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International Centre for Radio Astronomy Research

Galaxy Clusters, Axion Dark Matter and Bruce

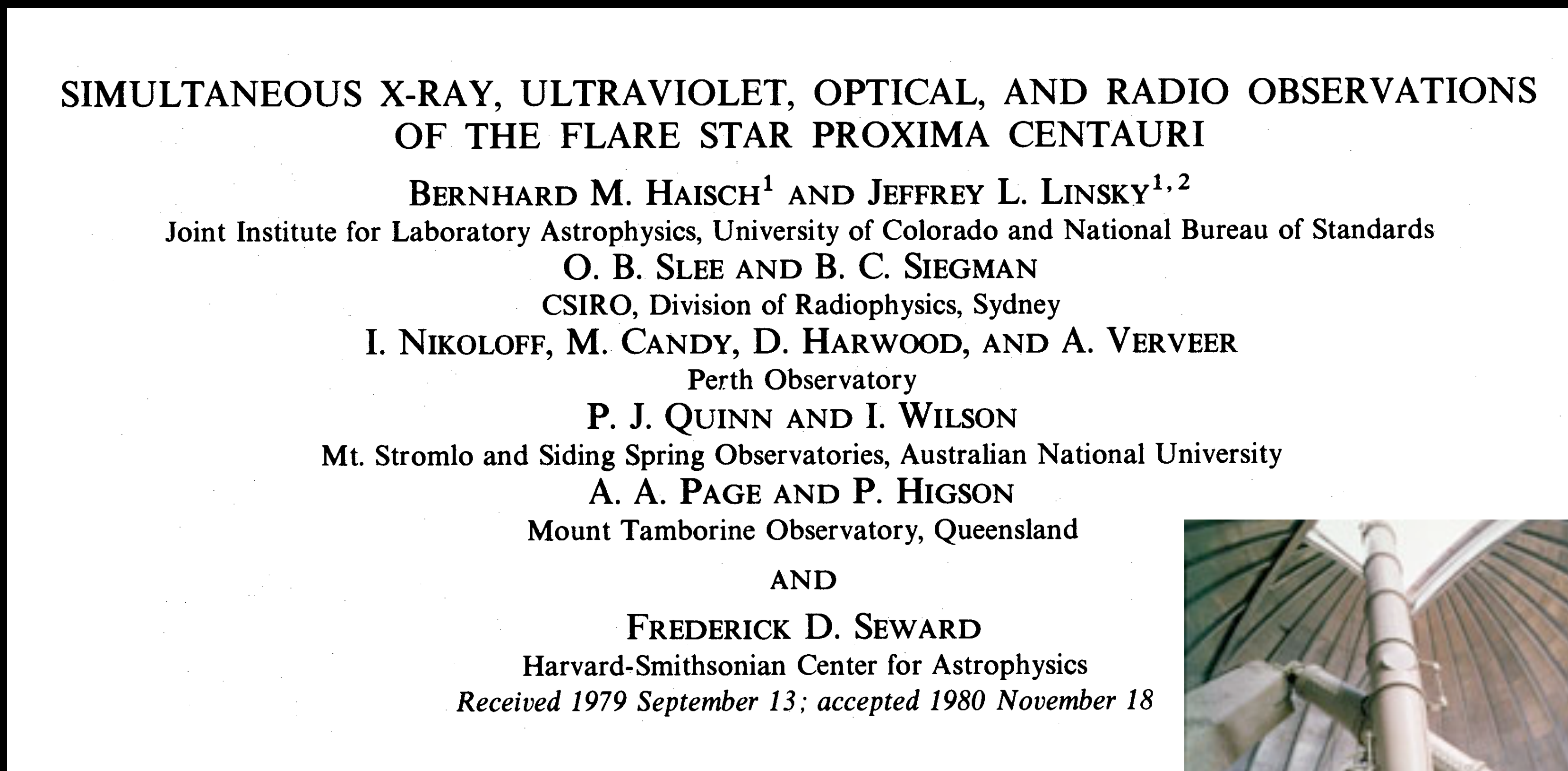
Peter Quinn
ICRAR

Curtin University

The University of Western Australia

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

Career choices Winter 1978


SIMULTANEOUS X-RAY, ULTRAVIOLET, OPTICAL, AND RADIO OBSERVATIONS OF THE FLARE STAR PROXIMA CENTAURI

BERNHARD M. HAISCH[1] AND JEFFREY L. LINSKY[1,2]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards
O. B. SLEE AND B. C. SIEGMAN
CSIRO, Division of Radiophysics, Sydney
I. NIKOLOFF, M. CANDY, D. HARWOOD, AND A. VERVEER
Perth Observatory
P. J. QUINN AND I. WILSON
Mt. Stromlo and Siding Spring Observatories, Australian National University
A. A. PAGE AND P. HIGSON
Mount Tamborine Observatory, Queensland
AND
FREDERICK D. SEWARD
Harvard-Smithsonian Center for Astrophysics
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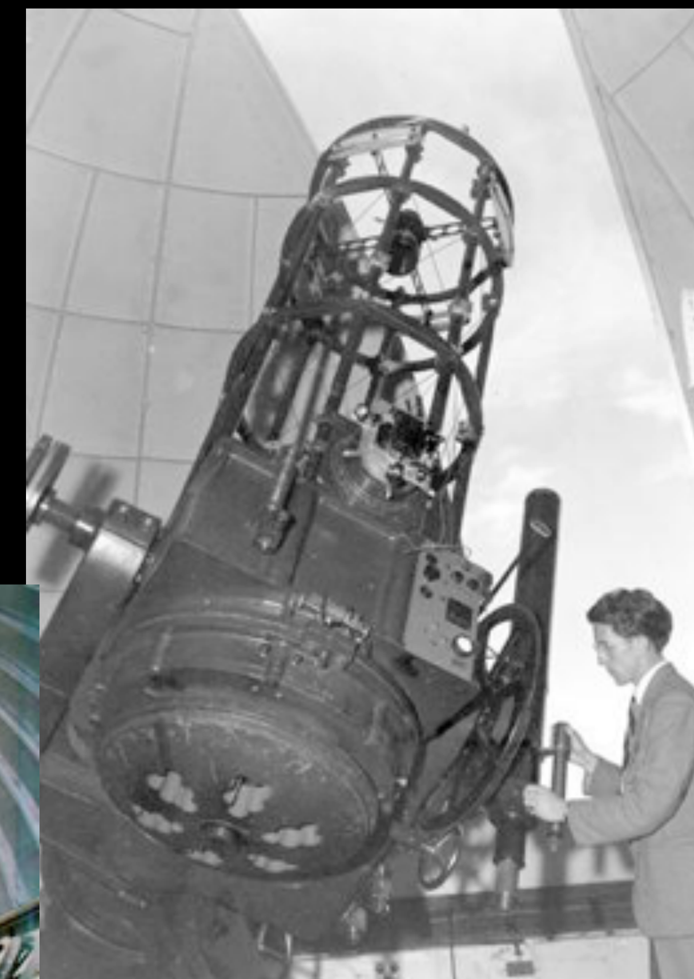
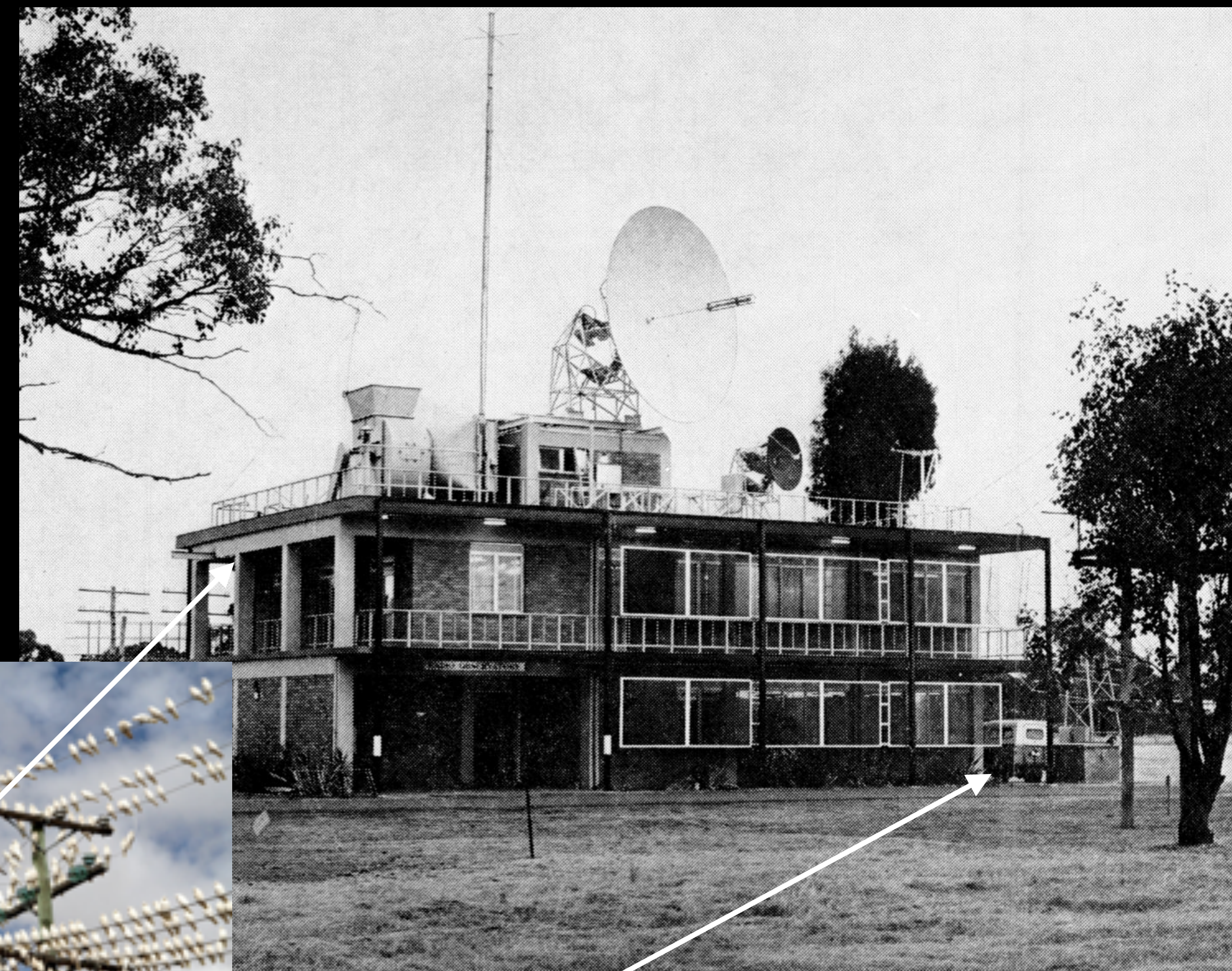
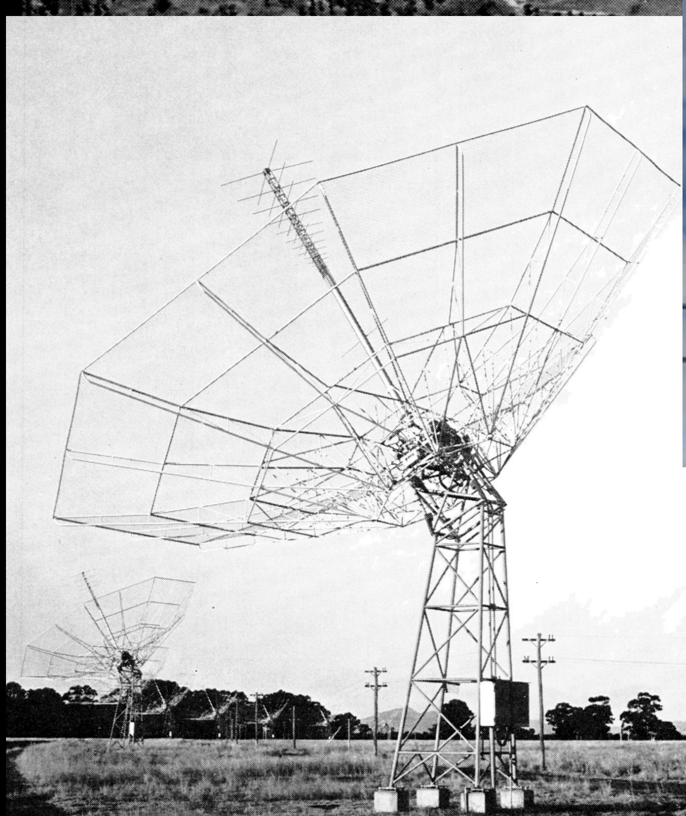


Glass plates, Kangaroos Canberra winter and black magic of photometry

Optical astronomy ?? !

Career choices Summer 1978





Series 1 Landrovers
Frogs and power transformers
A few birds on the wires
Narrabri Summer

Clusters of Galaxies 1979

Proc. ASA **3** (5) 1979

Observations with wide fractional bandwidths are clea-'-· unique. The problems of interference and analysis still n be fully solved before full application is possible to scintillation, pulsars, and to source variability in general

I gratefully acknowledge the help of O. B. Slee with the observations illustrated here.

Backer, D.C., *Nature,* **228,** 42 (1970).
Cole, T.W., and Milne, D.K., *Proc. Astron. Soc. Aust.,* **3,** 1 (1
Cole, T.W., Stewart, R.T., and Milne, D. K., *Astron. Astrophy*
277 (1978).

80 MHz Survey of Extra-Galactic X-ray Sources

O. B. Slee *Division of Radiophysics, CSIRO, Sydney*
P. J. Quinn *Mount Stromlo and Siding Spring Observatories, Australian National University, Canberra*

Proc. ASA **3** (5) 1979

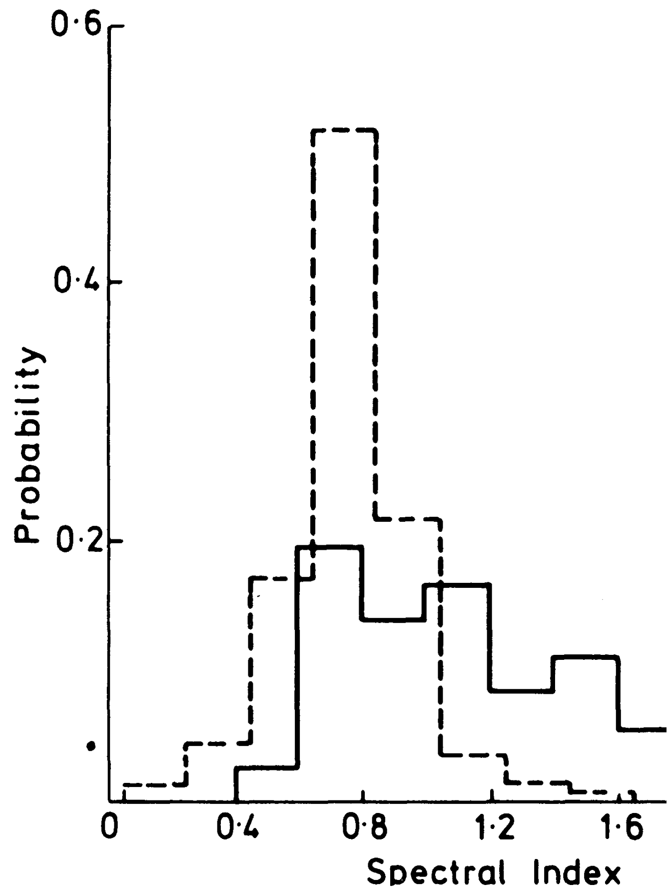


Figure 3. Probability distribution for equal interva frequency radio spectral index α_{80}^{160}. The full line r sources found near Ariel V error boxes, the dashe sources.

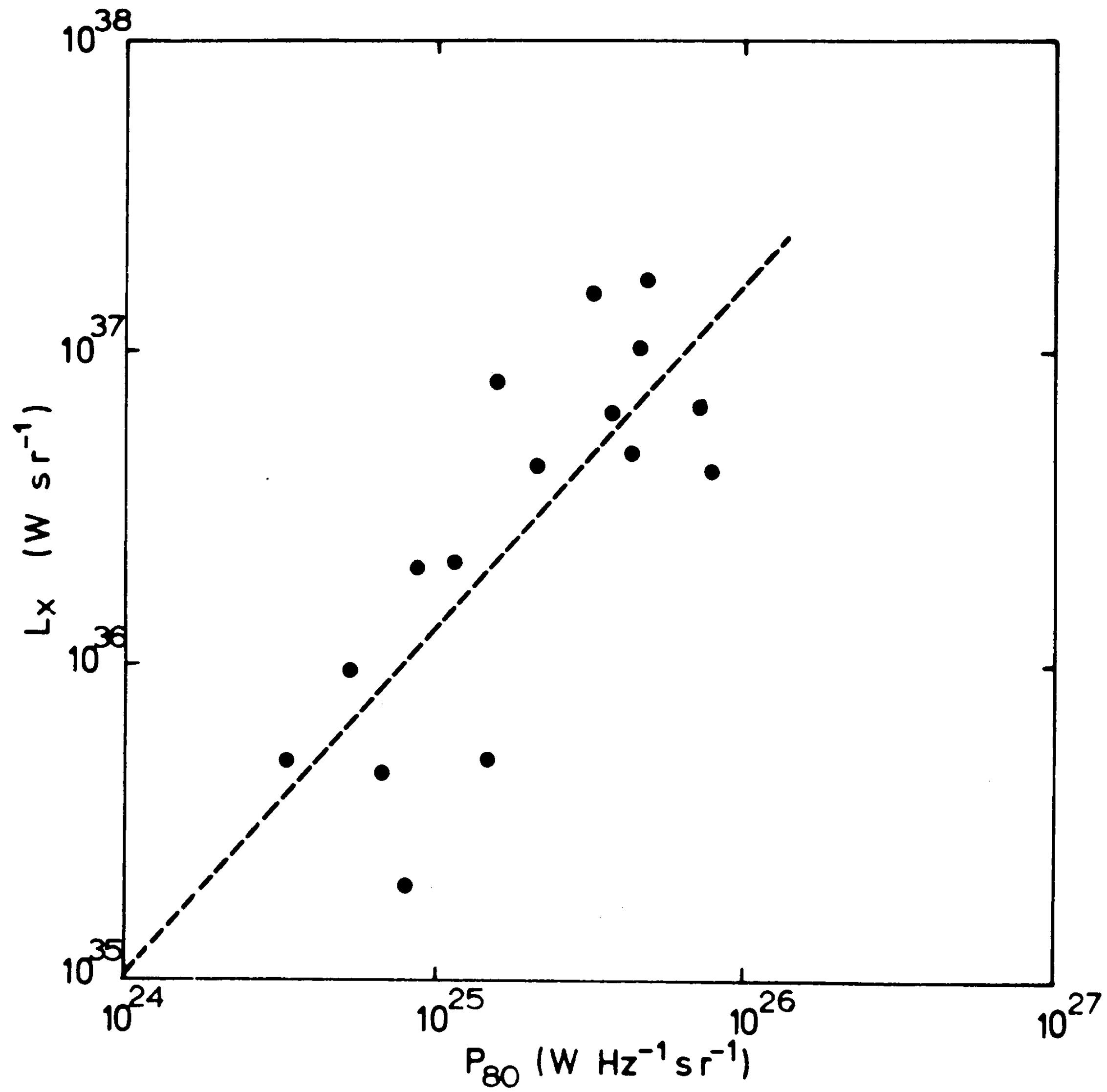


Figure 6. A plot of X-ray luminosity (L_x) against 80 MHz power (P_{80}) for all X-ray clusters in which 80 MHz sources were detected. The regression line for L_x on P_{80} has the equation log $L_x = 0.028 + 1.09 \log P_{80}$.

27 Ariel V X-ray clusters surveyed

17 of these have 29 radio sources at 80MHz and 160 MHz

Empty fields?

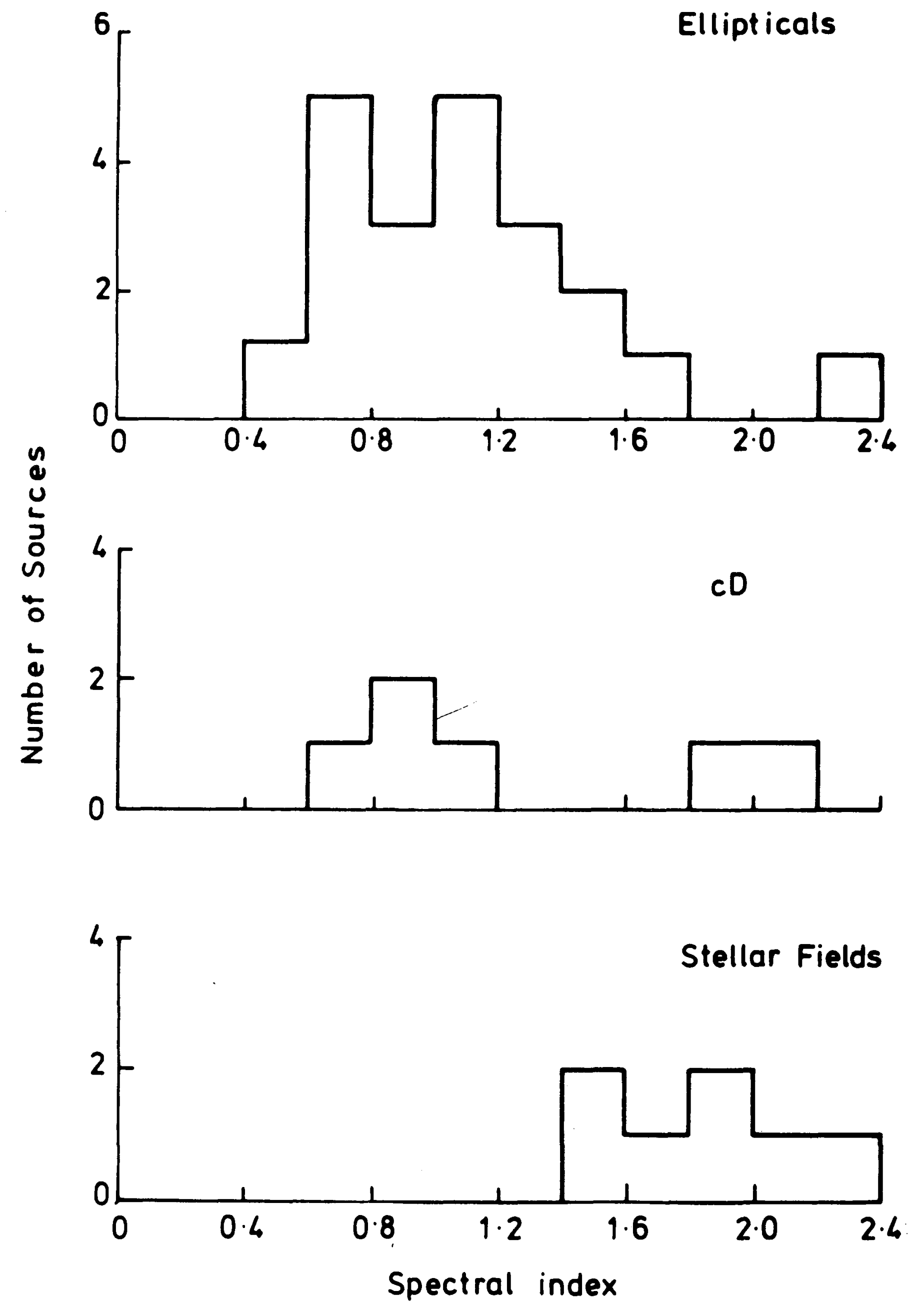


Figure 4. Distributions of spectral index α_{80}^{160} for radio sources in various types of optical field. (a) sources associated with one or more elliptical galaxies; (b) sources identified with cD galaxies; (c) unidentified sources.

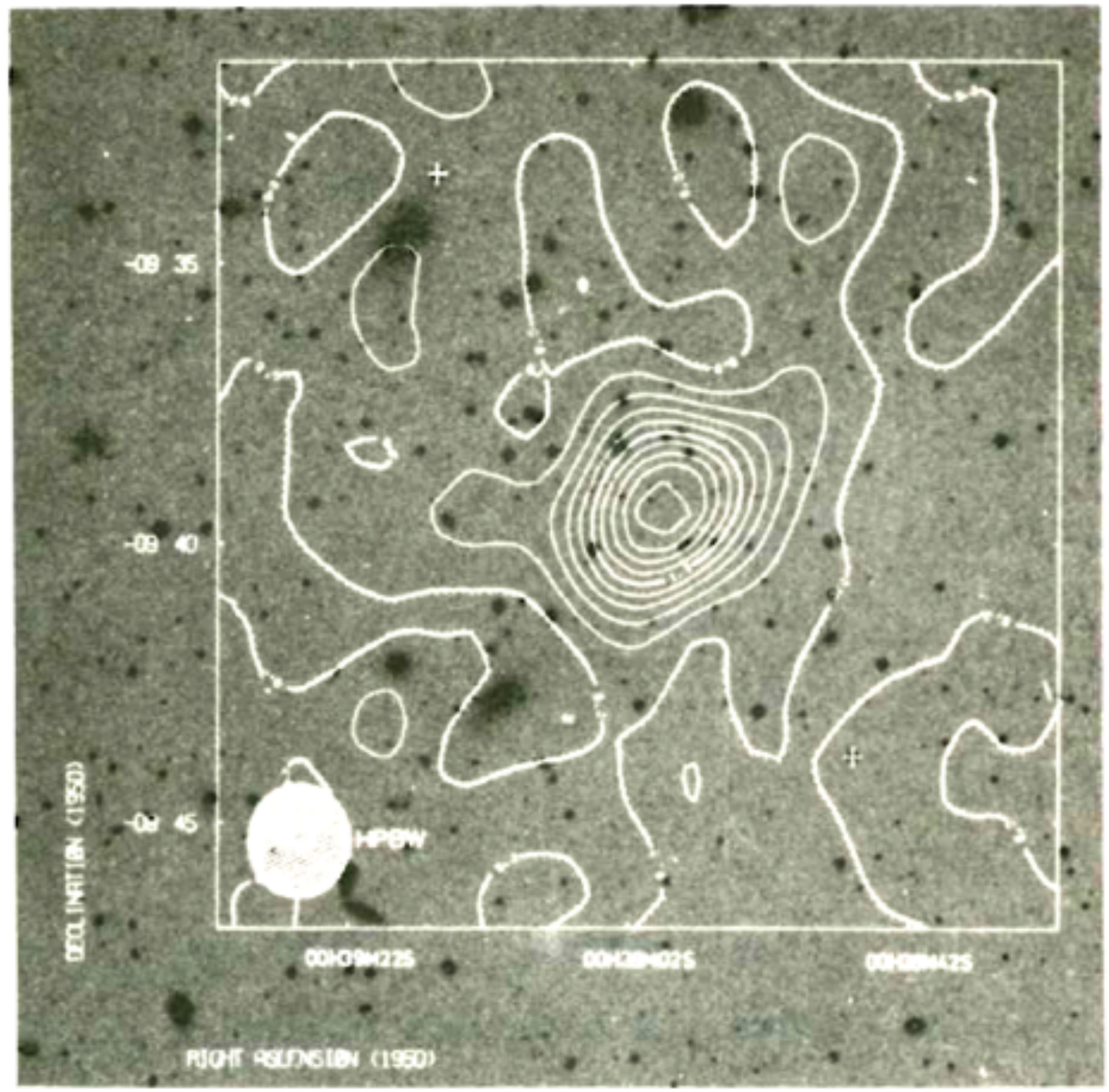


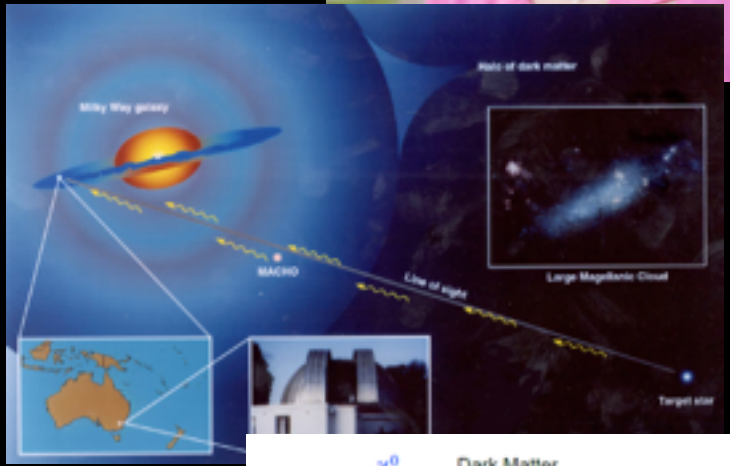
Figure 1. 160 MHz brightness contours of the steep-spectrum source 0038-096 superimposed on the SRC J plate of the sky near the centre of Abell 85. Contour interval is 0.38 Jy per beam with peak brightness of 3.82 Jy per beam. The half-power beam shape is shown in the bottom left-hand corner of the map.

Early signs of radio halos and relics?

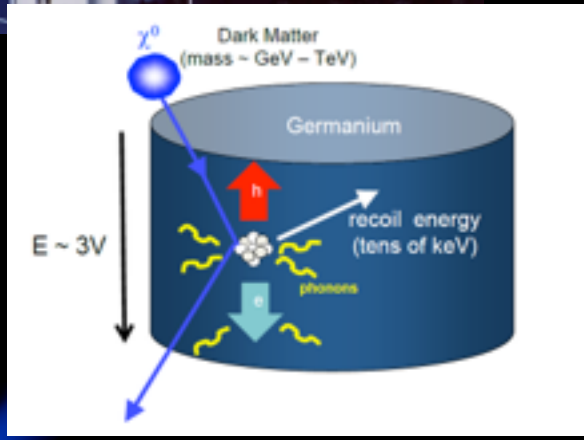
Searching for DM 1990-2016

Work with Katharine Kelly, ICRAR graduate student

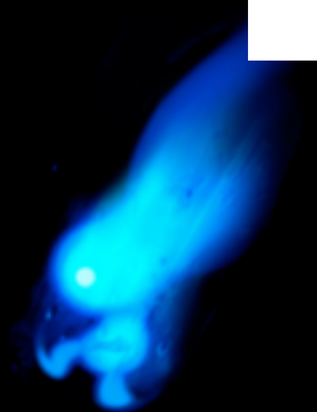
Three principal groups which could make up some portion of the dark matter density:



- ***MACHOs:*** generally accepted not to be in great enough abundance to account for all of dark matter - **Mass from lunar to solar masses**
- ***WIMPs:*** range of particles which are related only in that they are weakly interacting and massive, this is where the main effort has been in recent decades and there has, as yet, been no detections. The LHC is principally focused on searching for particles in this group – as are a number of other experimental groups - **Mass ~ 1 - 100s GeV**



- ***WISPs:*** group of very light particles of which the axion is a member, there has been renewed focus on the axion and axion like particles in recent history due to the lack of success in detecting WIMPs - the key difference being that WISP particles have a lower mass and are unlikely to be detectable in a particle accelerator - **Mass milli - micro eV, & < 10^{-22}**



Comparison with other Dark Matter Candidates

DM Candidate	Group	Thermal	Boson/ Fermion	Mass	Temp	Annihilates
Sterile Neutrino	*WIMP*	*Y*	*Fermion*			
Neutralino	*WIMP*	*Y*	*Fermion*	*GeV - TeV*	*Cold*	*Yes*
Axions	*WISP*	*N*	*Boson*	*Sub eV*	*Cold/ Warm/Hot*	*No*

Axions - good DM candidate

- Axion is still considered after almost 40 years to be the best correction for the strong CP problem in the Standard Model – one of only 2 unresolved issues in the standard model for the strong interactions

- Couplings to other particles and the axion mass are inversely proportional to the symmetry breaking scale f_a, currently accepted to be between 10^9-10^{12}GeV
  ➔ Very weakly interacting with other particles

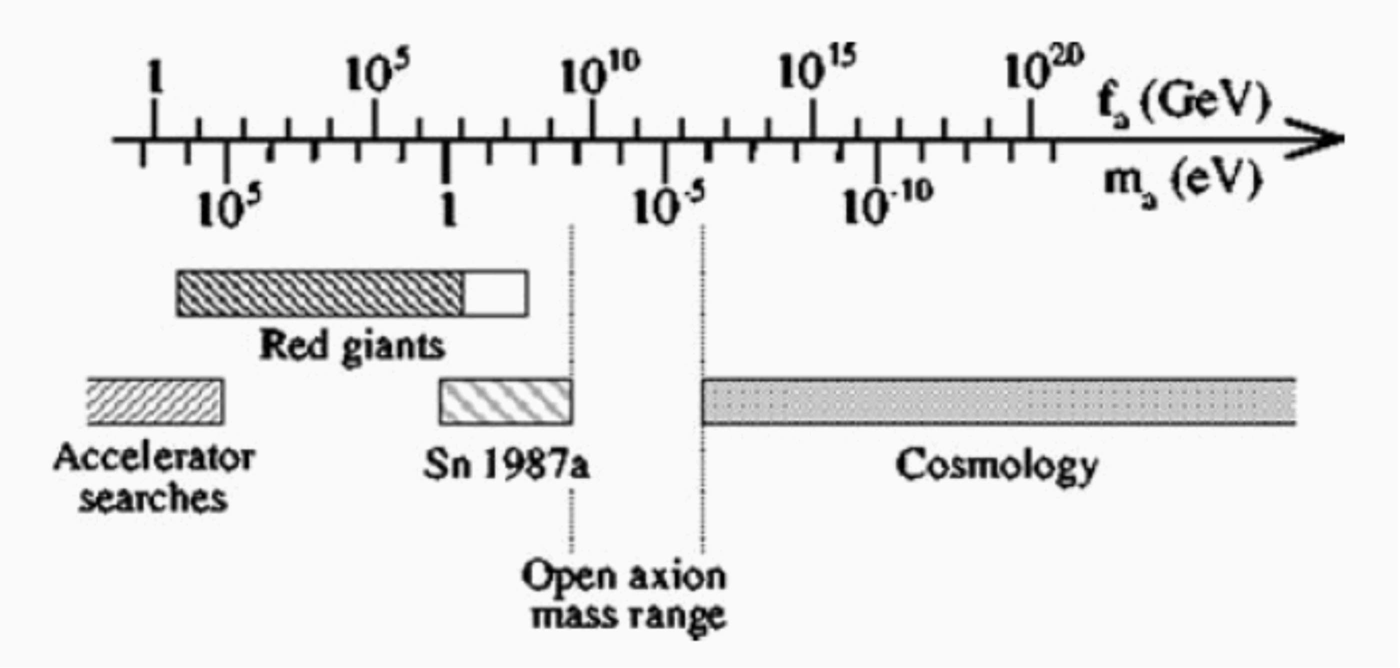
- Velocity of the primordial axion is non-relativistic, $v_a \ll c$

- Abundance,

  $\Omega_{CDM} \approx 0.22$

  $\Omega_a \propto f_a^{7/6}$

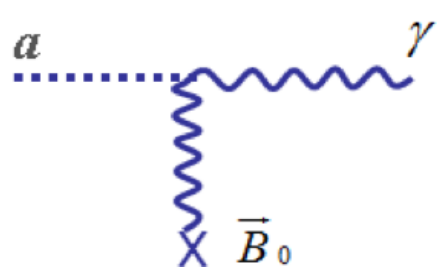
  In the currently accepted range this could account for the whole of the estimated dark matter density



Are Axions detectable?

- The Primakoff Effect is the decay of a particle into two real photons
  - This effect for the axion has a lifetime longer than the current age of the universe
  - The conversion of an axion into a single real photon can however be induced by providing a virtual photon to the interaction through applying a magnetic or electric field

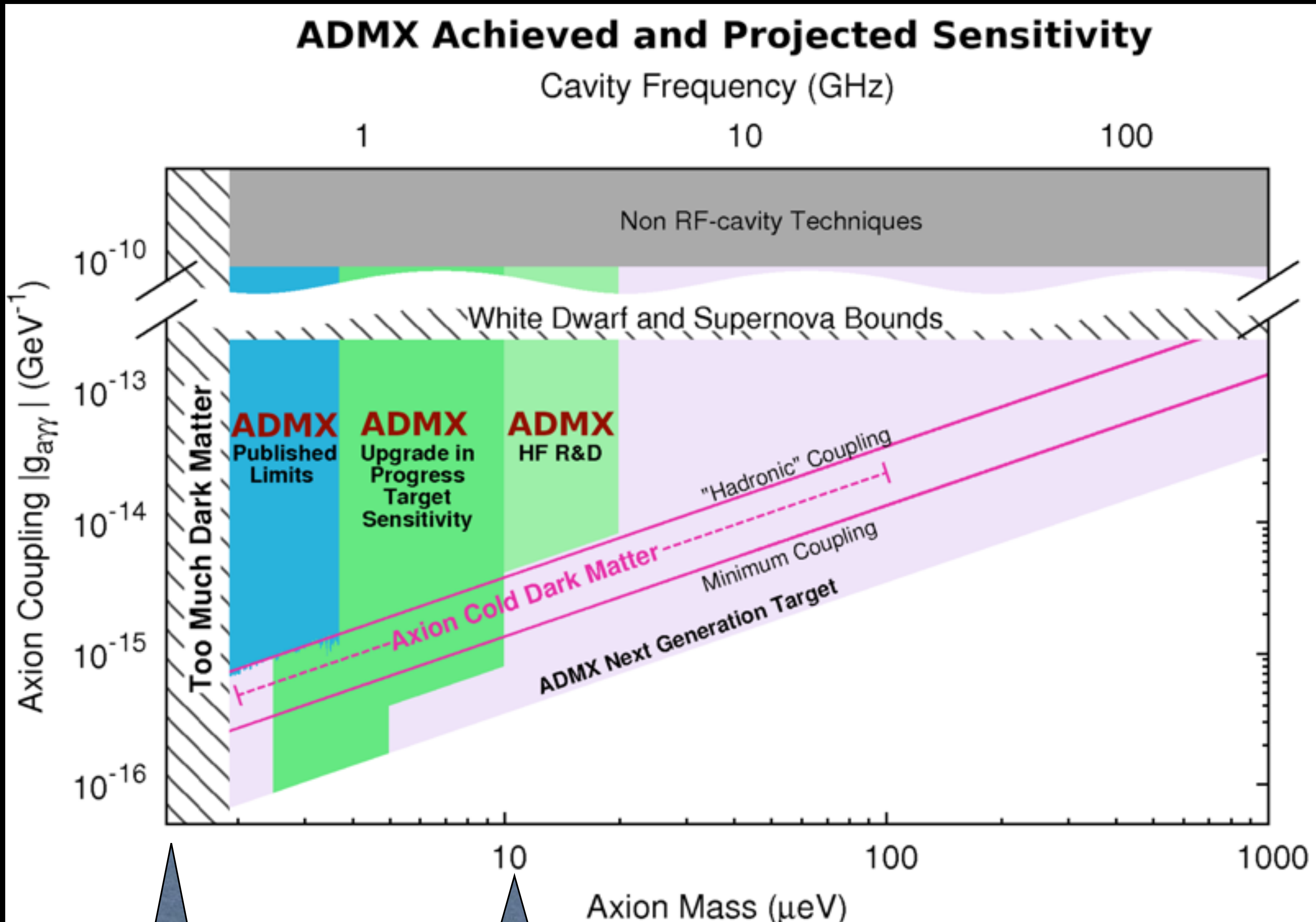
- In 1983 Sikivie published experimental methods which exploit this process and calculated the photon production rate to be inversely proportional to the magnetic field strength, B, squared



Photon production rate α B^2

- The magnetic field must be transverse to the axion, and
- Energy and momentum must be conserved

Never say never…radio astronomy 😉

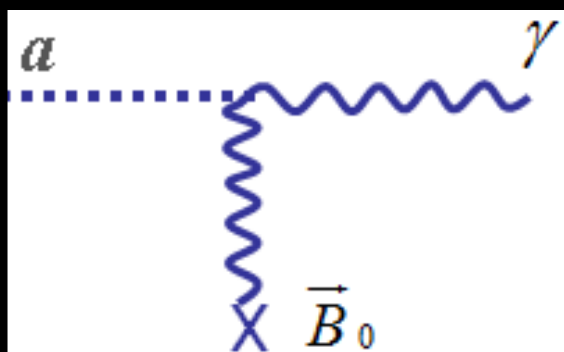


200 MHz

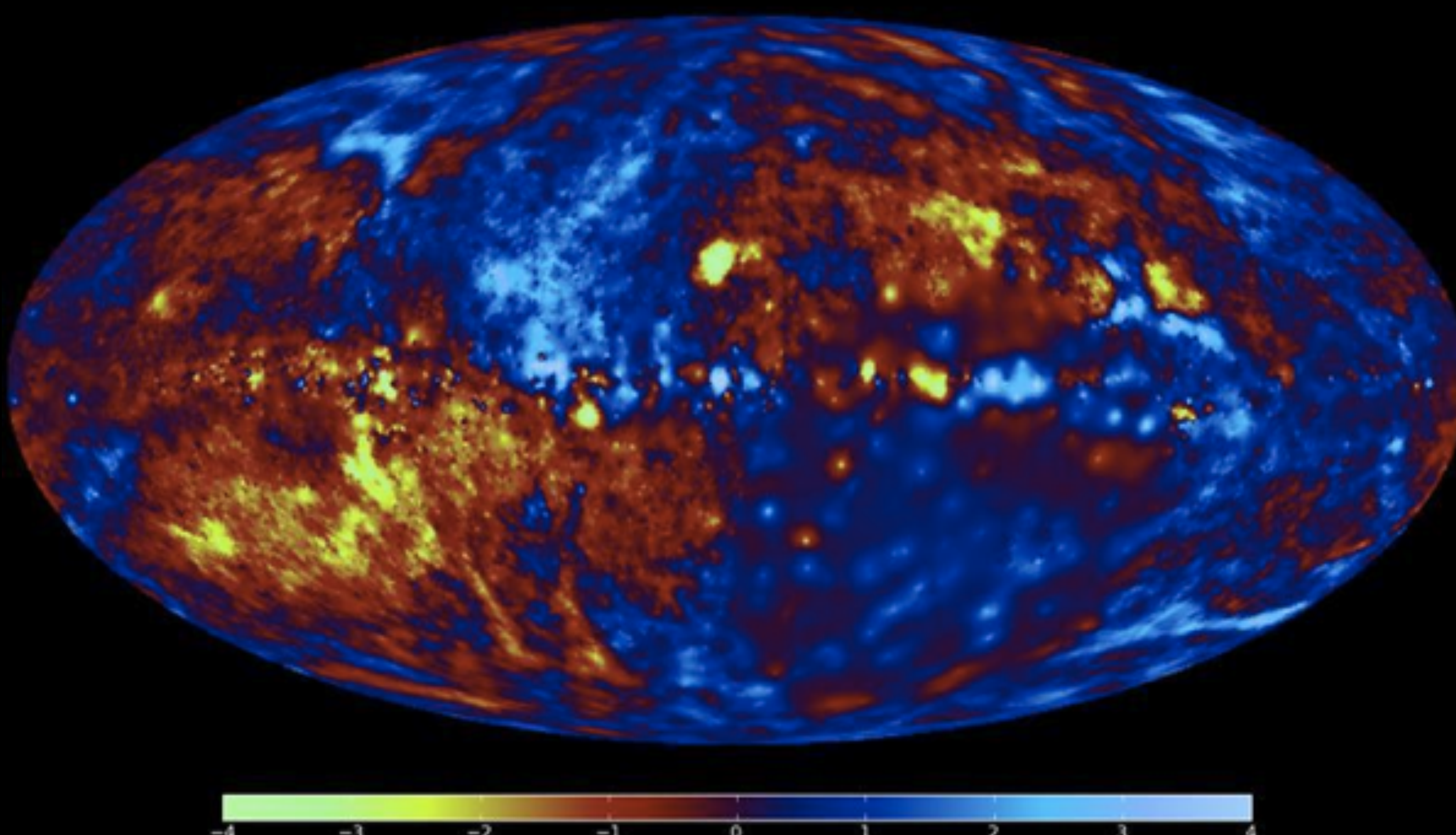
2 GHz

Broad Band - low Field - large Volume

Sivikie 1983



$$\frac{number\ of\ photons}{time} = \frac{\rho_{DM,avg}}{10gcm^{-23}}\left[\frac{1.6}{10^6 s}\right]\left[\frac{Volume}{1cm^3}\right]\left[\frac{B_{avg}}{10^4 G}\right]^2$$



Milky Way
B: 10^{-6} - 10^{-3} G
V: 10^{68} cm^3

Niels Oppermann, Georg Robbers, Torsten A. Enßlin, MPIA, 2011

Astrophysical Sources

$$\Gamma(\mathbf{k}_a \to \mathbf{k}_\gamma) \propto g^2_{a\gamma\gamma} \int_{\mathbf{k}_\gamma} \frac{d^3\mathbf{k}_\gamma}{(2\pi)^3} \delta\left(k_\gamma - m_a\right) \sum_{\lambda_\gamma} \left| |\mathbf{B}_i(\mathbf{k}_{\gamma'} = \mathbf{k}_\gamma)||\epsilon^\dagger_{\gamma i}| cos\alpha \right|^2$$

MILKY WAY

$$Flux \propto m_a c^2 \Gamma(\mathbf{k}_a \to \mathbf{k}_\gamma) \frac{\rho_a}{m_a} \frac{V}{4\pi d_i^2}$$

EXTRA-GALACTIC

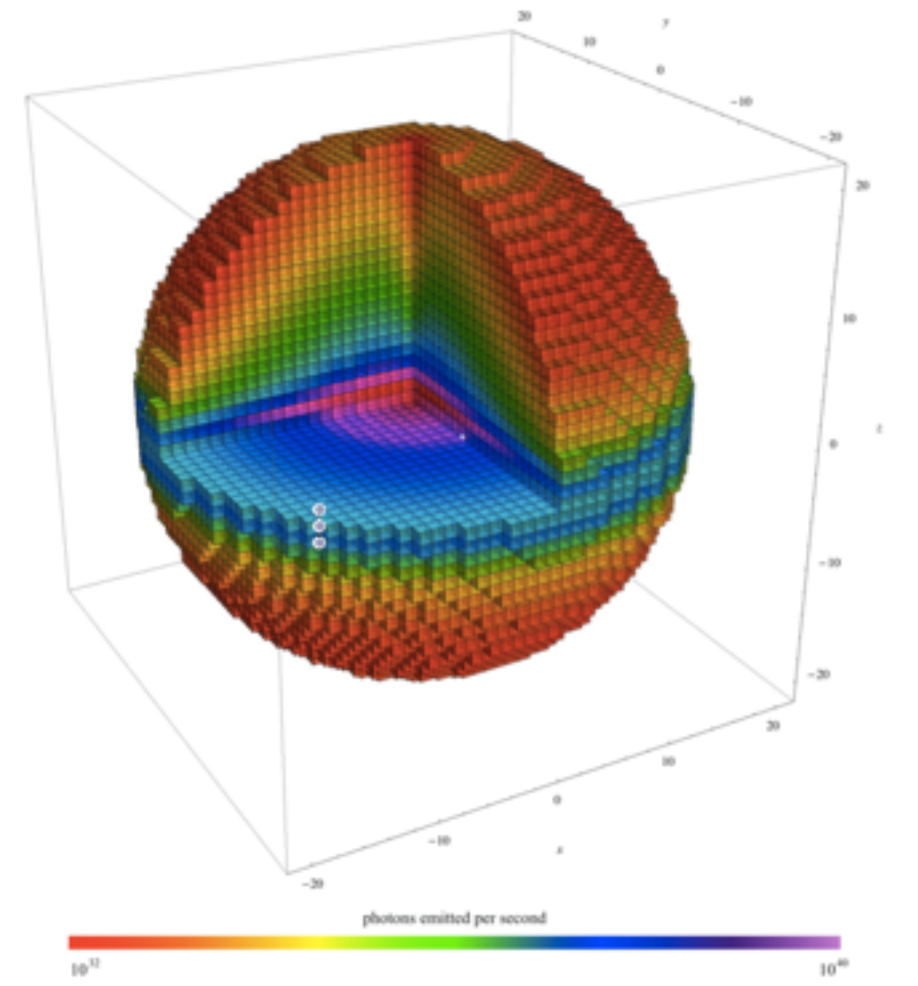
$$Flux \propto m_a c^2 \Gamma(\mathbf{k}_a \to \mathbf{k}_\gamma) \frac{\rho_a}{m_a} \theta^3 d_e$$

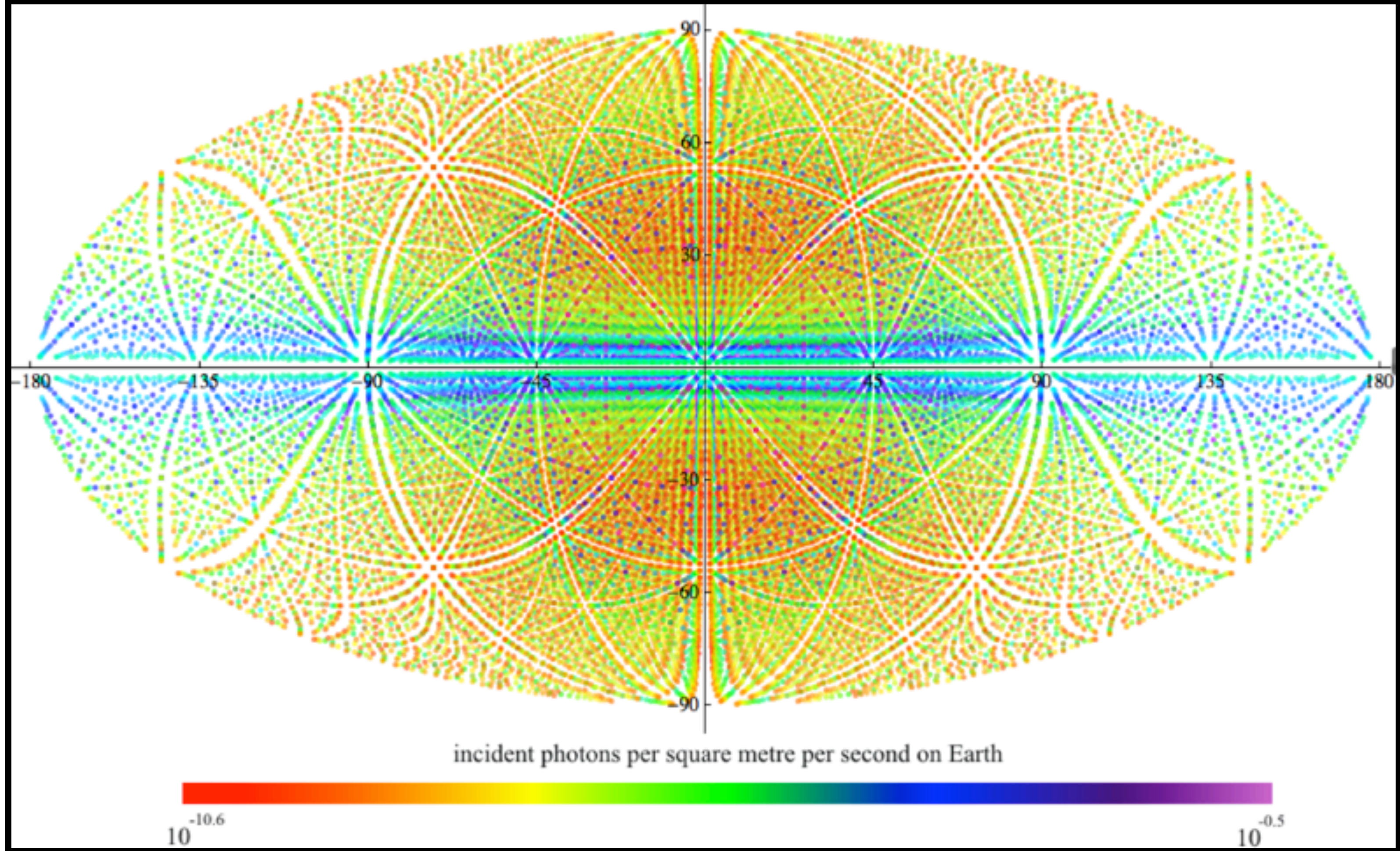
Milky Way

$$\mathcal{L}_{a\gamma\gamma} = g_{\gamma} a \vec{E} \cdot \vec{B}_0$$

- Max flux at 200MHz-500MHz corresponding to zero momentum modes for the axion - Expect spectral profile to be asymmetric when including the energy distribution of the axion
- Line width: 1MHz (changing with the seasons)
- Polarisation of the spectral profile should trace the magnetic field
- Flux 10^{-30} $Wm^{-2}Hz^{-1}$ – using magnetic field across whole sphere and assuming average magnetic field strength of 1µG
- 10^{-31} $Wm^{-2}Hz^{-1}$ - using only the Galactic Plane, assuming disc 3kpc think and average magnetic field strength of 1µG
- Opportunities:
  - high magnetic fields and high densities are co-located in the galactic centre which may enhance the conversion rate
  - Observations can be made over long integration times
- Challenges:
  - impact of the directionality of the polarisation and the knock on impact on detection
  - Damping of the conversion rate due to the spatial profile of the field
  - Difficult to use interferometers due to the removal of the diffuse background by the correlation process
  - Line is very broad

Axion emission maps - preliminary





Photon rates on Earth : $10^{-10.6}$ - $10^{-0.5}$ /sec/m^2

Total SKY signal ~ 20 photons/sec/m^2

~ 3x10^{-4} Jy (10^{-26}W/m^2/Hz) (BW=10^6Hz)

~ 3x10^{-21} W into 1000 m^2

work with Marc White

Dave Tanner

$$P = 4 \cdot 10^{-22}\ \mathrm{W} \left(\frac{V}{200\ \ell}\right) \left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 \left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_{\mathrm{a}}}{0.5 \cdot 10^{-24}\ \mathrm{g/cm^3}}\right) C_{nl} \left(\frac{m_{\mathrm{a}}}{1\ \mathrm{GHz}}\right) \left(\frac{\min(Q_{\mathrm{L}}, Q_{\mathrm{a}})}{1 \times 10^5}\right)$$

Clusters and other sources

- Line width: 2MHz, Based on velocity dispersion of $1{,}000 kms^{-1}$
- Polarisation should trace the structure of the magnetic field
- $10^{-33} - 10^{-35}$ $Wm^{-2}Hz^{-1}$ for Virgo, Perseus and Coma – with Virgo offering the highest Flux at 10^{-33}
- Mass density and magnetic field lower than that for Milky Way
- Averaging across the full volume gives a more accurate approximation than that for Milky Way:
- Opportunities:
  - Clusters can be stacked to improve the signal

54 M. Thierbach et al.: The diffuse radio emission from the Coma cluster

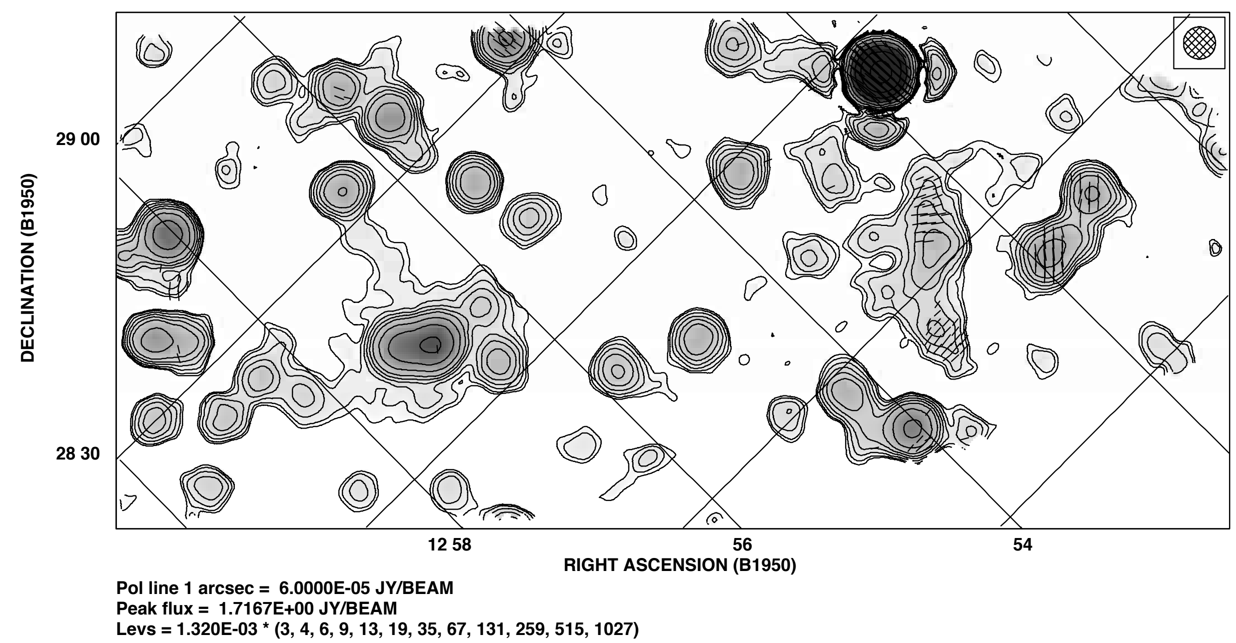
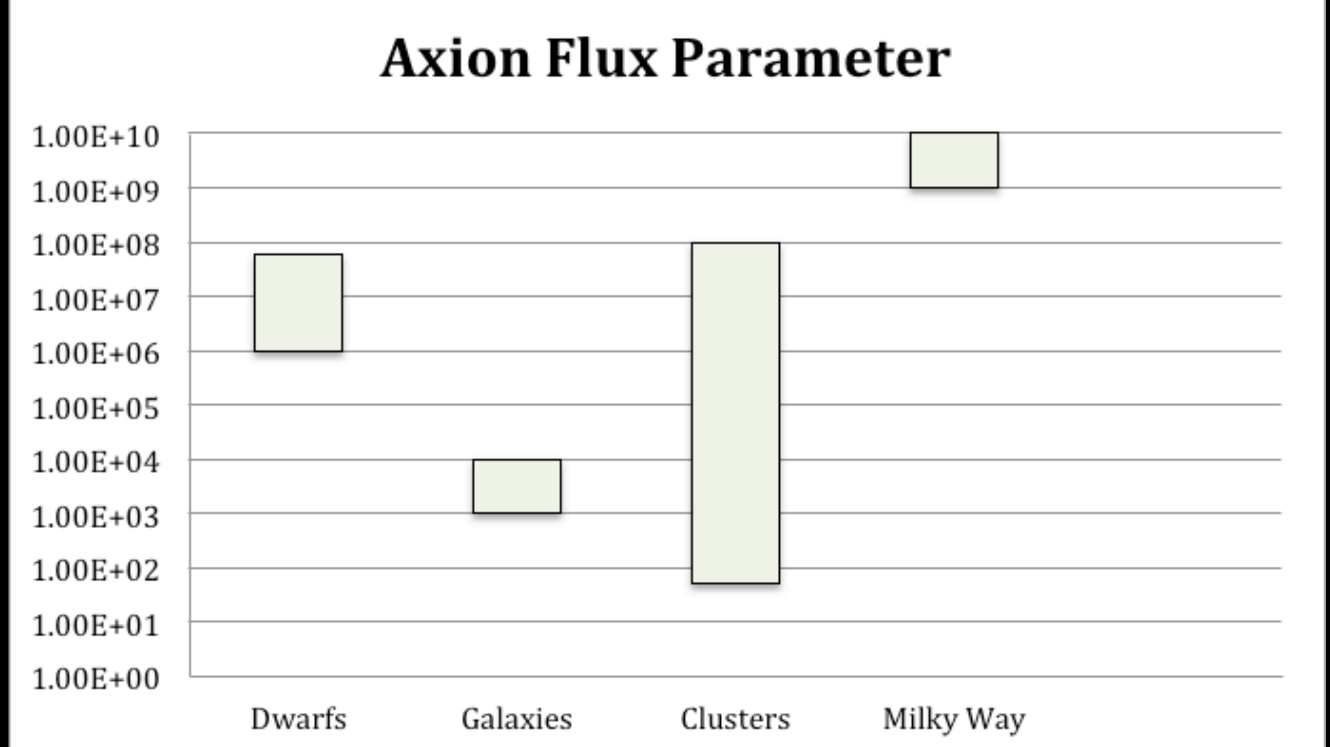


Fig. 1. The Coma cluster of galaxies at 2.675 GHz. NE is to the left. The lowest contour marks the 3σ level. The polarized intensity is represented by the length of the E–vectors. Note that the cluster center ($\alpha = 12^h57^m$, $\delta = 28°12'$) does not show any significant polarization.



Precursor and SKA

Axion sky signal
~ 0.1 mJy
~ 10^6 MWA sec
~ 1 year given
BG

Telescope	Aperture (A) (m^2)	$A/T_{receiver}$	Sensitivity mJy/SQRT(sec) @ BW=1MHz	Total Axion Power received (W)	Axion Antenna Temperature (K)
MWA	10^3	20	100	2.6×10^{-21}	0.2 mK
SKA Phase 1 Low	10^5	1000	1	2.6×10^{-19}	20 mK

Assumed description for SKA1 and SKA2

		SKA1_low	SKA1_mid	SKA2_low	SKA2_mid_dish	SKA2_AIP_AA	AIP_PAF	Comments
Collector type		Sparse AA [1]	15m dish [1]	Sparse AA [1]	15m dish [1]	Dense AA [1]	15m dish+PAF [1]	Offset feed dishes
No. of collectors		280 [3][9]	250 [1]	280 [3][10]	2,500 [11]	280 [3]	2000 [15]	
Frequency range	GHz	0.07 – 0.45 [1]	0.45 – 3.0 [1]	0.07 – 0.45 [2]	0.45 – 10 [11]	0.4 – 1.4 [2]	0.45 – 3.0 [13]	50MHz goal
Max bandwidth	GHz	0.38 [1]	1.5 [8]	0.38 [2]	*Depends on feed*	1.0 [8]	0.3	
Dish feeds: 1. 2. 3.	GHz GHz GHz		0.45 – 0.9 [1] 0.8 – 1.6 [1] 1.5 – 3.0 [1]		To be decided		0.45 – 0.9 [13] 0.8 – 1.6 [13] 1.5 – 3.0 [13]	
Effective FoV	deg^2		*1GHz:* 1.0 [1]	200 [4]	*1GHz:* 1.0 [1]		*0.5GHz:* 144 deg^2 [13] *1GHz:* 36 deg^2 [13] *2GHz:* 9 deg^2 [13]	15m dish FoV
No. of beams		160 [1]	1		1		36	
Sensitivity: /element	m^2K^{-1}	*131 MHz:* 7.2 [8]	*1-2GHz:* 4.0 [8]	*>90MHz:* 14.3 [8]	4.0 [8]	*<1.2GHz:* 36 [8]	*1-2GHz:* 3.5 [14]	
total sensitivity	m^2K^{-1}	*131MHz:* 1,515 [1] *300 MHz:* 889 [1]	*1-2GHz:* 1,031 [1] *0.45-1GHz:* 773 [1]	*>90MHz:* 4,000 [2]	10,000 [2]	*<1.2GHz:* 10,000 [2] *1.4GHz:* 5,000 [2]		Sensitivity of AA on boresight