Maximum Attainable Drag Limits for Atmospheric Deceleration via Supersonic Retropropulsion (SRP)

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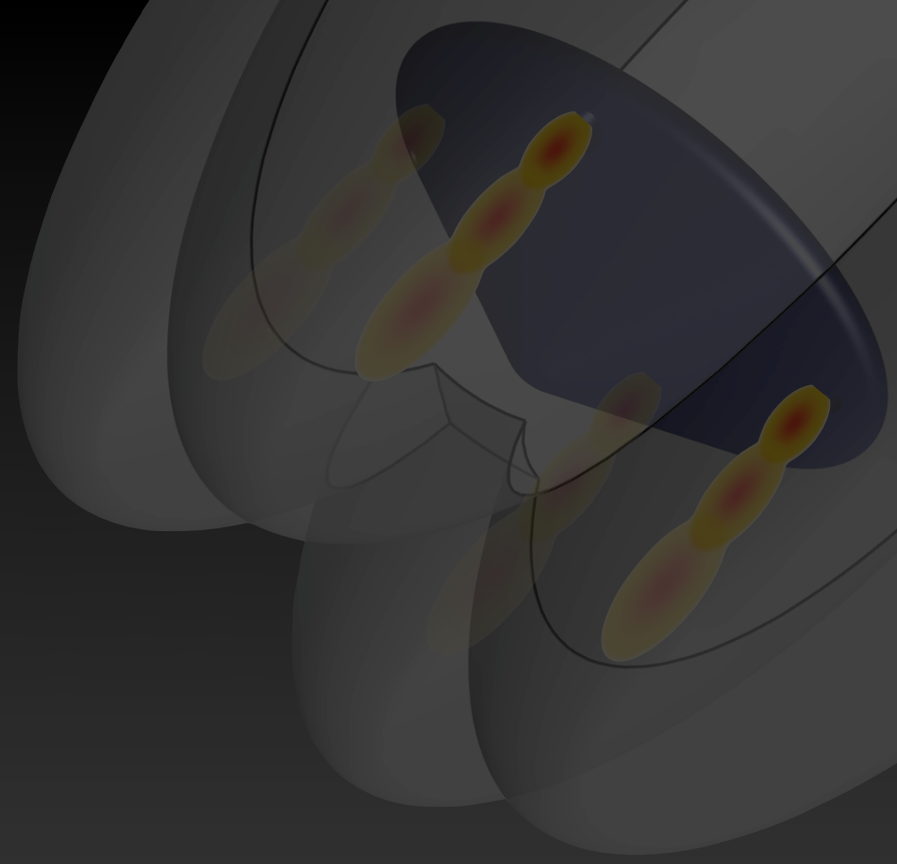
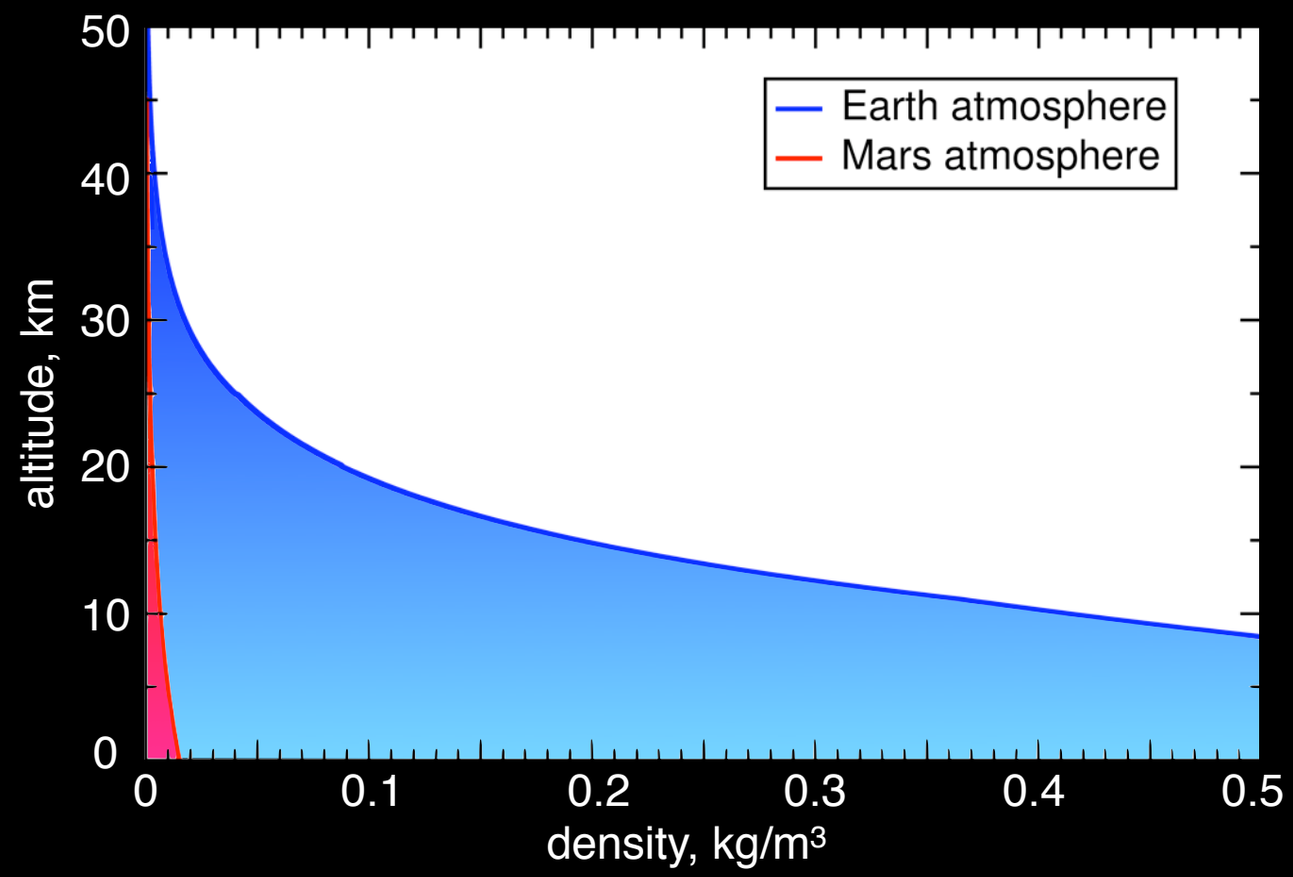
Session 4: EDL Technology

Overview



- Motivate SRP drag augmentation
- Analytical method
- Results
  - C_D trends
  - Drag trends
- Maximum Drag Potential
  - Drag Modulation Strategy
- Closing Thoughts

EDL Motivation



- Mars' low atmospheric density presents a deceleration challenge
- Heritage Viking EDL approaching max mass with MSL (2011)
- Future missions require 100x DGB mass-limit

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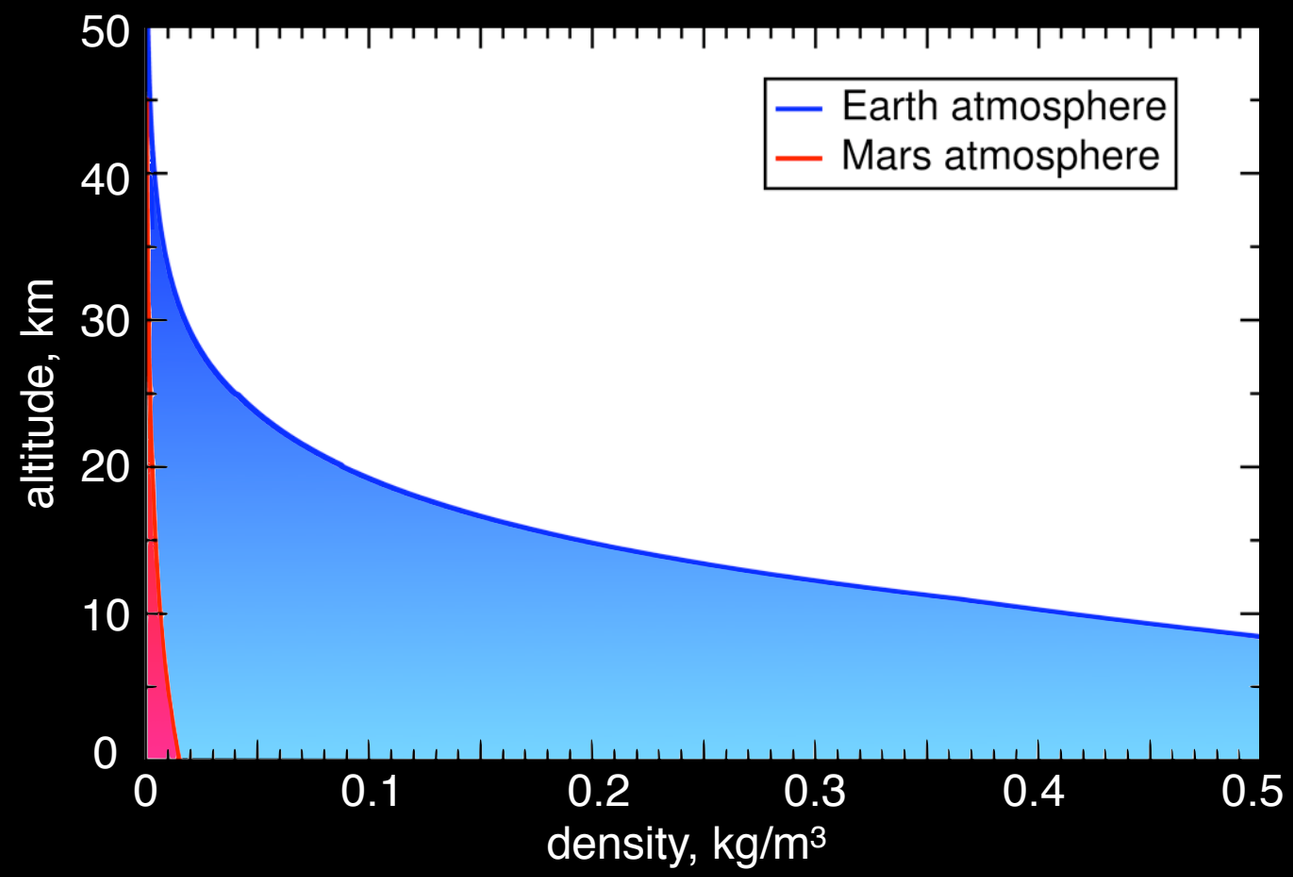

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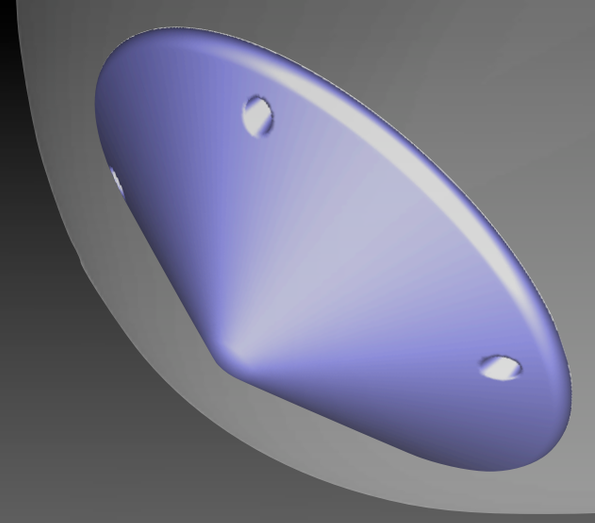
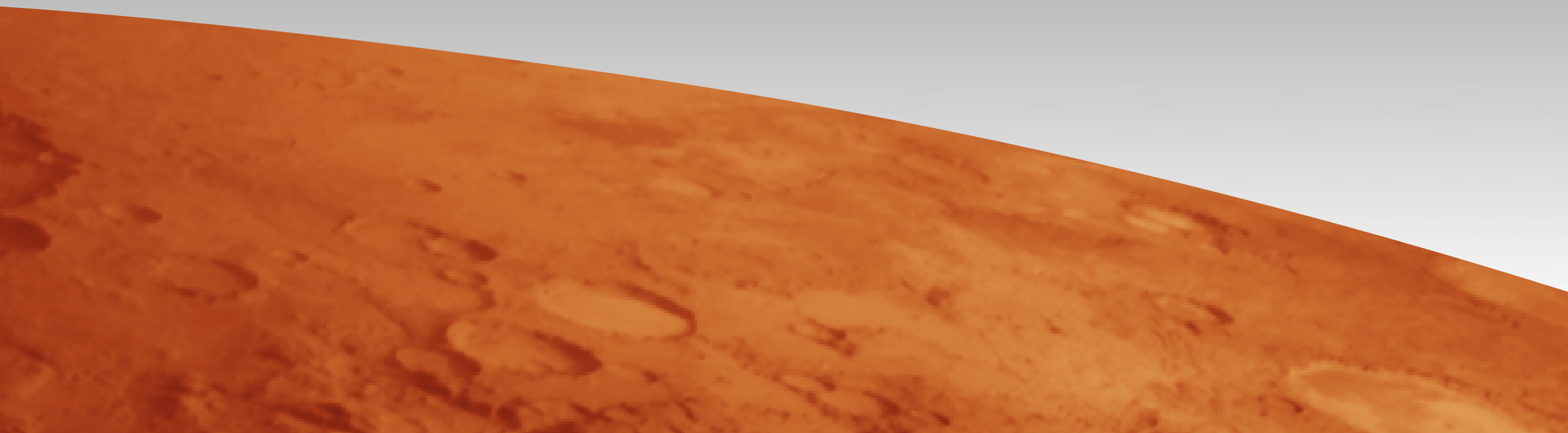
Supersonic retropropulsion proposed as an enabling deceleration technology

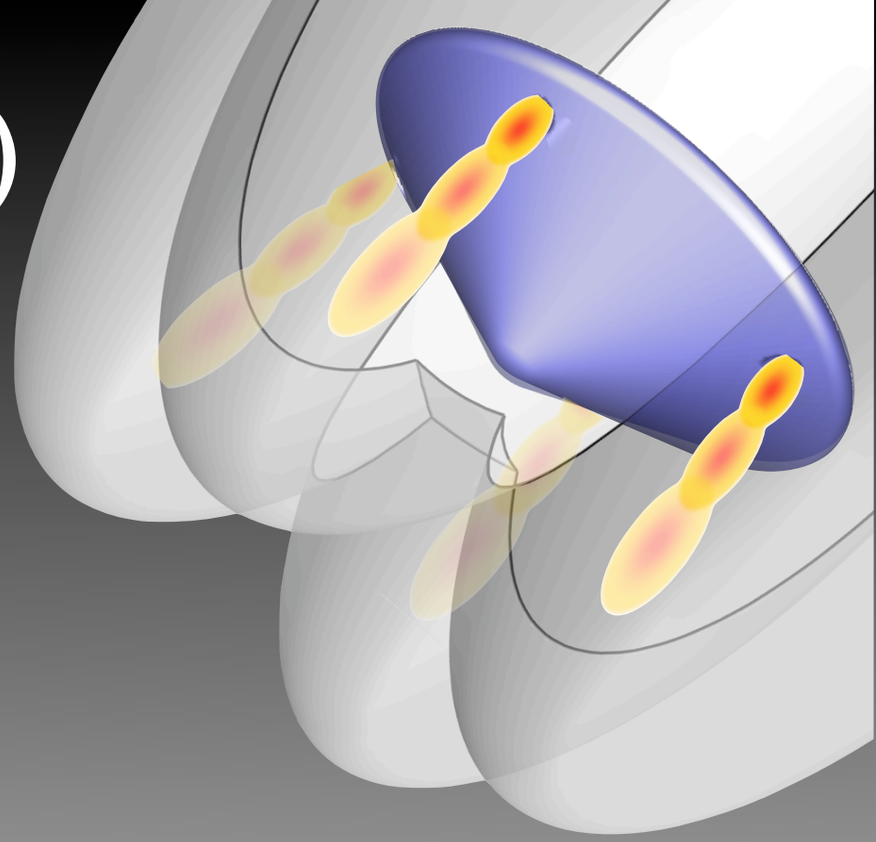
Supersonic Retropropulsion (SRP)



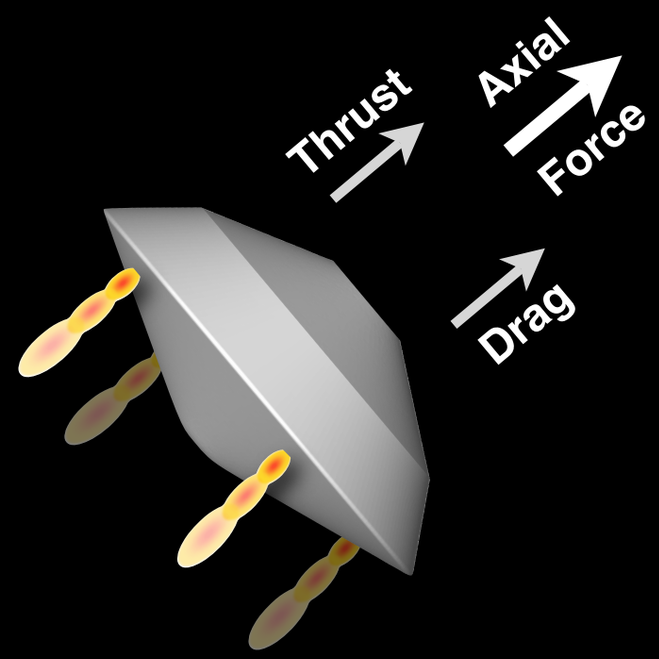


Supersonic Retropropulsion (SRP)

retrojets directed into the freestream
during the supersonic portion of entry

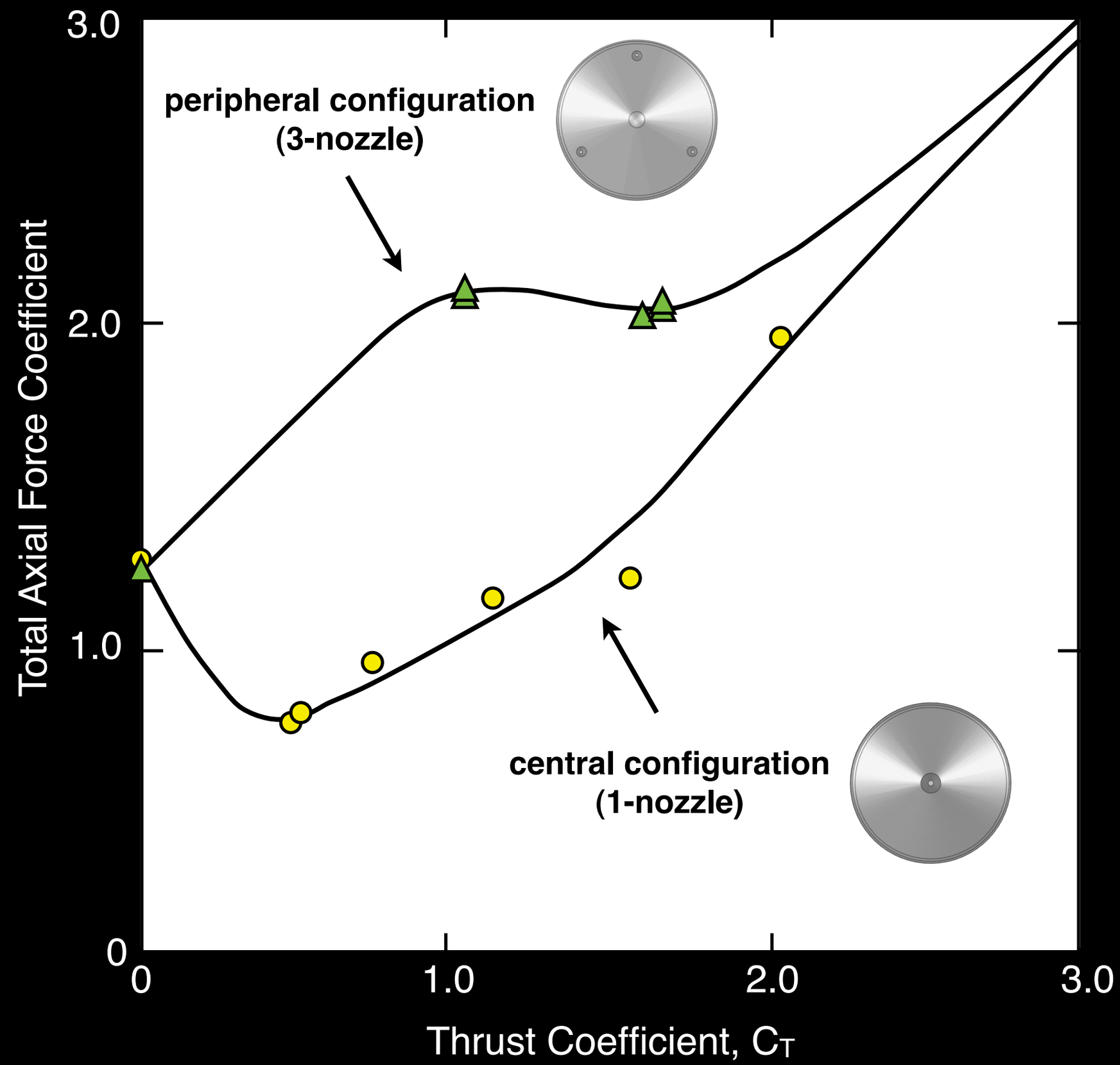


Previous Work



$$C_A = C_T + C_D$$

Total Axial Force Coefficient



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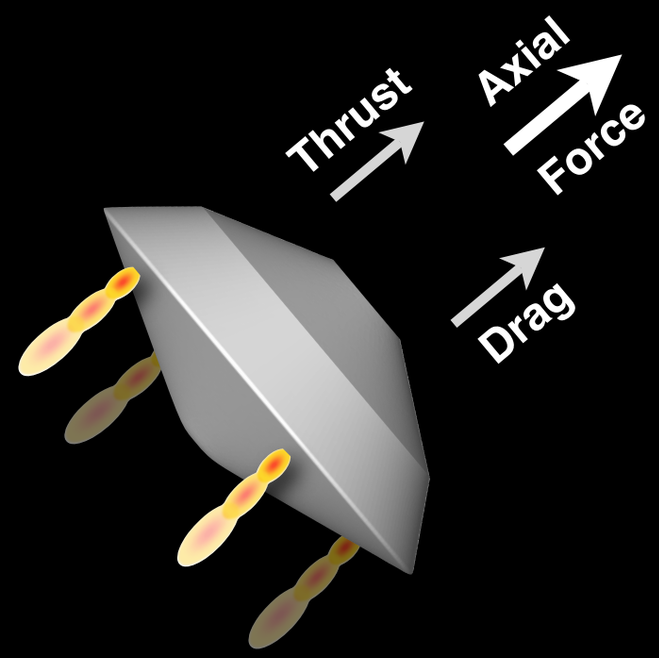

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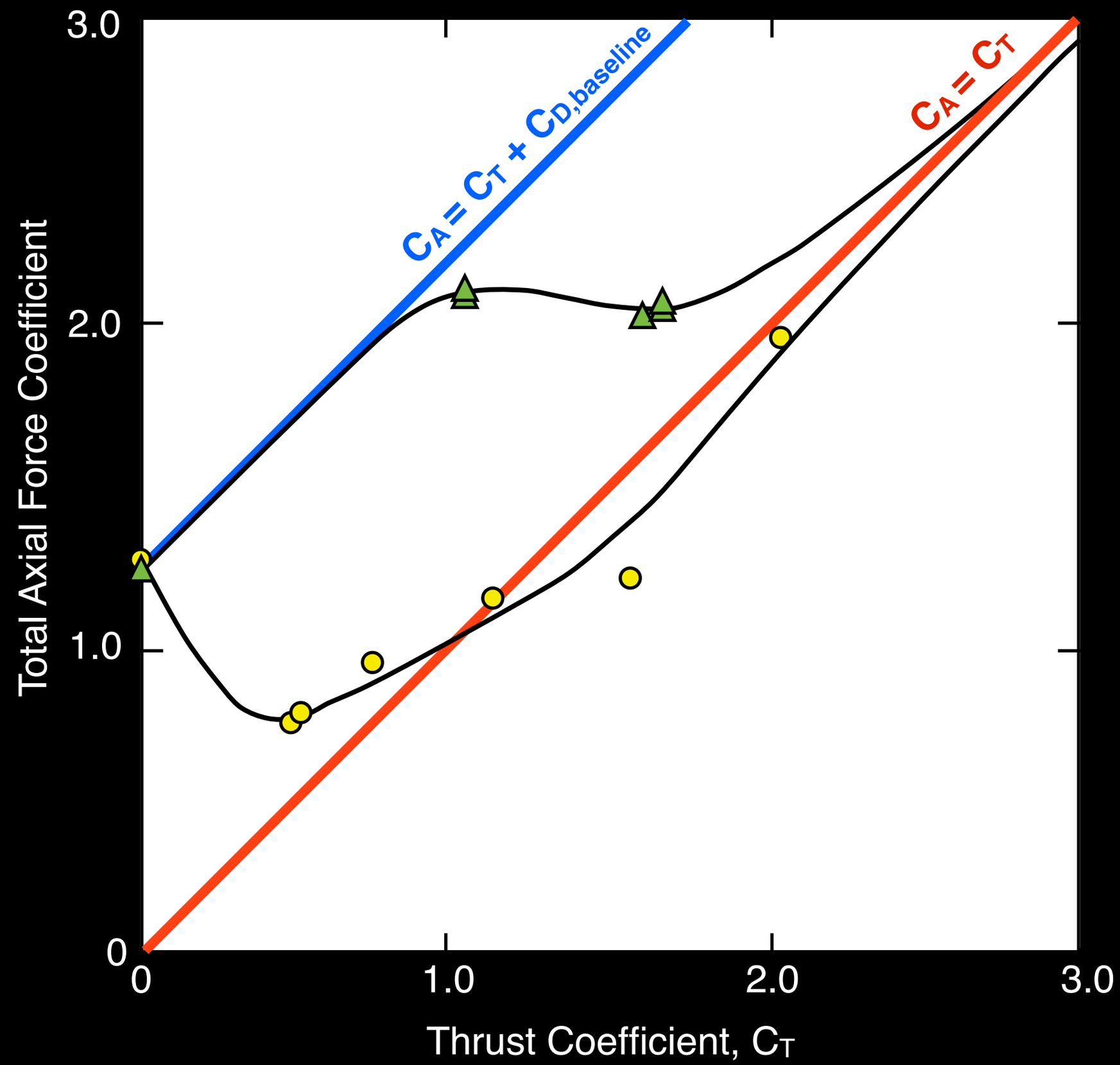

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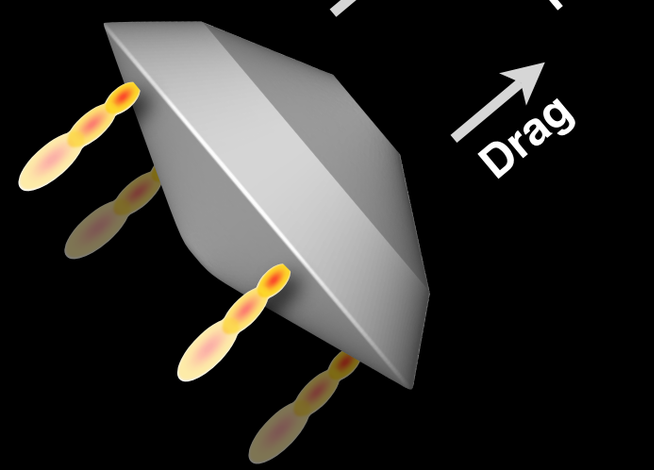

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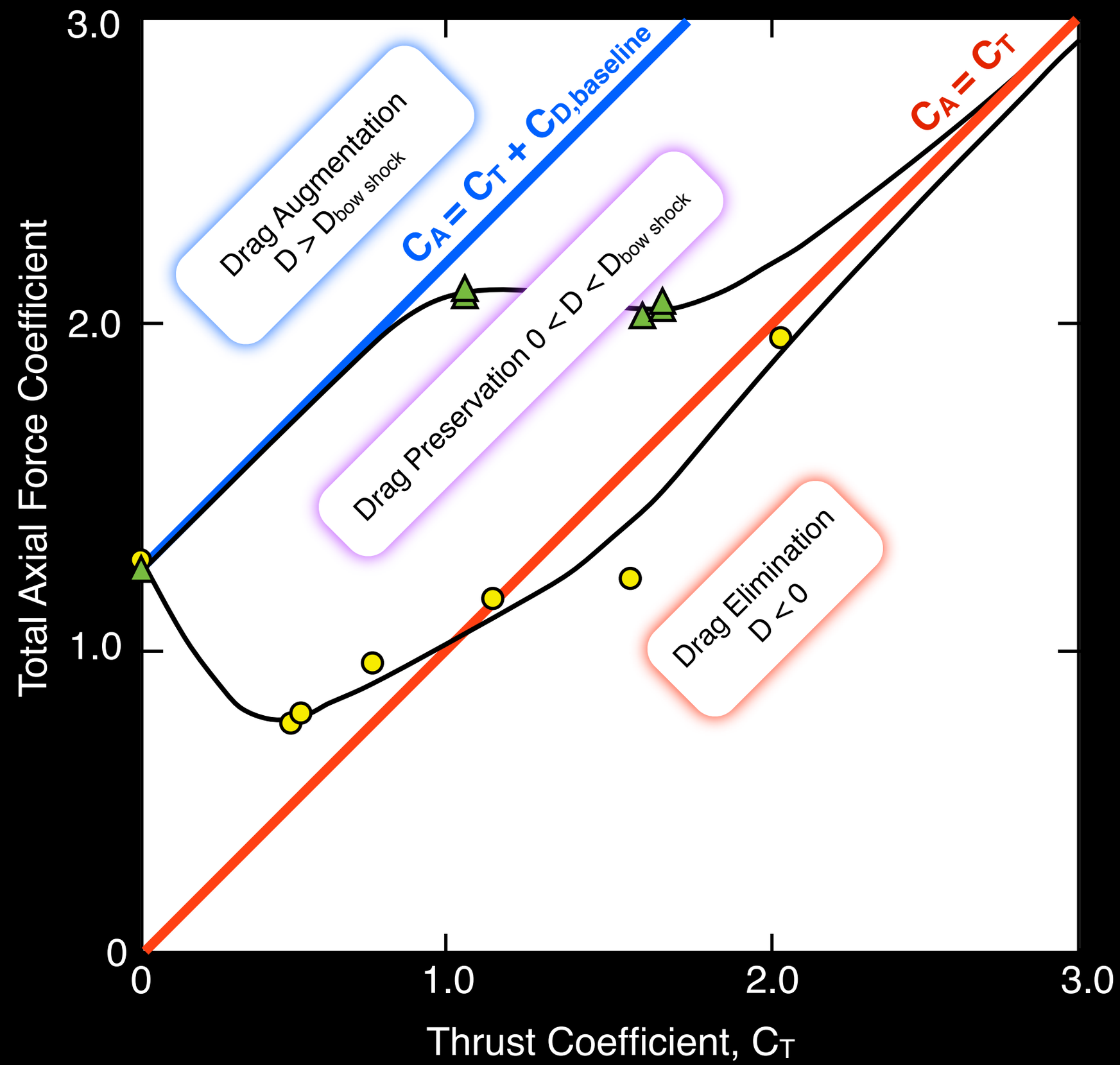


SRP Development

- Current SRP project moving towards thrust-dominant framework

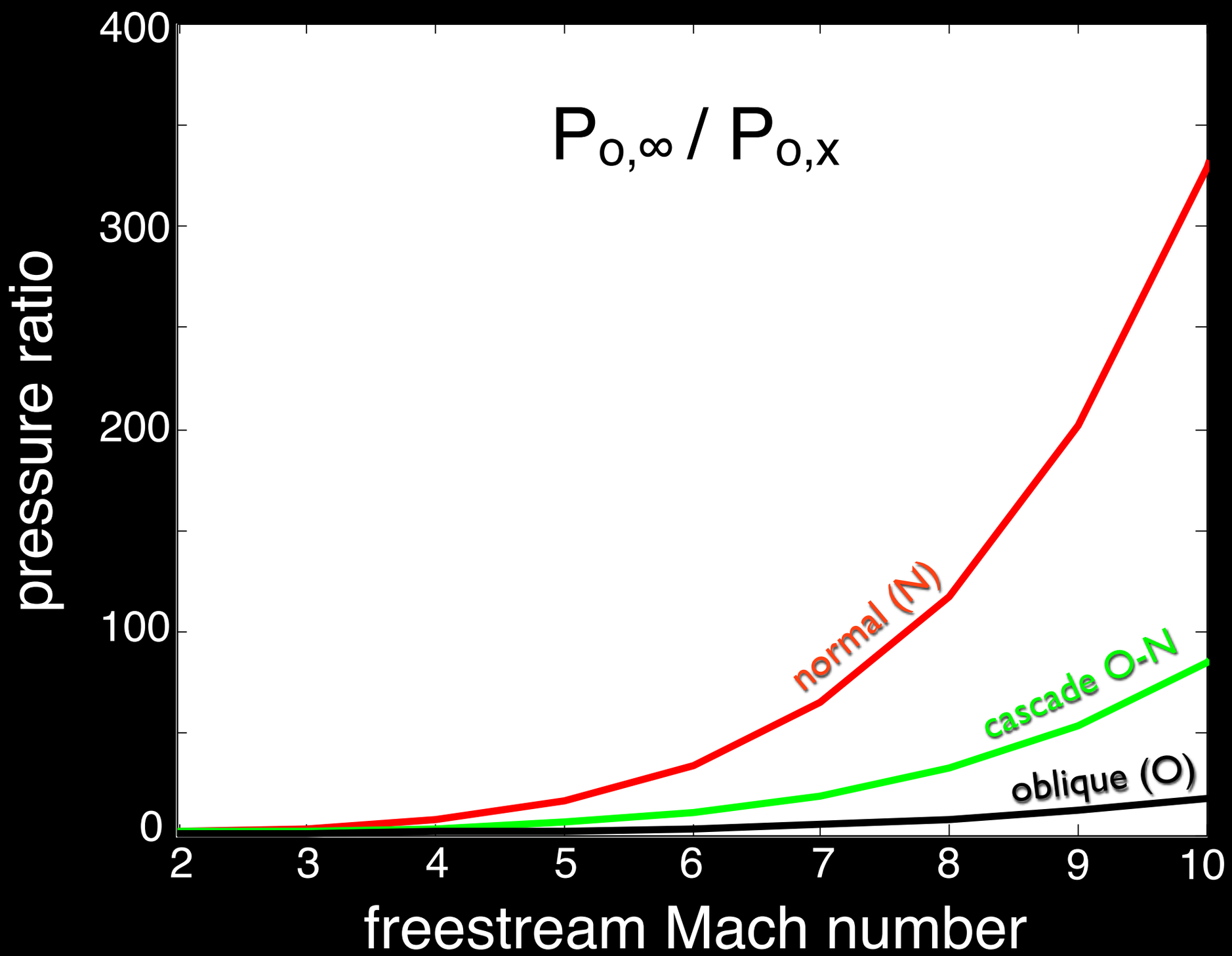
$$C_A = C_T$$

- Alternative SRP-based deceleration approach examined, emphasizing aerodynamic drag augmentation

$$C_A = C_D$$

  - Turn SRP jets into flow-control devices (JI) for drag modulation
  - Any increase in deceleration through drag reduces thrust/ propellant requirements which benefits payload mass

Drag Coefficient Augmentation



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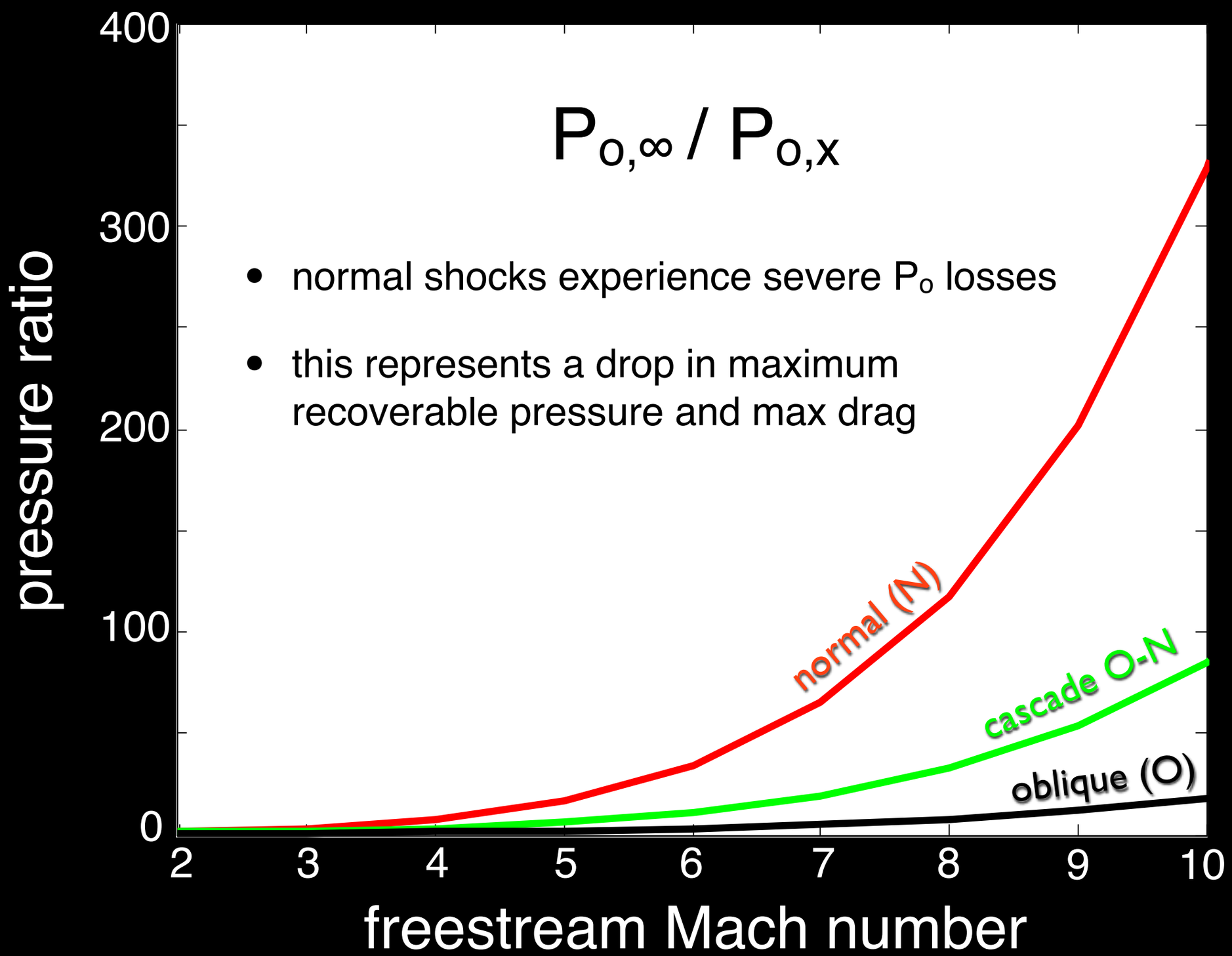

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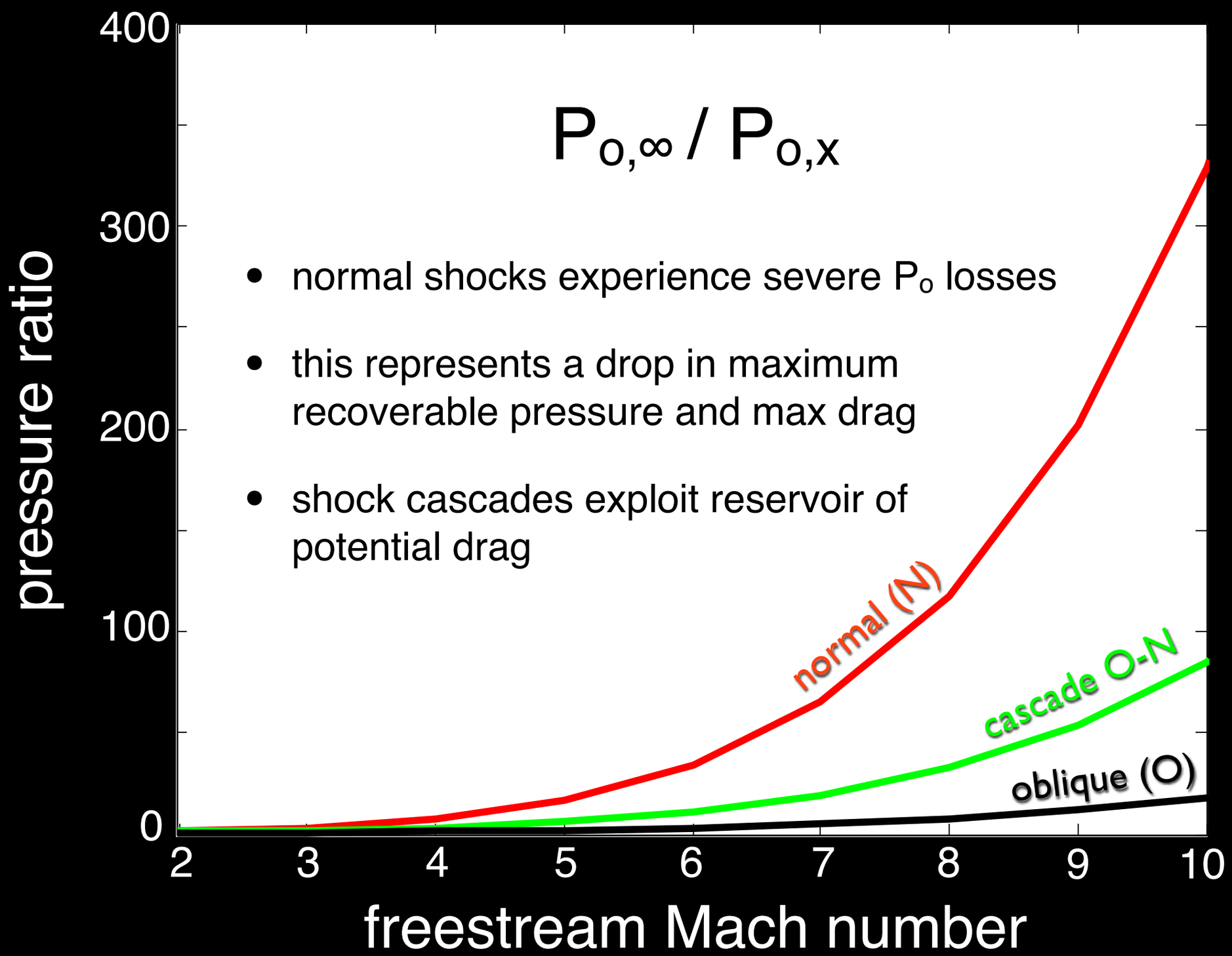
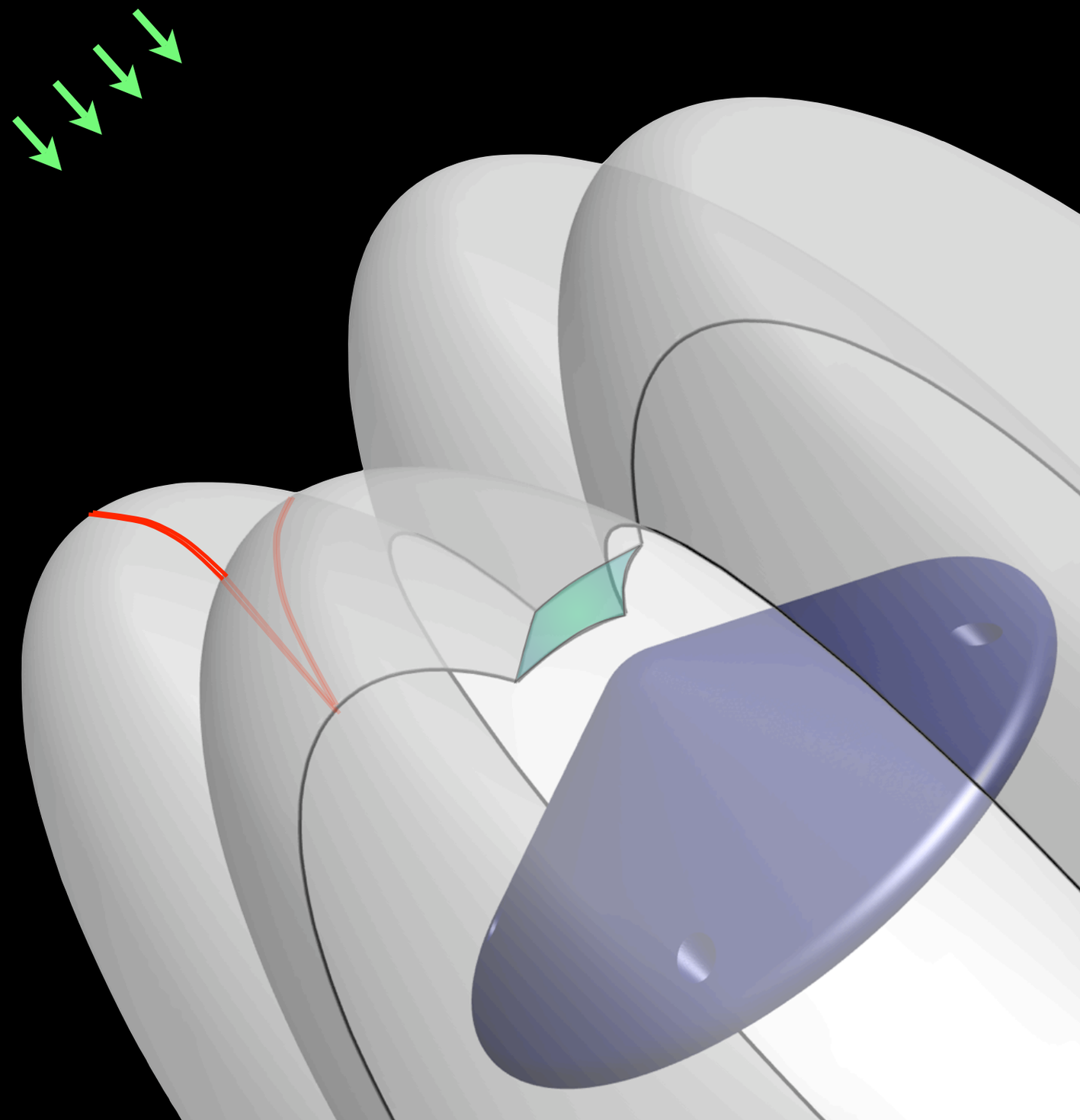


Model for SRP Drag Augmentation



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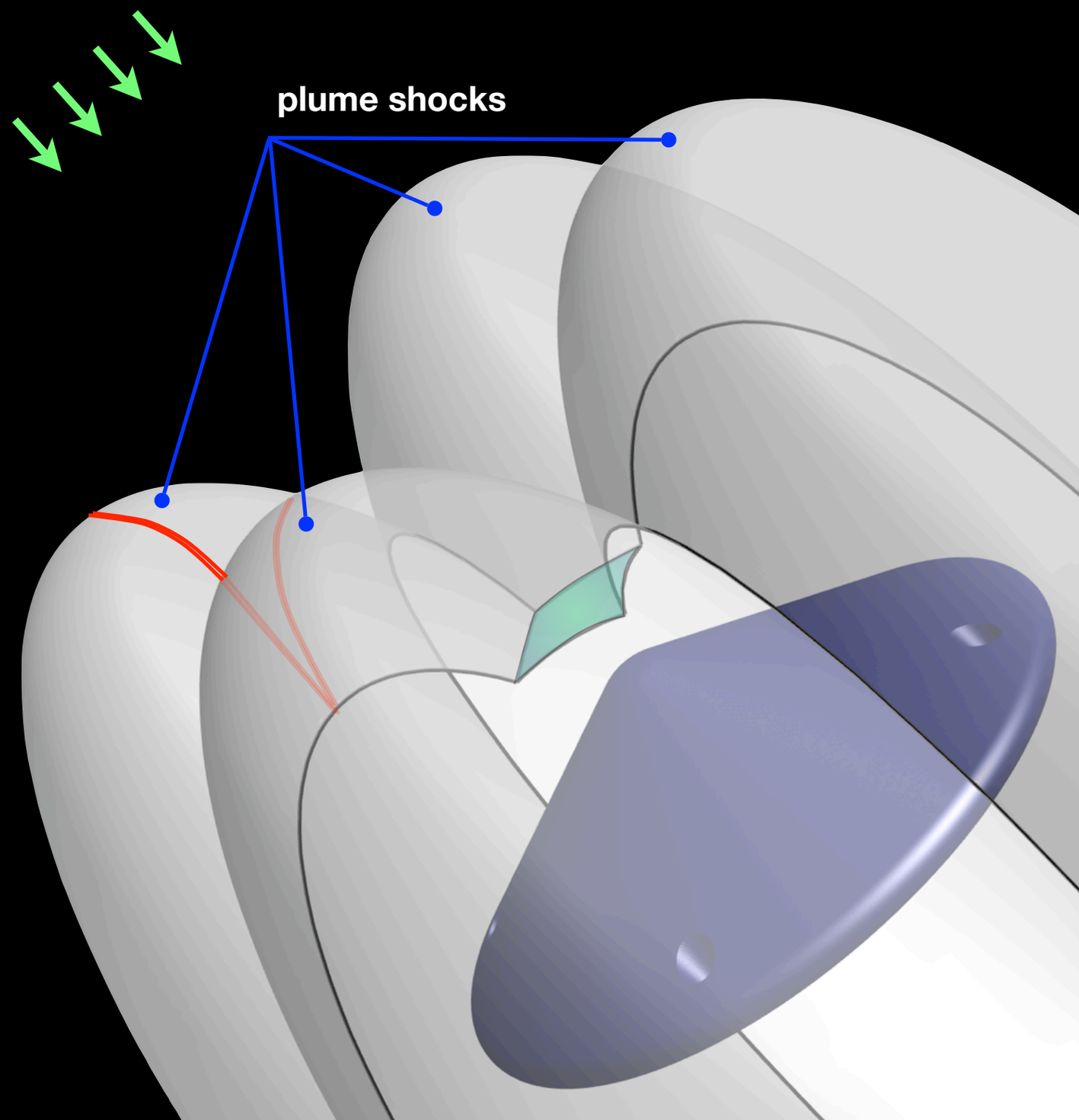

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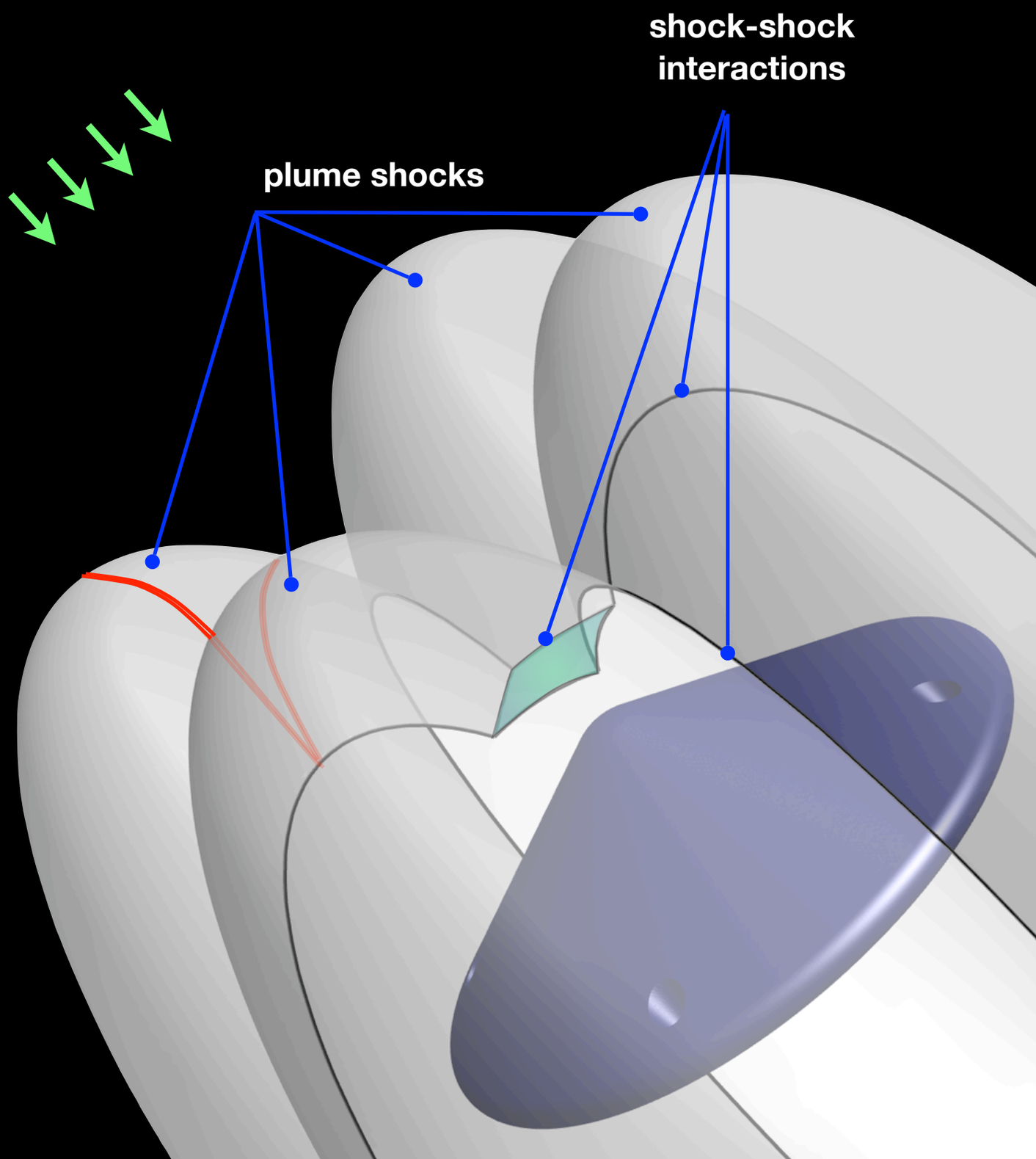

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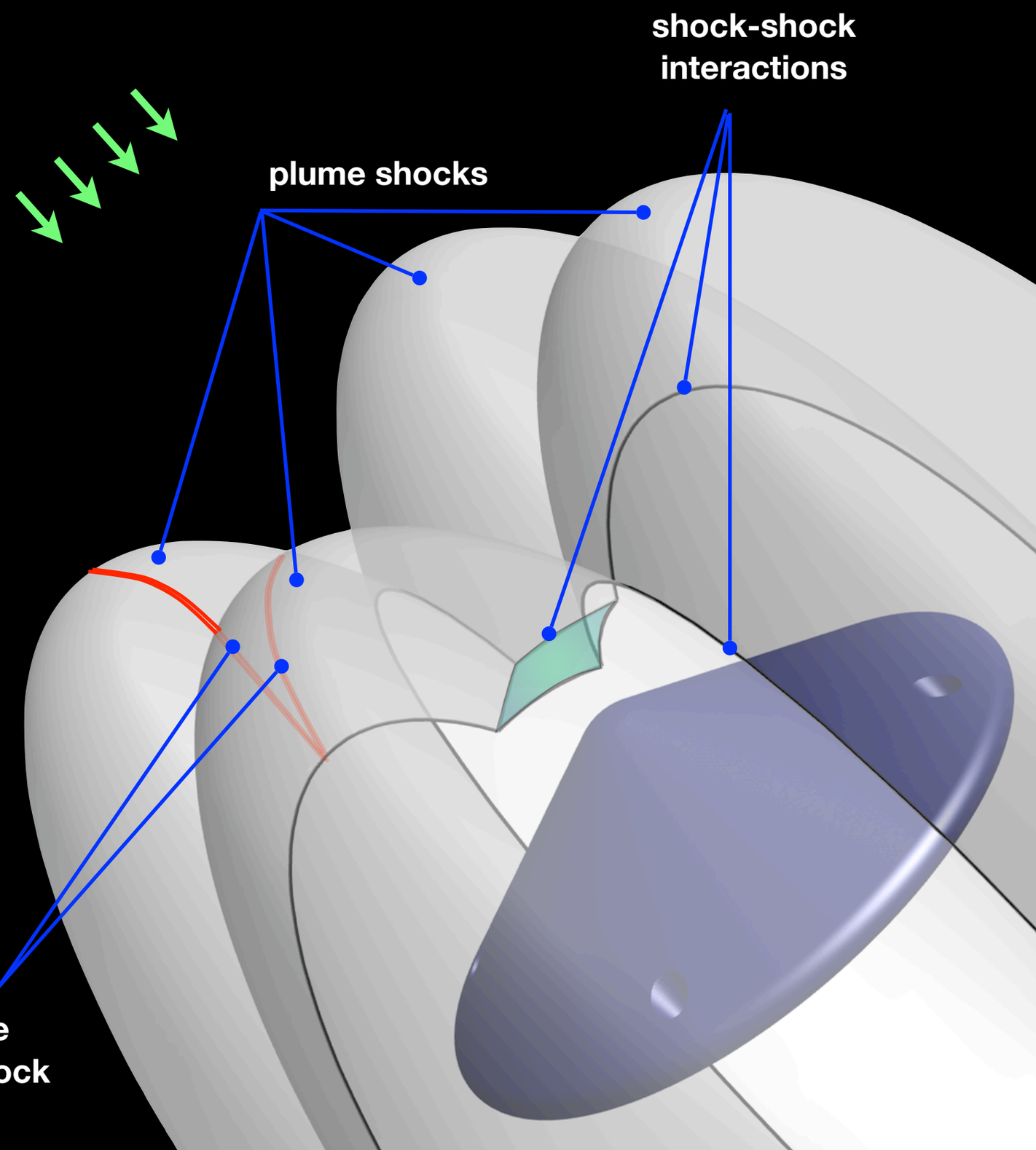
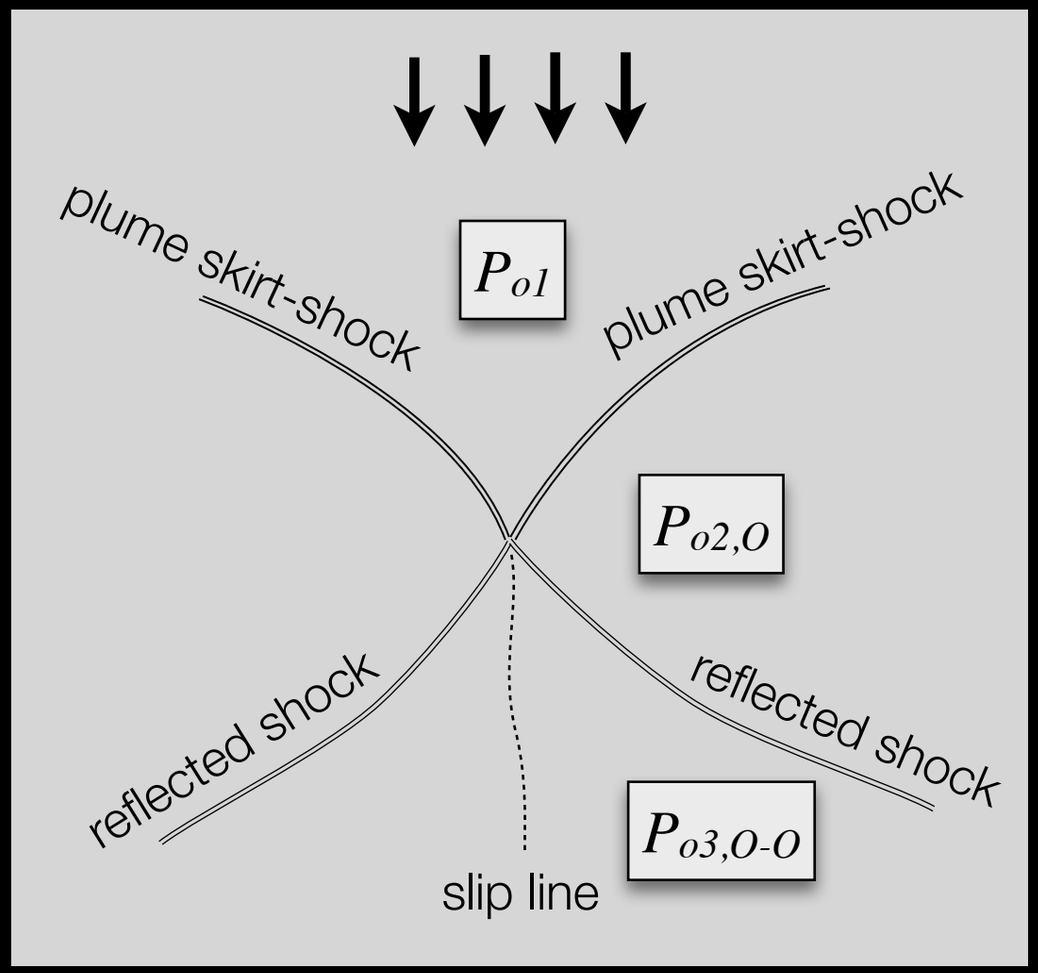
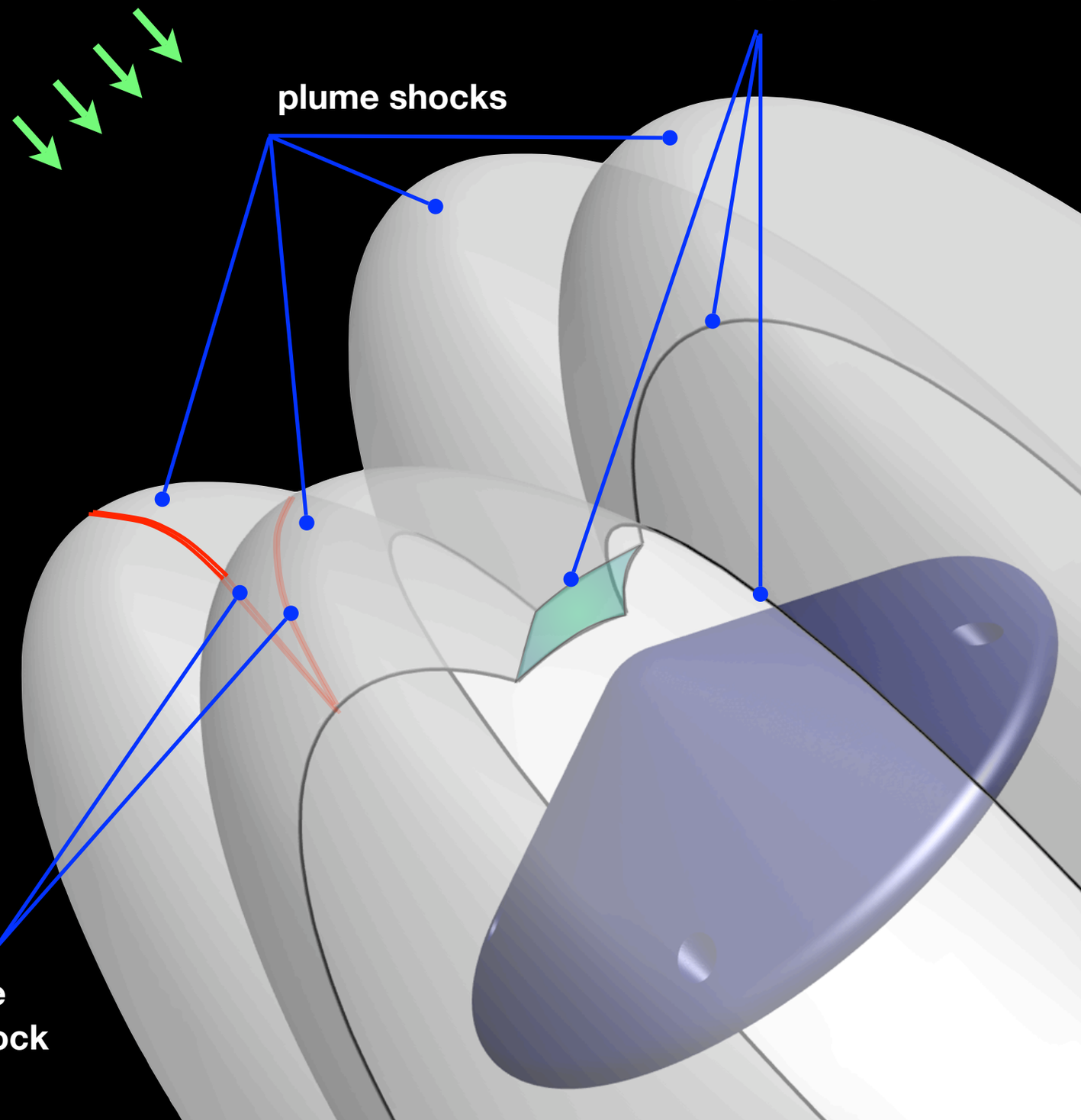


Model for SRP Drag Augmentation

Oblique Shock-Shock Interactions





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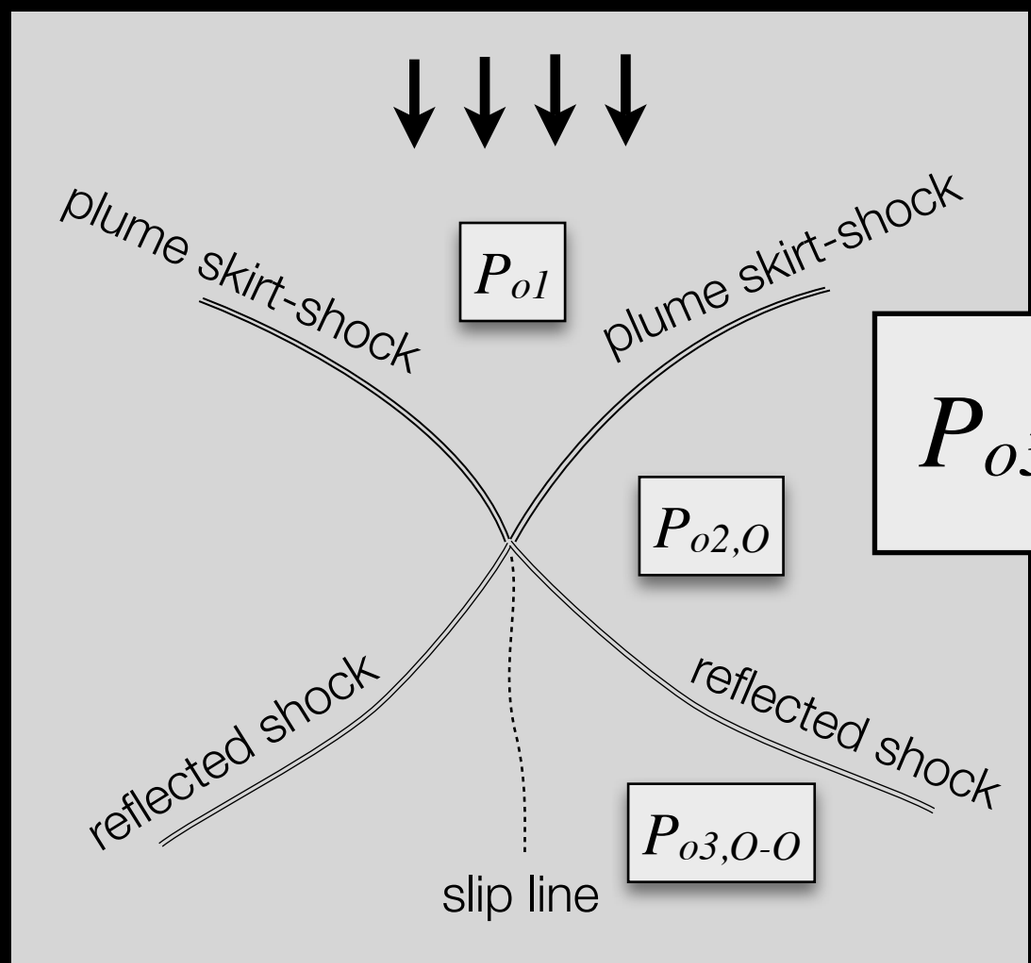
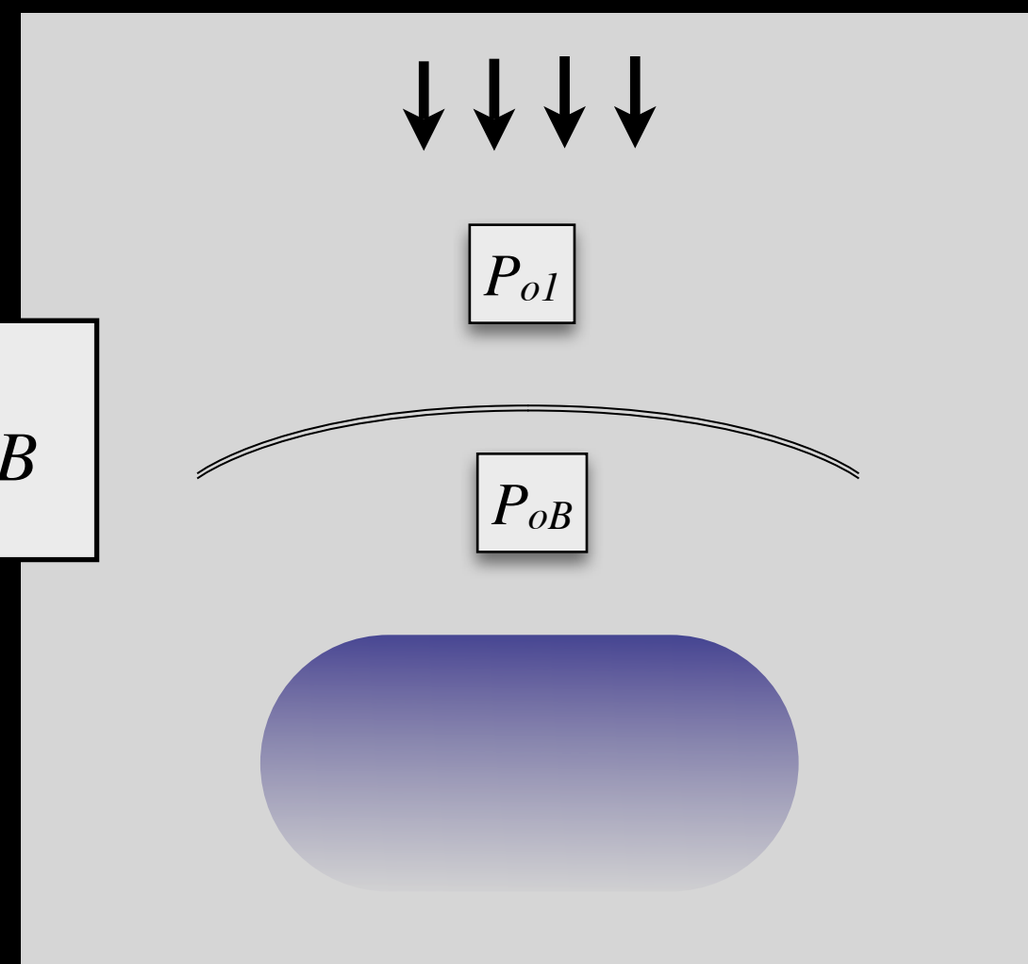


$$P_{o3,O\text{-}O} > P_{oB}$$

Typical Bow Shock



preserve P_o → increase surface P → significant D_{aug}

Model for SRP Drag Augmentation

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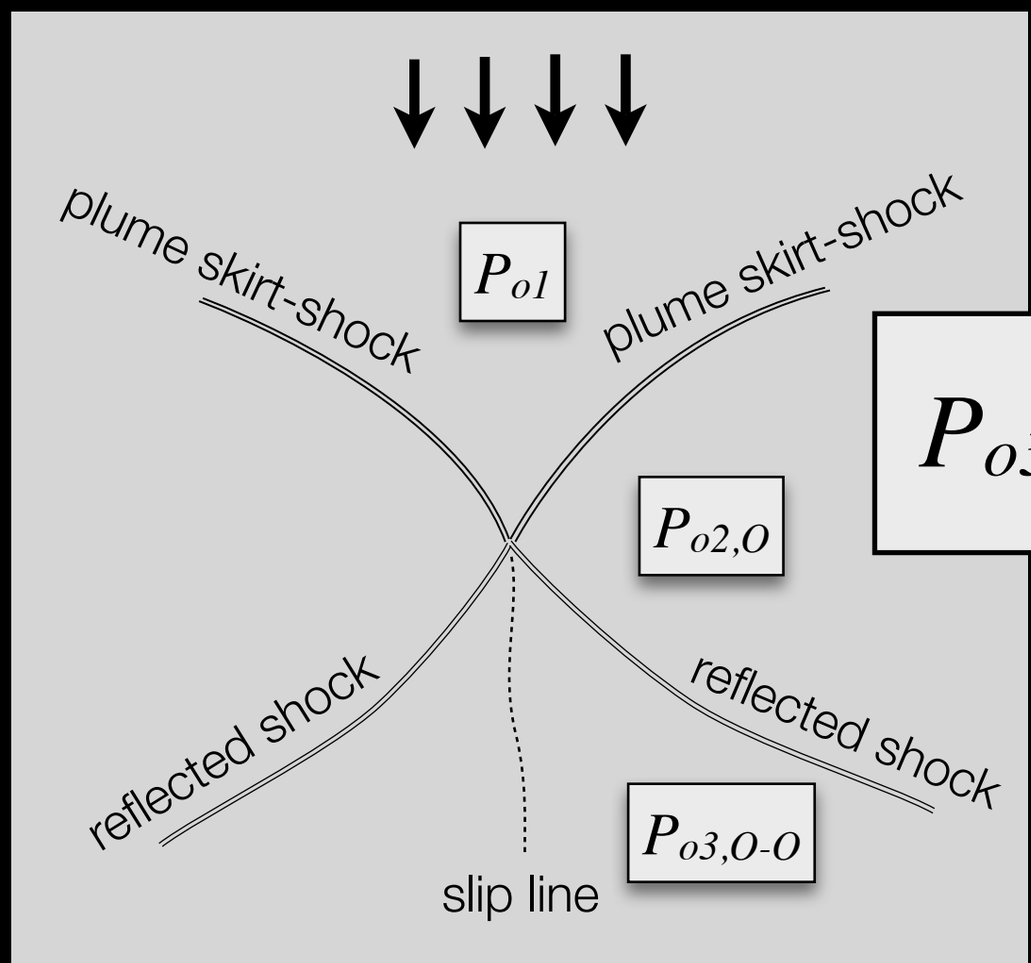

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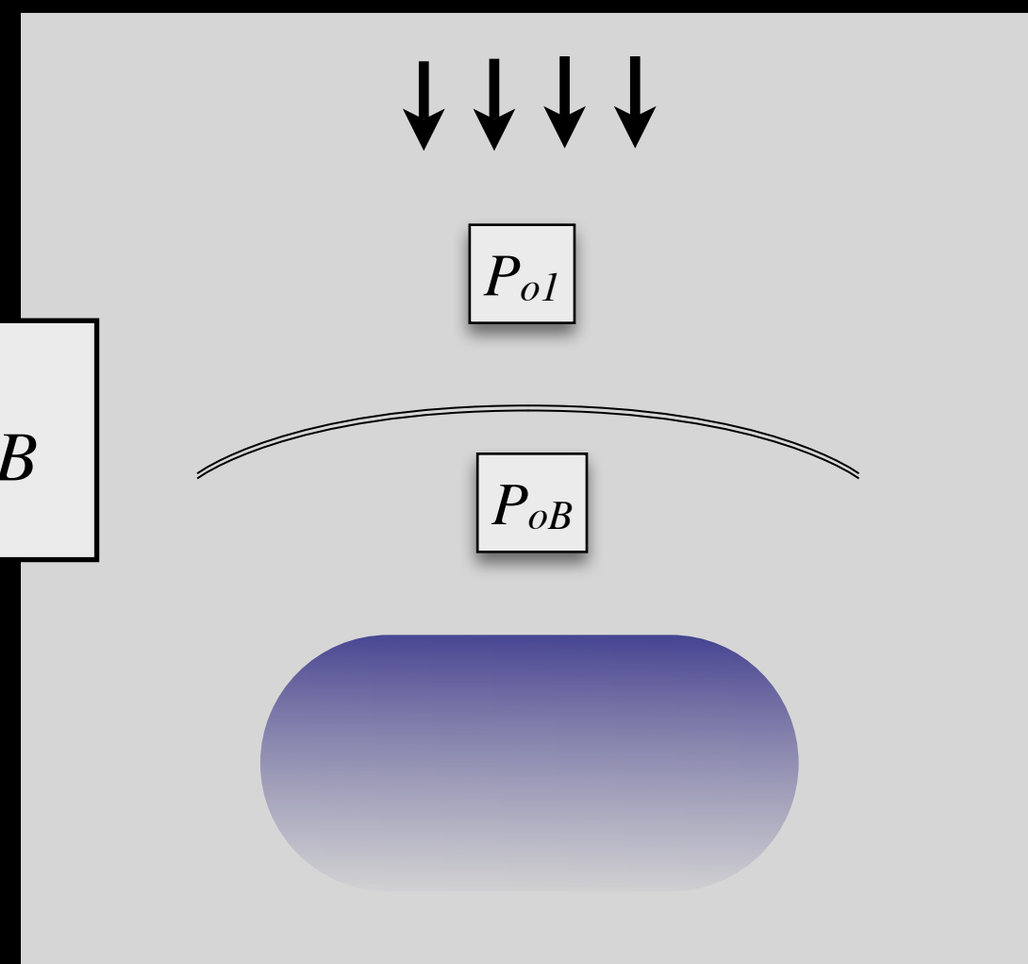

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How much drag is possible?

Max C_D: Analytical Method

Goal: Determine max C_D and trends by examining various shock structures

Method: Simplified analytical C_D model based solely on post-shock pressures

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$$\text{vehicle } C_D = C_P \text{ based on post-shock pressure}$$

Max C_D: Analytical Method

Starting with the drag definition $D = \int p \, dS_x$

and taking p_{front} and p_{back} to be the mean pressures on the front and back faces

$$D = p_{front} S_{front,x} - p_{back} S_{back,x}$$

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Using the standard definition $C_D = \dfrac{D}{q_\infty S_{ref}}$

and taking reference area to be the projected area, $S_{ref} = S_{front,x} = S_{back,x}$

$$C_D = \frac{p_{front} - p_{back}}{q_\infty}$$

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Highest P differential if $p_{back} = 0$ but $p_{back} = p_\infty$ is more conservative, and allows the approximation

$$C_D \approxeq \frac{p_{front} - p_\infty}{q_\infty}$$

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Assuming the mean front pressure results from flow processed through a shock structure,

$$\boxed{C_D = C_P = \frac{p - p_\infty}{q_\infty}}$$

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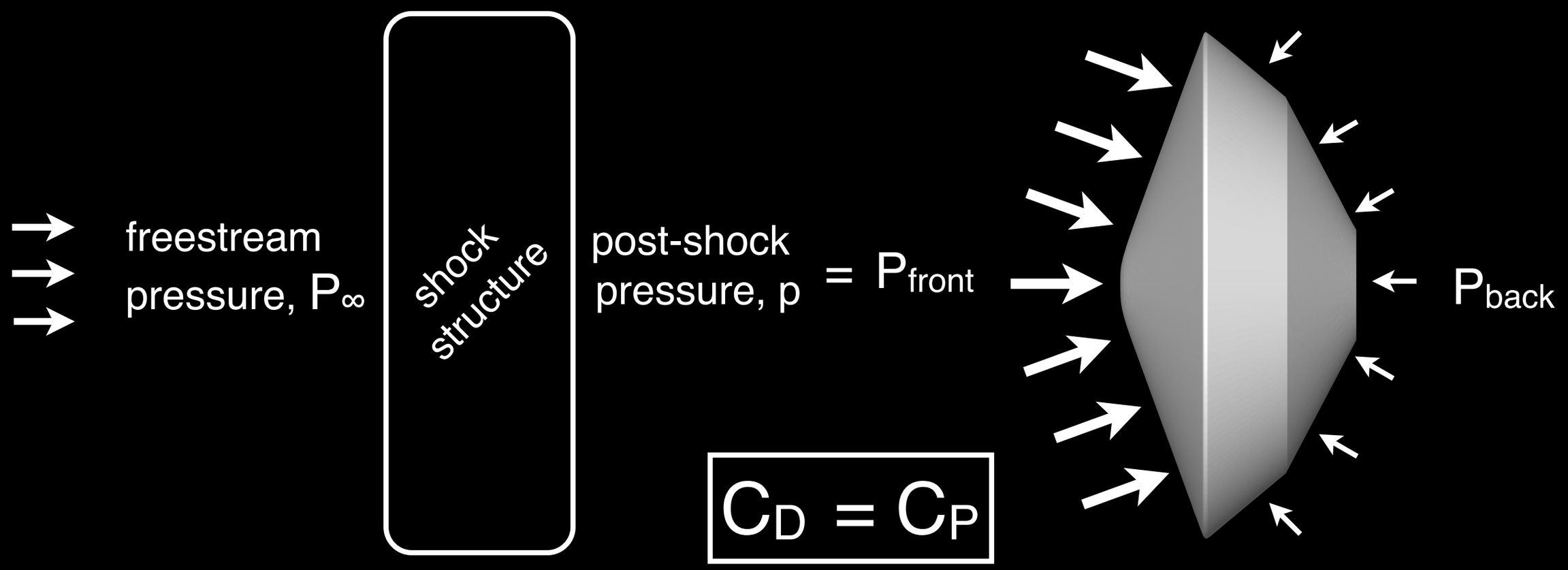

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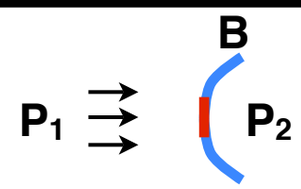
Terminology

Shock Structure	Notation	Drag Coefficient	
		Static	Stagnation
	**B**	$C_{D,B}$	$C_{Do,B}$

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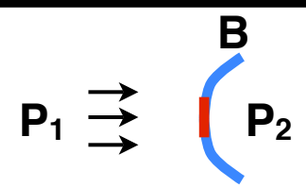
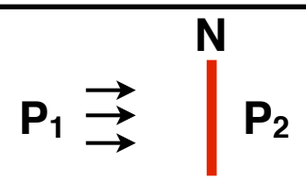
	**B**	$C_{D,B}$	$C_{Do,B}$
	**N**	$C_{D2,N}$	$C_{Do2,N}$

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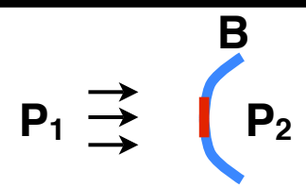
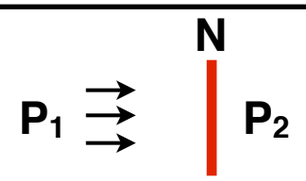
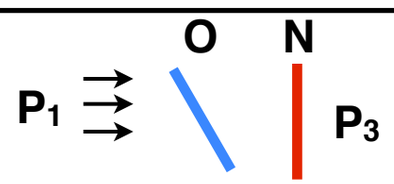
	**B**	$C_{D,B}$	$C_{Do,B}$
	**N**	$C_{D2,N}$	$C_{Do2,N}$
	**O-N**	$C_{D3,O\text{-}N}$	$C_{Do3,O\text{-}N}$

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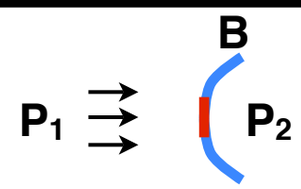
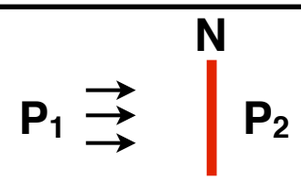
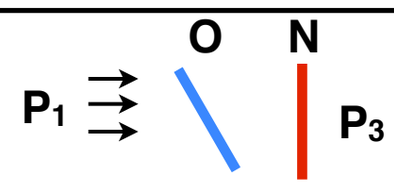
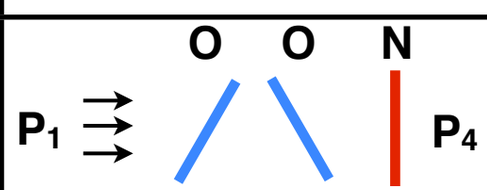
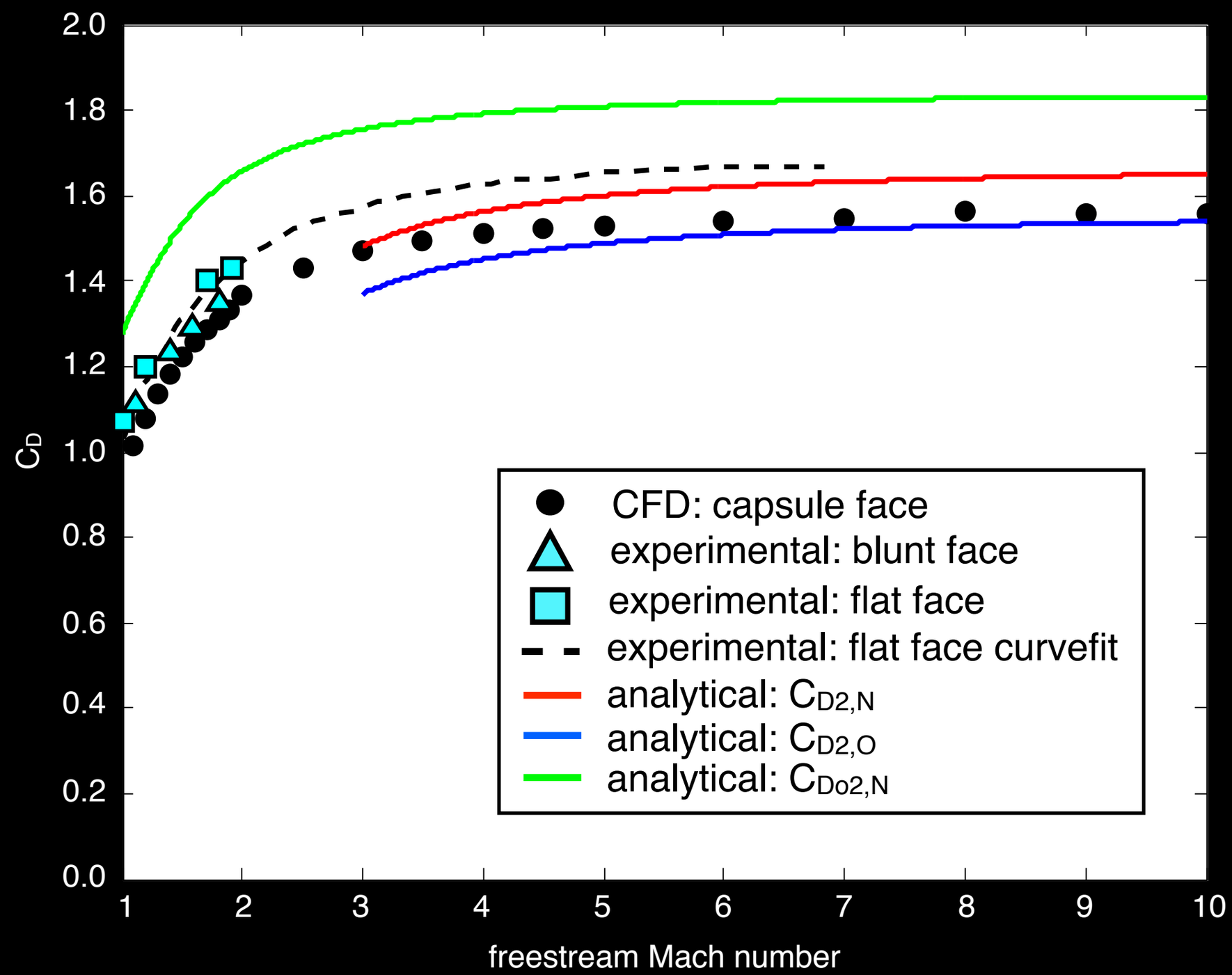
	**B**	$C_{D,B}$	$C_{Do,B}$
	**N**	$C_{D2,N}$	$C_{Do2,N}$
	**O-N**	$C_{D3,O\text{-}N}$	$C_{Do3,O\text{-}N}$
	**O-O-N**	$C_{D4,O\text{-}O\text{-}N}$	$C_{Do4,O\text{-}O\text{-}N}$

Validation of Analytical Method



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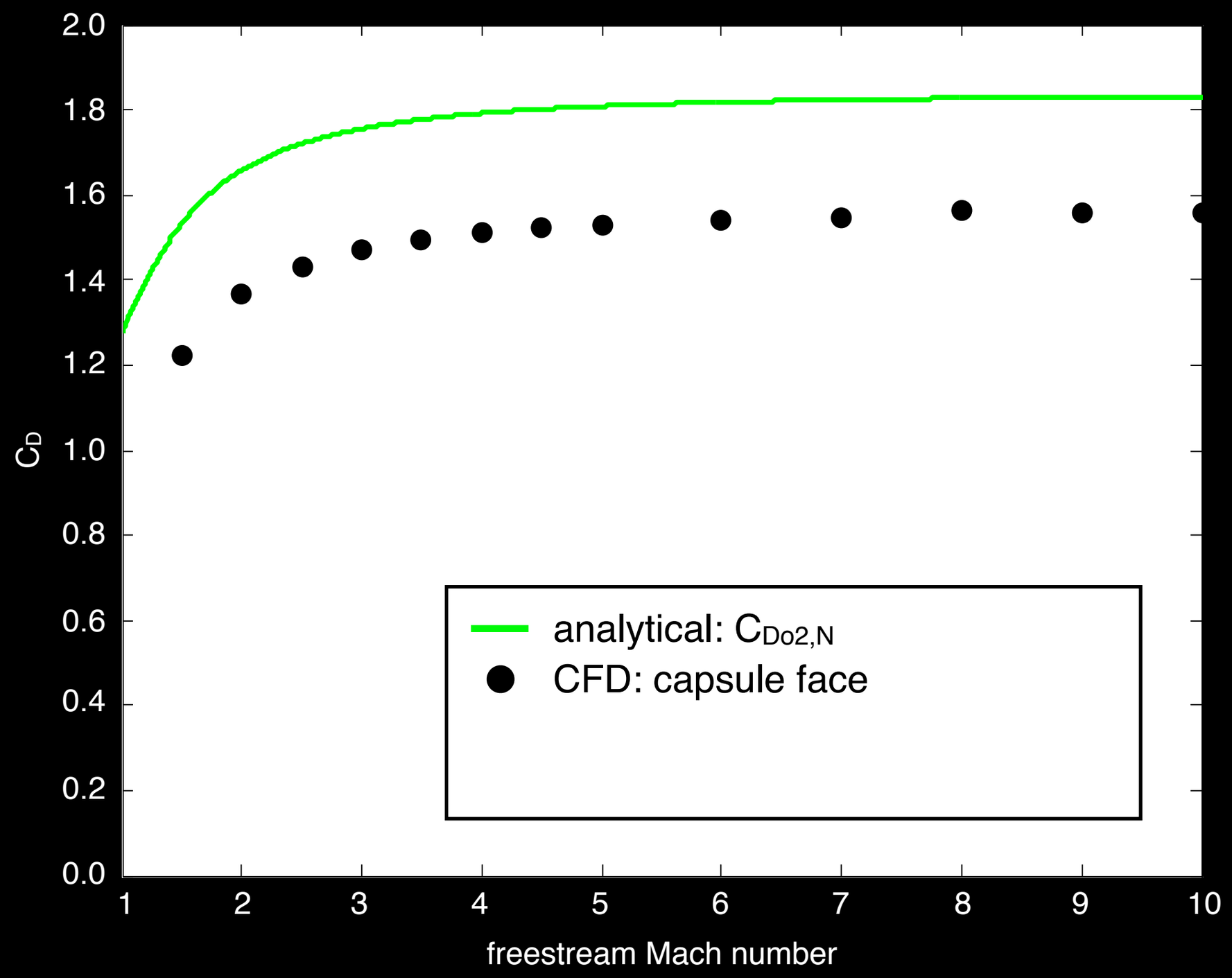

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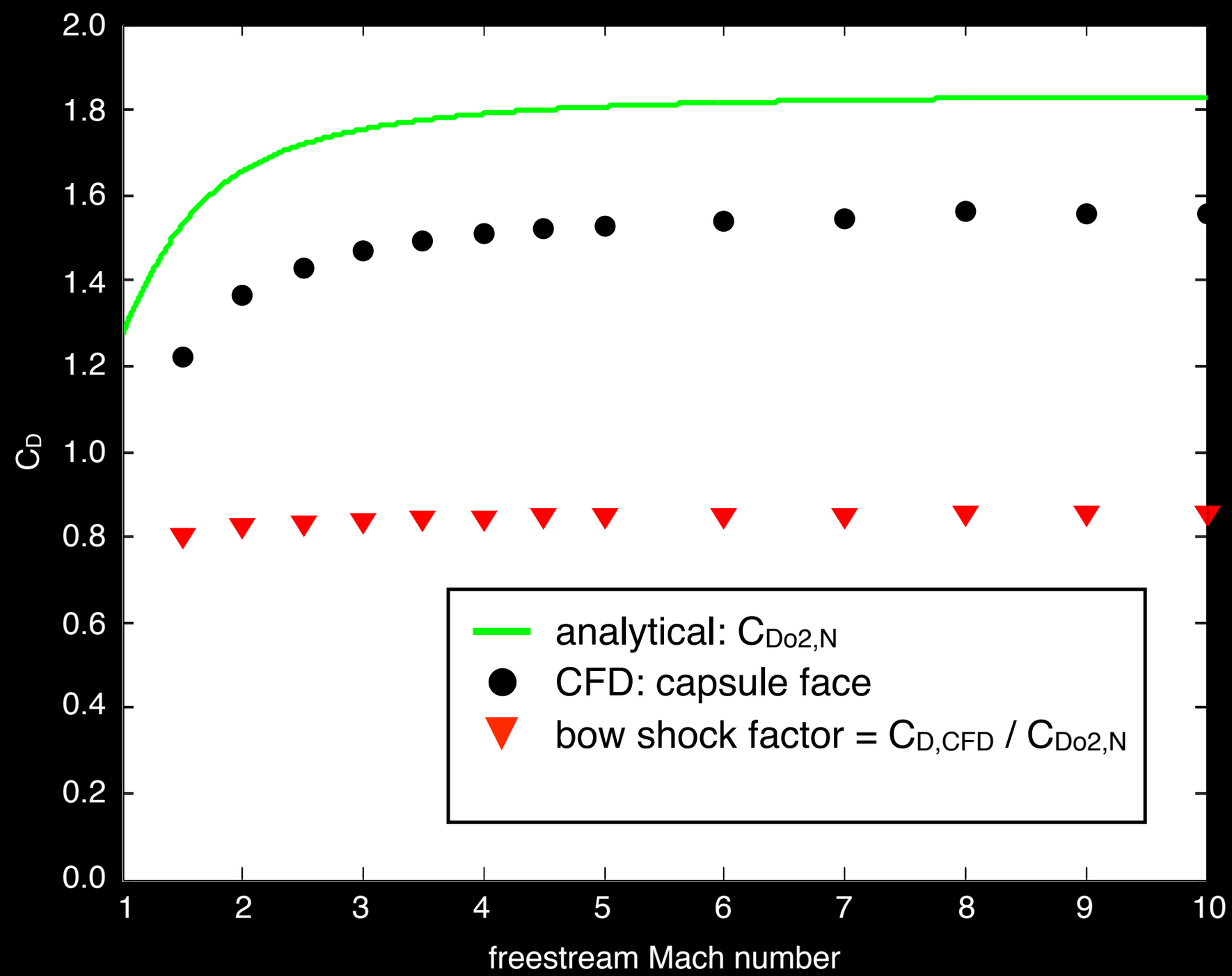

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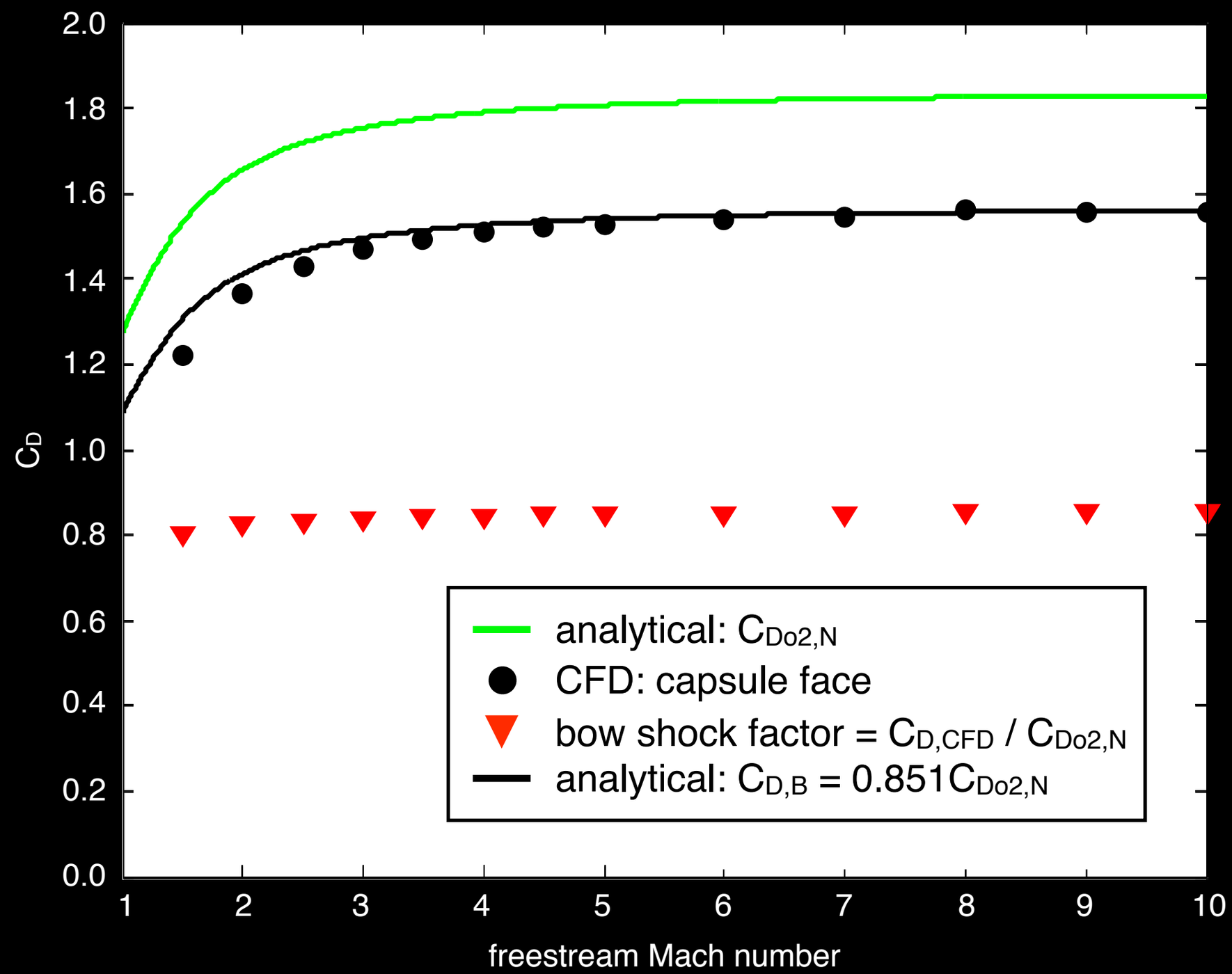
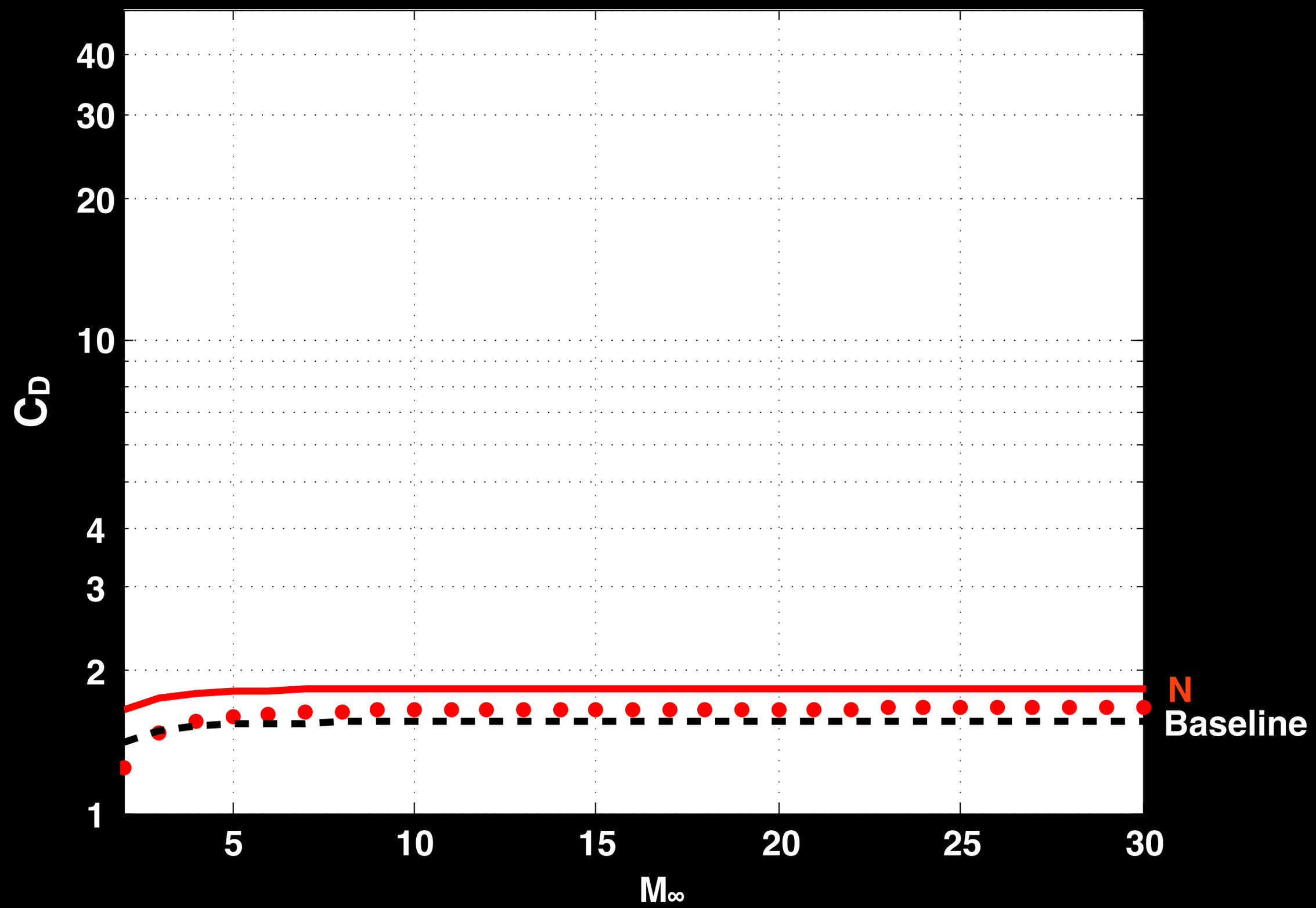


Drag Coefficient Augmentation



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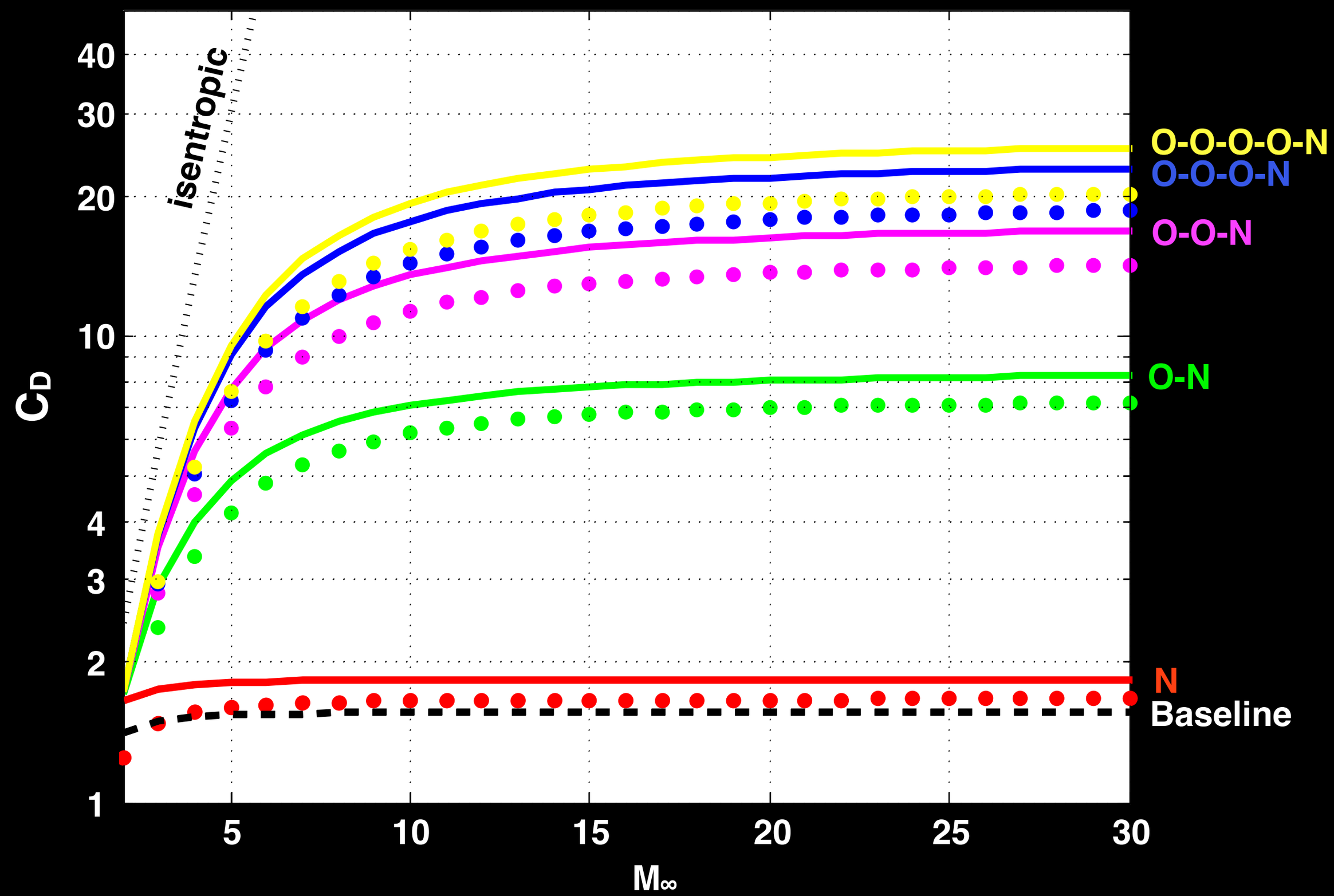
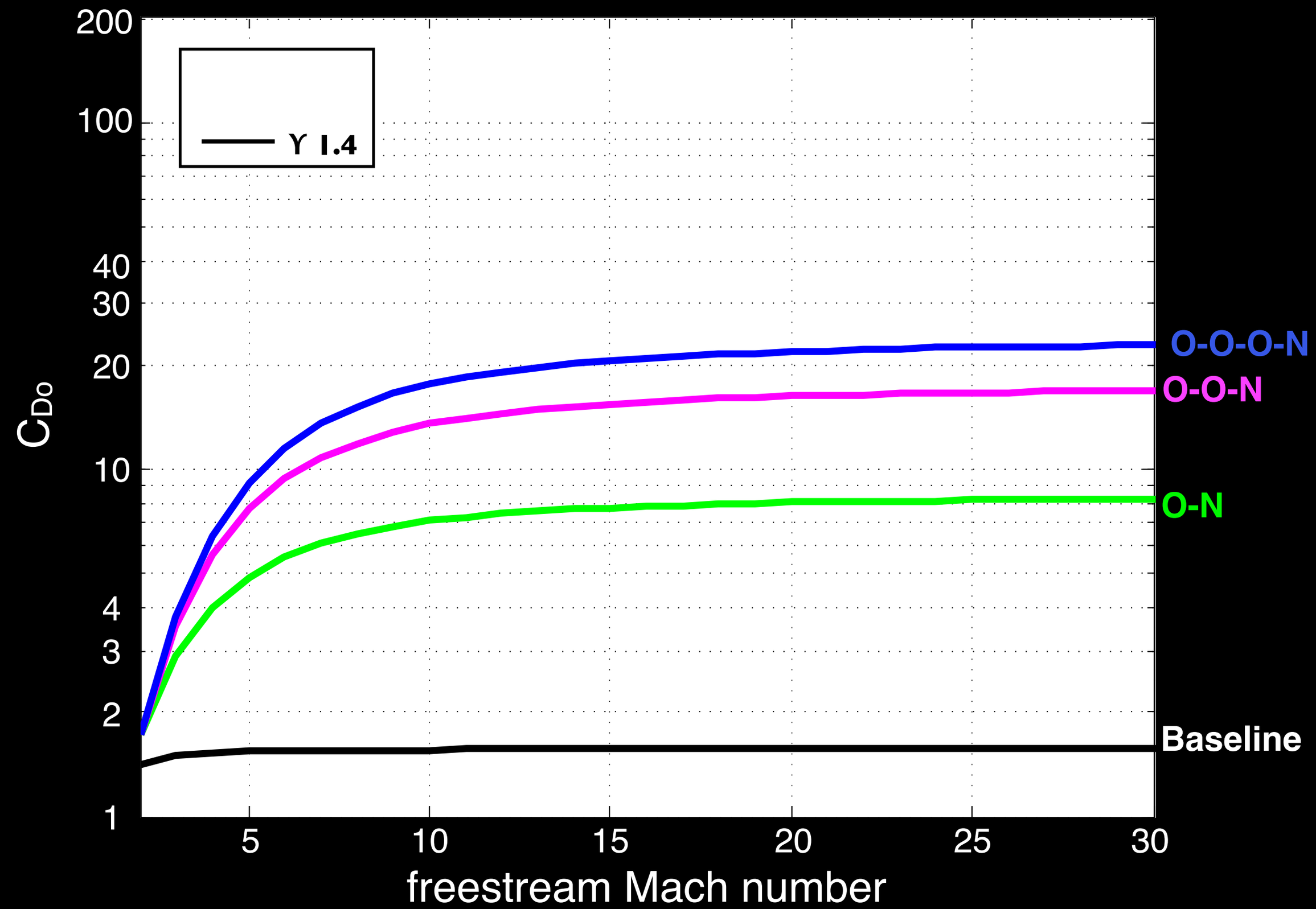
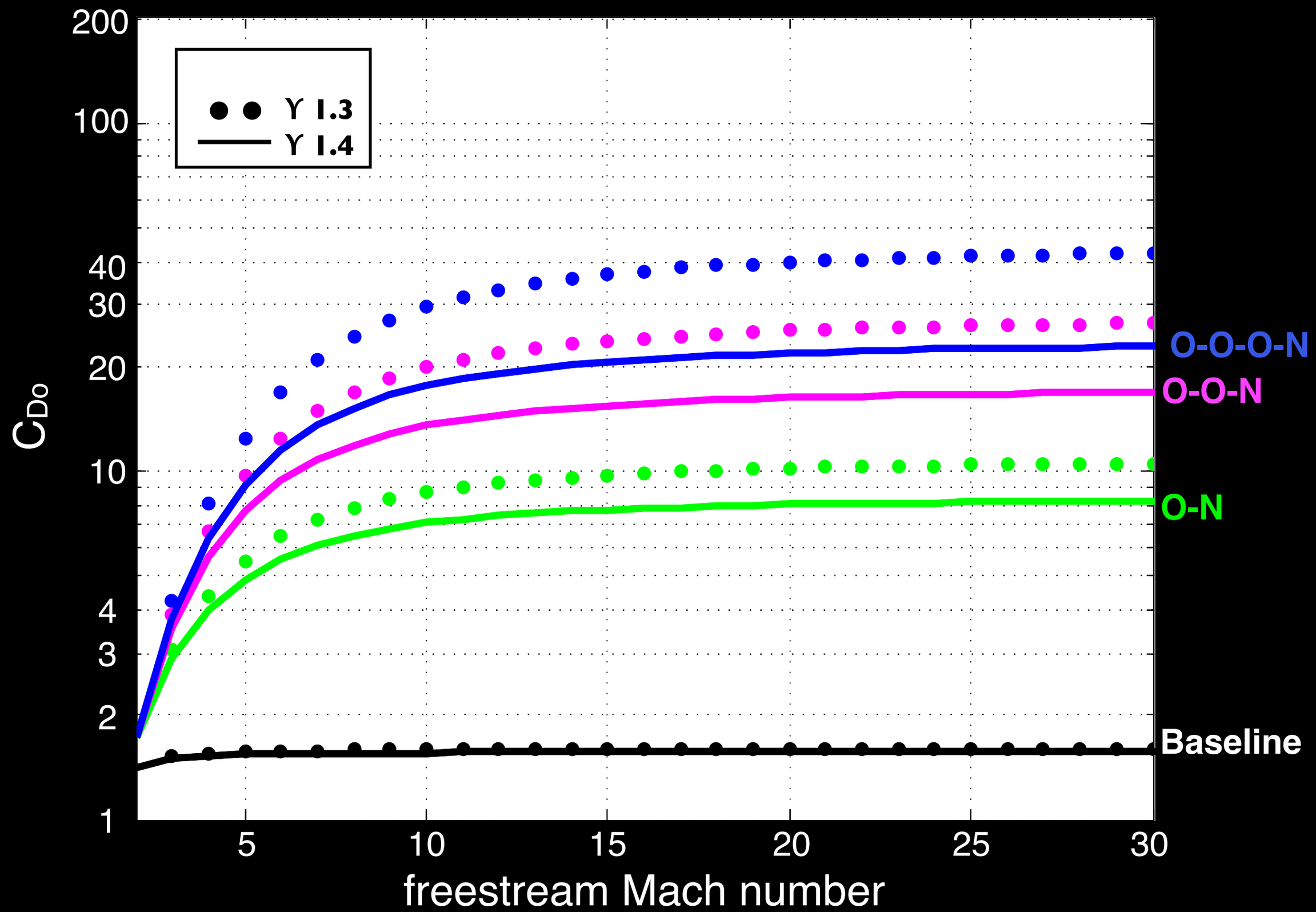


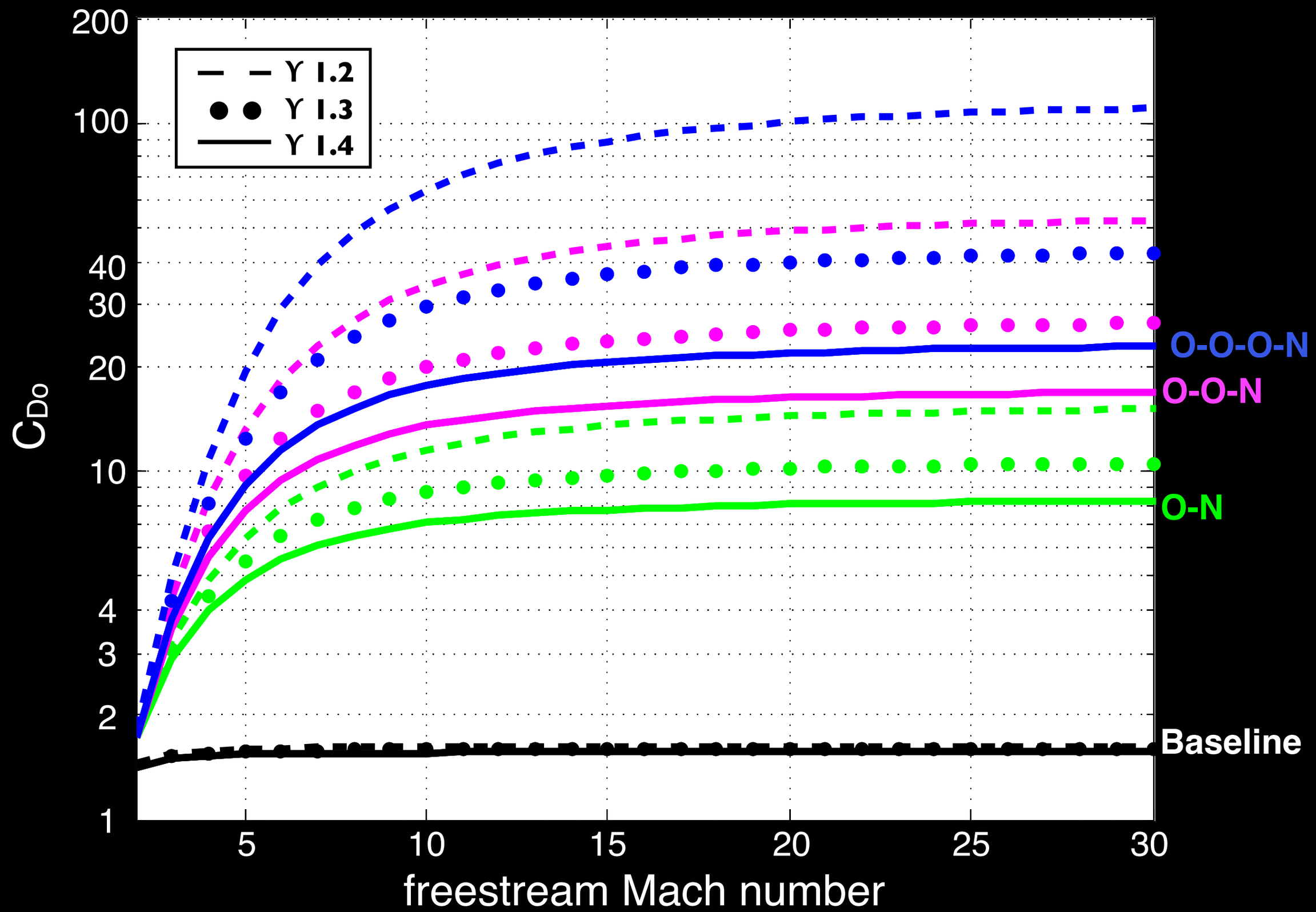
Effect of Υ


Υ 1.4
200
100
40
30
20
10
4
3
2
1
C_{Do}
5
10
15
20
25
30
freestream Mach number
O-O-O-N
O-O-N
O-N
Baseline

Effect of ϒ


ϒ 1.3
ϒ 1.4
200
100
40
30
20
10
4
3
2
1
C_{Do}
5
10
15
20
25
30
freestream Mach number
O-O-O-N
O-O-N
O-N
Baseline

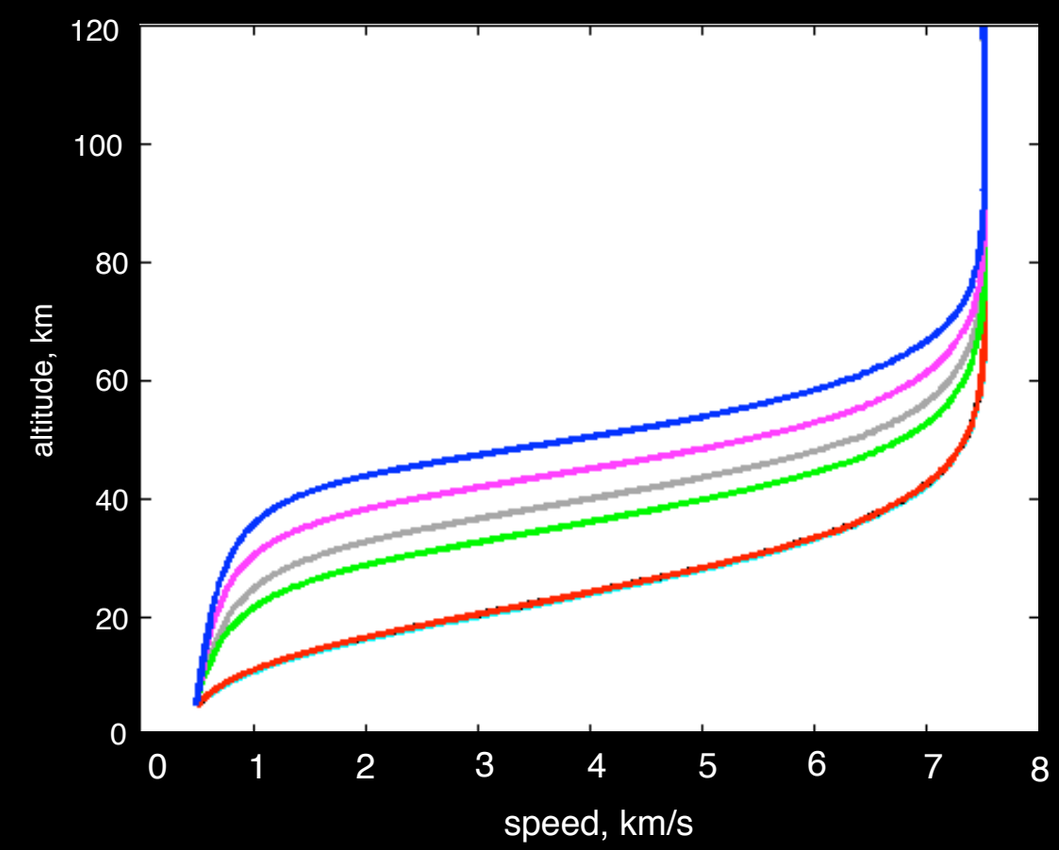
Effect of ϒ


ϒ 1.2
ϒ 1.3
ϒ 1.4
O-O-O-N
O-O-N
O-N
Baseline
C_{Do}
freestream Mach number
200
100
40
30
20
10
4
3
2
1
5
10
15
20
25
30

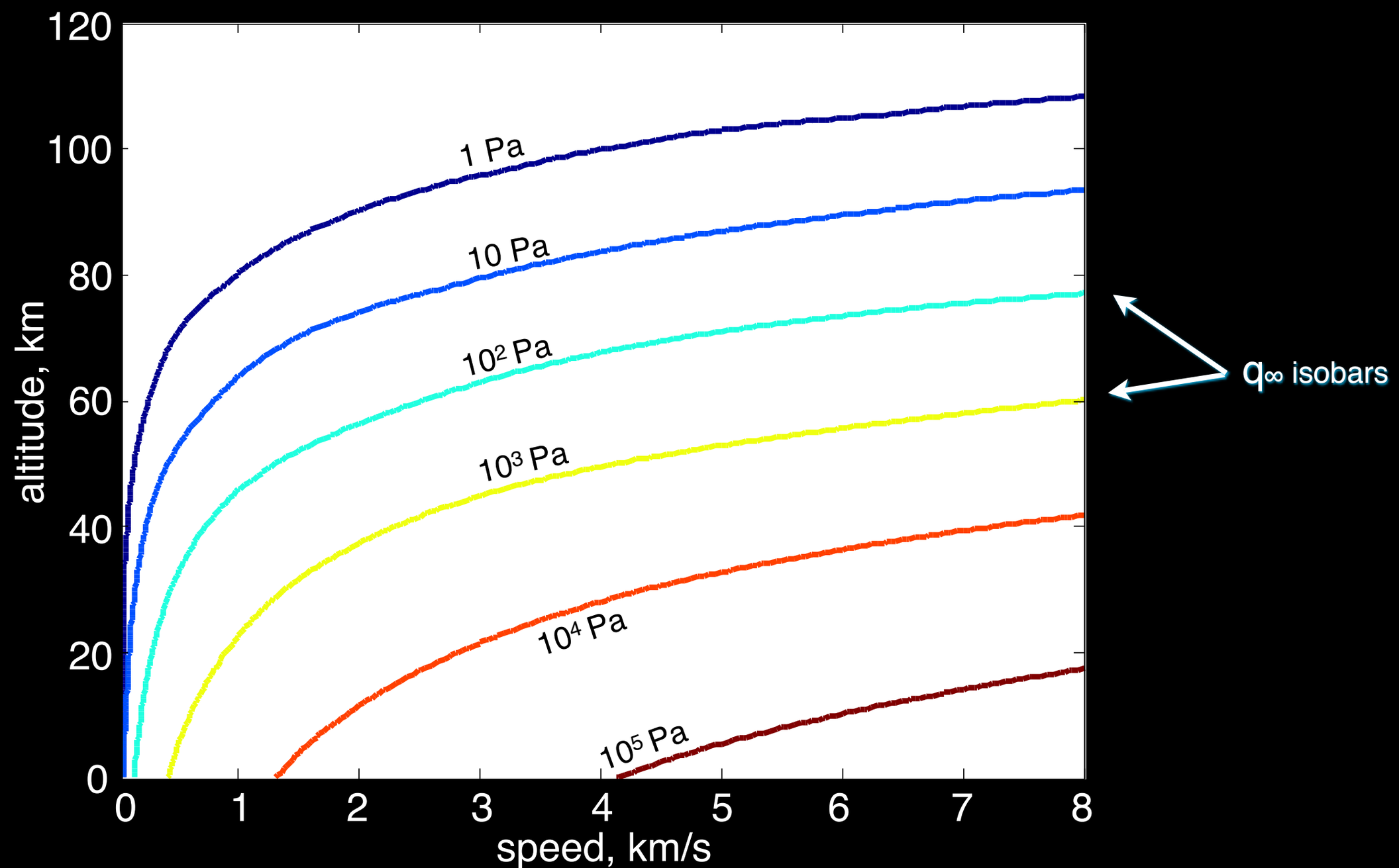
Drag Augmentation

- Established augmented C_D profiles as f(M,Y)
- Want to quantify potential D benefits
  - $D = C_D\, q_\infty\, S_{ref}$
  - q_∞ = f(altitude, speed)

Need to know trajectory for drag determination...



Drag Augmentation



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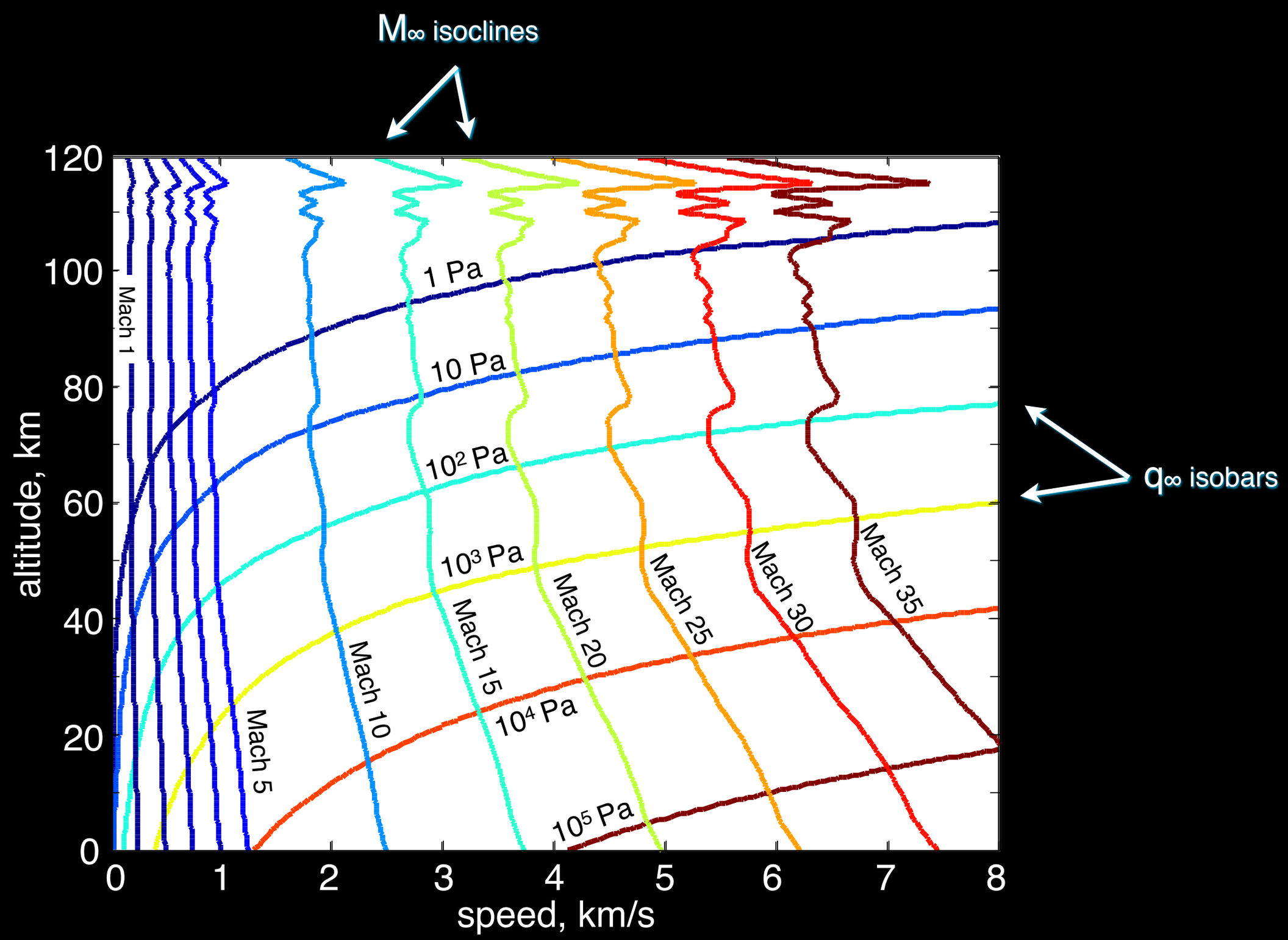
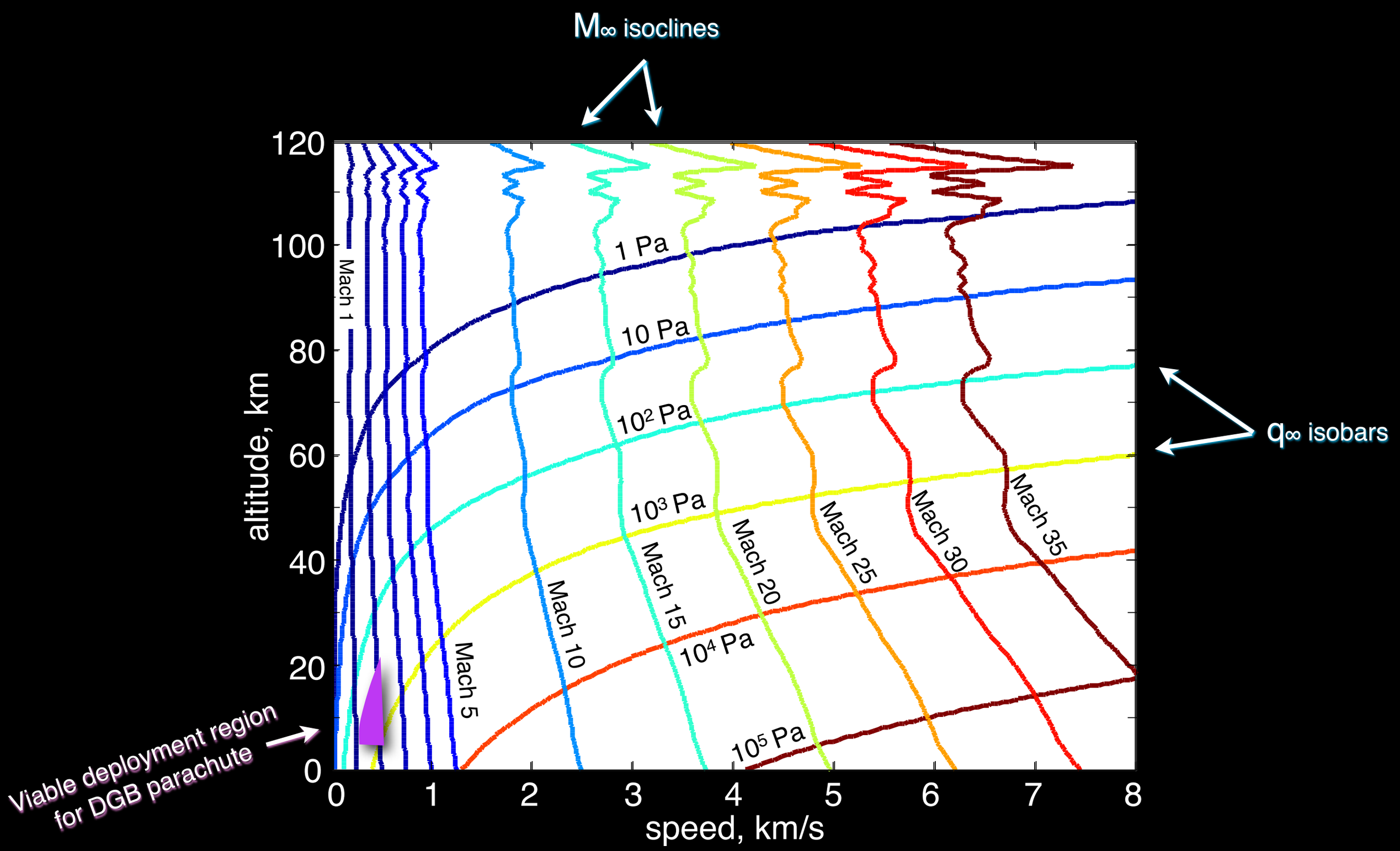
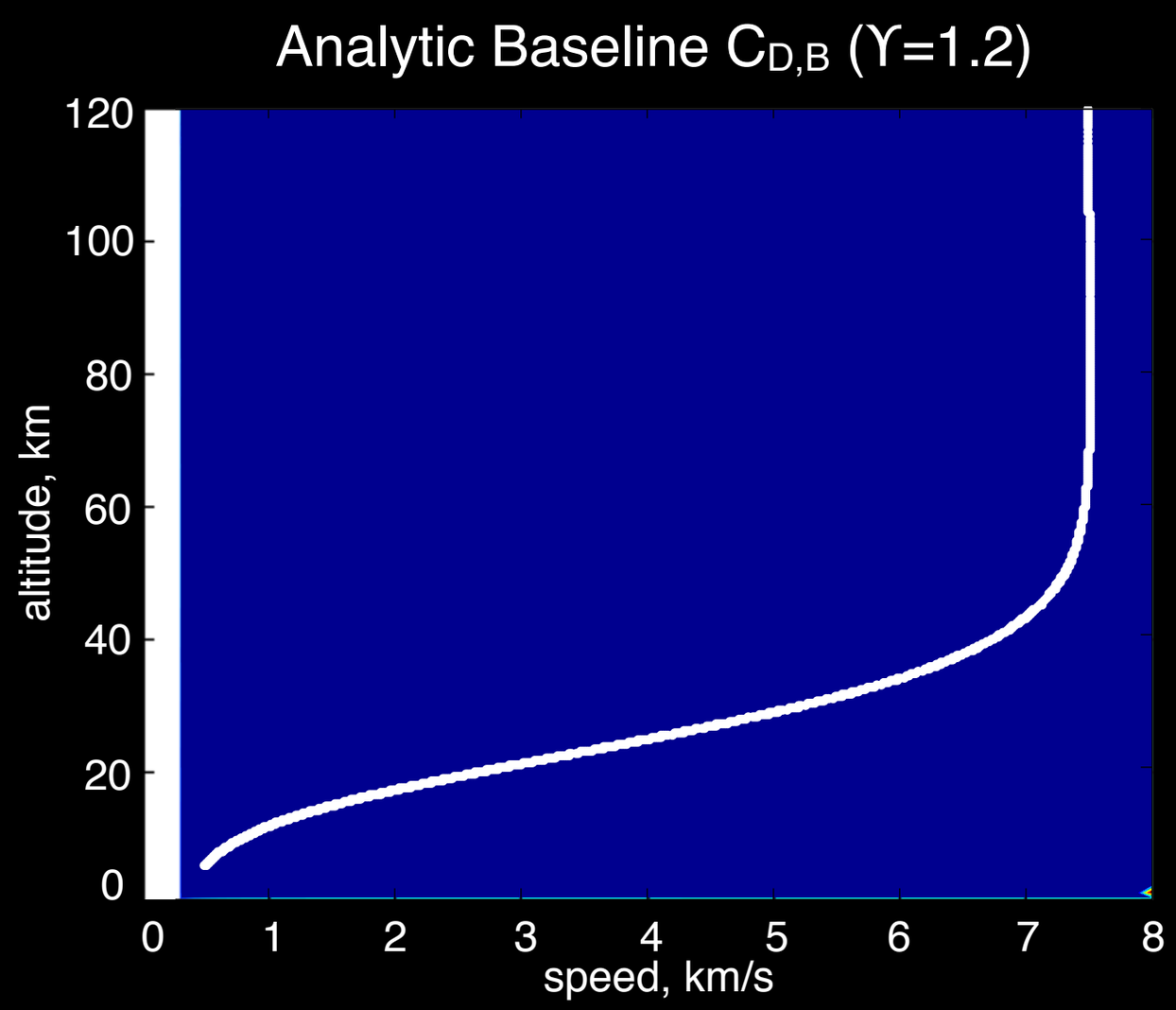


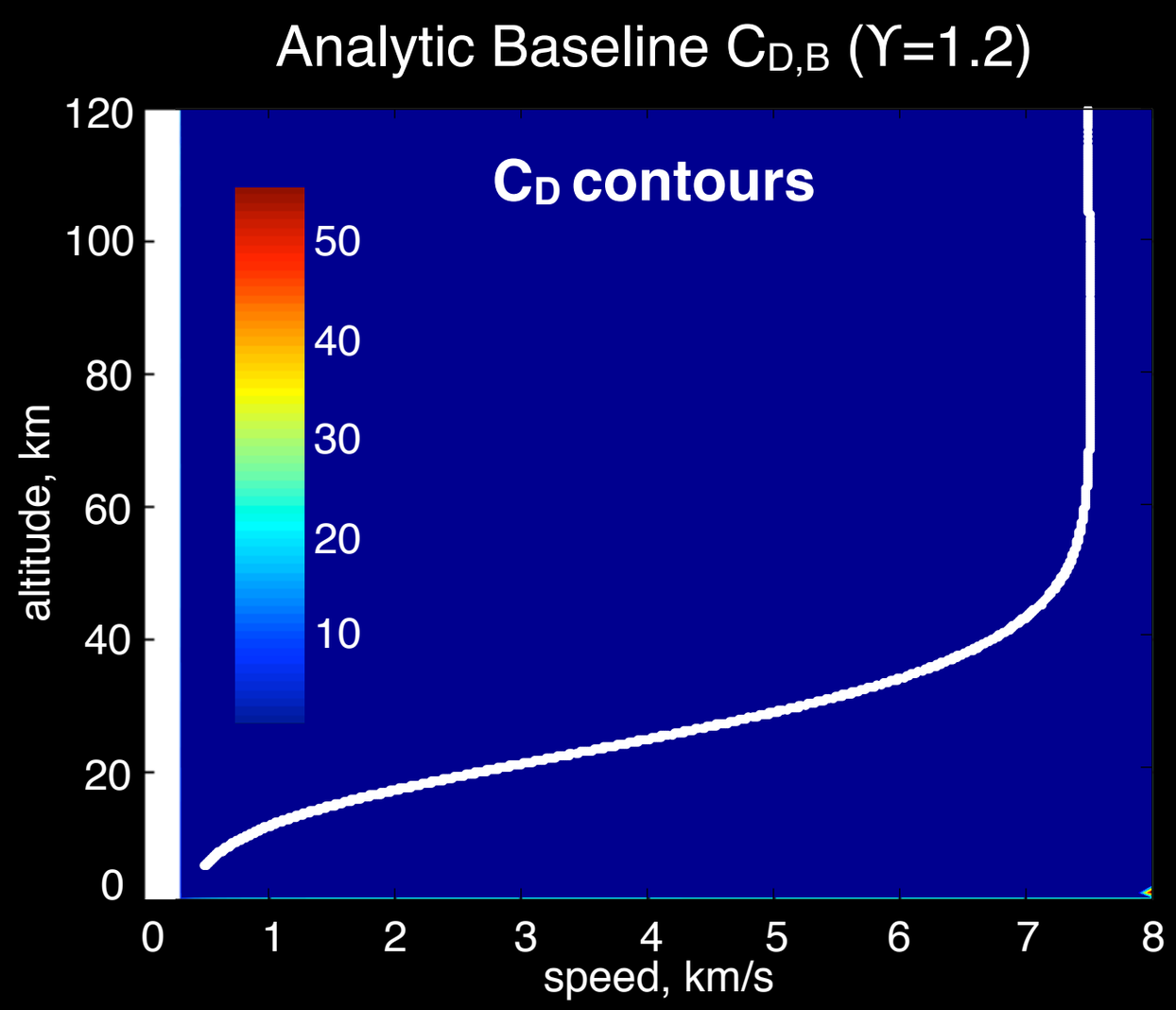
Drag Augmentation



C_D Contours


Analytic Baseline $C_{D,B}$ (Υ=1.2)
altitude, km
speed, km/s
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8

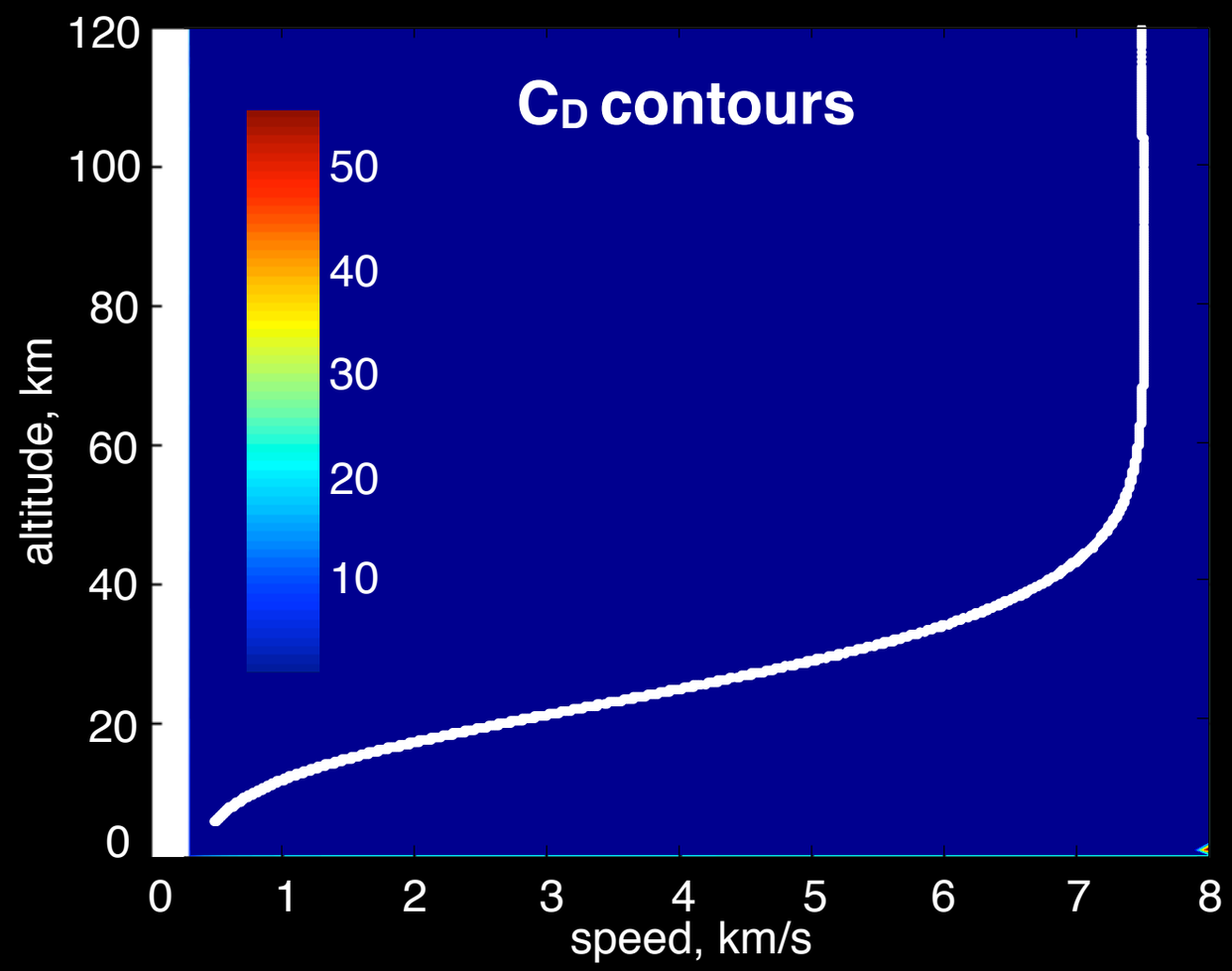
C_D Contours



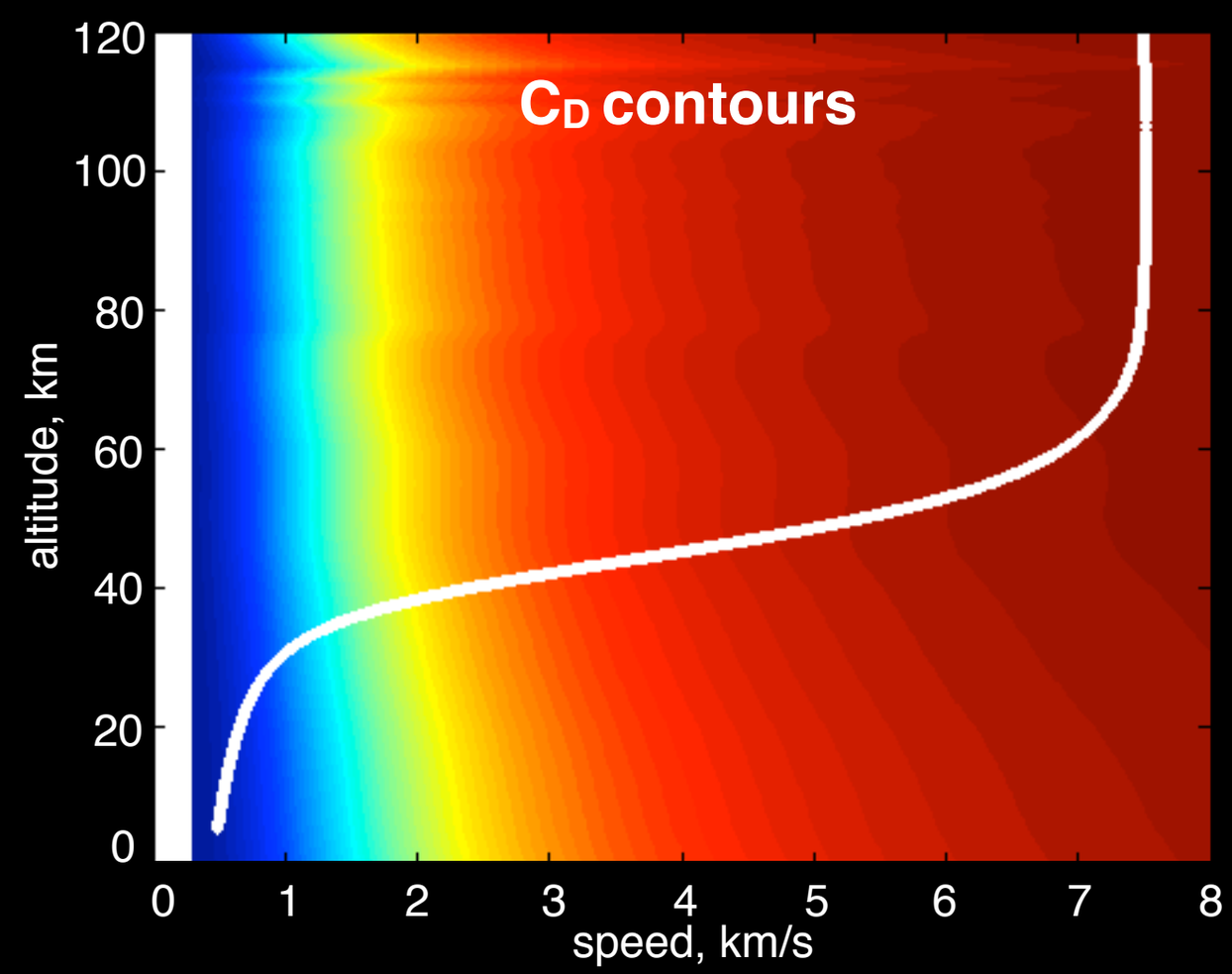
- Baseline C_D fairly constant over M_∞ range

C_D Contours

Analytic Baseline $C_{D,B}$ (Υ=1.2)



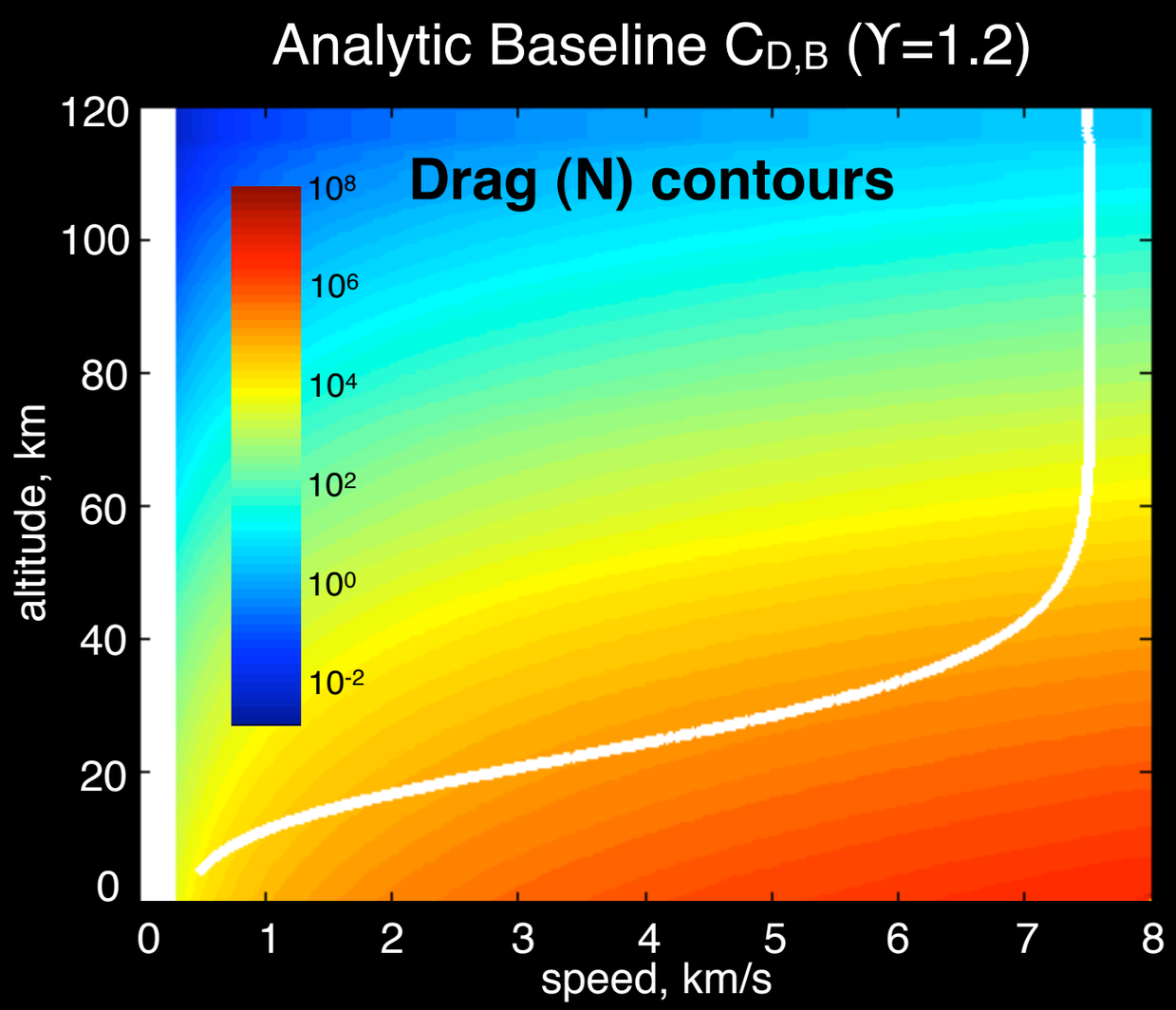
Analytic Shock Cascade $C_{Do4,O\text{-}O\text{-}N}$ (Υ=1.2)



- Baseline C_D fairly constant over M_∞ range
- Shock cascade allows $C_D > 50$

Drag Contours

$D = C_D \, q_\infty \, S_{ref}$



- For the fairly constant C_D case, drag contour trends as q_∞ and reaches 3×10^5 N

- Highest drag at high speed and low altitude

Drag Contours

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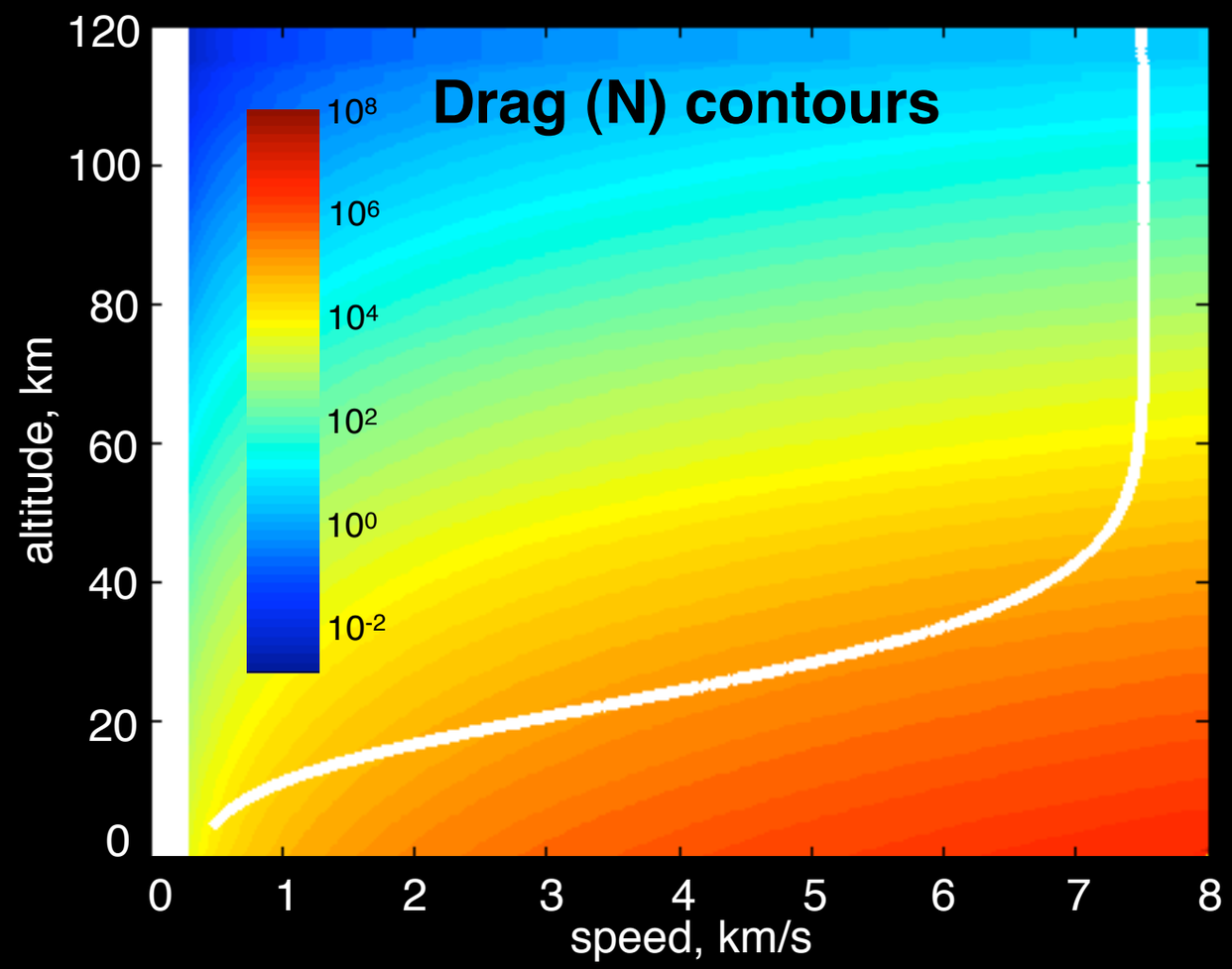
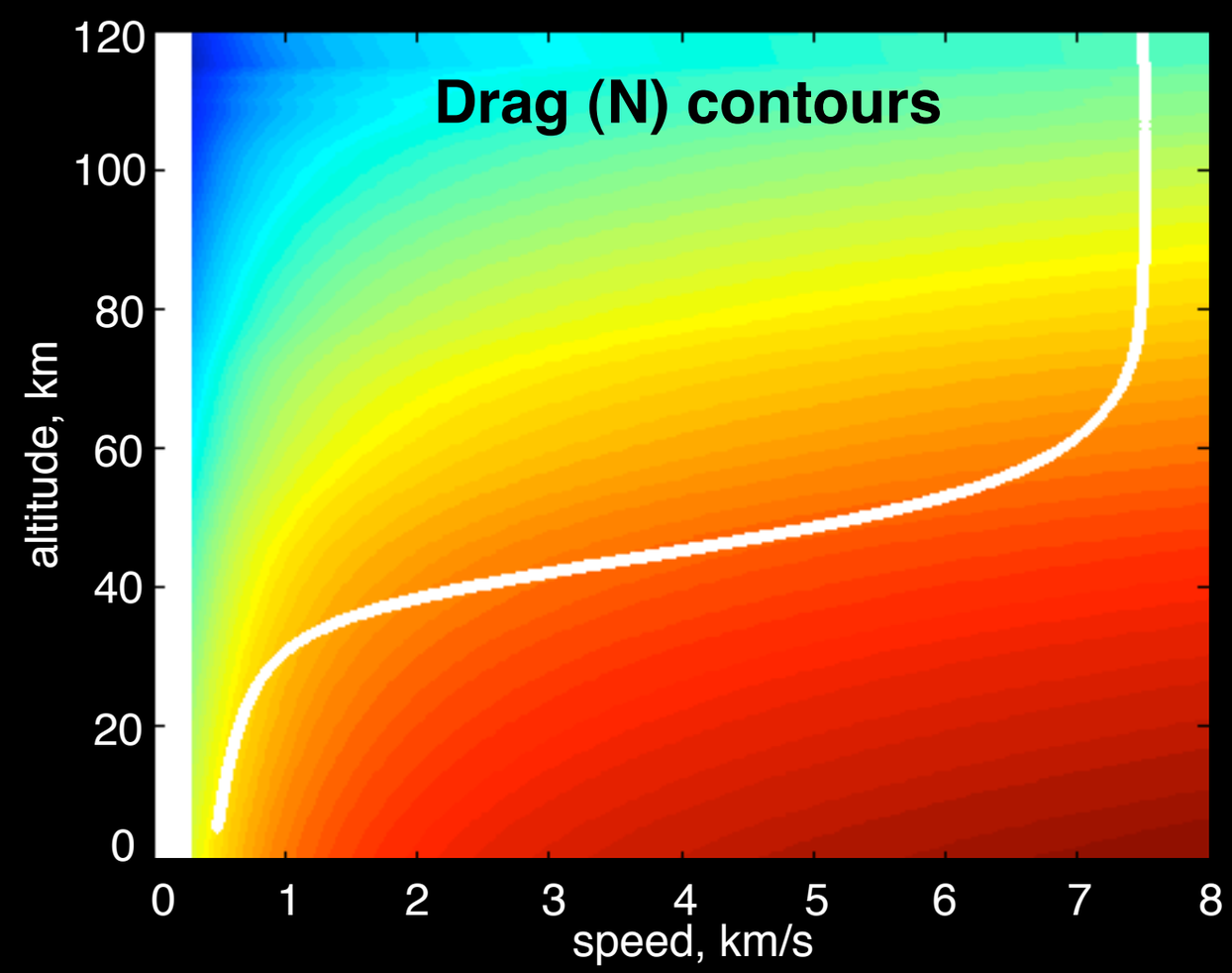
Analytic Baseline $C_{D,B}$ (Υ=1.2)



Analytic Shock Cascade $C_{Do4,O\text{-}O\text{-}N}$ (Υ=1.2)



- For the fairly constant C_D case, drag contour trends as q_∞ and reaches 3×10^5 N
- Highest drag at high speed and low altitude
- Note logarithmic scale spanning 11 orders of magnitude
- Shock cascade produces “red shift” of the drag map and values > 10^7 N

Drag Contours

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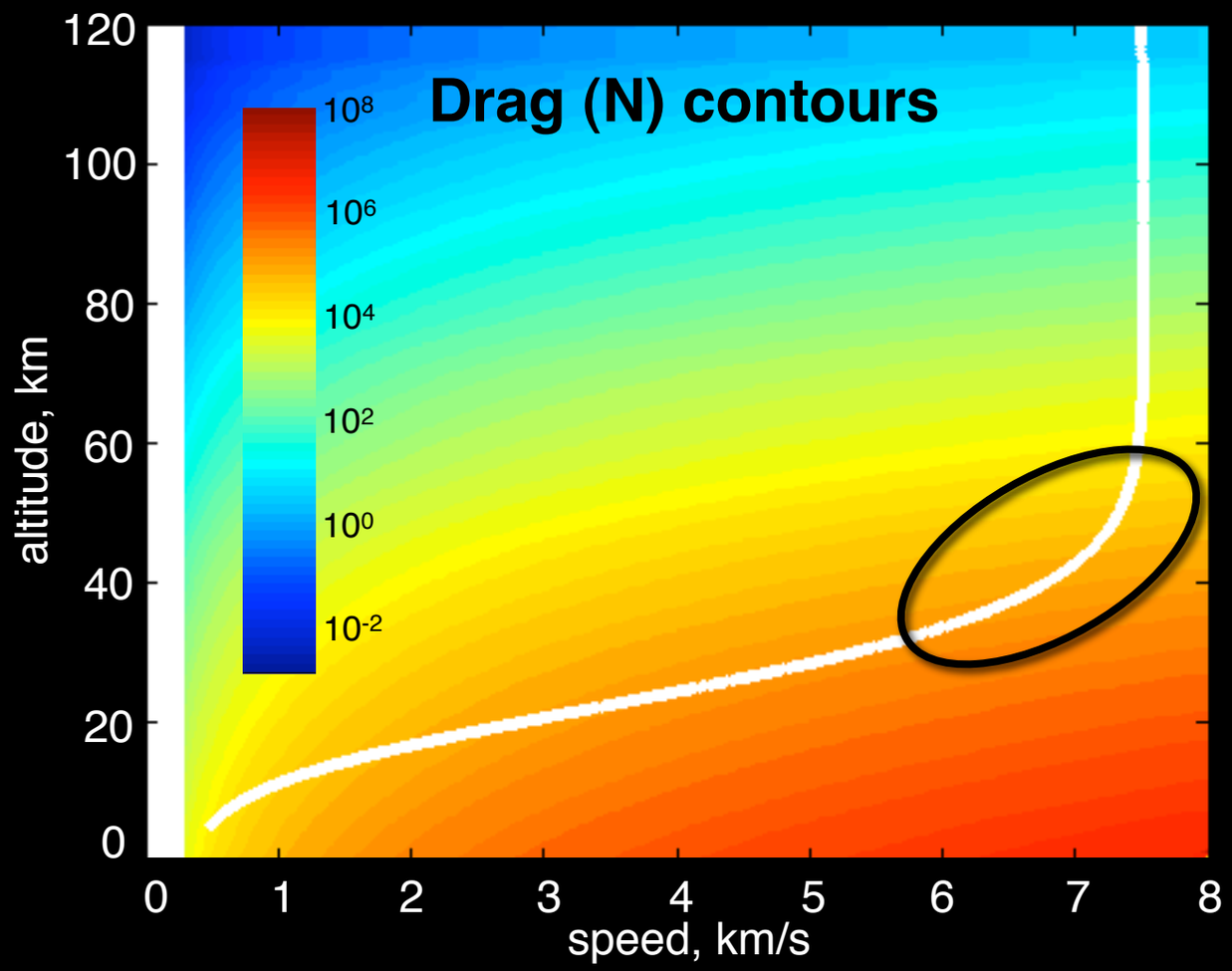

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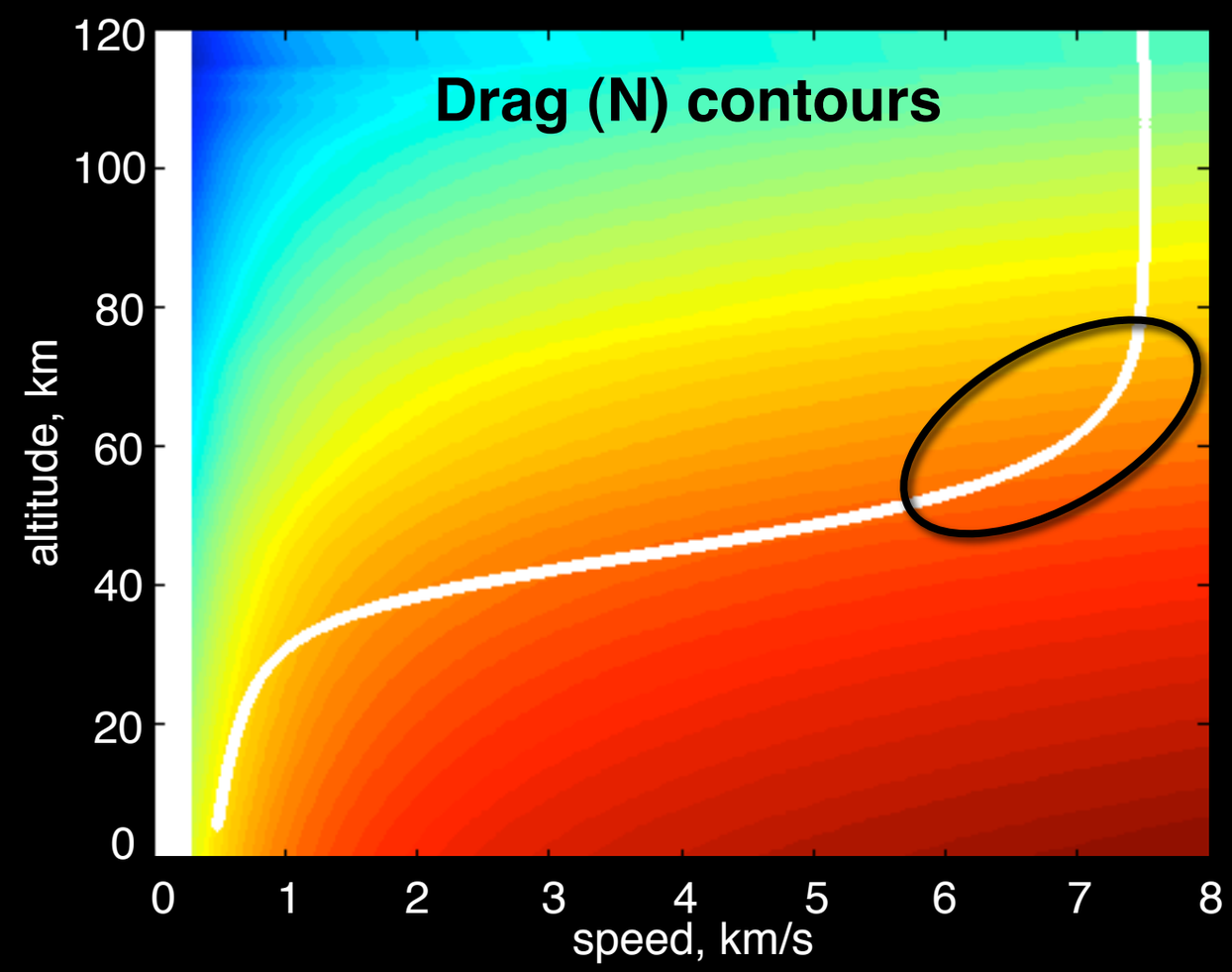

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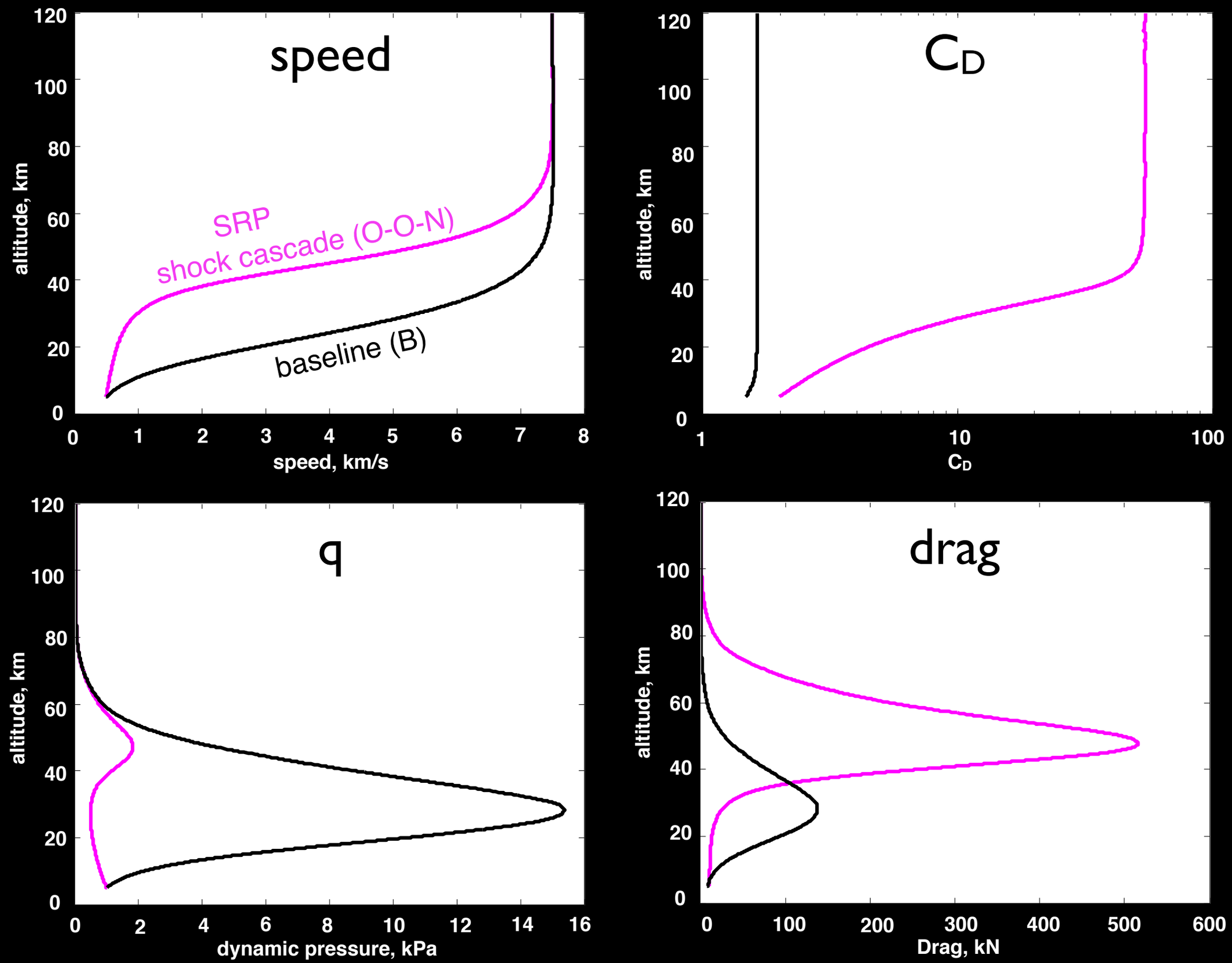
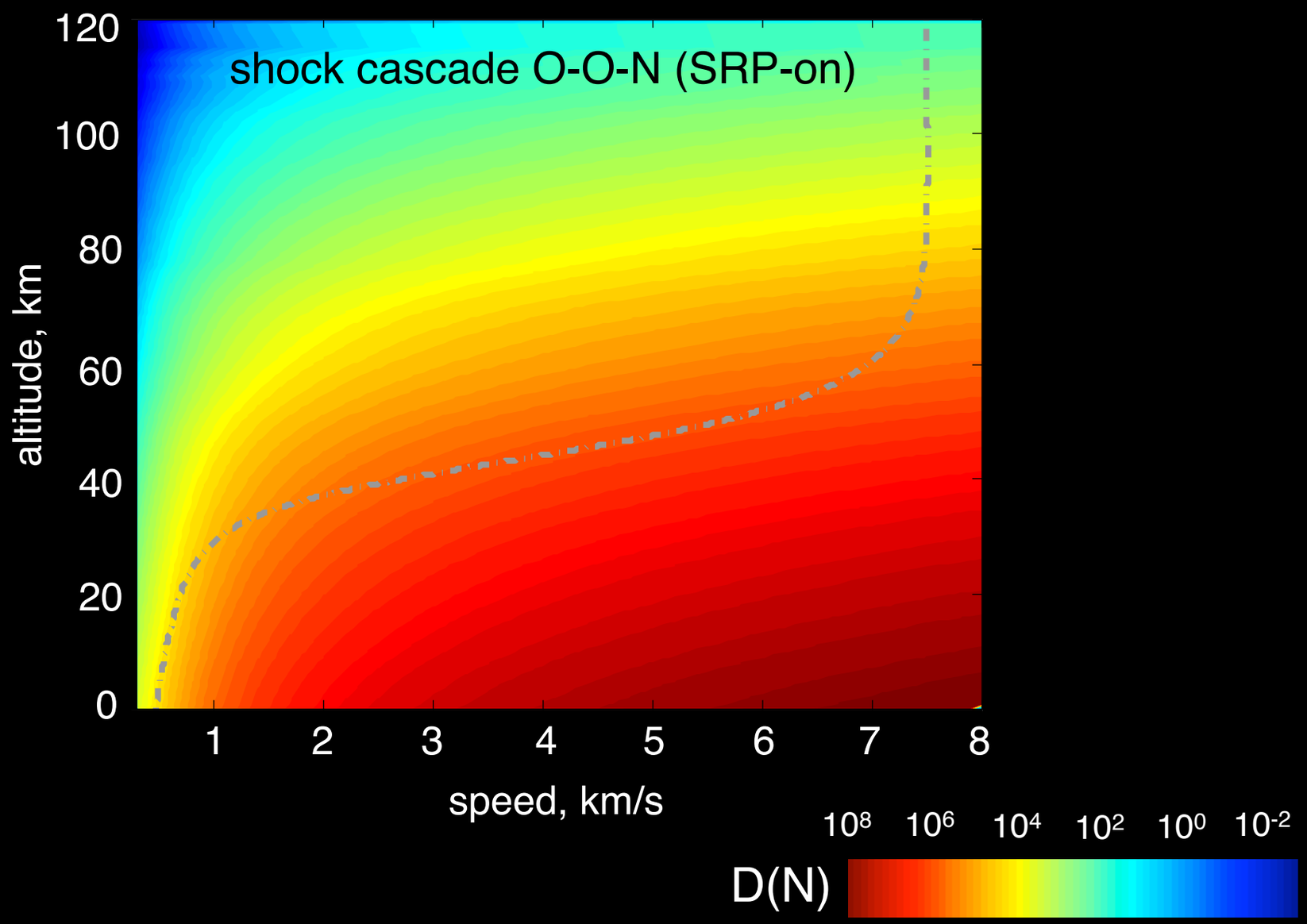
Drag over Trajectory

$$D = C_D \, q_\infty \, S_{ref}$$



Strategy: Delayed Activation for Drag Modulation

- Shock cascade (SRP-on) results in high-altitude deceleration (F=ma)
- Prevents vehicle from getting to the high drag values deeper in atmosphere



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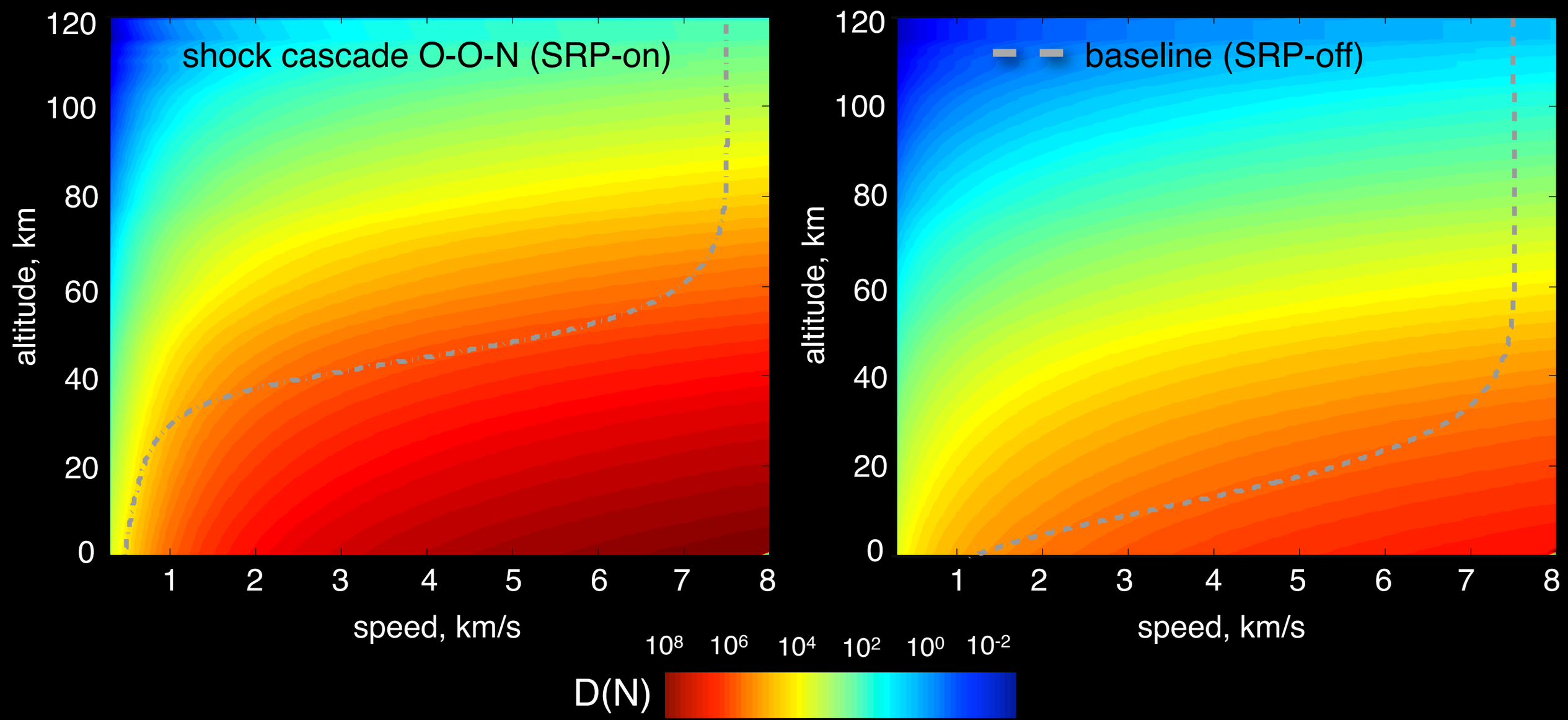

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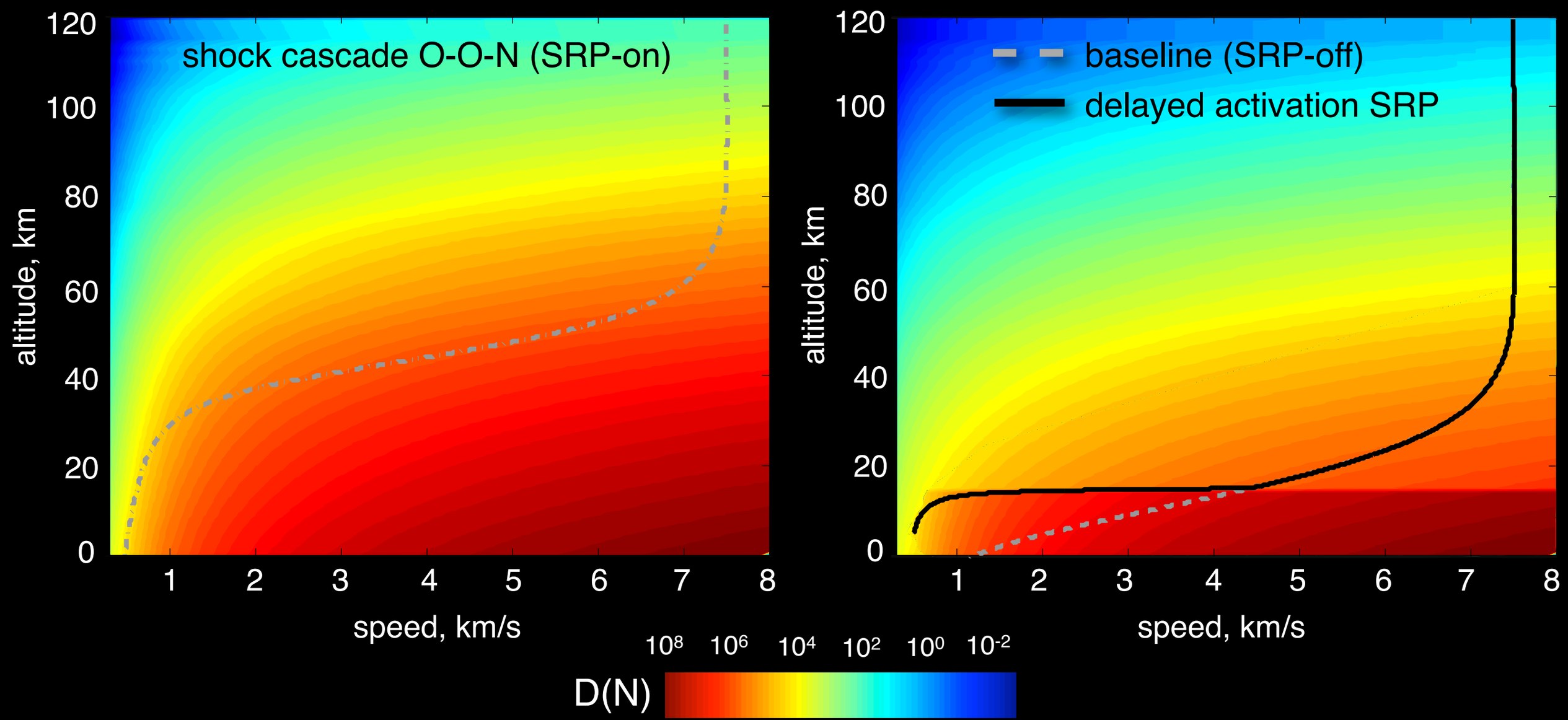

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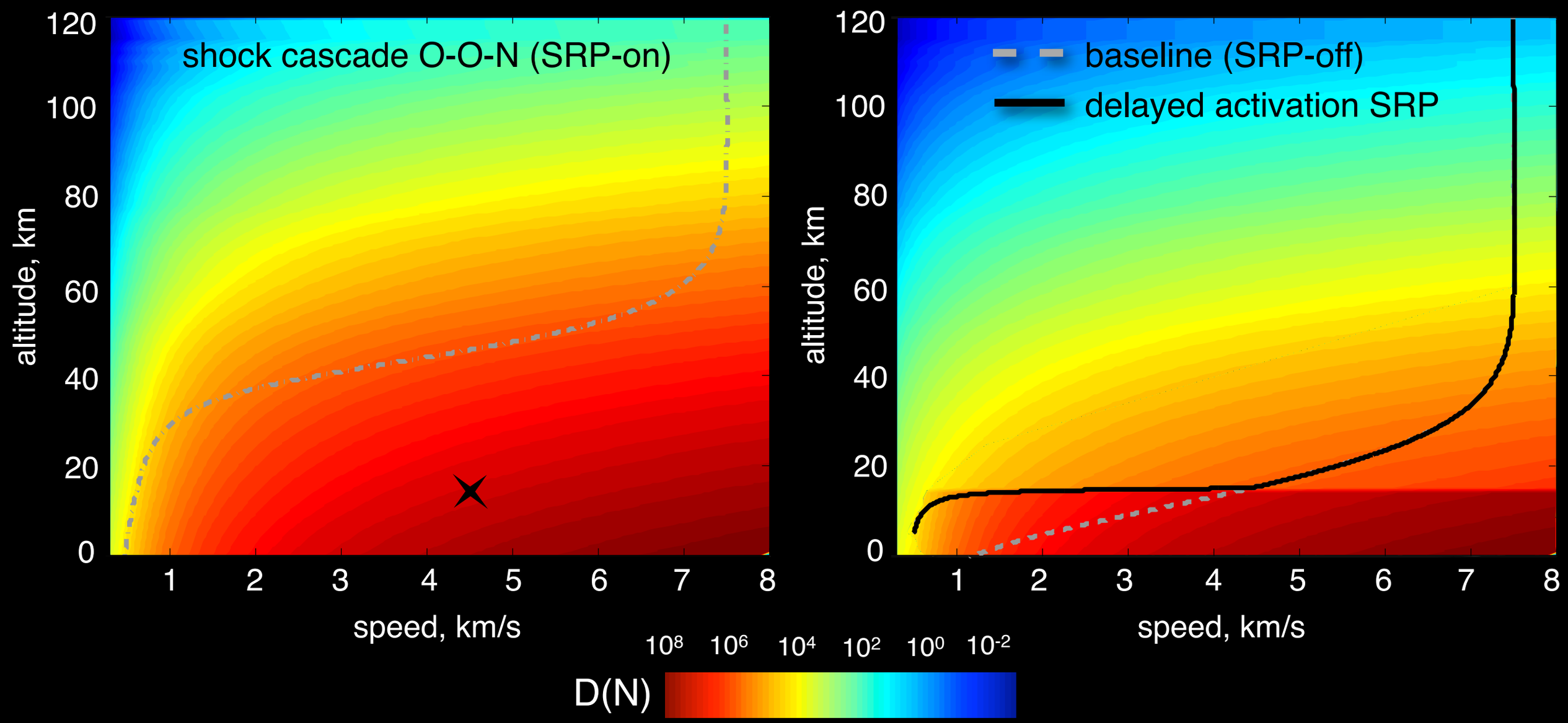

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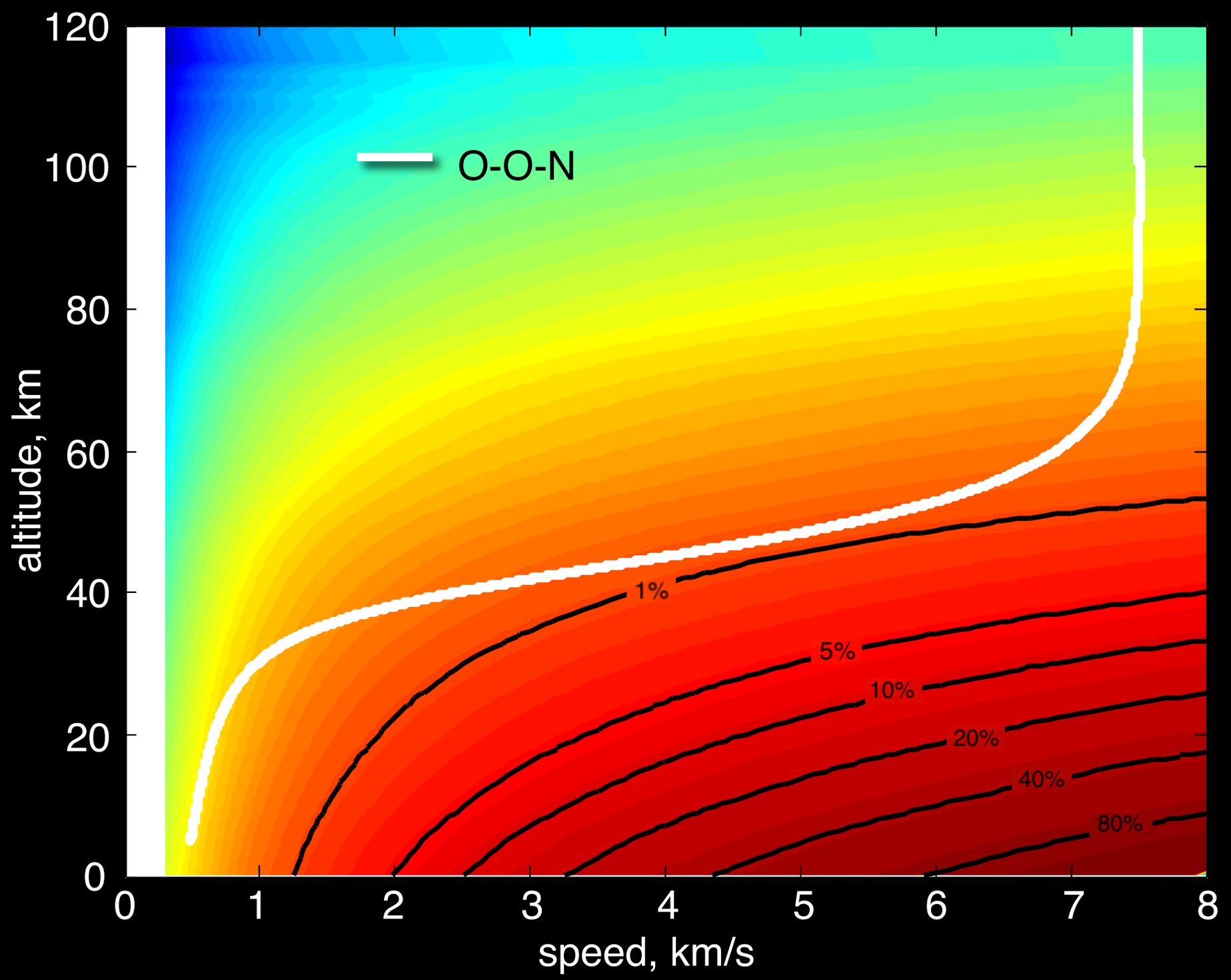

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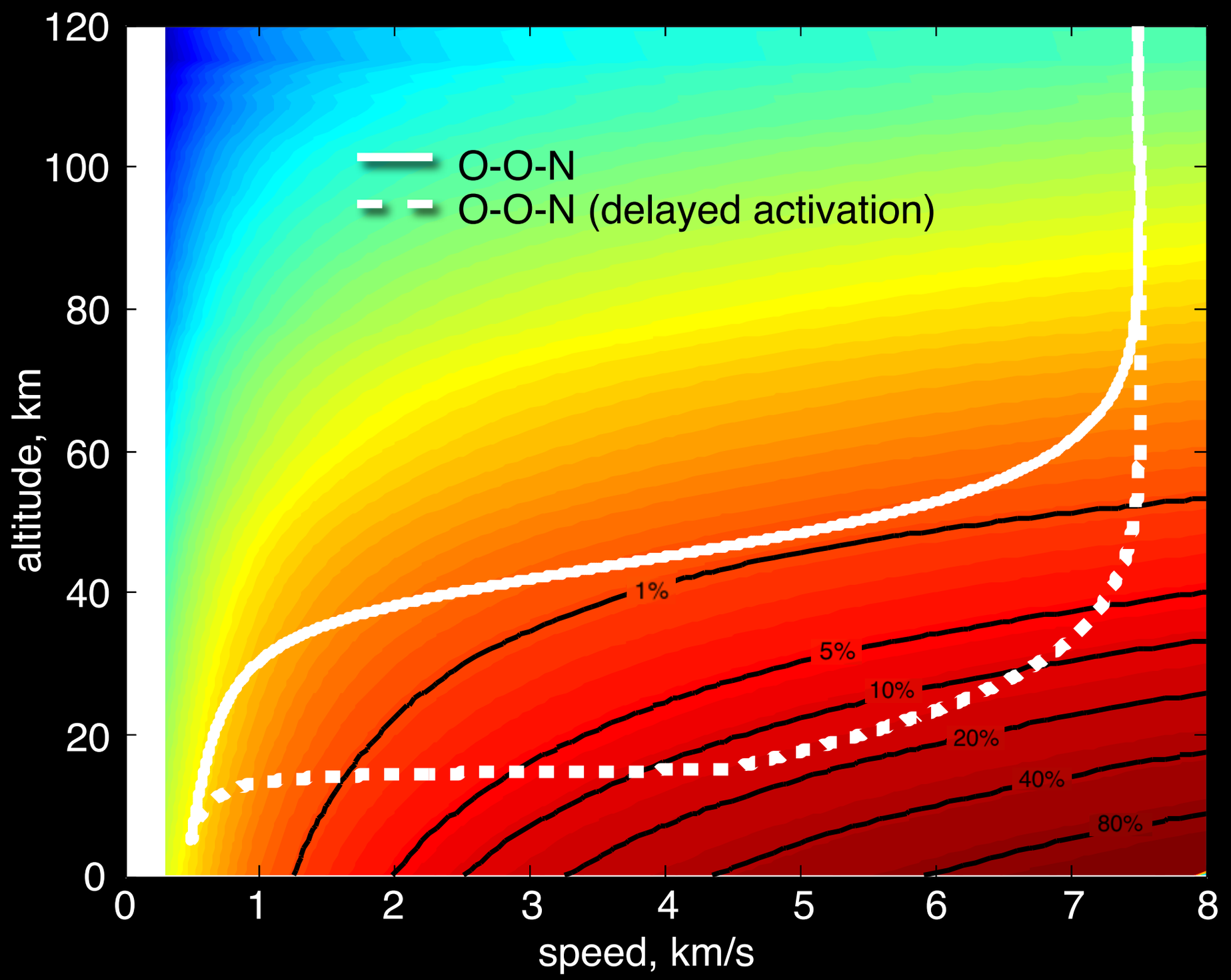
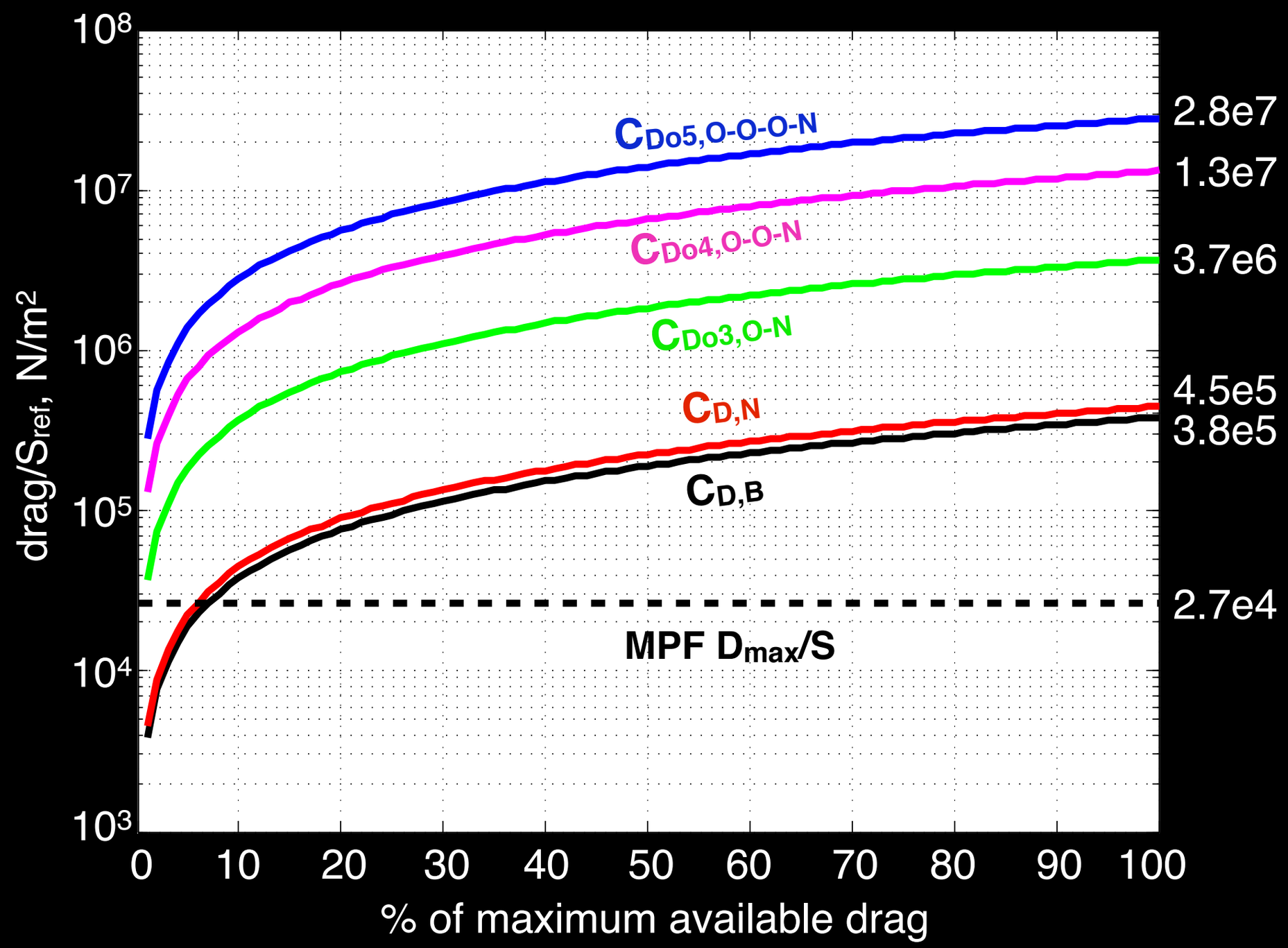


Drag Potential



Summary

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Summary

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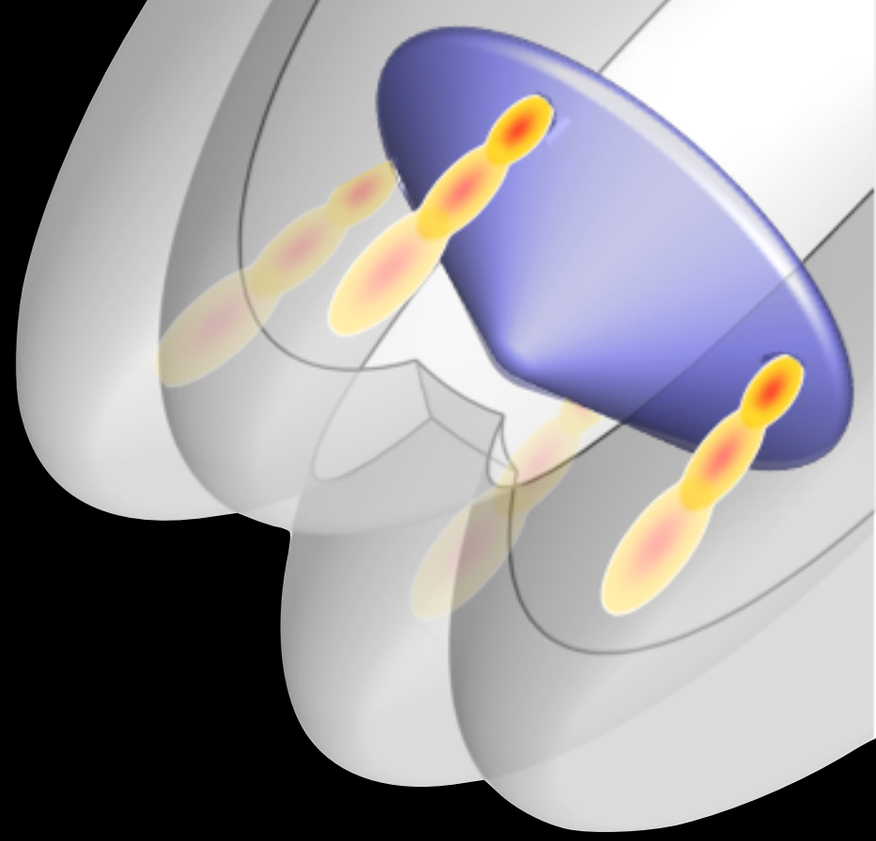
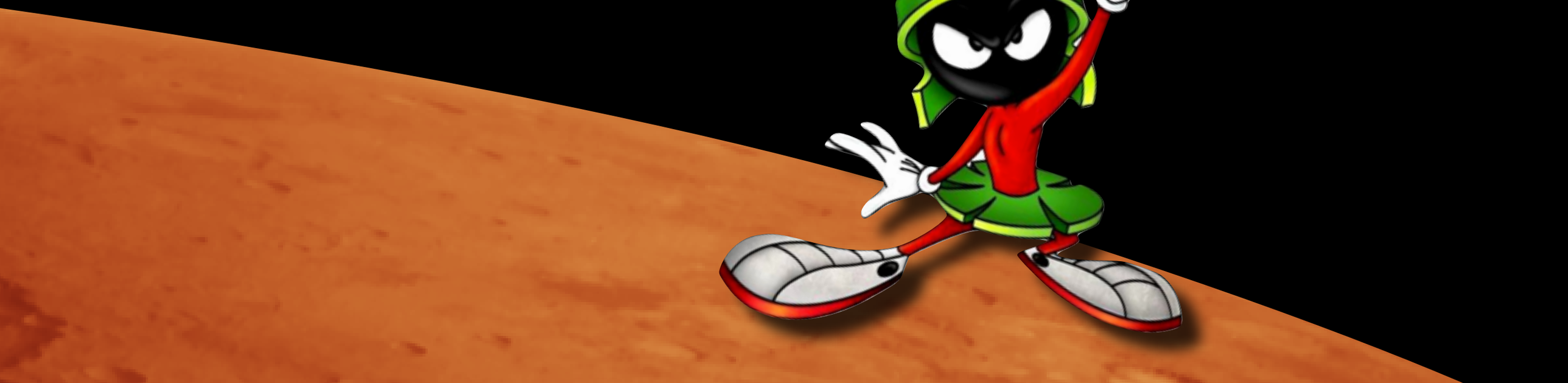
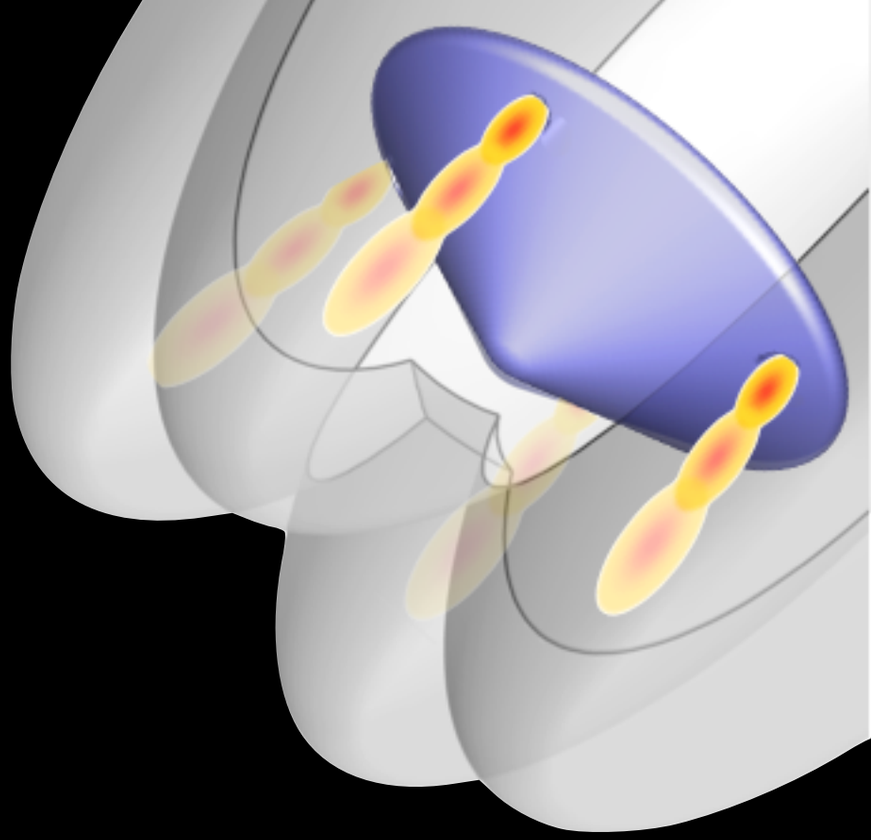
  - Simple shock cascades generate $C_D \sim 50$
  - Heavy dependence on specific heat ratio
- Drag values quantified through 3-DOF propagation of C_D's
  - Tremendous increase in drag starting at ~60km altitude
- Identified SRP's potential for providing on-demand drag
  - Explored strategy of delayed activation
    - example achieved D/S ~10^7 N/m^2
  - SRP drag modulation could satisfy decelerative needs of high-mass Mars entry scenarios

Future Work



- detailed SRP simulations to establish deliverable C_D values through shock manipulation using low thrust SRP jets
- trajectory studies exploiting optimal drag potential subject to heating and acceleration constraints
  - estimates of realizable drag
  - achievable payload mass



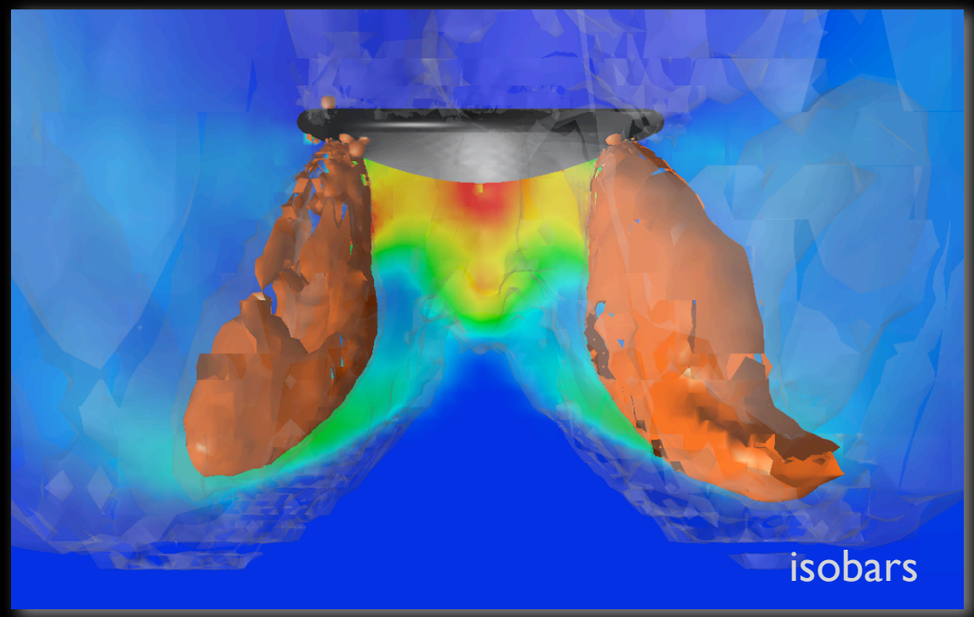


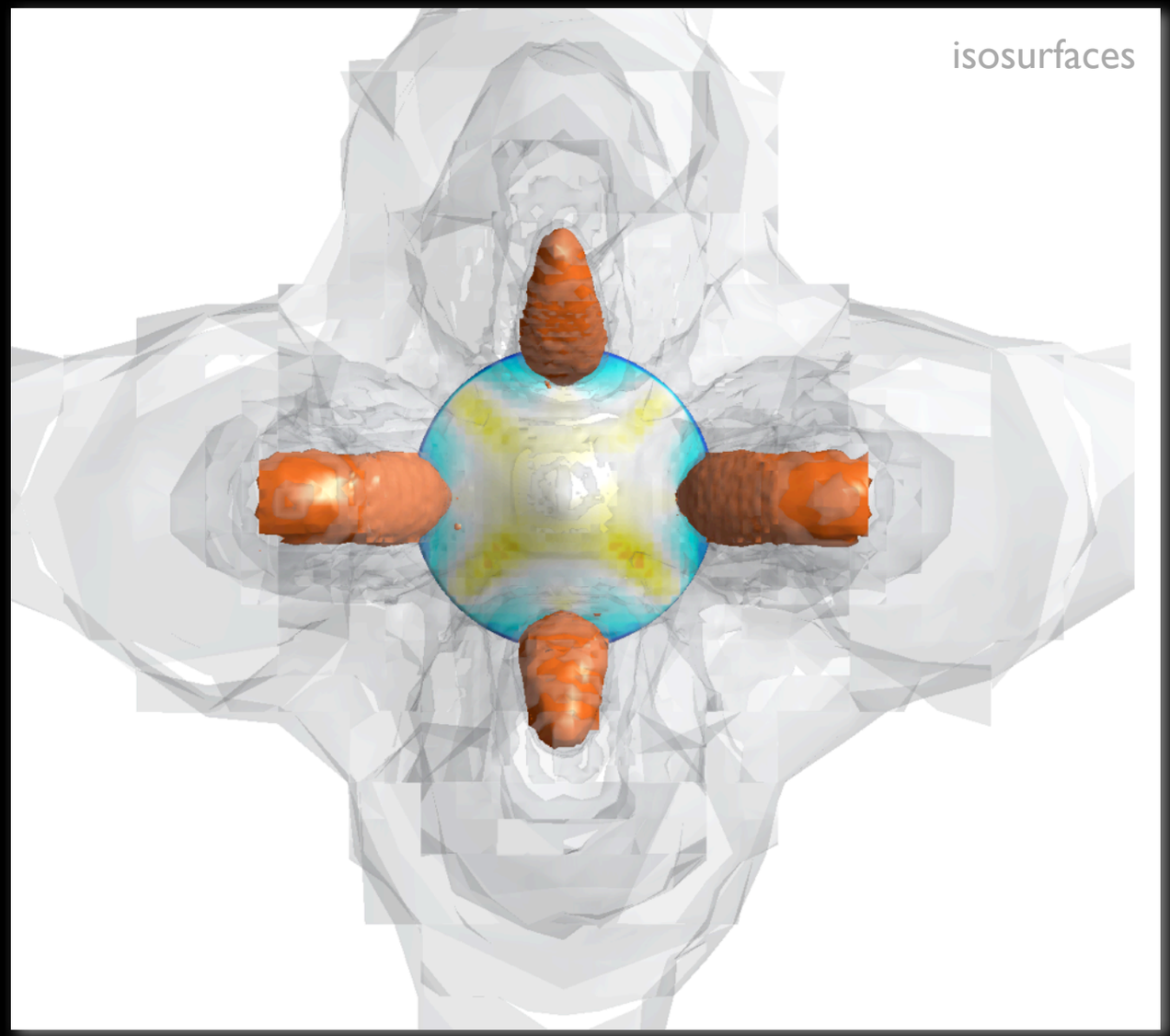
Questions?

Extra Slides

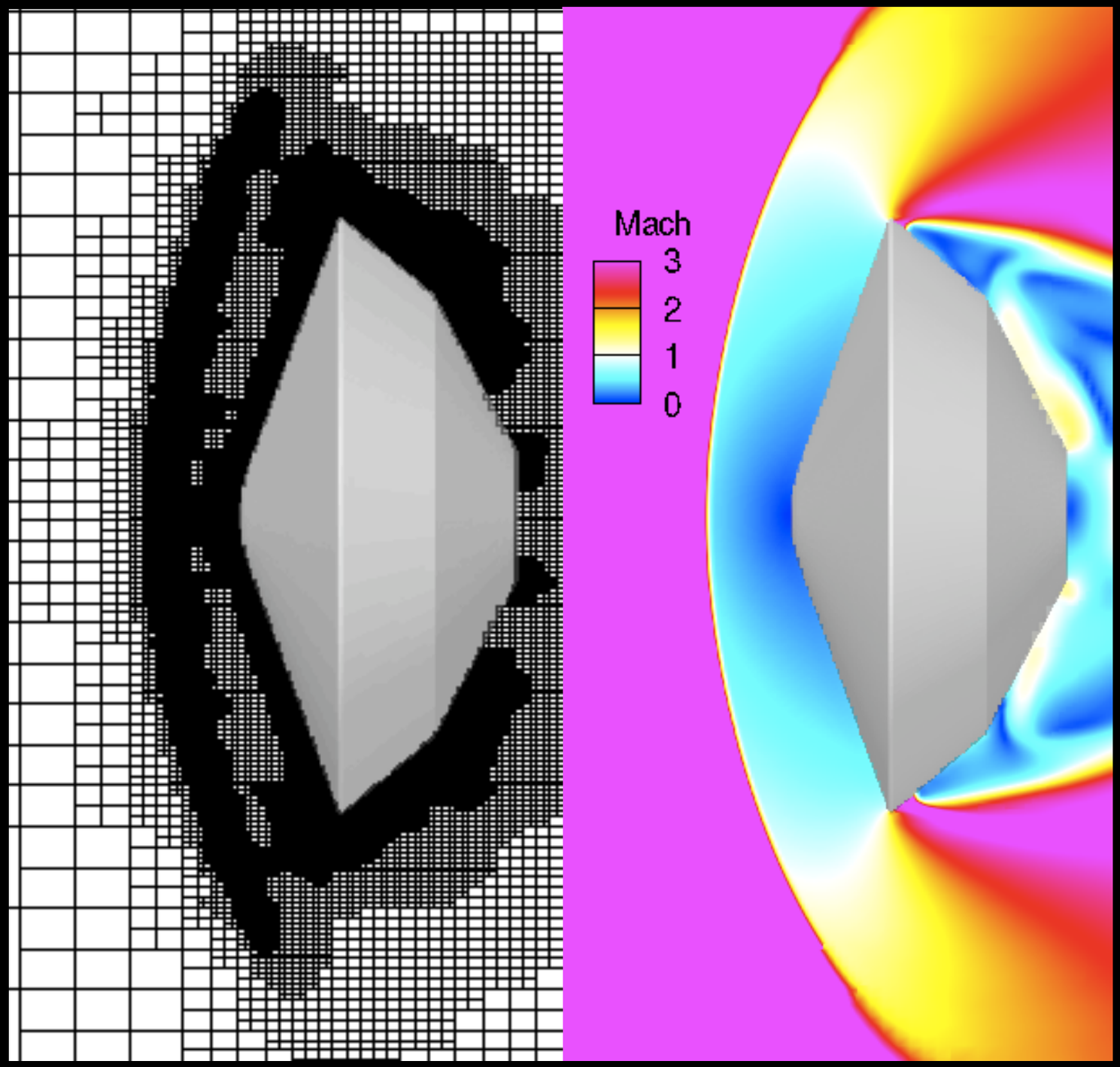
Model for Drag Augmentation

$$C_{Daug} = \frac{C_D - C_{D,ref}}{C_{D,ref}} \times 100\%$$

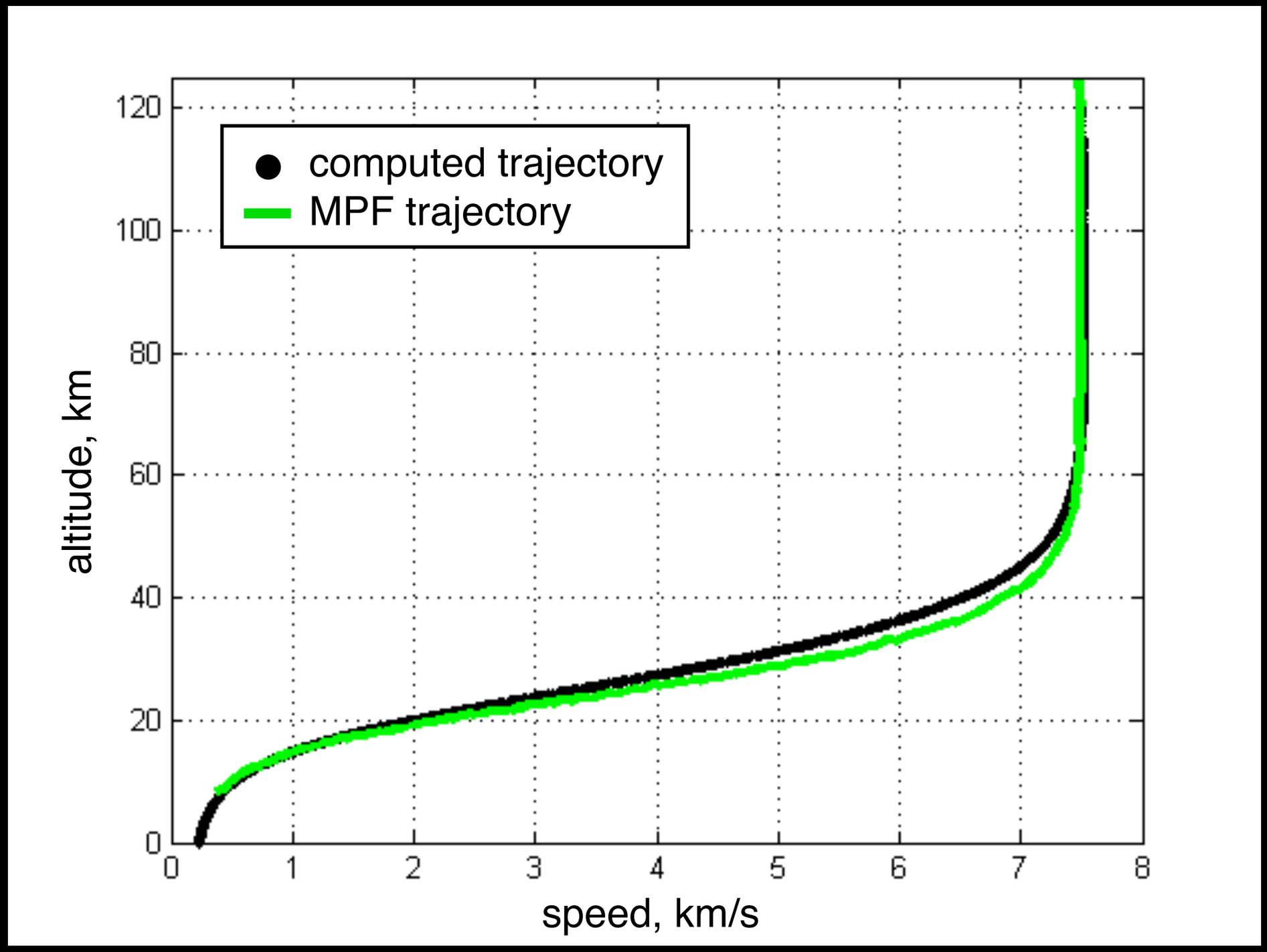




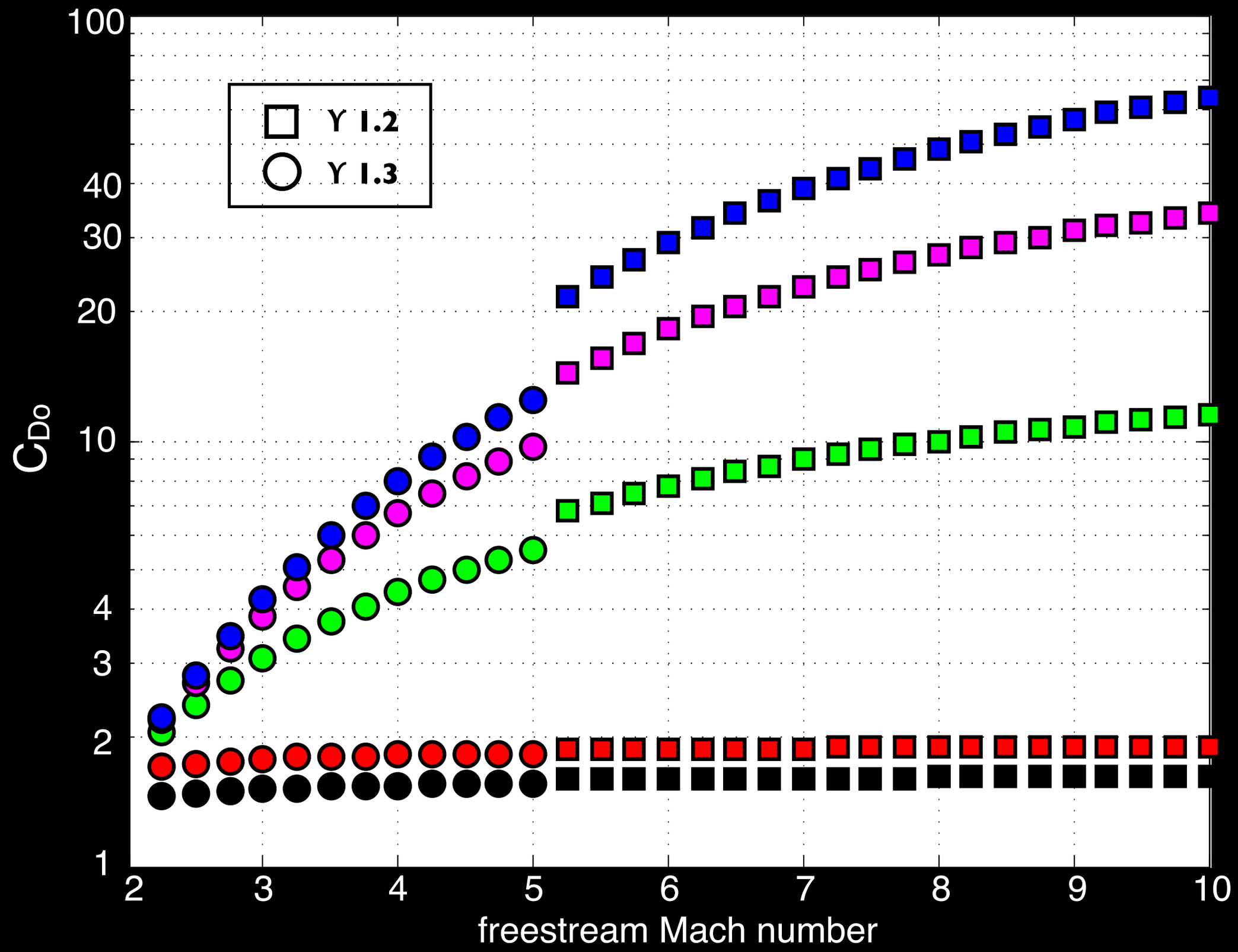
CFD for Validation of Analytical Method



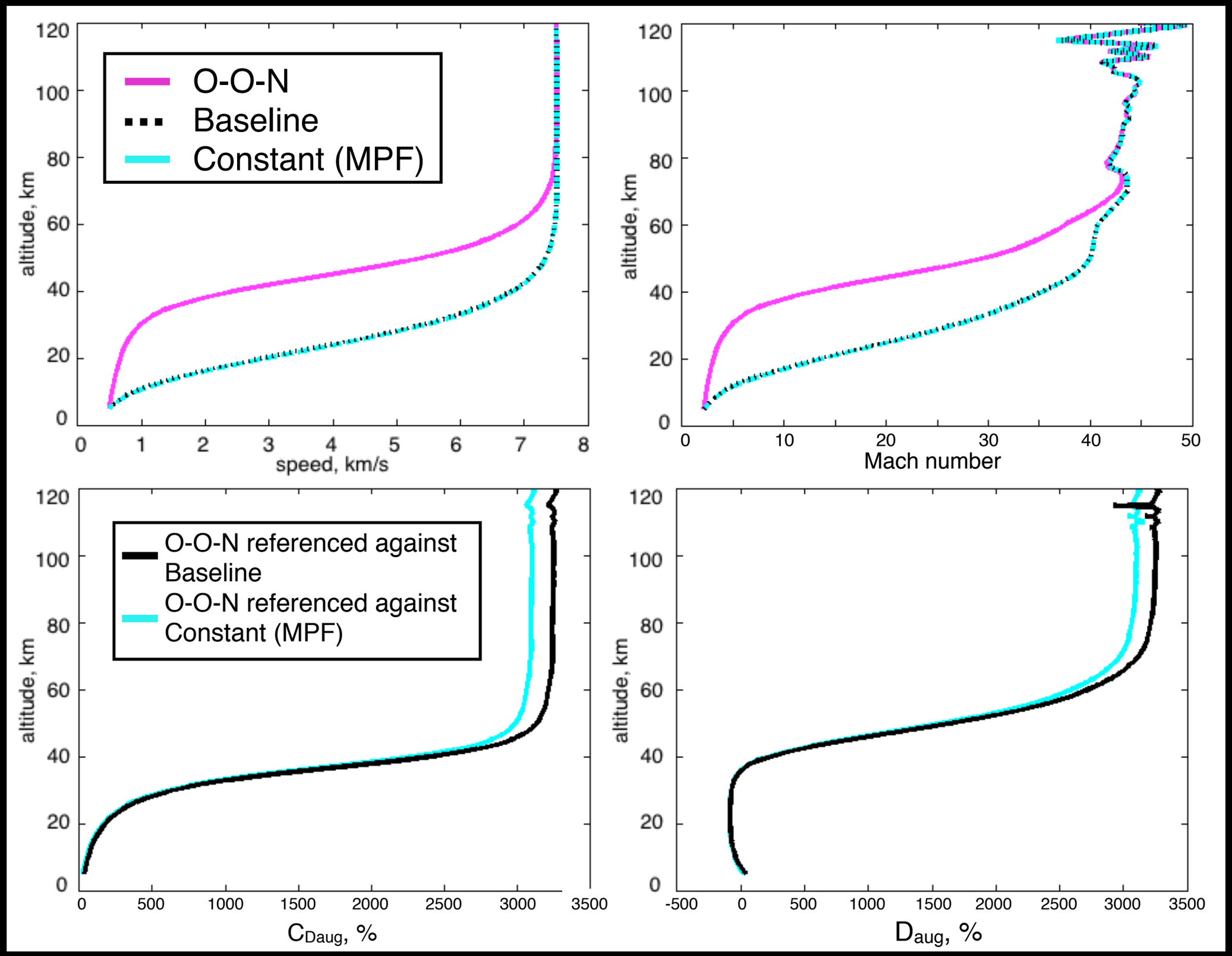
Trajectory Code Validation



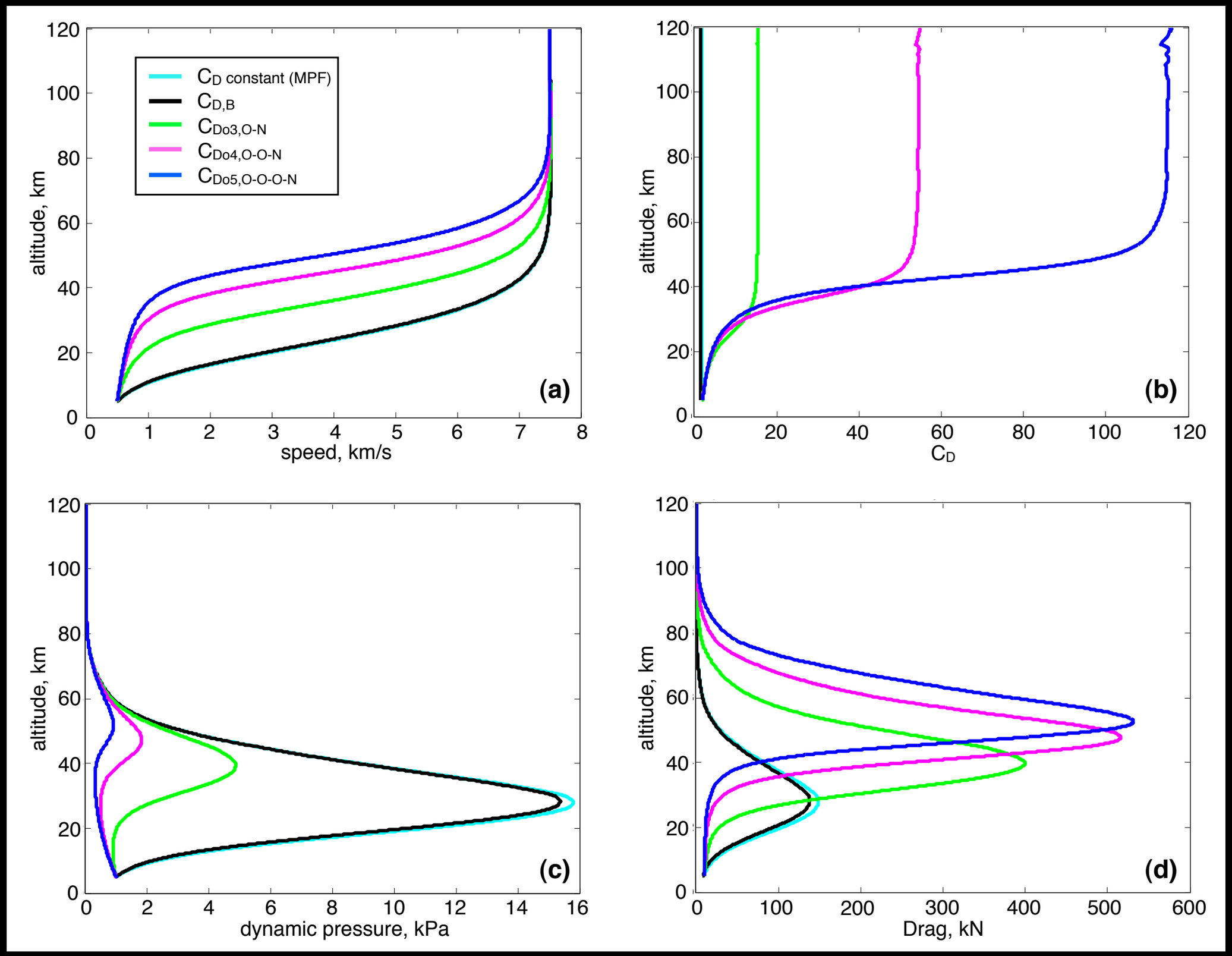
Effect of ϒ : Mars Entry Model



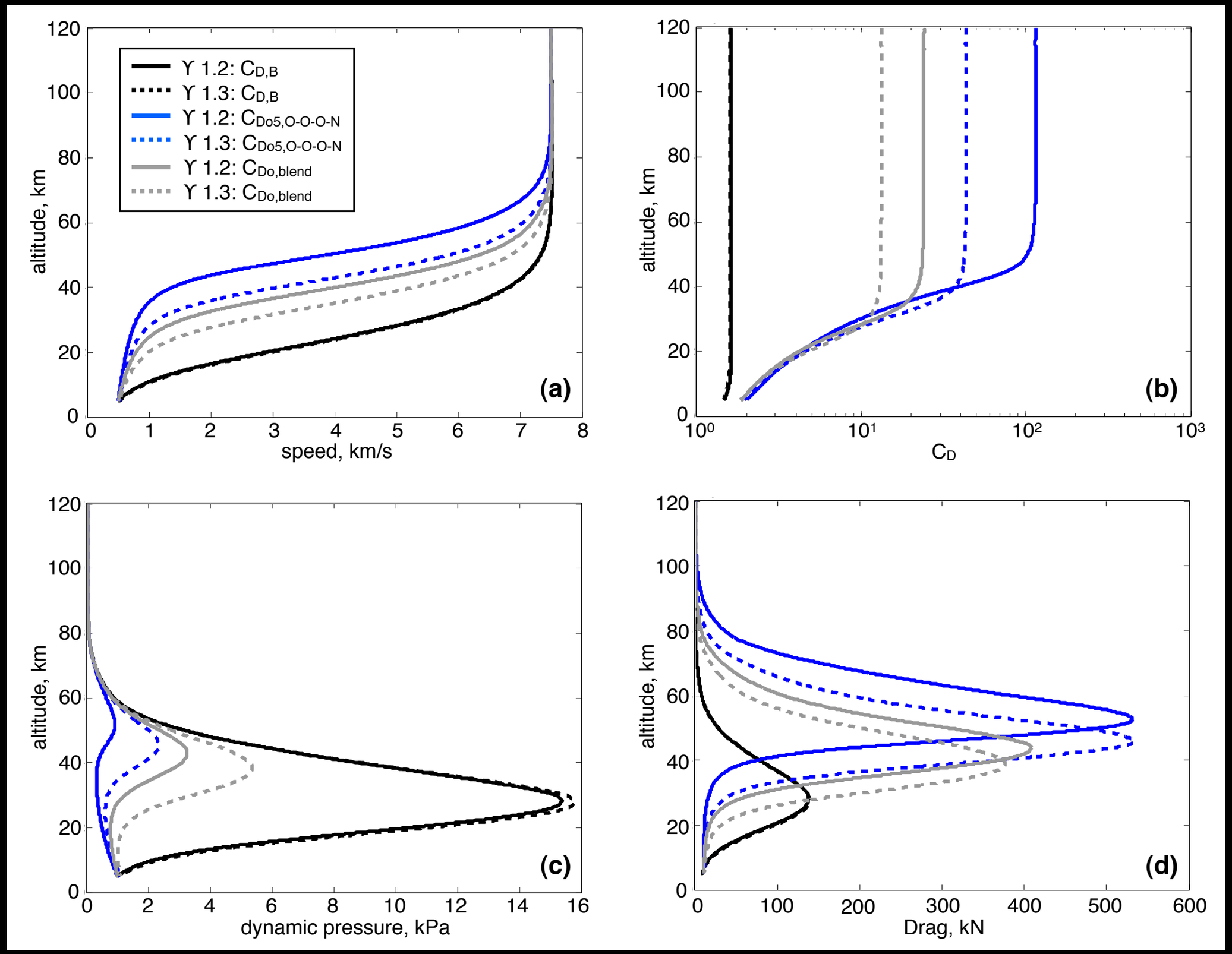
Results: O-O-N Detail



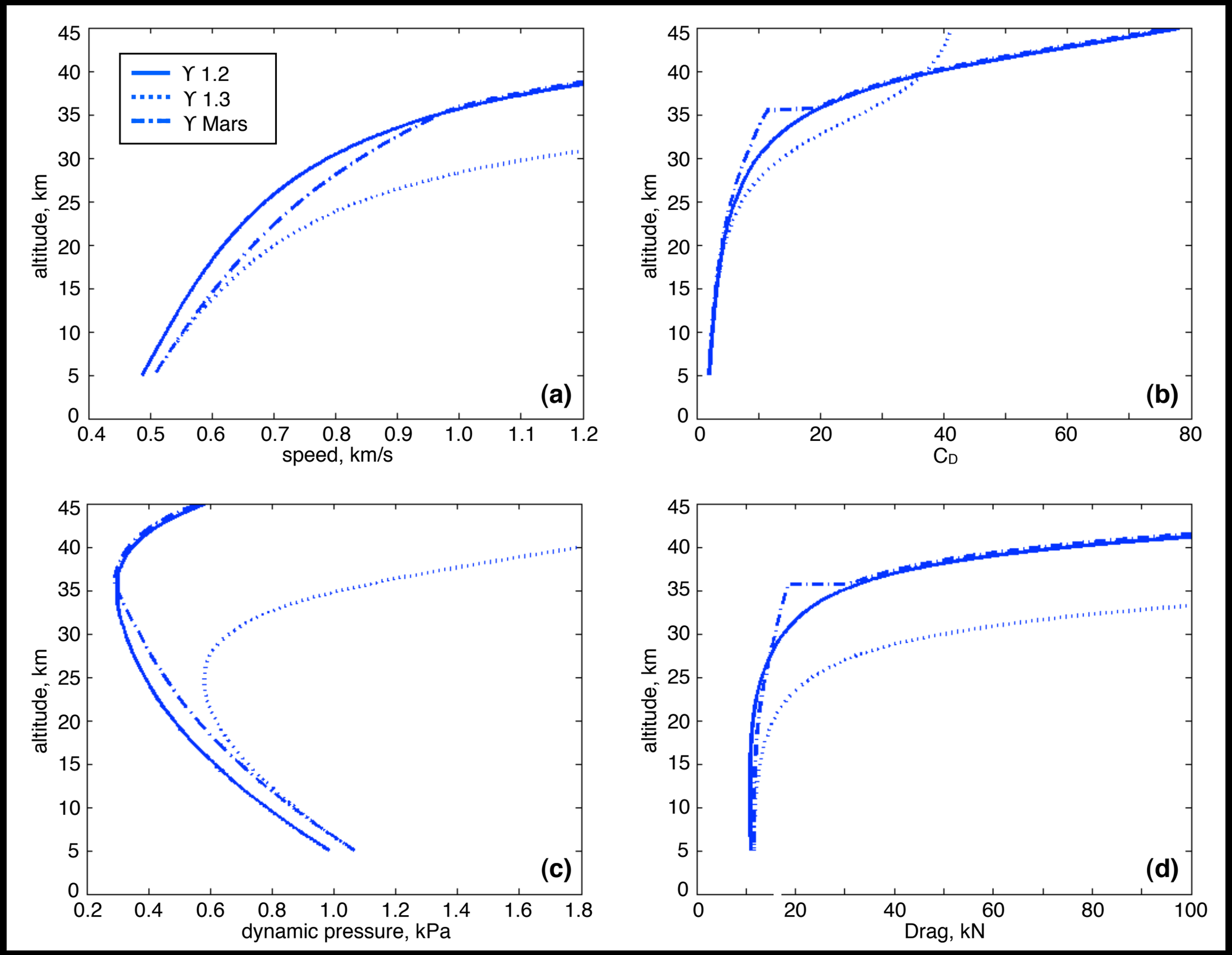
Results: All Shock Structures



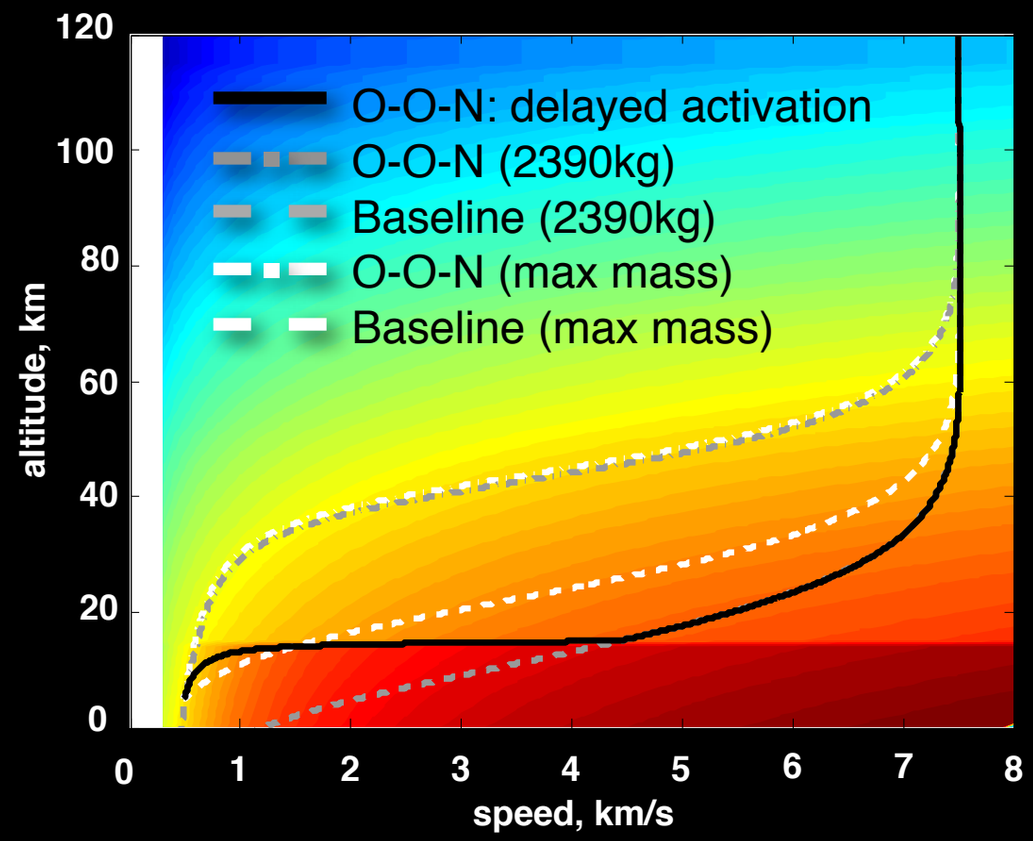
Results: ϒ Variation

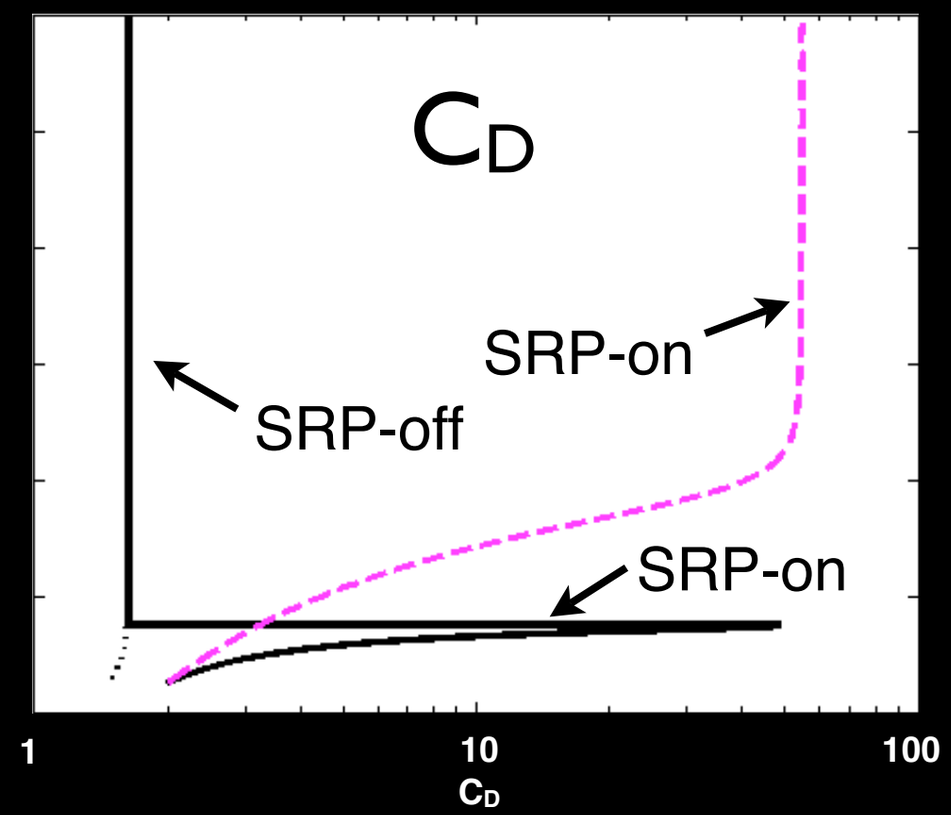


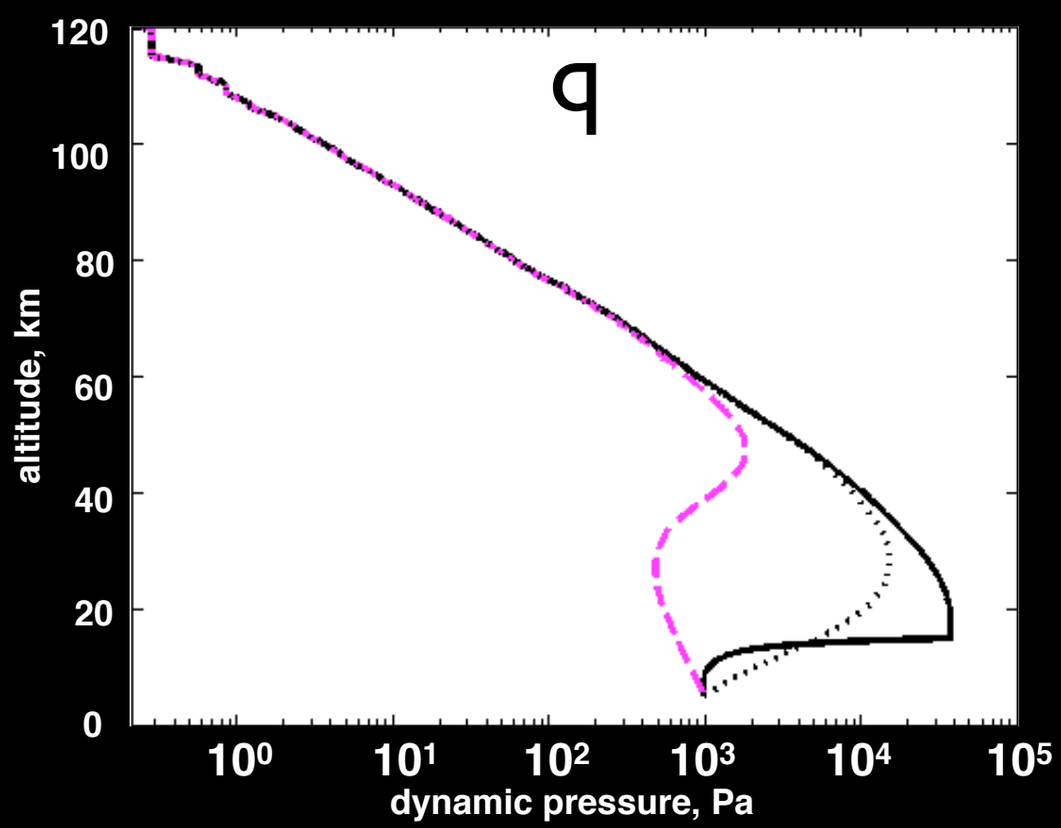
Results: Mars ϒ Model

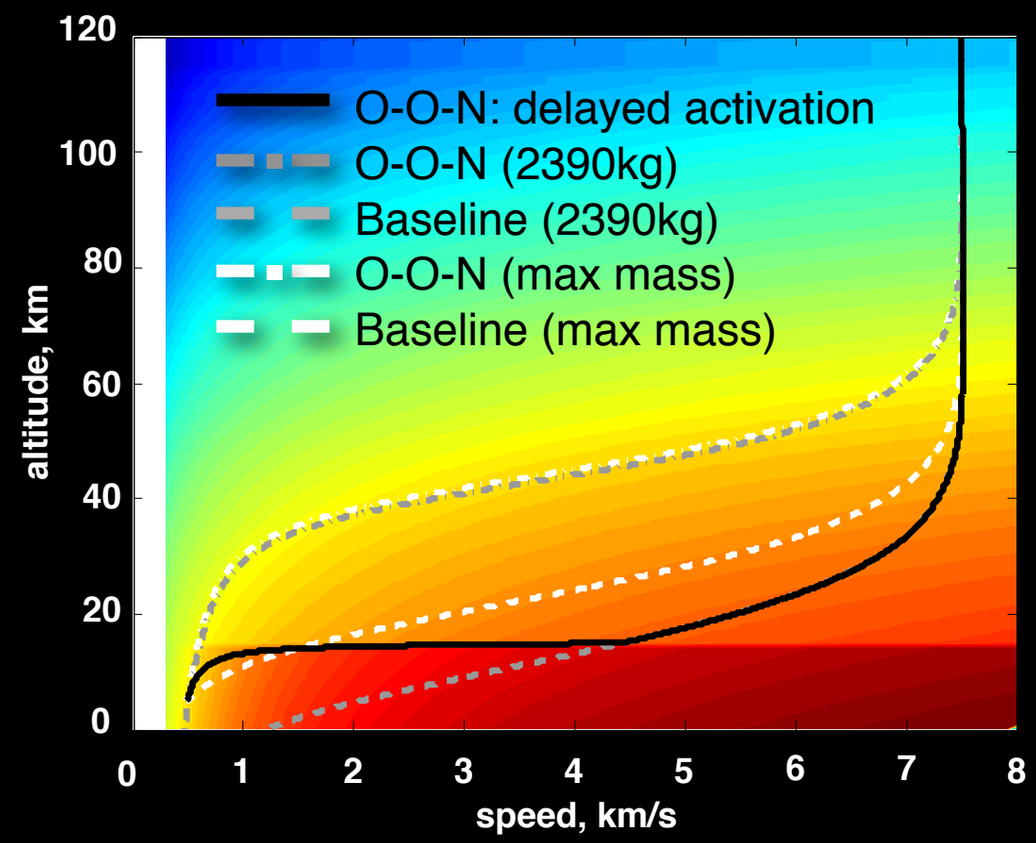
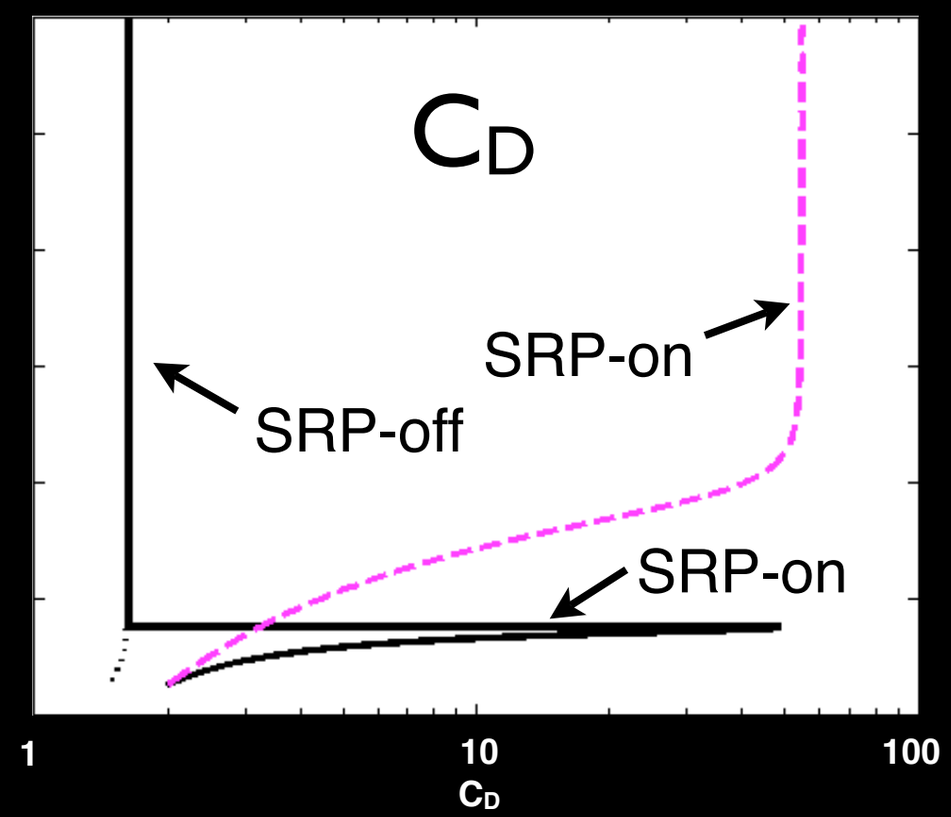
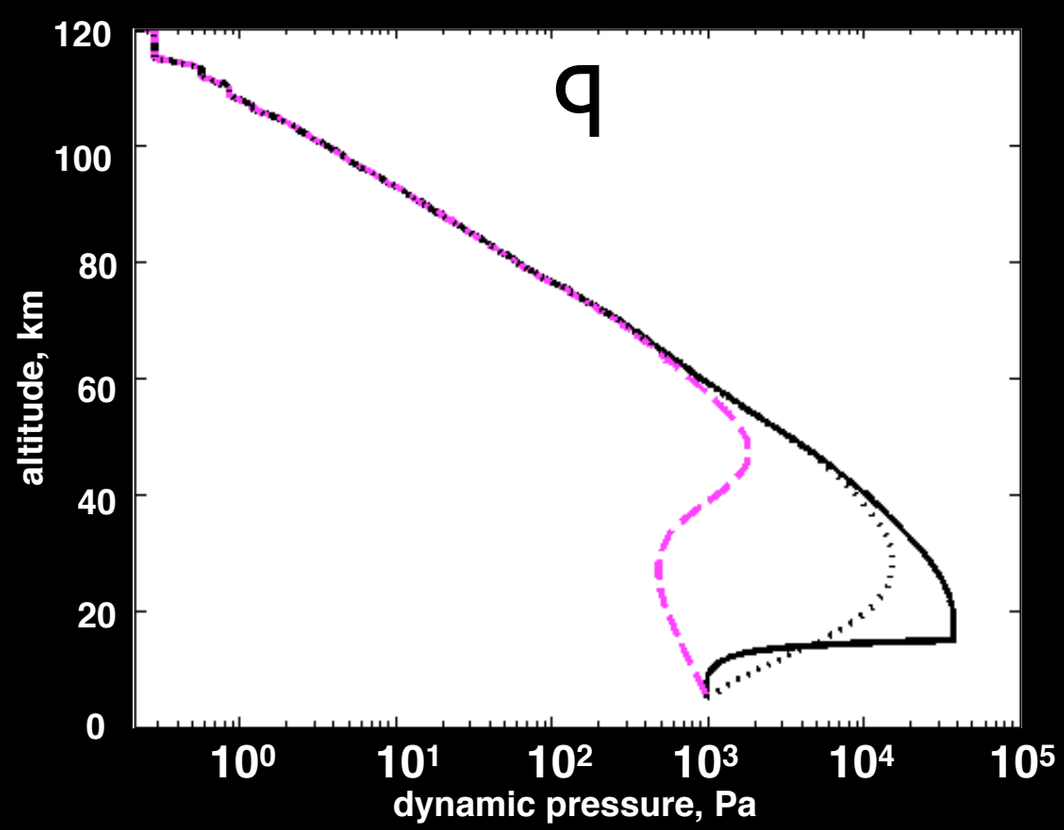
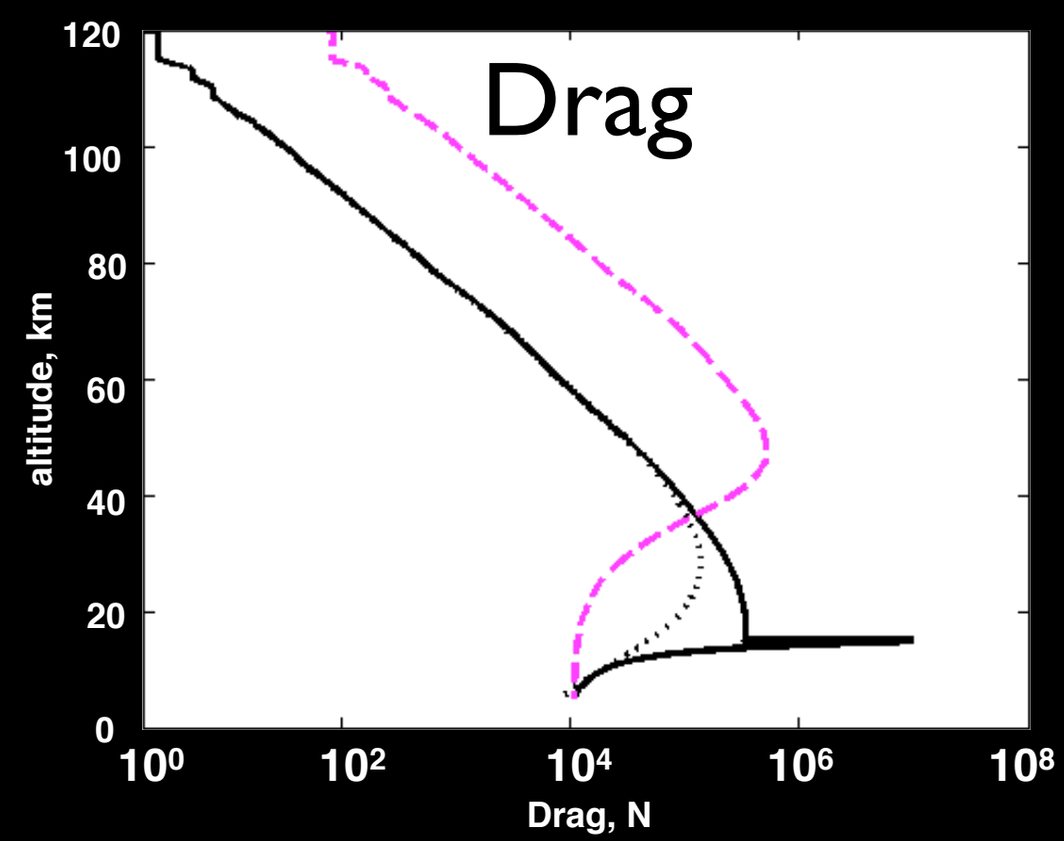


Strategy: Delayed Activation for Drag Modulation







O-O-N: delayed activation
O-O-N (max mass)
Baseline (max mass)

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