CubeSat (re-)entry can mean burning up in the atmosphere
Here, we discuss **surviving** atmospheric entry
We must model & understand **flight dynamics, aerodynamics, heating**

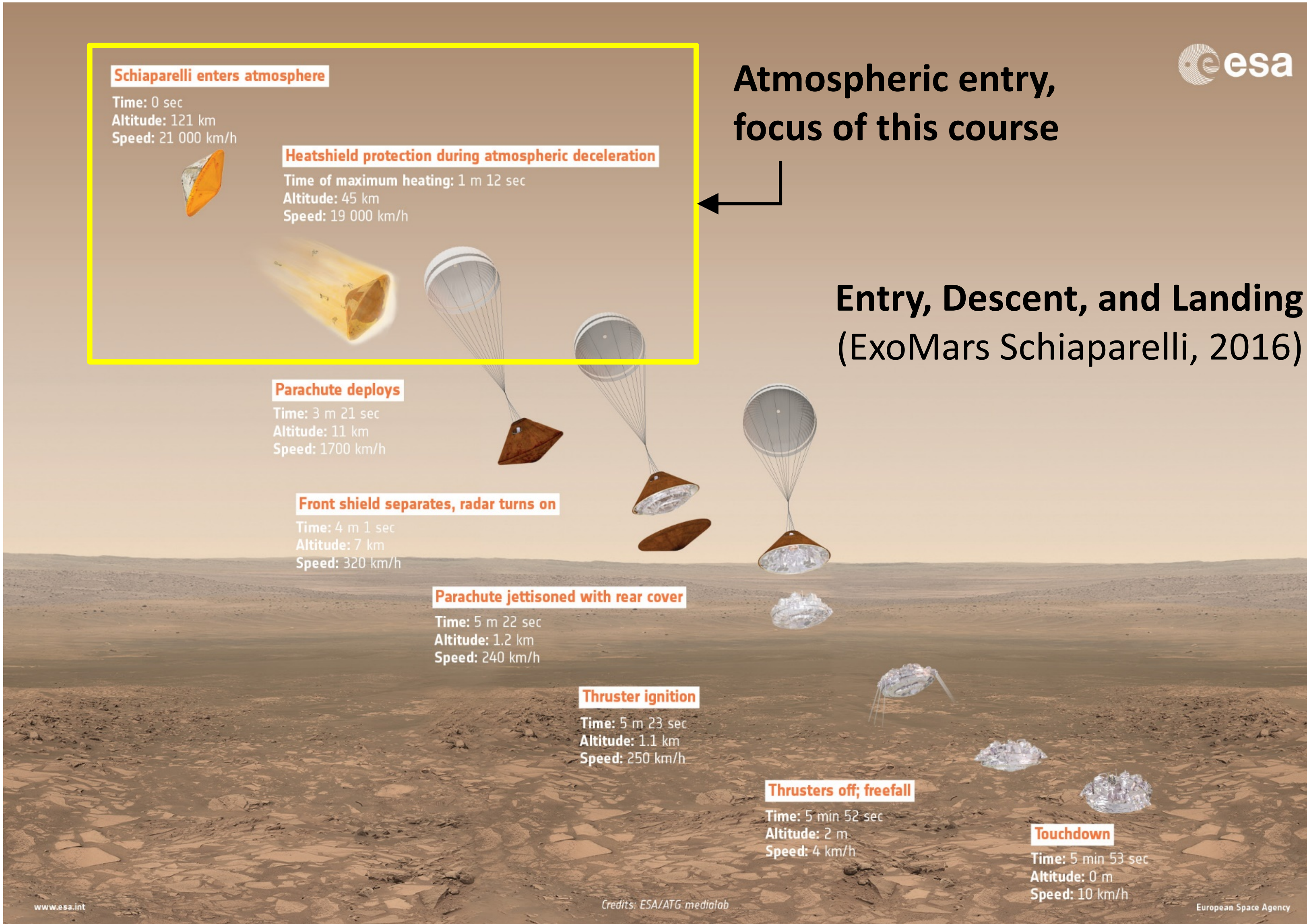
Motivation for CubeSat entry

- **Support larger entry vehicles** (e.g. Mars)
  - Atmospheric probe before EDL
  - Radio beacons on surface (navigation)
- **Explore planetary atmospheres** (e.g. Venus)
- Collect **aerothermodynamic flight data**
- **Surface science payload**

Challenges

EDL already risky: consequences of CubeSat **size, mass, form factor**
for trajectory conditions & flight dynamics?

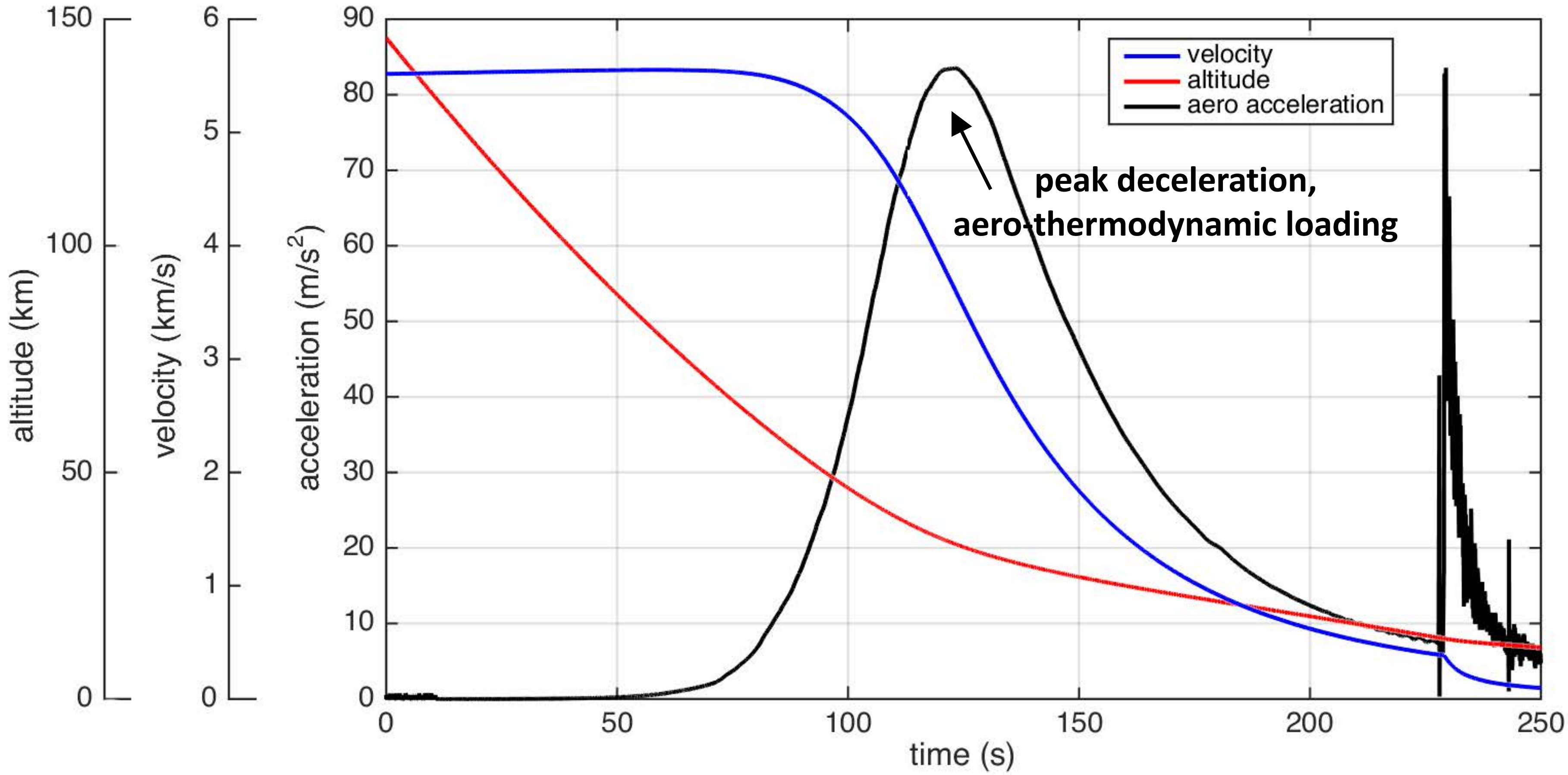
Small Entry Probe Trajectories for Mars



Atmospheric entry, focus of this course

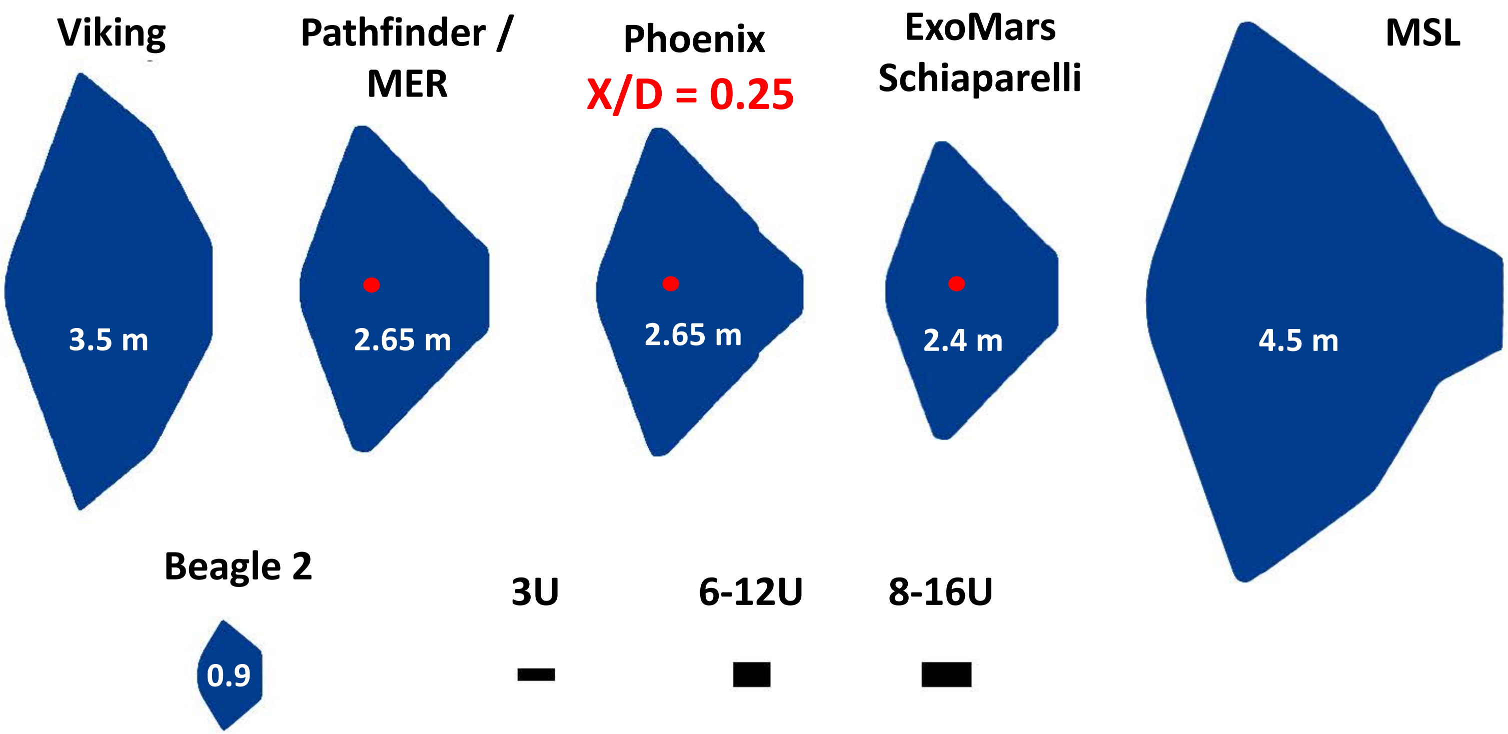
Entry, Descent, and Landing
(ExoMars Schiaparelli, 2016)

EDL example: Phoenix trajectory (2008)



Small Entry Probe Trajectories for Mars

How small are entry CubeSats?

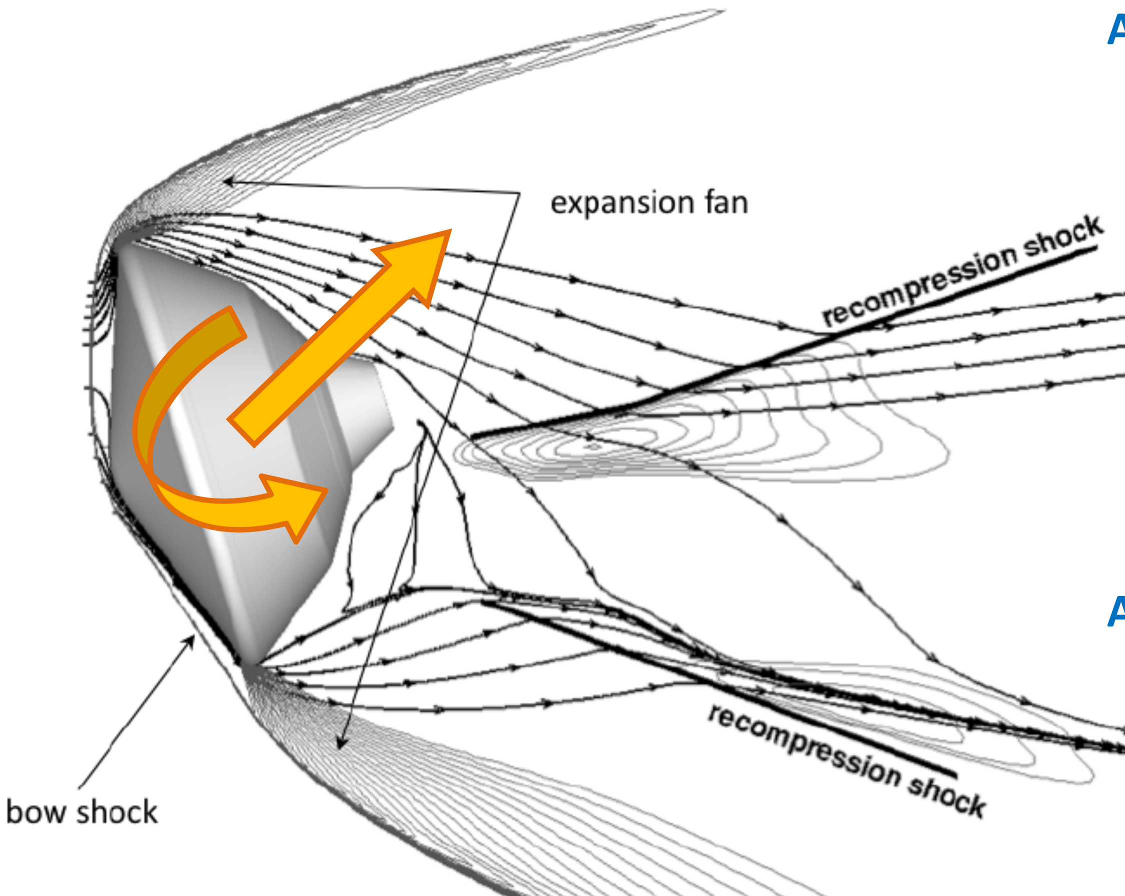


Mars entry aeroshells: blunt sphere-cone (70° half-angle)

- high drag + stable in hypersonic
- unstable in supersonic & transonic
- forward center-of-gravity (**CG**): typically X/D = 0.25 for ballistic (low AOA) flight

Small Entry Probe Trajectories for Mars

Aeroshell geometry → hypersonic/supersonic flow, aerodynamics, heating



2012 Dyakonov, et al.

Aerodynamic forces & moments

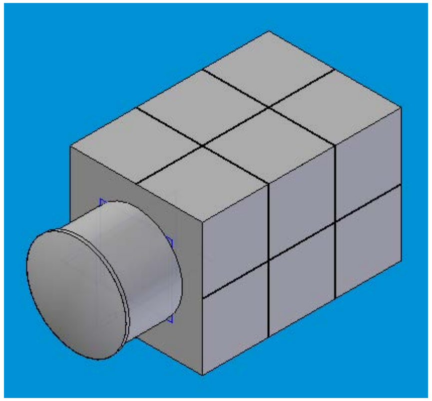
- cone angle, nose & shoulder radius always crucial
- Backshell flow becomes important in supersonic flight
- **Very complicated physics:** EQ/NEQ chemistry, radiation, boundary layer, material response…

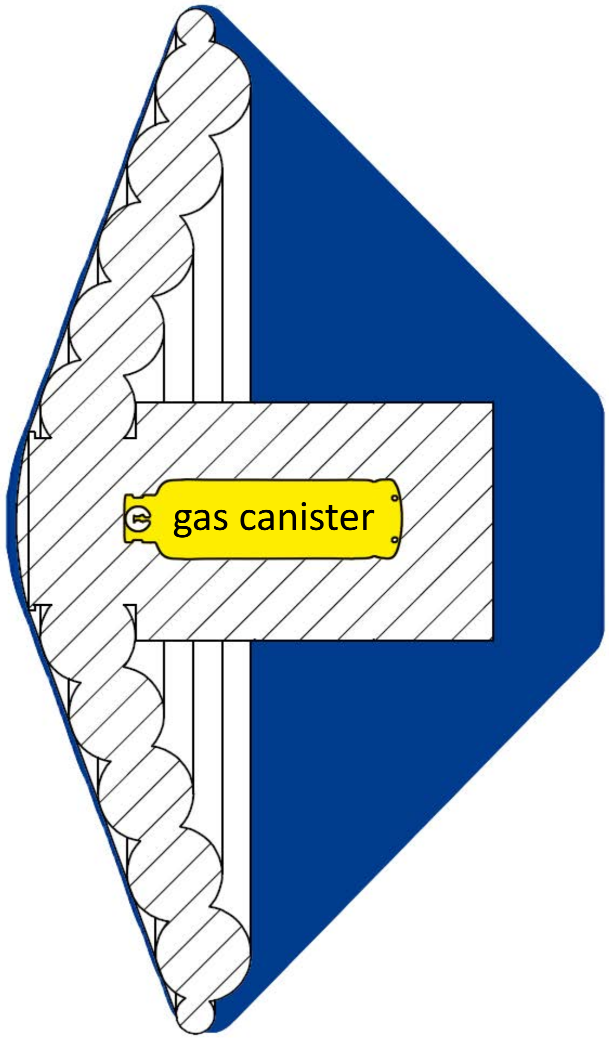
Attitude stability depends on

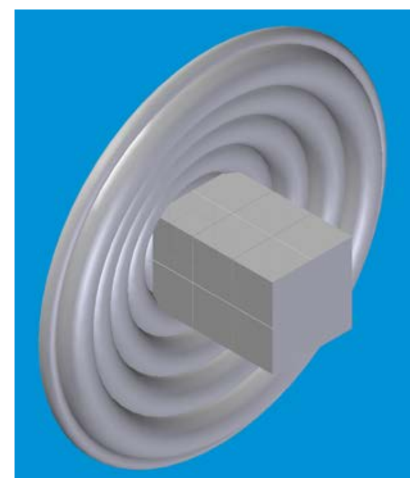
- Aerodynamic moments
- Mass distribution: forward CG improves stability

ROYAL OBSERVATORY OF BELGIUM

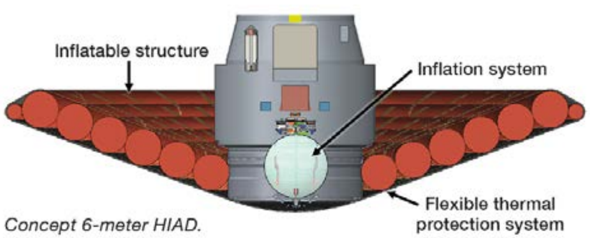
Let's imagine an entry CubeSat



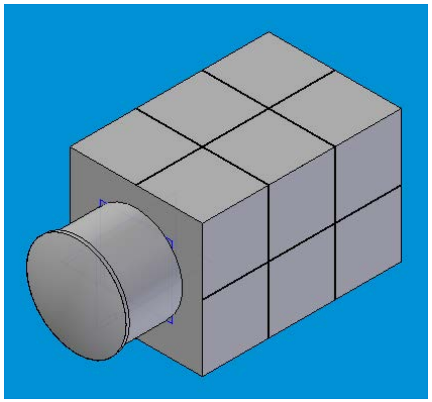


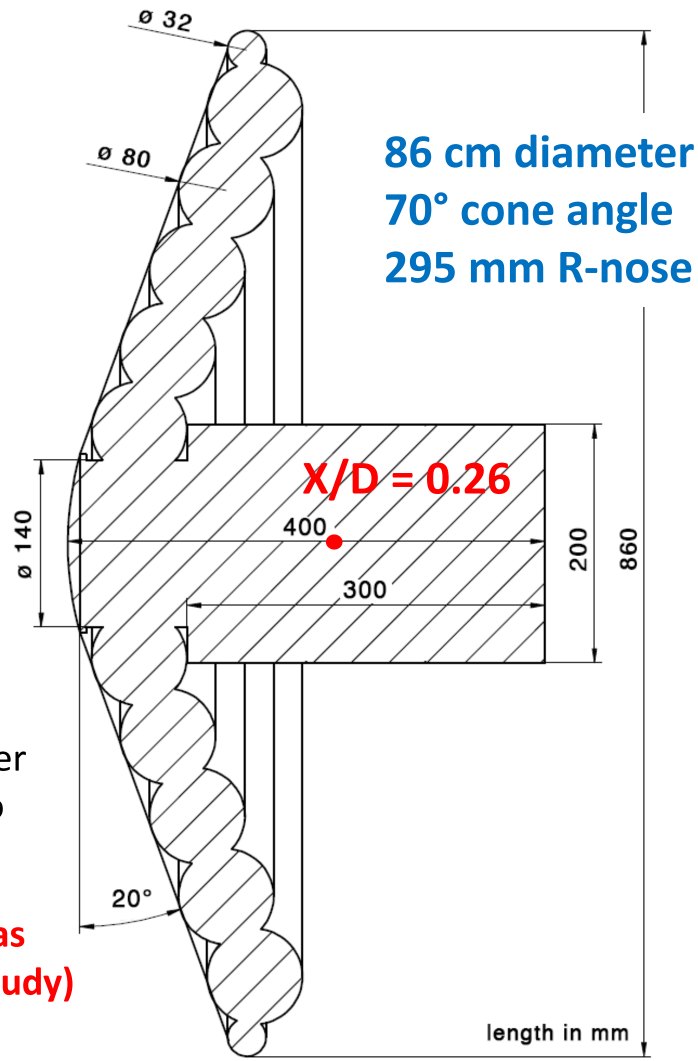


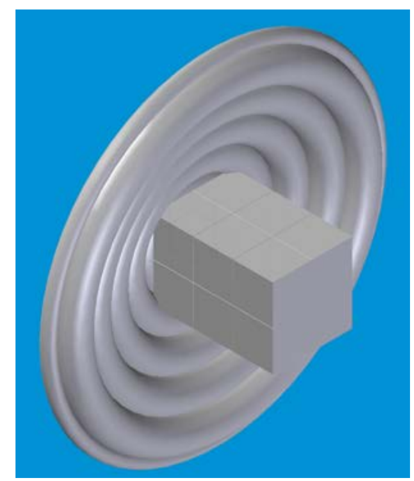
NASA HIAD design: see IPPW talks on Tuesday on HIAD, also ADEPT (deployable heat shield)



Let’s imagine an entry CubeSat





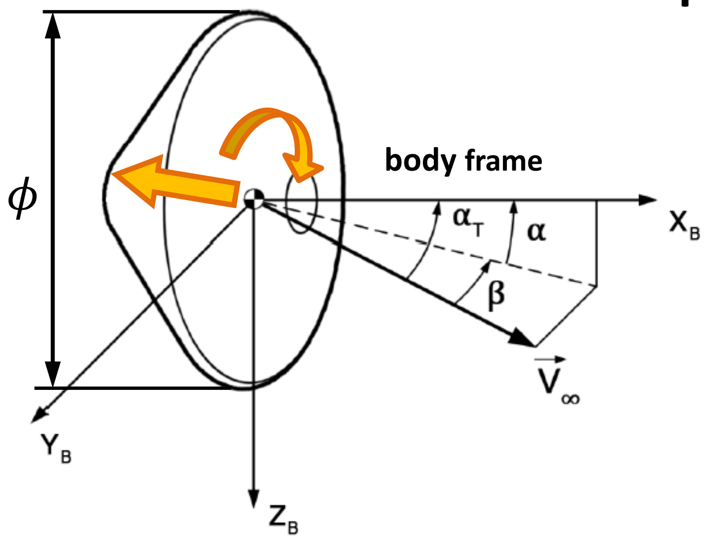


This gives us an aeroshell similar to historical missions, of which we have **aerodynamic models (e.g. Phoenix)**.

However no backshell here, remember importance in supersonic flight… Also **not rigid, but deformable aeroshell!**

→ use heritage aerodynamics only as 1st approximation (e.g. concept study)

Flight simulation



- Model **atmosphere / gravity / aerodynamics**
- Vehicle **mass distribution** (mass, GG, MOI)
- We desire state vectors $\{\boldsymbol{r} \quad \boldsymbol{V} \quad \boldsymbol{\omega} \quad \boldsymbol{q}\}^T$
- Equations of motion give state derivatives
- Numerical integration with Runge-Kutta 4th

<u>translation</u>

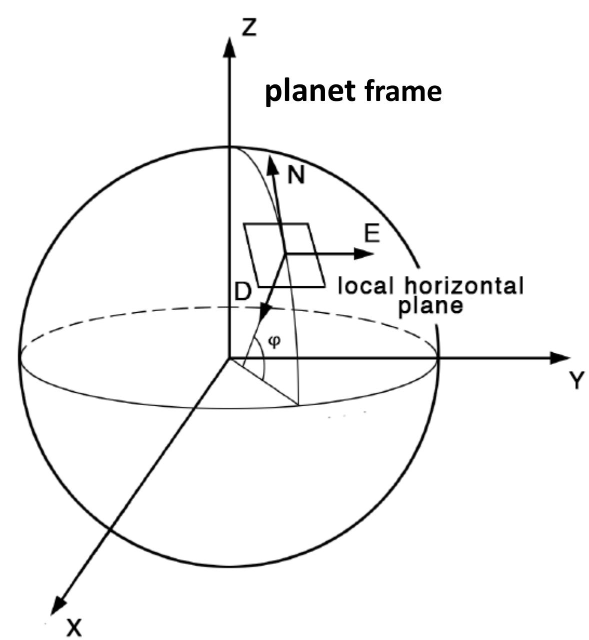
$$\dot{\boldsymbol{r}} = \boldsymbol{V}$$

$$\dot{\boldsymbol{V}} = \begin{Bmatrix} -C_A \\ +C_Y \\ -C_N \end{Bmatrix} \frac{\pi\phi^2}{4} 0.5\rho_\infty V_\infty^2 \frac{1}{m} + \boldsymbol{g}$$

<u>rotation</u>

$$\dot{\boldsymbol{q}} = f(\boldsymbol{q}, \boldsymbol{\omega})$$

$$I_B \dot{\boldsymbol{\omega}} = \begin{Bmatrix} C_l \\ C_m \\ C_n \end{Bmatrix} \phi \frac{\pi\phi^2}{4} 0.5\rho_\infty V_\infty^2 - \tilde{\omega} I_B \boldsymbol{\omega}$$



J. Cruz, Flight Mechanics (slides)
2004 R. F. Stengel, Flight Dynamics (book)
2010 P. Withers & D. Catling, Phoenix Reduced Data Records (report)

Simulation input: mass distribution

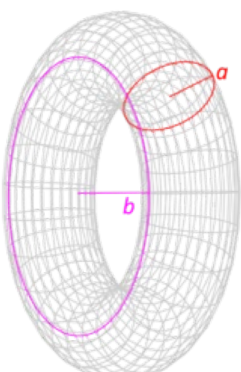
Assume mass per component:

- 12 kg body, 0.8 kg cylinder, 0.1 g/cm^2 per thorus (2x typical F-TPS areal weight)
- Compute MOI about centers of parts
- Compute CG of vehicle = $\sum \frac{r_i\, m_i}{m_{total}}$
- Transform MOI to CG location: parallel axis theorem $I_{new} = I_{old} + m_i * d^2$

Table 5. Flexible TPS Material Thicknesses, Areal Weight, and Maximum Use Temperatures

Material	Thickness (cm)	Areal Weight (g/cm^2)	Maximum Use Temperature (°C)
Nextel BF-20	0.0508	0.0505	1375
Nextel BF-10	0.0254	0.0265	1375
5 Harness Satin (26x26)	0.0506	0.0425	1800
8 Harness Satin (30x26)	0.0560	0.0431	1800
8 Harness Satin (26x34)	0.0620	0.0471	1800
8 Harness Satin (1.5 layer) (26x30)	0.0607	0.0443	1800
8 Harness Satin (1.5 layer) (26x34)	0.0604	0.0459	1800
8 Harness Satin (double cloth) (26x30)	0.0586	0.0428	1800
8 Harness Satin (double cloth) (26x34)	0.0608	0.0462	1800
12 Harness Satin (2.5 d) (40x40)	0.1142	0.0628	1800

2011 J. A. Del Corso, et al. - Advanced High-Temperature Flexible TPS for HIADs



	length-x	length-y	length-z	radius a	radius b	areal mass	area	mass	mass: with margin (x2)
	(m)	(m)	(m)	(m)	(m)	(g/cm2)	(cm2)	(g)	(g)
torus 1 (inner)				0.040	0.0958	0.05	1512.8	75.6	151.28
torus 2				0.040	0.1618	0.05	2555.0	127.8	255.50
torus 3				0.040	0.2285	0.05	3608.3	180.4	360.83
torus 4				0.040	0.2962	0.05	4677.4	233.9	467.74
torus 5				0.040	0.3634	0.05	5738.6	286.9	573.86
torus 6 (outer)				0.016	0.4142	0.05	2616.3	130.8	261.63
cylinder	0.100				0.0700				800.00
body (12U CubeSat)	0.300	0.200	0.200						12000.00

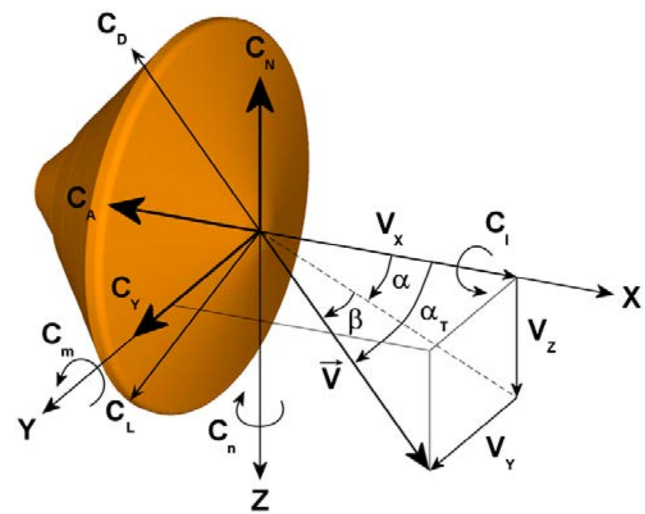
→ moments of inertia & CG in body frame:

272.80	281.97	281.97	g*m2
222.00	0.00	0.00	mm

Simulation input: aerodynamics & atmosphere

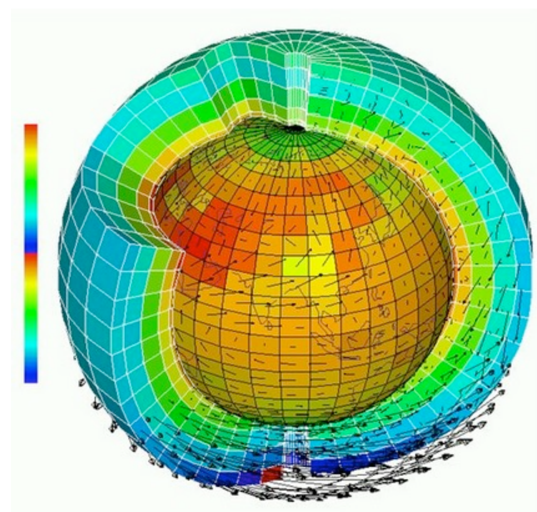
Phoenix aerodynamic database

- Described in Edquist et al., 2008
- Drag, static, dynamic moments as function of Mach number & attitude
- Should be good approximation for inflatable with low deformation
- Much worse model in supersonic flight (no backshell)

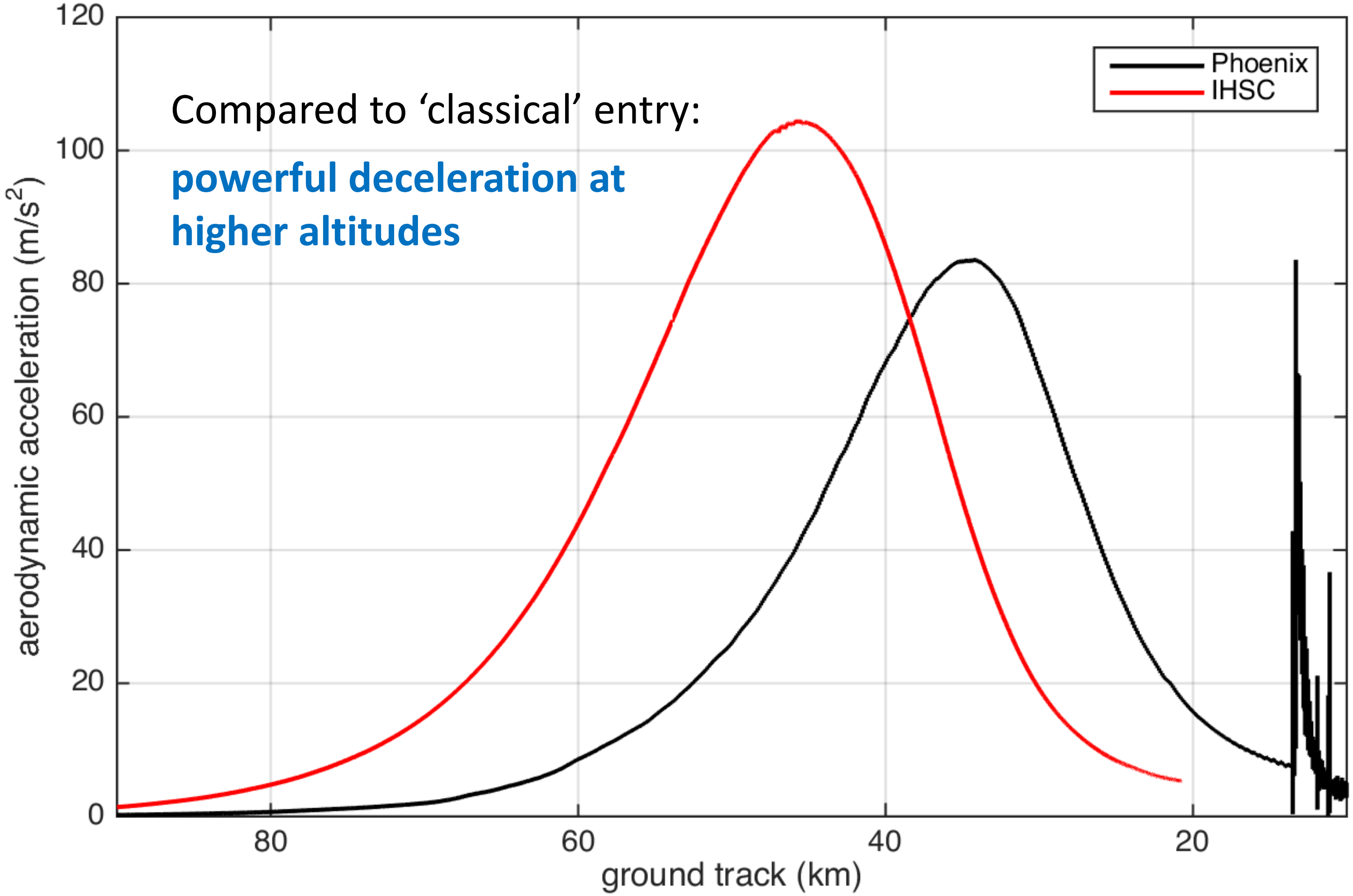


Atmospheric model

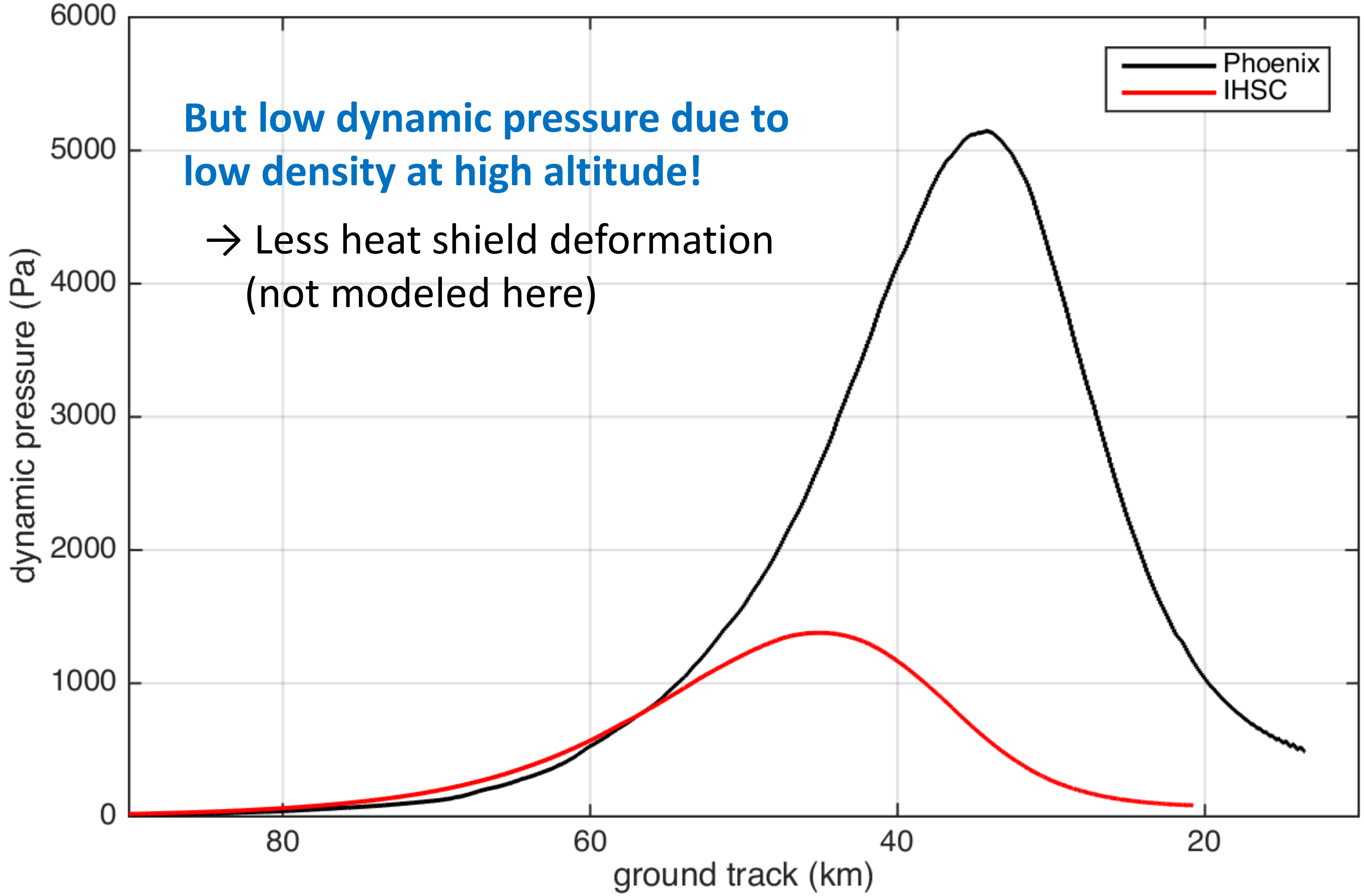
- Density, pressure, temperature as function of altitude
- From Mars Climate Database (GCM)



vs. Phoenix: acceleration profile



vs. Phoenix: dynamic pressure

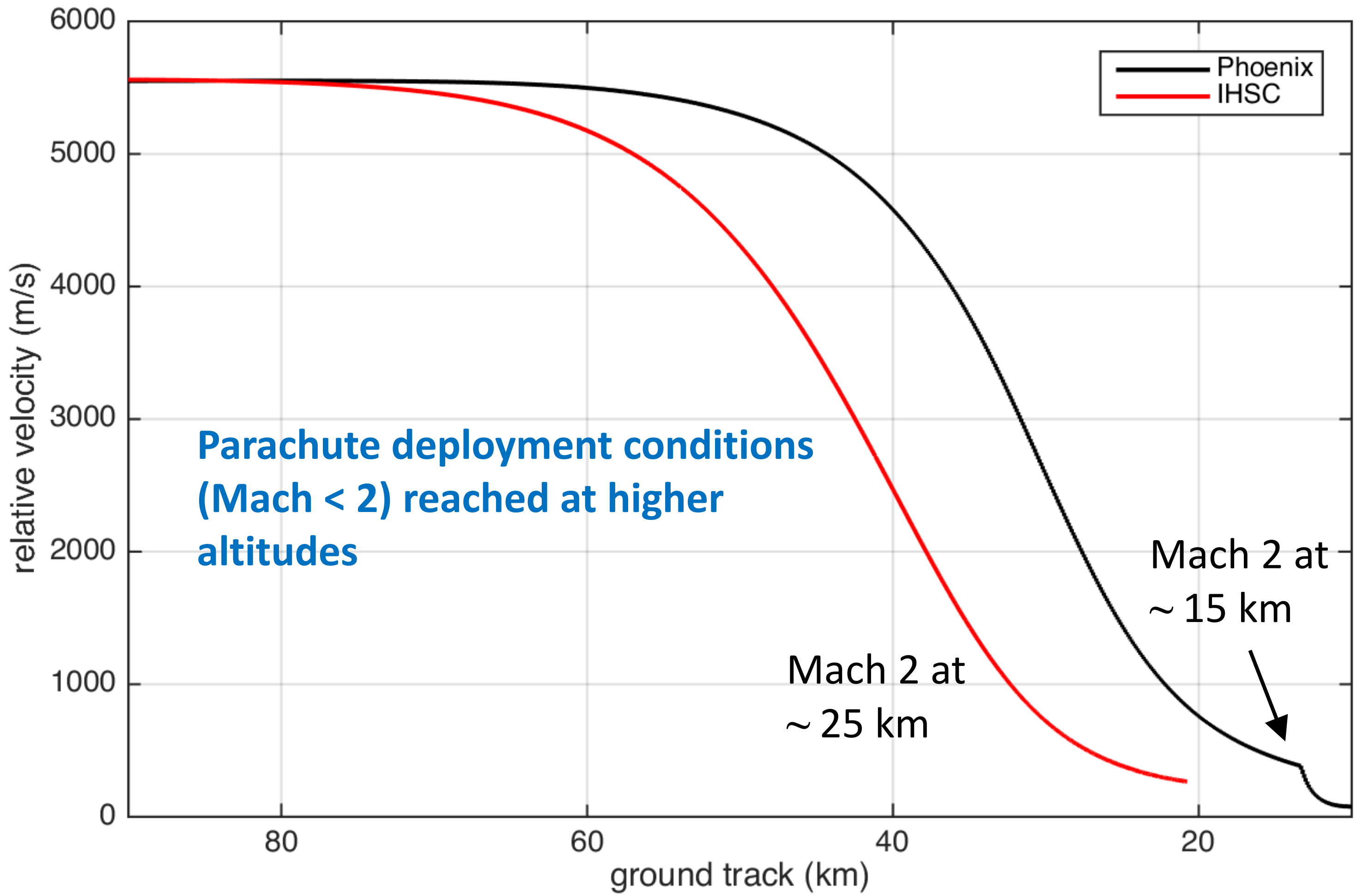


But low dynamic pressure due to low density at high altitude!

→ Less heat shield deformation (not modeled here)

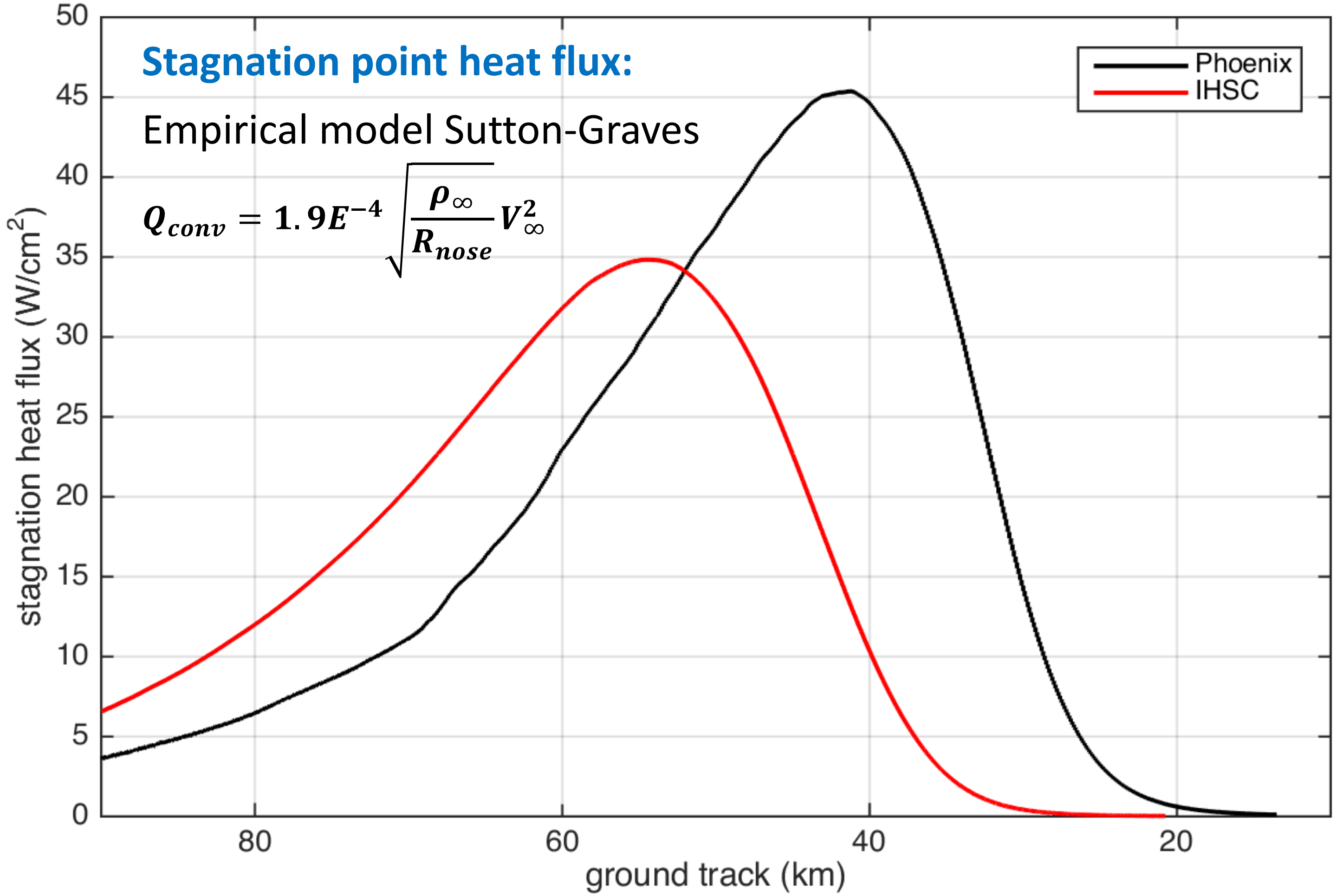
Small Entry Probe Trajectories for Mars

vs. Phoenix: atmosphere relative velocity

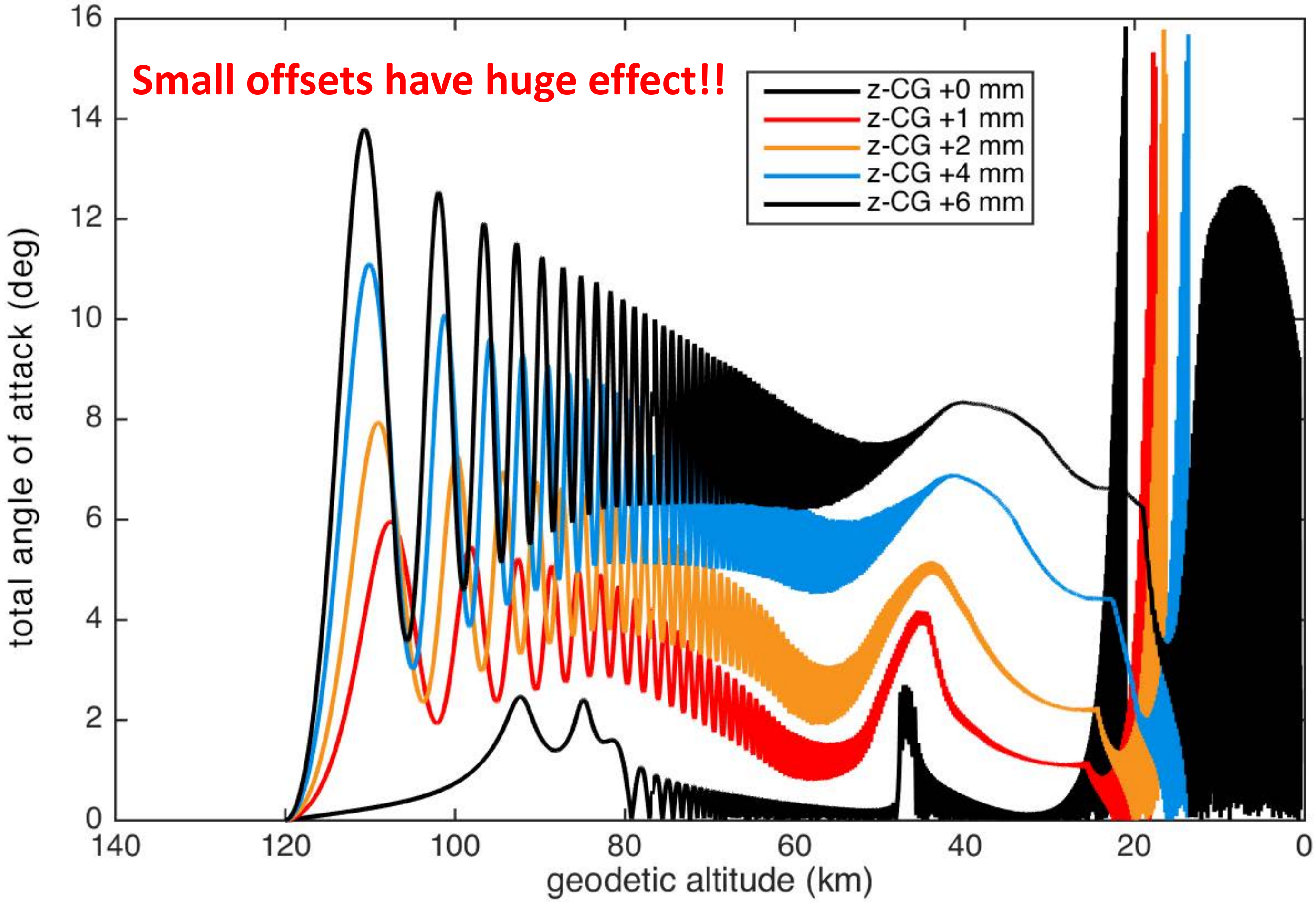


Small Entry Probe Trajectories for Mars

vs. Phoenix: heat flux at stagnation point



total angle of attack: sensitivity to off-center CG position



Conclusions

- Flight simulation is a very important tool, but depends on variety of models: so **garbage in = garbage out!**
- Given some assumptions (mass, Phoenix aerodynamics & entry state), the CubeSat performs atmospheric entry with **low ballistic coefficient**
- Results in favorable peak heat flux, acceleration at high altitude, parachute deployment (if any) at high altitude (more time for subsequent mission phases)

- Inflatable heat shields can increase performance (e.g. mass) of large missions, by lowering the ballistic coefficient
- For CubeSats they are more of a requirement: to **protect & stabilize the vehicle**
- Alternative concepts certainly exist: deployable heat shields (see ADEPT) or no large heat shield at all (see QARMAN)