Ultra-White Paints for Sub-Ambient Radiative Cooling: Materials, Physics, and Climate Crisis Mitigation

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CRRC Annual Meeting
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Introduction – Xiangyu Li, PhD

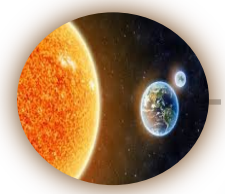
- Ph.D., Purdue University
  - Advisor: Xiulin Ruan
  - Nanoscale heat transfer, composite materials
- Postdoctoral Associate, MIT
  - Advisor: Evelyn N. Wang
  - Thermal energy storage, adsorption systems
- Assistant Professor, MABE, UTK
  - Water Innovation, Sustainable Energy (WISE)
  - **xli148@utk.edu**

PURDUE UNIVERSITY

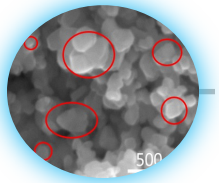
Massachusetts Institute of Technology

THE UNIVERSITY OF TENNESSEE KNOXVILLE

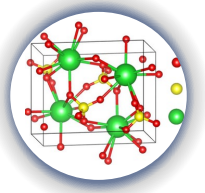
Outline



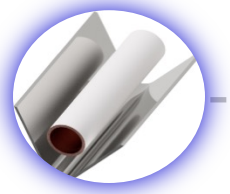
Motivation and Background



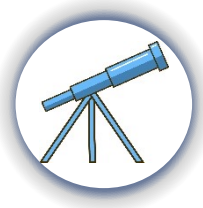
Materials



Physics

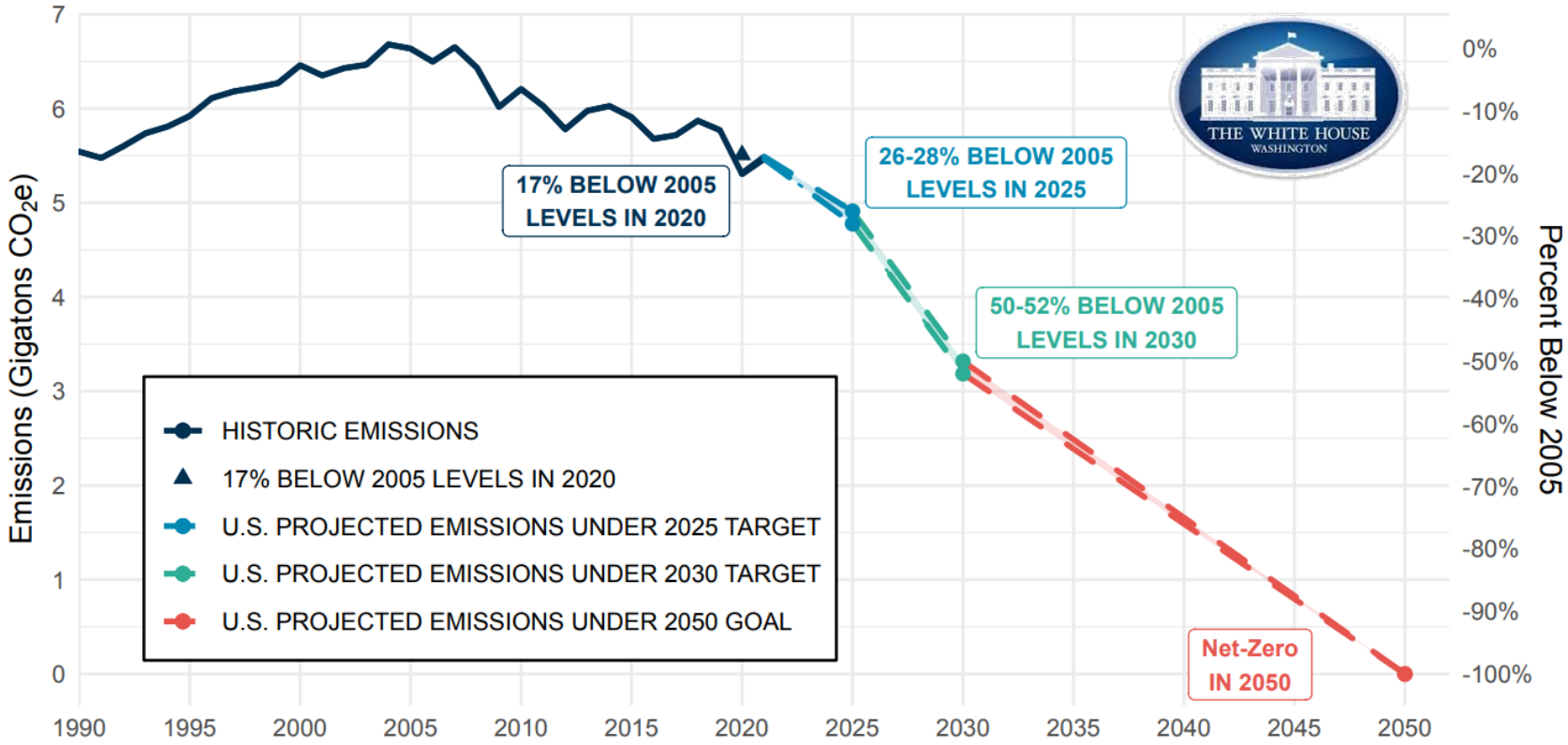


Energy Savings and Climate Crisis Mitigation



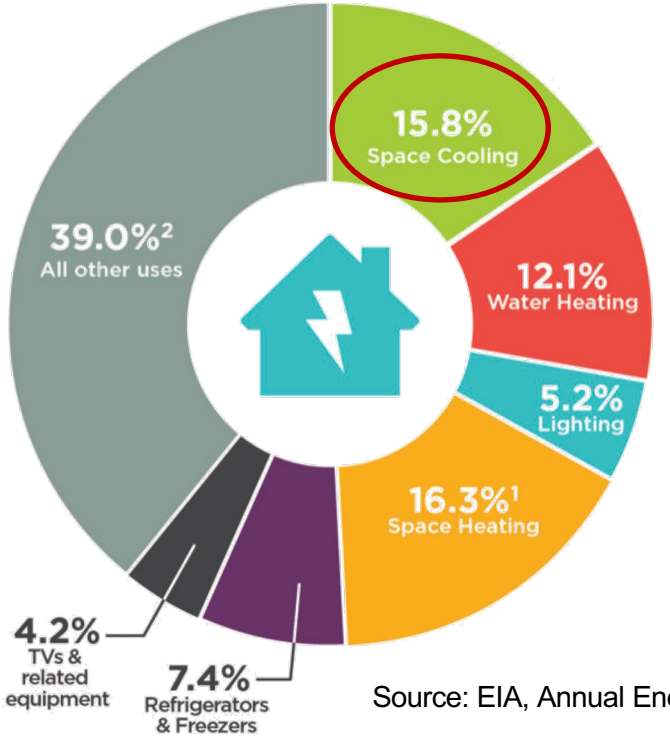
Outlook

US Commitment: Net-Zero Carbon Emission in 2050



Source: https://www.whitehouse.gov/

Space Cooling



Source: EIA, Annual Energy Outlook 2020

Source: https://depositphotos.com/

Conventional AC

Electricity consumption

More heat rejected outside

Heat island effect

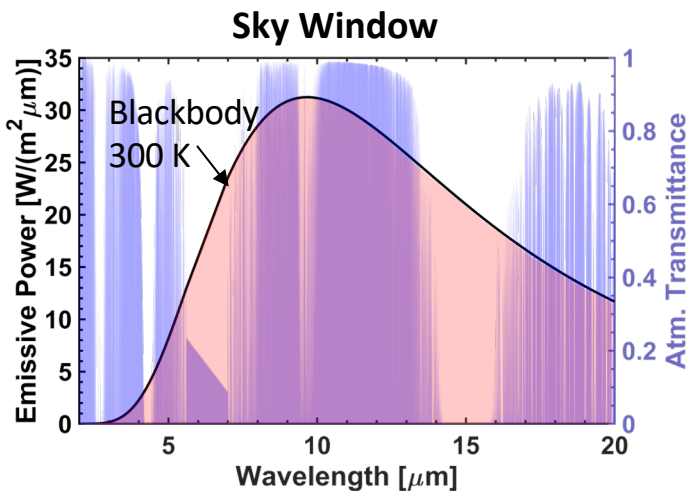
Carbon emission

Global warming

- Space cooling consumes 113 million tons of CO_2 emission
- Building envelope constitutes 70% of the total heat gain

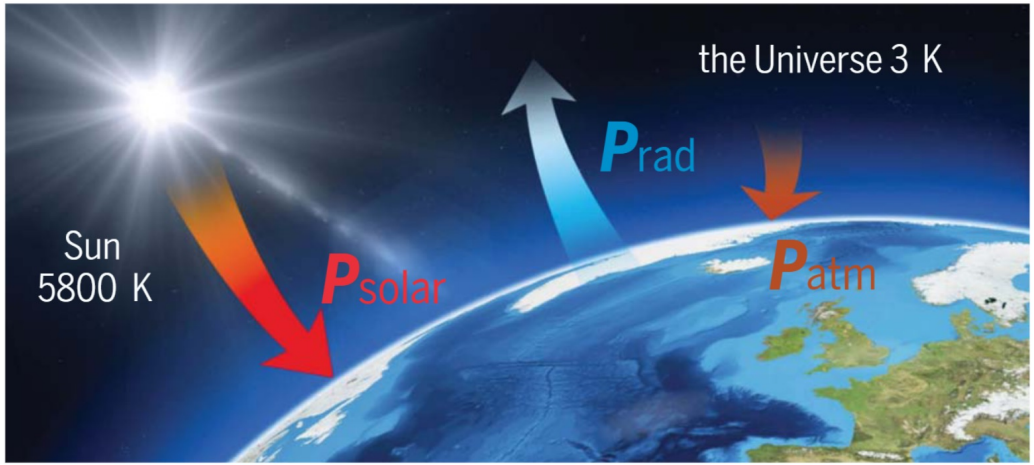
Radiative Cooling

- Passive radiative cooling
  - Radiation to deep sky (~ 3 K)
  - No energy consumption



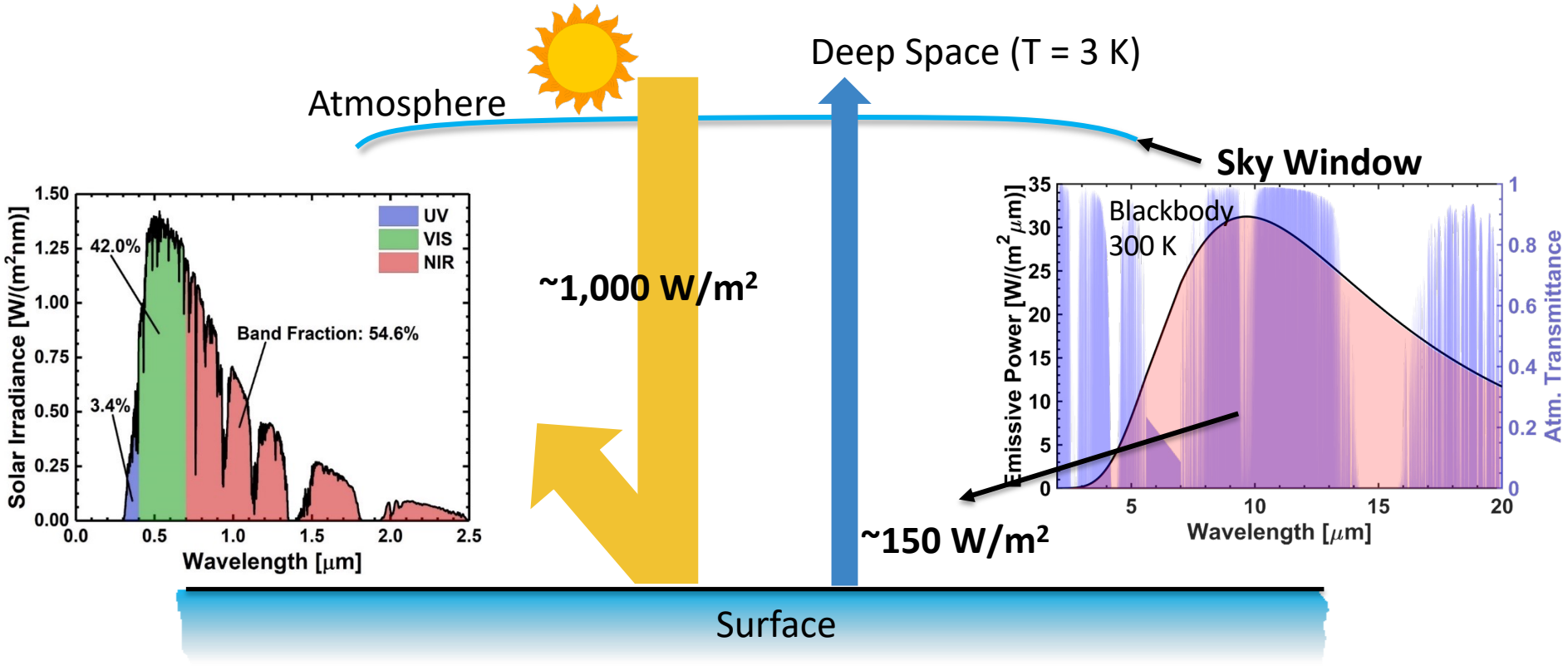
http://www.gemini.edu/?q=node/10789

(AM1.0, water vapor 1.0 mmH_2O)



Yin, X., et al. (2020). Science, 370(6518), 786-791.

Radiative Cooling



Passive cooling power $P_{rad} - P_{atm} - P_{sun}$

Thermal radiation

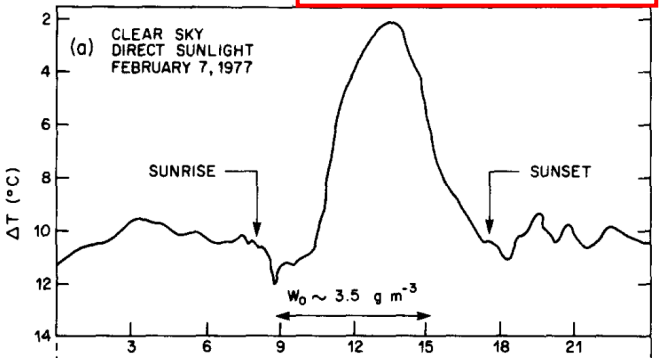
Heat transfer w/ atmosphere

Solar absorption

Pursuits of Radiative Cooling Paints

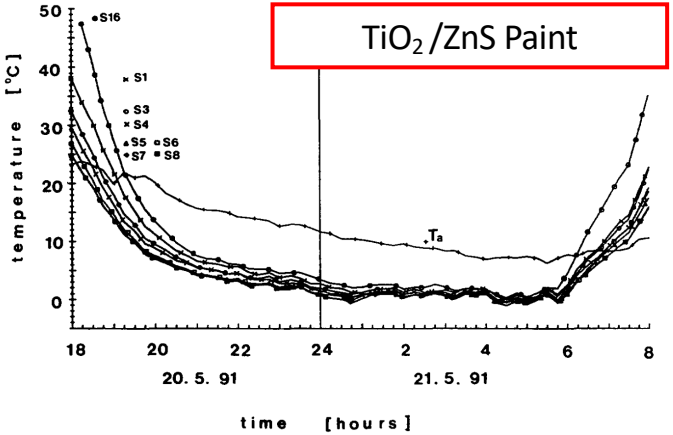
- Insufficient solar reflectance (80-90%)
- Weak daytime performance

TiO_2 Paint + Al Plate



Harrison, A. W *et al* (1978). *Solar Energy*, *20*(2), 185-188.

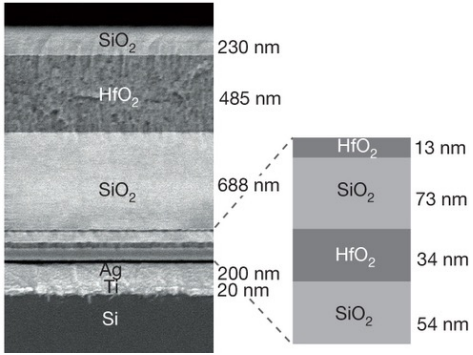
TiO_2 /ZnS Paint



Orel, B., *et al* (1993). *Solar Energy*, *50*(6), 477–482.

Daytime Radiative Cooling

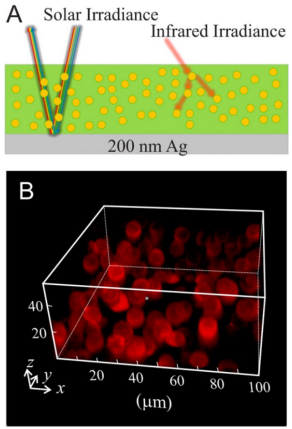
Multilayer film



Raman, et al. (2014) *Nature*

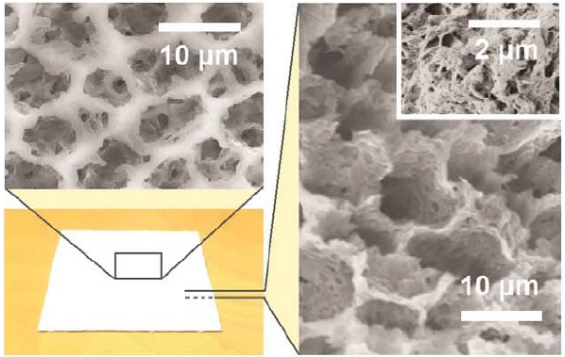
Silica mirror

Kou, et al., (2017) *ACS Photonics*



Zhai, et al., *(2017) Science*

Highly porous polymers



Mandal, *et al.* (2018) *Science*

Delignified wood

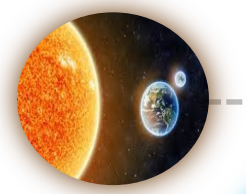
Li, et al., (2019) *Science*

Polyethylene aerogel

Leroy, et al. (2019) *Science Advances*

- **Limitations:**
  - High cost
  - Metallic components
  - High thickness

Outline



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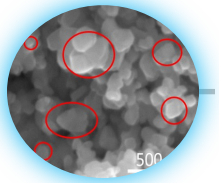

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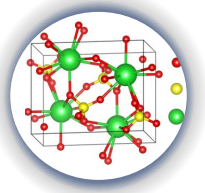

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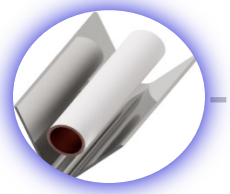

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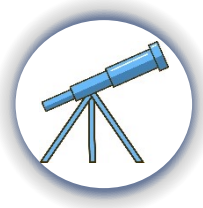
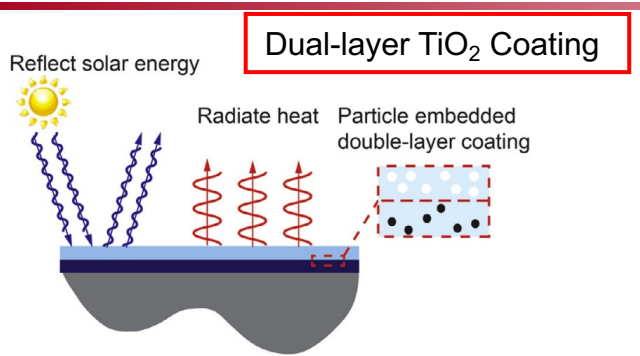


Outlook

Renaissance of the Paint Approach

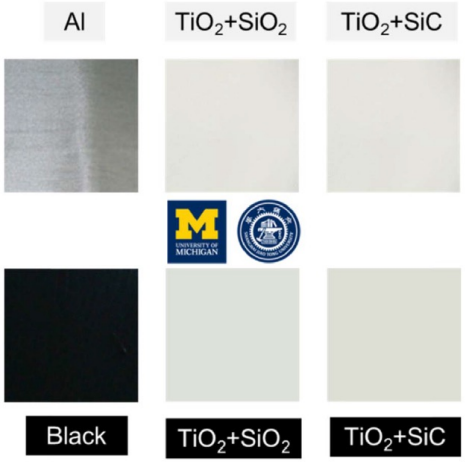


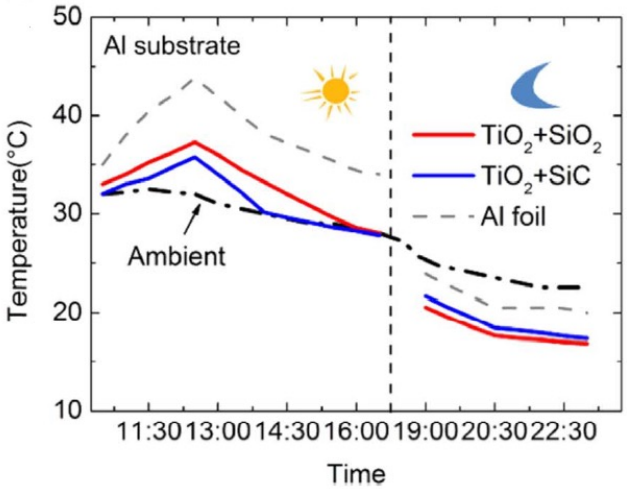
- Lorentz Mie theory analyzes a photon's interaction with a single particle
- Monte Carlo on effective medium is low computational cost

Prof. Zhifeng Huang
Wuhan Univ.

Huang and Ruan, (2017). *Int. J. Heat Mass Transf*, *104*, 890–896.

Clarivate Web of Science™ Highly Cited Paper





Prof. Hua Bao
SJTU

Bao, Yan, Wang, Fang, Zhao, and Ruan, Sol. Eng. Mat. Sol. Cell 168, 78-84 (2017).

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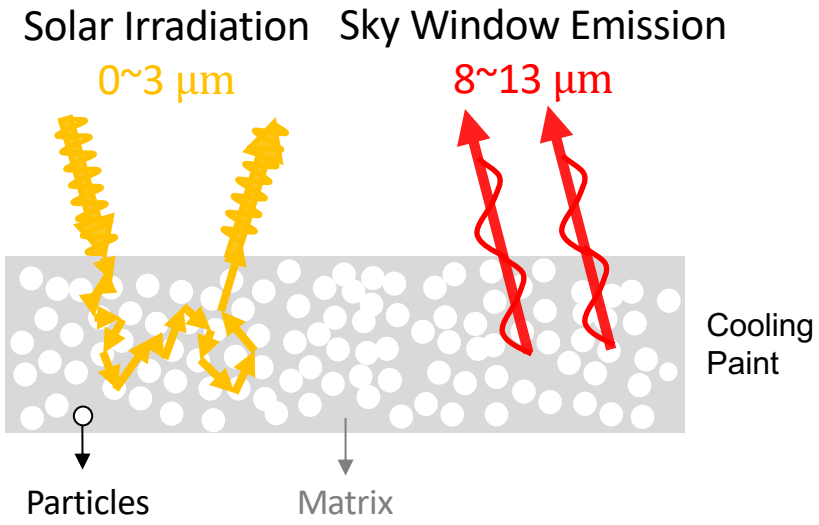
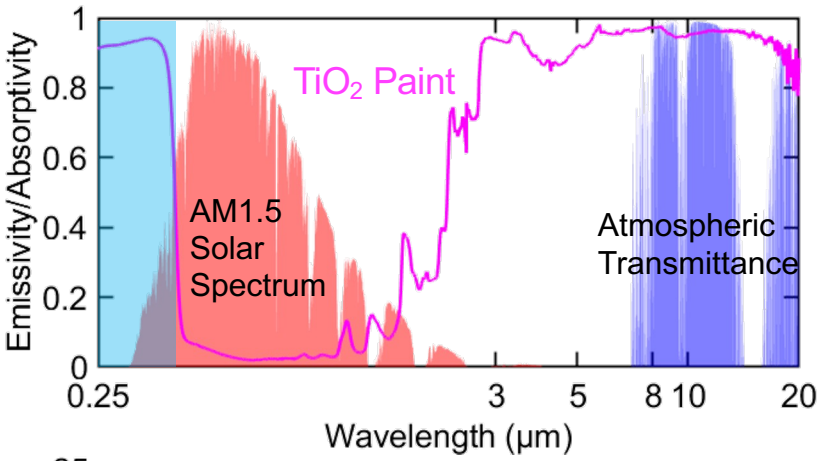
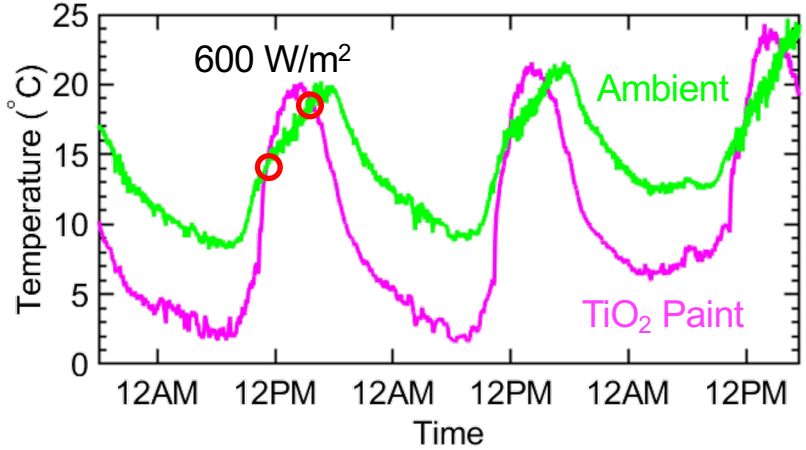
Renaissance of Cooling Paint



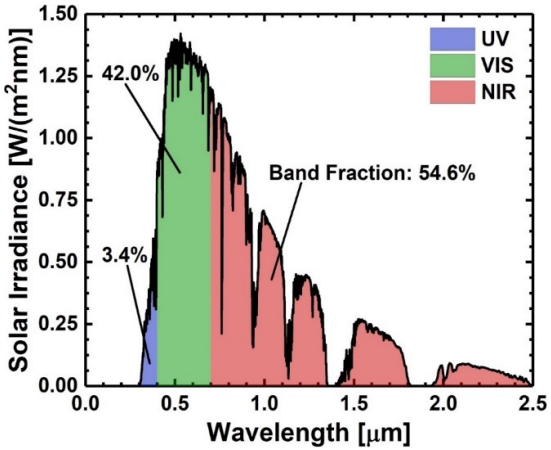


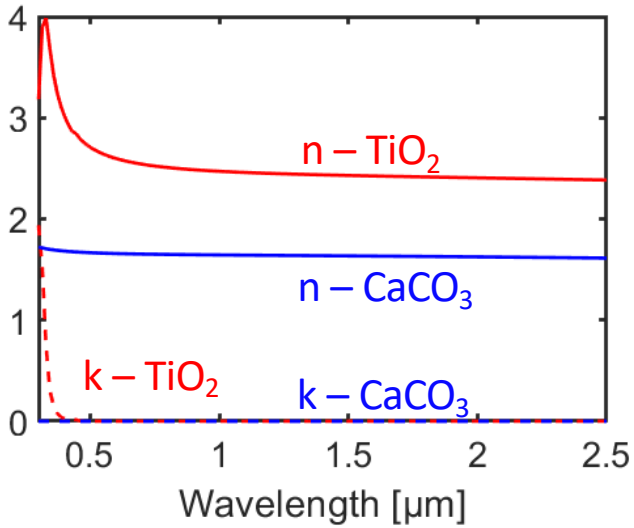


Passive Radiative Cooling Paints

- High electron band gap to reduce absorption of the UV band

Material	Band Gap (eV)	Wavelength (nm)	Refractive Index @ 633 nm
TiO_2	3.1	407	2.87
ZnS	3.5	350	2.36
Al_2O_3	4.6	267	1.77
$CaCO_3$	**5.1**	**245**	**1.66**





Complex refractive index

$m = n + ik$ → Extinction coefficient

↓

Refractive index

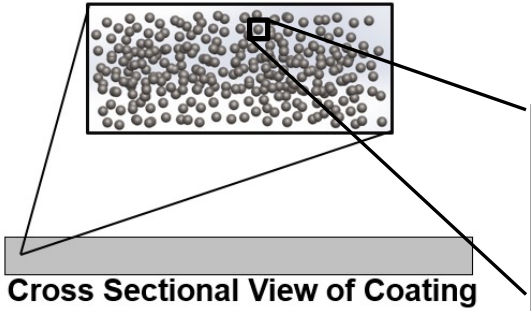
Low hiding power ⇒ High volume concentration

Low UV absorption

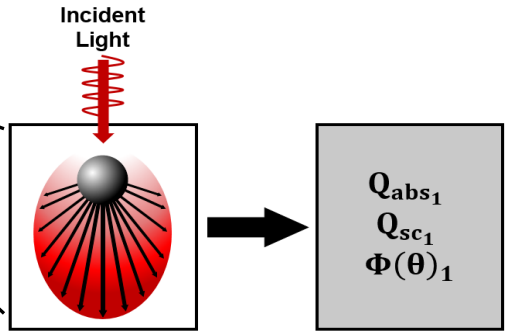
Passive Radiative Cooling Paints

Dr. Joseph Peoples
Intel

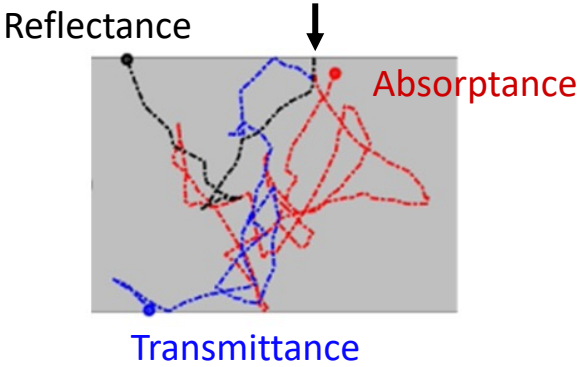
Composite Structure



Mie Theory Calculations



Monte Carlo Simulations



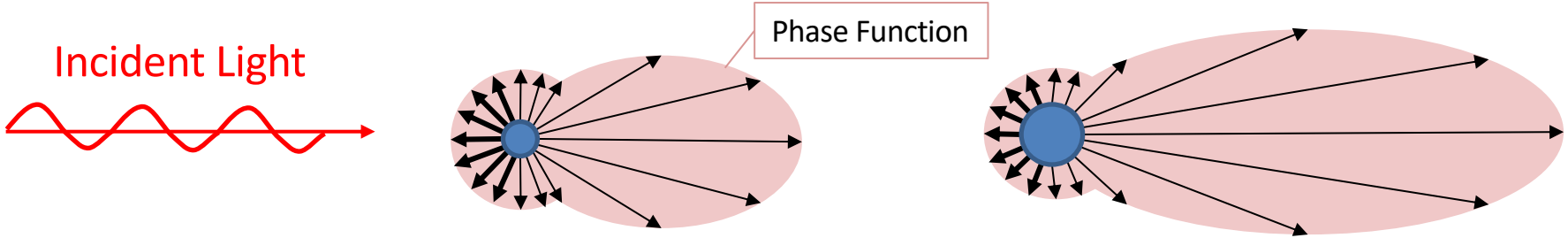
Peoples, J., **Li, X.,** et al., (2019) *IJHMT*, 131, 487-494

- Matrix Material
- Particle Material
- Particle Size
- Volume Concentration

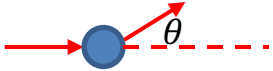
Coating thickness →

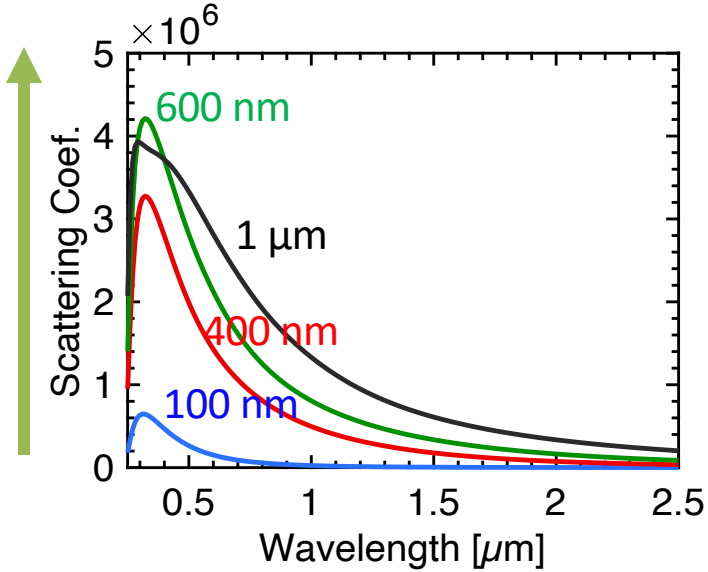
- Absorptance
- Reflectance
- Transmittance

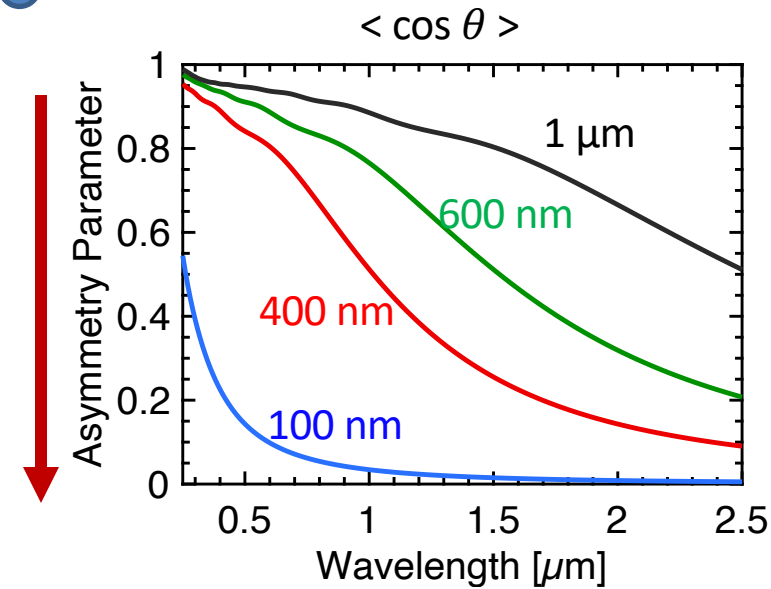
Passive Radiative Cooling Paints



- Single particle size optimization

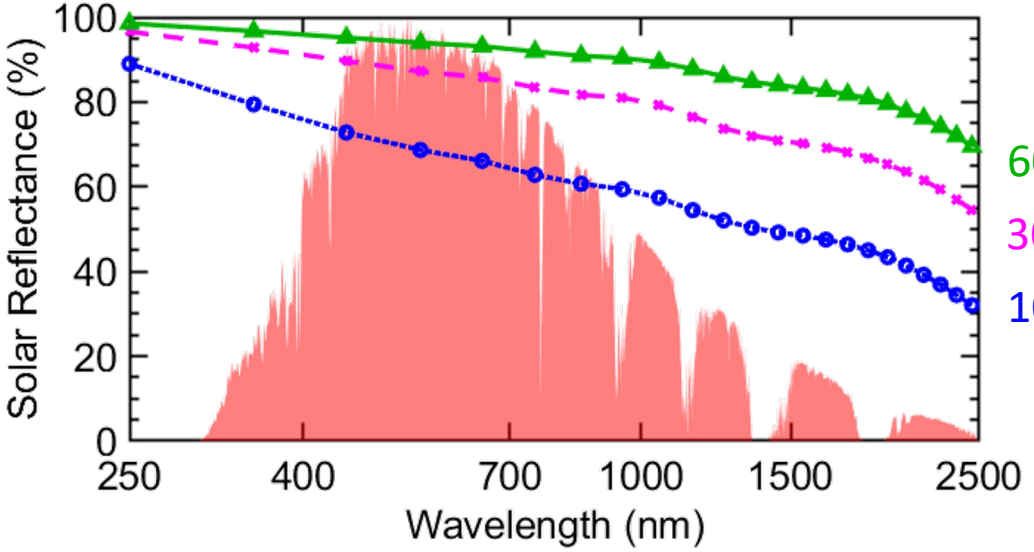






Benefits of Concentration and Particle Size

- High volume concentration
- Single particle size optimization

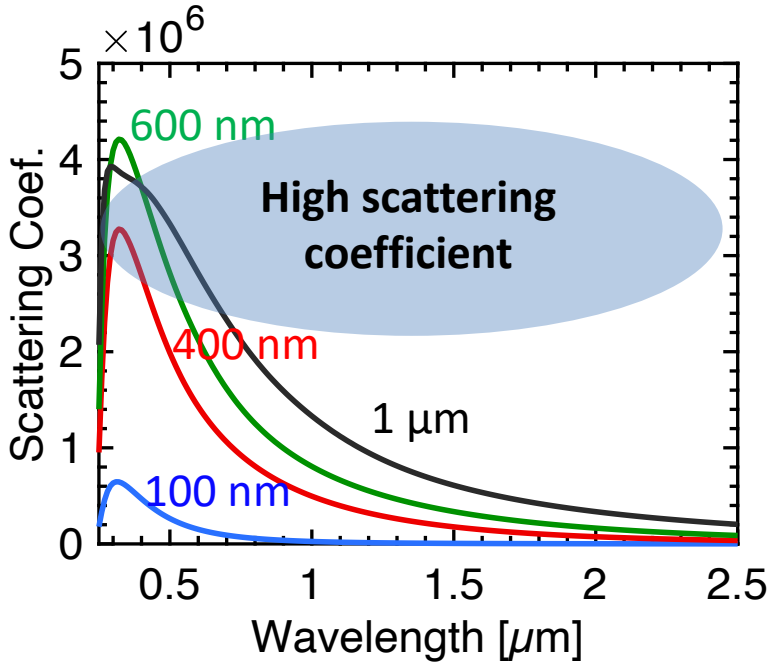


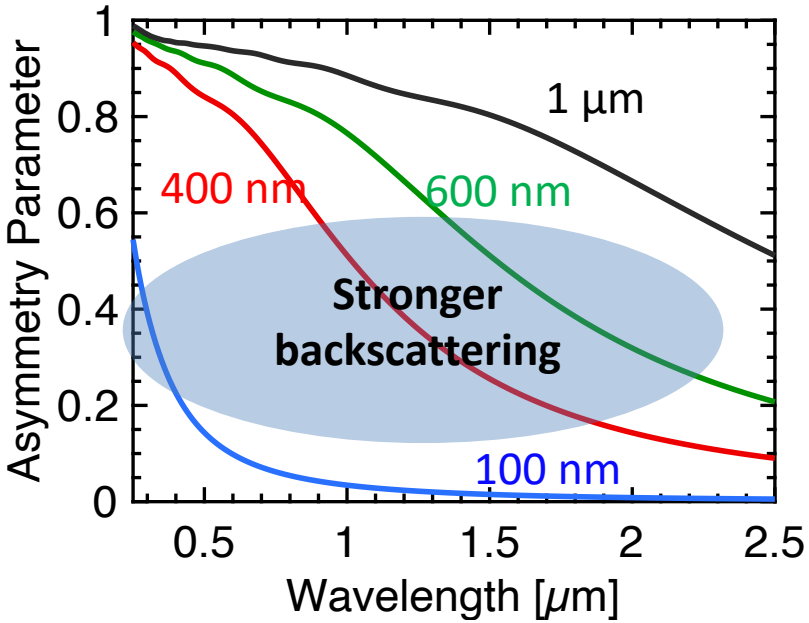
60 v%, Single Size, R = 90.9%

30 v%, Single Size, R = 82.2%

10 v%, Single Size, R = 62.3%

Benefits of Concentration and Particle Size

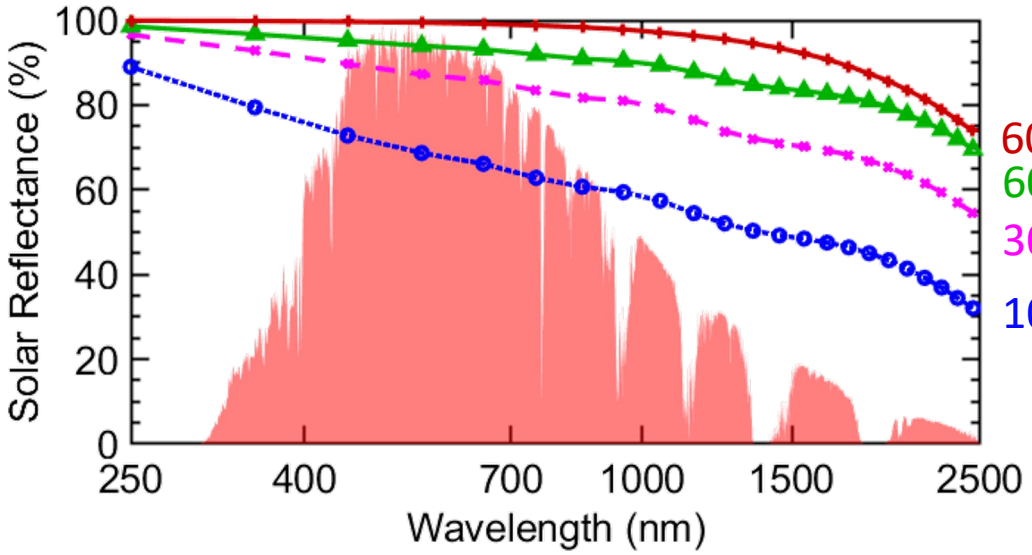




What about adding multiple particle sizes?

Benefits of Multiple Particle Sizes

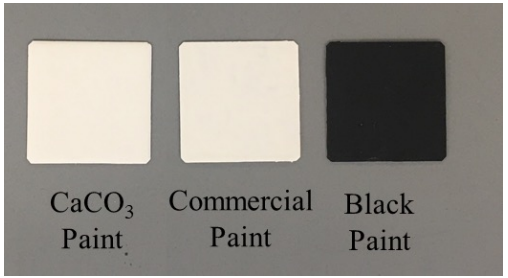
- High volume concentration
- Single particle size optimization
- Non-uniform size distribution

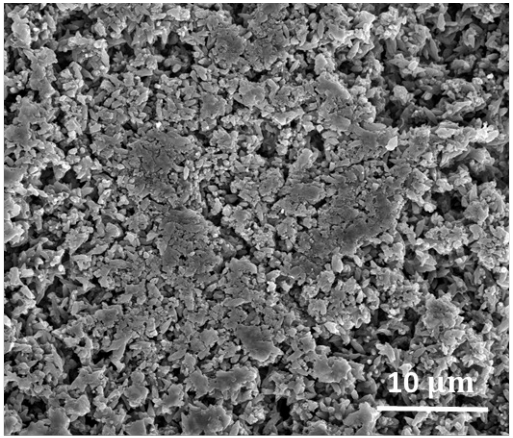


60 v%, Multiple Sizes, R = 97.3%
60 v%, Single Size, R = 90.9%
30 v%, Single Size, R = 82.2%
10 v%, Single Size, R = 62.3%

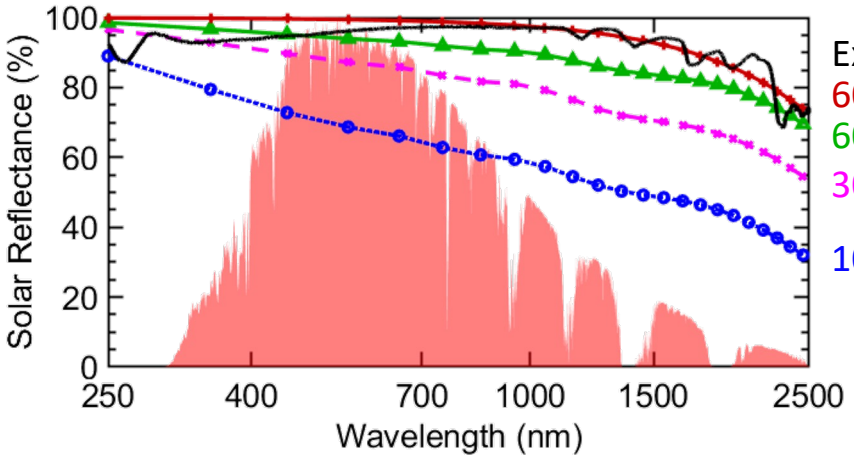
$CaCO_3$-Acrylic Paint

60 v%, 400 µm thickness





$CaCO_3$ 1.7 ± 0.4 µm (length)
518 ± 96 nm (diameter)



Experiment, R = 95.5%
60 v%, Multiple Sizes, R = 97.3%
60 v%, Single Size, R = 90.9%
30 v%, Single Size, R = 82.2%
10 v%, Single Size, R = 62.3%

Li, X., Peoples, J., Huang, Z., Zhao, Z., Qiu, J., & Ruan, X. (2020). *Cell Reports Physical Science*, *1*(10), 100221.
International Patent Application No. PCT/US2019/054566, Priority Date: 62/740,552 03.10.2018

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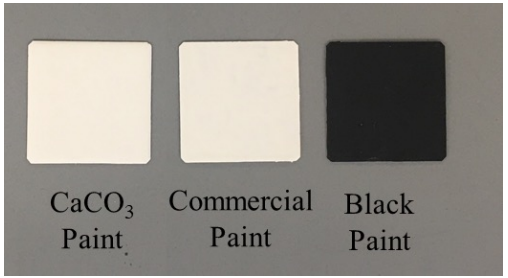

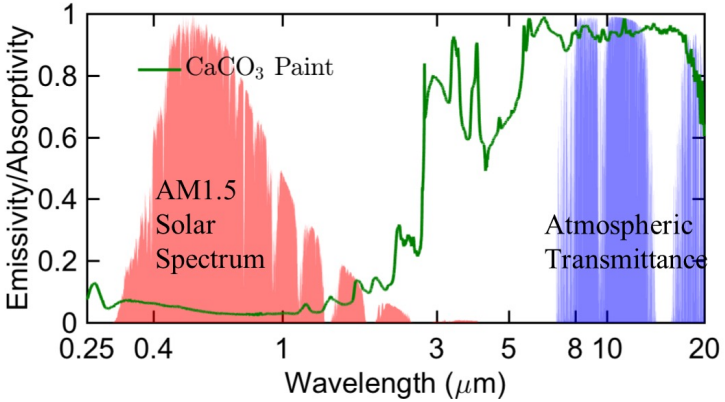

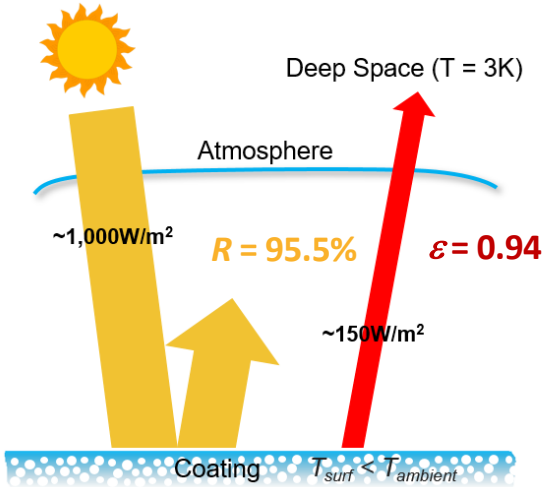

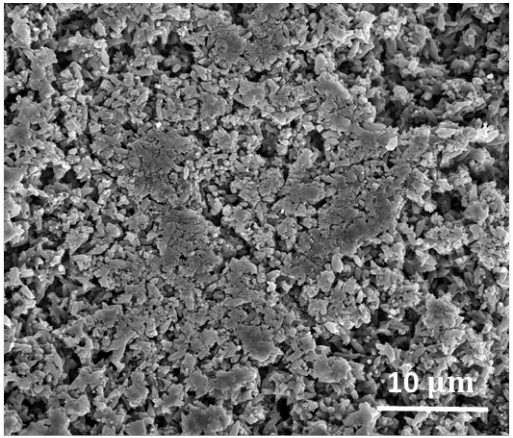

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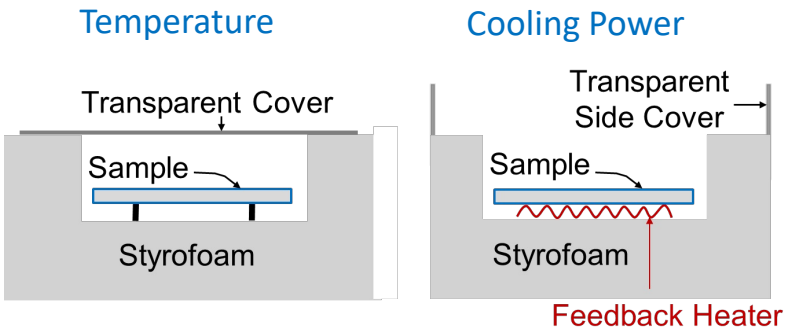
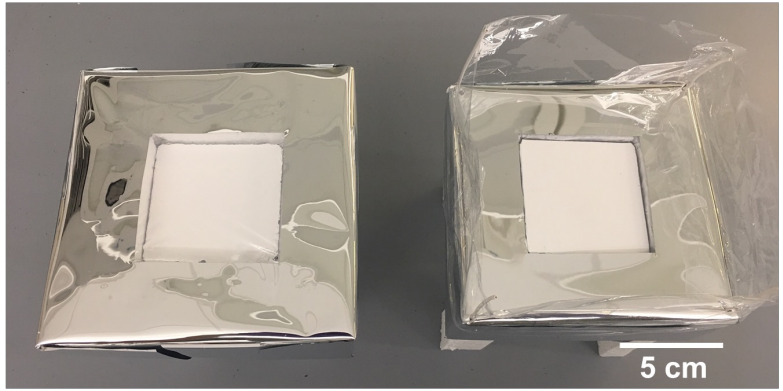
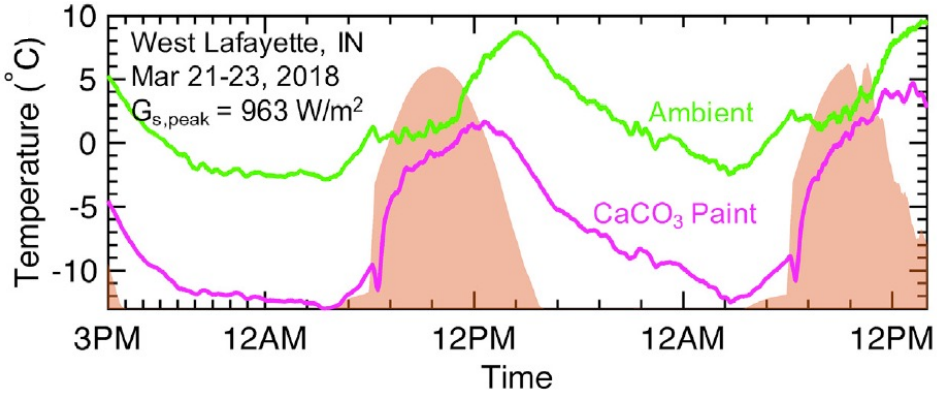
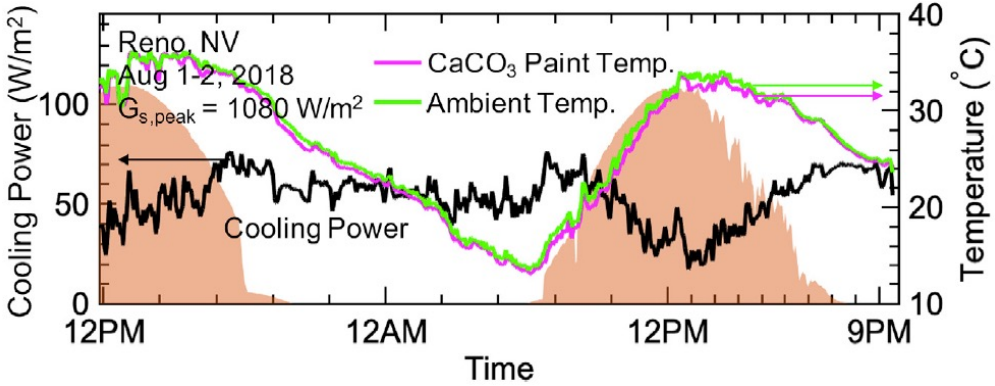
Characterization and Results



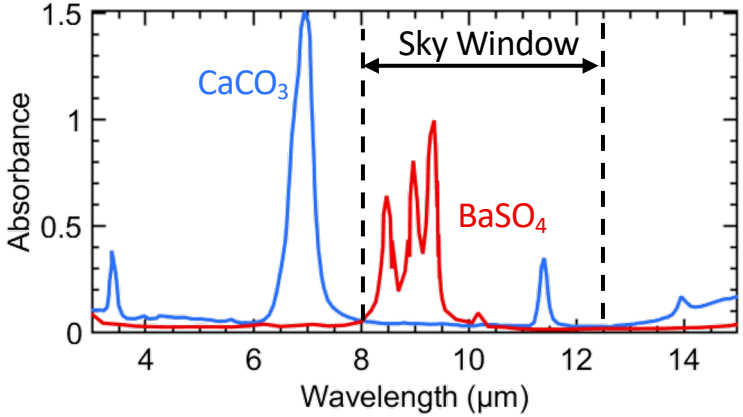




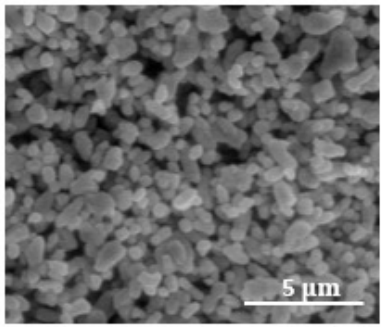


- Full daytime below ambient cooling
- 27 - 70 W/m^2 cooling

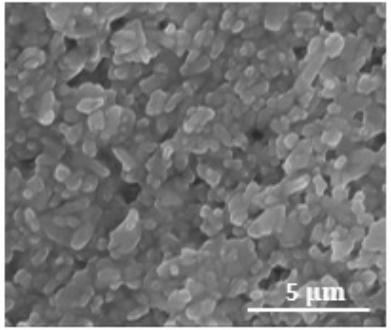
$BaSO_4$-Acrylic Paint



60 v%, 400 μm thickness

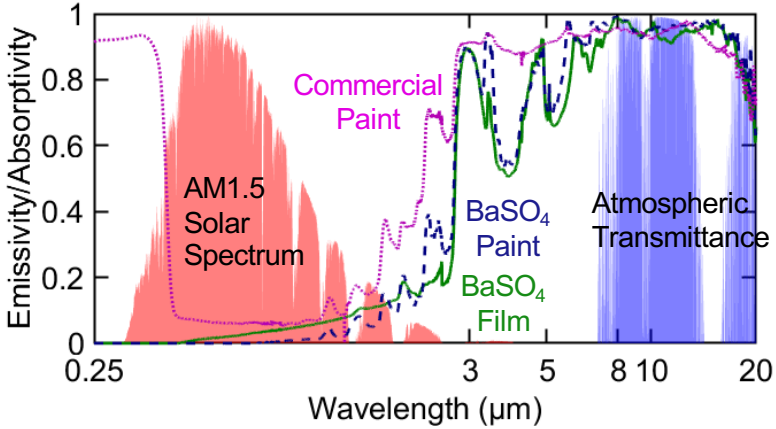


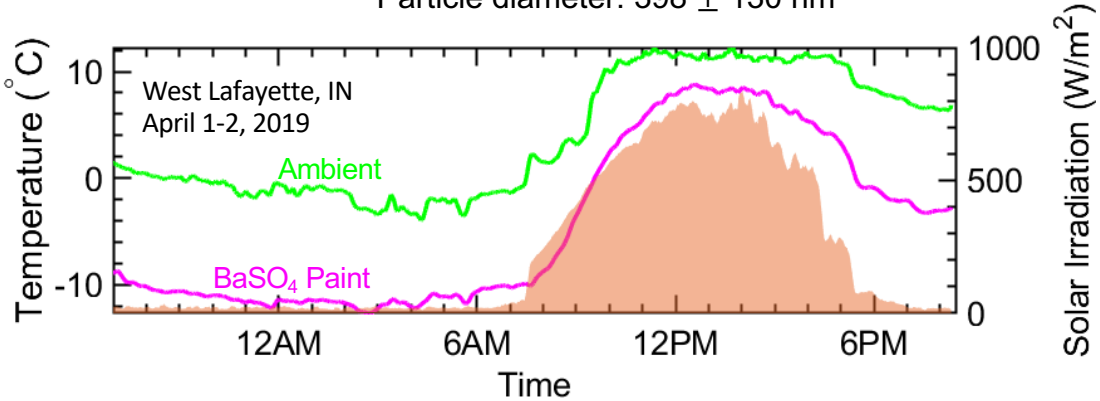
$BaSO_4$ Film



$BaSO_4$ Paint

Particle diameter: 398 ± 130 nm

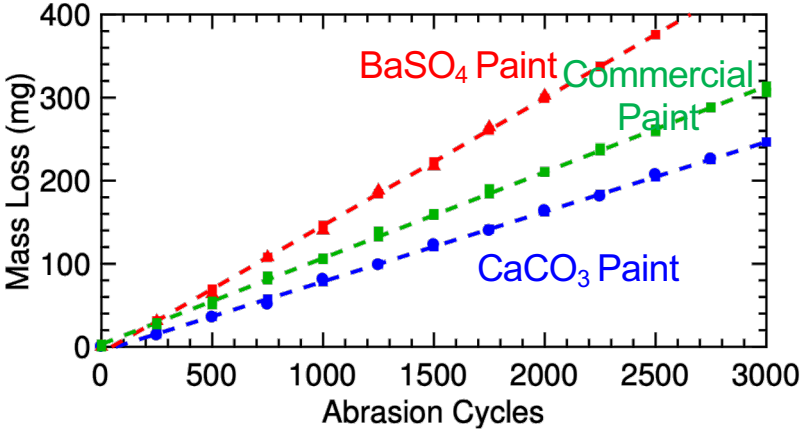


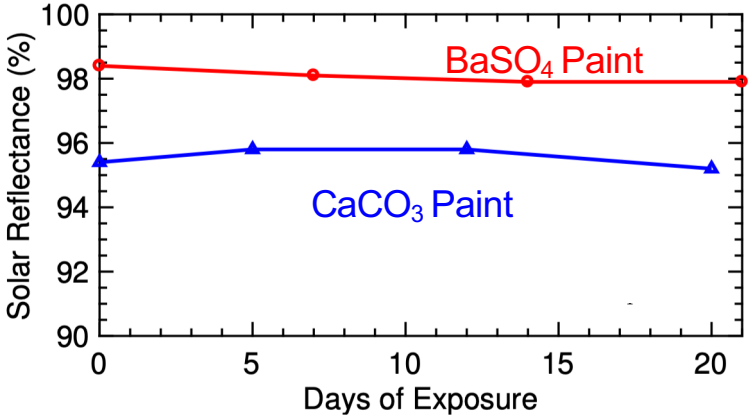


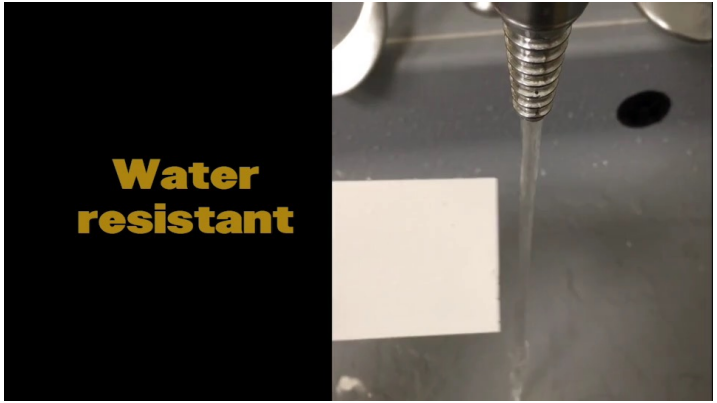
- 98.1% solar reflectance, 0.95 sky window emissivity
- 4.5 - 10°C, or > 110 W/m² cooling

Li, X., Peoples, J., Yao, P., & Ruan, X. (2021). *ACS AMI*, *13*(18), 21733-21739

Characterization and Results







sciencedirect.altmetric.com

561

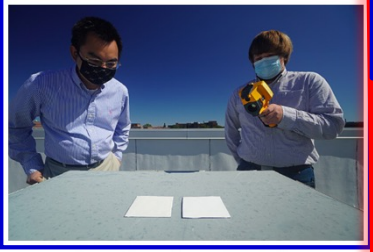
Report for: Full Daytime Sub-ambient Radiative Cooling in Commercial-like Paints with High Figure of Merit

PURDUE UNIVERSITY. News

Menu

October 21, 2020

This white paint could reduce the need for air conditioning by keeping surfaces cooler than surroundings



Ultrawhite BaSO4 Paints and Films for Remarkable Daytime Subambient Radiative Cooling

Overview of attention for article published in ACS Applied Materials & Interfaces, April 2021

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'Whitest ever' paint reflects 98% of sunlight

By Victoria Gill
Science correspondent, BBC News

16 April | Comments

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Superwhite paint can cool buildings even in hot sunlight

ENVIRONMENT 21 October 2020

By Adam Vaughan

CNN style

Call to Earth View

Design

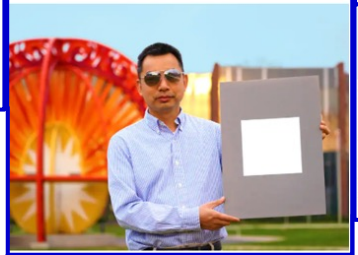
This ultra-white paint could cool buildings, cutting the need for air conditioning

The Washington Post
Democracy Dies in Darkness

Climate Solutions

Researchers say cool white paint could combat urban heat

How white is their paint? Whiter than virgin snow, they say.

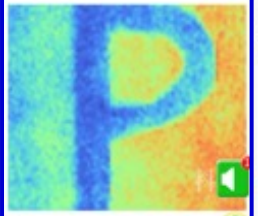


THE WALL STREET JOURNAL.

THE FUTURE OF EVERYTHING | CITIES & REAL ESTATE

TO OFFSET CLIMATE CHANGE, SCIENTISTS TOUT CITY TREES AND ULTRA-WHITE PAINT

新型白色涂料成降温小能手



《Cell Reports Physical Science》杂志

时间10月21日报道，美国普渡大学的科学家

에어컨도 안 켰는데 서늘… 햇빛 95% 반사 '신기한 페인트'

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Science

Climate change: 'Cooling paint' could cut emissions from buildings

By Matt McGrath
Environment correspondent

4 days ago

COP26

Ciência & Saúde | Ambiente | Aquecimento Global | Física | Termodinâmica

Cientistas criam tinta ultra-branca que ajuda a arrefecer as superfícies

Por ZAP – 30 Outubro, 2020

Purdue Research Foundation Retweeted

AFOSR @AFOSR 9m

As seen on @FallonTonight, engineers at @LifeAtPurdue have created the coolest white paint—literally! 😎 @AFResearchLab #AFOSRBoldResearch #HighRiskHighReward @BNCPurdue @MIT #AFOSRDURIP #MechanicalEngineering #Nanotechnology #CoolingTechnology #EarthDay2021

Purdue University @LifeAtPu...
In an effort to curb global

POPULAR MECHANICS

The Whitest Paint Ever Could Block the Sun and Cool Earth

It might make your air conditioner obsolete.

// BY CAROLINE DELBERT APR 16, 2021

Search | The Guardian | US edition

Environment

Whitest-ever paint could help cool heating Earth, study shows

New paint reflects 98% of sunlight as well as radiating infrared heat into space, reducing need for air conditioning

OPTICS & PHOTONICS NEWS

RESEARCH NEWS

Painting Away Heat

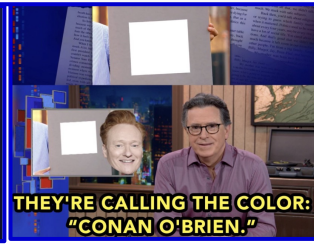
Molly Moser

Science Contents News Careers Journals

JOHN BRODY/FLICKR (DE

Ultrawhite paint could cool buildings and combat climate change

By Robert F. Service | Oct. 22, 2020, 1:55 PM



Thinner, and Lighter Paints for Daytime Radiative Cooling

Current best radiative cooling paints need 400 μm to several millimeters of coating thickness to reach at most 98.1% solar reflectance

Ultrawhite, thin, and lightweight cooling paints needed for weight sensitive applications

i.e. Reducing 1 kg per airplane can save 74 kg fuel for the airplane per year

Wearable Technologies

Vehicles

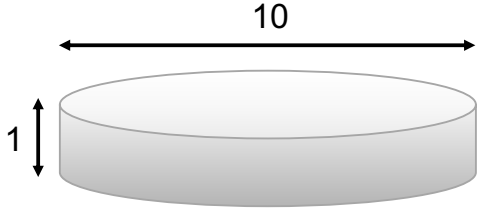
Aircraft

Felicelli, A., Katsamba, I., Barrios, F., Zhang, Y., Guo, Z., Peoples, J., Chiu, G., & Ruan, X., Thin layer lightweight and ultrawhite hexagonal boron nitride nanoporous paints for daytime radiative cooling. *Cell Reports Phys. Sci.* **3**, 101058 (2022).

Characteristics of hBN Nanoplatelets

Why hBN?

- → High refractive index
- → No UV absorption
- → Low density
- → Nanoplatelet morphology

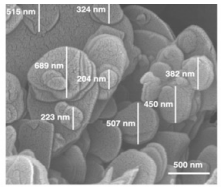


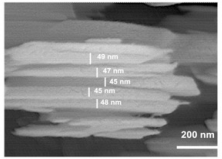
Bandgap: 5.96 eV

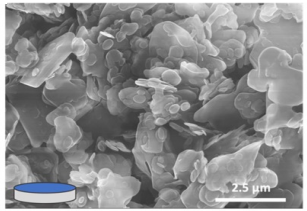
Refractive Index: 2.1-2.3

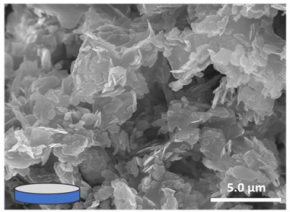
Density: 2.1 g/cm^3

Paint Sample







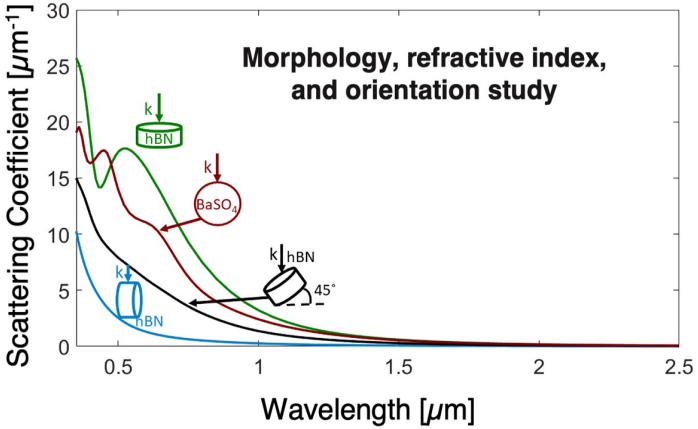


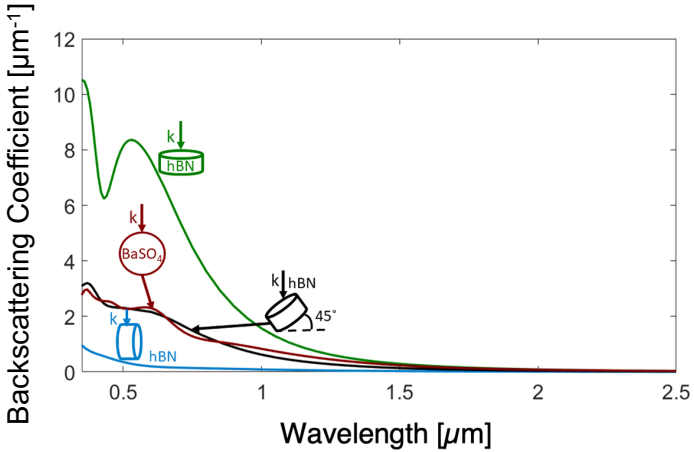
Composition:

33.4 % hBN nanoplatelets

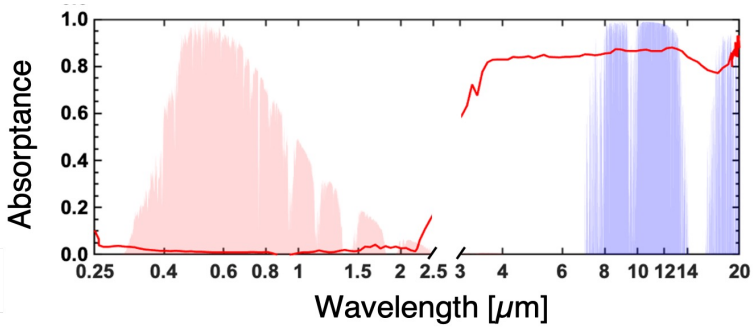
22.3% Acrylic matrix

44.3% Air nanopores



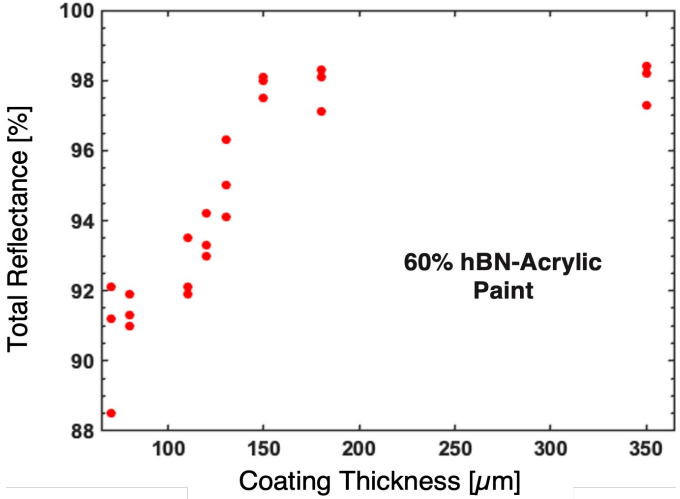


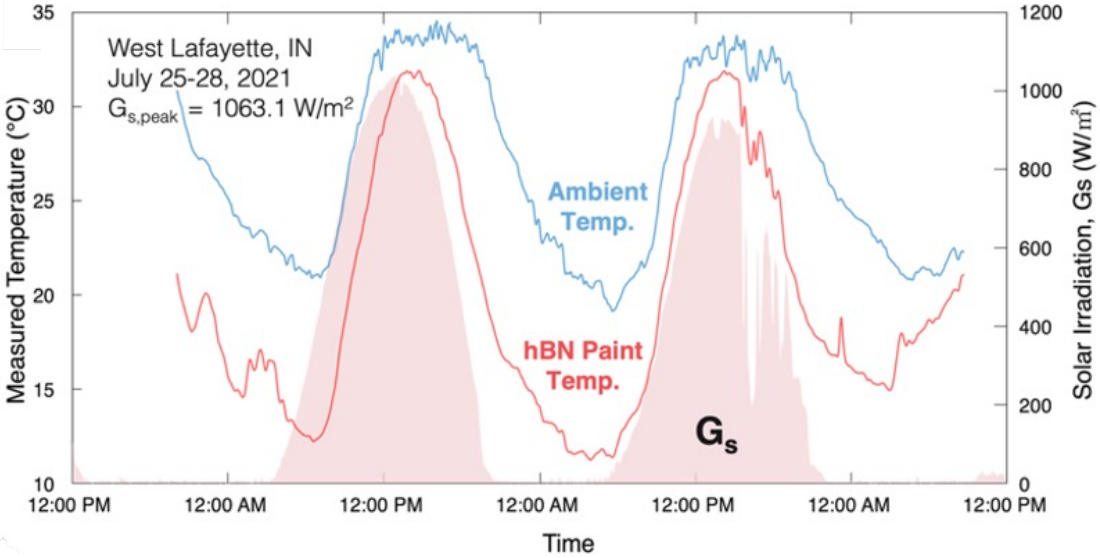
Radiative Cooling Performance of hBN-Acrylic Paints



Total solar reflectance: 97.9% with 150 μm thin layer

Sky window emissivity: 0.83

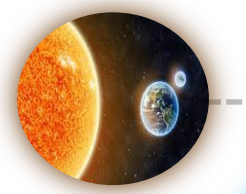




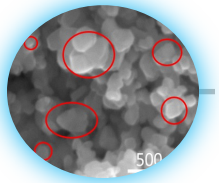
Felicelli, A., Katsamba, I., *et al., Cell Reports Phys. Sci.* **3**, 101058 (2022).

→ 5-6˚C below ambient temperature

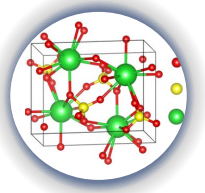
Outline



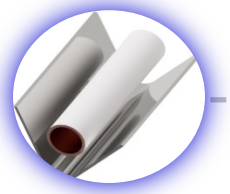
Motivation and Background



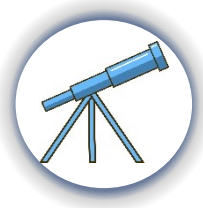
Materials



Physics



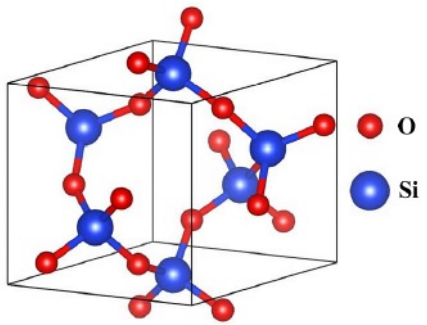
Energy Savings and Climate Crisis Mitigation

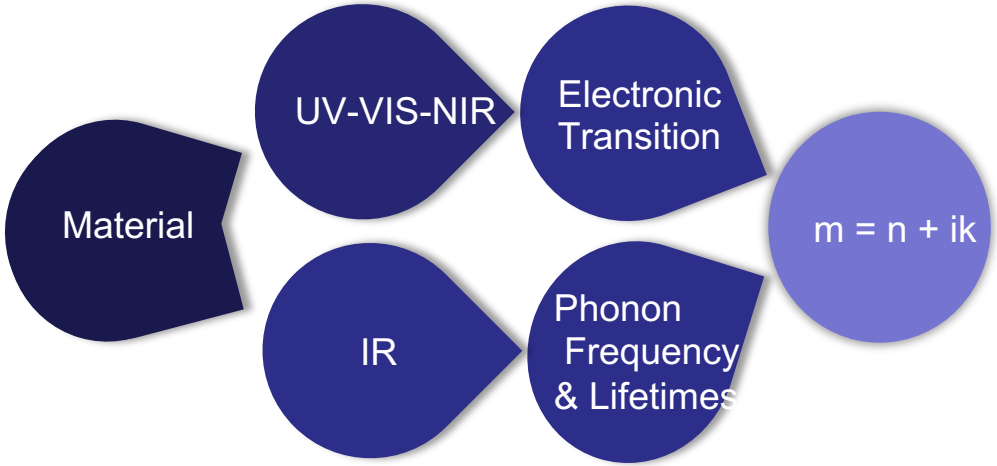


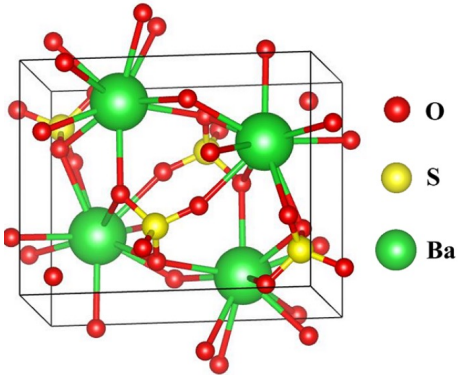
Outlook

First Principles Prediction of Optical Constants

- Using the atomic structure, we can predict the optical constants via first principles.





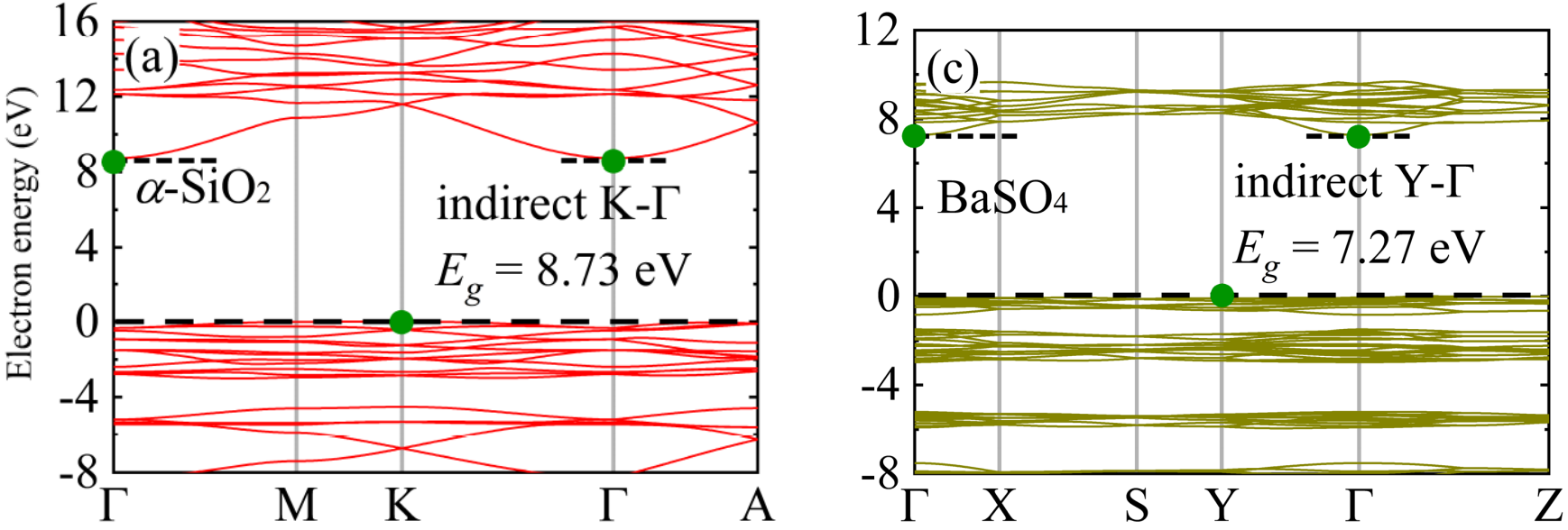


UV-VIS-NIR: Electronic Structure

Dr. Zhen Tong

Dr. Joseph Peoples
Intel

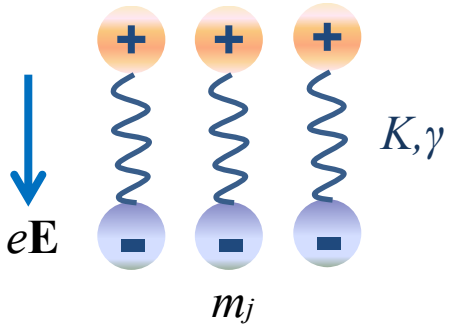
- SiO_2 and $BaSO_4$ both have a large bandgap, indicating that they do not absorb in the UV-VIS-NIR band. The band gap of $BaSO_4$ is smaller.



Tong, Peoples, **Li**, Yang, Bao, and Ruan, Materials Today Physics 24, 100658 (2022).

IR: Lorentz Oscillator Model

Spring mass system



Bound Charge

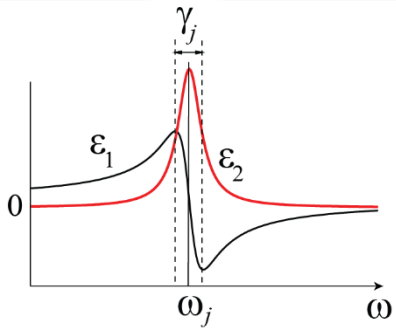
$$m_j\ddot{\mathbf{x}} - m_j\gamma_j\dot{\mathbf{x}} + K_j\mathbf{x} = e\mathbf{E}$$

Oscillator Strength

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_j \frac{S_j\omega_j^2}{\omega_j^2 - \omega^2 - i\gamma_j\omega}$$

Resonant Frequency

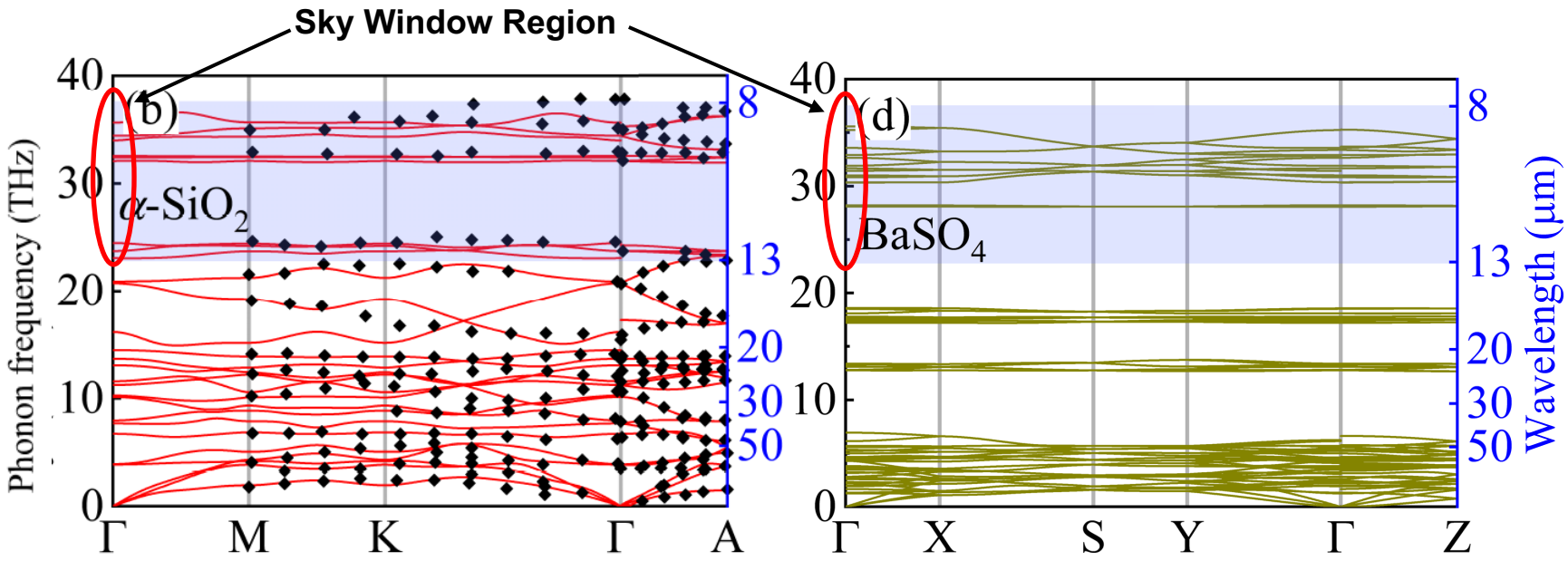
Damping Factor



- The **resonant frequency**, **oscillator strength** and **damping factor** were usually obtained by fitting to experiments.
- Can we predict them?

Phononic Structure

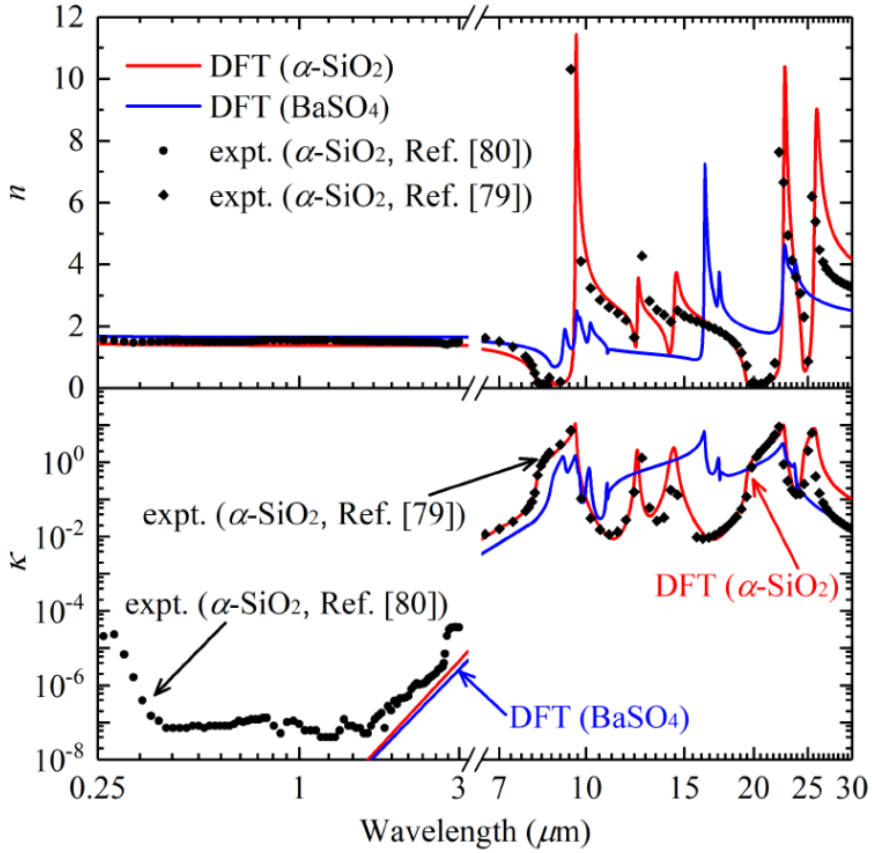
- BaSO4
  - More IR-active phonon modes at the Γ point, leading to higher absorptivity/emissivity in the sky window.



Experimental data from: Strauch, et. al., Journal of Physics: Condensed Matter 5, 6149 (1993), ISSN 0953-8984

Tong, Peoples, **Li**, Yang, Bao, and Ruan, Materials Today Physics 24, 100658 (2022).

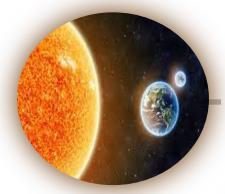
Spectrally Resolved Optical Constants



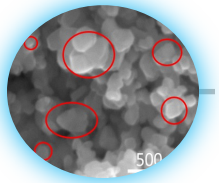
- Our predictions of n and κ for SiO_2 at room temperature agree well with experimental data.
- We predicted n and κ for $BaSO_4$ for the first time. Needs to be validated by experiments in the future.

Tong, Peoples, **Li**, Yang, Bao, and Ruan, Materials Today Physics 24, 100658 (2022).

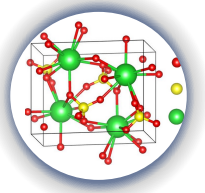
Outline



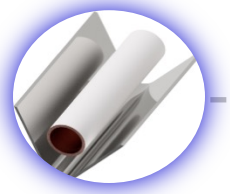
Motivation and Background



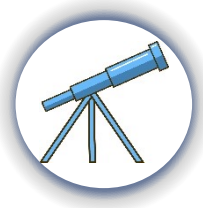
Materials



Physics



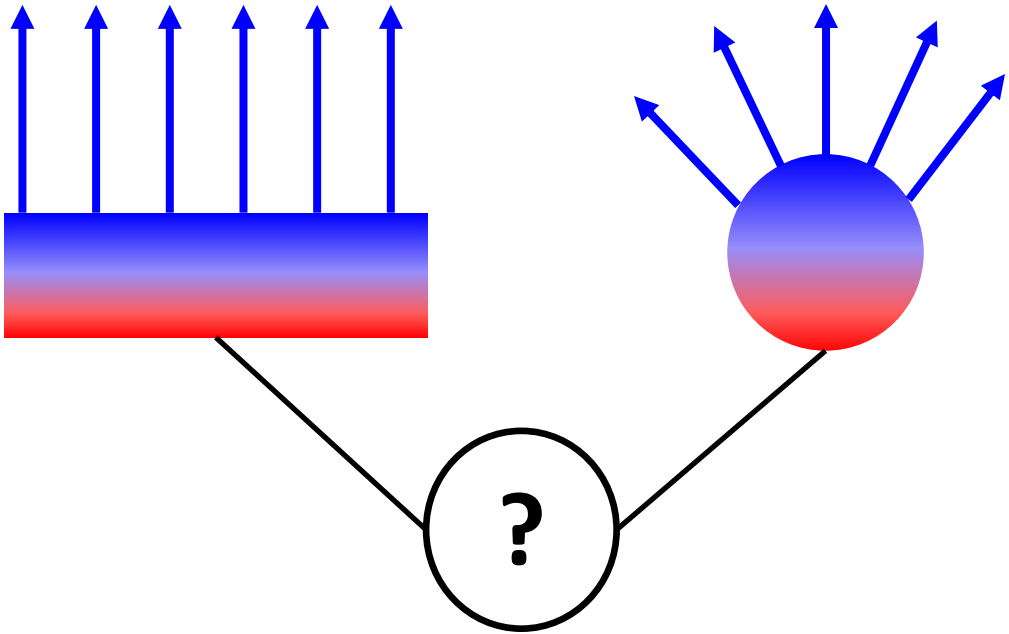
Energy Savings and Climate Crisis Mitigation



Outlook

Concentrated Radiative Cooling

$$Q = \varepsilon\sigma A_S (T_s^4 - T_{surr}^4)$$

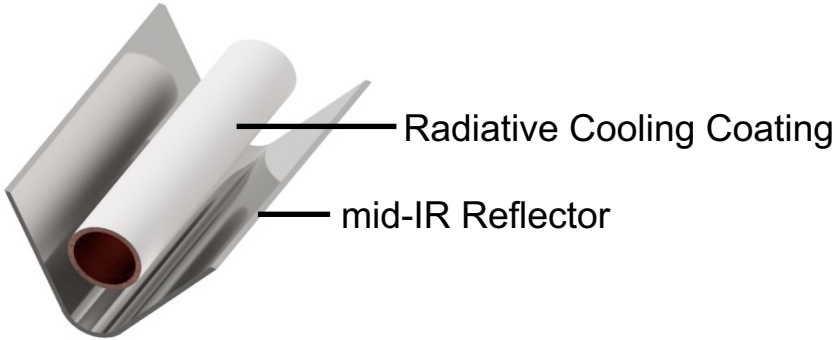


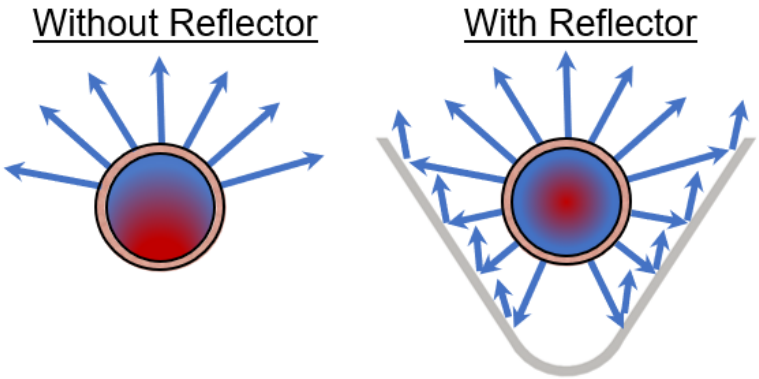
Motivation and Concept

Dr. Joseph Peoples
Intel

Source: https://tinyurl.com/y69f5l9k

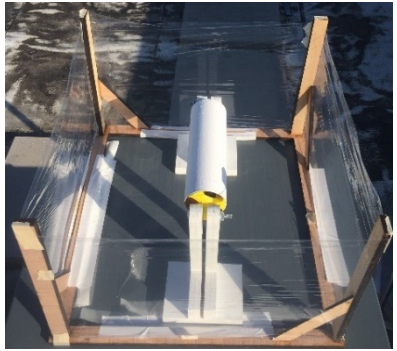
- Inspired by concentrated solar trough
- Using a mid-IR reflector, the pipes bottom surface can radiate to the sky
- ~2X concentration with respect to the material facing the sky

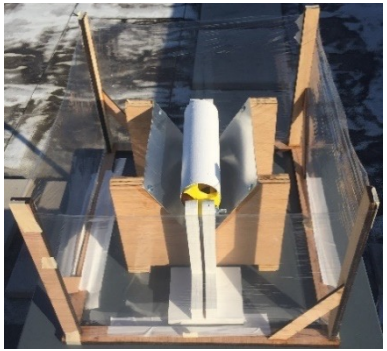


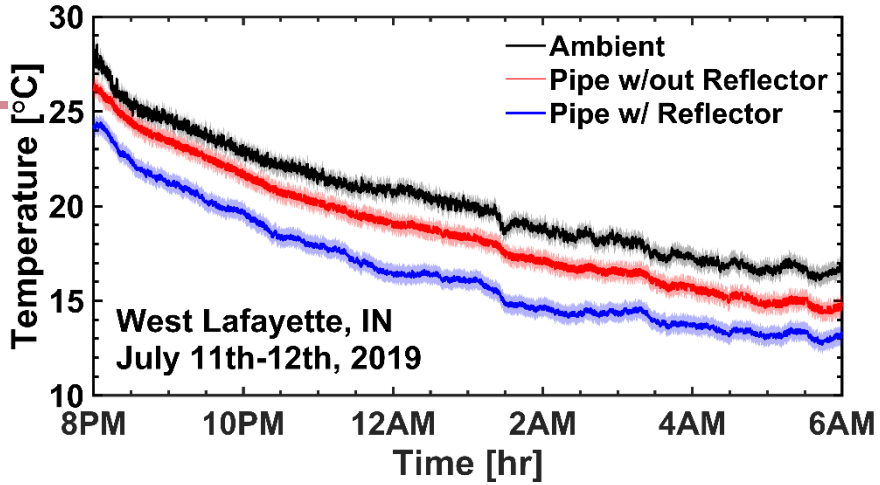


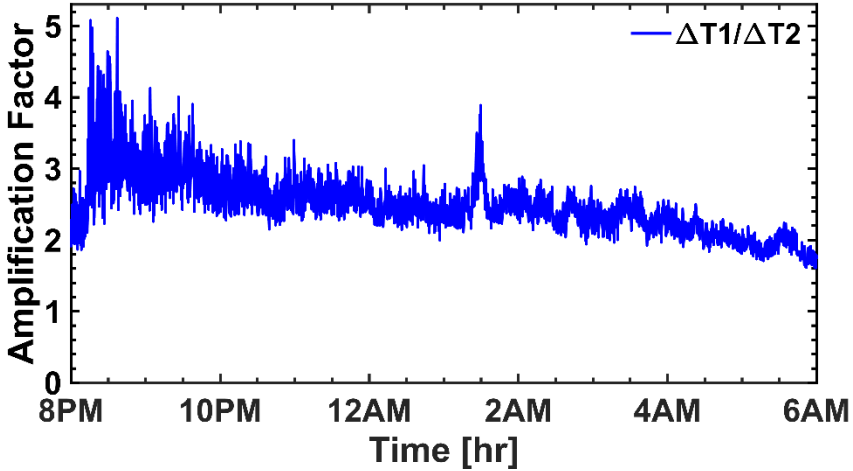
Peoples, Hung, **Li,** Gallagher, Fruehe, Pottschmidt, Breseman, Adams, Yuksel, Braun, Horton, and Ruan, "Concentrated Radiative Cooling," Applied Energy 310, 118368 (2022).

Field Testing





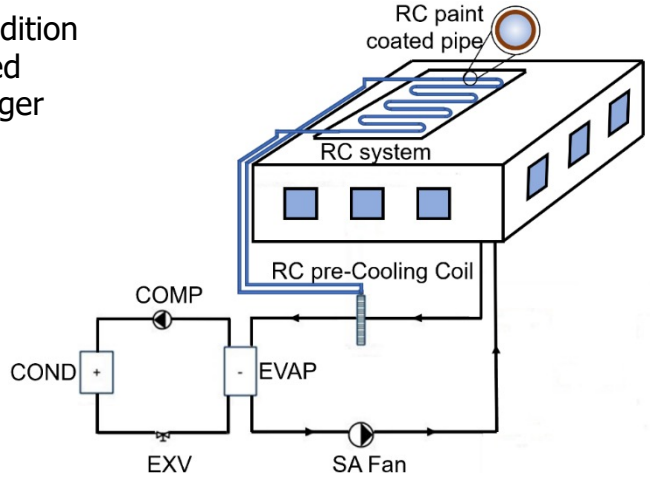


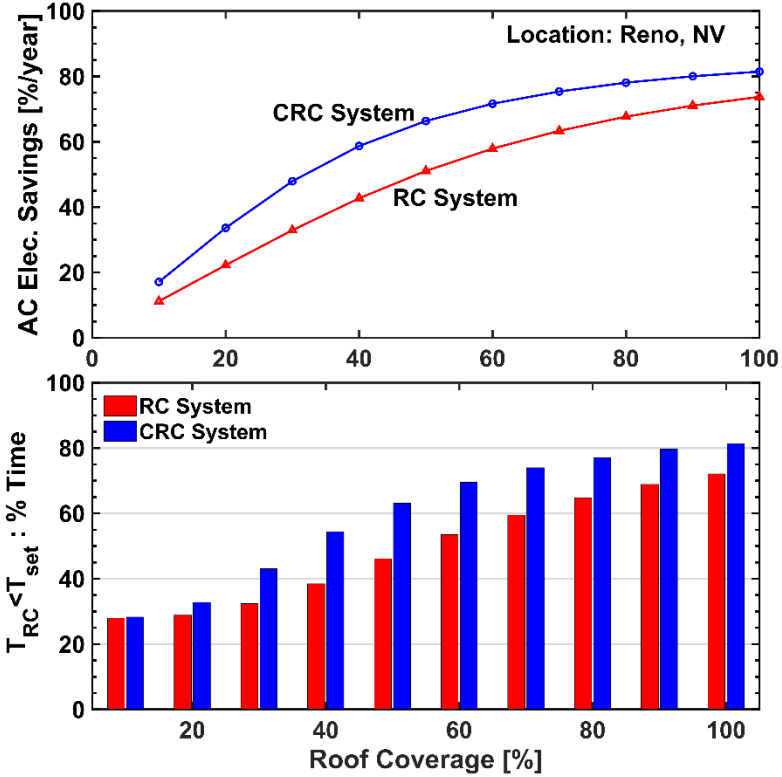


Ruan, X. & Peoples, J. (2021) S/N: 63/165,261; PRF No. 68864-02 (Non-Provisional Patent Application)

Energy Saving Benefits

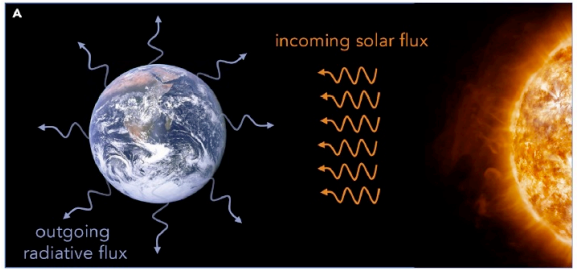
- Collaboration with Professor Braun (ME), Professor Horton (CE), and Yu-Wei Hung (CE)
- DOE Small Commercial Building (600m^2)
- Indoor Setpoint: 25 °C
- Radiative Cooling (RC) and Concentrated Radiative Cooling (CRC) pre-conditioner modeled
- Assumptions:
  - Ideal weather condition
  - Neglect wind speed
  - Ideal heat exchanger





Peoples, Hung, **Li,** Gallagher, Fruehe, Pottschmidt, Breseman, Adams, Yuksel, Braun, Horton, and Ruan, "Concentrated Radiative Cooling," Applied Energy 310, 118368 (2022).

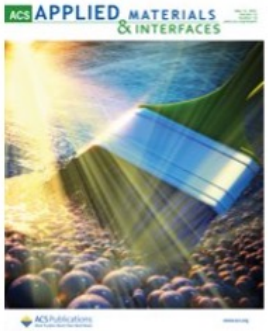
Promise for Mitigating Climate Crisis



Munday, Joule 3, 2057-2060 (2019).

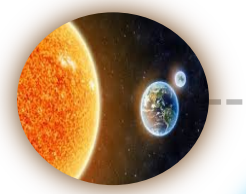
- According to Munday's model, painting ~1% of the earth's surface with our cooling paint can stop the warming trend.
- Effectively, carbon-negative!
- No refrigerant or water needed
- As easy to apply as commercial paints
- Both $CaCO_3$ and $BaSO_4$ are cheaper than commercial TiO_2 pigment.

https://www.wonderworksonline.com/science-library/atmosphere-climate/global-warming/

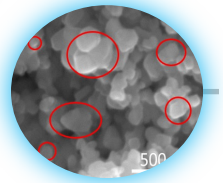


https://thedesigninspiration.com/blog/2009/06/21/cold-earth/

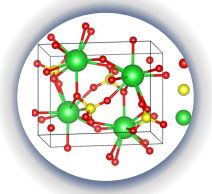
Outline



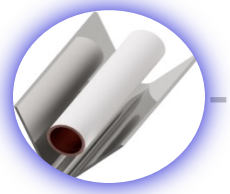
Motivation and Background



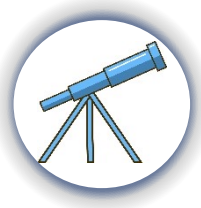
Materials



Physics



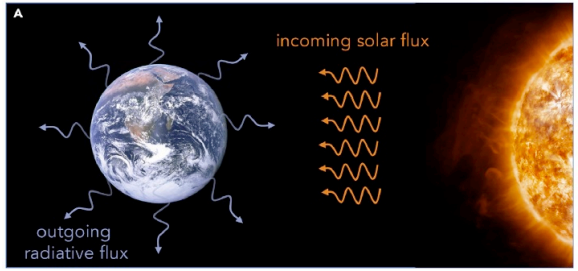
Energy Savings and Climate Crisis Mitigation



Outlook

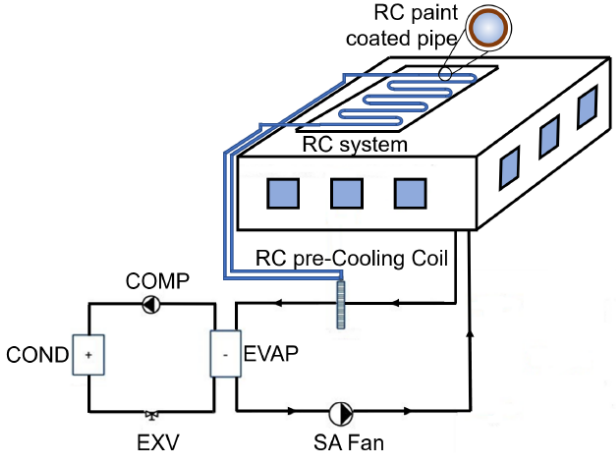
Future Opportunities in Cooling Paints

- Durability
- Colored paints
- Dynamic cooling and heating
- Multifunction
- Energy savings/benefits
- Climate crisis mitigation



Munday, Joule 3, 2057-2060 (2019).

- Materials development
- Machine learning
- Bio-inspired designs
- Advanced manufacturing



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