Space debris removal by *non-destructive* orbit modification using ground-based high-power lasers

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2nd International Orbital Debris Conference

December 6, 2023

Sugar Land, Texas, USA

The Kessler Syndrome from a “medical perspective“

συνδρομον (greek): *Concurrence (of symptoms)*

Relevant pathogens
παθοσ γενεσισ: *Disease Creation*

- Large derelicts
- Accidental / intentional fragmentations

→ Short term: Collision avoidance

→ Long term: Active debris removal missions

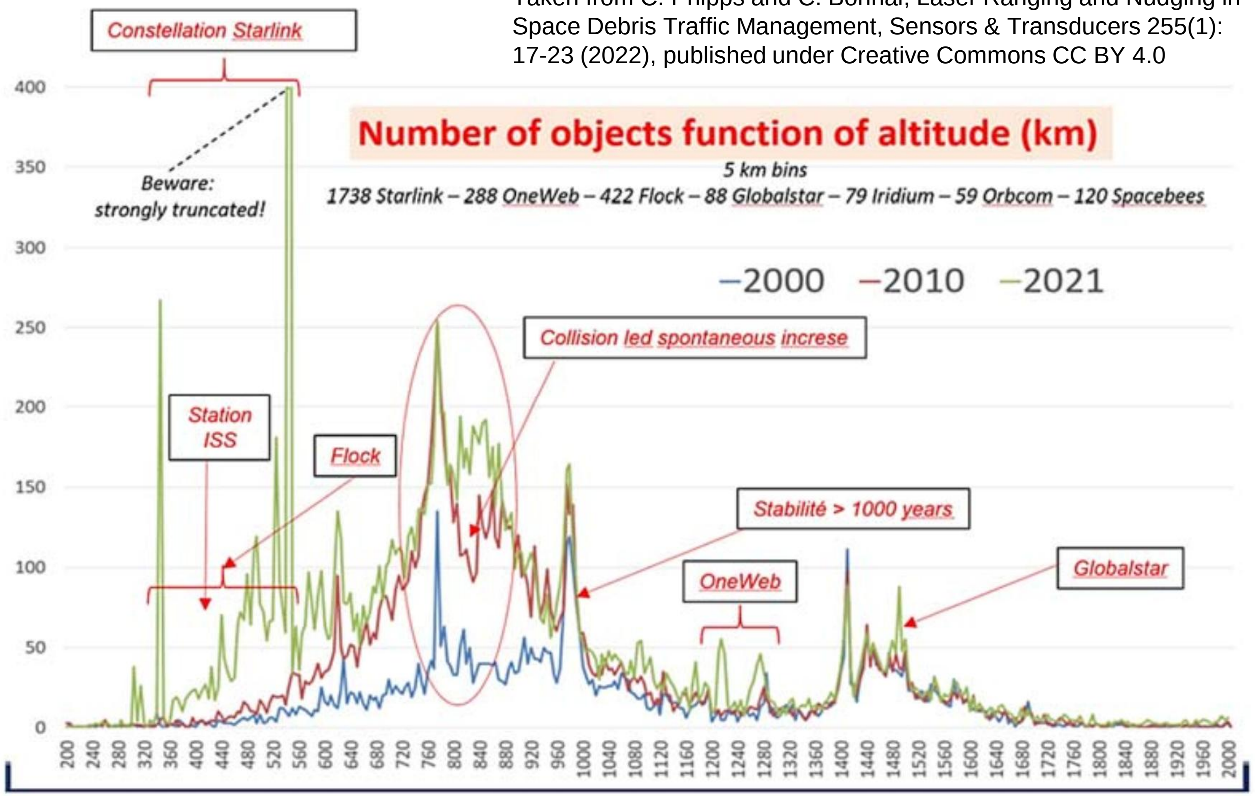
Heavy symptoms
συμπτωμα: *Random Inconvenience*

- Multitude of fragments
- ~1E6 LNTs (lethal non-trackables)

→ Short term: Space situational awareness

→ ***Long term: Laser-based removal?***

Taken from C. Phipps and C. Bonnal, Laser Ranging and Nudging in Space Debris Traffic Management, Sensors & Transducers 255(1): 17-23 (2022), published under Creative Commons CC BY 4.0



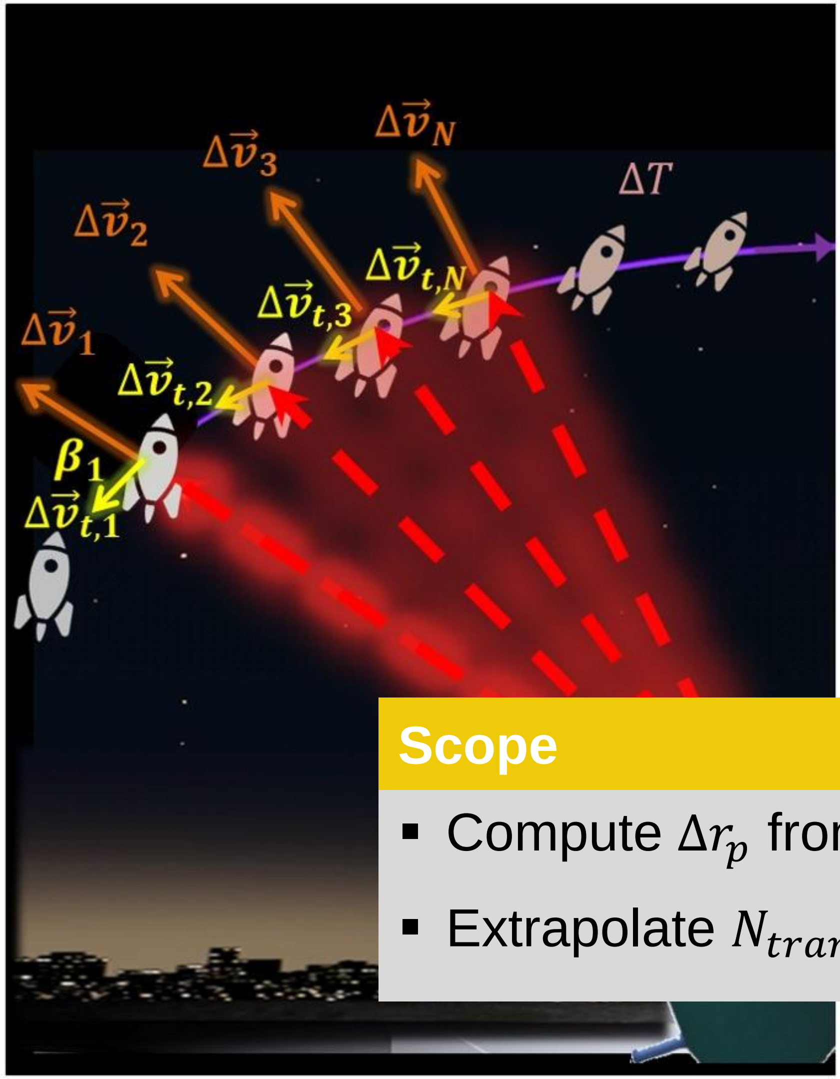
Aggrevation? ← ?

? → **Cure?**

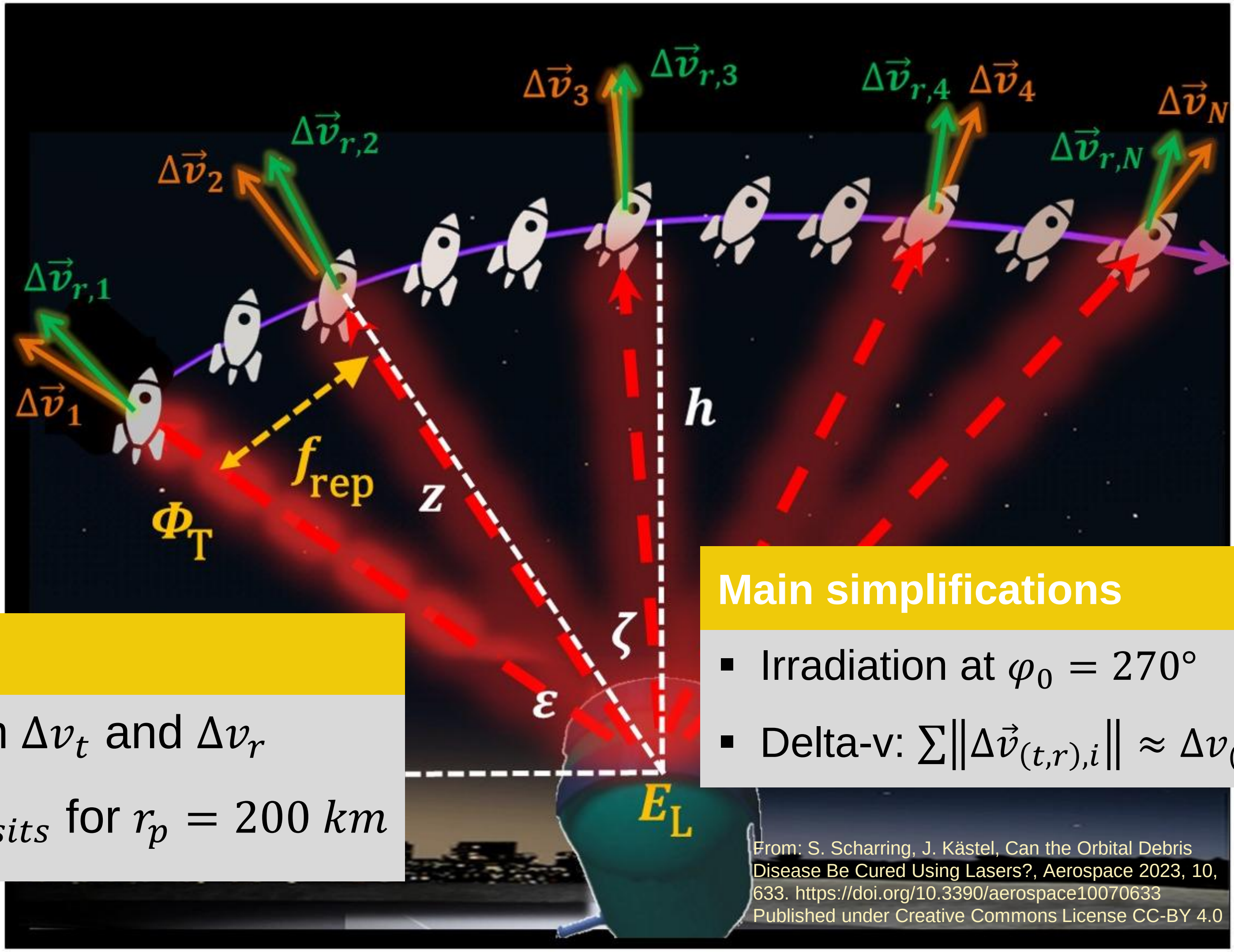
Numerical methods

Perigee lowering for space debris removal

Head-on irradiation



Outward irradiation



From: S. Scharring, J. Kästel, Can the Orbital Debris Disease Be Cured Using Lasers?, Aerospace 2023, 10, 633. https://doi.org/10.3390/aerospace10070633

Scope

- Compute Δr_p from Δv_t and Δv_r
- Extrapolate $N_{transits}$ for $r_p = 200\ km$

Main simplifications

- Irradiation at $\varphi_0 = 270°$
- Delta-v: $\sum\left\|\Delta\vec{v}_{(t,r),i}\right\| \approx \Delta v_{(t,r)}$

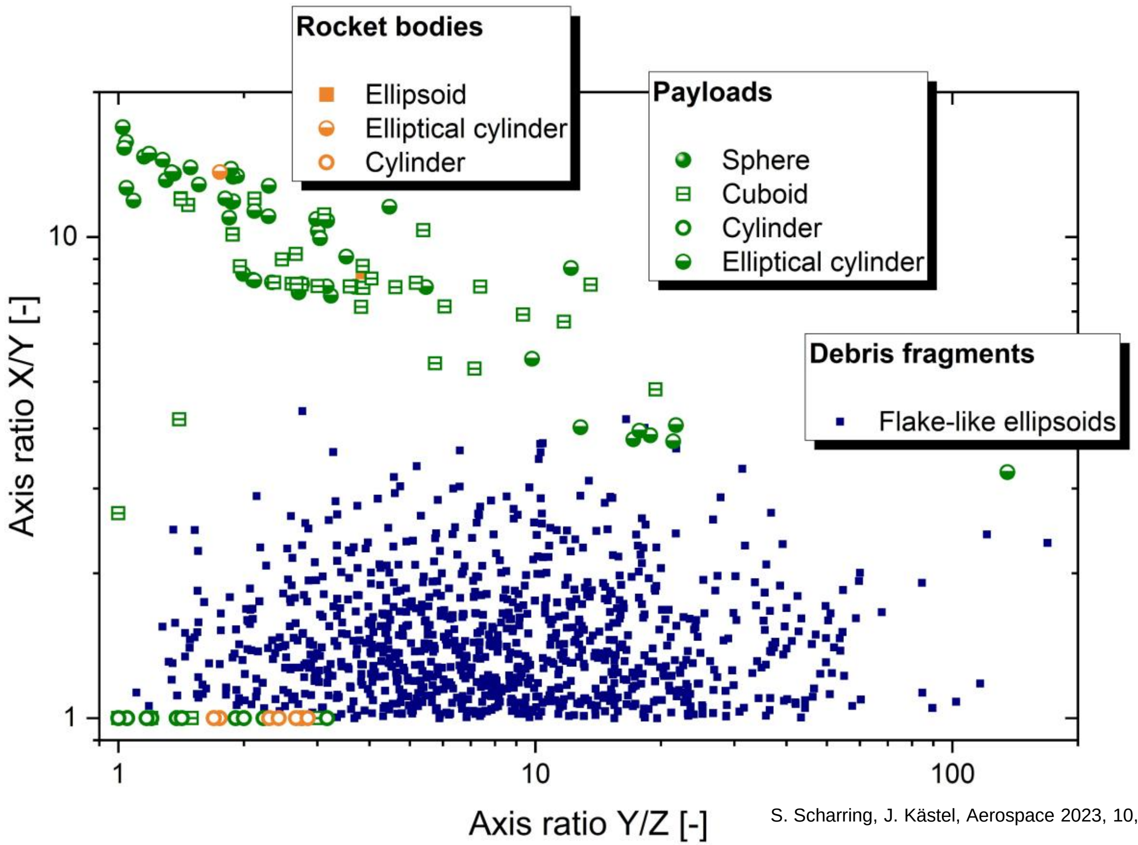
Δv: Velocity change, ΔT: Temperature increase, E_L: Laser pulse energy, Φ_L: Laser fluence, f_{rep}: Laser pulse repetition rate
r_p: Perigee altitude, φ: True anomaly

Debris targets

Orbital range

USSTRATCOM TLE **non-active** catalogued objects as of July 2, 2019 with

- Semi-major axis $a \in [6950\ km; 7550\ km]$
- Inclination $i \in [65°; 110°]$
- Numerical eccentricity $\varepsilon \in [0.0; 0.2]$



Target categories

- 1 large satellite (Envisat)
- 10 rocket bodies

11 out of „Top50" targets (1000 – 10000 kg)

cf. McKnight, Acta Astronaut. 181: 282 (2021)

- 100 medium-sized payloads (50 – 1000 kg)
- 1000 Fragmente (1 – 50 kg)

Geometric data from ESA DISCOS database

- Payloads, rocket bodies: Mass, shape, optical cross-section
- Fragments: Radar cross-section

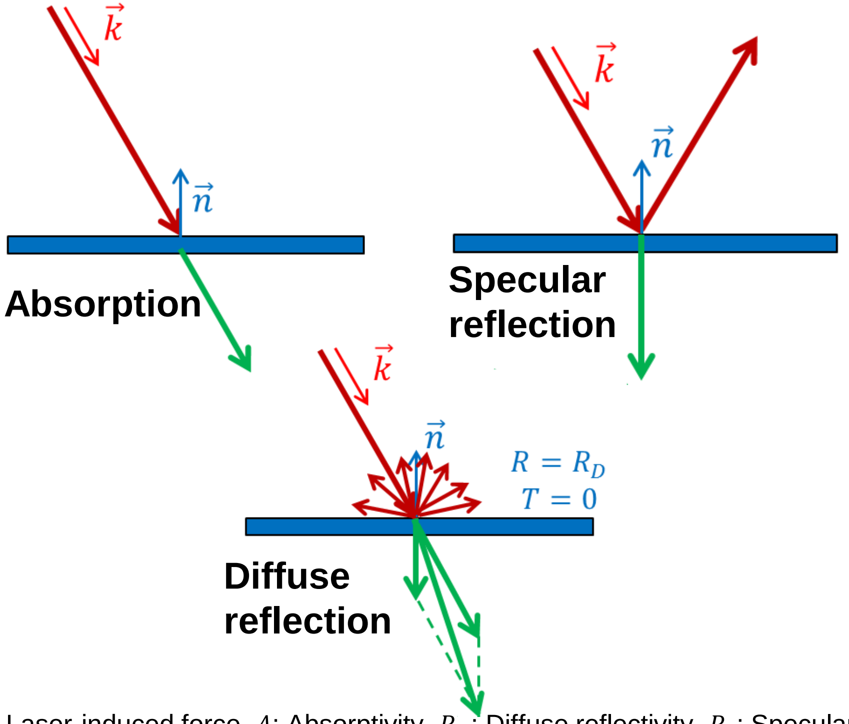
Laser-based mechanisms for momentum transfer

JCA: Just-in-time collision avoidance
ADR: Active debris removal

Photon pressure (JCA only)

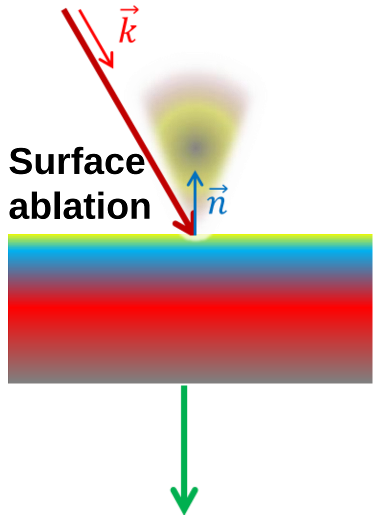
Linear power scaling:

$$\vec{F} = \left[(A + R_D)\hat{k} - (R_D/2 + 2R_S \cos\vartheta)\hat{n}\right] \cdot 3.3\ \mathbf{n}N/W \cdot P_L$$



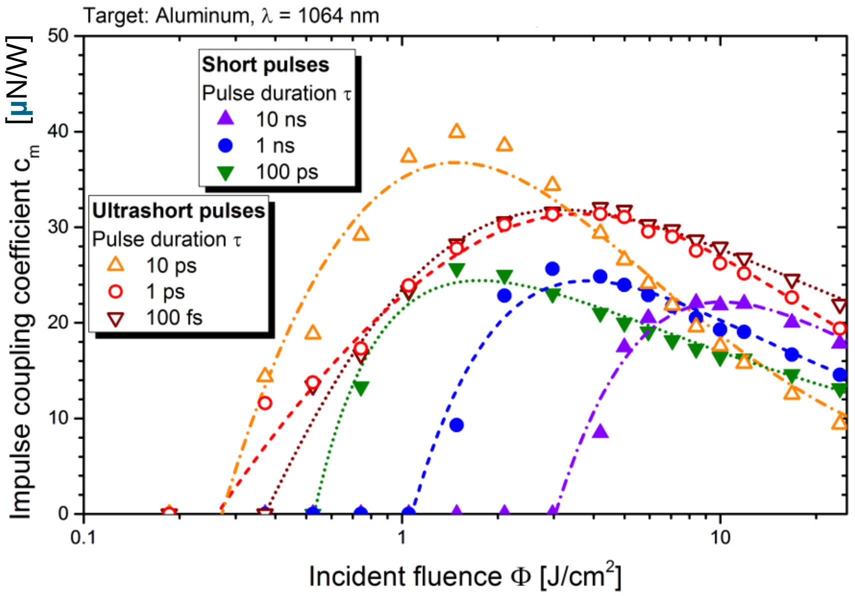
$\vec{F}$: Laser-induced force, A: Absorptivity, R_D: Diffuse reflectivity, R_S: Specular reflectivity, P_L: Laser power

Laser ablation (JCA and ADR)



Non-linear power scaling:

$$\vec{F} \approx \left[\frac{\Phi - \Phi_0}{\Delta\Phi + (\Phi - \Phi_0)} \cdot b \cdot \left(\frac{\sqrt{\tau}}{\lambda\Phi}\right)^c\right] \hat{n} \cdot \langle P_L \rangle$$



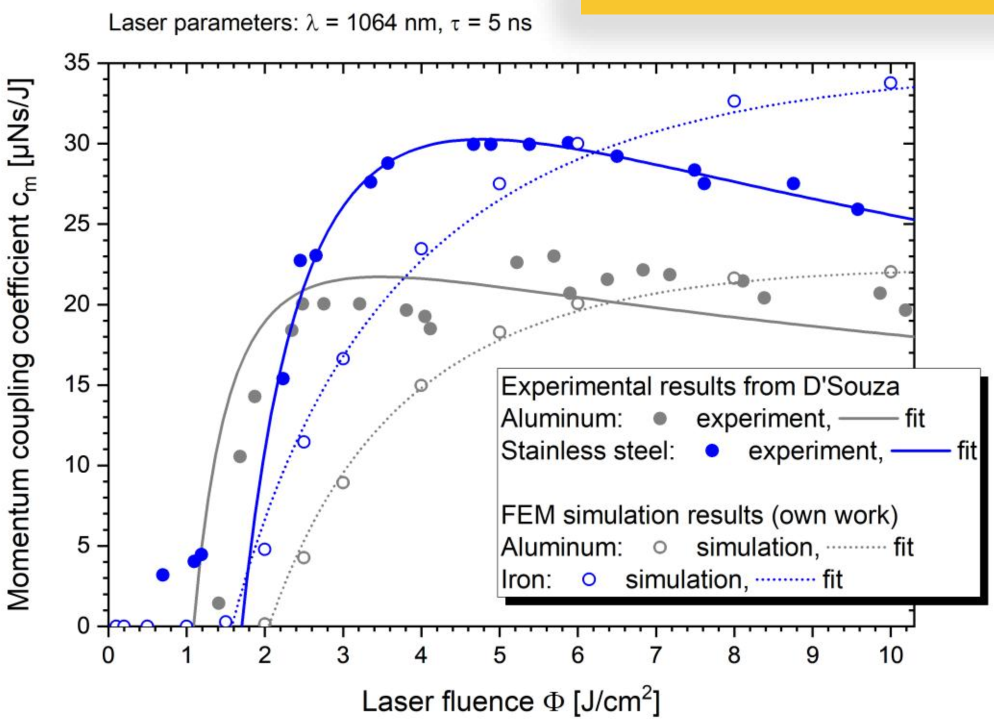
Φ: Laser fluence, $\Delta\Phi, b, c$: Non-linear fit parameters, λ: Laser wavelength, τ: Laser pulse length

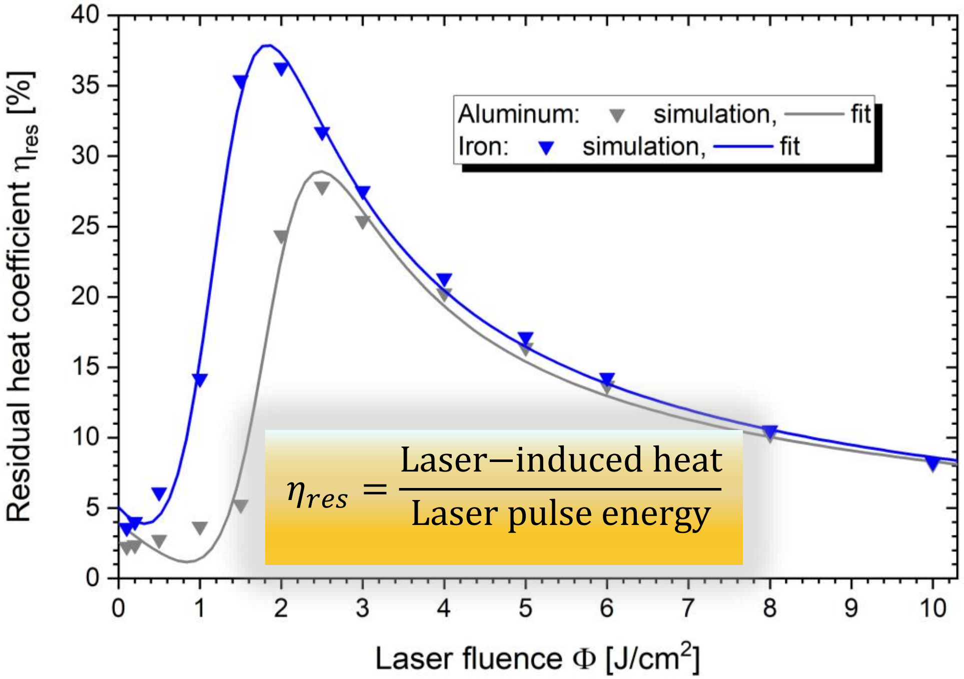
Simulation of thermo-mechanical coupling

Monte Carlo analysis of momentum

- Geometric target primitives (Wavefront.obj)
- Gaussian beam profile (Raytracing)
- Arbitrary orientation
- Pointing jitter

$$c_m = \frac{\text{Laser–induced momentum}}{\text{Laser pulse energy}}$$





$$\eta_{res} = \frac{\text{Laser–induced heat}}{\text{Laser pulse energy}}$$

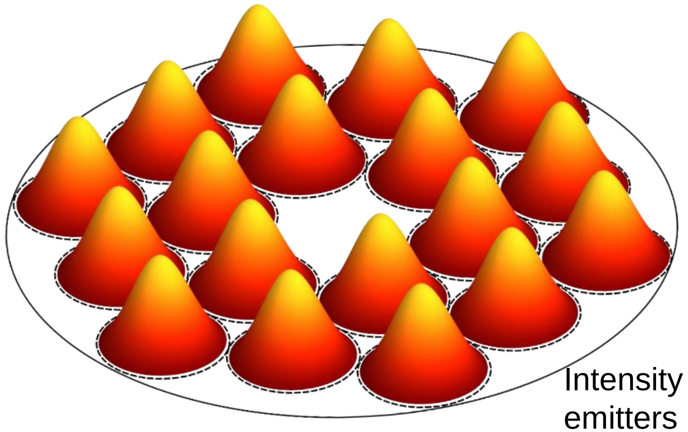
Simplified analytical computation of heat

- Homogeneous fluence over optical cross-sectional area
- Homogeneous distribution of residual heat inside the target
- No radiation cooling between laser pulses
- Thermal equilibration between laser station transits

High energy laser (phased array)

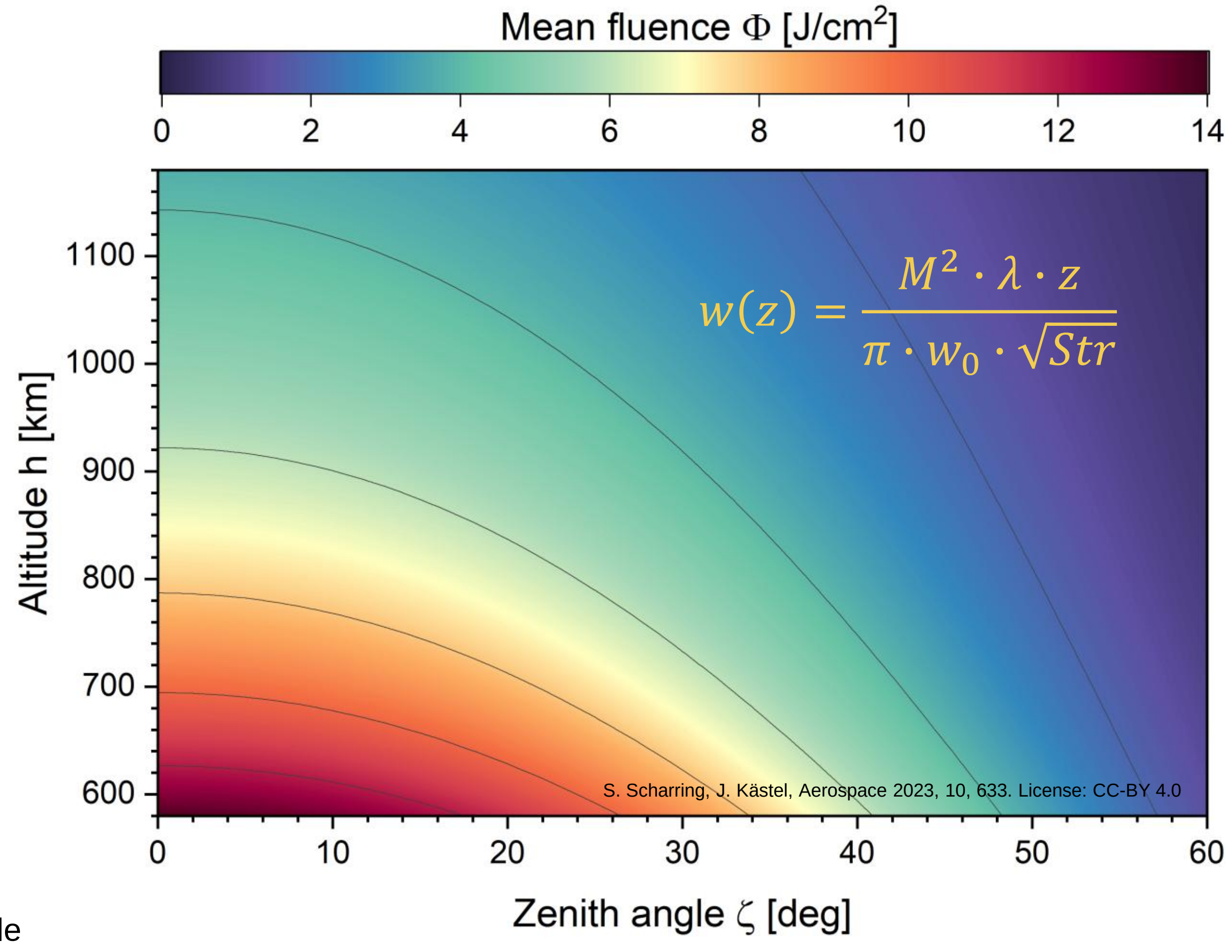
Station configuration

- Low energy single laser emitters ($E_L = 20\,J$, Yb:YAG, $\lambda = 1030\,nm, \tau = 5\,ns$)
- **Coherent coupling of 5000 laser emitters**
- **High pulse repetition rates feasible**
- Transmitter aperture diameter: 4 m

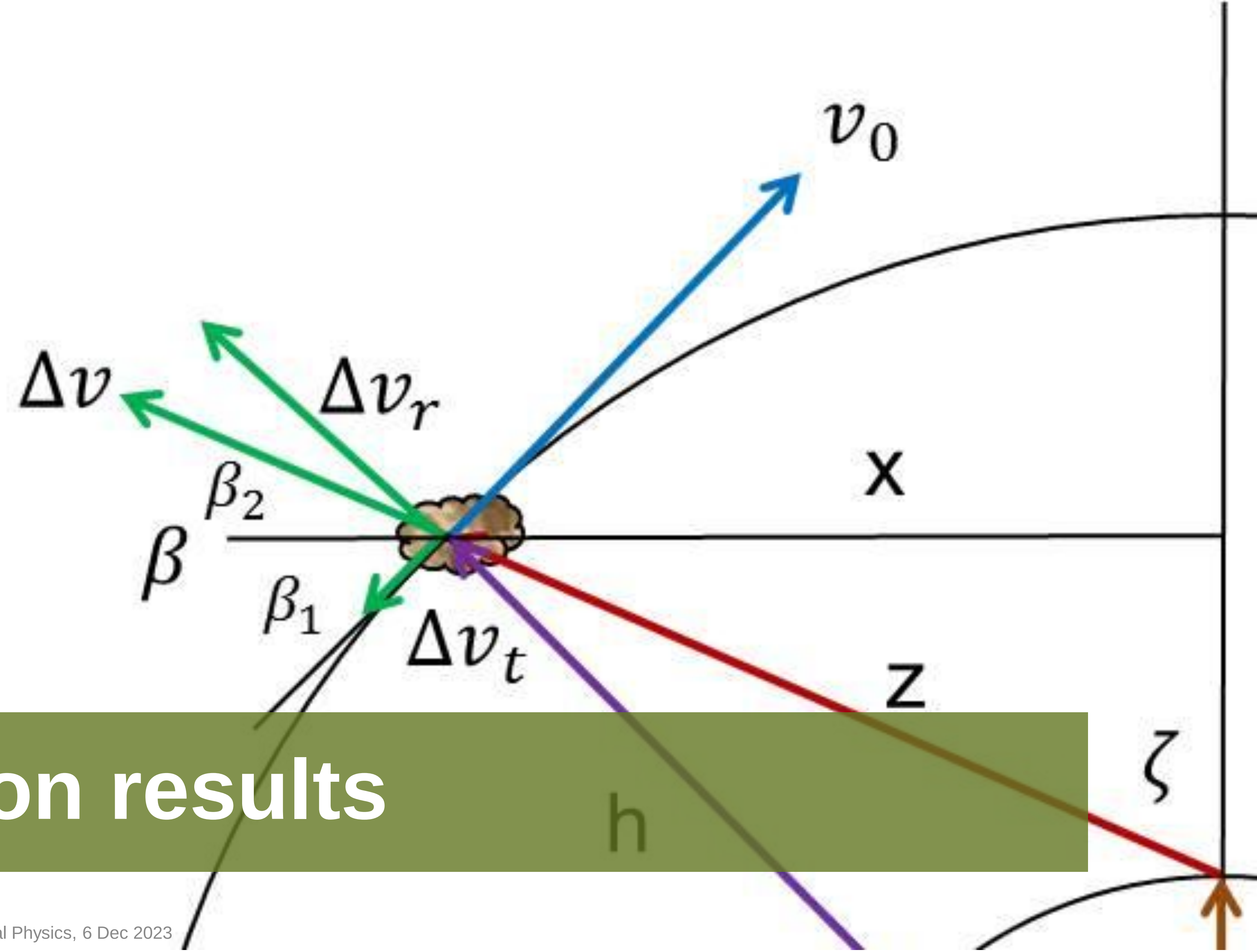


Intensity distribution of 18 single emitters in a tiled aperture transmitter

Beam focusing to LEO



E_L: Laser pulse energy, λ: Laser wavelength, τ: Laser pulse length
w: Beam radius, z: Distance, M^2: Beam quality parameter, Str: Strehl ratio

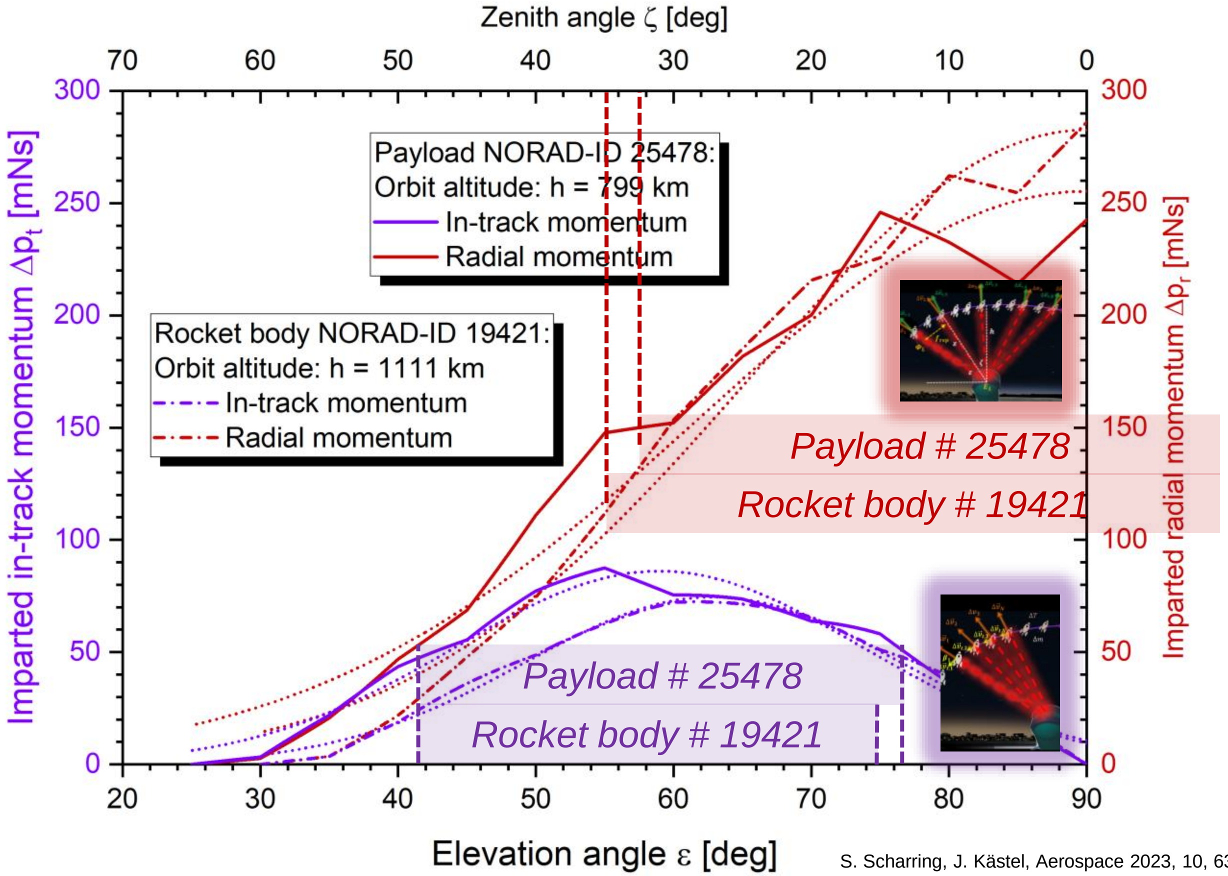


Simulation results

Irradiation interval

Target-specific Gaussian fit

- … of Δp_t (head-on irradiation) and
- … of Δp_r (outward irradiation), resp.
- FWHM = target-specific irradiation interval
- Avoidance of inefficient (but heating) irradiation



Linear fit irradiation range limits $\zeta_i(h)$

Object type specific irradiation

Category	$y_1[°]$	$m_1[°/km]$	$y_2[°]$	$m_2[°/km]$	$y_3[°]$	$m_3[°/km]$
Payload	59.9	-0.0145	17.4	-0.0052	41.1	-0.0105
Rocket Body	68.7	-0.0253	22.9	-0.0099	54.2	-0.0237
Al fragment	55.6	-0.0112	13.0	-0.0023	34.5	-0.0055
Steel fragment	56.9	-0.0158	14.9	-0.0046	36.5	-0.0092

y_i, m_i: linear fit parameters

Fragment irradiation at 6 – 9 Hz repetition rate

$$\Delta v = (A/m)\sum_{i=1}^{N} c_m(\Phi_i)\cdot\Phi_i$$

Thermal constraints

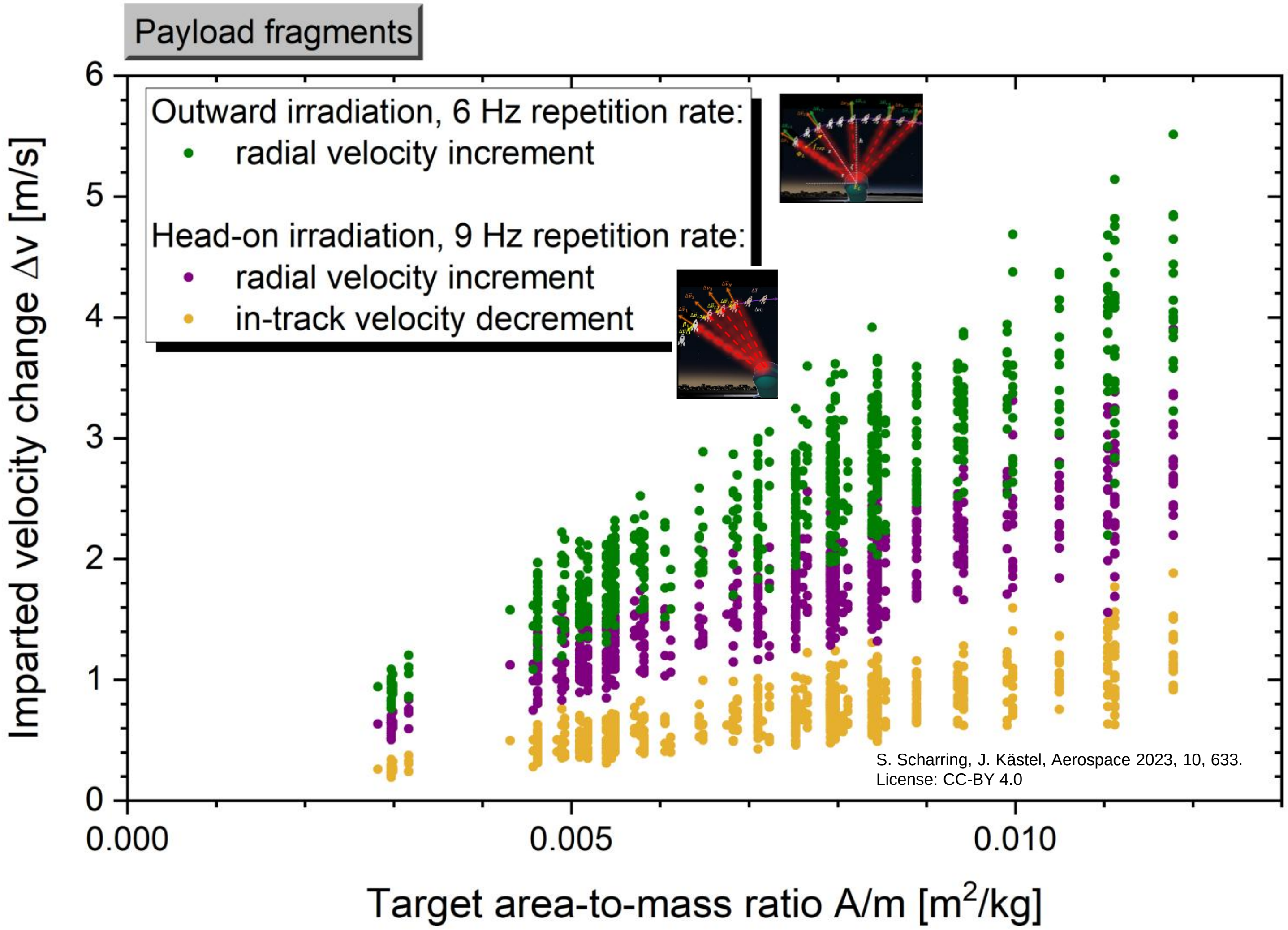
- $\Delta T \leq 100\ K \approx 20\% \cdot (T_{melt} - T_0)$
  → no meltdown
  → limitation of pulse rate needed

Delta-V scatter

- different target shapes
- altitude-dependent fluence
- altitude-dependent pulse number

Irradiation outcome

- $\Delta v \ll 100\ m/s$
  → no single-pass removal
  → multiple irradiations needed



Perigee lowering (single overpass)

Head-on irradiation

… outperforms outward irradiation despite…

- lower laser fluences in orbit,
- less Δv

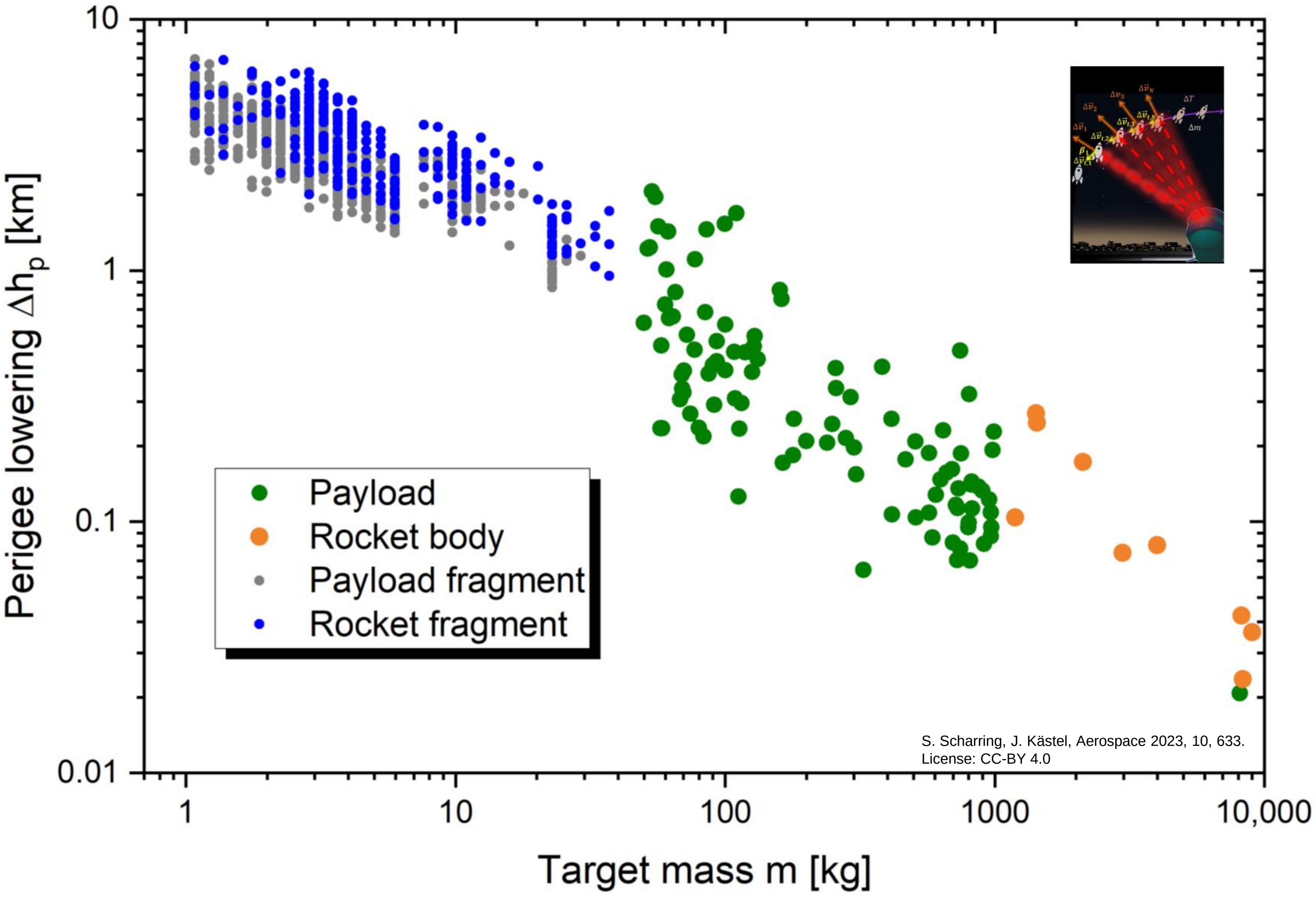
… but due to orbital mechanics:

$$\Delta r_p = (1 - e_0)\Delta a - (a_0 + \Delta a)\Delta e$$

with

$$\Delta e = [2e_0 \boldsymbol{\Delta v_t} + r_0\, \boldsymbol{\Delta v_r}/a_0]/v_0,$$
$$\Delta a = 2\, a_0^2 v_0 \boldsymbol{\Delta v_t}/GM$$

at $\varphi_0 = 270°$



Irradiation of satellites / rocket bodies: 1 – 6 Hz pulse rate

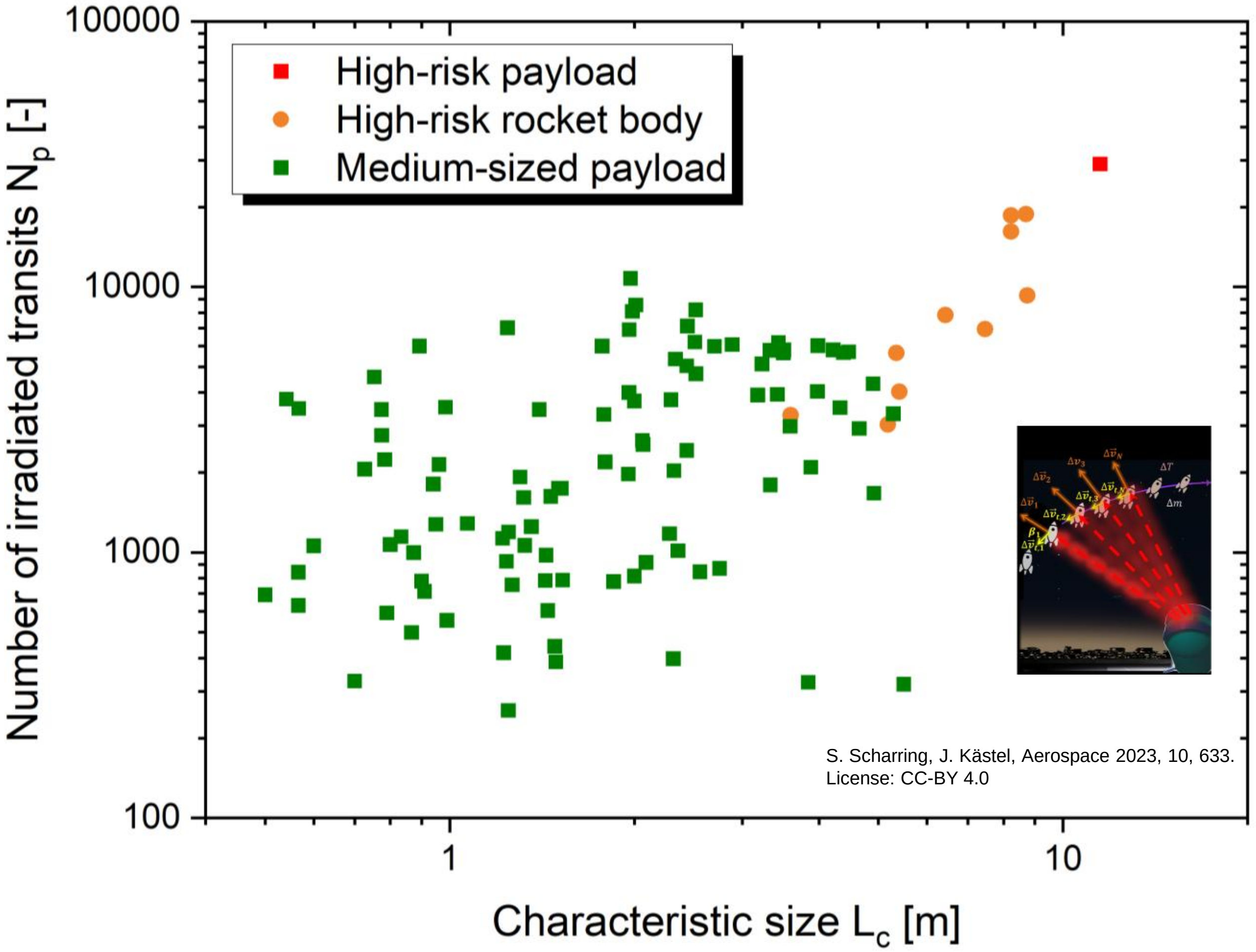
Thermal limitation → DE thresholds

- Missiles:
  - mechanical: $> 5\ kJ/cm^2$
  - thermal: $> 10\ kW/cm^2$
- Unhardened satellites:
  - thermal: $\ll 100\ W/cm^2$

Bloembergen, N. et al. Beam Material Interactions and Lethality. In *Report to The American Physical Society of the study group on science and technology of directed energy weapons*. **1987**, *59(3) Part II*, S119 – S143.

Altitude-dependent pulse repetition rate

- Selection of maximum intensity: $13.7\ W/cm^2 = 100\ I_{sun}$ at zenith
- Head-on irradiation: +50%
- Outward irradiation: 1.1 … 3.8 Hz
- Head-on irradiation: 1.6 … 5.7 Hz



De-orbiting

- Unrealistically high effort for massive targets (> 300 kg)
- Conceivable for light-weight objects (depends on Δr_p)

Conclusions and outlook

Laser-based removal works…

- … only considering thermal constraints
- … with head-on irradiation even from ground

- … possibly for satellites, rocket bodies < 300 kg
- … likely best for fragments

- … efficiently with a global station network
- … for removal of ~2000 fragments per year

Laser-based removal challenges

- Implementation of a global laser station network
- Acceptance of weapon-grade removal lasers
- Predictive avoidance with momentum uncertainty

Laser-based removal is …

- … not a hot topic in terms of sustainability
- … suited for “Kessler 2.0“ (CA overload) from
  - exponentially increasing awareness of increasingly small objects +
  - rise of megaconstellations
- … potentially an economically relevant painkiller

Thank you for your kind attention

Acknowledgments

- Wolfgang Riede, Jochen Speiser: Study supervision
- Jascha Wilken, Lukas Eisert, Erik Marten Klein: Code development
- Christoph Bamann: Compilation of debris data
- ESA: Provision of debris data from DISCOS and Master-8
- USSTRATCOM: TLE data

The things we see are the result of our past,

but the way we act is the result of our future.

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Aerospace **2023**, Volume 10, Issue 7, 633

Lasers and space