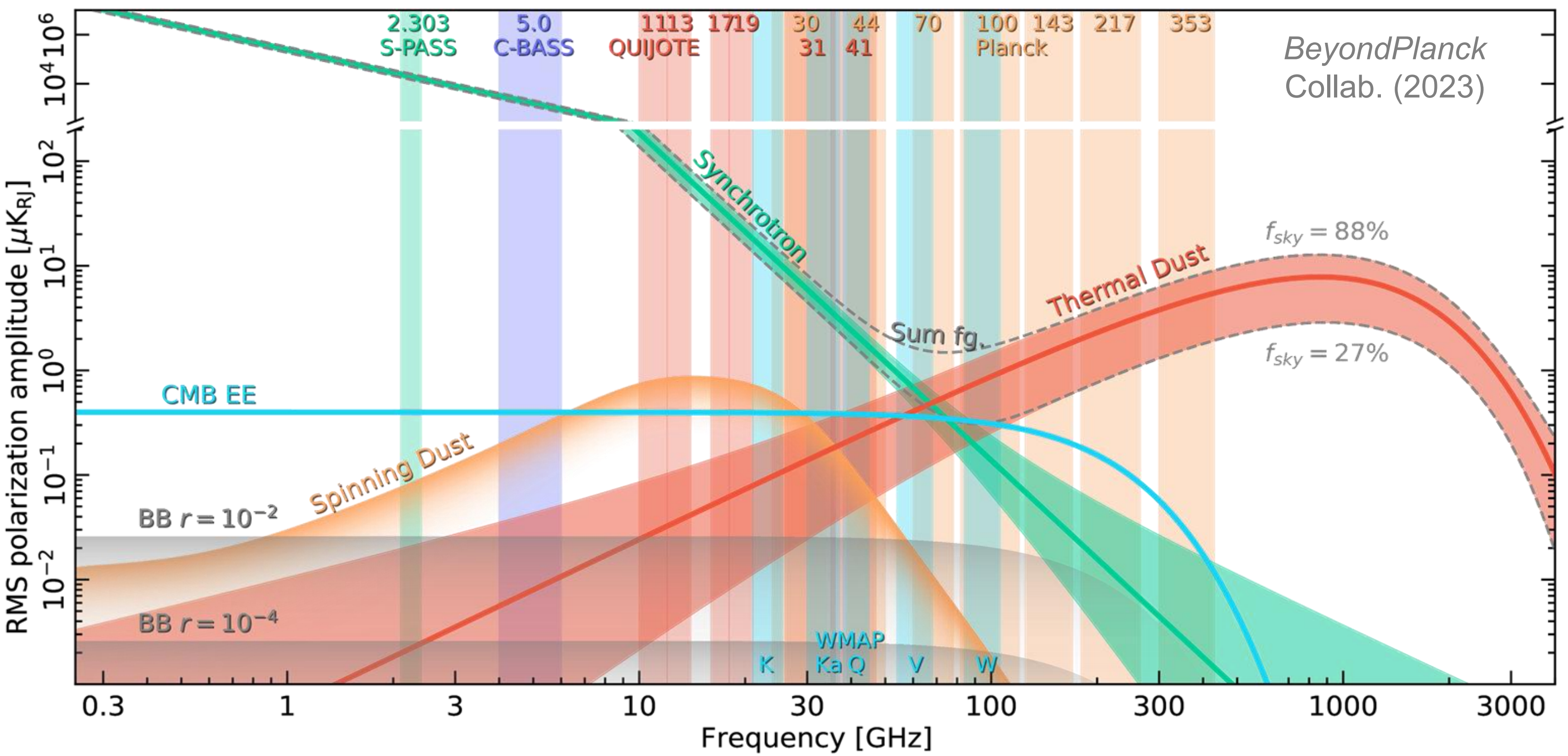
Treatment of Less-Known Foregrounds

Roke Cepeda-Arroita (IAC, Tenerife)

Introduction

Galactic Foregrounds Are Unavoidable

We observe the Universe from inside a bright, dusty galaxy



How We Separate Foregrounds (and Where It Fails)

Spectral

Model / Physics Driven

Assume SED models. Fit amplitudes + spectral parameters at pixel level.

e.g. Commander

- ✓ Physical foreground maps
- ⚠ Wrong spectral model → biased cosmology

Spatial

Template / Morphology Driven

Assume emission location on sky. Use external tracer maps.

e.g. Template fitting

- ✓ Powerful discovery tool for new foregrounds
- ⚠ Frequency decorrelation → map mismatch

Statistical

Data / Covariance Driven

Separate via statistical structure across frequencies and sky. Minimize variance.

e.g. ILC

- ✓ Minimal foreground assumptions
- ⚠ CMB-foreground correlations → biased cosmology

Most modern methods combine spectral + spatial + statistical information

Why Universal Spectral Models Do Not Exist

- Physics are known at micro scale but not macro
- The emission we see is a superposition (different β_s, T_d…):

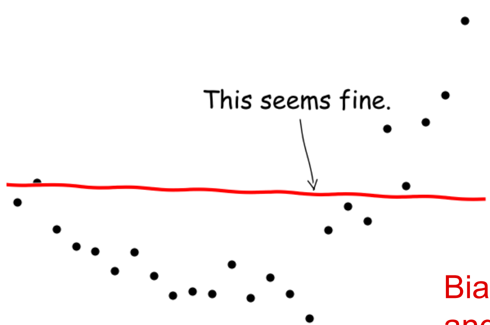
Σ power laws ≠ power law,
Σ blackbodies ≠ blackbody, etc.

→ Spectra are **emergent**, not intrinsic

Model complexity

Too simple

Too complex

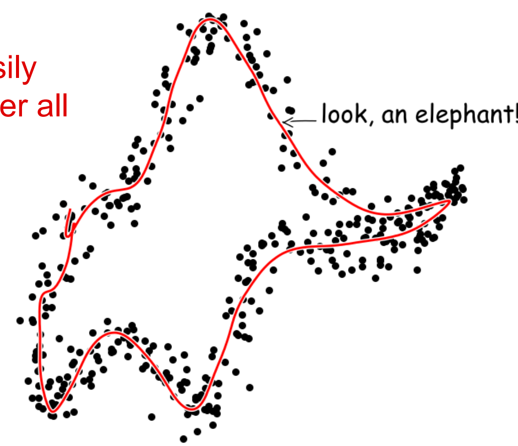


Biased astrophysics and cosmology

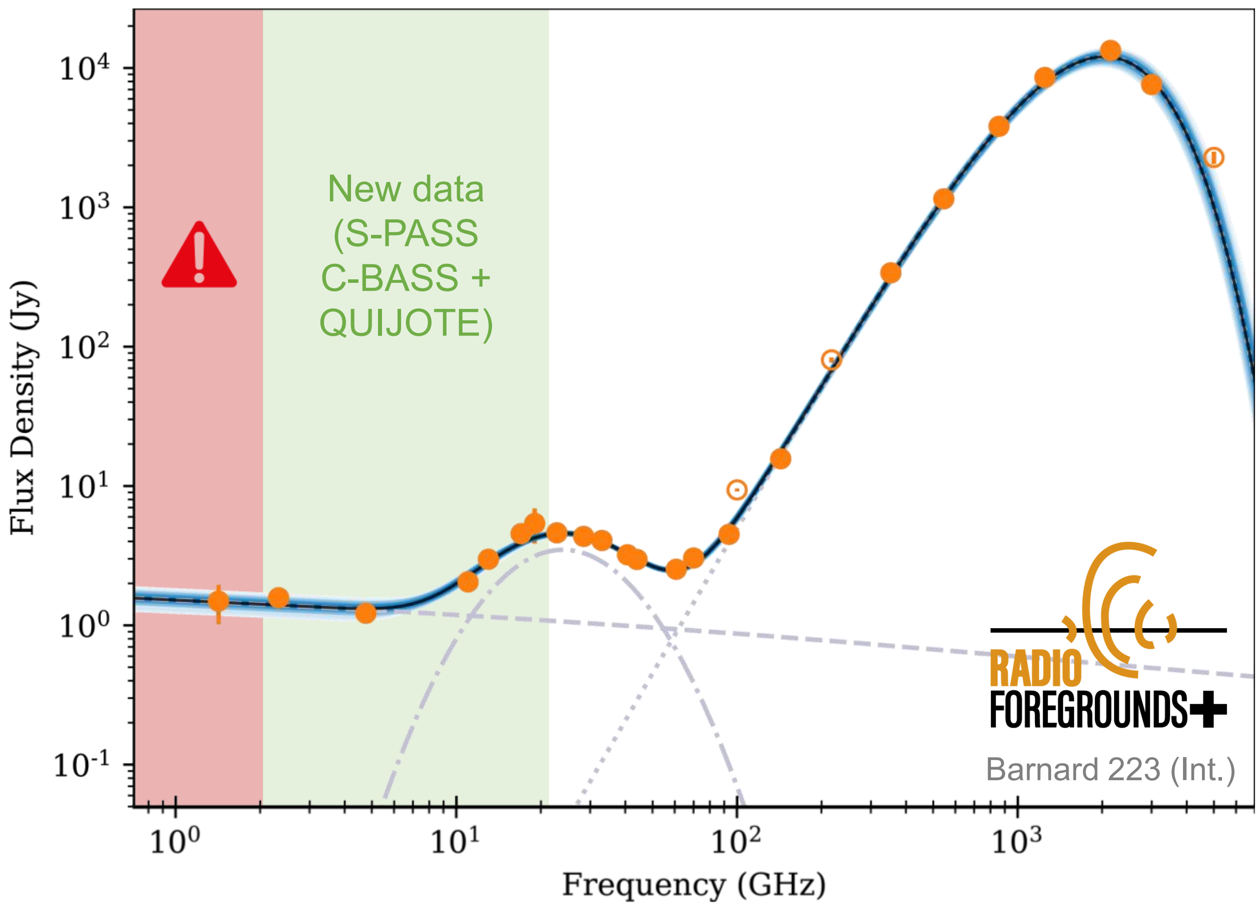
We cannot easily marginalize over all unknowns

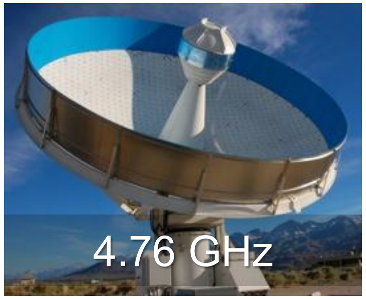
Degeneracies, overfitting

Overestimation of component uncertainties



QUIJOTE, C-BASS, S-PASS: What They Enable





Improved synchrotron, free-free and AME characterization!

QUIJOTE

2 × 2.25 m telescopes

10–40 GHz

56′–17′

Clean optics

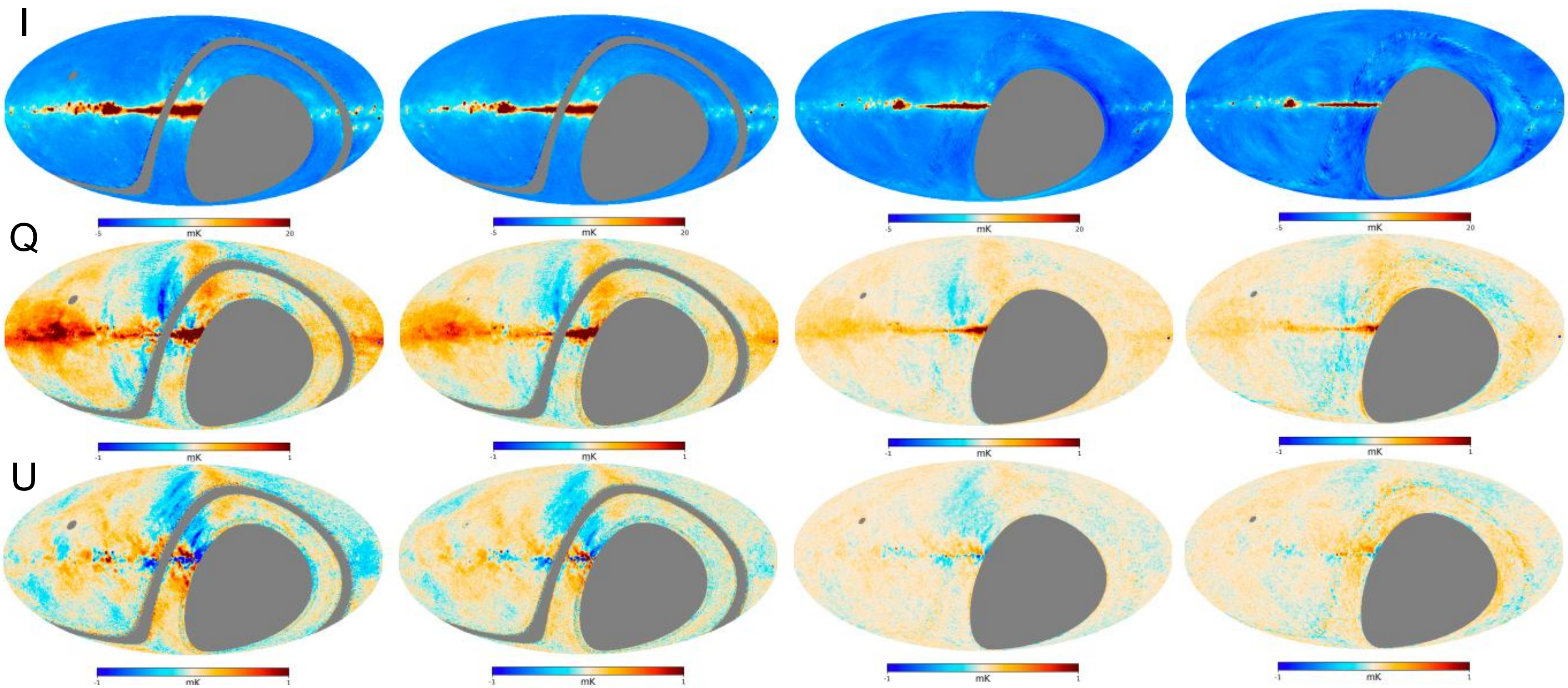
2026 upgrades: **MFI2** with FPGAs & improved receivers, 90 GHz camera…

Visit on Wednesday!

QUIJOTE

MFI Wide Survey (10-20 GHz)

Rubino-Martin et al. 2023



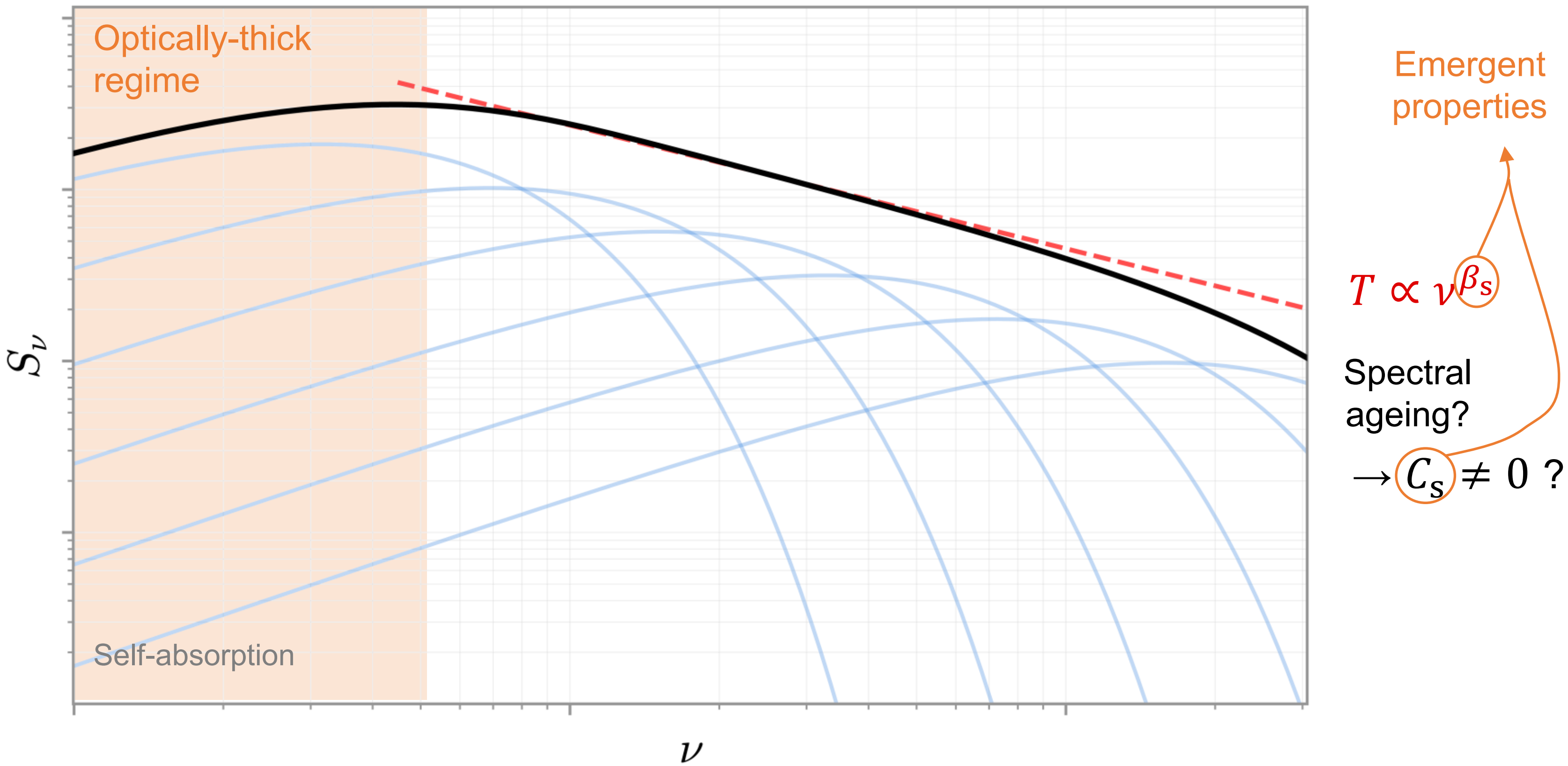
11 GHz 13 GHz 17 GHz 19 GHz

Polarization ~2 μK · arcmin at 100 GHz (if β=-3)

Part II: Synchrotron

Synchrotron *micro*physics vs *macro*physics

✓ The spectrum of a single electron averaged over its orbit is well known, and the summed emission is well approximated by a power law in the optically thin regime.

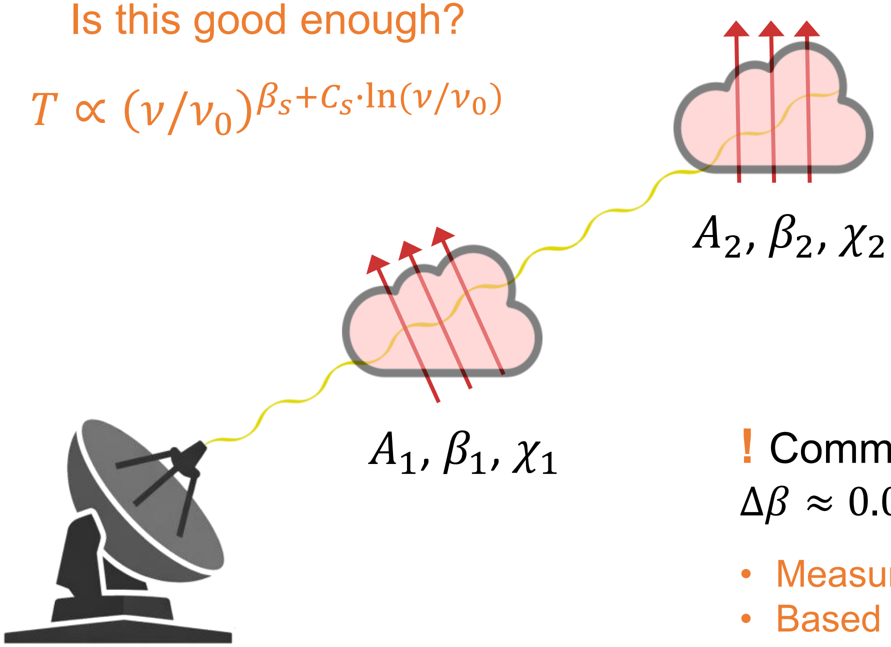


Synchrotron *micro*physics vs *macro*physics

✓ The spectrum of a single electron averaged over its orbit is well known, and the summed emission is well approximated by a power law in the optically thin regime

Is this good enough?

$$T \propto (\nu/\nu_0)^{\beta_s + C_s \cdot \ln(\nu/\nu_0)}$$



! Spectral index variations

! Multiple components along the line of sight

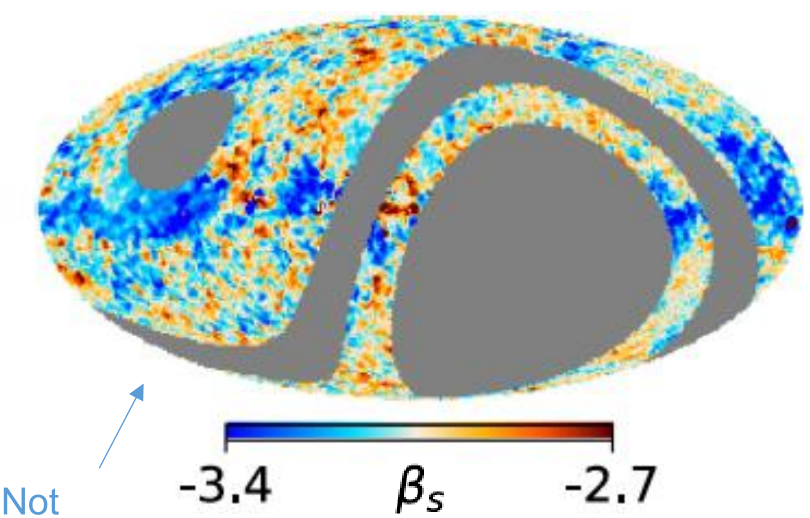
! Line of sight superposition, depolarization…

! Commonly assumed (PySM slightly lower):
$\Delta\beta \approx 0.07$ per octave or $C_s = 0.1$ (Kogut 2012)

- Measurement assumes homogeneity!!
- Based on 22 MHz – 10 GHz data → extrapolating to >10 GHz is unvalidated
- Fixed 0.31 GHz pivot

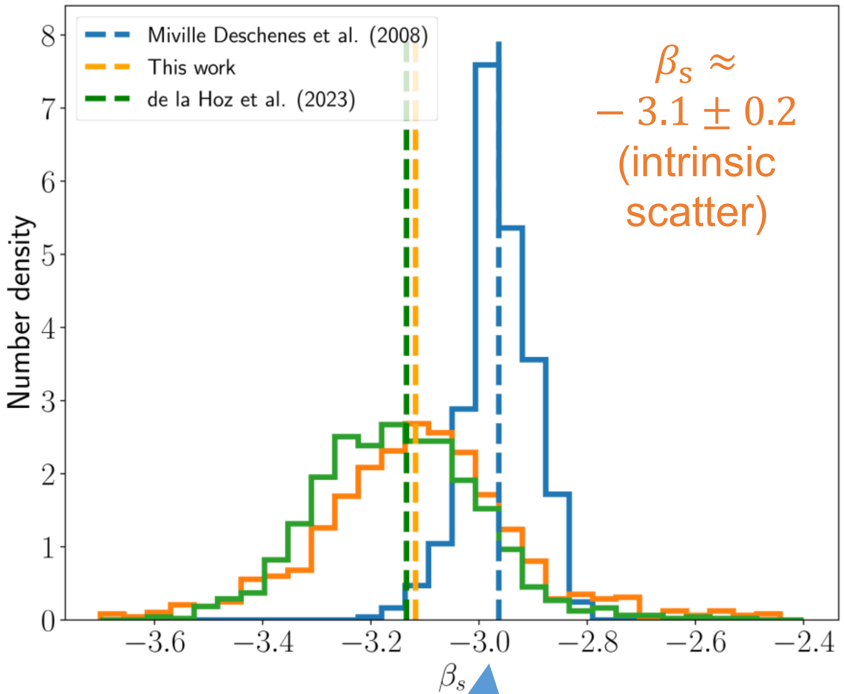
What Sky Simulations Still Miss

De la Hoz et al. 2023 (QUIJOTE)



Not possible with WMAP + Planck!

Adak et al. 2025 (QUIJOTE)

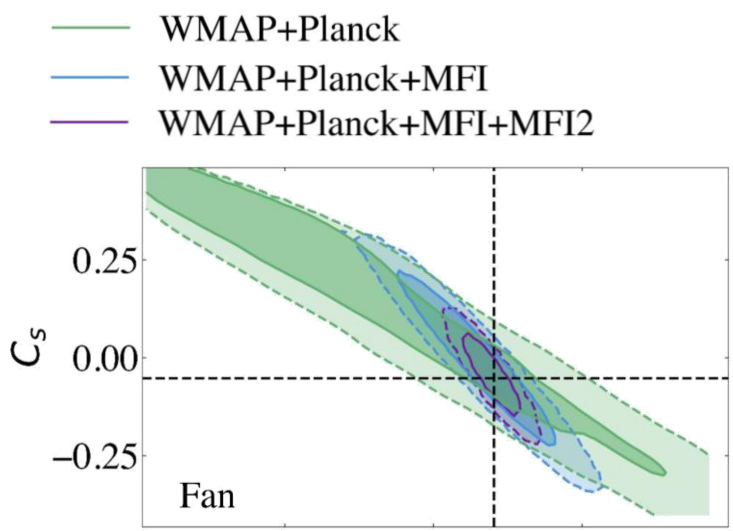


$\beta_s \approx -3.1 \pm 0.2$ (intrinsic scatter)

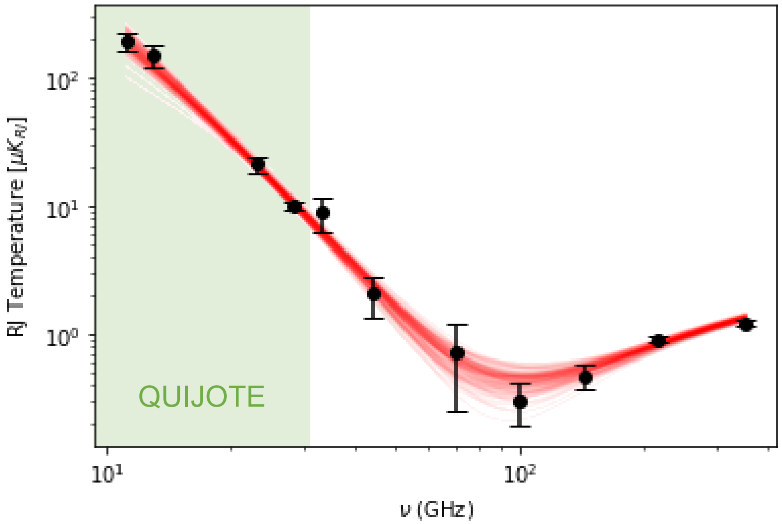
- Larger β_s variations, and different mean values than the PySM nominal model!
- Data cannot robustly detect curvature on a per-pixel basis (1° FWHM)

What Sky Simulations Still Miss

QUIJOTE MFI2 Forecasts
Almeida et al. 2025



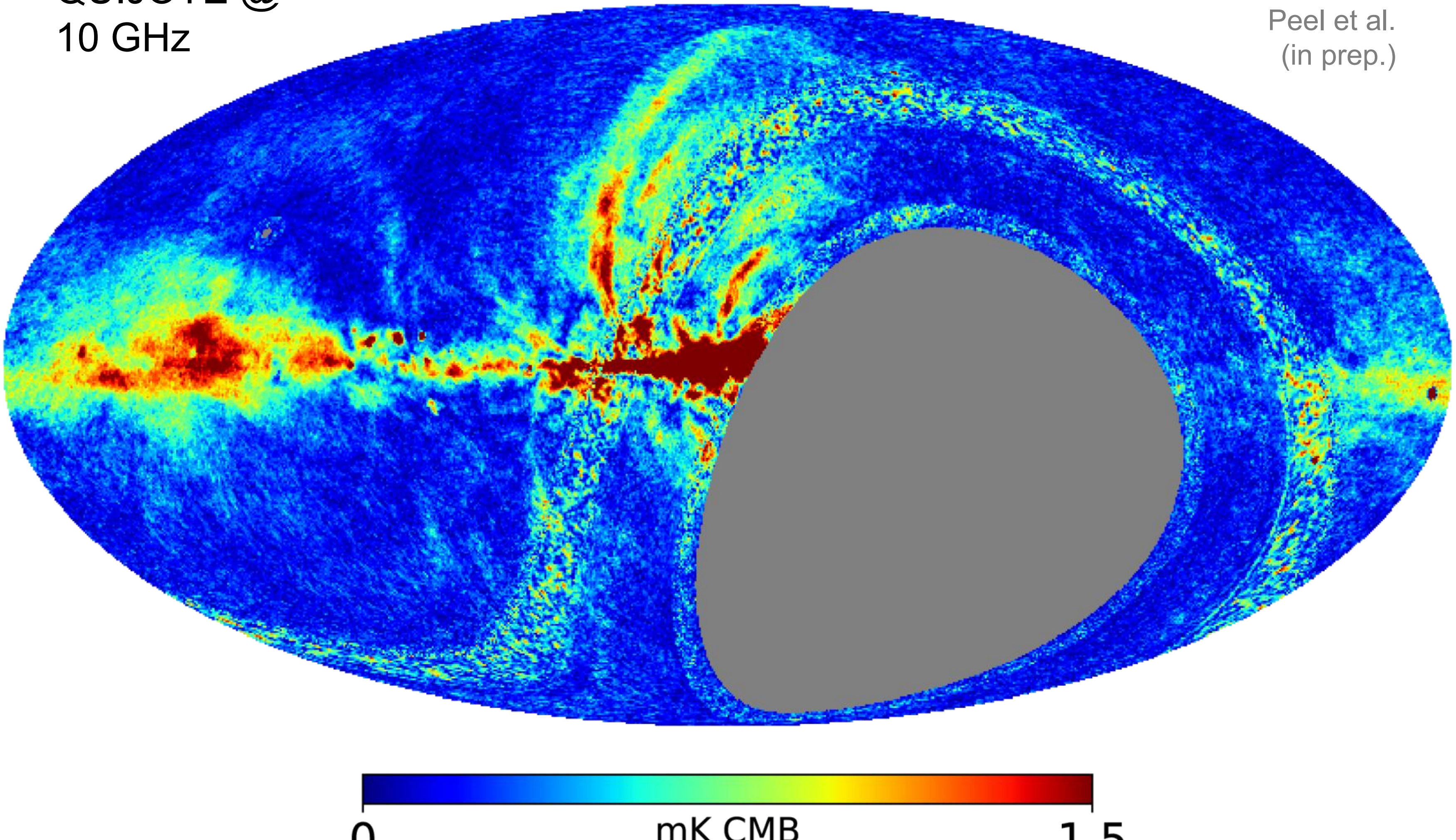
QUIJOTE+C-BASS Parametric Separation
Almeida et al. in prep.



- $C_s = -0.052$ remains undetectable pixel-by-pixel; a 2σ detection requires $|C_s| \gtrsim 0.18$ in the brightest regions! (1° FWHM)
- In low-brightness regions, MFI2 reduces the 100 GHz synchrotron residual by a factor ≈ 2, starts to constrain β_s

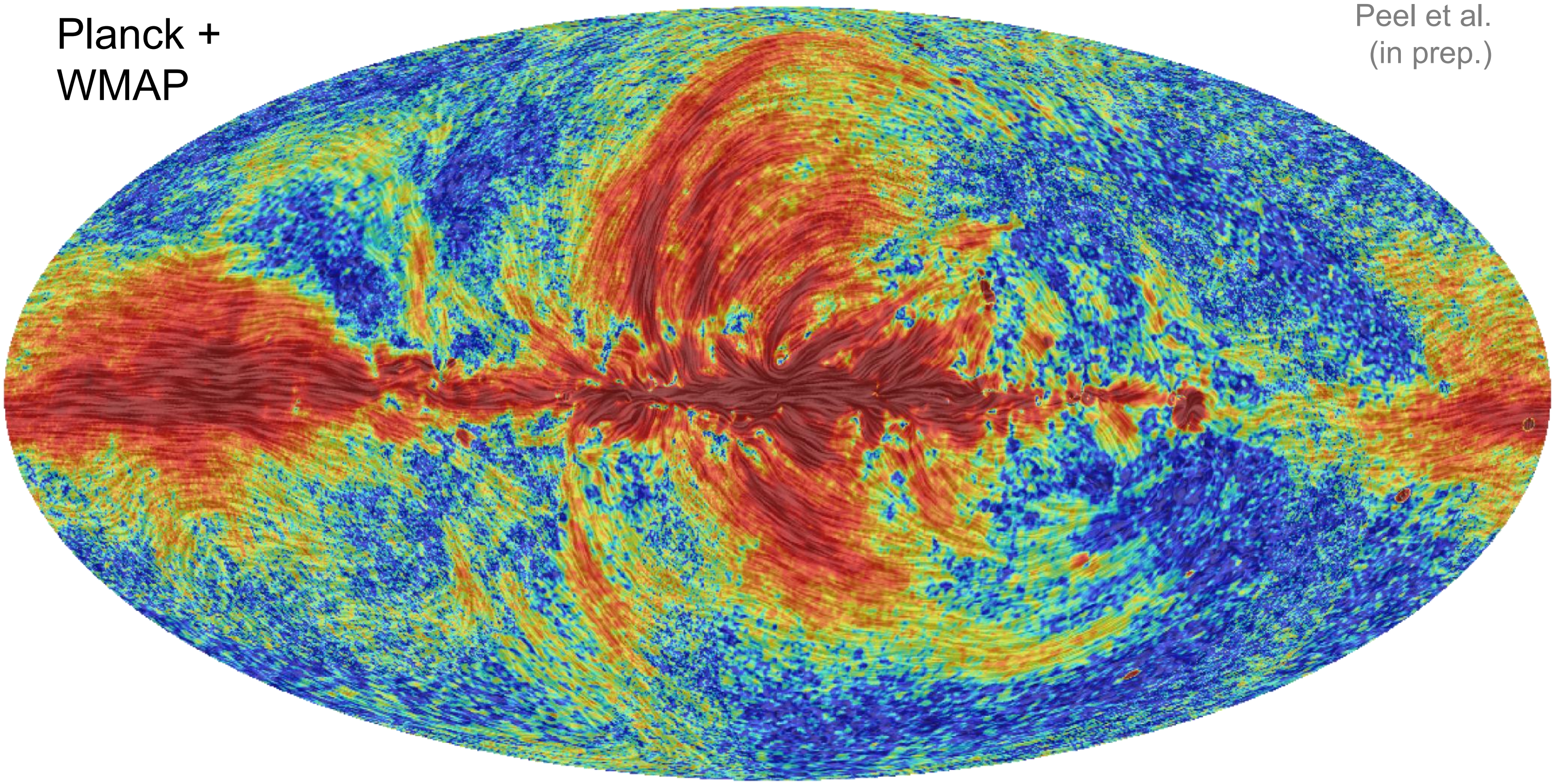
QUIJOTE View of Polarized Synchrotron

QUIJOTE @
10 GHz



QUIJOTE View of Polarized Synchrotron

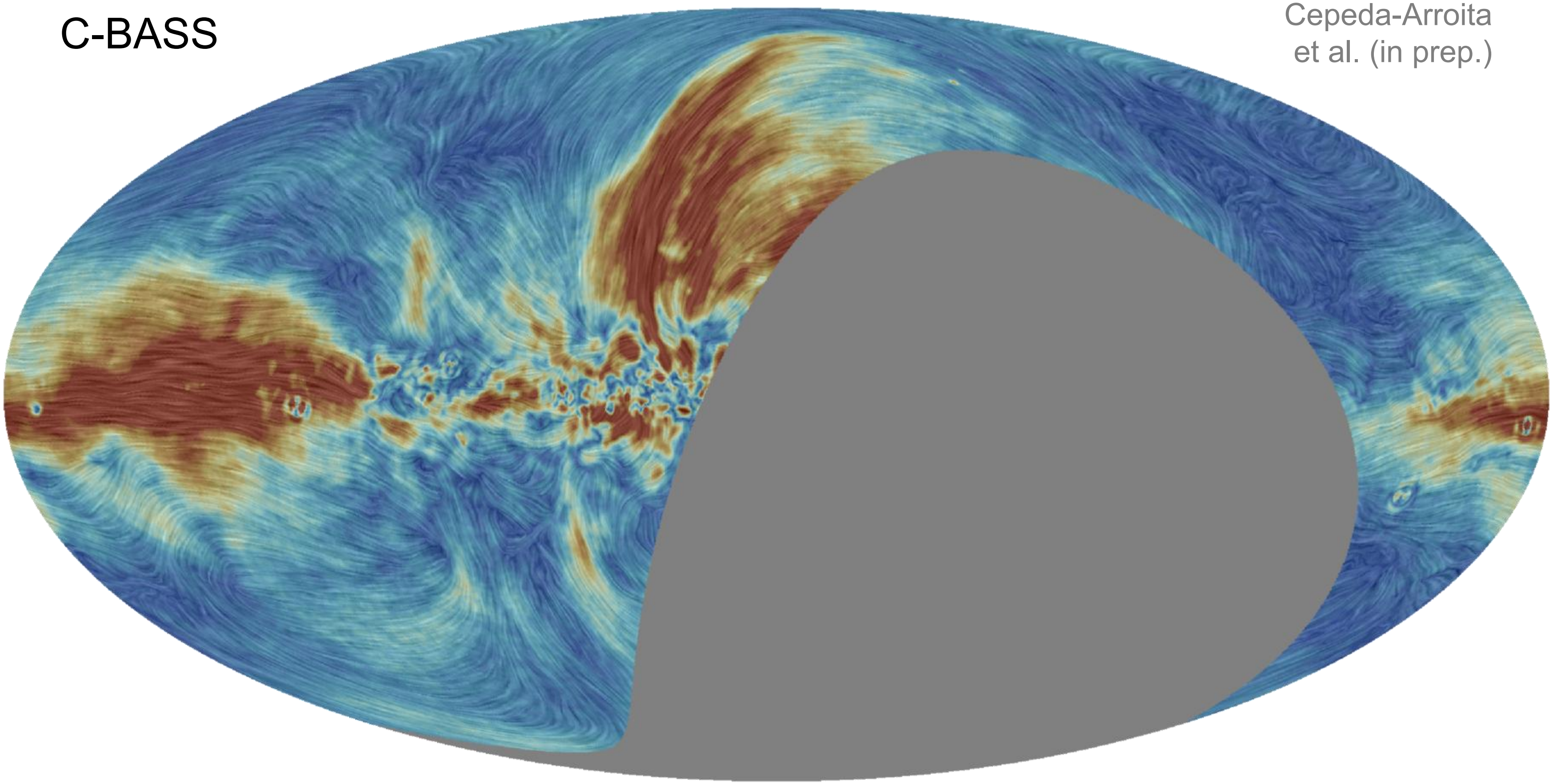
QUIJOTE +
Planck +
WMAP



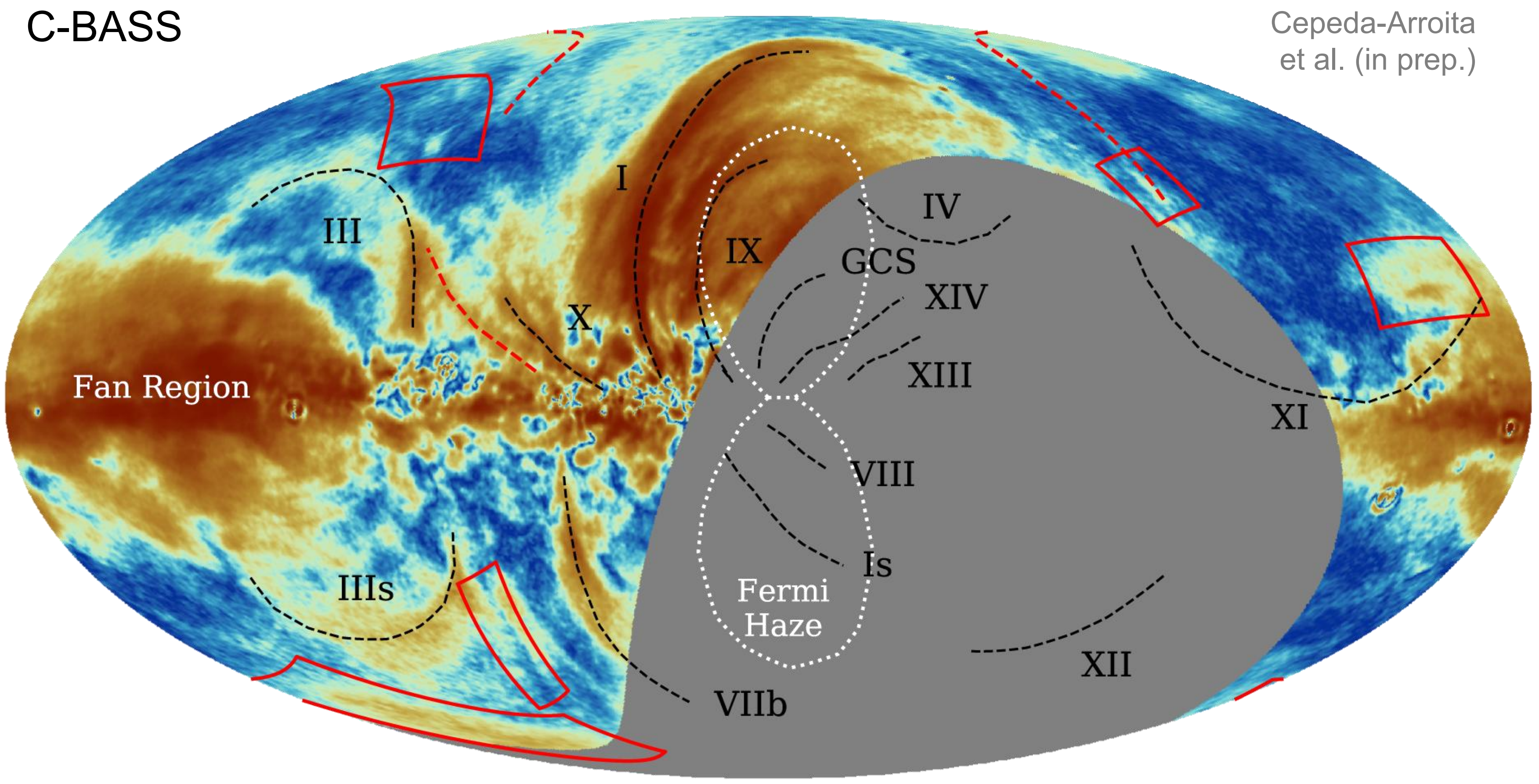
Peel et al.
(in prep.)

Large scale synchrotron loops are unavoidable, even in cosmological fields!

C-BASS View of Polarized Synchrotron



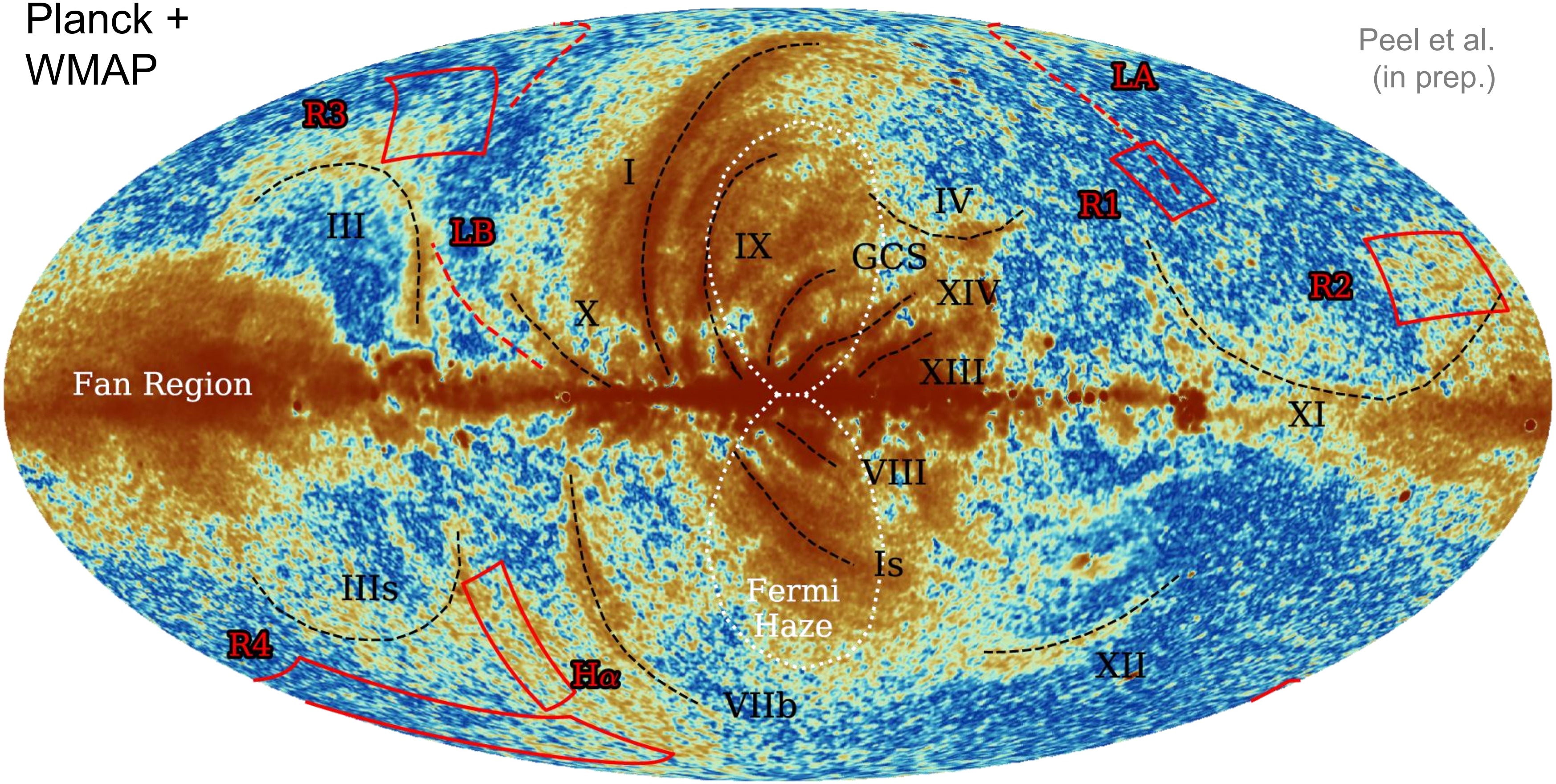
C-BASS View of Polarized Synchrotron



C-BASS View of Polarized Synchrotron

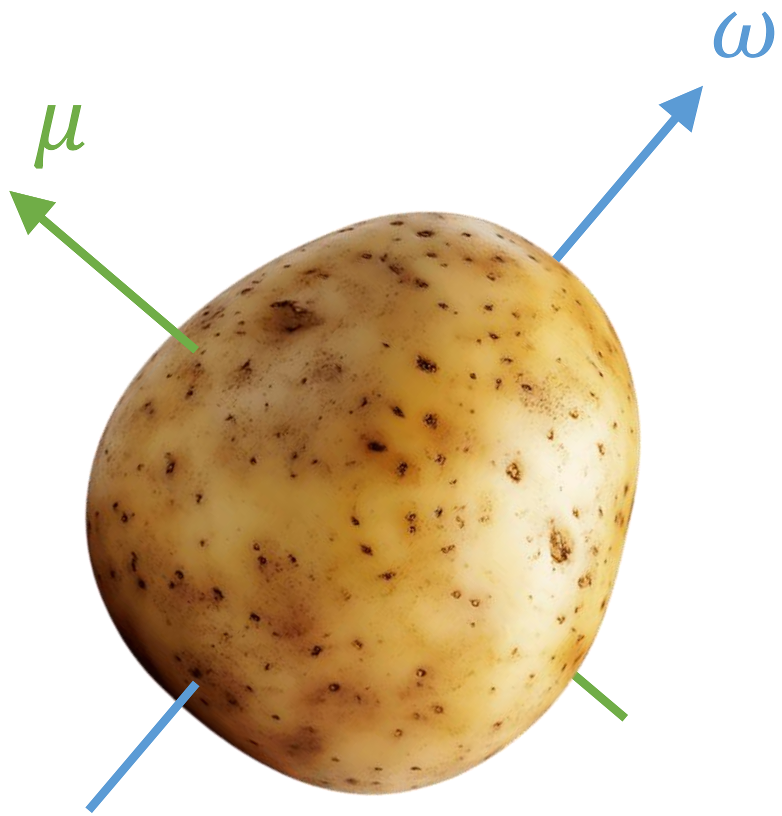
Planck + WMAP

Peel et al. (in prep.)



Part III: AME

Spinning Dust: From Single Grains to Emergent Spectra



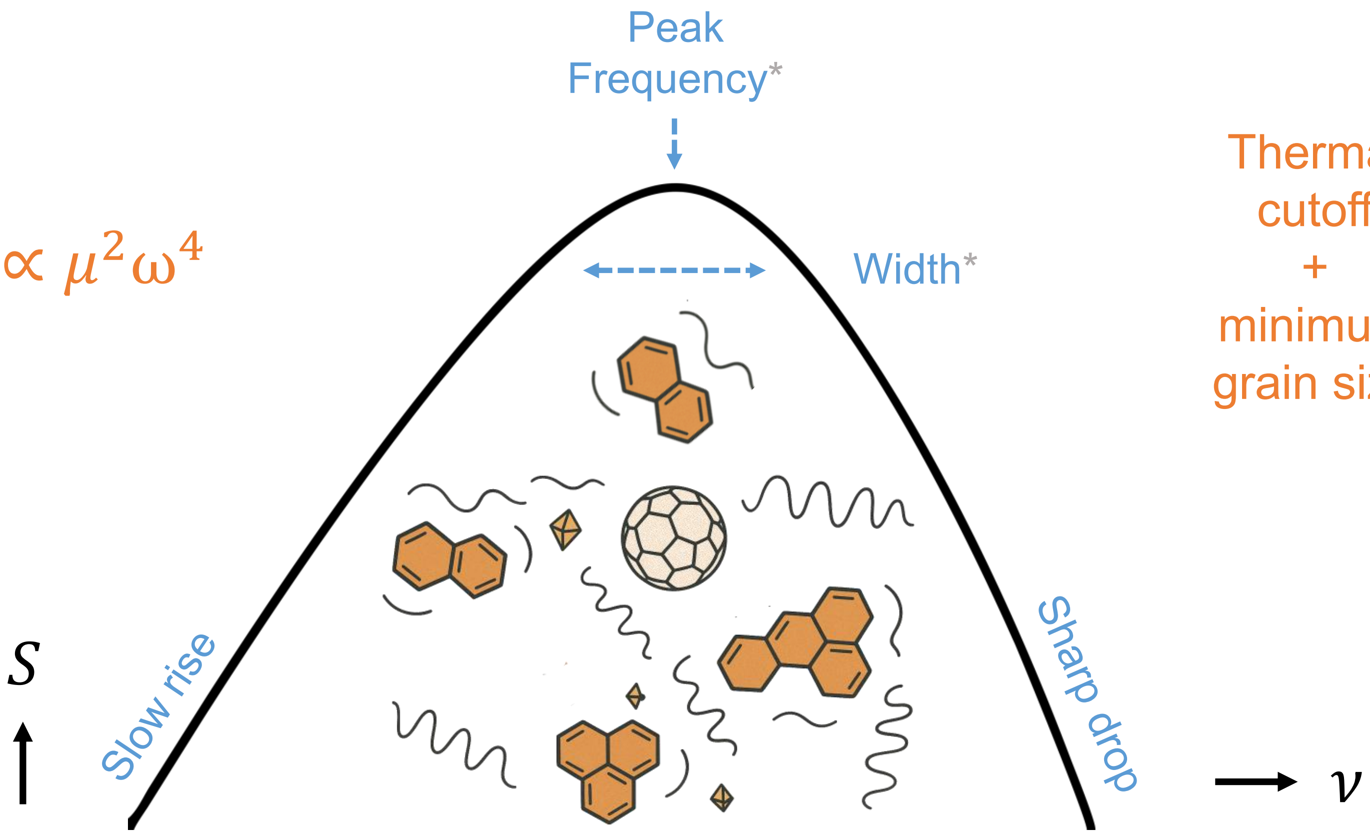
100% linear polarization from a single grain!

Radiation emitted concentrated in the equatorial plane:

$$\frac{dP}{d\Omega} \propto \mu^2 \omega^4 \sin^2 \theta$$

Spinning Dust: From Single Grains to Emergent Spectra

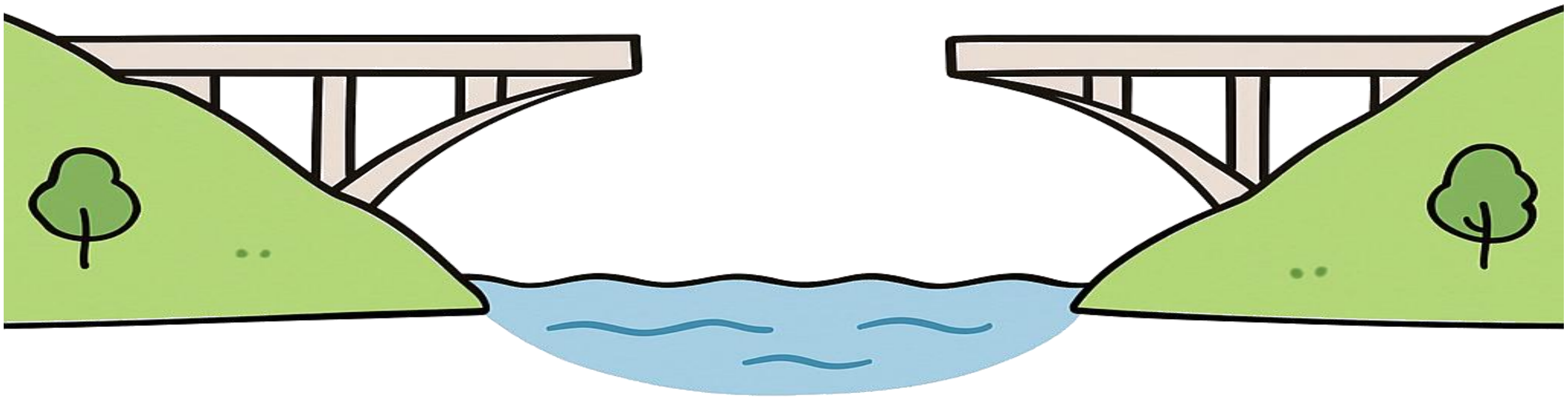
$P \propto \mu^2 \omega^4$



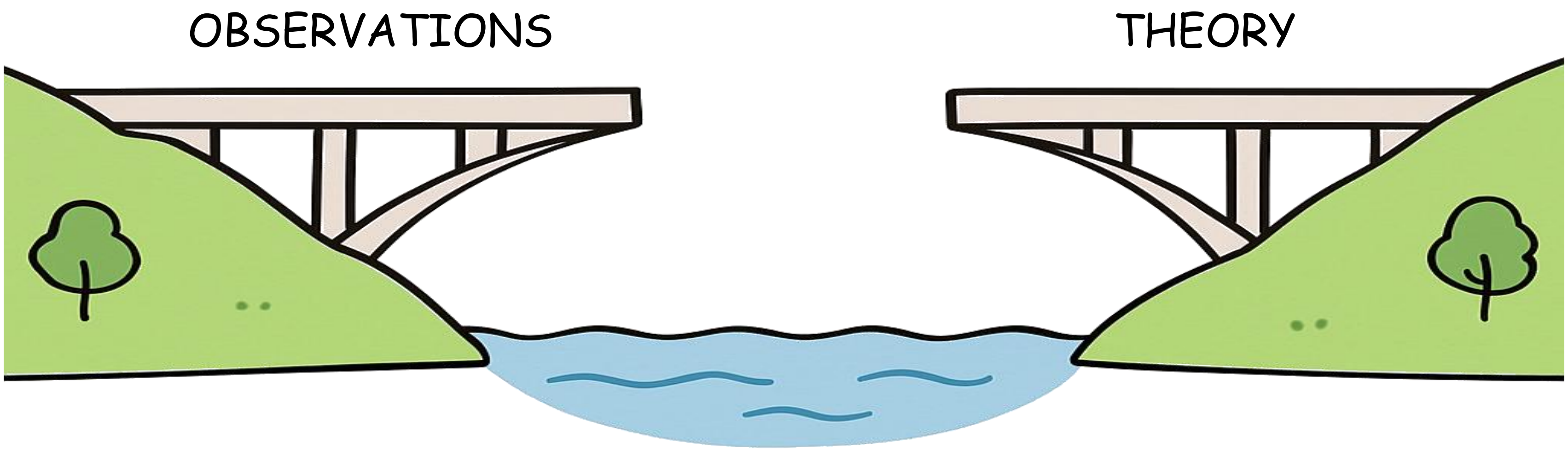
Thermal cutoff + minimum grain size

* emergent properties

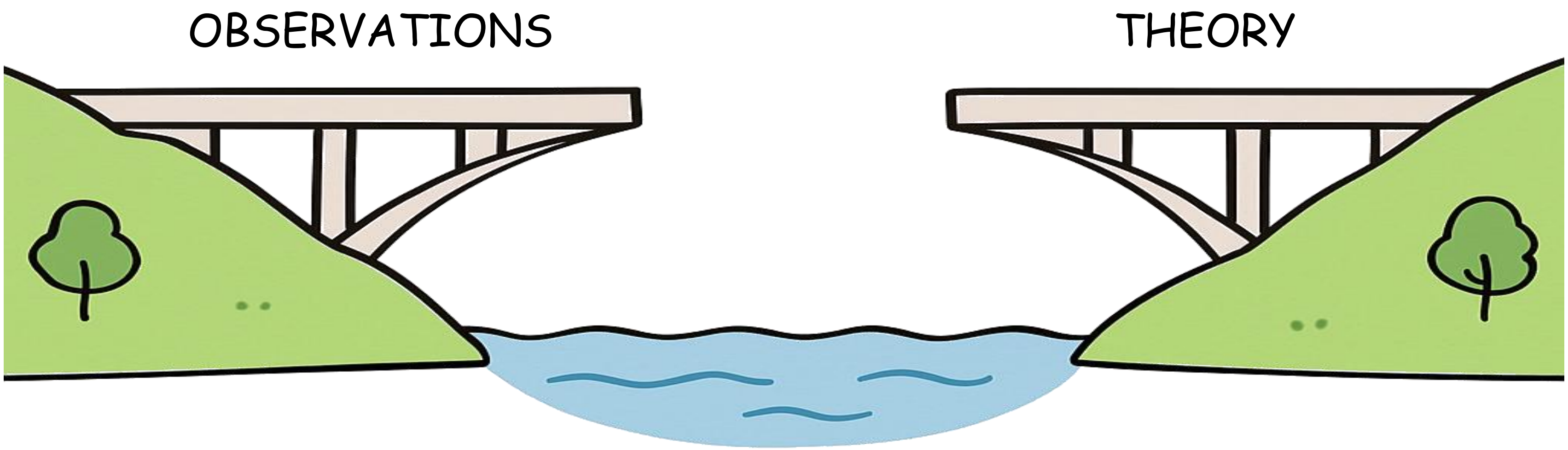
Mind the Gap: Theory and Observation



Mind the Gap: Theory and Observation



Mind the Gap: Theory and Observation



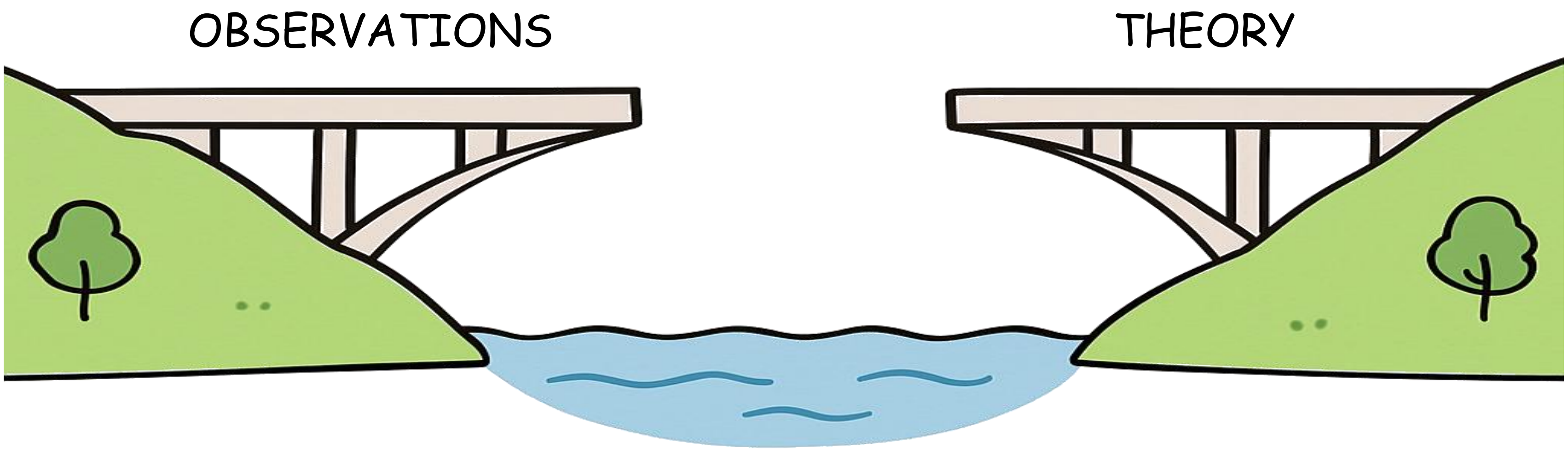
✓ Single grain physics well known

✗ Environmental conditions unknown, 7-9 free parameters! $\{n_{\mathrm{H}}, T, \chi, x_{\mathrm{H}}, n_{\mathrm{C}}, y, \gamma, \mu_{\mathrm{rms}}, \mathrm{r}_{\mathrm{grain}}\}$

✗ No coupling of environmental parameters

✗ Single ISM phase

Mind the Gap: Theory and Observation



✓ Reliable data > 20 GHz

✗ Unreliable data < 2 GHz

✓ S-PASS + C-BASS + QUIJOTE: we can now fit up to 3 free parameters

✓ Single grain physics well known

✗ Environmental conditions unknown, 7-9 free parameters! $\{n_{\mathrm{H}}, T, \chi, x_{\mathrm{H}}, n_{\mathrm{C}}, y, \gamma, \mu_{\mathrm{rms}}, \mathrm{r}_{\mathrm{grain}}\}$

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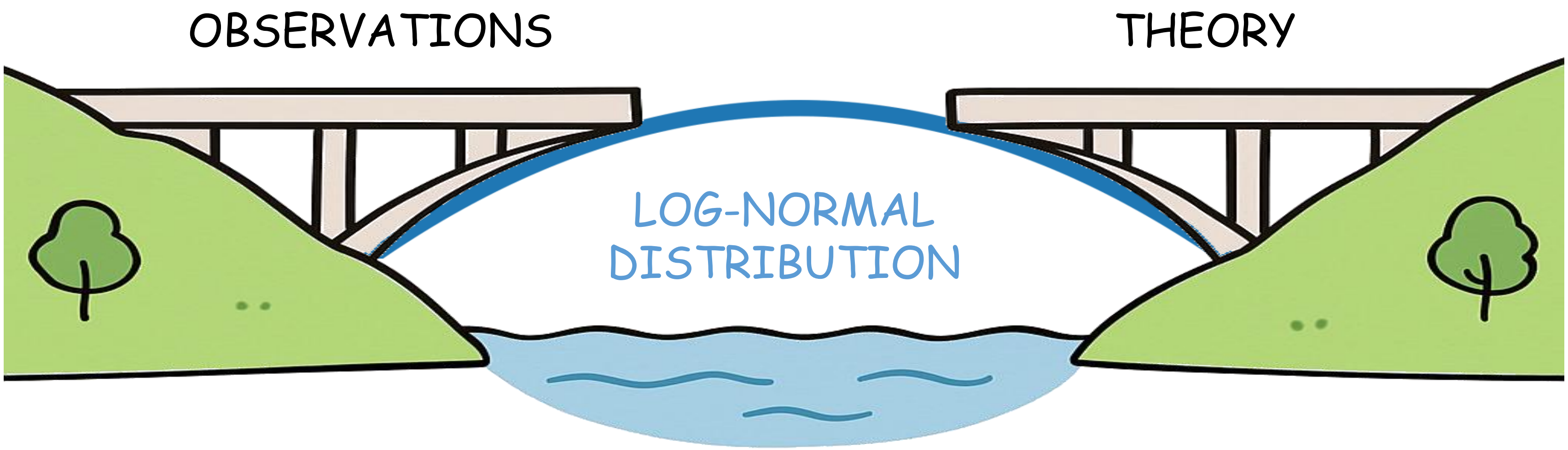
Mind the Gap: Theory and Observation



$$S_{\mathrm{AME}}(\nu) = A_{\mathrm{AME}} \cdot \exp\left\{-\frac{1}{2} \cdot \left[\frac{\ln(\nu/\nu_{\mathrm{AME}})}{W_{\mathrm{AME}}}\right]^2\right\}$$

✓ No environmental assumptions ✓ 3 free parameters ✗ No asymmetry

Phenomenological Correlation Search

Empirical AME observables:

A_{AME} ν_{AME} W_{AME}

Environmental observables and tracers:

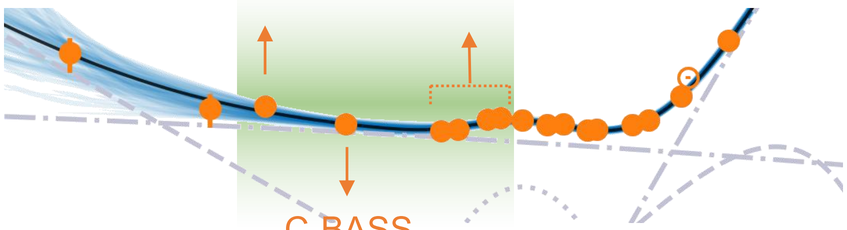
T_{d} β_{d} τ_{353} $\mathcal{R}_{\mathrm{d}}$ G_0

EM A_{sync} f_{AME} CO MIR PAH

Nature of AME
+ secondary
science

Phenomenological Correlation Search

- Unprecedented spectral coverage → fully constrained parameters



✓ A_{AME} > 1 Jy
✓ ν_{AME} within ~1 GHz
✓ W_{AME} within ~0.1

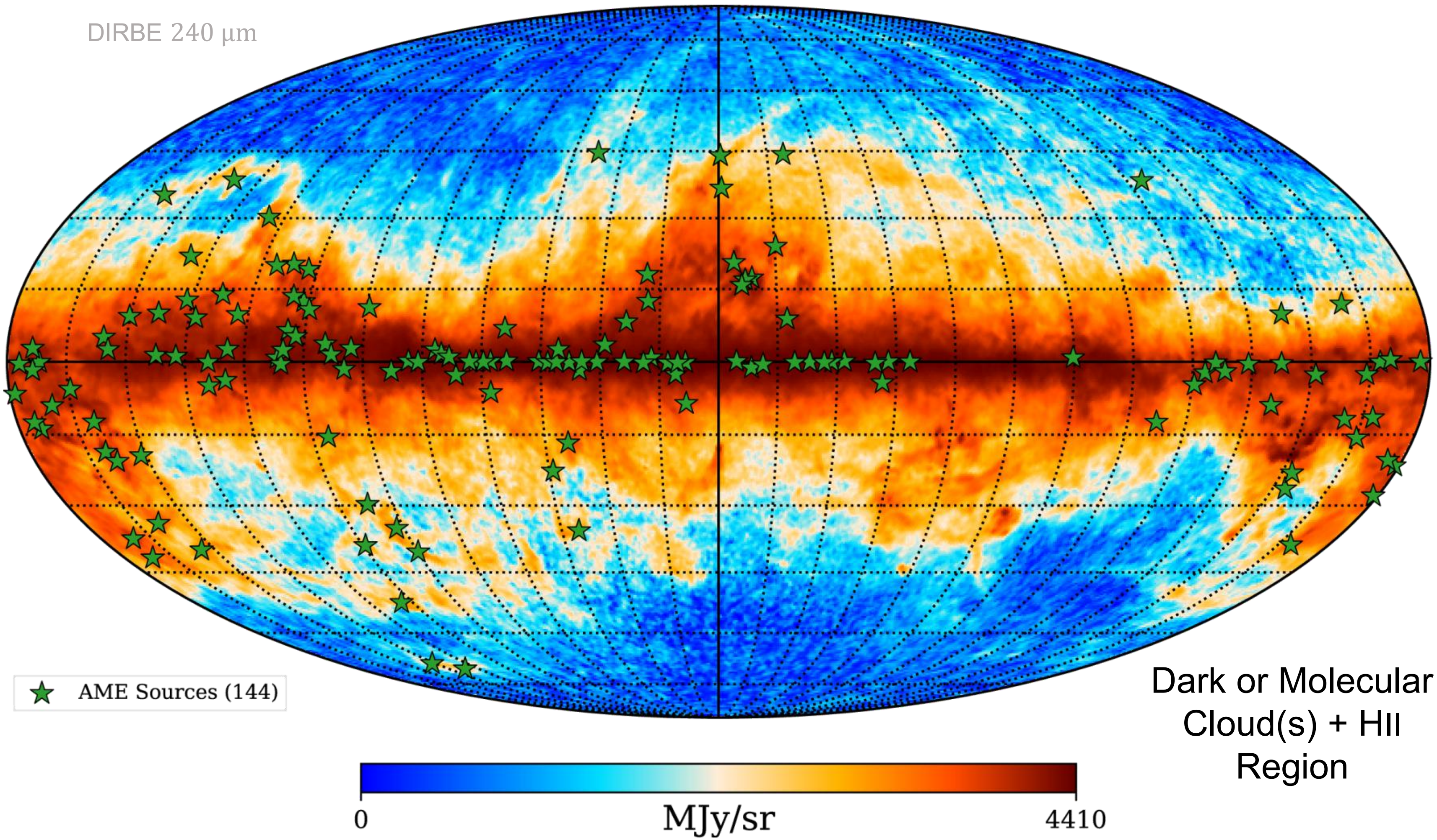
+ no ν_{AME} bias

- Spectral modelling + no informative priors*

$$\begin{aligned} S_{\mathrm{total}}(\nu) = & \; S_{\mathrm{sync}}(A_{\mathrm{sync}}, \alpha) + S_{\mathrm{ff}}(\mathrm{EM}) \\ & + S_{\mathrm{AME}}(A_{\mathrm{AME}}, \nu_{\mathrm{AME}}, W_{\mathrm{AME}}) \\ & + S_{\mathrm{CMB}}(\delta T_{\mathrm{CMB}}) + S_{\mathrm{d}}(\tau_{353}, T_{\mathrm{d}}, \beta) \end{aligned}$$

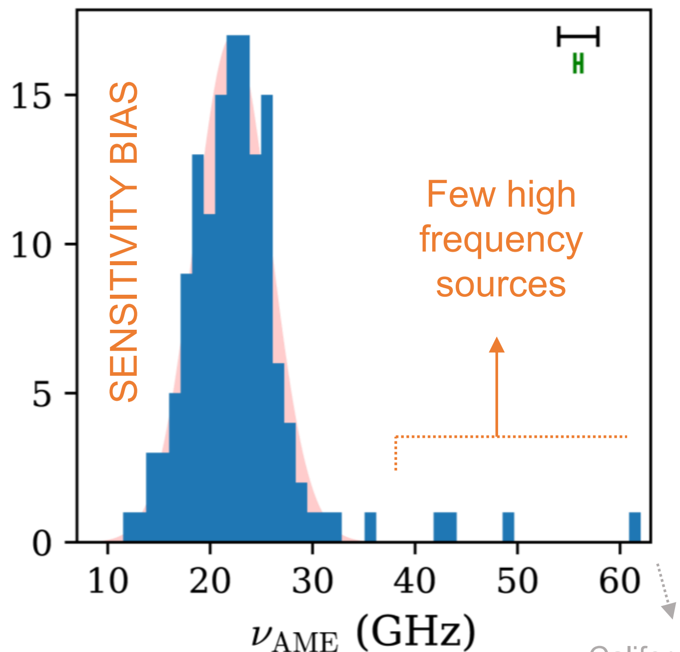
* except δT_{CMB}

Source Distribution



Dark or Molecular Cloud(s) + HII Region

Peak Frequencies



California nebula (62 ± 13 GHz)

- We detect faint, low peak frequency sources down to ~13 GHz!

We observe:

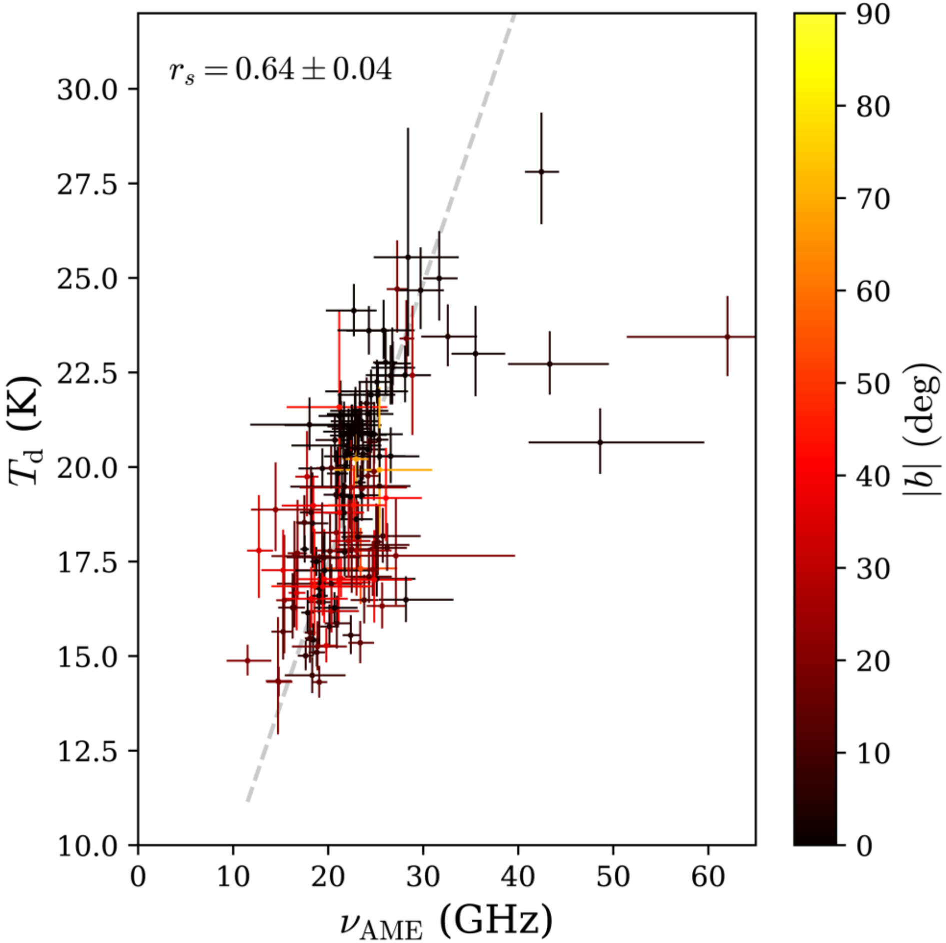
$\nu_{\mathrm{AME}} \sim \mathbb{N}\,(22, 4)$ GHz *

!! Exercise caution

Consistent with diffuse galactic plane distribution! Torreiro et al. 2023

Most sources $\nu_{\mathrm{AME}} < 35$ GHz, unlike predictions for PDR, RN, etc.

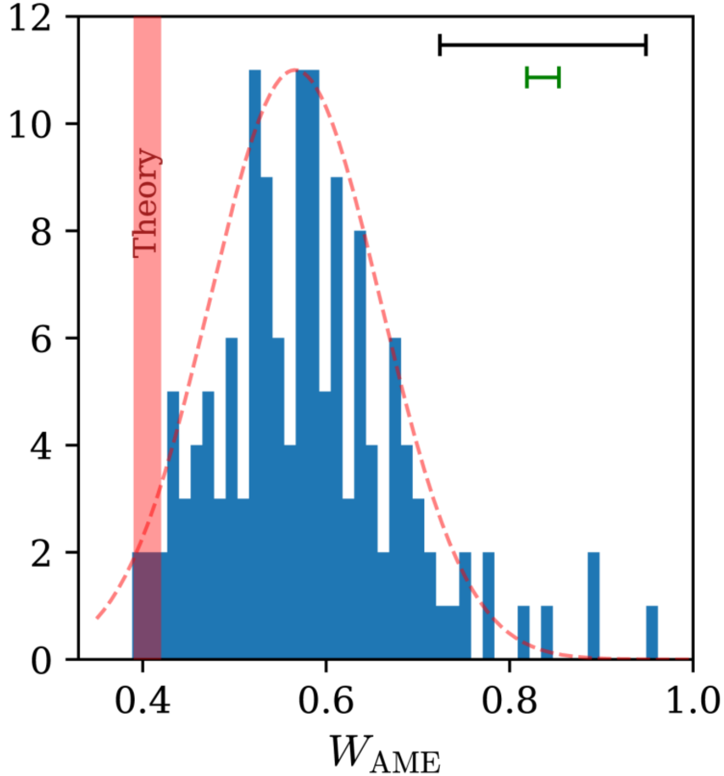
An Empirical “AME Wien’s Law”?



- Correlation expected but not reproduced by theory. We need DustEM + radiative transfer.
- Four outliers still not well understood (California, Sh2-280, W40, Tadpole Nebula), **all low AME contrast** and bright HII regions
- Index 1.10 ± 0.07:
  → “AME Wien’s law”?

$$\frac{\upsilon_{AME}}{GHz} = (0.70 \pm 0.15) \cdot \left(\frac{T_{dust}}{K}\right)^{1.17 \pm 0.08}$$

AME Widths Rule Out Single-Phase ISM



Theory predicts
$W_{\mathrm{AME}} = 0.39 - 0.42!$

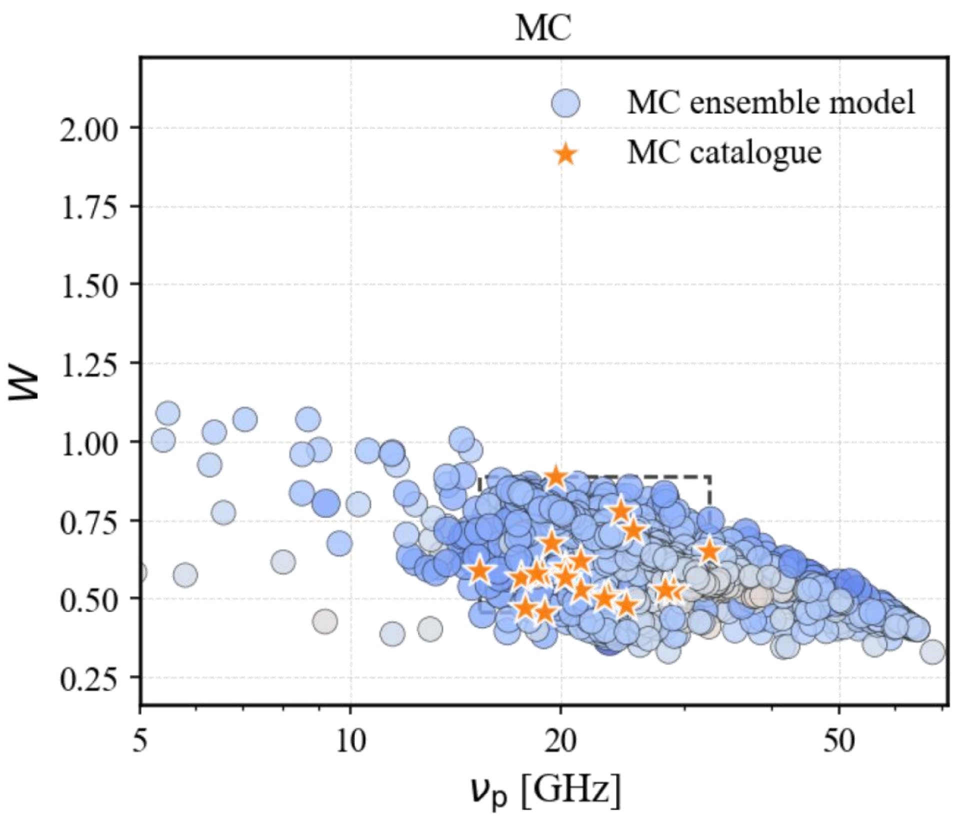
We observe:
$W_{\mathrm{AME}} \sim \mathbb{N}(0.56, 0.10)$

- No source narrower than a single component theoretical prediction
$\rightarrow$ multiple ISM phases along the line of sight

- Cutoff at $W_{AME} \approx 0.4$, no sources are narrower
$\rightarrow$ new evidence favouring spinning dust

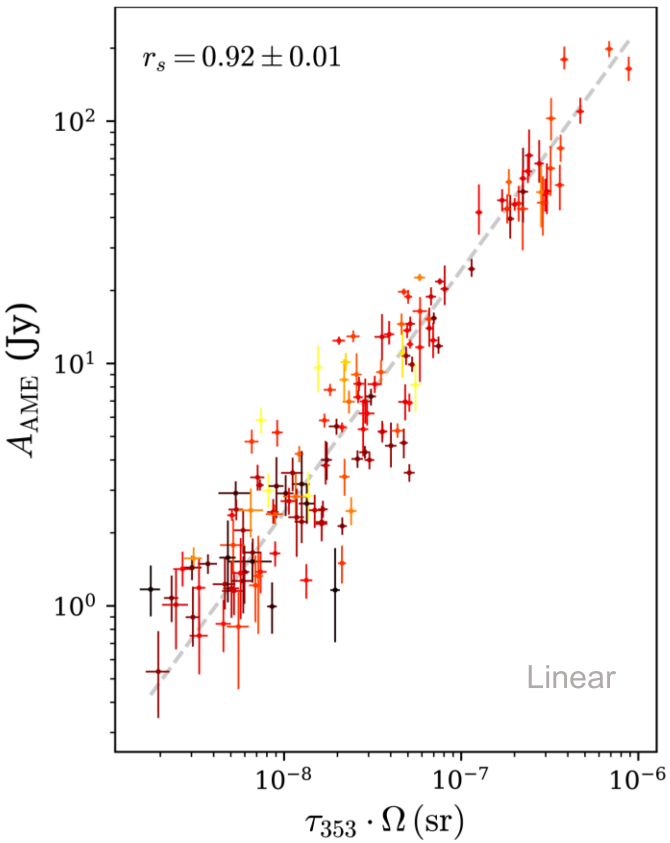
AME Widths Rule Out Single-Phase ISM

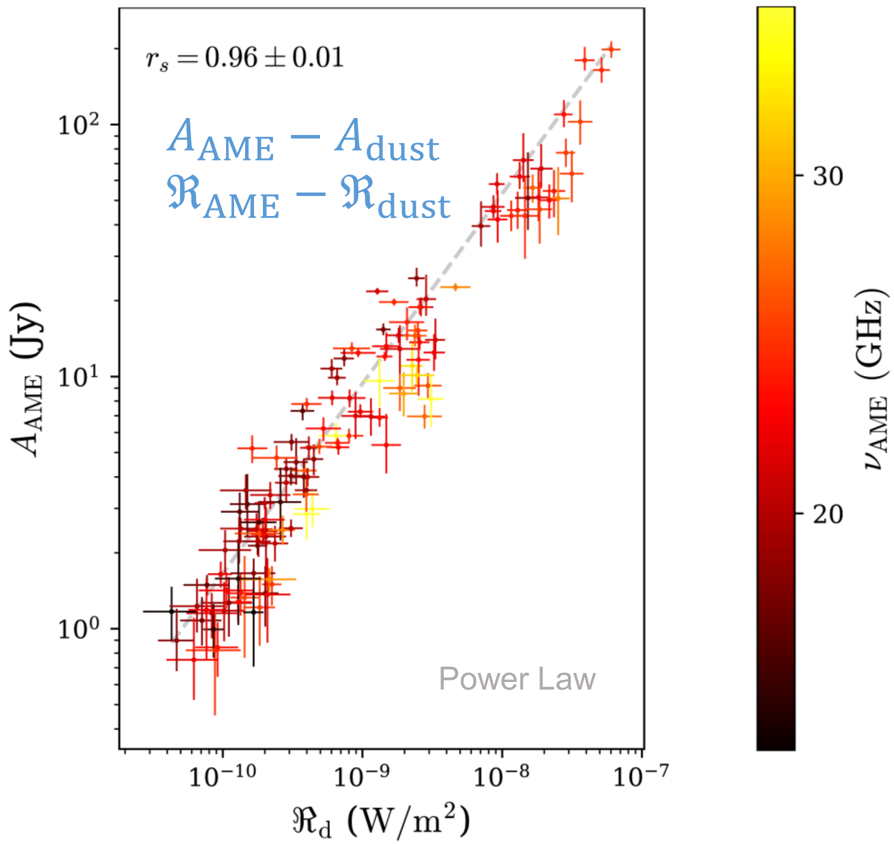
Zhang, Chluba, Cepeda-Arroita, Rubiño-Martín (2026)



- SpyDust (Python)
- Ensemble models can capture the observed width!
- 3 key parameters (out of 7):
  1. Grain size → ν_{AME}
  2. Grain shape → W_{AME}
  3. Carbon/hydrogen abundance (region dependent)
- Moment expansion method

What Traces AME Best?



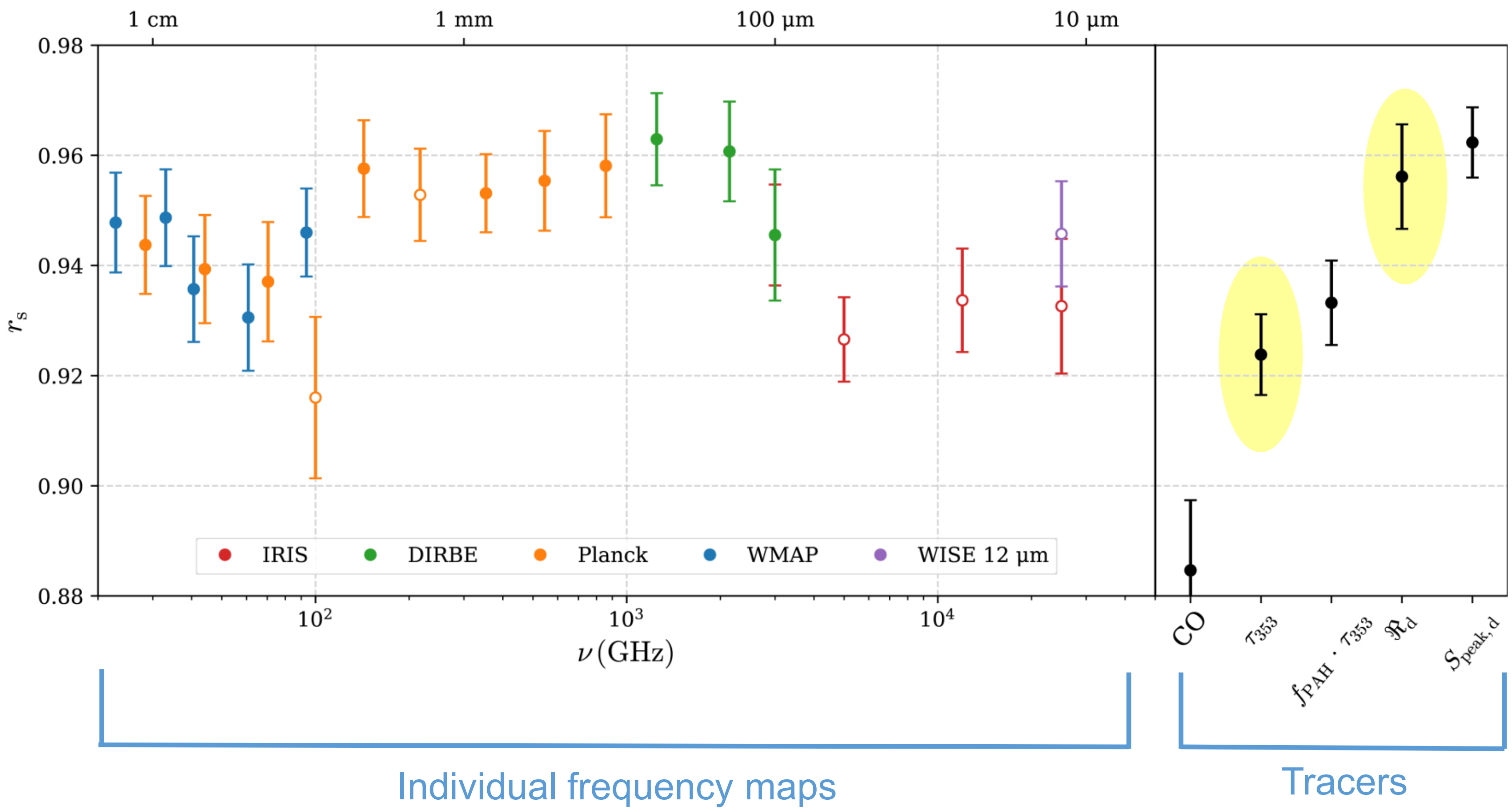


Linear, 50% scatter

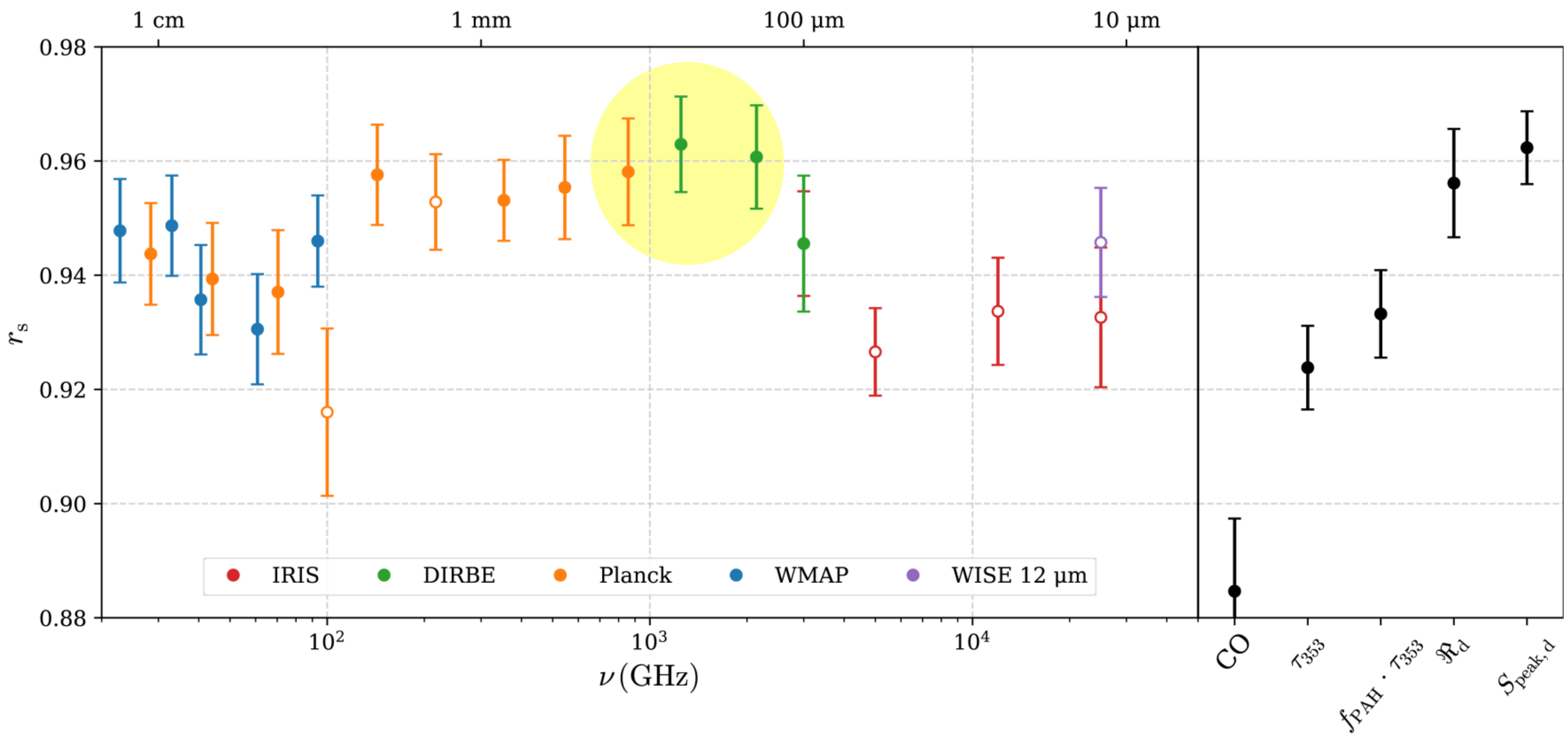
$A_{\rm AME} \propto \Re_{\rm dust}^{0.75 \pm 0.02}$, 30% scatter

Evidence of grain coagulation in dense clouds!

What Traces AME Best?

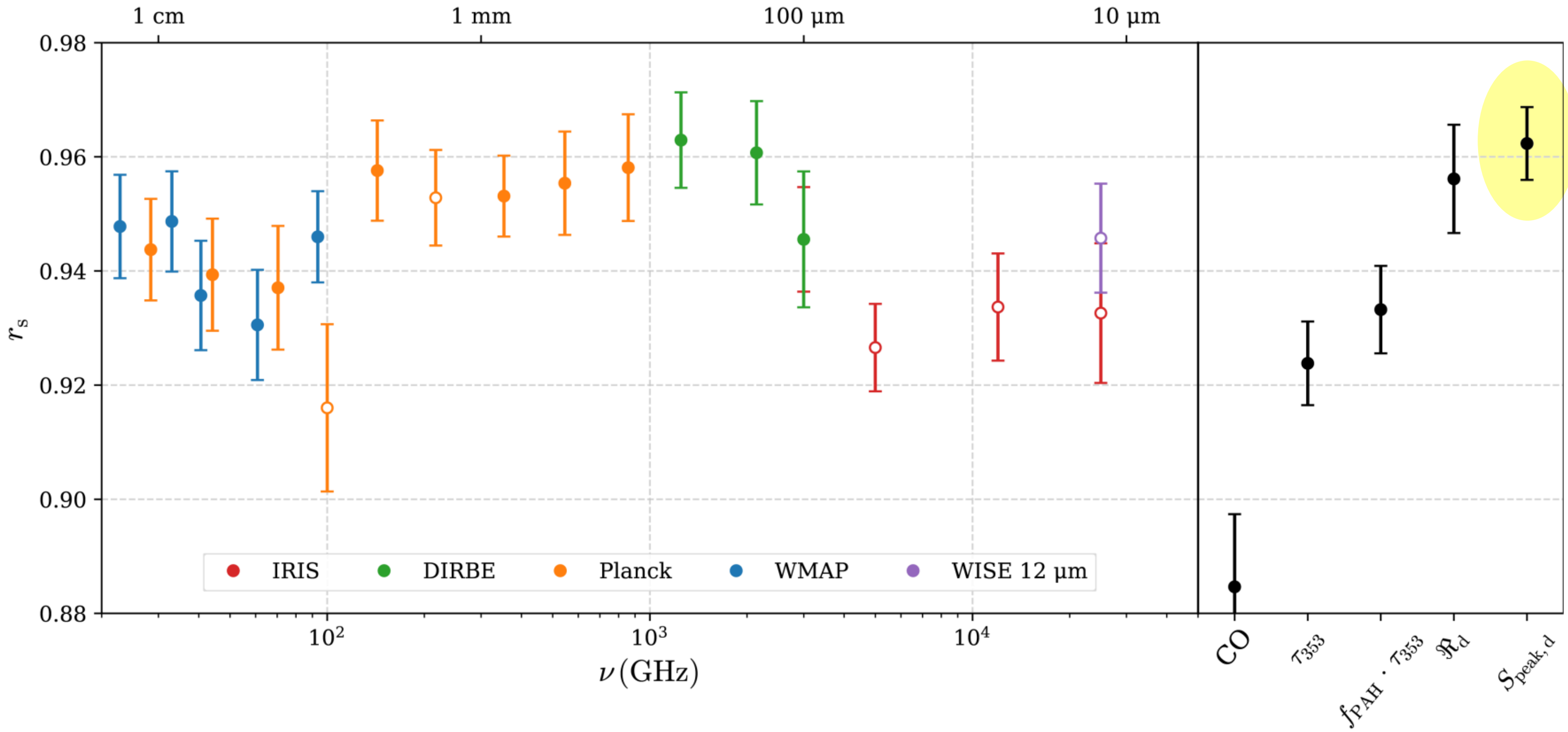


What Traces AME Best?

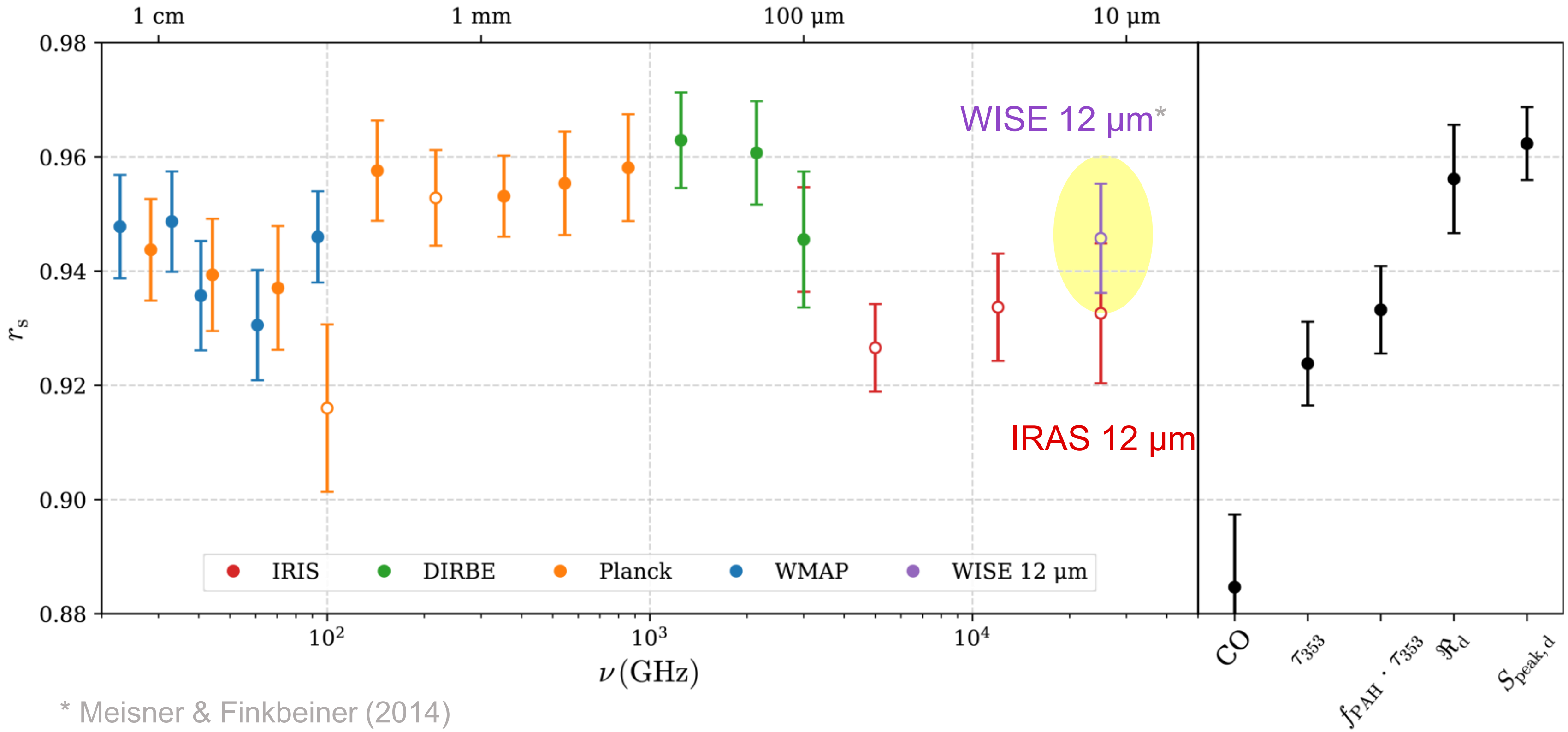


- DIRBE 240 μm is the best map tracer.

What Traces AME Best?



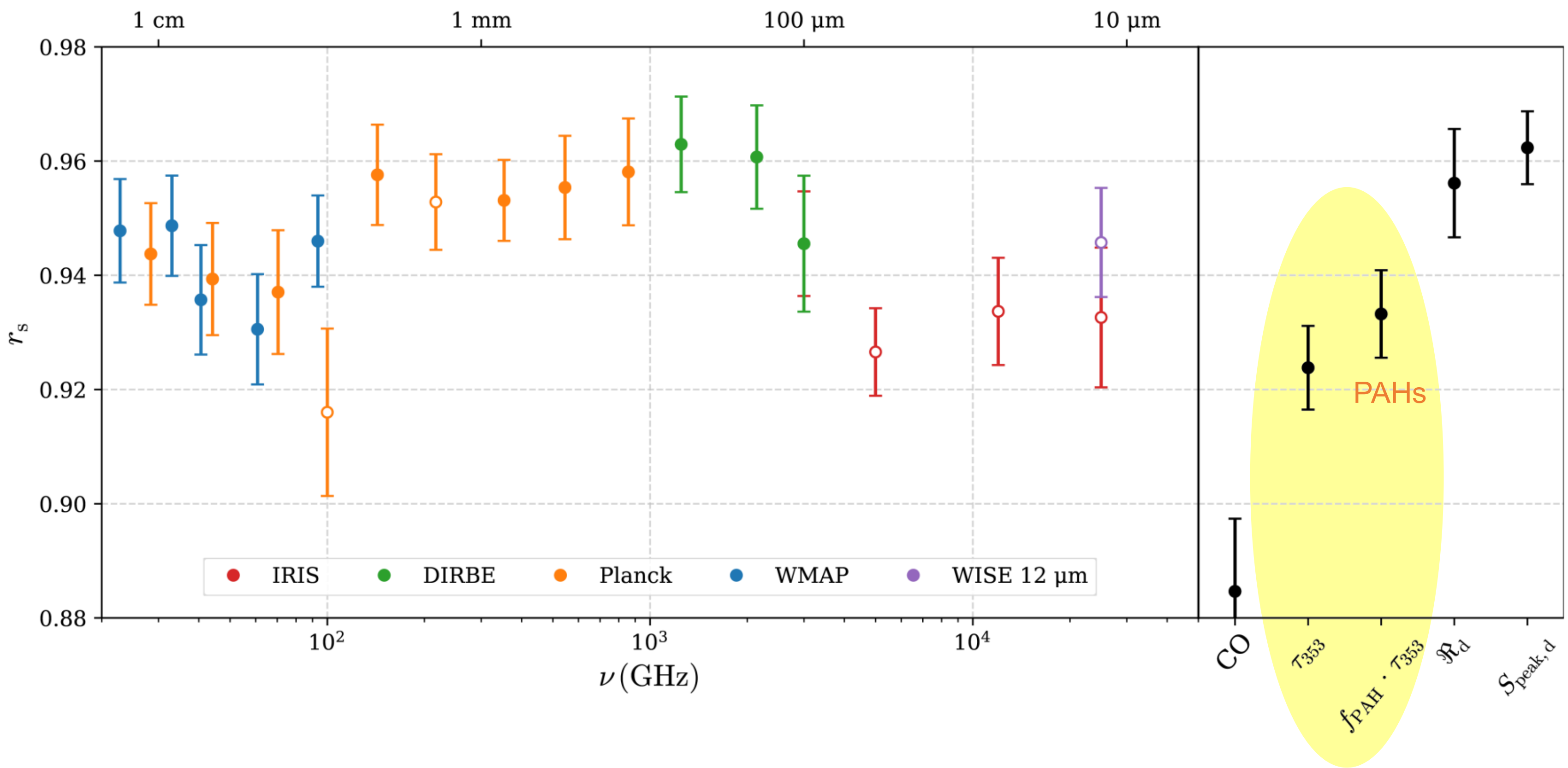
What Traces AME Best?



* Meisner & Finkbeiner (2014)

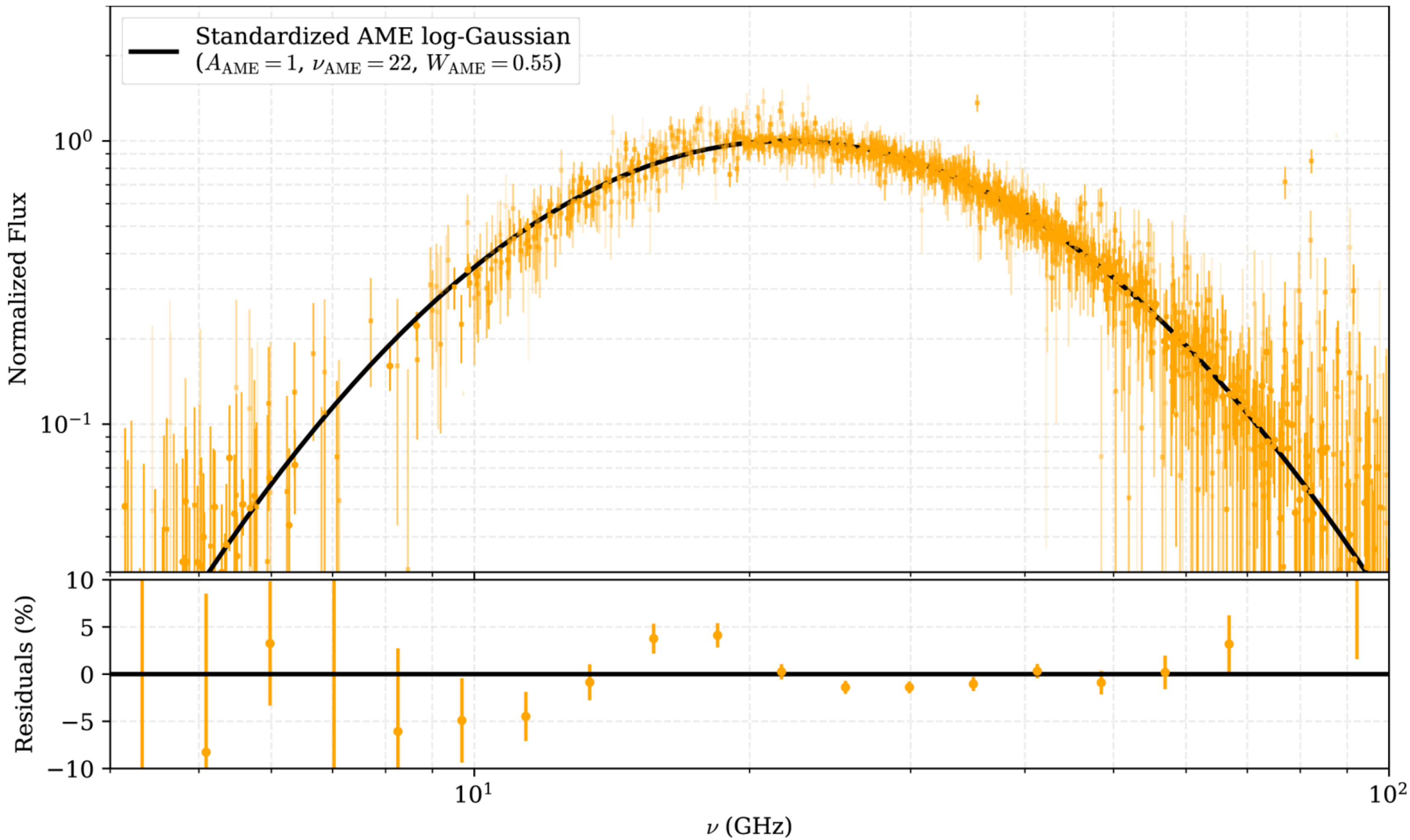
- PAHs co-located with AME. Lower correlations due to noise + systematics.

What Traces AME Best?



- Evidence for PAH-relationship: $A_{\rm AME} \propto f_{PAH} \cdot \tau_{353} \propto N_{\rm small\ grains}$

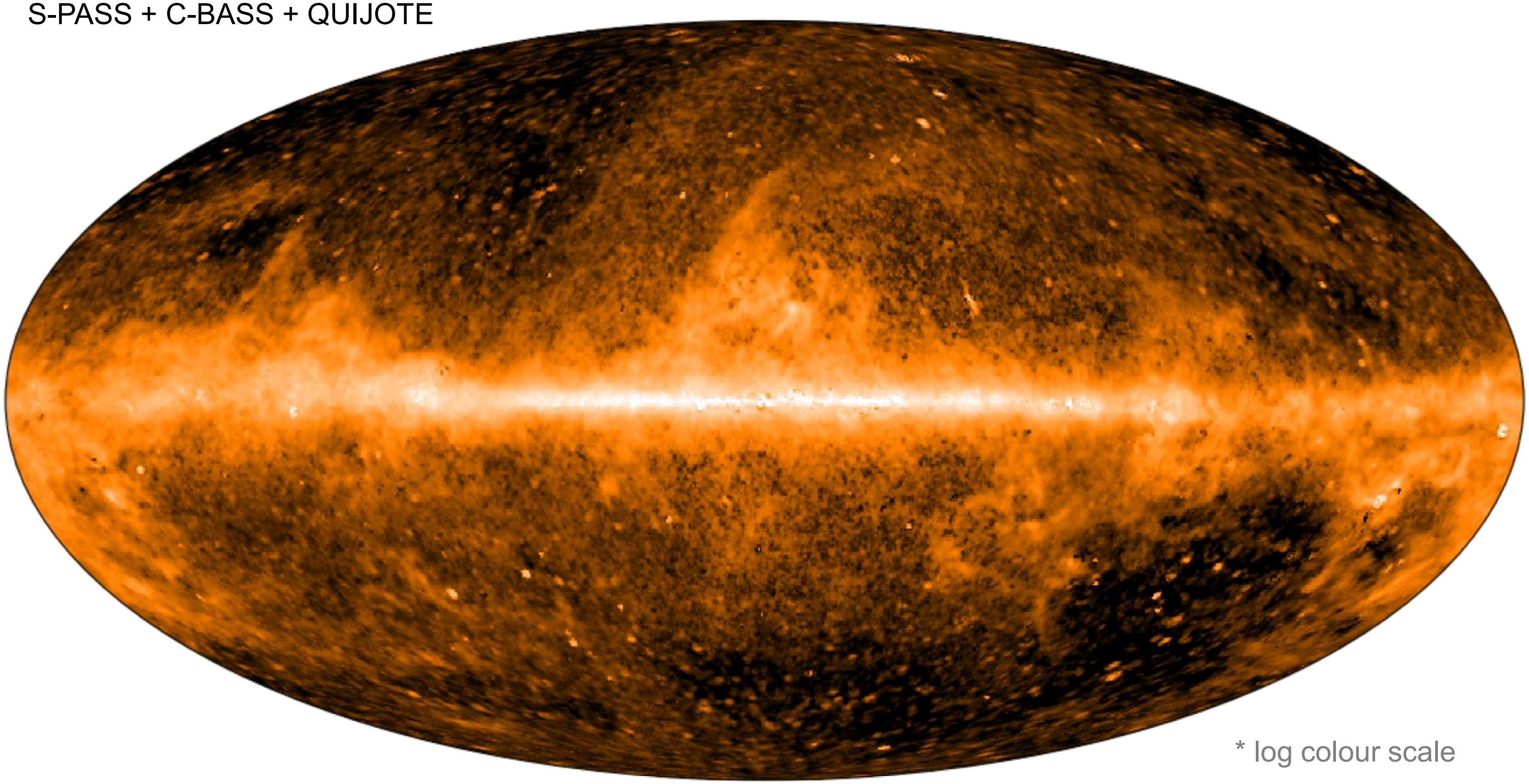
Log-normal Is Sufficient (For Now)



Updated COMMANDER Analysis

AME 22.8 GHz
S-PASS + C-BASS + QUIJOTE

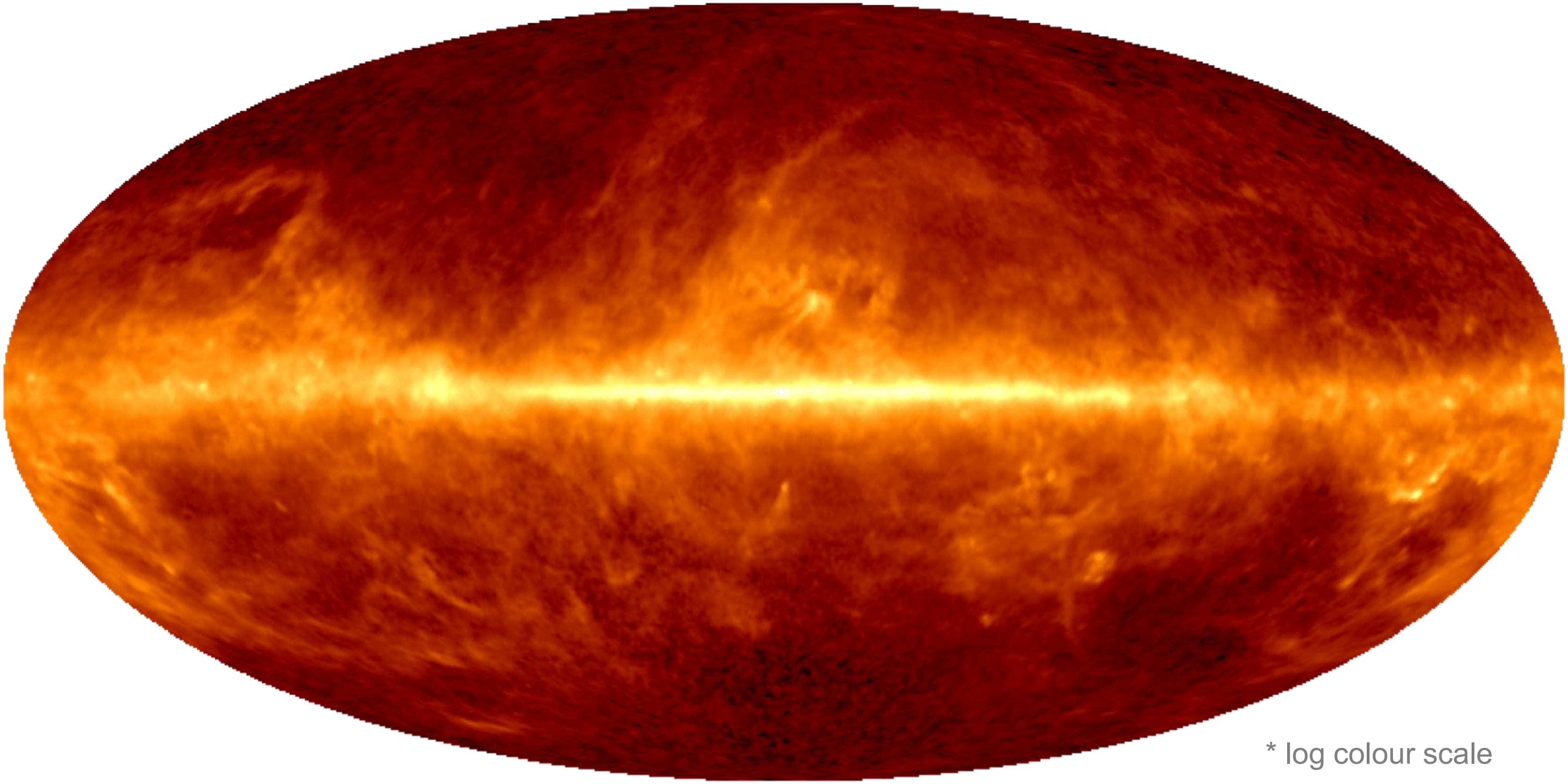
Hoerning et al. (in prep.)



* log colour scale

Updated COMMANDER Analysis

DIRBE 1.25 THz



* log colour scale

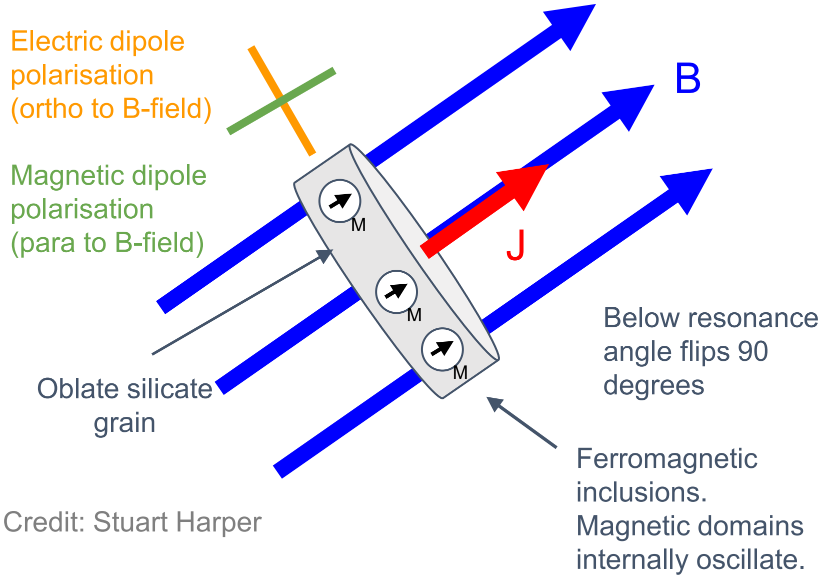
Polarized AME: Magnetic Dust Emission

Current limits $\Pi_{\mathrm{AME}} < 0.3 - 1.0\%$ (González-González et al. 2024)

- Problems for $r = 10^{-3}$ at $\Pi_{\mathrm{AME}} \sim 0.5\%$ level (Remazeilles et al. 2018)

Polarization requires macro-scale alignment!

- Possible problem for B-modes: Magnetic Dust Emission (MDE)



Credit: Stuart Harper

Magnetic dipole radiation from thermally fluctuating magnetization

Resonant peak near CMB frequencies

Π_{MDE} as high as ~40% (alignment with Galactic B-field)

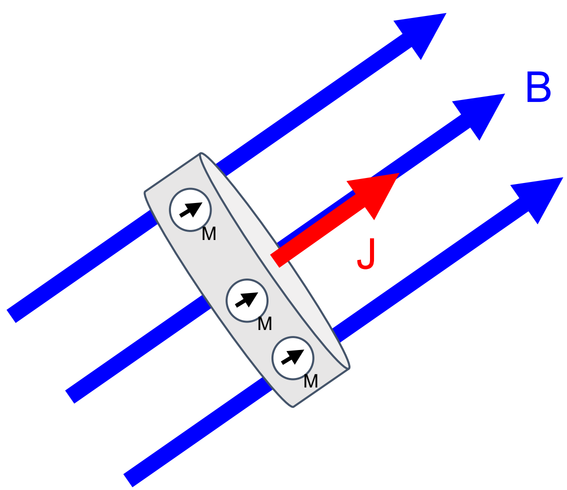
Polarized AME: Magnetic Dust Emission

- SED peak uncertain
- Spatial morphology ≈ thermal dust → easy to misattribute
- Potentially detectable with:

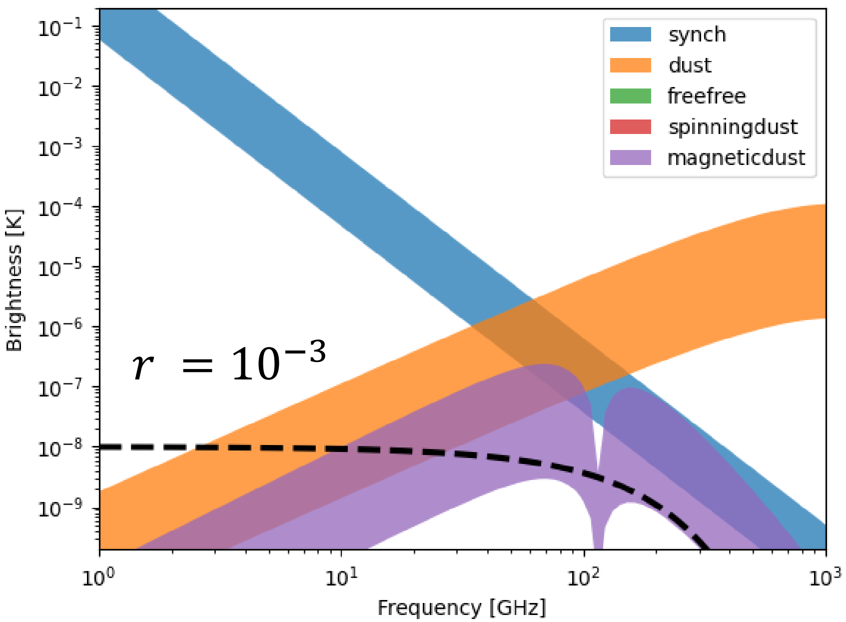
Template fitting (spatially degenerate) + spectral separation *

* verify through strong frequency dependence of Π_{MDE} and angle flip

Harper et al. in prep.



Credit: Stuart Harper



Key Takeaways

i. **Synchrotron & AME** are limited mainly by macro-scale complexity, not microphysics

ii. **No single separation method is sufficient**

iii. **Lessons from S-PASS + C-BASS + QUIJOTE:**

- Synchrotron β_s shows large spatial variability
- We can't detect C_s per-pixel
- AME is broader than models
- AME peak frequencies and widths vary in the sky
- AME correlates best with thermal dust peak amplitude

iv. **Foregrounds are not just contaminants, they are astrophysical probes**

Funded by
the European Union

~1.5M€. Period: 2024-2026
HORIZON-CL4-2023-SPACE-01, GA 101135036

RADIO FOREGROUNDS+

RadioForegroundsPlus

Conference in Tenerife,

~October 2026

TBA

https://research.iac.es/proyecto/radioforegroundsplus

Questions