Beyond the Envelope

Subambient Sky-Facing Surfaces under Sunlight & their Potential

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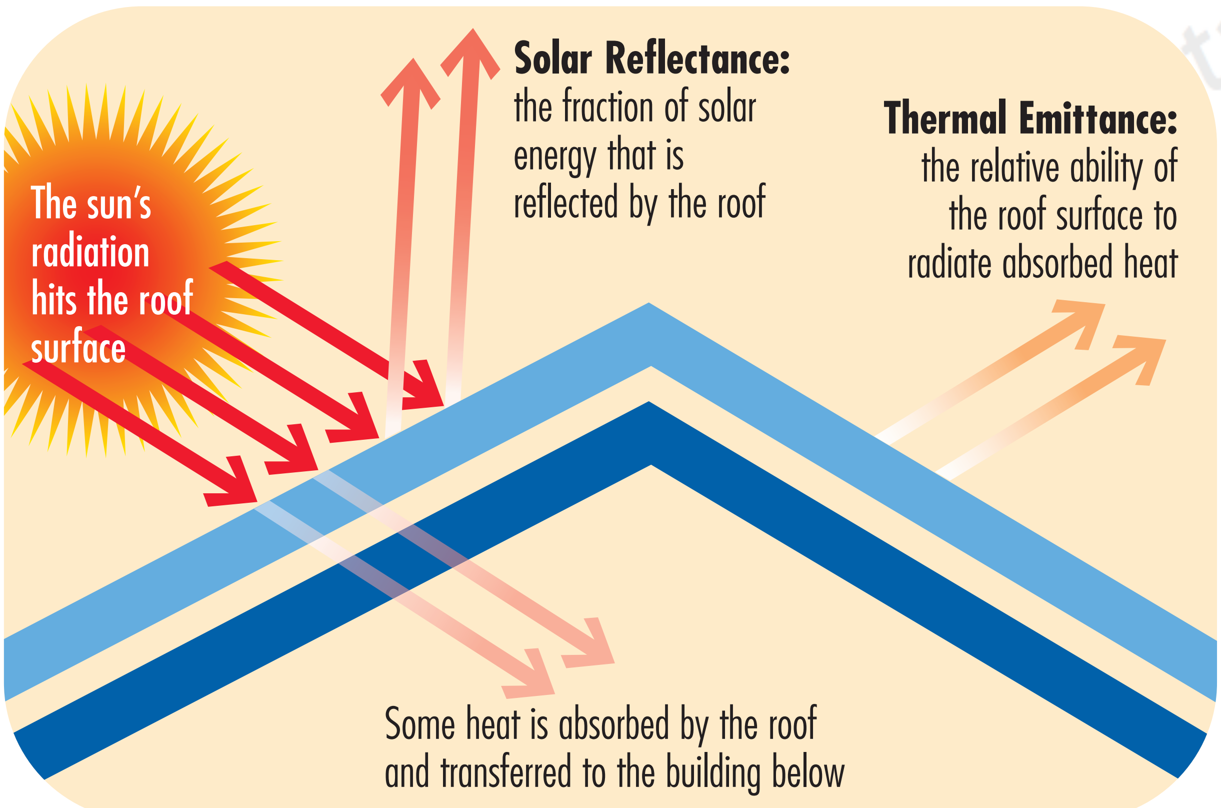
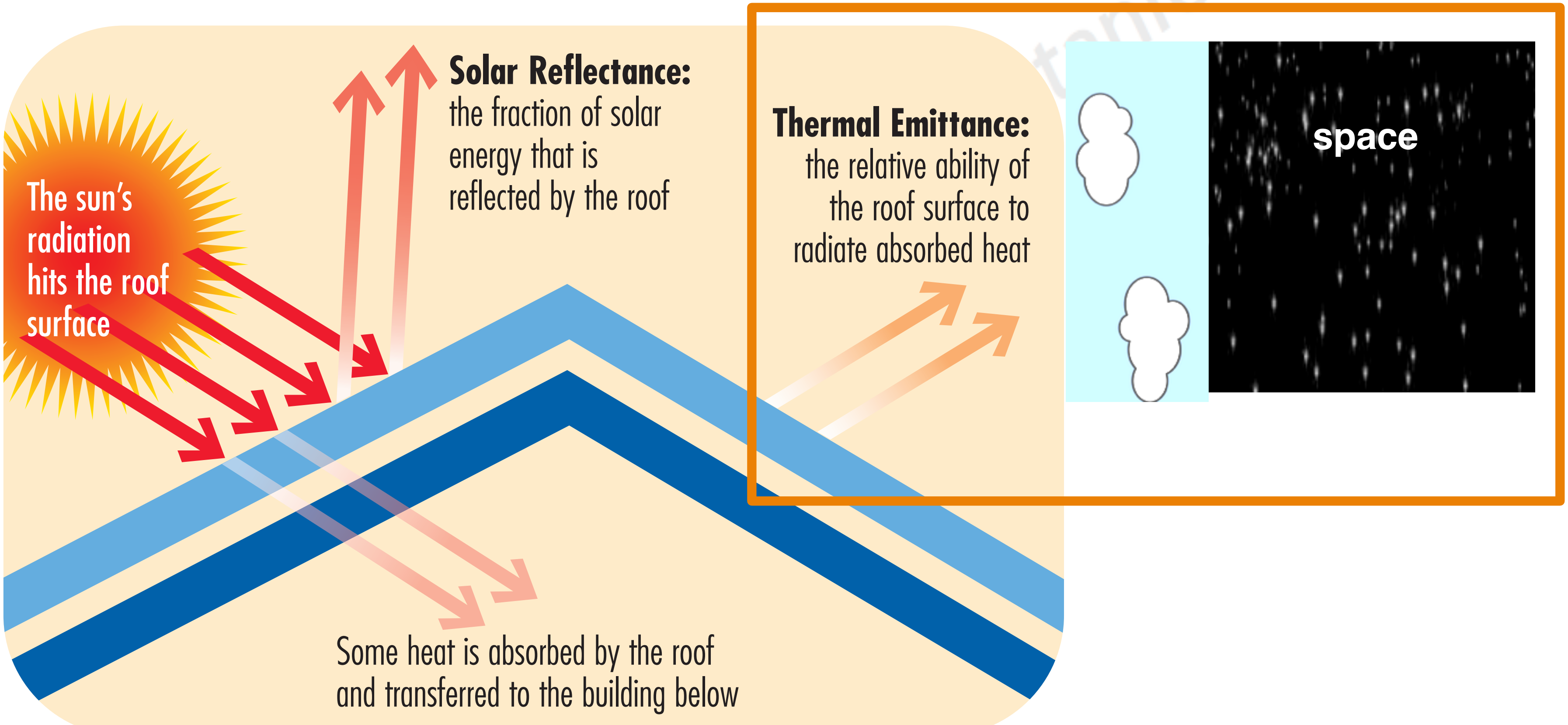
CRRC Annual Meeting 2015

The cool roof picture



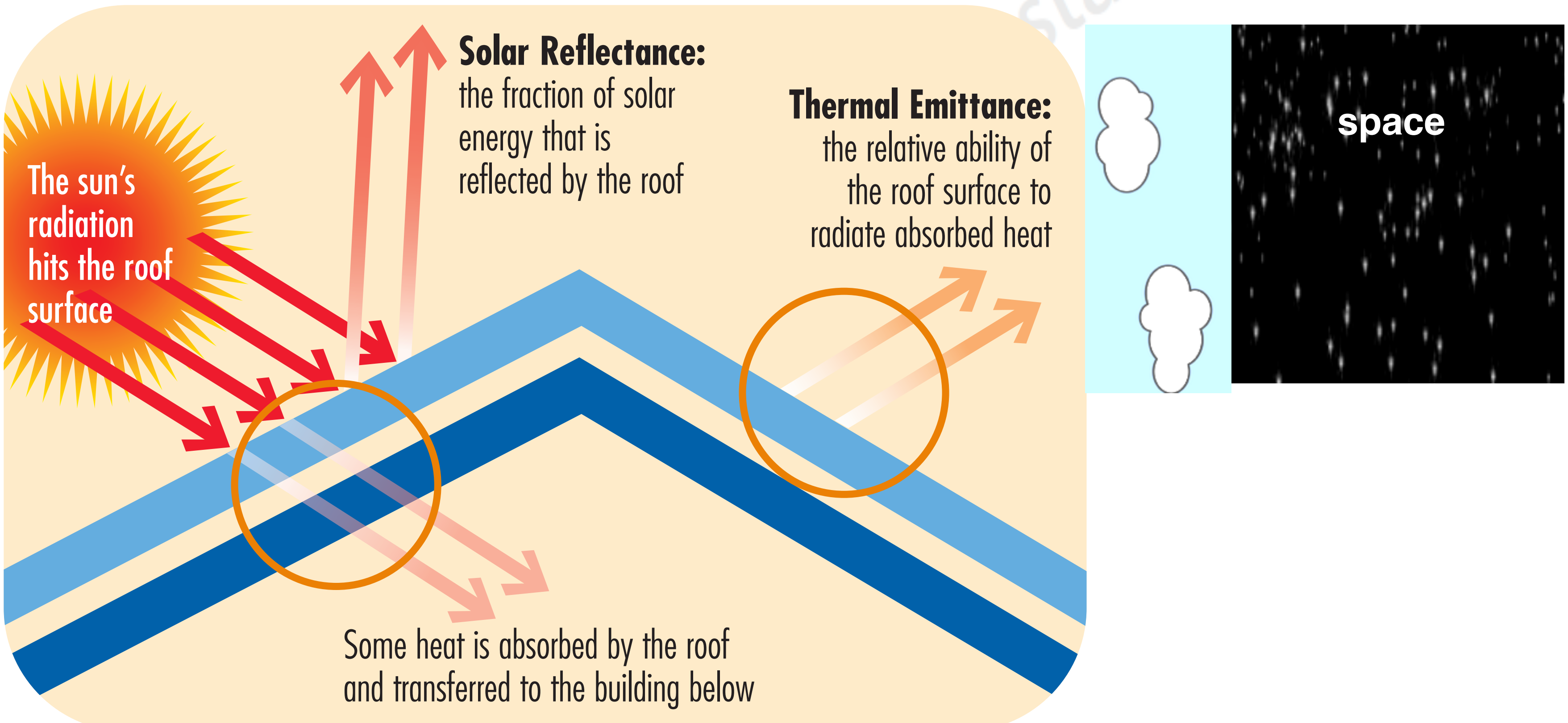
Cool Roof Rating Council Website

Thermal emittance accesses another ‘resource’



Radiative cooling to below ambient air temperature

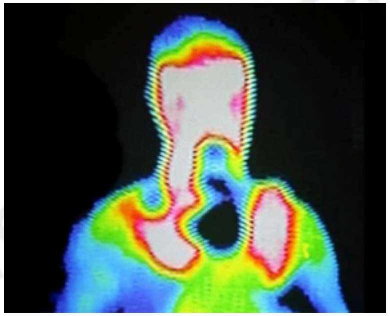
Thermal emission > **Solar absorption** = **Cooling below ambient**

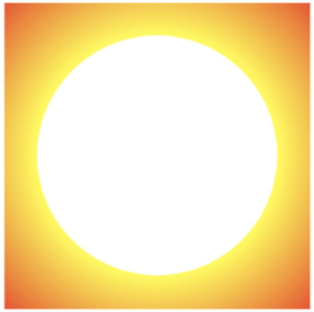


Talk Outline

- Radiative Cooling Fundamentals & History
- Cooling Under Sunlight: The Challenge
- Our Solution: Design & Results
- Outlook

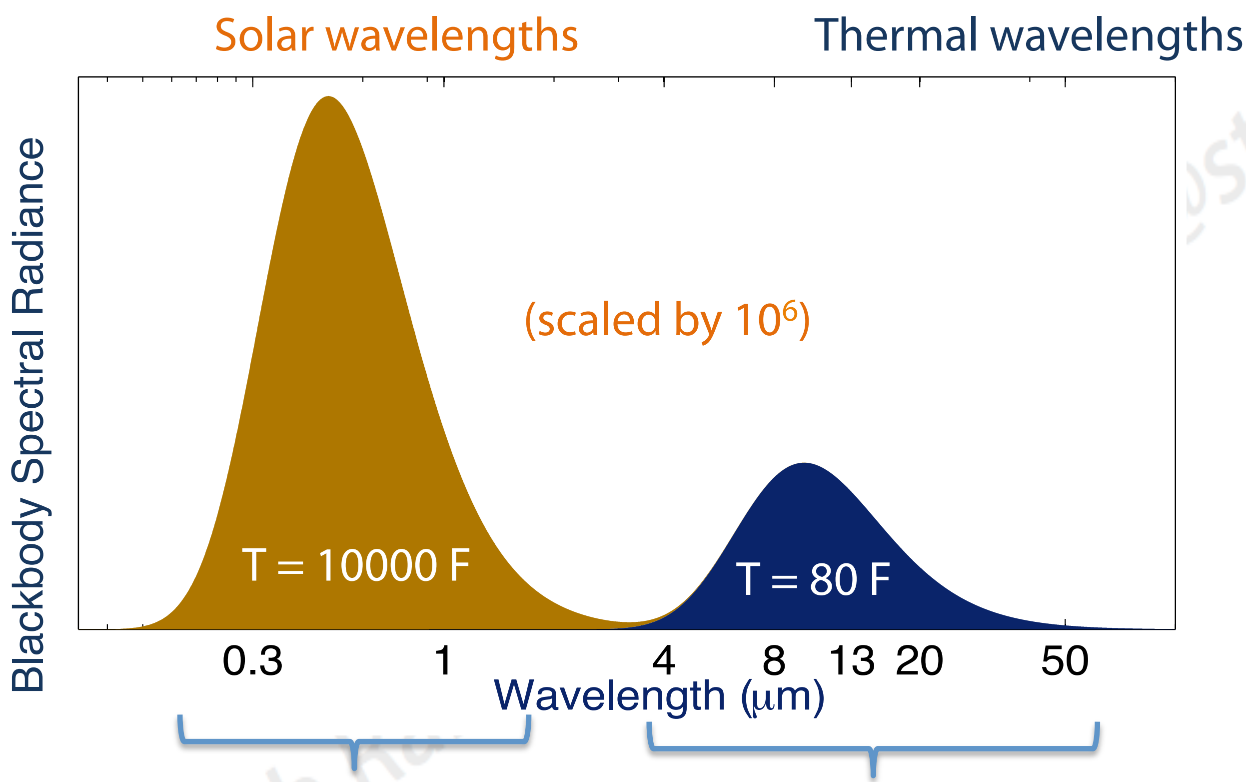
Electromagnetic waves carry energy: Thermal Radiation





Frequency (Hz)	$10^6 - 10^9$	3×10^{13}	6×10^{14}
Wavelength(m)	$10^2 - 10^{-1}$	10×10^{-6}	$\sim 0.5 \times 10^{-6}$

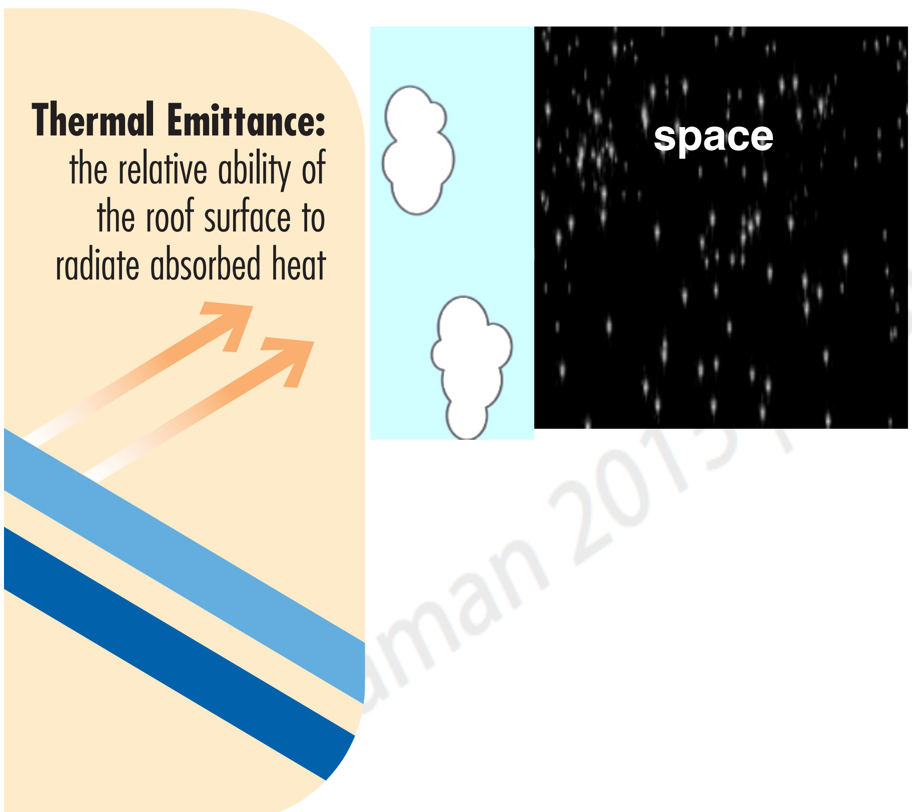
Photonics: Controlling Light with Nano-/ Micro-structures

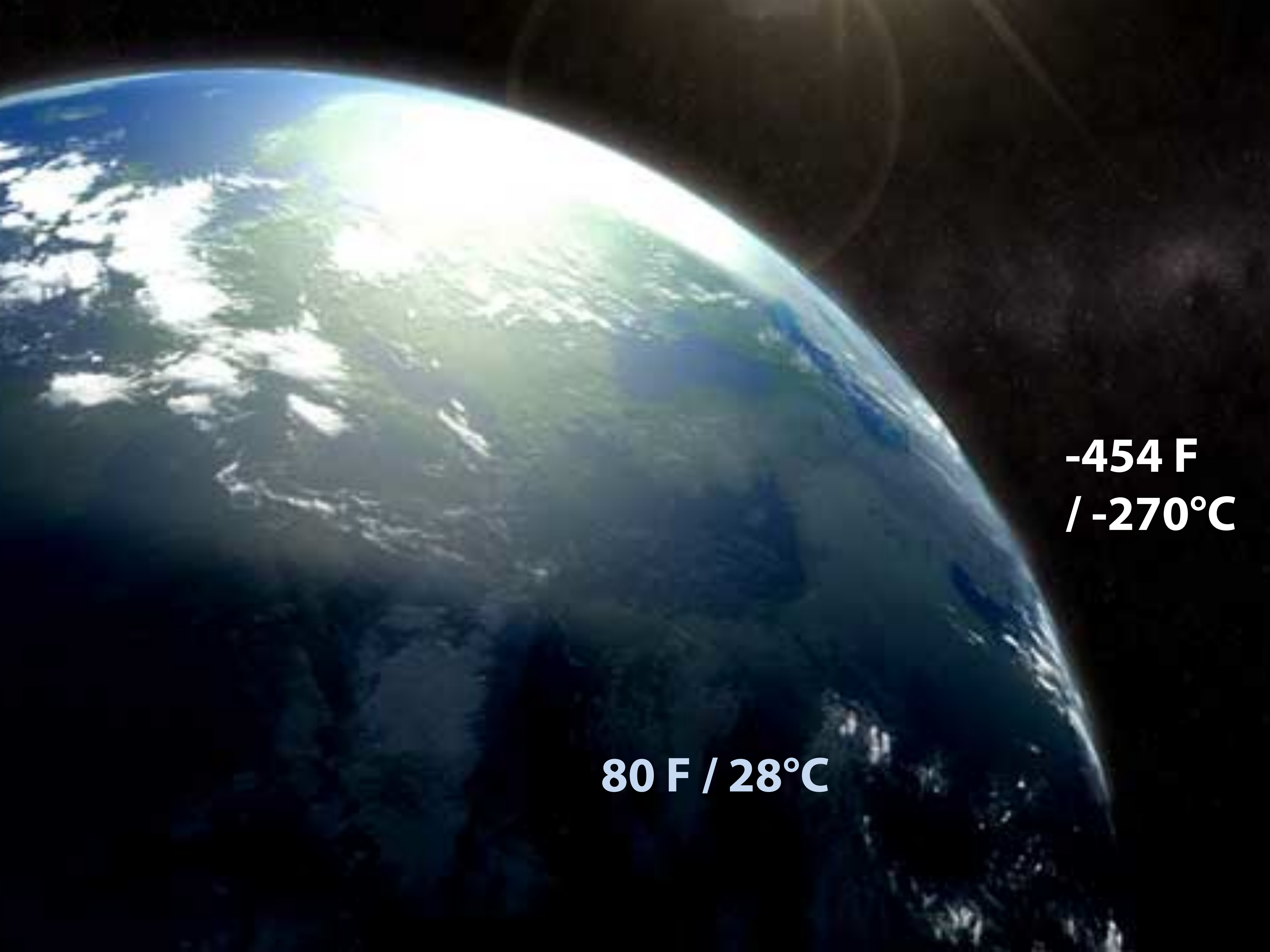


Reflectance and **Thermal Emittance** are not just single numbers**:**

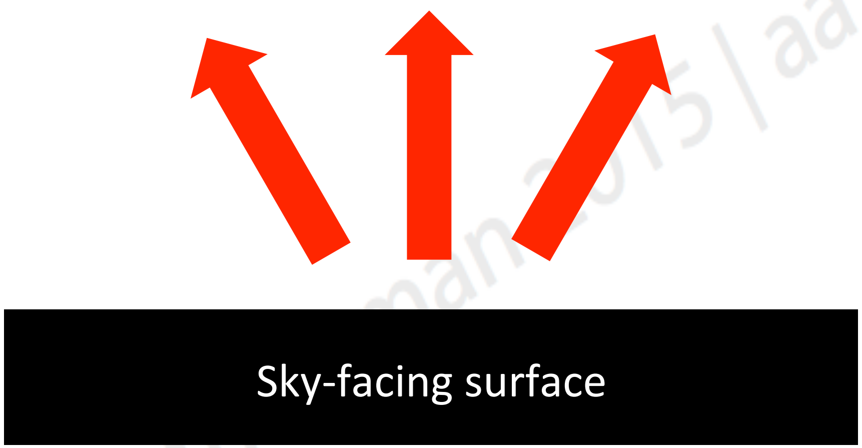
We can design photonic structures to cause them to vary over the above spectrum in remarkable ways

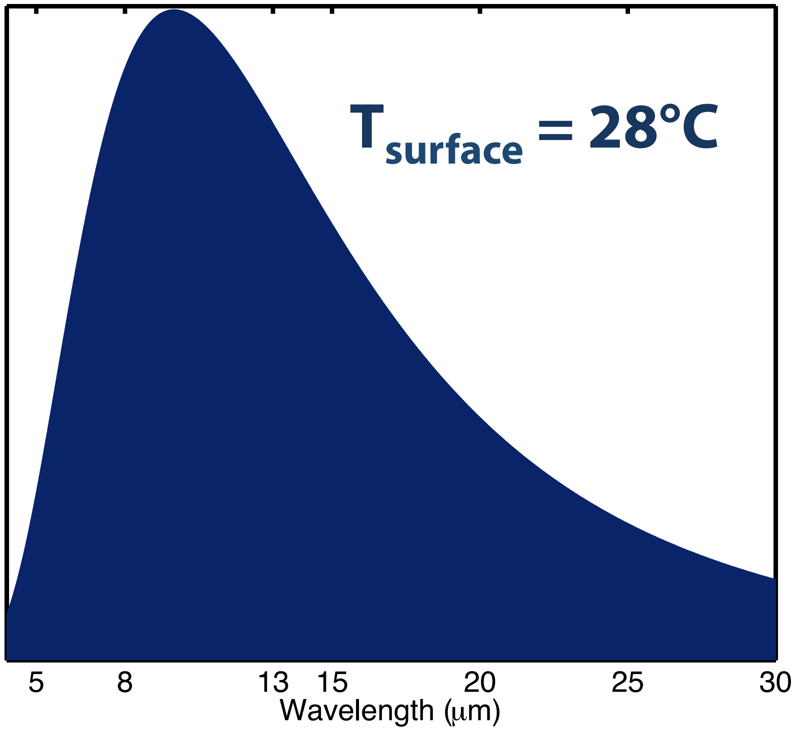
Sky-facing surfaces at night



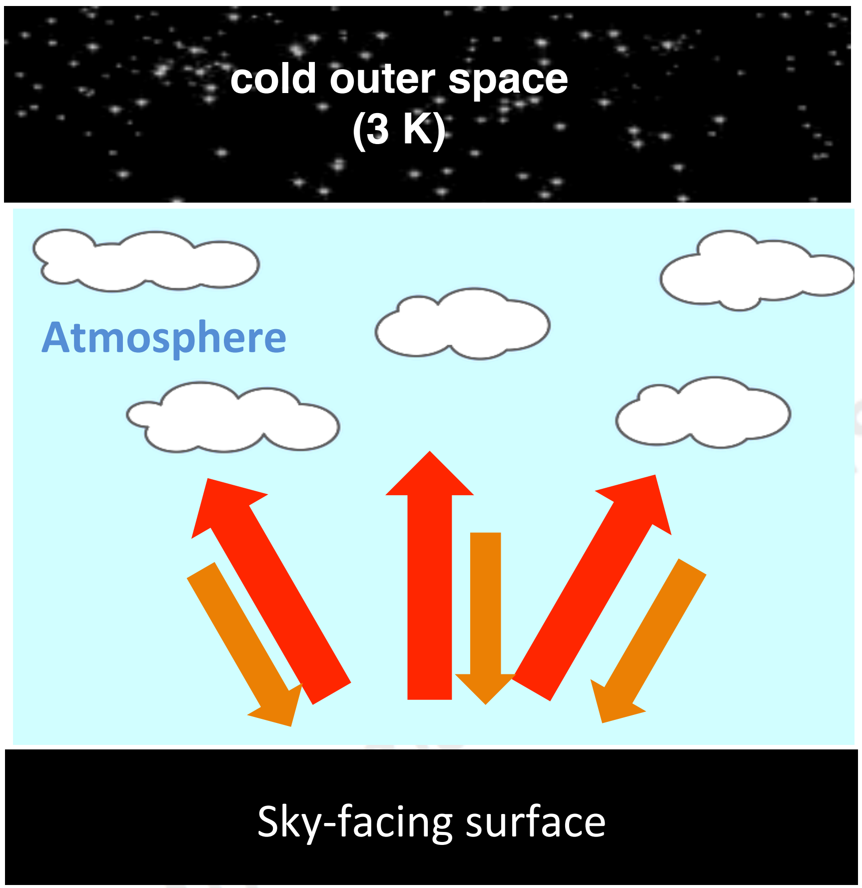

-454 F
/ -270°C
80 F / 28°C

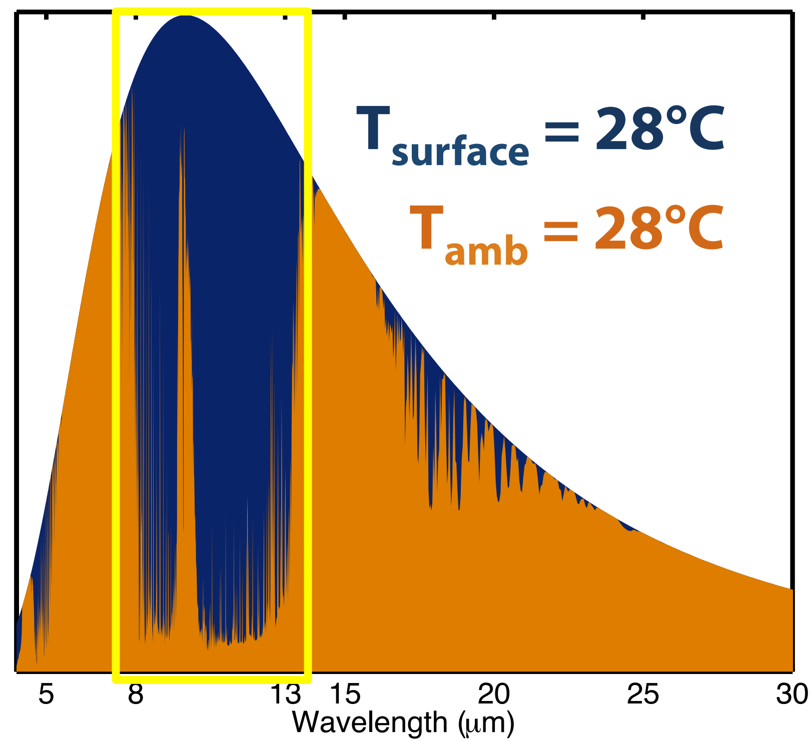
Radiative Cooling Mechanism





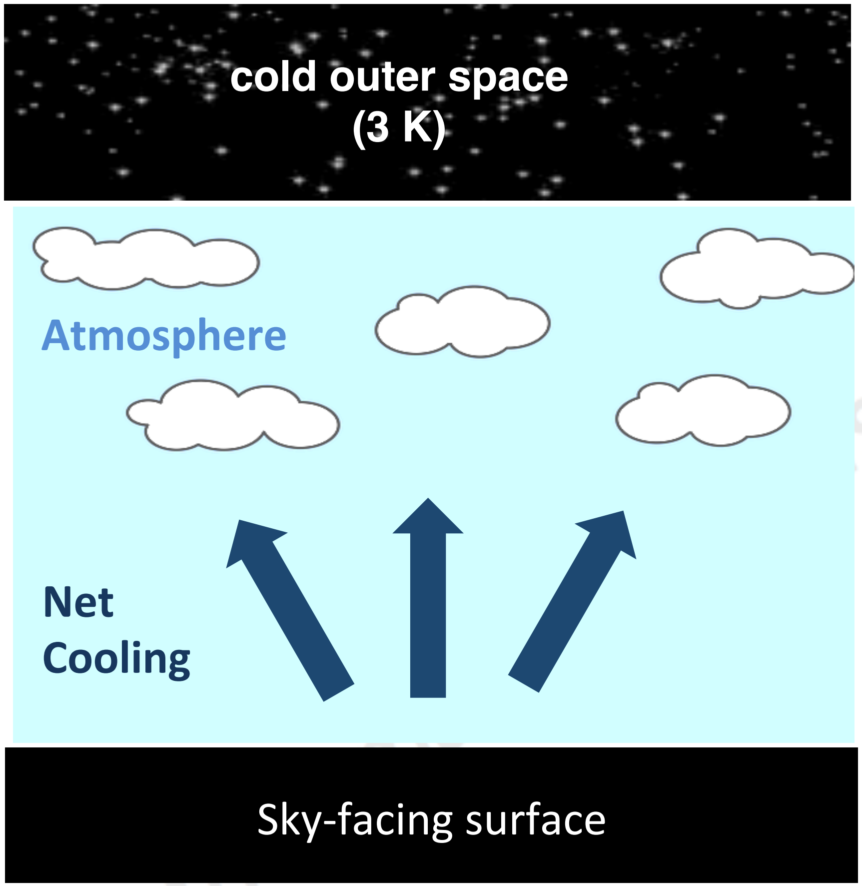
Radiative Cooling Mechanism

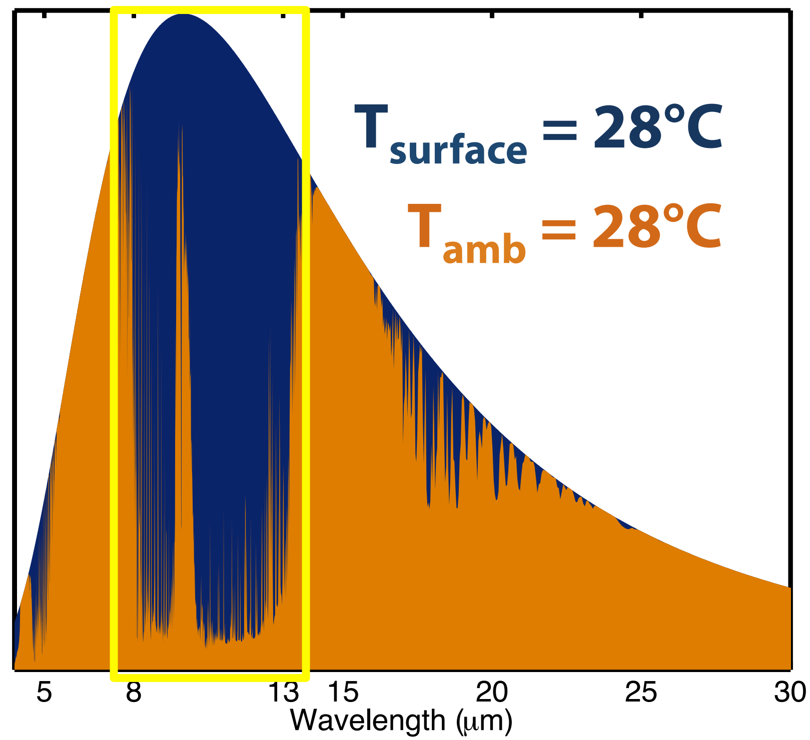




In the infrared transparency window the sky's thermal radiation is much cooler

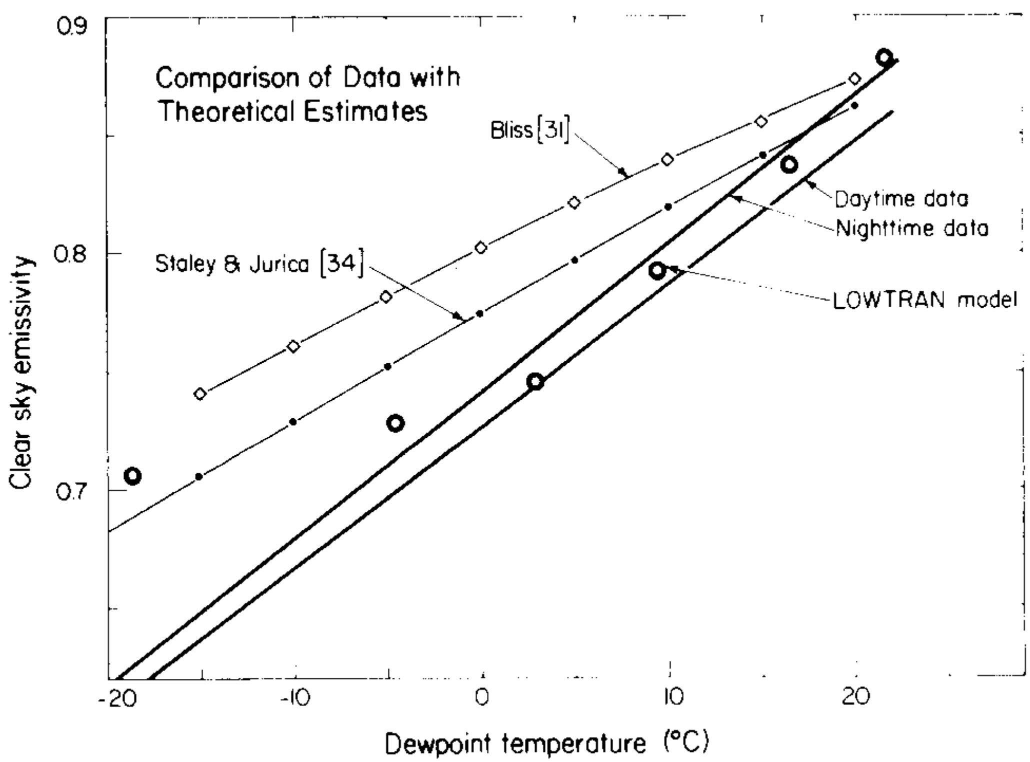
Radiative Cooling Mechanism





In the infrared transparency window the sky's thermal radiation is much cooler:
The sky has low emittance!

Humidity affects infrared atmospheric properties

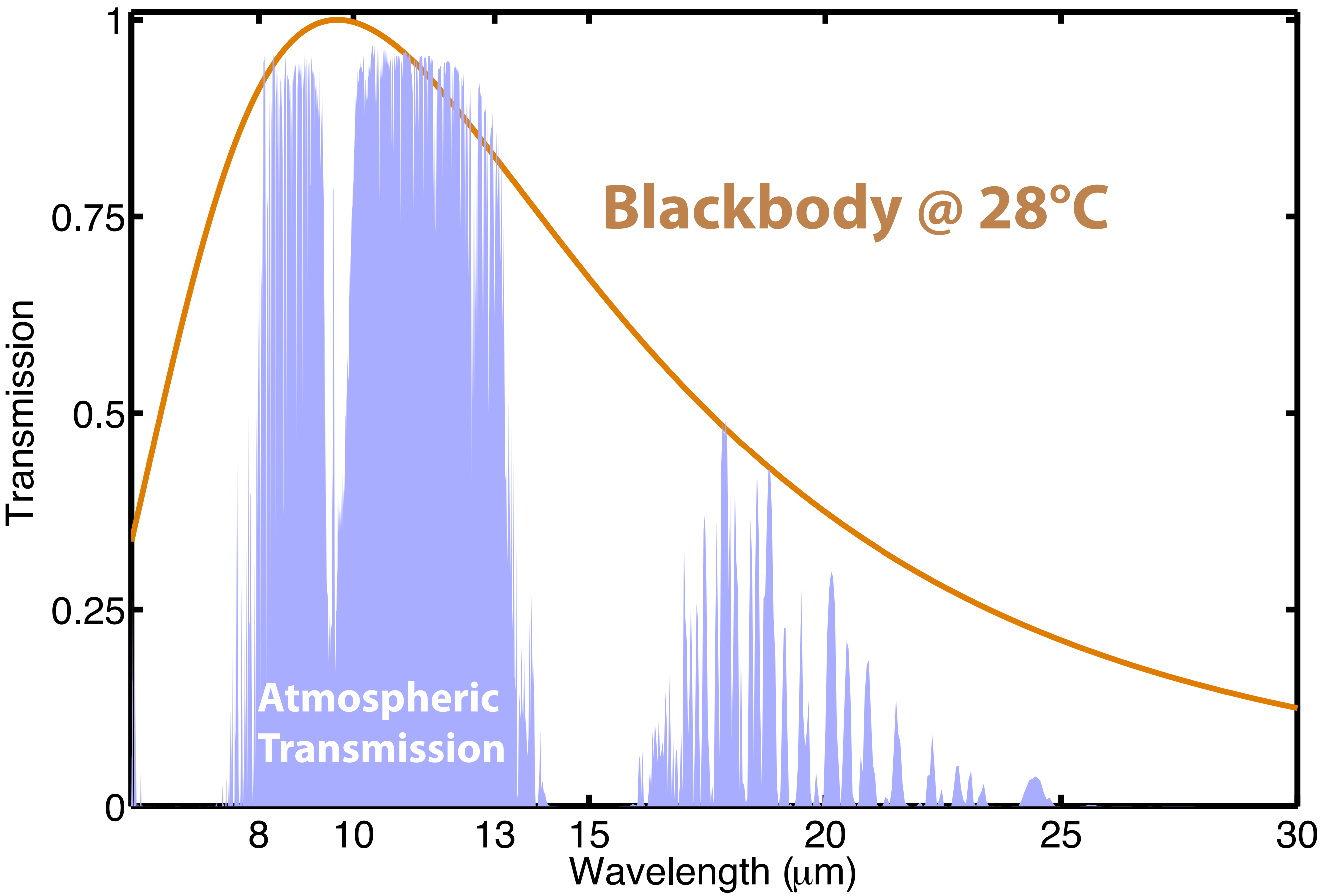


(Clouds too)

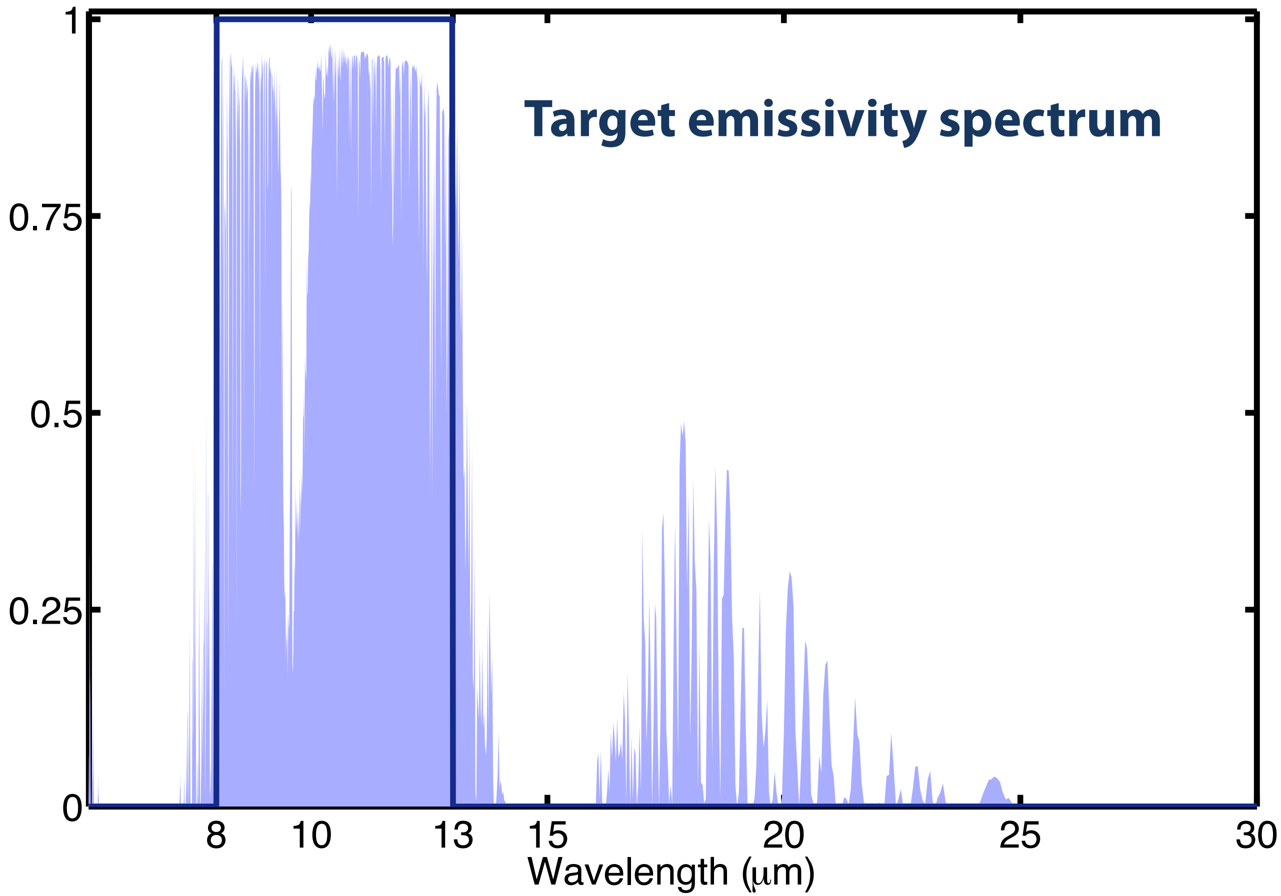
Berdahl and Fromberg, *Solar Energy* (1982)

- Radiative cooling works best in dry climates
- But, it works even better when it's hotter

Atmospheric transparency window

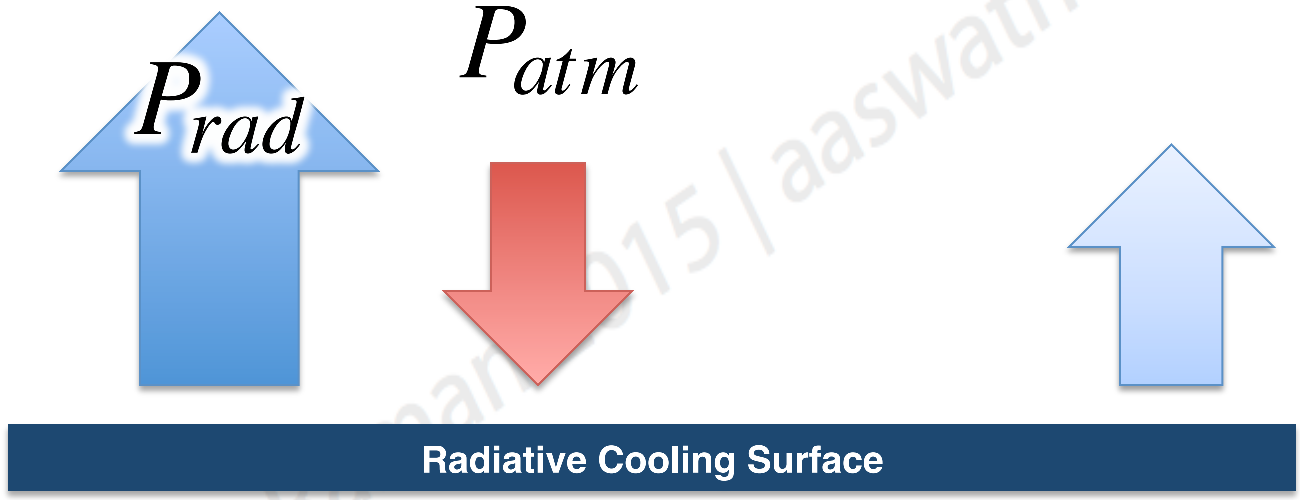


When going subambient the benefits of a *selective* thermal emitter



Power balance equation

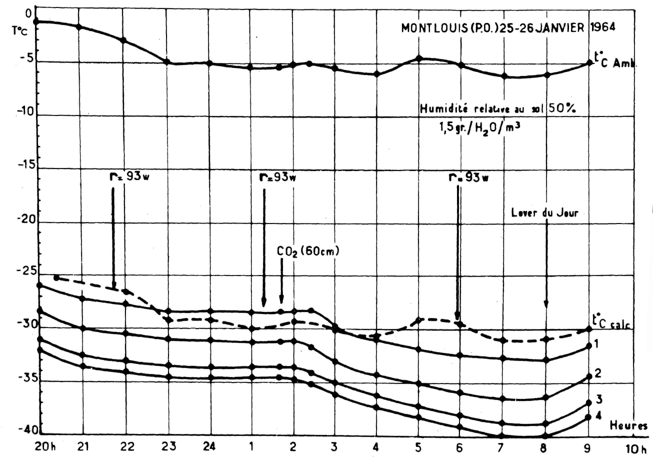
$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb})$$



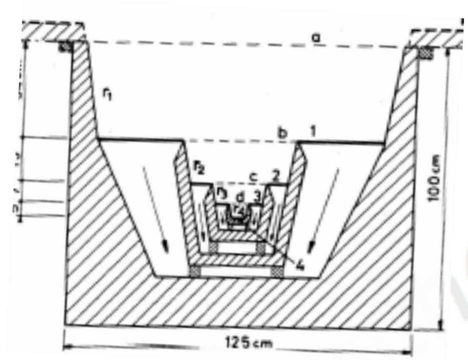
Cooling Power: Net radiating flux out of surface

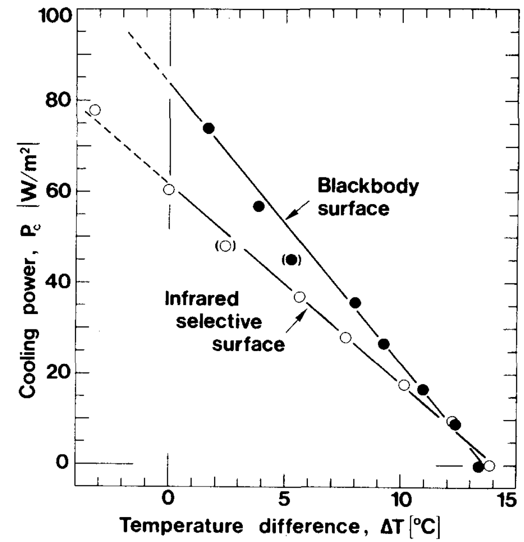
Steady-State Temperature: T when $P_{cool} = 0$

Radiative (sky) cooling: A long history

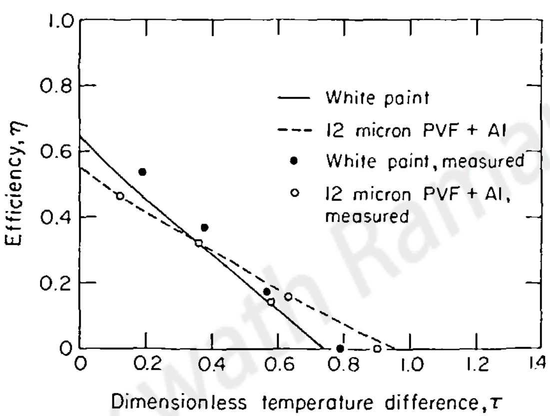


Trombe, F., *Rev. Gen. Therm.* (1967).

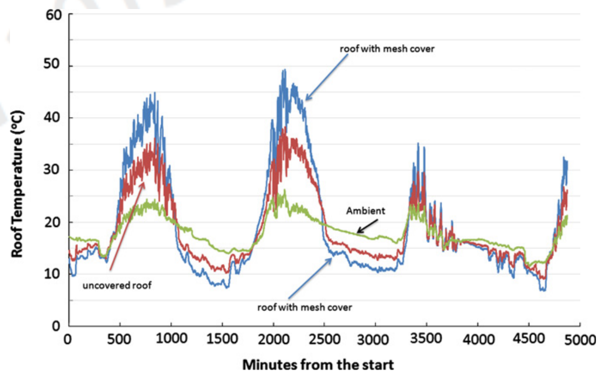




Granqvist & Hjortsberg (1980)



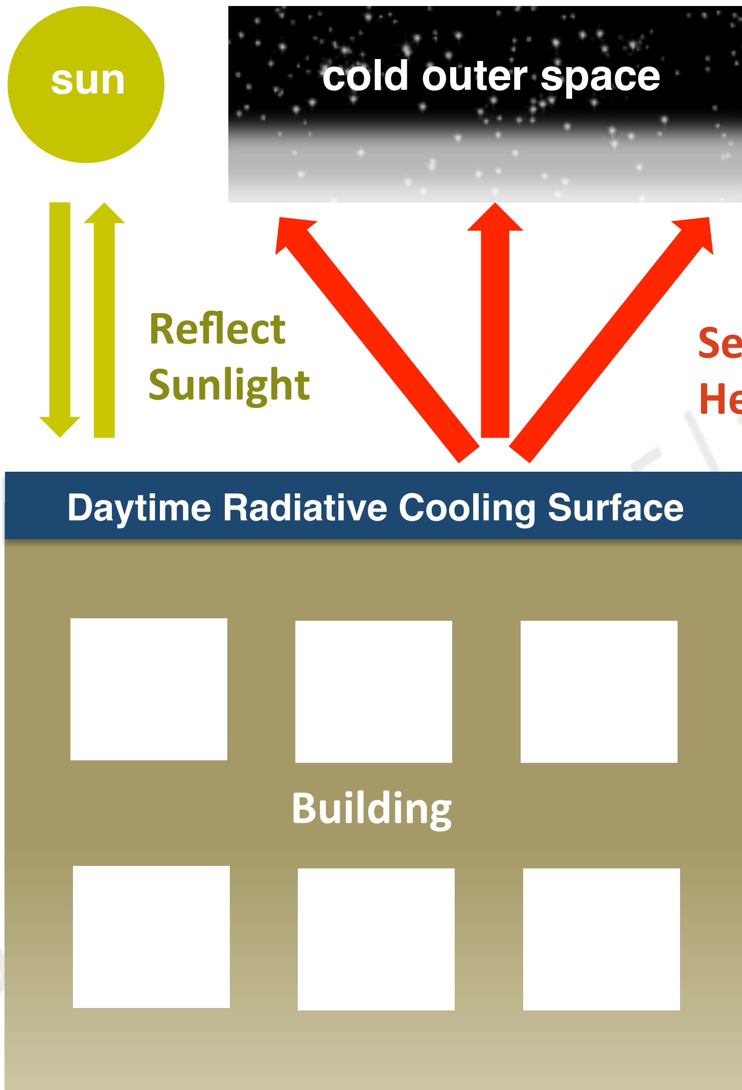
Berdahl, P., Martin, M. & Sakkal, F. *International Journal of Heat and Mass Transfer* 26, 871 – 880 (1983).



Gentle, A., Dybdal, K. L. and Smith, G.B. *Solar Energy and Materials* (2013).

Catalanotti, S. et al. *Solar Energy* 17, 83 – 89 (1975).
Orel, B., Gunde, M. & Krainer, A. *Solar Energy* 50, 477 – 482 (1993).
Gentle, A. R. & Smith, G. B. *Nano Letters* 10, 373–379 (2010).

The challenge: going subambient under sunlight



Sun: ~1000 W/m^2

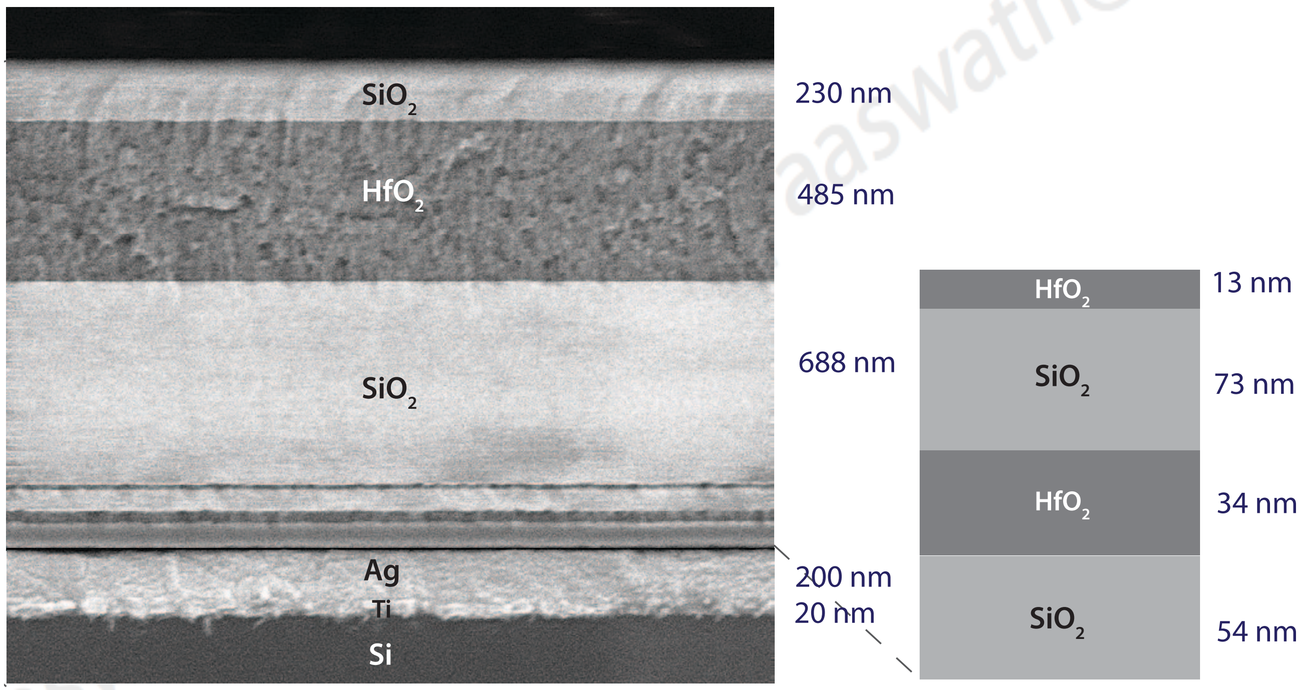
Net infrared radiation out: ~50-100 W/m^2

To get meaningful **cooling** in typical conditions:

Solar reflectance > **95-96%**

Our approach

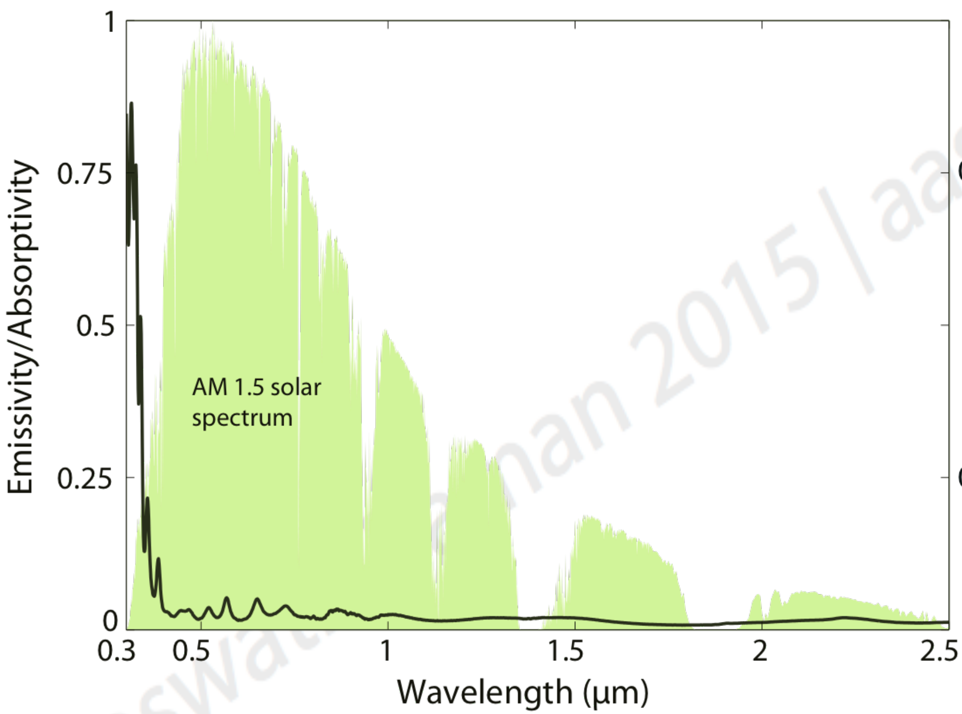
- Deliberately chosen materials and thicknesses to make possible both high solar reflectance and selective thermal emission
- Deposited by e-beam evaporation on 200 mm Si wafers



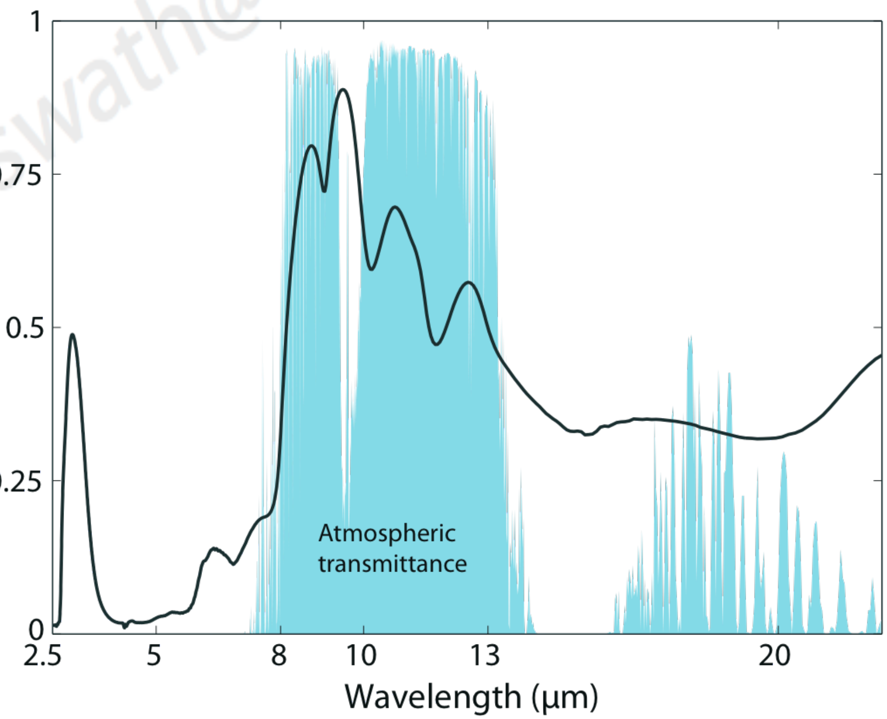
A. Raman, M. Anoma, L. Zhu, E. Rephaeli & S. Fan, *Nature*, **515**, 540-544 (2014)

Spectral characteristics

- 97% solar reflectance
- Selective emissivity within the atmospheric window



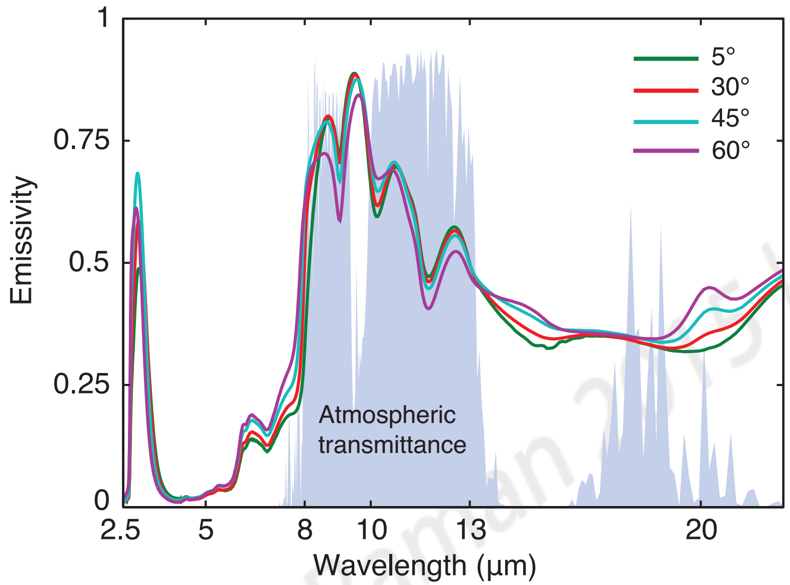
Strong solar reflection

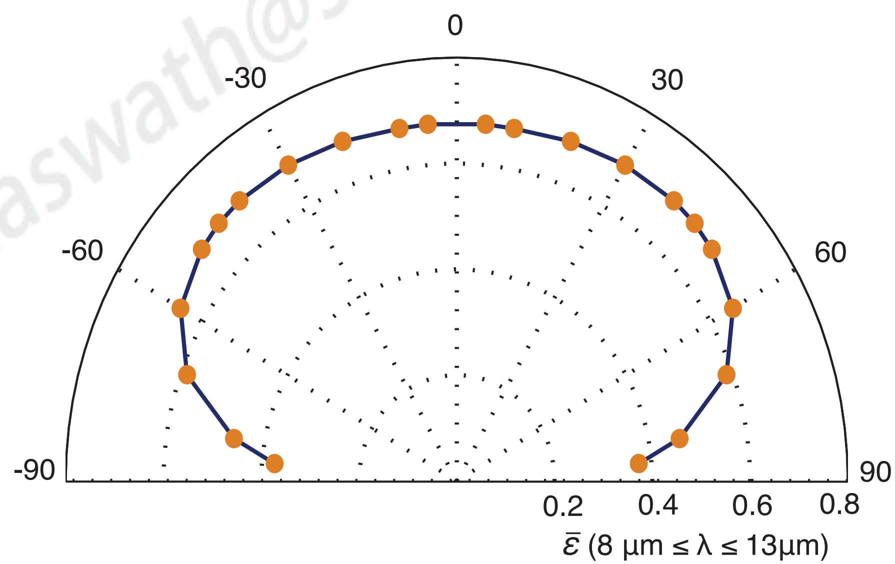


Strong and selective thermal emission

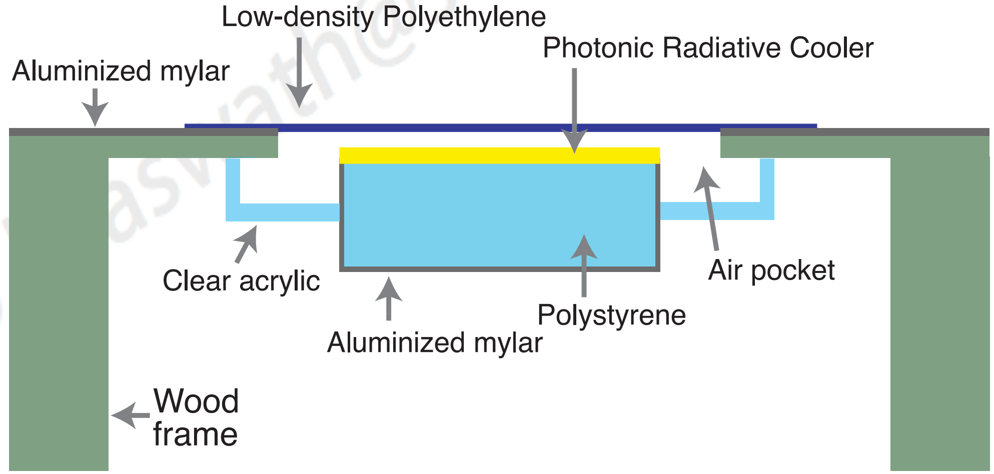
Spectral characteristics

- Strong selective emissivity to relatively large angles for a thin-film stack

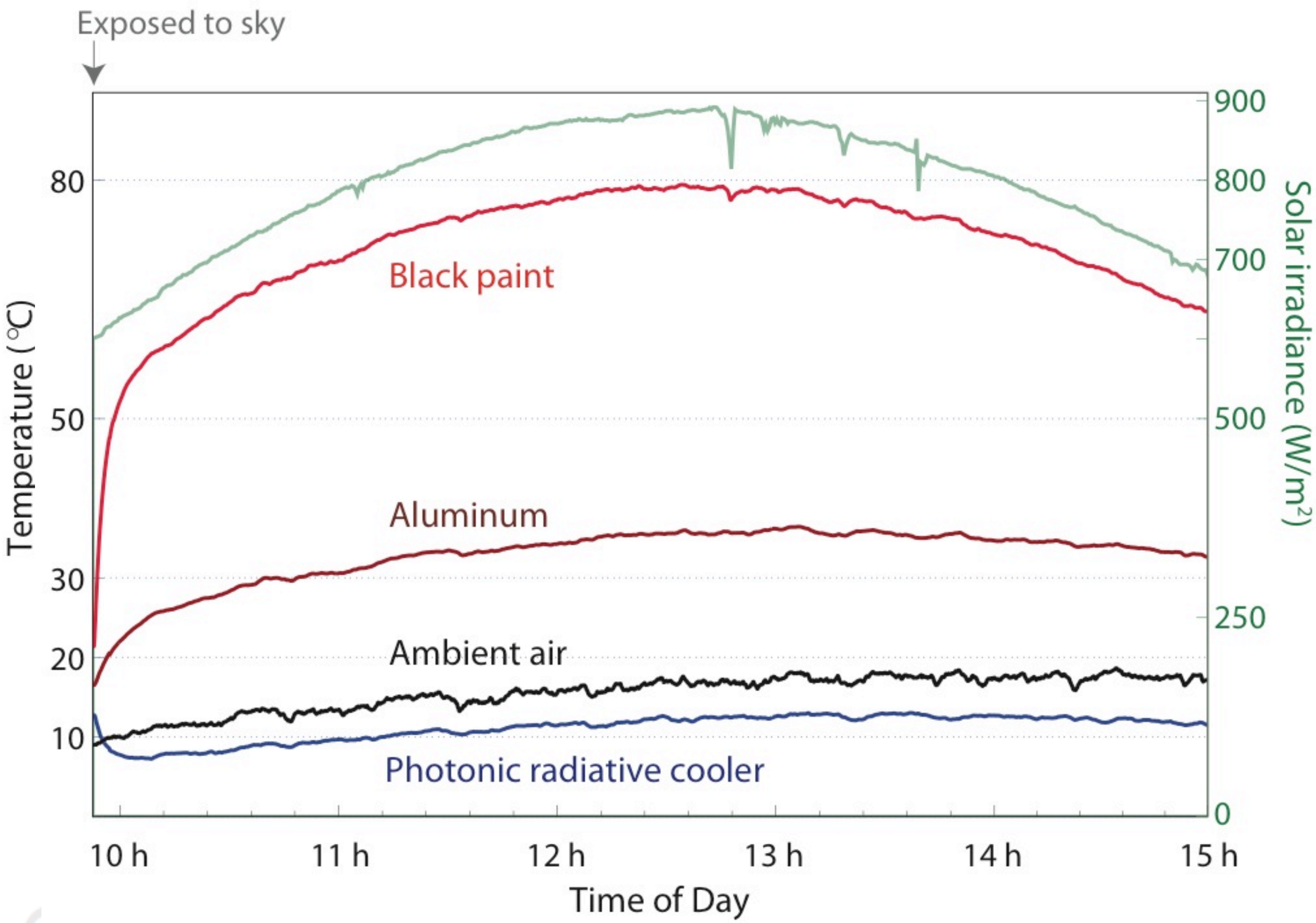




Rooftop testing



Performance under direct sunlight



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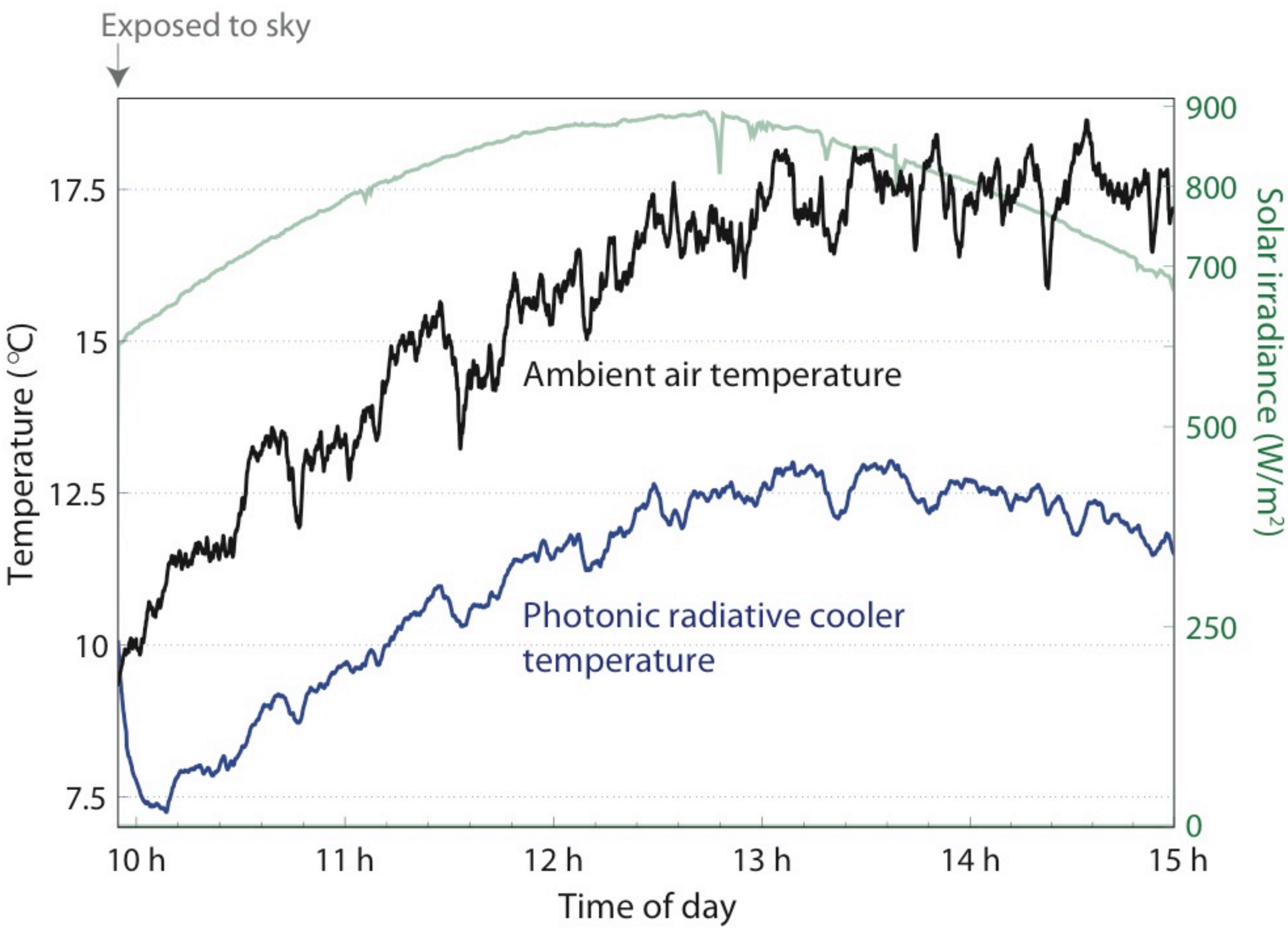
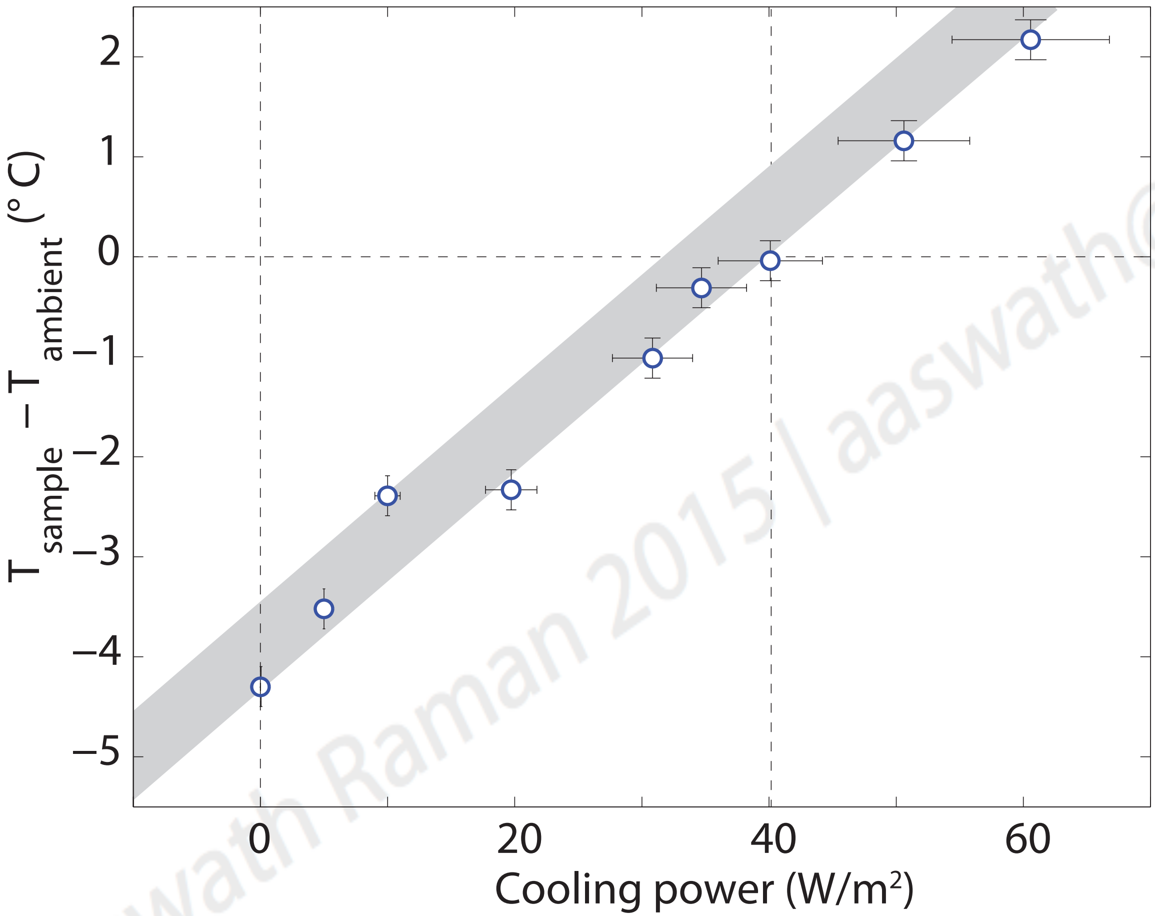


5°C below ambient under > **800 W/m²** solar irradiance

A. Raman et al., *Nature*, **515**, 540-544 (2014)

Cooling power measurement

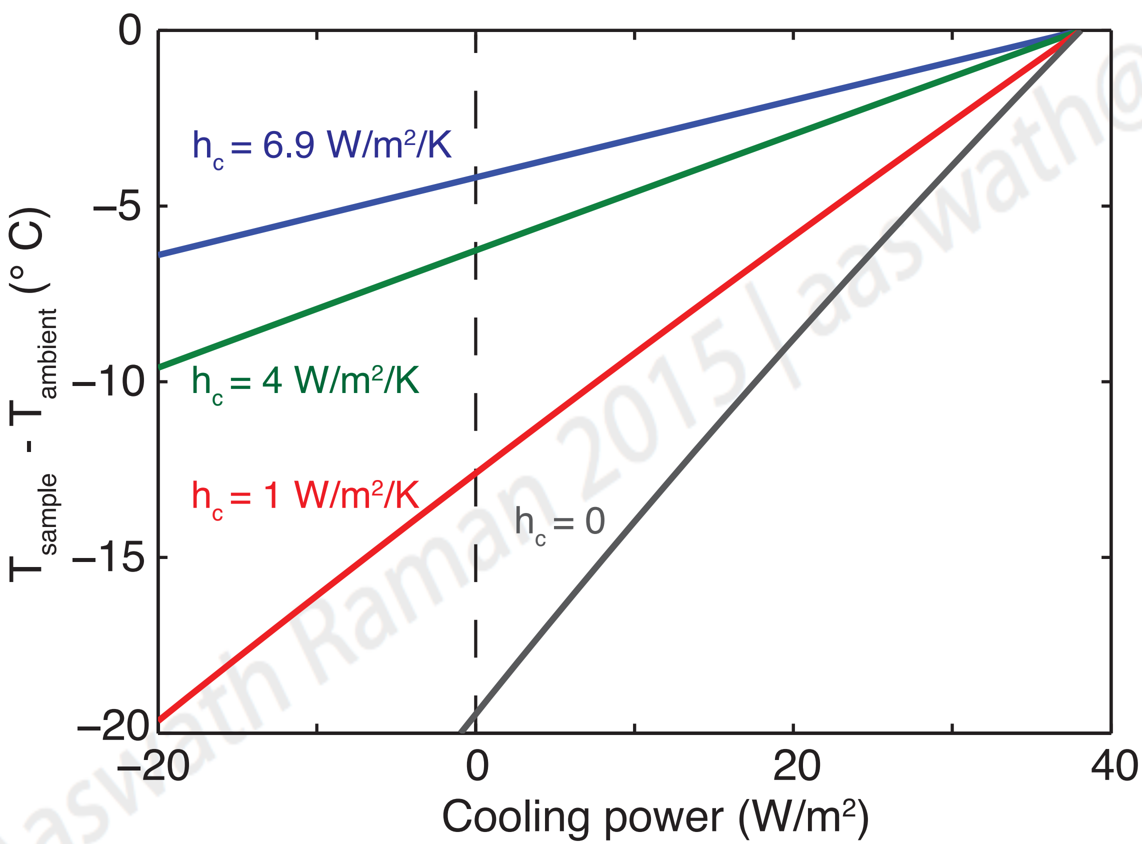


40 W/m² net radiative flux at ambient under > 800 W/m² solar irradiance

Gray line denotes theoretical model whose bounds are defined by varying atmospheric transmittance

Theoretical model: cooling power

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv}$$

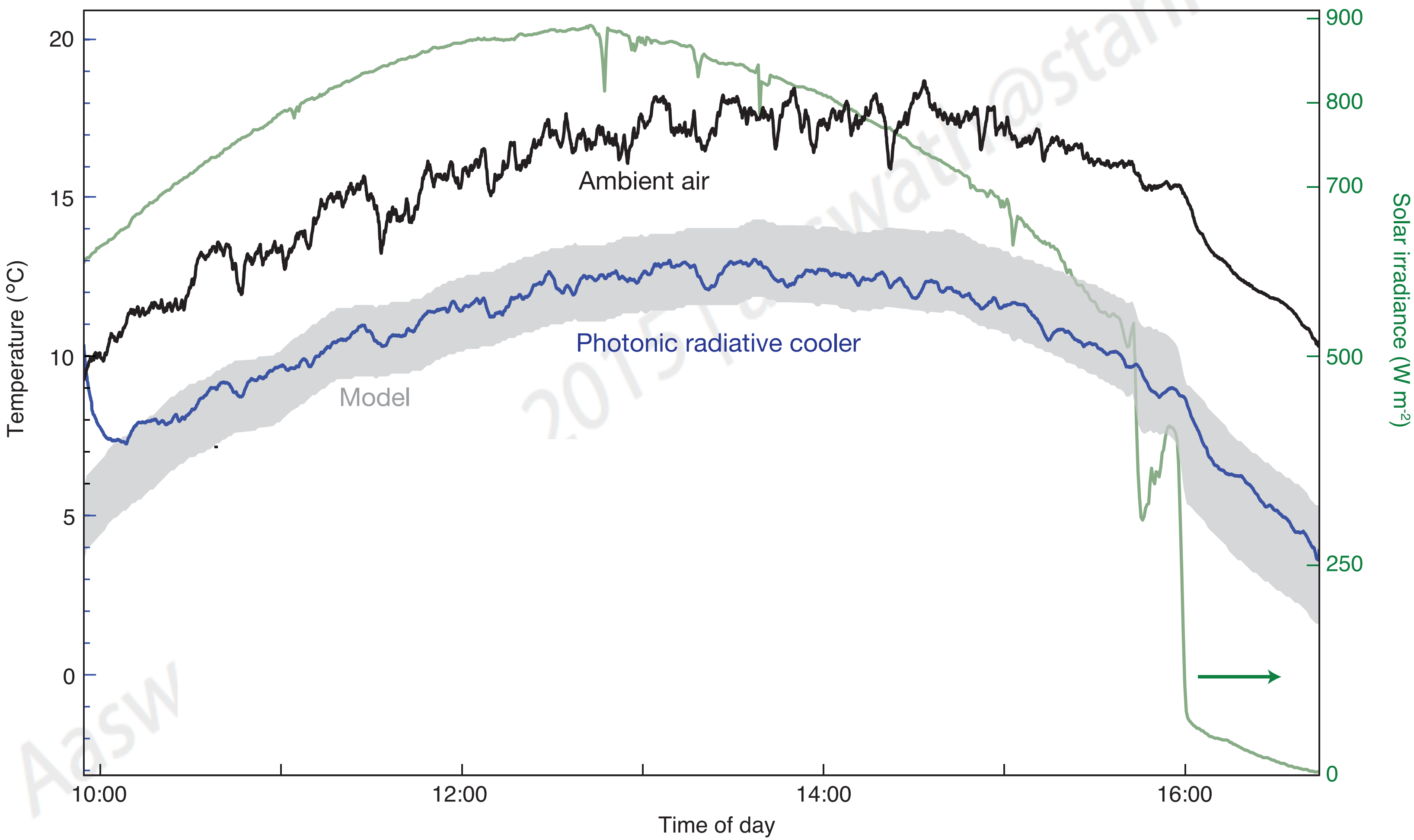


With better packaging and insulation:

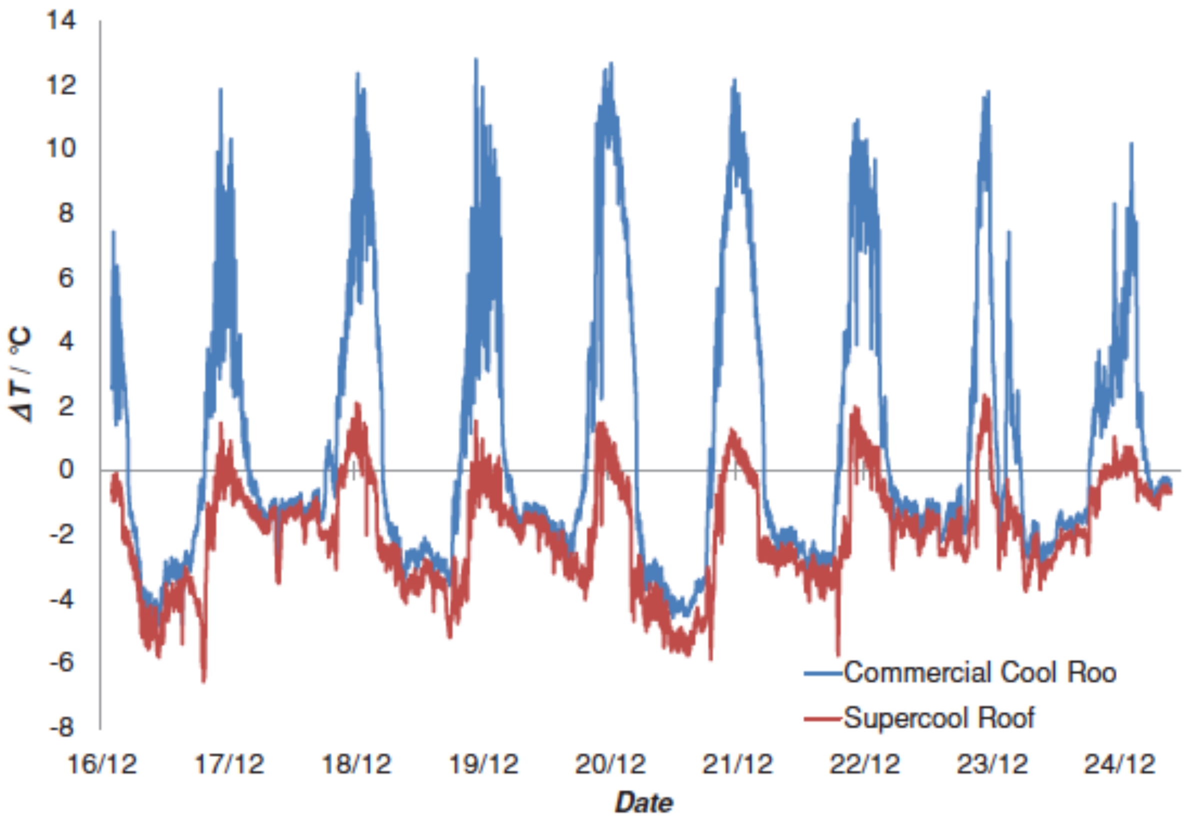
20°C below ambient under direct sunlight

Theoretical model: temperature

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv}$$



Recent demonstrations by other researchers:



Gentle and Smith, *Advanced Science* (2015)

Outlook

- *Challenges* to direct application for roofing: **cost**, **durability**, **appearance**, **wind shielding**

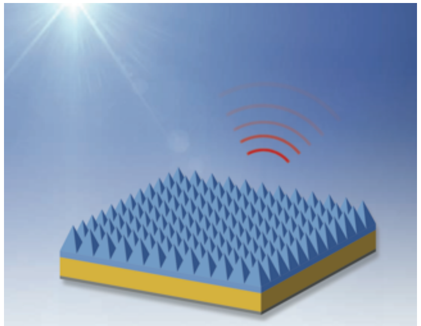
- *What's new:* Electricity and water-free way of dissipating heat loads to *below* ambient

- Rejecting interior heat loads and directly substituting for A/C electricity and water use: *beyond the envelope*

Tuning thermal emittance by design

- Tuning and optimizing thermal emittance makes possible new efficiency gains by using the sky's 'resource' more effectively: new energy opportunities!

- One example: **cooling solar cells** (lower operating temperature 10+°C)



A. Raman*, L. Zhu* and S. Fan (in review)
L. Zhu, A. Raman, K. Wang, M. Anoma & S. Fan, *Optica*, **1** (1), 32 (2014)

Direct roof applications?

Uninsulated structures, especially off-grid could directly benefit from a subambient cool roof: direct air flow beneath a sub-ambient cooling roof surface

(in western Kenya)

Some potential takeaways to consider for cool roofs

- Recent developments from the photonics and optics world could be leveraged to assist or improve cool roofs
- Deterministically manipulating (and increasing/decreasing) thermal emittance at certain wavelengths while increasing solar reflectance: new possibilities
- Subambient cooling by a module would be best achieved on a cool roof: complementary
- Night sky radiative cooling is already accessible and prominent in arid climates: opportunities to reconsider in today's energy and buildings landscape?

Acknowledgments

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Zach Weiner
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Ben Jensen

Dr. Eli Goldstein
Danielle Cotugno
Linxiao Zhu
Marc Anoma

Advanced Research Projects Agency - Energy

OPEN 2012 Awardee

Summary

- Recent developments from the photonics and optics world could be leveraged to assist or improve cool roofs
- Subambient surfaces can benefit from having spectrally selective thermal emittance behavior
- The coldness of the universe is an under-exploited thermodynamic resource for energy processes on Earth

[1] A. Raman, M. Anoma, L. Zhu, E. Rephaeli & S. Fan, *Nature,* **515**, 540-544 (2014)

[2] L. Zhu, A. Raman, K. Wang, M. Anoma & S. Fan, *Optica*, **1** (1), 32 (2014)

[3] L. Zhu*, A. Raman* & S. Fan, *Submitted* (2015)

[4] E. Rephaeli*, A. Raman* & S. Fan, *Nano Letters* (2013)