Modeling Dust Polarization from the UV to the Microwave

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Multiple Faces of Interstellar Dust
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The Inverse Problem

- Bohren and Huffman: Determining the composition of interstellar dust is like describing a dragon based on its tracks

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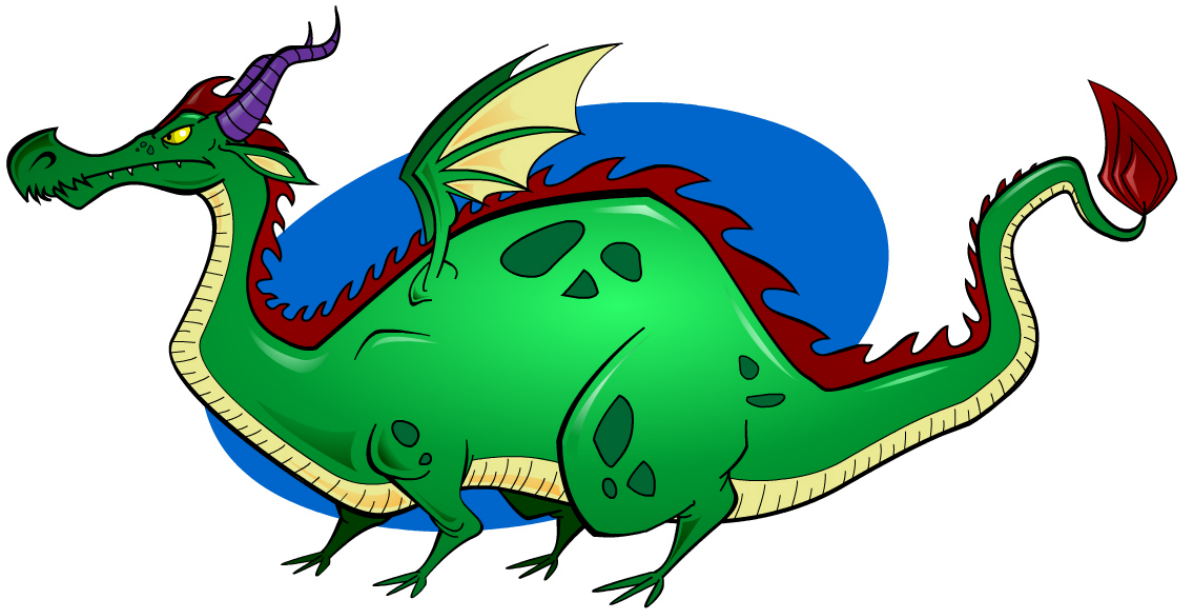
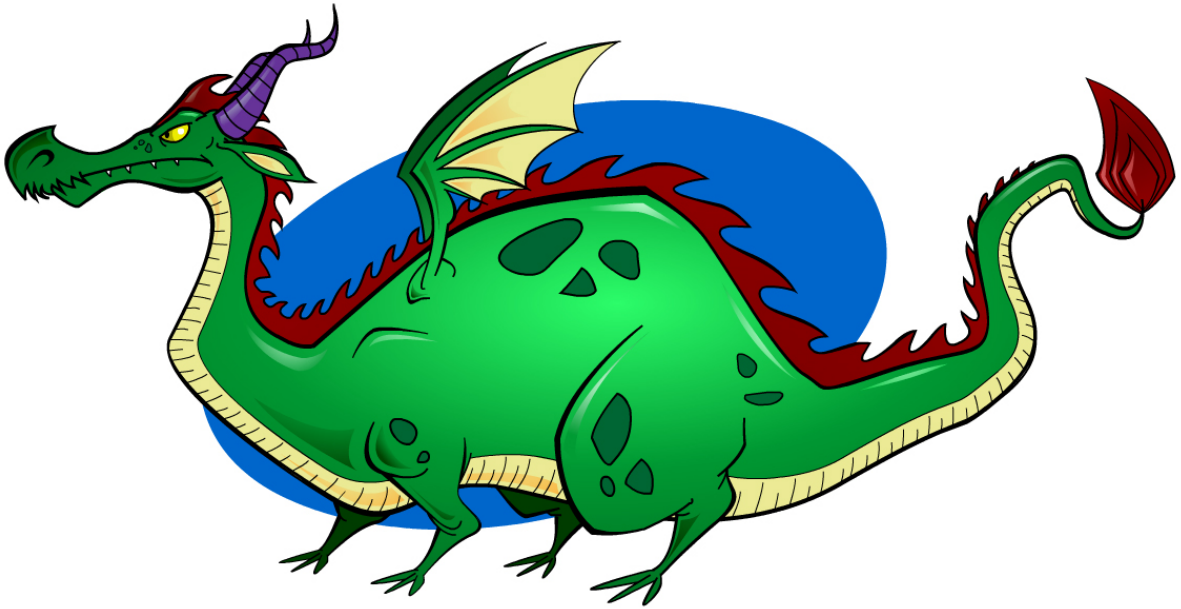


The Payoff

- Dragons are interesting creatures in their own right...



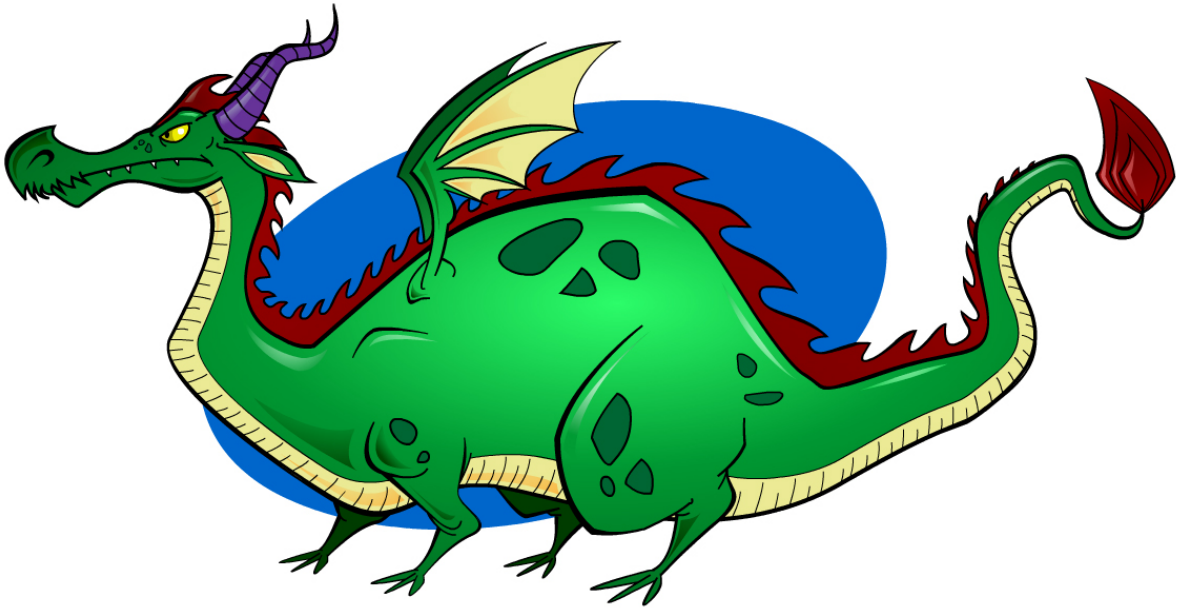
The Payoff

- Dragons are interesting creatures in their own right...
- ... but they also like to hide treasure

B-modes!

Dark Matter Annihilation!

High-z Galaxies!



Big Picture

Find observations that constrain:

- Abundances
- Extinction (total and polarized)
- Emission (total and polarized)

then build a model that satisfies all constraints simultaneously

Starting Points

Dust spectral features suggest two primary dust types

- Silicates (e.g. 9.7 μm extinction feature)
- Carbonaceous Grains (e.g. PAH emission, 3.4 μm extinction feature, 2175 Å feature)

Composition Effects

Grains are of different composition appear to have different polarization properties

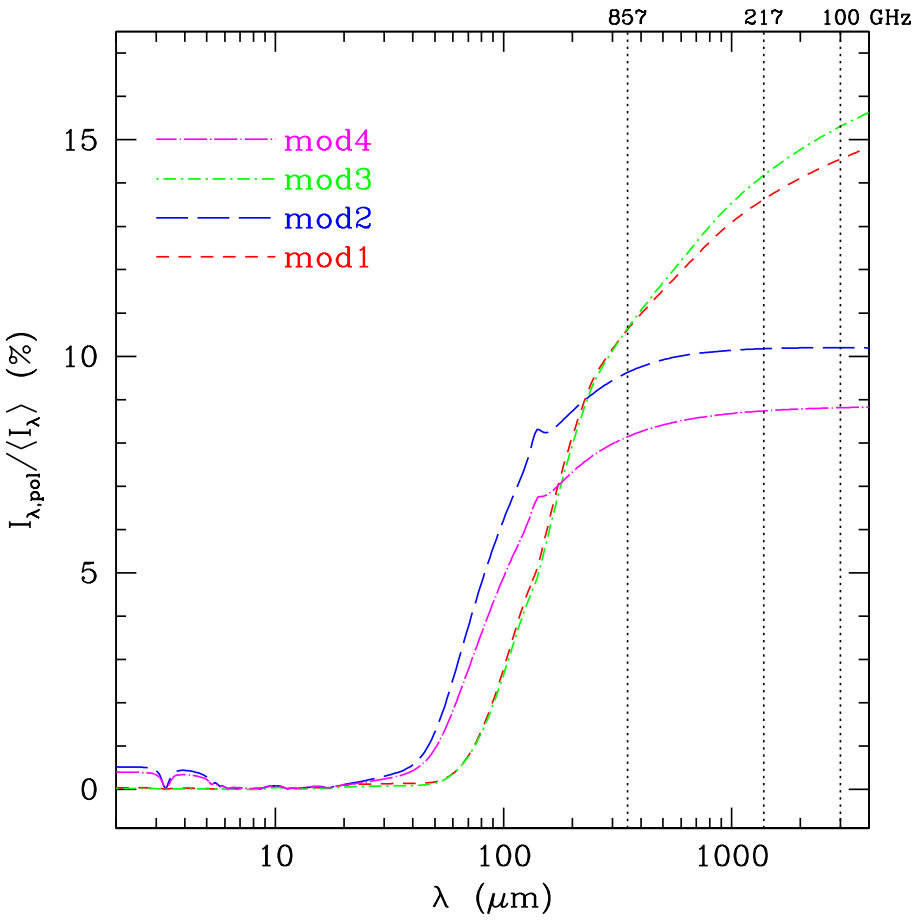
- Silicate Features– Polarization detected
- Carbonaceous Features– Unpolarized

Draine and Li 2007 Model

- Specified the material properties of astronomical silicates and carbonaceous material (graphite and PAHs)
- Model inputs: radiation field, PAH fraction, dust mass
- Successful modeling of Galactic dust emission and extinction, as well as dust emission from other galaxies (e.g. the SINGS galaxies)
- Spherical grains– no polarization

Draine and Fraisse 2009 Models

- Used Draine and Li dust materials to make predictions for polarized emission in the *Planck* bands
- Model predicts too much extinction per unit emission (Planck Int XXIX 2016)



Draine and Fraisse 2009

We Need...

- New Models of Interstellar Dust (with Polarization!)
- Hensley & Draine 2016. In prep.

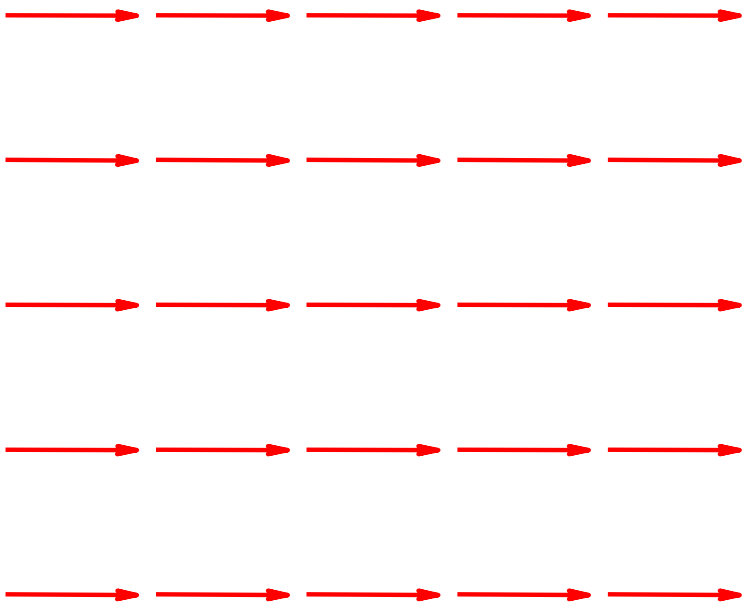
Polarized Dust Emission

- Models with silicate and carbonaceous grains alone have difficulty reproducing the observed decline in the polarization fraction with increasing wavelength
- A new ingredient– magnetic nanoparticles

Magnetic Materials

- **Ferromagnetic** materials, such as metallic Fe, have all unpaired spins aligned along a preferred axis
- Preferred direction of magnetization implies a minimum energy state with all unpaired spins aligned along preferred direction
- **Ferrimagnetic** grains such as Fe_3O_4 and γ-Fe_2O_3 are also viable

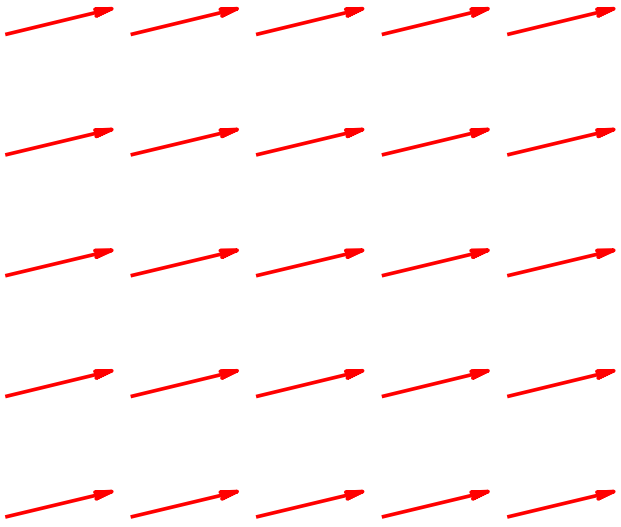
Ferromagnetic spin lattice



Magnetic Dipole Emission

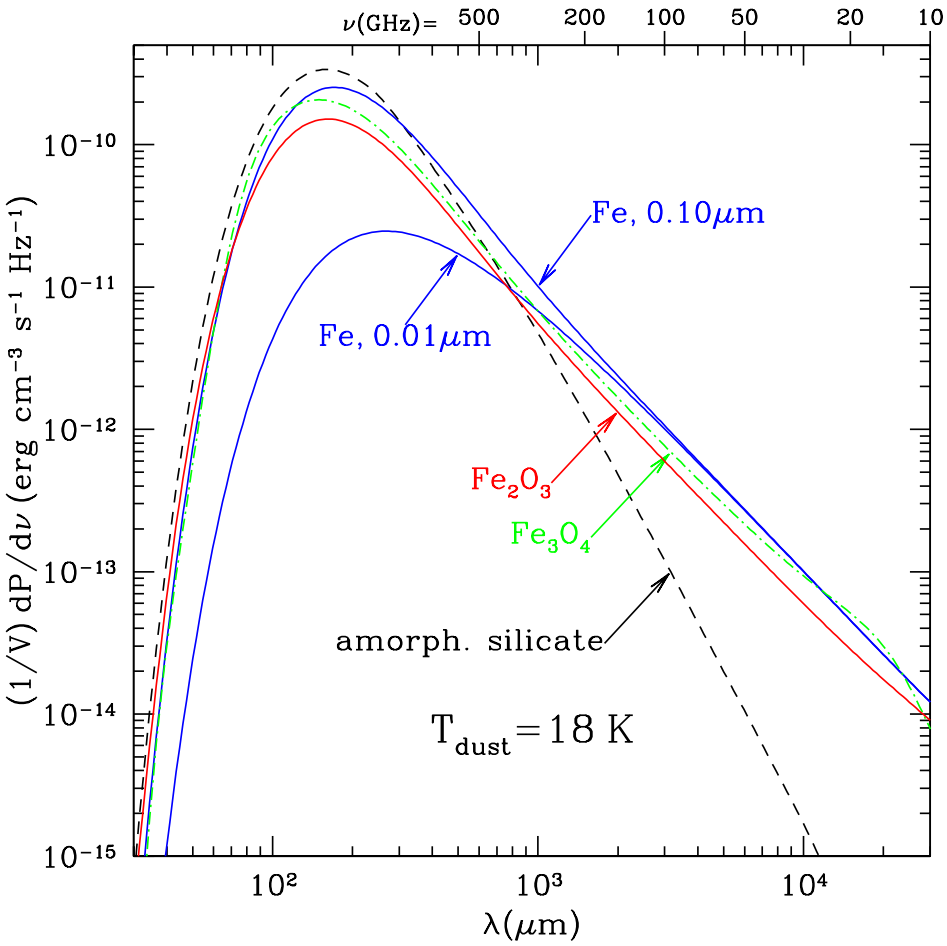
- Thermal fluctuations can move the spins away from this state
- Then magnetization vector precesses about the preferred direction and produces radiation

Response to a fluctuation



Emissivities

- **Emissivity per unit volume** of 0.01μm grains heated to 18K
- Emissivity in mm and sub-mm much stronger than amorphous silicate grains



Draine and Hensley 2013

Polarization

- Polarization depends on whether grains are **free-fliers** or **inclusions** in larger grains

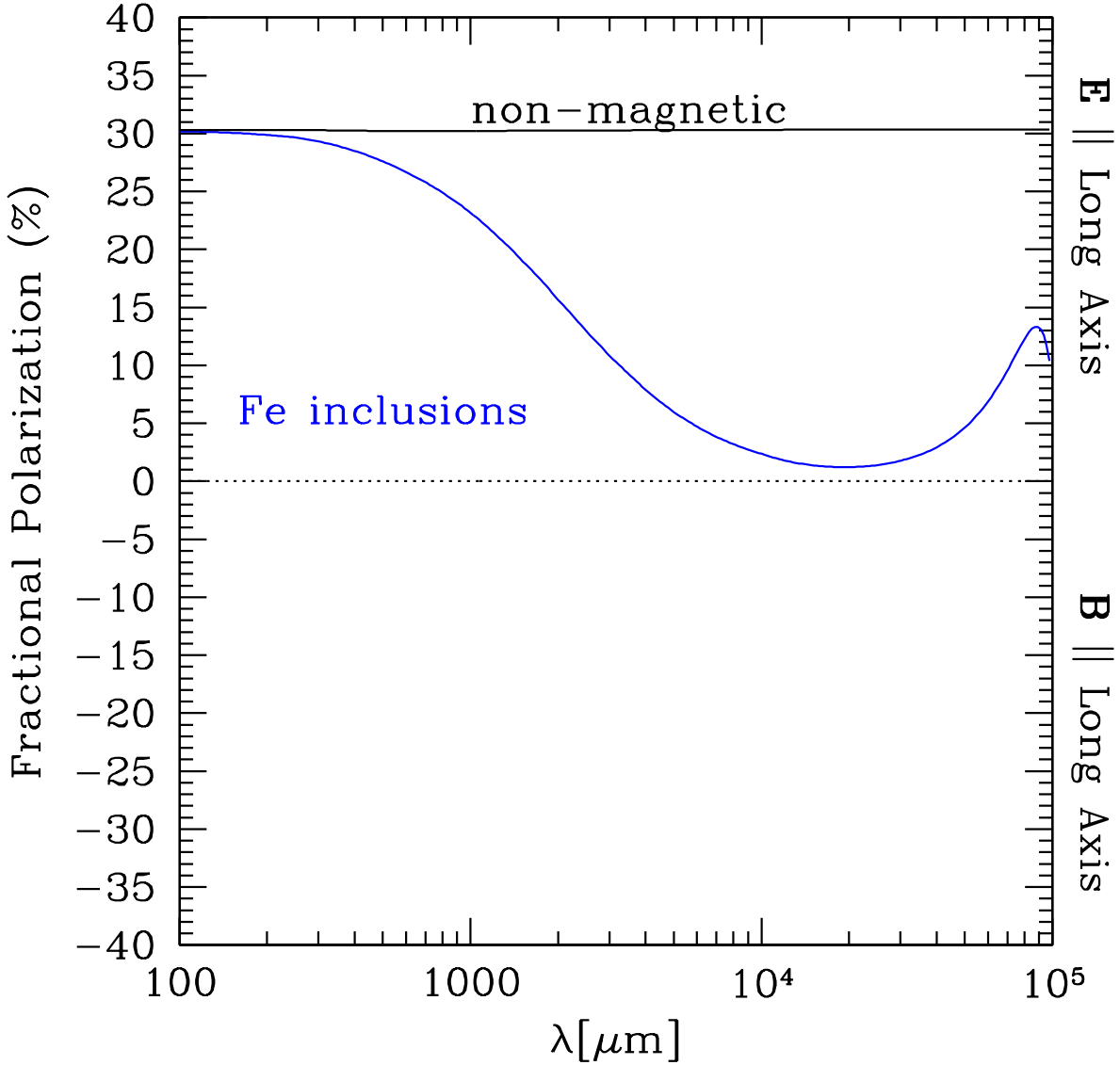
Free-Fliers

Inclusions

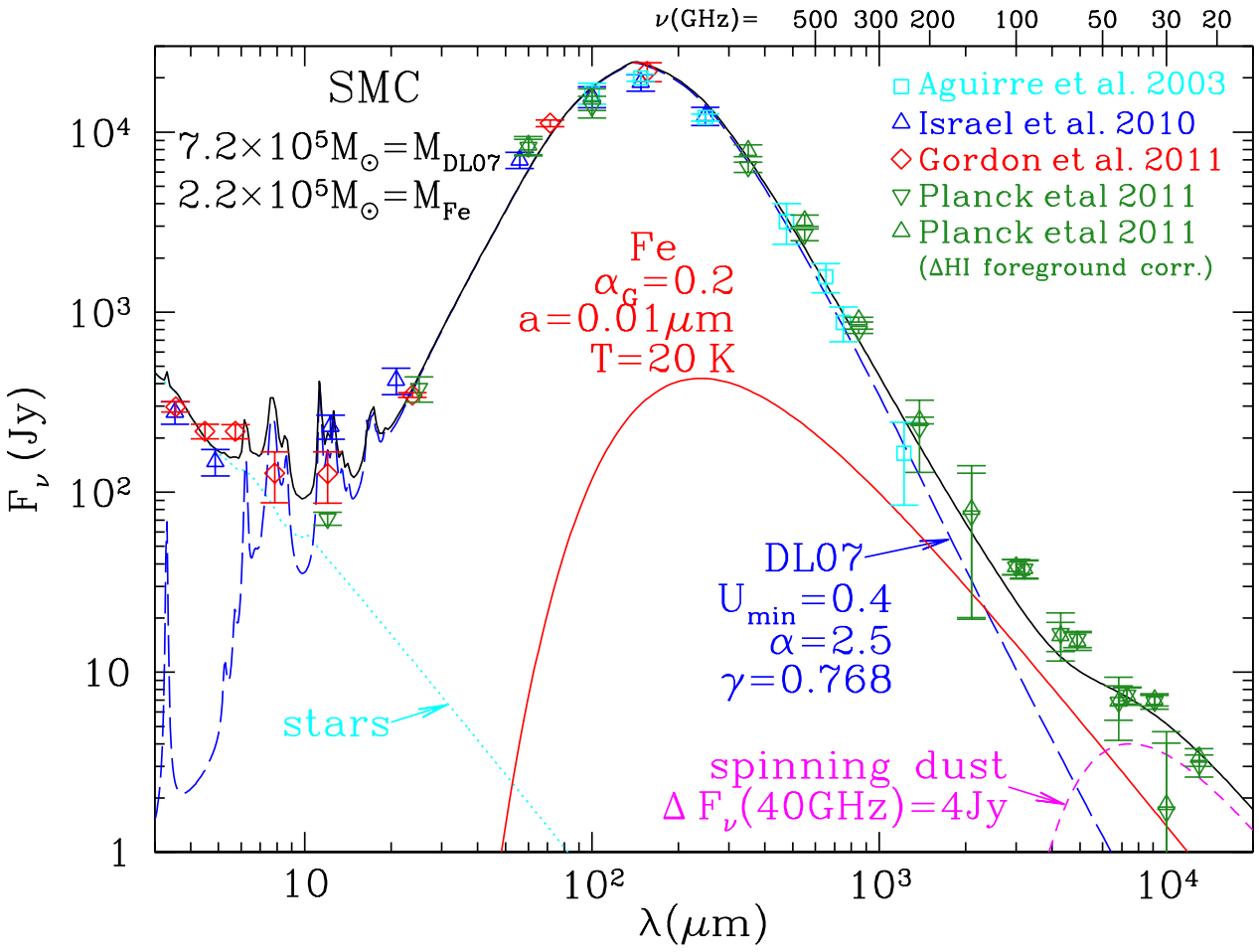
Inclusions

Of course, interstellar grains are nonspherical...

Polarization



Explaining the SMC SED



Draine and Hensley 2012

- Model with 20 K Fe grains

A New Model

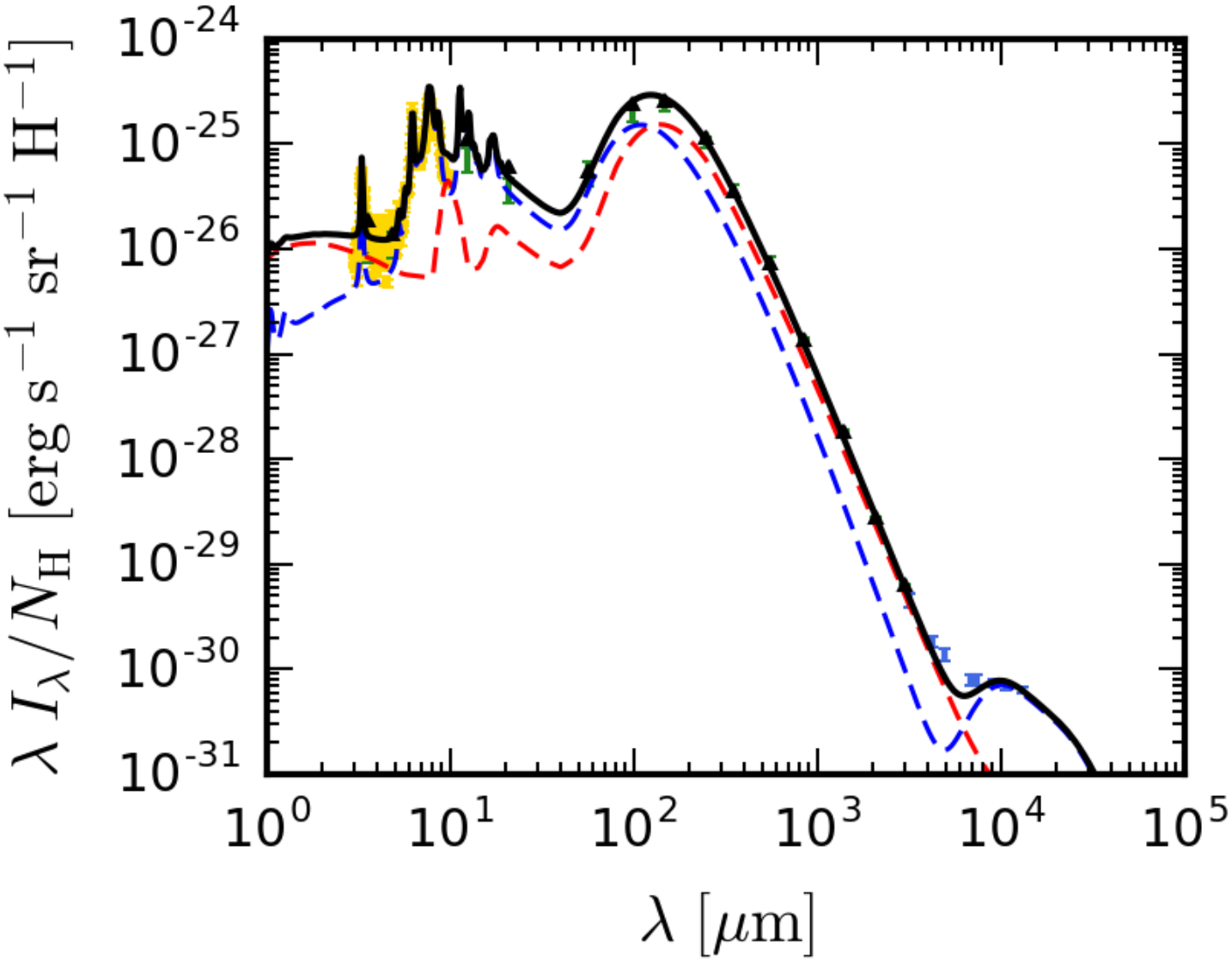
To construct a new model, we have:

- Updated the material properties of the silicate (Draine & Hensley 2016, in prep) and carbonaceous grains (Draine 2016) based on new astronomical observations and laboratory data
- Added magnetic nanoparticles as an optional model component
- Using new grain materials, found a best fit size distribution and alignment function

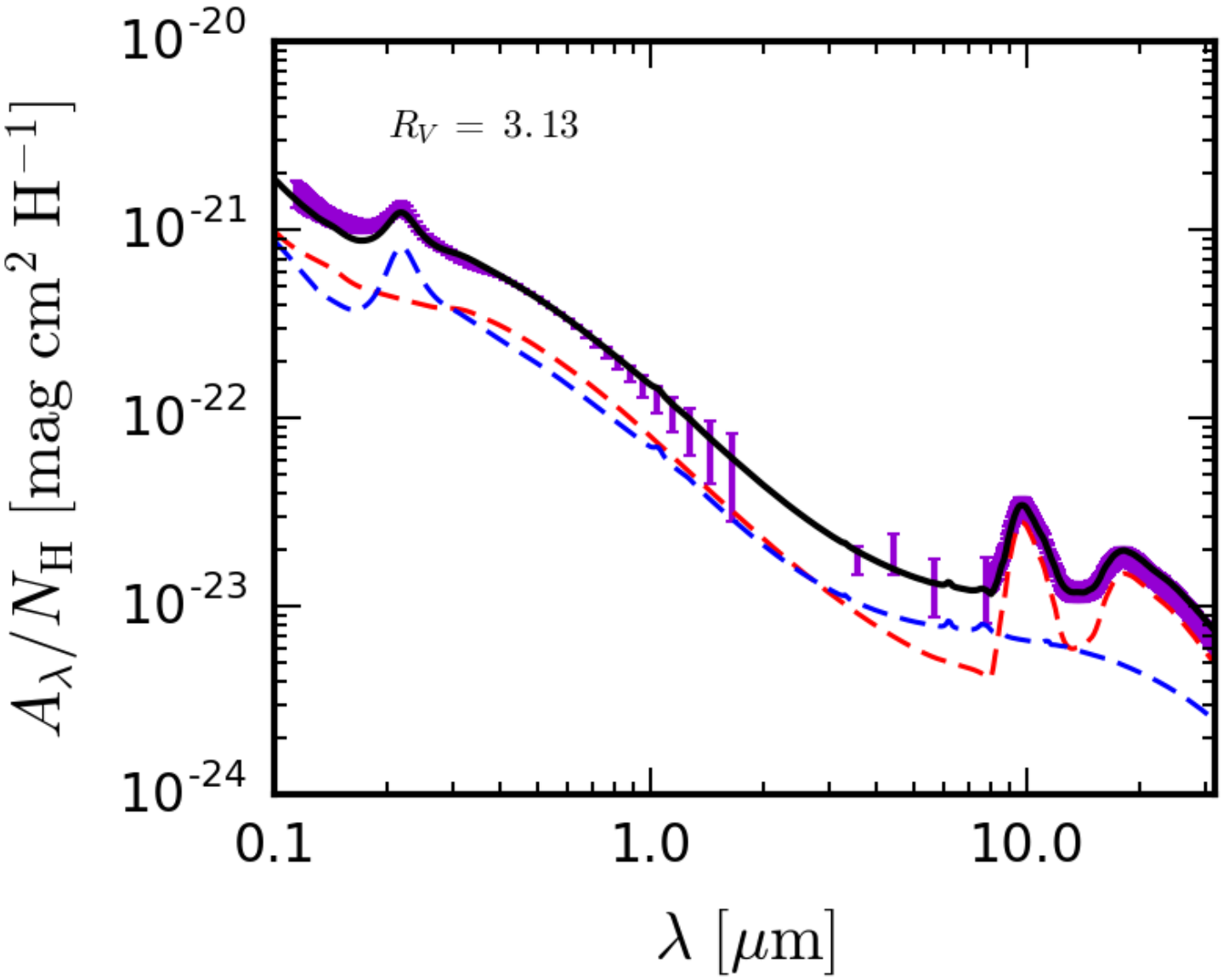
Example

- 2:1 spheroidal silicate grains with 5% iron nanoparticles by volume as inclusions
- Unaligned carbonaceous grains
- PAHs

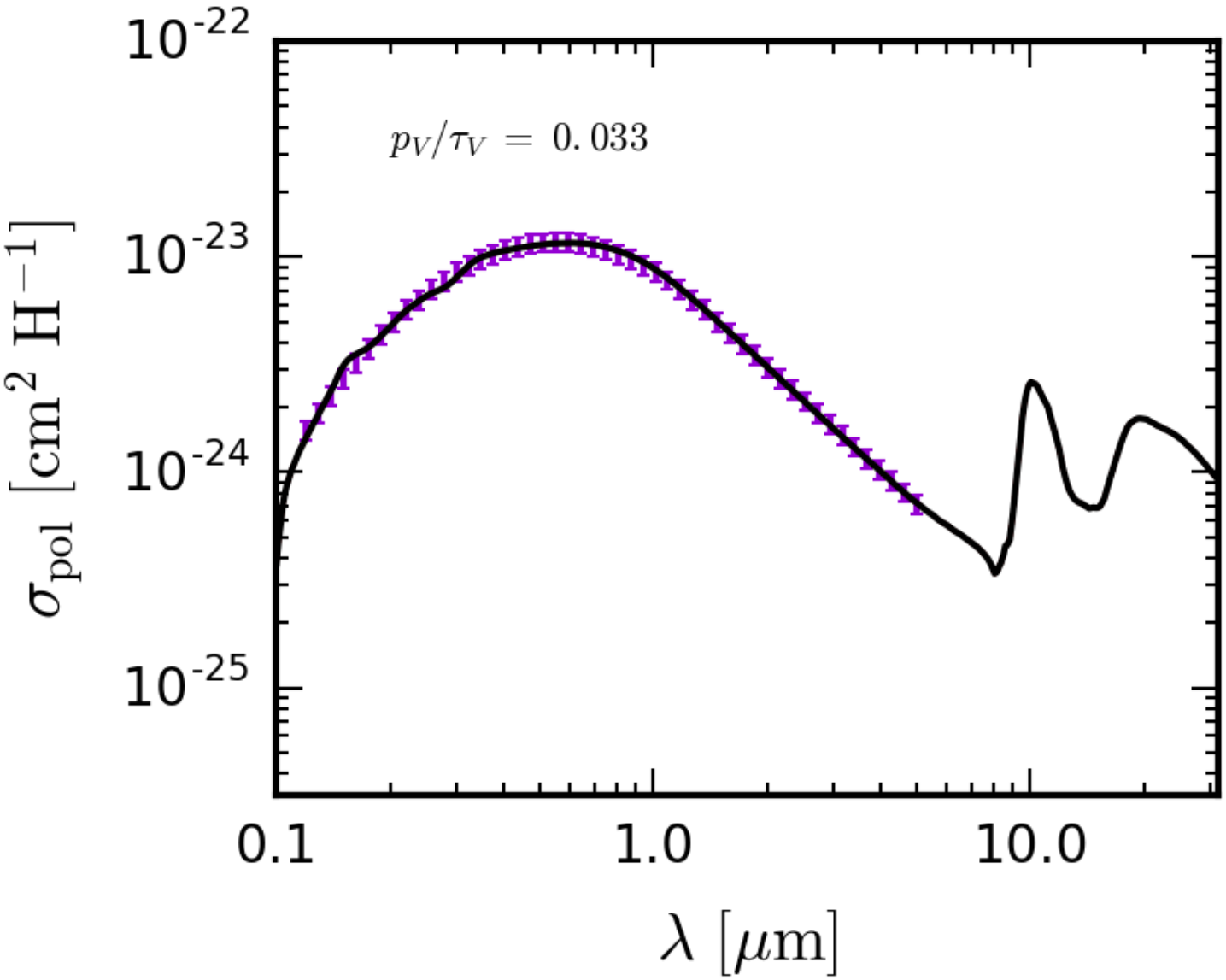
Emission


10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
$\lambda\ I_\lambda / N_{\rm H}$ [erg s^{-1} sr^{-1} H^{-1}]
10^0
10^1
10^2
10^3
10^4
10^5
λ [μm]

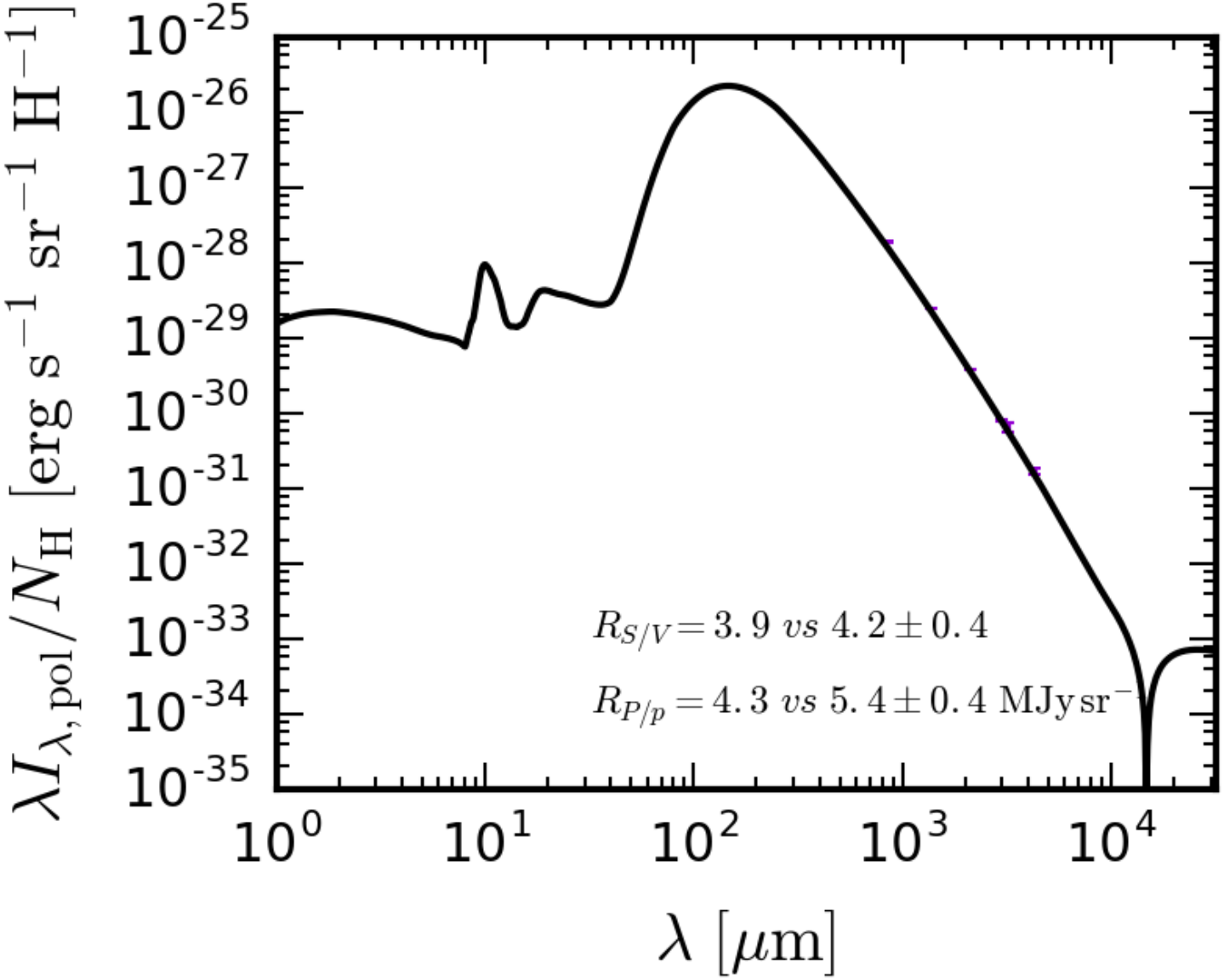
Extinction


$R_V = 3.13$
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
0.1
1.0
10.0
$A_\lambda / N_{\rm H}$ [mag cm^2 H^{-1}]
λ [μm]

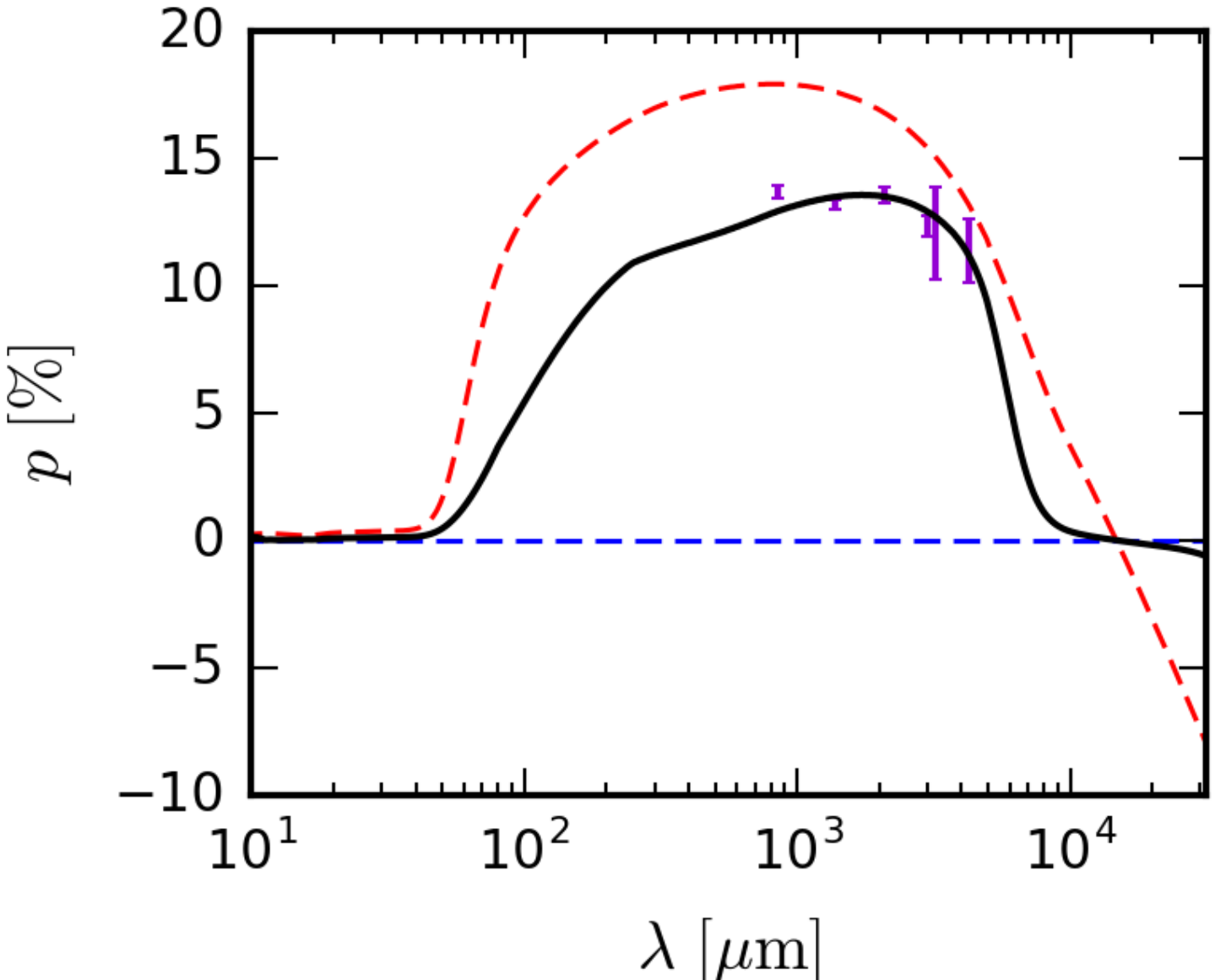
Polarized Extinction



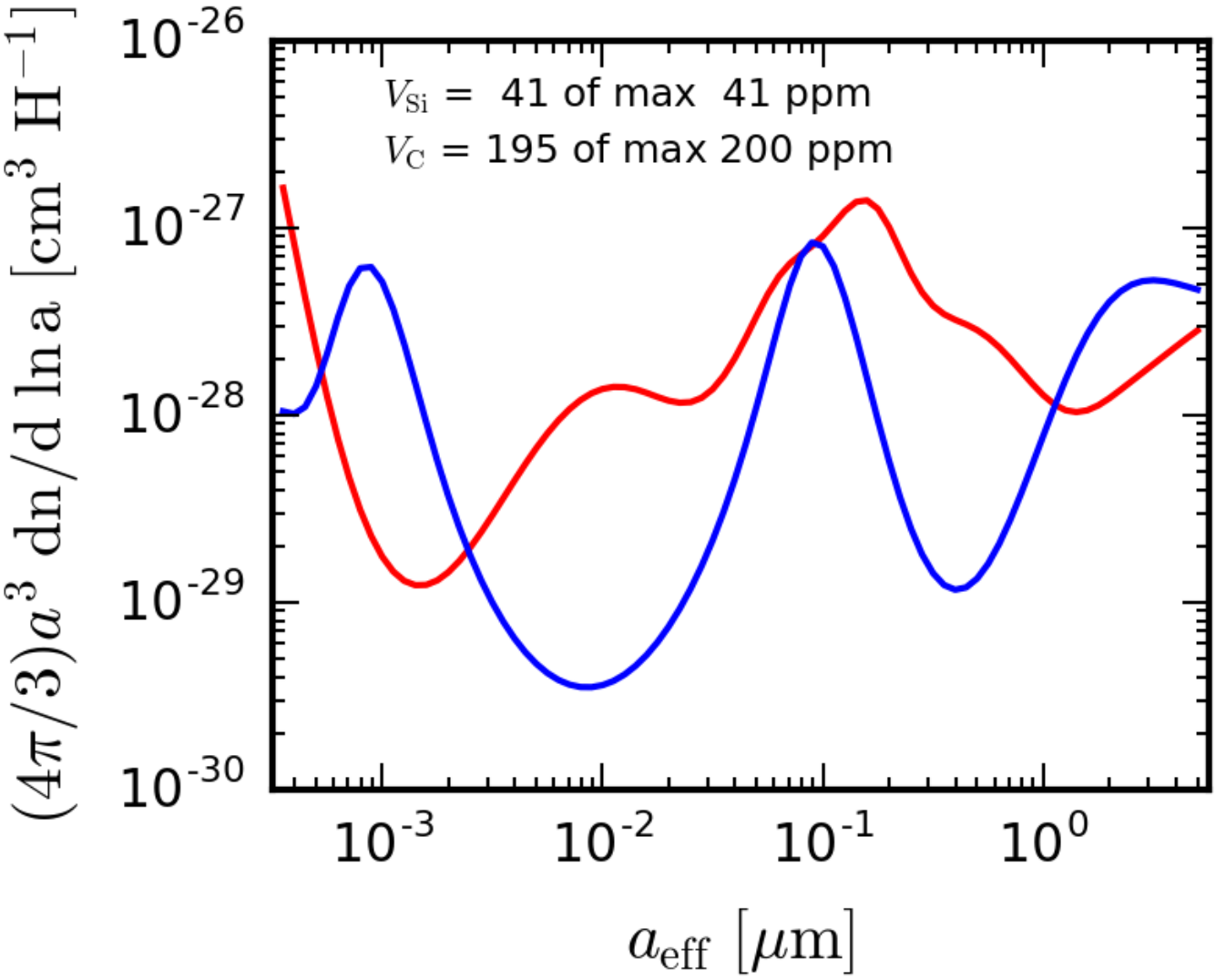
Polarized Emission



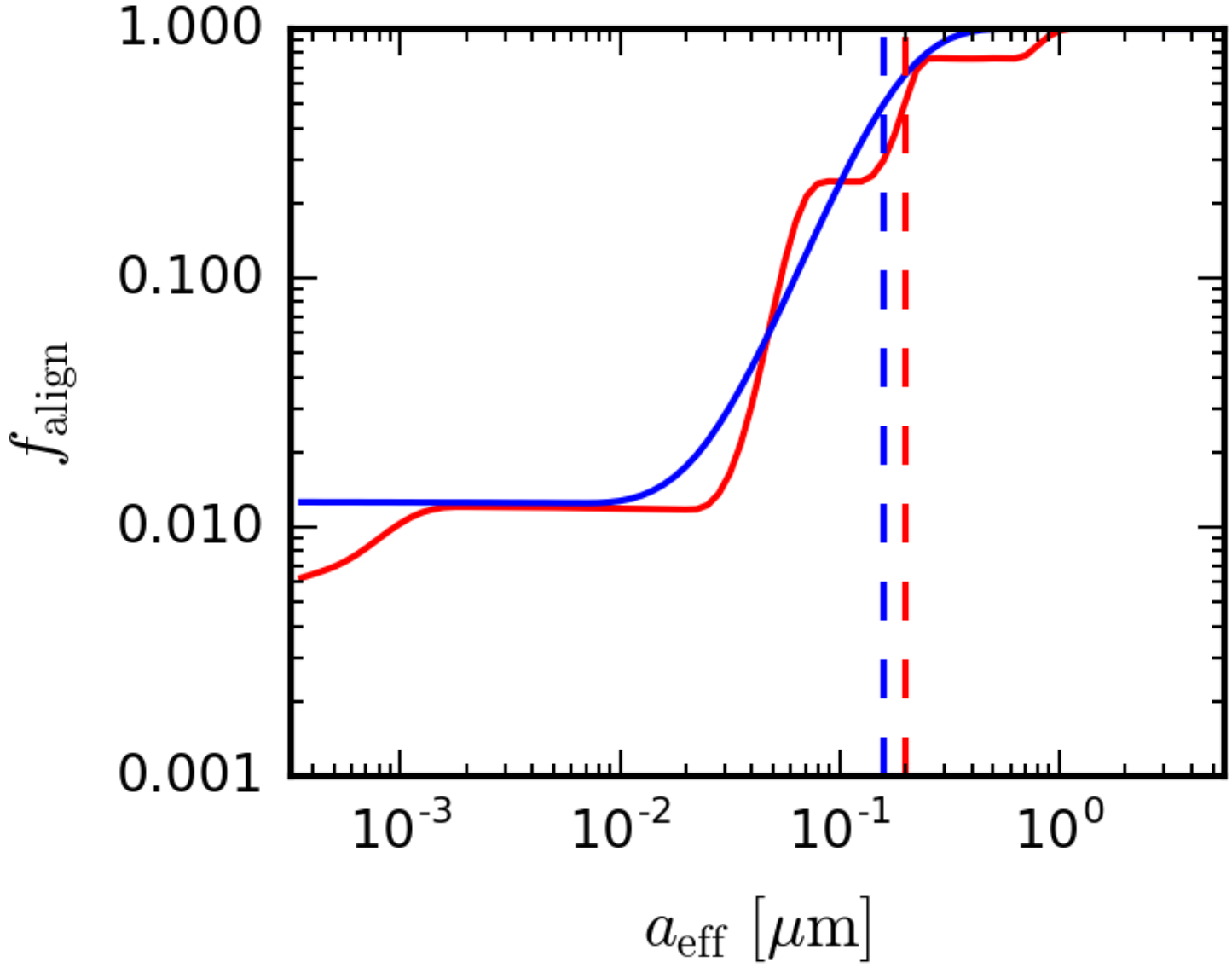
Polarization Fraction



Size Distribution



Alignment Function



Summary

- Inclusion of iron grains allows us to match the frequency-dependence of the polarized emission
- We alleviate the tension between emission and extinction in the Draine and Li 2007 model by making silicates more emissive at long wavelengths

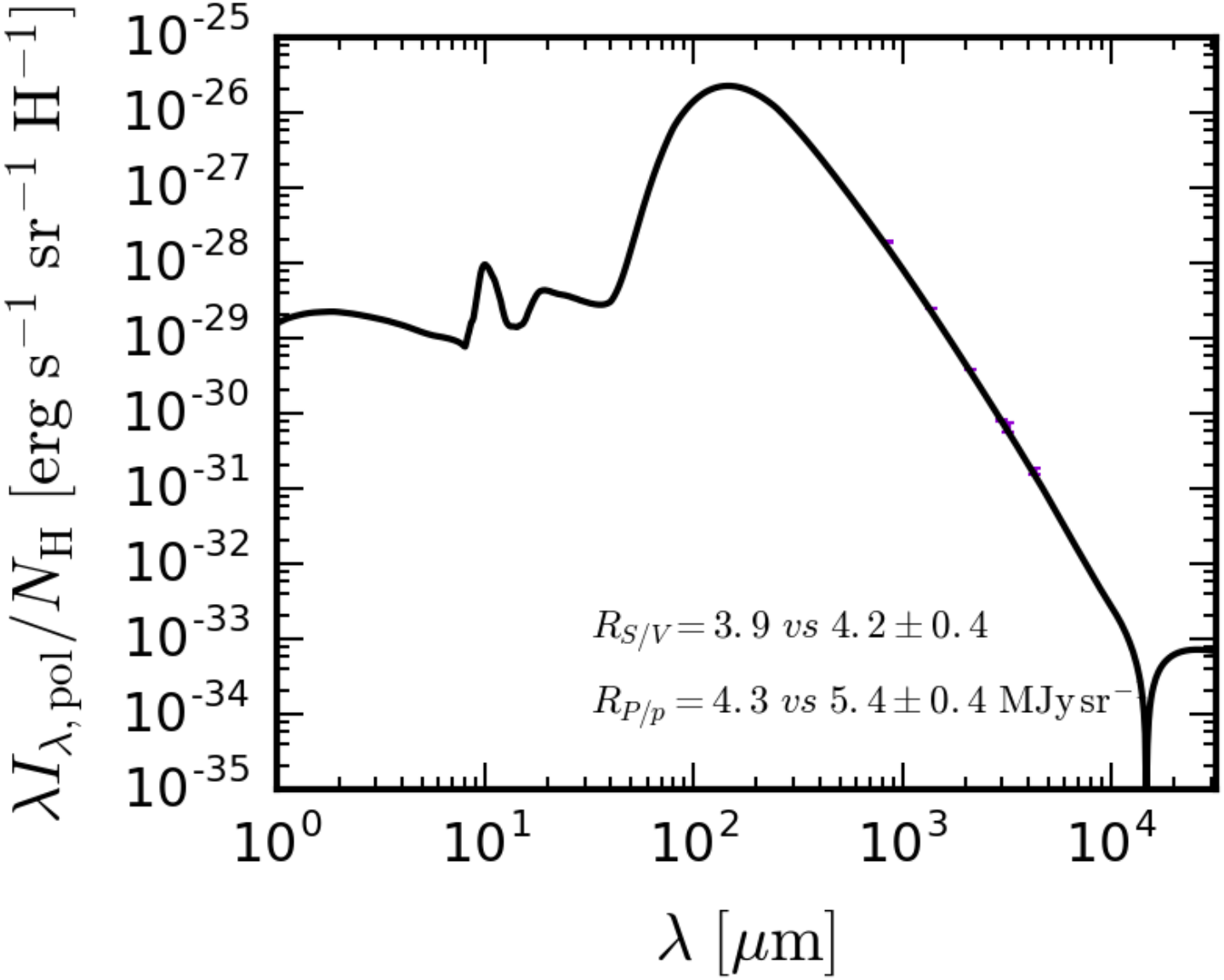
With a Model, We Can...

- Test the model against the *Planck* sky and learn what drives variations in dust properties
- Predict dust properties at all wavelengths given a model fit
- Simulate different realizations of dust properties and the implications for component separation

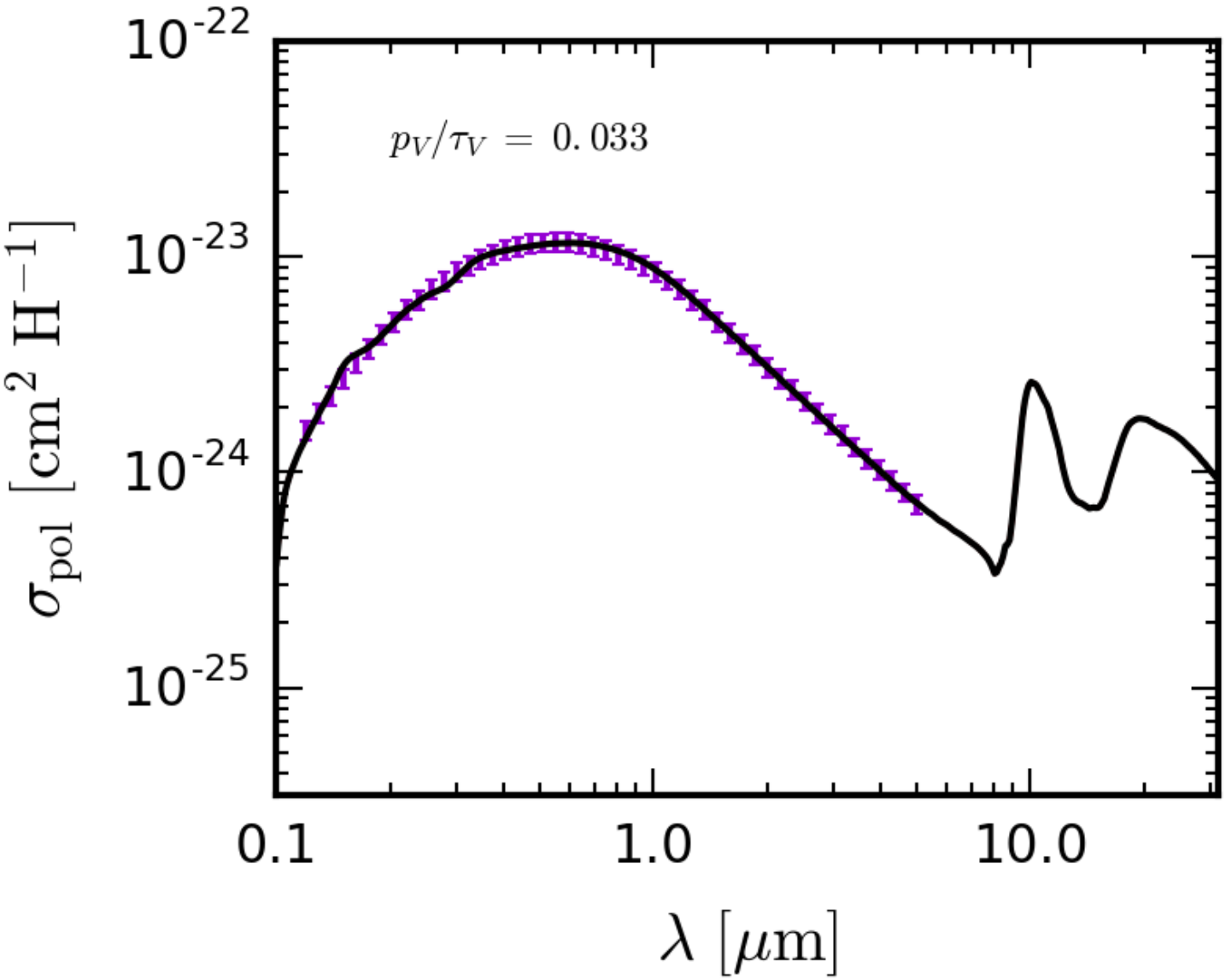
Testing the Model

- Model parameterized by radiation field strength and amount of dust in each silicate and carbonaceous components
- In progress: full-sky model fitting with *Planck* data
- In development: code interface to models to enable easy SED fitting, simulation construction, etc.

Predictions



Predictions



Conclusions

- Our new models of interstellar dust successfully reproduce the mean properties of dust in the diffuse ISM, including in polarization
- We make testable predictions of dust properties, particularly in polarization
- The new models enable future work on the properties of Galactic dust as well as next-generation component separation