

Physical Models for Diffuse ISM Dust in the Light of Planck

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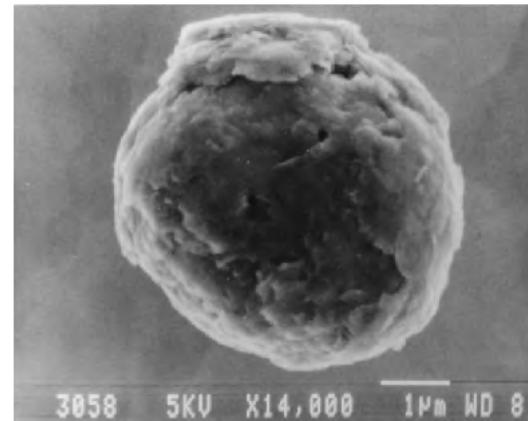
- Some Physical Dust Models
- Testing the DL07 dust model: *Planck Int. Results XXIX*
- Polarized Extinction and Emission from Galactic Dust
 - Planck observations
 - New dust model
- Anomalous Microwave Emission: What is the Source?

What do we mean by “Physical Dust Model”?

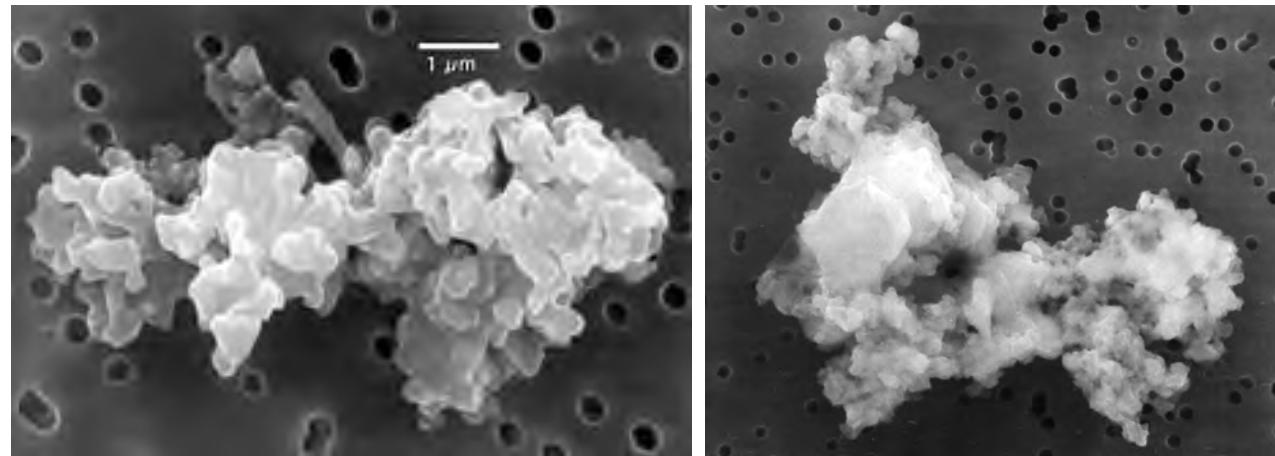
- Specify grain materials
 - may be real materials studied in lab (e.g., graphite, SiC, metallic Fe)
 - may be proxies for poorly-known interstellar materials (e.g., “astrosilicate” or “astro-PAHs”)
- Specify (adjust) distributions of grain **sizes** and **shapes**
(should be consistent with interstellar 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 $f_{\text{align}}(a)$
(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 $\sim 5 \mu\text{m}$). 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 $\sim 10 \mu\text{m}$).
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 $10 \mu\text{m}$ silicate feature
- apparent absence of polarization in the $3.4 \mu\text{m}$ 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

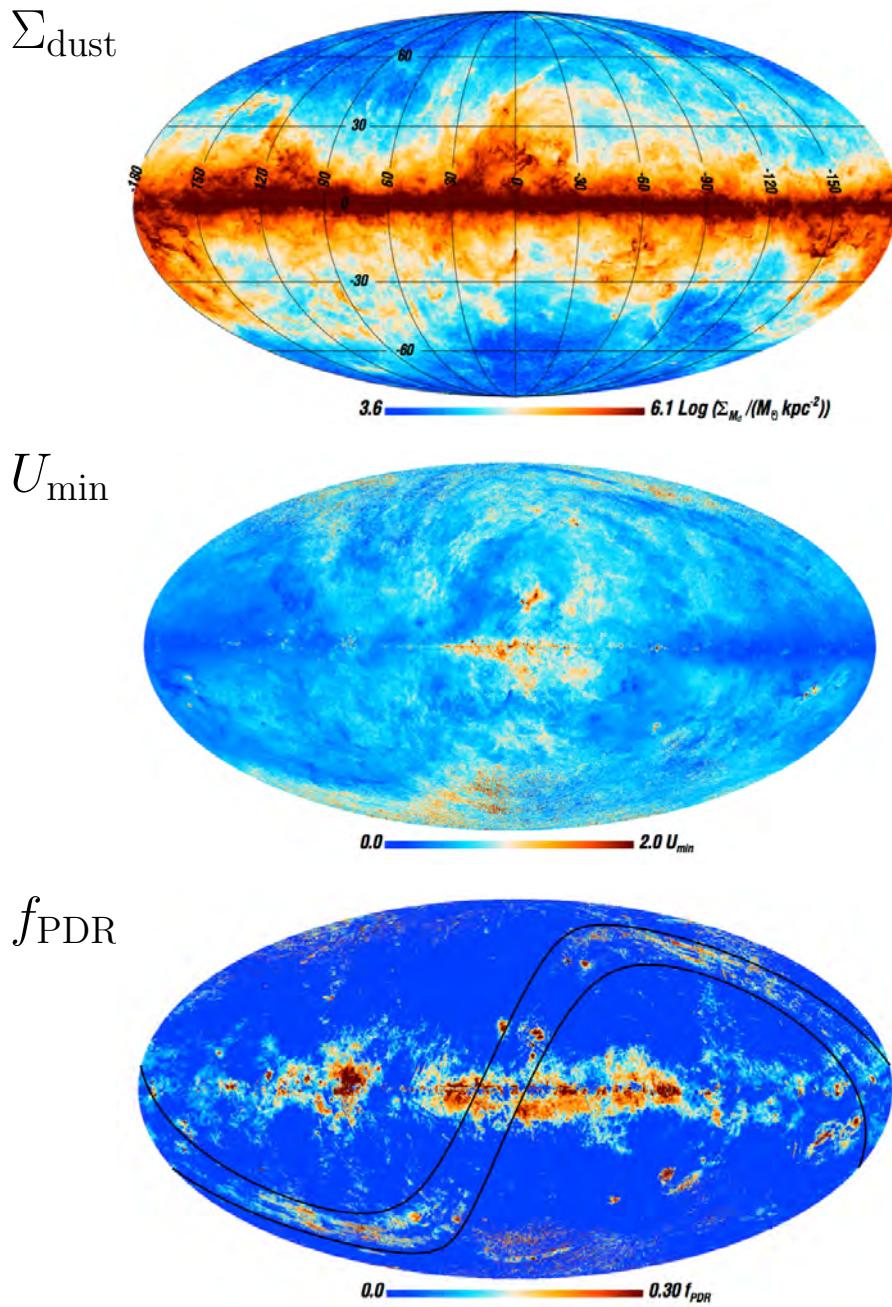
- All-sky diffuse Galactic emission:

- 5 Planck bands (143 GHz – 857 GHz)
- DIRBE 240, 140, 100 μm
- IRAS 100 μm , 60 μm
- WISE 12 μm

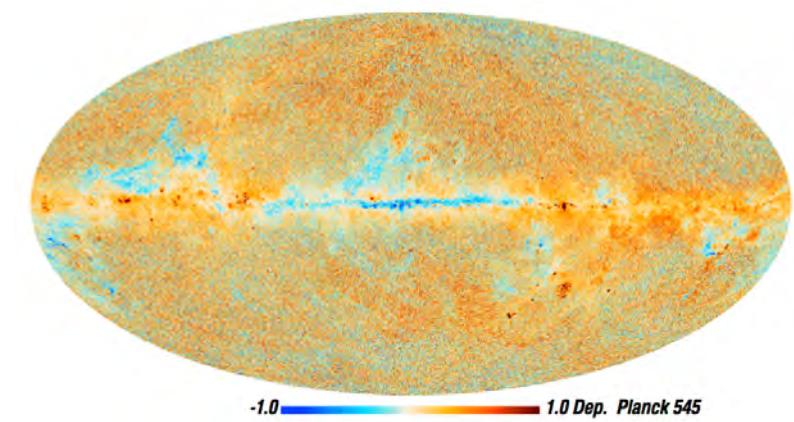
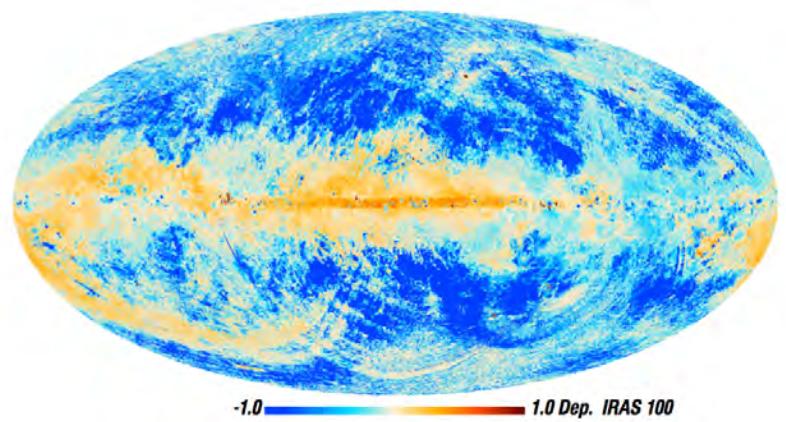
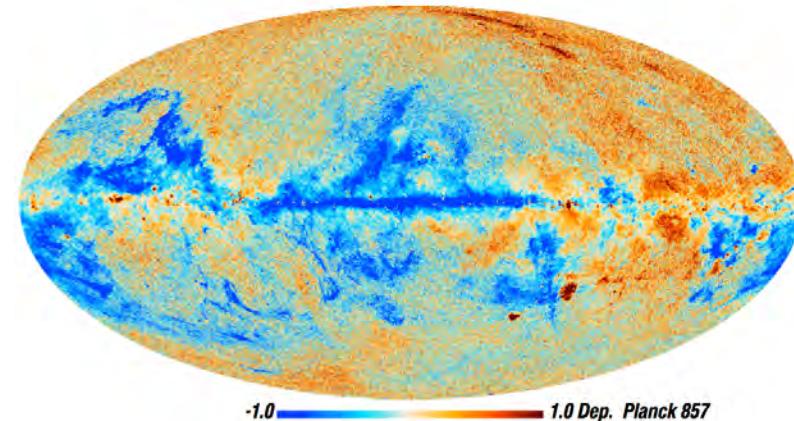
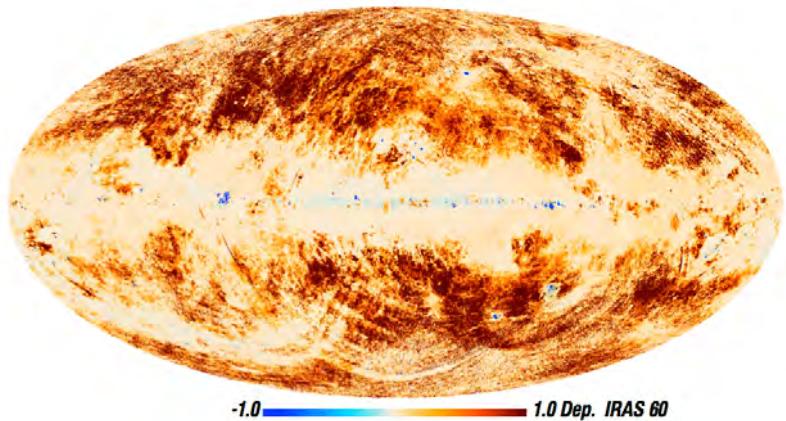
- Try to fit observed SED with DL07 dust, adjusting only

- total dust surface density Σ_{dust}
- starlight intensity parameter U_{min}
- starlight intensity parameter f_{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**

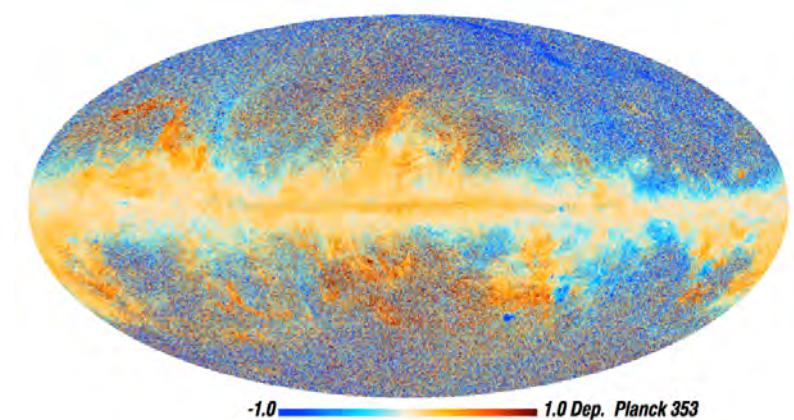


DL07 Model fit vs. Observation (5 arcmin PSF)



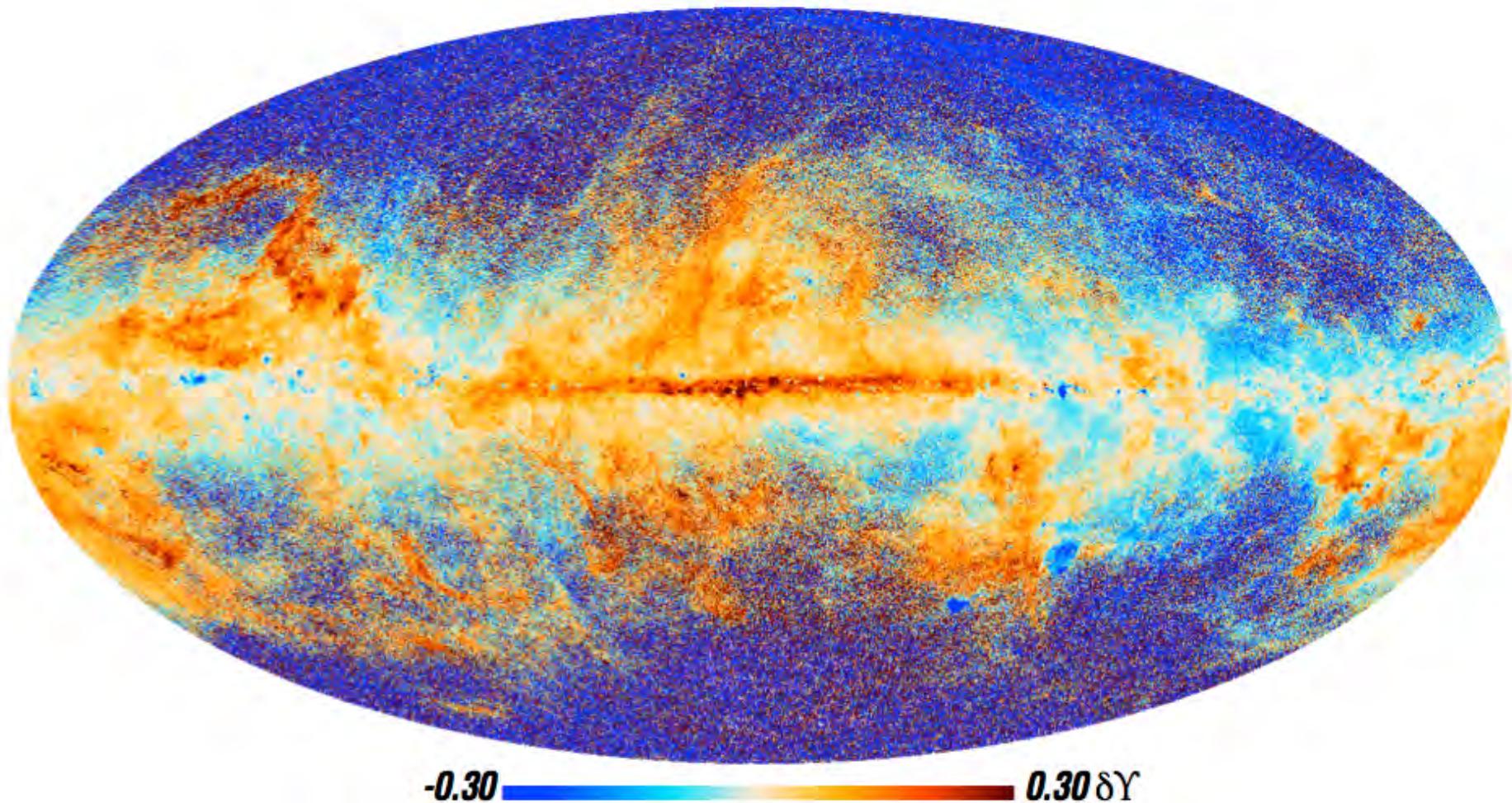
(from Planck Int. Results XXIX)

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



Regional Variations in Opacity

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



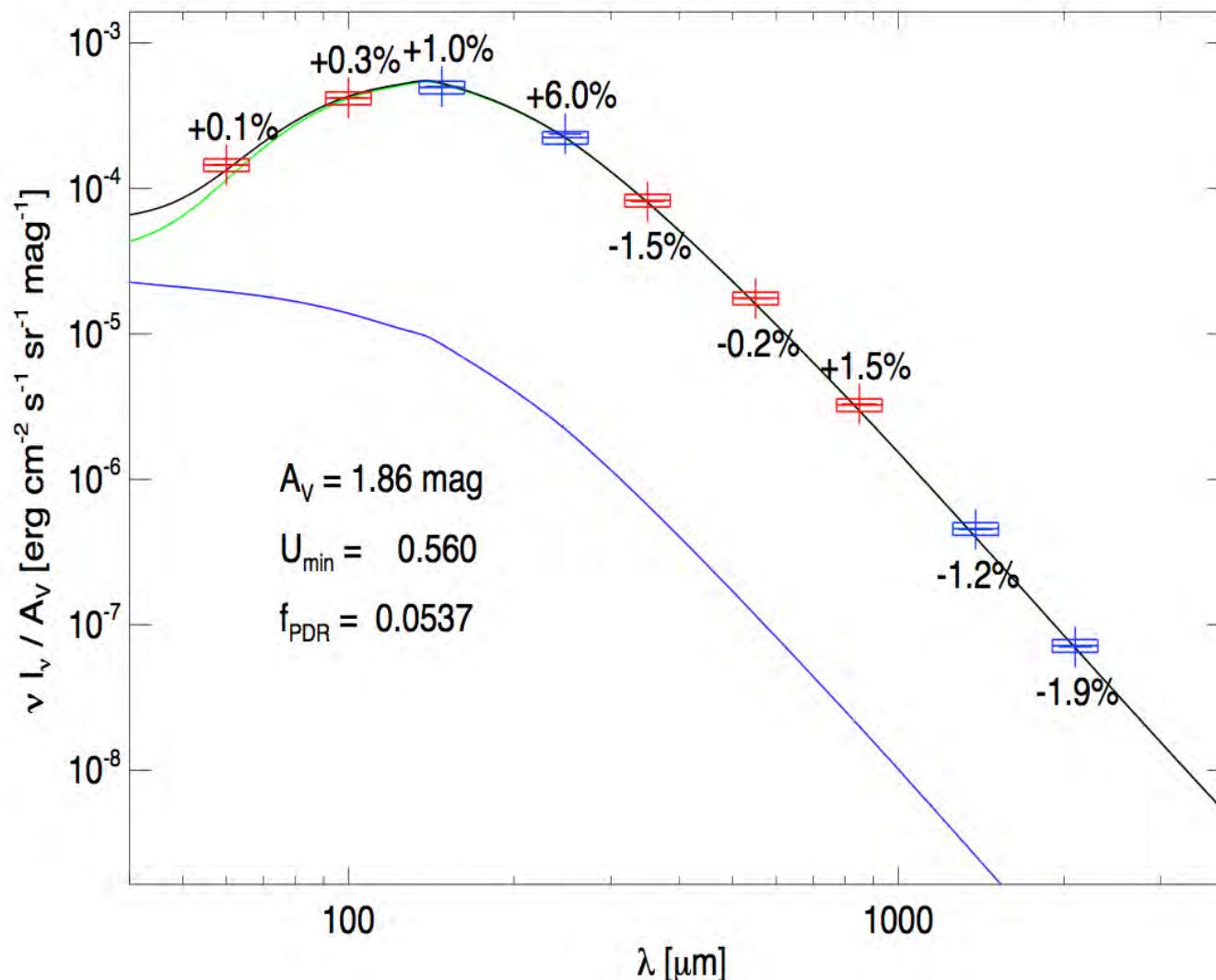
(from Planck Int. Results XXIX)

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

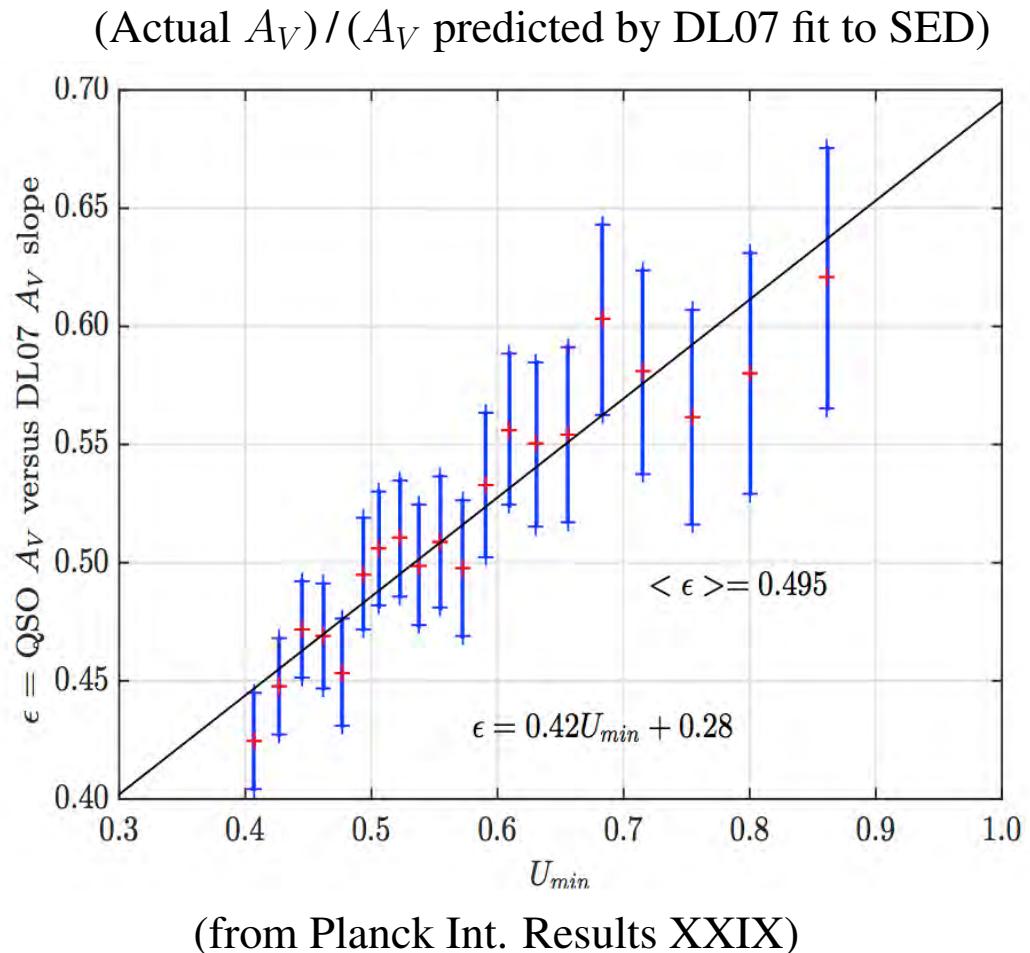
(from Planck Int. Results XXIX)

DL07 Model: Predicted A_V vs. Observation

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

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

Good estimator of actual A_V

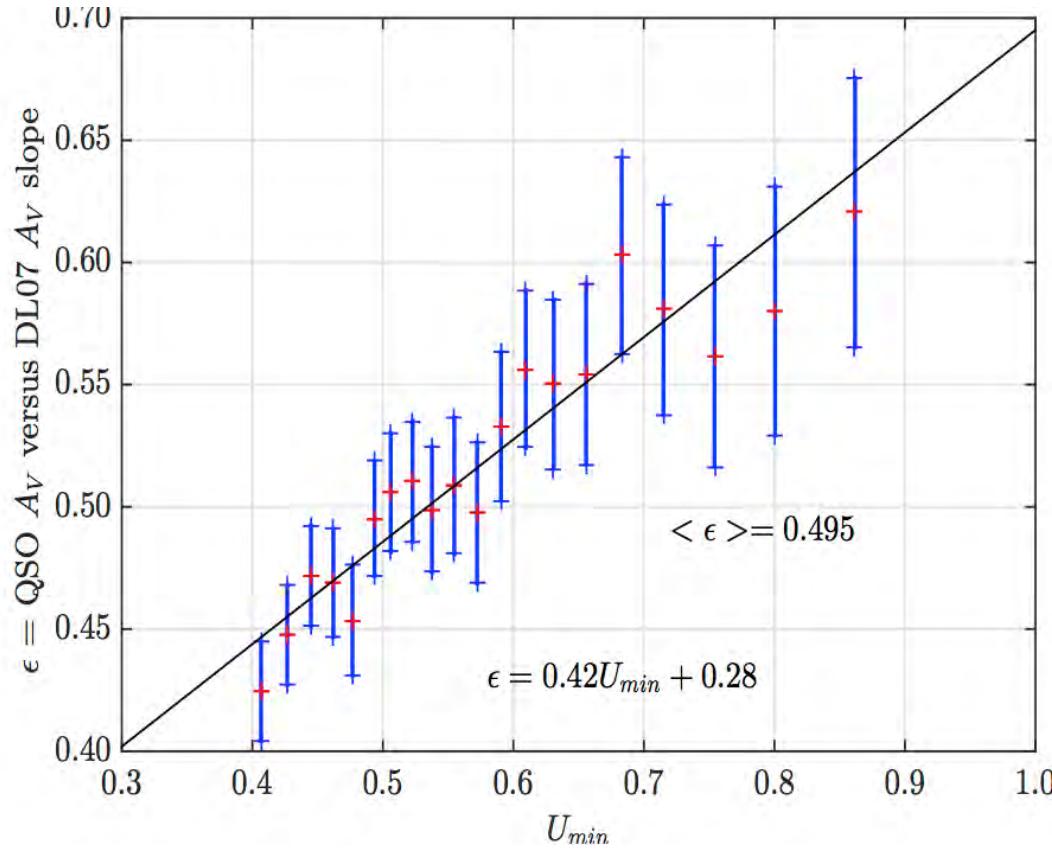


Empirical correction factors vs. fit parameter U_{\min} .

20 U_{\min} bins, each with $\sim 13,500$ QSOs.

For each bin, show weighted mean $A_{V,\text{QSO}} / A_{V,\text{DL07}}$

Overprediction of A_V by the DL07 Model



(from Planck Int. Results XXIX)

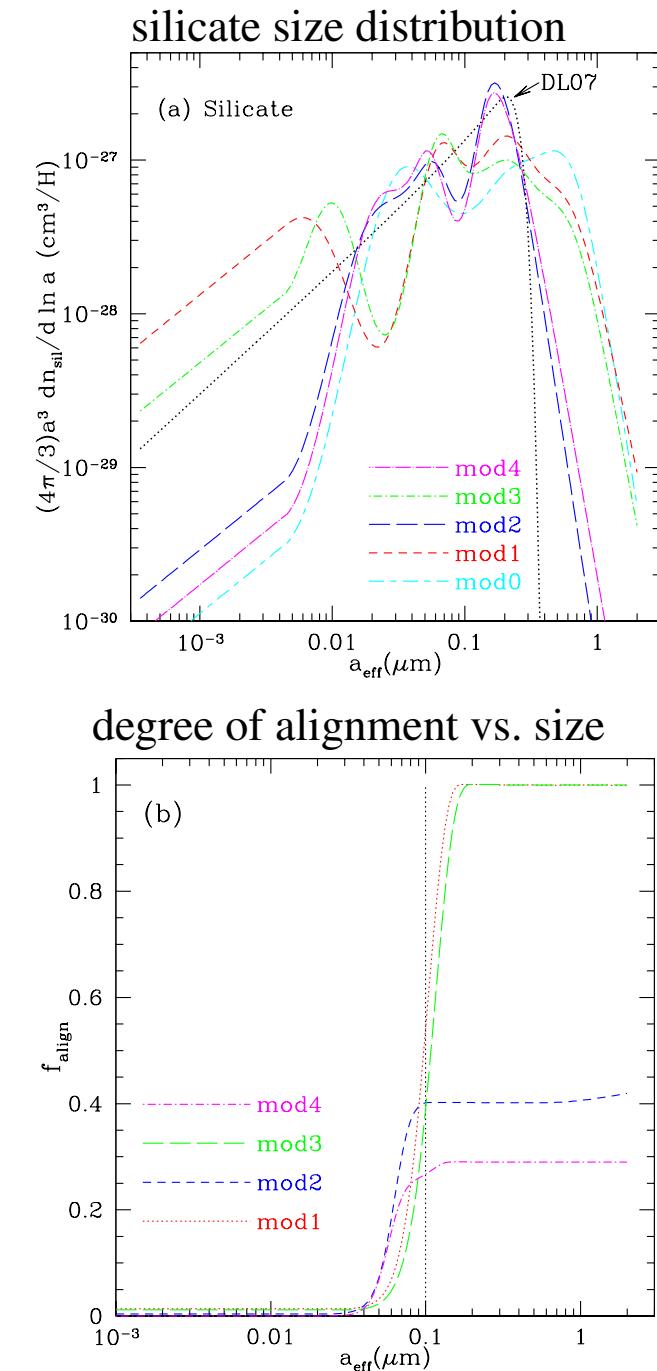
Conclusions:

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

Models for Interstellar Dust

What about Polarization?

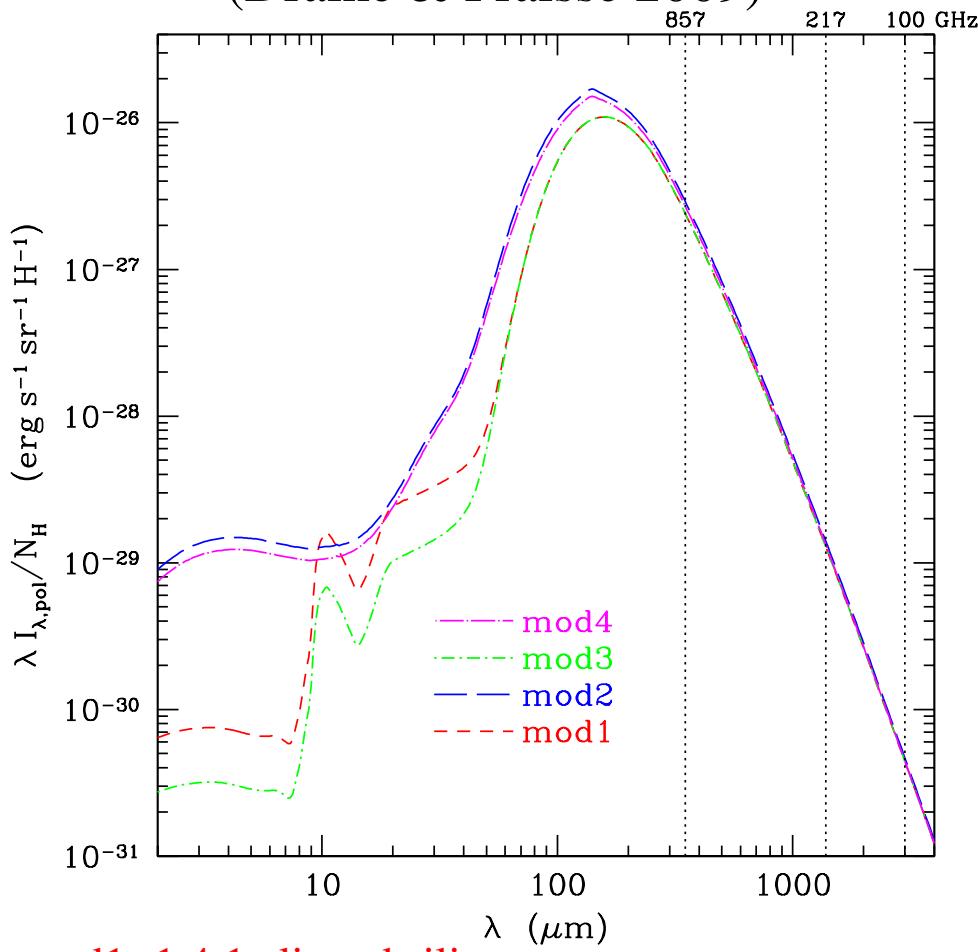
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amorphous silicate grains + graphite + PAHs
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spherical grains: no polarization
- **Draine & Fraisse (2009):** \Rightarrow
DL07 materials
spheroidal grains with alignment $f_{\text{align}}(a)$
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amorph. silicate + amorph. C + PAHs
spherical grains: no polarization
- Jones et al. (2013):
amorph. silicate + Fe nanoparticles + amorph. C + PAHs
spherical grains: no polarization



Models for Interstellar Dust

1.4:1 and 1.6:1 oblate spheroids

Polarized Emission/H
(Draine & Fraisse 2009)



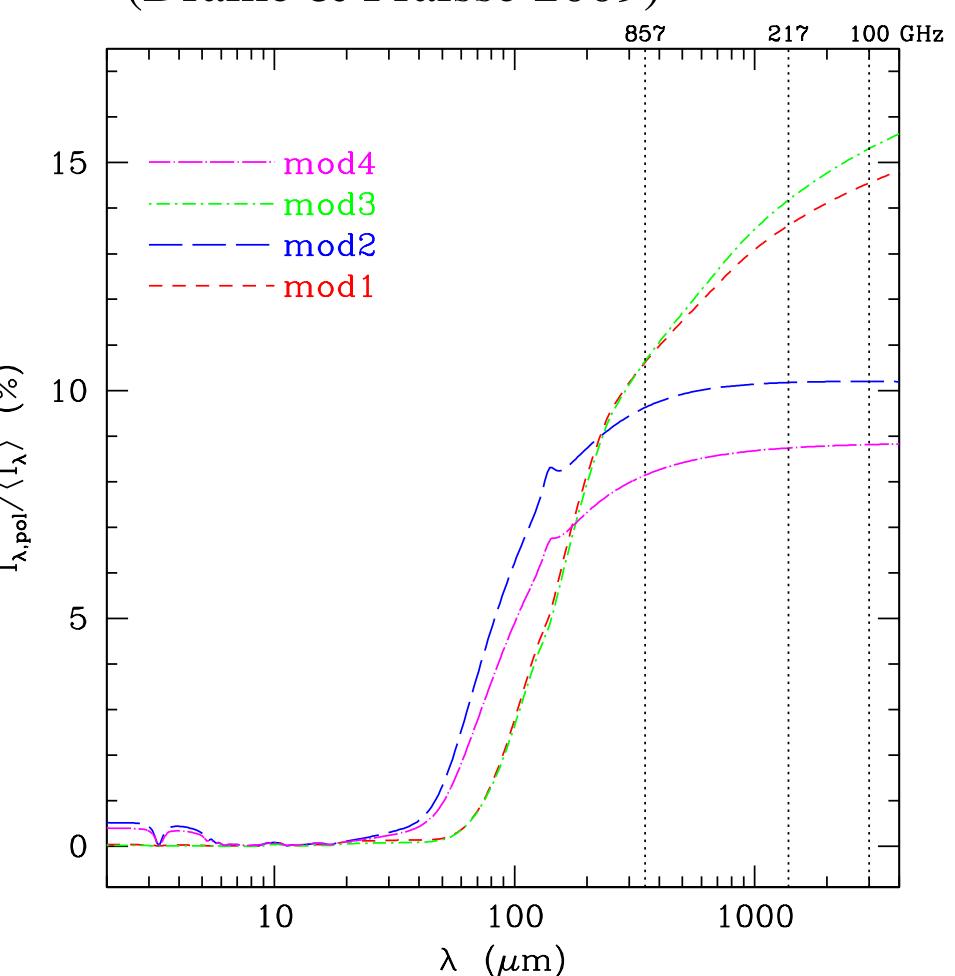
mod1: 1.4:1 aligned silicates

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

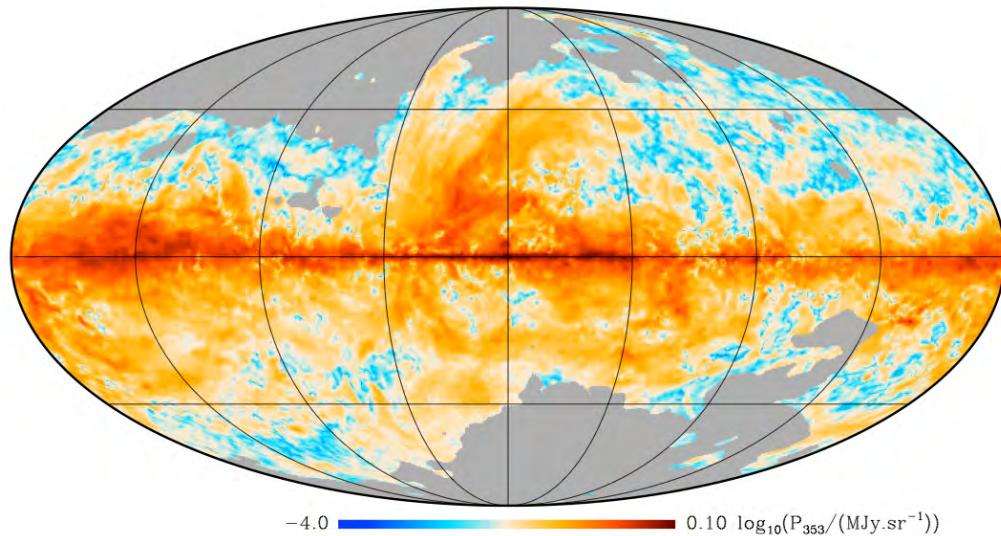
Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust

A&A 576, A106

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

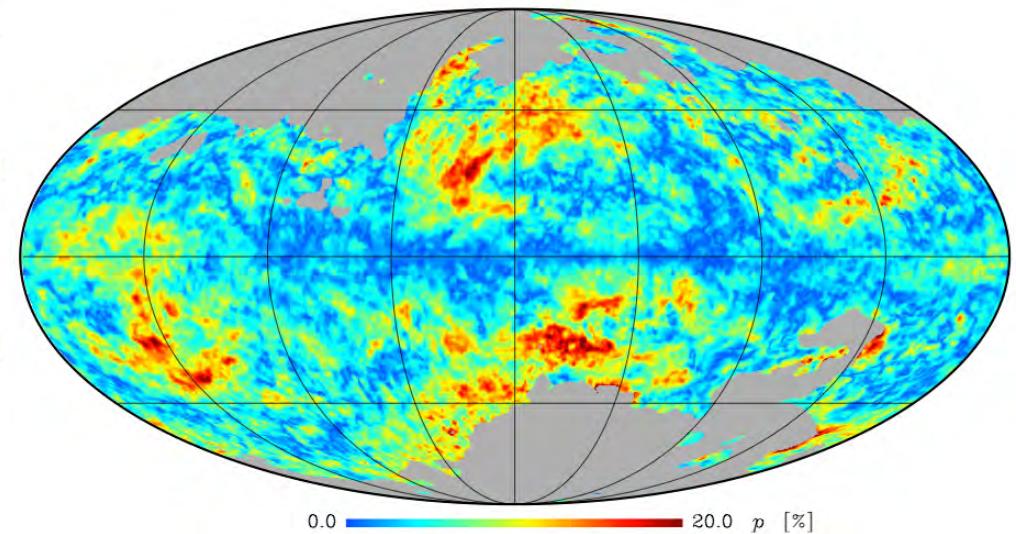
A&A 576, A107

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



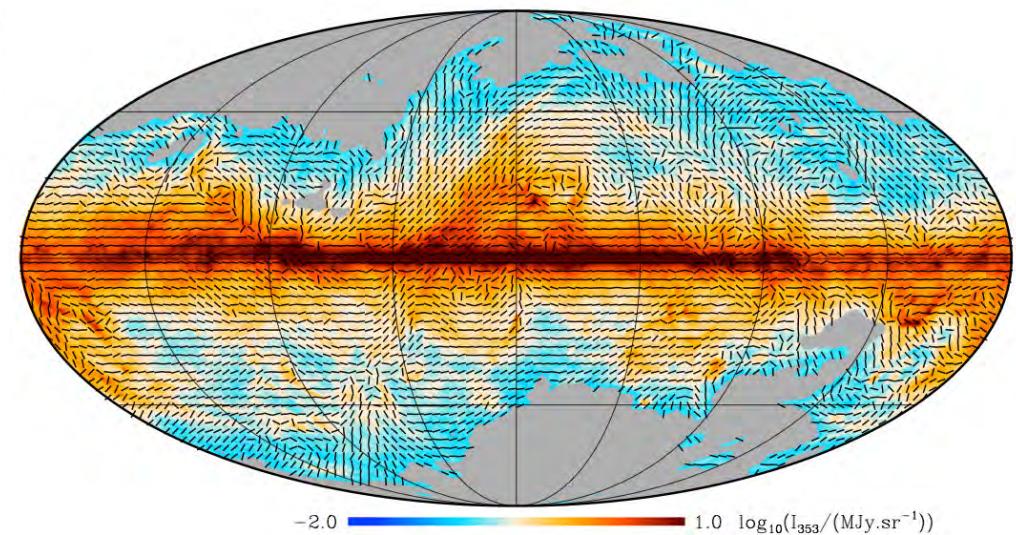
polarized emission @ 353 GHz = $850 \mu\text{m}$

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



polarized fraction @ 353 GHz

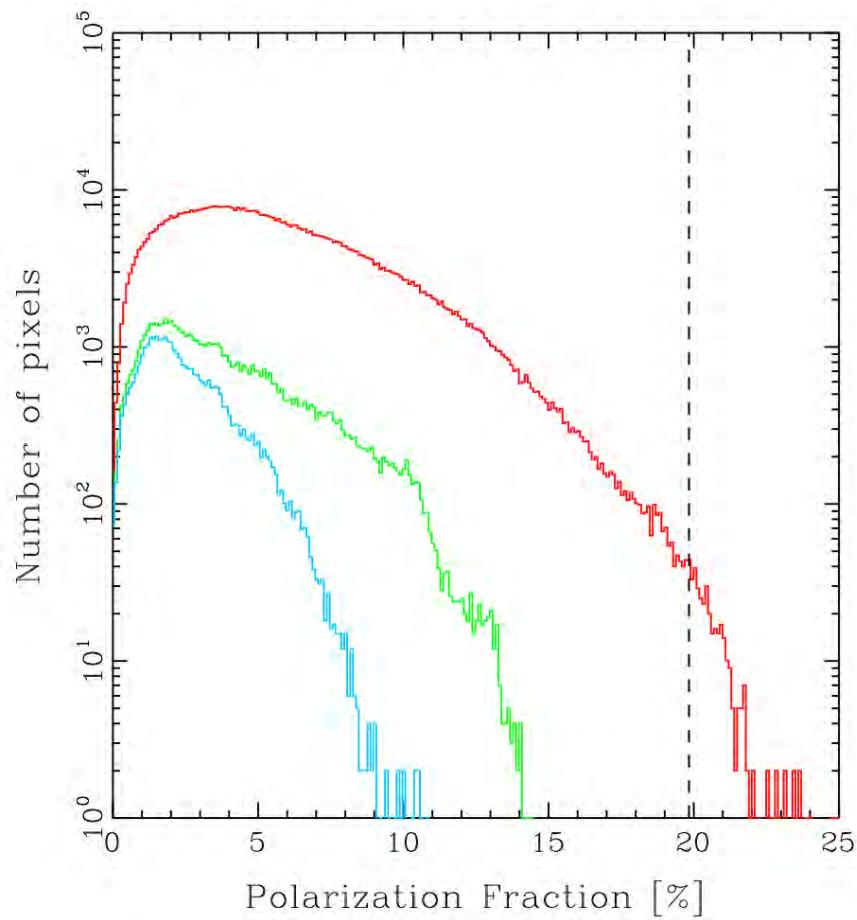
Planck int. results XIX (Planck Collaboration et al. 2015b)



polarization direction @ 353 GHz

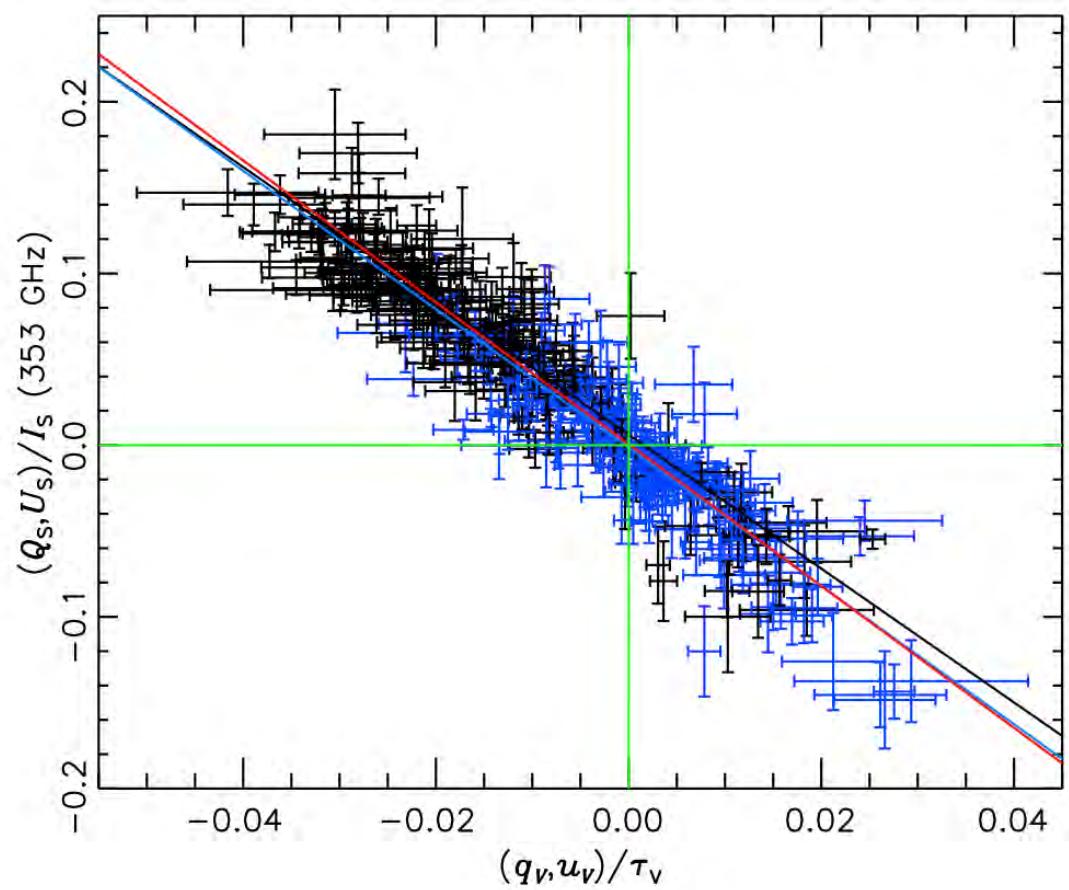
Planck int. results XIX (Planck Collaboration et al. 2015b)

Planck: Polarized Emission from Galactic Dust



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

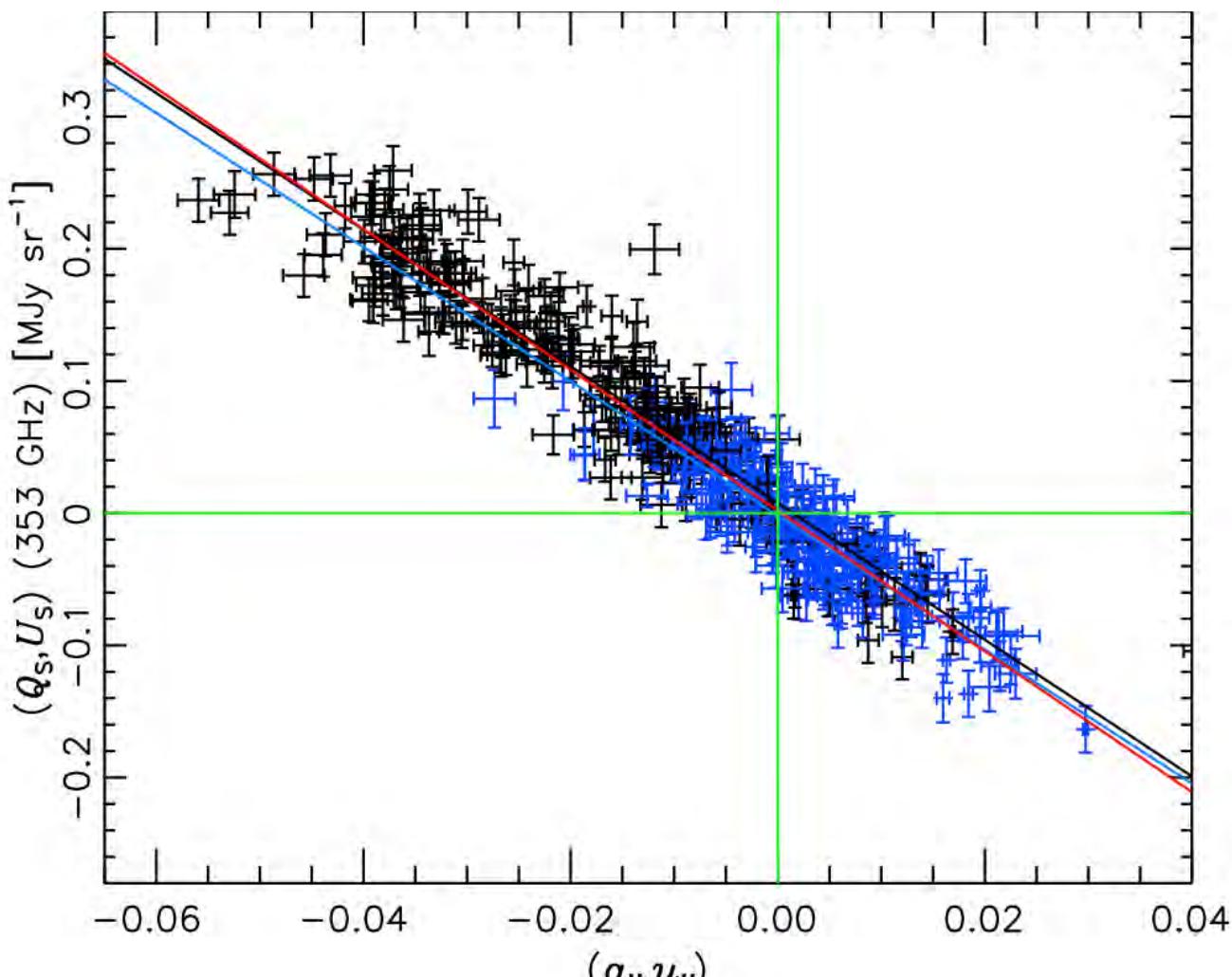
Most of the sky has polarization >5%
polarization >12% is uncommon
but a few points have $p > 20\%$



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

Submm Polarized Intensity vs. p_V



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

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

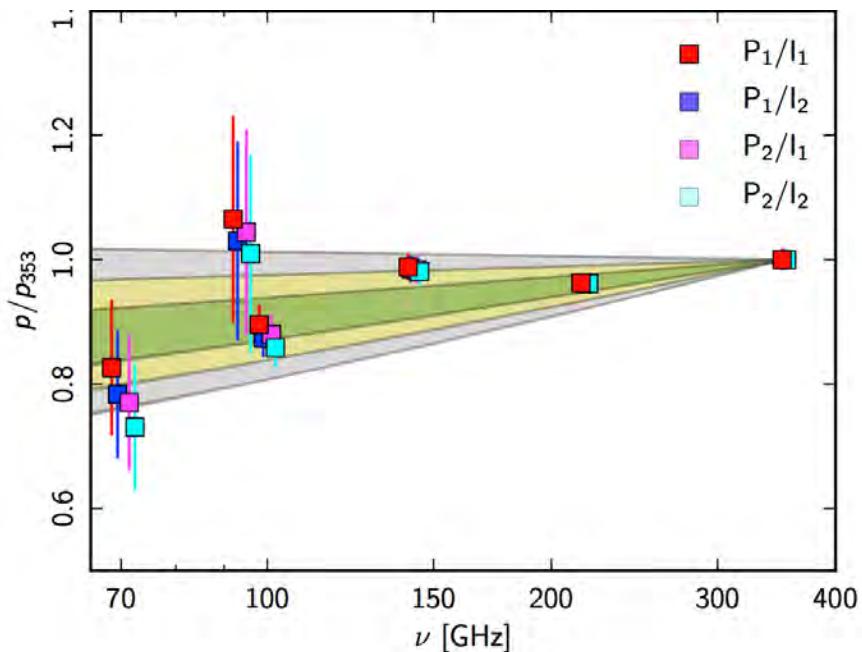
Observed slope: $-5.32 \pm 0.06 \text{ MJy sr}^{-1}$

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

DF09 Model: Polarized intensity low by factor ~ 2.5

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

Planck: Polarization Fraction vs. Frequency

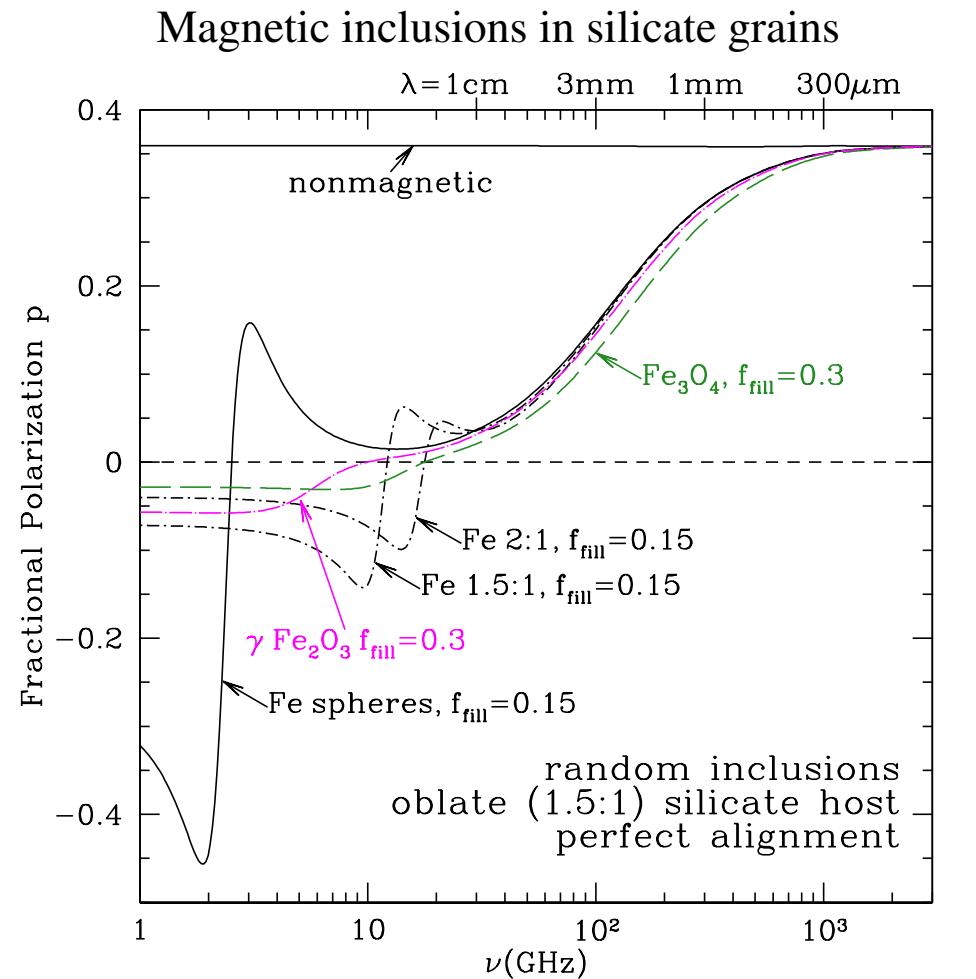


Planck int. results XXII (Planck Collaboration et al. 2015d)

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



Draine & Hensley (2013)

Predictions for 100% of Fe in ferromagnetic (metallic Fe) or ferrimagnetic (Fe_3O_4 or $\gamma\text{-Fe}_2\text{O}_3$) inclusions.

Work in Progress...

New models (with Brandon Hensley)

Hensley & Draine (2015, in prep.)

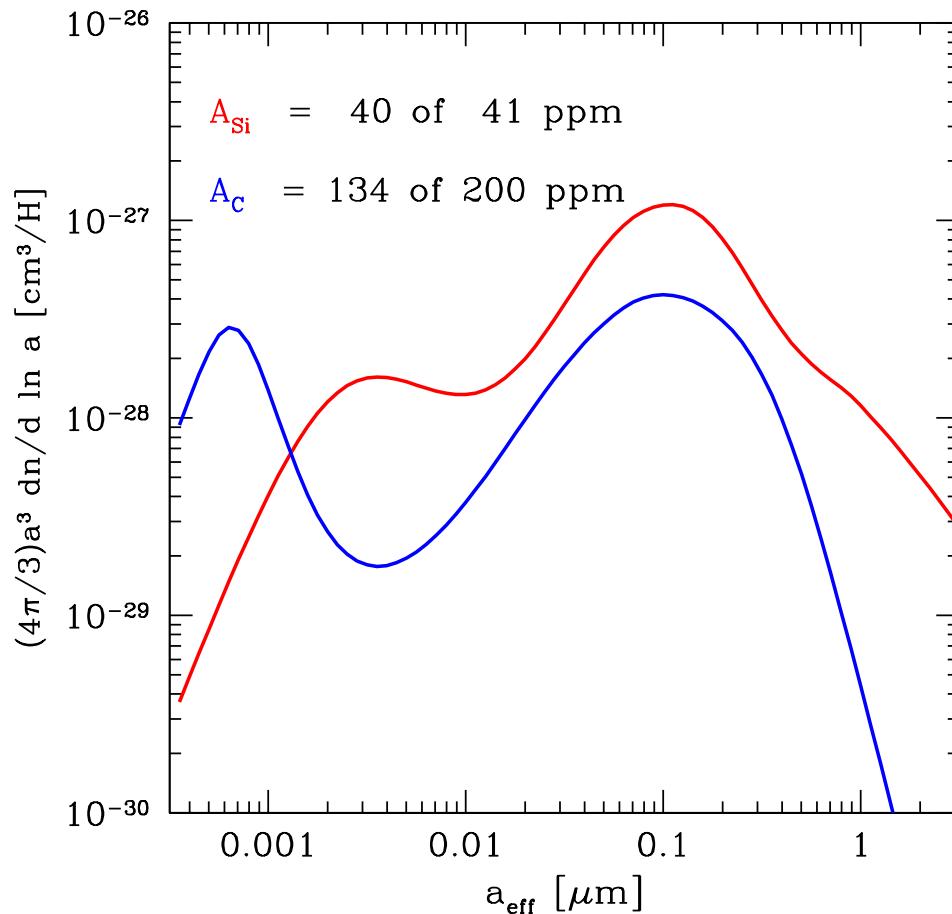


- Increase τ_{FIR}/τ_V to increase emission per unit τ_V
- Obtain “new” astrosilicate dielectric function $\epsilon_{\text{sil}}(\omega)$
 - *improved 10 μm silicate profile*
 - *adjust FIR-submm for consistency with Planck observations*
- Use Kramers-Kronig relations to relate $\text{Re}(\epsilon_{\text{sil}})$ and $\text{Im}(\epsilon_{\text{sil}})$.
- Increased FIR opacity requires simultaneous increase in assumed starlight intensity U_\star to get the right grain temperature.
- New ϵ_{sil} → modest increase in submm polarization p .
- Models include variable amounts of ferromagnetic inclusions

Work in Progress...

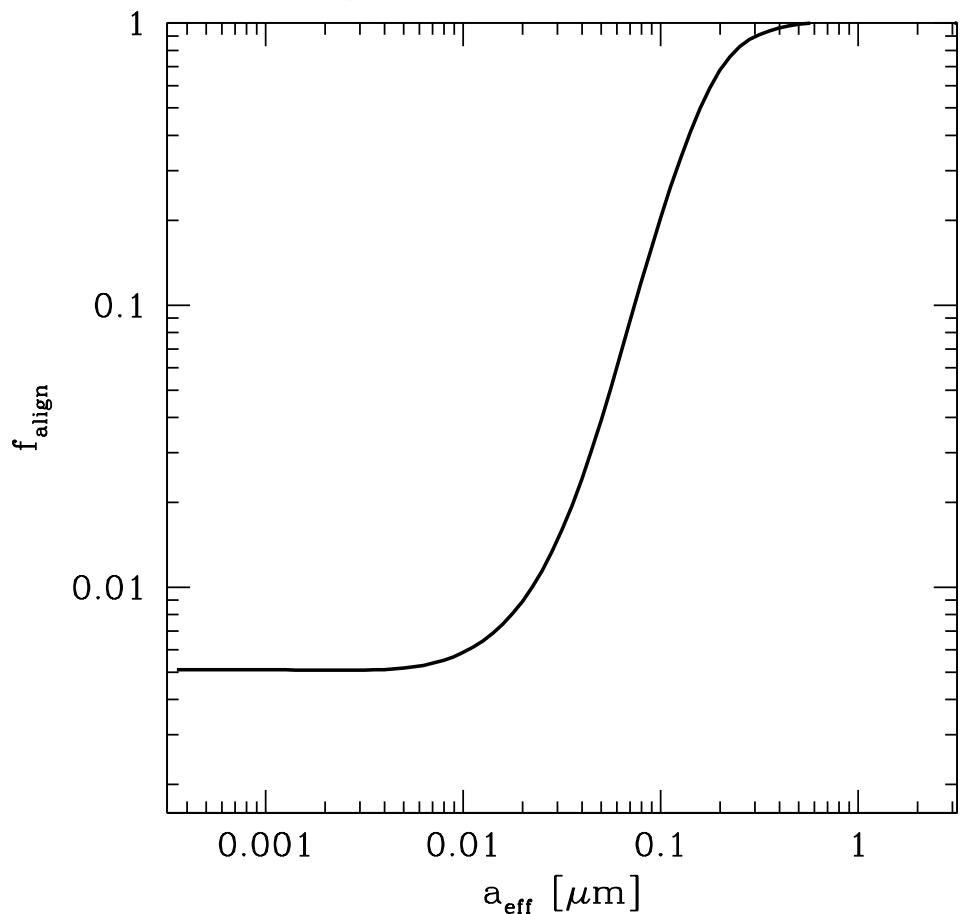
models with 25% of Fe as metallic inclusions in silicate hosts ($f_{\text{fill}} = 0.05$)

size distribution (spheroids)



most of the mass at $a > 0.05 \mu\text{m}$

alignment of silicates



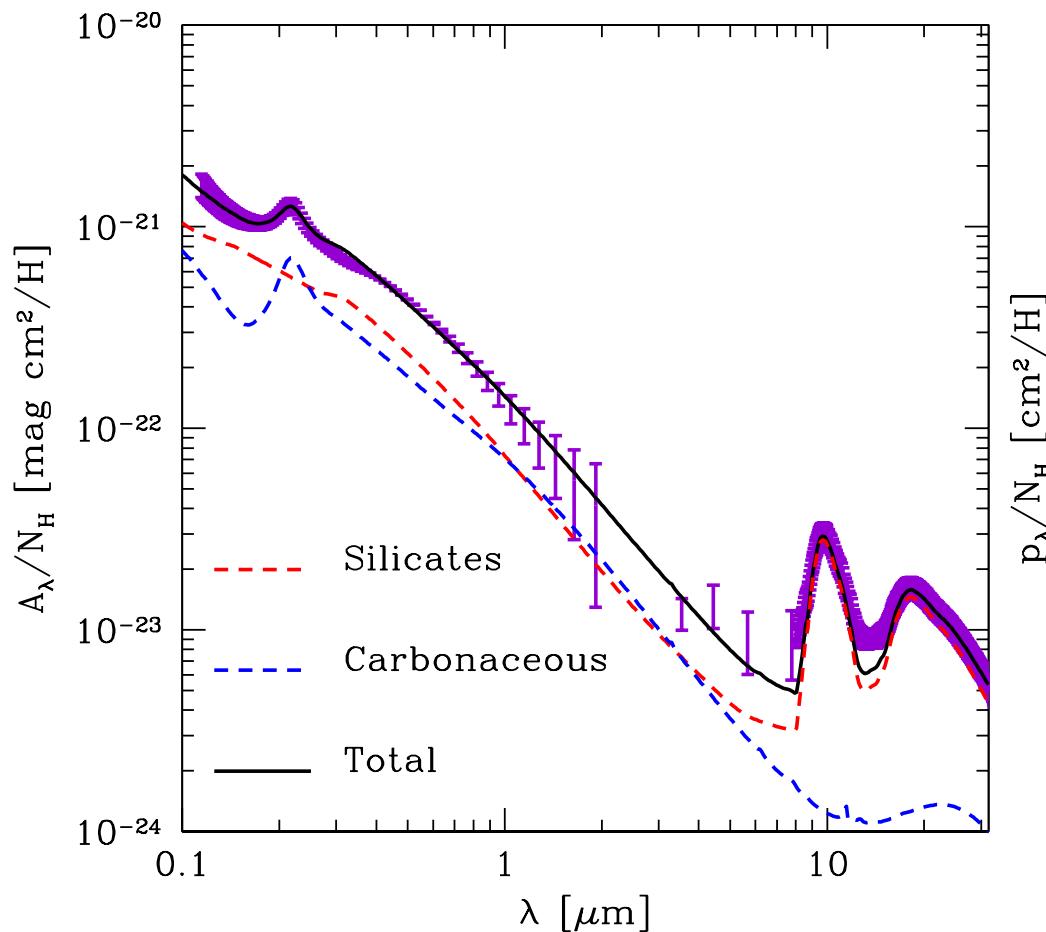
minimal alignment for $a < 0.05 \mu\text{m}$
substantial alignment for $a > 0.1 \mu\text{m}$

Work in Progress...

(Hensley & Draine 2015)

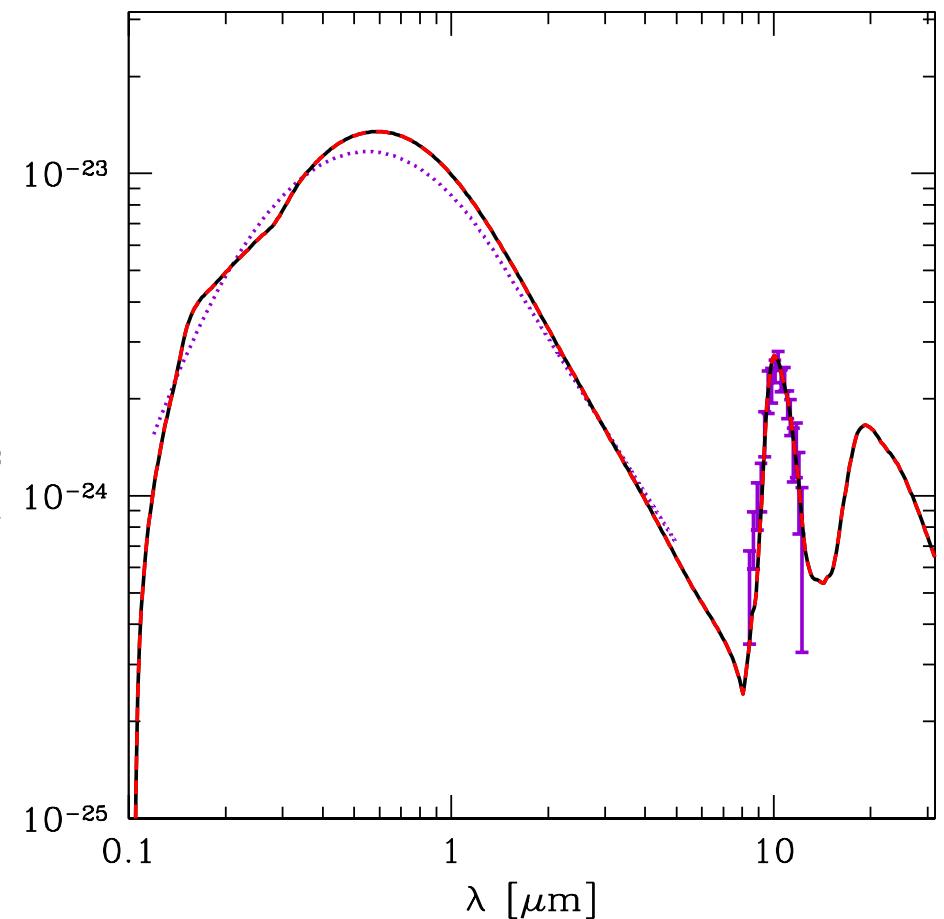
25% of Fe in metallic inclusions in silicates ($f_{\text{fill}} = 0.05$)

extinction



consistent with observations

starlight pol.



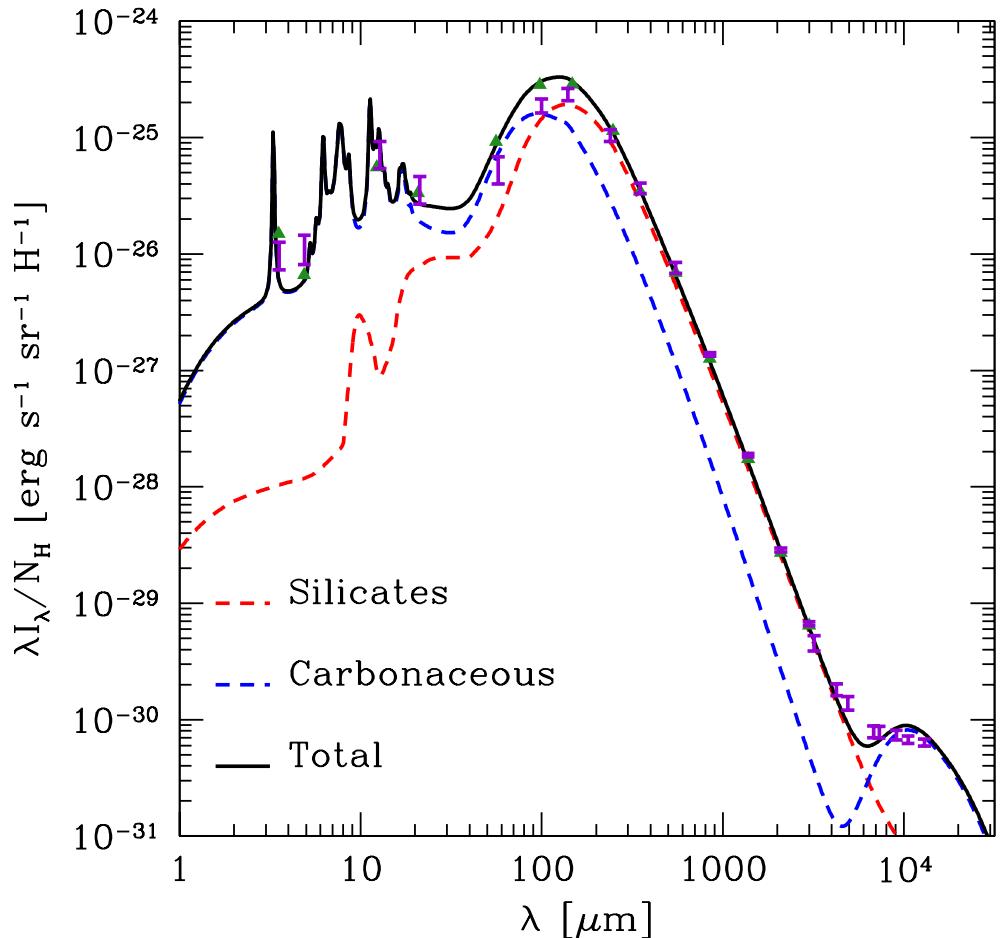
consistent with observations

Work in Progress...

(Hensley & Draine 2015)

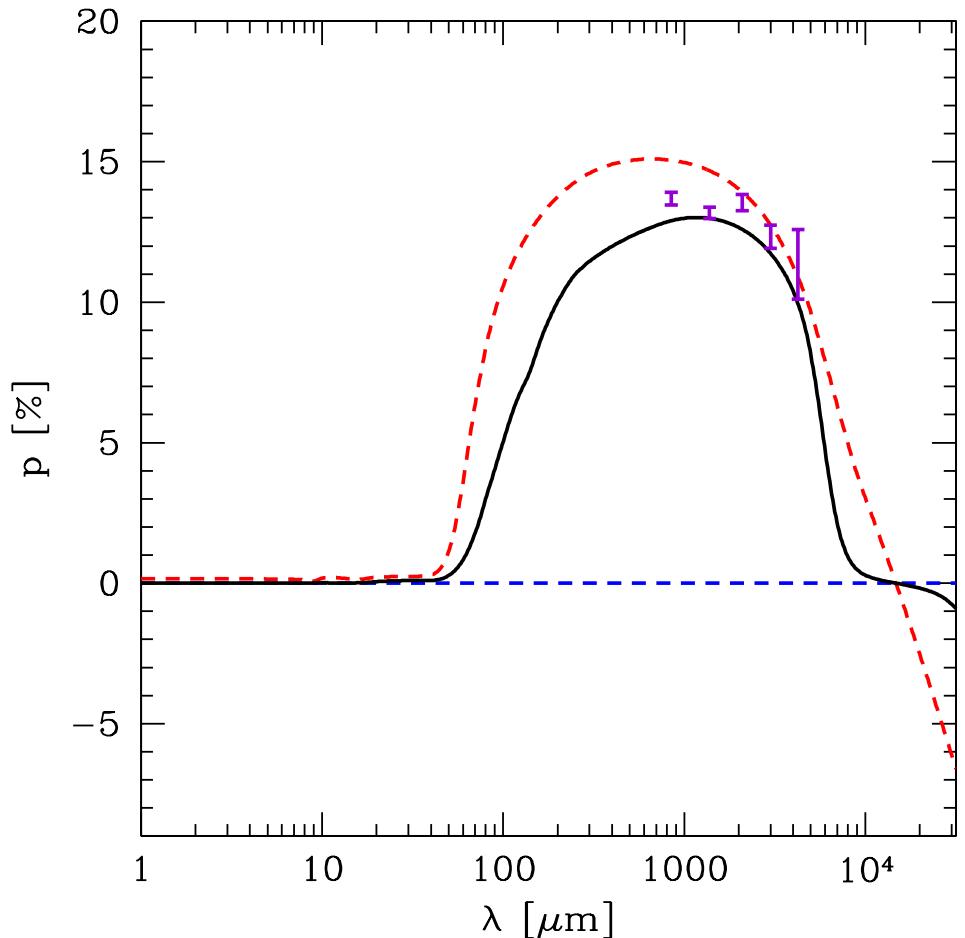
Starlight intensity $U = 1.6$

thermal emission



consistent with observations
somewhat high at 100 μm?

polarization fraction



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

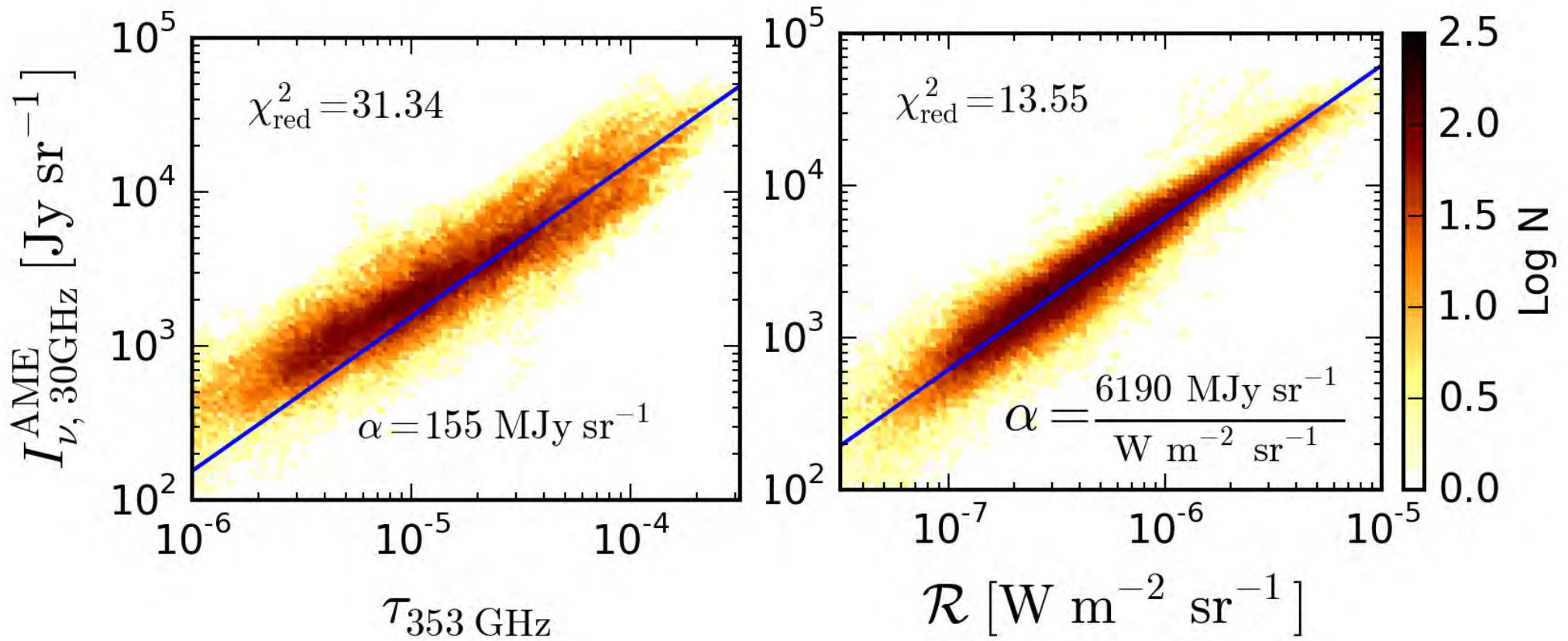
(Hensley, Draine, & Meisner 2015, in prep.)

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

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

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

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



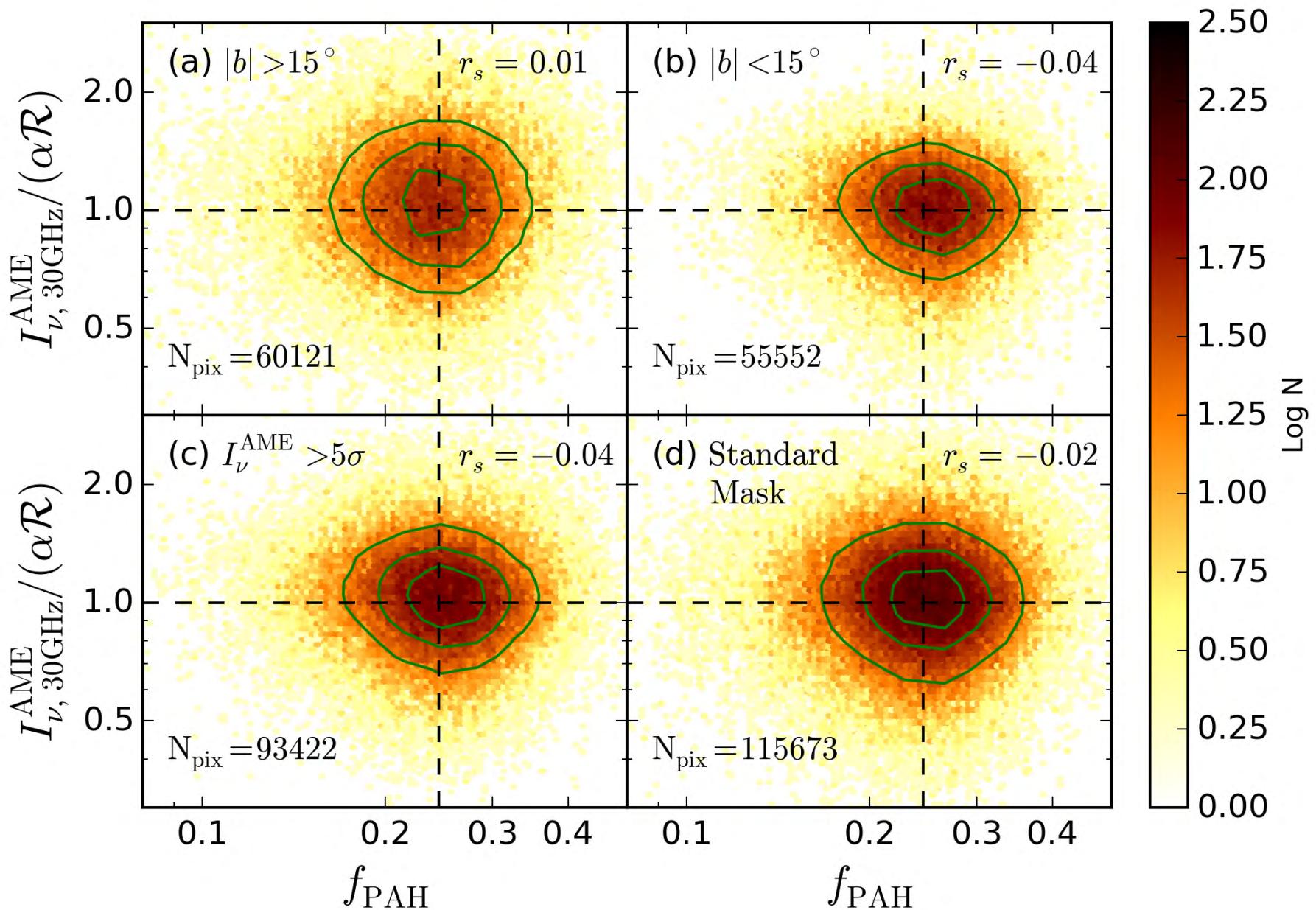
Surprise: Much better correlation with \mathcal{R} than with τ_{353} !

Expectation: spinning PAH rotational emission \propto PAH abundance

Is there a correlation with f_{PAH} ?

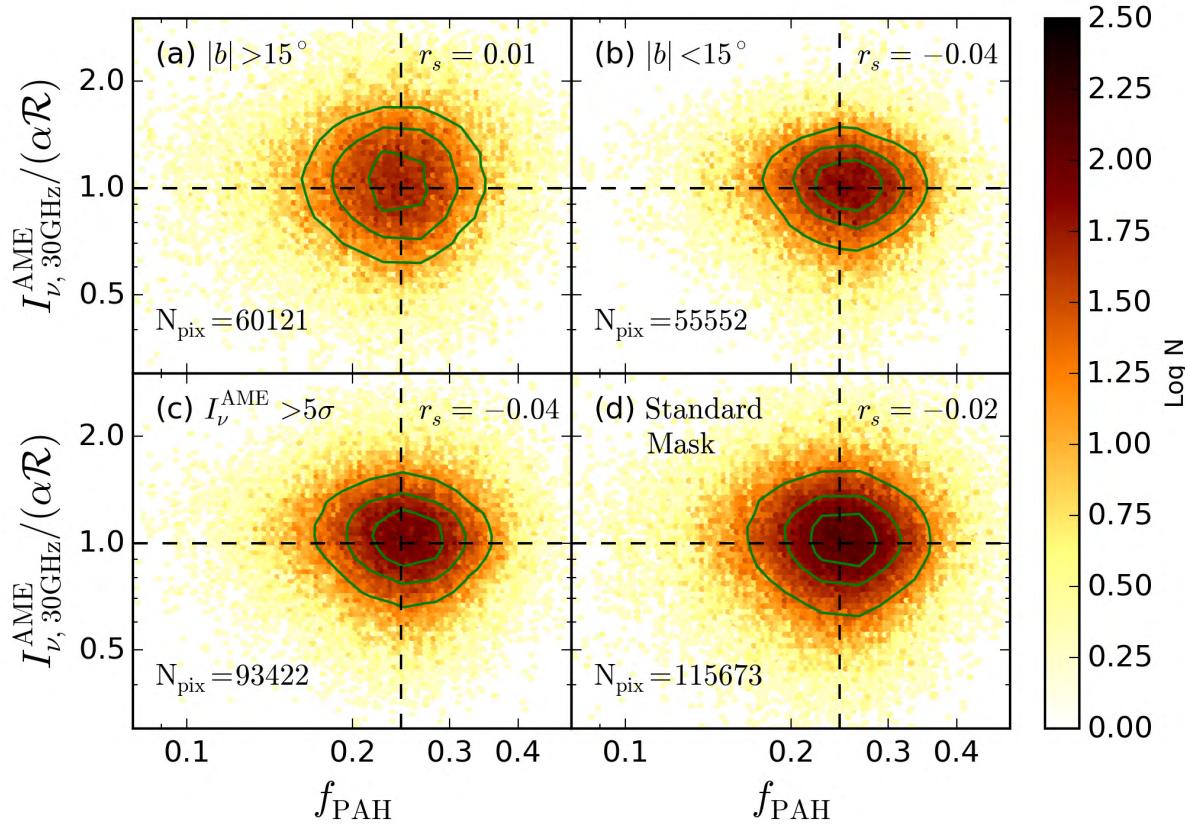
Does AME Come from Spinning PAHs?

(Hensley et al. 2015)



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

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?

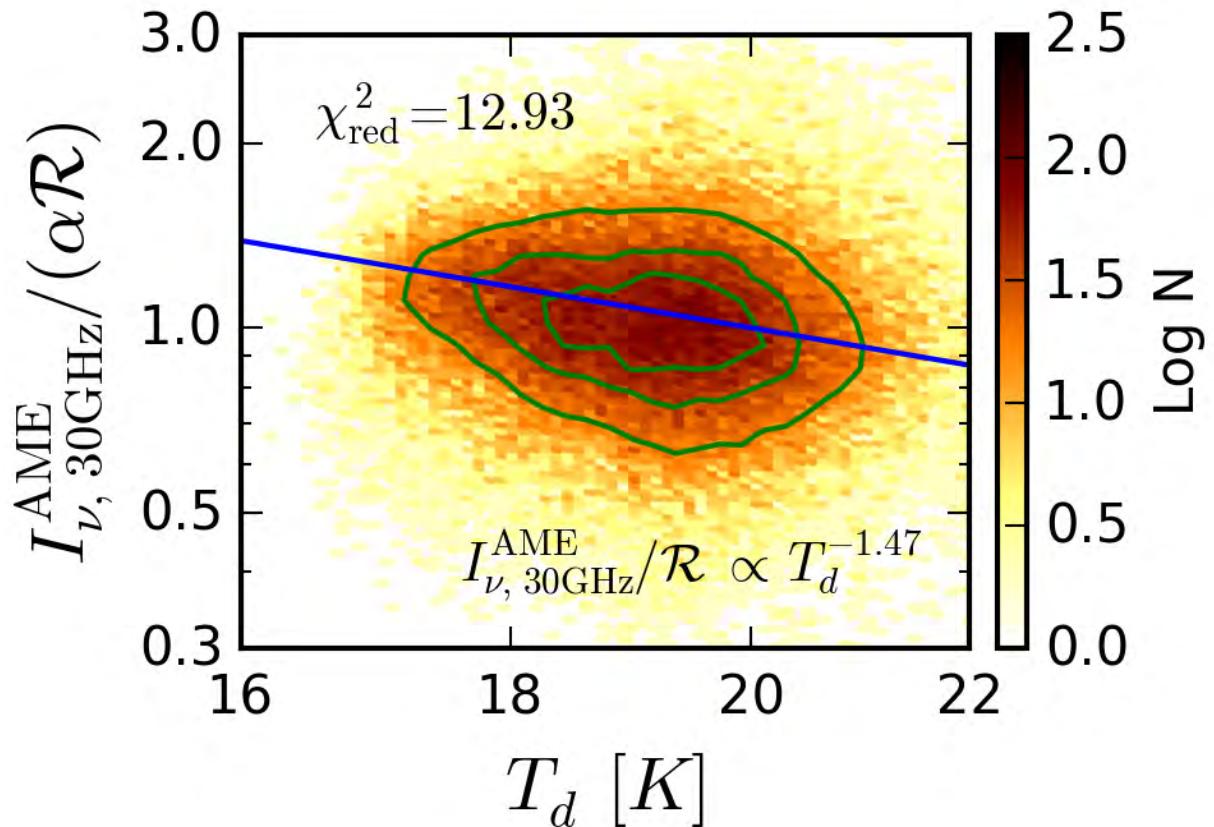
What is Source of AME? Test for Thermal Emission Process

If thermal emission:

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

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

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



(Hensley et al. 2015)

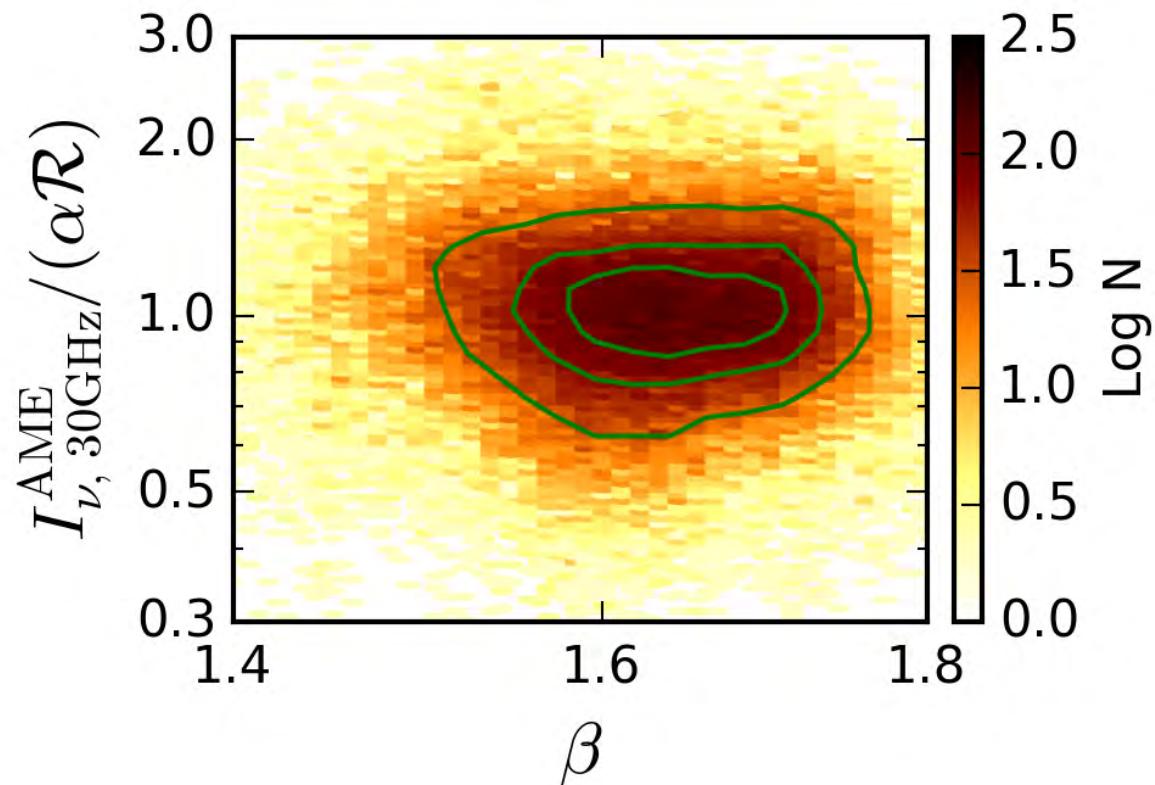
Observed AME is not consistent with thermal emission from dust unless dust opacity at 30 GHz is very sensitive to T_d , as in $\tau_{30}/\tau_{353} \propto T_d^{3.2}$

Does AME Correlate with β ?

- Suppose $\kappa_\nu \propto \nu^\beta$
- Best-fit β varies.
- Might expect dust opacity at $\sim 30\text{ GHz}$ to vary when β varies (higher $\beta \rightarrow$ lower $\tau_{30\text{ GHz}}$).
- 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 $\tau_{\text{FIR}}/\tau_{\text{optical}}$ too low by factor ~ 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 $\epsilon_{\text{sil}}(\omega)$, and Fe inclusions is able to reproduce:
 - Extinction and polarization of starlight
 - IR-microwave emission: total and polarized
- Apparent decrease of polarization fraction at $\nu \lesssim 120$ 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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- . 2015c, *Astr. Ap.*, 576, A106
- . 2015d, *Astr. Ap.*, 576, A107