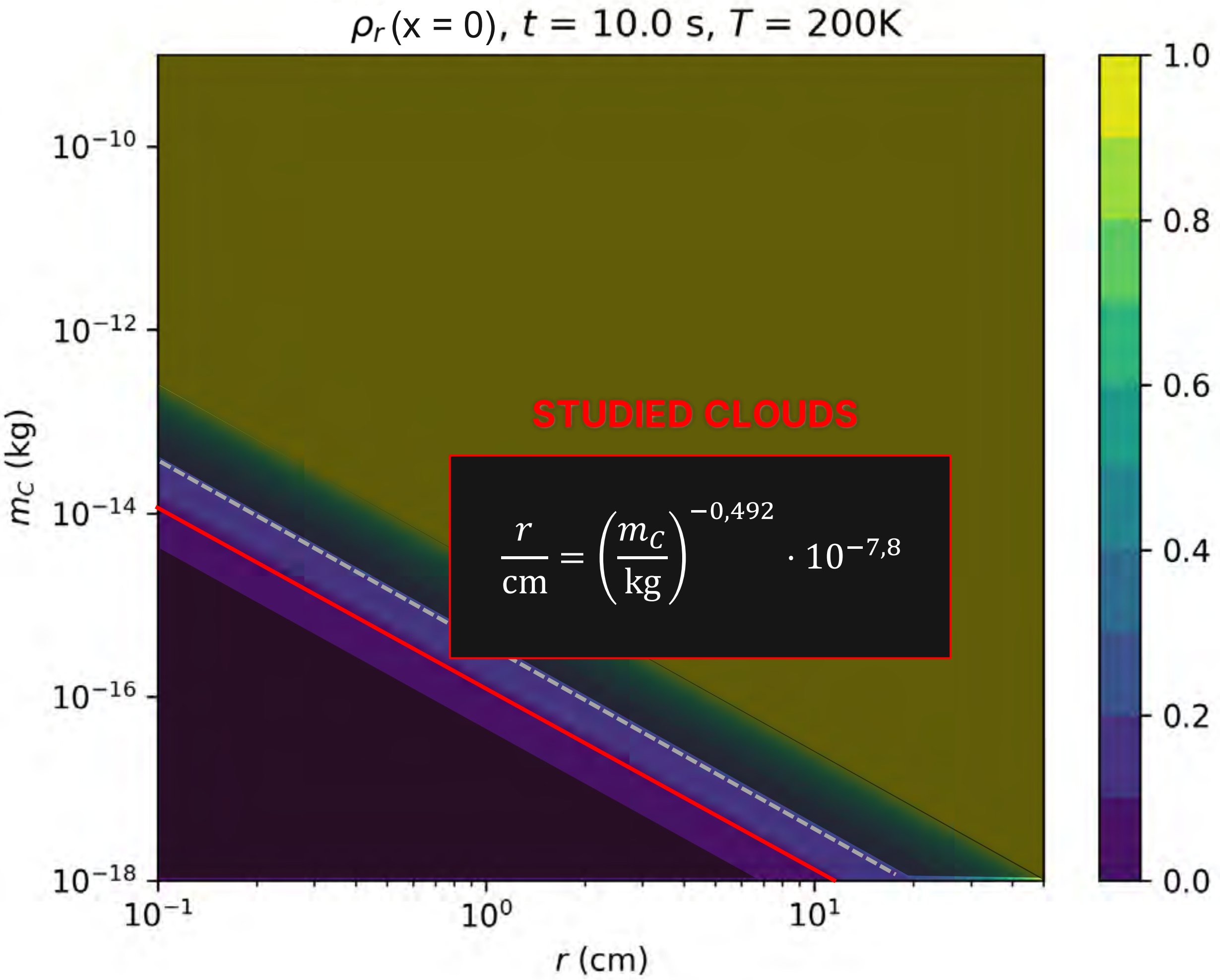


fit of relative 1D density with Gaussian

$$\rho_r(x,t) = A(t)\exp\left(-\frac{x^2}{2\sigma(t)^2}\right)$$


r = 5 cm, m_C = 1e-17 kg, T = 200
A (%)
σ_A · 10 (%)
hyperbolic fit A
σ (cm)
σ_σ (m)
linear fit σ
ρ_r v strede (%)
beginning of fit A, σ
100
80
60
40
20
0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
t (s)


ρ_r (x = 0), t = 10.0 s, T = 200K
m_C (kg)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-1}
10^{0}
10^{1}
r (cm)
1.0
0.8
0.6
0.4
0.2
0.0



STUDIED CLOUDS

$$\frac{r}{\mathrm{cm}} = \left(\frac{m_C}{\mathrm{kg}}\right)^{-0{,}492} \cdot 10^{-7{,}8}$$

THEORETICAL MODEL

DECELERATING IN DENSITY WITH CUBE GAUSSIAN PROFILE

Cross sectional area

Drag coefficient

We assume velocity $\Delta v \ll v$,
therefore v $\neq v(x)$ during fly-through

$$F_O(x,\Delta y,t) = \frac{1}{2} C_D S_D v^2 \rho_{3D}(x,\Delta y,t)$$

Newton drag force (fly-through along x-axis)

THEORETICAL MODEL

DECELERATING IN DENSITY WITH CUBE GAUSSIAN PROFILE

Cross sectional area

Drag coefficient

We assume velocity $\Delta v \ll v$, therefore $\mathrm{v} \neq v(x)$ during fly-through

$$F_O(x, \Delta y, t) = \frac{1}{2} C_D S_D v^2 \rho_{3D}(x, \Delta y, t)$$

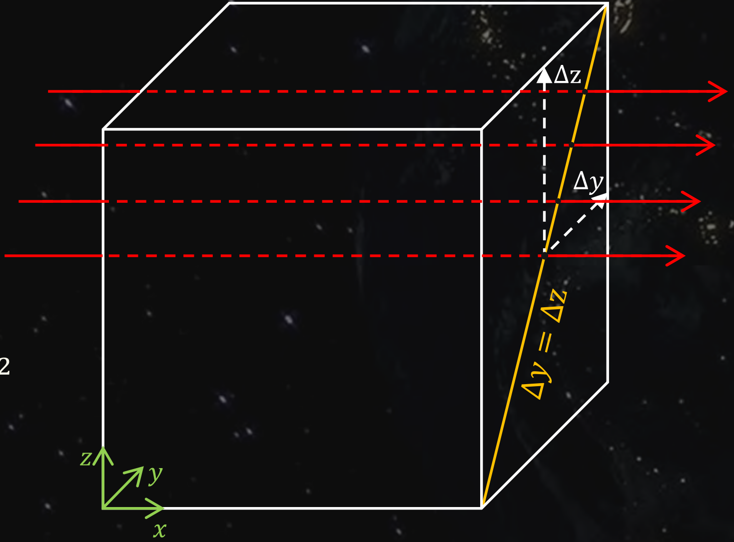
Newton drag force (fly-through along x-axis)

Mass of cloud

Gaussian

$$\rho_{3D}(x, \Delta y, t) = \frac{m}{(2r)^3} \rho_r(x, t)\, \rho_r(\Delta y, t)^2$$

Density profile of 3D cloud



THEORETICAL MODEL

DECELERATING IN DENSITY WITH CUBE GAUSSIAN PROFILE

Cross sectional area

Drag coefficient

We assume velocity $\Delta v \ll v$,
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Mass of
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Gaussian

$$\rho_{3D}(x, \Delta y, t) = \frac{m}{(2r)^3} \rho_r(x, t)\, \rho_r(\Delta y, t)^2$$

Density profile of 3D cloud

Velocity change of debris

$$\Delta v = \int_{-\infty}^{\infty} \frac{F_O(x)}{m_D v} \mathrm{d}x$$

Mass of debris

THEORETICAL MODEL

DECELERATING IN DENSITY WITH CUBE GAUSSIAN PROFILE

Cross sectional area

Drag coefficient

We assume velocity $\Delta v \ll v$,
therefore $\mathrm{v} \neq v(x)$ during fly-through

$$F_O(x,\Delta y,t) = \frac{1}{2} C_D S_D v^2 \rho_{3D}(x,\Delta y,t)$$

Newton drag force (fly-through along x-axis)

Mass of
cloud

Gaussian

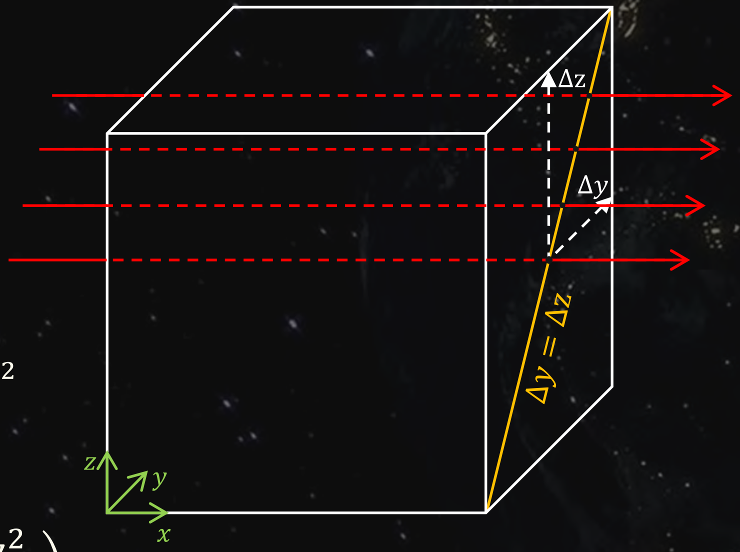
$$\rho_{3D}(x,\Delta y,t) = \frac{m}{(2r)^3}\, \rho_r(x,t)\, \rho_r(\Delta y,t)^2$$

Density profile of 3D cloud

Velocity change of debris

$$\Delta v = \int_{-\infty}^{\infty} \frac{F_O(x)}{m_D v}\,\mathrm{d}x = \frac{\sqrt{2\pi}}{16} C_D S_D \frac{v}{r^3} \frac{m}{m_D} A(t)^3 \sigma(t) \exp\left(\frac{\Delta y^2}{\sigma(t)^2}\right)$$

Mass of debris



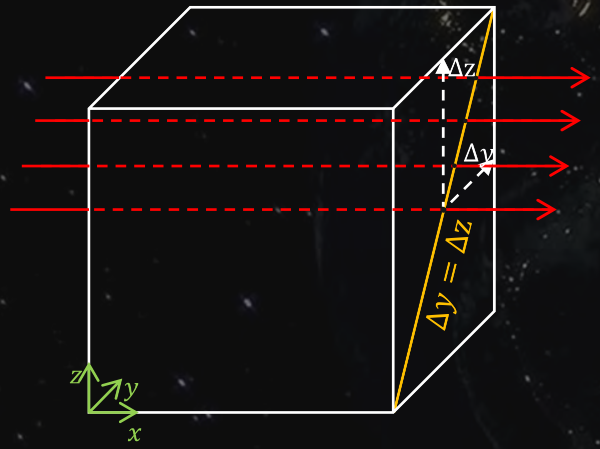
We assume diameter of
debris D_D to be significantly
smaller than σ of Gaussian

Theoretical model

decelerating in density with cube Gaussian profile

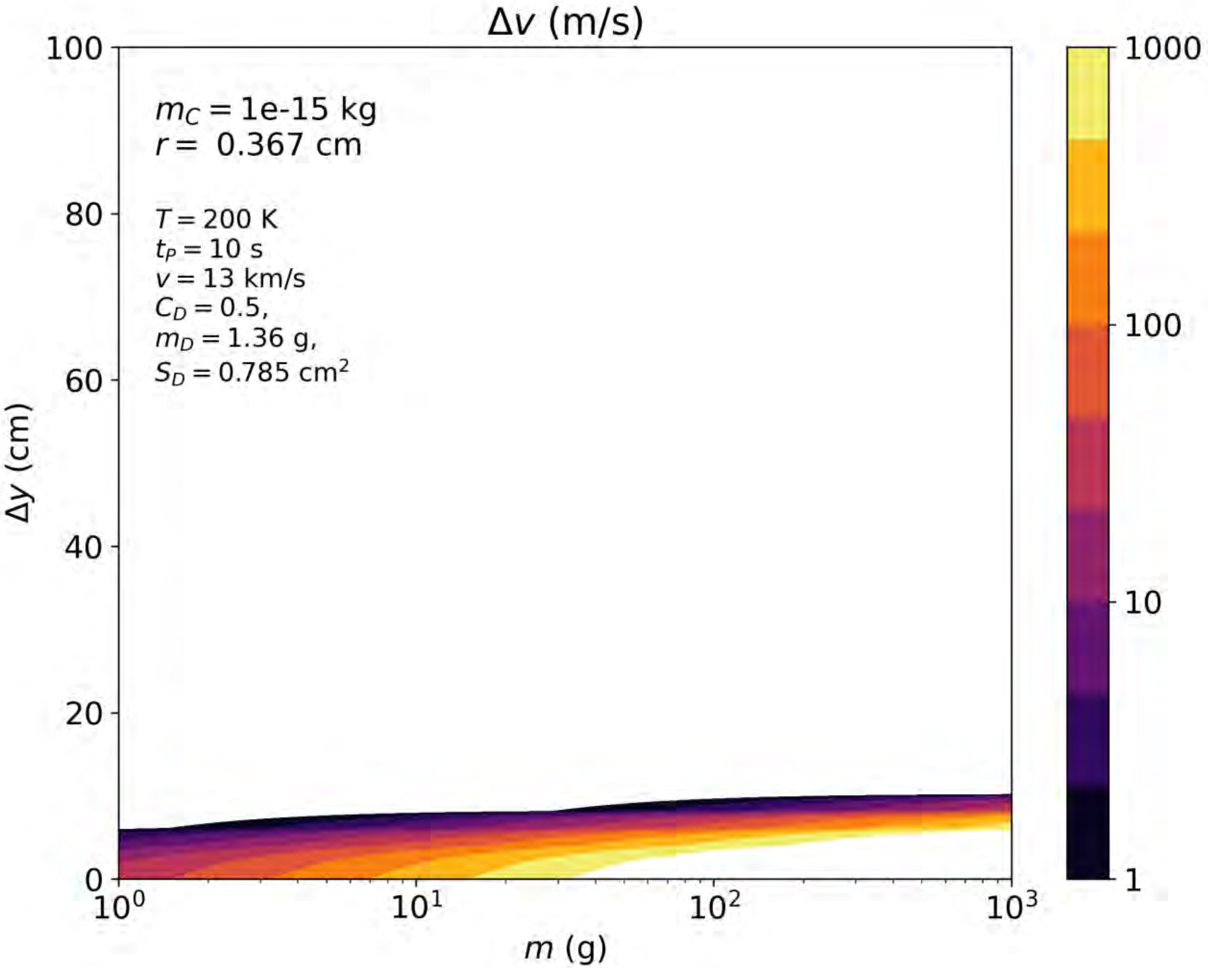
1cm diameter alluminium sphere

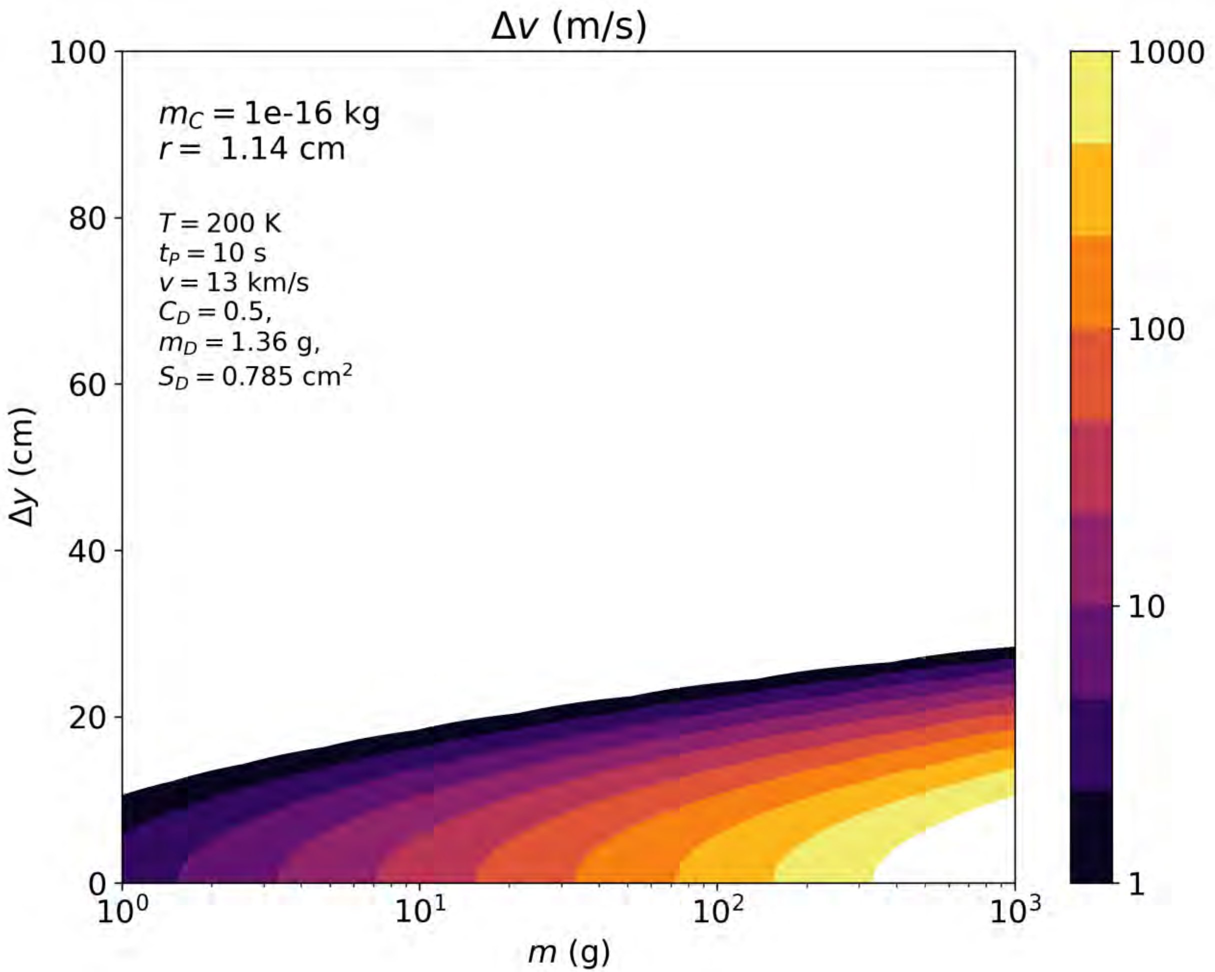
C_D	Drag coefficient of debris	0,5
S_D	Cross sectional area of debris	$0{,}785 \cdot \mathrm{cm}^2$
m_D	Mass of debris	1,36 g
v	Relative velocity	13 km/s
t	Time of collision	10 s

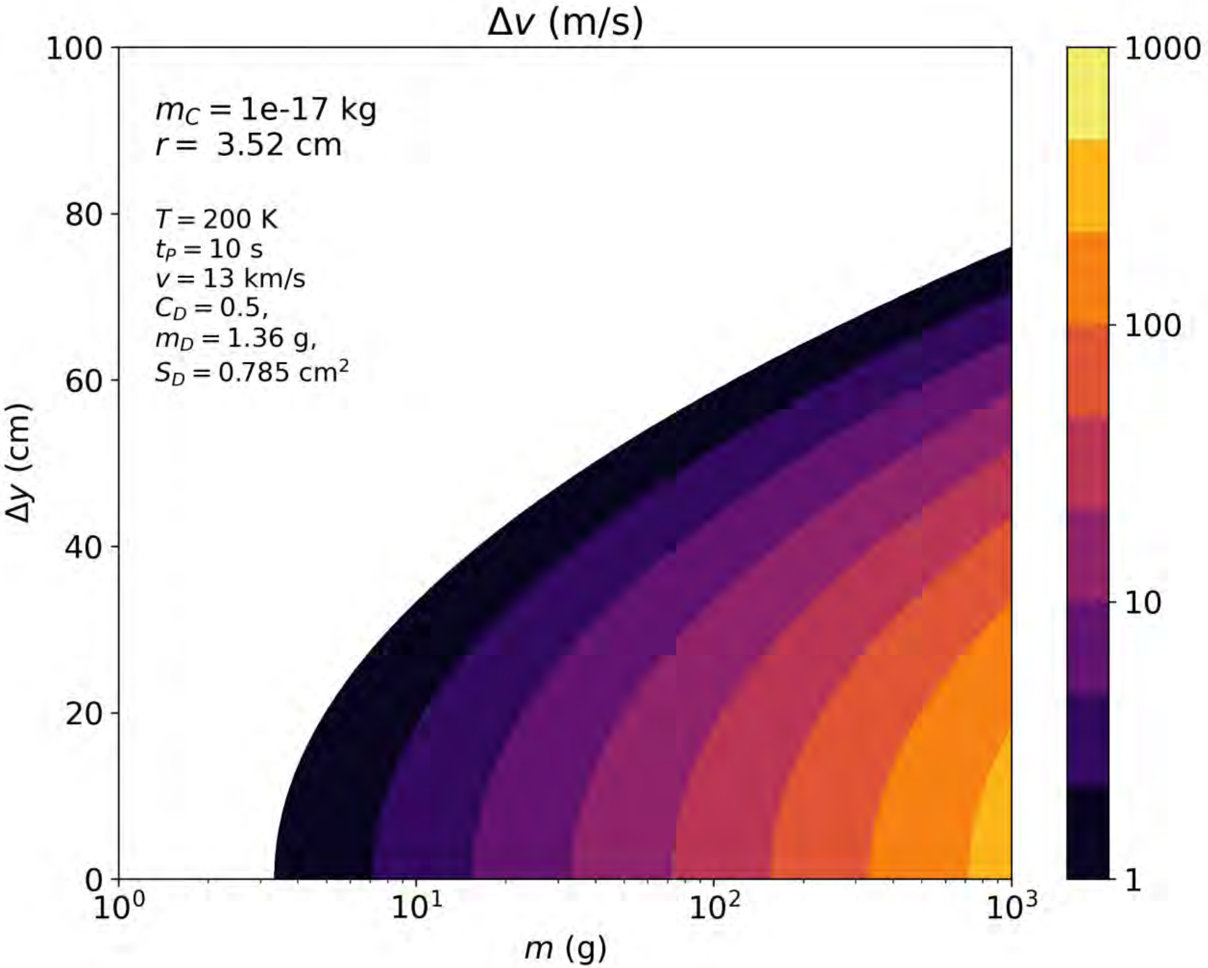


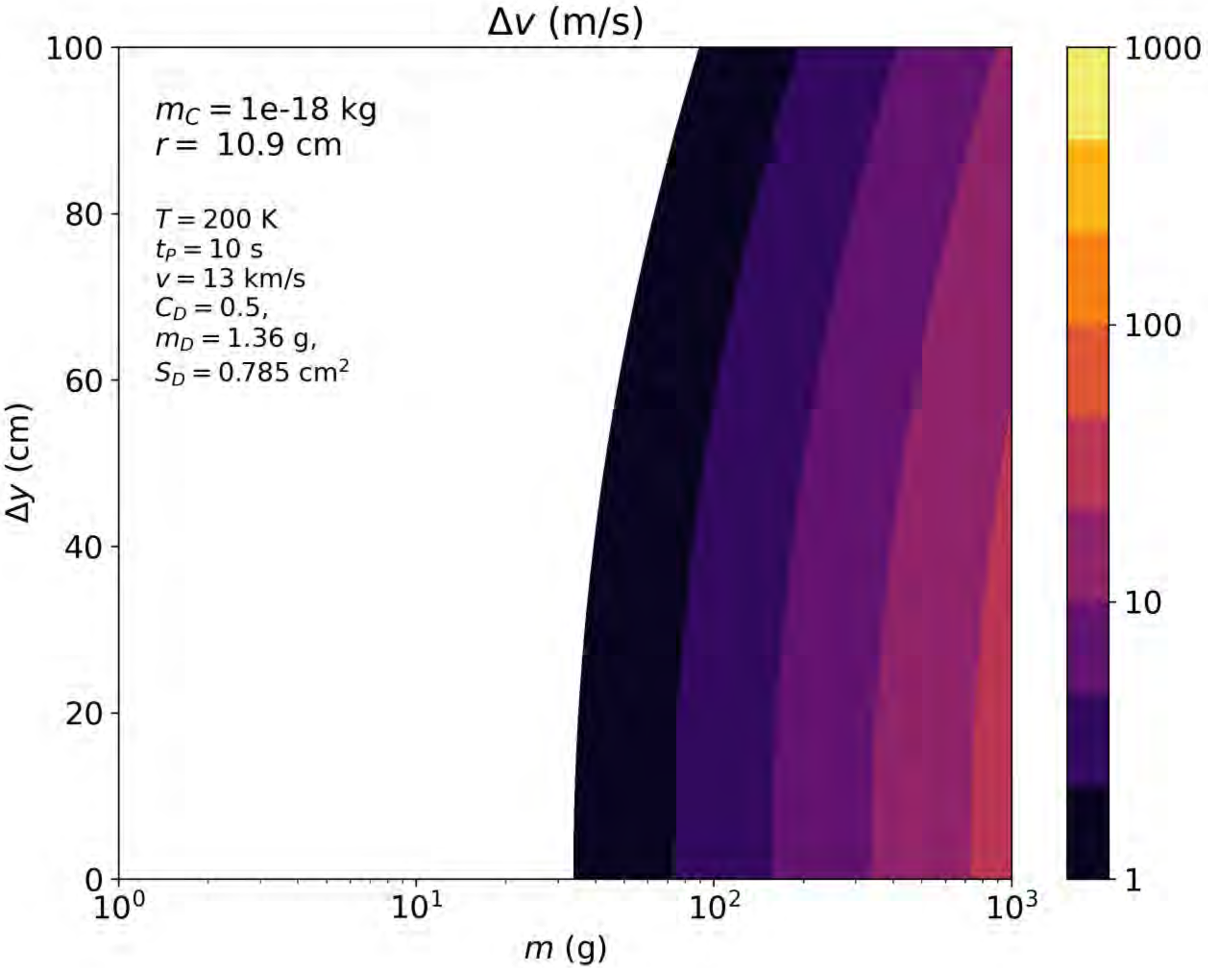
Velocity change of debris

$$\Delta v = \int_{-\infty}^{\infty} \frac{F_O(x)}{m_D v} \mathrm{d}x = \frac{\sqrt{2\pi}}{16} C_D S_D \frac{v}{r^3} \frac{m}{m_D} A(t)^3 \sigma(t) \exp\left(\frac{\Delta y^2}{\sigma(t)^2}\right)$$


Δv (m/s)
m_C = 1e-15 kg
r = 0.367 cm
T = 200 K
t_P = 10 s
v = 13 km/s
C_D = 0.5,
m_D = 1.36 g,
S_D = 0.785 cm^2
Δy (cm)
100
80
60
40
20
0
10^0
10^1
10^2
10^3
m (g)
1000
100
10
1


Δv (m/s)
m_C = 1e-16 kg
r = 1.14 cm
T = 200 K
t_P = 10 s
v = 13 km/s
C_D = 0.5,
m_D = 1.36 g,
S_D = 0.785 cm^2
Δy (cm)
100
80
60
40
20
0
10^0
10^1
10^2
10^3
m (g)
1000
100
10
1


Δv (m/s)
$m_C = $ 1e-17 kg
$r = $ 3.52 cm
$T = 200$ K
$t_P = 10$ s
$v = 13$ km/s
$C_D = 0.5$,
$m_D = 1.36$ g,
$S_D = 0.785$ cm^2
Δy (cm)
100
80
60
40
20
0
10^0
10^1
10^2
10^3
m (g)
1000
100
10
1



Δv (m/s)
$m_C = $ 1e-18 kg
$r = $ 10.9 cm
$T = 200$ K
$t_P = 10$ s
$v = 13$ km/s
$C_D = 0.5$,
$m_D = 1.36$ g,
$S_D = 0.785$ cm^2
Δy (cm)
100
80
60
40
20
0
10^0
10^1
10^2
10^3
m (g)
1000
100
10
1

THEORETICAL MODEL

LIFETIME OF DEBRIS

$$v_D = \sqrt{\frac{GM_\oplus}{R_\oplus + h}}$$

Velocity of debris on circular orbit

$$\longrightarrow$$

$$(v_D - \Delta v)^2 = GM_\oplus\left(\frac{2}{R_\oplus + h} - \frac{1}{a}\right)$$

Vis viva equation after velocity change

$$\longrightarrow$$

$$a(h, \Delta v)$$

Semi-major axis
of the new orbit

$$\downarrow$$

$$e = \frac{h}{a} - 1$$

Excentricity
of the new orbit

THEORETICAL MODEL

LIFETIME OF DEBRIS

$$v_D = \sqrt{\frac{GM_\oplus}{R_\oplus + h}}$$

Velocity of debris on circular orbit

$$(v_D - \Delta v)^2 = GM_\oplus \left(\frac{2}{R_\oplus + h} - \frac{1}{a} \right)$$

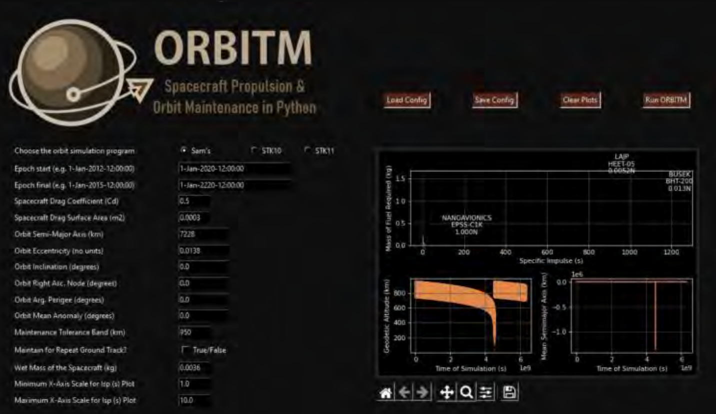
Vis viva equation after velocity change

$$a(h, \Delta v)$$

Semi-major axis
of the new orbit

$$e = \frac{h}{a} - 1$$

Excentricity
of the new orbit

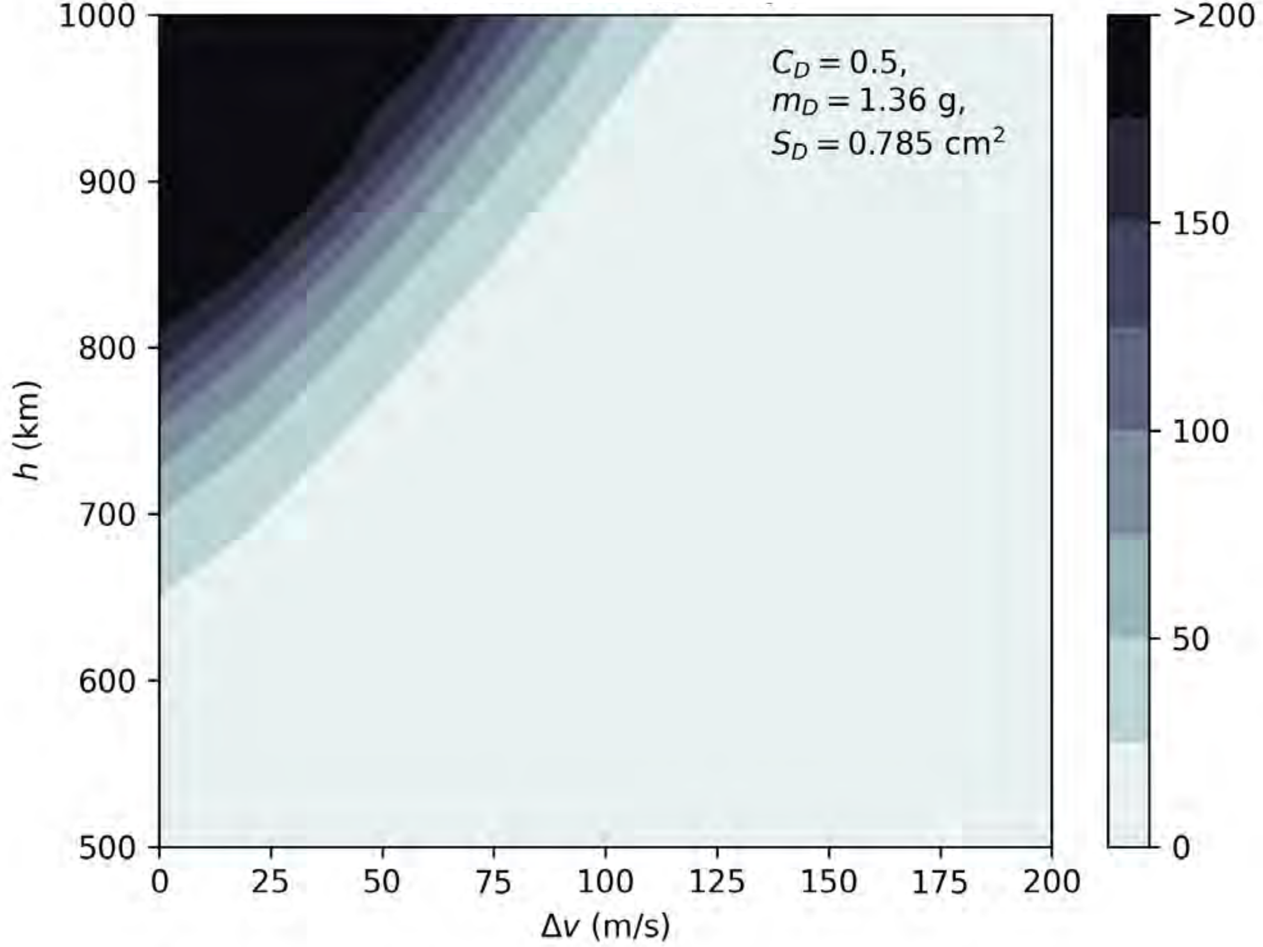


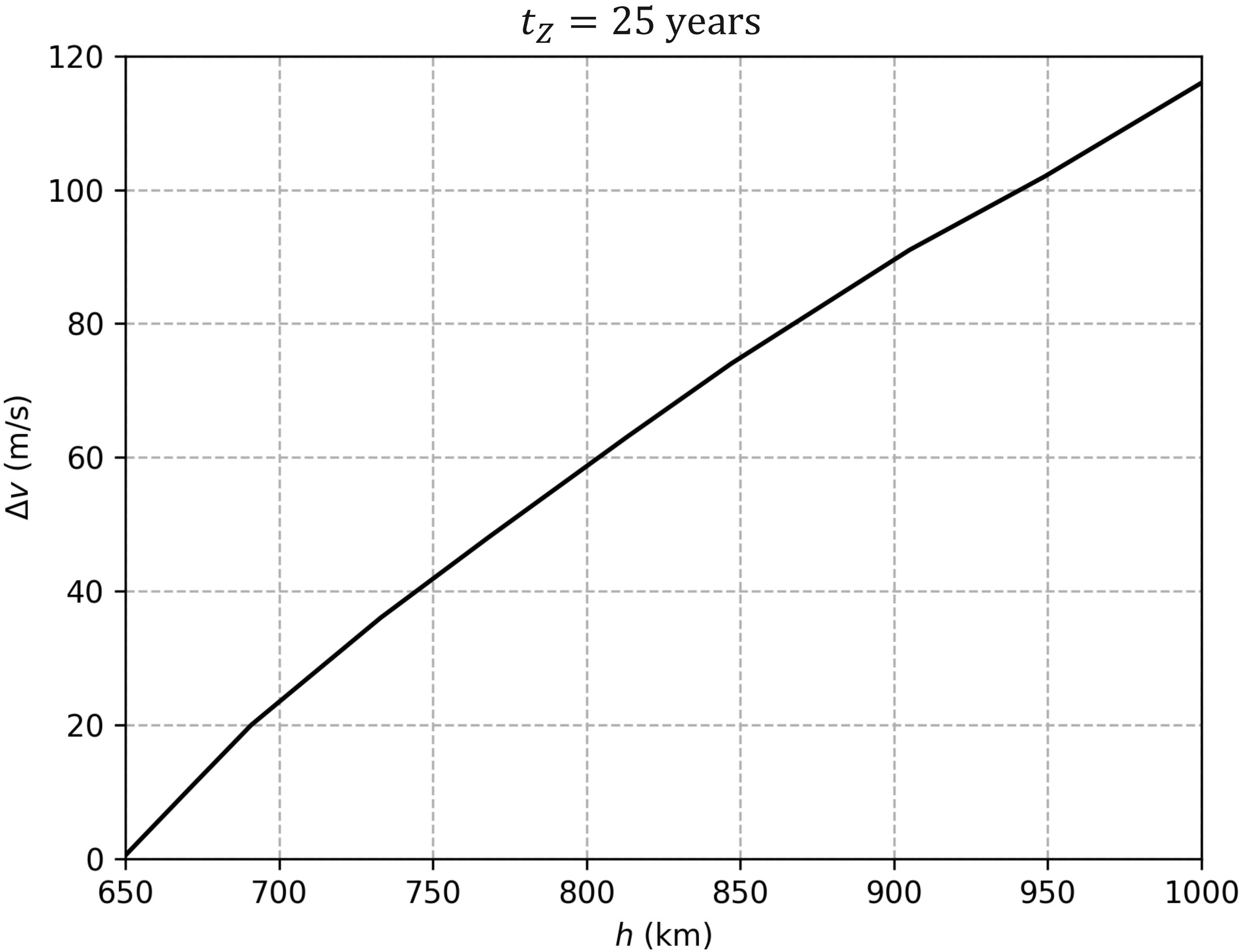
Choose the orbit simulation program	● Sam's ○ STK10 ○ STK11
Epoch start (e.g. 1-Jan-2012-12:00:00)	1-Jan-2020-12:00:00
Epoch final (e.g. 1-Jan-2015-12:00:00)	1-Jan-2220-12:00:00
Spacecraft Drag Coefficient (Cd)	0.5
Spacecraft Drag Surface Area (m2)	0.0003
Orbit Semi-Major Axis (km)	7228
Orbit Eccentricity (no units)	0.0138
Orbit Inclination (degrees)	0.0
Orbit Right Asc. Node (degrees)	0.0
Orbit Arg. Perigee (degrees)	0.0
Orbit Mean Anomaly (degrees)	0.0
Maintenance Tolerance Band (km)	950
Maintain for Repeat Ground Track?	☐ True/False
Wet Mass of the Spacecraft (kg)	0.0036
Minimum X-Axis Scale for Isp (s) Plot	1.0
Maximum X-Axis Scale for Isp (s) Plot	10.0

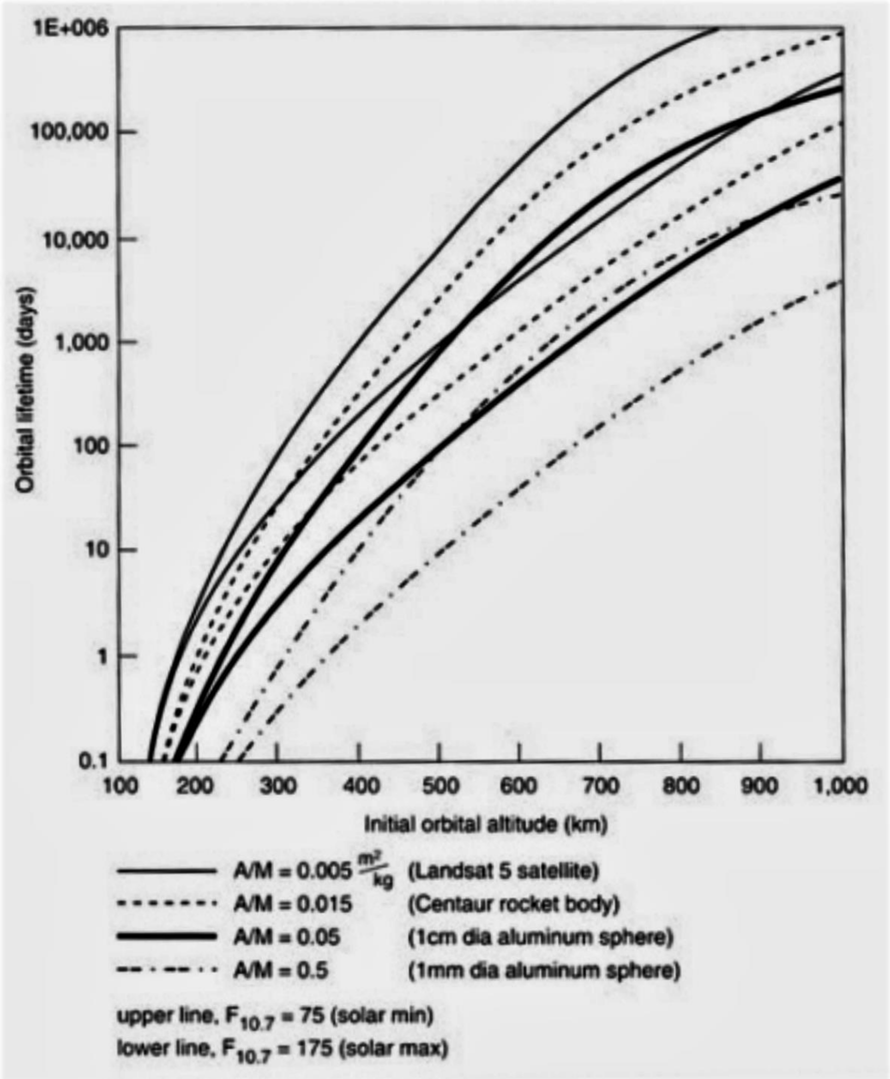
$$t_Z(h, \Delta v)$$

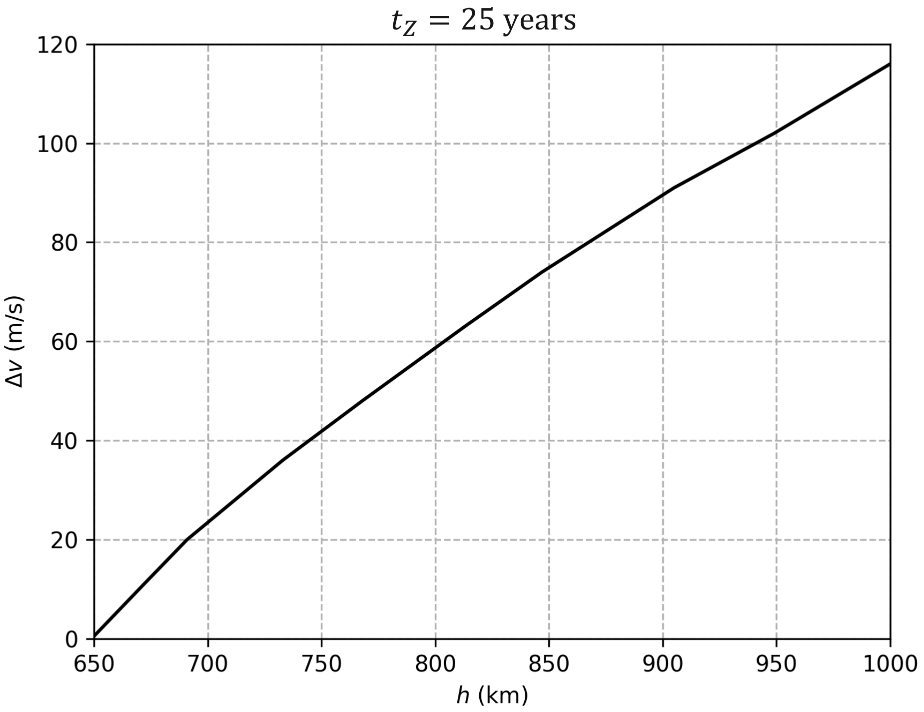
Lifetime of debris

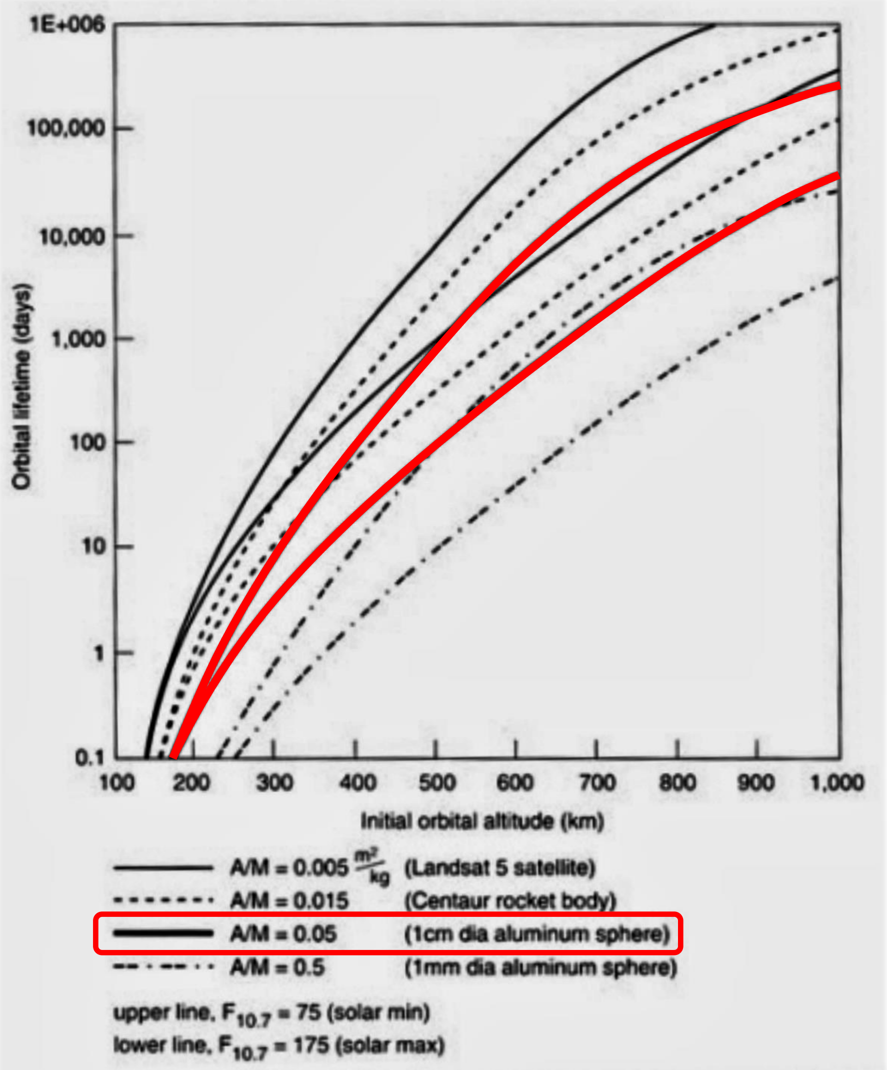
lifetime t_Z (years)




$t_Z = 25$ years
Δv (m/s)
0
20
40
60
80
100
120
h (km)
650
700
750
800
850
900
950
1000


1E+006
100,000
10,000
1,000
100
10
1
0.1
Orbital lifetime (days)
100
200
300
400
500
600
700
800
900
1,000
Initial orbital altitude (km)
A/M = 0.005 m²/kg (Landsat 5 satellite)
A/M = 0.015 (Centaur rocket body)
A/M = 0.05 (1cm dia aluminum sphere)
A/M = 0.5 (1mm dia aluminum sphere)
upper line, F10.7 = 75 (solar min)
lower line, F10.7 = 175 (solar max)


$t_Z = 25$ years
120
100
80
60
40
20
0
Δv (m/s)
650
700
750
800
850
900
950
1000
h (km)



1E+006
100,000
10,000
1,000
100
10
1
0.1
Orbital lifetime (days)
100
200
300
400
500
600
700
800
900
1,000
Initial orbital altitude (km)
A/M = 0.005 m²/kg (Landsat 5 satellite)
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A/M = 0.05 (1cm dia aluminum sphere)
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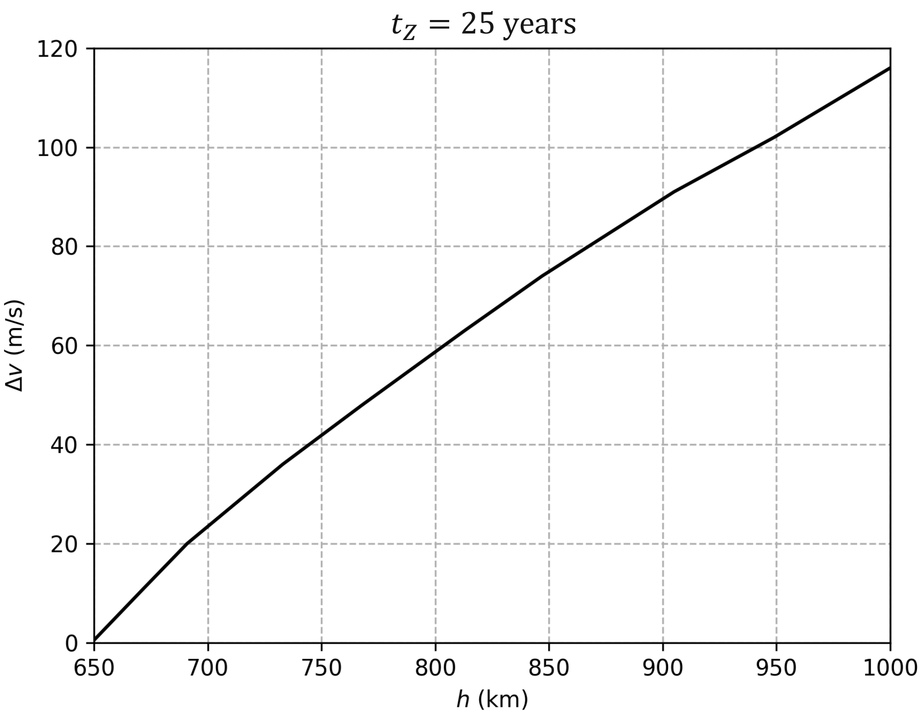
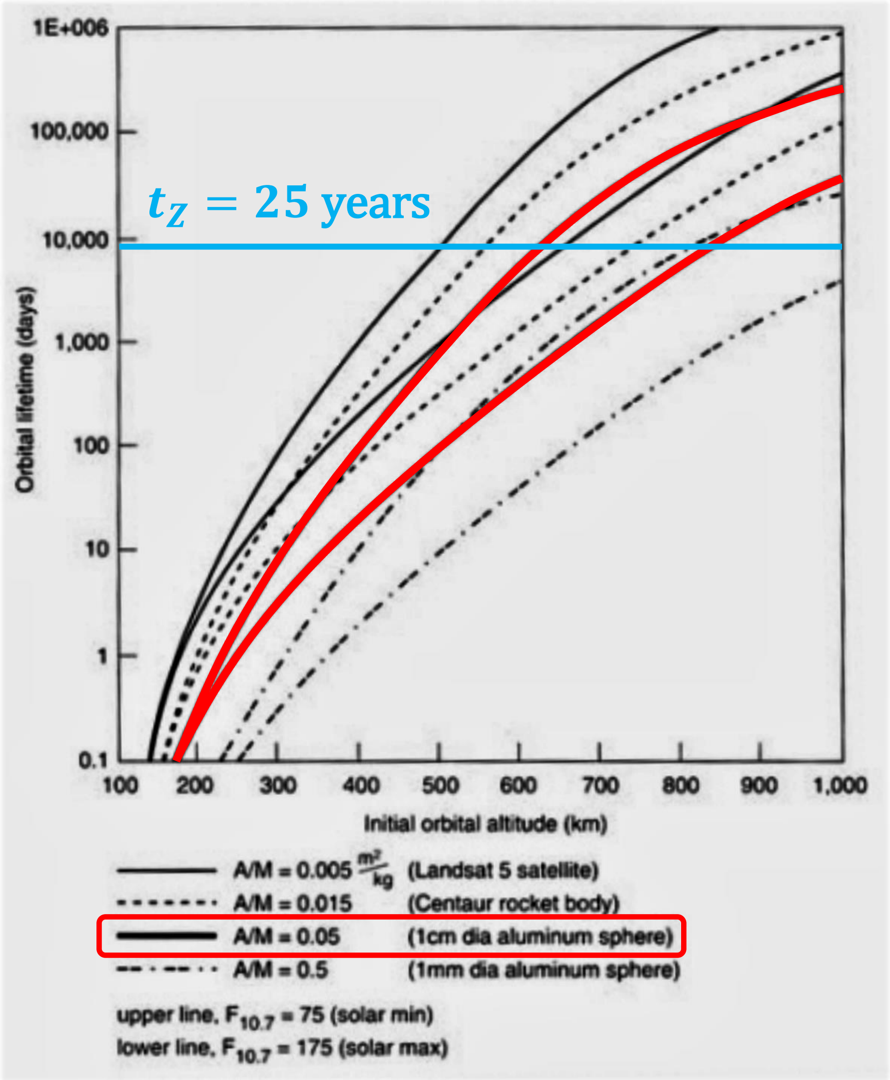
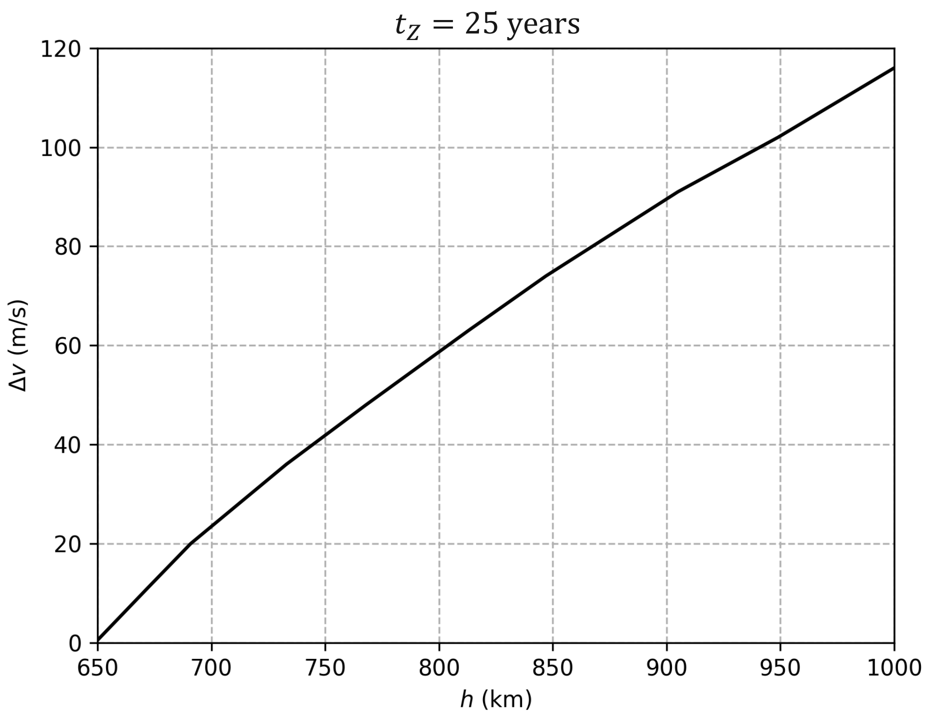
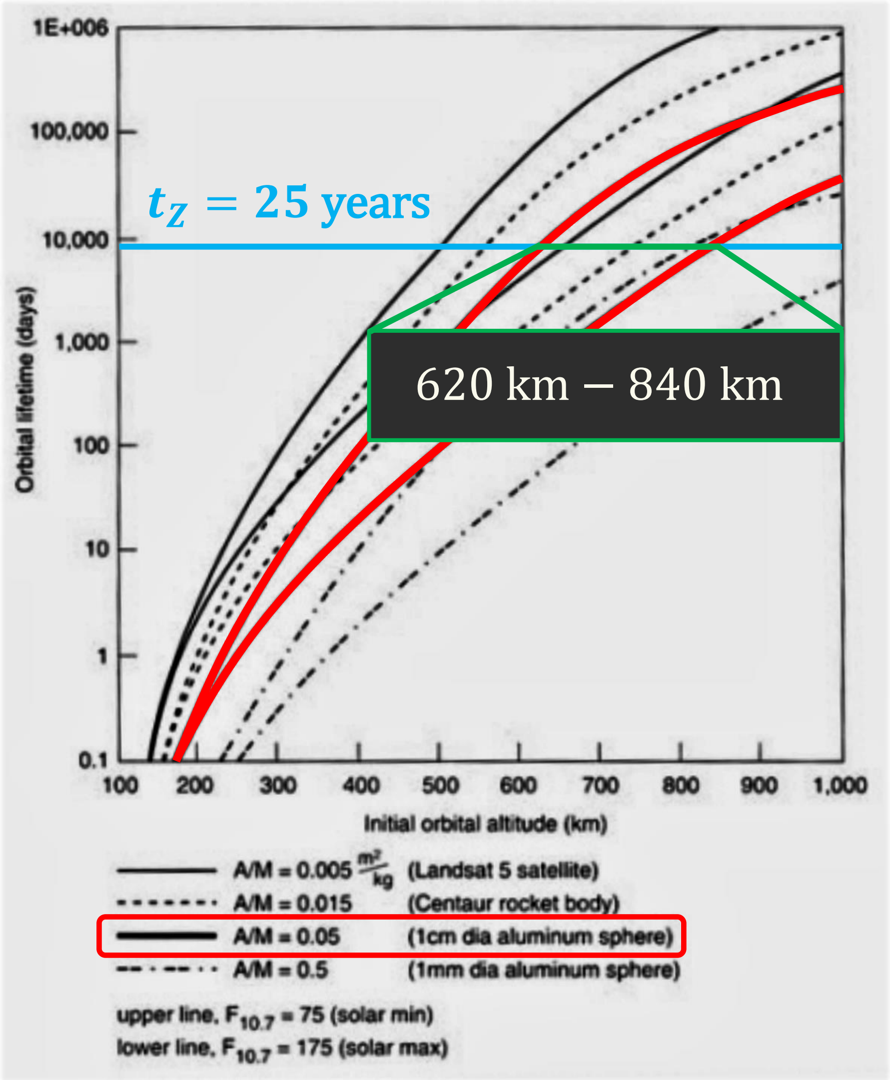
upper line, F10.7 = 75 (solar min)
lower line, F10.7 = 175 (solar max)



$t_Z = 25$ years
120
100
80
60
40
20
0
Δv (m/s)
650
700
750
800
850
900
950
1000
h (km)

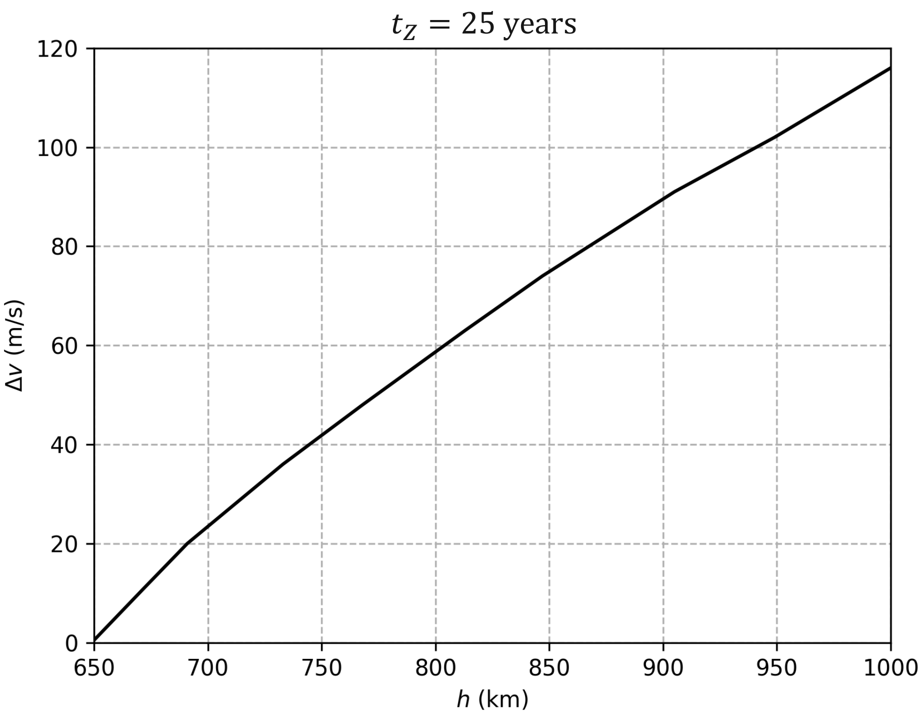

$t_Z = 25$ years
Orbital lifetime (days)
1E+006
100,000
10,000
1,000
100
10
1
0.1
100
200
300
400
500
600
700
800
900
1,000
Initial orbital altitude (km)
A/M = 0.005 $\frac{m^2}{kg}$ (Landsat 5 satellite)
A/M = 0.015 (Centaur rocket body)
A/M = 0.05 (1cm dia aluminum sphere)
A/M = 0.5 (1mm dia aluminum sphere)
upper line, $F_{10.7}$ = 75 (solar min)
lower line, $F_{10.7}$ = 175 (solar max)

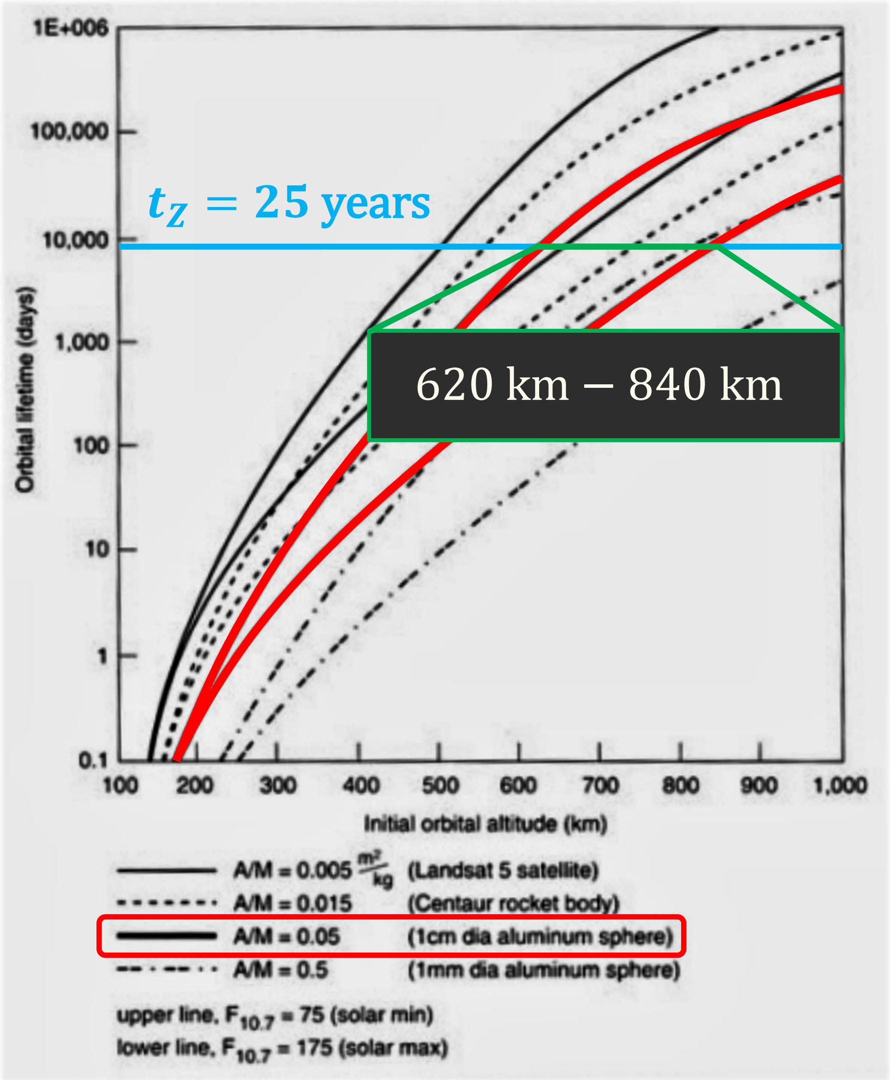

$t_Z = 25$ years
Δv (m/s)
0
20
40
60
80
100
120
650
700
750
800
850
900
950
1000
h (km)

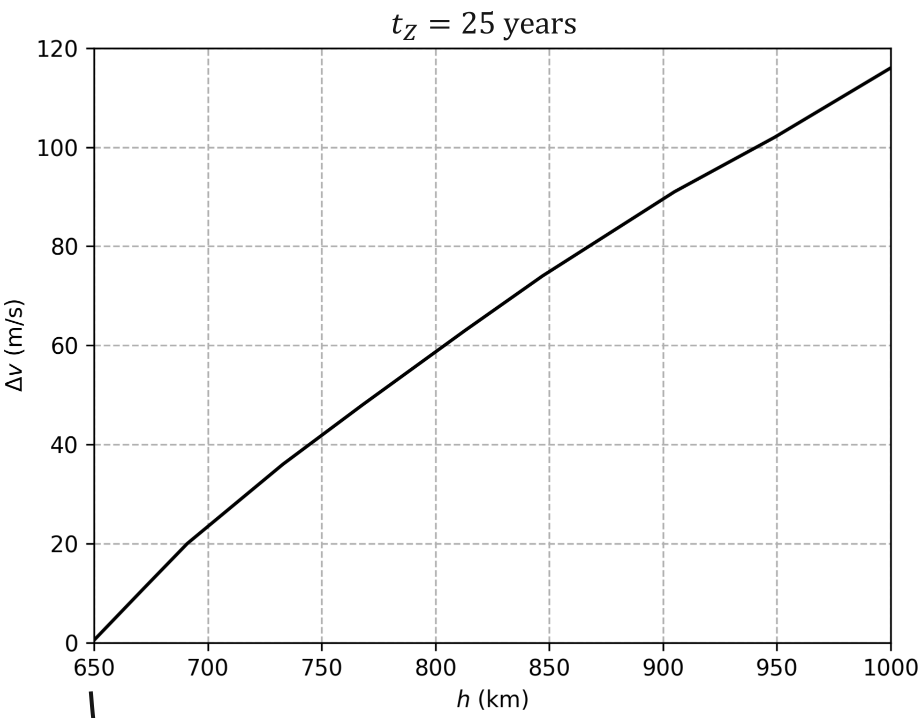


$t_Z = 25$ years

620 km – 840 km







We predict **650 km**

SUMMARY

SUMMARY

- Alluminium sphere, $D_D = 1\ \mathrm{cm}$

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- Relative velocity: $v = 13\ \mathrm{km/s}$

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- Time of collision: $t = 10\ s$

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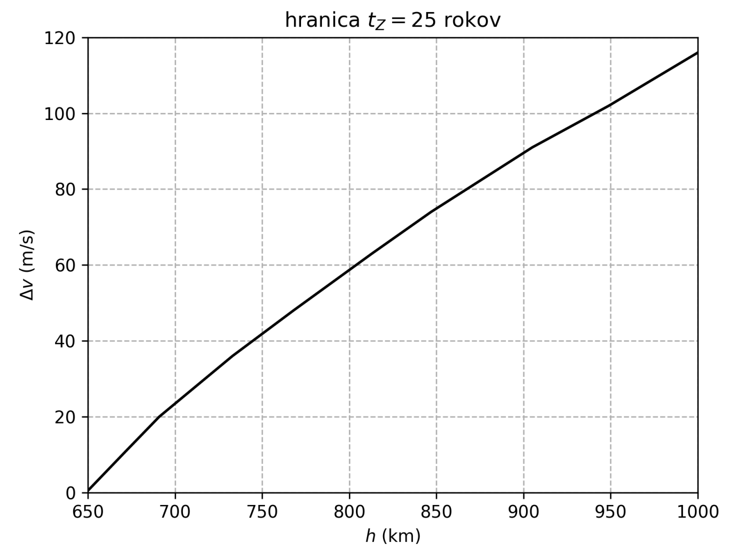
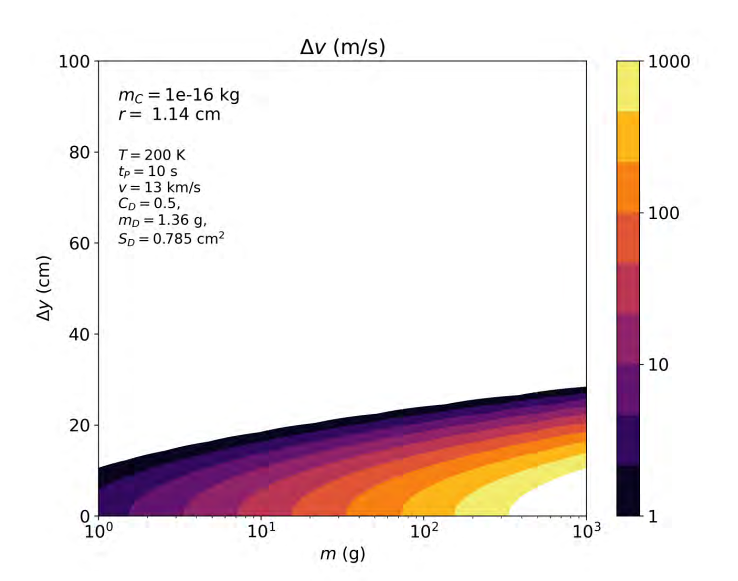
- Relative velocity: $v = 13\ \mathrm{km/s}$
- Time of collision: $t = 10\ \mathrm{s}$
- Starting altitude: **$h \approx 950\ \mathrm{km}$**

SUMMARY

- Alluminium sphere, $D_D = 1\ \mathrm{cm}$
- Relative velocity: $v = 13\ \mathrm{km/s}$
- Time of collision: $t = 10\ \mathrm{s}$
- Starting altitude: $\boldsymbol{h \approx 950\ \mathrm{km}}$
- Velocity change needed (for $t_Z \sim 25\ \mathrm{years}$): $\boldsymbol{\Delta v \approx 100\ \mathrm{m/s}}$



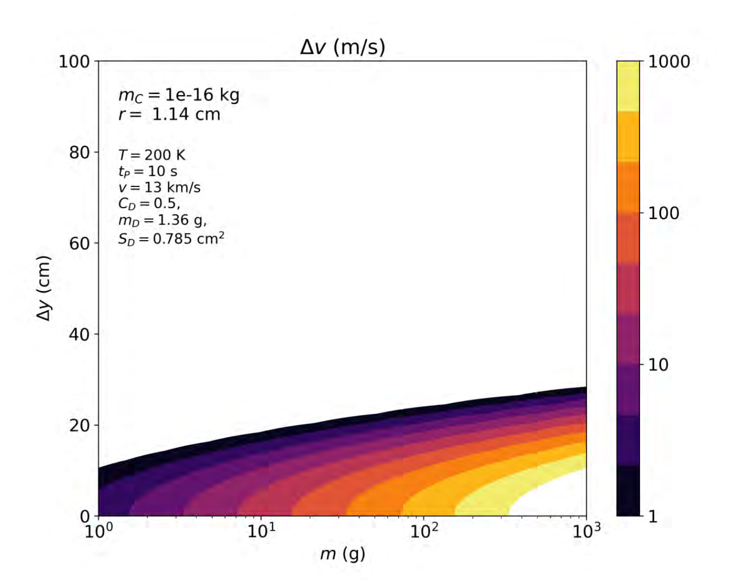
SUMMARY



- Alluminium sphere, $D_D = 1\ \mathrm{cm}$
- Relative velocity: $v = 13\ \mathrm{km/s}$
- Time of collision: $t = 10\ \mathrm{s}$
- Starting altitude: **$h \approx 950\ \mathrm{km}$**
- Velocity change needed (for $t_Z \sim 25$ years): **$\Delta v \approx 100\ \mathrm{m/s}$**
- If we can achieve **$\approx 10\ \mathrm{cm}$** accuracy of collision,

  then ideal mass of particles in cloud is **$m_C \sim 10^{-16}\ \mathrm{kg}$** (diameter $\approx 0{,}5\ \mathrm{cm}$).

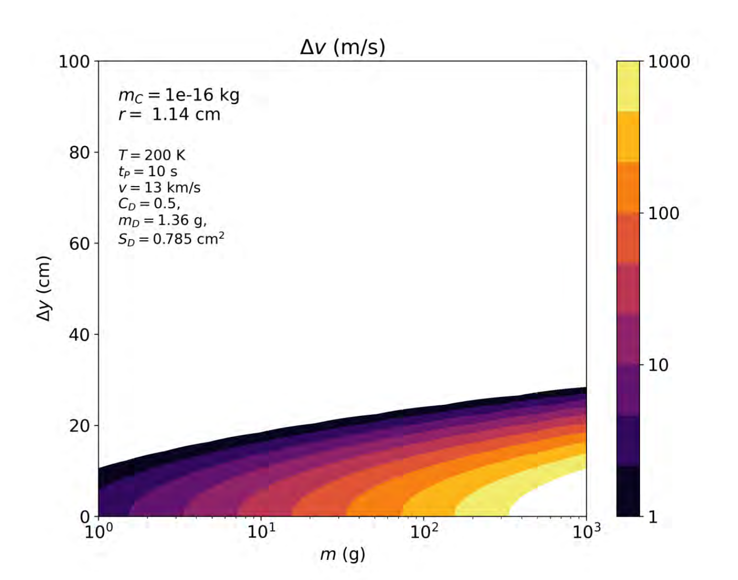
SUMMARY



- Alluminium sphere, $D_D = 1\ \mathrm{cm}$
- Relative velocity: $v = 13\ \mathrm{km/s}$
- Time of collision: $t = 10\ \mathrm{s}$
- Starting altitude: $\boldsymbol{h \approx 950\ \mathrm{km}}$
- Velocity change needed (for $t_Z \sim 25\ \mathrm{years}$): $\boldsymbol{\Delta v \approx 100\ \mathrm{m/s}}$
- If we can achieve $\boldsymbol{\approx 10\ \mathrm{cm}}$ accuracy of collision,

  then ideal mass of particles in cloud is $\boldsymbol{m_C \sim 10^{-16}\ \mathrm{kg}}$ (diameter $\approx 0{,}5\ \mathrm{cm}$).
- Mass of cloud: $\boldsymbol{m \approx 60\ \mathrm{g}}$

SUMMARY



- Alluminium sphere, $D_D = 1\ \mathrm{cm}$
- Relative velocity: $v = 13\ \mathrm{km/s}$
- Time of collision: $t = 10\ \mathrm{s}$
- Starting altitude: $\boldsymbol{h \approx 950\ \mathrm{km}}$
- Velocity change needed (for $t_Z \sim 25$ years): $\boldsymbol{\Delta v \approx 100\ \mathrm{m/s}}$
- If we can achieve $\approx$ **10 cm** accuracy of collision,

  then ideal mass of particles in cloud is $\boldsymbol{m_C \sim 10^{-16}\ \mathrm{kg}}$ (diameter $\approx 0{,}5\ \mathrm{cm}$).
- Mass of cloud: $\boldsymbol{m \approx 60\ \mathrm{g}}$
- We can clean **thousands** of debris with one satellite.

REMARKS

REMARKS

- Primordial divergence of cloud
- Material of cloud particles
- Temperature problem
- Drag coefficient
- Better models
- Other debris, scalability?

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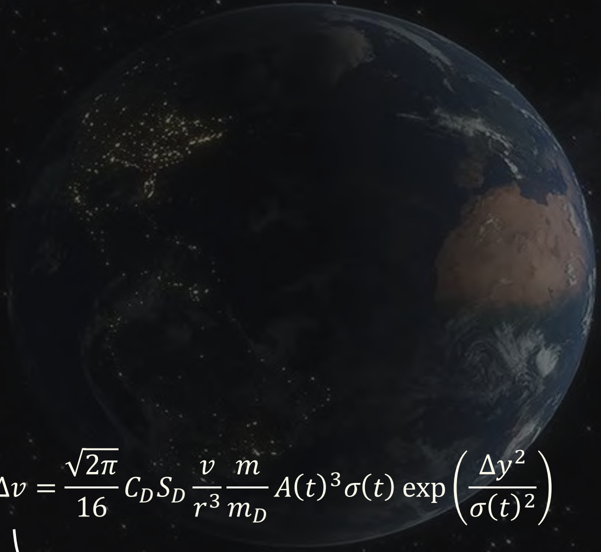

$$\Delta v = \frac{\sqrt{2\pi}}{16} C_D S_D \frac{v}{r^3} \frac{m}{m_D} A(t)^3 \sigma(t) \exp\left(\frac{\Delta y^2}{\sigma(t)^2}\right)$$

$$\Delta v \sim \frac{S_D}{m_D} m \sim \frac{m}{D_D}$$

for $\Delta v = \text{const.}$ we need $\boldsymbol{m \sim D_D}$

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- Primordial divergence of cloud
- Material of cloud particles
- Temperature problem
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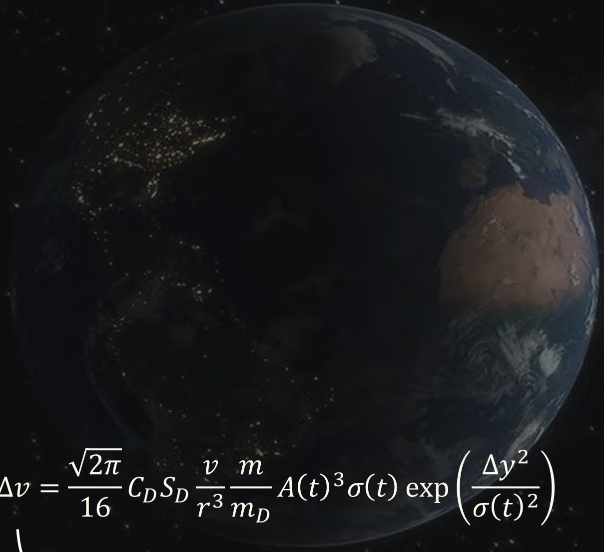

$$\Delta v = \frac{\sqrt{2\pi}}{16} C_D S_D \frac{v}{r^3} \frac{m}{m_D} A(t)^3 \sigma(t) \exp\left(\frac{\Delta y^2}{\sigma(t)^2}\right)$$

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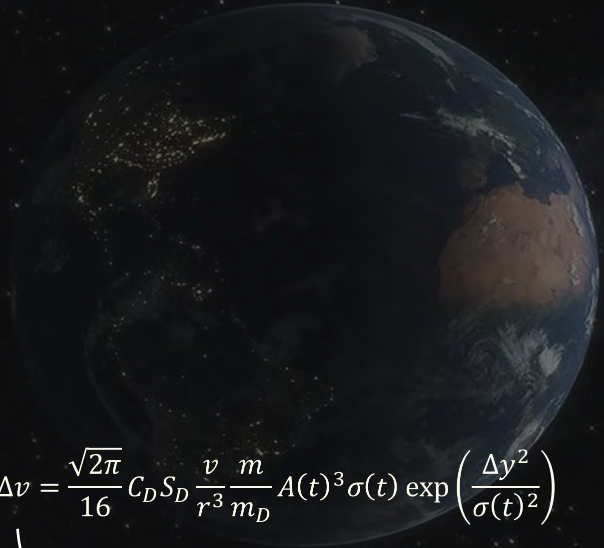
$\Rightarrow$ **linear scalability** for $\Delta v \gtrsim 150\ \mathrm{m/s}$

REMARKS

- Primordial divergence of cloud
- Material of cloud particles
- Temperature problem
- Drag coefficient
- Better models
- Other debris, scalability?
- Technological feasibility?



$$\Delta v = \frac{\sqrt{2\pi}}{16} C_D S_D \frac{v}{r^3} \frac{m}{m_D} A(t)^3 \sigma(t) \exp\left(\frac{\Delta y^2}{\sigma(t)^2}\right)$$

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$\Rightarrow$ **linear scalability** for $\Delta v \gtrsim 150\ \mathrm{m/s}$

Citations and references

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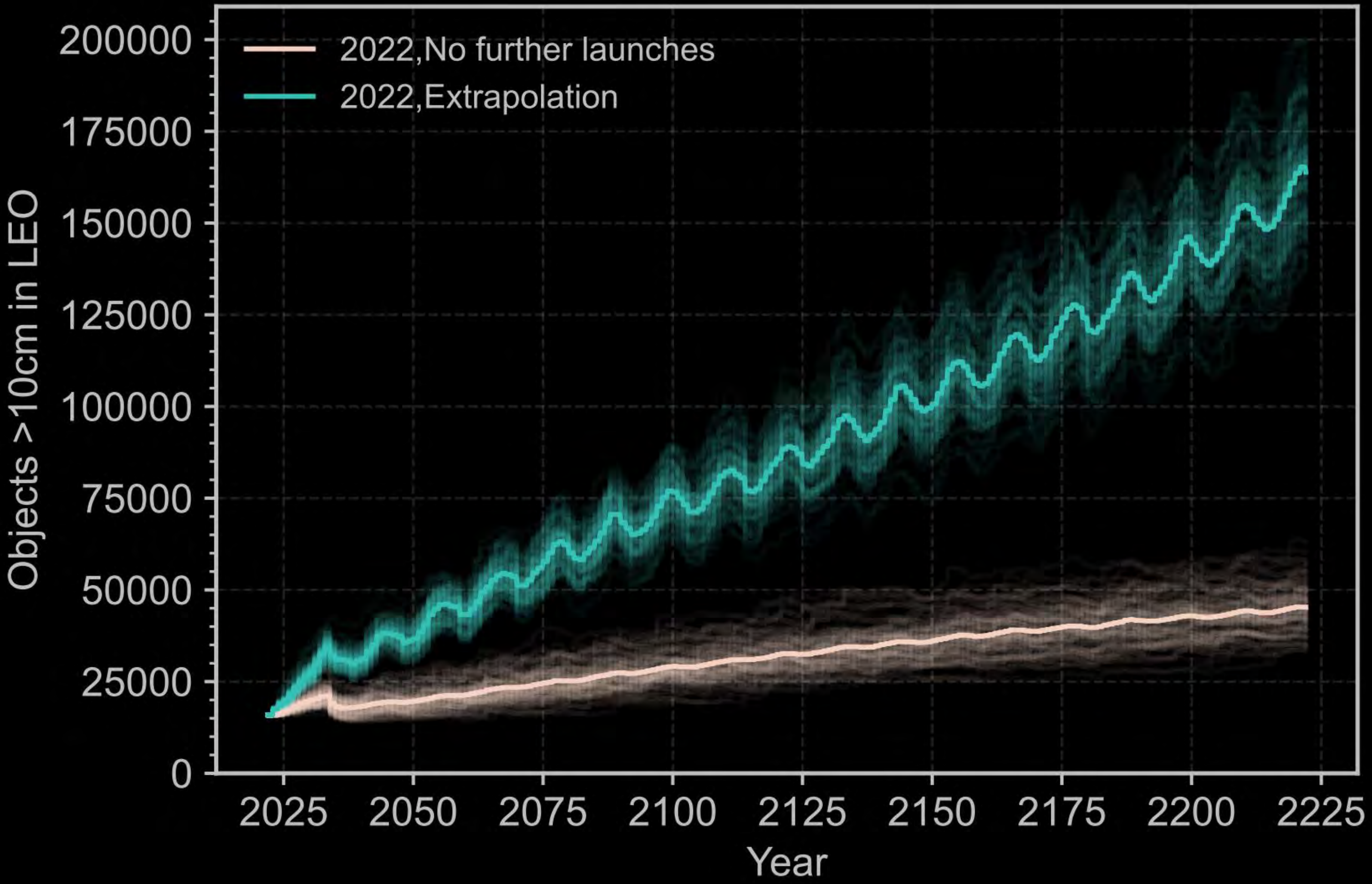
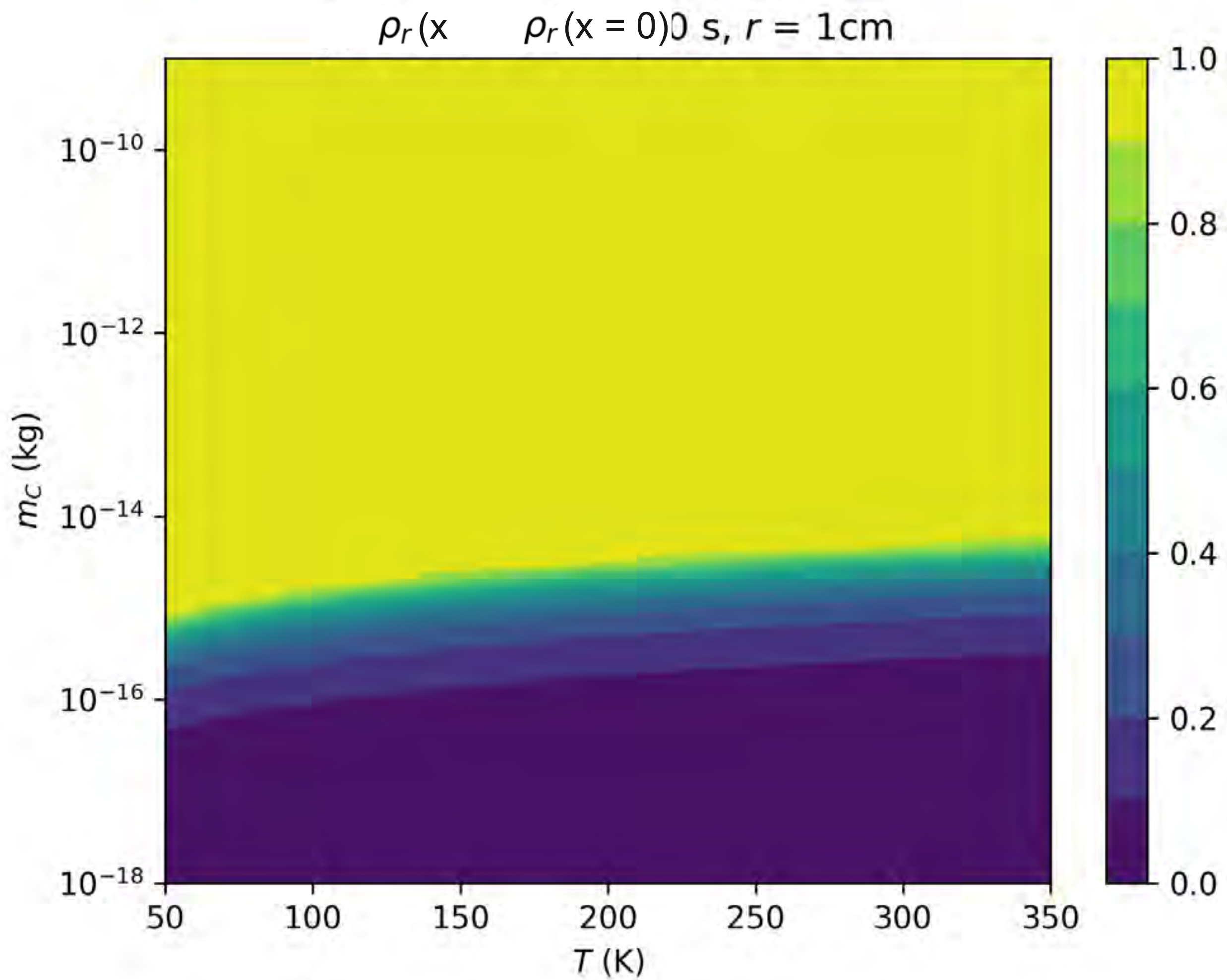
Thank you for your attention

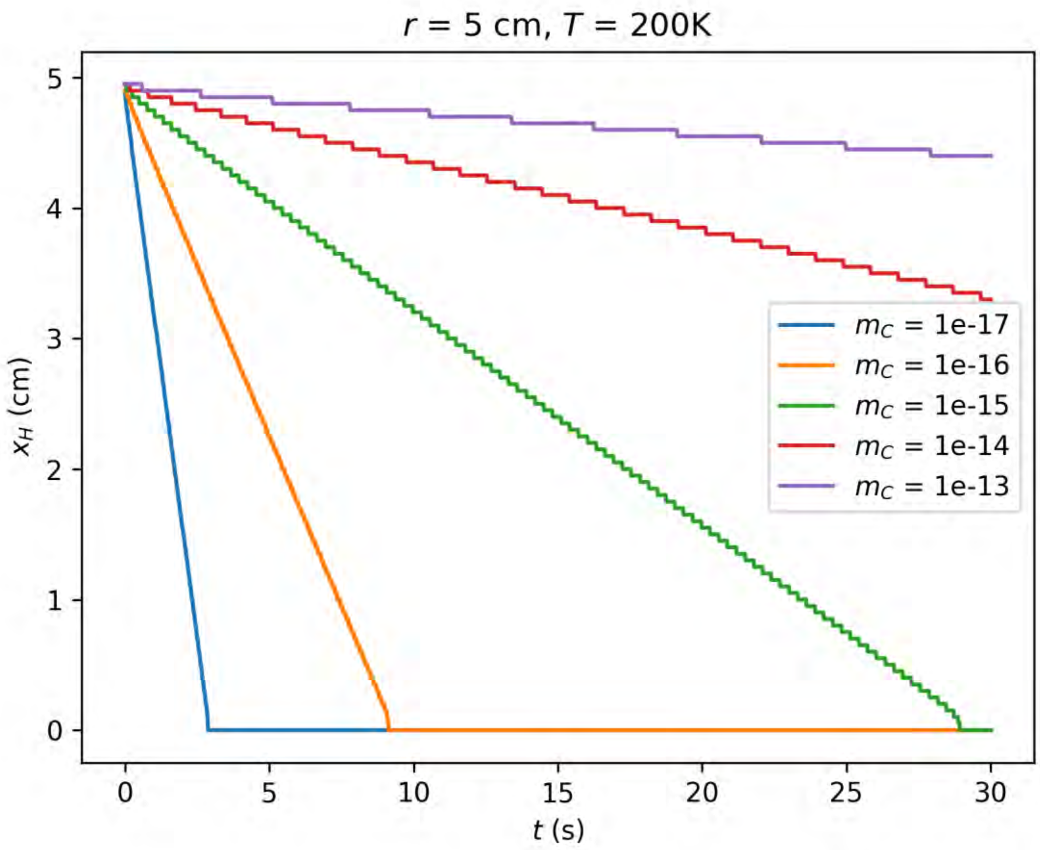
And thanks to:

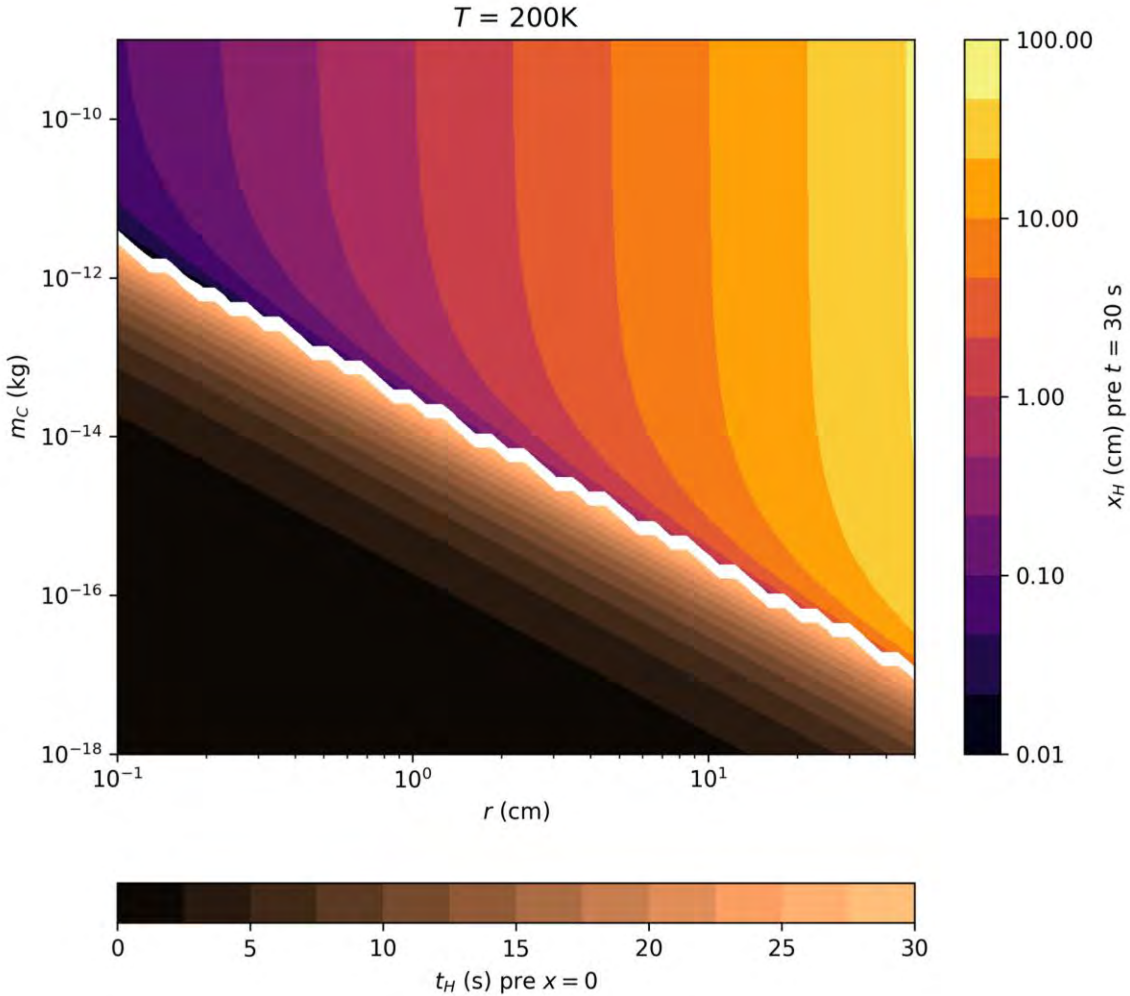
Samuel Amrich
Jiří Šilha
Aleš Bezděk
Pavel Koten
Matej Zigo

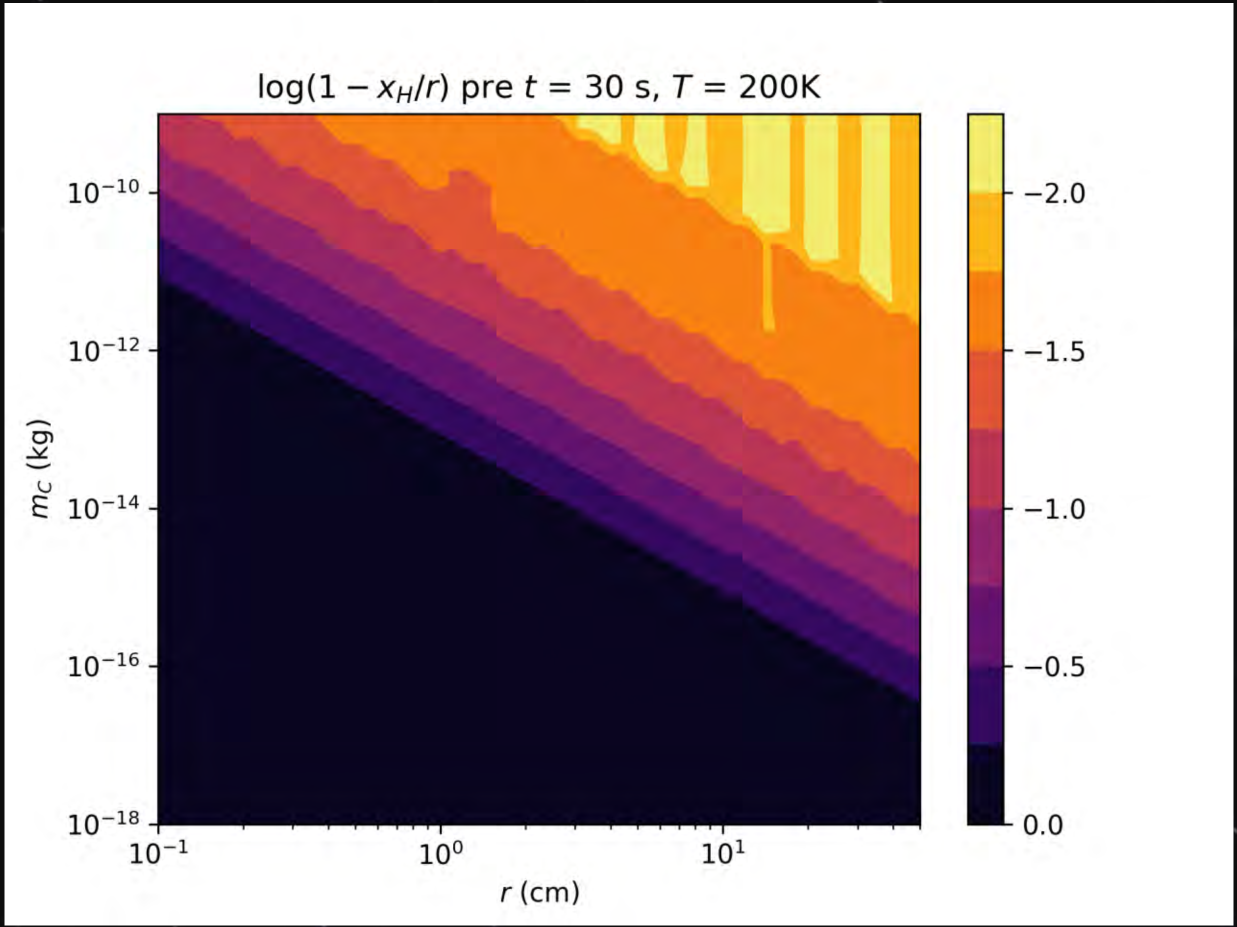
APPENDIX


2022,No further launches
2022,Extrapolation
Objects >10cm in LEO
0
25000
50000
75000
100000
125000
150000
175000
200000
2025
2050
2075
2100
2125
2150
2175
2200
2225
Year

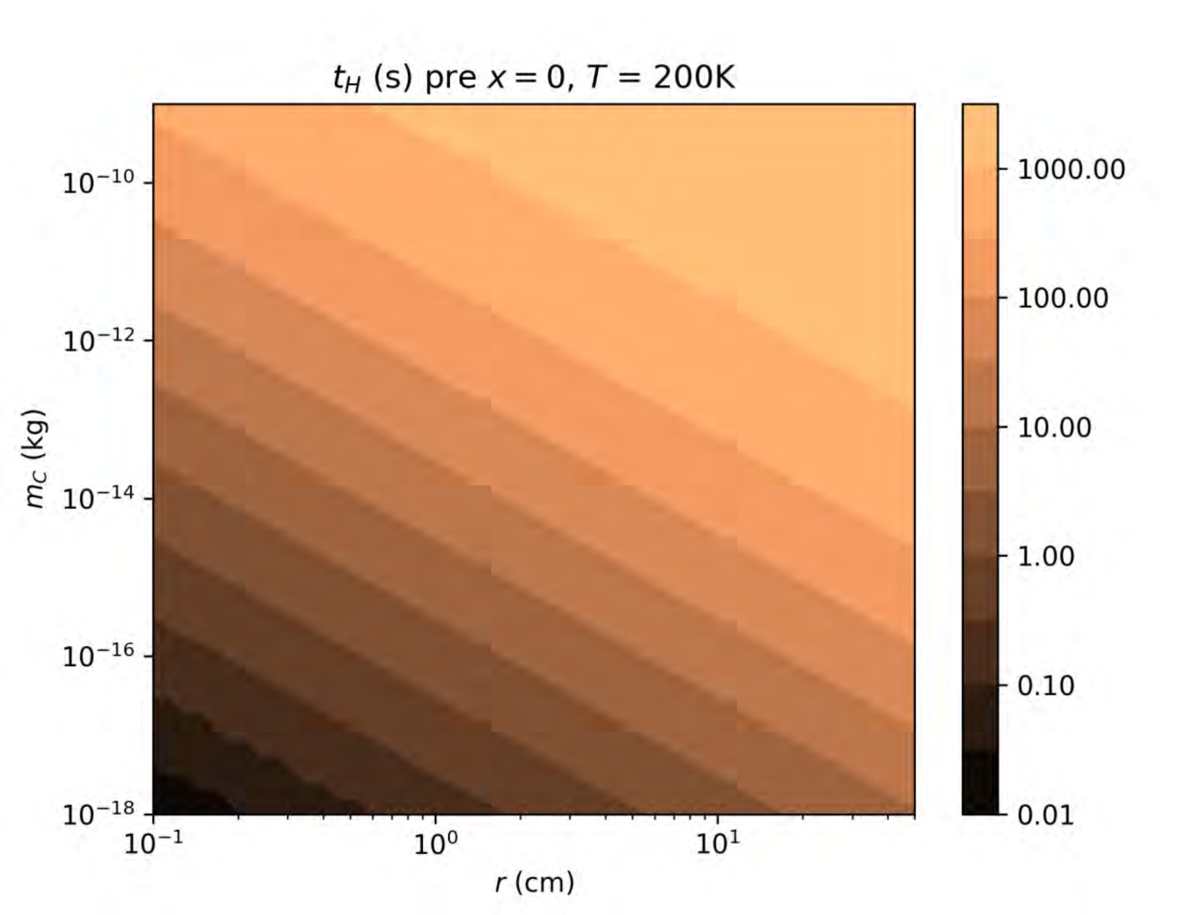

ρ_r(x
ρ_r(x = 0)0 s, r = 1cm
m_C (kg)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
50
100
150
200
250
300
350
T (K)
1.0
0.8
0.6
0.4
0.2
0.0


r = 5 cm, T = 200K
x_H (cm)
0
1
2
3
4
5
t (s)
0
5
10
15
20
25
30
m_C = 1e-17
m_C = 1e-16
m_C = 1e-15
m_C = 1e-14
m_C = 1e-13

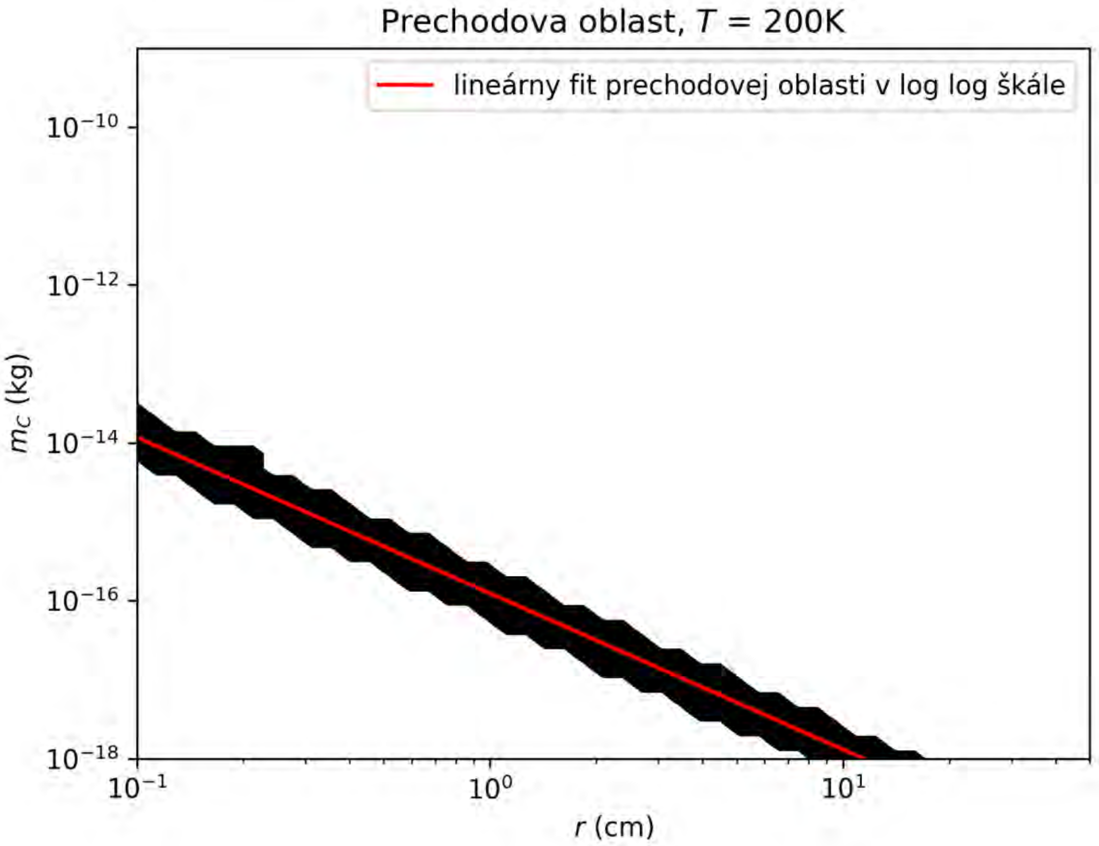

T = 200K
m_C (kg)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-1}
10^{0}
10^{1}
r (cm)
100.00
10.00
1.00
0.10
0.01
x_H (cm) pre t = 30 s
0
5
10
15
20
25
30
t_H (s) pre $x = 0$

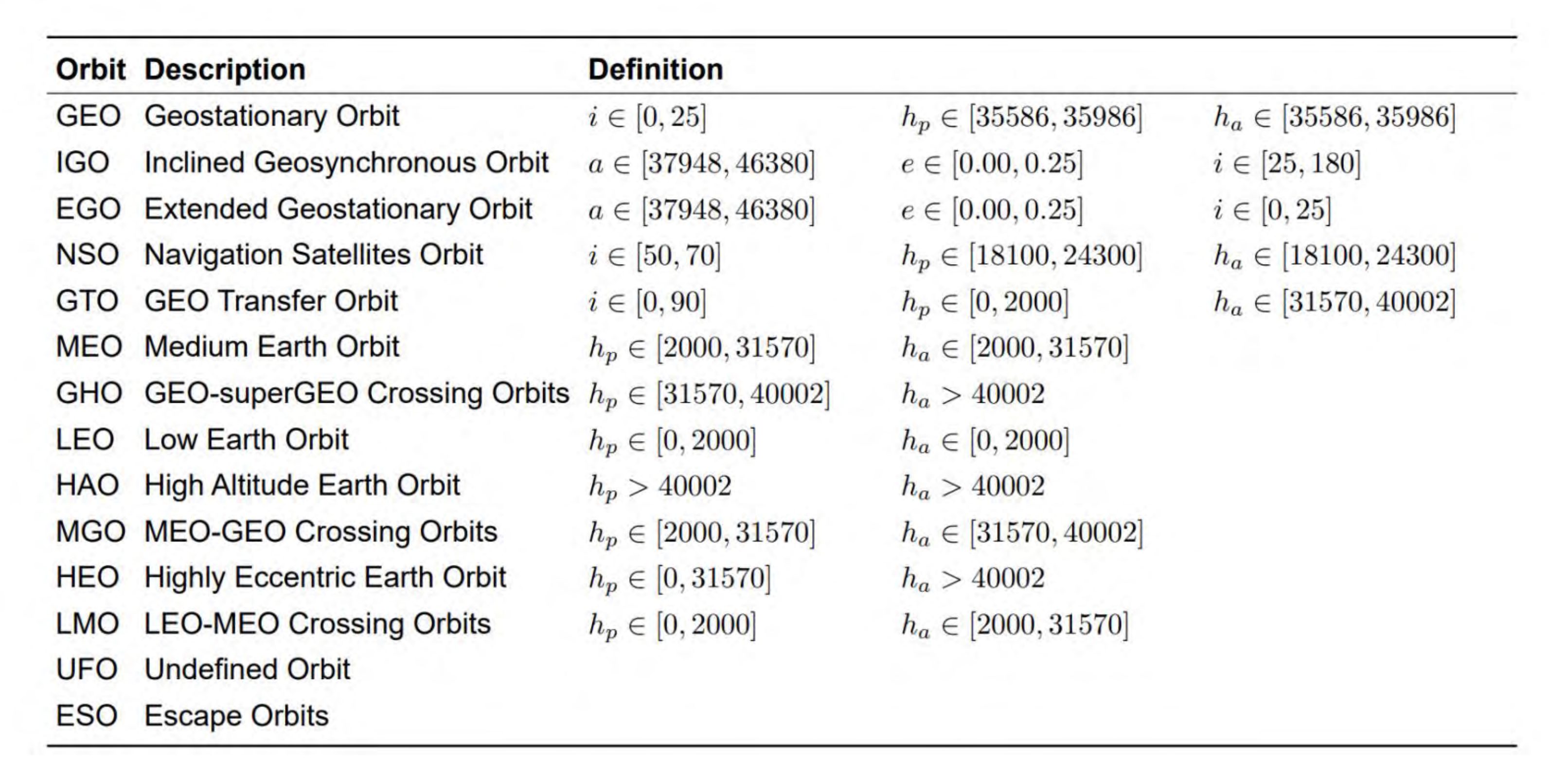


$\log(1 - x_H/r)$ pre t = 30 s, T = 200K



t_H (s) pre $x = 0$, T = 200K


Prechodova oblast, T = 200K
lineárny fit prechodovej oblasti v log log škále
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
m_C (kg)
10^{-1}
10^{0}
10^{1}
r (cm)



Orbit	Description	Definition		
GEO	Geostationary Orbit	$i \in [0, 25]$	$h_p \in [35586, 35986]$	$h_a \in [35586, 35986]$
IGO	Inclined Geosynchronous Orbit	$a \in [37948, 46380]$	$e \in [0.00, 0.25]$	$i \in [25, 180]$
EGO	Extended Geostationary Orbit	$a \in [37948, 46380]$	$e \in [0.00, 0.25]$	$i \in [0, 25]$
NSO	Navigation Satellites Orbit	$i \in [50, 70]$	$h_p \in [18100, 24300]$	$h_a \in [18100, 24300]$
GTO	GEO Transfer Orbit	$i \in [0, 90]$	$h_p \in [0, 2000]$	$h_a \in [31570, 40002]$
MEO	Medium Earth Orbit	$h_p \in [2000, 31570]$	$h_a \in [2000, 31570]$	
GHO	GEO-superGEO Crossing Orbits	$h_p \in [31570, 40002]$	$h_a > 40002$	
LEO	Low Earth Orbit	$h_p \in [0, 2000]$	$h_a \in [0, 2000]$	
HAO	High Altitude Earth Orbit	$h_p > 40002$	$h_a > 40002$	
MGO	MEO-GEO Crossing Orbits	$h_p \in [2000, 31570]$	$h_a \in [31570, 40002]$	
HEO	Highly Eccentric Earth Orbit	$h_p \in [0, 31570]$	$h_a > 40002$	
LMO	LEO-MEO Crossing Orbits	$h_p \in [0, 2000]$	$h_a \in [2000, 31570]$	
UFO	Undefined Orbit			
ESO	Escape Orbits			