Physical Models for Diffuse ISM Dust in the Light of Planck

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- **Some Physical Dust Models**
- **Testing the DL07 dust model:** *Planck Int. Results XXIX*
- **Polarized Extinction and Emission from Galactic Dust**
  - Planck observations
  - New dust model
- **Anomalous Microwave Emission: What is the Source?**

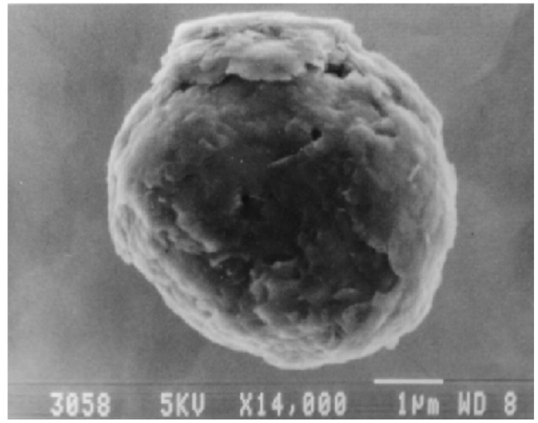
What do we mean by "Physical Dust Model"?

- Specify grain materials
  - may be real materials studied in lab (e.g., graphite, SiC, metallic Fe)
  - may be proxies for poorly-known interstellar materials (e.g., "astrosilicate" or "astro-PAHs")
- Specify (adjust) distributions of grain **sizes** and **shapes**
  (should be consistent with interstellar elemental abundances)
- Solve Maxwell's equations to calculate absorption and scattering cross sections
- In case of "astro-PAHs", use empirical estimates of absorption cross sections that are consistent with general knowledge
- For smaller grains, or weak radiation fields, need heat capacities
- Specify (adjust) grain alignment function $f_{\rm align}(a)$
  (Ideally would calculate this, but don't yet know how to...).
- Calculate extinction(λ) and emission SED.
- Calculate starlight polarization, and polarization of emission.
- Other: scattering of starlight, X-ray absorption and scattering...

The Question of Grain Geometry

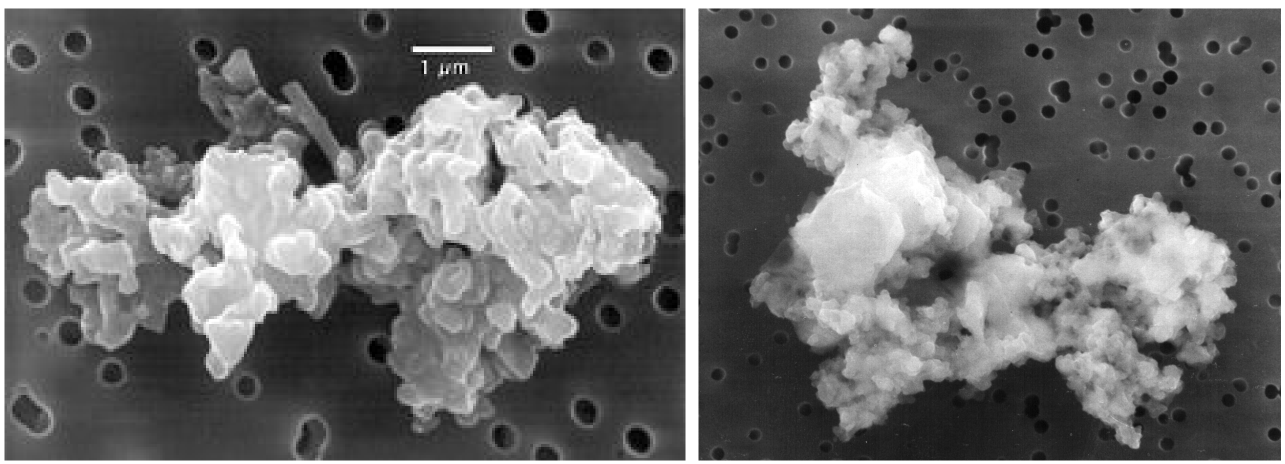
Optical properties of grains depends on grain **geometry** as well as composition.

Are interstellar grains fairly **smooth and compact**?



Presolar onion-like graphite grain (diameter $\sim 5\,\mu\mathrm{m}$). Photo from S. Amari.

Or are they typically **loose aggregates** of smaller particles, with a large "porosity"?



Two interplanetary dust particles collected from stratosphere (diameter $\sim 10\,\mu\mathrm{m}$).
Images courtesy E.K. Jessberger and Don Brownlee.

Which does Nature favor? We don't know.

Modeling Uncertainties...

We continue to seek ways to discriminate among **grain geometries**, e.g.,

- X-ray scattering halos
- observations of optical – submm polarization
- polarization profile of the 10 μm silicate feature
- apparent absence of polarization in the 3.4 μm C-H stretch feature

Another important uncertainty: **composition**.

- Amorphous silicate: what exactly is composition and $\epsilon(\omega)$?
- What exactly is the carbonaceous material?
- What else: metallic Fe? Fe oxides? SiC?

Some Models for Interstellar Dust

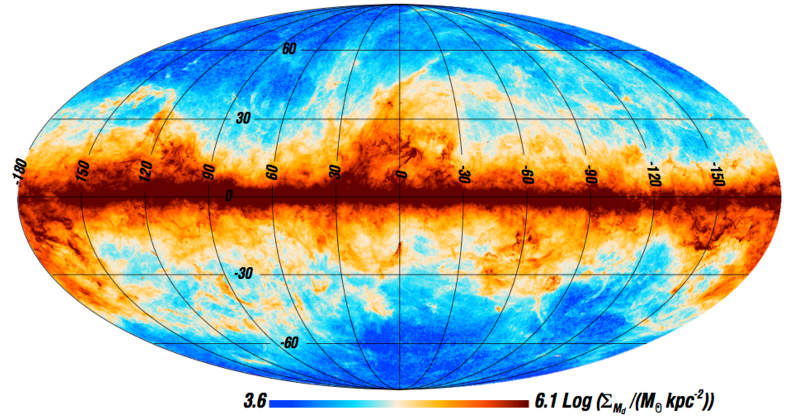
- Li & Draine (2001): pre-Spitzer model
  amorphous silicate grains + graphite + PAHs
  spherical grains: no polarization
- Draine & Li (2007) (**DL07**):
  amorph. sil. and graphite from Li & Draine (2001)
  PAHs adjusted slightly to match early Spitzer results
  spherical grains: no polarization
- Draine & Fraisse (2009):
  DL07 materials
  spheroidal grains grains with partial alignment
- Compiègne et al. (2011) ("DUSTEM" model)
  amorph. silicate + amorph. C + PAHs
  spherical grains: no polarization
- Jones et al. (2013):
  amorph. silicate + Fe nanoparticles + amorph. C + PAHs
  spherical grains: no polarization
- Hensley & Draine (2015):
  amorph. silicate (new dielectric fn.) + Fe + graphite + PAHs
  spheroidal grains with partial alignment

Testing the DL07 model

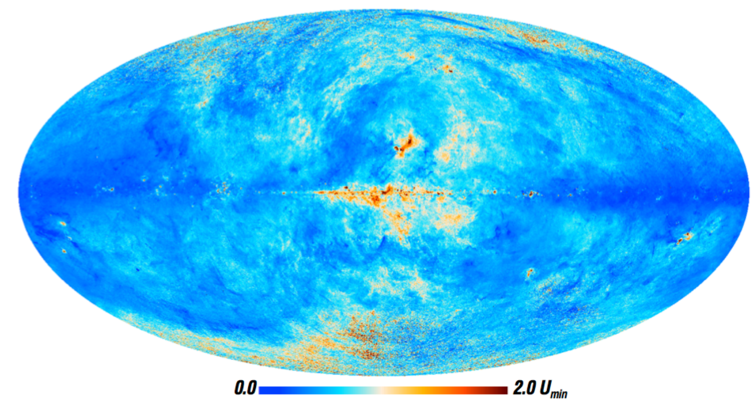
Planck Intermediate Results XXIX.
arXiv:1409.2495
corresponding authors: G. Aniano, F. Boulanger

- **All-sky diffuse Galactic emission:**
  - 5 Planck bands (143 GHz – 857 GHz)
  - DIRBE 240, 140, 100 μm
  - IRAS 100 μm, 60 μm
  - WISE 12 μm
- **Try to fit observed SED with DL07 dust, adjusting only**
  - total dust surface density $\Sigma_{\rm dust}$
  - starlight intensity parameter $U_{\rm min}$
  - starlight intensity parameter $f_{\rm PDR}$ (fraction of starlight heating from regions with $U > 100$)
- Does this reproduce the SED?
  Yes – quite good agreement
- But: predicted A_V vs. reddening of SDSS QSOs: **systematic overestimation of A_V**

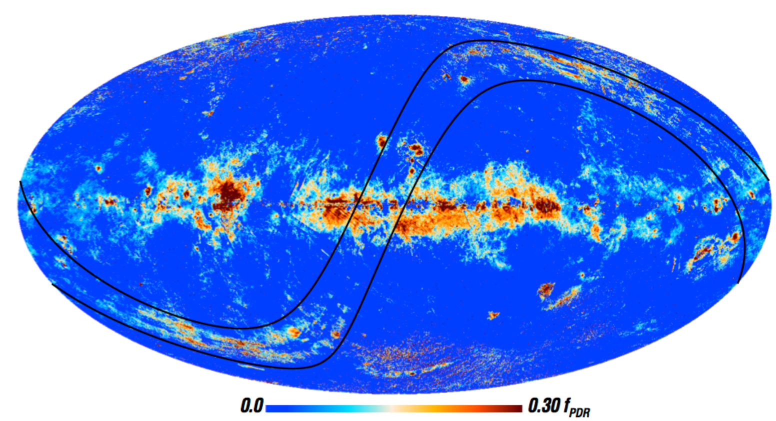
$\Sigma_{\rm dust}$



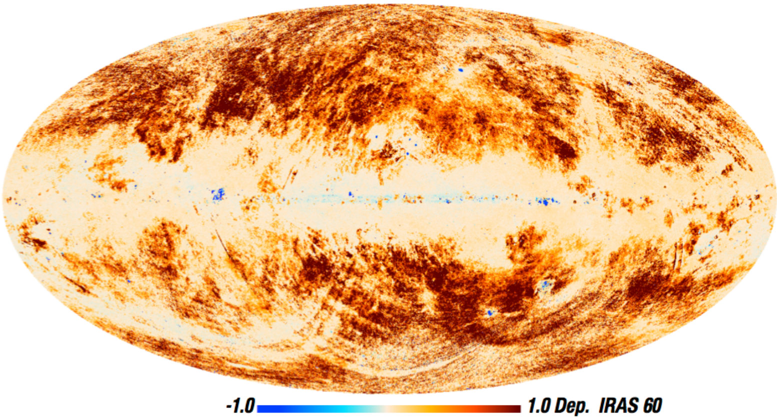
$U_{\rm min}$

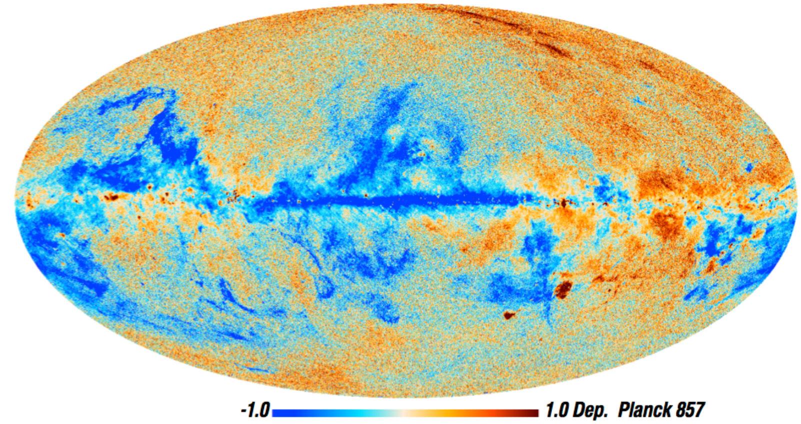


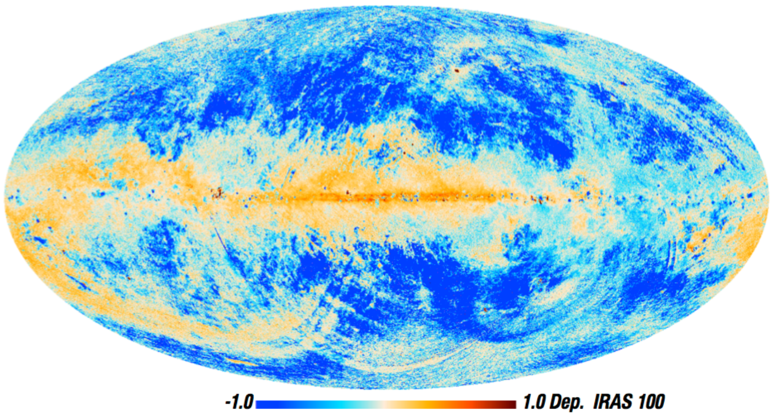
$f_{\rm PDR}$

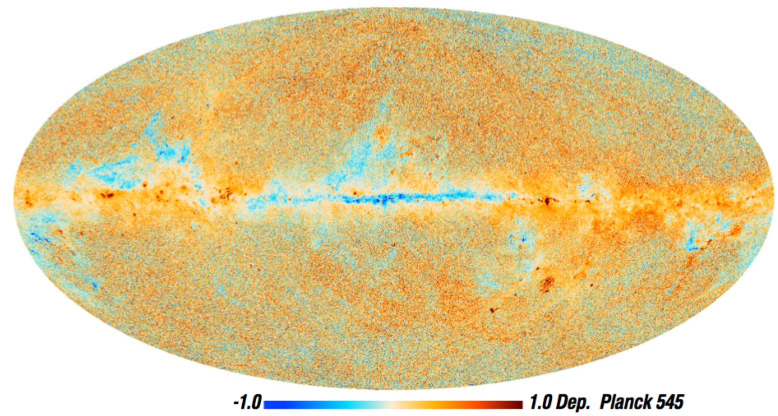


DL07 Model fit vs. Observation (5 arcmin PSF)



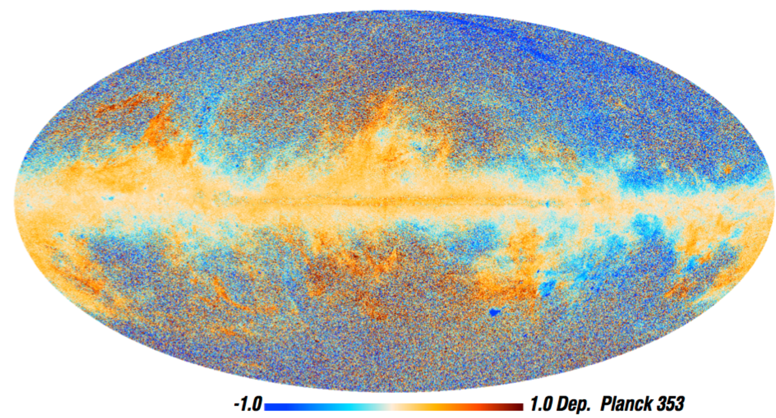






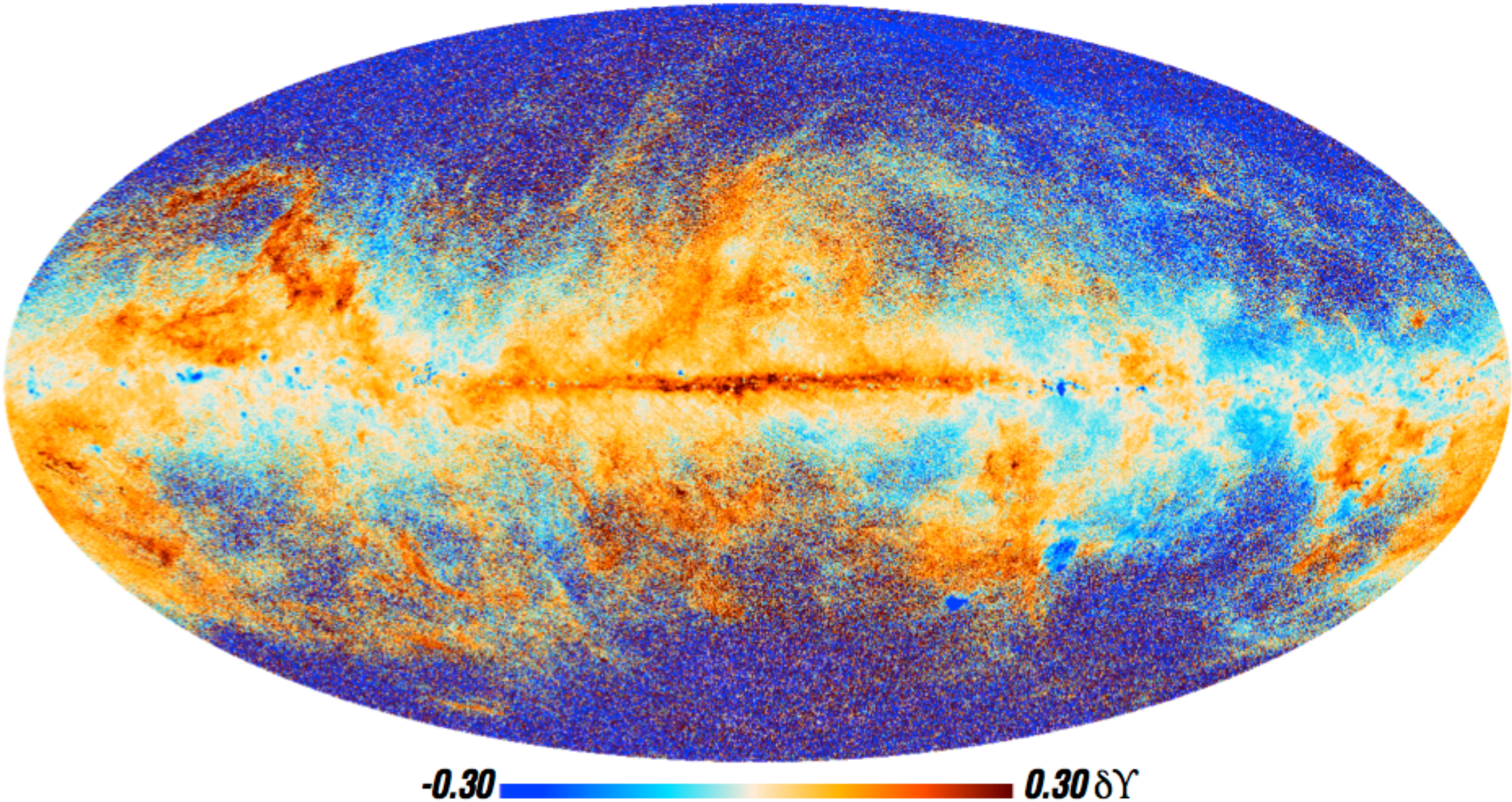
(from Planck Int. Results XXIX)

$$\text{Dep.} \equiv \frac{Model - Obs}{Uncertainty}$$



Regional Variations in Opacity

Could improve on DL07 fit by adjusting $\beta \equiv d \ln \kappa_\nu / d \ln \nu$
at long wavelengths $(350 - 850\,\mu\mathrm{m})$: $\beta \rightarrow \beta + \delta\Upsilon$



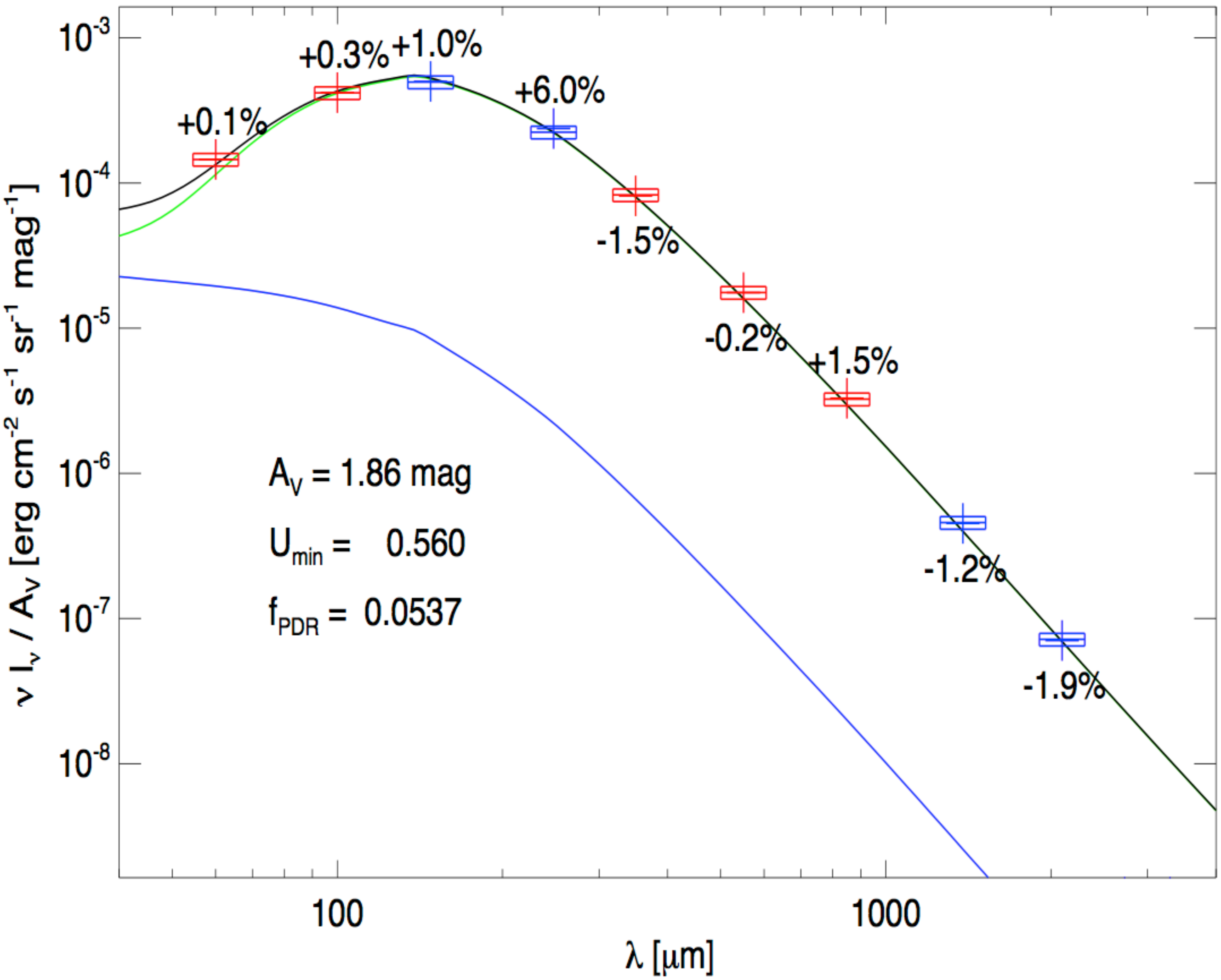
(from Planck Int. Results XXIX)

Changes are modest, with $\delta\Upsilon$ both negative and positive.

FIR-Submm SED

Sample: 273000 pixels containing SDSS QSOs

Mean SED for these pixels



- **Red: used in fit**
- **Blue: not used in fit**

- *Excellent agreement with mean SED*

(from Planck Int. Results XXIX)

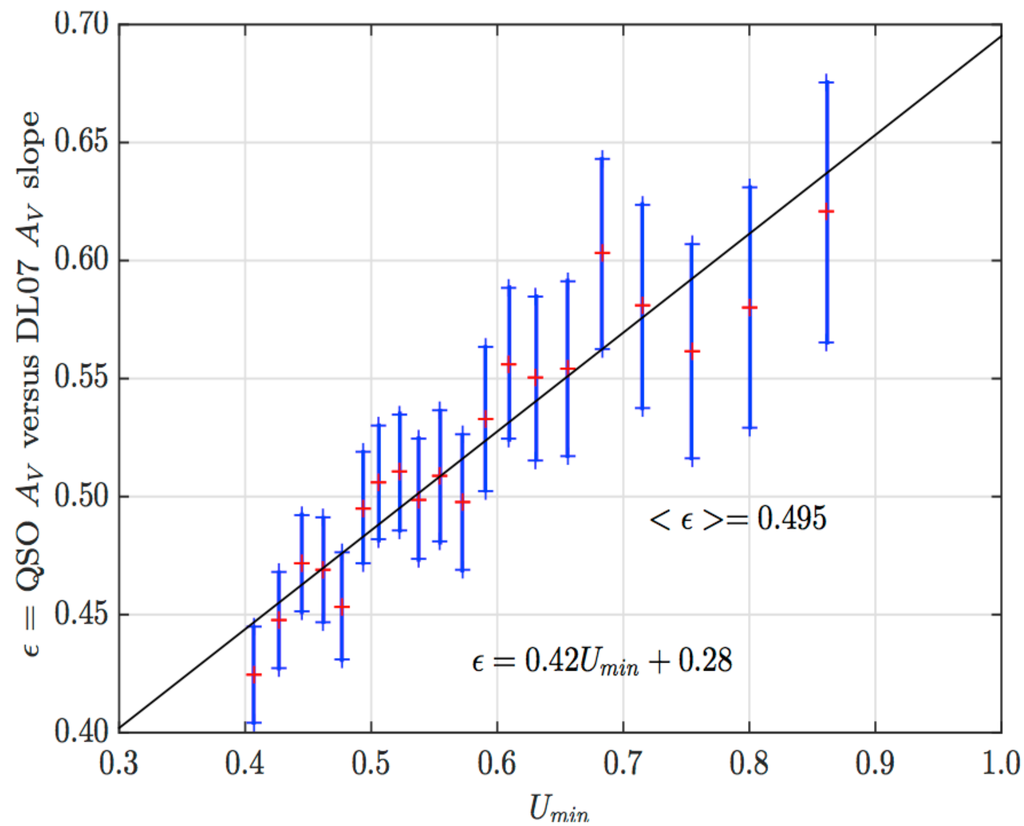
DL07 Model: Predicted A_V vs. Observation

- 270,000 SDSS QSOs.
- for each Planck pixel with QSO, have an estimate of $\Sigma_{\rm dust} \Rightarrow E(B-V)$
- For fixed redshift, correlate observed QSO color vs. predicted $E(B-V)$.
- Good correlation, but DL07 model *OVERPREDICTS* $A_{\rm V}$ by factor **$\sim$2**
- Overprediction is function of fit parameter $U_{\rm min}$
- Empirical correction:

$$A_{V,{\rm corr}} = (0.28 + 0.42 U_{\rm min})\, A_{V,{\rm DL07}}$$

Good estimator of actual A_V

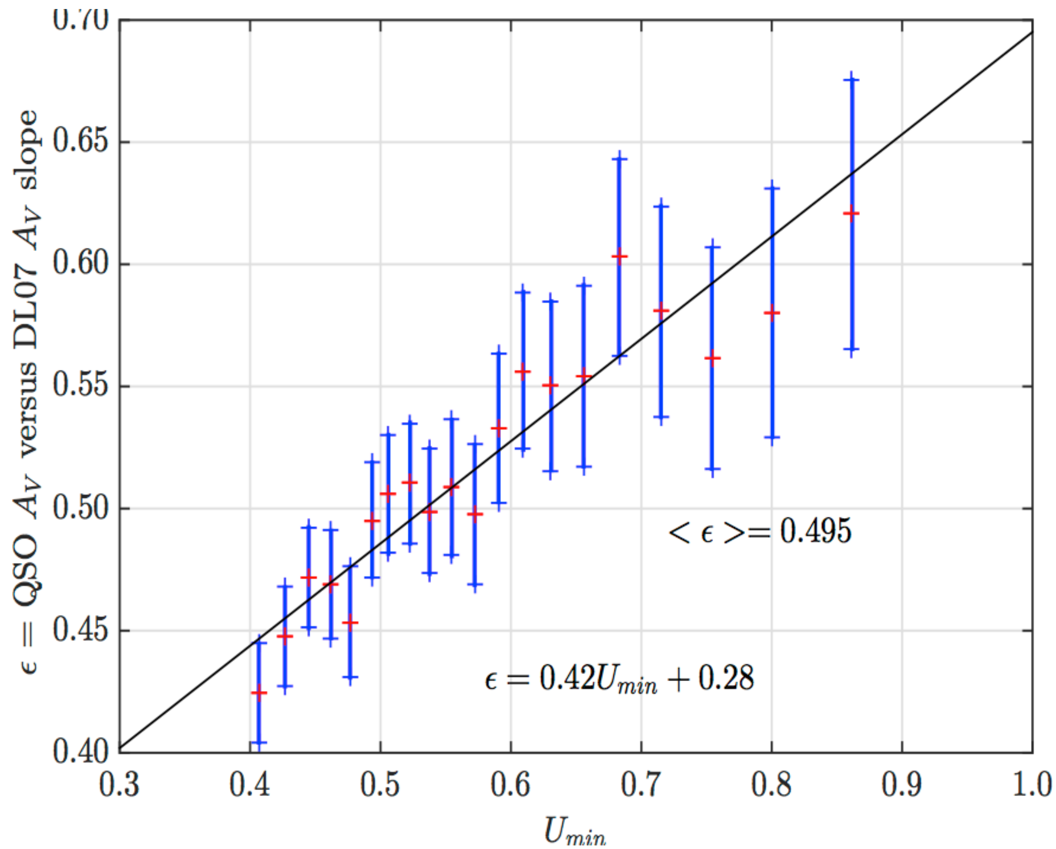
(Actual A_V) / (A_V predicted by DL07 fit to SED)



(from Planck Int. Results XXIX)

Empirical correction factors vs. fit parameter $U_{\rm min}$.
20 $U_{\rm min}$ bins, each with $\sim$13,500 QSOs.
For each bin, show weighted mean $A_{V,{\rm QSO}}/A_{V,{\rm DL07}}$

Overprediction of A_V by the DL07 Model



(from Planck Int. Results XXIX)

Conclusions:

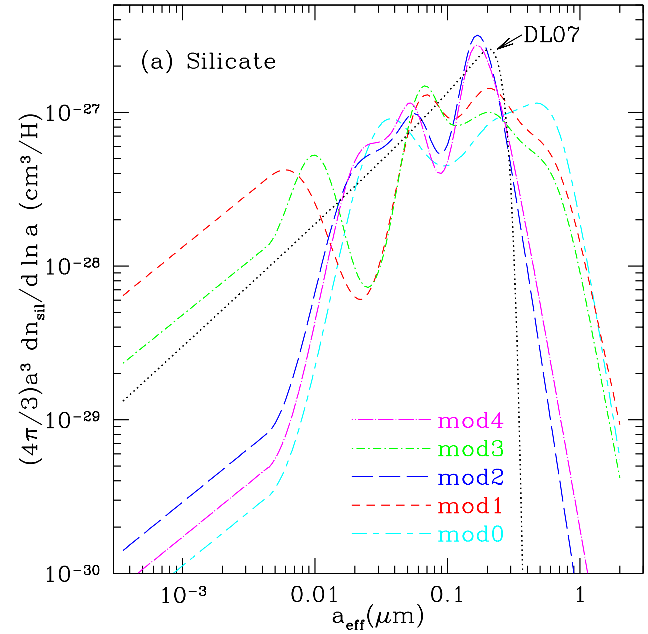
- $\tau_{\mathrm{abs,FIR}}/\tau_{\mathrm{ext,optical}}$ **too low in DL07 model**
- Remedy: new models should have $\tau_{\mathrm{FIR}}/\tau_{\mathrm{optical}}$ increased by factor $\sim$2.
- If raise $\tau_{\mathrm{FIR}}/\tau_{\mathrm{optical}}$ *and* starlight U by same factor, T_{dust} and SED shape unchanged.
- Empirical correction depends on fit $U_{\mathrm{min}} \Rightarrow$ Regional variations in FIR dust properties ("space weathering"?)

Models for Interstellar Dust

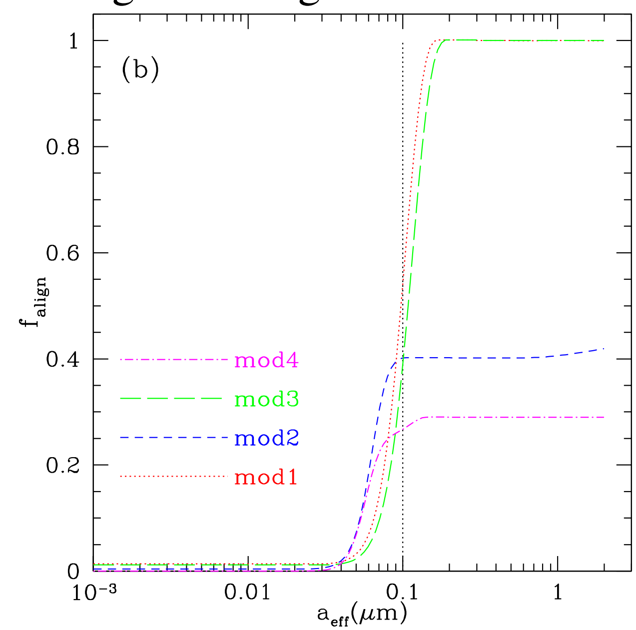
What about Polarization?

- Li & Draine (2001): pre-Spitzer model
  amorphous silicate grains + graphite + PAHs
  spherical grains: no polarization
- Draine & Li (2007):
  amorph. sil. and graphite from Li & Draine (2001)
  PAHs adjusted slightly to match early Spitzer results
  spherical grains: no polarization
- **Draine & Fraisse (2009):** $\Longrightarrow$
  DL07 materials
  spheroidal grains with alignment $f_{\rm align}(a)$
- Compiègne et al. (2011) ("DUSTEM" model)
  amorph. silicate + amorph. C + PAHs
  spherical grains: no polarization
- Jones et al. (2013):
  amorph. silicate + Fe nanoparticles + amorph. C + PAHs
  spherical grains: no polarization

silicate size distribution



degree of alignment vs. size

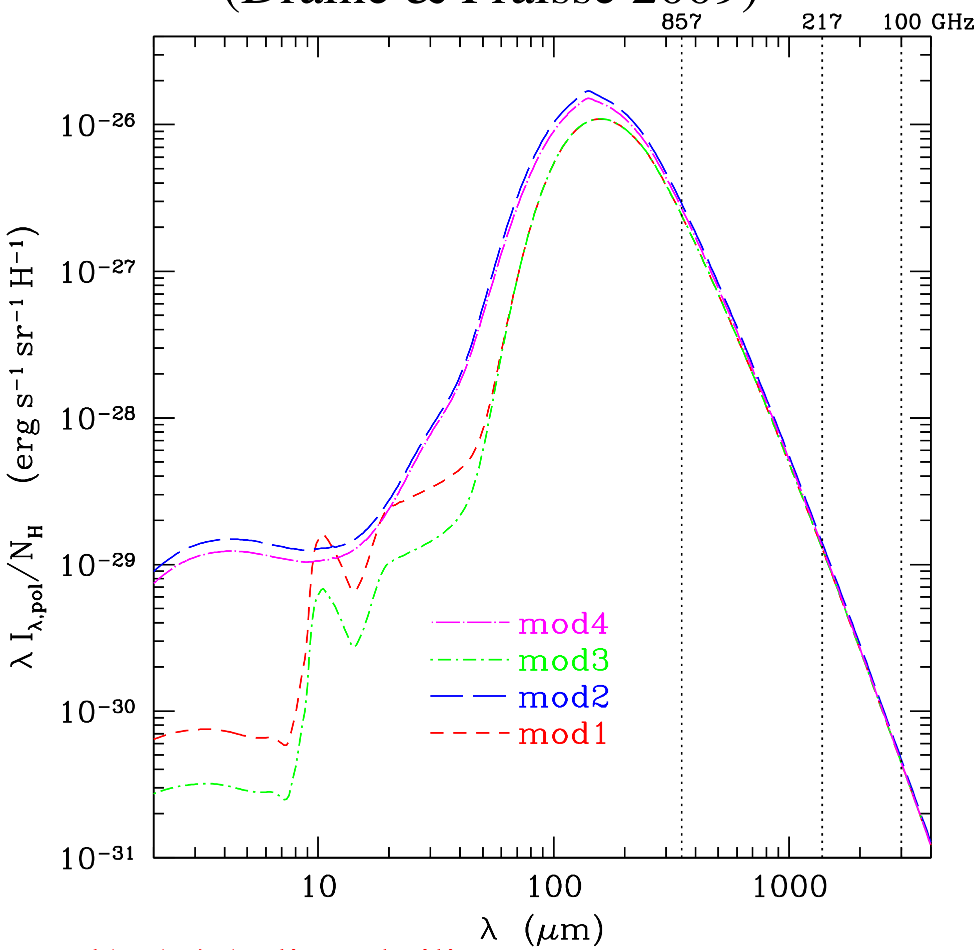


(Draine & Fraisse 2009)

Models for Interstellar Dust

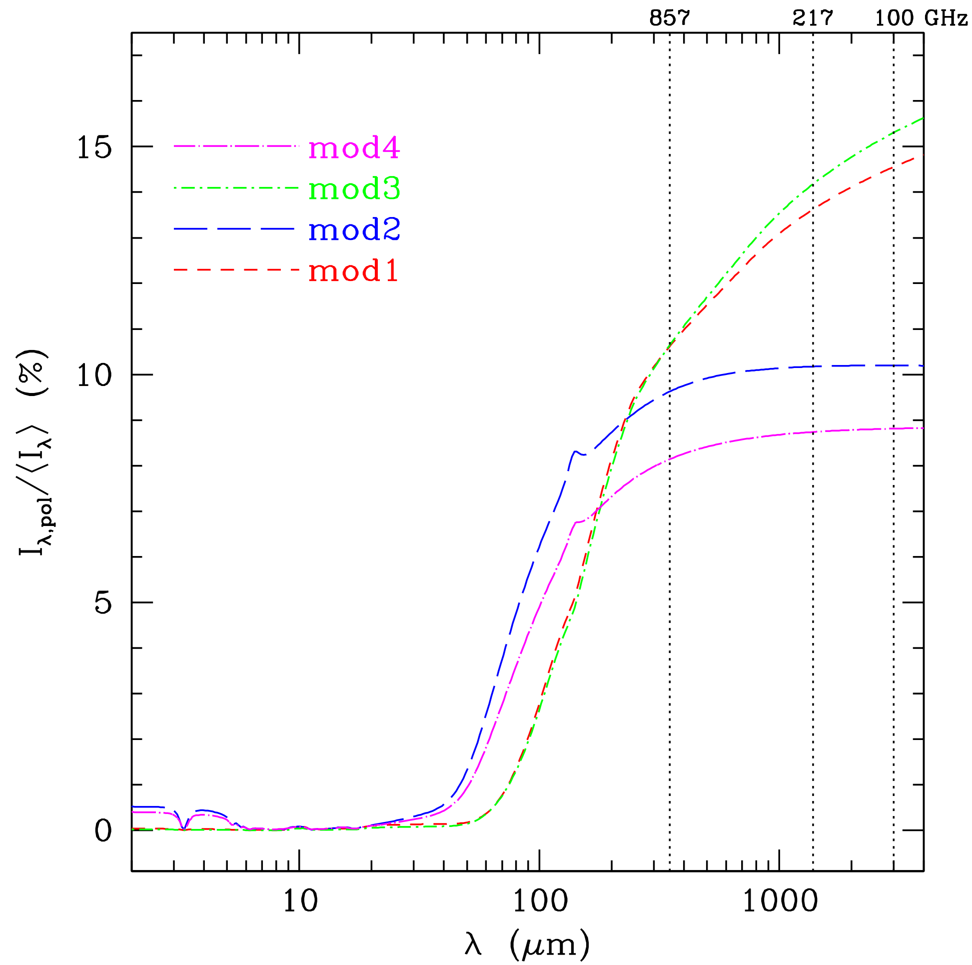
1.4:1 and 1.6:1 oblate spheroids

Polarized Emission/H
(Draine & Fraisse 2009)



mod1: 1.4:1 aligned silicates
mod2: 1.4:1 aligned silicates, aligned C
mod3: 1.6:1 aligned silicates
mod4: 1.6:1 aligned silicates, aligned C

fractional polarization
(Draine & Fraisse 2009)



models have $p \approx 9 - 13\%$ @ 353 GHz
$p(\lambda)$ rising with increasing λ

Planck Observations of Polarized Emission from Galactic Dust

A&A 576, A104

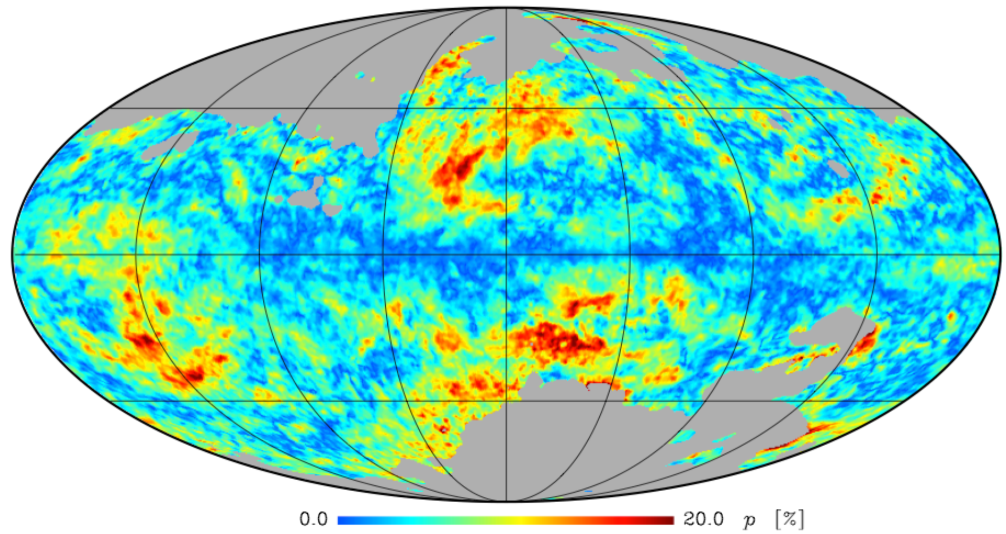
***Planck* intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust**

A&A 576, A106

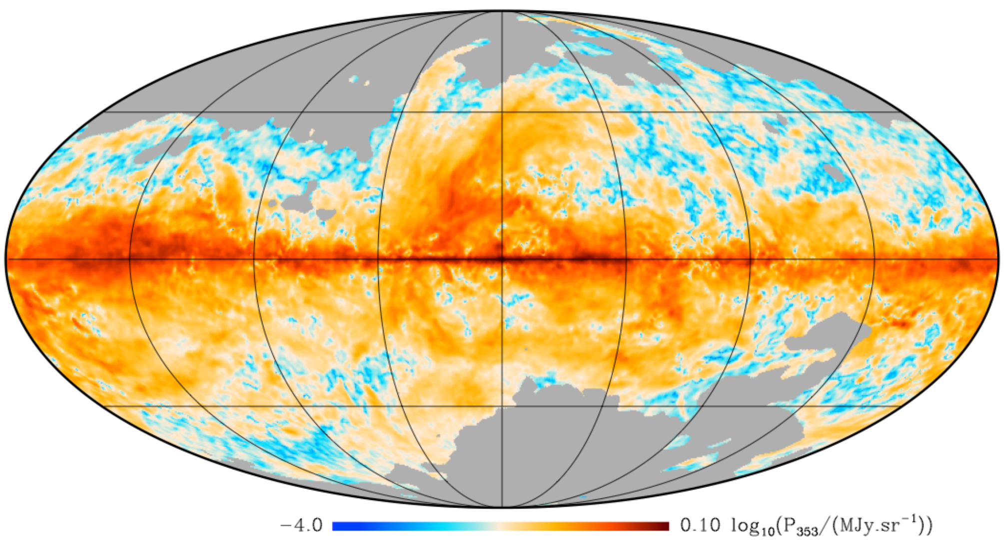
***Planck* intermediate results. XXI. Comparison of polarized thermal emission from Galactic dust at 353 GHz with optical interstellar polarization**

A&A 576, A107

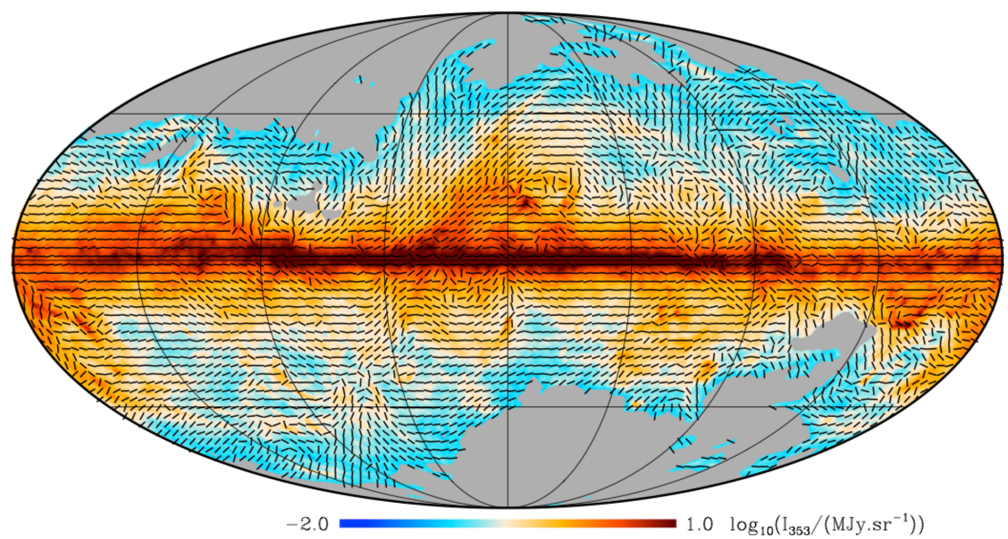
***Planck* intermediate results. XXII. Frequency dependence of thermal emission from Galactic dust in intensity and polarization**



polarized fraction @ 353 GHz
Planck int. results XIX (Planck Collaboration et al. 2015b)

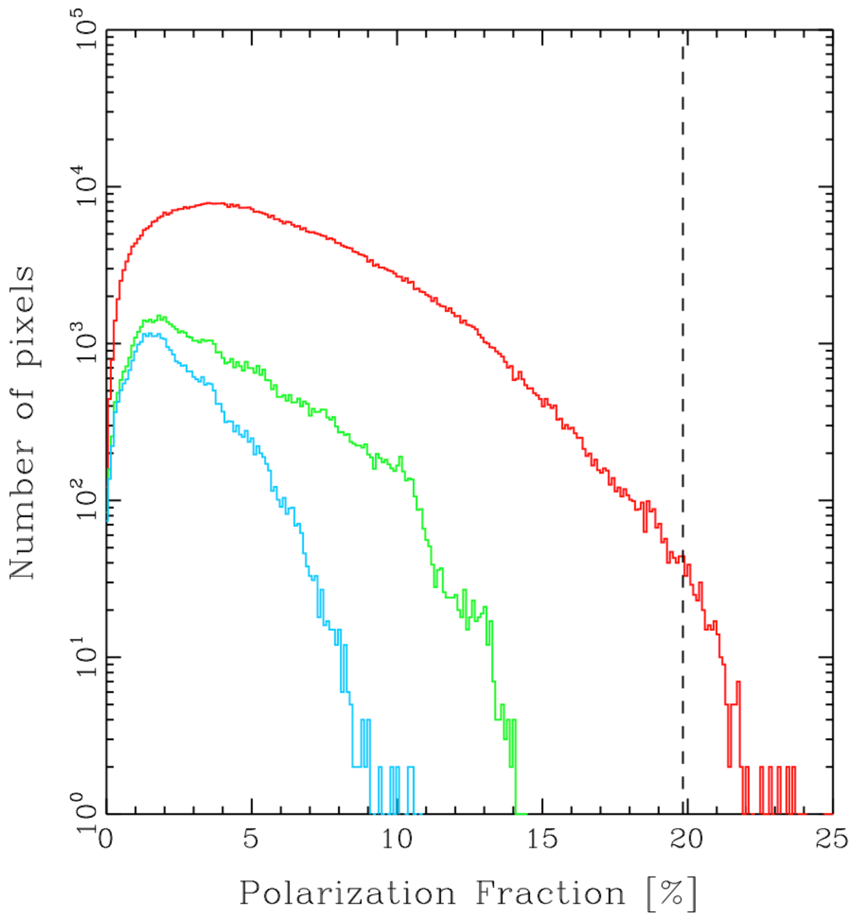


polarized emission @ 353 GHz = 850 μm
Planck int. results XIX (Planck Collaboration et al. 2015b)



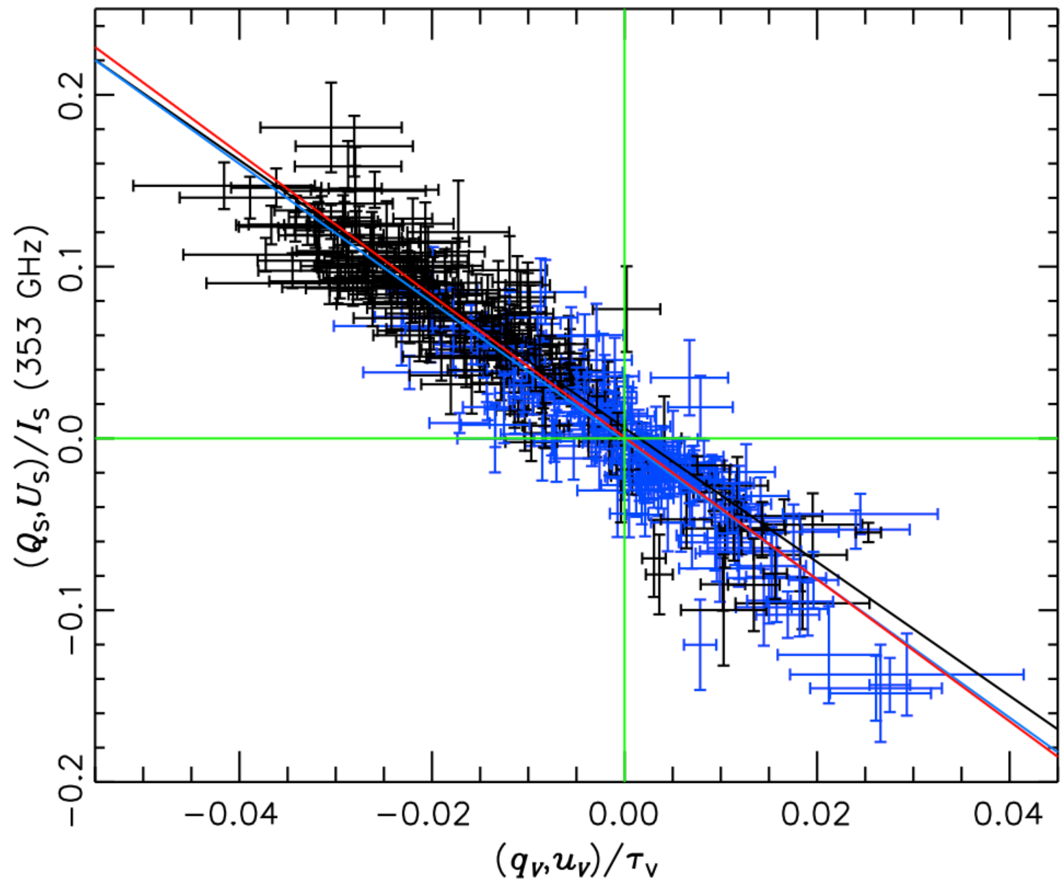
polarization direction @ 353 GHz
Planck int. results XIX (Planck Collaboration et al. 2015b)

Planck: Polarized Emission from Galactic Dust



Planck int. results XIX (Planck Collaboration et al. 2015b)

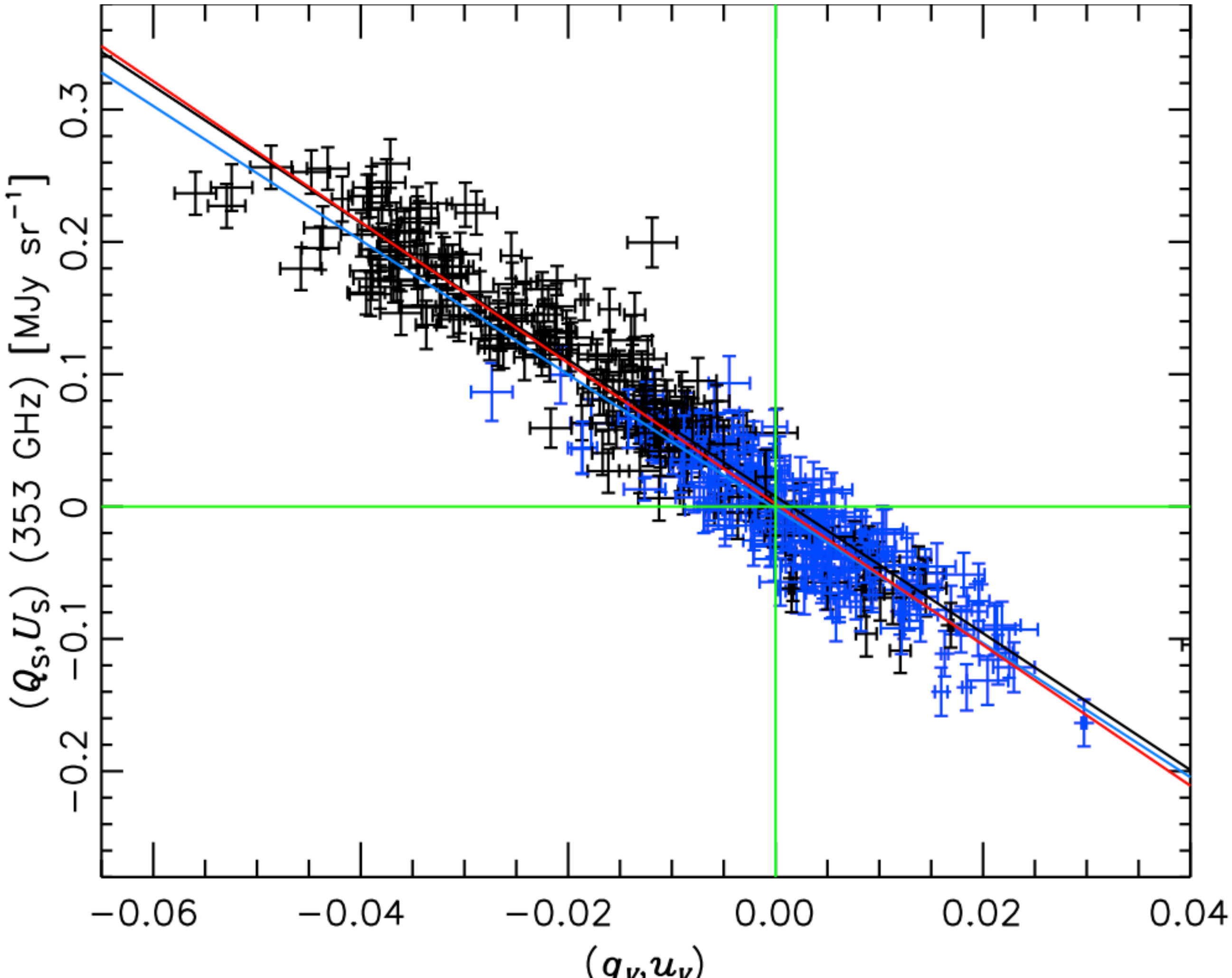
Most of the sky has polarization >5%
polarization >12% is uncommon
but a few points have p >20%



353 GHz polarization fraction $(Q_S, U_S)/I_S$ vs.
starlight polarization/τ $(q_V, u_V)/\tau_V$
Planck int. results XXI (Planck Collaboration et al. 2015c)

Observed slope: -4.13 ± 0.06
DF09 prediction: -3.8

Submmm Polarized Intensity vs. p_V



353 GHz **polarized intensity** vs. **starlight polarization fraction**

Planck int. results XXI (Planck Collaboration et al. 2015c)

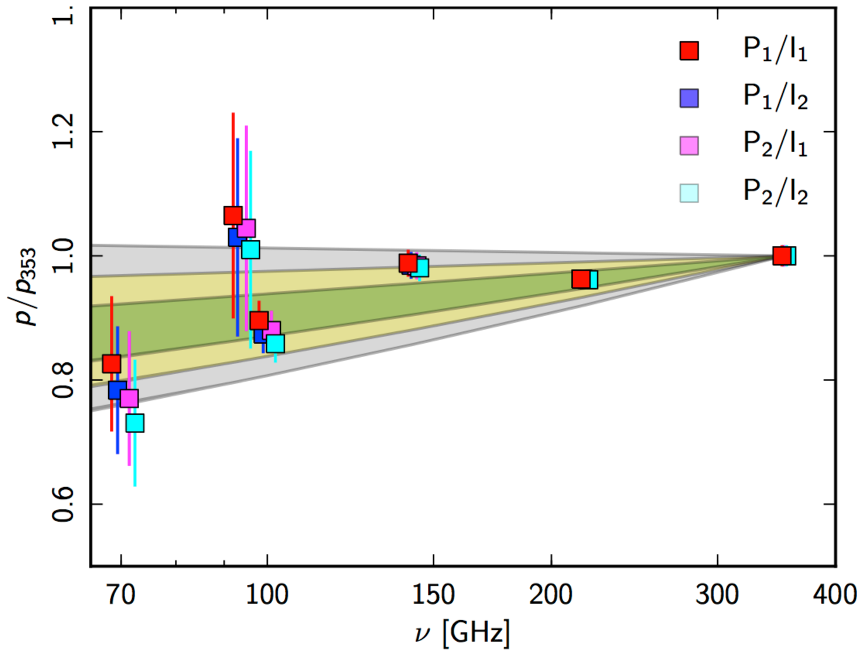
Observed slope: $-5.32 \pm 0.06\,\mathrm{MJy\,sr^{-1}}$

Draine & Fraisse (2009) prediction: -2.0 $\mathrm{MJy\,sr^{-1}}$

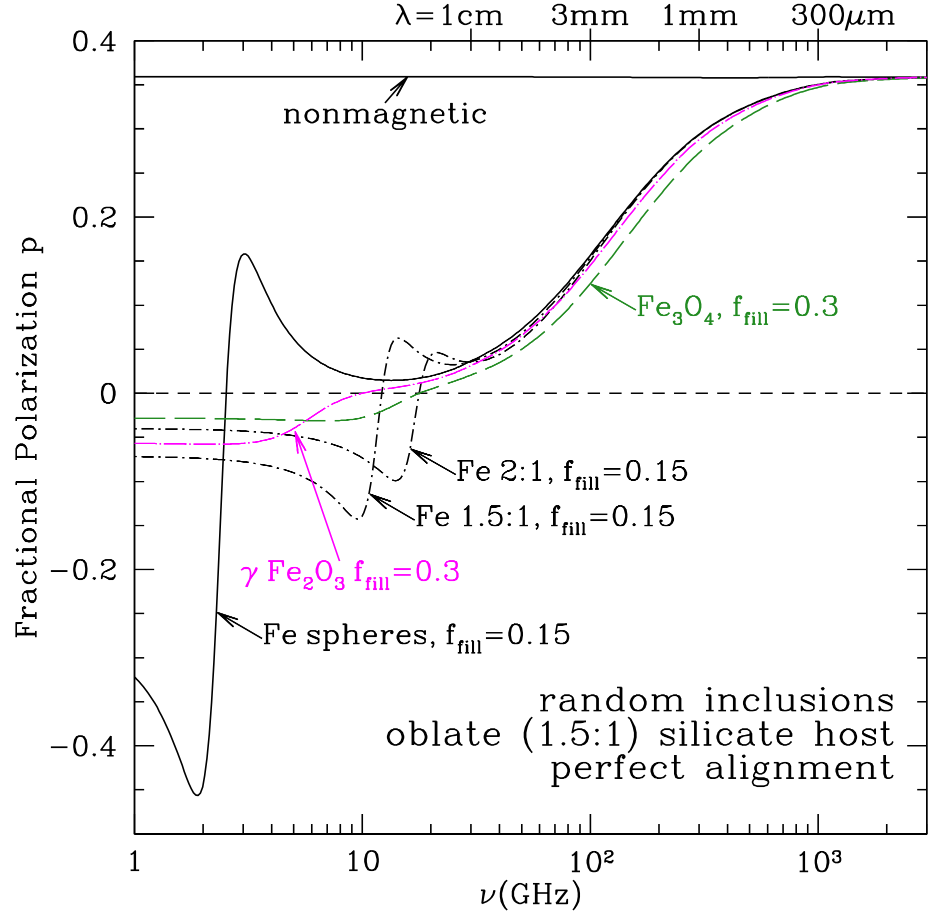
DF09 Model: Polarized intensity low by factor ∼2.5

Consistent with $\tau_{\rm FIR}/\tau_{\rm opt}$ too low by factor ∼2 in DL07 model

Planck: Polarization Fraction vs. Frequency



Planck int. results XXII (Planck Collaboration et al. 2015d)



Draine & Hensley (2013)

Predictions for 100% of Fe in ferromagnetic (metallic Fe) or ferrimagnetic (Fe_3O_4 or γ-Fe_2O_3) inclusions.

Apparent drop in p with decreasing ν: Why?

Possibilities:

- two types of grains present, fractional contribution of less-aligned grains increases with decreasing ν ?
- ferromagnetic inclusions in aligned grains? magnetic dipole radiation polarized $\perp$ to "electric dipole" emission

Work in Progress...

New models (with Brandon Hensley)

Hensley & Draine (2015, in prep.)

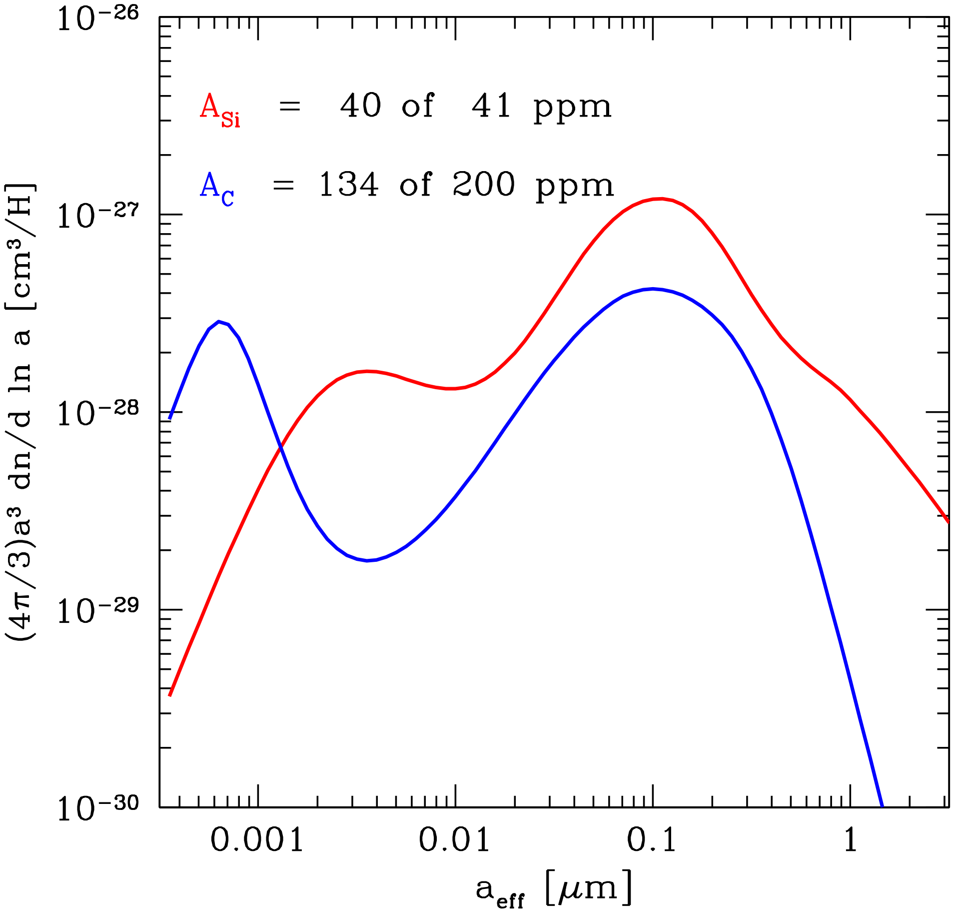
- Increase $\tau_{\rm FIR}/\tau_{\rm V}$ to increase emission per unit τ_V
- Obtain "new" astrosilicate dielectric function $\epsilon_{\rm sil}(\omega)$
  - *improved* $10\,\mu{\rm m}$ *silicate profile*
  - *adjust FIR-submm for consistency with Planck observations*

  Use Kramers-Kronig relations to relate Re$(\epsilon_{\rm sil})$ and Im$(\epsilon_{\rm sil})$.
- Increased FIR opacity requires simultaneous increase in assumed starlight intensity $U_\star$ to get the right grain temperature.
- New $\epsilon_{\rm sil} \rightarrow$ modest increase in submm polarization p.
- Models include variable amounts of ferromagnetic inclusions

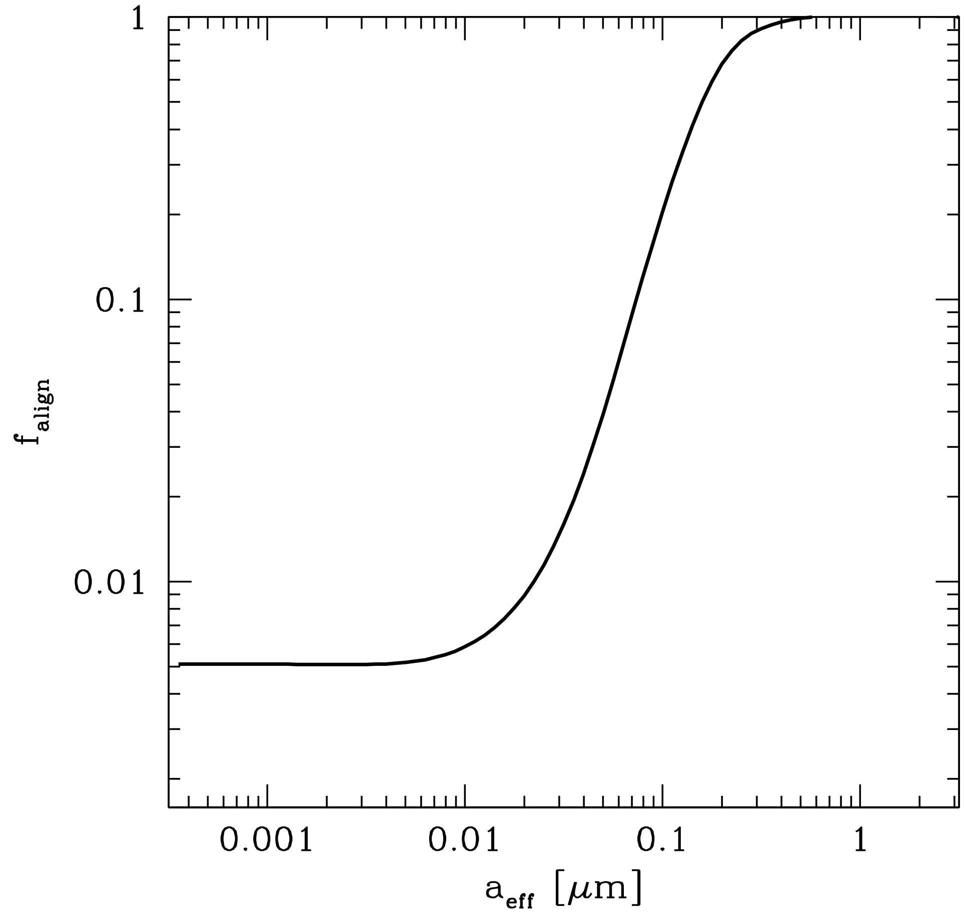
Work in Progress...

models with 25% of Fe as metallic inclusions in silicate hosts ($f_{\rm fill} = 0.05$)

size distribution (spheroids)



alignment of silicates



most of the mass at $a > 0.05\,\mu$m

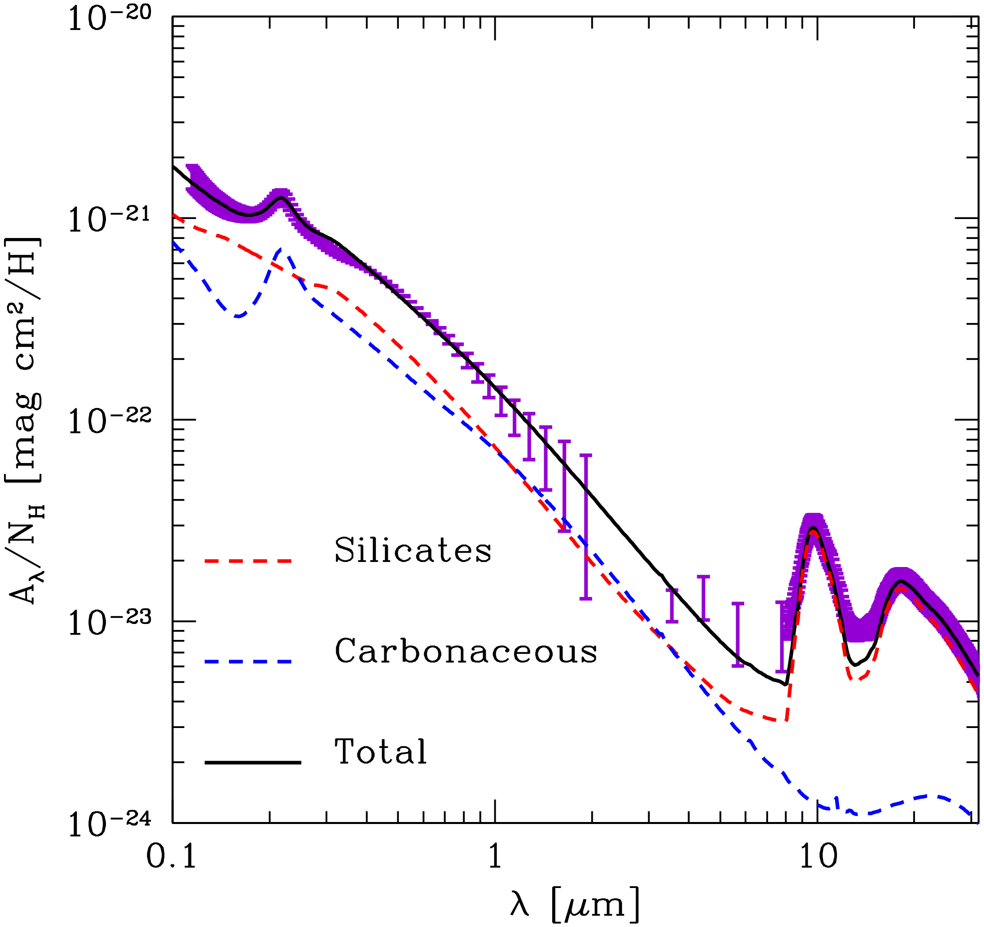
minimal alignment for $a < 0.05\,\mu$m
substantial alignment for $a > 0.1\,\mu$m

Work in Progress...

(Hensley & Draine 2015)

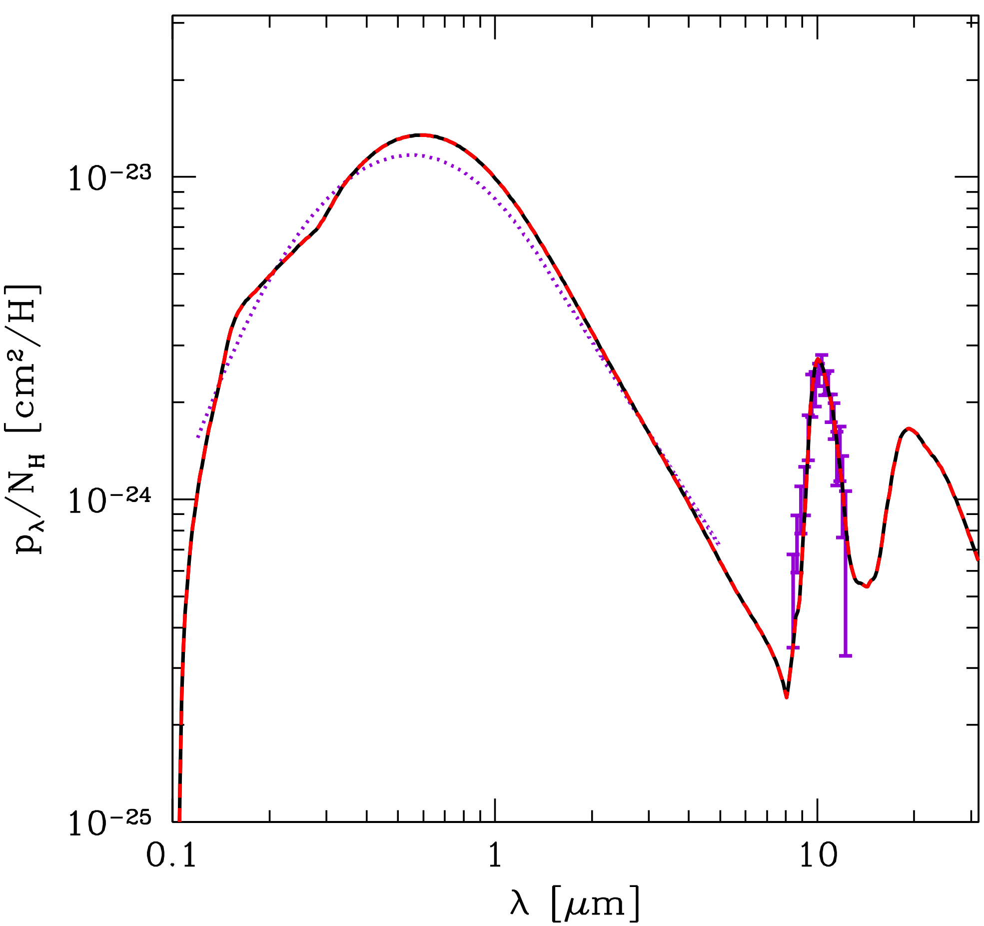
25% of Fe in metallic inclusions in silicates ($f_{\rm fill} = 0.05$)

extinction



consistent with observations

starlight pol.



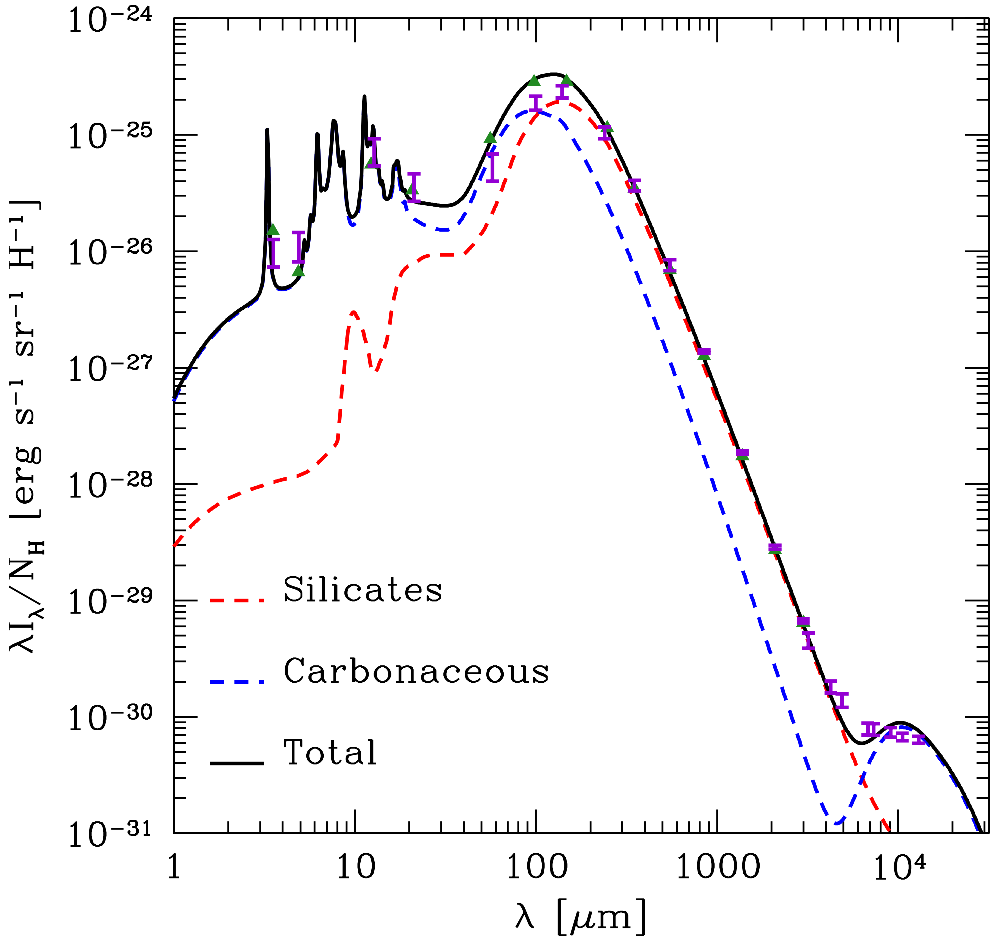
consistent with observations

Work in Progress...

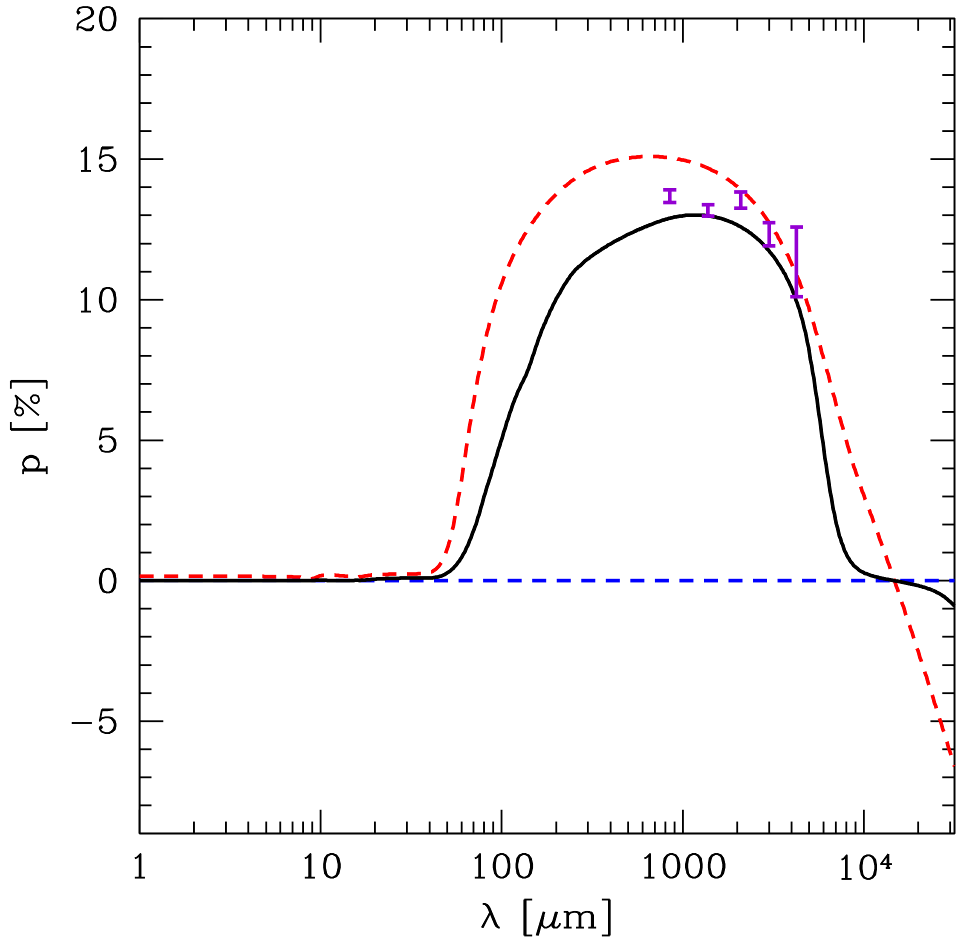
(Hensley & Draine 2015)

Starlight intensity $U = 1.6$

thermal emission



polarization fraction



consistent with observations

somewhat high at 100 μm?

consistent with observations

25% of Fe in metallic inclusions

Anomalous Microwave Emission

- **History:** dust-correlated microwave emission discovered by COBE-DMR (Kogut et al. 1996)
  much stronger than expected from "normal" dust emission
- **Proposal:** rotational emission from spinning dust, particularly PAHs (Draine & Lazarian 1998)
- *Prediction* of spinning dust models:
  - AME should be minimally polarized
  - PAH size distribution $\Rightarrow j_\nu$ peaking in the 20-40 GHz range
  - *if spinning PAHs:*
    variations in PAH abundance
    $\Rightarrow$ variations in AME
    (consistent with relatively weak AME emission from SMC)

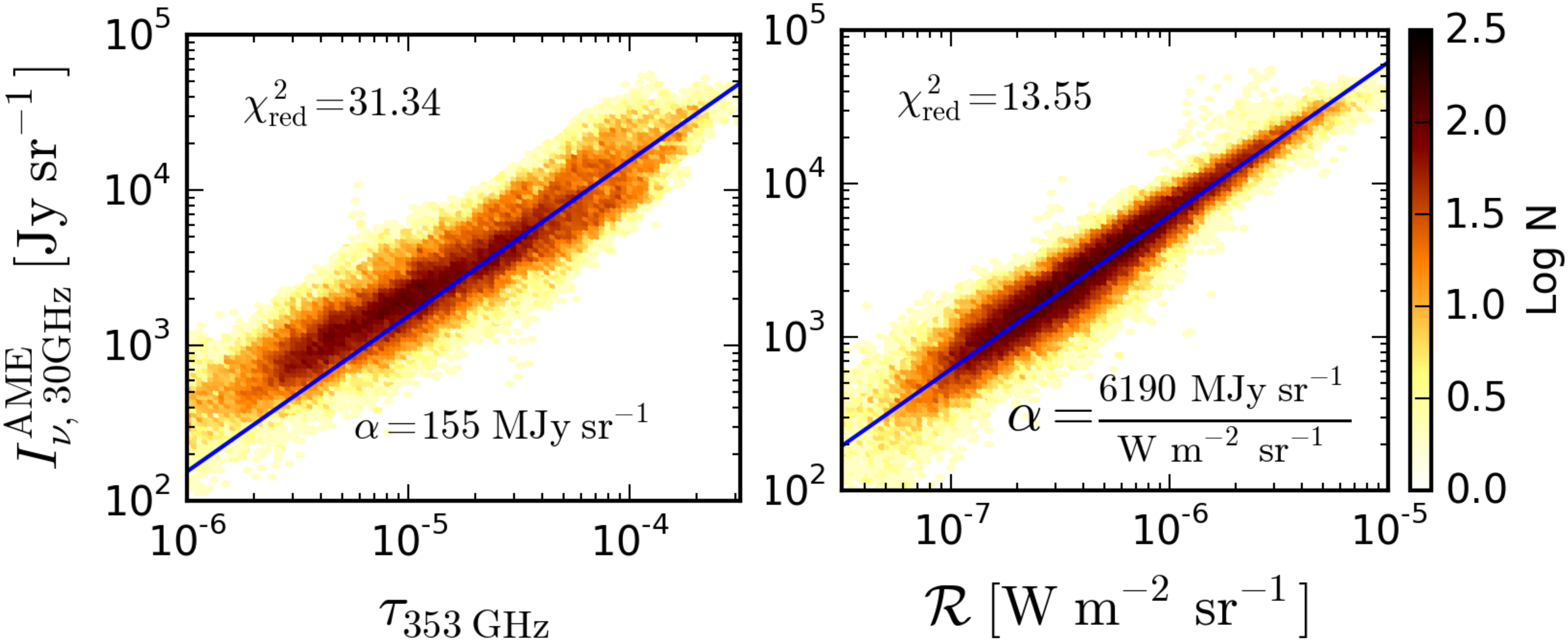
TEST
(Hensley, Draine, & Meisner 2015, in prep.)

- AME map from Planck ("Commander" analysis; Planck Collaboration et al. 2015a)
  maps of τ_{353}, $T_{\rm dust}$, β, and total dust radiance $\mathcal{R}$ from Planck 2013 results XI (Planck Collaboration et al. 2014)
- $12\,\mu{\rm m}$ map from WISE (Meisner & Finkbeiner 2014) (diffuse $12\,\mu{\rm m}$ dominated by PAH emission).
- PAH abundance assumed to be $\propto$

$$f_{\rm PAH} \equiv \frac{{\rm WISE}12\,\mu{\rm m}}{\mathcal{R}}$$

Correlation of AME with τ_{353} and radiance $\mathcal{R}$

Expectation: spinning dust rotational emission $\propto \tau_{353}$



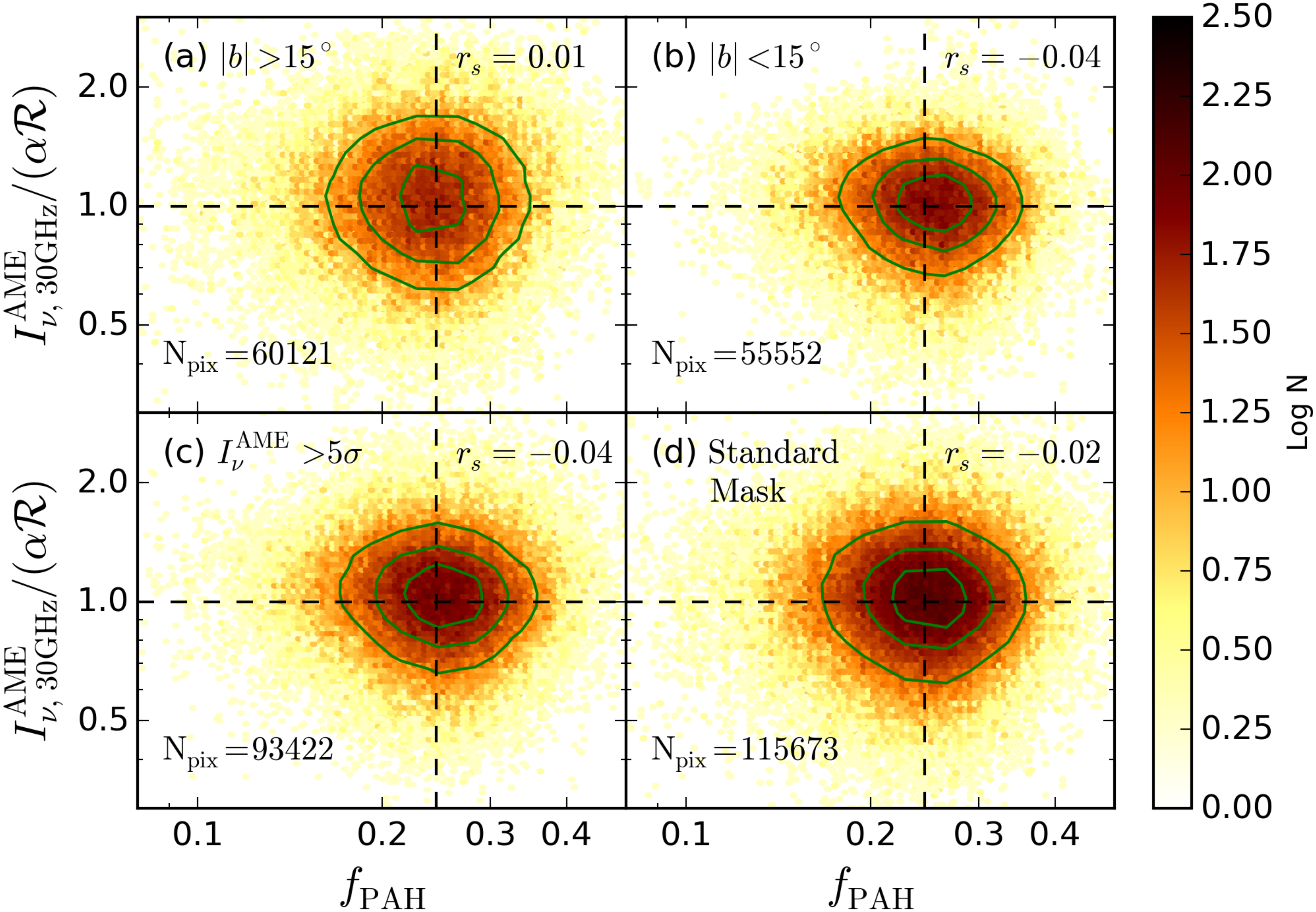
Surprise: Much better correlation with $\mathcal{R}$ than with τ_{353}!

Expectation: spinning PAH rotational emission $\propto$ PAH abundance

Is there a correlation with f_{PAH}?

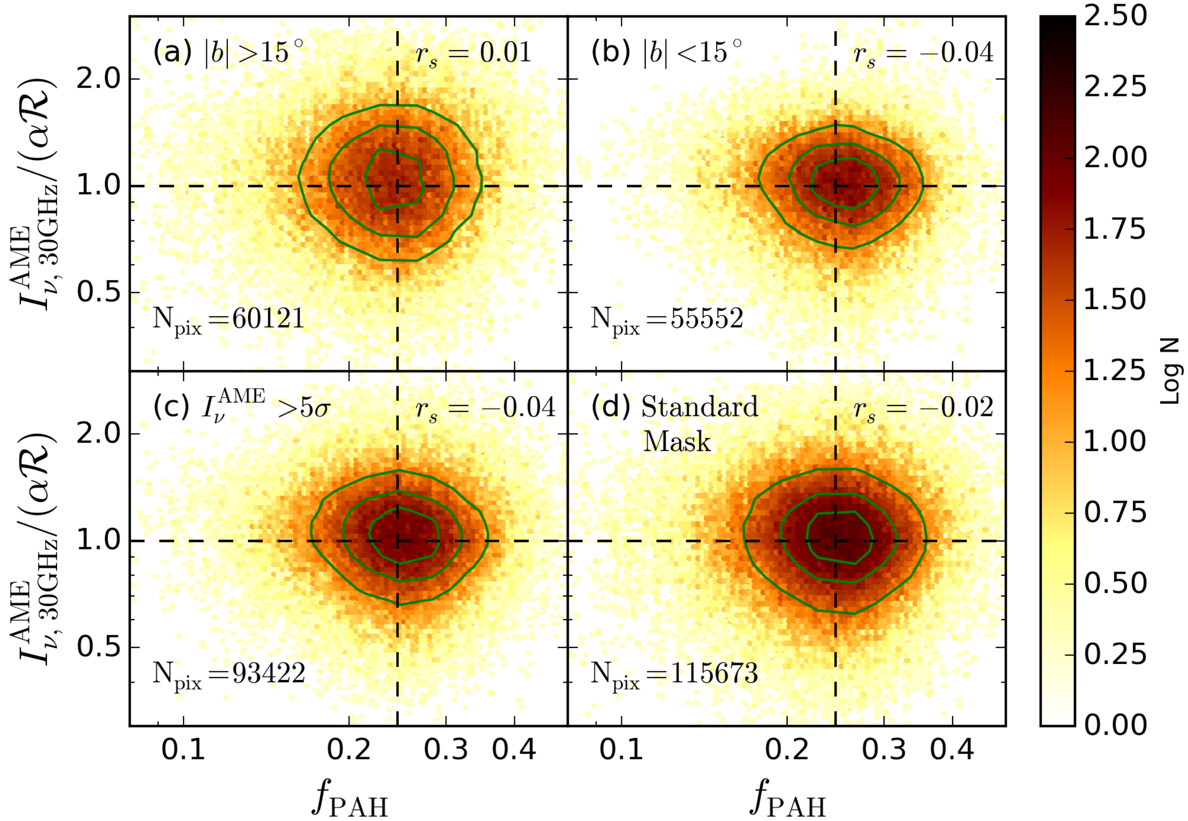
Does AME Come from Spinning PAHs?

(Hensley et al. 2015)



Doesn't look like it: No evidence of variation in AME $\propto f_{\rm PAH}$

Anomalous Microwave Emission: *What is the Source?*



Hensley et al. (2015)

- **No** evidence of variation of AME/$\mathcal{R}$ when f_{PAH} varies!
- If free-fliers, PAHs *must* be spinning, but perhaps have small electric dipole moments, with most AME coming from some other source.
- Alternative sources of AME:
  - Perhaps other spinning dust (silicates?) dominate AME
  - Perhaps something else entirely, such as thermal emission from magnetic fluctuations in ferromagnetic particles?

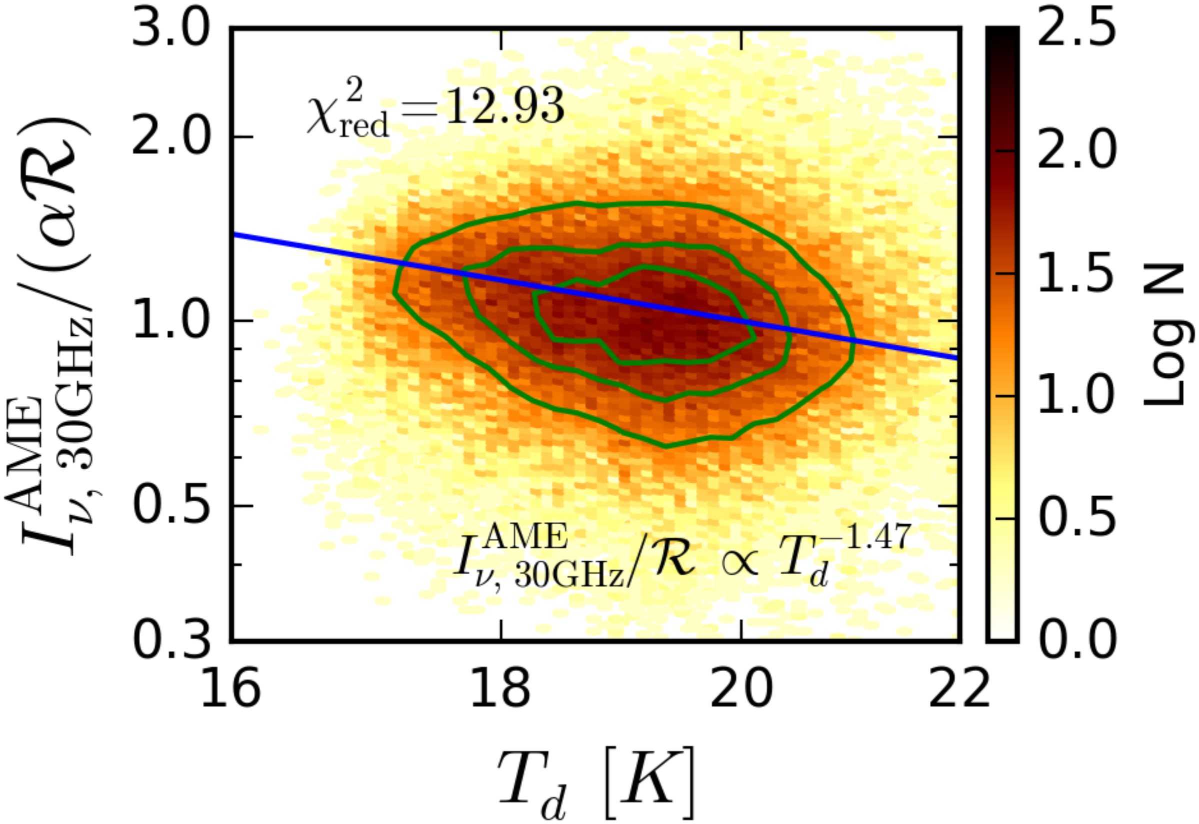
What is Source of AME? Test for Thermal Emission Process

If thermal emission:

$$\mathrm{AME} \propto \tau_{30} \times T_d$$

$$\mathcal{R} \propto \tau_{353} \times T_d^{4+\beta} \qquad (\beta \approx 1.65)$$

$$\frac{\mathrm{AME}}{\mathcal{R}} \propto \frac{\tau_{30}}{\tau_{353}} T_d^{-(3+\beta)} \approx T_d^{-4.65}$$

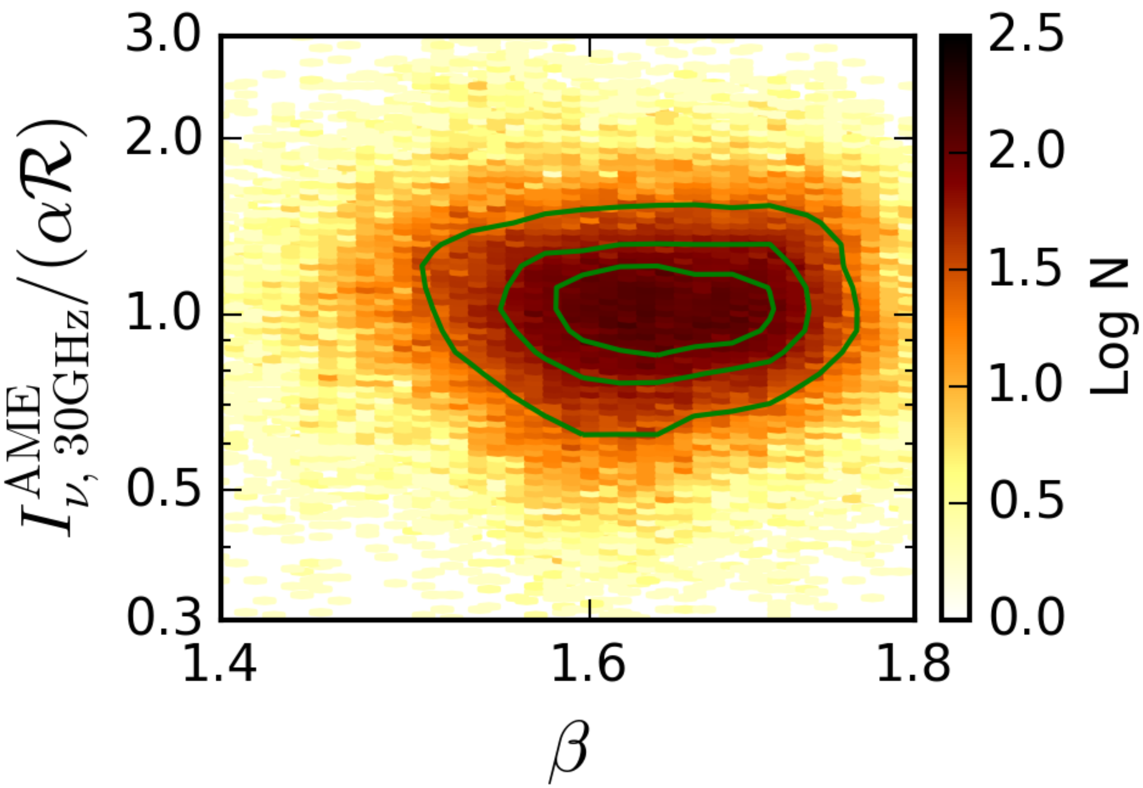


(Hensley et al. 2015)

Observed AME is <u>not</u> consistent with thermal emission from dust <u>unless</u> dust opacity at 30 GHz is very sensitive to T_d, as in $\tau_{30}/\tau_{353} \propto T_d^{3.2}$

Does AME Correlate with β?

- Suppose $\kappa_\nu \propto \nu^\beta$
- Best-fit β varies.
- Might expect dust opacity at $\sim$30 GHz to vary when β varies (higher $\beta \rightarrow$ lower $\tau_{30\,\mathrm{GHz}}$).
- If AME is thermal emission, then expect **NEGATIVE** correlation of AME with β



No indication of correlation of AME with β

Summary

- Planck: DL07 model has $\tau_{\rm FIR}/\tau_{\rm optical}$ too low by factor $\sim$2
- Planck: there are regional variations in FIR dust properties in the diffuse ISM
- Planck: submm polarization $\propto$ starlight polarization
- Planck: possible variation in submm polarization fraction with ν
- Model with partially-aligned compact spheroidal grains, new $\epsilon_{\rm sil}(\omega)$, and Fe inclusions is able to reproduce:
  - Extinction and polarization of starlight
  - IR-microwave emission: total and polarized
- Apparent decrease of polarization fraction at $\nu \lesssim 120\,{\rm GHz}$
  - due to magnetic dipole emission from ferromagnetic inclusions?
  - (but could also be due to increasing contribution from non-aligned grains)
- Anomalous Microwave Emission
  - *No evidence of expected connection to PAHs*
  - *No evidence for thermal emission process*
  - Is AME primarily from non-PAH (silicate?) spinning nanoparticles?

Many open questions; much interesting work ahead...


THANK YOU

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