Synchrotron self-Compton models and VHE emission of extragalactic sources

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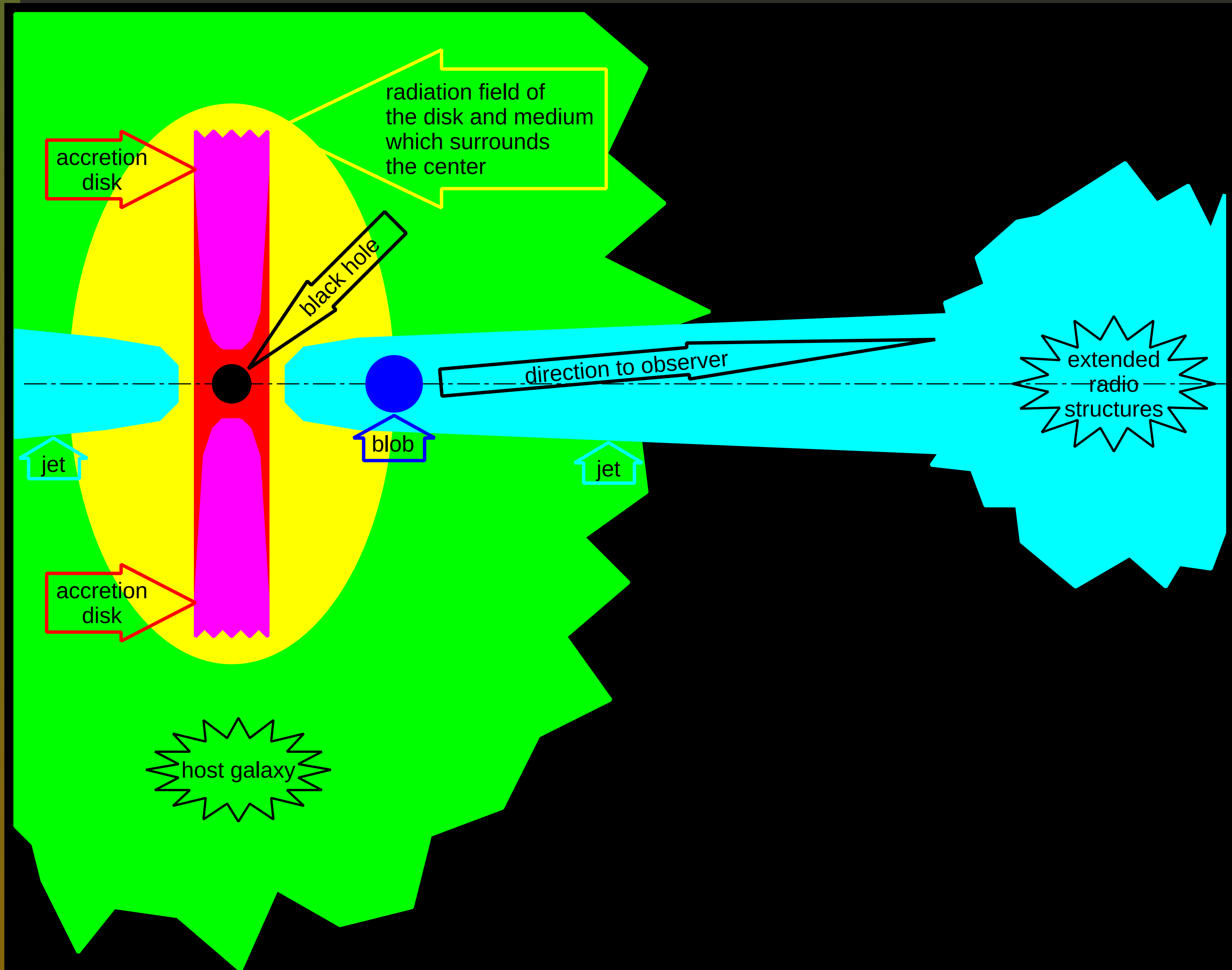
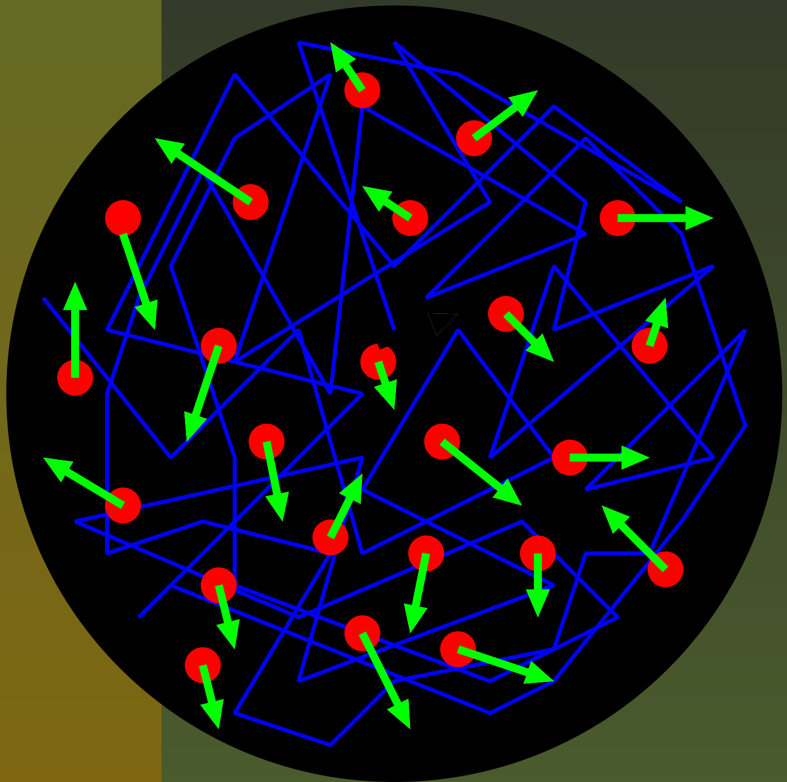
Outline

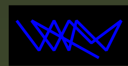
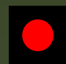
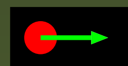
- basic assumptions for SSC emission:
  - simple homogeneous source
  - particle energy spectrum
  - synchrotrnon and IC spectra
  - an example of the modeling - Mrk 501
- time dependent modeling:
  - evolution of the particle energy spectrum
  - light crossing time effect
  - variability of PKS 2155-304

blazar structure



synchrotron emission



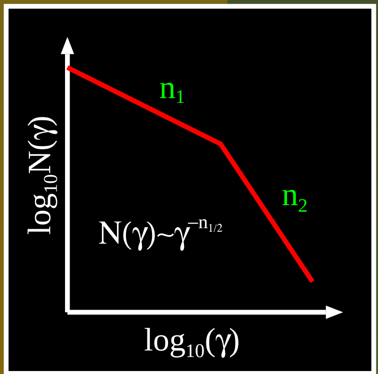
Spherical blob filled up by tangled magnetic field  and relativistic electrons , where the electrons spinning around the magnetic field lines are producing synchrotron emission .

basic assumptions

- spherical homogeneous source (R [cm])
- uniform electron density (K [cm^{-3}])
- uniform magnetic field intensity (B [G])
- power law electron energy distribution:

$$N(\gamma) = K\gamma^{-n} \quad \text{for} \quad \gamma_{\rm min} \le \gamma \le \gamma_{\rm max},$$

or double (broken) power law distribution:

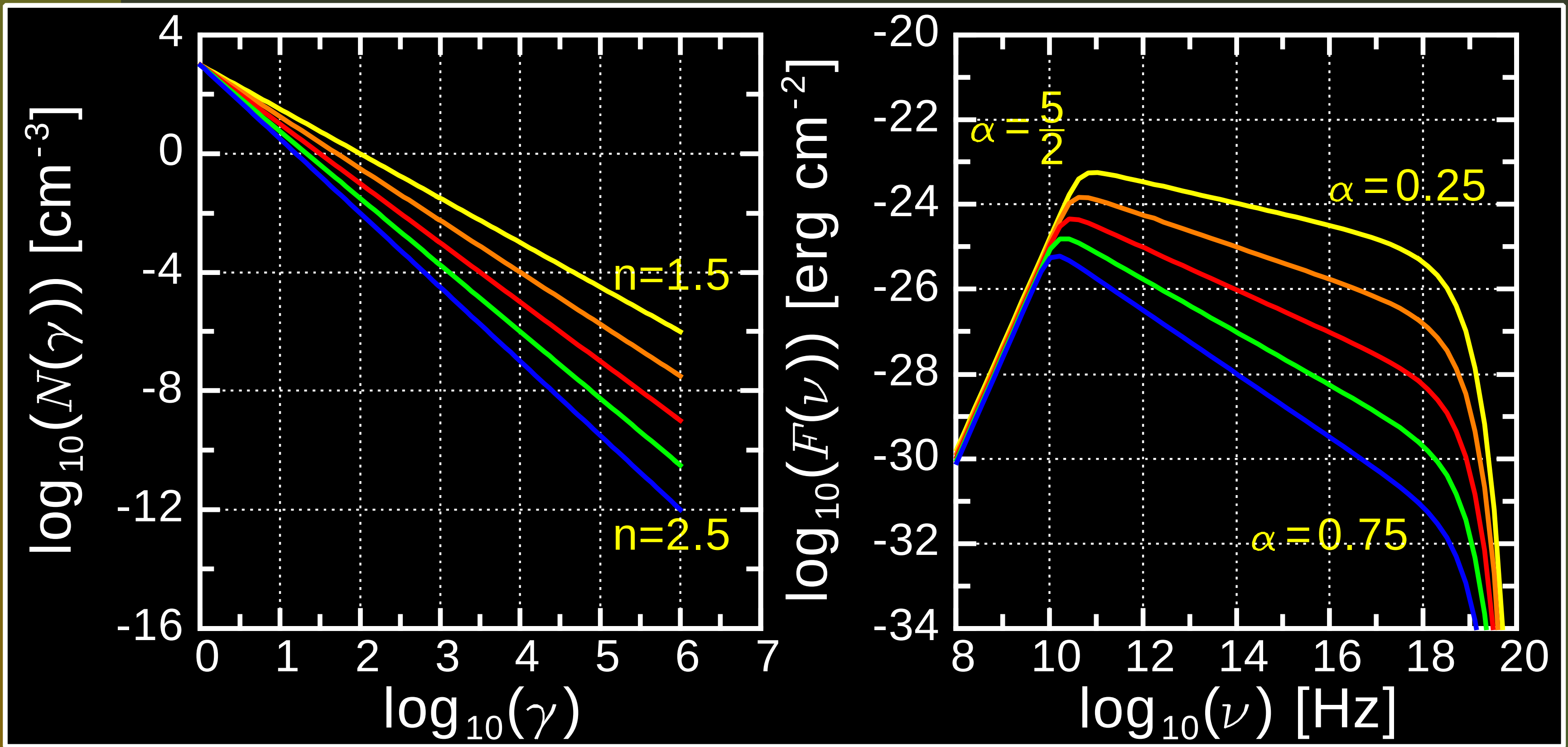


$$N(\gamma) = \begin{cases} K_1\gamma^{-n_1}, & \gamma_{\rm min} \le \gamma \le \gamma_{\rm brk} \\ K_2\gamma^{-n_2}, & \gamma_{\rm brk} < \gamma \le \gamma_{\rm max} \end{cases}$$

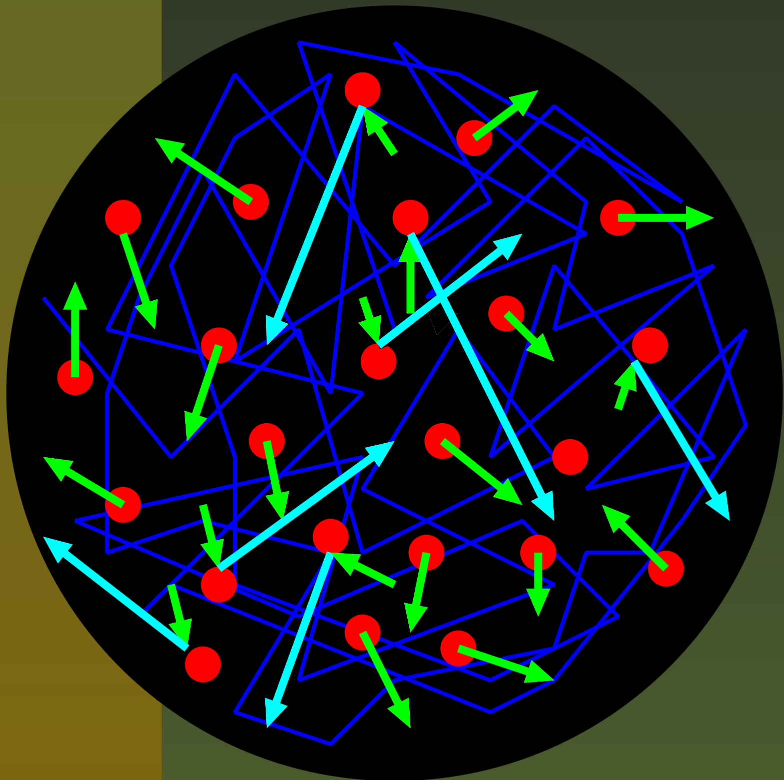
where $E = \gamma m_e c^2$ and $K_2 = K_1 \gamma_{\rm brk}^{n_2 - n_1}$.

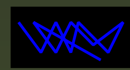
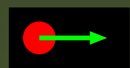
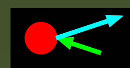
synchrotron spectrum

$$N(\gamma) \sim \gamma^{-n} \;\rightarrow\; \alpha = (n-1)/2 \;\rightarrow\; F(\nu) \sim \nu^{-\alpha}$$

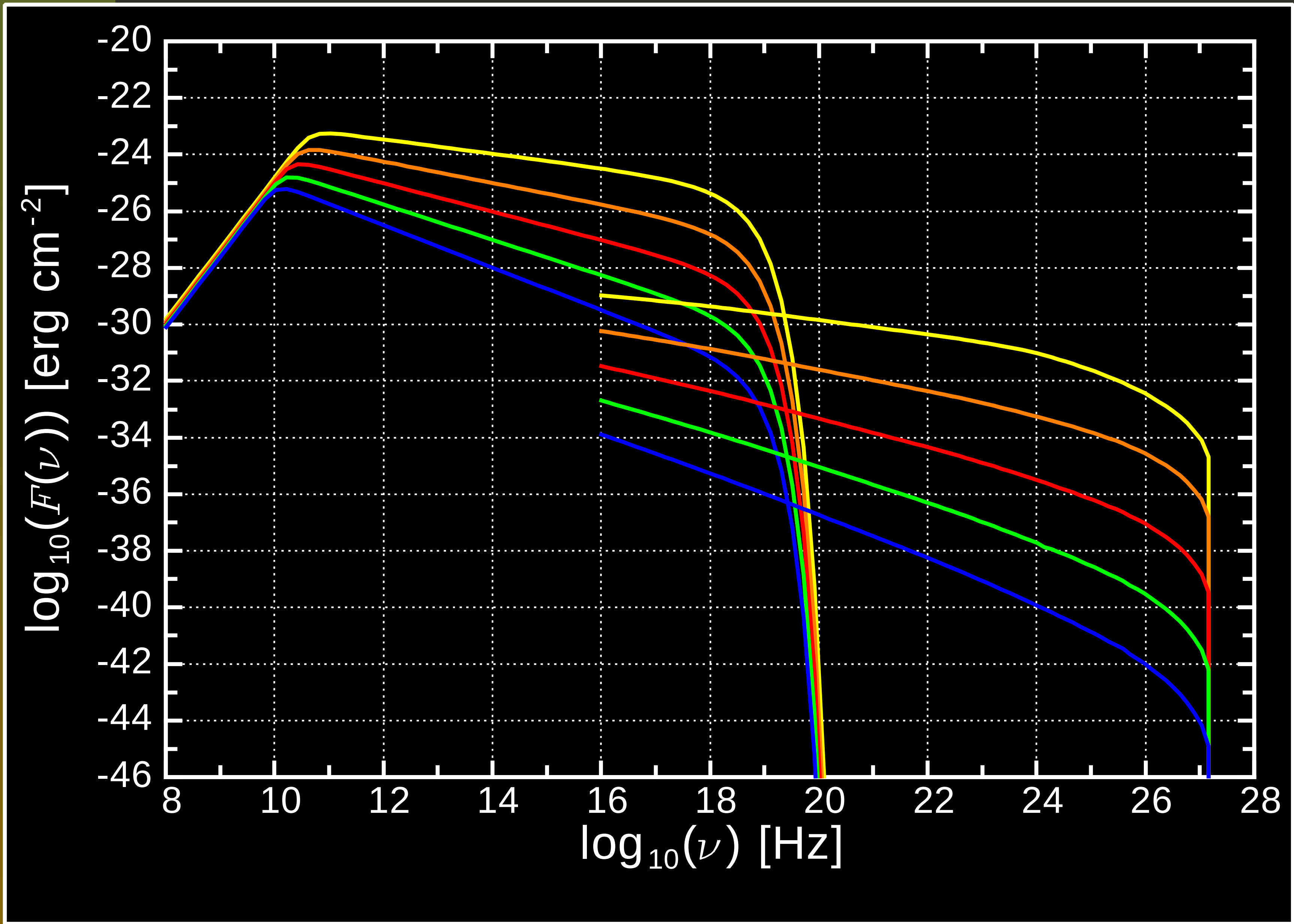


synchrotron self-Compton emission

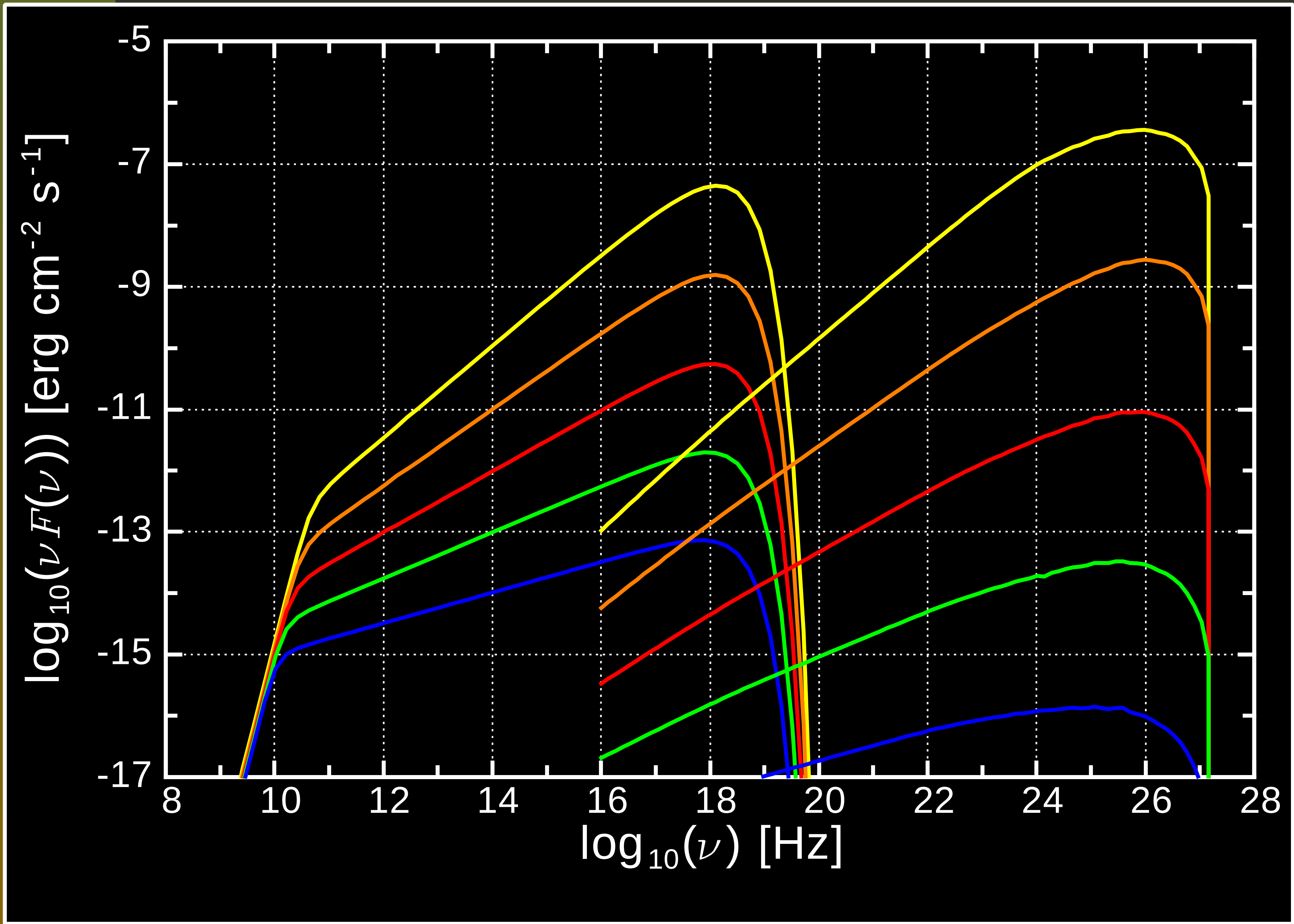


A blob filled up by tangled magnetic field  and relativistic electrons . The electrons generate synchrotron emission  and up-scatter the synchrotron radiation field  (inverse-Compton radiation).

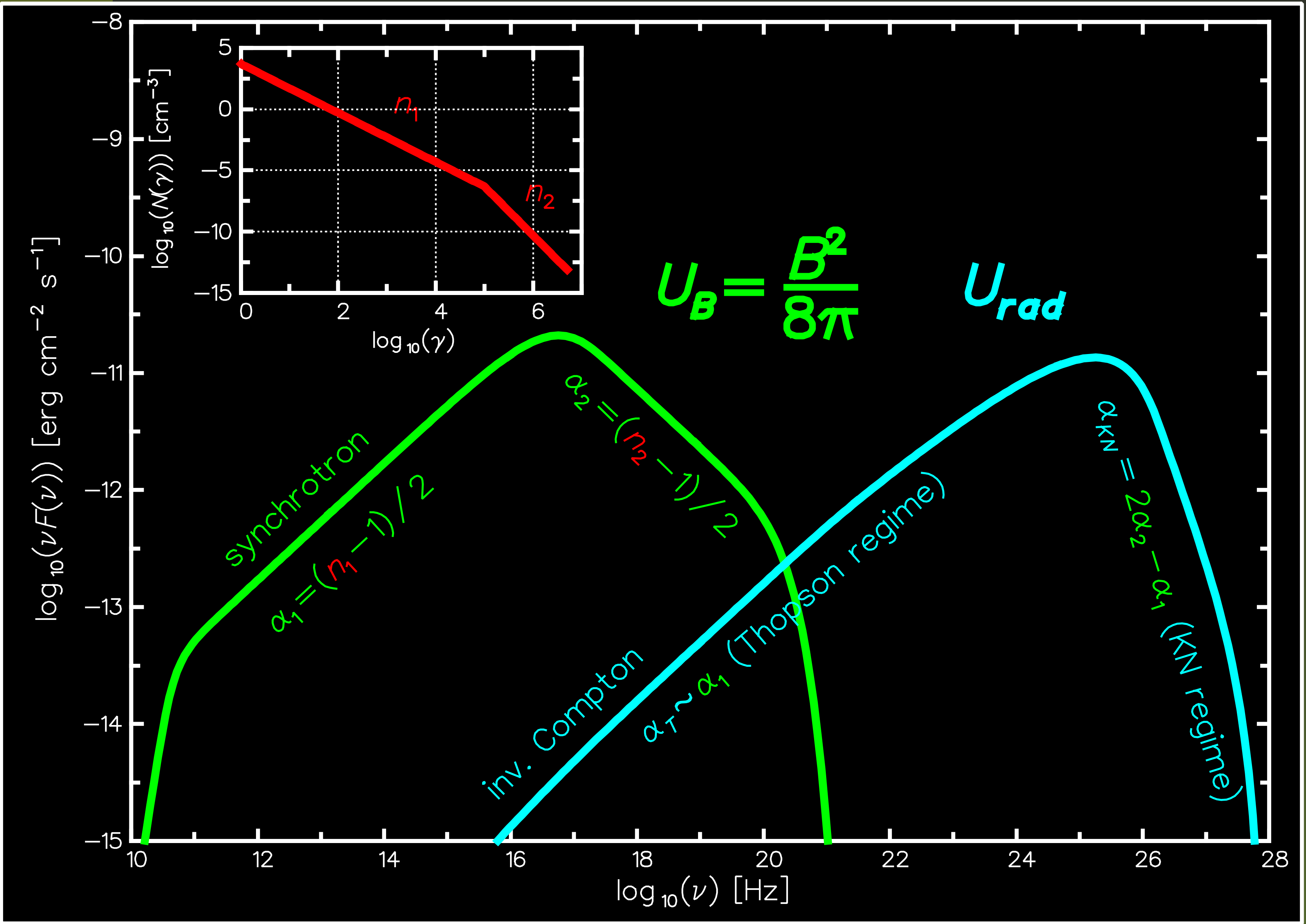
synch & inv Compton spectra $\nu \rightarrow F(\nu)$



synch & IC spectra $\nu \to \nu F(\nu)$



double power law spectrum



transformation to the observer's frame

- frequency transformation:

$$\nu_{s/c} = \frac{\delta}{1+z}\nu'_{s/c}$$

- flux transformation:

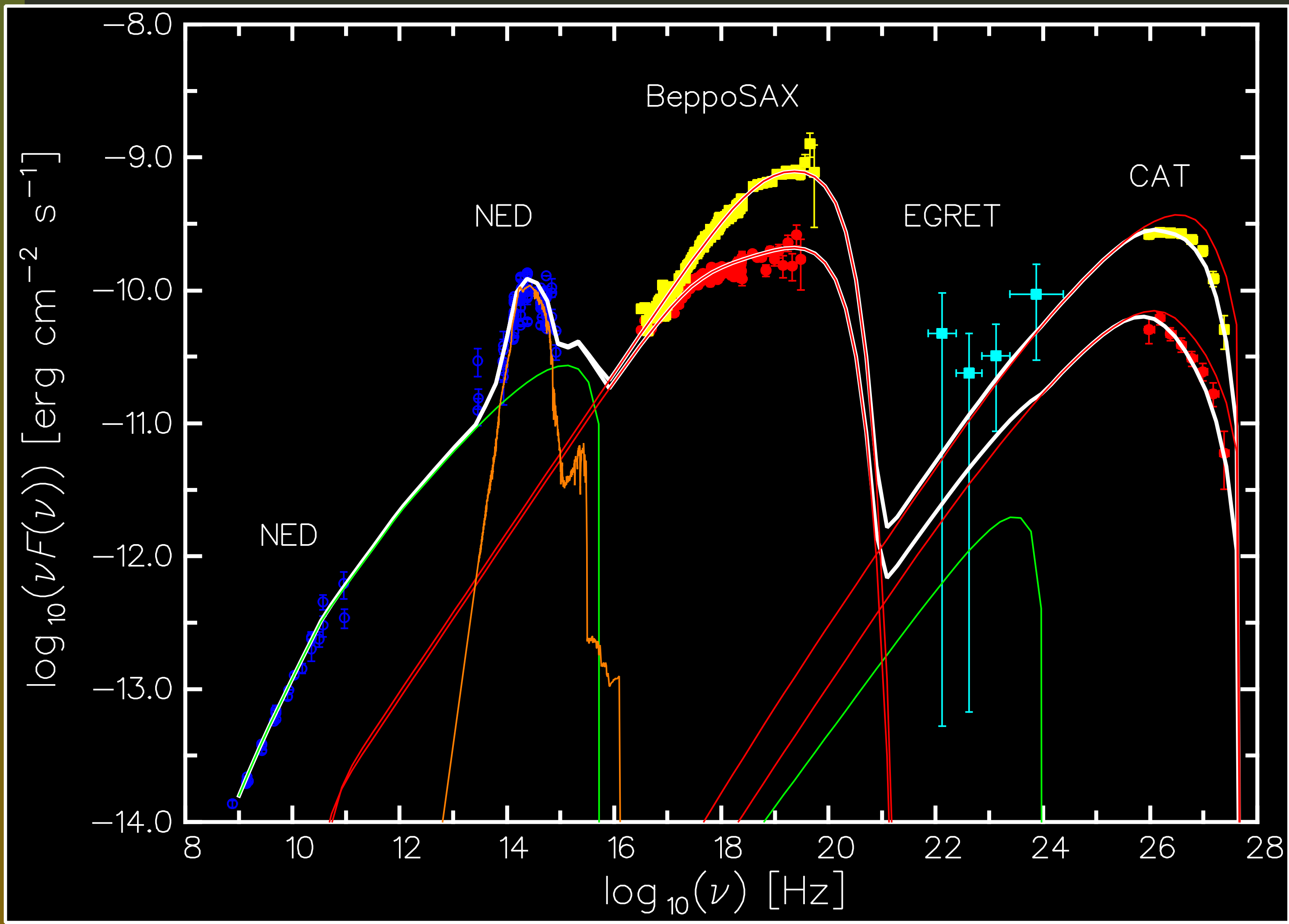
$$F_{s/c} \propto \delta^3(1+z)I'_{s/c}$$

where:

$$\delta = [\Gamma(1-(v/c)\cos\theta)]^{-1}$$

is the Doppler factor.

Mrk 501 – multifrequency emission



(NED, Pian et al. 1998, Djannati-Atai et al. 1999 – observations, Katarzyński et al. 2001 – modeling)

evolution of particle energy spectrum

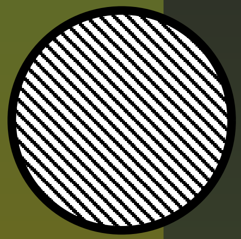
$$\frac{\partial N(\gamma,t)}{\partial t} + \frac{\partial}{\partial\gamma}\left\{\left[C_{\rm acc}(\gamma,t) - C_{\rm adia}(\gamma,t) - C_{\rm rad}(\gamma,t)\right] N(\gamma,t)\right\} + \frac{N(\gamma,t)}{t_{\rm esc}} = Q(\gamma,t) \leftarrow \text{kinetic equation}$$

- acceleration by a shock wave $C_{\rm acc} = \frac{\gamma}{t_{\rm acc}}$
- cooling due to adiabatic 3D expansion $C_{\rm adia} = \frac{\gamma}{t}$
- radiative cooling $C_{\rm rad} = \frac{4}{3}\frac{\sigma_{\rm T}}{m_e c}\gamma^2 \left[U_{\rm B} + U_{\rm rad}(\gamma,t)\right]$,
  where $U_{\rm rad} = \frac{4\pi}{c}\int_{\nu_{\rm min}}^{\nu_{\rm max}(\gamma,t)} I_{\rm syn}(\nu,t)d\nu$
- particle injection $Q(\gamma,t) = Q_0\gamma^{-n}$ for $0 < t < t_{\rm inj}$

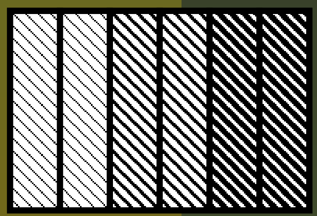
problems with the evolution

- To solve kinetic equation ($N(\gamma, t) =?$) we have to describe radiative cooling that depends on the synchrotron radiation filed ($U_{\rm rad}$) that in turn is directly connected with the particle energy spectrum ($N(\gamma, t)$)!
- It's quite difficult to get double power law particle energy distribution, where $n_1 \simeq 2$ and $n_2 > 3$. The radiative cooling is increasing the index only by factor one ($n+1$). Injecting for example power law spectrum $Q \sim \gamma^{-2}$ that gives $n_1 = 2$ we may obtain $n_2 = 3$. On the other hand to explain most of the observations it's necessary to use $n_1 \simeq 2$ and $n_2 = 4 \rightarrow 5$!

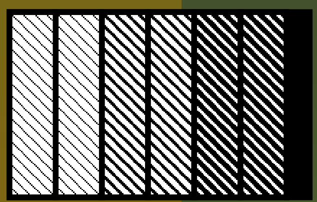
different approaches



Particle acceleration all over a source with the same efficiency $\frac{\partial N}{\partial t} + \frac{\partial}{\partial \gamma}\{[C_{\rm acc} - C_{\rm rad}]\, N\} = 0$, $N(t=0) \neq 0$ (e.g. Katarzyński et al. 2006).

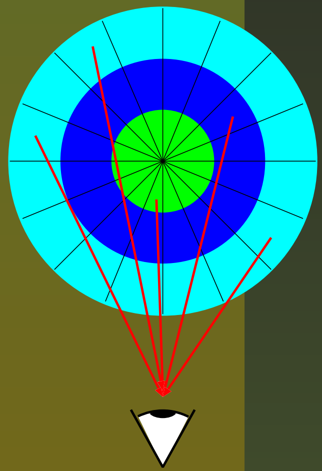


One side injection into box like source, the injection is mimicking shock wave $\frac{\partial N}{\partial t} + \frac{\partial}{\partial \gamma}\{C_{\rm rad} N\} = Q$, $N(t=0) = 0$ (e.g. Chiaberge & Ghisellini 1999).

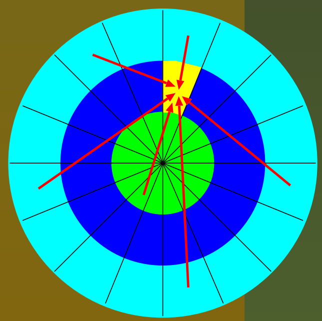


Precise description of the acceleration inside a shock wave and the spectrum evolution inside downstream region of the shock. Two different kinetic equations are required (e.g. Kirk, Rieger & Mastichiadis 1998).

light crossing time effects (LCTE)



External LCTE - external observer receives at given time emission produced by different parts of a source at different times.

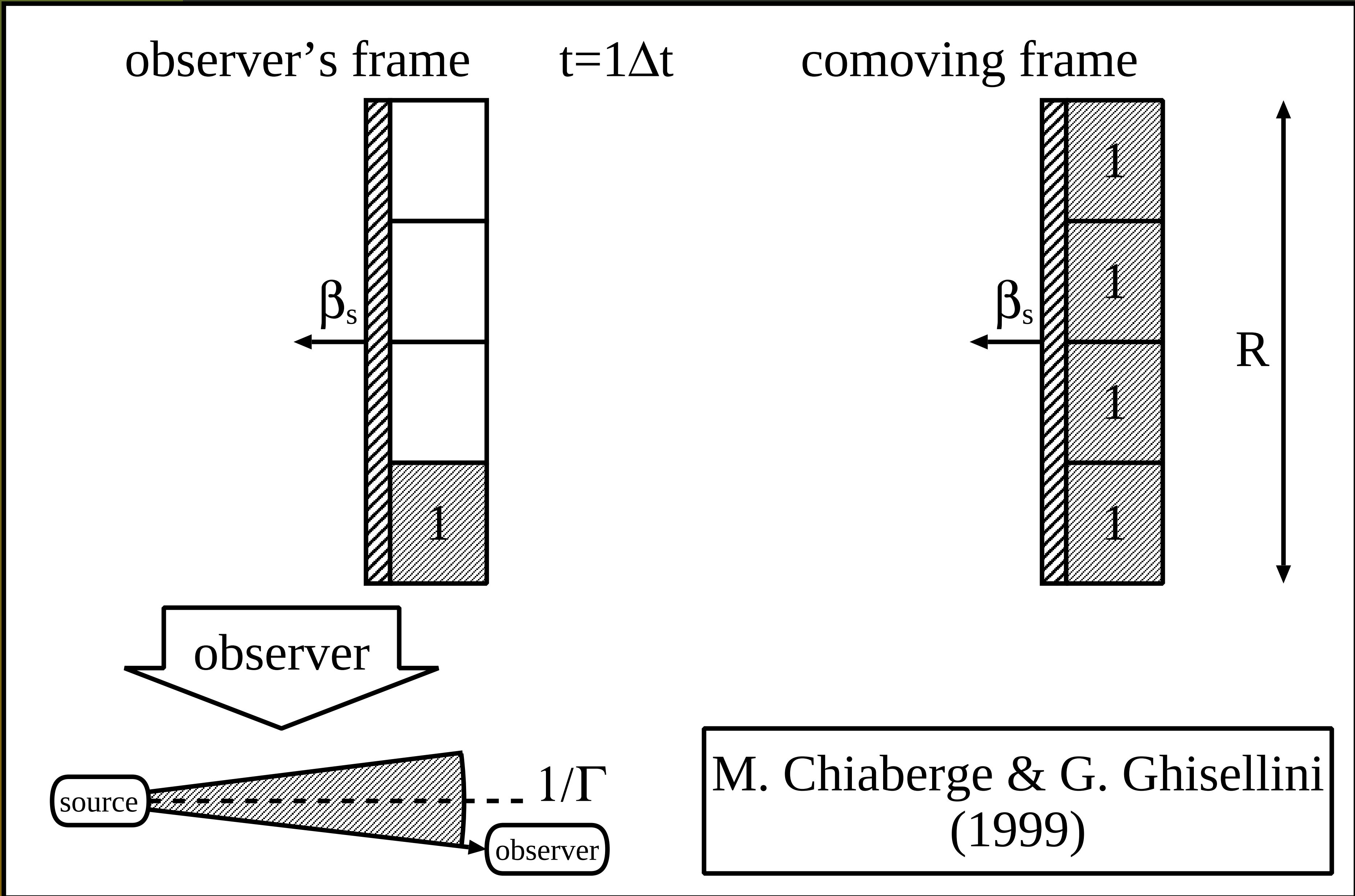


Internal LCTE - radiation field at given position and time inside a source is a sum of local emission and contributions from other parts of the source created at different times.

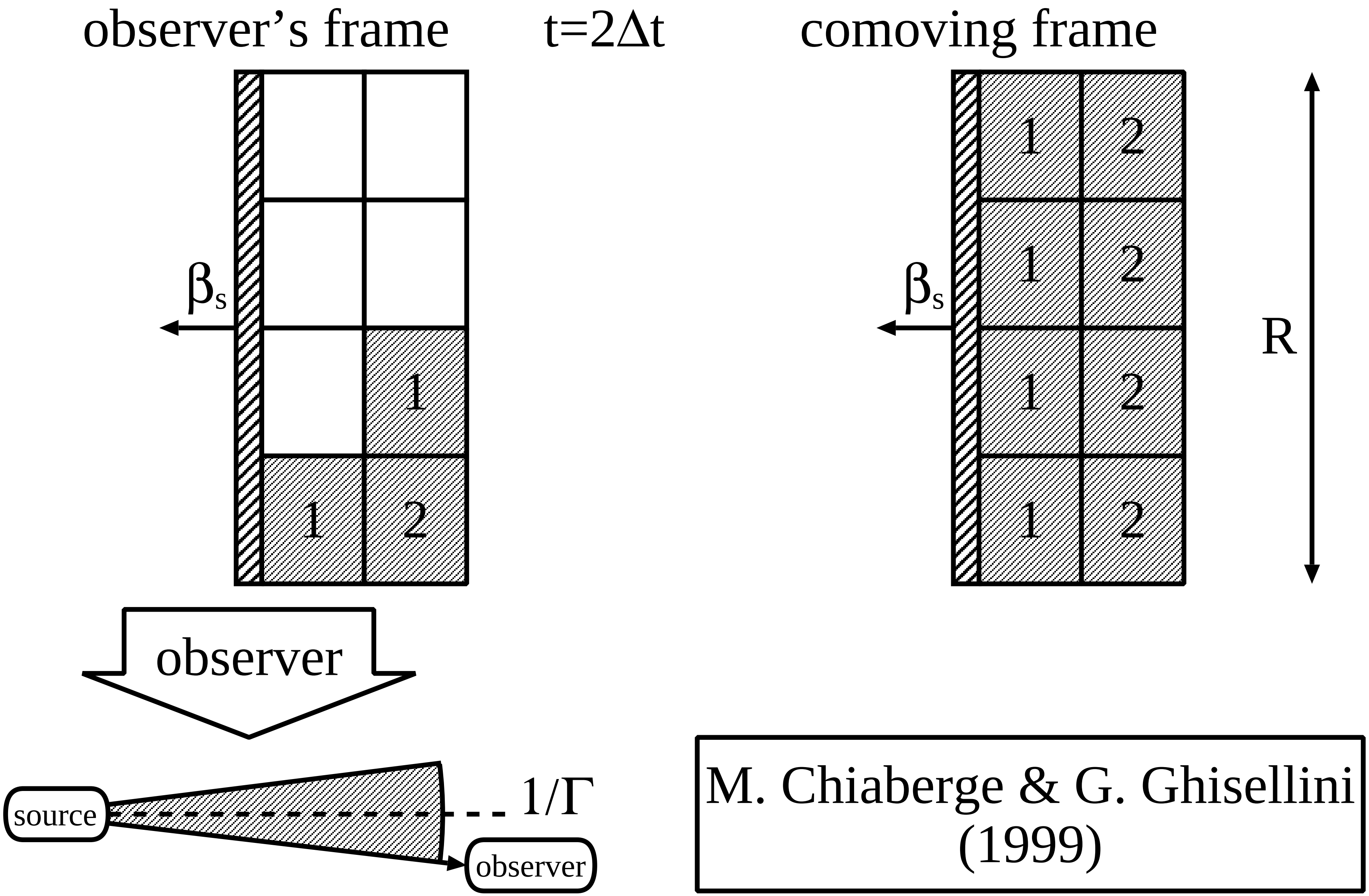
selected models

- How to describe in relatively easy way external LCTE was shown for the first time in the model proposed by Chiaberge & Ghisellini (1999). They assumed a box like source created by relativistically moving shock wave, however, they do not describe particle acceleration inside the shock.
- Internal LCTE for the first time was taken into account in the model developed by Sokolov, Marscher and McHardy (2004). However, they assume $U_B \gg U_{\mathrm{rad}}$ therefore synchrotron radiation field has no impact for the evolution of the particle energy spectrum.

External LCTE

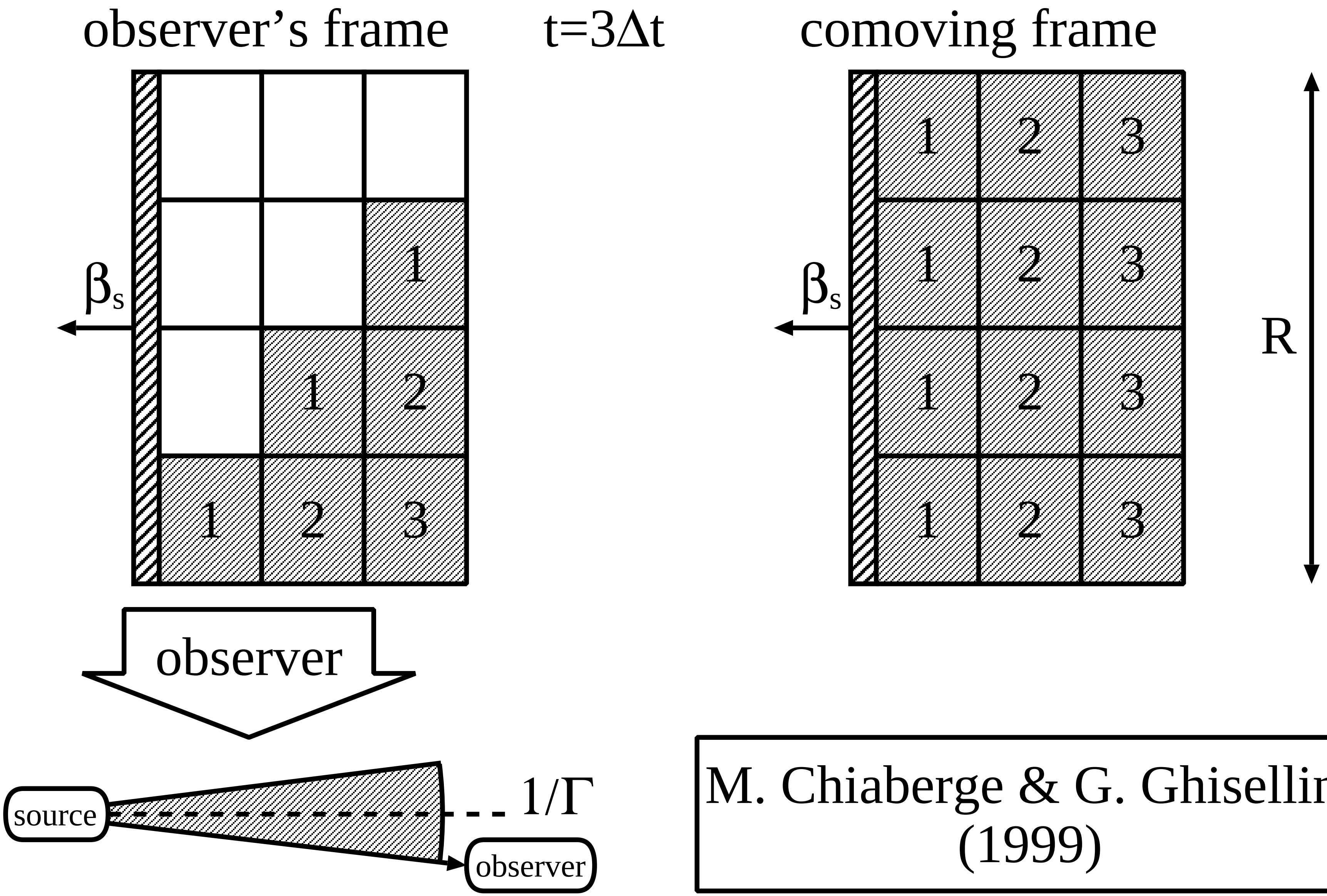


External LCTE



M. Chiaberge & G. Ghisellini (1999)

External LCTE



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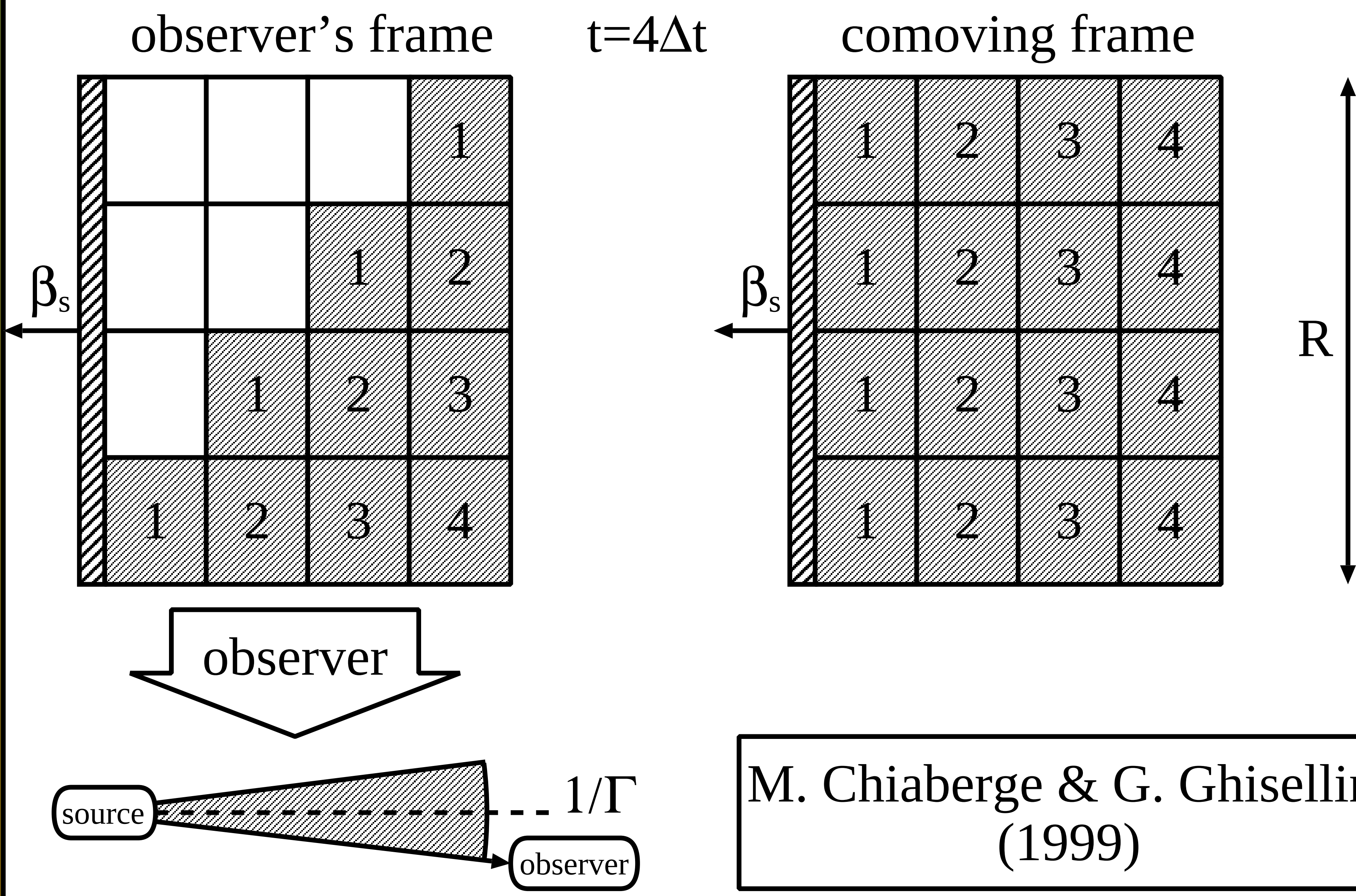

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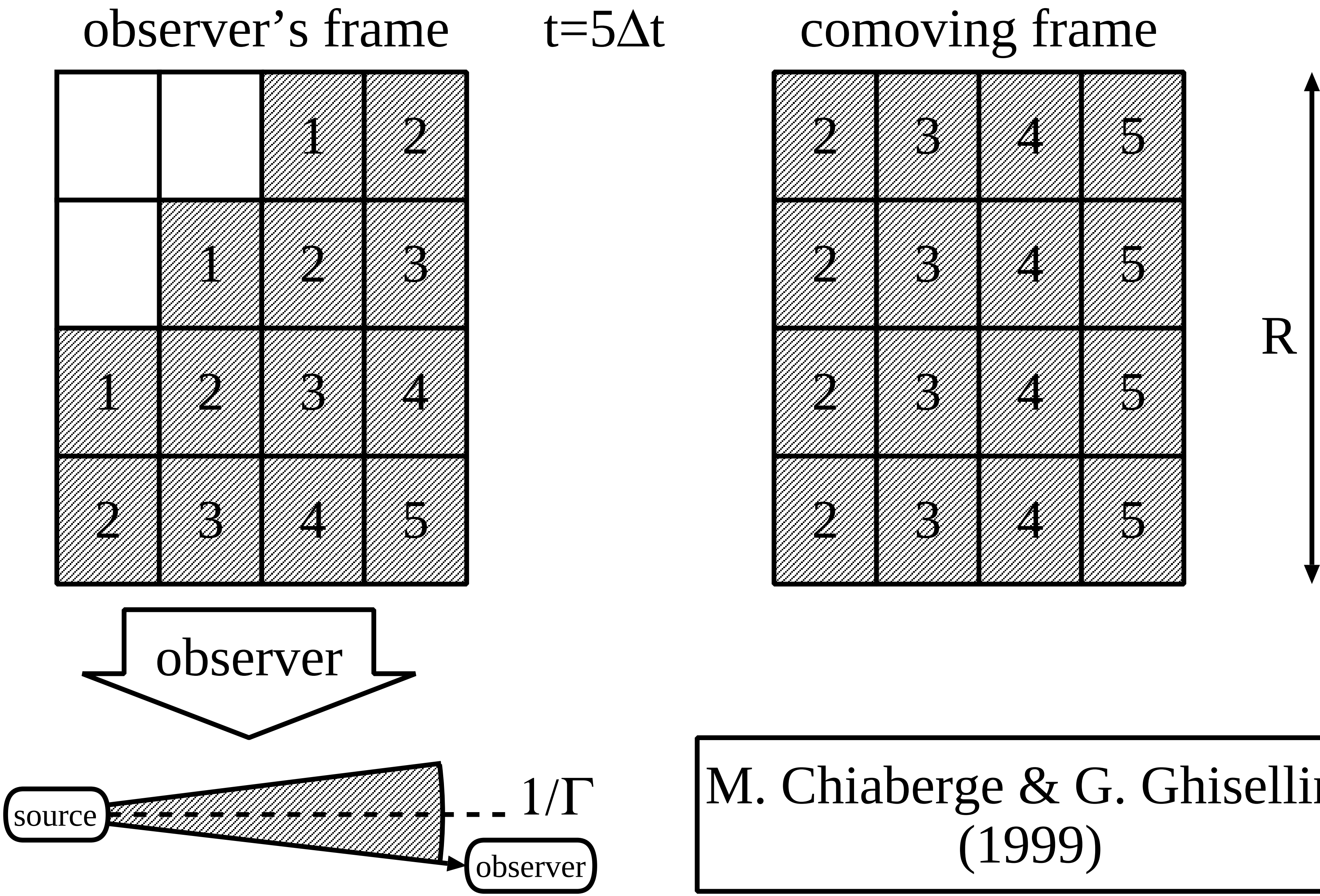
External LCTE



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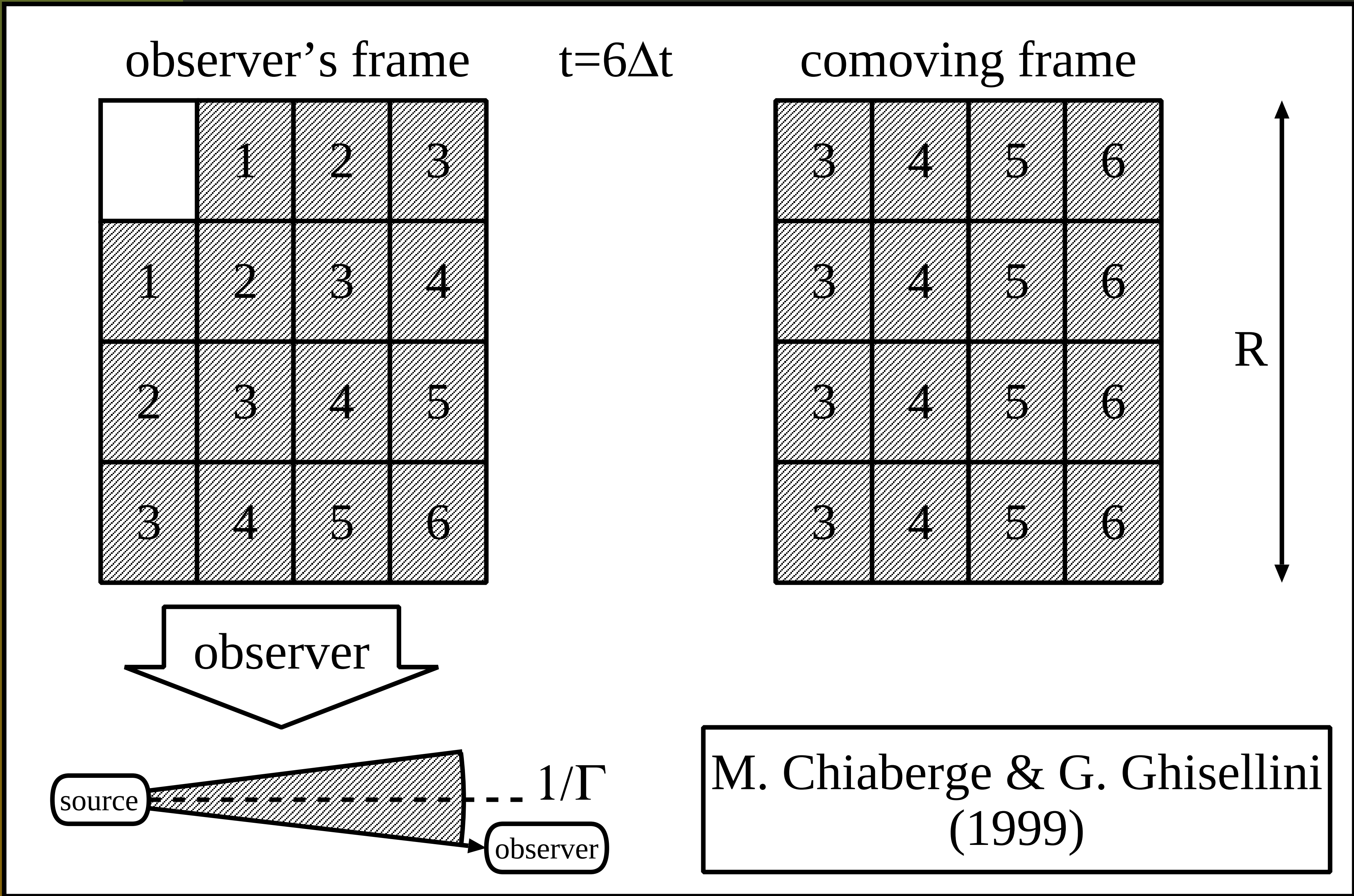
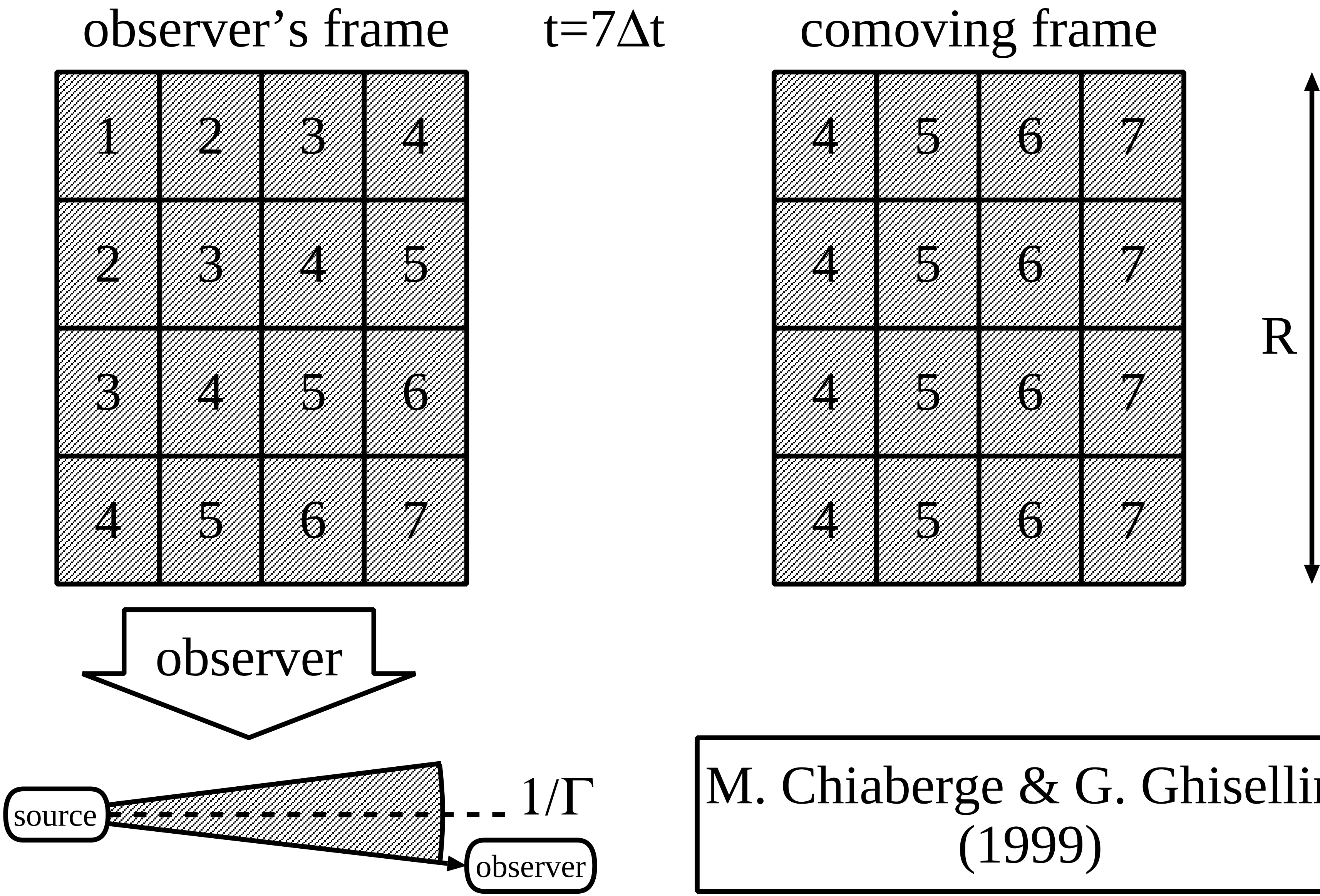
External LCTE

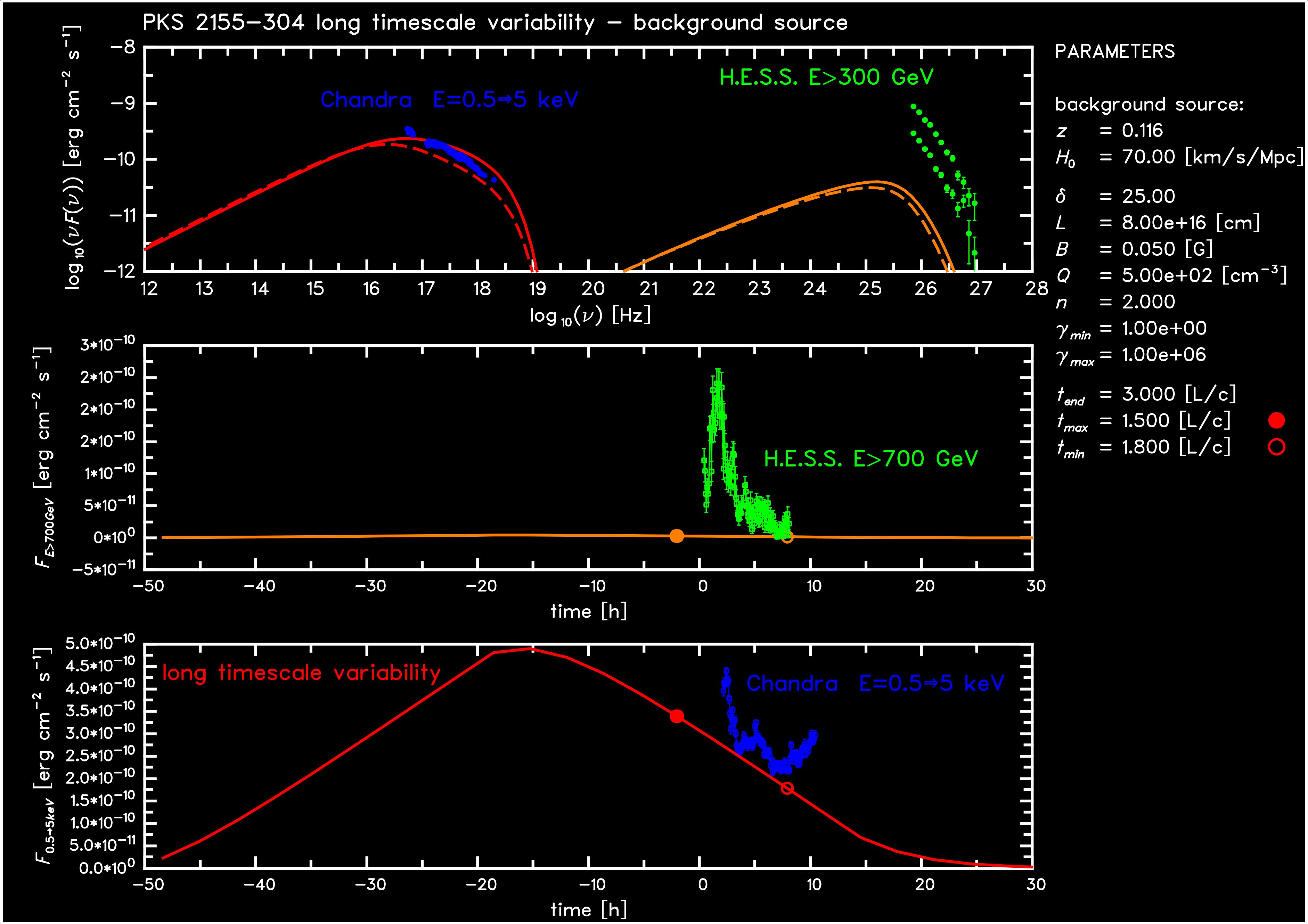


External LCTE

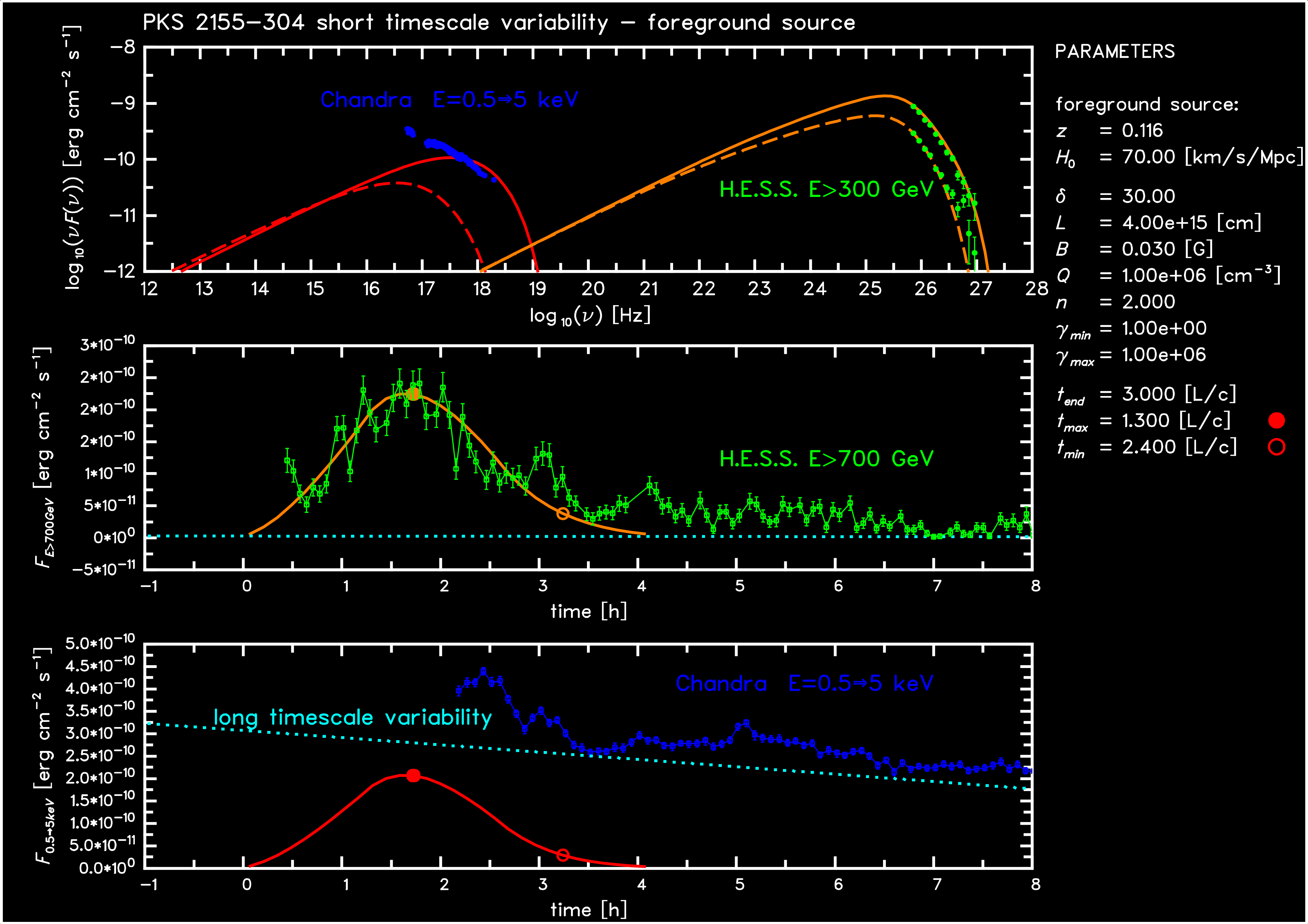


M. Chiaberge & G. Ghisellini (1999)

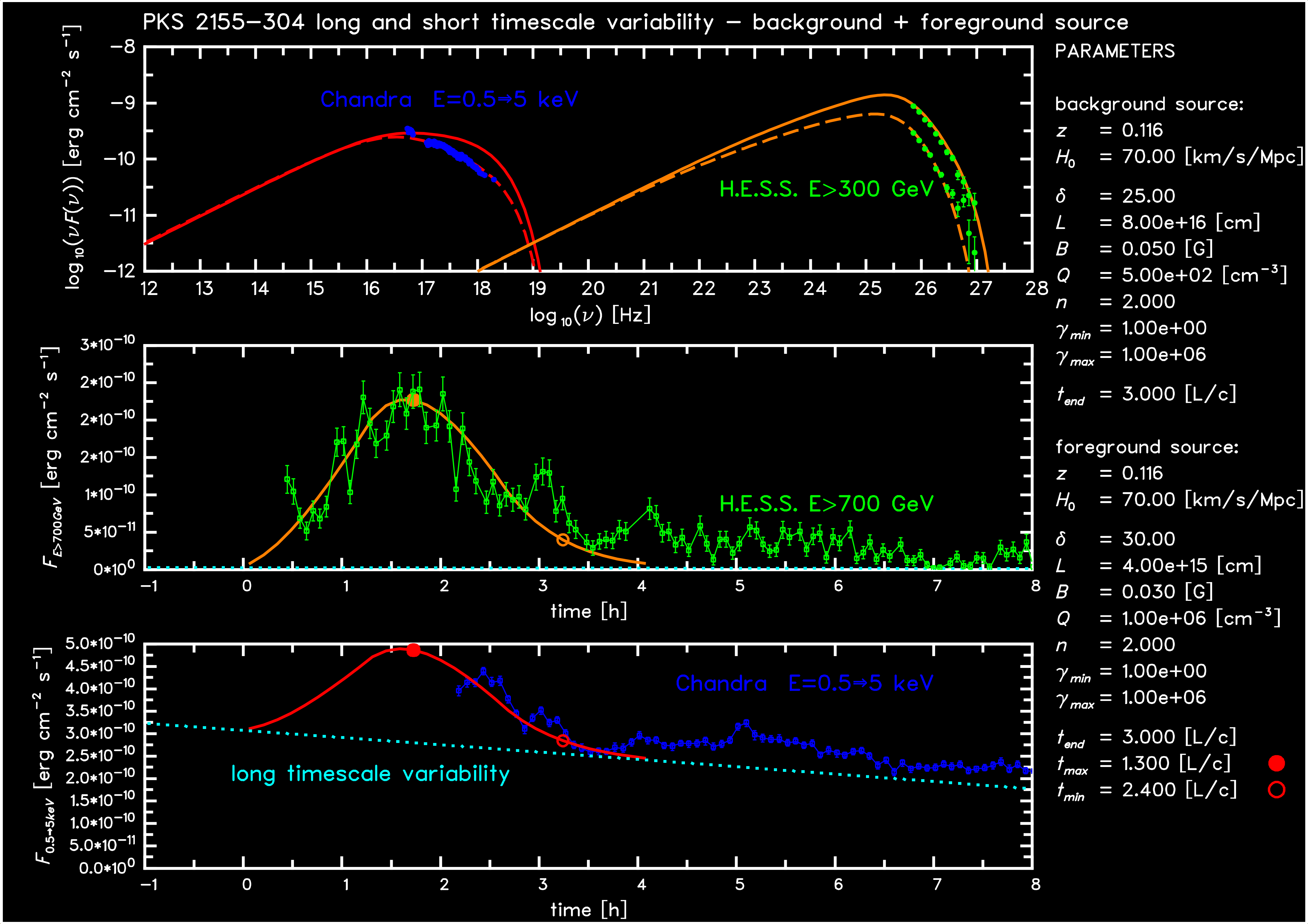
PKS 2155-304 - H.E.S.S. & Chandra observations in 2006



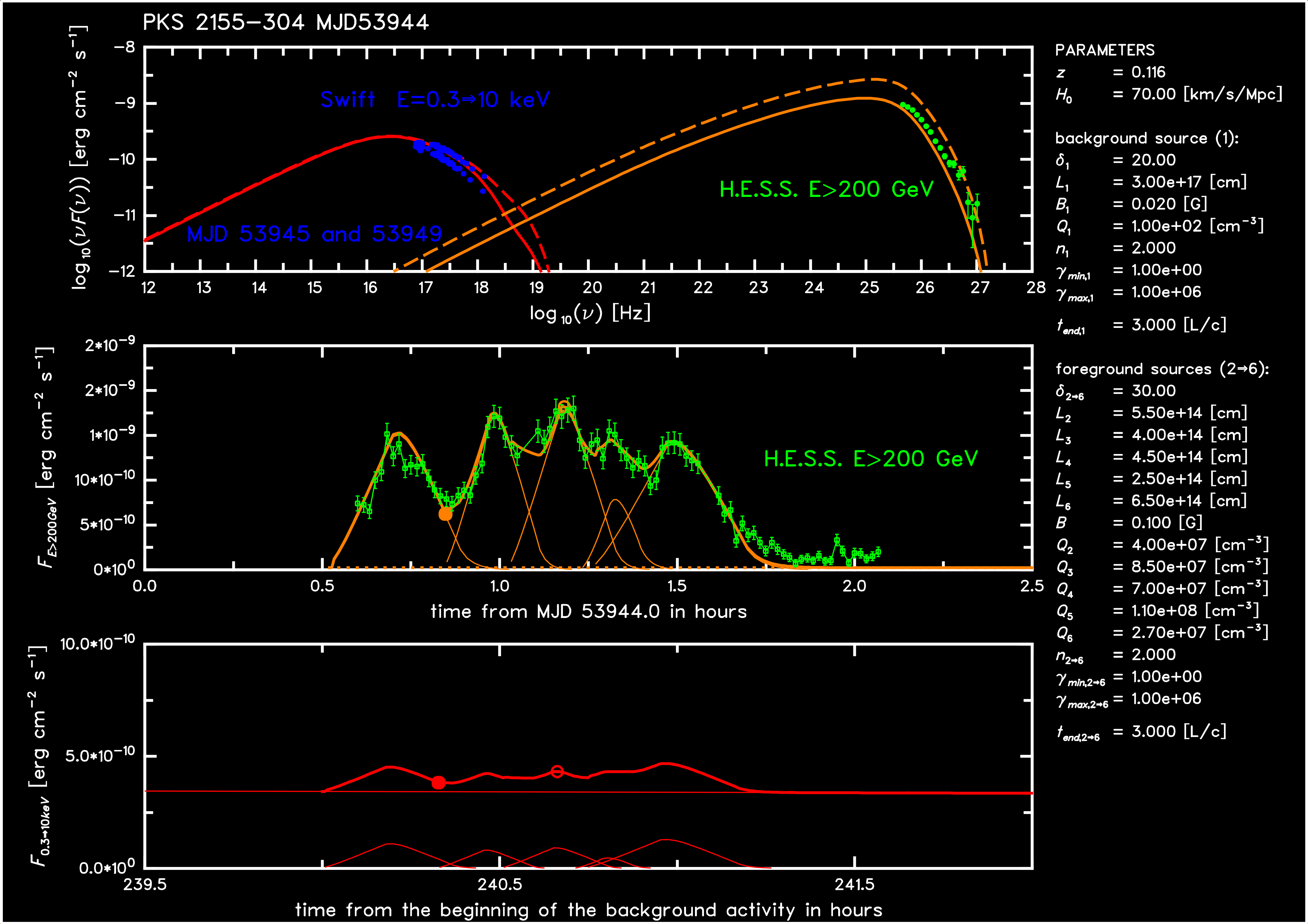
PKS 2155-304 - H.E.S.S. & Chandra observations in 2006



PKS 2155-304 - H.E.S.S. & Chandra observations in 2006



PKS 2155-304 - H.E.S.S. & Swift observations in 2006



Summary

- There is no scenario that is able to precise describe SSC emission taking into account light crossing time effect and the particle evolution!
- Simple models are able to well explain observed spectra, however, some of the assumptions made in such modeling seems to be not realistic.
- More complex scenarios are able to explain not only the spectra but also observed light curves. However, as stated above such models are not precise.

References

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Pian, E., Vacanti, G., Tagliaferri, G., et al., 1998, ApJ , 492, L17

Sokolov, A., Marscher, A. P., McHardy, I. M., 2004, ApJ, 613, 725