The Continuing Mystery of the Anomalous Microwave Emission

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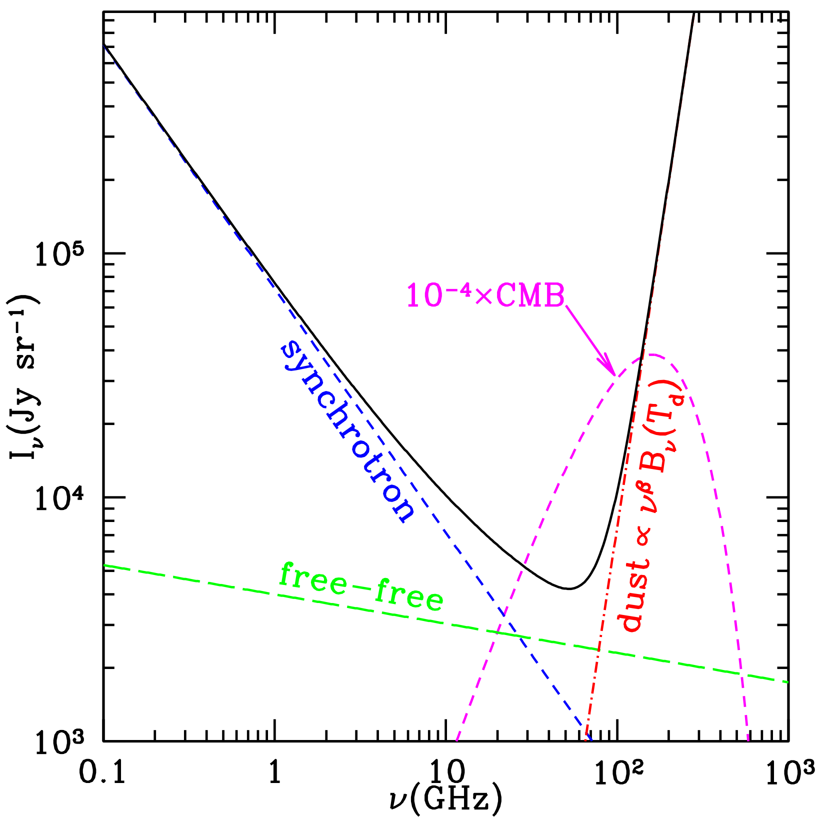
- **Discovery of the AME**
- **The Spinning Dust Hypothesis and PAHs**
  - Physics of Rotational Excitation and Deexcitation
  - Predictions for PAHs
- **Other Emission Mechanisms?**
- **Tests?**
  - Planck observations
  - Extragalactic observations
- **Combining Planck and WISE – Unexpected Results**
- **Current Hypotheses for the AME**

CMB Studies: Annoying Galactic Foregrounds...

Expected Diffuse Backgrounds ca. 1995:

- **Synchrotron**: dominant at low frequencies
- **Free-Free**: traced by Hα
- **Thermal Dust**: traced by IRAS 100μm (3000 GHz)



Observational Surprise:

- **Dust-correlated microwave emission** discovered by COBE-DMR (Kogut et al. 1996): 4σ correlation between COBE-DMR $I_\nu(31.5\,\mathrm{GHz})$ and COBE-DIRBE $I_\nu(140\mu\mathrm{m})$
- **Much** stronger than expected from "normal" dust emission, and with unexpected frequency dependence, hence termed **Anomalous Microwave Emission (AME)**
- Initially controversial: Many followup studies from ground, balloon, and space (WMAP and Planck)
- Present-day consensus:
  - **AME is real**
  - Emission mechanism uncertain (but I favor spinning dust...)

What is the AME?

Possible emission mechanisms:

- Free-free emission from hot plasma? (Kogut et al. 1996; Leitch et al. 1997)
- Synchrotron with unusual spectrum? (Leitch et al. 1997; Gold et al. 2011)
- Spinning dust emission? (Draine & Lazarian 1998a,b)
  - including radiation from spinning magnetic dipoles (Hoang & Lazarian 2016)
- Thermal emission from grains with "opacity bump" at 30 GHz?
  - e.g., magnetic grain materials (Draine & Lazarian 1999; Draine & Hensley 2013)
- Something entirely different?

Spectrum of the AME

Poster Child

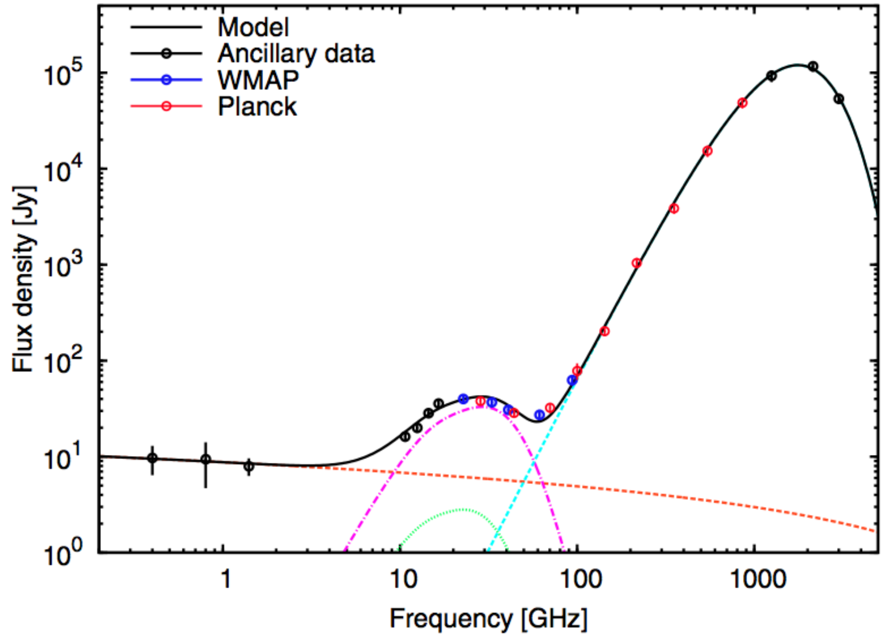


Fig. 4. Spectrum of AME-G160.26−18.62 in the Perseus molecular cloud. The best-fitting model consisting of free-free (orange dashed line), spinning dust, and thermal dust (light blue dashed line) is shown. The two-component spinning dust model consists of high density molecular gas (magenta dot-dashed line) and low density atomic gas (green dotted line).

Planck Collaboration et al. (2011)

More Cases...

Planck Collaboration: A study of AME in Galactic clouds

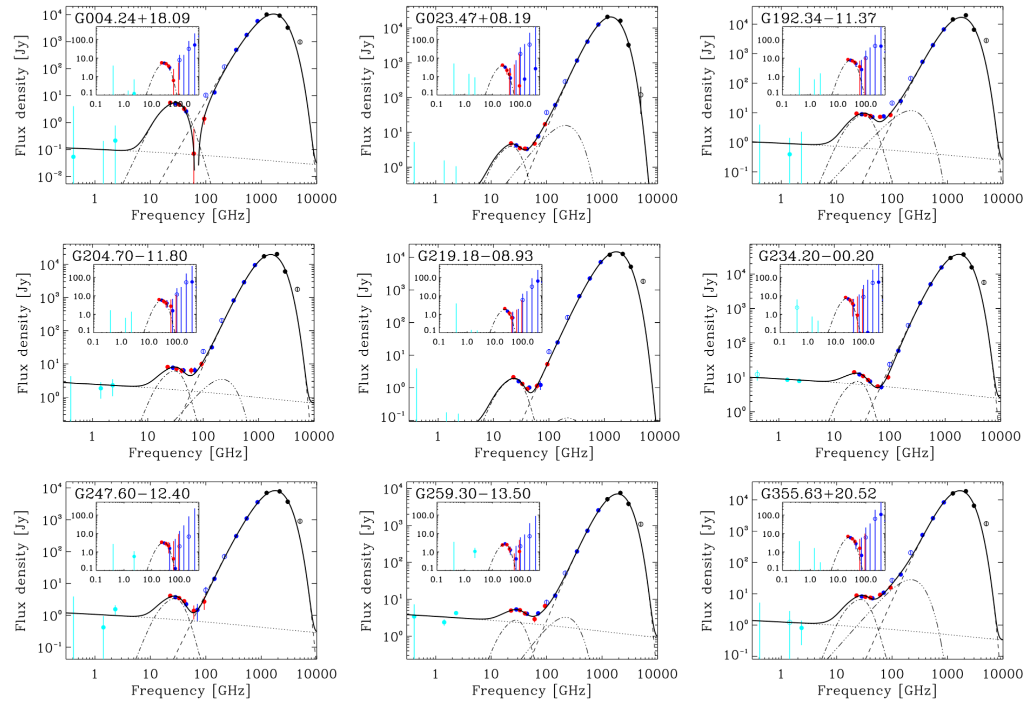


Fig. 8. SEDs for the sources with very significant AME and $f_{\rm max}^{\rm UCH\,II} < 0.25$. Data points are shown as circles with errors and are colour-coded for radio data (light blue), WMAP (red), *Planck* (blue), and DIRBE/ IRAS (black). The best-fitting model of free-free (dotted line), thermal dust (short-dashed line), CMB (triple-dot dashed line), and spinning dust (dot-dashed line) is shown. Data included in the fit are shown as filled circles, while the other data are unfilled. The residual spectrum, after subtraction of free-free, synchrotron, CMB, and thermal dust components, is shown in the *insert*. The best-fitting spinning dust model is also shown.

Planck Collaboration et al. (2014b)

spectrum inconsistent with synchrotron or free-free

AME peaks near ∼30 GHz

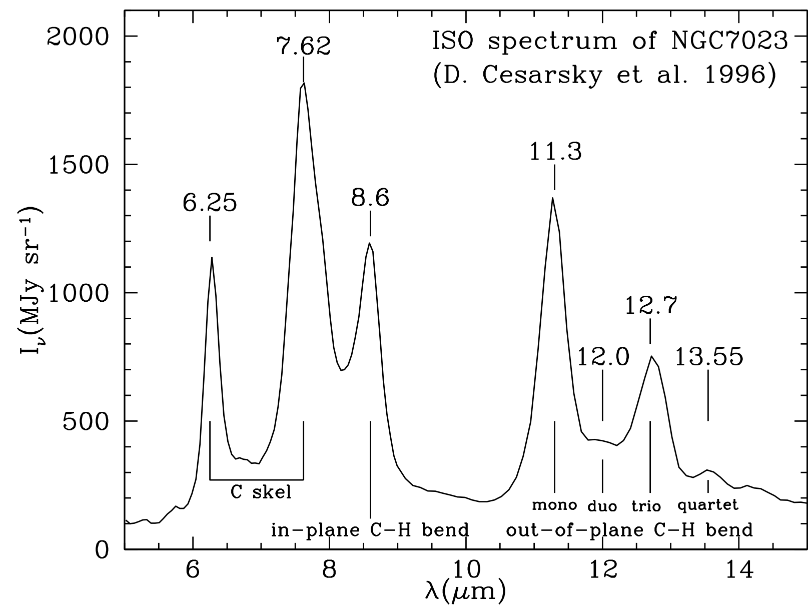
peak frequency appears to vary from region-to-region

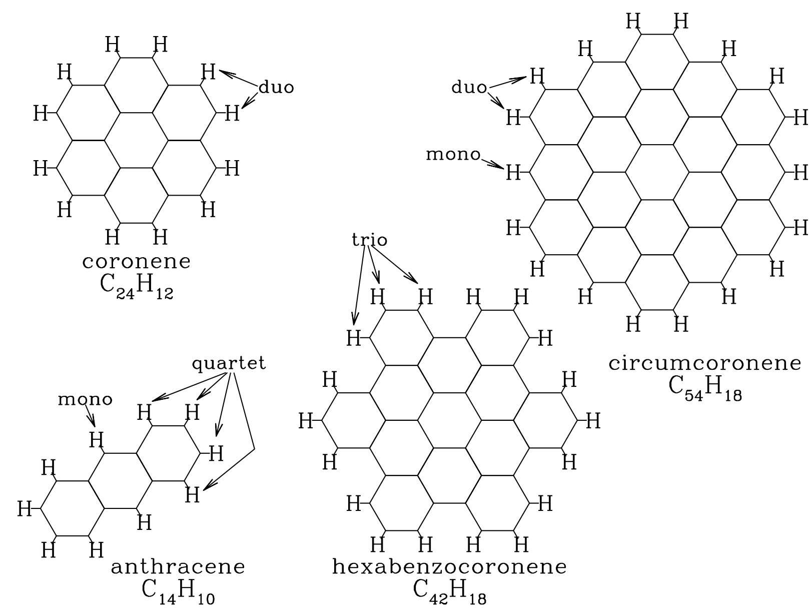
AME is ∼30 times stronger than power-law extrapolation of dust opacity to 30 GHz

What is the AME?

Proposal: **Rotational emission from spinning dust** (Draine & Lazarian 1998a)

- Estimate rate of rotation of very small grains in ISM
- If electric dipole moment $\vec{\mu}$ has component $\perp \vec{\omega}$
  then electric dipole radiation at frequency ω.
- If grains spinning at $\sim$30 GHz are sufficiently numerous: could account for AME
- Previous observations of 3.3-13μm IR emission features: already required very large population of PAH nanoparticles to account for IR emission as result of single-photon heating of PAHs
- PAH size distribution required to account for IR emission:
  $\Rightarrow j_\nu$ peaking in the 20-40 GHz range





Rotational Excitation and Damping

- Collisions with neutral atoms: excitation and damping
  Rigid sphere, no other J-changing processes: "Brownian rotation" with

$$\frac{1}{2}I\langle\omega^2\rangle = \frac{3}{2}kT_{gas} \qquad\qquad I = \frac{2}{5}Ma^2 = \frac{8\pi}{15}\rho a^5$$

$$\frac{\langle\omega^2\rangle^{1/2}}{2\pi} = 32\,\mathrm{GHz}\left(\frac{T_{gas}}{100\,\mathrm{K}}\right)^{1/2}\left(\frac{2\,\mathrm{g\,cm^{-3}}}{\rho}\right)^{1/2}\left(\frac{5\,\text{Å}}{a}\right)^{5/2}$$

$$\frac{M}{12m_{\mathrm{H}}} = 52\left(\frac{\rho}{2\,\mathrm{g\,cm^{-3}}}\right)\left(\frac{a}{5\,\text{Å}}\right)^3$$

- However: *There are other J-changing processes:*
  - Collisions with ions
  - Interaction of charged grain with plasma ("plasma drag")
  - Interaction of grain dipole moment $\vec{\mu}$ with plasma
  - Absorption of optical photons (electronic transitions)
  - Emission of IR photons (vibrational transitions)
  - Emission of microwave photons (rotational transitions)
  - Emission of photoelectrons
  - Formation of H_2
- Usually: *sub*-thermal rotation: $\langle\omega^2\rangle < 3kT_{gas}/I$

Predicted Rotational Emission from PAH Population

Modeling (Draine & Lazarian 1998a,b):

- Adopt PAH size distribution required to reproduce IR emission
- Assume electric dipole moment

$$\mu \approx \beta_0 \sqrt{N_c} \qquad \beta_0 \approx 0.4\mathrm{D}$$

- Calculate charge distribution for each PAH size
- Balance excitation and damping to find $\langle\omega^2\rangle$
- Calculate emissivity j_ν

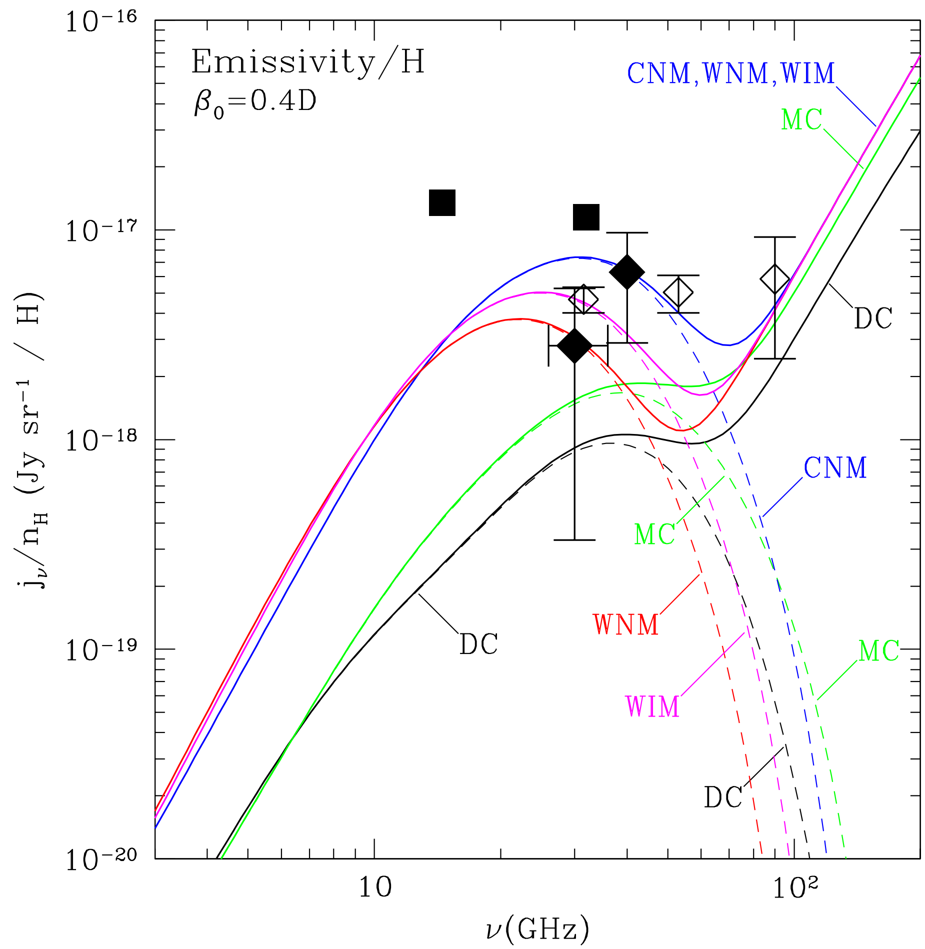


Fig. 9 from Draine & Lazarian (1998b)

[ordinate units should be $\mathrm{Jy\,cm^2\,sr^{-1}\,H^{-1}}$]

Using previously-fixed PAH distribution and seemingly-reasonable assumption for μ, spinning PAHs can account for observed AME

Improvements to Modeling of Spinning Dust Spectrum

- Factor of two correction in IR damping coefficient (Ali-Haïmoud et al. 2009)
- Fokker-Planck treatment of high-ω tail (Ali-Haïmoud et al. 2009)
- rotation around non-principal axis (Hoang et al. 2010; Silsbee et al. 2011)
- transient spin-up events (Hoang et al. 2010)
- effect of triaxiality on rotational spectrum (Hoang et al. 2011)
- effects of transient heating on emission from triaxial grains (Hoang et al. 2011)
- magnetic dipole radiation from ferromagnetic spinning dust (Hoang & Lazarian 2016)
- quantum suppression of dissipation (Draine & Hensley 2016)

Will Emission from Spinning Dust be Polarized?

- Emission from single spinning nanoparticle will be highly polarized
- Will spinning nanoparticles have net alignment of $\vec{\mathbf{J}}$ with $\pm\vec{\mathbf{B}}_0$?
- If Davis-Greenstein paramagnetic dissipation mechanism operated, then spinning nanoparticles would be aligned with $\vec{\mathbf{J}} \parallel \vec{\mathbf{B}}_0$
- But:
  When nanoparticle is in vibrational ground state, there are no vibrational modes within $\Delta E = \hbar\omega_{rot}$:
  Quantization of low-lying vibrational modes leads to suppression of paramagnetic dissipation in spinning $a < 20\,\text{Å}$ nanoparticles in ISM
  (Lazarian & Draine 2000)

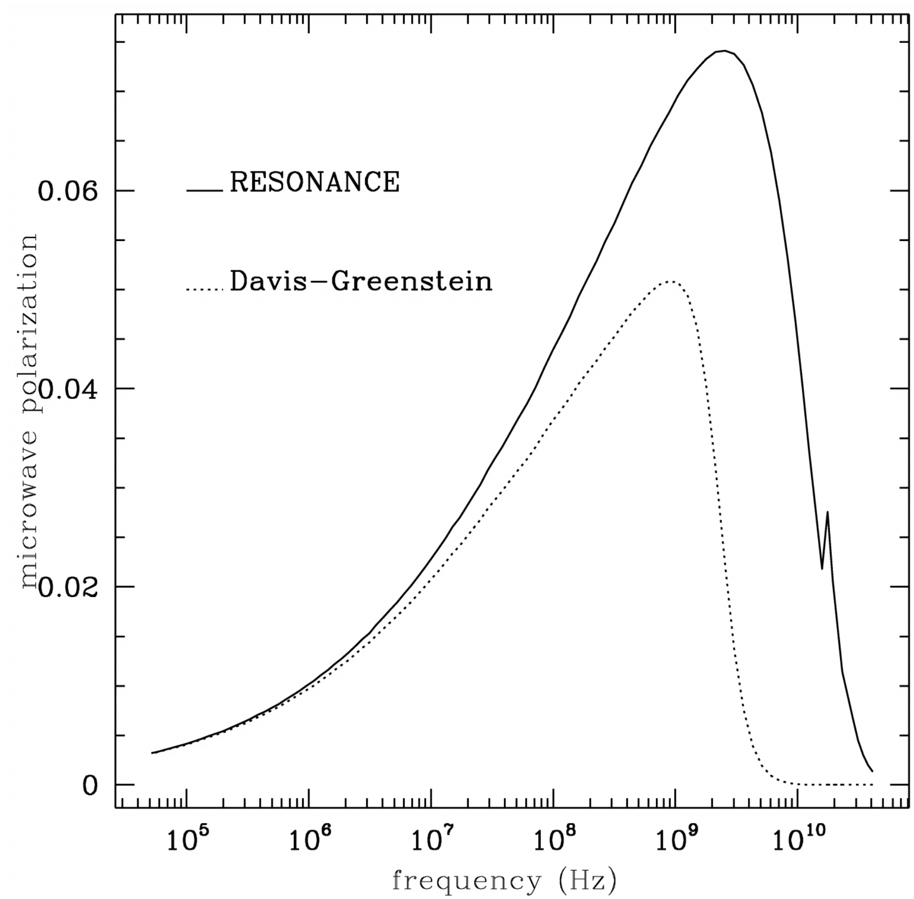


Fig. 1a from Lazarian & Draine (2000)

Prediction: $> 20\,\mathrm{GHz}$ rotational emission from spinning dust should be $< 2\%$ polarized

What is the AME?

- **Proposal:** AME = rotational emission from spinning dust, particularly PAHs (Draine & Lazarian 1998a)

Prediction of spinning dust models:

- $> 10\,\mathrm{GHz}$ AME 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 (Draine & Hensley 2012)

Brandon Hensley

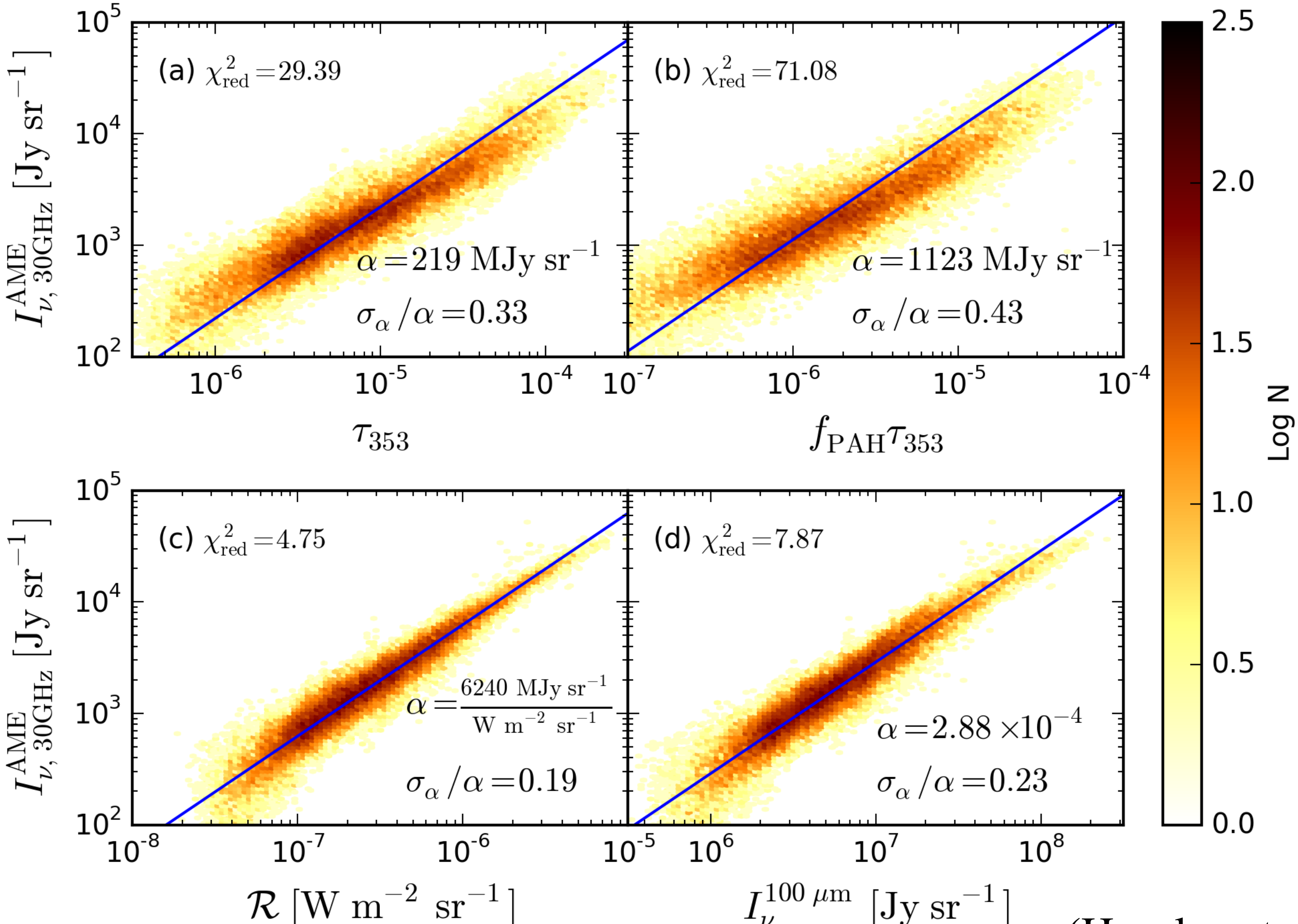
First indication of problems with PAH-AME connection: AME in nearby spiral galaxy NGC6946 did not appear to follow estimates of $\Sigma_{\rm PAH}$ (Hensley et al. 2015)

Can we test this in local ISM?

see talks tomorrow by
Aaron Bell and Brandon Hensley

Use WMAP, Planck, IRAS, WISE maps: look for AME correlations

Expectation: $I_\nu^{\rm AME}(30\,{\rm GHz}) \propto f_{\rm PAH} \times \tau_{353}$

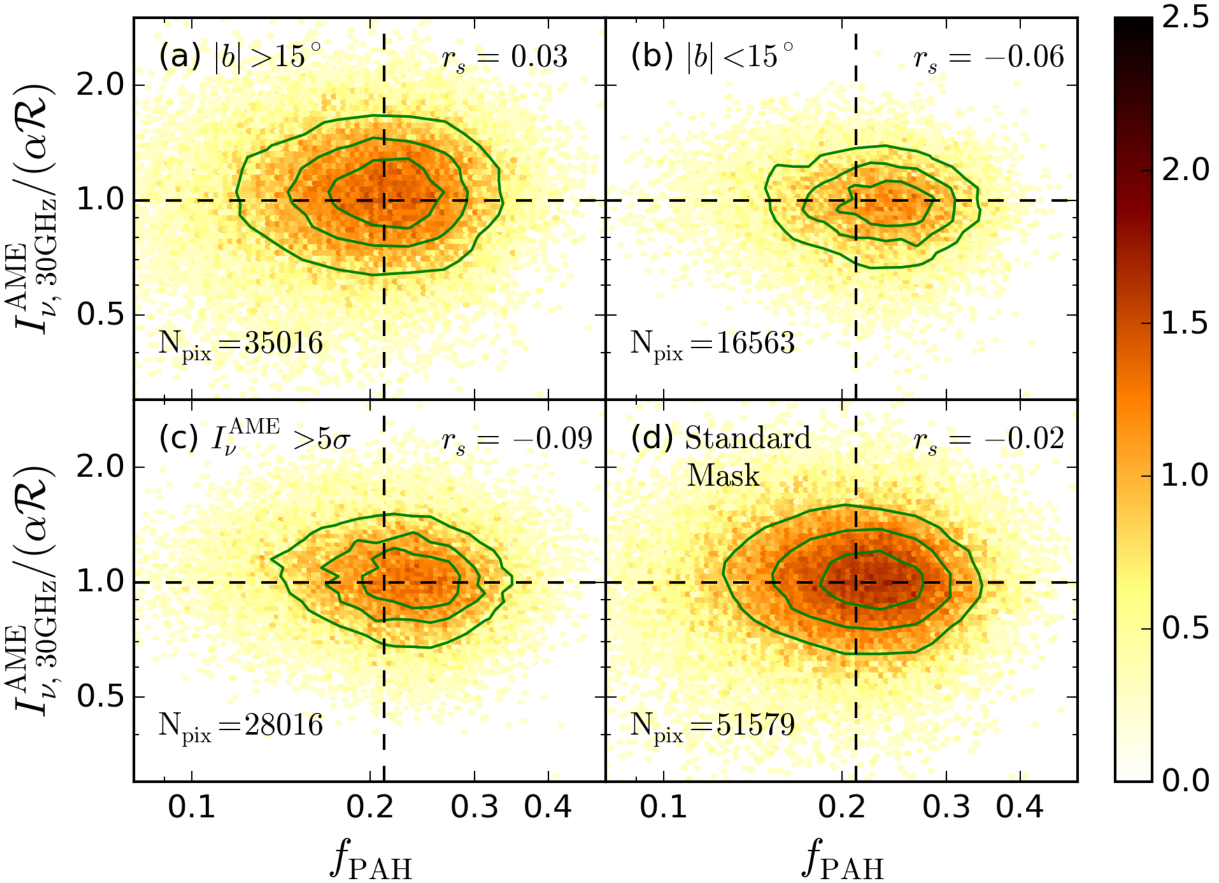


(Hensley et al. 2016)

Surprise #1: __Better__ correlation with τ_{353} than $f_{\rm PAH}\tau_{353}$!

Surprise #2: Much better correlation with $\mathcal{R}$ than with τ_{353} or $f_{\rm PAH}\tau_{353}$!!

Does AME Come from Spinning PAHs?



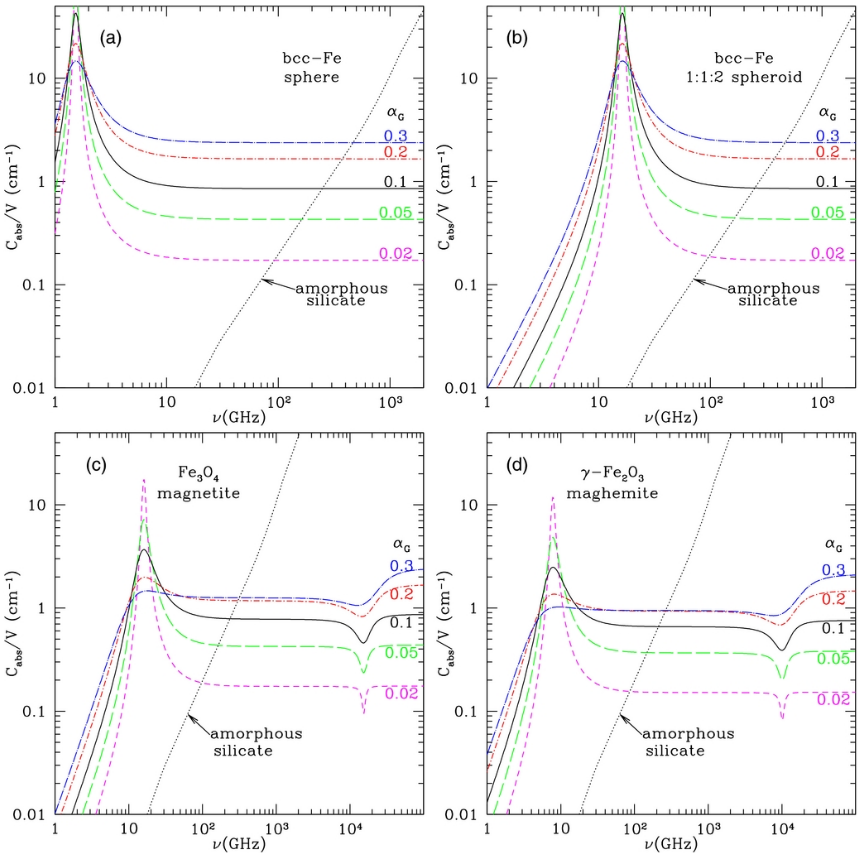
Hensley et al. (2016)

- **No** evidence of variation of AME/$\mathcal{R}$ when f_{PAH} varies!
- 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?) dominates AME
  - Perhaps something else, e.g. thermal emission from magnetic fluctuations in ferromagnetic particles?
- Is the AME consistent with thermal emission?
  Look for variations with T_{dust}

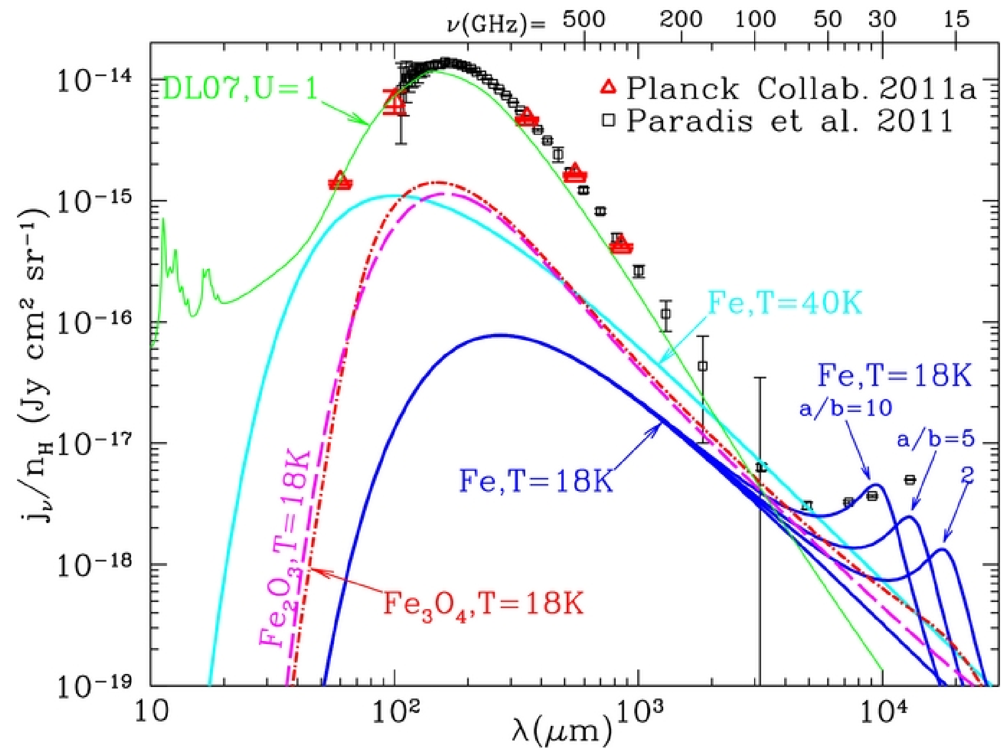
Could the AME be Thermal Emission?

- Suppose some component of dust has very large opacity in 20-50 GHz range
- $I_\nu \propto \kappa_\nu B_\nu(T_d) \propto \nu^2 \kappa_\nu T_d$ – need to have $\nu^2 \kappa_\nu$ peaking near 30 GHz
- One possibility: **magnetic** absorption in ferromagnetic Fe (Draine & Lazarian 1999; Draine & Hensley 2013):

  Fe sphere: ferromagnetic resonance near 1.5 GHz $\Rightarrow$ 10:1 prolate spheroid: resonance at 30.5 GHz



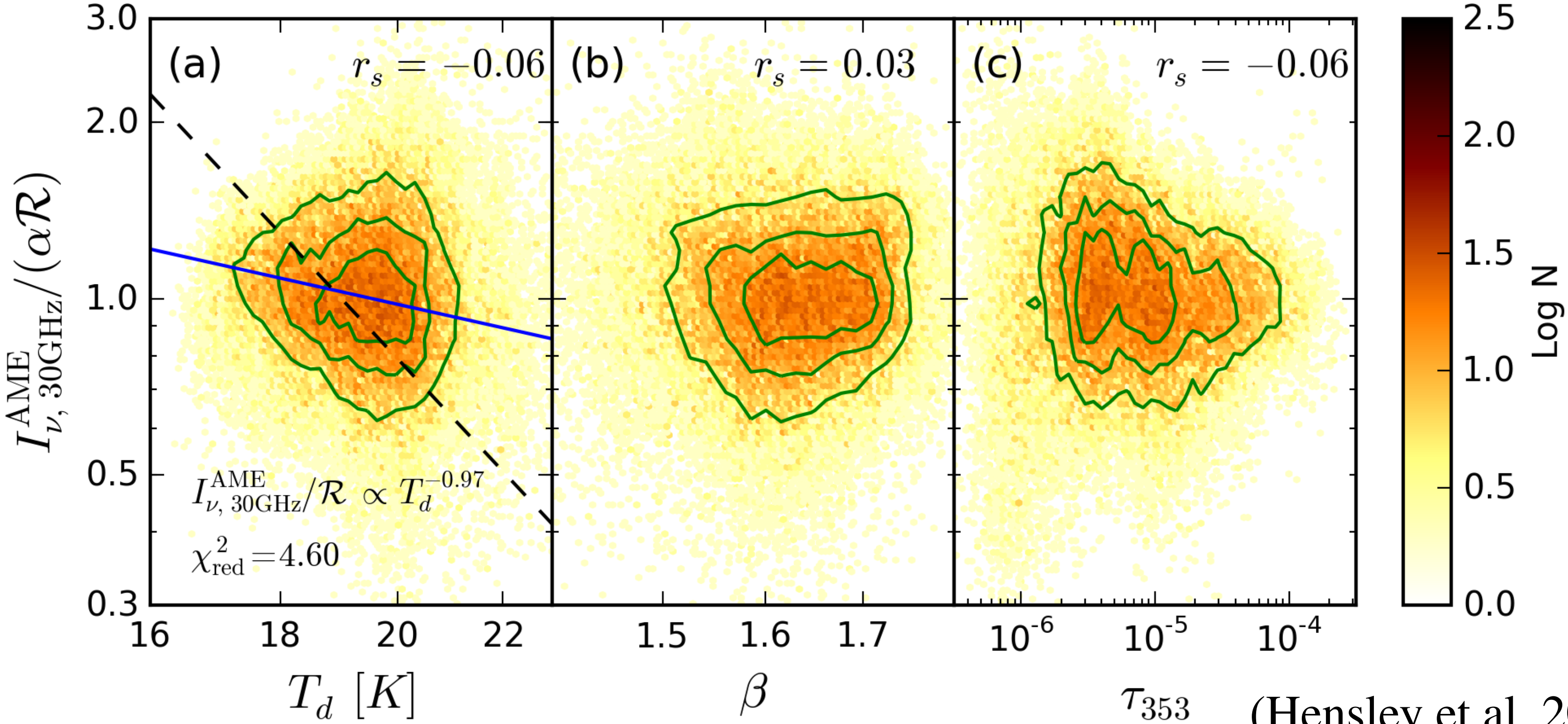
from Draine & Hensley (2013)



Dust model with metallic Fe in grains

from Draine & Hensley (2013)

Test for Thermal Emission Process



(Hensley et al. 2016)

If thermal emission:

$$\mathrm{AME} \;\propto\; \tau_{30}\times B_\nu(T_d) \;\propto\; \tau_{30}\times T_d$$

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

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

Best fit: $\mathrm{AME}/\mathcal{R}\propto T_d^{-0.97}$ *(violet line)*

Observed AME does not appear to be consistent with thermal emission from dust unless dust opacity at 30 GHz is very sensitive to T_d*, as in* $\tau_{30}/\tau_{353}\propto T_d^{3.7}$

[but: $\mathrm{AME}/\mathcal{R}\propto T_d^{-4.65}$ isn't a terrible fit...

thermal emission maybe not (yet) ruled out]

More Careful Treatment of Alignment Physics...

(Draine & Hensley 2016)

Excitation and damping of grain rotation by

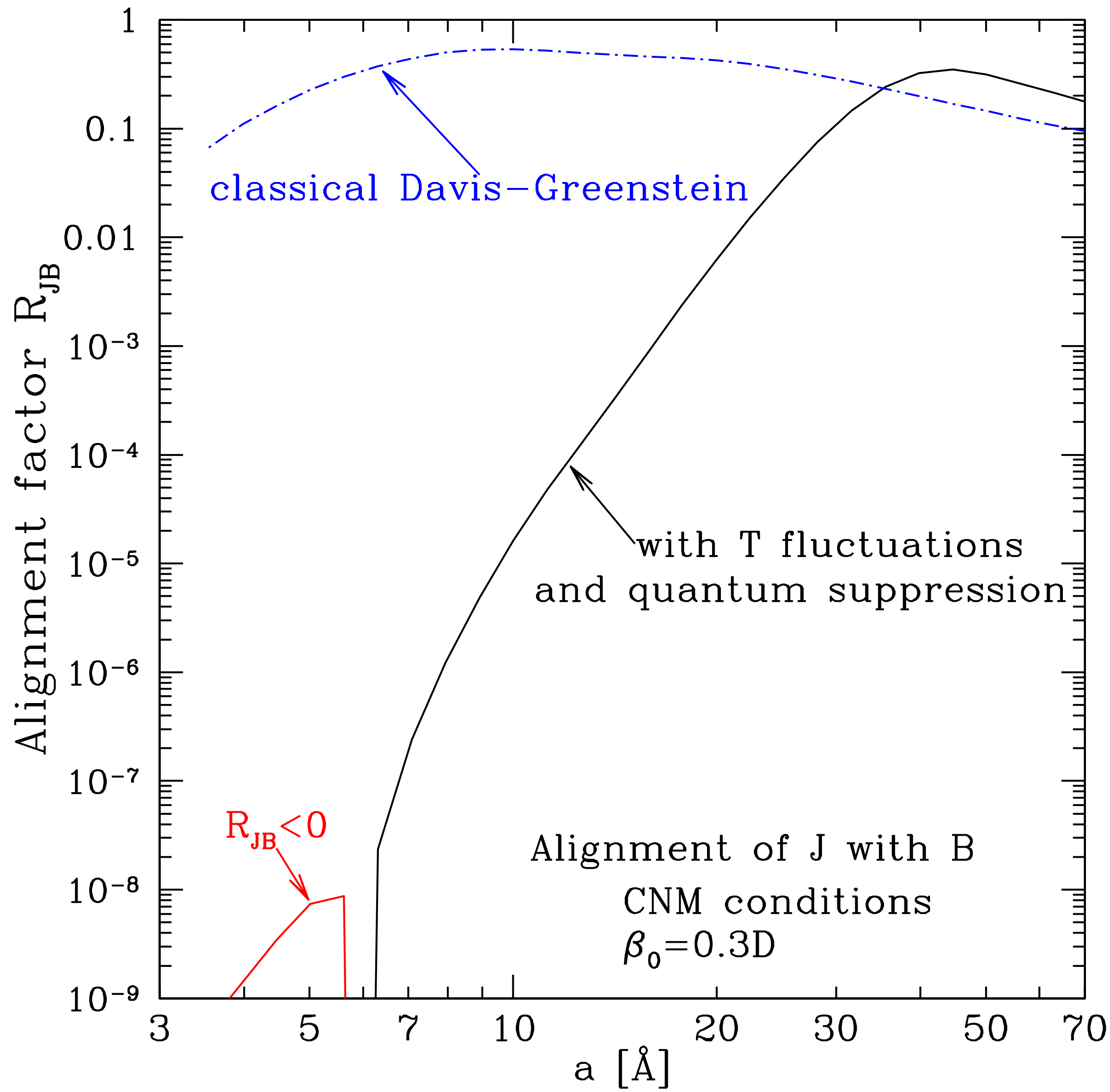
- collisions
- "plasma drag"
- absorption of starlight
- emission of IR photons
- rotational emission
- paramagnetic dissipation

Find rotation $\parallel \mathbf{B}_0$ and $\perp \mathbf{B}_0$:

$$\langle \cos^2\theta \rangle = \frac{\langle J_\parallel^2 \rangle}{(\langle J_\parallel^2 \rangle + \langle J_\perp^2 \rangle)}$$

Alignment measure:

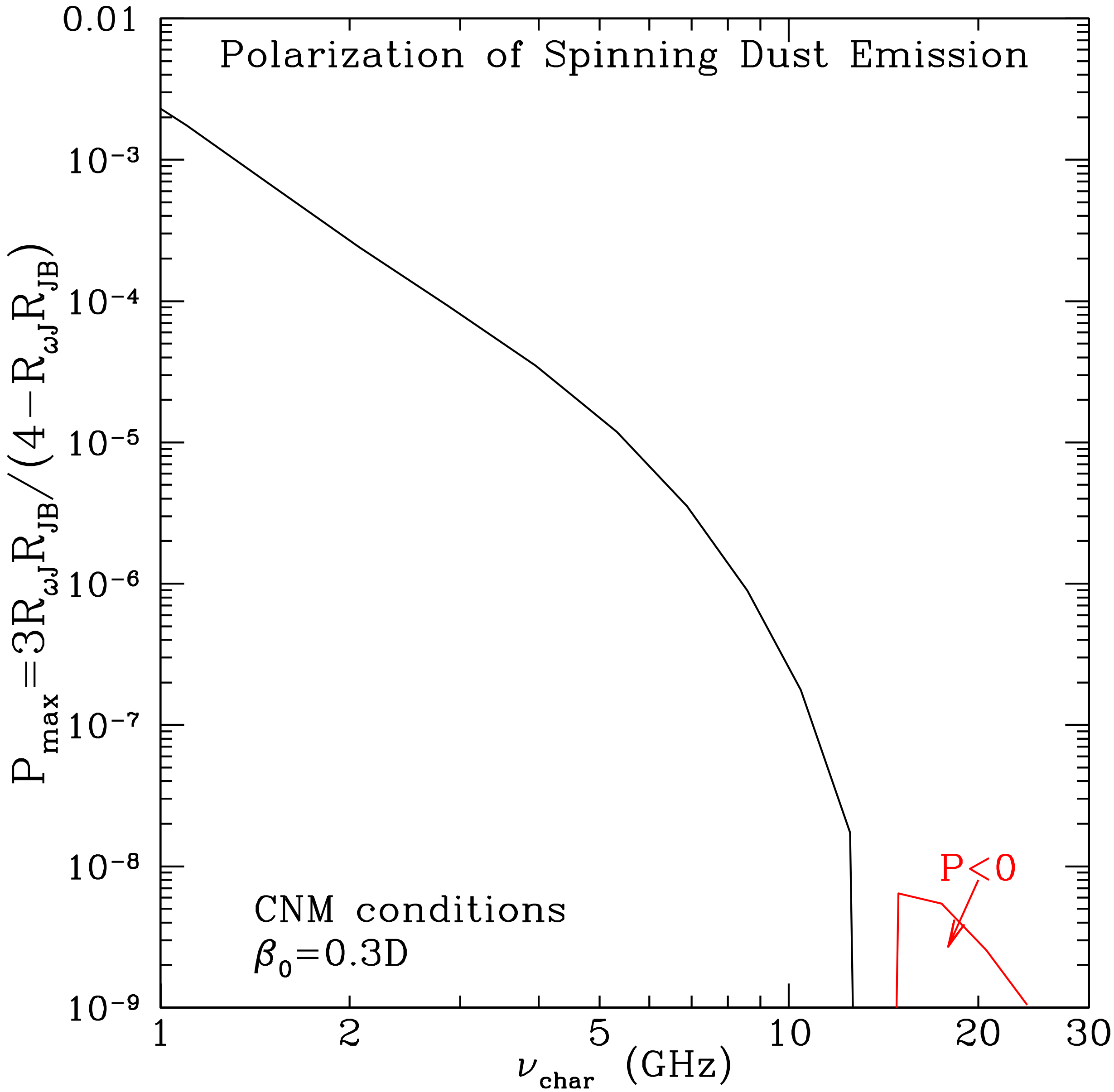
$$R_{\mathbf{JB}} \equiv {}^3\!/_2 \left(\langle \cos^2\theta \rangle - {}^1\!/_3 \right)$$



Polarization of Rotational Emission

(Draine & Hensley 2016)

- Observer's line-of-sight $\perp \mathbf{B}_0$
- Assume each size to spin at characteristic frequency $\langle\omega^4\rangle^{1/4}$
- Allow for imperfect alignment of $\boldsymbol{\omega}$ with $\mathbf{J}$ ($R_{\omega\mathbf{J}} \approx 0.9$)



Anomalous Microwave Emission: *Still a Mystery*

- *No evidence of expected connection to PAHs*
- *No evidence for thermal emission process*

  (but perhaps not yet ruled out...)
- *Is AME primarily from spinning non-PAH nanoparticles?*

  (silicates? SiO_2? Fe? non-PAH carbon?)

How to proceed?

- Further studies of polarization
  - spinning dust expected to be minimally polarized
  - many "big" grains are aligned:
    thermal emission from material in "big" dust grains likely to be polarized
- non-PAH spinning dust hypothesis:
  model (and look for) IR emission following single-photon heating
- thermal emission not (yet) ruled out:
  lab studies of candidate (ferromagnetic?) materials to find absorption spectrum
- more sensitive studies of AME spectrum
  - from ground
  - future CMB missions


THANK YOU

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Testing the PAH-AME Connection

(Hensley, Draine, & Meisner 2016, submitted to ApJ.)

- AME map from Planck ($\sim 1^\circ$ resolution)
  ("Commander" analysis; Planck Collaboration et al. 2015)
  maps of τ_{353}, $T_{\rm dust}$, β, and total dust radiance $\mathcal{R}$ from Planck 2013 results XI (Planck Collaboration et al. 2014a)

- map of diffuse $12\mu\mathrm{m}$ from WISE (Meisner & Finkbeiner 2014)
  (diffuse $12\mu\mathrm{m}$ is dominated by PAH emission).

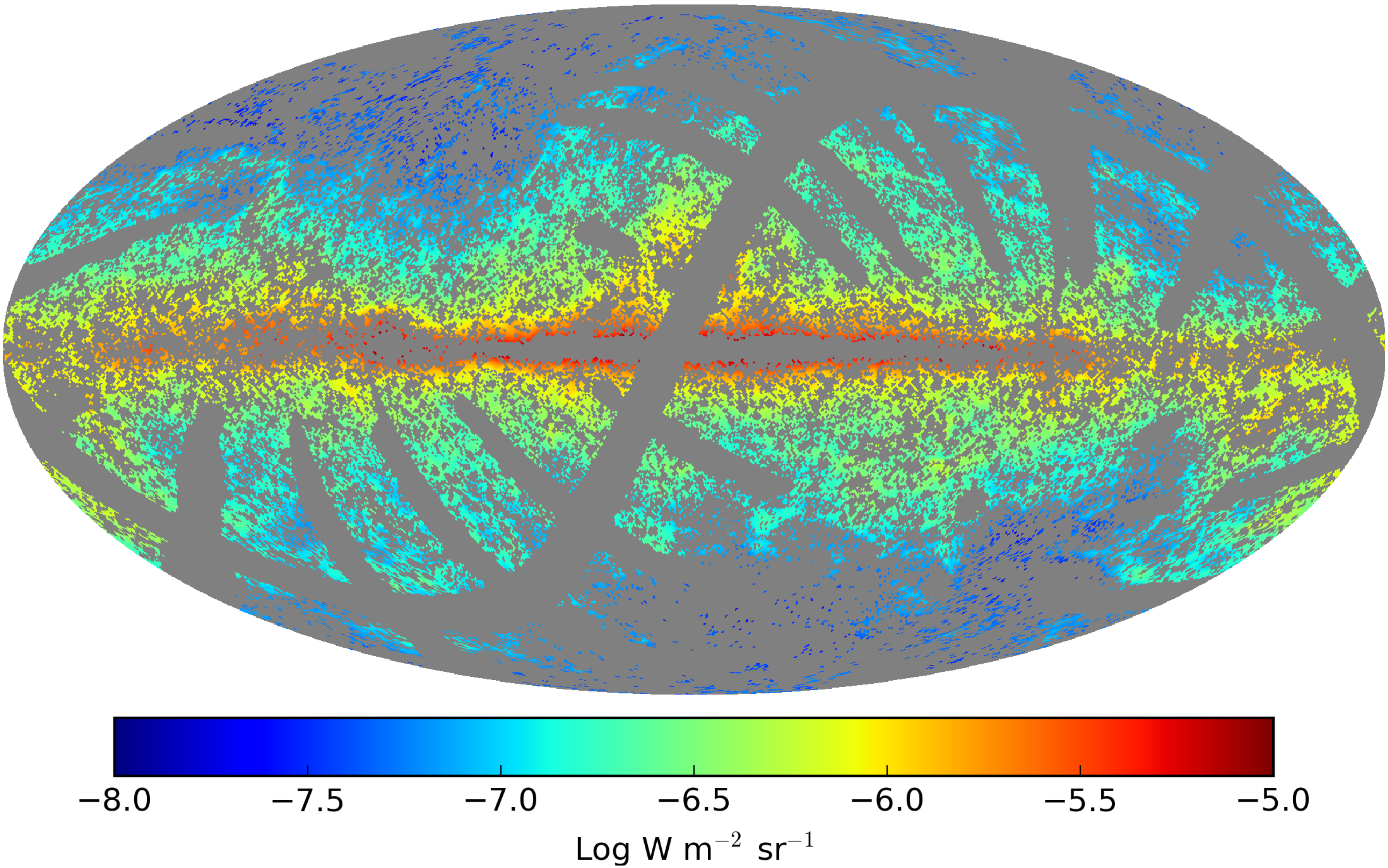
- PAH abundance assumed to be measured by

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

within each $\sim 1^\circ$ pixel

Area Studied

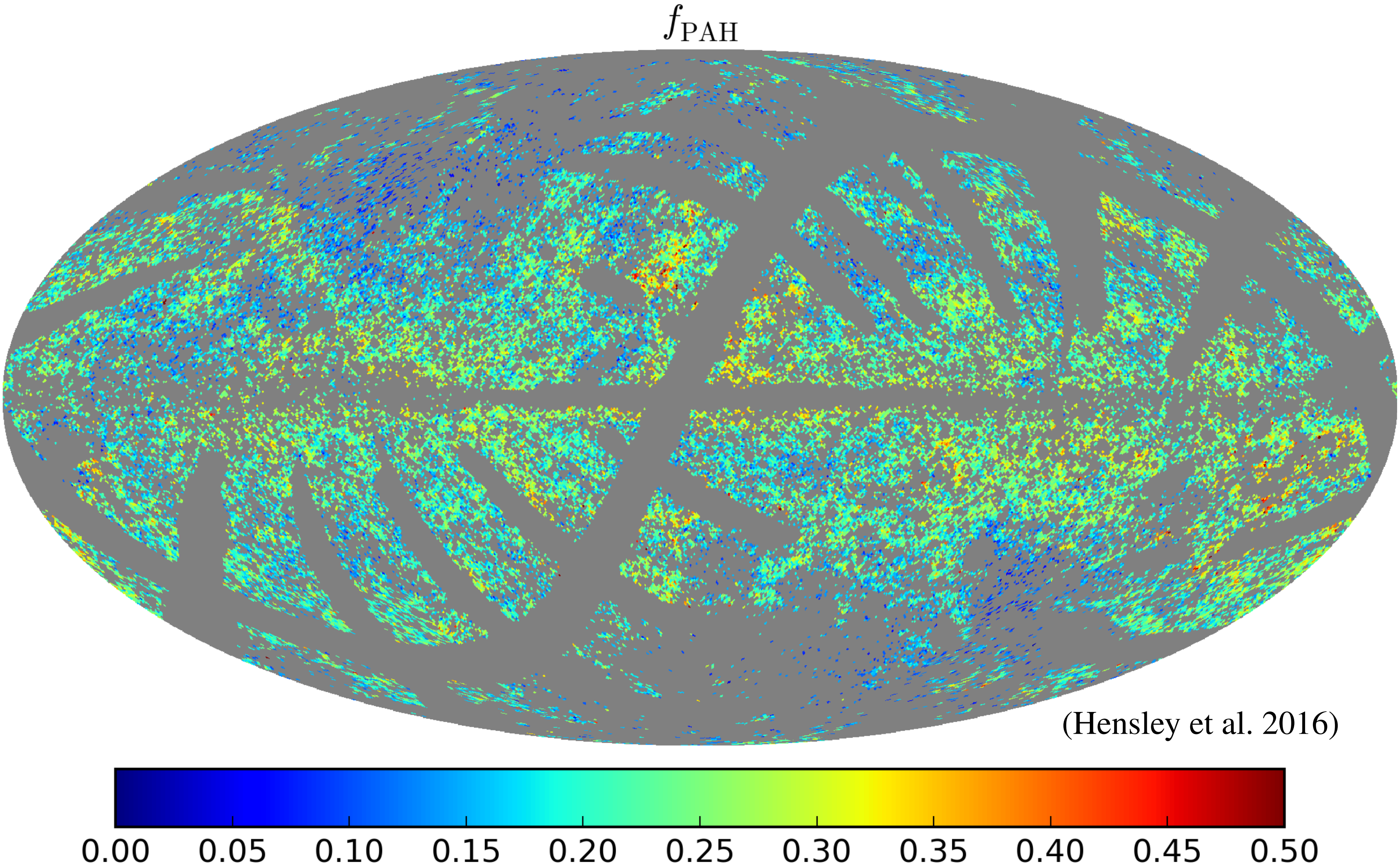
Dust Radiance $\mathcal{R}$ =Total dust power at $\lambda > 30\mu\mathrm{m}$.



Masked: Ecliptic, Galactic plane, $12\mu\mathrm{m}$ moon, point sources, faint regions: 26% remains

PAH Abundance Measure $f_{\rm PAH} \equiv (\nu I_\nu)_{W3}/\mathcal{R} \propto \Sigma_{\rm PAH}/\Sigma_{\rm dust}$

$$(\nu I_\nu)_{W3} \propto \Sigma_{\rm PAH} \times U_\star \quad , \quad \mathcal{R} \propto \Sigma_{\rm dust} \times U_\star$$



- **Appear to be real variations in $f_{\rm PAH}$ over the sky**

What do we expect AME to depend on?

- **Model calculations of rotational excitation:**
  spinning dust emission per grain is relatively insensitive to
  - moderate variations in starlight illumination
  - moderate variations in gas density
- Therefore expect

$$I_\nu(\mathrm{AME}) \quad \propto \quad \Sigma_{\mathrm{dust}} \quad \propto \quad \tau_{\mathrm{FIR}}$$

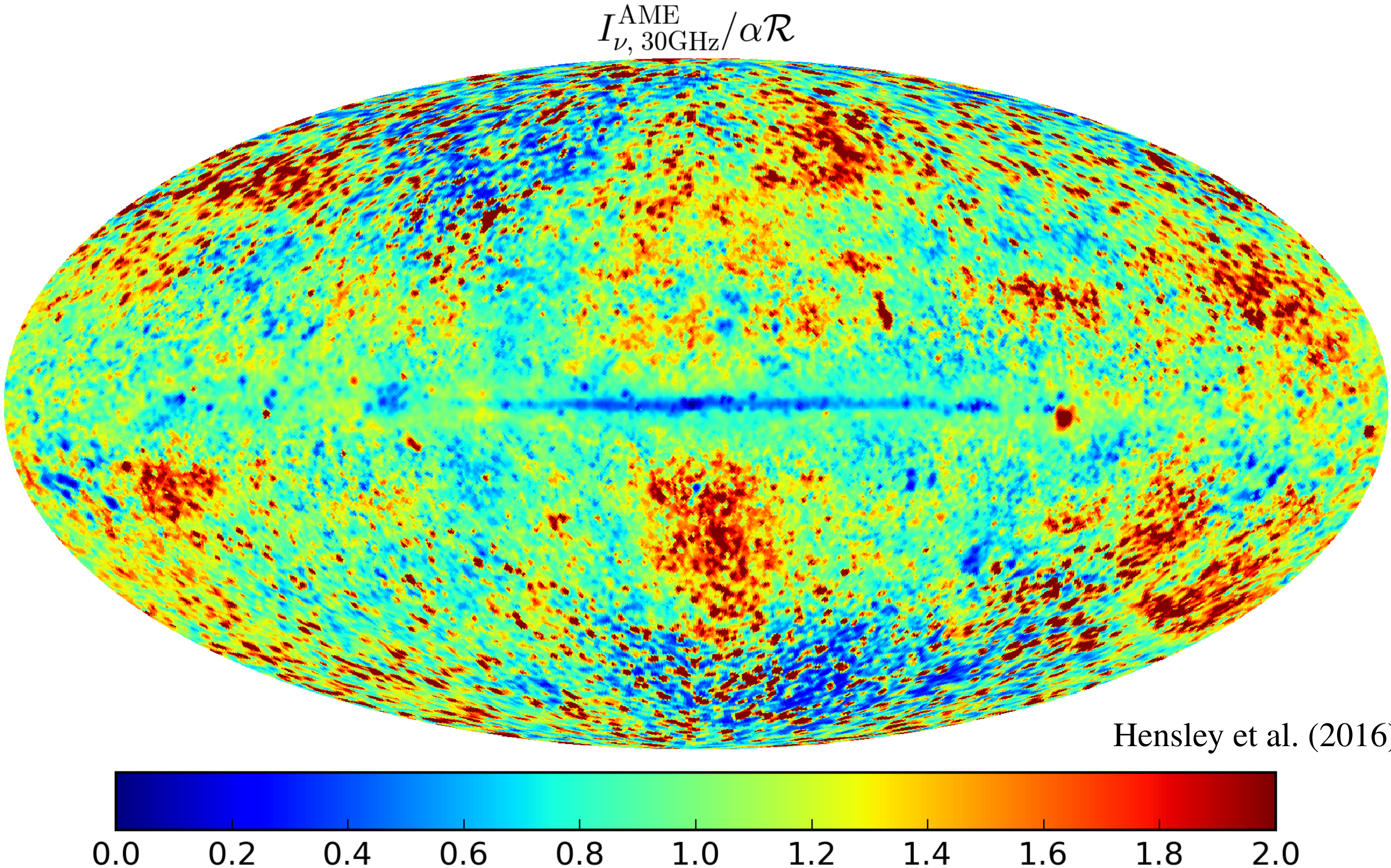
- Therefore expect good correlation of two quantities from Planck:

$$I_\nu(\mathrm{AME}) \qquad \mathrm{with} \qquad \tau_{353\mathrm{GHz}} \quad (\propto \Sigma_{\mathrm{dust}})$$

- And if PAH abundance is variable, expect *better* correlation of

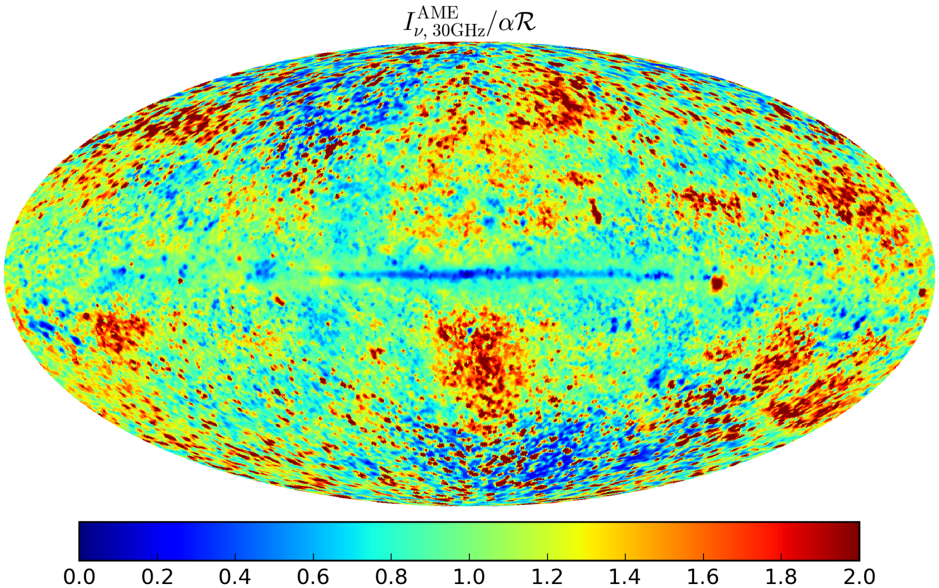
$$I_\nu(\mathrm{AME}) \qquad \mathrm{with} \qquad f_{\mathrm{PAH}}\,\tau_{353\mathrm{GHz}}$$

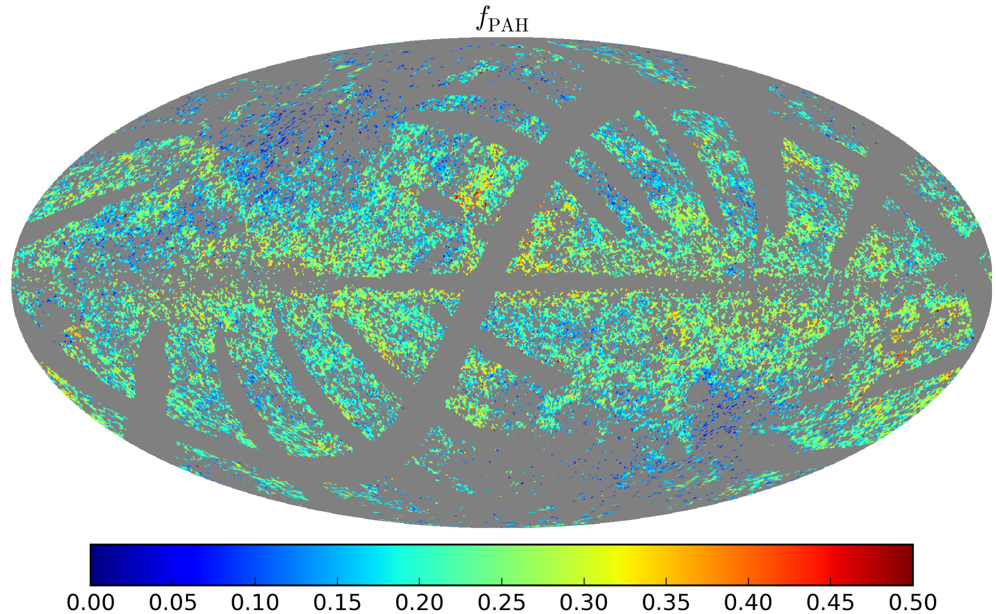
Regional Variations in AME/$\mathcal{R}$



Are regions of high or low AME/$\mathcal{R}$ correlated with high or low f_{PAH}?

Are variations in AME/$\mathcal{R}$ correlated with $f_{\rm PAH}$?



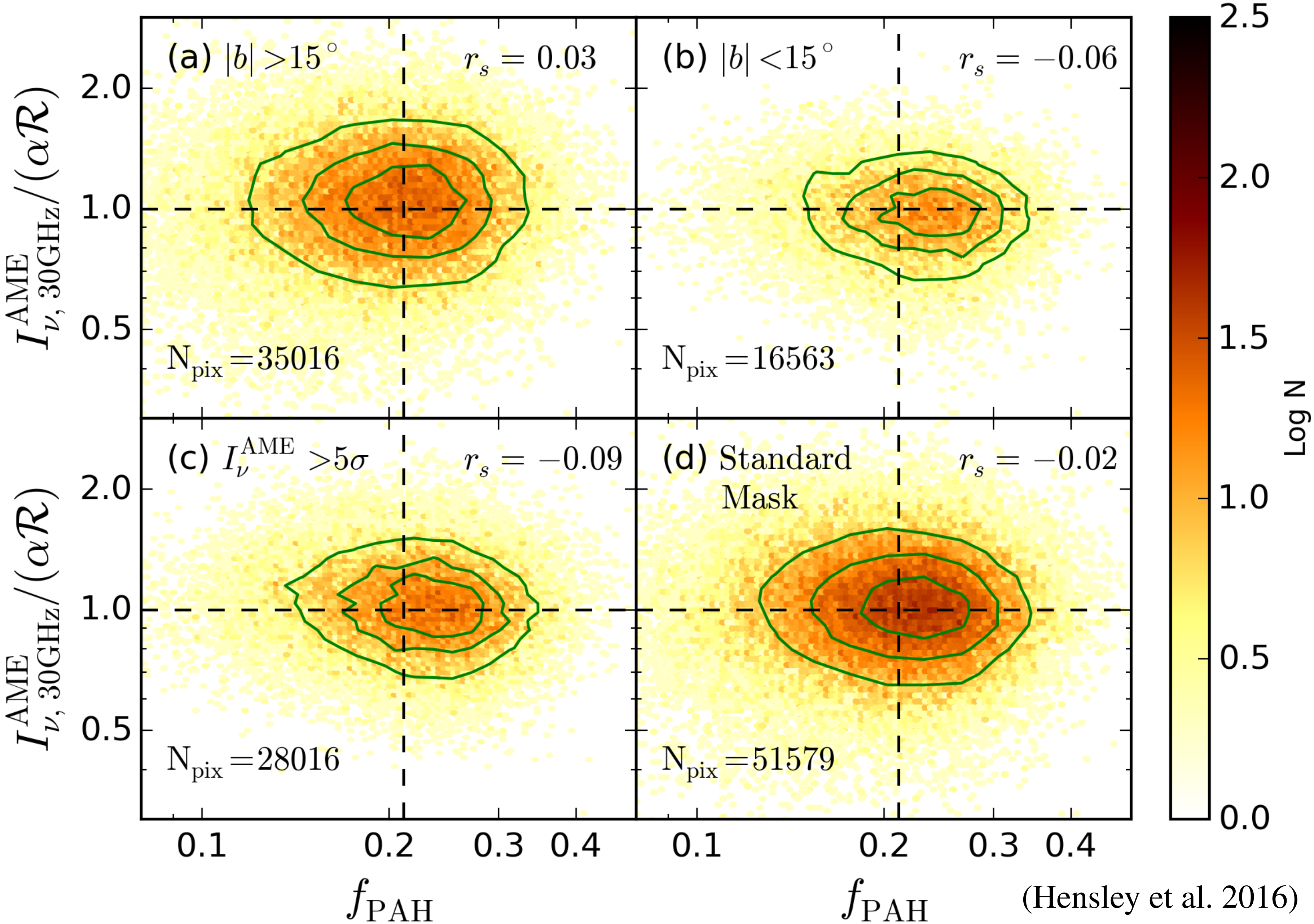


(Hensley et al. 2016)

If any relationship, it is not apparent.

Let's look at a scatter plot...

Does AME Come from Spinning PAHs?



(Hensley et al. 2016)

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