Constraints on magnetization of jets in luminous blazars

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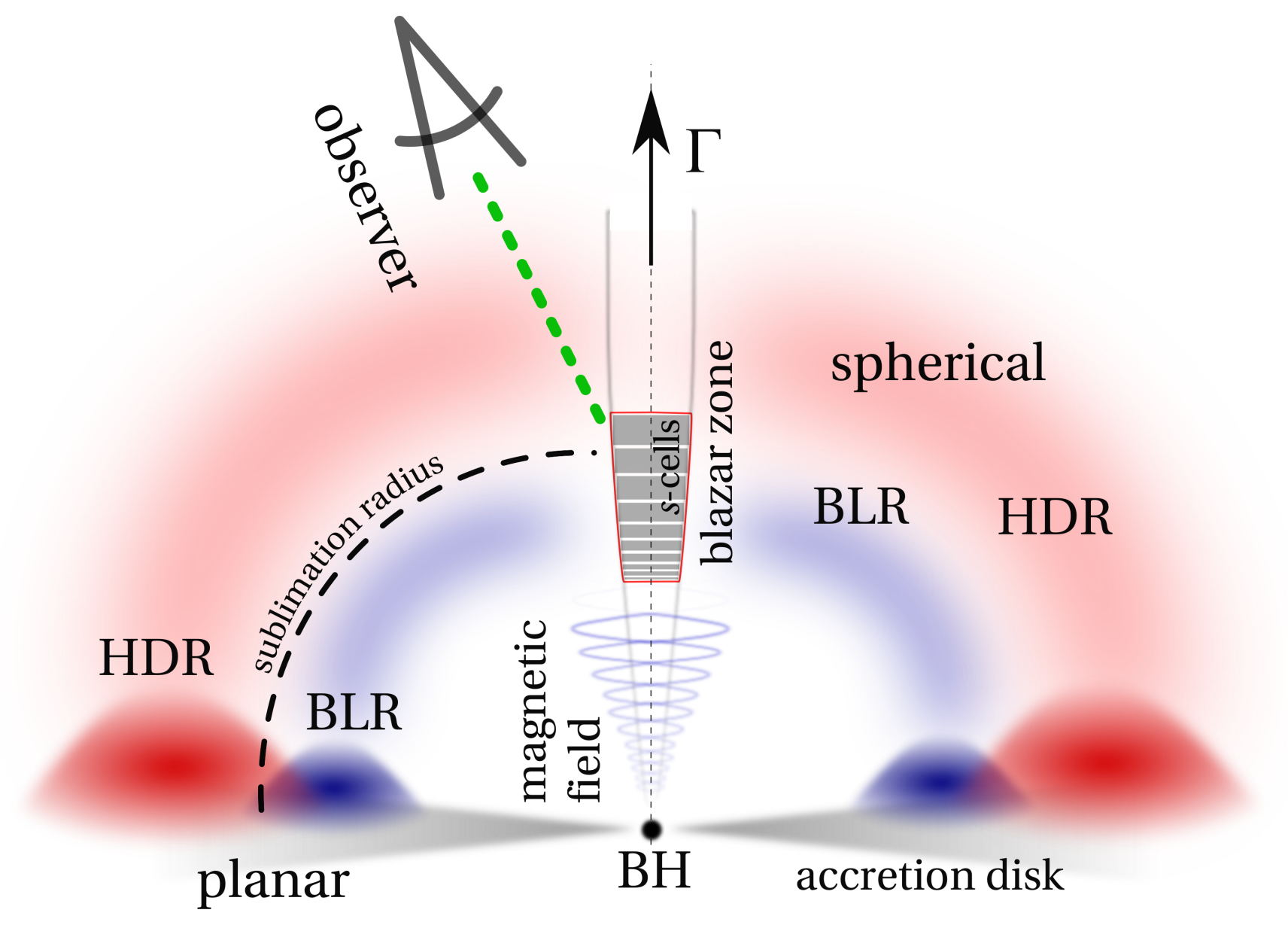
Abstract

The broadband spectra of majority of luminous blazars are dominated by high energy component peaking in γ-rays which is thought to be produced by Comptonization of radiation from outside the jet. We study the dependence of Compton dominance (the γ-ray-to-synchrotron luminosity peak ratio) on the jet magnetization (the magnetic-to-matter energy flux ratio) and on the location of the emission region (the 'blazar zone'). We perform calculations for two extreme cases of external photon field geometries, planar and spherical, and including broad-line region and dusty torus. We also include radiation from flat accretion disk. We find that the jet magnetization corresponding to typically observed high Compton dominance is of the order of $0.01(\theta_{\rm jet}\Gamma)^2$ for flat geometry models and $0.1(\theta_{\rm jet}\Gamma)^2$ for spherical models. These results disagree with recent measurements of jet magnetization based on the frequency-dependent shifts of radio-core locations which indicated that the jet magnetization is of the order of unity. This may indicate that blazar radiation takes place in reconnection layers or in weakly magnetized spines of transversely stratified jets.

Motivation

Observations indicate that spectra of the majority of flat spectrum radio quasars (FSRQs) are strongly dominated by high-energy component peaking in γ-rays and in many cases the Compton dominance exceeds a factor of 10. The high-energy component is most likely produced via external-radiation-Compton (ERC) mechanism and with the assumption of the 'one-zone' model the γ-to-synchrotron luminosity ratio can be approximated by the ratio of the external radiation energy density, $u'_{\rm ext}$, to the internal magnetic energy density, $u'_{\rm B}$, both as measured in the jet co-moving frame. By comparing observed Compton dominance, jet energetics, and knowledge about external radiation fields we can determine the magnetic field intensity in the 'blazar zone'. A direct comparison of the magnetic energy flux $L_{\rm B}$ with the total jet energy flux $L_{\rm jet}$ enables us to determine the jet magnetization $\sigma = (L_{\rm B}/L_{\rm jet})/[1-(L_{\rm B}/L_{\rm jet})]$.

Studies of the σ parameter are important not only for better understanding of the dynamical structure and evolution of relativistic jets, but also because its value determines the dominant particle acceleration mechanism (shock vs. reconnection) and its efficiency. In our considerations we take into account such uncertainties as the location of the blazar zone and the geometry of the external radiation fields. We present results of such studies by mapping theoretical blazar spectral features as a function of distance, the geometry of external photon sources, and jet magnetization and comparing them with observations. Our theoretical models of broad band spectra are constructed using knowledge of the typical parameters of radio-loud quasars: BH masses, Eddington ratios, and jet powers. We assume strong coupling between protons and electrons as indicated by particle-in-cell (PIC) simulations.



The model and numerical code

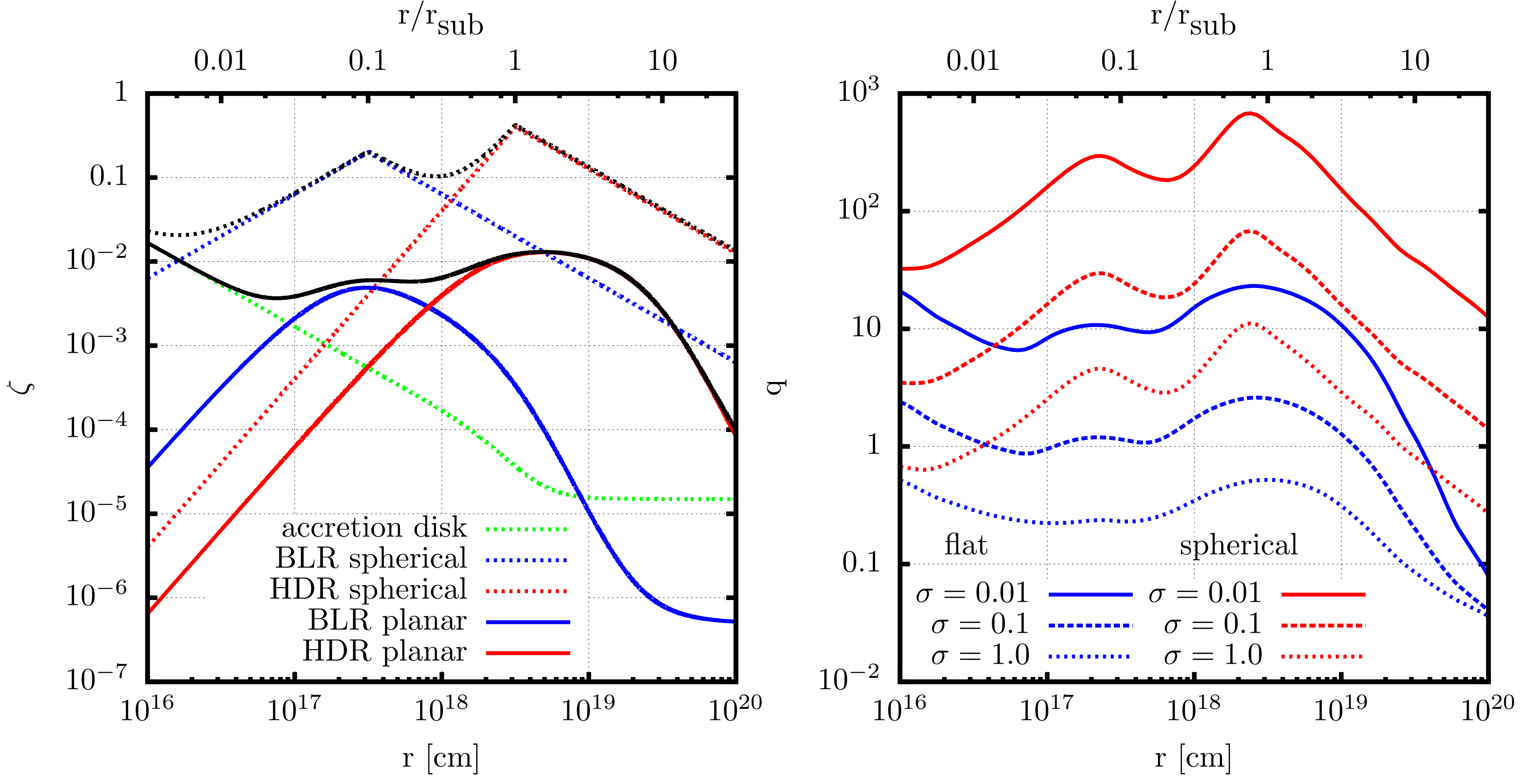
- We use the numerical code *BLAZAR* which calculates the quasi-steady-state electron distribution and produced radiation given various radiation processes and adiabatic losses,
- model involves a source of non-thermal radiation propagating down the jet (with collimation $\Gamma\theta_{jet} = 1$) with bulk Lorentz factor $\Gamma = 15$,
- we assume a one-zone leptonic model where radiation is produces by the same population of relativistic electrons,
- we cover four distance decades from 10^{16} cm up to 10^{20} cm and spectra are calculated for three different jet magnetization values: $\sigma = 1.0$, 0.1, and 0.01,
- for a one-zone model $L_{syn} \propto u'_B$ and $L_{ERC} \propto u'_{ext}$, the Compton dominance is

$$q \sim \frac{u'_{\rm ext}}{u'_{\rm B}} = \frac{(1+\sigma)\Gamma^2(\theta_{\rm j}\Gamma)^2\zeta\eta_{\rm d}}{4\sigma\eta_{\rm jet}}$$

  where $\eta_{disk} = L_{disk}/\dot{M}c^2$ is accretion disk radiative efficiency, $\eta_{jet} = L_{jet}/\dot{M}c^2$ is jet production efficiency and ζ accounts for external photon source geometry and covering factor ξ_{CF}.
- sources of external seed photons in ERC process:
  - broad line region (BLR) - $\xi_{CF}^{BLR} = 0.1$, $0.1 r_{sub} < r_{BLR} < r_{sub}$,
  - hot dust region (HDR) - $\xi_{CF}^{HDR} = 0.3$, $r_{sub} < r_{HDR} < 10.0 r_{sub}$ where $r_{sub} \approx 1.0 pc$
  - accretion disk.
- we consider both planar and quasi-spherical geometries of external photon sources which lead to different photon energy densities in the jet co-moving frame u'_{ext} where

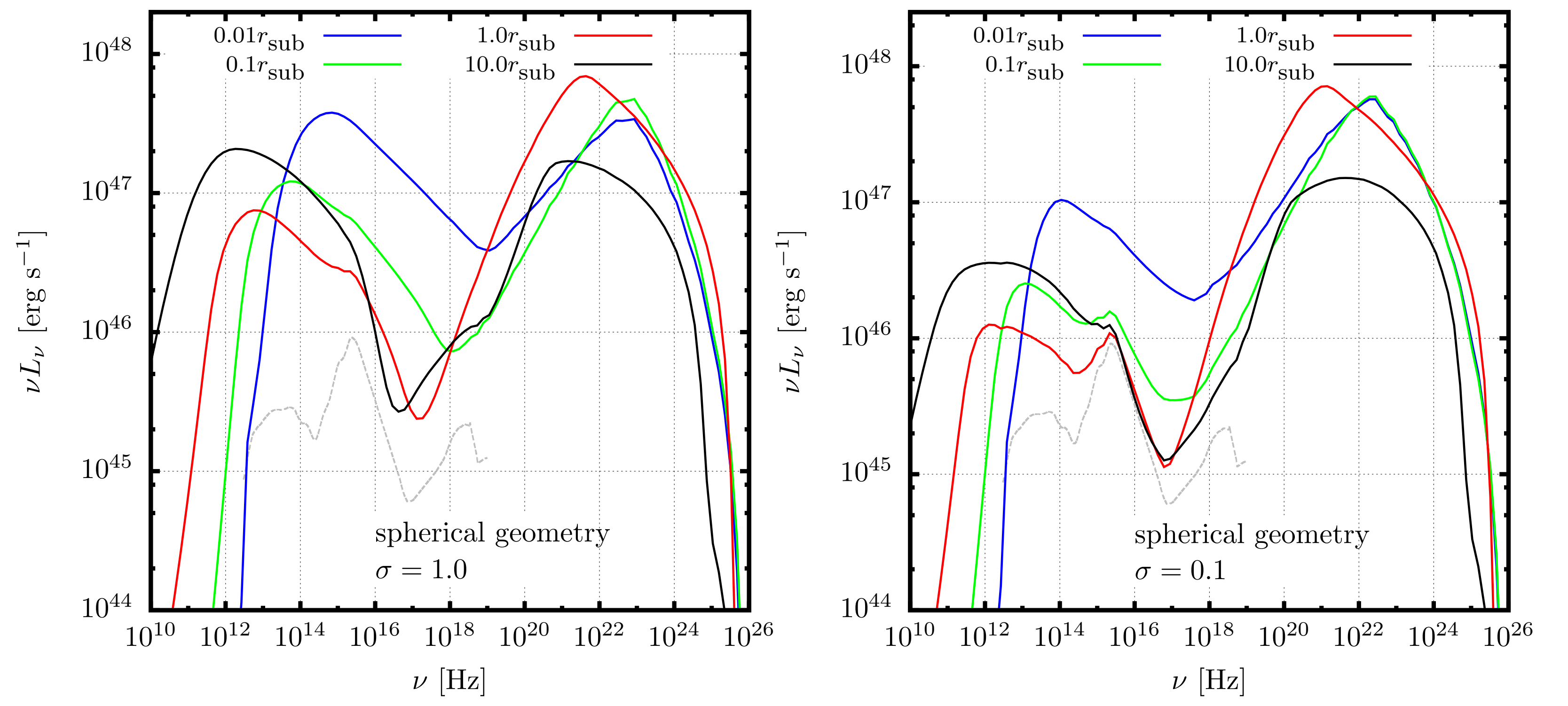
$$\zeta = \frac{4\pi r^2 c u'_{\rm ext}}{L_{\rm d}\Gamma^2}.$$

External radiation geometry and Compton dominance



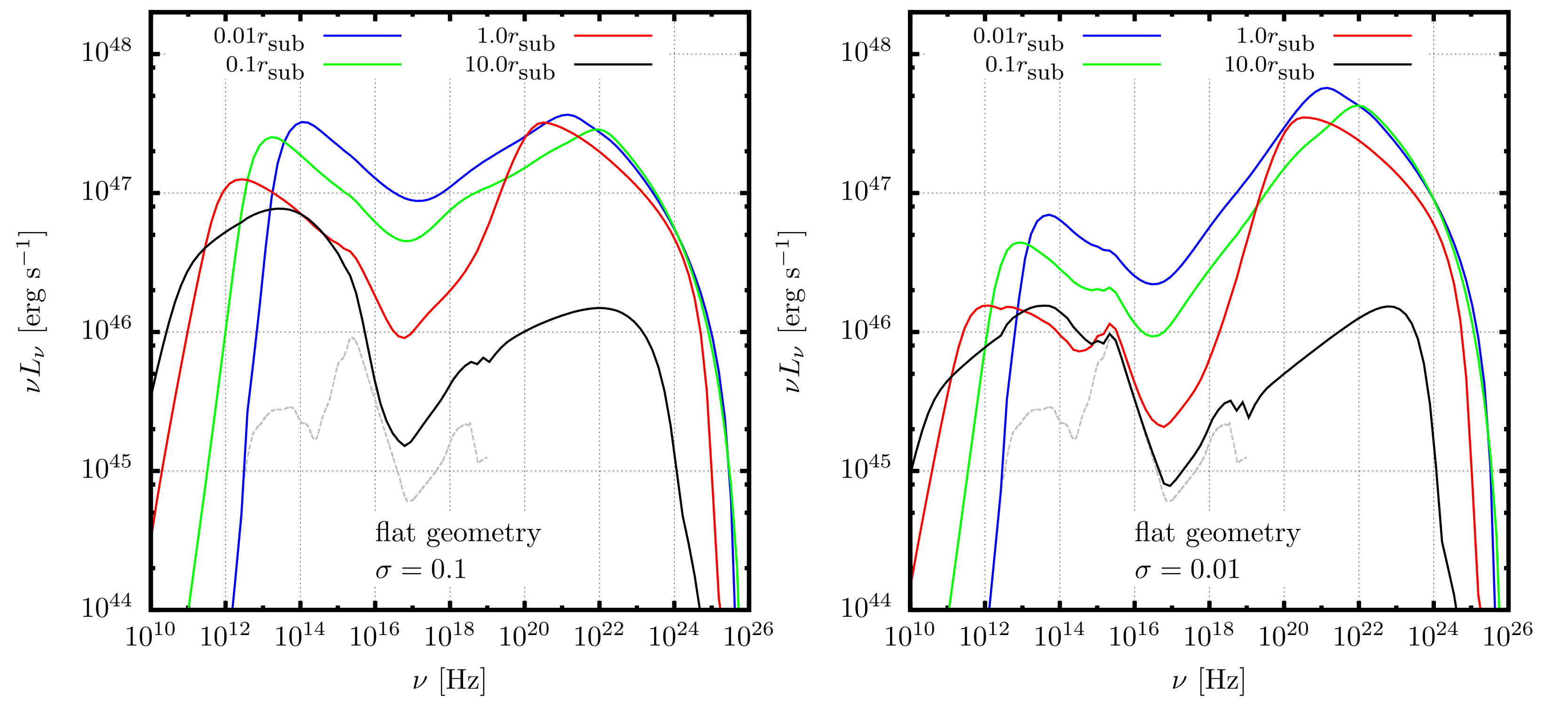
Left panel: ζ vs radius for spherical and flat geometries of external radiation sources. Black dotted line is a total ζ for spherical case and black solid line presents a total ζ for planar geometry. *Right panel:* Compton dominance parameter q vs radius for different external source geometries and values of magnetization σ.

Spherical geometry models



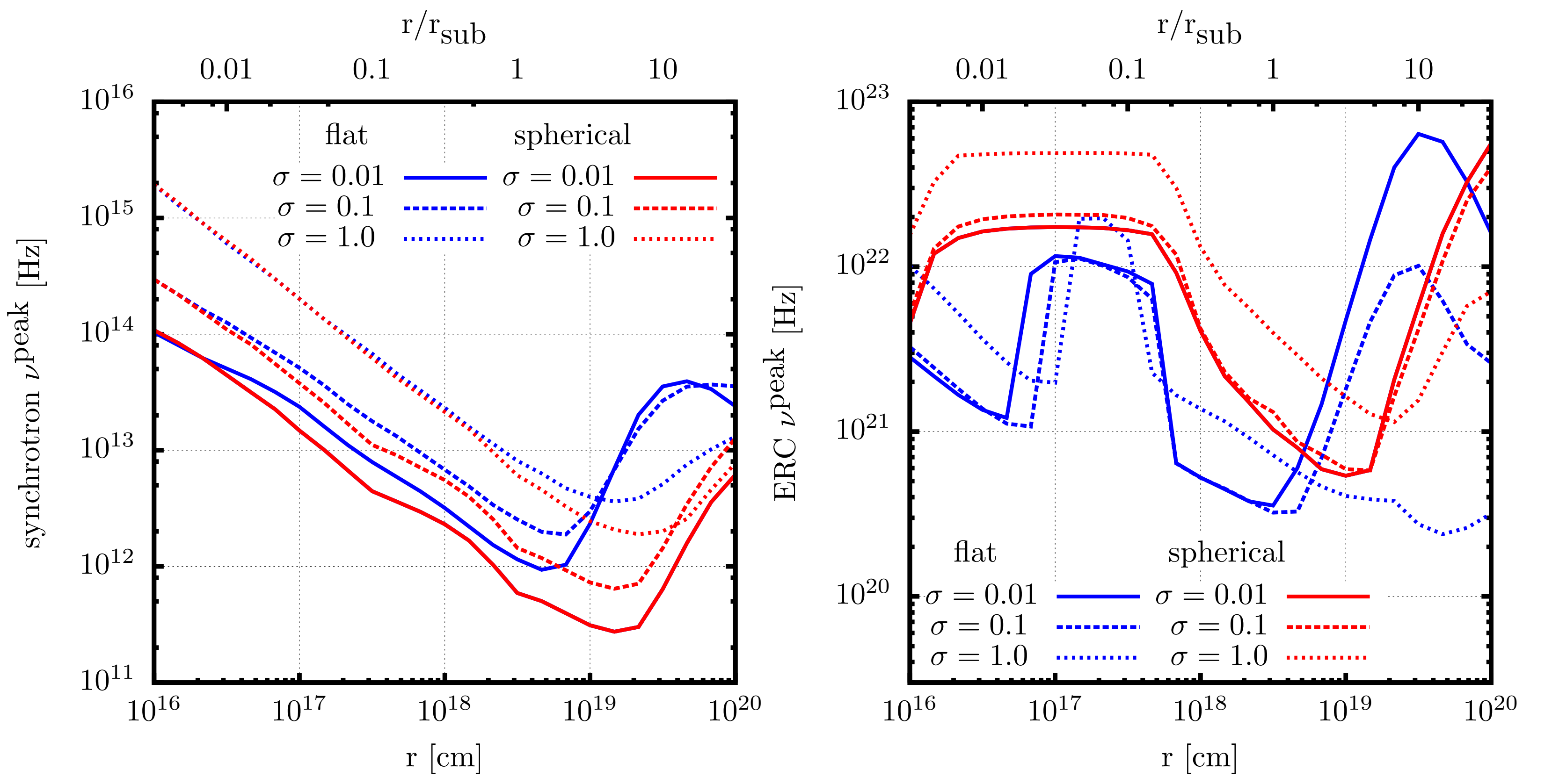
SEDs calculated using quasi-spherical models of external radiation (BLR and HDR).
Left panel: $\sigma = 1.0$, *right panel:* $\sigma = 0.1$. Gray curve corresponds to radio-loud quasar radiation template.

Planar geometry models



SEDs calculated using planar models of external radiation (BLR and HDR).
Left panel: $\sigma = 0.1$, *right panel:* $\sigma = 0.01$.

Spectral peaks



Location of spectral peaks calculated for synchrotron (left panel) and ERC components (right panel) for different values of σ and for both planar and spherical geometries of BLR and HDR and flat accretion disk.

Conclusions

- too large $\nu_{\rm syn}^{\rm peak}$ at distances $r < 0.03$ pc and low radiative efficiencies at $r > 3$ pc seem to favour the location of the blazar zone in FSRQs within a distance range $0.03 - 3$ pc,
- typical values of FSRQ Compton dominance parameter, $q \sim 10$, can be recovered within a distance range $0.03 - 3$ pc for $\sigma \sim 0.1(\theta_{\rm j}\Gamma)^2$ in case of spherical BLR and HDR and $\sigma \sim 0.01(\theta_{\rm j}\Gamma)^2$ for their planar geometries,
- due to the value of $\gamma_{\rm b}$ being fixed by the fixed dissipation efficiency $\eta_{\rm diss}$ and $\nu_{\rm BLR}/\nu_{\rm HDR} \sim 30$, the spectral peak of ERC(HDR) is located at ~ 30 times lower energy than the spectral peak of ERC(BLR); noting that $\nu_{\rm HDR}^{\rm peak} \sim (n_{\rm p}/n_{\rm e})^2$ MeV, the ERC(HDR) models with significant pair content are rather excluded;
- noting that the real geometries of the BLR and HDR are suggested by observations to be significantly flattened, one may conclude that typical values of the Compton dominance imply $\sigma \ll 1$, and therefore, that the conversion of initially Poynting flux dominated jet to the matter dominated jet takes place in the region located closer to the BH than the blazar zone.

Obtained constraints on the jet magnetization can be at least quantitatively relaxed, if noting the possibility that jets in blazars are magnetically very inhomogeneous and that most blazar emission takes place in weaker magnetized sites being associated with reconnection layers and/or the jet spine region. (see Nalewajko et al. 2014, ApJ, 796, 5).
For a broader view of this topic see **Janiak et al. 2015, MNRAS, 449, 431.**

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