Missile threats

Cruise missiles:

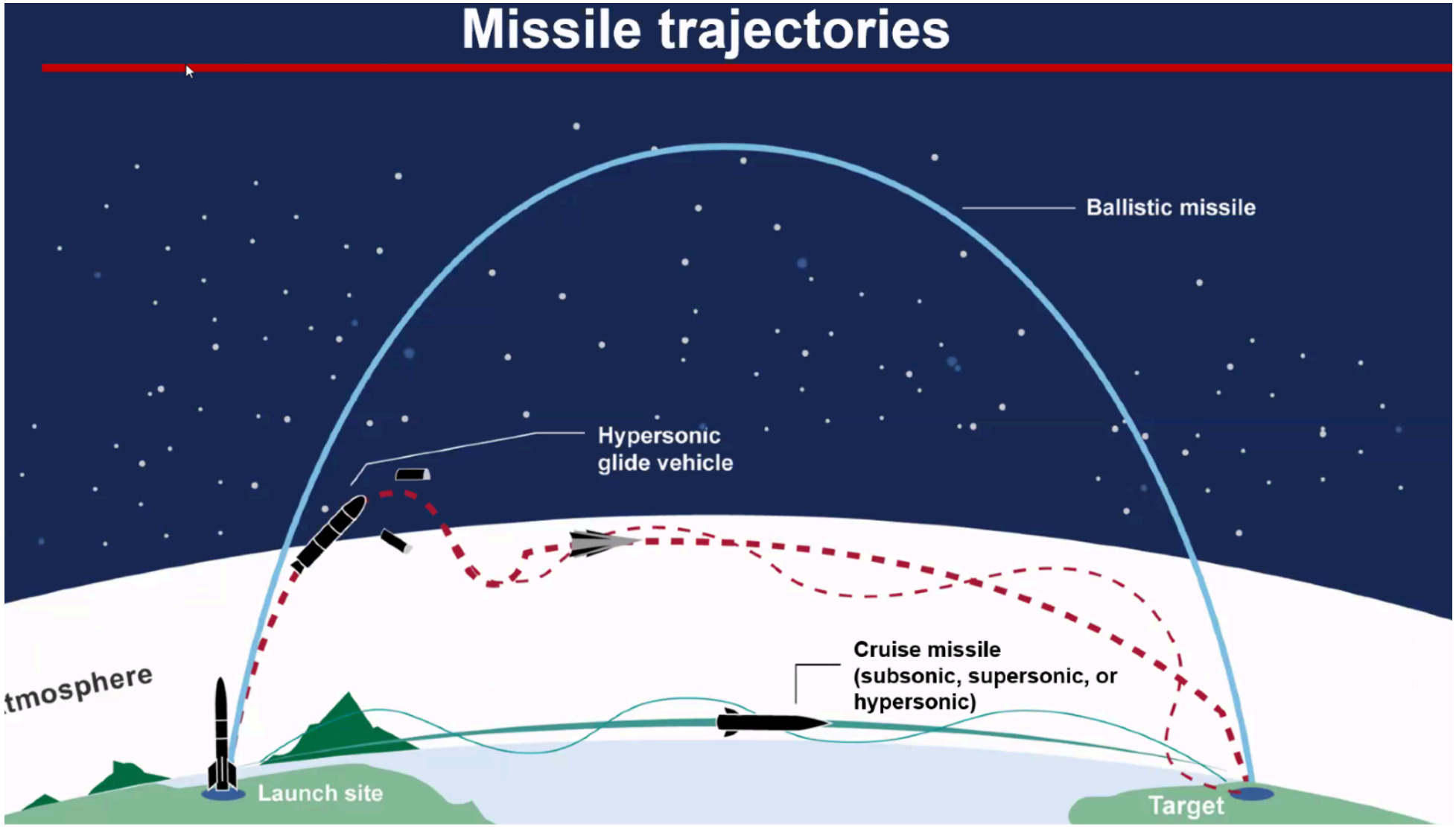
- Powered flight, carrying their engines with them
- Analogous to an uncrewed airplane
- Relatively slow but highly maneuverable

Ballistic missiles:

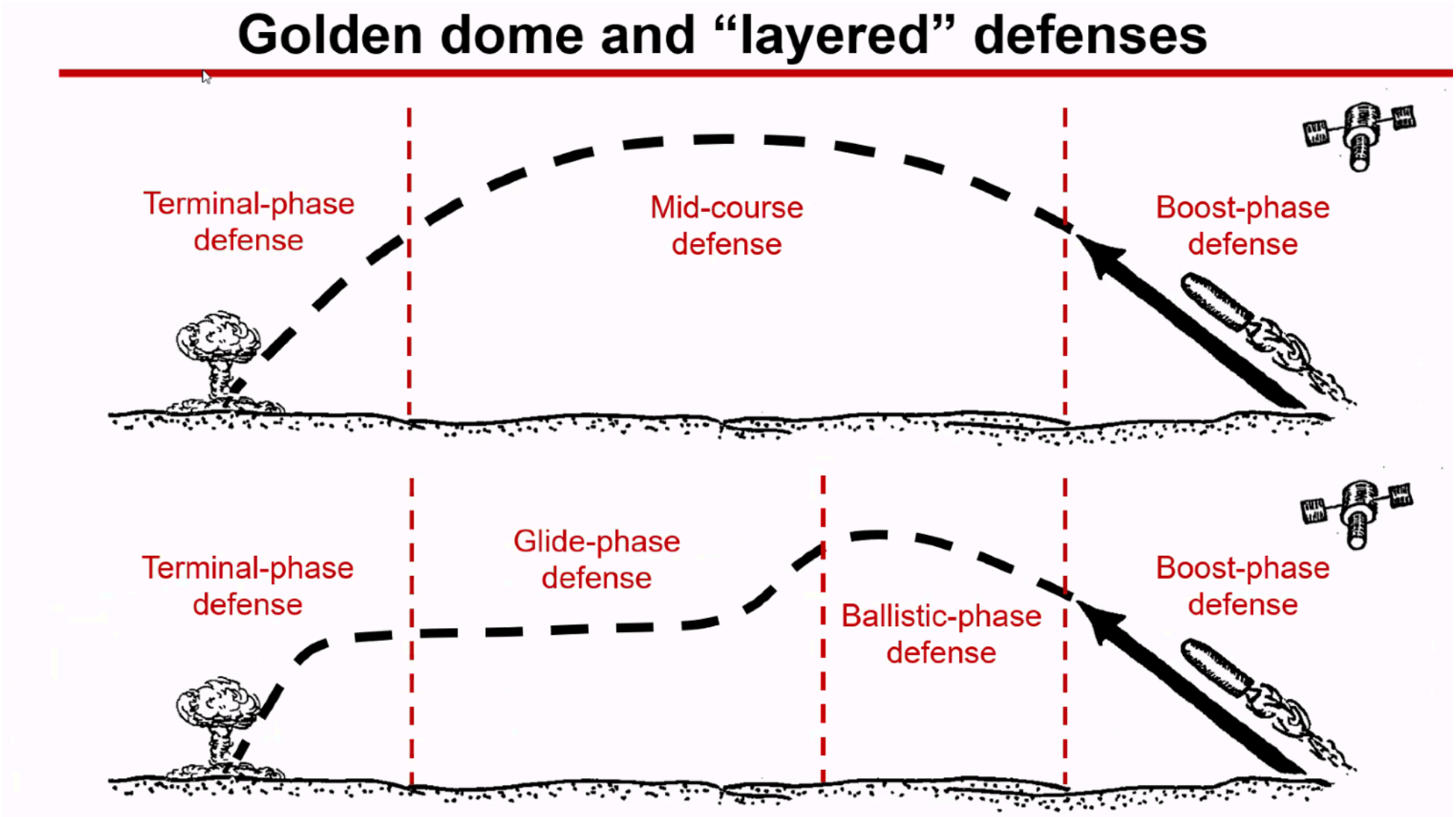
- Unpowered after rocket burn-out
- Analogous to a space launch vehicle
- Fast, but much less maneuverable

Hypersonic glide missiles:

- Ballistic missiles equipped with gliders
- Ballistic trajectory followed by atmospheric glide
- Intermediate speed and maneuverability

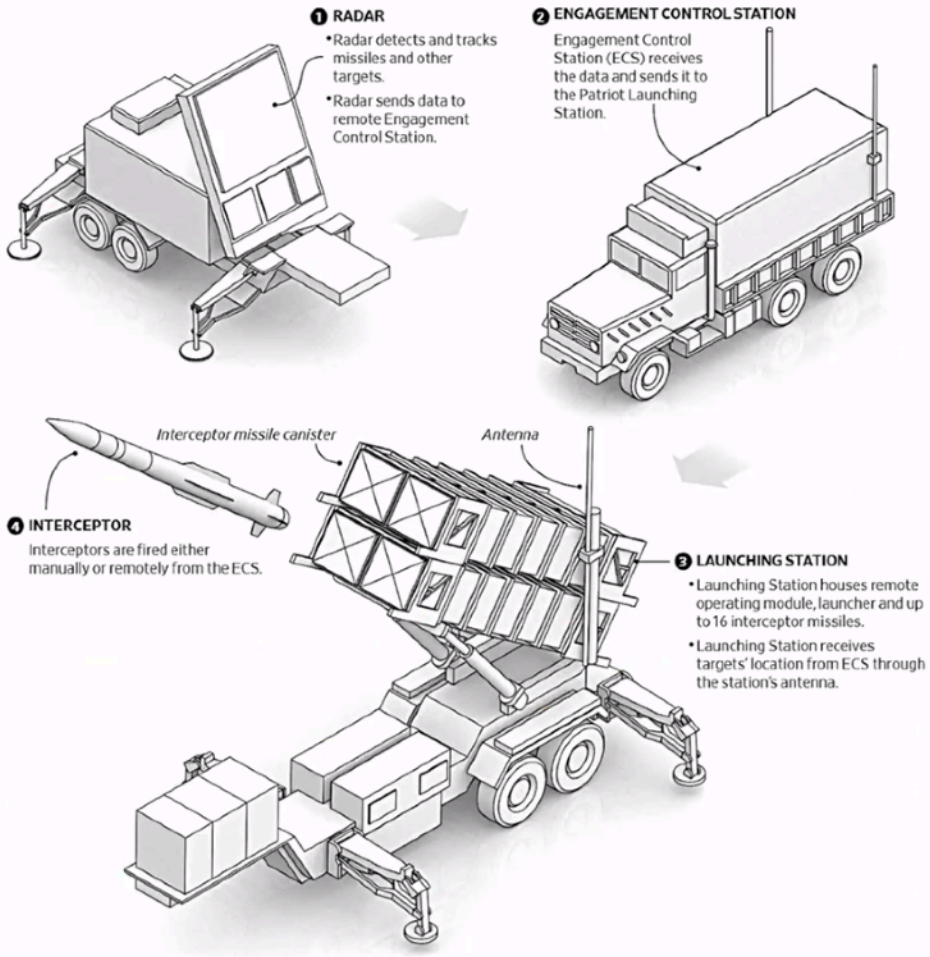

Missile trajectories
Ballistic missile
Hypersonic
glide vehicle
tmosphere
Cruise missile
(subsonic, supersonic, or
hypersonic)
Launch site
Target

Golden dome and “layered” defenses



Terminal-phase defense

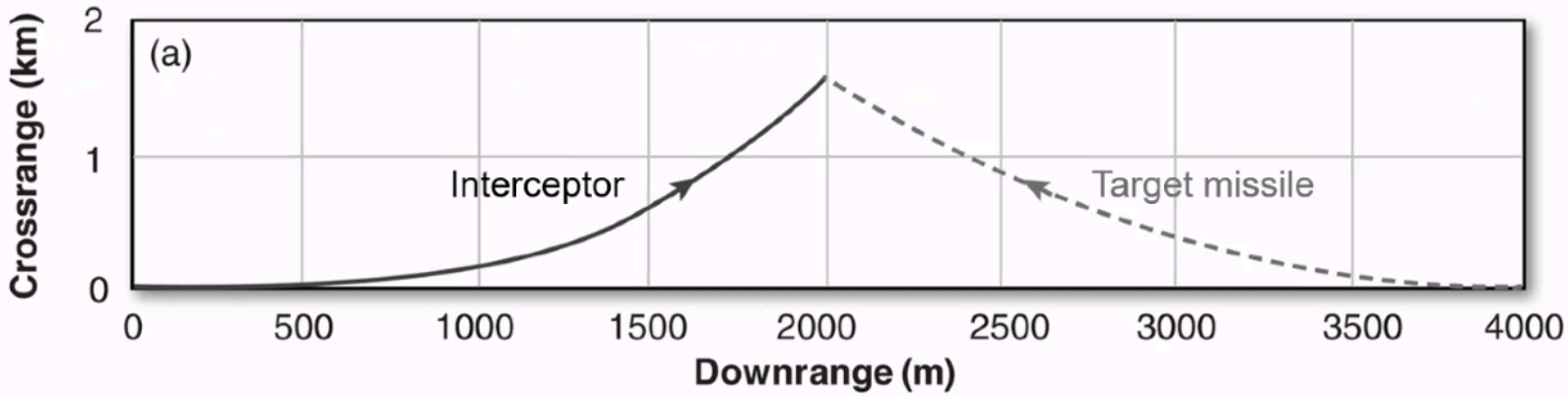
- Interception of a missile as it approaches its target, in the final minutes of flight
- Allows for the use of short-range interceptors, without any need for forward deployment
- Defends only a small area near the defensive system
- **US systems:** MIM-104 Patriot (shown right), Terminal High Altitude Area Defense (THAAD)



Intercepting a maneuverable threat

The challenge:

- **Jinking:** rapid, lateral acceleration by a missile to fly around an incoming interceptor.



Intercepting a maneuverable threat

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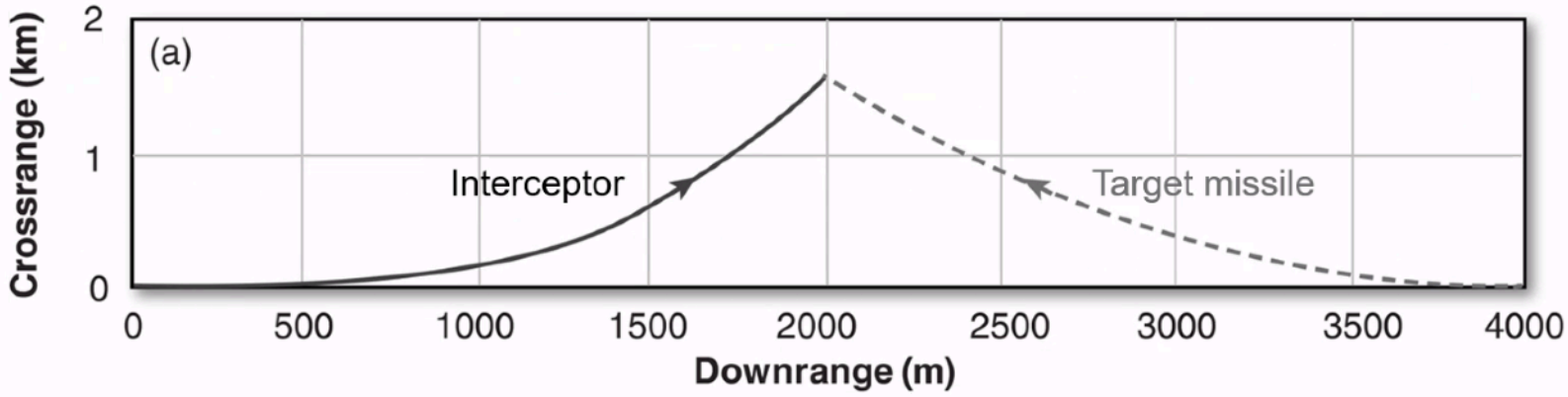
The solution:

- **Proportional navigation:** interceptor maneuvers to match those of the target missile.
- "Proportional navigation requires three times the acceleration of the target to effect an intercept; hence, the well-known **3-to-1 ratio** rule of thumb." – Palumbo et al., *APL Tech. Digest* (2010)



Intercepting a maneuverable threat

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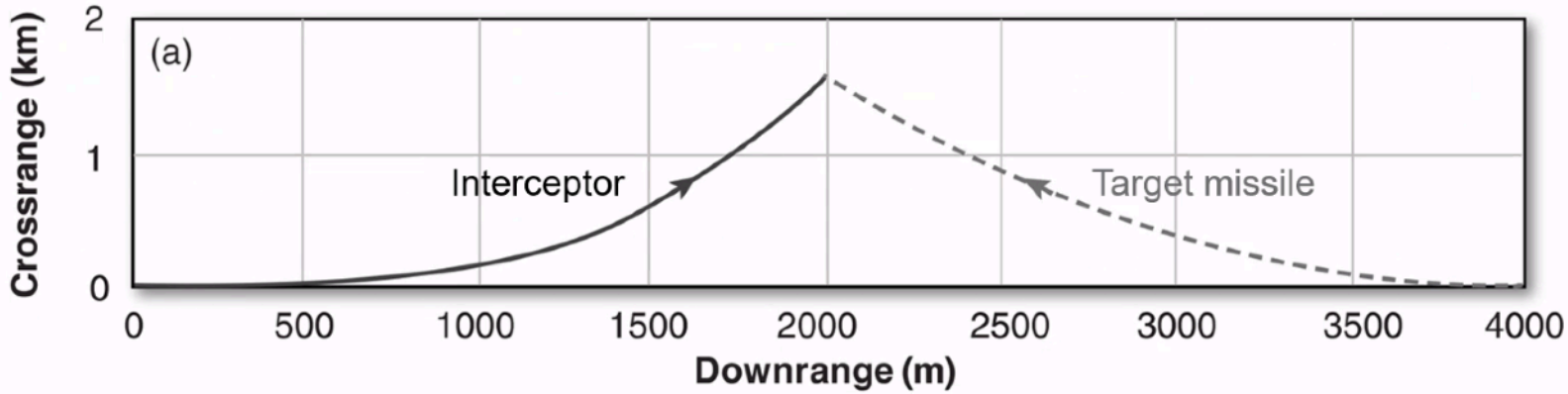
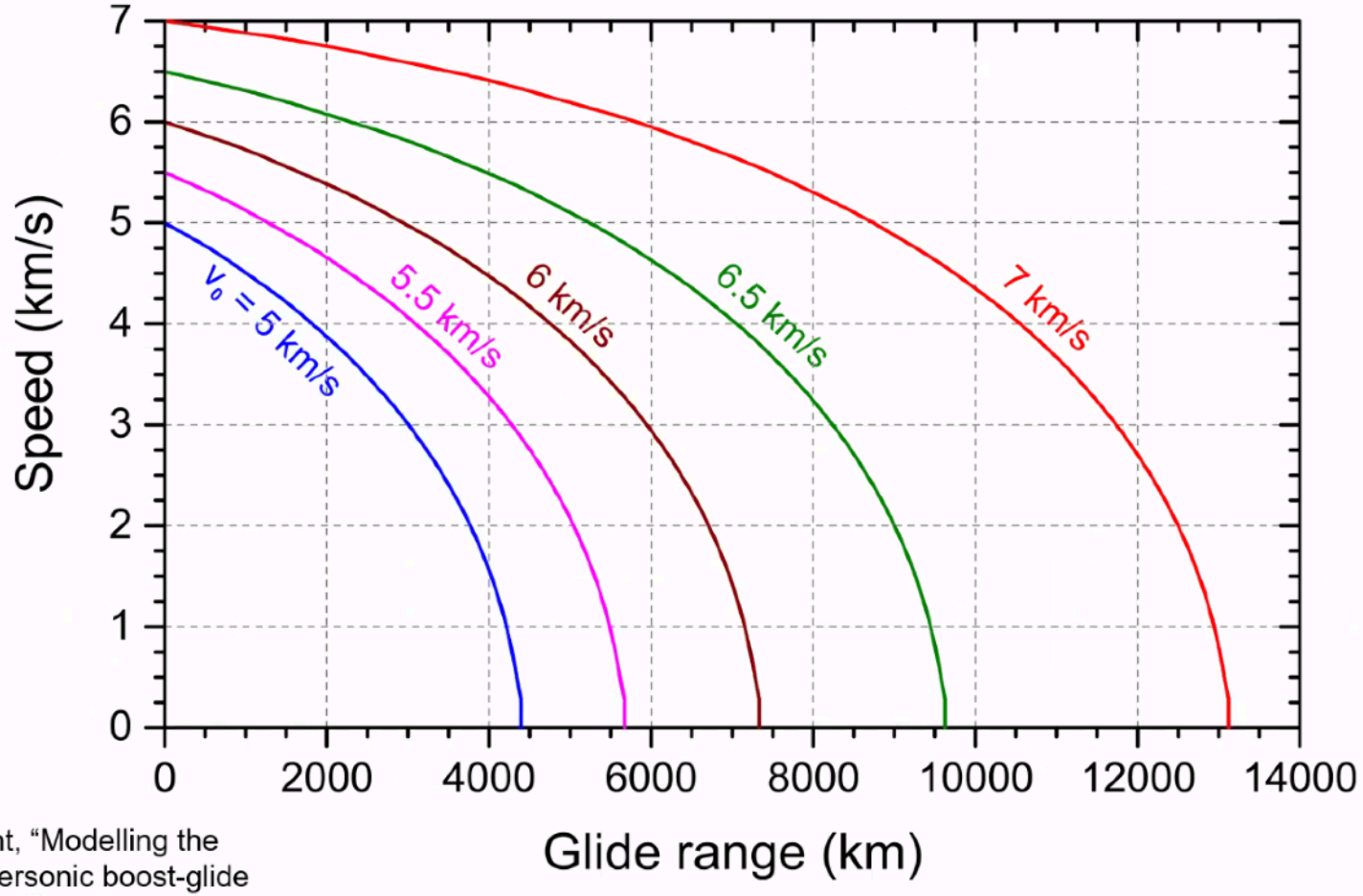
$$\frac{a_{target}}{a_{int}} = \left(\frac{m_{int}}{m_{target}}\right)\left(\frac{(C_L A)_{target}}{(C_L A)_{int}}\right)\left(\frac{V_{target}}{V_{int}}\right)^2$$

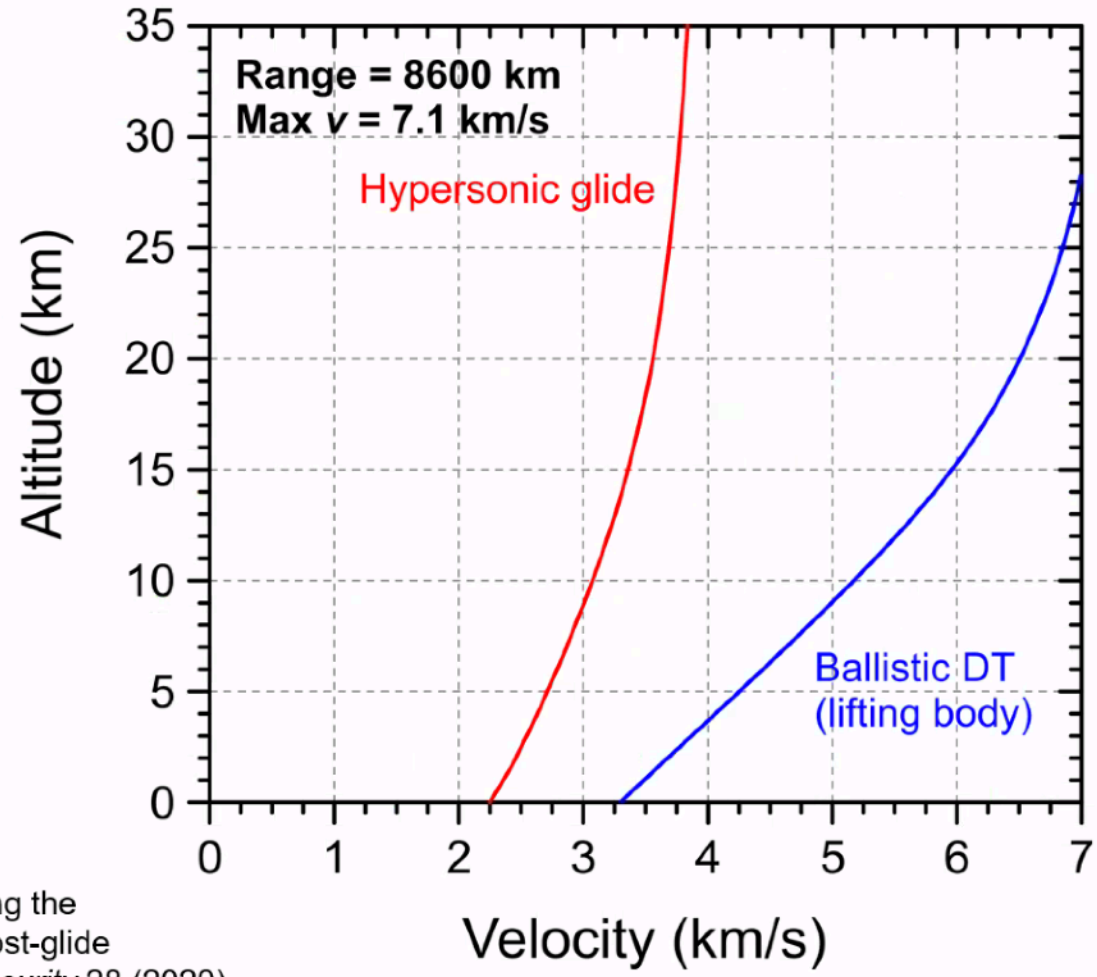


Drag slows hypersonic missile flight during glide



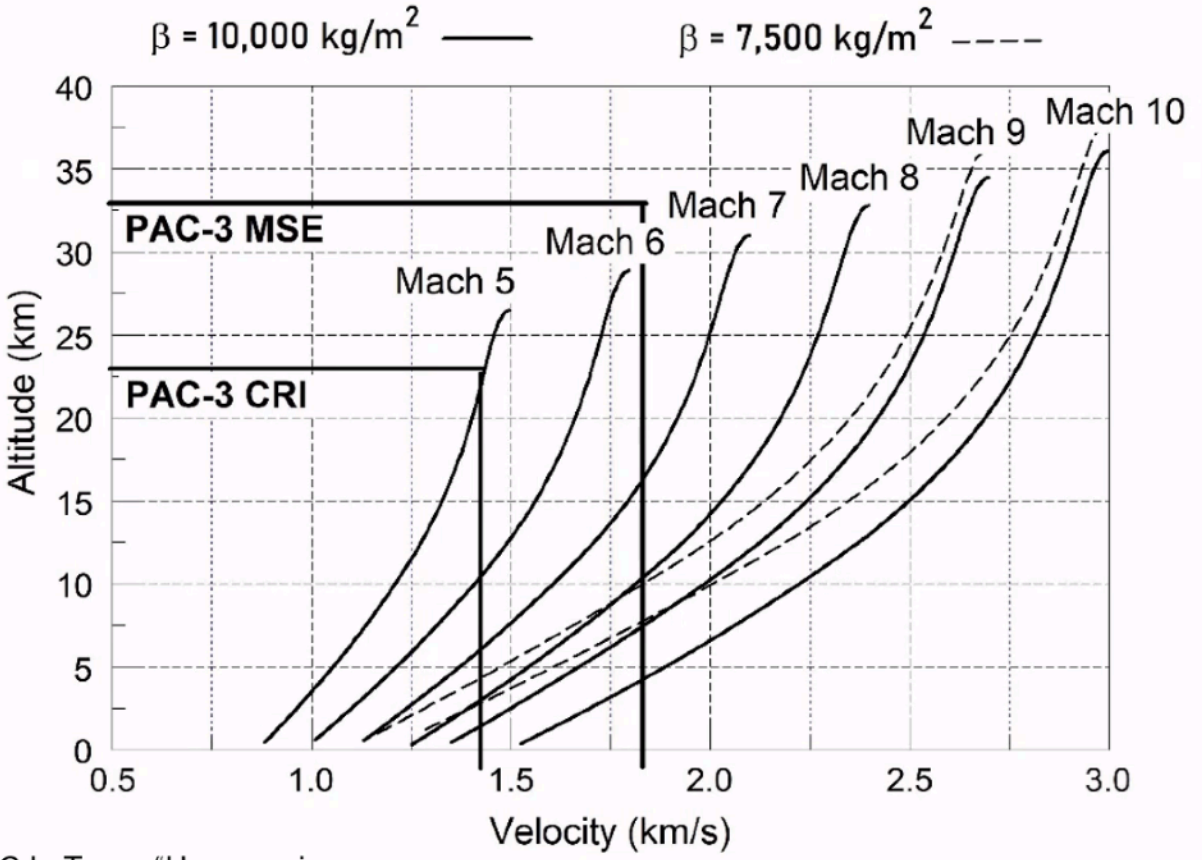
C.L. Tracy, D. Wright, "Modelling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28 (2020)

Hypersonics fly slowly in the terminal phase



C.L. Tracy, D. Wright, "Modelling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28 (2020)

Hypersonics are vulnerable to Patriot defenses



. Wright, C.L. Tracy, "Hypersonic weapons:
ılnerability to missile defenses and comparison
MaRVs," *Science & Global Security* 31 (2023)

Patriot interceptors:

- **PAC-3 Cost Reduction Initiative:** $3.4 million each, developed 2000
- **PAC-3 Missile Segment Enhancer:** $3.9 million each, developed 2014

Russian hypersonics:

- **Kinzhal:** ~Mach 10
- **Tsirkon:** ~Mach 9
- **Avangard:** ~Mach 25

Battlefield experience confirms these findings

Ukraine says it used US-made Patriot system to intercept Russian hypersonic missile

By Maria Kostenko and Nick Paton Walsh, CNN
2 minute read · Updated 8:25 AM EDT, Sat May 6, 2023

Air defenses intercepted nearly half of Russia's Kinzhal hypersonic missiles

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Gilles Doucet

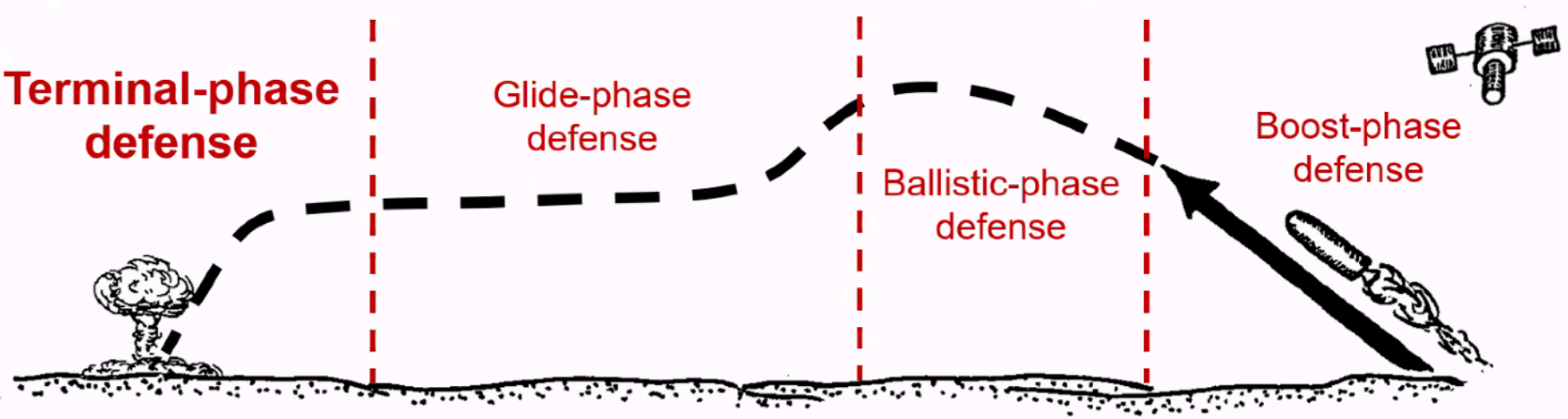
Ukraine says Russia's unstoppable hypersonic missiles had another bad night

Jake Epstein

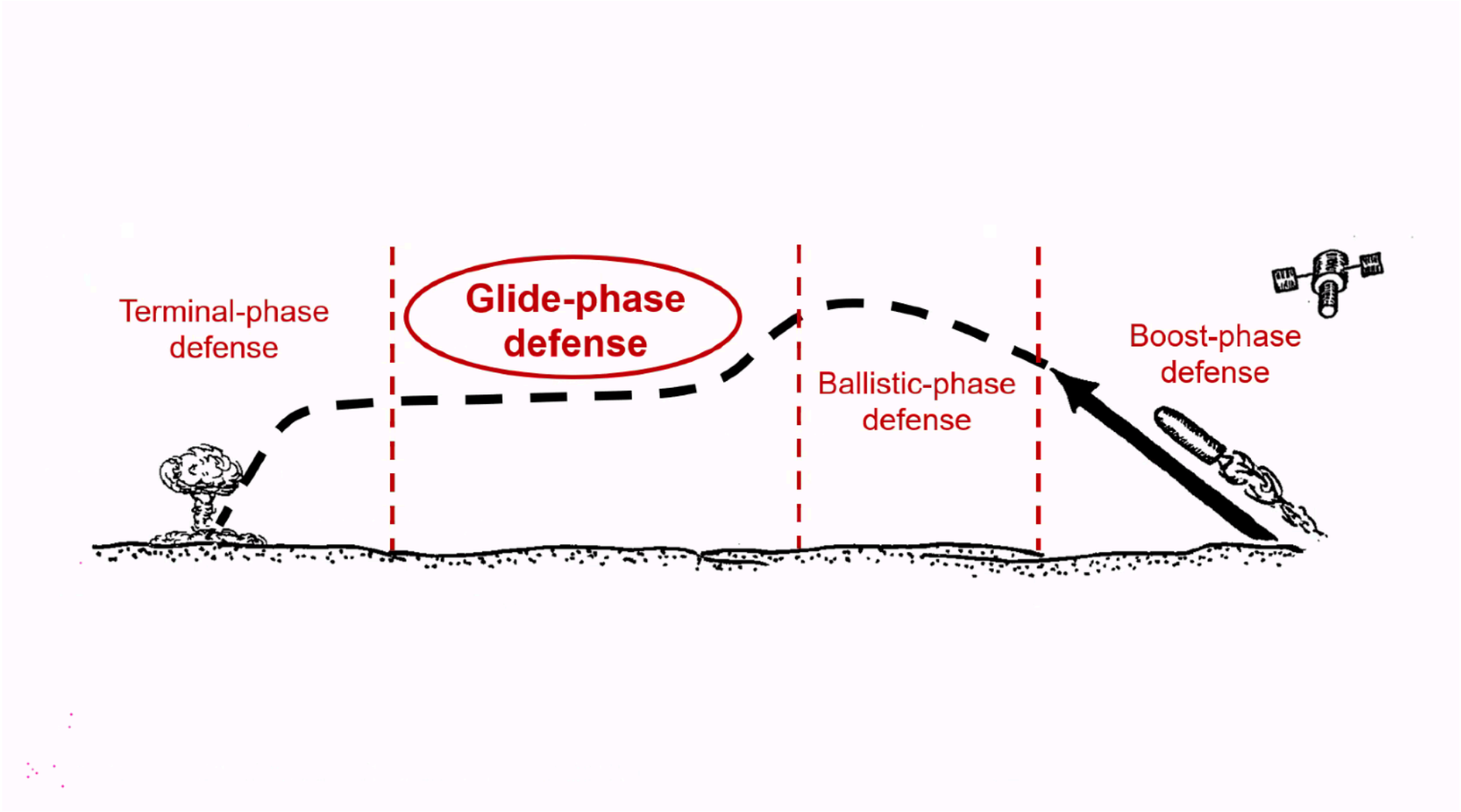
Updated Wed, November 20, 2024 at 4:24 AM PST · 4 min read

Interception rates, 2024:

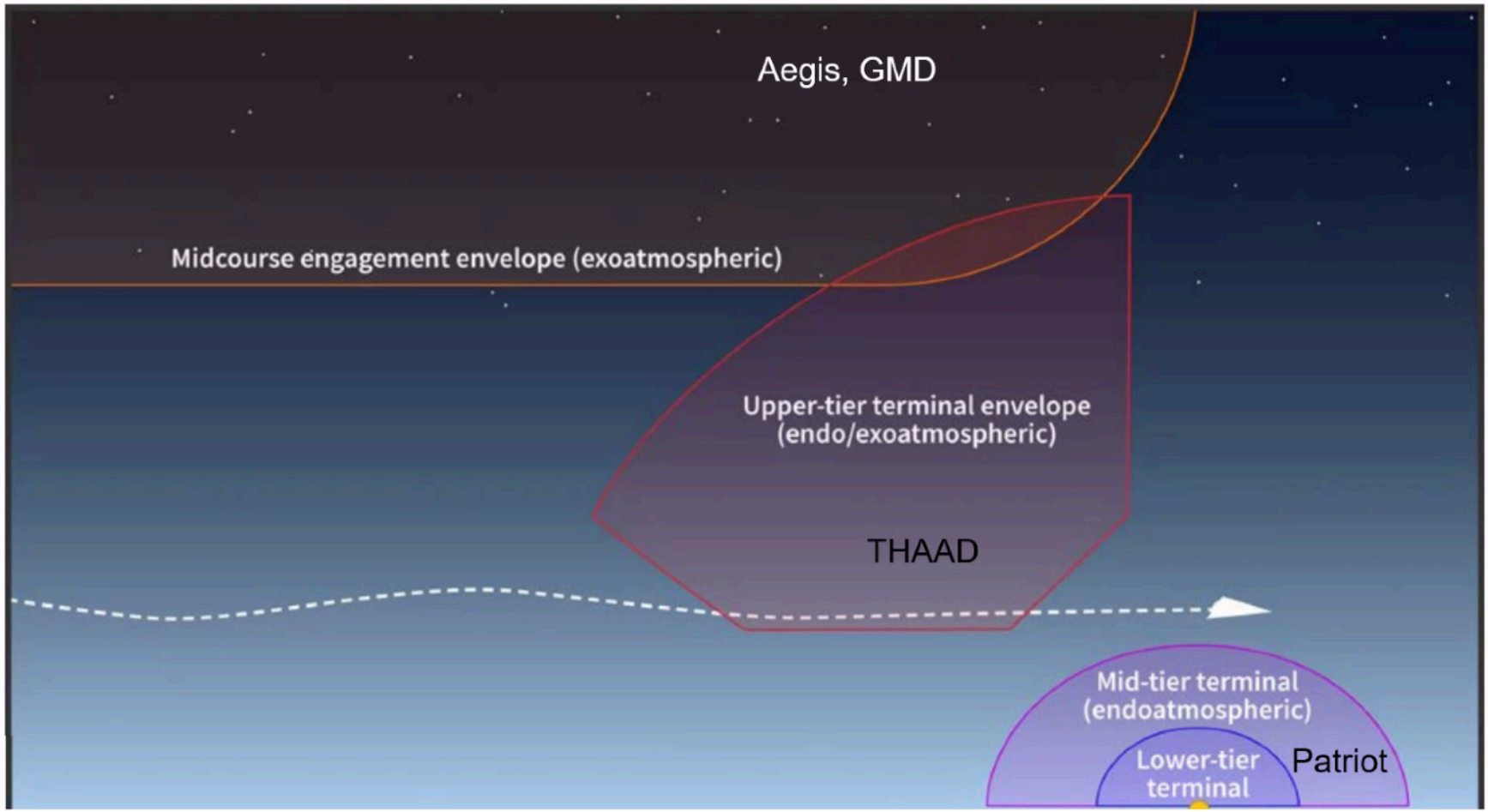
- **Kalibr:** ~50%
- **Kh-69:** ~22%
- **Iskander-M:** ~8%
- **Kinzhal:** ~25%
- **Tsirkon:** ~33%



Terminal-phase defense against hypersonic missiles is possible if attempted sufficiently late in the target missile's flight, though still challenging.


Terminal-phase defense
Glide-phase defense
Ballistic-phase defense
Boost-phase defense

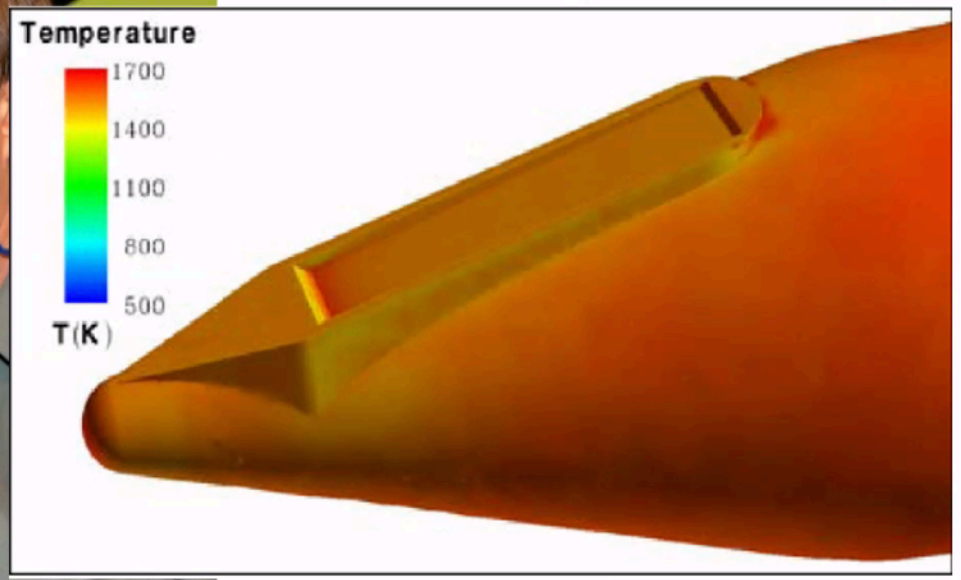
Gliders underfly current mid-course defenses



The challenge of aerothermal heating

THAAD IR seeker window

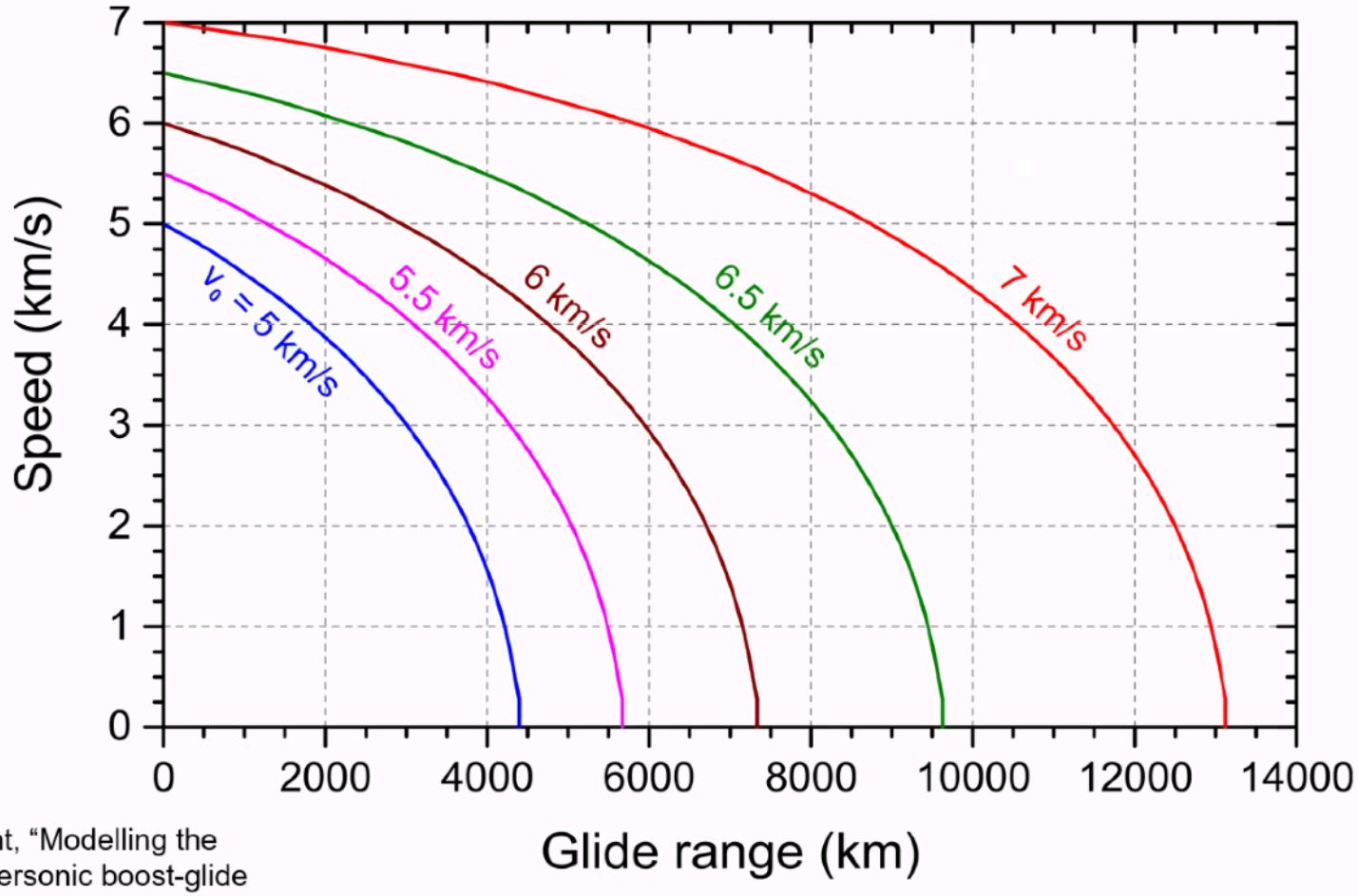
Window heating from Mach 7 flight



A potential solution: radio frequency (RF) seekers

Diehl Defence, developer of the EU HYDEF interceptor: "A combination of radar and multispectral infrared seeker technologies is used for target acquisition. The seeker component is a newly developed system adapted to the endo-atmospheric conditions above 20 km altitude."

The target speed/maneuverability challenge



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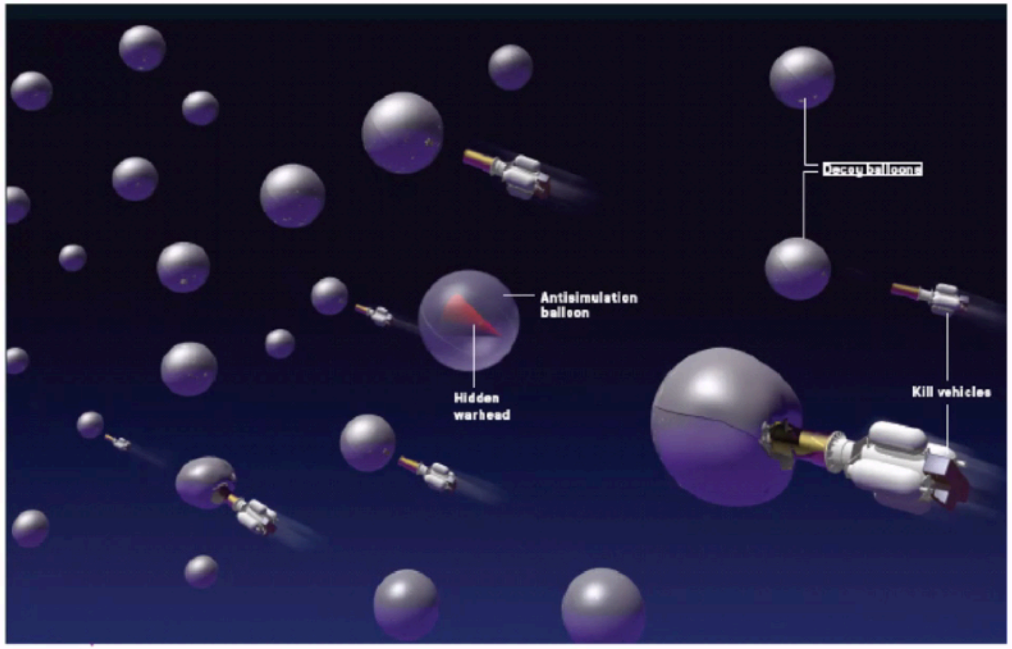
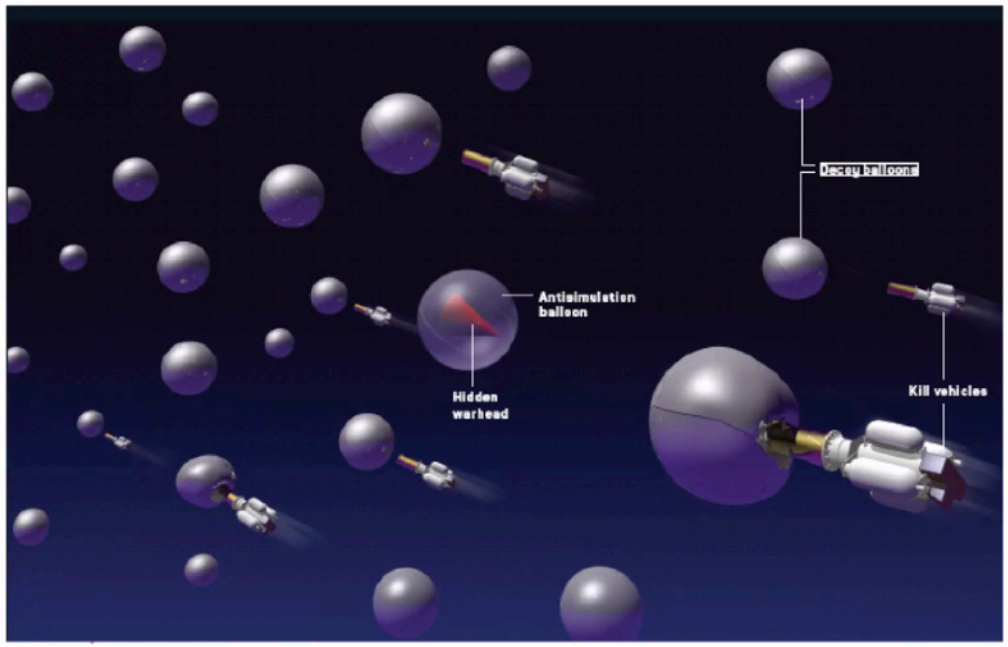
Endoatmospheric interception opportunities



Decoys don't work well:

- Any object flying the same trajectory as the glider suffers the same aerothermal heating
- Decoys that can survive this environment are nearly as costly as gliders

Endoatmospheric interception opportunities



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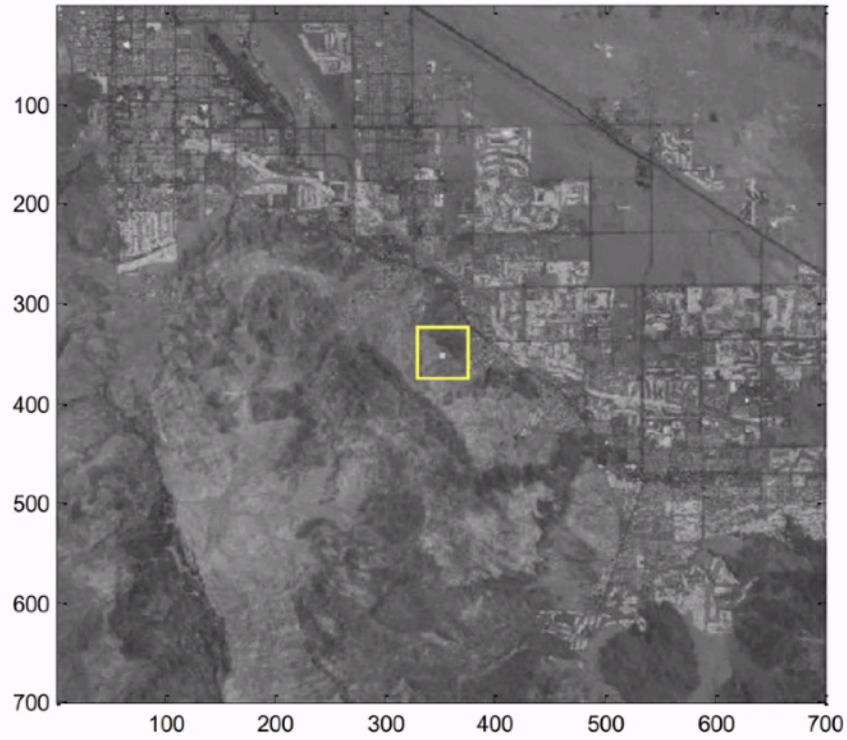
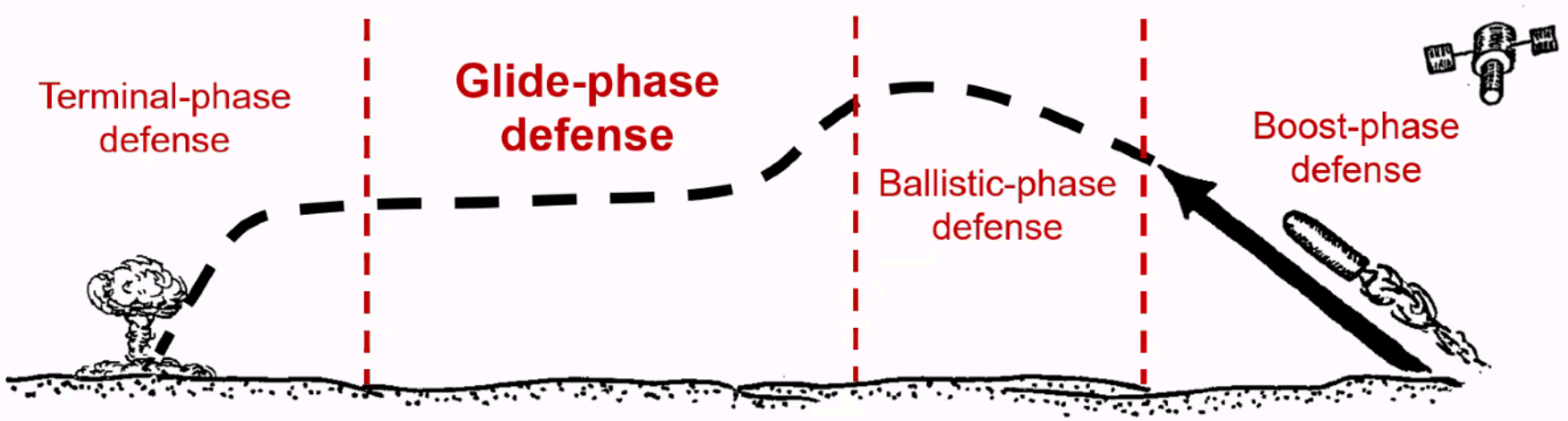
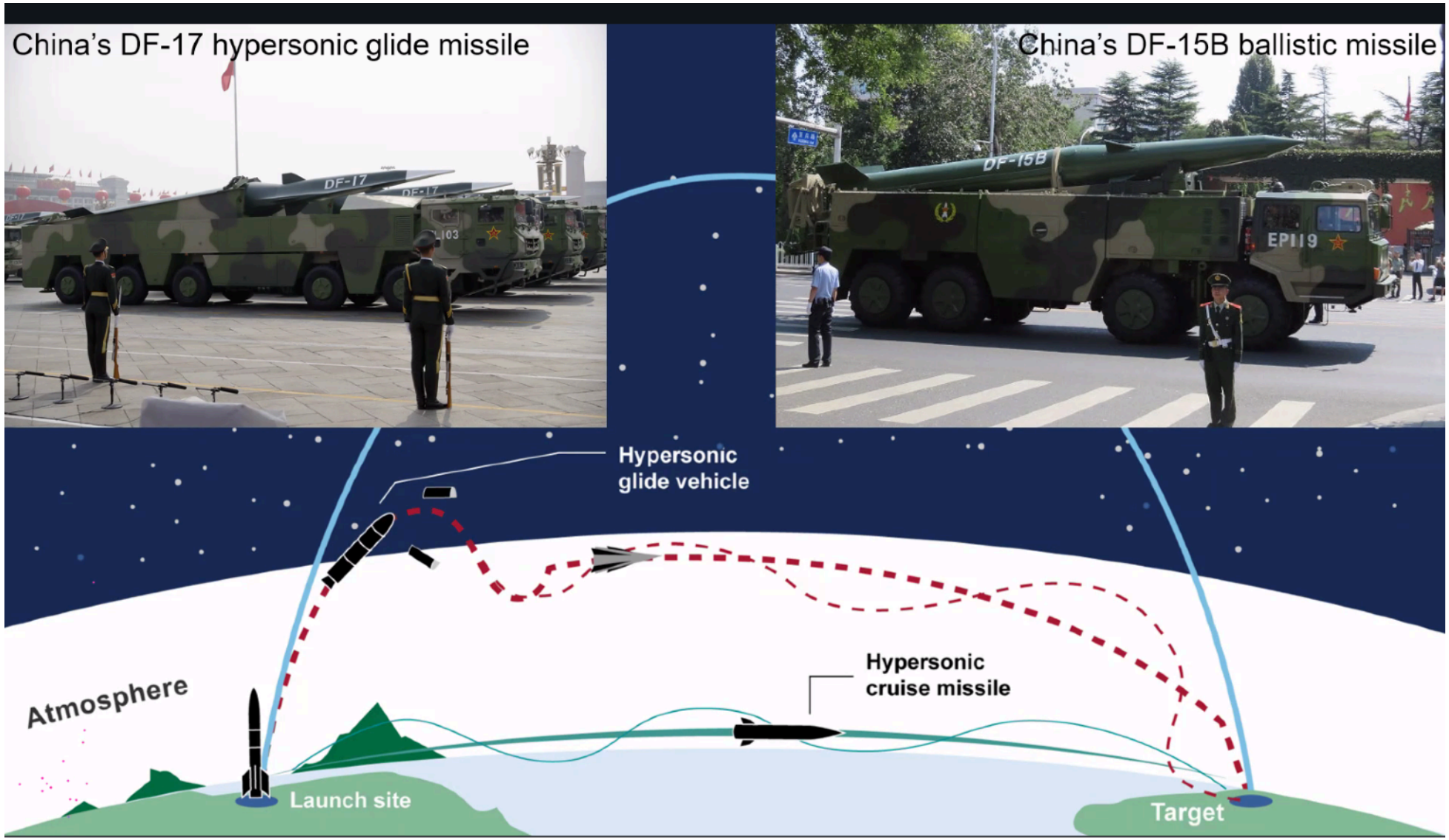


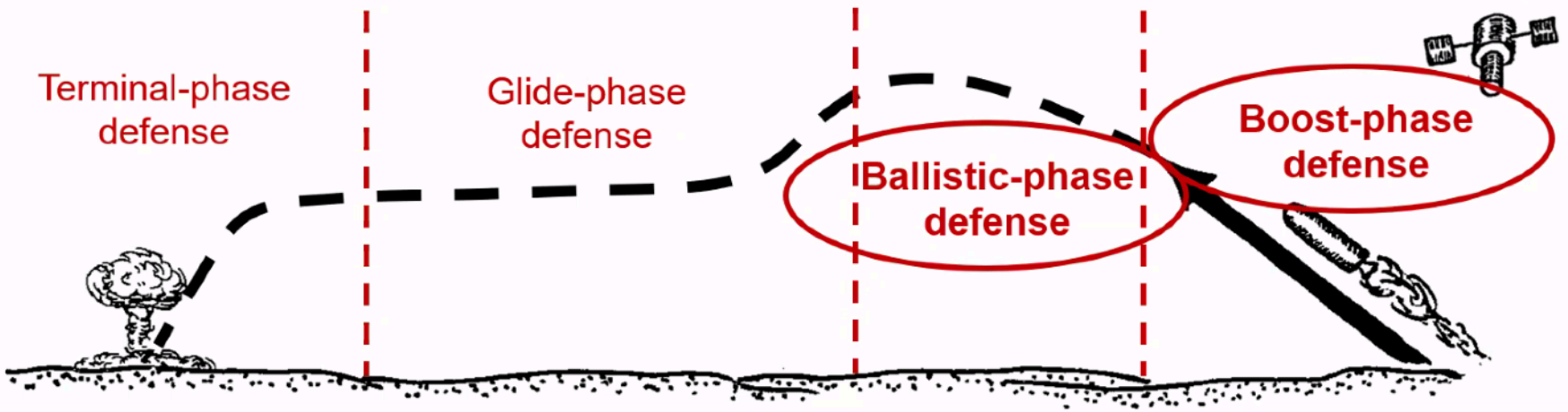
Space-based tracking is straightforward:

- Gliders reach 1000-2000 K
- Hot gliders give off strong IR signatures



Glide-phase defense presents challenges and opportunities. The lack of decoys probably makes it more practicable than mid-course defense against ballistic missiles, but interceptor costs will likely by similar (~$30-70 million).


China's DF-17 hypersonic glide missile
China's DF-15B ballistic missile
Hypersonic glide vehicle
Hypersonic cruise missile
Atmosphere
Launch site
Target



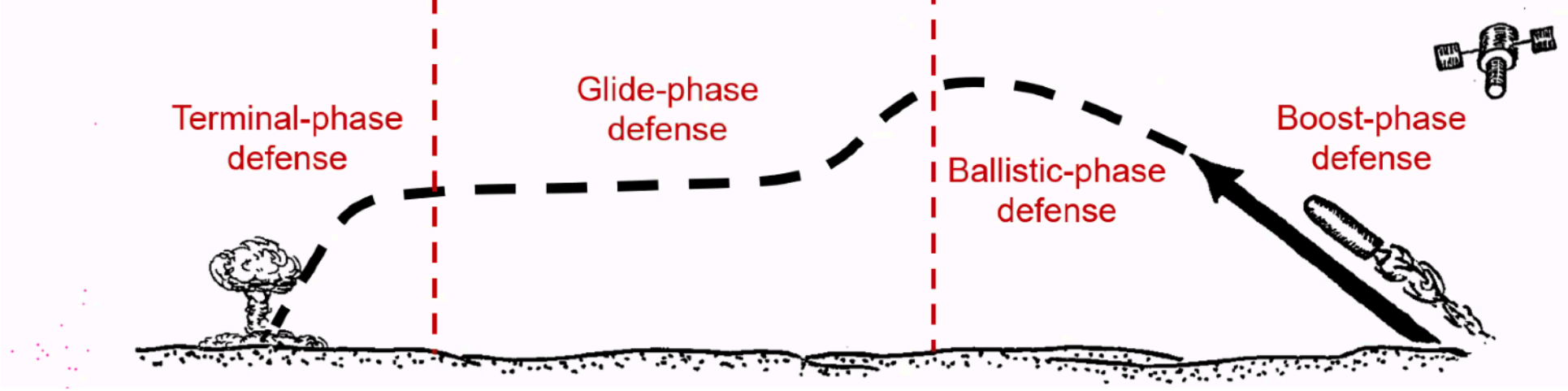
Boost-phase defense against a hypersonic missile is identical to boost-phase defense against a ballistic missile. Ballistic-phase defense against a hypersonic missile is identical to mid-course defense against a ballistic missile.

Conclusions: hypersonic defense is nothing new

- Easier than ballistic missile intercept because hypersonics fly more slowly
- Still challenging

- Requires new seeker designs and agile interceptors
- Decoys are not a problem, nor is tracking
- Challenges and costs similar to mid-course ballistic missile intercept

- Identical to mid-course and boost-phase defense against ballistic missiles



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D. Wright, C.L. Tracy, “Hypersonic weapons: vulnerability to missile defenses and comparison to MaRVs,” *Science & Global Security* 31 (2023)

D. Wright, C.L. Tracy, “Hypersonic cruise missiles,” *Science & Global Security* 32 (2024)

C.L. Tracy, “Weapons design, engineering ethics, and the duty to inform: A case study on U.S. hypersonic missile development,” *Technology and Society* 43(2024)

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