Radio-γ response in blazars as a signature of adiabatic blob expansion: a self-consistent approach

Tramacere+ 2022 https://arxiv.org/pdf/2112.03941.pdf accepted A&A

JetSeT

Jets SED modeler and fitting Tool

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in collaboration with
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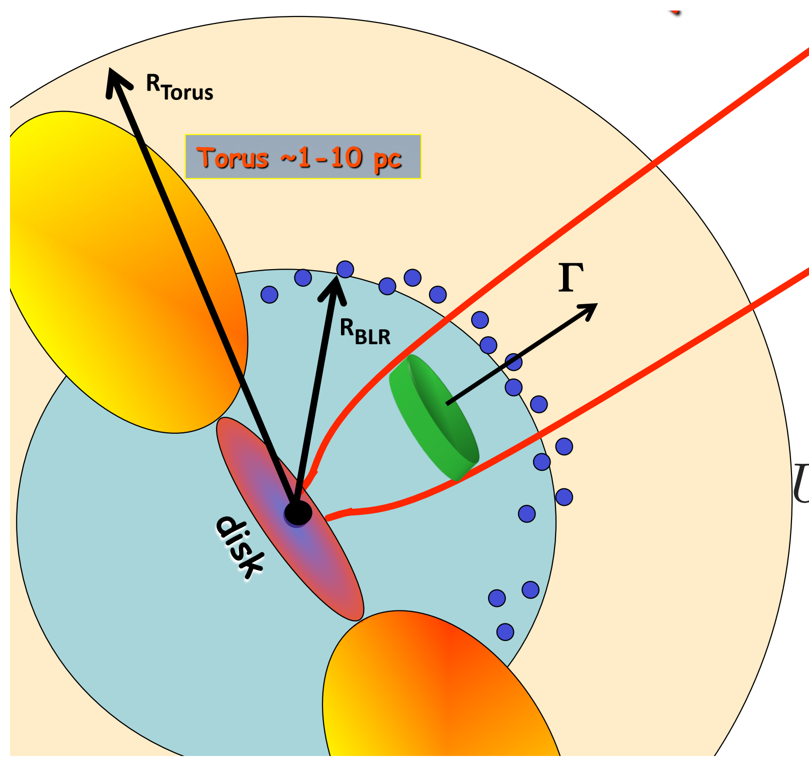
https://jetset.readthedocs.io/en/latest/
https://github.com/andreatramacere/jetset
https://www.facebook.com/jetsetastro/

Blazars in a nutshell

FSRQs
HERGs

rad eff.
$L_d > 10^{-2} L_{EDD}$

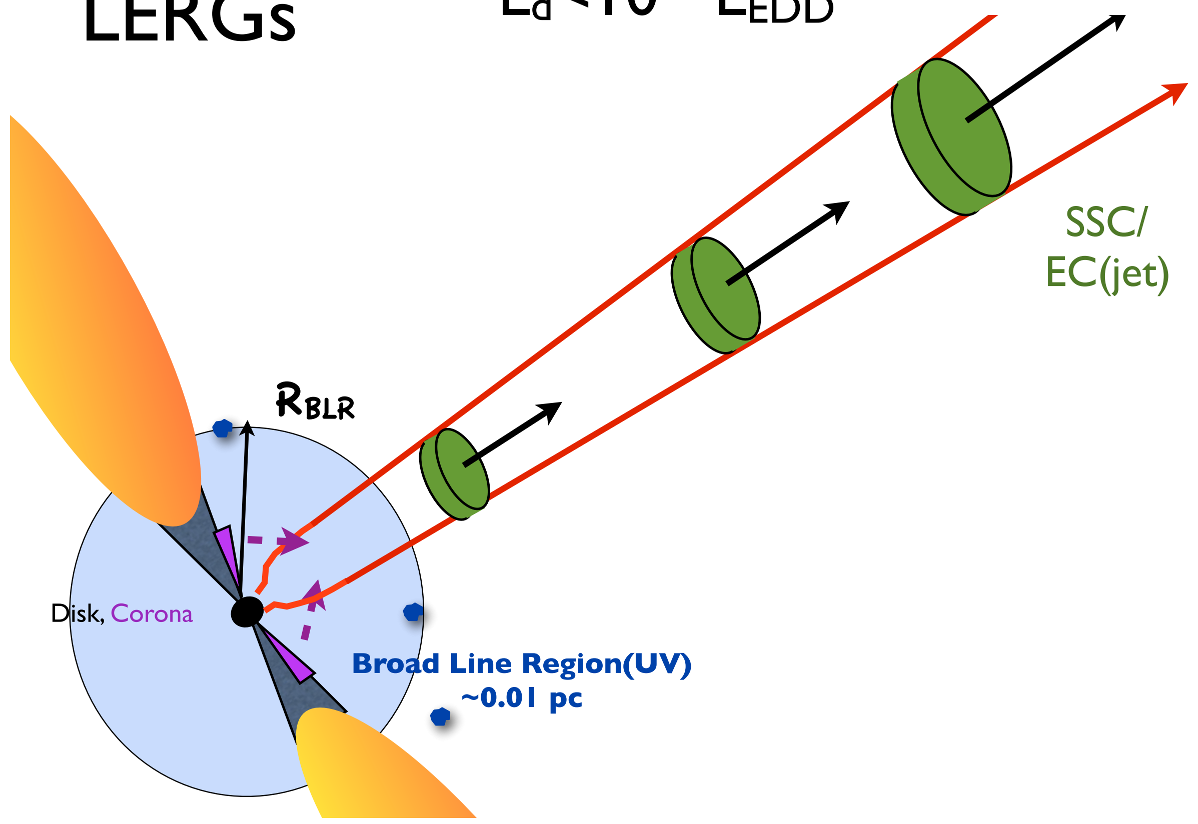


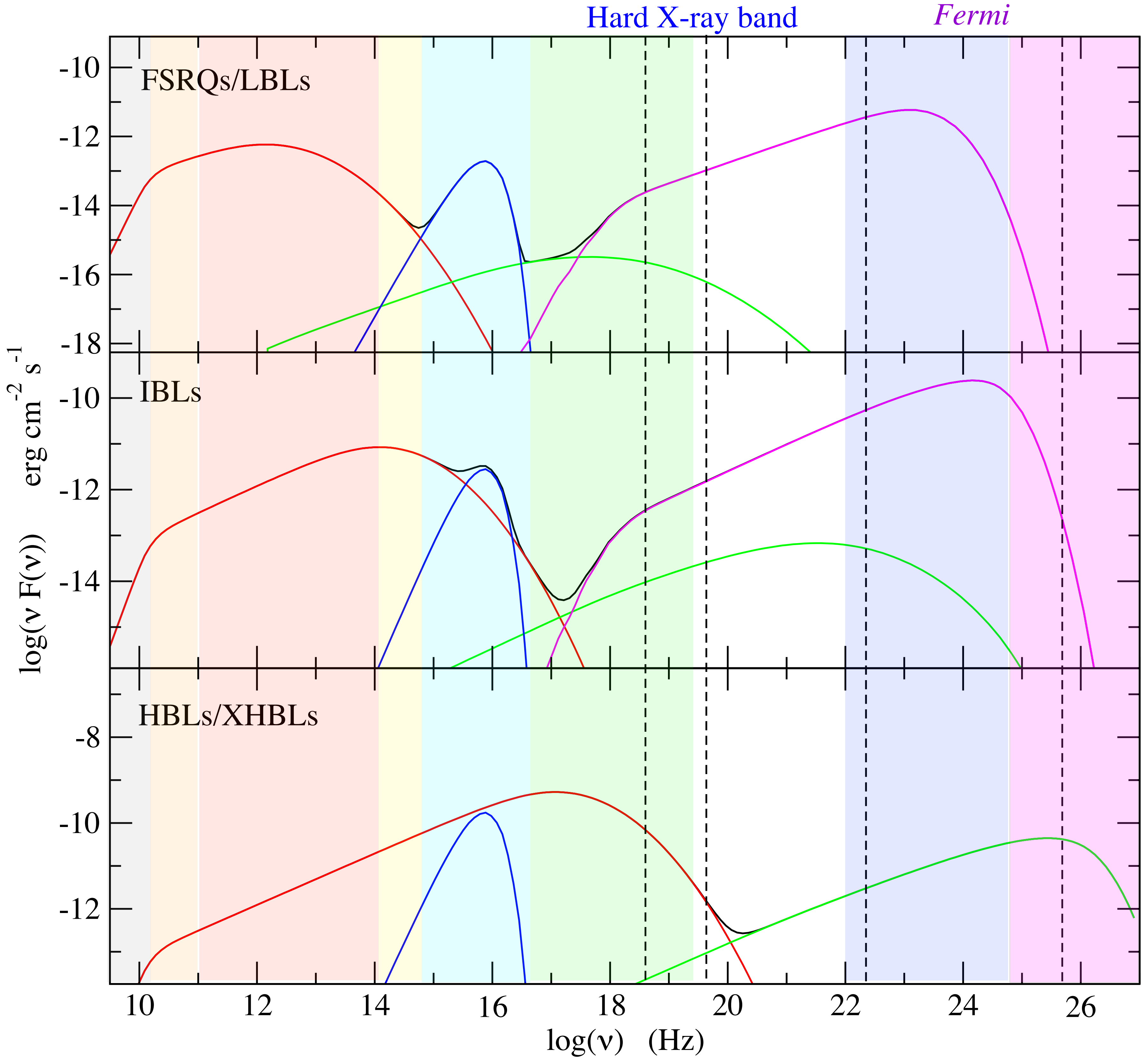
$U_{ext} \simeq \frac{L_d}{R^2_{ext} c}$

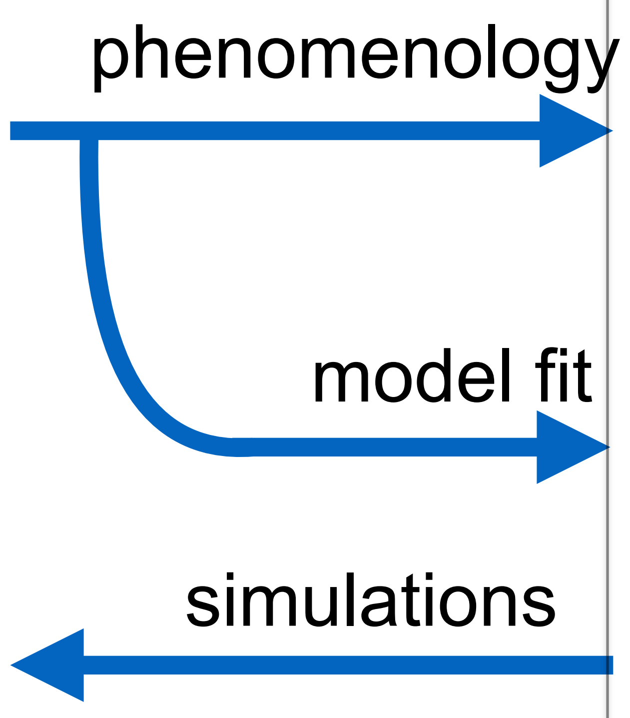
$R_{ext} \simeq L_d^{1/2}$

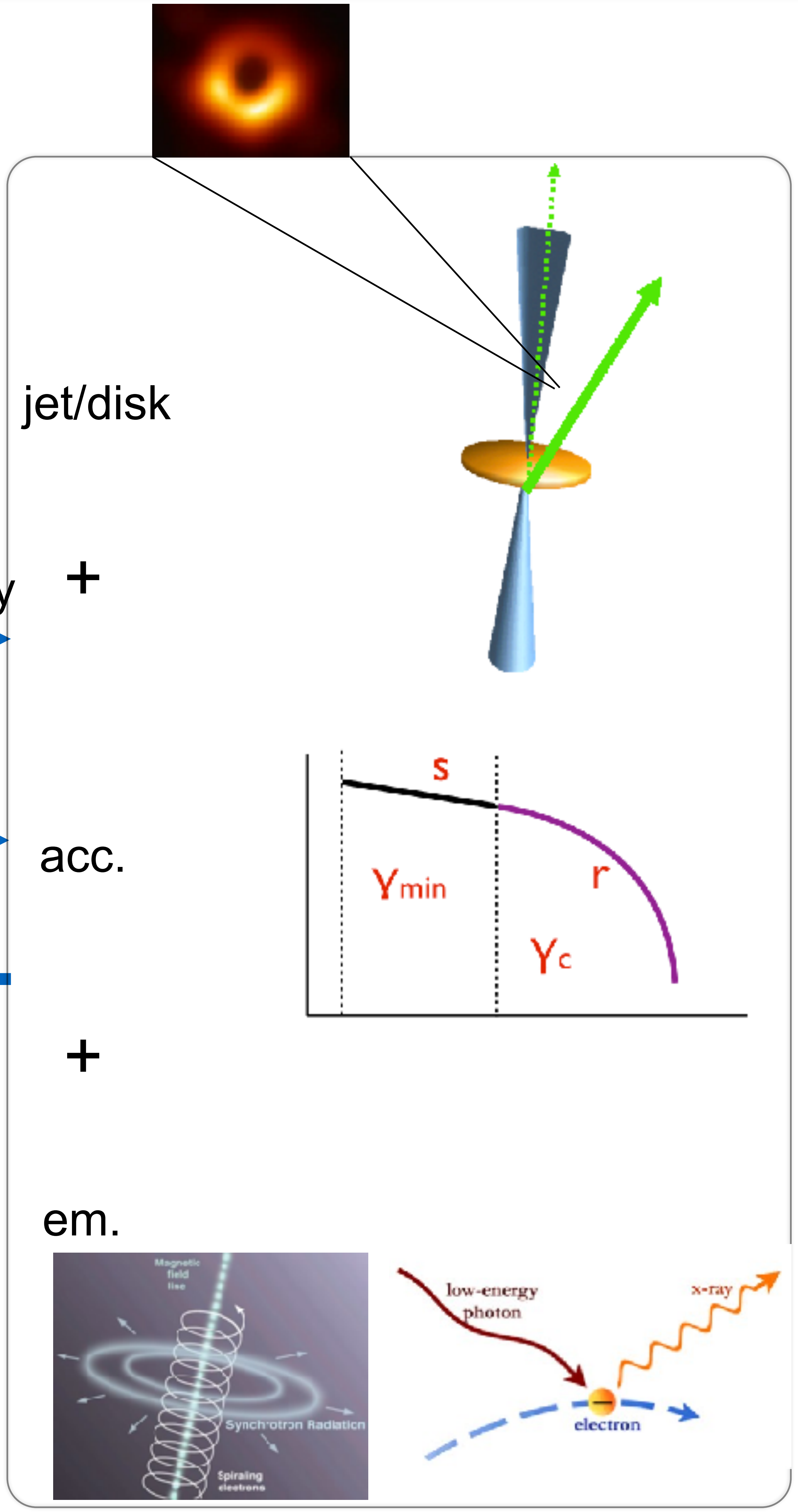
BL Lacs
LERGs

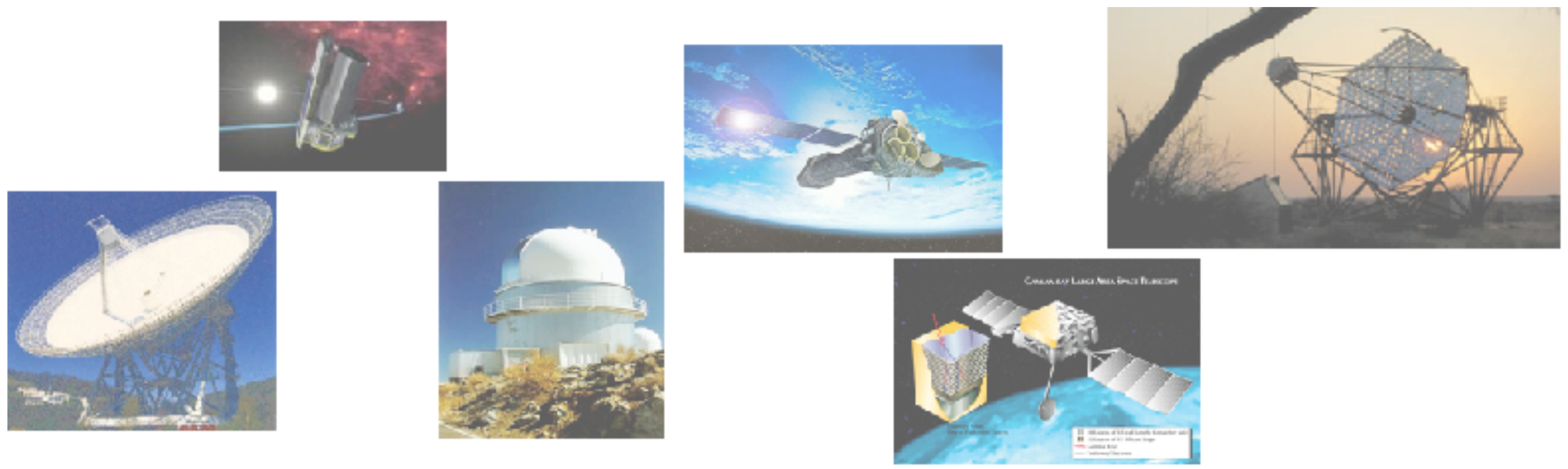
rad ineff.
$L_d < 10^{-2} L_{EDD}$











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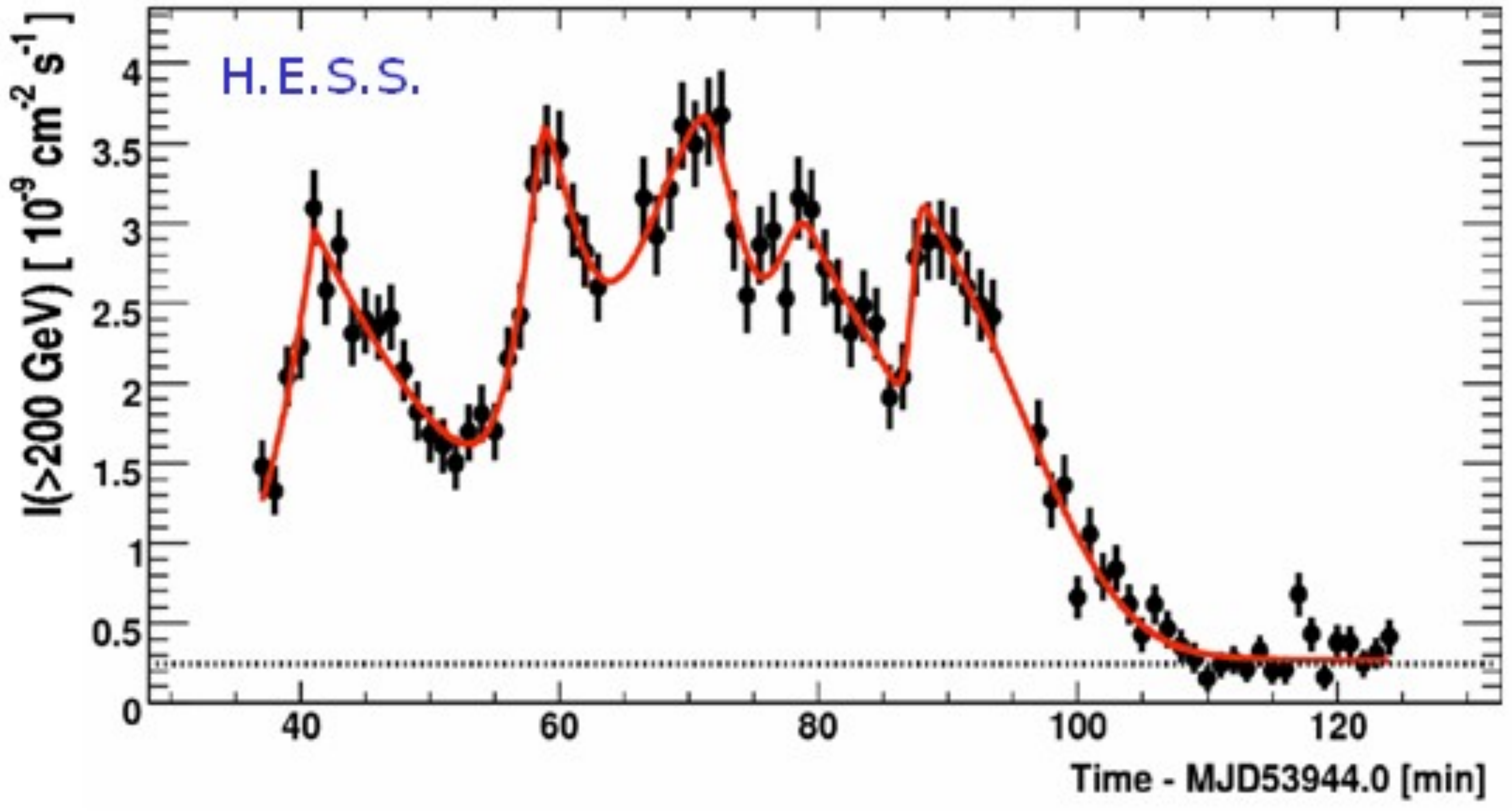
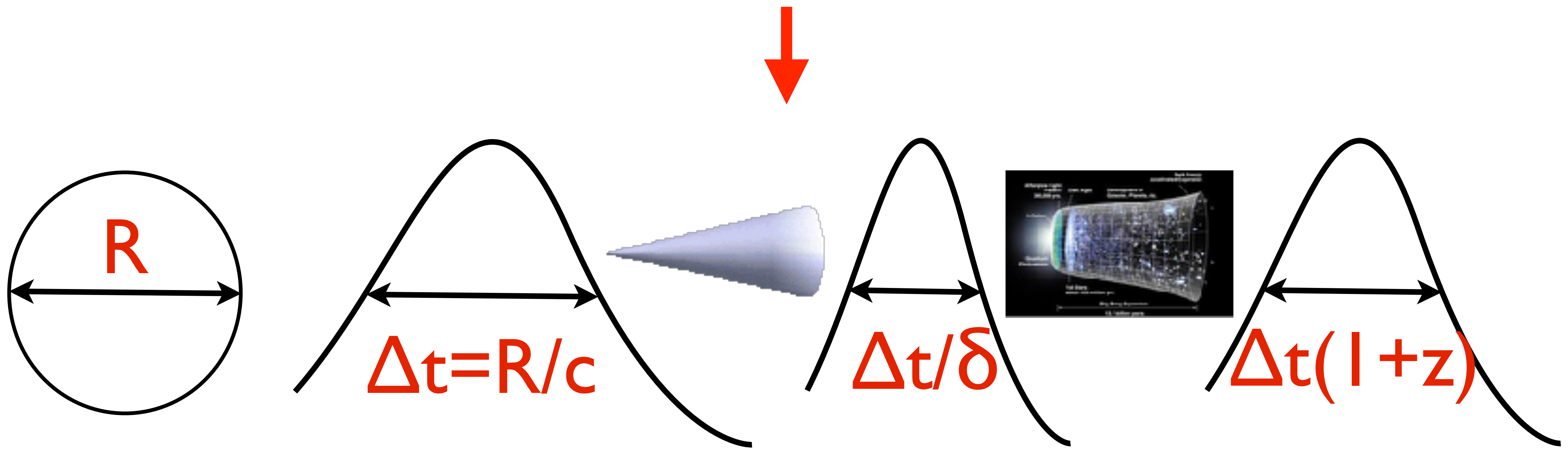
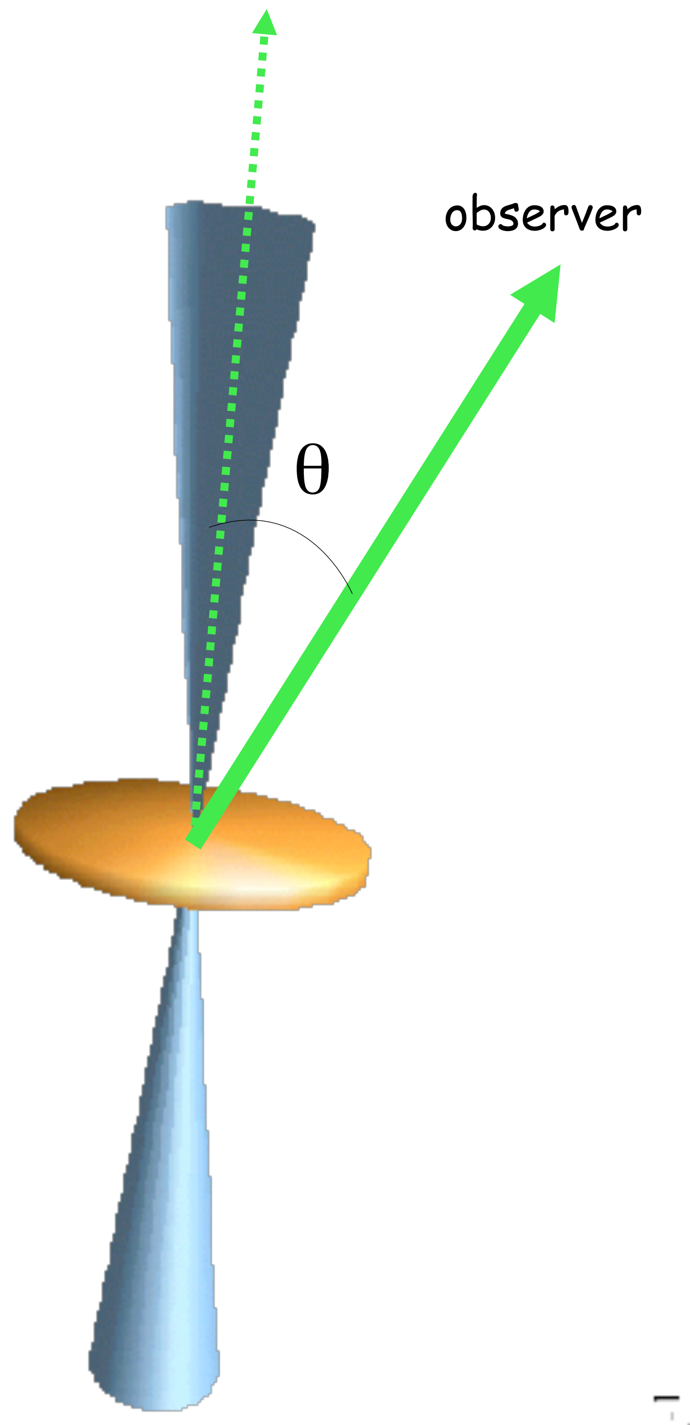
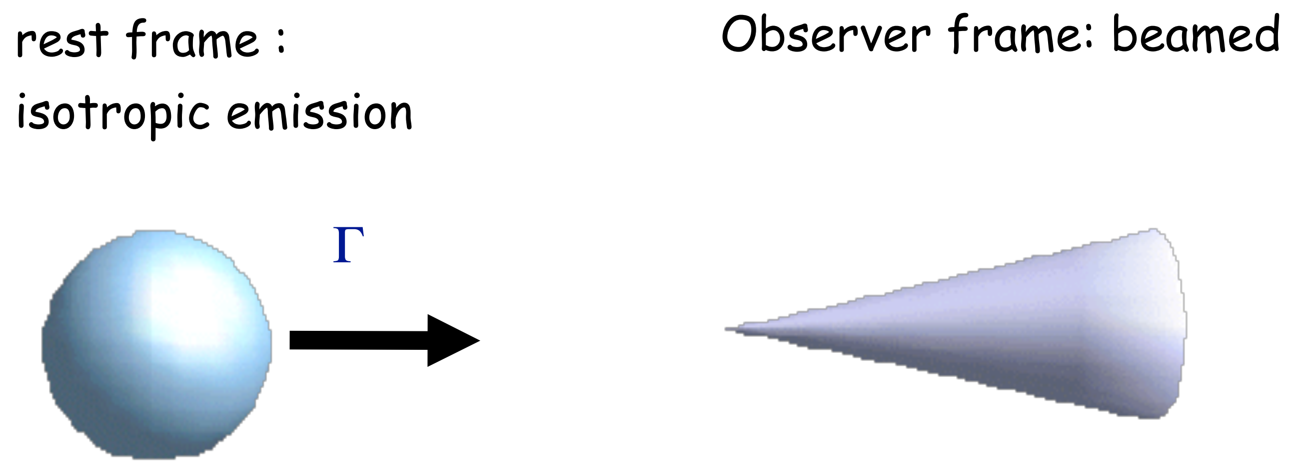
Beamed Emission (achromatic var.)





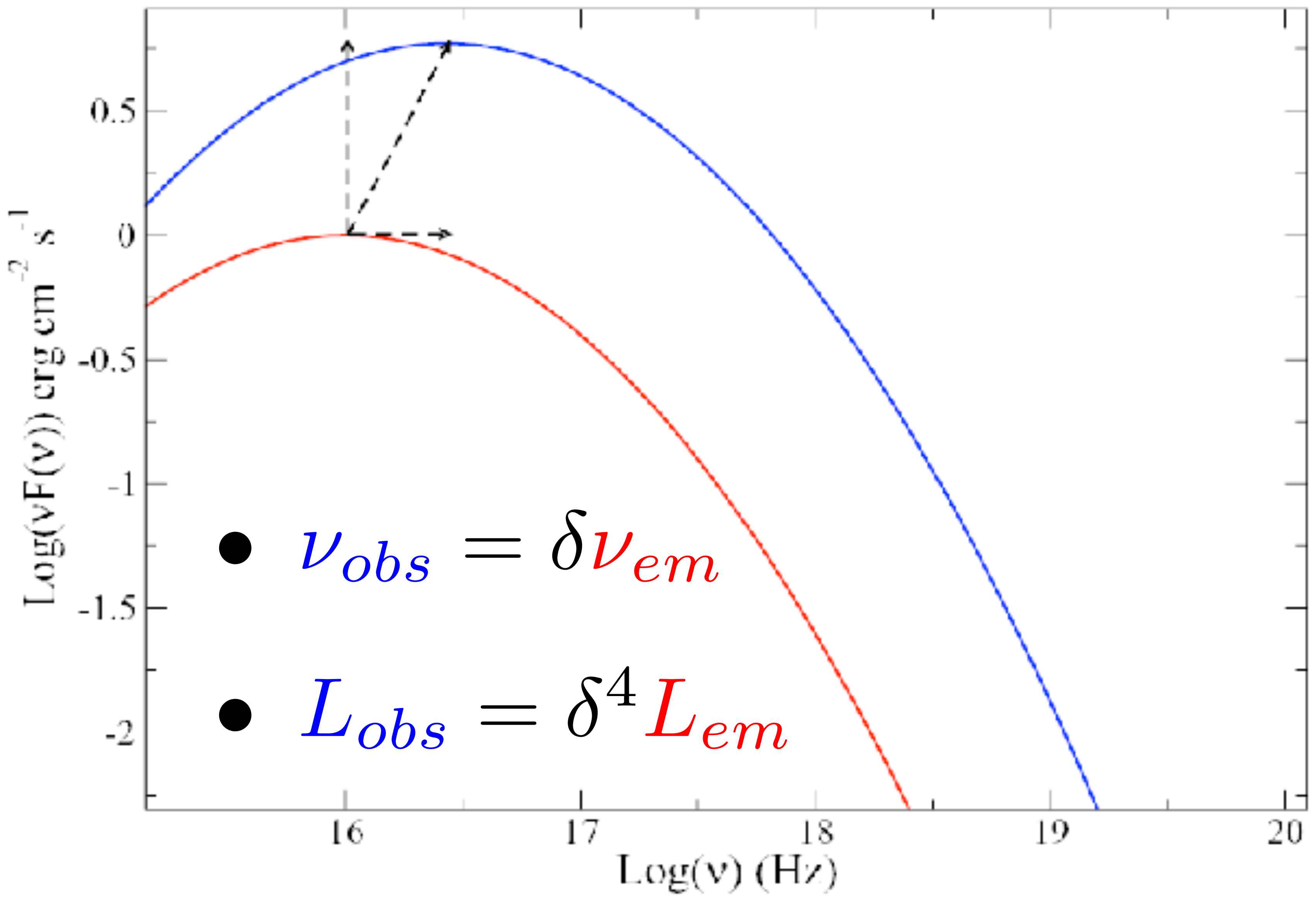
R<= c Δtδ/(1+z)





Beaming factor:

- $\delta = \frac{1}{\Gamma(1-\beta cos(\theta))}$
- $\theta = 1/\Gamma$



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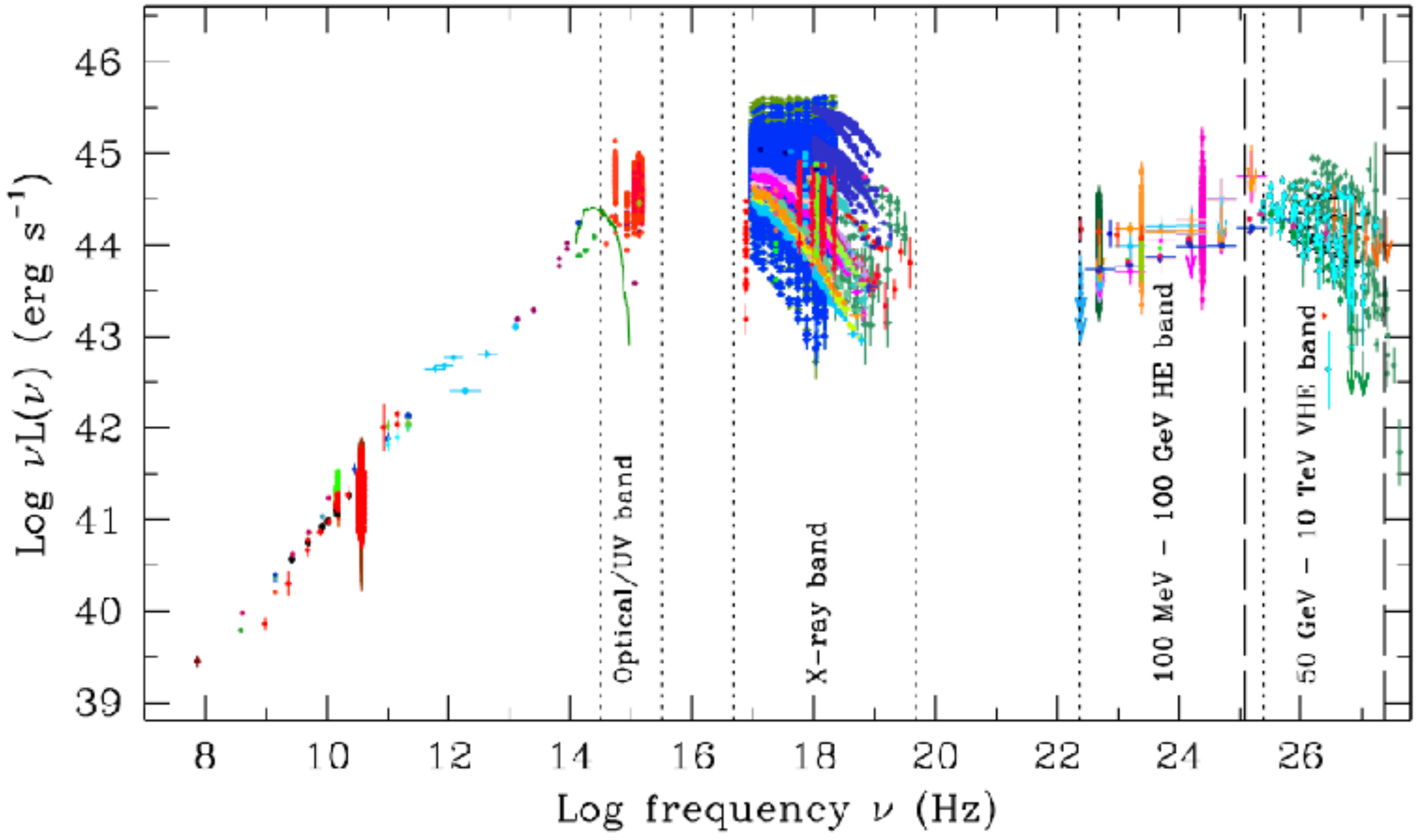
variability: acc. and cooling (lags,hyst. cycle etc..)

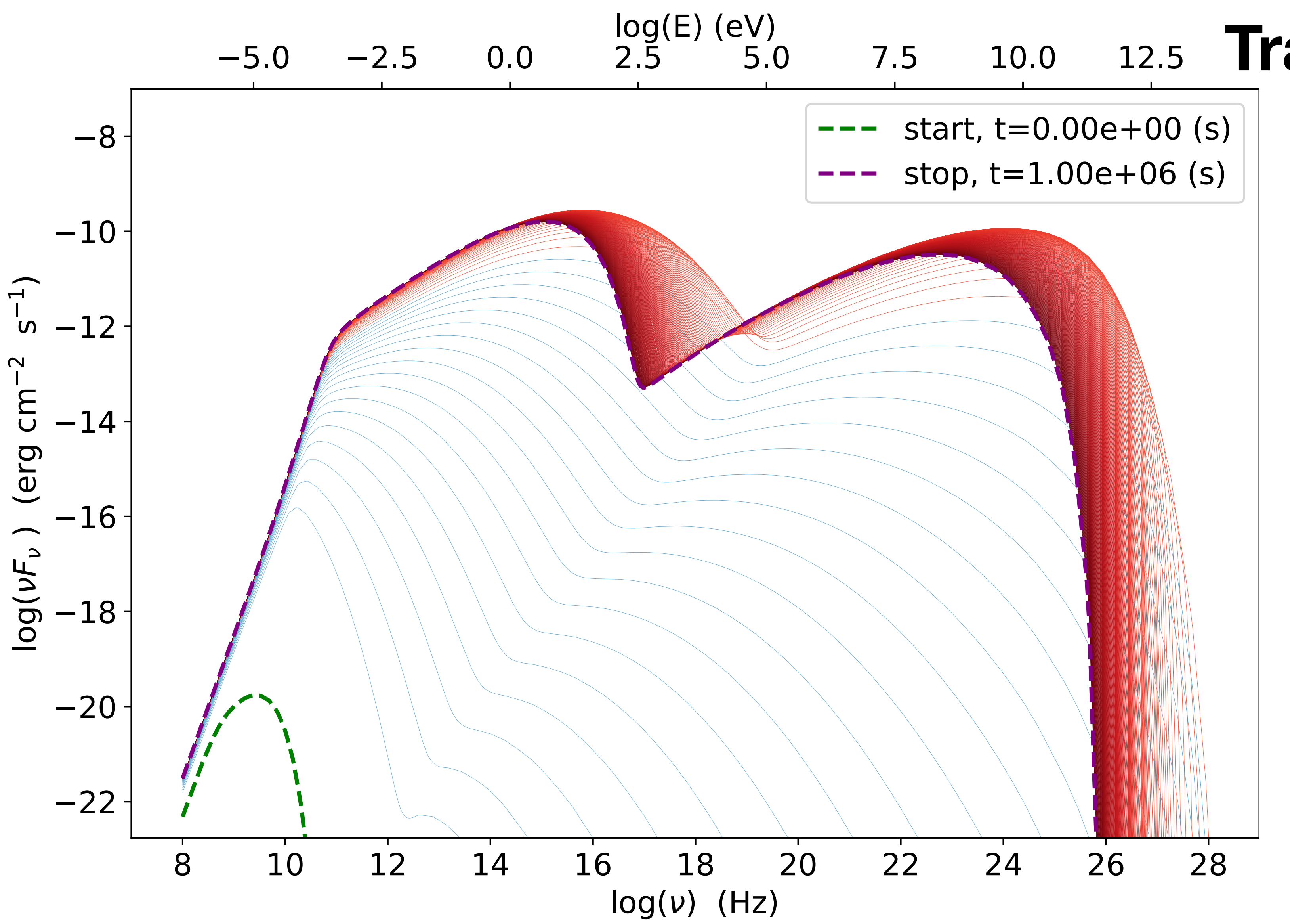
Padovani+ 2017 **mrk 421**

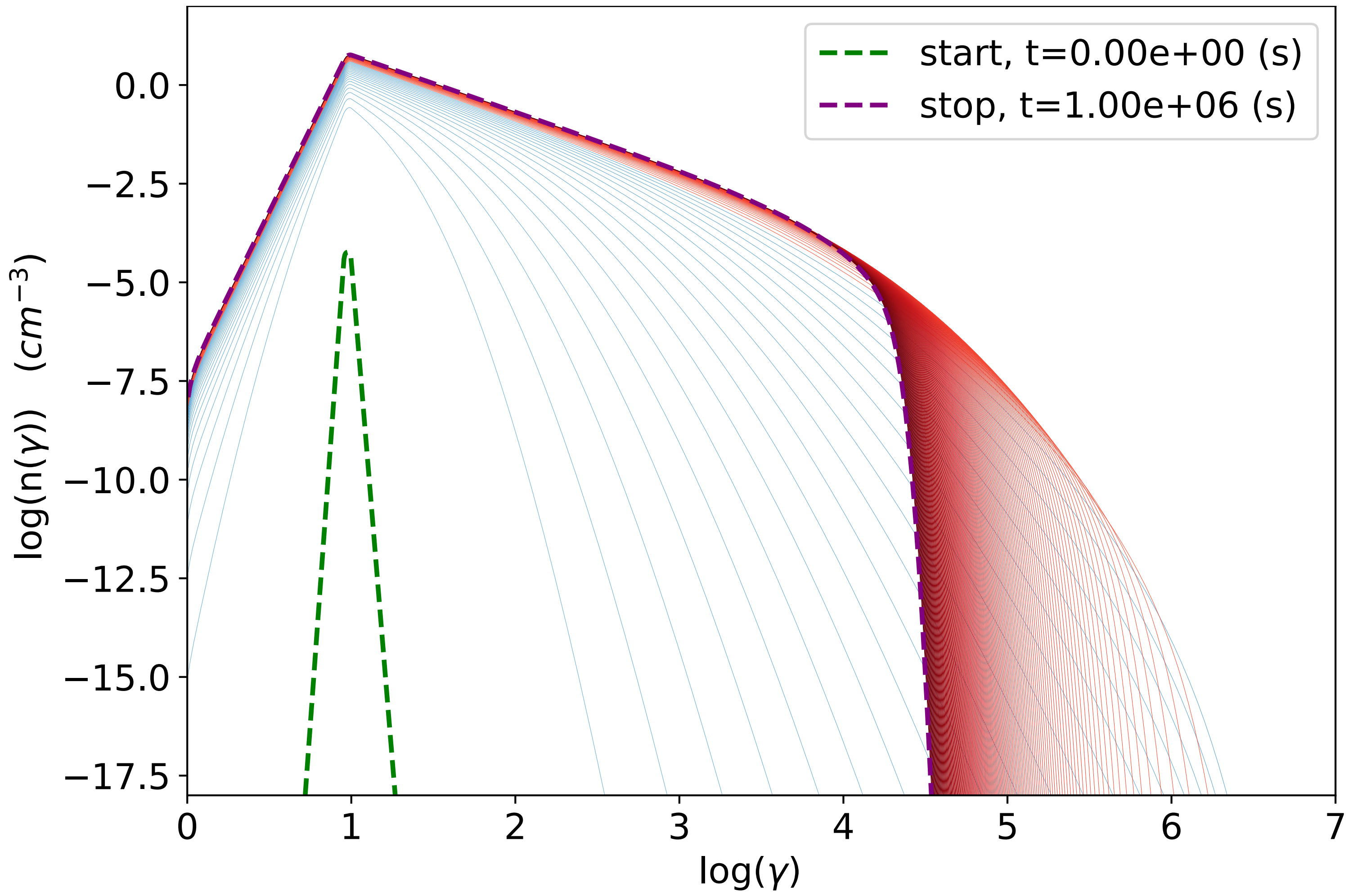


t_{var} depends on $t_{acc,cool.}$ and properties of radiative process plus geometry

Acc+cooling

Tramacere+ 2022,2011





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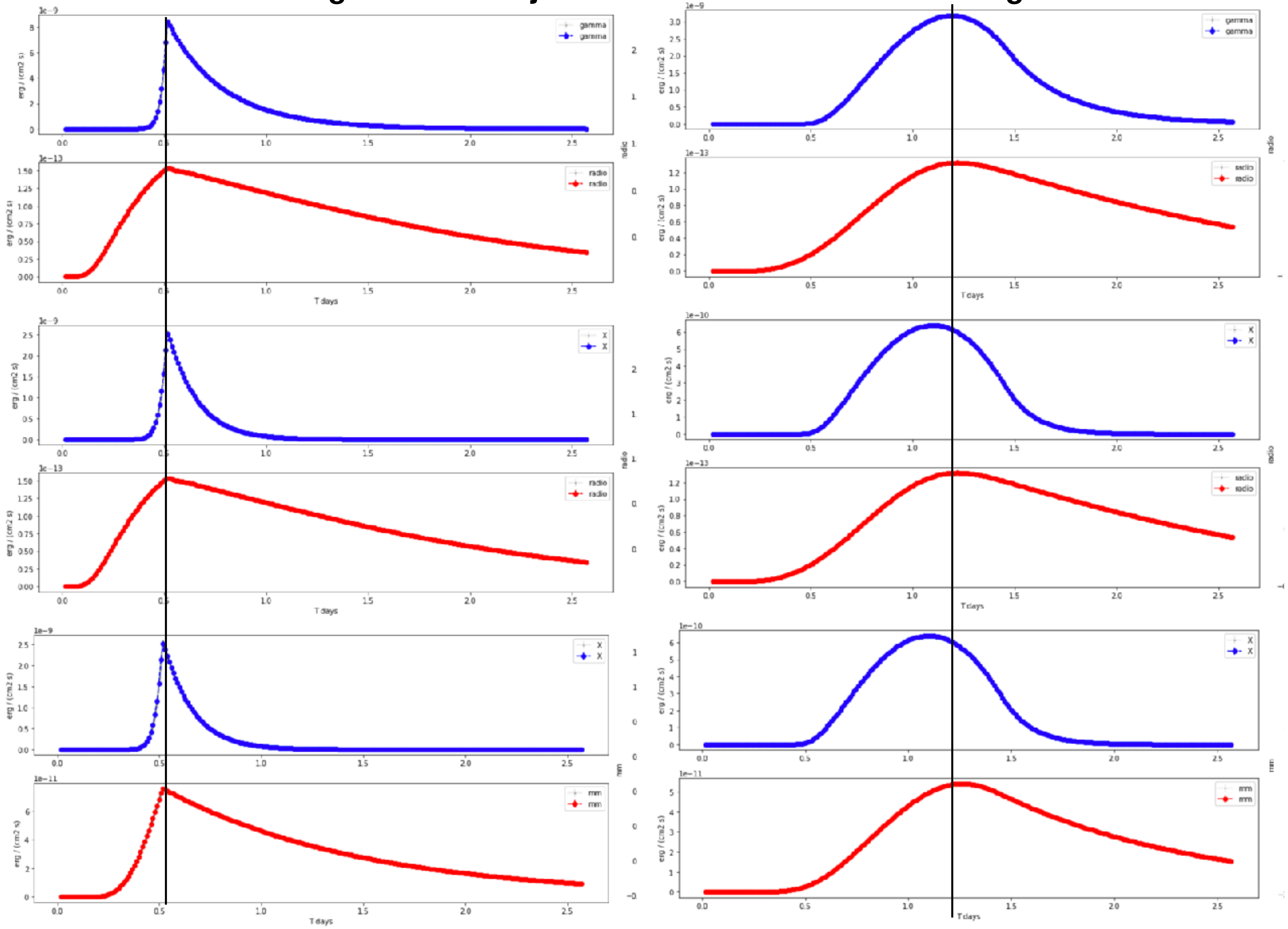
delays from crossing time, cooling, acc., inj.

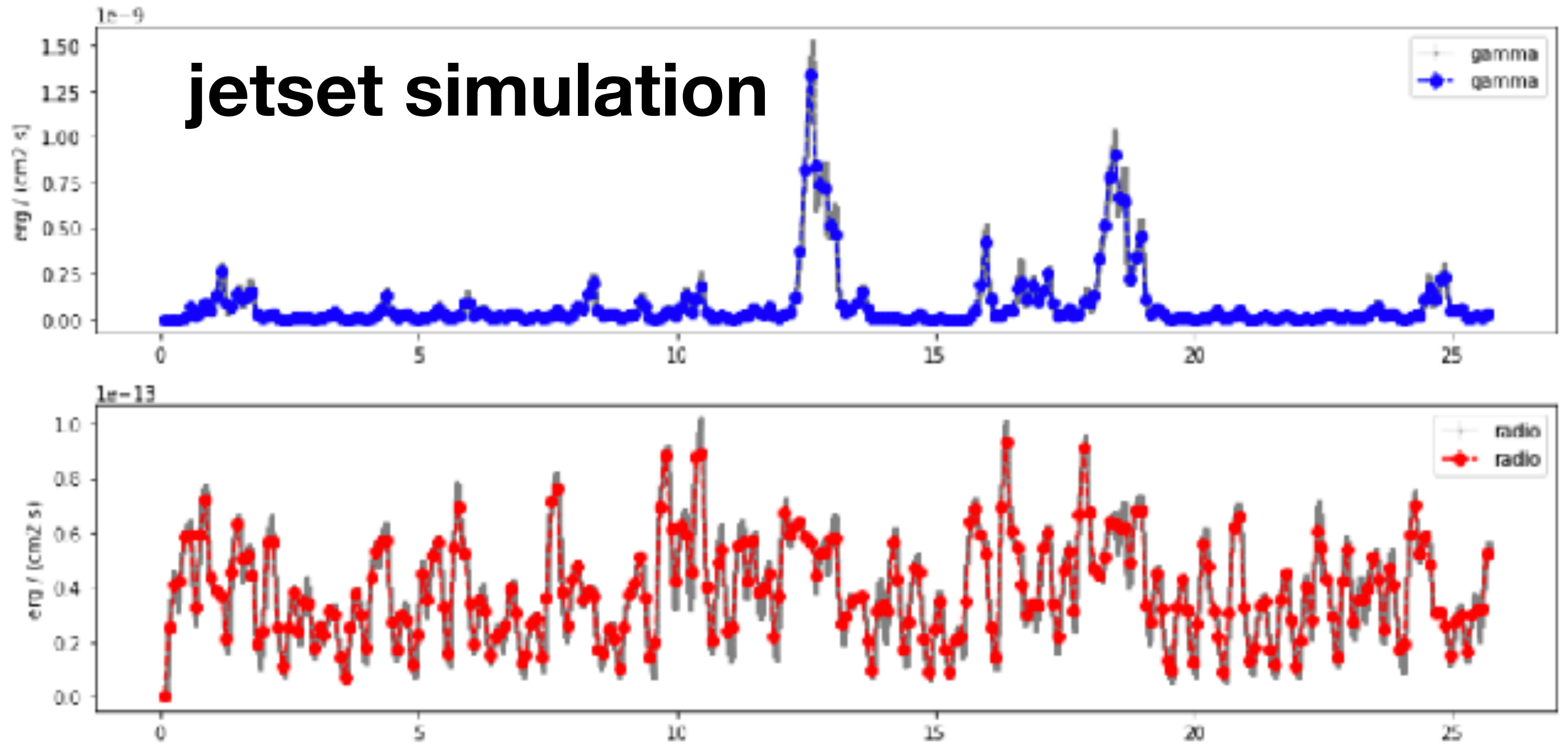
no crossing time **jetset simulation** **with crossing time**

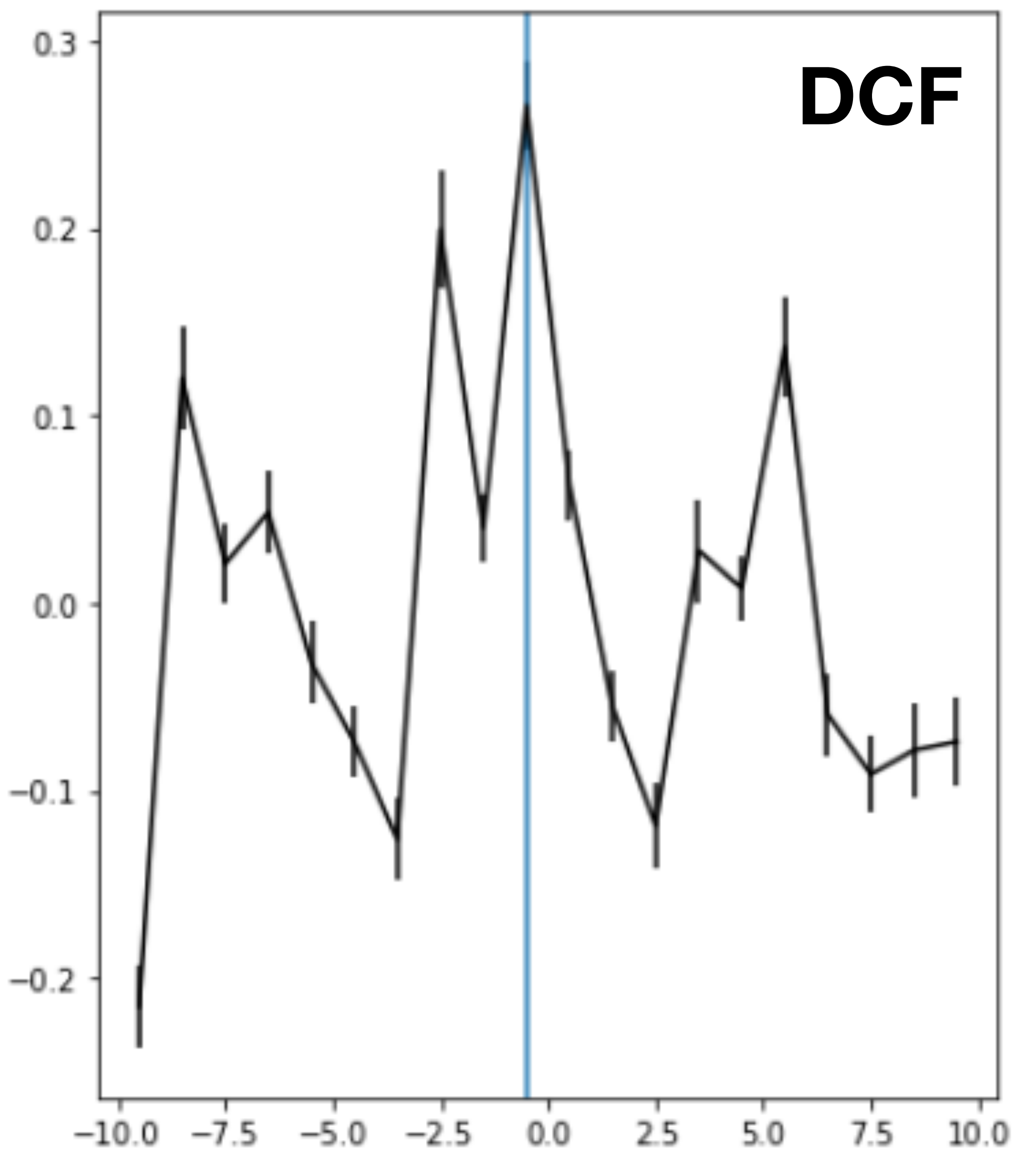


hours to days

$\Delta_T \sim R/c, t_{cool}$

dispersion on $\Delta_T \sim R/c, t_{cool}$





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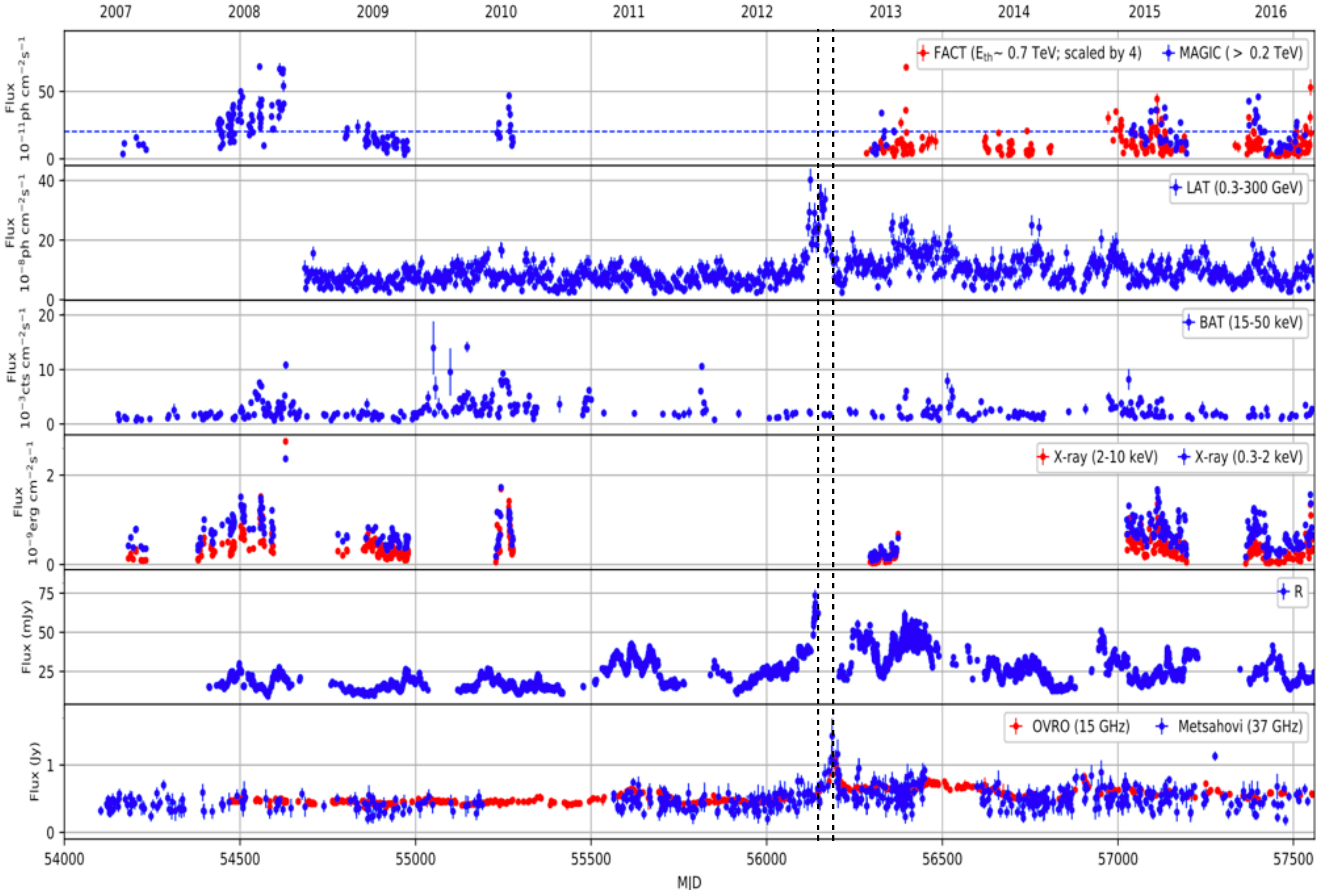
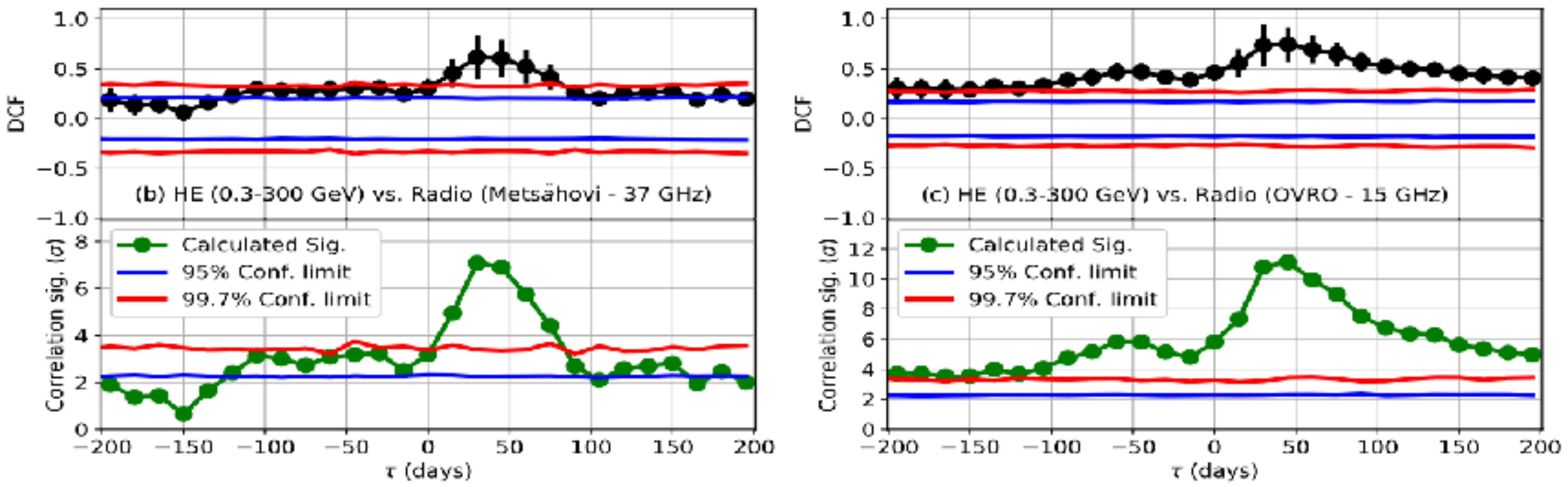
delays on weeks to years timescales

MW variability and correlation studies of Mrk 421 during historically low X-ray and γ-ray activity in 2015-2016

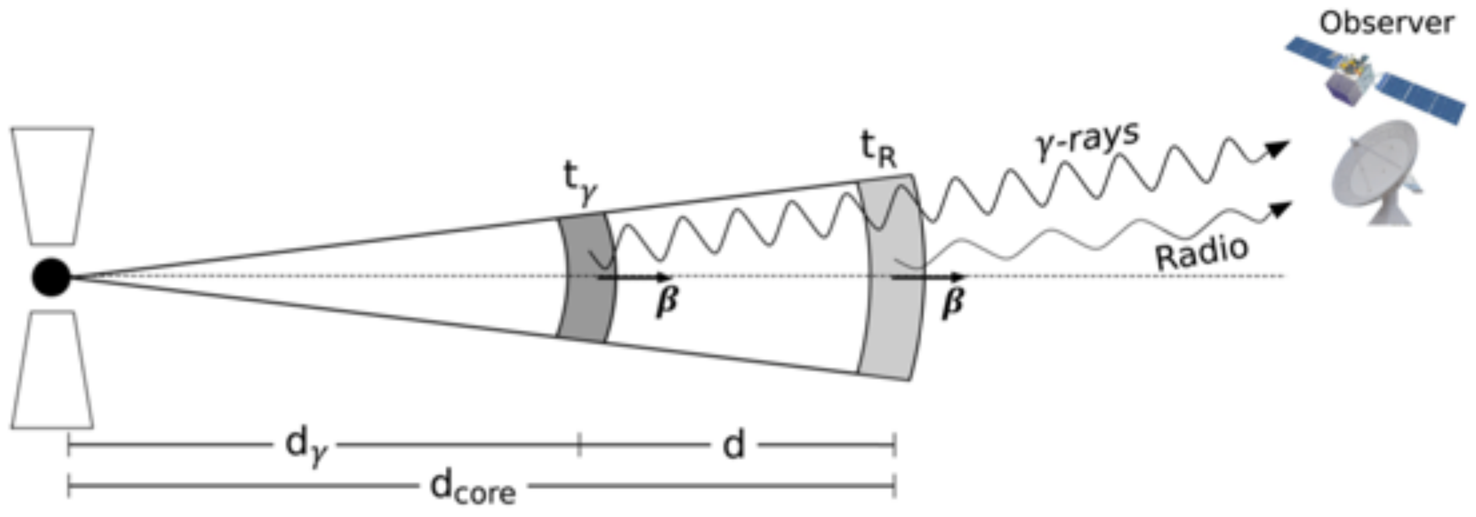
Magic coll. 2020

Radio-γ delay in Mrk 421 (months)





Radio-γ delay ~ 1/ν



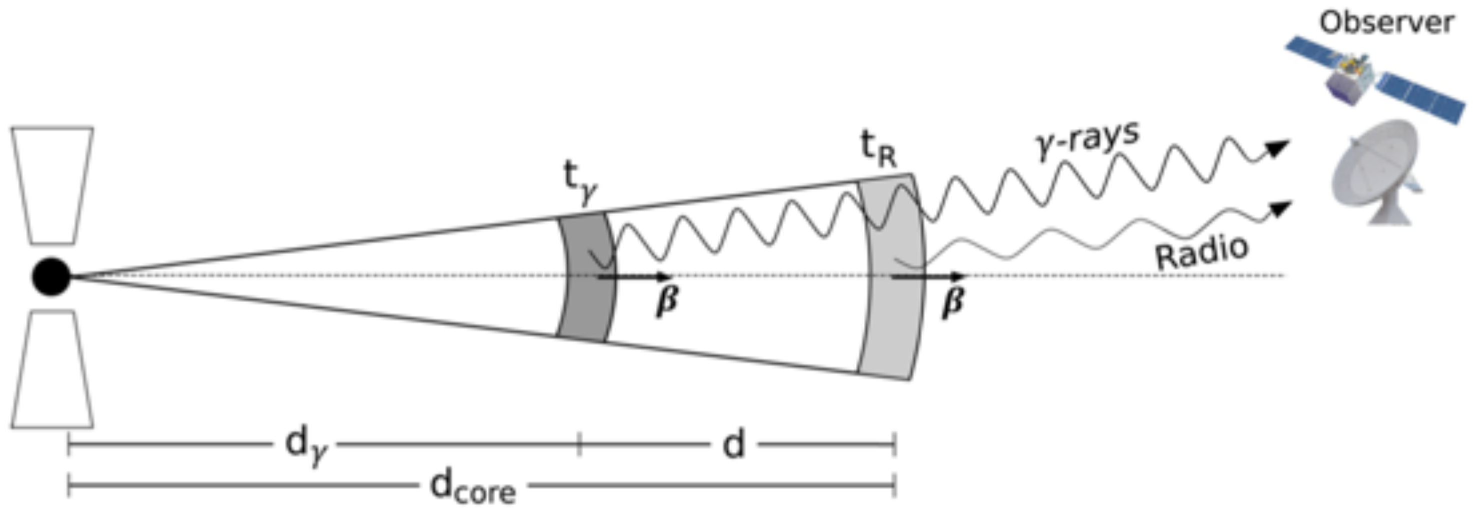
W. Max-Moerbeck+ 2014
B. Pushkarev+ 2010
Ghisellini+1985
McCray,R. 1968

what we want to test

- Observed lags are not compatible with cooling, acc., crossing (unless strong fine tuning)

- Explanations based on reacceleration, would be challenging due to MW observations

We want to test if it is possible to reproduce a radio-γ due (T>>d) due to blob expansion



W. Max-Moerbeck+ 2014
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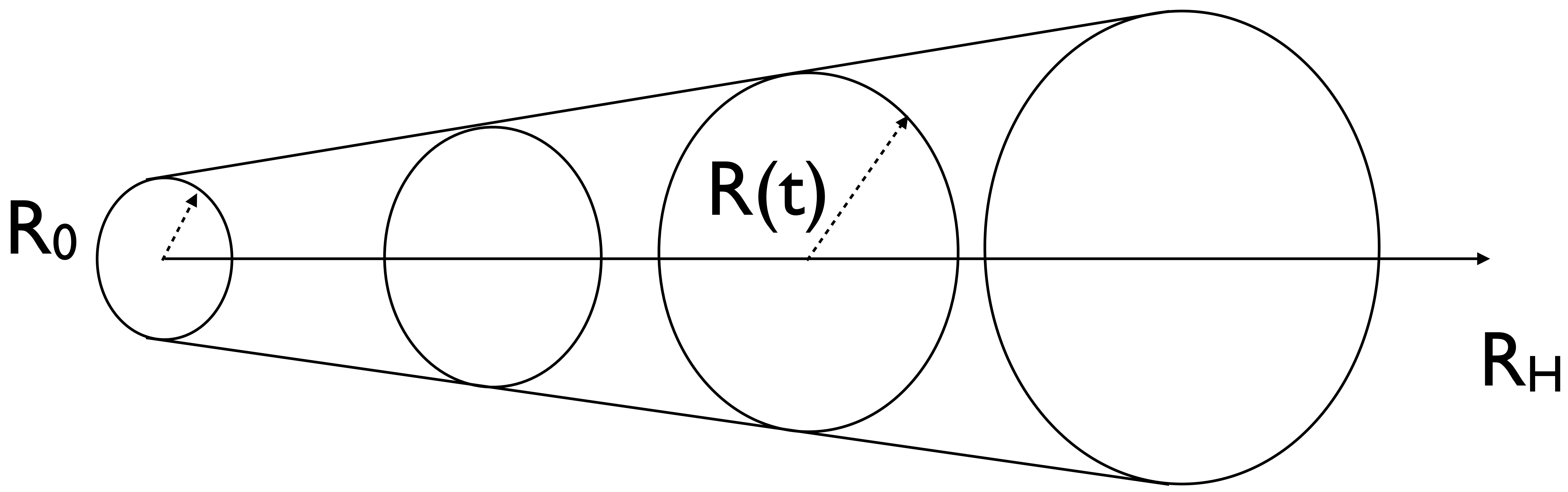
Ghisellini+1985
McCray,R. 1968

blob expansion

$$\beta_{\rm exp} = v_{exp}/c$$

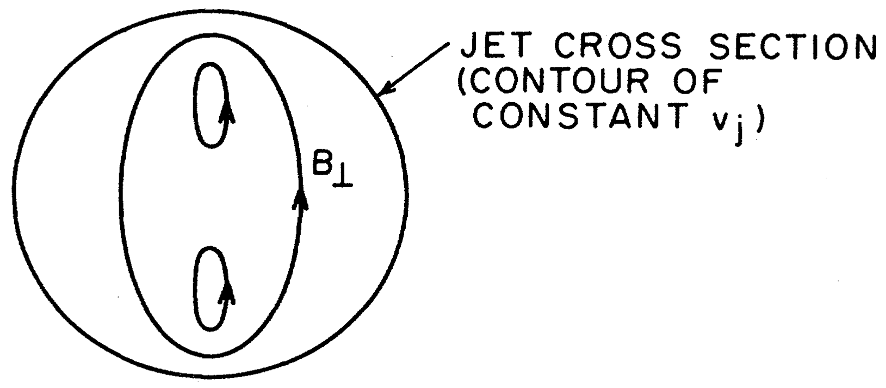
$$R(t) = R_0 + \beta_{\rm exp} c(t - t_{exp}) H(t - t_{exp})$$

$$B(t) = B_0 \left(\frac{R_0}{R(t)}\right)^{m_B} \qquad m_B \in [1,2]$$



Magnetic field (flux freezing and conservation): (Begelman, Blandford, and Rees 1984)

- $B|| \, \alpha R^{-2}$ (poloidal) m_B=2
- $B\perp \alpha R^{-1}$ (toroidal) m_B=1
- for initial mixed configuration, **and no velocity gradient**, B⊥ will dominate with $m_B \sim m_R$



blob expansion

$$R(t) = R_0 + \beta_{\rm exp} c (t - t_{exp}) H(t - t_{exp})$$

$$B(t) = B_0 \left(\frac{R_0}{R(t)}\right)^{m_B} \qquad m_B \in [1,2]$$

Geom.

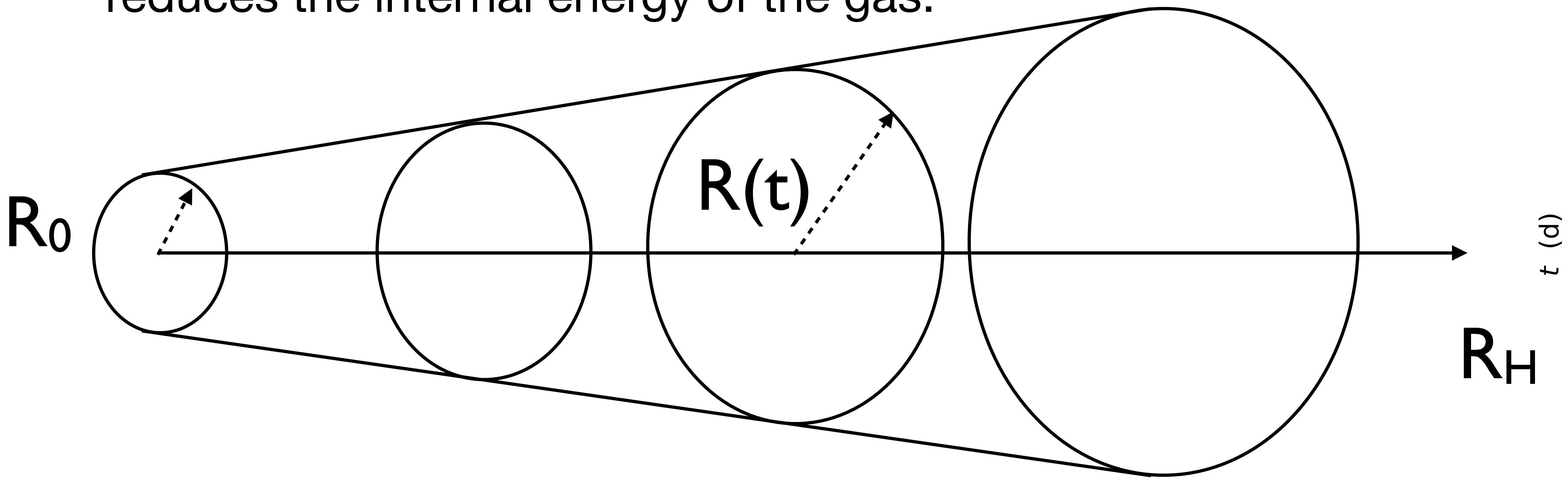
$$|\dot\gamma_{synch}(t)| = \frac{4\sigma_T c}{3 m_e c^2}\gamma^2 U_B(t) = C_0 \gamma^2 U_B(t)$$

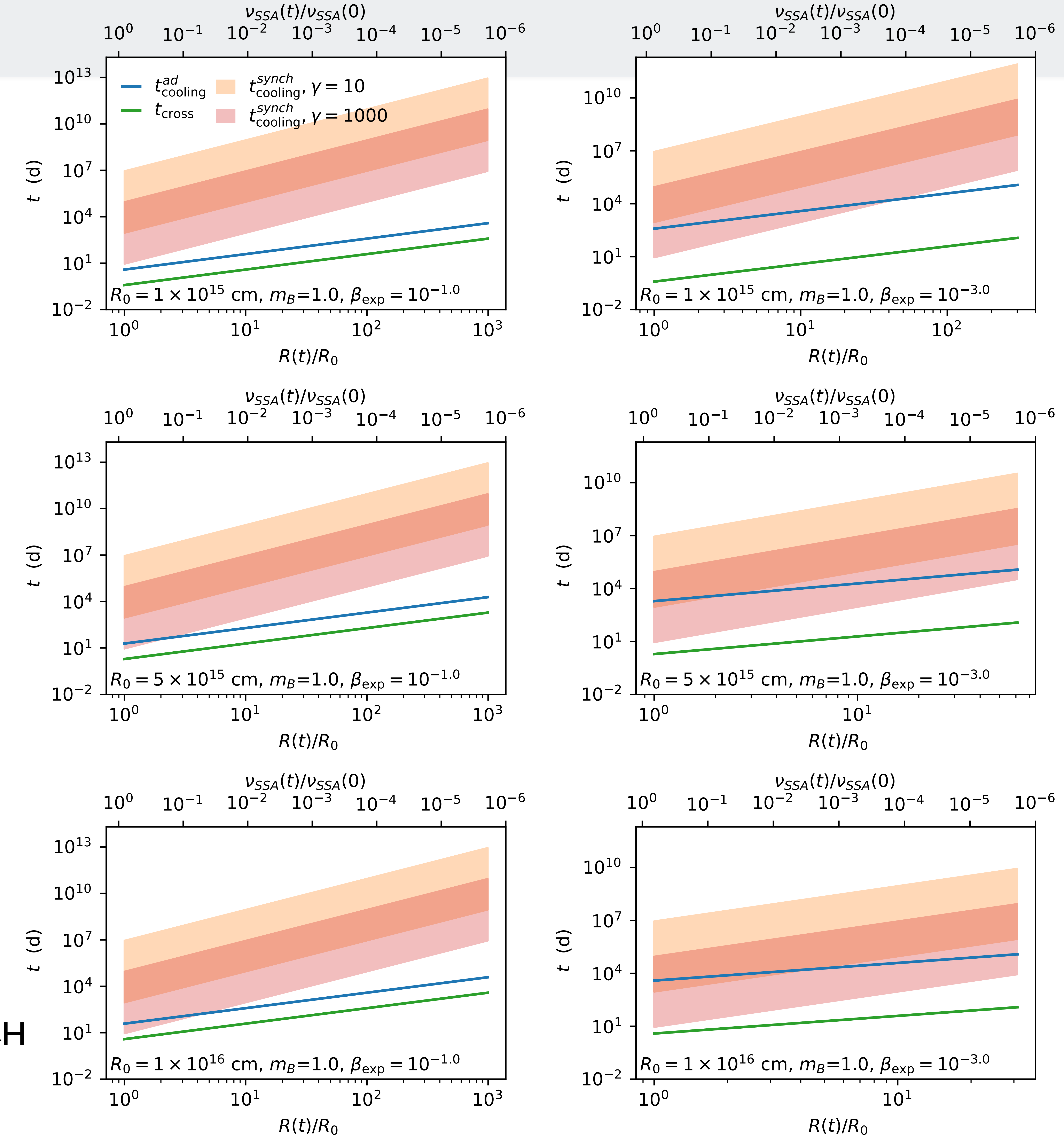
$$|\dot\gamma_{IC}(t)| = \frac{4\sigma_T c}{3 m_e c^2}\gamma^2 \int f_{KN}(4\gamma\epsilon_0)\epsilon_0 n_{ph}(\epsilon_0, t) d\epsilon_0 = C_0 \gamma^2 F_{KN}(\gamma, t)$$

$$|\dot\gamma_{ad}(t)| = \frac{1}{3}\frac{\dot V}{V}\gamma = \frac{\dot R(t)}{R(t)}\gamma = \frac{\beta_{\rm exp} c}{R(t)}\gamma$$

Cooling

If the electrons are confined within an expanding volume, they are subject to adiabatic losses as they do work which reduces the internal energy of the gas.





self-consistent approach

here we add adiabatic cooling
(t=time elapsed from the expansion)

$$|\dot{\gamma}_{ad}| = \frac{1}{3}\frac{\dot{V}}{V}\gamma = \frac{\dot{R}(t)}{R(t)}\gamma = \frac{\beta_{\rm exp} c}{R(t)}\gamma$$

Tramacere+2022, Tramacere+2011

injection term

$$L_{inj} = V_{\rm acc}\int \gamma m_e c^2 Q(\gamma,t)d\gamma \quad (erg/s)$$

systematic term

$$S(\gamma,t) = -C(\gamma,t) + A(\gamma,t)$$

cooling term

$$C(\gamma) = |\dot{\gamma}_{synch}| + |\dot{\gamma}_{IC}| + |\dot{\gamma}_{ad}|$$

syst. acc. term

$$A(\gamma) = A_{p0}\gamma,\ t_A = \frac{1}{A_0}$$

$$\frac{\partial n(\gamma,t)}{\partial t} = \frac{\partial}{\partial\gamma}\left\{-[S(\gamma,t) + D_A(\gamma,t)]n(\gamma,t)\right\} + \frac{\partial}{\partial\gamma}\left\{D_p(\gamma,t)\frac{\partial n(\gamma,t)}{\partial\gamma}\right\} - \frac{n(\gamma,t)}{T_{esc}(\gamma)} - \frac{n(\gamma,t)}{T_{ad}} + Q(\gamma,t)$$

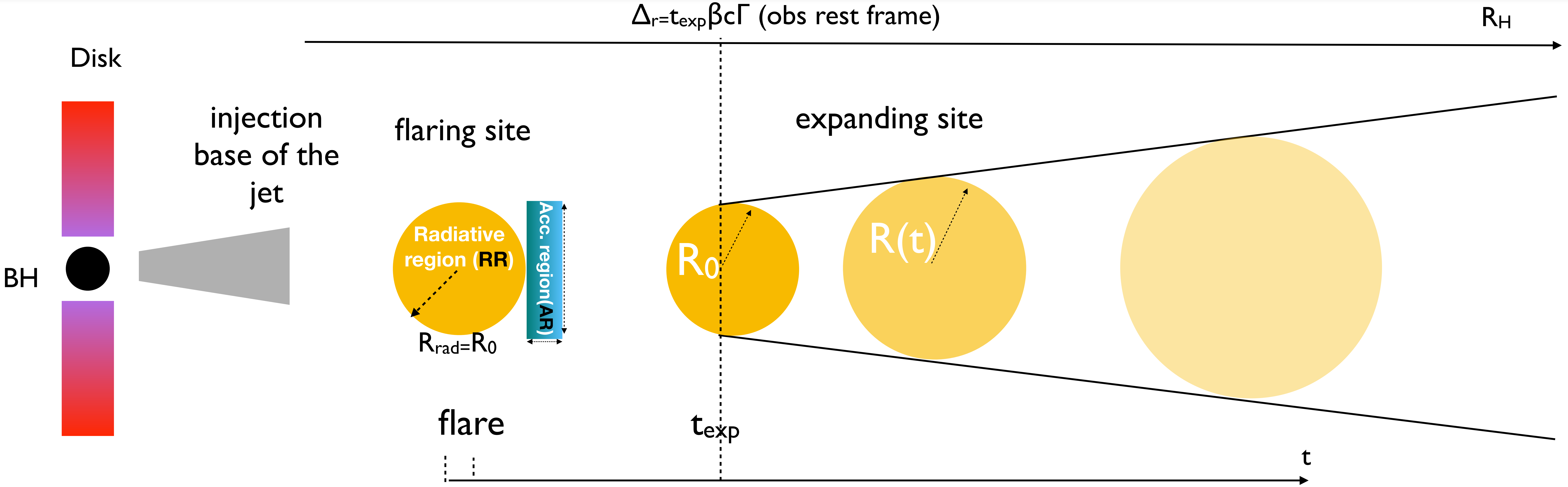
$$T_{ad} = \frac{1}{3}\frac{R(t)}{\beta_{\rm exp} c} \quad \text{(Gould 1975)}$$

Turbulent magnetic field → momentum diffusion term

$$W(k) = \frac{\delta B(k_0^2)}{8\pi}\left(\frac{k}{k_0}\right)^{-q}$$

$$D_p \approx \beta_A^2\left(\frac{\delta B}{B_0}\right)^2\left(\frac{\rho_g}{\lambda_{\rm max}}\right)^{q-1}\frac{p^2c^2}{\rho_g c}$$

self-consistent approach



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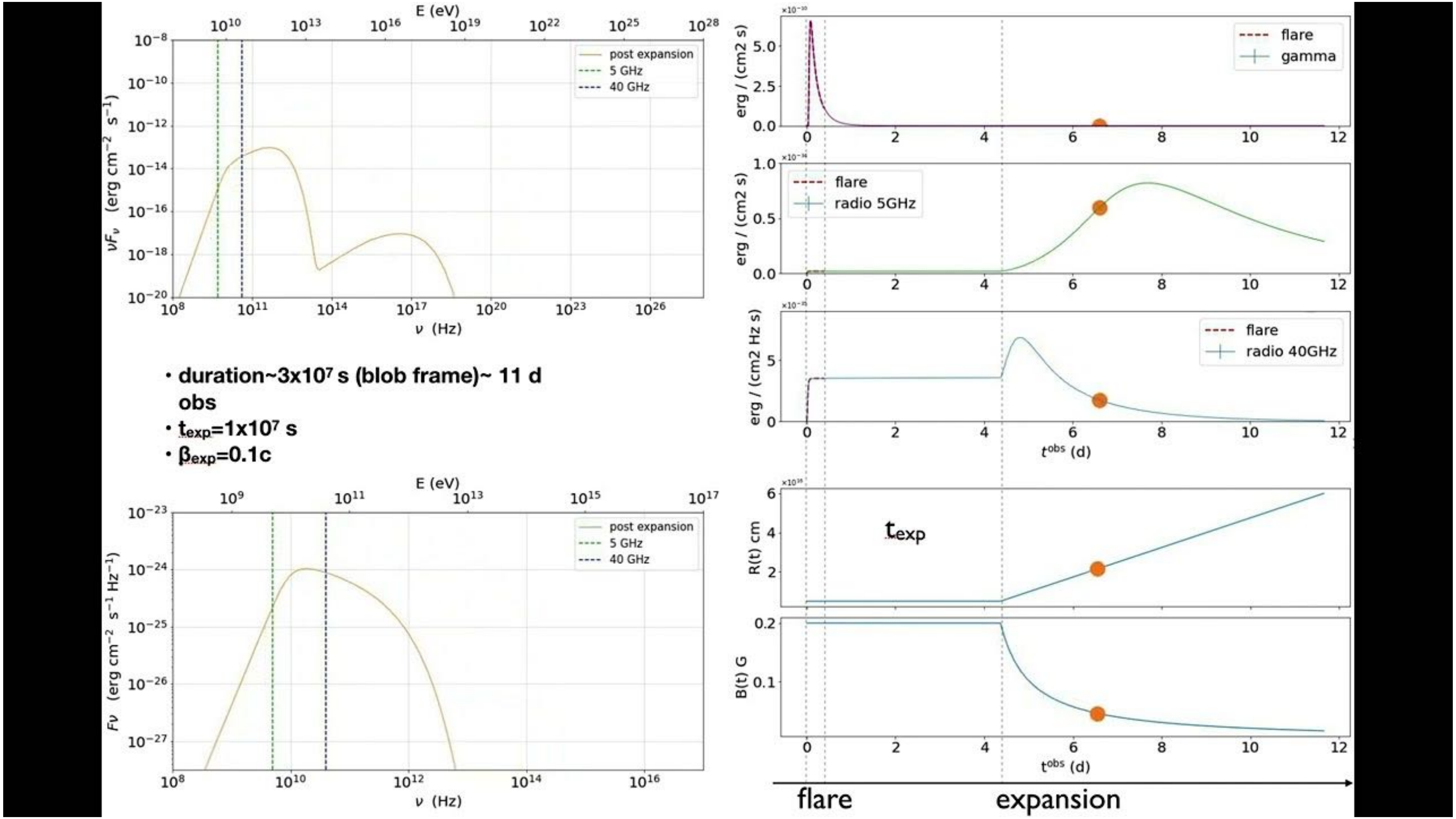
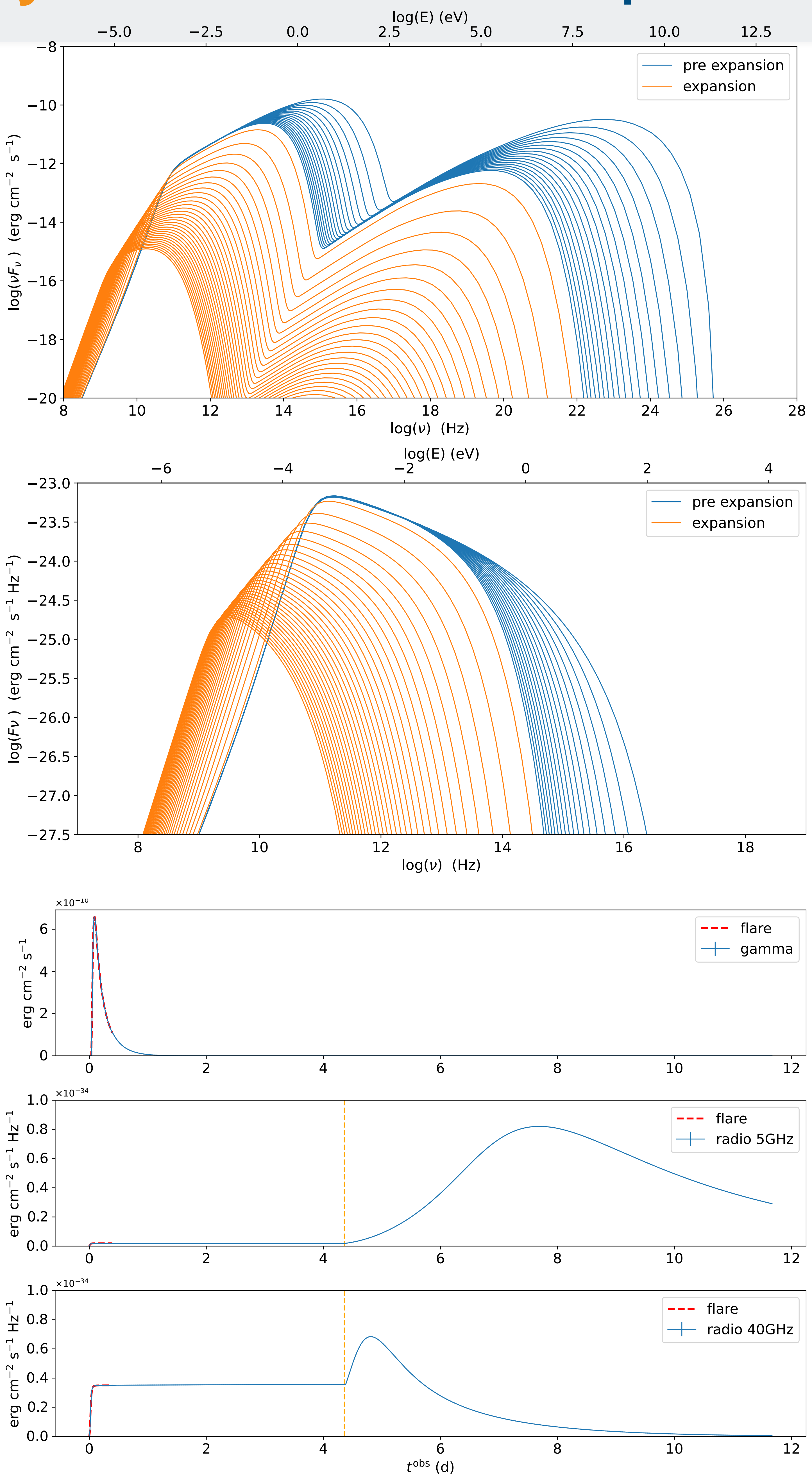
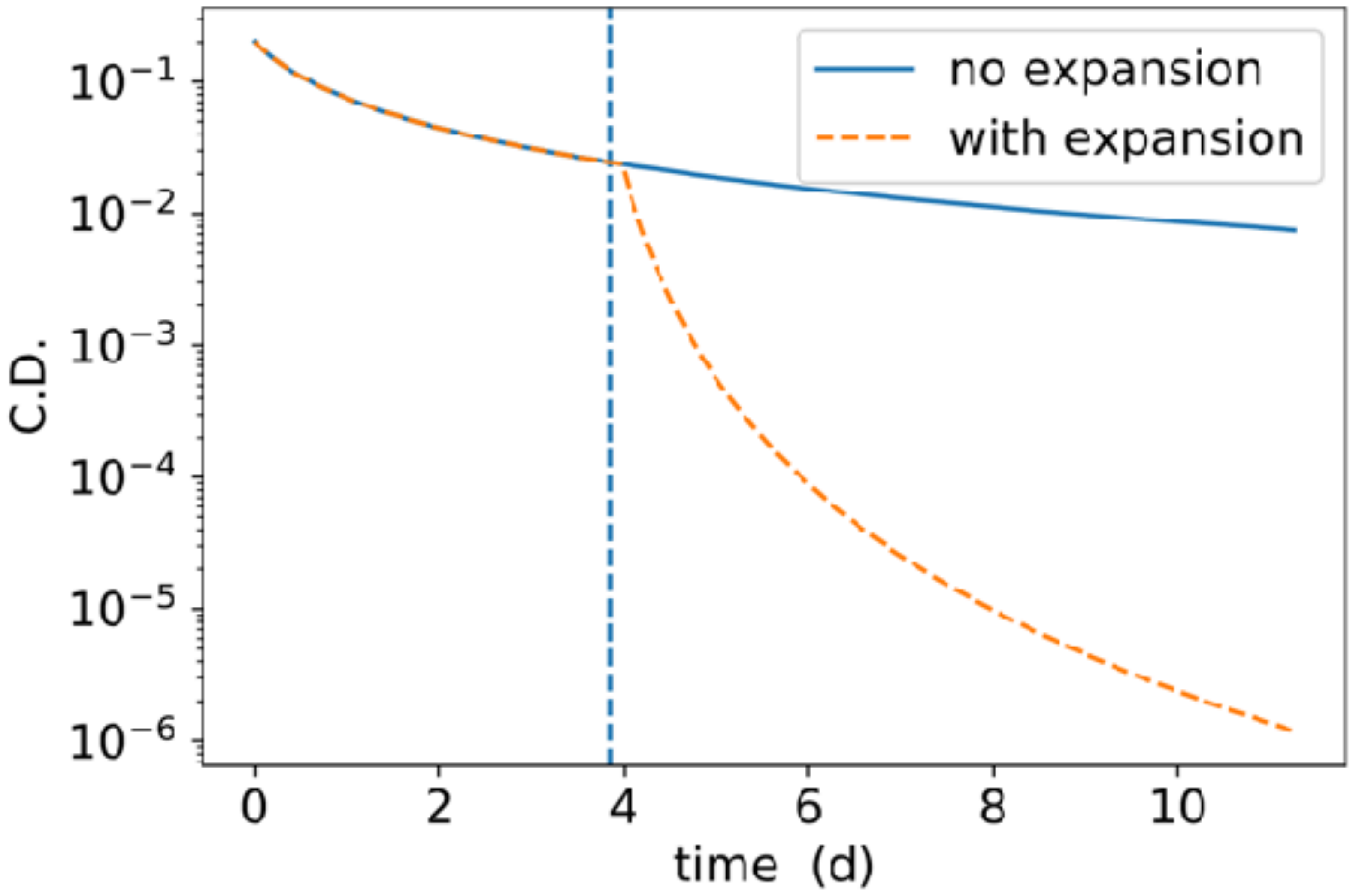
self-consistent approach

Click on the image to reproduce the animation on youtube



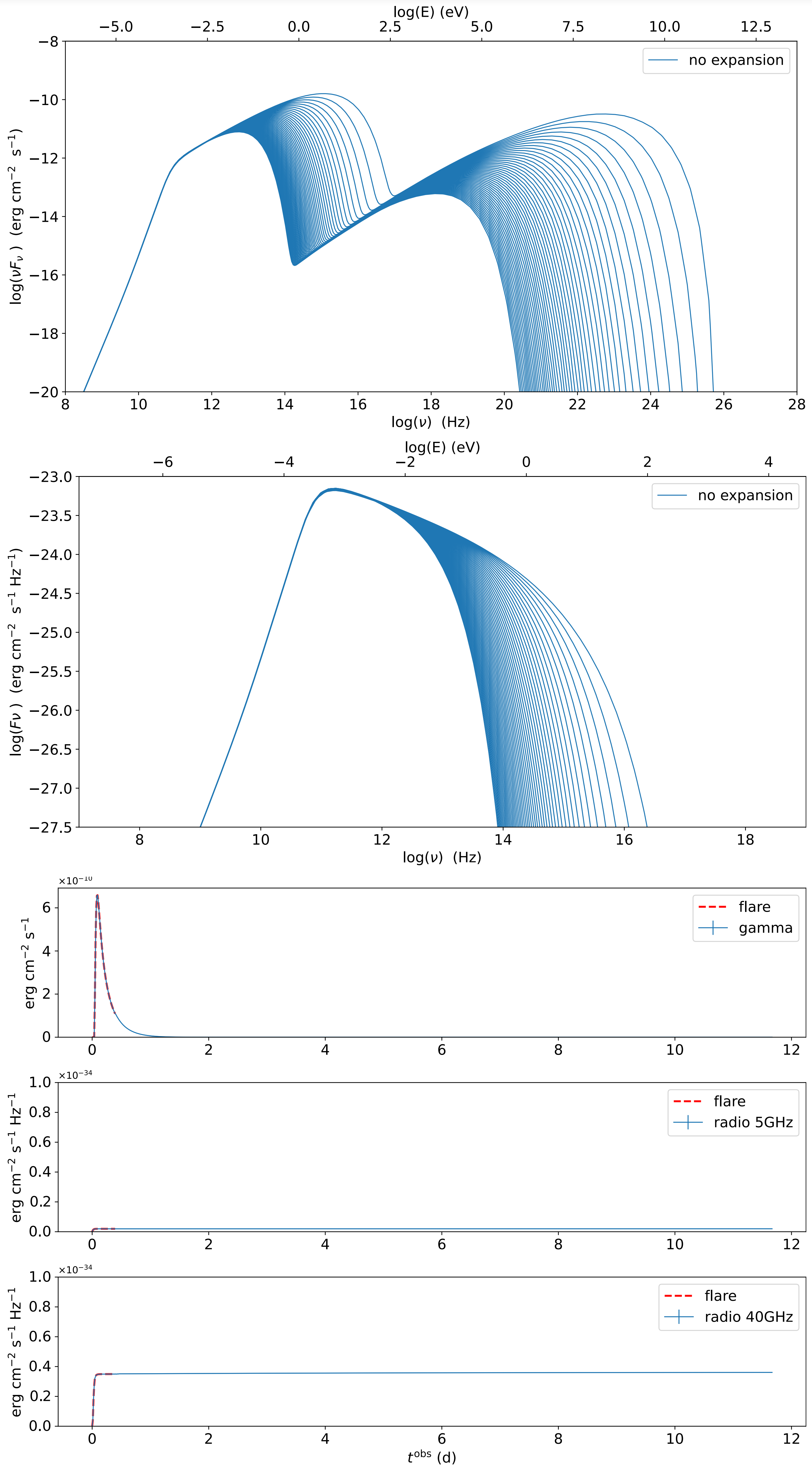
JetSeT Expansion vs no Expansion





The impact of the expansion on the Compton Dominance is significant and might be tested if the expansion begins already at the flaring stage

In agreement with MAGIC 2021 paper on Mrk 421 2017 obs



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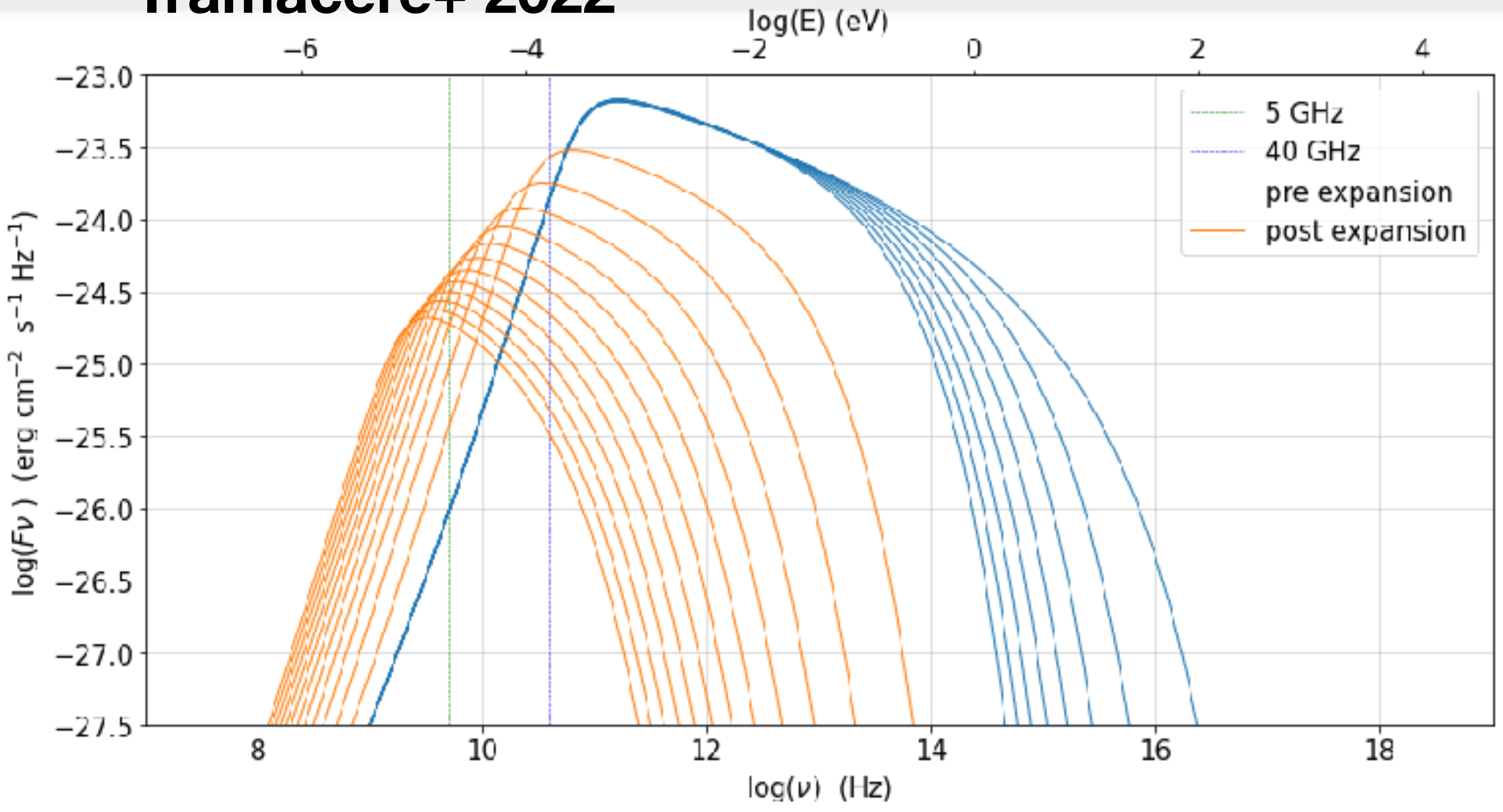
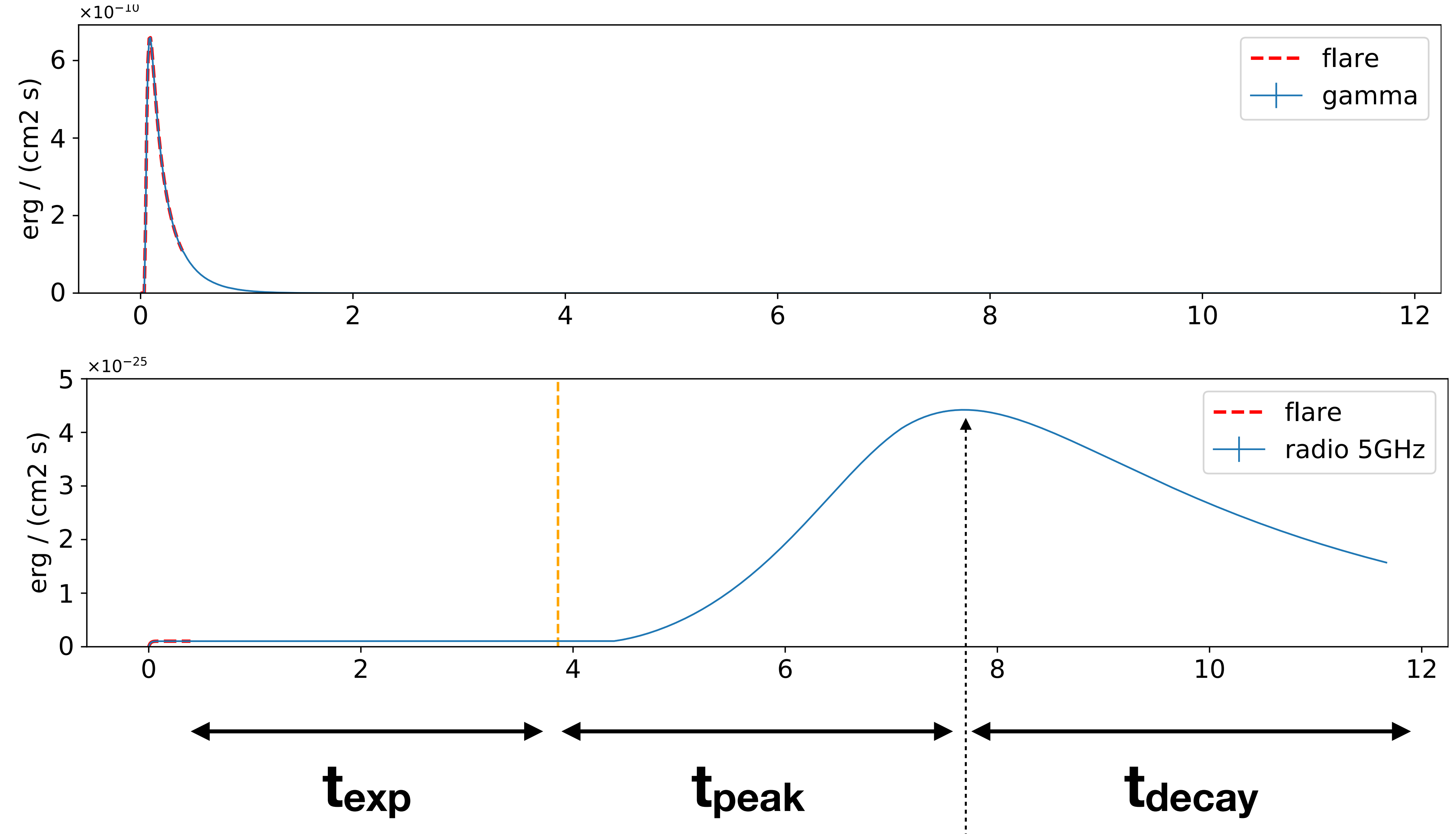
deriving phenomenological trends

synch self. abs

Tramacere+ 2022

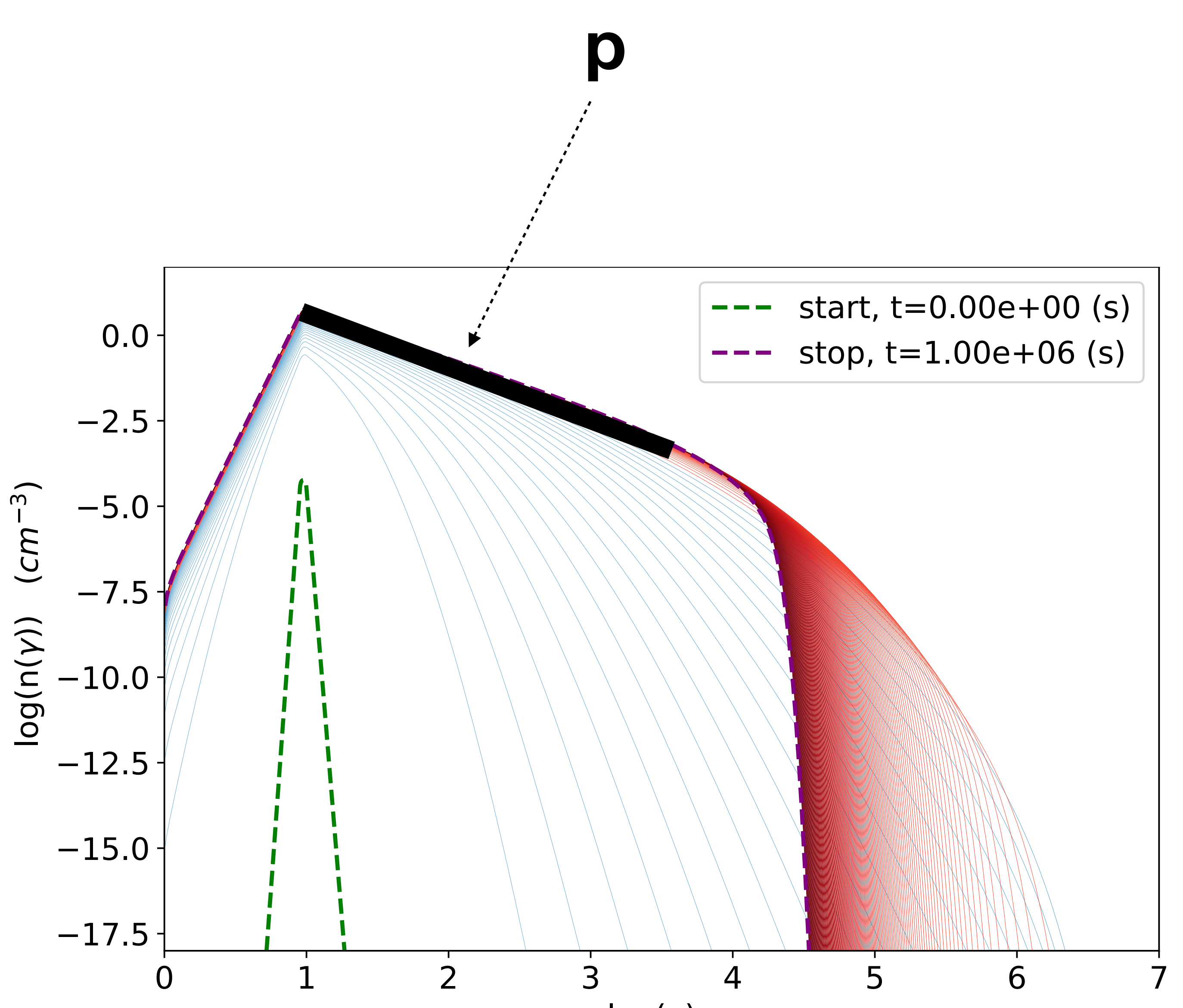




src transp
at ν^*_{SSA}
R=R*

Rybicki&Lightman (1985) standard synchrotron theory

$$\nu_{SSA}(t) = \nu_L(t)\left[\frac{\pi\sqrt{\pi}}{4}\frac{eR(t)N(t)}{B(t)}f_k(p)\right]^{\frac{2}{p+4}}$$



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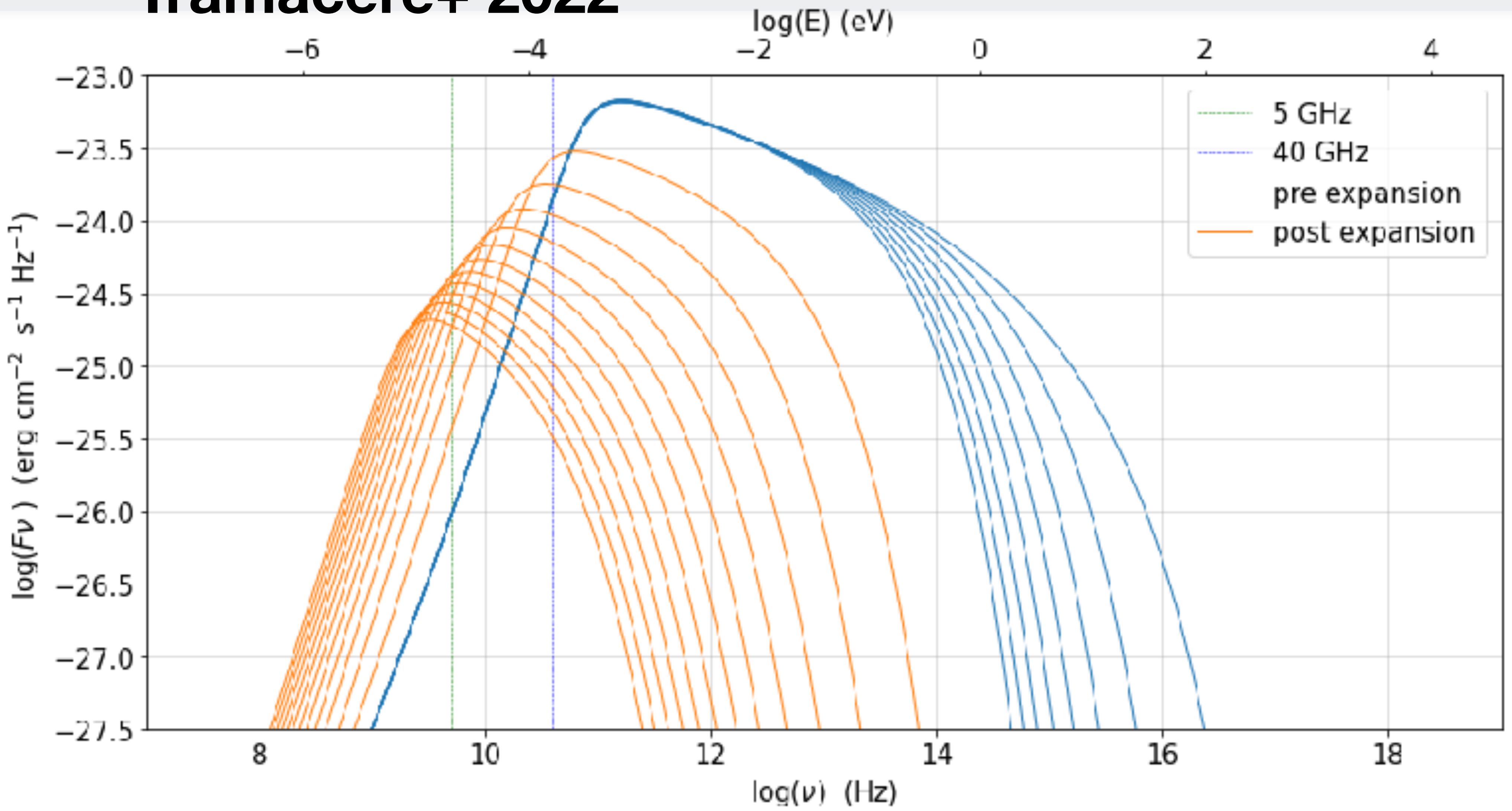
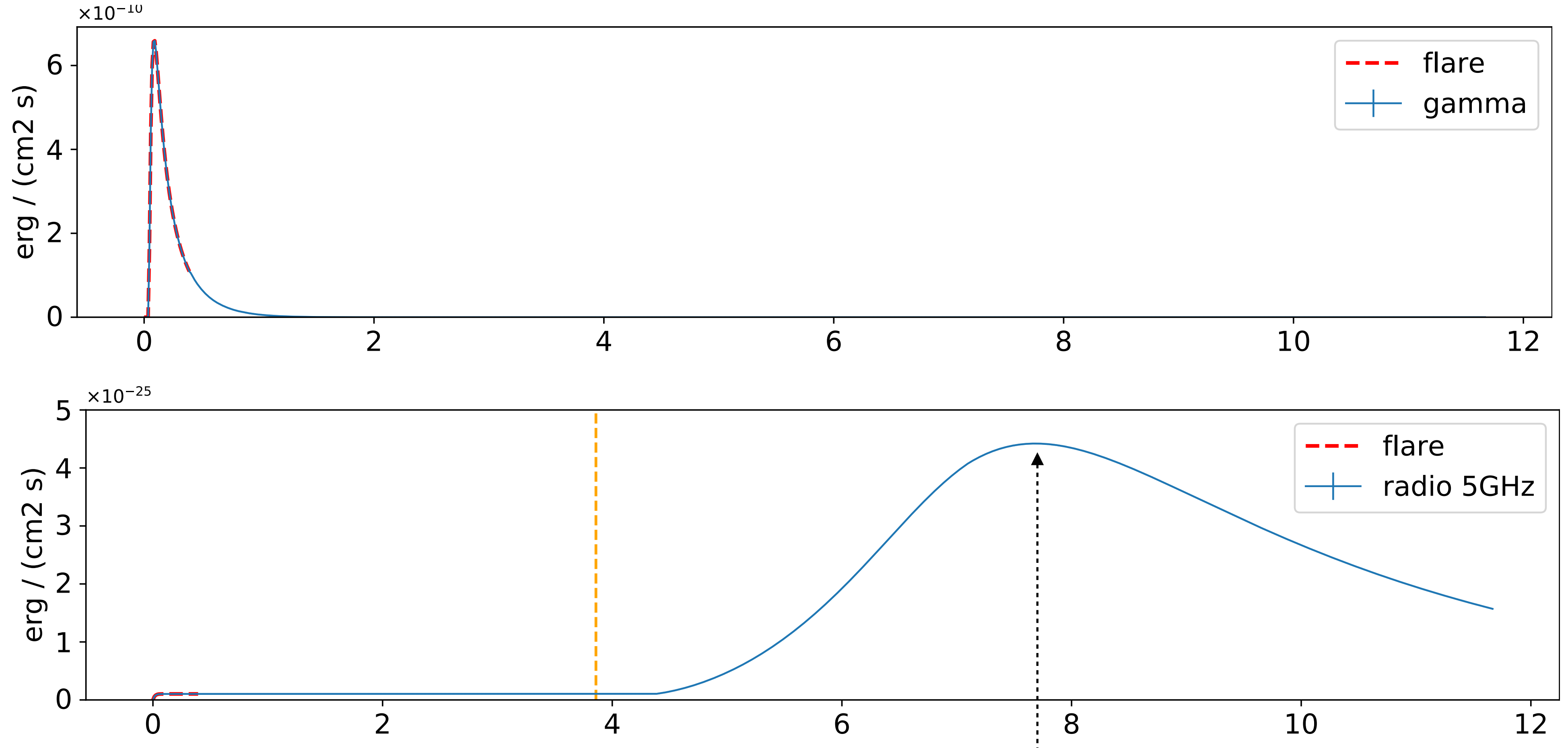


$$R(t) = R_0 + \beta_{\rm exp} c(t - t_{exp})H(t - t_{exp})$$

$$\nu_{\rm SSA}(t) = \nu_L(t)\Big[\frac{\pi\sqrt{\pi}}{4}\frac{eR(t)N(t)}{B(t)} f_k(p)\Big]^{\frac{2}{p+4}}$$

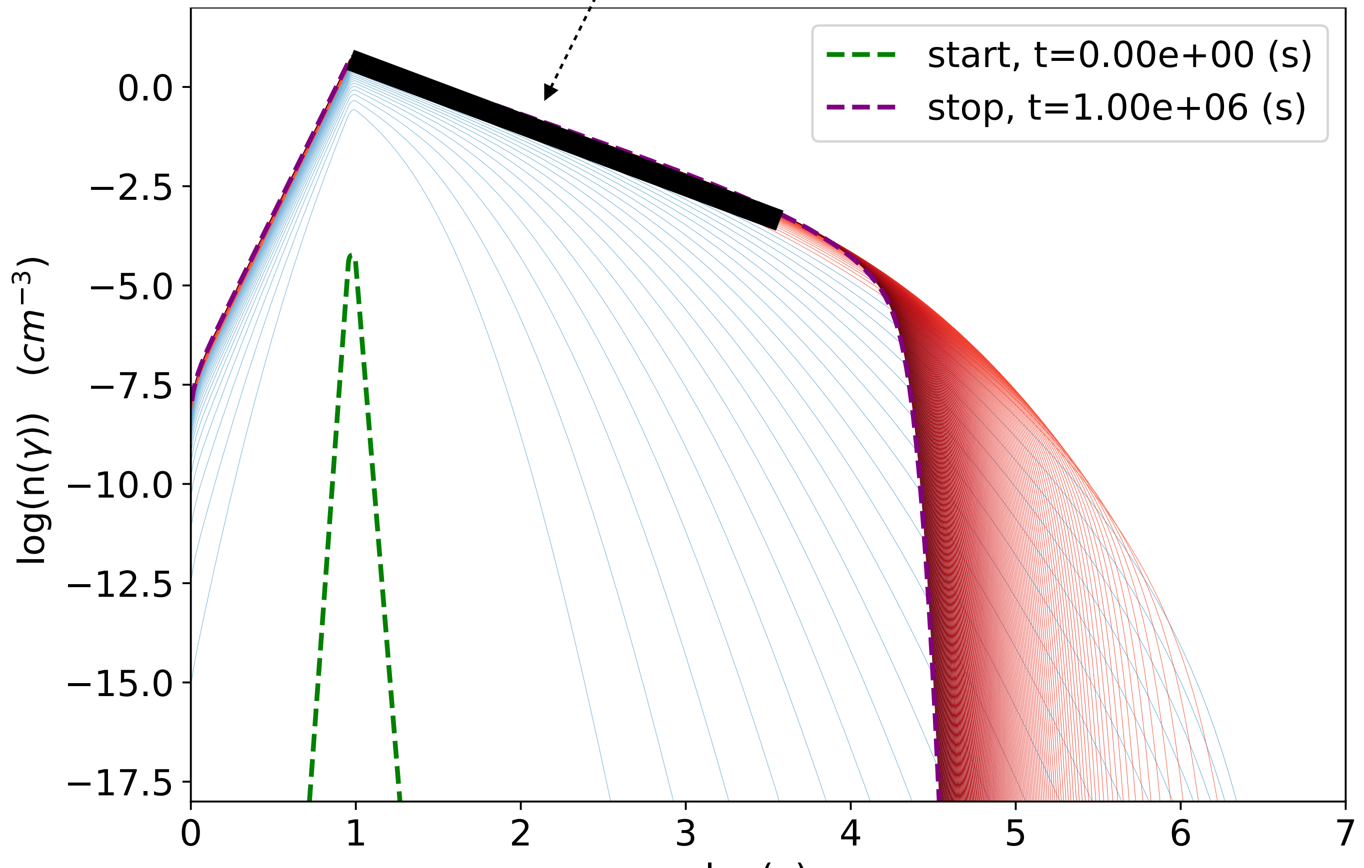
$$B(t) = B_0(\frac{R_0}{R(t)})^{m_B}$$



$t_{\rm exp}$ $t_{\rm peak}$ $t_{\rm decay}$

src transp
at $\nu^*_{\rm SSA}$
R=R*

p



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synch self. abs

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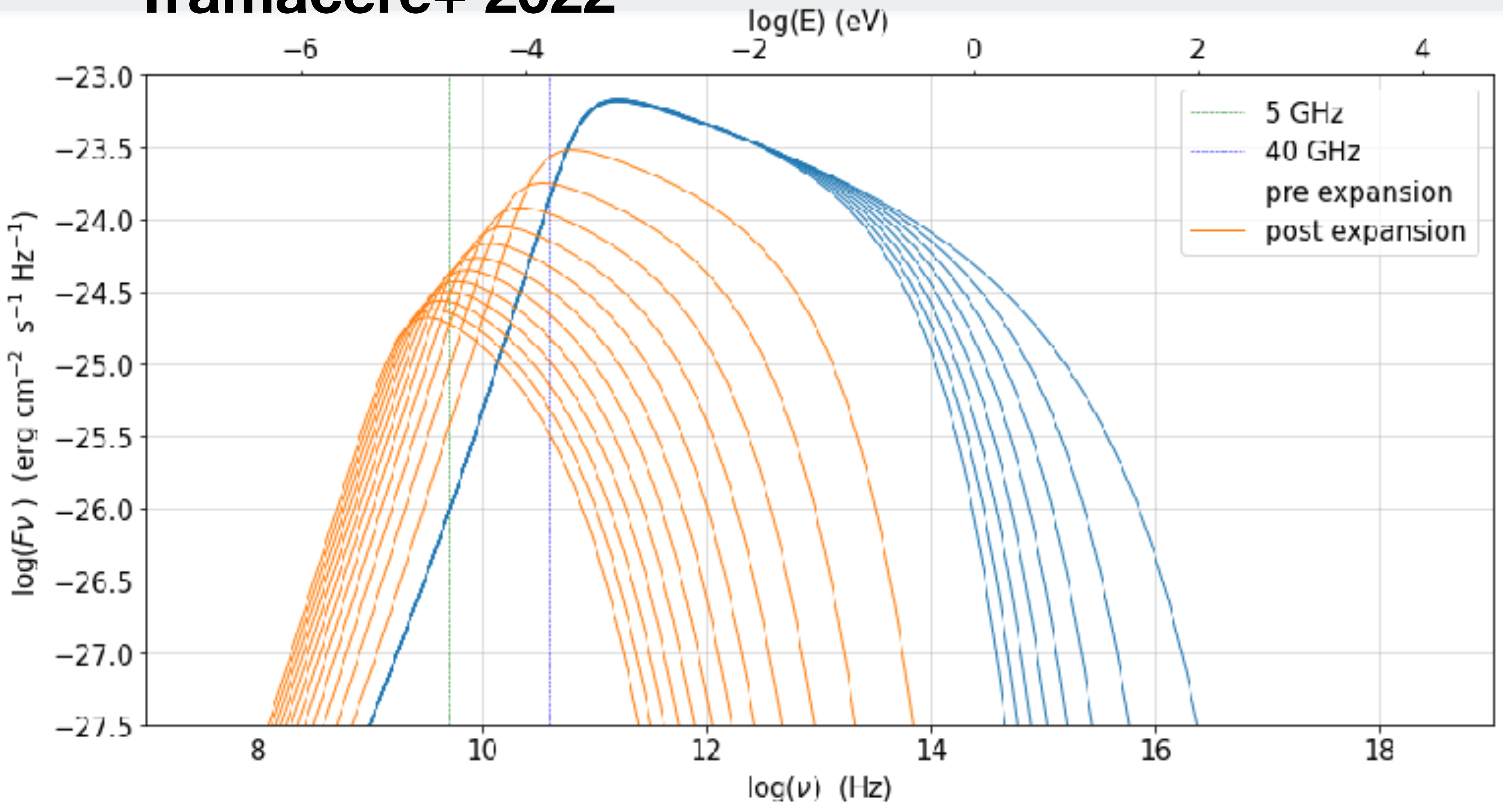
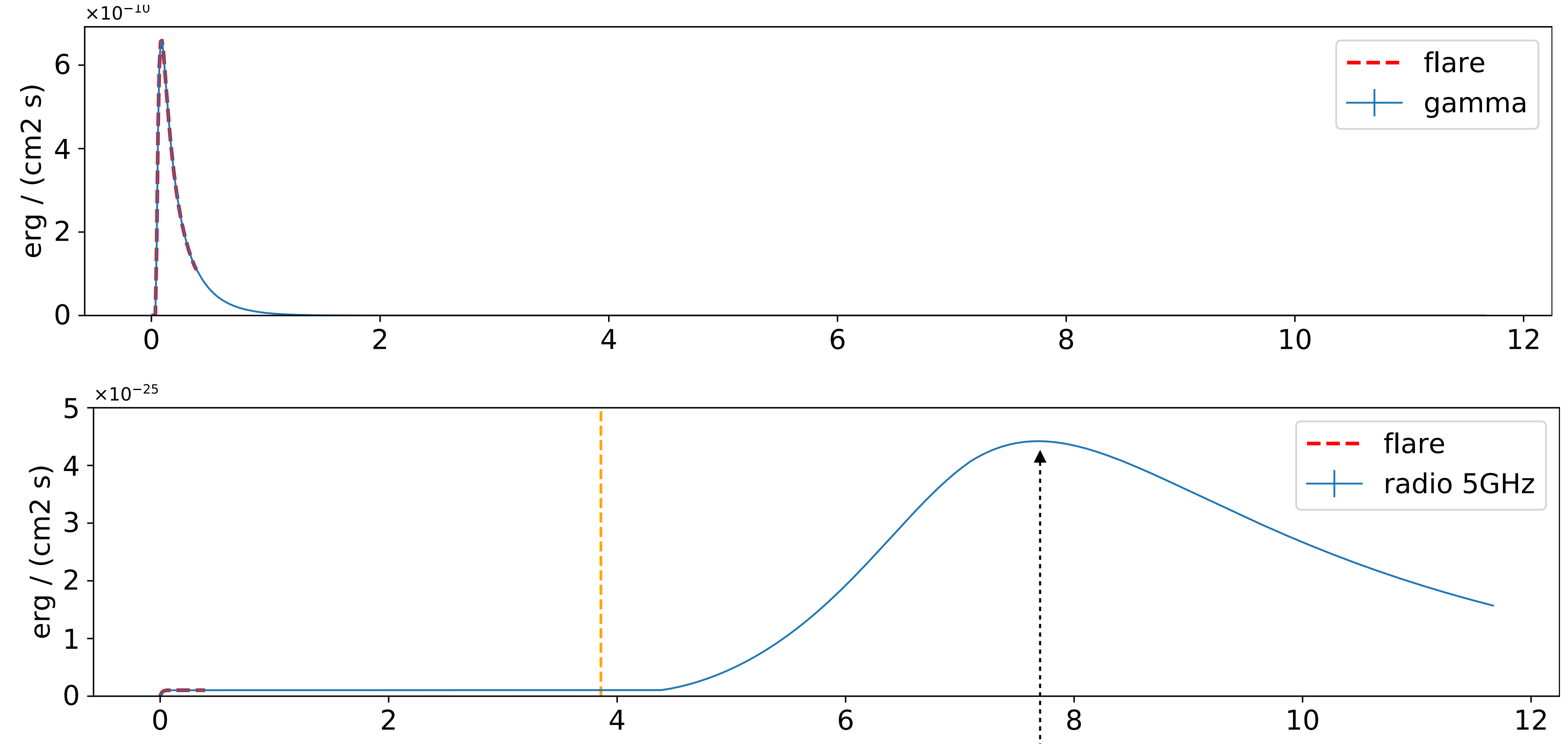


$$R(t) = R_0 + \beta_{\exp} c(t - t_{exp}) H(t - t_{exp})$$

$$\nu_{\rm SSA}(t) = \nu_L(t)\left[\frac{\pi\sqrt{\pi}}{4}\frac{eR(t)N(t)}{B(t)} f_k(p)\right]^{\frac{2}{p+4}}$$

$$B(t) = B_0\left(\frac{R_0}{R(t)}\right)^{m_B}$$

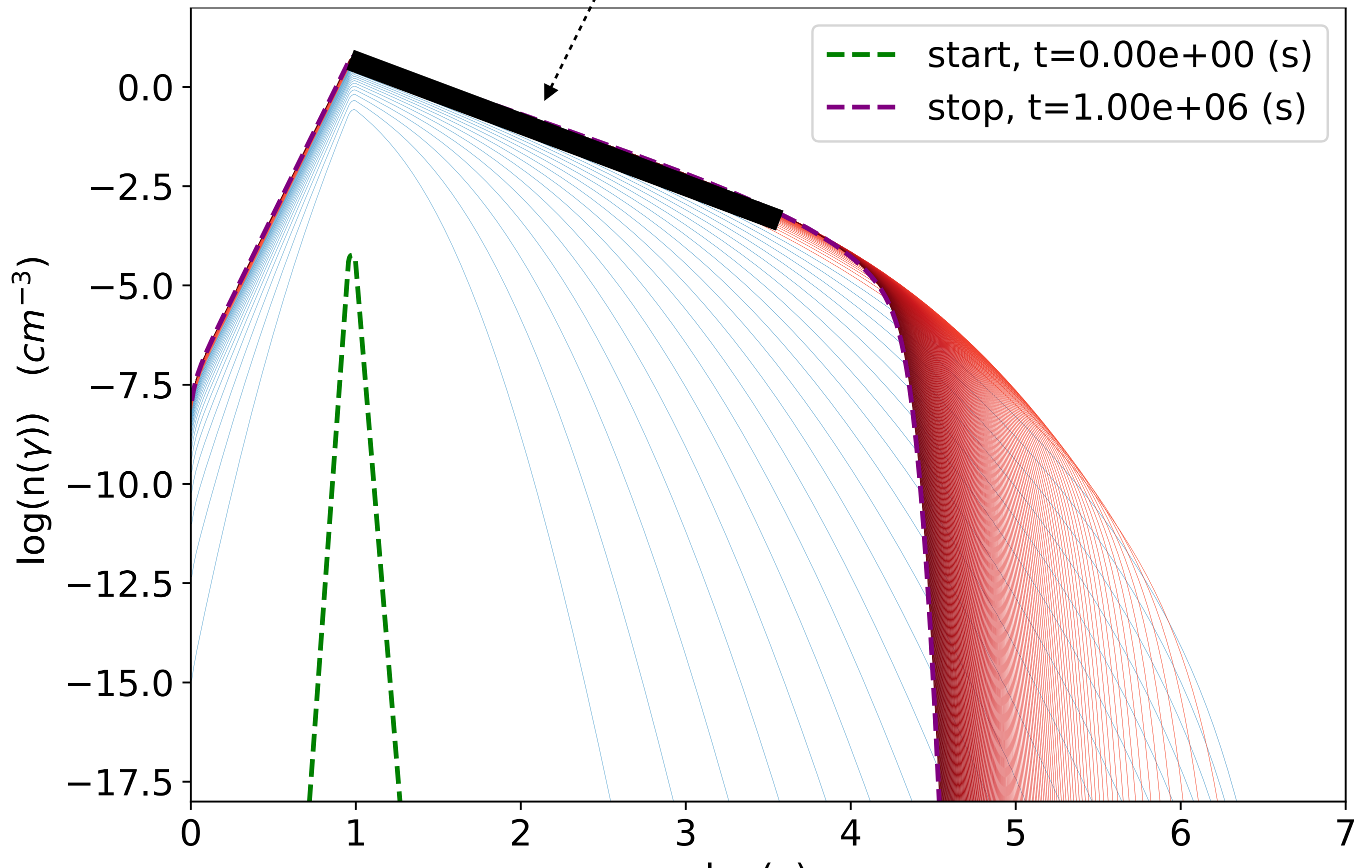
$$\frac{\nu^*_{\rm SSA}}{\nu^0_{\rm SSA}} = \left[\left(\frac{B^*}{B_0}\right)^{\frac{p+2}{2}}\left(\frac{R_0}{R^*}\right)^2\right]^{\frac{2}{p+4}} = \left[\frac{R_0}{R^*}\right]^{\frac{m_B(p+2)+4}{p+4}}$$



t_{exp} t_{peak} t_{decay}

src transp
at ν^*_{SSA}
R=R*

p



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synch self. abs

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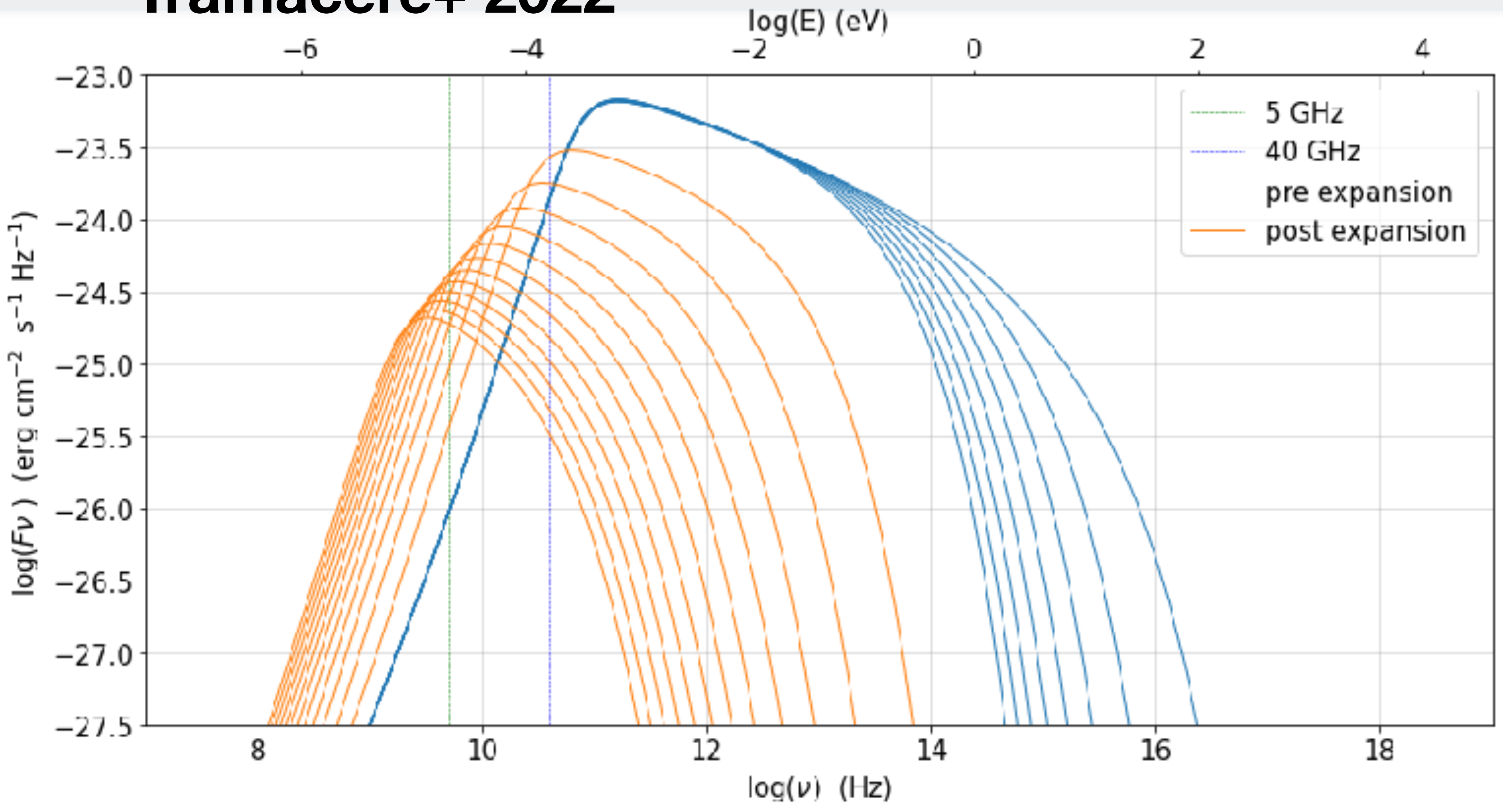
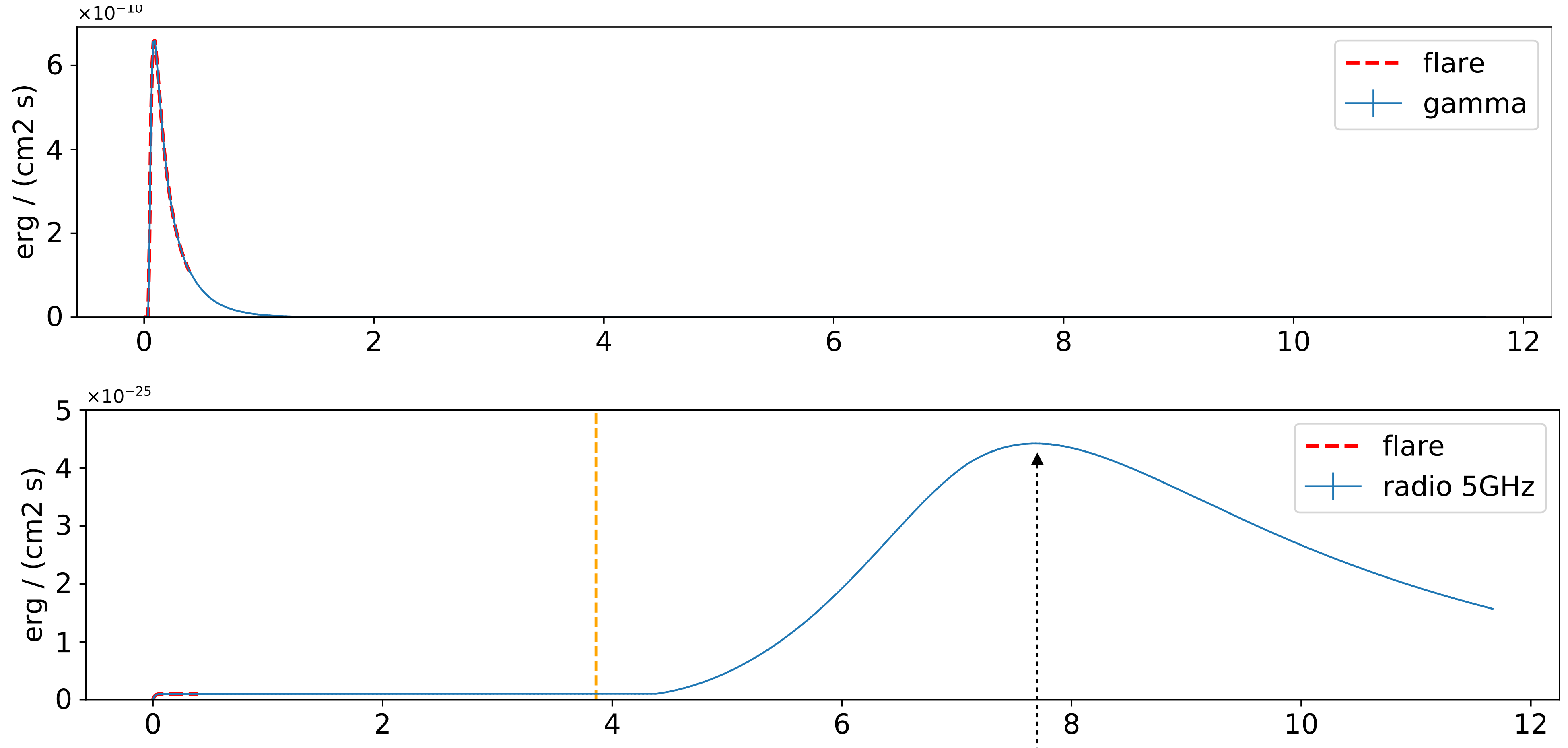




t_{exp} t_{peak} t_{decay}

src transp

at ν^*_{SSA}

$R=R^*$

$$R(t) = R_0 + \beta_{\exp} c(t - t_{exp}) H(t - t_{exp})$$

$$\nu_{\rm SSA}(t) = \nu_L(t)\left[\frac{\pi\sqrt{\pi}}{4}\frac{eR(t)N(t)}{B(t)} f_k(p)\right]^{\frac{2}{p+4}}$$

$$B(t) = B_0\left(\frac{R_0}{R(t)}\right)^{m_B}$$

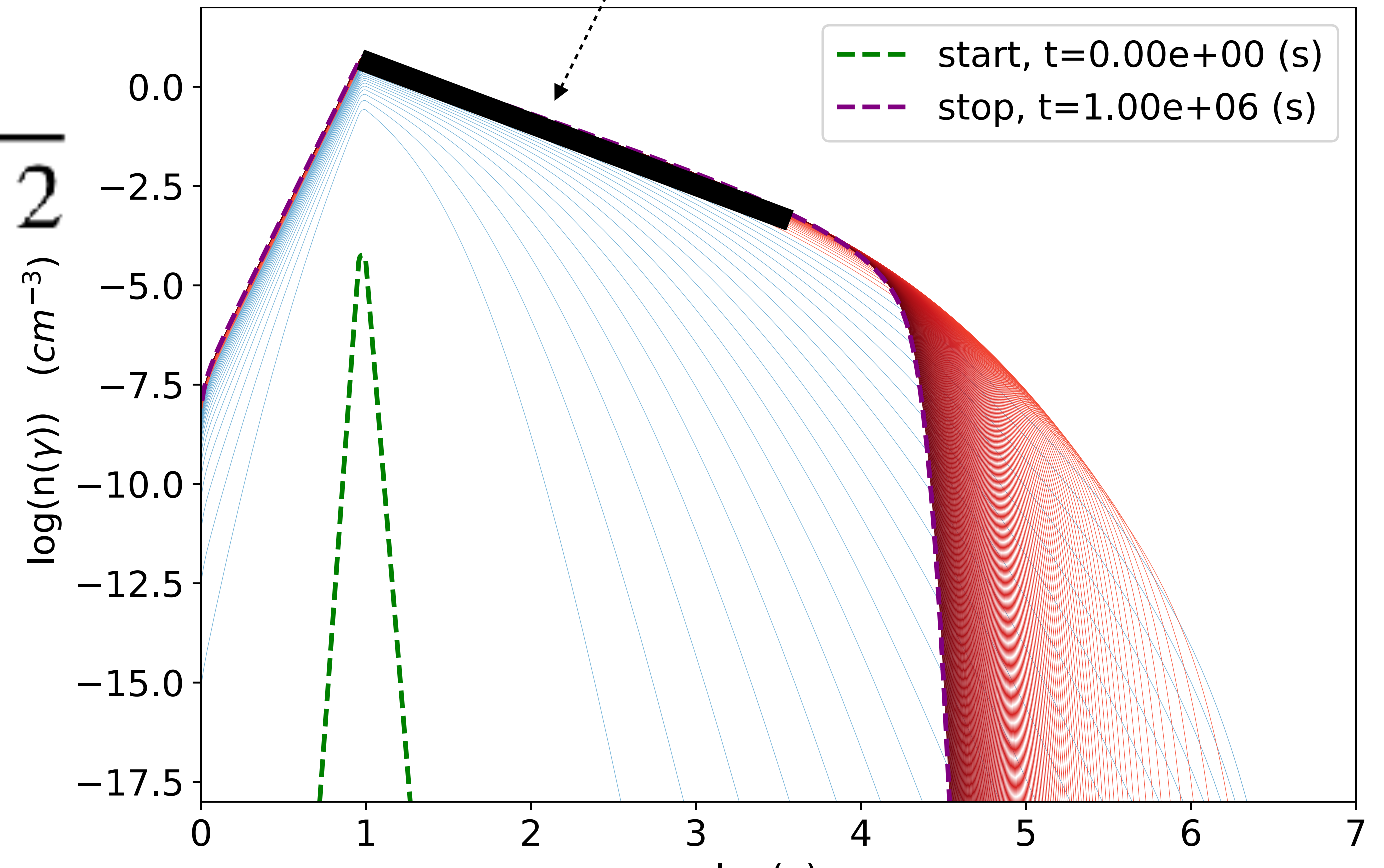
$$\frac{\nu^*_{\rm SSA}}{\nu^0_{\rm SSA}} = \left[\left(\frac{B^*}{B_0}\right)^{\frac{p+2}{2}}\left(\frac{R_0}{R^*}\right)^2\right]^{\frac{2}{p+4}} = \left[\frac{R_0}{R^*}\right]^{\frac{m_B(p+2)+4}{p+4}}$$

invert

$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

$$\psi = \frac{p+4}{m_B(p+2)-2}$$

p



breaking down the process

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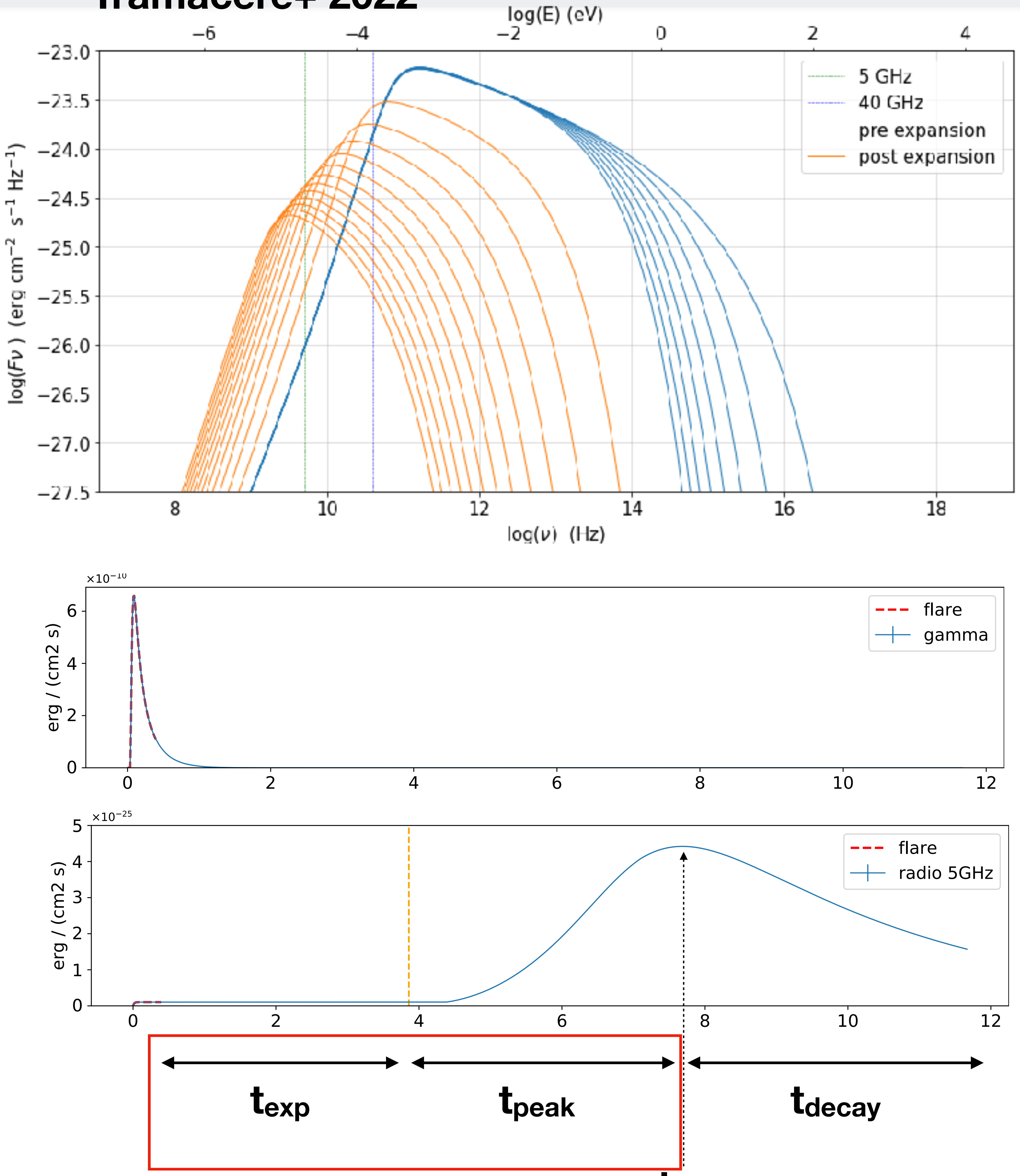
Tramacere+ 2022



src transp

at ν^*_{SSA}

R=R*

$$\Delta t_{\nu^0_{\rm SSA}\rightarrow\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak}$$

$$R^* = R_0\Big(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\Big)^{\psi}$$

$$\psi = \frac{p+4}{m_B(p+2)-2}$$

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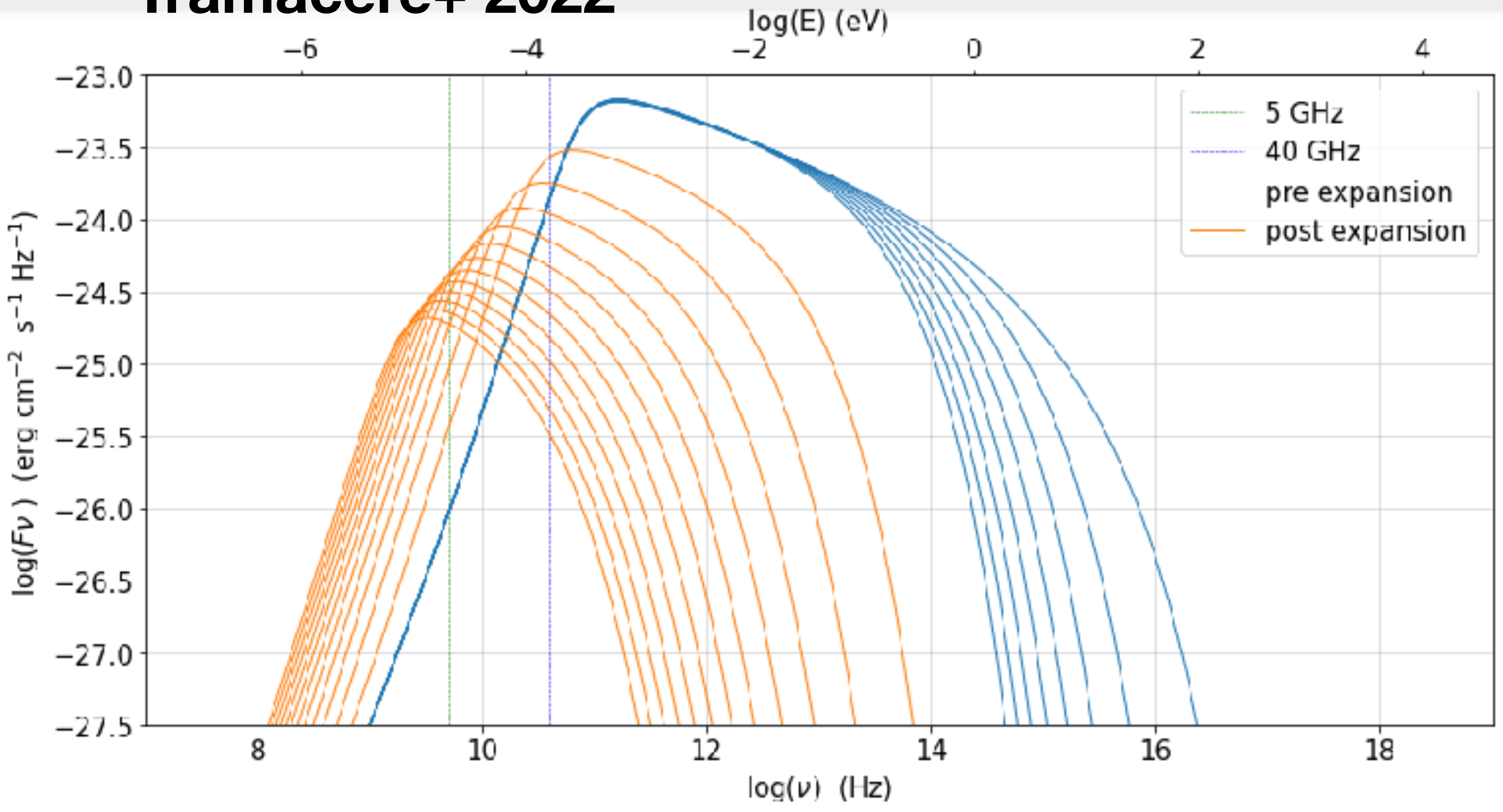
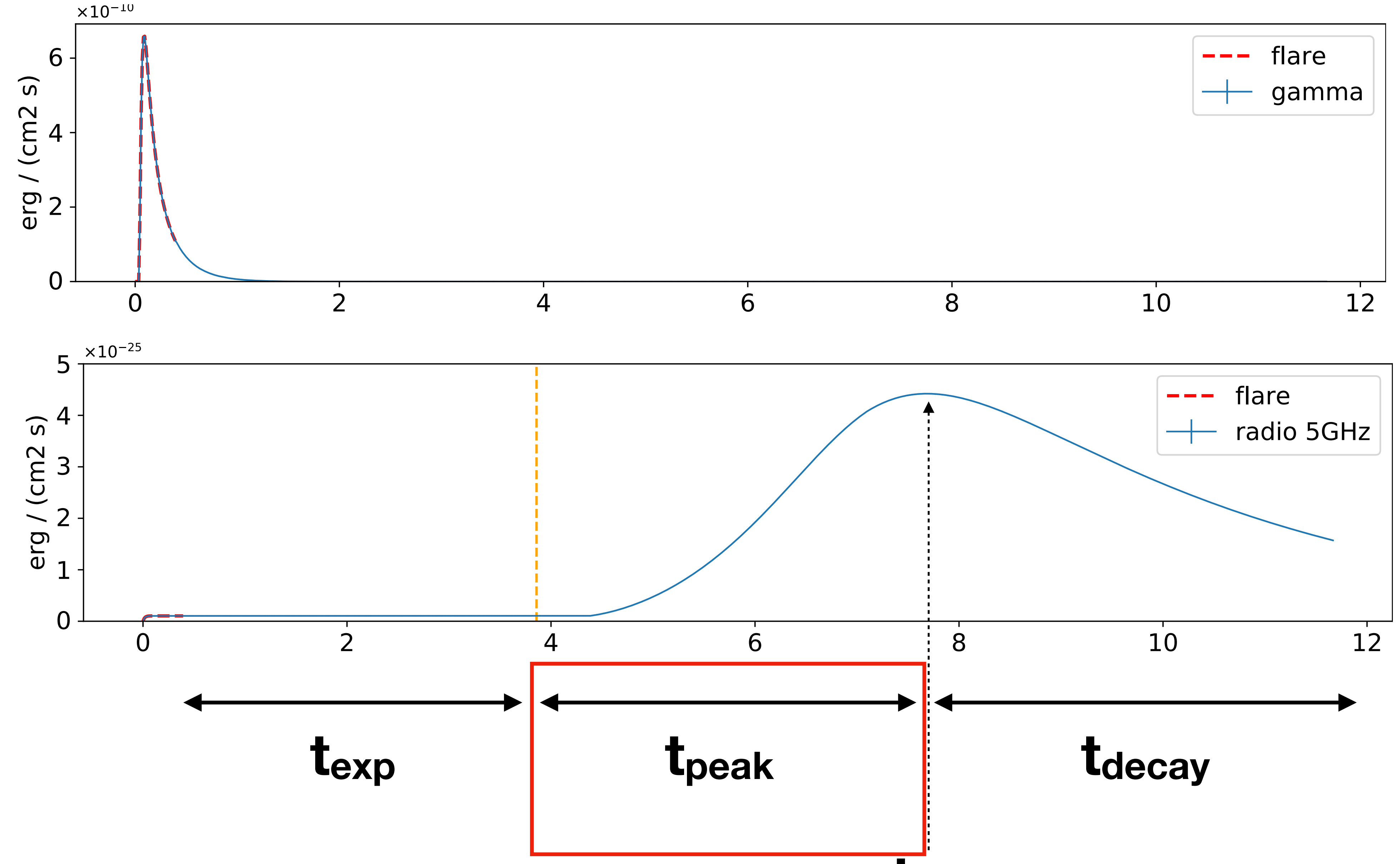
breaking down the process

Tramacere+ 2022





src transp at ν^*_{SSA}
R=R*

$$\Delta t_{\nu^0_{\rm SSA}\to\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak}$$

$$t_{\rm peak} = \Delta t_{R_0\to R^*} = \frac{R^* - R_0}{\beta_{\rm exp} c} = \frac{R_0}{\beta_{\rm exp} c}\left[\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi} - 1\right]$$

$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

$$\psi = \frac{p+4}{m_B(p+2)-2}$$

breaking down the process

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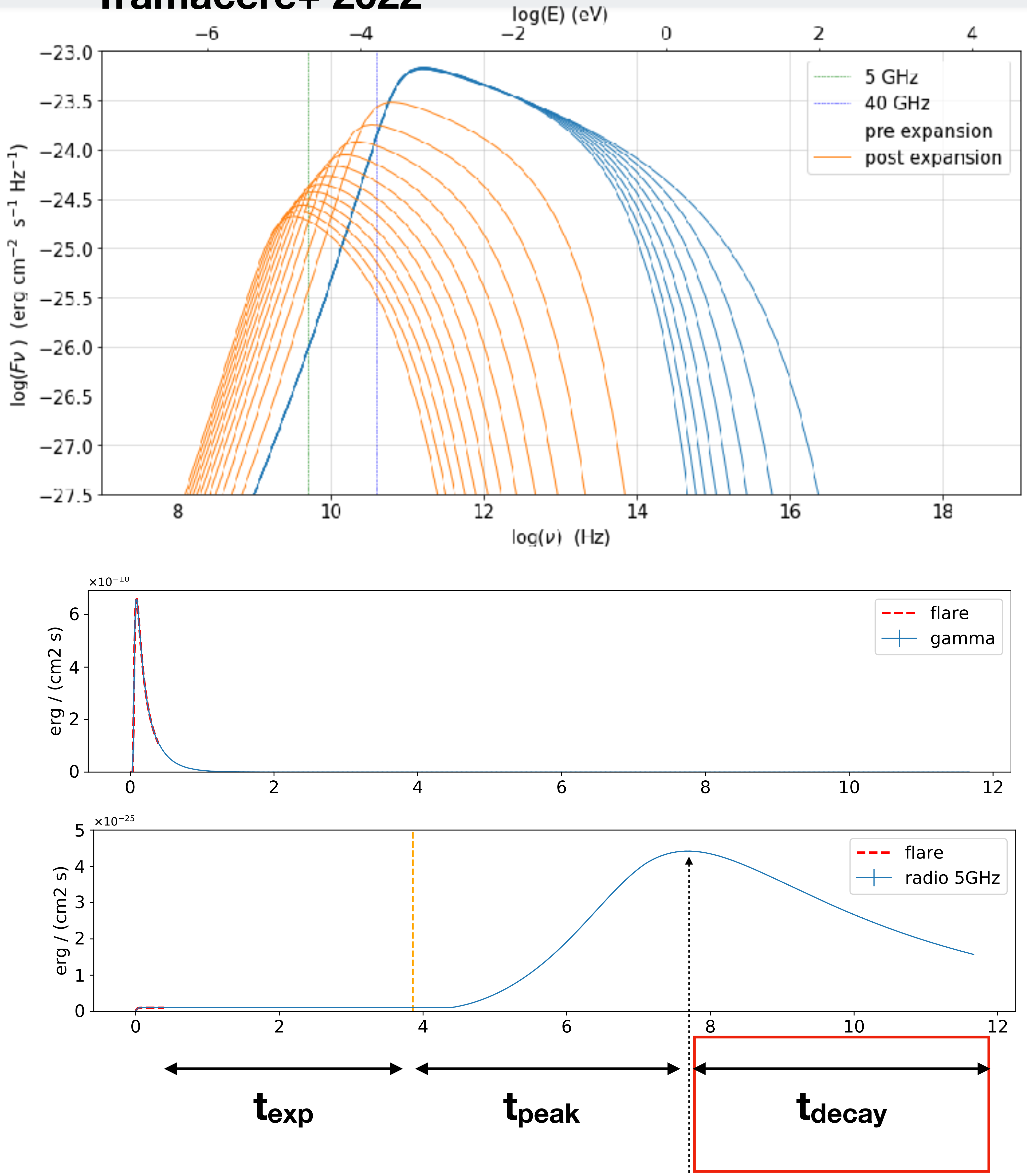


$$\Delta t_{\nu^0_{\rm SSA}\rightarrow\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak}$$

$$t_{\rm peak} = \Delta t_{R_0\rightarrow R^*} = \frac{R^* - R_0}{\beta_{\rm exp}c} = \frac{R_0}{\beta_{\rm exp}c}\left[\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi} - 1\right]$$

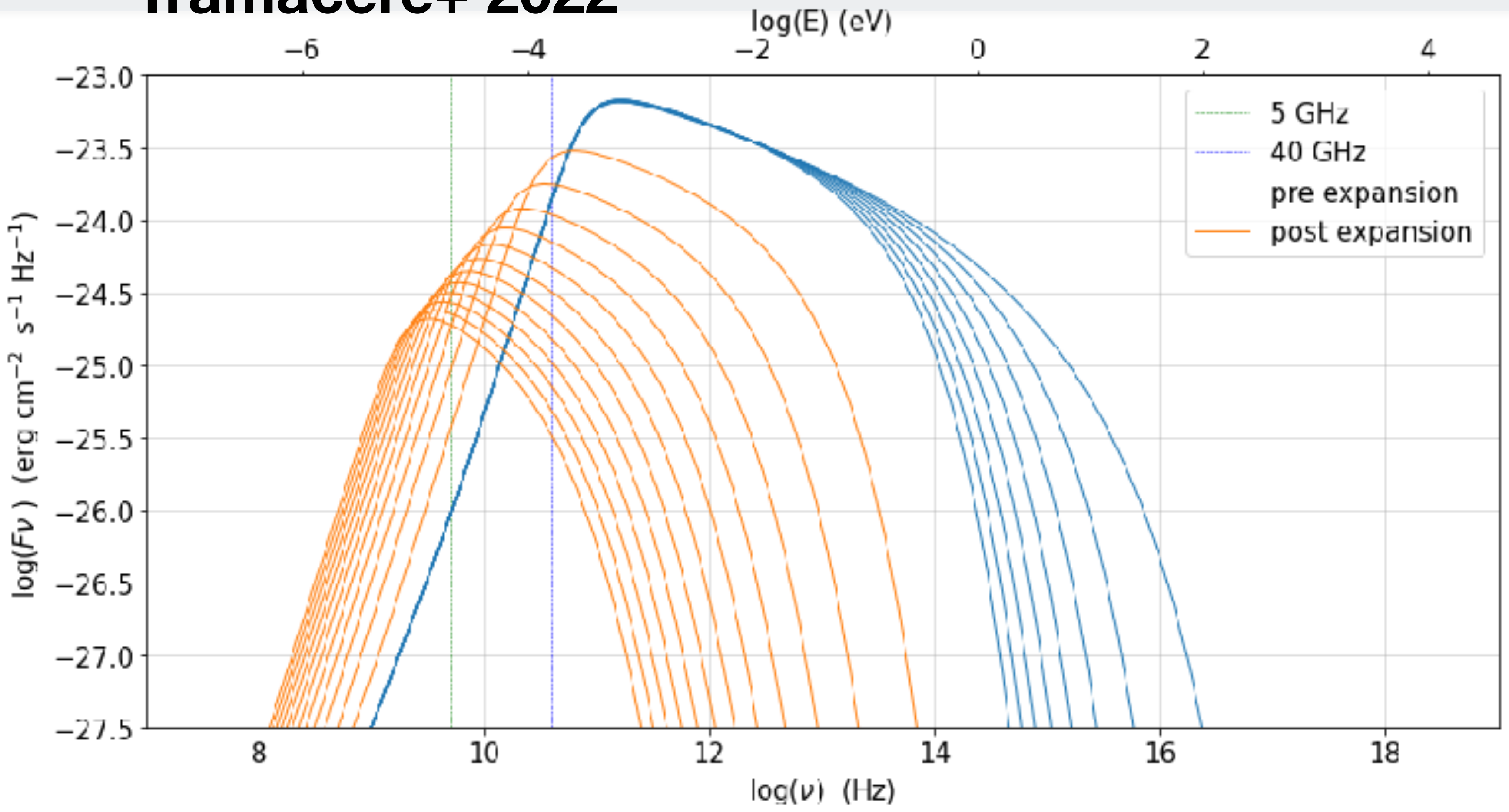
$$t_{decay} \dashrightarrow t^{ad}_{\rm decay}(t^*) \propto \frac{R^*}{\beta_{\rm exp}c} = \frac{R_0}{\beta_{\rm exp}c}\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi}$$

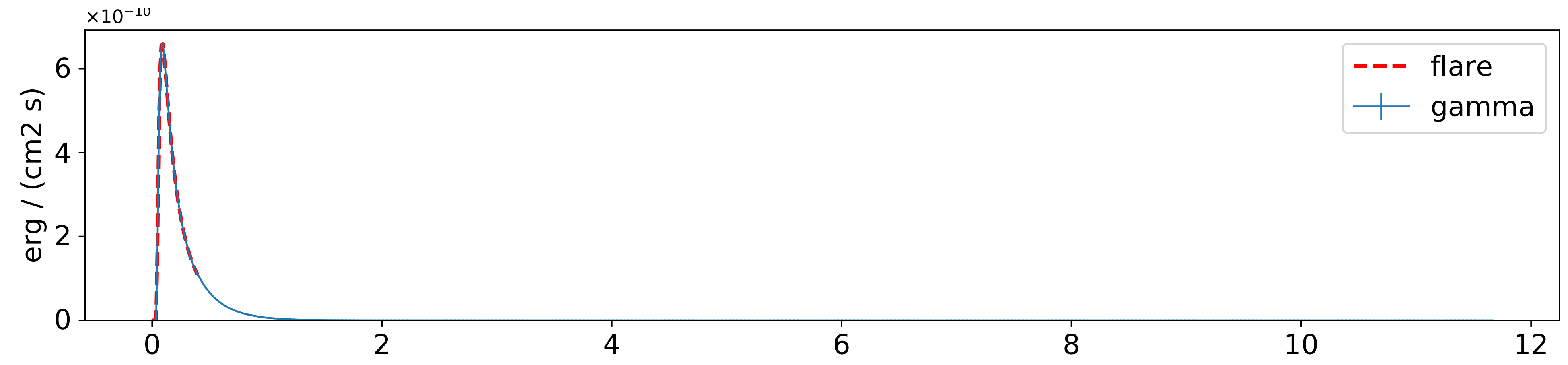
$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

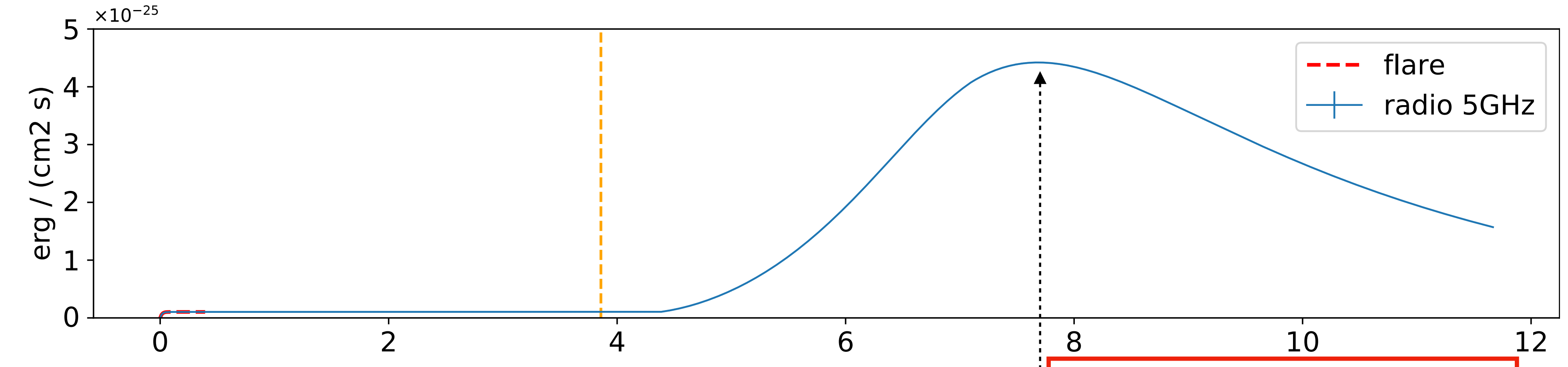
$$\psi = \frac{p+4}{m_B(p+2)-2}$$

breaking down the process

Tramacere+ 2022







t_{exp} t_{peak} t_{decay}

src transp at ν^*_{SSA}

$R=R^*$

$$\Delta t_{\nu^0_{\rm SSA}\rightarrow\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak}$$

$$t_{\rm peak} = \Delta t_{R_0\rightarrow R^*} = \frac{R^* - R_0}{\beta_{\rm exp} c} = \frac{R_0}{\beta_{\rm exp} c}\left[\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi} - 1\right]$$

t_{decay} →

$$t^{ad}_{\rm decay}(t^*) \propto \frac{R^*}{\beta_{\rm exp} c} = \frac{R_0}{\beta_{\rm exp} c}\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi}$$

radiative

$$t^{geom}_{\rm decay}(t^*) \propto \frac{F_{\nu_{\rm SSA}}(t^*)}{\dot{F}_{\nu_{\rm SSA}}(t^*)} \propto \frac{R^*}{m_B \beta_{\rm exp} c} = \frac{t^{ad}_{\rm decay}(t^*)}{m_B}$$

$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

$$\psi = \frac{p+4}{m_B(p+2)-2}$$

trends in the obs. frame

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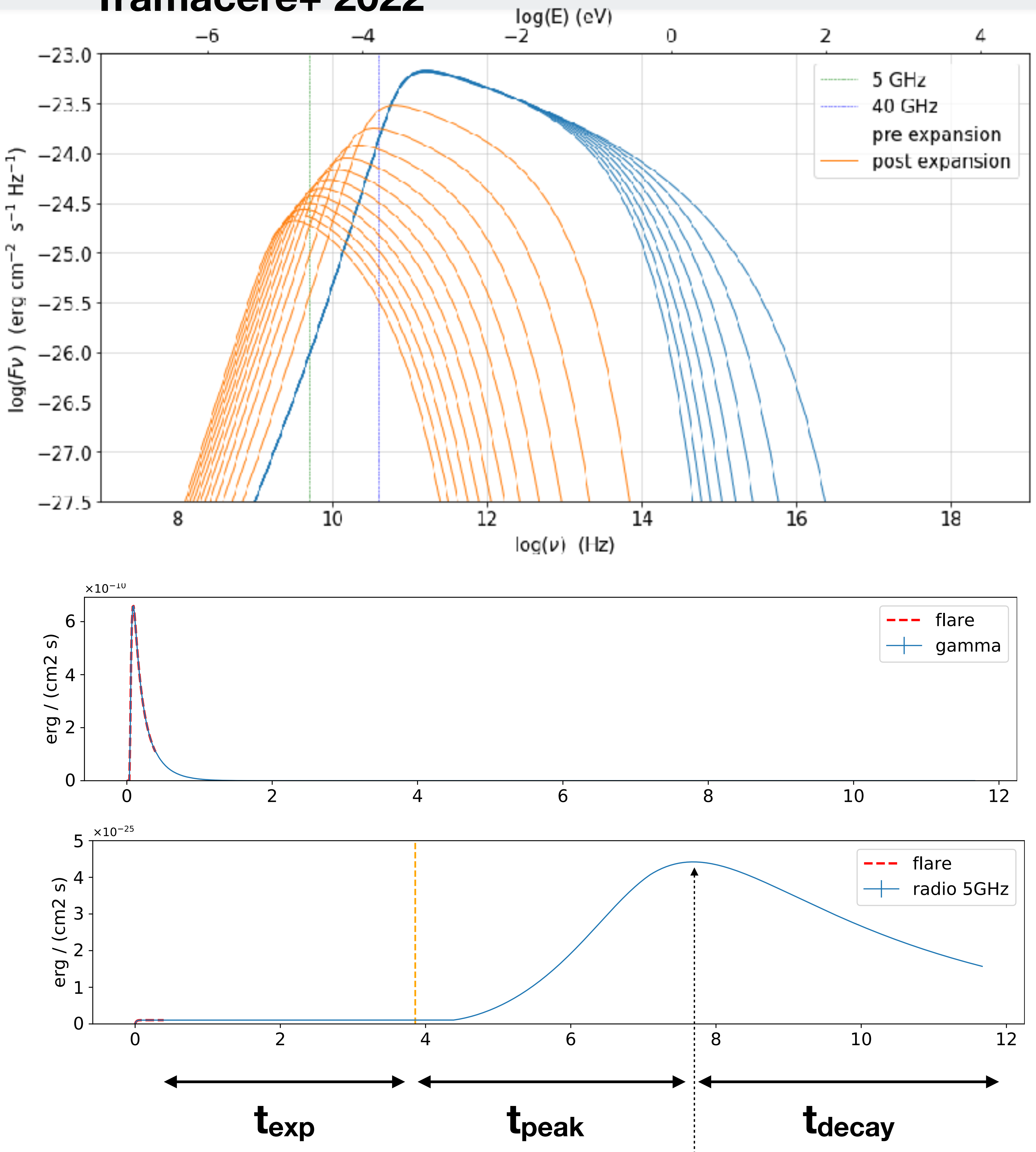

src transp at ν^*_{SSA}

R=R*

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$$\Delta t_{\nu^0_{\rm SSA}\rightarrow\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{t^{\rm obs}_{var}}{\beta_{\rm exp}}\Big[\Big(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\Big)^{\psi} - 1\Big]$$

$$t^{\rm obs}_{\rm peak} = \frac{t^{\rm obs}_{var}}{\beta_{\rm exp}}\Big[\Big(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\Big)^{\psi} - 1\Big]$$

$$t^{\rm obs}_{\rm decay} = \frac{t^{\rm obs}_{var}}{m_B\beta_{\rm exp}}\Big(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\Big)^{\psi},$$

$$\delta = \frac{1}{\Gamma(1-\beta_\Gamma\cos(\theta))}$$

$$\nu^{\rm obs} = \nu\frac{\delta}{z+1}$$

$$t^{\rm obs}_{var} = \frac{(1+z)R_0}{\delta c}$$

$$R^0_{\rm obs} = R_0\frac{1+z}{\delta}$$

$$R^* = R_0\Big(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\Big)^{\psi}$$

$$\psi = \frac{p+4}{m_B(p+2)-2}$$

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trends vs ν^*SSA.   trends vs β_{exp}

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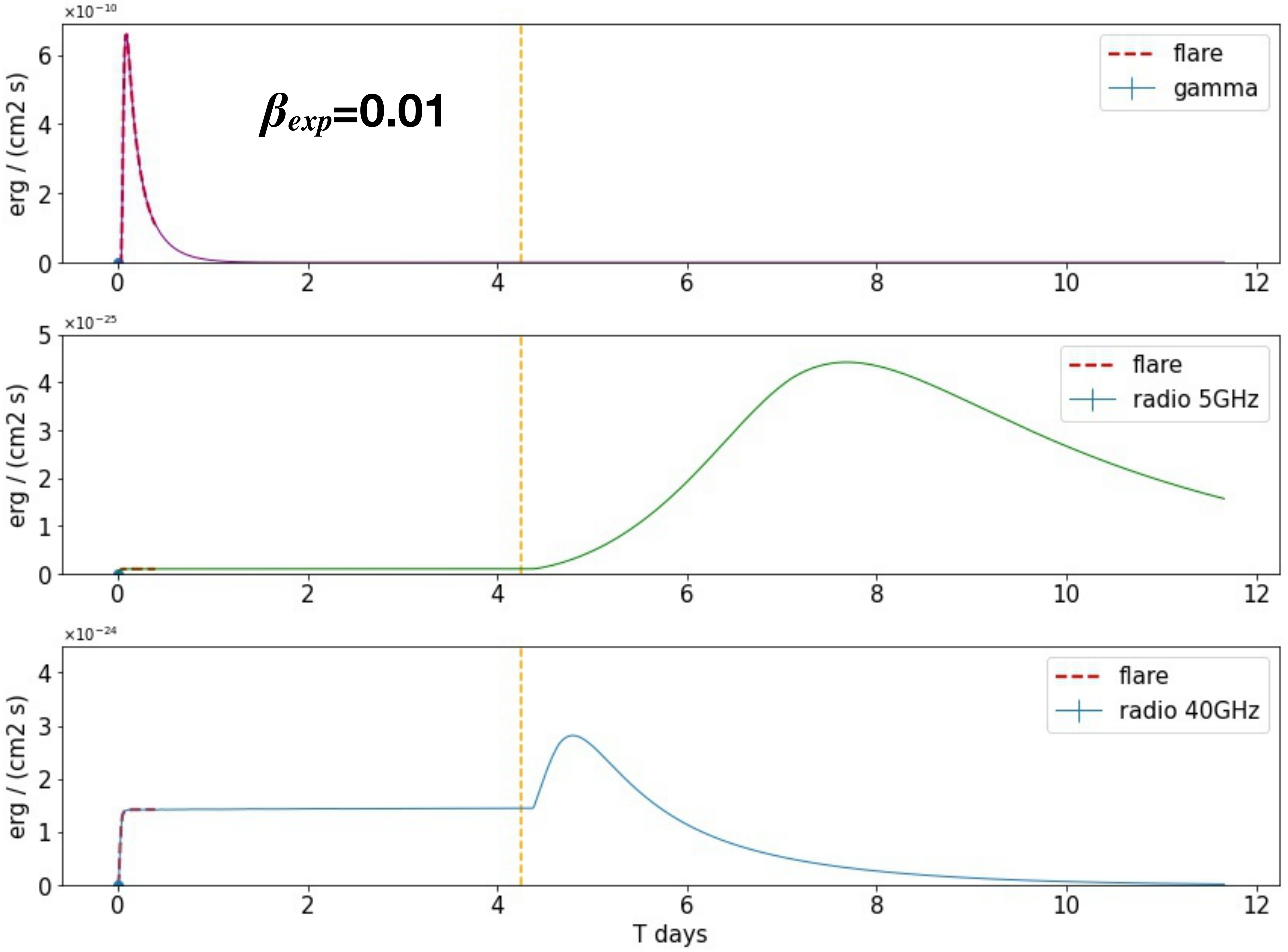
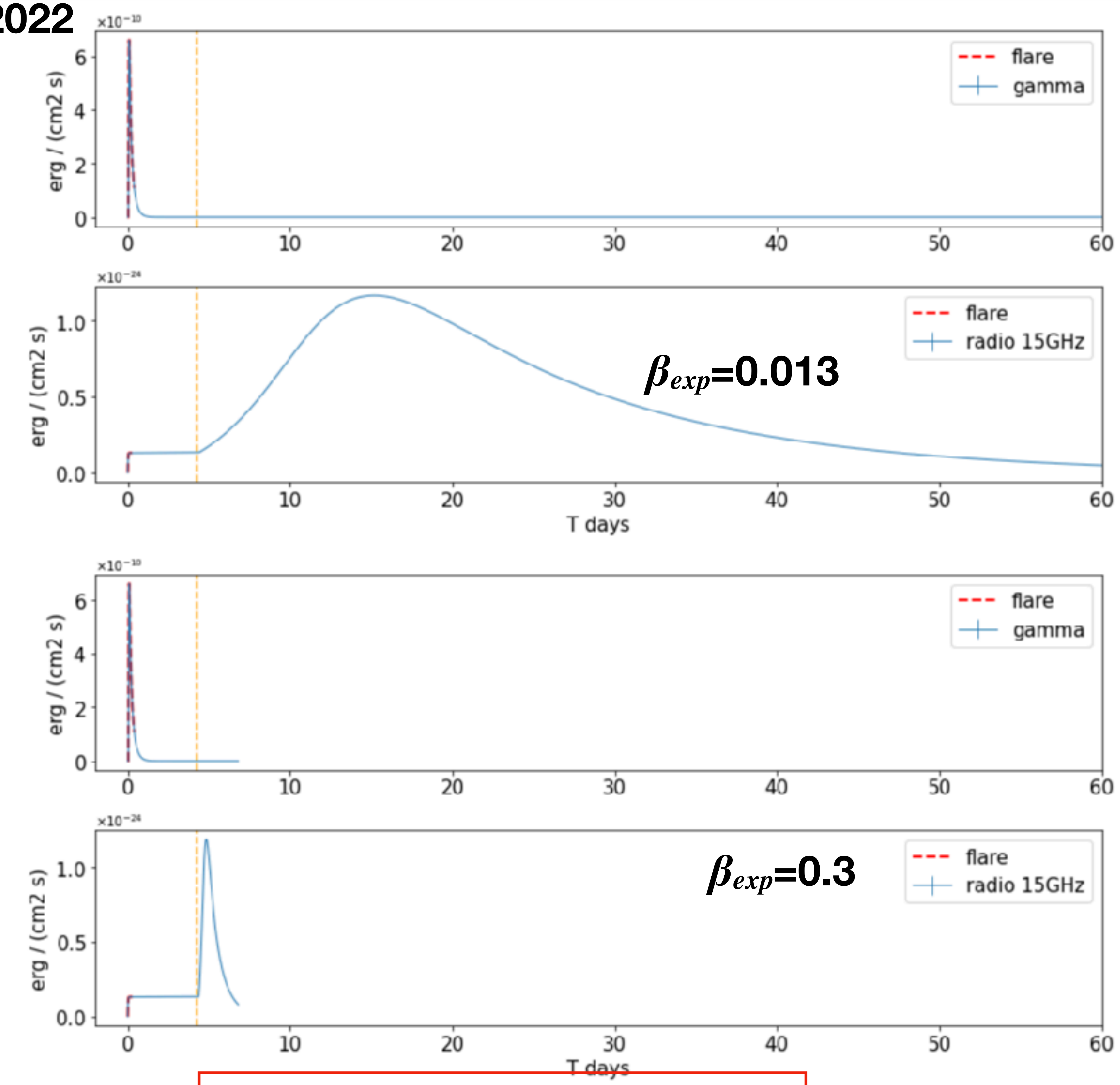




$t_r \sim \nu^0_{SSA}/\nu^*_{SSA}$

$t_d \sim \nu^0_{SSA}/\nu^*_{SSA}$

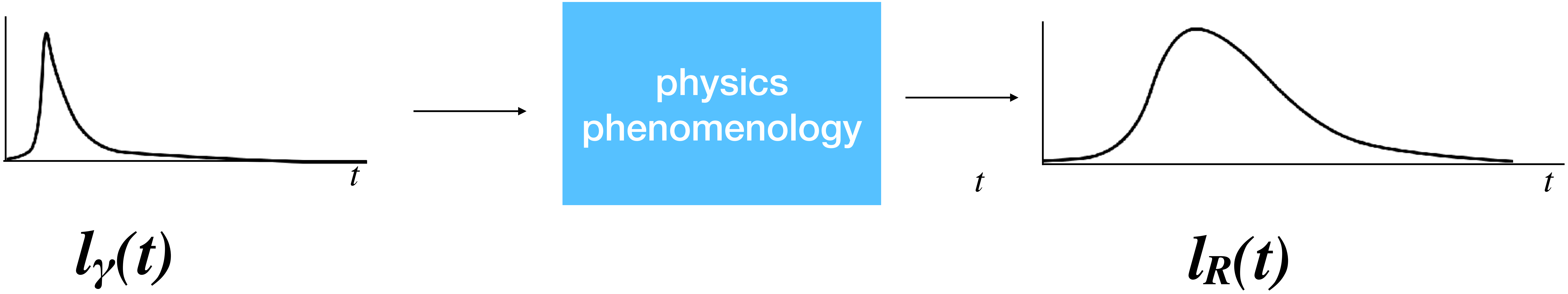
$\Delta t \sim t_{exp} + t_r$

$t_r \sim 1/\beta_{exp}$

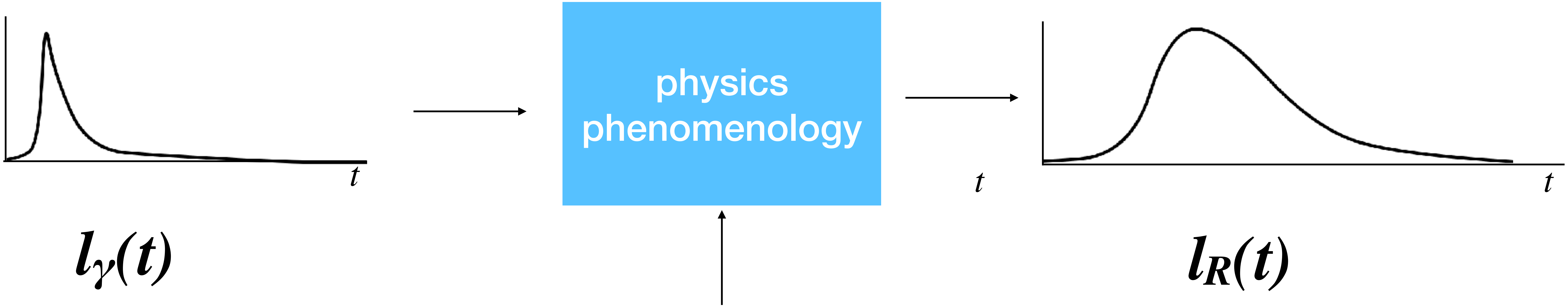
$t_d \sim 1/\beta_{exp}$

$\Delta t \sim t_{exp} + t_r$

Radio-γ response

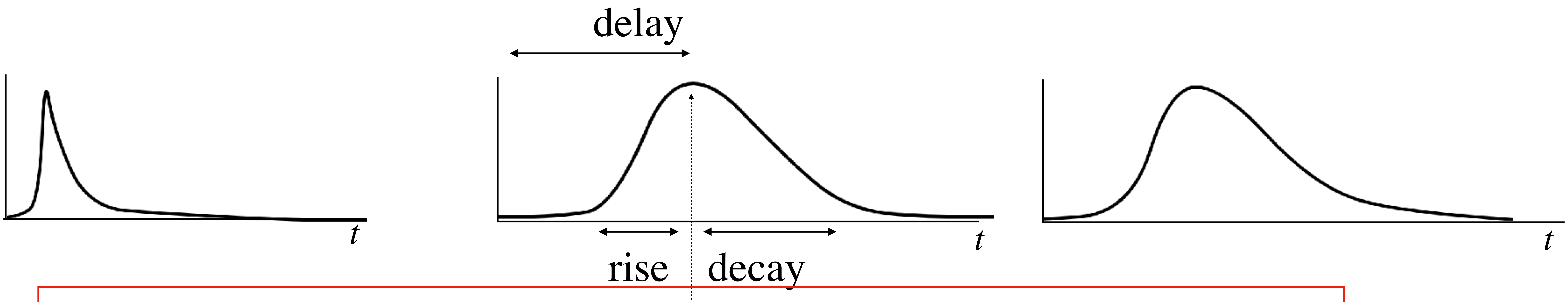


Radio-γ response



$$
\begin{aligned}
t^{\rm obs}_{\rm decay} &= \frac{R_0^{\rm obs}}{m_B \beta_{\rm exp} c}\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} \\
t^{\rm obs}_{\rm rise} &= \frac{1}{2} t^{\rm obs}_{\rm peak} = \begin{cases} \frac{1}{2}\frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right] & \text{if } \nu^{0,\rm obs}_{\rm SSA} > \nu^{*,\rm obs}_{\rm SSA} \\ 0 & \text{otherwise} \end{cases} \\
\Delta t^{\rm obs} &= t^{\rm obs}_{\rm exp} + t^{\rm obs}_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right].
\end{aligned}
$$

Radio-γ response



$$l_\gamma(t) \quad * \quad S(t, t_{rise}, t_{decay}, t_{delay}) \quad = \quad l_R(t)$$

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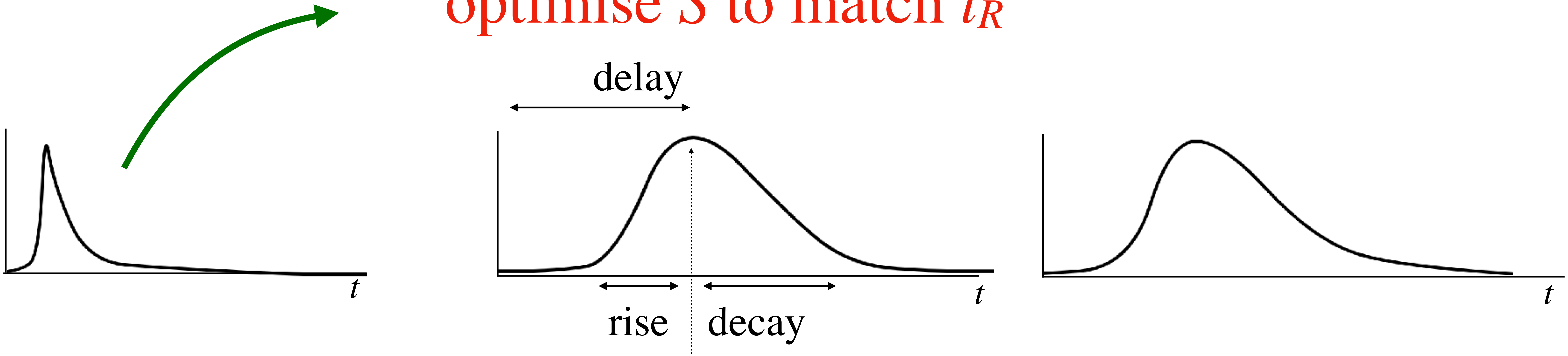
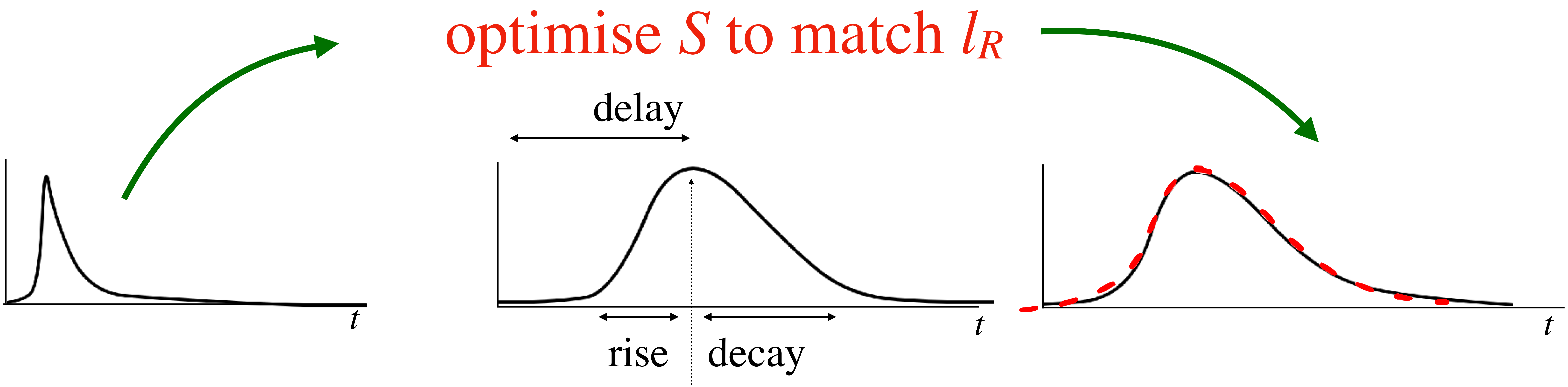
Radio-γ response

optimise S to match l_R



$$l_\gamma(t) \; * \; S(t, t_{rise}, t_{decay}, t_{delay}) \; = \; l_R(t)$$

Radio-γ response



$$l_\gamma(t) \quad * \quad S(t, t_{rise}, t_{decay}, t_{delay}) \quad = \quad l_R(t)$$

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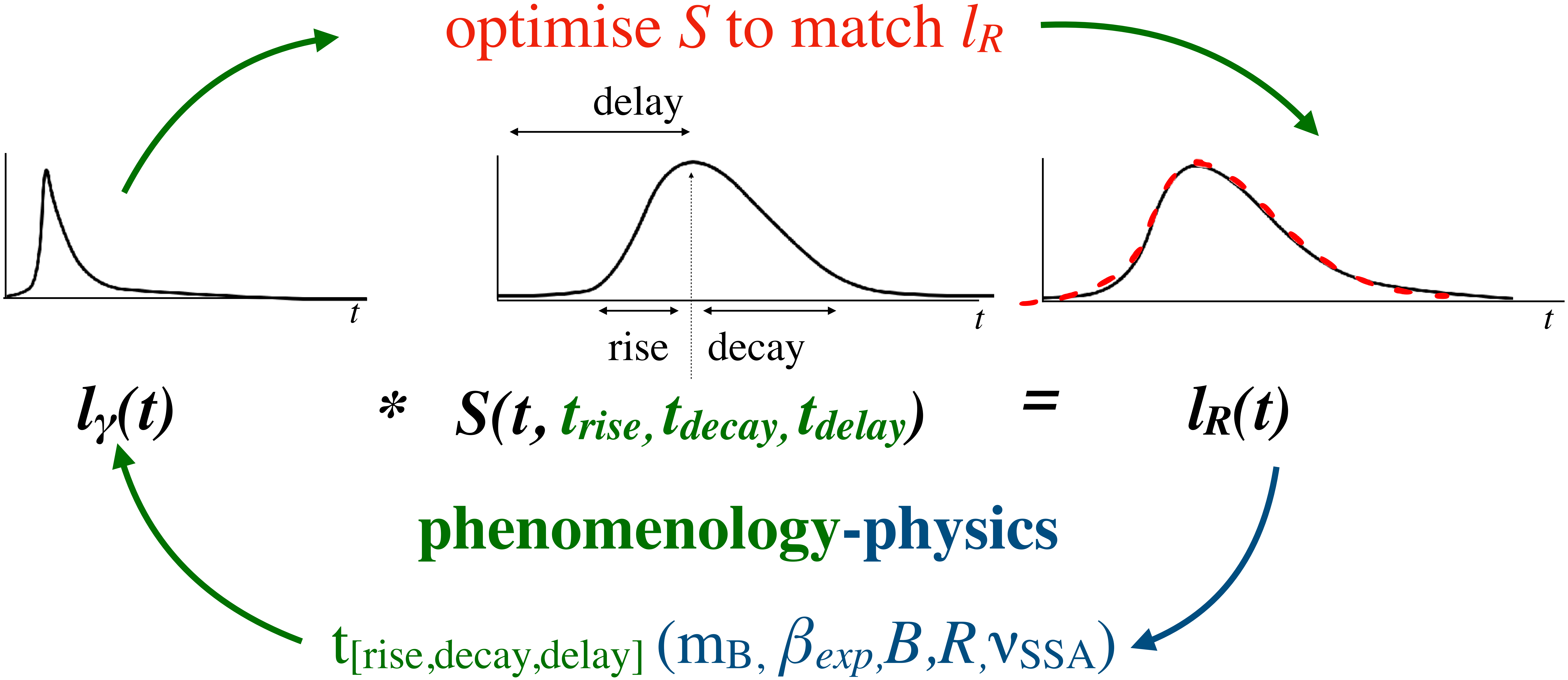
Radio-γ response



Radio-γ response

exp-logistic

$$S(t) = A\,\frac{\exp^{-(t-\Delta_t)/t^{*}_{\rm decay}}}{1+\exp^{-(t-\Delta_t)/t_{\rm rise}}}$$

$t^{\rm obs}_{\rm decay}$

$t^{\rm obs}_{\rm rise}$

$\Delta t^{\rm obs}_{\nu^{0,\rm obs}_{\rm SSA} \to \nu^{*,\rm obs}_{\rm SSA}}$

The proposal is a simplified and physically motivated (within the context of expansion) version of Turler+ 1999, Sliusar+ 2019

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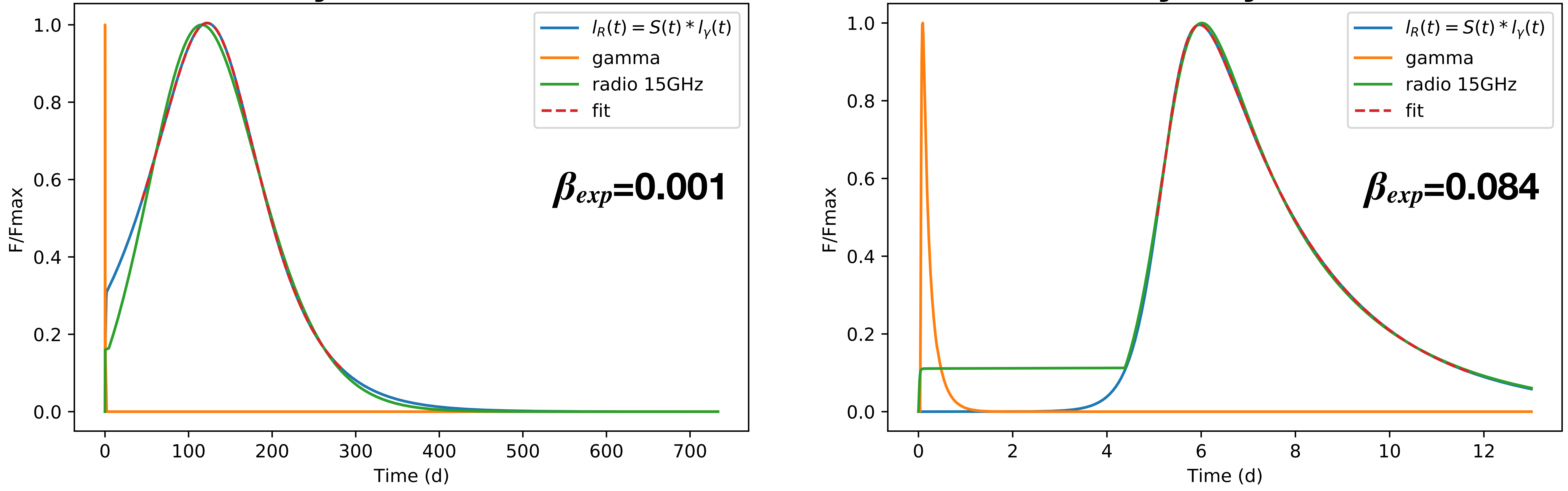
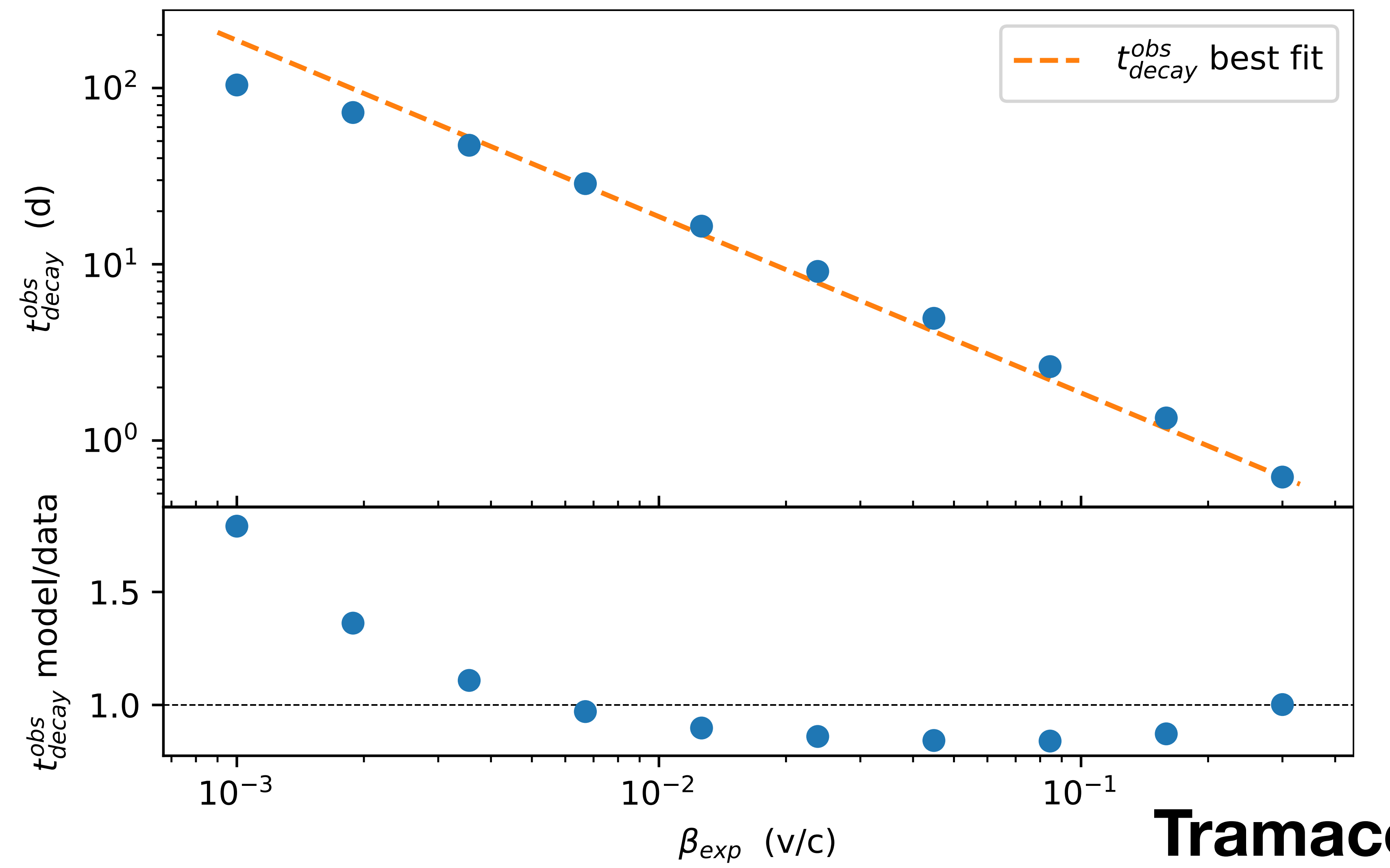
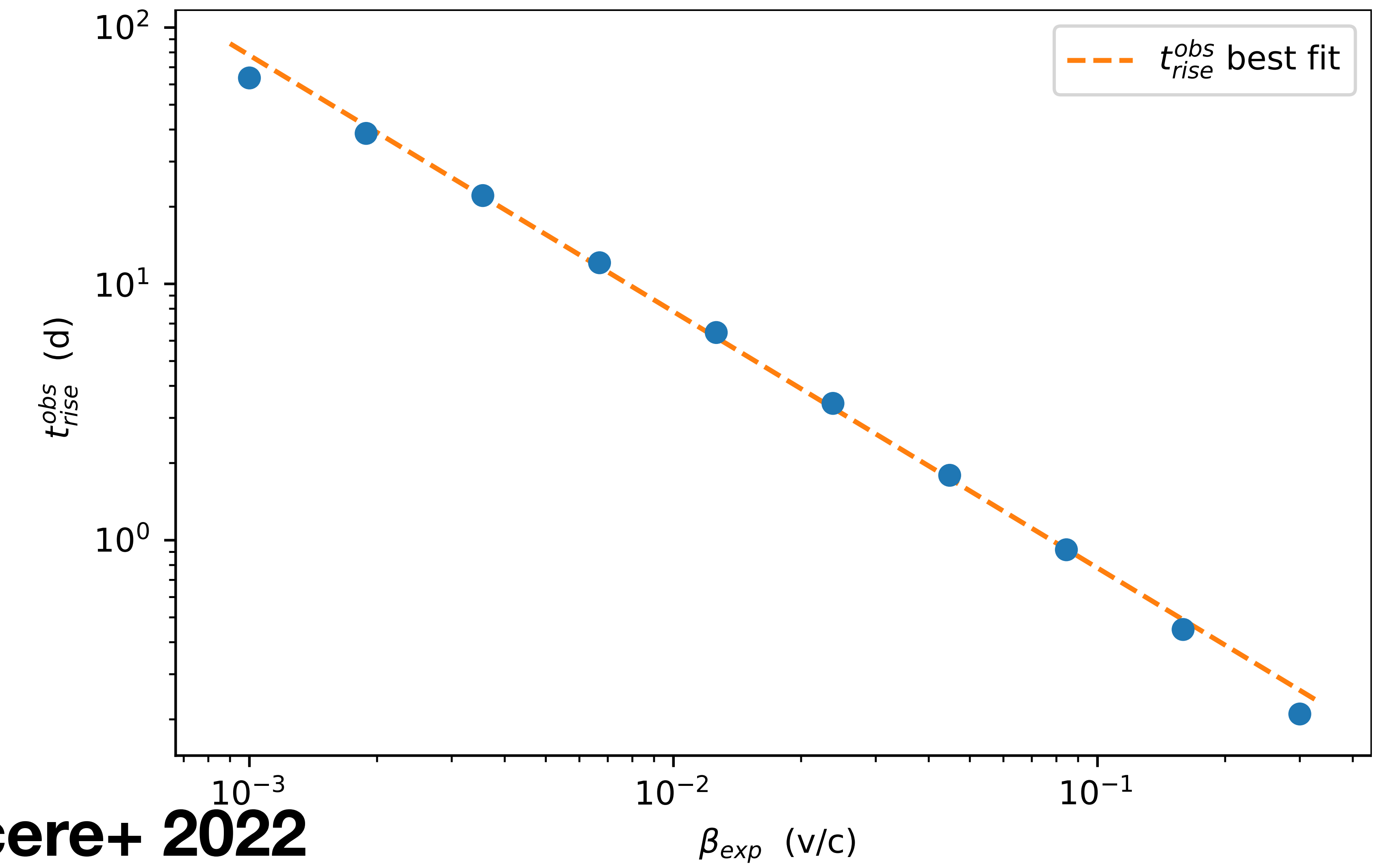
delay: months **delay: days/week**



Best fit for the radio-γ response, at 15 GHz, for $\beta_{\rm exp} = 0.001$ (*left panel*), and at 15 GHz for $\beta_{\rm exp} = 0.084$ (*right panel*), and $t_{\rm exp} = 1 \times 10^7$ s. The lightcurves are in the observer frame. The red dashed line represents the actual fit interval, the orange line the simulate $\gamma - ray$ lightcurve, the green one the simulated radio lightcurve, and the blue one is the best-fit of the radio lightcurve obtained from the convolution of the $\gamma - ray$ lightcurve with the best fit response

trends vs β_{exp}





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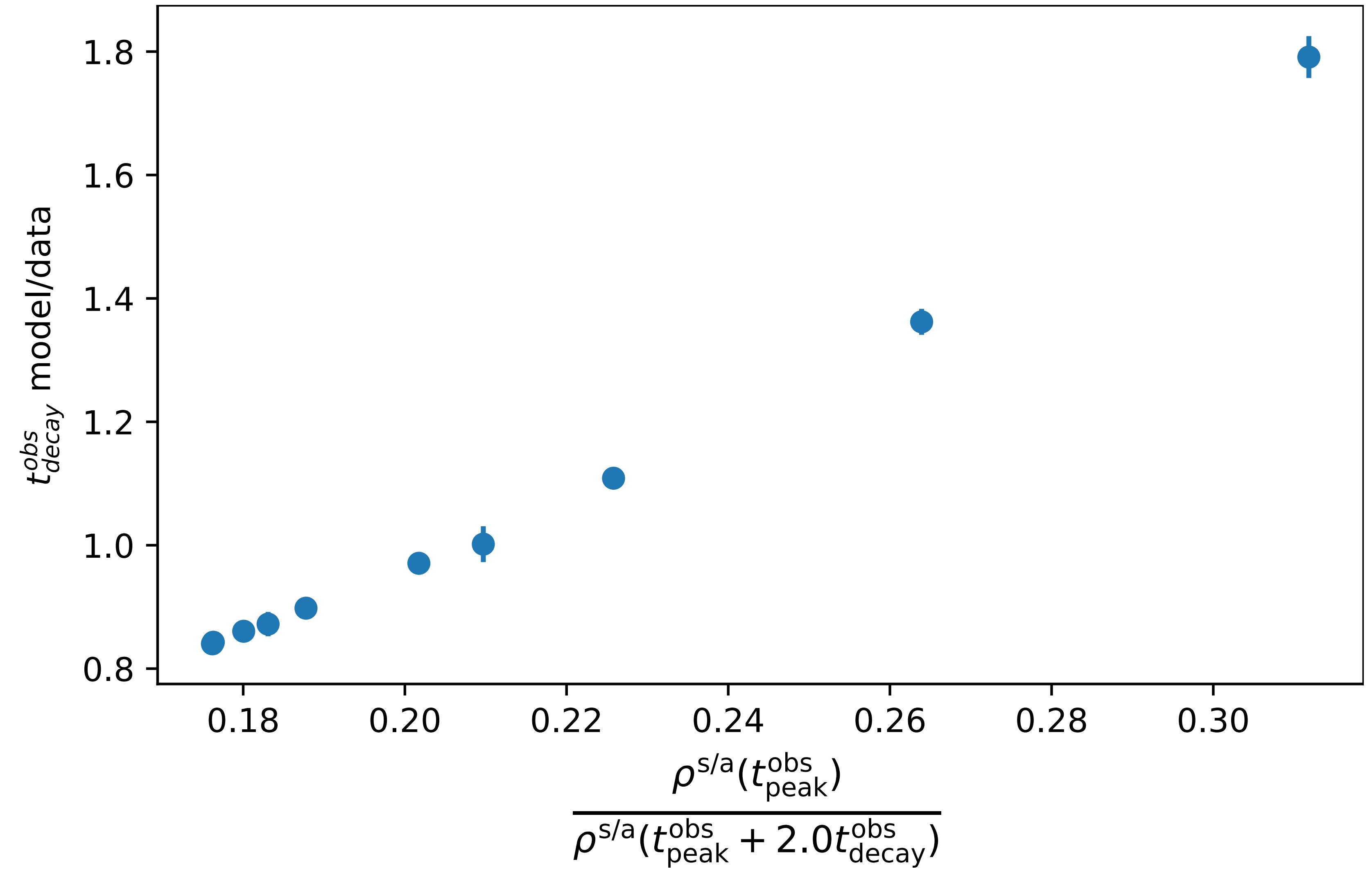
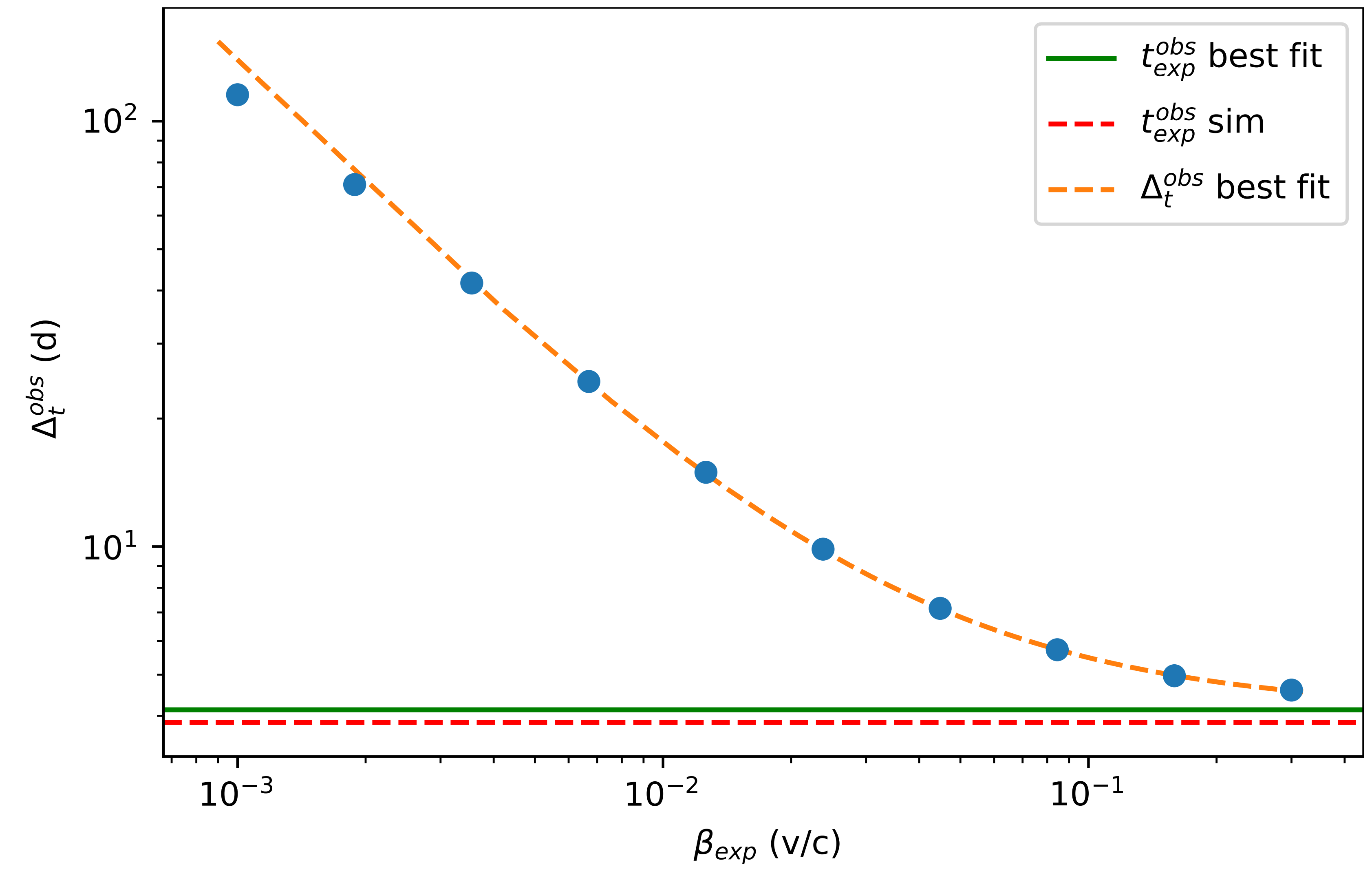
β_{exp}=[0.001-0.3]





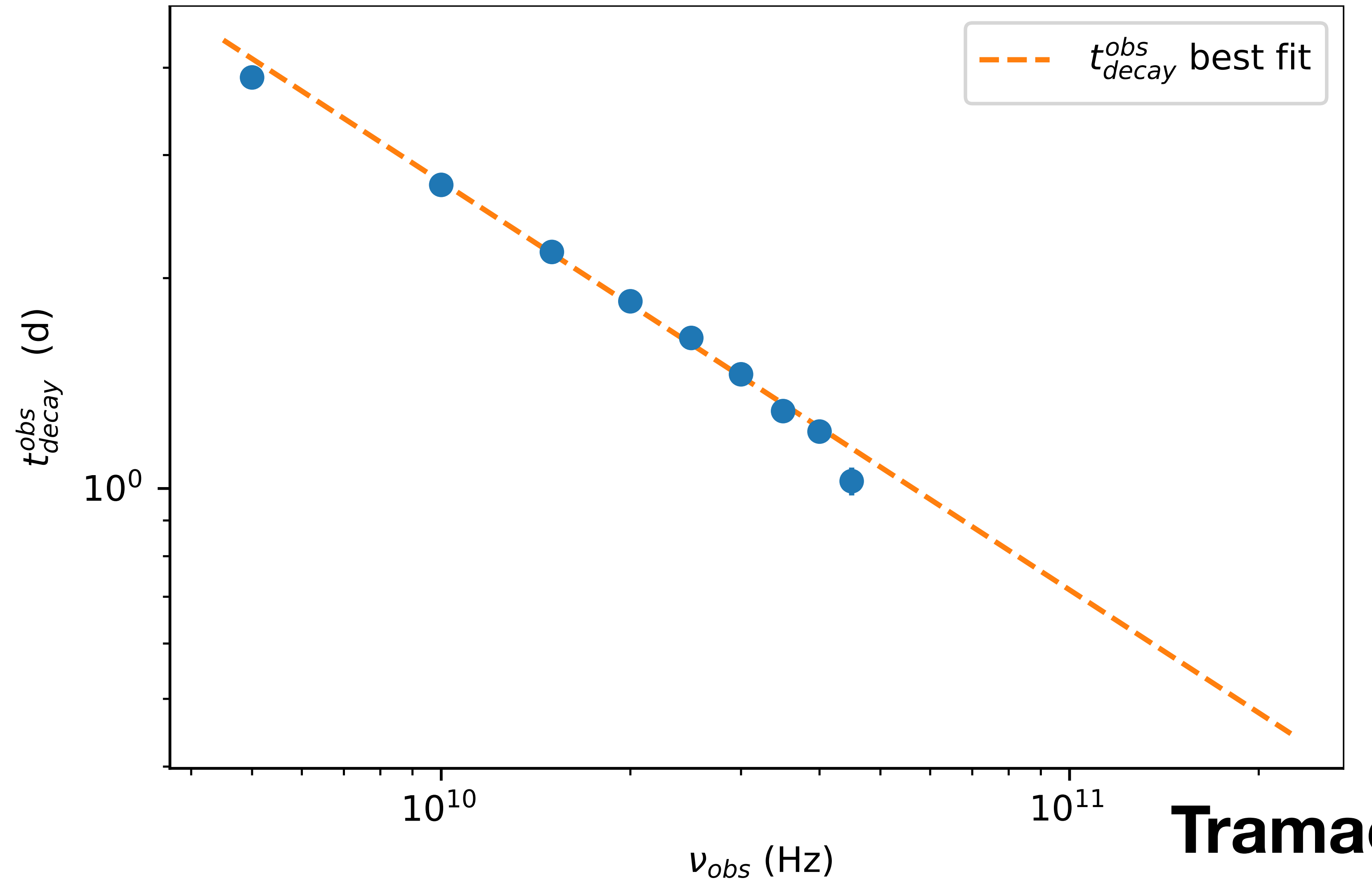
$$t^{\rm obs}_{\rm decay} = \frac{R_0^{\rm obs}}{m_B \beta_{\rm exp} c}\Big(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\Big)^{\phi}$$

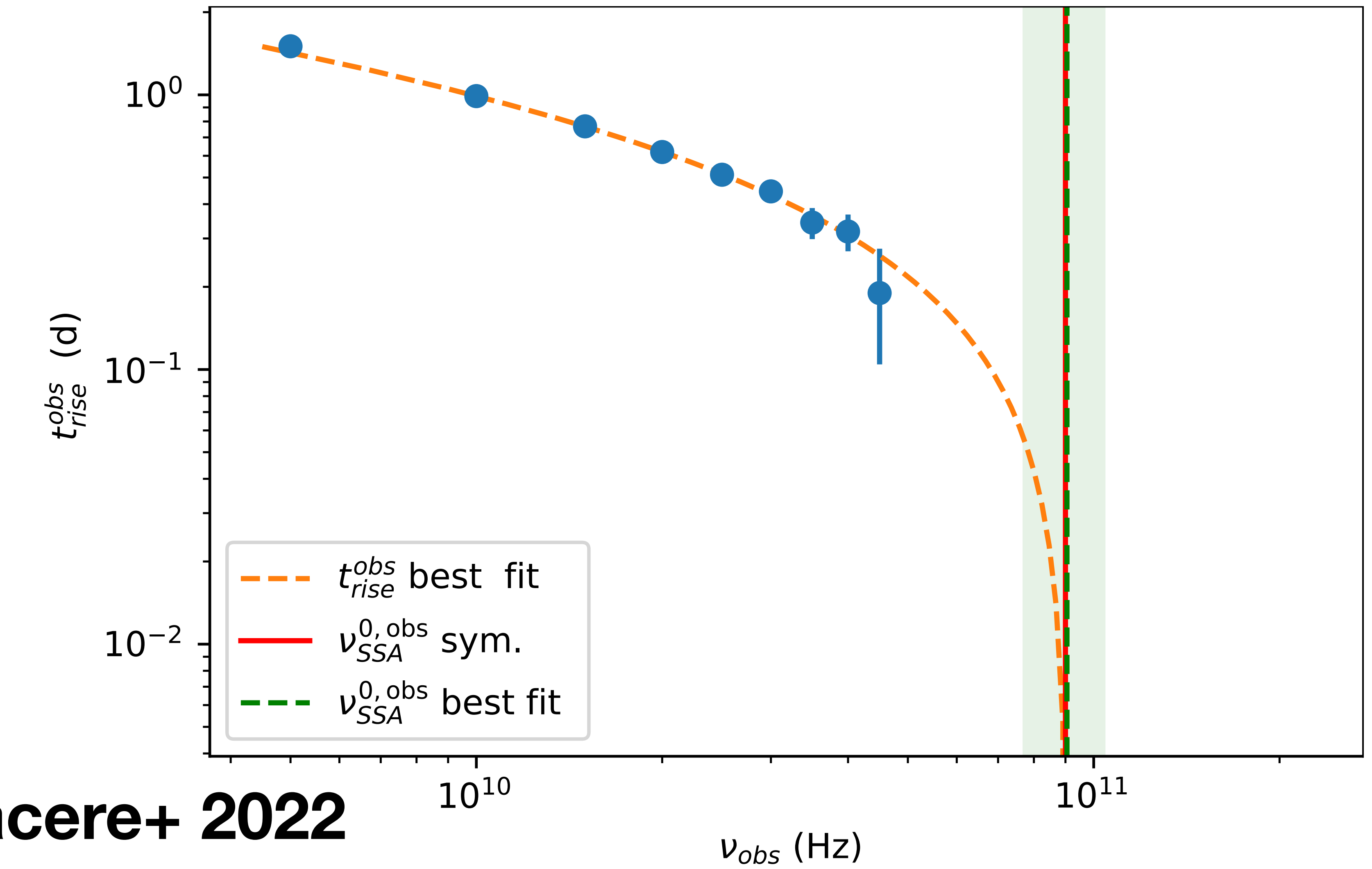
$$t^{\rm obs}_{\rm rise} = \frac{1}{2} t^{\rm obs}_{\rm peak} = \begin{cases} \frac{1}{2}\frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\Big[\Big(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\Big)^{\phi} - 1\Big] & \text{if } \nu^{0,\rm obs}_{\rm SSA} > \nu^{*,\rm obs}_{\rm SSA} \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta t^{\rm obs} = t^{\rm obs}_{\rm exp} + t^{\rm obs}_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\Big[\Big(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\Big)^{\phi} - 1\Big].$$

		actual values		values from β trend best fit		
		blob	obs	$t^{\rm obs}_{\rm rise}$	$t^{\rm obs}_{\rm decay}$	$\Delta t^{\rm obs}$
R_0	cm	5×10^{15}	1.66×10^{14}	$(1.9\pm0.5)\times10^{14}$	$(1.7\pm0.1)\times10^{14}$	$(1.8\pm0.1)\times10^{14}$
$\nu^0_{\rm SSA}$	GHz	3	90	110 ± 40	100 ± 10	100 ± 5
$t_{\rm exp}$	s	1×10^7	3.3×10^5			$(3.57\pm0.01)\times10^5$
m_B		1			0.96 ± 0.06	
ϕ				0.6 ± 0.1	0.52 ± 0.04	0.54 ± 0.02
p		1.46		1.6 ± 0.3	1.5 ± 0.01	1.57 ± 0.05

trends vs ν_{obs}





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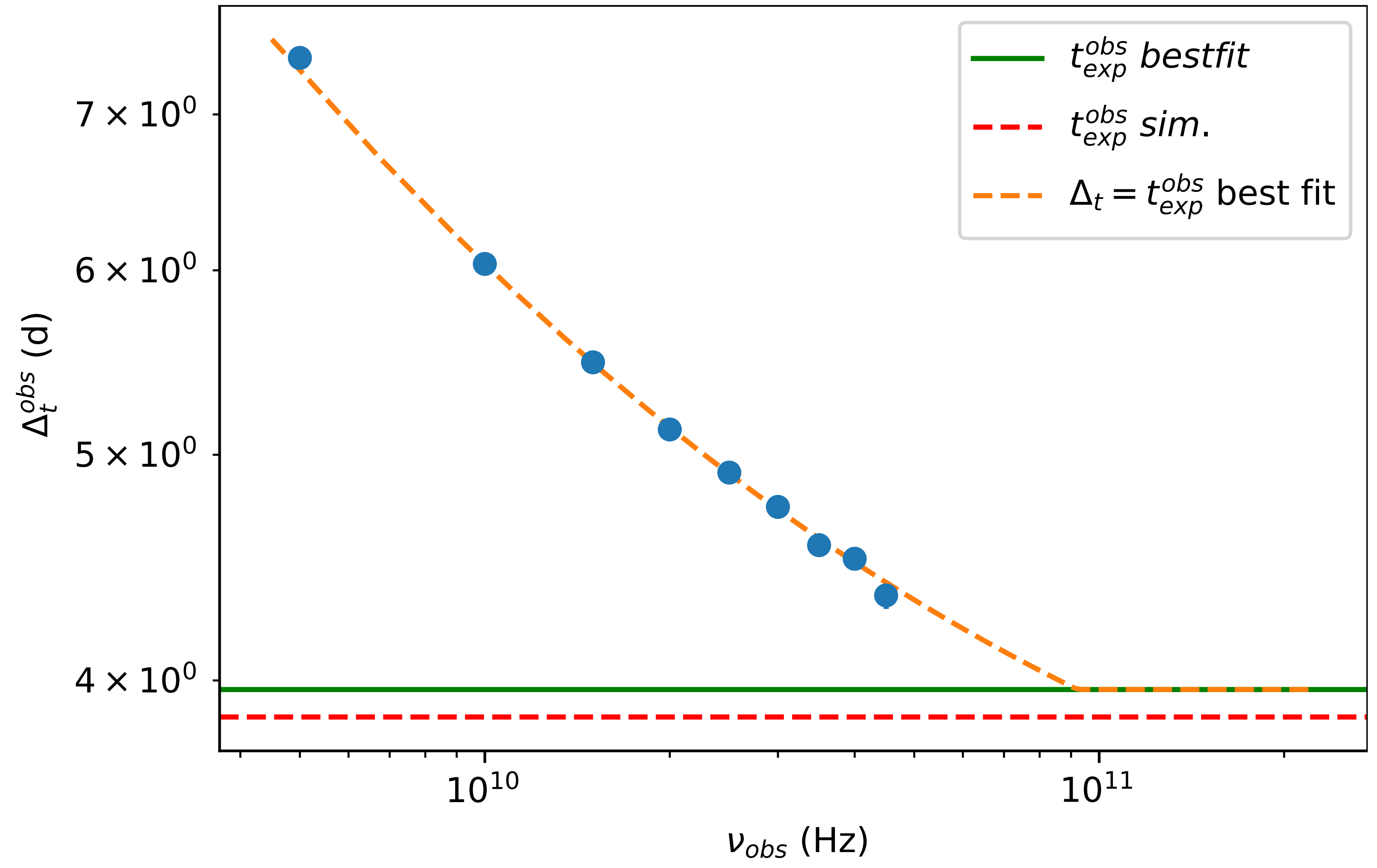

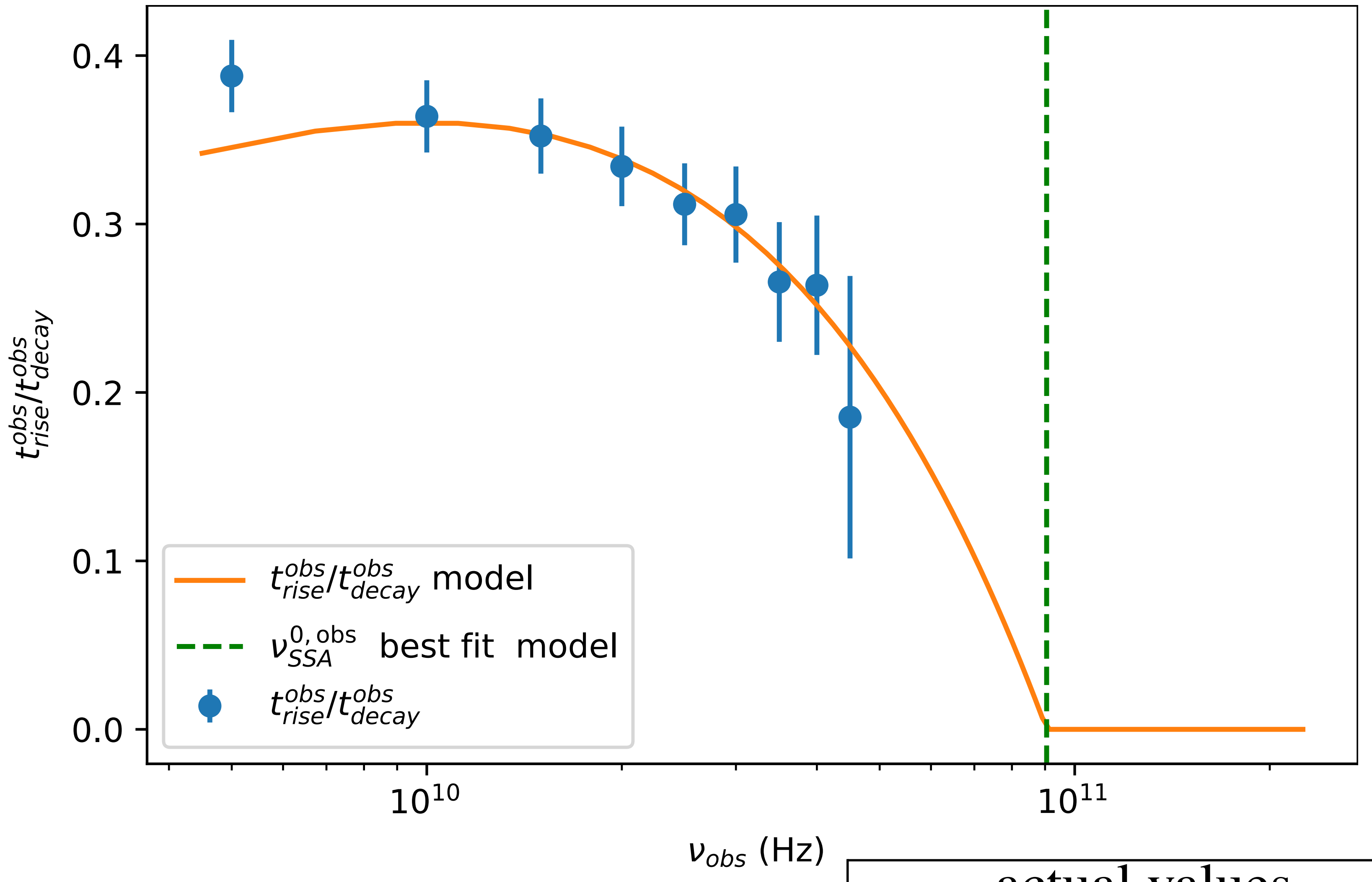

β_{exp}=[0.1]

$$t^{\rm obs}_{\rm decay} = \frac{R^{\rm obs}_0}{m_B \beta_{\rm exp} c}\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi}$$

$$t^{\rm obs}_{\rm rise} = \frac{1}{2} t^{\rm obs}_{\rm peak} = \begin{cases} \frac{1}{2}\frac{R^{\rm obs}_0}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right] & \text{if } \nu^{0,\rm obs}_{\rm SSA} > \nu^{*,\rm obs}_{\rm SSA} \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta t^{\rm obs} = t^{\rm obs}_{\rm exp} + t^{\rm obs}_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{R^{\rm obs}_0}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right].$$

		actual values		values from ν trend best fit		
		blob	obs	$t^{\rm obs}_{\rm rise}$	$t^{\rm obs}_{\rm decay}$	$\Delta t^{\rm obs}$
R_0	cm	5×10^{15}	1.66×10^{14}	$(2.4 \pm 1.0) \times 10^{14}$	$(1.7 \pm 0.2) \times 10^{14}$	$(1.6 \pm 0.1) \times 10^{14}$
$\nu^0_{\rm SSA}$	GHz	3	90	90 ± 10	100 ± 20	90 ± 10
$t_{\rm exp}$	s	1×10^7	3.3×10^5			$(3.4 \pm 0.1) \times 10^5$
m_B		1			1.0 ± 0.1	
$\beta_{\rm exp}$	c	0.1		0.03 ± 0.01	0.09 ± 0.01	0.06 ± 0.01
ϕ				0.24 ± 0.07	0.58 ± 0.02	0.50 ± 0.02
p		1.46		0.6 ± 0.2	1.7 ± 0.1	1.4 ± 0.1

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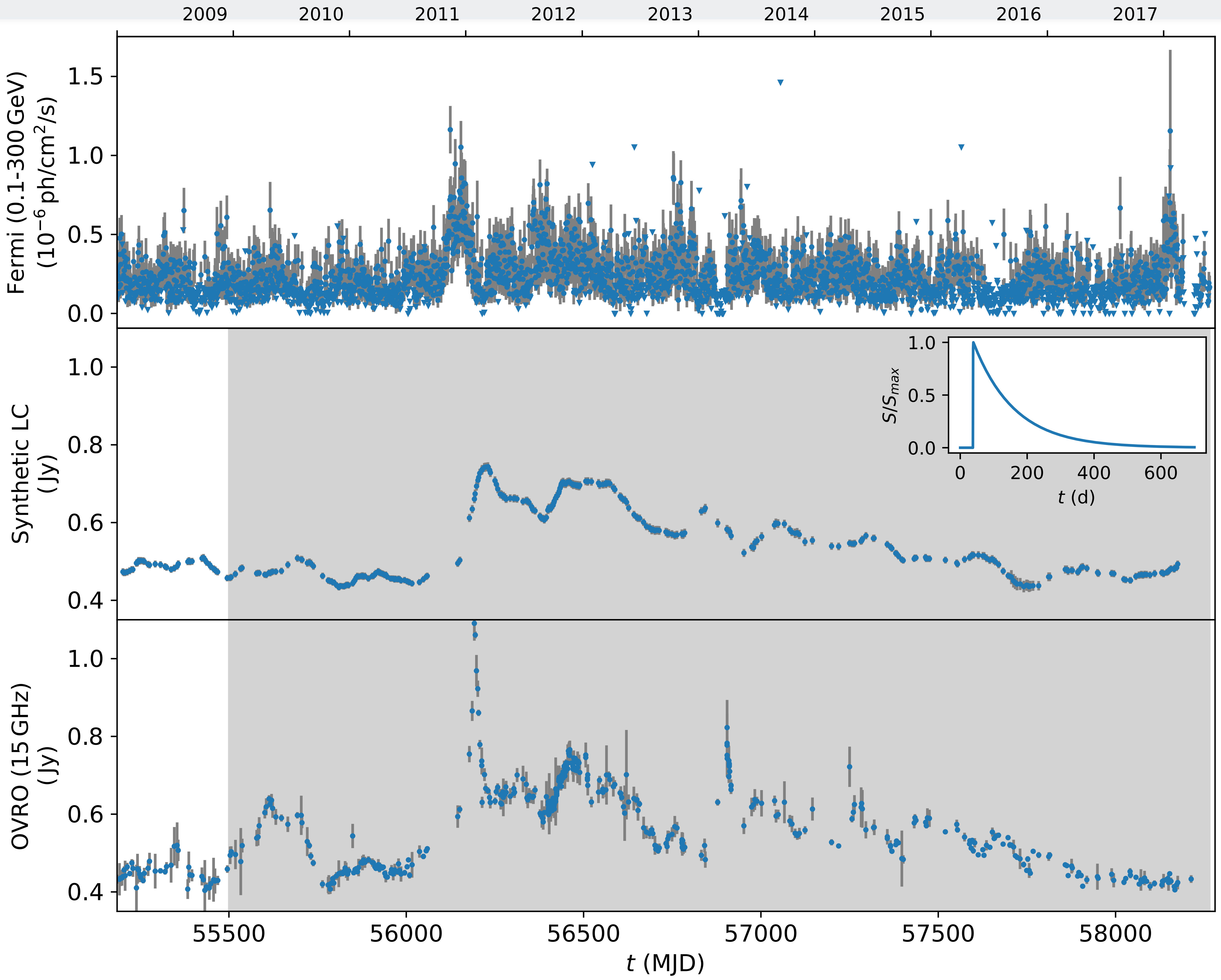
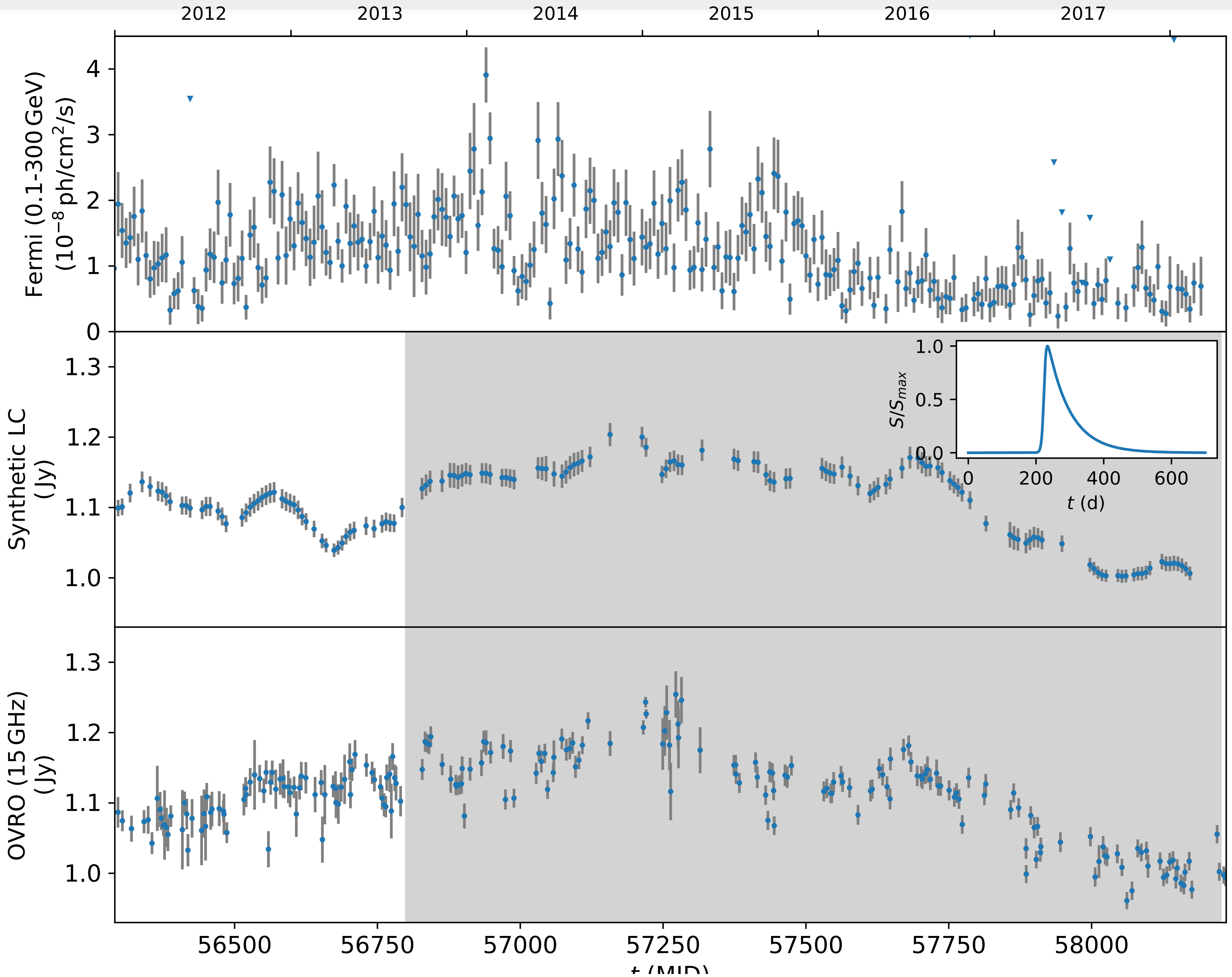
comparison with observed data





Parameter	Value
A	$12.5^{+0.5}_{-0.013} \times 10^3$ Jy cm^2 s/ph
t_{rise}	$\lesssim 1$ day
t_{decay}	$126.5^{+1.3}_{-1.3}$ days
Δt	$37.58^{+0.13}_{-0.13}$ days
$F_{background}$	$0.18^{+0.008}_{-0.0004}$ Jy

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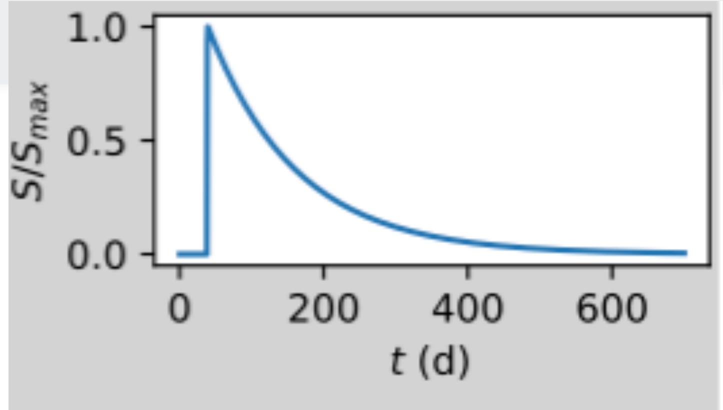
$$S(t) = A \frac{\exp^{-(t-\Delta_t)/t^*_{\rm decay}}}{1 + \exp^{-(t-\Delta_t)/t_{\rm rise}}}$$

Parameter	Value
A	$166^{+5}_{-3} \times 10^4$ Jy cm^2 s/ph
t_{rise}	12^{+4}_{-4} days
t_{decay}	$73^{+3.6}_{-3.6}$ days
Δt	234^{+10}_{-10} days
$F_{background}$	$0.915^{+0.004}_{-0.004}$ Jy

MCMC sampling

$$\mathcal{L} = \mathcal{L}_{\rm rise} + \mathcal{L}_{\rm decay} + \mathcal{L}_{\rm delay}$$

$$\mathcal{L} \propto \sum_{i=[1,2,3]} -\frac{1}{2}\frac{(x_i - \mu_i)^2}{2\sigma_i^2} - \frac{1}{2}\ln(\sigma_i^2)$$



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conv analysis best fit values

$$\Delta_t,\ t^{\rm obs}_{\rm rise},\qquad t^{\rm obs}_{\rm decay}$$

Model

$$t^{\rm obs}_{\rm decay} = \frac{R_0^{\rm obs}}{m_B \beta_{\rm exp} c}\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi}$$

$$t^{\rm obs}_{\rm rise} = \frac{1}{2} t^{\rm obs}_{\rm peak} = \begin{cases} \frac{1}{2}\frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right] & \text{if } \nu^{0,\rm obs}_{\rm SSA} > \nu^{*,\rm obs}_{\rm SSA} \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta t^{\rm obs} = t^{\rm obs}_{\rm exp} + t^{\rm obs}_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{R_0^{\rm obs}}{\beta_{\rm exp} c}\left[\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi} - 1\right].$$

flat priors

$$m_B \in [1, 2]$$

$$\nu^{0,\rm obs}_{\rm SSA} \in [10, 10^4]\ \text{GHz}$$

$$\phi \in [1/3, 1]$$

$$t^{\rm var}_{\gamma} \in [0.25, 14]\ \text{days}$$

$$R^0_{\rm obs} = R_0 \frac{1+z}{\delta} \qquad R_0^{\rm obs} \in [6.5 \times 10^{13}, 3.6 \times 10^{17}]\ \text{cm}$$

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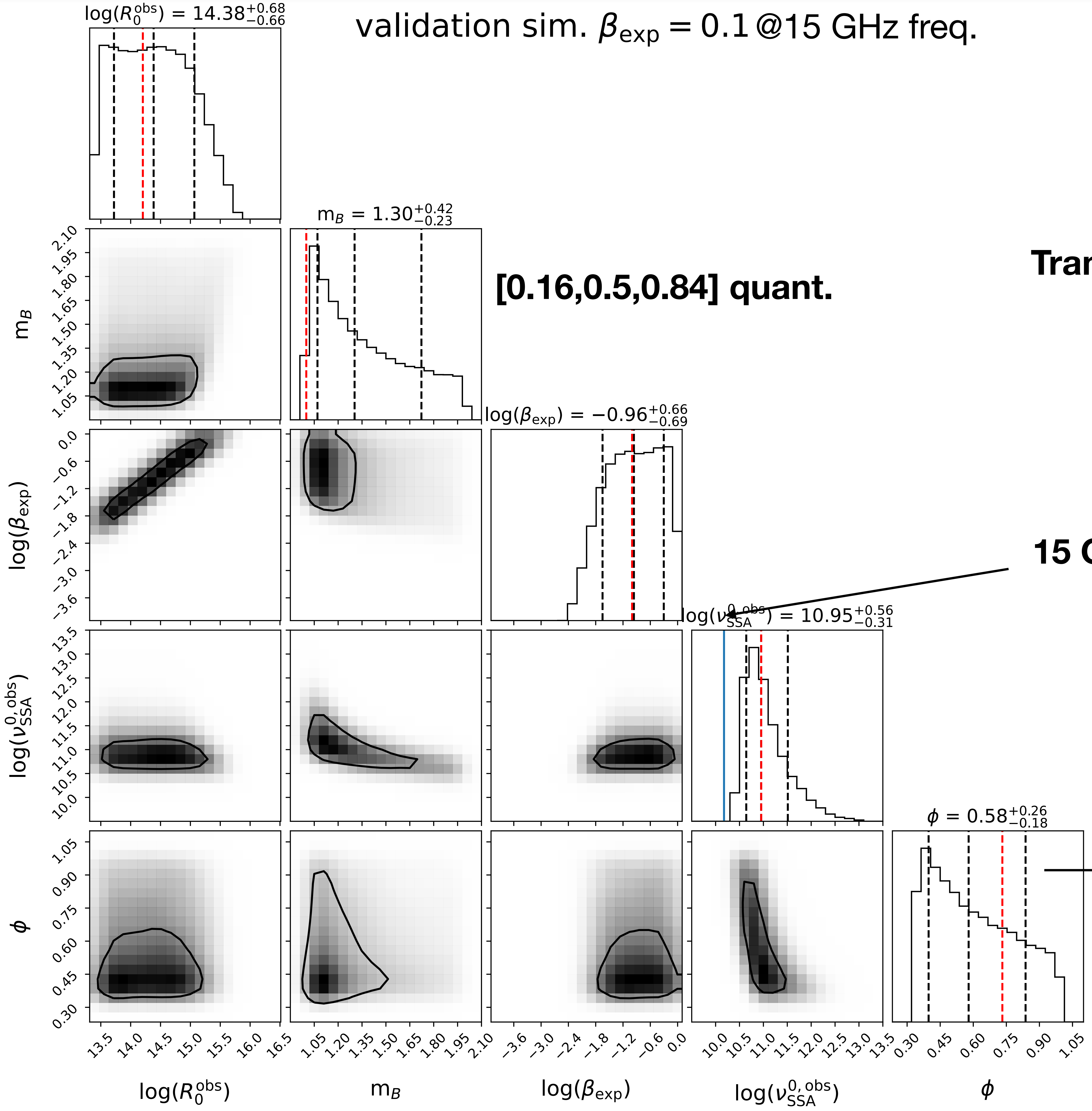
MCMC validation with simulations

validation sim. $\beta_{\rm exp} = 0.1$ @15 GHz freq.



red dashed line simualtion values

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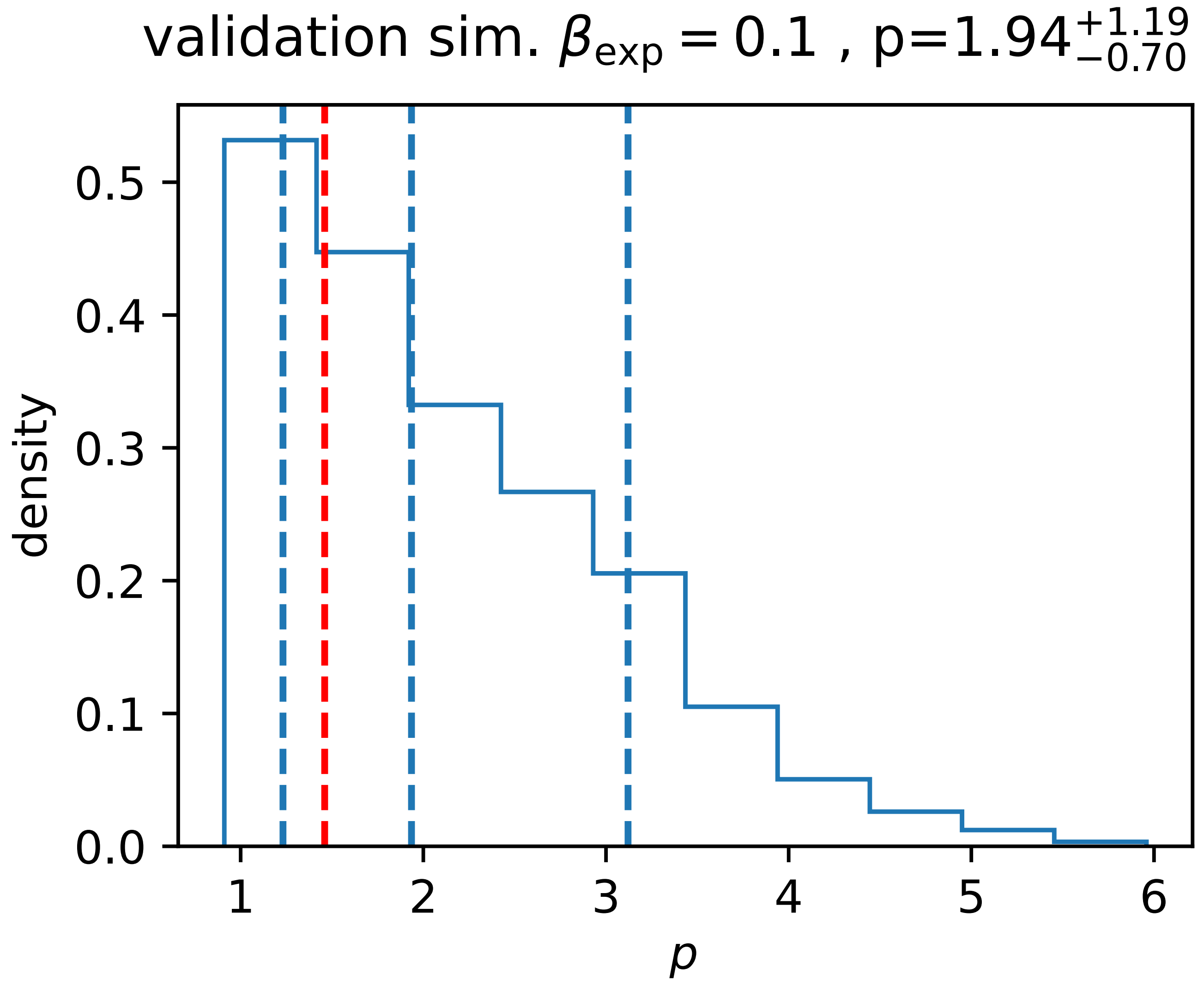
[0.16,0.5,0.84] quant.

15 GHz freq.



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MCMC validation with real data

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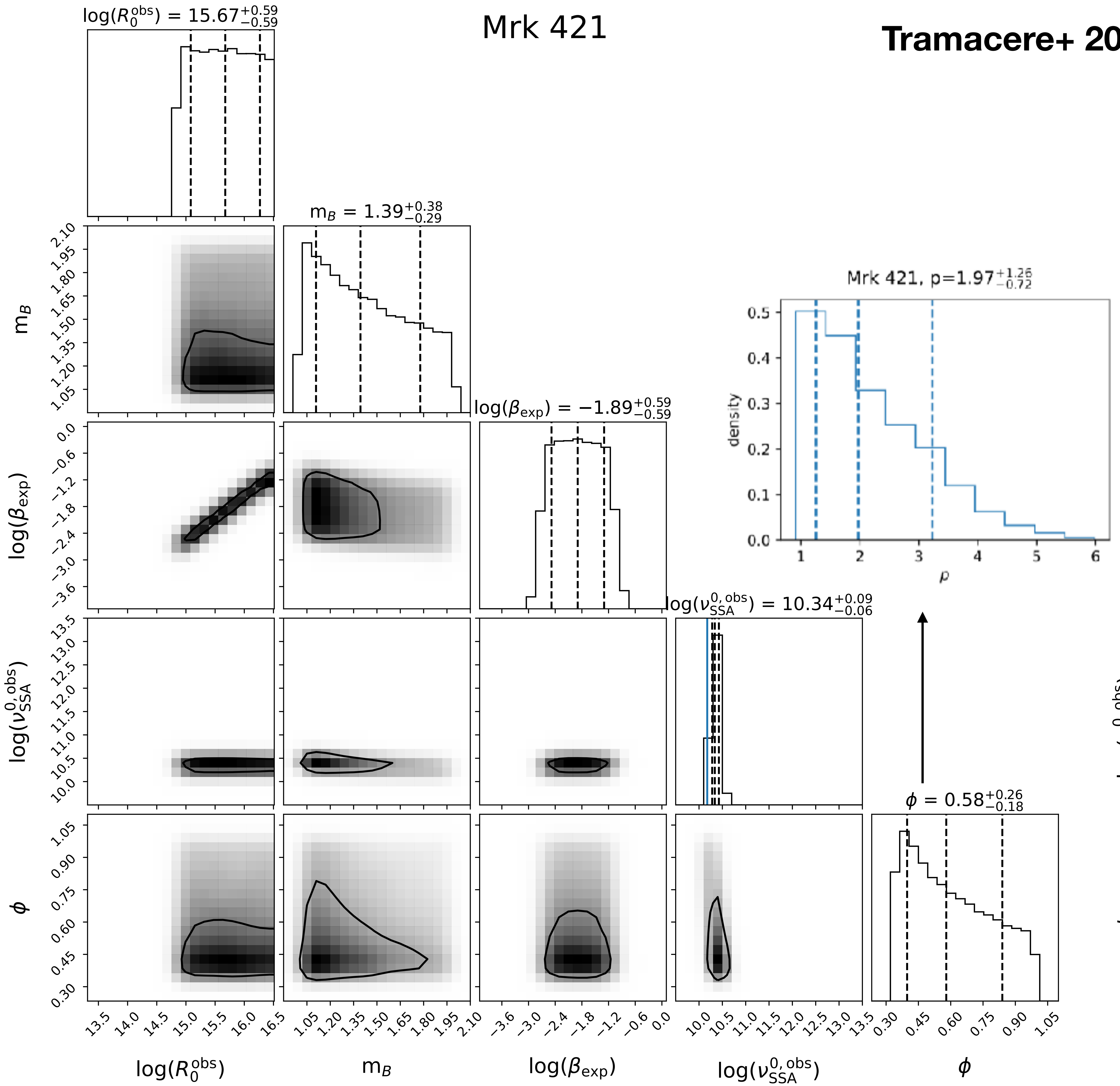

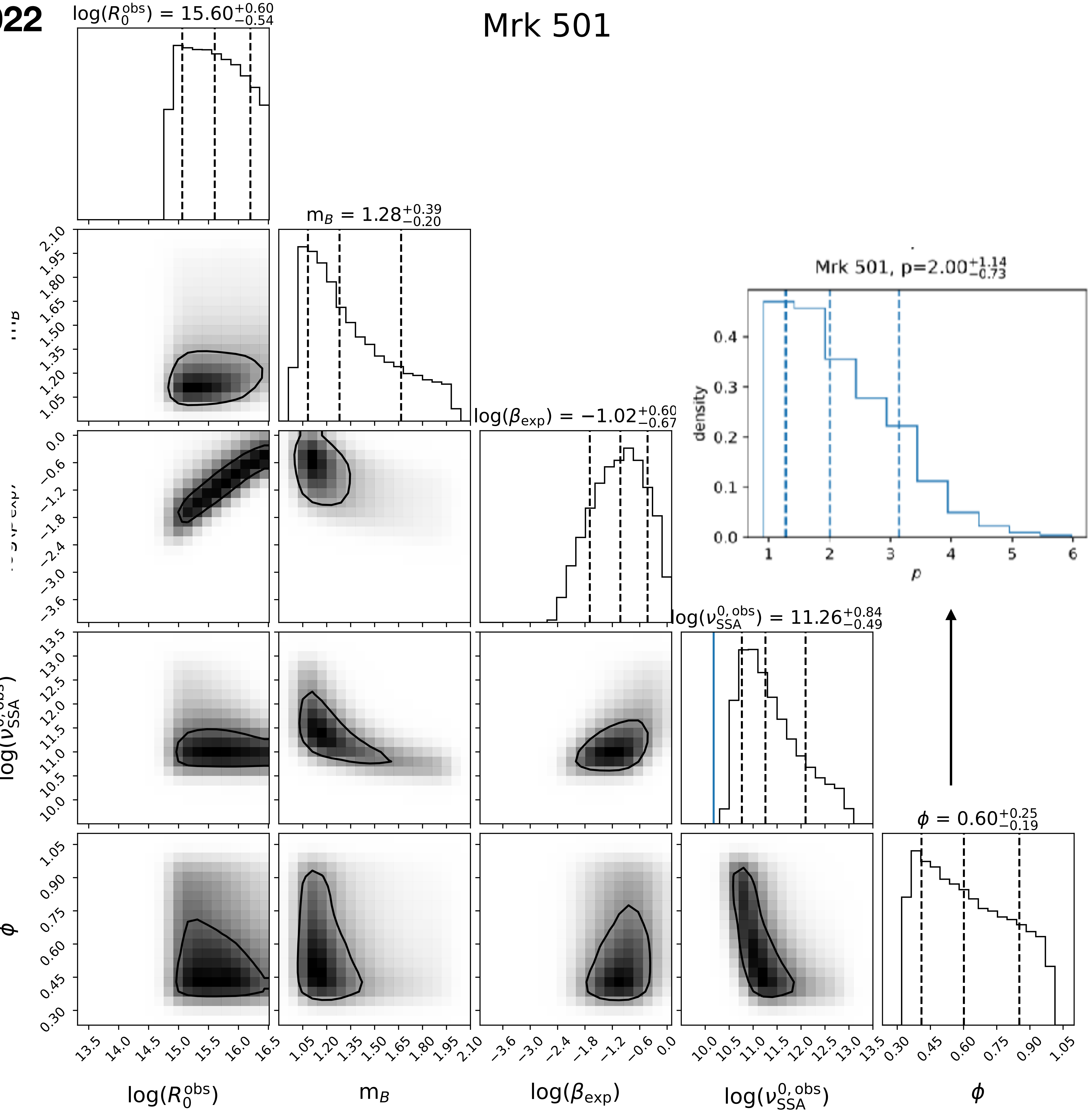

conclusions

- Radio-gamma delays on weeks to year timescales can be self consistently reproduced by adiabatic blob expansion

- We derived phenomenological relations, validated via accurate numerical simulations, and plugged to a response function, providing a direct link between the radio delay timescales and physics of the jet

- Implication on structure of magnetic fields, jet expansion, and MW connection open an interesting path to a deeper understanding of the how the engine of the jets work, and how jets evolve on larger scales, providing connection between micro and macro physics in relativistic jets

- **Analysis fully reproducible with JetSeT and convolution tool:**

https://github.com/andreatramacere/adiabatic_exp_radio_gamma_delay

adiabatic_exp_radio_gamma_delay

Response

$$S(t) = A\frac{\exp\frac{-(t-\Delta)}{t_f}}{1+\exp\frac{-(t-\Delta)}{t_u}}$$

Analytical

$$\longrightarrow \quad \Delta t = \Delta - t_u \ln\left(\frac{t_u}{t_f - t_u}\right)$$

Numerical

$$S(t) = \frac{A}{2} \quad \longrightarrow \quad t_{\mathrm{rise}} = t_u\left(0.54 + 1.34\left(\frac{t_f}{t_u}\right)^{1/4}\right)$$

$$S(t) = \frac{A}{e} \quad \longrightarrow \quad t_{\mathrm{decay}} = t_f\left(1.00 + 1.33\left(\frac{t_f}{t_u}\right)^{-1.11}\right)$$

adb./rad. cooling competition