GARRA Group

Instituto Argentino de Radioastronomía

I A R
CCT La Plata
CONICET

ISSN: 1853-5461

Coherent flares from non-pulsar galactic sources

Gustavo E. Romero

IAR-CONICET/FCAyG-UNLP, Argentina

Florencia Vieyro (UB, Barcelona)

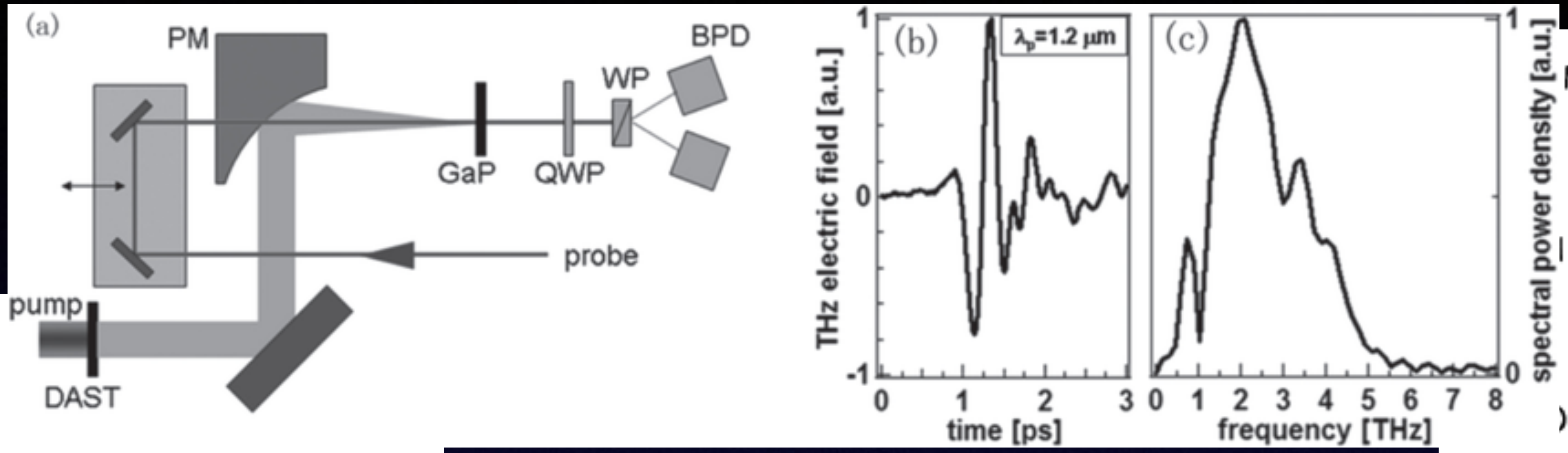
María V. del Valle (IPA, Potsdam)

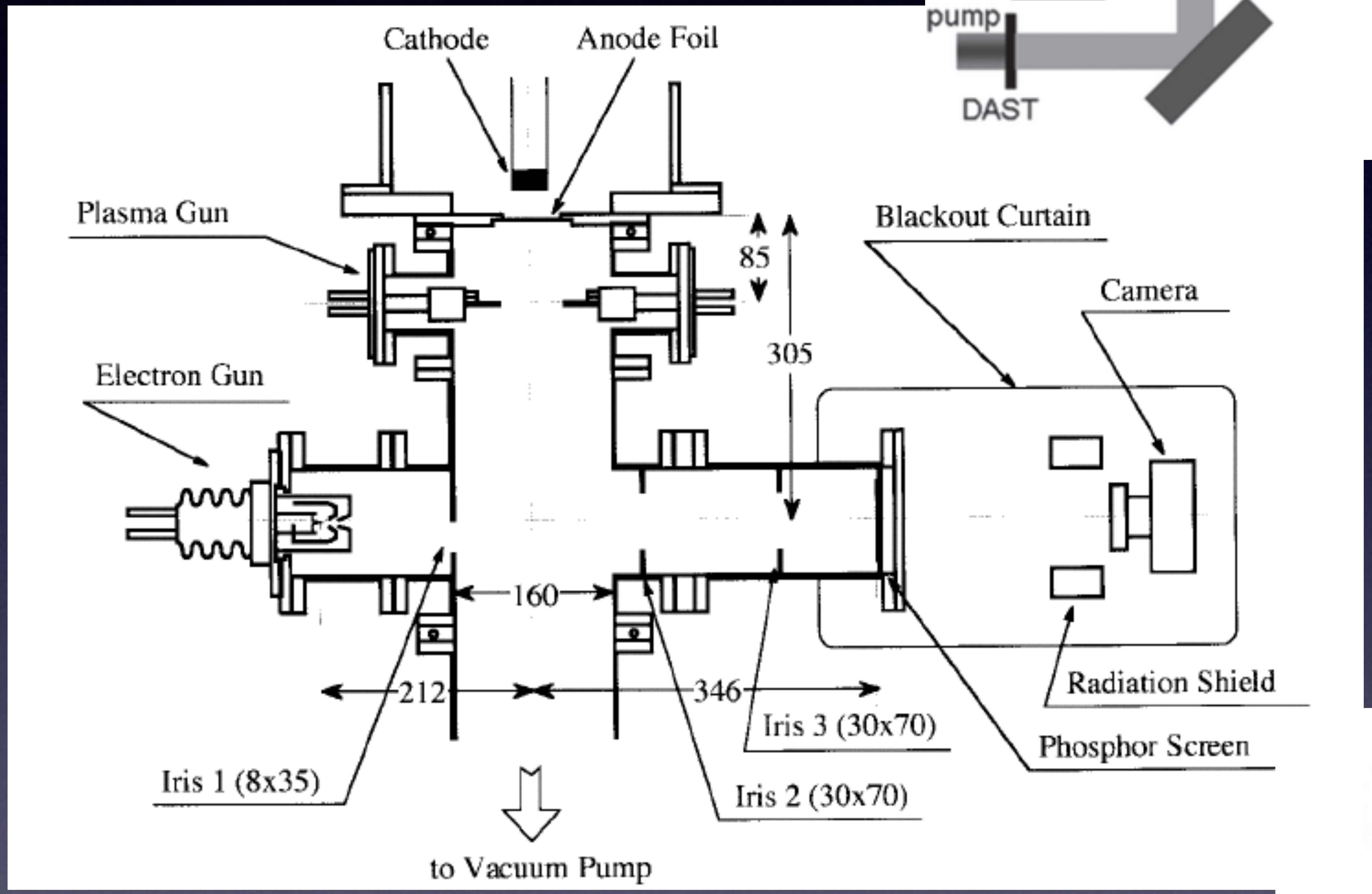
Variable Galactic Gamma-Ray Sources 2017
Rikkyo University, Tokyo, Japan

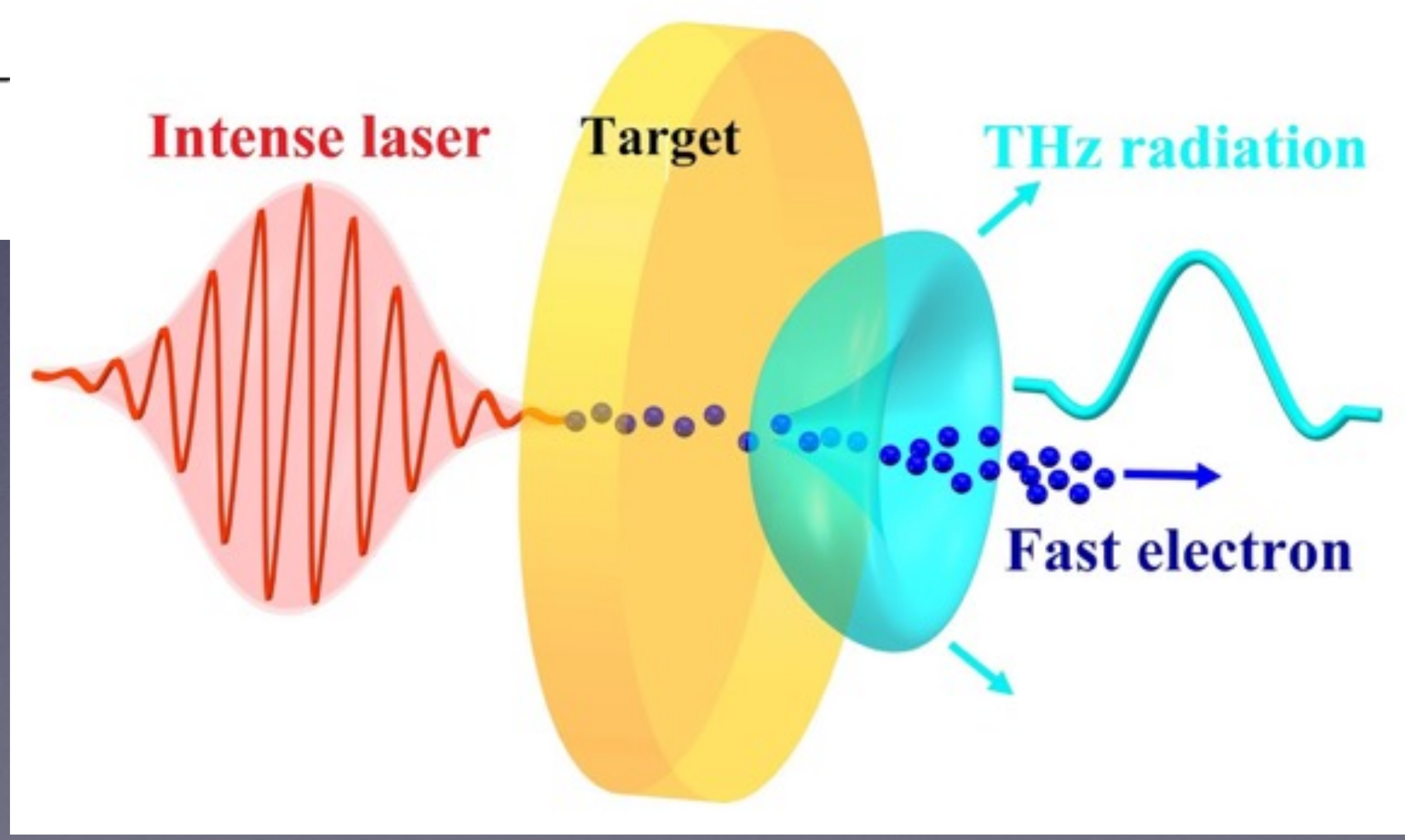
Coherent radiation in astrophysical scenarios is usually associated with pulsars and magnetized neutron stars.

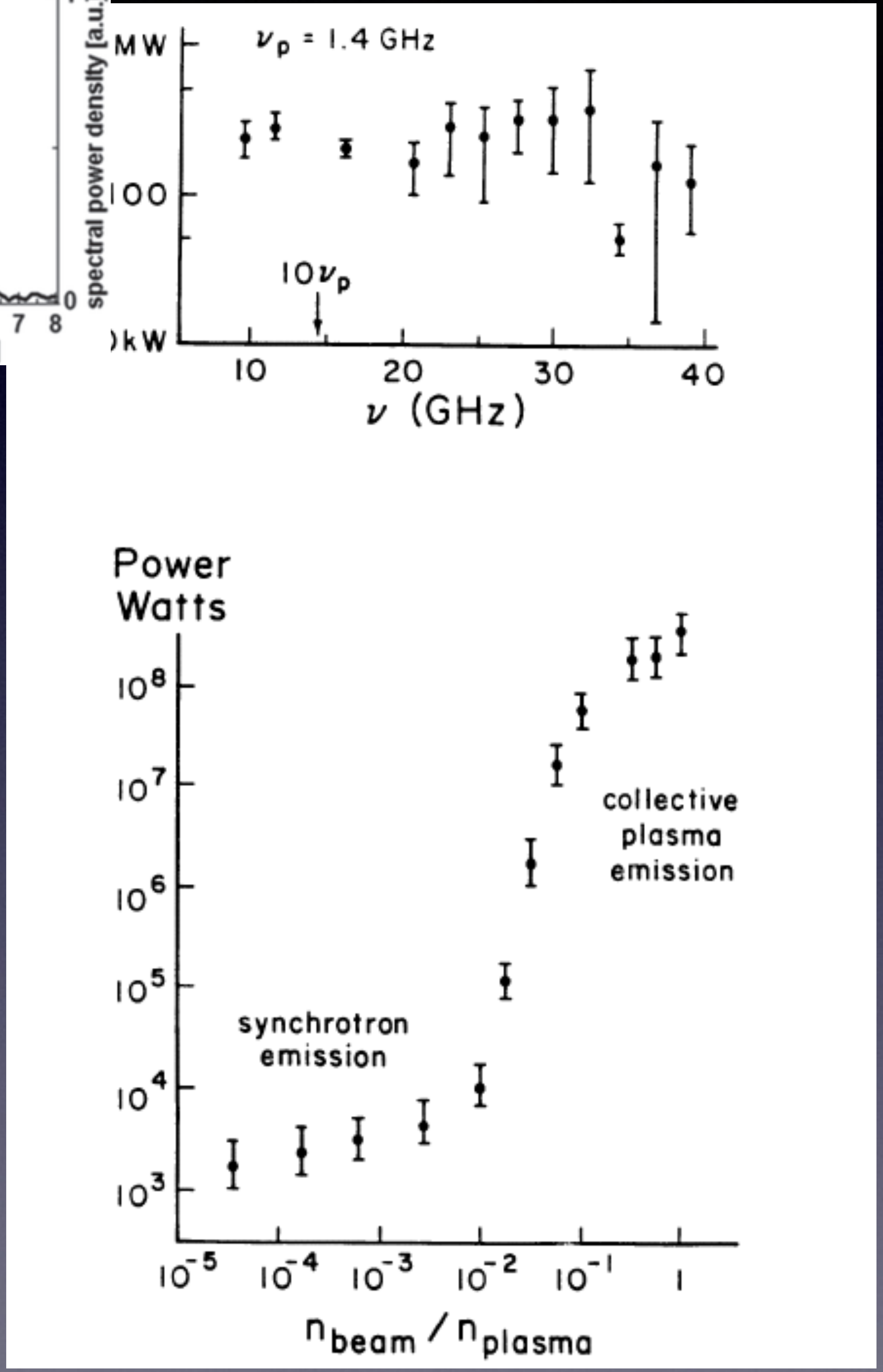
However, plasma experiments show that coherent radiation results in conditions that obtain in the solar corona and the medium surrounding accreting black holes in microquasars.

Experiments with electron beams in dense plasmas show coherent emission









Kato et al. 1983, Phys. Fluids
Ando et al.1999, IEEE
Zhang et al. 2016, IEEE

Electron streams moving through a dense plasma produce turbulence that collapses in soliton-like structures called cavitons (Zakharov 1972). The size of the cavitons is ~ 15 Debye lengths.

$$D \sim 327.3 \left(\frac{T_c}{10^{11}\,\mathrm{K}}\right)^{1/2} \left(\frac{n_c}{10^{10}\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm}.$$

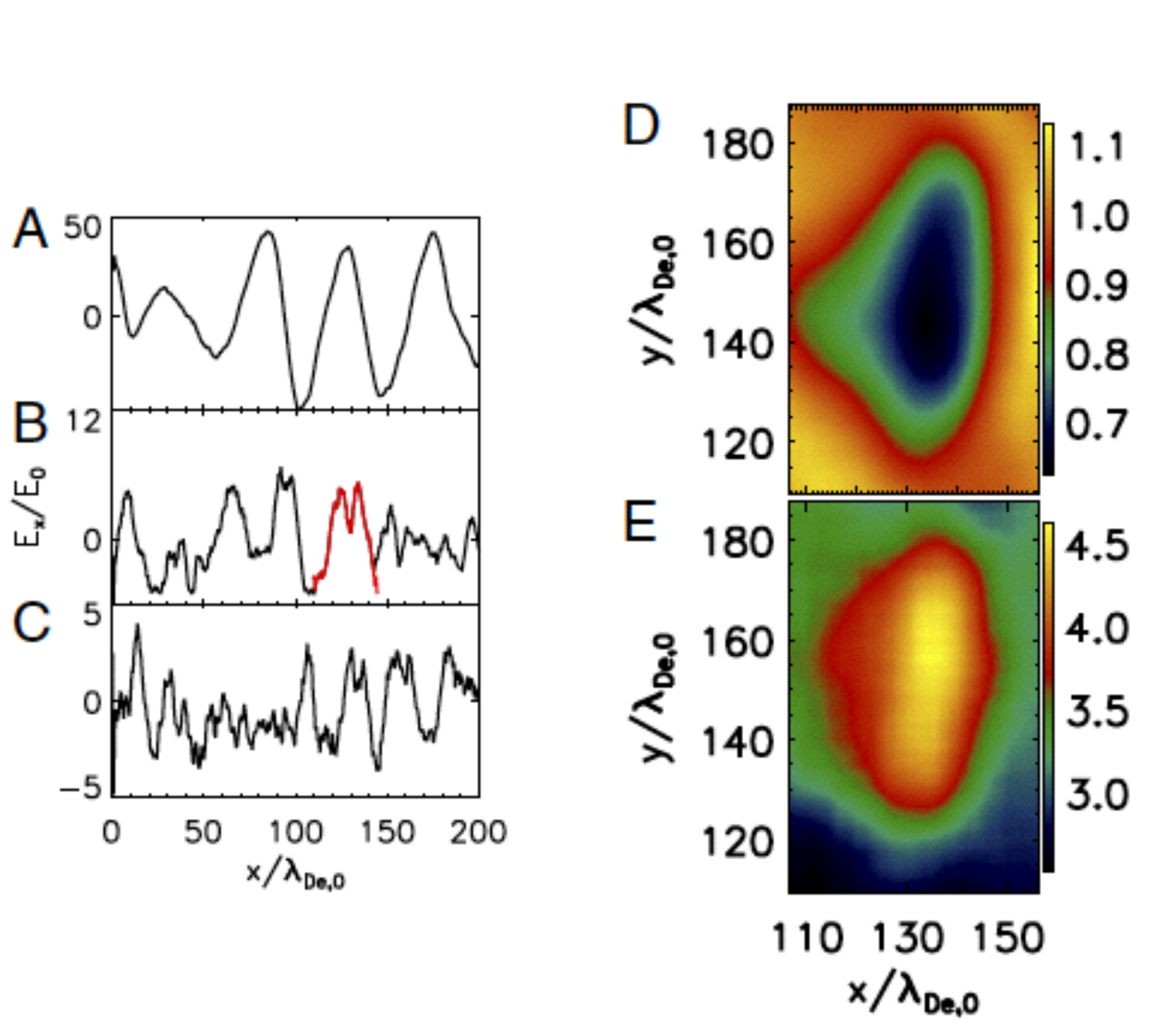
$$E_0 \sim 18 \left(\frac{W}{10^{-4}}\right) \left(\frac{n_c}{10^{10}\,\mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{T_c}{10^{11}\,\mathrm{K}}\right)^{1/2} \mathrm{statV\,cm}^{-1}.$$

W is the dimensionless energy density of the caviton in terms of the background plasma energy.

The collapse can be induced if the plasma is inthe strong turbulence regime; this takes place for values of W = 10^{-4} -10^{-6} (Weatherall & Benford 1991).

Results of massive particle-in-cell (PIC) simulations

electric field



ion density

electron temperature

Simulations of caviton formation by an electron stream
(Che et al. 2017, PNAS)

Two-stream instability in the plasma results in electron bunching.

Particle bunches radiate as macro-particles of $e(\delta n)\lambda^3$, with λ the scale of the density fluctuations.

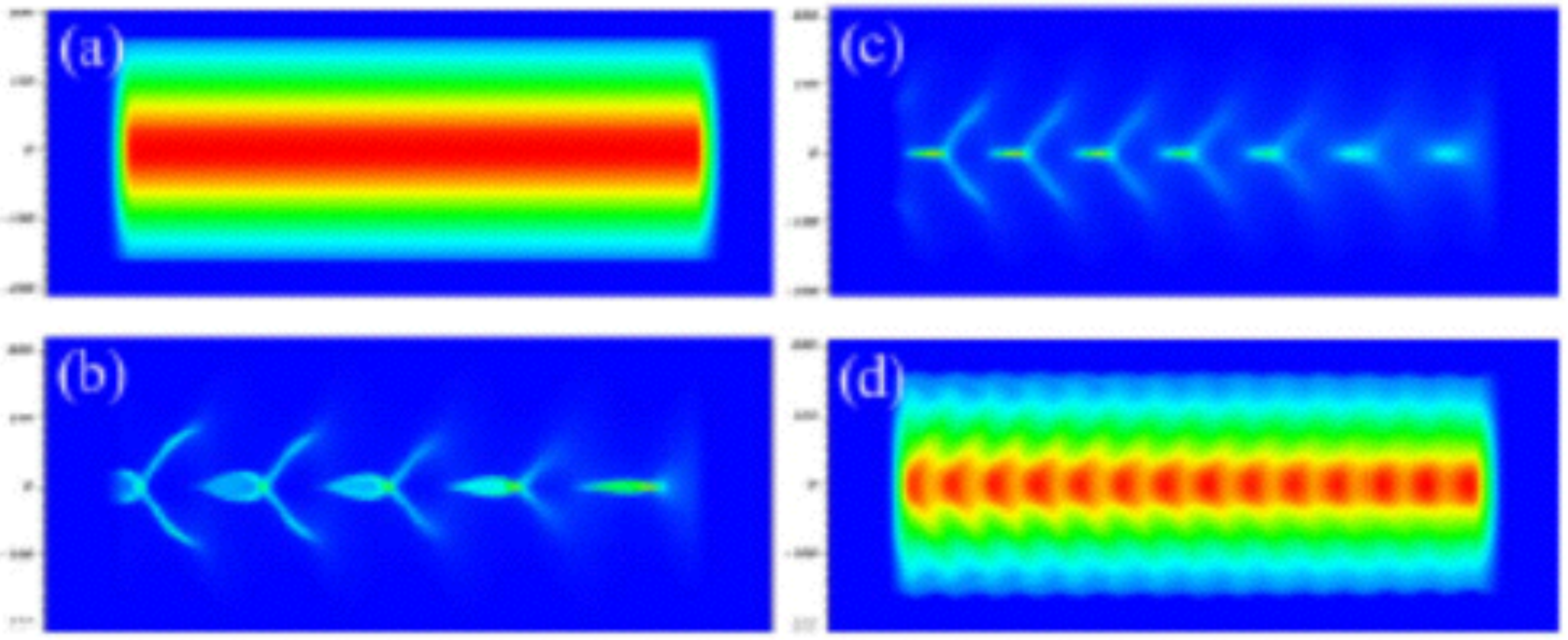


Fig.1. Beam density distribution versus plasma density. (a) Initial beam distribution; (b)-(d) Beam density distribution after propagating 1.8cm through plasmas with densities of $1.24\times10^{22}/m^3$, $2.84\times10^{22}/m^3$ and $11.2\times10^{22}/m^3$ respectively. The corresponding plasma wavelengths are 300 μm, 200 μm and 100 μm.

Zhang et al. 2016

Radiation of a single electron:

$$\langle I(\omega)\rangle = \frac{3}{4\pi} E_0^2 \sigma_T c \frac{D^2}{c^2} \quad \omega_e < \omega < \frac{2\gamma^2 c}{D}$$
$$= 0 \quad \omega \text{ other} .$$

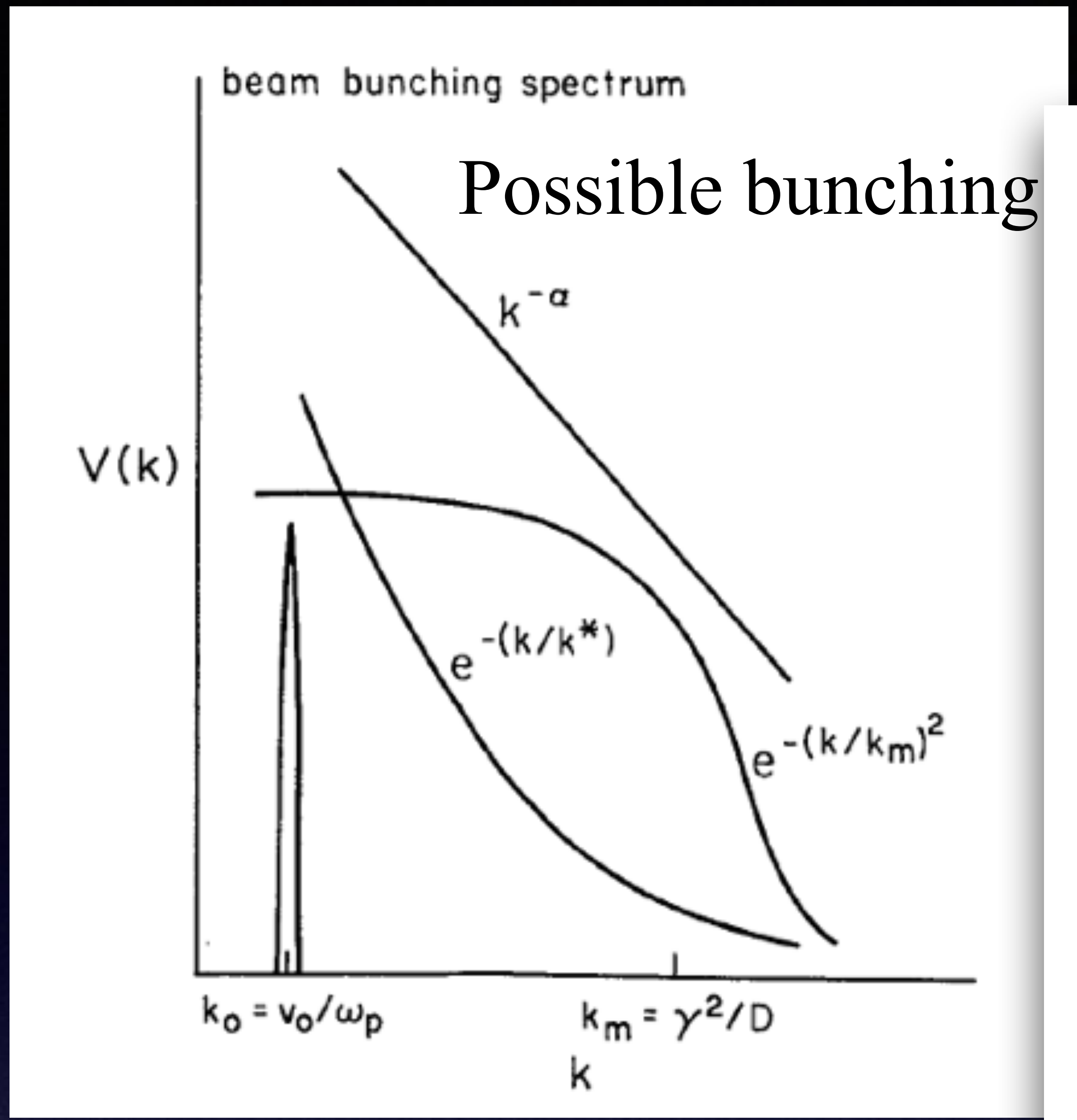
(averaged over the orientations of the cavitons)

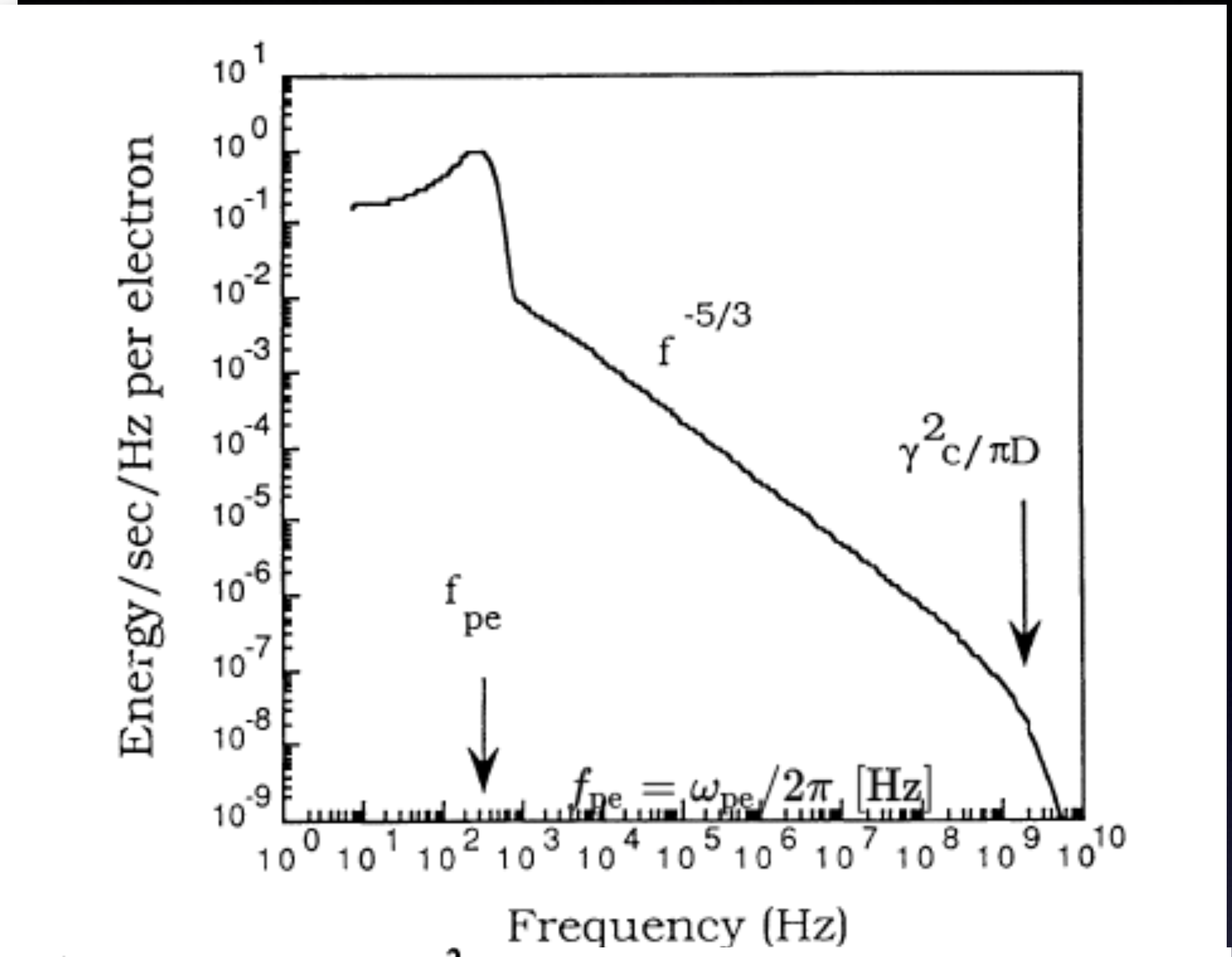
A uniform beam will produce incoherent Bremsstrahlung and synchrotron radiation (if a B field es present).

Fluctuations in the electron beam will cause enhancements in density, which radiate with the power of macroparticles. The magnitude of these fluctuations of scale length λ can be described by a one-dimensional spectral density function *V(k)*, where $k = 2\pi/\lambda$

$$\delta n^2(\lambda) = \int_0^\infty V(k)\exp(ik\lambda)\frac{dk}{2\pi} .$$

No existing experiments directly measure *V(k)*.





The upper bound $2\gamma^2 c/D$ is the highest frequency emitted by electrons scattering on solitons of scale length *D*.

If turbulence has a power-law spectrum ($V \sim k^{-\text{alpha}}$),

$$V(k) = n_{\rm b}\left(\frac{\delta n}{n}\right)^2 \frac{\Gamma(\alpha)}{\pi} \frac{r_0}{(1+kr_0)^\alpha},$$

$$r_0 = c/w_e$$

$$\omega_{\rm pe} = \sqrt{\frac{4\pi n_{\rm e} e}{m^*}},$$

Beam radiation per electron

$$P_{e,\omega} = \langle I(\omega)\rangle f \frac{3}{2}\pi^2 D n_{\rm b} c^2 \left\{\delta(\omega-\omega_e) + \frac{V[(\omega-\omega_e)/c]}{n_{\rm b}^2 c}\right\}$$

with f~0.1 the fraction of the plasma filled with cavitons

Weatherall & Benford 1991

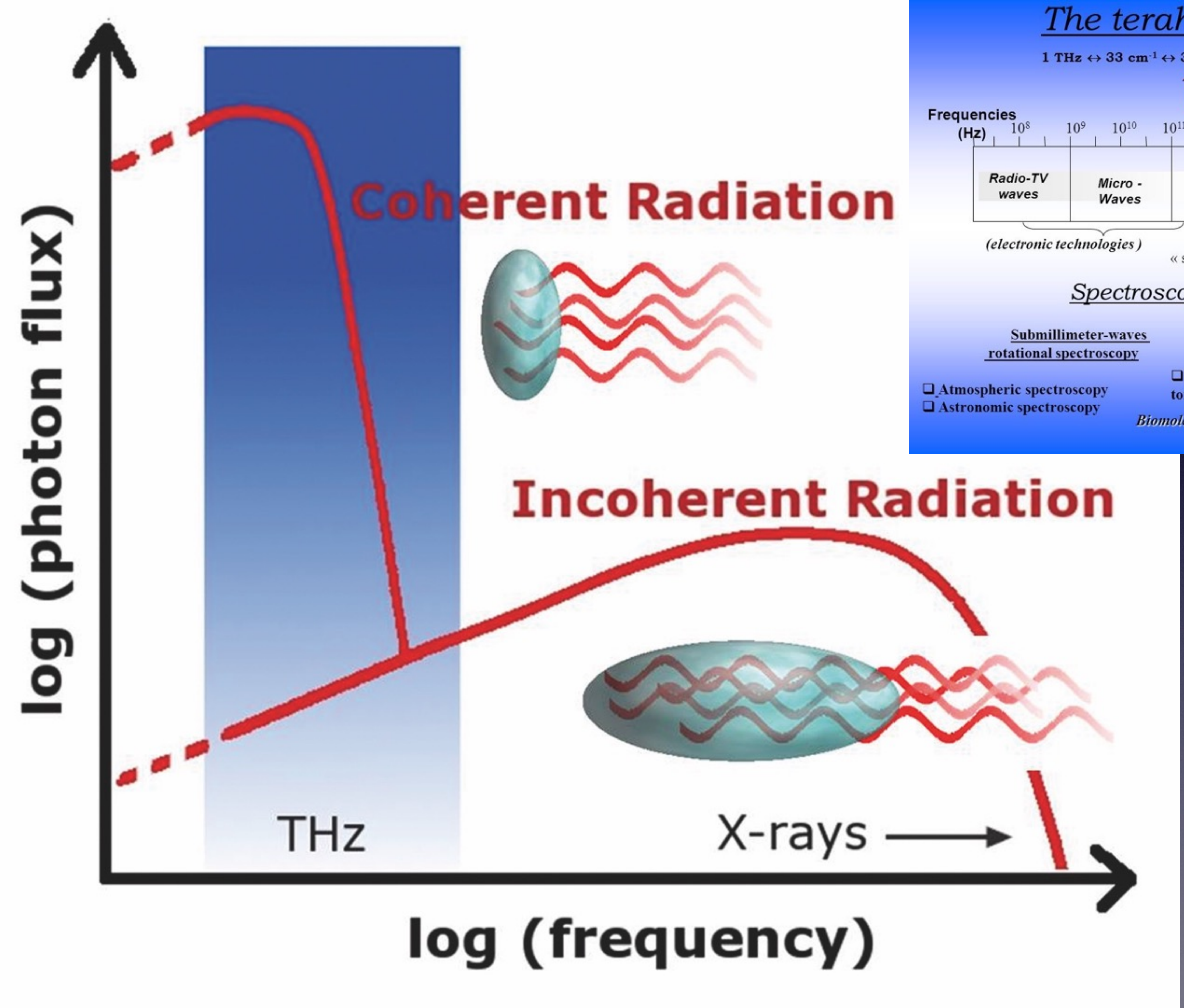
$$P_{e,\omega} = \langle I(\omega)\rangle\, f\frac{3}{2}\pi^2 D n_{\rm b} c^2 \left\{\delta(\omega-\omega_e) + \frac{V[(\omega-\omega_e)/c]}{n_{\rm b}^2 c}\right\}$$

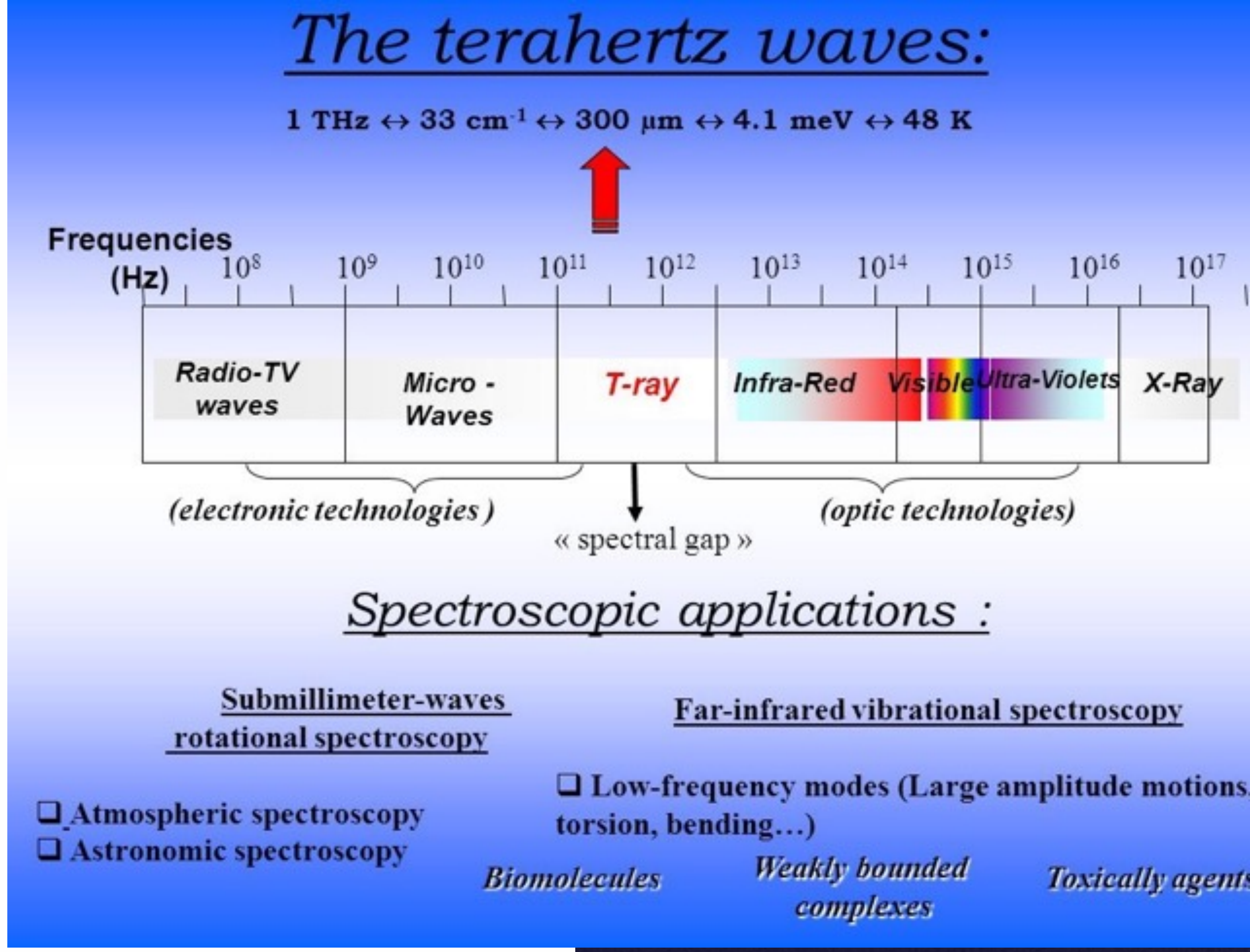
To find total emitted power $P_{\rm T}$, one must multiply by the number of beam electrons in the radiating volume, $N_e \sim \pi\, n_{\rm b} R_{\rm c}^2 h$

The first term in brackets in this equation represents emission that is coherent in the plasma line. This is due to the oscillation of the soliton at the plasma frequency, and occurs independently of modulation in the beam.

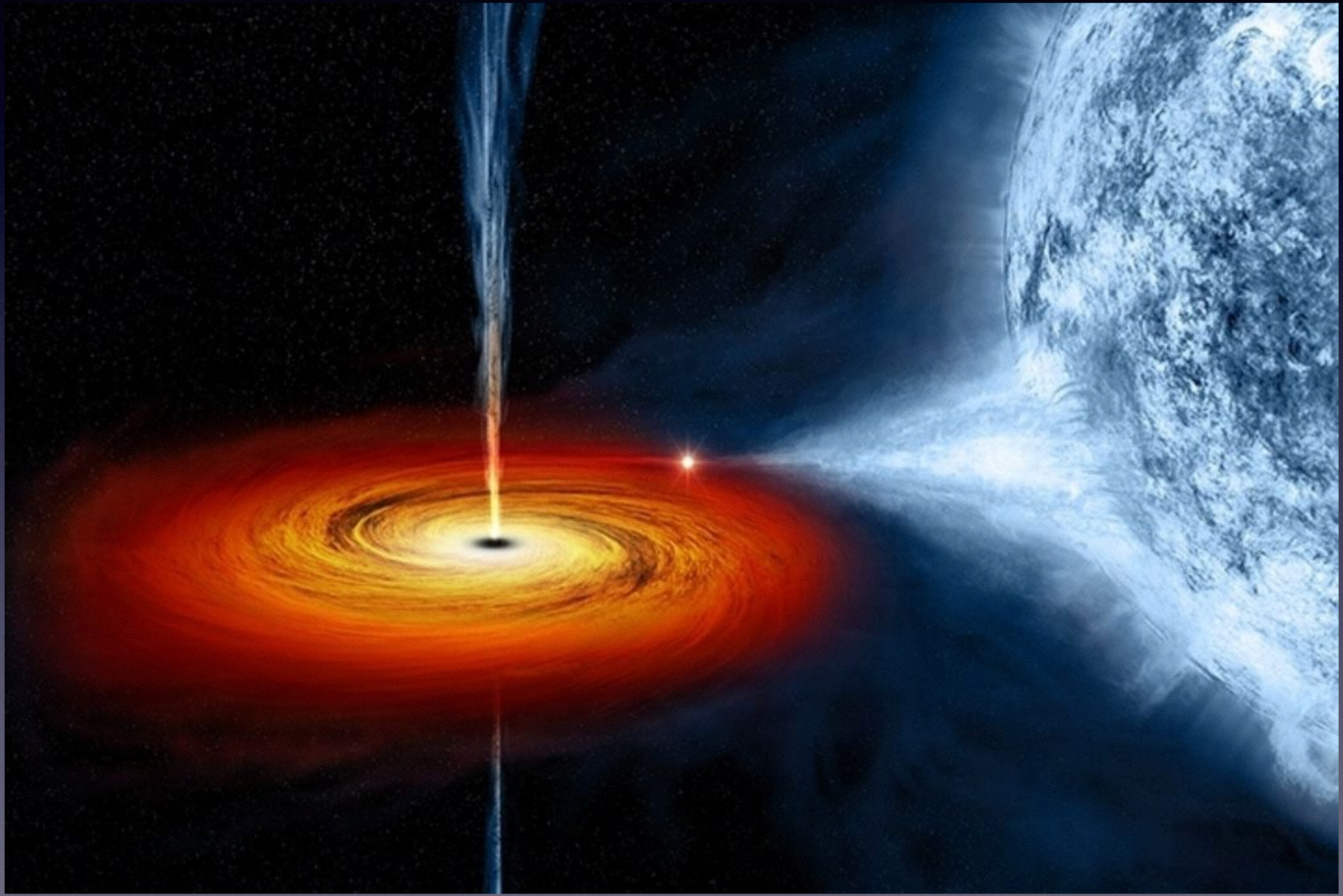
Emission at the plasma frequency will be re-abosorbed, leaving only the power law contribution.

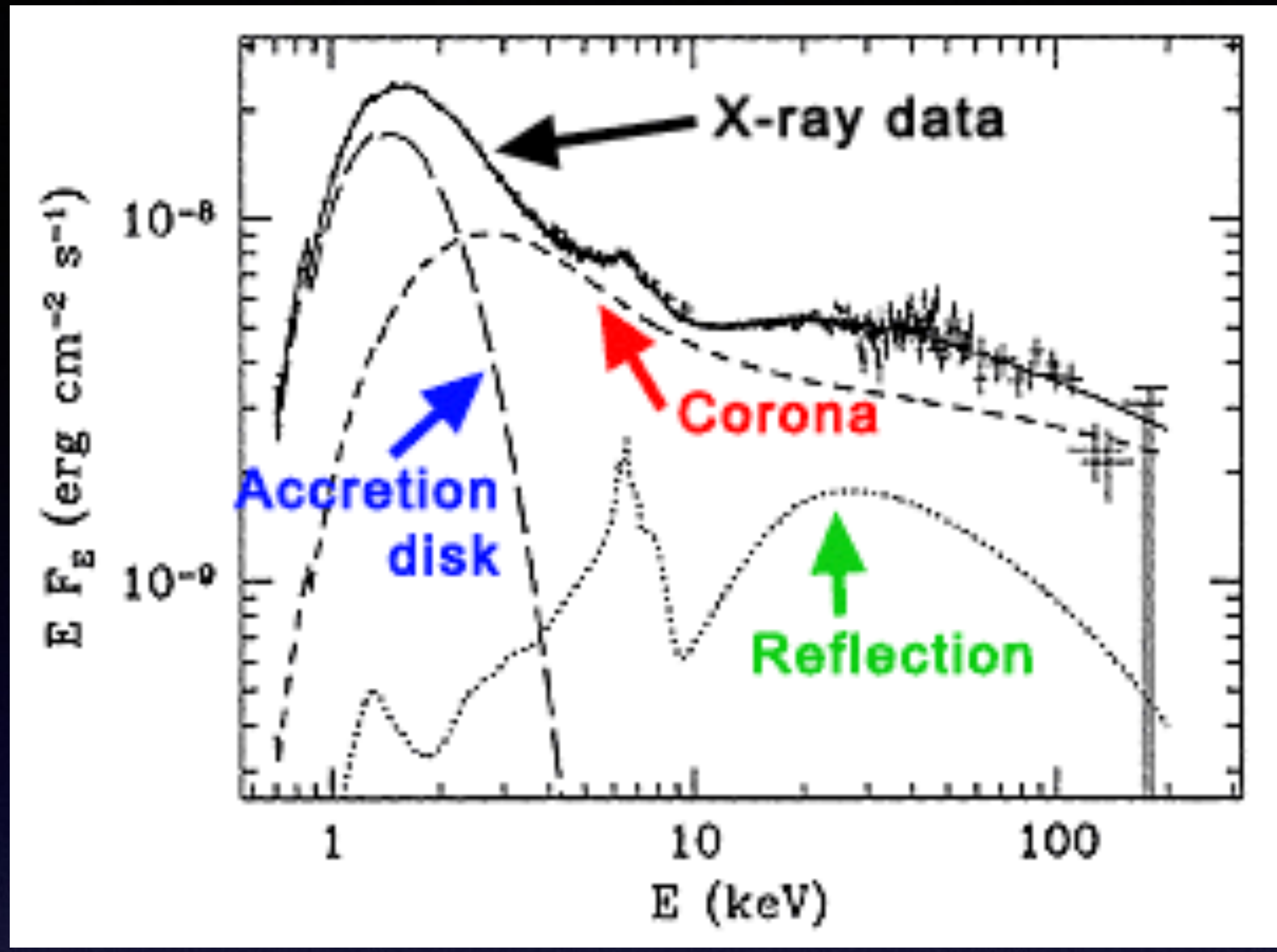
$n \sim 10^{11\text{-}12}$ cm^3

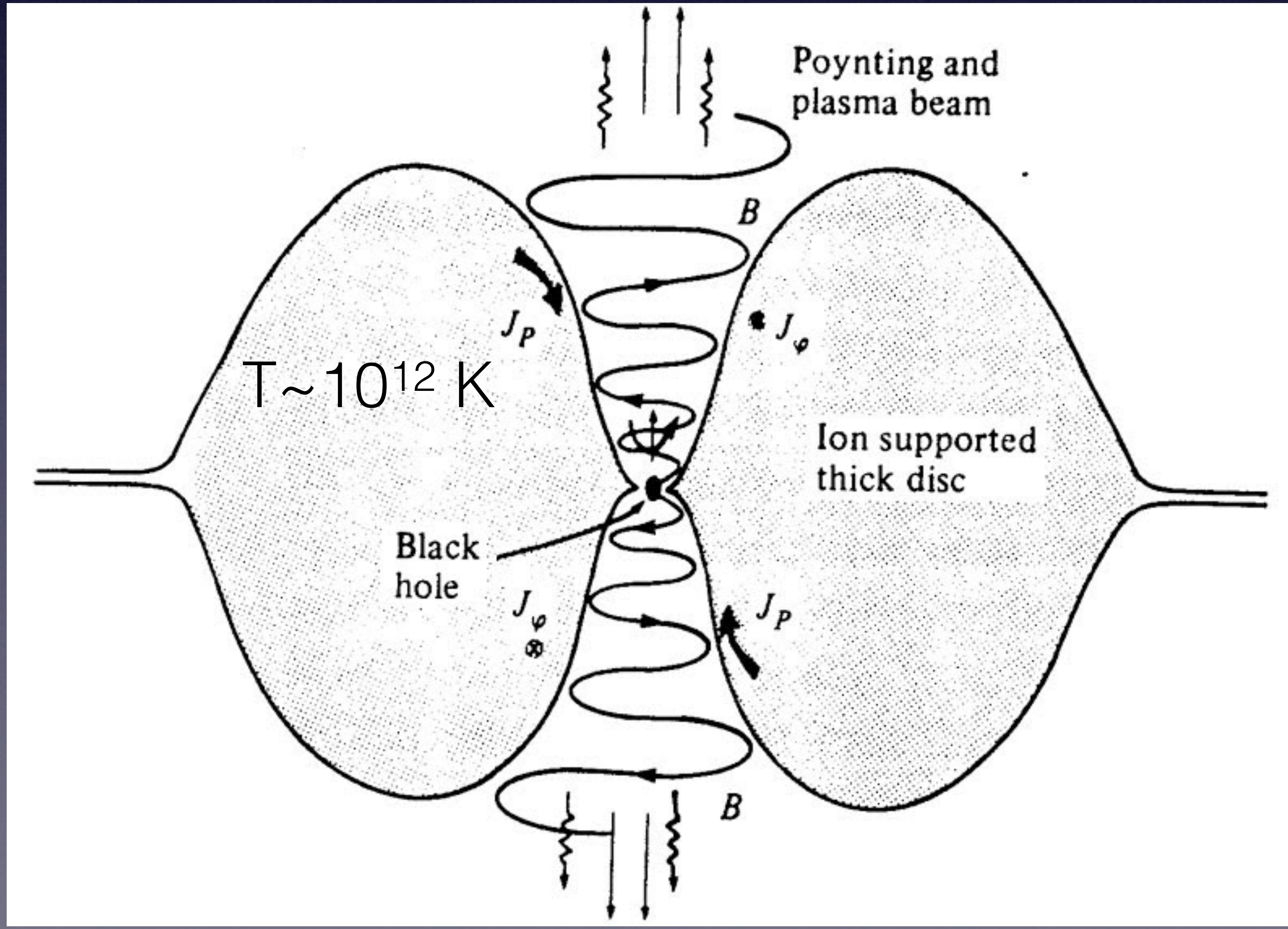




Galactic black hole binaries

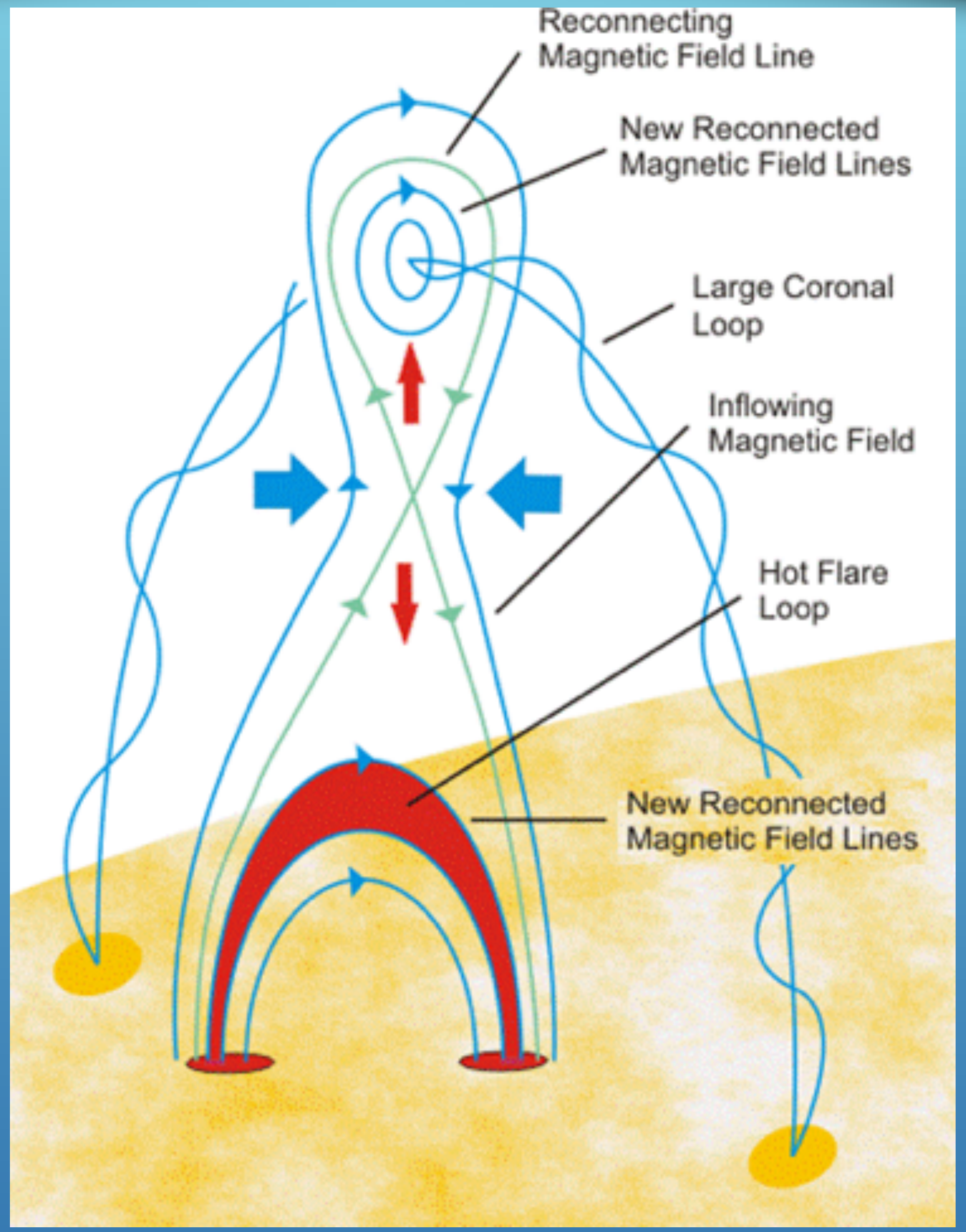






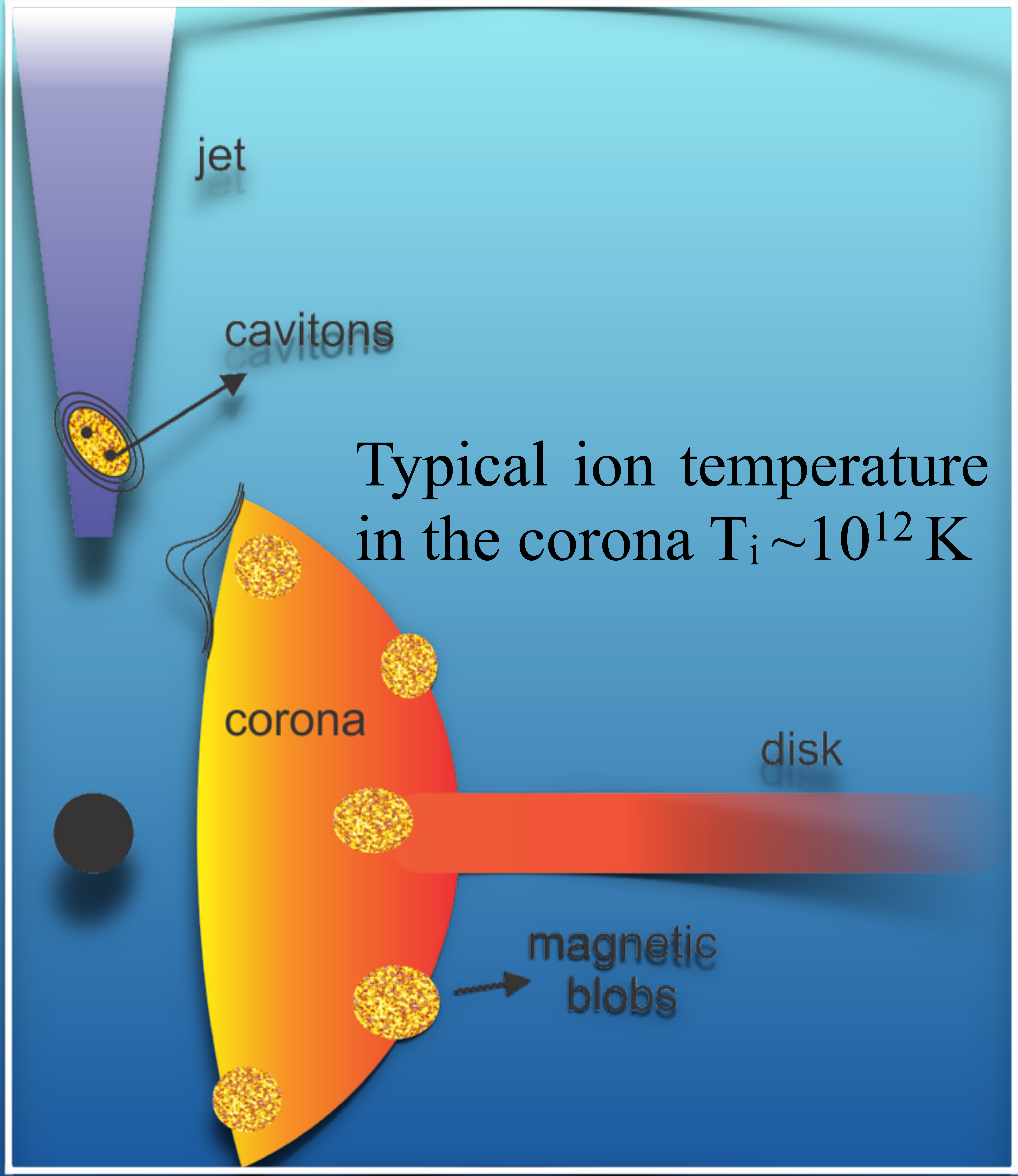
BZ power:

$$L_j = 10^{35} \mathrm{erg\ s}^{-1} \left(\frac{M_{BH}}{10 M_\odot}\right)^2 \left(\frac{a}{0.98}\right)^2 \left(\frac{B_0}{10^7 \mathrm{G}}\right)^2$$



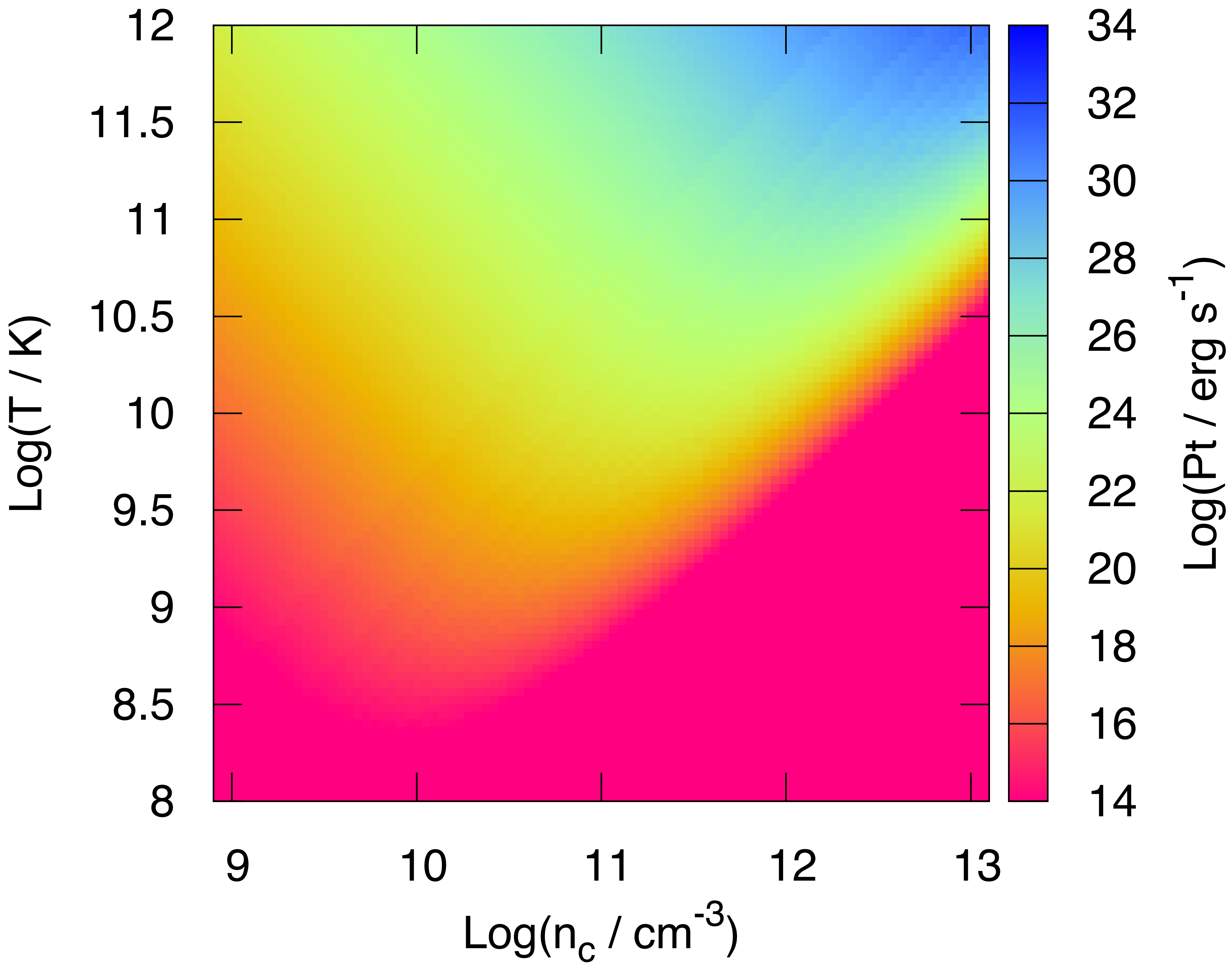
Size of the blobs (Gaalev et al. 1979):

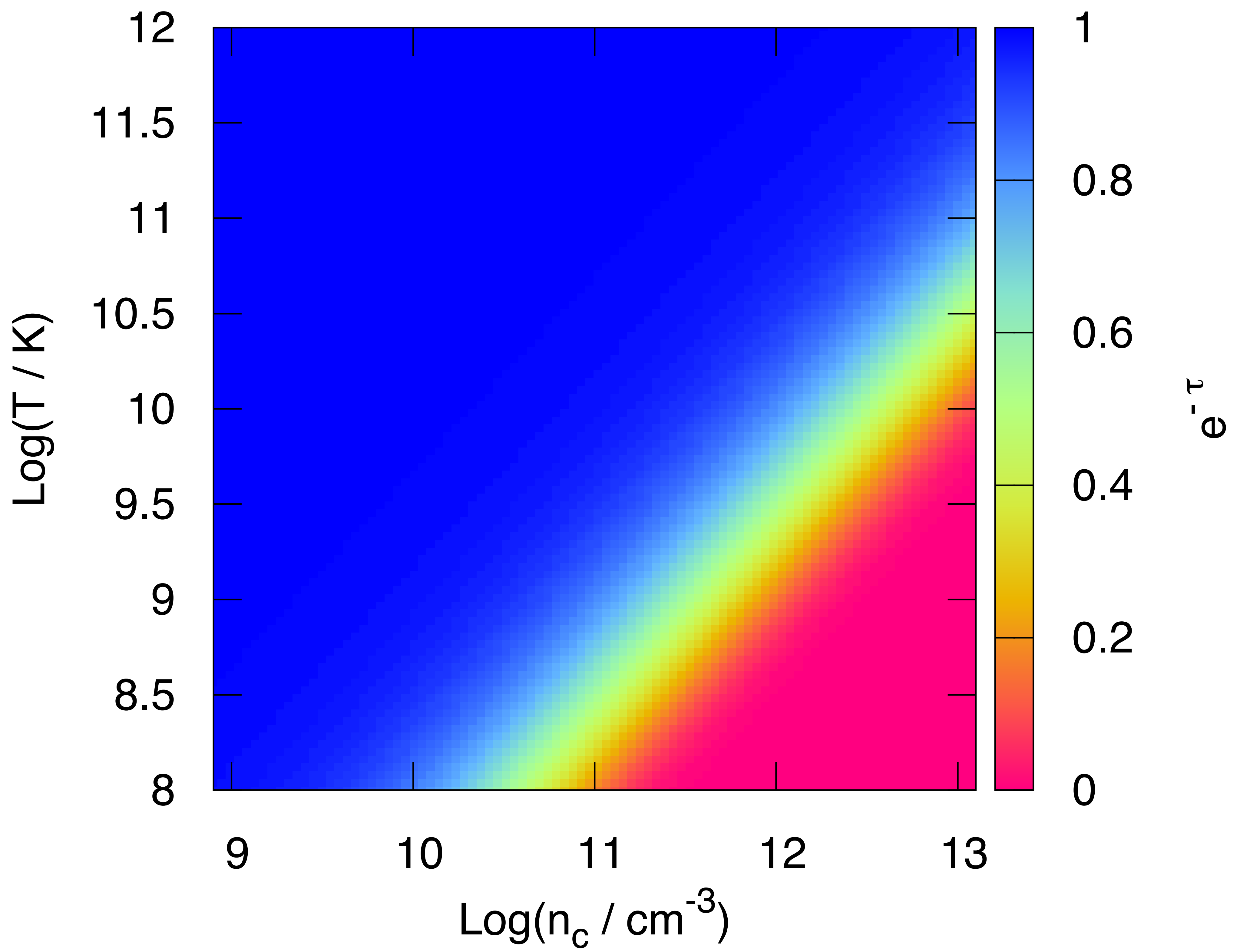
$$R_c = 18 \frac{r_g}{\alpha^{1/3}} \frac{L_c}{L_{Edd}} \left(1 - \sqrt{6 r_g / r}\right). \quad R_c^i \sim 10^6 \ \mathrm{cm}.$$



Typical ion temperature in the corona $T_i \sim 10^{12}$ K

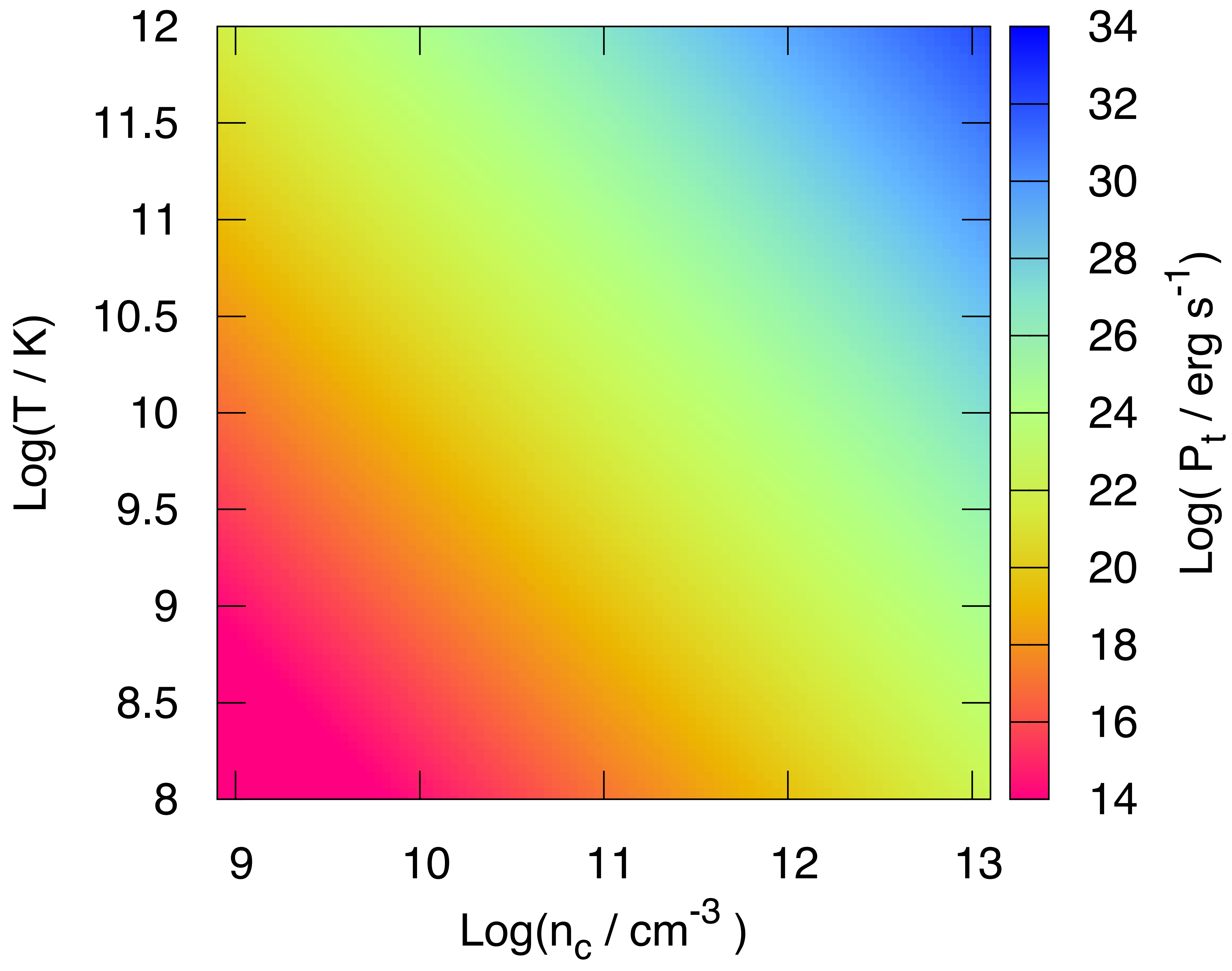
$L_e \sim 10^{35}$ erg/s





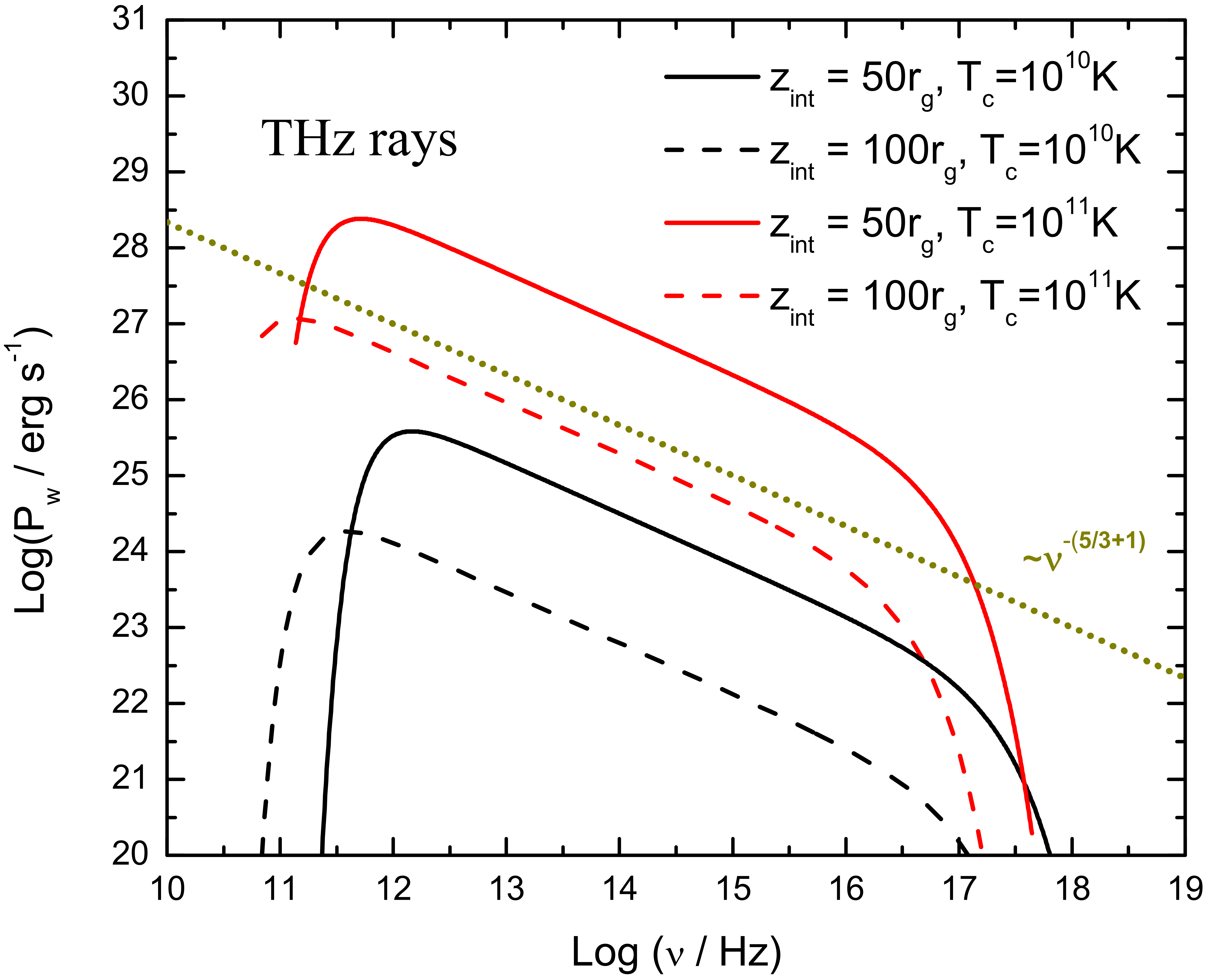
$W = 10^{-5}$, $\delta n/n = 10^{-2}$

Coherent emission from an irradiated plasmon

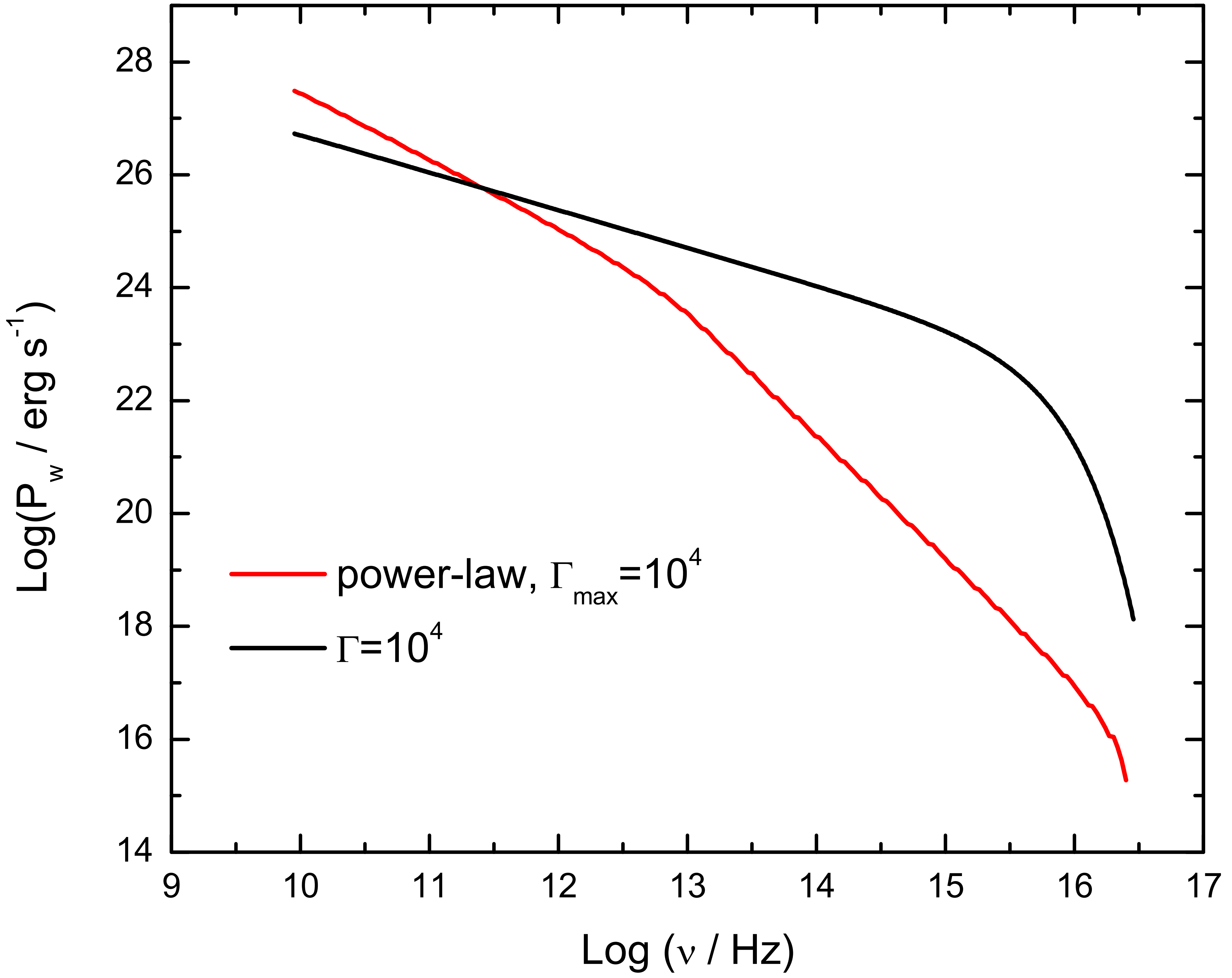


$L_e \sim 10^{35}$ erg/s

$W = 10^{-5}$, $\quad \delta n/n = 10^{-2}$



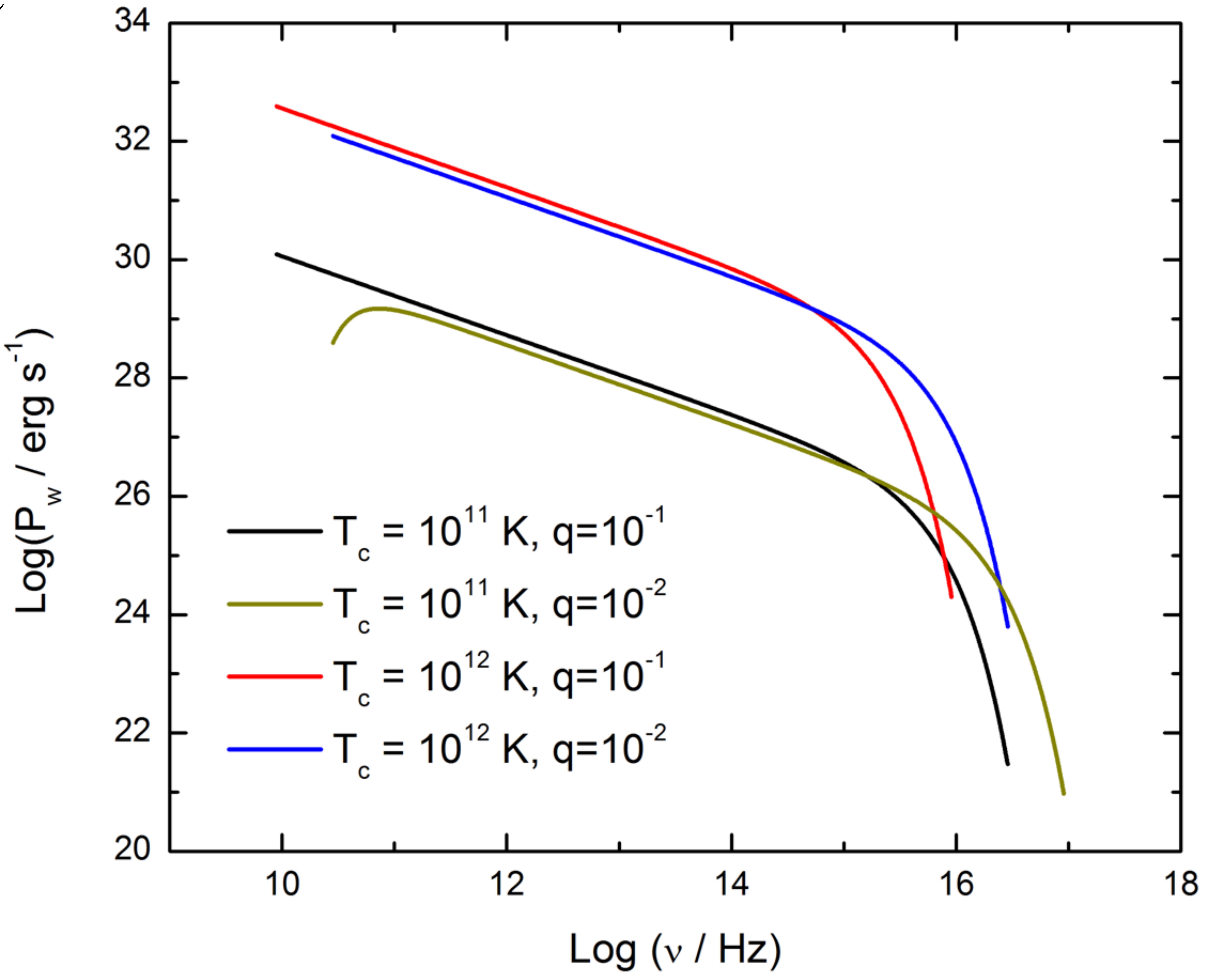
$L_e \sim 10^{35}$ erg/s



$L_e \sim 10^{35}$ erg/s

$W = 10^{-5}$, $\delta n/n = 10^{-2}$

Energetic flare



$L_e = 10^{37}$ erg/s
Gamma = 10^4
W = 10^{-5}
dn/n = 10^{-2}

Duration of the events

$$t_c \sim \frac{2R_c}{\sqrt{q}c} \sim 10^{-3} \left(\frac{R_c}{10^6 \text{ cm}}\right) \left(\frac{q}{10^{-2}}\right)^{-1/2} \text{ s},$$

$$q = n_b/n_c$$

$$f_j = \frac{2\pi}{4\pi} \int_0^\theta \sin\alpha d\alpha.$$

Fractional solid angle subtended by the electron beam

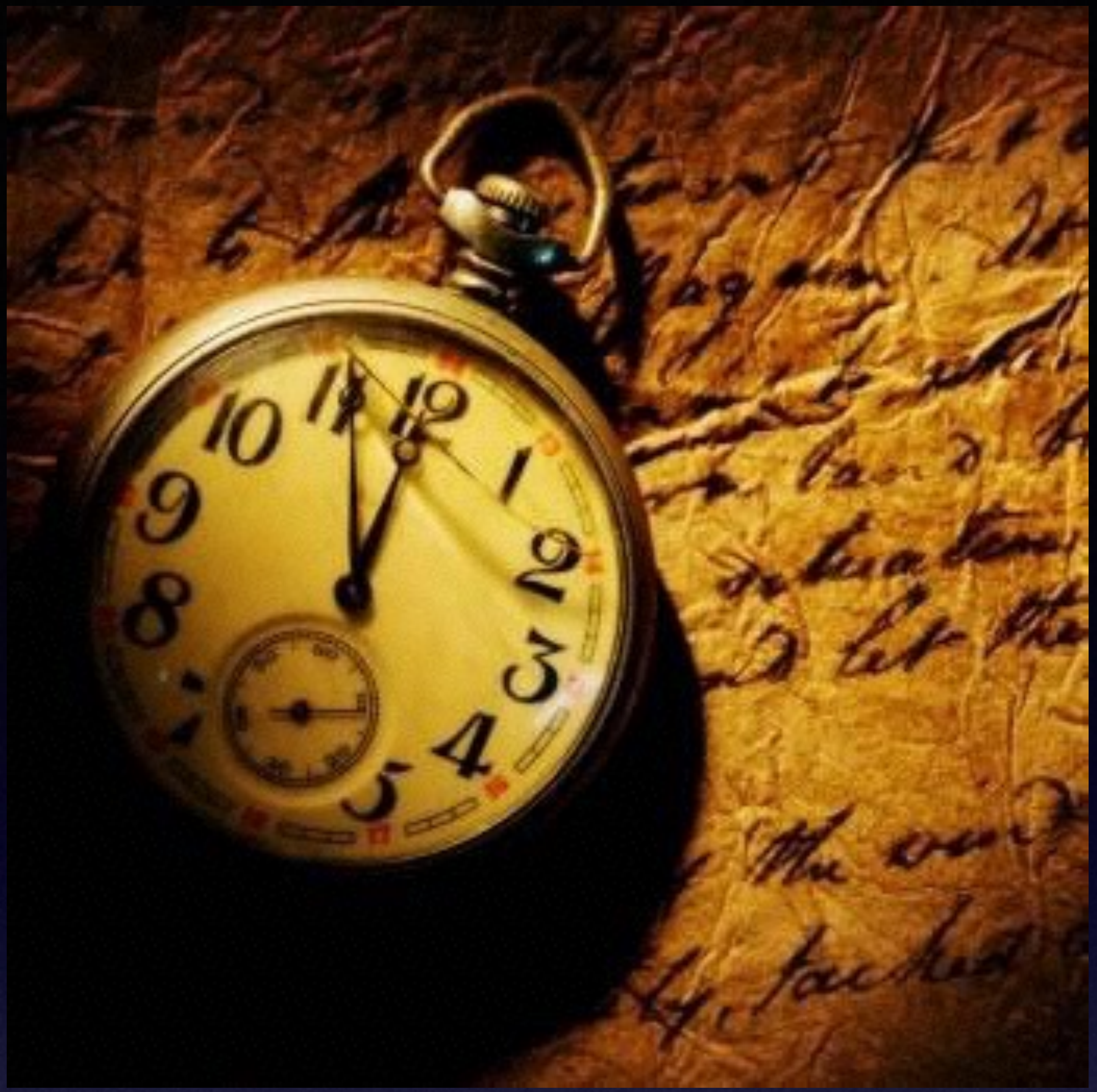
$$\text{Duty cycle} = f_c f_j t_{\text{DC, j}}^{-1} \sim 0.1 \%$$

$f_c \sim 0.3$ (plasmons filling factor; Nayakshin & Dove 2001)

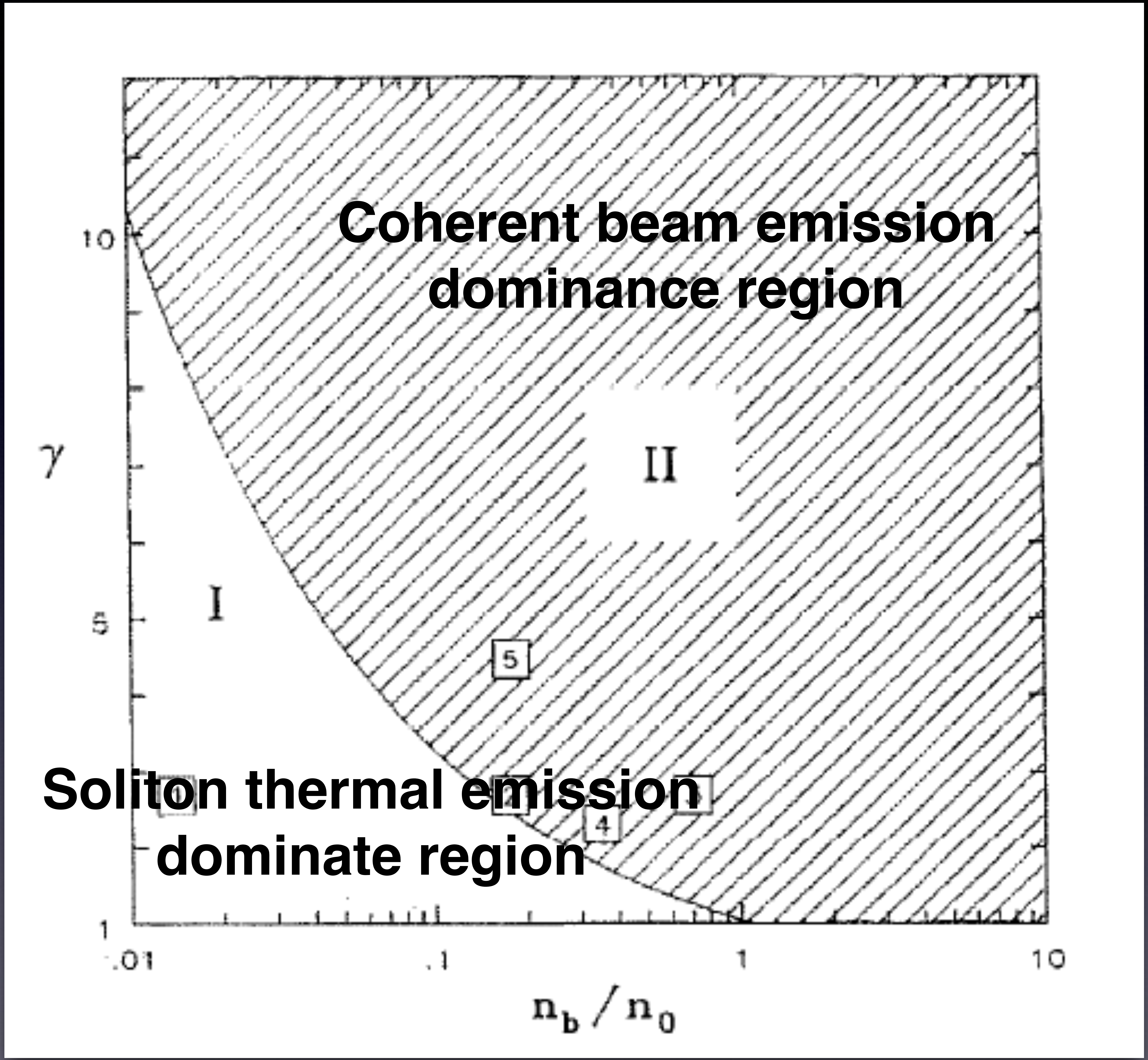
$$t_{\text{DC, j}}^{-1} \sim 0.9$$

Conclusions

- Coherent rapid flares of THz radiation can occur close to the central engine of MQs (and other galactic sources).
- Typical durations would be ~1 ms with fluxes that might exceed fluxes of 1 Jy for objects such as Cyg X-1.
- The spectrum would be a power-law that would reflect the power spectrum of the density fluctuations in the beam produced by non-linear plasma effects.
- Sub-mm telescopes with hybrid arrays of bolometers and interferometric horns might detect such flares in the future.



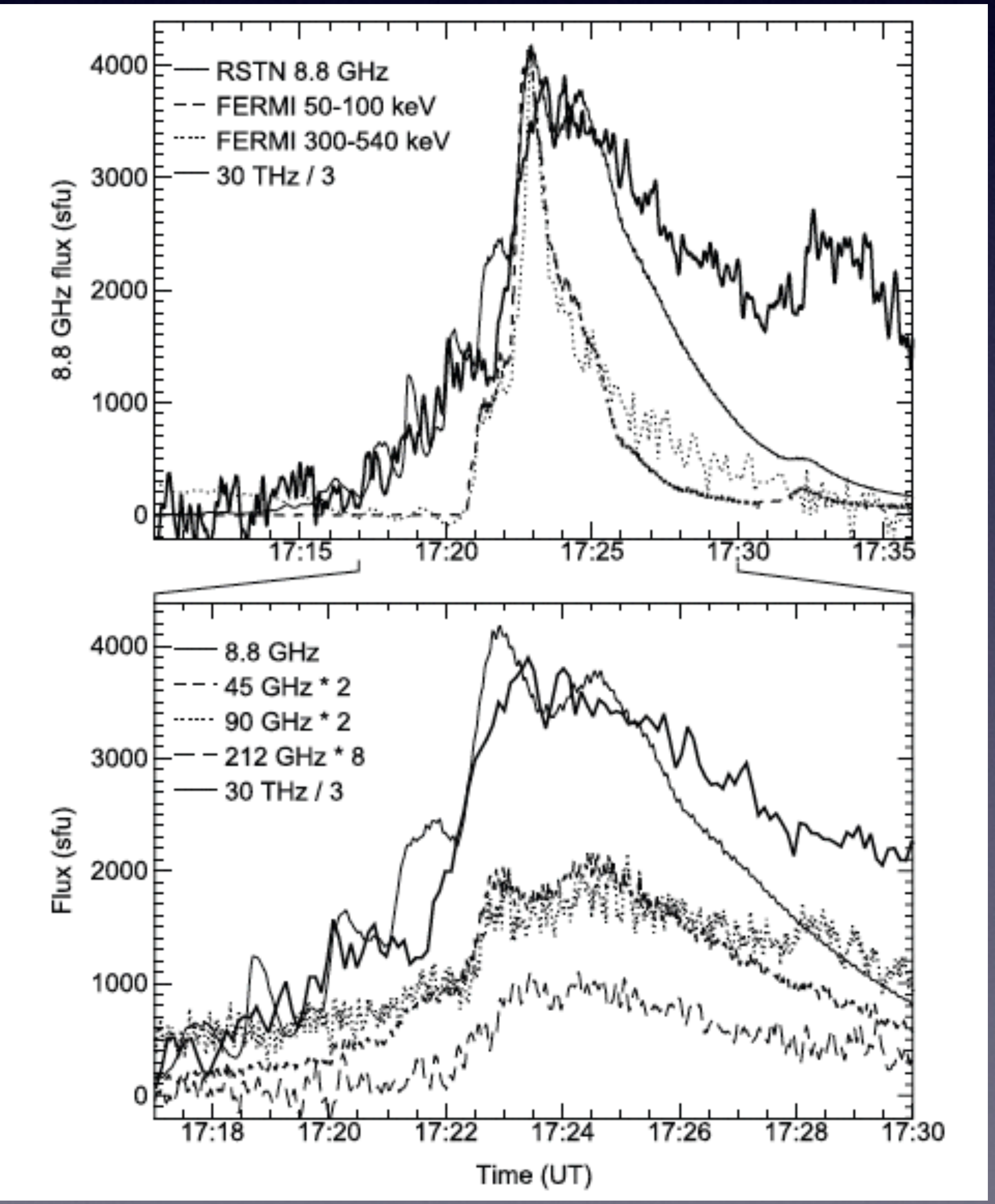
Thanks!

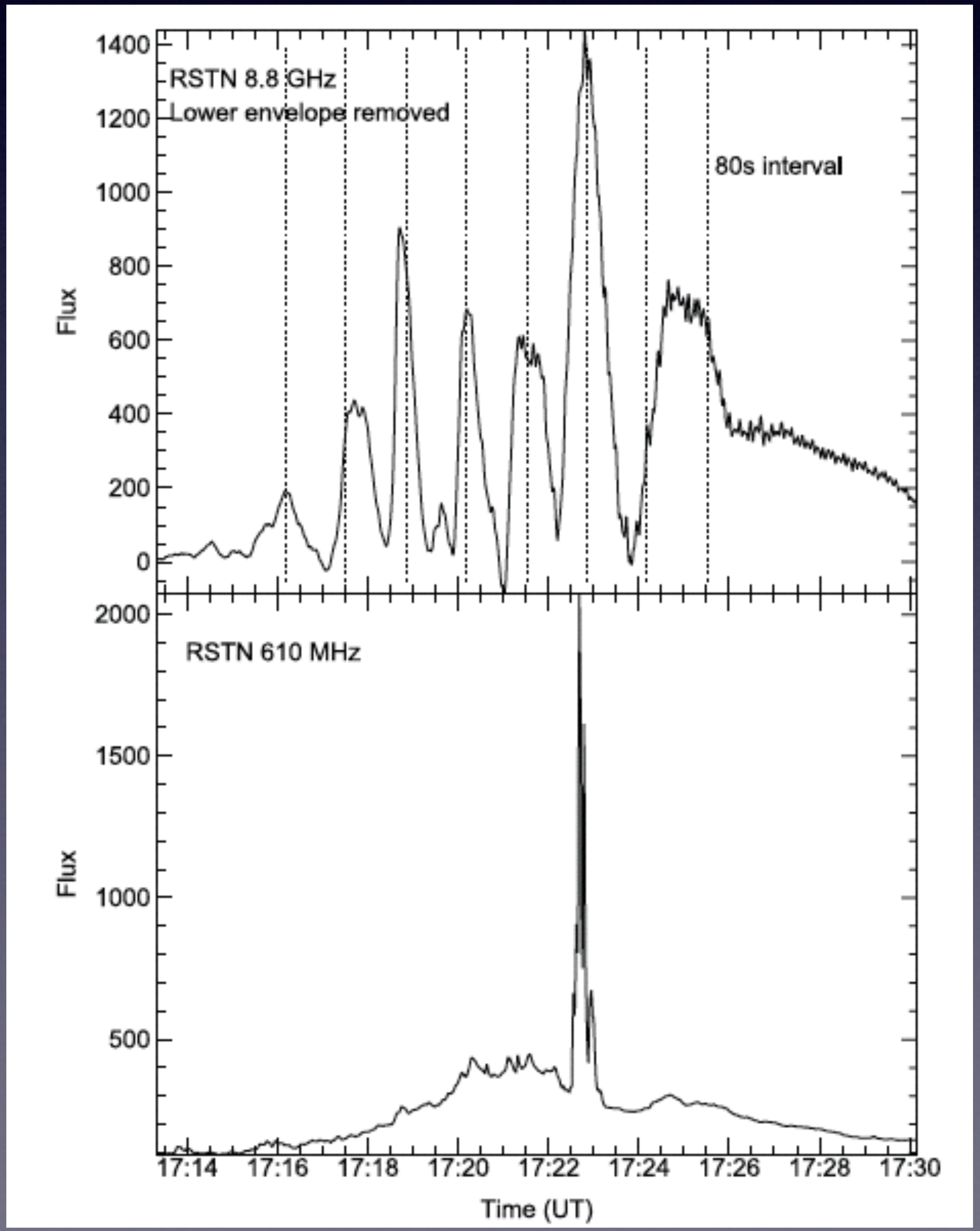

Coherent beam emission
dominance region
Soliton thermal emission
dominate region
II
I
5
4
γ
10
5
1
.01
.1
1
10
n_b / n_0

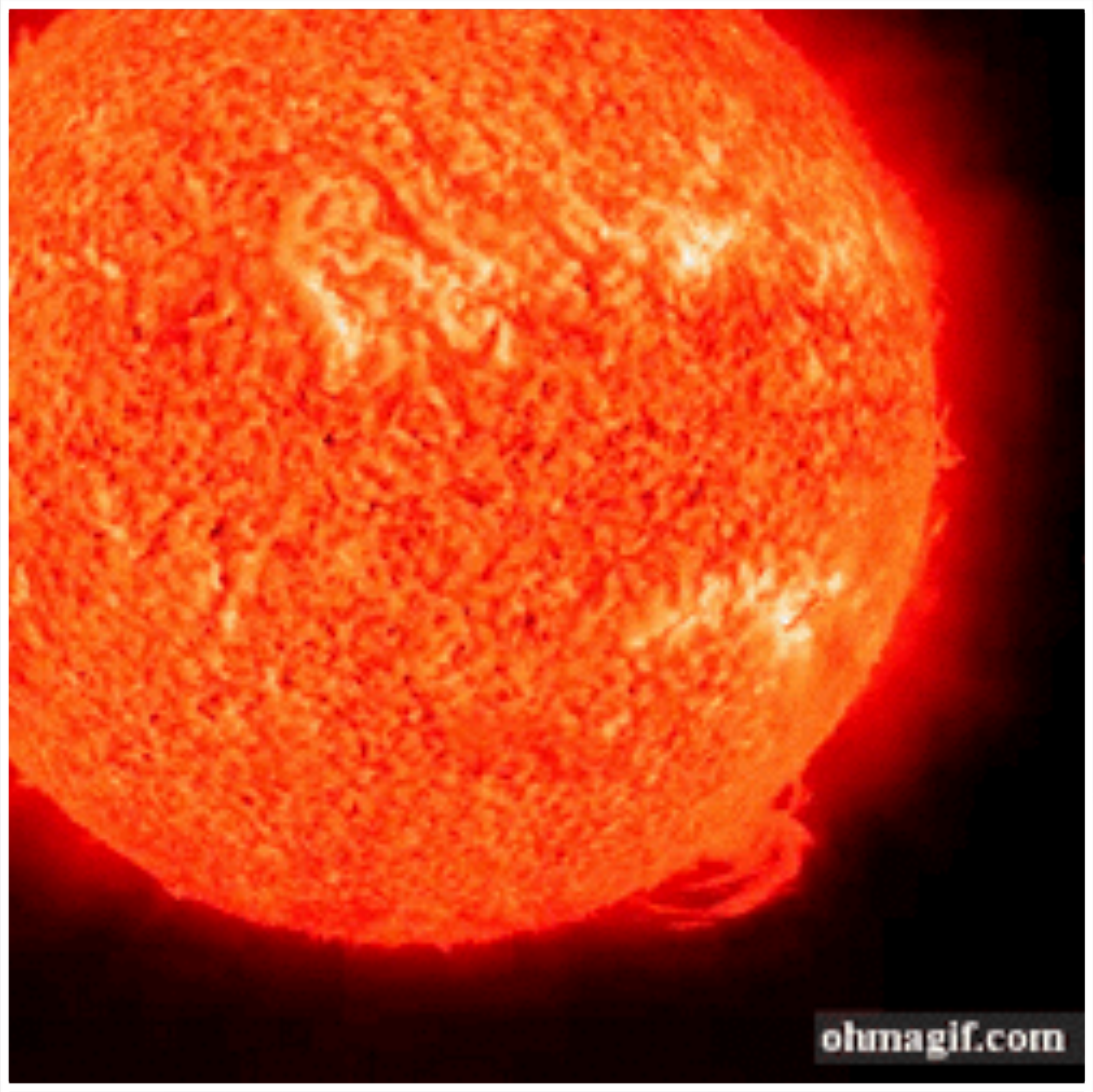
The Astrophysical Journal, 768:134 (9pp), 2013 May 10 doi:10.1088/0004-637X/768/2/134

A BRIGHT IMPULSIVE SOLAR BURST DETECTED AT 30 THz

P. Kaufmann[1,2,8], S. M. White[3], S. L. Freeland[4], R. Marcon[5,6], L. O. T. Fernandes[1], A. S. Kudaka[1], R. V. de Souza[1], J. L. Aballay[7], G. Fernandez[7], R. Godoy[7], A. Marun[7], A. Valio[1], J.-P. Raulin[1], and C. G. Giménez de Castro[7]





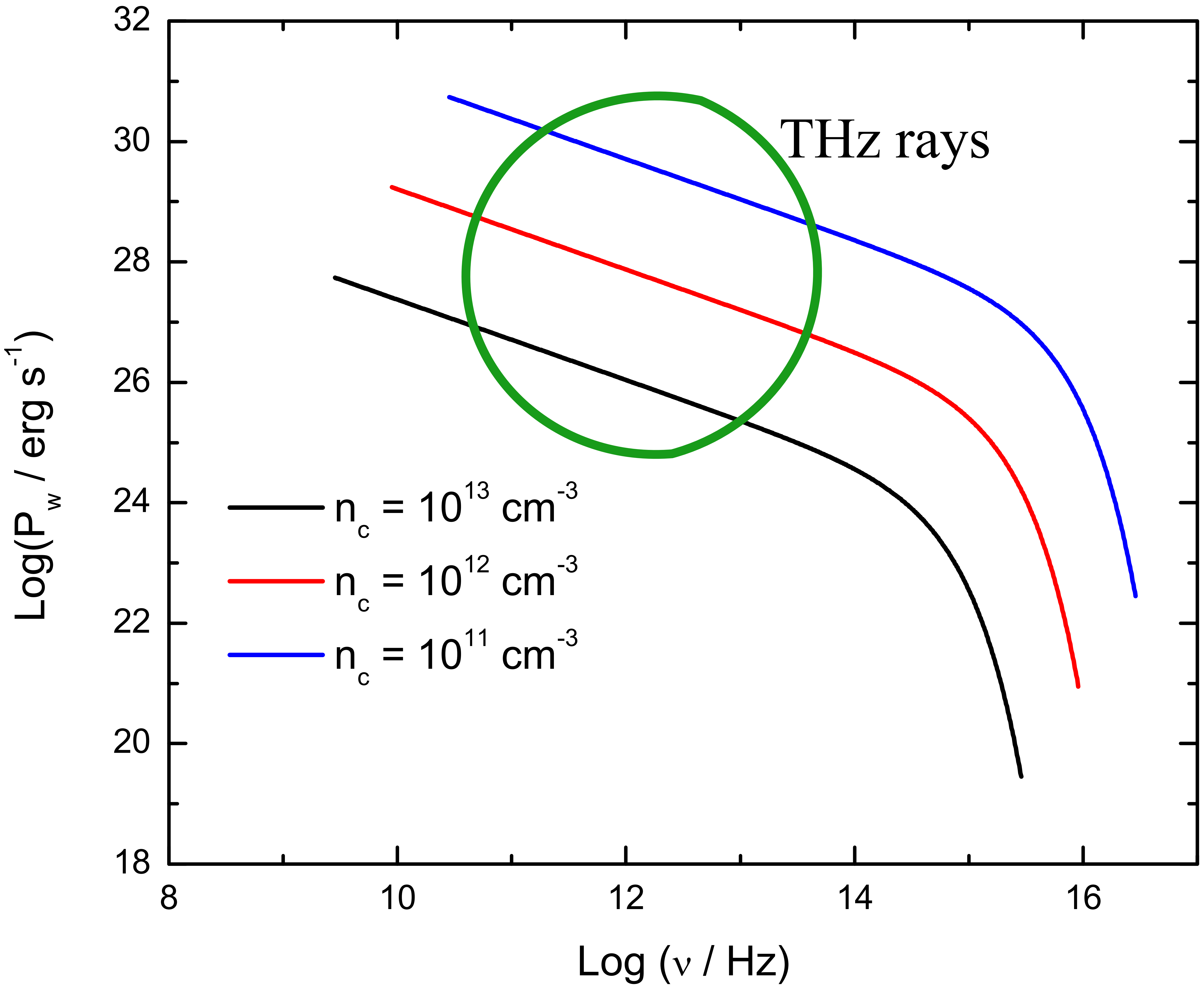

ohmagif.com

Levinson & Blandford (1995) studied stimulated Raman scattering as a limit to coherent emission, employing a weak turbulence approach. Neglecting magnetic fields, they found that high brightness temperatures inhibited propagation of coherent emission.

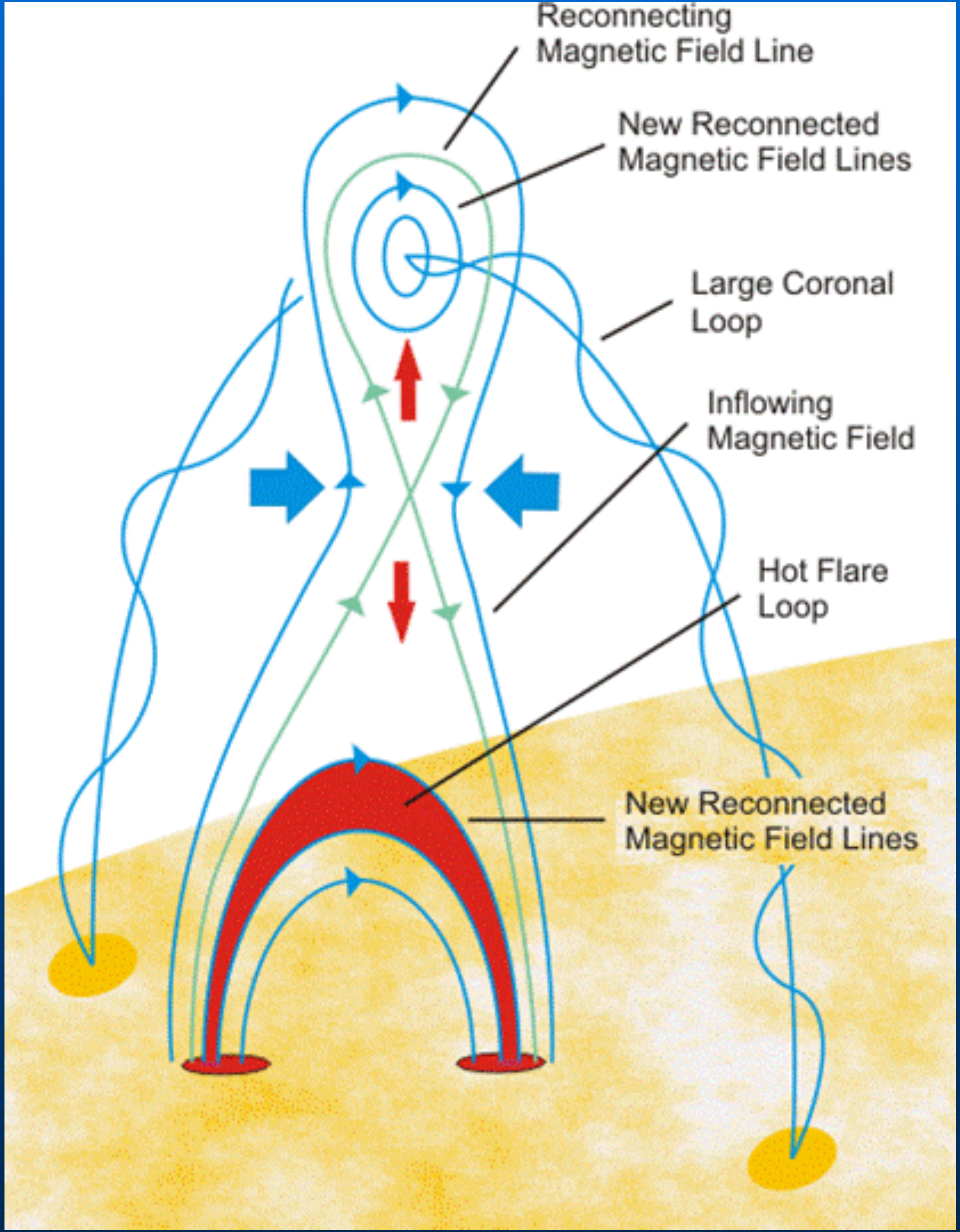
In the experiments, collective effects produced strong electromagnetic emission in the 1- to 100-GHz bands, which then propagated through cool surrounding plasma, finally passing through transparent chamber walls to be received by a variety of directional horn antennas. This echoes the general conditions expected within which Raman instability is possible.

What is wrong here? Growth rates for Raman instability decline as the emission broadens, and weak turbulence theory assumes that field amplitudes are small. Strong-field, broad-band emission violates such assumptions. Yet experiment finds that these conditions provide the most powerful emission.

See Benford & Lesch 1998



$L_e \sim 10^{35}$ erg/s


Reconnecting
Magnetic Field Line
New Reconnected
Magnetic Field Lines
Large Coronal
Loop
Inflowing
Magnetic Field
Hot Flare
Loop
New Reconnected
Magnetic Field Lines

Equation of state for the tat plasma

$$P = P_{\text{gas}} + P_{\text{mag}} = \frac{\rho k}{m_p}\left(\frac{T_e}{\mu_e} + \frac{T_i}{\mu_i}\right) + \frac{B^2}{8\pi}.$$