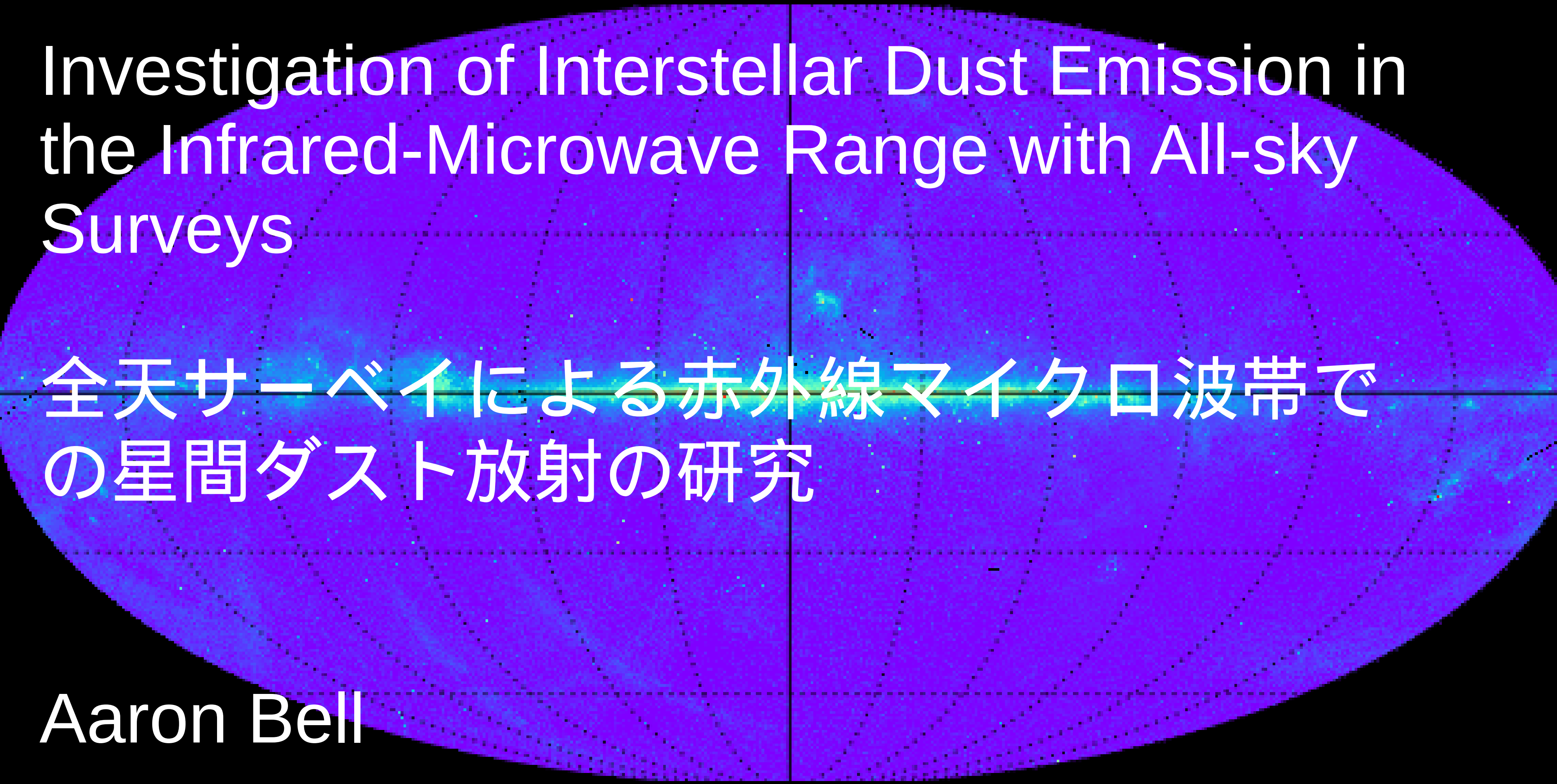


Investigation of Interstellar Dust Emission in the Infrared-Microwave Range with All-sky Surveys

全天サーベイによる赤外線マイクロ波帯での星間ダスト放射の研究

Aaron Bell

Introduction *What is AME?*

Data

All-sky analysis

λ Orionis

Conclusion *Spinning PAHs?*

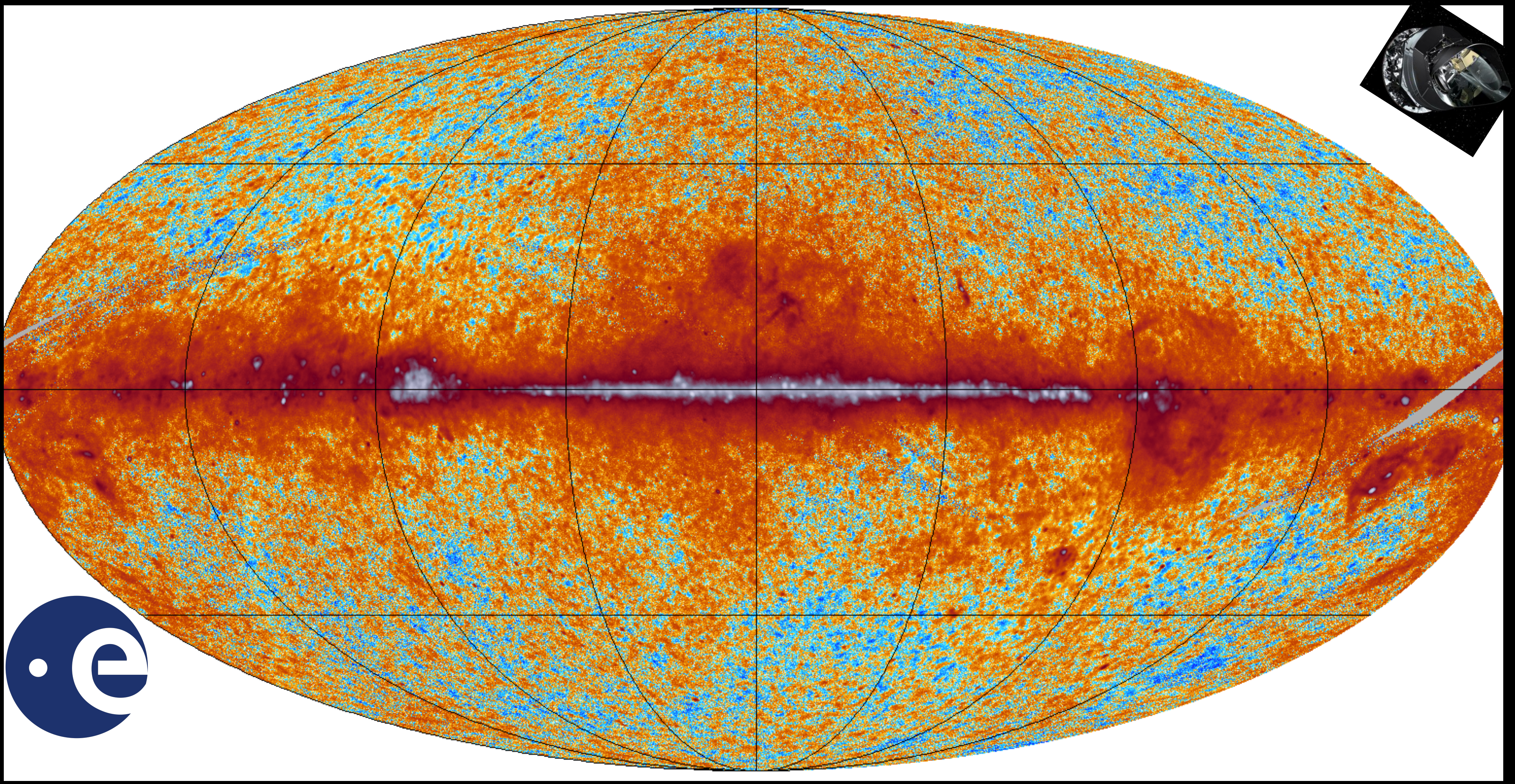
Future work *New data needed?*

Introduction

What is Anomalous Microwave Emission?

Introduction: What is AME?

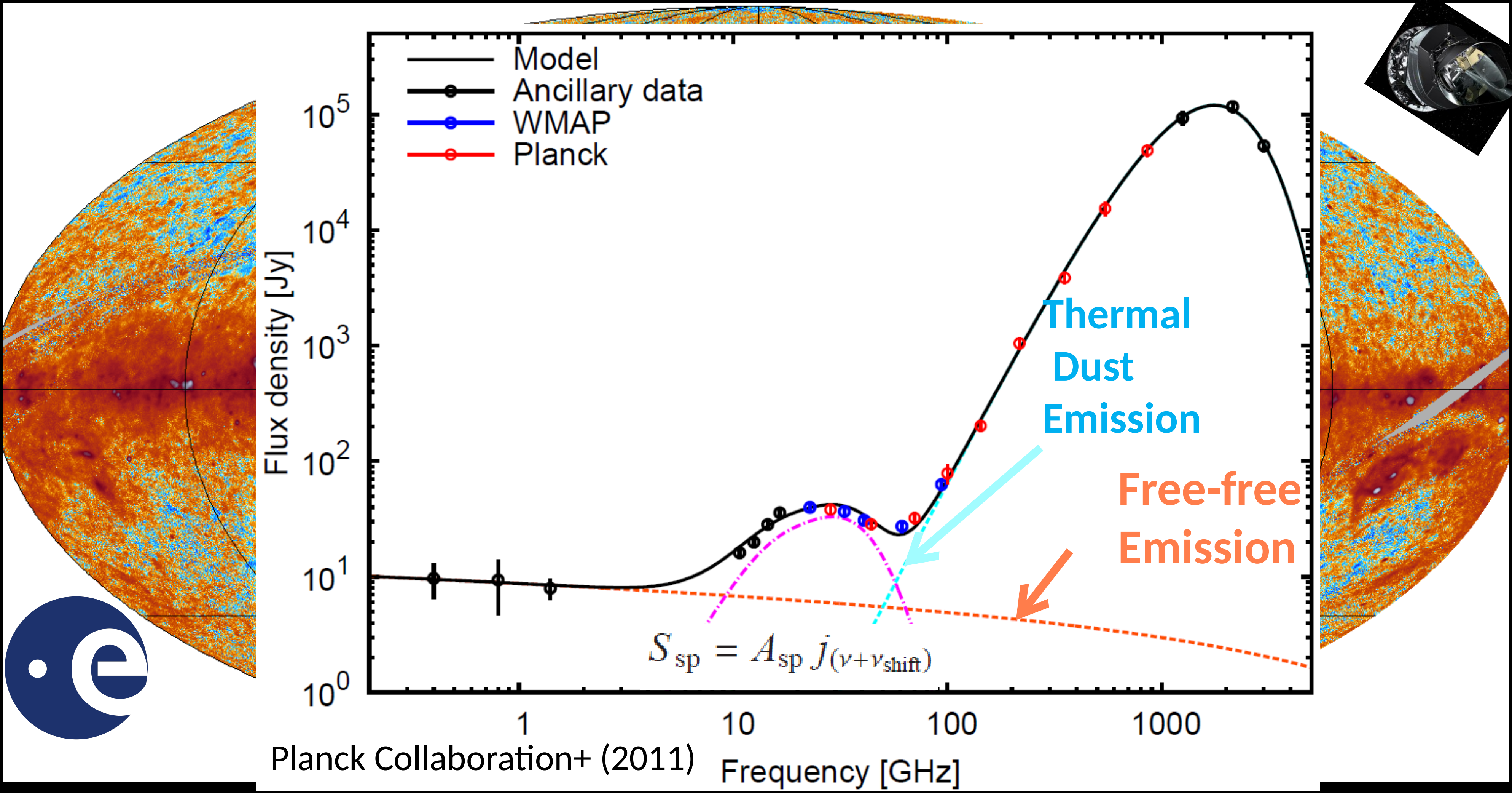
- An unexplained microwave foreground



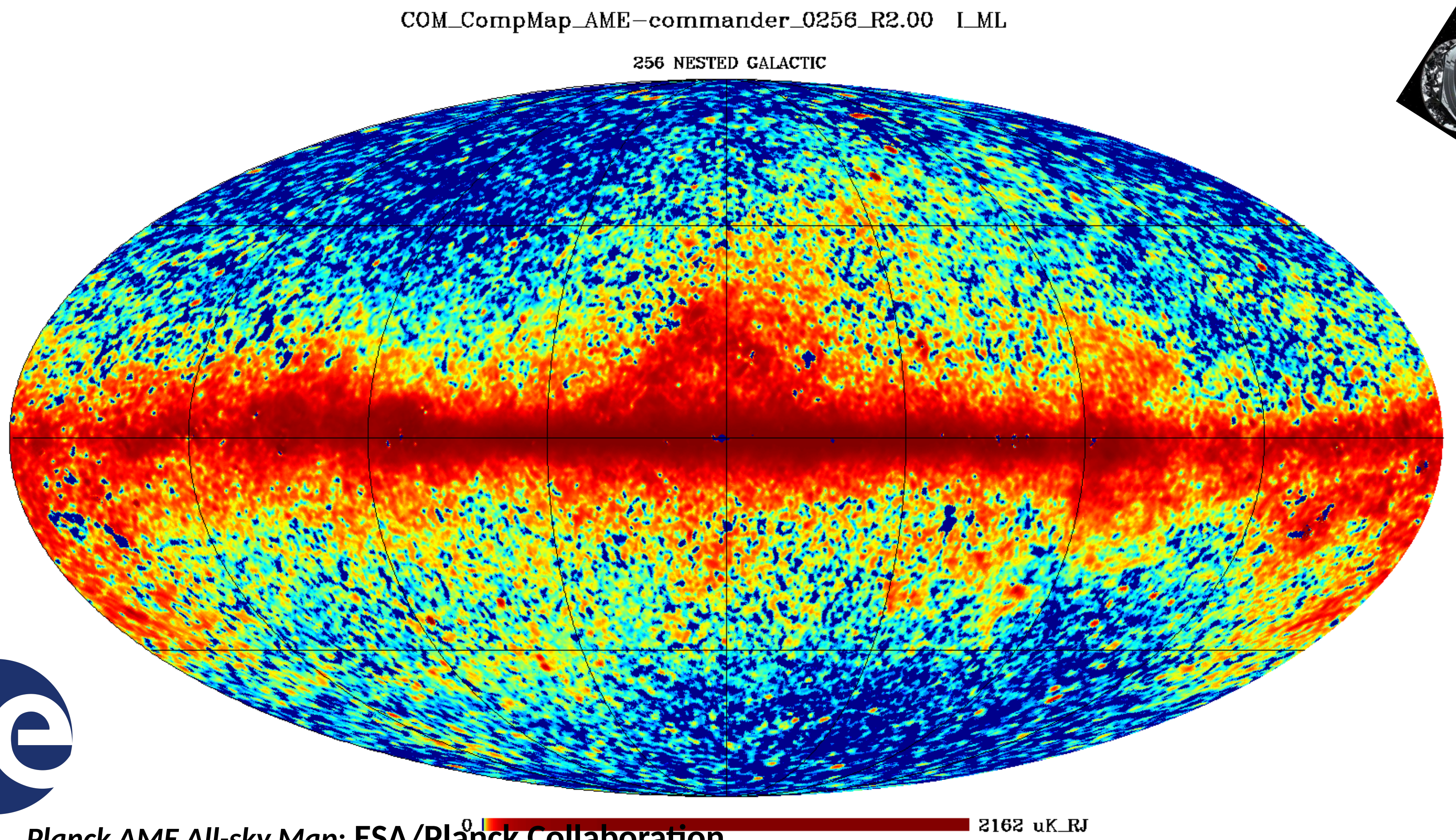
Planck LFI 28 GHz All-sky Map: ESA/Planck Collaboration

Introduction: What is AME?

- An unexplained microwave foreground



Introduction: What is AME?

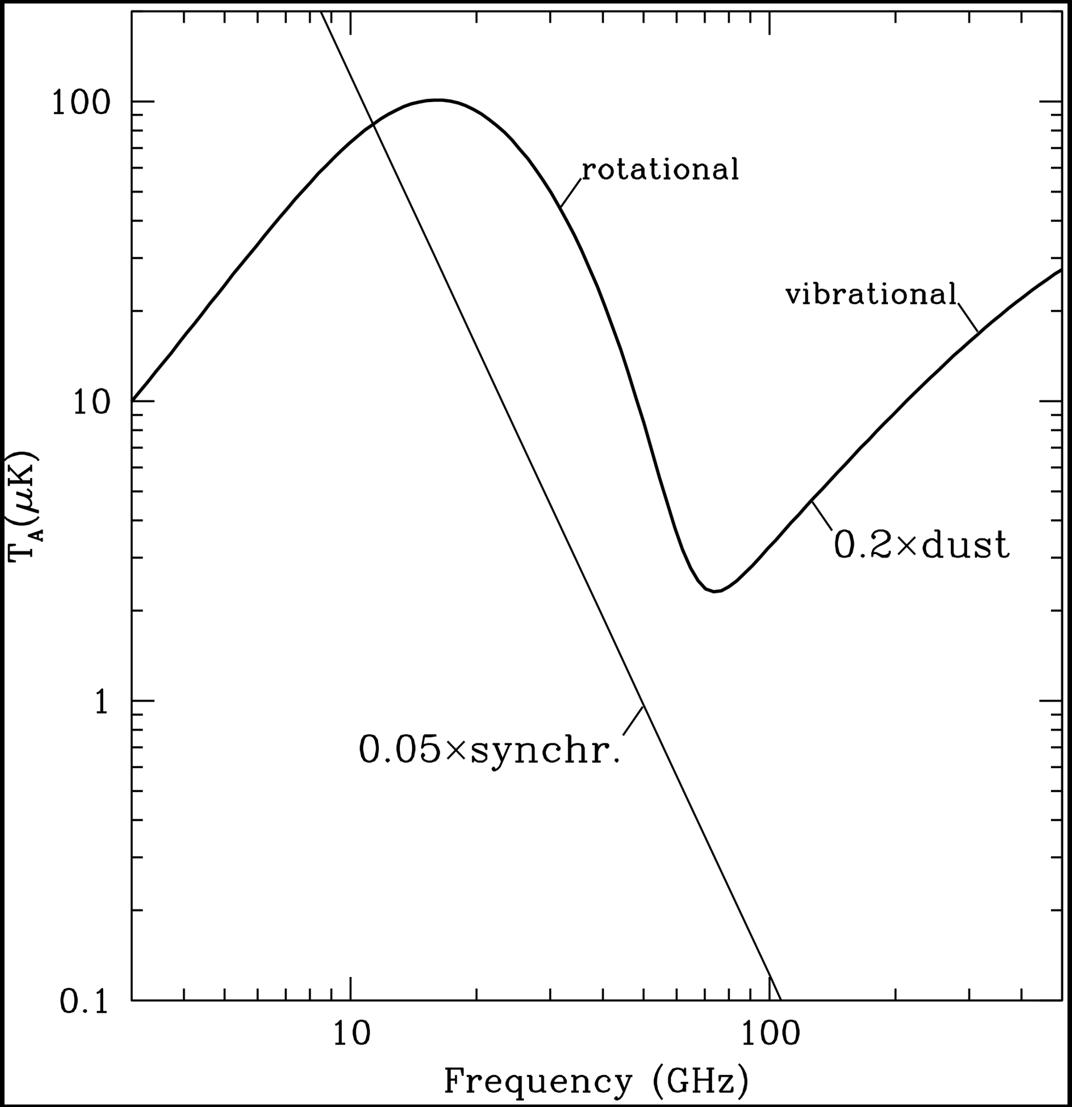


Planck AME All-sky Map: **ESA/Planck Collaboration**

Prevailing AME Explanation:

Rotational emission from dust

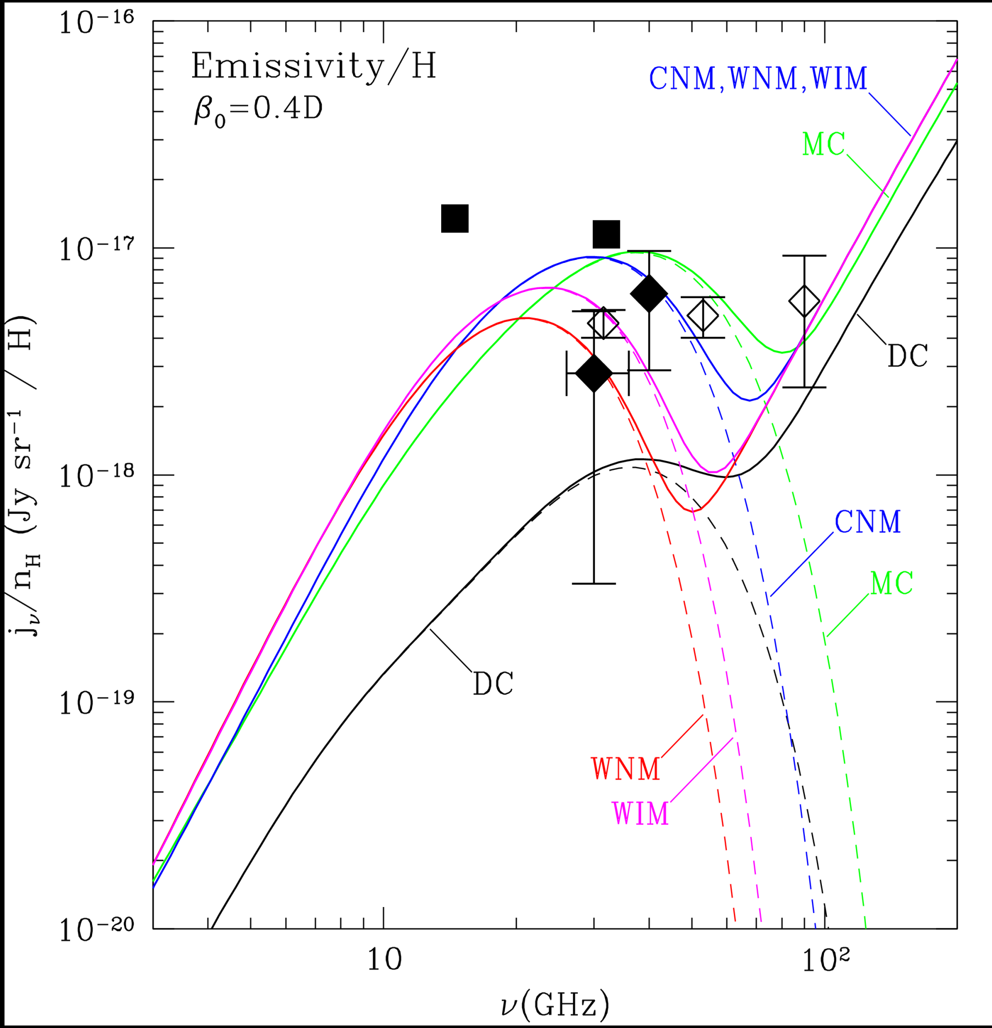
Via electric dipole emission



Introduction - Past Works - Draine & Lazarian (1998b)

Spinning Dust SED:

- Varies with environment



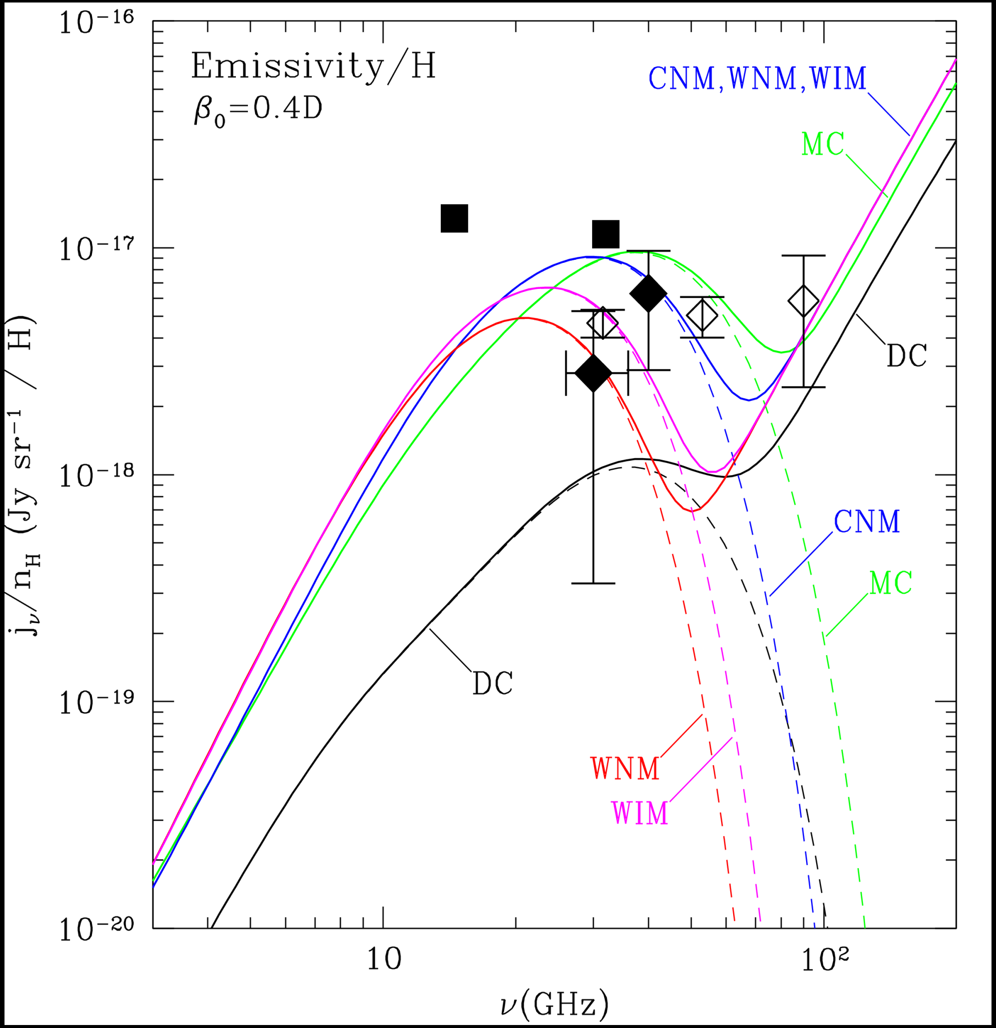
Introduction - Past Works - Draine & Lazarian (1998b)

Spinning Dust SED:

- Varies with environment

- Various excitation factors

1) Collision
2) Photon emission
3) H_2 formation



Introduction - Past Works - Draine & Lazarian (1998b)

$$\frac{\omega}{2\pi}=21\,GHz\left(\frac{T}{100\,K}\right)^{1/2}\left(\frac{\rho}{3\,g\,cm^{-3}}\right)^{-1/2}\left(\frac{a}{5\,\mathring{A}}\right)^{-5/2}$$

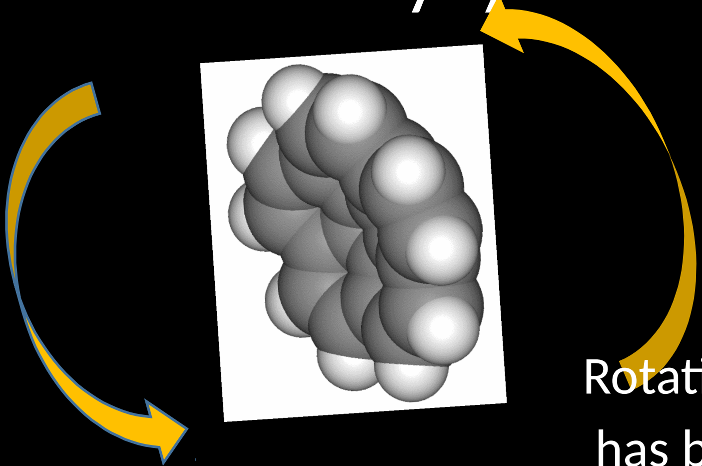
Introduction - Past Works - Draine & Lazarian (1998b)

$$\frac{\omega}{2\pi} = 21\,GHz \left(\frac{T}{100\,K}\right)^{1/2} \left(\frac{\rho}{3\,g\,cm^{-3}}\right)^{-1/2} \left(\frac{a}{5\,\mathring{A}}\right)^{-5/2}$$

Draine & Lazarian (1998)

Implies rotators ~1 nm

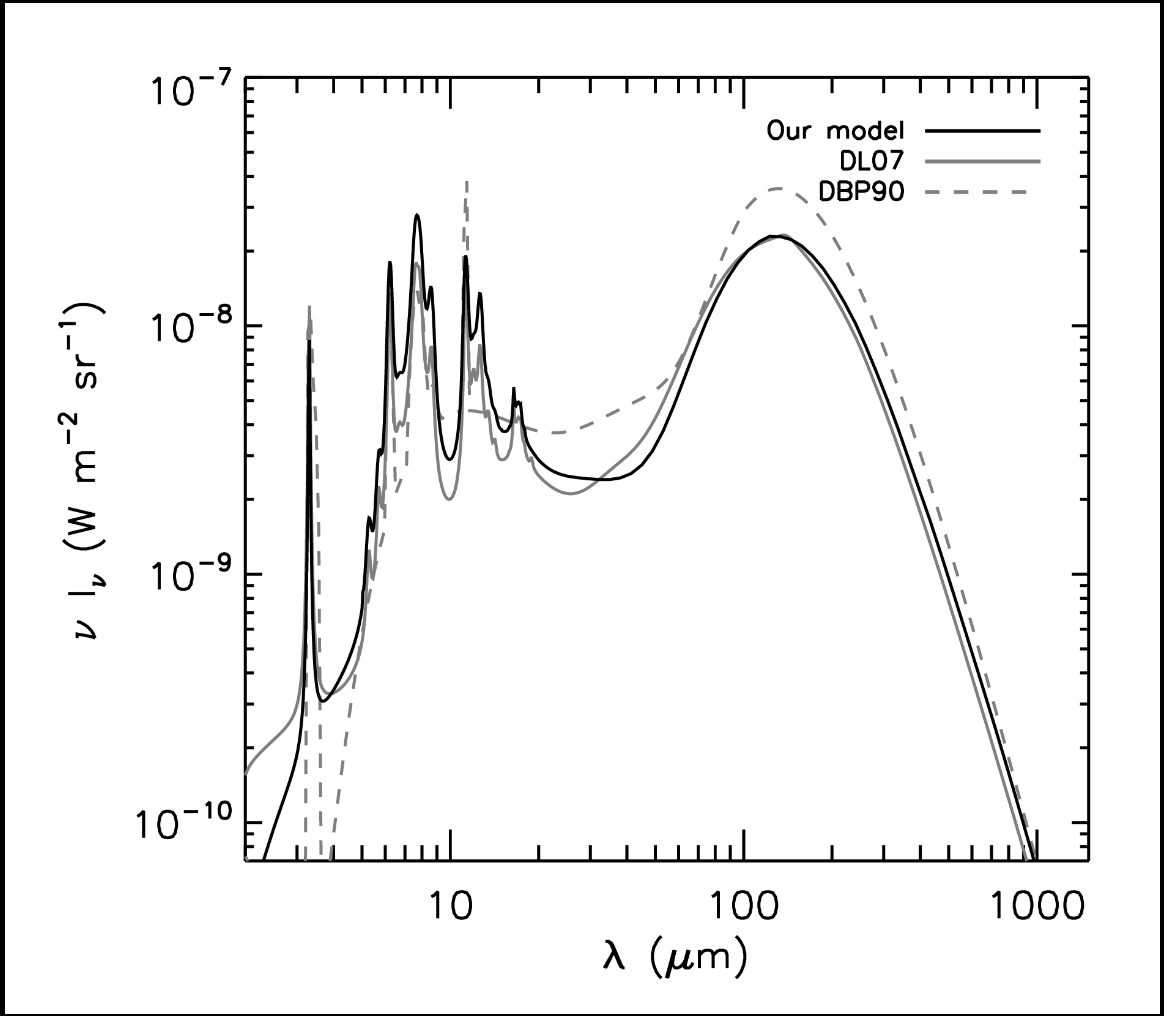
Polycyclic Aromatic Hydrocarbons ???



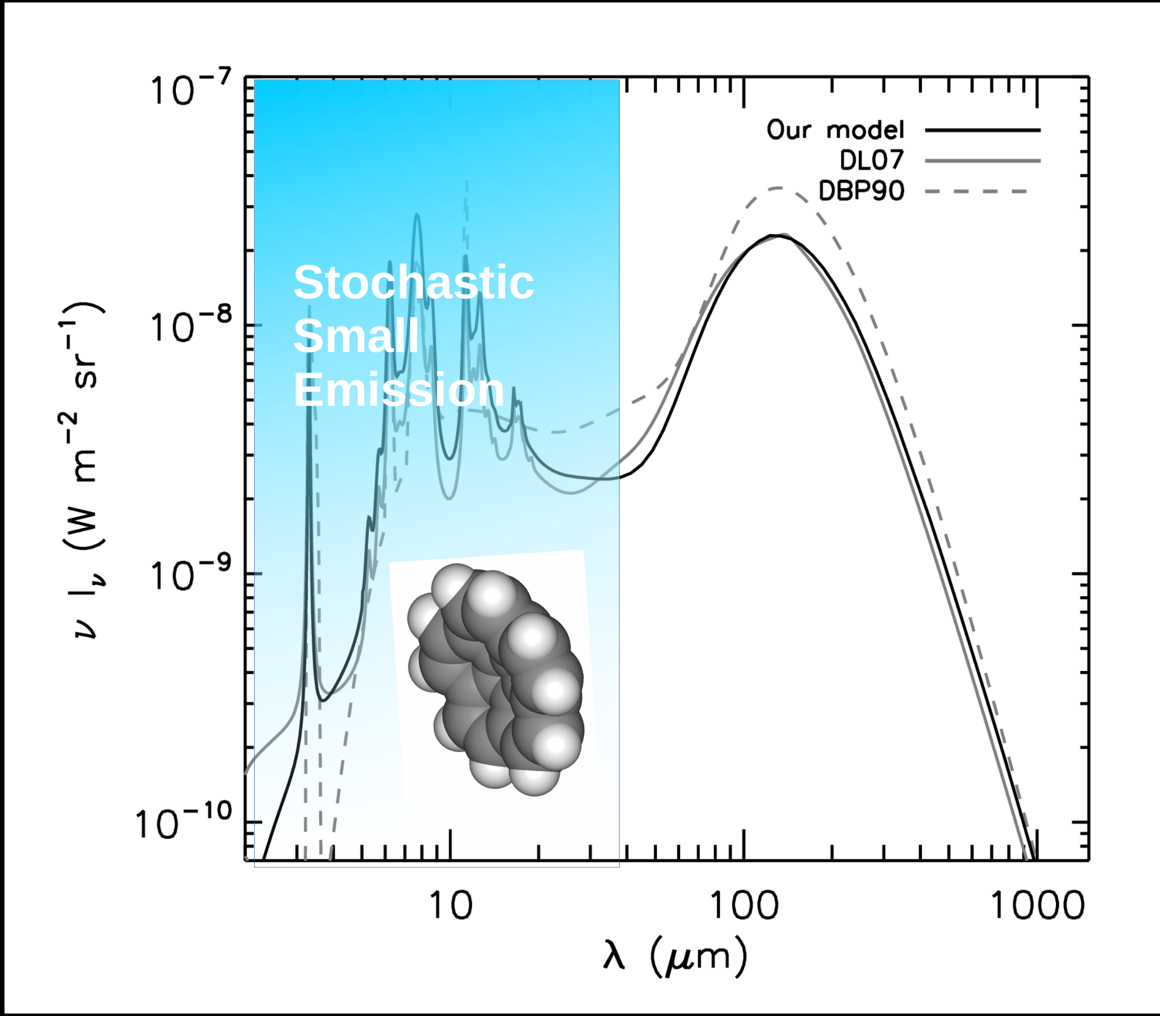
Rotational emission from corranulene $C_{20}H_{10}$ (~2.07D)

has been searched for in the Red Rectangle, by Pilleri et al. (2009)

Introduction - Past Works – Compiegne, et al. (2011)



Introduction - Past Works – Compiegne, et al. (2011)



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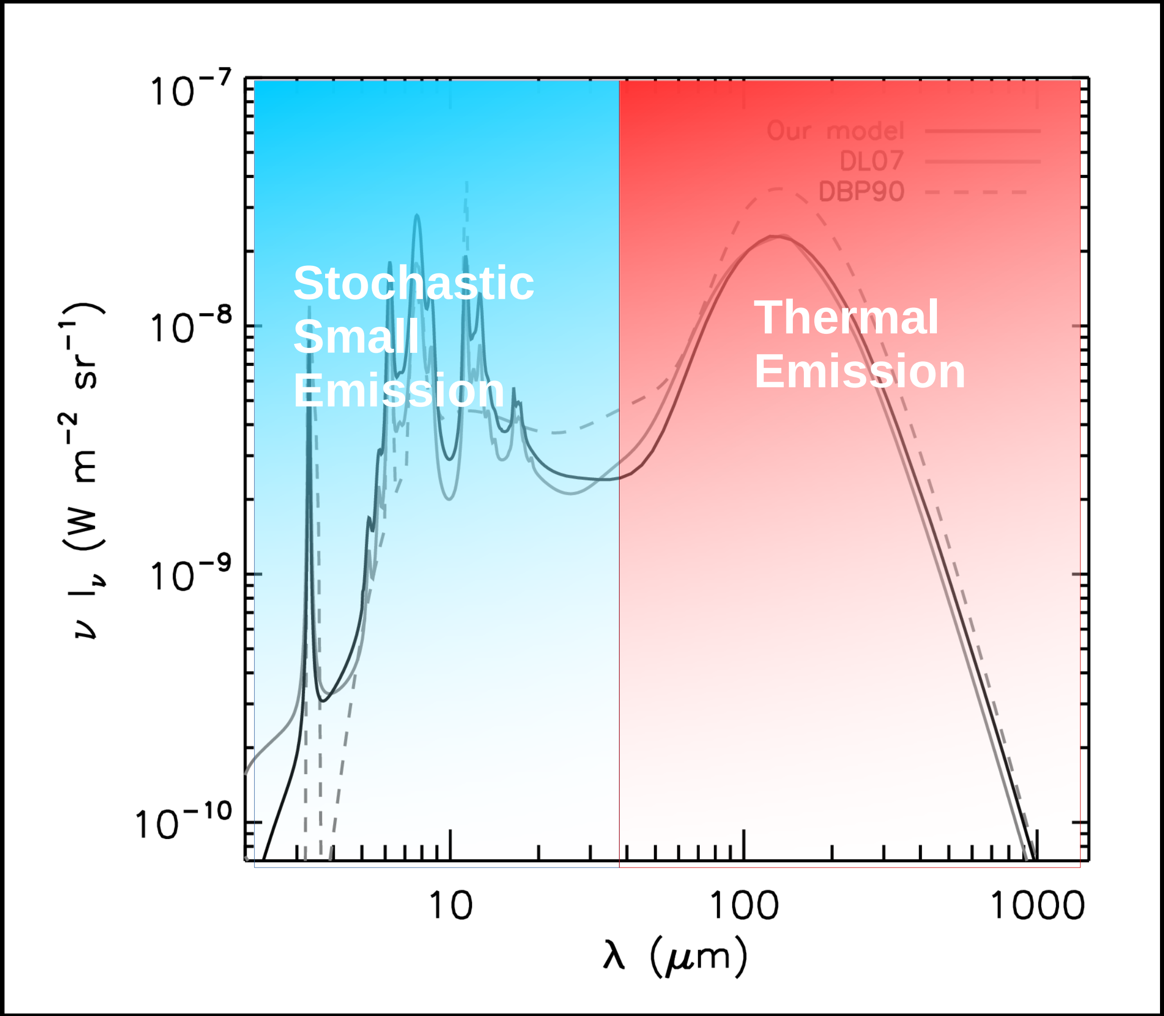
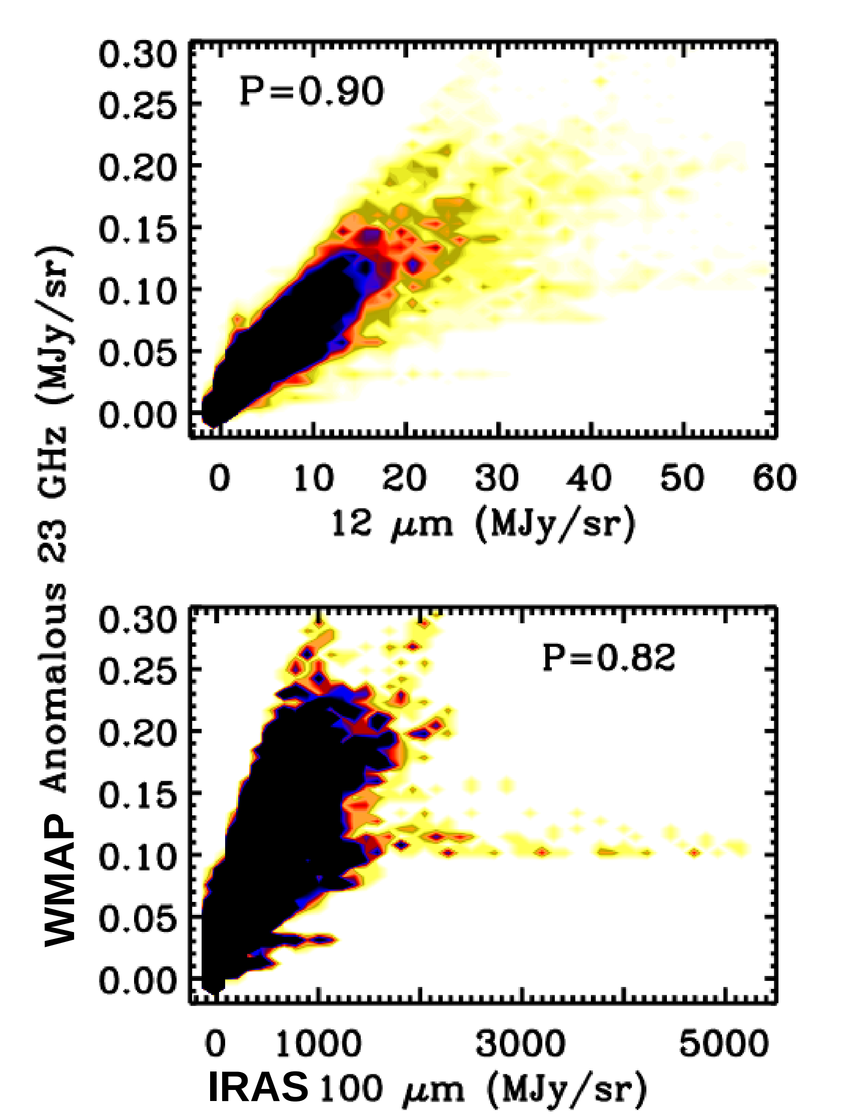


Introduction - Past Works – N. Ysard, et al. (2010)



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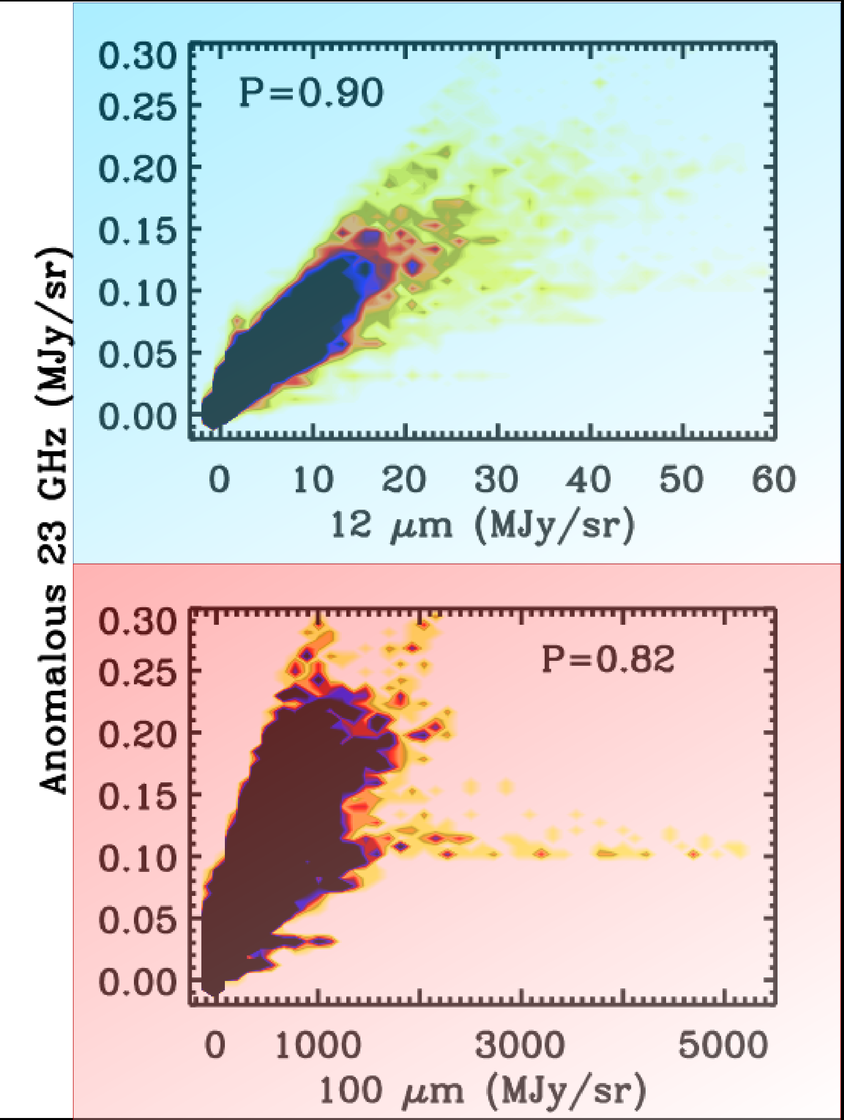
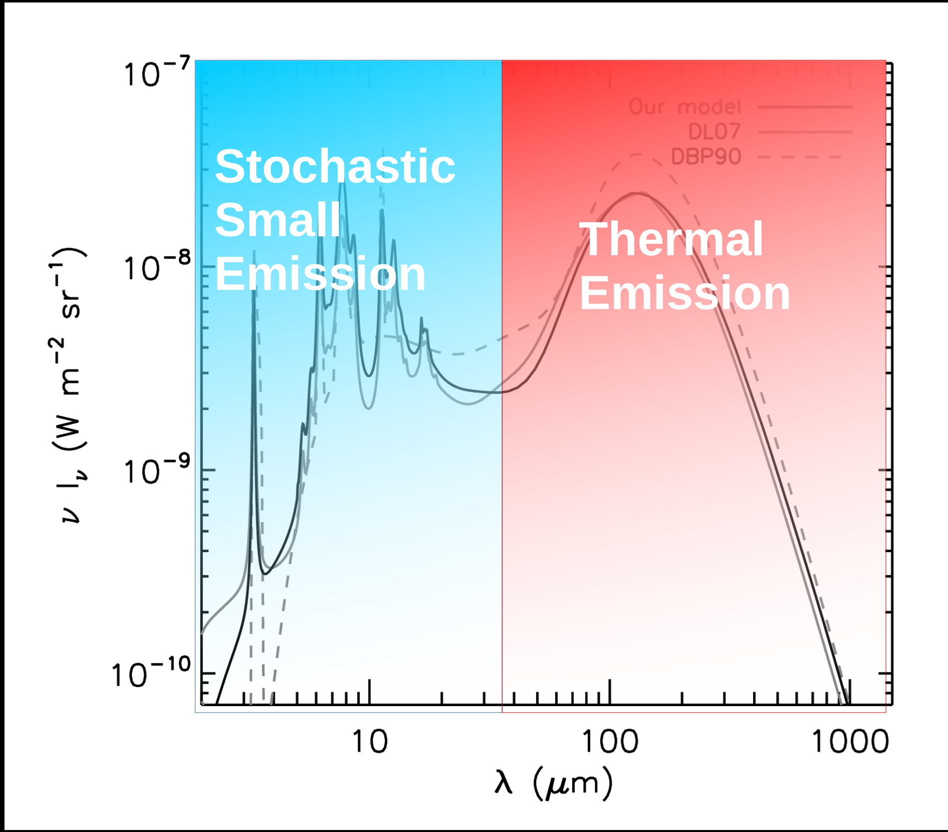
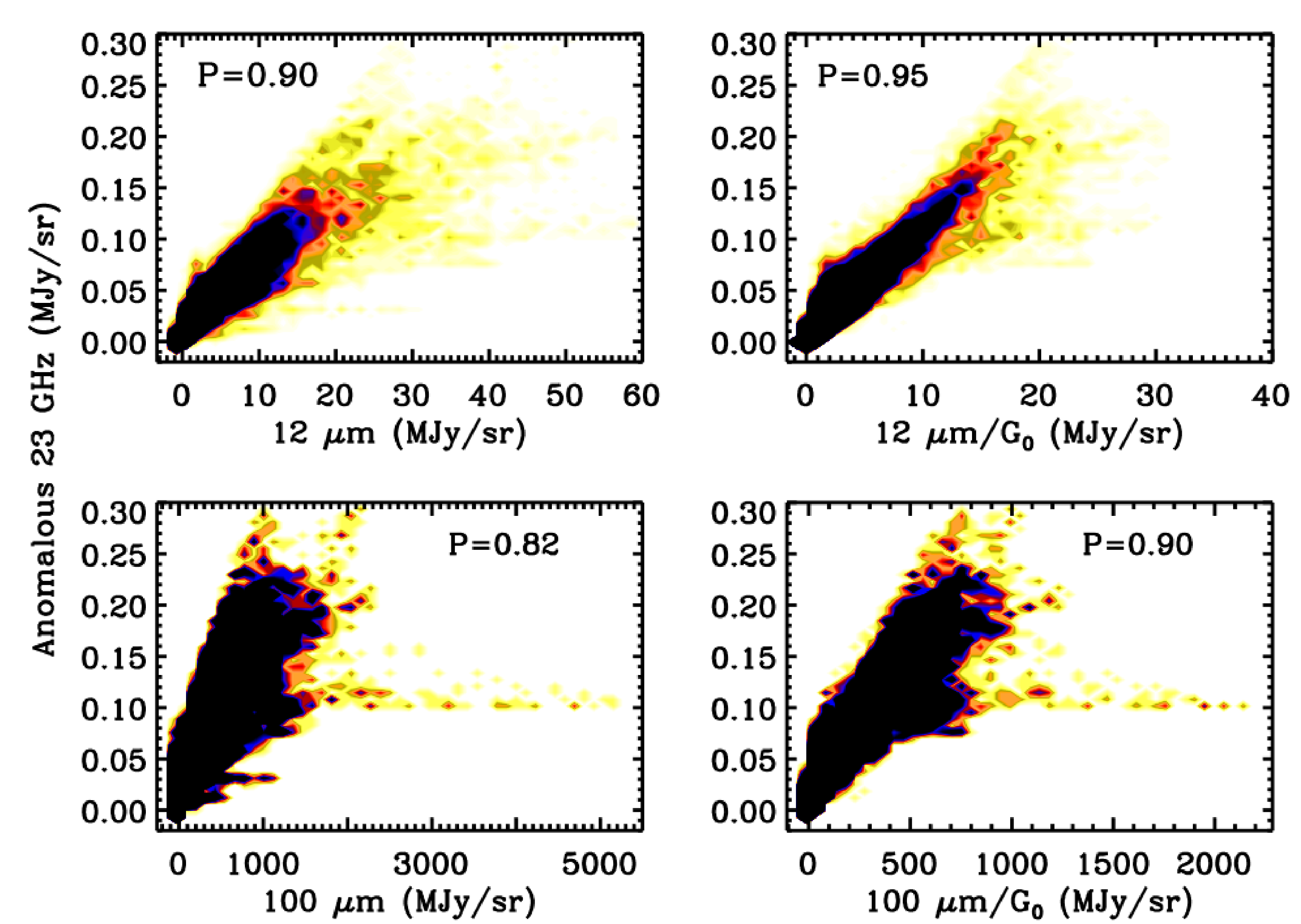


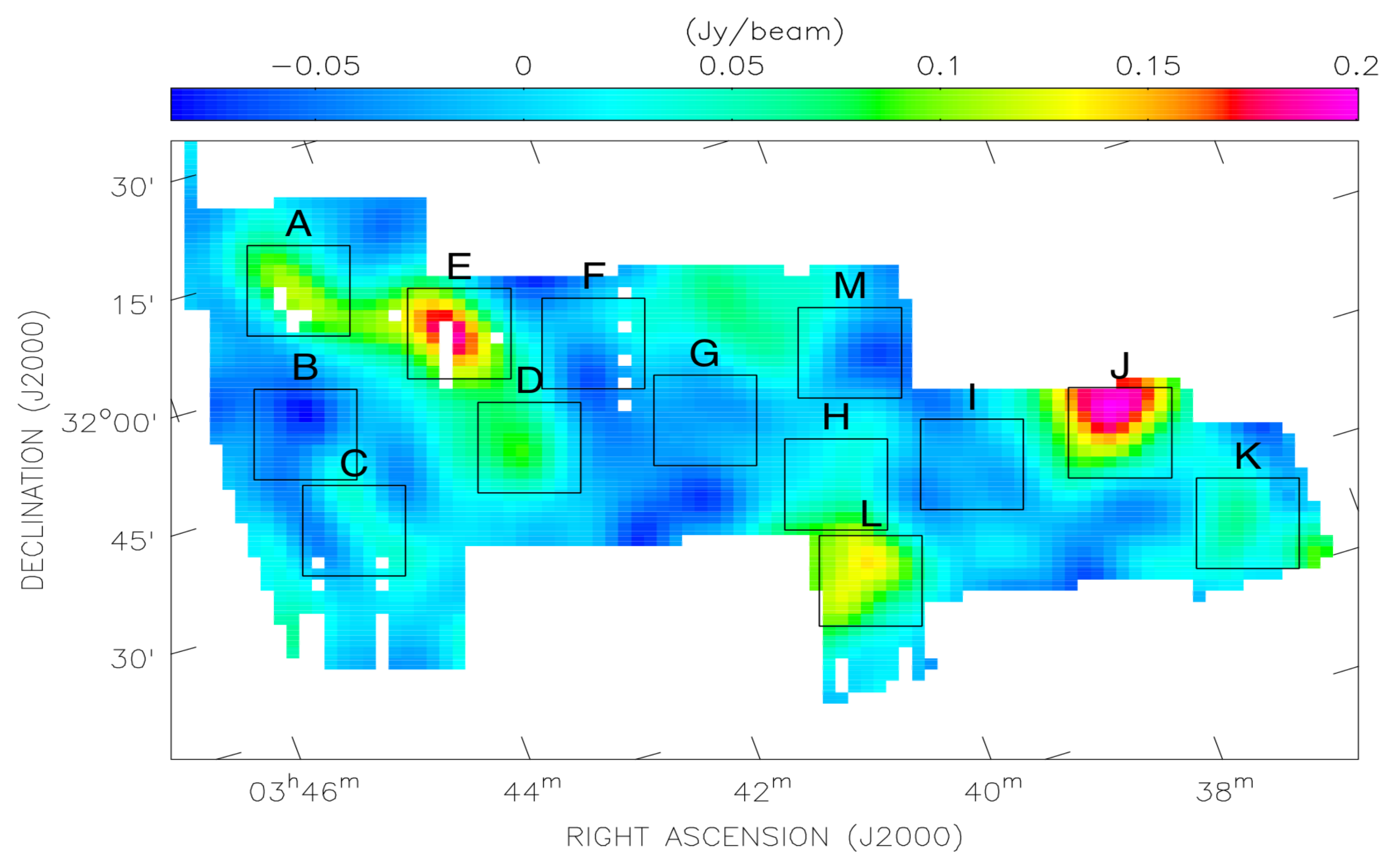


Model interstellar dust mixture SED
Compiegne+ (2011)

Introduction - Past Works – N. Ysard, et al. (2010)

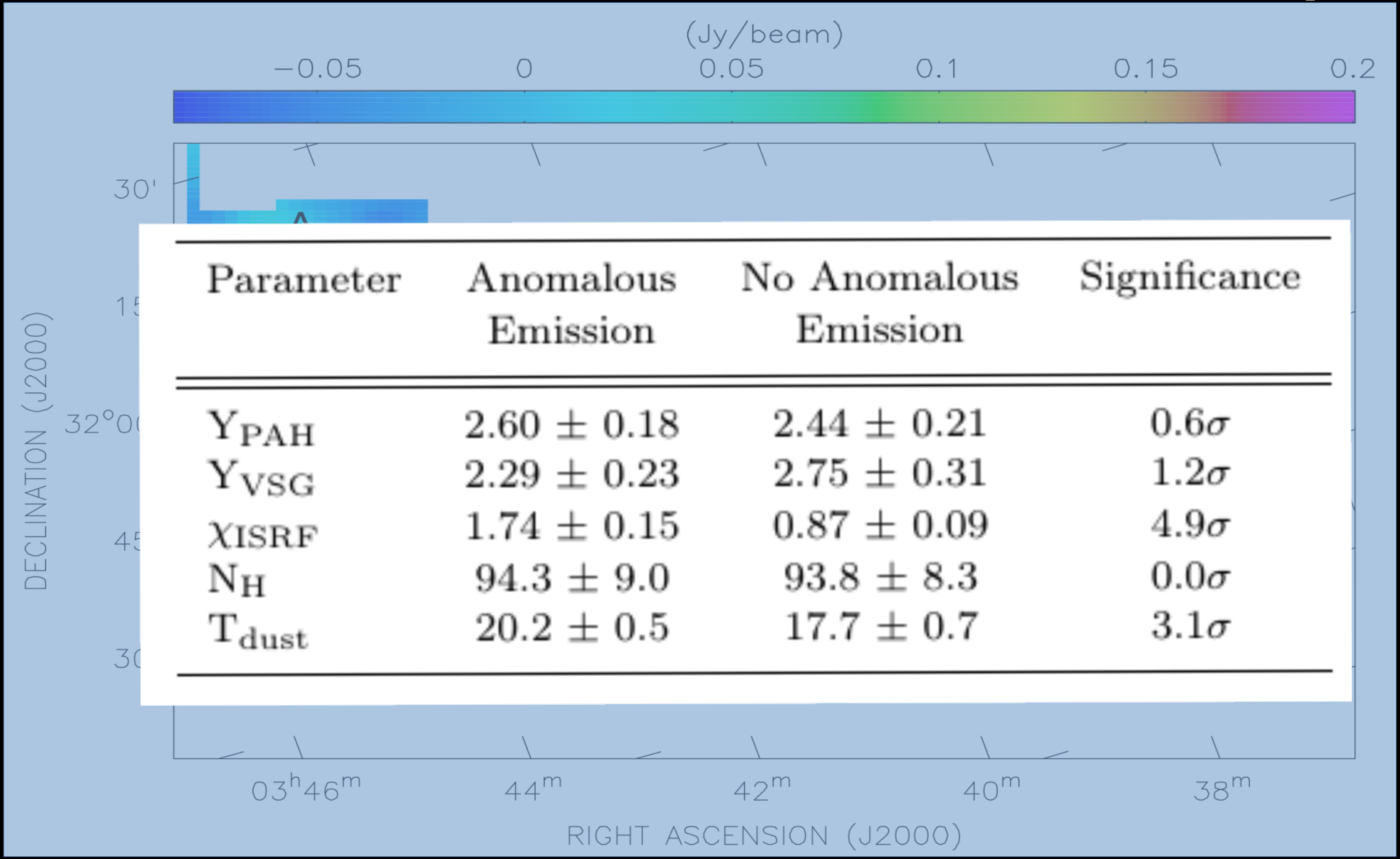


Introduction – Previous Works – C. Tibbs et al. (2011)



C. Tibbs+ (2011) - "Spitzer characterisation of dust in an anomalous emission region: the Perseus cloud"

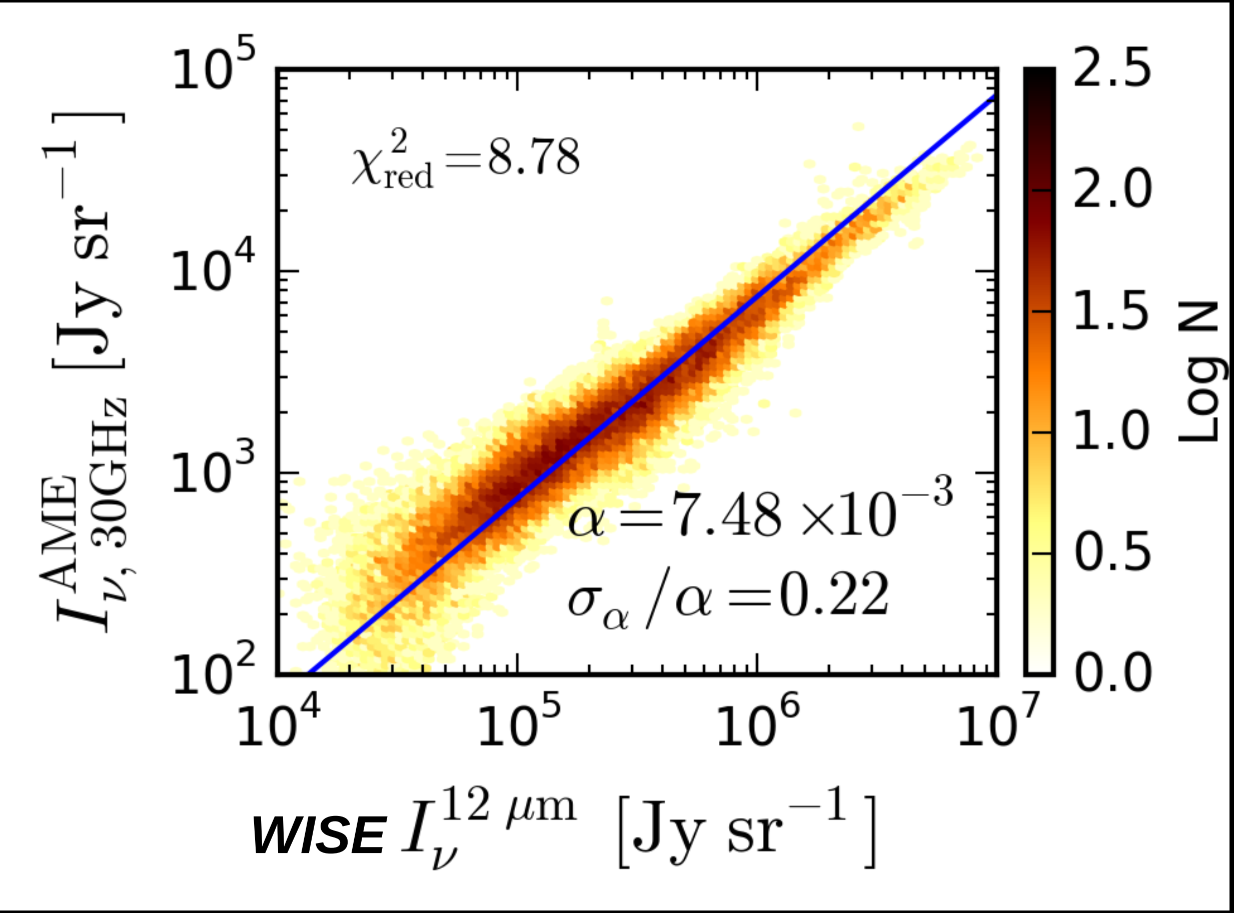
Introduction – Previous Works – C. Tibbs et al. (2011)



Parameter	Anomalous Emission	No Anomalous Emission	Significance
Y_{PAH}	2.60 ± 0.18	2.44 ± 0.21	0.6σ
Y_{VSG}	2.29 ± 0.23	2.75 ± 0.31	1.2σ
χ_{ISRF}	1.74 ± 0.15	0.87 ± 0.09	4.9σ
N_H	94.3 ± 9.0	93.8 ± 8.3	0.0σ
T_{dust}	20.2 ± 0.5	17.7 ± 0.7	3.1σ

C. Tibbs+ (2011) - “Spitzer characterisation of dust in an anomalous emission region: the Perseus cloud”

Introduction - Past Works – B. Hensley, et al. (2016)



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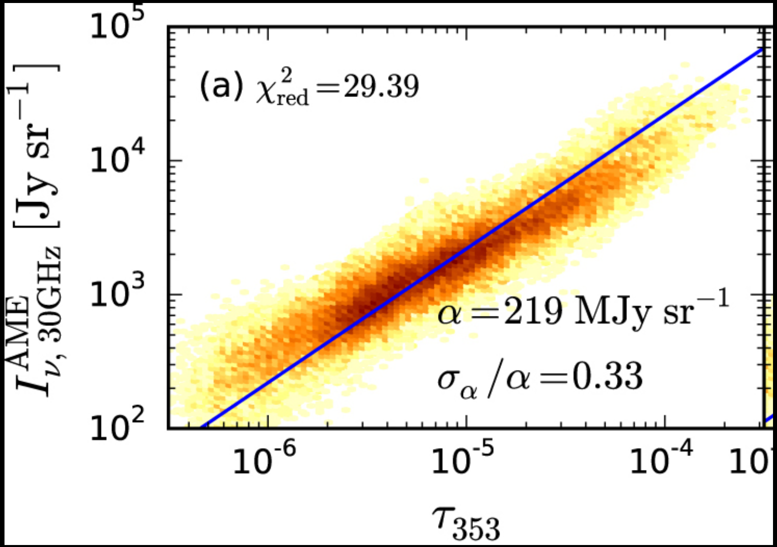

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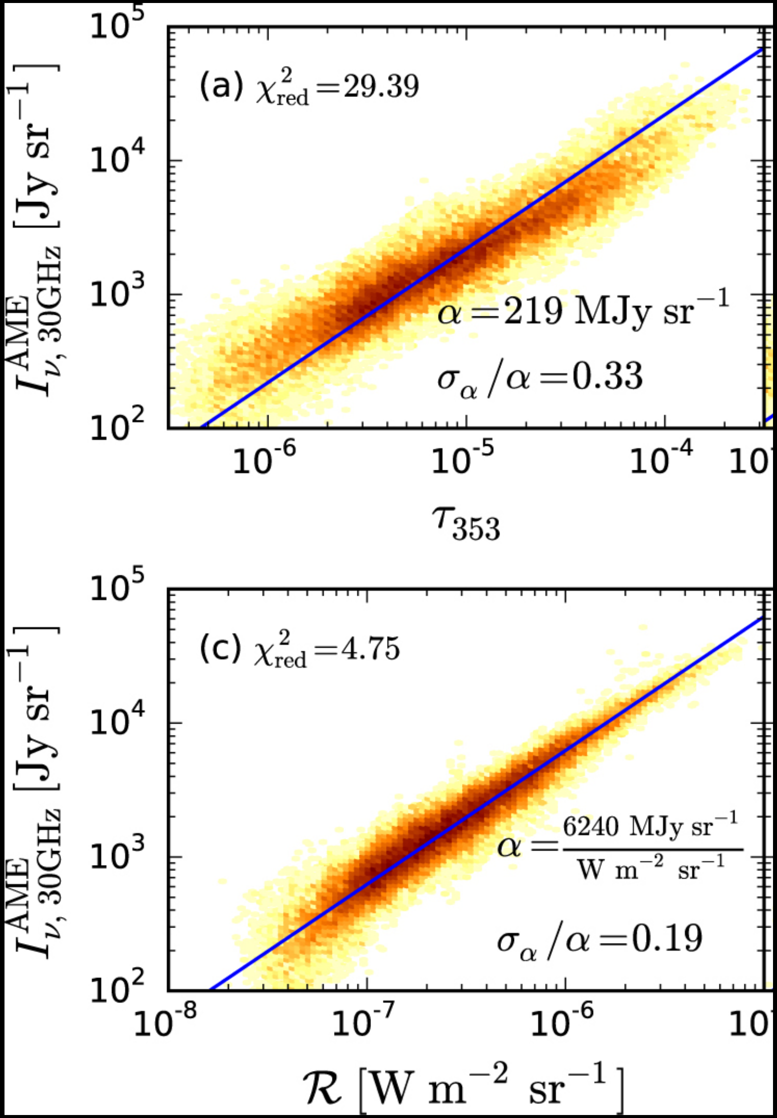

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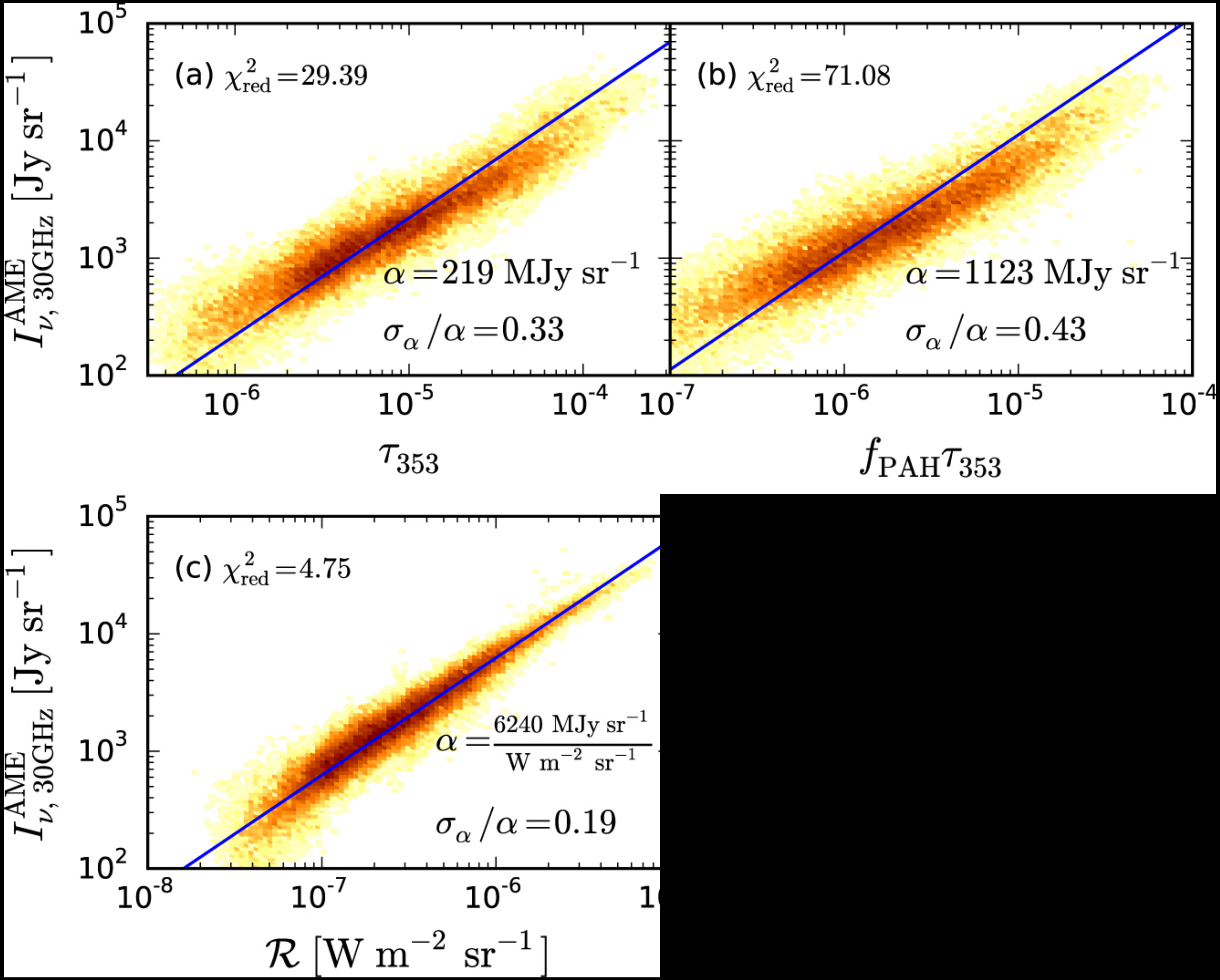

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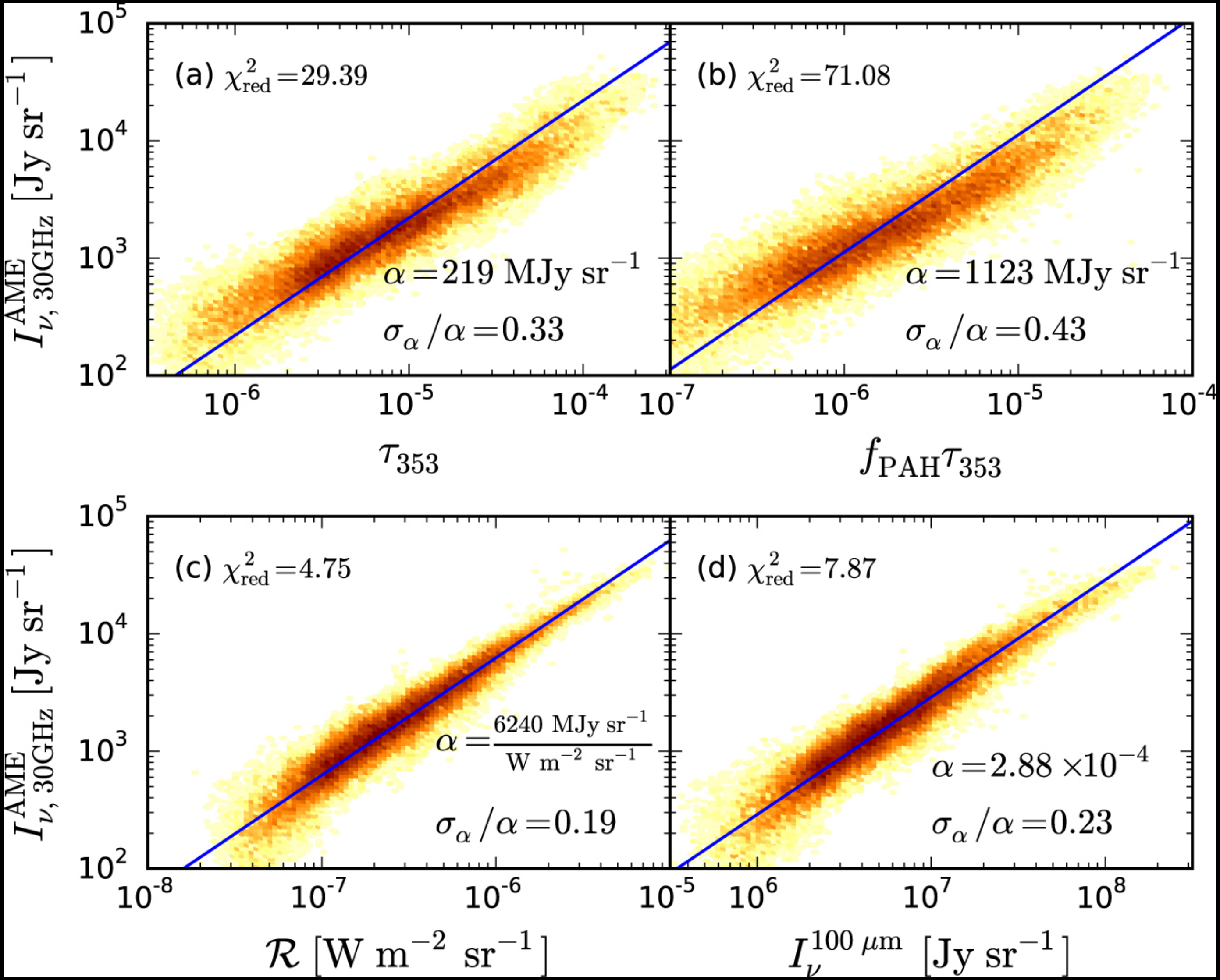

Introduction – Testing a Spinning PAH Hypothesis

Dust parameters:

- PAH luminosity: $L_{PAH} \propto I_{9\mu m}$
- Radiation field: U
- PAH abundance: $\sigma_{PAH} \propto \frac{I_{9\mu m}}{U}$

AME Parameters:

- AME Intensity: via Planck Coll. (2015)
- Carrier abundance: $\sigma_{AME} \propto \frac{I_{AME}}{U_{AME}} (?)$

$$P = \frac{2}{3} \frac{\omega^4 \mu^2 \sin^2 \theta}{c^3}$$

Data - Infrared

- Which IR data can help solve the AME puzzle?

Instrument	Central Wavelength	FWHM
AKARI/IRC	9 μm	~10”
AKARI/IRC	18 μm	~10”
AKARI/FIS	65 μm	63”
AKARI/FIS	90 μm	78”
AKARI/FIS	140 μm	88”
AKARI/FIS	160 μm	88”
IRAS/IRIS	12 μm	4.0$'$
IRAS/IRIS	25 μm	4.0$'$
IRAS/IRIS	60 μm	4.2$'$
IRAS/IRIS	100 μm	4.5$'$
Planck/HFI	345 μm	4.7$'$
Planck/HFI	550 μm	4.3$'$

Data - Microwave

- Which data can help solve the AME puzzle?

Product	Relevant Freq./Wavelen	FWHM
$H\alpha$	658.5 nm	$36'$
$N(H)$	21 cm	$36'$
PC R (PR1)	353 GHz	$5'$
PC τ_{353} (PR1)	353 GHz	$5'$
Haslam MHz	408 MHz	$56'$
PC Synchrotron (PR2)	408 MHz	$60'$
PC AME_{var} (PR2)	22.8 GHz	$60'$
PC AME_{fix} (PR2)	41.0 GHz	$60'$
PC free-free (PR2)	N/A	$60'$

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AME Data limits our analysis to ~1 degree resolution!

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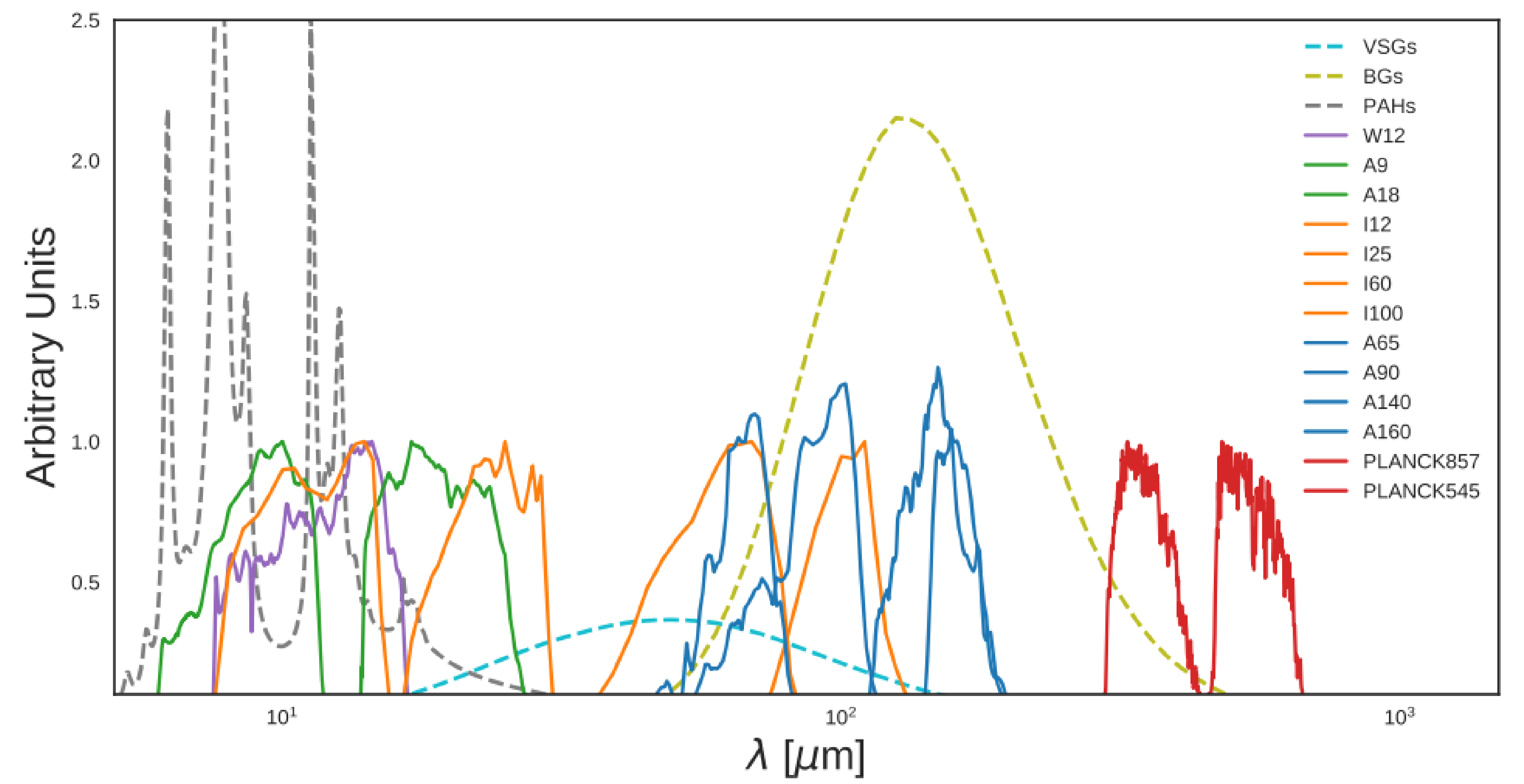
- ***AME Data limits our analysis to ~1 degree resolution!***
- ***AME resolution is limited by use of Haslam+ (1982) synchrotron constraints***

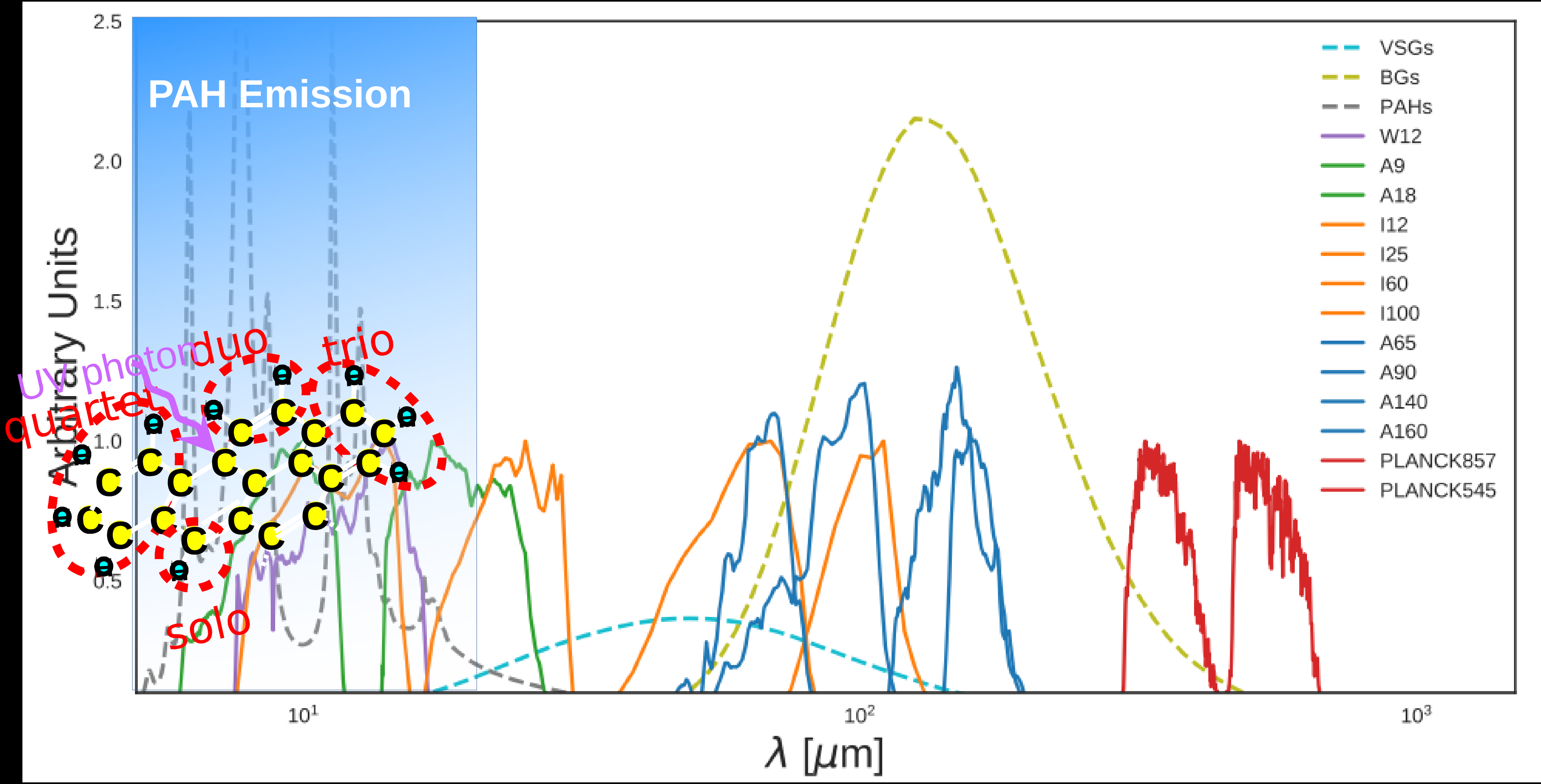
Data - Infrared

- Which data can help solve the AME puzzle?



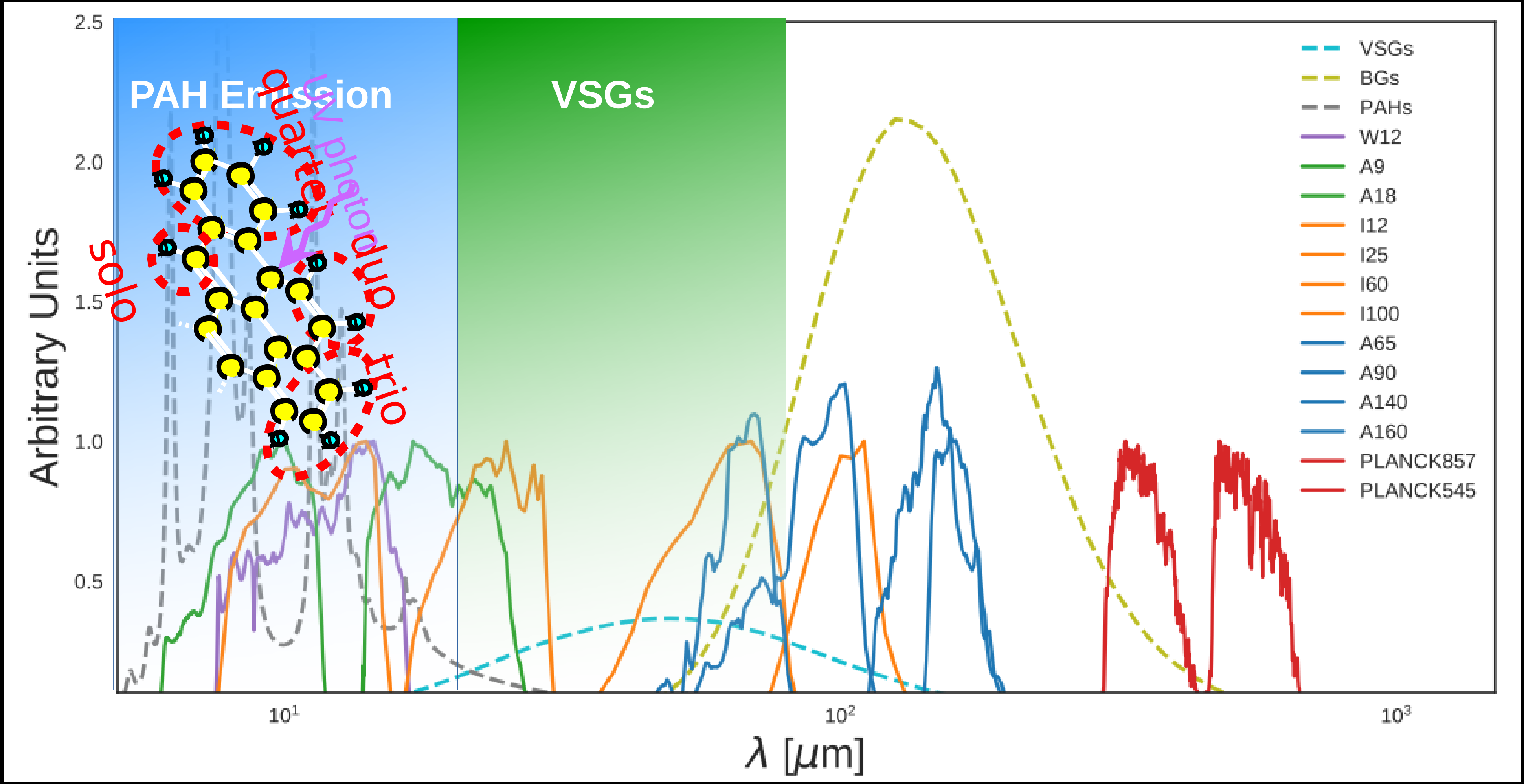
Data – Infrared – PAH Features

- Which data can help solve the AME puzzle?

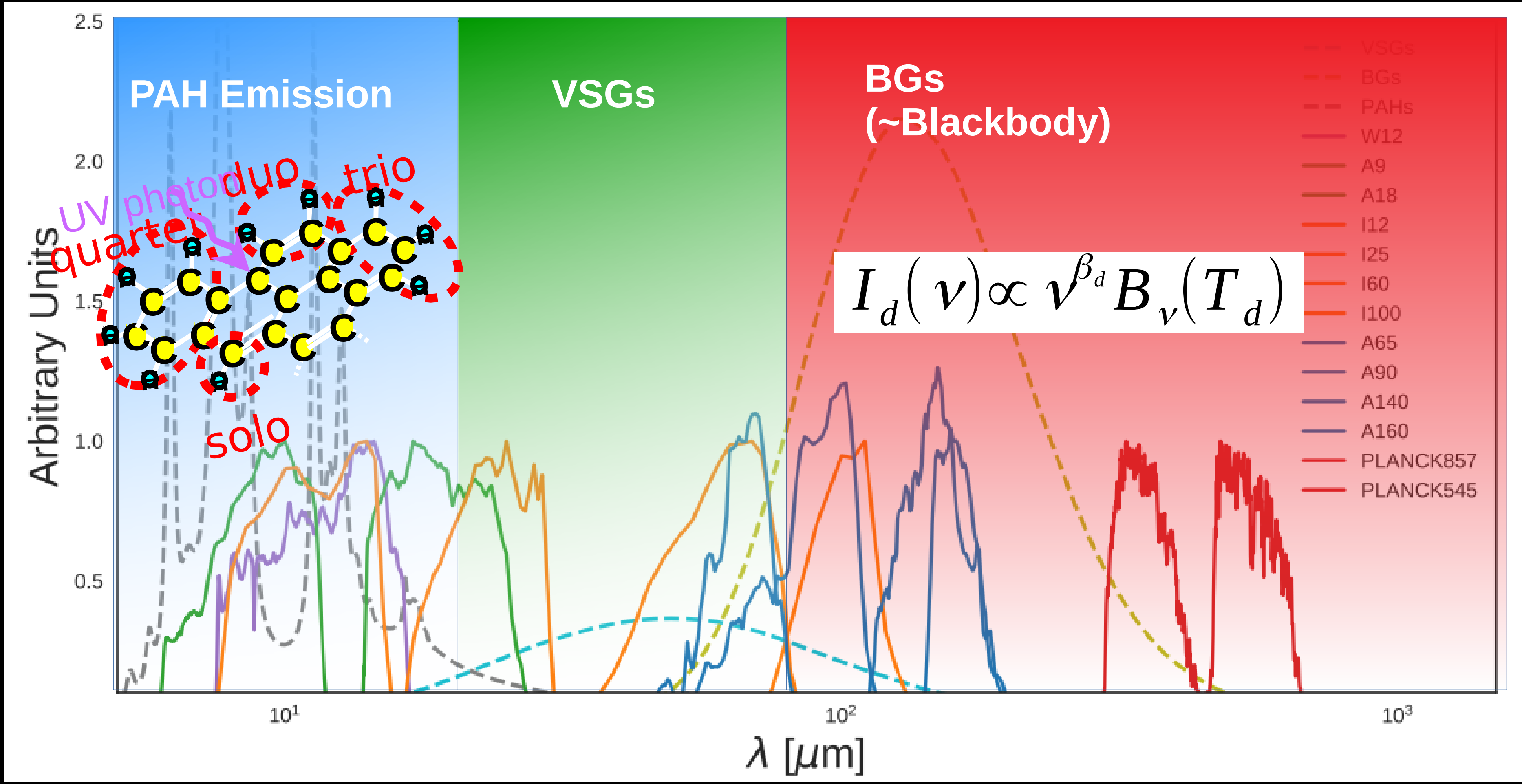


Data – Infrared – Very Small Grains

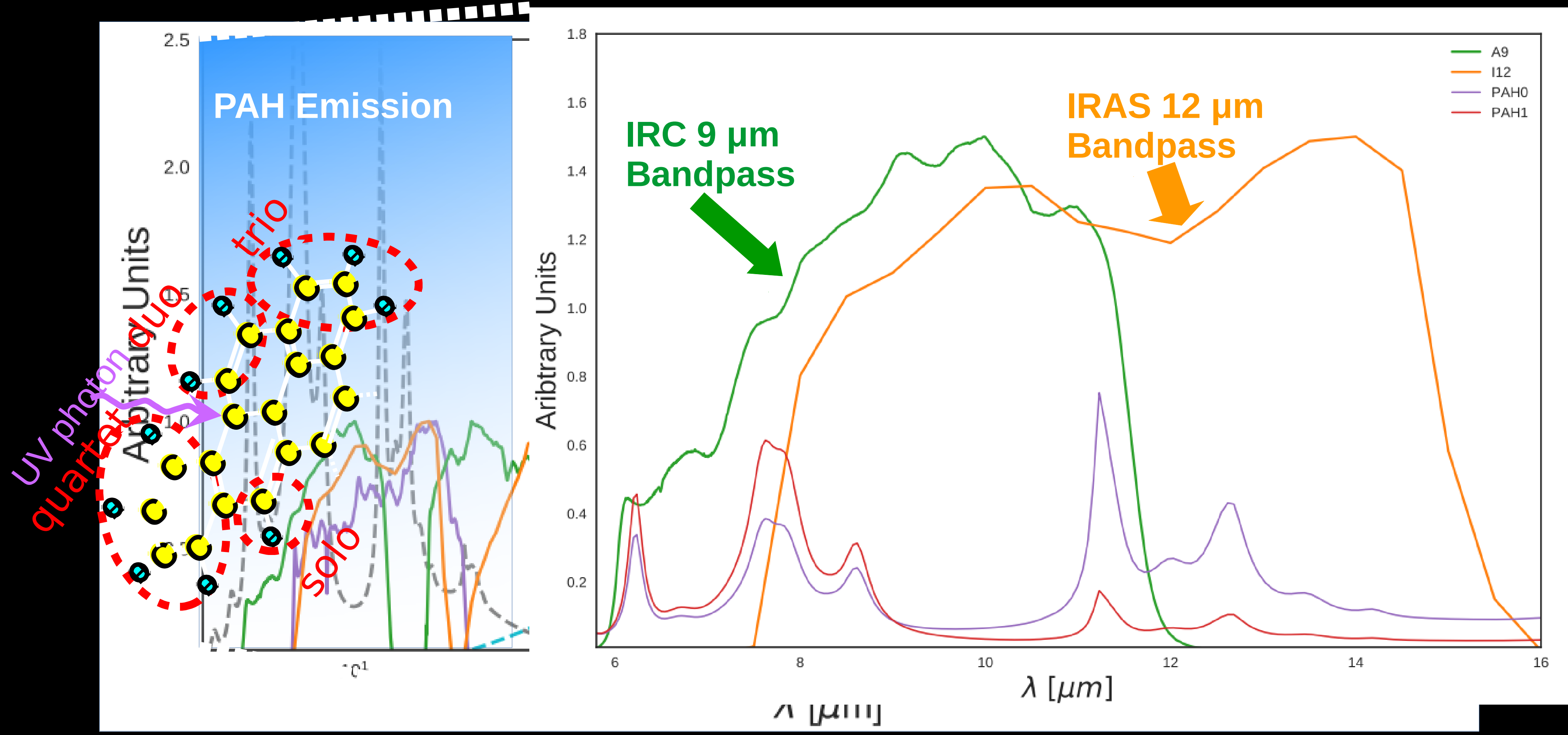
- Which data can help solve the AME puzzle?



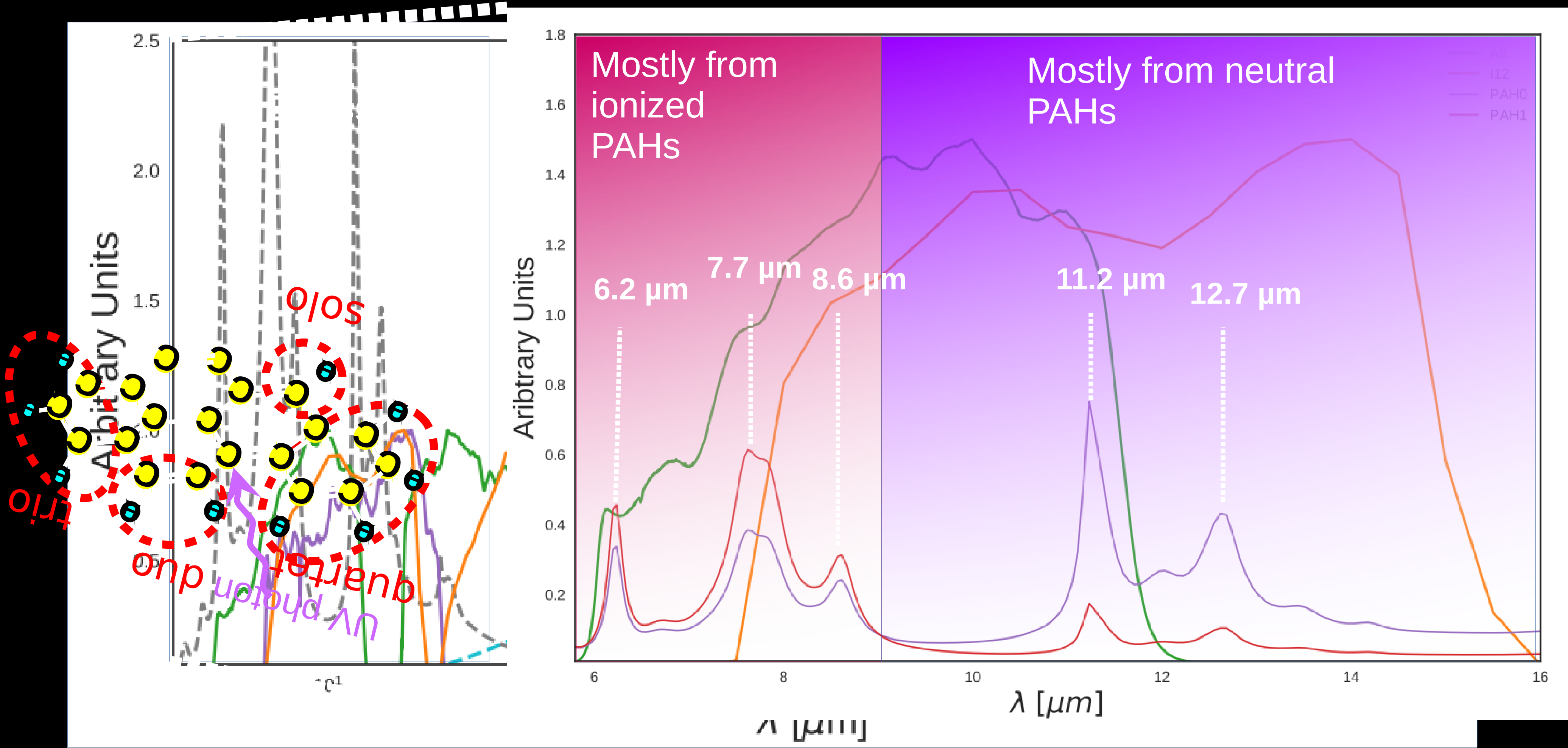
Data – Infrared – Thermal Equilibrium Grains



Data – Infrared – PAH Features



Data – Infrared – PAH Features – PAH Ionization



Analysis: Overview

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All-sky
Intensity Correlation Matrix: “How do IR intensities vary with AME? Each other?”
Bootstrap: “How precise are the correlation tests?”
Implication for Spinning PAHs: Essentially inconclusive...

Analysis: Overview

All-sky	*λ Orionis*
Intensity Correlation Matrix: "How do IR intensities vary with AME? Each other?"	**Intensity Correlation Matrix**
Bootstrap: "How precise are the correlation tests?"	**Bootstrap**
Implication for Spinning PAHs: Essentially inconclusive...	**SED Fitting** "What if we look at physical parameters of dust?"
	Implication for Spinning PAHs: Supported

Analysis: All-sky

All-sky Analysis

- Data mask

All-sky Analysis

- Data mask
- Masked correlation test

All-sky Analysis

- Data mask
- Masked correlation test
- Bootstrap analysis

All-sky Analysis

- Data mask
- Masked correlation test
- Bootstrap analysis

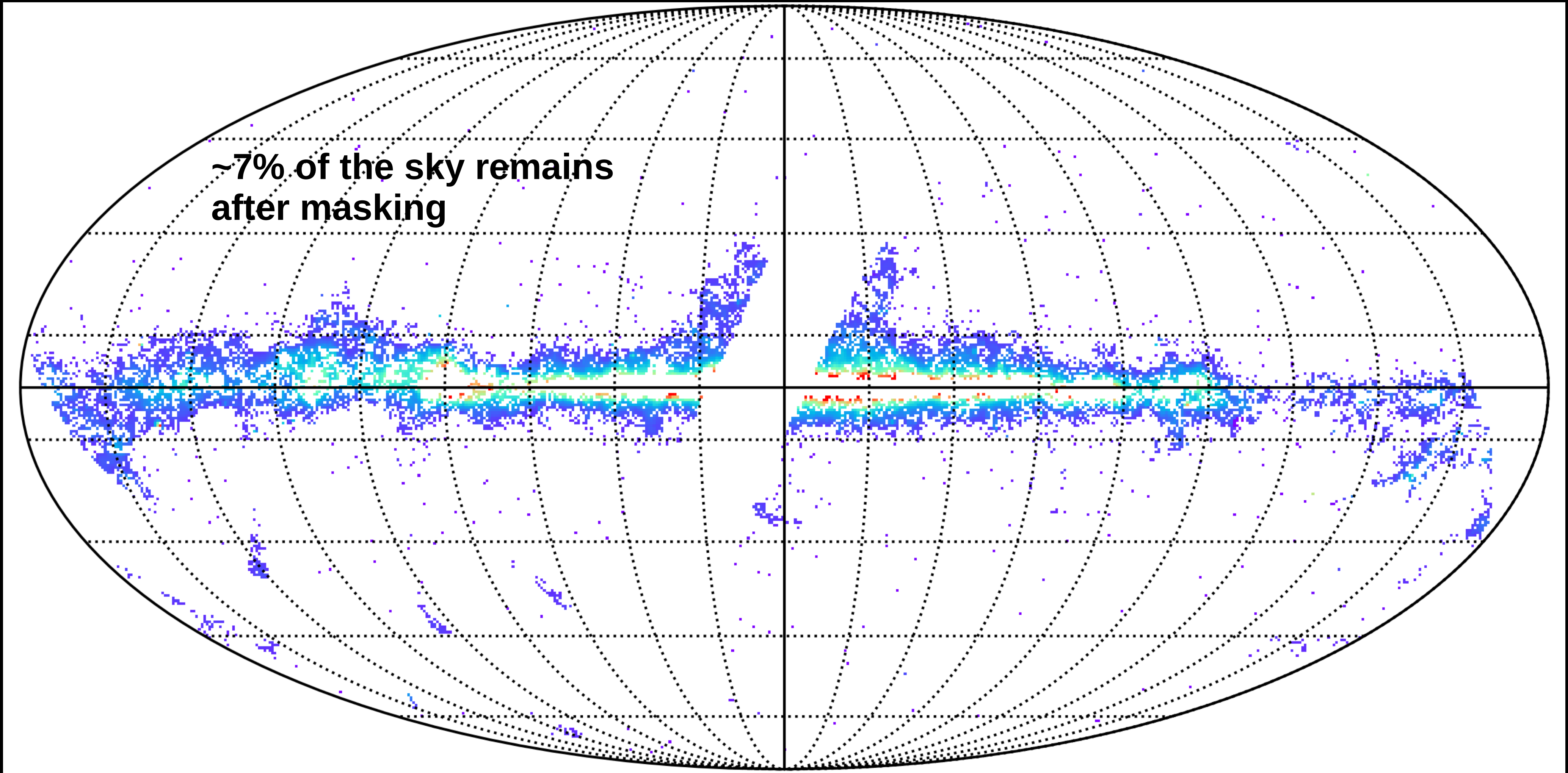
All-sky Analysis

- Data mask
- Masked correlation test
- Bootstrap analysis
- Conclusions
- Future work?

All-sky Analysis – Data mask

- **Pixel mask conditions:**
  1) Zodiacal light
  2) Point-sources
  3) 3σ signal:noise limit
  4) Galactic plane confusion

All-sky Analysis – Data Mask



All-sky Analysis

- Do AKARI-based results mirror previous works?

All-sky Analysis – Masked Analysis – Corr Matrix

	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.91	0.92	0.89	0.86	0.85	0.89	0.91	0.93	0.93	0.87	0.84	0.77	0.83	0.67	0.62	0.71	0.41	0.64
I12	0.91	1	0.81	0.95	0.81	0.86	0.85	0.86	0.89	0.9	0.86	0.83	0.76	0.8	0.62	0.69	0.63	0.26	0.71
A18	0.92	0.81	1	0.85	0.82	0.74	0.84	0.85	0.86	0.86	0.8	0.77	0.69	0.76	0.63	0.55	0.69	0.41	0.58
I25	0.89	0.95	0.85	1	0.83	0.81	0.85	0.88	0.9	0.91	0.88	0.85	0.75	0.79	0.61	0.67	0.66	0.25	0.69
I60	0.86	0.81	0.82	0.83	1	0.92	0.99	0.99	0.93	0.92	0.78	0.73	0.73	0.83	0.7	0.75	0.63	0.56	0.79
A65	0.85	0.86	0.74	0.81	0.92	1	0.94	0.92	0.9	0.89	0.77	0.73	0.72	0.81	0.69	0.75	0.58	0.47	0.78
A90	0.89	0.85	0.84	0.85	0.99	0.94	1	1	0.96	0.95	0.83	0.79	0.77	0.86	0.71	0.74	0.66	0.53	0.78
I100	0.91	0.86	0.85	0.88	0.99	0.92	1	1	0.97	0.96	0.85	0.81	0.78	0.87	0.71	0.74	0.68	0.51	0.78
A140	0.93	0.89	0.86	0.9	0.93	0.9	0.96	0.97	1	1	0.93	0.9	0.81	0.89	0.71	0.68	0.76	0.46	0.7
A160	0.93	0.9	0.86	0.91	0.92	0.89	0.95	0.96	1	1	0.94	0.91	0.81	0.88	0.71	0.68	0.76	0.43	0.7
P857	0.87	0.86	0.8	0.88	0.78	0.77	0.83	0.85	0.93	0.94	1	1	0.79	0.84	0.68	0.53	0.85	0.32	0.55
P545	0.84	0.83	0.77	0.85	0.73	0.73	0.79	0.81	0.9	0.91	1	1	0.76	0.82	0.67	0.49	0.87	0.31	0.5
AMEvar	0.77	0.76	0.69	0.75	0.73	0.72	0.77	0.78	0.81	0.81	0.79	0.76	1	0.9	0.45	0.61	0.65	0.3	0.62
AMEfix	0.83	0.8	0.76	0.79	0.83	0.81	0.86	0.87	0.89	0.88	0.84	0.82	0.9	1	0.6	0.59	0.73	0.48	0.62
ff	0.67	0.62	0.63	0.61	0.7	0.69	0.71	0.71	0.71	0.71	0.68	0.67	0.45	0.6	1	0.34	0.58	0.7	0.4
Sync	0.62	0.69	0.55	0.67	0.75	0.75	0.74	0.74	0.68	0.68	0.53	0.49	0.61	0.59	0.34	1	0.33	0.13	0.99
N_H	0.71	0.63	0.69	0.66	0.63	0.58	0.66	0.68	0.76	0.76	0.85	0.87	0.65	0.73	0.58	0.33	1	0.4	0.33
H_a	0.41	0.26	0.41	0.25	0.56	0.47	0.53	0.51	0.46	0.43	0.32	0.31	0.3	0.48	0.7	0.13	0.4	1	0.2
H408	0.64	0.71	0.58	0.69	0.79	0.78	0.78	0.78	0.7	0.7	0.55	0.5	0.62	0.62	0.4	0.99	0.33	0.2	1

AME correlates best with 140-160 micron emission.

But is it statistically better than AME vs. MIR emission?

All-sky Analysis - Unmasked correlation test

- Do AKARI-based results mirror previous works?
  - Generally, yes.

All-sky Analysis – Masked Analysis – Corr Matrix

	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.91	0.92	0.89	0.86	0.85	0.89	0.91	0.93	0.93	0.87	0.84	0.77	0.83	0.67	0.62	0.71	0.41	0.64
I12	0.91	1	0.81	0.95	0.81	0.86	0.85	0.86	0.89	0.9	0.86	0.83	0.76	0.8	0.62	0.69	0.63	0.26	0.71
A18	0.92	0.81	1	0.85	0.82	0.74	0.84	0.85	0.86	0.86	0.8	0.77	0.69	0.76	0.63	0.55	0.69	0.41	0.58
I25	0.89	0.95	0.85	1	0.83	0.81	0.85	0.88	0.9	0.91	0.88	0.85	0.75	0.79	0.61	0.67	0.66	0.25	0.69
I60	0.86	0.81	0.82	0.83	1	0.92	0.99	0.99	0.93	0.92	0.78	0.73	0.73	0.83	0.7	0.75	0.63	0.56	0.79
A65	0.85	0.86	0.74	0.81	0.92	1	0.94	0.92	0.9	0.89	0.77	0.73	0.72	0.81	0.69	0.75	0.58	0.47	0.78
A90	0.89	0.85	0.84	0.85	0.99	0.94	1	1	0.96	0.95	0.83	0.79	0.77	0.86	0.71	0.74	0.66	0.53	0.78
I100	0.91	0.86	0.85	0.88	0.99	0.92	1	1	0.97	0.96	0.85	0.81	0.78	0.87	0.71	0.74	0.68	0.51	0.78
A140	0.93	0.89	0.86	0.9	0.93	0.9	0.96	0.97	1	1	0.93	0.9	0.81	0.89	0.71	0.68	0.76	0.46	0.7
A160	0.93	0.9	0.86	0.91	0.92	0.89	0.95	0.96	1	1	0.94	0.91	0.81	0.88	0.71	0.68	0.76	0.43	0.7
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P545	0.84	0.83	0.77	0.85	0.73	0.73	0.79	0.81	0.9	0.91	1	1	0.76	0.82	0.67	0.49	0.87	0.31	0.5
AMEvar	0.77	0.76	0.69	0.75	0.73	0.72	0.77	0.78	0.81	0.81	0.79	0.76	1	0.9	0.45	0.61	0.65	0.3	0.62
AMEfix	0.83	0.8	0.76	0.79	0.83	0.81	0.86	0.87	0.89	0.88	0.84	0.82	0.9	1	0.6	0.59	0.73	0.48	0.62
ff	0.67	0.62	0.63	0.61	0.7	0.69	0.71	0.71	0.71	0.71	0.68	0.67	0.45	0.6	1	0.34	0.58	0.7	0.4
Sync	0.62	0.69	0.55	0.67	0.75	0.75	0.74	0.74	0.68	0.68	0.53	0.49	0.61	0.59	0.34	1	0.33	0.13	0.99
N_H	0.71	0.63	0.69	0.66	0.63	0.58	0.66	0.68	0.76	0.76	0.85	0.87	0.65	0.73	0.58	0.33	1	0.4	0.33
H_a	0.41	0.26	0.41	0.25	0.56	0.47	0.53	0.51	0.46	0.43	0.32	0.31	0.3	0.48	0.7	0.13	0.4	1	0.2
H408	0.64	0.71	0.58	0.69	0.79	0.78	0.78	0.78	0.7	0.7	0.55	0.5	0.62	0.62	0.4	0.99	0.33	0.2	1

AME correlates best with 140-160 micron emission.

But is it statistically better than AME vs. MIR emission?

All-sky Analysis – Masked Analysis – Corr Matrix

	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.91	0.92	0.89	0.86	0.85	0.89	0.91	0.93	0.93	0.87	0.84	0.77	0.83	0.67	0.62	0.71	0.41	0.64
I12	0.91	1	0.81	0.95	0.81	0.86	0.85	0.86	0.89	0.9	0.86	0.83	0.76	0.8	0.62	0.69	0.63	0.26	0.71
A18	0.92	0.81	1	0.85	0.82	0.74	0.84	0.85	0.86	0.86	0.8	0.77	0.69	0.76	0.63	0.55	0.69	0.41	0.58
I25	0.89	0.95	0.85	1	0.83	0.81	0.85	0.88	0.9	0.91	0.88	0.85	0.75	0.79	0.61	0.67	0.66	0.25	0.69
I60	0.86	0.81	0.82	0.83	1	0.92	0.99	0.99	0.93	0.92	0.78	0.73	0.73	0.83	0.7	0.75	0.63	0.56	0.79
A65	0.85	0.86	0.74	0.81	0.92	1	0.94	0.92	0.9	0.89	0.77	0.73	0.72	0.81	0.69	0.75	0.58	0.47	0.78
A90	0.89	0.85	0.84	0.85	0.99	0.94	1	1	0.96	0.95	0.83	0.79	0.77	0.86	0.71	0.74	0.66	0.53	0.78
I100	0.91	0.86	0.85	0.88	0.99	0.92	1	1	0.97	0.96	0.85	0.81	0.78	0.87	0.71	0.74	0.68	0.51	0.78
A140	0.93	0.89	0.86	0.9	0.93	0.9	0.96	0.97	1	1	0.93	0.9	0.81	0.89	0.71	0.68	0.76	0.46	0.7
A160	0.93	0.9	0.86	0.91	0.92	0.89	0.95	0.96	1	1	0.94	0.91	0.81	0.88	0.71	0.68	0.76	0.43	0.7
P857	0.87	0.86	0.8	0.88	0.78	0.77	0.83	0.85	0.93	0.94	1	1	0.79	0.84	0.68	0.53	0.85	0.32	0.55
P545	0.84	0.83	0.77	0.85	0.73	0.73	0.79	0.81	0.9	0.91	1	1	0.76	0.82	0.67	0.49	0.87	0.31	0.5
AMEvar	0.77	0.76	0.69	0.75	0.73	0.72	0.77	0.78	0.81	0.81	0.79	0.76	1	0.9	0.45	0.61	0.65	0.3	0.62
AMEfix	0.83	0.8	0.76	0.79	0.83	0.81	0.86	0.87	0.89	0.88	0.84	0.82	0.9	1	0.6	0.59	0.73	0.48	0.62
ff	0.67	0.62	0.63	0.61	0.7	0.69	0.71	0.71	0.71	0.71	0.68	0.67	0.45	0.6	1	0.34	0.58	0.7	0.4
Sync	0.62	0.69	0.55	0.67	0.75	0.75	0.74	0.74	0.68	0.68	0.53	0.49	0.61	0.59	0.34	1	0.33	0.13	0.99
N_H	0.71	0.63	0.69	0.66	0.63	0.58	0.66	0.68	0.76	0.76	0.85	0.87	0.65	0.73	0.58	0.33	1	0.4	0.33
H_a	0.41	0.26	0.41	0.25	0.56	0.47	0.53	0.51	0.46	0.43	0.32	0.31	0.3	0.48	0.7	0.13	0.4	1	0.2
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	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.91	0.92	0.89	0.86	0.85	0.89	0.91	0.93	0.93	0.87	0.84	0.77	0.83	0.67	0.62	0.71	0.41	0.64
I12	0.91	1	0.81	0.95	0.81	0.86	0.85	0.86	0.89	0.9	0.86	0.83	0.76	0.8	0.62	0.69	0.63	0.26	0.71
A18	0.92	0.81	1	0.85	0.82	0.74	0.84	0.85	0.86	0.86	0.8	0.77	0.69	0.76	0.63	0.55	0.69	0.41	0.58
I25	0.89	0.95	0.85	1	0.83	0.81	0.85	0.88	0.9	0.91	0.88	0.85	0.75	0.79	0.61	0.67	0.66	0.25	0.69
I60	0.86	0.81	0.82	0.83	1	0.92	0.99	0.99	0.93	0.92	0.78	0.73	0.73	0.83	0.7	0.75	0.63	0.56	0.79
A65	0.85	0.86	0.74	0.81	0.92	1	0.94	0.92	0.9	0.89	0.77	0.73	0.72	0.81	0.69	0.75	0.58	0.47	0.78
A90	0.89	0.85	0.84	0.85	0.99	0.94	1	1	0.96	0.95	0.83	0.79	0.77	0.86	0.71	0.74	0.66	0.53	0.78
I100	0.91	0.86	0.85	0.88	0.99	0.92	1	1	0.97	0.96	0.85	0.81	0.78	0.87	0.71	0.74	0.68	0.51	0.78
A140	0.93	0.89	0.86	0.9	0.93	0.9	0.96	0.97	1	1	0.93	0.9	0.81	0.89	0.71	0.68	0.76	0.46	0.7
A160	0.93	0.9	0.86	0.91	0.92	0.89	0.95	0.96	1	1	0.94	0.91	0.81	0.88	0.71	0.68	0.76	0.43	0.7
P857	0.87	0.86	0.8	0.88	0.78	0.77	0.83	0.85	0.93	0.94	1	1	0.79	0.84	0.68	0.53	0.85	0.32	0.55
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All-sky Analysis – IR Intensity to AME Comparison

Bootstrap Analysis

All-sky Analysis – What is bootstrapping?

- Why bootstrap?
  - De-weight outliers
  - Assess error in a statistic

All-sky Analysis – What is bootstrapping?

	Original sample	Re-sample #1
	50	
	4	
	3	
	2	
	1	
Mean	12	

...Repeat...

- Ideally, nPn times
- Practically, n*log(n)

All-sky Analysis – What is bootstrapping?

Original sample

Re-sample #1

Original sample	Re-sample #1
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Mean 12	

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All-sky Analysis – What is bootstrapping?

	Original sample	Re-sample #1
	50	4
	4	4
	3	3
	2	2
	1	1
Mean	12	2.8

...Repeat...

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All-sky Analysis – What is bootstrapping?

	Original sample	Re-sample #1	Re-sample #2
	50	4	50
	4	4	4
	3	3	3
	2	2	3
	1	1	1
Mean	12	2.8	12.2

...Repeat...

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- Practically, n*log(n)

All-sky Analysis – What is bootstrapping?

	Original sample	Re-sample #1	Re-sample #2	Re-sample #3
	50	4	50	1
	4	4	4	4
	3	3	3	3
	2	2	3	3
	1	1	1	1
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	Original sample	Re-sample #1	Re-sample #2	Re-sample #3
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	4	4	4	4
	3	3	3	3
	2	2	3	3
	1	1	1	1
Mean	12	2.8	12.2	2.4

...Repeat…

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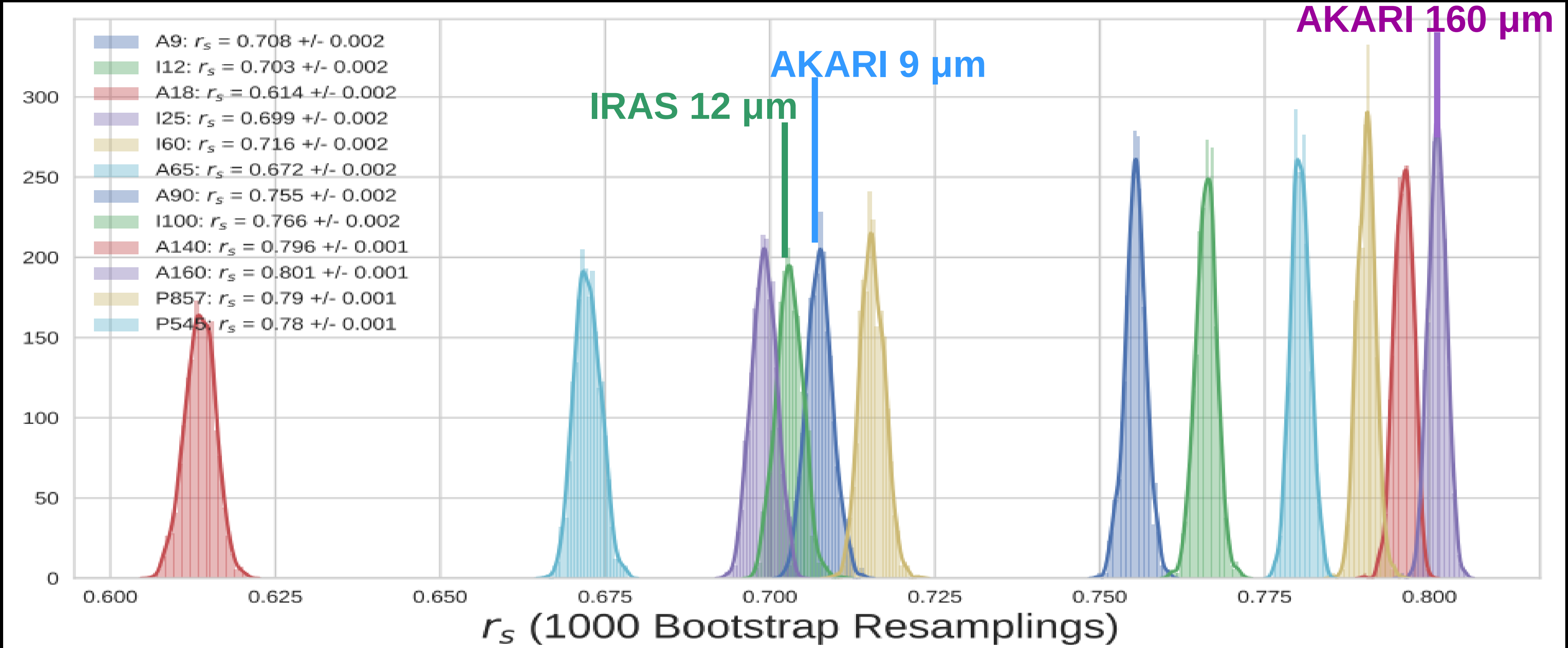
- **Practically, n*log(n)**

All-sky Analysis – Masked Analysis – Bootstrap



A140 and A160 vs. AME score stands-up to the bootstrap test.
FIR bands correlate best, within correlation errors.
A9 vs. AME shows best score among MIR.

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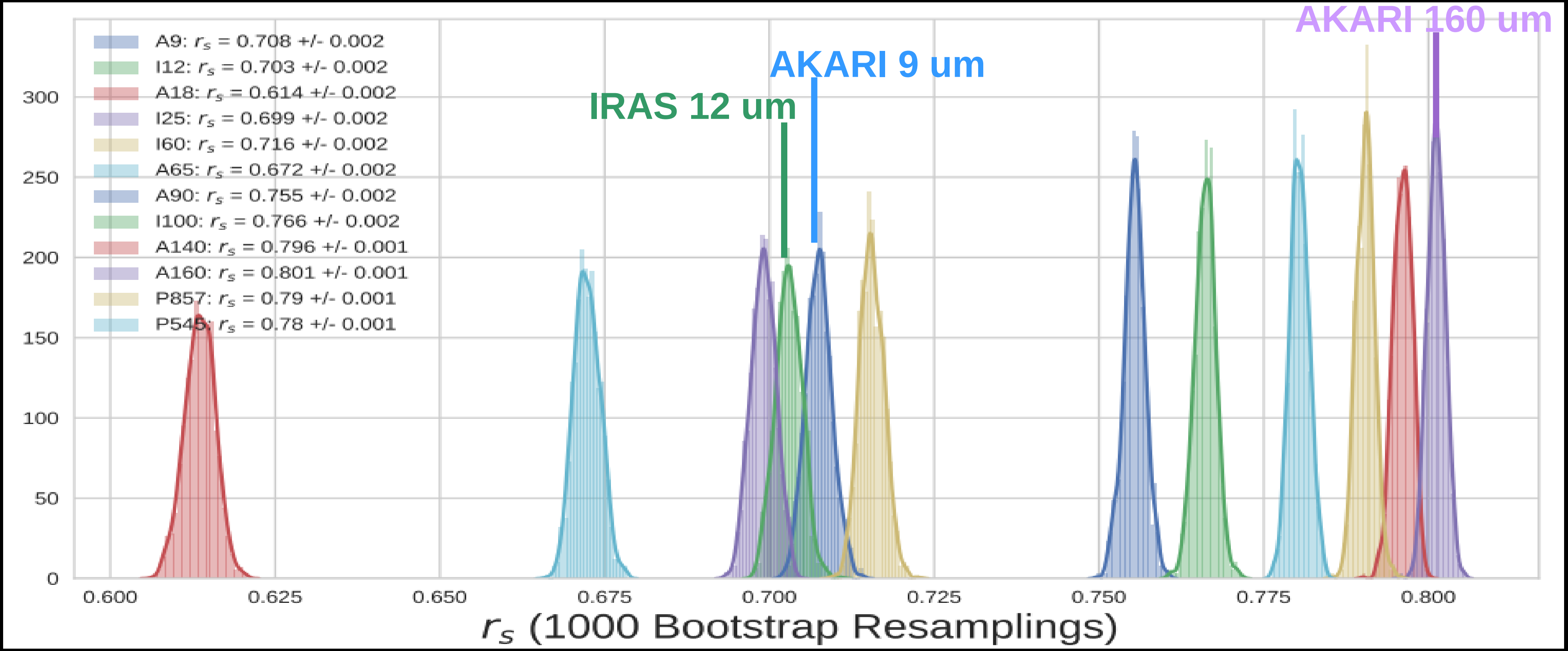

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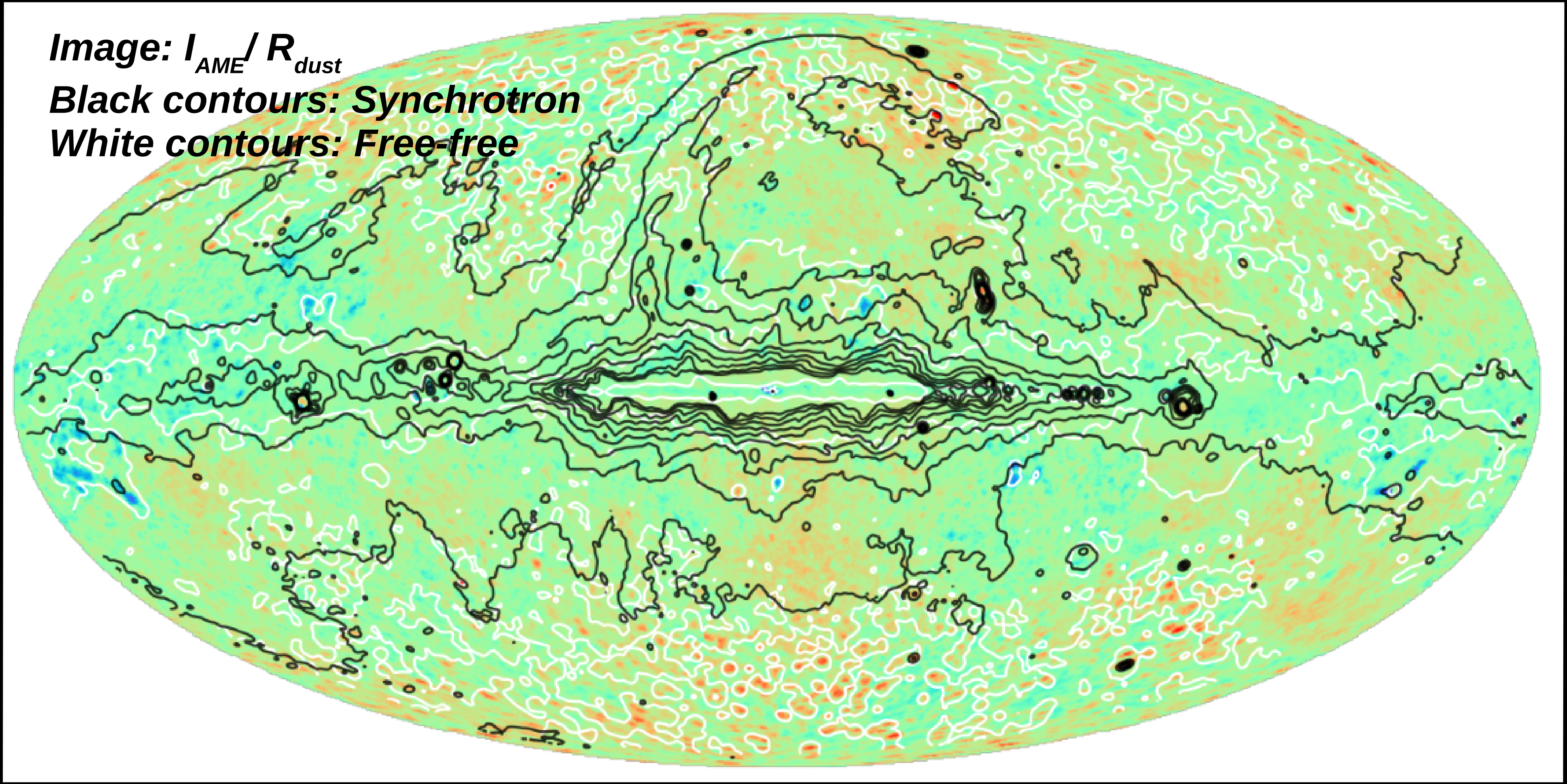
Discussion: Component separation artifacts



Conclusions – All sky

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- **Signal-to-noise limits prevents a truly all-sky comparison with IR**
- Previous works:
  - Ysard+ (2010): Inconsistent
  - Hensley+ (2016): Consistent (but different interpretation)
- If component separation quality varies across the sky:
  - Different results may be seen with different regions.

Analysis: λ Orionis Region

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But first: A note on publication plans

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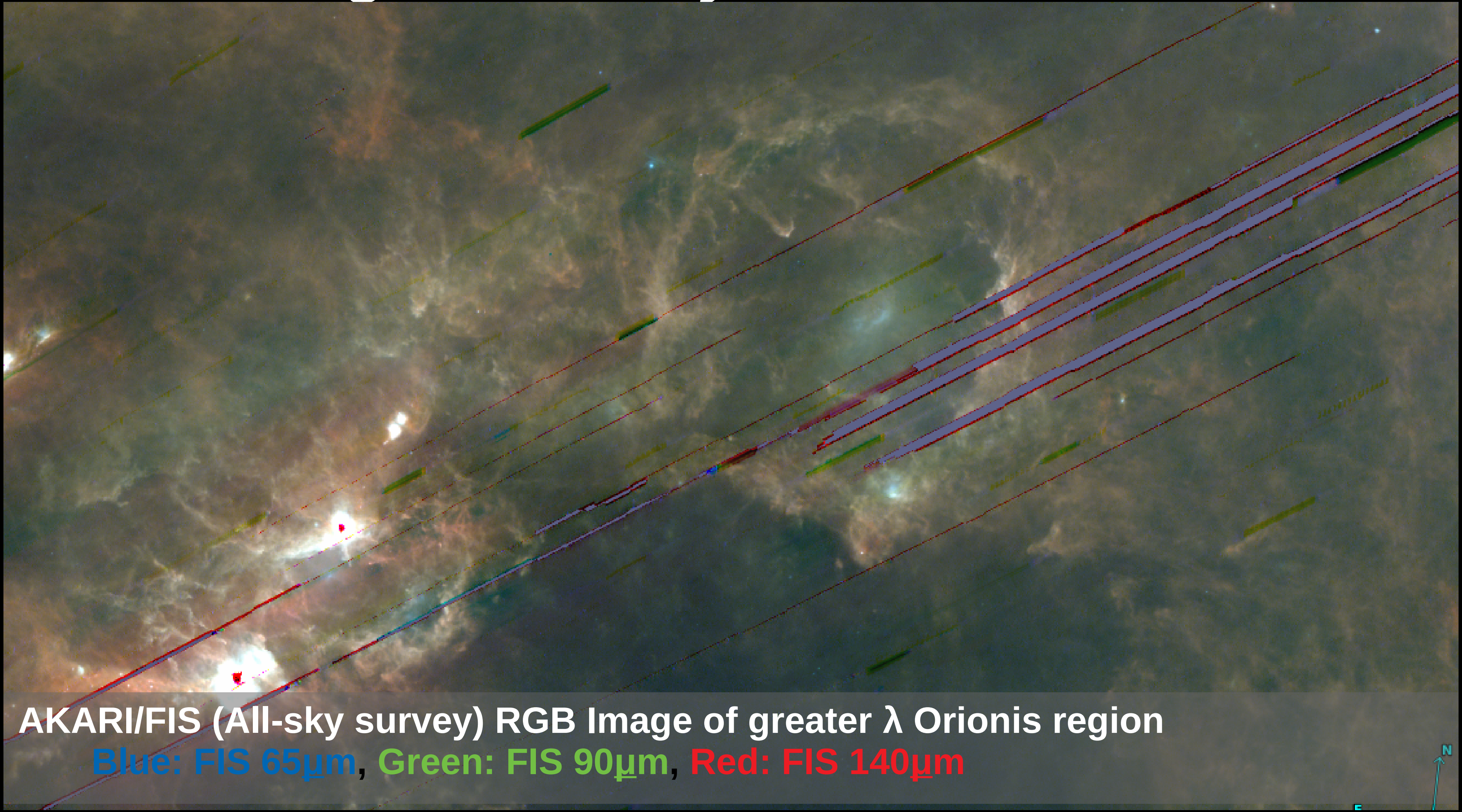
- **All-sky: Only Highlighted results from thesis**

Analysis: λ Orionis Region

But first: A note on publication plans

- **All-sky: Only Highlighted results from thesis**
- **λ Orionis: Essentially all analysis shown in thesis**

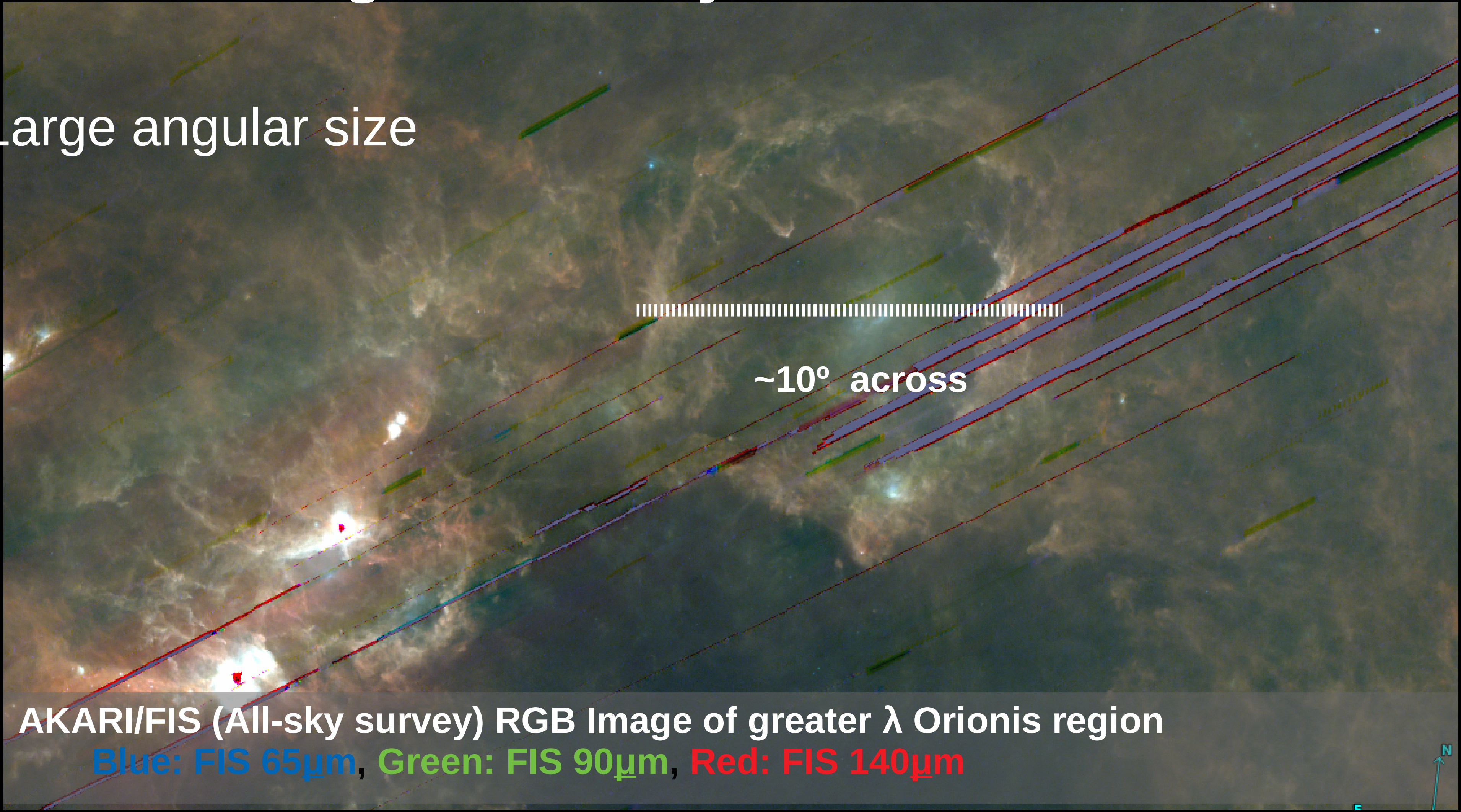
λ Orionis Region – "Why λ Orionis?"



AKARI/FIS (All-sky survey) RGB Image of greater λ Orionis region
Blue: FIS 65µm, Green: FIS 90µm, Red: FIS 140µm

λ Orionis Region – “Why λ Orionis?”

- Large angular size



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λ Orionis Region – "Why λ Orionis?"

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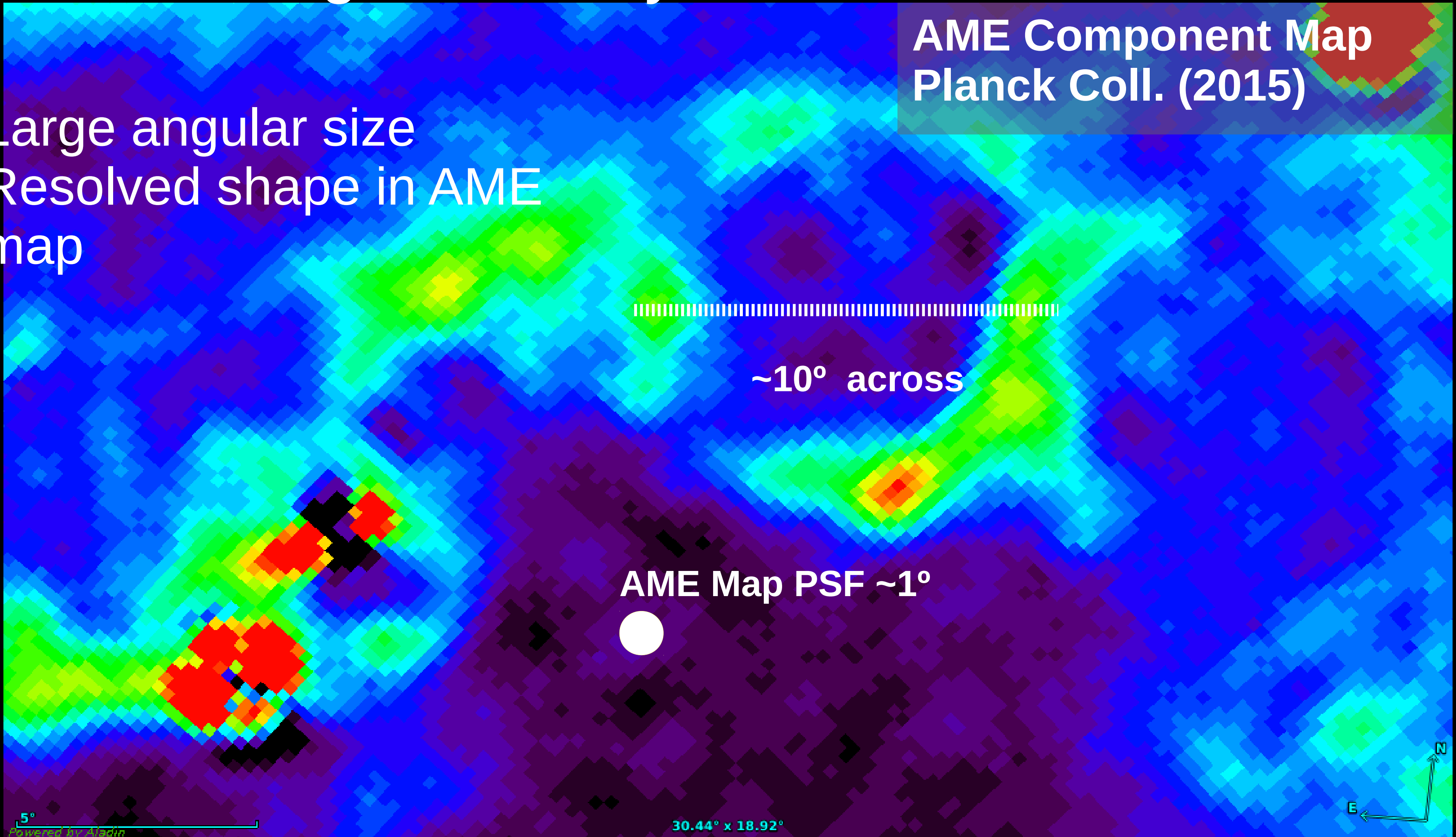
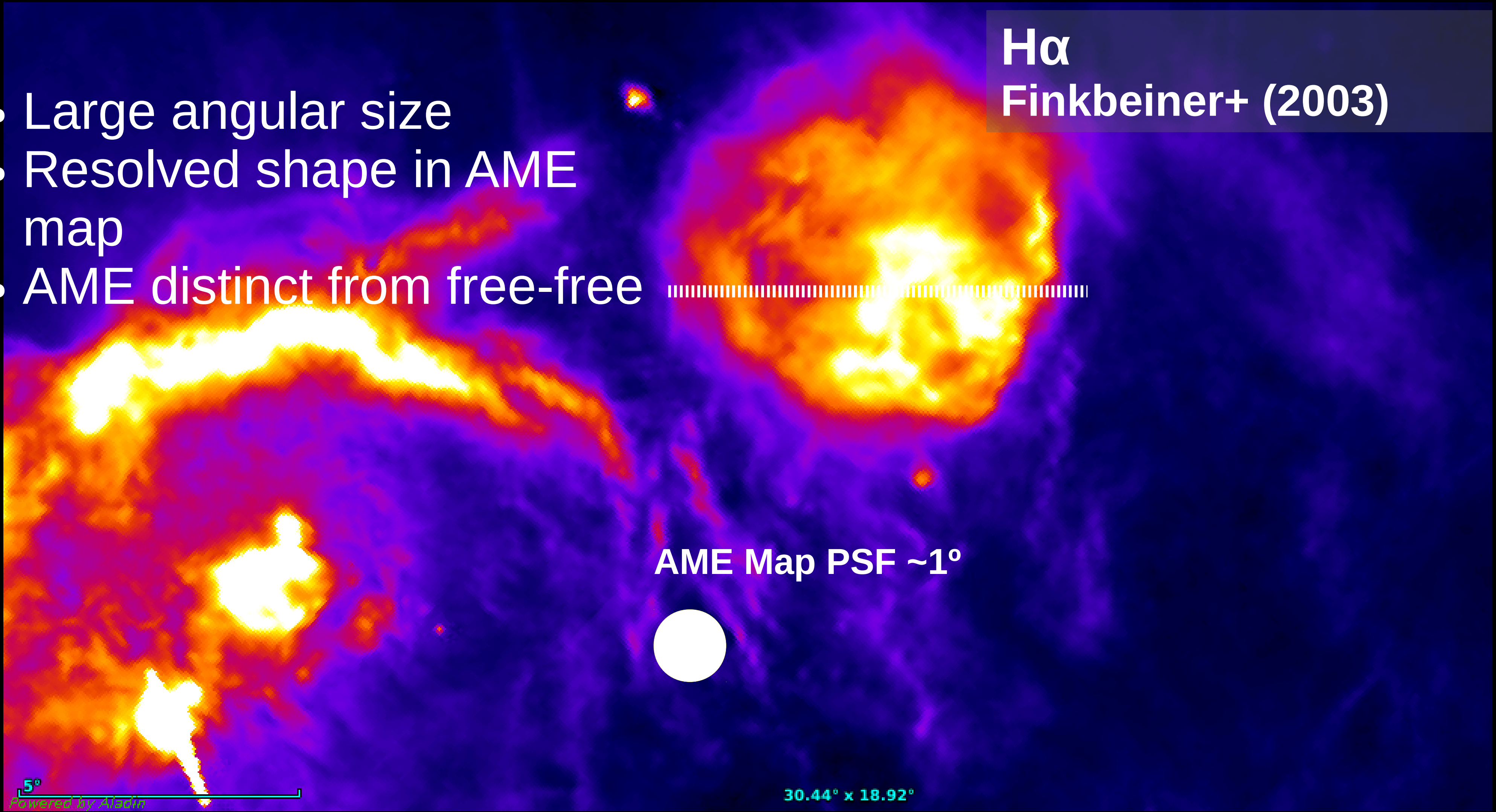
- Resolved shape in AME map



λ Orionis Region – “Why λ Orionis?”

- Large angular size
- Resolved shape in AME map
- AME distinct from free-free



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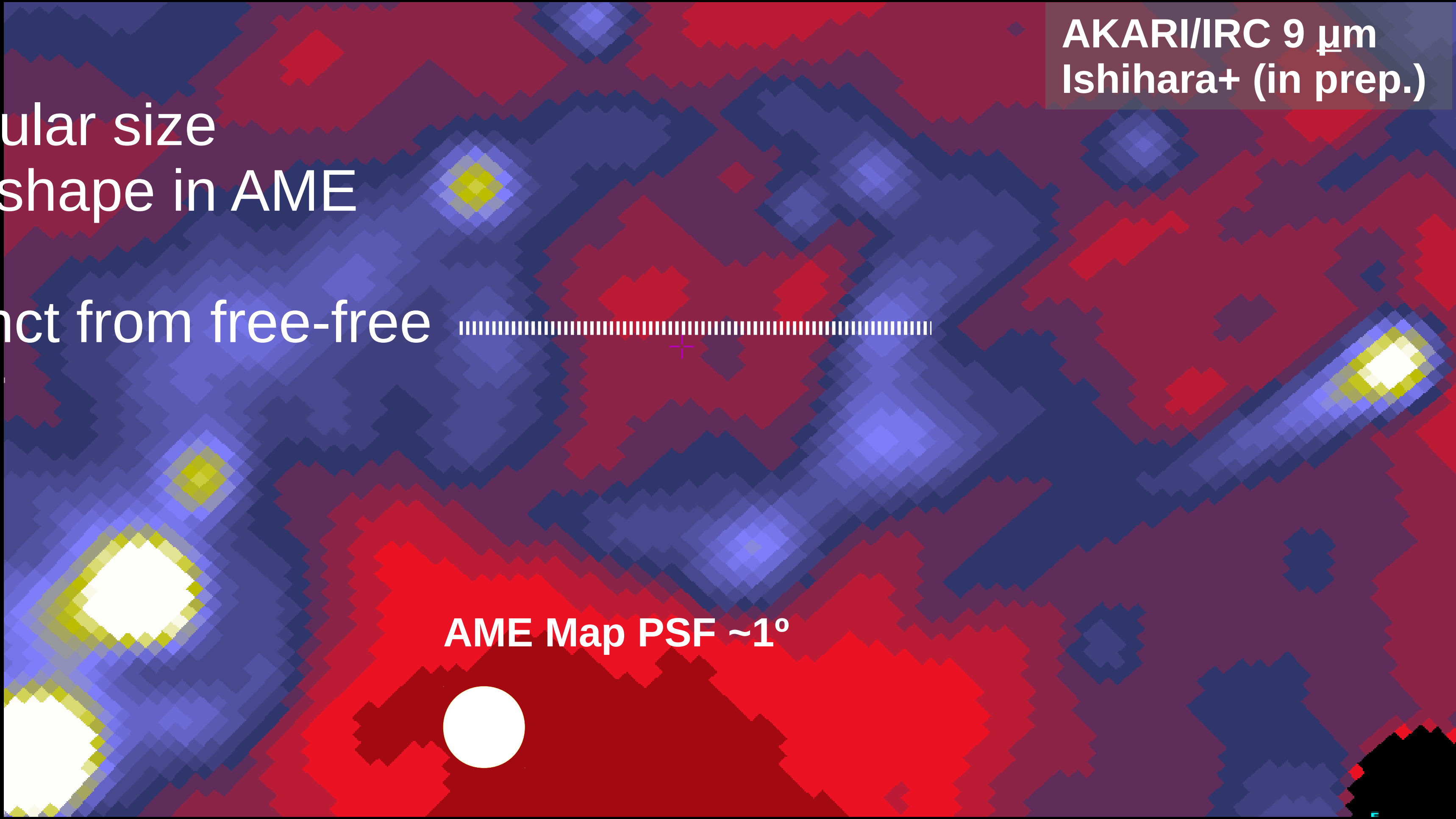
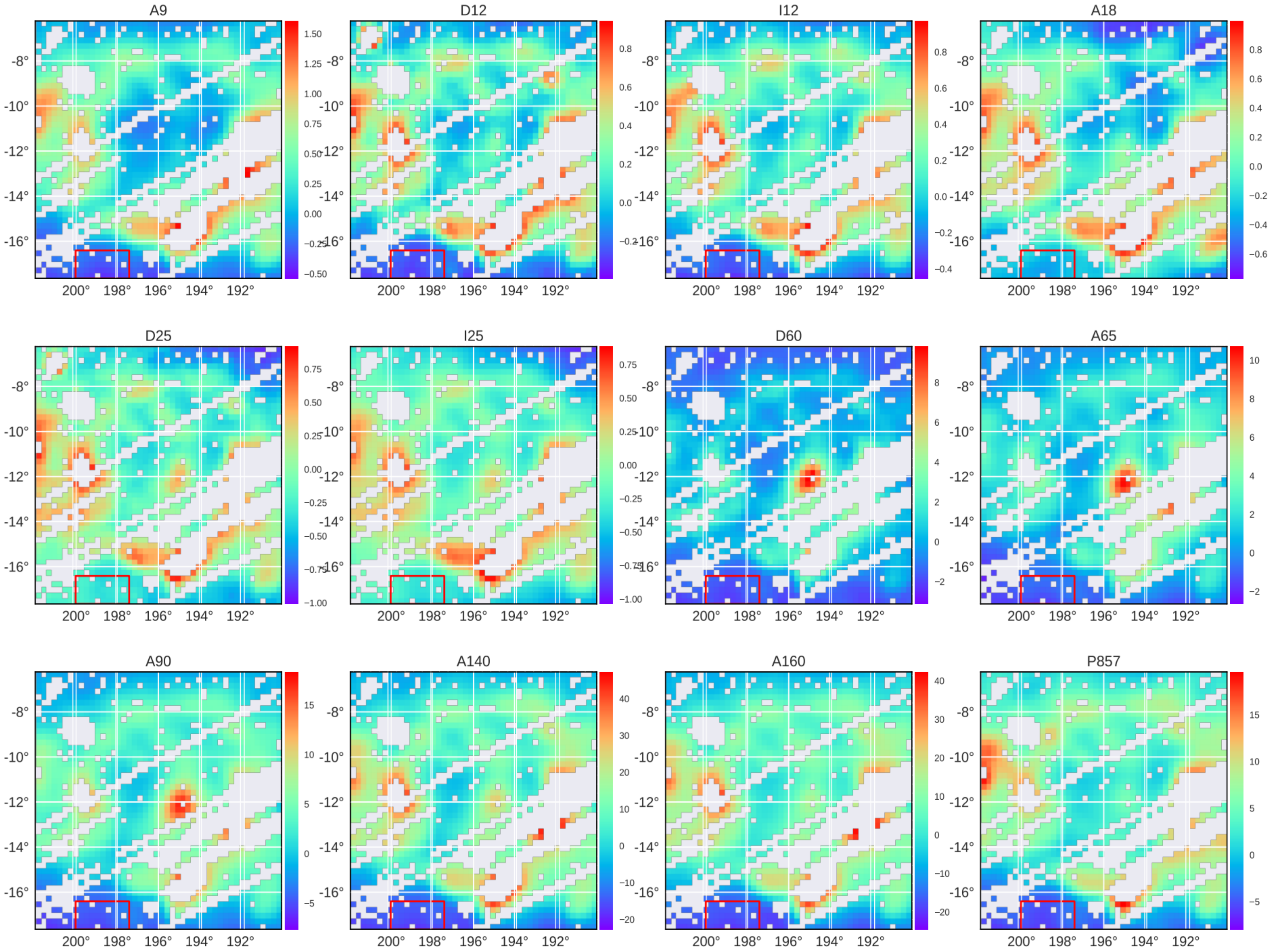
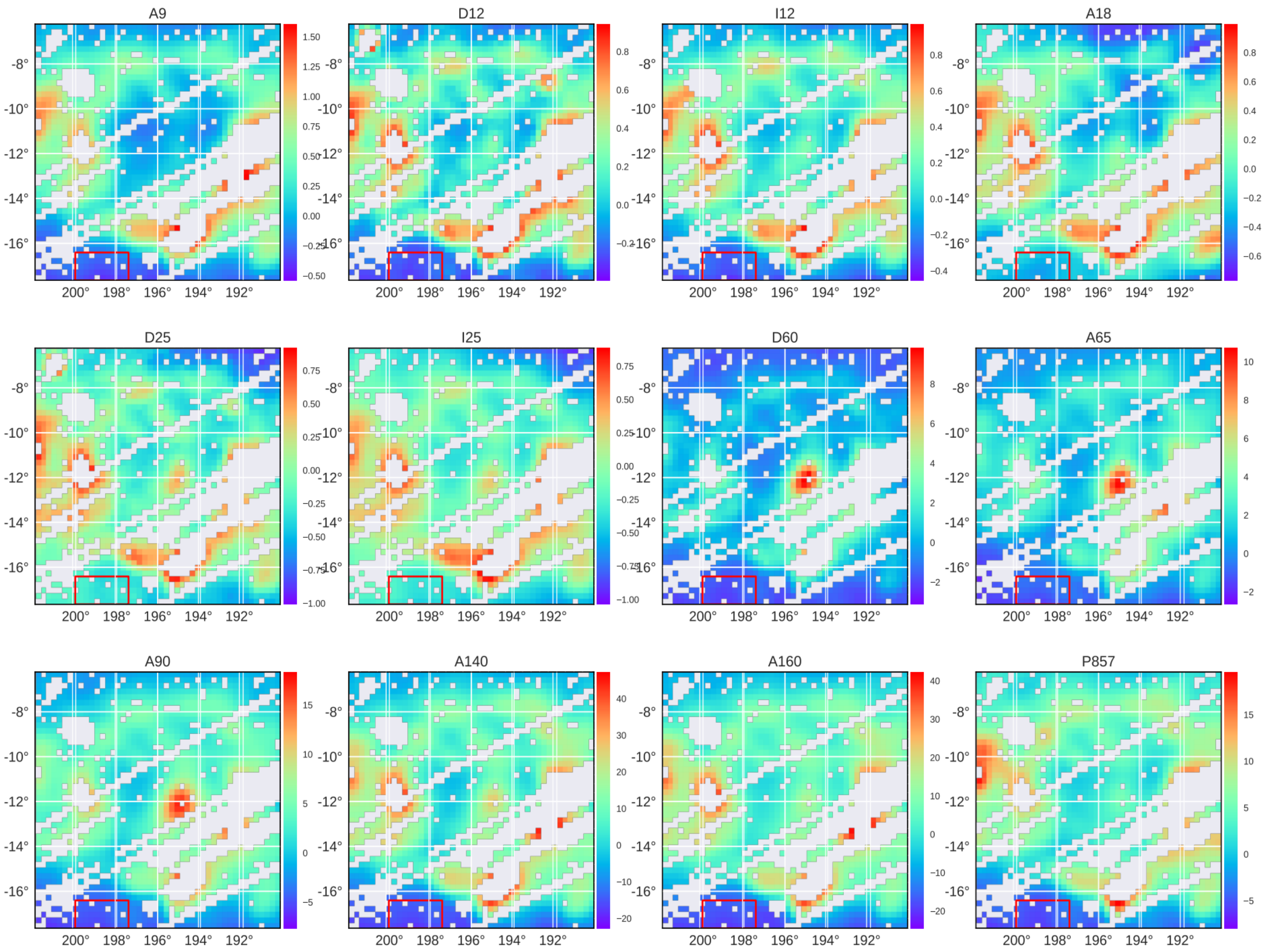


λ Orionis - Analysis

Compare AME and multi-band IR on common grid



A9
D12
I12
A18
D25
I25
D60
A65
A90
A140
A160
P857


A9
D12
I12
A18
D25
I25
D60
A65
A90
A140
A160
P857

AKARI/IRC 9 μm band

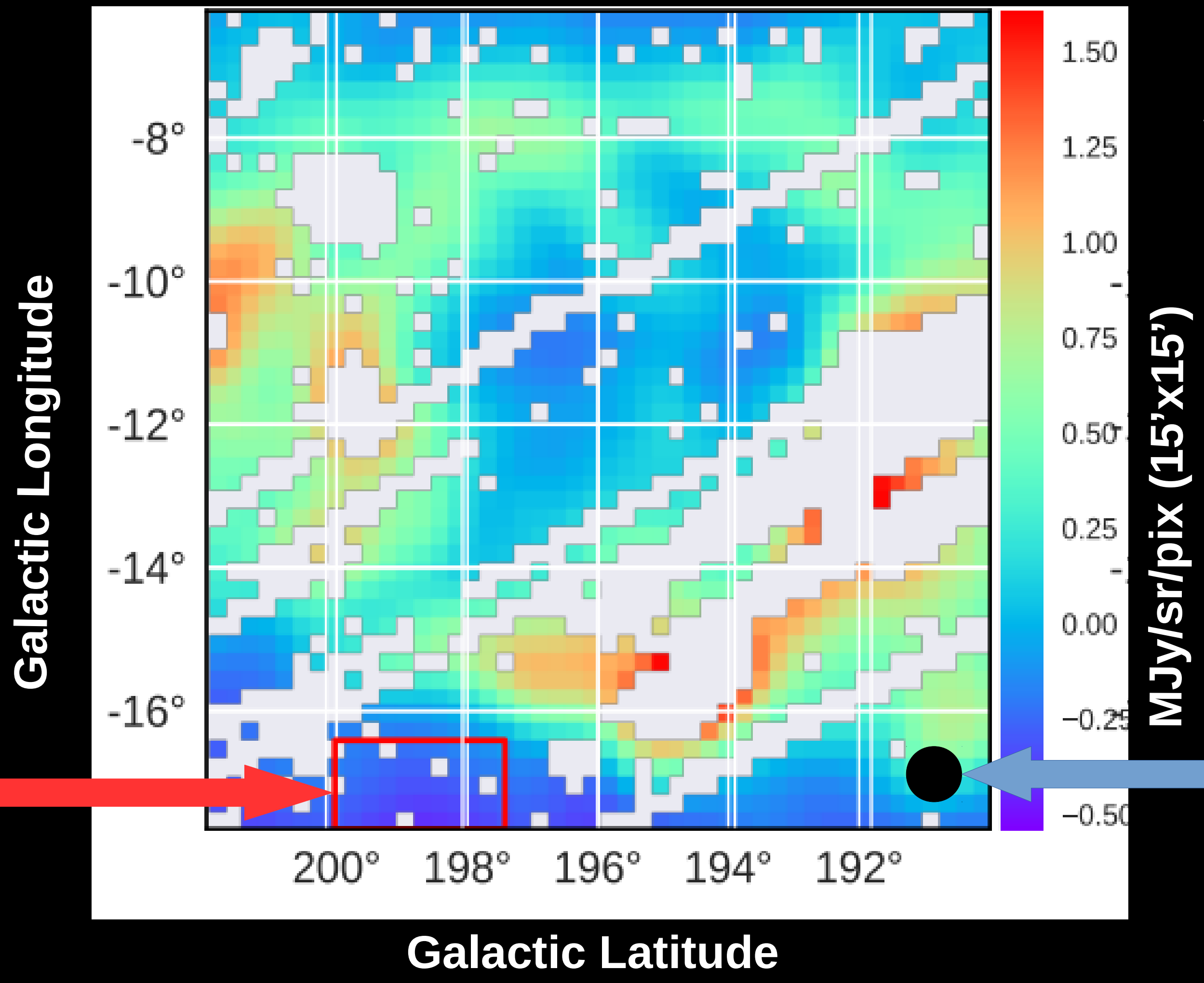


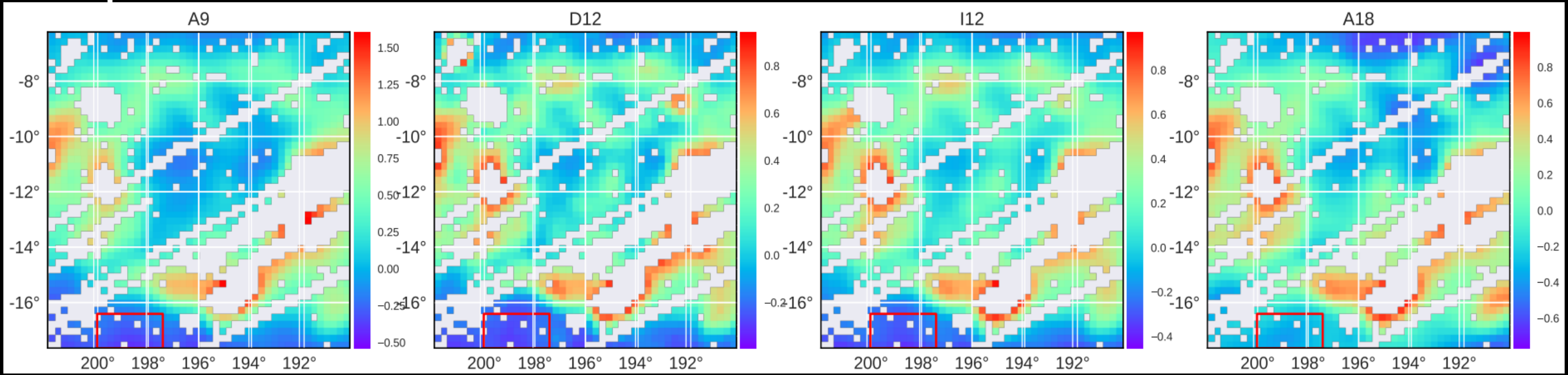
Image size: 50 x 50 pixels

Background subtraction box

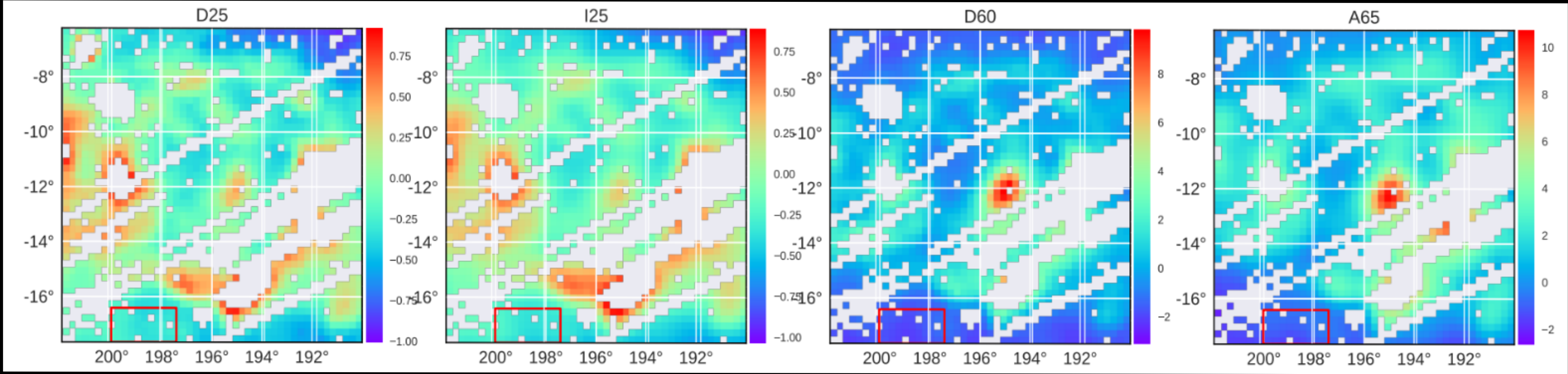
Effective PSF: ~60’ FWHM

Orionis in the MIR

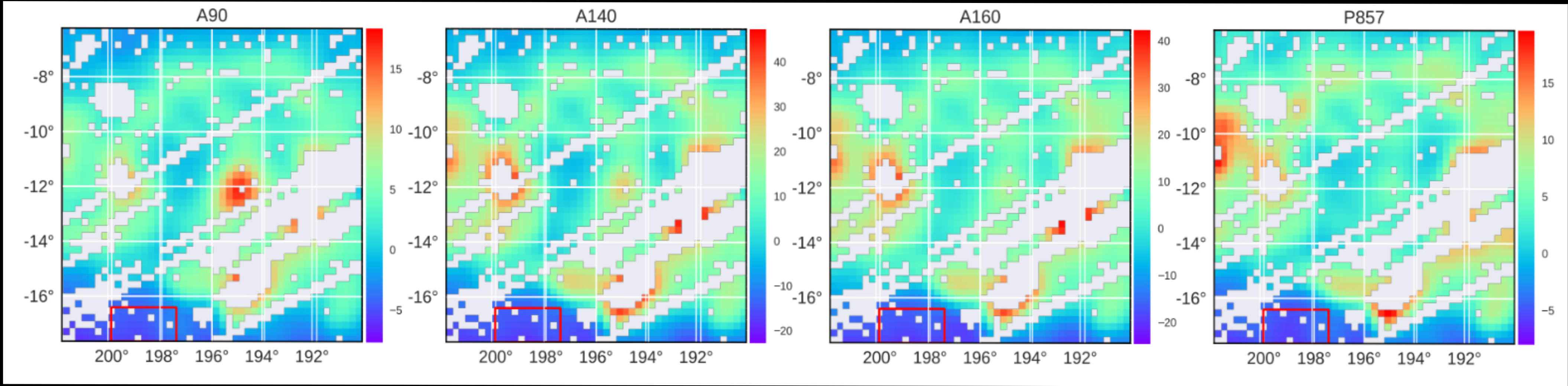
AKARI/IRC 9 μm | DIRBE 12 μm | IRAS 12 μm | AKARI/IRC 18 μm



Central region is relatively dimmer in MIR



D25
I25
D60
A65
-8°
-10°
-12°
-14°
-16°
200°
198°
196°
194°
192°
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
8
6
4
2
0
−2
10


A90
A140
A160
P857
-8°
-10°
-12°
-14°
-16°
200°
198°
196°
194°
192°

λ Orionis

- Which band correlates best with AME?

λ Orionis – IR Intensity to AME Comparison – Corr. Matrix

	A9	D12	I12	A18	D25	I25	D60	A65	A90	A140	A160	P857	P545	AMEvar	AMEfix
A9	1	0.93	0.94	0.84	0.75	0.78	0.64	0.66	0.72	0.85	0.84	0.92	0.9	0.89	0.58
D12	0.93	1	0.97	0.83	0.84	0.83	0.76	0.74	0.81	0.91	0.89	0.93	0.91	0.84	0.6
I12	0.94	0.97	1	0.84	0.82	0.85	0.78	0.77	0.84	0.93	0.92	0.93	0.91	0.85	0.62
A18	0.84	0.83	0.84	1	0.89	0.91	0.68	0.57	0.67	0.77	0.75	0.72	0.69	0.61	0.39
D25	0.75	0.84	0.82	0.89	1	0.97	0.77	0.58	0.7	0.77	0.76	0.69	0.66	0.56	0.41
I25	0.78	0.83	0.85	0.91	0.97	1	0.79	0.62	0.73	0.8	0.79	0.7	0.66	0.58	0.43
D60	0.64	0.76	0.78	0.68	0.77	0.79	1	0.88	0.94	0.86	0.86	0.67	0.61	0.48	0.57
A65	0.66	0.74	0.77	0.57	0.58	0.62	0.88	1	0.96	0.9	0.88	0.76	0.7	0.58	0.62
A90	0.72	0.81	0.84	0.67	0.7	0.73	0.94	0.96	1	0.94	0.93	0.8	0.75	0.63	0.65
A140	0.85	0.91	0.93	0.77	0.77	0.8	0.86	0.9	0.94	1	0.99	0.91	0.86	0.75	0.63
A160	0.84	0.89	0.92	0.75	0.76	0.79	0.86	0.88	0.93	0.99	1	0.89	0.85	0.73	0.63
P857	0.92	0.93	0.93	0.72	0.69	0.7	0.67	0.76	0.8	0.91	0.89	1	0.99	0.89	0.62
P545	0.9	0.91	0.91	0.69	0.66	0.66	0.61	0.7	0.75	0.86	0.85	0.99	1	0.89	0.59
AMEvar	0.89	0.84	0.85	0.61	0.56	0.58	0.48	0.58	0.63	0.75	0.73	0.89	0.89	1	0.63
AMEfix	0.58	0.6	0.62	0.39	0.41	0.43	0.57	0.62	0.65	0.63	0.63	0.62	0.59	0.63	1

λ Orionis – IR Intensity to AME Comparison – Corr. Matrix

	A9	D12	I12	A18	D25	I25	D60	A65	A90	A140	A160	P857	P545	AMEvar	AMEfix
A9	1	0.93	0.94	0.84	0.75	0.78	0.64	0.66	0.72	0.85	0.84	0.92	0.9	0.89	0.58
D12	0.93	1	0.97	0.83	0.84	0.83	0.76	0.74	0.81	0.91	0.89	0.93	0.91	0.84	0.6
I12	0.94	0.97	1	0.84	0.82	0.85	0.78	0.77	0.84	0.93	0.92	0.93	0.91	0.85	0.62
A18	0.84	0.83	0.84	1	0.89	0.91	0.68	0.57	0.67	0.77	0.75	0.72	0.69	0.61	0.39
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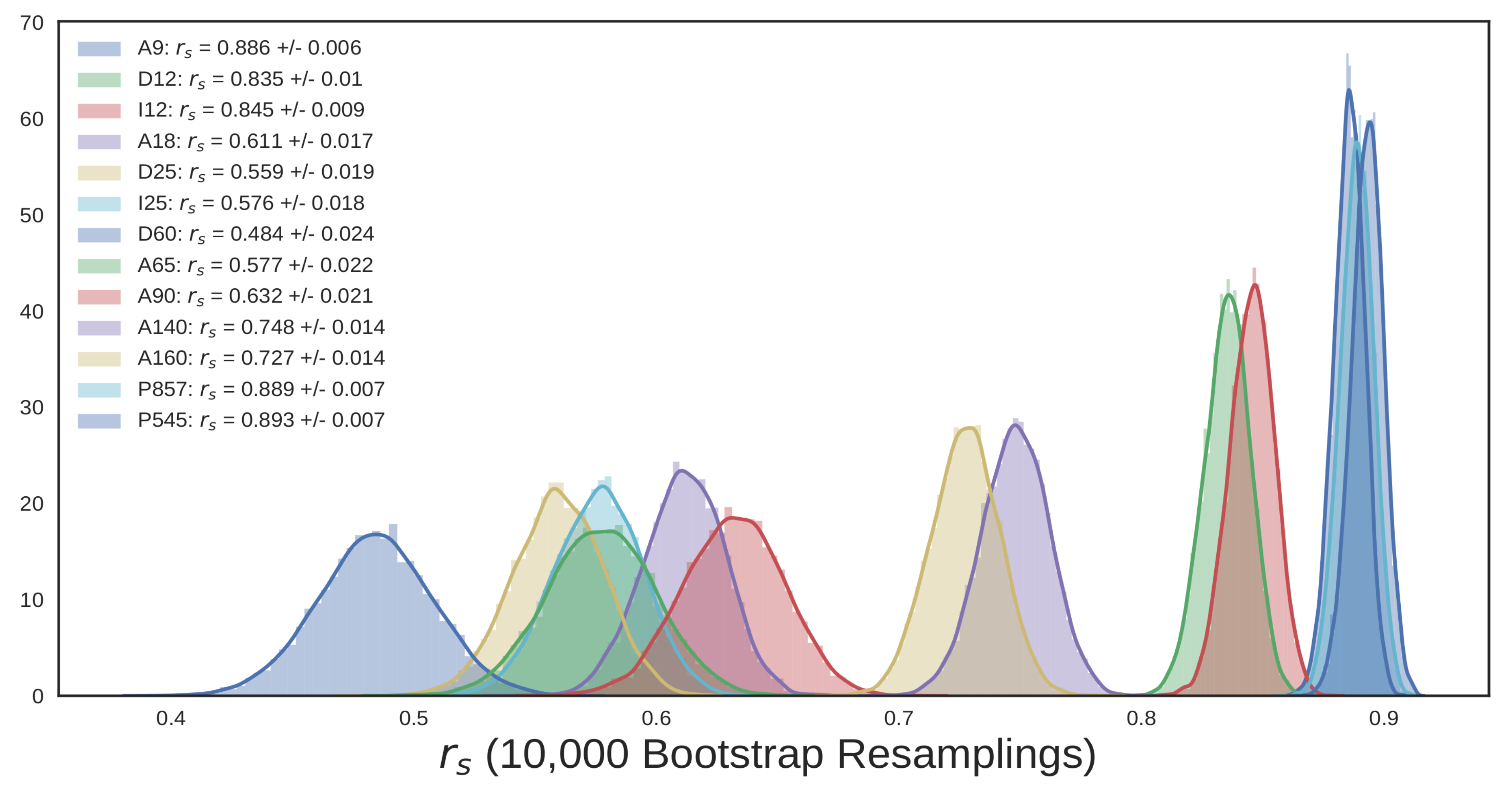
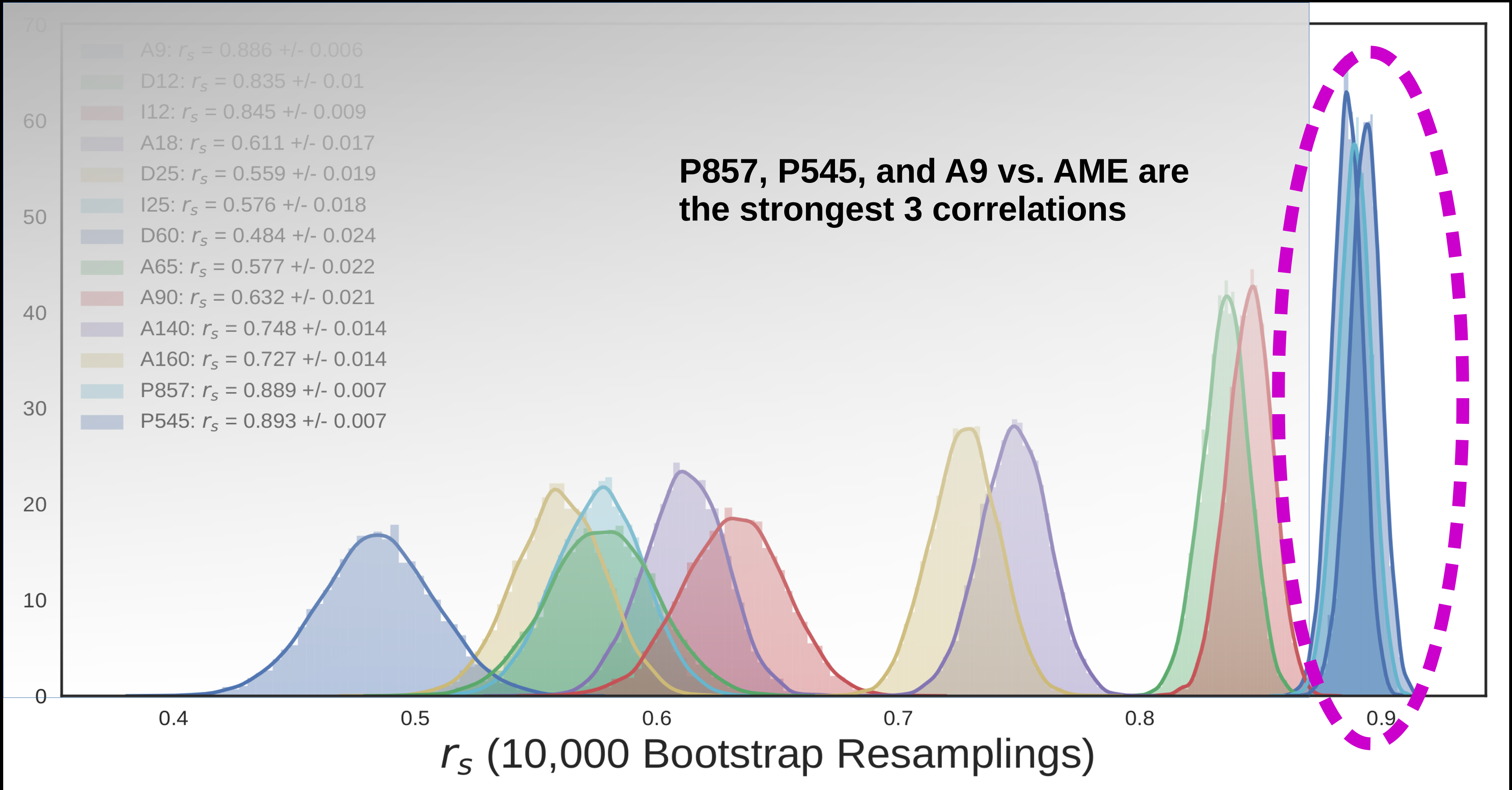
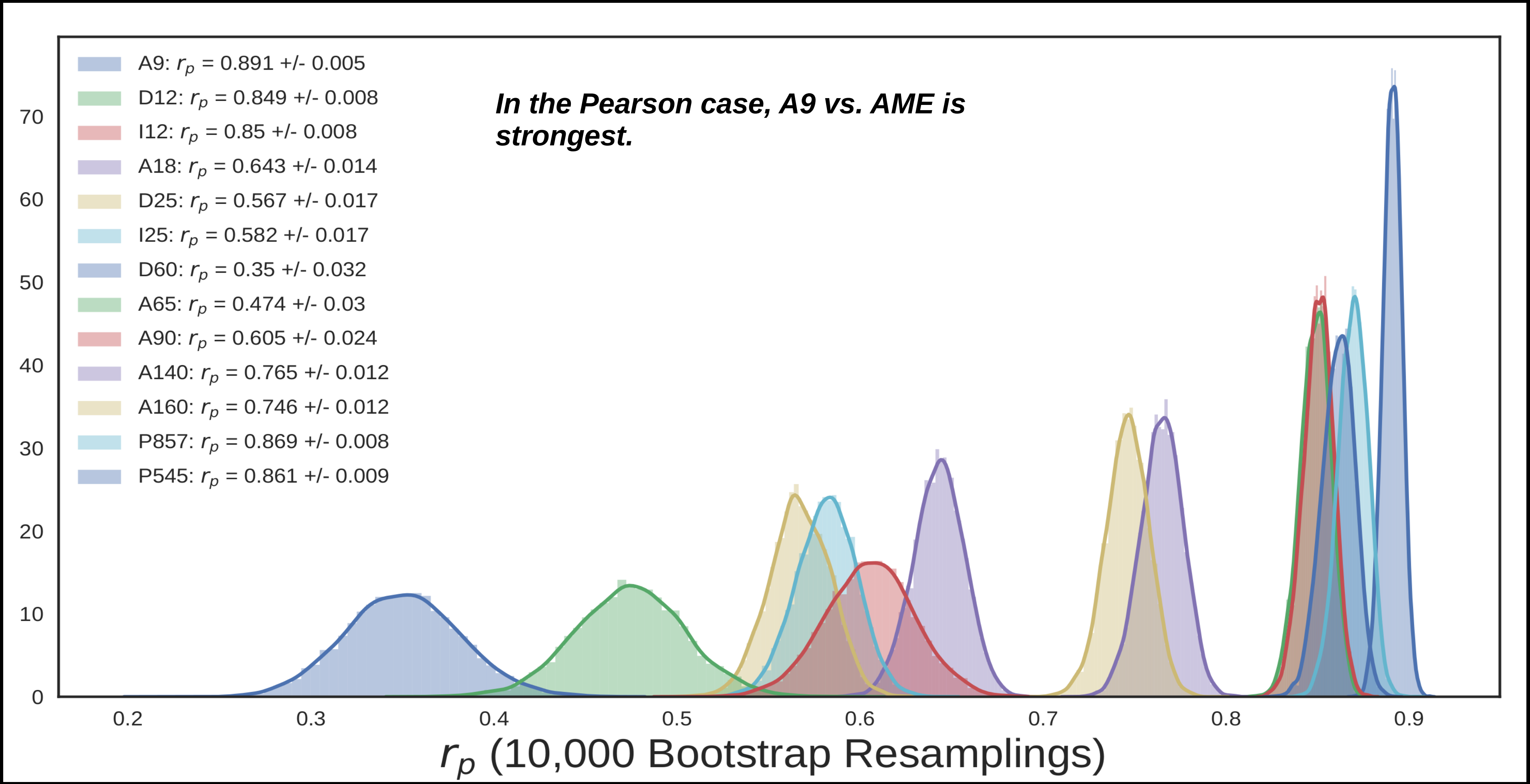
λ Orionis – IR Intensity vs AME – Bootstrap Results - rs



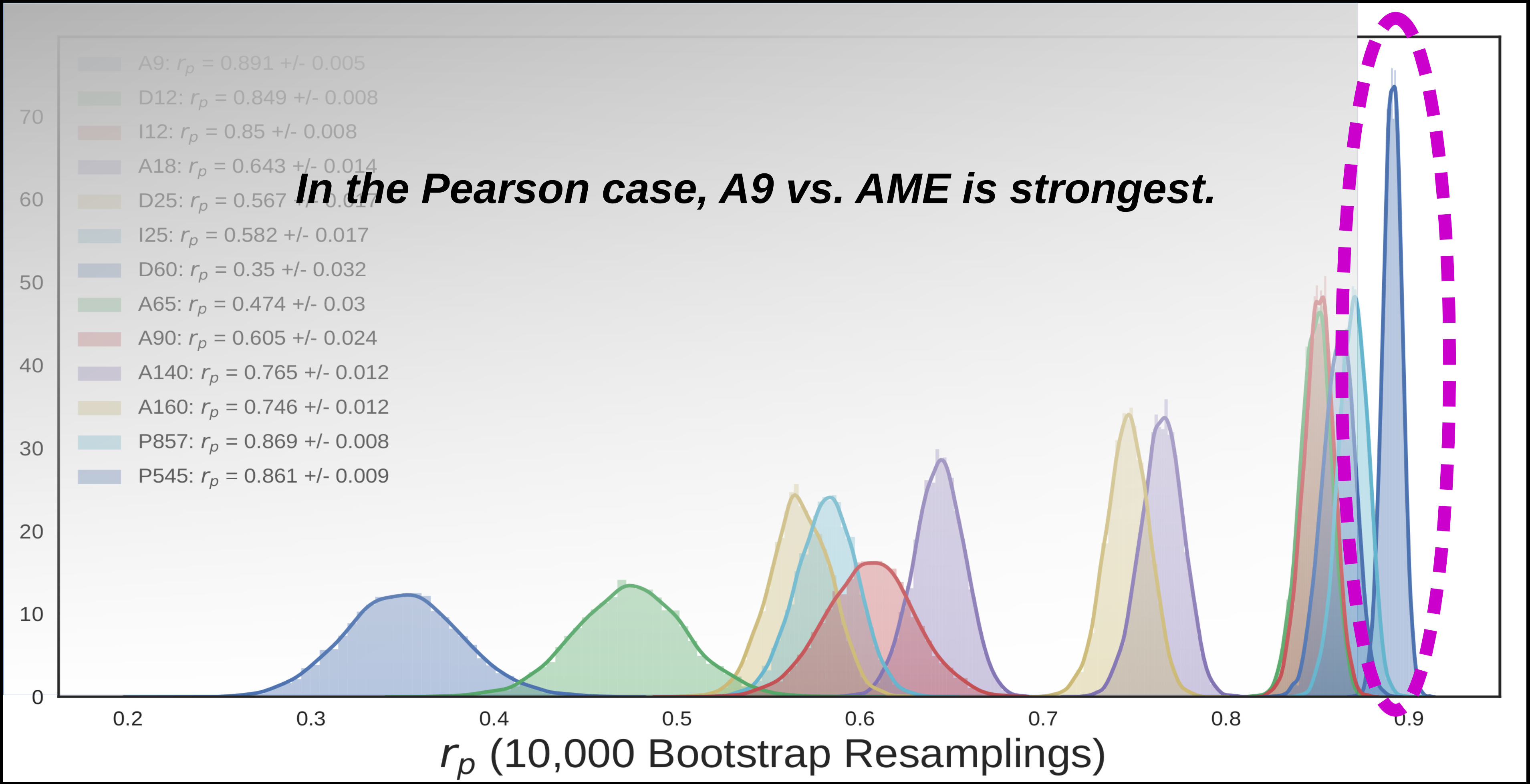
λ Orionis – IR Intensity vs AME – Bootstrap Results - r_s



λ Orionis – IR Intensity vs AME – Bootstrap Results - r_p



λ Orionis – IR Intensity vs AME – Bootstrap Results - r_p



λ Orionis – SED Fitting (in collaboration With F. Galliano)

- Which dust property correlates best with AME?
  - Dust model fitting
  - With the Hierarchical Bayesian framework, “HerBIE”, implemented by F. Galliano (2018)

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- Advantages of Hierarchical Bayesian approach:
  - Prior is inferred from data itself (No need to manually select a prior)

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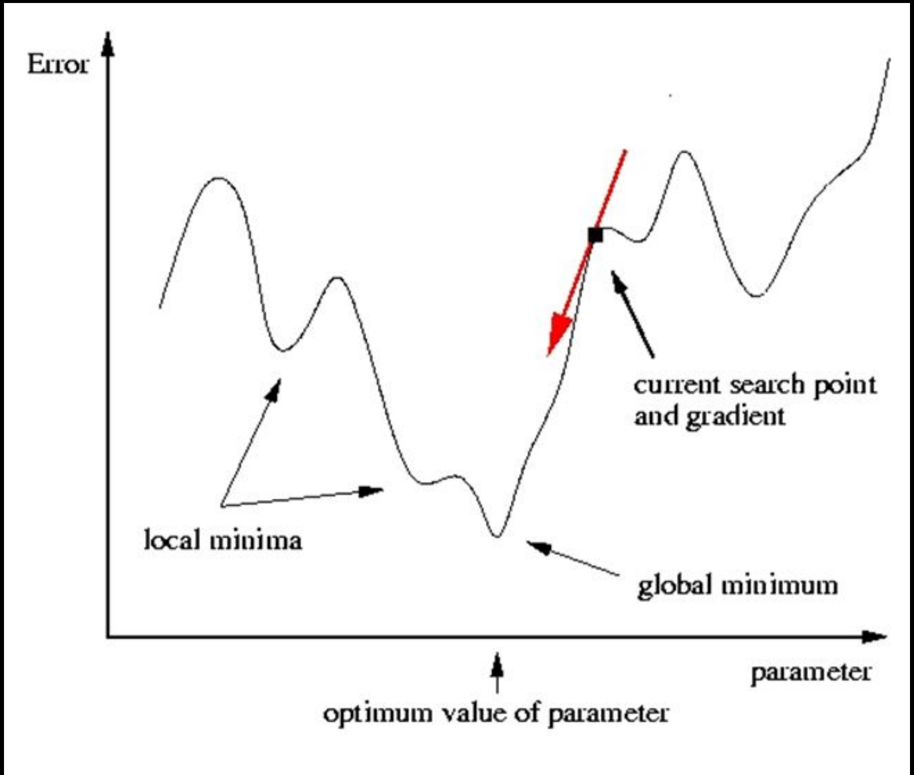

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  - Robust error-propagation

- Disadvantages:
  - Computationally expensive (relative to least-squares)
  - Not valid for a single source. (Can’t infer prior)
  - No benefit when S/N < intrinsic parameter scatter

λ Orionis – SED Fitting (in coll. With F. Galliano)

- Fit dust SED model to IR photometry:
  - 4 Free parameters:
    - M_{DUST}: Total dust mass

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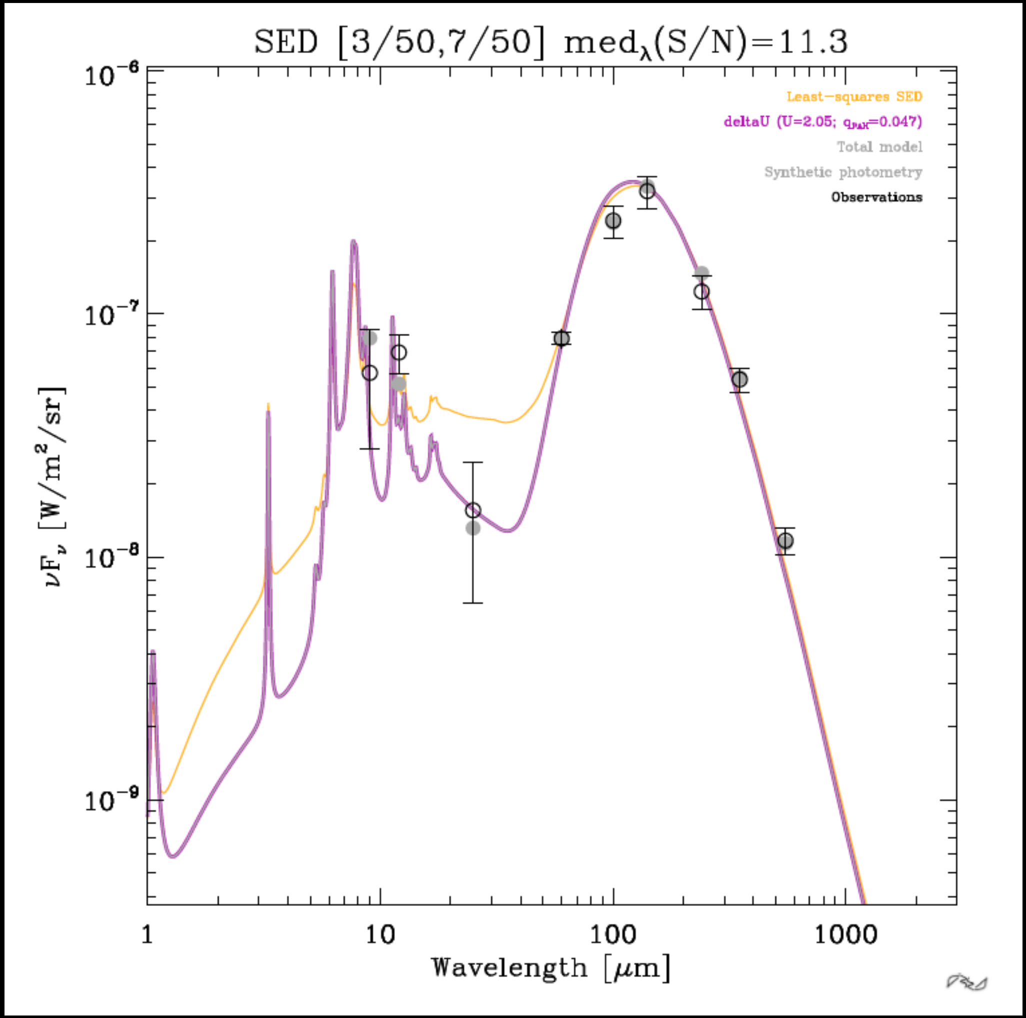
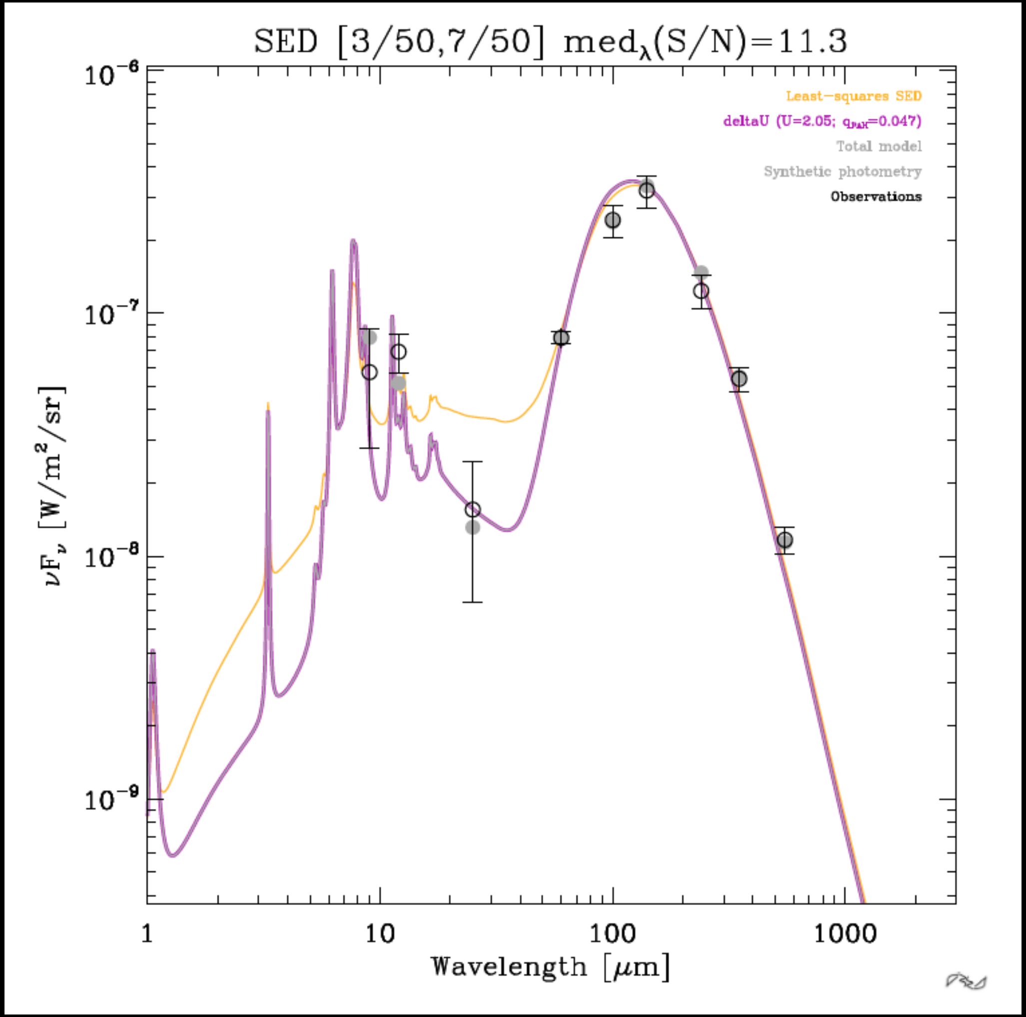
- Fit dust SED model to IR photometry:
  - 4 Free parameters:
    - M_{DUST}: Total dust mass
    - *qPAH*: Fraction of M_{DUST} in PAHs
    - *U*: Radiation field strength
    - *qPAH+*: Fraction of chargedPAHs

λ Orionis – SED Fitting – Example Fit



λ Orionis – SED Fitting – Example Fit

Yellow curve: Least-squares fit

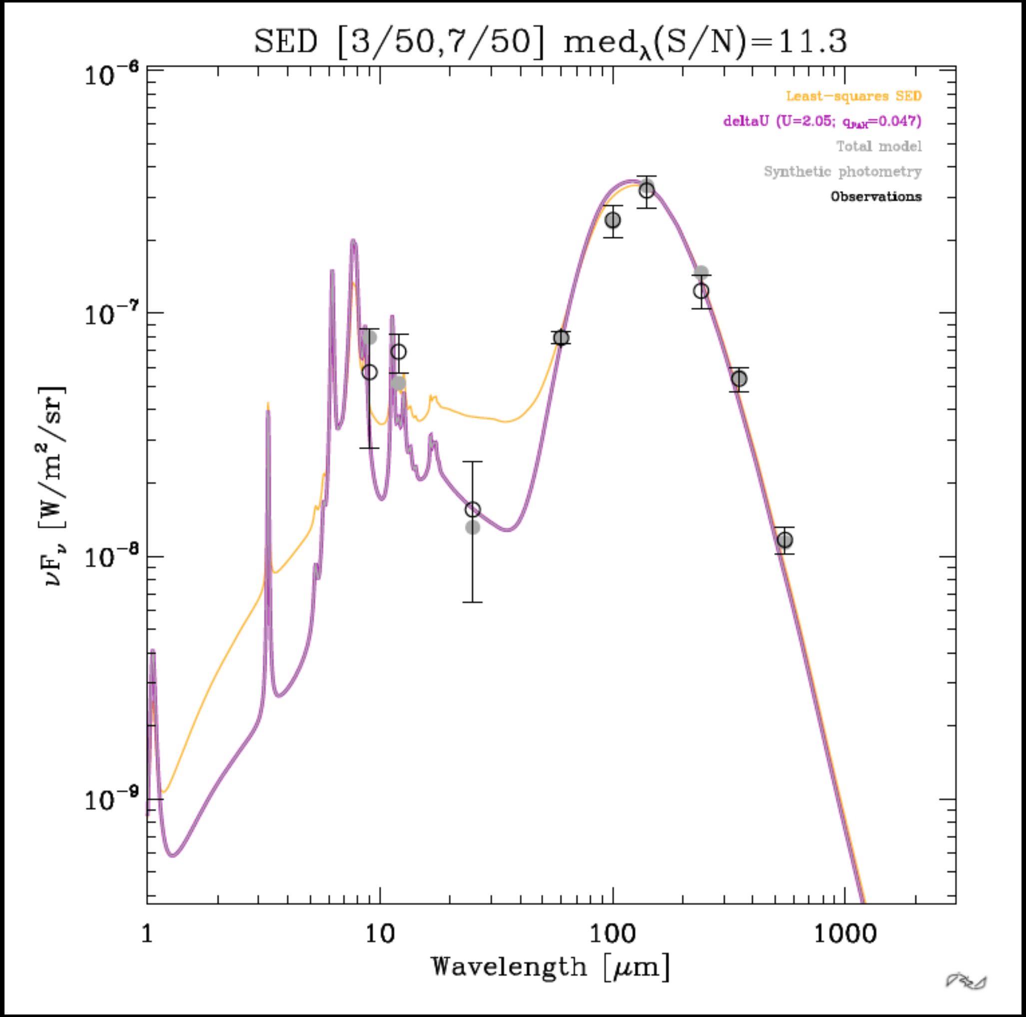


One SED fit produced per pixel

λ Orionis – SED Fitting – Example Fit

Yellow curve: Least-squares fit

Purple curve: HB fit



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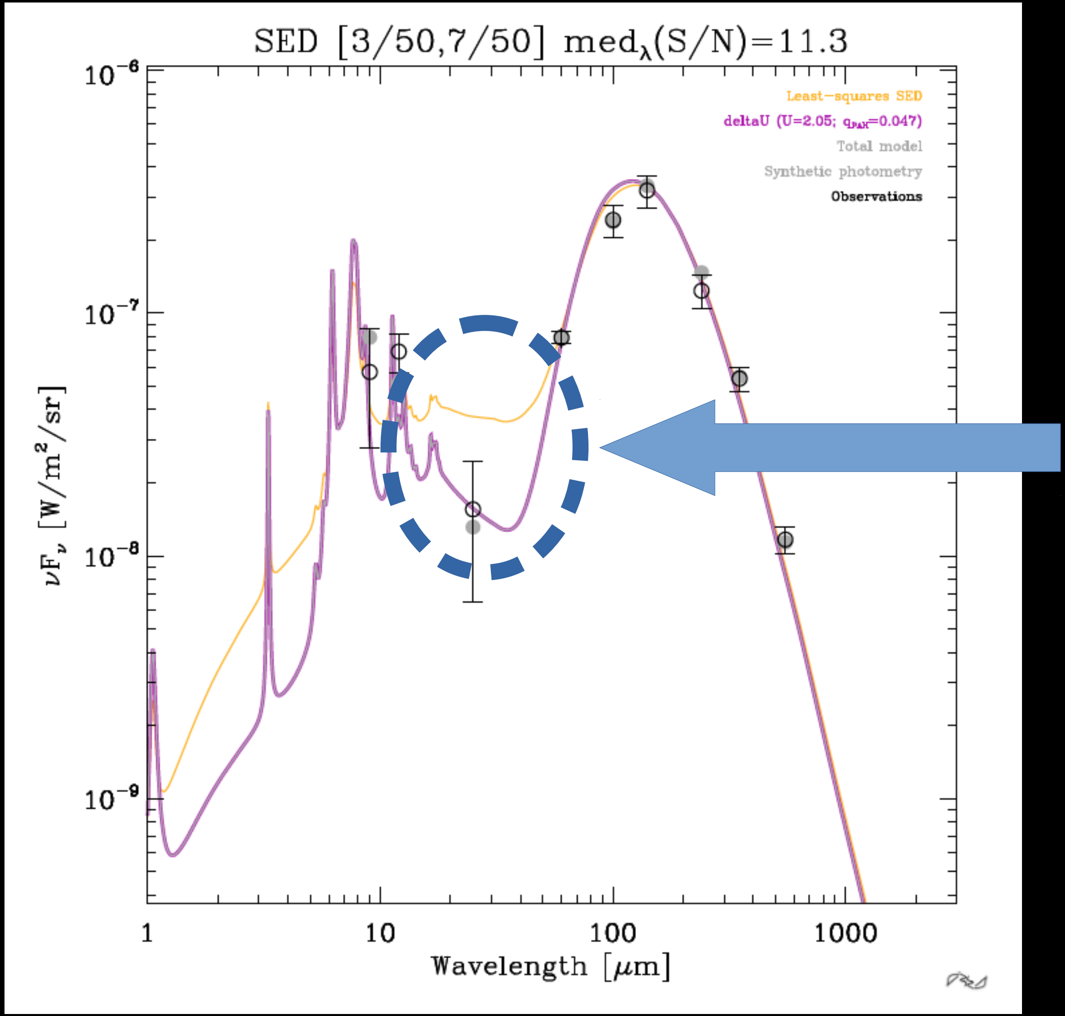
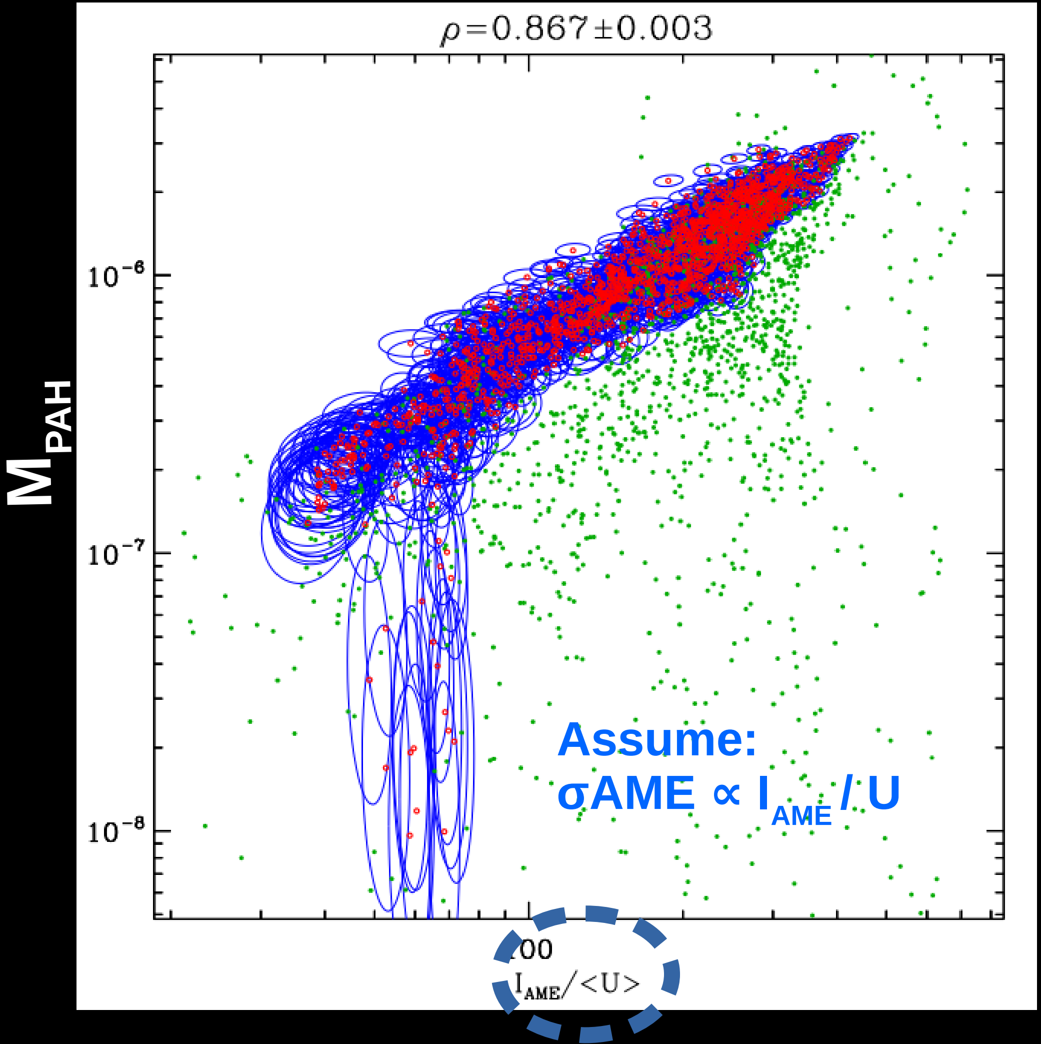


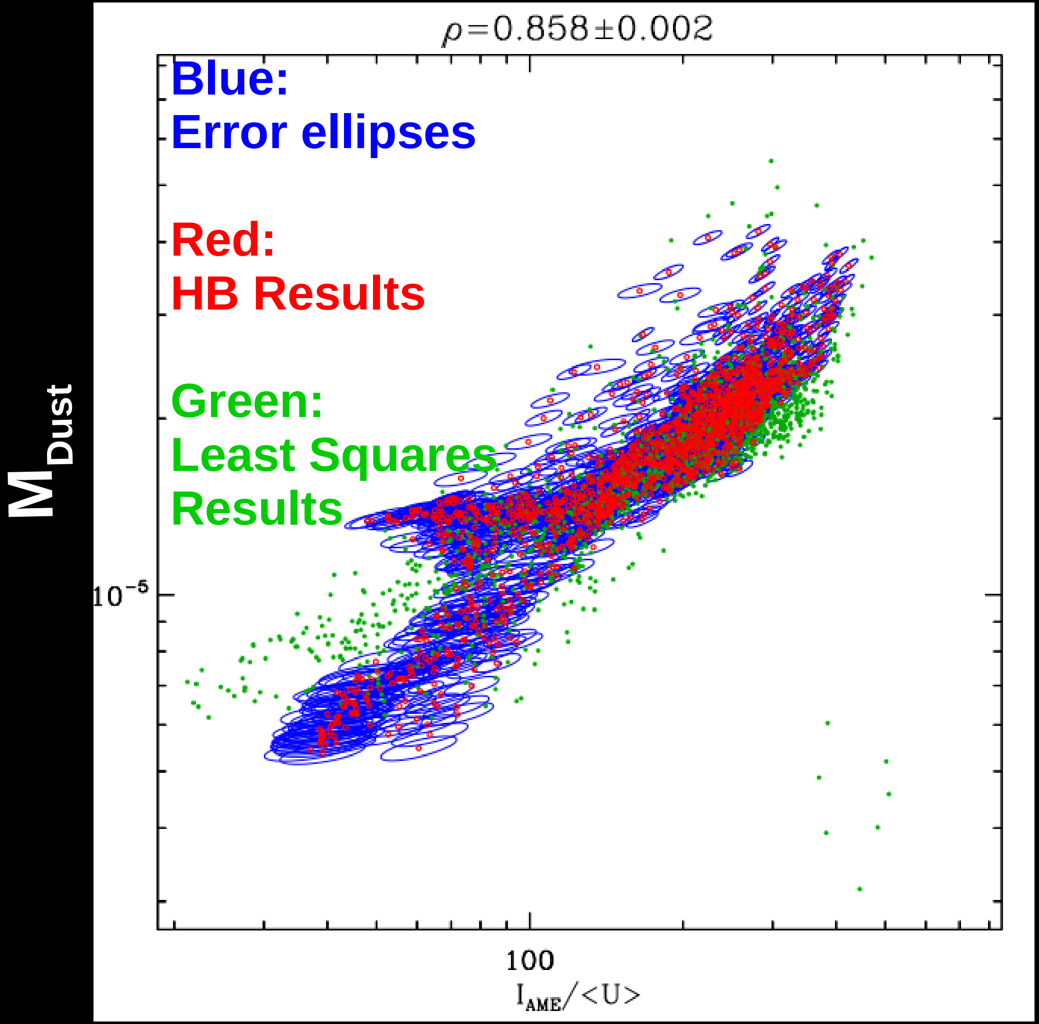
One SED fit produced per pixel

HB fits some cases where least-squares fails:

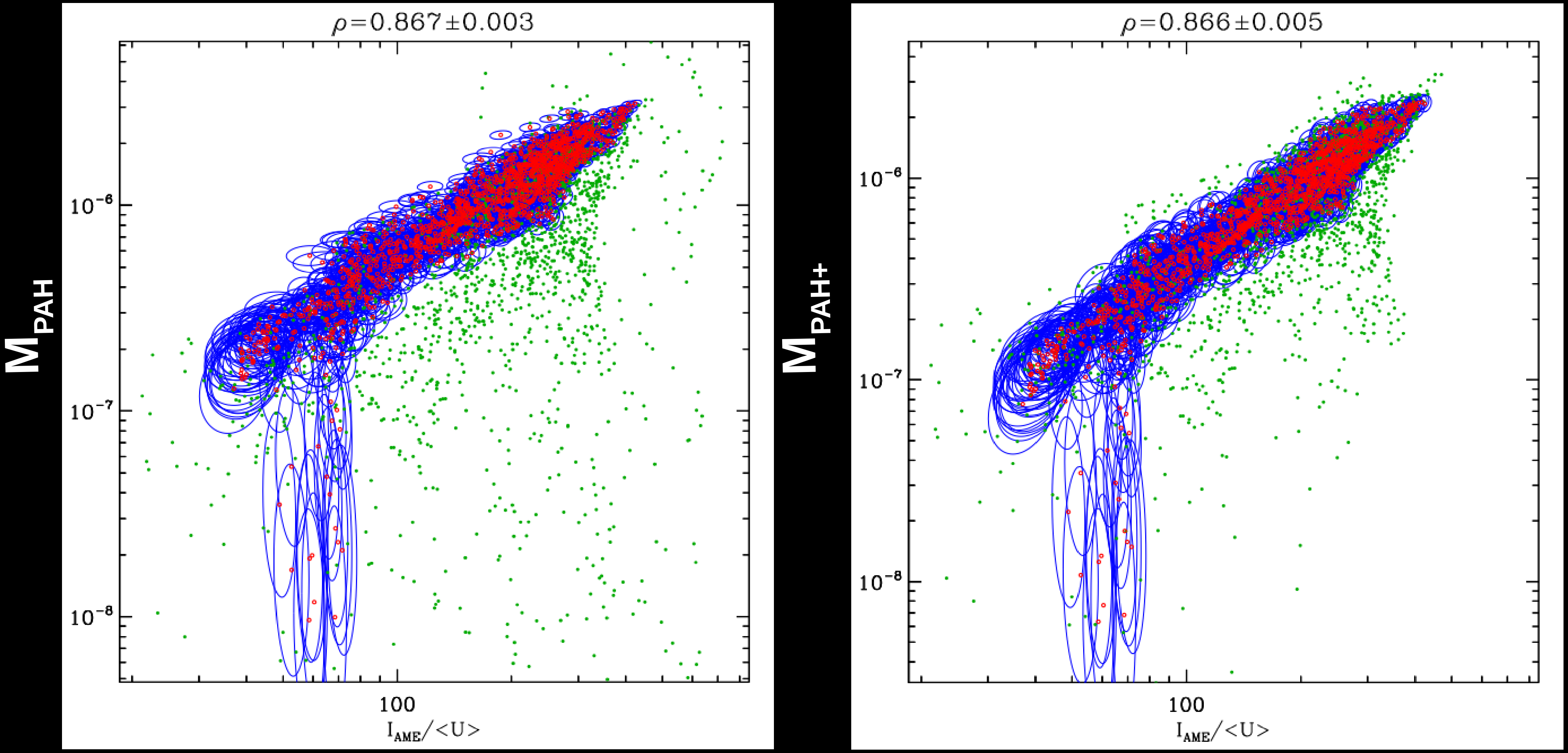
- Stuck in minima?
- Error overestimation?

λ Orionis – SED Fitting – Dust Parameters vs AME





λ Orionis – SED Fitting - Dust Parameters vs AME -MPAH+

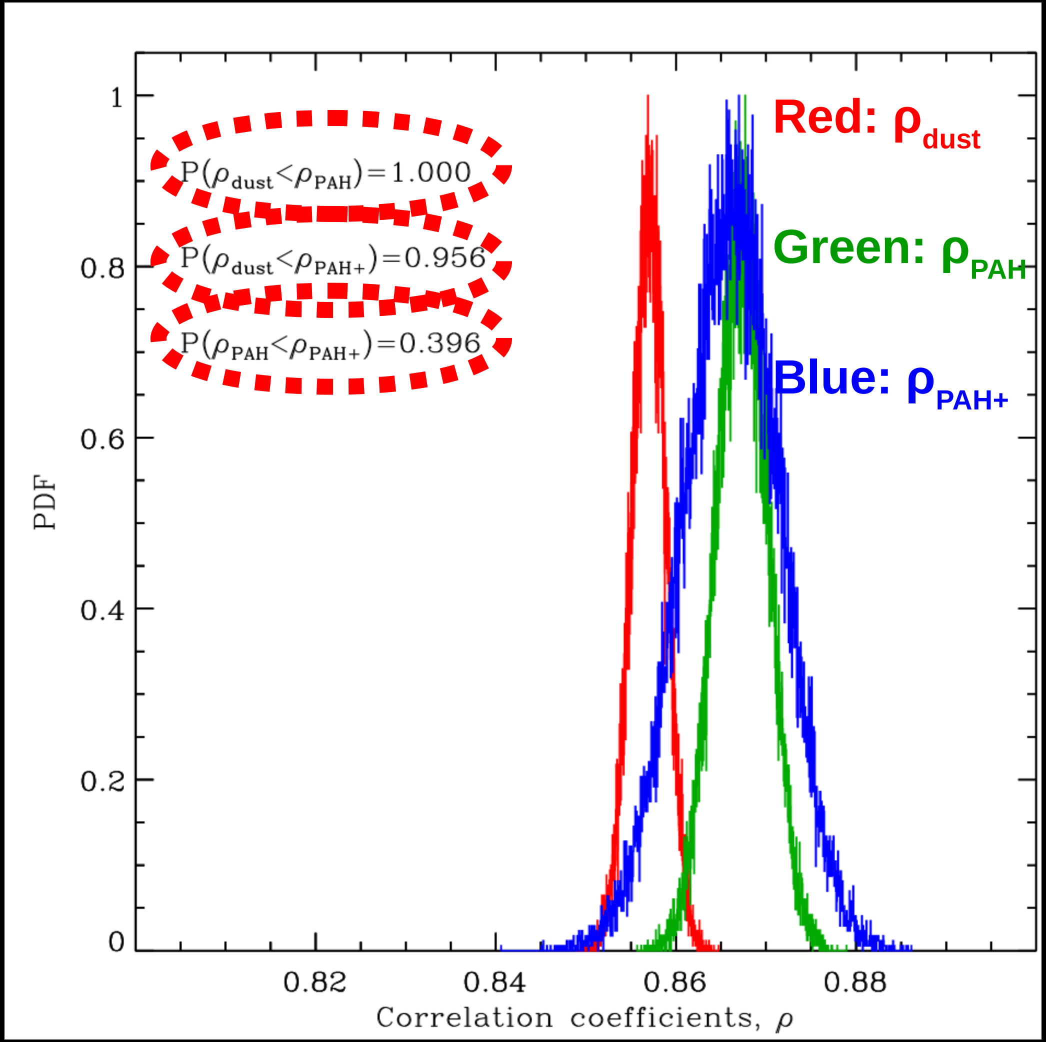


λ Orionis – SED Fitting – Correlation scores vs. AME

M_{PAH} correlates better than M_{dust}

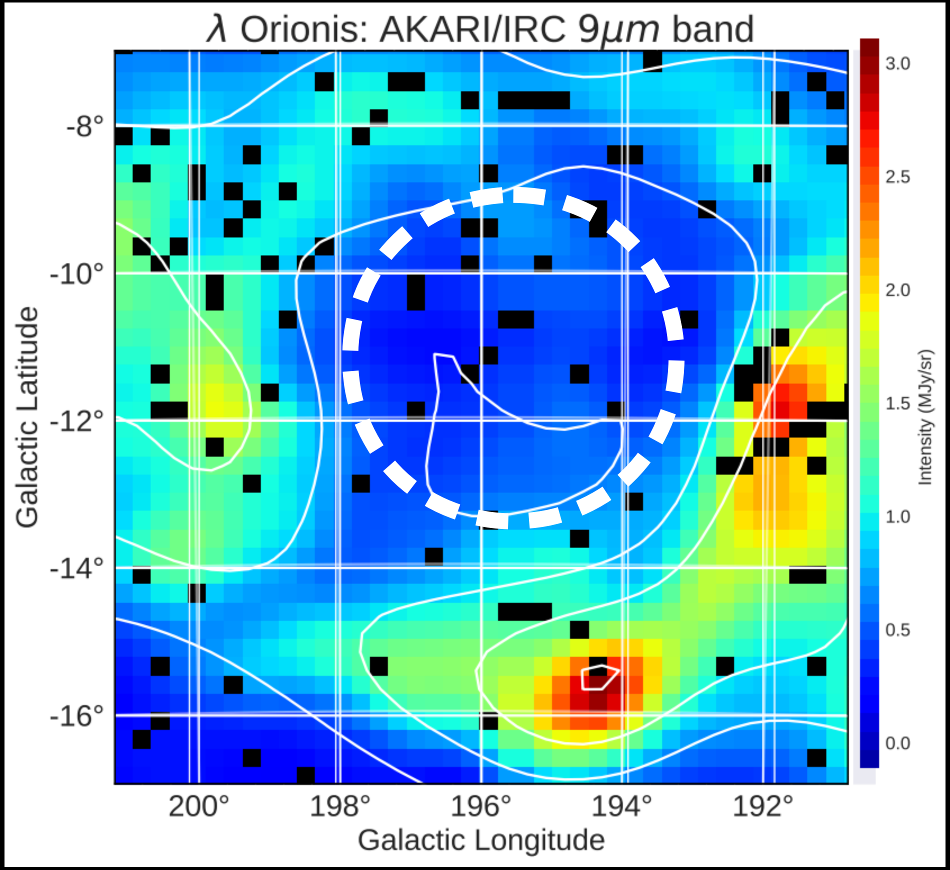
...so does M_{PAH+}

M_{PAH+} doesn't correlate better than M_{PAH}



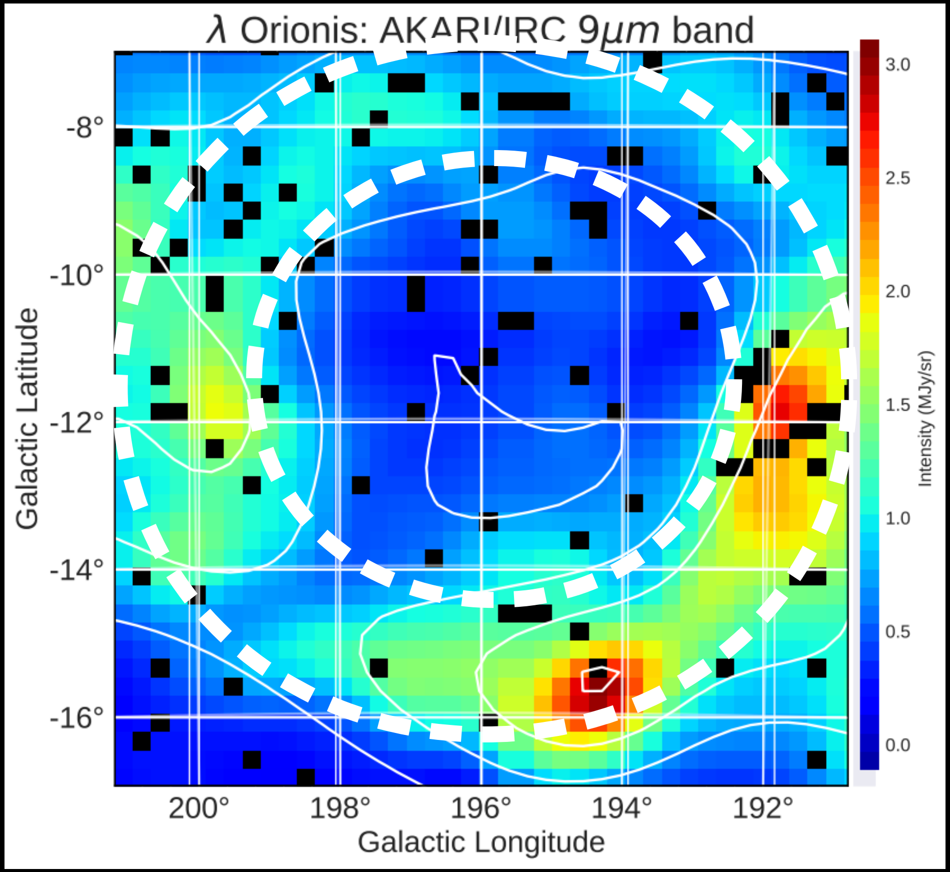
λ Orionis – Conclusions

- ***Central region:***
  - Stronger ISRF, Warmer dust, free-free
  - Less abundant PAHs → Less AME



λ Orionis – Conclusions

- ***Central region:***
  - Stronger ISRF, Warmer dust, free-free
  - Less abundant PAHs → Less AME
- ***Outer Ring:***
  - Cooler dust emission
  - Shielding from ISRF
  - Stronger PAH emission and AME
  - More abundant PAHs → More AME



Conclusions - λ Orionis

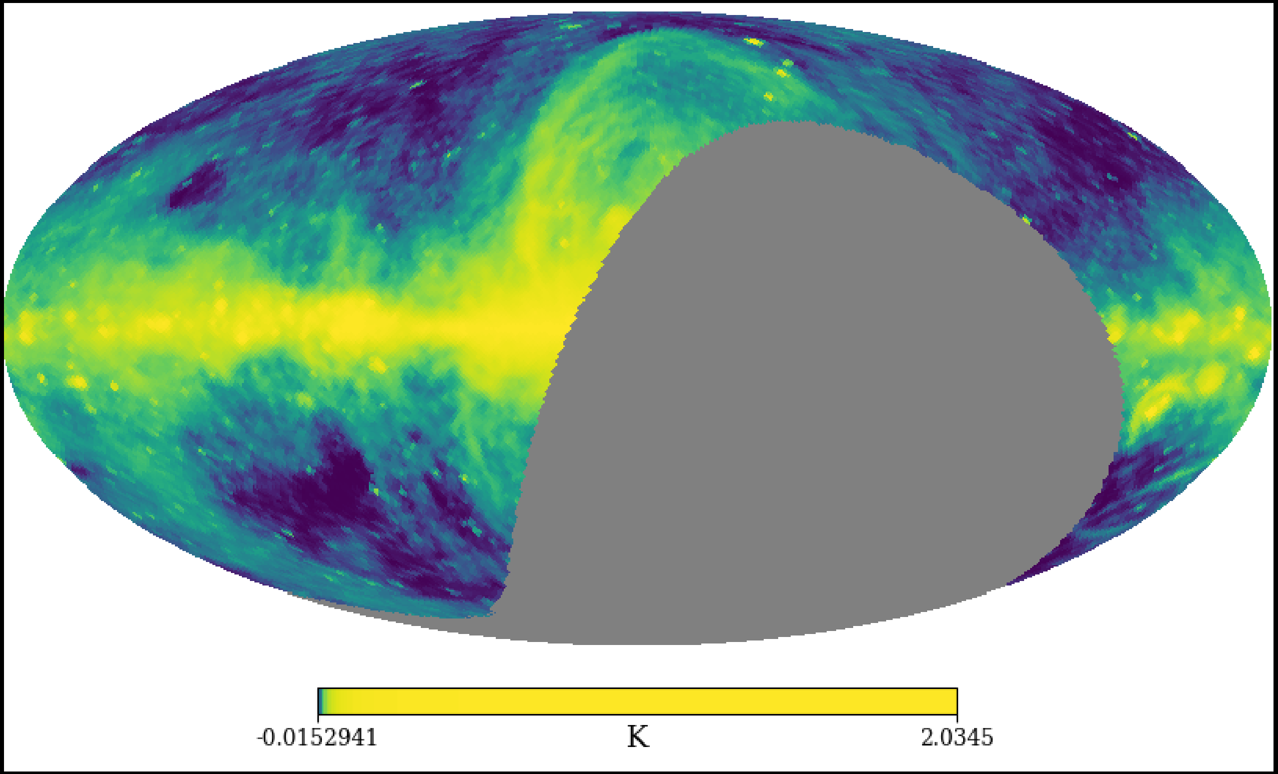
- AME-from-PAHs: Supported
- AME-from-PAH+: Further investigation justified
- Residual free-free emission: Unlikely (**not** ruled out.)
- Consistent with previous literature:
  - Ysard (2010): Yes – MIR vs. AME is stronger.
  - Tibbs (2011): Yes: – PAH hypothesis supported
    No: – AME-ISRF relationship is flipped
  - Hensley (2016): No

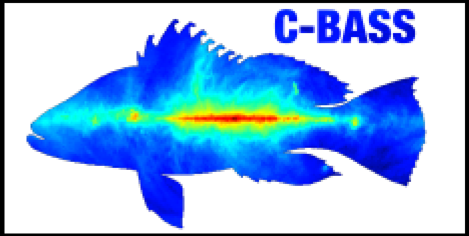
Take away:

- Current AME data may be too low resolution
- Localized investigation results may differ from all-sky
- We must consider characteristics of each region.
- λ Orionis may show the first evidence of a preferential PAH-AME relationship.
- Further all-sky analysis with present data is not likely to solve the mystery.

Future possibilities: Data

- Improved all-sky low-freq. constraints from C-BASS





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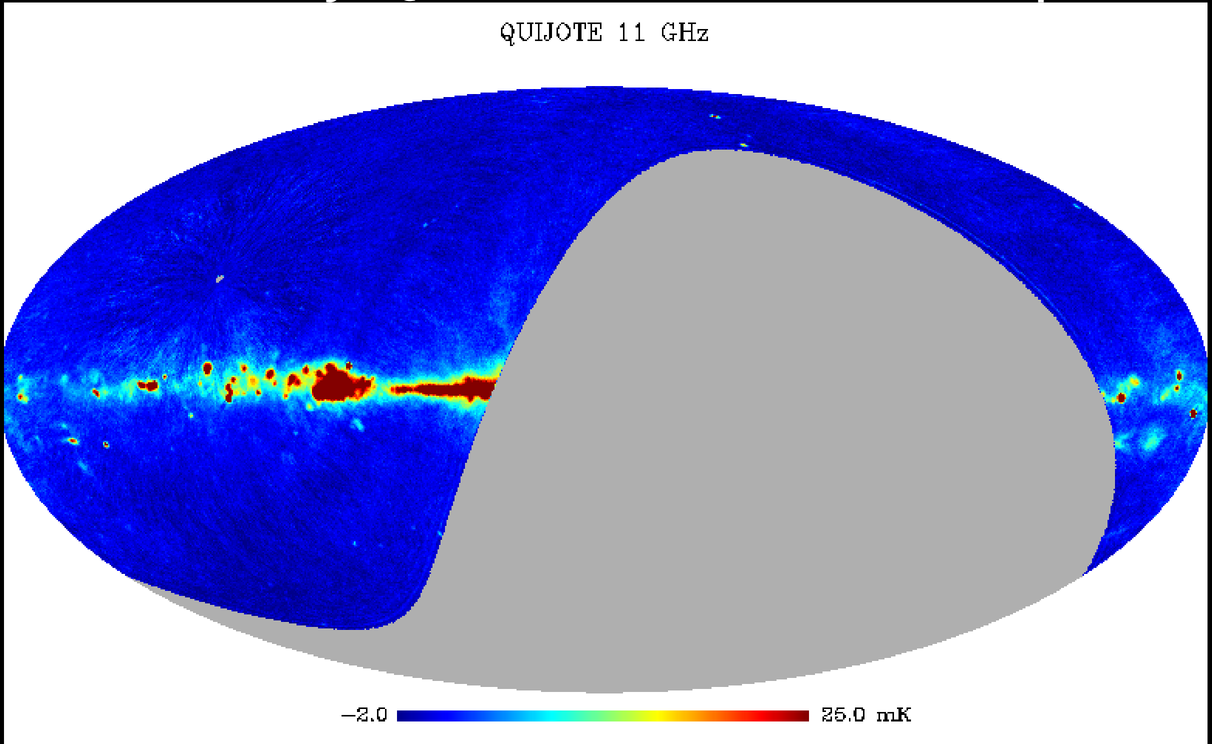
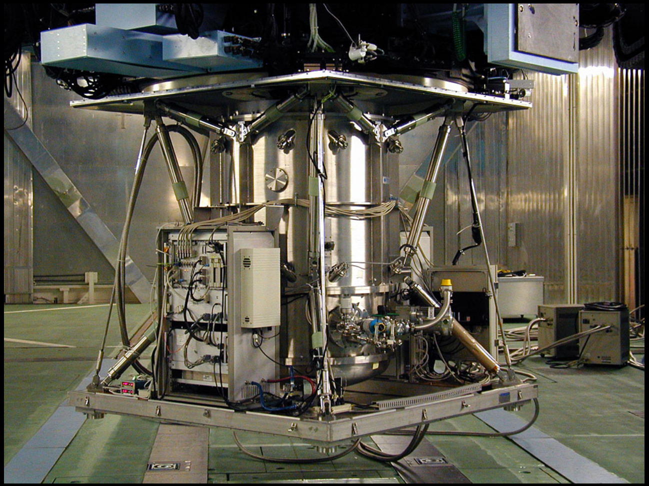


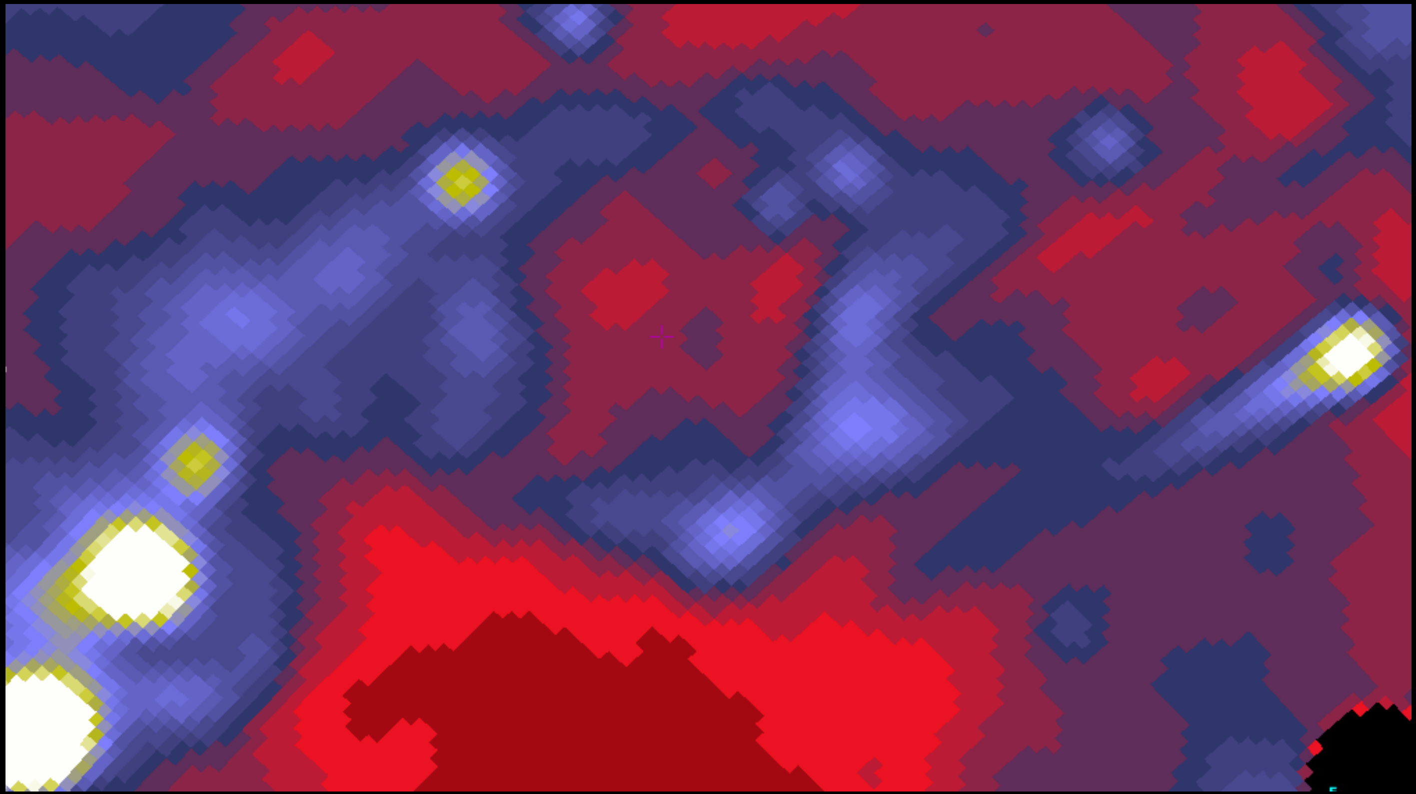
Future possibilities: Data

- Improved all-sky low-freq. constraints from C-BASS
- Higher resolution AME data by Q-U-I JOint Tenerife Experiment (QUIJOTE)
- Detailed comparison of Lambda Orionis AME spectrum with PAH MIR spectroscopy (via COMICS?)



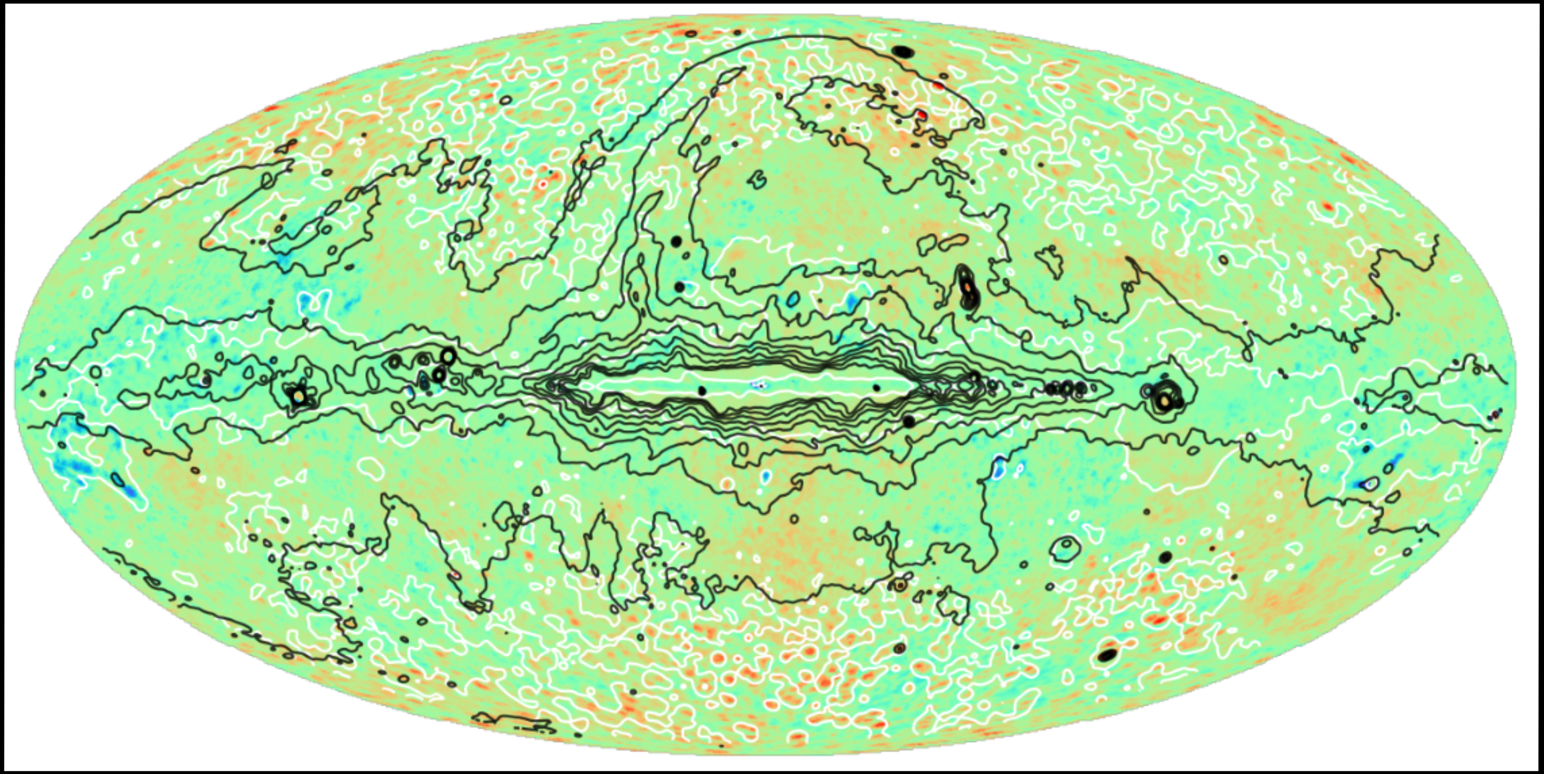
Future possibilities: Analysis

- Analyze surrounding λ Orionis region:



Future possibilities: Analysis

- Analyze surrounding λ Orionis region
- Improve AME Component Separation?



Future possibilities: Analysis

- Analyze surrounding λ Orionis region
- Improve AME Component Separation?
- Machine Learning approach:
  - Blind component separation (Independent Component Analysis, etc.)

WARNING:

The Following Contents are Backup Slides

Proceed at your own risk.

Introduction: *What is AME?*

- Unexplained dust-correlated emission

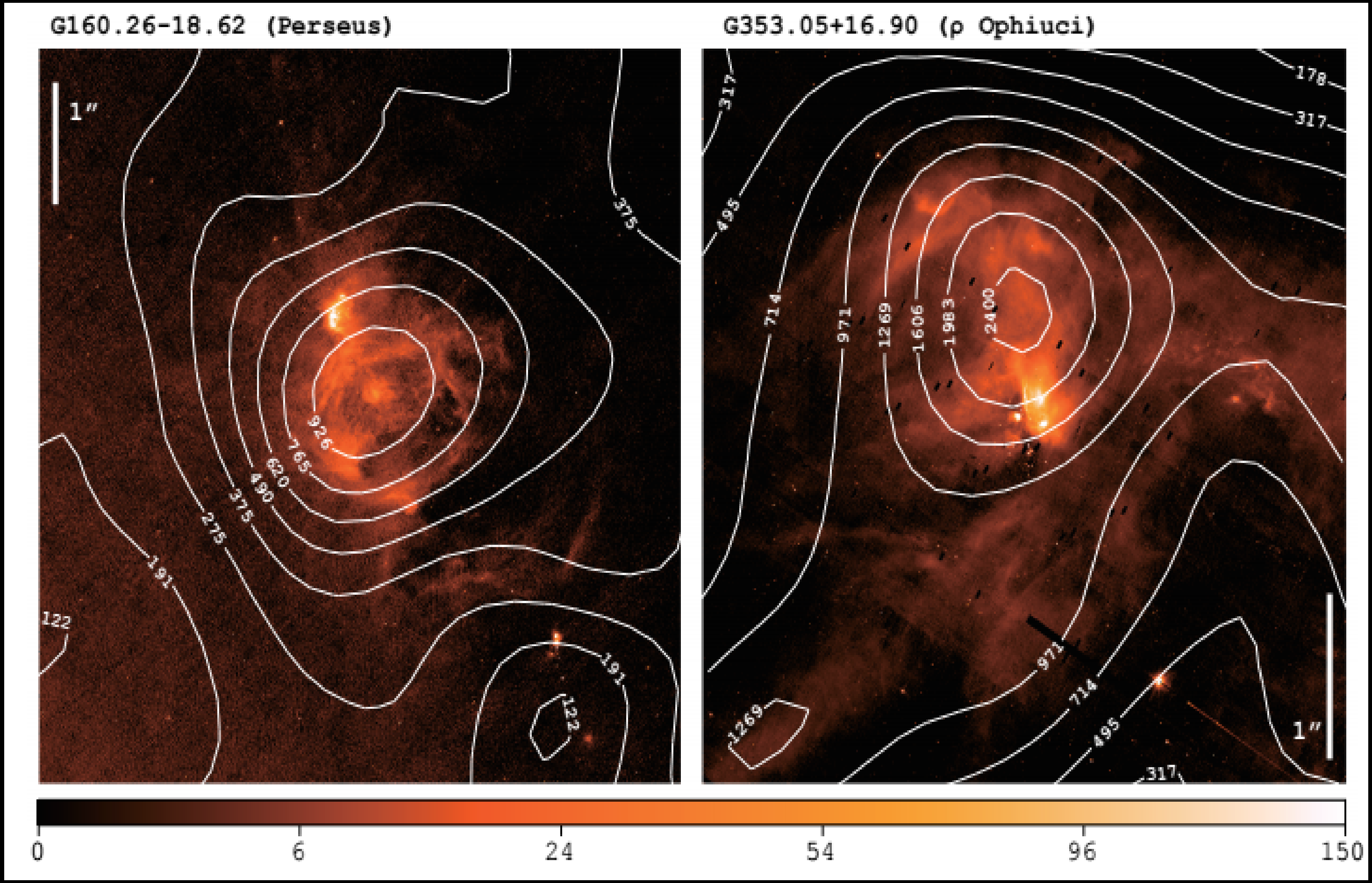
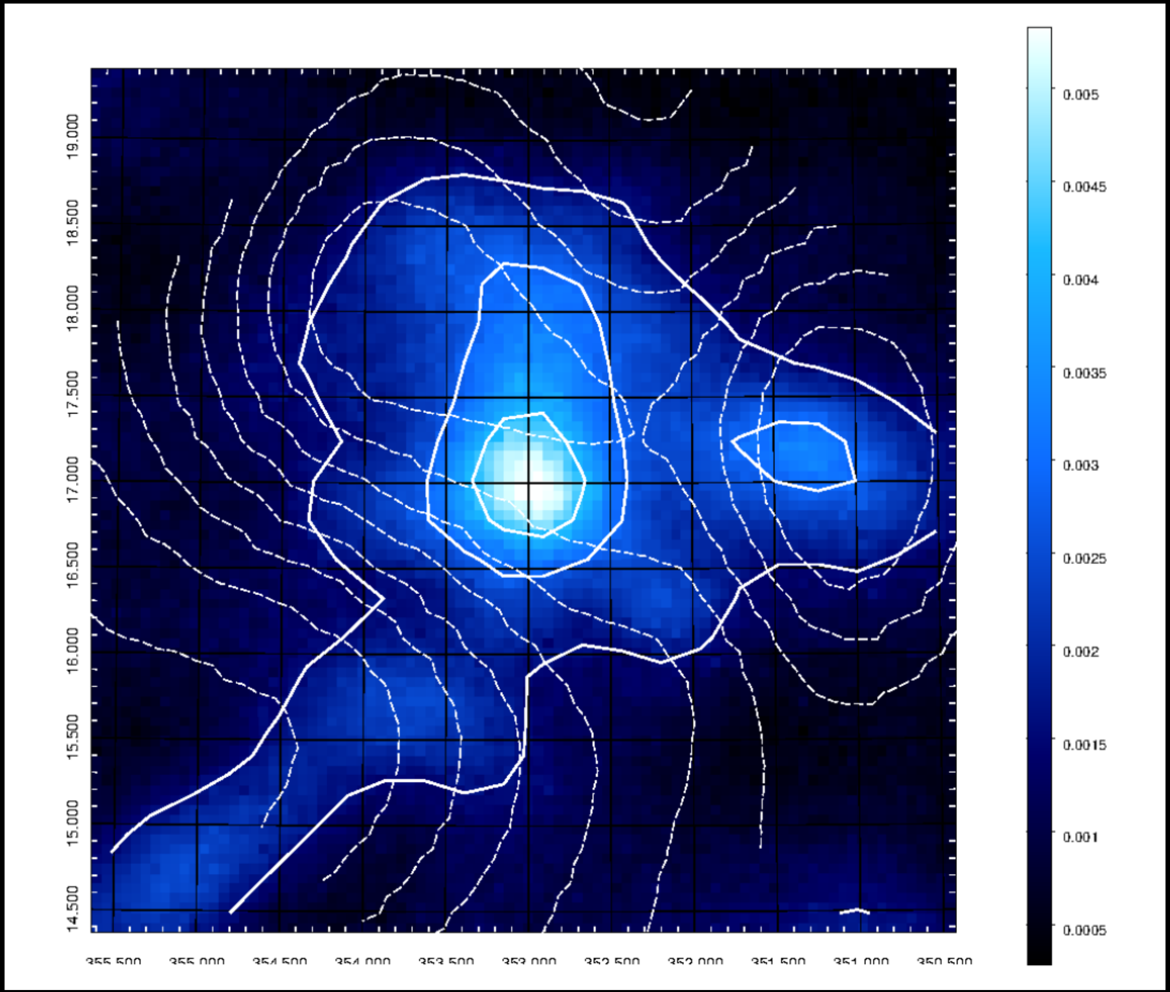
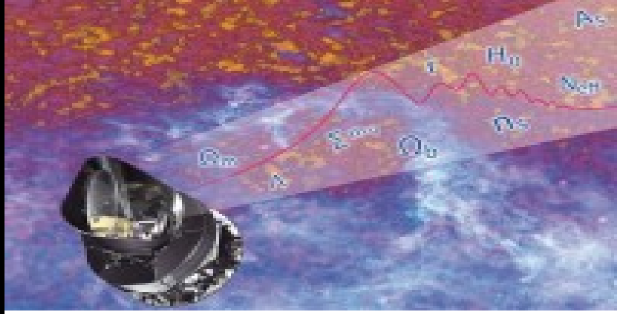


Image: AKARI/ IRC 9 micron data of famous AME regions, Perseus and rho Oph.

rho Ophiuchi at 30GHz via Planck LFI



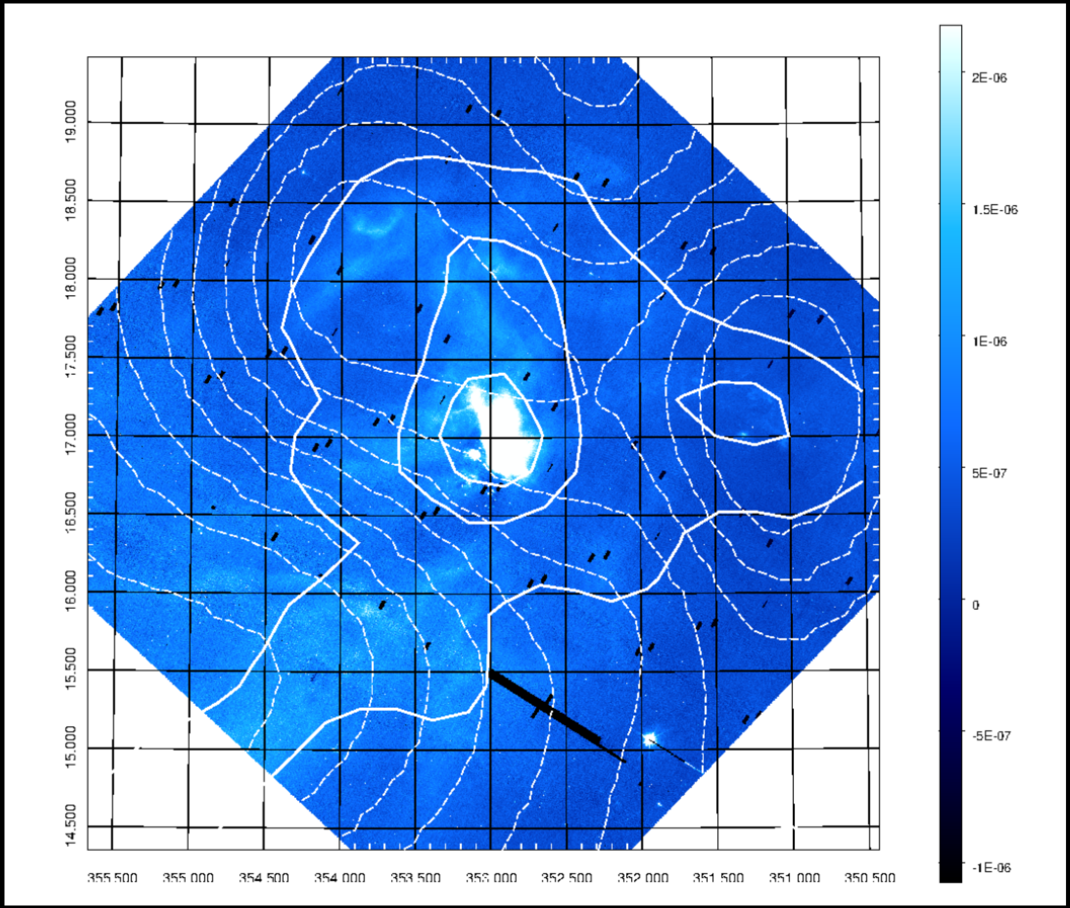


Solid contours: Planck 30Ghz

Two local maxima-
Left peak =
Star forming region

Dashed contours:
T^6 (A rough ISRF approximation.
Assuming a dust emissivity of)

rho Ophiuchi at 9um via AKARI



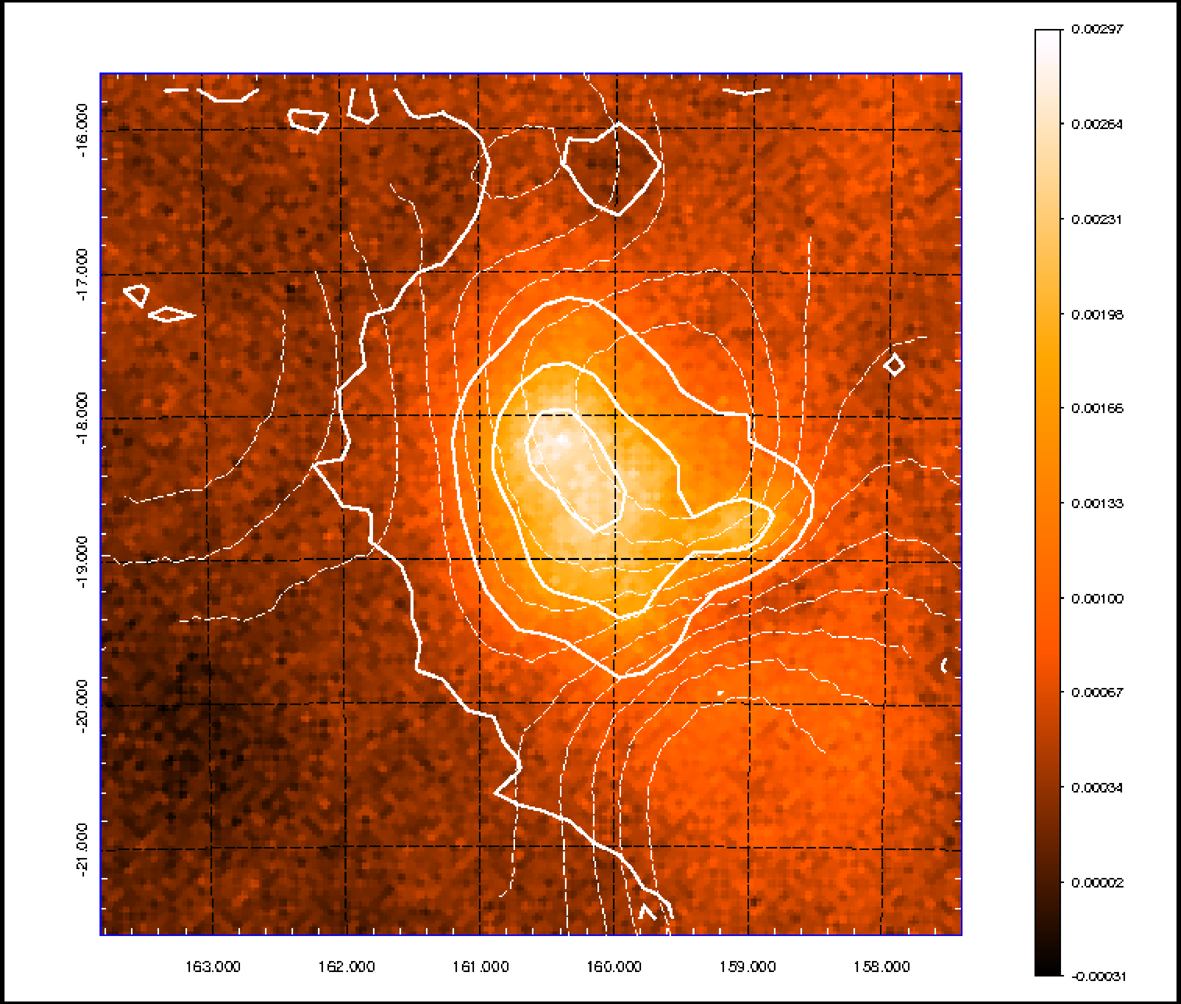
Solid contours:
Planck 30Ghz

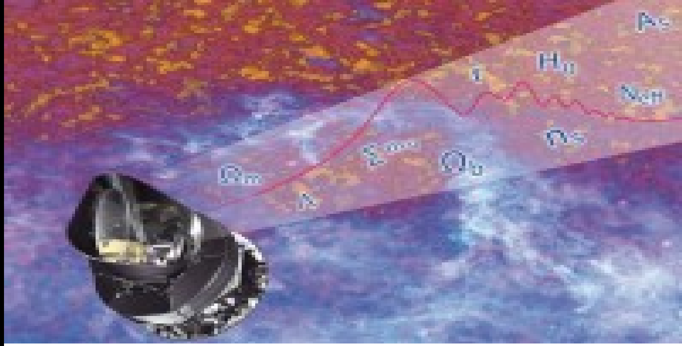
Dashed contours:
T^6 (A rough ISRF approximation)

A ratio map of 9um / ISRF

Note that the peak on the right side disappears after dividing by T^6.

Perseus at 30 GHz via Planck

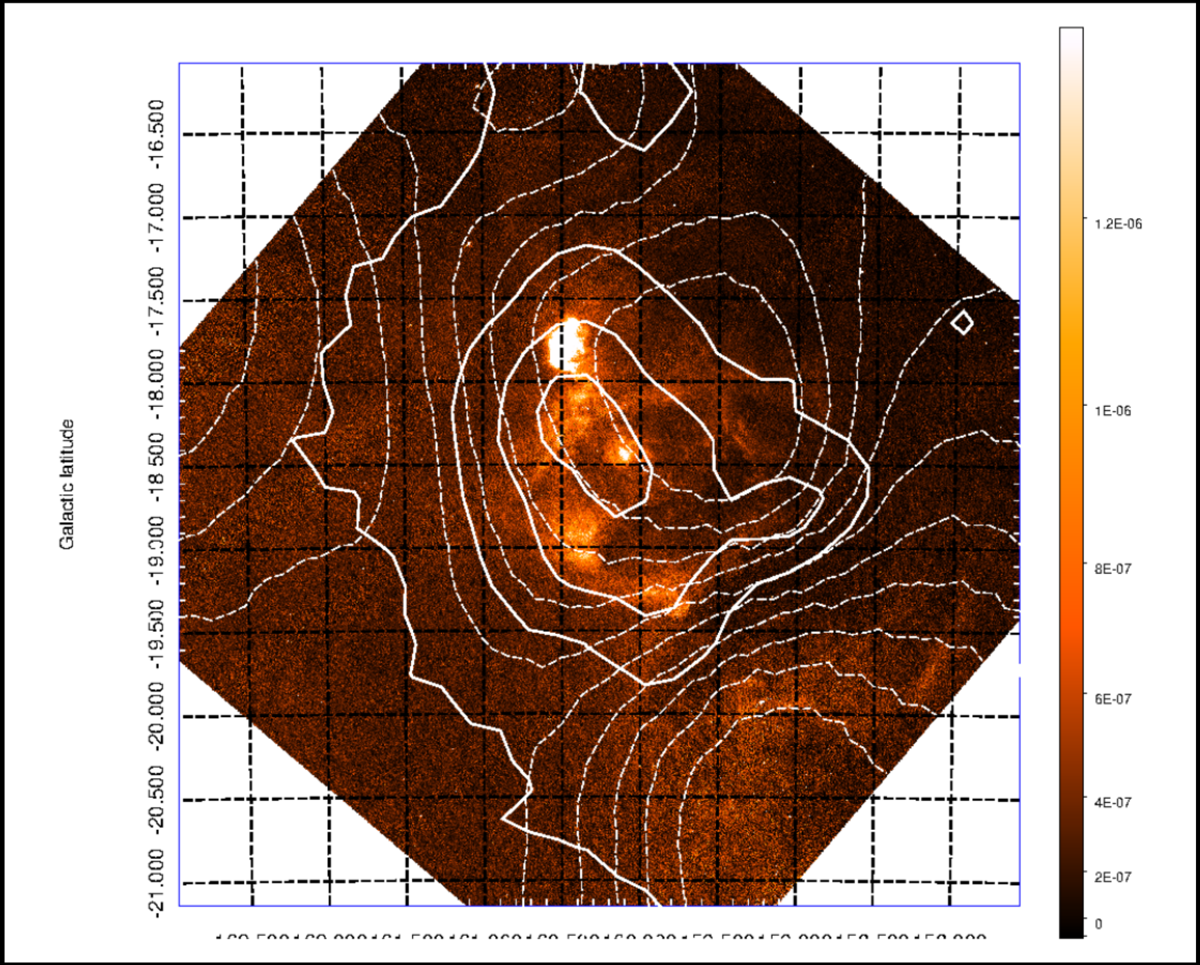




Solid contours: Planck 30Ghz (this image)

Dashed contours: T^6 (A rough ISRF approximation)

Perseus at 9um via AKARI/IRC



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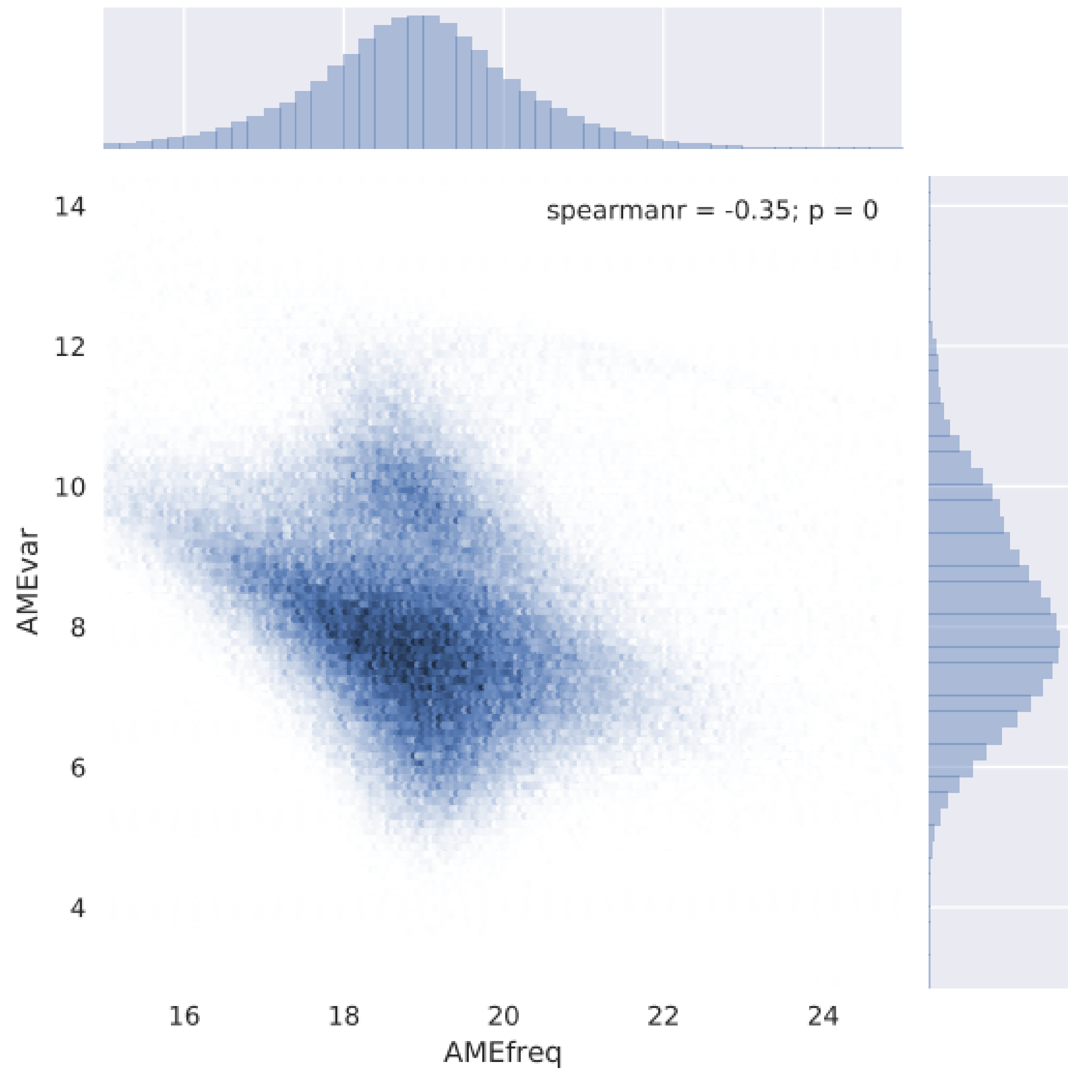
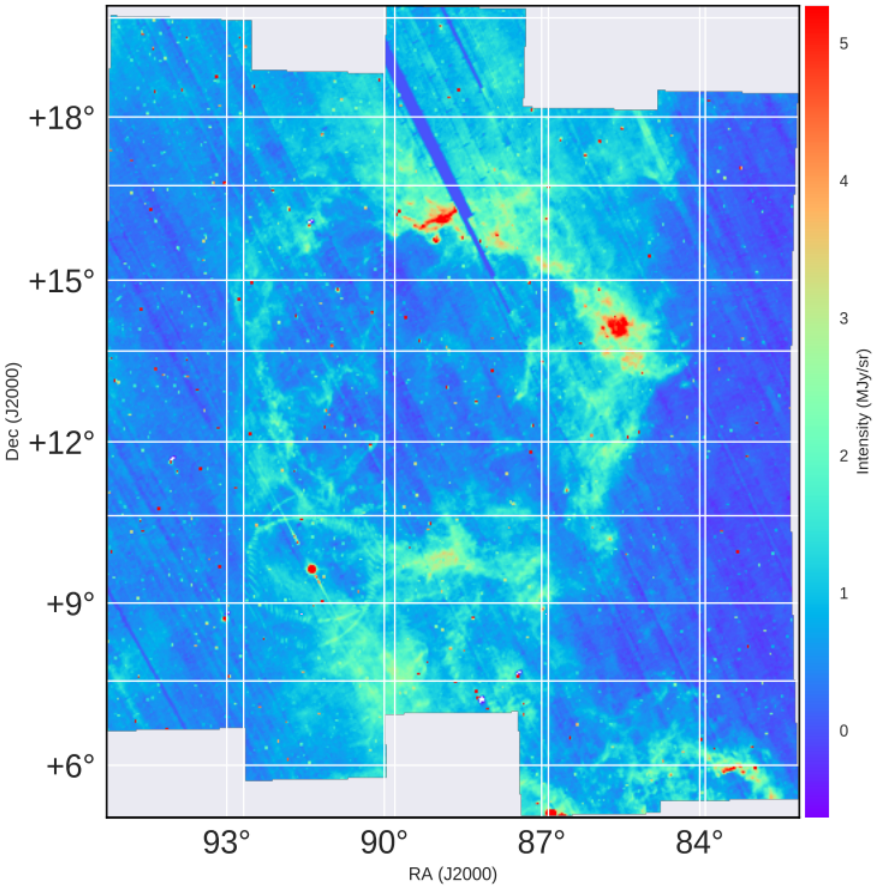
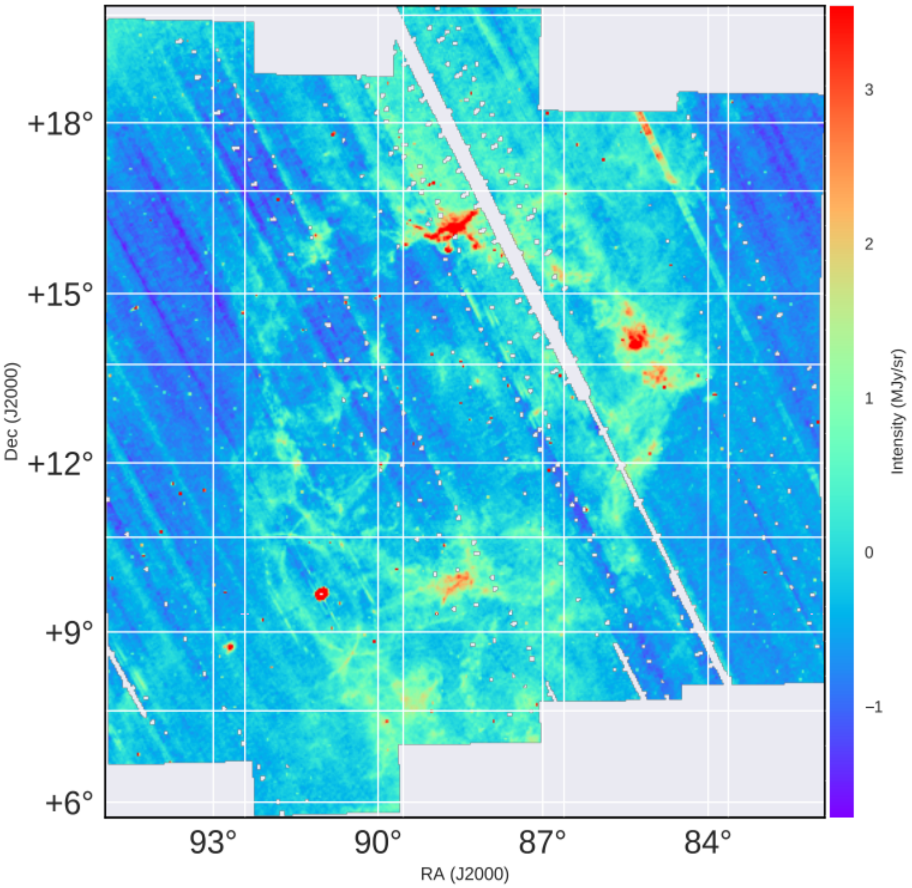


spearmanr = -0.35; p = 0
AMEvar
AMEfreq
14
12
10
8
6
4
16
18
20
22
24


+18°
+15°
+12°
+9°
+6°
Dec (J2000)
93°
90°
87°
84°
RA (J2000)
5
4
3
2
1
0
Intensity (MJy/sr)


+18°
+15°
+12°
+9°
+6°
Dec (J2000)
93°
90°
87°
84°
RA (J2000)
3
2
1
0
−1
Intensity (MJy/sr)

Predictions of Spinning PAH Hypothesis

If PAHs are a dominant AME carrier:

AND

A9 band emission is dominated by PAH luminosity

AND

Measuring the ISRF gives PAH abundance from PAH luminosity

THEN

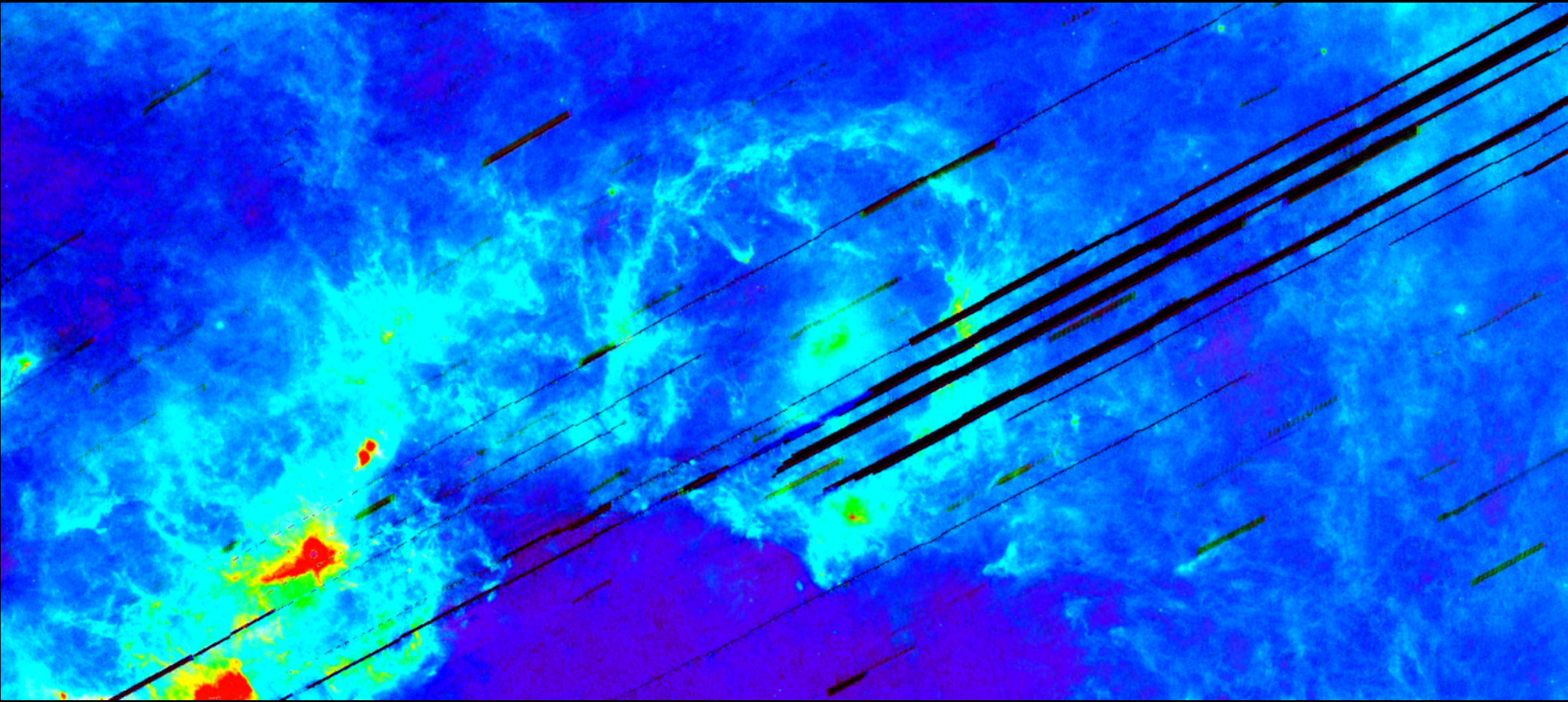
We ***might*** expect a stronger correlation between A9 and AME than with other bands and AME

IF

We don’t see a tighter correlation in intensity, either PAHs are not the carrier OR
ISRF variations, radiative transfer, blur the A9 intensity:AME intensity correlation.

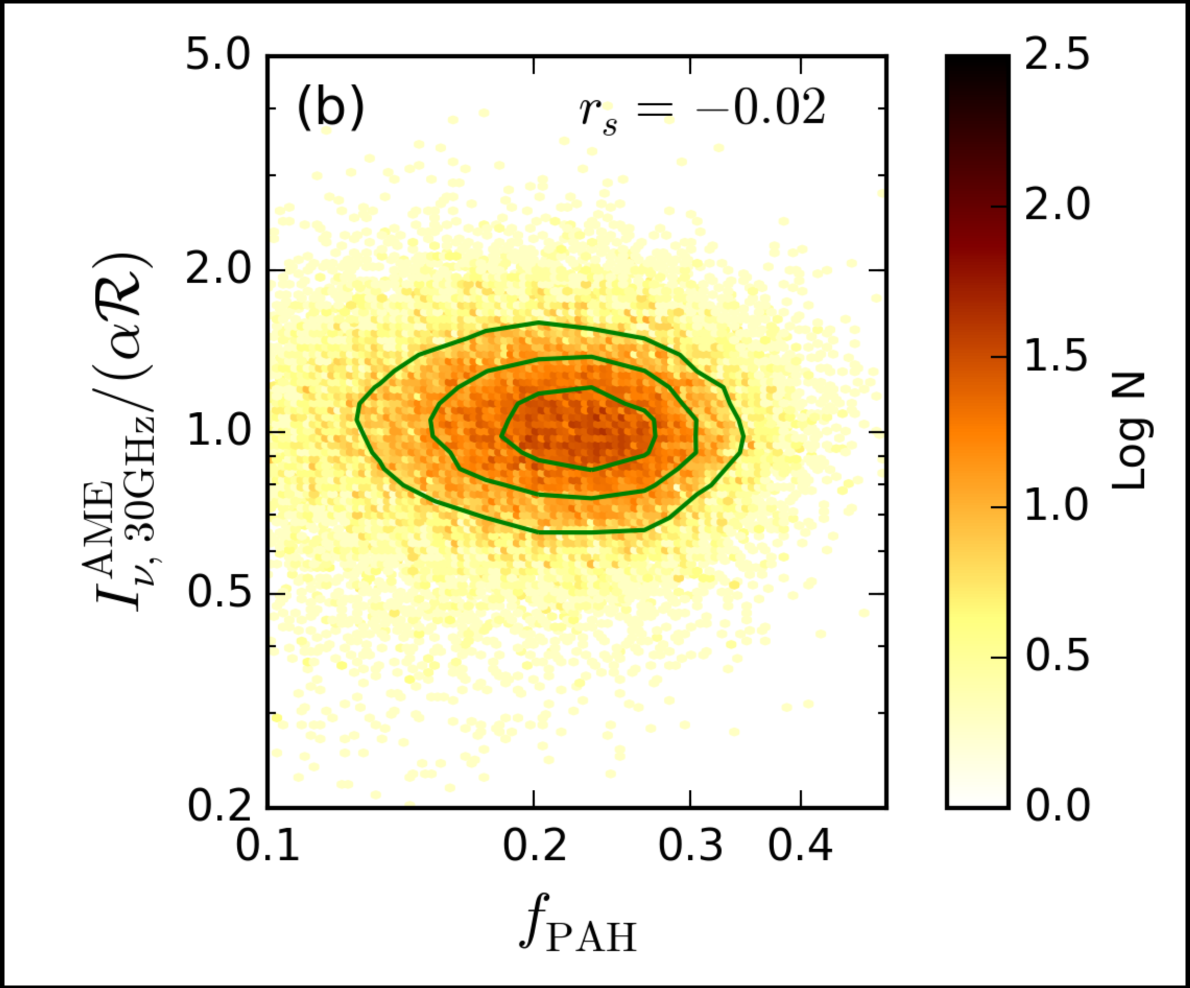
THEN:

λ Orionis

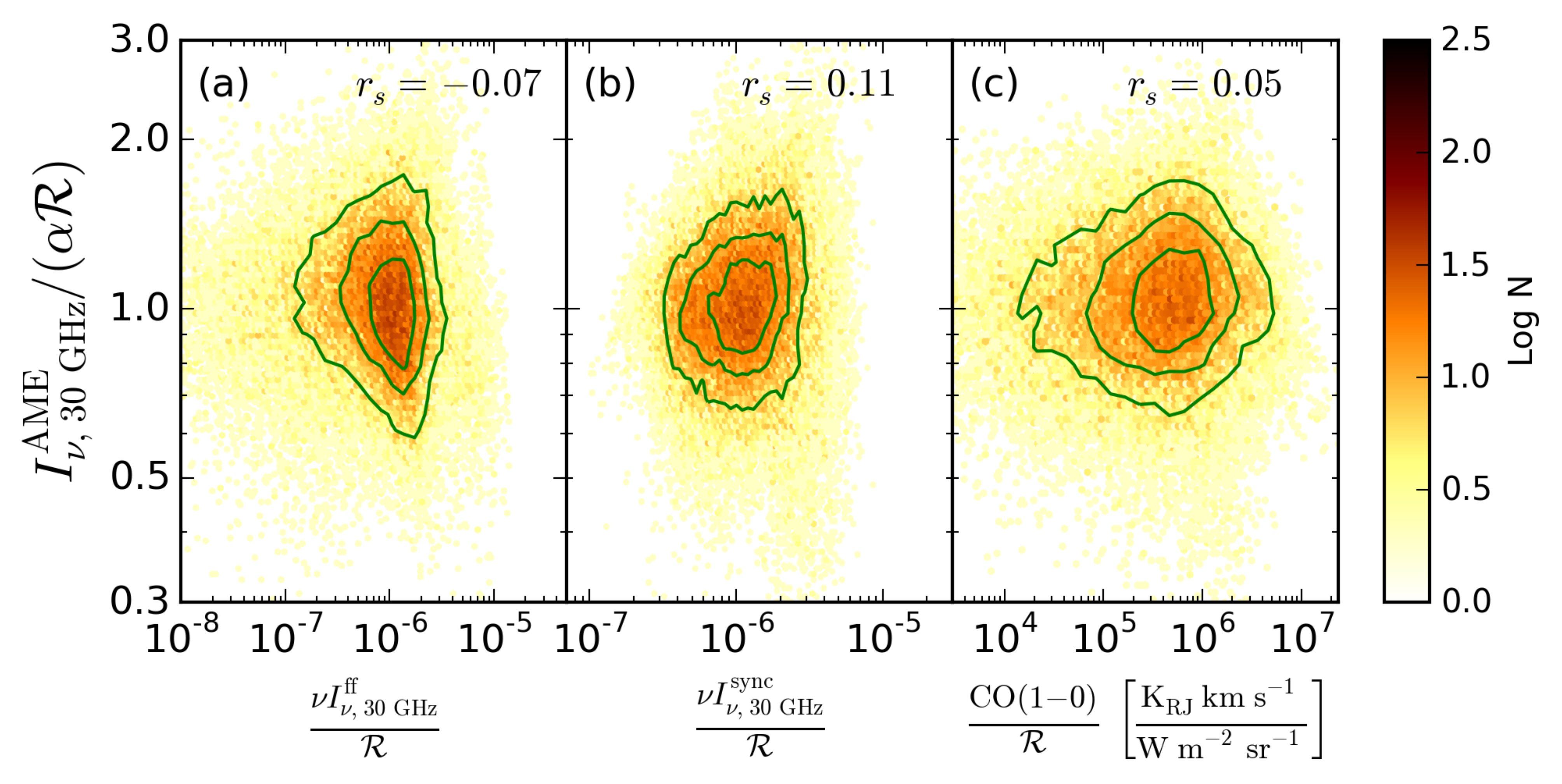


AKARI FIS: Total FIR Emission Image of greater λ Orionis region: http://aladin.unistra.fr/AladinLite/?

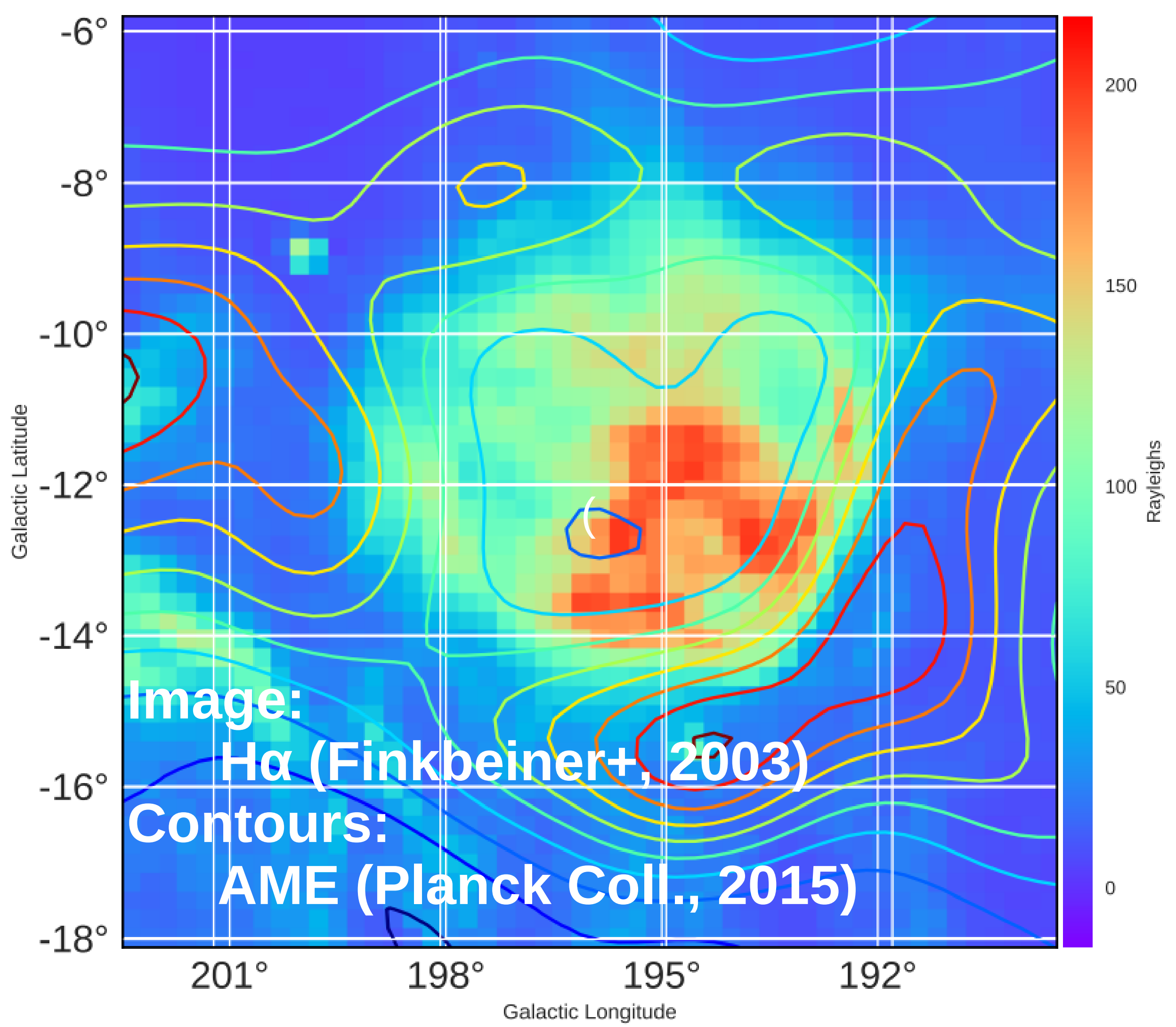
Introduction - Past Works – B. Hensley, et al. (2016)



Introduction - Past Works – B. Hensley, et al. (2016)



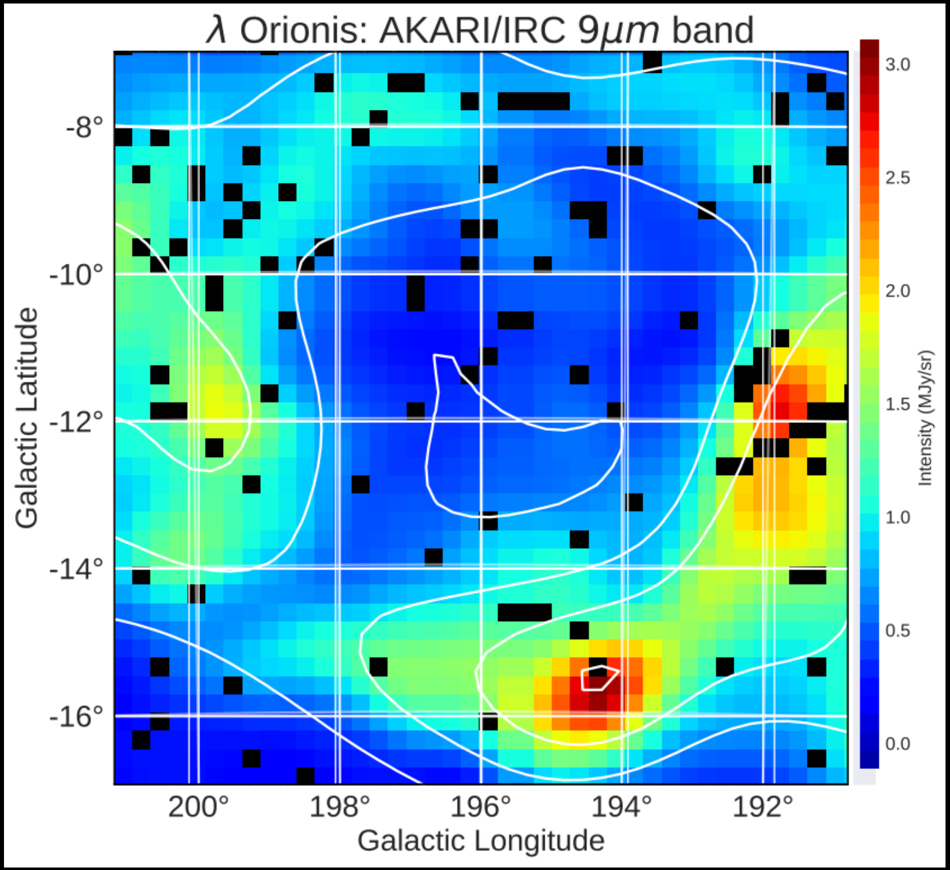
λ Orionis

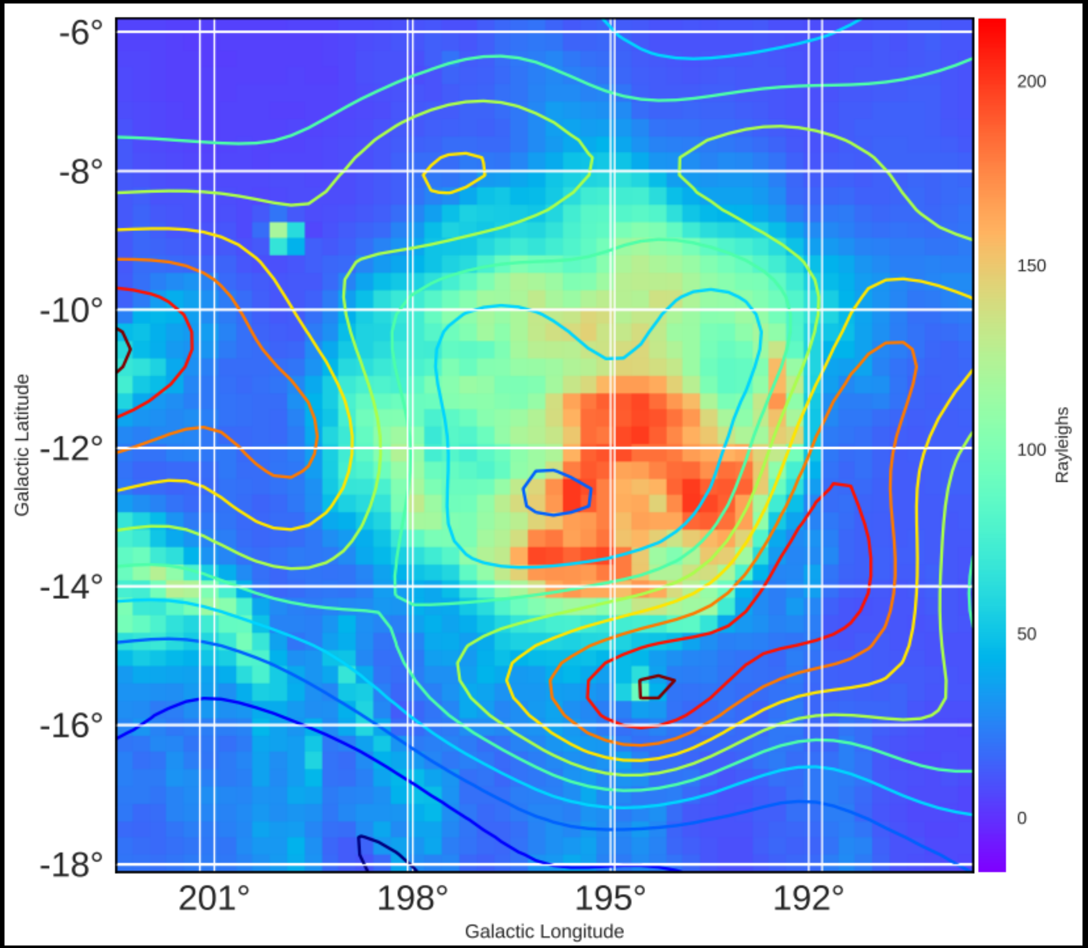


-6°
-8°
-10°
-12°
-14°
-16°
-18°
Galactic Latitude
201°
198°
195°
192°
Galactic Longitude
200
150
100
50
0
Rayleighs
Image:
Hα (Finkbeiner+, 2003)
Contours:
AME (Planck Coll., 2015)

λ Orionis

- Ionized center with molecular ring showing AME





Introduction: Dust SED Parameters

PAH Abundance	$PAH \propto \frac{I_{MIR}}{G_0}$	
Temperature and Emissivity Index from the modified blackbody fitting	$I_{\mathrm{d}}(v) \propto v^{\beta_d} B_v(T_d)$ $\sigma_{PAH} \propto \frac{I_{9\mu m}}{U}$	T = temperature, β = emissivity index
Total Far-Infrared Emission	$FIR = \tau_{100\mu m} \int_0^\infty \left(\frac{100\mu m}{\lambda}\right)^\beta B_\lambda(T) d\lambda$	τ is optical depth at 100μm λ = wavelength B_λ(T) is the Planck function.
Interstellar Radiation Field Strength	$G_0 = \frac{T^{4+\beta}}{(17.5K)^{4+2}}$	U is the ISRF
AME Carrier Abundance??	$\sigma_{AME} \propto \frac{I_{AME}}{U_{AME}}$	

Introduction: Dust SED Parameters

PAH Abundance

$$PAH \propto \frac{I_{MIR}}{G_0}$$

Temperature and Emissivity Index from the modified blackbody fitting

$$I_{\mathrm{d}}(\nu) \propto \nu^{\beta_d} B_\nu(T_d)$$

T = temperature,
β = emissivity index

Total Far-Infrared Emission

$$FIR = \tau_{100\,\mu m} \int_0^\infty \left(\frac{100\,\mu m}{\lambda} \right)^\beta B_\lambda(T)\, d\lambda$$

τ is optical depth at 100μm
λ = wavelength
$B_\lambda(T)$ is the Planck function.

Interstellar Radiation Field Strength

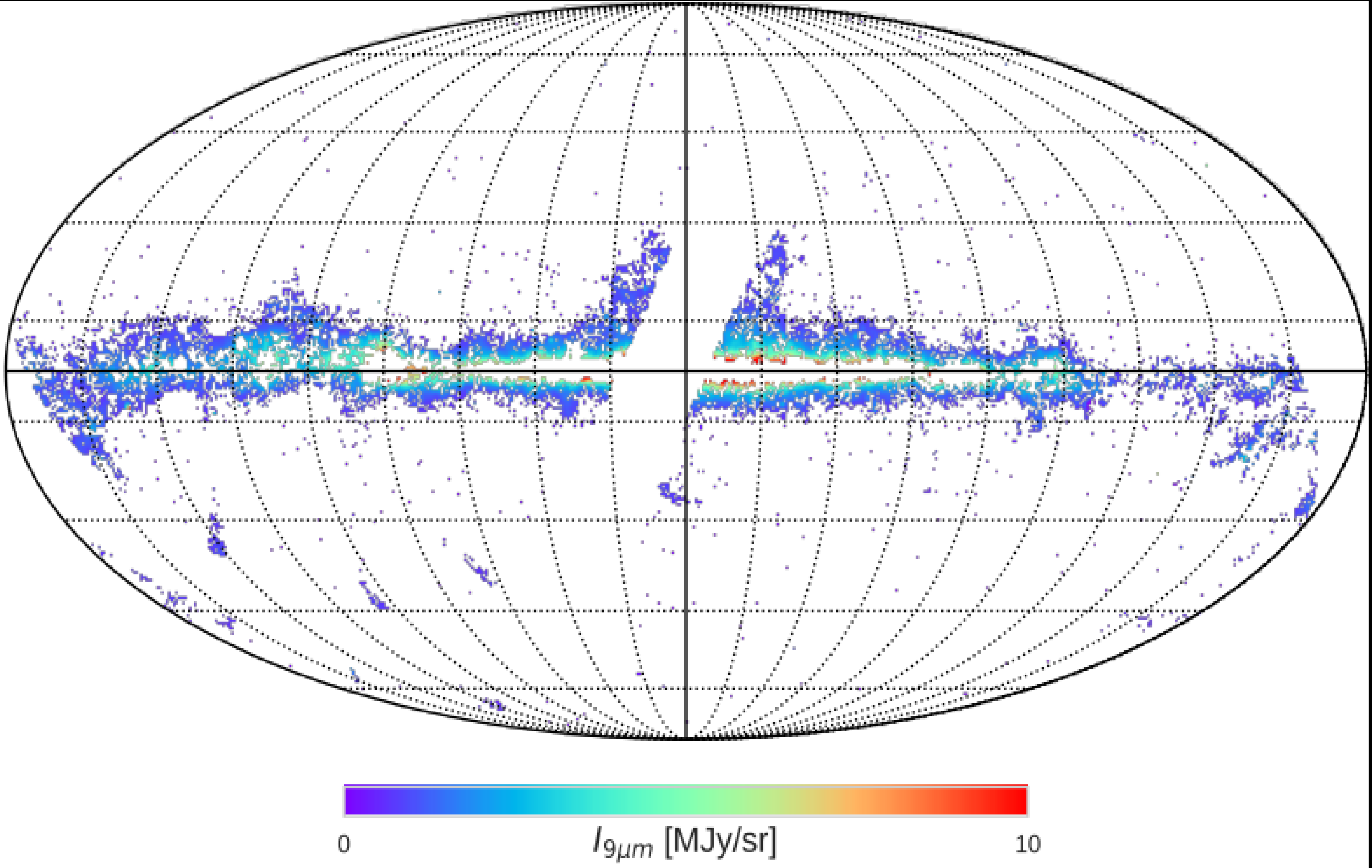
$$G_0 = \frac{T^{4+\beta}}{(17.5K)^{4+2}}$$

U is the ISRF

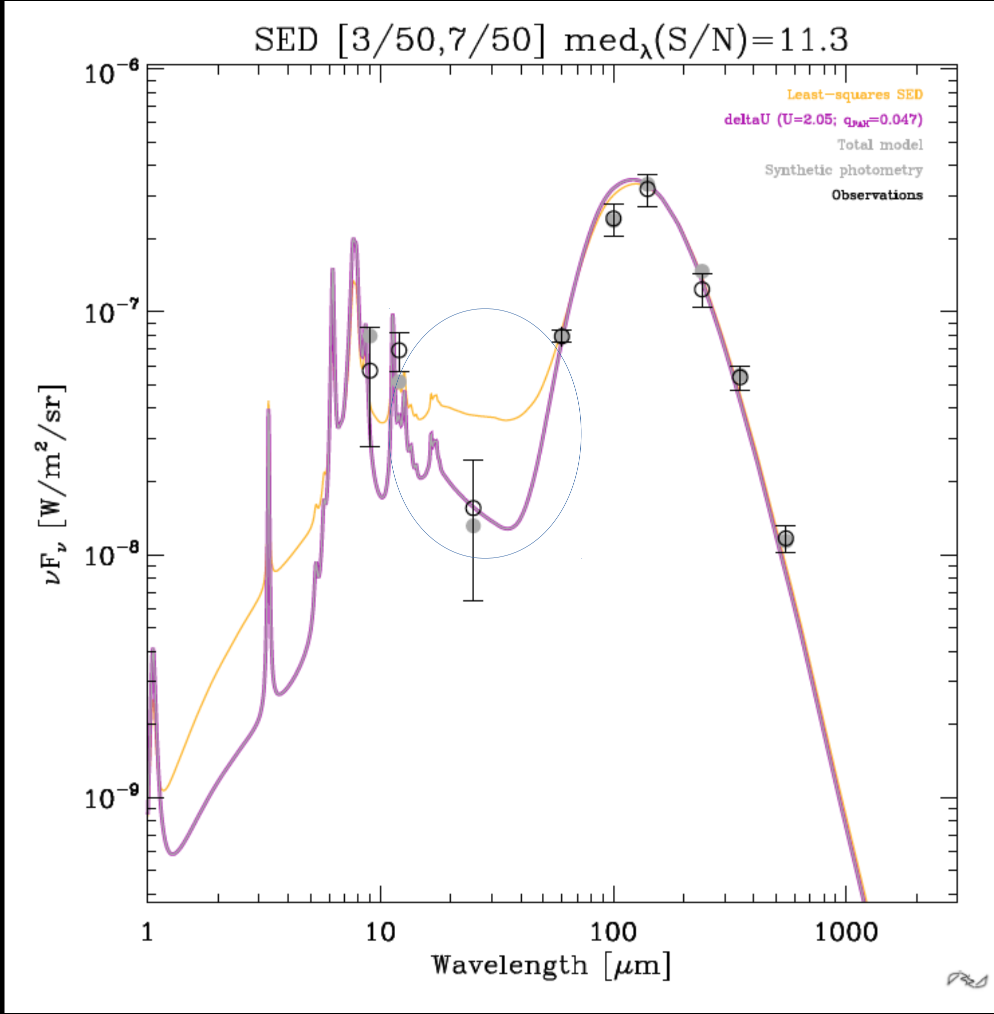
AME Carrier Abundance??

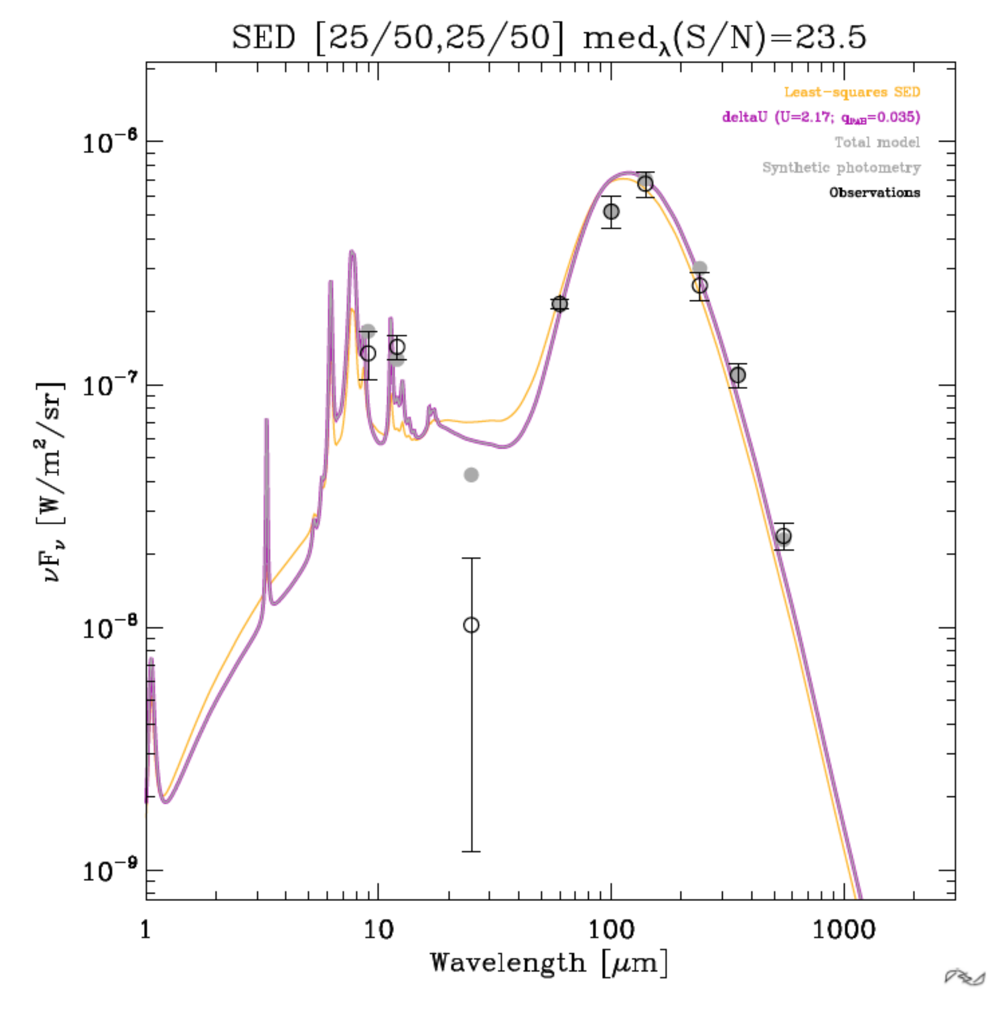
$$\frac{I_{AME}}{U_{AME}}$$

What’s left of the all-sky data, after applying the mask?

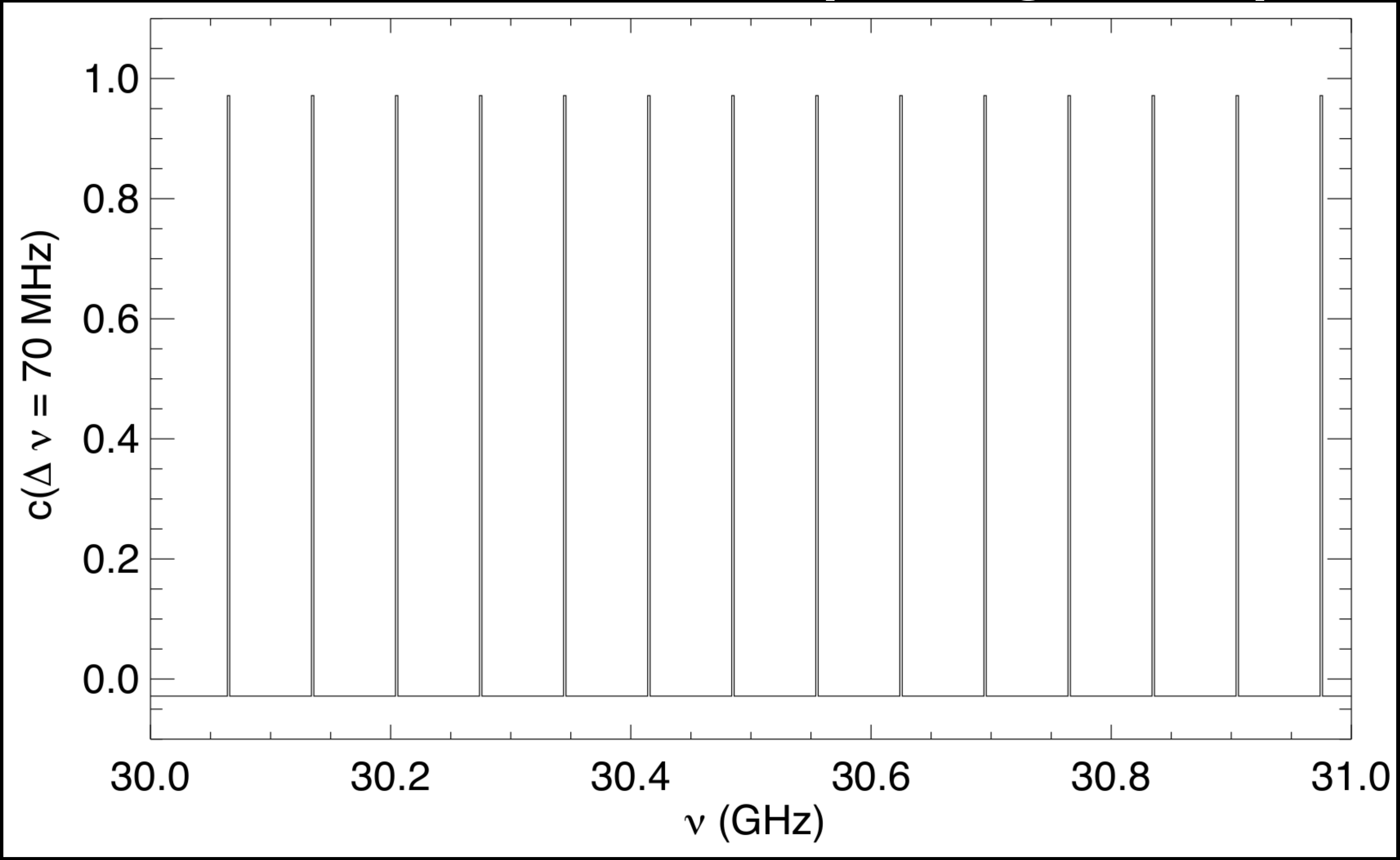


λ Orionis – SED Fitting – Example Fits





Introduction – What is AME? - Spinning PAH Spectrum



Y. Ali-Haimoud (2013) - "Rotational Spectroscopy of PAHs"

Introduction – What is AME? - Perseus Cloud

C. Tibbs+ (2011) - “Spitzer characterisation of dust in an anomalous emission region: the Perseus cloud”

Introduction - Past Works – Y. Ali-Haimoud (2008)

$$\frac{j_\nu}{n_H} = \frac{1}{4\pi} \int_{a_{min}}^{a_{max}} da \frac{1}{n_H} \frac{dn_{gr}}{da} 4\pi \omega^2 f_a(\omega) 2\pi \frac{2}{3} \frac{\mu_{a\perp}^2 \omega^4}{c^3}$$

$$f_a(\omega) \propto \exp\left(\frac{-F}{G} \frac{I\omega^2}{2kT} - \frac{\tau_H}{3G\tau_{ed}} \left(\frac{I\omega^2}{2kT}\right)^2\right)$$

All-sky Analysis - Unmasked correlation test

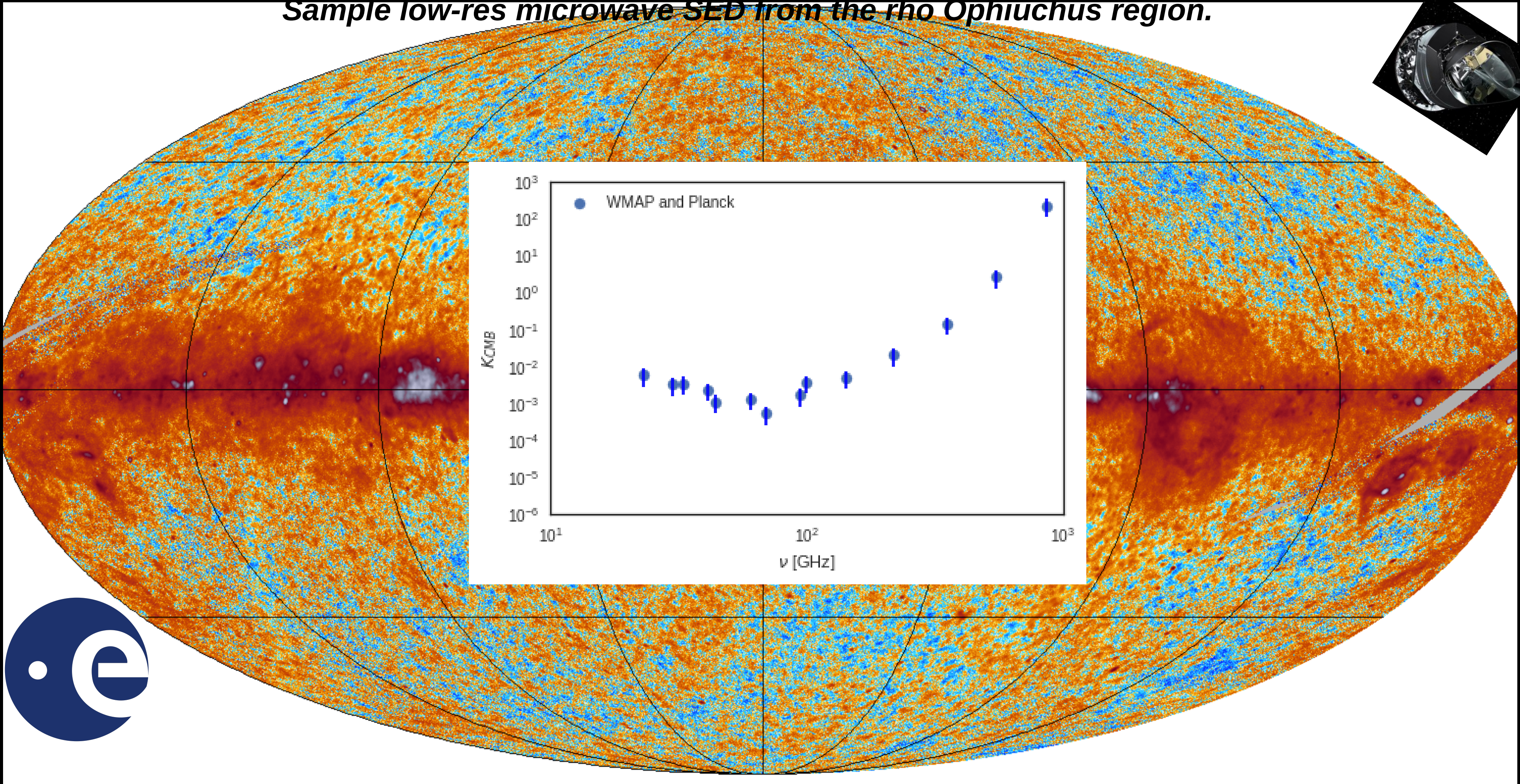
	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.58	0.5	0.25	0.52	0.48	0.64	0.62	0.59	0.6	0.59	0.58	0.52	0.49	0.31	0.31	0.54	0.31	0.33
I12	0.58	1	0.15	0.77	0.32	0.62	0.57	0.39	0.35	0.38	0.34	0.33	0.41	0.28	0.12	0.32	0.26	0.026	0.38
A18	0.5	0.15	1	0.18	0.13	-0.065	0.036	0.067	0.053	0.051	0.053	0.049	0.069	0.032	0.088	0.057	0.052	-0.062	0.089
I25	0.25	0.77	0.18	1	0.11	0.28	0.16	0.036	-0.0019	0.017	-0.0057	-0.016	0.13	-0.024	-0.065	0.16	-0.075	-0.21	0.22
I60	0.52	0.32	0.13	0.11	1	0.34	0.67	0.9	0.88	0.86	0.88	0.88	0.6	0.73	0.49	0.53	0.86	0.69	0.51
A65	0.48	0.62	-0.065	0.28	0.34	1	0.79	0.52	0.5	0.54	0.47	0.47	0.46	0.43	0.21	0.28	0.4	0.3	0.27
A90	0.64	0.57	0.036	0.16	0.67	0.79	1	0.85	0.83	0.83	0.82	0.81	0.64	0.68	0.4	0.46	0.75	0.52	0.45
I100	0.62	0.39	0.067	0.036	0.9	0.52	0.85	1	0.98	0.97	0.98	0.97	0.69	0.81	0.53	0.57	0.95	0.72	0.57
A140	0.59	0.35	0.053	-0.0019	0.88	0.5	0.83	0.98	1	0.99	0.98	0.98	0.67	0.81	0.53	0.55	0.95	0.73	0.55
A160	0.6	0.38	0.051	0.017	0.86	0.54	0.83	0.97	0.99	1	0.97	0.97	0.67	0.81	0.53	0.54	0.94	0.73	0.54
P857	0.59	0.34	0.053	-0.0057	0.88	0.47	0.82	0.98	0.98	0.97	1	1	0.68	0.81	0.53	0.55	0.96	0.72	0.53
P545	0.58	0.33	0.049	-0.016	0.88	0.47	0.81	0.97	0.98	0.97	1	1	0.67	0.81	0.53	0.53	0.96	0.73	0.51
AMEvar	0.52	0.41	0.069	0.13	0.6	0.46	0.64	0.69	0.67	0.67	0.68	0.67	1	0.66	0.45	0.45	0.63	0.45	0.42
AMEfix	0.49	0.28	0.032	-0.024	0.73	0.43	0.68	0.81	0.81	0.81	0.81	0.81	0.66	1	0.58	0.5	0.78	0.68	0.46
ff	0.31	0.12	0.088	-0.065	0.49	0.21	0.4	0.53	0.53	0.53	0.53	0.53	0.45	0.58	1	0.3	0.51	0.49	0.28
Sync	0.31	0.32	0.057	0.16	0.53	0.28	0.46	0.57	0.55	0.54	0.55	0.53	0.45	0.5	0.3	1	0.54	0.32	0.94
N_H	0.54	0.26	0.052	-0.075	0.86	0.4	0.75	0.95	0.95	0.94	0.96	0.96	0.63	0.78	0.51	0.54	1	0.7	0.53
H_a	0.31	0.026	-0.062	-0.21	0.69	0.3	0.52	0.72	0.73	0.73	0.72	0.73	0.45	0.68	0.49	0.32	0.7	1	0.27
H408	0.33	0.38	0.089	0.22	0.51	0.27	0.45	0.57	0.55	0.54	0.53	0.51	0.42	0.46	0.28	0.94	0.53	0.27	1

	A9	I12	A18	I25	I60	A65	A90	I100	A140	A160	P857	P545	AMEvar	AMEfix	ff	Sync	N_H	H_a	H408
A9	1	0.94	0.9	0.87	0.91	0.86	0.94	0.95	0.96	0.96	0.94	0.93	0.81	0.86	0.74	0.7	0.83	0.42	0.73
I12	0.94	1	0.83	0.93	0.88	0.88	0.92	0.92	0.94	0.94	0.92	0.91	0.8	0.83	0.69	0.77	0.78	0.28	0.79
A18	0.9	0.83	1	0.84	0.86	0.71	0.85	0.87	0.87	0.86	0.84	0.82	0.72	0.77	0.72	0.59	0.75	0.45	0.65
I25	0.87	0.93	0.84	1	0.86	0.76	0.84	0.87	0.87	0.87	0.85	0.84	0.75	0.76	0.64	0.73	0.71	0.24	0.77
I60	0.91	0.88	0.86	0.86	1	0.85	0.98	0.98	0.94	0.93	0.87	0.85	0.78	0.85	0.77	0.75	0.75	0.52	0.81
A65	0.86	0.88	0.71	0.76	0.85	1	0.92	0.88	0.88	0.88	0.83	0.82	0.74	0.8	0.7	0.76	0.72	0.4	0.77
A90	0.94	0.92	0.85	0.84	0.98	0.92	1	0.99	0.97	0.97	0.92	0.9	0.81	0.87	0.77	0.76	0.8	0.49	0.8
I100	0.95	0.92	0.87	0.87	0.98	0.88	0.99	1	0.99	0.98	0.94	0.92	0.81	0.88	0.78	0.74	0.82	0.49	0.79
A140	0.96	0.94	0.87	0.87	0.94	0.88	0.97	0.99	1	1	0.98	0.97	0.83	0.88	0.78	0.7	0.86	0.45	0.74
A160	0.96	0.94	0.86	0.87	0.93	0.88	0.97	0.98	1	1	0.98	0.97	0.83	0.88	0.77	0.7	0.87	0.43	0.74
P857	0.94	0.92	0.84	0.85	0.87	0.83	0.92	0.94	0.98	0.98	1	1	0.81	0.86	0.75	0.63	0.91	0.38	0.65
P545	0.93	0.91	0.82	0.84	0.85	0.82	0.9	0.92	0.97	0.97	1	1	0.8	0.85	0.74	0.6	0.92	0.37	0.62
AMEvar	0.81	0.8	0.72	0.75	0.78	0.74	0.81	0.81	0.83	0.83	0.81	0.8	1	0.9	0.55	0.68	0.72	0.31	0.68
AMEfix	0.86	0.83	0.77	0.76	0.85	0.8	0.87	0.88	0.88	0.88	0.86	0.85	0.9	1	0.65	0.64	0.8	0.47	0.67
ff	0.74	0.69	0.72	0.64	0.77	0.7	0.77	0.78	0.78	0.77	0.75	0.74	0.55	0.65	1	0.43	0.67	0.68	0.5
Sync	0.7	0.77	0.59	0.73	0.75	0.76	0.76	0.74	0.7	0.7	0.63	0.6	0.68	0.64	0.43	1	0.47	0.11	0.98
N_H	0.83	0.78	0.75	0.71	0.75	0.72	0.8	0.82	0.86	0.87	0.91	0.92	0.72	0.8	0.67	0.47	1	0.41	0.49
H_a	0.42	0.28	0.45	0.24	0.52	0.4	0.49	0.49	0.45	0.43	0.38	0.37	0.31	0.47	0.68	0.11	0.41	1	0.19
H408	0.73	0.79	0.65	0.77	0.81	0.77	0.8	0.79	0.74	0.74	0.65	0.62	0.68	0.67	0.5	0.98	0.49	0.19	1

Introduction: What is AME?

- An unexplained microwave foreground

Sample low-res microwave SED from the rho Ophiuchus region.



Planck LFI 28 GHz All-sky Map: ESA/Planck Collaboration

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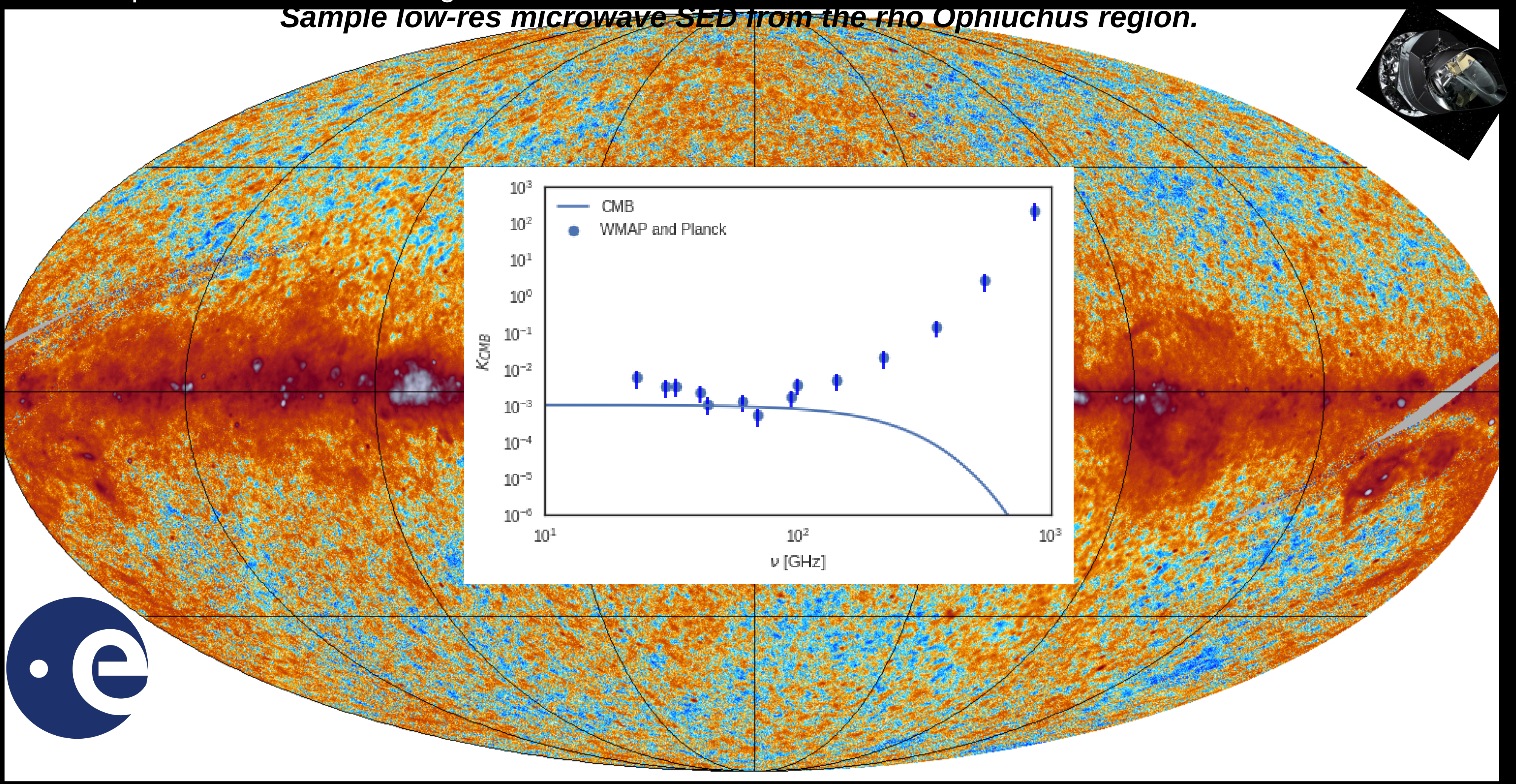

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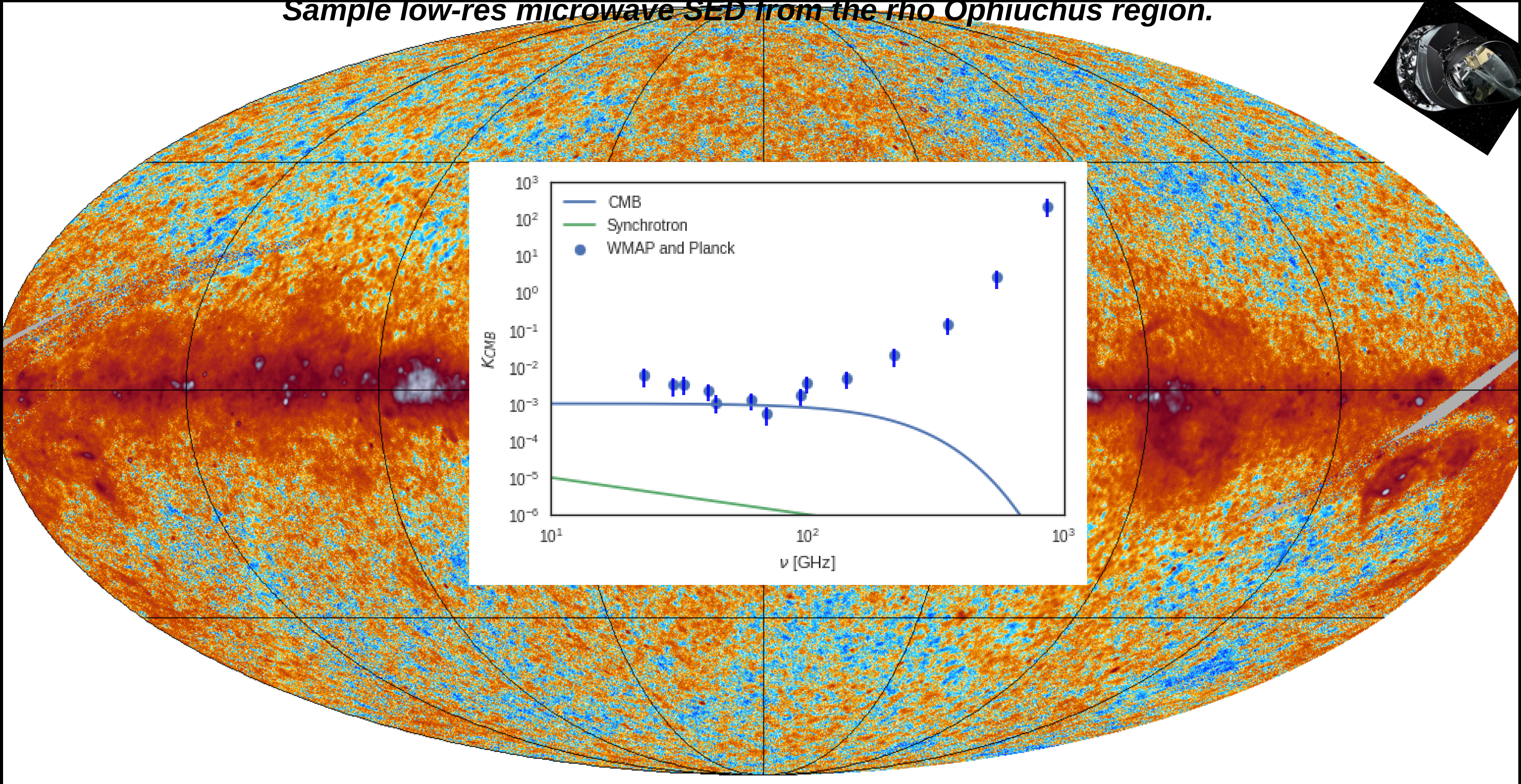

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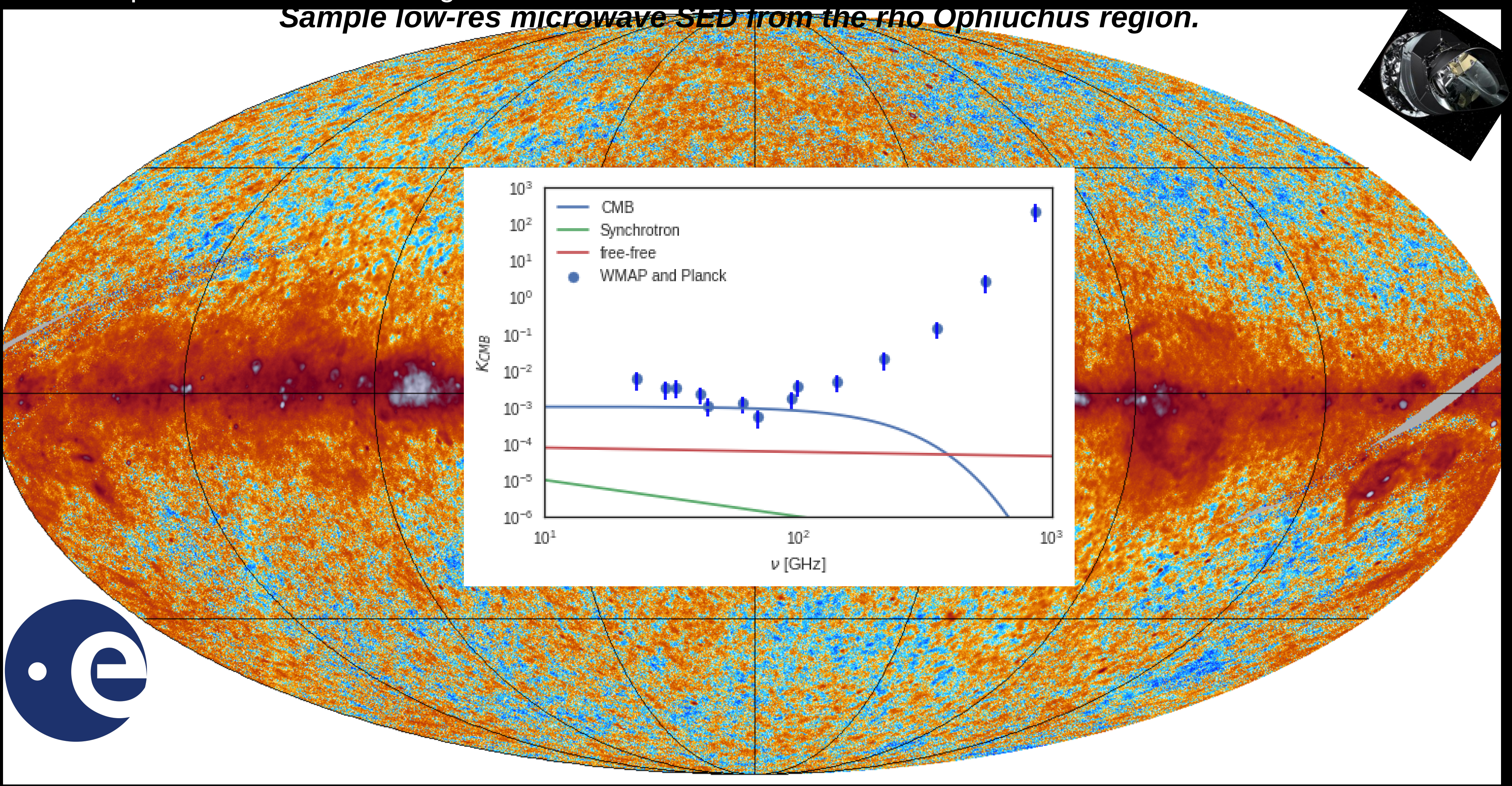

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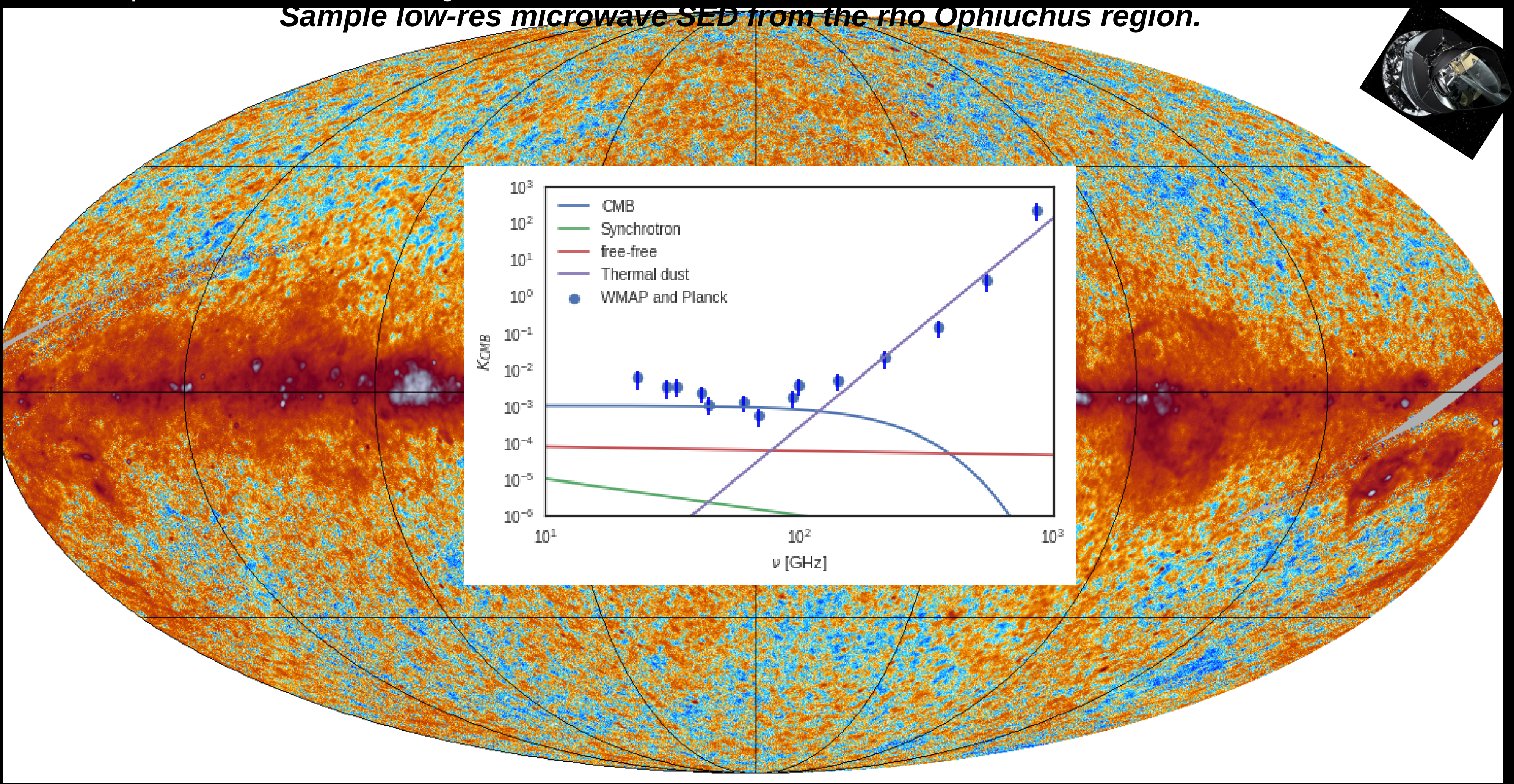

Planck LFI 28 GHz All-sky Map: ESA/Planck Collaboration