GHENT UNIVERSITY

FACULTY OF SCIENCES

Our Galactic Ecosystem: Opportunities and Diagnostics in the Infrared and Beyond
Feb 28th – Mar 4th 2022

DUST PROPERTIES IN THE CRAB NEBULA

Using HAWC+ Polarisation

Jérémy Chastenet, Ilse De Looze, Brandon Hensley, Bert Vandenbroucke, Mike Barlow, Jeonghee Rho, Aravind P. Ravi, Haley L. Gomez, Anthony P. Jones, Florian Kirchschlager, Juan Macìas-Pérez, Mikako Matsuura, Kate Pattle, Nicolas Ponthieu, Felix D. Priestley, Monica Relaño, Alessia Ritacco, Roger Wesson

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A WORK IN PROGRESS

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DUST & SUPERNOVA REMNANTS

- Dust at low redshift
  - formed in the atmospheres of AGB stars; in the ejecta of SNe and SNRs; other kind of inflows and circulation
  - but! destroyed by strong winds of the very same SNRs that formed it; hot gas, cosmic rays, all kinds of collisions

→ grain growth must happen (but is hard to constrain)

→ overestimated destruction rates from SN shocks?

- Also! dust at high redshift → (significant?) production from SNRs

➔ Really need to know how much SNRs produce and destroy

DUST MASSES IN SNRS (A VERY NON-EXHAUSTIVE LIST)

- Cassiopeia A: 0.02 – 1.1 $M_\odot$ (Rho et al. 2008, Arendt et al. 2014, Barlow et al. 2010, Bevan et al. 2017, De Looze et al. 2017, Niculescu-Duvaz et al. 2021)
- G54.1+0.3: 0.06 – 1.1 $M_\odot$ (Temim et al. 2010, Temim et al. 2017, Rho et al. 2018)
  up to 3.38 in Priestley et al. (2020)
- SN1987A: 0.5 – 0.7 $M_\odot$ (Matsuura et al. 2011)
- G11.2–0.3: 0.34 – 1.86 $M_\odot$ (Chawner et al. 2020, Priestley et al. 2020)
- G21.5 – 0.9: 0.032 – 0.29 $M_\odot$ (Chawner et al. 2020, Priestley et al. 2020)
- G29.7–0.3: 0.018 – 0.51 $M_\odot$ (Chawner et al. 2020, Priestley et al. 2020)

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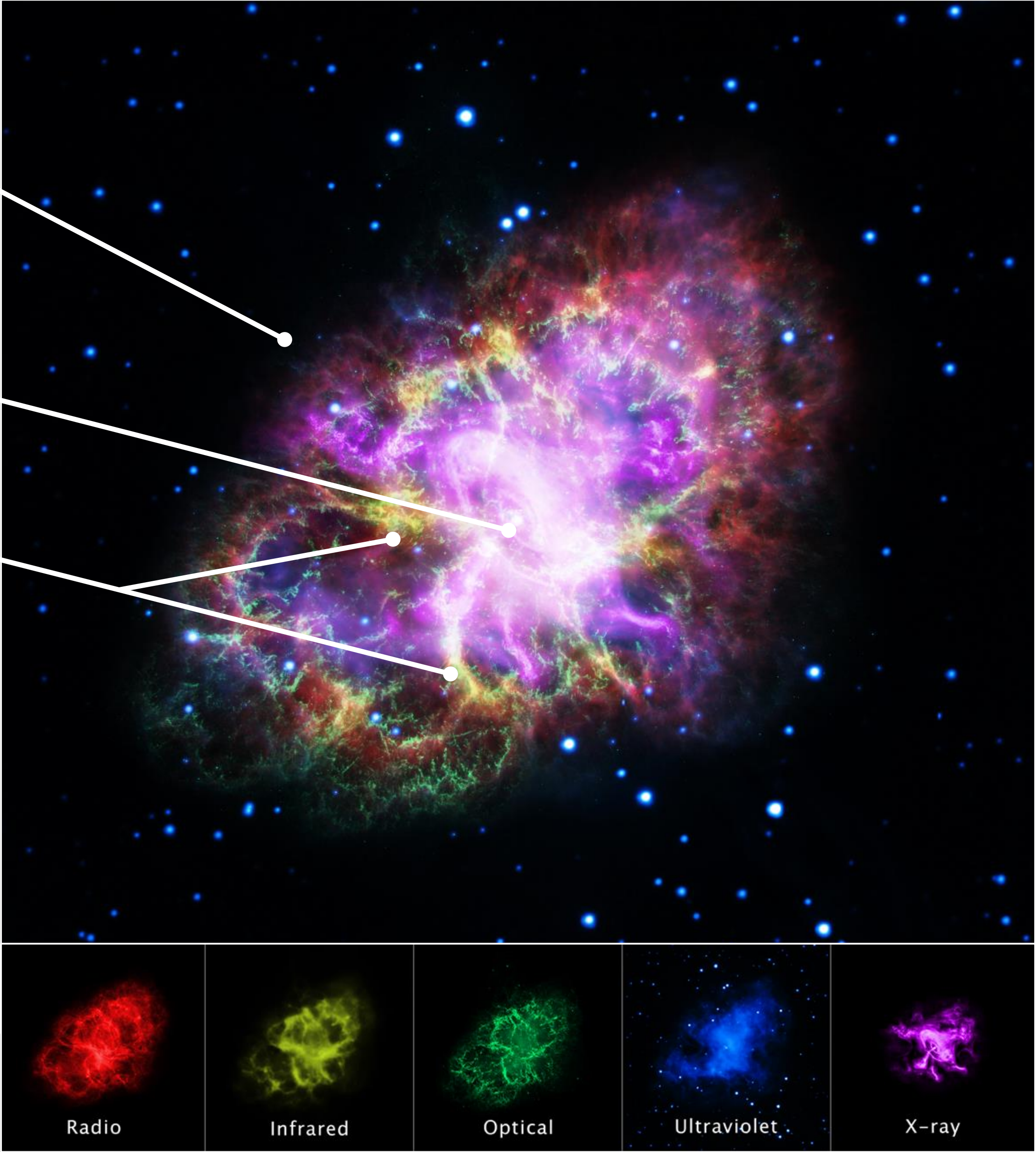
In the Crab:

Gomez et al. (2012):	0.24 $M_\odot$ of 28 K carbon grains 0.11 $M_\odot$ of 34 K silicate grains 0.14 + 0.08 $M_\odot$ of both	near-IR – radio fitting
Temim & Dwek (2013):	0.019 $M_\odot$ of ~56 K carbon grains	
Owen & Barlow (2015):	0.18 – 0.27 $M_\odot$ of carbon grains 0.11 – 0.13 + 0.39 – 0.47 $M_\odot$ of both	radiative transfer
De Looze et al. (2019):	0.032 – 0.049 $M_\odot$ of 41 K carbon grains similar masses for $MgSiO_3$ implausible masses for e.g. Fe or $Mg_{0.7}SiO_{2.7}$	
Priestley et al. (2020):	0.05 $M_\odot$ (0.026 – 0.076) of carbon grains 0.076 – 0.218 $M_\odot$ of $MgSiO_3$	mid- – far-IR fitting

THE CRAB NEBULA



Exploded in 1054 AD*
2 kpc distance
Type II-P
8 – 11 $M_\odot$ progenitor

Pulsar Wind Nebula

85 – 90% He and lots of C, O, Ne, S, Ar

© NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.;A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC;Spitzer/JPL-Caltech; XMM-Newton/ESA; Hubble/STScI

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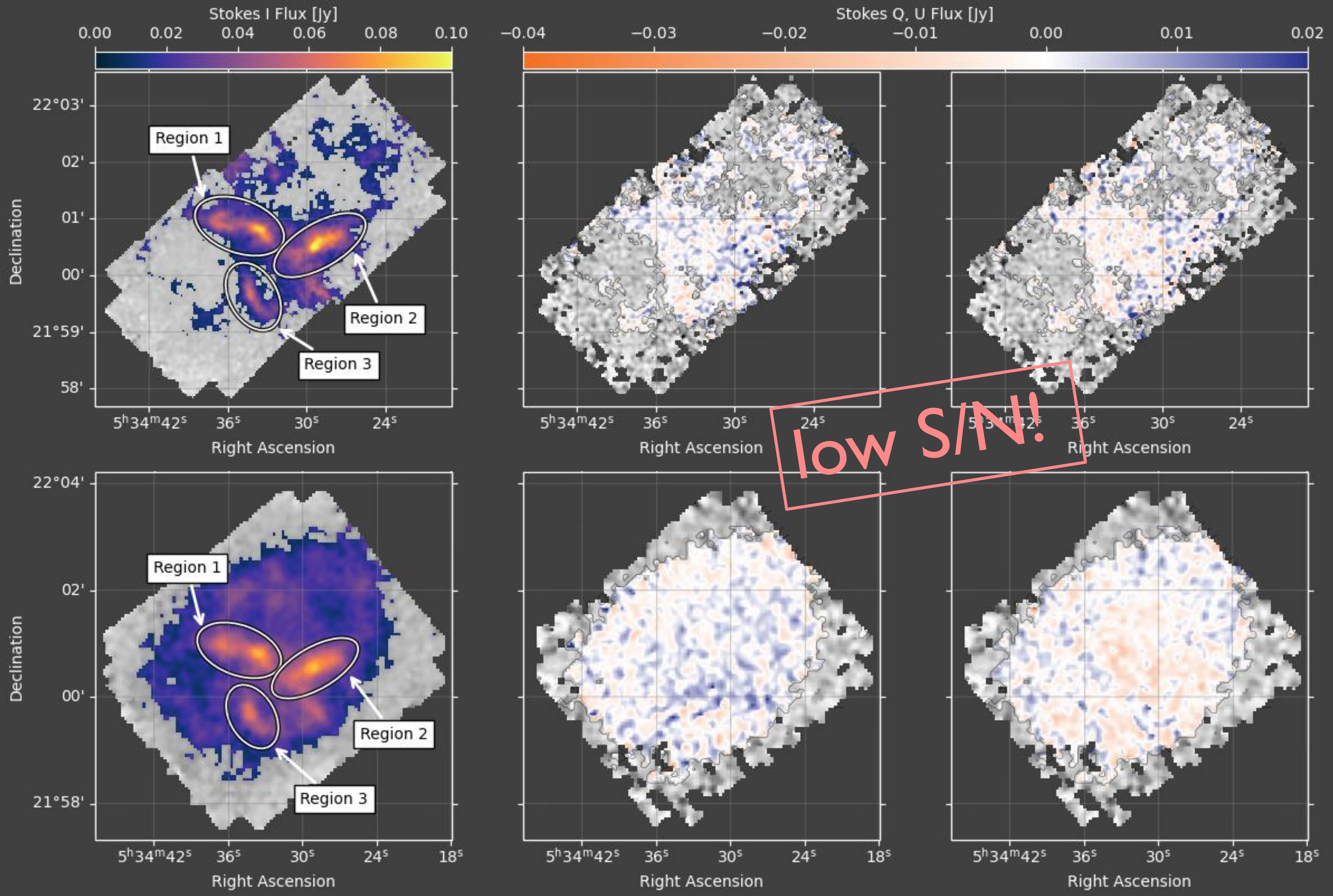
*Also happened that year: William the Conqueror beat the French, Siward invades Scotland against Macbeth, Ghana looses its control of trade routes, Lý Nhật Tôn renames his country Đại Việt, Terry Pratchett arrived on Earth, and someone lost a tooth.

THE POLARISED CRAB NEBULA WITH SOFIA



low S/N!

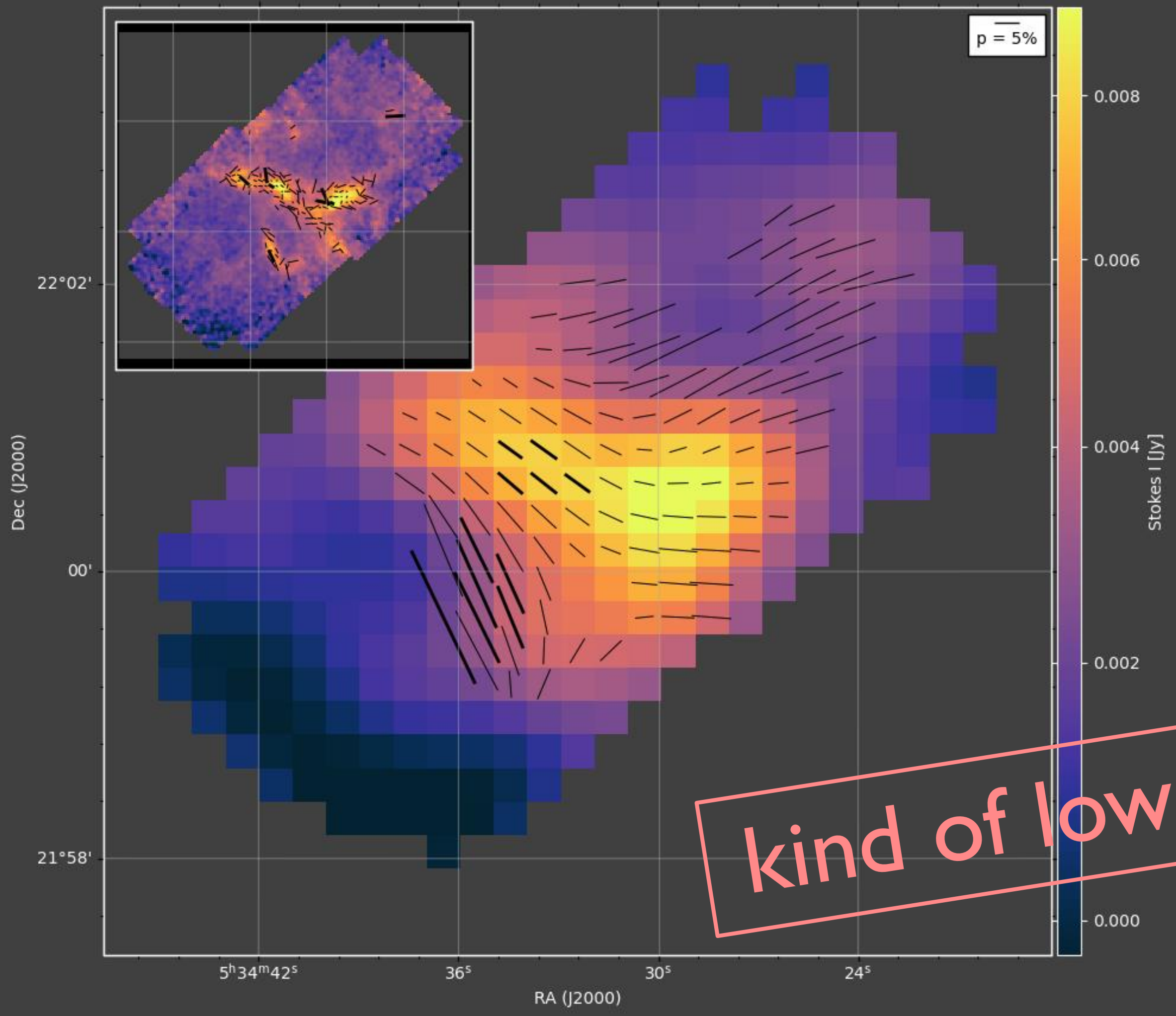
HAWC+ C
89 µm

HAWC+ D
154 µm

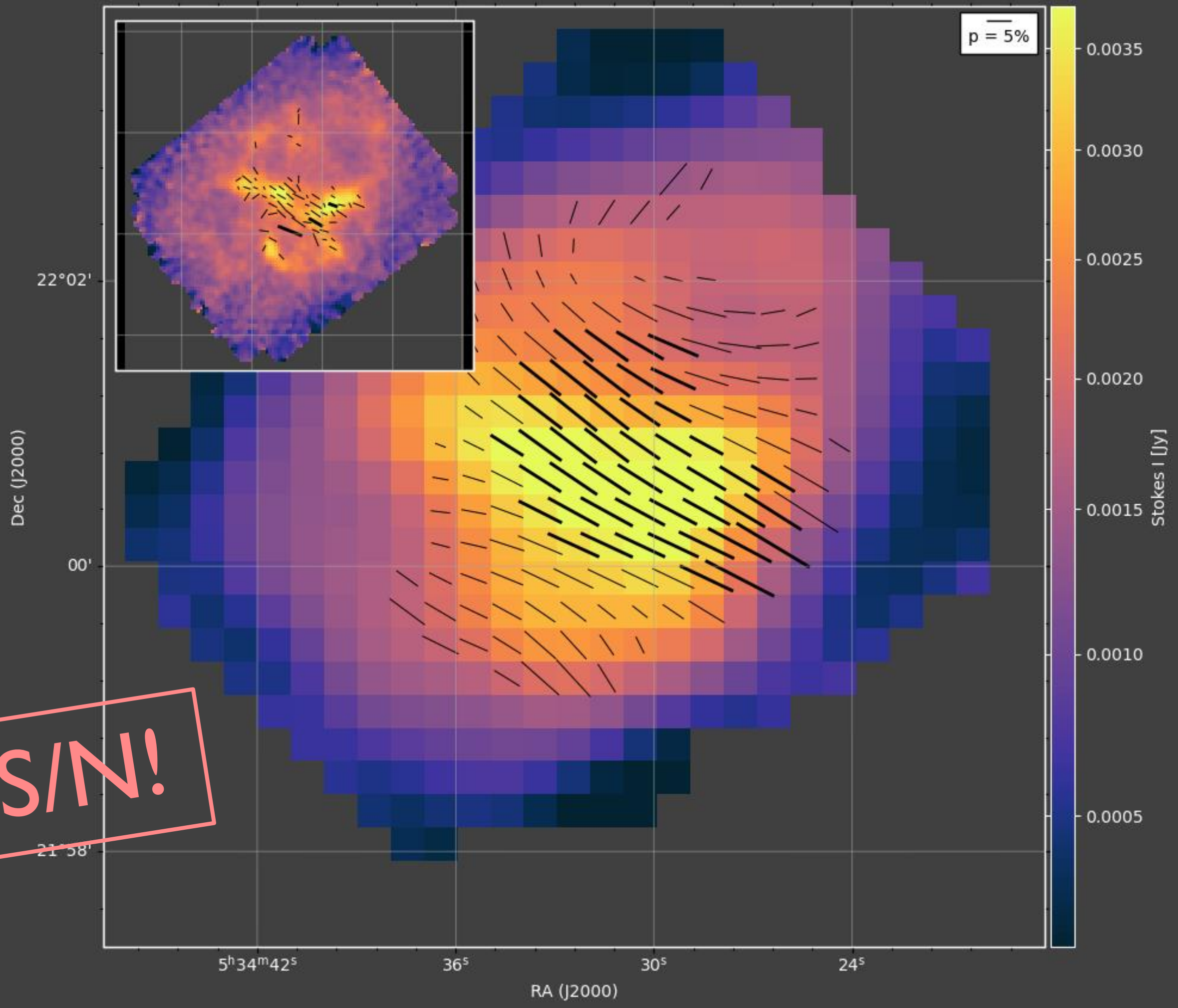
Jérémy Chastenet

POLARISATION*

HAWC+ C 89 µm



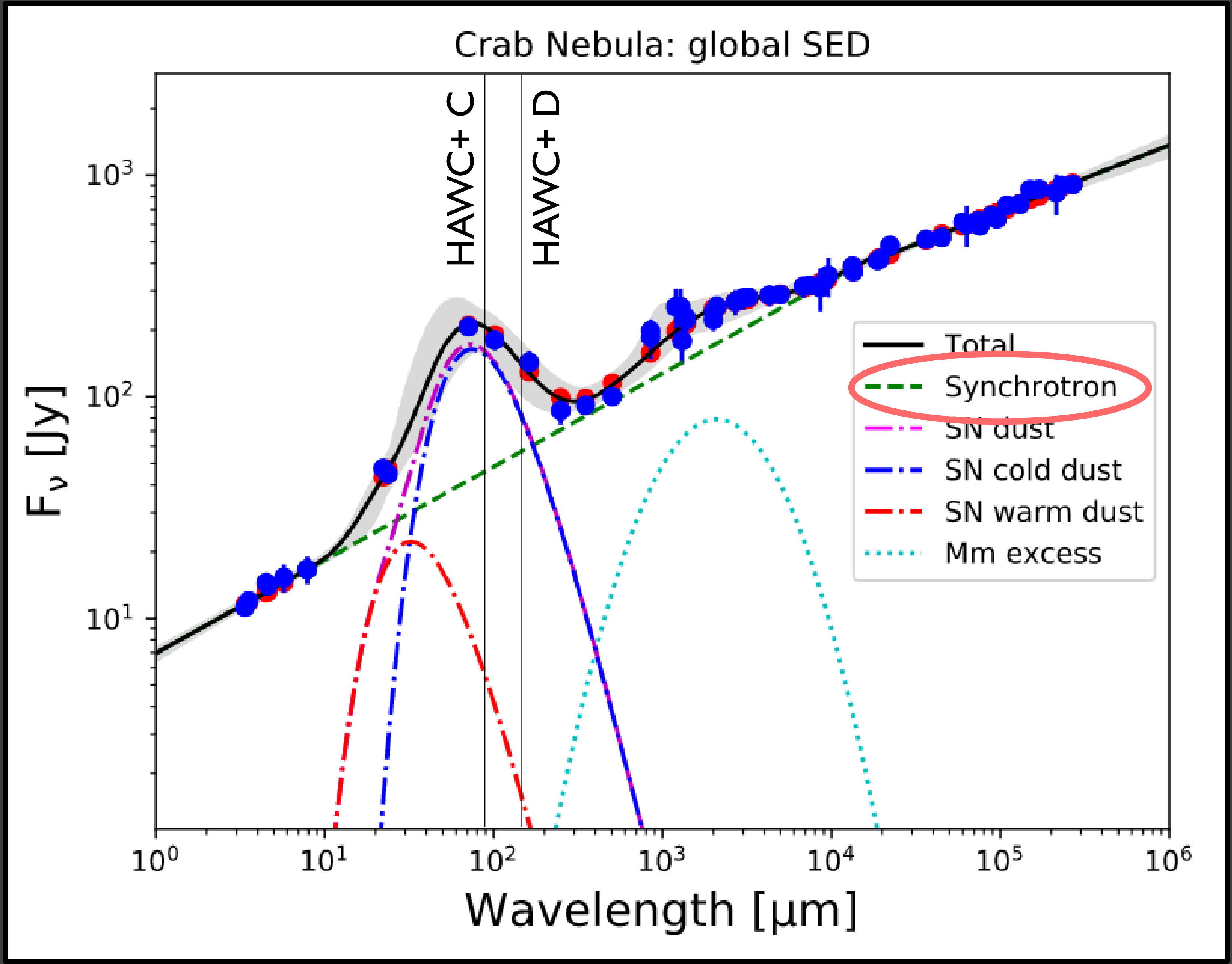
HAWC+ D 154 µm



kind of low S/N!

*using the Modified Asymptotic estimator from Plaszczynski et al. (2014)

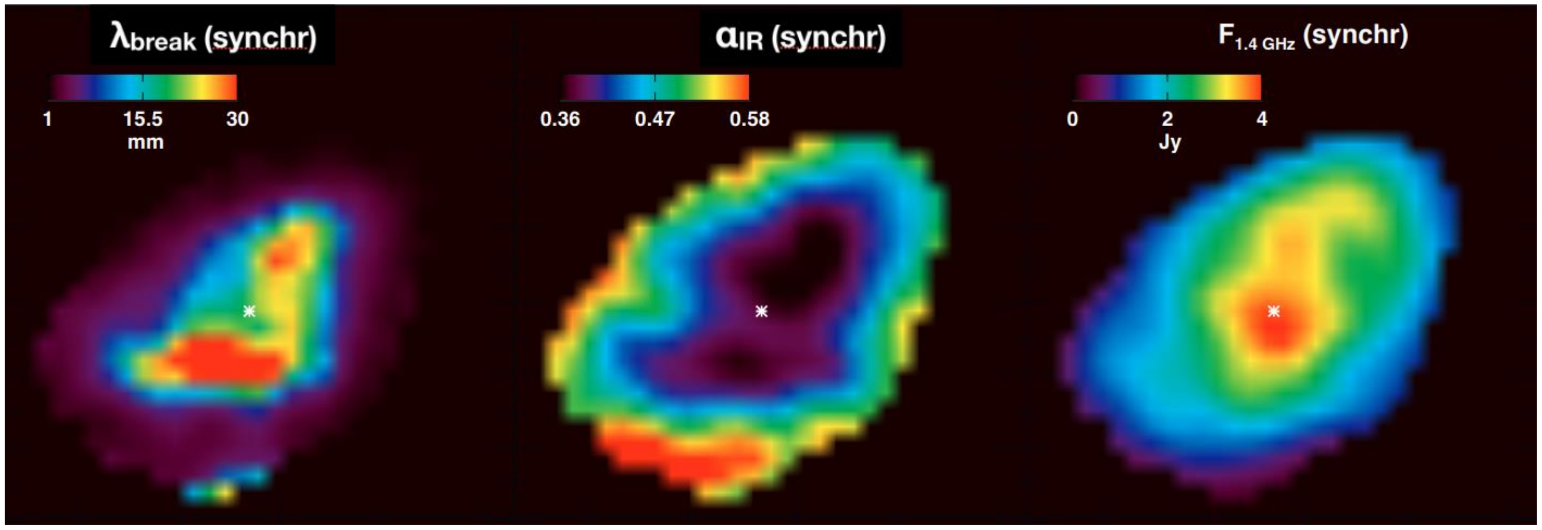
POLARISATION, BUT!



De Looze et al. (2019)

SYNCHROTRON RADIATION REMOVAL

$$F_\nu = \begin{cases} F_{\nu_0}\left(\dfrac{\nu}{\nu_0}\right)^{-\alpha_{\mathrm{radio}}} & \text{if } \lambda \geq \lambda_{\mathrm{break}} \\ F_{\nu_0}\left(\dfrac{\nu}{\nu_0}\right)^{-\alpha_{\mathrm{IR}}} \times \left(\dfrac{\nu_{\mathrm{break}}}{\nu_0}\right)^{-\alpha_{\mathrm{radio}}} \left(\dfrac{\nu_{\mathrm{break}}}{\nu_0}\right)^{\alpha_{\mathrm{IR}}} & \text{if } \lambda < \lambda_{\mathrm{break}} \end{cases}$$

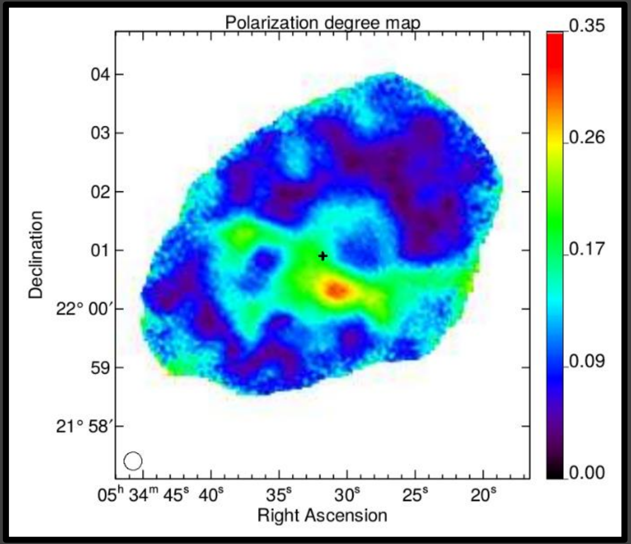


De Looze et al. (2019)

$p_{\mathrm{radio}}, \theta_{\mathrm{radio}}$

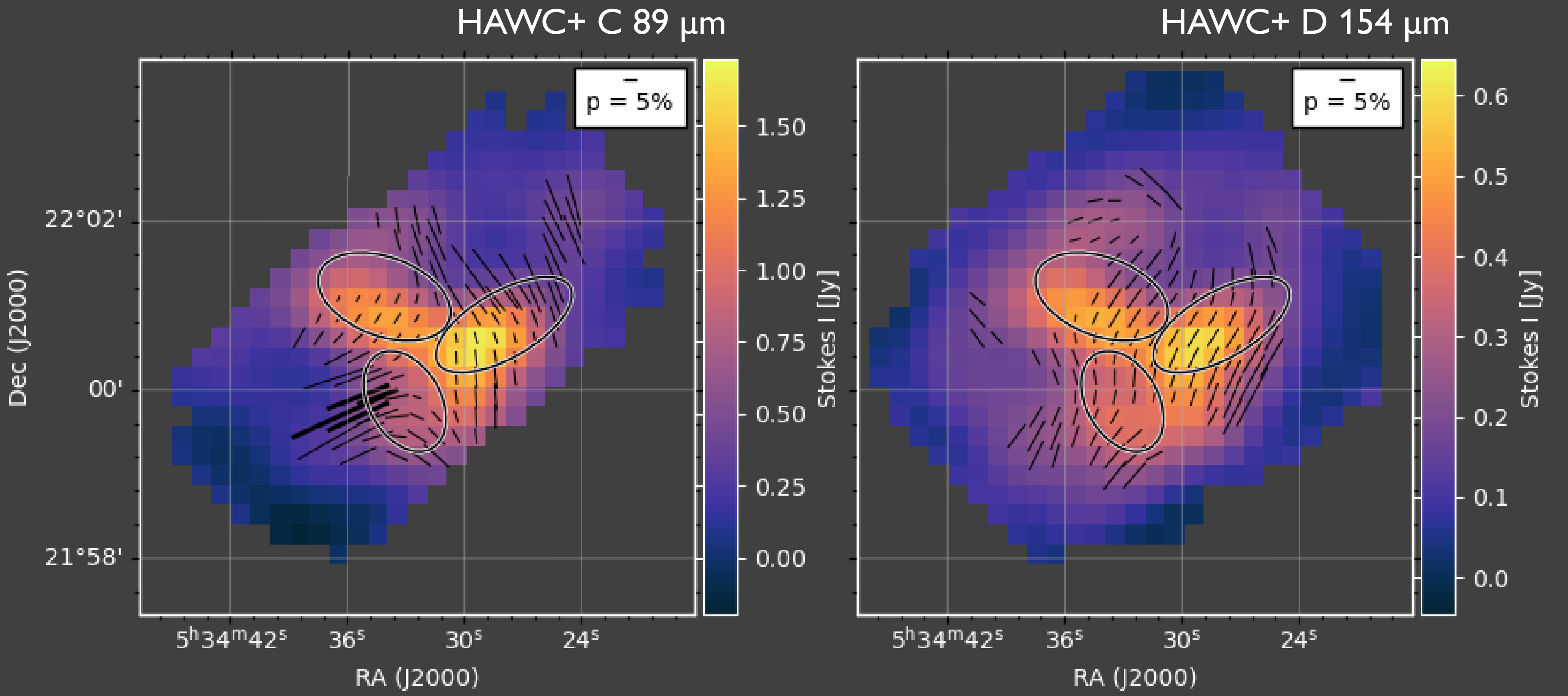
↑

NIKA 150 GHz



Ritacco et al. (2018)

SYNCHROTRON-FREE MAPS



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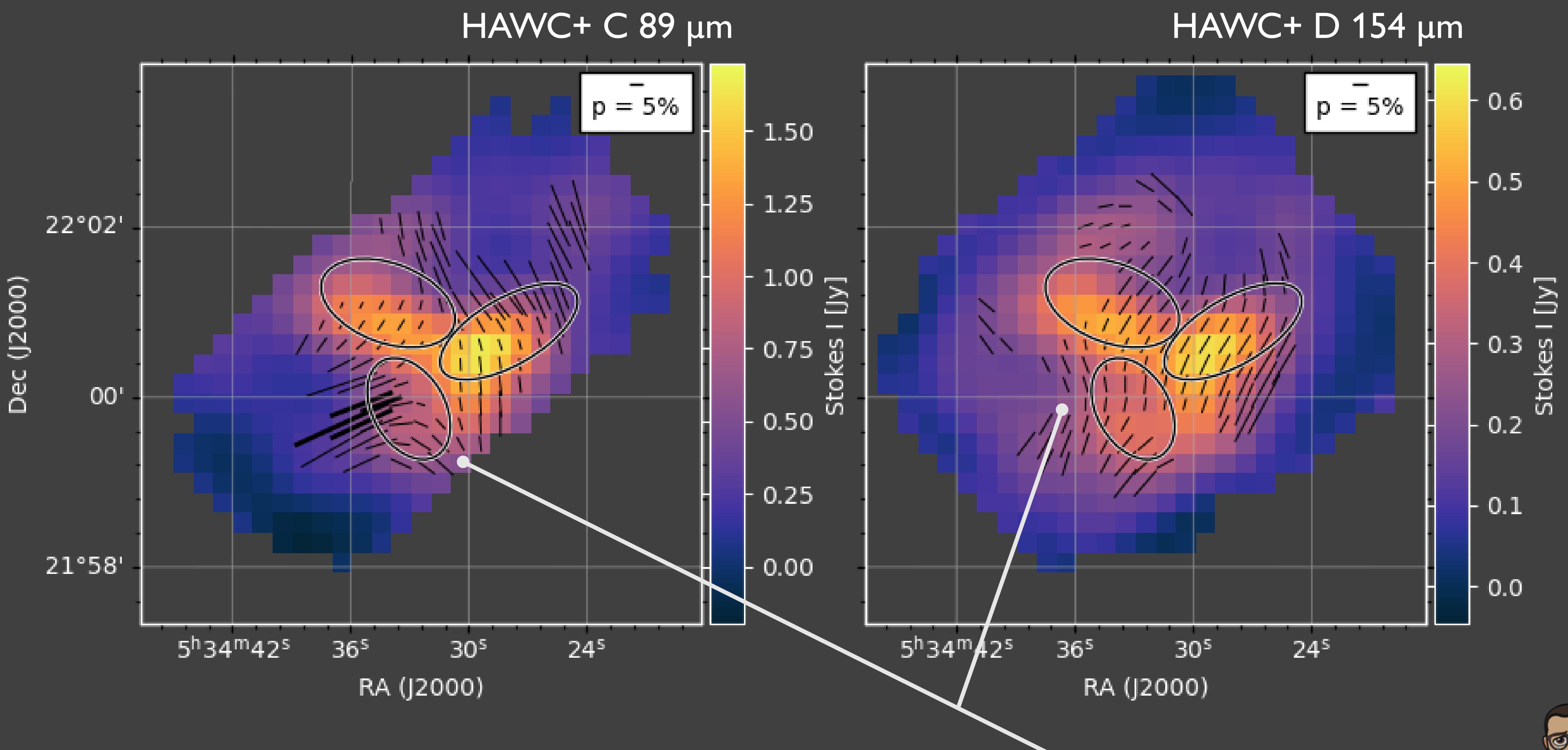
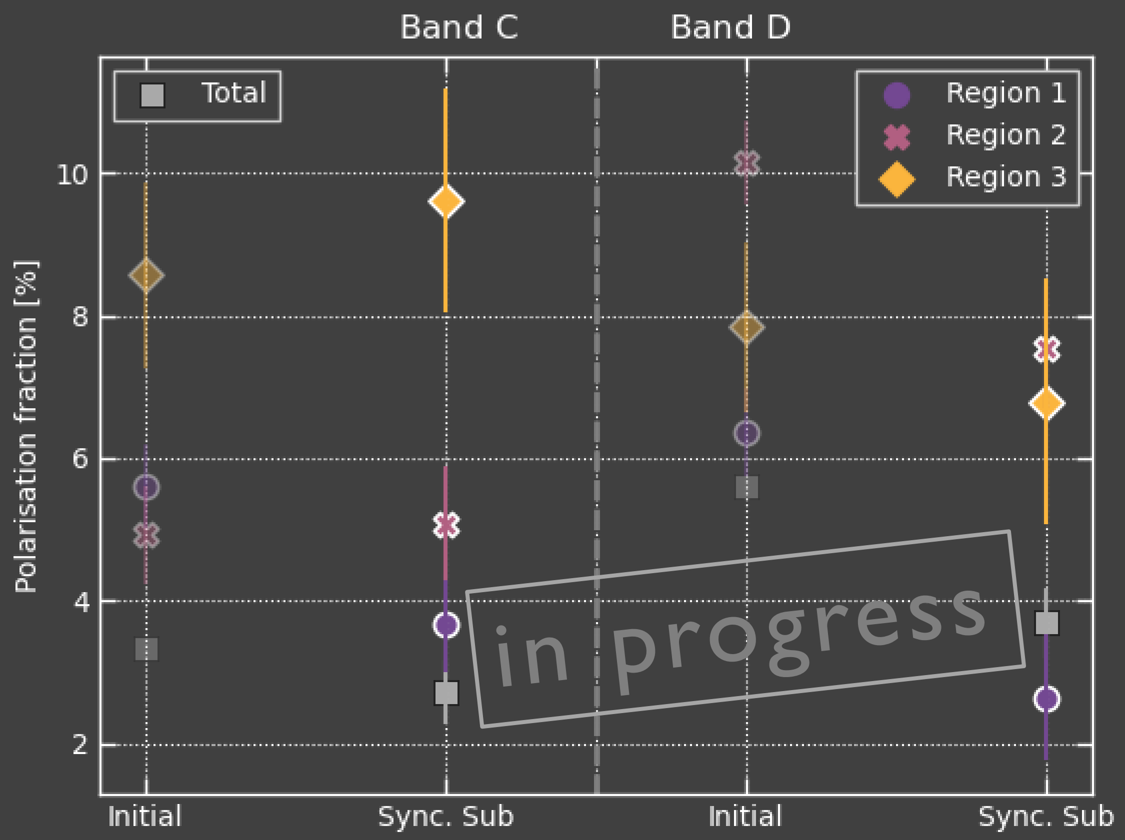
SYNCHROTRON-FREE MAPS


HAWC+ C 89 µm

HAWC+ D 154 µm

few to no $S/N_p > 3$ vectors
→ sum fluxes within regions

SYNCHROTRON-FREE POLARISATION



	HAWC+ C 89 µm	HAWC+ D 154 µm
Total	2.7 ± 0.4	3.7 ± 0.5
Reg 1	3.7 ± 0.7	2.7 ± 0.9
Reg 2	5.1 ± 0.8	7.6 ± 0.9
Reg 3	9.6 ± 1.6	6.8 ± 1.7

After synchrotron subtraction:

- *p* decreases in all regions at 154 µm
- *p* decreases only in region 1 at 89 µm (-ish)

Between bands:

- regions 1 and 3 have lower *p* at 154 µm
- region 2 has higher *p* at 154 µm

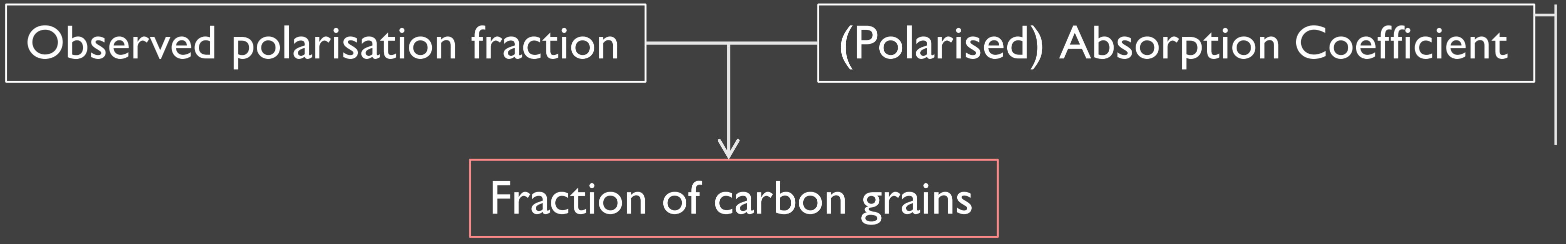
HOW TO CONSTRAIN DUST PROPERTIES?

Observed polarisation fraction

(Polarised) Absorption Coefficient

- CosTuuM (Vandenbroucke et al. 2020)
- Grain size
- Composition (JENA, OCCD)

HOW TO CONSTRAIN DUST PROPERTIES?



Observed polarisation fraction

(Polarised) Absorption Coefficient

Fraction of carbon grains

- CosTuuM (Vandenbroucke et al. 2020)
- Grain size
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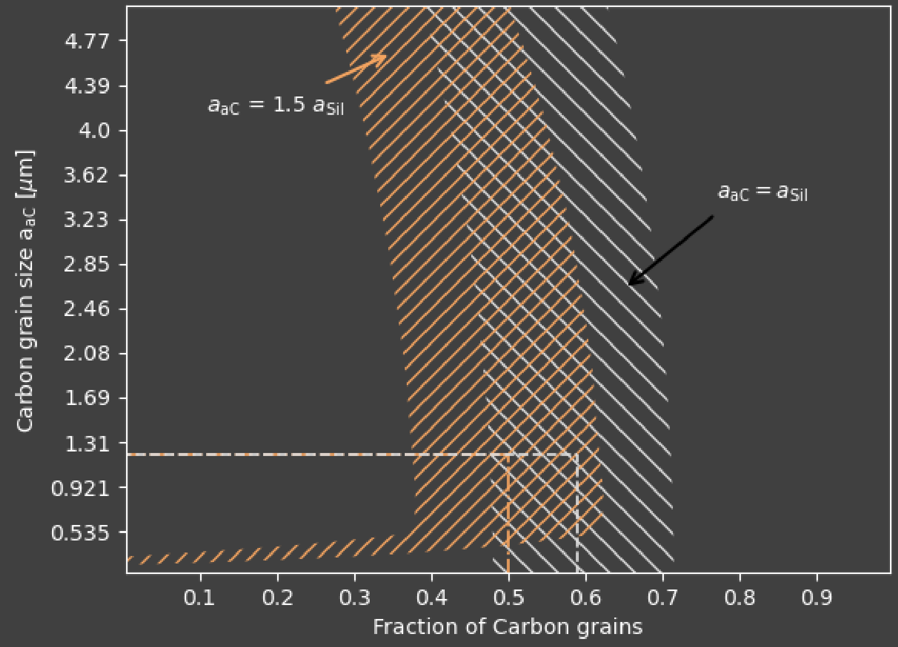
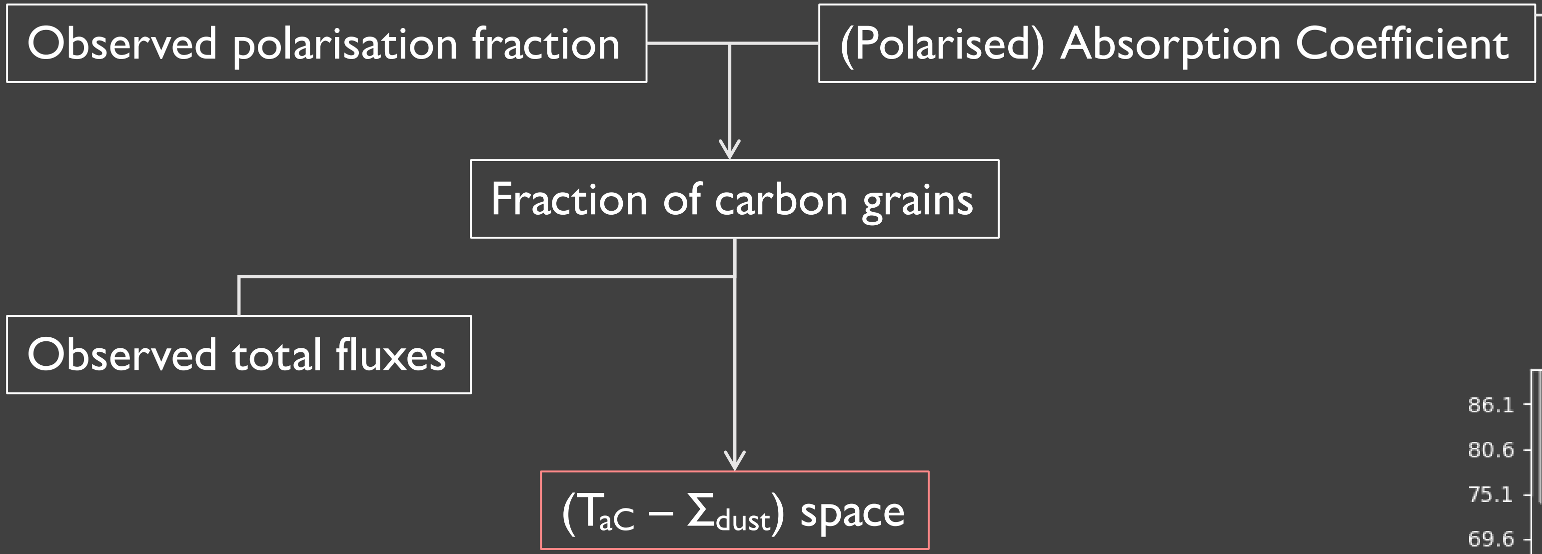


$$p = \frac{(1 - f_{aC})\ Q_{abs,\,pol,\,Sil}(\lambda, a)}{f_{aC}\ Q_{abs,\,aC}(\lambda, a) + (1 - f_{aC})\ Q_{abs,\,Sil}(\lambda, a)}$$

HOW TO CONSTRAIN DUST PROPERTIES?



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(Polarised) Absorption Coefficient

Fraction of carbon grains

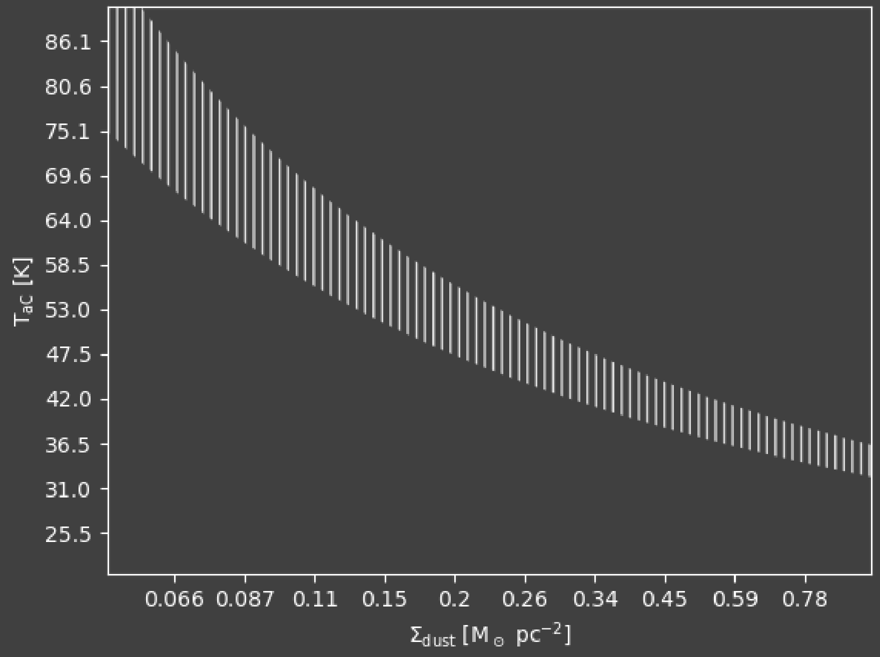
Observed total fluxes

(T_{aC} – Σ_{dust}) space

- CosTuuM (Vandenbroucke et al. 2020)
- Grain size
- Composition (JENA, OCCD)

$$S_{\nu,\mathrm{tot}} = f_{\mathrm{aC}}\, S_{\nu,\,\mathrm{aC}} + (1 - f_{\mathrm{aC}}) S_{\nu,\,\mathrm{Sil}}$$

$$S_{\nu} = \kappa(\lambda, a)\, \Sigma_{\mathrm{dust}}\, B(\lambda, T_{\mathrm{dust}})$$



Jérémy Chastenet

HOW TO CONSTRAIN DUST PROPERTIES?

Observed polarisation fraction

(Polarised) Absorption Coefficient

- CosTuuM (Vandenbroucke et al. 2020)
- Grain size
- Composition (JENA, OCCD)

Fraction of carbon grains

Observed total fluxes

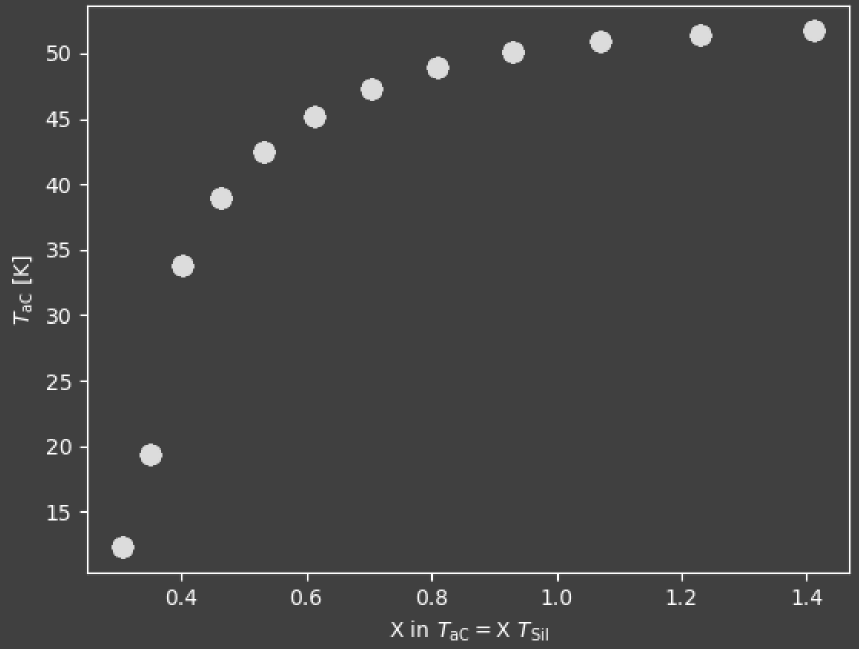
Ratio of total fluxes

T_{aC} upper-limit

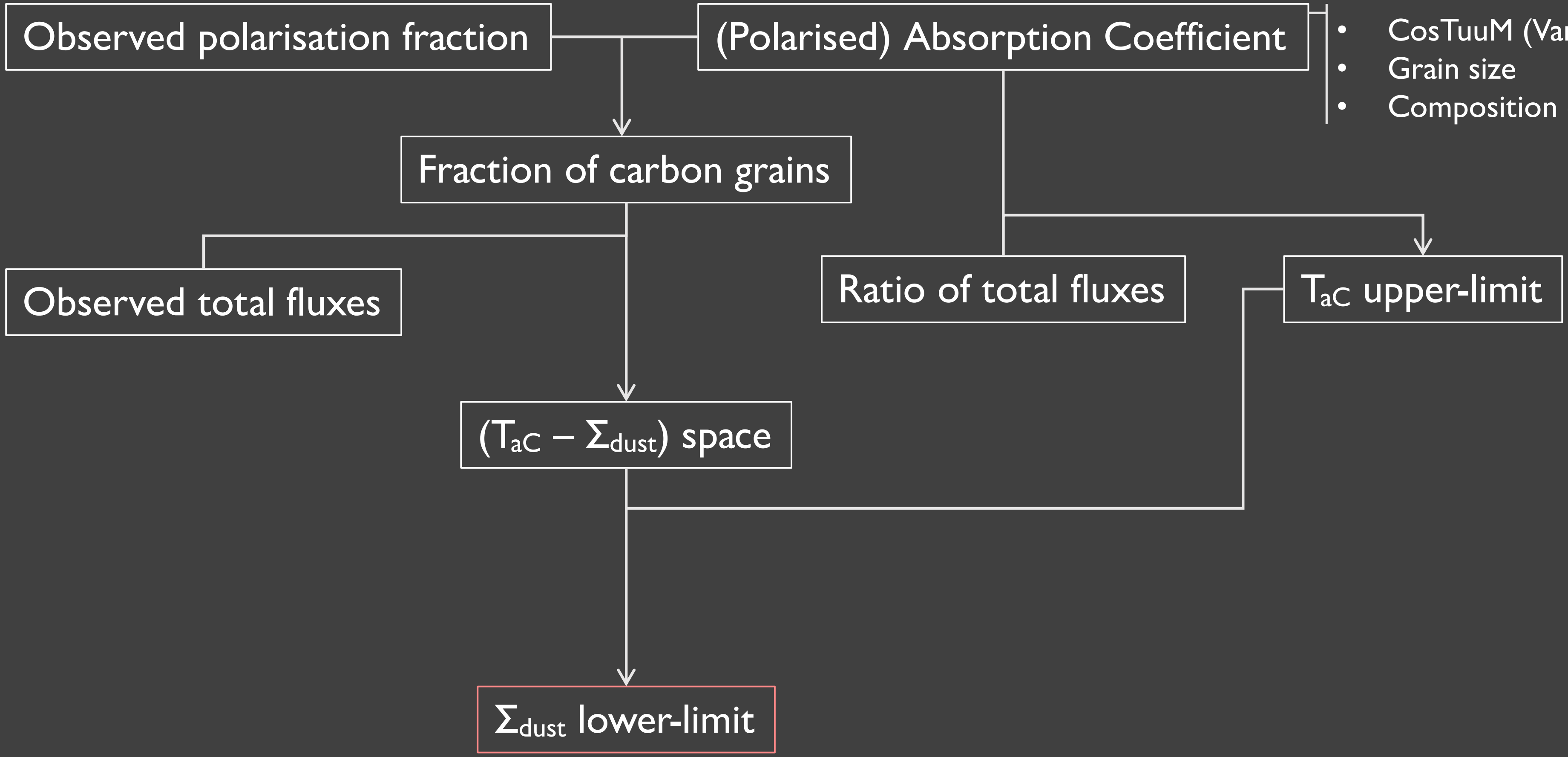
(T_{aC} – Σ_{dust}) space

$$\frac{S_{\mathrm{tot},\,\lambda_1}}{S_{\mathrm{tot},\,\lambda_2}} = \frac{f_{\mathrm{aC}}\,\kappa_{\mathrm{aC},\,\lambda_1}\,B_{\lambda_1}(T_{\mathrm{aC}}) + (1 - f_{\mathrm{aC}})\kappa_{\mathrm{Sil},\,\lambda_1} B_{\lambda_1}(T_{\mathrm{aC}}/X)}{f_{\mathrm{aC}}\,\kappa_{\mathrm{aC},\,\lambda_2}\,B_{\lambda_2}(T_{\mathrm{aC}}) + (1 - f_{\mathrm{aC}})\kappa_{\mathrm{Sil},\,\lambda_2} B_{\lambda_2}(T_{\mathrm{aC}}/X)}$$

from Hankins et al. (2019)

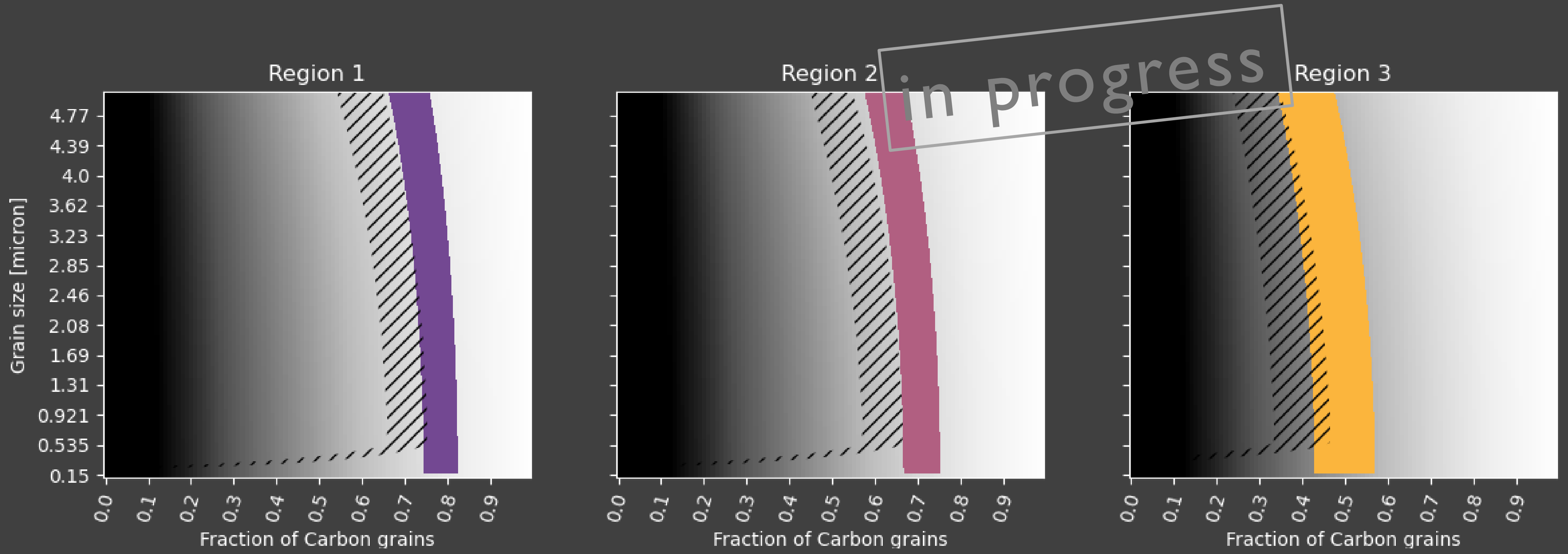


How to Constrain Dust Properties?



- CosTuuM (Vandenbroucke et al. 2020)
- Grain size
- Composition (JENA, OCCD)

Example: aC:H & MgSiO$_3$

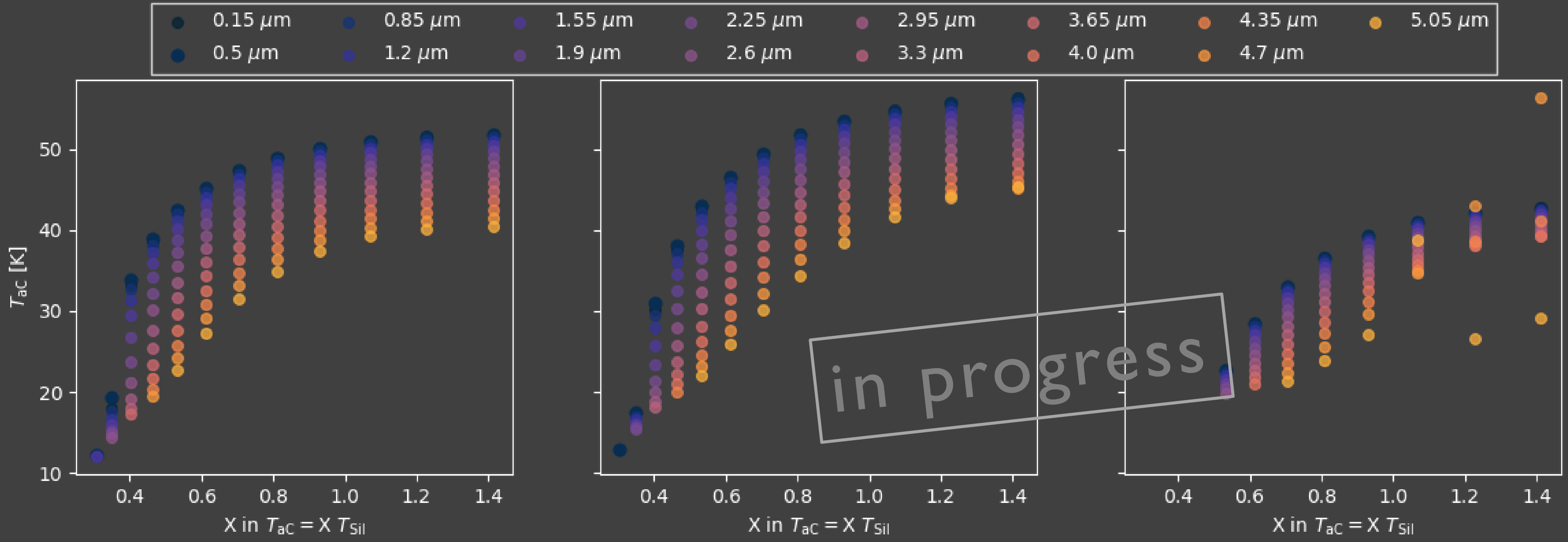


$$p = \frac{(1 - f_{aC})\, Q_{\text{abs, pol, Sil}}(\lambda, a)}{f_{\text{aC}}\, Q_{\text{abs, aC}}(\lambda, a) + (1 - f_{\text{aC}})\, Q_{\text{abs, Sil}}(\lambda, a)}$$

Refractive indices (n, k) and density

- MgSiO$_3$: Jäger et al. (2003)
- aC:H: optECs Eg = 0.1 eV (Jones et al. 2012)

Example: aC:H & MgSiO$_3$



→ derive $T_{aC,\ max}$ in each region

$$\frac{S_{\mathrm{tot},\,\lambda_1}}{S_{\mathrm{tot},\,\lambda_2}} = \frac{f_{\mathrm{aC}}\,\kappa_{\mathrm{aC},\,\lambda_1}\,B_{\lambda_1}(T_{\mathrm{aC}}) + (1-f_{\mathrm{aC}})\kappa_{\mathrm{Sil},\,\lambda_1}B_{\lambda_1}(T_{\mathrm{aC}}/X)}{f_{\mathrm{aC}}\,\kappa_{\mathrm{aC},\,\lambda_2}\,B_{\lambda_2}(T_{\mathrm{aC}}) + (1-f_{\mathrm{aC}})\kappa_{\mathrm{Sil},\,\lambda_2}B_{\lambda_2}(T_{\mathrm{aC}}/X)}$$

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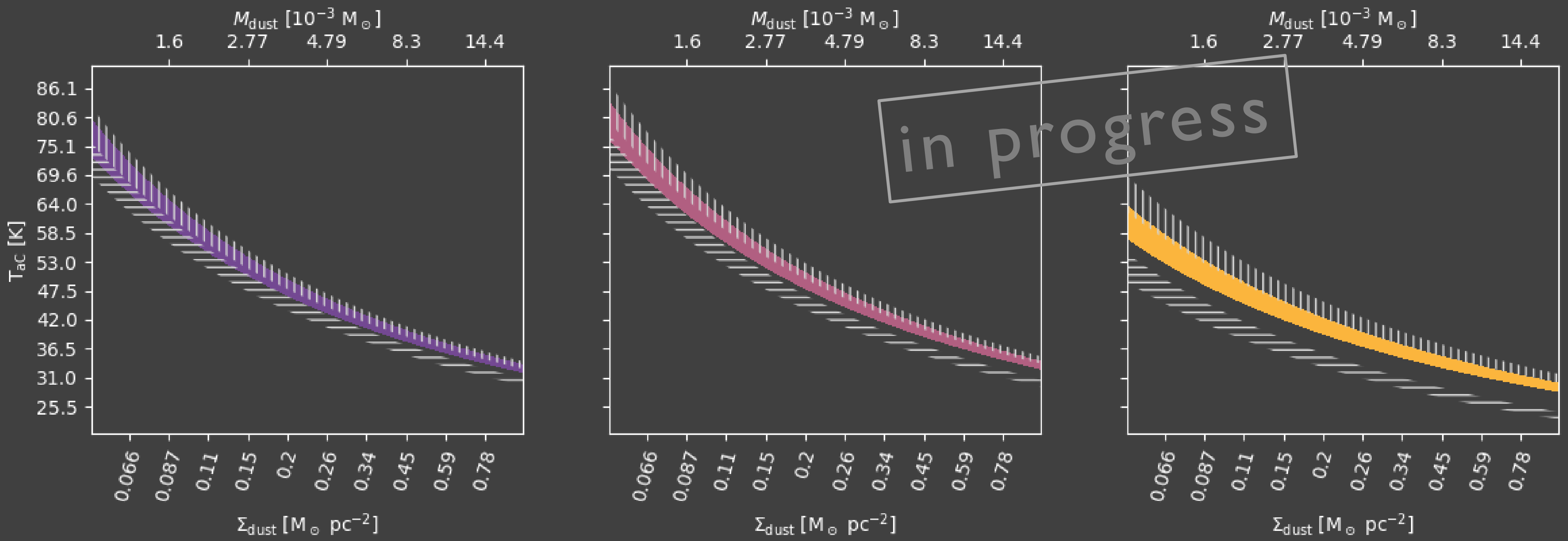

$$M_{\rm dust} \gtrsim 2.65^{0.27}_{0.24} \times 10^{-3} M_\odot$$

$$M_{\rm dust} \gtrsim 2.31^{0.23}_{0.21} \times 10^{-3}\, M_\odot$$

$$M_{\rm dust} \gtrsim 2.84^{0.41}_{0.37} \times 10^{-3}\, M_\odot$$

SO MANY VARIATIONS

- Composition:
  - $Mg_{0.5}Fe_{0.5}SiO_3$ → f_{aC} increases
  - $MgFeSiO_4$ → f_{aC} increases
  - $Mg_{0.7}SiO_{2.7}$ → f_{aC} decreases

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  - Include size distribution and non-polarising grains

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- Shape distributions:
  - Oblate grains → increases f_{aC}
  - Prolate grains → decreases f_{aC}
- Alignment angle:
  - f_{aC} increases with the alignment angle

CONCLUSIONS

- Confirmed polarisation detection in the Crab Nebula, the second SNR after Cassiopeia A!
  → implies the existence of large grains ($a > 0.05 – 0.1$ µm)
  → synchrotron-free polarisation fractions range from 3.7 to 9.1% at 89 µm and from 2.7 to 7.6% at 154 µm, in three dusty regions.
- We constrain and compute the fraction of carbon grains using the observed polarisation and computing the (polarised) absorption coefficients for a range of grain sizes (and composition).
- Combining polarisation fraction, total fluxes and making (a lot of) assumptions, we can derive lower-limits for the total dust masses in these regions
  → assuming optECs properties for aC grains and MgSiO3 for Sil grains, with similar effective radii of 0.5 µm, we find ~ $2.3 – 3.1 \times 10^{-3}$ $M_\odot$.

Work supported by the ERC starting grant #851622

Alan Pham

EXTRA – THE MODIFIED ASYMPTOTIC ESTIMATOR

- Normalized Stokes vectors:

$$q = Q/I \quad u = U/I$$

- Biased polarisation and polarisation angle:

$$p = \sqrt{q^2 + u^2} \quad \theta_p = 0.5 \arctan(u/q)$$

- Debiased polarisation and error:

$$\boxed{p_{MAS} = p - b^2 \frac{1 - e^{-p^2/b^2}}{2p}}$$

$$b^2 = \sigma_u^2 \cos^2(\theta_p) + \sigma_q^2 \sin^2(\theta_p)$$

$$\boxed{\sigma_p^2 = \sigma_q^2 \cos^2(\theta_p) + \sigma_u^2 \sin^2(\theta_p)}$$

EXTRA – SYNCHROTRON REMOVAL

- Interpolation of the (resolved) synchrotron radiation at 89 and 154 µm

- Synchrotron polarisation fraction and angle from NIKA 150 GHz

  $p_{\mathrm{radio}}, \theta_{\mathrm{radio}}$

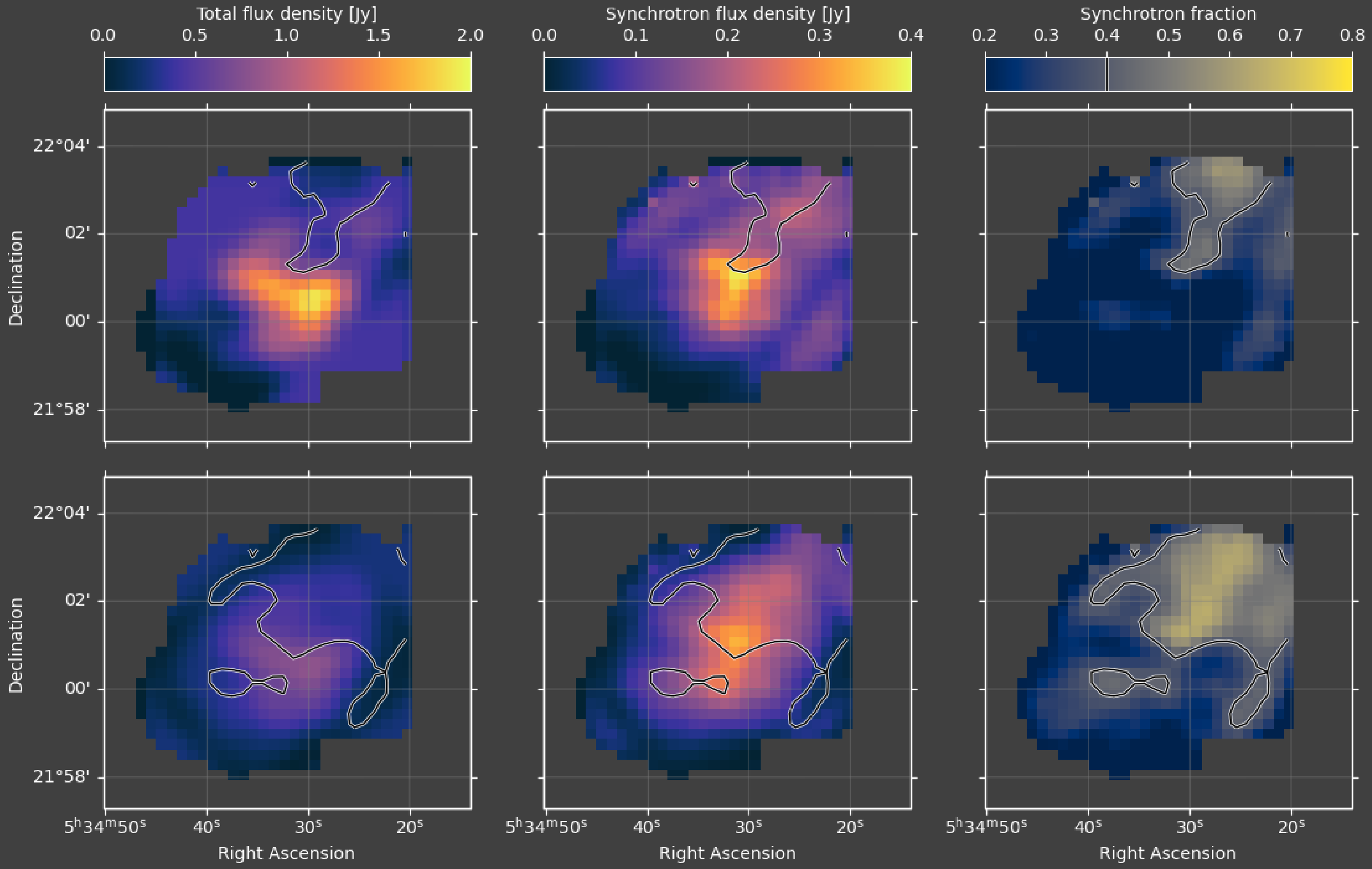
- Synchrotron Stokes vectors:

$$P_{\mathrm{sync}} = p_{\mathrm{radio}}\, I_{\mathrm{sync}}$$
$$Q_{\mathrm{sync}} = P_{\mathrm{sync}} \cos(2\,\theta_{\mathrm{radio}})$$
$$U_{\mathrm{sync}} = P_{\mathrm{sync}} \sin(2\,\theta_{\mathrm{radio}})$$

- Synchrotron-free Stokes vectors:

$$I_{\mathrm{final}} = I_{\mathrm{HAWC}} - I_{\mathrm{sync}}$$
$$Q_{\mathrm{final}} = Q_{\mathrm{HAWC}} - Q_{\mathrm{sync}}$$
$$U_{\mathrm{final}} = U_{\mathrm{HAWC}} - U_{\mathrm{sync}}$$

EXTRA – SYNCHROTRON MAPS



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