Quantifying light absorption by black carbon (BC), brown carbon (brC), & nanochar

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Today:

1. Why should we care about nanochar in [wildfire] smoke?
2. Can a simple theory quantify the "brownness" of carbon?

Part 1

Char

Kitchen Carbon

vapours
primary organic aerosol

Heat

bread
lignocellulosic
biomass

butter
semi-volatile
organic

blue flame
$\cdot C_2$ radicals

macro-char
solid fuel

macro-char
from liquid
...and aerosols?

soot BC
gases in flame

Wildfire

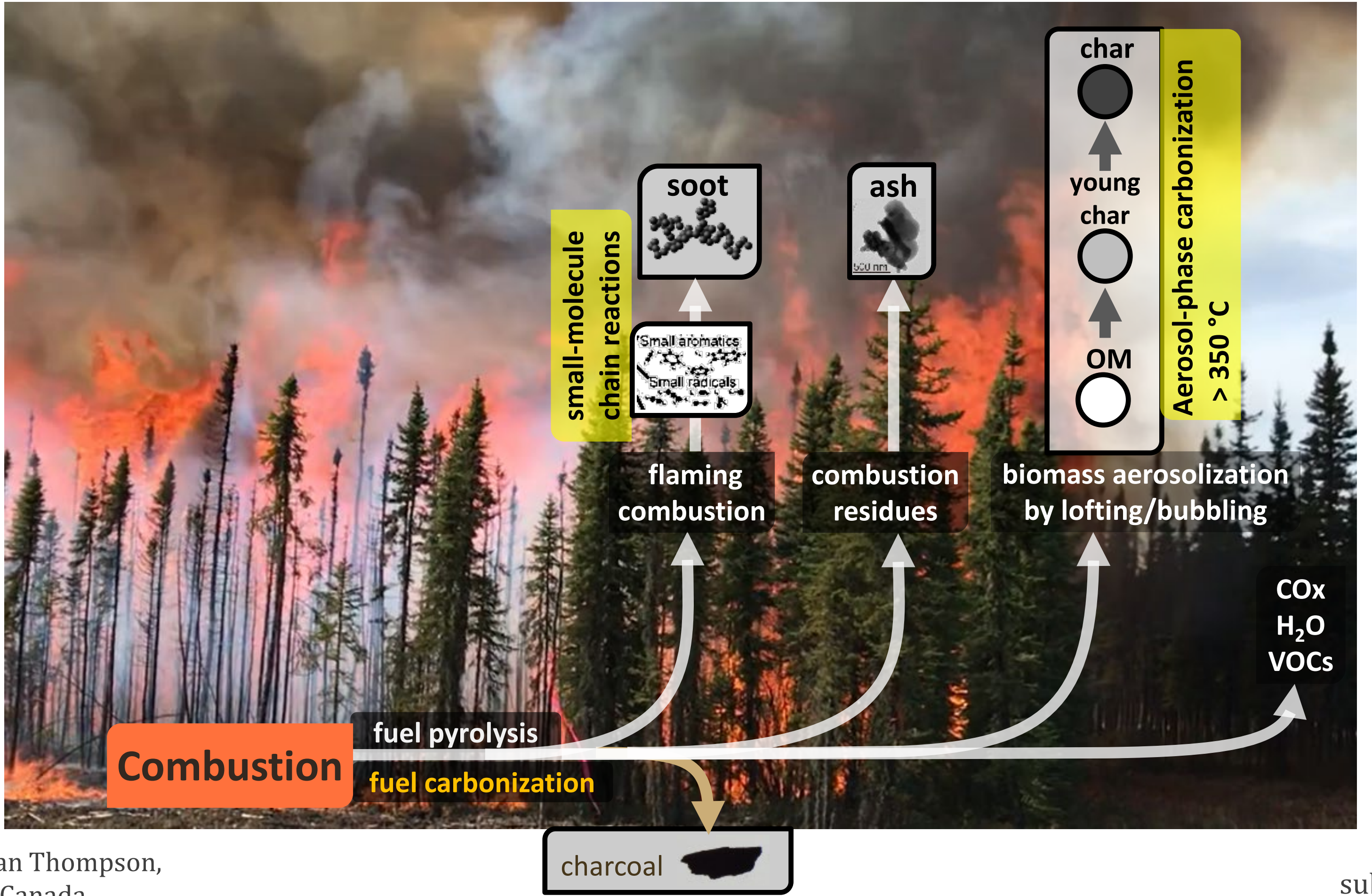


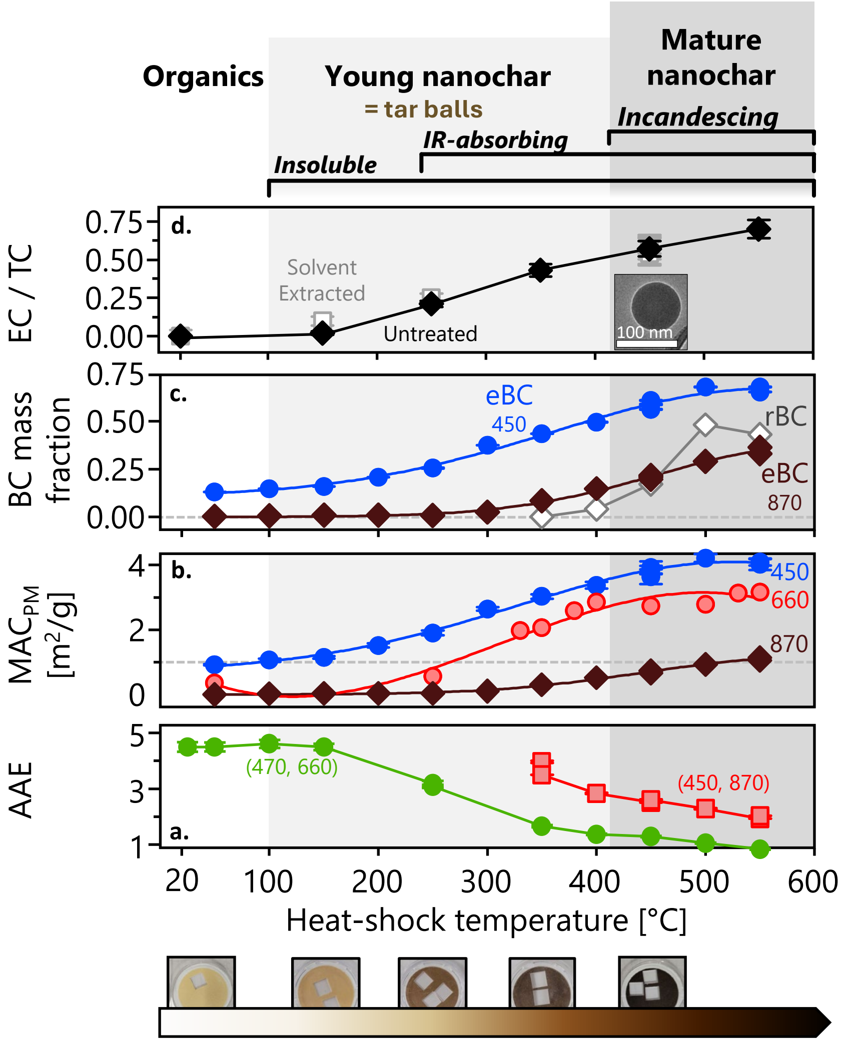
Photo credit: Dan Thompson, Government of Canada

Corbin et al., submitted 2026

The Char Continuum

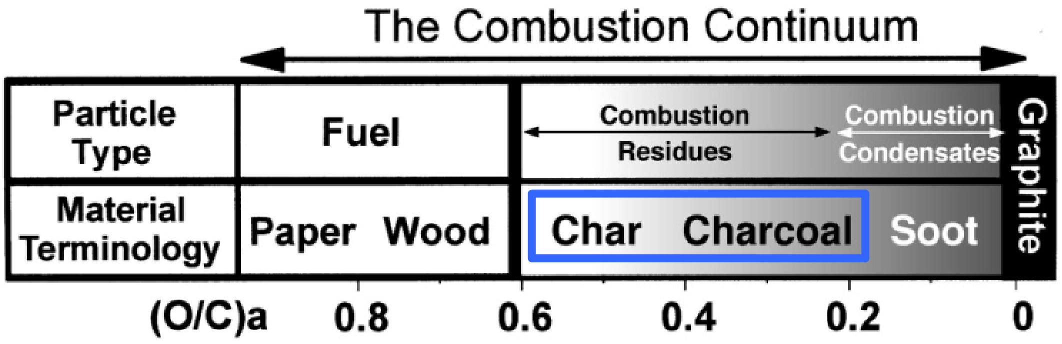
→ All BC instruments respond to nanochar with ~50% sensitivity

→ Formed in 1 second under wildfire-like conditions



Corbin et al., submitted 2026

"Char" is a widely recognized form of BC in geochemistry



Hedges et al., Organic Geochemistry, 2000
(940 citations)

"Like soot, char comprises partially graphitized carbon and is therefore also highly light absorbing, insoluble, thermally refractory, and resistant to chemical degradation. However, unlike soot, char is formed by fuel carbonization rather than gas-to-particle synthesis, thus its morphology and composition reflect its parent fuel rather than its formation mechanism alone"

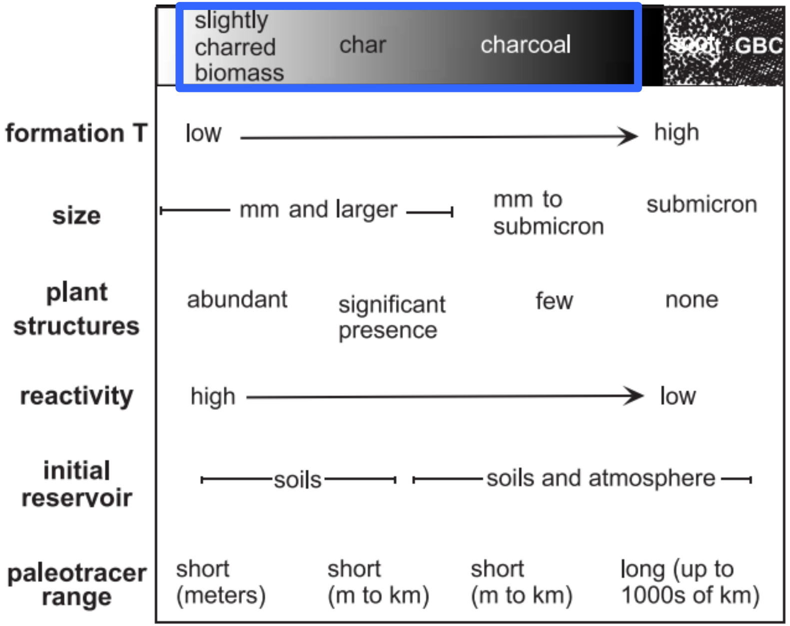


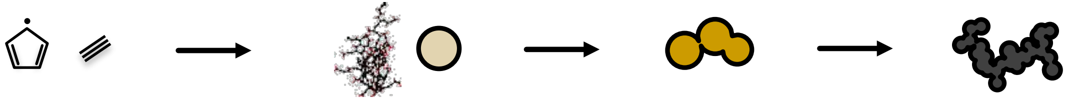
Fig. 1. The black carbon combustion continuum.

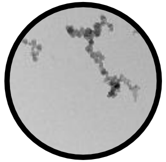
Masiello, Marine Chemistry, 2004
(1060 citations)

The Char Continuum

Soot

Gaseous precursors → Incipient soot → Young soot → Mature soot



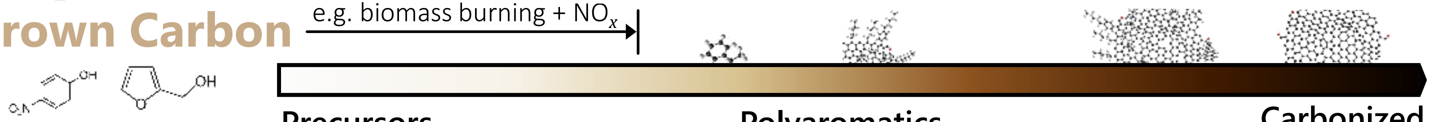


ℓ = 800 nm

Char

Brown Carbon

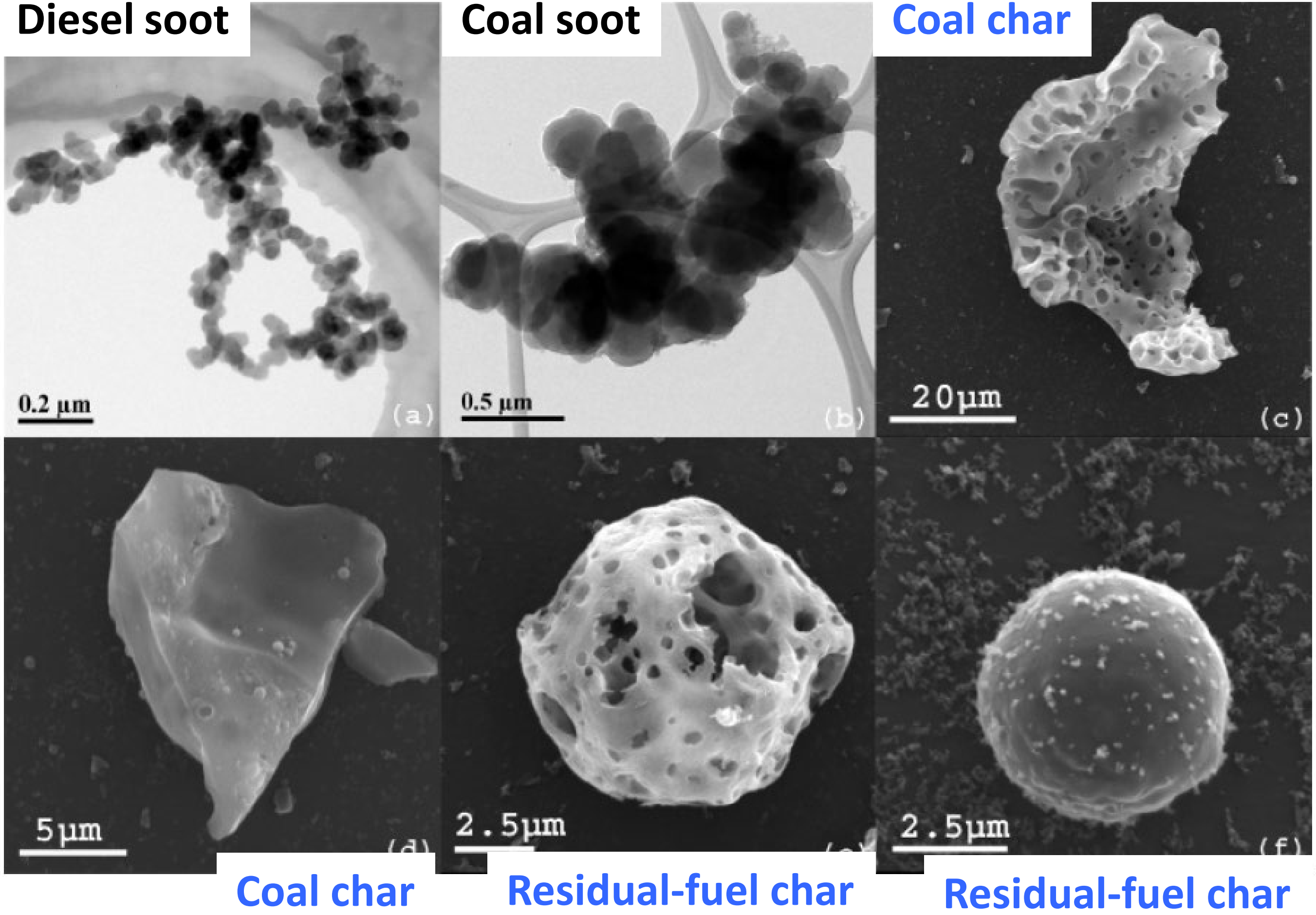
e.g. biomass burning + NO_x



Precursors — Polyaromatics — Carbonized macromolecules

Corbin et al., submitted 2026

Microchar aerosols



Many other examples...

Chen et al., 2005

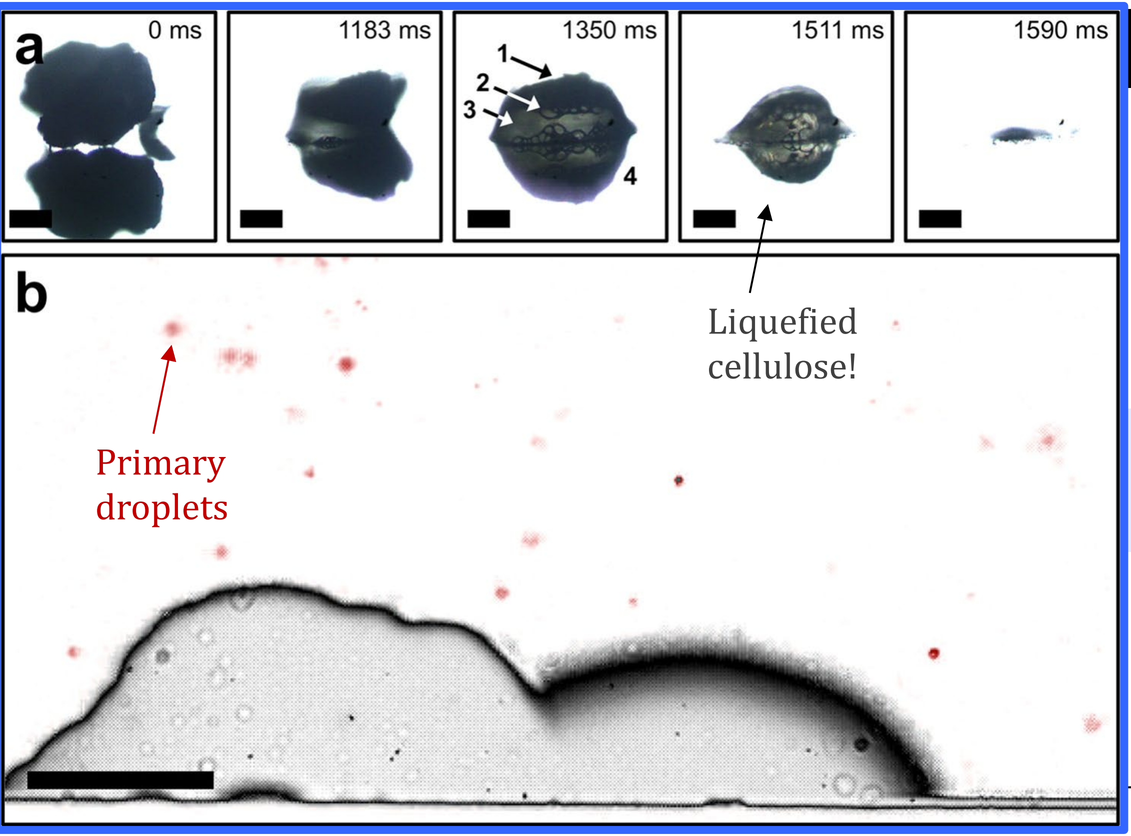
Nanochar aerosols

Table from Corbin et al., 2026 (submitted)

Name	Source
Black carbon / heavy liquid-phase hydrocarbons	Flame-free smoke from iQoS heated tobacco product
Gray carbon	Biomass burning (e.g. wildfires)
Tar balls, Dark-brown carbon, methanol-insoluble brC	Biomass burning, marine engines, residual fuel
Primary “oil” droplets	Primary droplets ejected from transient liquid phases during biomass burning
Brown, amorphous-carbon spheres	Biomass burning, marine engines, residual fuel
Intermediate [BC/brC] absorber spheres	Biomass burning
Extremely low volatility organic compounds	Biomass burning
Micro-char cenospheres	Marine engines

Primary droplets generated during cellulose pyrolysis

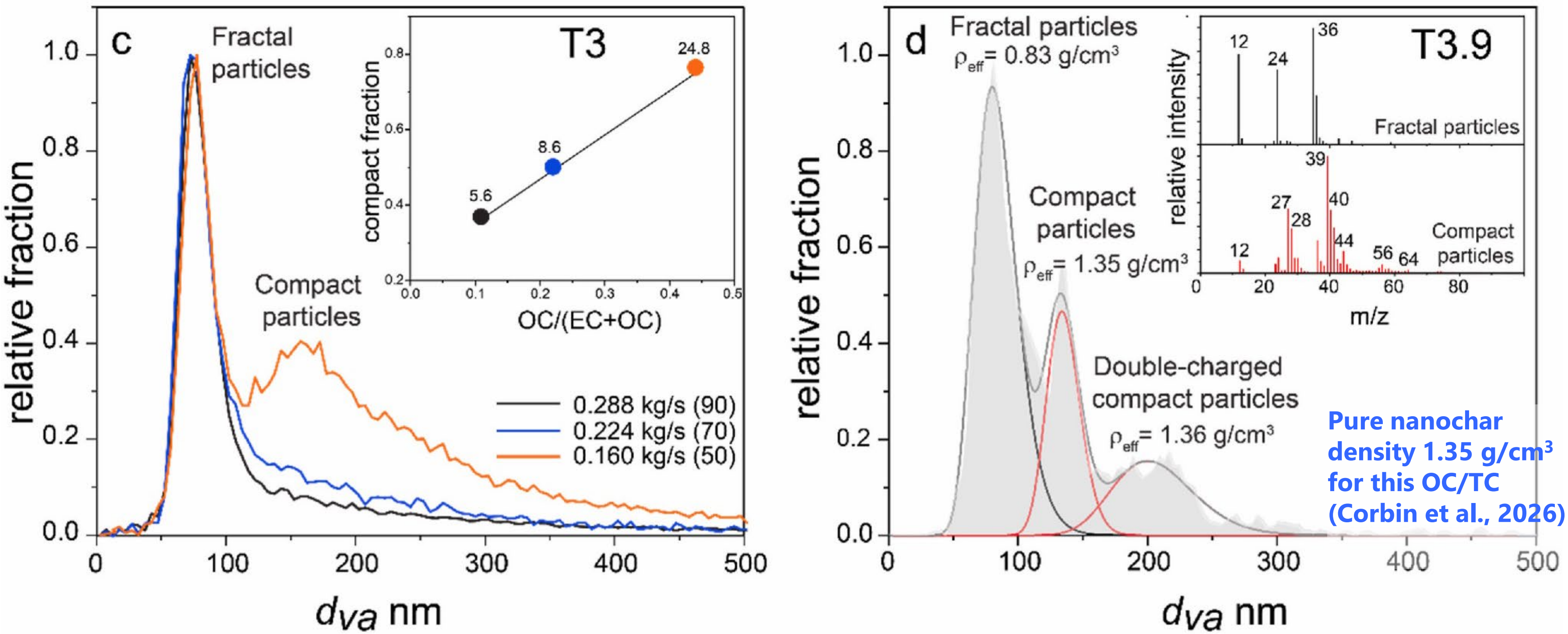
Table from Corbin et al., 2026 (submitted)



Source
Flame-free smoke from iQoS heated tobacco product
BB (Biomass burning; e.g. wildfires)
BB, marine engines, residual fuel
Primary droplets ejected from transient liquid phases during BB
BB, marine engines, residual fuel
BB
BB

Andrew et al., 2016

Prof. Kittelson's 2nd mode: nanochar from carbonized fuel-droplet residues?



Pure nanochar density 1.35 g/cm³ for this OC/TC (Corbin et al., 2026)

Gianelli, Stevens, Kinsey, … Kittelson … JAS 2024 10.1016/j.jaerosci.2024.106352

Numerous recent studies indicating nanochar's atmospheric importance

nature geoscience

Article https://doi.org/10.1038/s41561-026-01972-9

Strong global radiative effects from wildfire dark brown carbon

nature geoscience

Article https://doi.org/10.1038/s41561-023-01237-9

Shortwave absorption by wildfire smoke dominated by dark brown carbon

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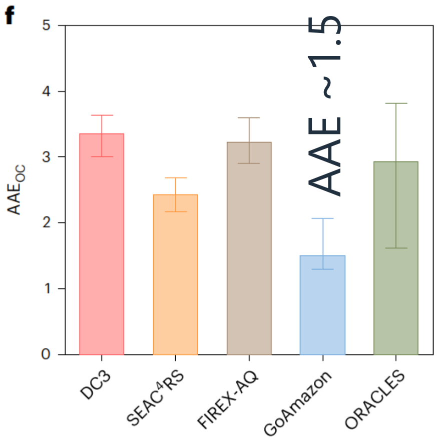
Check for updates

Rajan K. Chakrabarty[1], Nishit J. Shetty[1,15], Arashdeep S. Thind[2,15], Payton Beeler[1], Benjamin J. Sumlin[1], Chenchong Zhang[1], Pai Liu[1,12], Juan C. Idrobo[4,13], Kouji Adachi[5], Nicholas L. Wagner[6,7,14], Joshua P. Schwarz[6], Adam Ahern[6,7], Arthur J. Sedlacek III[8], Andrew Lambe[9], Conner Daube[9], Ming Lyu[10], Chao Liu[11], Scott Herndon[9], Timothy B. Onasch[9] & Rohan Mishra[2,3]

AAE ~1.5 → dark-brC (nanochar)



Nanochar BC $\neq$ soot BC

Nanochar is less graphitized and often more-oxygenated than soot.

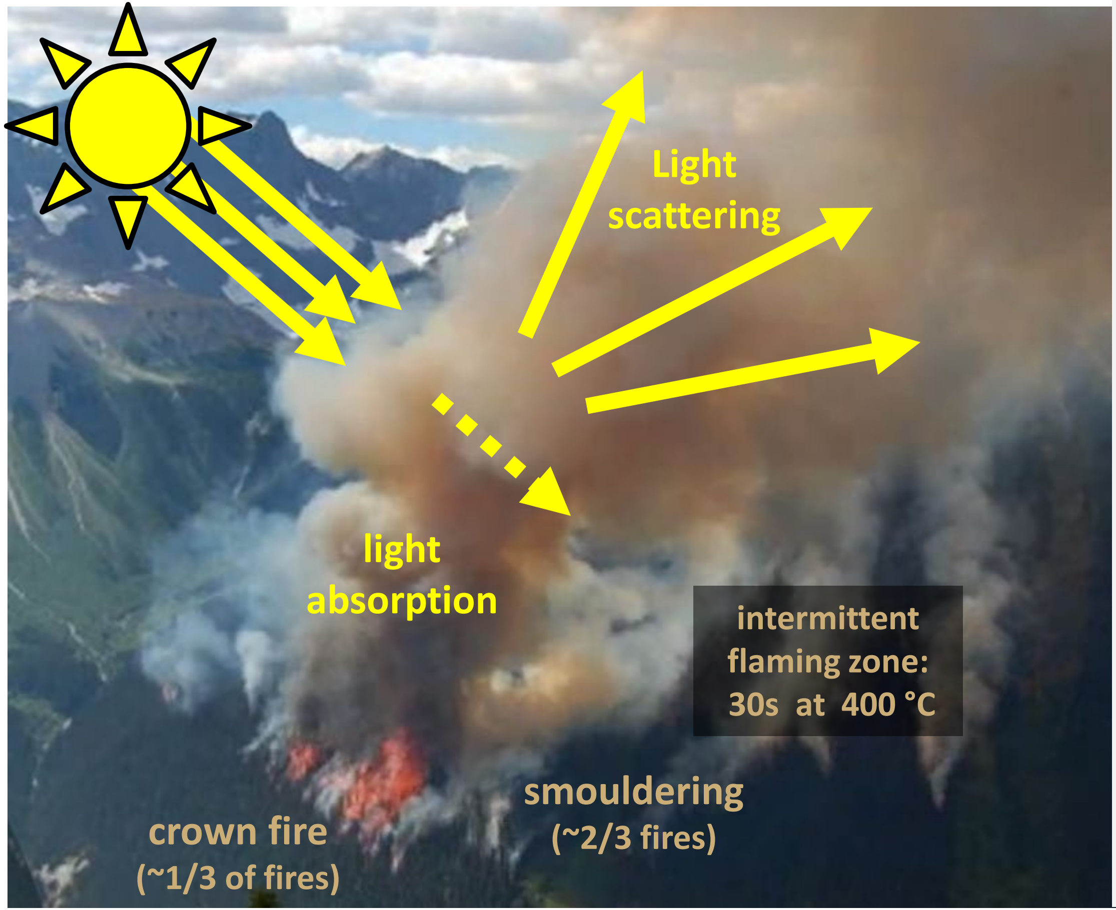
Thus, differences in:

- Chemical composition (mass spectra) Poster this afternoon
- EC/OC
- Raman spectra
- **Optical properties**

Part 2

Sipkens-Tauc theory for light absorption

Smoke & Optics



$\mathbf{ext} = \mathbf{sca} + \mathbf{abn}$

$\mathbf{SSA} = (\mathbf{albedo}) = \mathbf{sca/ext}$

$\mathbf{MAC} = \mathbf{abn/mass}$

All change with

- light λ,
- Particle…
  - d_p,
  - shape if large d_p
  - $\mathbf{RI} = \mathbf{n} + \mathbf{jk}$

Image: Kootenay prescr. burn; Parks Canada, 2014; Numbers: Dan Thompson (pers. comm.); Equations: e.g. Moosmuller et al 2009

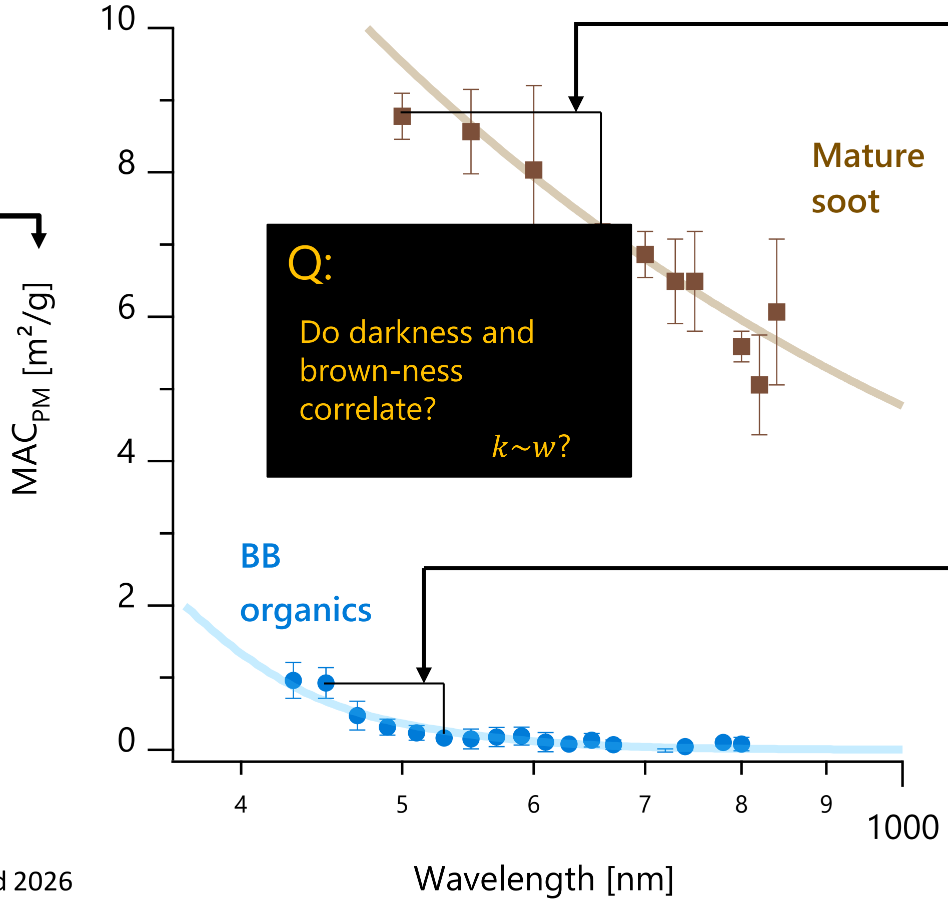
Nanochar BC ≠ soot BC

Darkness

$$\mathrm{MAC_{PM}} = \frac{\beta}{M_{\mathrm{PM}}}$$

$$= \frac{4\pi \boldsymbol{k}}{\lambda M_{\mathrm{PM}}}$$

for $d_p \ll \lambda$, else use Mie theory.



Brown-ness

$$\mathbf{AAE} = -1\,\frac{\ln \mathrm{MAC}}{\ln \lambda}$$

→ Direct! Observable! Any size/morphology!

Brown-ness

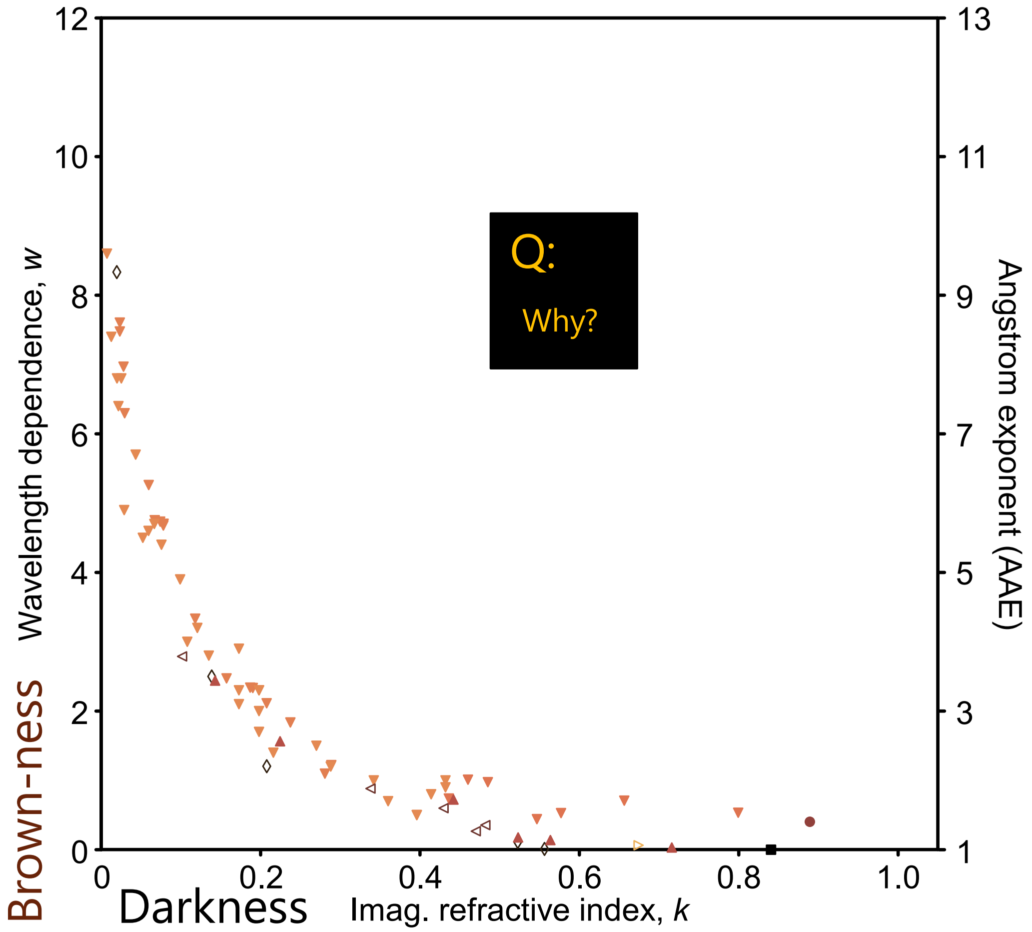
$$w = \mathbf{AAE} - 1$$

$$w = \frac{d \ln \boldsymbol{k}}{d \ln \lambda}$$

→ material property! Needed for theory!

Data: Corbin et al., submitted 2026
Theory: Sun, Biedermann, Bond 2007

Correlation of k & w=AAE – 1



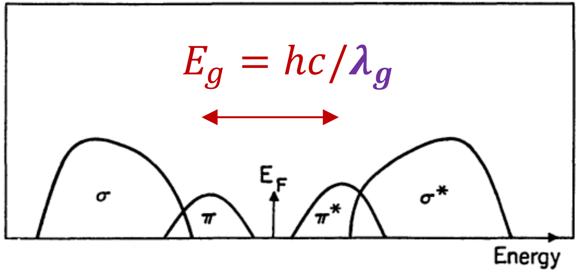
Soot (various studies and maturities)

- **Soot**, mature (Liu et al., 2019)
- **Soot**, propane (Schnaiter et al., 2006)
- **Soot**, miniCAST (Heuser et al., 2025)
- **Soot** (Kumar et al., 2018)
- **Soot**, propane (Ess et al., 2021)
- **Soot**, benzene/toluene (Cheng et al., 2019)
- **brC**, benzene/toluene (Cheng et al., 2019)
- **brC**, benzene/toluene (Saleh et al., 2018)
- **Soot**, diesel (Schnaiter et al., 2003)
- **Soot**, propane/ethylene (Vernocchi et al., 2022)

Sipkens–Tauc Theory predicts (k, w) relationship.

Standard Tauc theory:

$$\beta_\lambda = \frac{B^2 (E - E_g)^2}{E}$$



B = proportionality constant

E = photon energy

E_g = optical band gap

Substitute $E = hc/\lambda$,

$$\beta_\lambda = B^2 \frac{hc}{\lambda} \left(1 - \frac{\lambda}{\lambda_g}\right)^2$$

Sipkens–Tauc theory for k:

Treat B^2 as constant.
Calculate B^2 for a ref. material,
e.g. soot for which $\lambda_g \to \infty$, so

$$B^2 = \frac{\beta_0 \lambda}{hc} = \frac{4\pi k_0}{hc}$$

From which,

$$\boldsymbol{k_\lambda = k_0 \left(1 - \frac{\lambda}{\lambda_g}\right)^2}$$

NEW

Sipkens–Tauc theory for w:

$w = \frac{\partial \ln k}{\partial \ln \lambda}$ giving

$$\boldsymbol{k_\lambda = k_0 \left(\frac{2}{w_\lambda + 2}\right)^2}$$

NEW

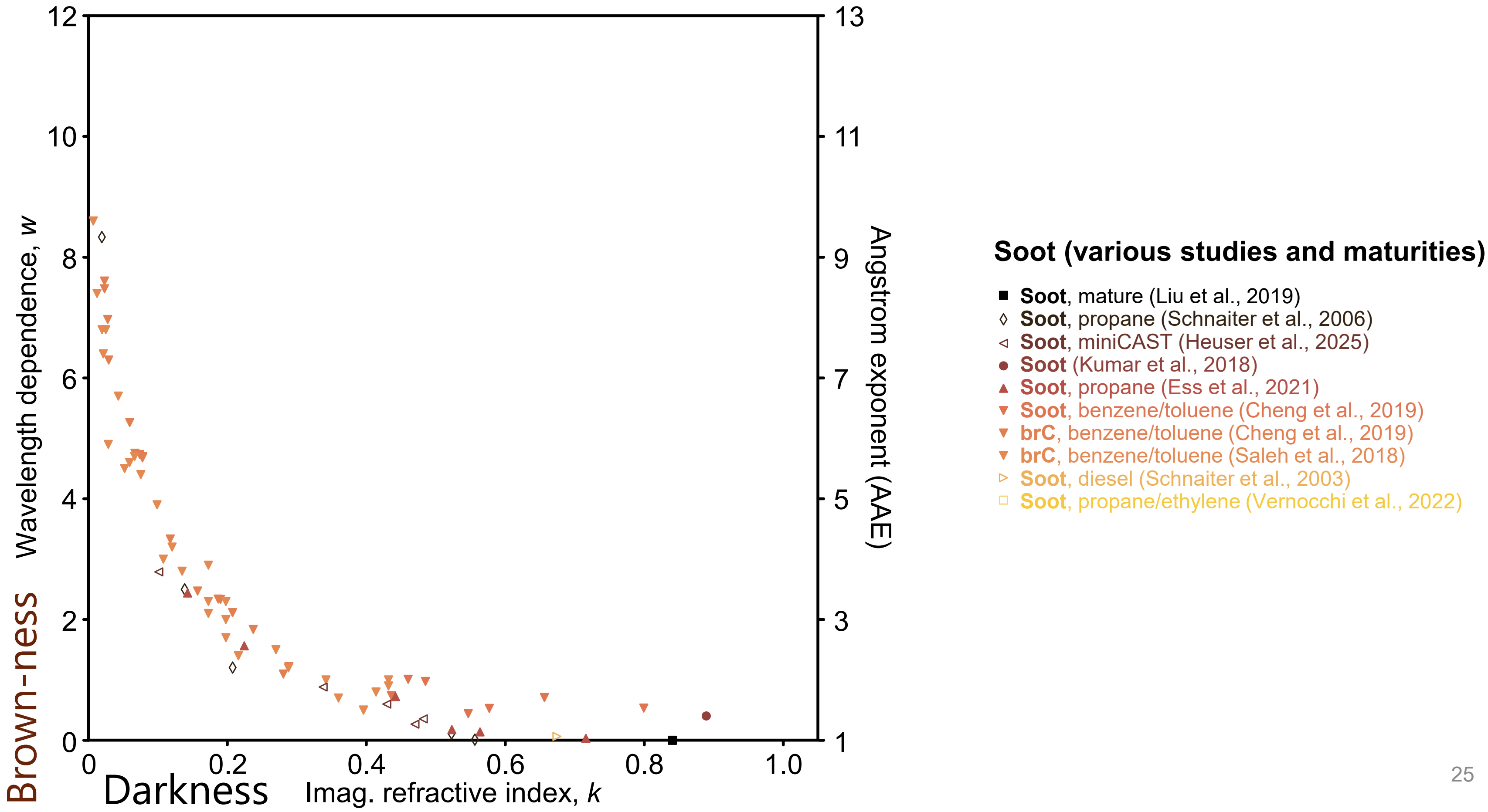
→ **A single parameter (λ_g) physically based model**

→ **Describes all brown and black carbon**
(size/shape must still be considered separately)

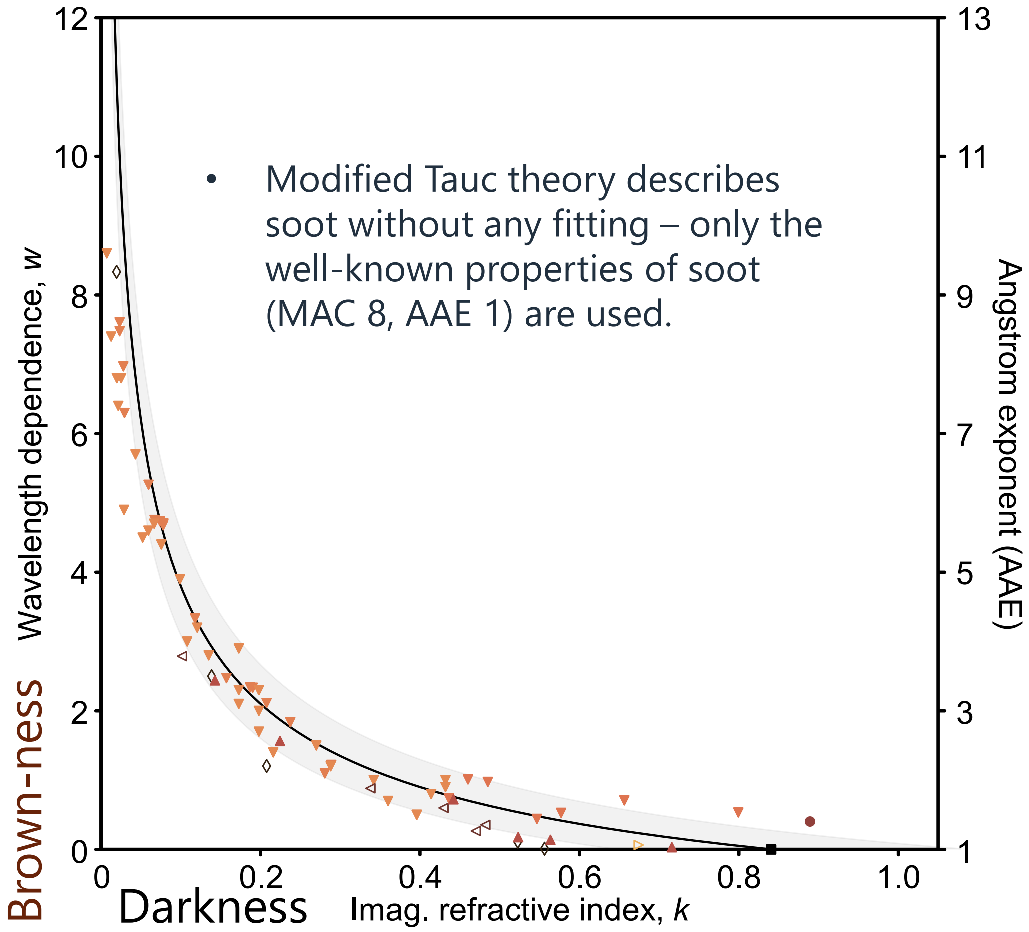
Sun, Biedermann and Bond, GRL 2007; Robertson, 1991; Tauc 1966

Sipkens 2026, in prep.

Back to this plot…



Back to this plot... and add the fit for soot



- Modified Tauc theory describes soot without any fitting – only the well-known properties of soot (MAC 8, AAE 1) are used.

– **Modified Tauc model**

$$k_\lambda = k_{\mathrm{soot}}\left(1 - \frac{\lambda}{\lambda_g}\right)^2$$

Soot (various studies and maturities)

- **Soot**, mature (Liu et al., 2019)
- **Soot**, propane (Schnaiter et al., 2006)
- **Soot**, miniCAST (Heuser et al., 2025)
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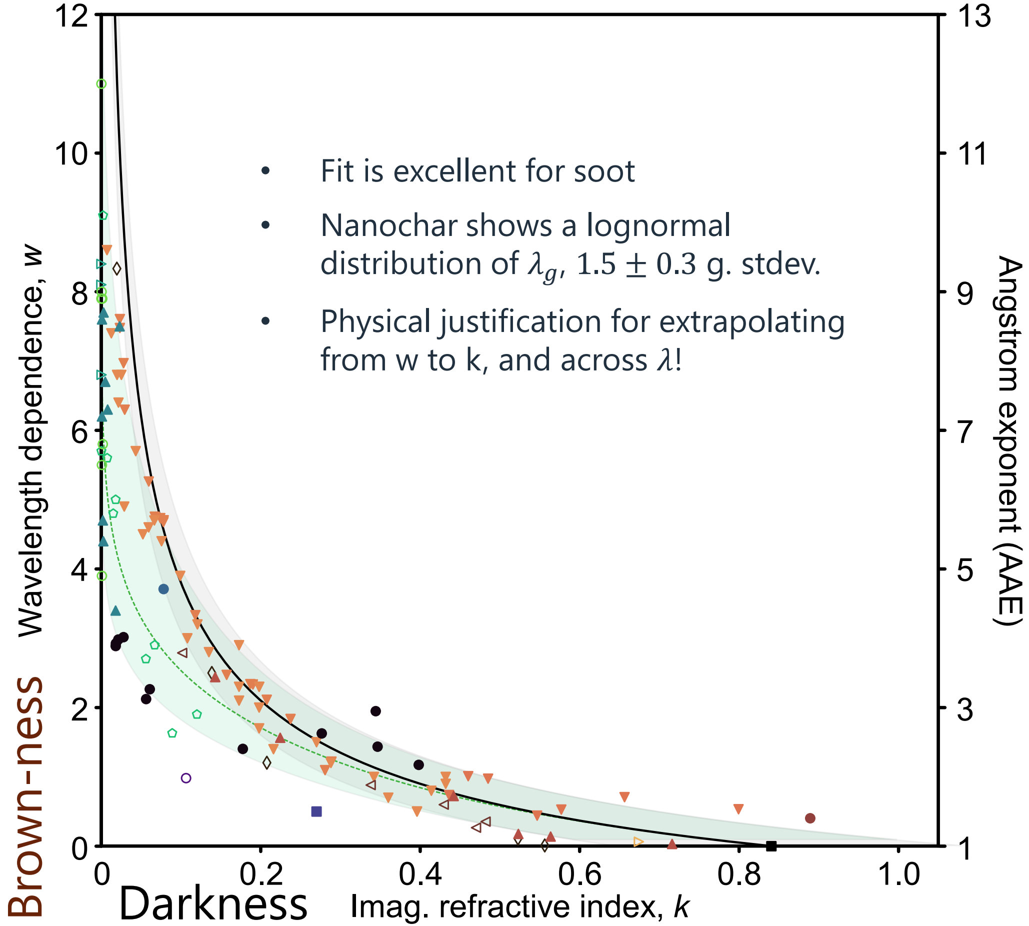
- **brC**, benzene/toluene (Saleh et al., 2018)
- **Soot**, diesel (Schnaiter et al., 2003)
- **Soot**, propane/ethylene (Vernocchi et al., 2022)

Adding brown carbon and nanochar



- Fit is excellent for soot
- Nanochar shows a lognormal distribution of λ_g, 1.5 ± 0.3 g. stdev.
- Physical justification for extrapolating from w to k, and across λ!

– Modified Tauc model

– With LogNorm, σ_g = 1.50 (± 0.3)

$$k_\lambda = k_{\mathrm{soot}}\left(1 - \frac{\lambda}{\mathrm{LogN}(\lambda_g, \sigma_g)}\right)^2$$

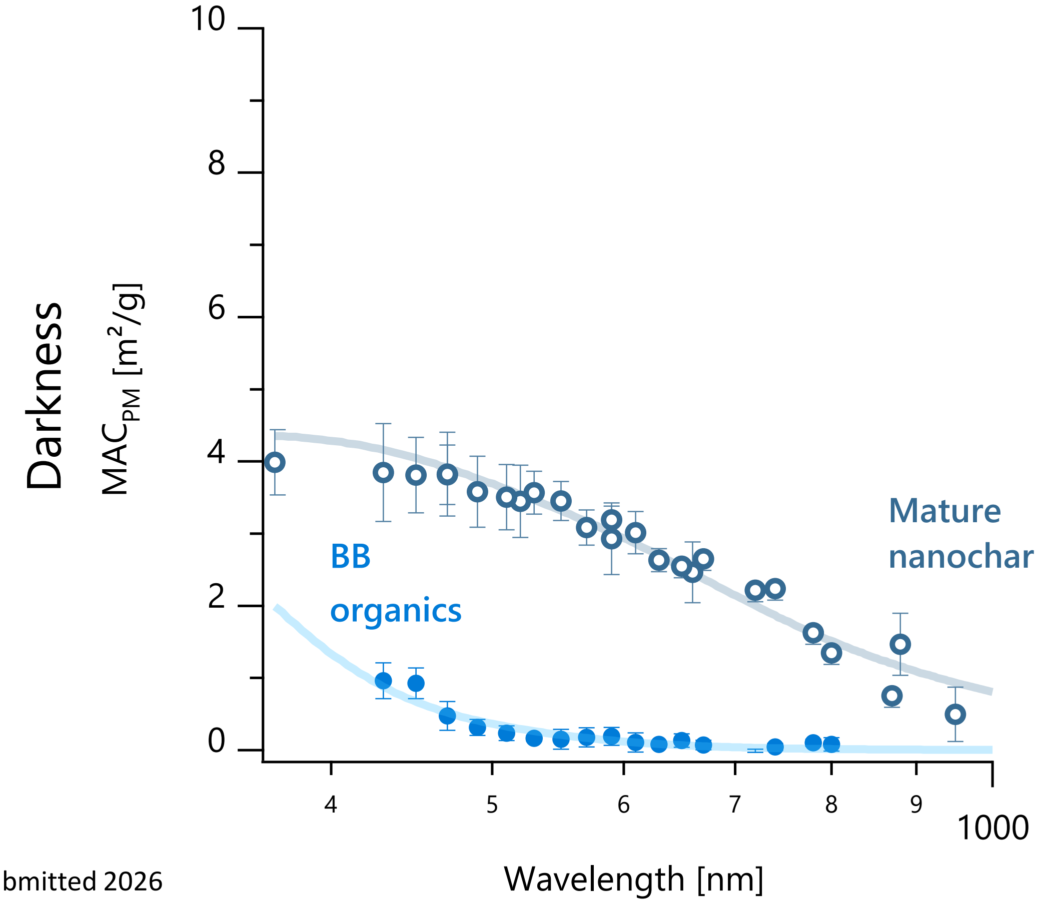
Soot (mature and young)

- ■ **Soot**, mature (Liu et al., 2019)
- ◊ **Soot**, propane (Schnaiter et al., 2006)
- ◁ **Soot**, miniCAST (Heuser et al., 2025)
- ● **Soot** (Kumar et al., 2018)
- ▲ **Soot**, propane (Ess et al., 2021)
- ▼ **Soot**, benzene/toluene (Cheng et al., 2019)
- ▼ **brC**, benzene/toluene (Cheng et al., 2019)
- ▼ **brC**, benzene/toluene (Saleh et al., 2018)
- ▷ **Soot**, diesel (Schnaiter et al., 2003)
- □ **Soot**, propane/ethylene (Vernocchi et al., 2022)

Nanochar & brown carbon

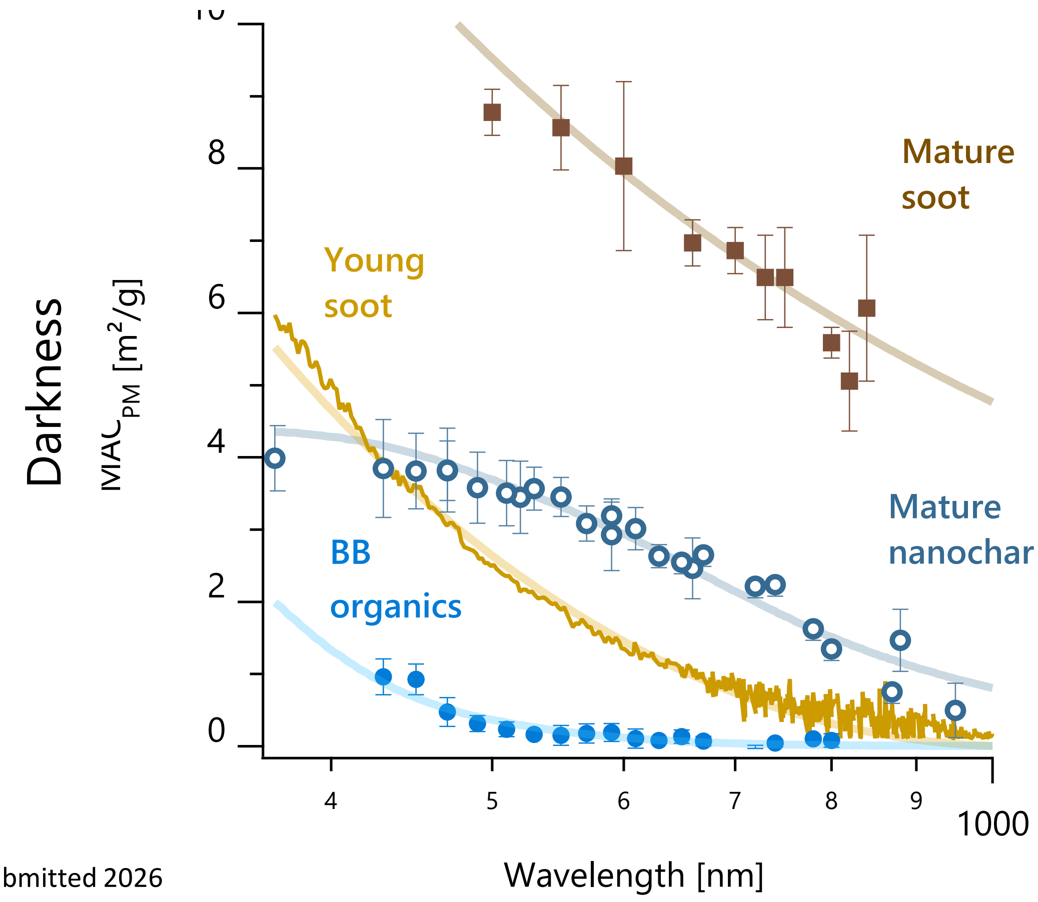
- ● **Nanochar** (Corbin et al., Submitted)
- ○ **d-brC** (Chakrabarty et al., 2023)
- ■ **Nanochar**, Yellow Sea (Alexander et al., 2008)
- ● **POA** (Kumar et al., 2018)
- ▲ **Biomass**, smouldering
- ▷ **Tarball**
- ⬠ **Humic acid**
- ⬠ **Fulvic acid**
- ○ **SOA**

Application: fitting k_λ with Mie theory for 300 nm nanochar



Data: Corbin et al., submitted 2026
Theory: Sun, Biedermann, Bond 2007

Application: fitting k_λ for soot with RDG-FA theory



Data: Corbin et al., submitted 2026
Theory: Sun, Biedermann, Bond 2007

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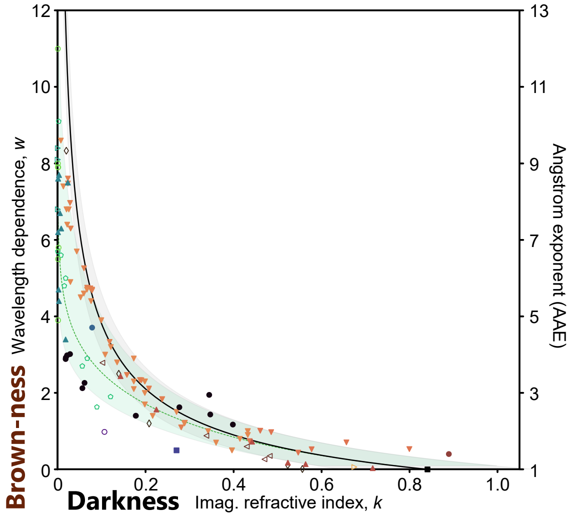
Conclusions

Nanochar has unique properties to soot/brC, should be recognized as a unique category, and unifies numerous disparate literature reports.

$$\textbf{Darkness} = k_\lambda = k_0\left(1-\frac{\lambda}{\lambda_g}\right)^2$$

$$\textbf{Brownness} = k_\lambda = k_0\left(\frac{2}{w_\lambda+2}\right)^2$$



Applications:

→ Improved data inversion for…

- → imaging nephelometers,
- → Retrieving brC properties,
- → simple Aethalometer models ("UVPM", BB/Fossil")

End