A Search for Thermal Gyrosynchrotron Emission from Hot Stellar Coronae

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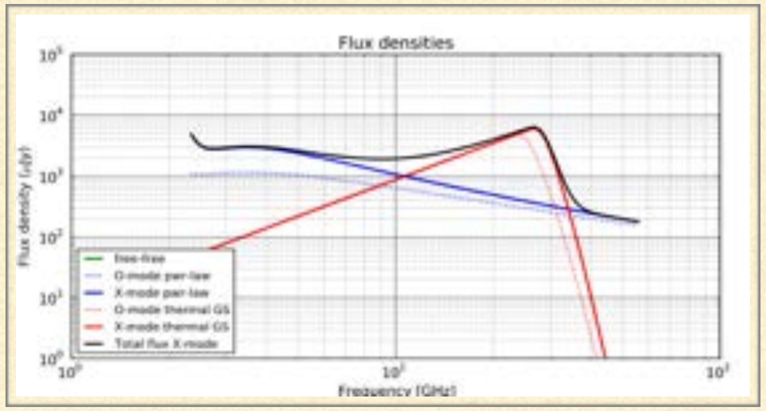
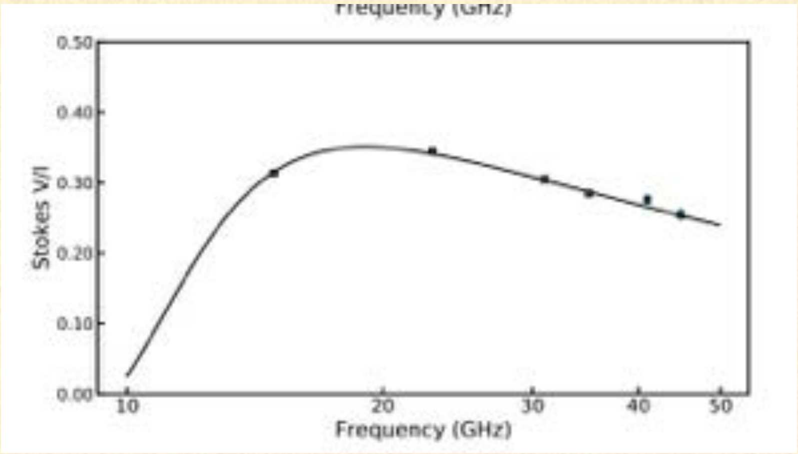
Outline

Summary of radio emission from power-law, thermal gyrosynchrotron sources

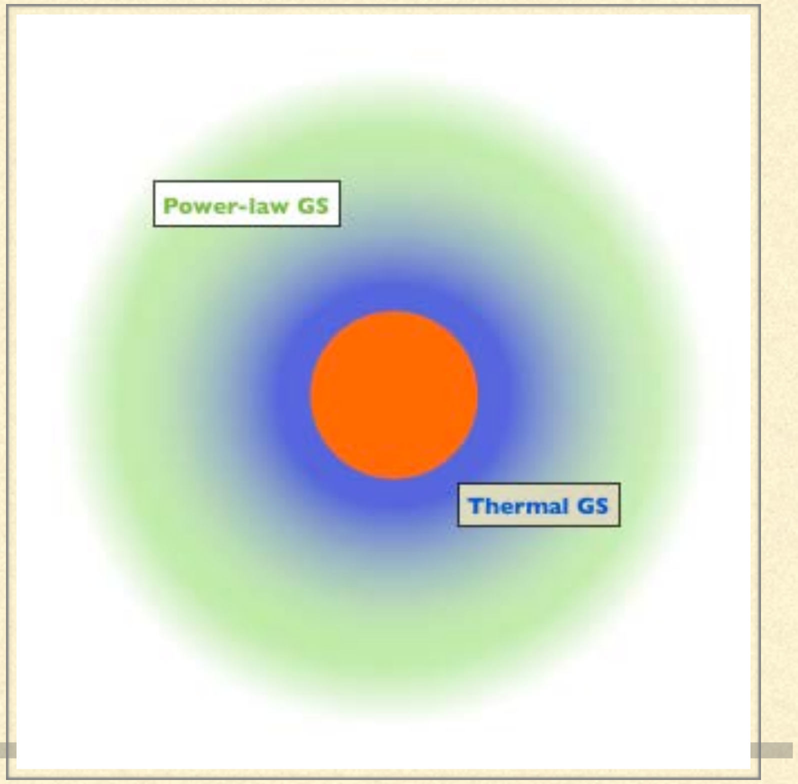


VLA survey of 8 radio-loud stars



Model-fitting SEDs (Stokes I, V)

Derived physical parameters (T, B)



Note on terminology

Need to differentiate between descriptions of :

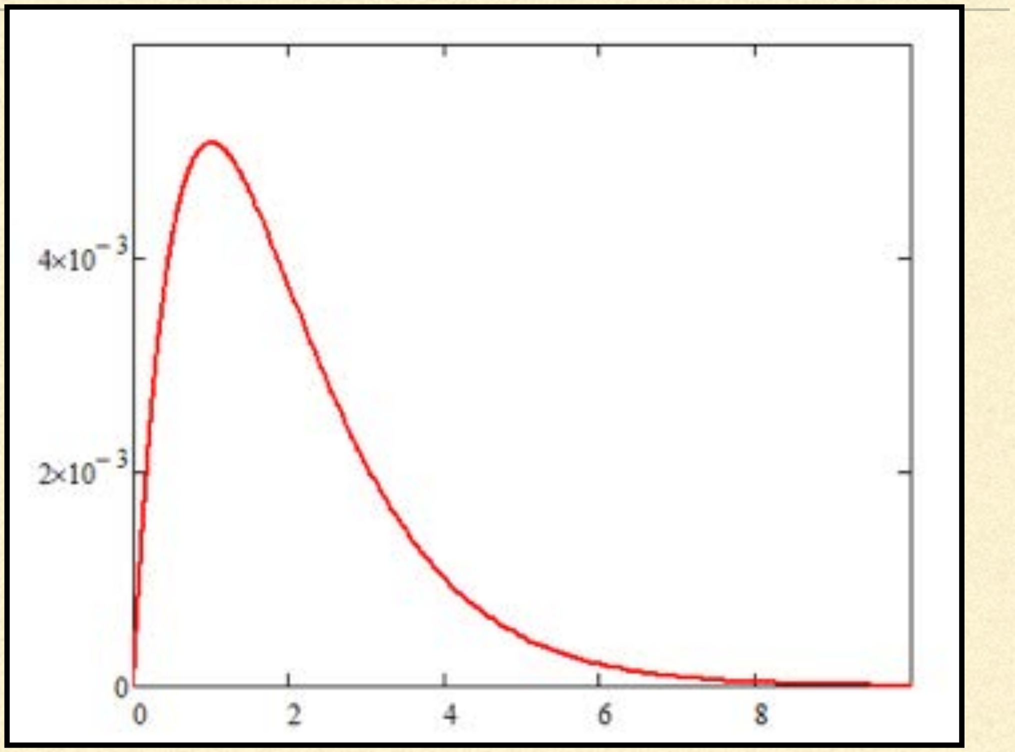
- ✓energy (velocity) distribution of emitting electrons
- ✓radio emission process

Electron velocity distributions: Maxwellian (“thermal”), power-law, kappa, nu, etc. (N.B. some assert that most astrophysical plasmas are closer to kappa rather than Maxwellian)

Emission processes: Bremsstrahlung (‘free free’), Magneto-bremsstrahlung (gyro-resonance, gyro-synchrotron, synchrotron), Coherent (ECMI, plasma)

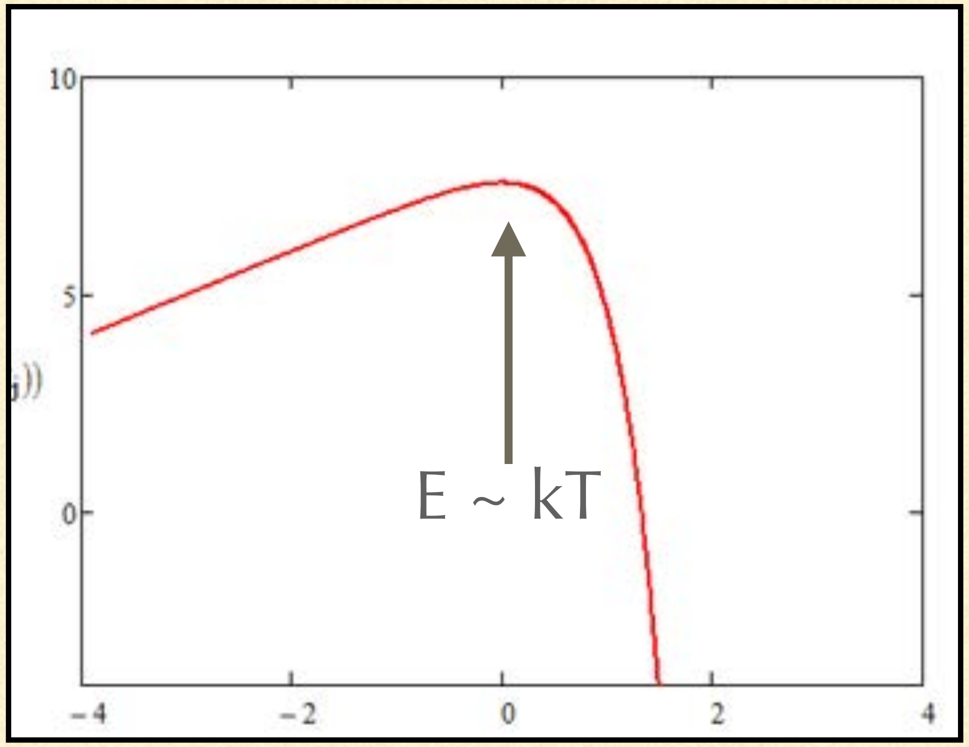
Avoid using the term ‘thermal emission’

Thermal gyro-synchrotron emission is driven by high-energy tail of Maxwellian [thermal] energy distribution



Thermal energy pdf (linear)

Thermal gyro-synchrotron emission is sharply peaked near E~ kT



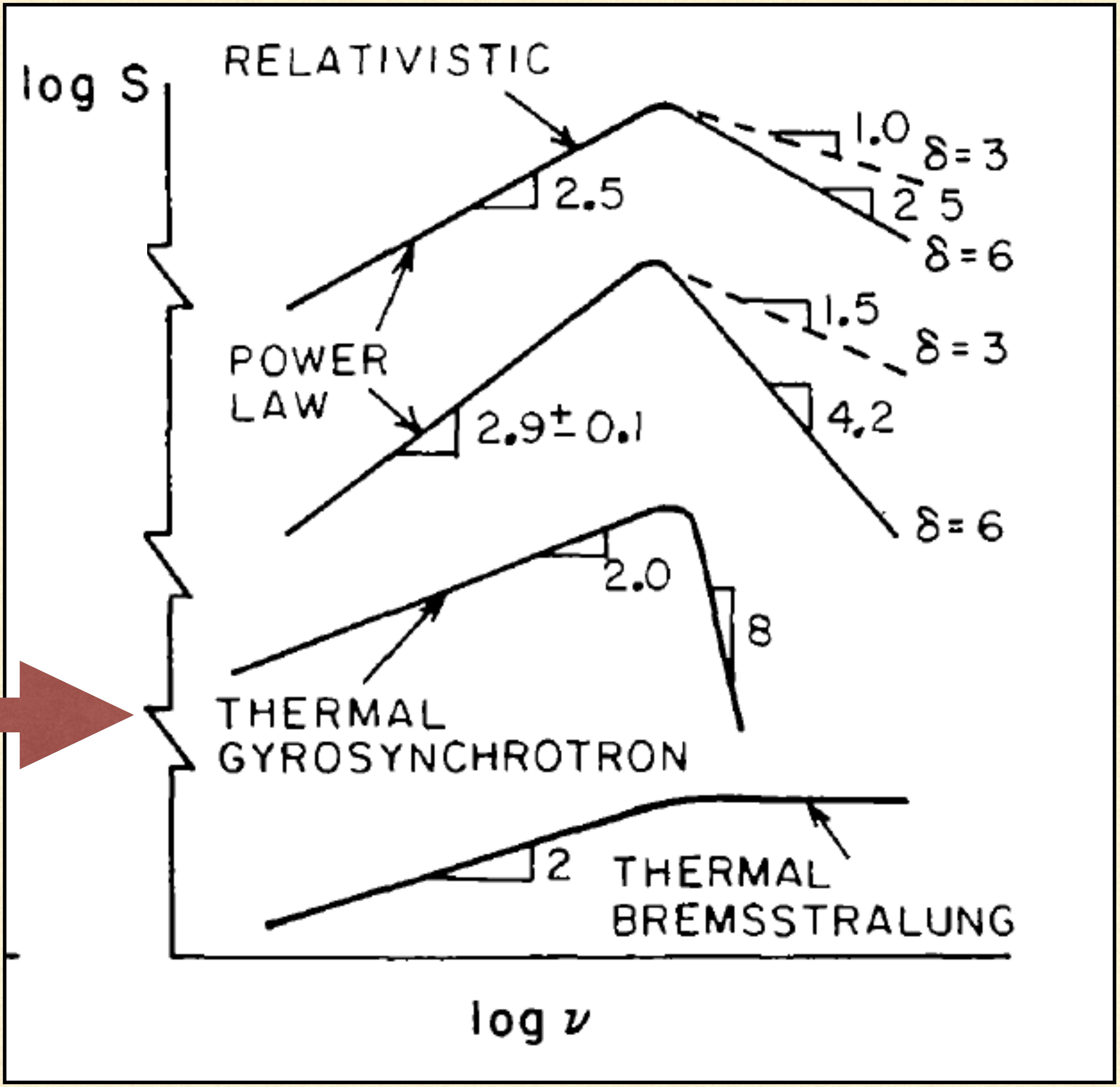
Thermal energy pdf (log-log)

Optical depth for thermal GS emission: Strong function of T,B

$$\tau_\nu (B,T) = 1.2 \boxed{\left[\frac{T}{10^8\,K}\right]^7} \cdot \boxed{\left[\frac{B}{kG}\right]^9} \cdot \left[\frac{\upsilon}{10\,GHz}\right]^{-10} \left[\frac{N_e}{10^5\,cm^{-3}}\right] \cdot \left[\frac{L}{R_\odot}\right]$$

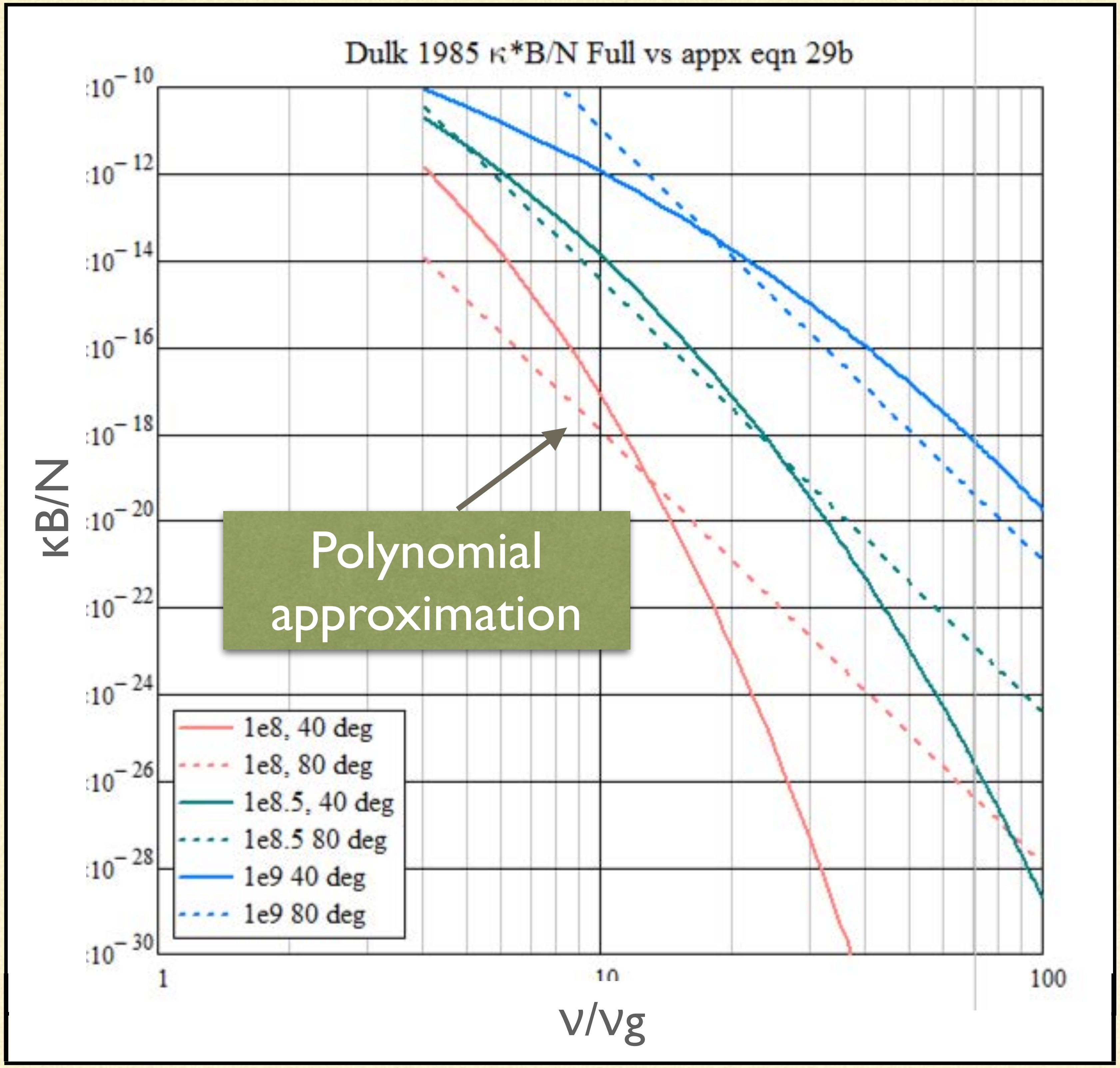
- Very optically thin until $T \sim 10^{7.5}$ K, $B \sim 10^3$ G
- Spectral peak near optical depth $\tau \sim 1$ => $f > 10$ GHz

SED's of various
emission processes



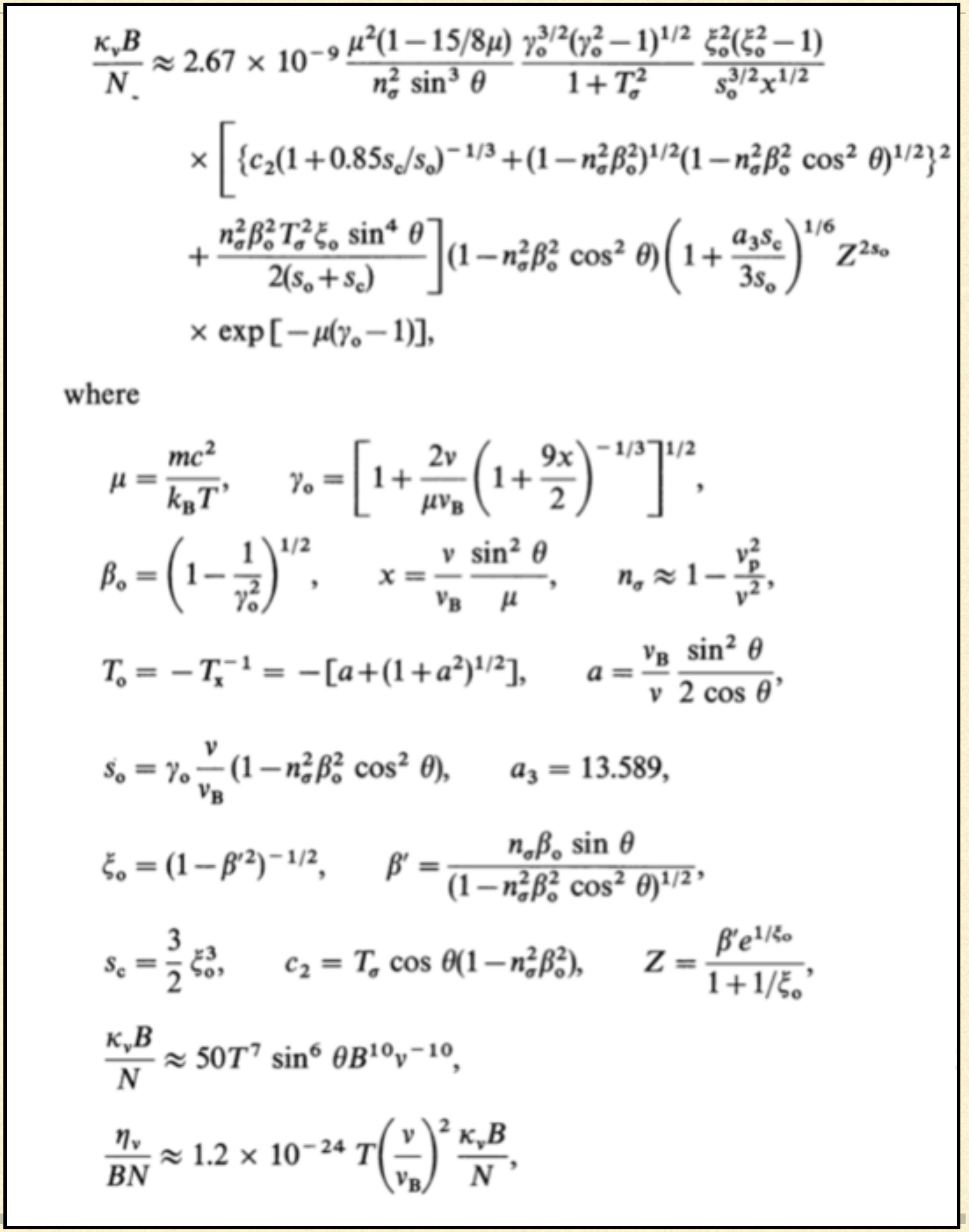
Dulk 1985

Thermal GS absorption coefficient
Full expression vs. Dulk & Marsh 1982; Dulk ARAA 1985 polynomial (eqn 29b)



Polynomial approximation

Thermal GS absorption coefficient Full expression Dulk ARAA 1985 ; also Robinson & Melrose 1984



$$\frac{\kappa_\nu B}{N} \approx 2.67 \times 10^{-9} \frac{\mu^2(1-15/8\mu)}{n_\sigma^2 \sin^3\theta} \frac{\gamma_o^{3/2}(\gamma_o^2-1)^{1/2}}{1+T_\sigma^2} \frac{\xi_o^2(\xi_o^2-1)}{s_o^{3/2}x^{1/2}}$$

$$\times \left[\{c_2(1+0.85s_c/s_o)^{-1/3} + (1-n_\sigma^2\beta_o^2)^{1/2}(1-n_\sigma^2\beta_o^2\cos^2\theta)^{1/2}\}^2 \right.$$

$$\left. + \frac{n_\sigma^2\beta_o^2T_\sigma^2\xi_o\sin^4\theta}{2(s_o+s_c)} \right] (1-n_\sigma^2\beta_o^2\cos^2\theta)\left(1+\frac{a_3s_c}{3s_o}\right)^{1/6} Z^{2s_o}$$

$$\times \exp[-\mu(\gamma_o-1)],$$

where

$$\mu = \frac{mc^2}{k_BT}, \qquad \gamma_o = \left[1+\frac{2\nu}{\mu\nu_B}\left(1+\frac{9x}{2}\right)^{-1/3}\right]^{1/2},$$

$$\beta_o = \left(1-\frac{1}{\gamma_o^2}\right)^{1/2}, \qquad x = \frac{\nu}{\nu_B}\frac{\sin^2\theta}{\mu}, \qquad n_\sigma \approx 1-\frac{\nu_p^2}{\nu^2},$$

$$T_o = -T_x^{-1} = -[a+(1+a^2)^{1/2}], \qquad a = \frac{\nu_B}{\nu}\frac{\sin^2\theta}{2\cos\theta},$$

$$s_o = \gamma_o\frac{\nu}{\nu_B}(1-n_\sigma^2\beta_o^2\cos^2\theta), \qquad a_3 = 13.589,$$

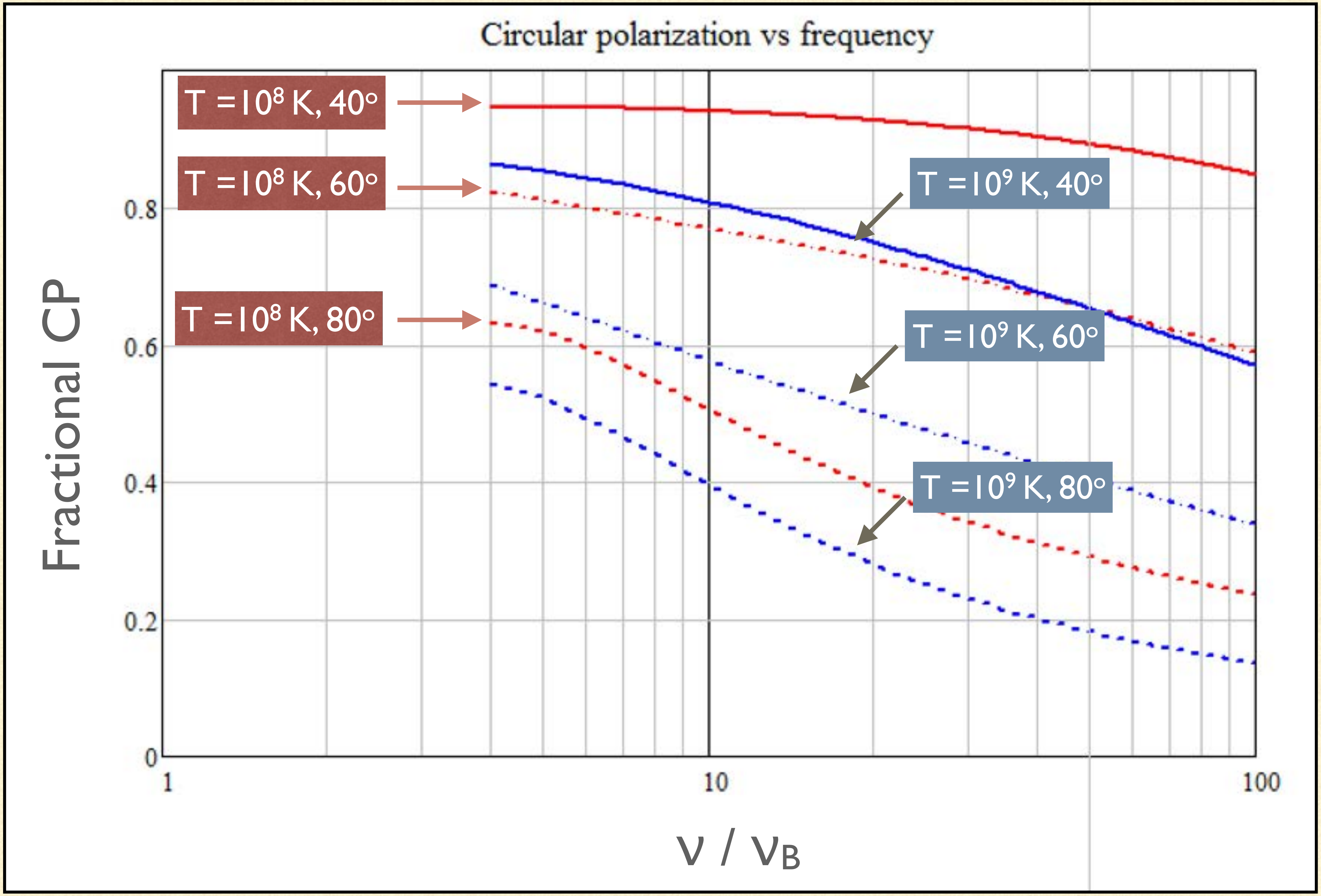
$$\xi_o = (1-\beta'^2)^{-1/2}, \qquad \beta' = \frac{n_\sigma\beta_o\sin\theta}{(1-n_\sigma^2\beta_o^2\cos^2\theta)^{1/2}},$$

$$s_c = \frac{3}{2}\xi_o^3, \qquad c_2 = T_\sigma\cos\theta(1-n_\sigma^2\beta_o^2), \qquad Z = \frac{\beta' e^{1/\xi_o}}{1+1/\xi_o},$$

$$\frac{\kappa_\nu B}{N} \approx 50T^7\sin^6\theta B^{10}\nu^{-10},$$

$$\frac{\eta_\nu}{BN} \approx 1.2\times 10^{-24}\,T\left(\frac{\nu}{\nu_B}\right)^2\frac{\kappa_\nu B}{N},$$

Thermal GS emission: Fractional circular polarization



T =10^8 K, 40°

T =10^8 K, 60°

T =10^8 K, 80°

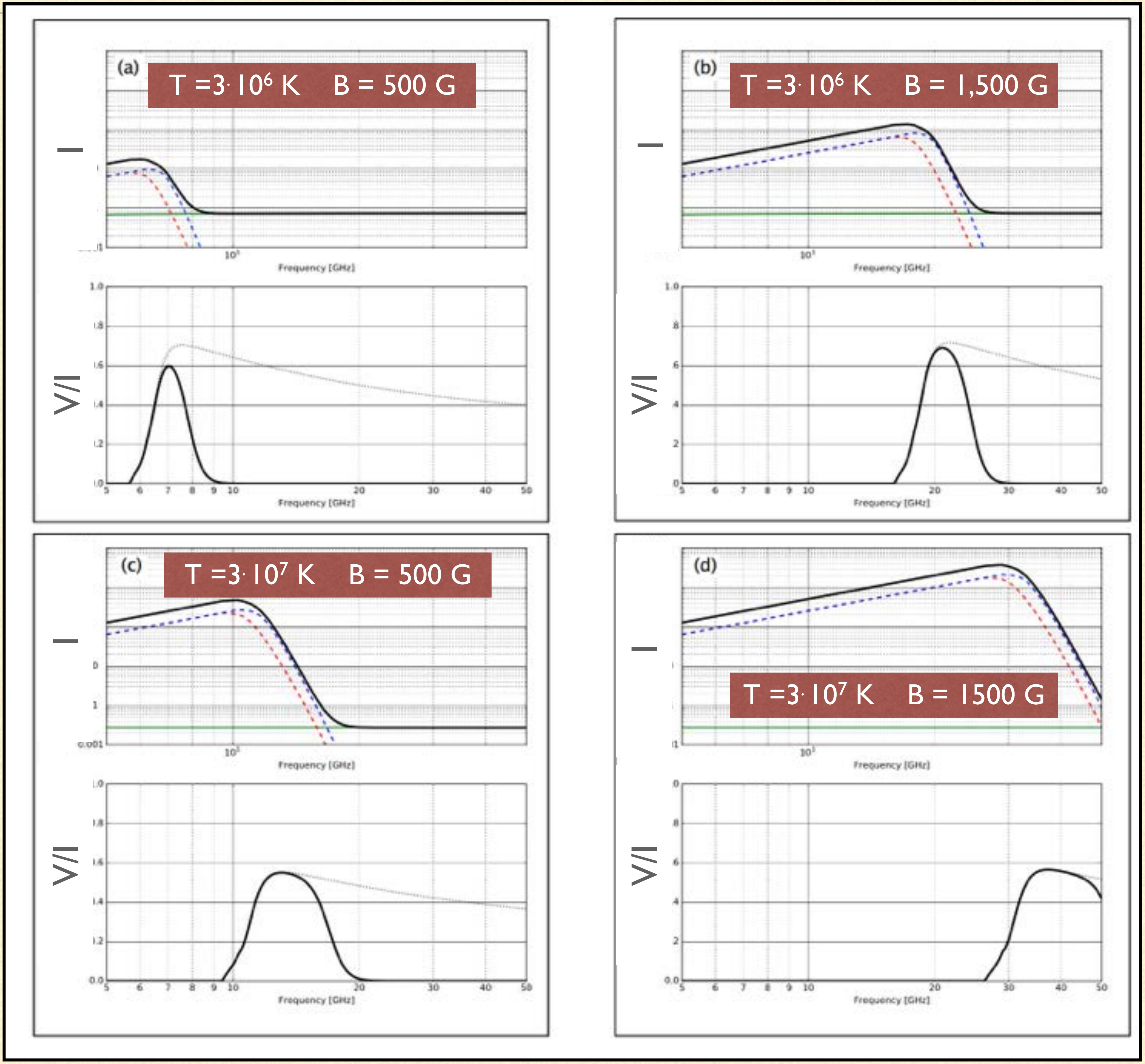
T =10^9 K, 40°

T =10^9 K, 60°

T =10^9 K, 80°

Thermal GS SED is a strong function of T, B

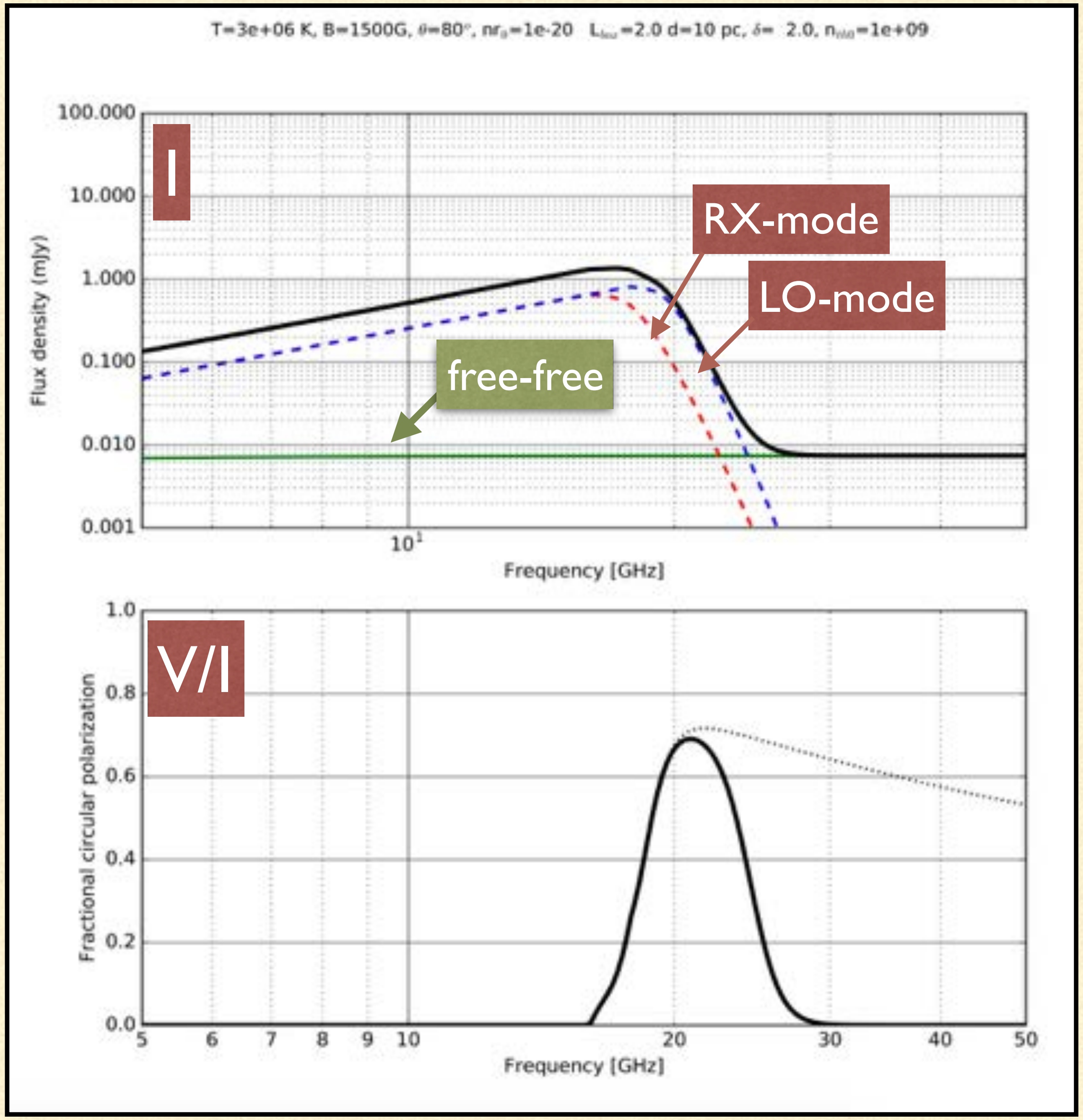
red = O mode
blue = X mode
green = free-free
black = sum



Thermal Gyrosynchrotron SED's

B= 1500 G, φ= 80° n_{th} = 10^9

T= $3 \cdot 10^6$ K



I

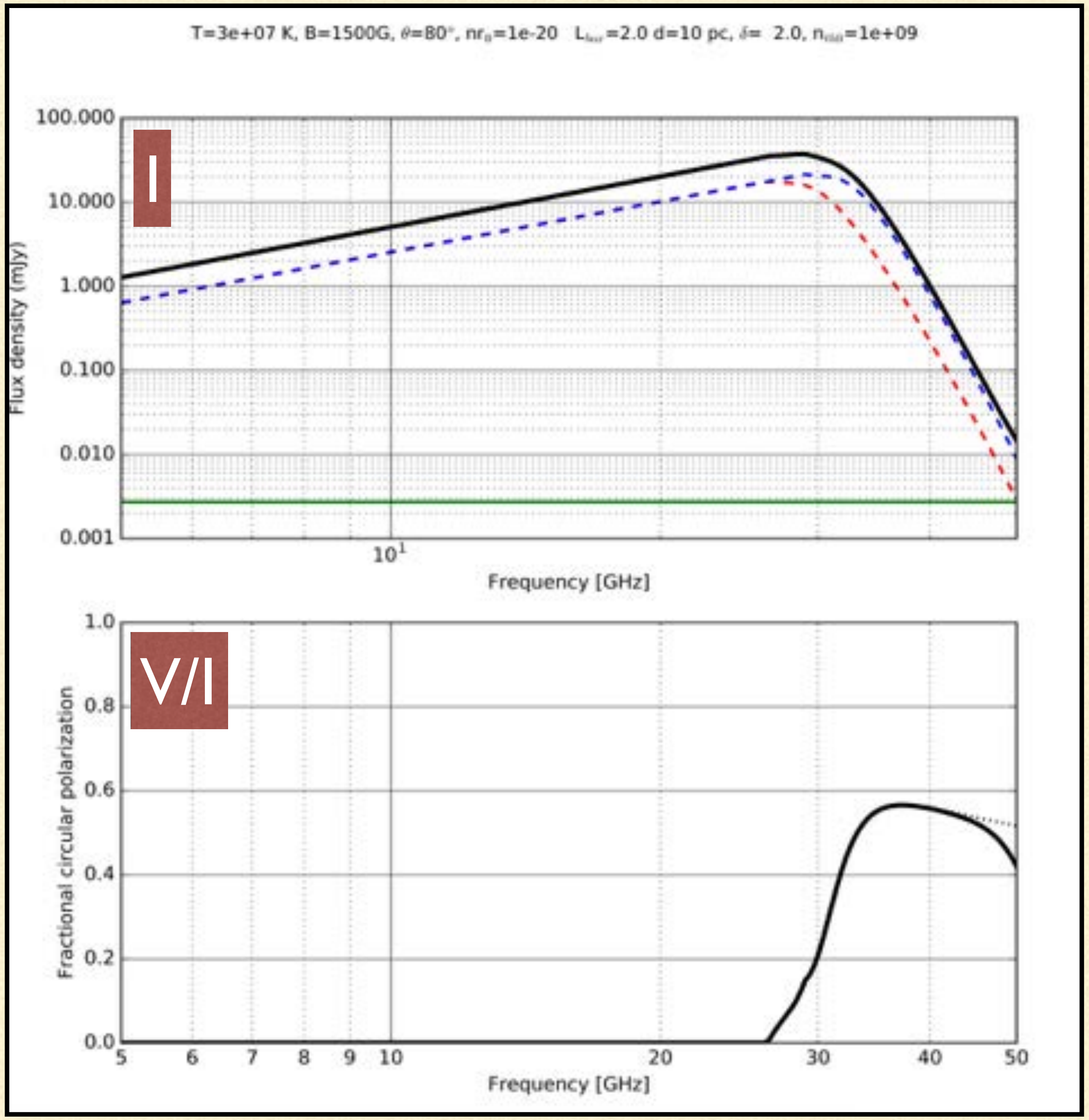
RX-mode

LO-mode

free-free

V/I

T= $3 \cdot 10^7$ K



I

V/I

Power-law + thermal GS emission model

$n_{th} = 3 \cdot 10^8$

$n_{pwr} = 3 \cdot 10^5$

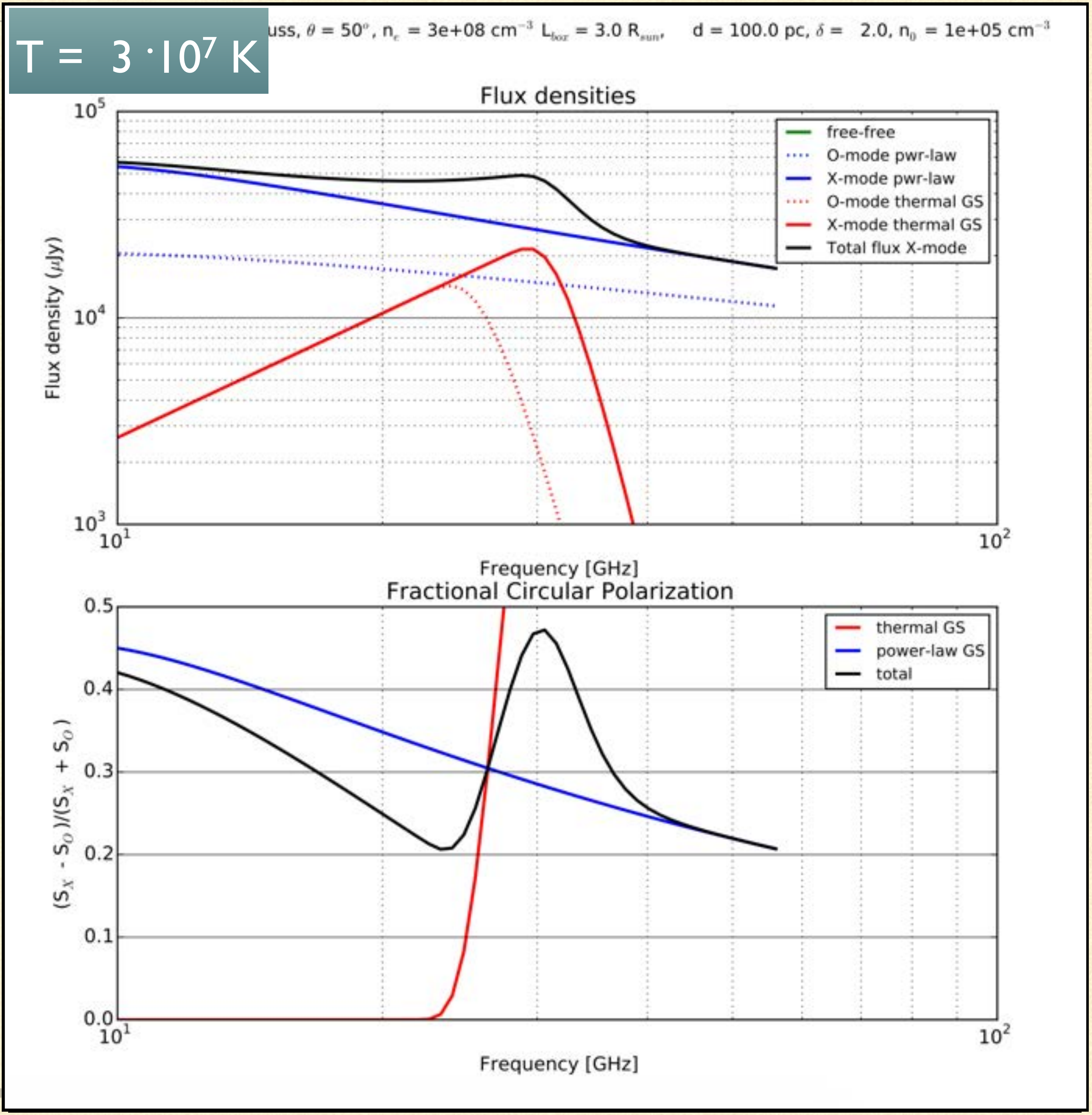
$B = 2000$ G

$L = 3\ R_{sun}$

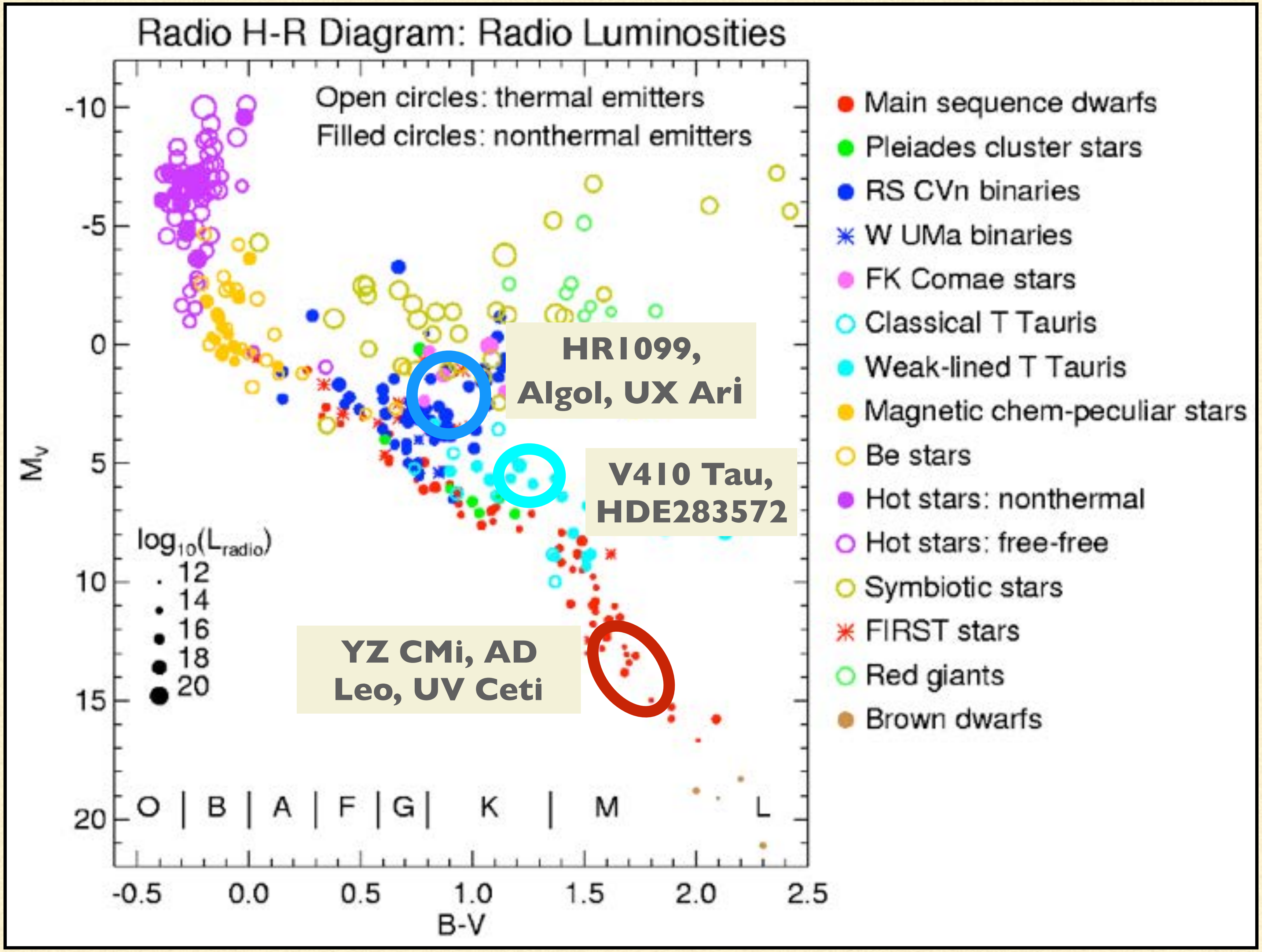
$d = 100$ pc

$\delta = 2.0$

$T = 3 \cdot 10^7$ K



VLA survey: 8 radio-loud stars



HR1099, Algol, UX Ari

V410 Tau, HDE283572

YZ CMi, AD Leo, UV Ceti

VLA observations

f = 15, 23, 31, 36, 41, 45 GHz, 2 GHz BW

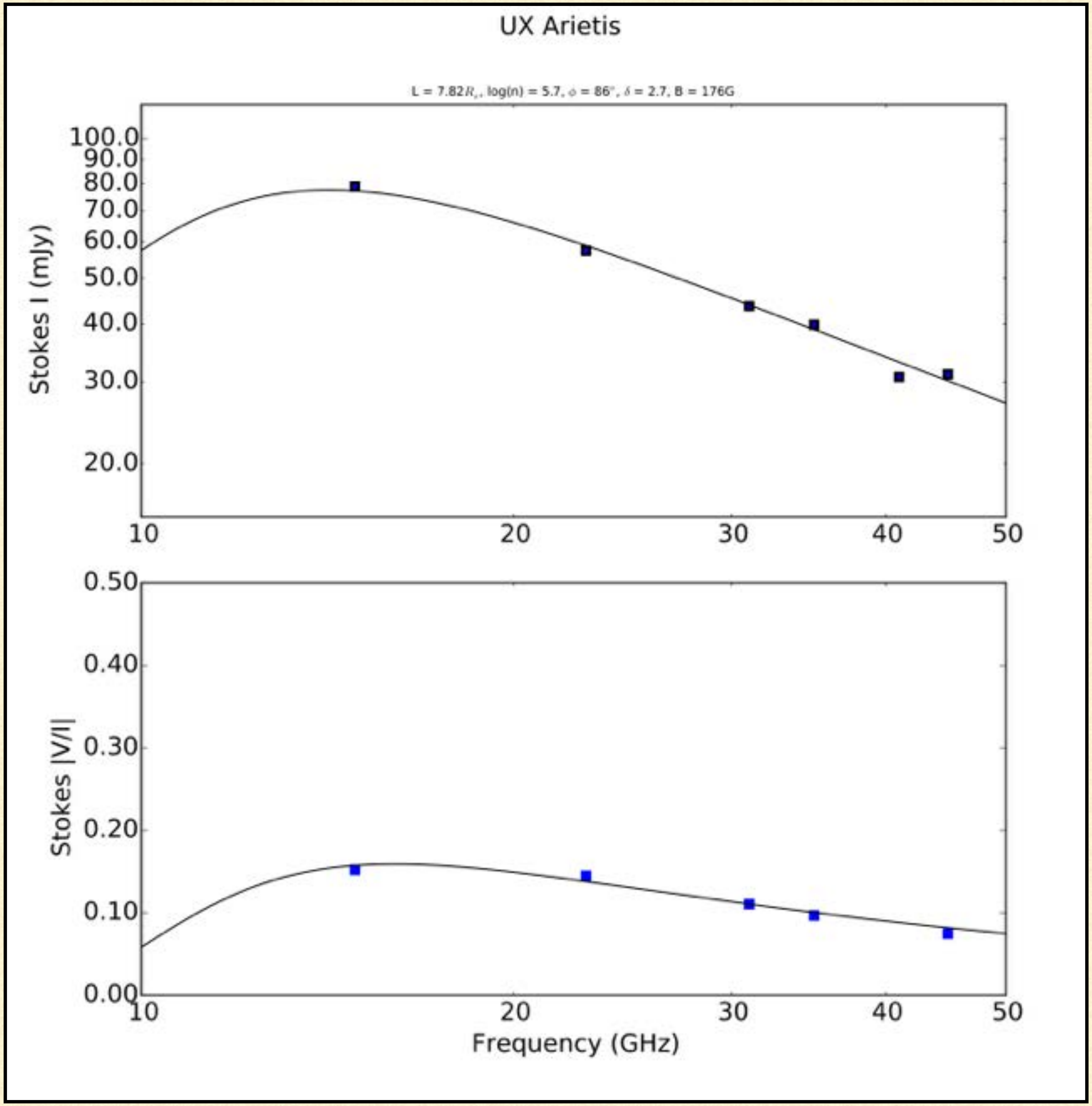
2 hour total [each star]

STAR	SP. TYPE	R/RSUN	T (MK)	B (KG)	REFS
Algol	**K0IV** + B8V	3.5	1.7	-	Peterson 2011. van den Oord 1989; Ness 2002
UX Arietis	**K0IV** + G5V	3.0	3.1	-	Guedel 1999; Ness 2002
HR1099	**K1IV** + G5IV	3.7	2.5	0.5-6	Ness 2002; Audard 2001
YZ Cmi	dM4.5e	0.26	1.3	2.0-2.5	Shuylak 2010; Raassen 2007
AD Leo	dM3.5e	0.39	2.2	3.0-3.5	Shuylak 2010
UV Ceti	M6V+M5V	0.14	3-6	6.7	Kochukhov 2017; Audard 2003
V410 Tau	K3V (WTTS)	2.3	14.8	2.0	Carroll 2012
HD 283572	G5III (WTTS)	2.7	13.0	-	Telleschi 2007

UX Arietis

$L = 7.8\ R_{sun}$
$B = 176\ G$
$\log(n_e) = 5.7$
$\varphi_B = 86^o$
$\delta = 2.2$

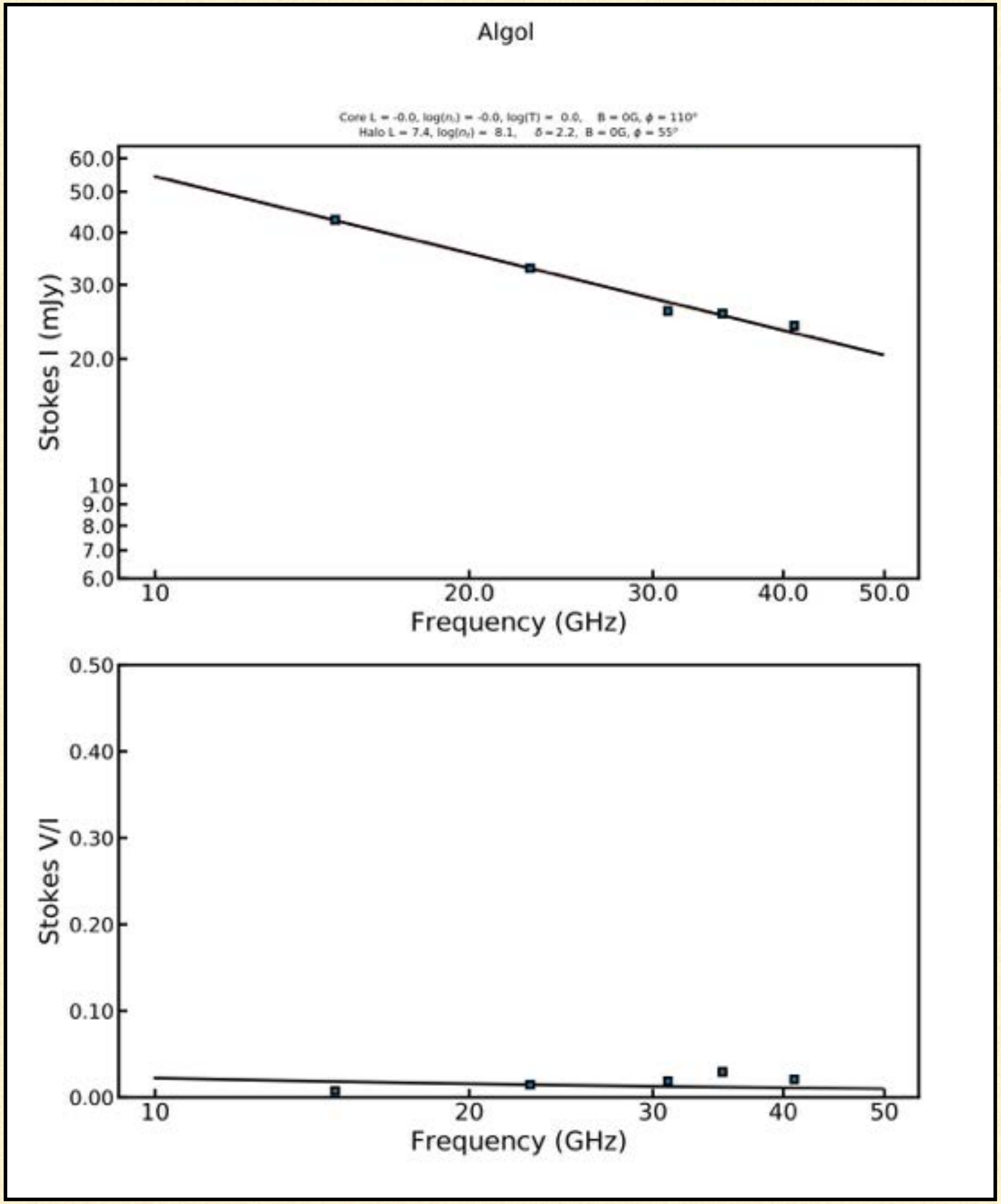
Size agrees with VLBI (15 GHz)
(Peterson et al. 2012)



Algol

$L = 7.4\ R_{sun}$
$B = 176\ G$
$\log(n_e) = 8.1$
$\varphi_B = 55^o$
$\delta = 2.2$

Size agrees with VLBI (15 GHz)
(Peterson et al. 2012)



HR 1099

$L = 2.6\ R_{sun}$

$B = 241$ G

$\log(n_e) = 6.8$

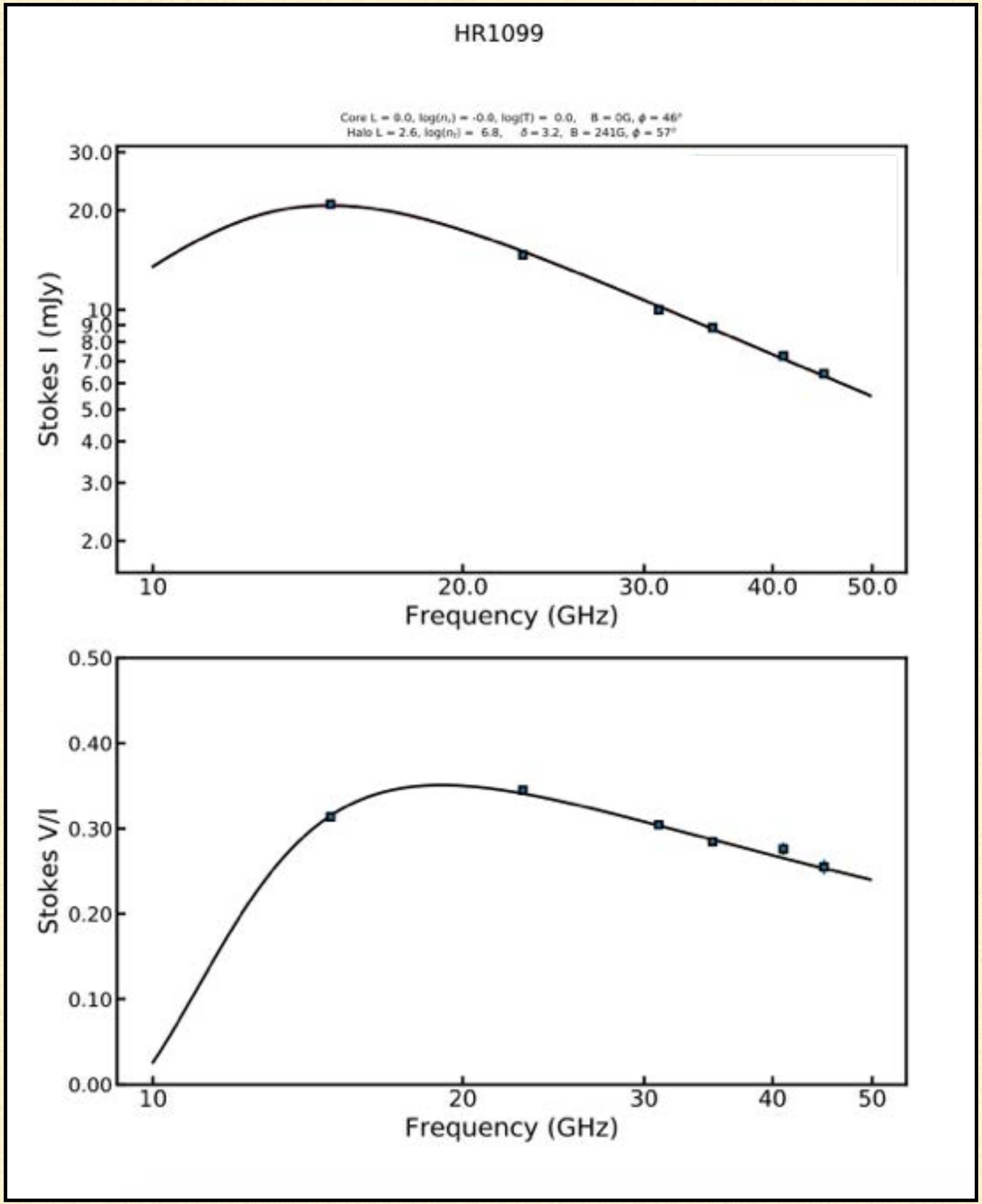
$\varphi_B = 57^o$

$\delta = 3.2$

Size disagrees with VLBI

22 GHz $L \sim 7\ R_{sun}$

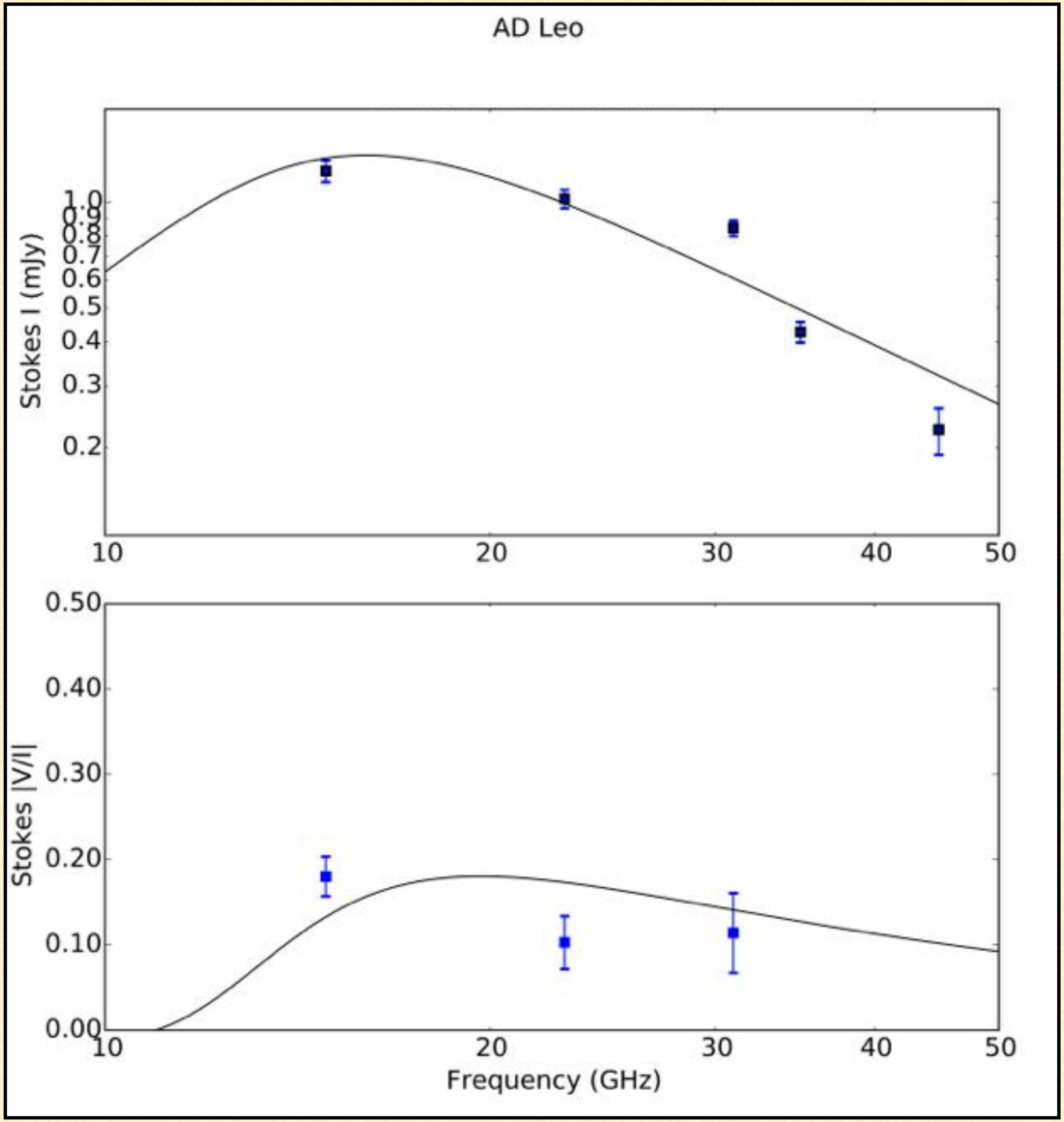
(Abbuhl et al. 2017)



AD Leo

$L = 0.08\ R_{sun}$
$B = 129\ G$
$\log(n_e) = 10.6$
$\varphi_B = 88^o$
$\delta = 3.9$

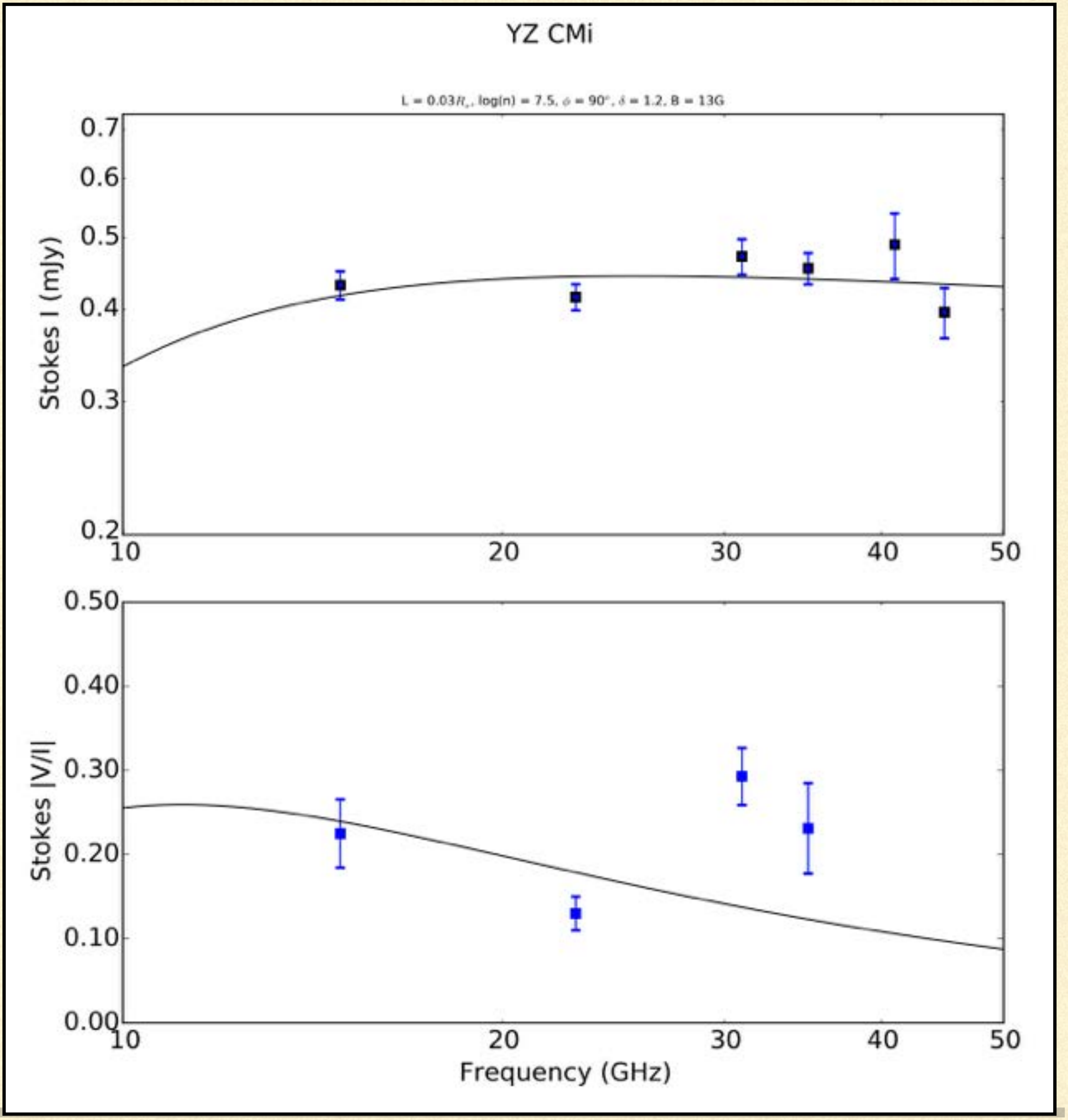
Much smaller corona, steeper power-law index, higher density



YZ CMi

$L = 0.03\ R_{sun}$
$B = 13\ G$
$\log(n_e) = 7.5$
$\varphi_B = 88^o$
$\delta = 1.2$

Much smaller corona, flatter power-law index



Extended Power-law corona

$L = 14.6\ R_{sun}$

$B = 11\ G$

$\log(n_e) = 5.0$

$\varphi_B = 138^o$

$\delta = 2.3$

Thermal hot corona

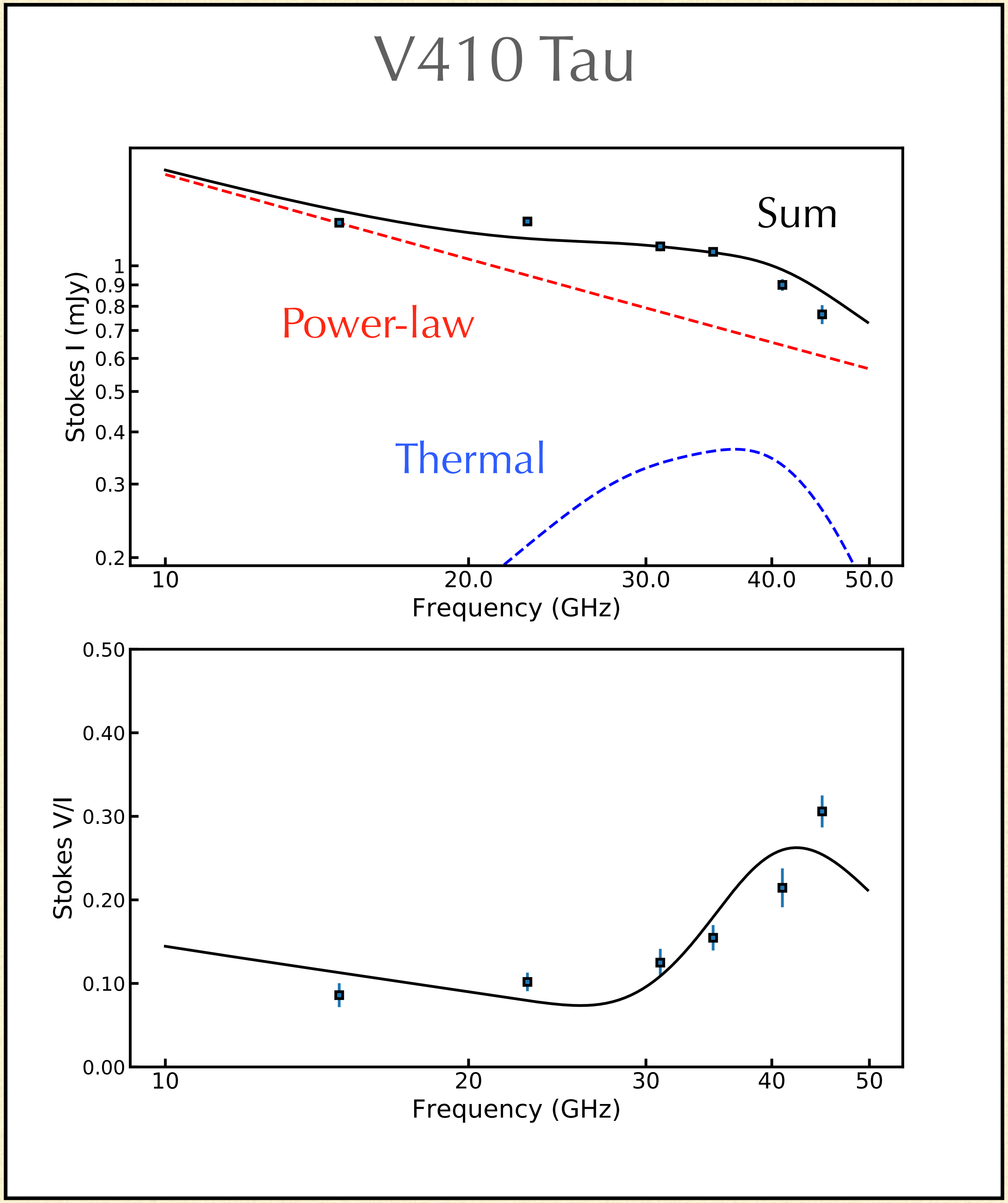
$L = 0.8\ R_{sun}$

$\log(T) = 7.5$

$B = 2.9\ kG$

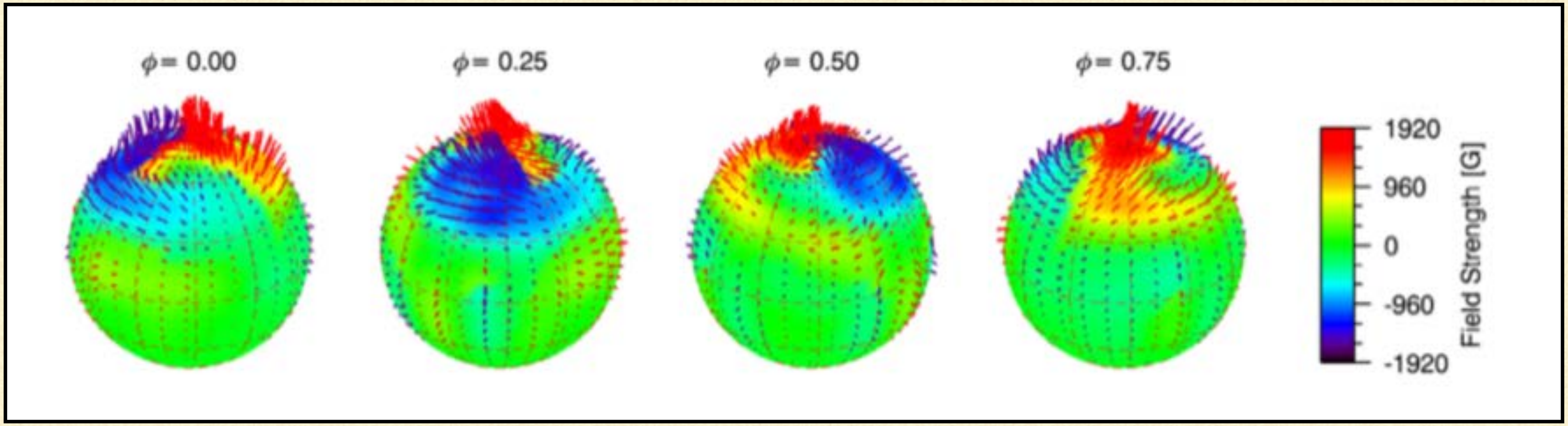
$\log(n_e) = 11.2$

$\varphi_B = 138^o$

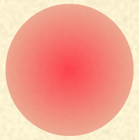


V410 Tau

1. Magnetic field from Doppler imaging



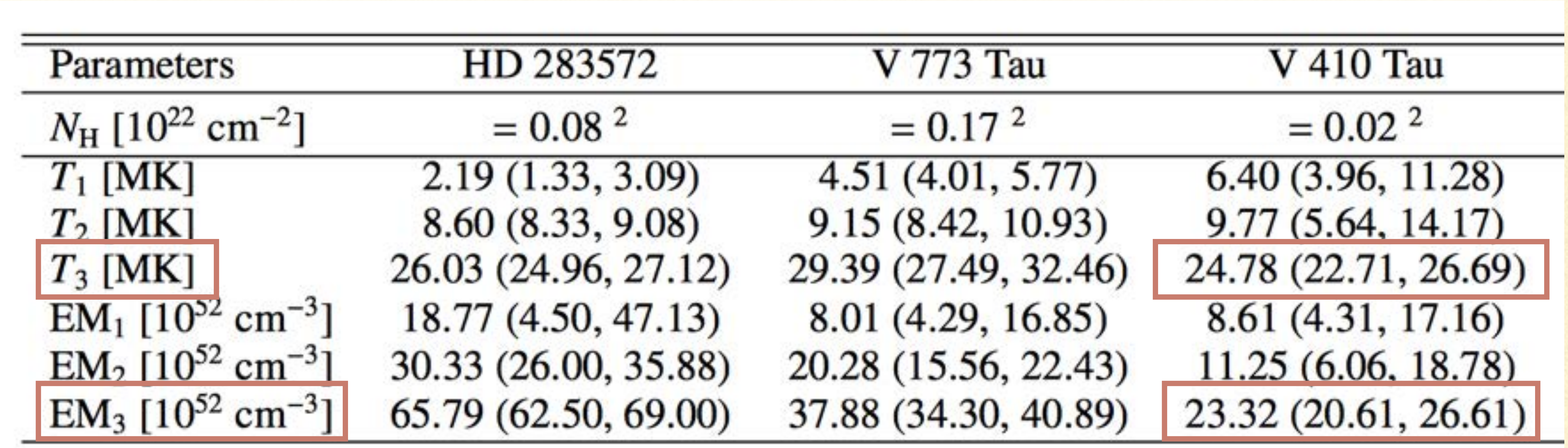
Carroll et al. 2012



Model size hot coronal component (B = 2.8 kG)

V410 Tau

2. Coronal temperature, EM from Xray obs.



Parameters	HD 283572	V 773 Tau	V 410 Tau
N_H [10^{22} cm^{-2}]	= 0.08 [2]	= 0.17 [2]	= 0.02 [2]
T_1 [MK]	2.19 (1.33, 3.09)	4.51 (4.01, 5.77)	6.40 (3.96, 11.28)
T_2 [MK]	8.60 (8.33, 9.08)	9.15 (8.42, 10.93)	9.77 (5.64, 14.17)
T_3 [MK]	26.03 (24.96, 27.12)	29.39 (27.49, 32.46)	24.78 (22.71, 26.69)
EM_1 [10^{52} cm^{-3}]	18.77 (4.50, 47.13)	8.01 (4.29, 16.85)	8.61 (4.31, 17.16)
EM_2 [10^{52} cm^{-3}]	30.33 (26.00, 35.88)	20.28 (15.56, 22.43)	11.25 (6.06, 18.78)
EM_3 [10^{52} cm^{-3}]	65.79 (62.50, 69.00)	37.88 (34.30, 40.89)	23.32 (20.61, 26.61)

Telleschi et al. 2007

Thermal GS model:

$T = 30$ MK

$EM = n_e^3 L = 44 \cdot 10^{52}$ cm^{-3}

HD 283572

Extended Power-law corona

$L = 4.5\ R_{sun}$

$B = 216$ G

$\log(n_e) = 5.8$

$\varphi_B = 80^o$

$\delta = 2.8$

Thermal hot corona

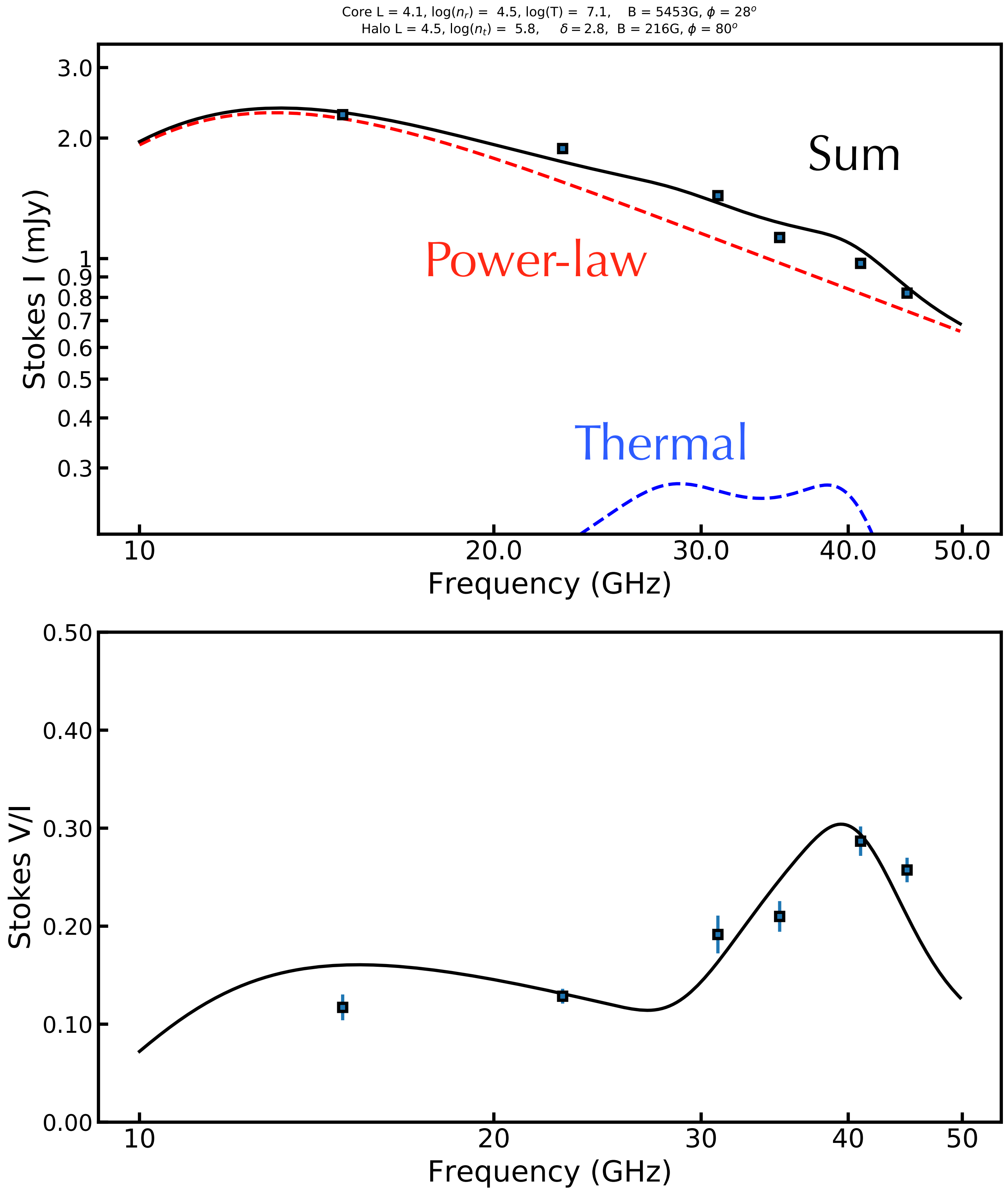
$L = 4.1\ R_{sun}$

$\log(T) = 7.1$

$B = 5.4$ kG

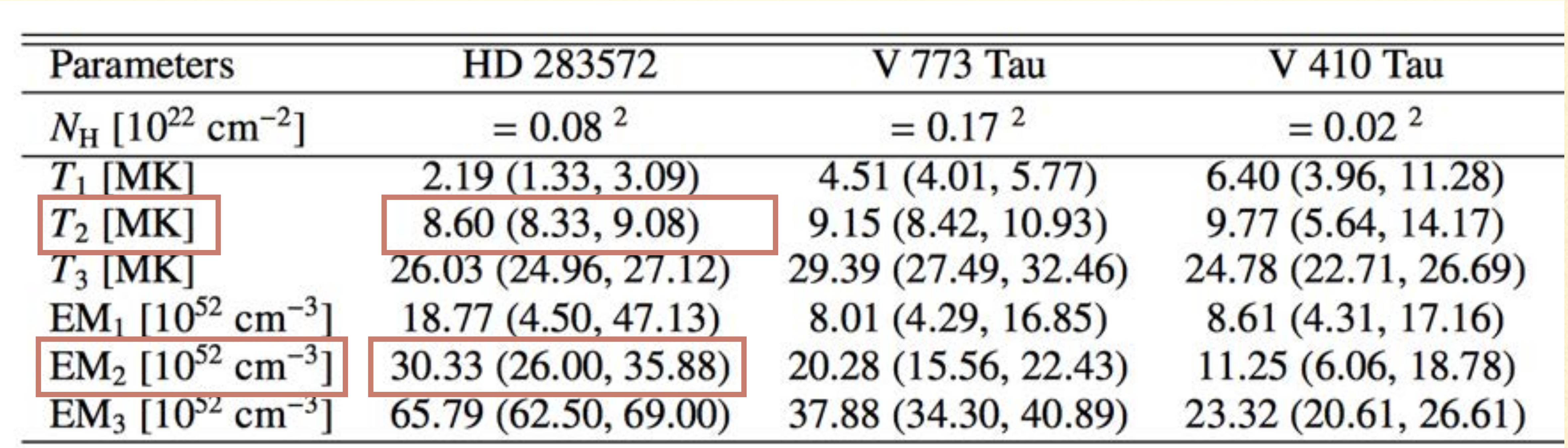
$\log(n_e) = 9.5$

$\varphi_B = 28^o$



HD 283572

2. Coronal temperature, EM from Xray obs.



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EM_3 [10^{52} cm^{-3}]	65.79 (62.50, 69.00)	37.88 (34.30, 40.89)	23.32 (20.61, 26.61)

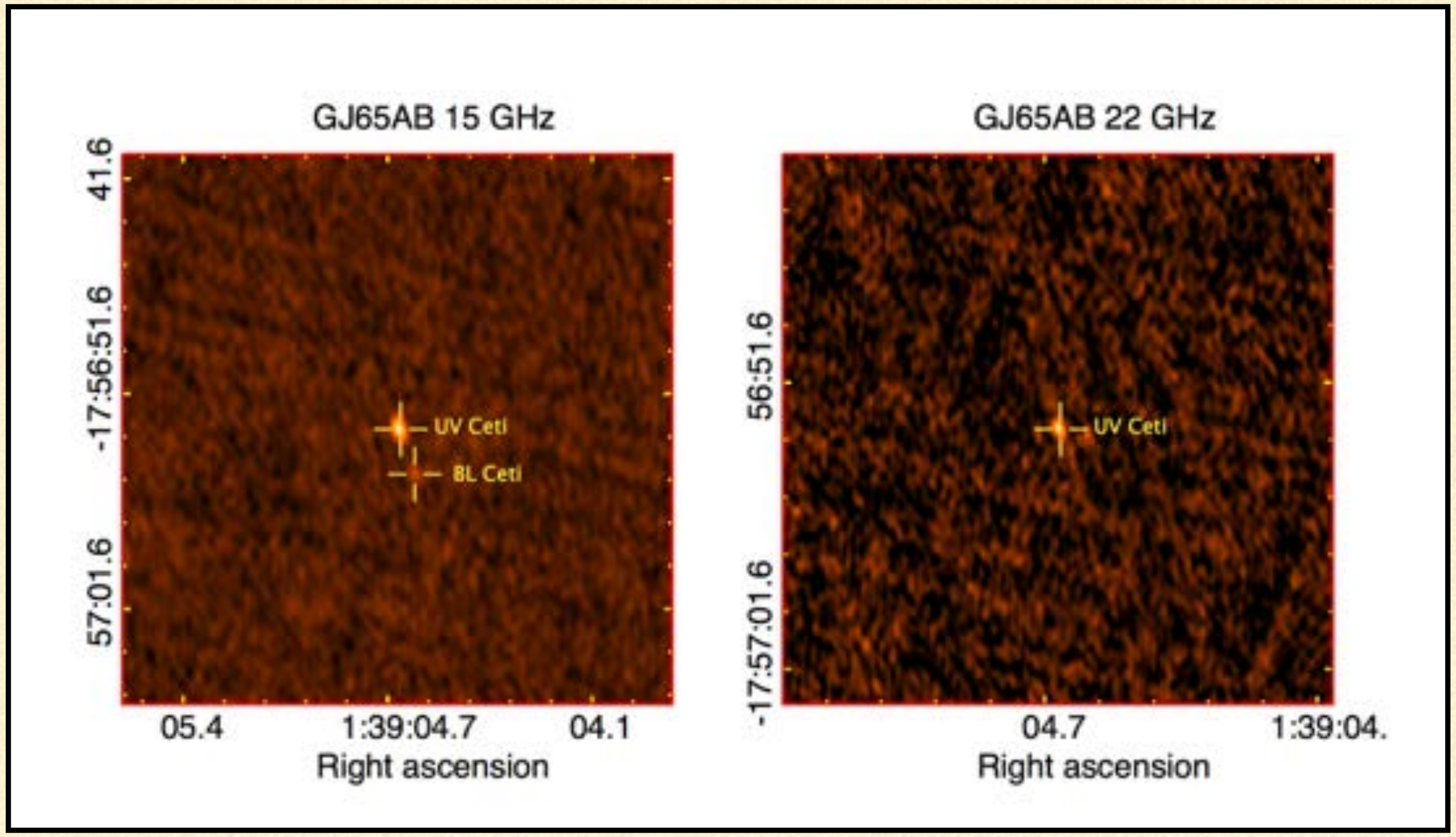
Telleschi et al. 2007

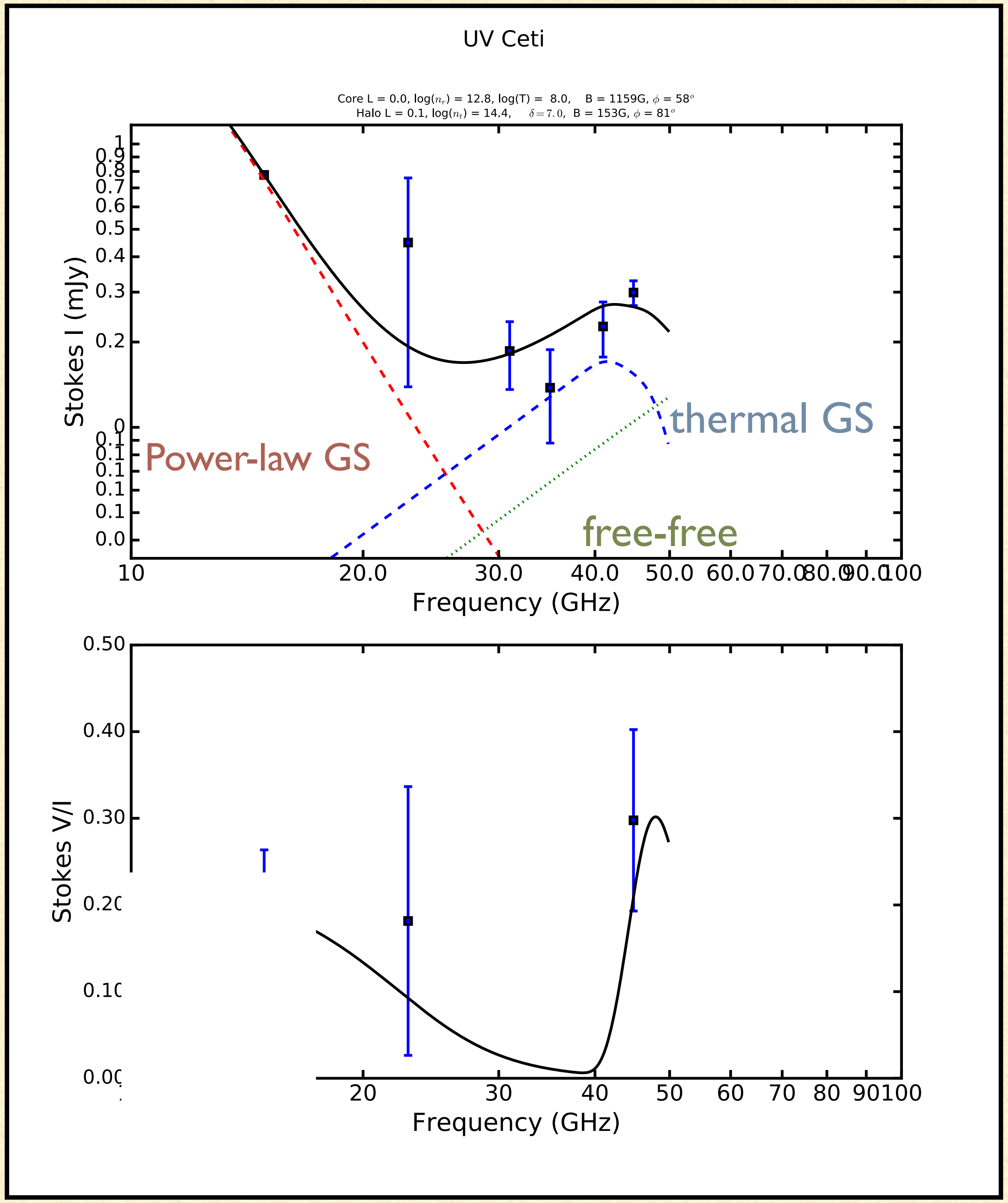
Thermal GS model:

$T = 12$ MK

$EM = n_e^3 L = 31 \cdot 10^{52}$ cm^{-3}

UV Ceti





Extended Power-law corona

L = 0.1 R_{sun}
B = 153 G
log(n_e) = 14.4
φ_B = 81^o
δ = 7.0

Thermal hot corona

L = 0.05 R_{sun}
log(T) = 8.0
B =1.2 kG
log(n_e) = 12.8
φ_B = 58^o

Rapid time variability may be confusing SED

SUMMARY

- This paper reports on the first observational evidence for thermal gyrosynchrotron (GS) emission from hot coronal plasmas

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- Thermal GS emission intensity is strongly dependent on temperature and B-field: Coronae must have $T>10^{7.5}$ K and B > 1-2 kG for thermal GS to be detectable in presence of power-law GS
- Wideband SED survey of 8 radio-loud stars:
  - 5 (3 CABS, 2 dMe flare stars) are well-fit by power-law spectra, no thermal GS
  - 2 (V410 Tau, HD283572, both WTTS) are well-fit by power-law GS 'halo' + thermal GS hot 'core' with strong B-field
  - 1 (UV Ceti) poor fit, but strong indication of a thermal component