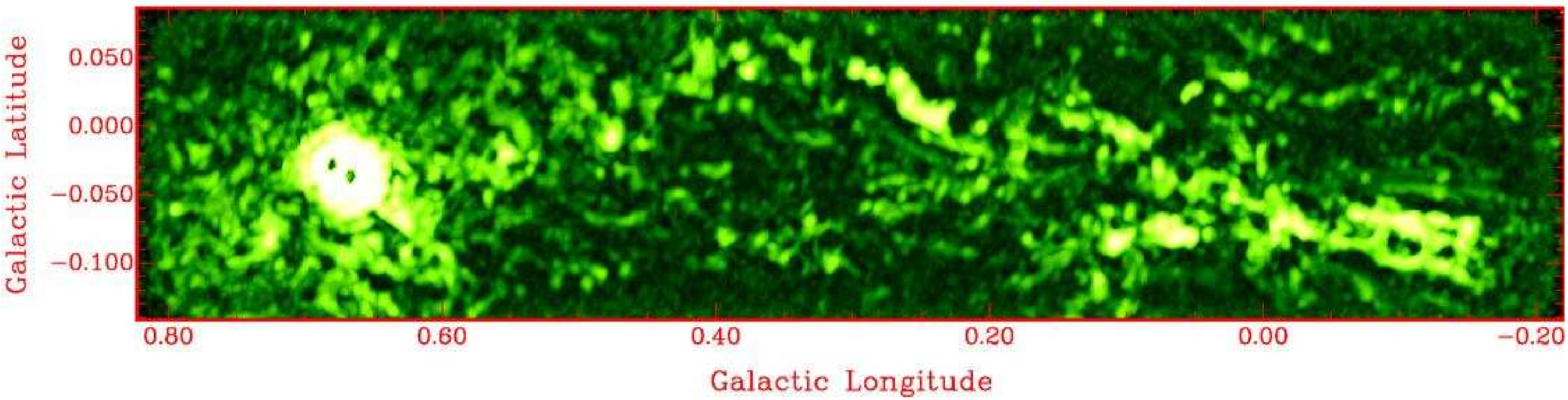
Sgr B2:
free-free and synchrotron emission, and implications for cosmic rays



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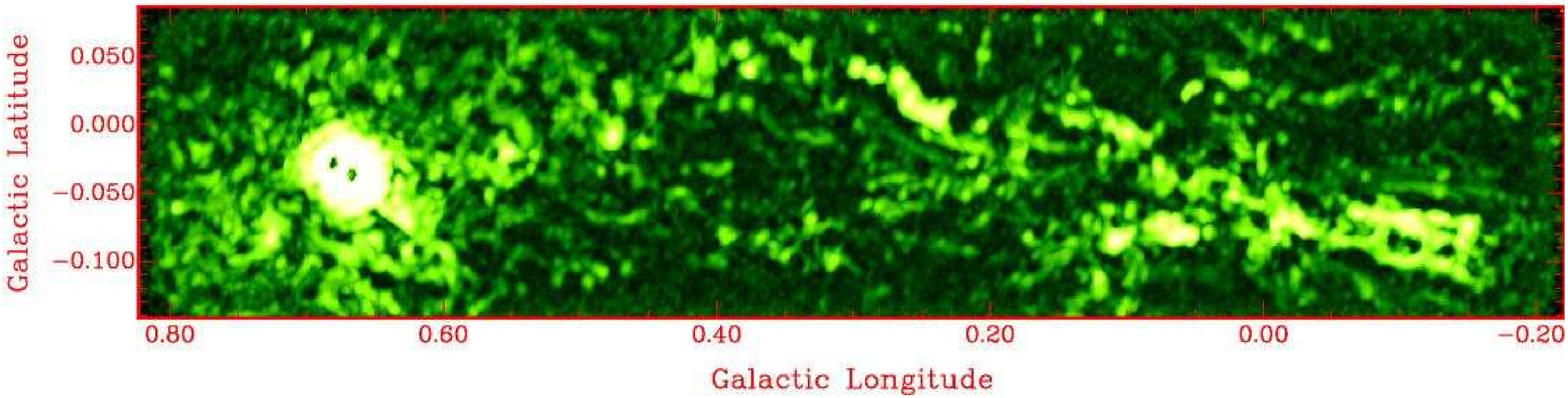
Contents

1 Motivation

- We expect that the cosmic ray flux in the central region of the Galaxy is higher than in the Solar neighbourhood because of the higher supernova activity there.
- Higher cosmic ray flux and higher ISM target density give a higher rate of pion production and $\pi^0 \rightarrow \gamma\gamma$ and $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$.
- Giant molecular clouds (GMC) should appear as intense gamma-ray sources.
- Giant molecular clouds have high magnetic fields and so should be intense non-thermal radio sources due to $e^\pm$ production followed by synchrotron radiation.
- Sgr B2 is the most massive GMC, is located in GC region, and has a very high magnetic field $B_{LOS} = 0.5$ mG.
- Sgr B2 shows up strongly in TeV gamma-rays observed by HESS (Aharonian et al 2006), but is not seen in GeV gamma-rays by EGRET. Why not?
- Sgr B2 is a good candidate to study synchrotron emission by secondary e$^\pm$.

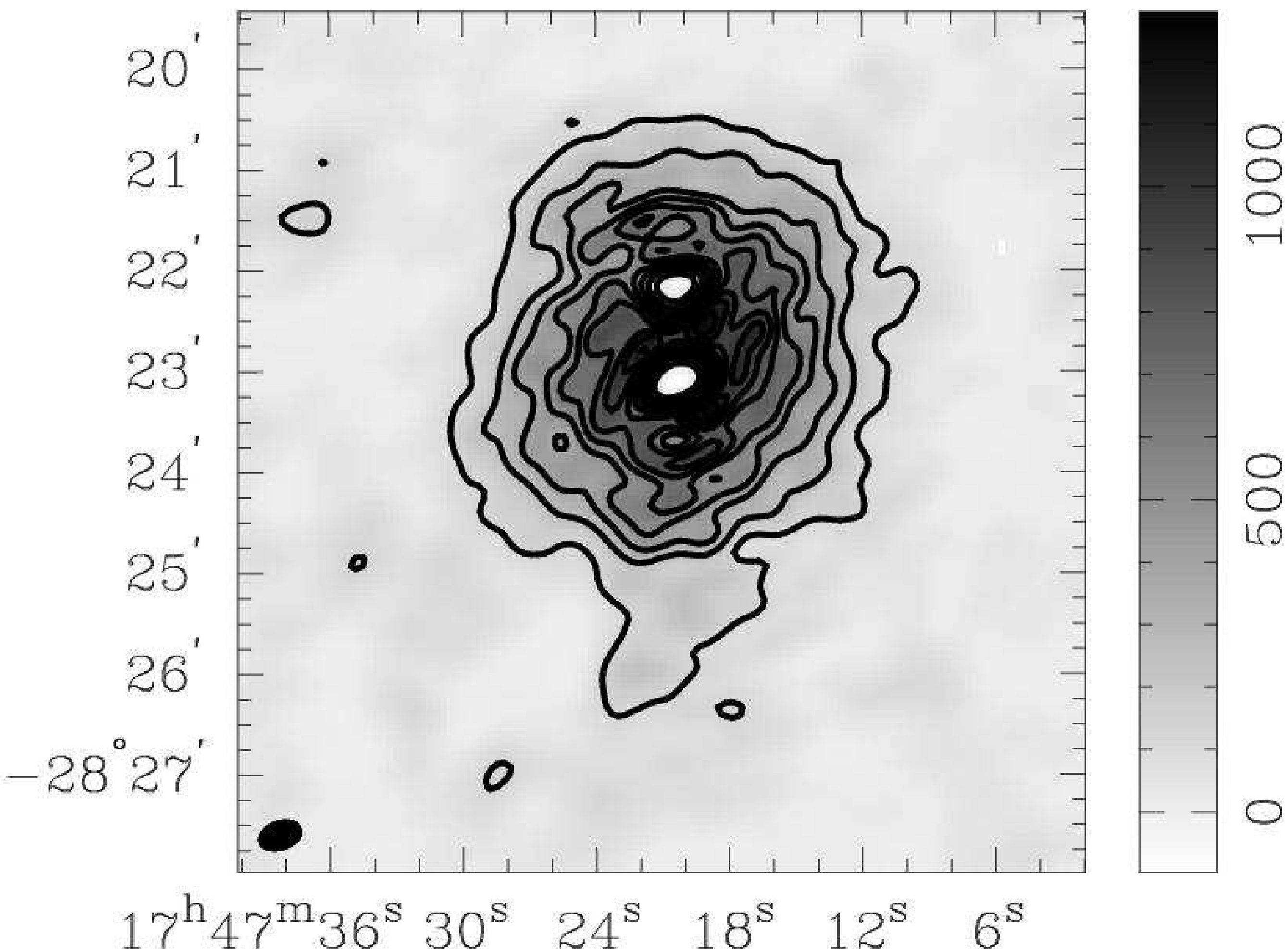
2 The Sgr B2 Giant Molecular Cloud

- Compact Array ammonia $(J, K) = (1, 1)$ peak intensity map of the Galactic Centre Region (J. Ott, ATNF News, Oct 2005).



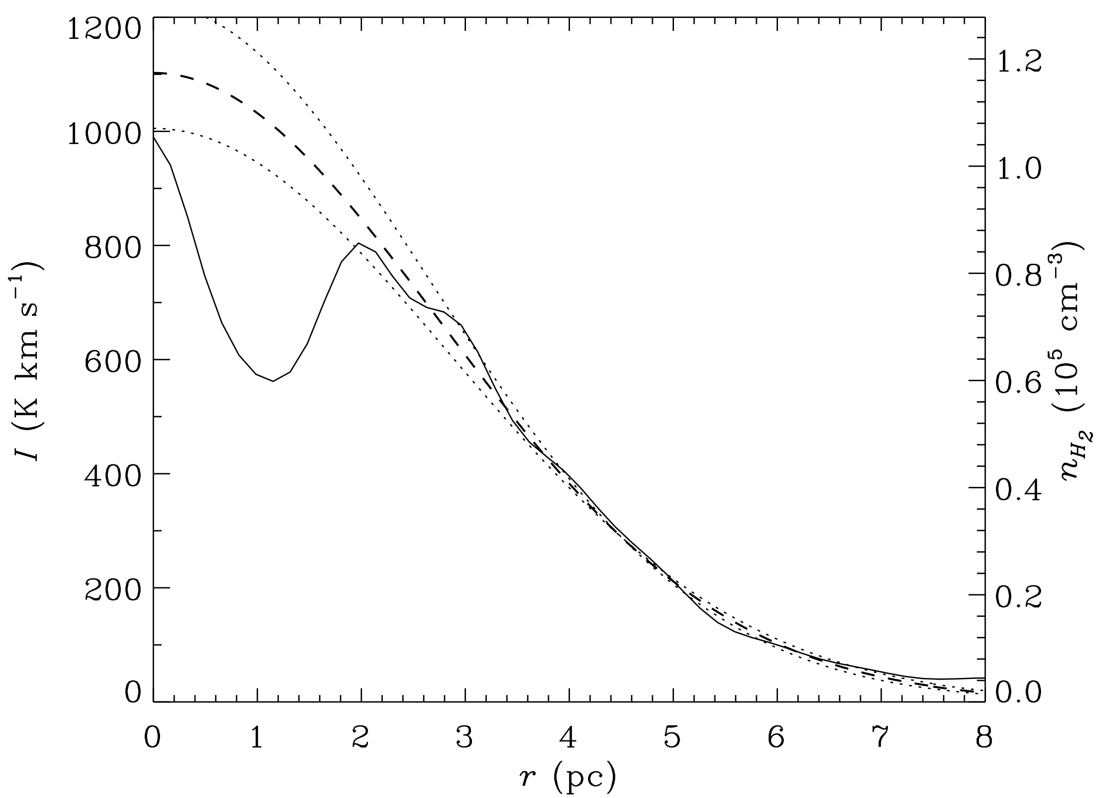
- The NH_3 line emission is optically thin and so traces the H_2 better than CO surveys.
- The very prominent emission to the left is emitted by Sgr B2.
- Notable are also the two 'holes' on top of Sgr B2 which exhibit ammonia in free-free absorption due to HII regions M and N.
- Note that Sgr B2 appears large, dense and circular.

- (1,1) line of NH_3 for the region around Sgr B2 (Contours 10%–90% peak intensity).



- The intensity scale (right of image) is from -96 to 1280 K km s^{-1}.

- Azimuthally averaged intensity of (1,1) line of NH_3assuming a distance of 8.5 kpc.



- Assume a Gaussian spherical density

$$n_{\mathrm{H}_2}(\vec{r}) = \frac{M_{\mathrm{H}_2}}{2m_H} \frac{e^{-(x^2+y^2+z^2)/(2\sigma^2)}}{(\sqrt{2\pi}\sigma)^3}$$

- Then the column density is also Gaussian

$$N_{\mathrm{H}_2} = \frac{M_{\mathrm{H}_2}}{2m_H} \frac{1}{2\pi\sigma^2} e^{-b^2/(2\sigma^2)}.$$

- Gaussian fit: σ=2.75$\pm$0.1 pc.

- At radii less than 2 pc: absorption against Sgr B2 (N) and (M) HII regions.

3 Virial mass of a Gaussian spherical cloud

- Here we derive, for the first time, the virial mass of a cloud complex with a radial Gaussian density profile.
- If a cloud is supported by turbulent motion with RMS radial velocity σ_v, its kinetic energy is

$$K = \frac{3}{2} M \sigma_v^2.$$

- The mass inside radius r of a Gaussian spherical cloud is

$$M(< r) = -M \frac{2}{\sqrt{\pi}} \int_0^{r^2/2\sigma^2} x^{1/2} e^{-x} dx = M \frac{2}{\sqrt{\pi}} \Gamma(3/2, r^2/2\sigma^2).$$

where $\Gamma(a, x)$ is the incomplete Gamma function.

- The gravitational potential energy of a Gaussian spherical cloud is then

$$U = -\int_0^{\infty} GM \frac{2}{\sqrt{\pi}} \Gamma(3/2, r^2/2\sigma^2) \frac{4\pi r^2 \rho(r)}{r} dr = -\frac{GM^2}{2\sqrt{\pi}\sigma}.$$

- If the emission is optically thin, the line has a Gaussian profile with standard deviation (measured in m/s) of σ_v.

- From the virial theorem, $K = -\frac{1}{2}U$, we obtain

$$M_{\rm vir} = \frac{6\sqrt{\pi}\sigma}{G}\sigma_v^2.$$

- Putting this in practical units, we obtain

$$\frac{M_{\rm vir}}{M_\odot} = 444\left(\frac{\sigma}{1\ {\rm pc}}\right)\left(\frac{v_{FWHM}}{1\ {\rm km\,s^{-1}}}\right)^2.$$

- This is a factor 2.1 higher than the usual formula for a uniform density sphere of radius $R = \sigma$.

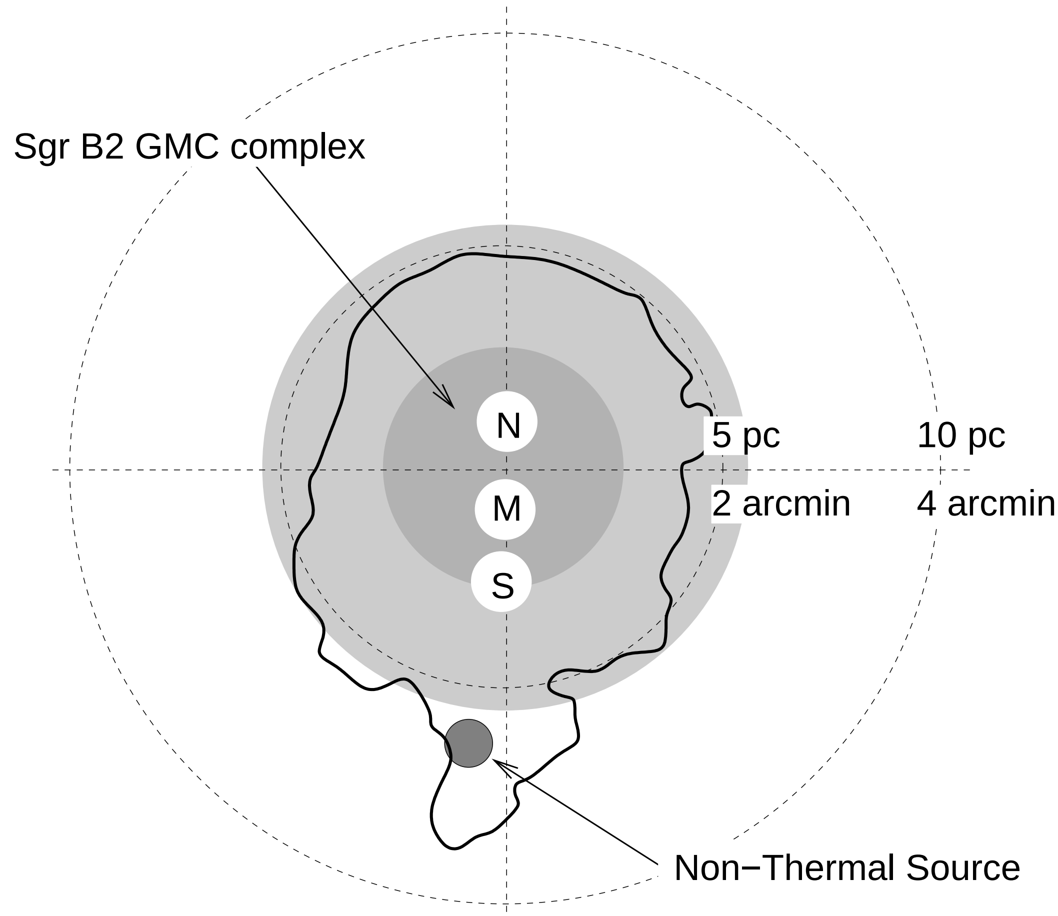
- The velocity FWHM of the ammonia (1,1) line observations of Sgr B2 is

$$v_{FWHM} \;=\; 39.7\ \text{km s}^{-1}.$$

- Hence, the virial mass of Sgr B2 for σ=2.75$\pm$0.1 pc is

$$M_{\rm vir} \;=\; (1.9 \pm 0.1) \times 10^6\ {\rm M}_\odot.$$

- Sketch of the morphology of Sgr B2 showing the locations of the prominent HII regions, M, N and S.



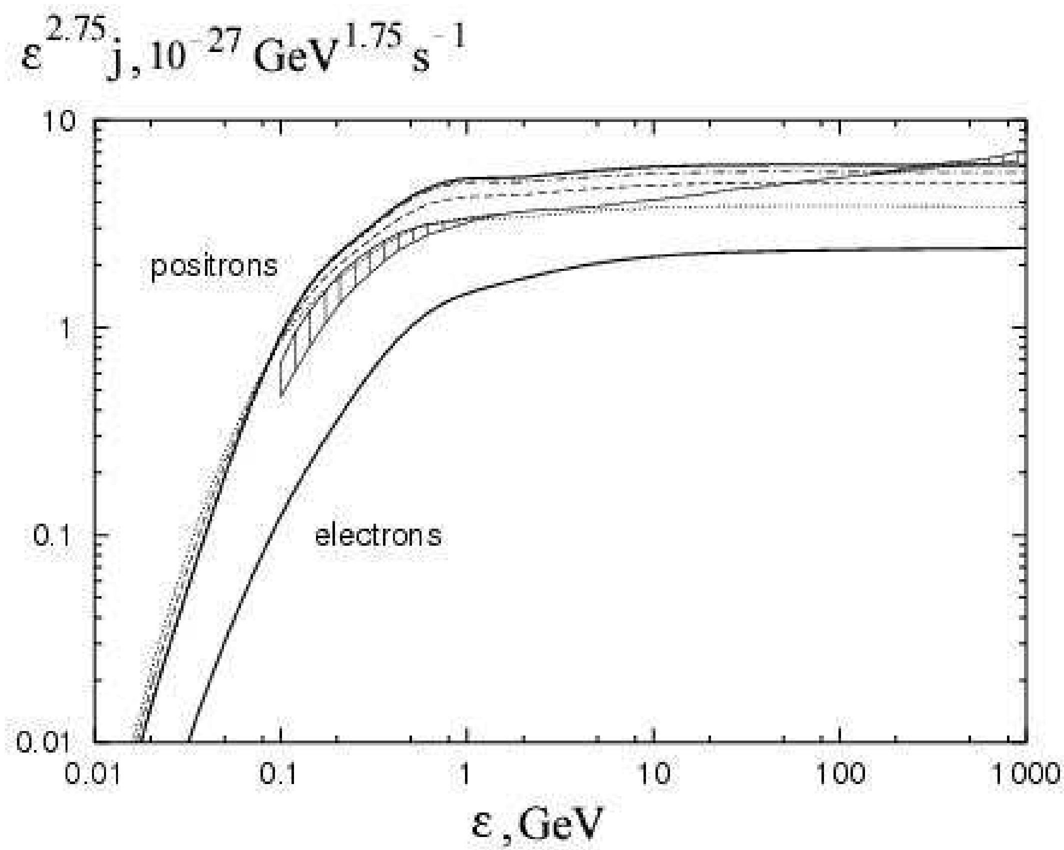
- Shaded regions have radius equal to one and two standard deviations of the the assumed radial Gaussian density profile.

4 Synchrotron emission by cosmic ray secondary electrons

- The Galactic synchrotron emission is due to accelerated (primary) cosmic ray electrons, and to electrons and positrons produced as secondaries.

- The production rate of secondary $e^{\pm}$ depends only on the spectrum and intensity of cosmic ray nuclei, and the density of the interstellar matter.

- We use the production rate of e$^{\pm}$, $q_1(E)$, per interstellar nucleon per unit energy (nucleon^{-1} GeV^{-1} s^{-1}) near Earth.



- The production spectrum of electrons and positrons ($e^{\pm}$ cm^{-3} GeV^{-1}s^{-1}) at position $\vec{r}$ is the H_2 density

$$q(E,\vec{r}) = f_{CR}\, n_{H_2}(\vec{r})\, q_1(E).$$

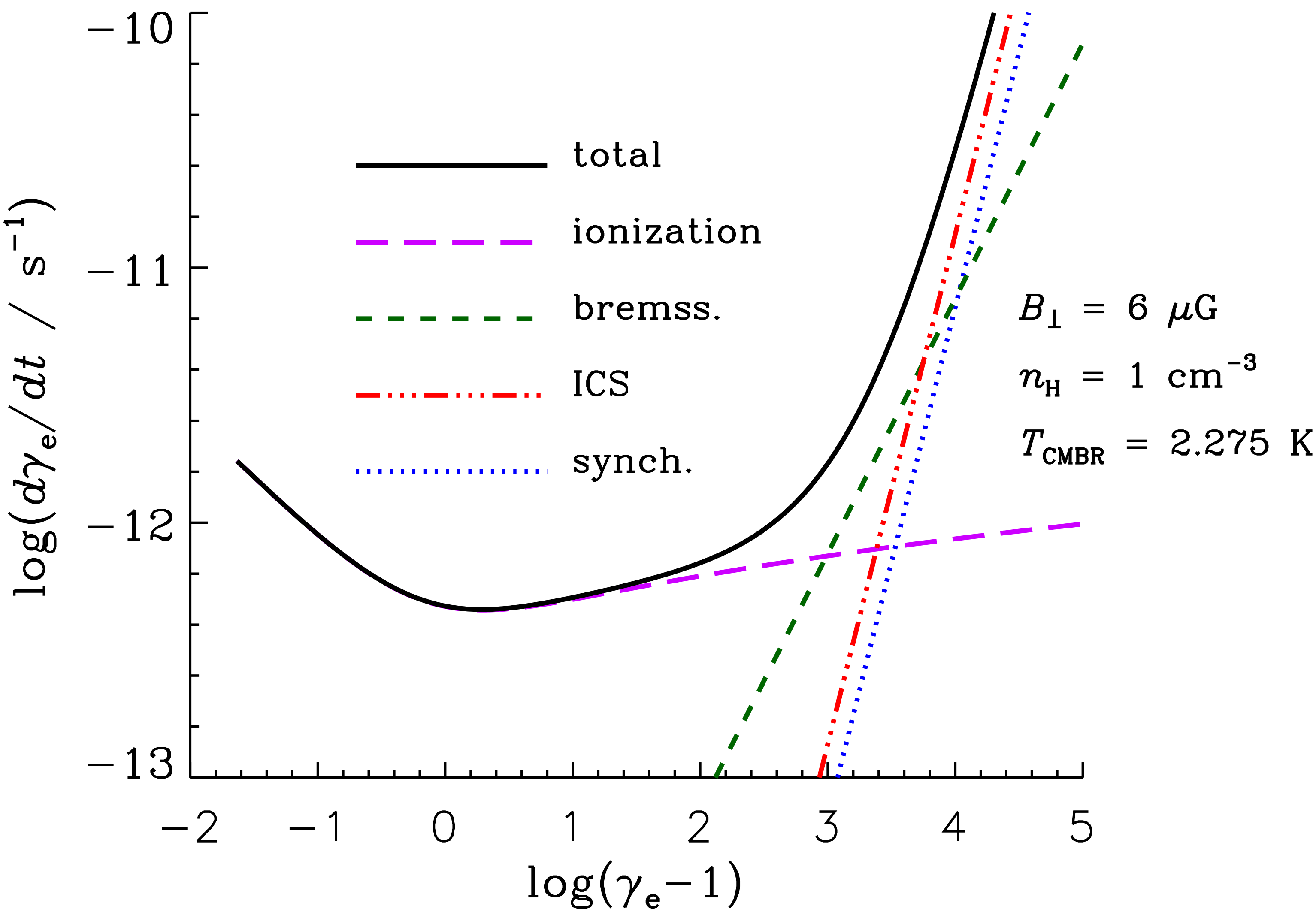
f_{CR} is the ratio of the CR flux at Sgr B2 to that at Earth.

- The ambient number density of electrons and positrons, per unit energy, $n^{\pm}(E,r)$ ($e^{\pm}$ cm^{-3} GeV^{-1}), at various positions $\vec{r}$ within the molecular cloud complex is:

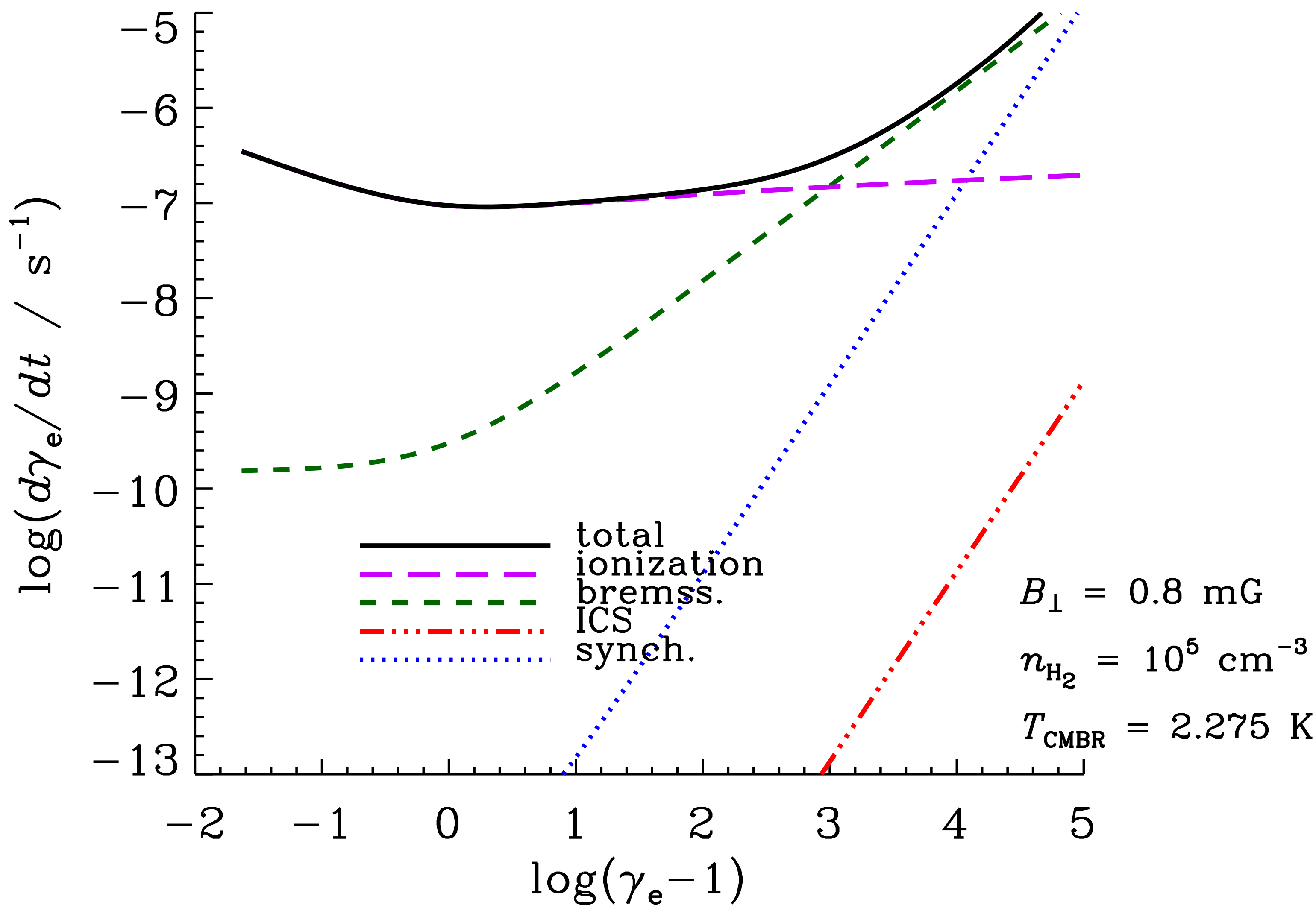
$$n(E,\vec{r}) = \frac{\int_E^{\infty} q(E,\vec{r}) dE}{dE/dt},$$

- dE/dt is the total rate of energy loss of electrons at energy E due to ionization, bremsstrahlung and synchrotron emission.

- "Typical" interstellar medium.



- Centre of Sgr B2.



- The synchrotron emission is calculated using standard formulae in synchrotron radiation theory (Rybicki & Lightman 1979)

$$j_\nu = \frac{\sqrt{3}\, e^3}{4\pi m_e c^2}\left(\frac{B_\perp}{1\ \mathrm{gauss}}\right) \times \int_{m_e c^2}^{\infty} F(\nu/\nu_c) n(E,\vec{r}) dE$$

$$\mathrm{erg\ cm^{-3}\ s^{-1}\ sr^{-1}\ Hz^{-1}},$$

$$\nu_c = 4.19\times 10^6 (E/m_e c^2)^2 \left(\frac{B_\perp}{1\ \mathrm{gauss}}\right) \quad \mathrm{Hz},$$

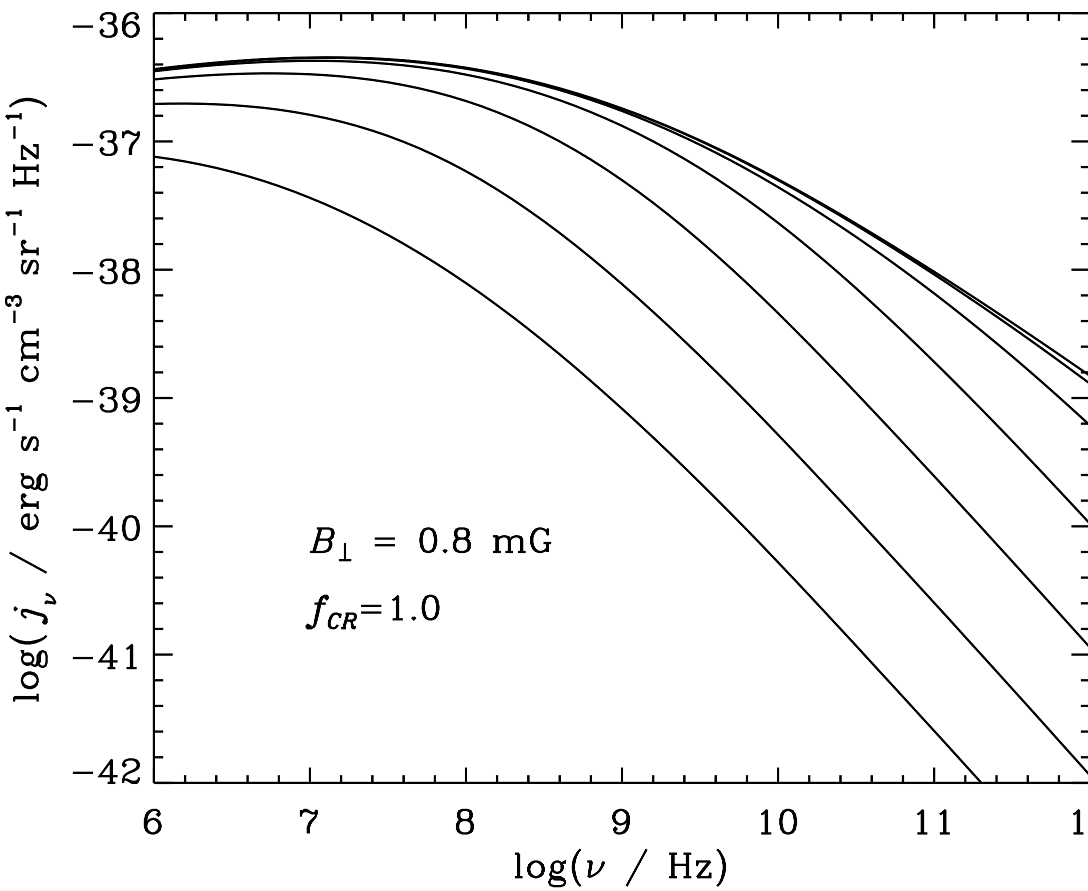
$$e = 4.8\times 10^{-10} \quad \mathrm{esu},$$

$$m_e c^2 = 8.18\times 10^{-7} \quad \mathrm{erg},$$

$$F(x) = x\int_x^\infty K_{\frac{5}{3}}(\xi) d\xi.$$

and $K_{\frac{5}{3}}(x)$ is the modified Bessel function of order 5/3.

- Synchrotron emission coefficient of secondary $e^{\pm}$ produced by cosmic ray interactions for densities $n_{H_2} = 10^0$ (bottom curve), 10^1, 10^2, $\ldots 10^6$ cm^{-3} (top curve).



5 Penetration of Cosmic Ray Nuclei into Sgr B2

- Work on this subject has been motivated mainly by gamma-ray observations, particularly of the central region of the Galaxy.
- An important contribution to the Galactic gamma-ray intensity comes from interactions of cosmic ray nuclei through pion production and subsequent decay $\pi^0 \to \gamma\gamma$, and $\pi^\pm \to \mu^\pm \to e^\pm$ followed by bremsstrahlung or inverse Compton.
- Of course primary accelerated electrons are also important for the latter two processes.
- Put simply, if cosmic rays can freely enter molecular clouds then the gamma-ray flux will be higher than if they cannot.
- In the present work we are interested in synchrotron radiation by the same secondary $e^\pm$.
- Following Gabici et al. (2007), we adopt a diffusion coefficient

$$D(E) = 3 \times 10^{27} \chi \left[\frac{E/(1 \text{ GeV})}{B/(3 \ \mu G)} \right]^{0.5} \text{cm}^2 \text{ s}^{-1}$$

- where $\chi \leq 1$ is a suppression factor to account for slowing of diffusive transport.
- by analogy with scattering ('s') and absorption ('a') of radiation and we define an effective optical thickness $\tau_\star = \tau_a(\tau_a + \tau_s)$ analogous to that used when considering radiative diffusion – see, e.g., Rybicki & Lightman (1979).
- In our case, for penetration from an outer boundary R to distance r from the Centre we have

$$\tau_a(r) \approx \int_r^R 0.5[2n_{H_2}(r')]\sigma_{pp} c dr'$$

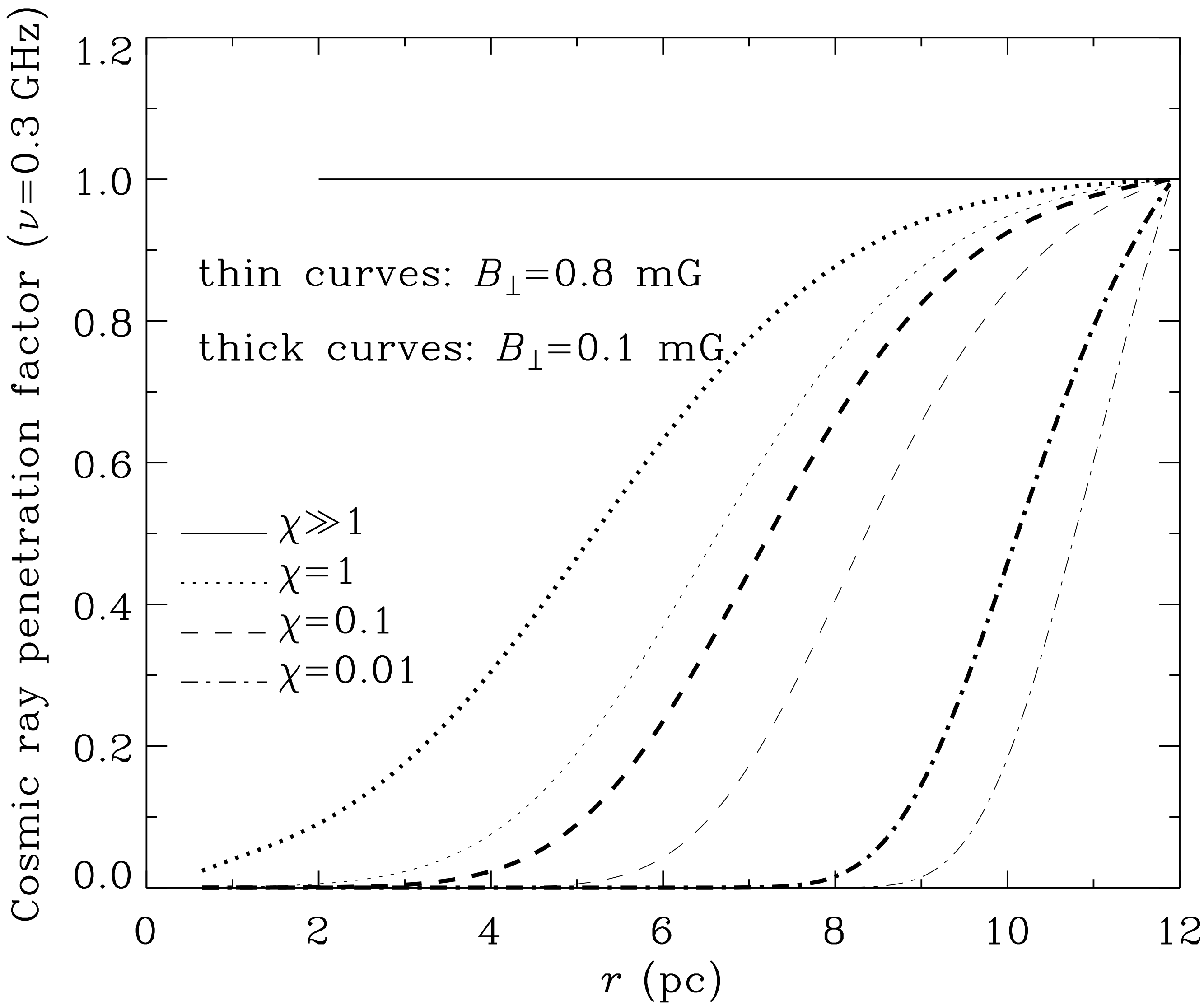
where $\sigma_{pp}(E) \approx 35$ mb above threshold, and the 0.5 factor is approximately the mean inelasticity (fractional energy lost) in pp collisions, and

$$\tau_s(E, r) \approx \int_r^R \frac{c}{3D(E, r')} dr'$$

since for isotropic diffusion, the mean effective free path is $3D/c$.

- Then the cosmic ray intensity at radius r is $I_{CR} \approx e^{-\tau_\star(E,r)} I_{CR}(E, R)$.

- The cosmic ray penetration factor $e^{-\tau_*[E_p(\nu,r),r]}$ appropriate to ν=0.3 GHz.



6 Predicted synchrotron intensity

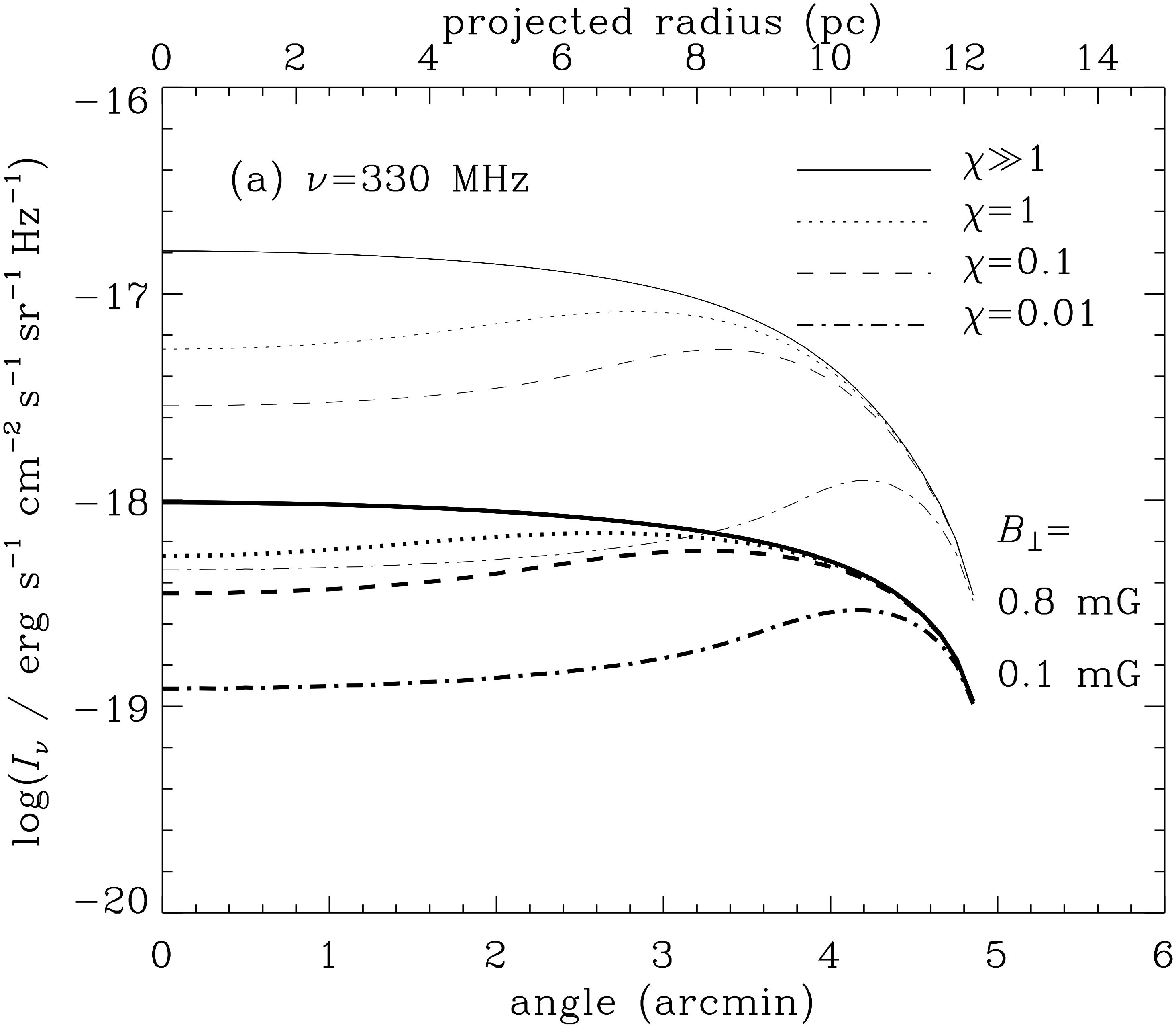
- We obtain the intensity $I_\nu(\theta)$ as a function of angular distance θ as a function of the impact parameter (perpendicular distance from the cloud Centre), $b = \theta d$, for various frequencies by integrating through the cloud complex, assuming the synchrotron emission is optically thin,

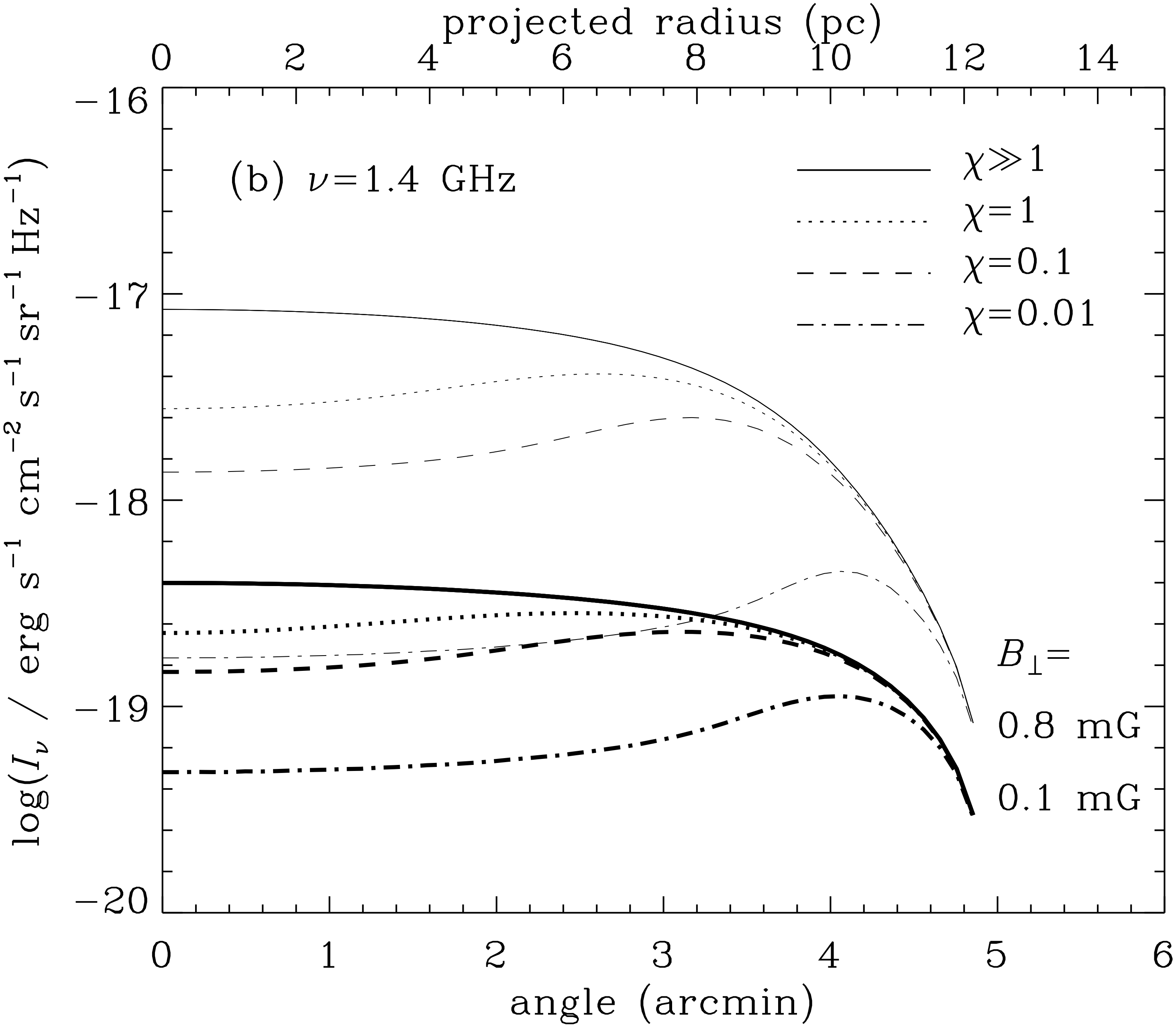
$$I_\nu(\theta) = \int j_\nu(\vec{r}) d\ell,$$

where d=8.5 kpc is the assumed distance to Sgr B2.

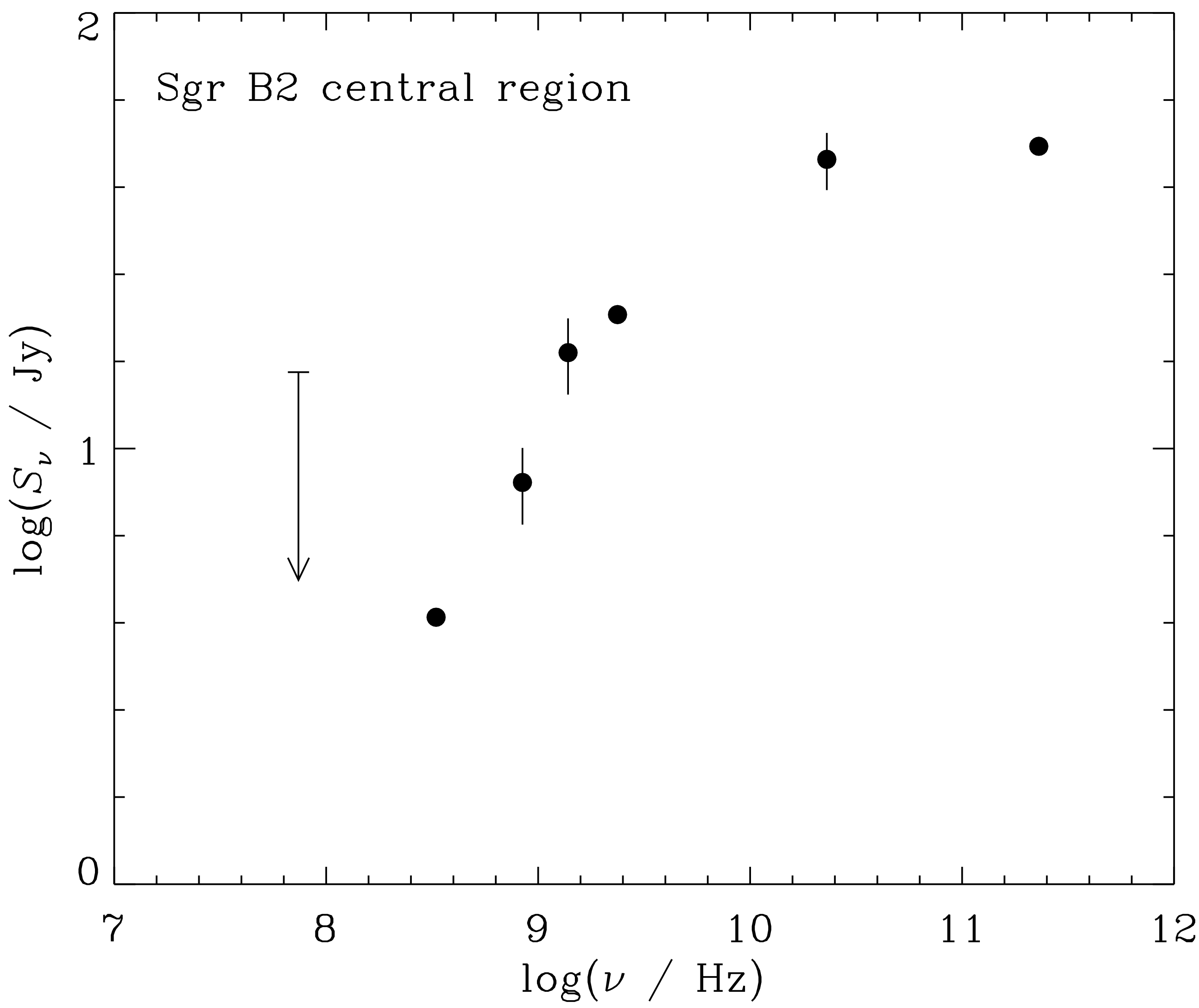
- Depending on the diffusive transport suppression factor χ, we may expect significant "limb brightening" of the synchrotron emission.

- We find that in the case of the Sgr B2 complex most of the predicted flux comes from within $\sim$11 pc of its Centre.


projected radius (pc)
0 2 4 6 8 10 12 14
−16 −17 −18 −19 −20
$\log(I_\nu$ / erg s^{-1} cm^{-2} s^{-1} sr^{-1} Hz^{-1})
(a) ν=330 MHz
$\chi \gg 1$
χ=1
χ=0.1
χ=0.01
$B_\perp$=
0.8 mG
0.1 mG
0 1 2 3 4 5 6
angle (arcmin)


projected radius (pc)
0 2 4 6 8 10 12 14
−16
−17
−18
−19
−20
(b) ν=1.4 GHz
χ≫1
χ=1
χ=0.1
χ=0.01
B⊥=
0.8 mG
0.1 mG
log(I_ν / erg s⁻¹ cm⁻² s⁻¹ sr⁻¹ Hz⁻¹)
0 1 2 3 4 5 6
angle (arcmin)

- Observed fluxes summarized by Jones et al (2008) from the central region.

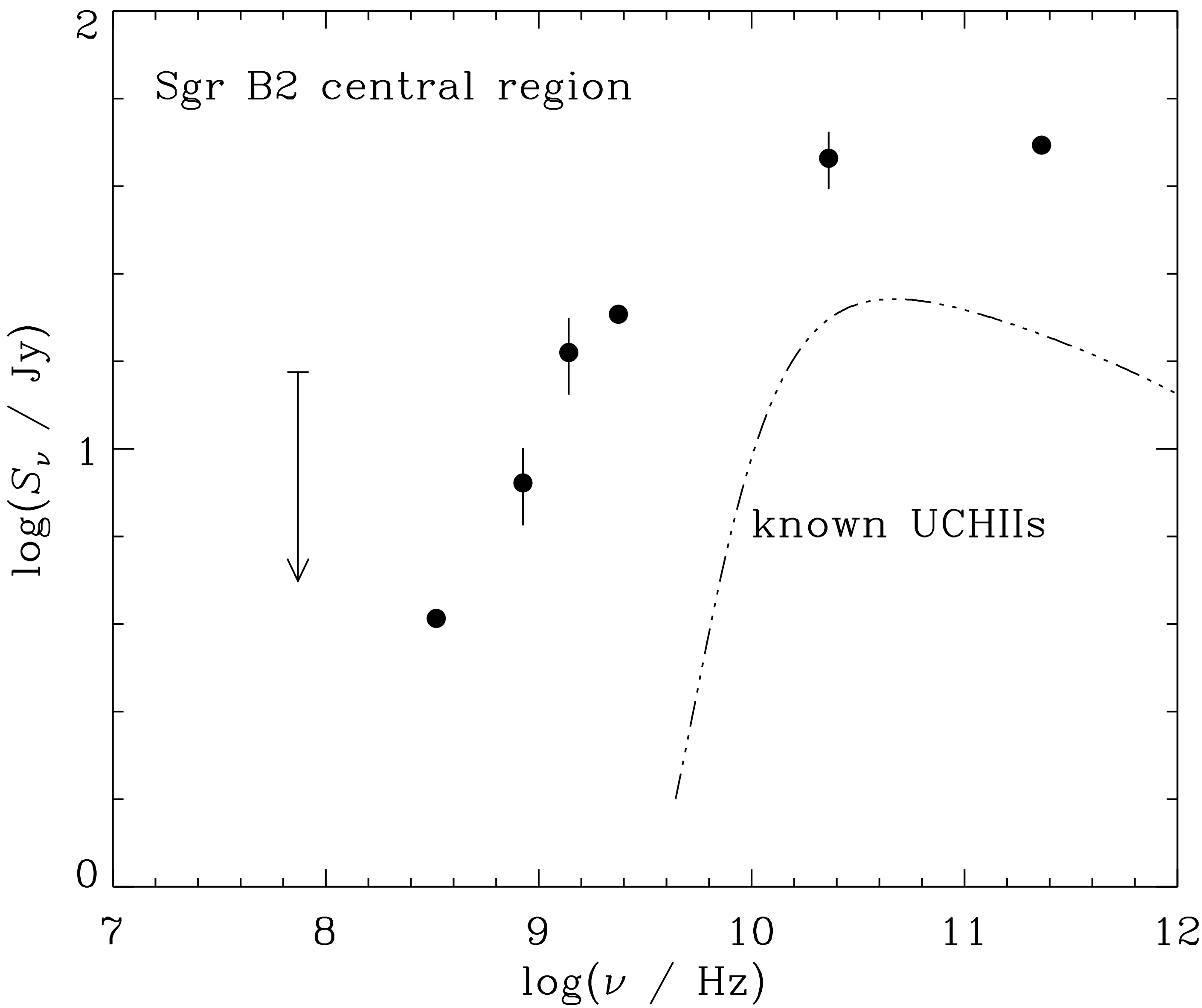


7 Free-free emission from UCHII regions

- The emission at the higher frequencies (22 GHz and 43 GHz) is clearly thermal.
- Regions with very low emission measures and high 22 GHz and 43 GHz fluxes could potentially affect the emission at low frequencies.
- In order to investigate how much of the flux at these lower frequencies could be attributed to UCHII regions, we modeled the emission from the ∼60 known individual compact and UCHII regions reported in Gaume et al (1995) and dePree et al (1998).
- This was achieved by "bootstrapping" the flux at the respective frequencies such that

$$S_\nu = \sum_k S_{\nu_i}^{(k)} \left(\frac{\nu}{\nu_i^{(k)}}\right)^2 \left(\frac{1 - e^{-\tau_\nu^{(k)}}}{1 - e^{-\tau_{\nu_i}^{(k)}}}\right)$$

where $\nu_i = 22$ GHz or 43 GHz, the sum over the ∼60 UCHII regions with the label (k) relates to the kth UCHII region, and the frequency dependence of the thermal bremsstrahlung absorption coefficient is taken from Rybicki & Lightman (1979).


Sgr B2 central region
known UCHIIs
log(S_ν / Jy)
log(ν / Hz)
2
1
0
7
8
9
10
11
12

8 Free-free emission from envelopes or winds

- Between 330 MHz and 1.4 GHz the spectrum may be fitted with a single power-law $S_\nu \sim \nu^{0.6}$ characteristic of optically thick emission from a spherical envelope or wind with a density gradient of the form

$$n_e(r) = n_i(r) = n_0 \left(\frac{r}{r_0}\right)^{-2}$$

as described by Panagia & Felli (1975) who give the expected flux at low frequencies

$$S_\nu^{\rm thick} = 0.611 \left(\frac{n_0}{1\ \mathrm{cm}^{-3}}\right)^{4/3} \left(\frac{r_0}{1\ \mathrm{pc}}\right)^{8/3} \left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{0.6} \left(\frac{T}{10^4\ \mathrm{K}}\right)^{0.1} \left(\frac{d}{1\ \mathrm{kpc}}\right)^{-2}.$$

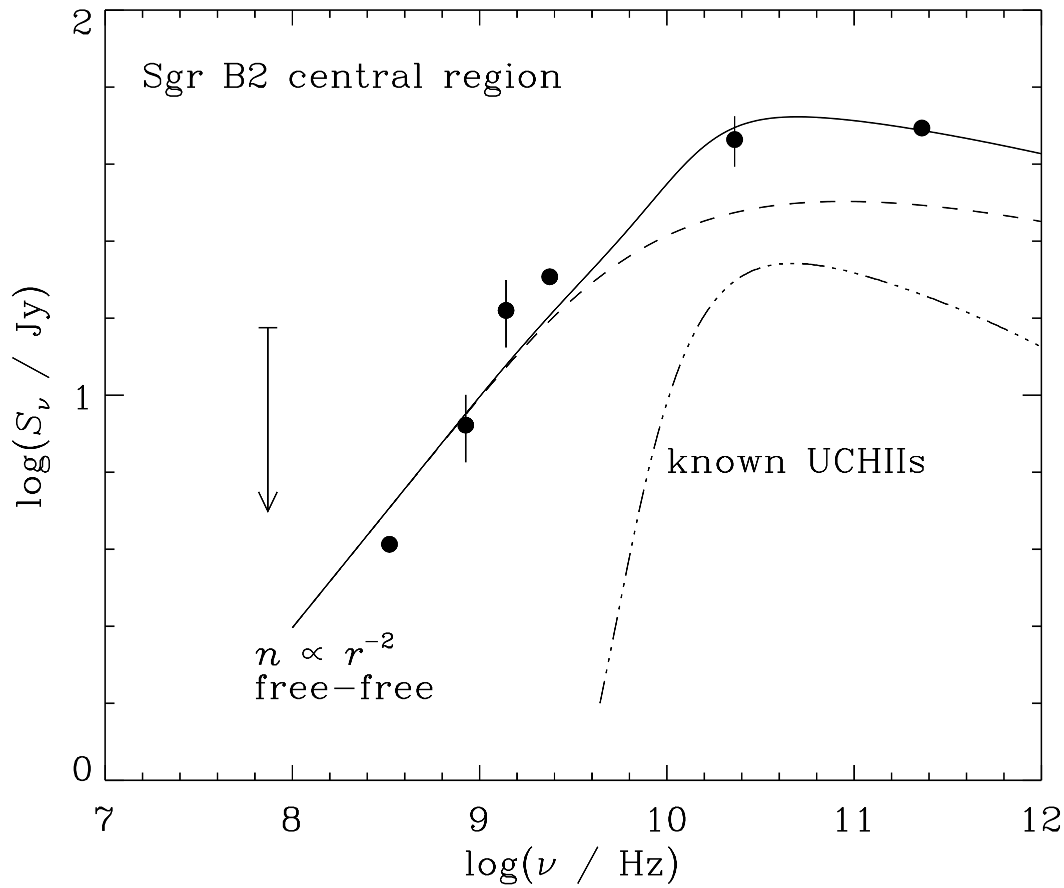
- For the case of optically thin emission we can use

$$\int_{r_0}^{\infty} 4\pi r^2\, n_e(r)\, n_i(r)\, dr = 4\pi {n_0}^2 r_0^3$$

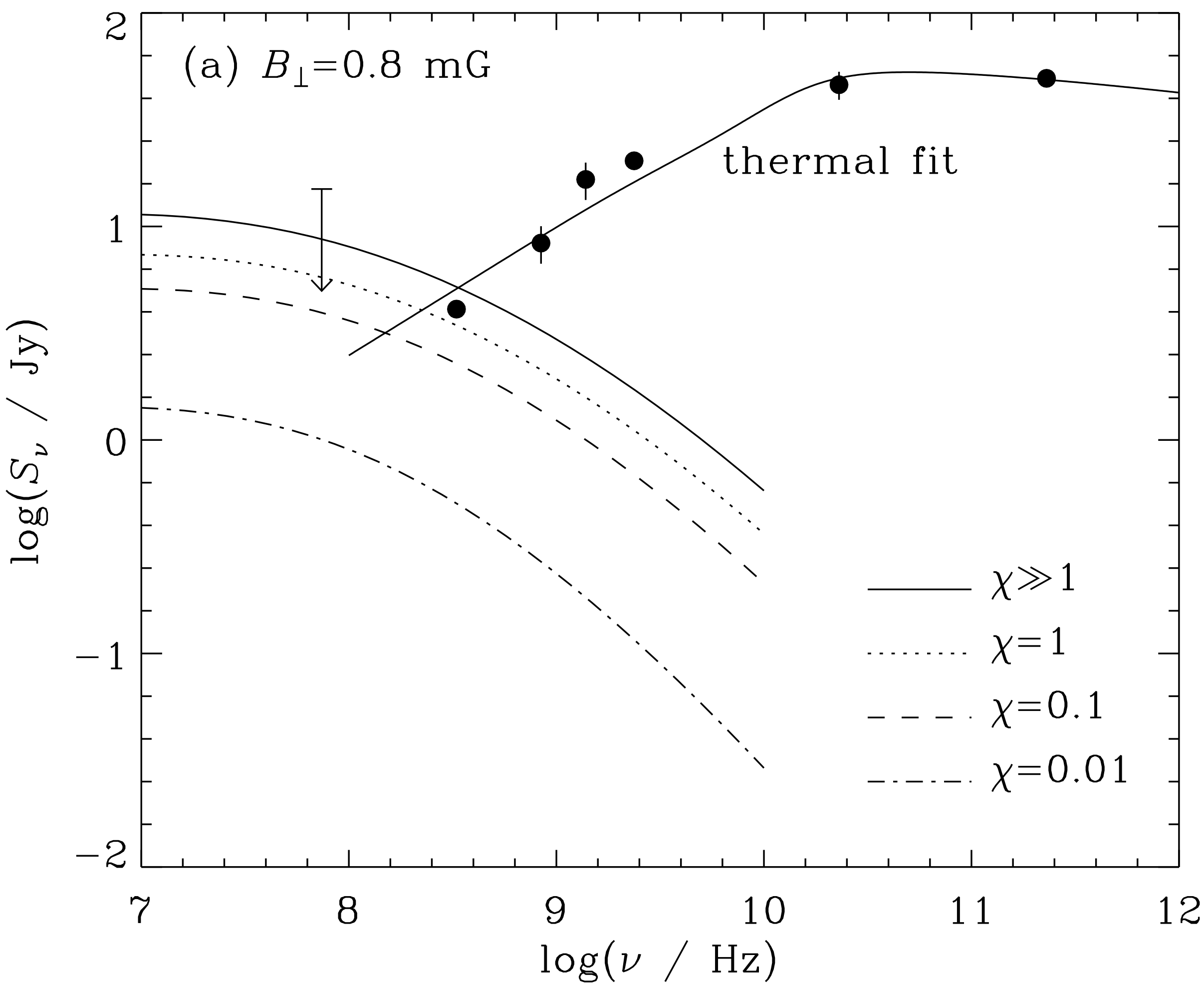
together with the free-free emission coefficient and Gaunt factor $g(T,\nu)$ from Rybicki & Lightman (1979) to obtain the flux at high frequencies where it is expected to be optically thin

$$S_\nu^{\rm thin} = 1.6 \times 10^{-5} \left(\frac{n_0}{1\ {\rm cm}^{-3}}\right)^2 \left(\frac{r_0}{1\ {\rm pc}}\right)^3 \left(\frac{T}{10^4\ {\rm K}}\right)^{-0.5} g(T,\nu) \left(\frac{d}{1\ {\rm kpc}}\right)^{-2}.$$

- Taking the optical depth to be $\tau_\nu = S_\nu^{\rm thin}/S_\nu^{\rm thick}$ the flux is $S_\nu = S_\nu^{\rm thick}(1 - e^{-\tau_\nu})$.
- For a temperature $T = 10^4$ K the best fitting parameters are $n_0 = 3.47 \times 10^7$ cm^{-3} and $r_0 = 4.12 \times 10^{-3}$ pc.
- The high density and small size would indicate that the emission is likely to have come from winds off, or excited by, young stars within the HII regions.
- If the flux is due to N separate identical objects, their wind parameters would be $n_0 = 3.47 \times 10^7 \times N$ cm^{-3} and $r_0 = 4.12 \times 10^{-3}/N$ pc.



9 Synchrotron emission by secondary electrons



10 Conclusion

- We have no evidence that synchrotron emission by secondary $e^{\pm}$.
- The most likely explanation for this is that, for reasonable diffusion models, cosmic rays with multi-GeV energies (that produce secondary electrons with the right energy to radiate at GHz frequencies in ∼0.5 mG fields) cannot penetrate into the dense central regions of Sgr B2 GMC where much of the potential mass of target nuclei is located.
- This exclusion is also the likely explanation for non-observation of the Sgr B2 GMC by EGRET because it is again the same multi-GeV energy protons producing pions in pp collisions followed by $\pi^0 \to \gamma\gamma$ that make an important contribution to 100 MeV to multi-GeV gamma-rays.
- The observation of the Sgr B2 GMC by HESS Aharonian et al (2006) at TeV energies is consistent with more complete penetration of cosmic rays at higher energies into the dense central regions.

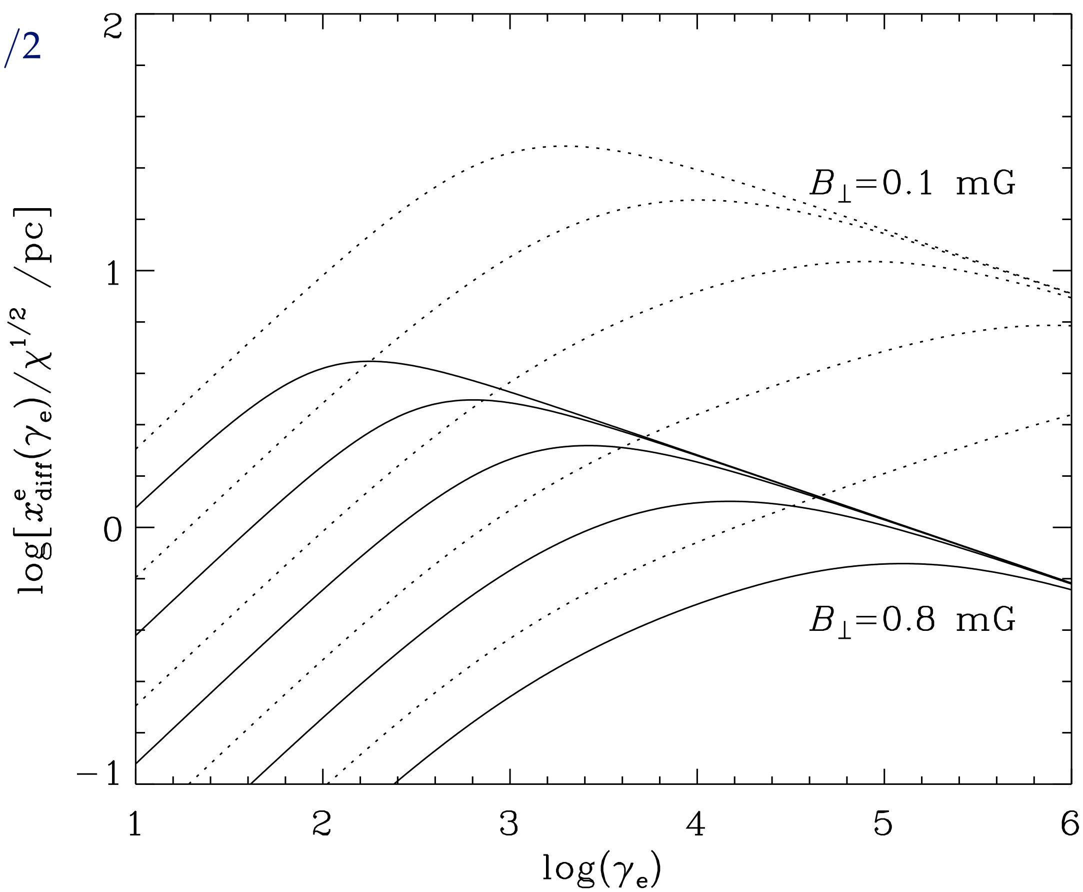
The End

- In choosing giant molecular clouds in the central region of the Galaxy for future investigation of their synchrotron emission by secondary electrons, one would look for a GMC with with a mass of a few 10^5 $M_\odot$, a lower central density than Sgr B2, e.g. $n_{H_2}{\sim}10^4$ cm^{-3} so that low energy cosmic rays may more easily penetrate it, a magnetic field above 0.1 mG and little star formation.
- We do not know of any, but such clouds may become apparent with the aid of new infrared surveys.

Diffusion of $e^{\pm}$ inside and into the Sgr B2 Cloud Complex

- How far an electron can propagate by diffusion before losing a significant fraction of its energy is given by what we shall refer to as the "diffusion-loss distance"

$$x^e_{\rm diff}(\gamma_e) = \left[\frac{D(\gamma_e m_e c^2)\gamma_e}{(d\gamma_e/dt)_{\rm total}}\right]^{1/2}$$



n_{H_2}=10^5 cm^{-3} (bottom curves), 10^4 cm^{-3} ... 10^1 cm^{-3} (top curves).