Radiative Cooling
New Opportunities & Enabling Technologies

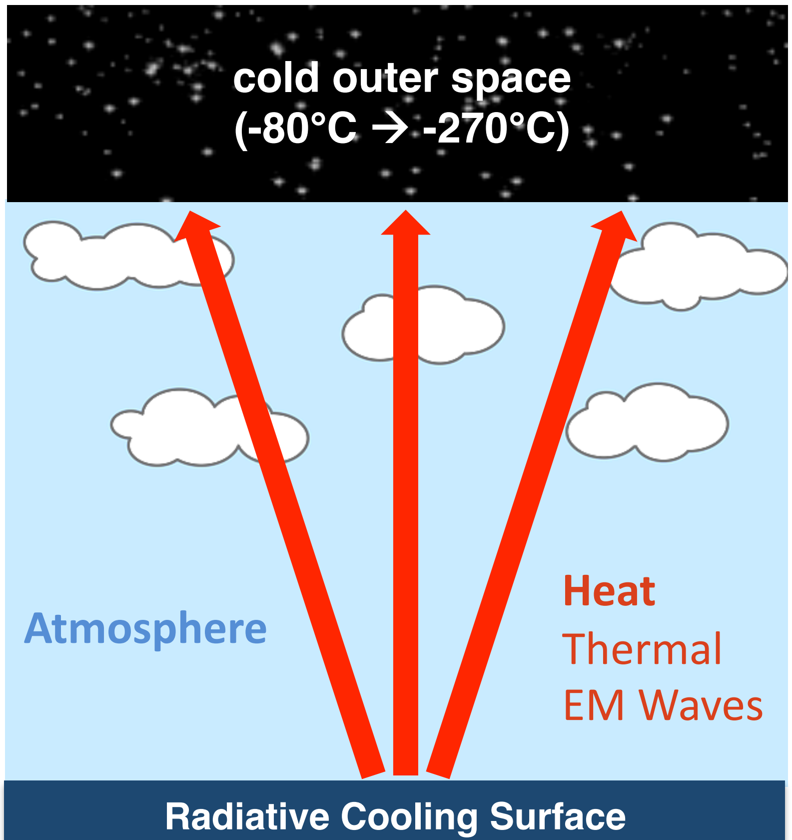
Aaswath P. Raman, Ph.D.
aaswath@stanford.edu

Research Associate,
Fan Group, Ginzton Laboratory

Stanford University

ARPA-E Alternative Power Plant Cooling Workshop, May 12, 2014

An opportunity to tap an underutilized resource

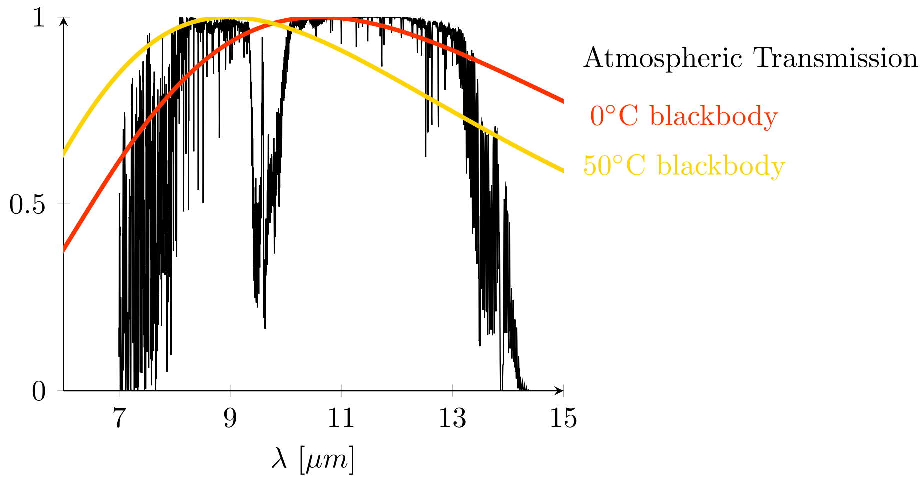


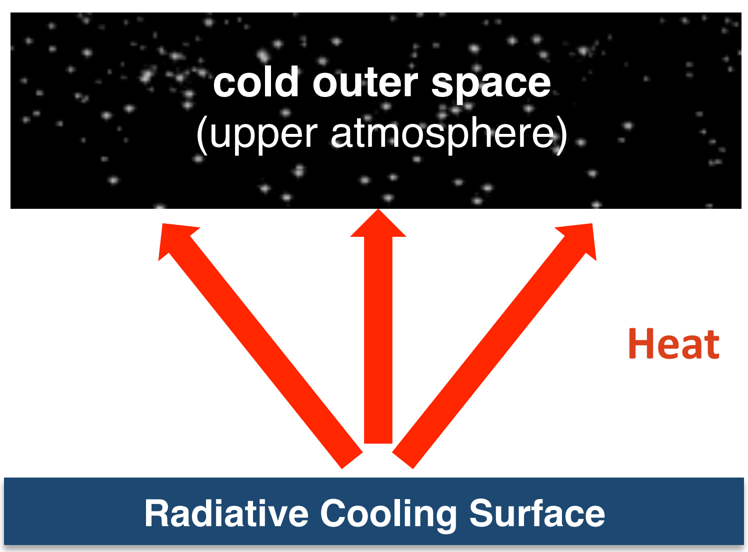
Use the cold of outer space to radiatively pump heat from the ground through sky access

New: Possible at **all hours** of the day through photonic design of thermally emissive layers

Meaningful cooling power that scales with area: analogies to PV

Atmospheric transmittance





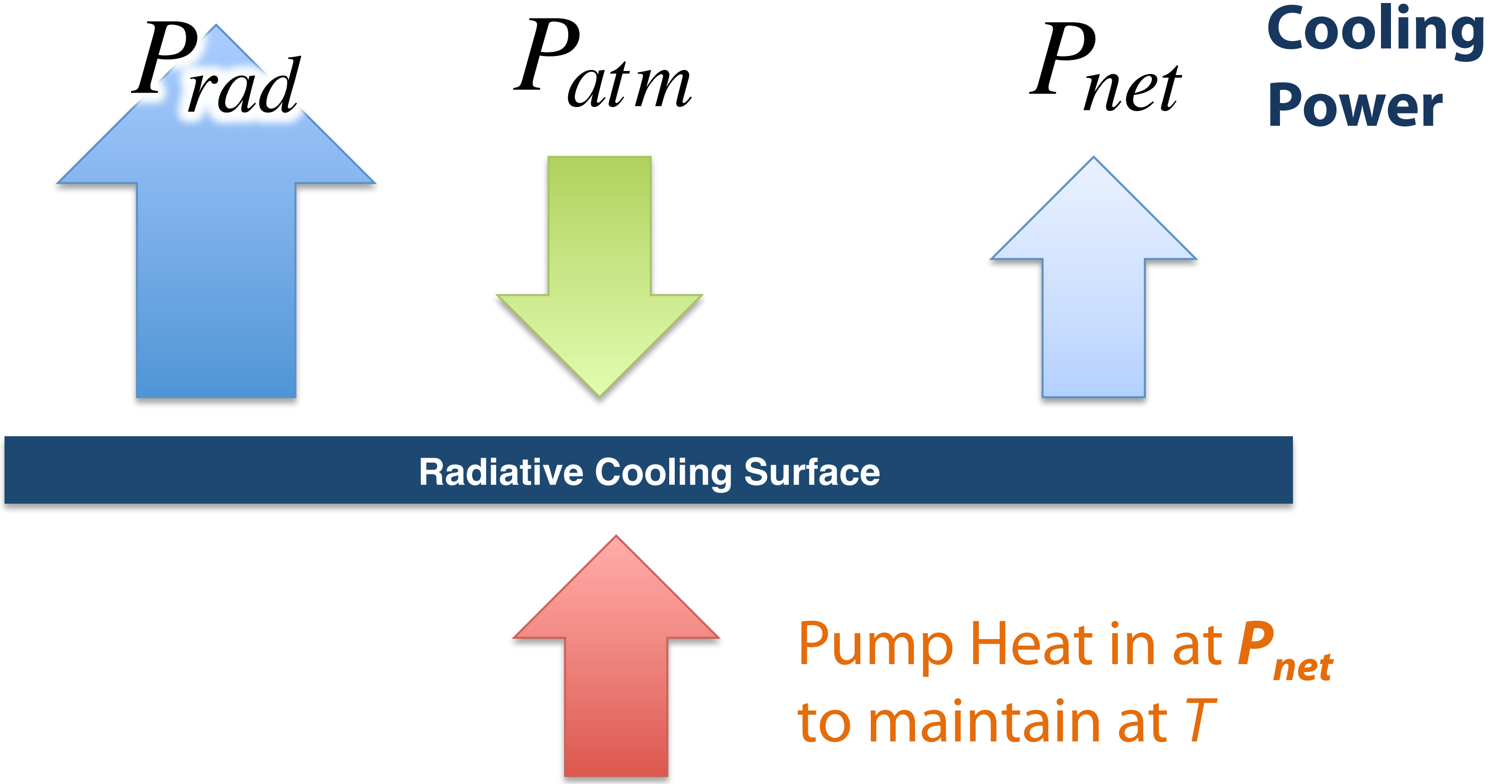
Radiative cooling is enabled by an atmospheric transparency window between 8 – 13 μm

Blackbody spectrum of typical Earth temperature objects overlap with window

Varies with cloud cover, geographic location and ozone pollution

Power balance equation

$$P_{net}(T) = P_{rad}(T) - P_{atm}(T_{amb})$$



The need for *selective* thermal emission

$$P_{net}(T) = P_{rad}(T) - P_{atm}(T_{amb})$$

Hemispherical integrals:

$$P_{rad}(T) \propto I_{BB}(T, \lambda)\varepsilon(\lambda, \theta)$$

$$P_{atm}(T_{amb}) \propto I_{BB}(T_{amb}, \lambda)\varepsilon(\lambda, \theta)\varepsilon_{atm}(\lambda, \theta)$$

Emissivity of atmosphere

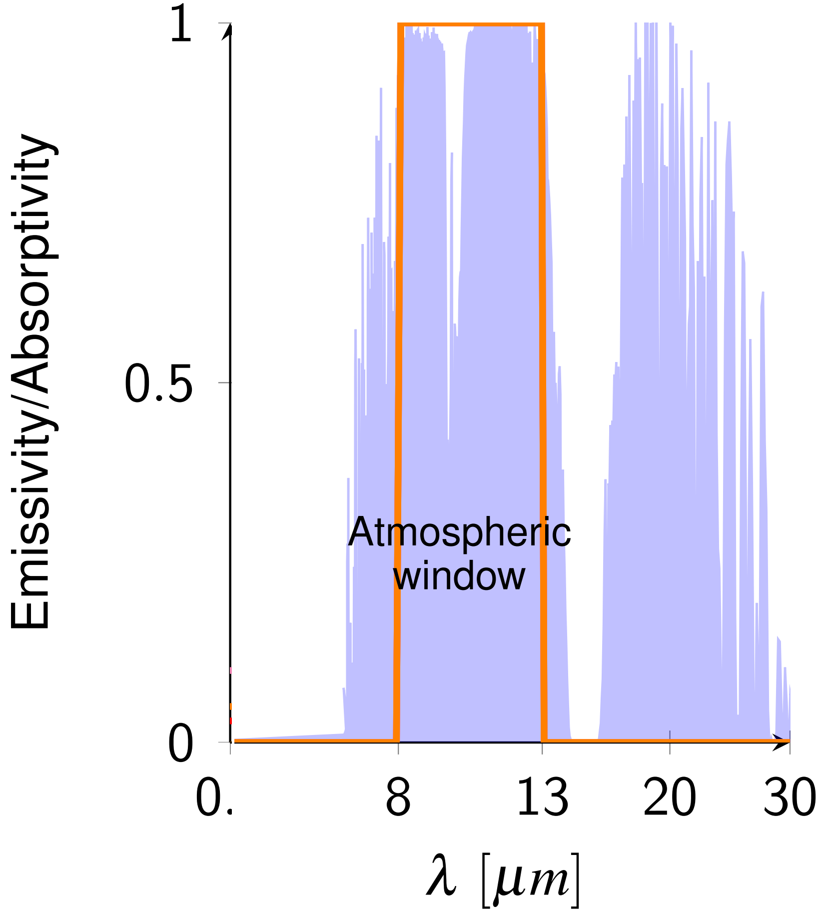
Emissivity of radiating surface

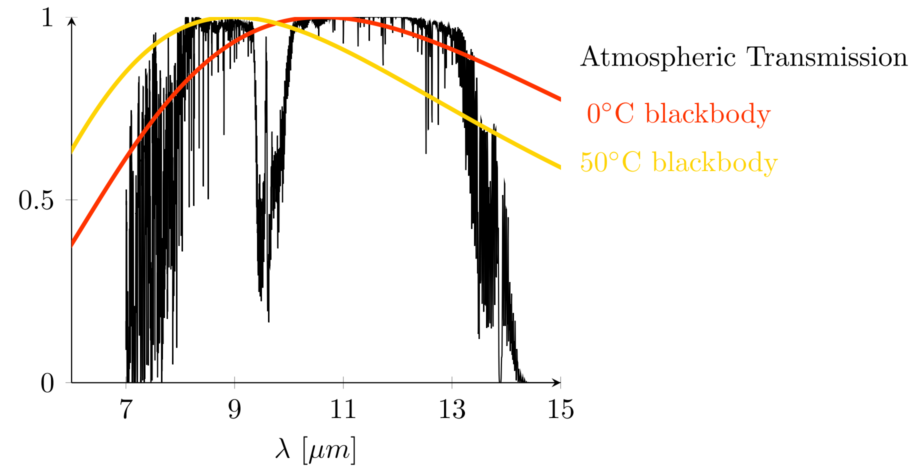
Thermal emissivity is not a fixed number:

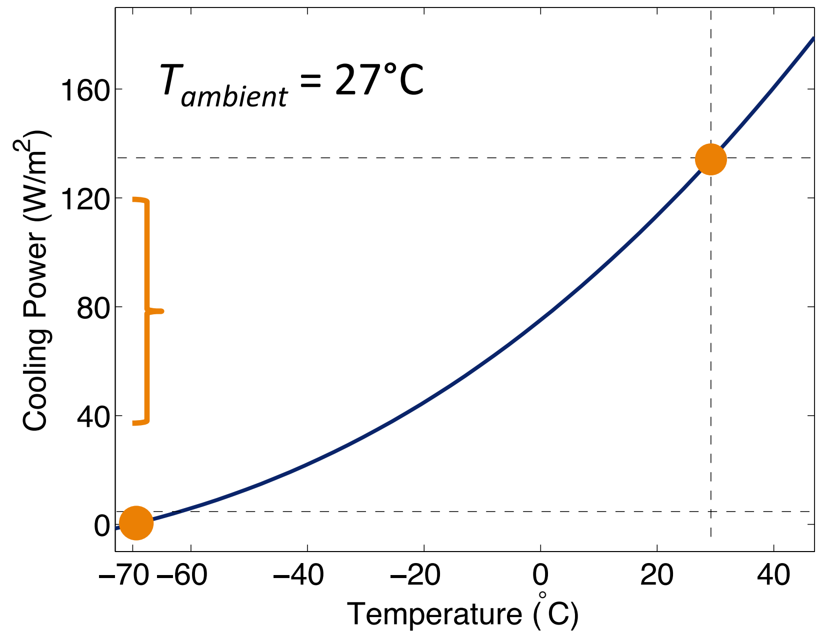
It can be engineered by *photonic design*

Hemispherical sky access for maximal cooling power

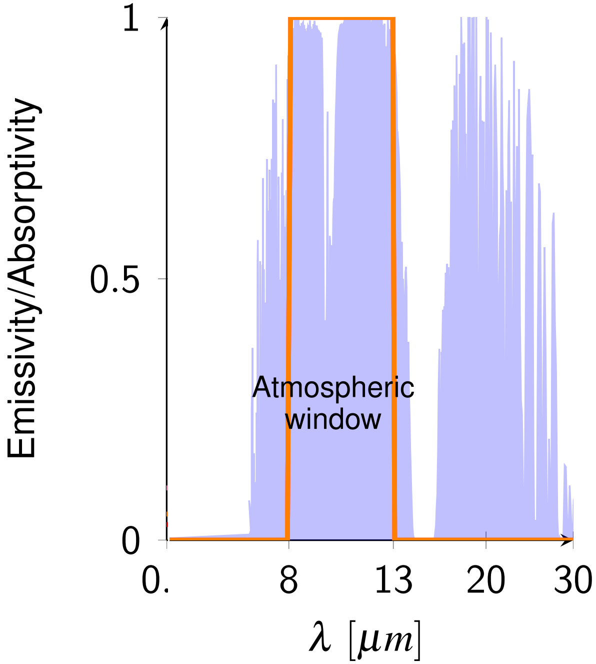
Potential of an ideal selective emitter

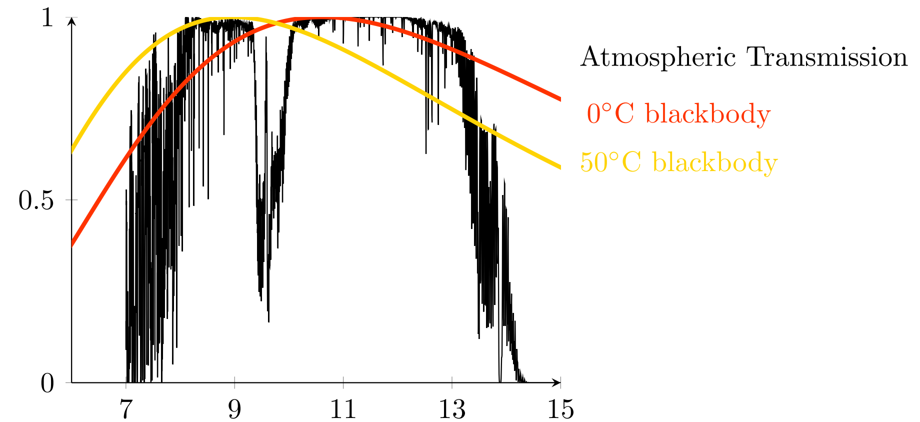






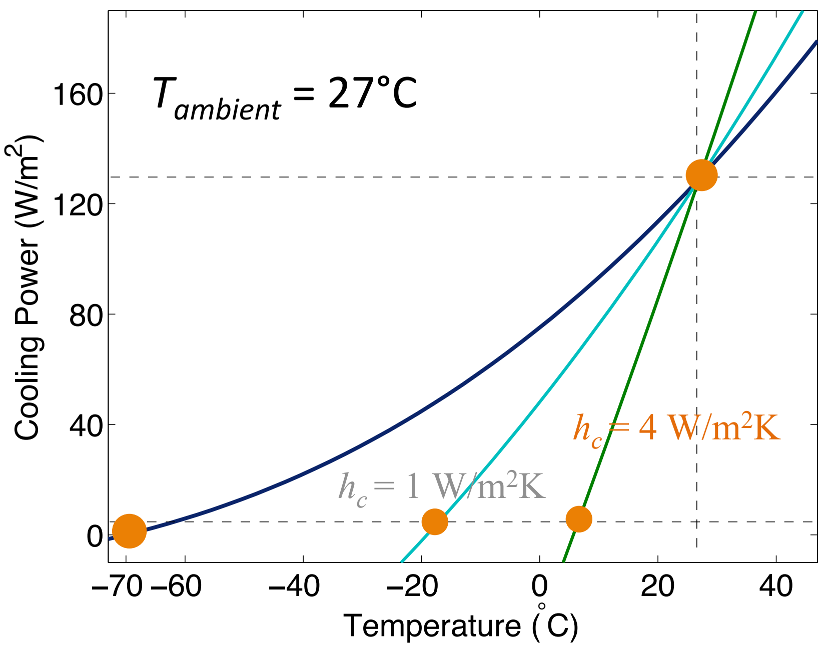
Potential of an ideal selective emitter



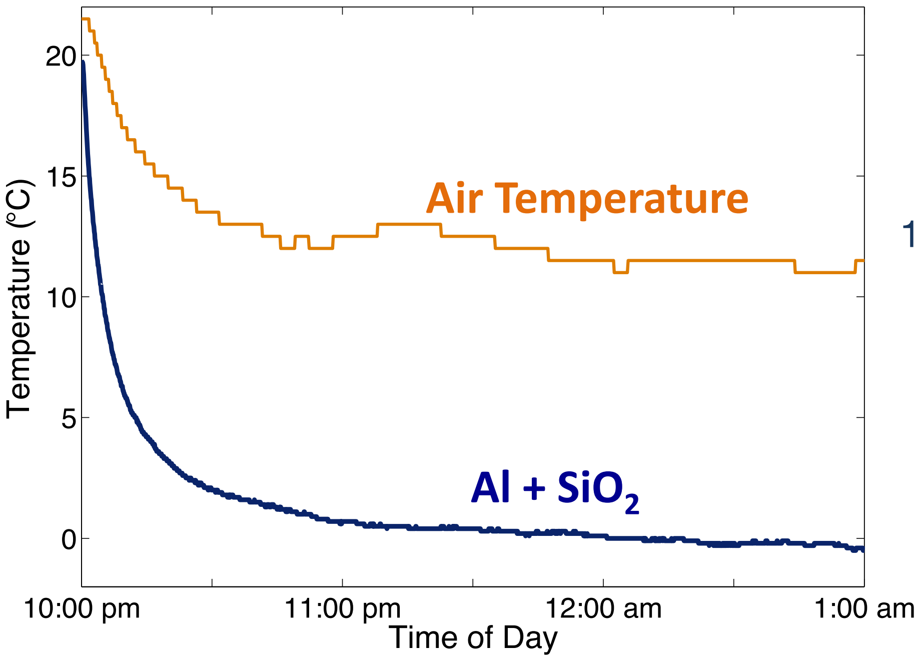


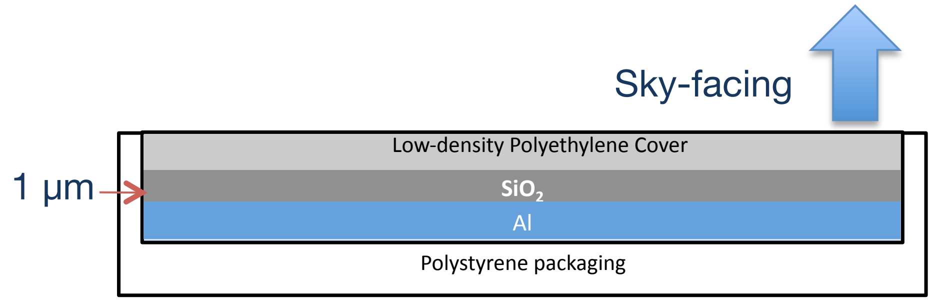
Effective of parasitic ambient *heating* when below air temperature:

$$P_{nonrad} = h_c \Delta T$$



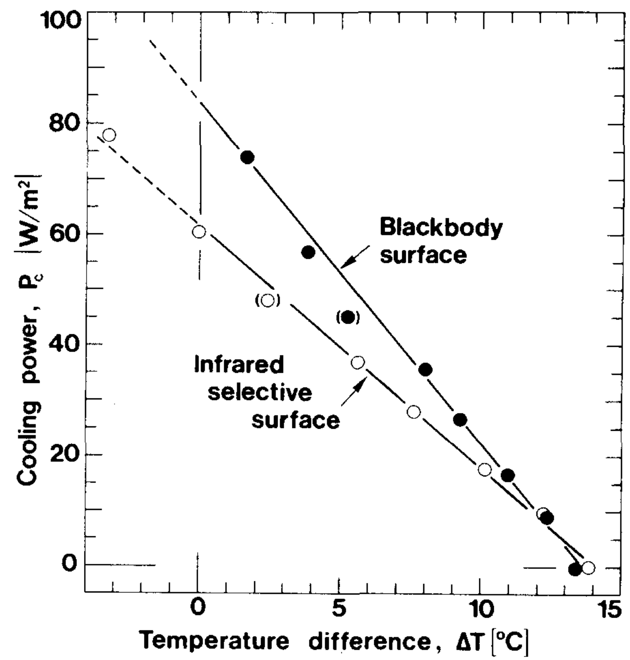
Radiative Cooling at Night: Experimental Data





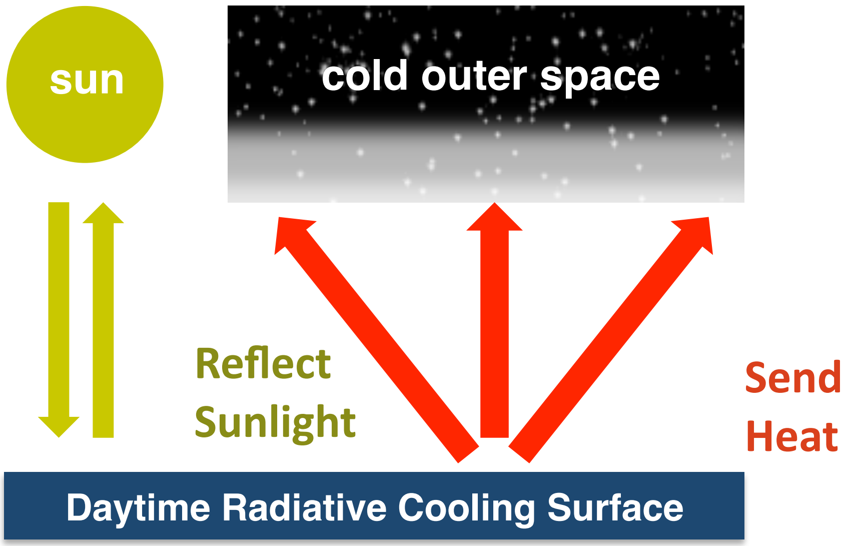
Other night-sky radiators: Tedlar, paints

Catalanotti, S. et al. *Solar Energy* 17, 83 – 89 (1975).
Granqvist, C. G. & Hjortsberg, A. *Applied Physics Letters* 36, 139–141 (1980).
Granqvist, C. G. & Hjortsberg, A. *Journal of Applied Physics* 52, 4205–4220 (1981).
Berdahl, P., Martin, M. & Sakkal, F. *International Journal of Heat and Mass Transfer* 26, 871 – 880 (1983).
Orel, B., Gunde, M. & Krainer, A. *Solar Energy* 50, 477 – 482 (1993).
Suryawanshi, C. N. & Lin, C.-T. *ACS Applied Materials and Interfaces* 1, 1334–1338 (2009).
Gentle, A. R. & Smith, G. B. *Nano Letters* 10, 373–379 (2010).



Granqvist & Hjortsberg (1980)

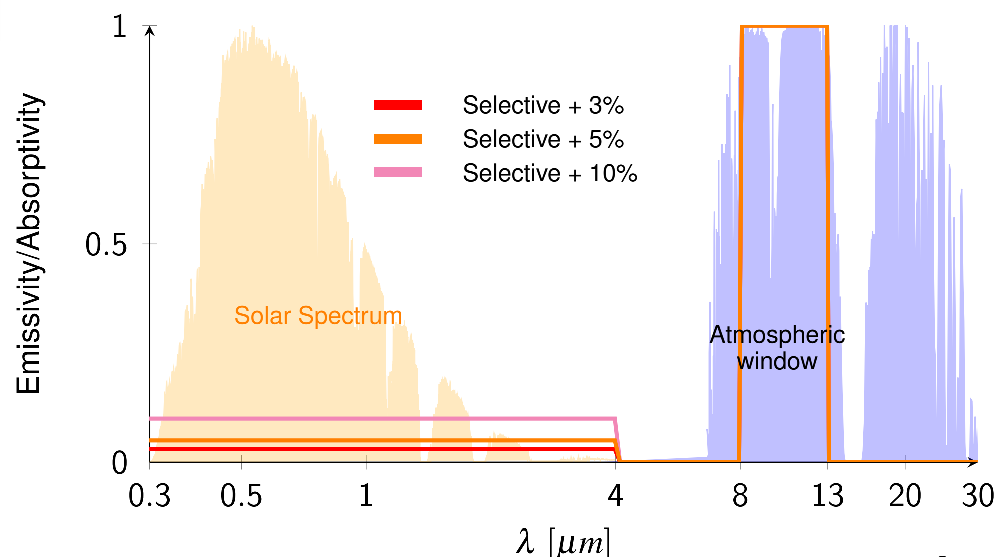
The challenge during the day



T^4 intuition:

Sun: 6000 K

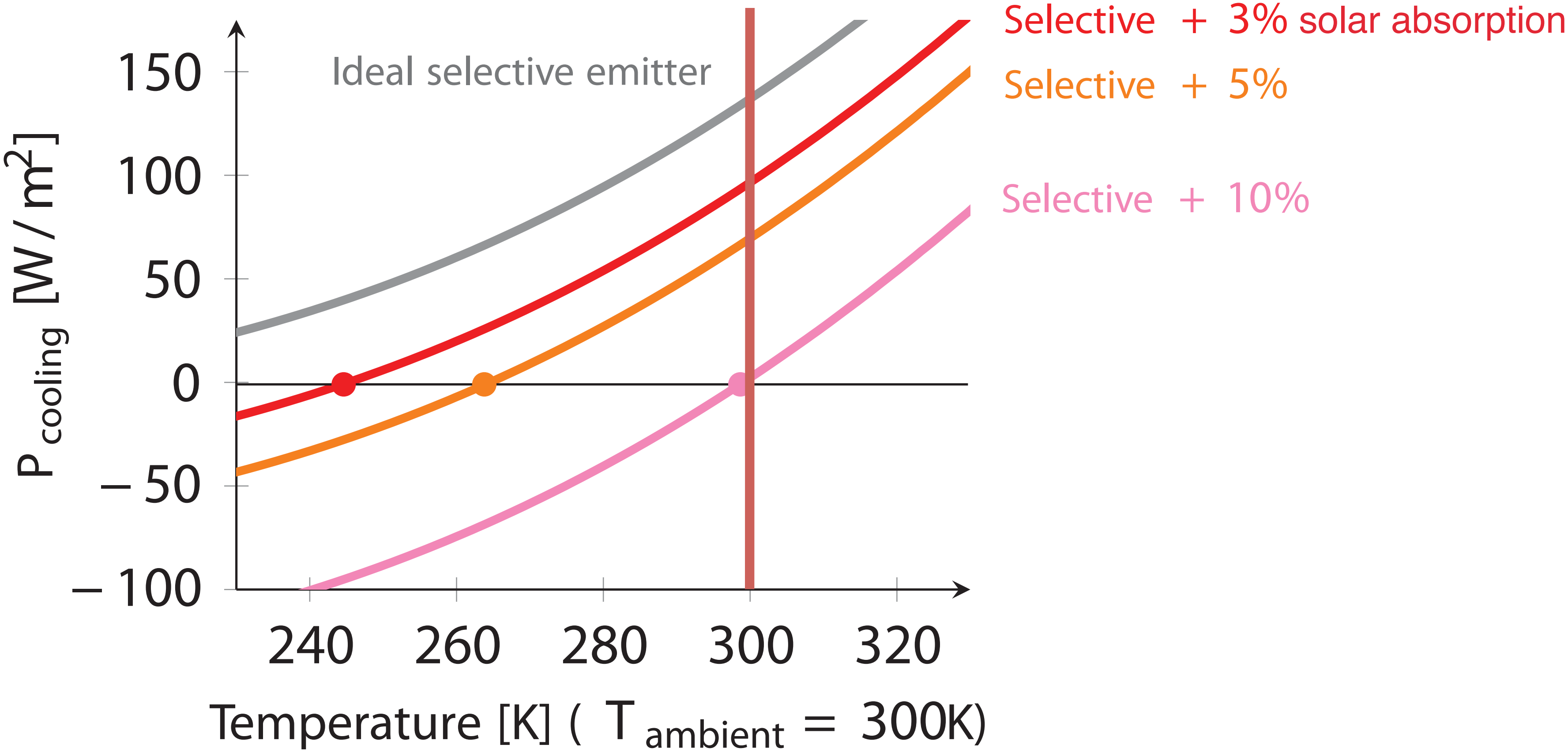
Earth objects: 300 K



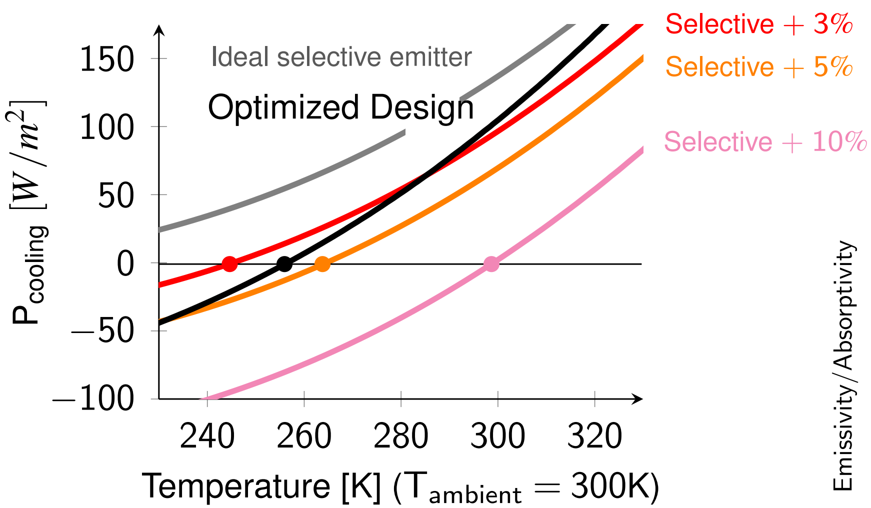
Cooling demand peaks during the day:

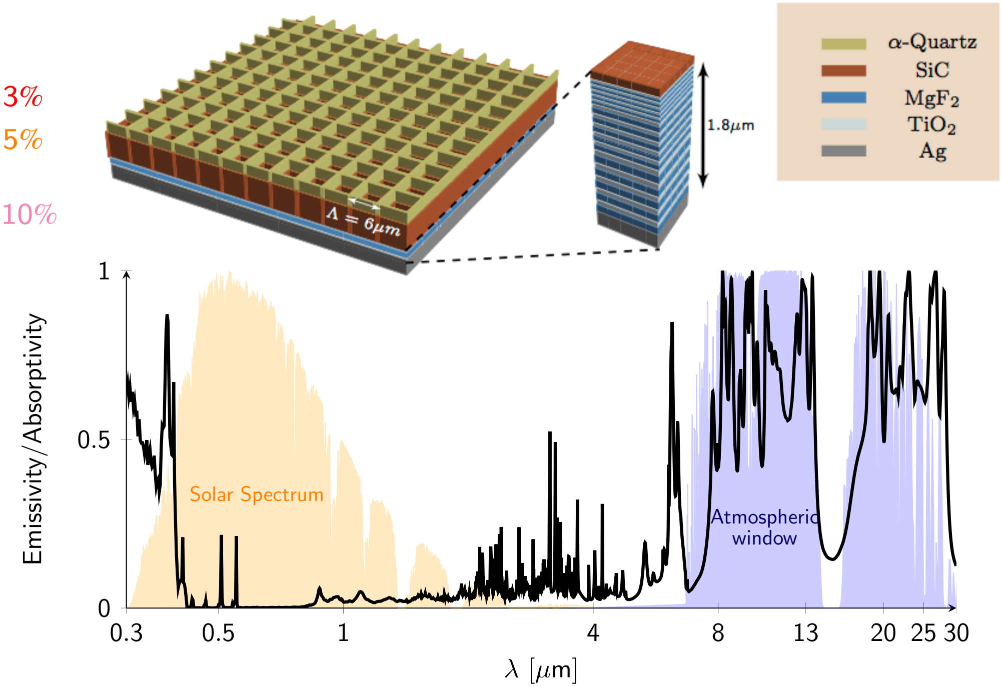
Can we achieve meaningful cooling then?

Simultaneously emit thermal radiation and reflect sunlight strongly



Photonic design enables daytime radiative cooling





Achieve desired thermal emissivity by photonic design

Overcome material limitations

Rephaeli*, Raman* and Fan, *Nano Letters* (2013)

Benefits & challenges of radiative cooling

Passive (electricity-free) cooling powers of **~30-90 W/m²** to drop temperatures **5-10°C** below ambient

With advanced photonic design, available at all hours of the day

Operating costs limited to maintenance and pumping energy

Can work in the hottest (and even humid) days

Can be additive to other cooling mechanisms

Inherently large-area

Geometrical constraints: flat surface with access to full sky hemisphere ideal

Atmospheric constraints: performance can drop by 1/2 if cloudy/rainy

Efficient packaging needed to ensure minimal parasitic losses to the ambient

Maximal benefit available at night

Acknowledgements

Marc Anoma

Eli Goldstein

Prof. Shanhui Fan

Linxiao Zhu

Dr. Eden Rephaeli

arpa·e

Advanced Research Projects Agency - Energy

OPEN 2012 Awardee