Potential of using ground-based high-power lasers to decelerate the evolution of space debris in LEO

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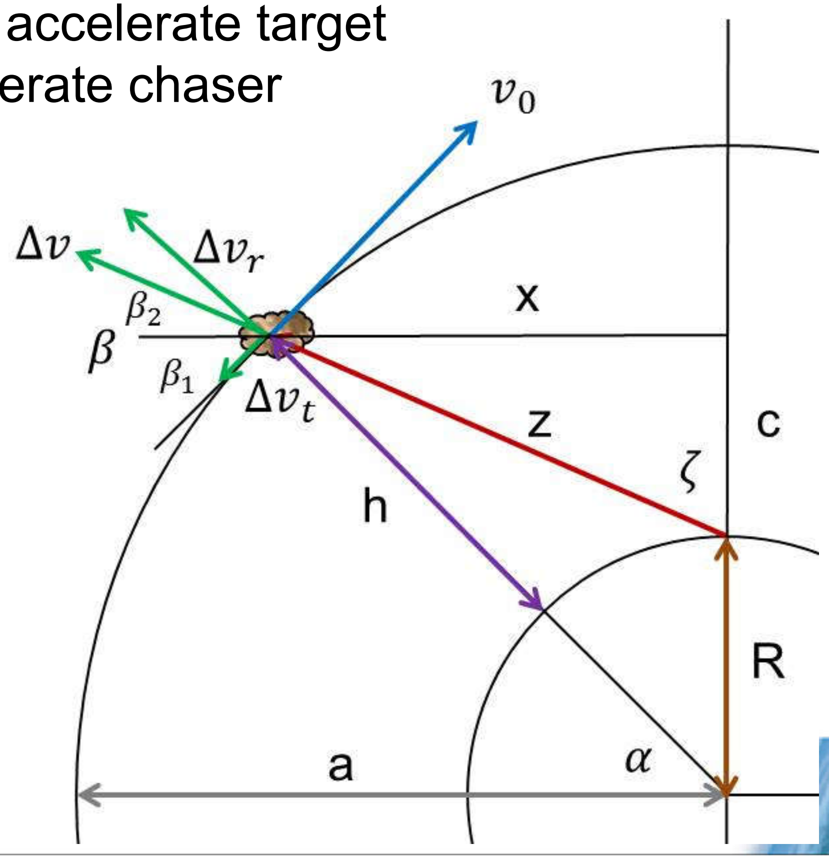
Space Debris Mitigation Methods

Collision Avoidance

Rationale: UN COPUOS Guideline „Long-Term Sustainability of Outer Space Activities”:
→ D.2: Techniques to prevent collision with and among debris

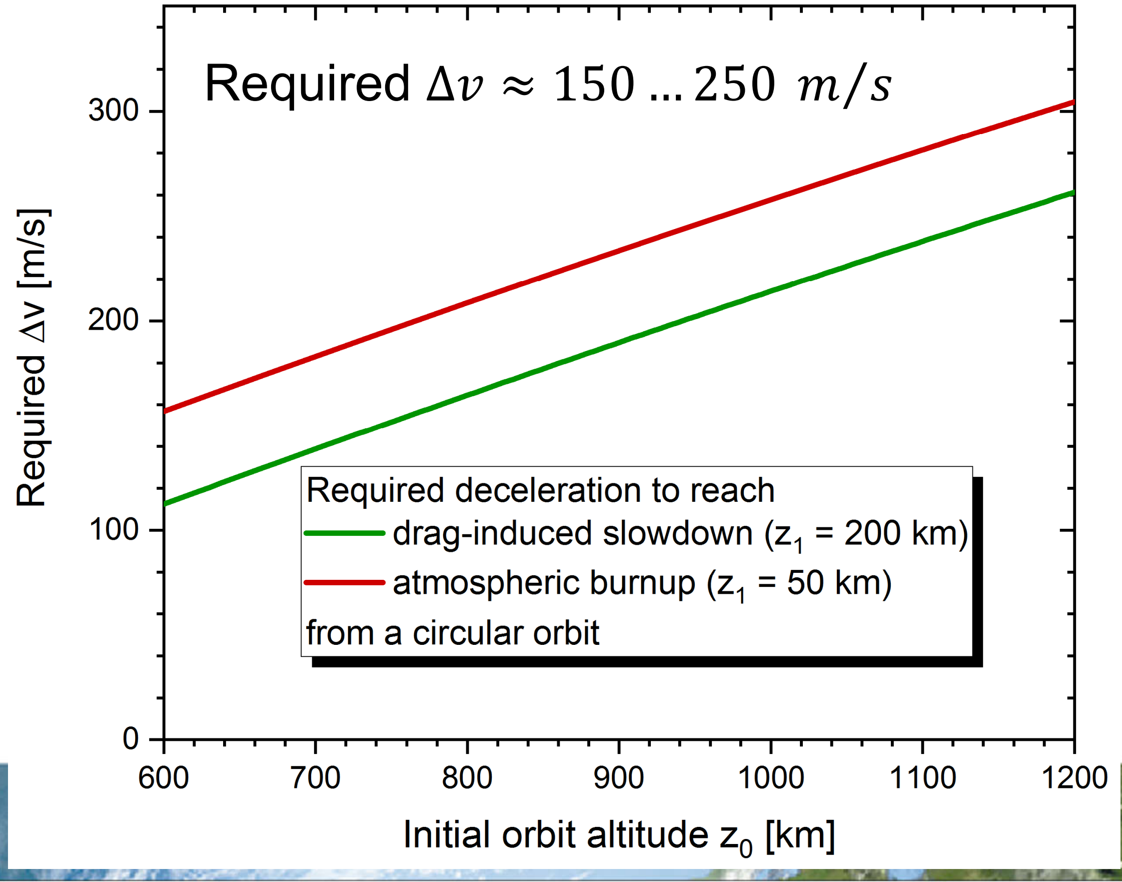
- Deceleration by $\Delta v = 1\,mm/s$
  → in-track displacement by
  $\Delta x/\Delta t = 259.2\,m/d$
- D2D: accelerate target decelerate chaser



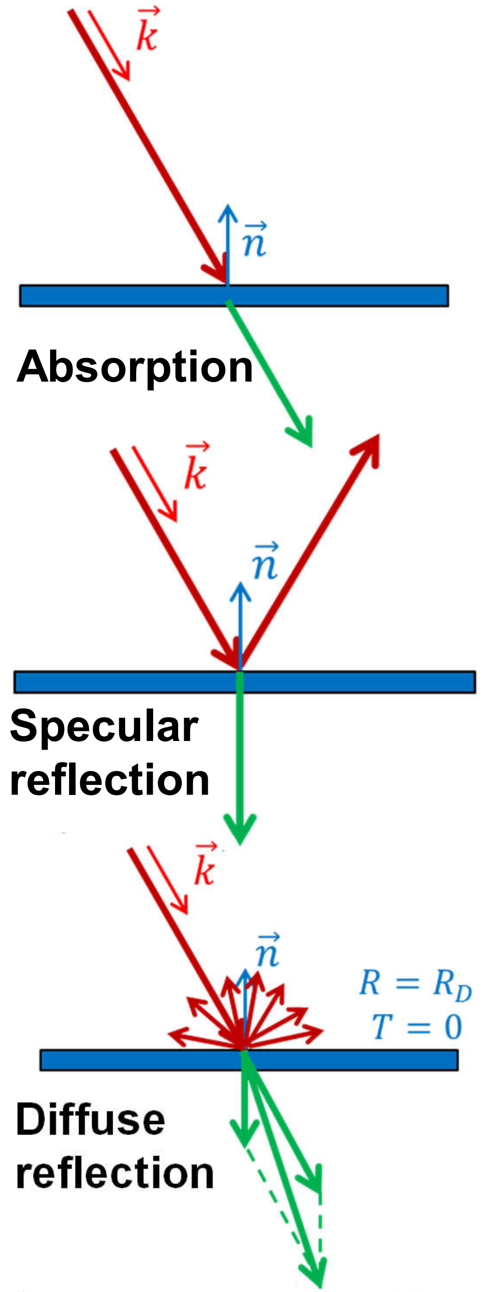
Removal by atmospheric burnup

Rationale: Outer Space Treaty:
- Art. I para. 2: Foster “free exploration and use”
- Art. VII: International liability of launching states
- Art. IX: Avoidance of “harmful contamination”

- In-track Δv_t → Hohmann transfer → perigee lowering
- Radial Δv_r → apogee lift



Laser-matter Interaction: Photon Pressure



Laser-induced force to debris: $\vec{F} = \left[(A + R_D)\hat{k} - (R_D/2 + 2R_S \cos\vartheta)\hat{n}\right] \cdot 3.3\ nN/W \cdot P_L$

Momentum coupling coefficient: $c_m = F/P_L = \Delta p/E_L$

Heat accumulation at debris: $Q = \int A \cdot P_L\, dt$

Coefficient of residual heat: $\eta_{res} = \dot{Q}/P_L = Q/E_L$

Laser backreflection from debris: $P_{refl} = (R_S + R_D)P_L$

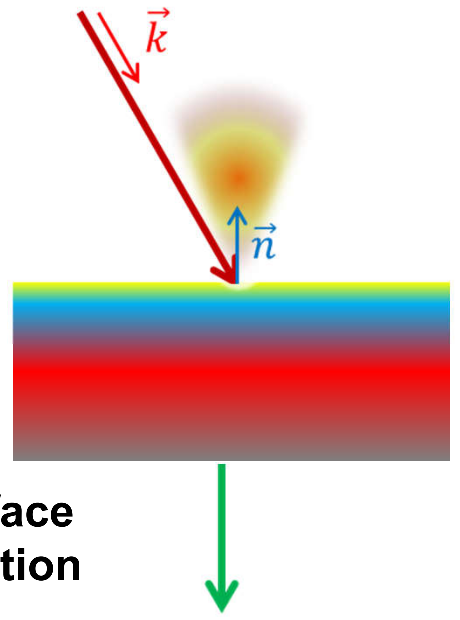
Reflectivity: $R = P_{refl}/P_L = E_{refl}/E_L$

Key parameter: Albedo $R_A = R_S + R_D = 1 - A - T$

Interaction dependencies: Material, temperature, wavelength λ
Scaling of $\vec{F}, Q, P_{refl}$ with laser power: (mostly) linear

A absorptivity
ϑ incidence angle
R_D reflectivity (diffuse)
R_S reflectivity (specular)
P_L laser power
E_L laser pulse energy
R_A albedo
T transmissivity

Laser-matter Interaction: Laser Ablation



Surface ablation

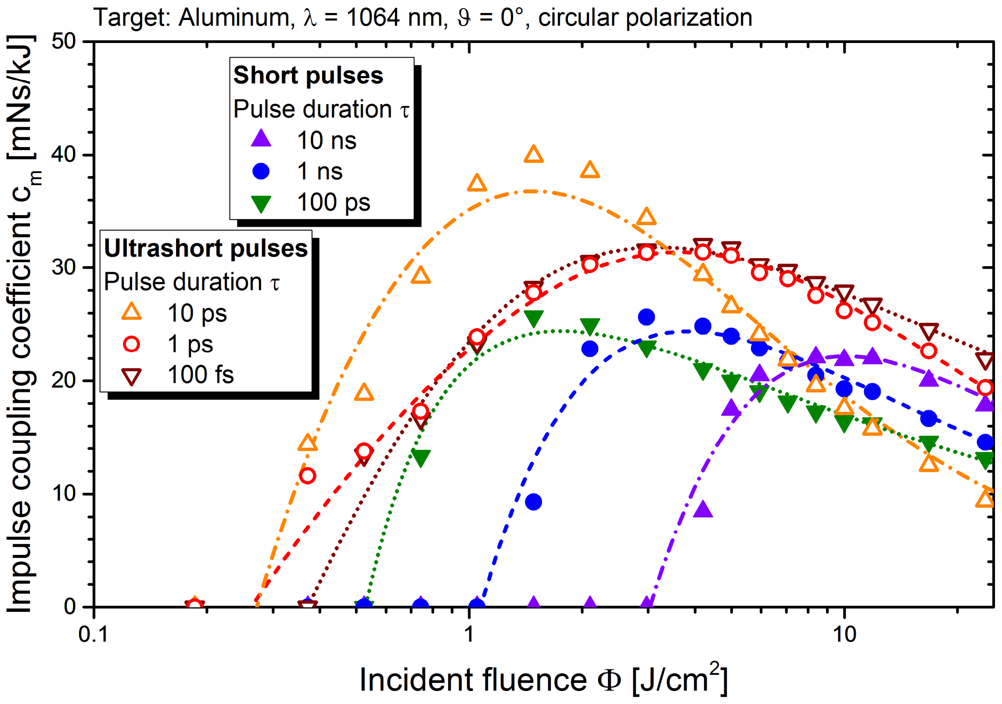
Momentum: $c_m = 1 \ldots 1000\ \mu N/W$

(Photon pressure: $c_m \approx 5\ nN/W$)

Ablation threshold $\Phi_0 \propto \sqrt{\tau}$

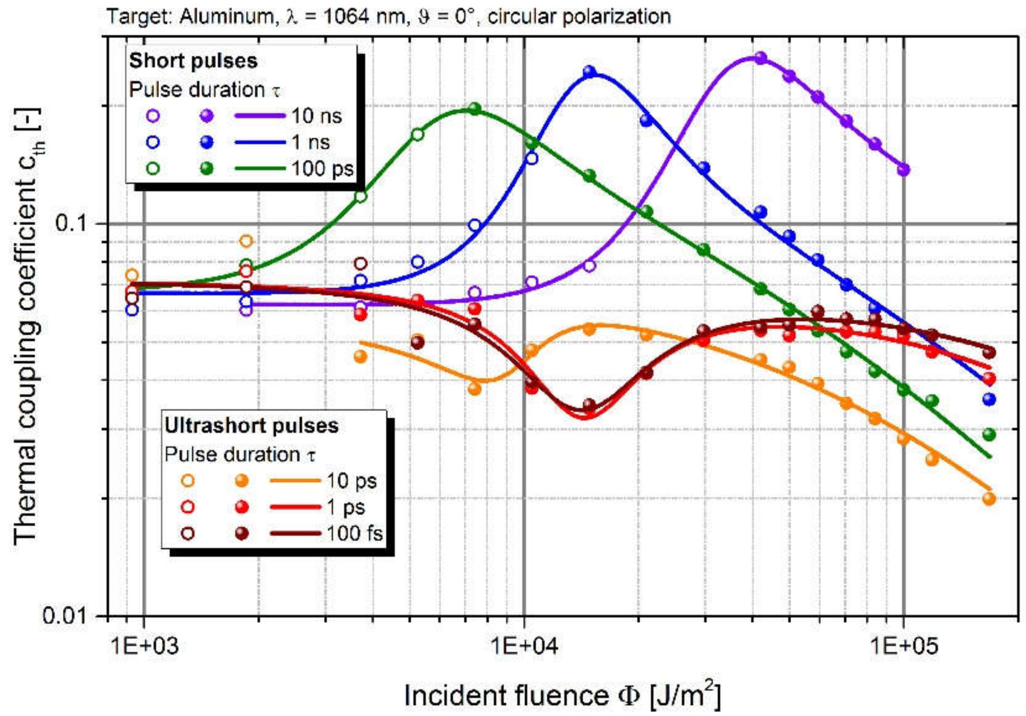
Example: Metals, ns-pulses: $\Phi_0 = 1 \ldots 10\ J/cm^2$

Momentum coupling coefficient



S. Scharring et al, *Opt. Eng.* **58**(1): 011004 (2018)
doi: 10.1117/1.OE.58.1.011004

Coefficient of residual heat



C.R. Phipps et al., *J. Appl. Phys.* **122**: 193103 (2017)
doi: 10.1063/1.4997196

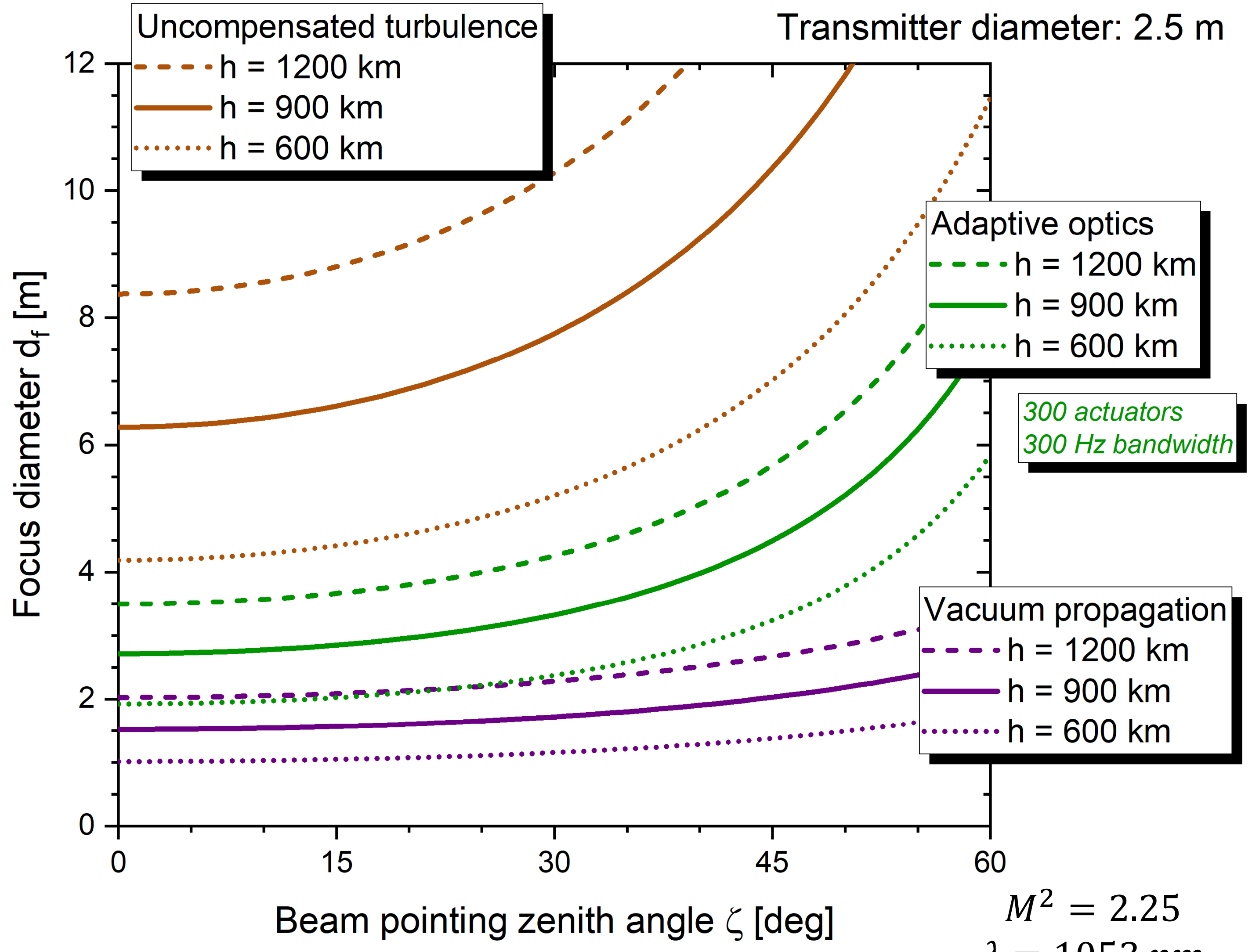
Key parameter: Fluence $\Phi = E_L/A$

*Dependencies: Material, temperature, λ, **pulselength τ, fluence Φ***

*Scaling of $\vec{F}, Q, P_{refl}$ with laser power: **non**-linear*

Laser Beam Propagation through the Atmosphere

Compensation of MT Laser Beam Broadening



$M^2 = 2.25$

$\lambda = 1053\ nm$

$$w_f(z) = \sqrt{\left(\frac{M^2\lambda\, z}{\pi\, w_0}\right)^2 + 8\left(\frac{\lambda\, z}{\pi\, r_0}\right)^2\left(1 - 0.26\left(\frac{r_0}{w_0}\right)^{1/3}\right)^2}$$

$$w_f(z) = \frac{M^2\lambda\, z}{\pi\, w_0\sqrt{\boldsymbol{Str}}}$$

M^2 laser beam quality parameter
λ laser wavelength
z distance to debris
w_0 initial beam radius
r_0 coherence diameter
Str Strehl ratio

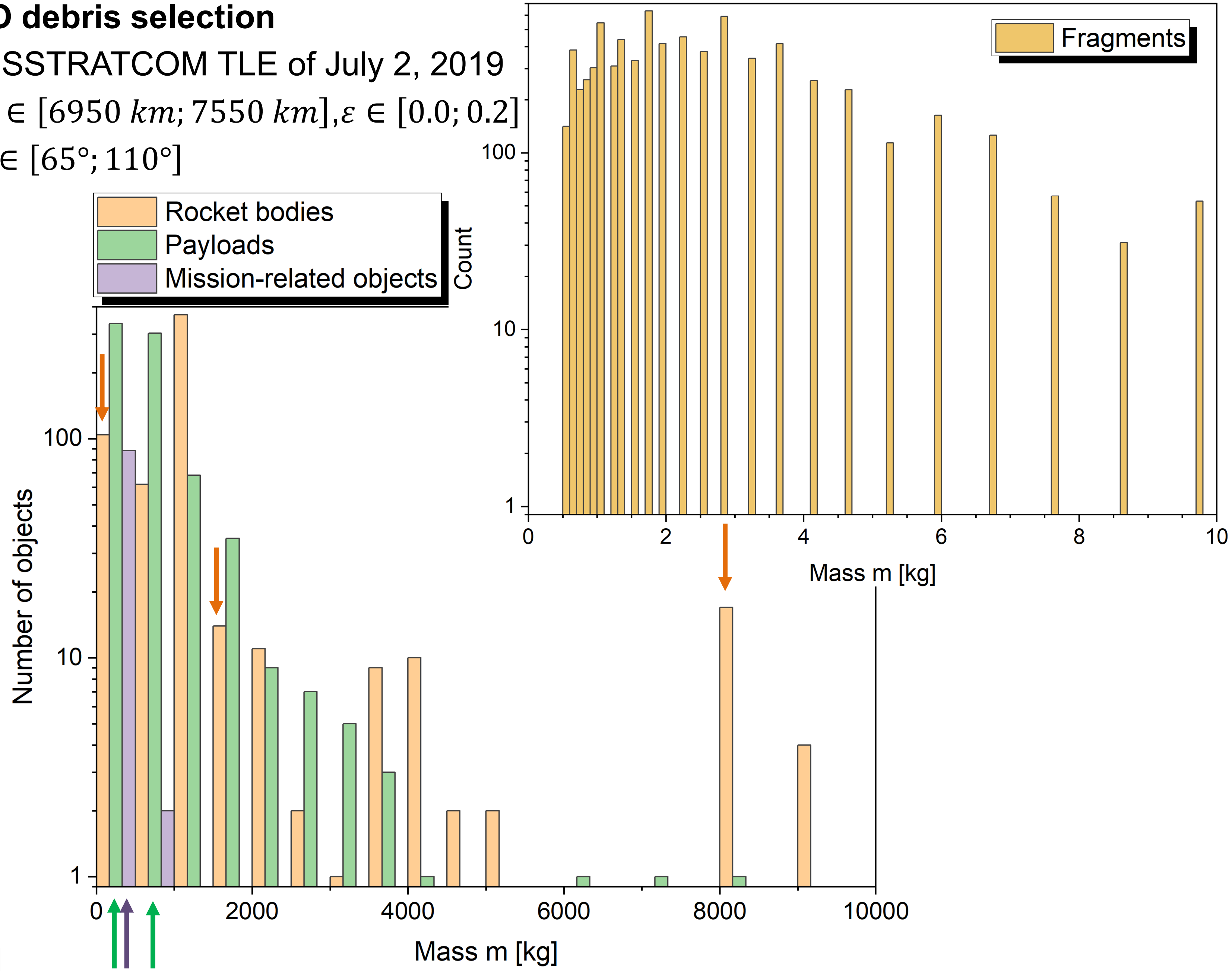
Constraints

- *Tracking jitter*
  → adaptive optics, laser guidestar, tip/tilt compensation, $\sigma = 0.1\ arcsecs$
- *Cloud cover (CF)*
  → no compensation
  Statistical approach: feasibility up to 50% CF
- *Aerosol attenuation*
  → ~ 20%, no compensation
- *Molecular absorption*
  → transmission windows
- *Air breakdown*
  → pulselength $\tau \gtrsim 100\ ps$

Selection of Sample Targets

LEO debris selection

- USSTRATCOM TLE of July 2, 2019
- $a \in [6950\ km; 7550\ km], \varepsilon \in [0.0; 0.2]$
- $i \in [65°; 110°]$



Type	#	NORAD -ID	h $[km]$	m $[kg]$	L_C $[m]$	A/m $[m^2/kg]$
Rocket body	A	19421	1111	23.8	1.15	0.026
	B	23279	937	1421.2	5.18	0.010
	C	22566	859	8226.0	8.23	0.005
Payload	A	43018	649	1.0	0.10	0.015
	B	25478	799	42.0	2.38	0.076
	C	11326	983	802.8	2.07	0.006
Mission-related object	A	37734	706	1.0	0.20	0.025
	B	23250	737	5.0	0.80	0.071
	C	33398	661	50.0	2.50	0.079
Fragment	A	42383	867	0.6	0.10	0.014
	B	33920	790	1.8	0.15	0.010
	C	33859	772	3.7	0.19	0.008

Data source:
ESA DISCOS database
Fragment properties estimated using ESA MASTER-8 model

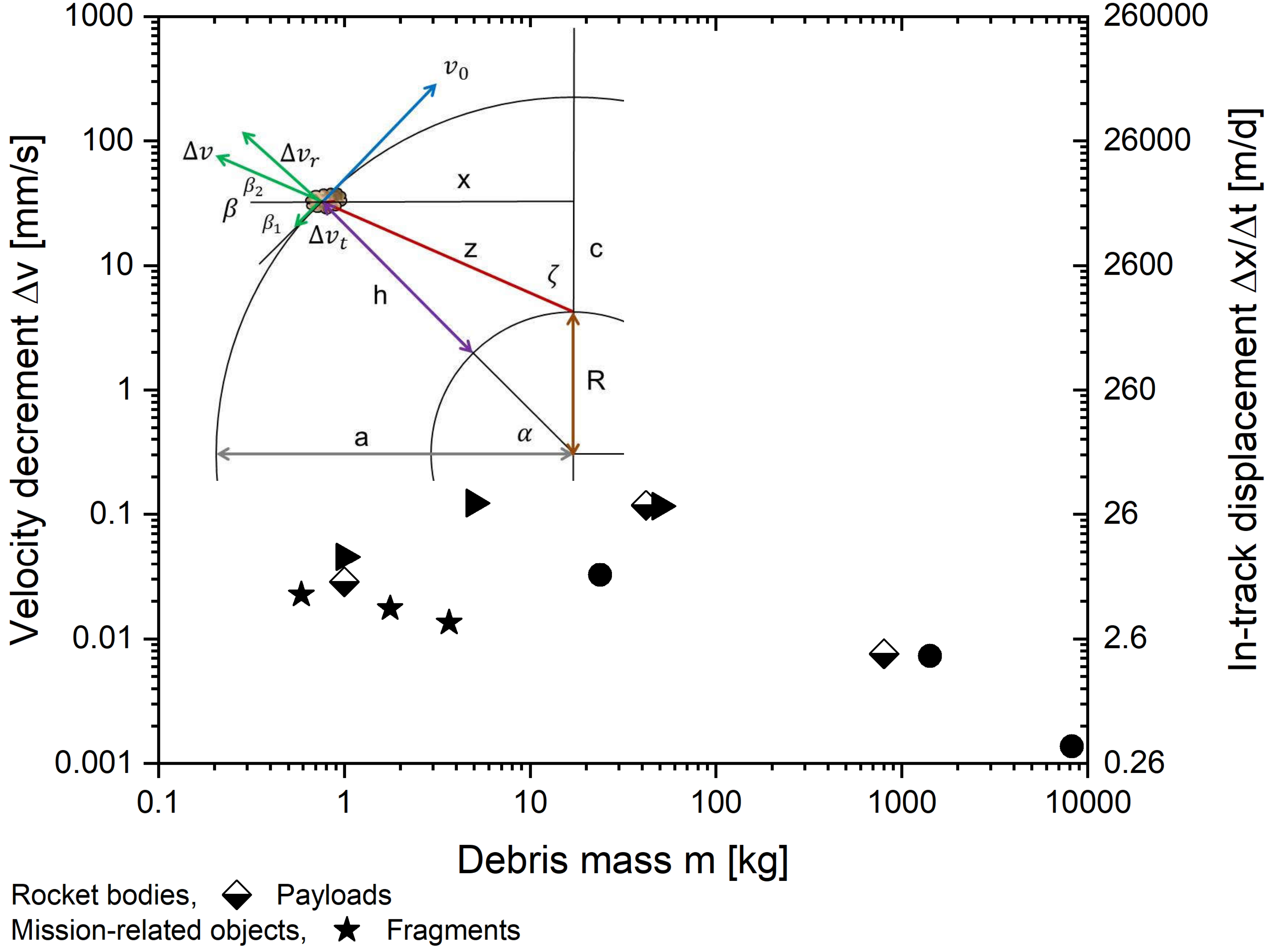
Target Deceleration – Photon Pressure

Laser configuration:

High power laser:

$P = 40\ kW, \lambda = 1064\ nm, M^2 = 1.5, cw$ (i.e., not pulsed)

Direct station transit, irradiation for $\zeta \in [15°; 65°]$



Assumptions:

- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
- Atmospheric attenuation
- Photon pressure: debris albedo

Neglected:

- Tracking uncertainty
- Beam pointing jitter
- Shape, orientation

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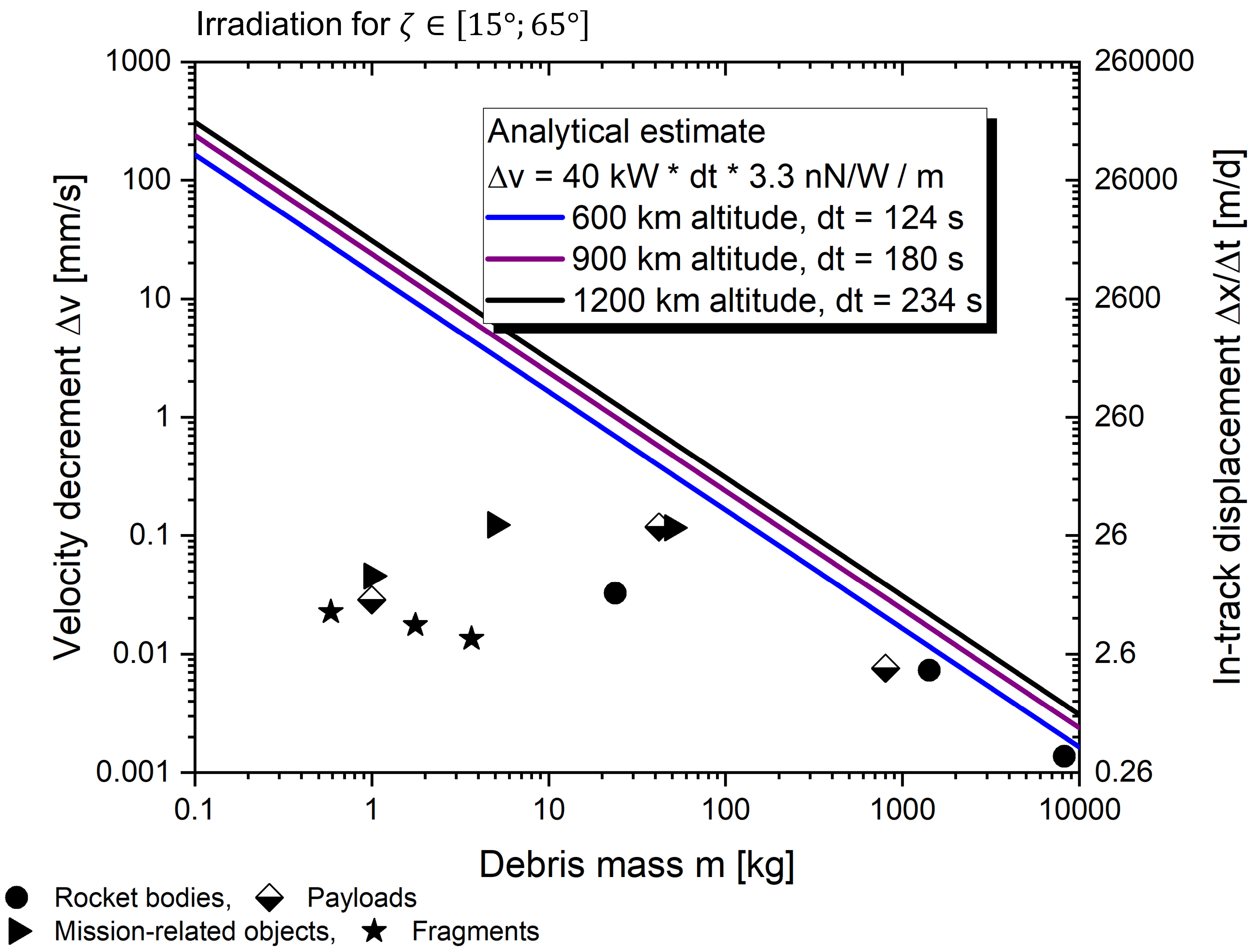

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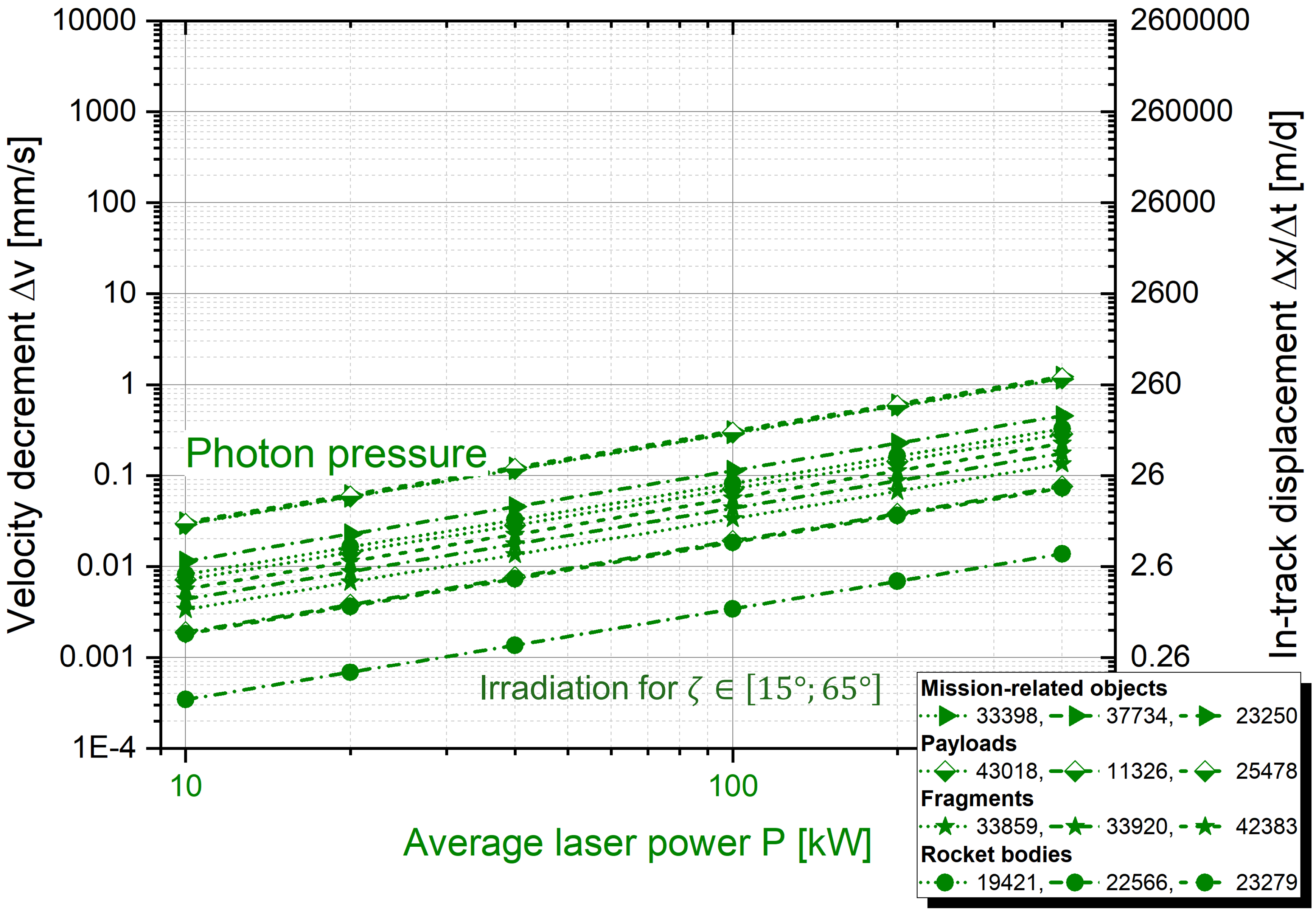

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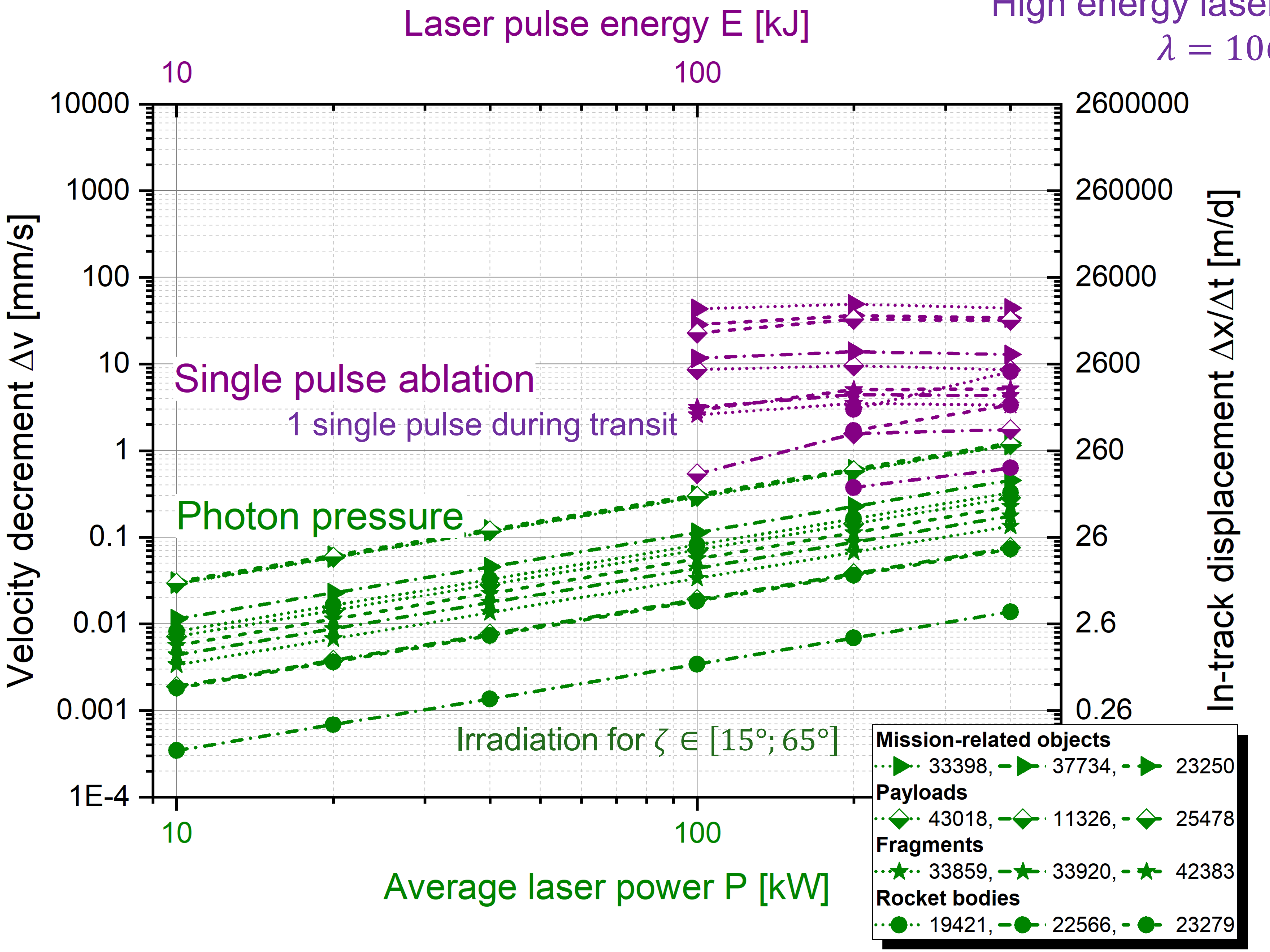
Target Deceleration – Laser Ablation



Laser configurations:

High power laser:

$$\lambda = 1064\,nm, M^2 = 1.5, cw$$

High energy laser:

$$\lambda = 1064\,nm, M^2 = 2.25, \tau = 5\,ns$$

Assumptions:

- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
- Atmospheric attenuation
- Photon pressure: debris albedo
- Ablation: Exp. c_m data (Al, Steel)

Neglected:

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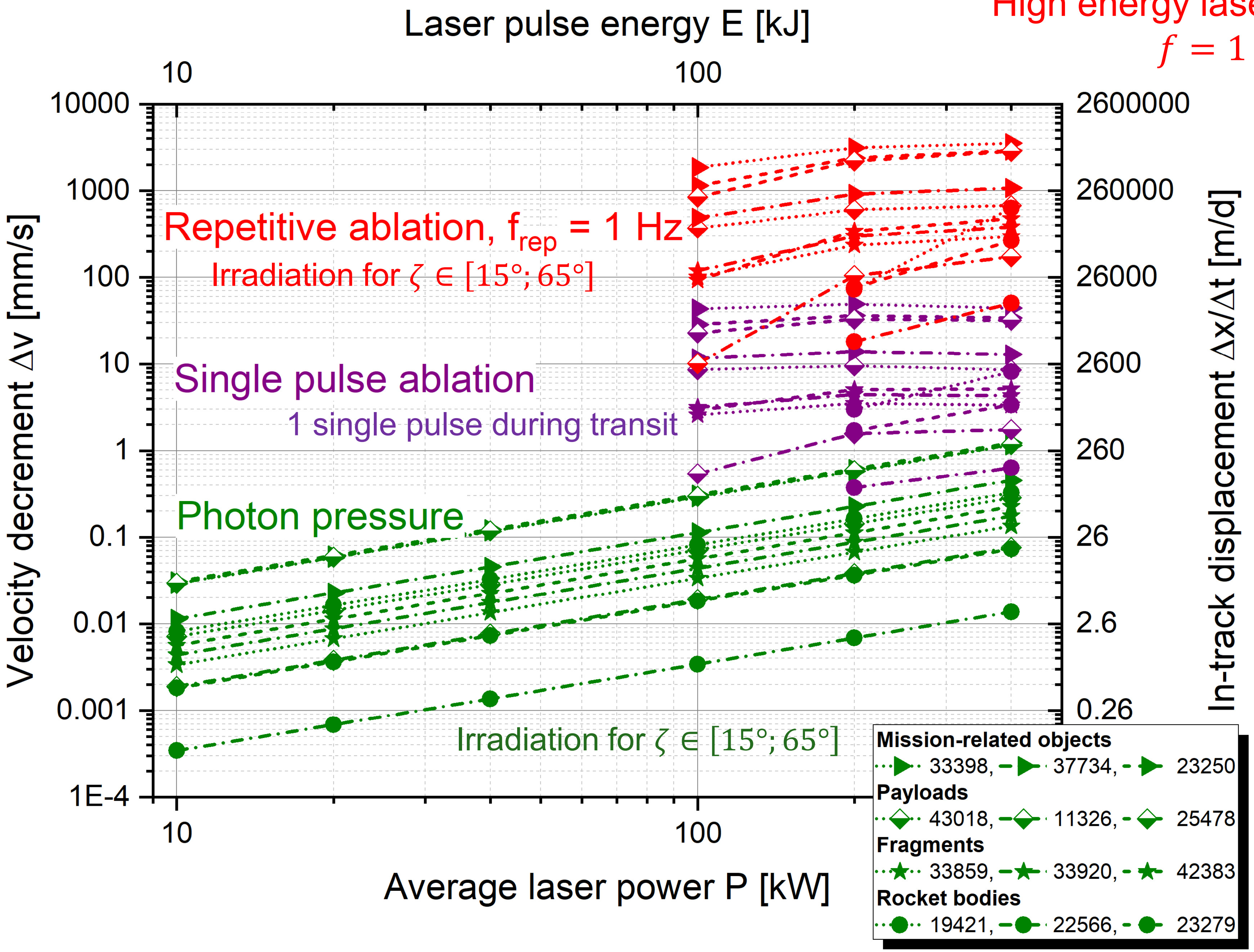
- Beam pointing jitter
- Shape, orientation

Target Deceleration – Laser Ablation



Laser configurations:

High power laser:

$$\lambda = 1064\ nm, M^2 = 1.5, cw$$

High energy laser:

$$f = 1\ Hz, \lambda = 1064\ nm, M^2 = 2.25, \tau = 5\ ns$$

Assumptions:

- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
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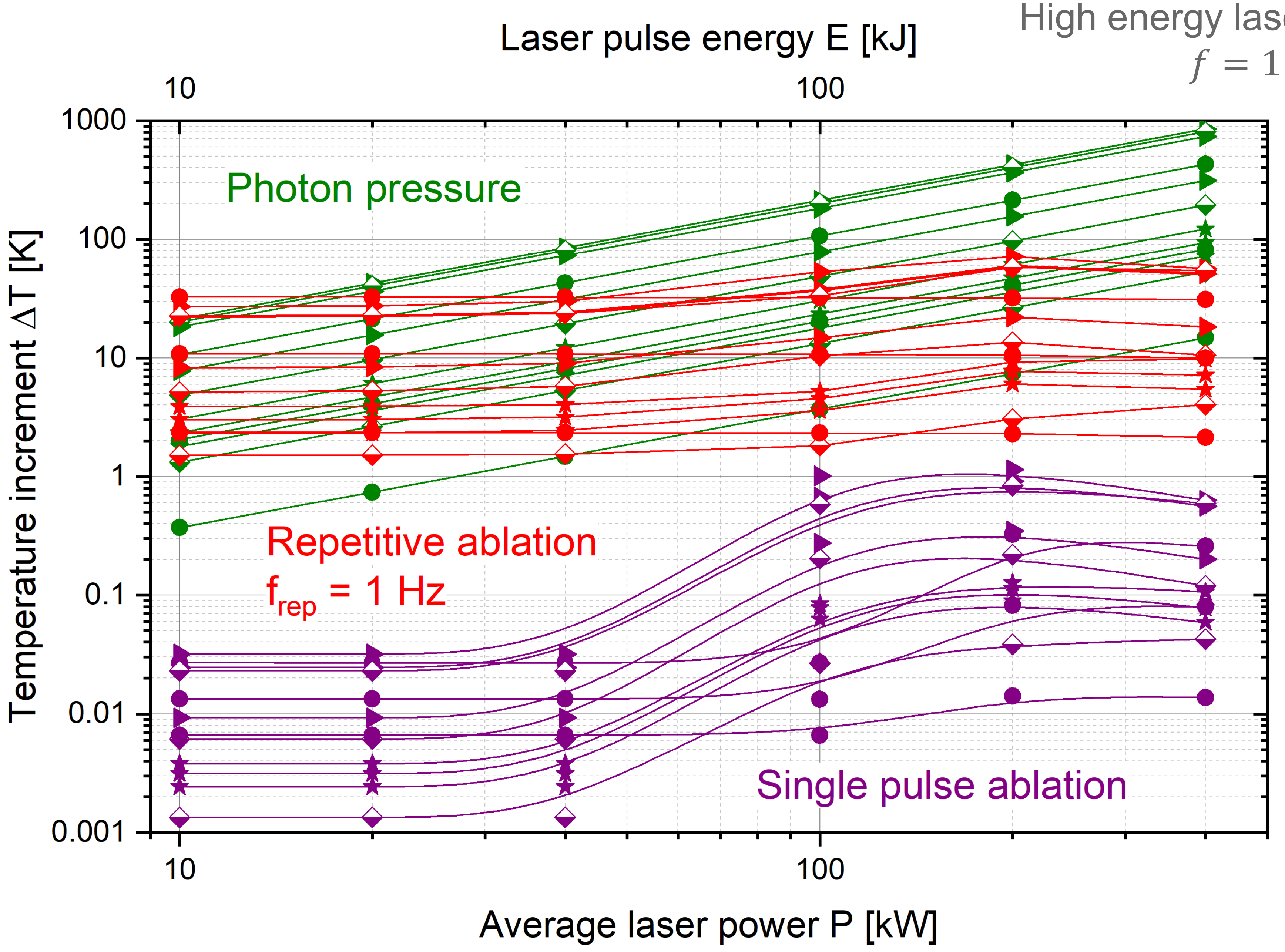
Target Heating



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High energy laser:

$$f = 1\,Hz, \lambda = 1064\,nm, M^2 = 2.25, \tau = 5\,ns$$

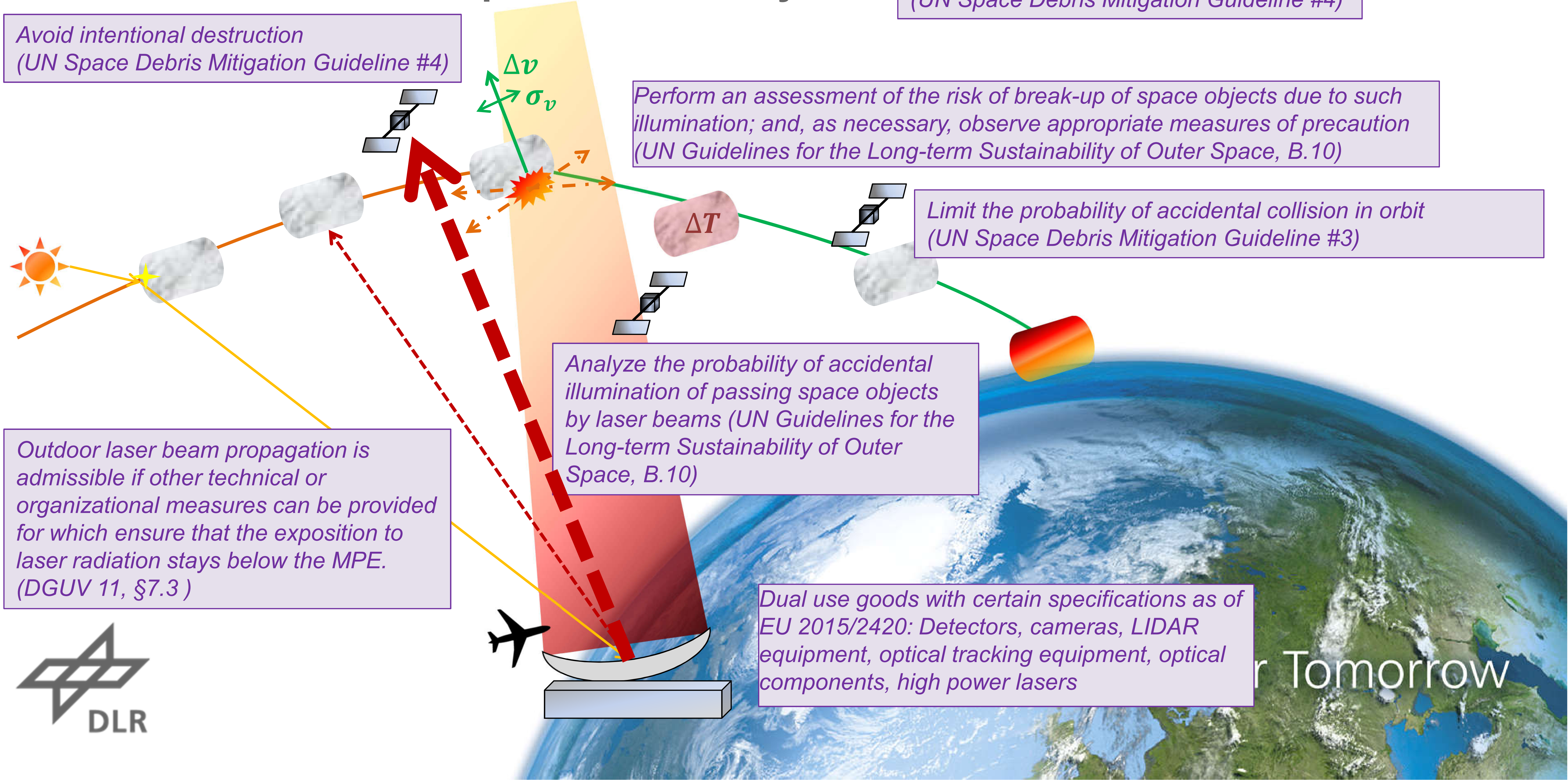
Risks:

- Target meltdown
- Fragmentation
- Detonation of partially passivated objects

Global Framework for Operational Safety

Avoid harmful activities
(UN Space Debris Mitigation Guideline #4)

Avoid intentional destruction
(UN Space Debris Mitigation Guideline #4)



Perform an assessment of the risk of break-up of space objects due to such illumination; and, as necessary, observe appropriate measures of precaution (UN Guidelines for the Long-term Sustainability of Outer Space, B.10)

Limit the probability of accidental collision in orbit
(UN Space Debris Mitigation Guideline #3)

Analyze the probability of accidental illumination of passing space objects by laser beams (UN Guidelines for the Long-term Sustainability of Outer Space, B.10)

Outdoor laser beam propagation is admissible if other technical or organizational measures can be provided for which ensure that the exposition to laser radiation stays below the MPE. (DGUV 11, §7.3)

Dual use goods with certain specifications as of EU 2015/2420: Detectors, cameras, LIDAR equipment, optical tracking equipment, optical components, high power lasers

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Summary: Rationales and Risks of Laser-based Debris Mitigation (LDM)

Benefits

- Debris vs. debris collision avoidance
- Access to many small debris objects
- Operation from ground
- Photon pressure: COTS technology
- Laser ablation: suitable even for debris removal

Risks

- Laser dazzling
- Debris meltdown / fragmentation
- Stored energy detonation
- Weaponization

Challenges

- High power laser technology
- Turbulence compensation
- High-precision tracking
- Debris reconnaissance

Outlook (reverse roadmap)

- T_K — Onset of Kessler syndrome in LEO
- $T_K - 3y$ — Start of LDM operations
- $T_K - 6y$ — Implementation of an LDM station network
- $T_K - 9y$ — In-orbit verification of LDM
- $T_K - 12y$ — Proof of technical feasibility
- $T_K - 15y$ — LDM concept validation

Thank you for your kind attention

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