An Attenuated Emission (ATEM) model for the infrared spectrum of SN2010jl

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JWST spectrum of SN2010jl

Smith et al. 2024

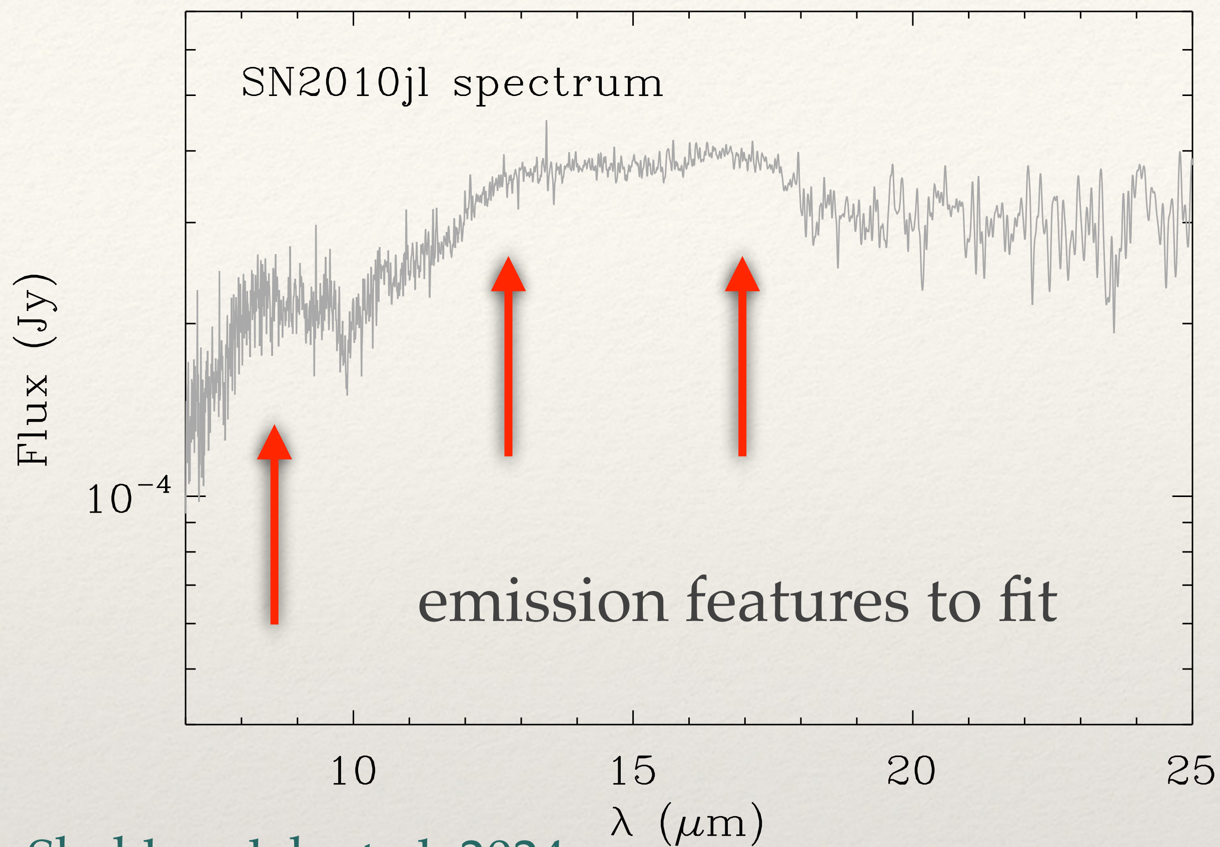
Traditional interpretation:

The observed spectrum is comprised of the emission from different type grains characterized by their:

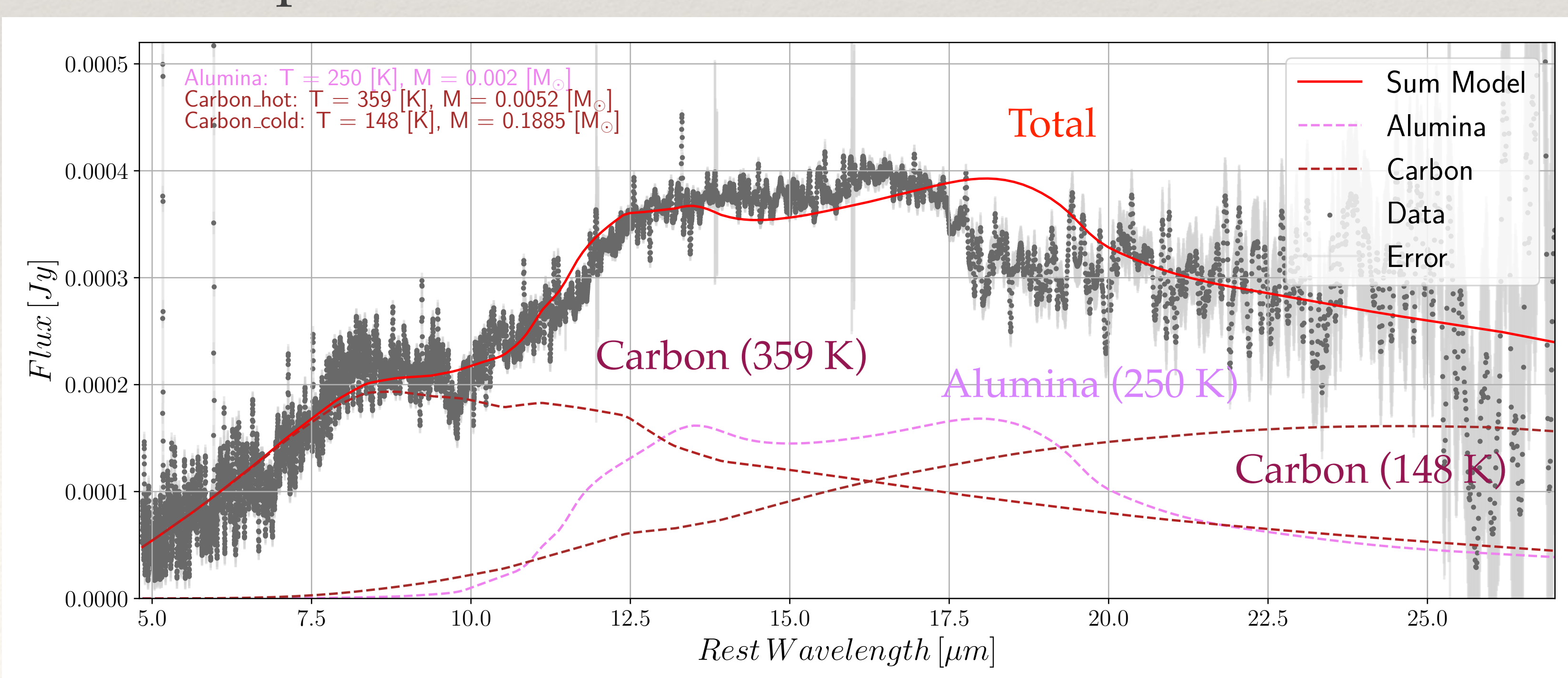
composition

mass

temperature.



Example: Smith, N. et al. 2024, Shahbandeh et al. 2024



PROBLEM:

Why

Alumina (Al_2O_3)

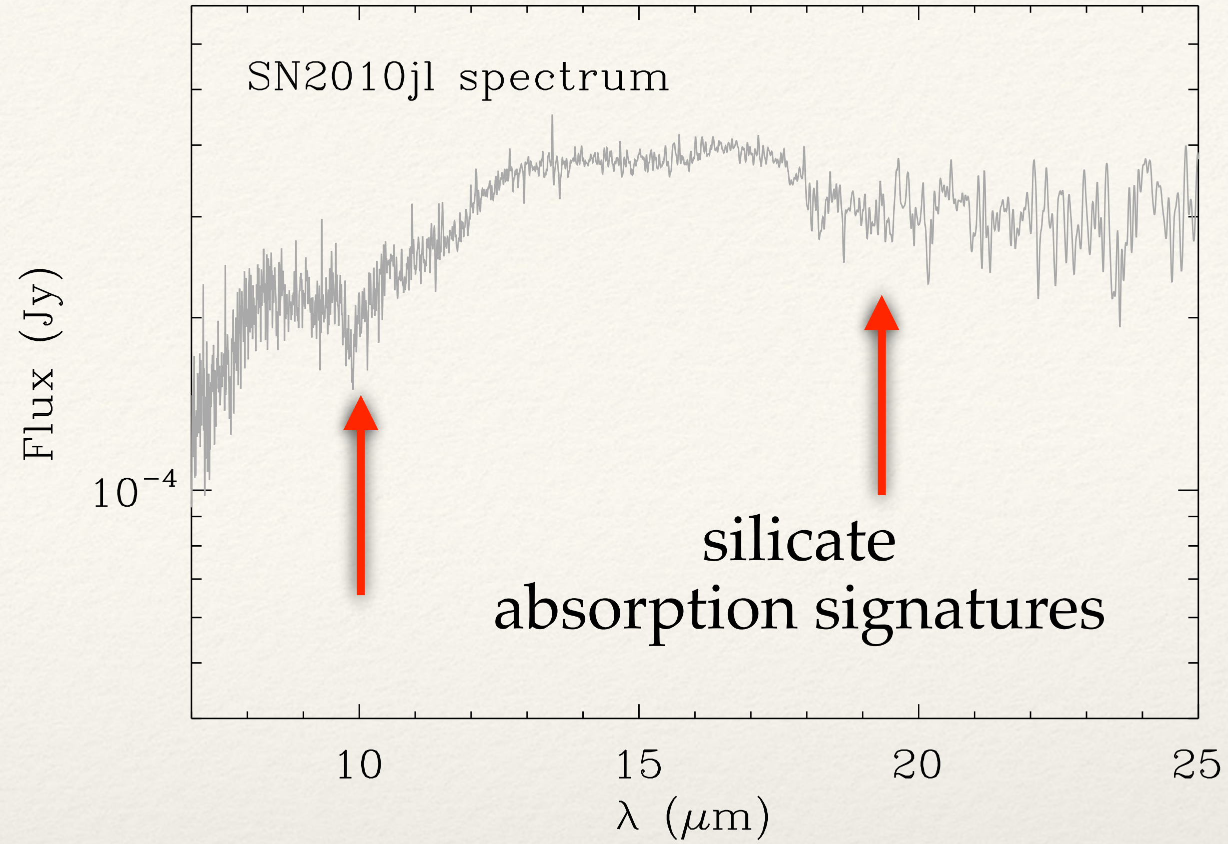
and no

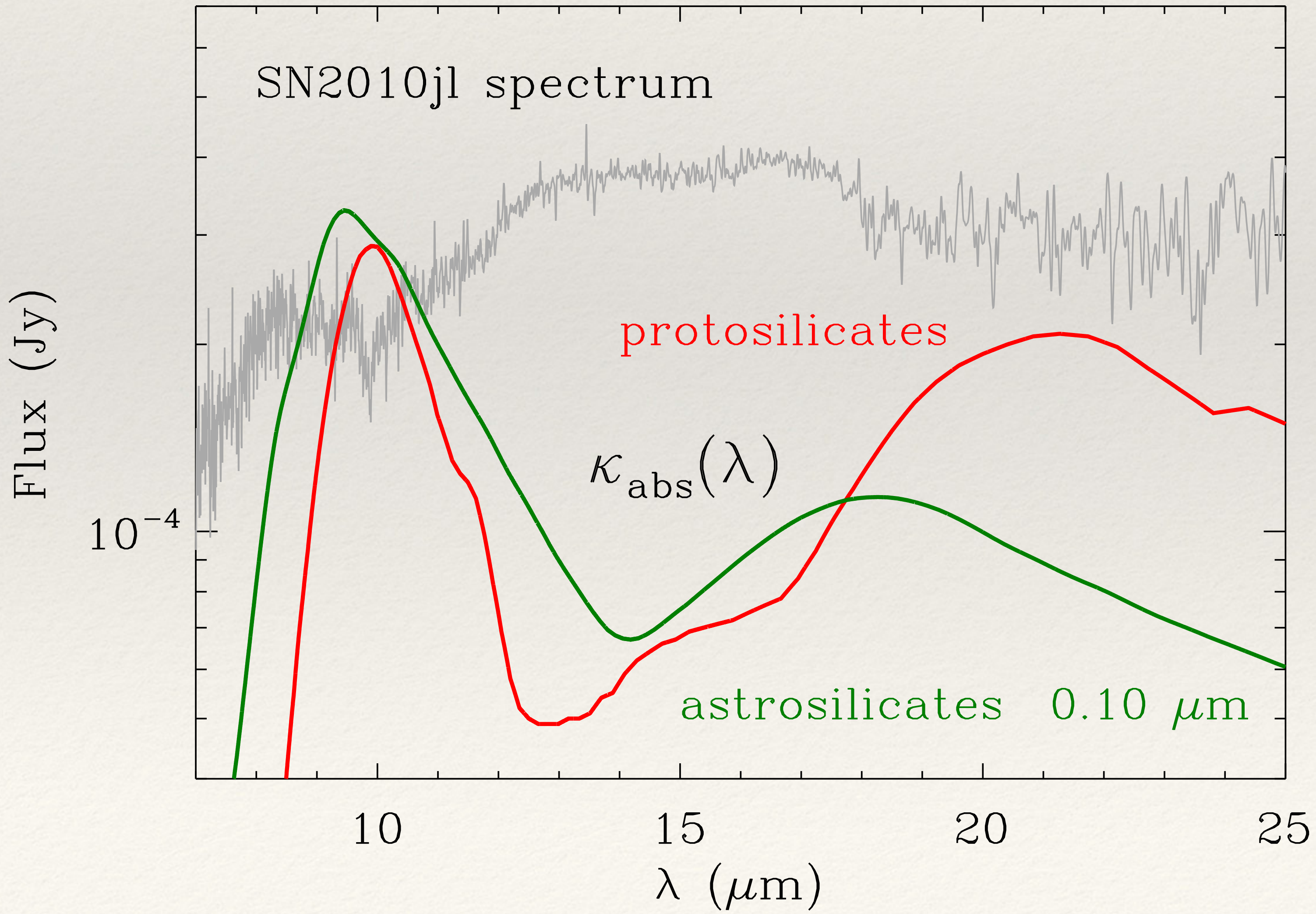
Silicates (Mg_2SiO_4)

(either too little – 0.007 M_{sun}, or too much – 2.0 M_{sun})

The attenuated ejecta emission model

Instead of looking at the spectrum as a pure emission spectrum, we can look at it as an absorbed emission spectrum





Mathematical formalism
(fit parameters)

$$F_\nu^{obs}(\lambda) = F_\nu^{em}(\lambda) \times exp[-\tau_{abs}(\lambda)] \,+\, F_\nu^{abs}(\lambda)$$

Flux from emitting source

$$F_\nu^{em}(\lambda) = \frac{4M_{em}}{4\pi d^2} \int_0^\infty \pi B_\nu(\lambda, T_{em})\, \kappa_{em}(\lambda) d\nu$$

κ_{em}

M_{em} T_{em}

Absorber opacity

$$\tau_{abs}(\lambda) = \left[\frac{M_{abs}}{\pi R_{abs}^2}\right] \kappa_{abs}(\lambda)$$

κ_{abs}

M_{abs} R_{abs}

Mathematical formalism
(derived parameters)

Emitter luminosity L_{em}

Blackbody radius
$$R_{BB}^2 = \left[\frac{L_{em}}{4\pi\sigma T_{em}^4} \right]$$

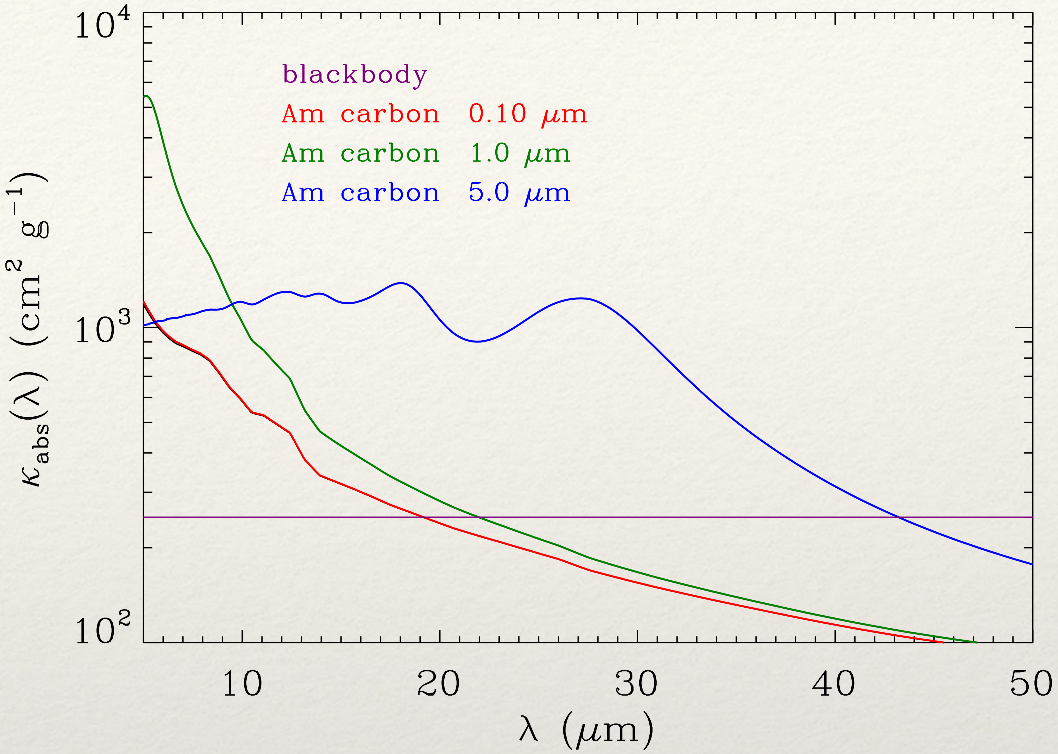
Relation
$$M_{abs} \propto R_{abs}^2$$

Emitter and absorber characteristics

Mass absorption coefficient $\kappa[\mathrm{cm}^2/\mathrm{gr}]$ vs wavelength

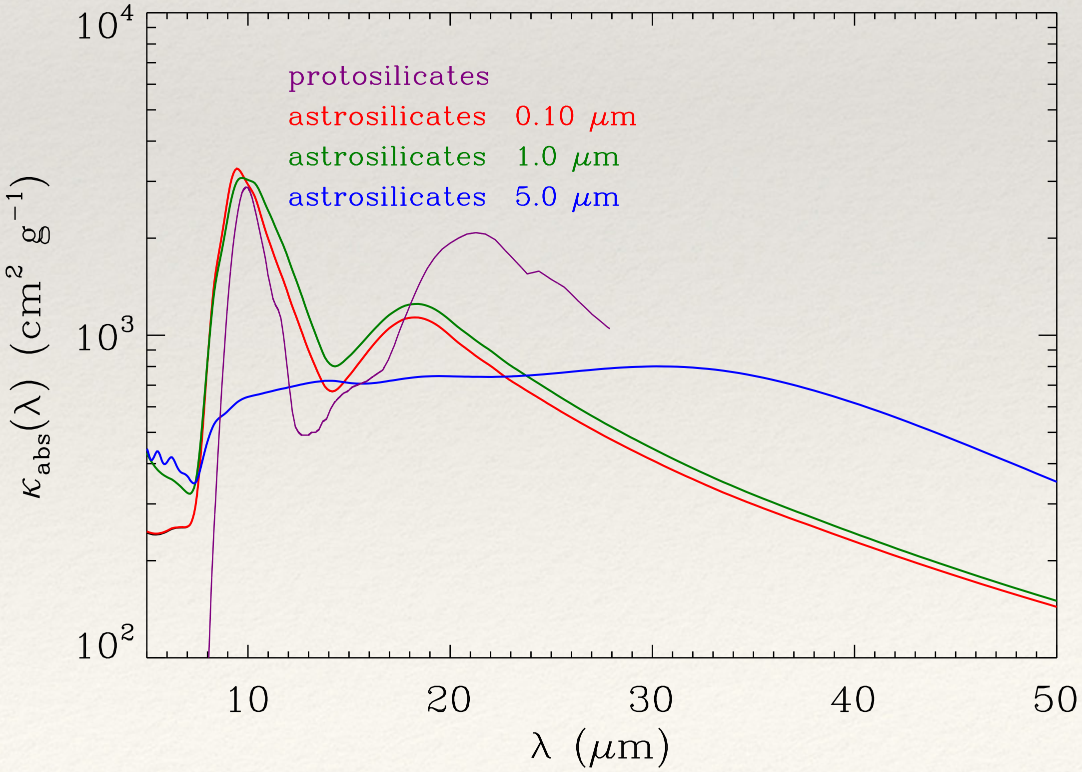
Requirements of emission spectrum

- smooth featureless spectrum in the ~ 5-30 μm region
- carbon dust , large silicates

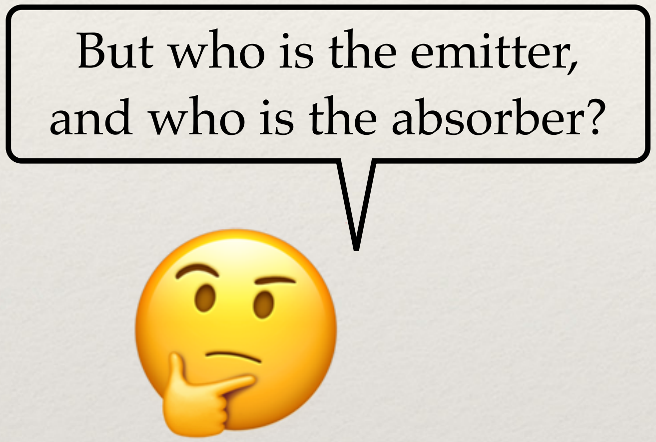


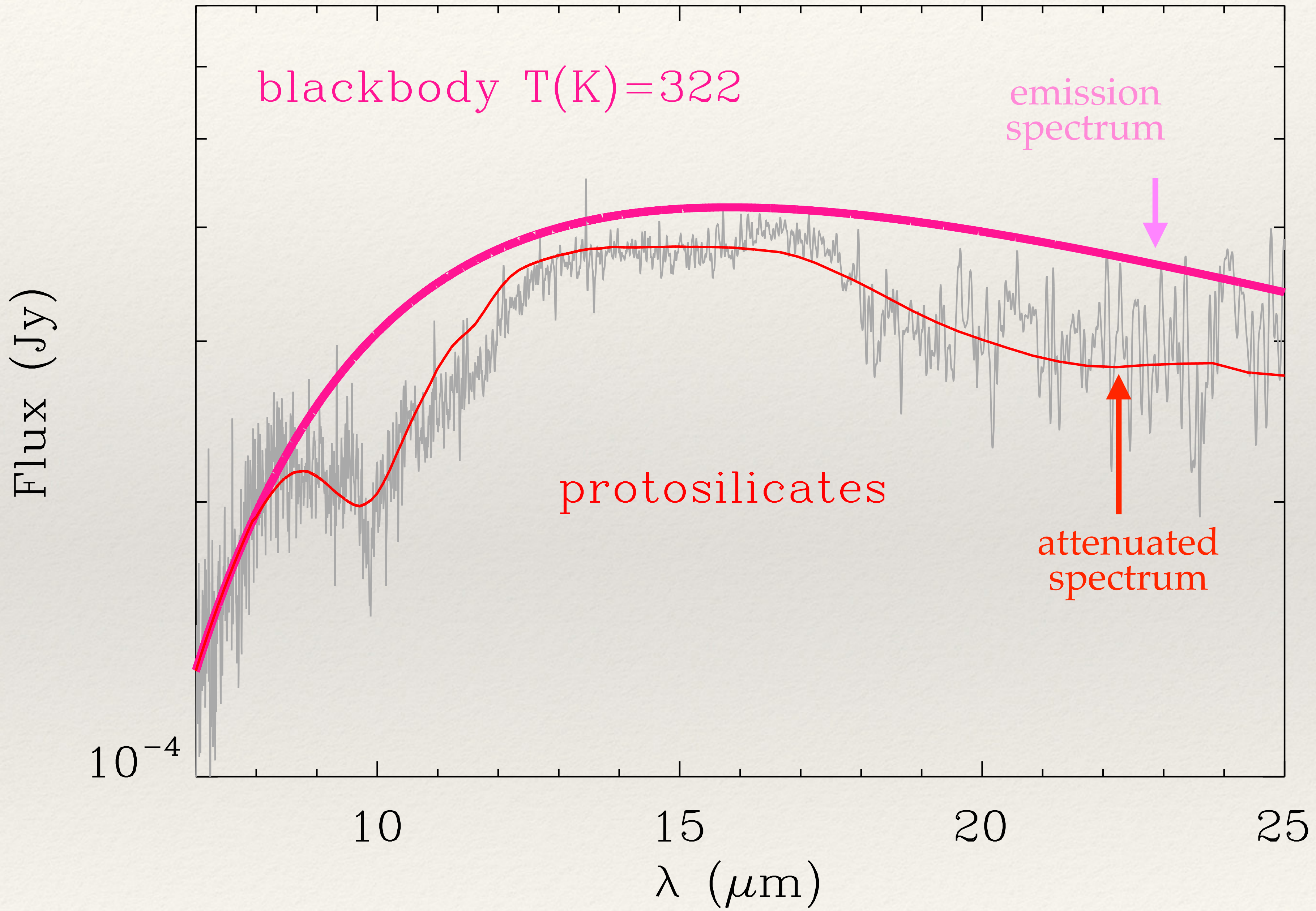
Requirements of the absorber

- strong absorption features at ~10 and 20 μm
- silicates

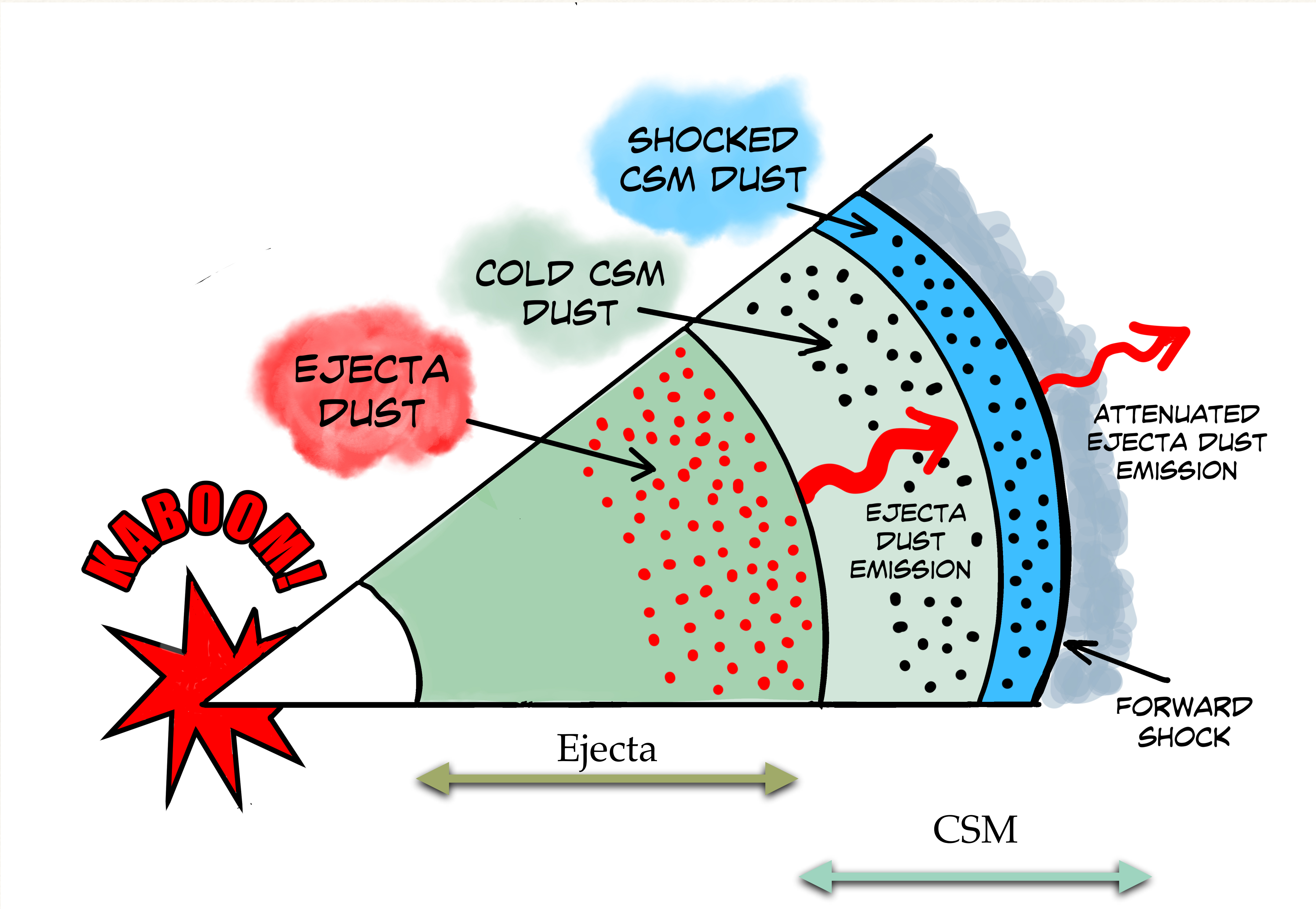


A simple attenuated emission spectrum



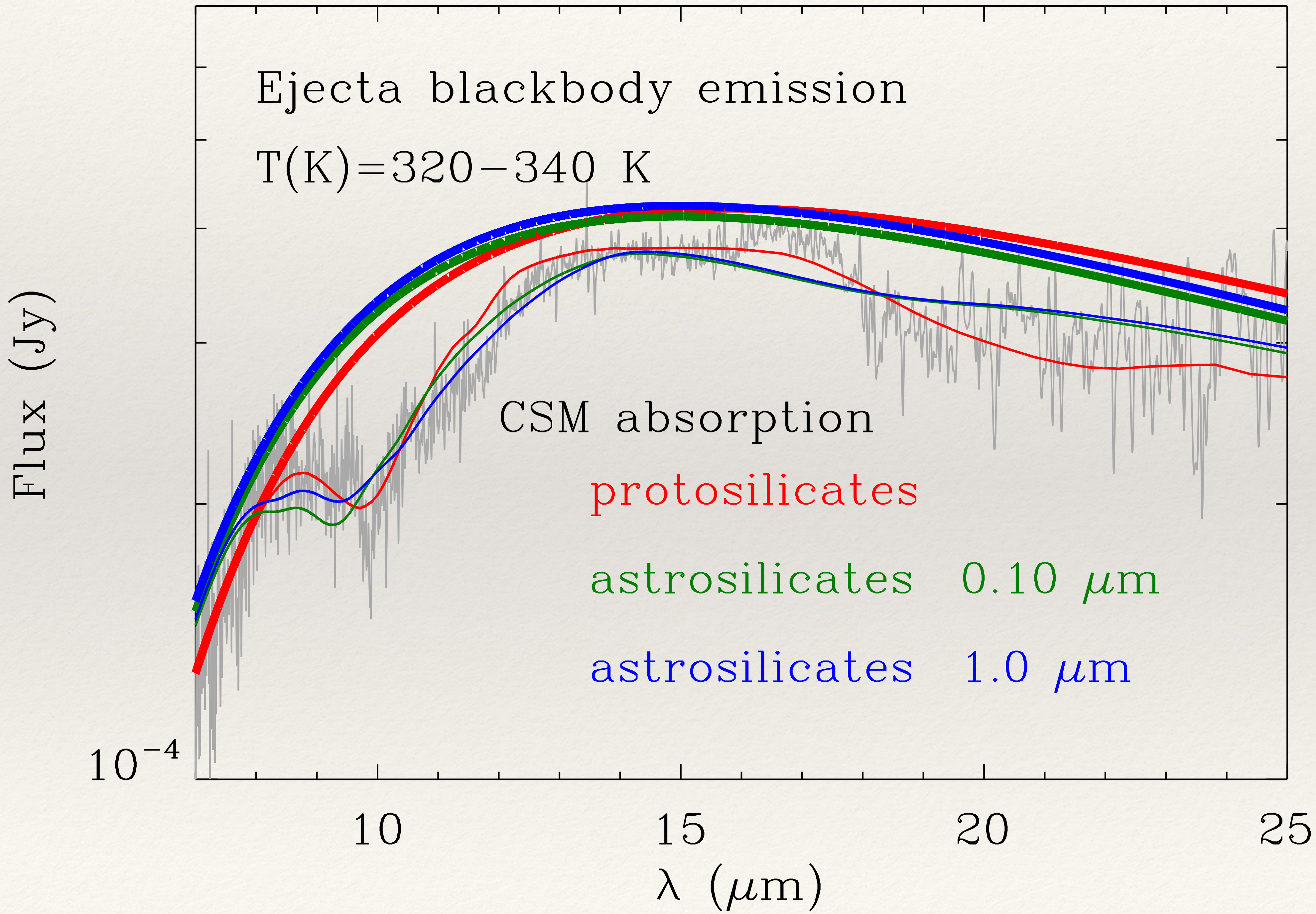


(1) The Ejecta-CSM scenario

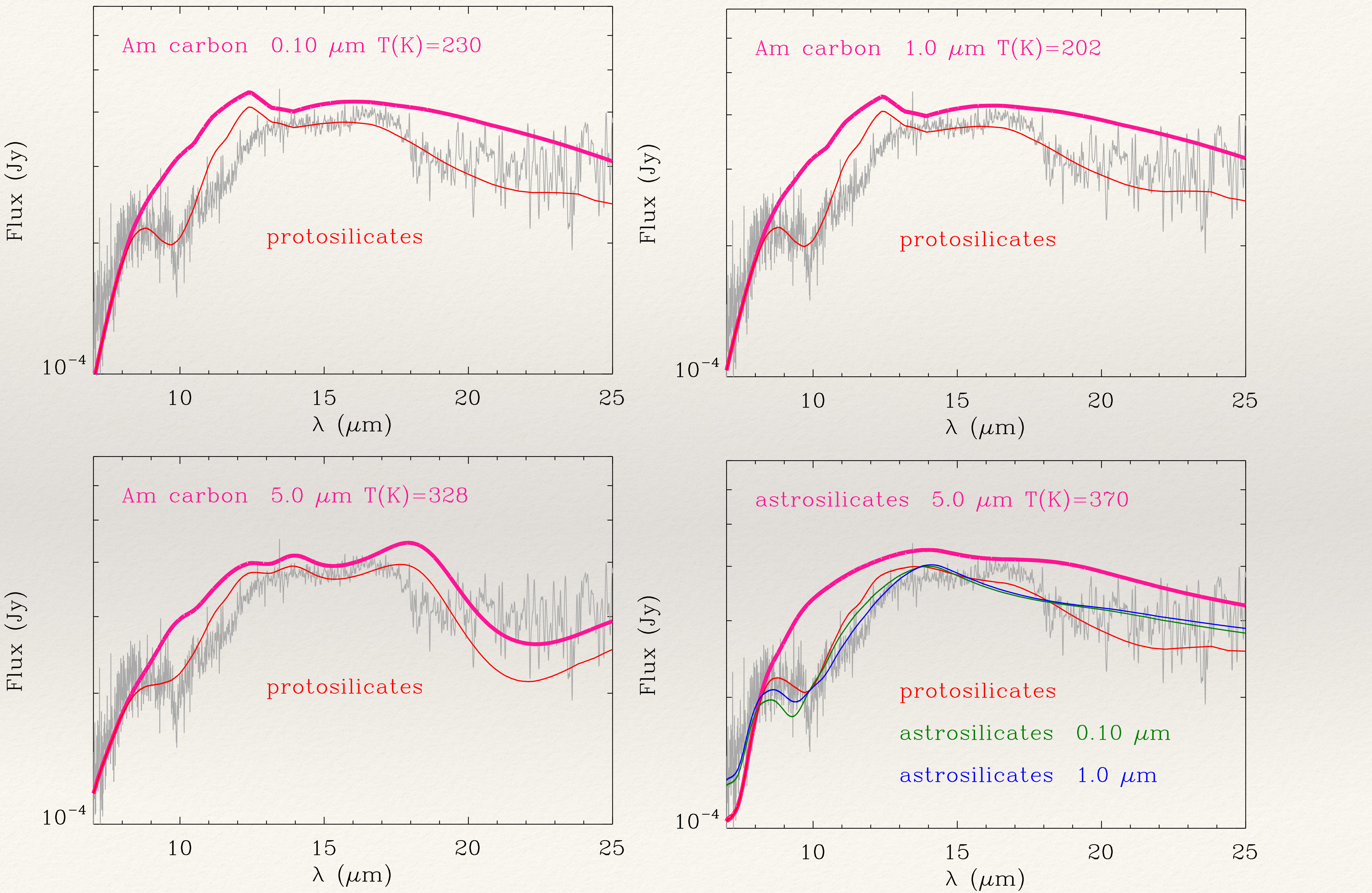


Sample result for a blackbody representation of the ejecta

Each choice of CSM dust composition requires a different ejecta spectrum

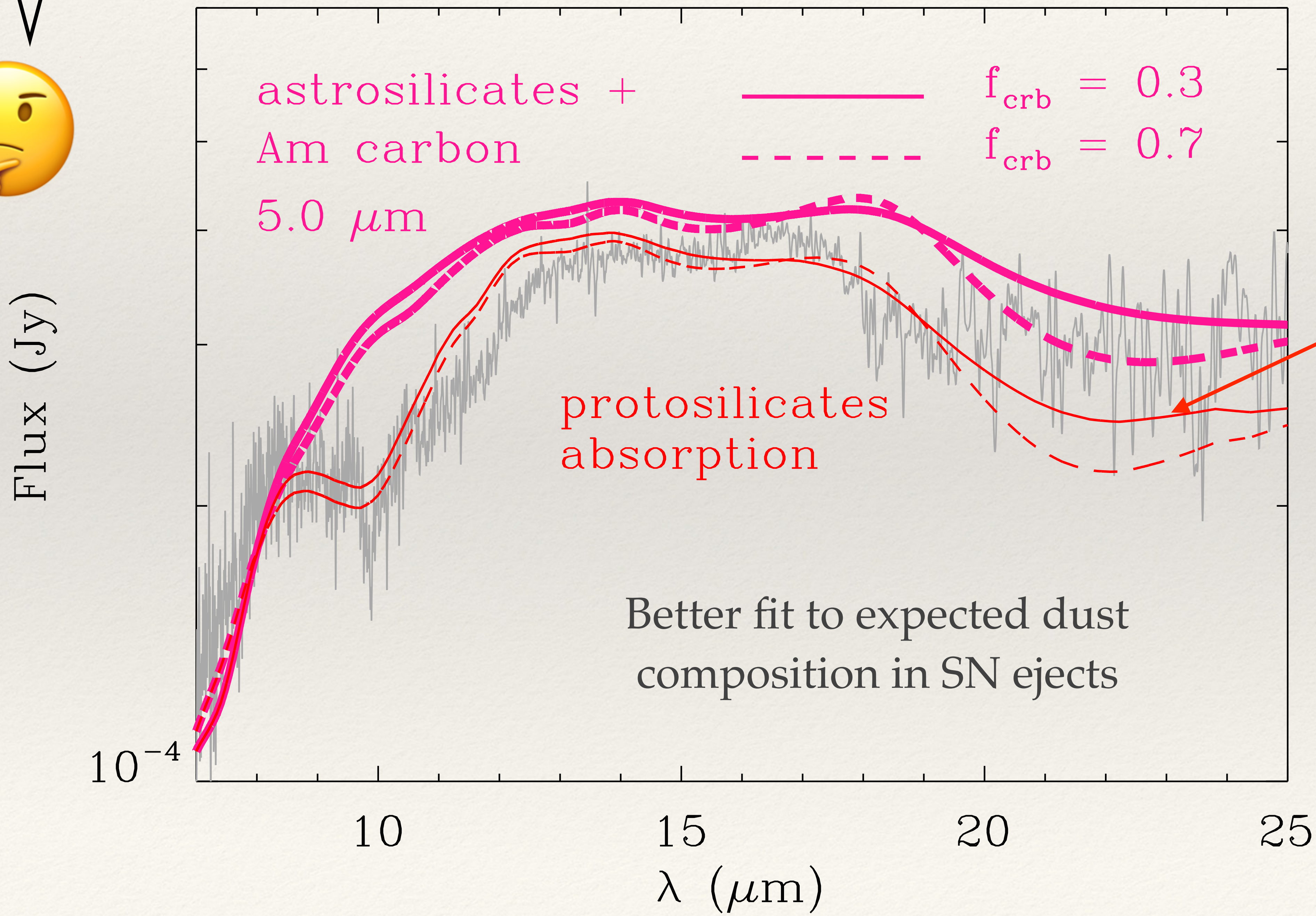


Fit results for different ejecta compositions



Mixed ejecta composition

Hmmm … if the observed spectrum can be fit by either a carbonaceous OR silicate ejecta, can a mixture of carbon AND silicate provide a good fit as well?



Better fit when silicates are the dominant dust component

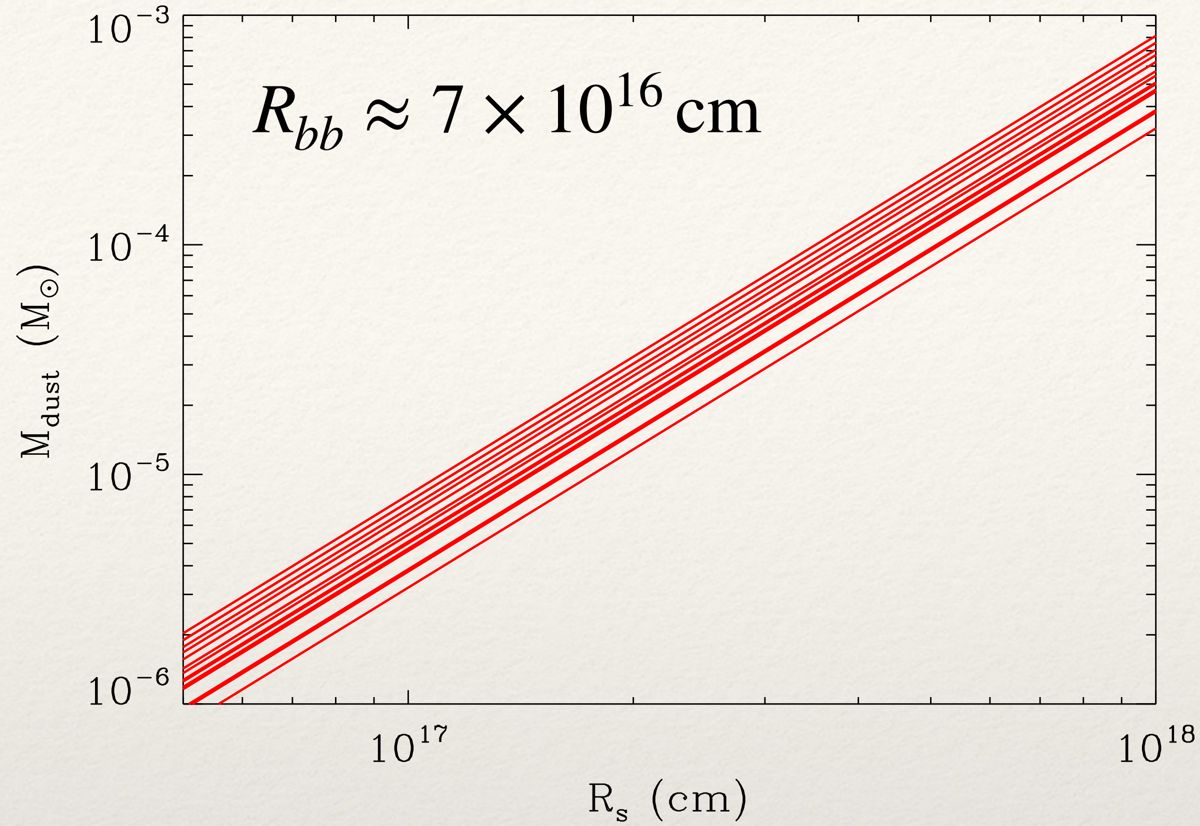
silicate-to-carbon mass ratio ≈ 2:1

Model results – Ejecta

Ejecta dust mass (5 μm sil+crb mix / blackbody dust)	$M_{ej} \approx 0.007 - 0.1\ M_{\odot}$
Dust temperature	$T_{ej} \approx 330 - 370\ K$
Ejecta luminosity	$L_{ej} \approx 8 \times 10^{6}\ L_{\odot}$
Blackbody radius	$R_{bb} \approx 5 \times 10^{16}$ cm

Model results: Circumstellar medium

Circumstellar
dust mass-radius
degeneracy



Limit on CSM silicate dust temperature

A dust temperature that is too high will wipe out the silicate absorption features.

$$T_{csm} \lesssim 250\ K$$

CSM 10 μm opacity

$$\tau_{csm}(10\,\mu\text{m}) \approx 0.40$$

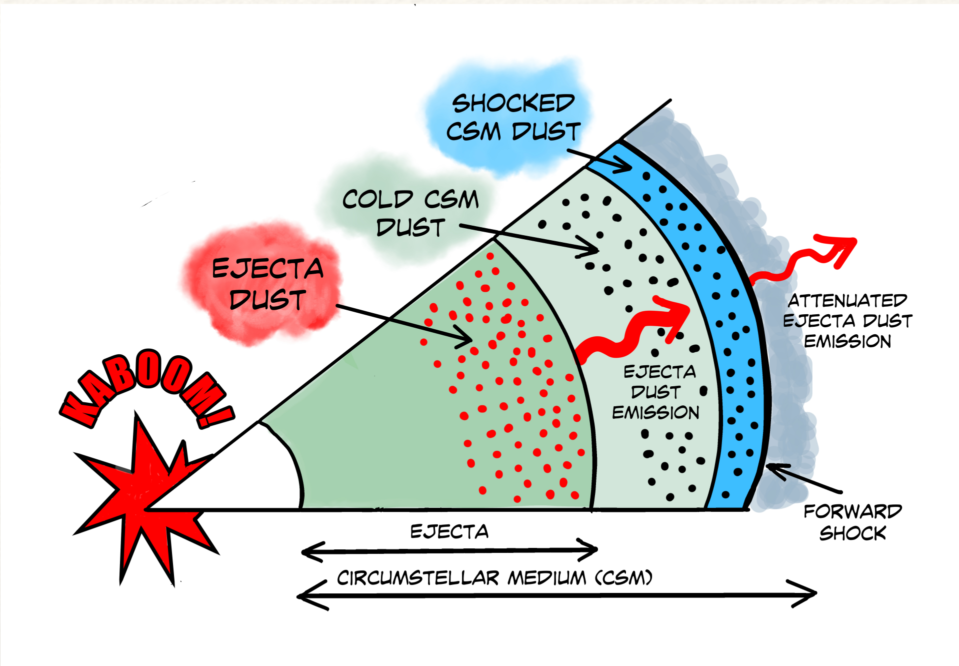
Model challenges

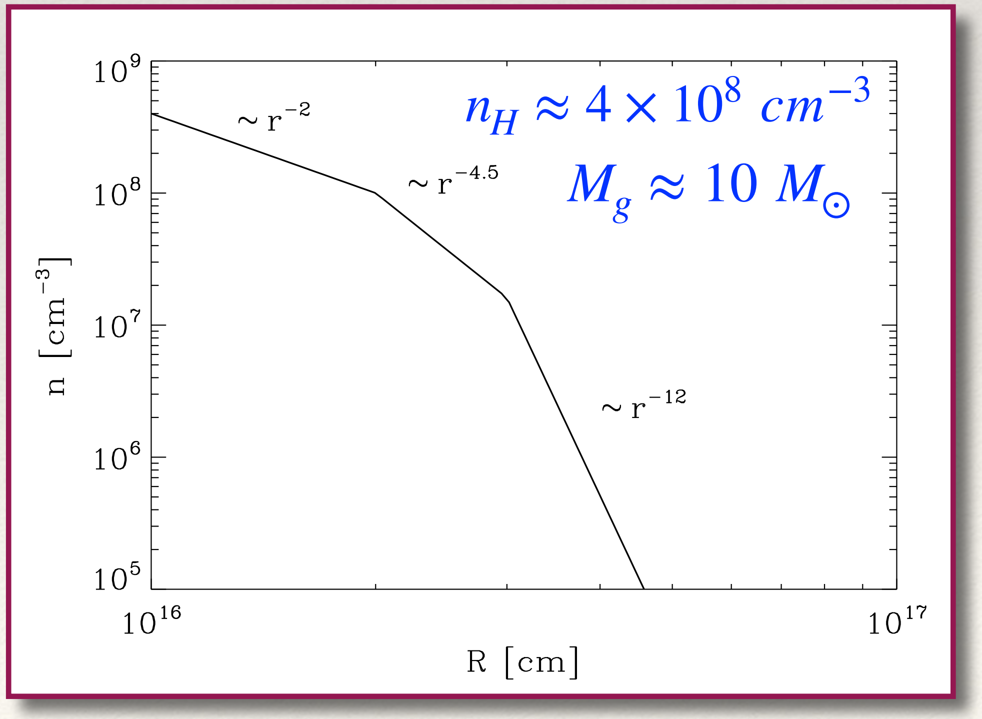
- Upper limit on the CSM dust temperature constrains the dust heating mechanism (collisional and/or radiative) and therefore the parameters of the forward shock

- But if the forward/reverse shock heat the CSM dust, why is the further removed ejecta dust hotter than the CSM dust?

- An additional heating mechanism is needed to heat the ejecta dust
REVERSE, REFLECTED shocks?

- The blackbody radius is larger than the dimension of the CSM as inferred from X-ray observations.
(Chandra et al. 2015, Dwek et al. 2021).





Possible solution to the challenges

Ballistic injection of ejecta dust into the CSM

- Dust travels farther than the gas
- Relative dust-gas motion heats the ejecta dust

Relative dust-gas motion needed to heat dust to 300 K
(calculated for 10 μm radius grains)

$$\mathscr{H} = \pi a^2 \rho_{gas} v^3 = 4\pi a^2 \sigma T^4 = \mathscr{L} \qquad v \gtrsim 700 \text{ km/sec}$$

Stopping legth of dust

$$\pi a^2 \ell \, \rho_{gas} \approx \frac{4\pi}{3} \rho a \qquad \ell \approx 10^{14} \text{ cm}$$

Number of grains, N

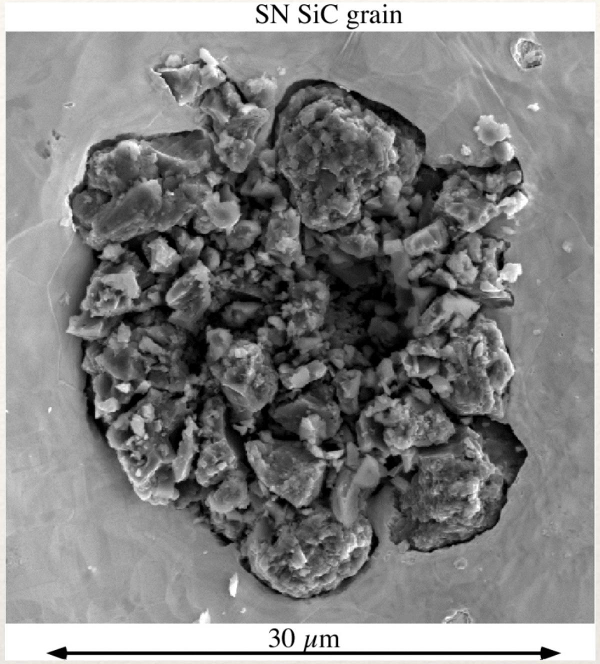
$$N = \frac{4\pi R_{bb}^2 \, \sigma T^4}{4\pi a^2 \, \sigma T^4} \approx 10^{40}$$

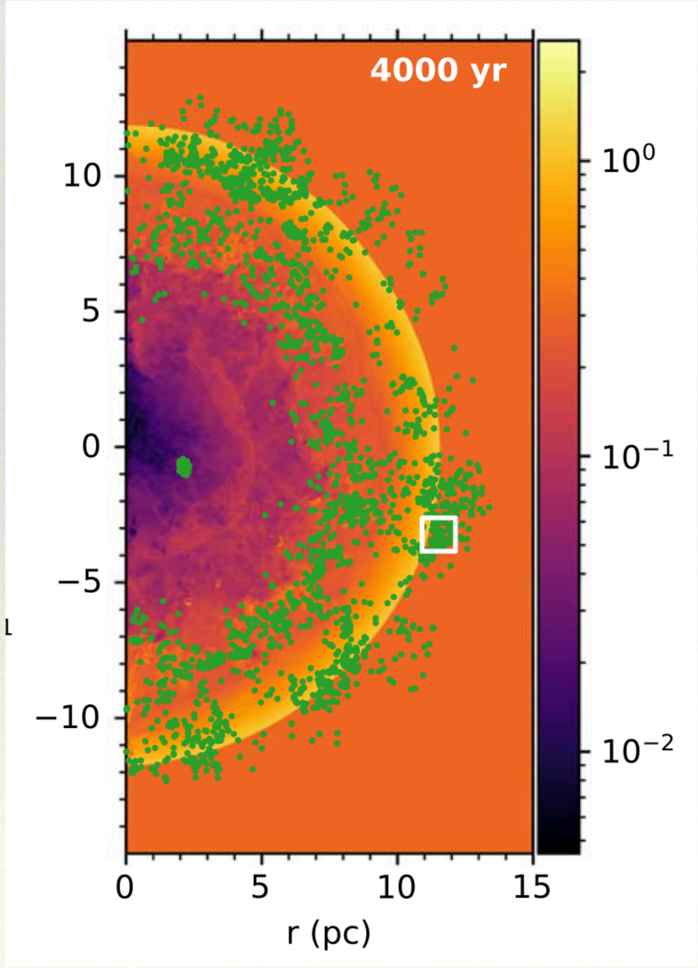
Dust mass, M_d

$$M_d = N \frac{4\pi}{3} \rho \, a^3 = \frac{4\pi}{3} \rho \, a \, R_{bb}^2 \quad \approx 0.1 \text{ M}_\odot$$

Is it possible?

Large dust grains can form by coagulation in SN ejecta. Shown is the so-called BONANZA dust grain . (Zinner et al 2011)





Detailed dynamical models follow the injection of SN produced dust grains into the ISM.

The injection model needs to take the effect of grain destruction by kinetic sputtering and evaporative grain-grain collision into account. (Slavin et al. 2020)

A survey

Is the association of the emitter with ejecta dust and the absorber with CSM dust a credible scenario?

Express your feelings:

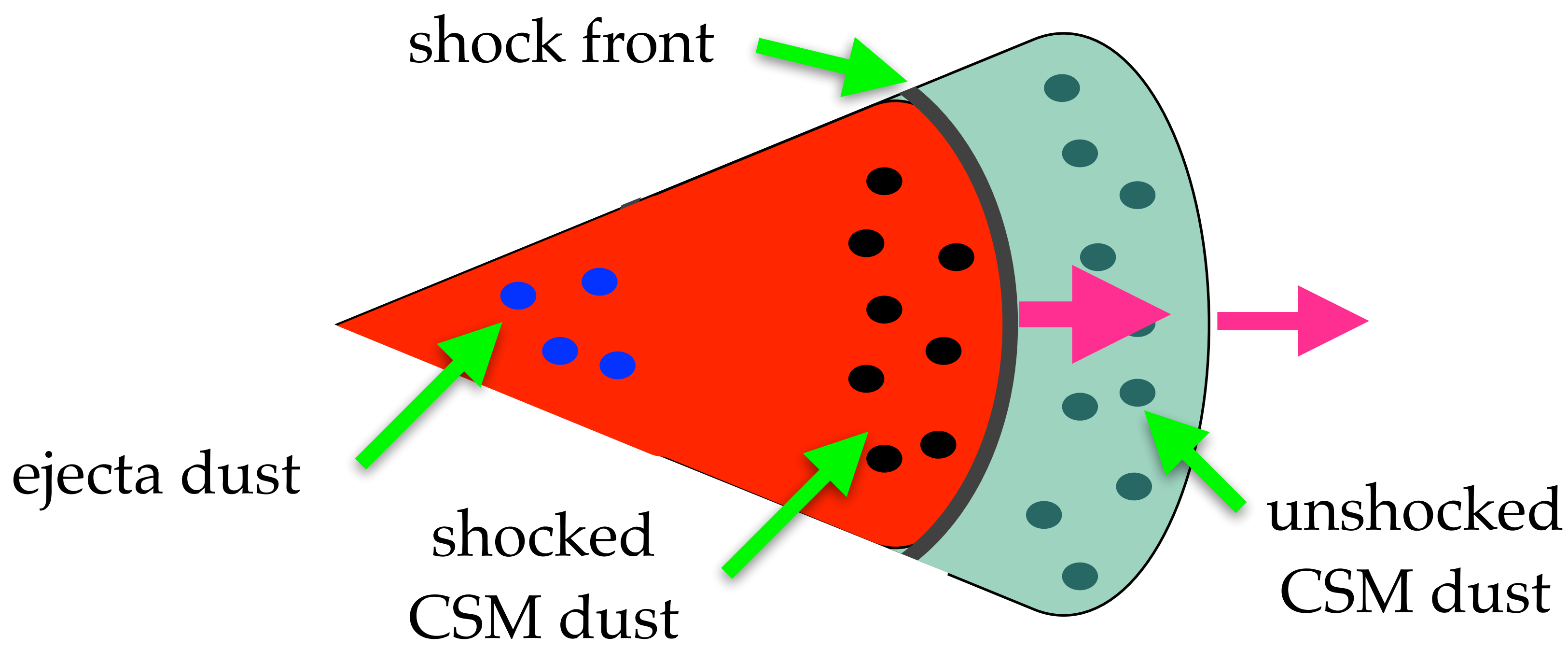
If you selected:

Consider the following alternative scenarios

(2) CSM– CSM scenario

Emitter: Shocked CSM dust

Absorber: Unshocked CSM dust



Less exciting than the 1st scenario

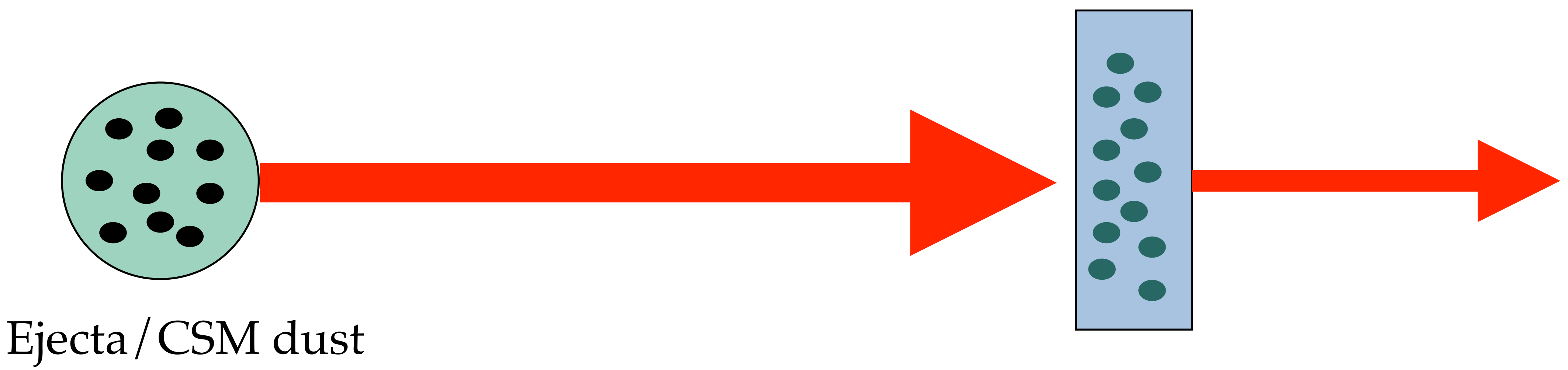
Constrains CSM dust heating mechanism, and CSM morphology.

(3) Ejecta/CSM – ISM scenario

Emitter: Ejecta and or CSM dust

Absorber: Interstellar dust

interstellar dust



Least exciting scenario.

Constrains CSM dust heating scenario,

and interstellar dust composition, mass surface density

Conclusions

- The attenuated emission (ATEM) model model provides a very good fit to the observed spectrum of SN2010jl

- The model accomodates several scenarios of emitter-absorber combinations

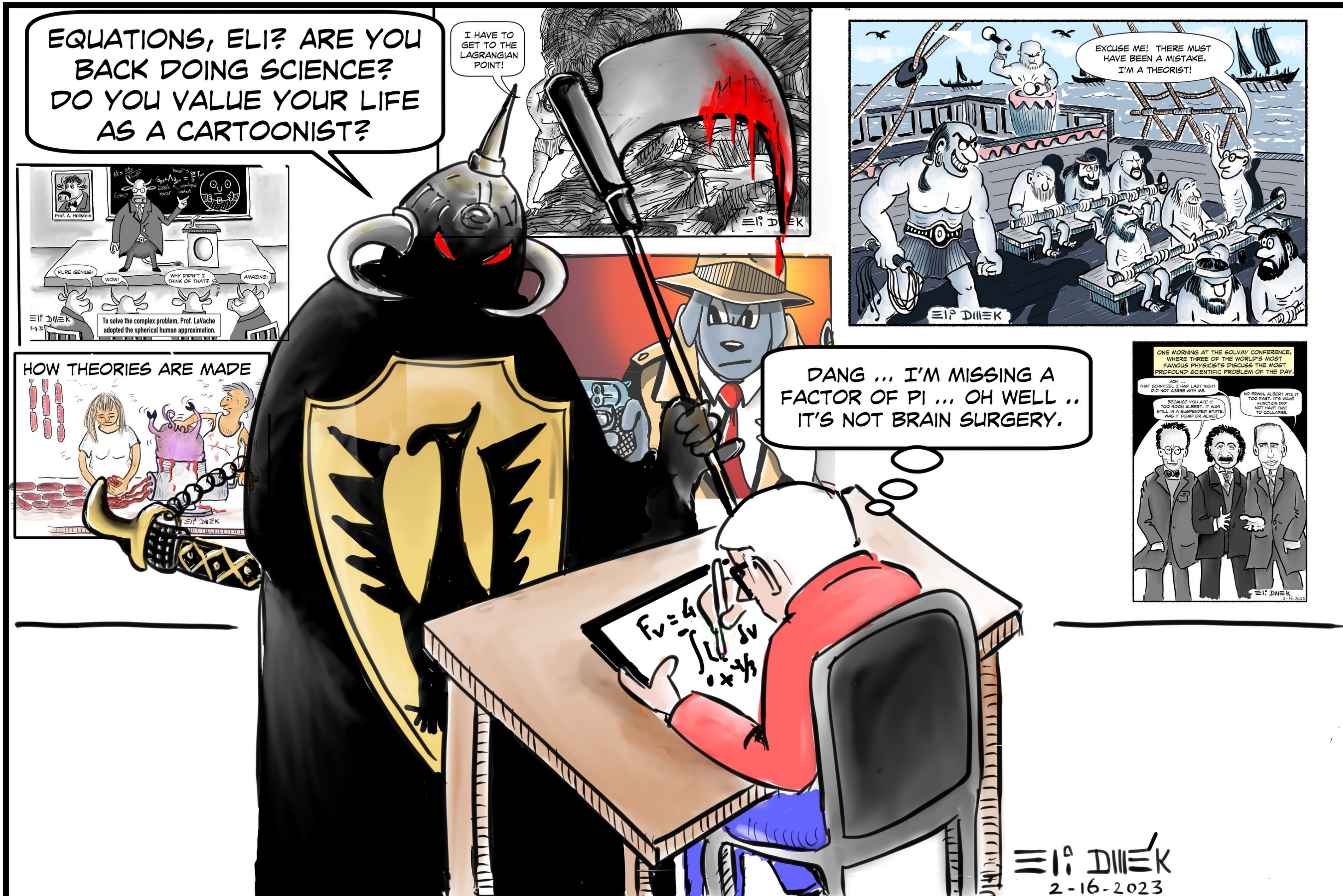
- All scenarios require a featureless emission spectrum arising from amorphous carbon and/or large silicate dust with

$$M_d \approx 0.007 - 0.1\ \mathrm{M}_\odot \qquad L_d \approx 8 \times 10^6\ \mathrm{L}_\odot \qquad T_d \approx 350\ K$$

and a silicate dominated absorber with

$$\tau(10\,\mu\mathrm{m}) \approx 0.4 \qquad \tau(\mathrm{UVO}) \approx 1 - 5$$

Better data and a detailed magnetohydrodynamic model are needed to follow the ejecta-dense CSM interaction


EQUATIONS, ELI? ARE YOU BACK DOING SCIENCE? DO YOU VALUE YOUR LIFE AS A CARTOONIST?
I HAVE TO GET TO THE LAGRANGIAN POINT!
EXCUSE ME! THERE MUST HAVE BEEN A MISTAKE. I'M A THEORIST!
Prof. A. Hollstein
PURE GENIUS!
WOW!
WHY DIDN'T I THINK OF THAT?
AMAZING!
To solve the complex problem, Prof. LaVache adopted the spherical human approximation.
HOW THEORIES ARE MADE
ONE MORNING AT THE SOLVAY CONFERENCE, WHERE THREE OF THE WORLD'S MOST FAMOUS PHYSICISTS DISCUSS THE MOST PROFOUND SCIENTIFIC PROBLEM OF THE DAY.
ACH ... THAT SCHNITZEL I HAD LAST NIGHT DID NOT AGREE WITH ME.
BECAUSE YOU ATE IT TOO SOON ALBERT. IT WAS STILL IN A SUSPENDED STATE. WAS IT DEAD OR ALIVE?
NO ERWIN, ALBERT ATE IT TOO FAST. IT'S WAVE FUNCTION DID NOT HAVE TIME TO COLLAPSE.
DANG ... I'M MISSING A FACTOR OF PI ... OH WELL .. IT'S NOT BRAIN SURGERY.
ELI DIIIEK
2-16-2023

Thank you for your attention

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