Interstellar Dust: New Views after Spitzer, Herschel, and Planck

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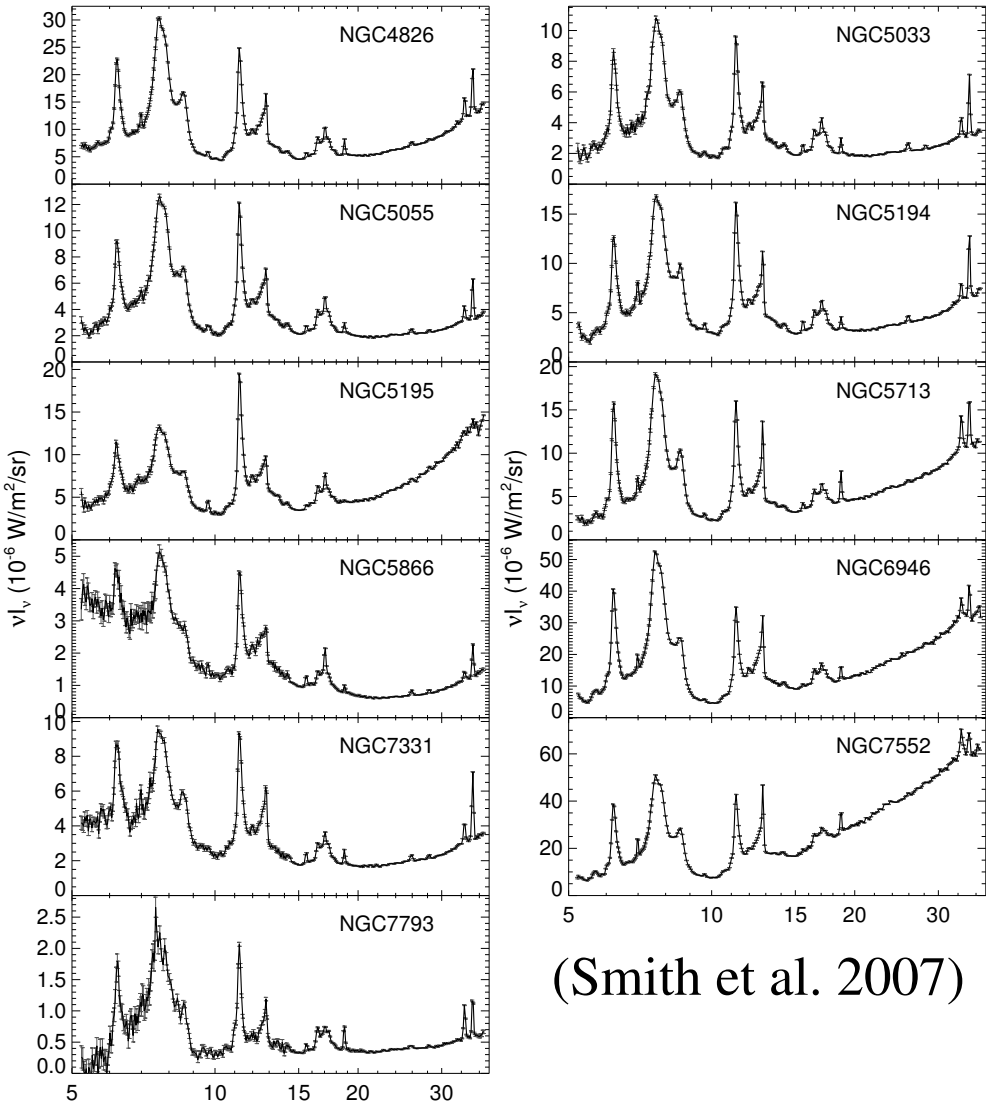
- **Composition**
  - PAHs
  - Silicates
  - Where's the Iron?
  - Where's the Oxygen?
- **SED of Galactic Dust, from 5 μm to microwave**
  - Testing the DL07 dust model
- **Polarized Extinction and Emission from Galactic Dust**
  - Planck observations
  - New dust model
- **Anomalous Microwave Emission vs. PAHs**

Composition of Interstellar Dust: PAHs are Ubiquitous

Central few kpc of star-forming galaxies

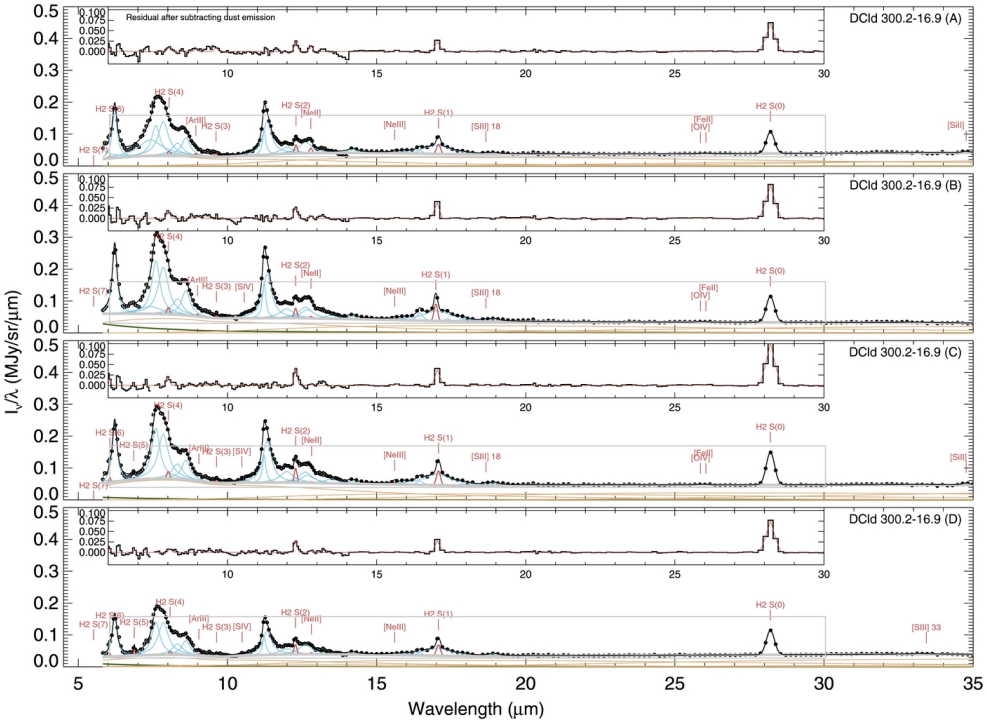
(11 SINGS galaxies)



(Smith et al. 2007)

local high latitude translucent cloud

(4 pointings near $\ell = 300°, b = -17°$)



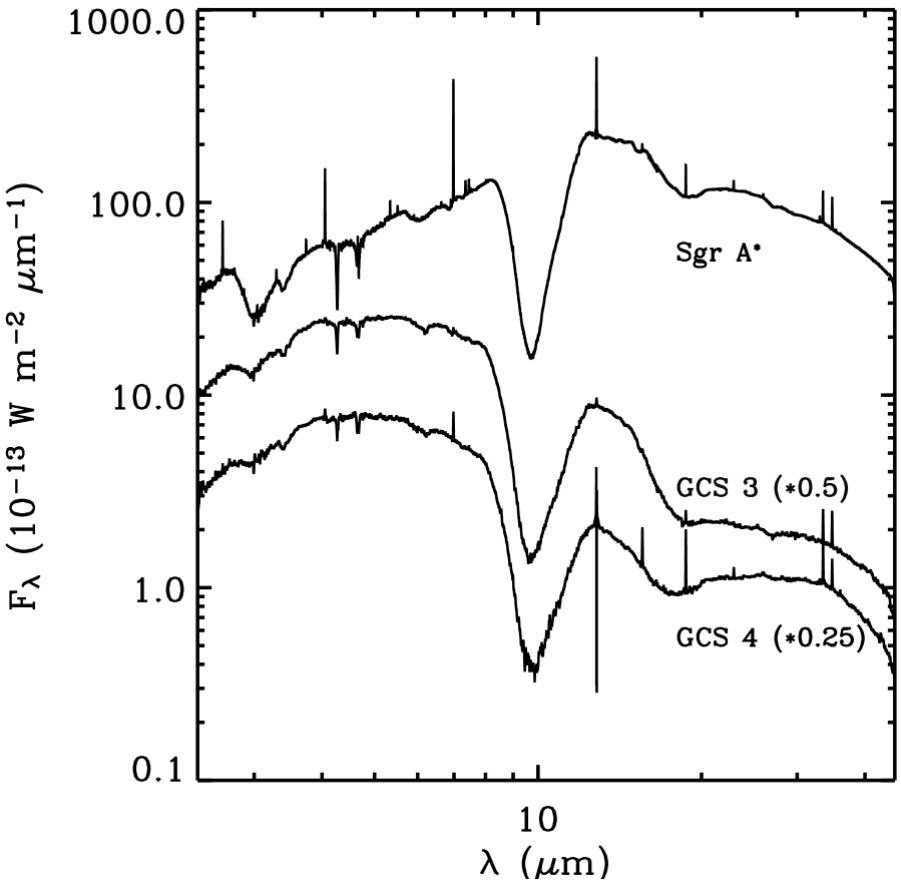
(Ingalls et al. 2011)

$$\nu I_\nu = 0.9 \times 10^{-6}\,\mathrm{Wm^{-2}\,sr^{-1}} \quad \leftrightarrow \quad I_\nu/\lambda = 0.3\,\mathrm{MJy\,sr^{-1}\,\mu m^{-1}}$$

Composition of Interstellar Dust: Silicates

Silicate Resonances near 10 μm (Si-O stretching mode) and 18 μm (O-Si-O bending mode).

- crystalline silicates: 10 μm feature has sharp substructure characteristic of different crystal types (olivine, pyroxene).
- ISO Spectra of IR Sources near Galactic Center: broad 10 μm feature, **No discernible fine structure:**
  $\Rightarrow$ upper limit on fraction of silicate that can be crystalline:
  $< 5\%$ (Li & Draine 2001b)
  $< 2\%$ (Kemper et al. 2005)
  < 3-5% (Li et al. 2007)

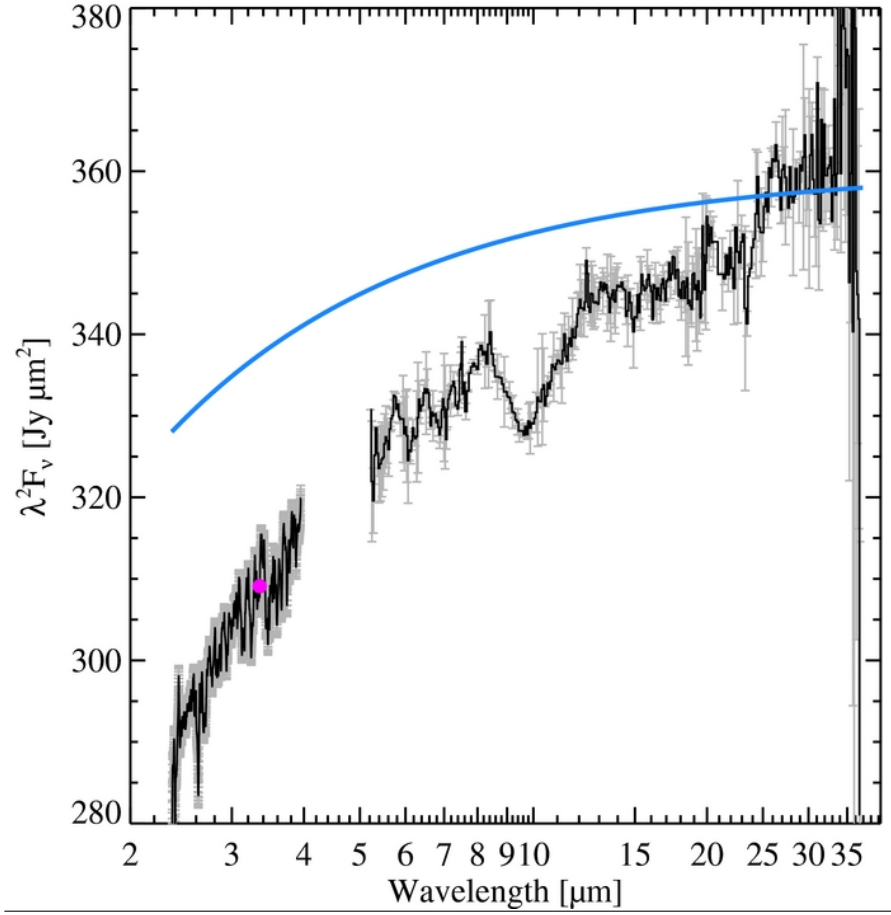


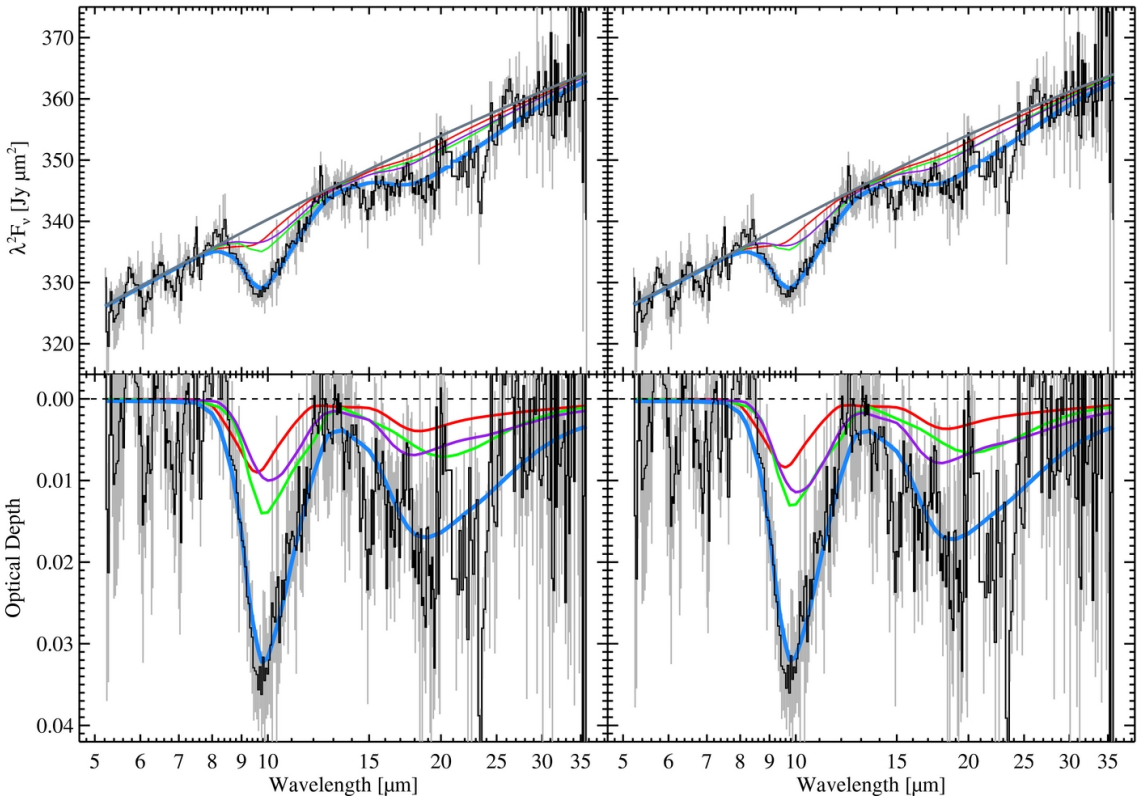
(Kemper et al. 2005)

ISM Silicates are predominantly amorphous

Dust on Sightline to ζ Oph (Poteet et al. 2015)

- best-studied sightline in ISM: detailed knowledge of atomic and molecular abundances in gas
- $E(B-V) \approx 0.32$, $A_V \approx 0.82$ (Valencic et al. 2004)
- ISO-SWS and Spitzer-IRS: measure extinction to star in IR





Silicate features: fit by **sum** of

amorphous Mg_2SiO_4 ($\tau = 0.013 \pm 0.007$)

amorphous $MgFeSiO_4$ ($\tau = 0.011 \pm 0.007$)

amorphous $MgSiO_3$ ($\tau = 0.008 \pm 0.004$)

$$\tau_{\rm sil} = 0.031 \pm 0.011$$

- Attempt elemental inventory for O, Mg, Si, Fe in both gas and dust.

Elemental Inventory toward ζ Oph

Assumed total interstellar abundances:
Protosolar + Galactic Chemical Evolution (Asplund et al. 2009; Chiappini et al. 2003)

Abundances (ppm wrt. H) toward ζ Oph

	O	Mg	Si	Fe
total	589 ± 68	47.9 ± 4.4	42.7 ± 4.0	47.9 ± 4.4
gas phase	307 ± 30	1.9 ± 0.1	1.6 ± 0.1	0.18 ± 0.01
silicates	126 ± 45	$49. \pm 19$	$33. \pm 11$	$10. \pm 7$
Unidentified	$\mathbf{156 \pm 87}$	-3 ± 20	8 ± 12	$\mathbf{38 \pm 8}$

- **observations consistent with solid-phase Mg and Si being entirely in silicates.**
- $\sim$20% of Fe is in silicates, but
  $\sim$80% of Fe (38ppm) is unaccounted for. Possibilities:
  - FeO (wustite): upper limit on 22 μm feature: < 23ppm
  - Fe_3O_4 (magnetite): upper limit on 16 μm feature; < 14ppm
  - γ-Fe_2O_3 (maghemite): broad resonances near 17 and 27 μm, hard to identify
  - α-Fe_2O_3 (hematite): broad resonances near 19 and 27 μm, hard to identify
  - Fe metal could be present (featureless in IR)

Bottom line: most Fe appears to be in Fe oxides and/or metallic Fe

Where is the Missing Oxygen?

Abundances (ppm wrt. H) toward ζ Oph

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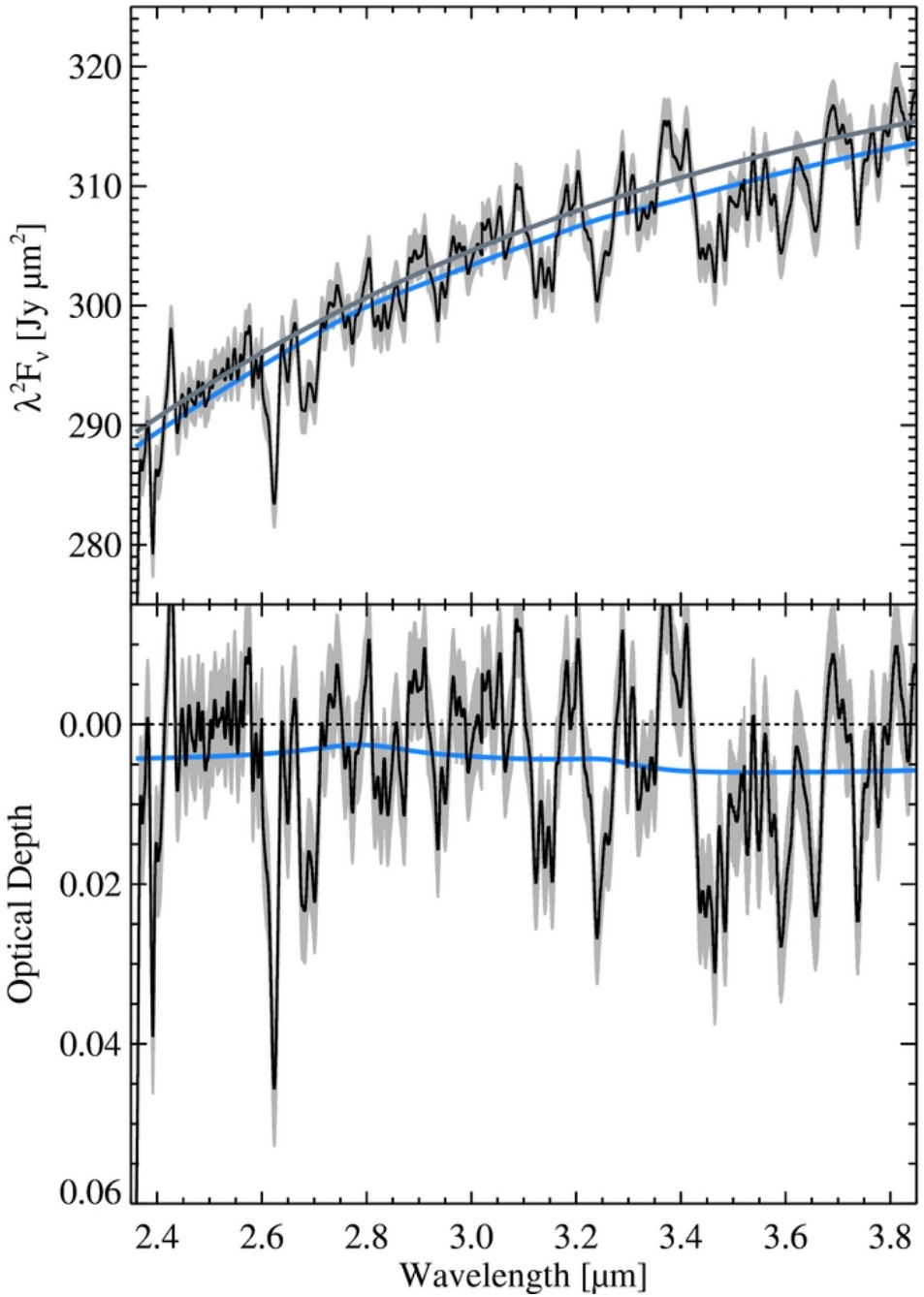
ζ Oph is one example of trend found by Jenkins (2009): surprising depletion of O in high-depletion regions

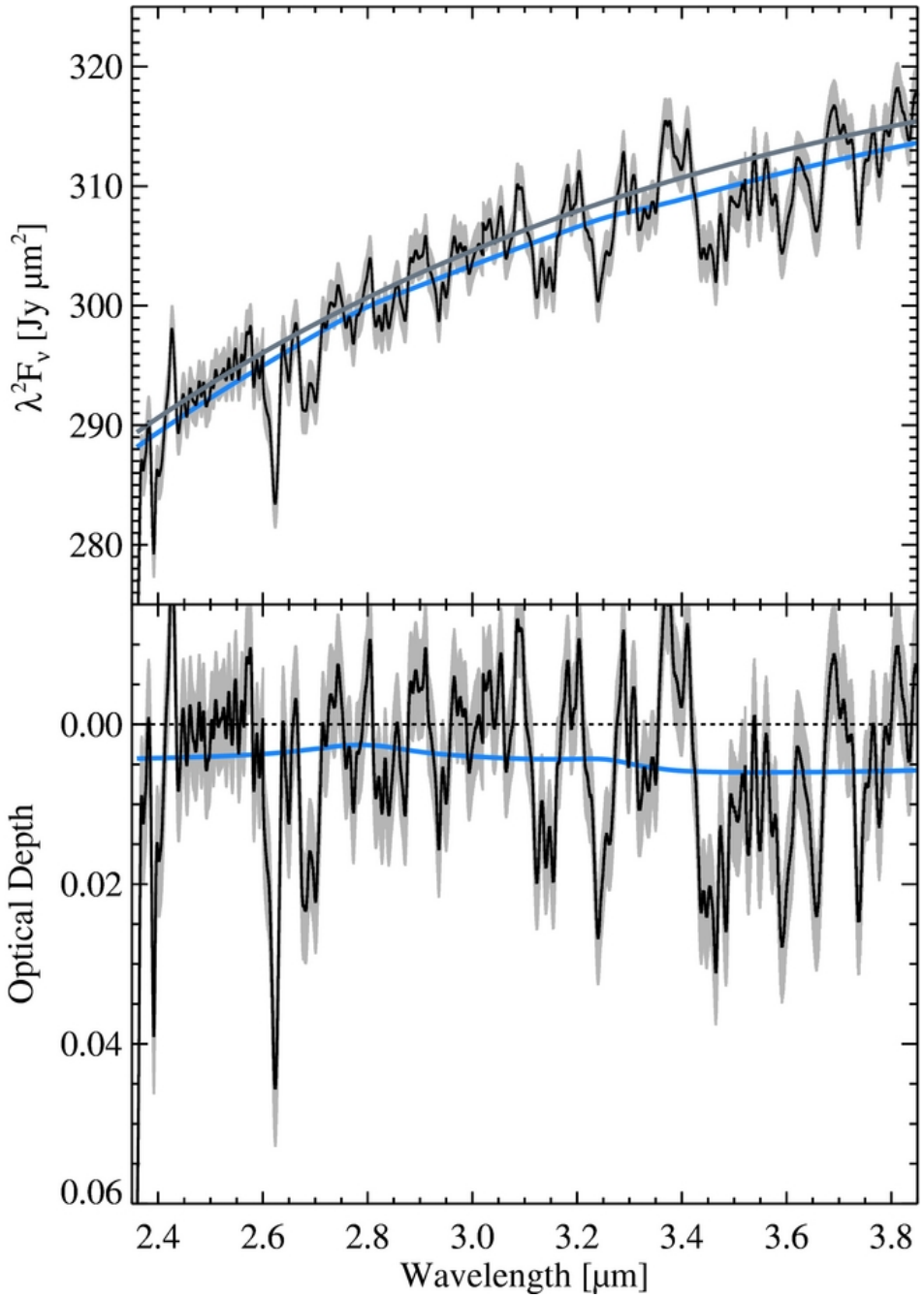
even when no evidence of H_2O absorption feature at 3.1μm

< 9 ppm O in submicron H_2O grains

Bottom line: Could have ~40ppm O in Fe oxides, but that still leaves ~110 ppm unaccounted for!



Where is the Missing Oxygen?



Only possibilities (Poteet et al. 2015):

- organic compounds, e.g., polyoxymethylene ((-CH_2O-)$_n$)? No: < 7 ppm O in POM toward ζ Oph (absence of 8.95 μm C-O-C vibrational mode)
- H_2O in very large $a \gtrsim 3\,\mu$m grains?
- O_2 ice? Should not survive in diffuse ISM UV.

None of these seems plausible...

The Missing O:
A Crisis in our understanding of interstellar dust?

Some Models for Interstellar Dust

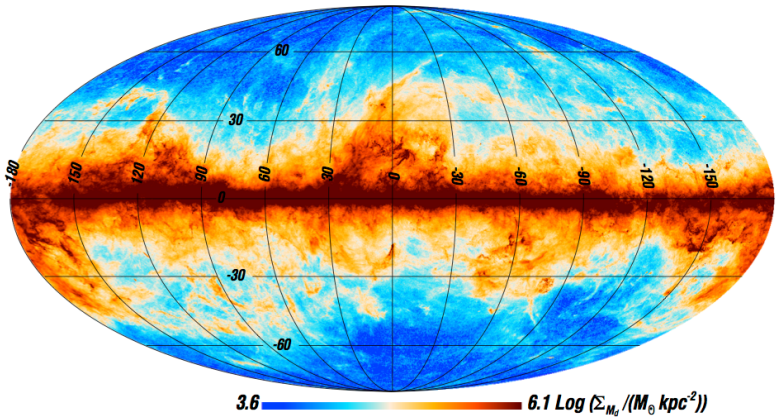
- Li & Draine (2001a): pre-Spitzer model
  amorphous silicate grains + carbonaceous grains (incl. PAHs)
  spherical grains (no polarization)
- Draine & Li (2007):
  PAHs adjusted to match early Spitzer results
  spherical grains (no polarization)
- Draine & Fraisse (2009):
  DL07 materials
  spheroidal 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 np + 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

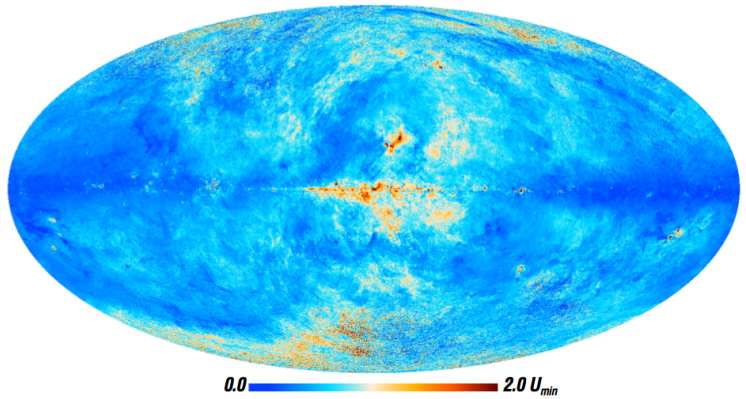
Planck Intermediate Results XXIX.
arXiv:1409.2495
corresponding authors: G. Aniano, F. Boulanger

- **All-sky diffuse Galactic emission:**
  - 6 Planck bands (100 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**

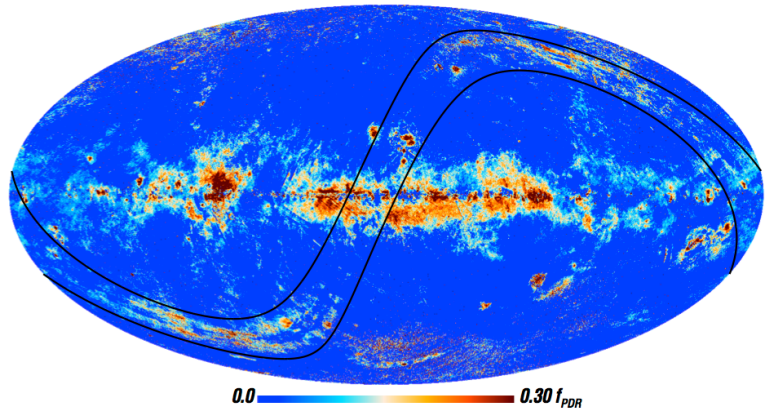
$\Sigma_{\rm dust}$



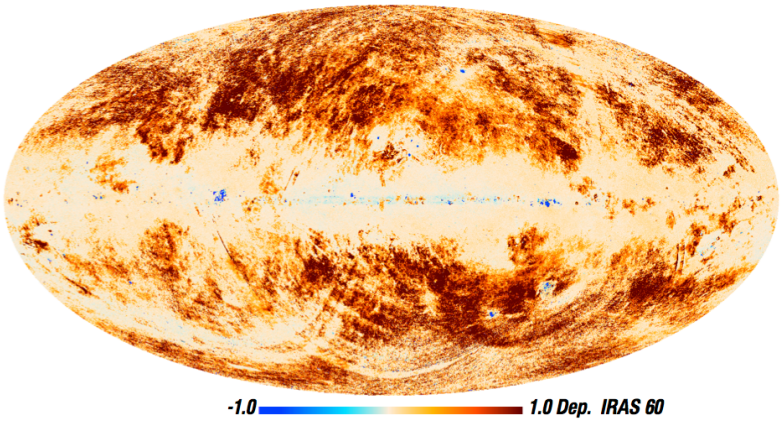
$U_{\rm min}$

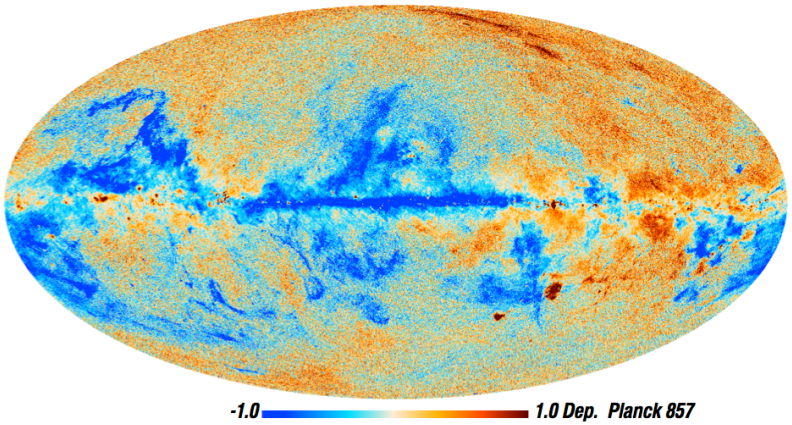


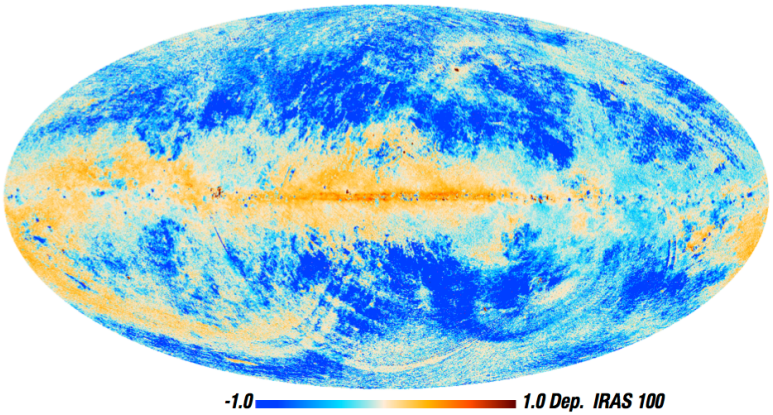
$f_{\rm PDR}$

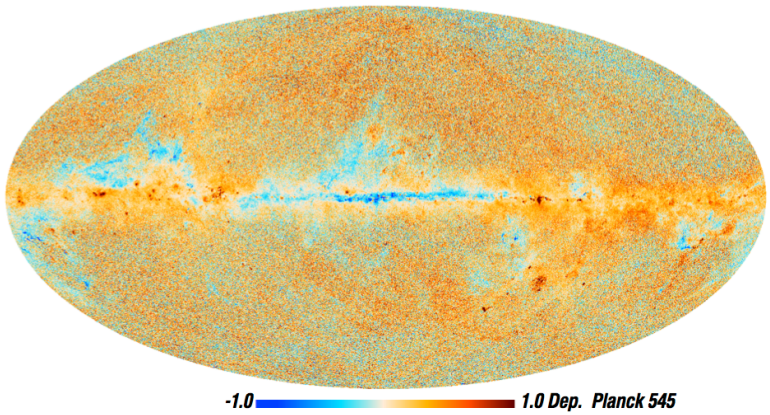


DL07 Model fit vs. Observation (5 arcmin PSF)



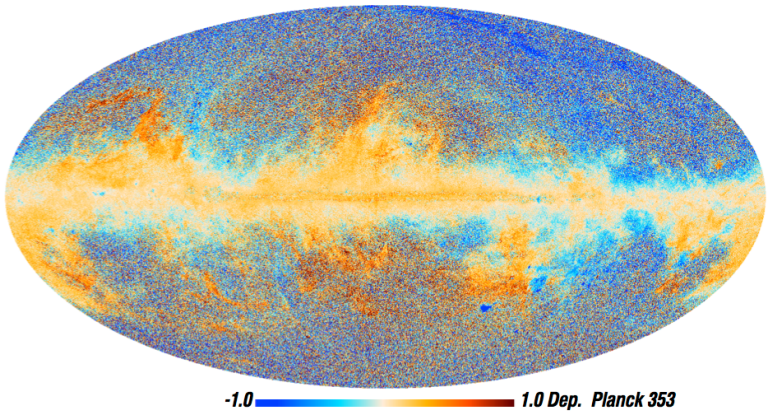






(from Planck Int. Results XXIX)
(Planck Collaboration et al. 2015d)

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



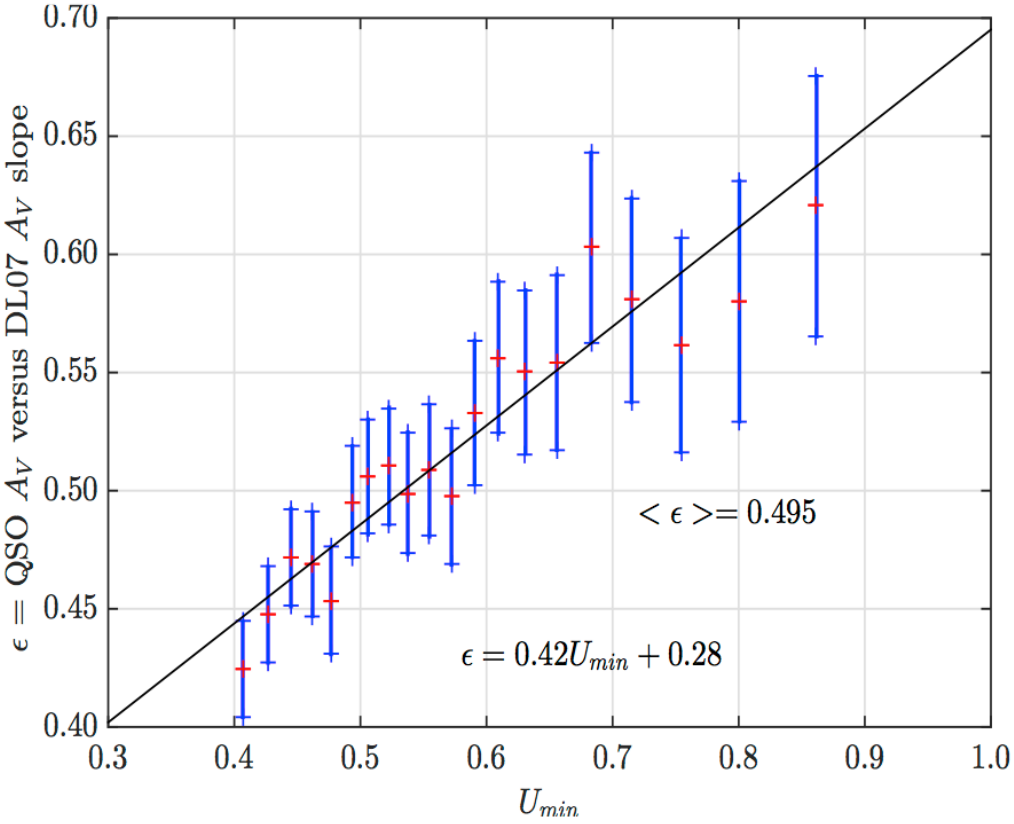
DL07 Model: Predicted A_V vs. Observation

- 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 **~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

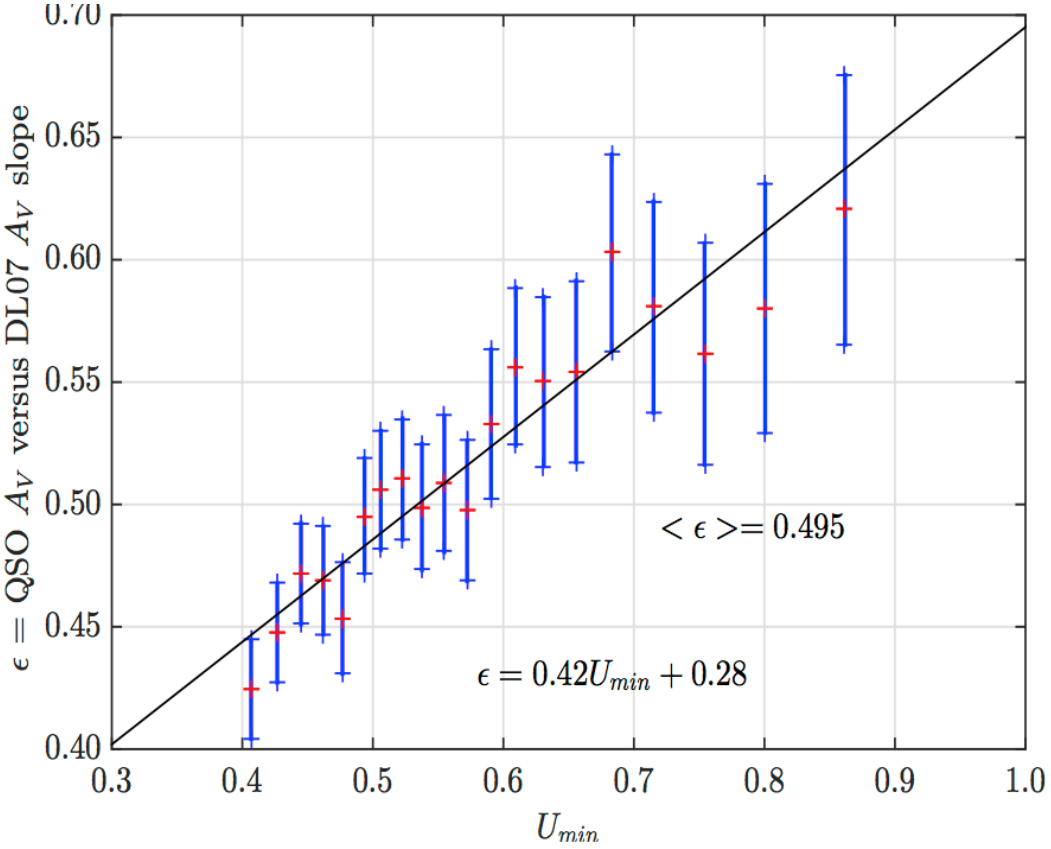
(Actual A_V) / (A_V predicted by DL07 fit to SED)



(from Planck Int. Results XXIX)

Empirical correction factors vs. fit parameter $U_{\rm min}$.
20 $U_{\rm min}$ bins, each with ~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)
(Planck Collaboration et al. 2015d)

Conclusions:

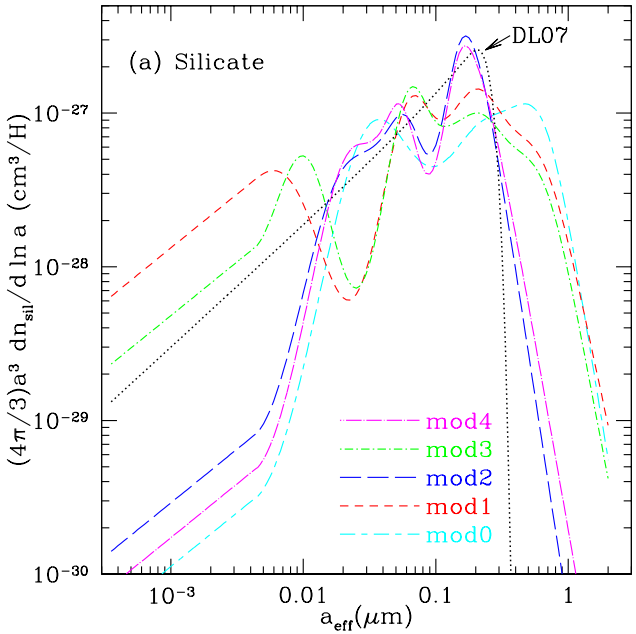
- $\tau_{\rm abs,FIR}/\tau_{\rm ext,optical}$ **too low in DL07 model**
- Remedy: new models should have $\tau_{\rm FIR}/\tau_{\rm optical}$ increased by factor $\sim$2.
- If raise $\tau_{\rm FIR}/\tau_{\rm optical}$ *and* starlight U by same factor, $T_{\rm dust}$ and SED shape unchanged.
- Empirical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

Models for Interstellar Dust

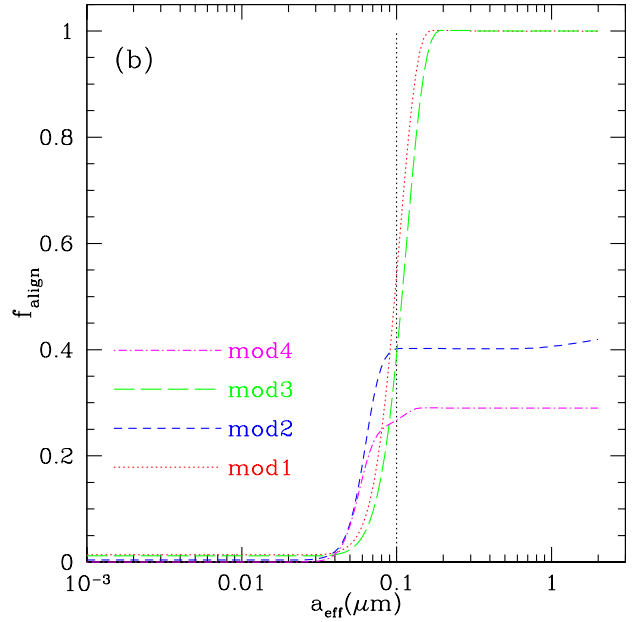
What about Polarization?

- Li & Draine (2001a): pre-Spitzer model
  amorphous silicate grains + carbonaceous grains (incl. PAHs)
  spherical grains: no polarization
- Draine & Li (2007):
  PAHs adjusted to match early Spitzer results
  spherical grains: no polarization
- **Draine & Fraisse (2009):** ⟹
  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 np + amorph. C + PAHs
  spherical grains: no polarization

silicate size distribution



degree of alignment vs. size

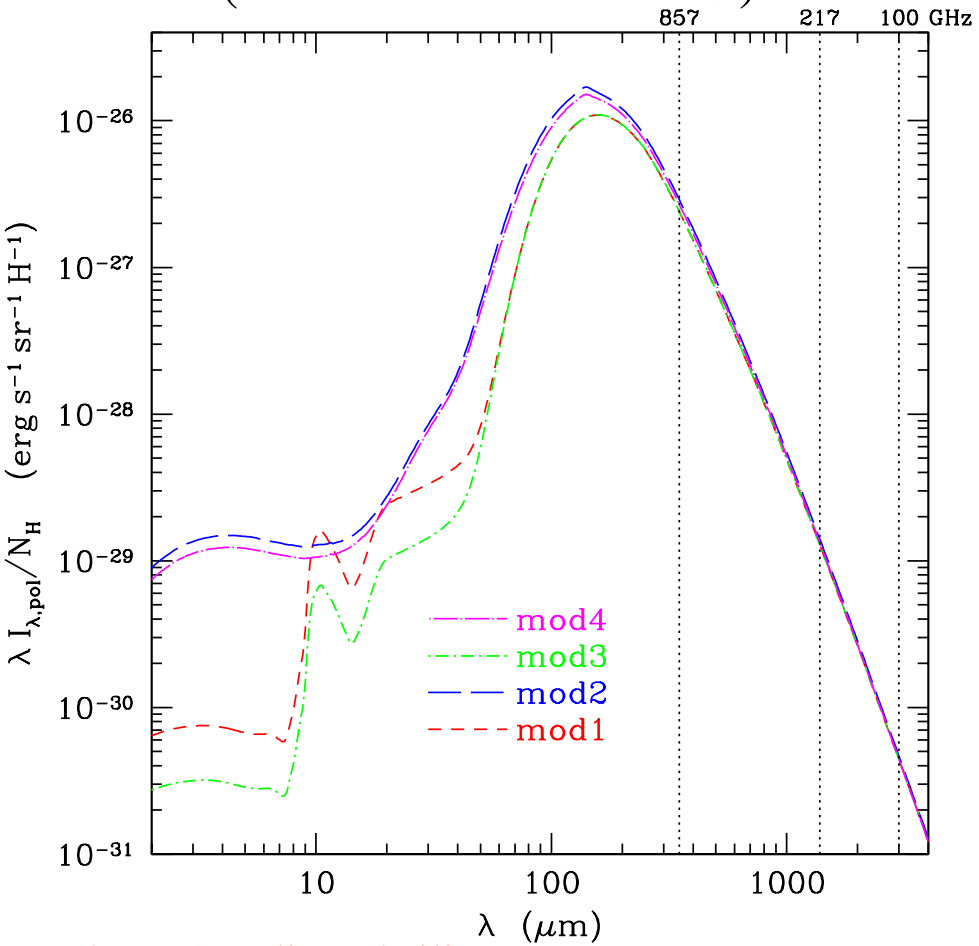


(Draine & Fraisse 2009)

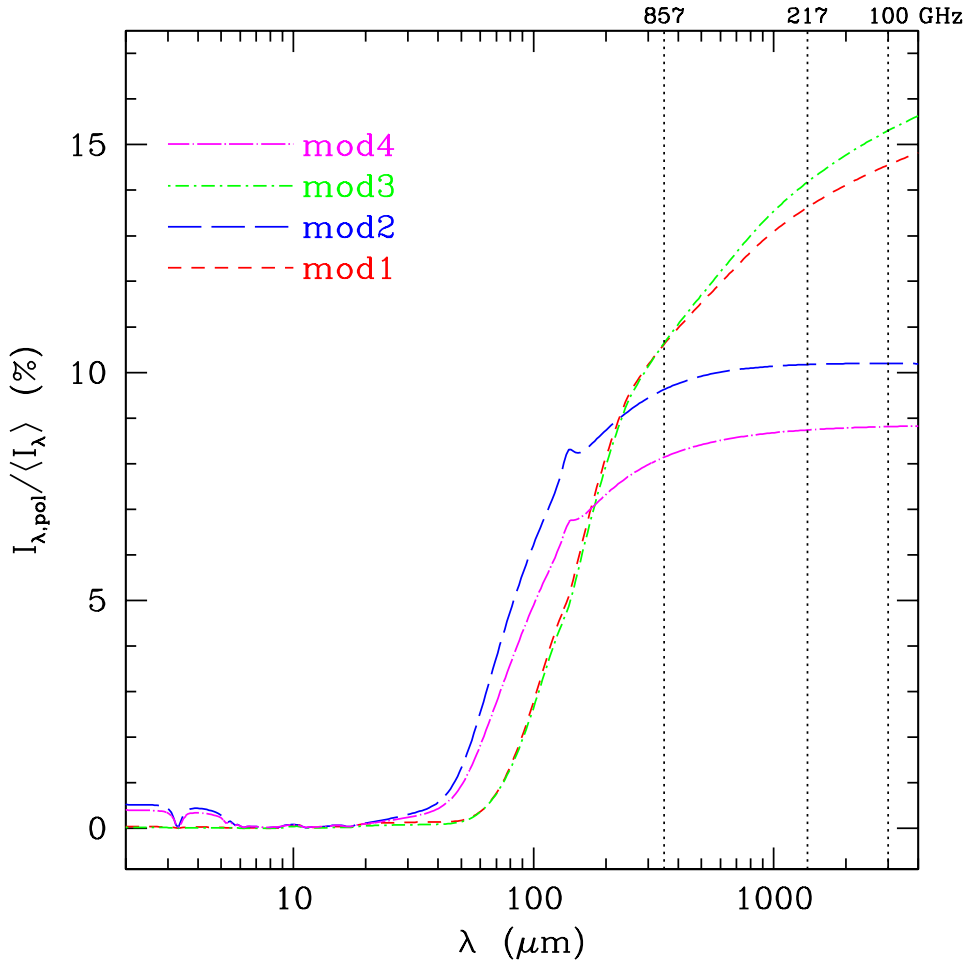
Models for Interstellar Dust

1.4:1 and 1.6:1 oblate spheroids

Polarized Emission/H
(Draine & Fraisse 2009)



fractional polarization
(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

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

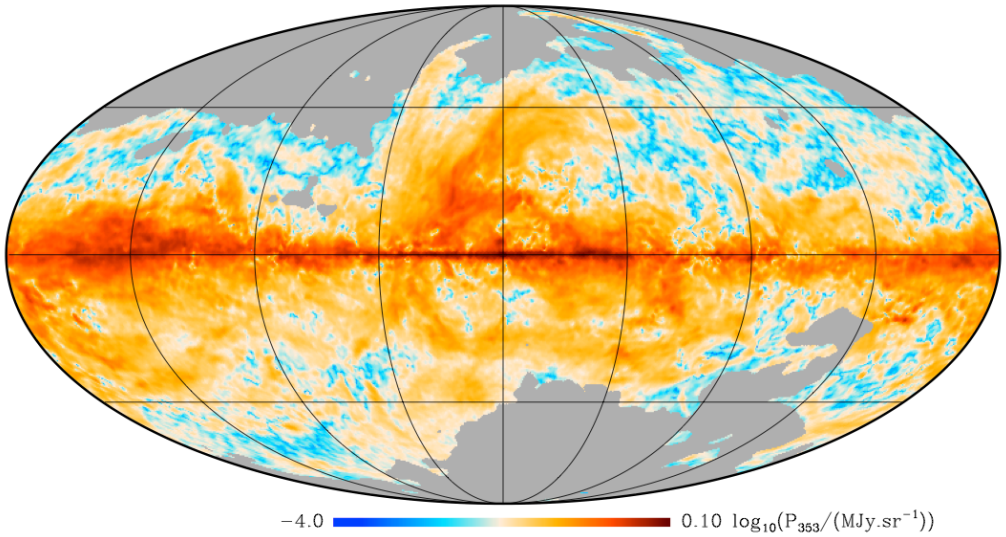
Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust

A&A 576, A106

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

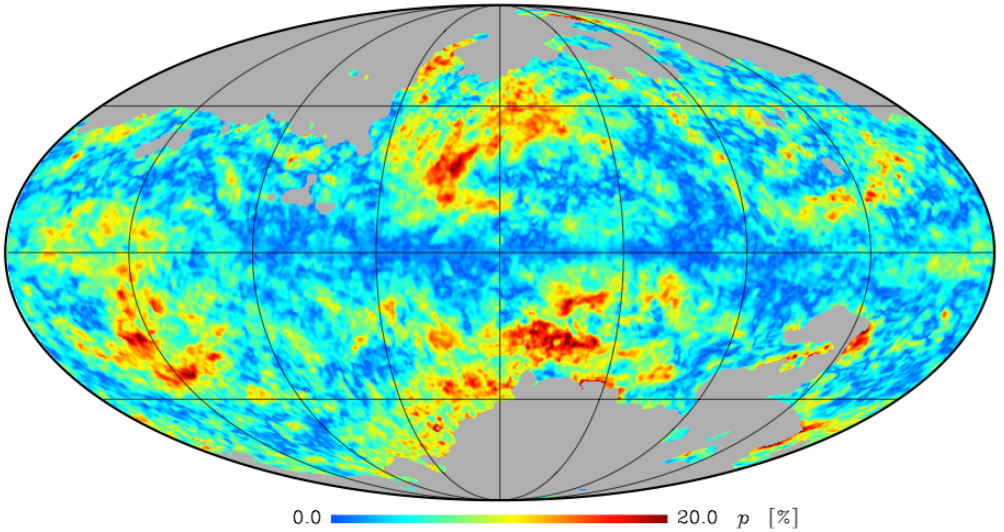
A&A 576, A107

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



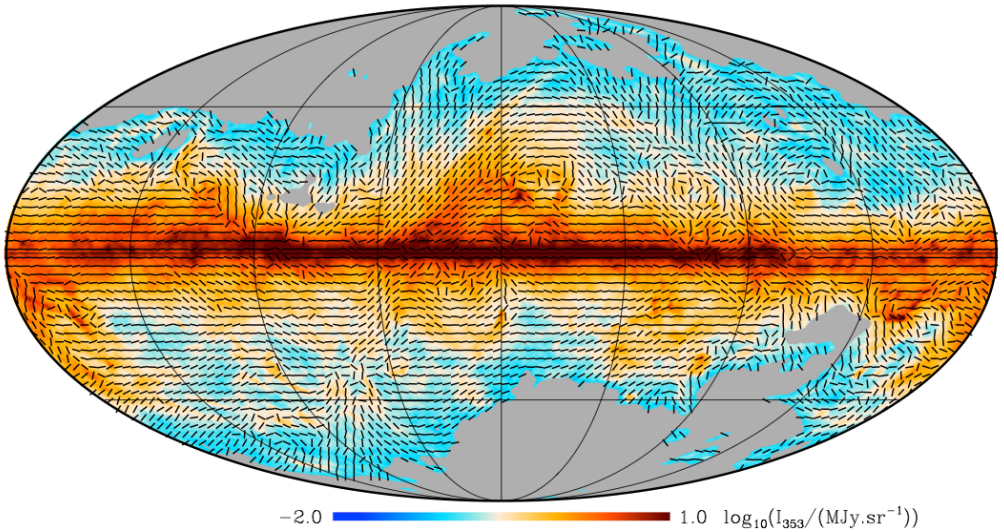
polarized emission @ 353 GHz = 850 μm

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



polarized fraction @ 353 GHz

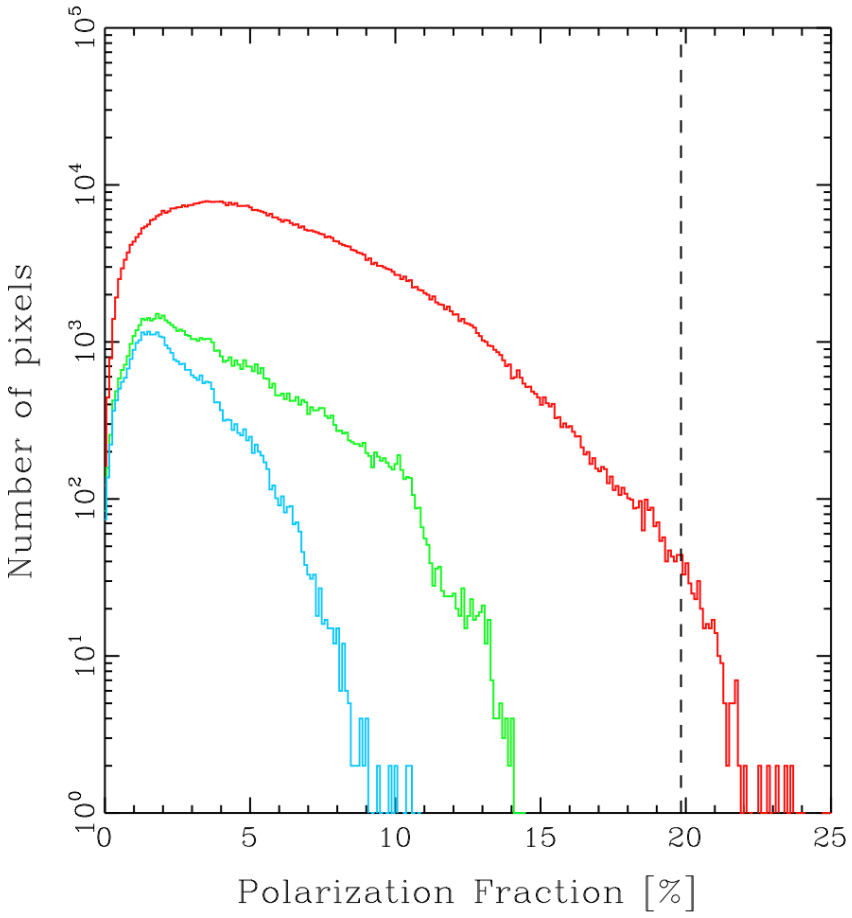
Planck int. results XIX (Planck Collaboration et al. 2015b)



polarization direction @ 353 GHz

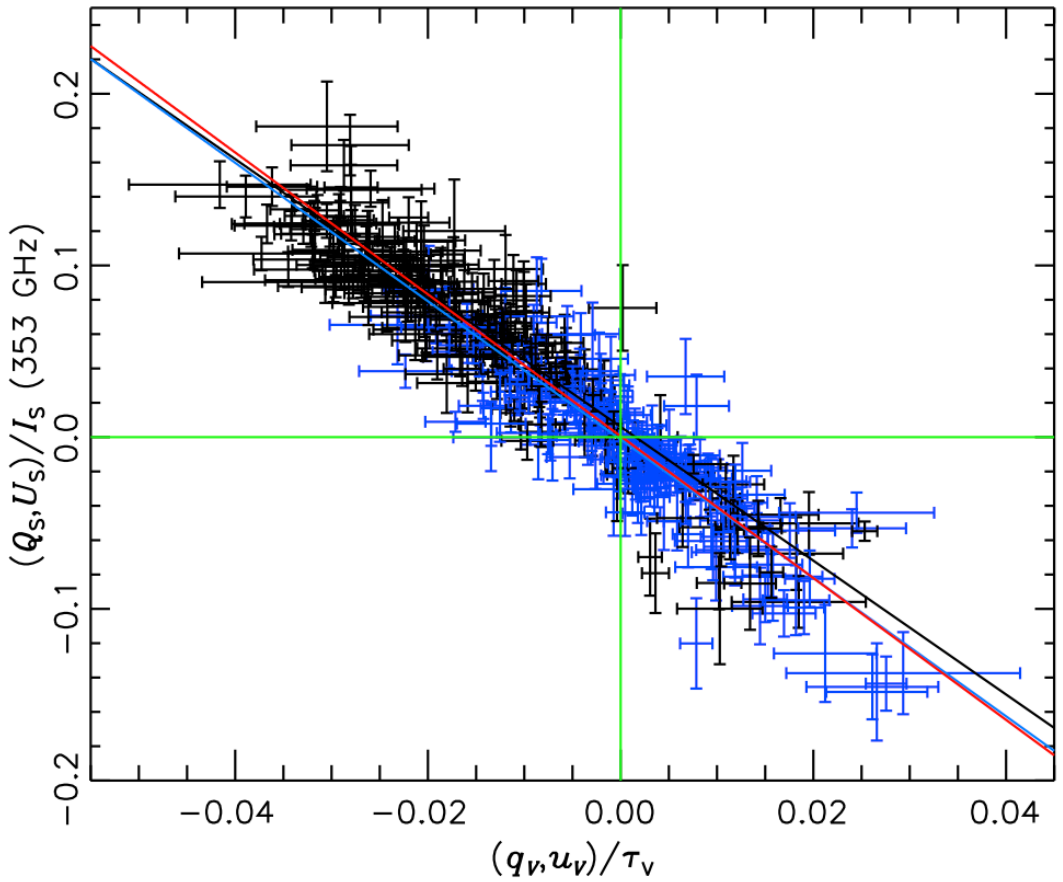
Planck int. results XIX (Planck Collaboration et al. 2015b)

Planck: Polarized Emission from Galactic Dust



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

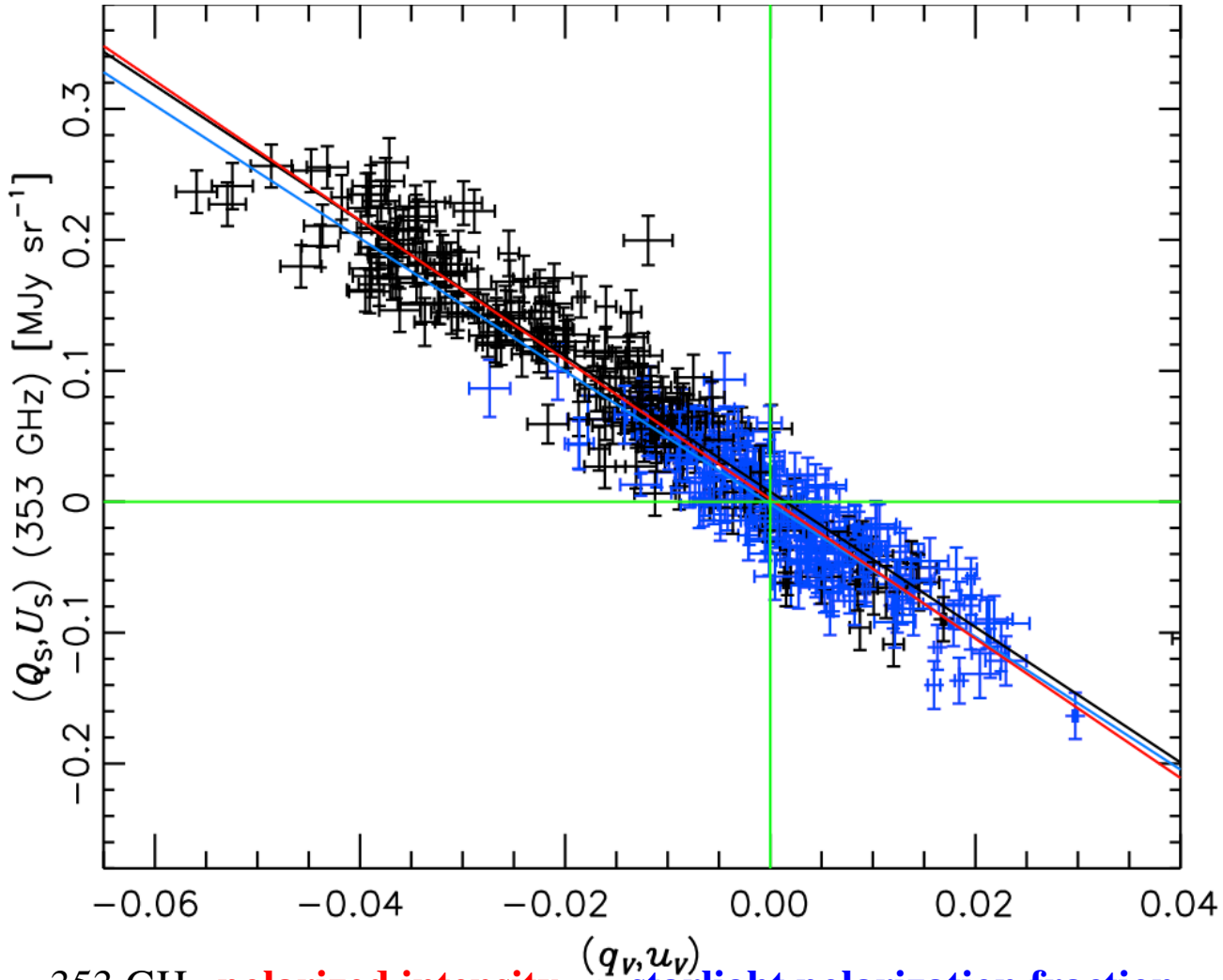
Most of the sky has polarization >5%
polarization >12% is uncommon
but a few points have p >20%



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
Draine & Fraisse (2009) 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)

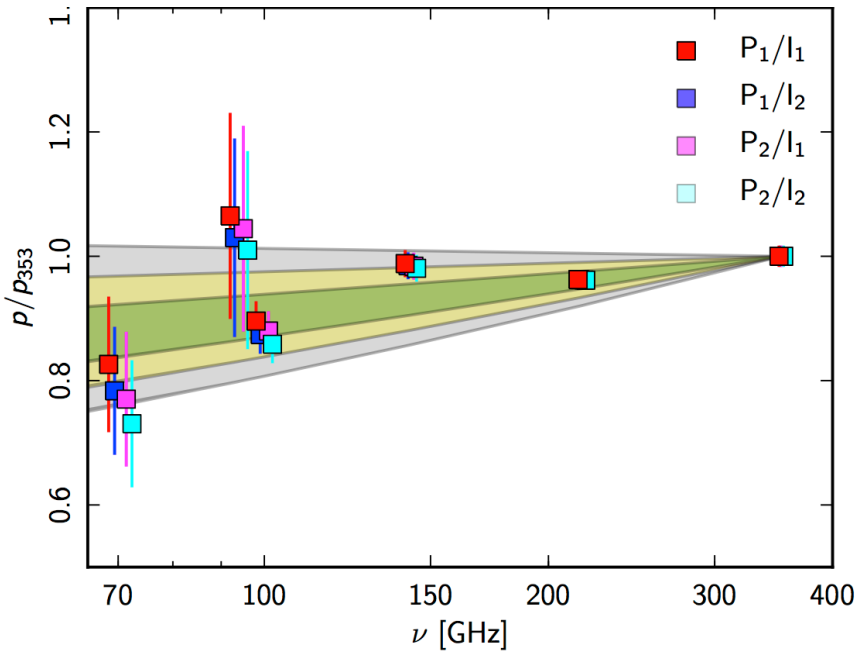
Observed slope: $-5.32 \pm 0.06\,\mathrm{MJy\,sr^{-1}}$

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

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

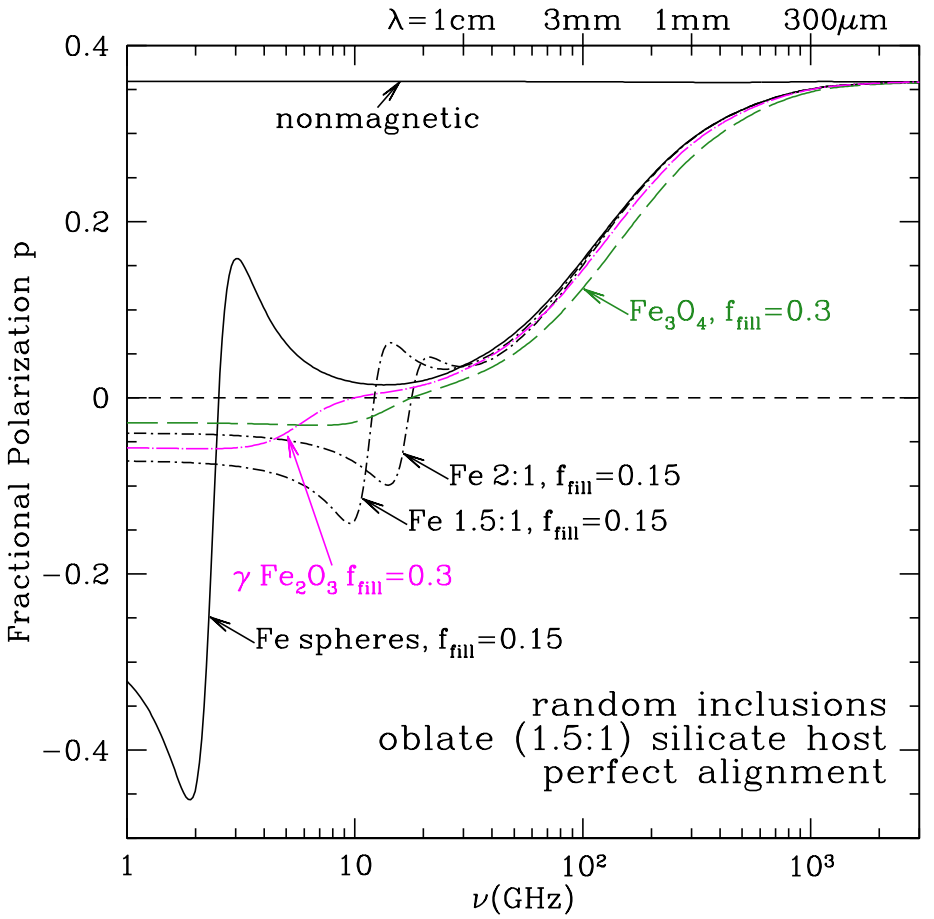


Planck int. results XXII (Planck Collaboration et al. 2015e)

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

Magnetic inclusions in silicate grains



(Draine & Hensley 2013)

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

Work in Progress...

New models (with Brandon Hensley)

Hensley & Draine (2015, in prep.)

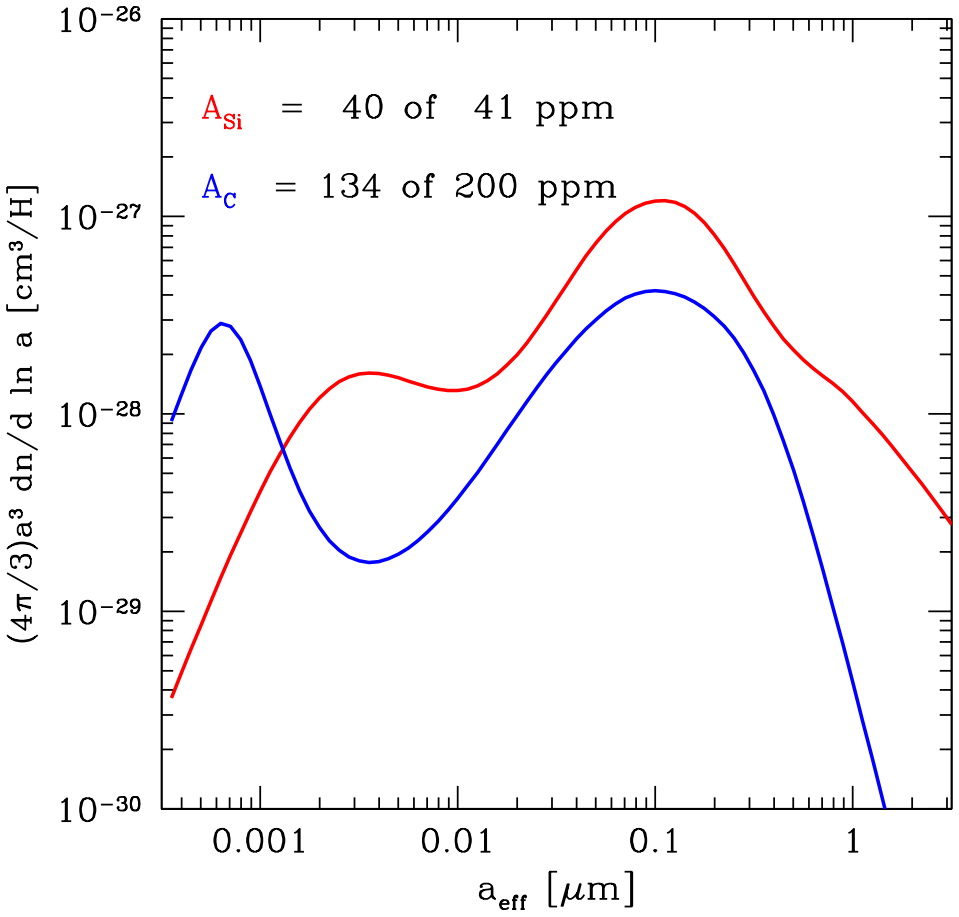
- Increase $\tau_{\rm FIR}/\tau_{\rm V}$ to increase emission per unit τ_V
- Obtain "new" astrosilicate dielectric function $\epsilon_{\rm sil}(\omega)$
  - *improved* $10\,\mu{\rm m}$ *silicate profile*
  - *adjust FIR-submm for consistency with Planck observations*

  Use Kramers-Kronig relations to relate ${\rm Re}(\epsilon_{\rm sil})$ and ${\rm Im}(\epsilon_{\rm sil})$.
- 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...

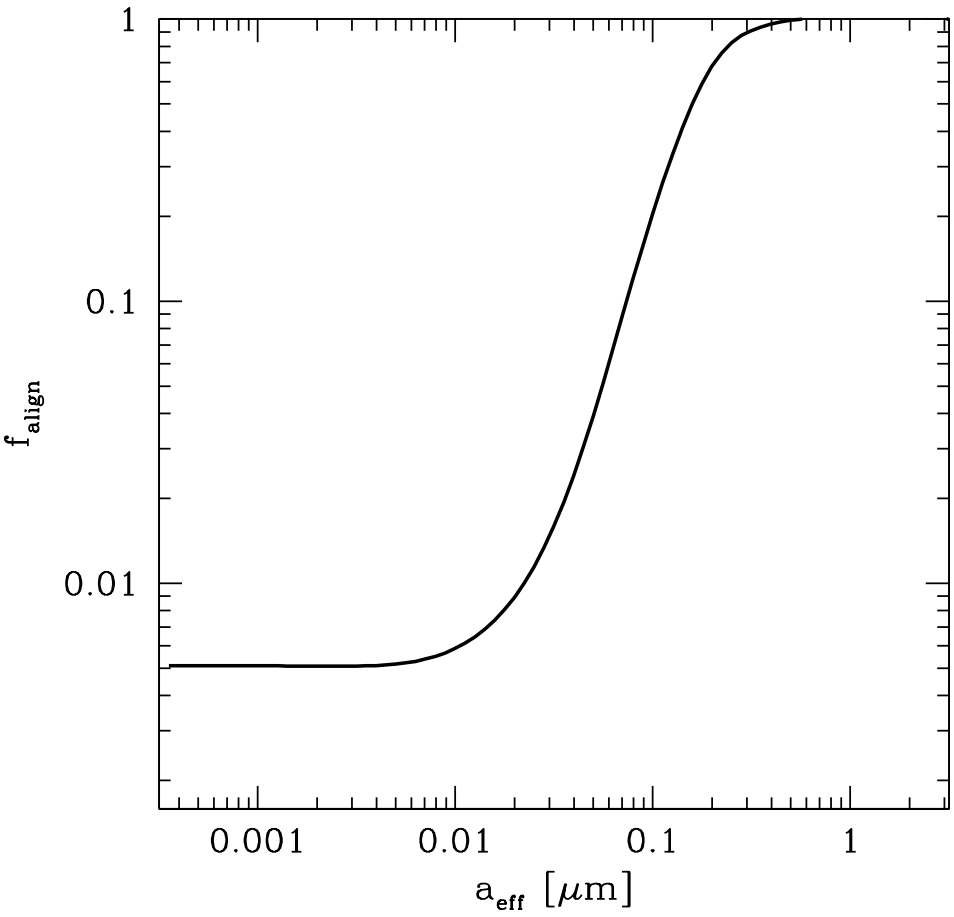
models with 25% of Fe as metallic inclusions in silicate hosts ($f_{\rm fill} = 0.05$)

size distribution (spheroids)



most of the mass at $a_{\rm eff} > 0.05\,\mu{\rm m}$

alignment of silicates



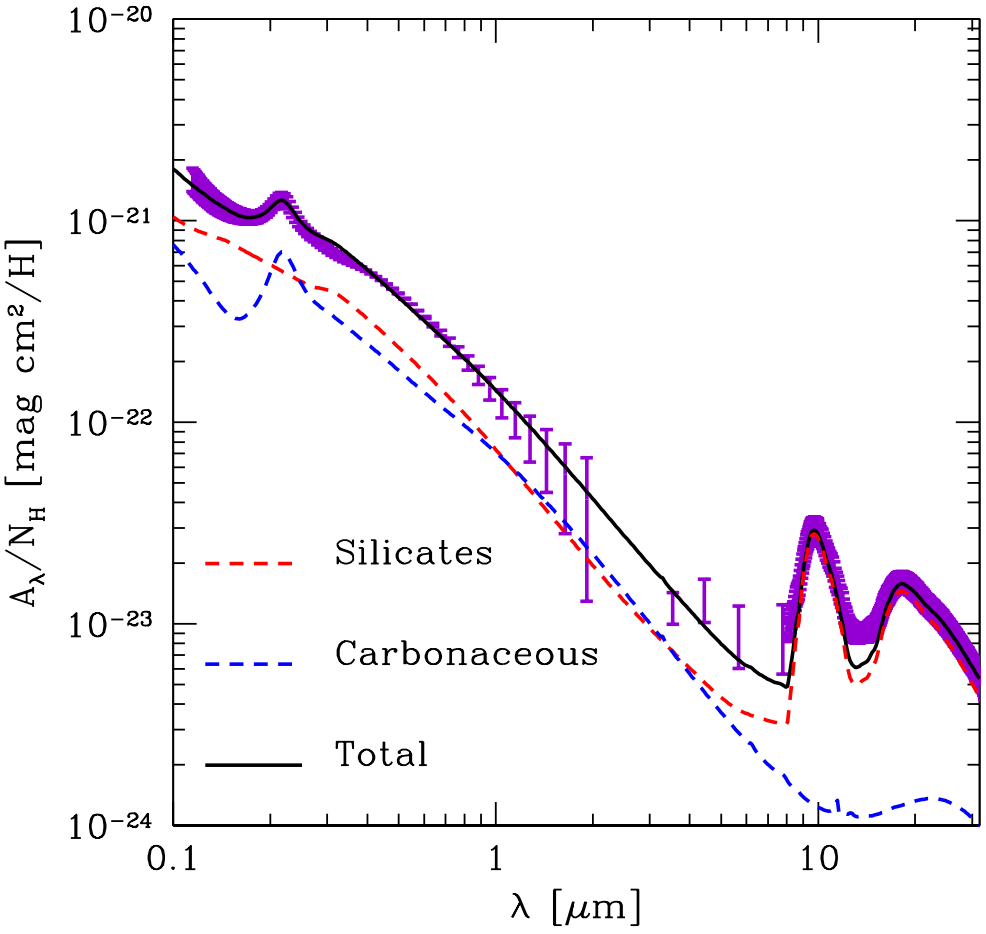
minimal alignment for $a_{\rm eff} < 0.05\,\mu{\rm m}$
substantial alignment for $a_{\rm eff} > 0.1\,\mu{\rm m}$

Work in Progress...

(Hensley & Draine 2015)

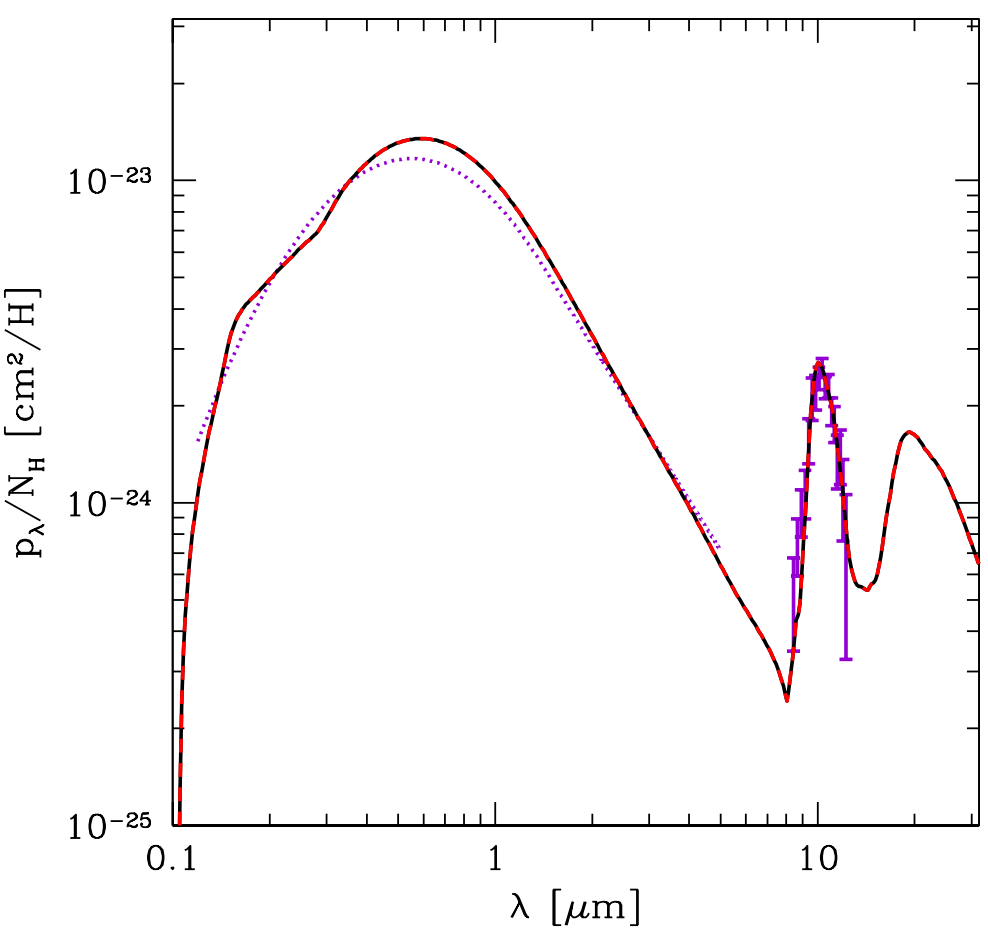
25% of Fe in metallic inclusions in silicates ($f_{\rm fill} = 0.05$)

extinction



consistent with observations

starlight pol.



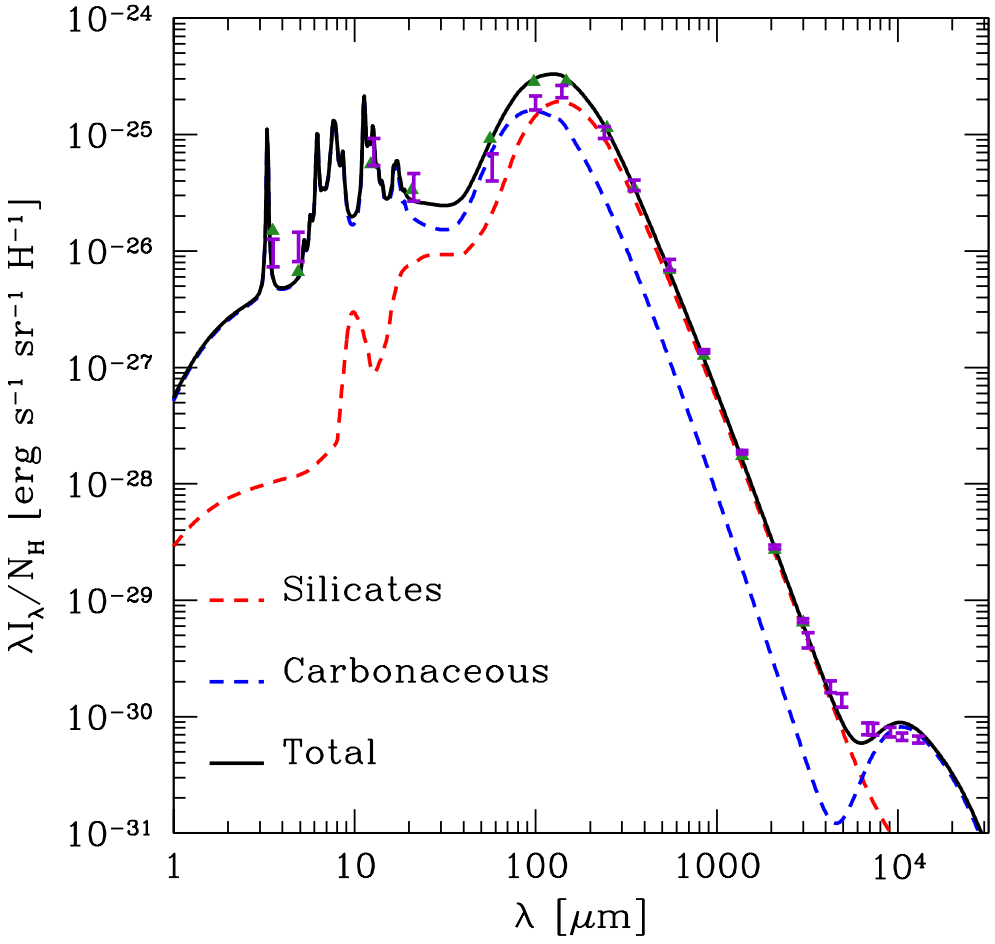
consistent with observations

Work in Progress...

(Hensley & Draine 2015)

Starlight intensity $U = 1.6$

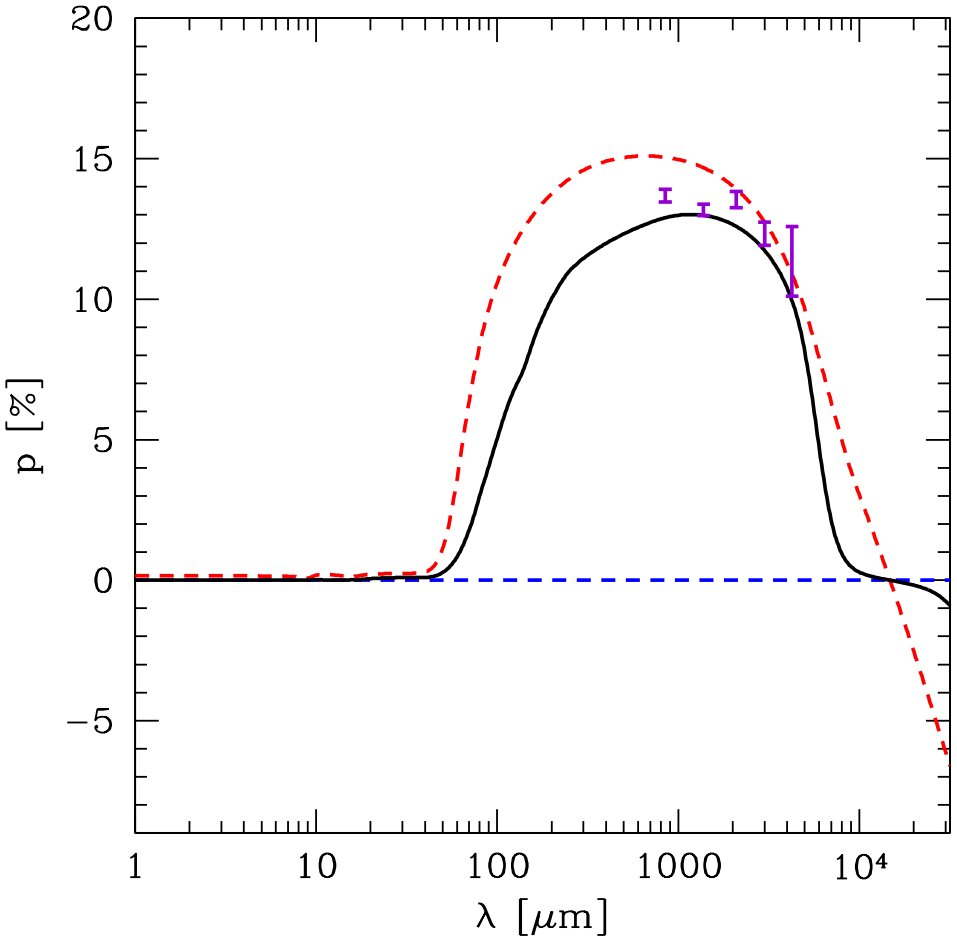
thermal emission



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

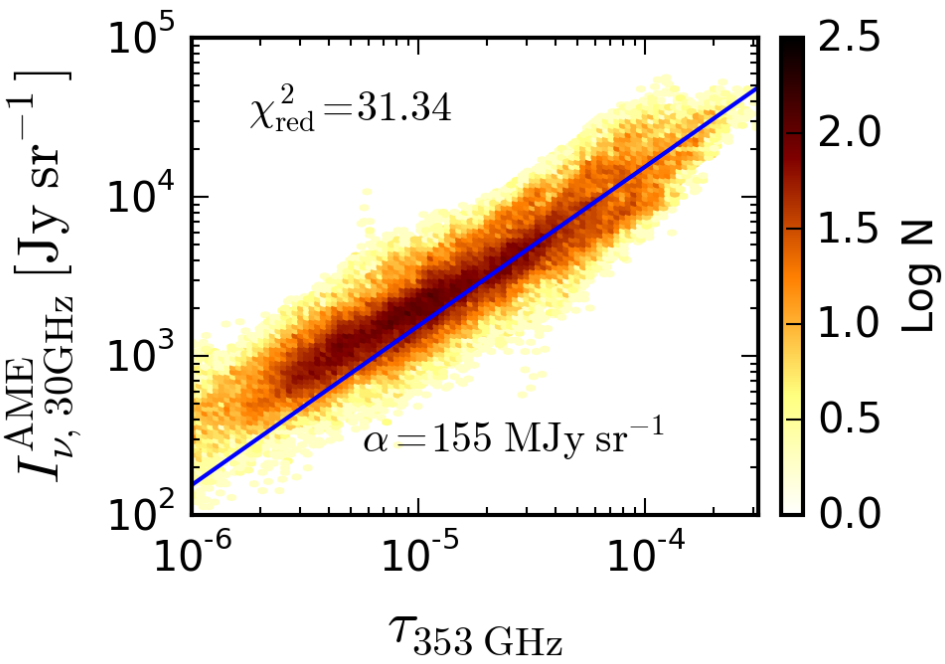
(Hensley, Draine, & Meisner 2015, in prep.)

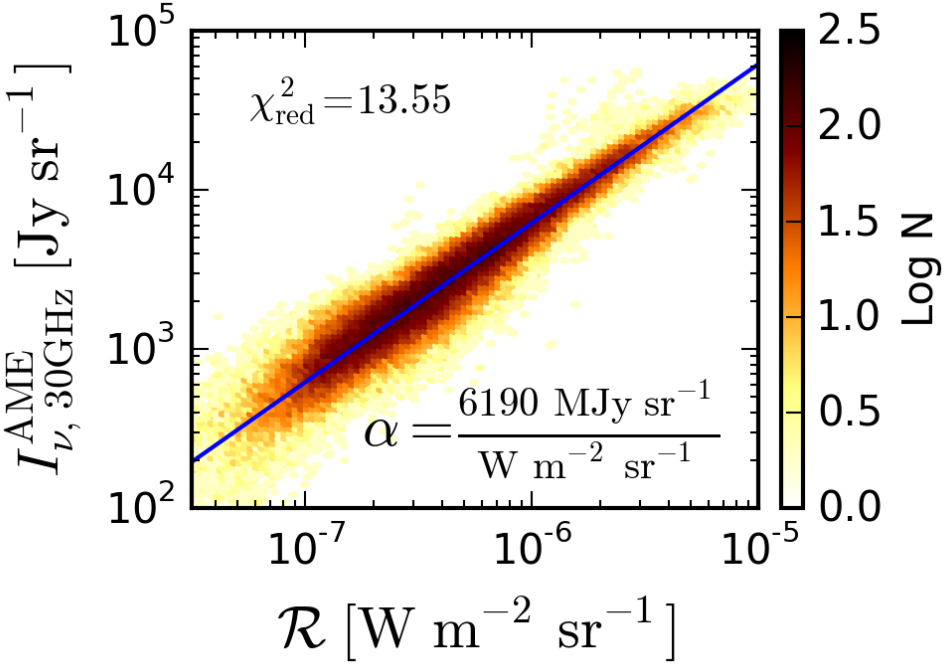
- AME map from Planck ("Commander" analysis; Planck Collaboration et al. 2015a)
  maps of τ_{353}, $T_{\rm dust}$, β, and dust radiance $\mathcal{R}$ from Planck 2013 results XI (Planck Collaboration et al. 2014)
- $12\,\mu$m map from WISE (Meisner & Finkbeiner 2014) (diffuse $12\,\mu$m dominated by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

$$f_{\rm PAH} \equiv \frac{\rm WISE12\,\mu m}{\mathcal{R}}$$

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

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



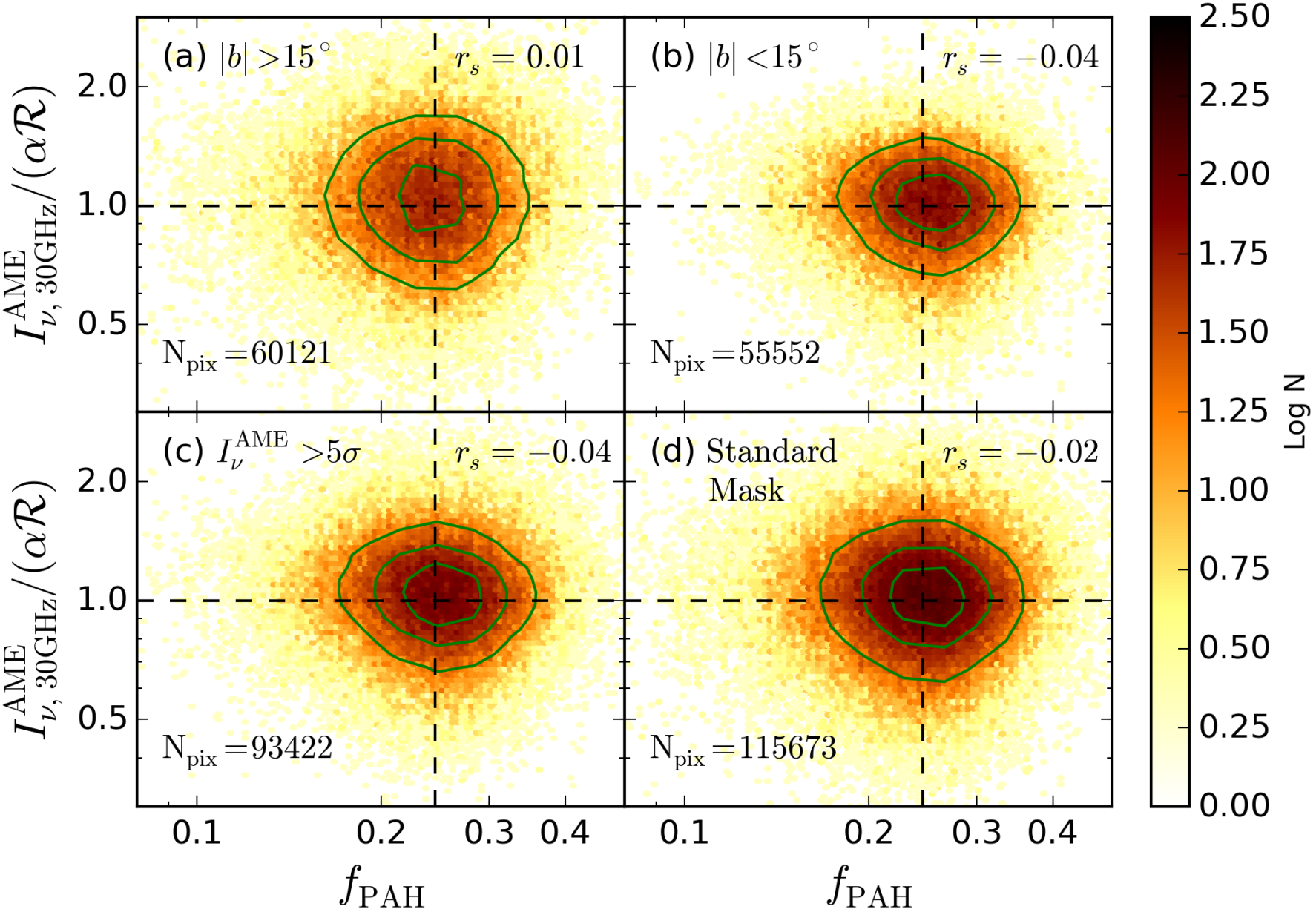


Surprise: Much better correlation with $\mathcal{R}$ than with τ_{353}!

Is there a correlation with $f_{\rm PAH}$?

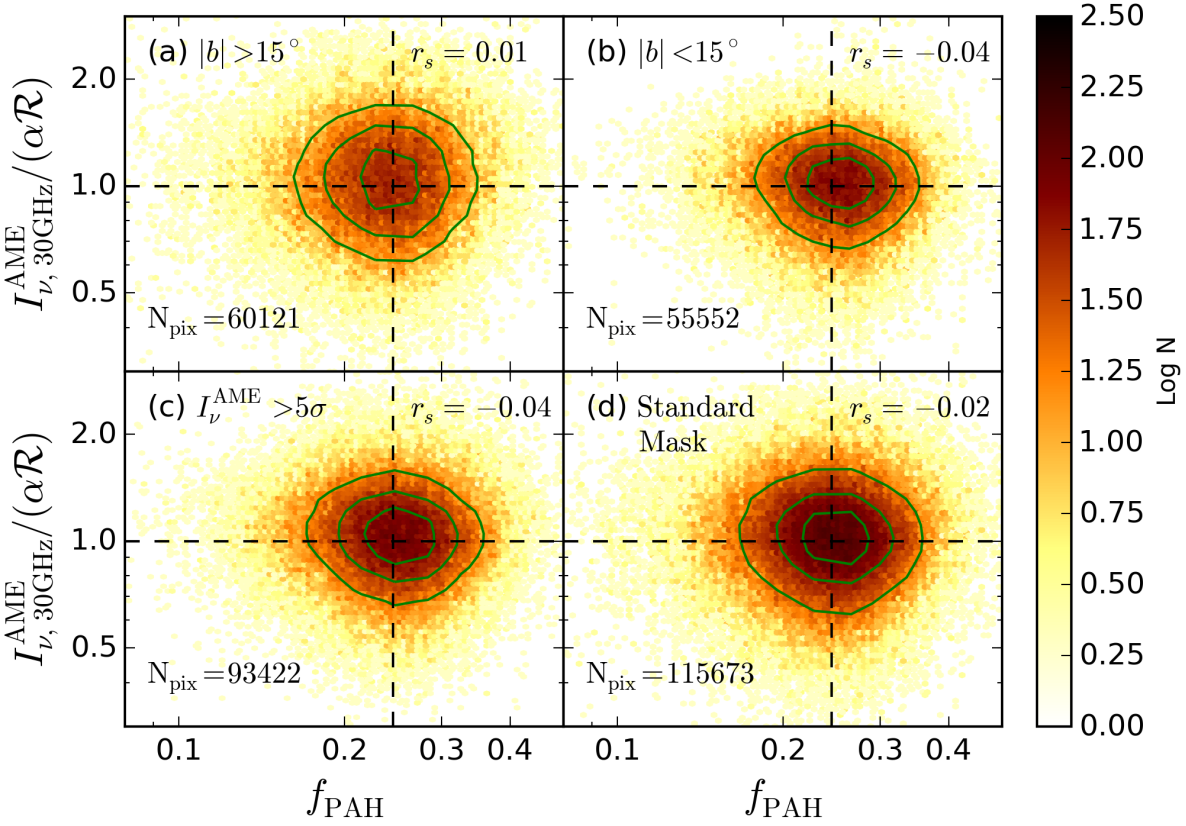
Does AME Come from Spinning PAHs?

(Hensley et al. 2015)



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

Anomalous Microwave Emission: *What is the Source?*



Hensley et al. (2015)

- **No** evidence of variation of AME/$\mathcal{R}$ when $f_{\rm PAH}$ 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?

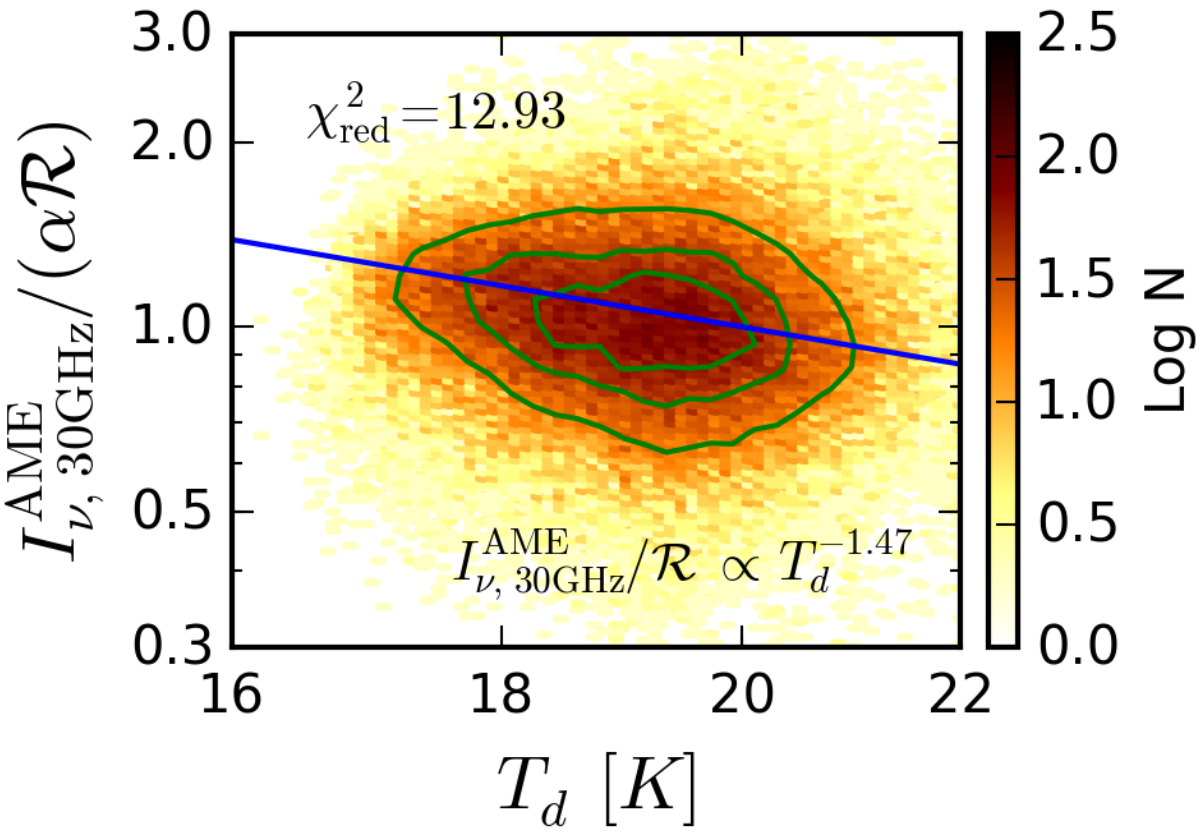
What is Source of AME? Test for Thermal Emission Process

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 (unless 30 GHz opacity is very sensitive to T_d, as in $\tau_{30}/\tau_{353} \propto T_d^{3.2}$)

Summary

- Chemical form of Fe in interstellar grains is uncertain,
  - Some of the Fe may be in metallic form.
- Mystery: where is the missing oxygen in diffuse molecular clouds?
  Very troubling...
- 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*
  - *Does not appear to be thermal emission*
  - Is AME primarily from spinning non-PAH (silicate?) nanoparticles?

THANK YOU

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