Dark matter and diffuse radio emission in spiral galaxies

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Masters dissertation

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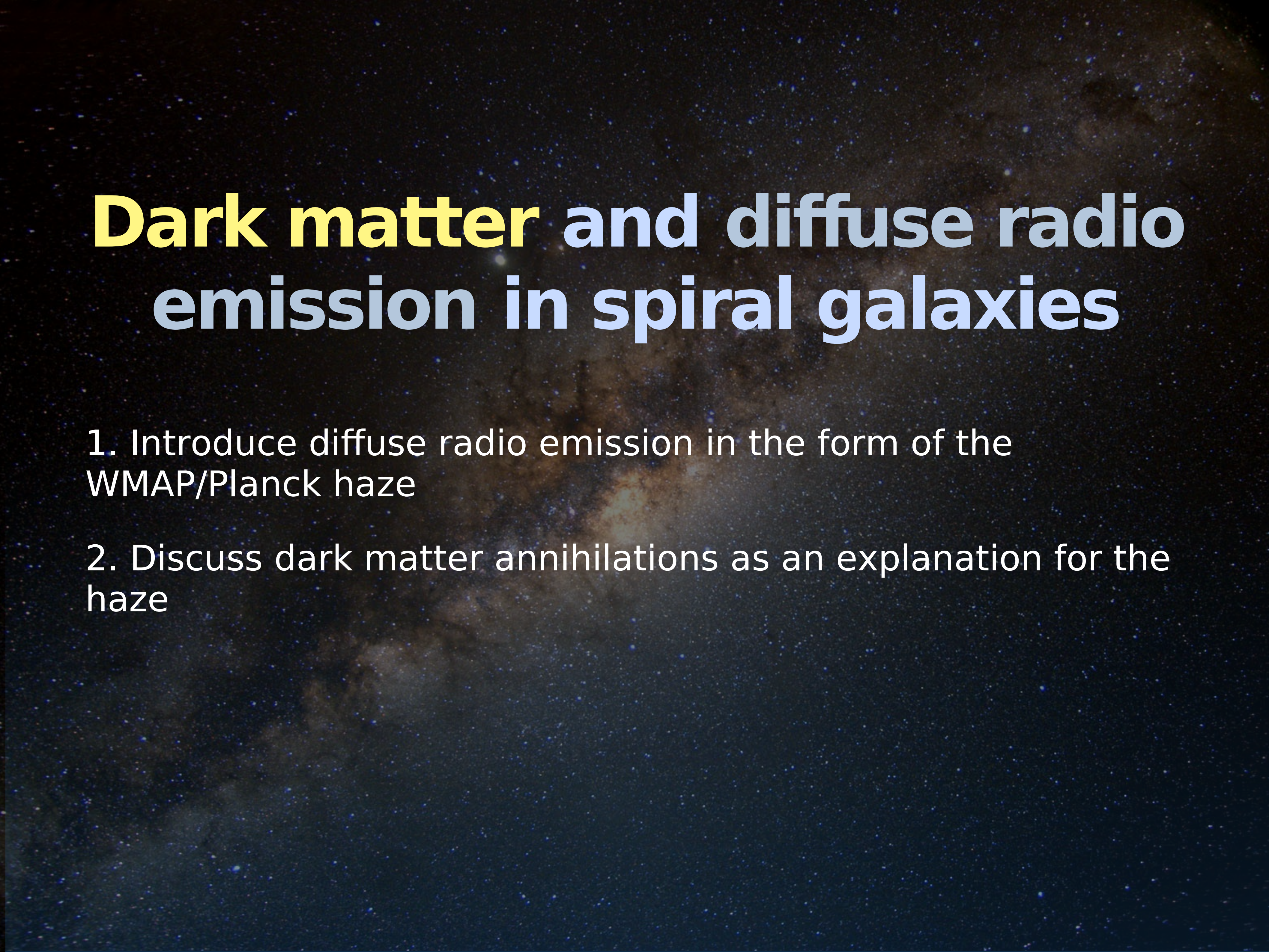
Fermi Symposium
12 April 2021

NRF
National Research Foundation
SARAO
South African Radio Astronomy Observatory
WITS UNIVERSITY

Dark matter and diffuse radio emission in spiral galaxies

1. Introduce diffuse radio emission in the form of the WMAP/Planck haze



Dark matter and diffuse radio emission in spiral galaxies

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2. Discuss dark matter annihilations as an explanation for the haze

Dark matter and diffuse radio emission in spiral galaxies

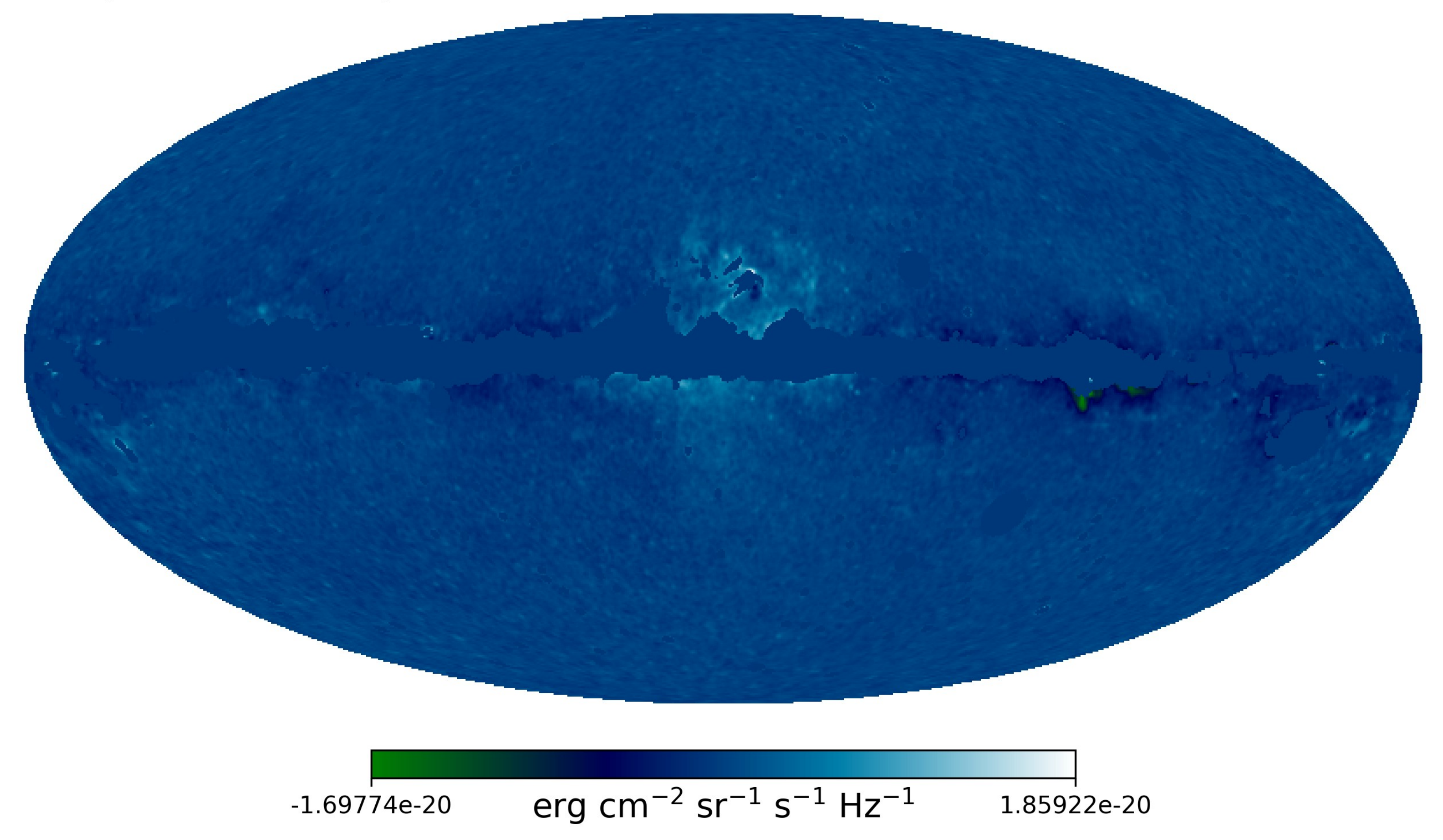
1. Introduce diffuse radio emission in the form of the WMAP/Planck haze

2. Discuss dark matter annihilations as an explanation for the haze

3. Present our results, and a list of spiral galaxies for MeerKAT observations that could provide tight constraints on dark matter parameters

WMAP/Planck haze

Synchrotron intensity map of WMAP/Planck haze in the radio K-band (Finkbeiner et. al., 2004)



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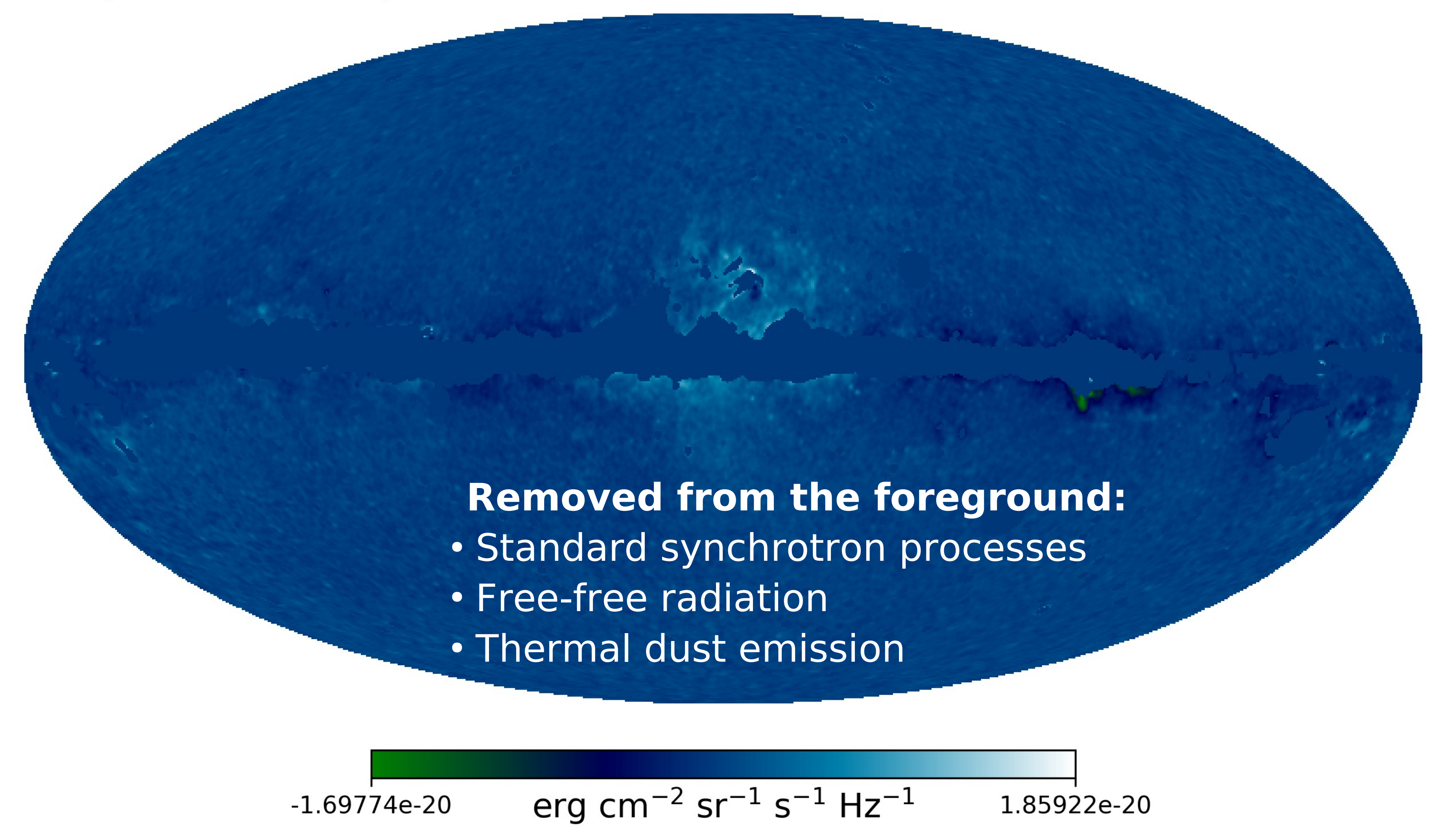
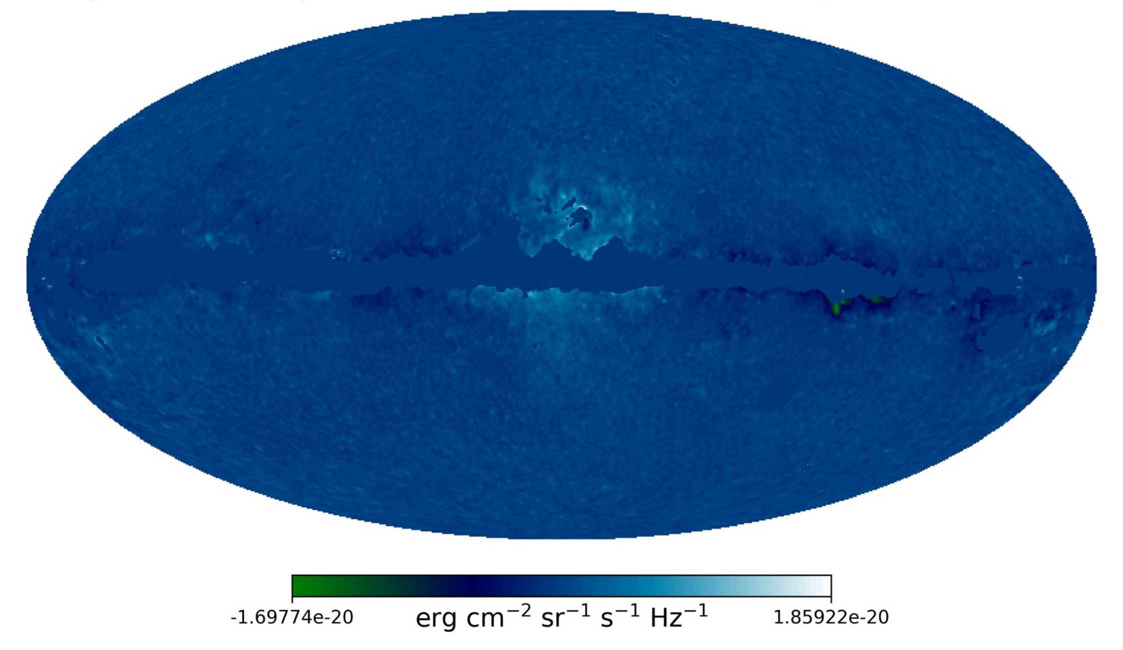


Removed from the foreground:

- Standard synchrotron processes
- Free-free radiation
- Thermal dust emission

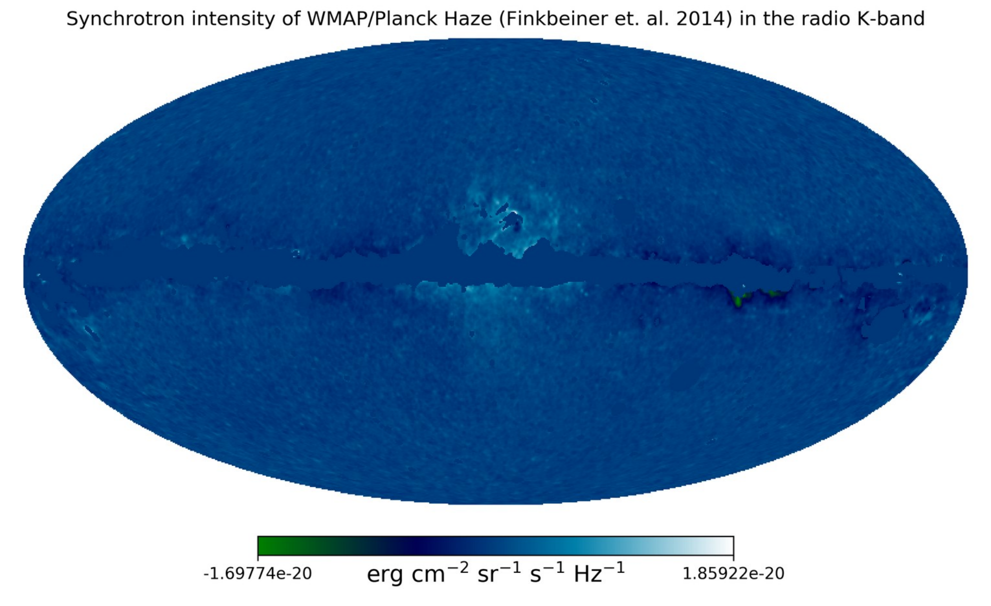
WMAP/Planck haze

properties

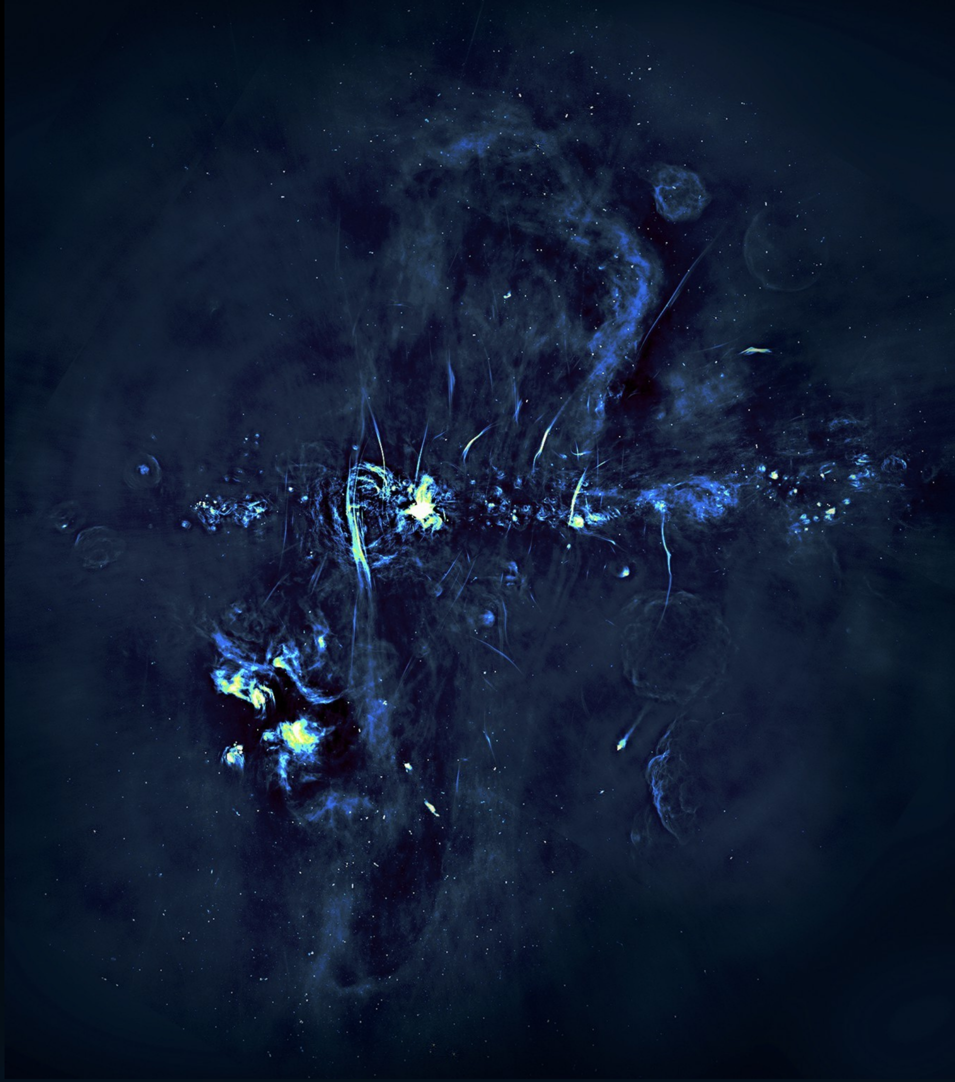


- Centered around the Galactic Center

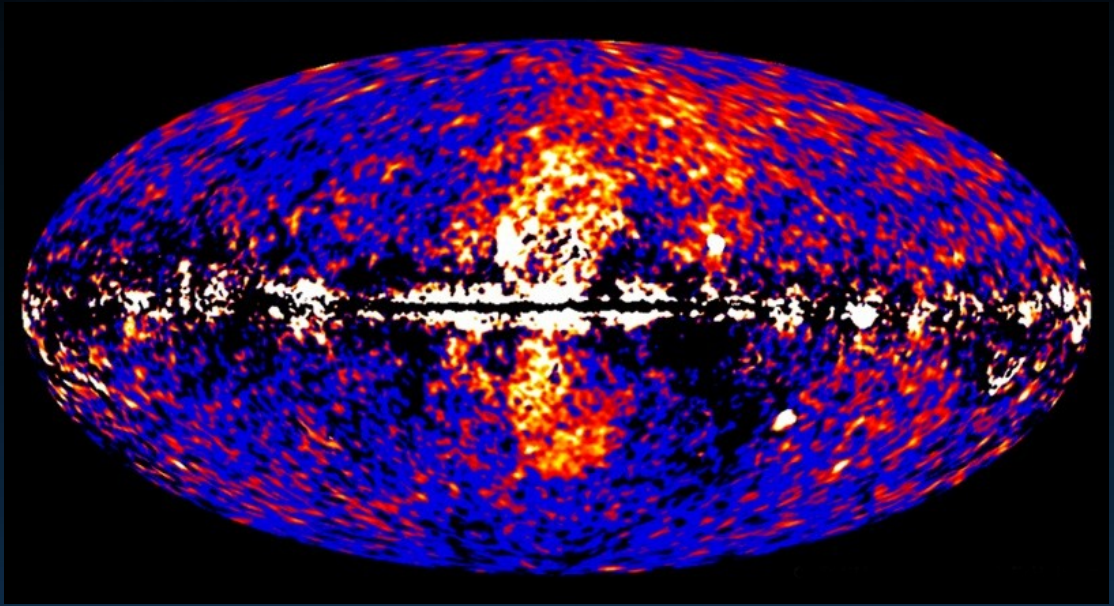
  extends ~ 30° in latitude and ~ 15° in longitude (inner 1-2 kpc)
- Spectrum is harder than standard synchrotron emission *and* softer than free-free emission
- The total power is $(1-5)\times 10^{36} erg/s$
- Morphology is consistent over 23 – 44 GHz



WMAP/Planck **radio** haze
∼30° from the GC
Finkbeiner et al. 2004



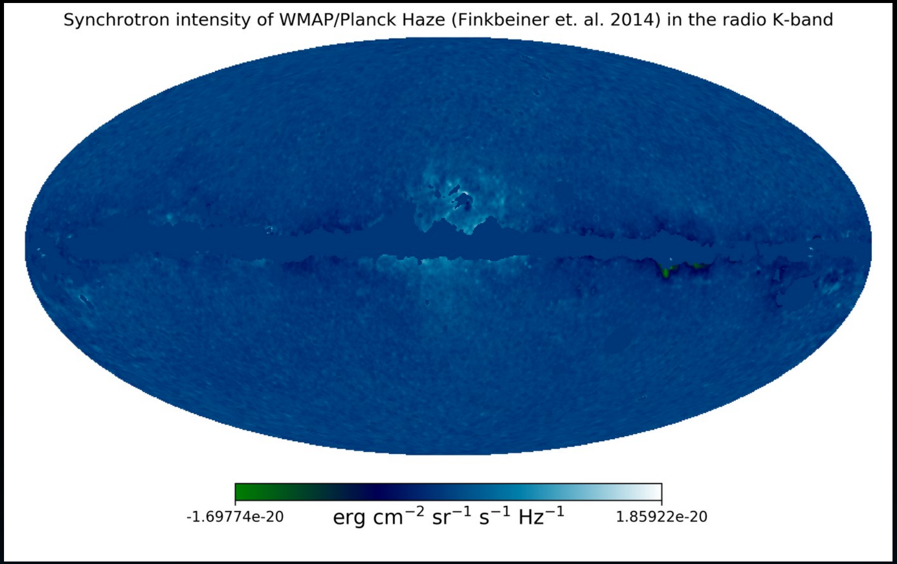
Radio bubbles
∼1° from the GC
SARAO/Oxford 2019



Fermi **gamma-ray** bubbles
∼55° from the GC
NASA/DOE/Fermi LAT/D. Finkbeiner, et al.

WMAP/Planck haze

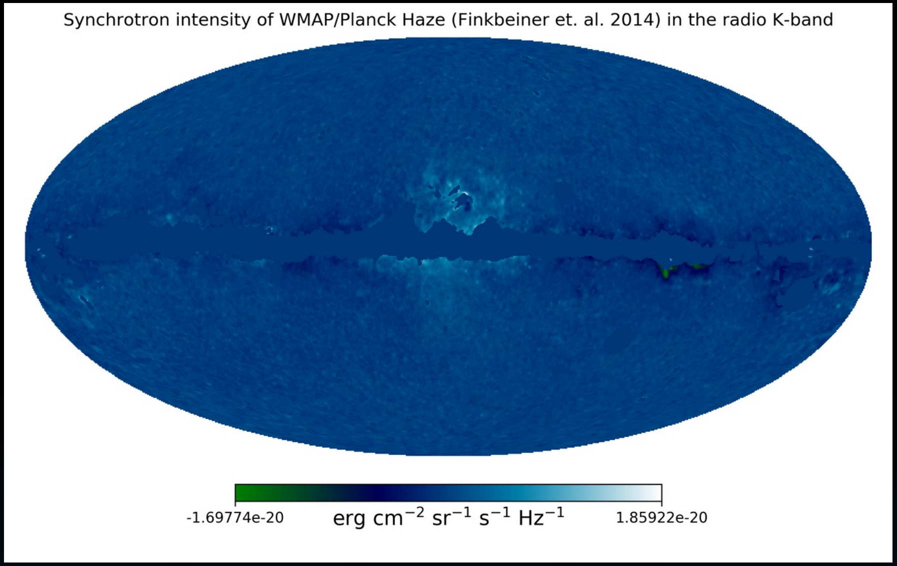
interpretations



- Emission from energetic activity near the SMBH

WMAP/Planck haze

interpretations



- Emission from energetic activity near the SMBH

- Reverse shocks associated with galactic outflows

WMAP/Planck haze

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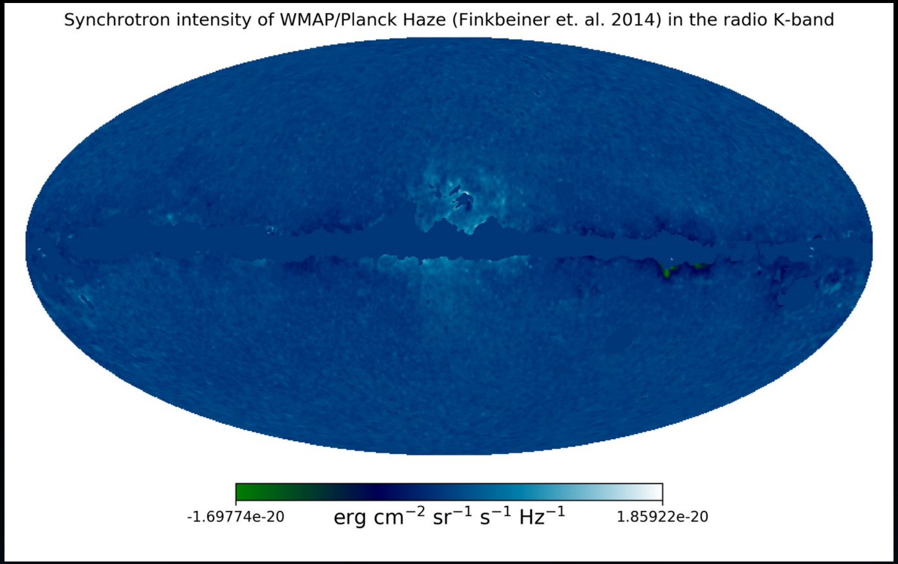
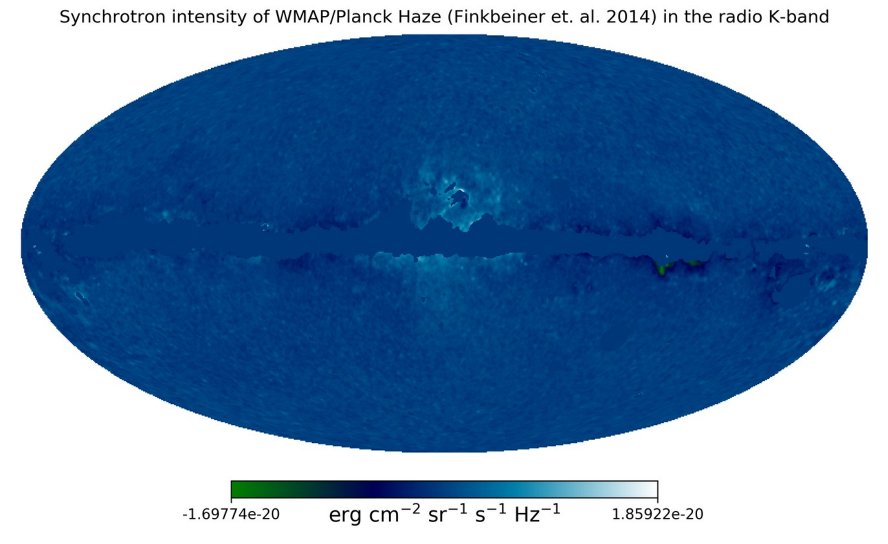


Synchrotron intensity of WMAP/Planck Haze (Finkbeiner et. al. 2014) in the radio K-band

- Emission from energetic activity near the SMBH
- Reverse shocks associated with galactic outflows
- Pulsars

WMAP/Planck haze

interpretations


Synchrotron intensity of WMAP/Planck Haze (Finkbeiner et. al. 2014) in the radio K-band

- Emission from energetic activity near the SMBH
- Reverse shocks associated with galactic outflows
- Pulsars
- Dark matter

“WMAP microwave emission interpreted as **dark matter annihilation** in the inner galaxy” by **Finkbeiner (2004)**
“Evidence of **dark matter annihilations** in the WMAP haze” by **Hooper, Finkbeiner, and Dobler (2007)**
“High energy positrons and the WMAP haze from exciting **dark matter**” by **Cholis, Goodenough, and Weiner (2009)**
“Morphology of the galactic **dark matter** synchrotron emission with self-consistent cosmic-ray diffusion models” by **Linden, Profumo, Anderson (2010)**
“**Dark matter** implications of the WMAP-Planck Haze” by **Egorov, Gaskins, Pierpaoli, Pietrobon (2016)**
“Spatial structure of the WMAP-Planck haze” **by Rubstov, Zhezher (2020)**

Dark matter

Weakly Interacting Massive Particles (WIMPs)

A well-motivated extension to the Standard Model (SM) of particles physics is that of **WIMPs**.

Dark matter

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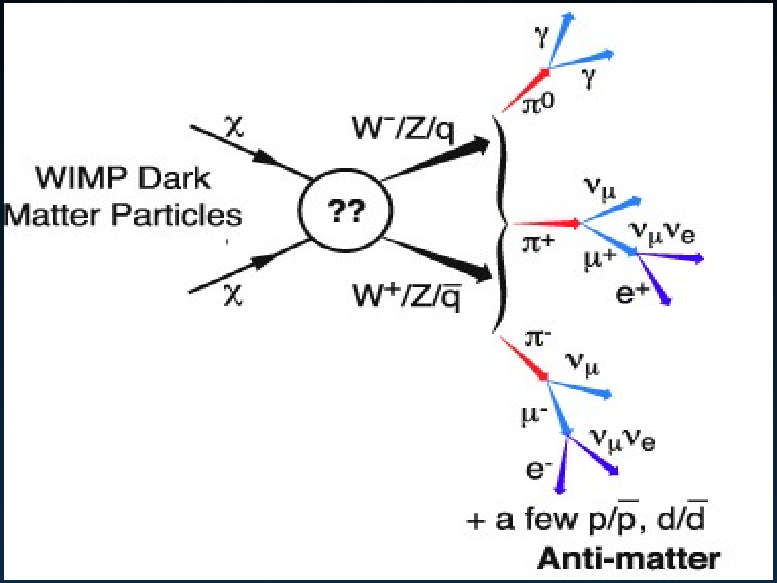
WIMPs are theorised to **annihilate on collision** and produce SM particles such as electrons.



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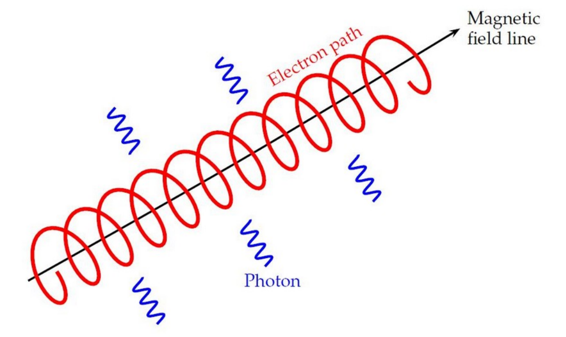
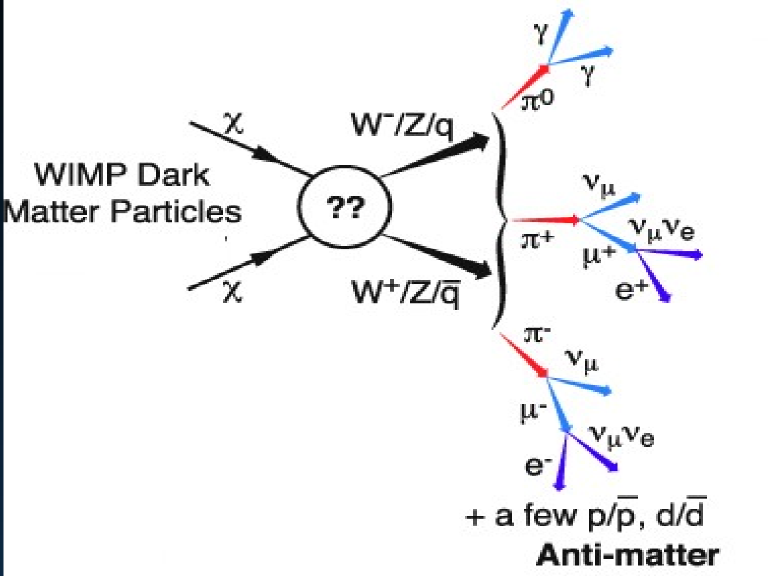
In galaxies, these electrons spiral around the galactic magnetic field and produce **synchrotron radiation in radio frequencies**.





Dark matter

sample models

Range of
dark matter
particle masses

Model	DM particle mass (GeV)	Annihilation channel
Soft	40	$b\bar{b}$
Hard	1 500	μ+ μ-
Wino	200	W+ W-

Linden et. al. (2010)

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Linden et. al. (2010)

SUperSYmmetric (SUSY)

- Extension to the standard model in an attempt to unify the strong, weak and electromagnetic forces

- Lightest (stable) candidate is the neutralino

Leptophilic

- Developed to explain the PAMELA positron excess

Dark matter

constraints

$$\frac{\text{Observed flux}}{\text{Expected flux}}$$

Dark matter

constraints

The dark matter annihilation cross section experimental limit is defined as

$$\frac{\langle \sigma \nu \rangle}{3 \times 10^{-26} cm^3/s} \leq \frac{\text{Observed flux}}{\text{Expected flux}}$$

Annihilation
cross section

Dark matter

constraints

The dark matter annihilation cross section experimental limit is defined as

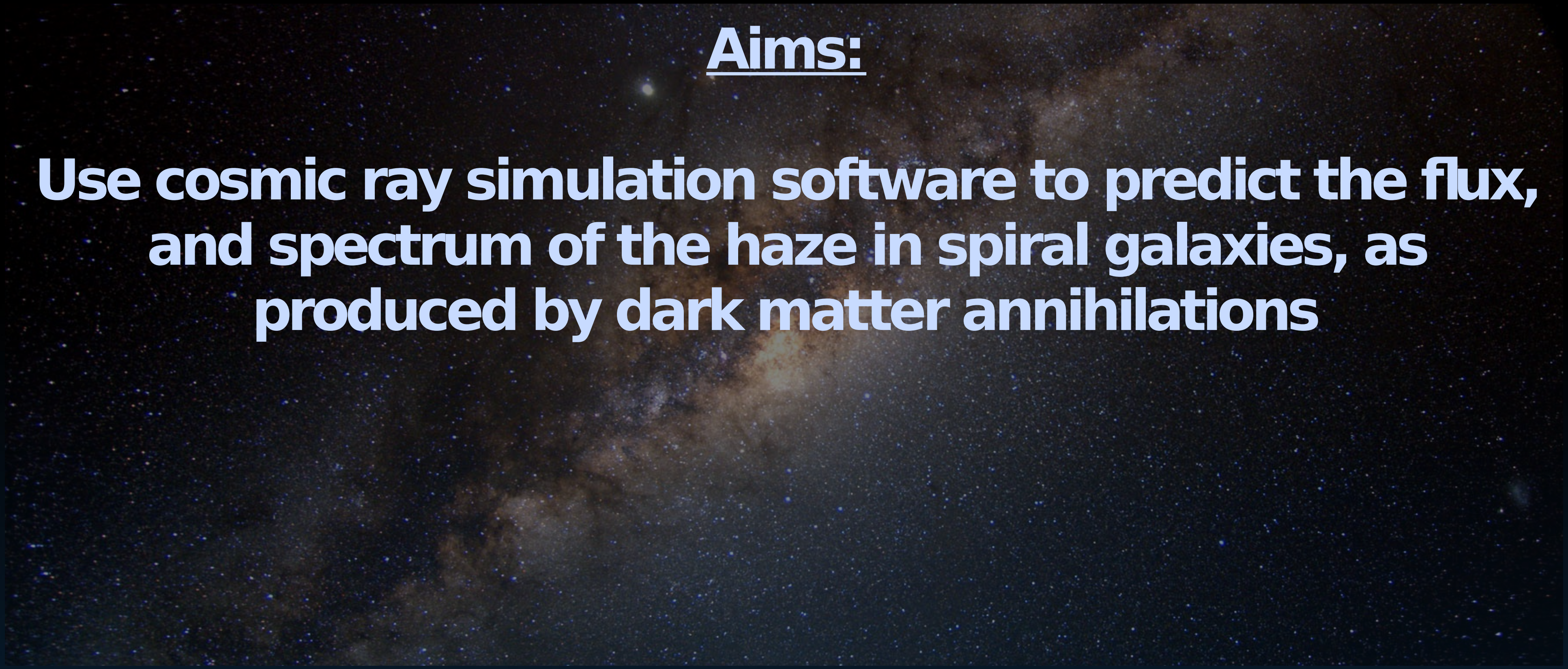
$$\frac{\langle\sigma\nu\rangle}{3\times10^{-26}cm^3/s} \leq \left.\frac{\text{Observed flux}}{\text{Expected flux}}\right\}\text{Boost factor (BF)}$$

$$\Big\downarrow$$

Annihilation
cross section

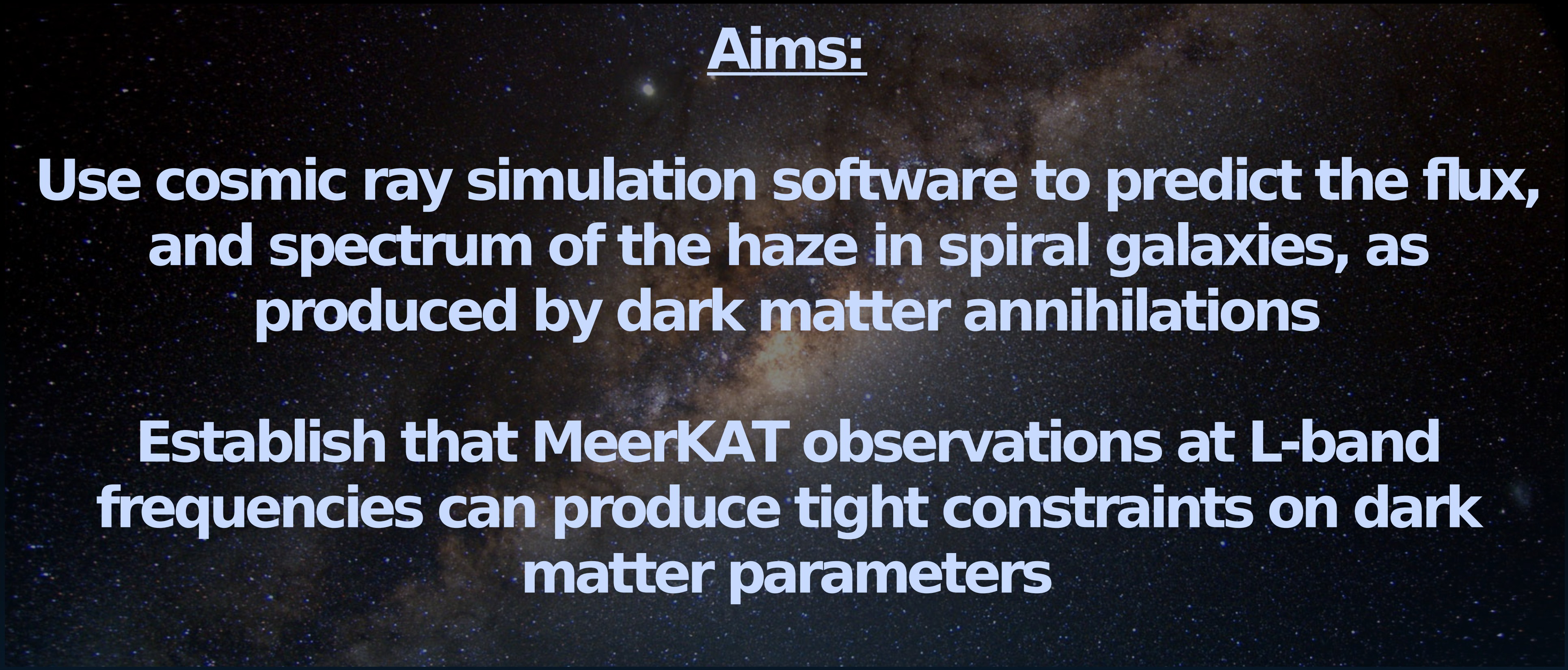
Model	DM particle mass (GeV)	Annihilation channel	Upper limit BF from dwarf gals
Soft	40	$b\bar{b}$	0.53
Hard	1 500	μ+ μ-	401
Wino	200	W+W-	2.2

Aims:



Aims:

Use cosmic ray simulation software to predict the flux, and spectrum of the haze in spiral galaxies, as produced by dark matter annihilations



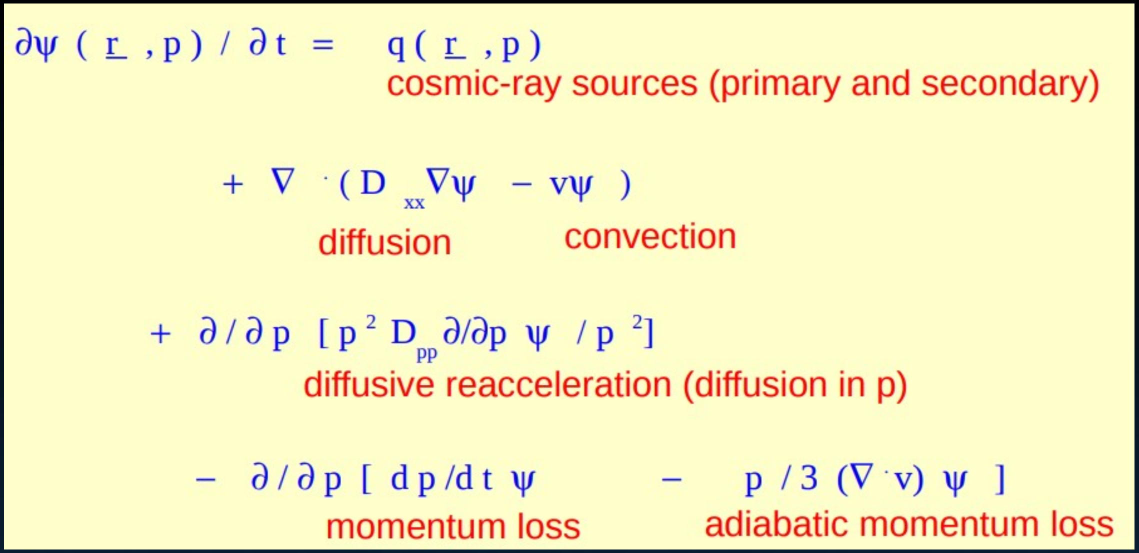
Aims:

Use cosmic ray simulation software to predict the flux, and spectrum of the haze in spiral galaxies, as produced by dark matter annihilations

Establish that MeerKAT observations at L-band frequencies can produce tight constraints on dark matter parameters

Galprop
implementation

Galprop is a code that **solves the cosmic ray propagation equation** with the ability for the user to fine-tune parameters. *Galprop* also calculates the diffuse emission produced by these cosmic rays.



$$\partial\psi(\underline{r},p)/\partial t = q(\underline{r},p)$$

cosmic-ray sources (primary and secondary)

$$+\nabla\cdot(D_{xx}\nabla\psi - v\psi)$$

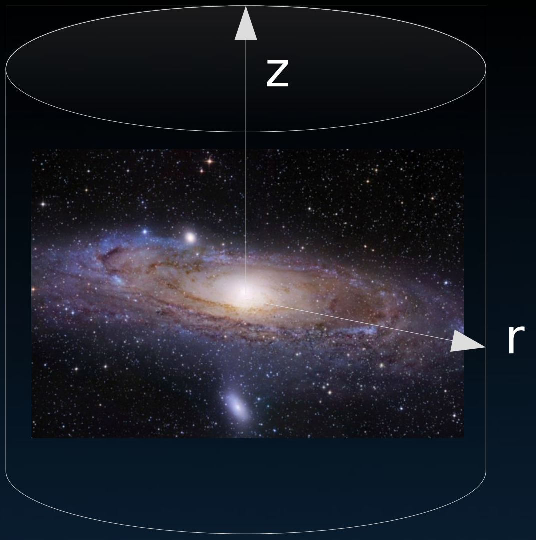
diffusion convection

$$+\partial/\partial p\,[p^2 D_{pp}\,\partial/\partial p\,\psi/p^2]$$

diffusive reacceleration (diffusion in p)

$$-\partial/\partial p\,[dp/dt\,\psi - p/3\,(\nabla\cdot v)\,\psi]$$

momentum loss adiabatic momentum loss



Previous study

by Carlson et. al. (2013)

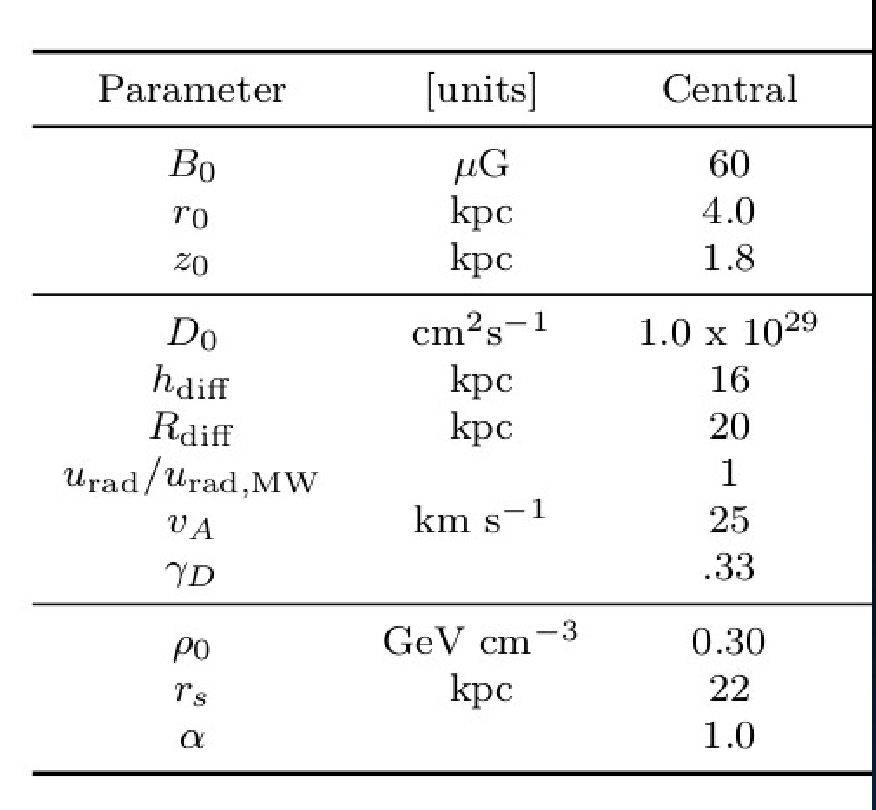
Magnetic field

$$B(r,z) = B_0 \exp\left(\frac{-r}{r_0}\right) \exp\left(\frac{-z}{z_0}\right)$$

CR diffusion

Dark matter density profile

$$\rho_{NFW}(r) = \frac{\rho_0}{r/r_s(1+r/r_s)^{3-\alpha}}$$



Parameter	[units]	Central
B_0	μG	60
r_0	kpc	4.0
z_0	kpc	1.8
D_0	cm^{2}s^{-1}	1.0 x 10^{29}
$h_{\rm diff}$	kpc	16
$R_{\rm diff}$	kpc	20
$u_{\rm rad}/u_{\rm rad,MW}$		1
v_A	km s^{-1}	25
γ_D		.33
ρ_0	GeV cm^{-3}	0.30
r_s	kpc	22
α		1.0

Carlson et. al. (2013)

Galprop simulations

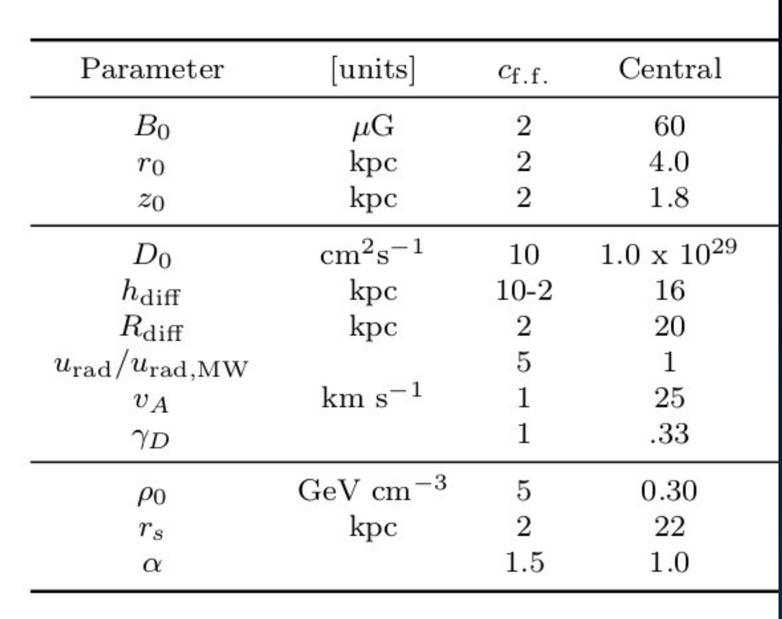
in this work

Central values for all the galaxy parameters
from Carlson et. al., with an **exp magnetic field**

$$B(r,z) = B_0 \exp\left(\frac{-r}{r_0}\right) \exp\left(\frac{-z}{z_0}\right)$$

and **NFW** dark matter density profile

$$\rho(r) = \rho_s \left(\frac{r_s}{r}\right)^{\alpha} \left(1 + \frac{r_s}{r}\right)^{-3+\alpha}$$



Parameter	[units]	$c_{\mathrm{f.f.}}$	Central
B_0	μG	2	60
r_0	kpc	2	4.0
z_0	kpc	2	1.8
D_0	$\mathrm{cm^2 s^{-1}}$	10	1.0 x 10^{29}
h_{diff}	kpc	10-2	16
R_{diff}	kpc	2	20
$u_{\mathrm{rad}}/u_{\mathrm{rad,MW}}$		5	1
v_A	km $\mathrm{s^{-1}}$	1	25
γ_D		1	.33
ρ_0	GeV $\mathrm{cm^{-3}}$	5	0.30
r_s	kpc	2	22
α		1.5	1.0

Sample dark matter particle models

Model	DM particle mass	Ann. channel
Soft	40 GeV	$b\bar{b}$
Hard	1 500 GeV	μ+ μ-
Wino	200 GeV	W+W-

Results

constraints from the WMAP/Planck haze

Derived from 1-year WMAP data (Finkbeiner, 2004)

$$\frac{\text{Observed integrated synchrotron intensity}}{\text{Simulated integrated synchrotron intensity}} = BF$$

Calculated from *Galprop* simulations of our dark matter models

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Model	DM particle mass (GeV)	Annihilation channel	BF constraints from this analysis	Upper limit BF from dwarf gals	Norm. factors Linden+2010
Soft	40	$b\bar{b}$	**1.61**	0.53	36
Hard	1 500	μ+ μ-	**648**	401	415
Wino	200	W+W-	**8.04**	2.2	27.7

Results

predicted flux of NGC 1350

The preliminary results of this study for NGC 1350

Located in the Fornax cluster

Distance = 20 Mpc

Observed flux at 1.4 GHz = 1.1 mJy (VLA)

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Model	DM particle Mass (GeV)	Annihilation channel	Upper limit BF from dwarf gals	BFs from NGC 1350 at 1.4 GHz (mJy)
Soft	40	$b\bar{b}$	0.53	**0.65**
Hard	1 500	μ+ μ-	401	**2.7**
Wino	200	W+W-	2.2	**1.3**

Outlook

target galaxies for MeerKAT

Spiral galaxy criteria:

- Angular diameter between 0.5 and 10 arcmin (MeerKAT resolves 5 arcsec)

- DEC < - 45°

- Rotational velocities between 180 and 280 km/s

- Luminosity that is comparable to – or lower than – that of NGC 1350

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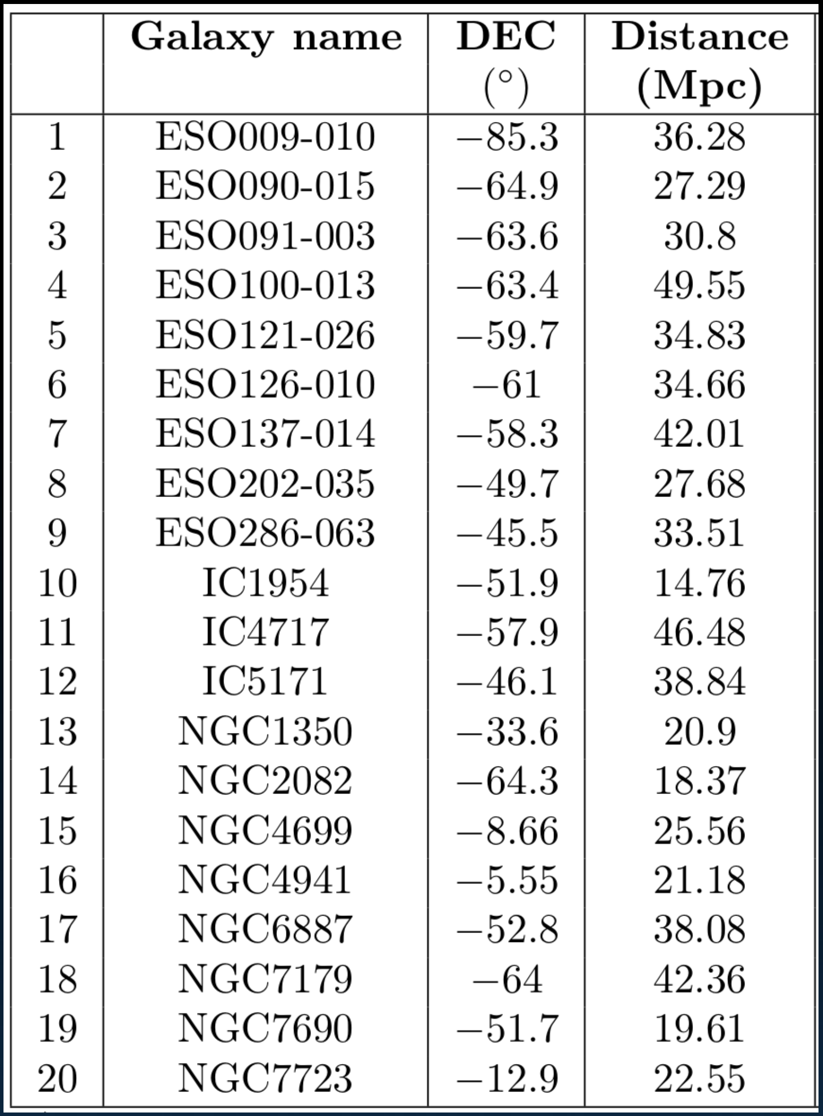


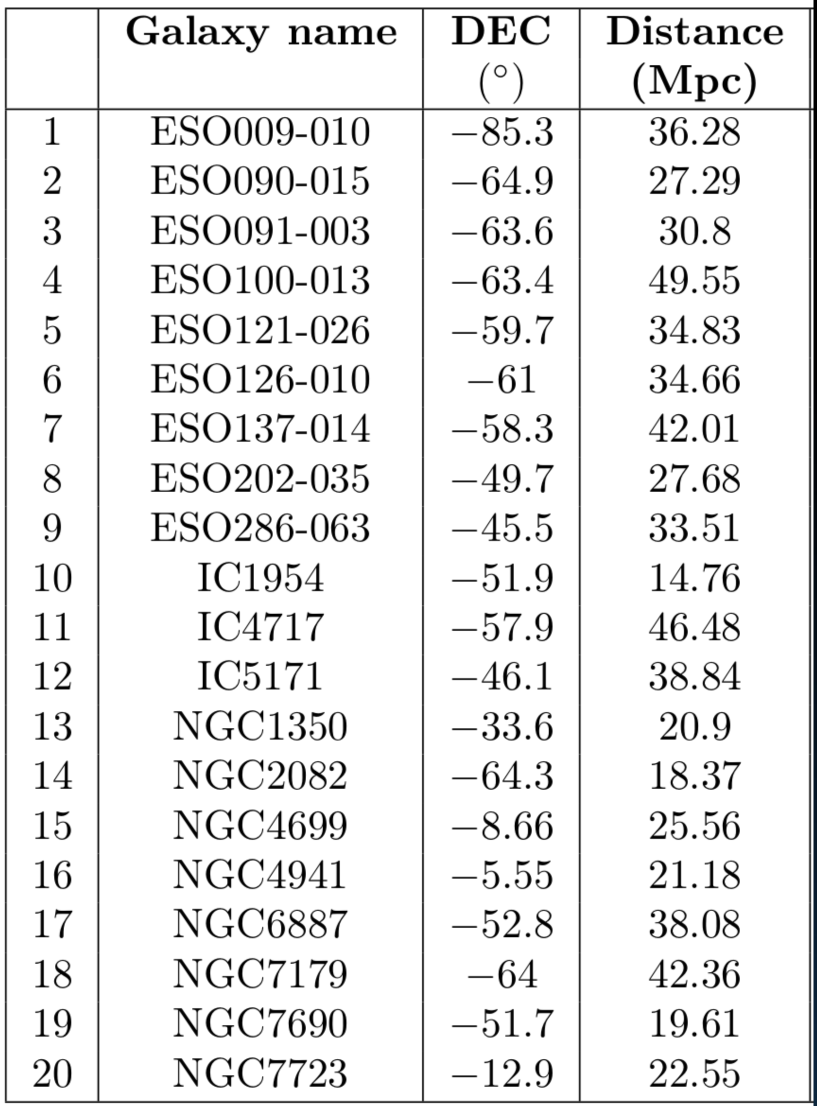
	Galaxy name	DEC (°)	Distance (Mpc)
1	ESO009-010	−85.3	36.28
2	ESO090-015	−64.9	27.29
3	ESO091-003	−63.6	30.8
4	ESO100-013	−63.4	49.55
5	ESO121-026	−59.7	34.83
6	ESO126-010	−61	34.66
7	ESO137-014	−58.3	42.01
8	ESO202-035	−49.7	27.68
9	ESO286-063	−45.5	33.51
10	IC1954	−51.9	14.76
11	IC4717	−57.9	46.48
12	IC5171	−46.1	38.84
13	NGC1350	−33.6	20.9
14	NGC2082	−64.3	18.37
15	NGC4699	−8.66	25.56
16	NGC4941	−5.55	21.18
17	NGC6887	−52.8	38.08
18	NGC7179	−64	42.36
19	NGC7690	−51.7	19.61
20	NGC7723	−12.9	22.55

Outlook

target galaxies for MeerKAT

These radio observations with MeerKAT will be **complementary** to similar indirect dark matter searches at gamma-ray frequencies with **Fermi-LAT**.

MeerKAT's **high sensitivity** will enable us to disentangle very diffuse radio signals around nearby galaxies.



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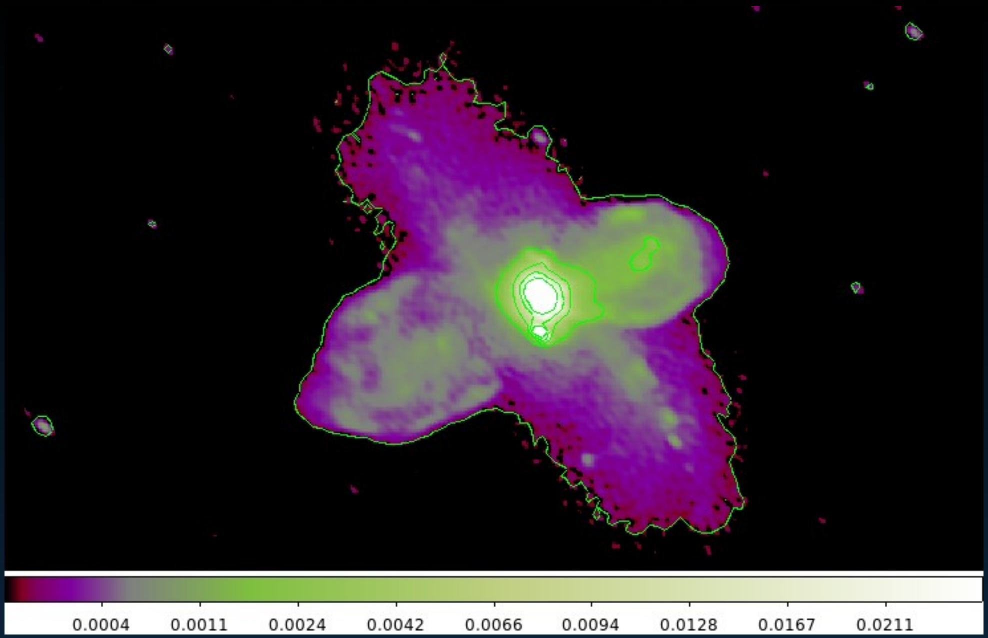
Outlook

MANGOES

Extra-planar observations have already begun with the **MANGOES** survey
MeerKAT **A**rray **N**earby **G**alaxies **O**bservations for **E**xtra-planar **S**tudies

(See Rozeena Ebrahim’s poster on outflows from the Circinus galaxy)



MeerKAT radio map at 1.4 GHz of Circinus
SARAO, Ebhrahim et al., Thorat et al, in prep

Conclusions

MeerKAT observations of target spiral galaxies will be able to **set tight constraints** on the properties of **dark matter particle models** and critically assess dark matter annihilation as an explanation for the WMAP/Planck haze.

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Thank you!

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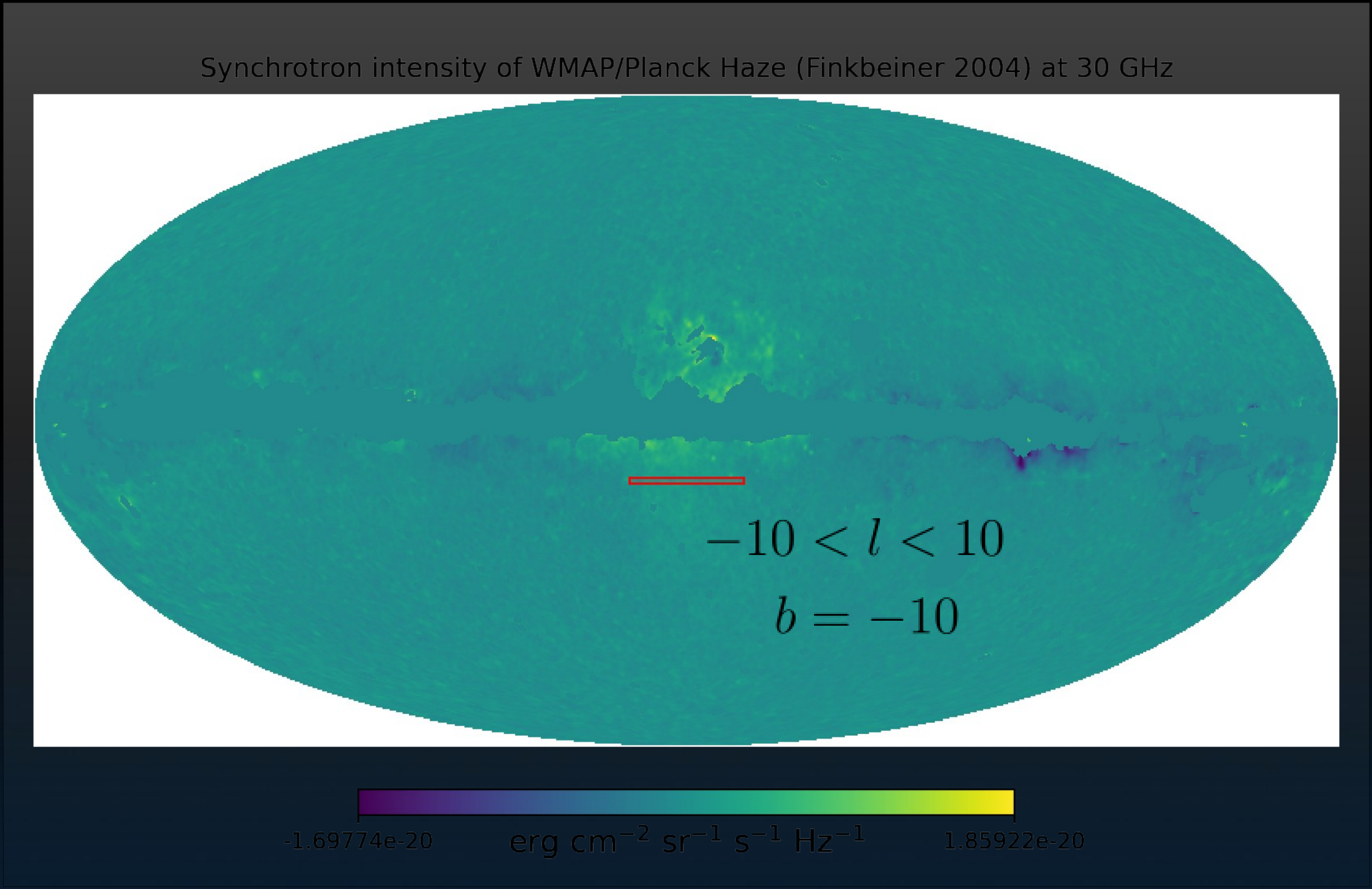
The ROI in which the synchrotron intensity was calculated



Synchrotron intensity of WMAP/Planck Haze (Finkbeiner 2004) at 30 GHz

$-10 < l < 10$

$b = -10$

Results

constraints from the WMAP/Planck haze

To analyse constraints for our three dark matter models, it is sufficient to use:

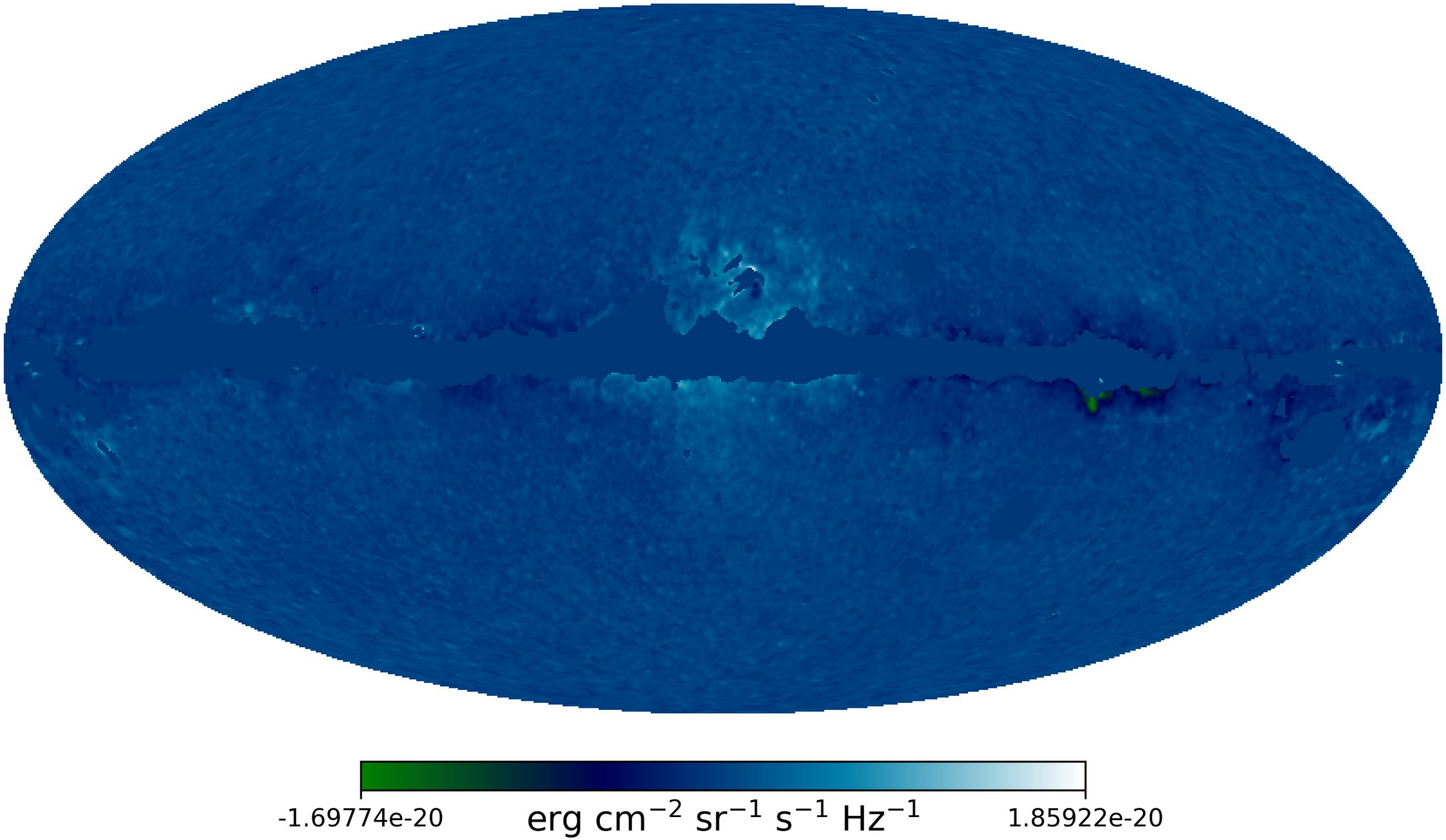
Calculated from 1-year WMAP data
(Finkbeiner, 2004; Zhezher et al., 2020)

$$\frac{\text{Observed integrated synchrotron intensity}}{\text{Simulated integrated synchrotron intensity}} = BF$$

Calculated from *Galprop* simulations of our dark matter models

Model	DM particle mass (GeV)	Annihilation channel	Upper limit BF from dwarf gals	BF constraints Finkbeiner 2004	BF constraints Zhezher+ 2020
Soft	40	$b\bar{b}$	0.53	**1.61**	**0.65**
Hard	1 500	μ+ μ-	401	**648**	**263**
Wino	200	W+W-	2.2	**8.04**	**3.26**

Synchrotron intensity of WMAP/Planck Haze (Finkbeiner et. al. 2014) in the radio K-band



MeerKAT

South African precursor to the Square Kilometer Array (SKA)

- 64 dishes, each 13.5m in diameter
- Angular resolution of 5 arcsec
- Frequency bands: 900 – 1670 MHz
- Sensitivity (5σ): 0.04mJy in 1 hour
- Co-ordinates 30º 43’ 15.6’’ S; 21º 24’ 39.6’’ E (Karoo in South Africa)